

Higgs Pairs and the Higgs Potential, Today and at the HL-LHC

Collider Physics in the Northwest

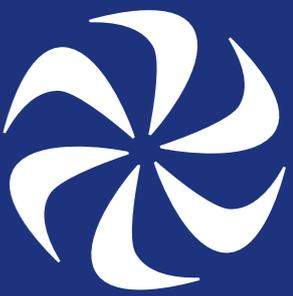
Maximilian Swiatlowski

TRIUMF

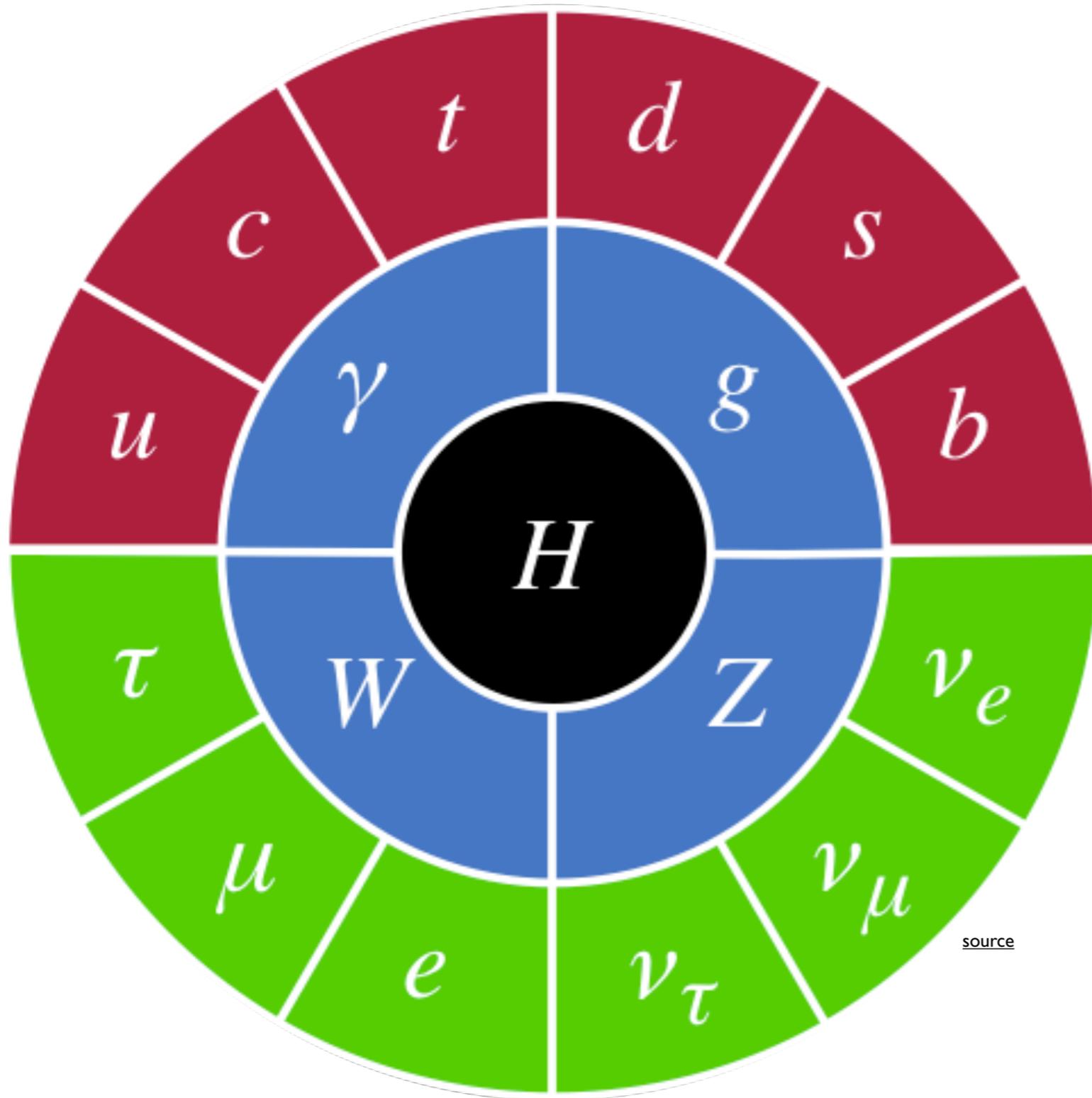
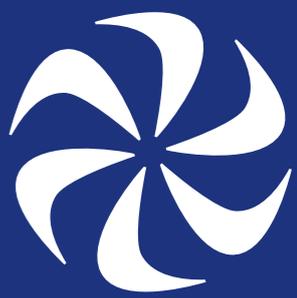


The Higgs Potential and Higgs Pairs

The Higgs in the SM

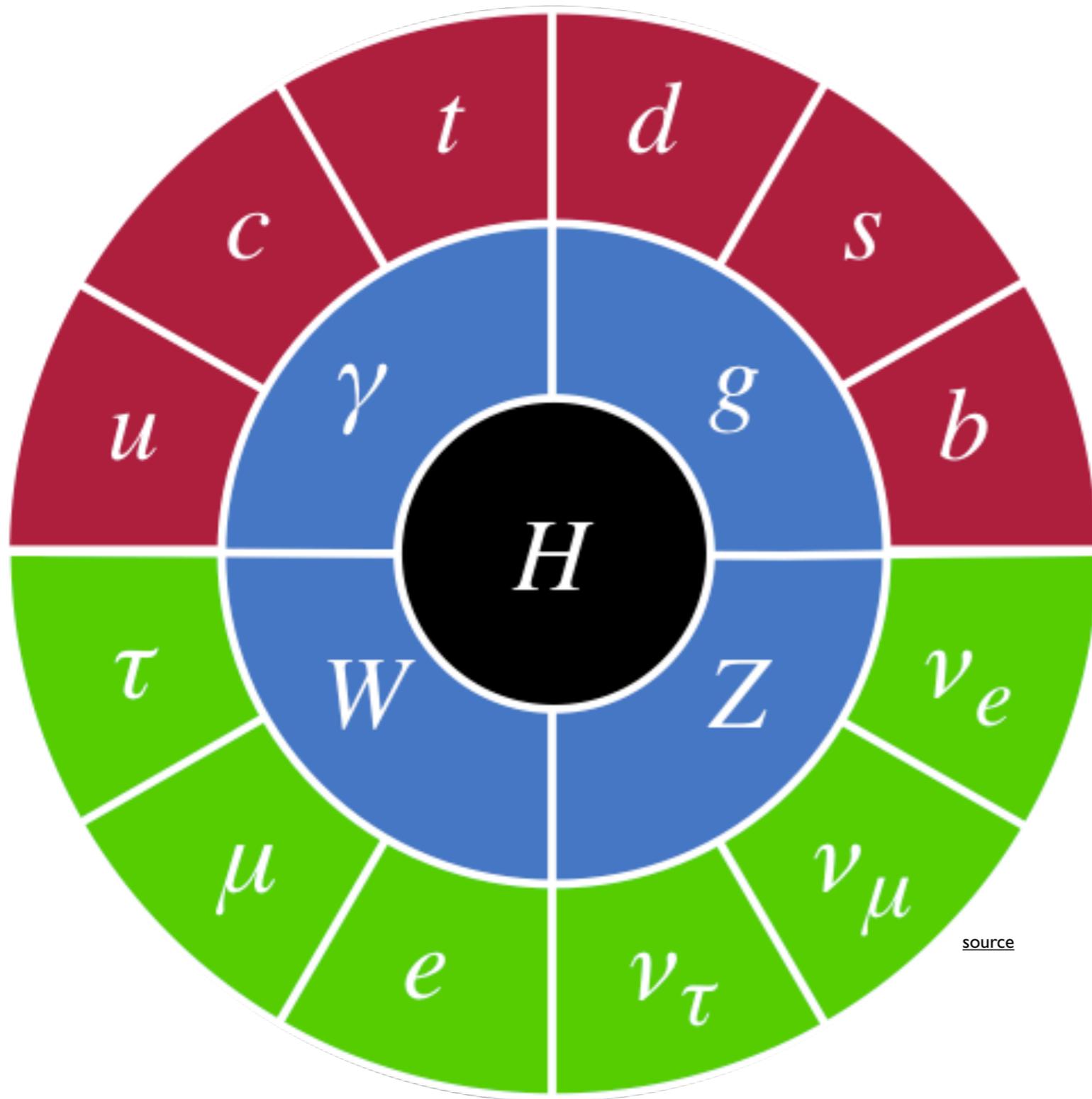
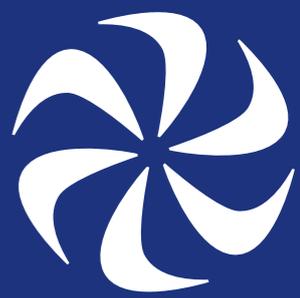


The Higgs in the SM



source

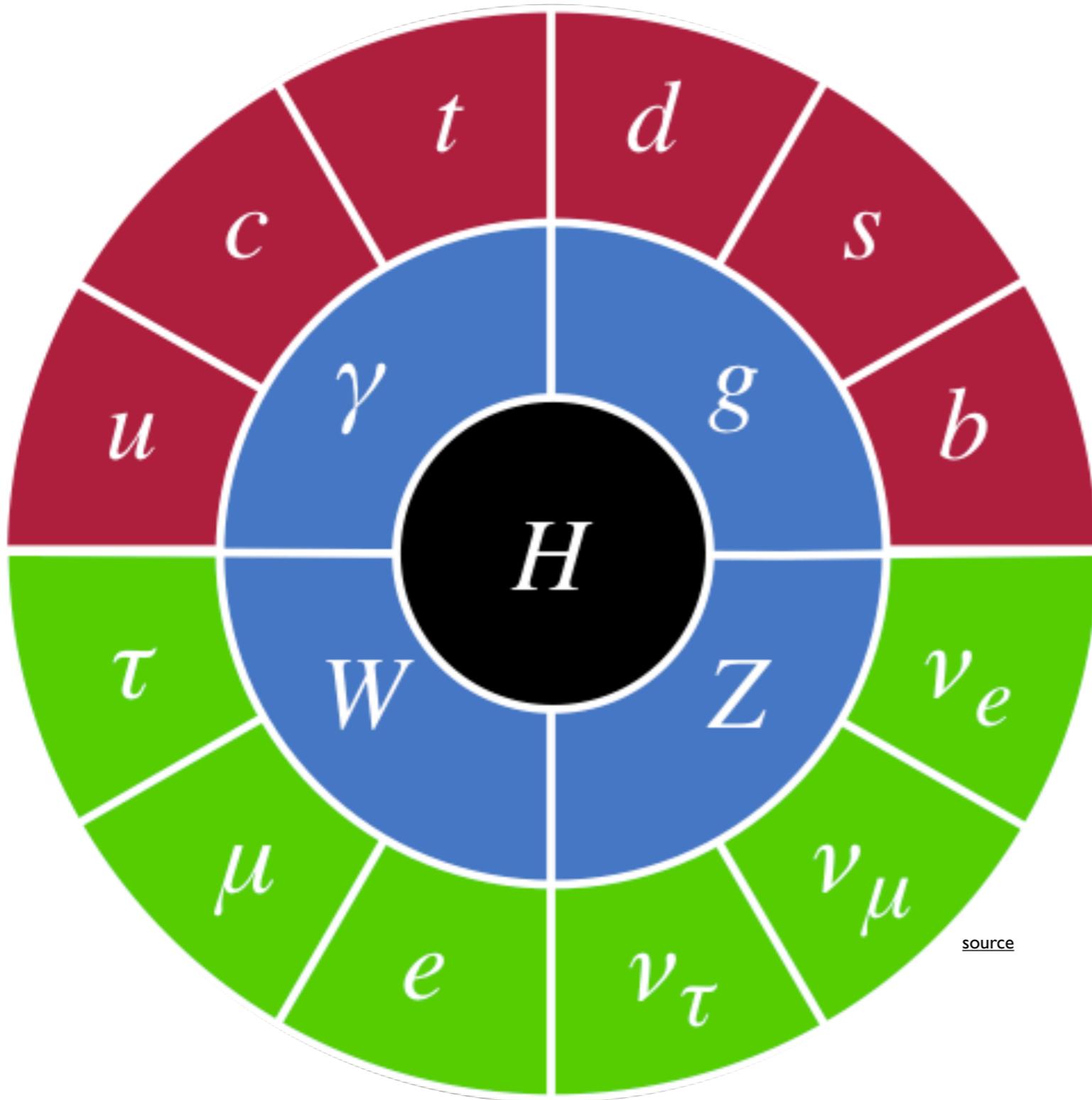
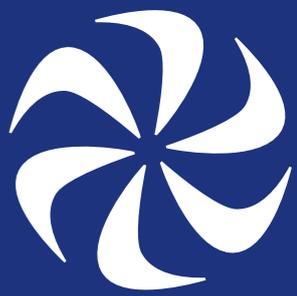
The Higgs in the SM



- The Higgs field is crucial to the SM as we know it

source

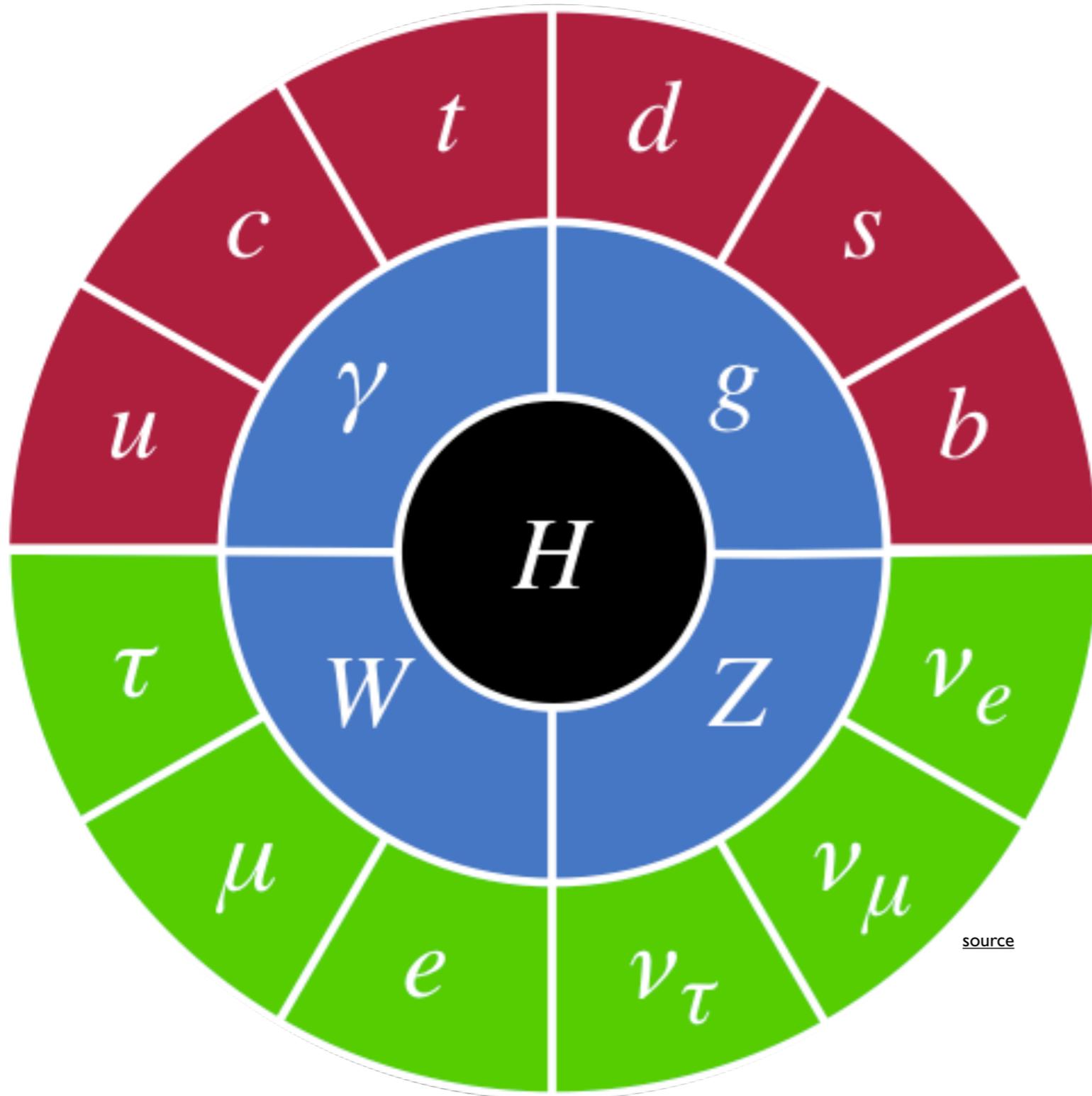
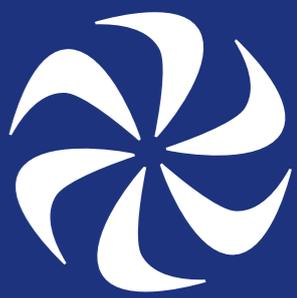
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- The Higgs field is crucial to the SM as we know it
- Gives masses to the fermions

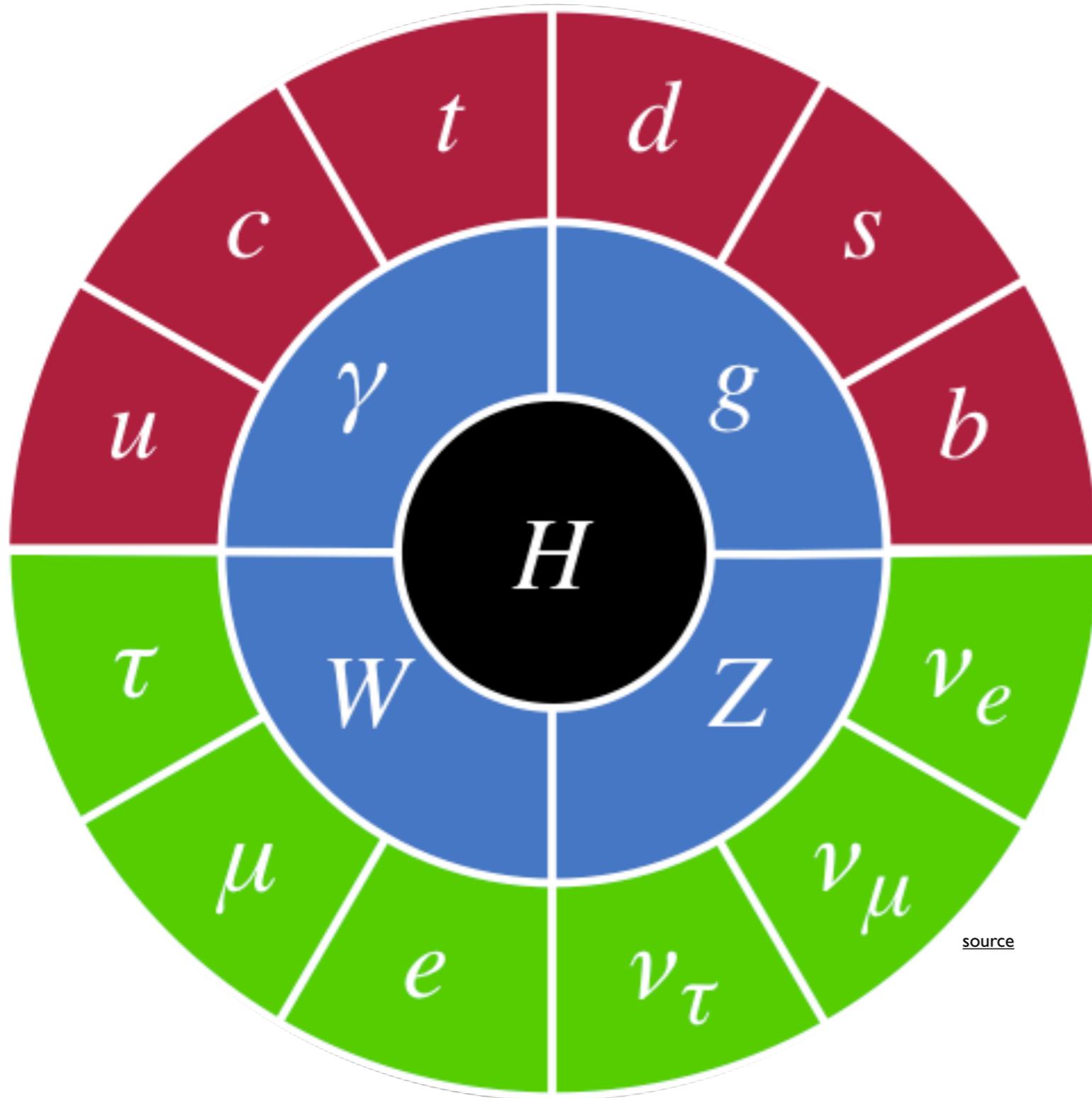
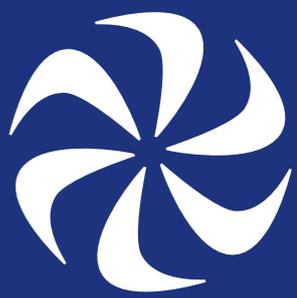
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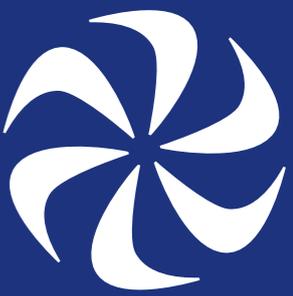
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- Electroweak symmetry breaking gives masses to W/Z , splits off γ

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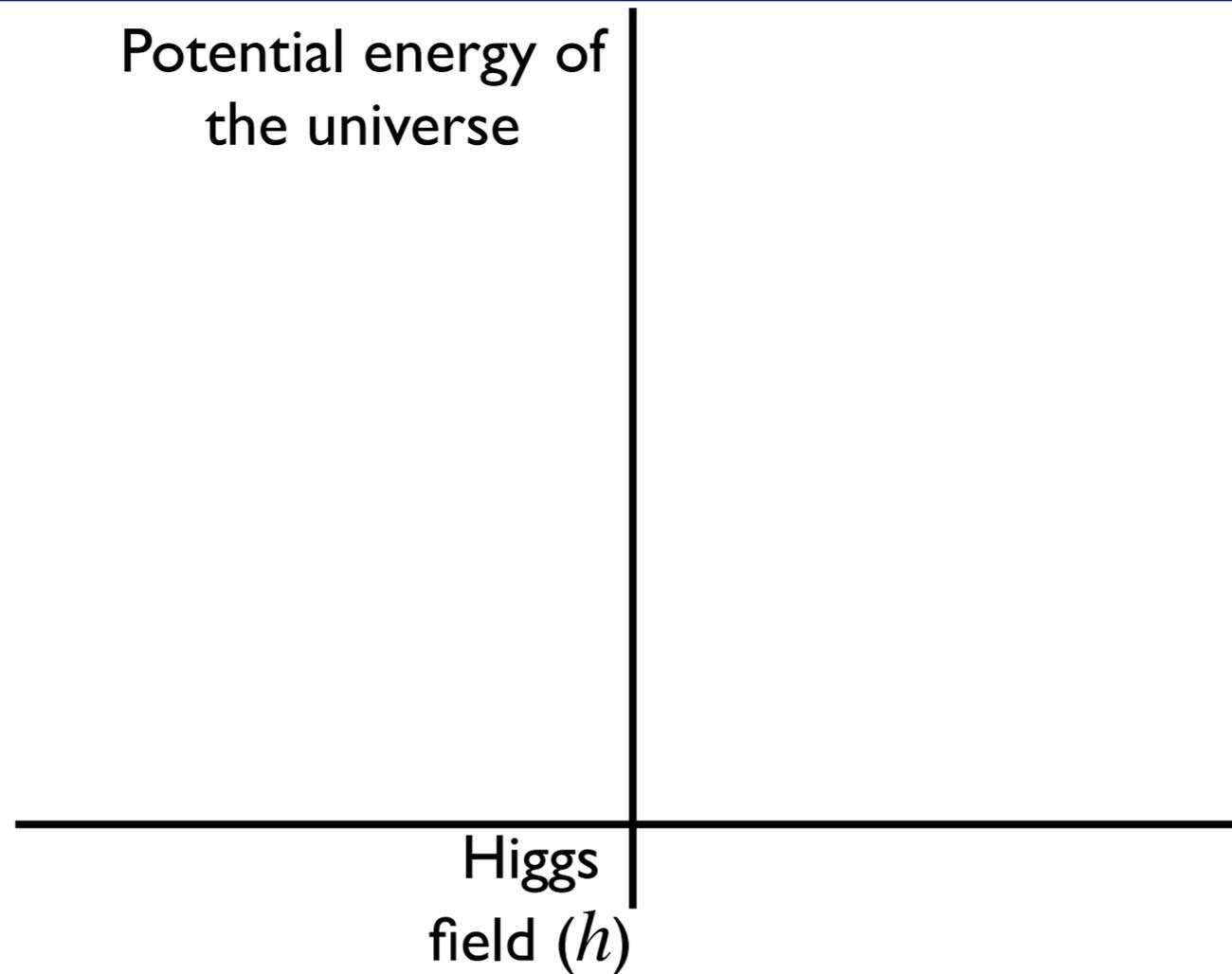
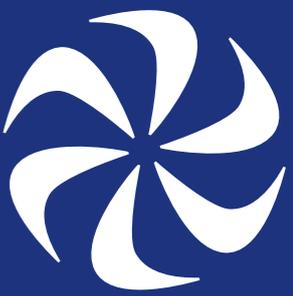


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- Electroweak symmetry breaking gives masses to W/Z , splits off γ
- All rises from the unique shape of the Higgs potential

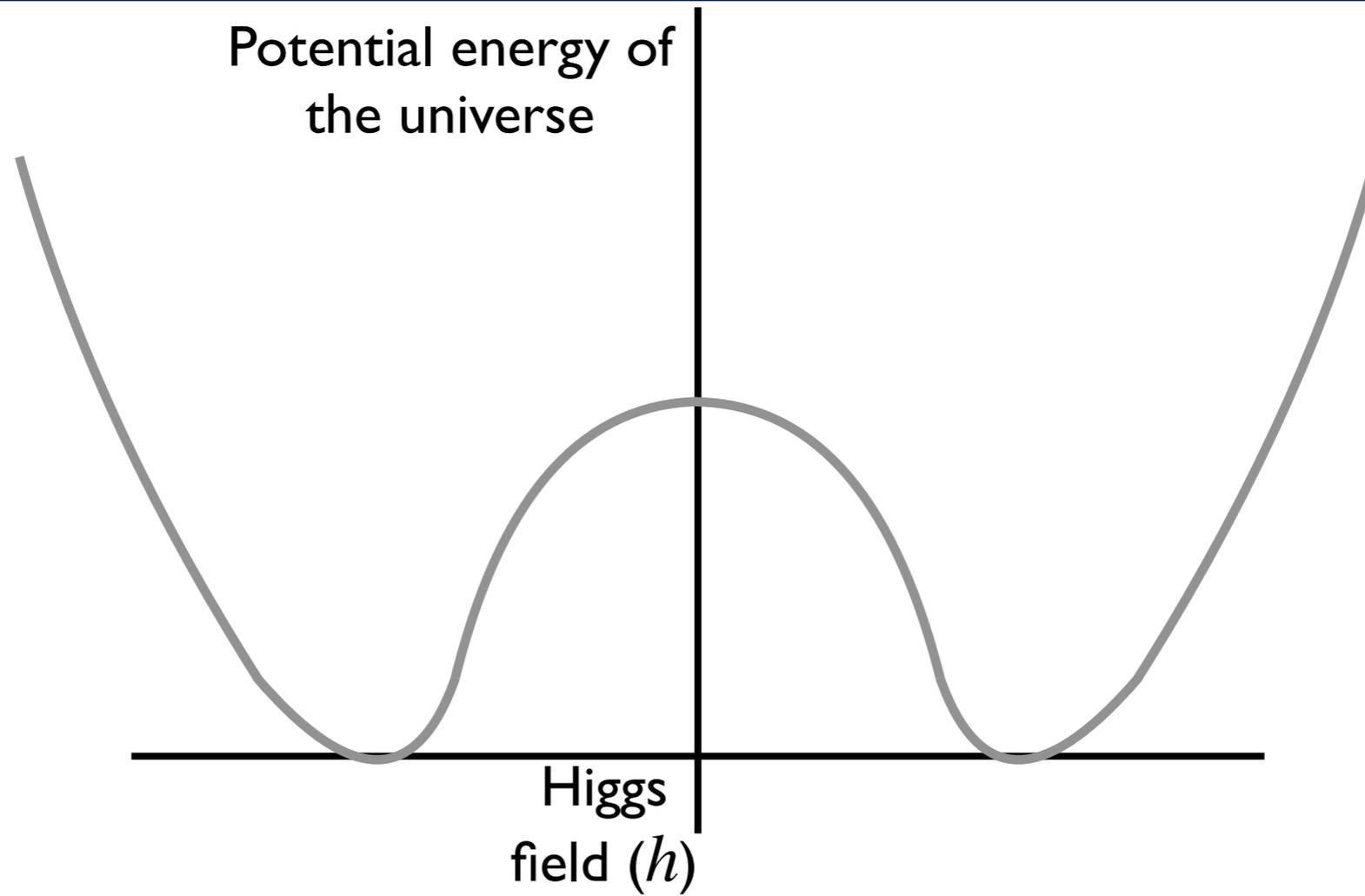
The BEH Mechanism



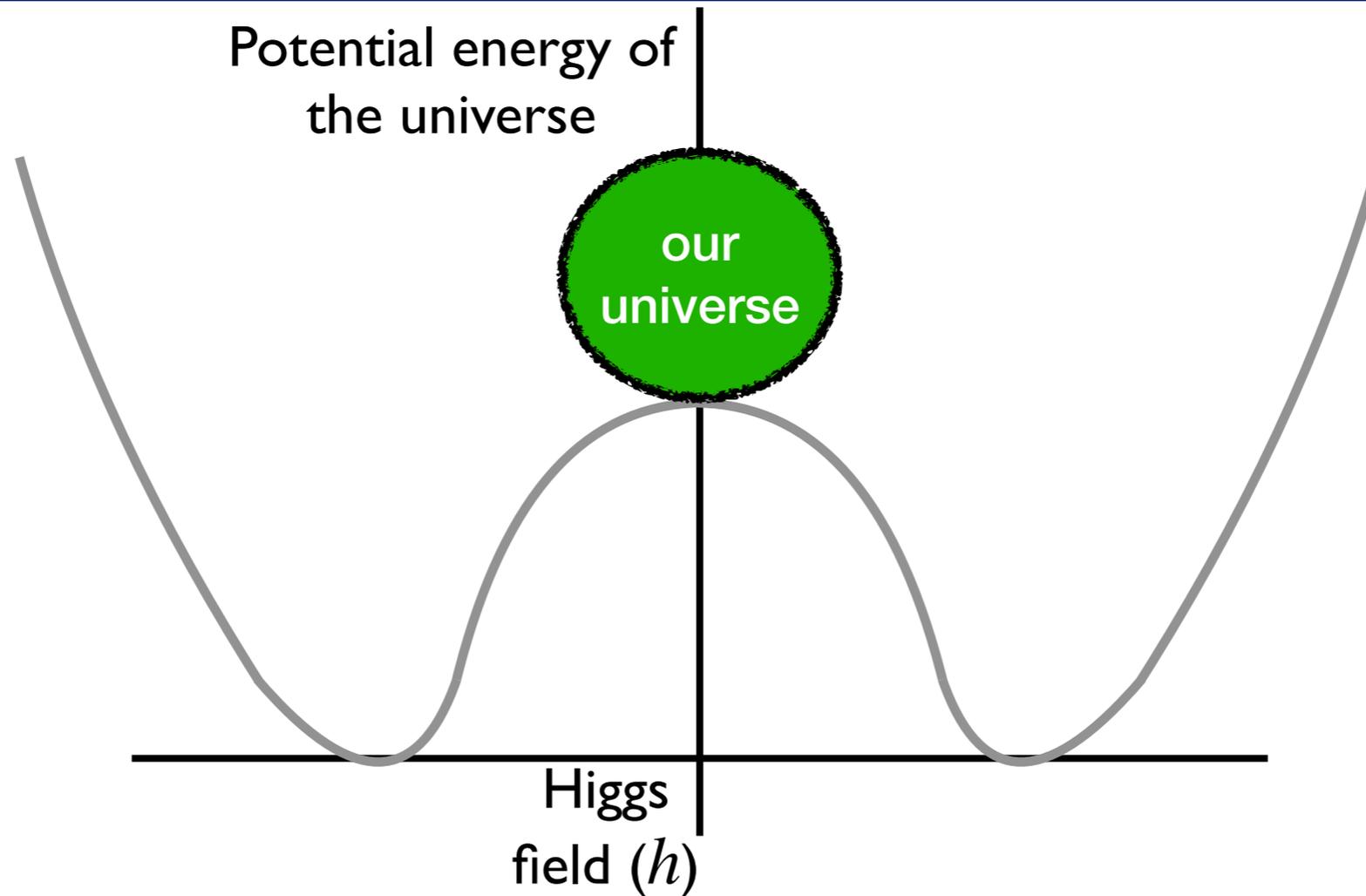
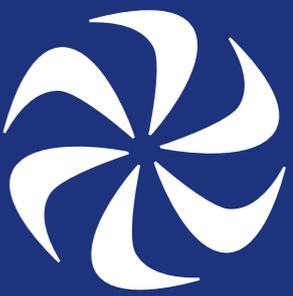
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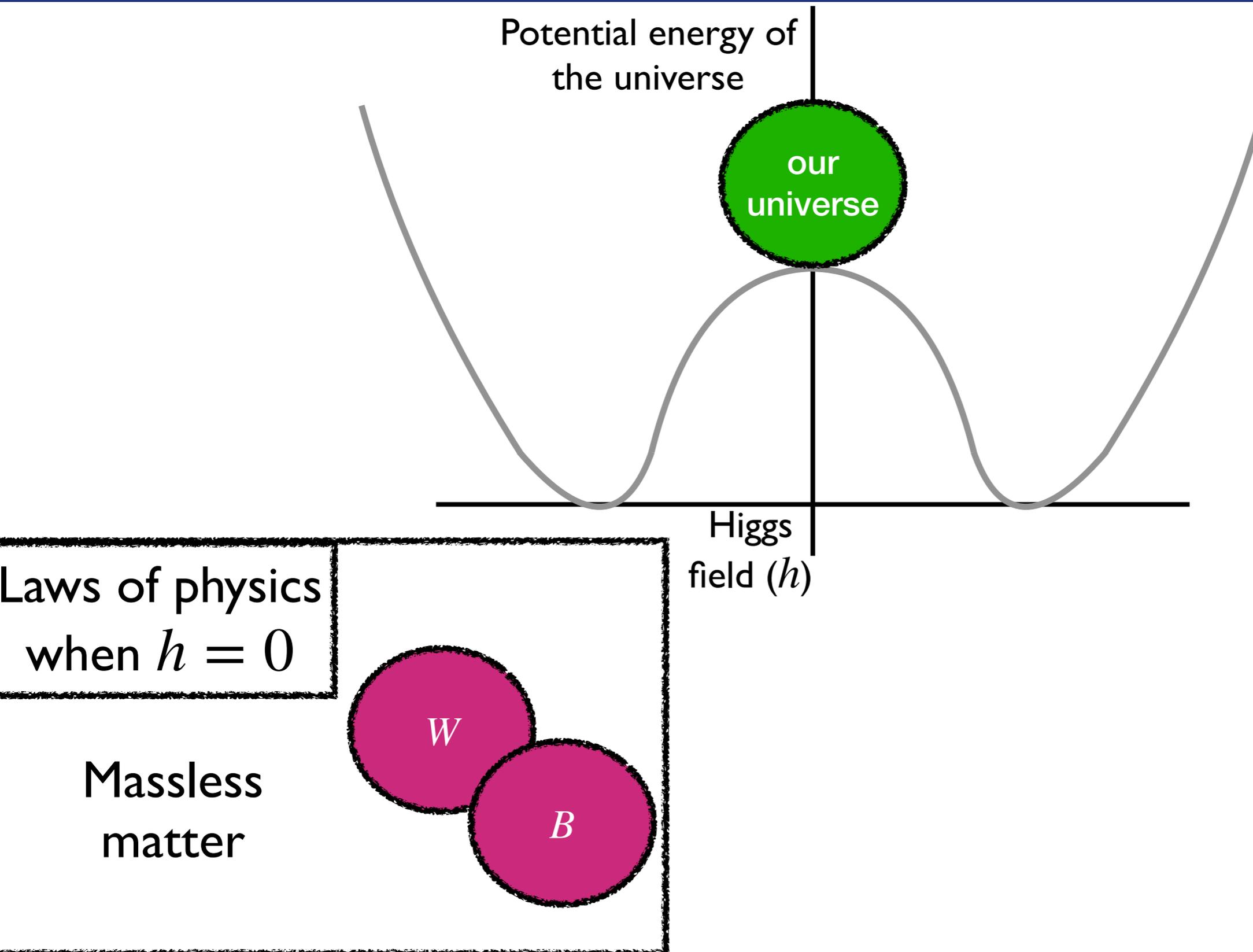
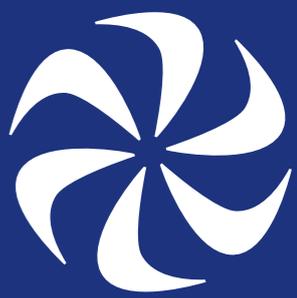
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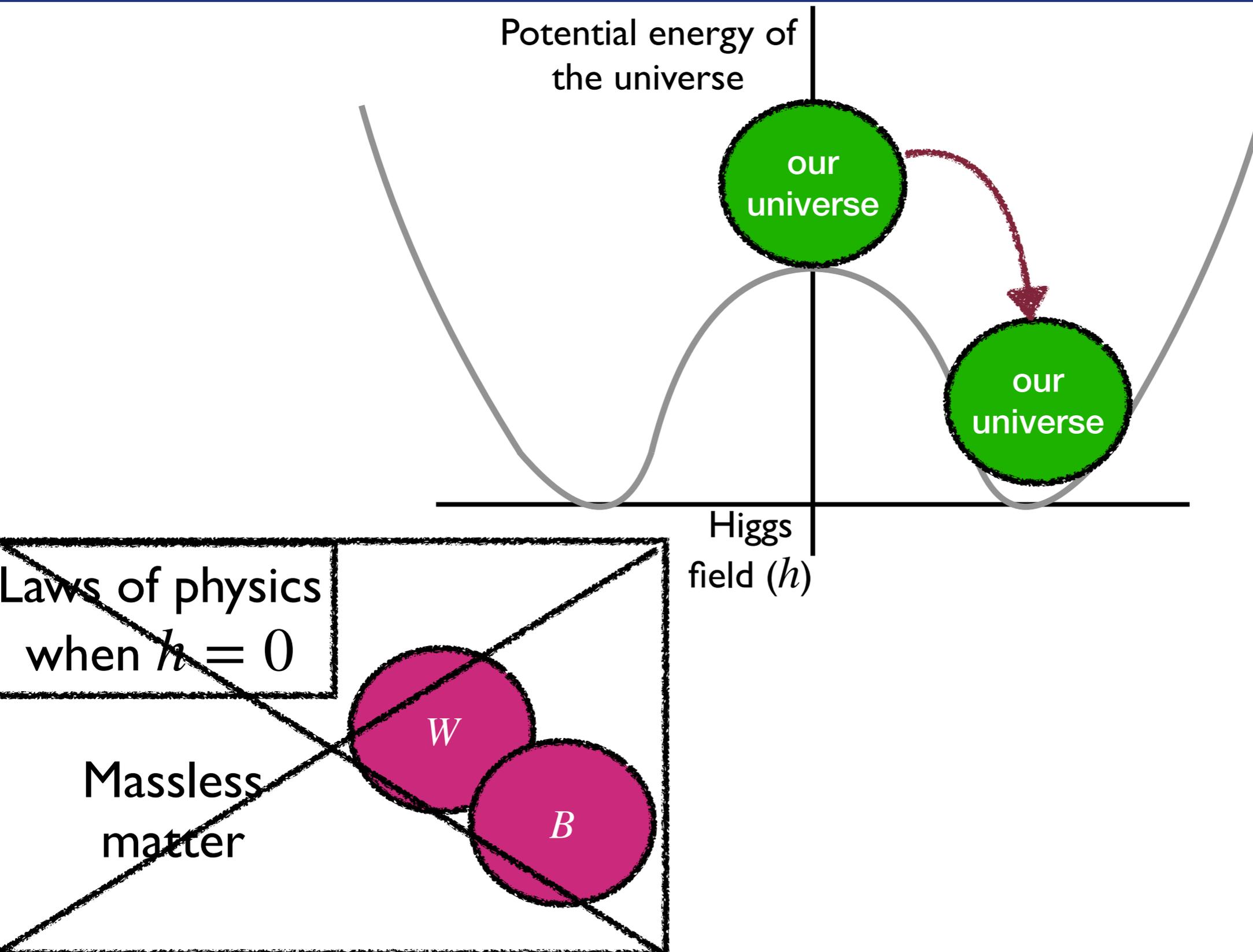
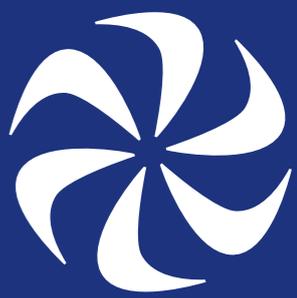
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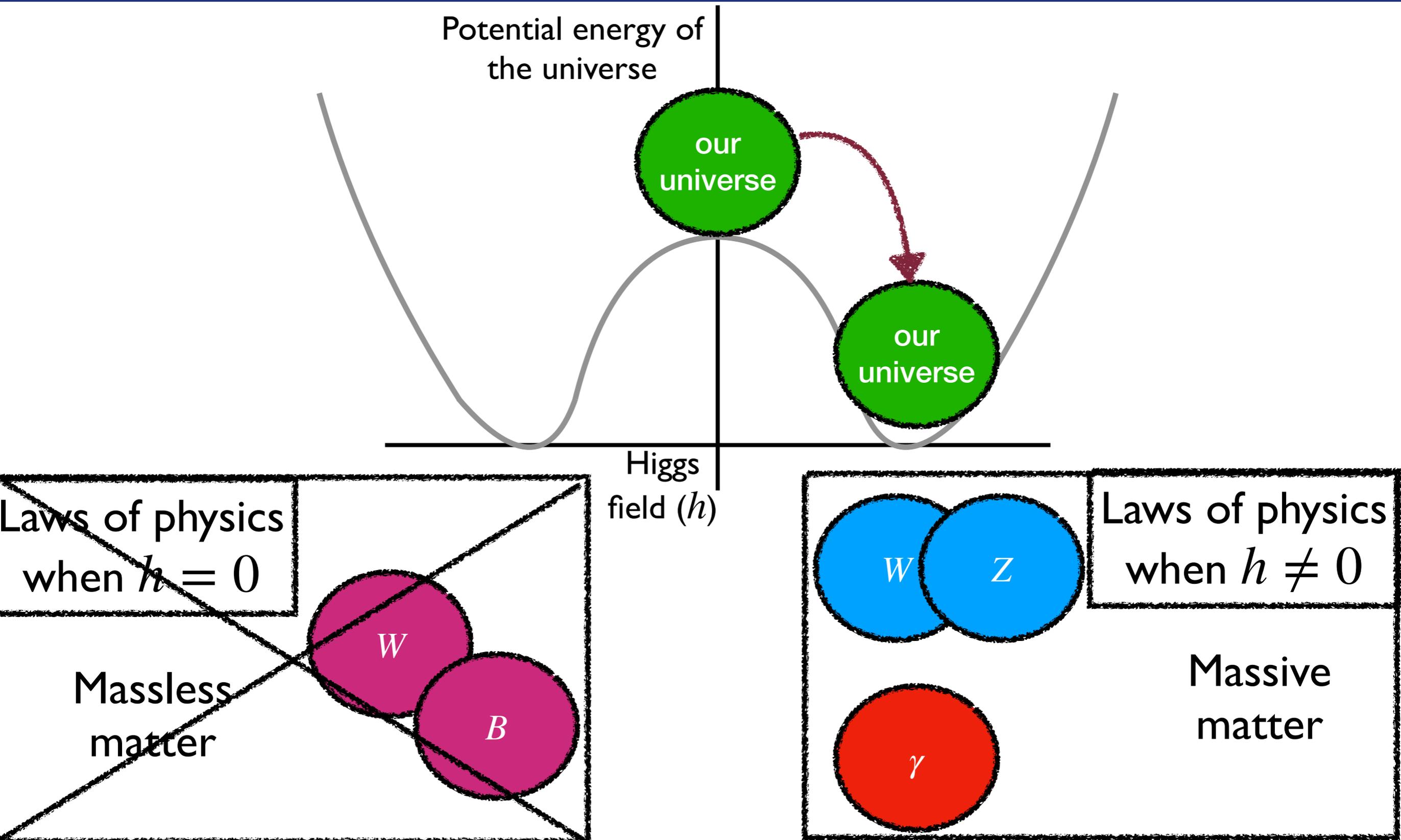
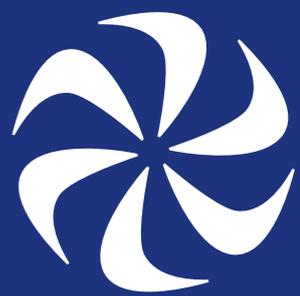
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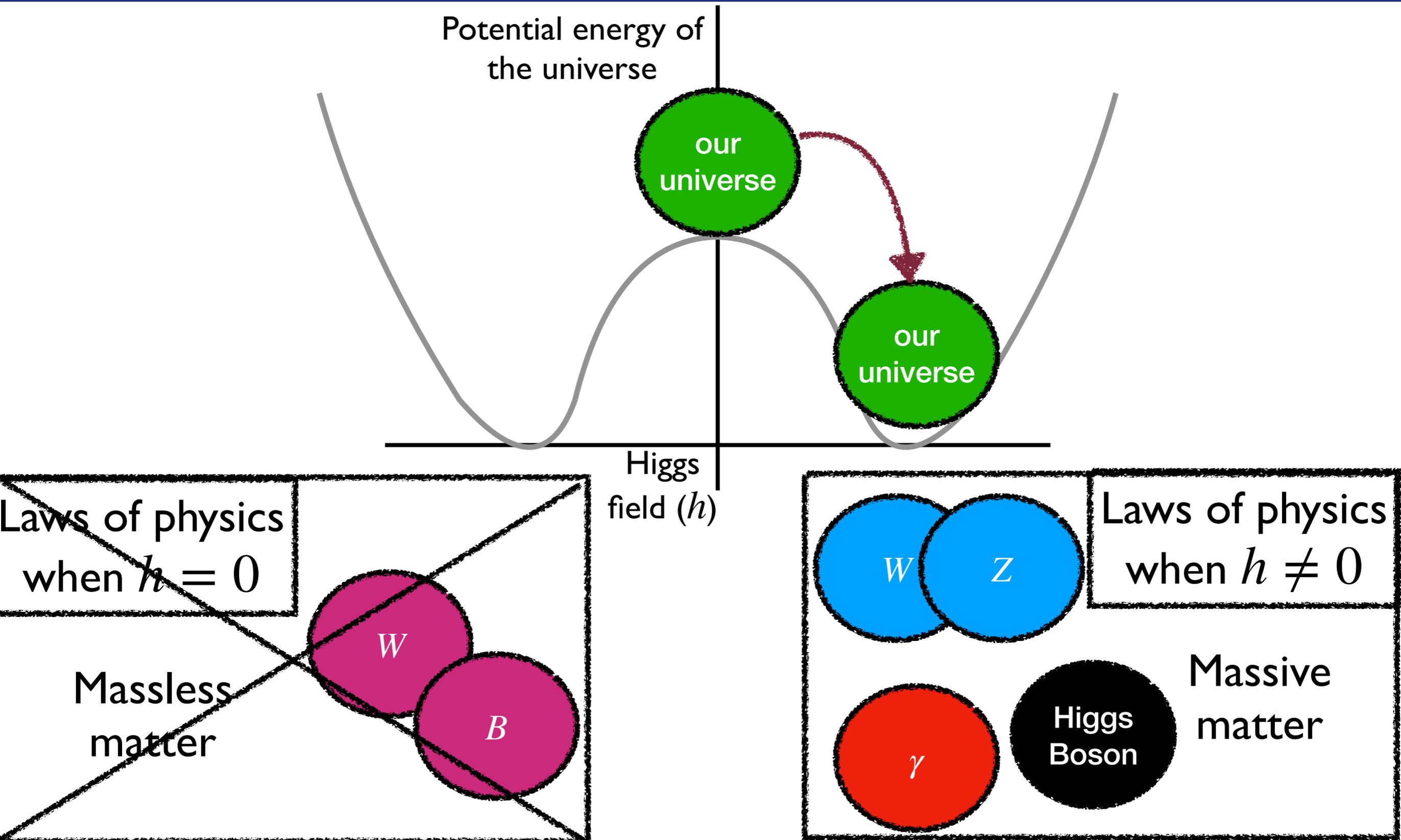
The BEH Mechanism



The BEH Mechanism



The BEH Mechanism



**Dark Energy
Accelerated Expansion**

**Afterglow Light
Pattern
375,000 yrs.**

Dark Ages

**Development of
Galaxies, Planets, etc.**

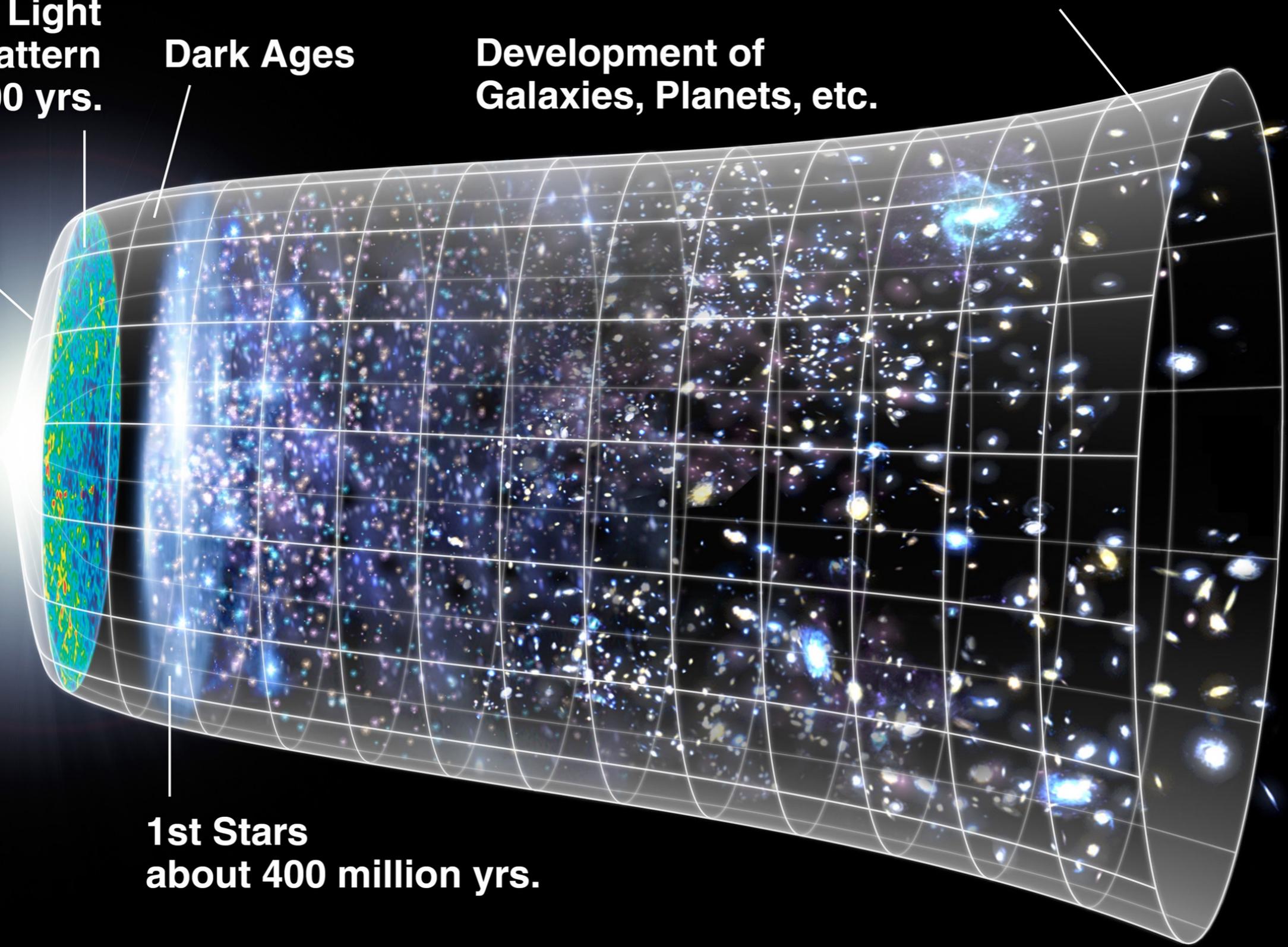
Inflation

**Quantum
Fluctuations**

**1st Stars
about 400 million yrs.**

Big Bang Expansion

13.77 billion years



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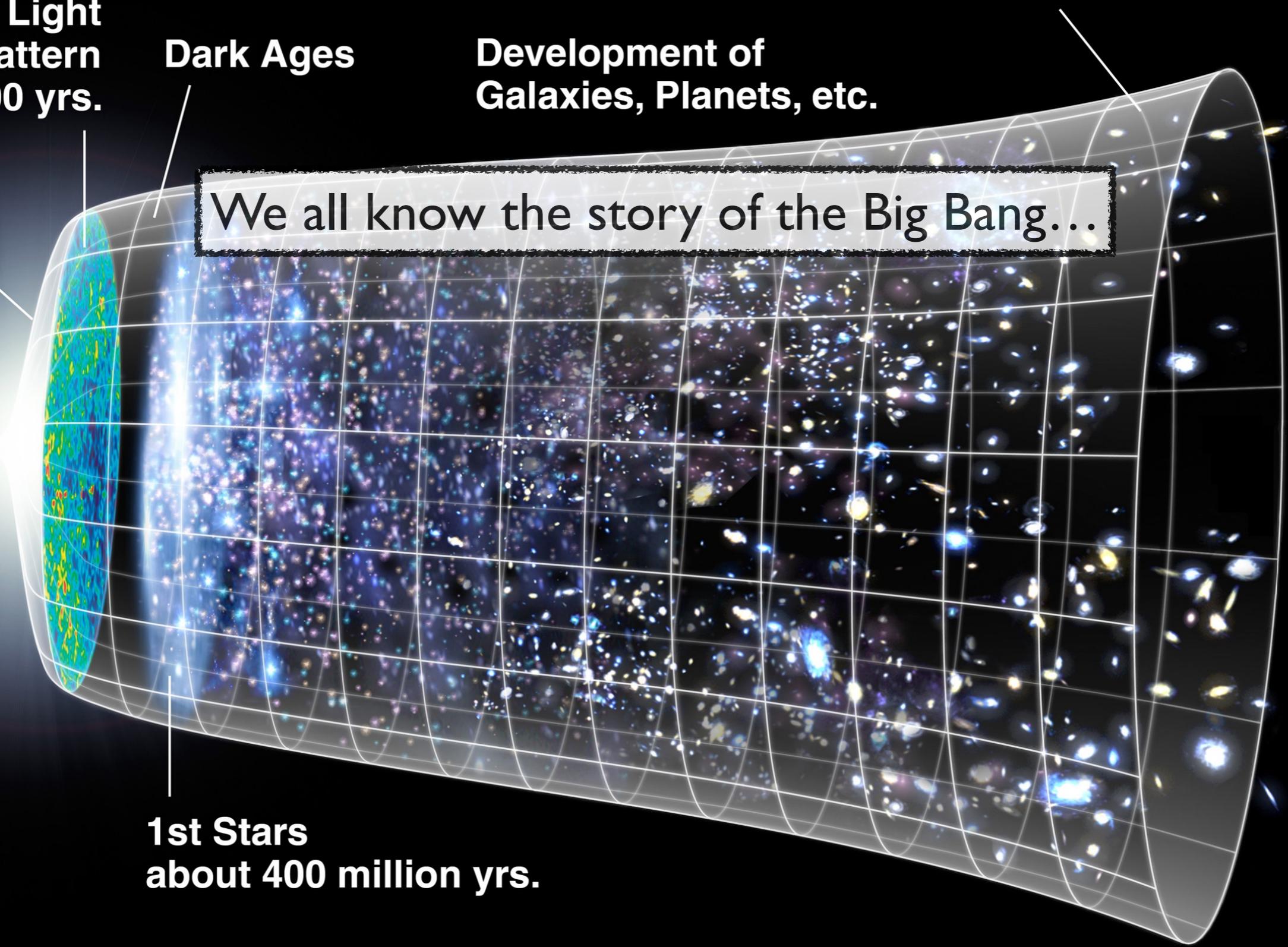
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But what about the future of the universe?

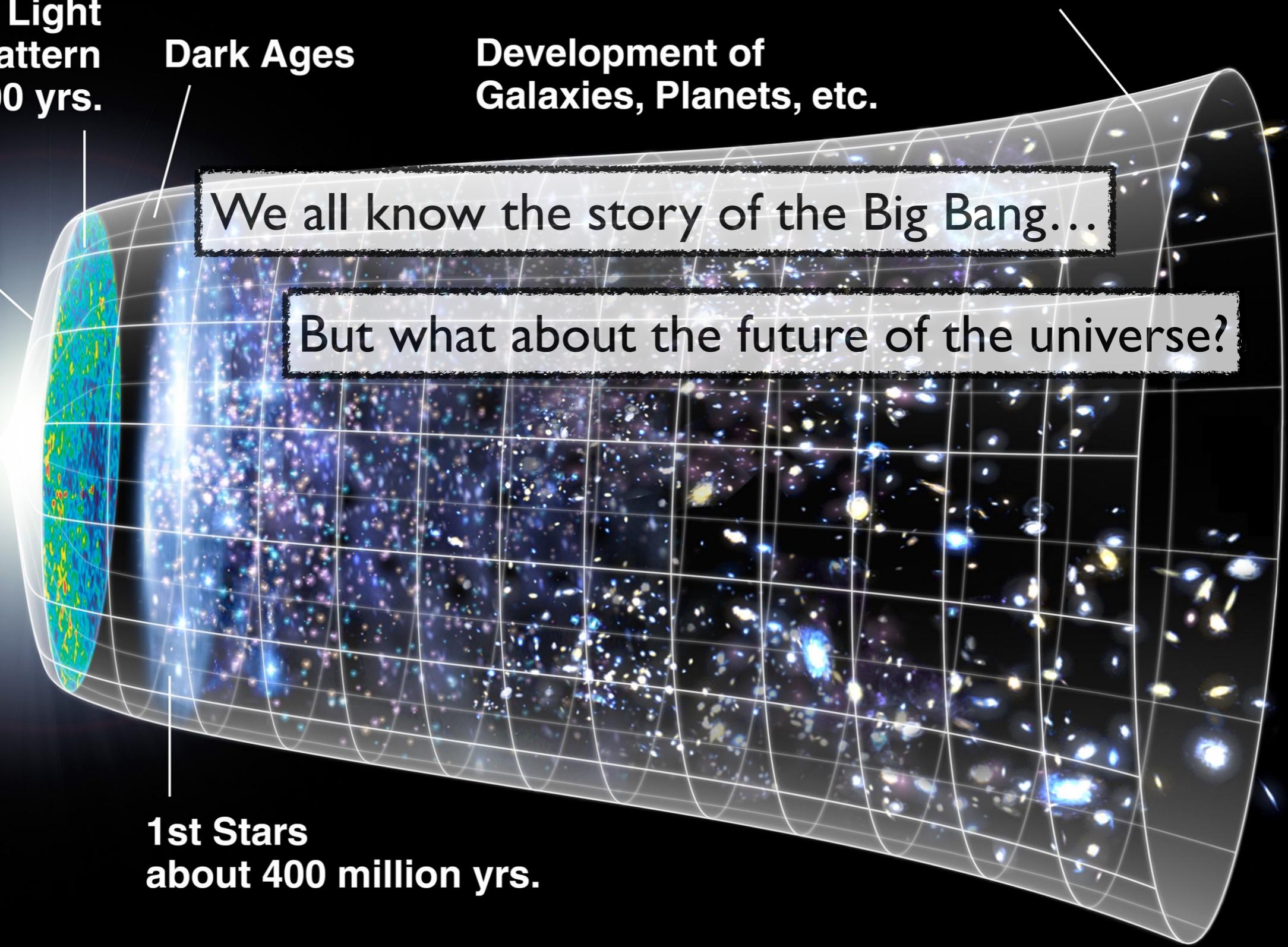
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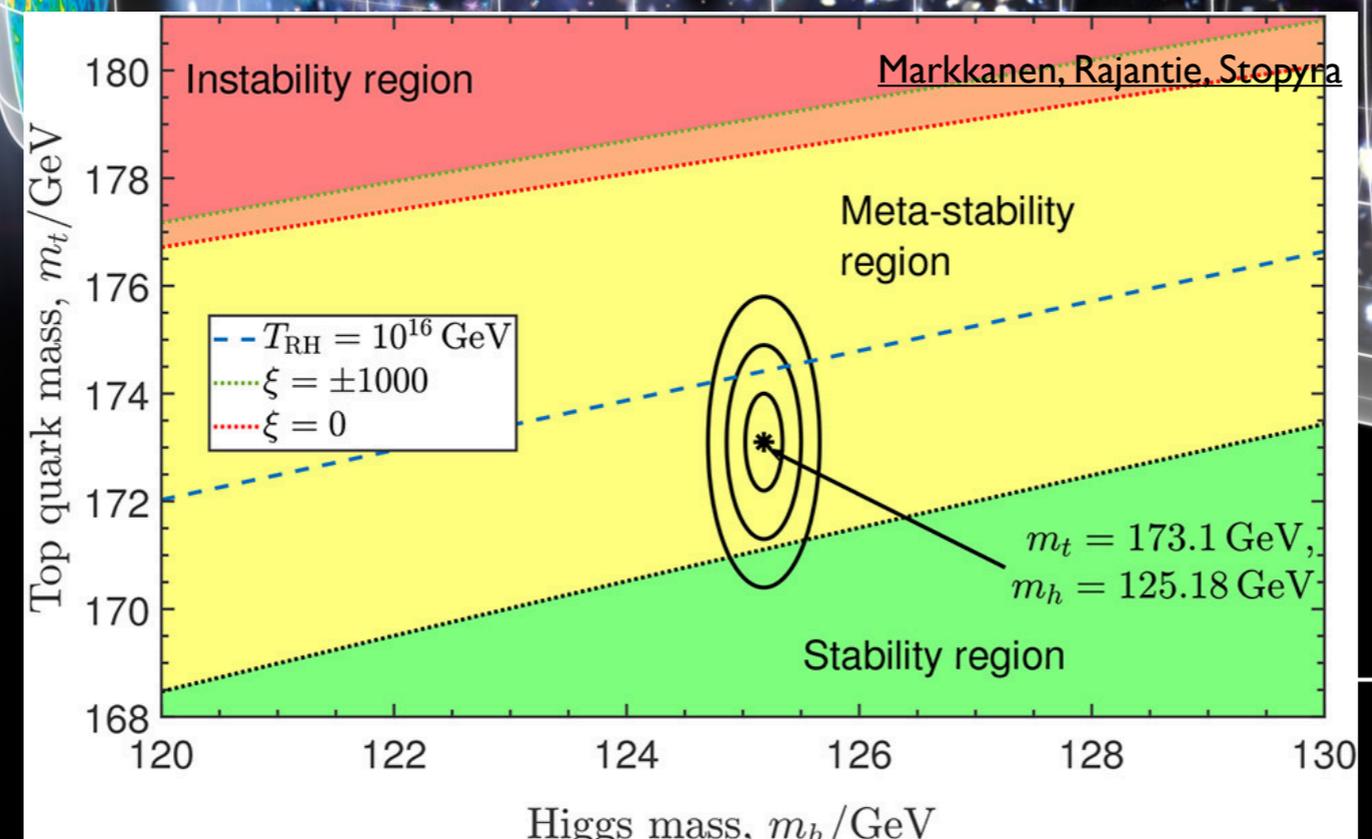
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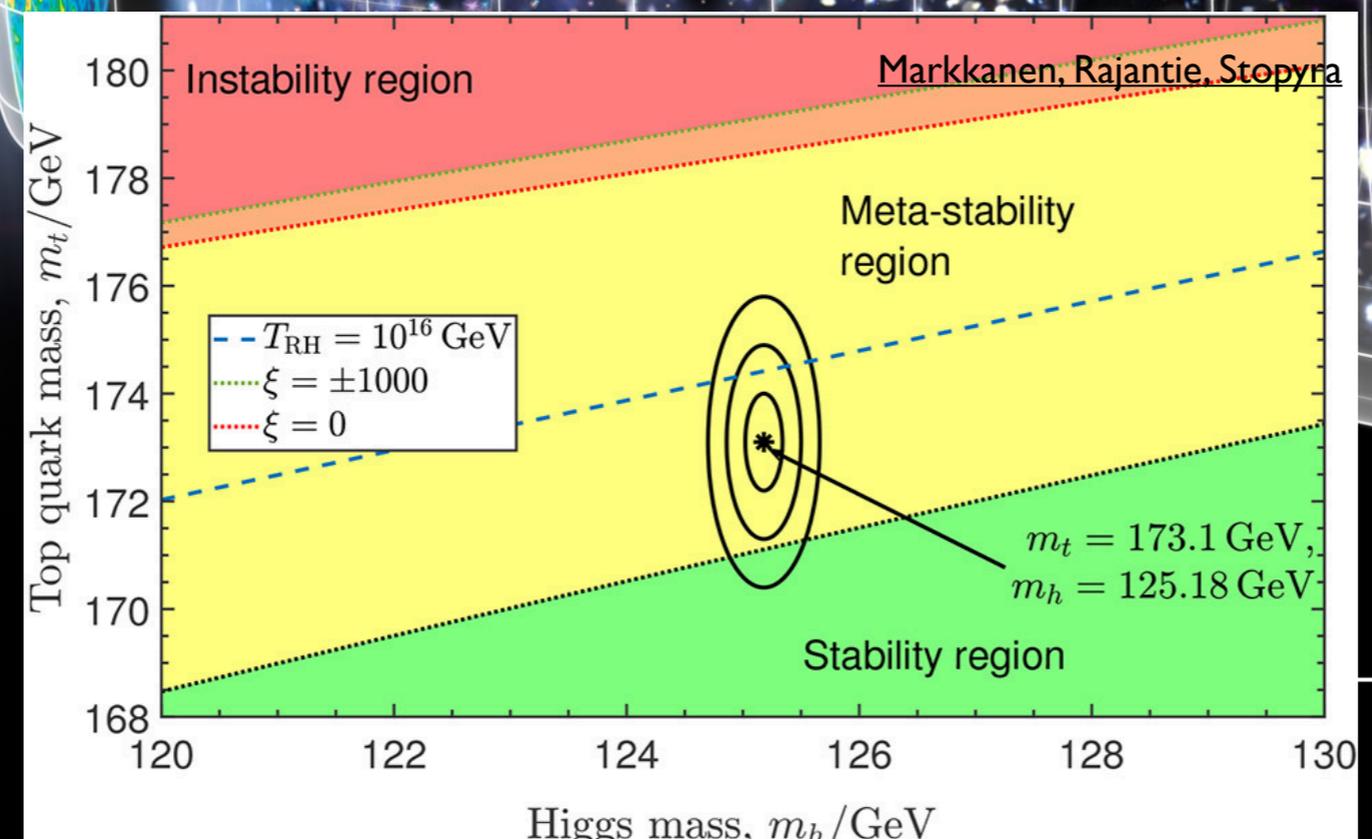
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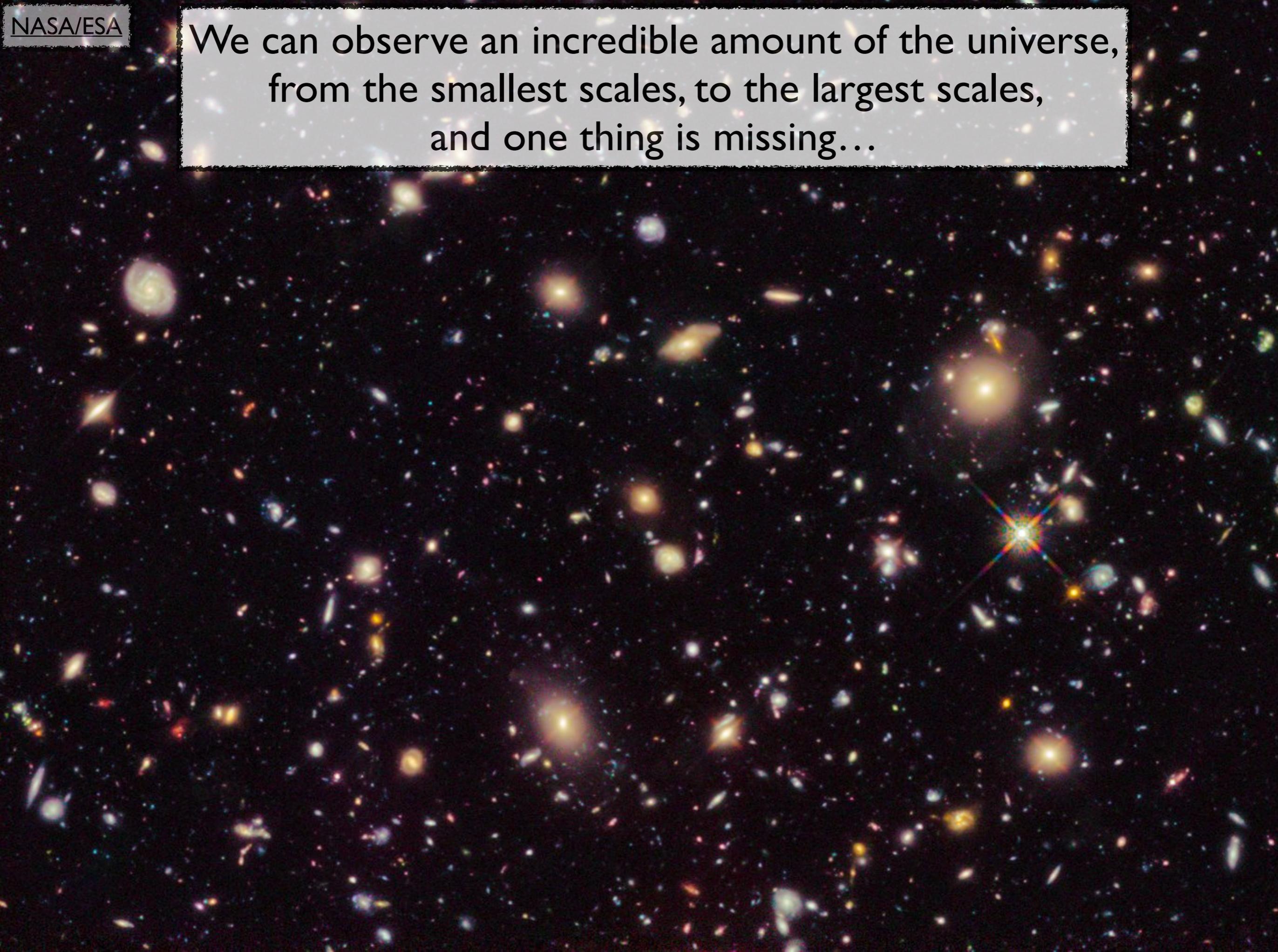
Is our universe stable? What can we test?
New physics can affect these conclusions!

Quantum
Fluctuations

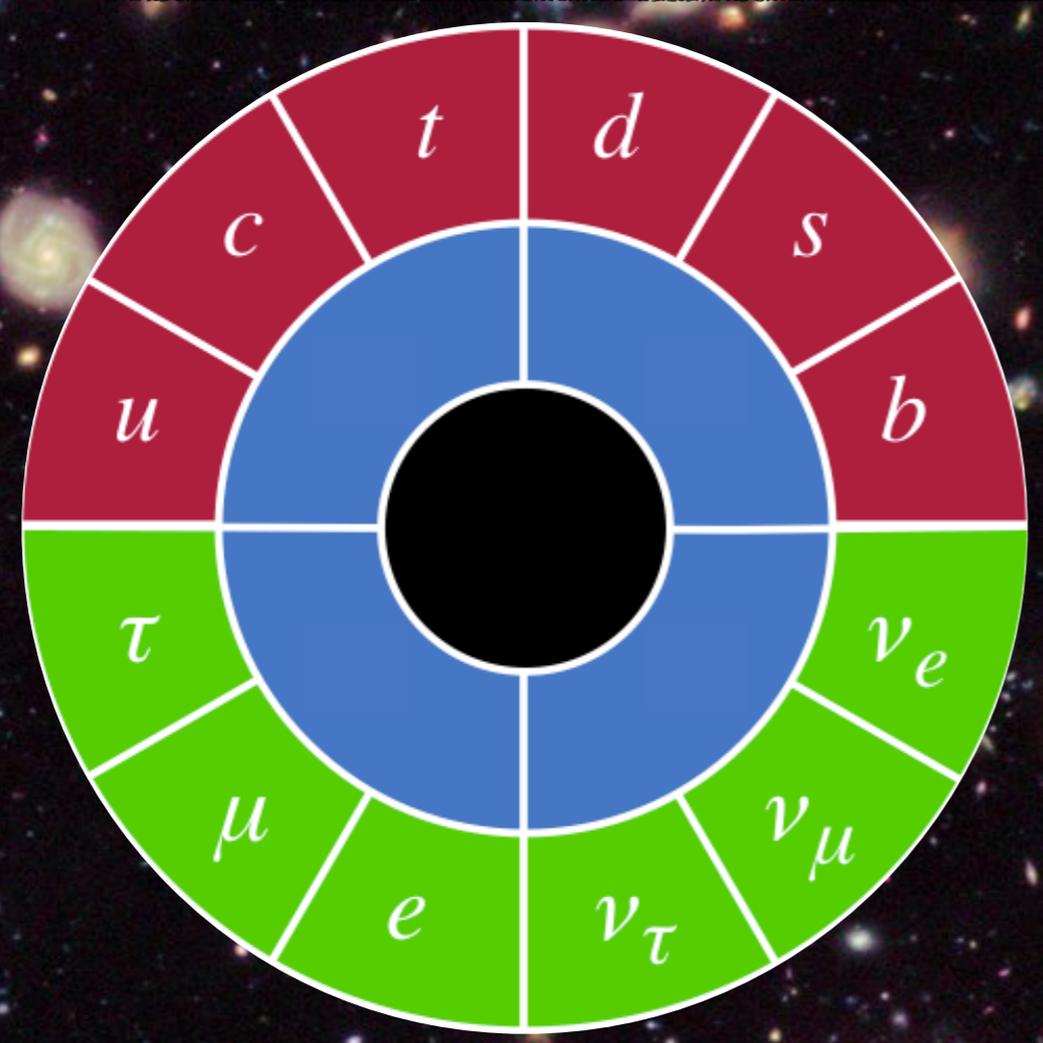




We can observe an incredible amount of the universe,
from the smallest scales, to the largest scales,
and one thing is missing...

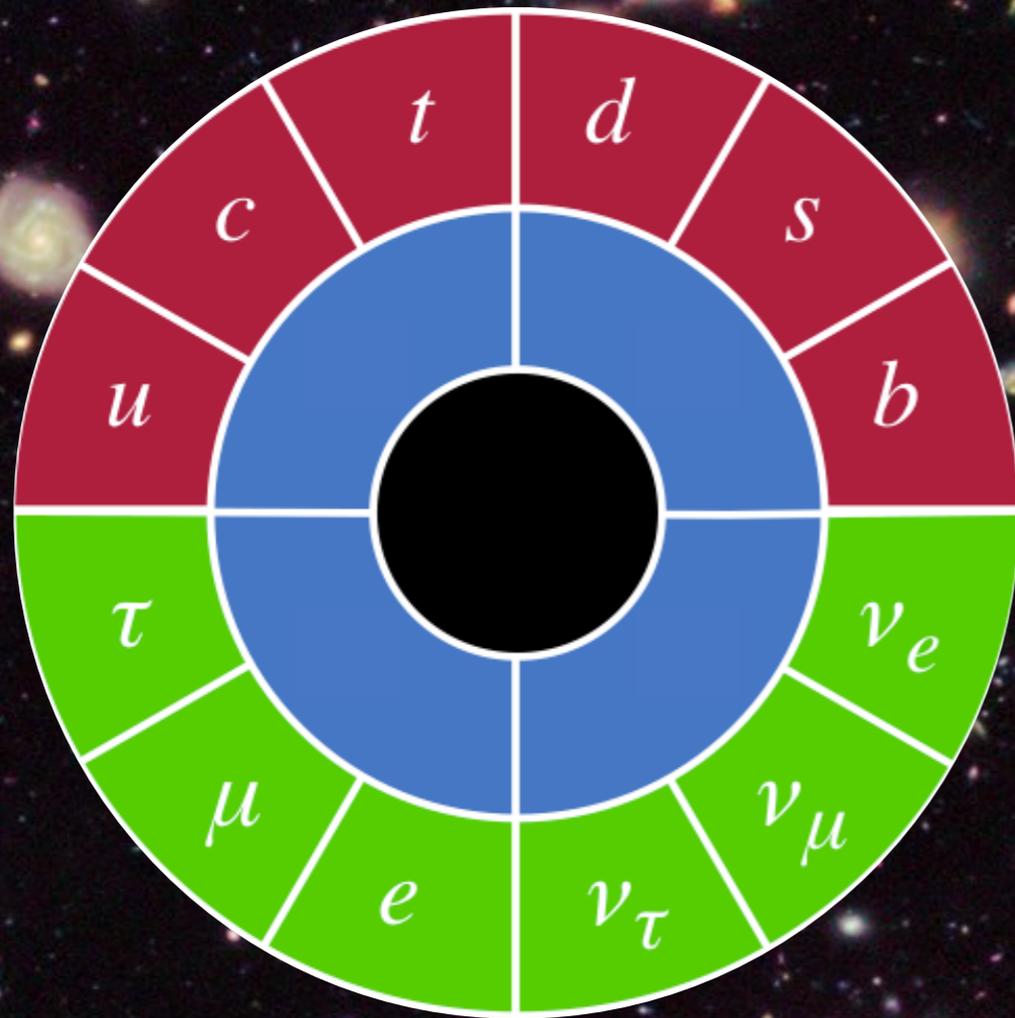


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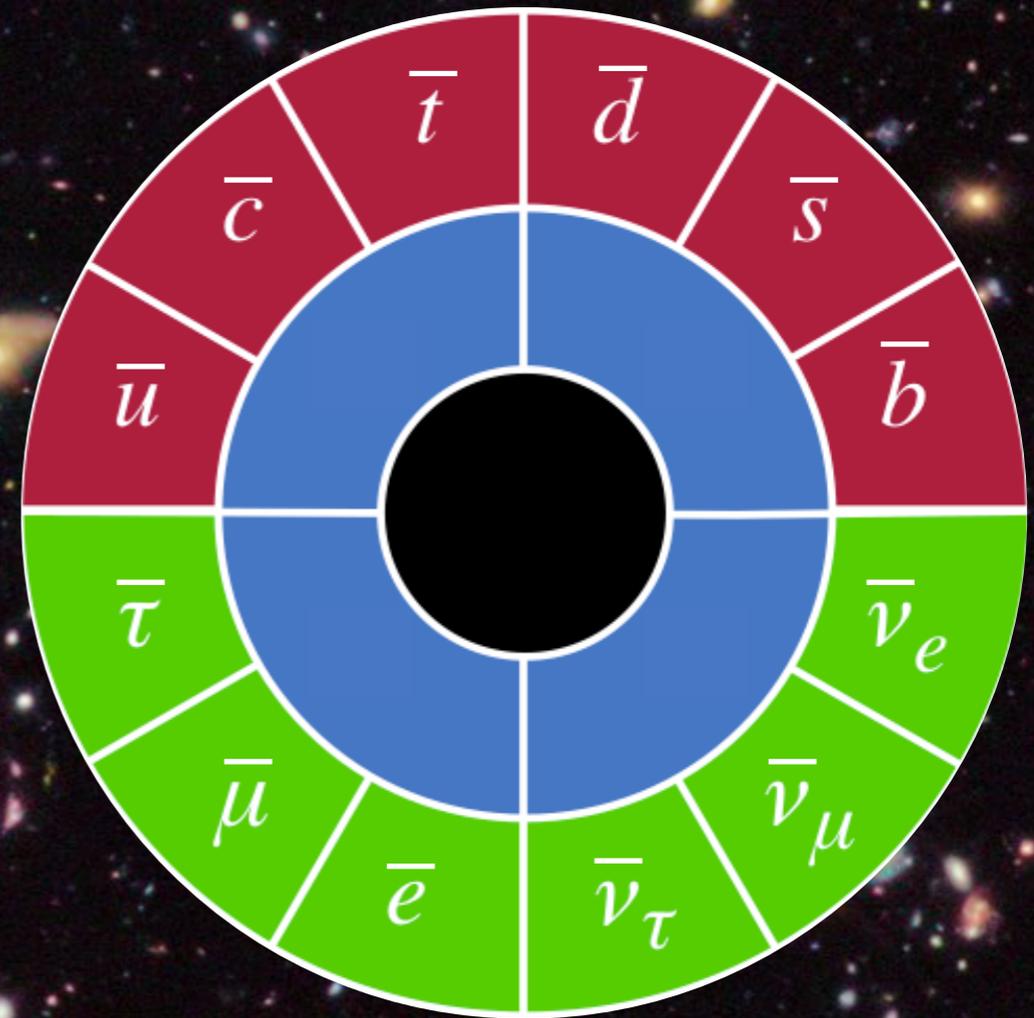


Everything we see is **matter**

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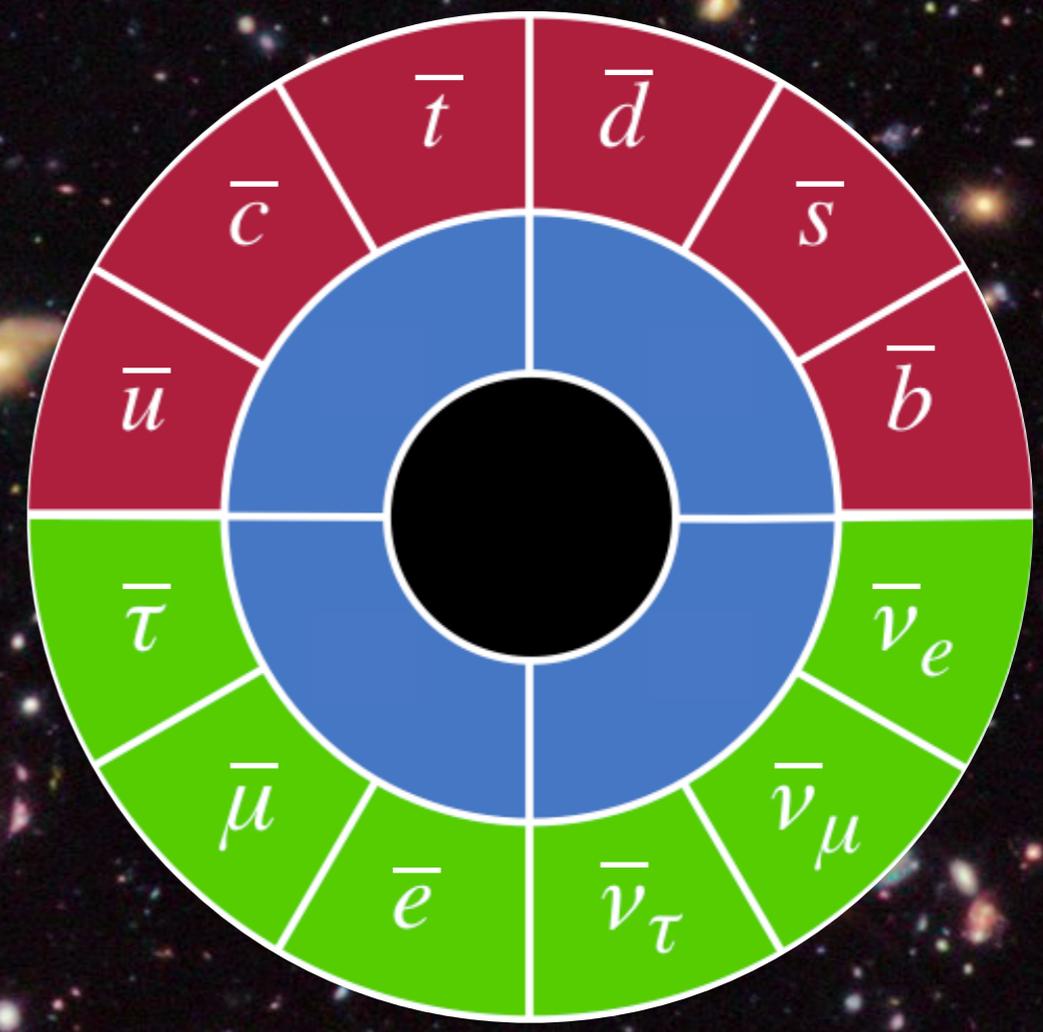
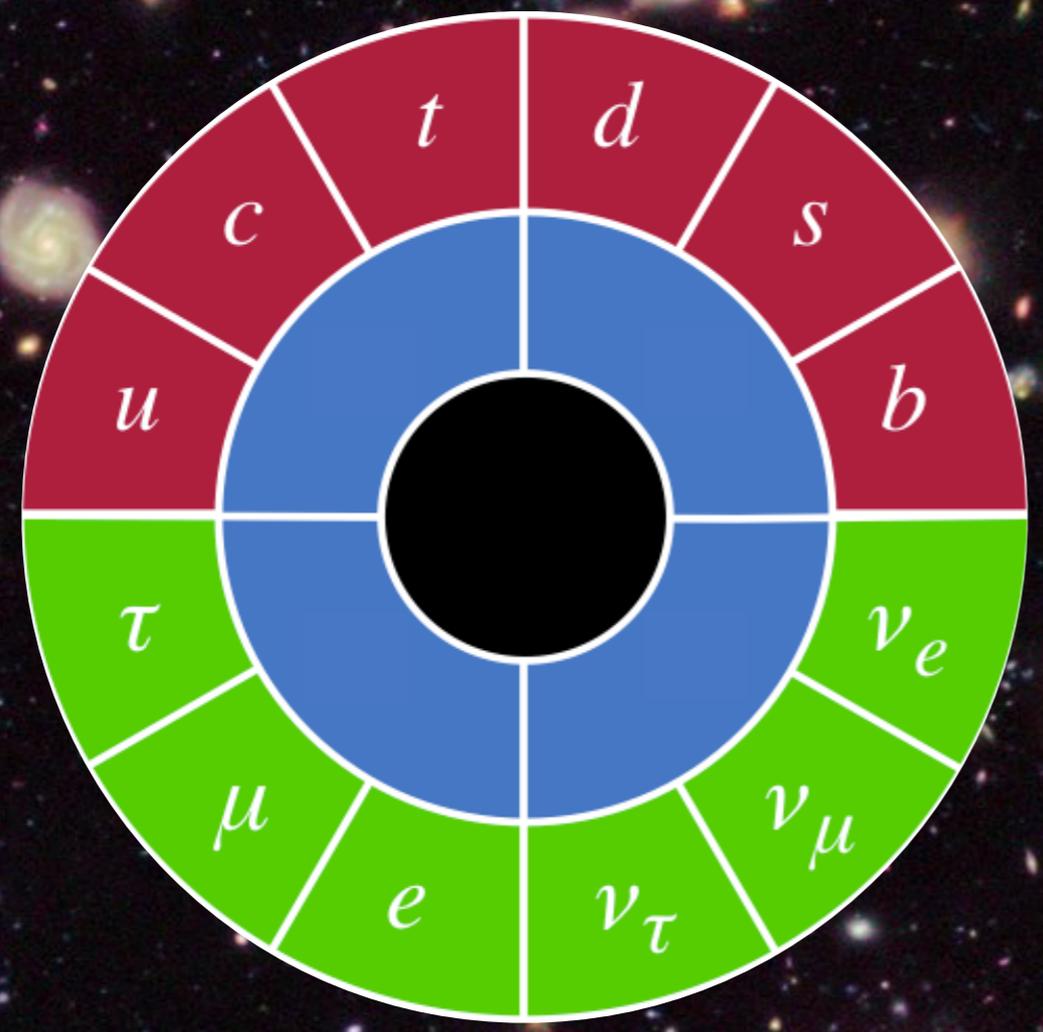


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Where is the **anti-matter**?

