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

Collider Physics in the Northwest

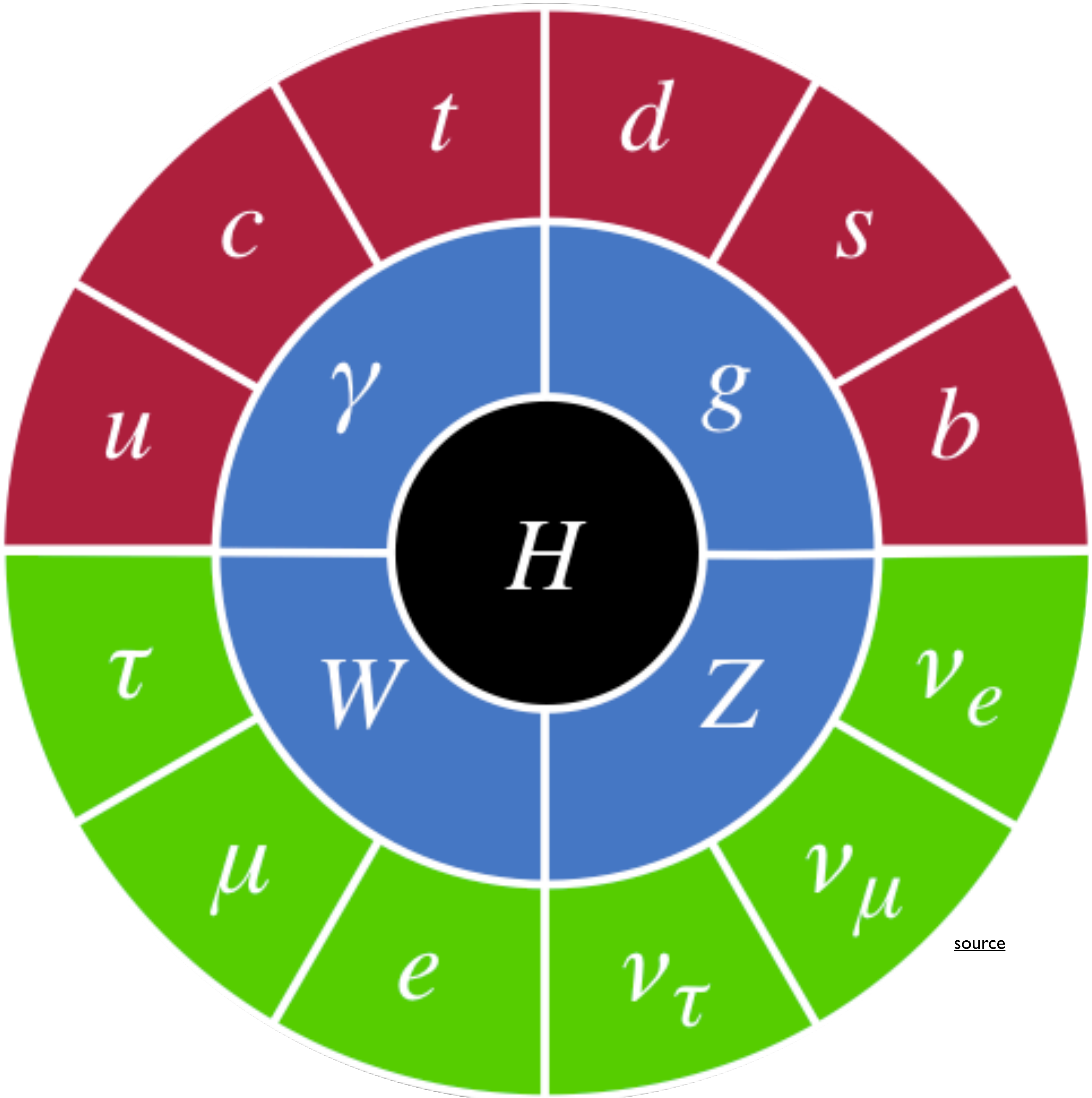
Maximilian Swiatlowski

TRIUMF

ATLAS EXPERIMENT

The Higgs Potential and Higgs Pairs

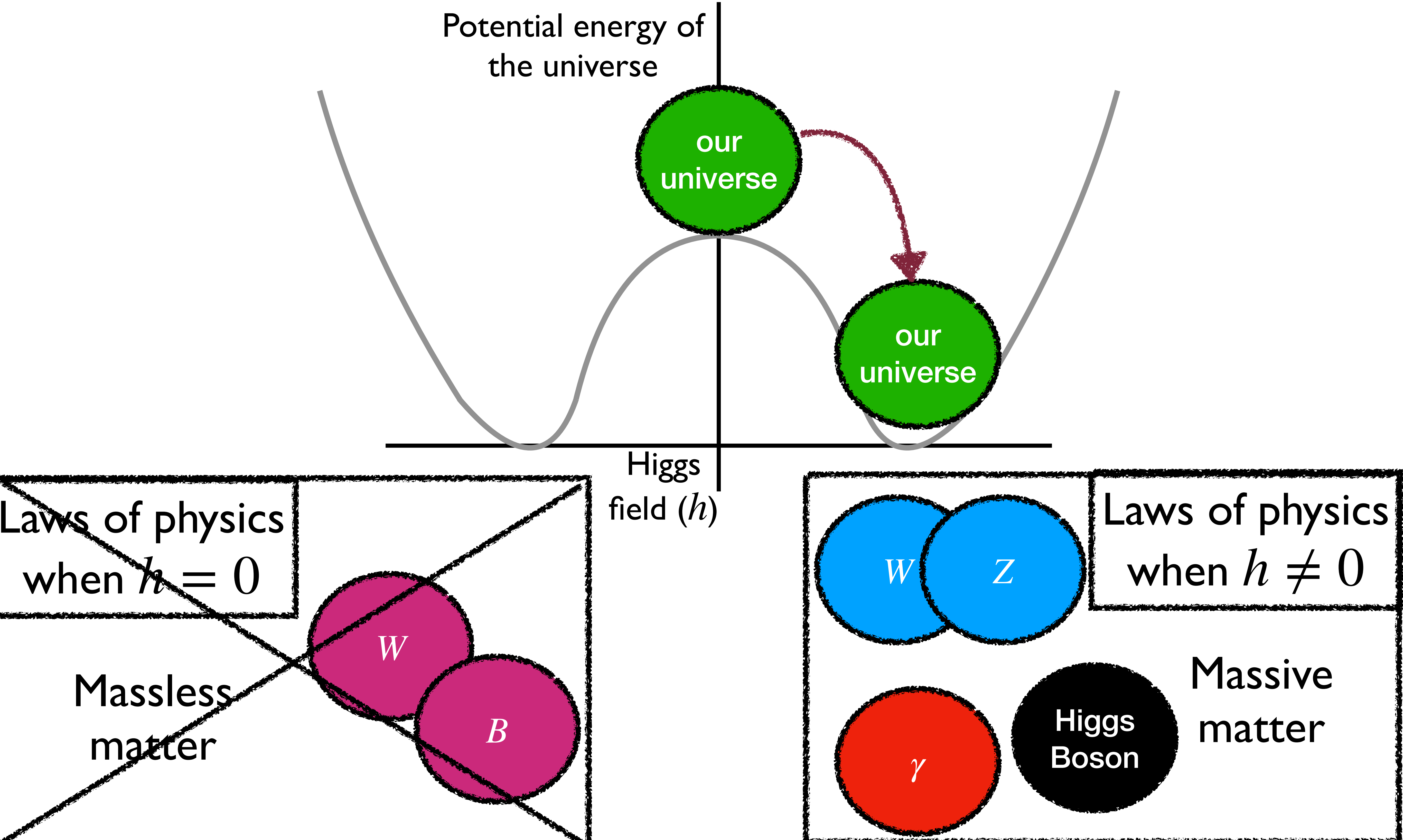
The Higgs in the SM

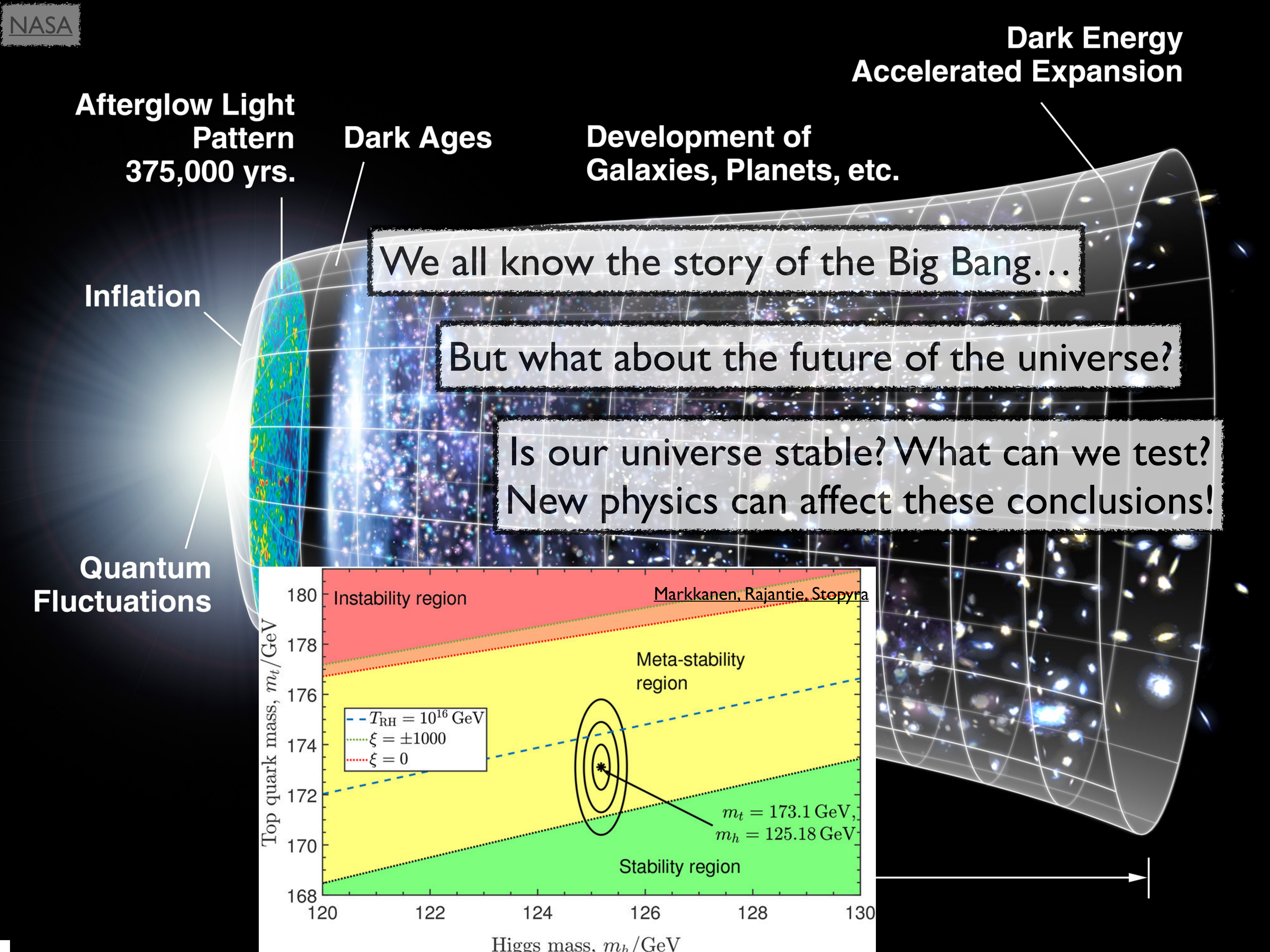


source

- The Higgs field is crucial to the SM as we know it
- Gives masses to the fermions
- Electroweak symmetry breaking gives masses to W/Z, splits off γ
- All rises from the unique shape of the Higgs potential