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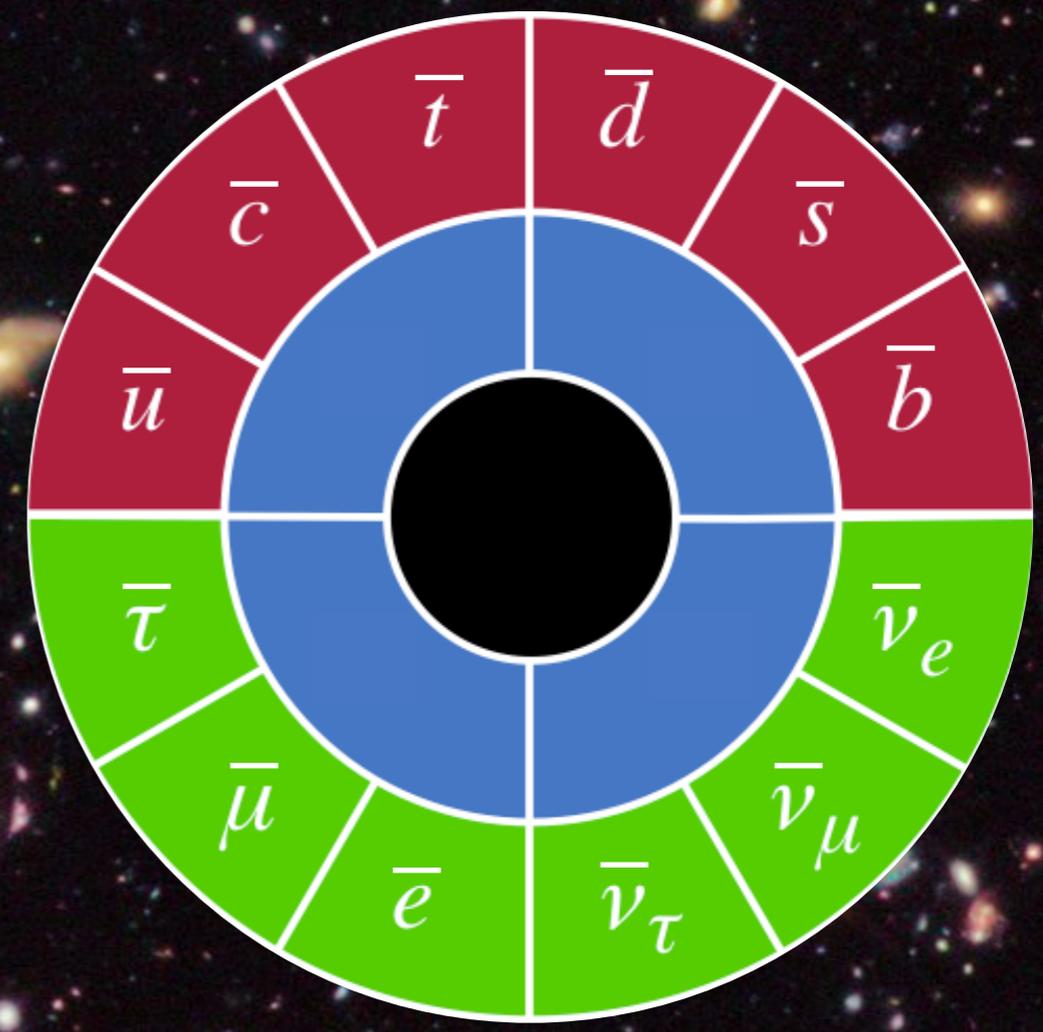
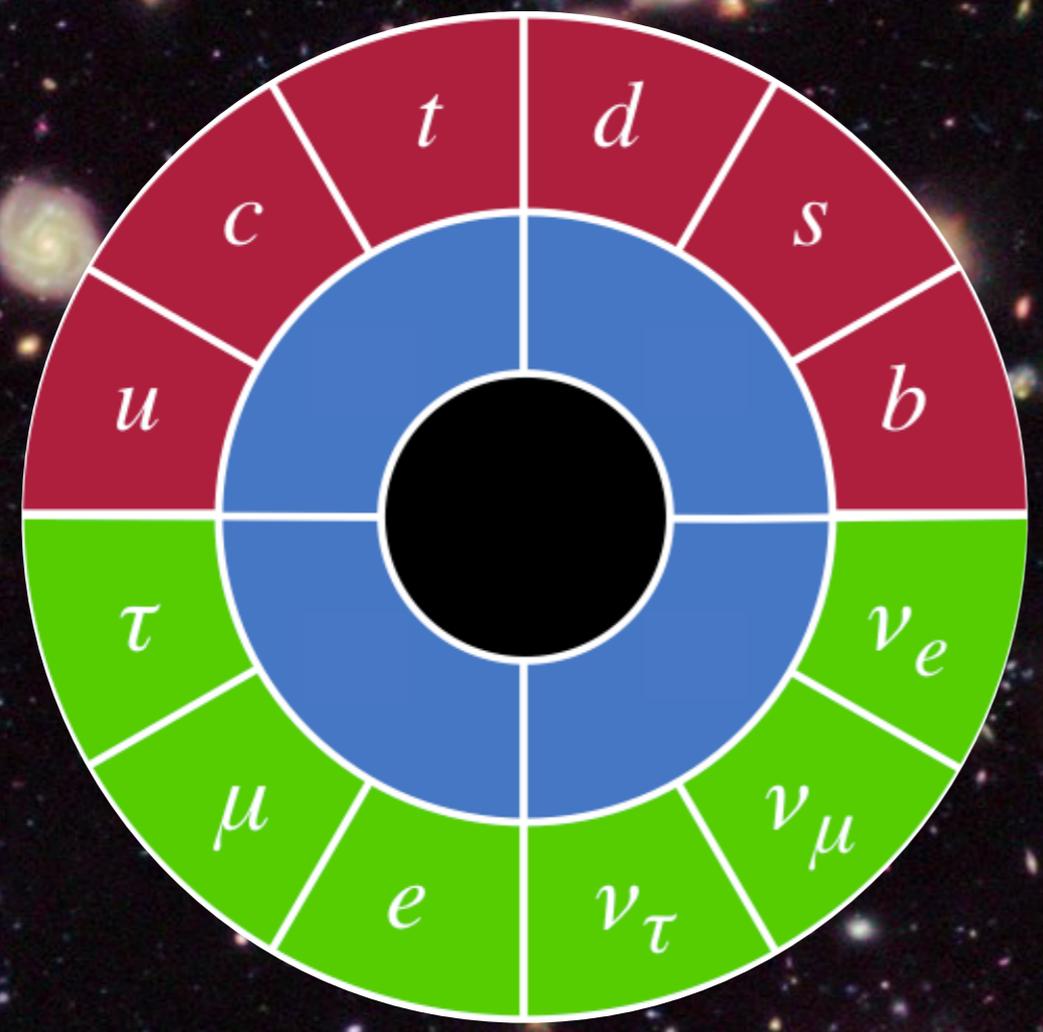


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The Big Bang should have produced them equally!

We can observe an incredible amount of the universe, from the smallest scales, to the largest scales, and one thing is missing...



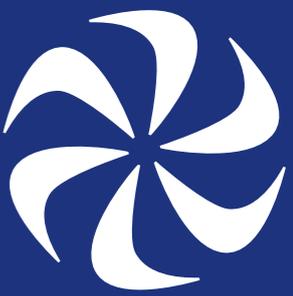
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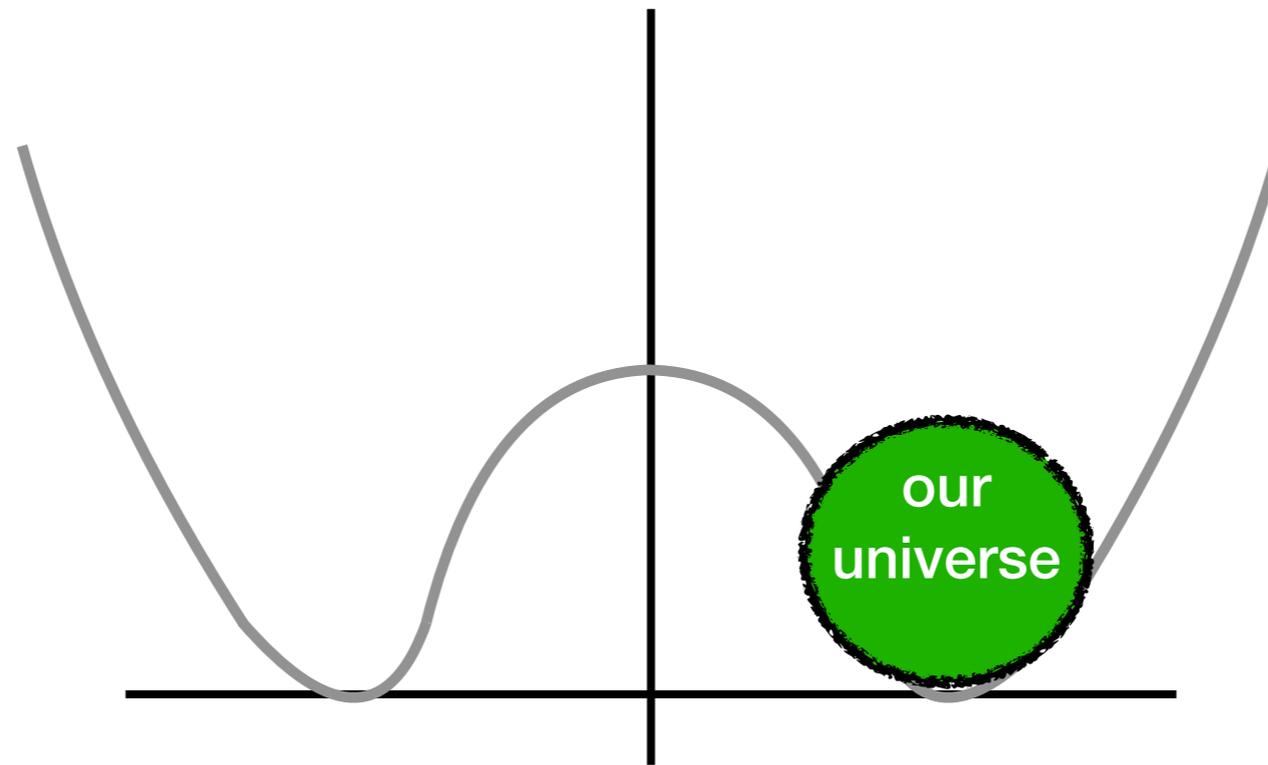
The Big Bang should have produced them equally!

The SM cannot explain anti-matter's disappearance

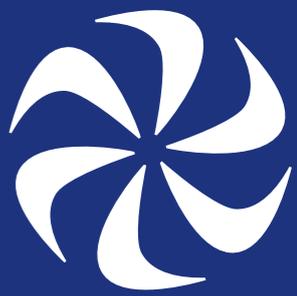
Understanding the Higgs Potential



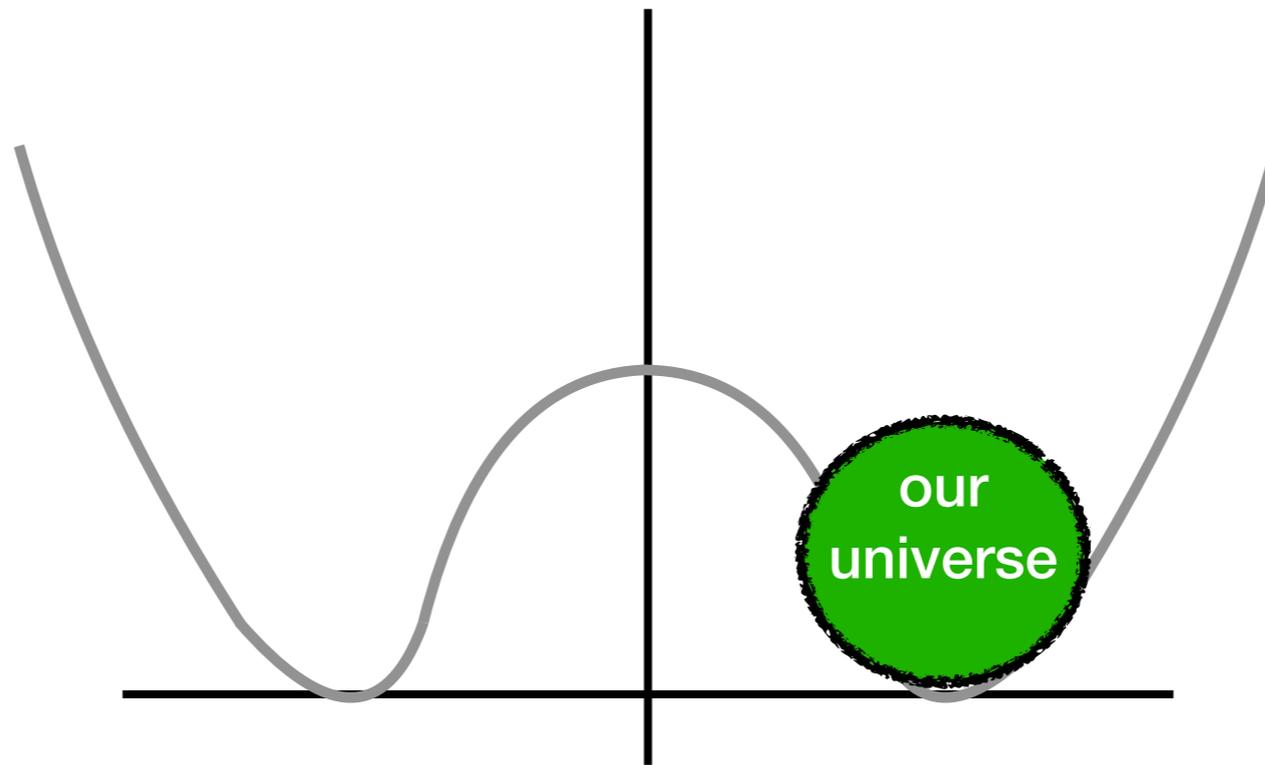
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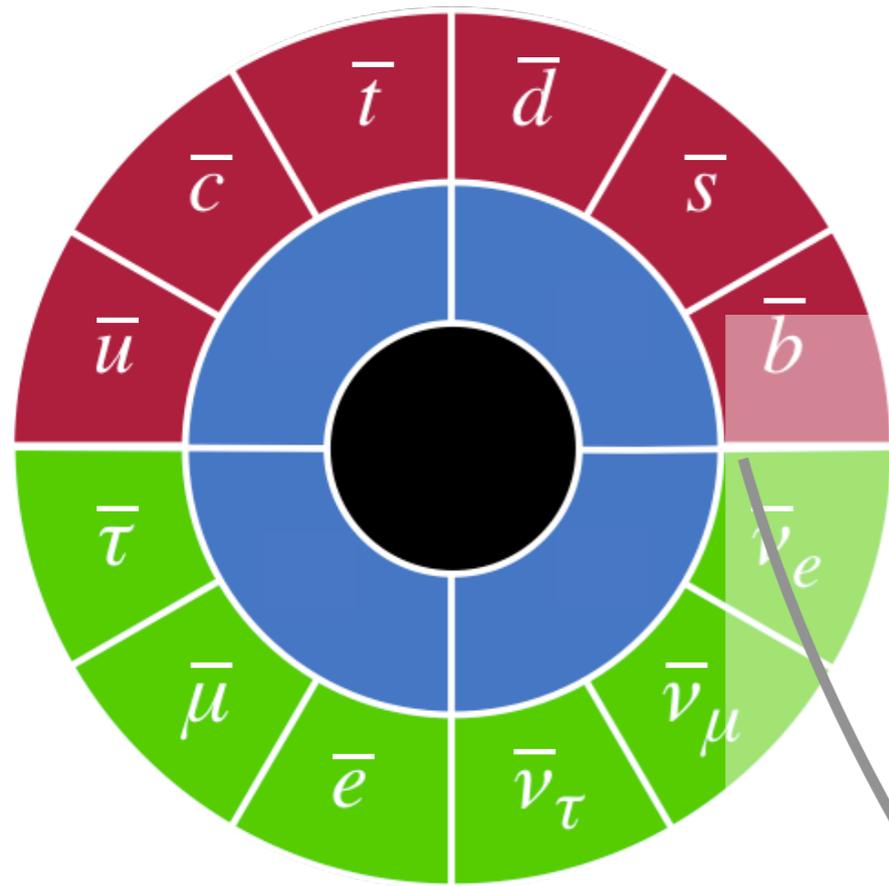
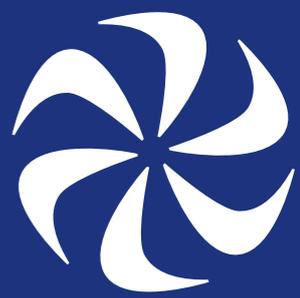
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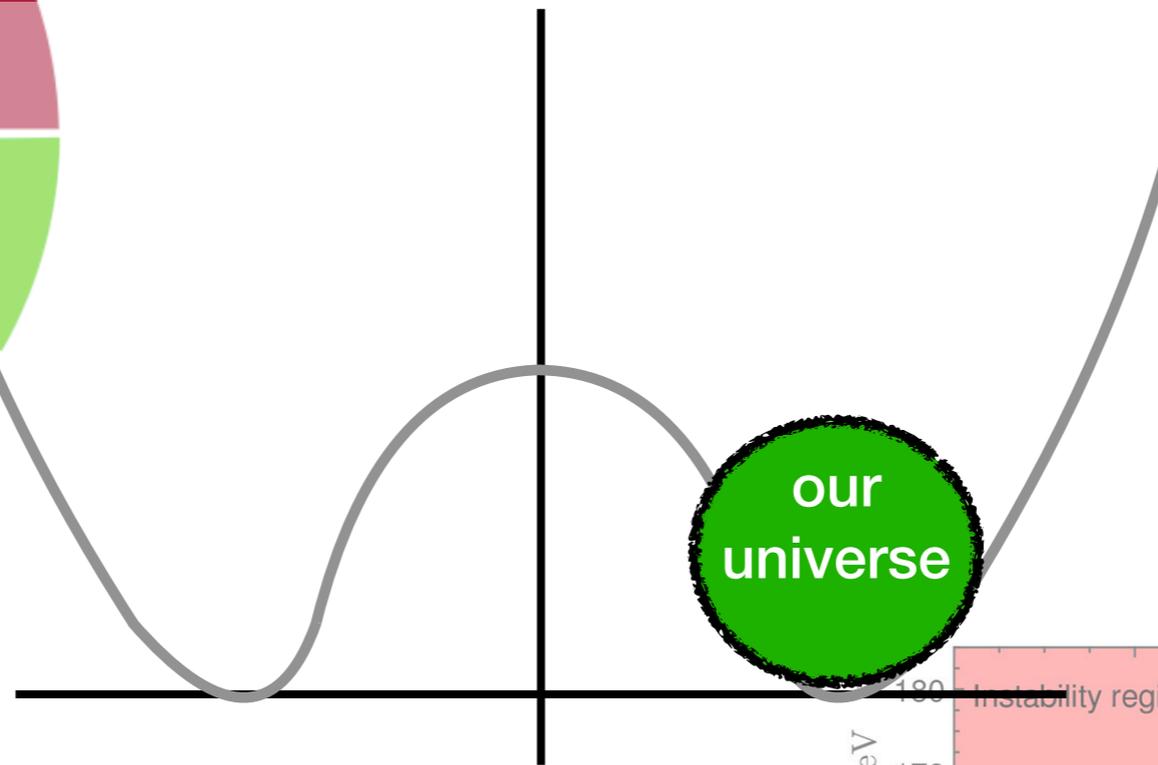
The Higgs potential plays a central role in the SM



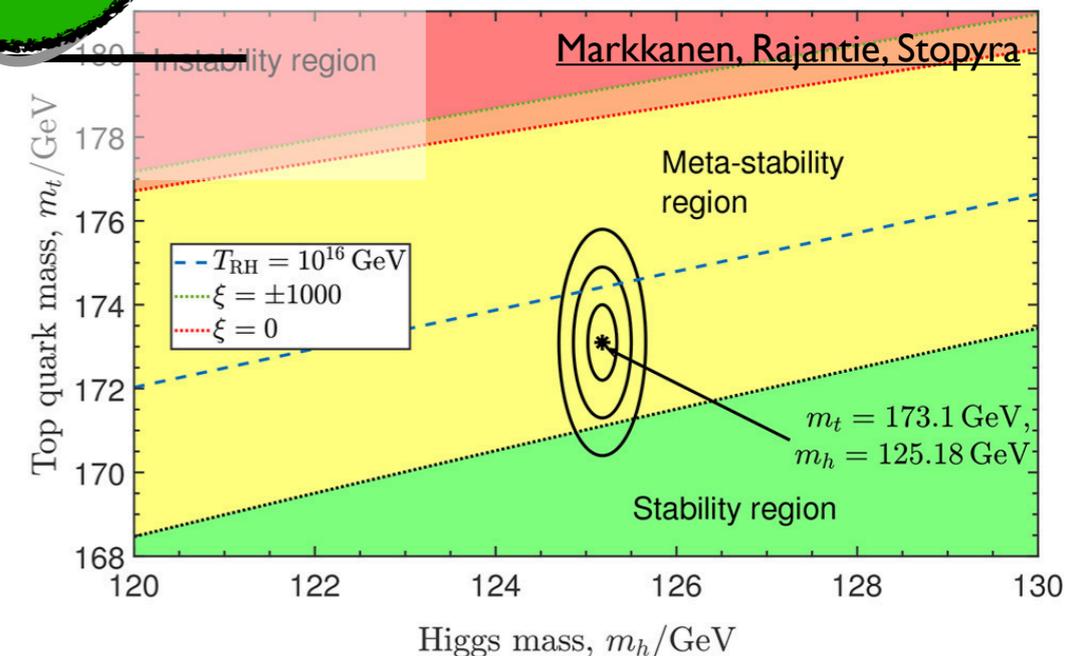
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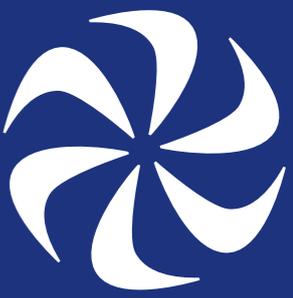
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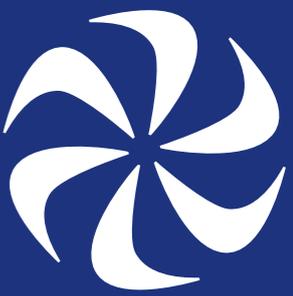
Can it interact with new physics to explain some of our most pressing new questions?



Potential and Pairs

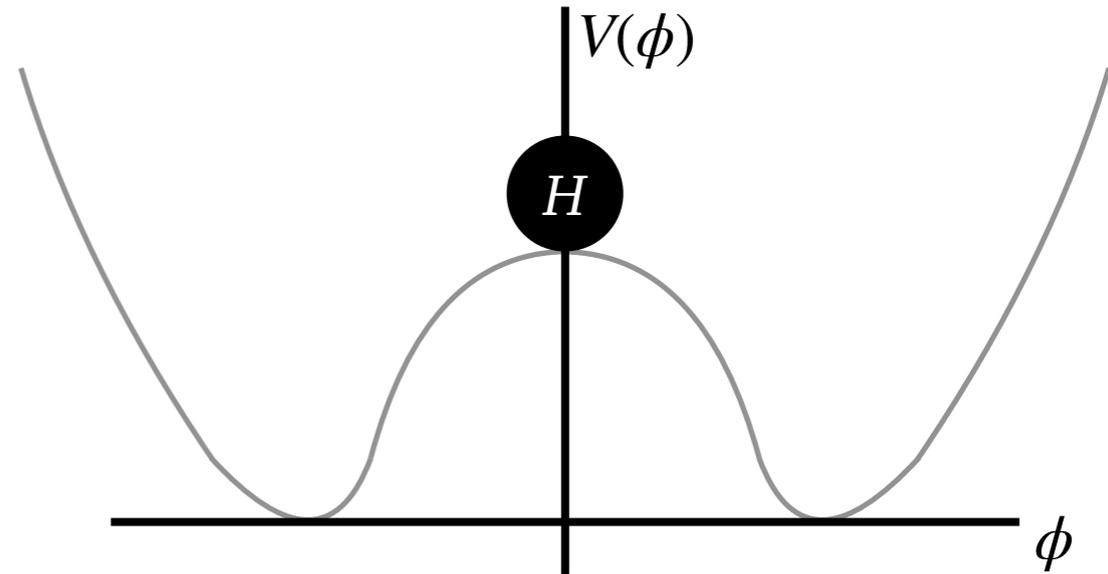


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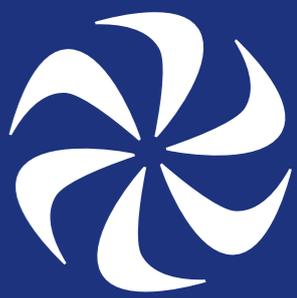


The SM Higgs potential is:

$$V(\phi) = -\mu^2\phi^2 + \lambda\phi^4$$



Potential and Pairs

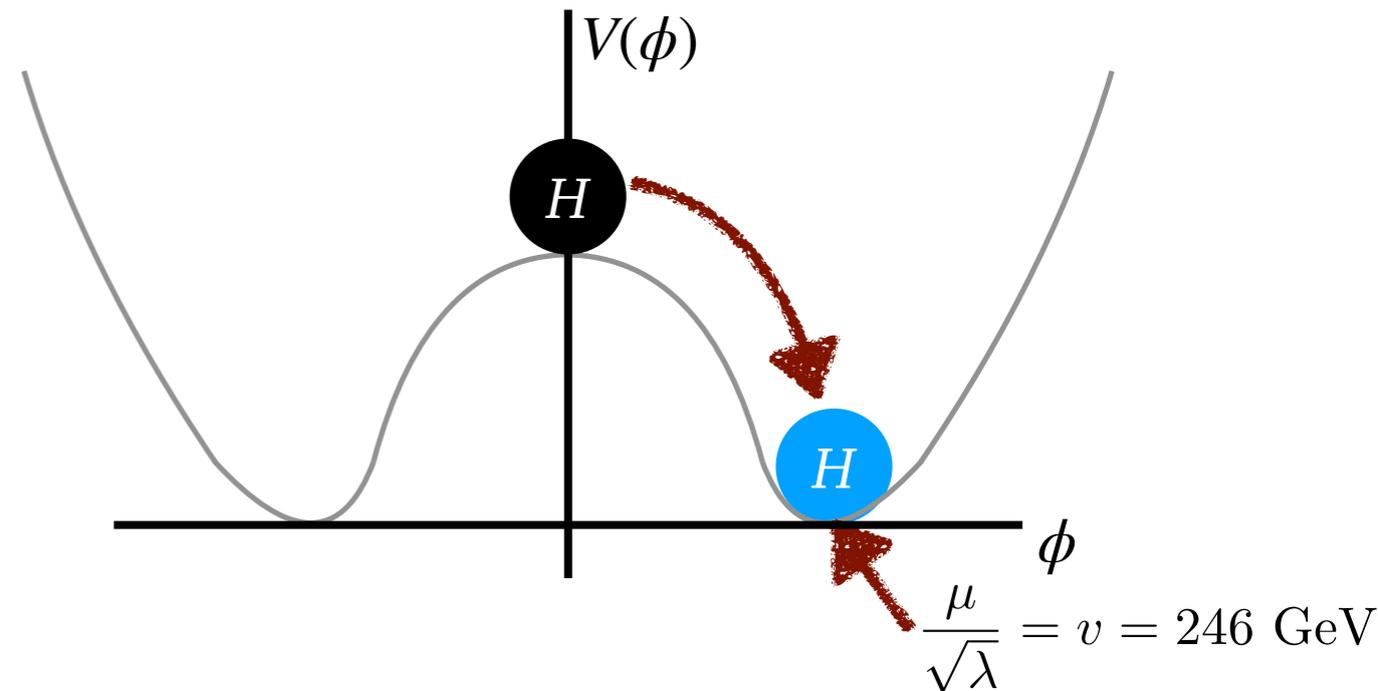


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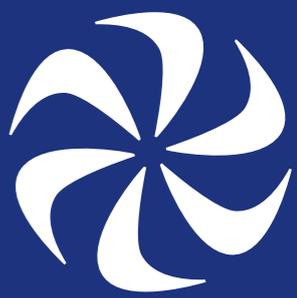
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Our universe lives in the minimum:

$$\begin{aligned} V &= V_0 + \lambda v^2 h^2 + \lambda v h^3 + \dots \\ &= V_0 + \frac{1}{2} m_H^2 h^2 + \frac{m_h^2}{2v^2} v h^3 + \dots \end{aligned}$$



Potential and Pairs



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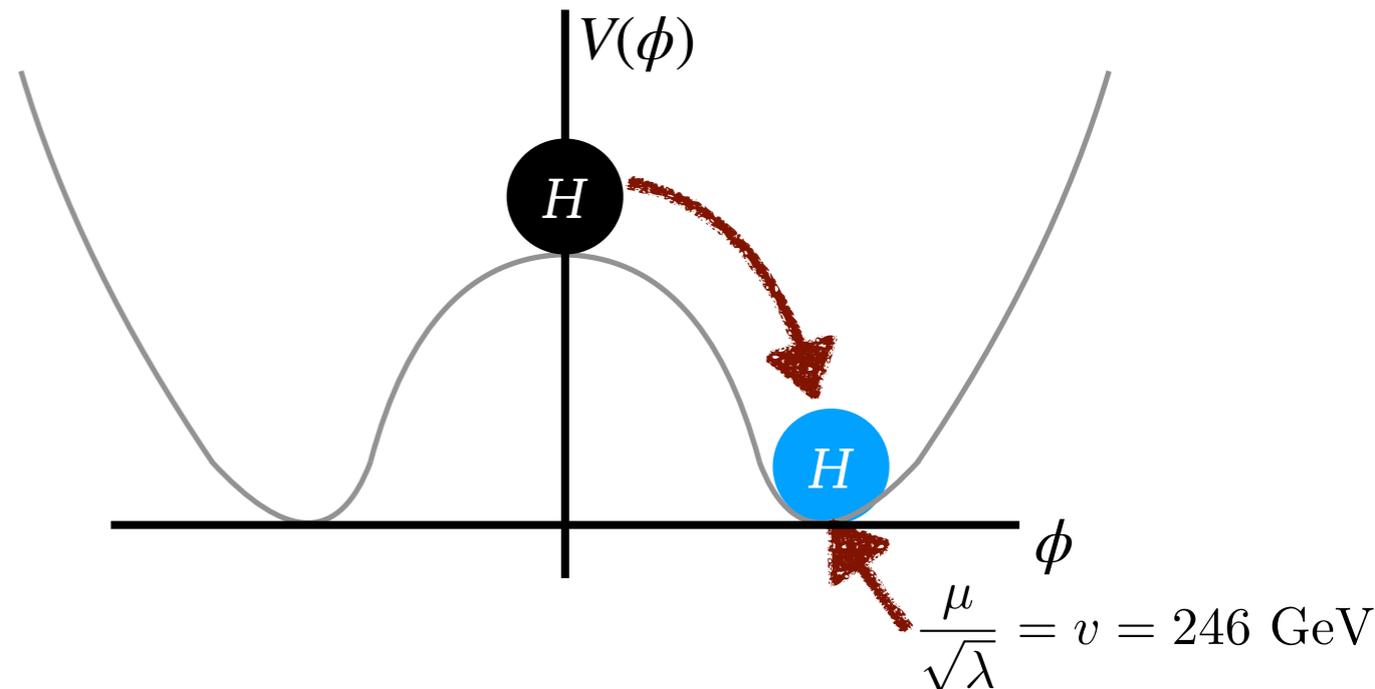
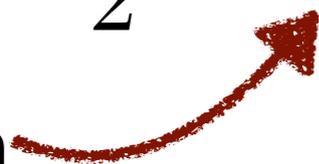
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Mass term



Potential and Pairs



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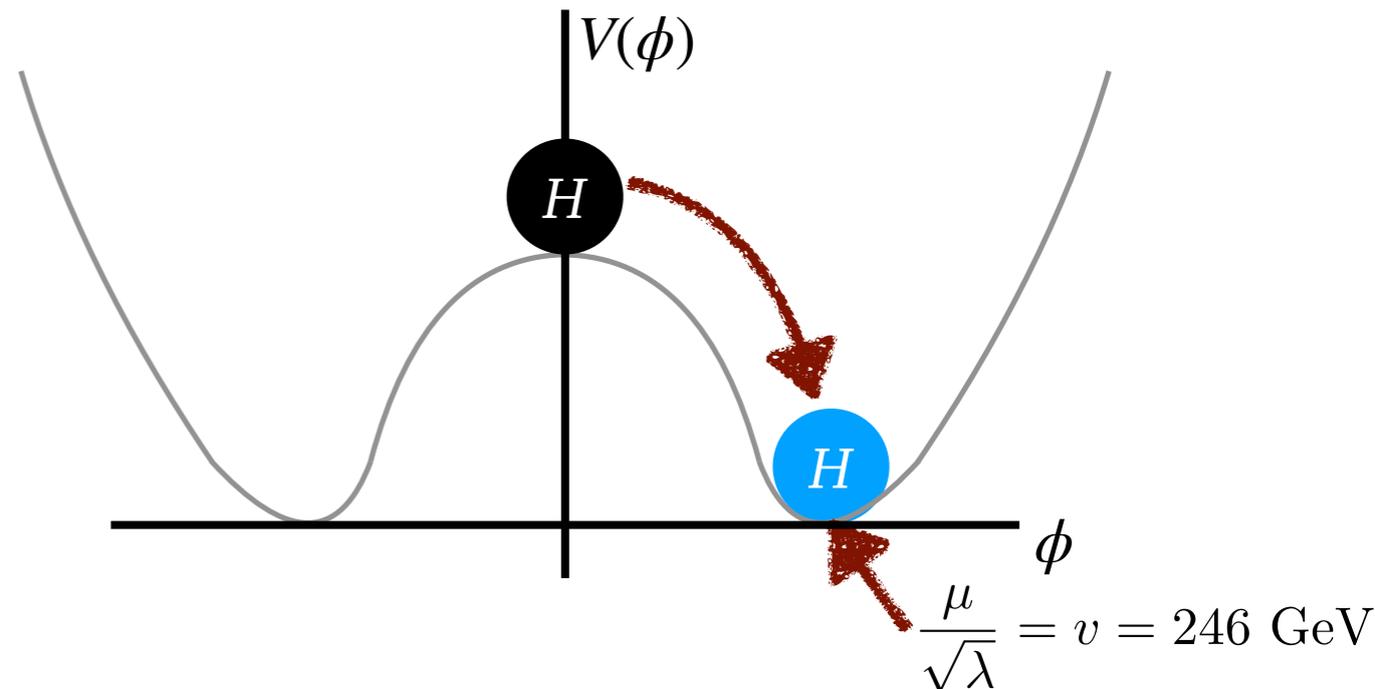
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Mass term \rightarrow Self-interaction



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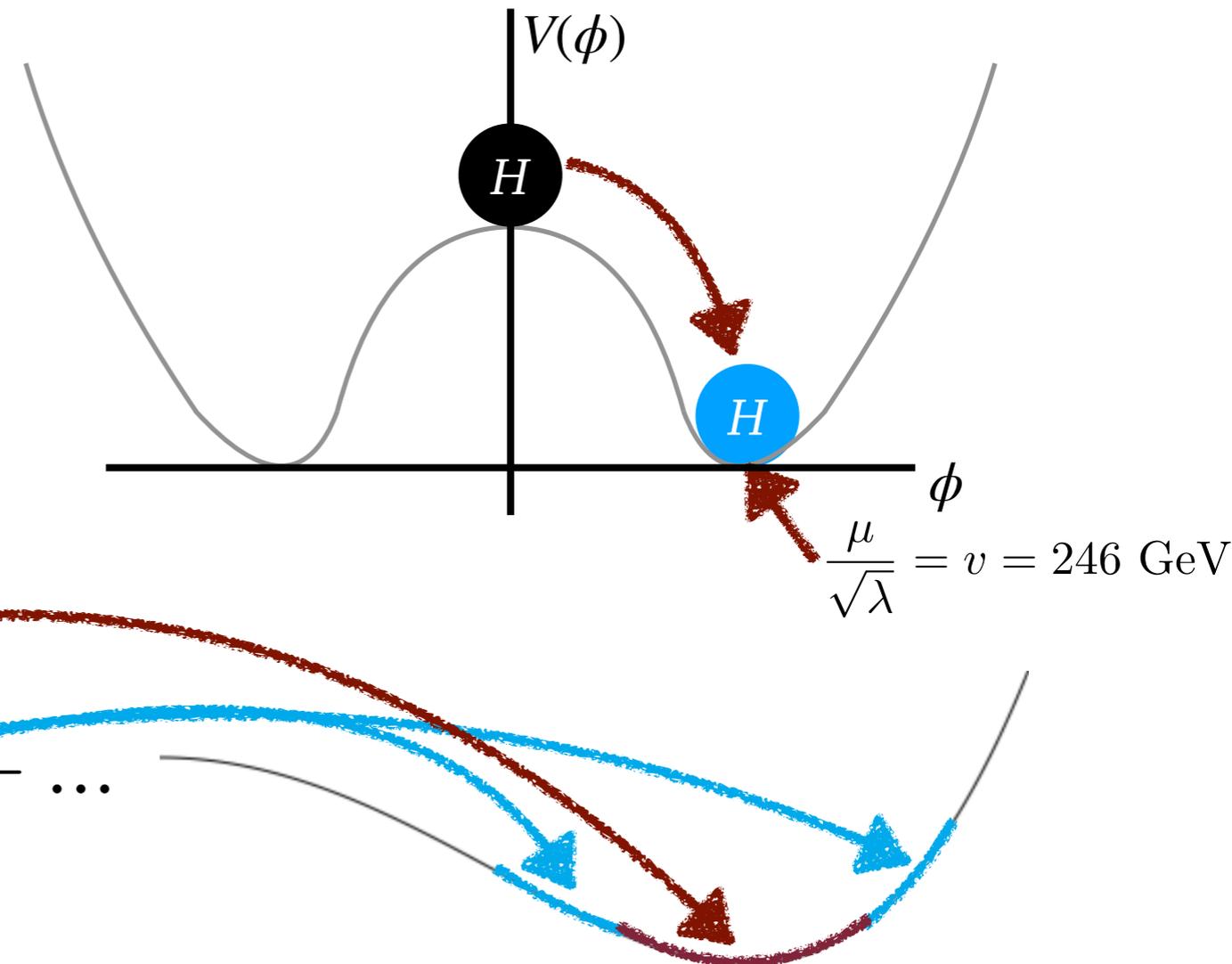
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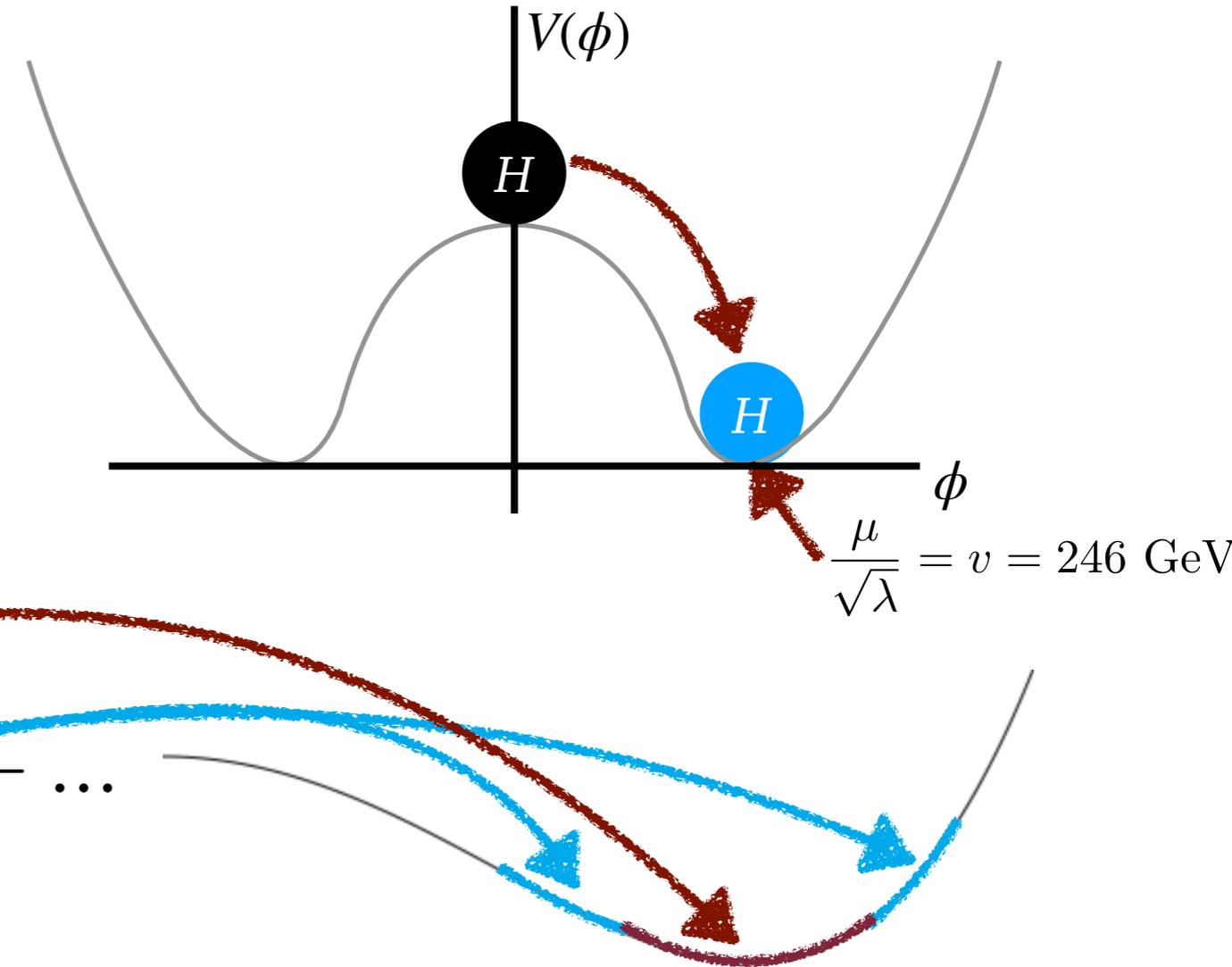
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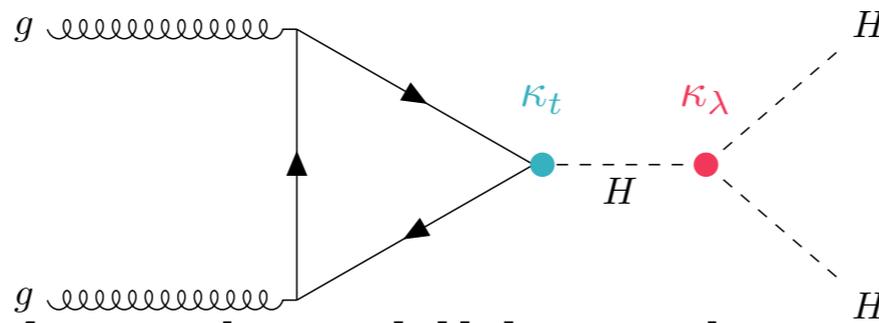
Mass term

Self-interaction



$$\lambda_{HHH}^{SM} = \frac{m_h^2}{2v^2}$$

$$\kappa_\lambda = \frac{\lambda_{HHH}}{\lambda_{HHH}^{SM}}$$



SM predicts HH production,
and allows to measure potential

Potential and Pairs



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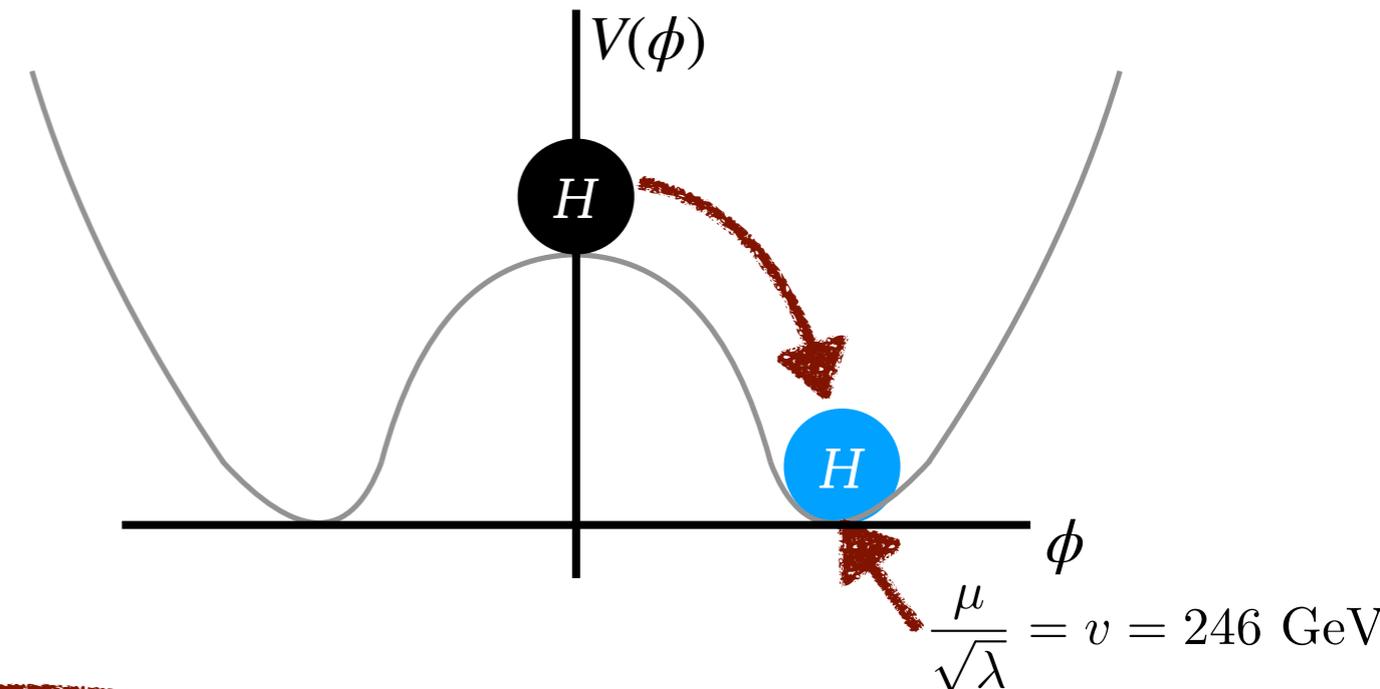
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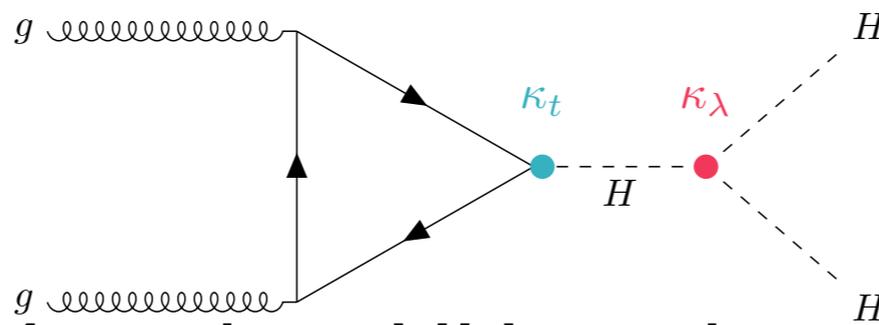
Mass term Self-interaction



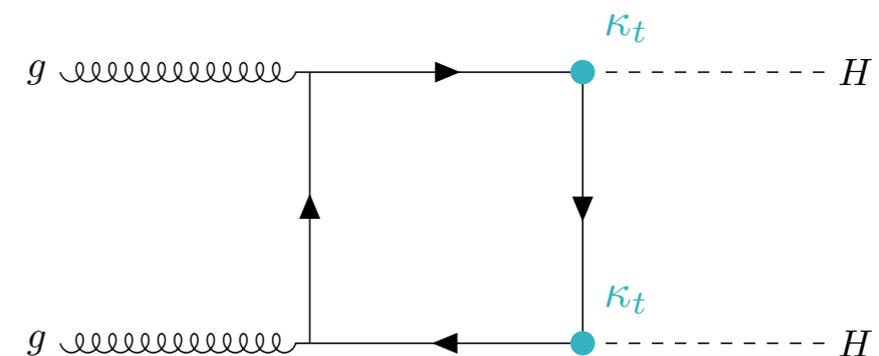
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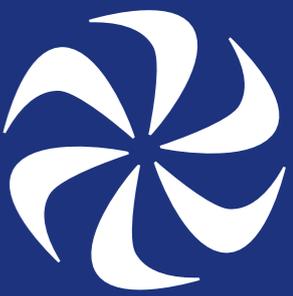
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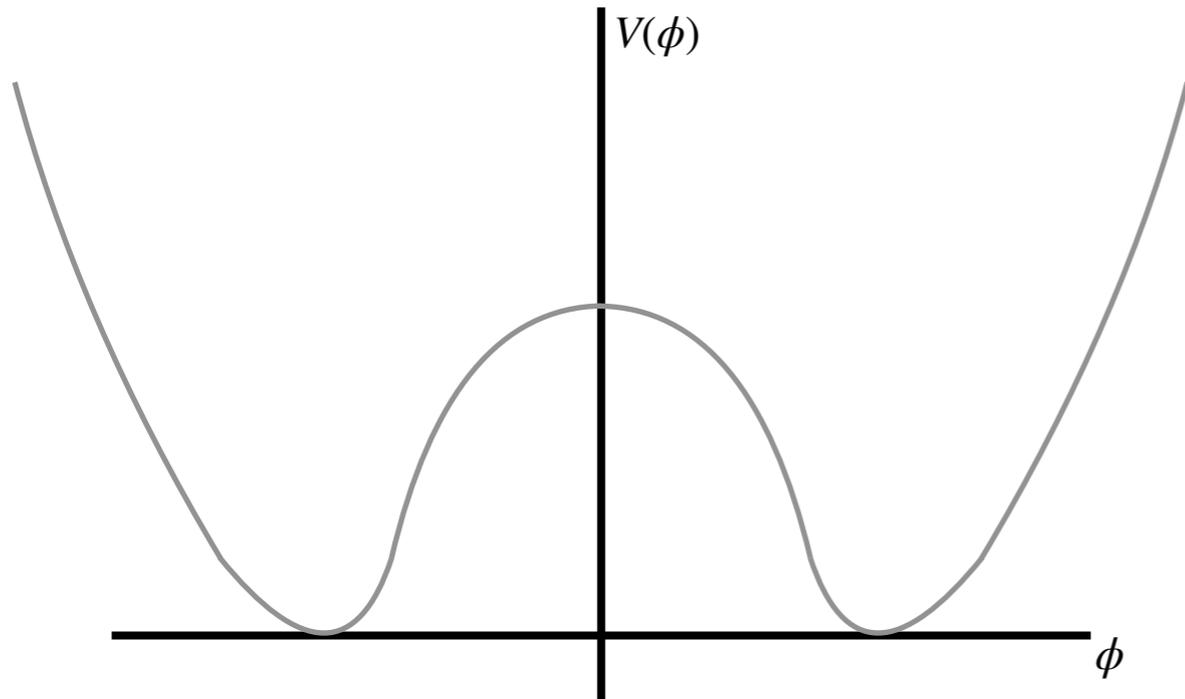
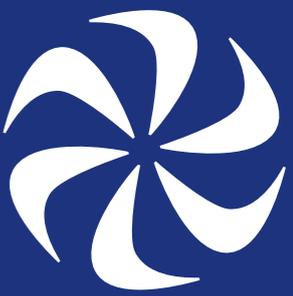
But interference means x-sec is very low



Potential Higgs Potentials

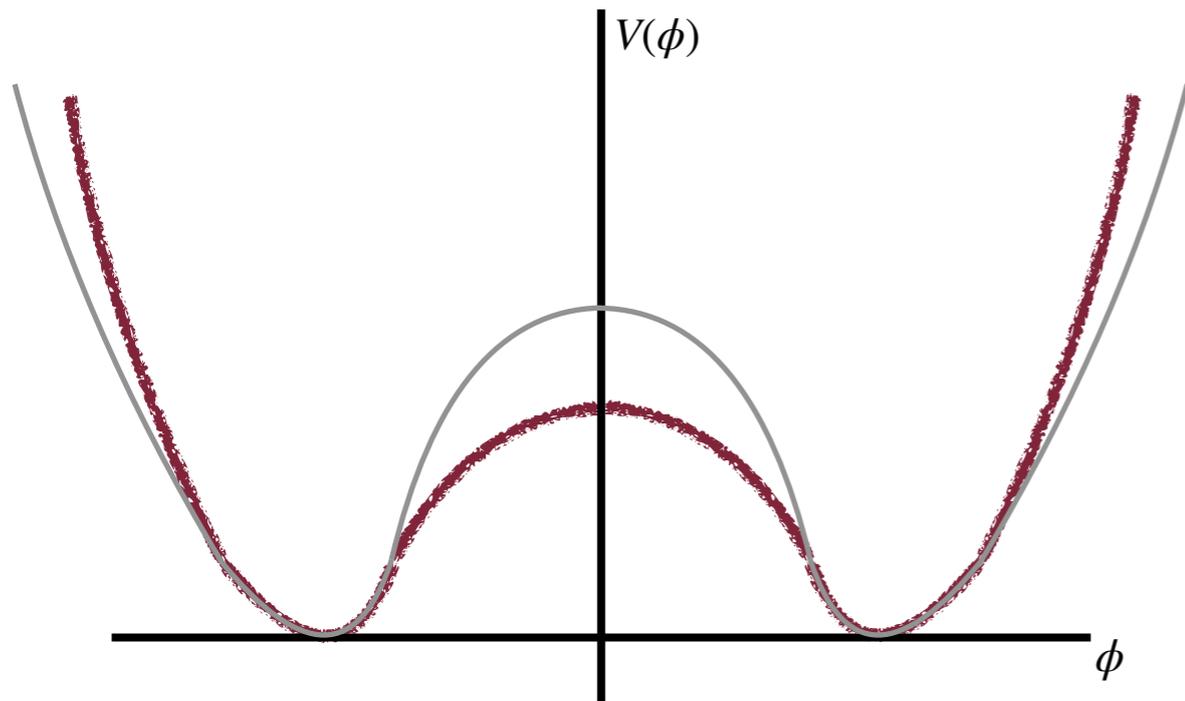
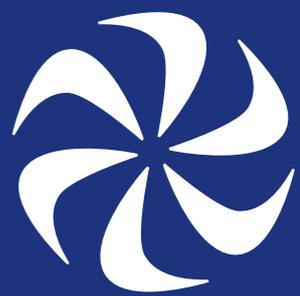


Potential Higgs Potentials



We have a prediction for the shape
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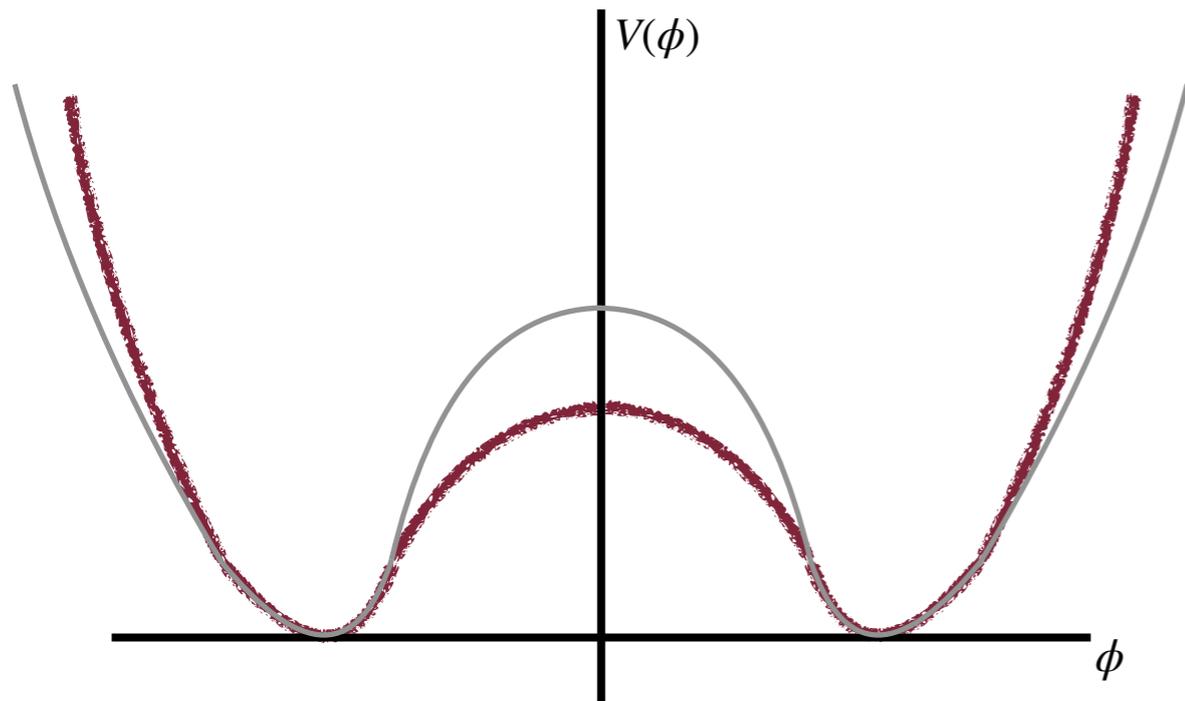
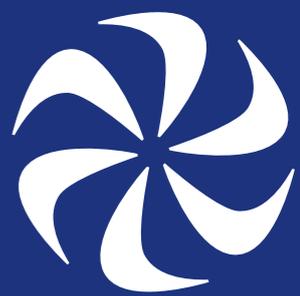
Potential Higgs Potentials



We have a prediction for the shape
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But **other shapes** of the potential
still allow for
Electroweak Symmetry Breaking

Potential Higgs Potentials

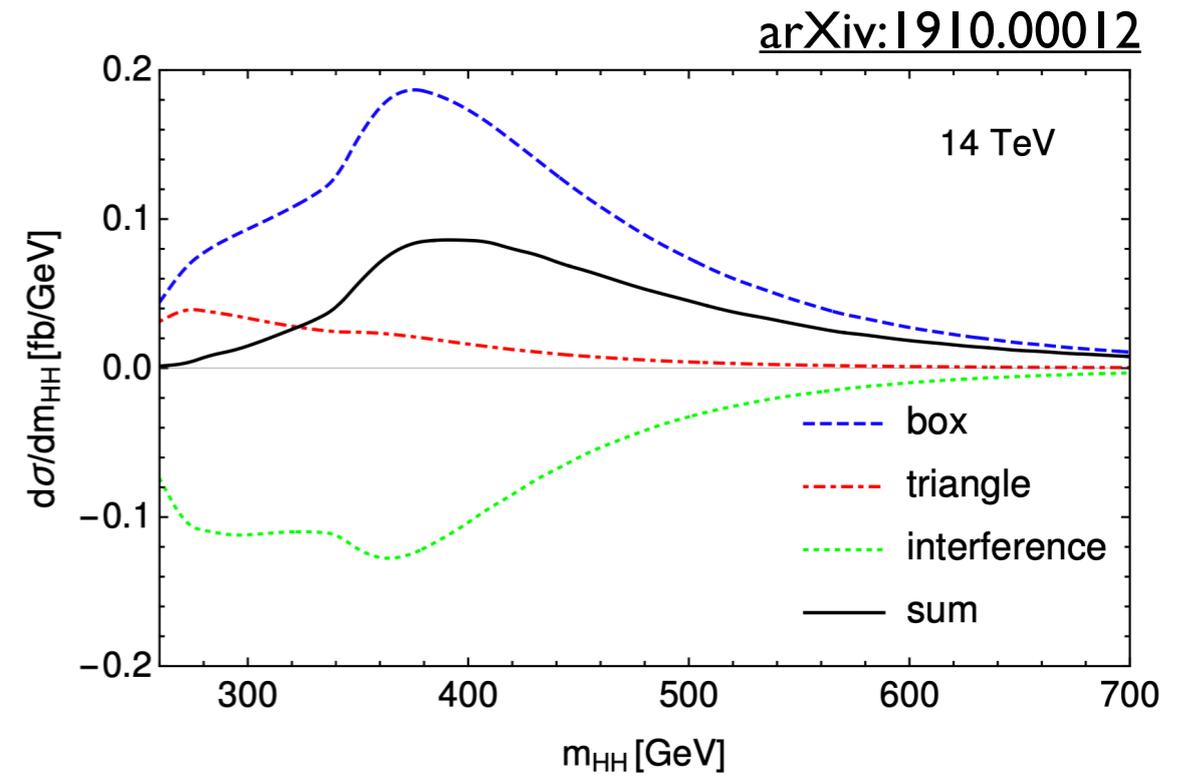
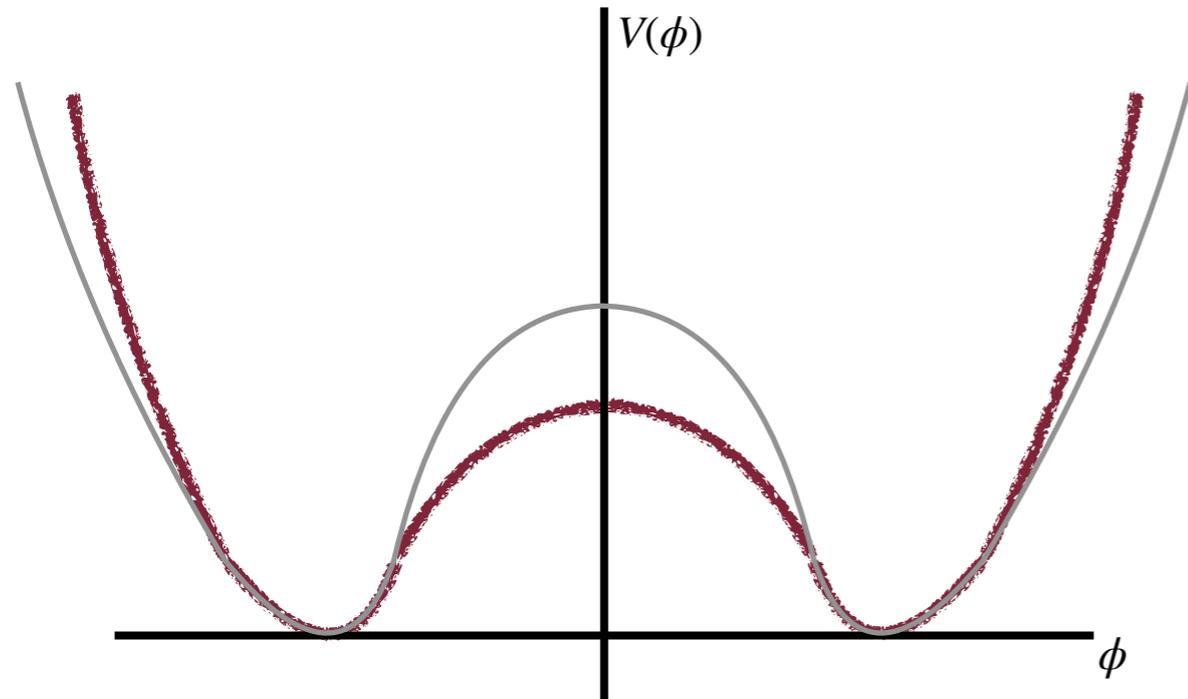
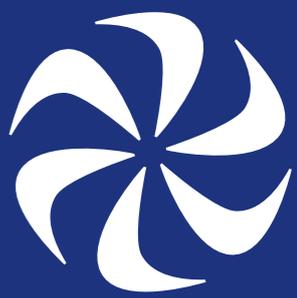


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Other shapes could reveal evidence
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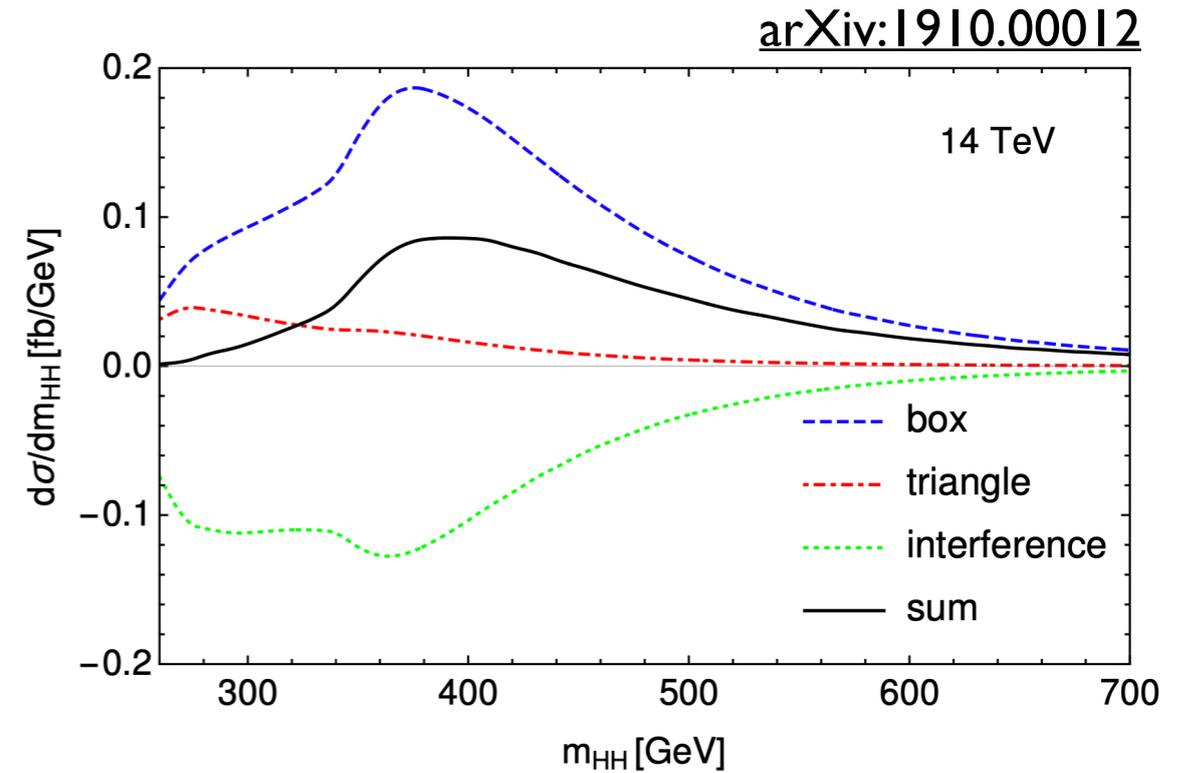
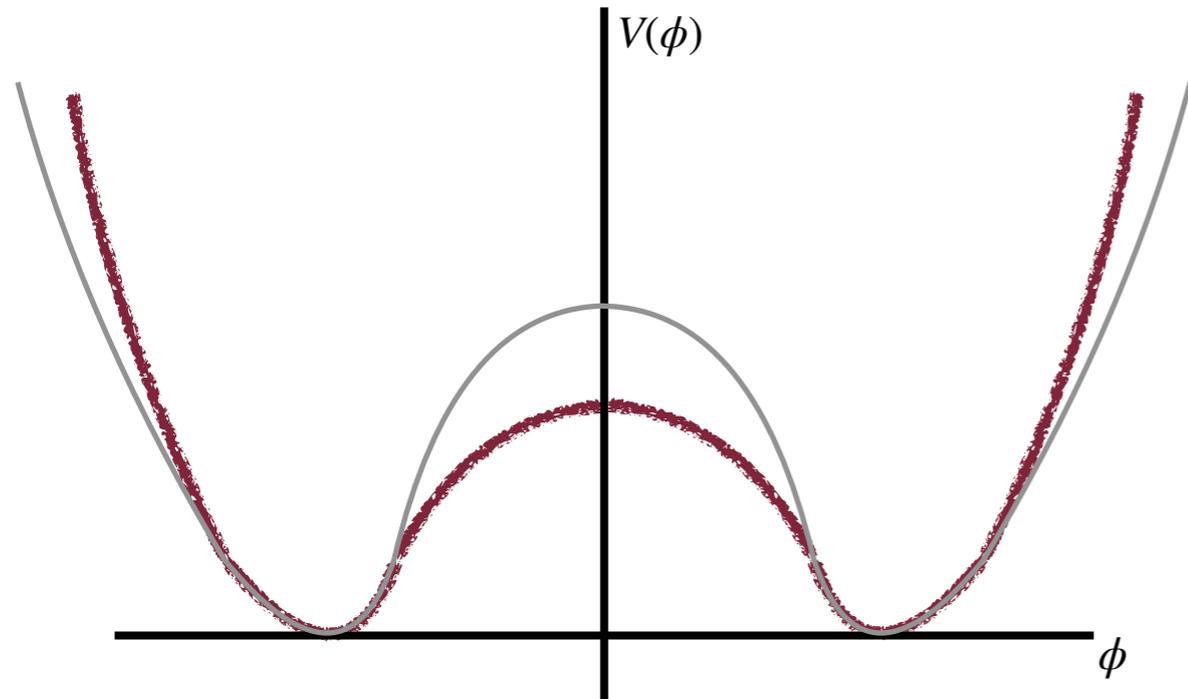
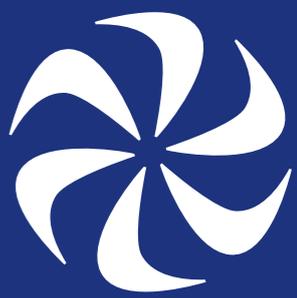


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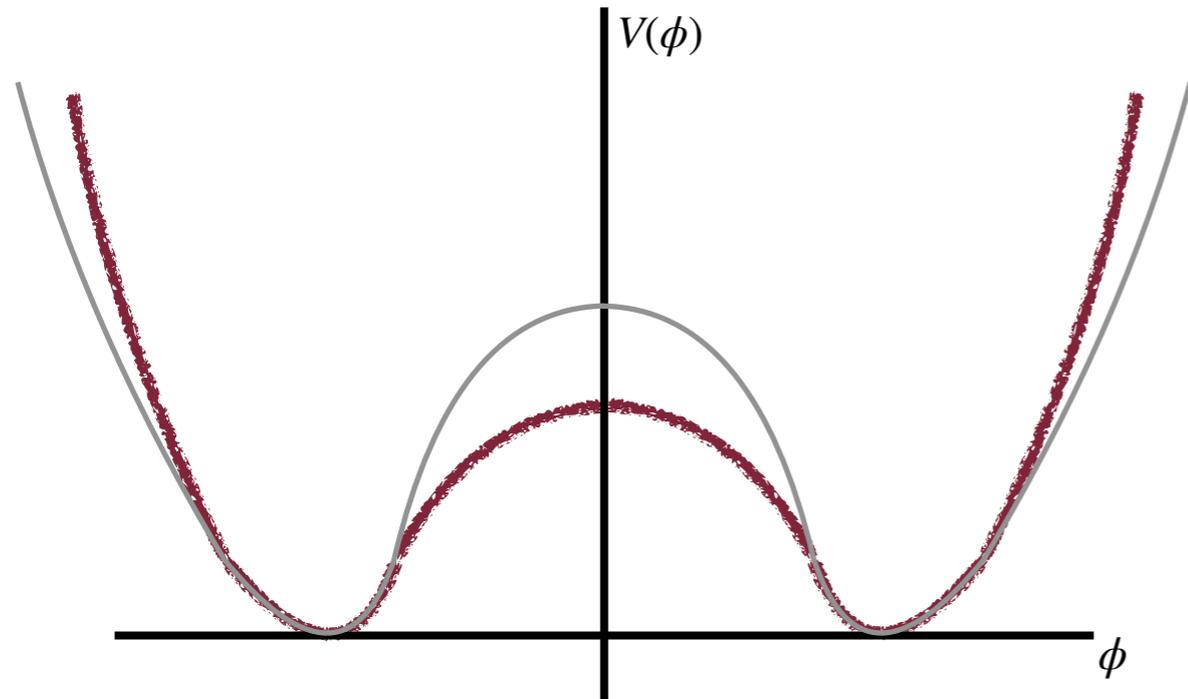
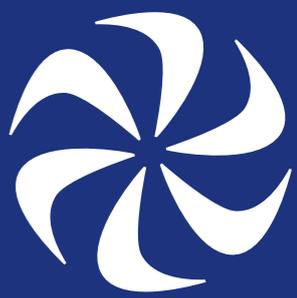
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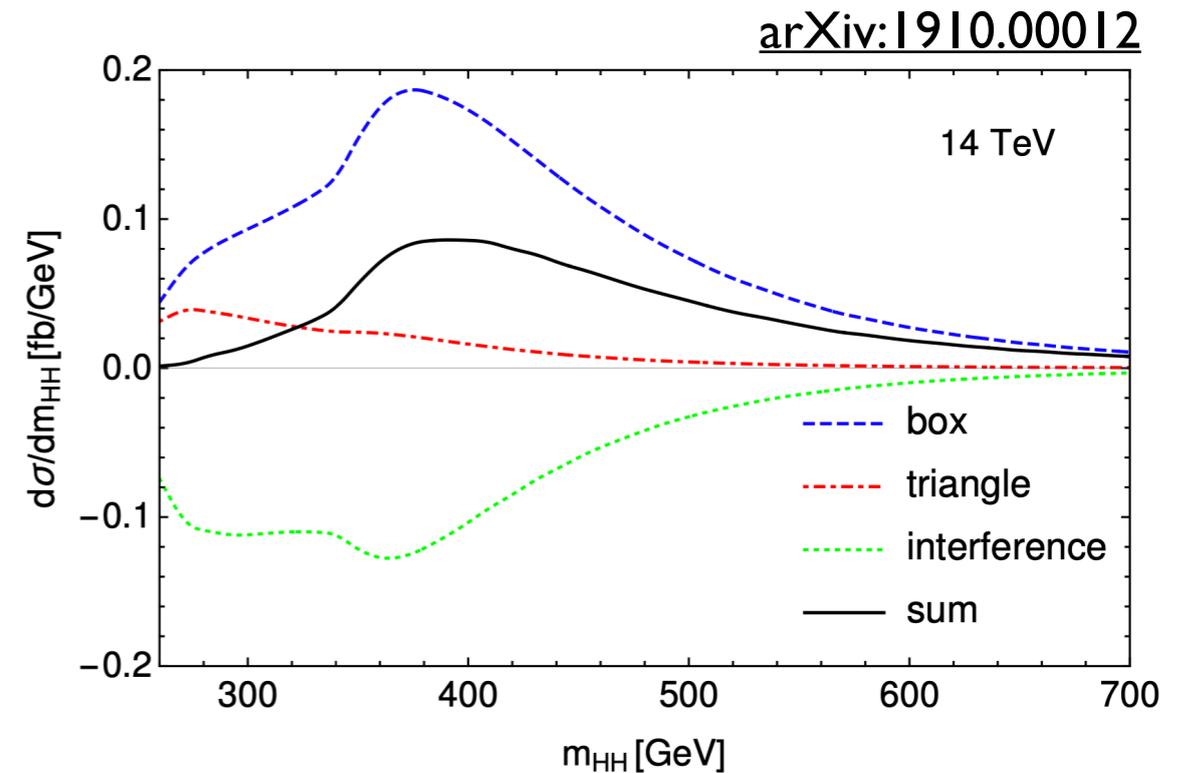
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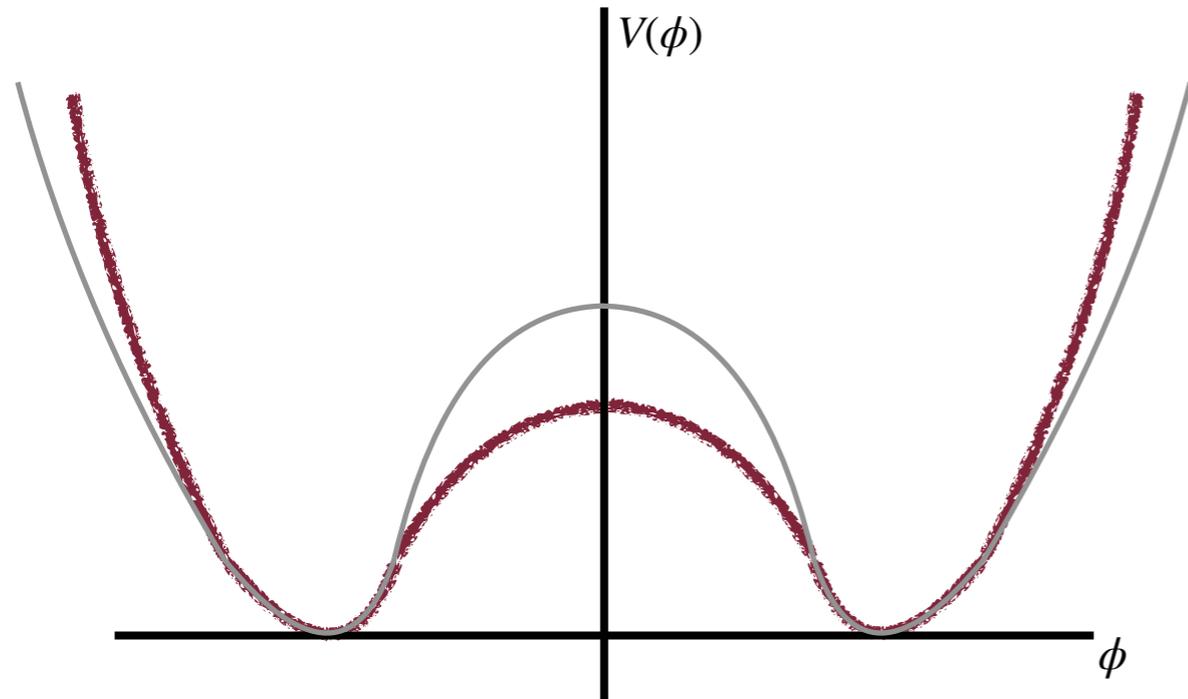
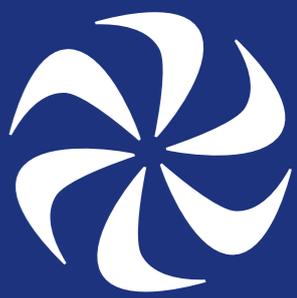
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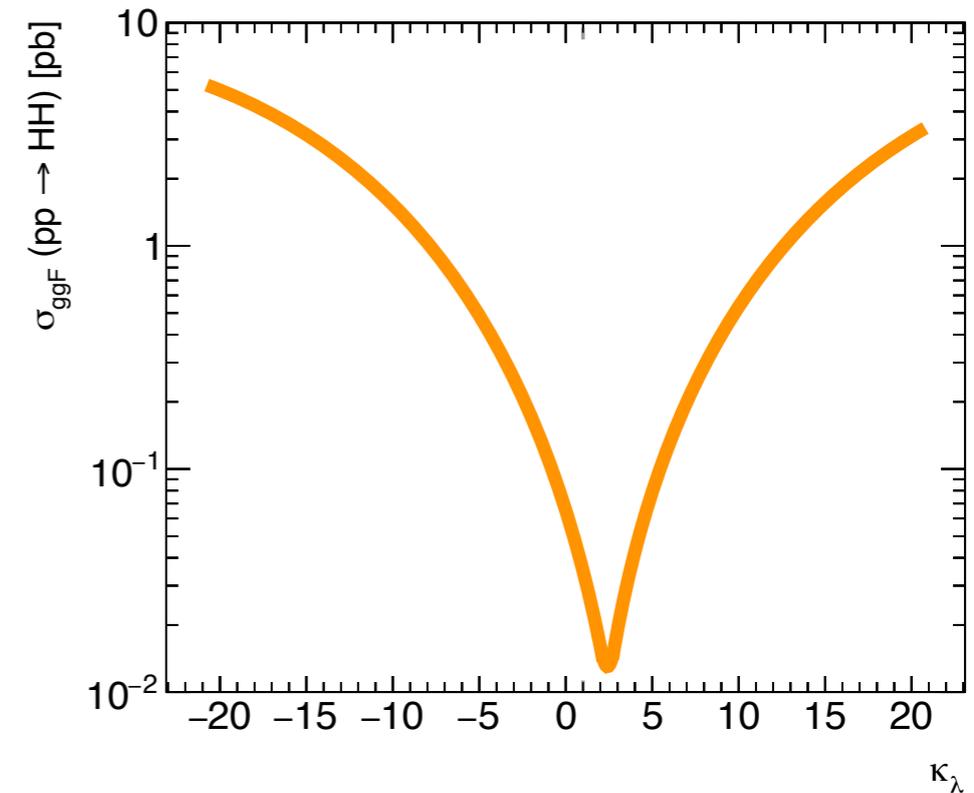
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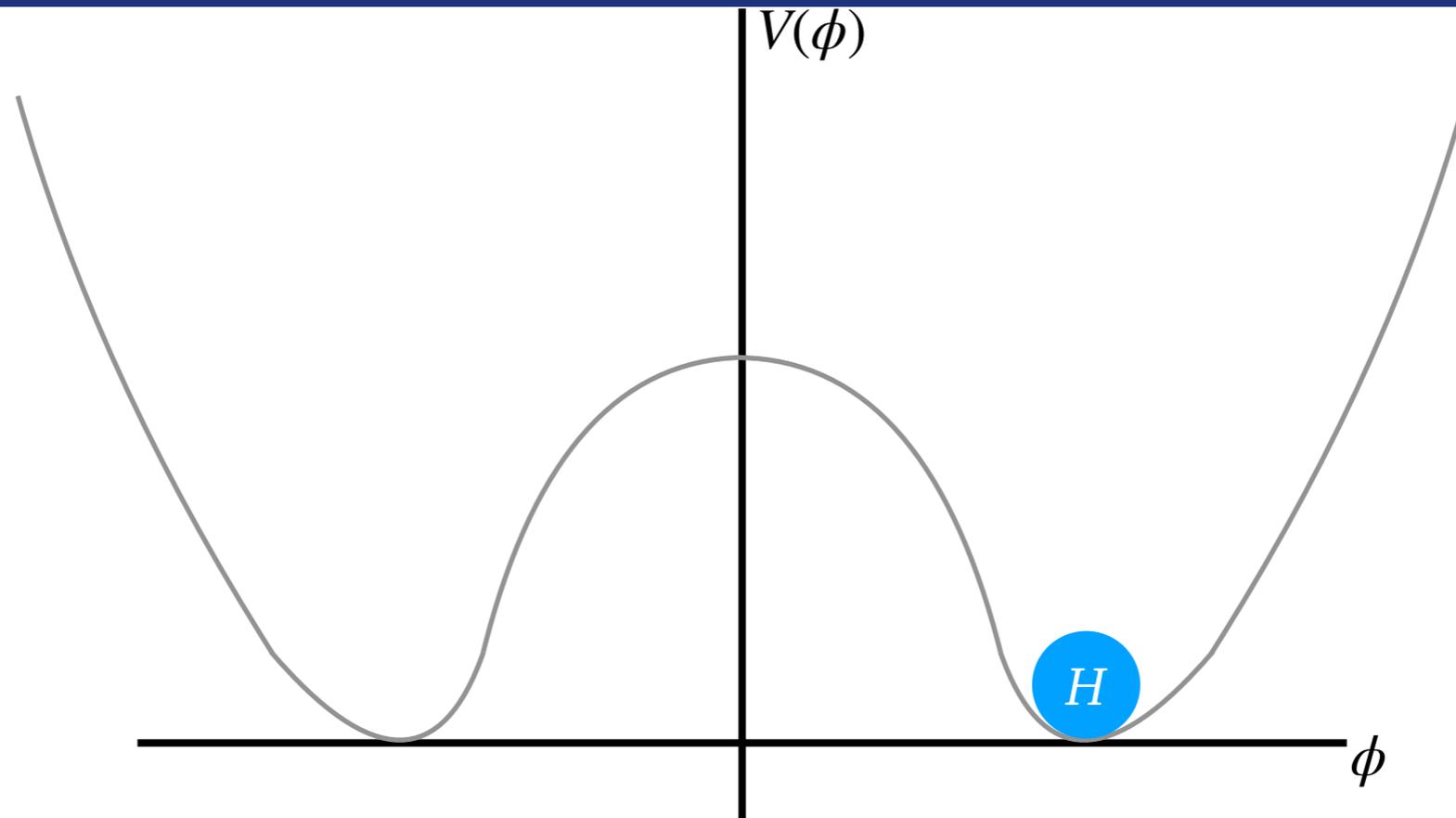
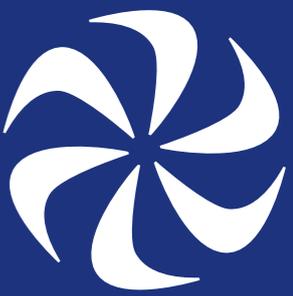
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Cross-section also depends on κ_λ : discoverable now!

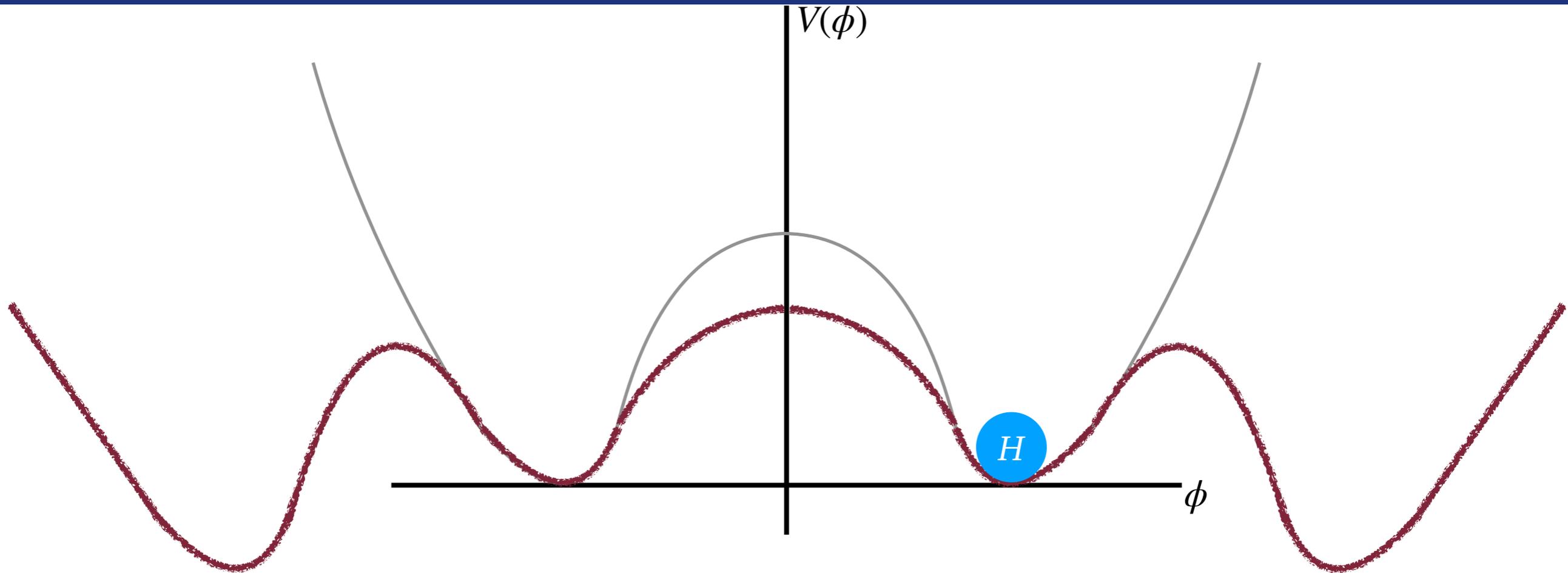
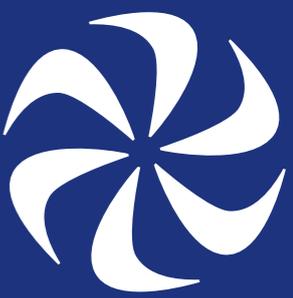
Is the Universe Stable?