The BEH Mechanism





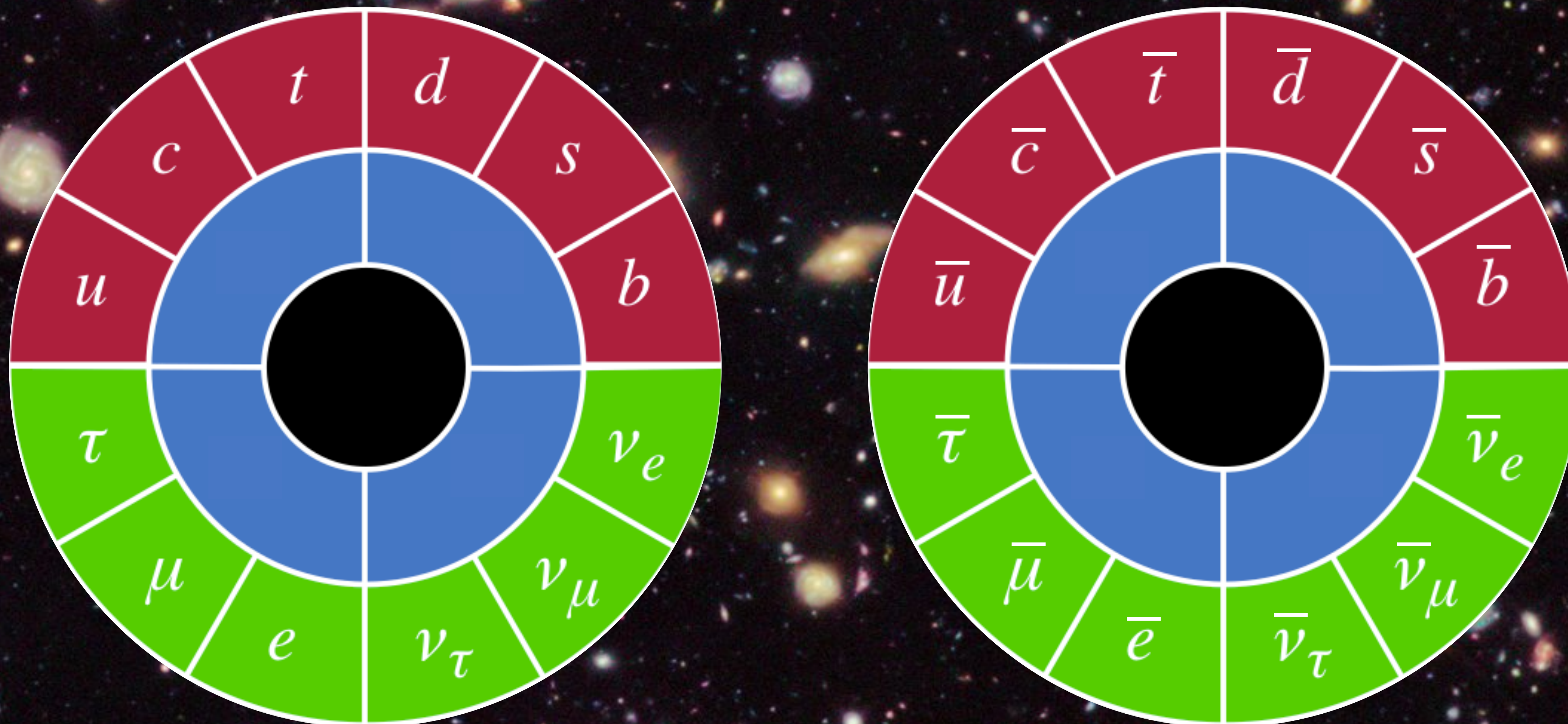
We all know the story of the Big Bang…

But what about the future of the universe?

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

NASA/ESA

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



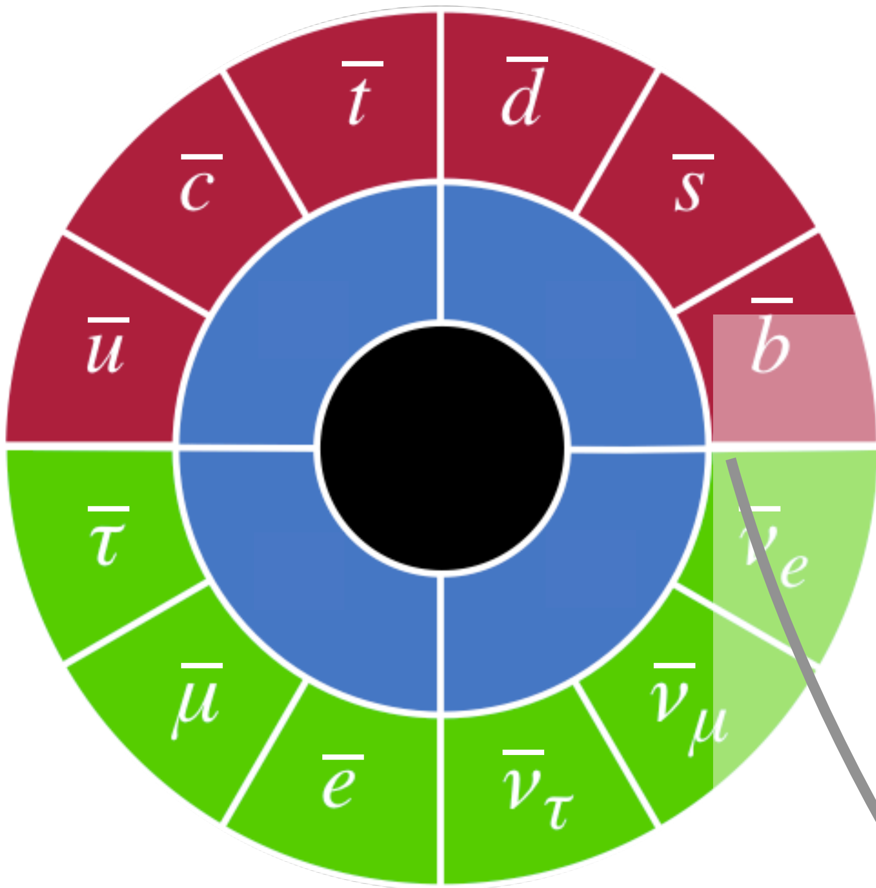
Everything we see is **matter**

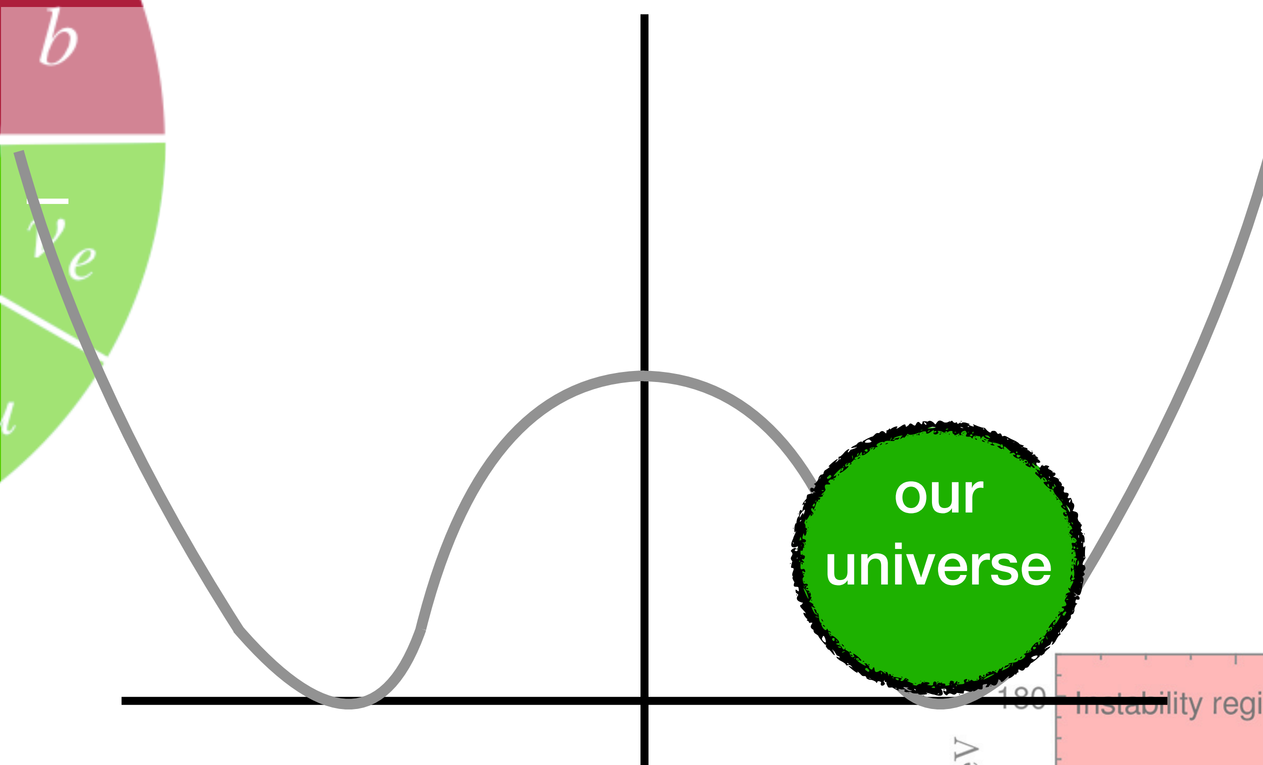
Where is the **anti-matter**?

The Big Bang should have produced them equally!