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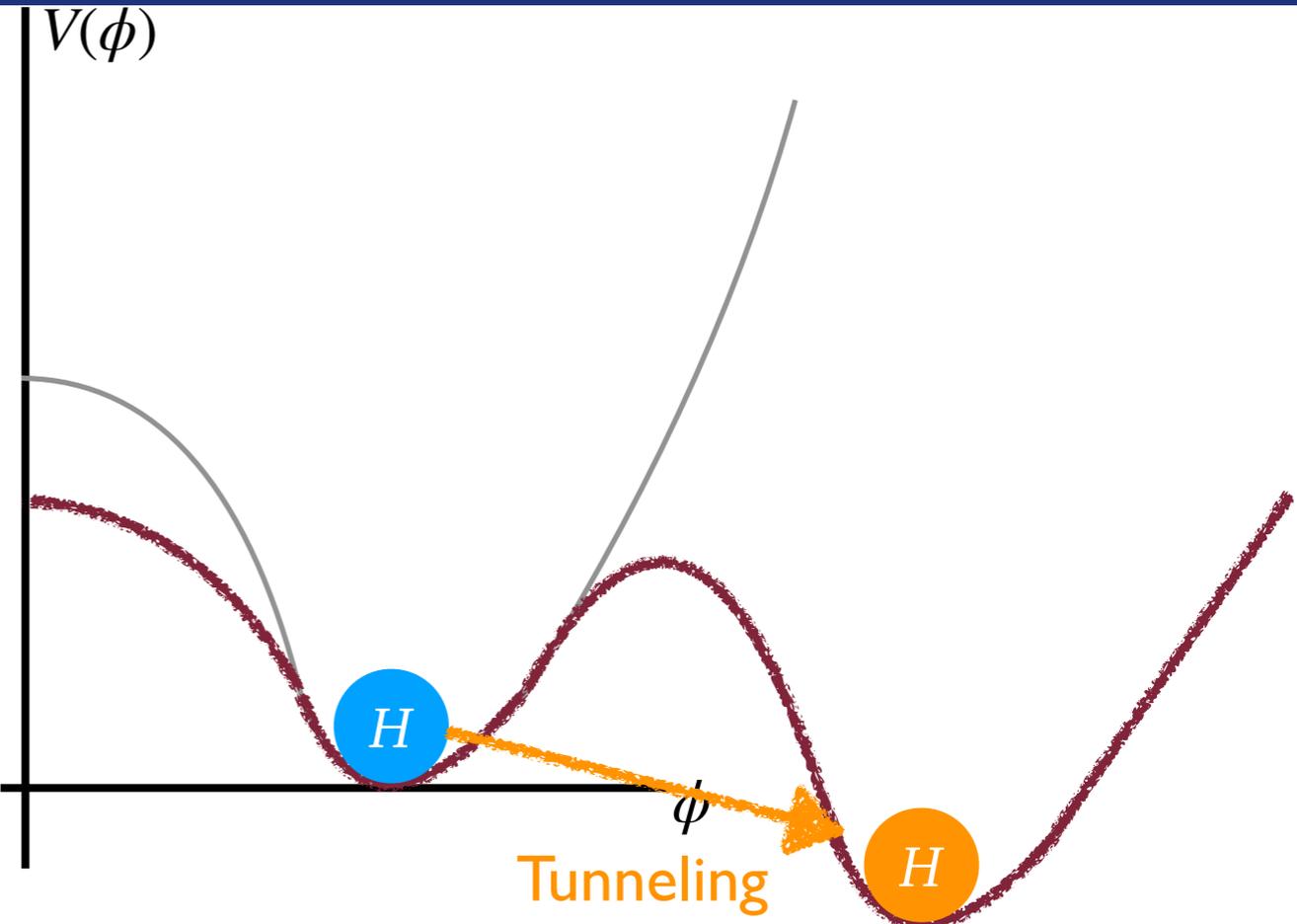
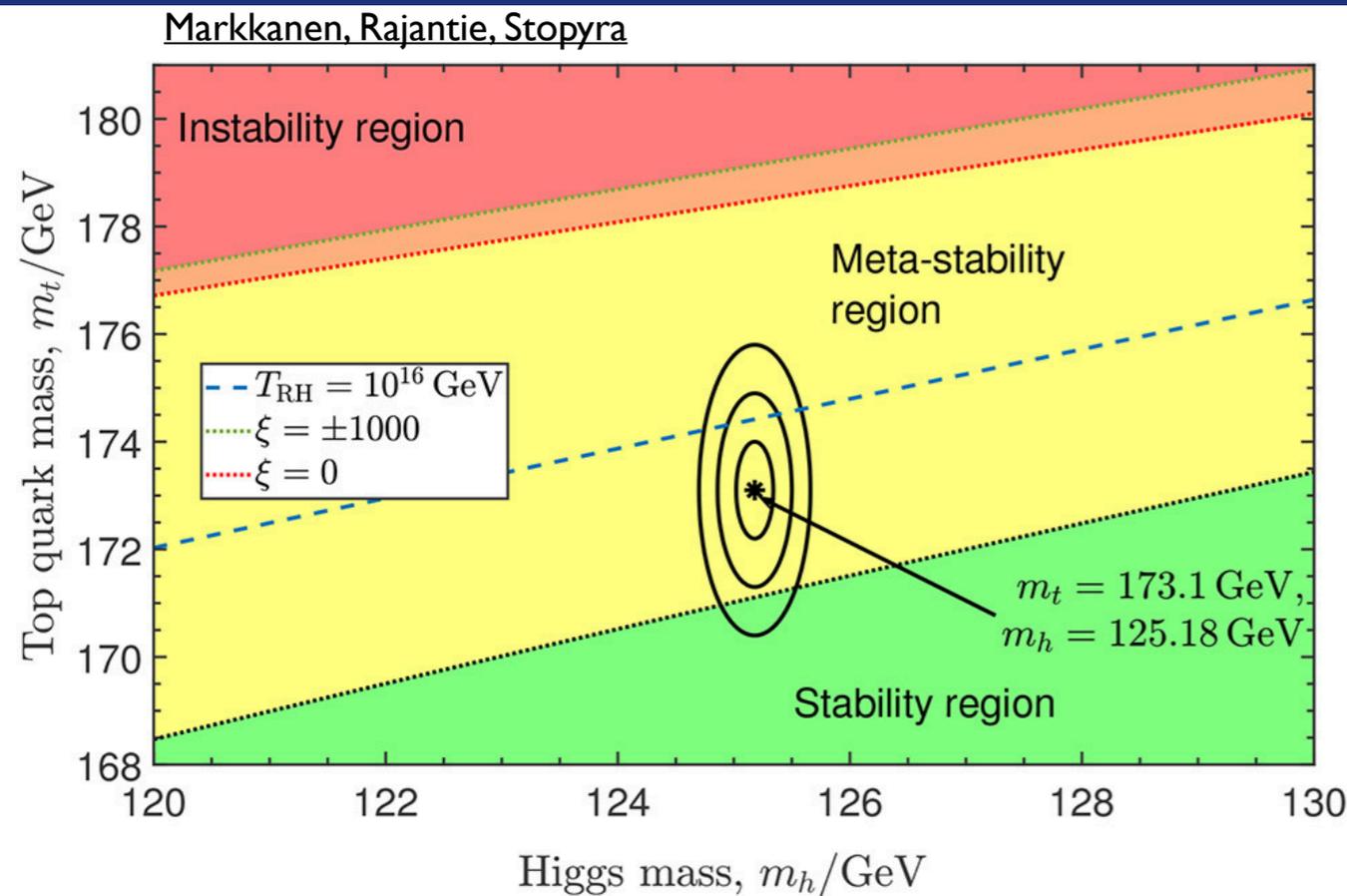
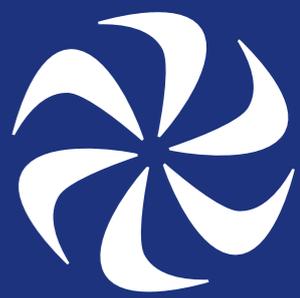


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Quantum corrections (i.e. interactions with other particles) mean that the effective shape can be quite different from \mathcal{L}

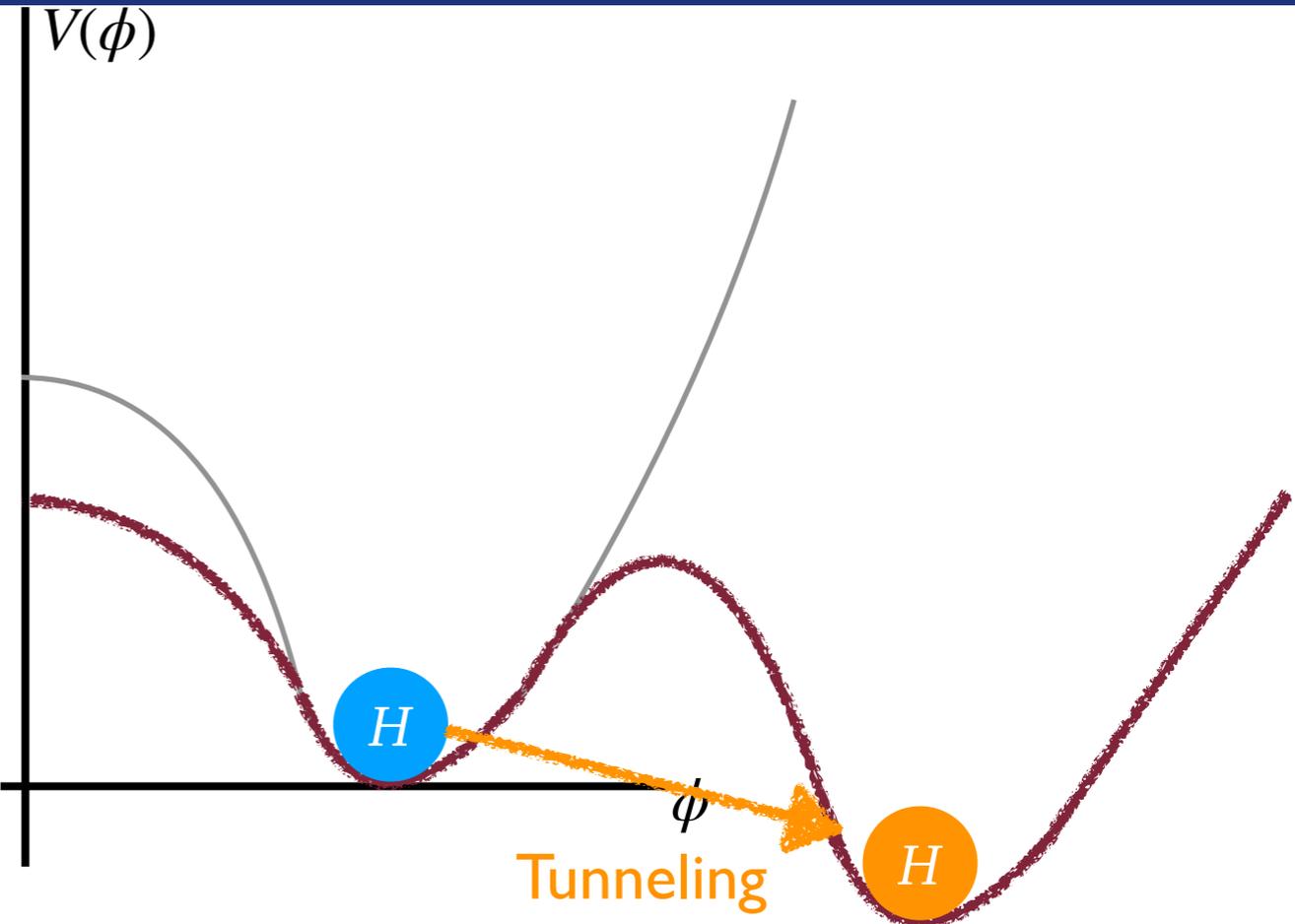
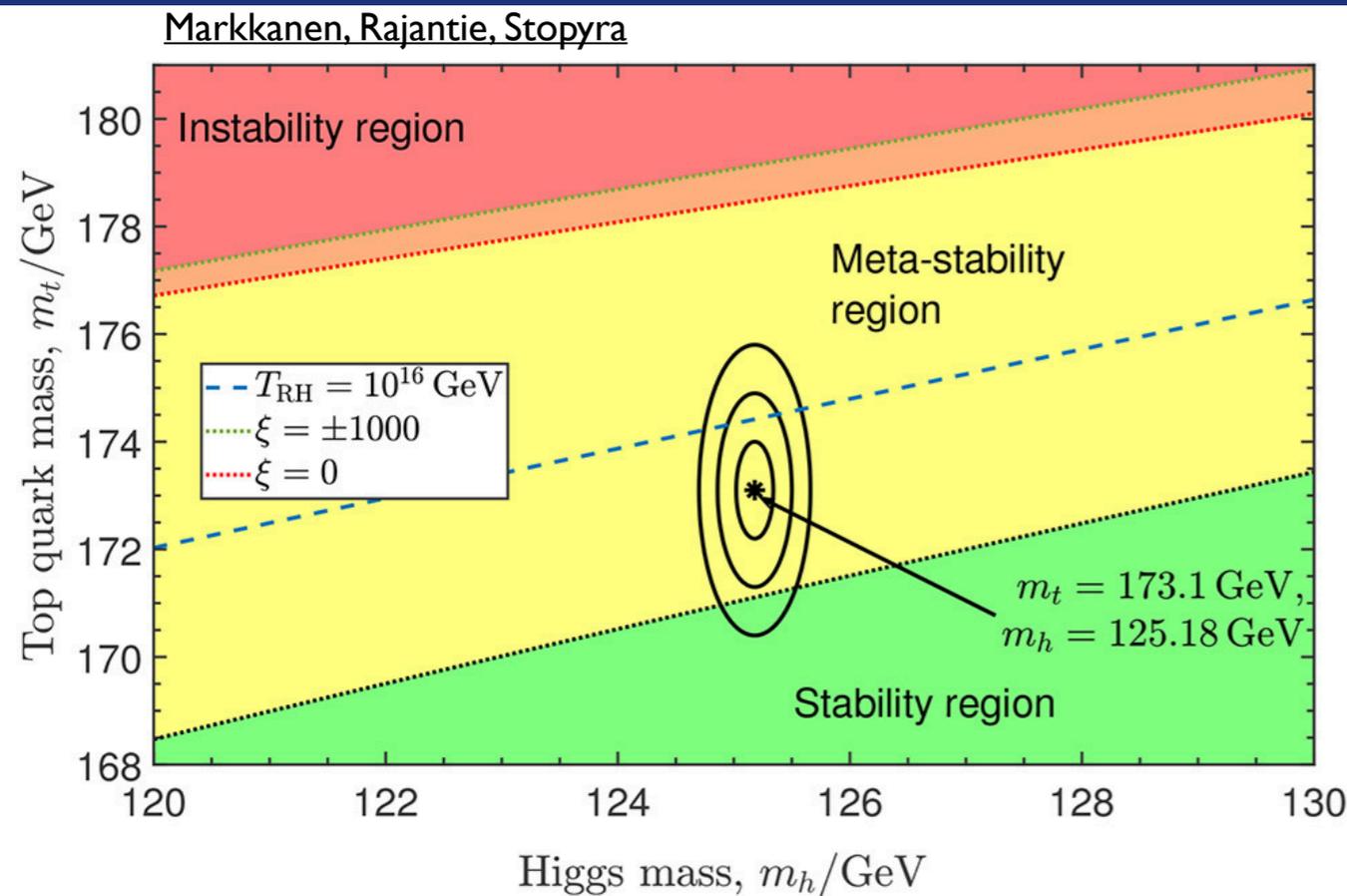
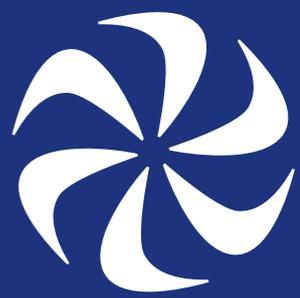
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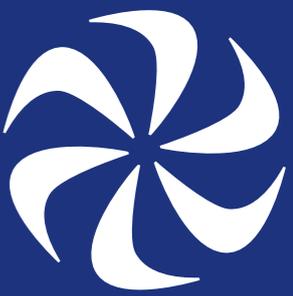


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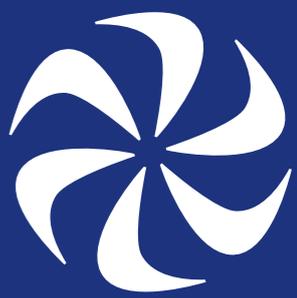
Measuring the potential as best as we can is critical: BSM physics can move our universe between stability and instability

Baryogenesis

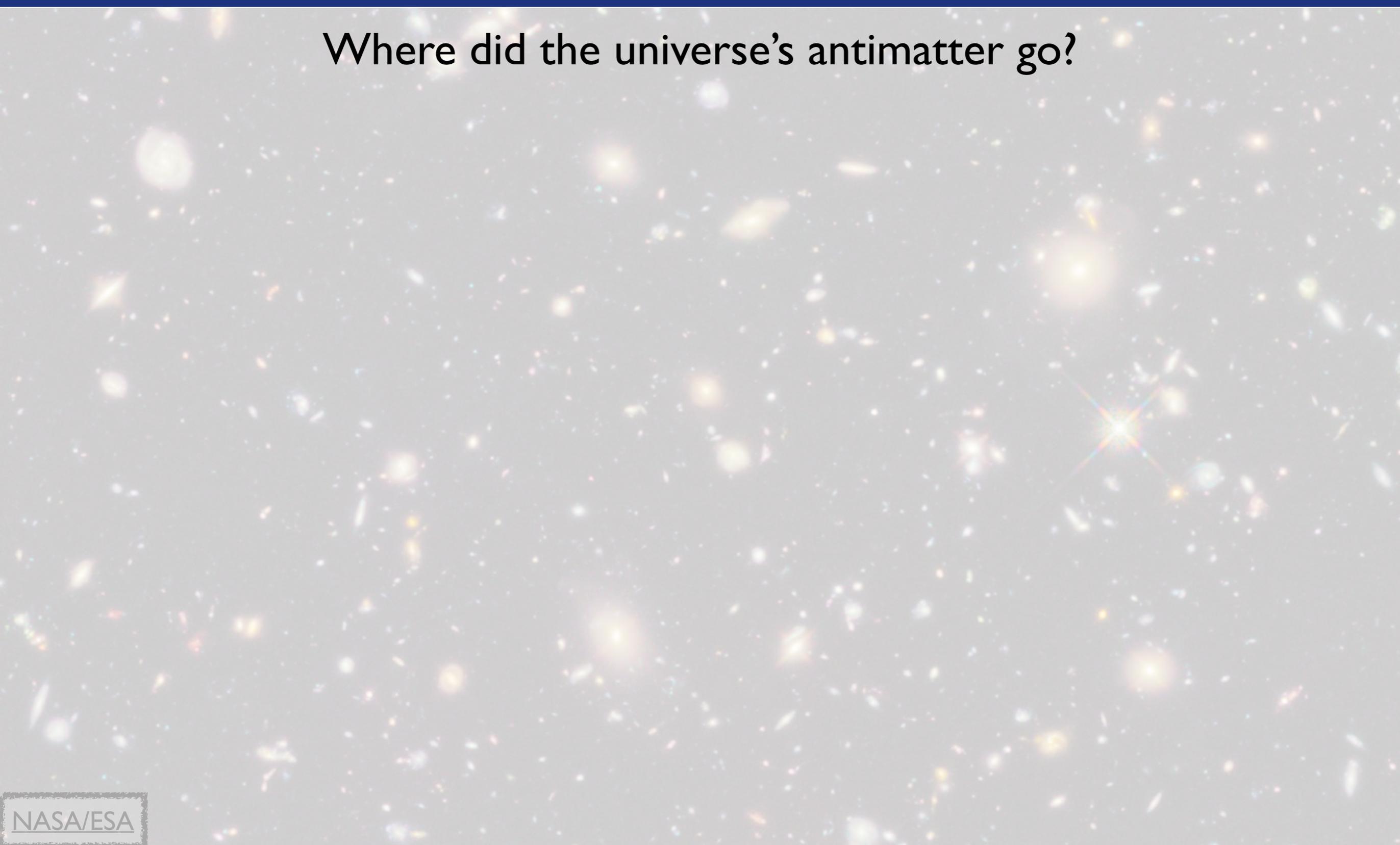


NASA/ESA

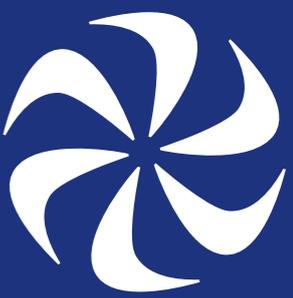
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Where did the universe's antimatter go?



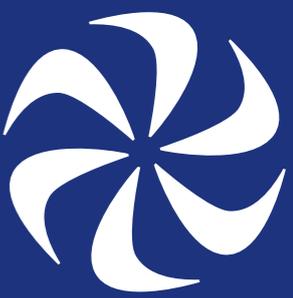
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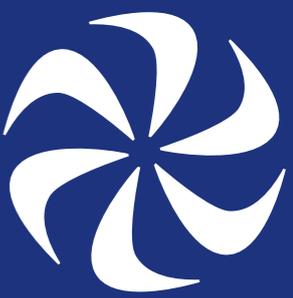


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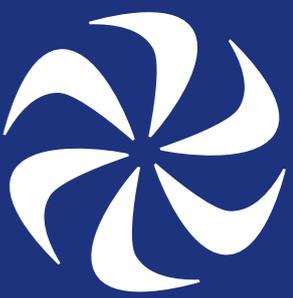
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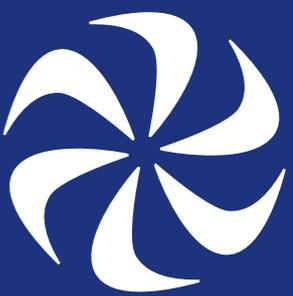
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Measuring the Higgs potential critical to test this possibility!

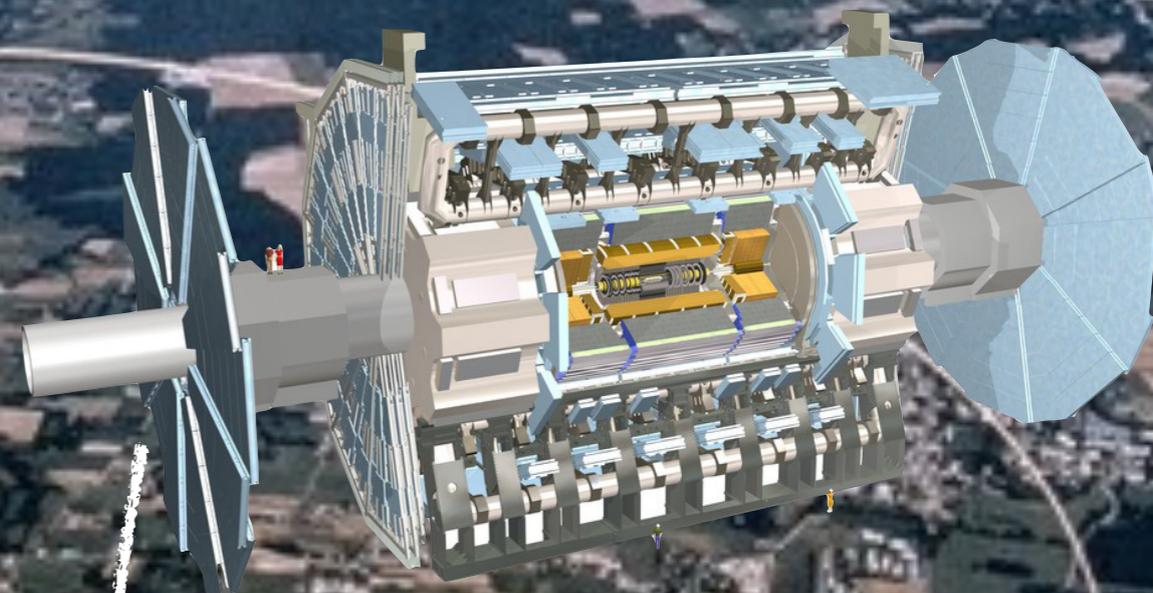
The Higgs Potential Today



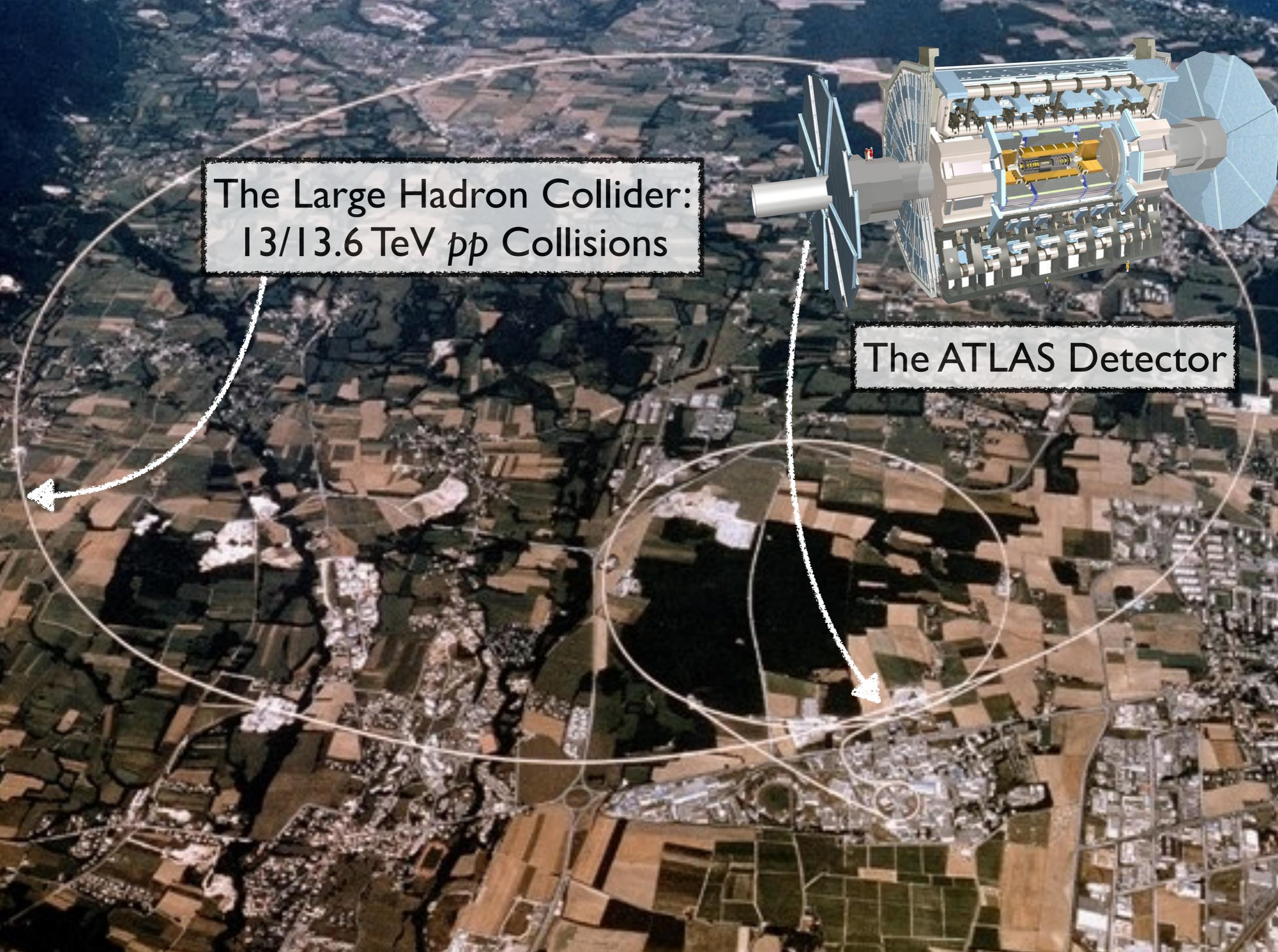
The Large Hadron Collider:
13/13.6 TeV pp Collisions



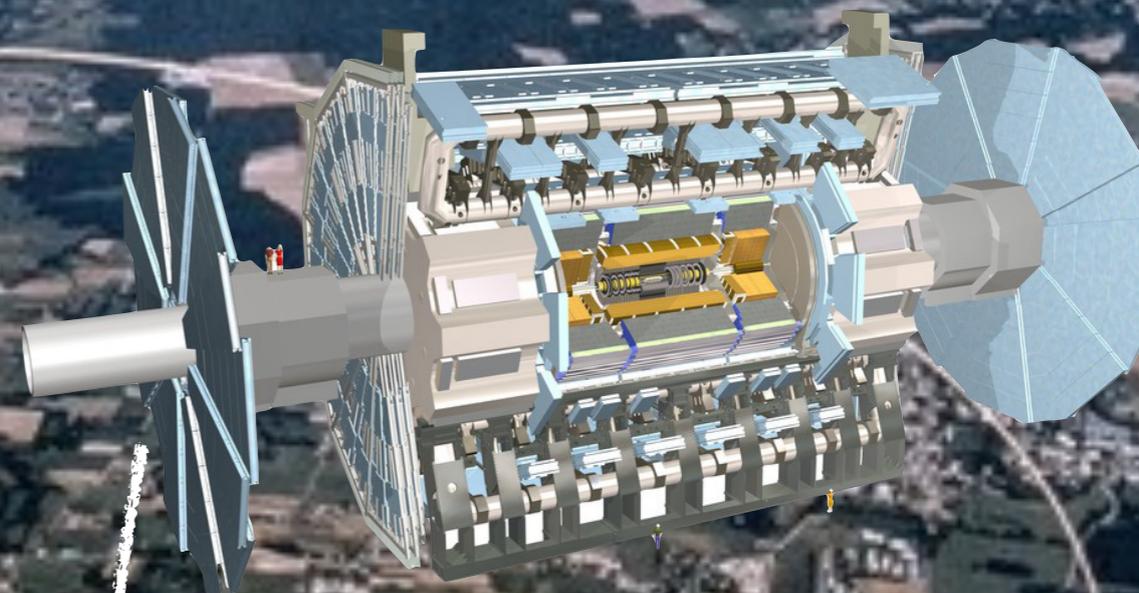
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The ATLAS Detector

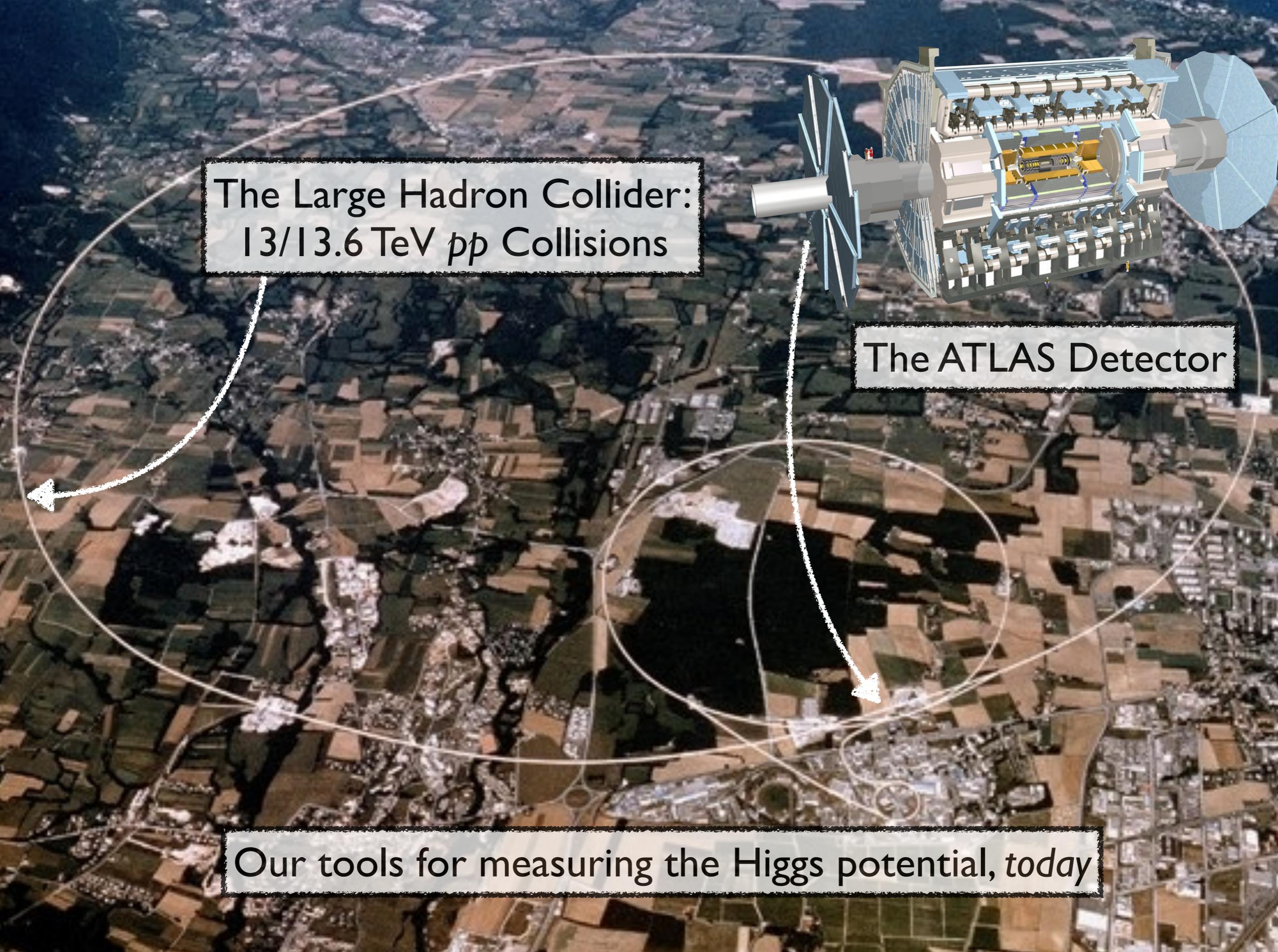


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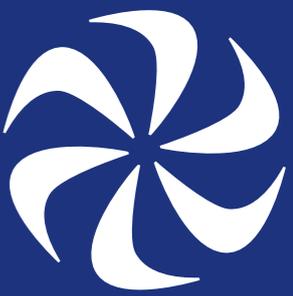


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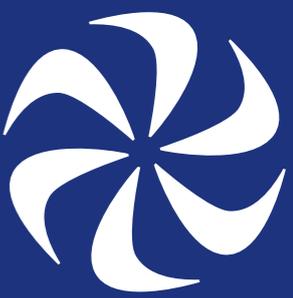
Our tools for measuring the Higgs potential, *today*



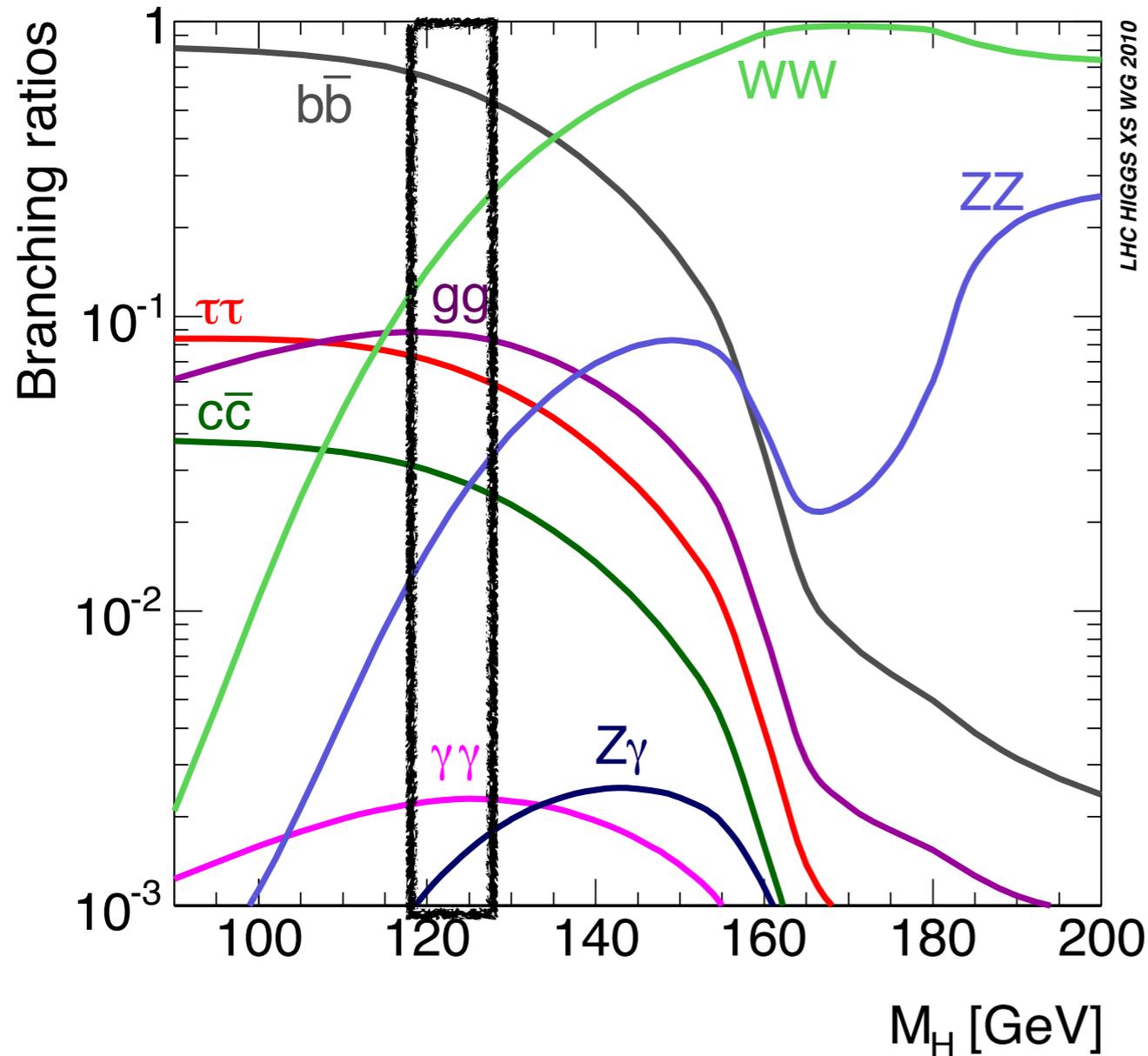
Searching at the LHC



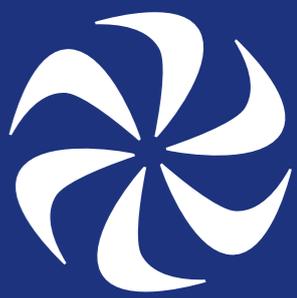
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The Higgs decays instantly, to a range of particle types

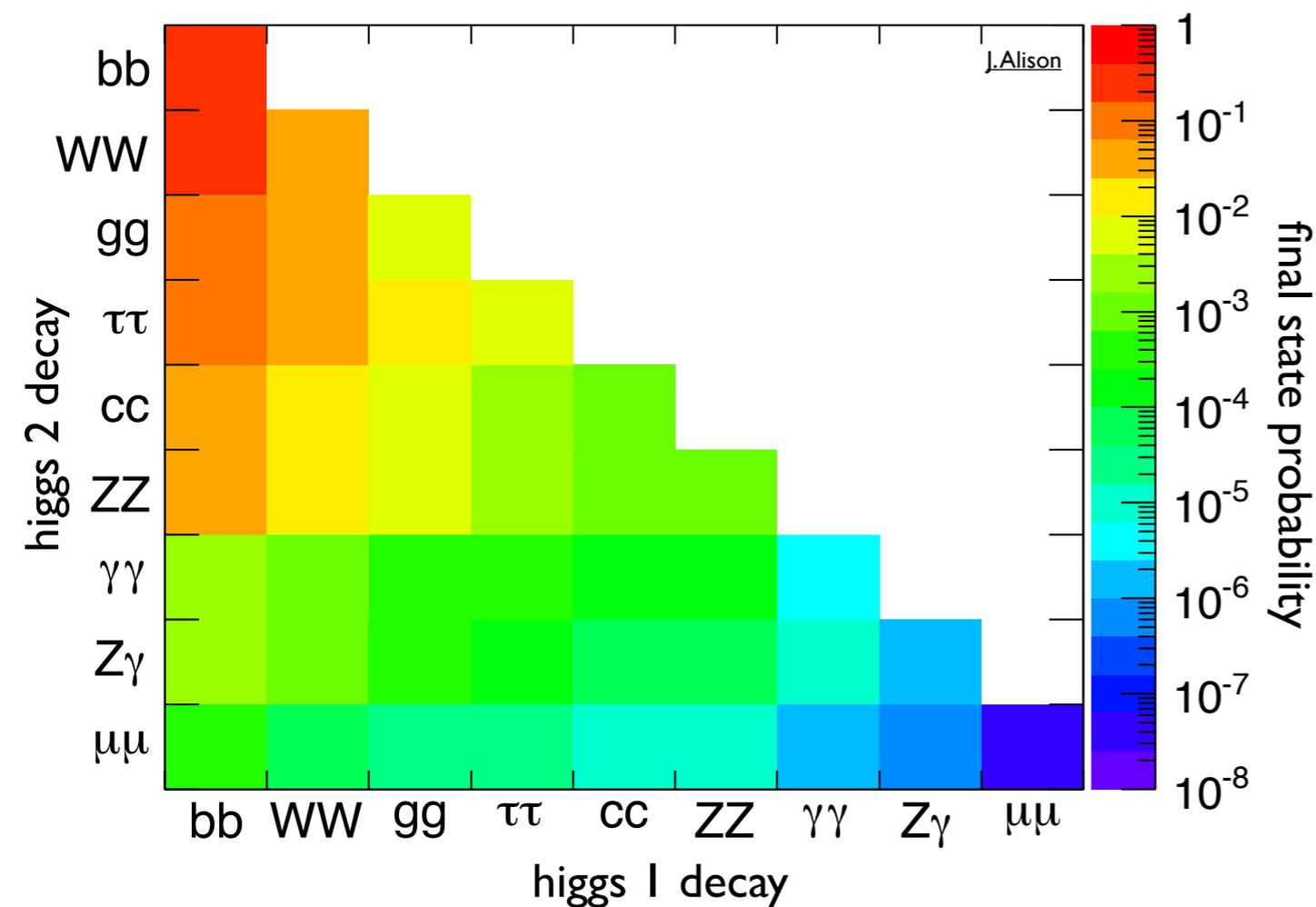


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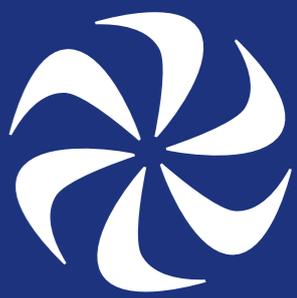


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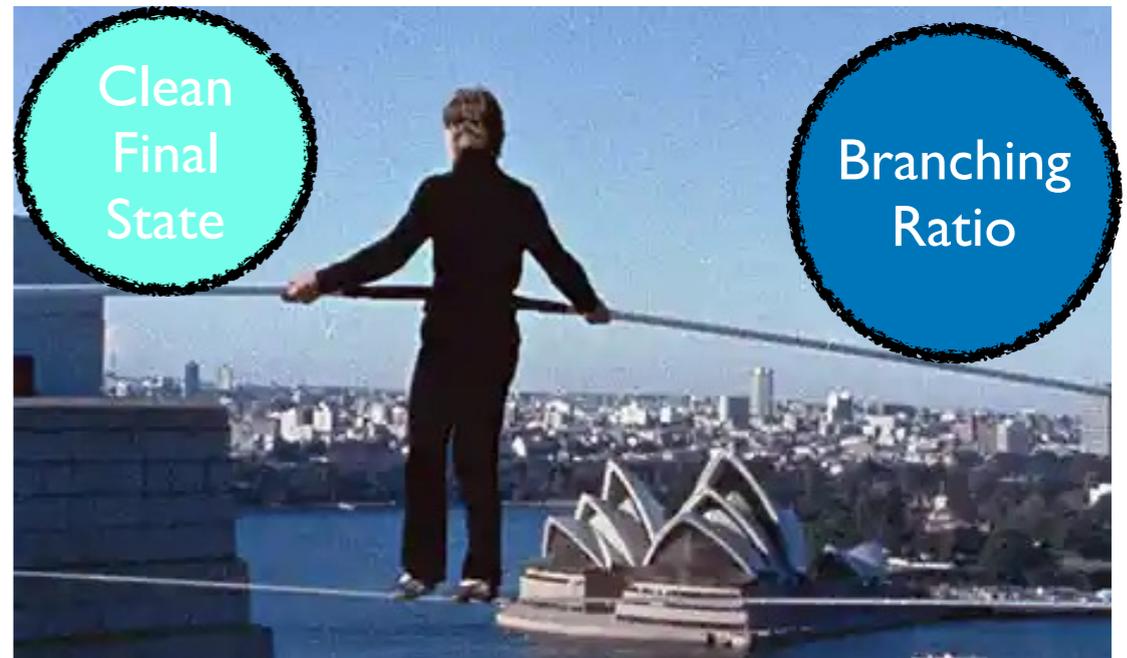
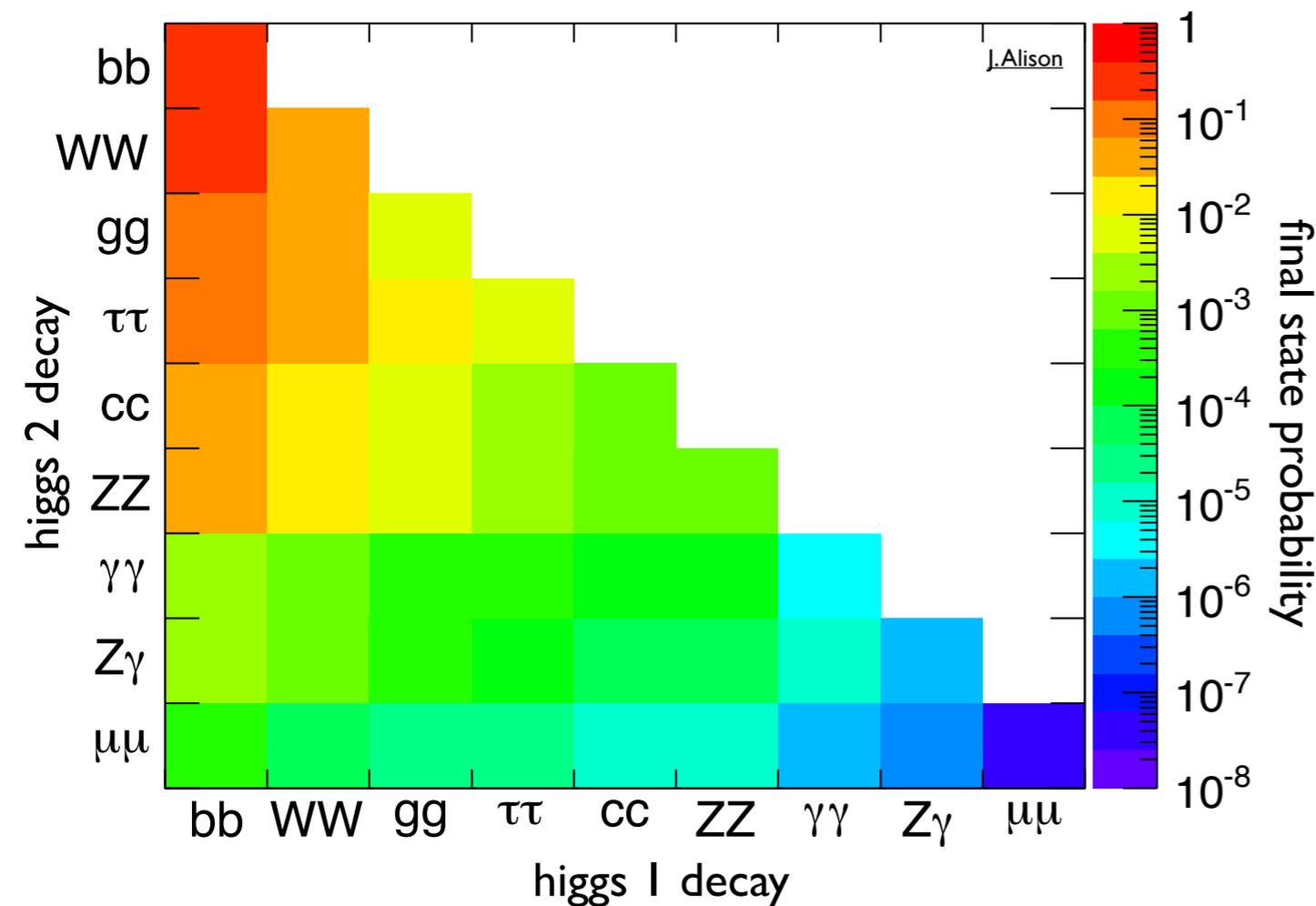


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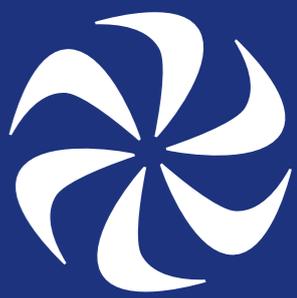
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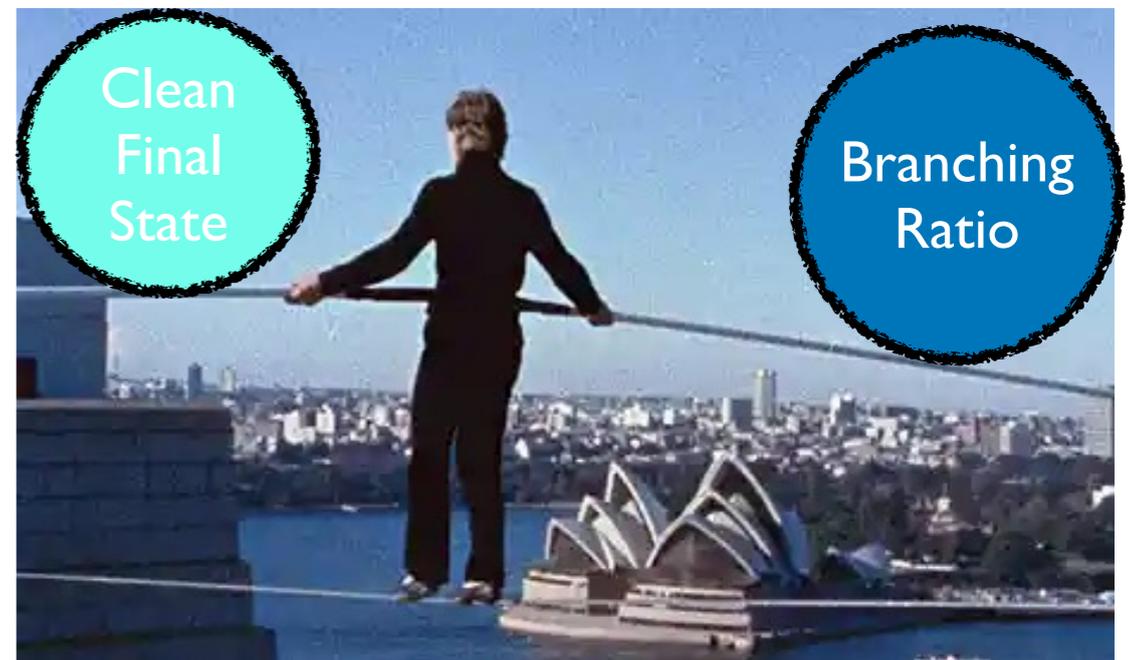
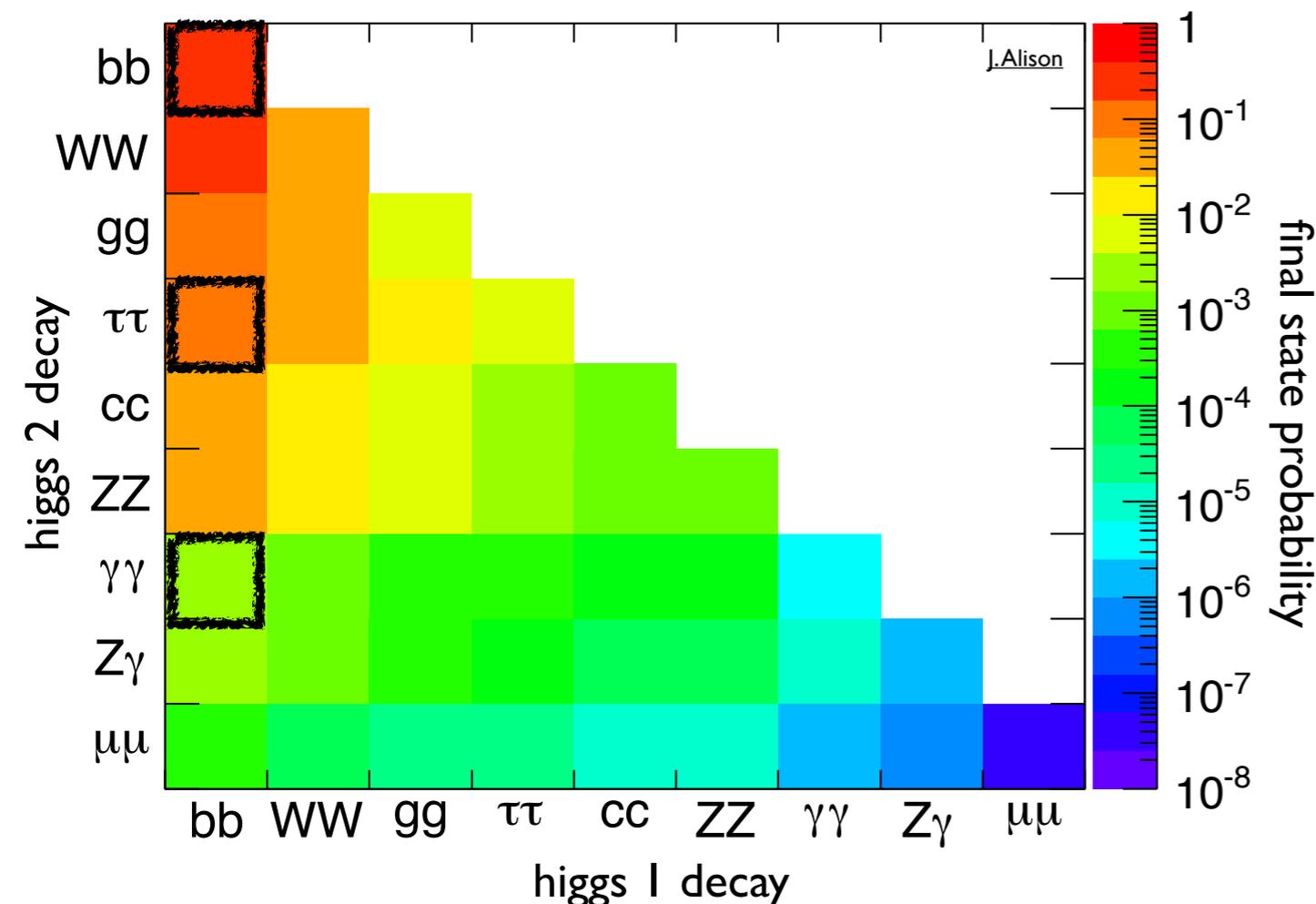
Man on Wire, Guardian

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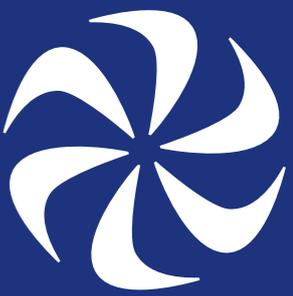
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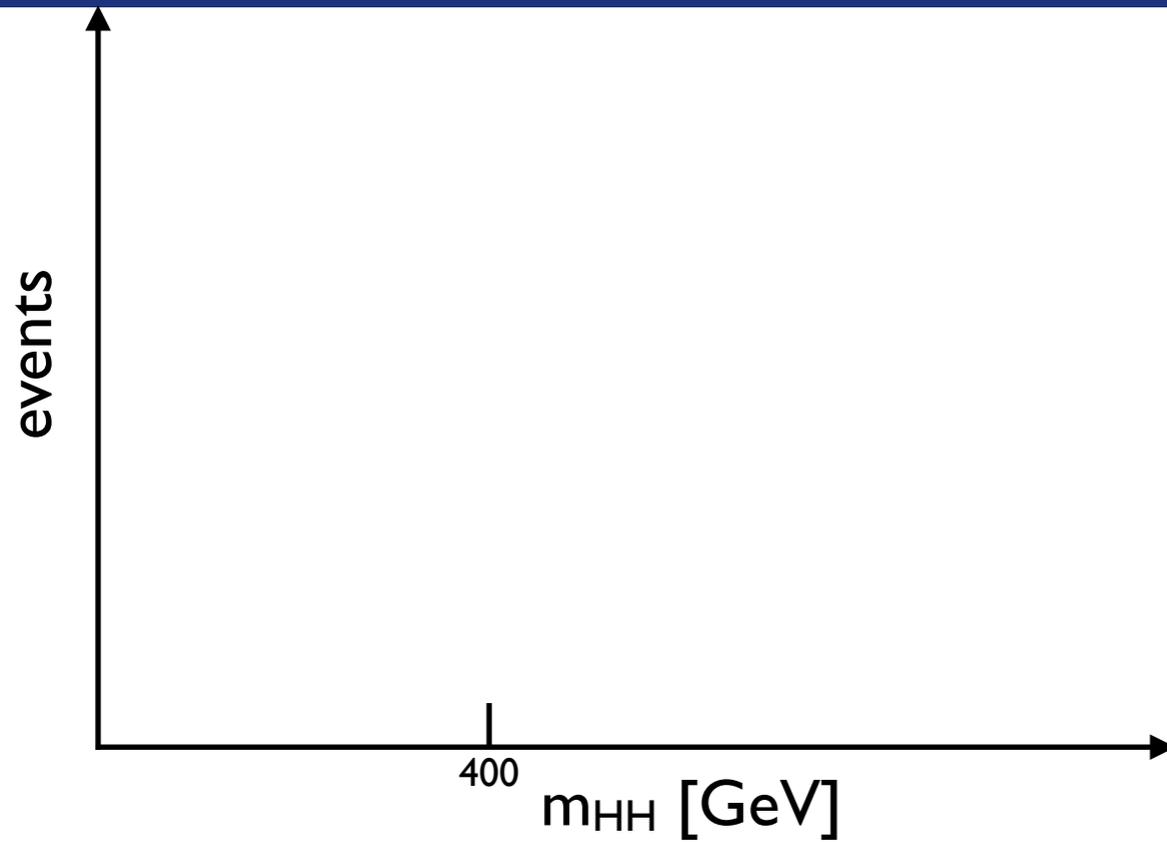
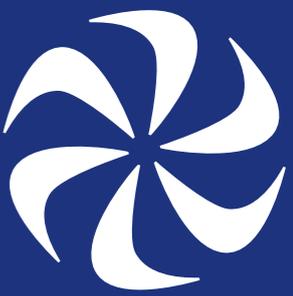
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$4b$, $b\bar{b}\tau\bar{\tau}$, and $b\bar{b}\gamma\gamma$ are the most powerful, but all final states needed!

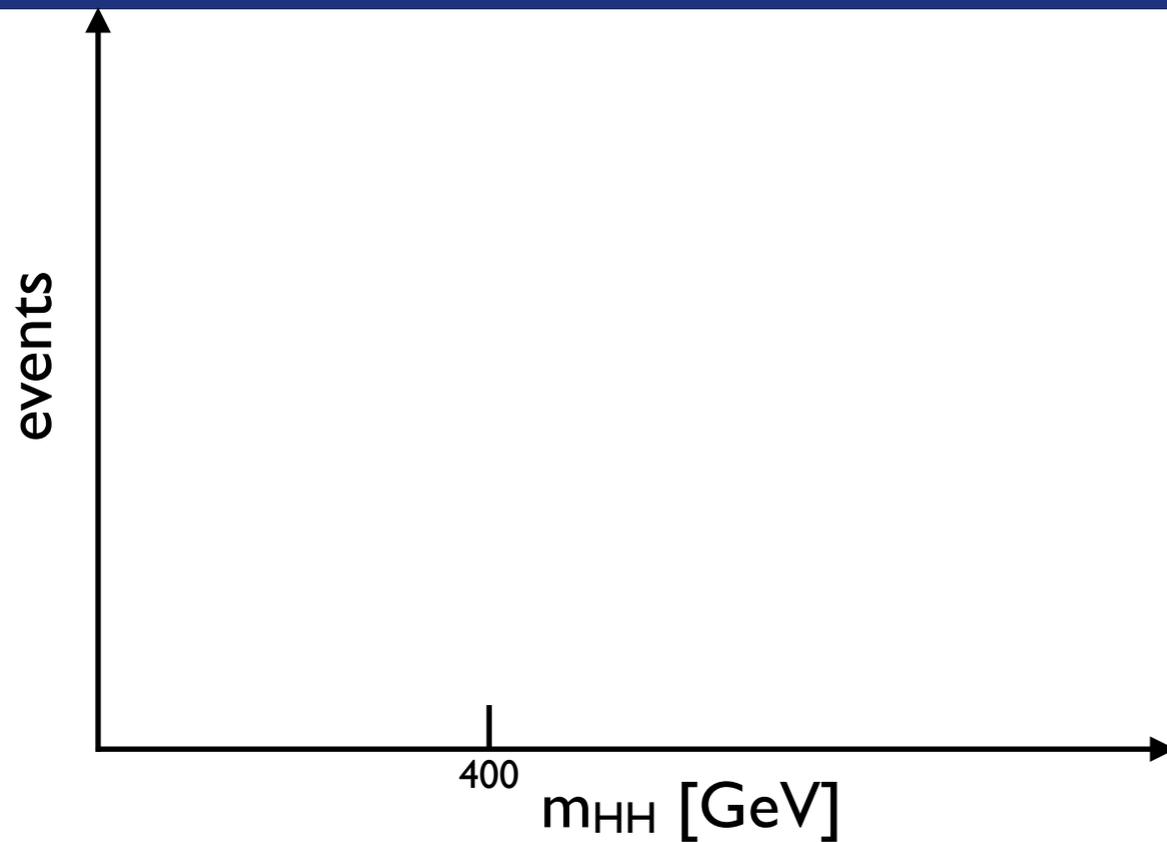
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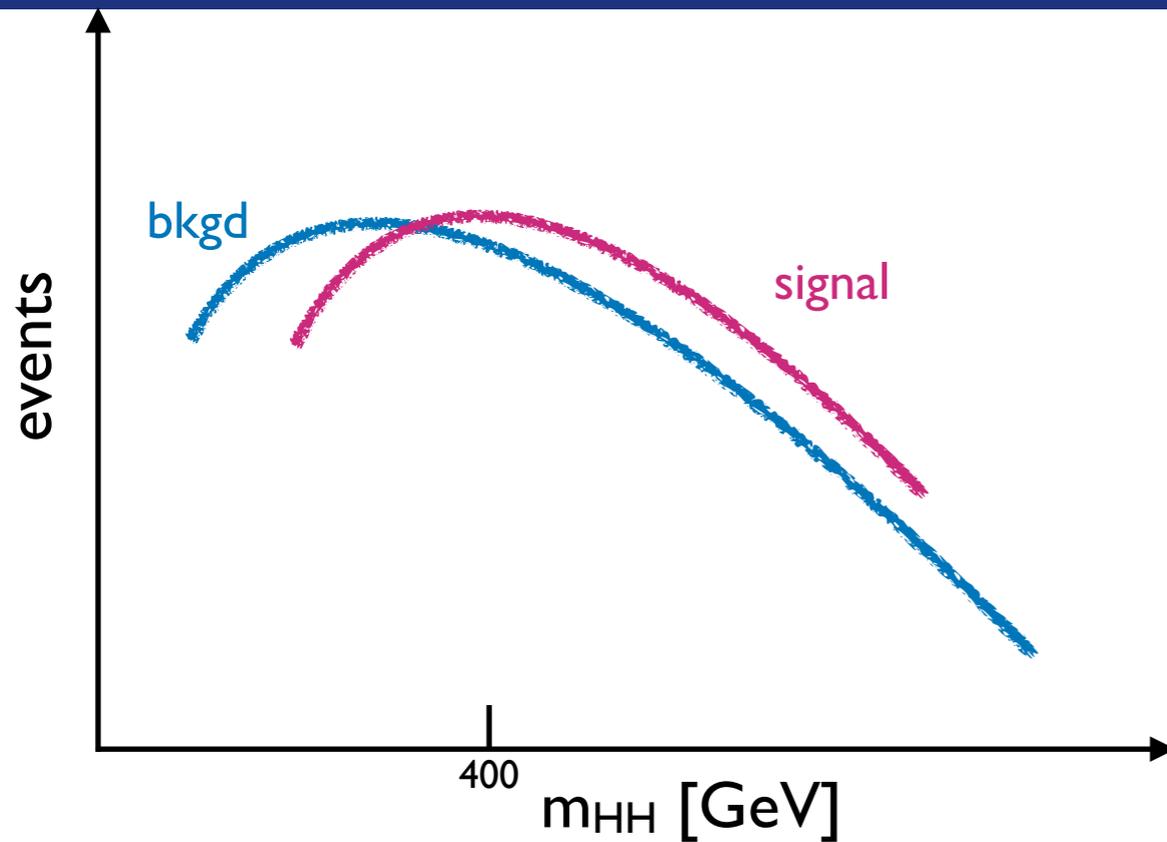
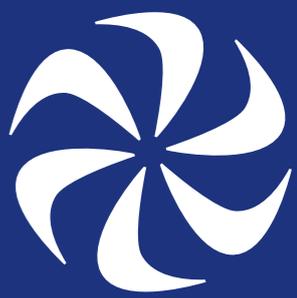


Searching for Higgs Pairs



The invariant mass m_{HH} is a standard observable

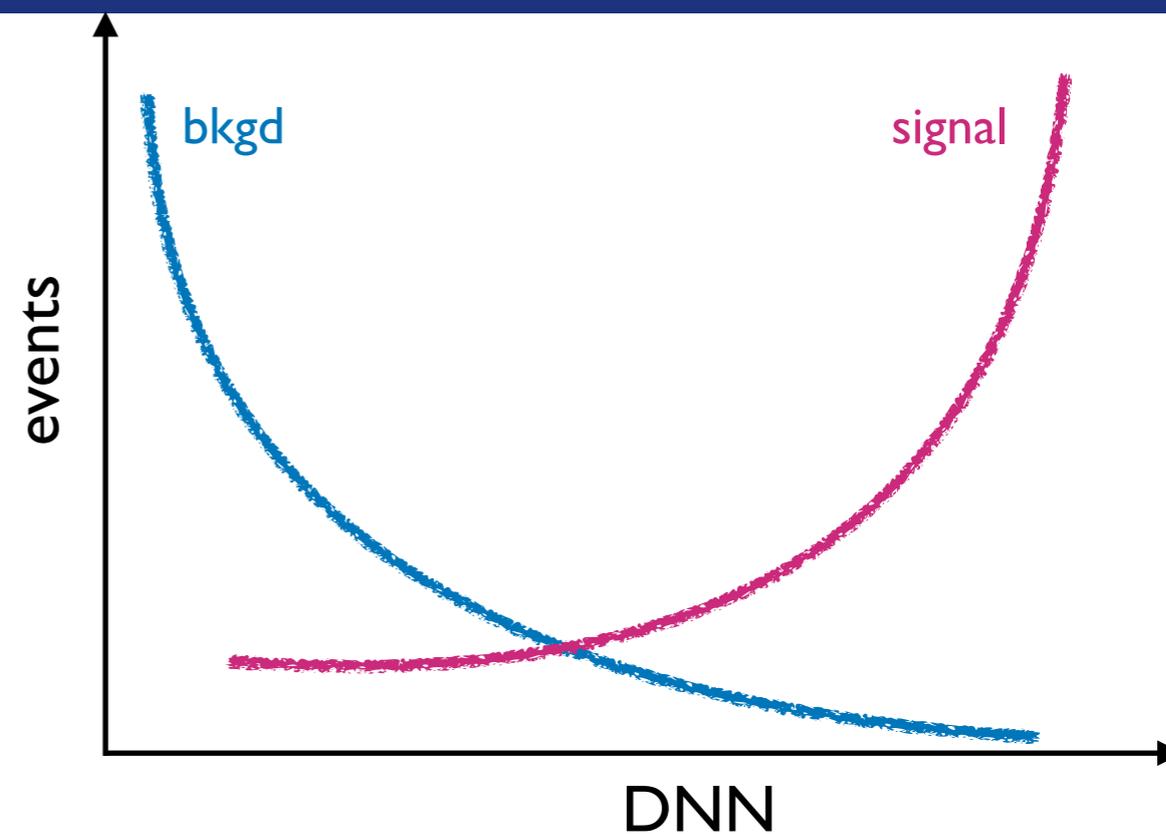
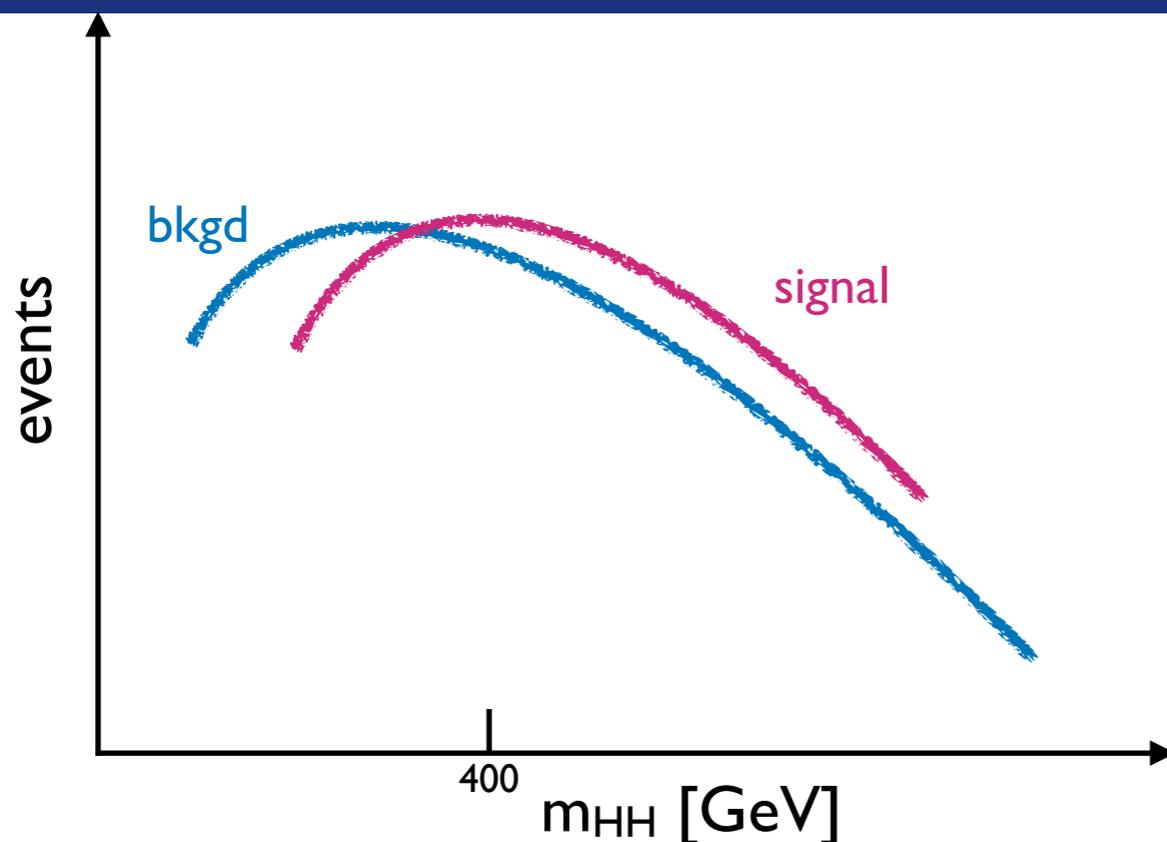
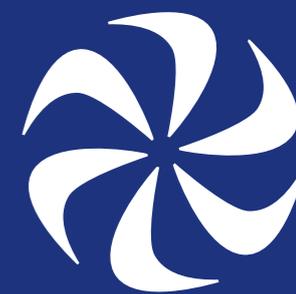
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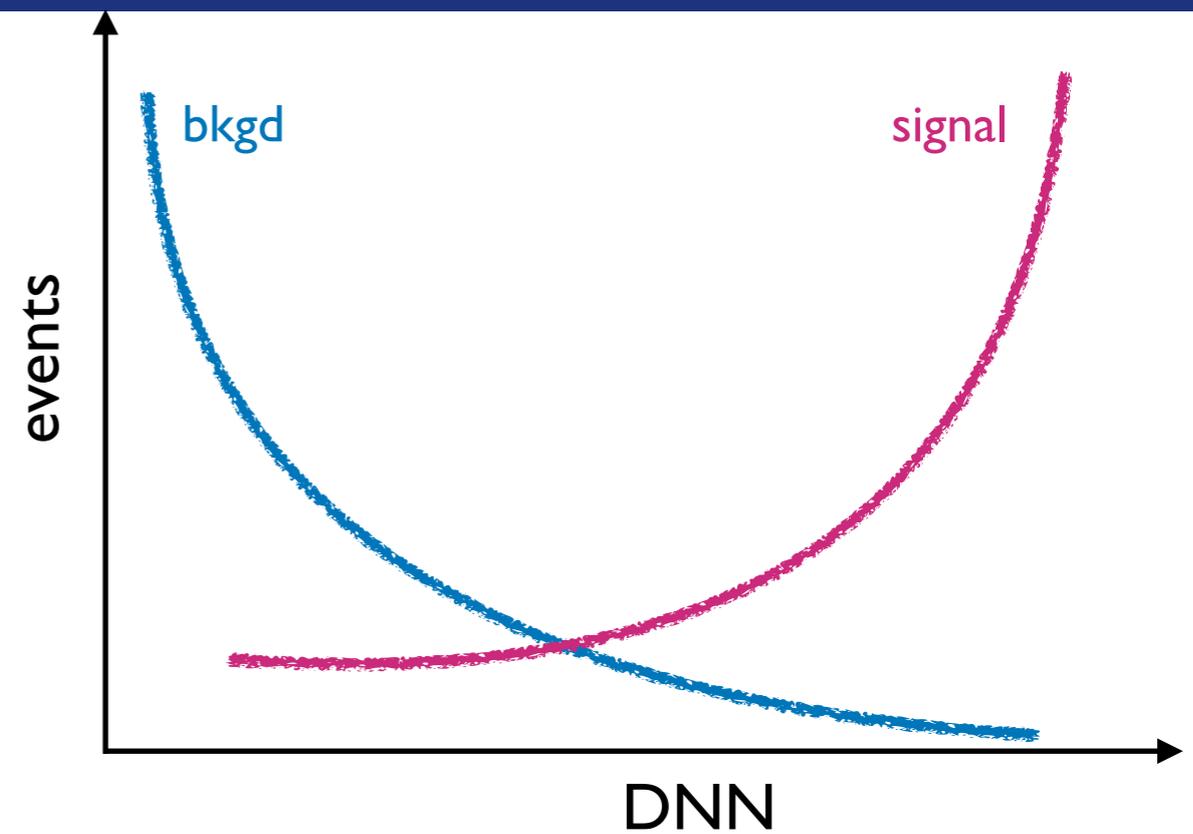
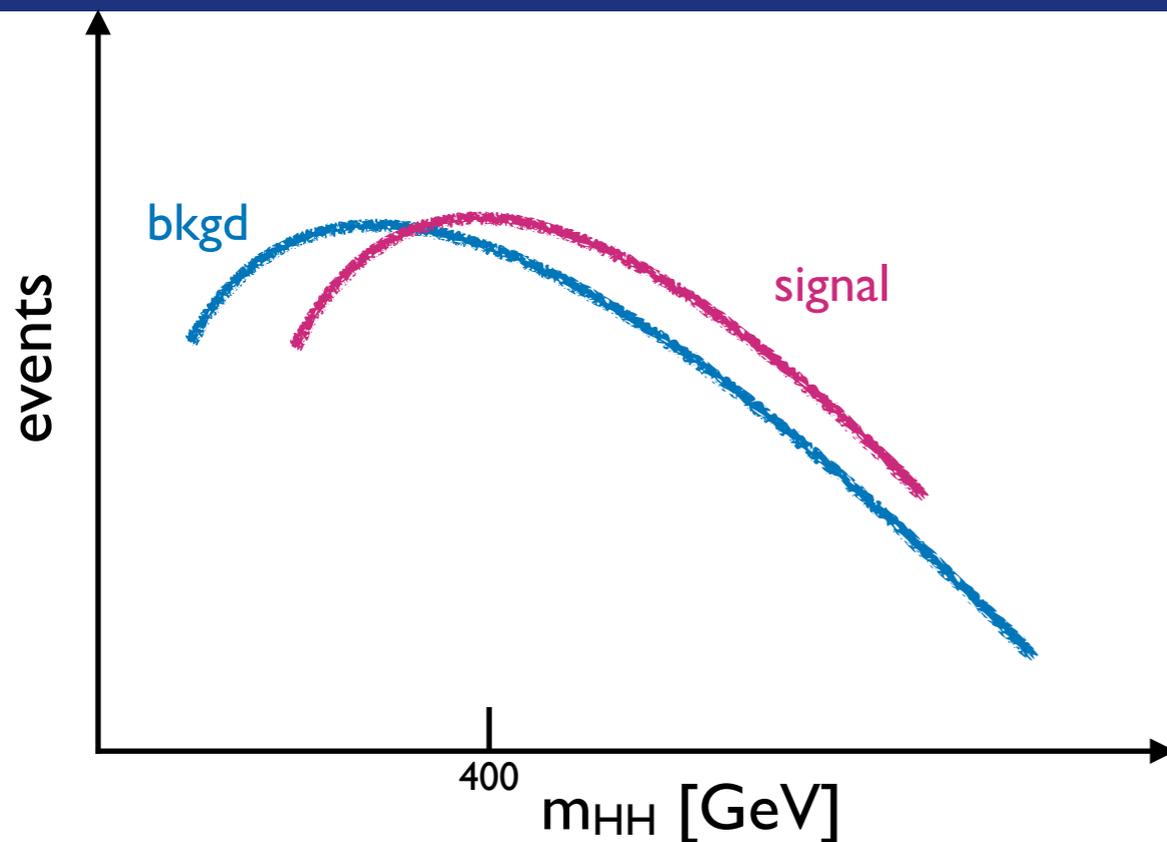
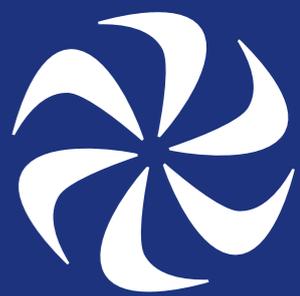


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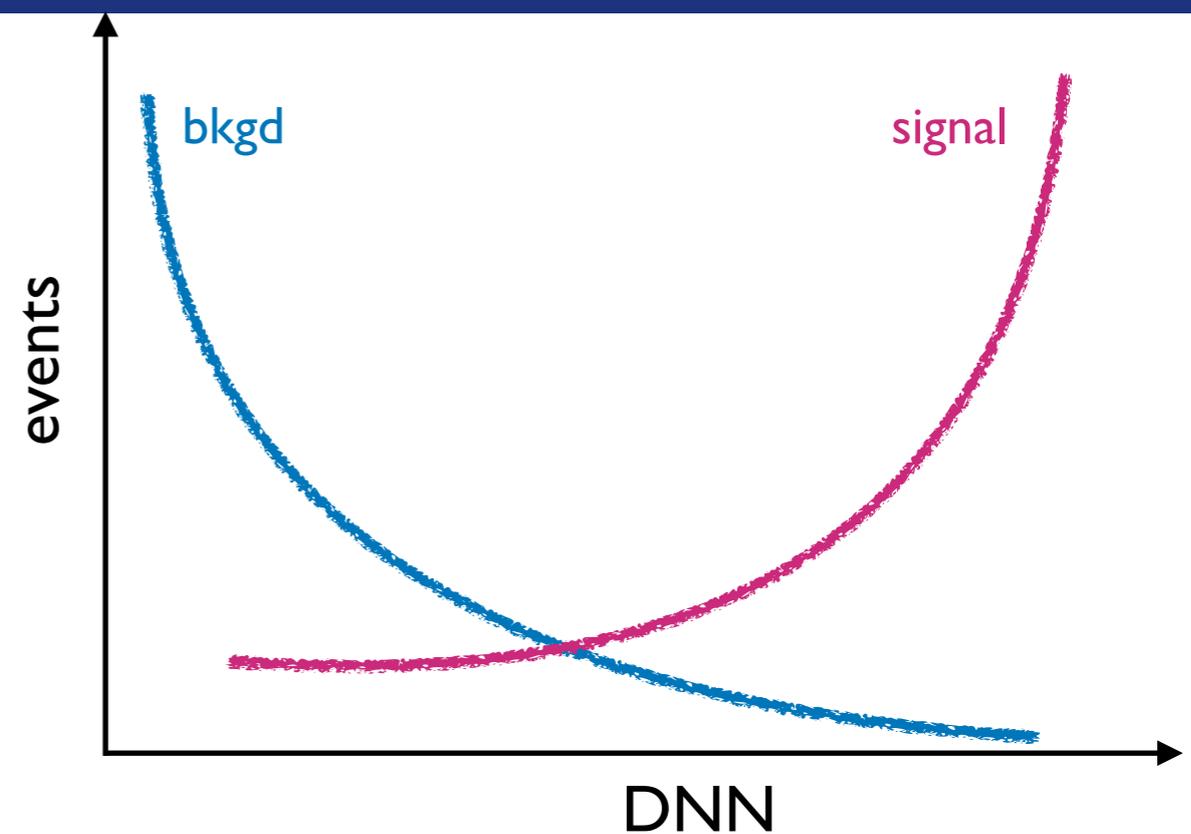
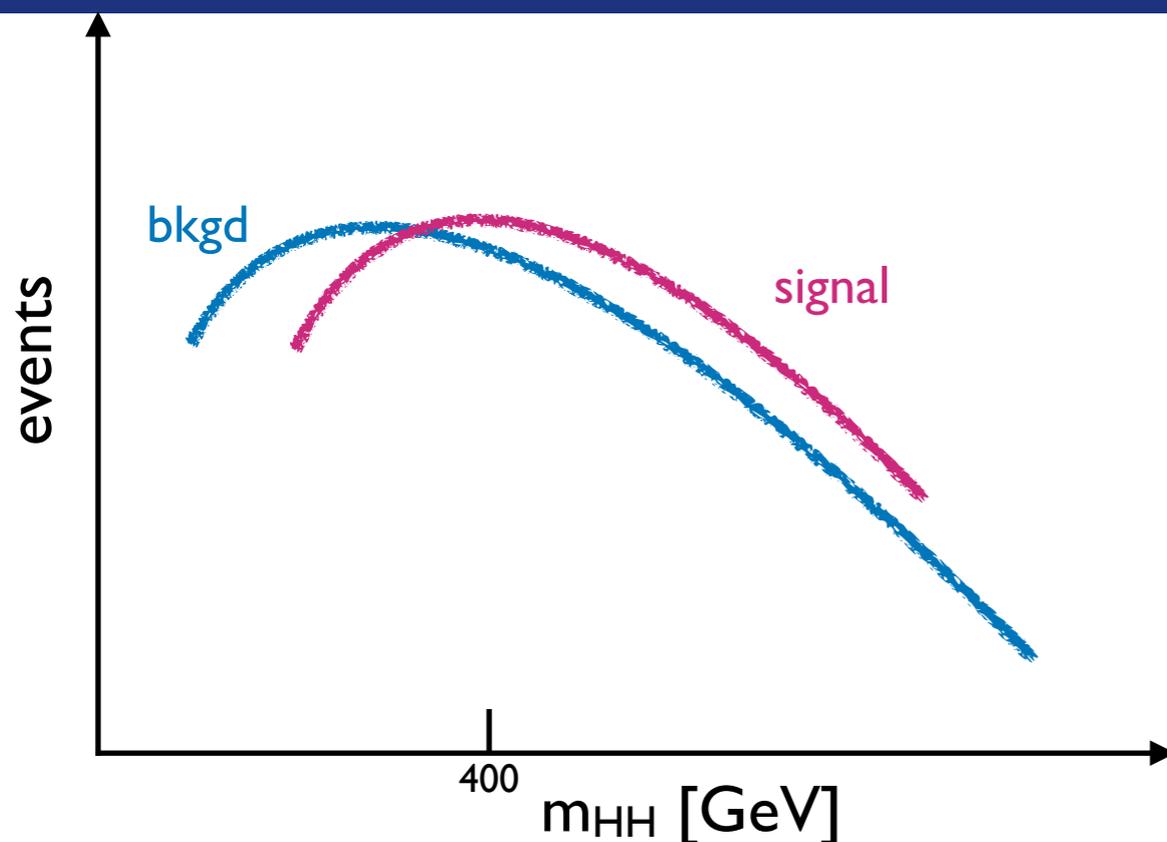
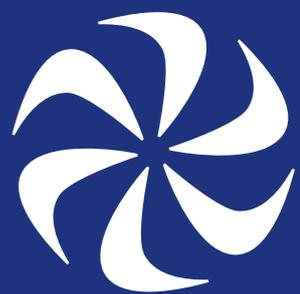
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b-tagging and jet reconstruction key to everything!