The SM cannot explain anti-matter's disappearance

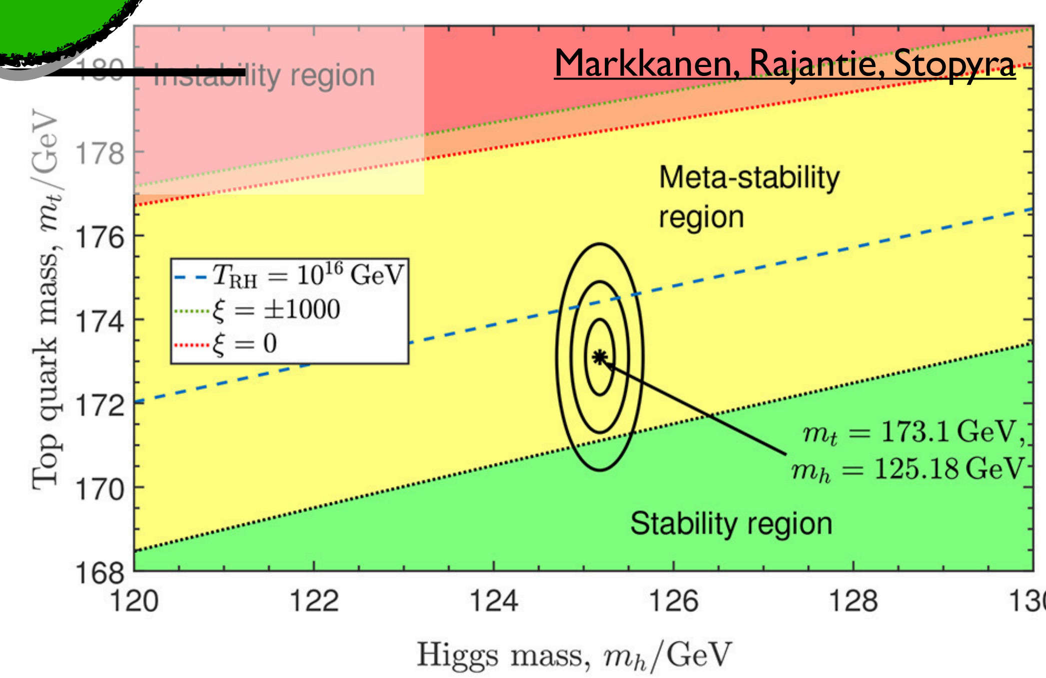
Understanding the Higgs Potential





The Higgs potential plays a central role in the SM

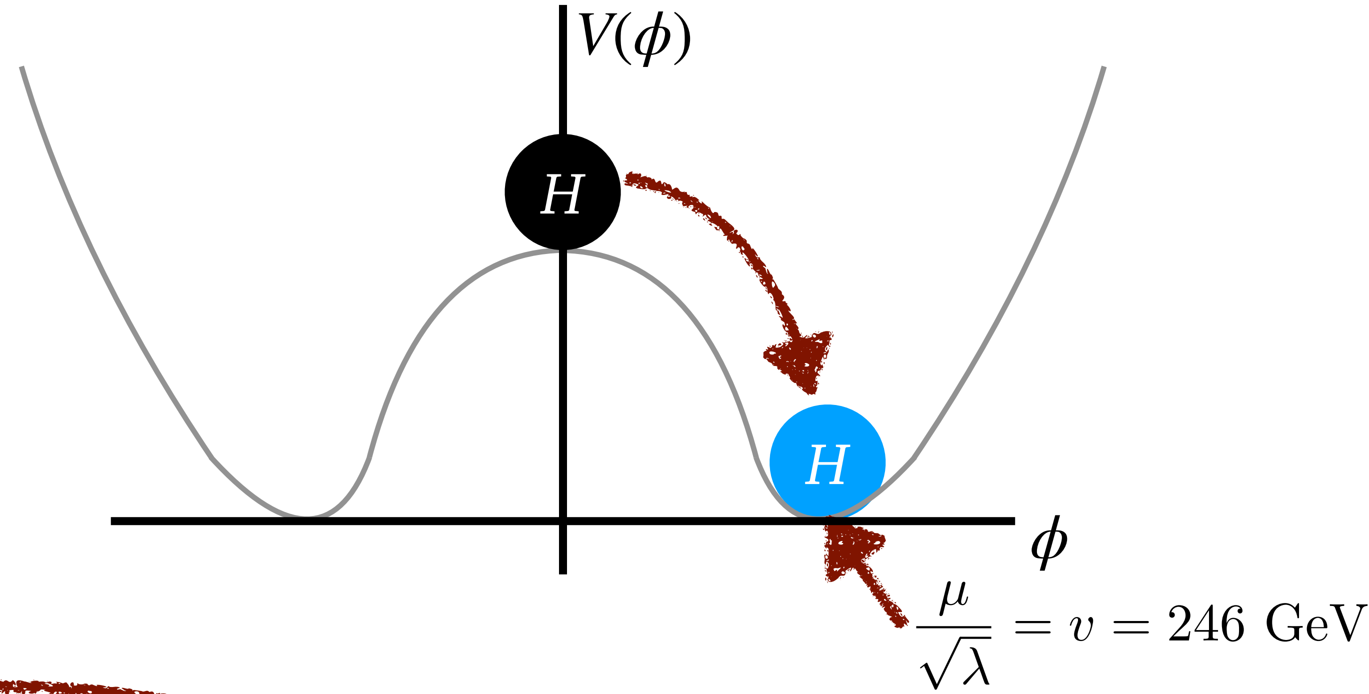
Can it interact with new physics to explain some of our most pressing new questions?



Potential and Pairs

The SM Higgs potential is:

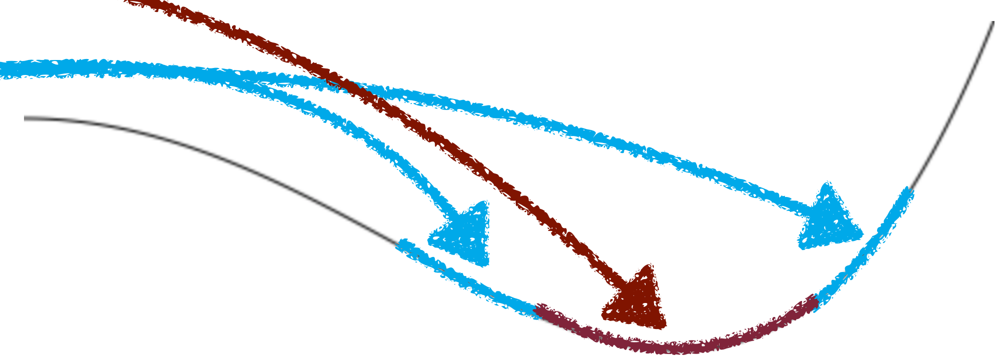
$$V(\phi) = -\mu^2\phi^2 + \lambda\phi^4$$



Our universe lives in the minimum:

$$V = V_0 + \lambda v^2 h^2 + \lambda v h^3 + \ldots$$

$$= V_0 + \frac{1}{2} m_H^2 h^2 + \frac{m_h^2}{2v^2} v h^3 + \ldots$$

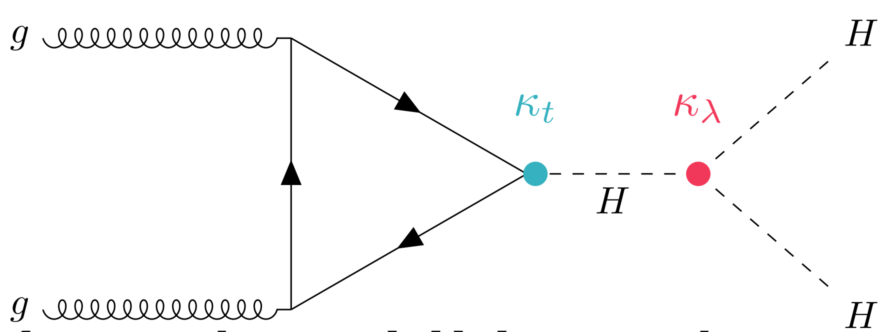


Mass term

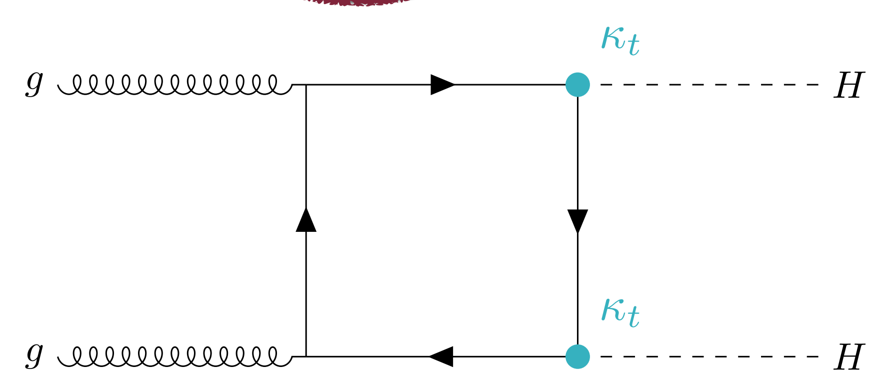
Self-interaction

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

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

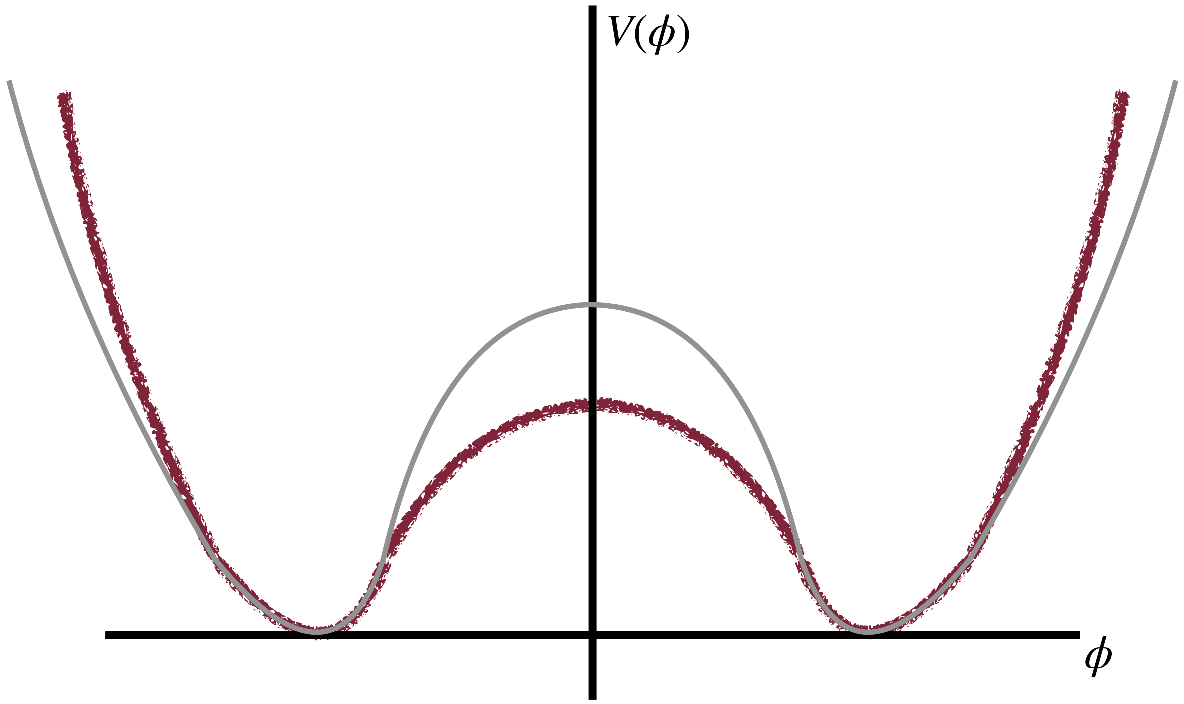


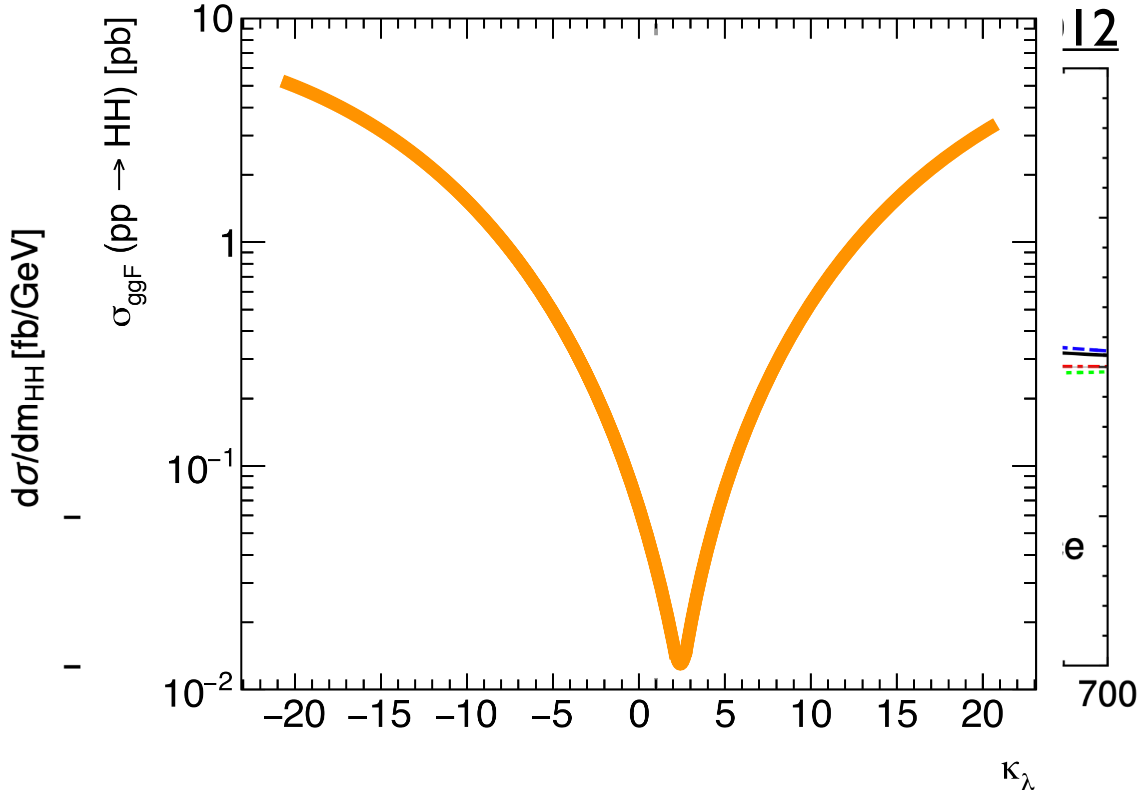
SM predicts HH production, and allows to measure potential



But interference means x-sec is very low

Potential Higgs Potentials





We have a prediction for the shape from the SM…

But other shapes of the potential still allow for Electroweak Symmetry Breaking

Other shapes could reveal evidence for *Electroweak Baryogenesis*, or hints to vacuum stability

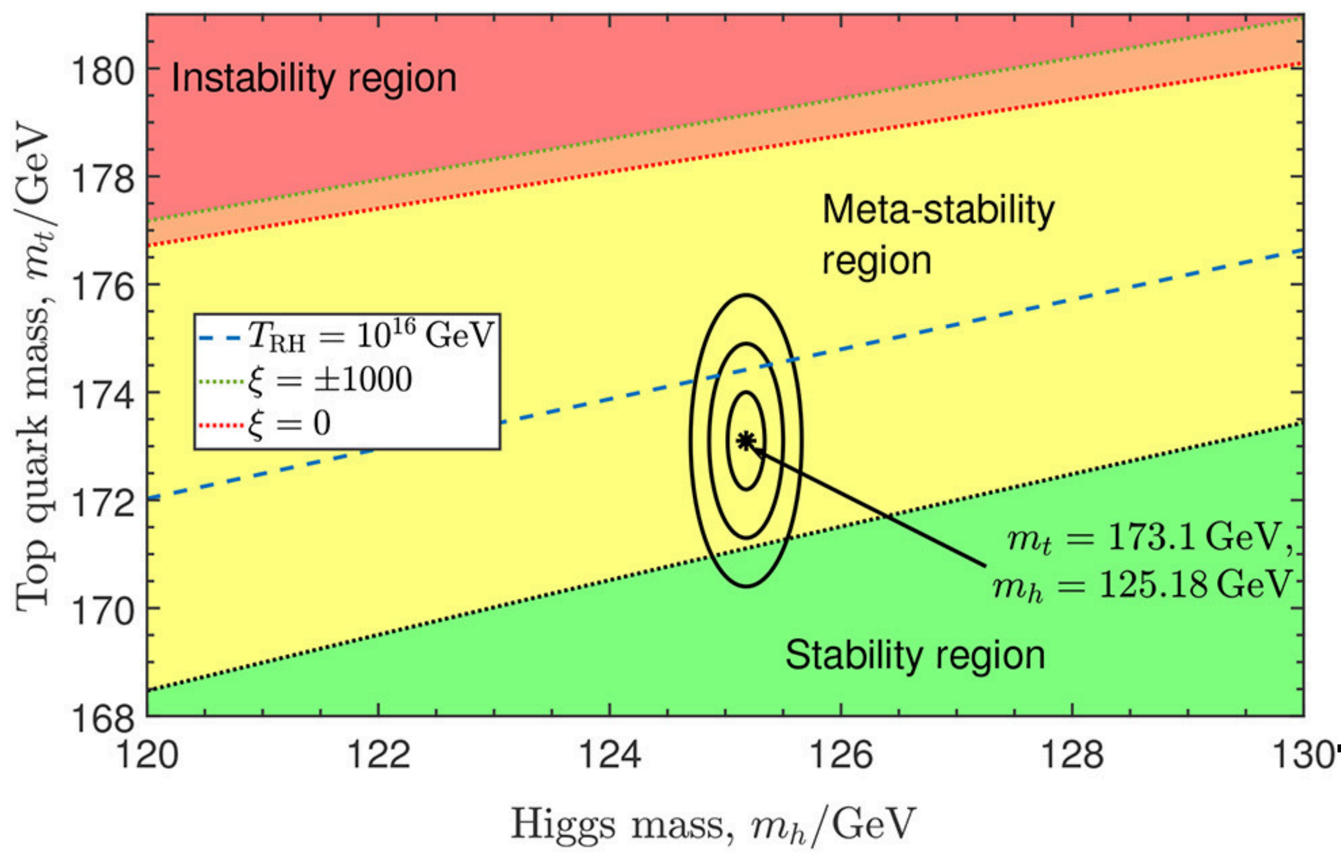
Signal distribution strongly depends on κ_λ

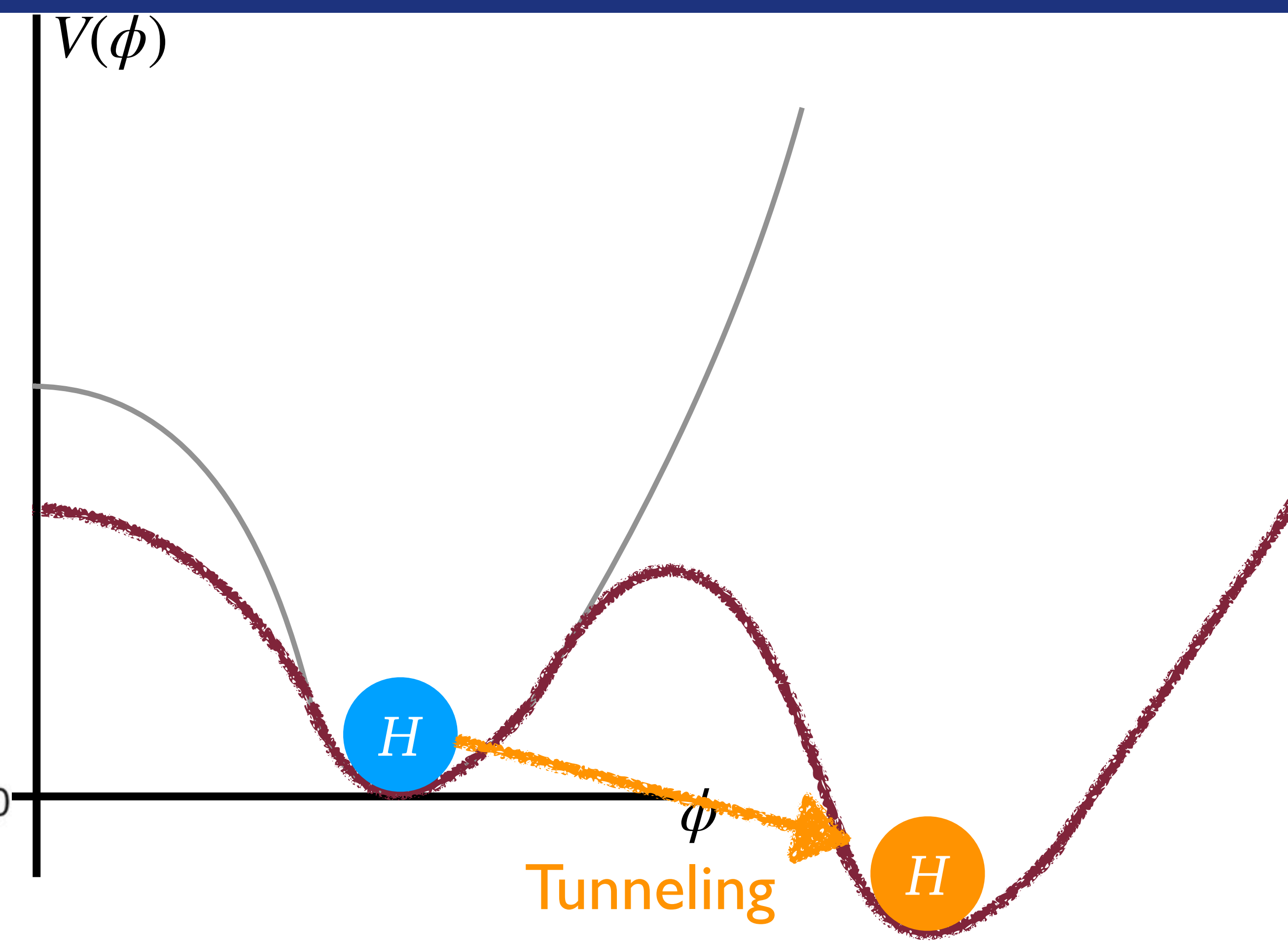
Increasing κ_λ leads the 'triangle diagram' to dominate: signal peak shifts to lower m_{HH}

Cross-section also depends on κ_λ: discoverable now!

Is the Universe Stable?

Markkanen, Rajantie, Stopyra





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

Even in the SM, our universe may be *meta-stable*: able to tunnel to a lower energy state!

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

Baryogenesis

Where did the universe's antimatter go?

In 1967, Sakharov described 3 conditions to explain its disappearance:

1. Baryon-number violating processes
2. CP-violating processes
3. Out-of-equilibrium dynamics

Exists in the SM!
Please find CPV, Belle2!

The Higgs potential can play a critical part in this story:
Electroweak baryogenesis

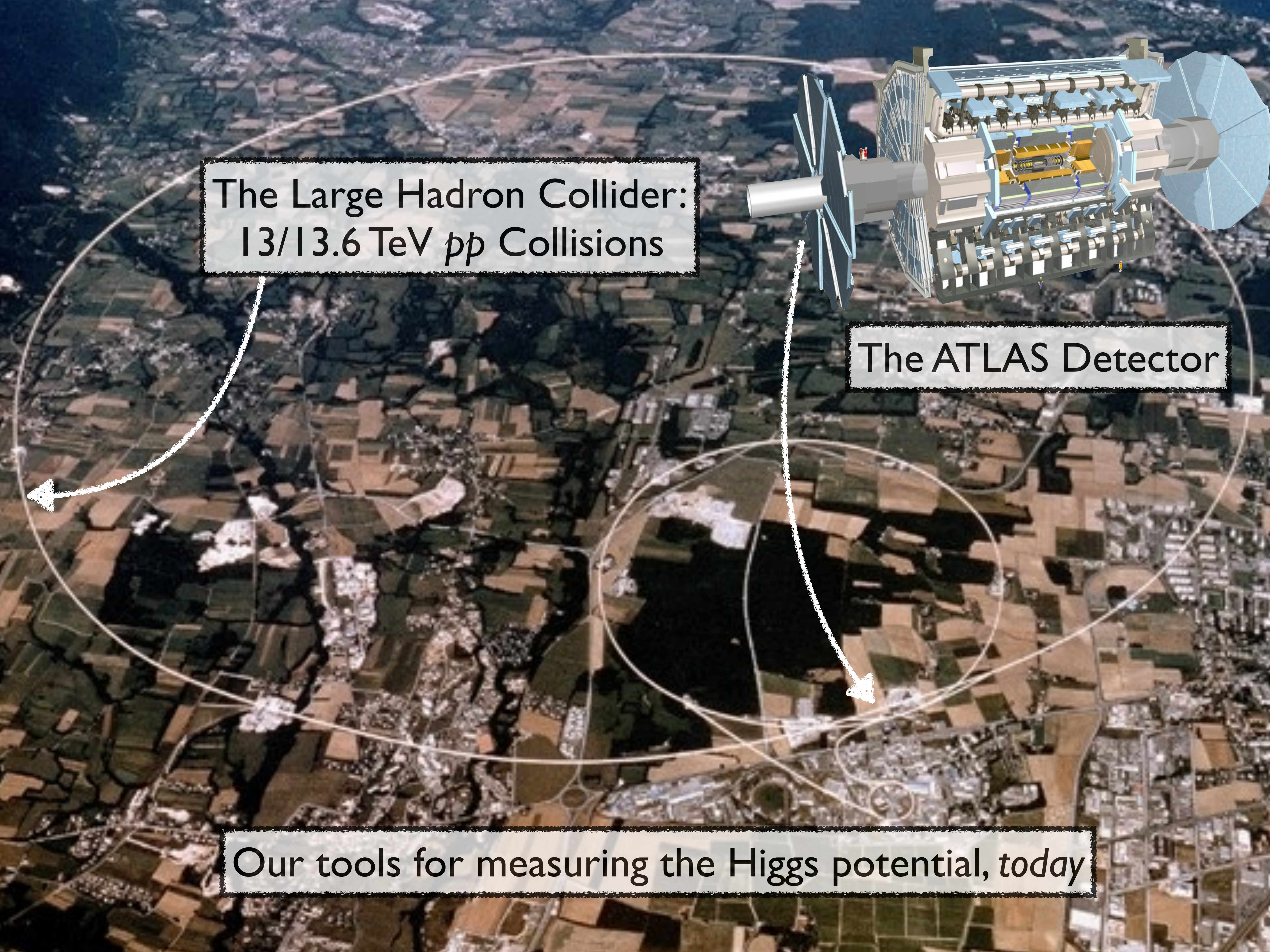
Long story short:

1. The shape of the Higgs potential changes during the early universe
2. The nature of this "phase change" can introduce "dynamics" (3)
3. But the SM phase change is not sufficient: need BSM with higher κ_λ to introduce a strongly first-order phase transition