Comparing the Main Channels



[Phys. Rev. D 106 \(2022\) 052001](#)

[Phys. Rev. D 110 \(2024\) 032012](#)

[Phys. Rev. D 108 \(2023\) 052003](#)

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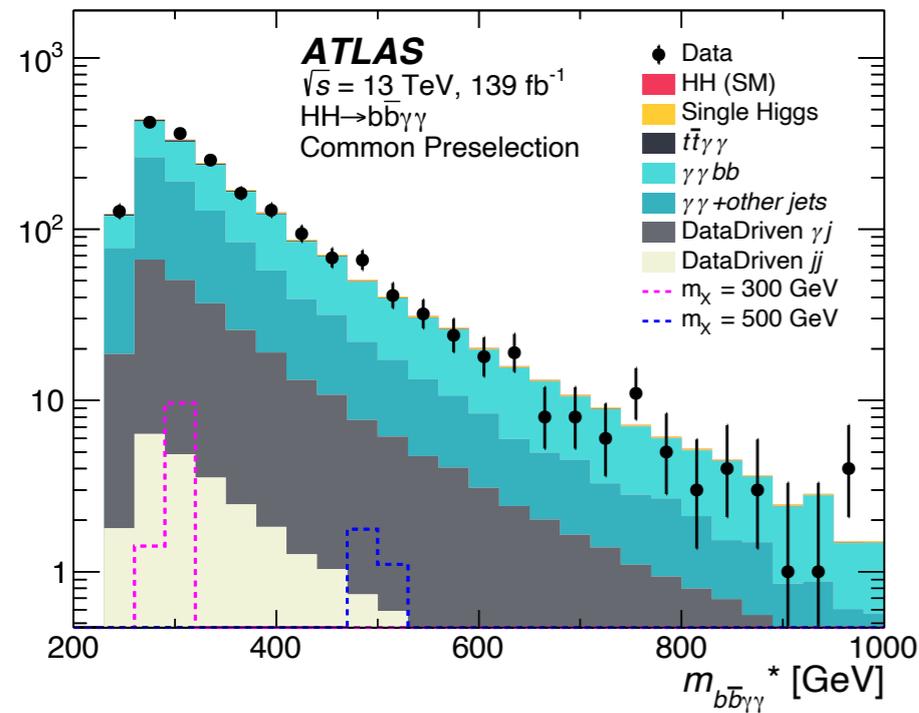


Phys. Rev. D 106 (2022) 052001

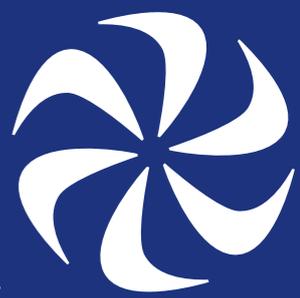
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$b\bar{b}\gamma\gamma$



Comparing the Main Channels

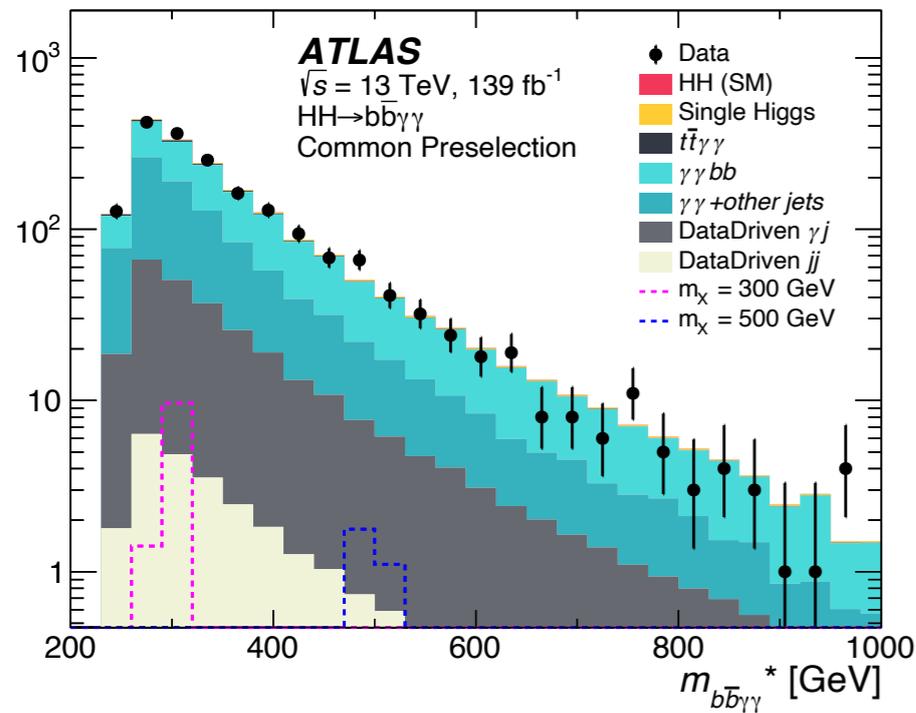


Phys. Rev. D 106 (2022) 052001

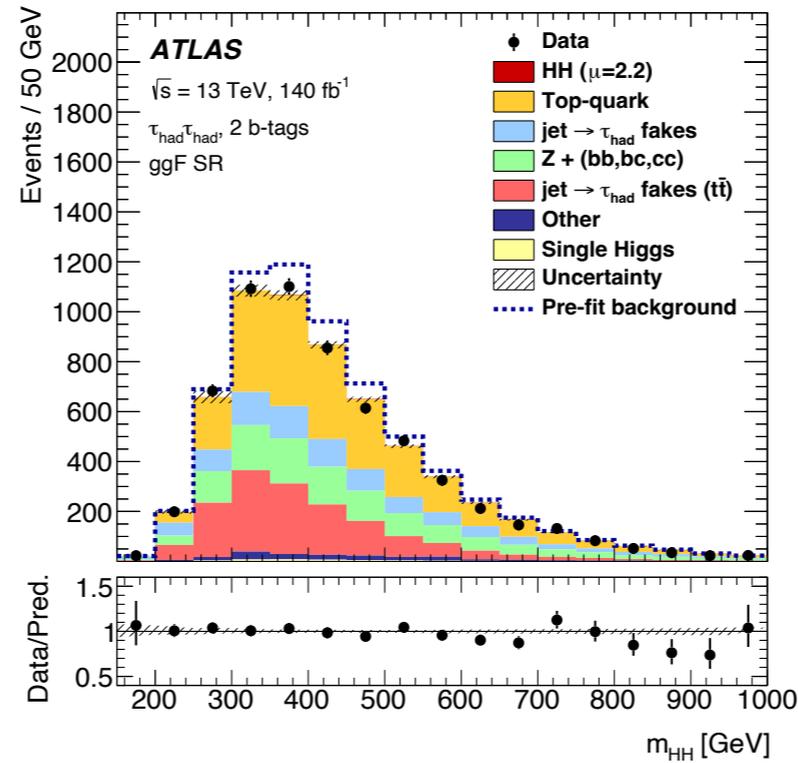
Phys. Rev. D 110 (2024) 032012

Phys. Rev. D 108 (2023) 052003

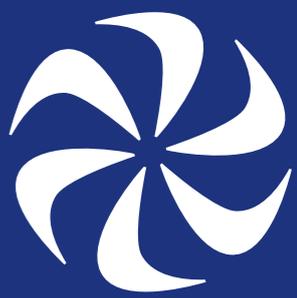
$b\bar{b}\gamma\gamma$



$b\bar{b}\tau\tau$



Comparing the Main Channels

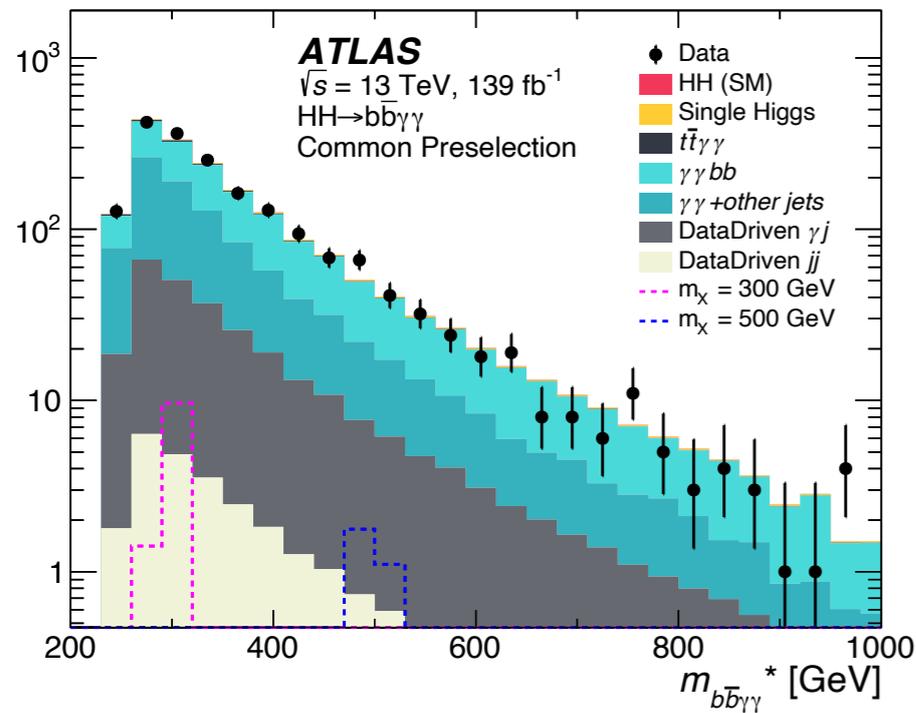


Phys. Rev. D 106 (2022) 052001

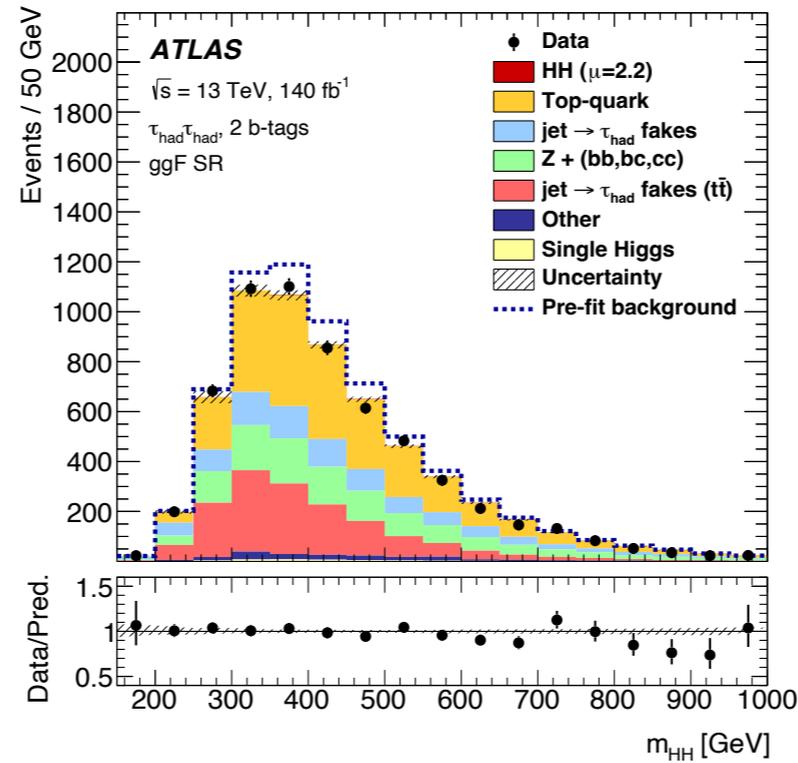
Phys. Rev. D 110 (2024) 032012

Phys. Rev. D 108 (2023) 052003

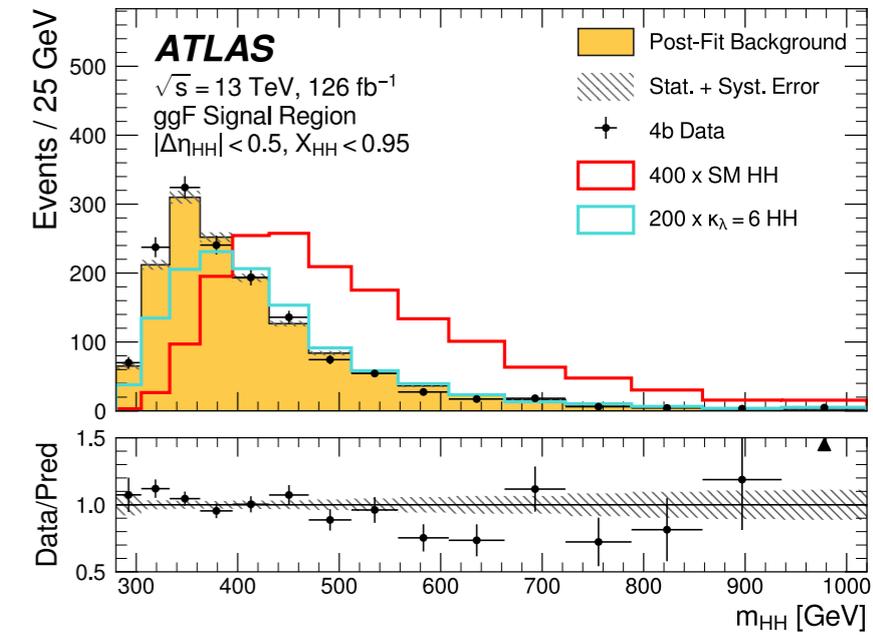
$b\bar{b}\gamma\gamma$



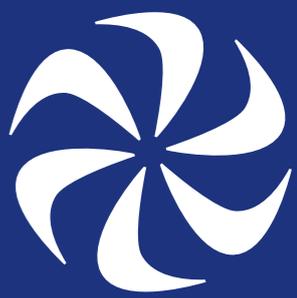
$b\bar{b}\tau\tau$



$b\bar{b}b\bar{b}$



Comparing the Main Channels

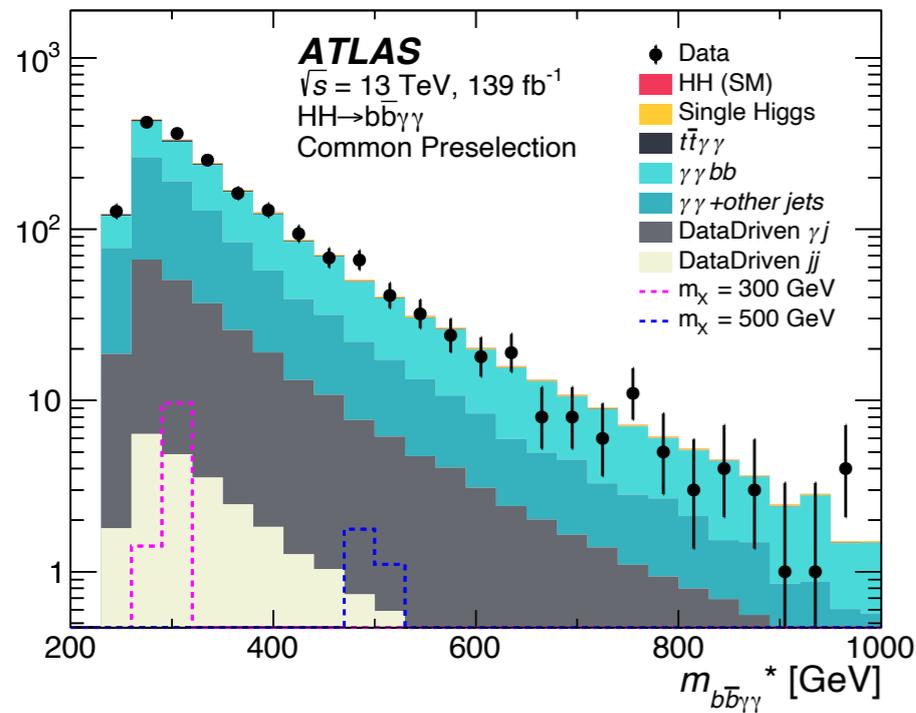


Phys. Rev. D 106 (2022) 052001

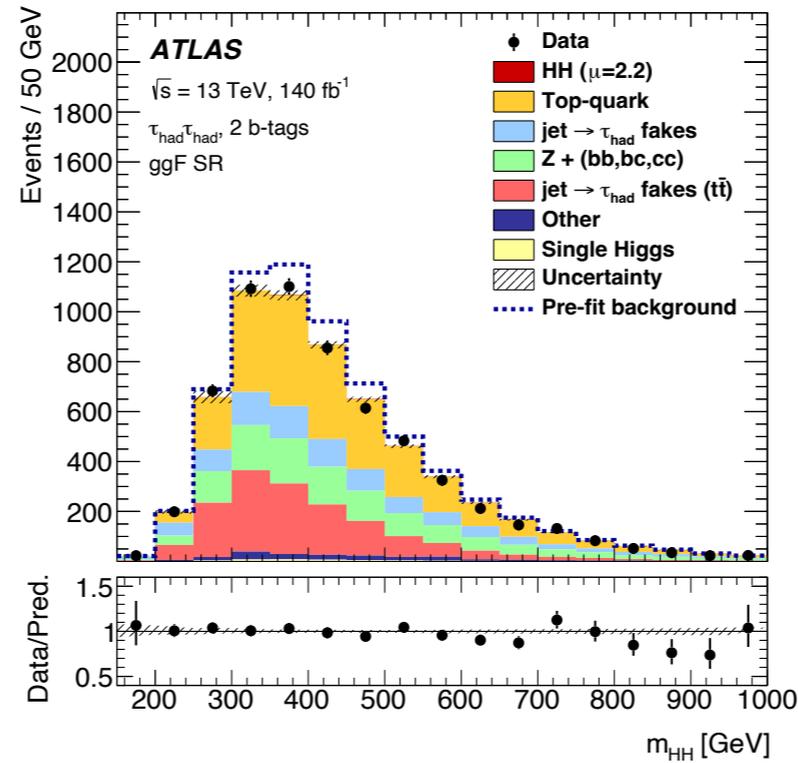
Phys. Rev. D 110 (2024) 032012

Phys. Rev. D 108 (2023) 052003

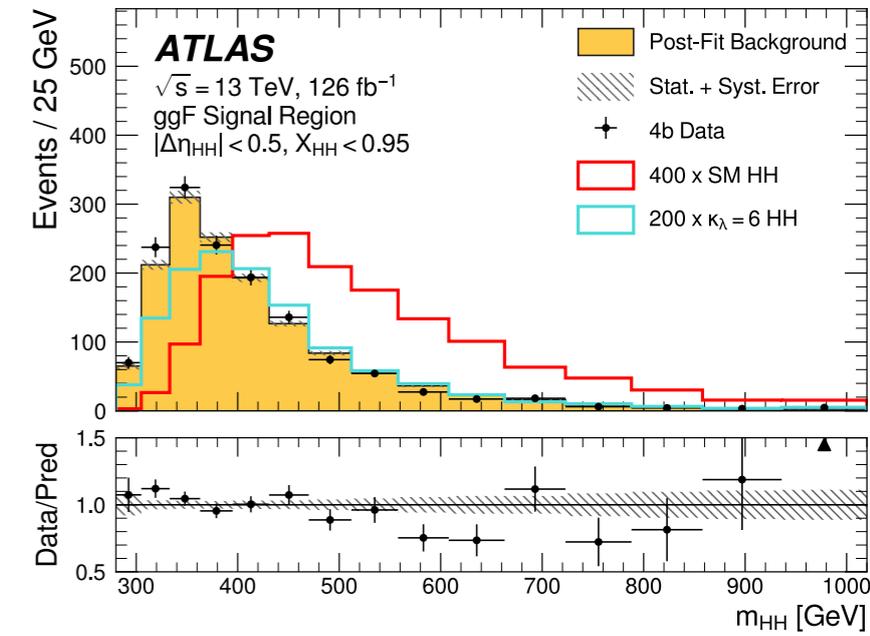
$b\bar{b}\gamma\gamma$



$b\bar{b}\tau\tau$



$b\bar{b}b\bar{b}$



Rarest signal,
lowest bkgd

Comparing the Main Channels

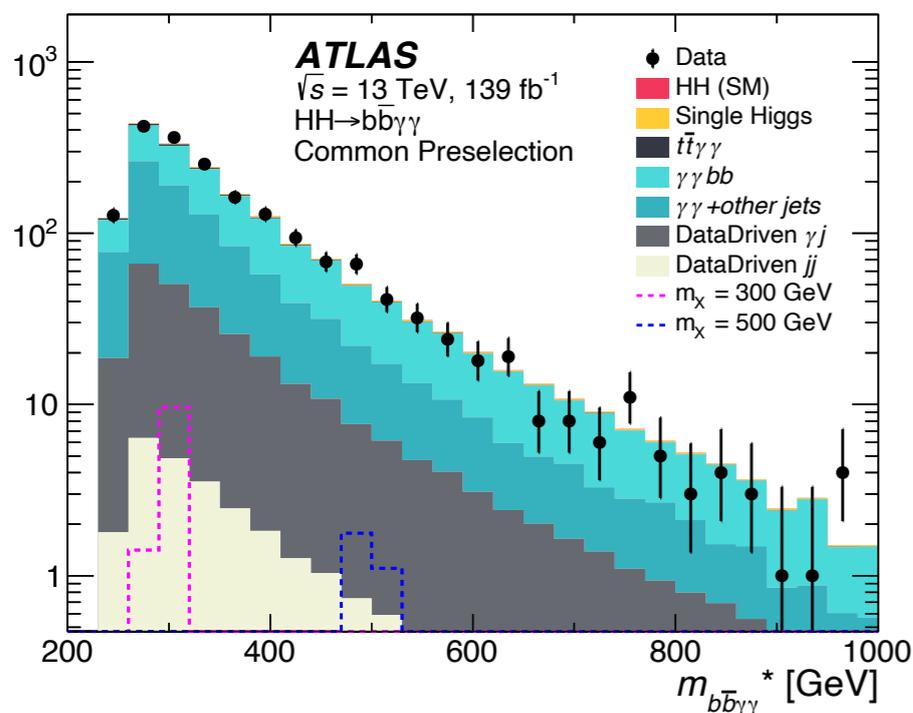


Phys. Rev. D 106 (2022) 052001

Phys. Rev. D 110 (2024) 032012

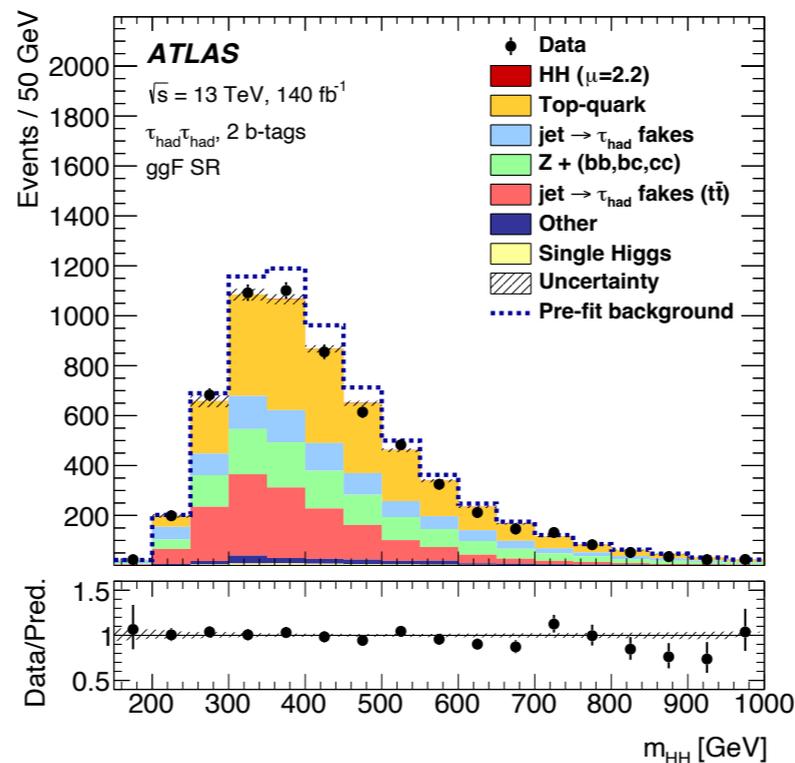
Phys. Rev. D 108 (2023) 052003

$b\bar{b}\gamma\gamma$



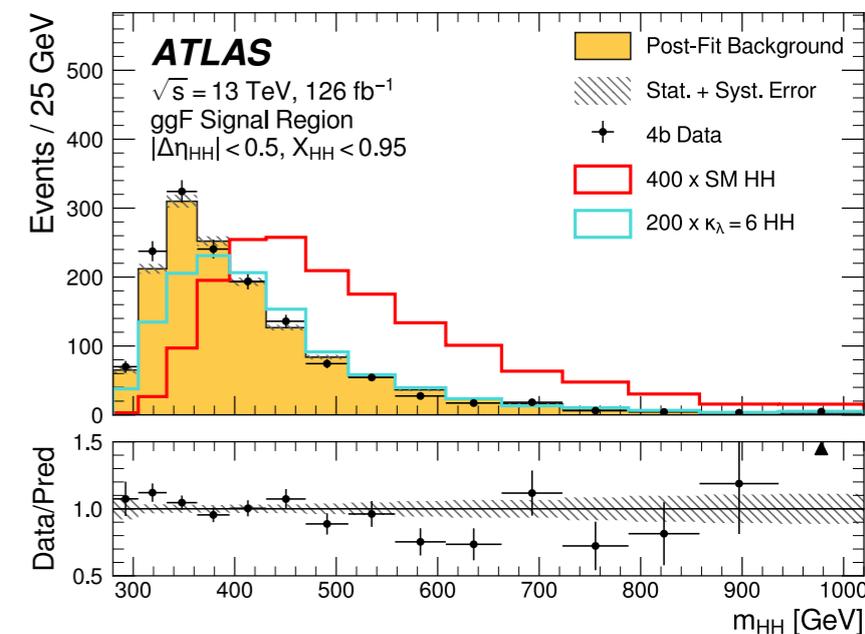
Rarest signal,
lowest bkgd

$b\bar{b}\tau\tau$

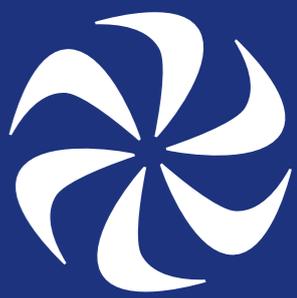


Medium signal,
medium bkgd

$b\bar{b}b\bar{b}$



Comparing the Main Channels

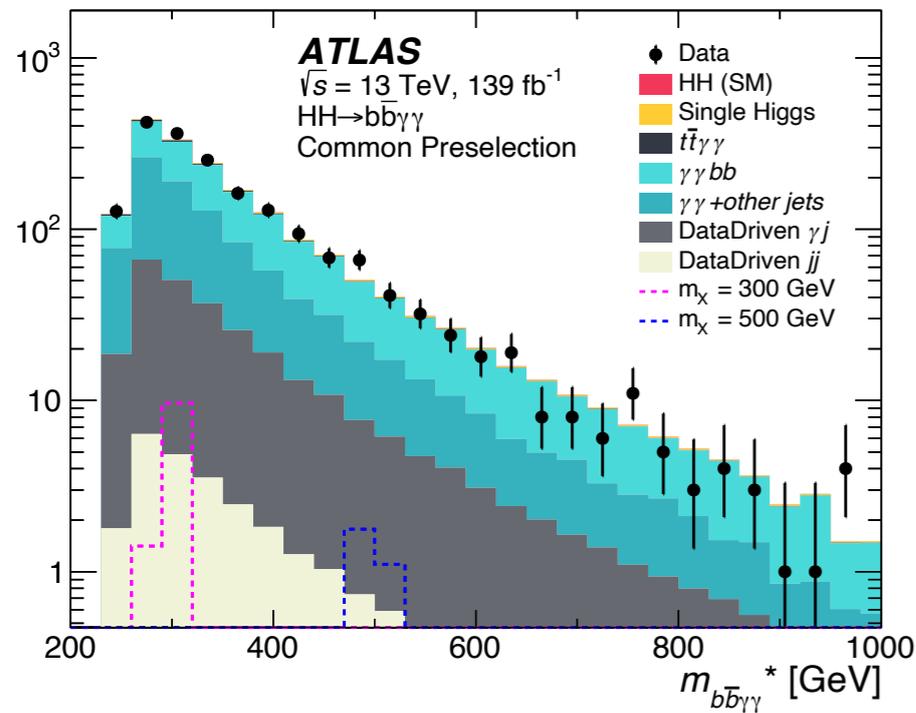


Phys. Rev. D 106 (2022) 052001

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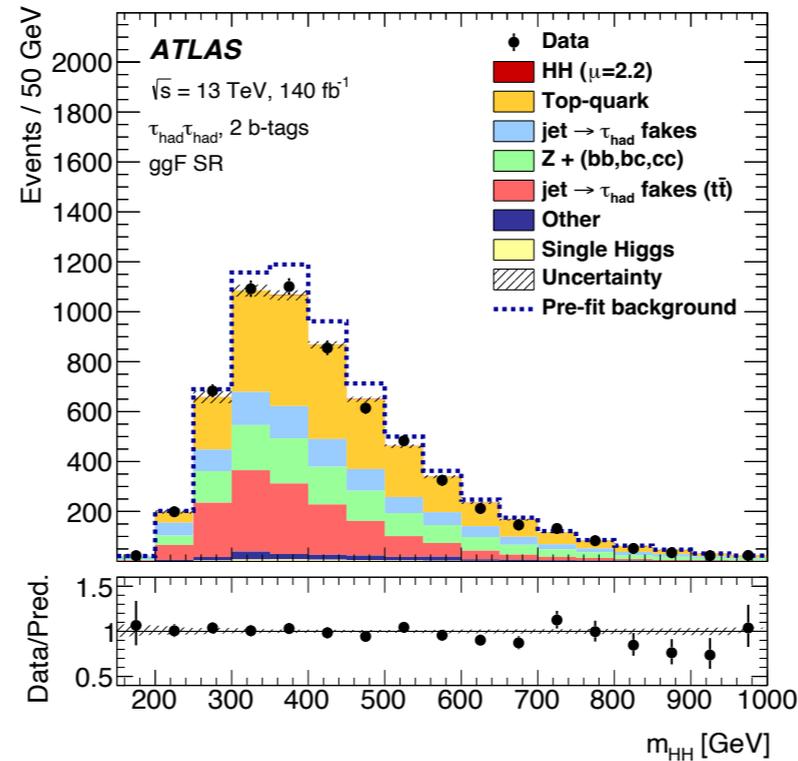
Phys. Rev. D 108 (2023) 052003

$b\bar{b}\gamma\gamma$



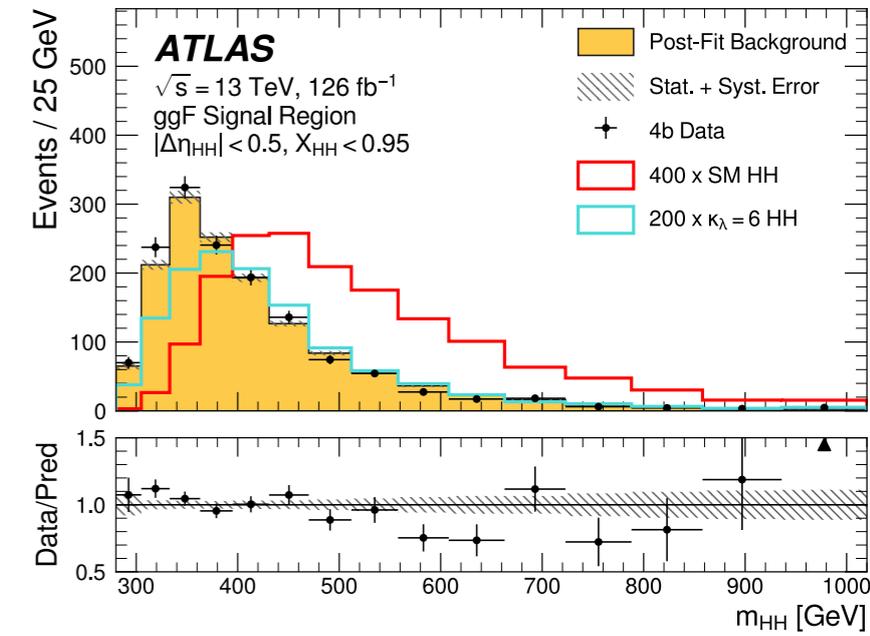
Rarest signal,
lowest bkgd

$b\bar{b}\tau\tau$



Medium signal,
medium bkgd

$b\bar{b}b\bar{b}$



Largest signal,
Largest background

Comparing the Main Channels

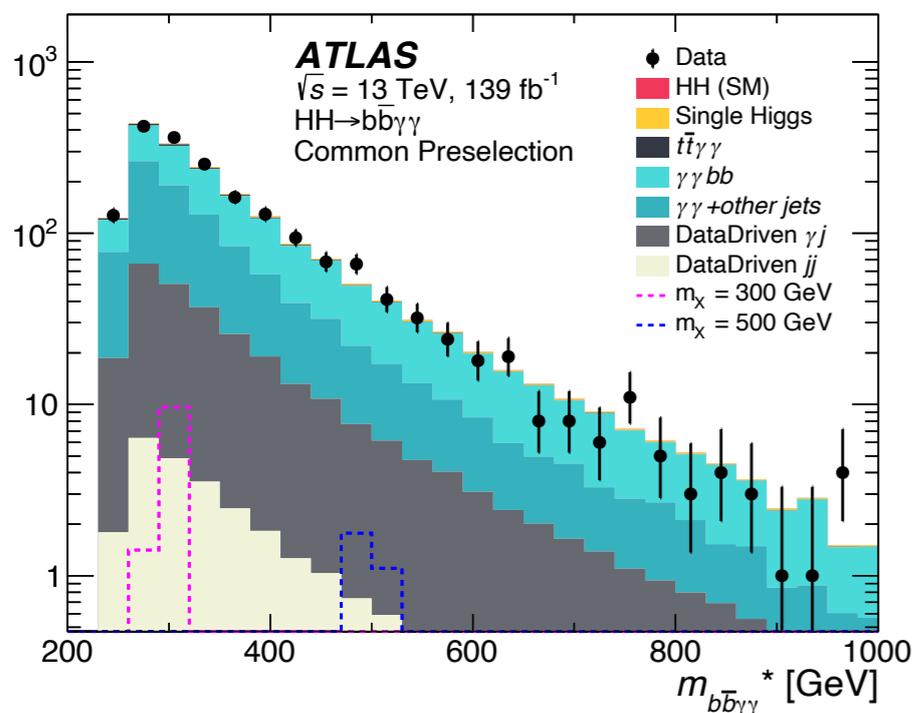


Phys. Rev. D 106 (2022) 052001

Phys. Rev. D 110 (2024) 032012

Phys. Rev. D 108 (2023) 052003

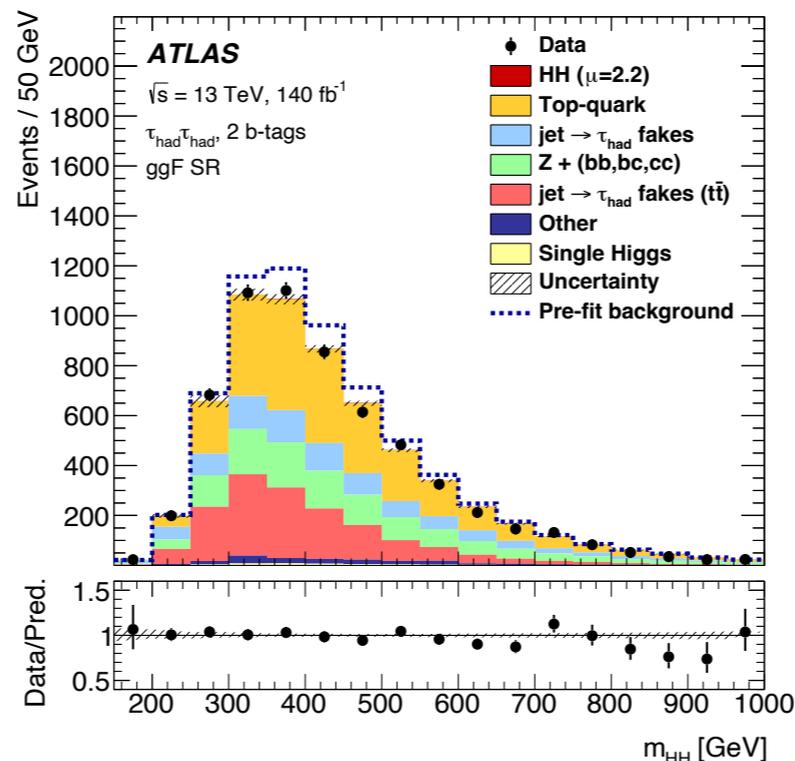
$b\bar{b}\gamma\gamma$



Rarest signal,
lowest bkgd

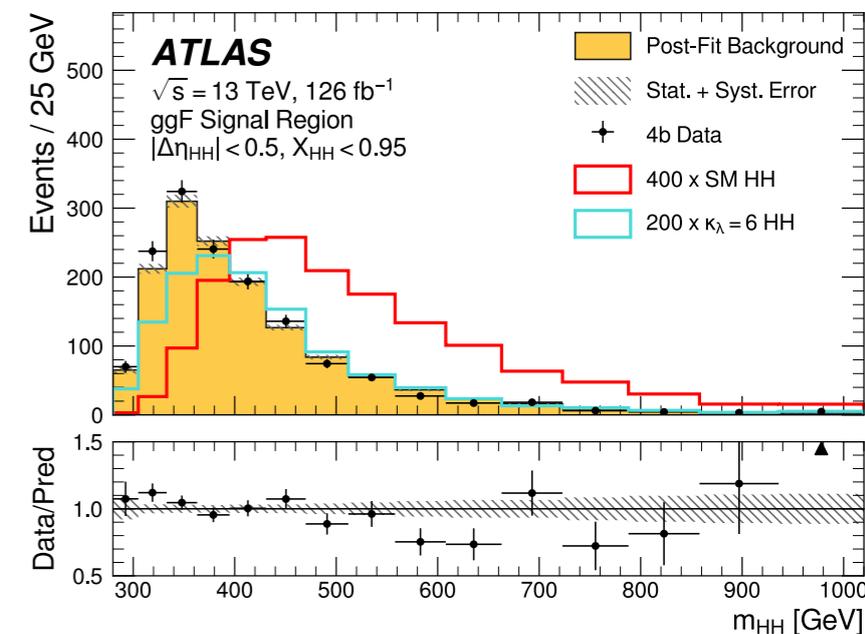
Low trigger threshold:
Critical for κ_λ

$b\bar{b}\tau\tau$



Medium signal,
medium bkgd

$b\bar{b}b\bar{b}$



Largest signal,
Largest background

Comparing the Main Channels

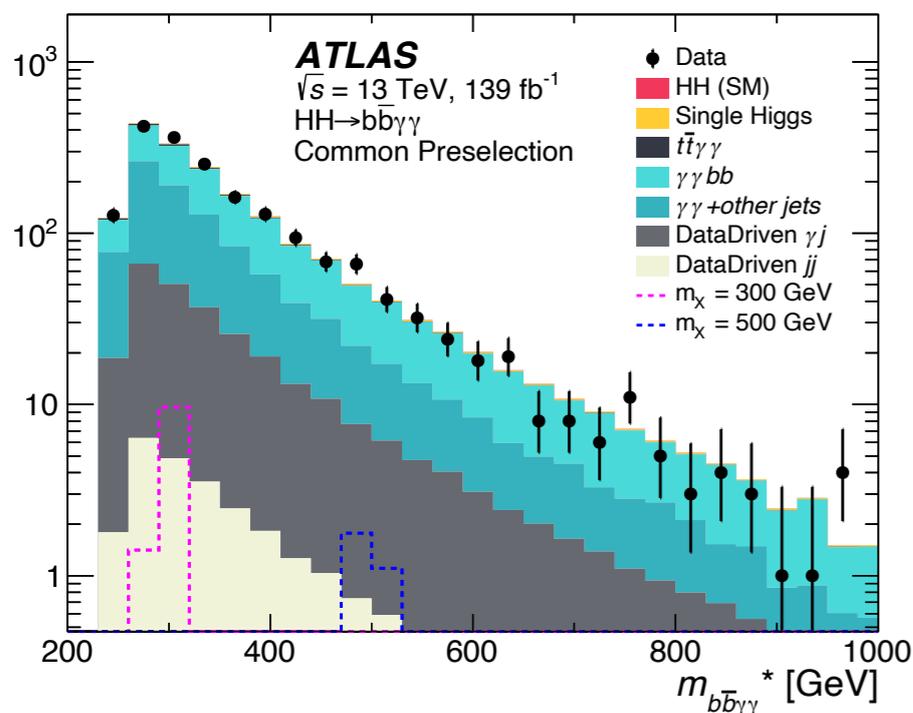


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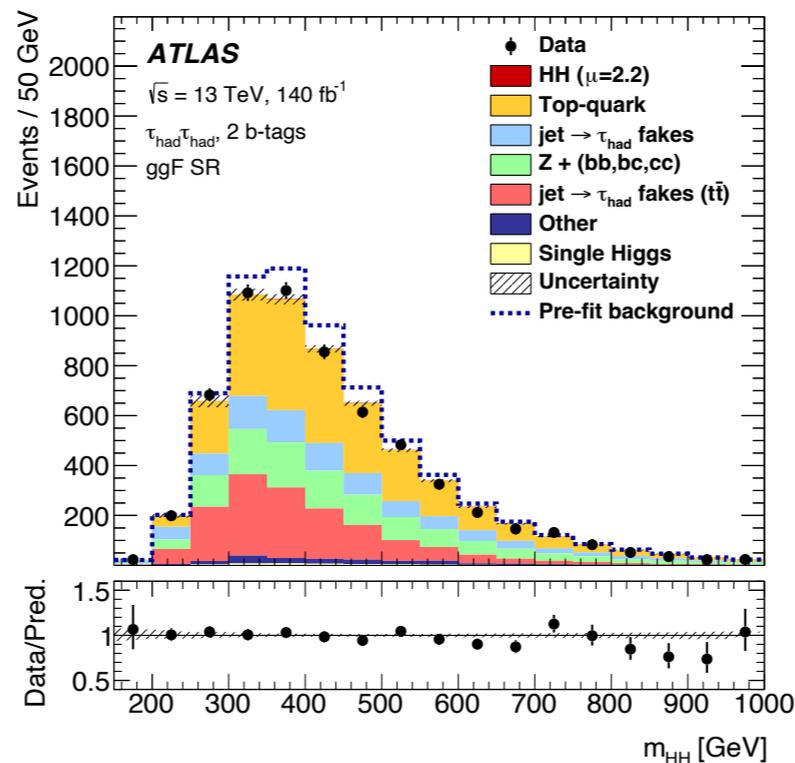
$b\bar{b}\gamma\gamma$



Rarest signal,
lowest bkgd

Low trigger threshold:
Critical for κ_λ

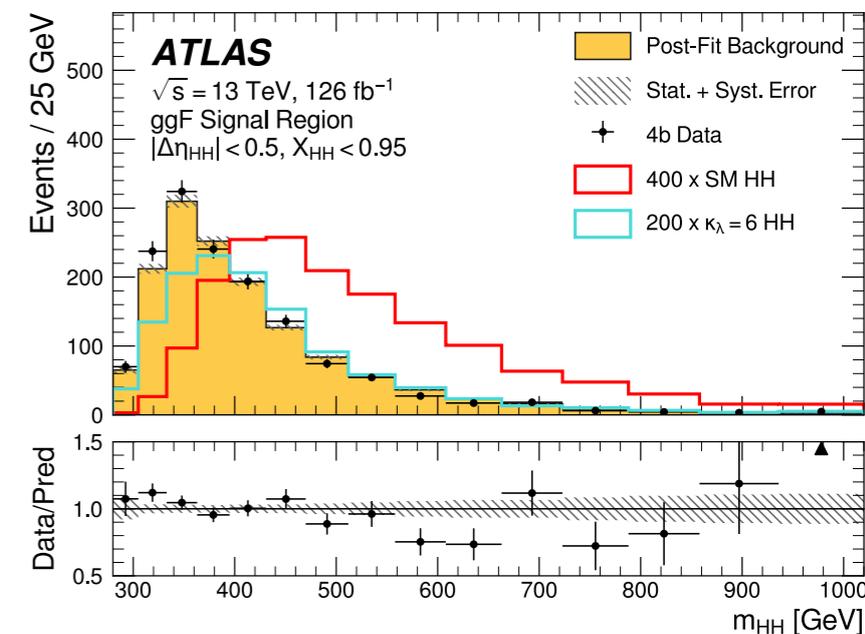
$b\bar{b}\tau\tau$



Medium signal,
medium bkgd

Medium trigger
thresholds: still
important for κ_λ

$b\bar{b}b\bar{b}$



Largest signal,
Largest background

Comparing the Main Channels

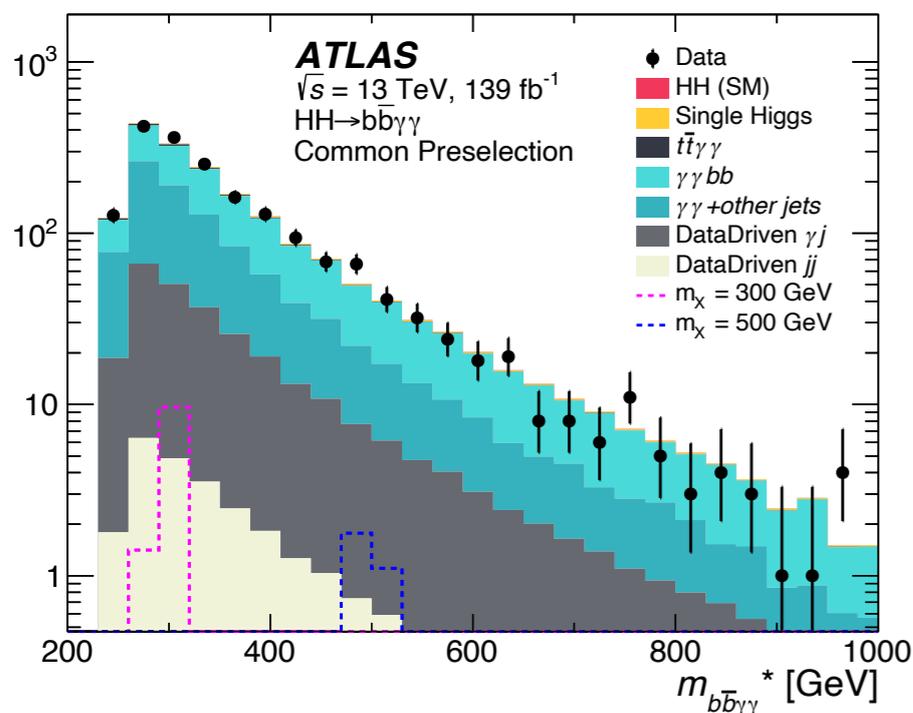


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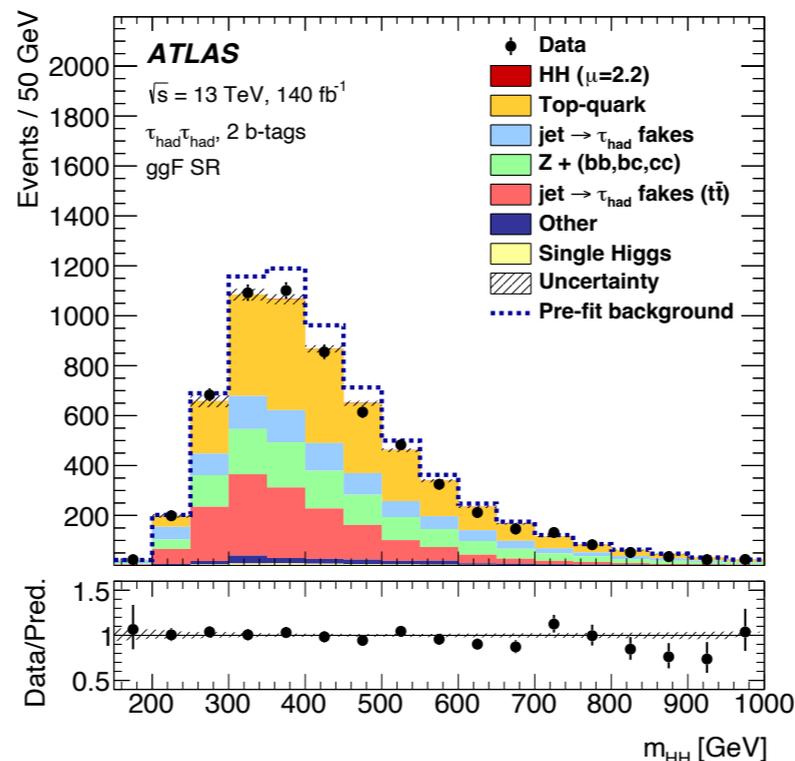
$b\bar{b}\gamma\gamma$



Rarest signal,
lowest bkgd

Low trigger threshold:
Critical for κ_λ

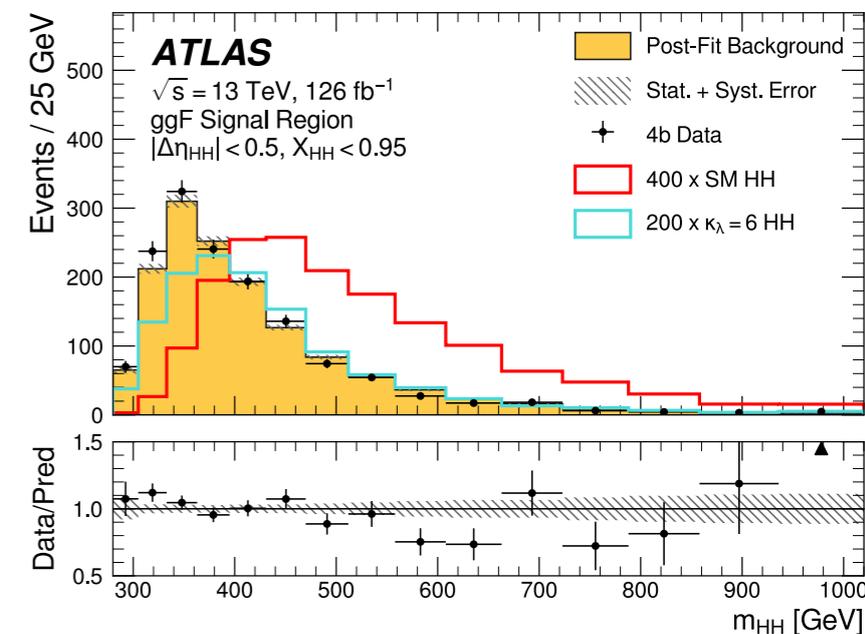
$b\bar{b}\tau\tau$



Medium signal,
medium bkgd

Medium trigger
thresholds: still
important for κ_λ

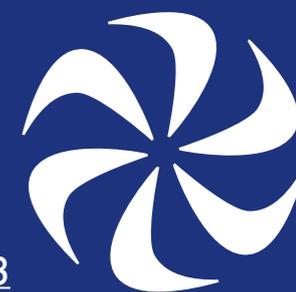
$b\bar{b}b\bar{b}$



Largest signal,
Largest background

Challenging trigger:
b-tagging at trigger level

Comparing the Main Channels

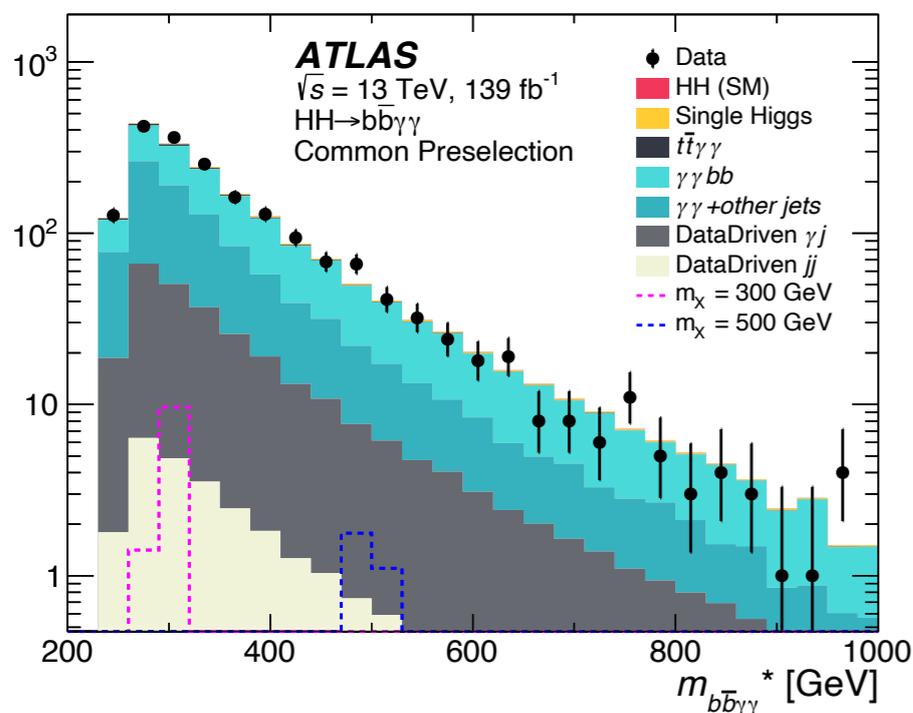


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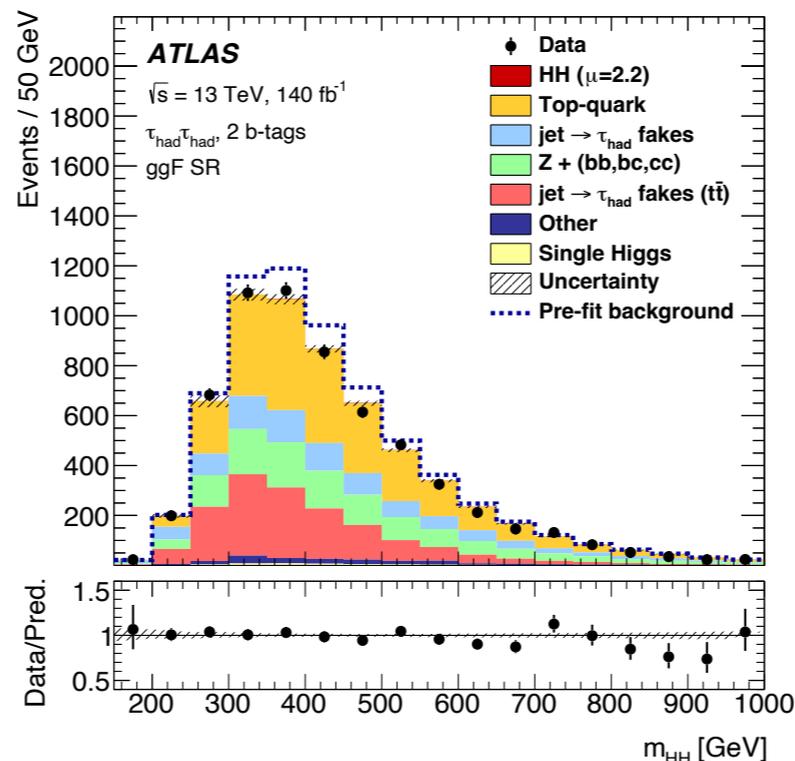
$b\bar{b}\gamma\gamma$



Rarest signal,
lowest bkgd

Low trigger threshold:
Critical for κ_λ

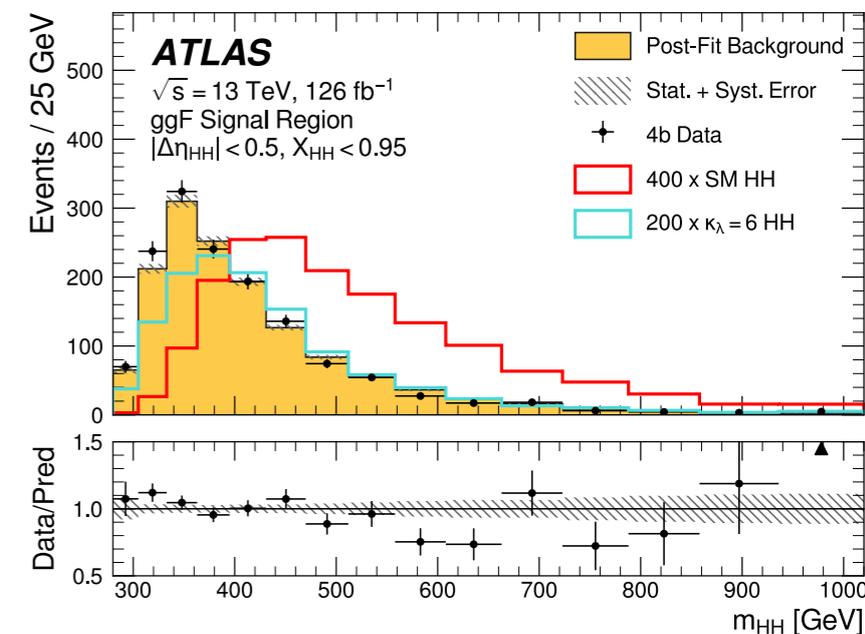
$b\bar{b}\tau\tau$



Medium signal,
medium bkgd

Medium trigger
thresholds: still
important for κ_λ

$b\bar{b}b\bar{b}$



Largest signal,
Largest background

Challenging trigger:
b-tagging at trigger level

BDT/DNN for main observables

Comparing the Main Channels

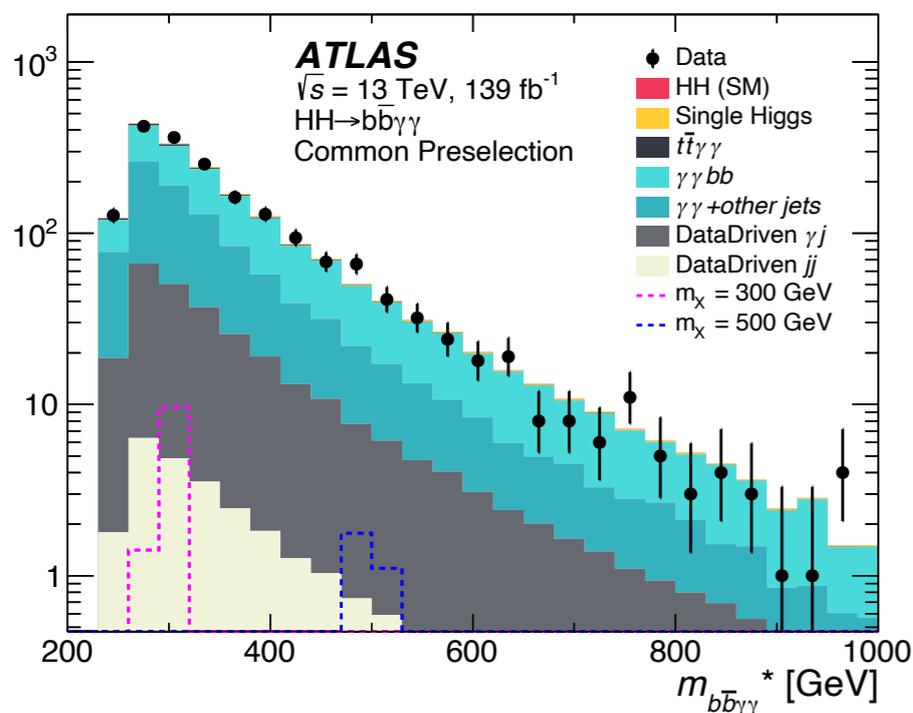


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$b\bar{b}\gamma\gamma$

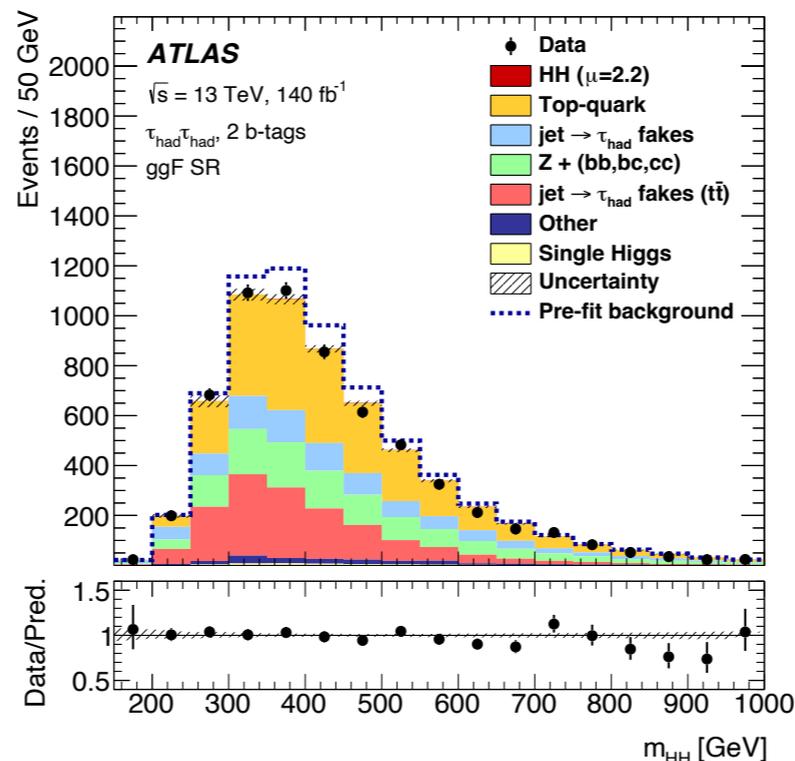


Rarest signal,
lowest bkgd

Low trigger threshold:
Critical for κ_λ

BDT/DNN for main observables

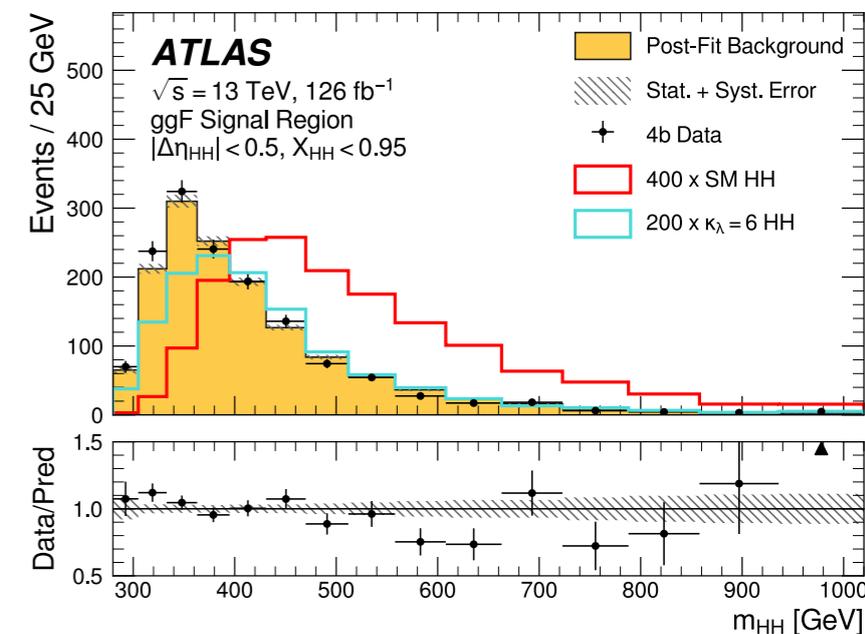
$b\bar{b}\tau\tau$



Medium signal,
medium bkgd

Medium trigger
thresholds: still
important for κ_λ

$b\bar{b}b\bar{b}$

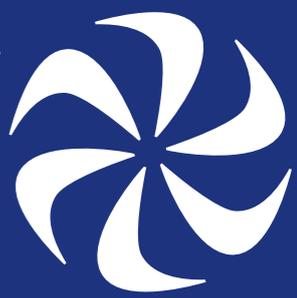


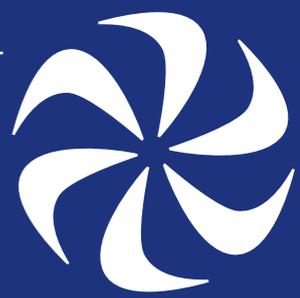
Largest signal,
Largest background

Challenging trigger:
b-tagging at trigger level

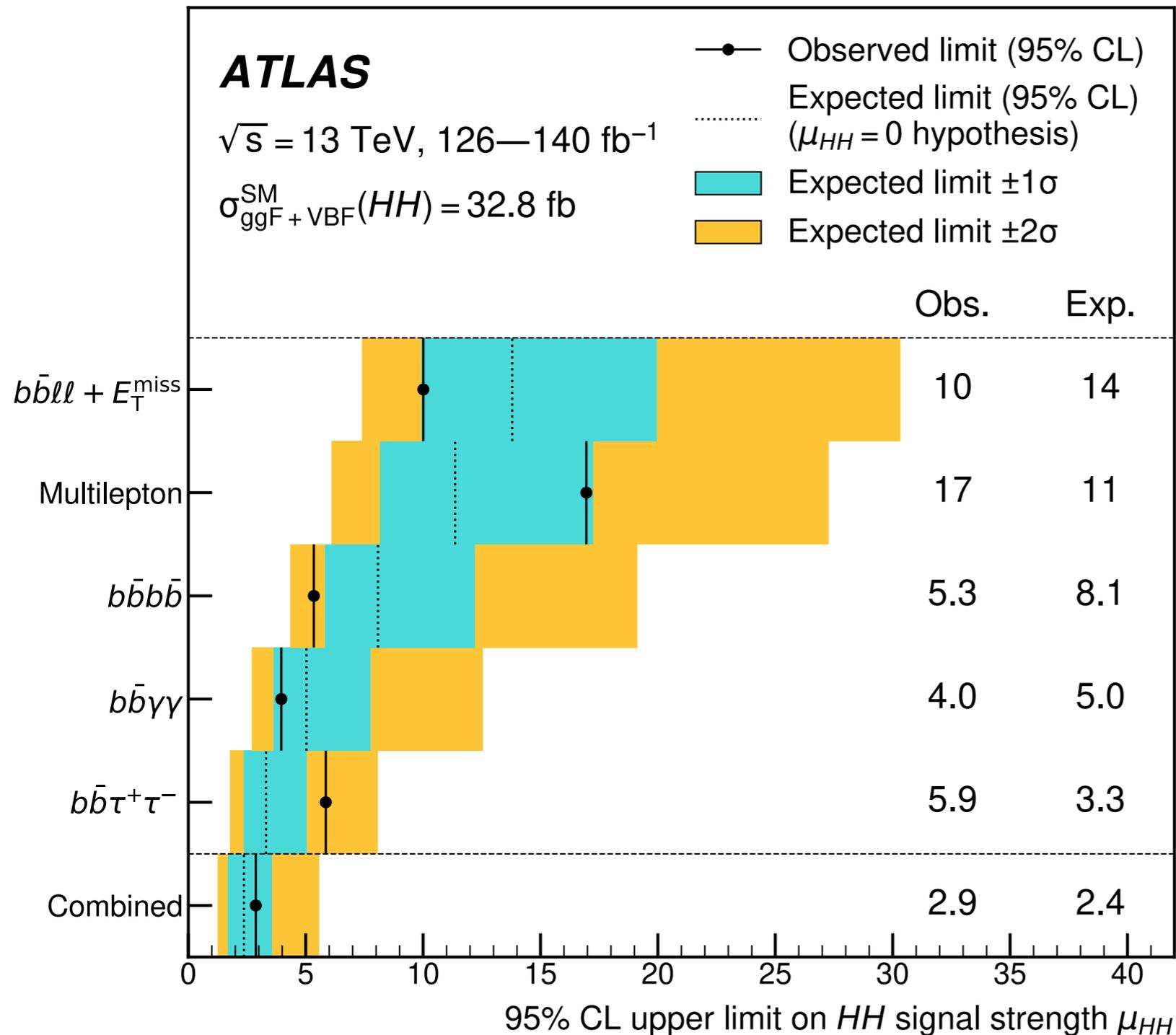
Novel DNN bkgd
estimate

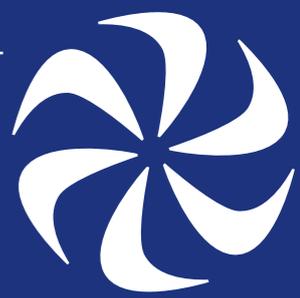
ATLAS Combination



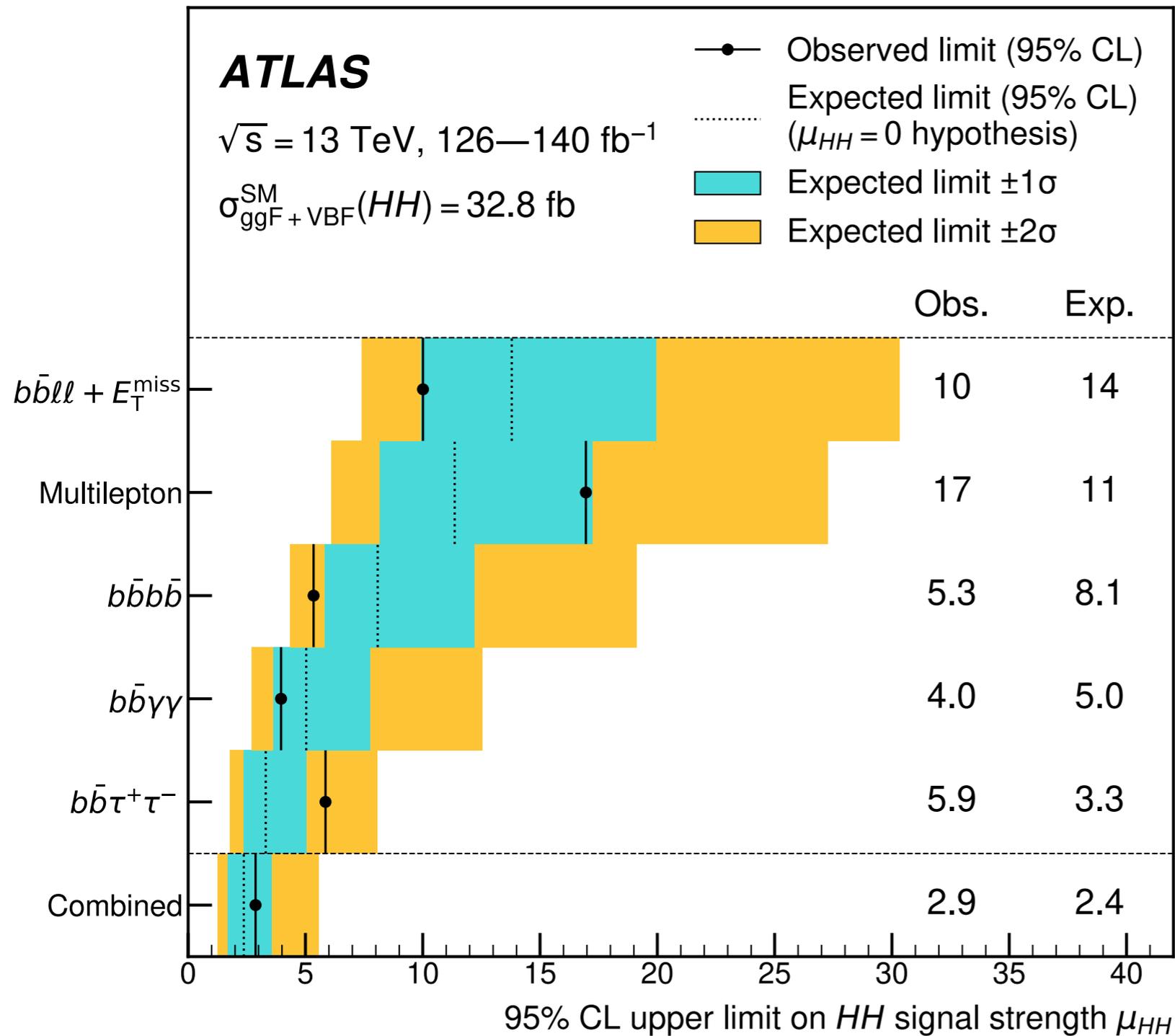


ATLAS Combination

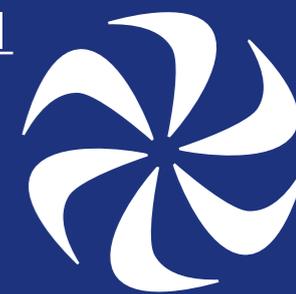




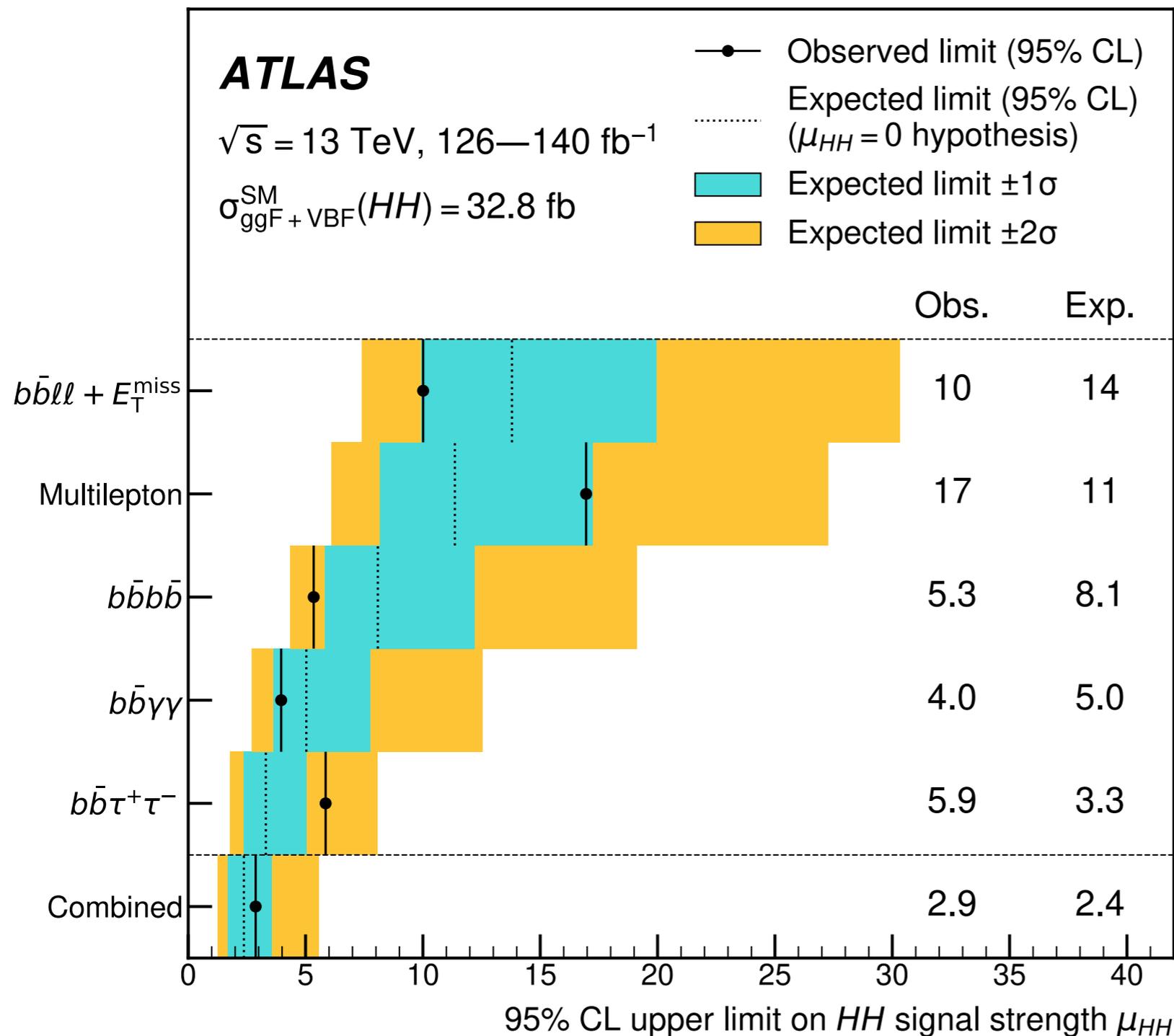
ATLAS Combination



Combined limits strongly improve over inputs

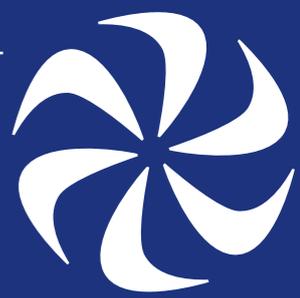


ATLAS Combination

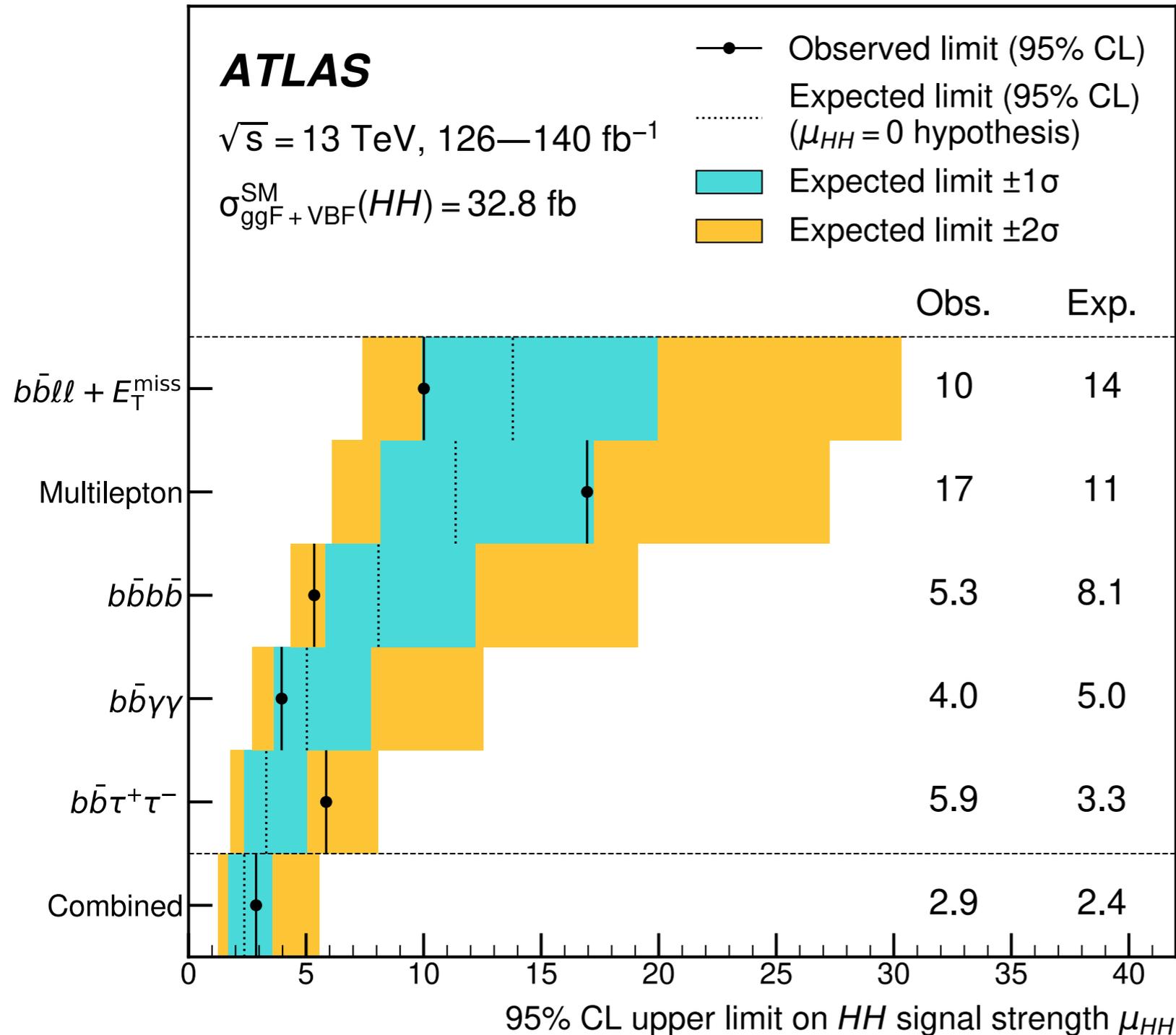


Combined limits strongly improve over inputs

All channels contribute, but top 3 contribute the most



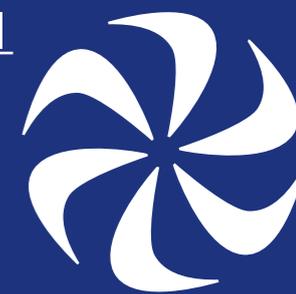
ATLAS Combination



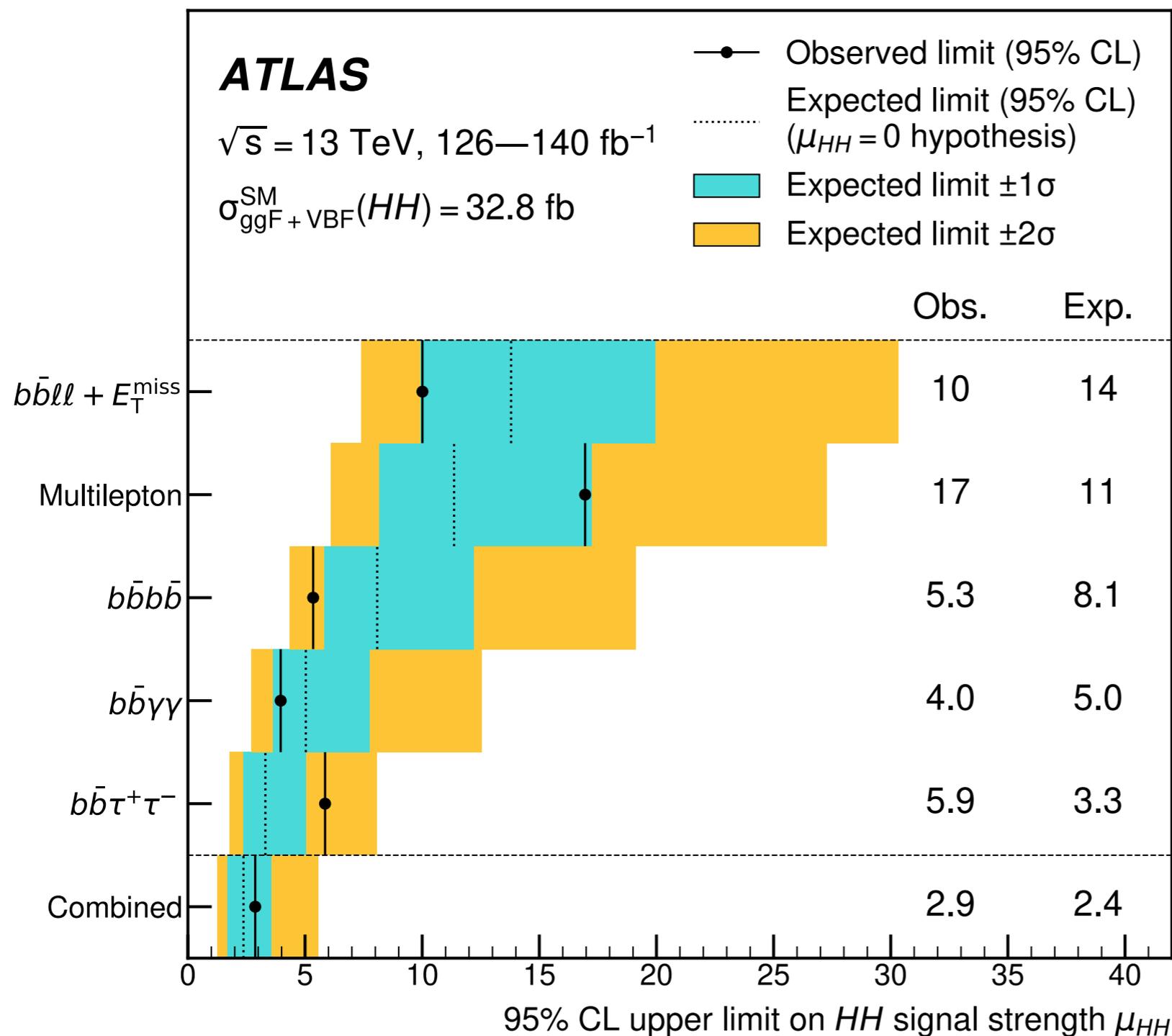
Combined limits strongly improve over inputs

All channels contribute, but top 3 contribute the most

Expected sensitivity at 2.4xSM, observed at 2.9xSM



ATLAS Combination

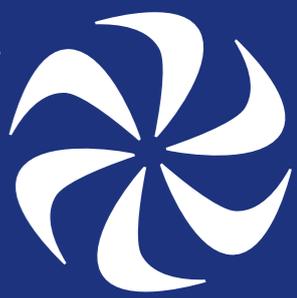


Combined limits strongly improve over inputs

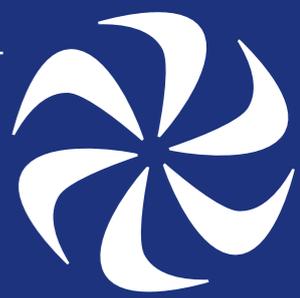
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Expected sensitivity at 2.4xSM, observed at 2.9xSM

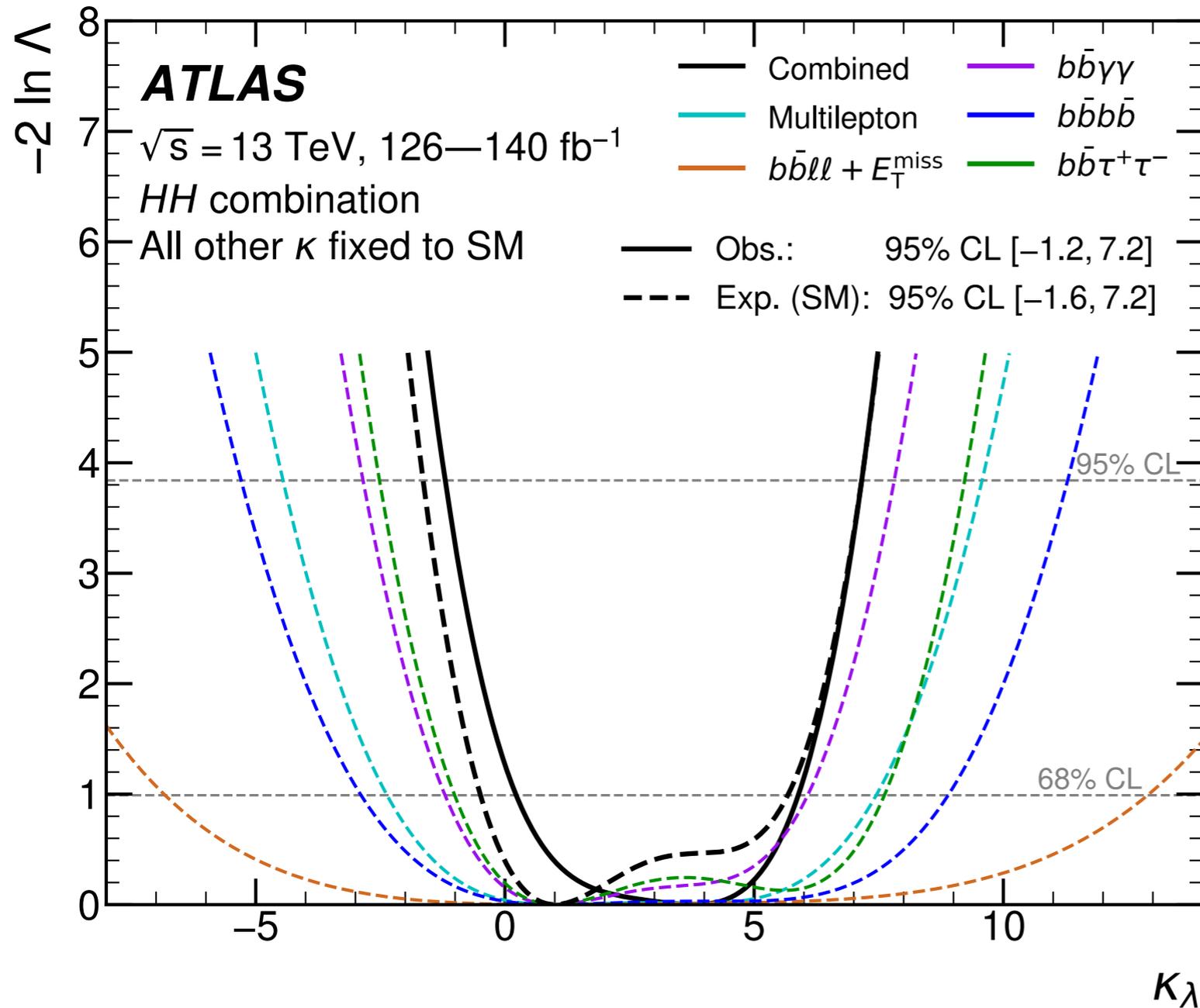
Still a ways to go for evidence...

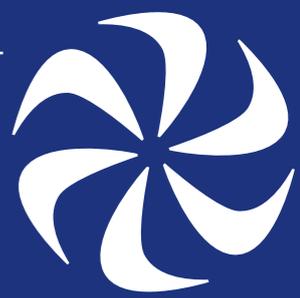


Sensitivity to κ_λ

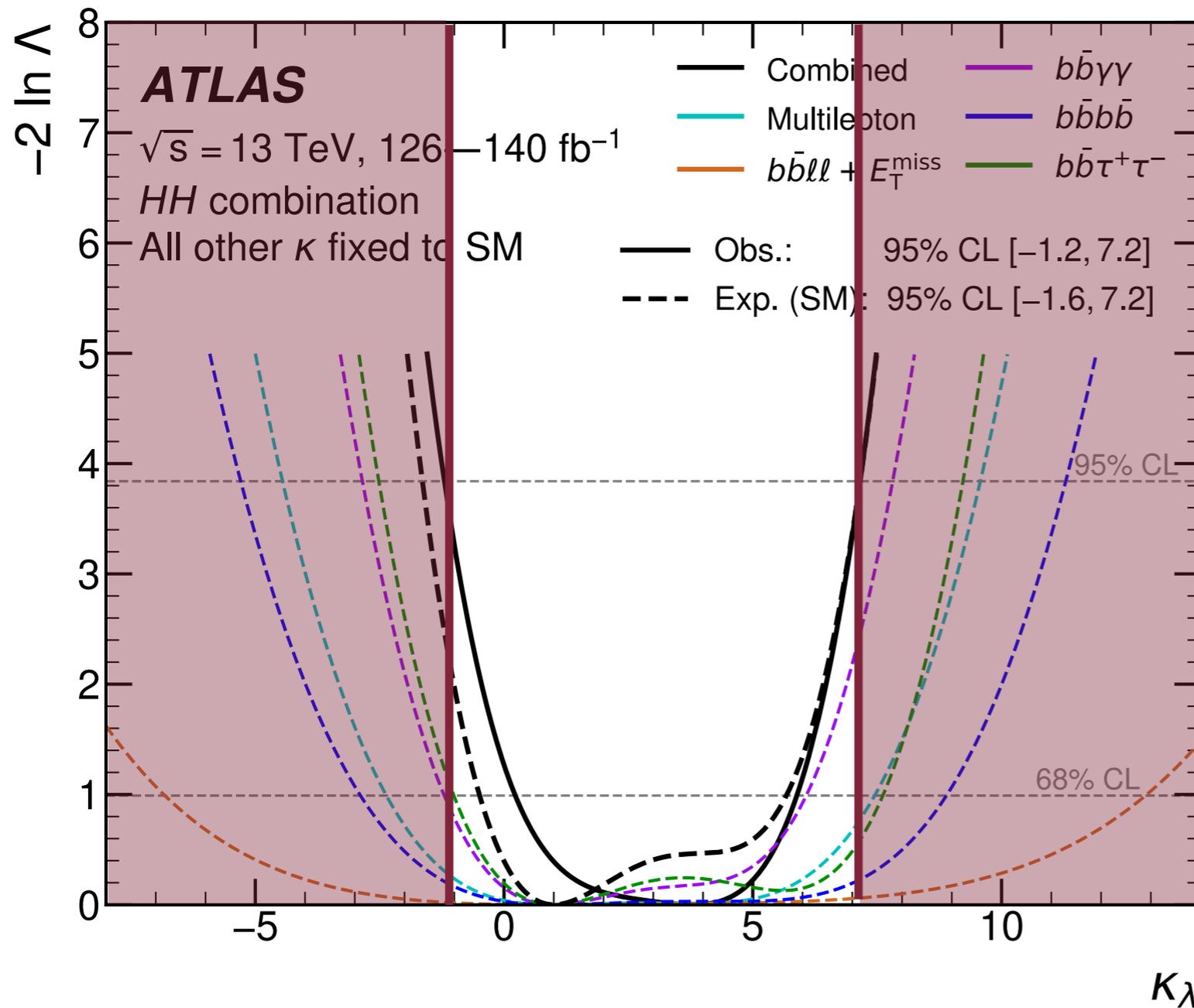


Sensitivity to κ_λ

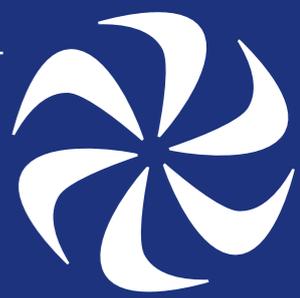




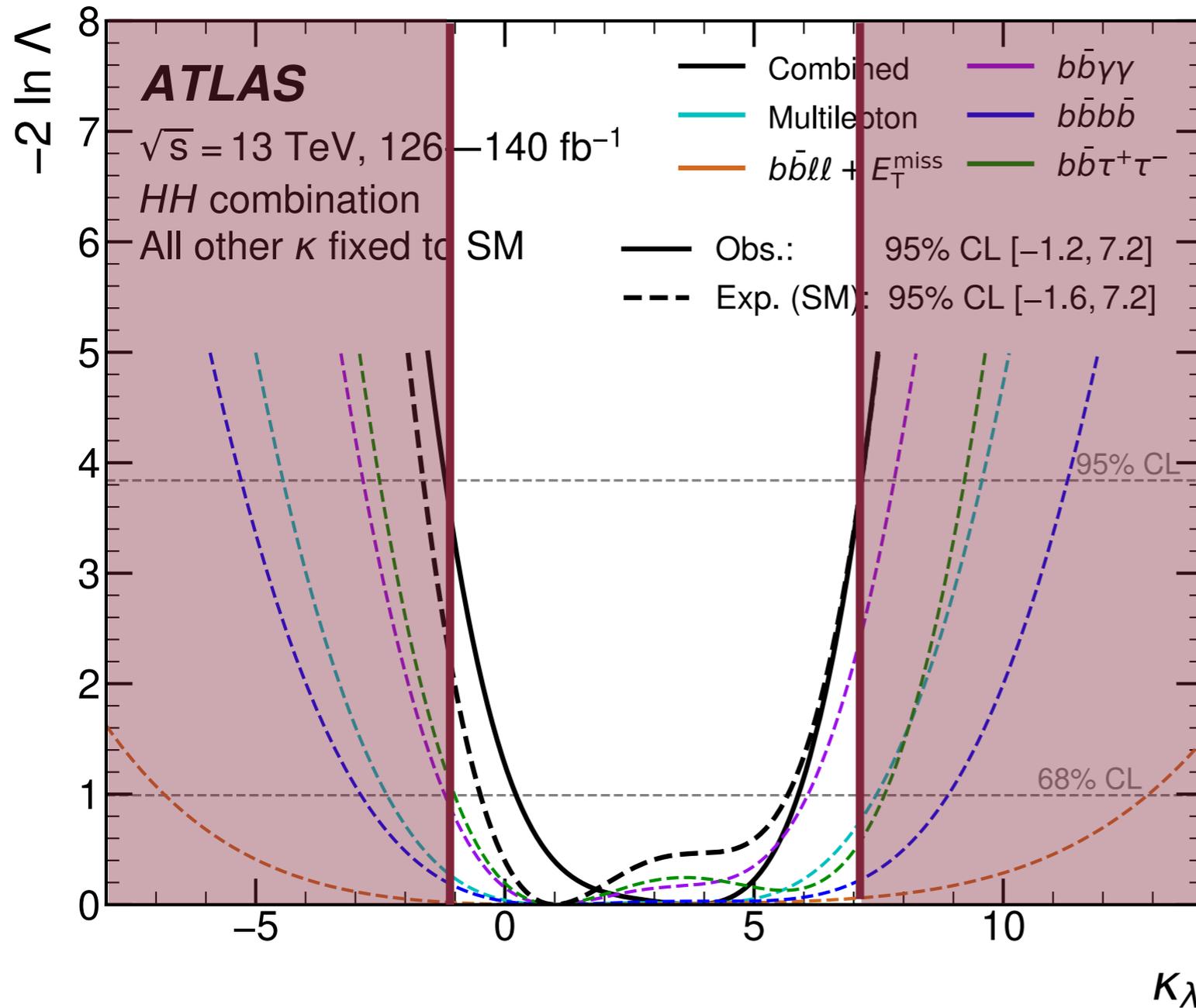
Sensitivity to κ_λ



Combined limits (again)
 strongly improve
 over inputs

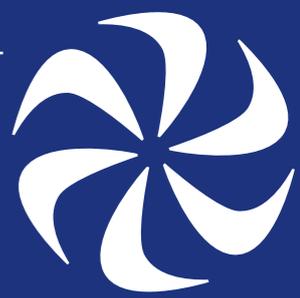


Sensitivity to κ_λ

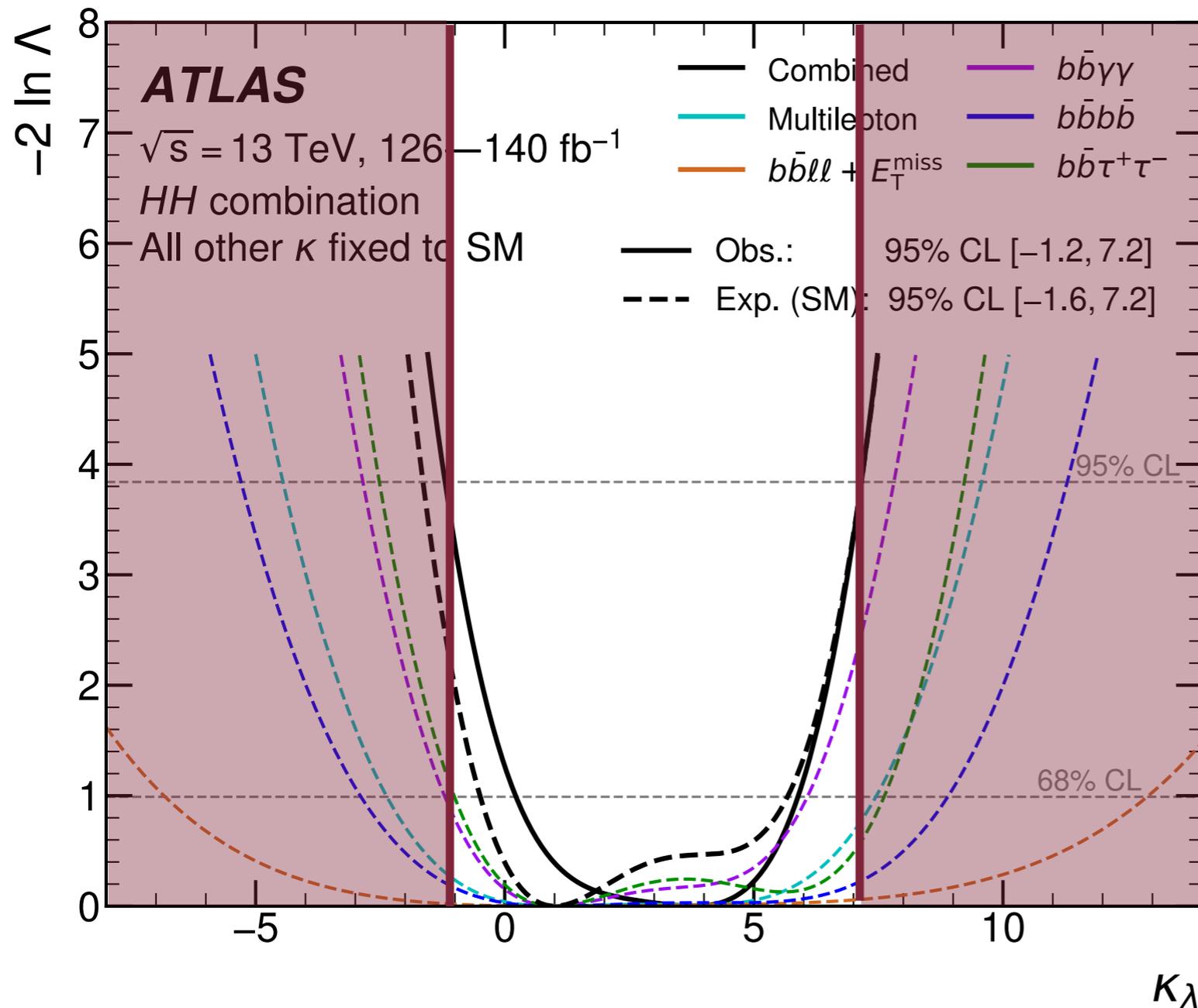


Combined limits (again)
 strongly improve
 over inputs

Trigger and background
 dramatically affect
 sensitivity to κ_λ



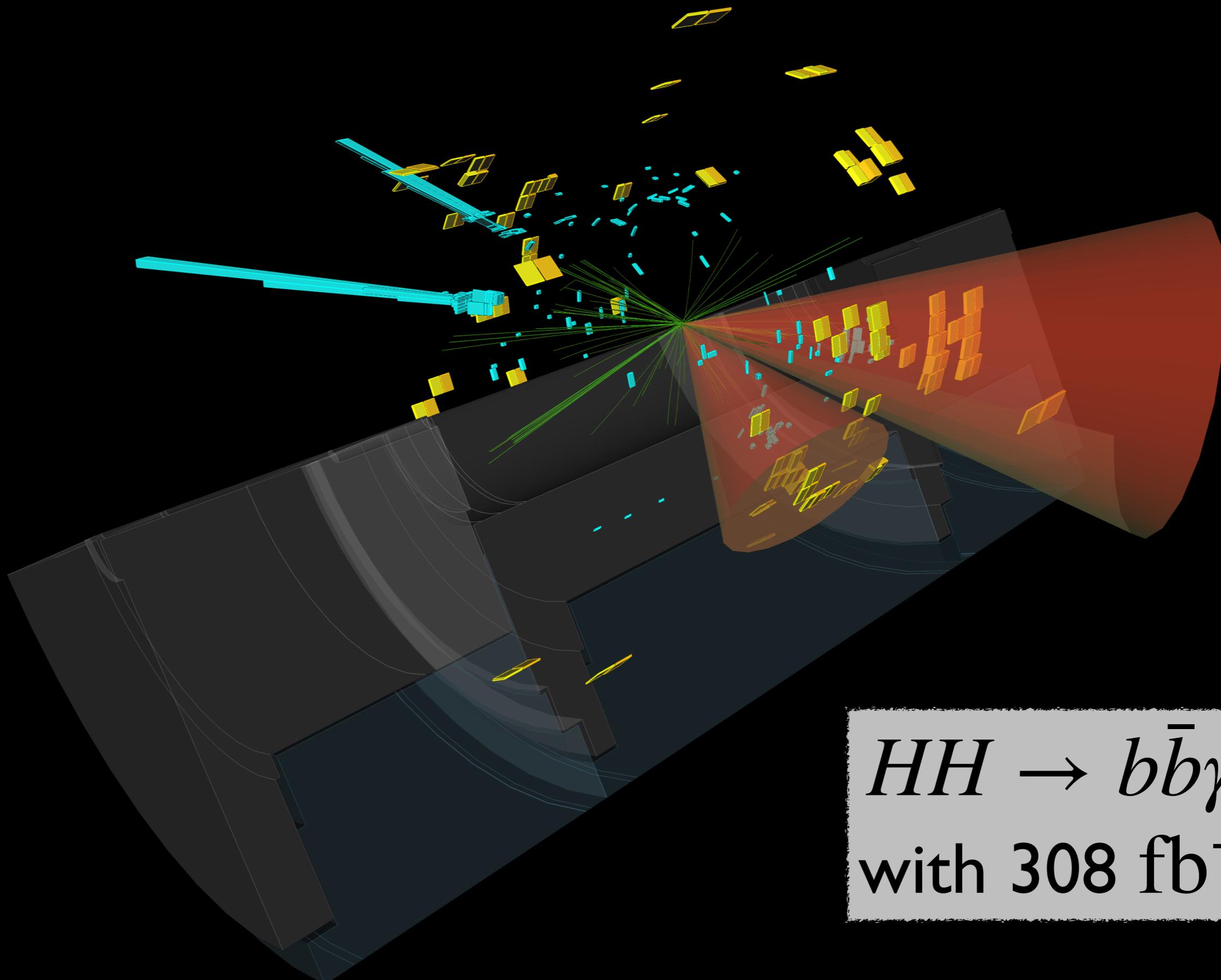
Sensitivity to κ_λ



Combined limits (again)
 strongly improve
 over inputs

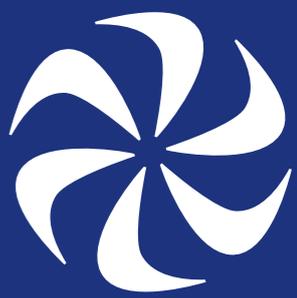
Trigger and background
 dramatically affect
 sensitivity to κ_λ

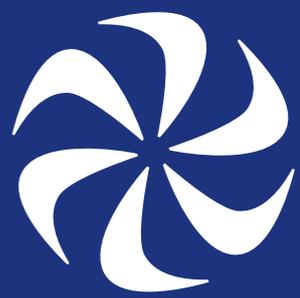
Multilepton moves to
 third-best measurement:
 better triggers than $4b$!



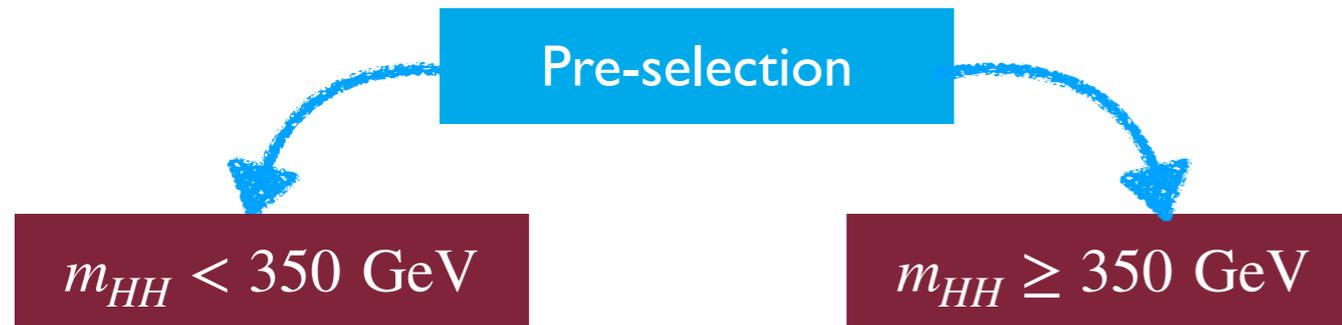
$HH \rightarrow b\bar{b}\gamma\gamma$
with 308 fb^{-1}

$b\bar{b}\gamma\gamma$ Analysis Strategy

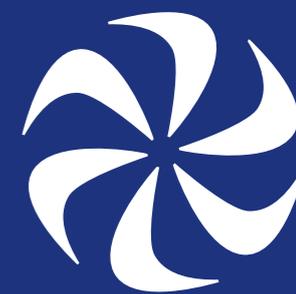




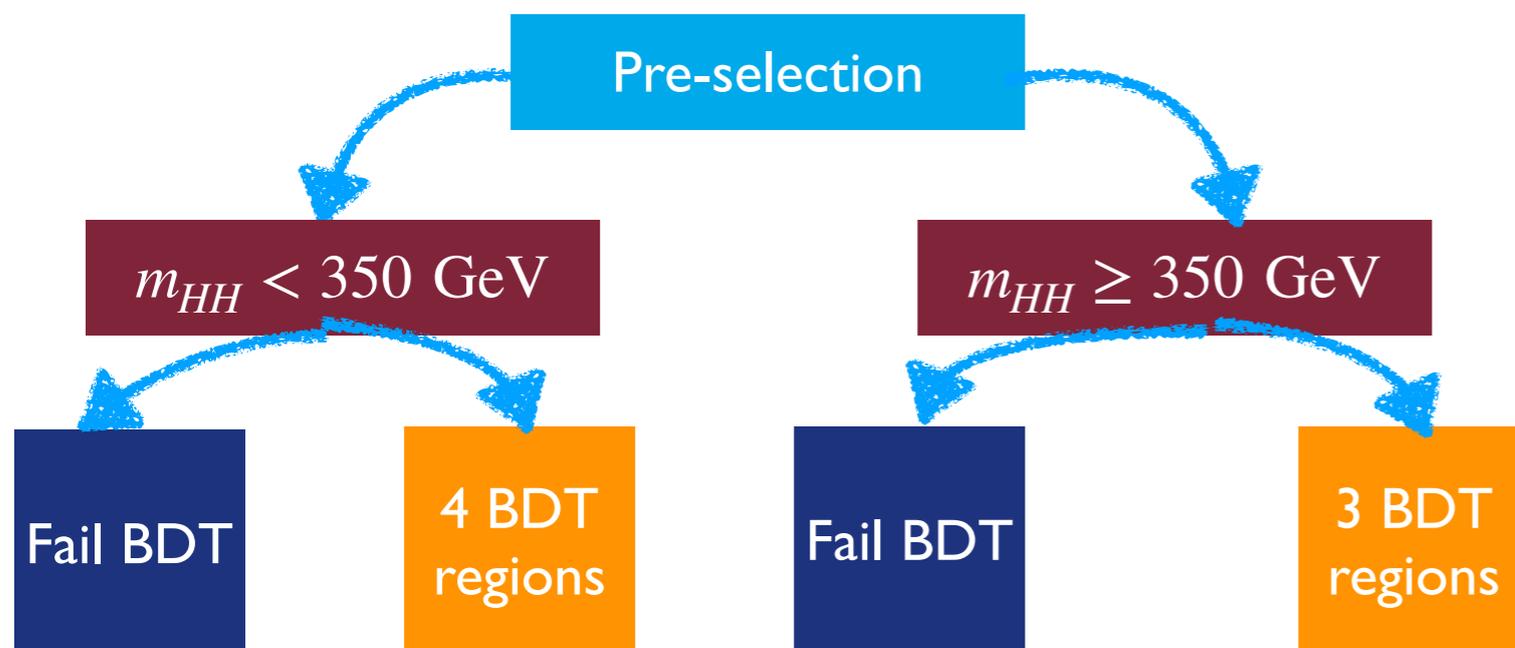
$b\bar{b}\gamma\gamma$ Analysis Strategy



After **pre-selection**, split into **high-mass** and **low-mass** selections

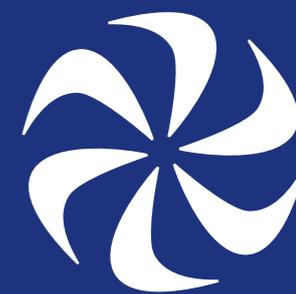


$b\bar{b}\gamma\gamma$ Analysis Strategy

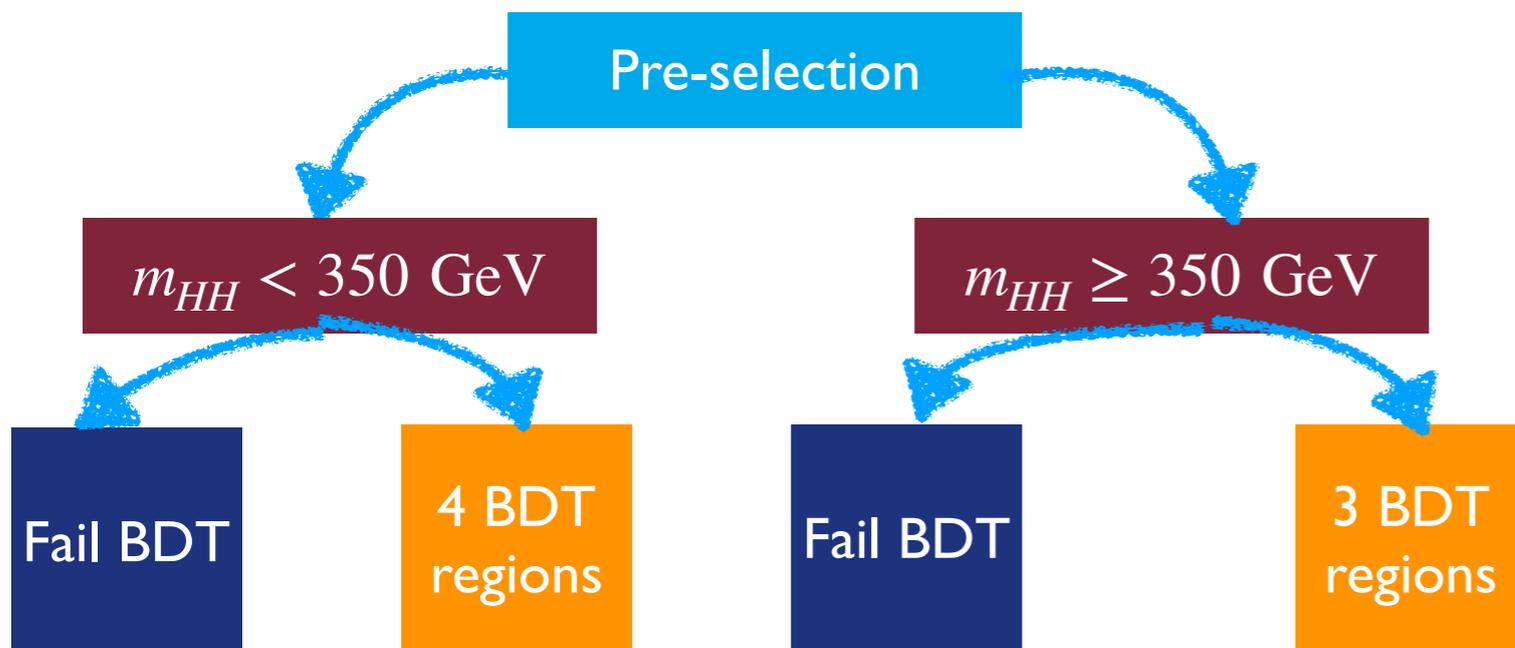


After **pre-selection**, split into **high-mass** and **low-mass** selections

BDT trained in each region: select low- and high-purity **signal regions** with BDT

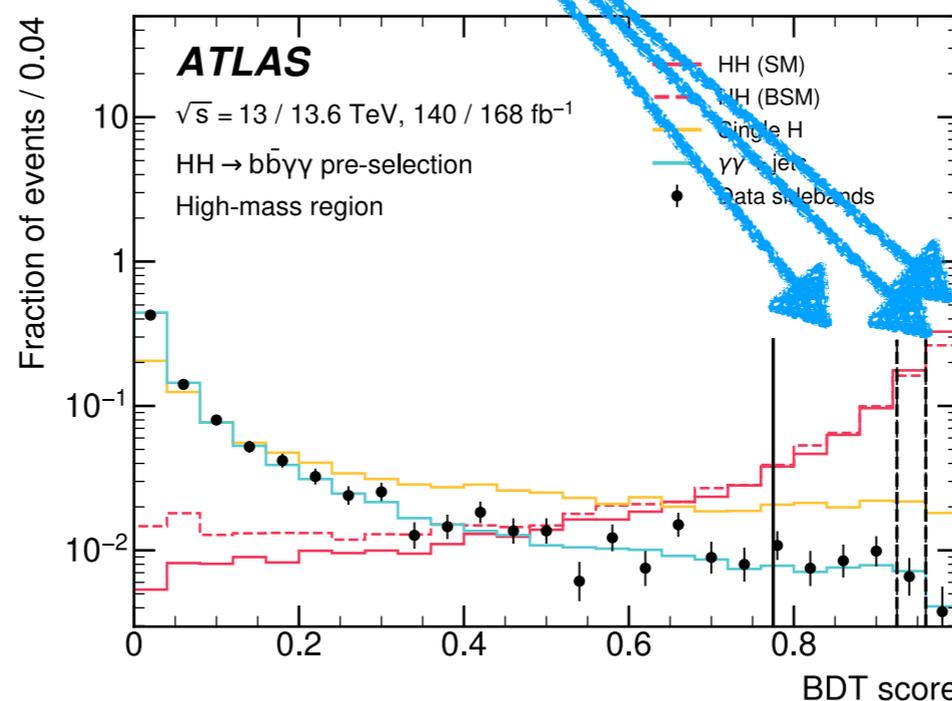
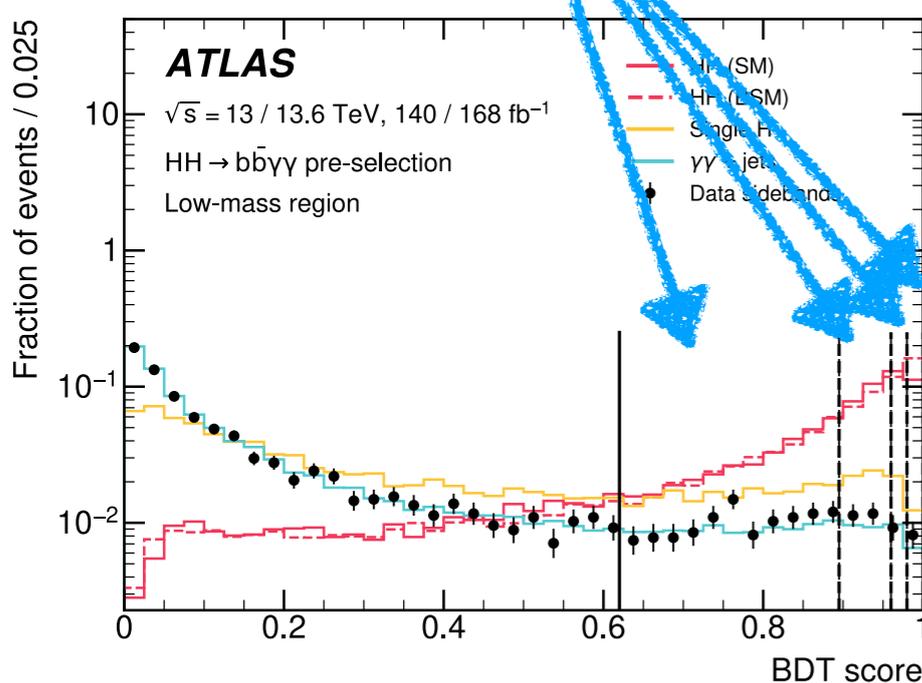


$b\bar{b}\gamma\gamma$ Analysis Strategy



After **pre-selection**, split into **high-mass** and **low-mass** selections

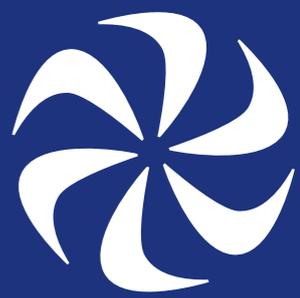
BDT trained in each region: select low- and high-purity **signal regions** with BDT



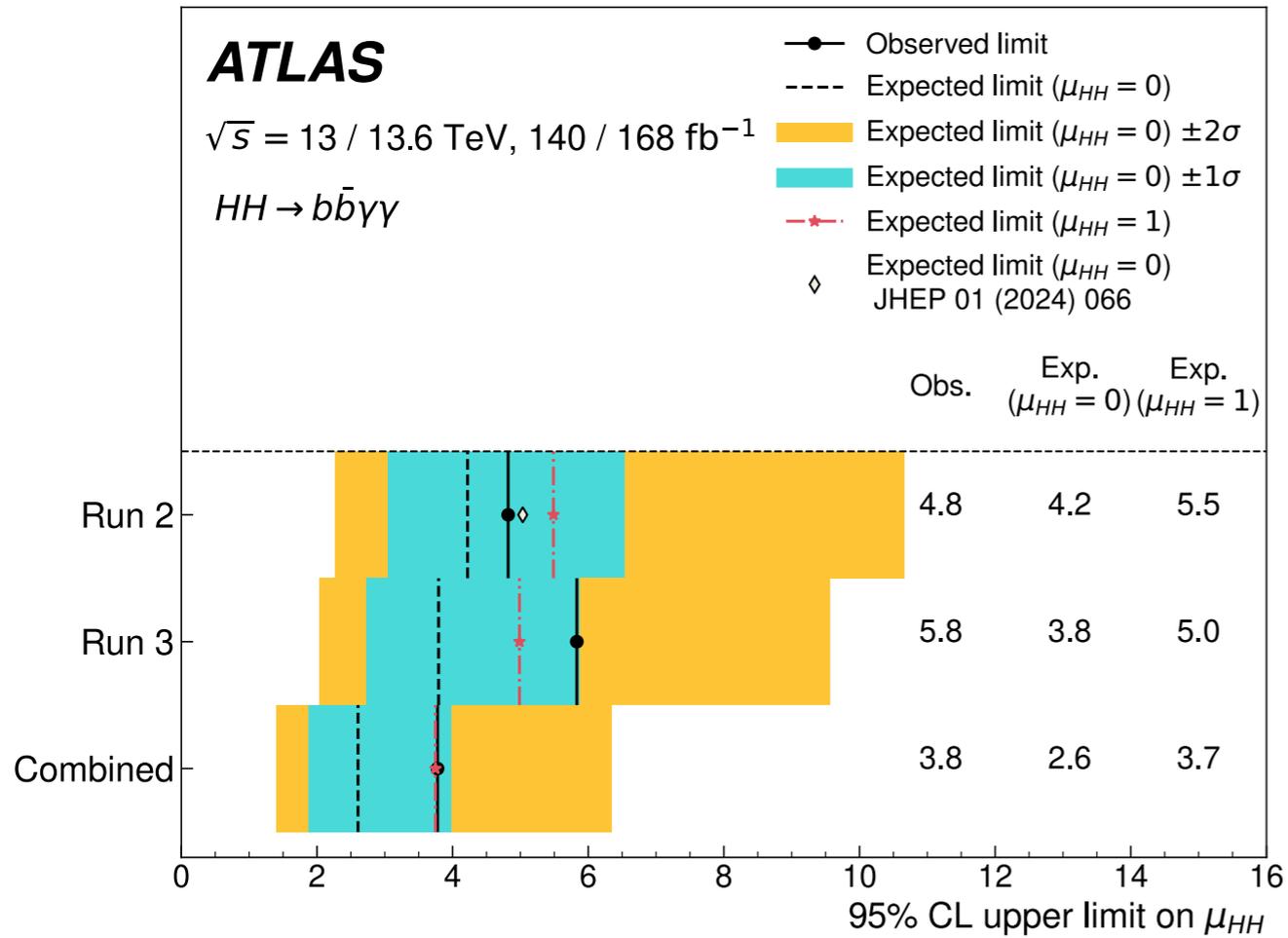
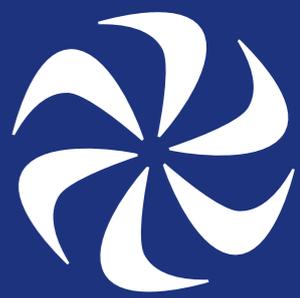
Fit $m_{\gamma\gamma}$ in 7 SR's simultaneously to extract signal

$b\bar{b}\gamma\gamma$ Results

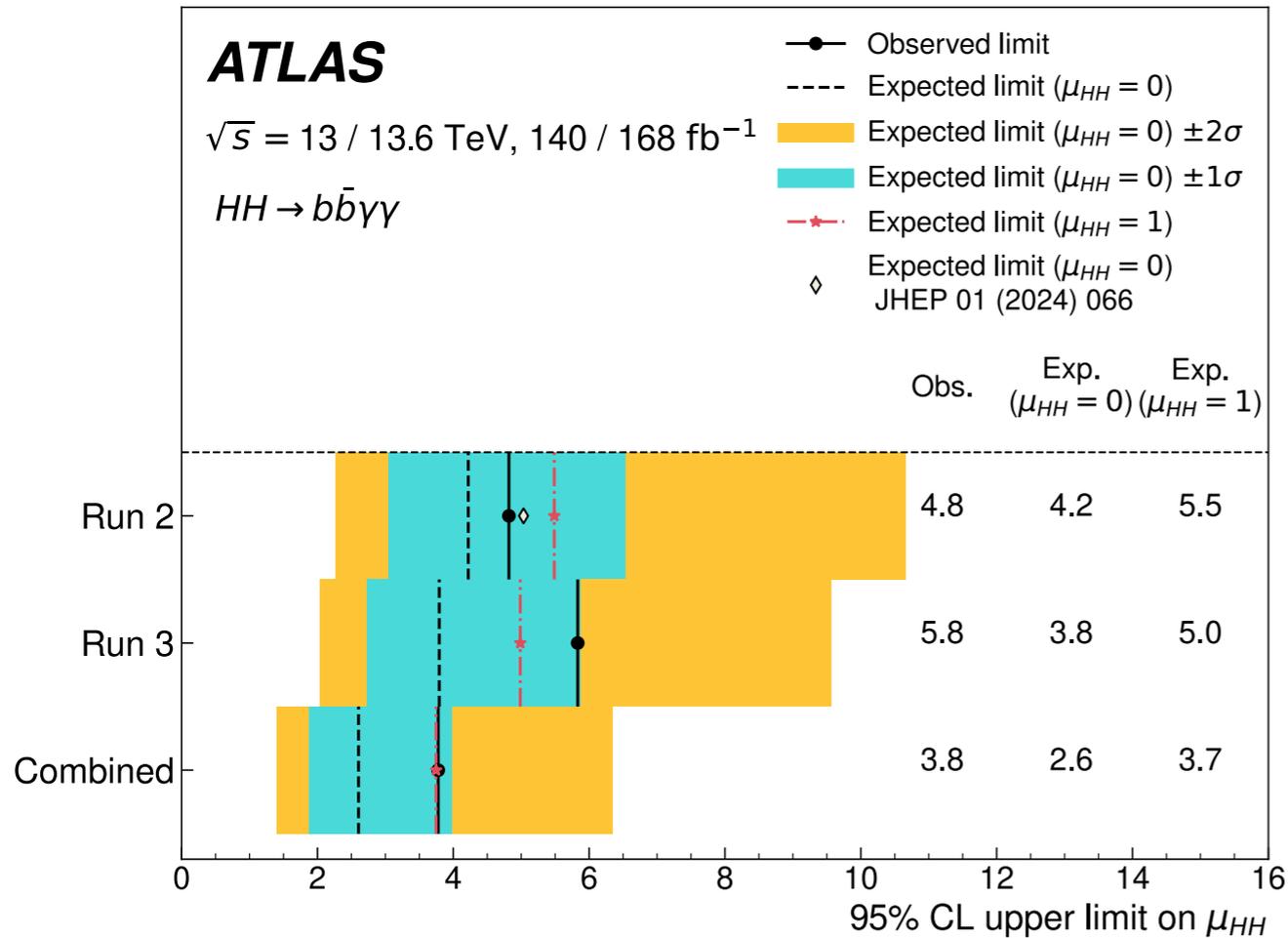
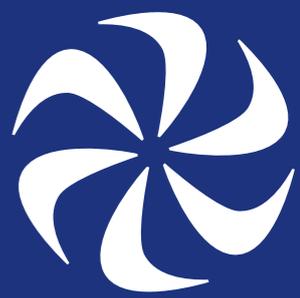
[arXiv:2507.0349](https://arxiv.org/abs/2507.0349)



$b\bar{b}\gamma\gamma$ Results

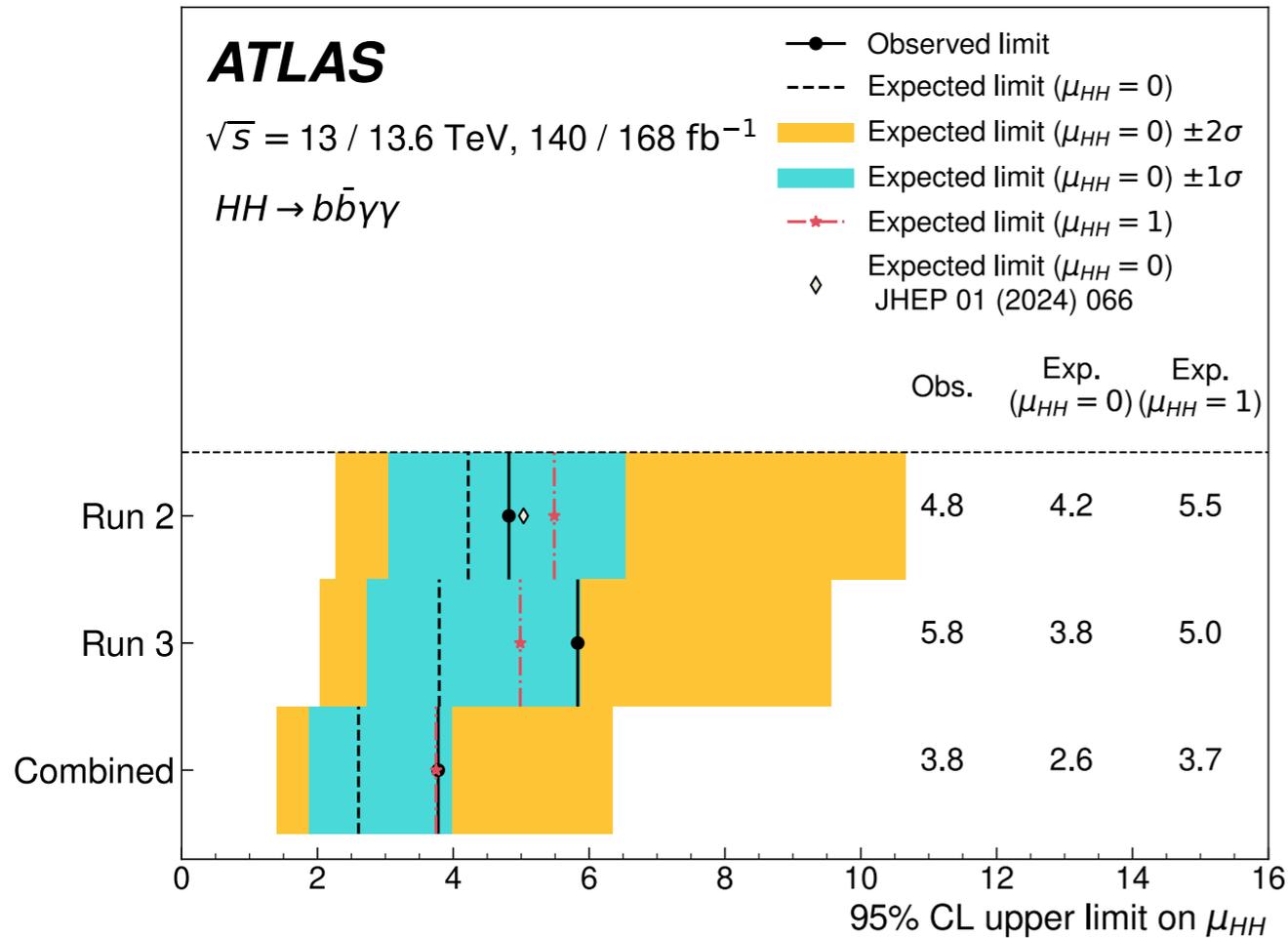
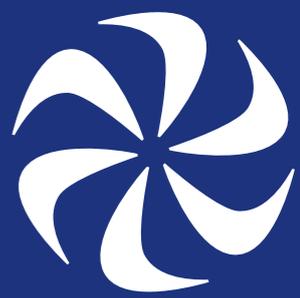


$b\bar{b}\gamma\gamma$ Results



2.6xSM expected limit

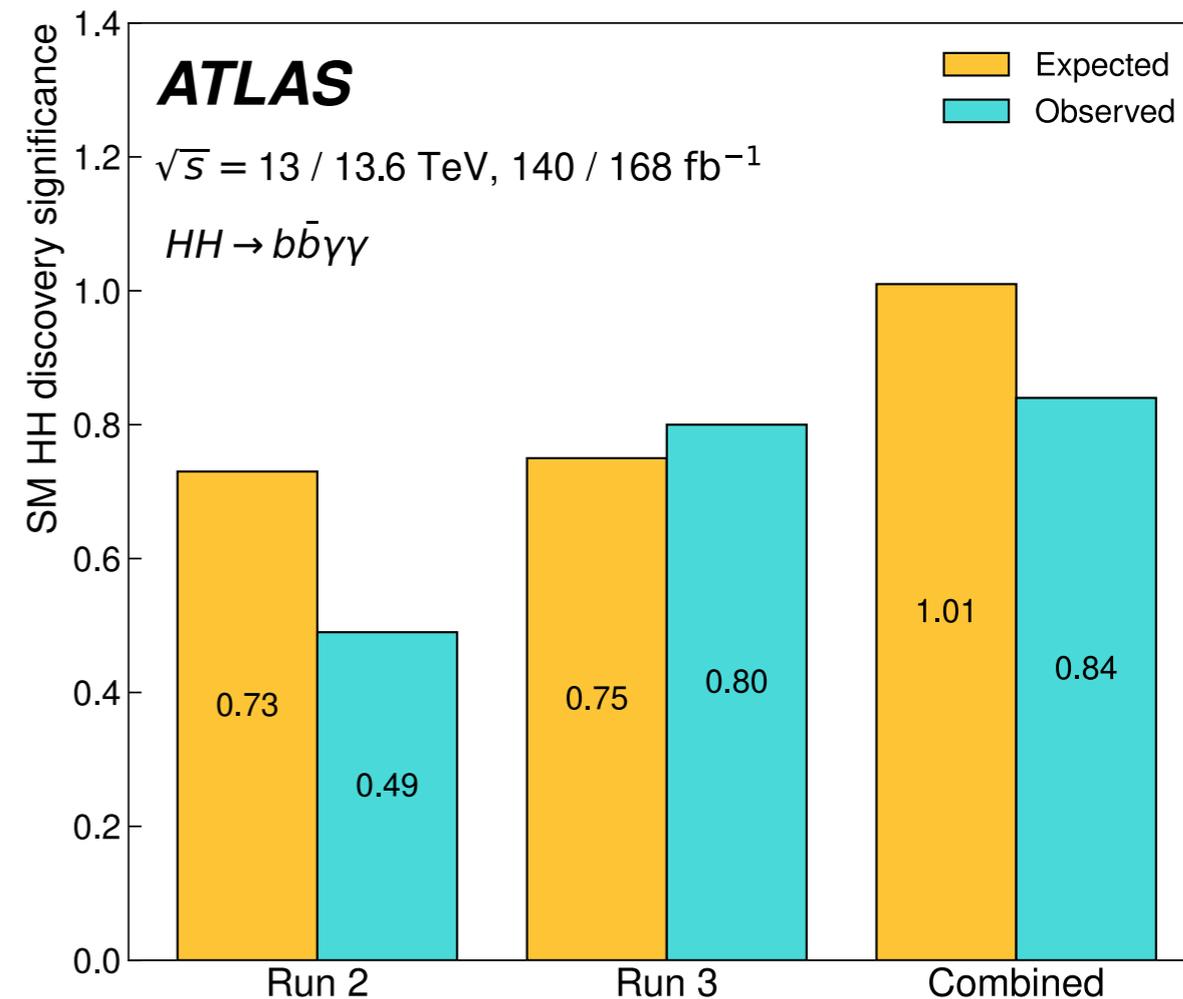
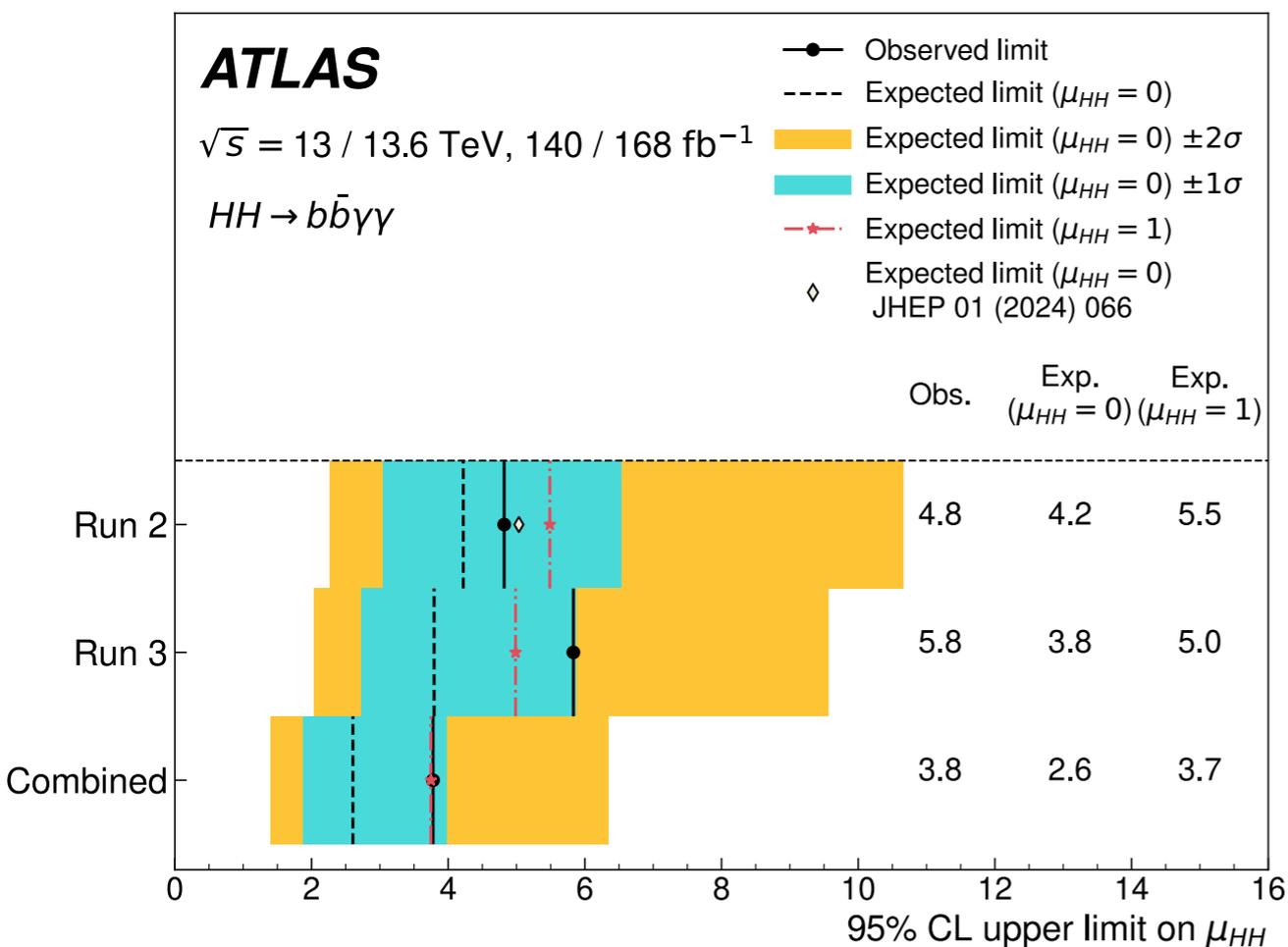
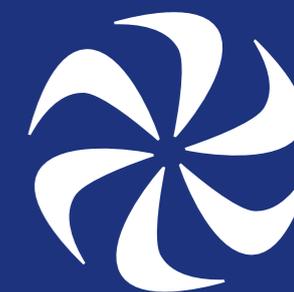
$b\bar{b}\gamma\gamma$ Results



2.6xSM expected limit

Entire Run2 combination was 2.4!

$b\bar{b}\gamma\gamma$ Results

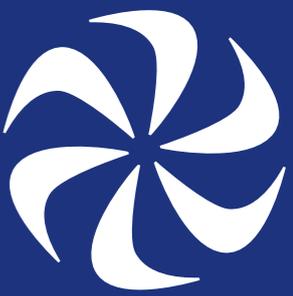


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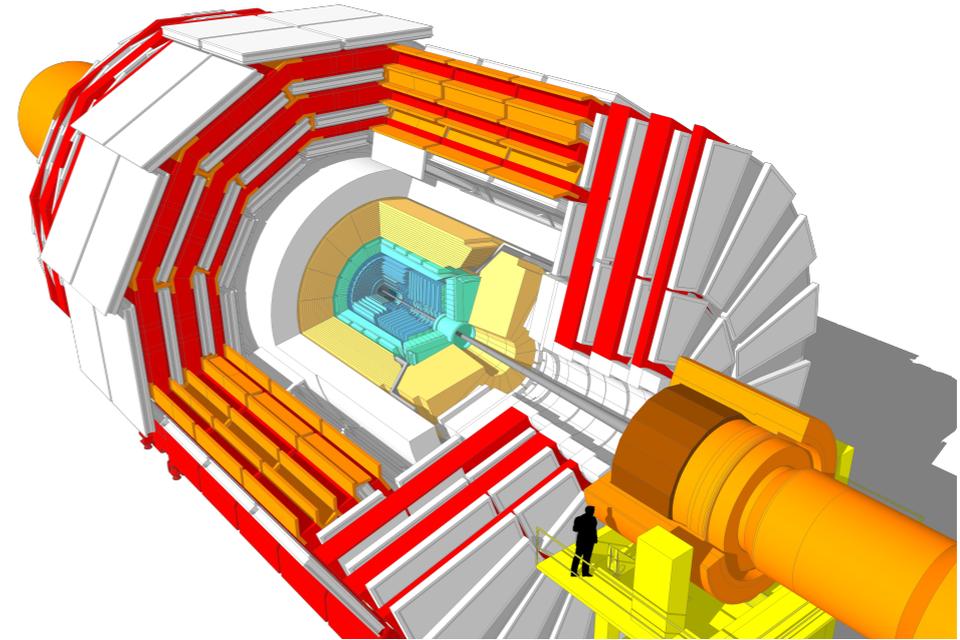
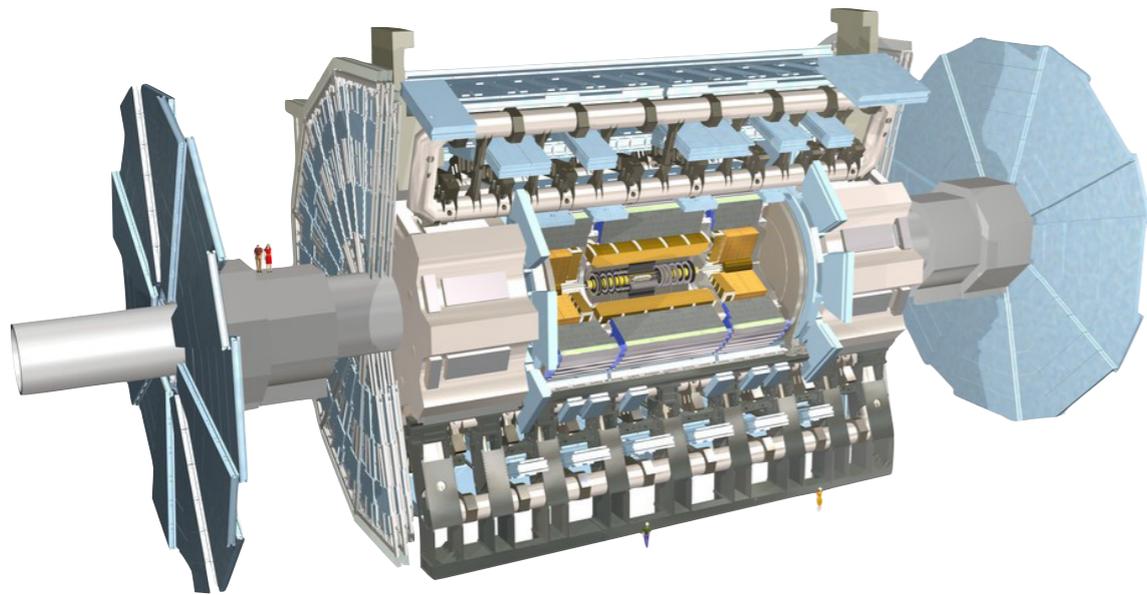
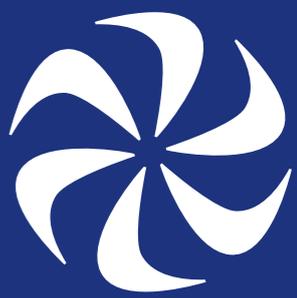
Entire Run2 combination was 2.4!

0.84 σ signal strength: long way to go but signal strength starting to emerge!

ATLAS and CMS

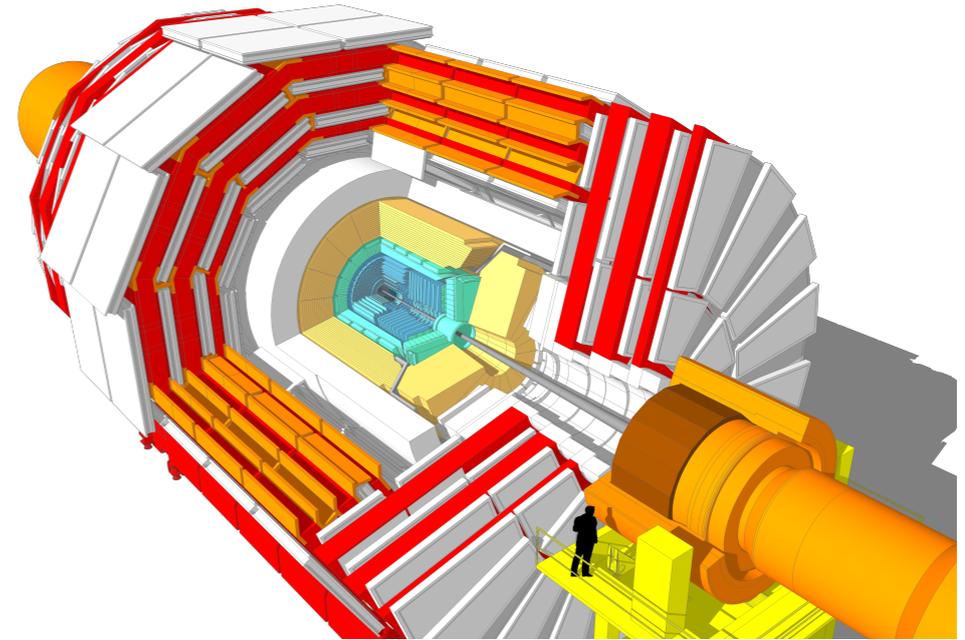
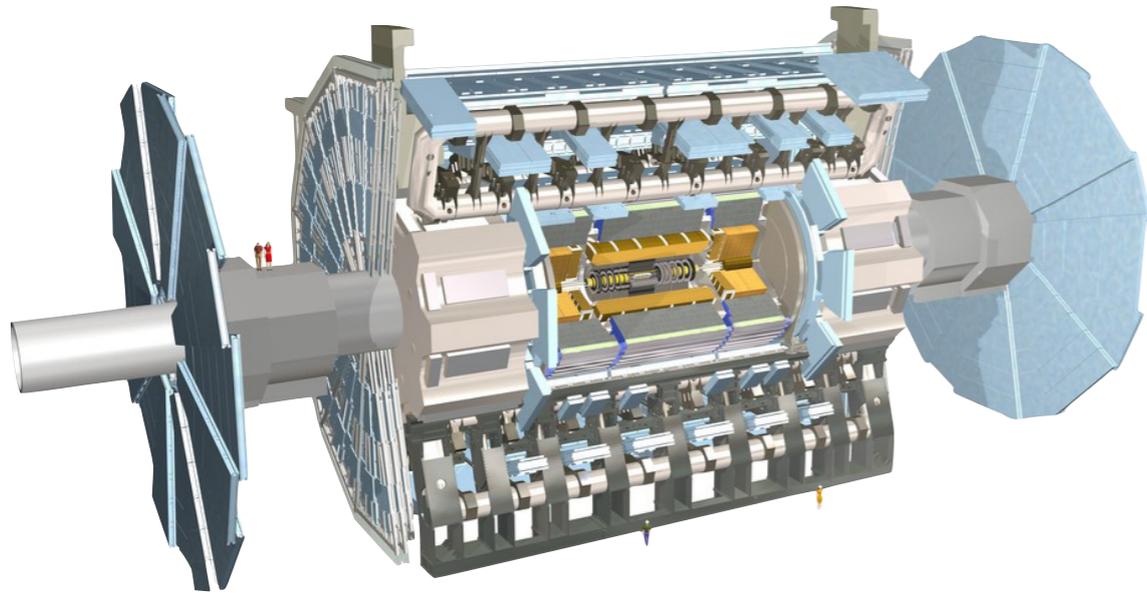


ATLAS and CMS



Run 2 analysis had a huge range of improvements
from both ATLAS and CMS

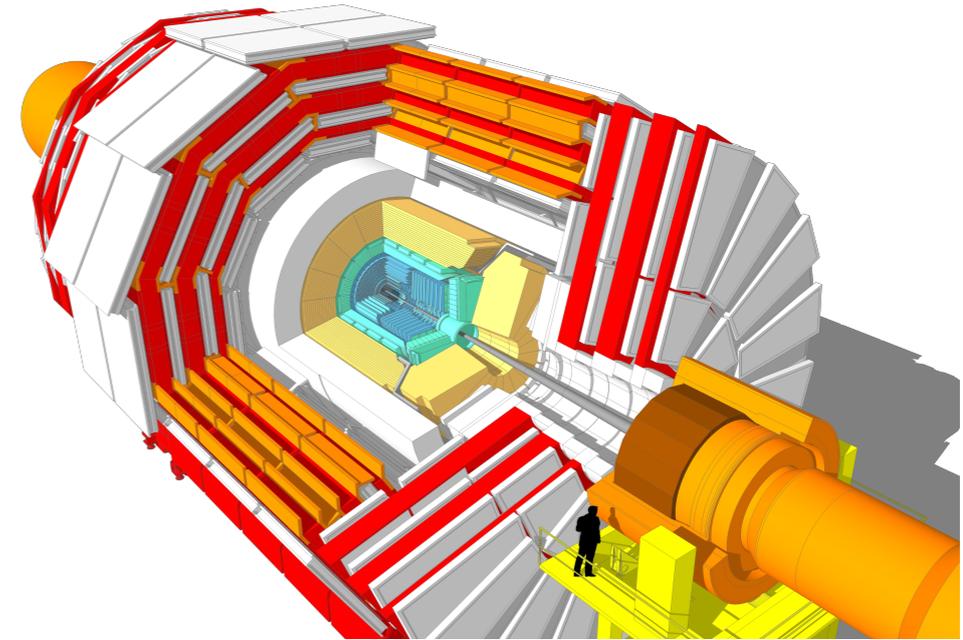
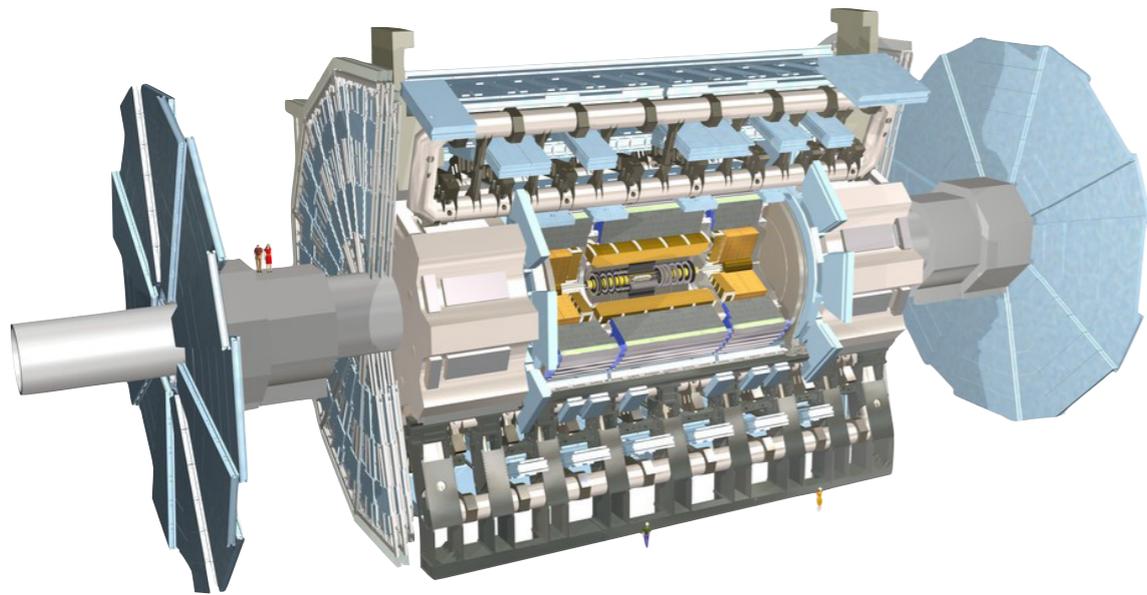
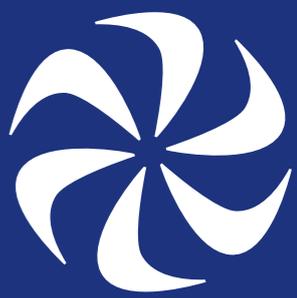
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Broadly similar approaches, but many differences in strategy

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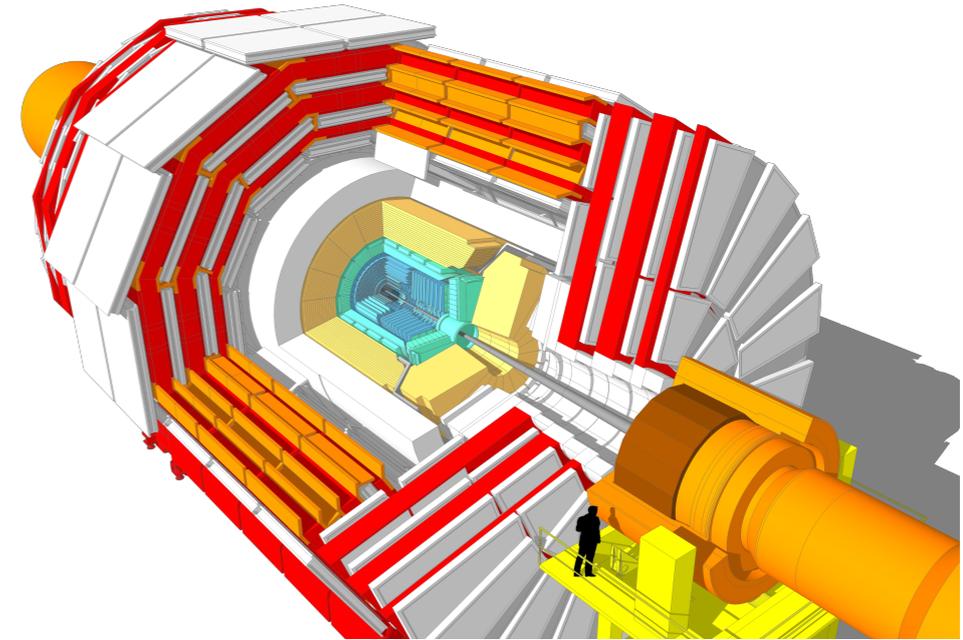
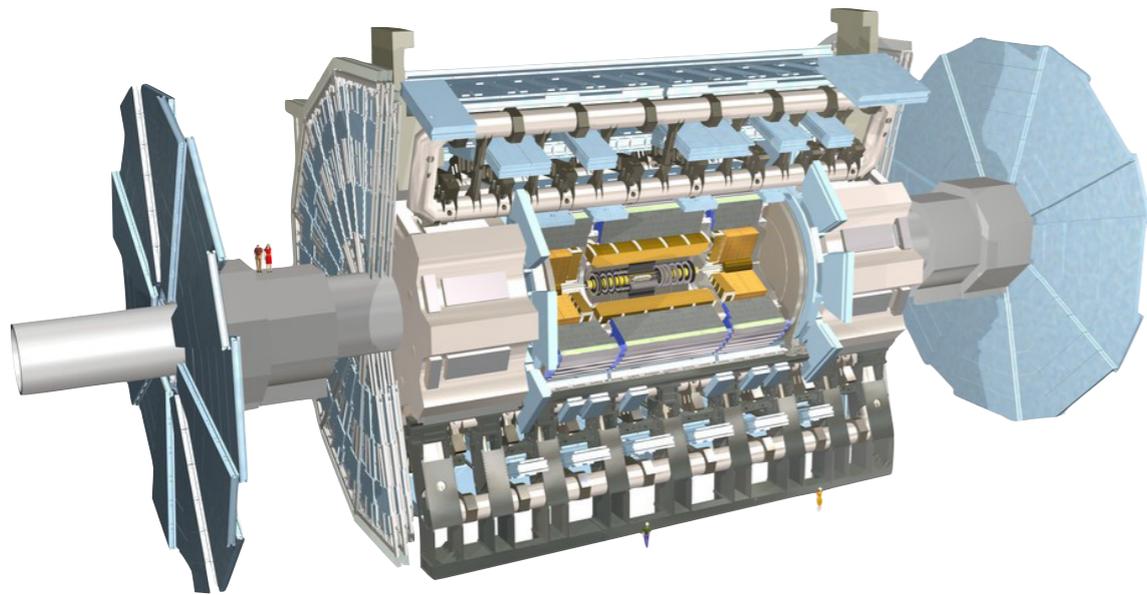
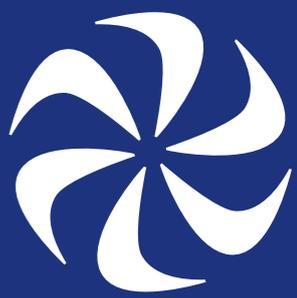


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Broadly similar approaches, but many differences in strategy

Ultimately very similar sensitivity

ATLAS and CMS

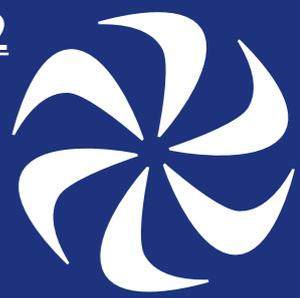


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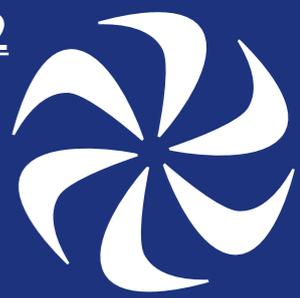
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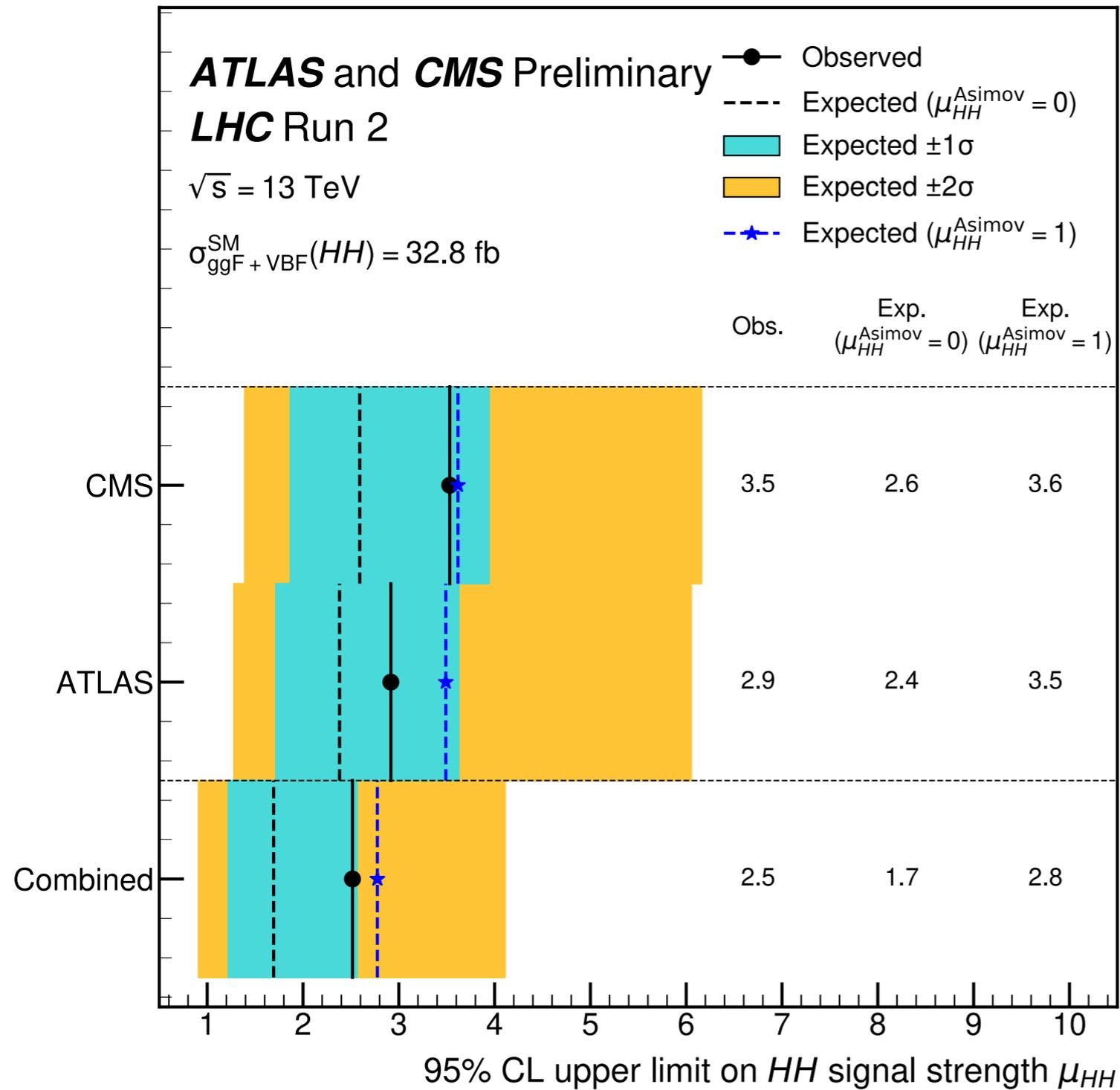
Perfect time for a first combination to see what is possible!

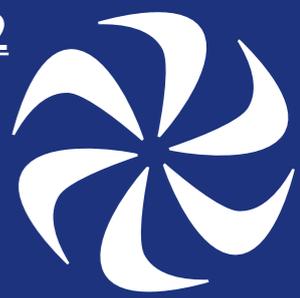


The Results

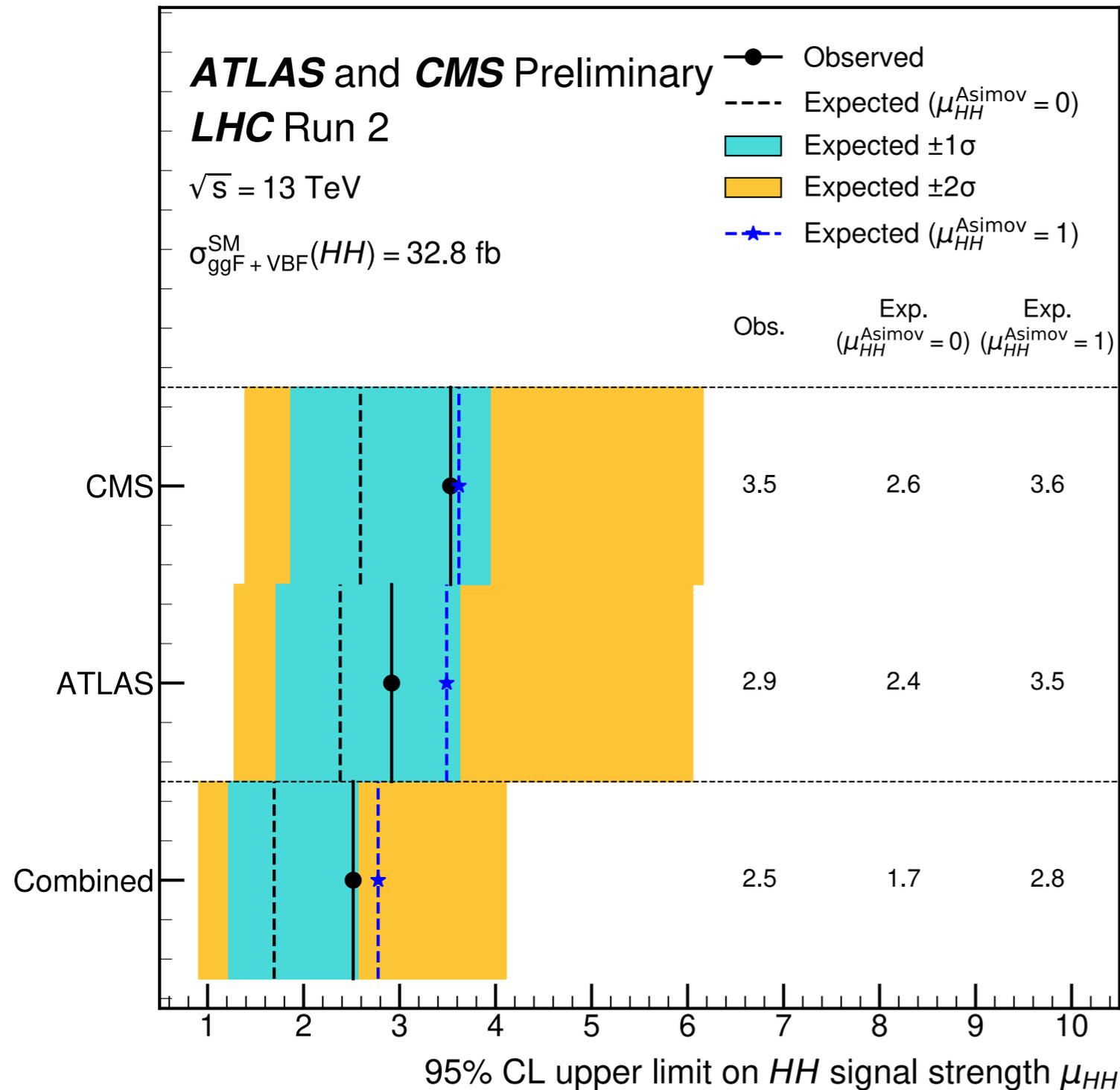


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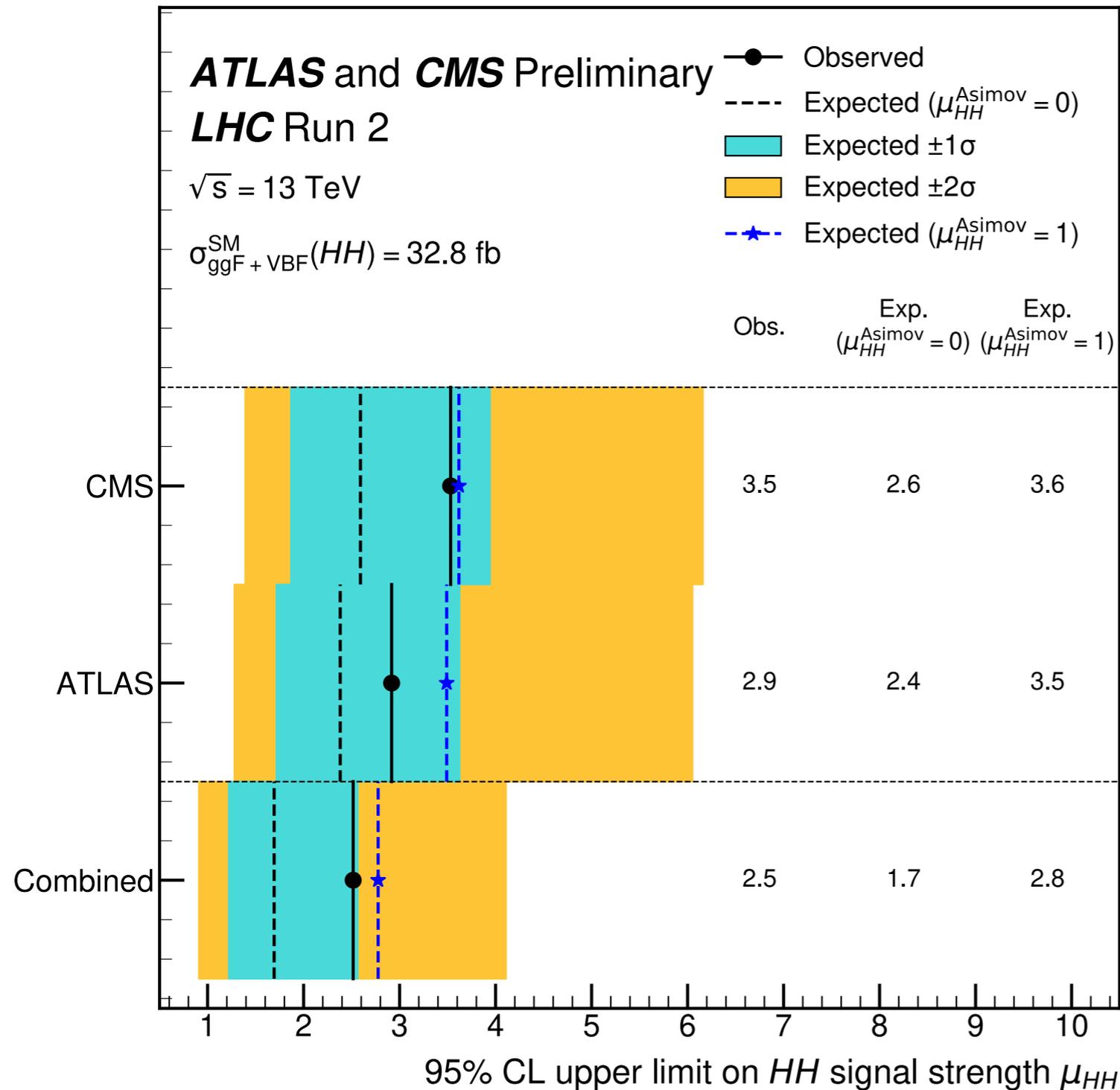
The Results



ATLAS and CMS individually
 exclude $\sim 3\times\text{SM}$ signal

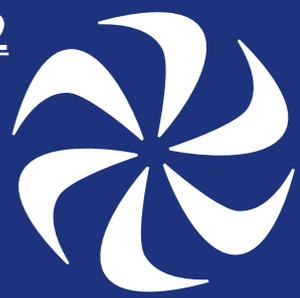


The Results

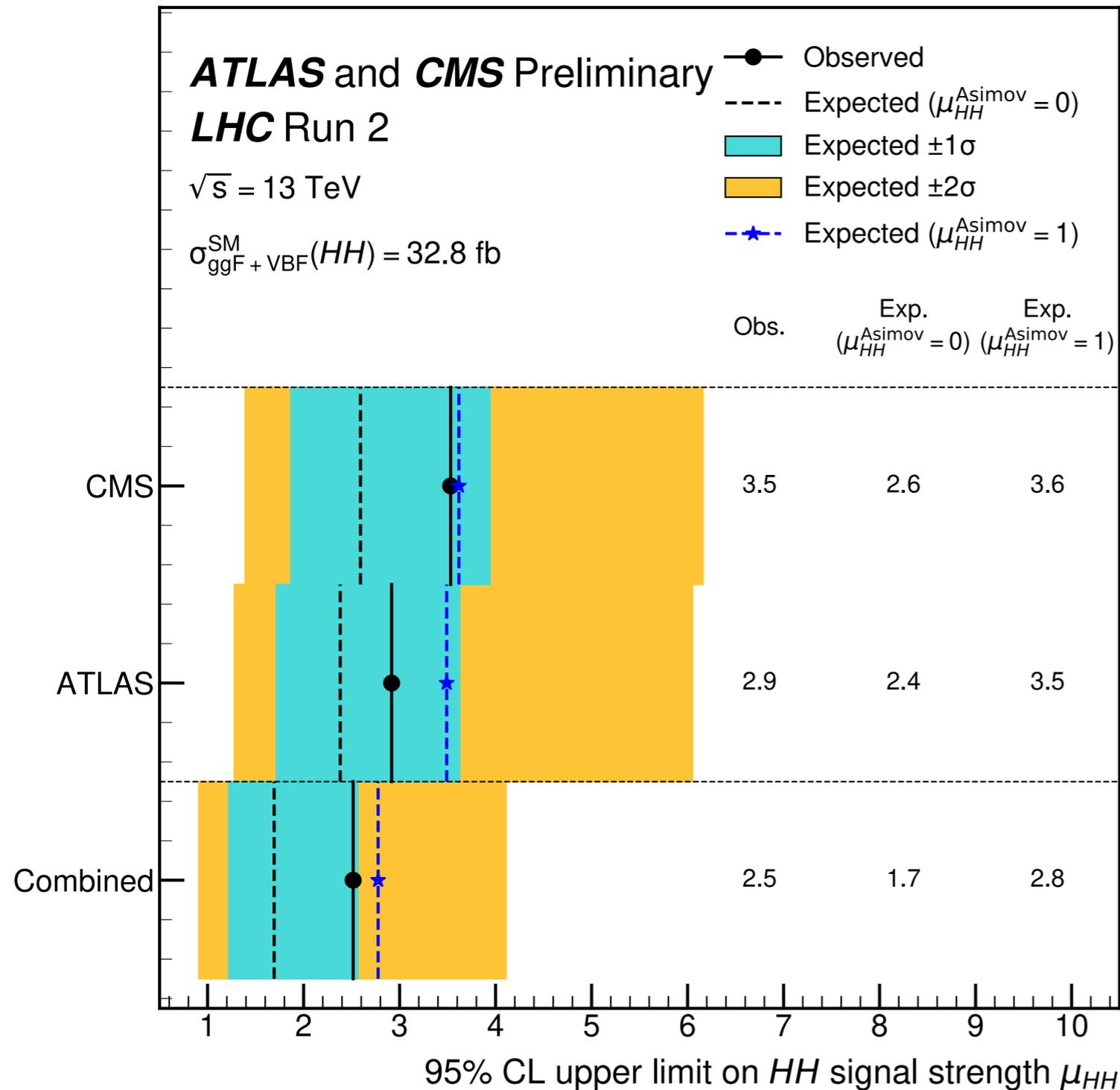


ATLAS and CMS individually
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Combined, expected limit
 at $1.7x\text{SM}$, and observed
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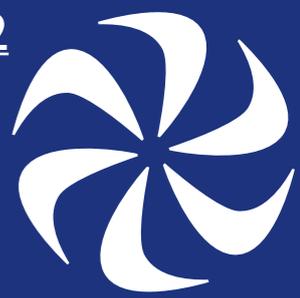
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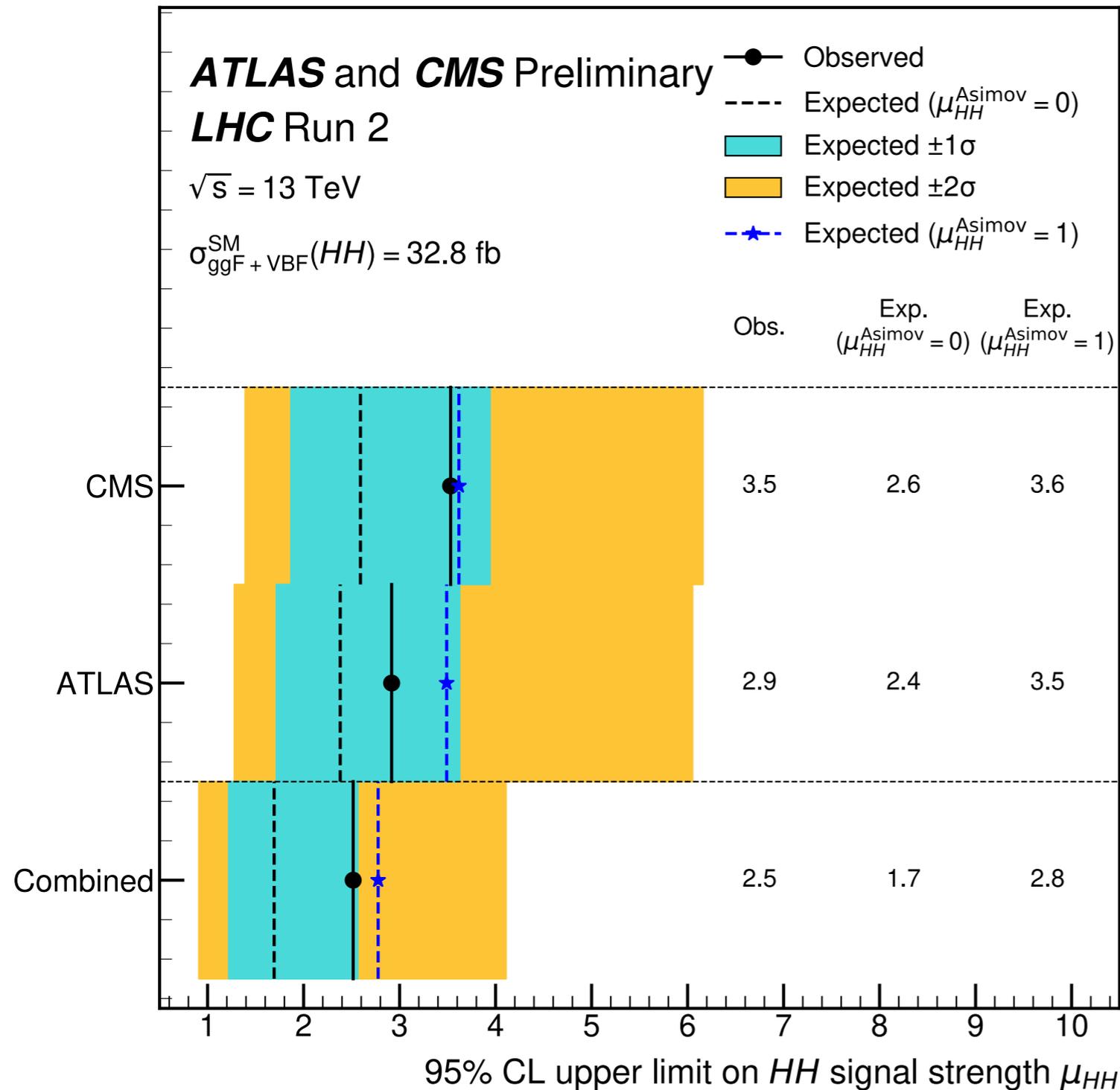
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Corresponds to 1.1σ ,
 observed signal
 (1.3σ expected)



The Results

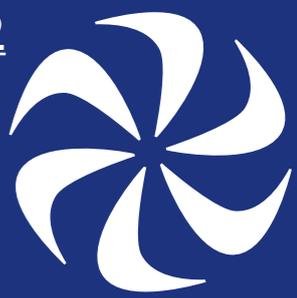


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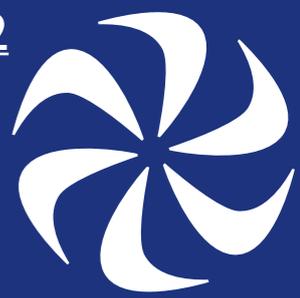
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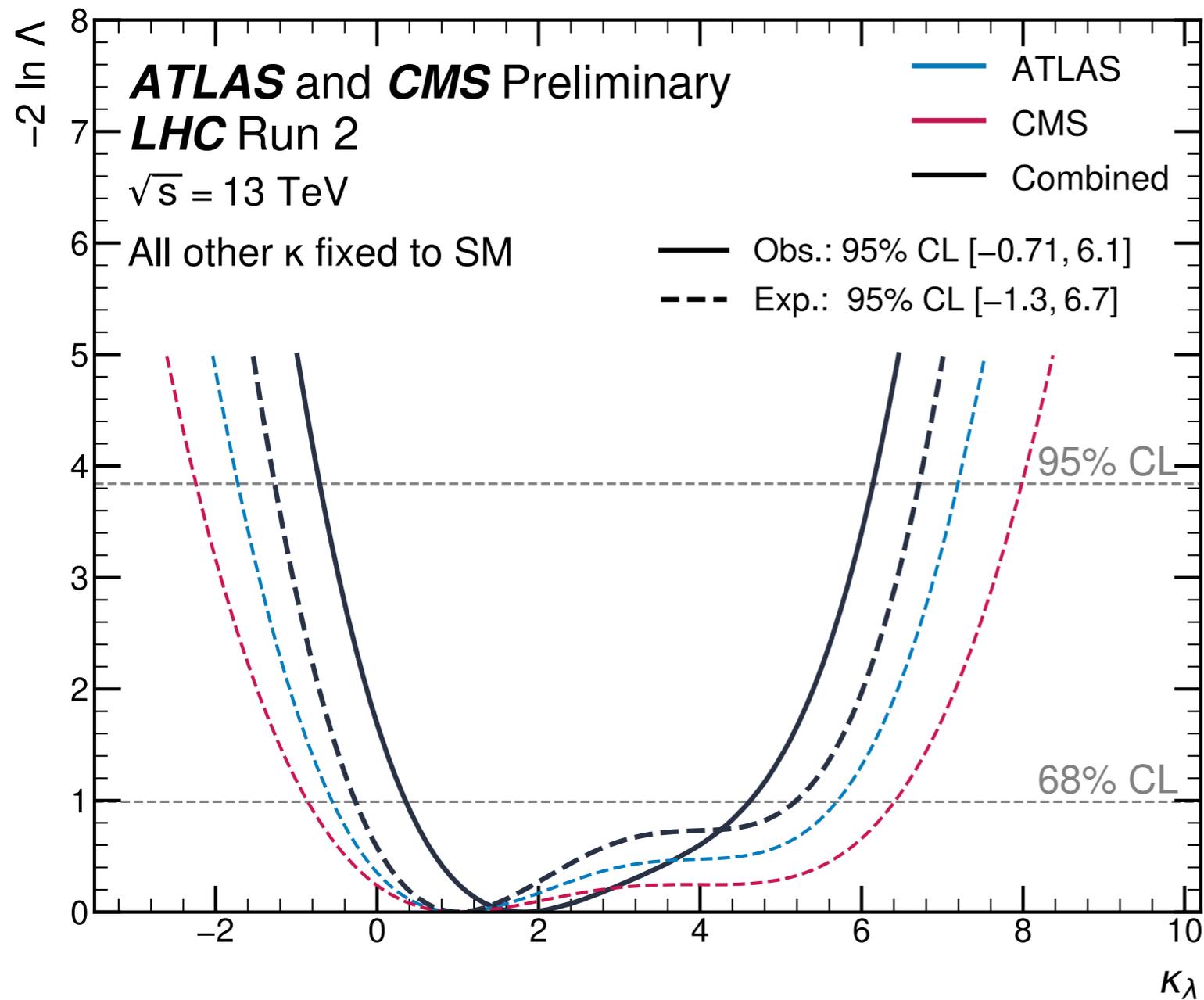
Not celebrating yet, but
coming into view!

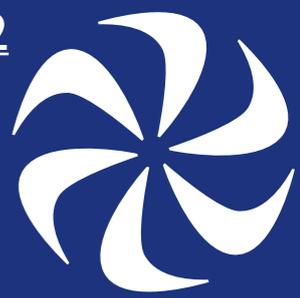


κ_λ Sensitivity

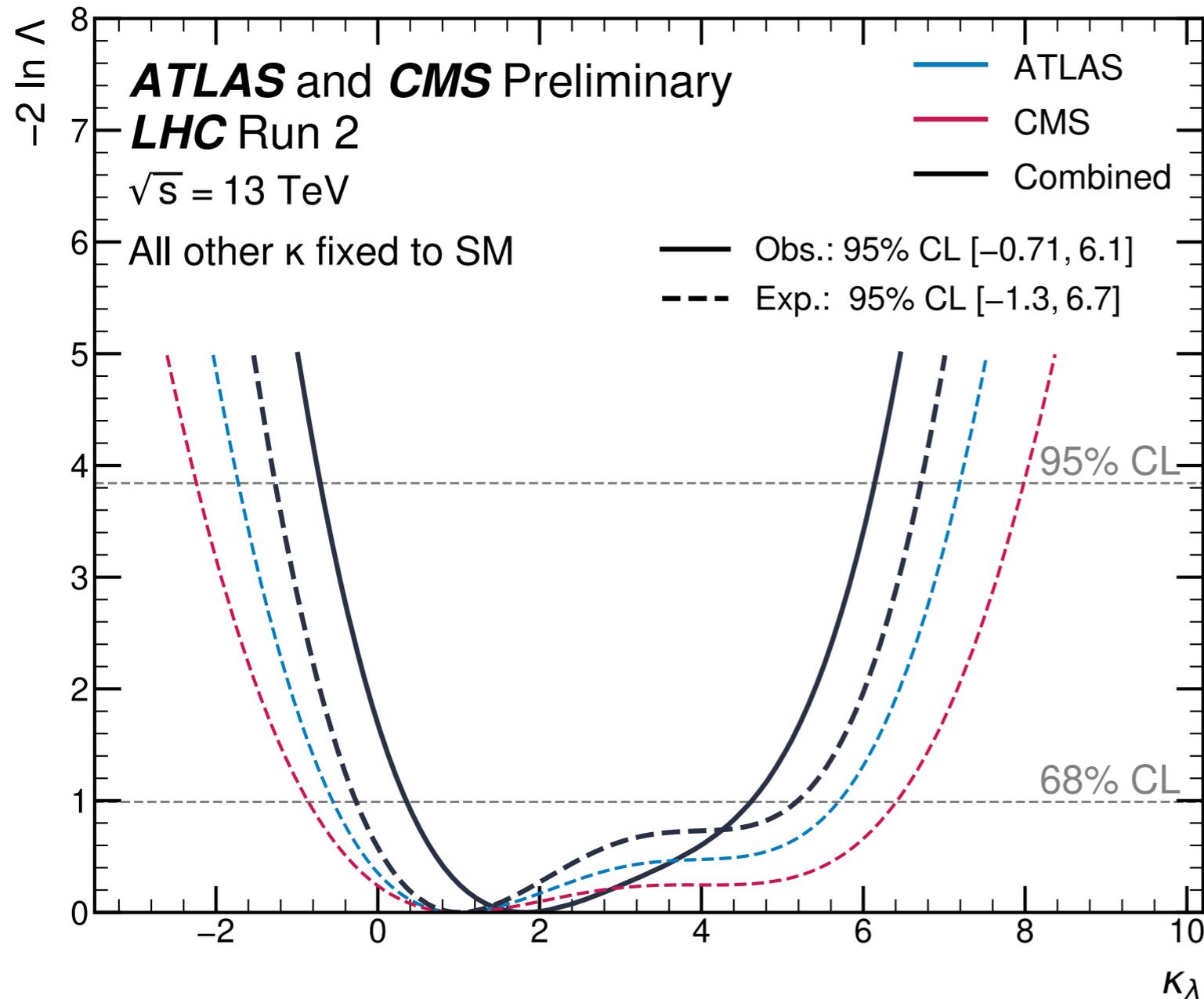


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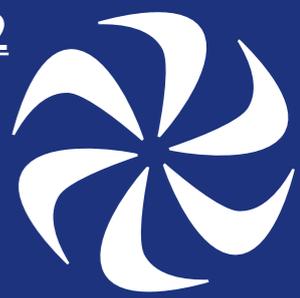




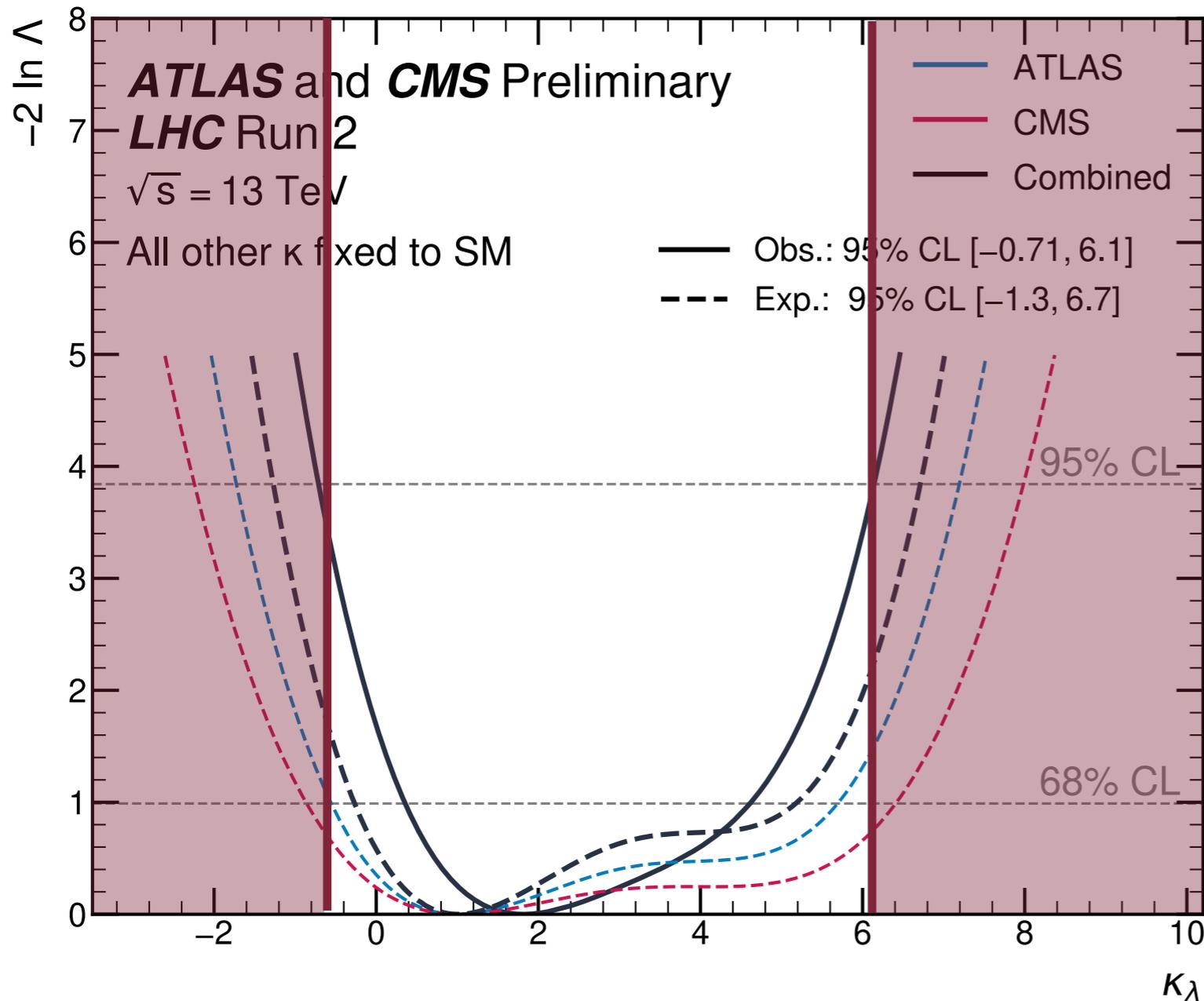
κ_λ Sensitivity



With actual production
 coming into view,
 κ_λ becomes the next target

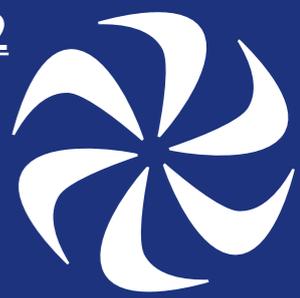


κ_λ Sensitivity

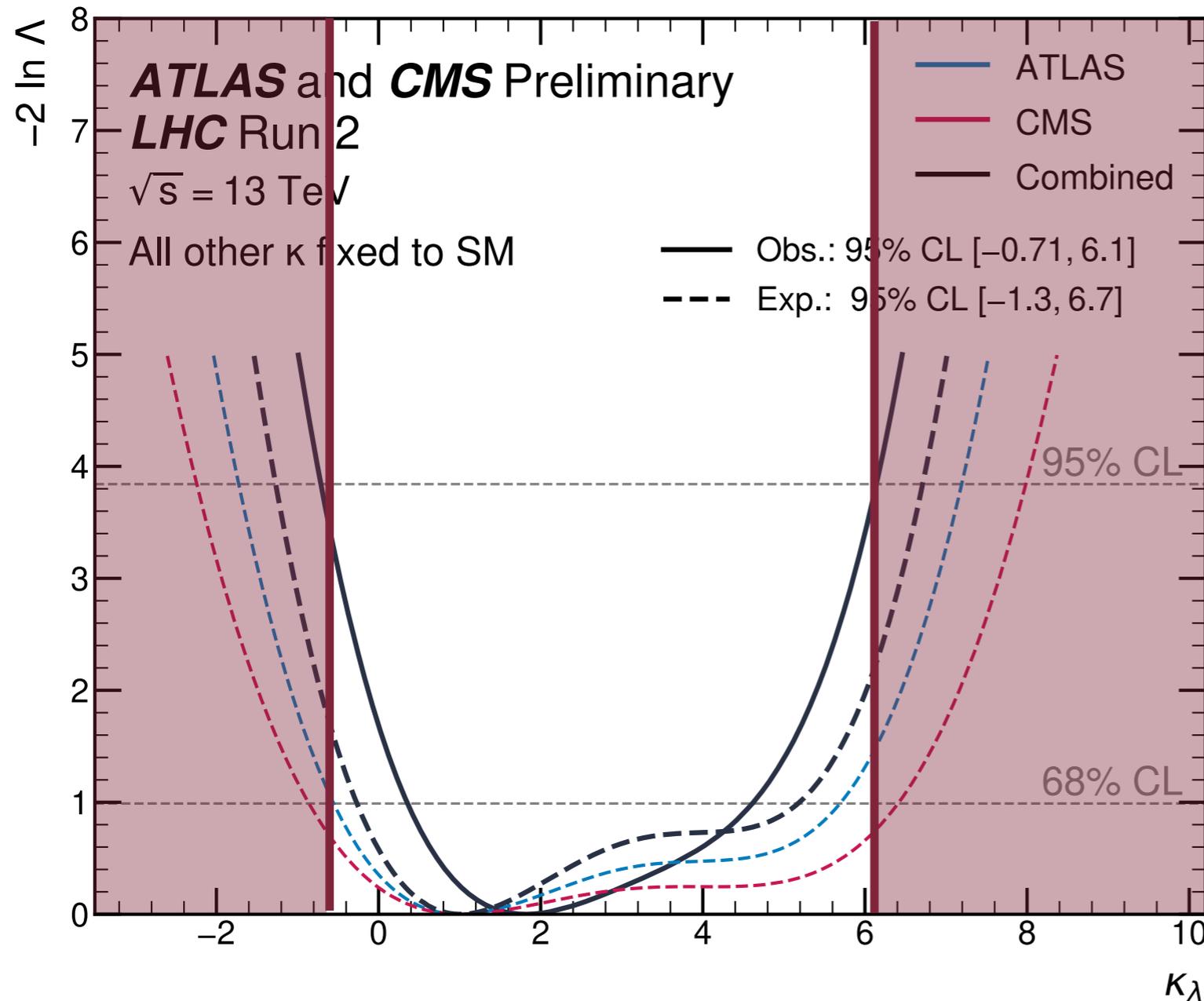


With actual production coming into view, κ_λ becomes the next target

Combined limits strongly improve over inputs



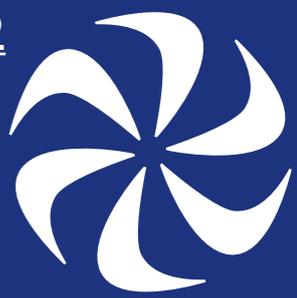
κ_λ Sensitivity



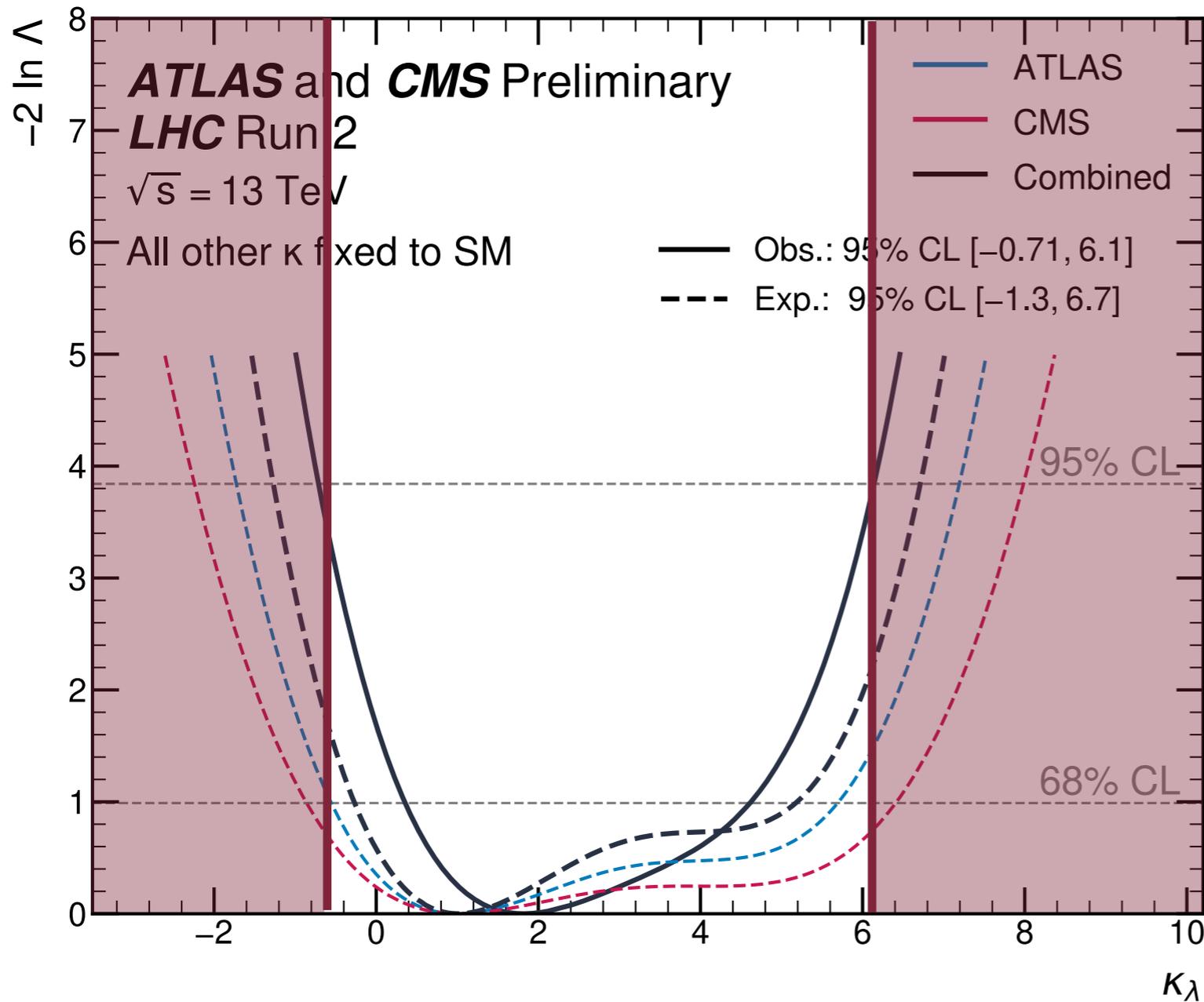
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More data needed to improve measurements: all statistically limited



κ_λ Sensitivity



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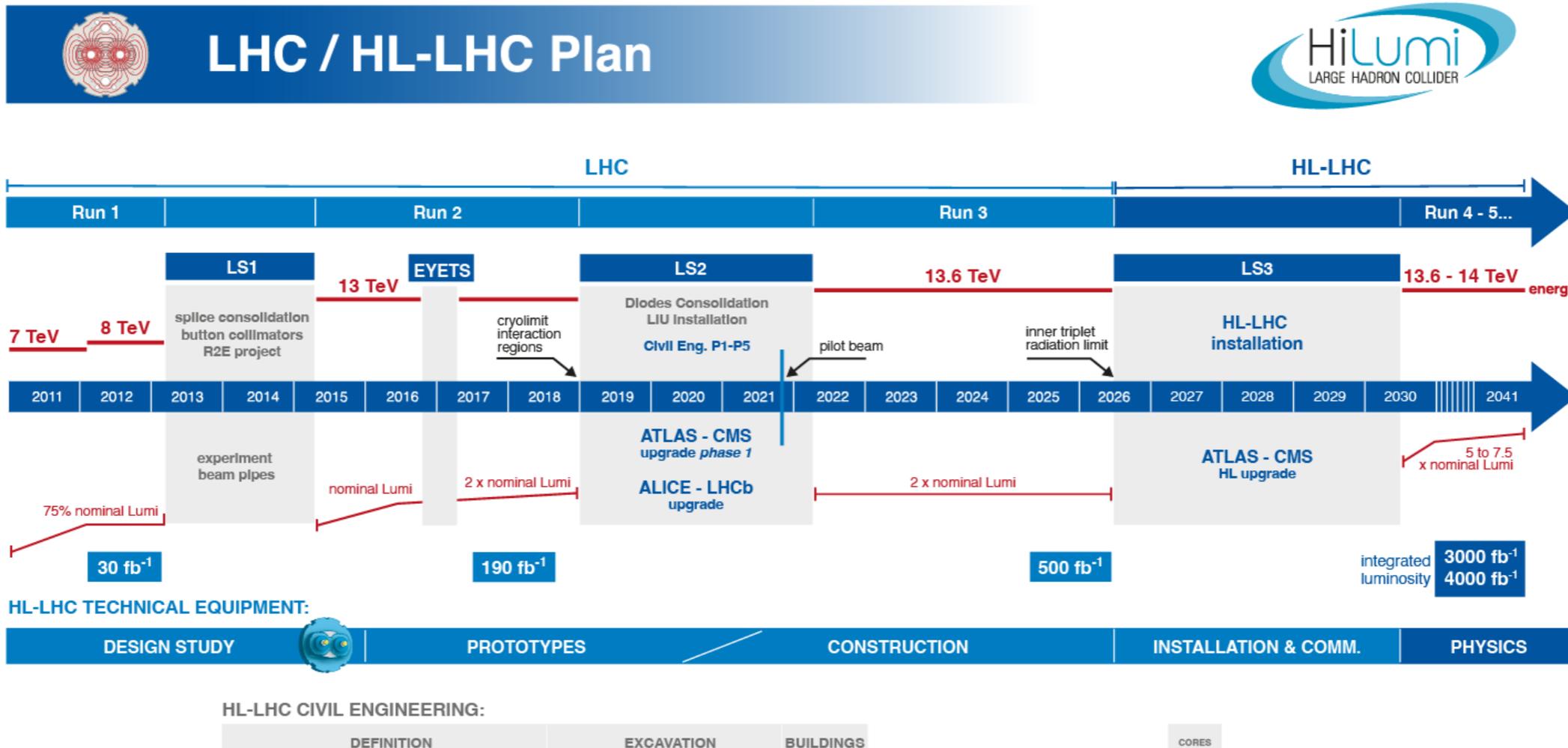
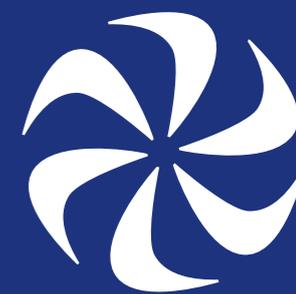
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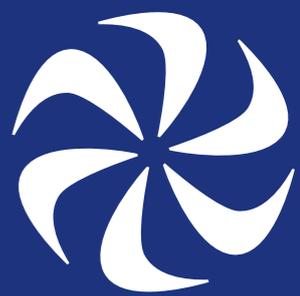
Looking forward to full Run 3 analysis and beyond!