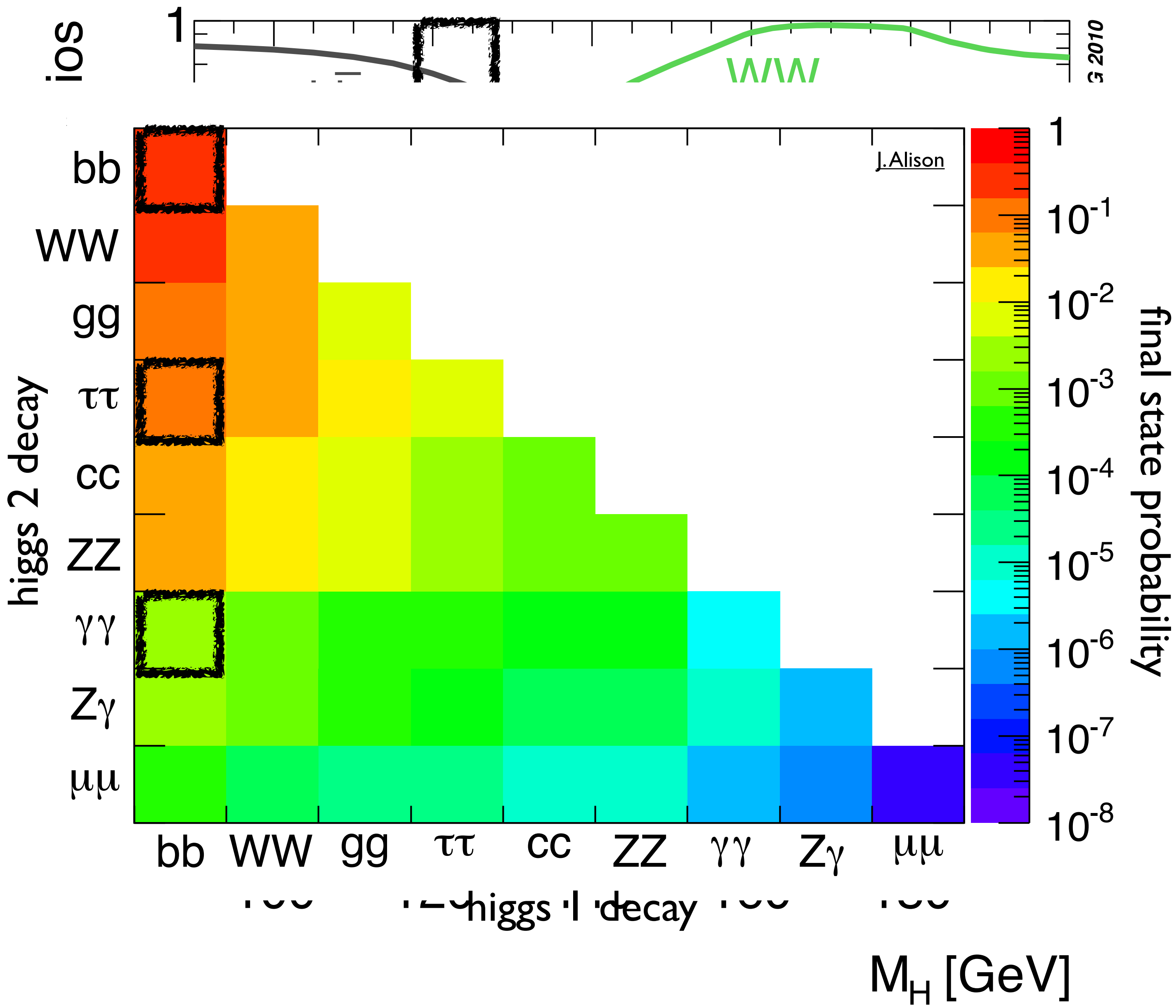
Measuring the Higgs potential critical to test this possibility!

NASA/ESA

The Higgs Potential Today


The Large Hadron Collider:
13/13.6 TeV *pp* Collisions
The ATLAS Detector
Our tools for measuring the Higgs potential, *today*

Searching at the LHC



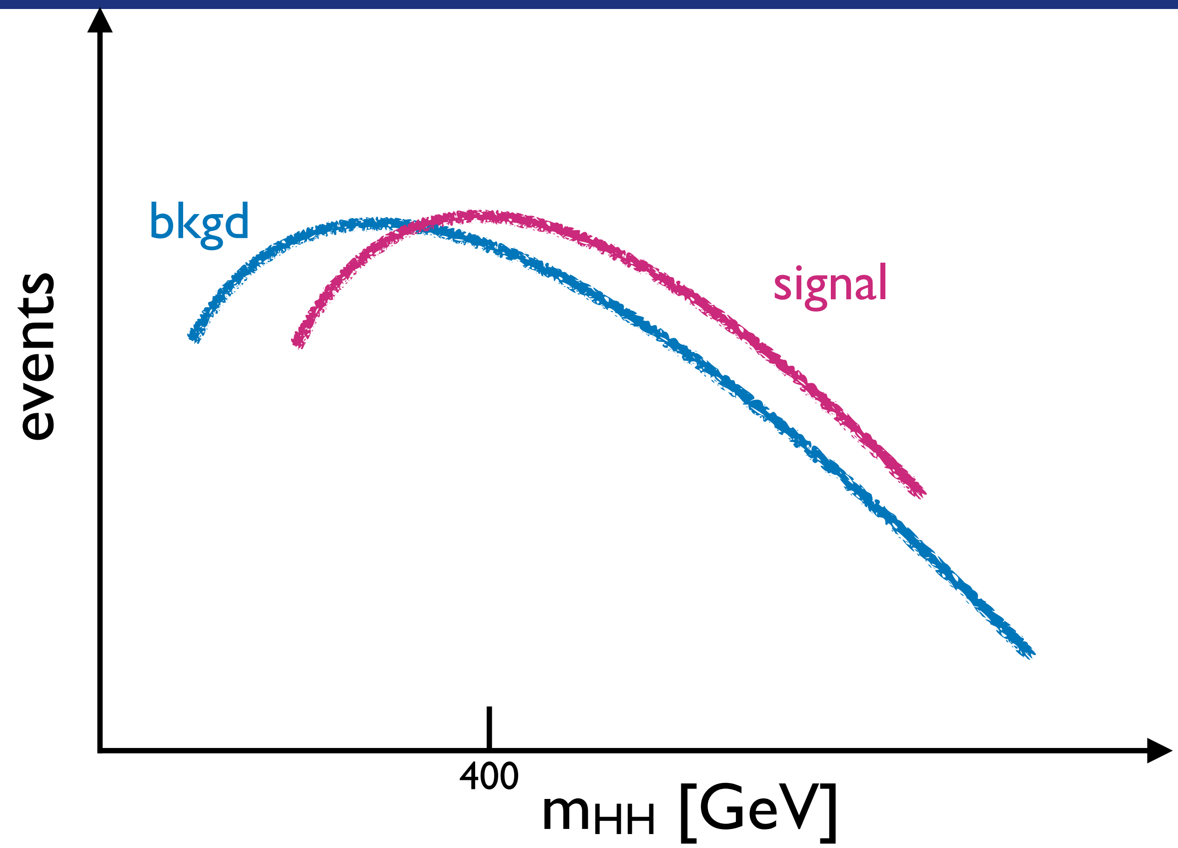
The Higgs decays instantly, to a range of particle types

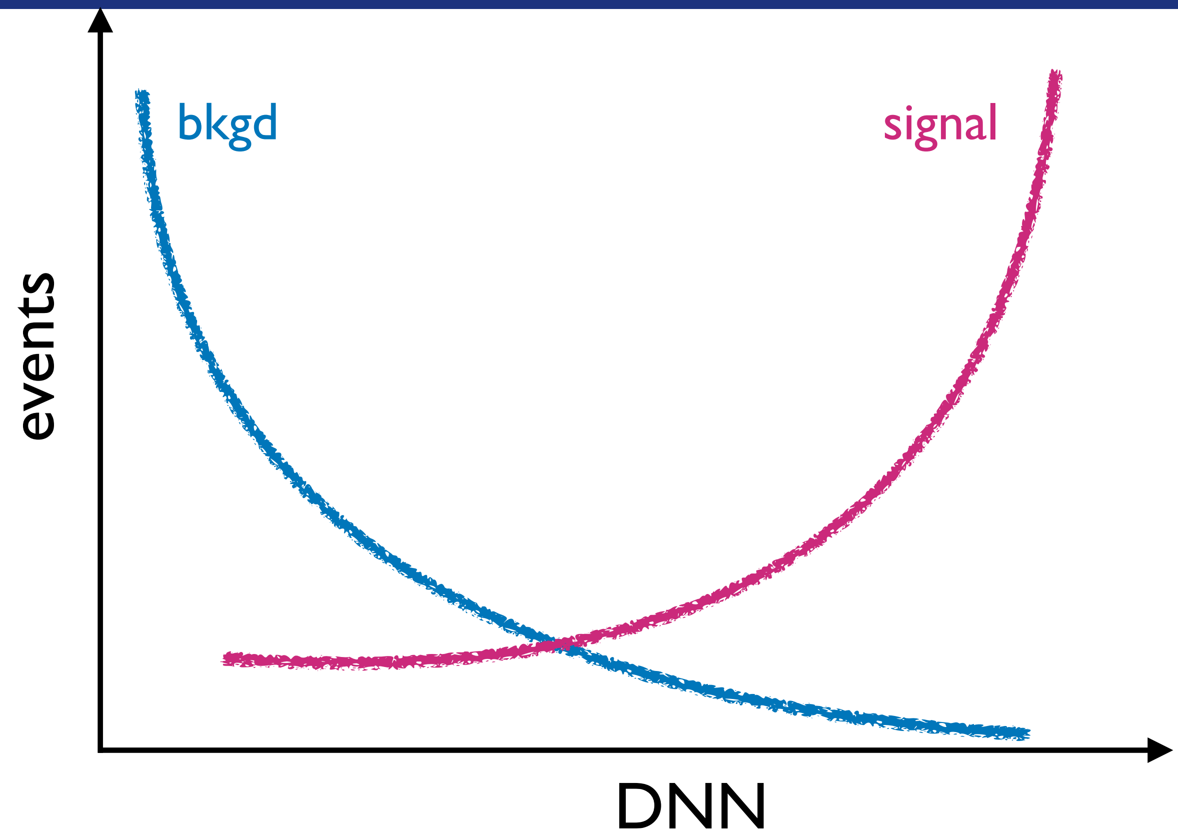
Higgs pairs are rare, and have a hugely rich structure of final states

Man on Wire, Guardian

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

Searching for Higgs Pairs





The invariant mass m_{HH} is a standard observable

Multivariate analysis with ML also extremely common

SM signal peaks at 400, with long tail ($\kappa_\lambda \neq 1$ peaks lower)

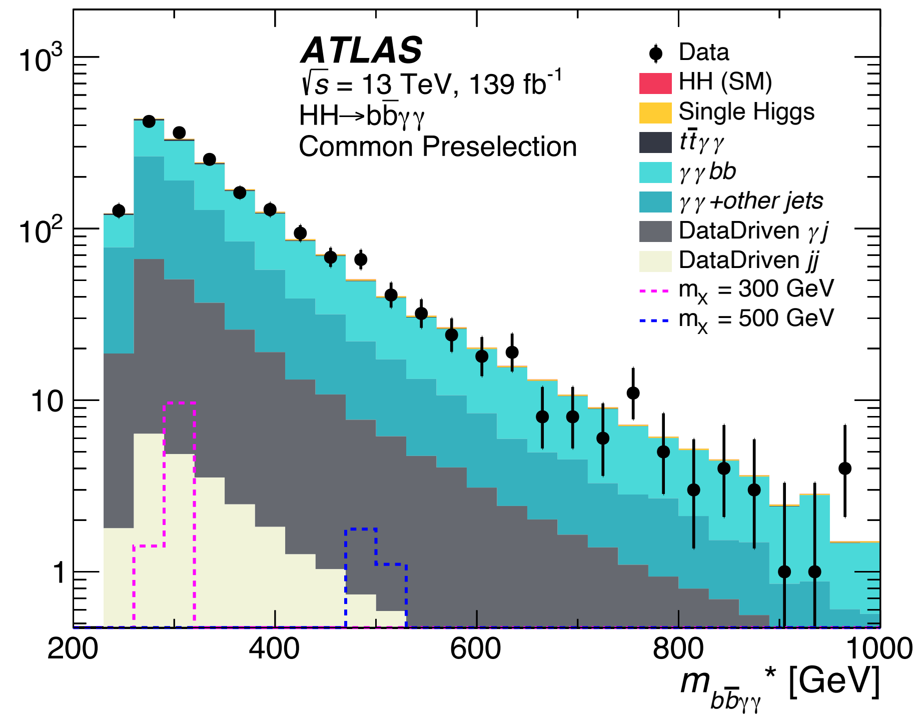
Can use m_{HH} to design SM and BSM targeting regions