The Higgs Potential Tomorrow

The HL-LHC

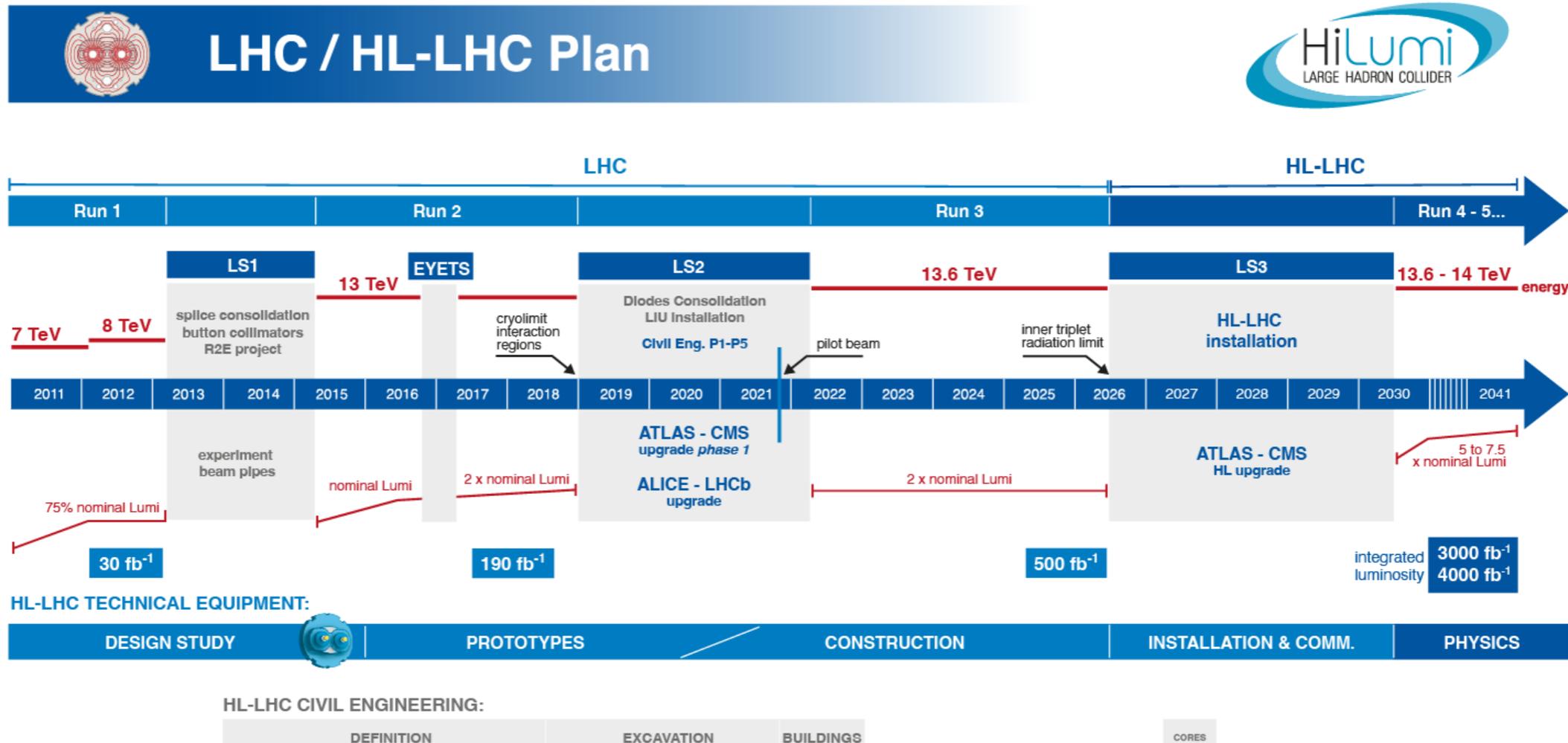
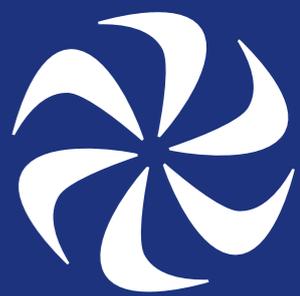


The HL-LHC



The HL-LHC will be installed 2026-203, and run in 2030-2041(++)

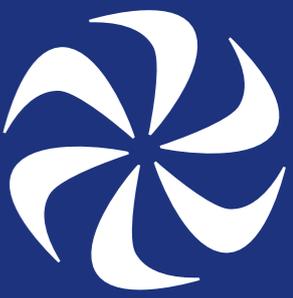
The HL-LHC



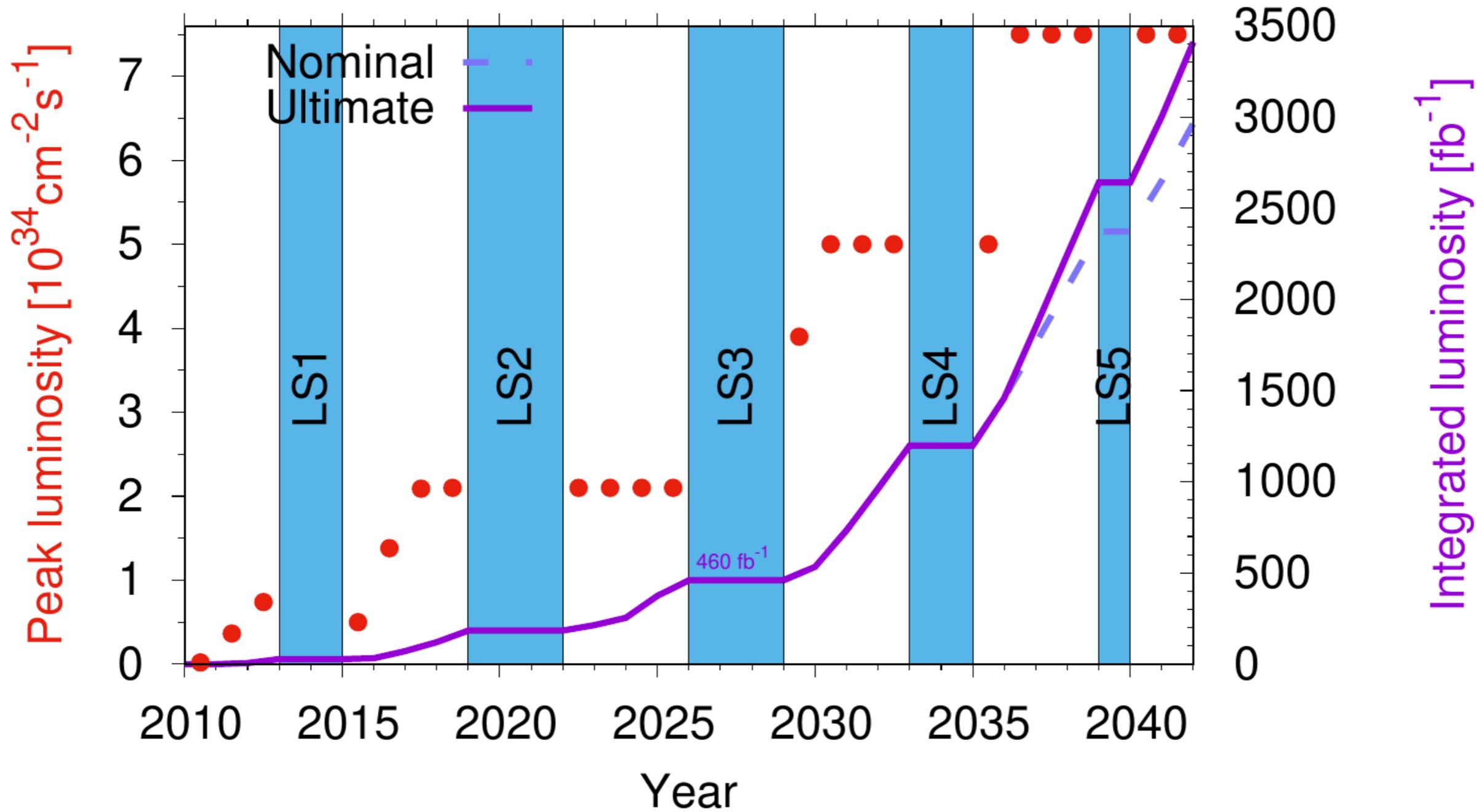
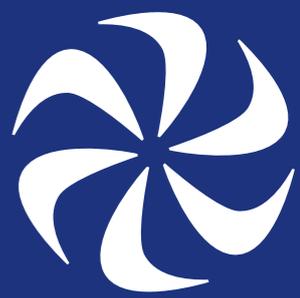
The HL-LHC will be installed 2026-2030, and run in 2030-2041(++)

Increase energy to **14 TeV**,
and instantaneous luminosity to **5-7.5x10³⁴ cm⁻²s⁻¹**

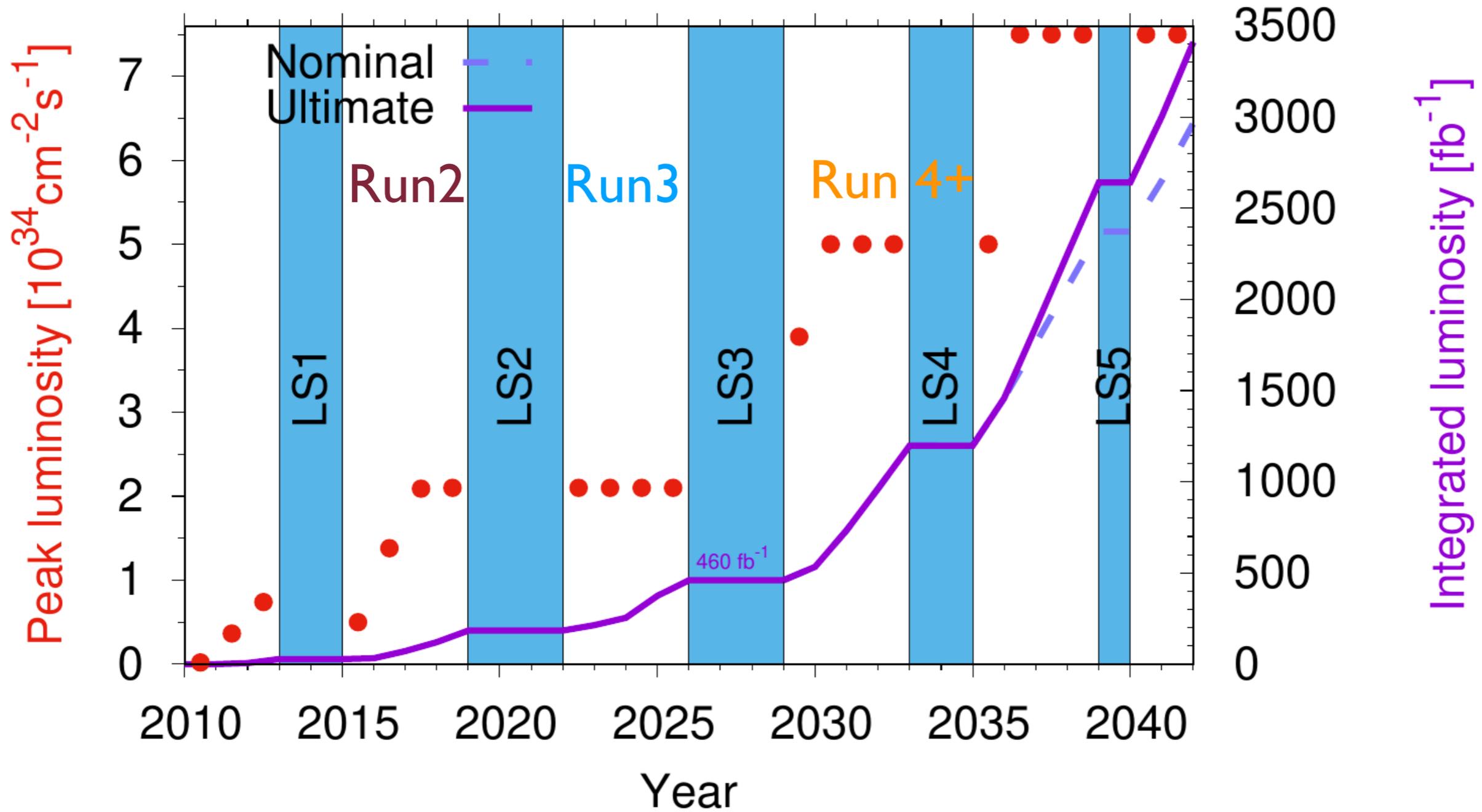
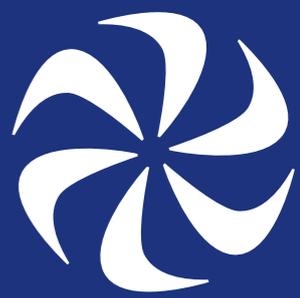
Datasets



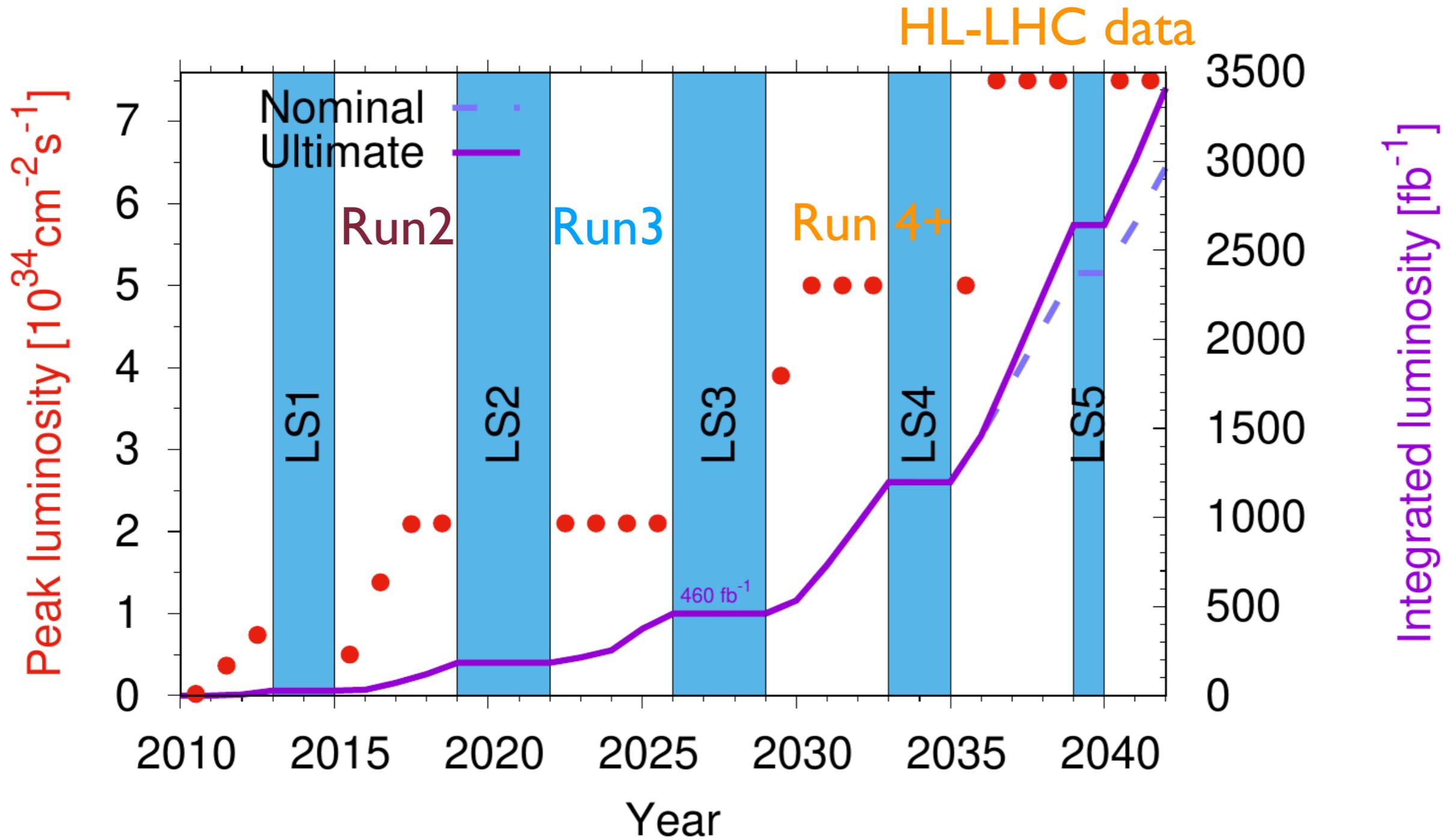
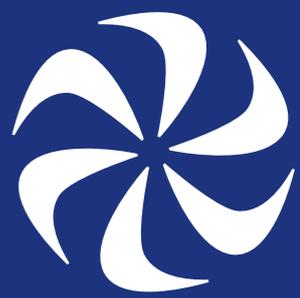
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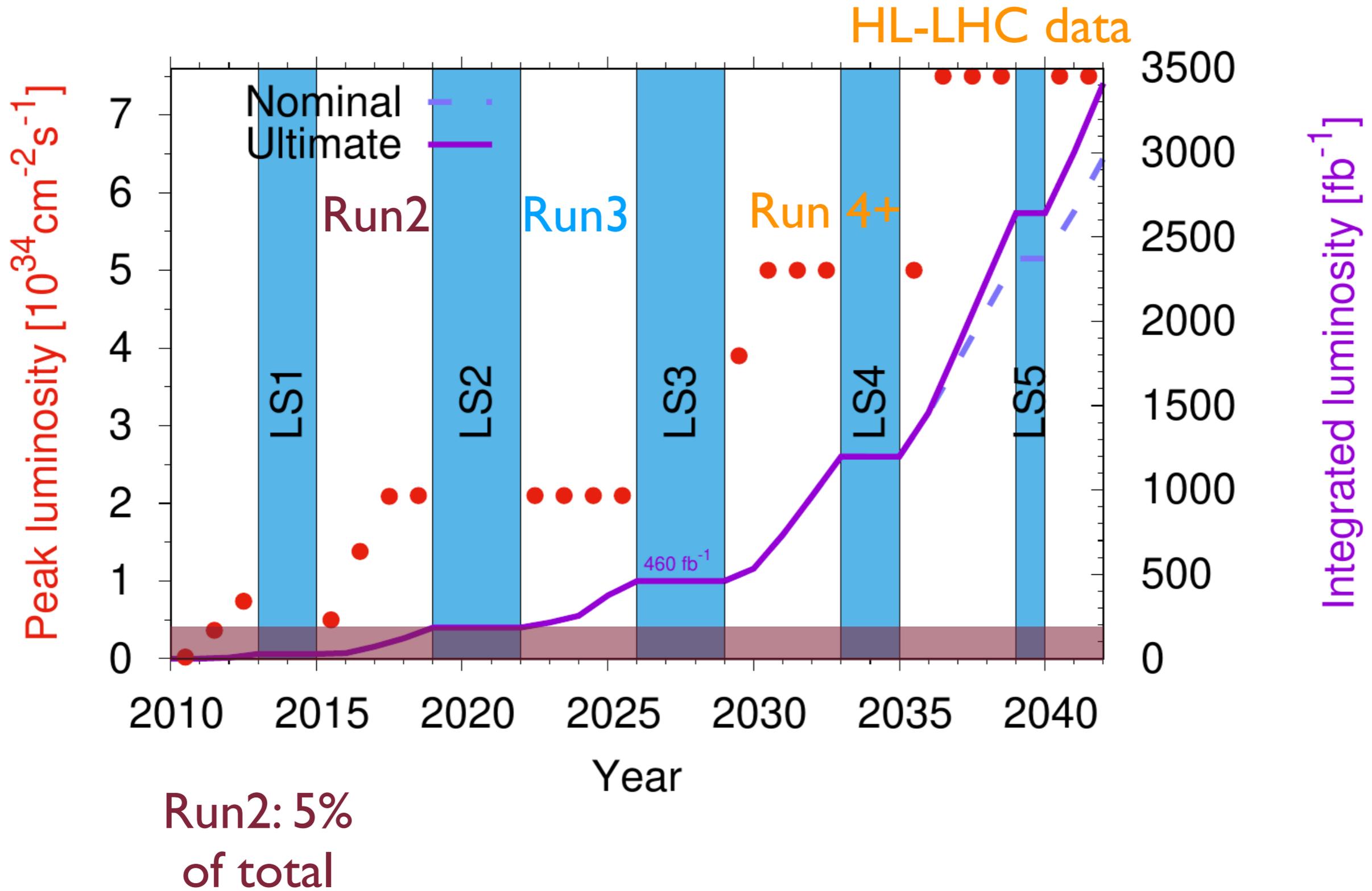
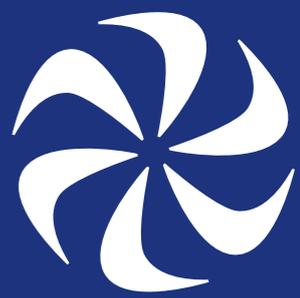
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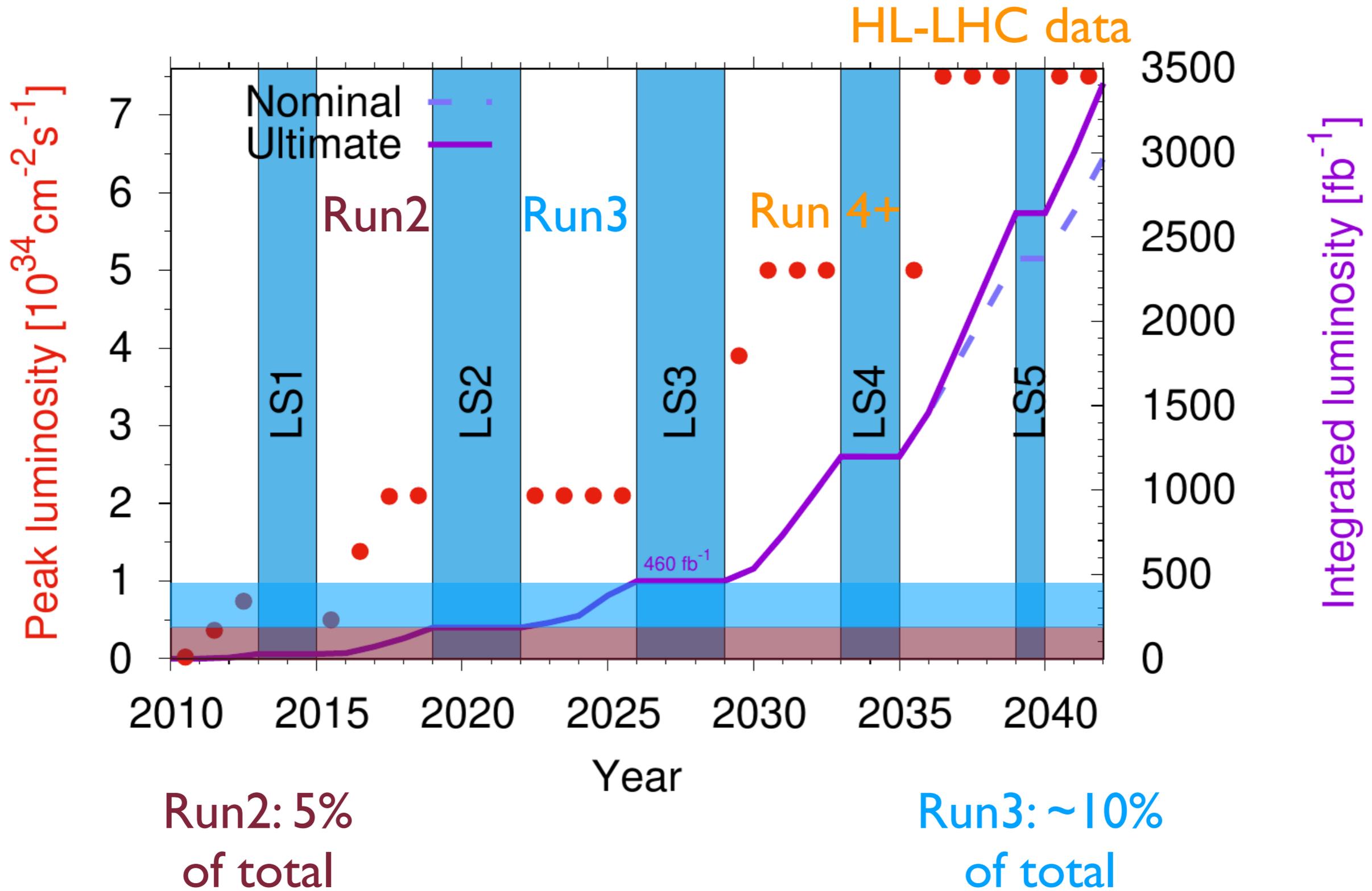
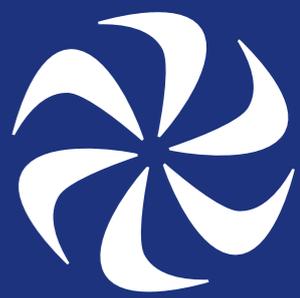
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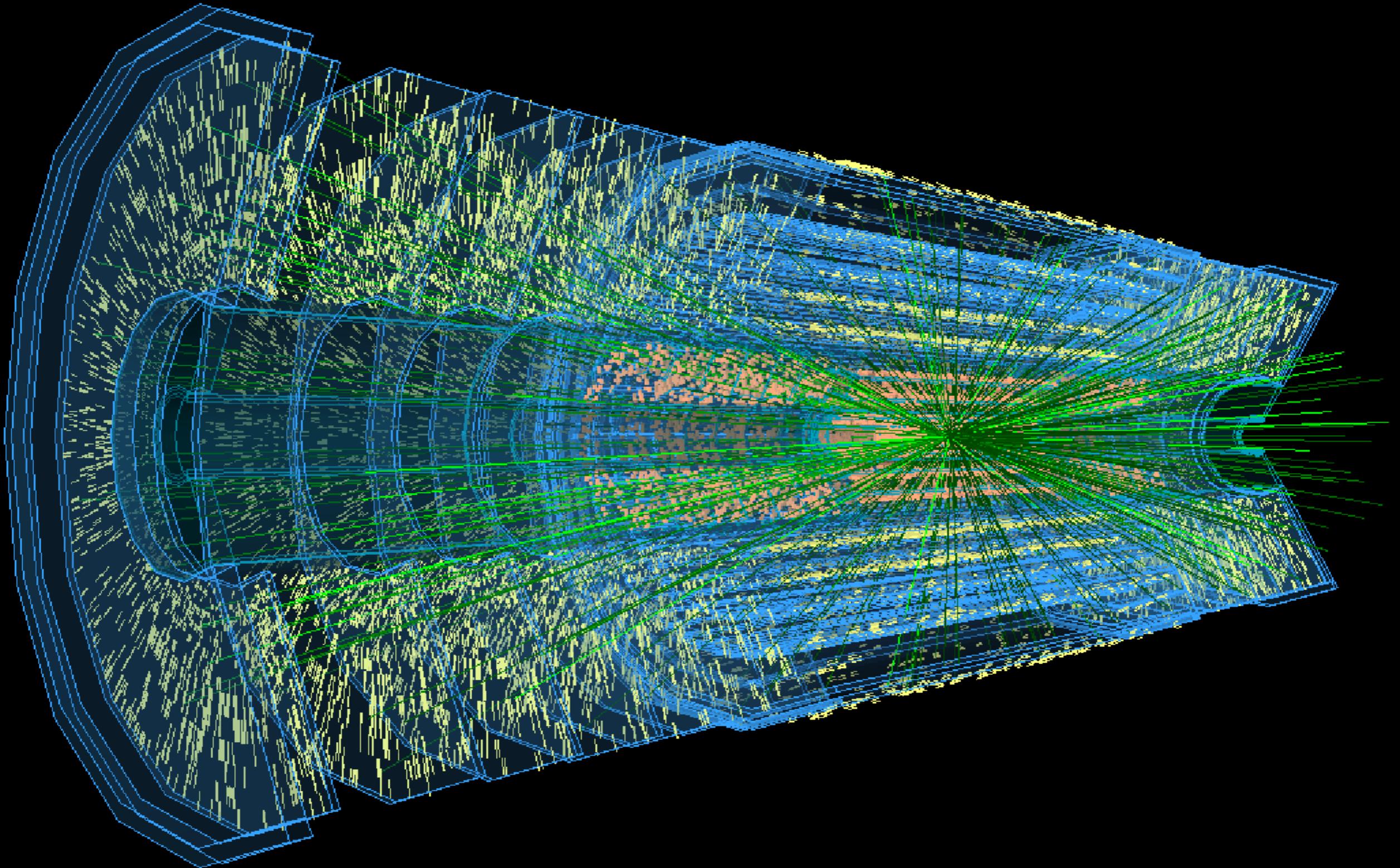
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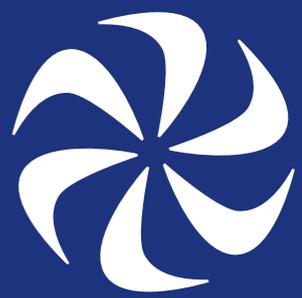
The Price of Rate: Pileup



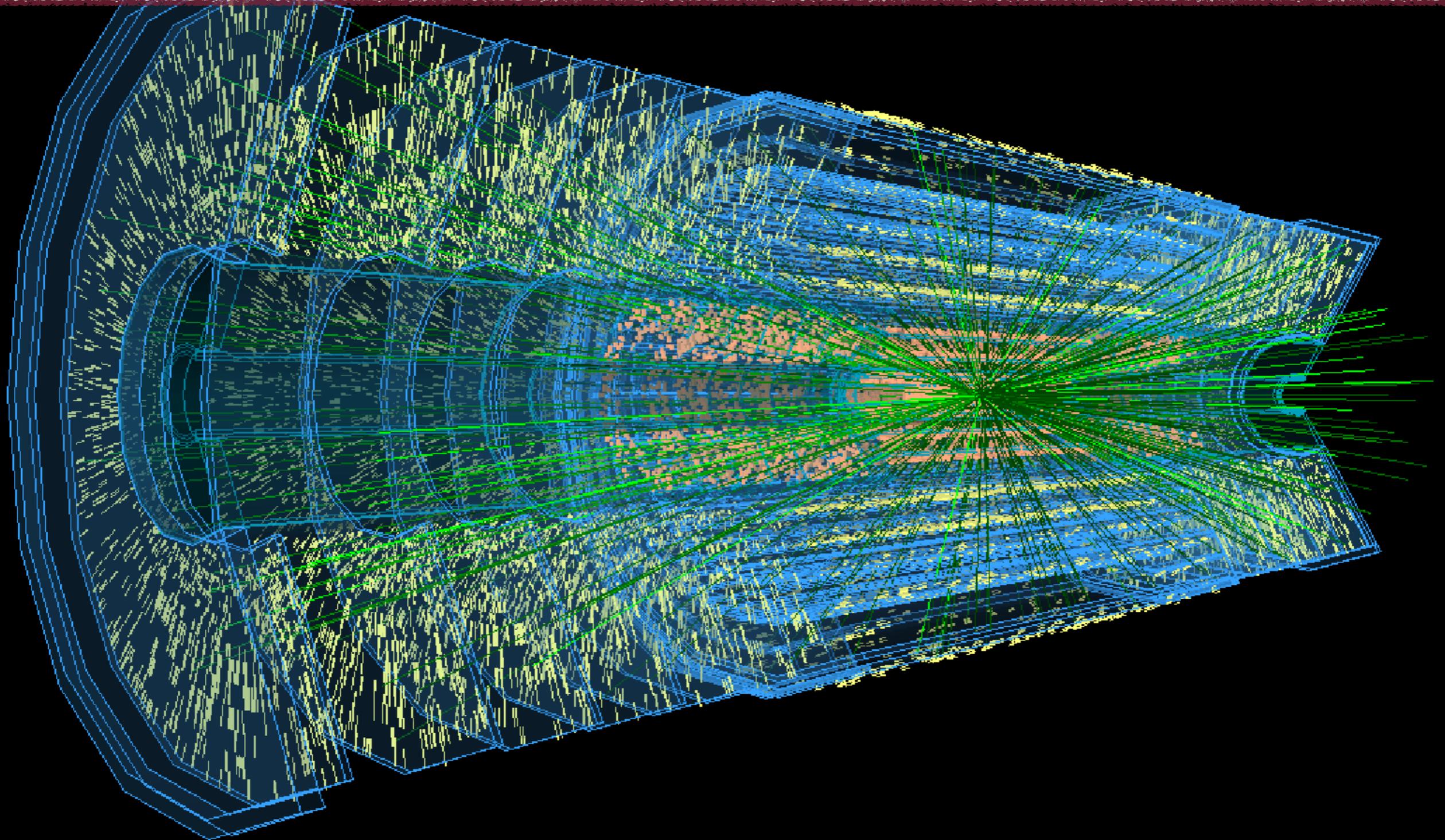
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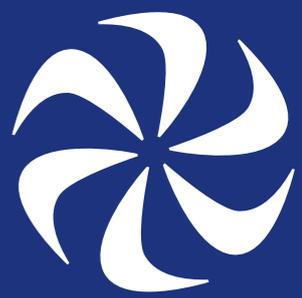
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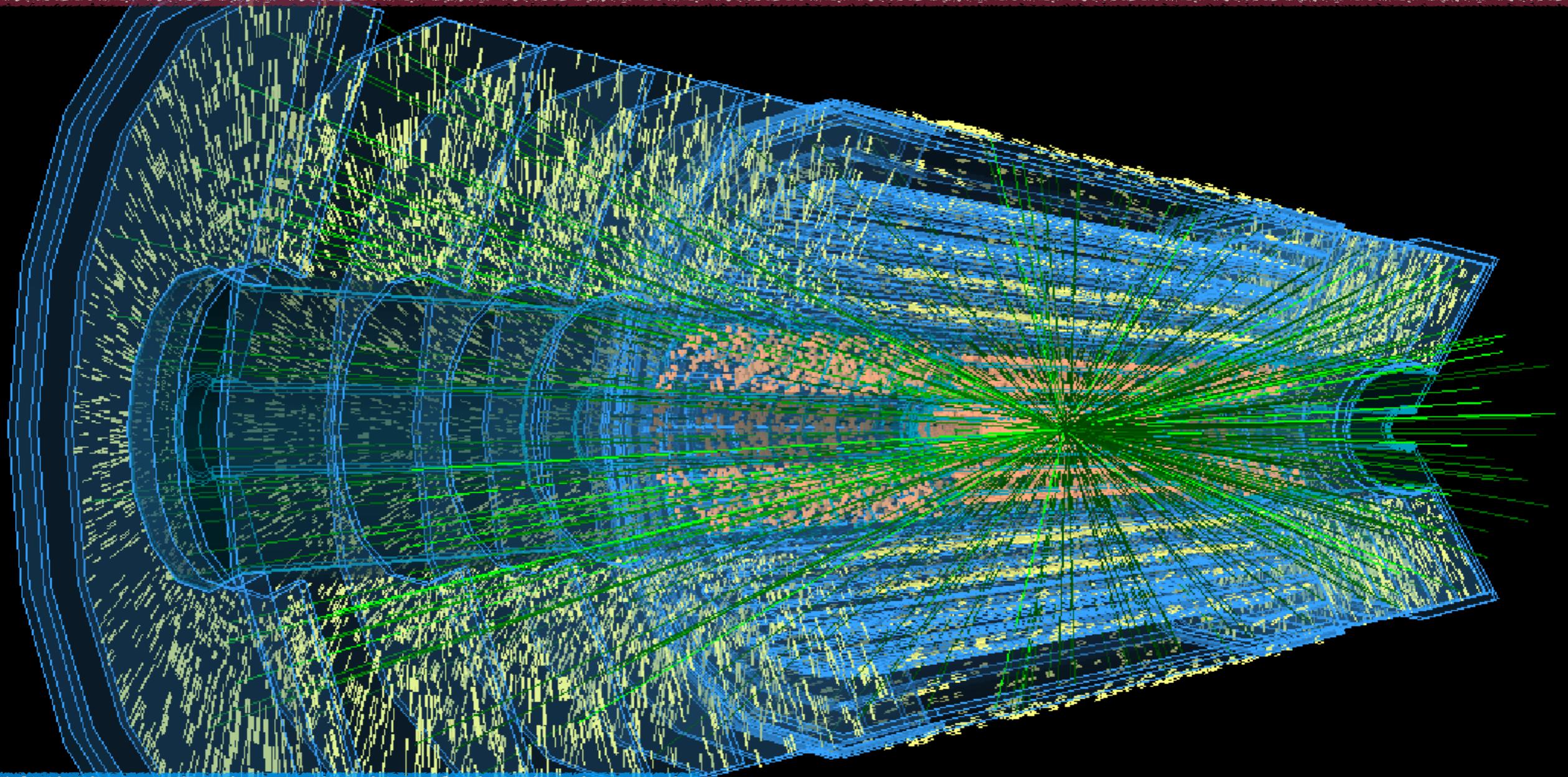
To enable increased luminosity, collisions need to be more frequent



The Price of Rate: Pileup

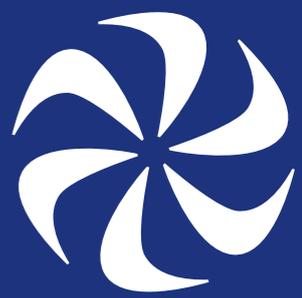


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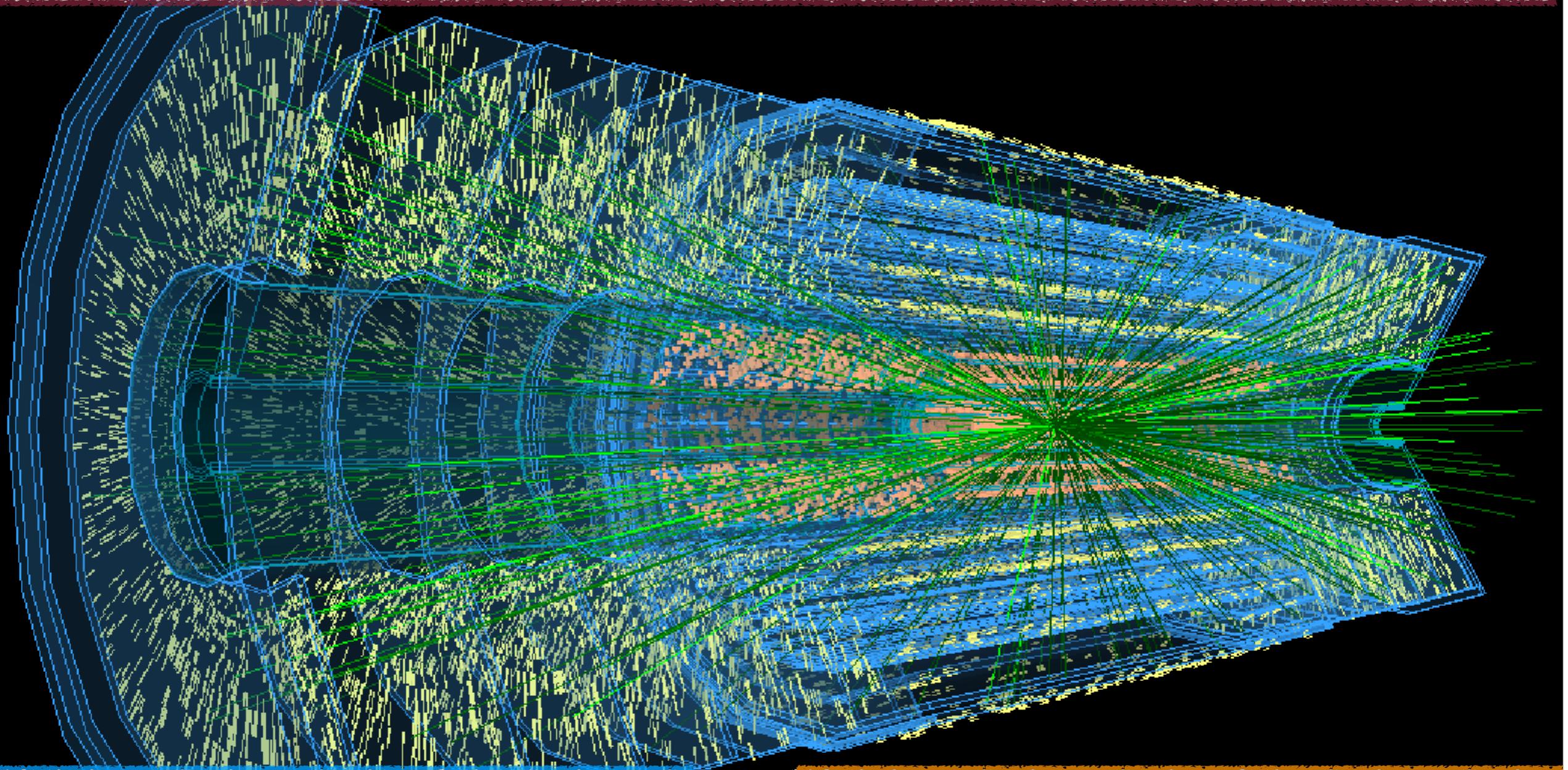


Bunch spacing fixed at 25 ns
Only option: increase **pileup**

The Price of Rate: Pileup



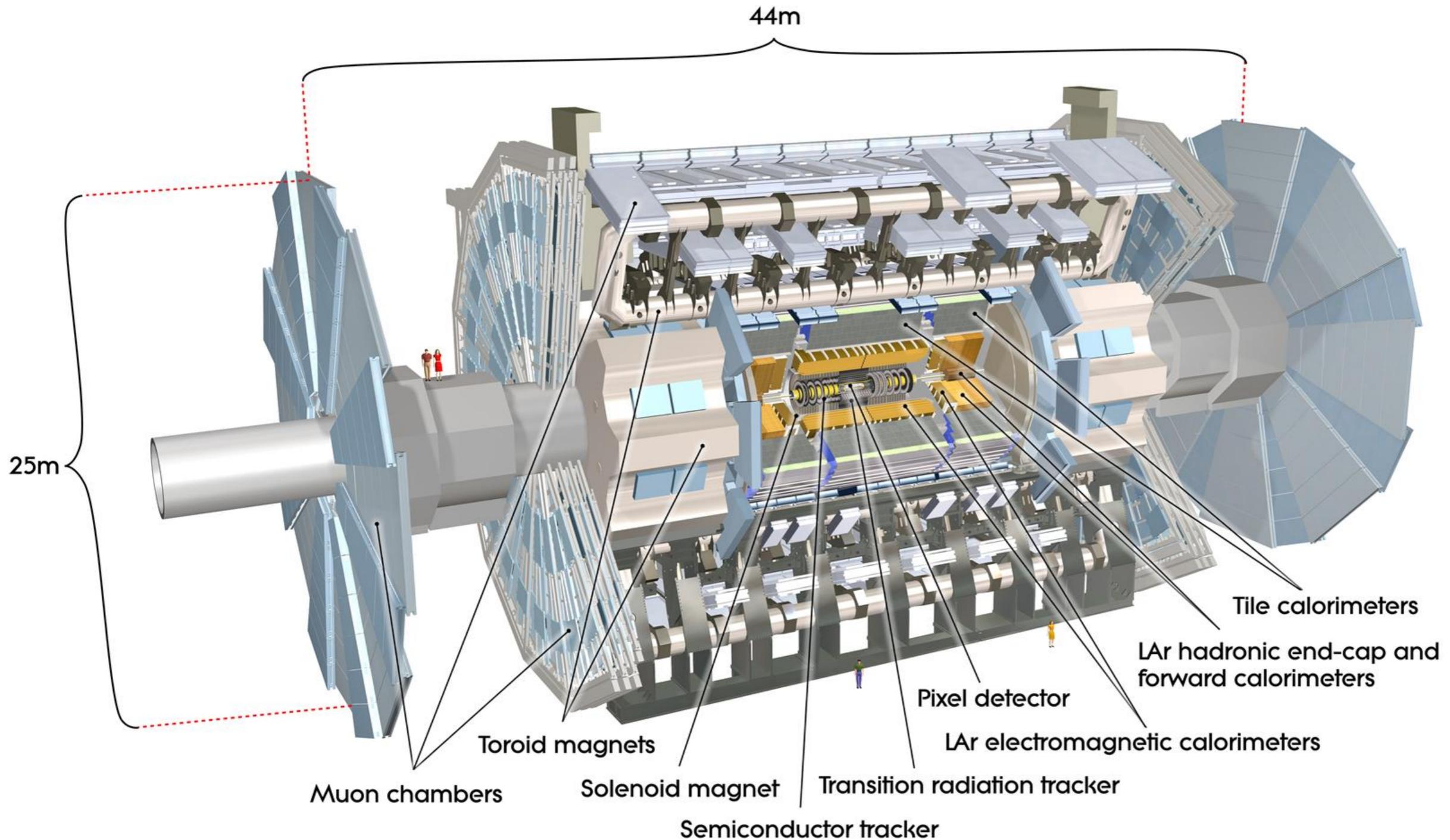
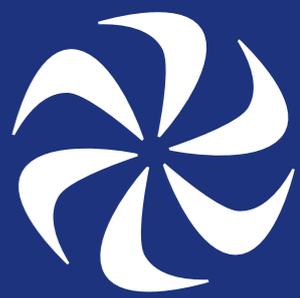
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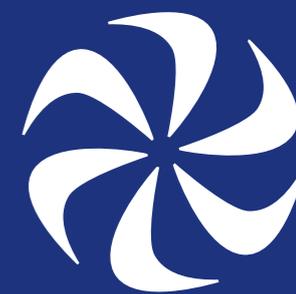
Bunch spacing fixed at 25 ns
Only option: increase **pileup**

Expect **200 collisions** per crossing!
Compare to ~60 today

Upgrades



Upgrades



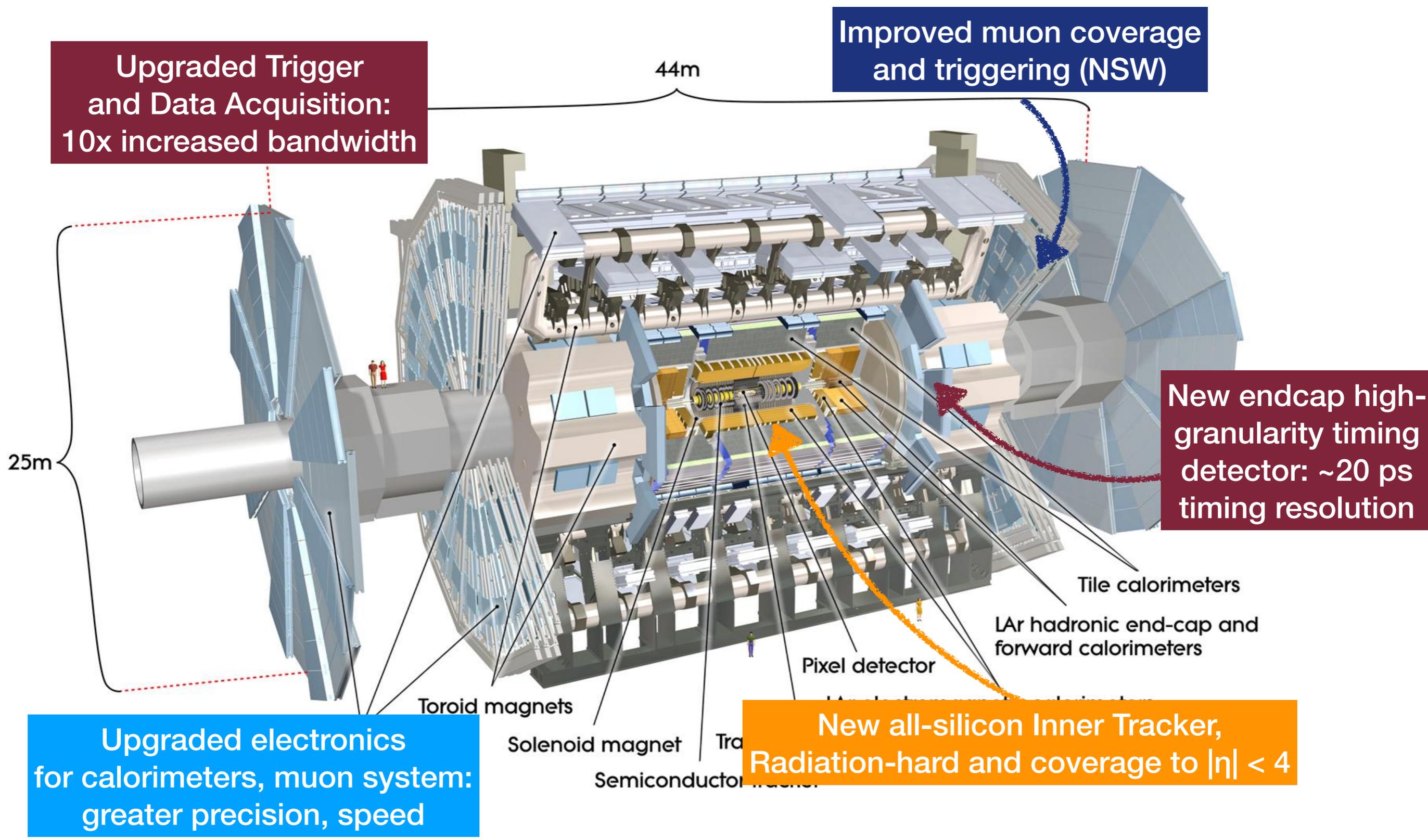
Upgraded Trigger and Data Acquisition: 10x increased bandwidth

Improved muon coverage and triggering (NSW)

New endcap high-granularity timing detector: ~20 ps timing resolution

New all-silicon Inner Tracker, Radiation-hard and coverage to $|\eta| < 4$

Upgraded electronics for calorimeters, muon system: greater precision, speed

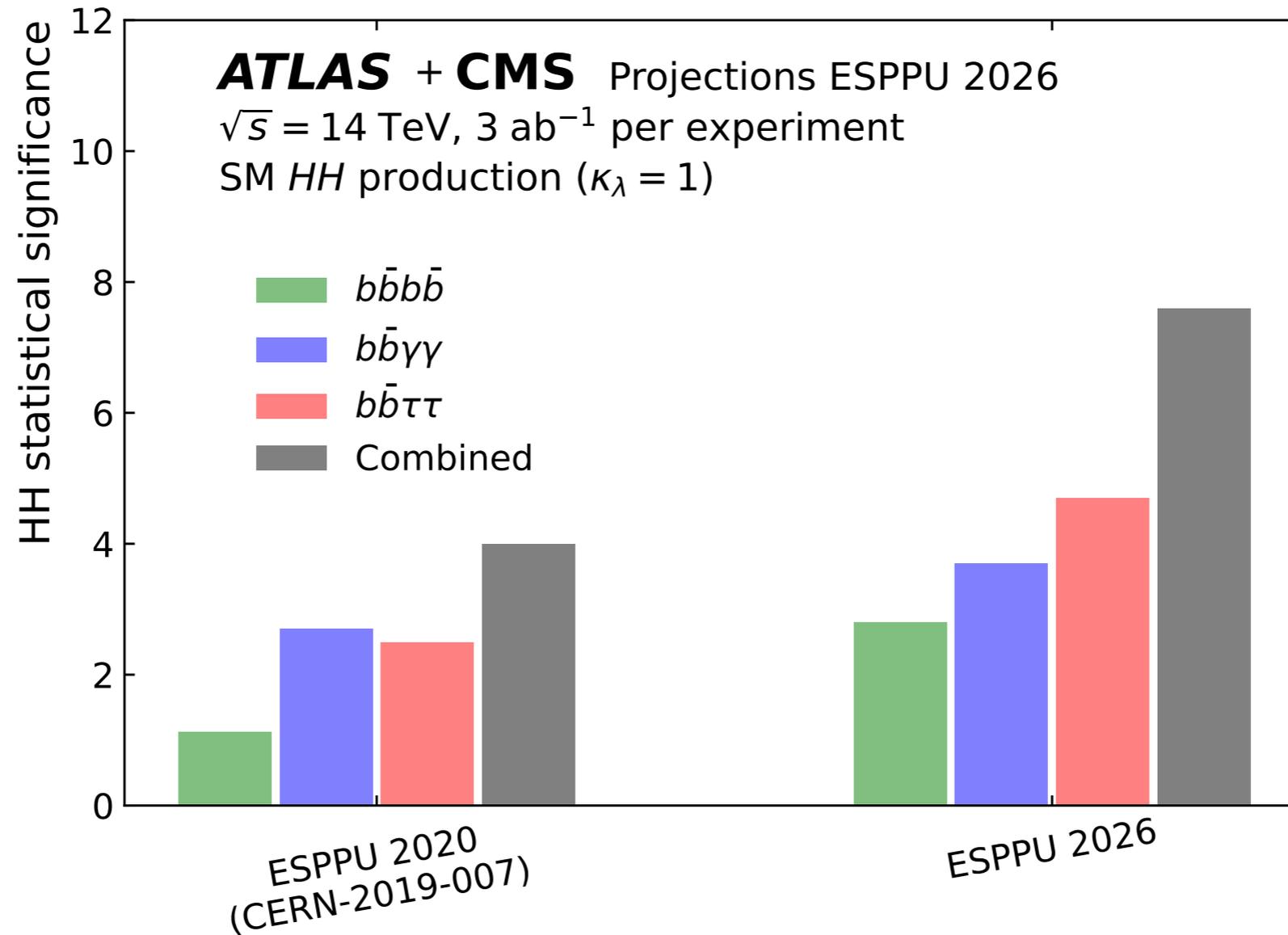




Higgs Pairs Sensitivity

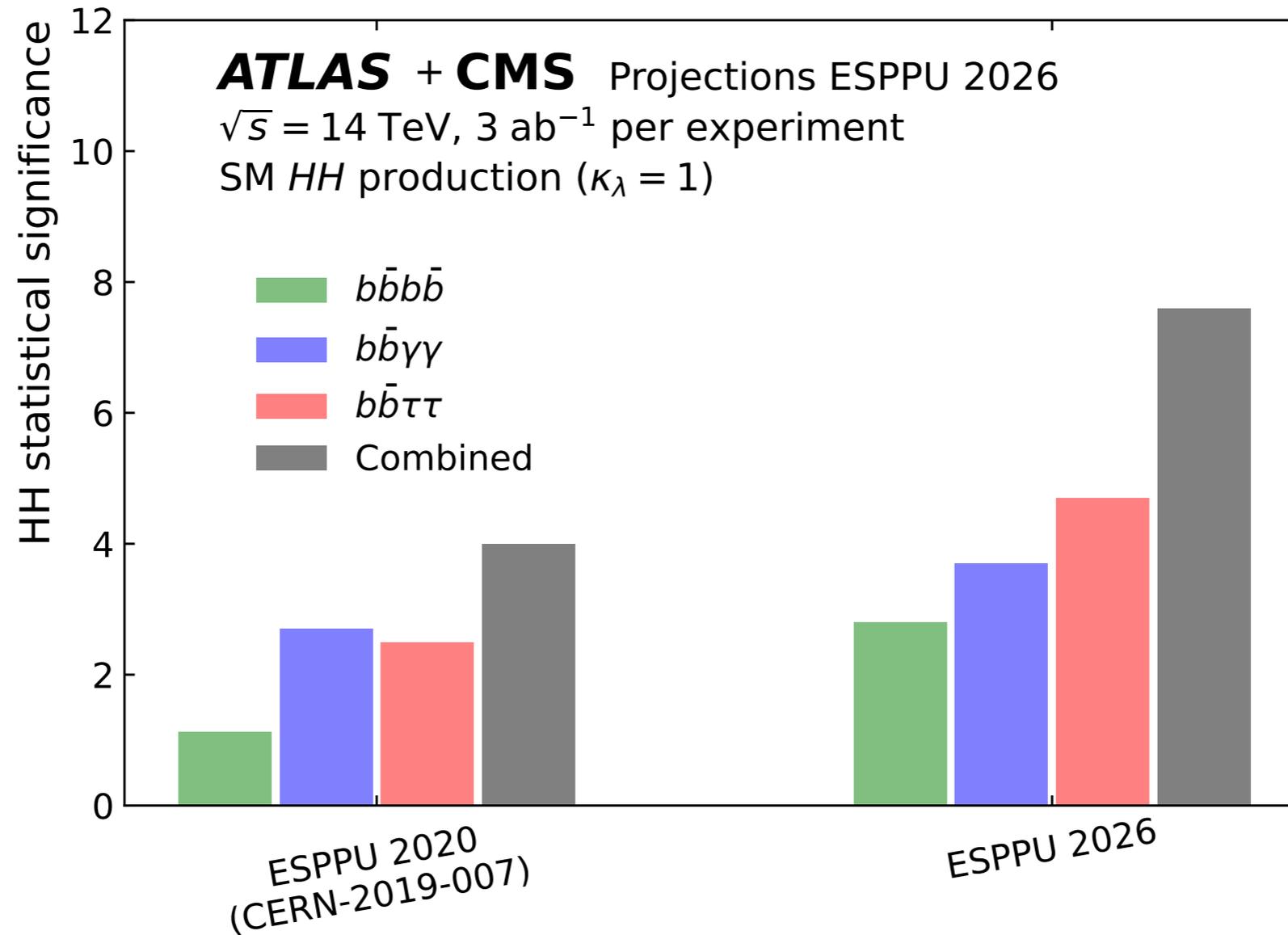


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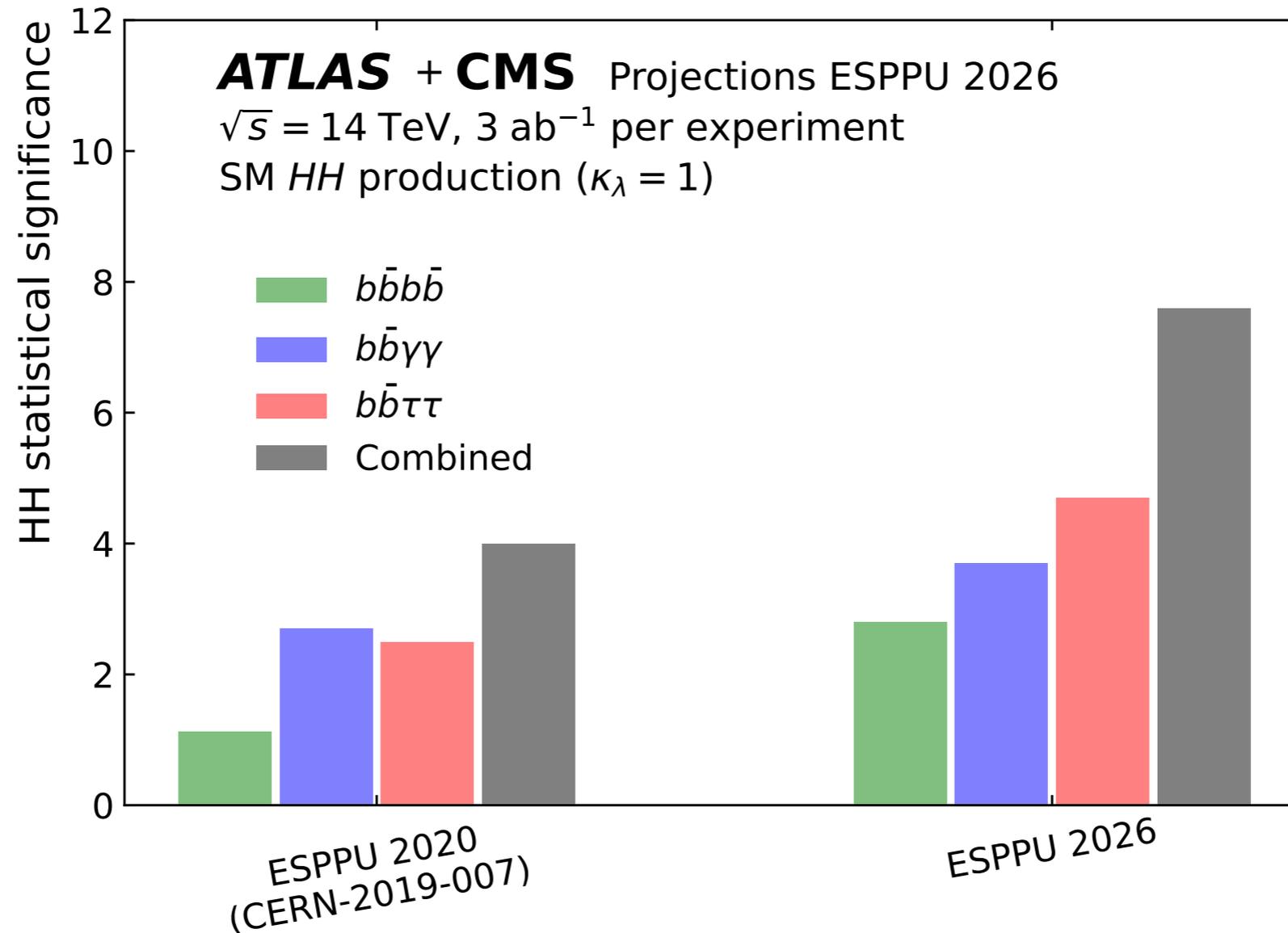
Higgs Pairs Sensitivity



Previous round of projections: 4σ sensitivity



Higgs Pairs Sensitivity

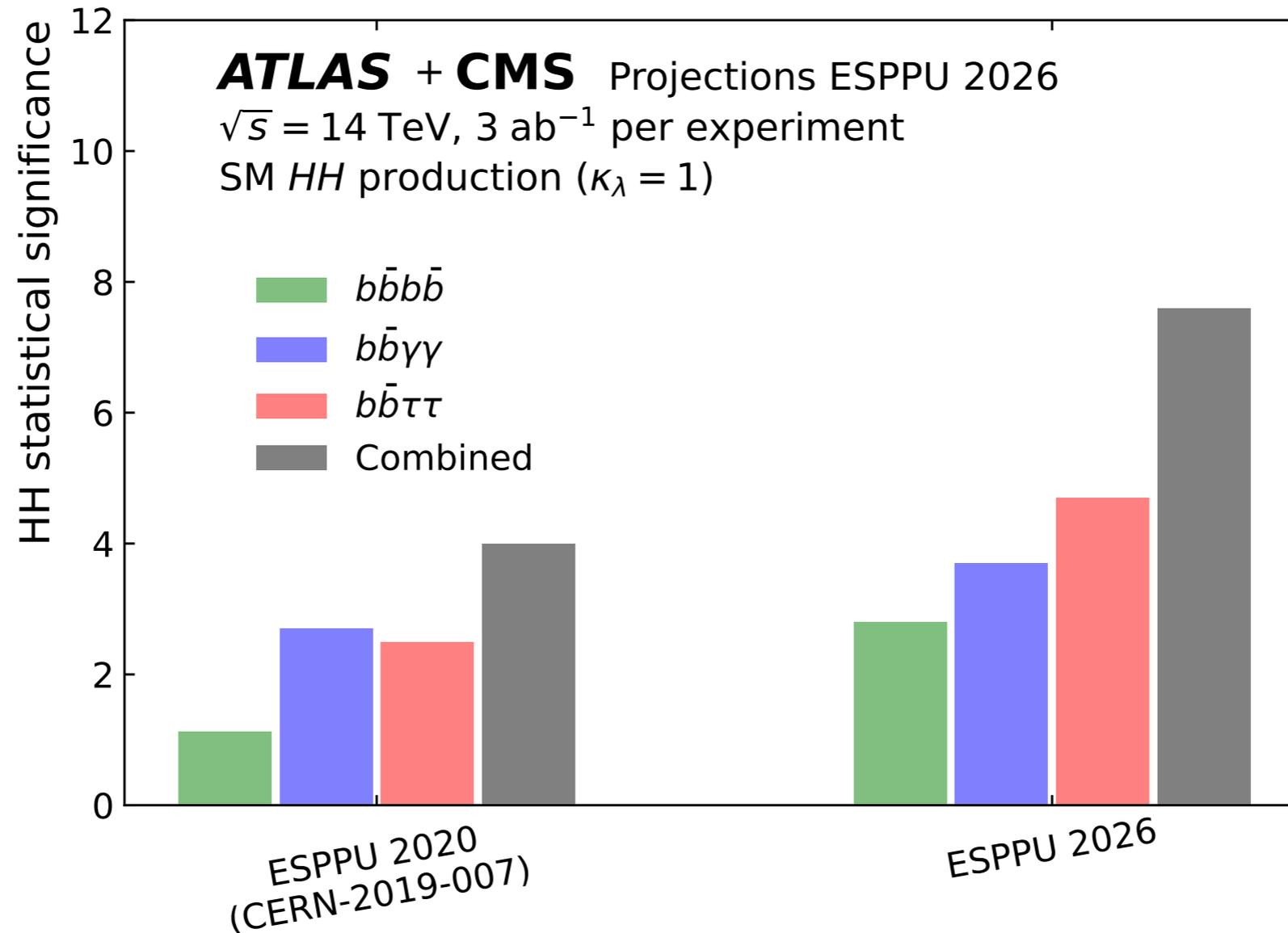


Previous round of projections: 4σ sensitivity

Latest results: **8σ sensitivity**



Higgs Pairs Sensitivity



Previous round of projections: 4σ sensitivity

Latest results: **8σ sensitivity**

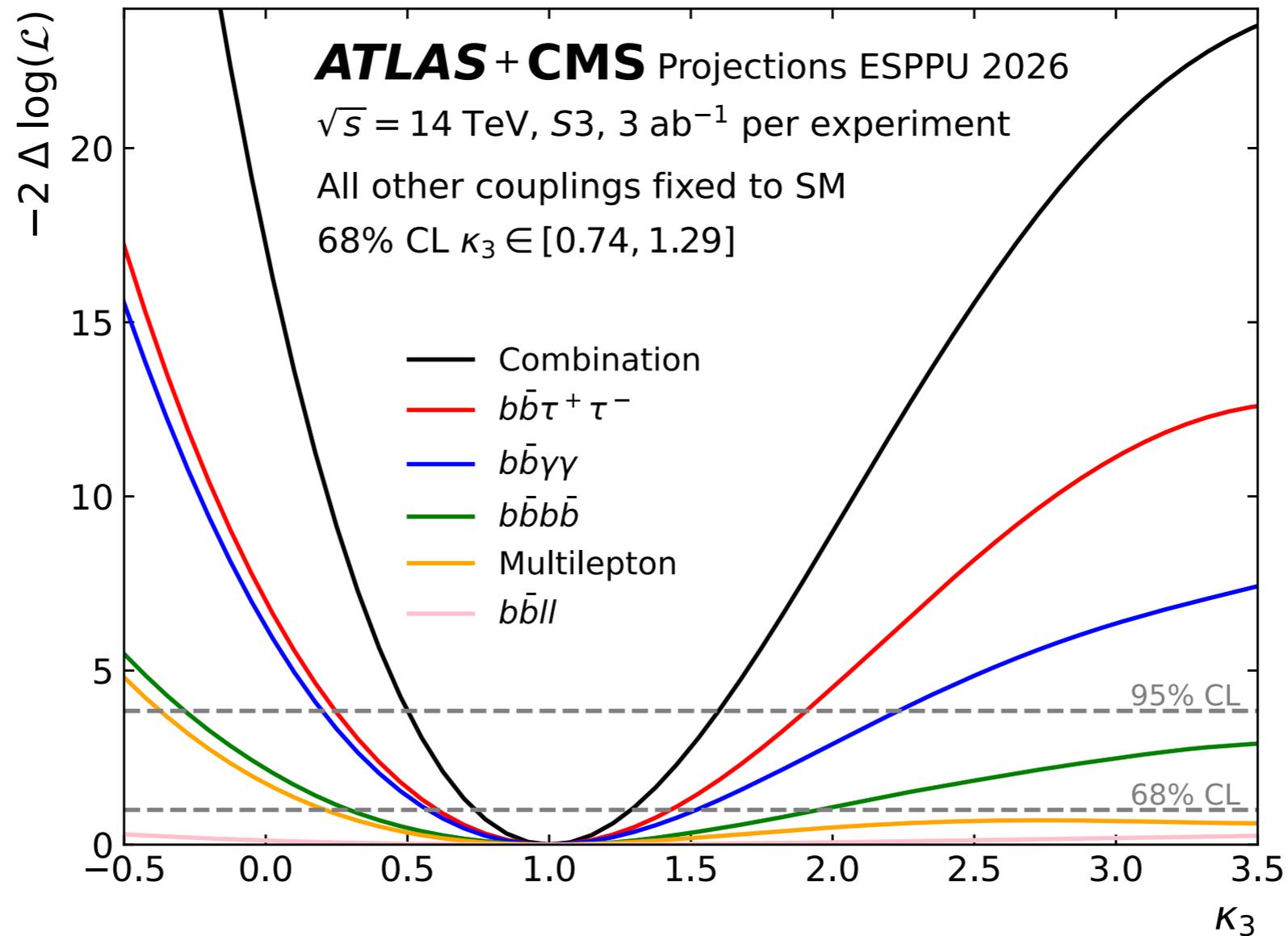
Likely to keep growing as techniques continue to improve!



κ_λ Sensitivity

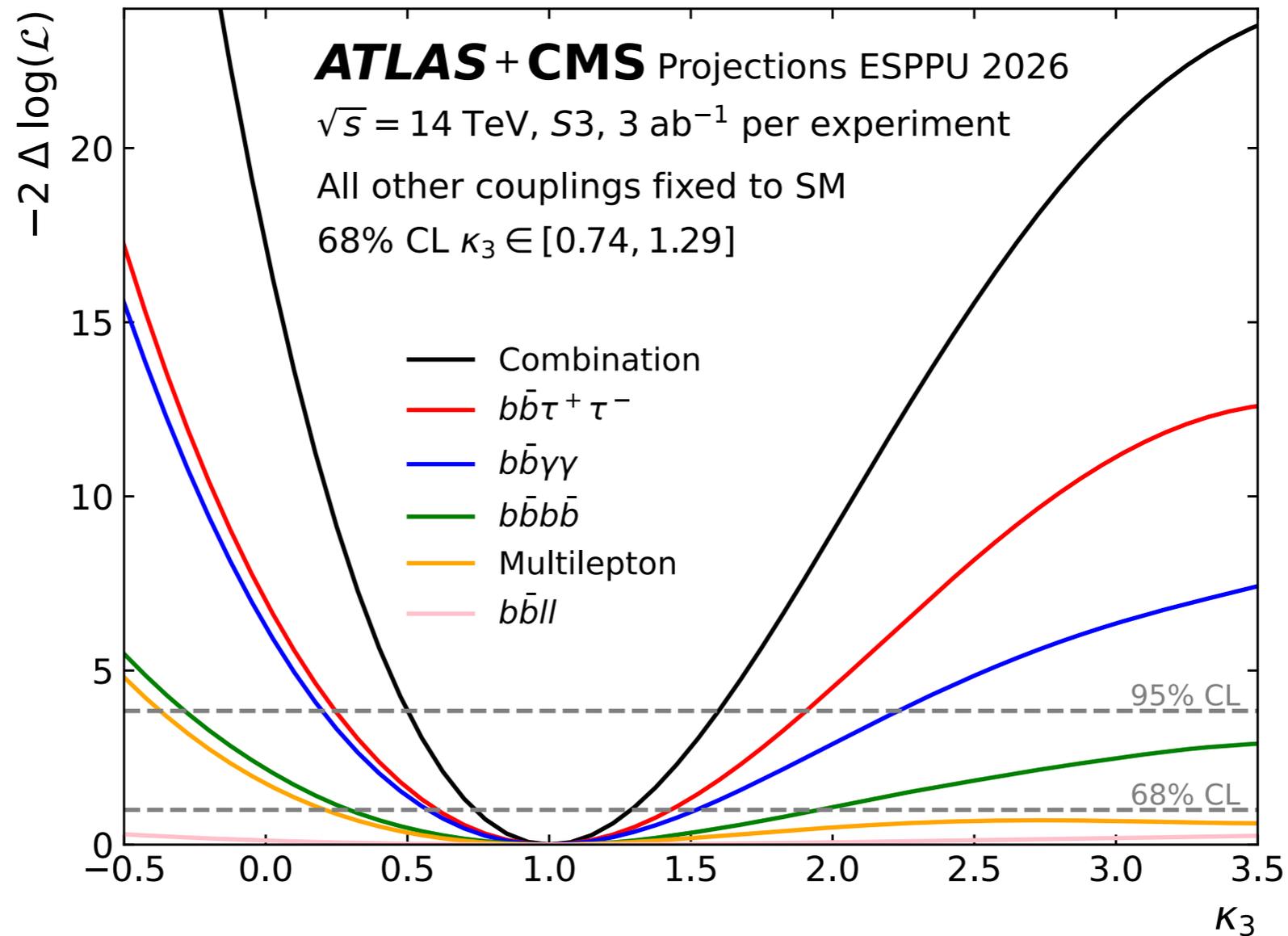


κ_λ Sensitivity





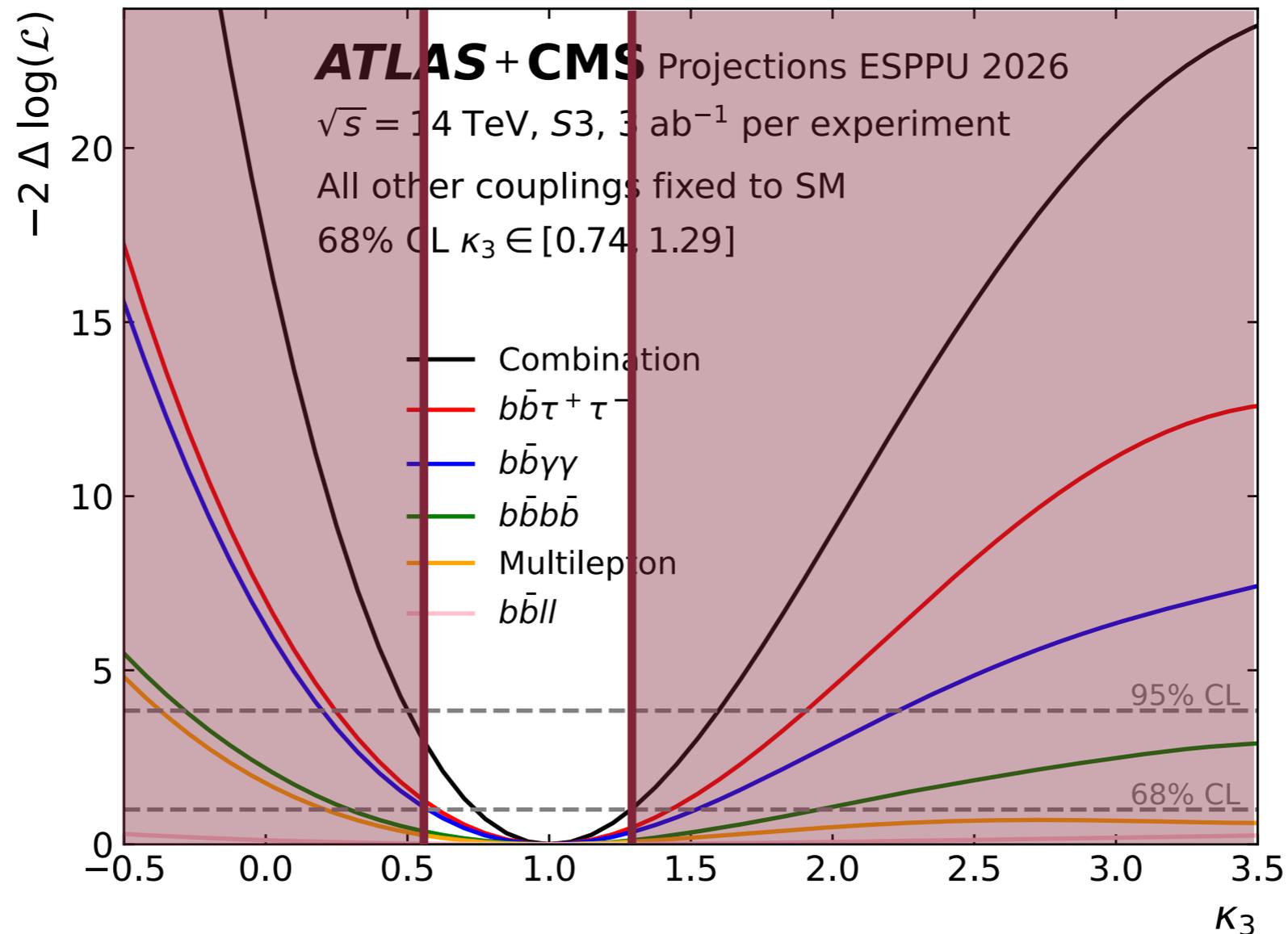
κ_λ Sensitivity



κ_λ sensitivity also significantly improved



κ_λ Sensitivity



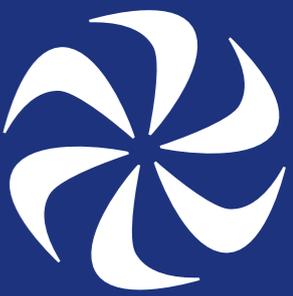
κ_λ sensitivity also significantly improved

Roughly $\sim 30\%$ precision (at 1σ)

The Nathaniel Sketch

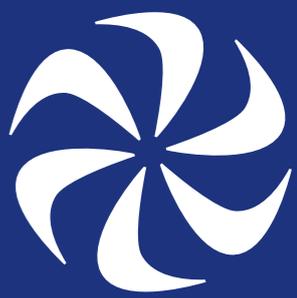


The Nathaniel Sketch

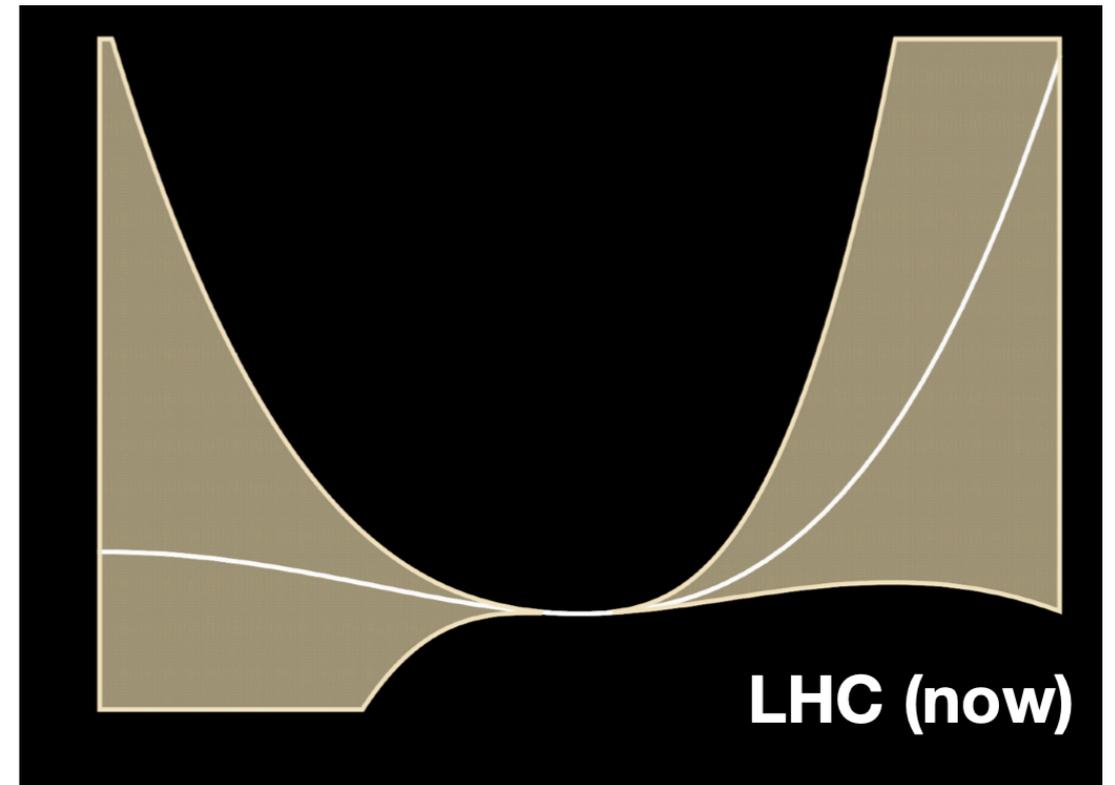


Very helpful way of visualizing our precision: what Higgs potentials are possible with our measurements today?