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]

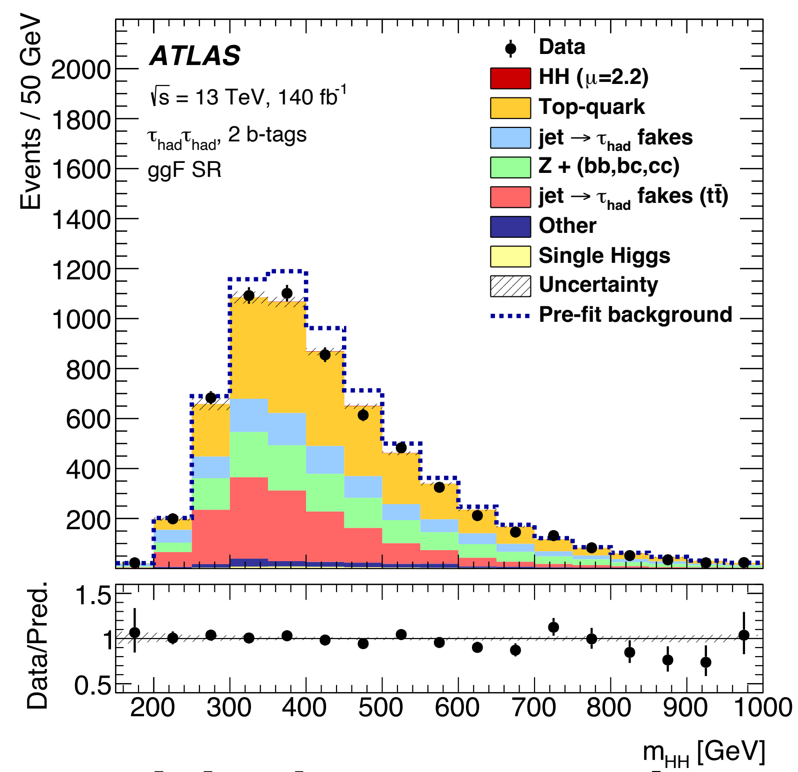
$b\bar{b}\gamma\gamma$



Rarest signal, lowest bkgd

Low trigger threshold: Critical for κ_λ

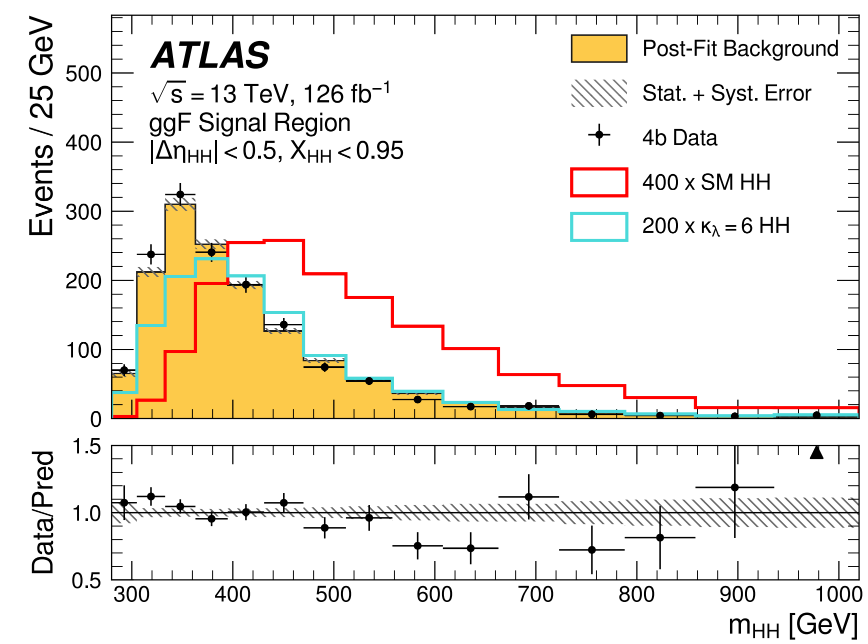
$b\bar{b}\tau\tau$



Medium signal, medium bkgd

Medium trigger thresholds: still important for κ_λ

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



Largest signal, Largest background

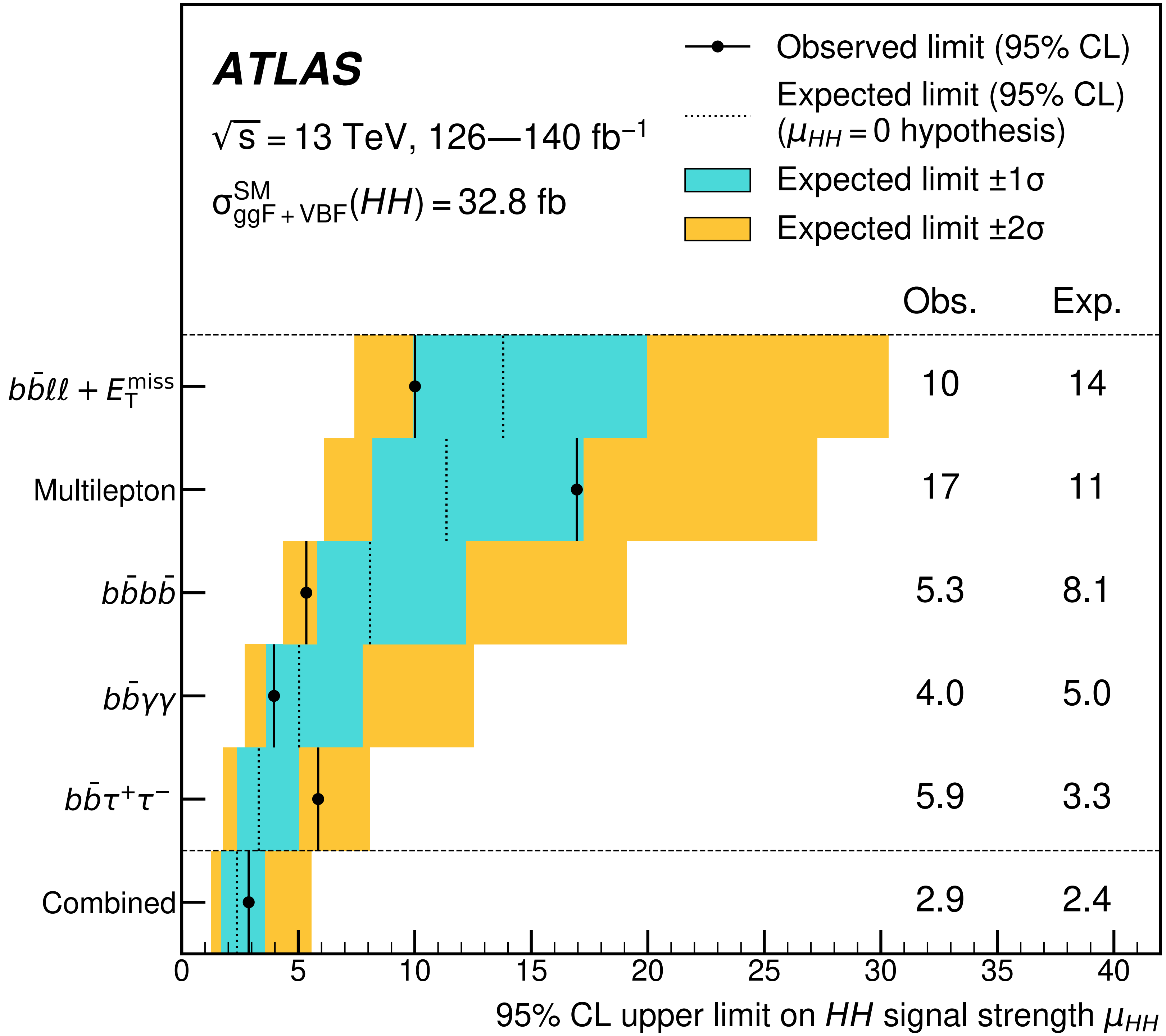
Challenging trigger: b-tagging at trigger level

Novel DNN bkgd estimate

BDT/DNN for main observables

Phys. Rev. Lett. 133 (2024) 101801

ATLAS Combination



Combined limits strongly improve over inputs

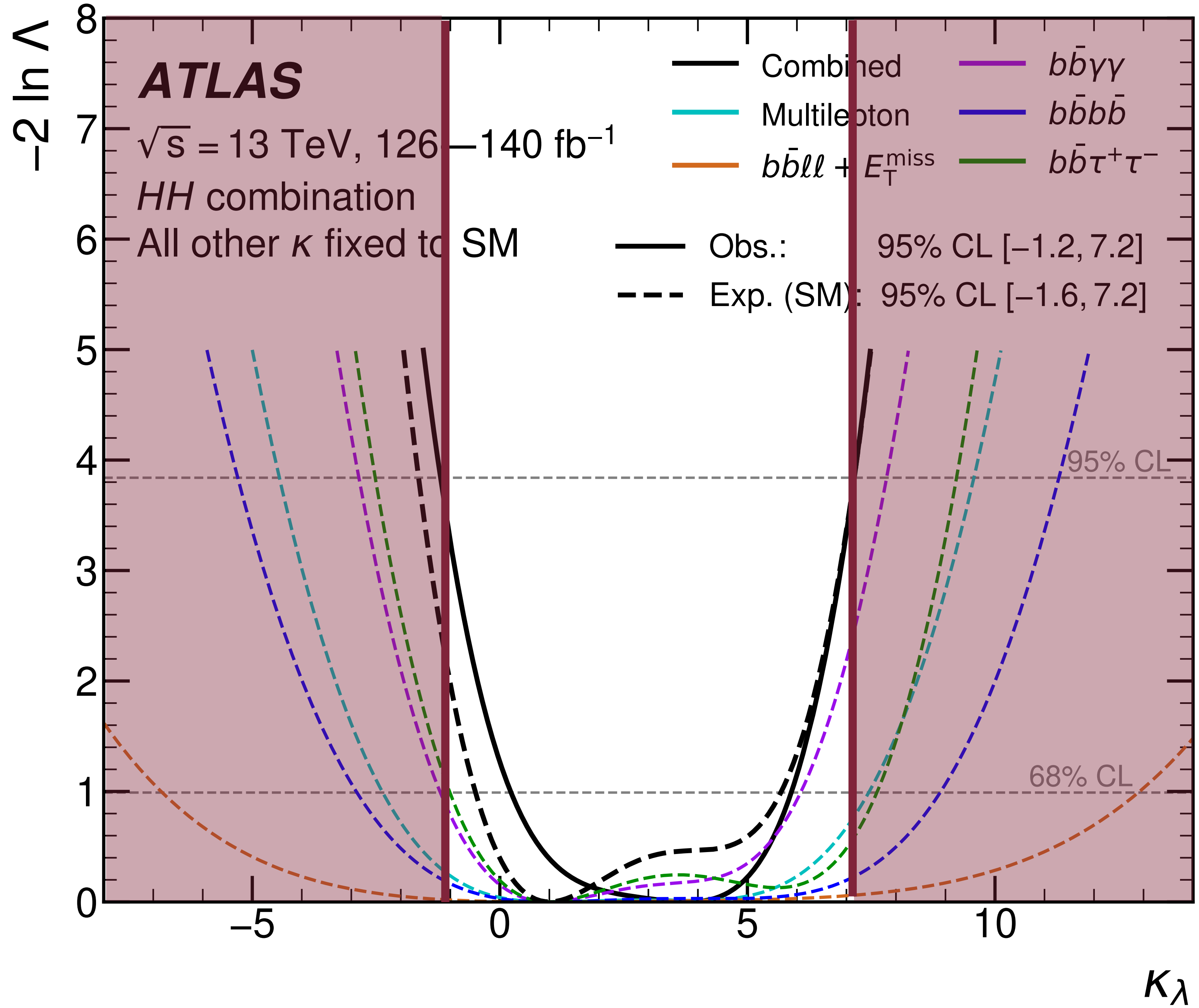
All channels contribute, but top 3 contribute the most

Expected sensitivity at 2.4xSM, observed at 2.9xSM

Still a ways to go for evidence…

Phys. Rev. Lett. 133 (2024) 101801

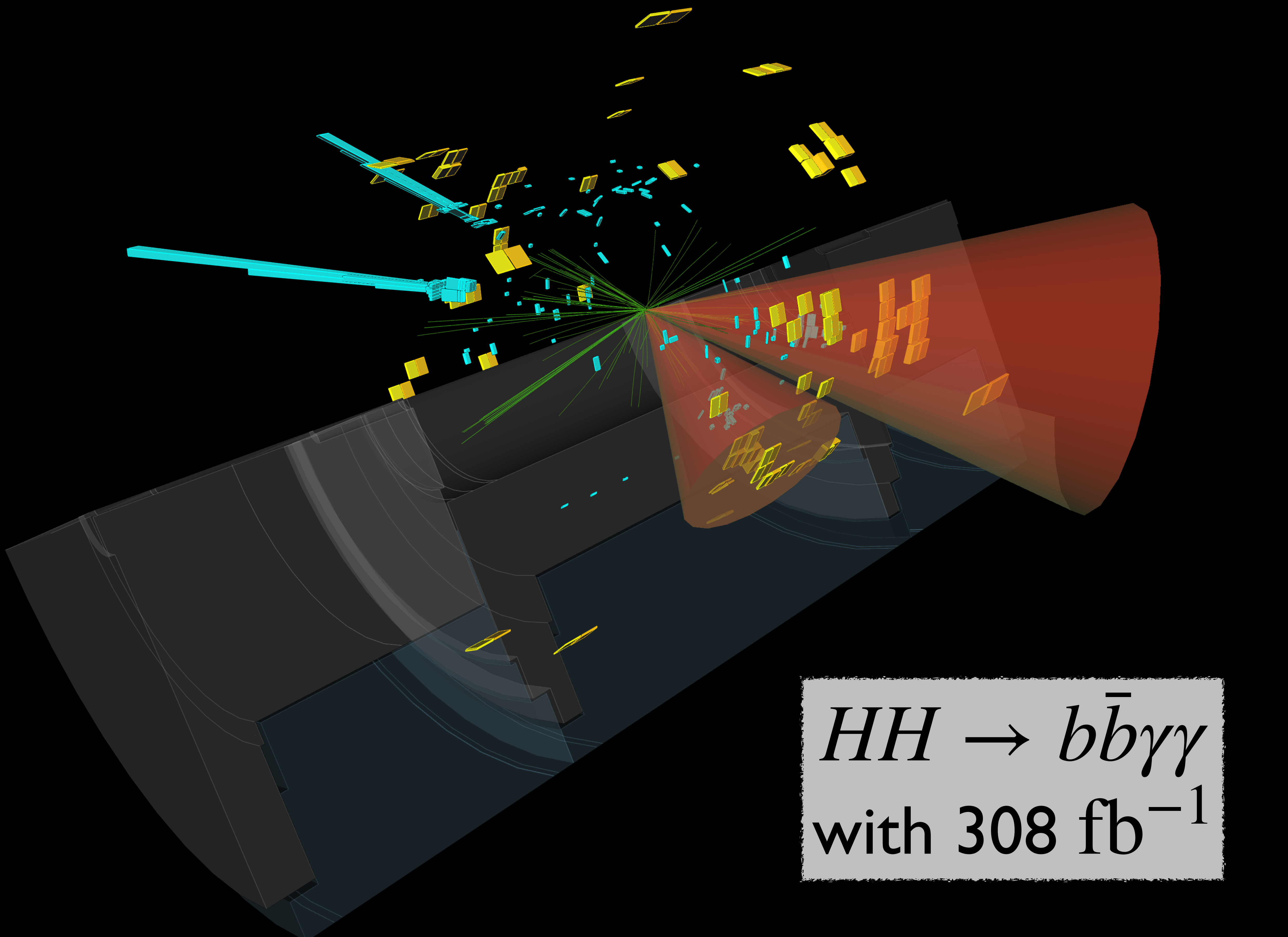
Sensitivity to κ_λ



Combined limits (again) strongly improve over inputs

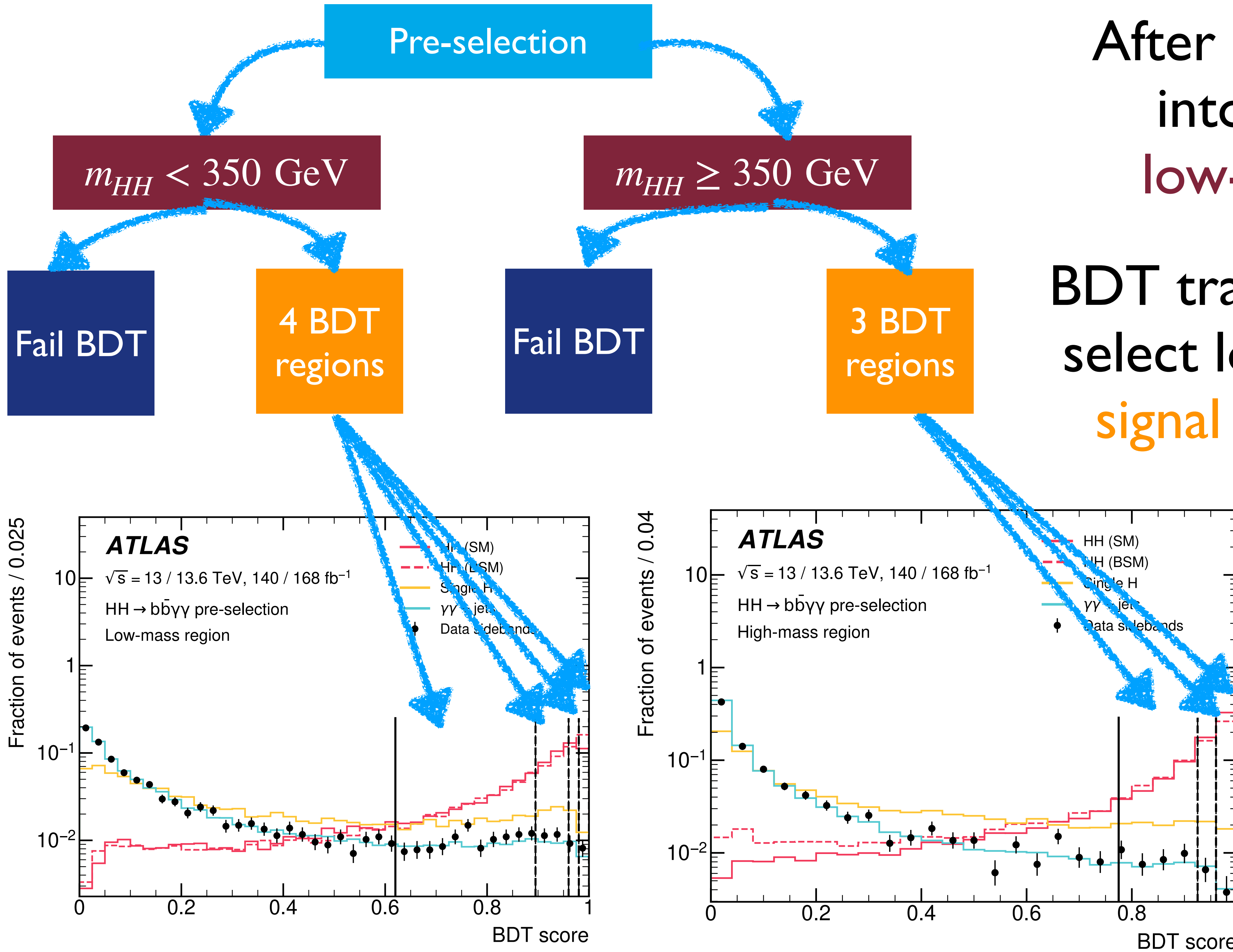
Trigger and background dramatically affect sensitivity to κ_λ

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


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

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

arXiv:2507.0349



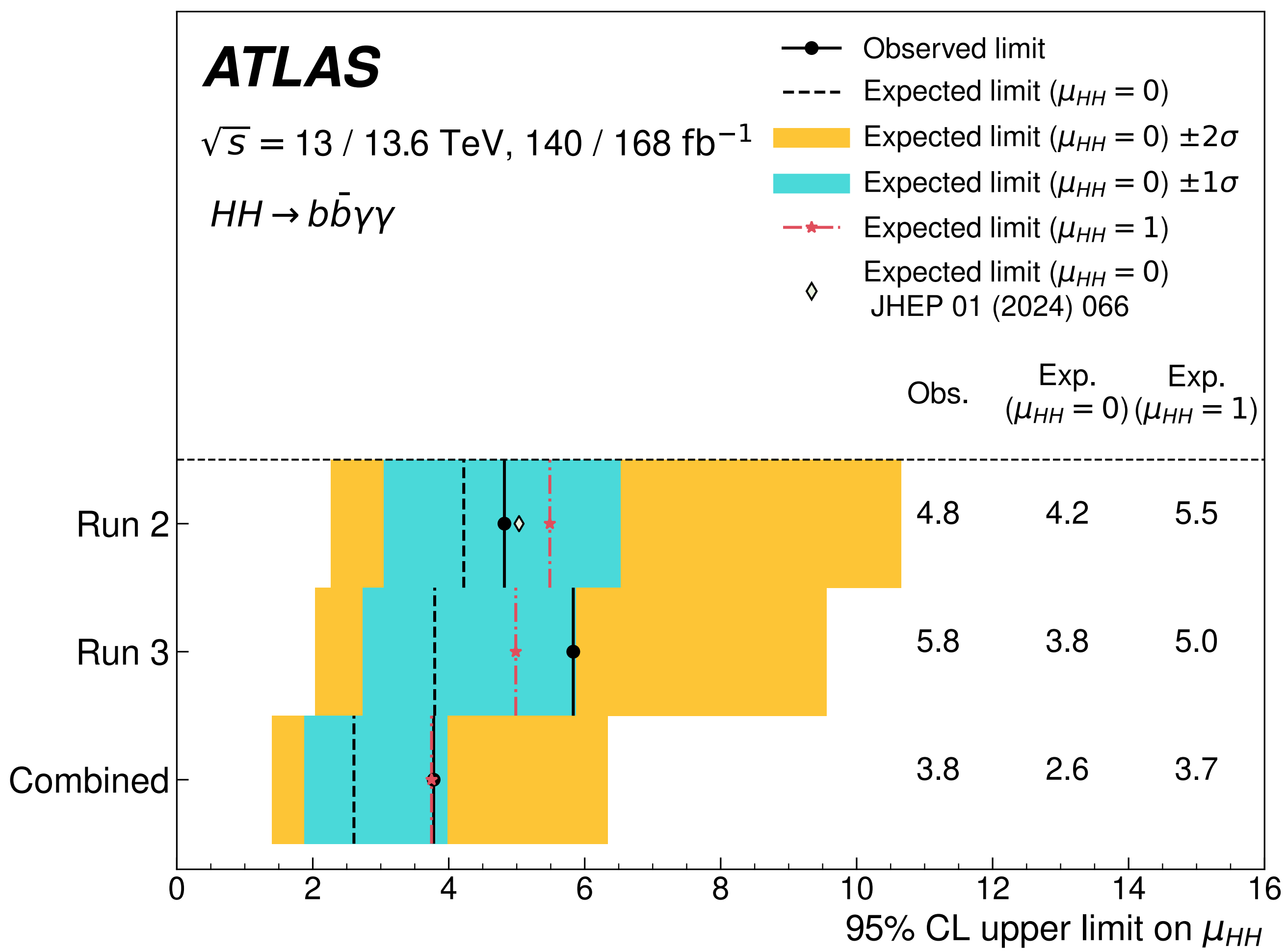
After pre-selection, split into high-mass and low-mass selections