The Nathaniel Sketch



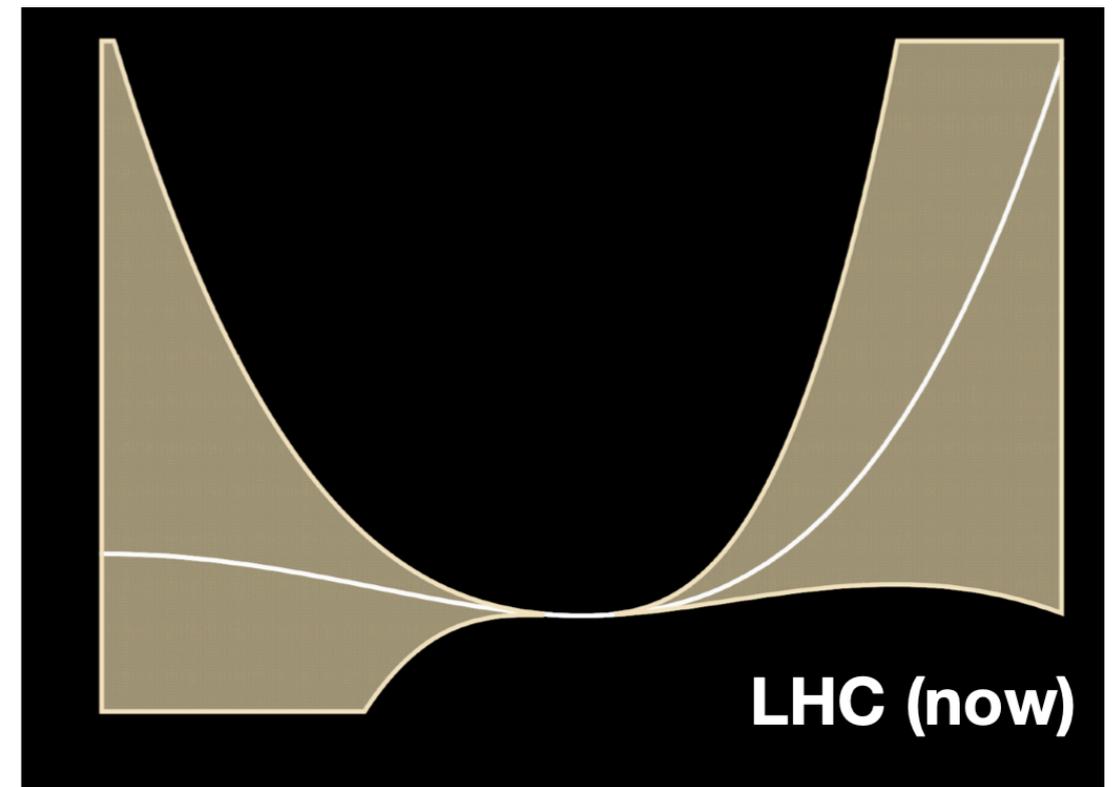
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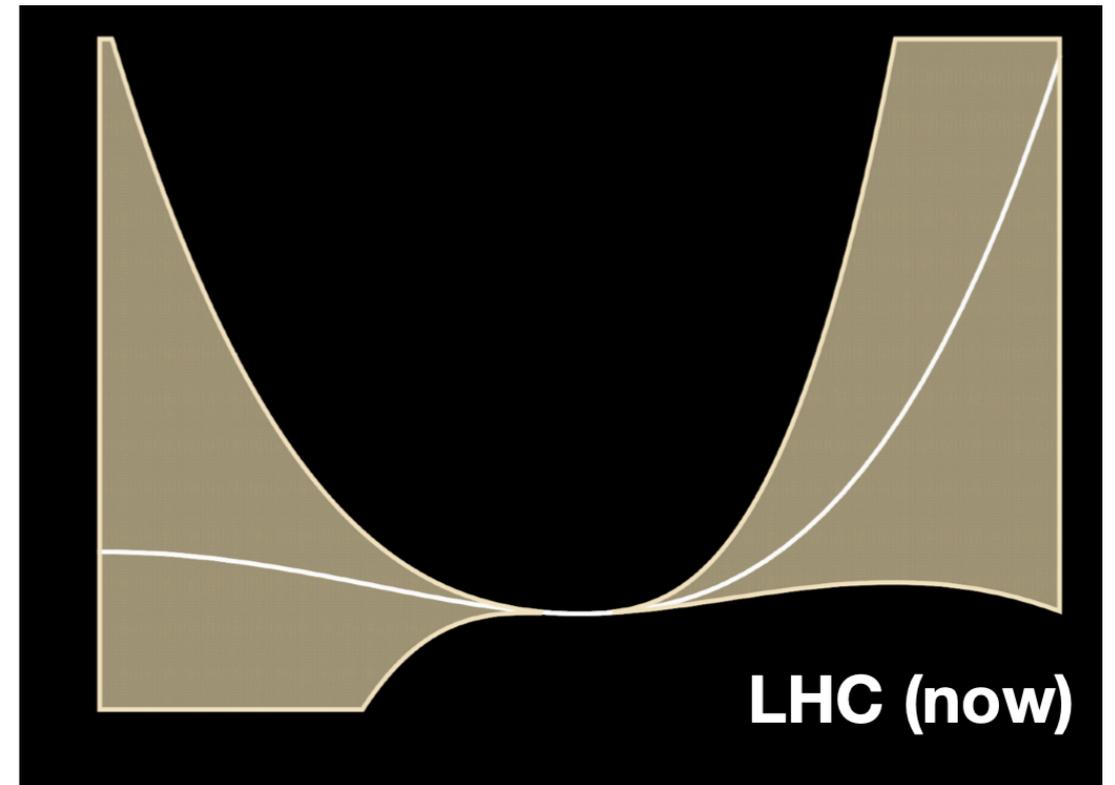


And what's possible at the HL-LHC?

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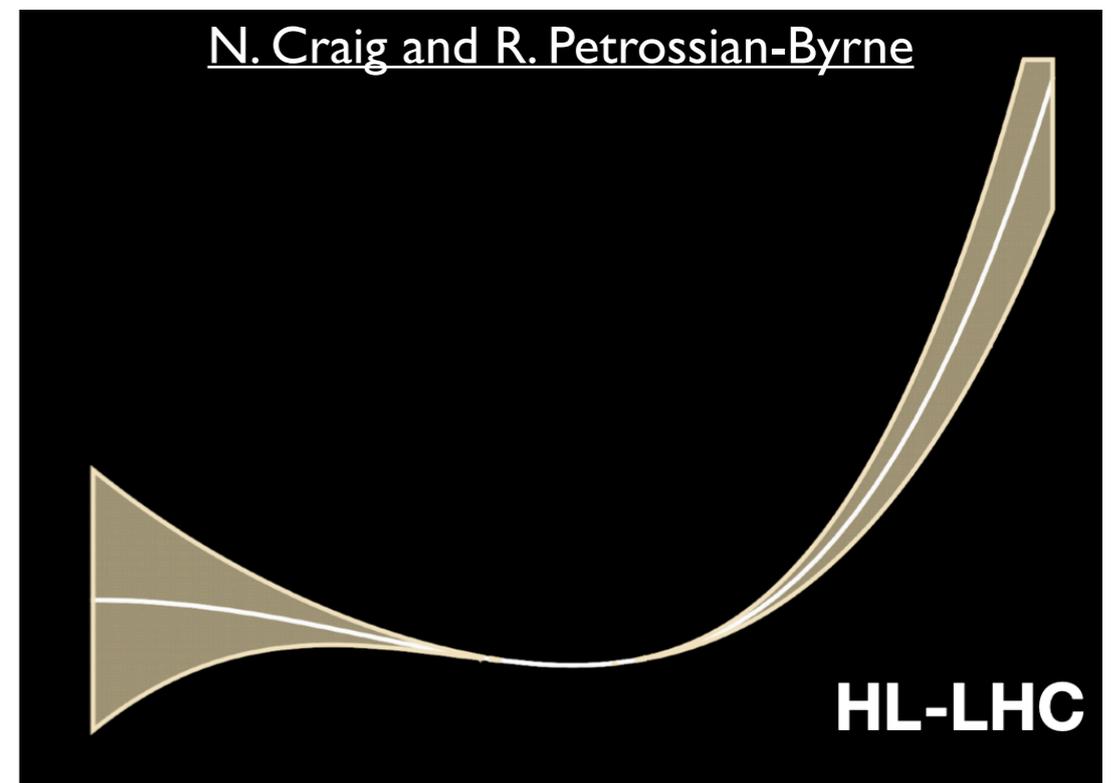


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N. Craig and R. Petrossian-Byrne

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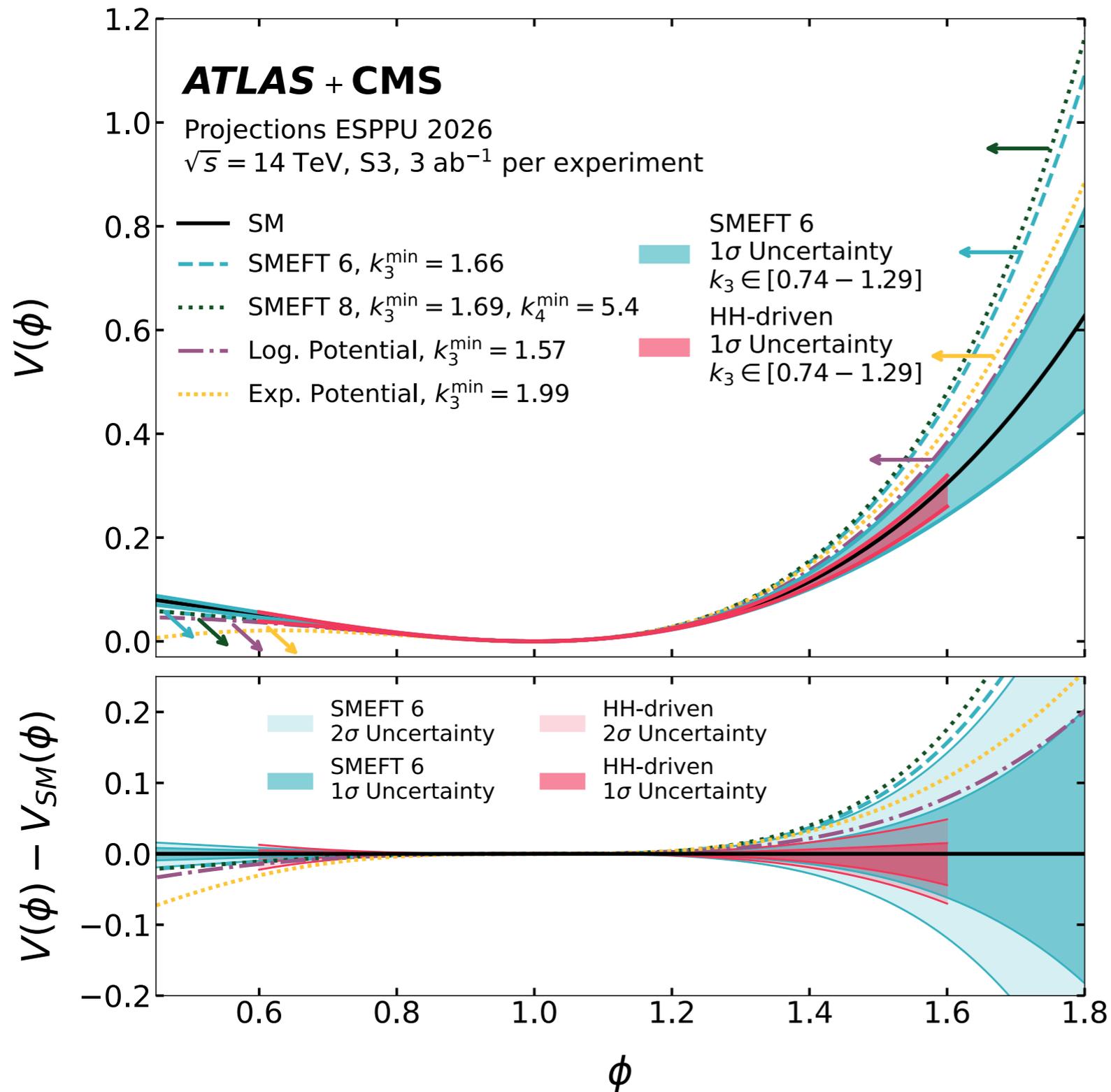




The Nathaniel Plot

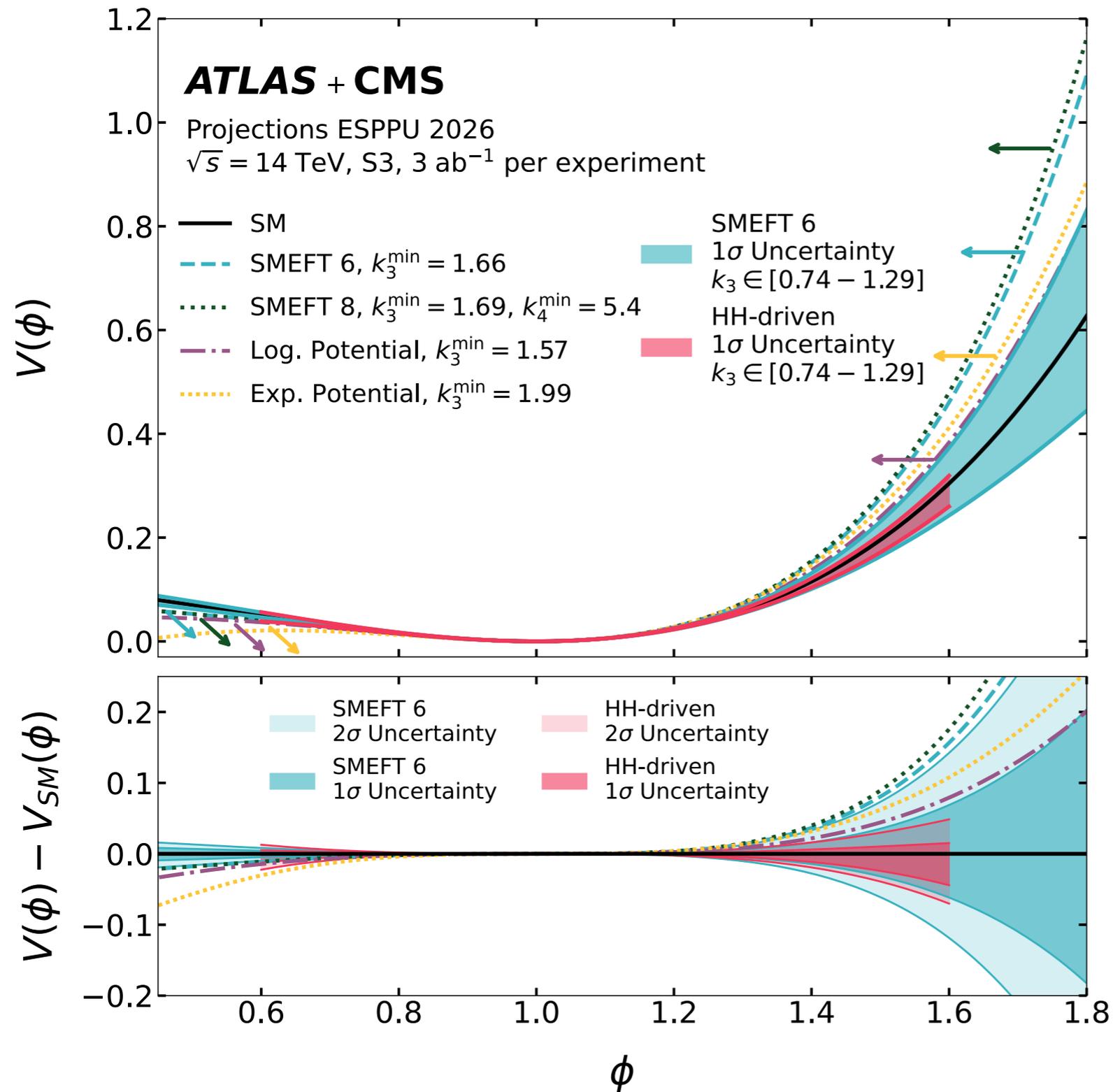


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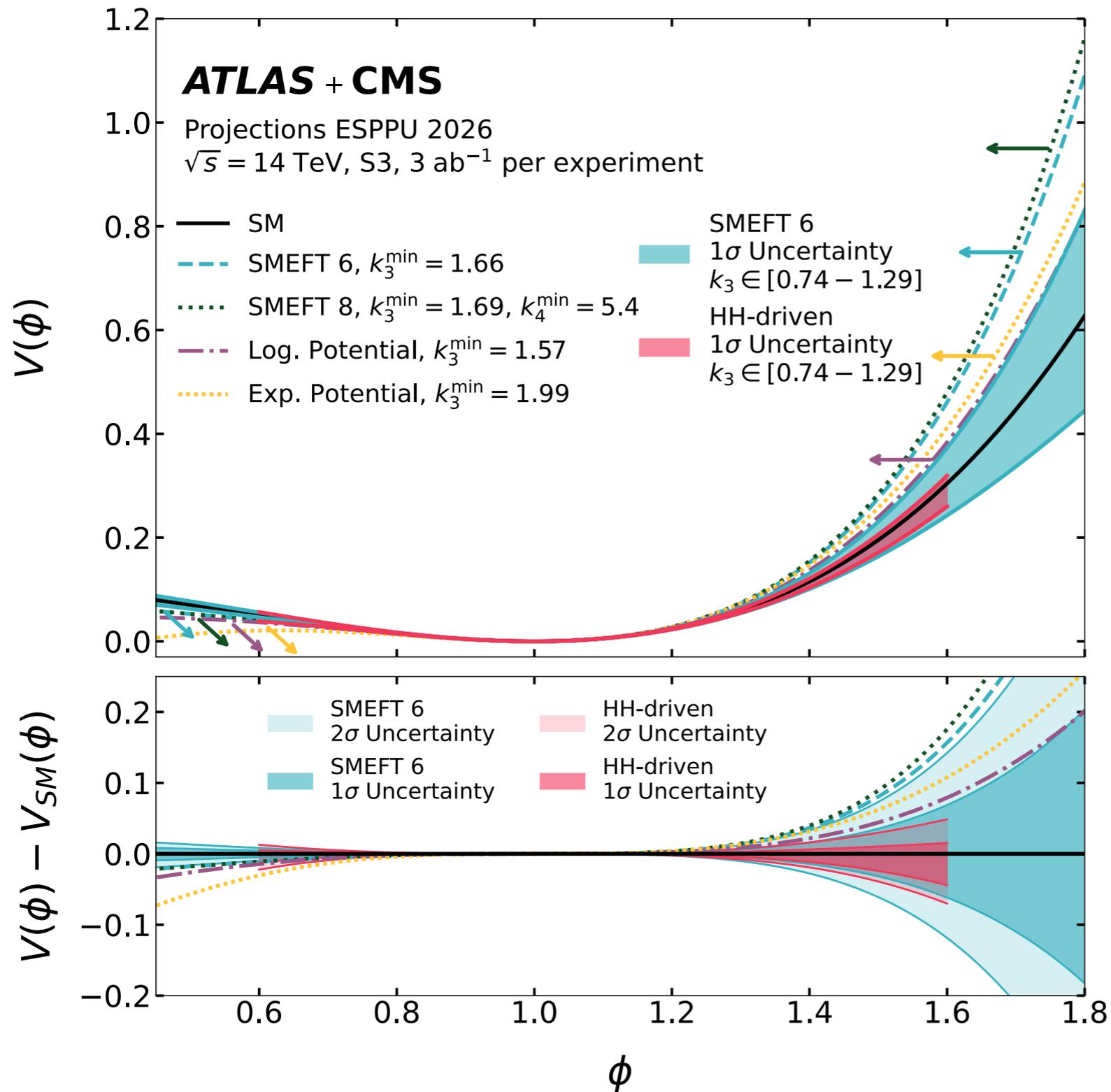
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What does this tell us about EWBG?



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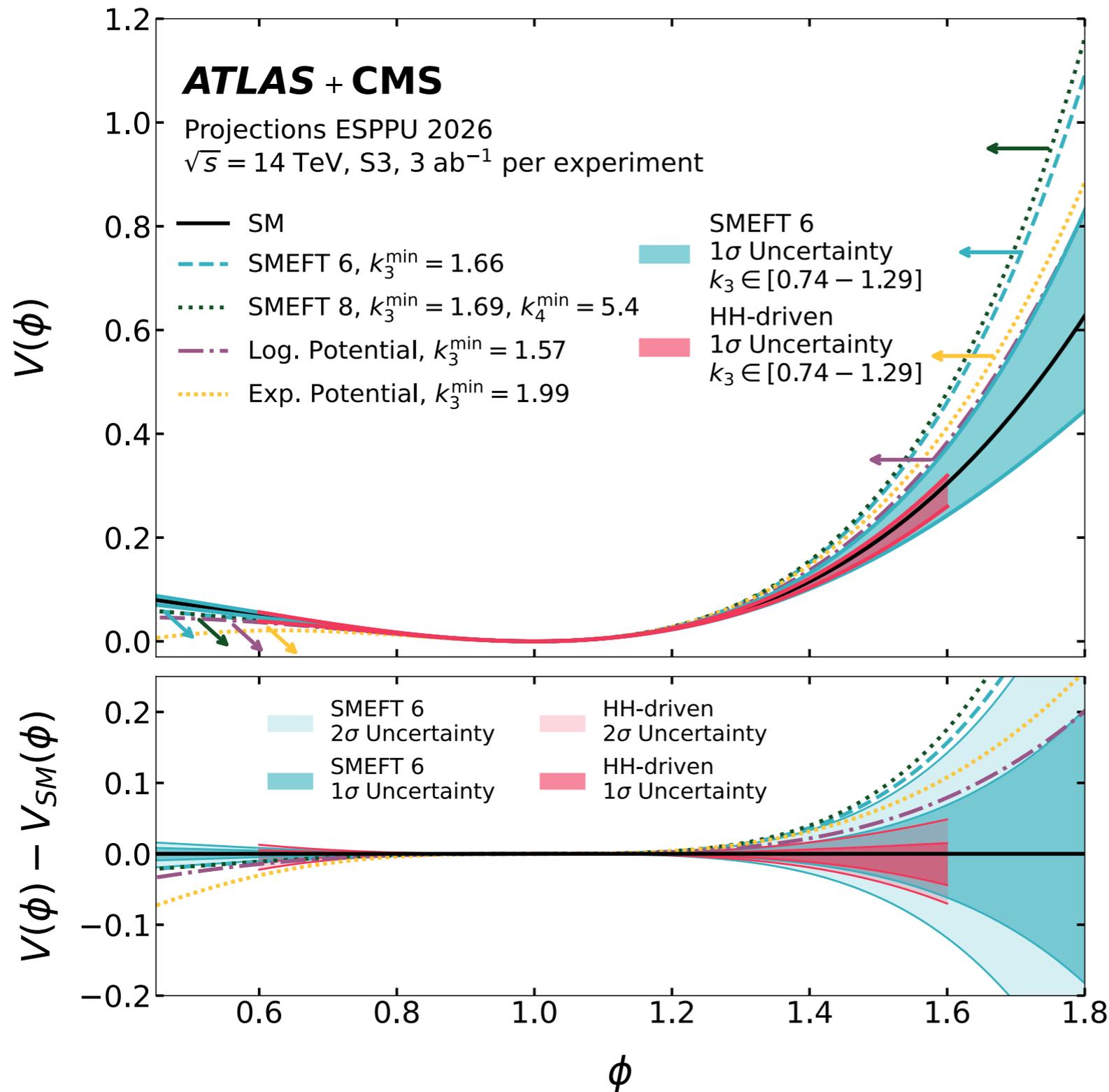


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Here, compare precision
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The Nathaniel Plot



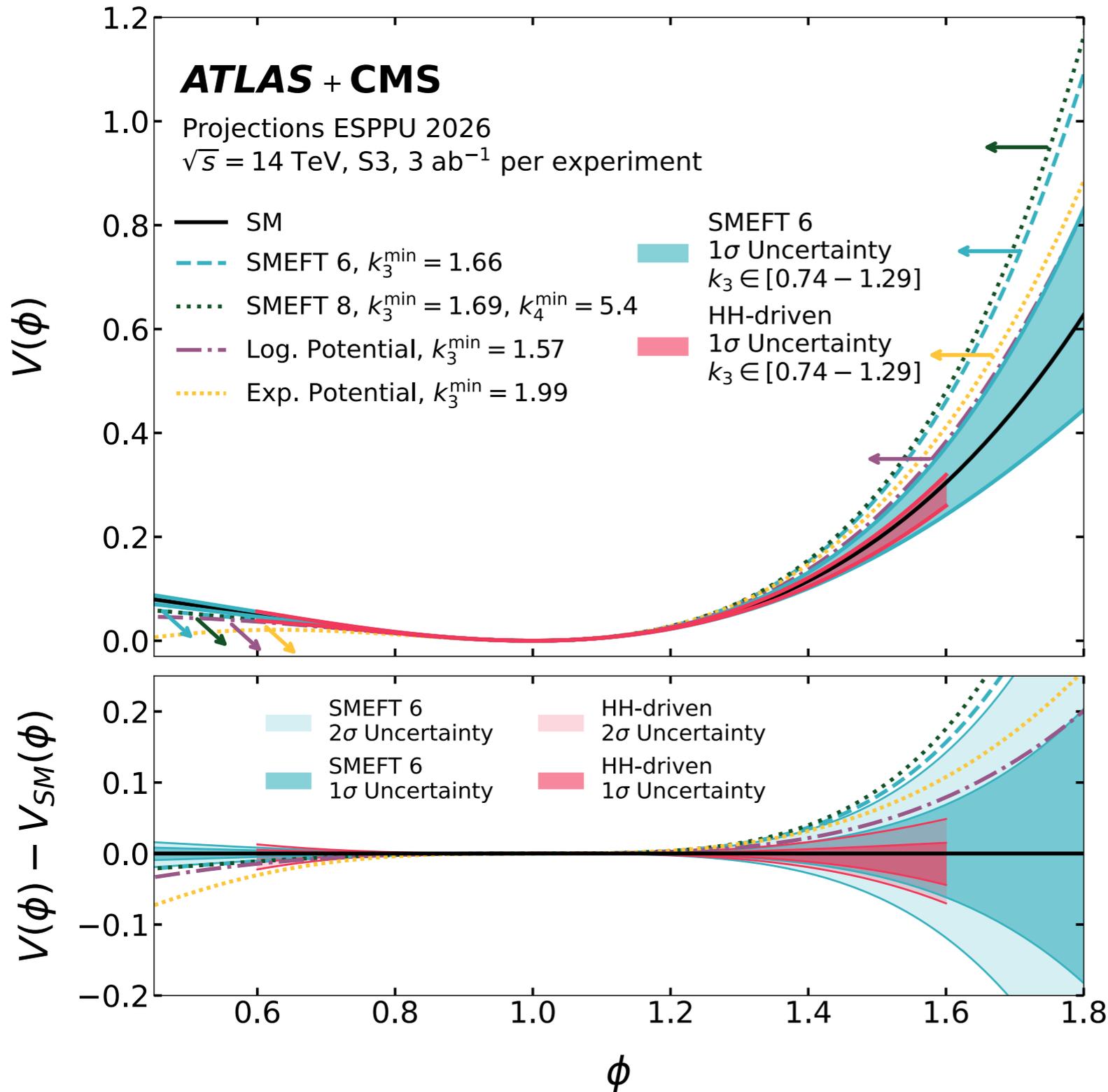
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“Realistic” theory models
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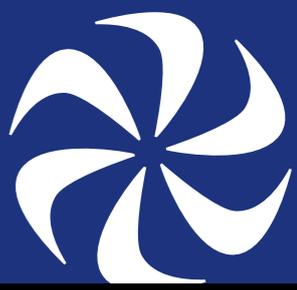
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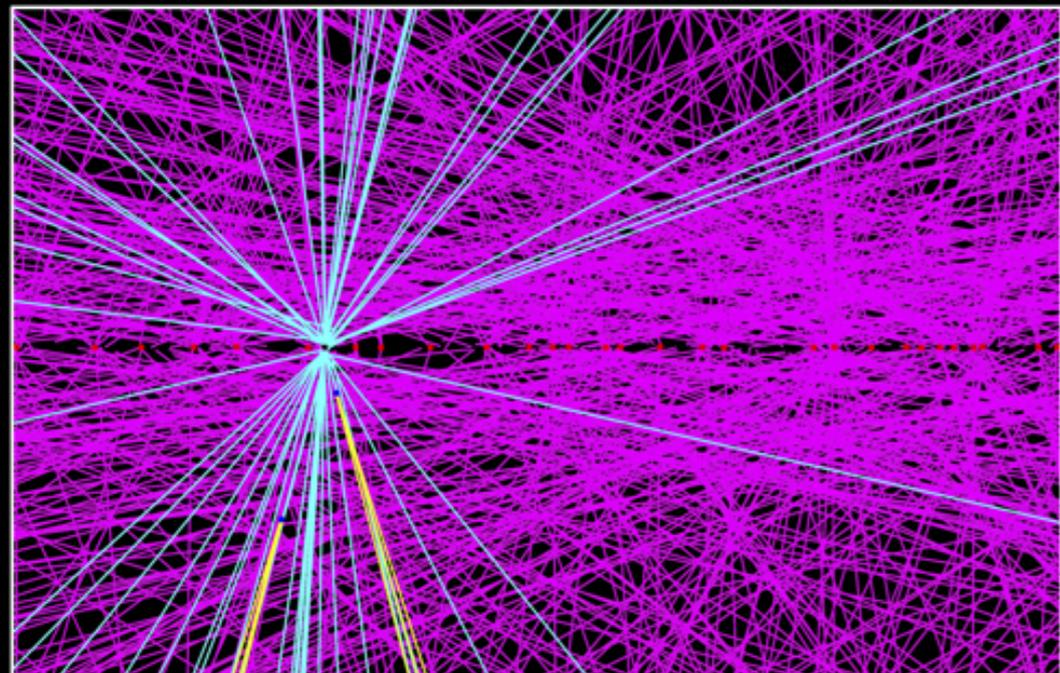
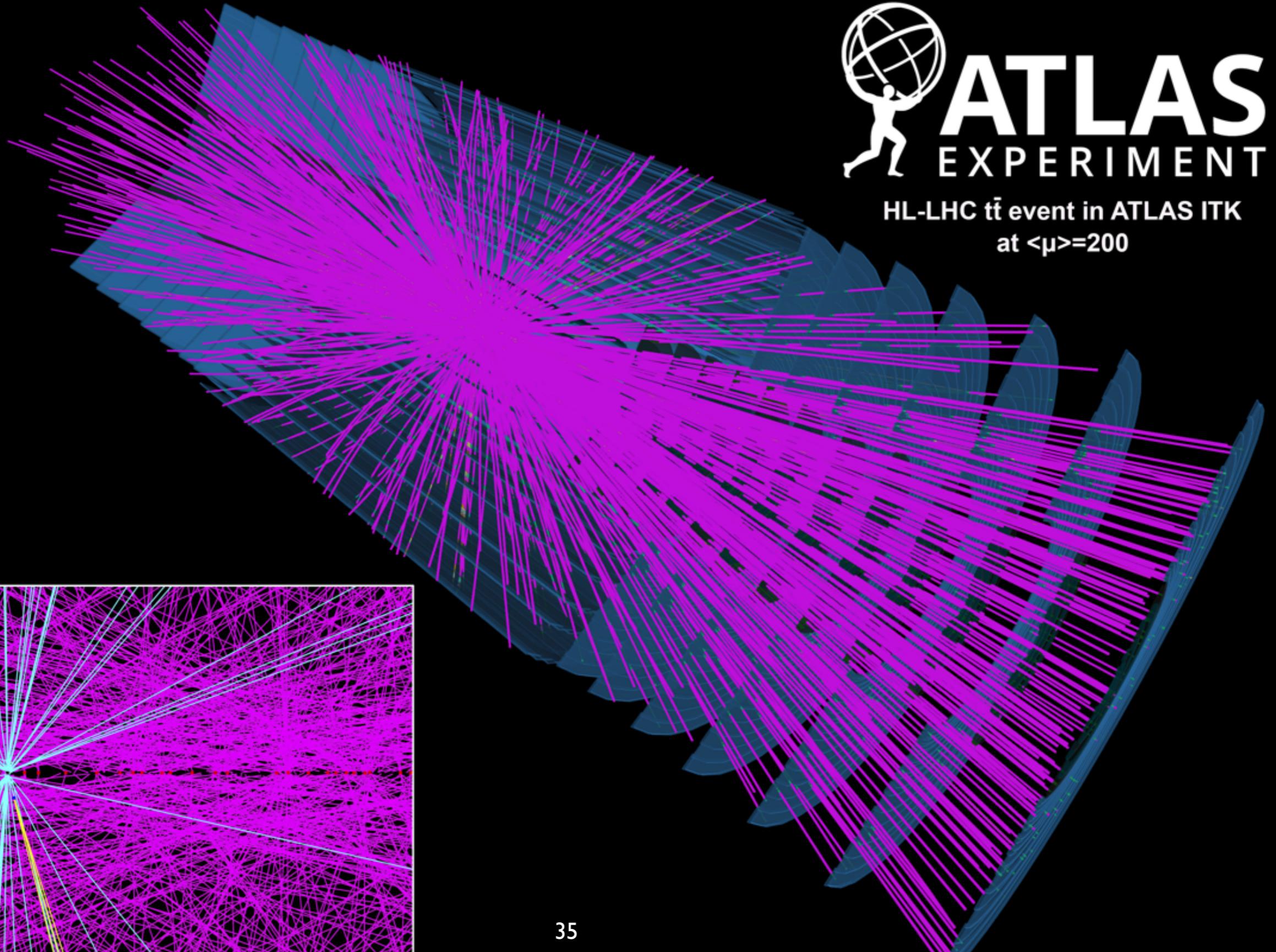
We will be probing the electroweak phase transition at HL-LHC!

Conclusions

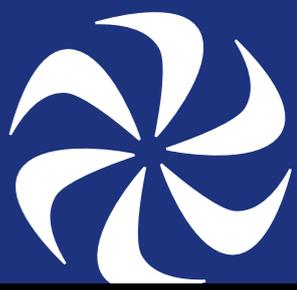
Conclusions



 **ATLAS**
EXPERIMENT
HL-LHC $t\bar{t}$ event in ATLAS ITK
at $\langle\mu\rangle=200$

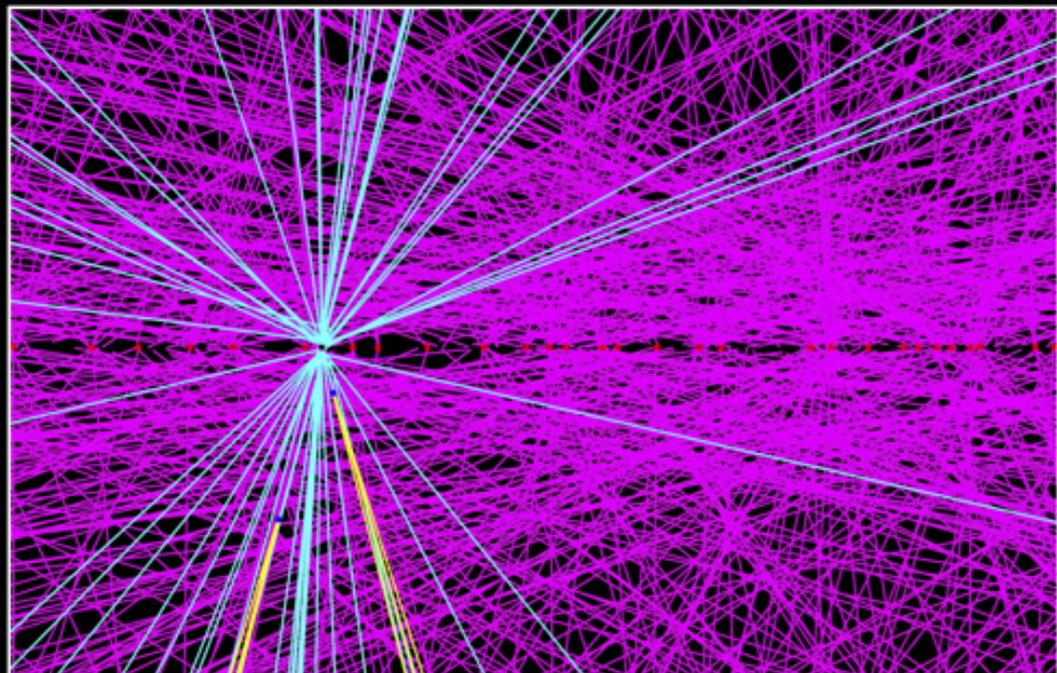


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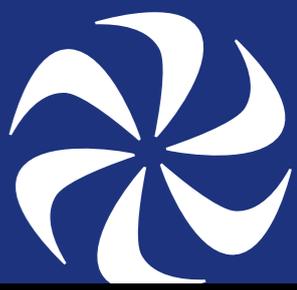


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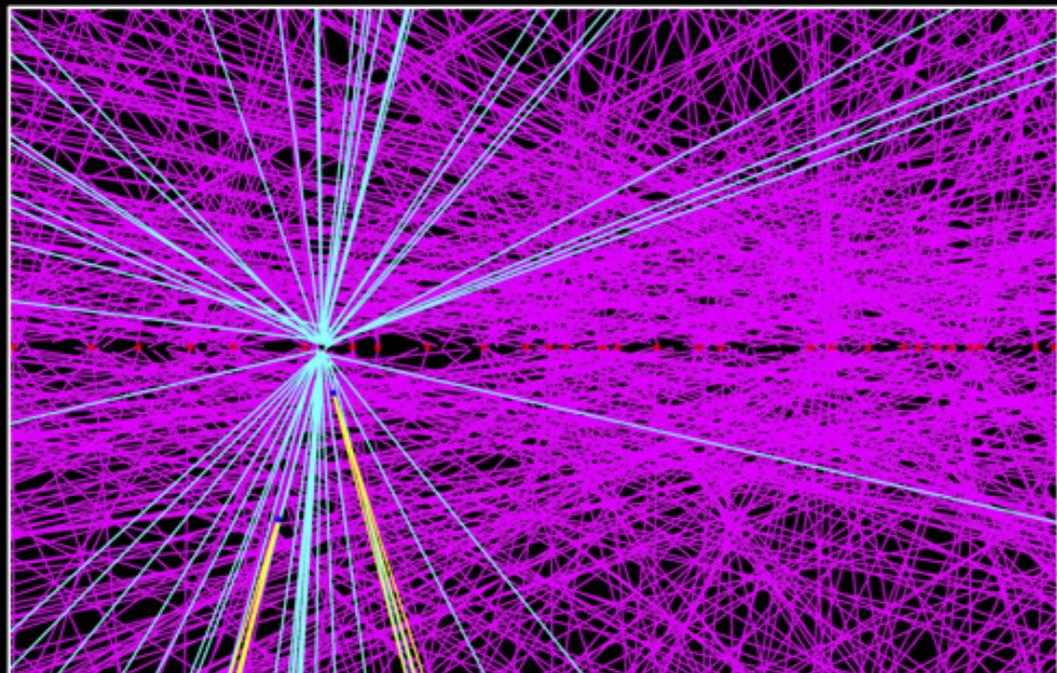
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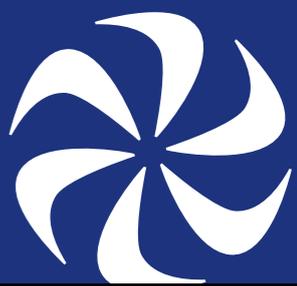
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Extrapolations likely underestimate our sensitivity: can't project how clever we will be!



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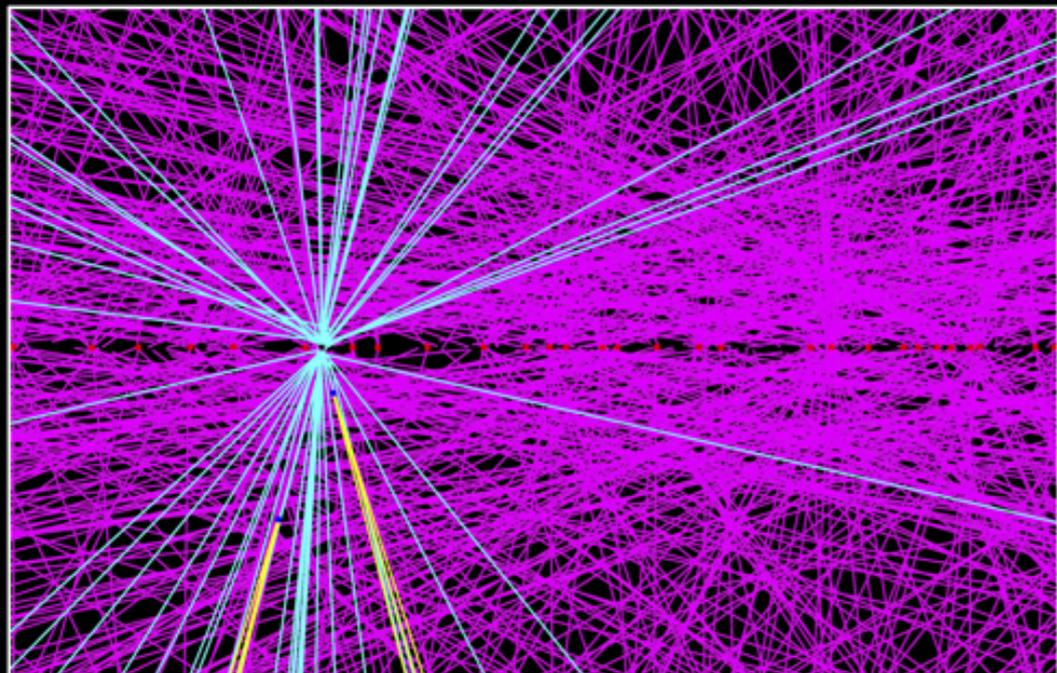


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Extrapolations likely underestimate our sensitivity: can't project how clever we will be!

Many credible models for EWBG will be tested at the HL-LHC: exciting times ahead!



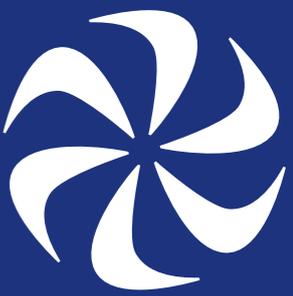
Thank you!

Backup

Very technical warning

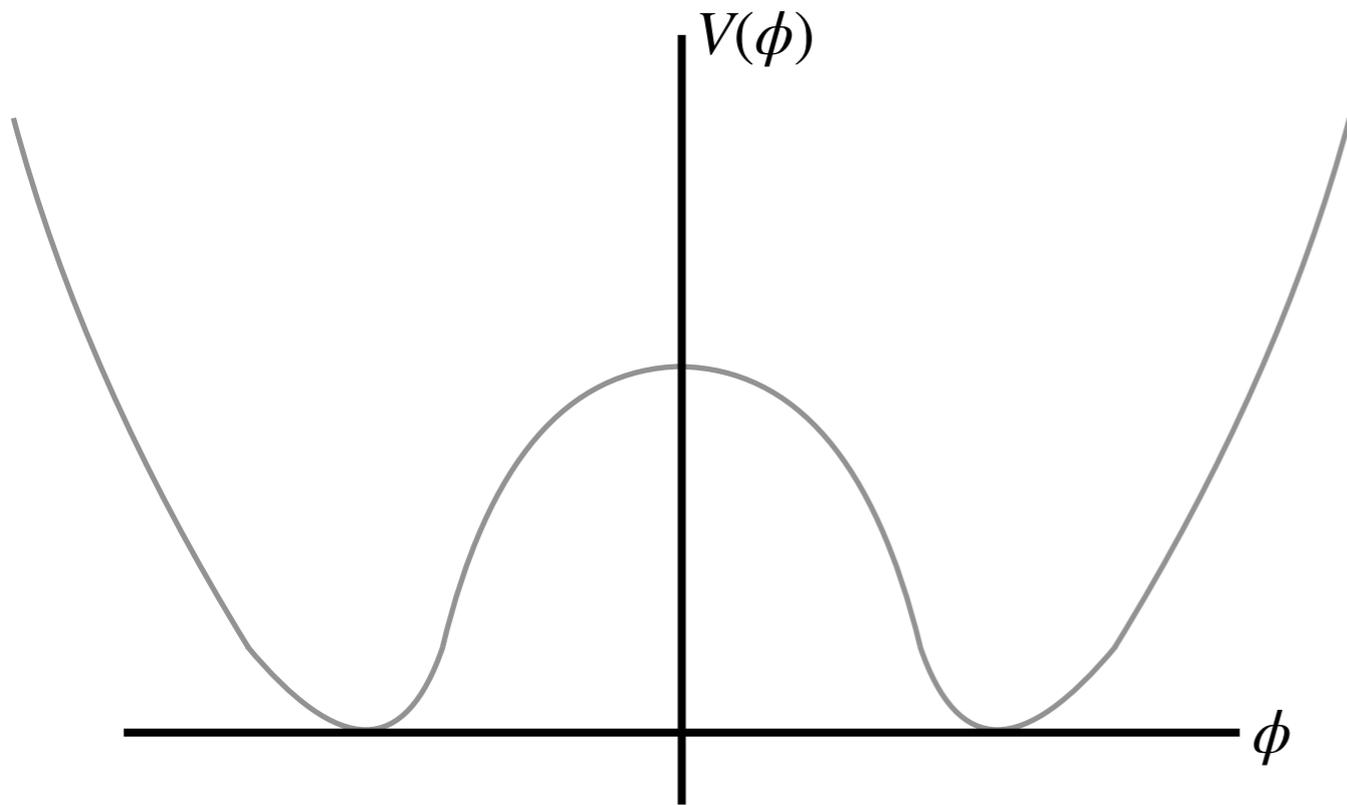
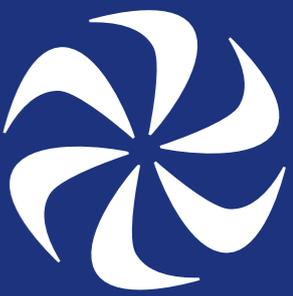
If I lose you here, I'll come back for you
in 5 slides!

The Electroweak Phase Transition



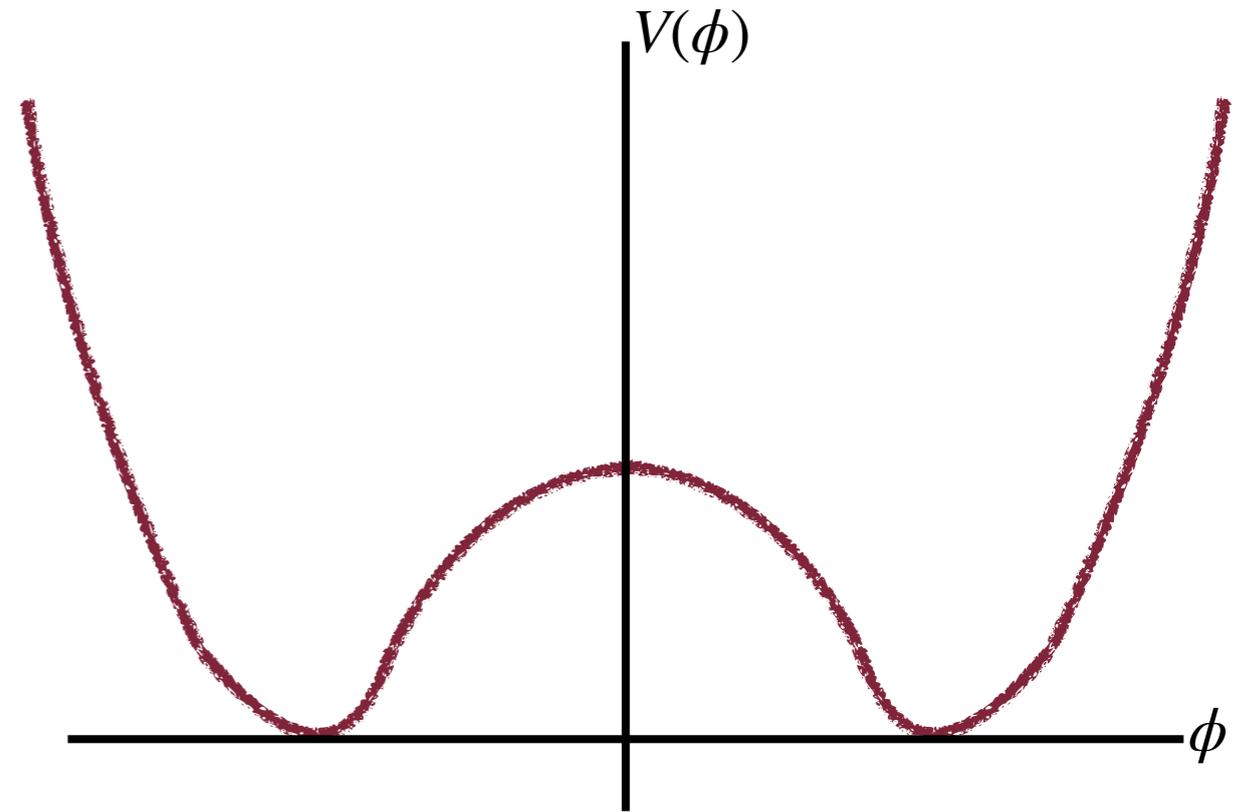
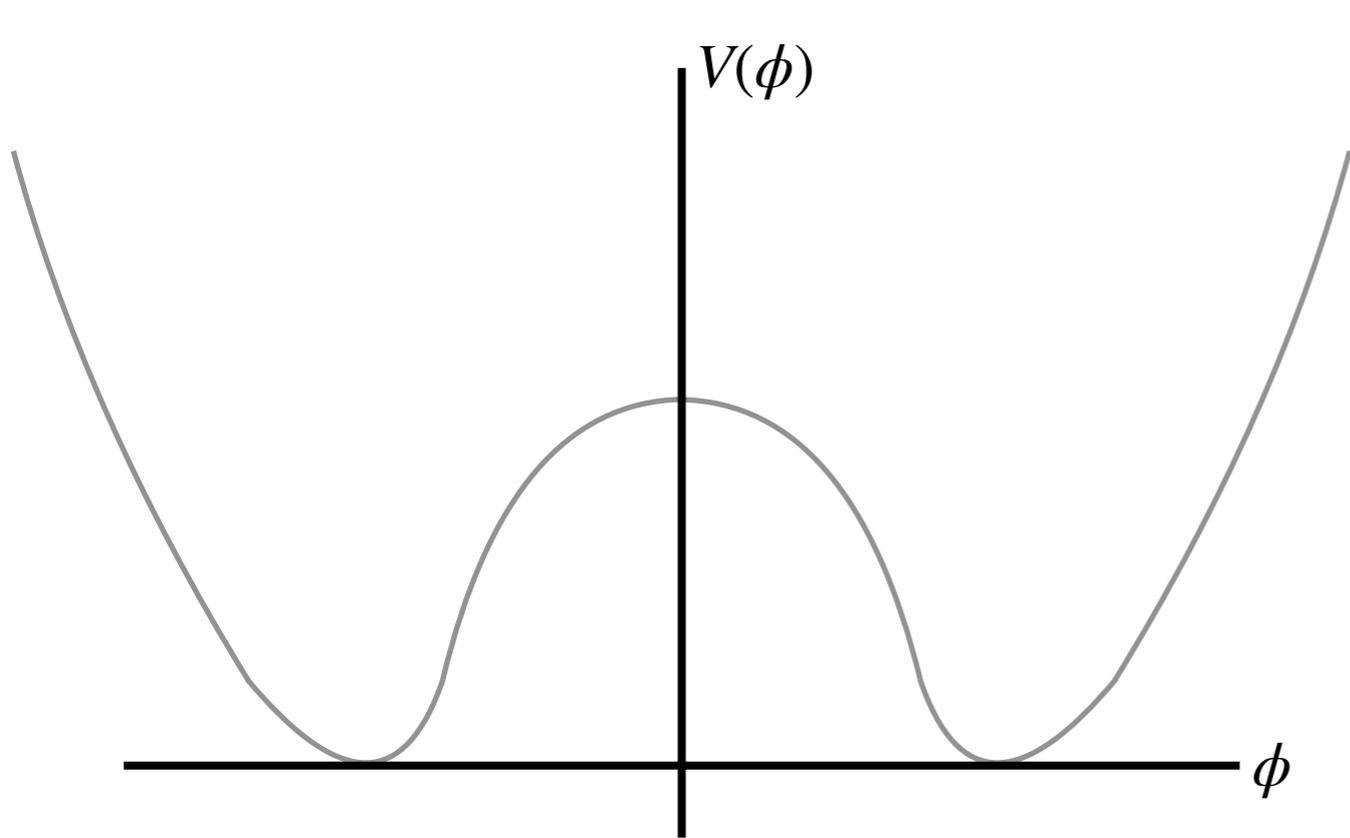
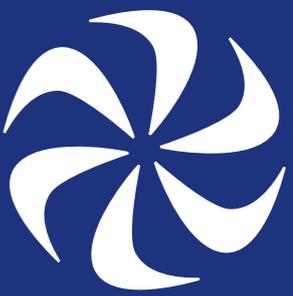
Adapted from [T.Tait](#) and [G.White](#)

The Electroweak Phase Transition



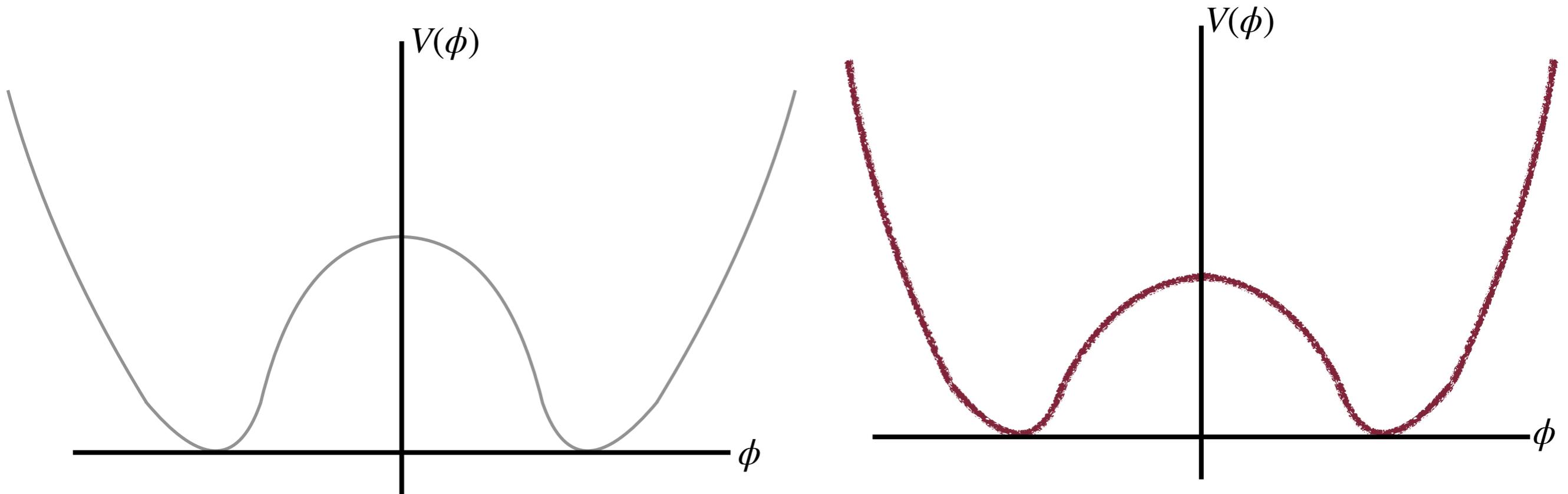
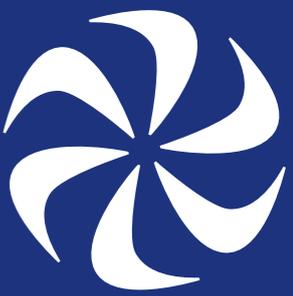
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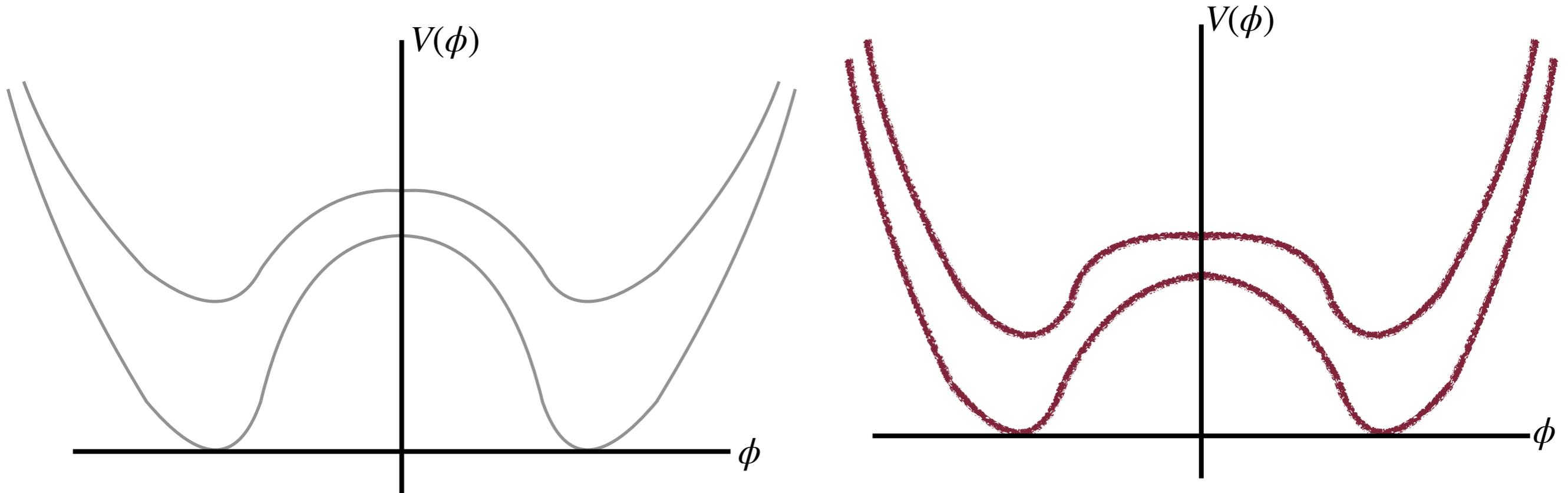
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What happens as we increase the temperature:
Go back in time towards the Big Bang

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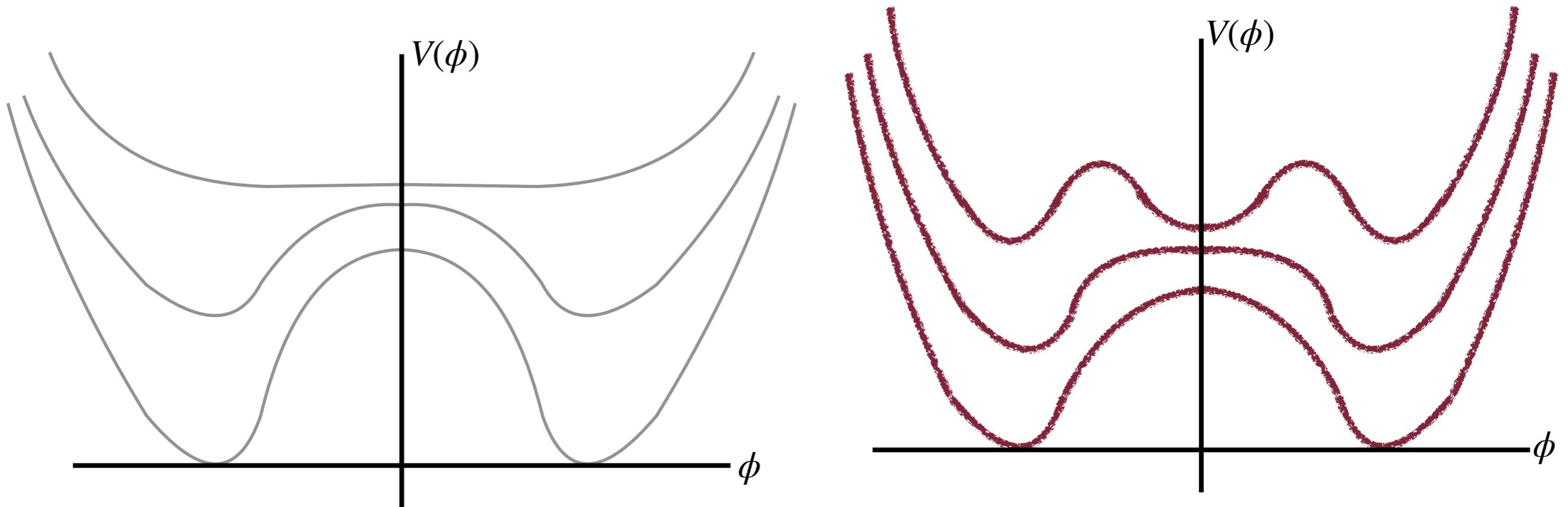
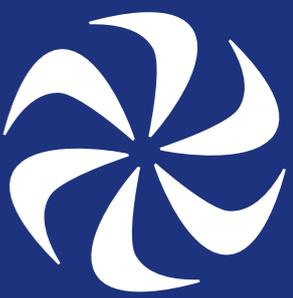
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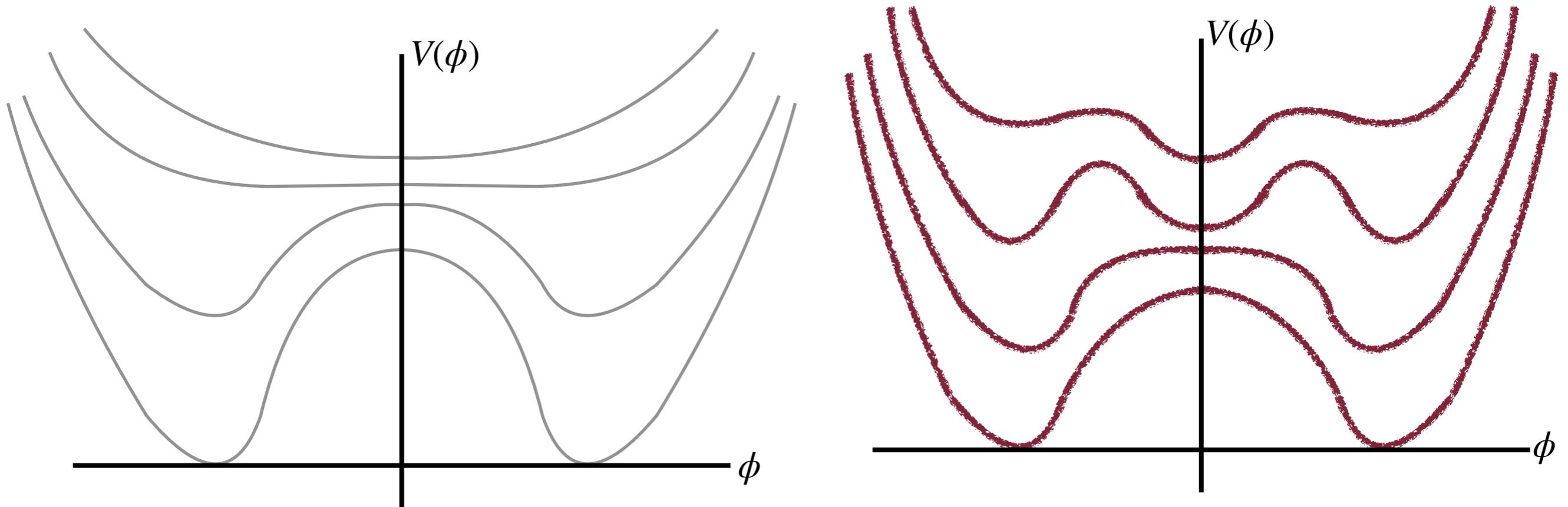
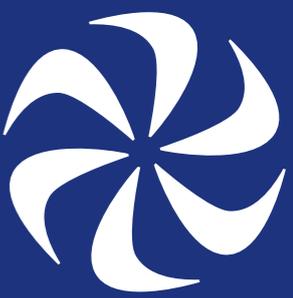
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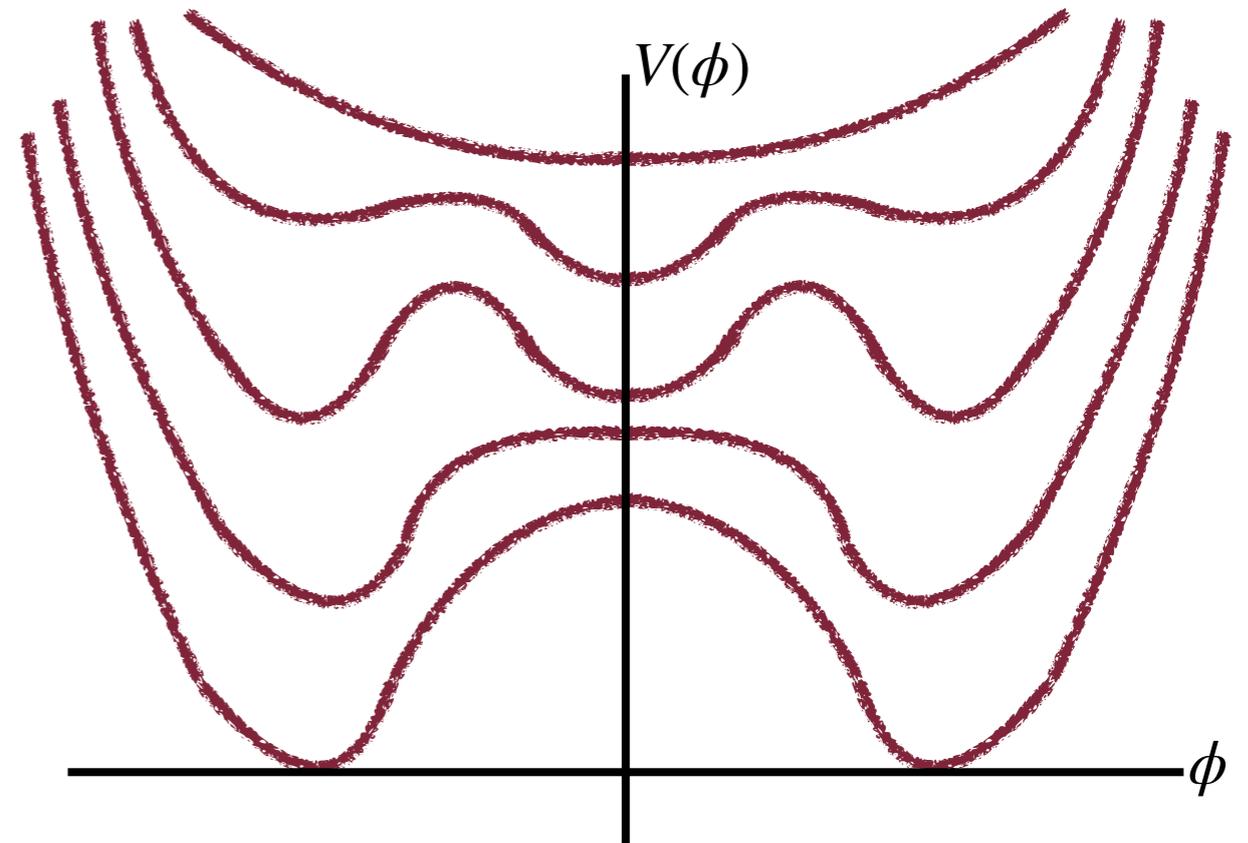
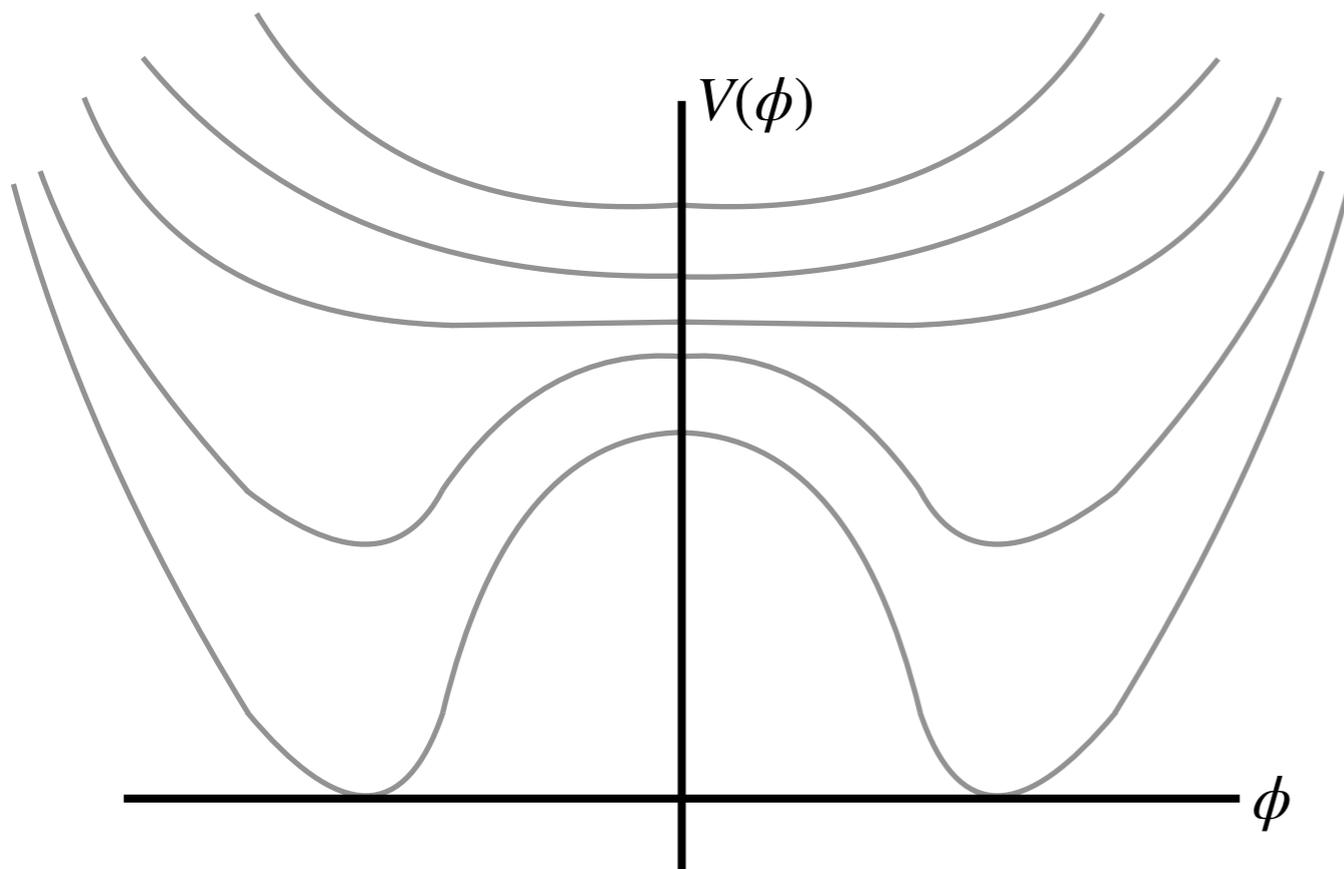
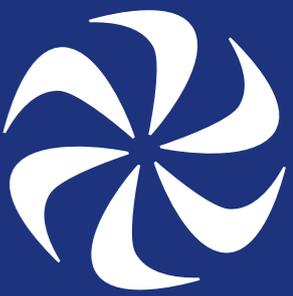
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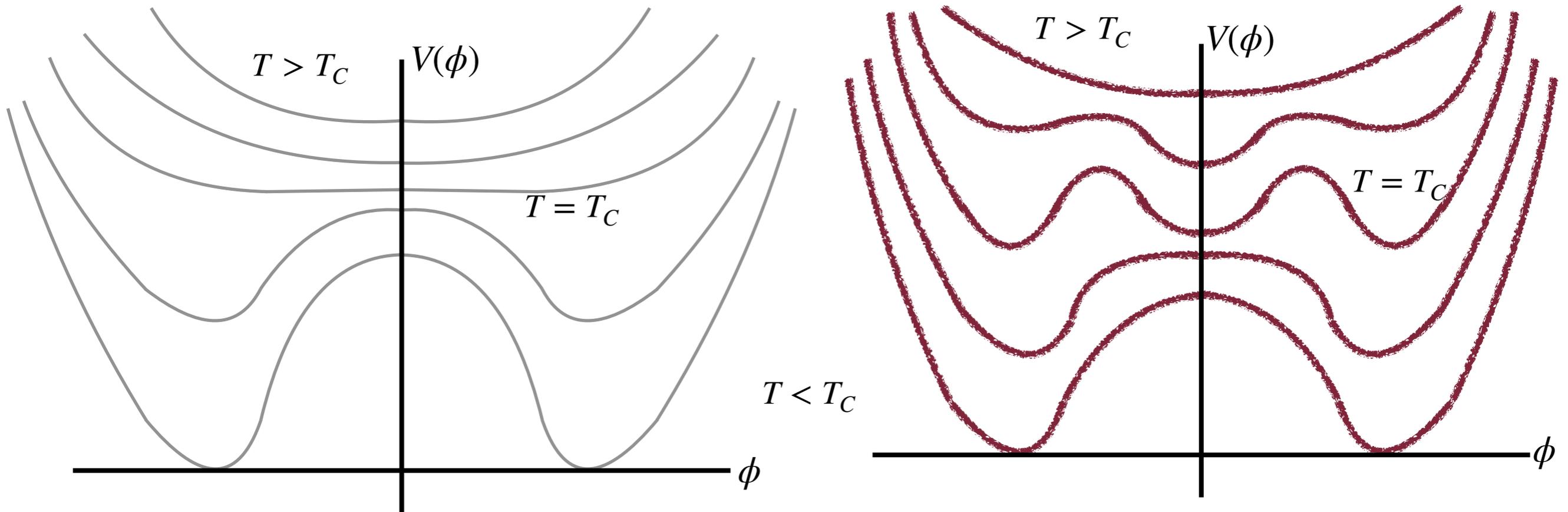
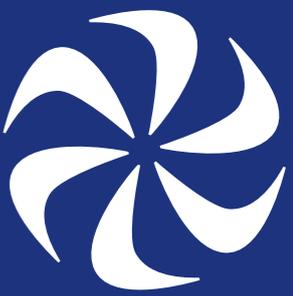
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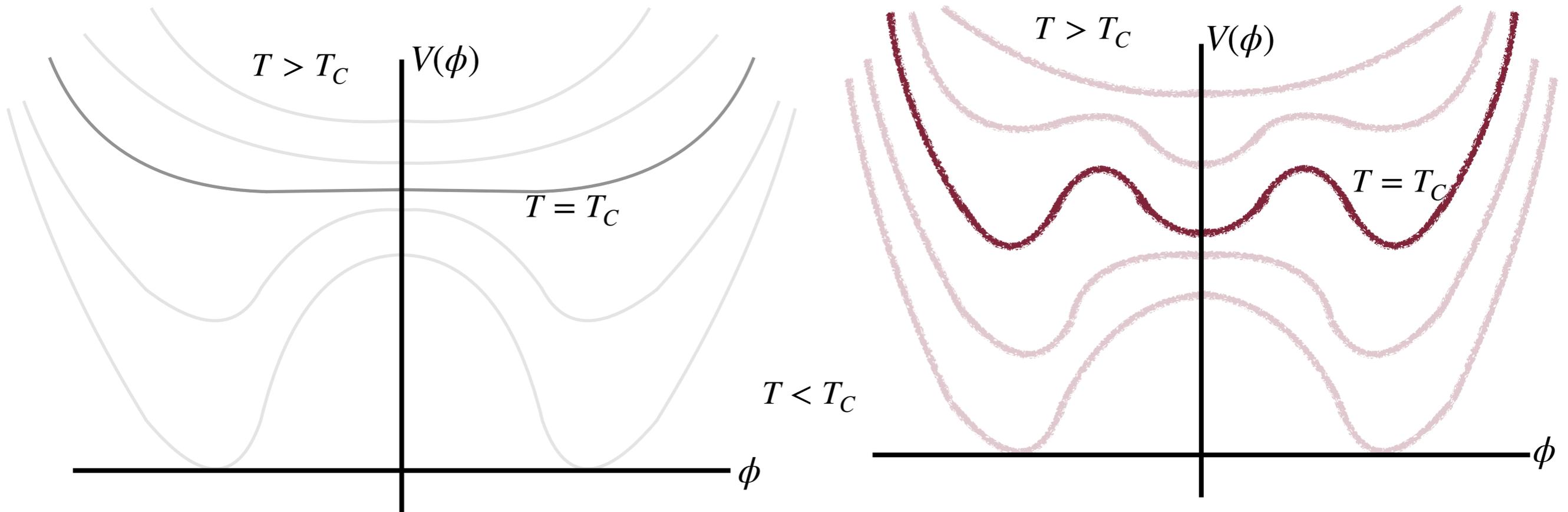
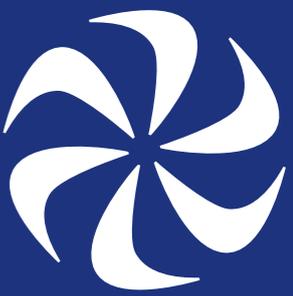


What happens as we increase the temperature:
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Both the SM, and modified models, undergo a **phase transition**:
Minimum at $\phi = 0$ vs $\phi \neq 0$

Adapted from T.Tait and G.White

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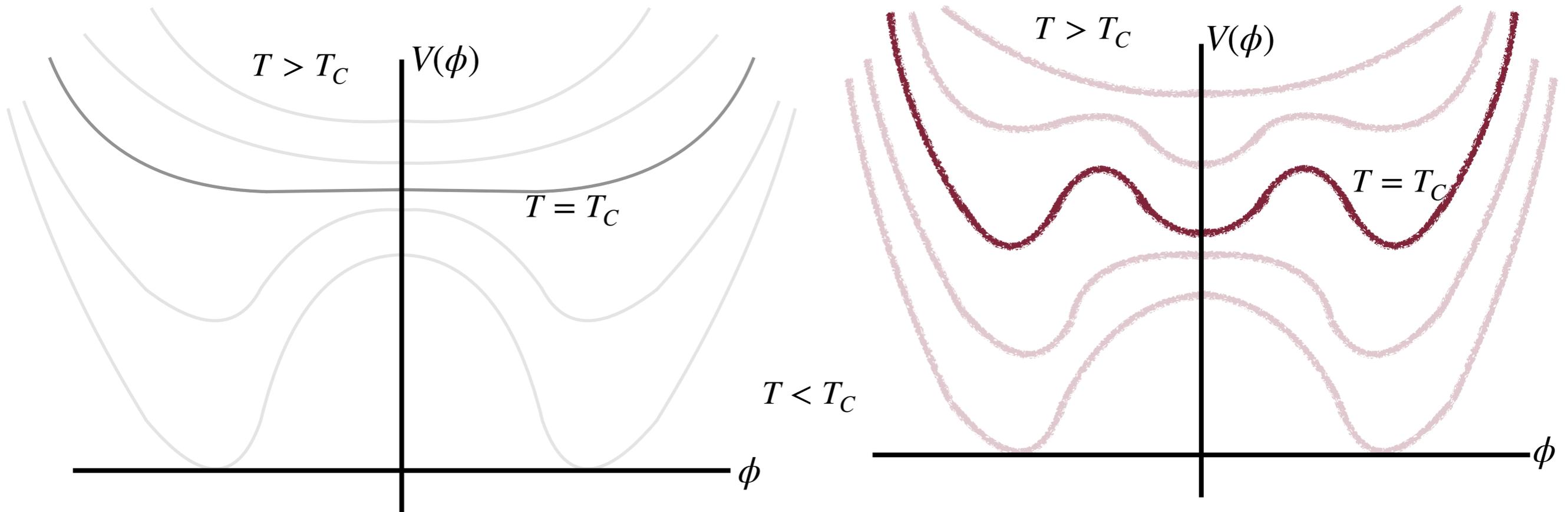
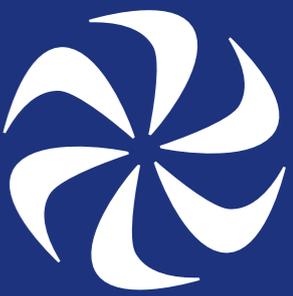


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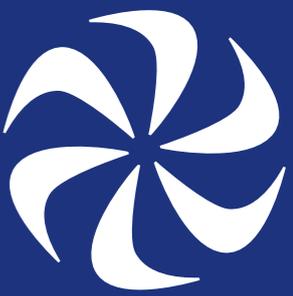
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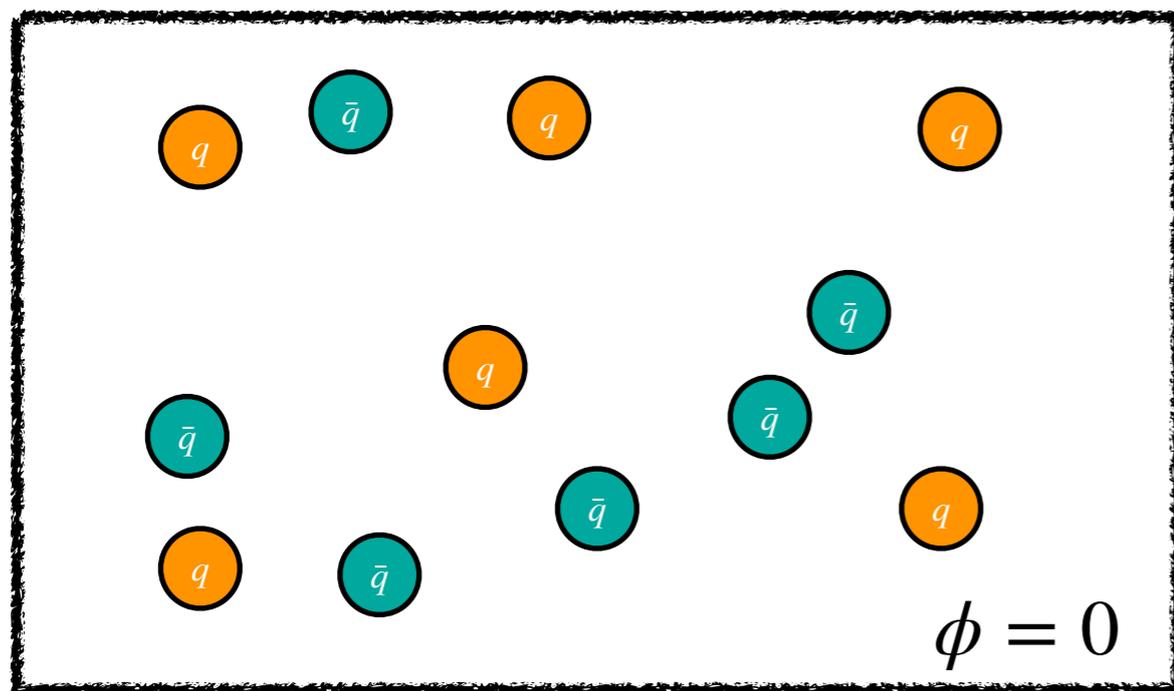
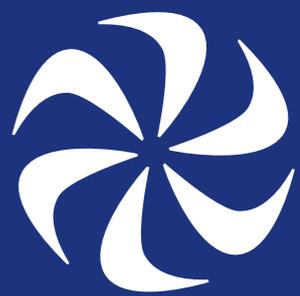
Modified models lead to **out of equilibrium dynamics**
in the early universe

Adapted from T.Tait and G.White

Electroweak Baryogenesis

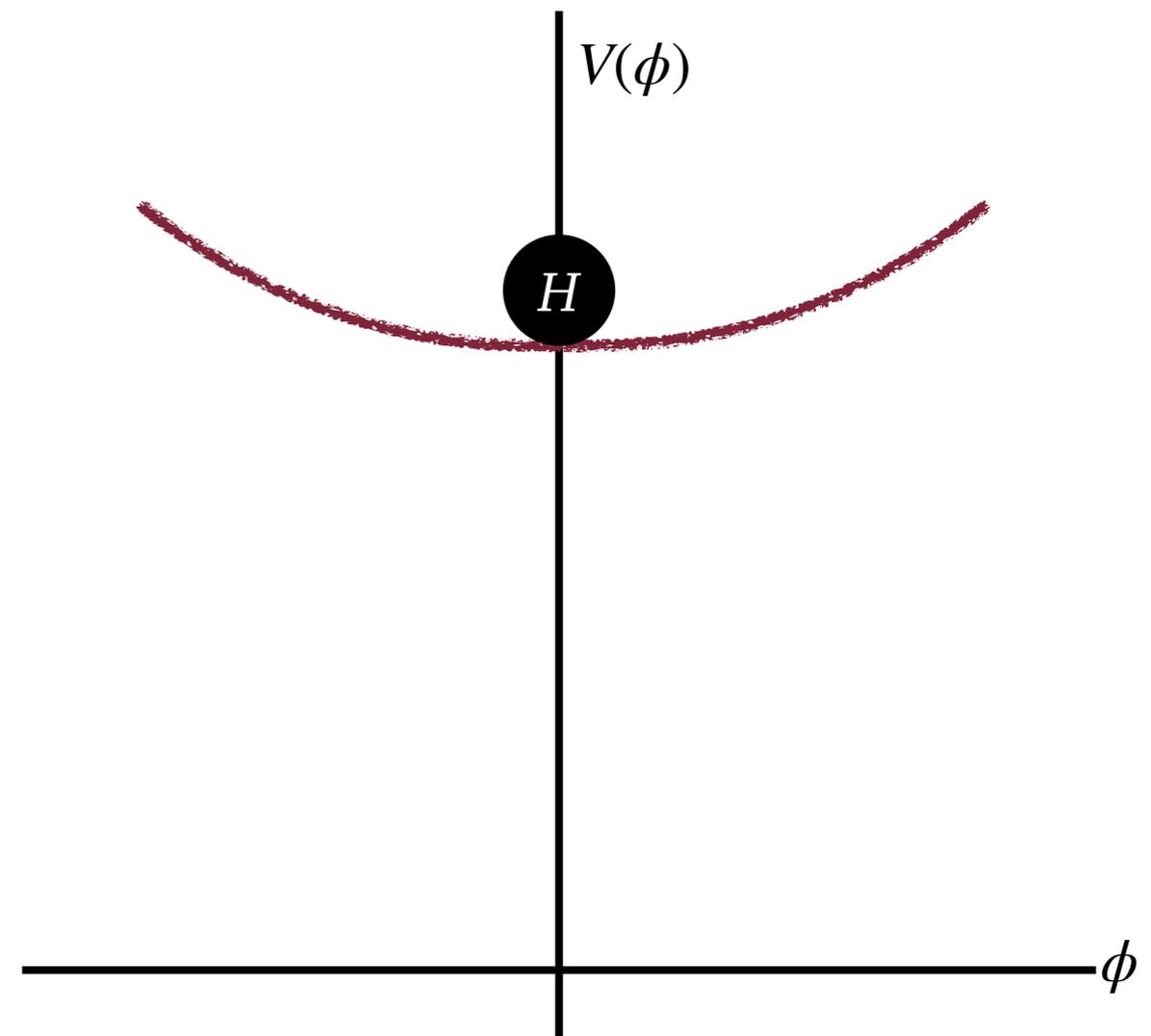
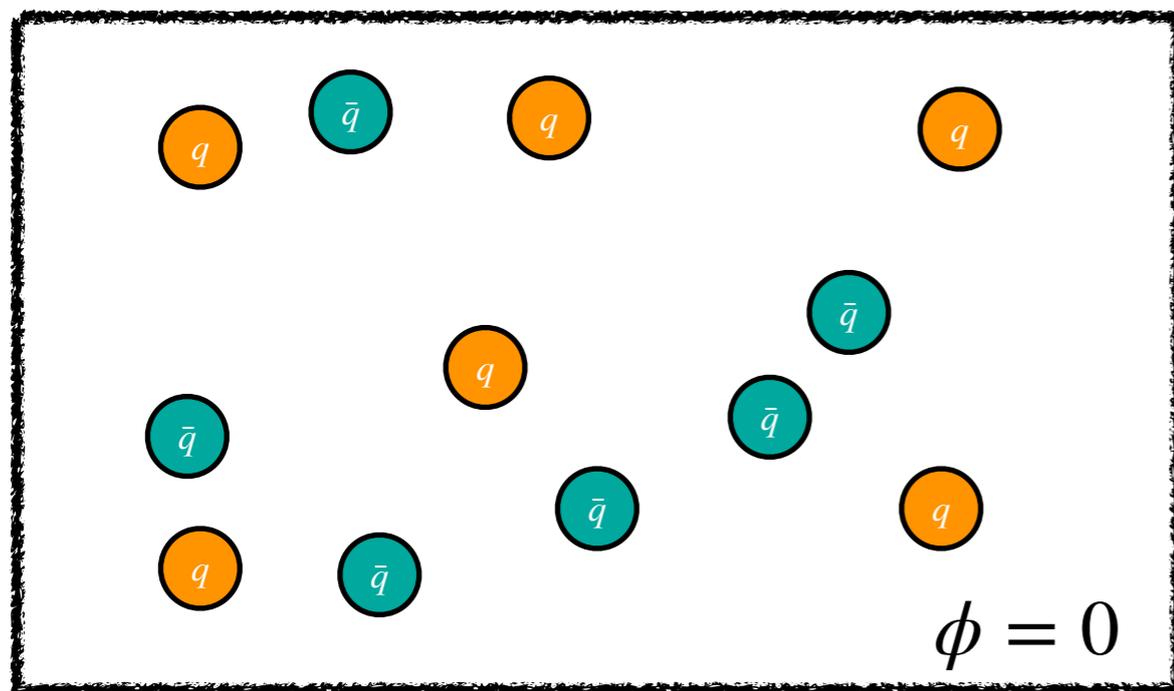


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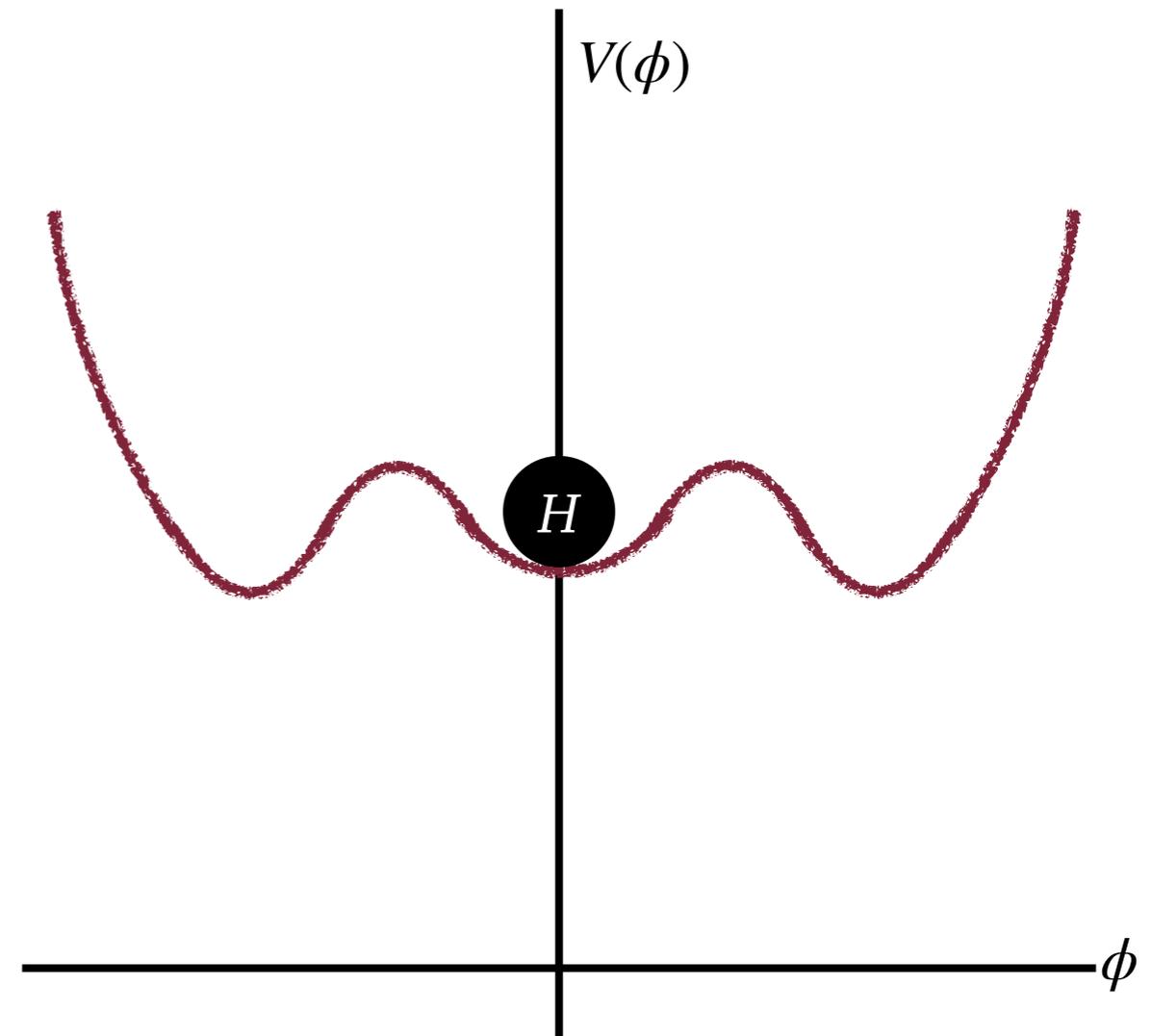
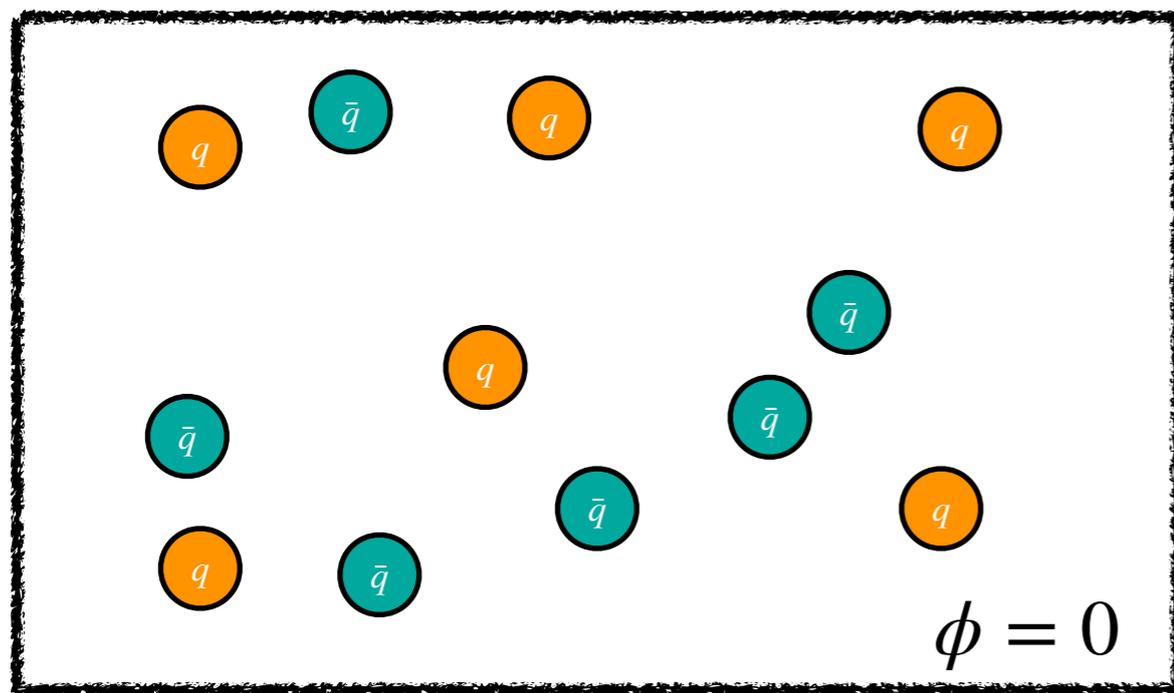
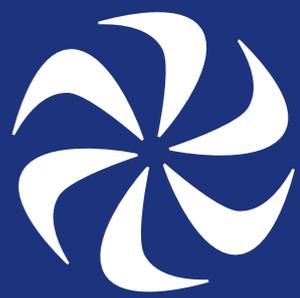
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Electroweak Baryogenesis



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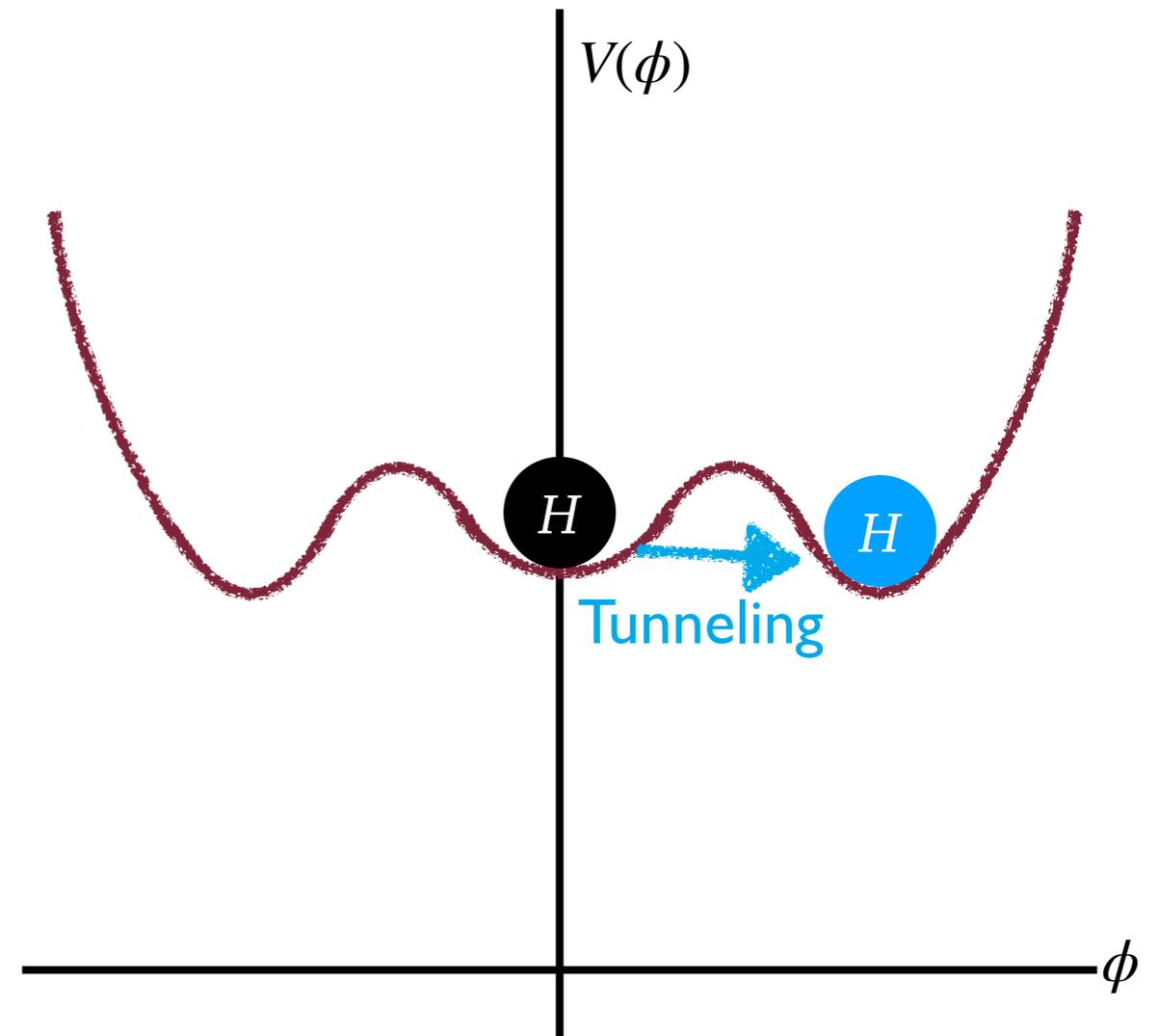
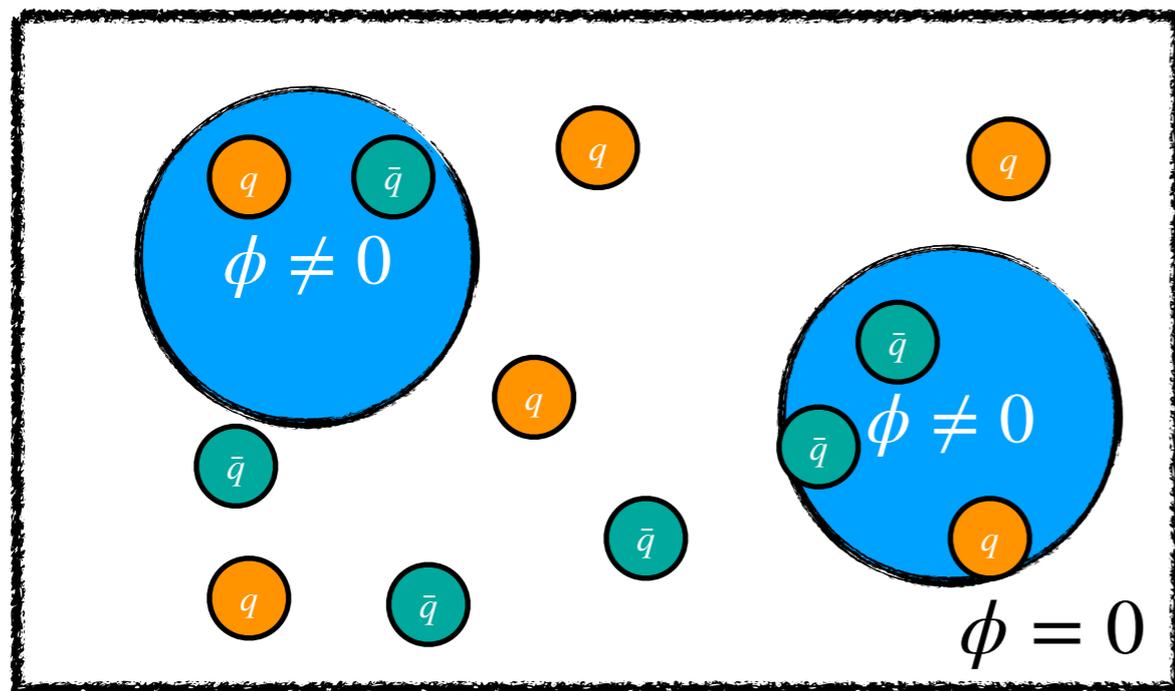
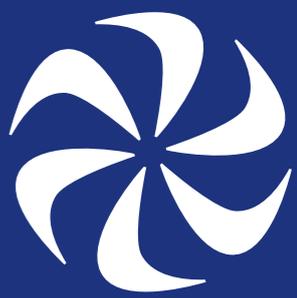
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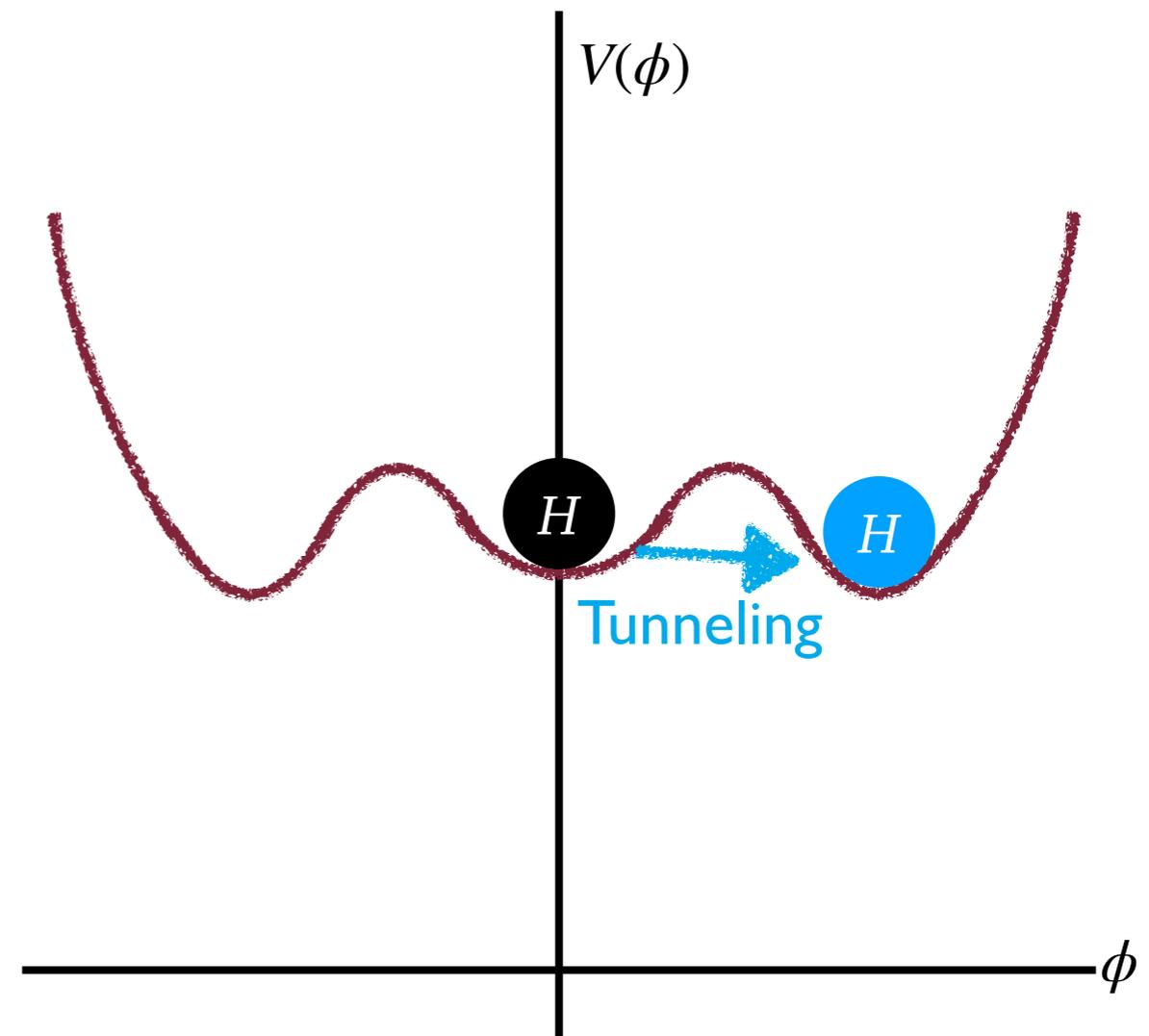
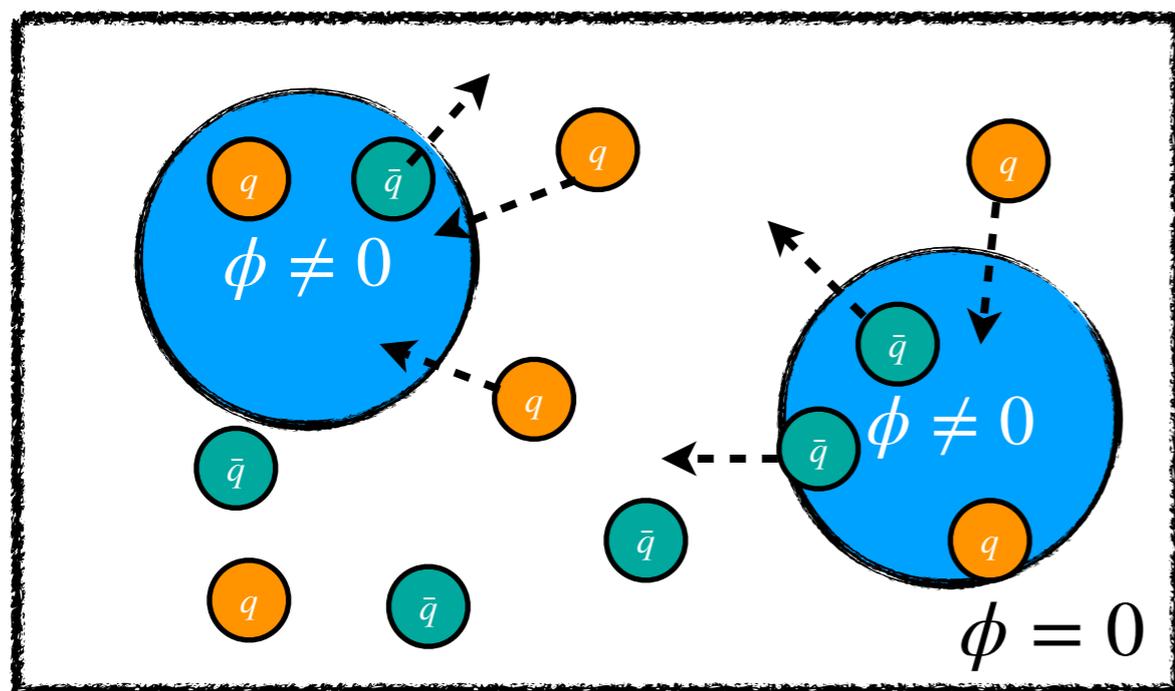
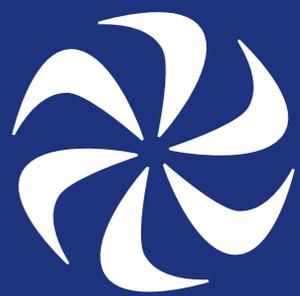
As the universe cools, the potential changes...

Electroweak Baryogenesis



Step I: At T_C , pockets of EWSB form via tunneling

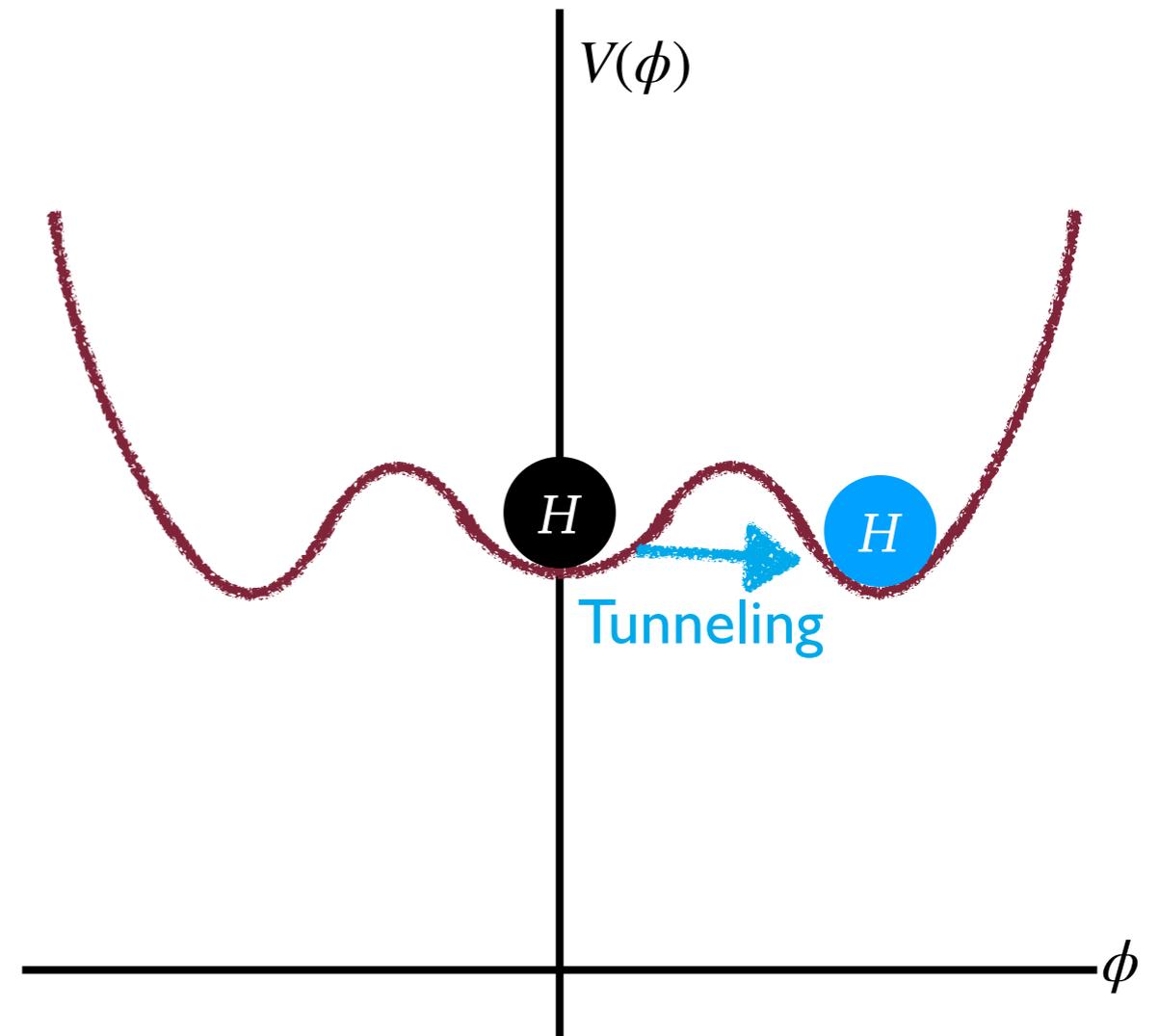
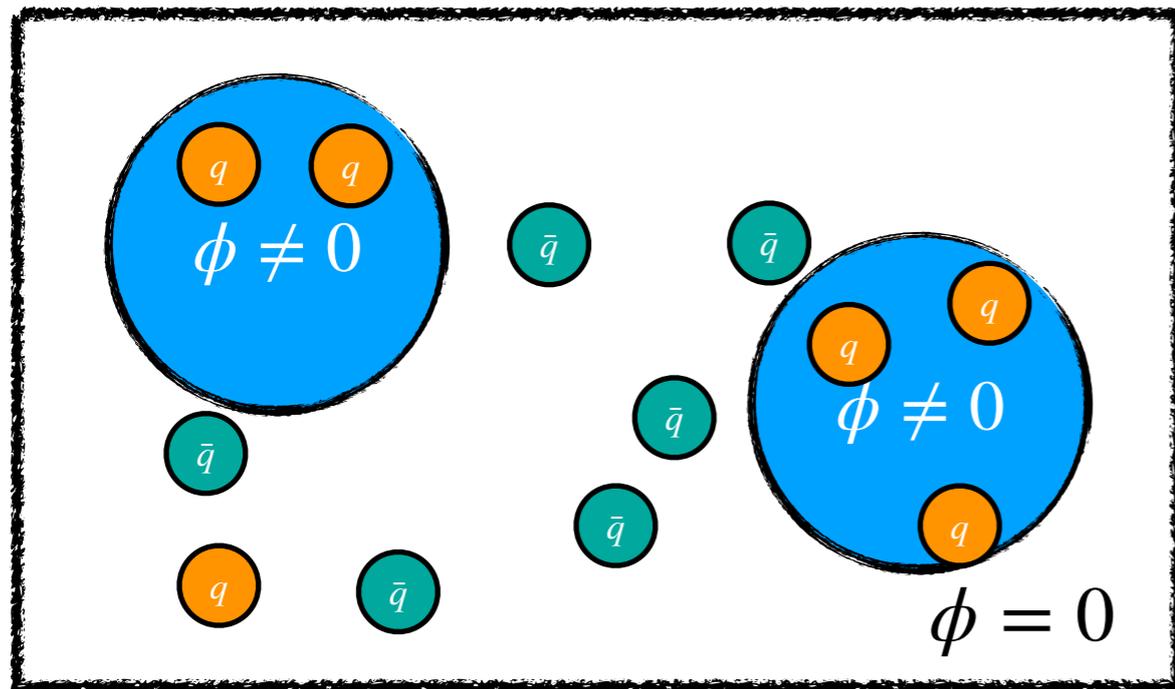
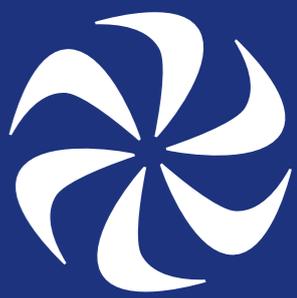
Electroweak Baryogenesis



Step 2: CP Violation (NB: requires BSM) creates baryon flux due to interactions at the boundary

Matter and anti-matter have different transmission/reflection probabilities at the boundary

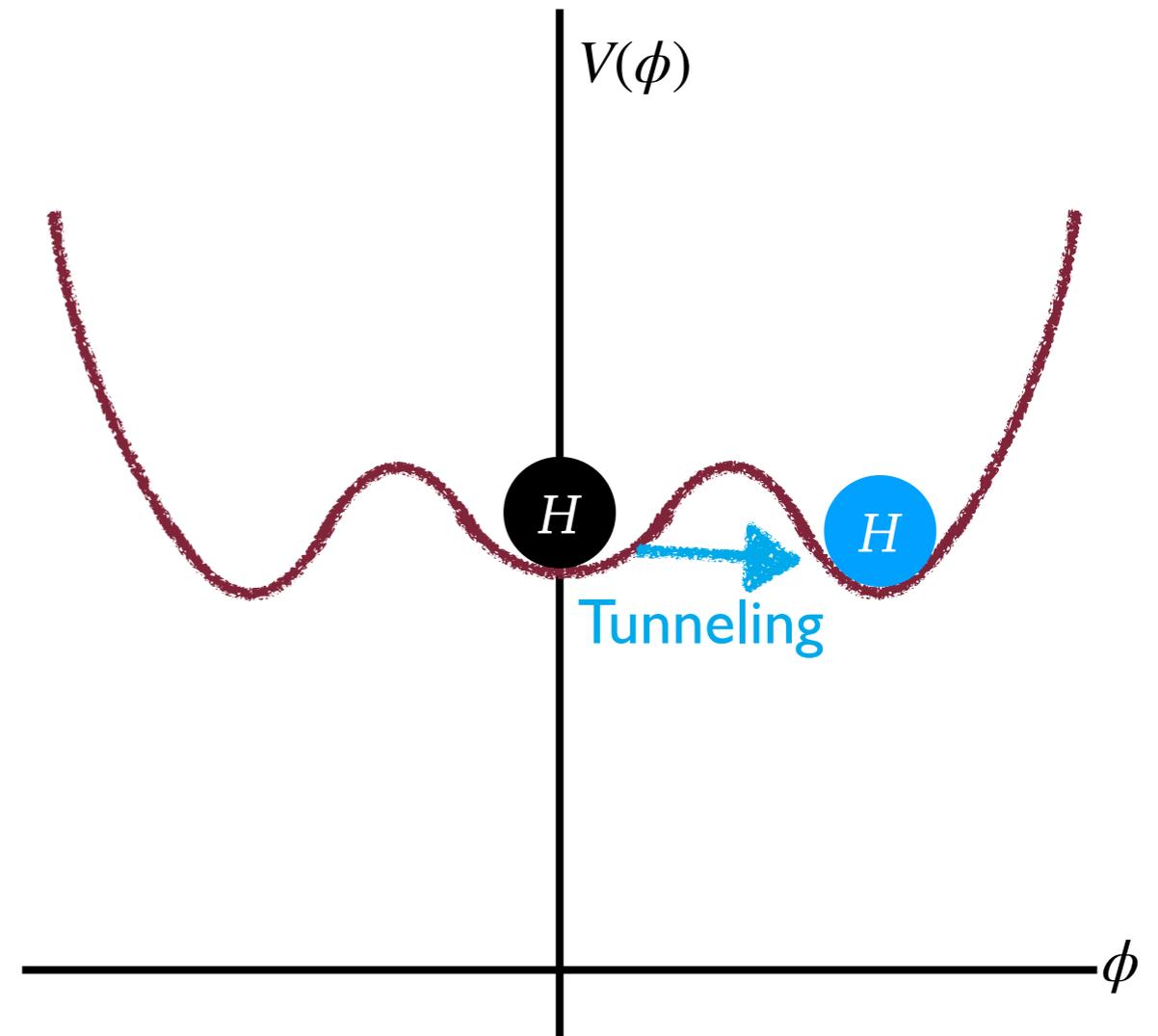
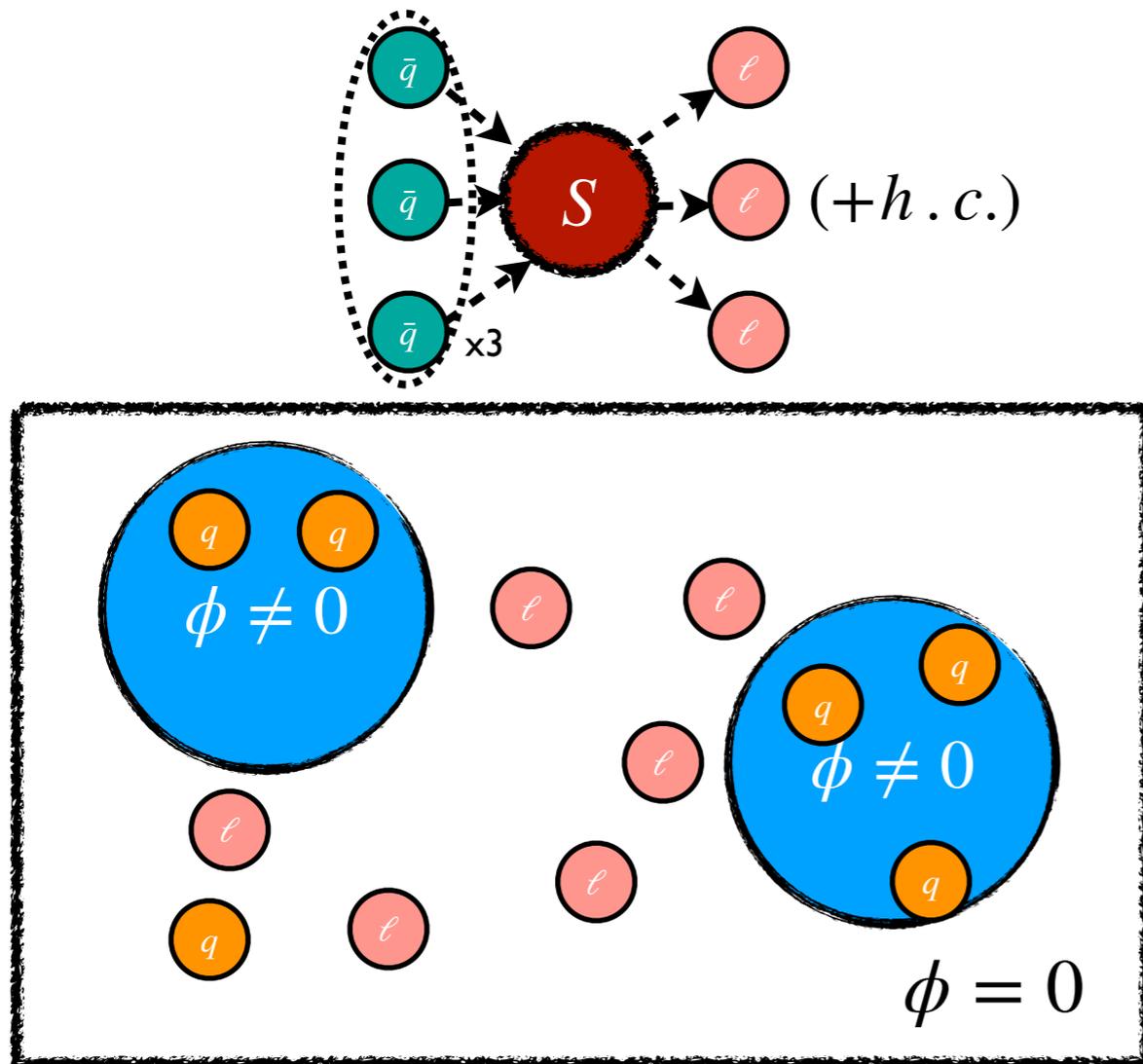
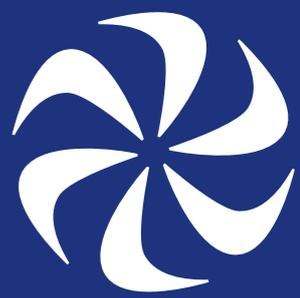
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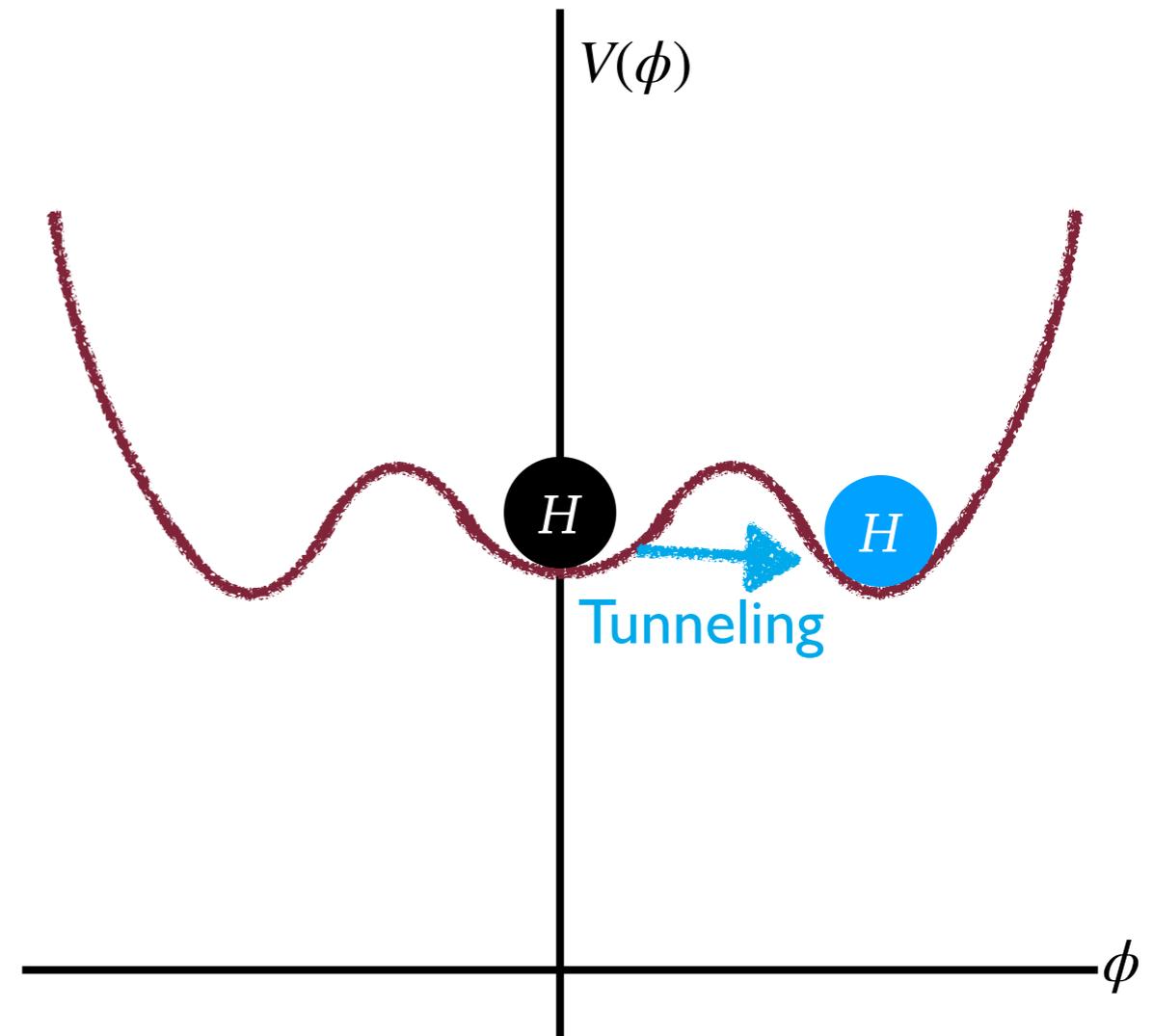
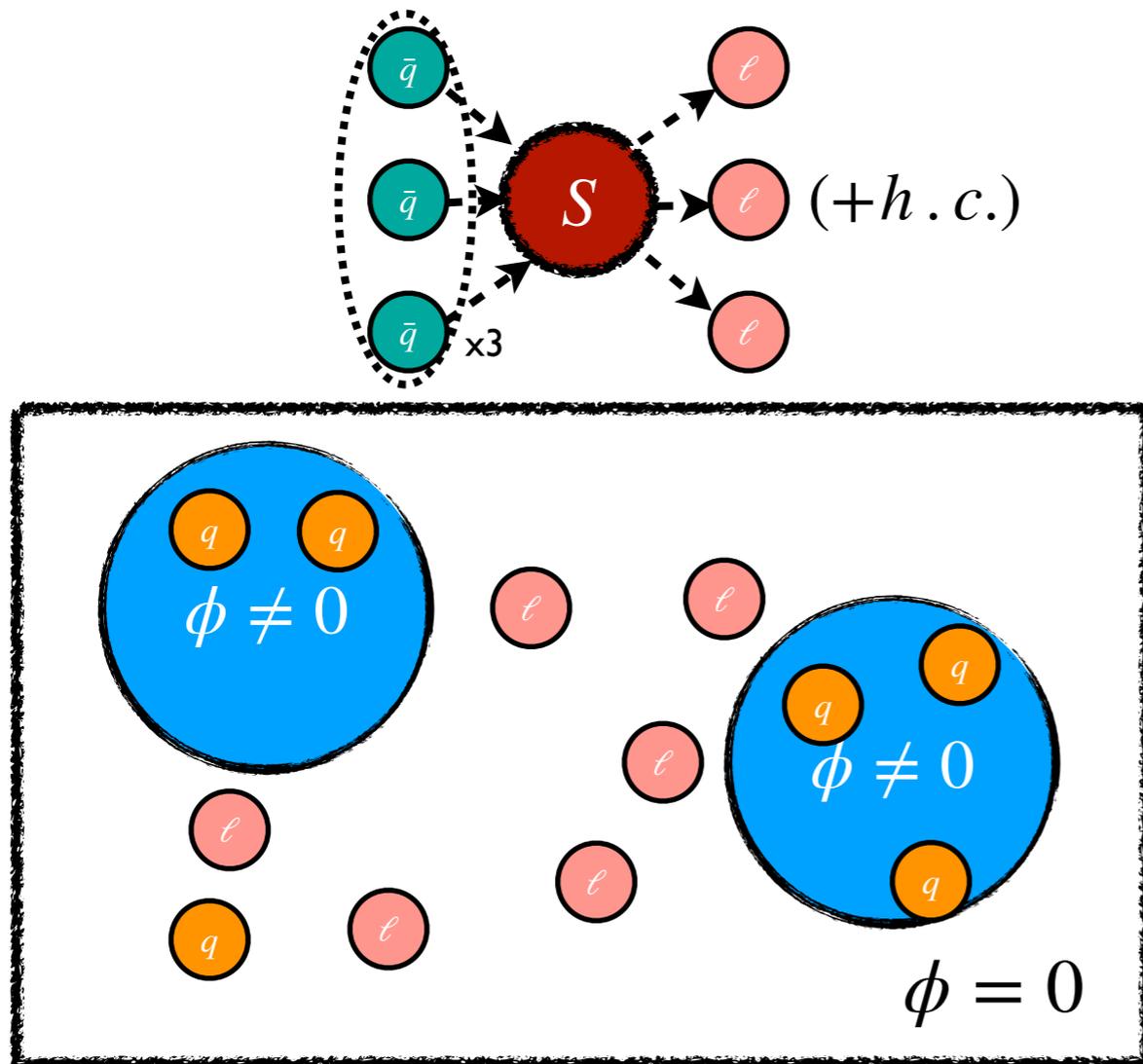
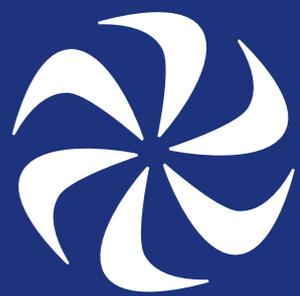
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Electroweak Baryogenesis



Step 3: High-temperature baryon-violating processes (*sphalerons*) at $\phi = 0$ remove anti-baryons

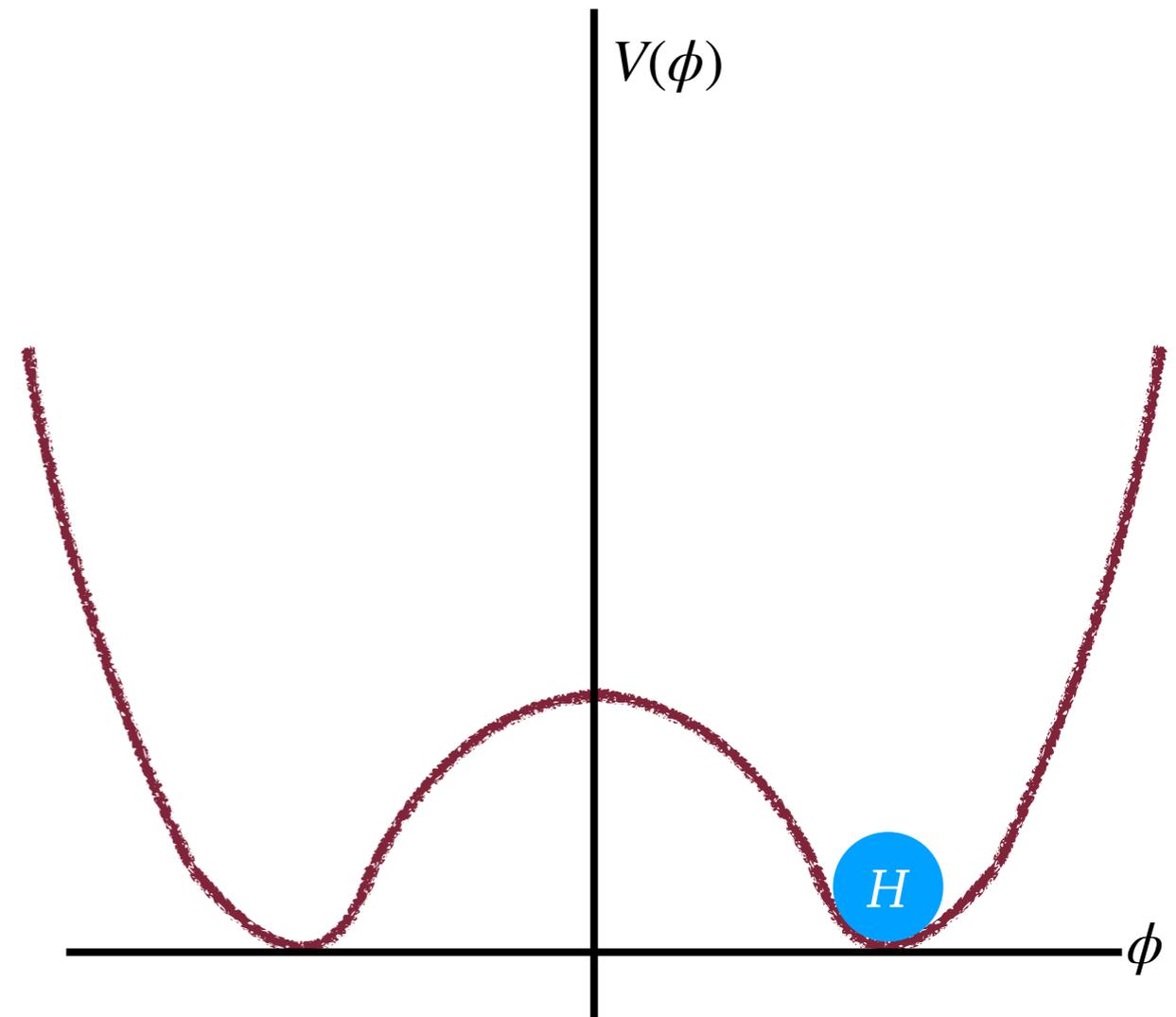
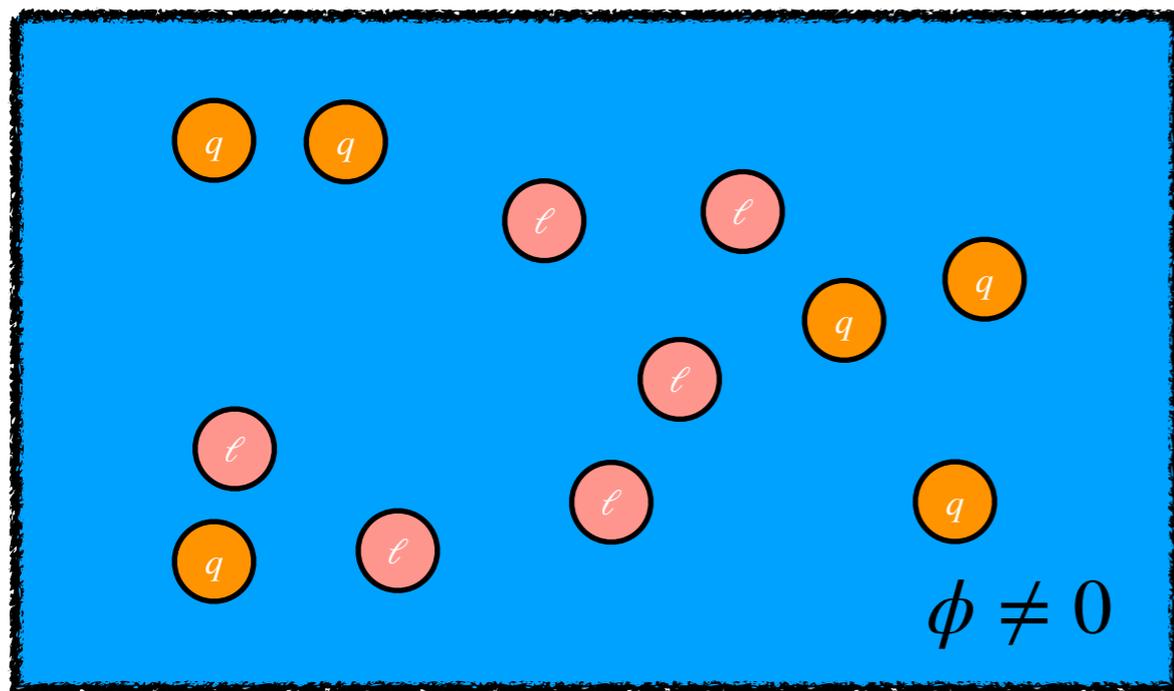
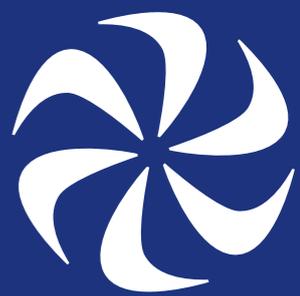
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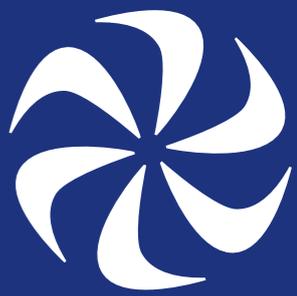
These processes don't occur in the $\phi \neq 0$ state: **electroweak symmetry breaking leads to matter symmetry breaking**

Electroweak Baryogenesis

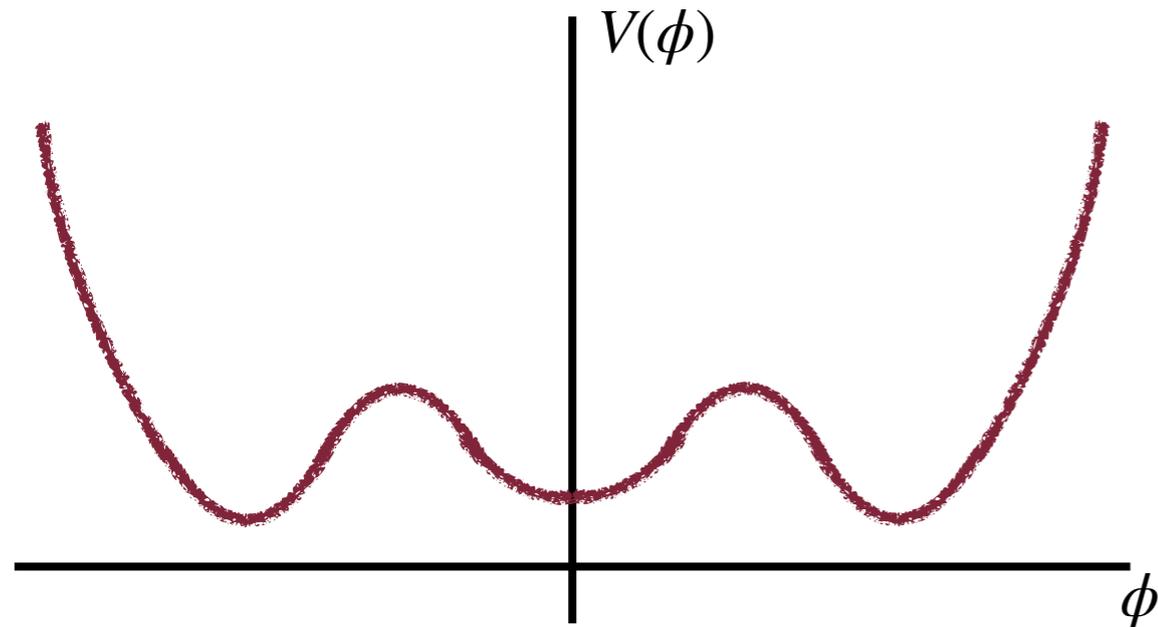
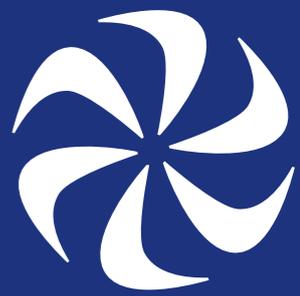


Step 4: Universe continues to cool to fully broken symmetry, but anti-baryons have been removed

The Higgs Potential and EWSBG

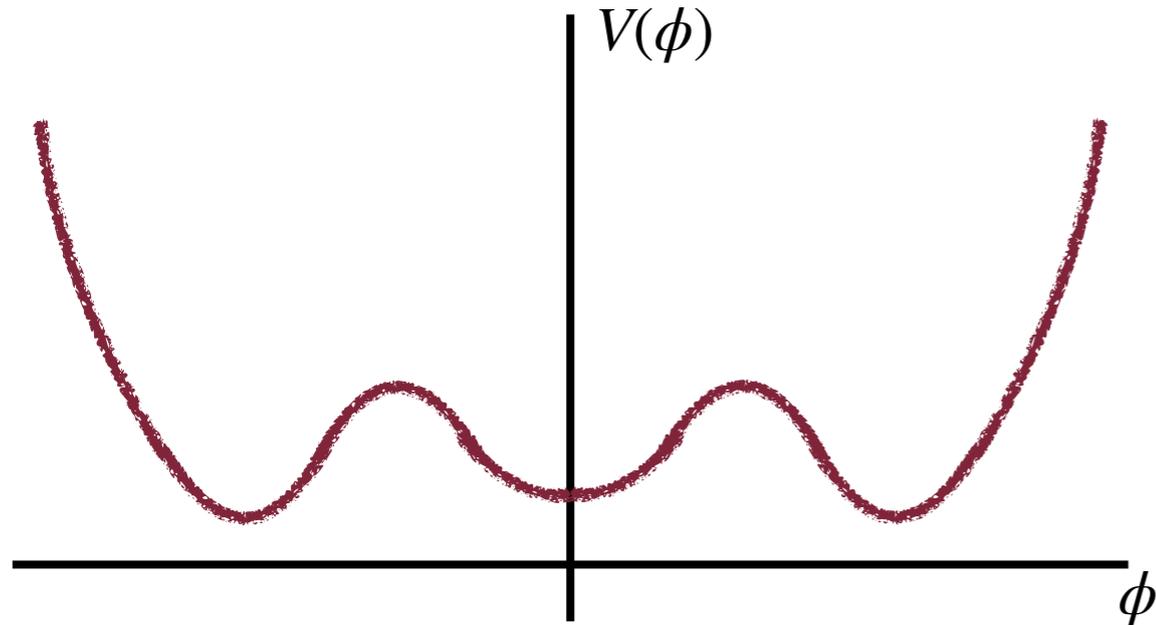


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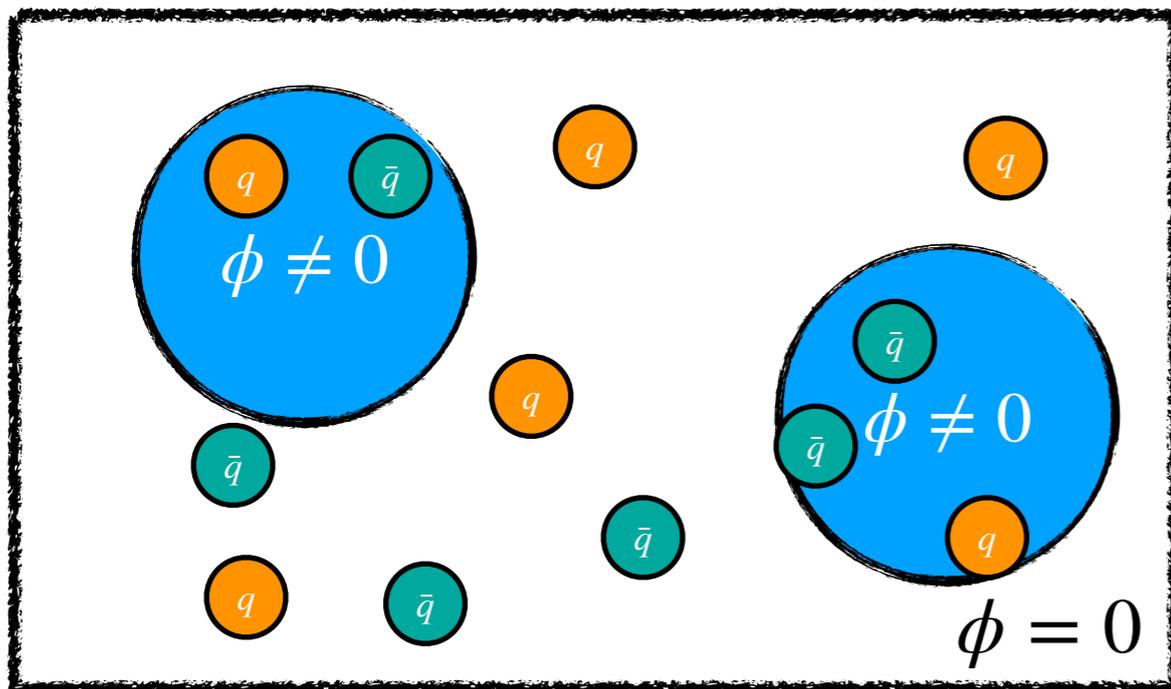
The shape of the Higgs potential at T_C is critical: needs to be a first-order phase transition

The Higgs Potential and EWBG

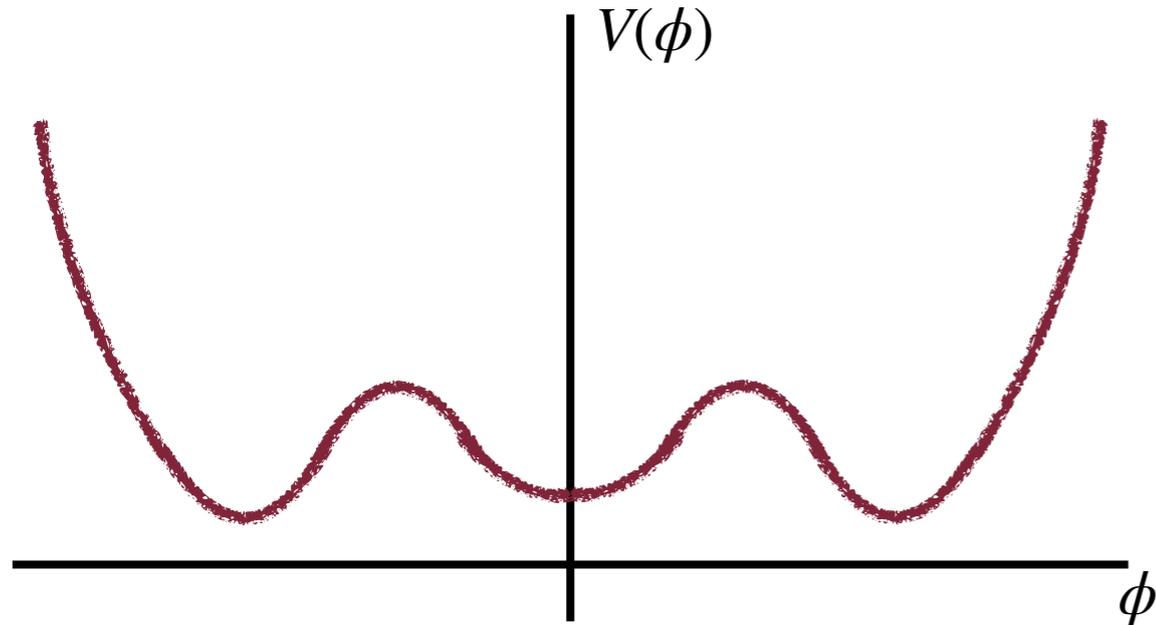
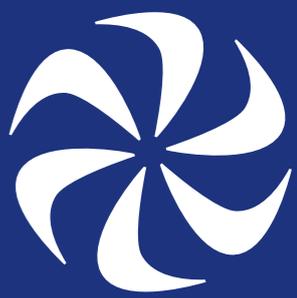


The shape of the Higgs potential at T_C is critical: needs to be a first-order phase transition

Can't smoothly crossover the whole universe at once: need 'bubbles' of broken symmetry

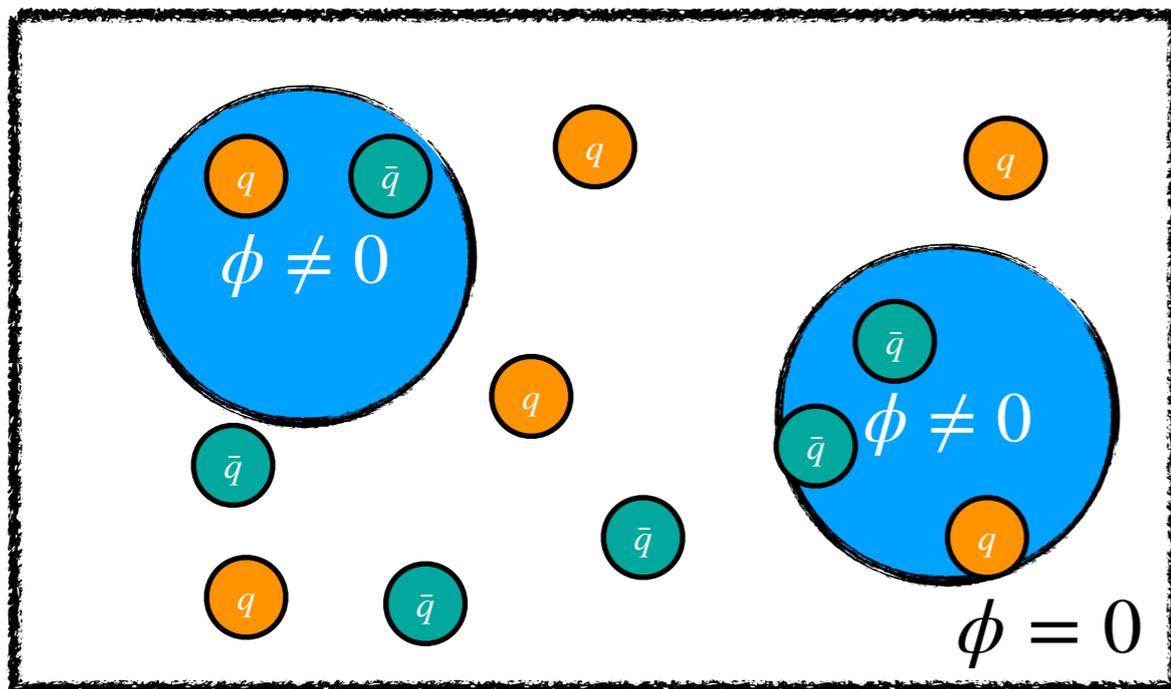


The Higgs Potential and EWBG



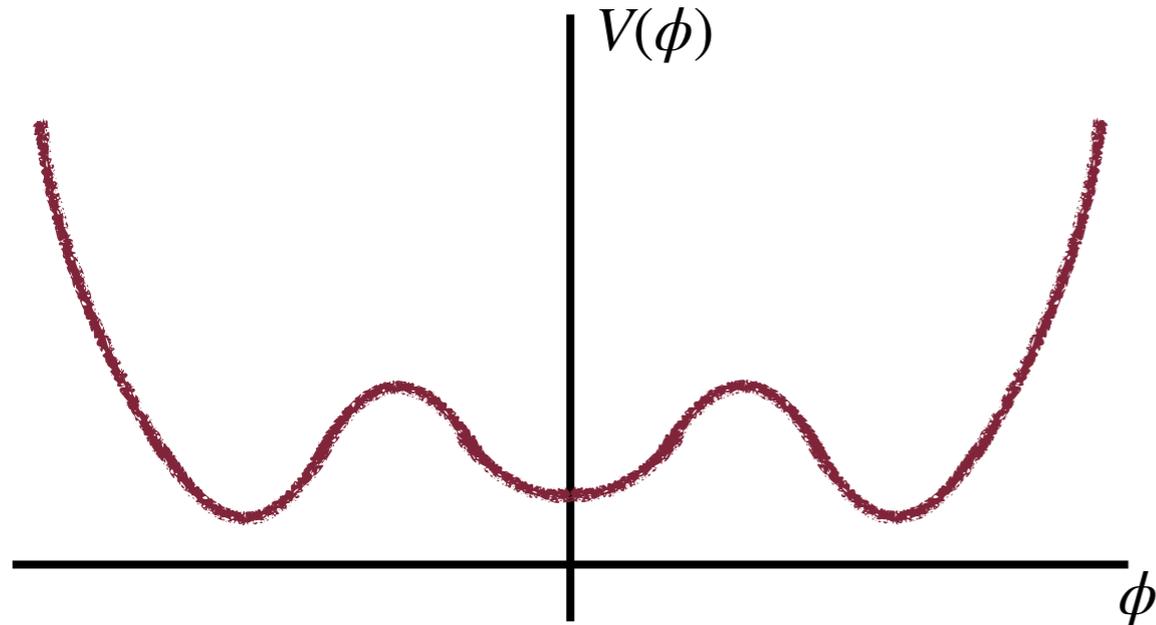
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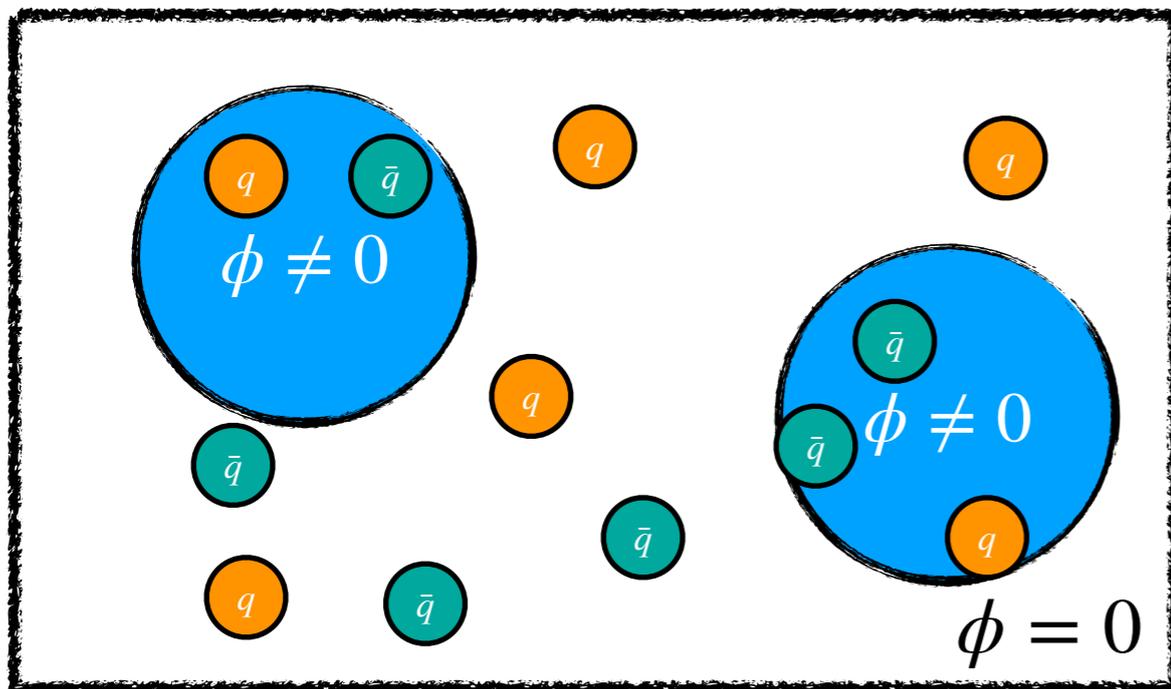
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 κ_λ could be between 1.2 and 6
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And we could see this at the LHC with di-Higgs!

End very technical warning

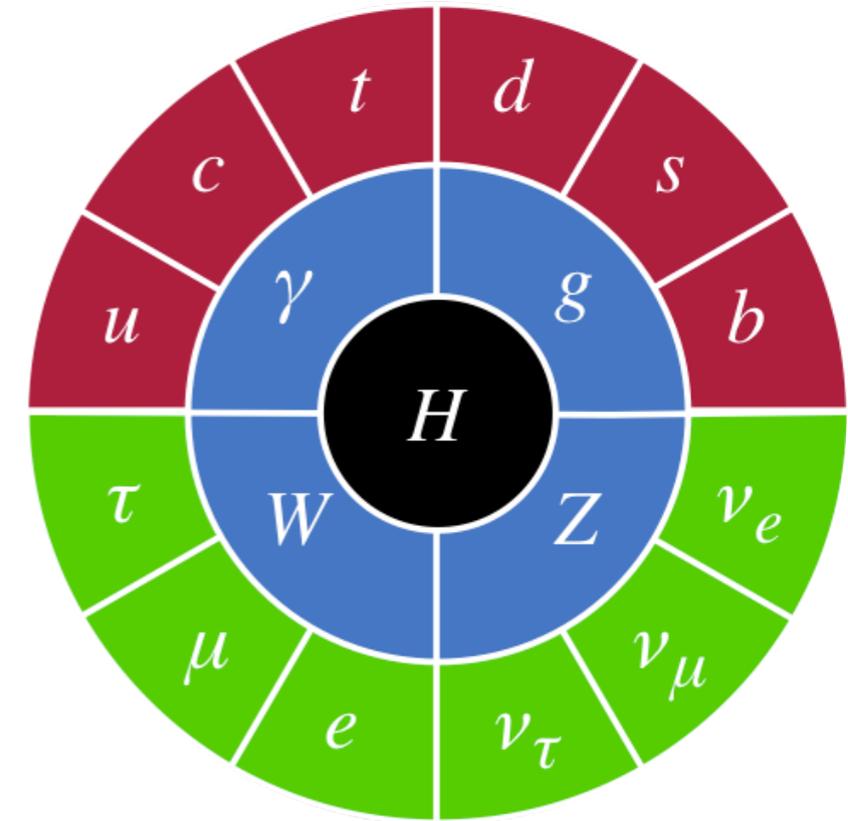
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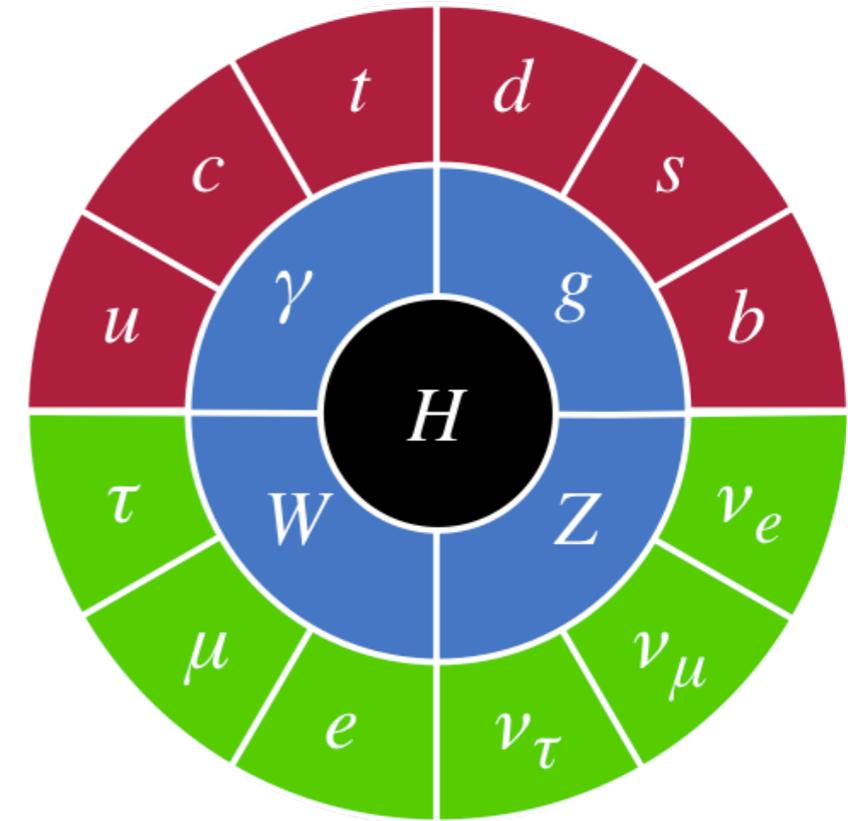
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The earliest moments of the universe are determined by the Higgs potential and its shape!

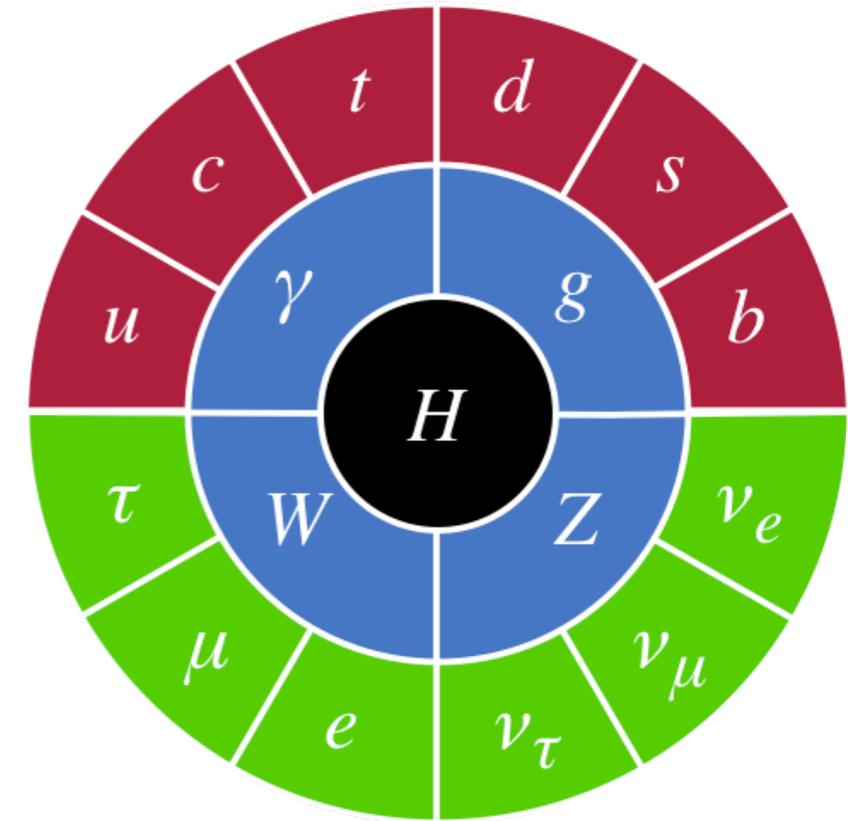
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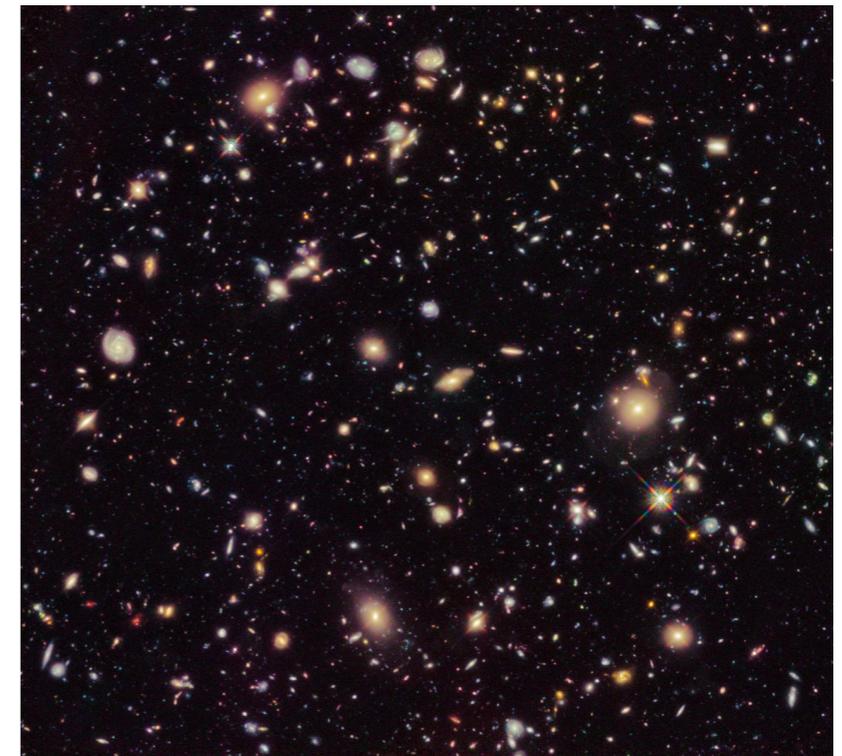
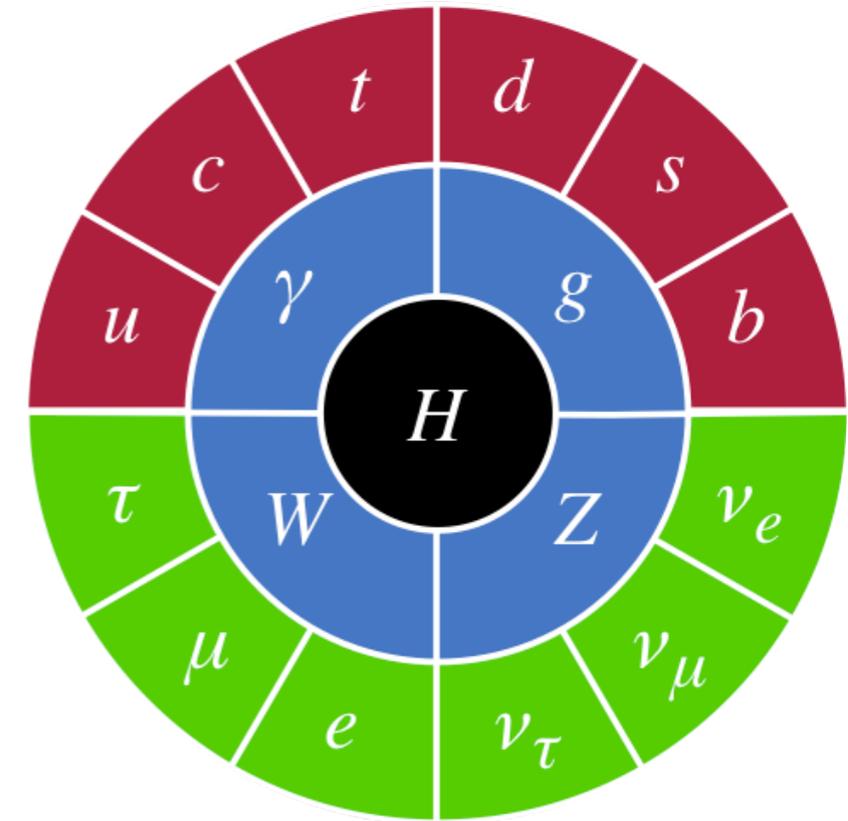


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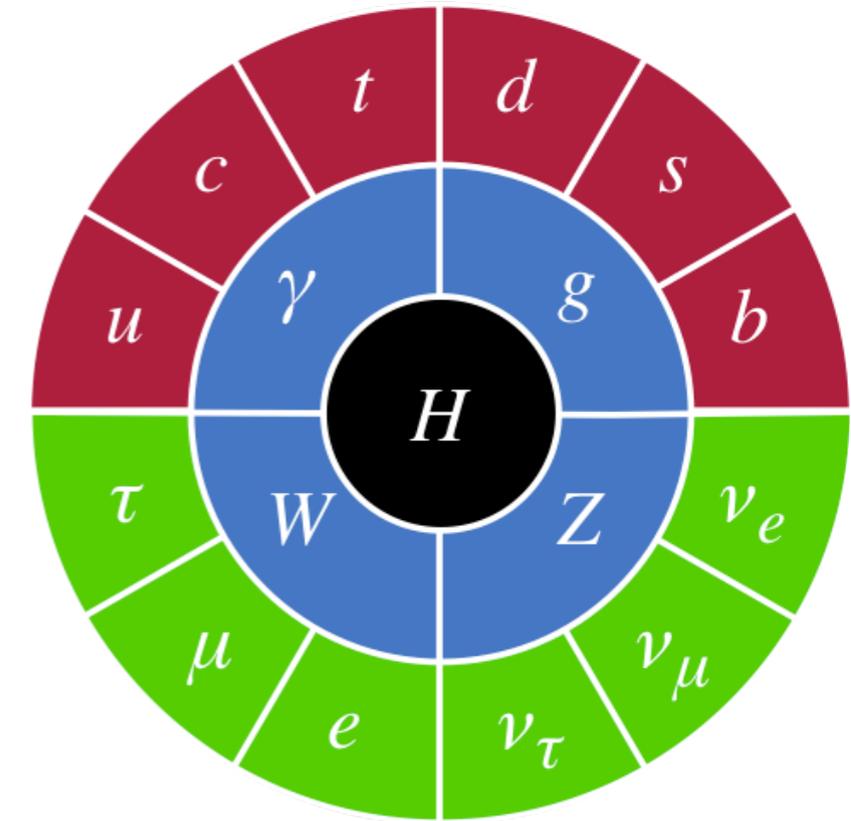


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The SM leaves huge questions:

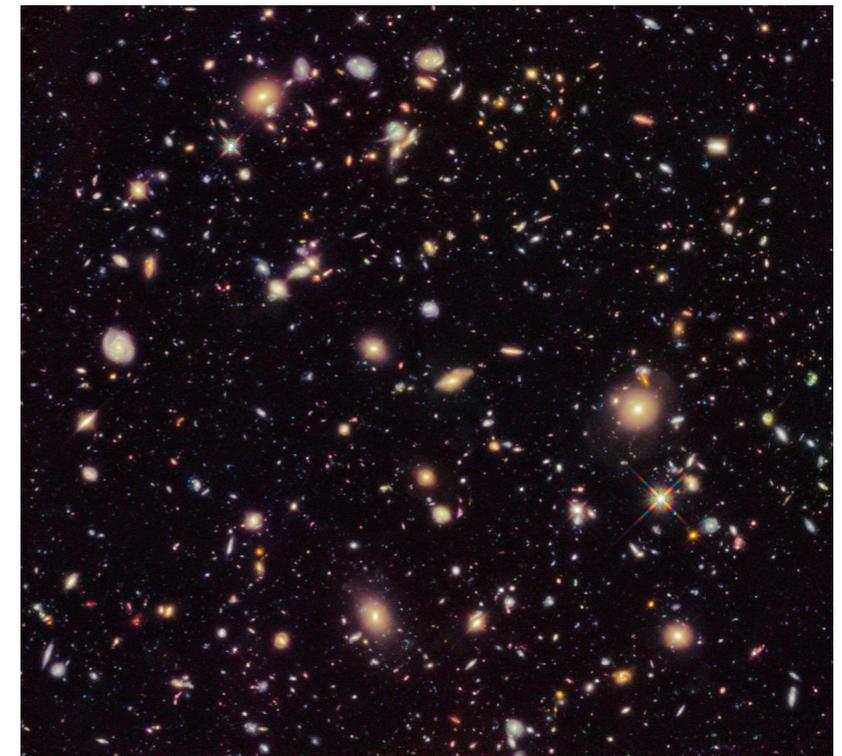


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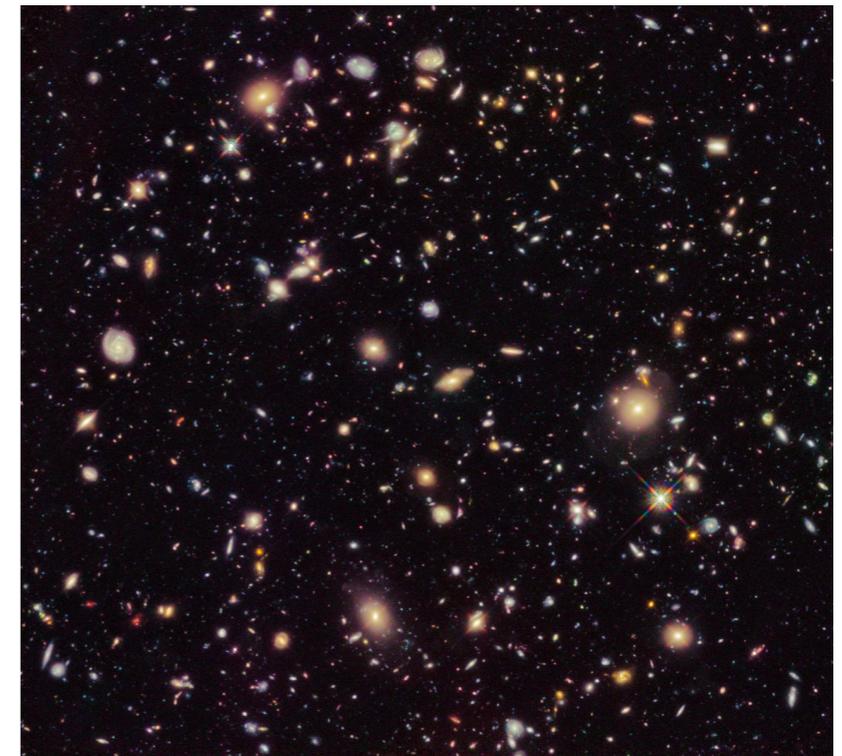
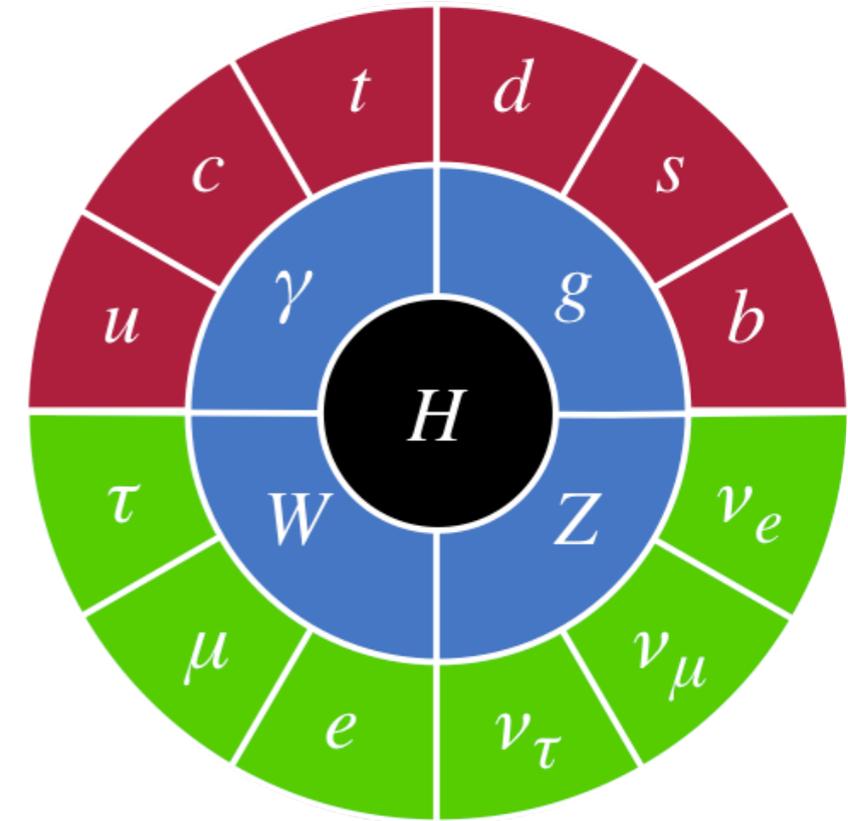
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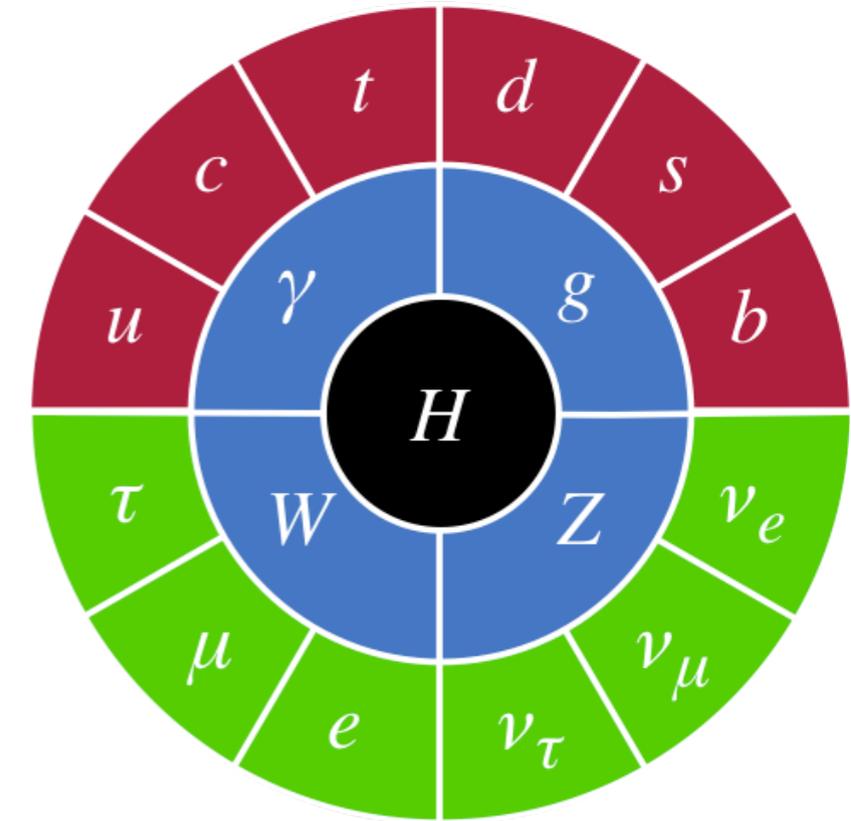
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Where's the missing anti-matter?



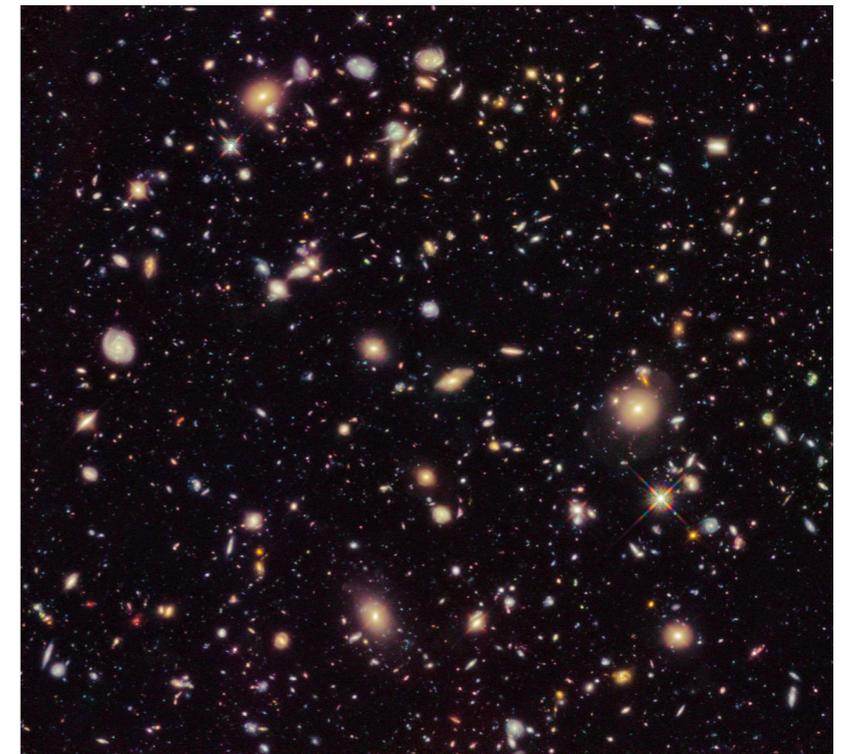
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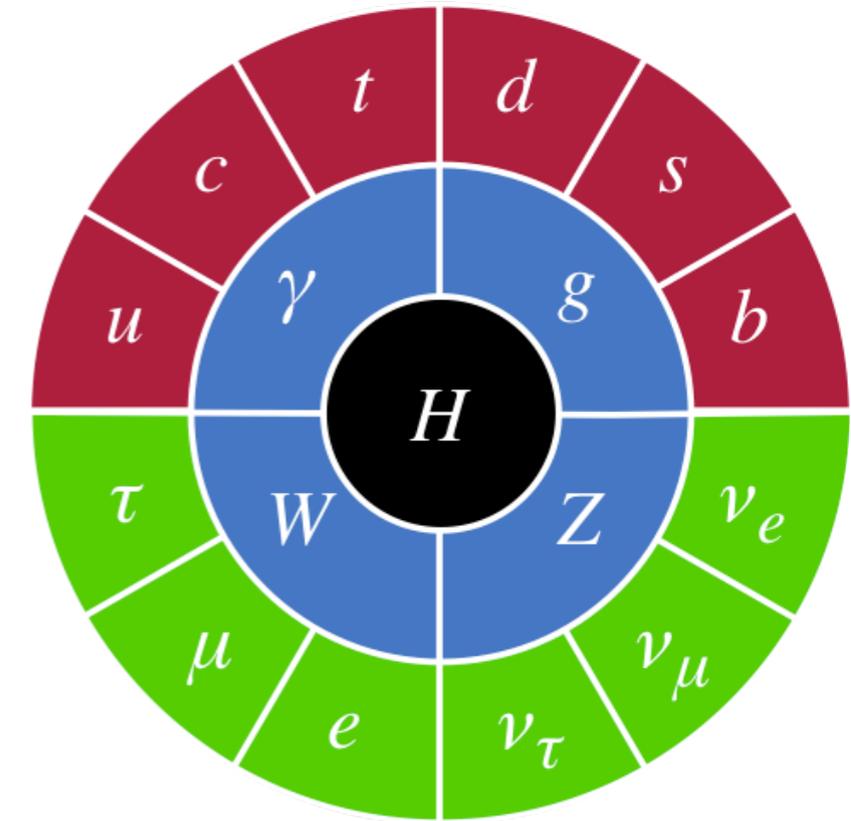
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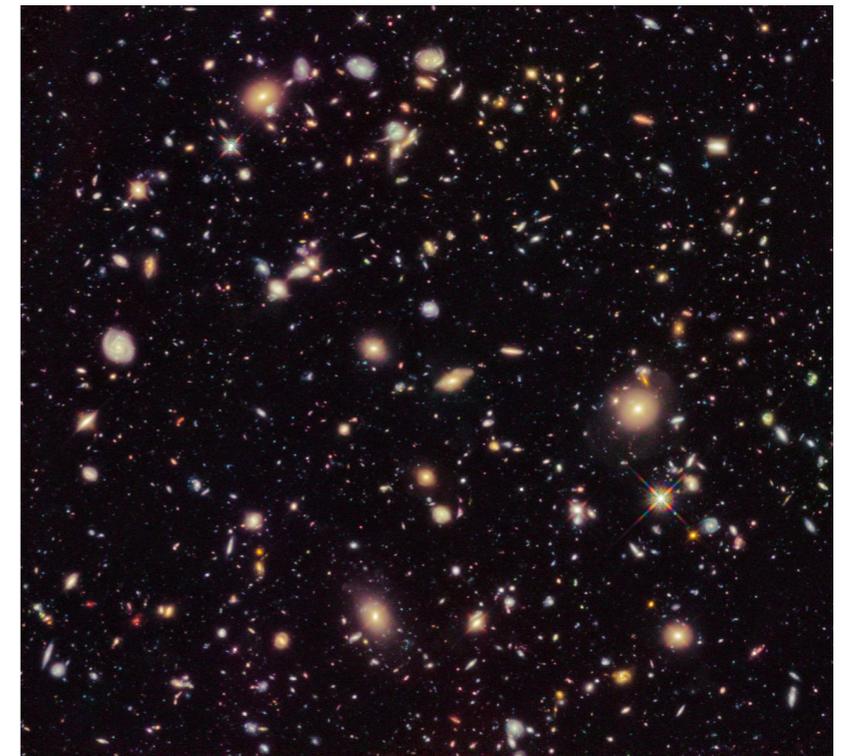
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**Higgs pairs are the next frontier to understanding
the Standard Model and Beyond**