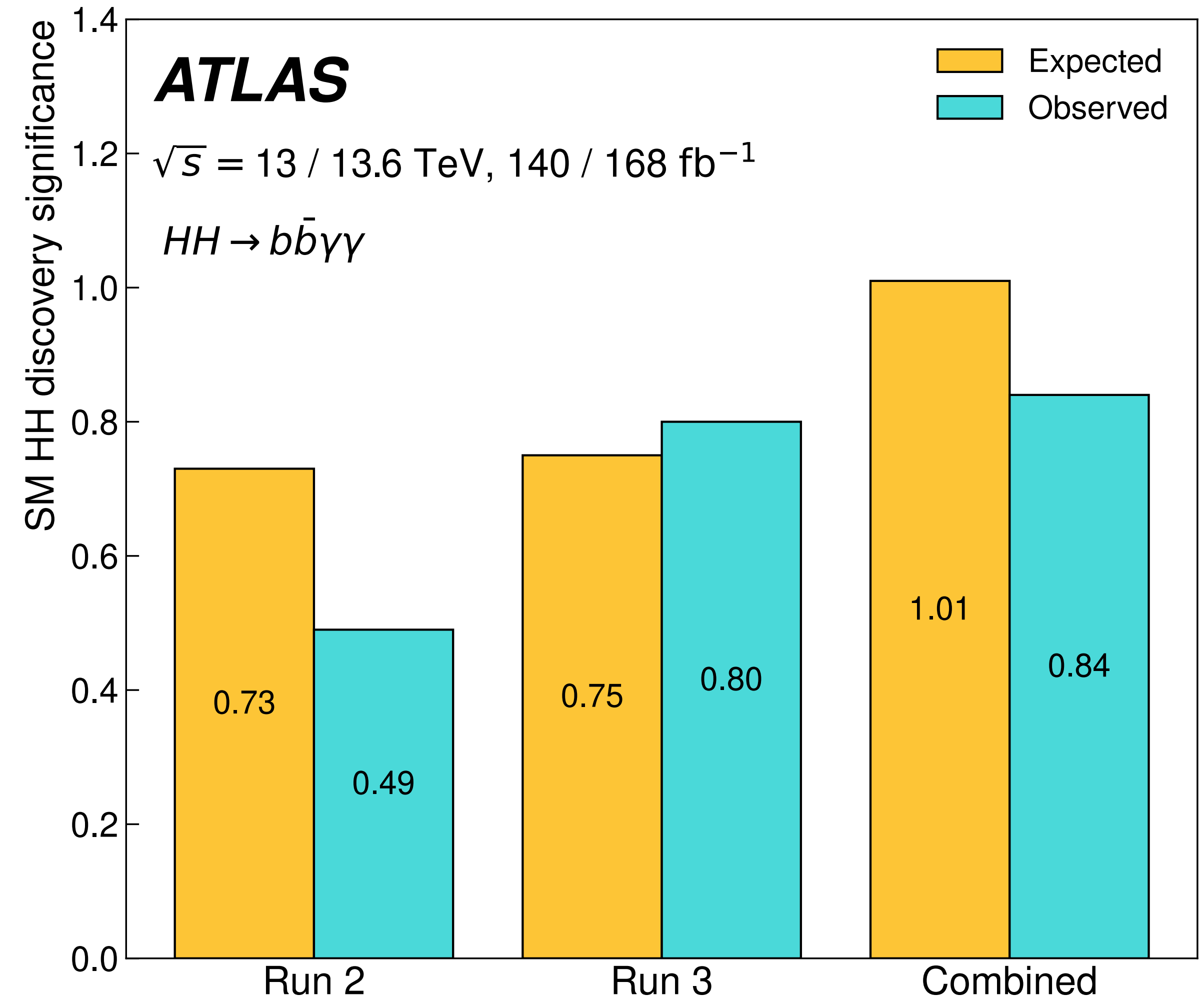
BDT trained in each region: select low- and high-purity signal regions with BDT

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

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

arXiv:2507.0349



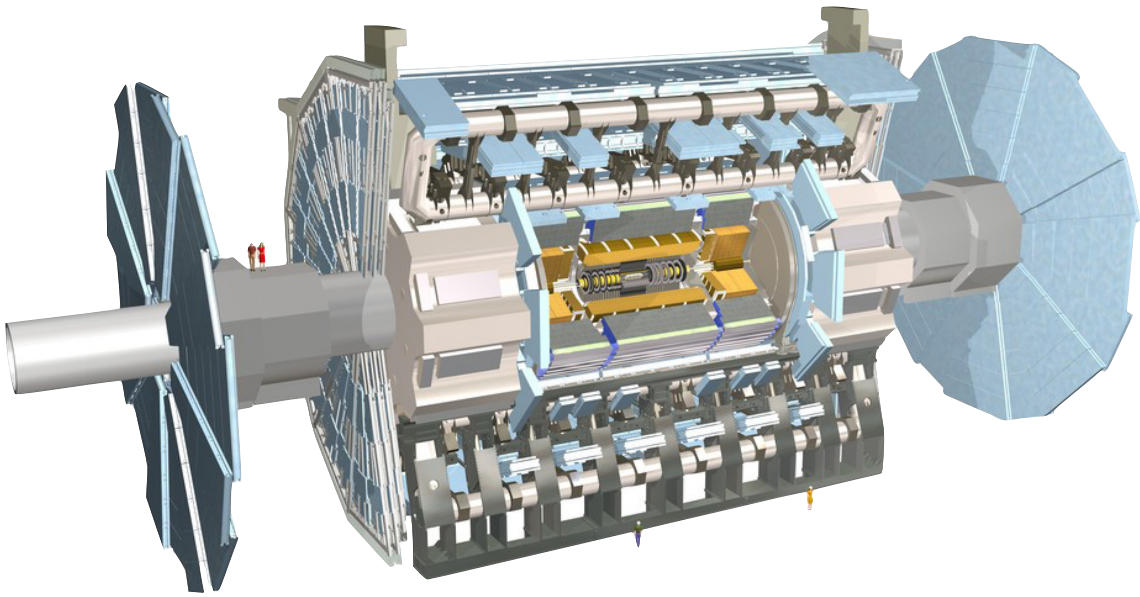


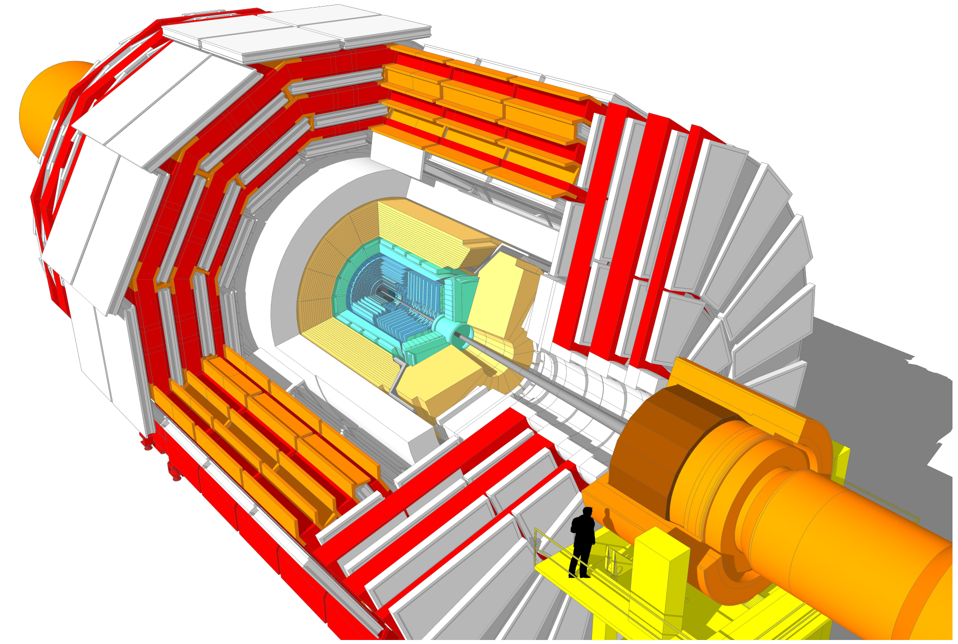
2.6xSM expected limit

Entire Run2 combination was 2.4!

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

ATLAS and CMS





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

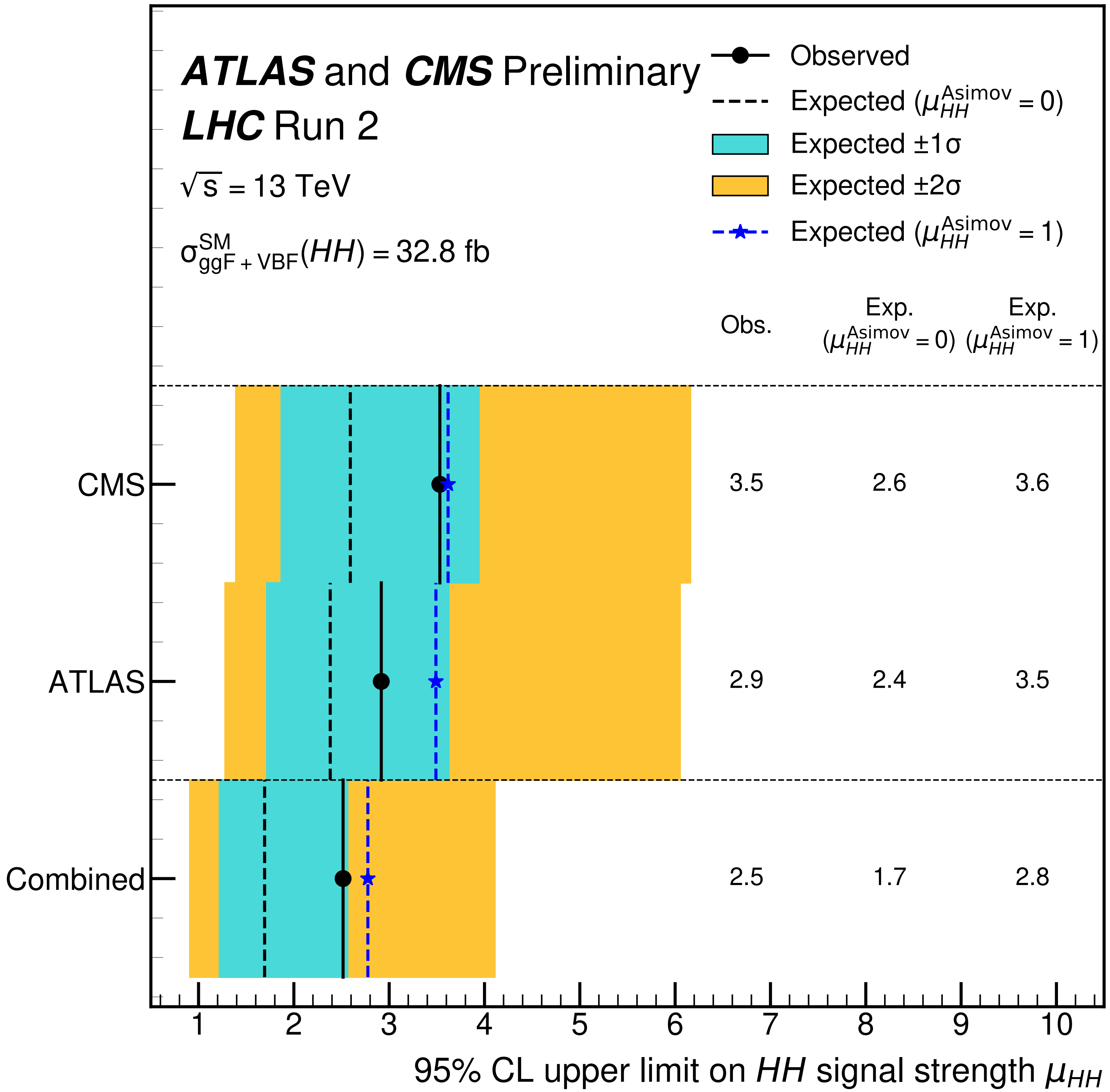
Broadly similar approaches, but many differences in strategy

Ultimately very similar sensitivity

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

ATLAS-CONF-2025-012

The Results



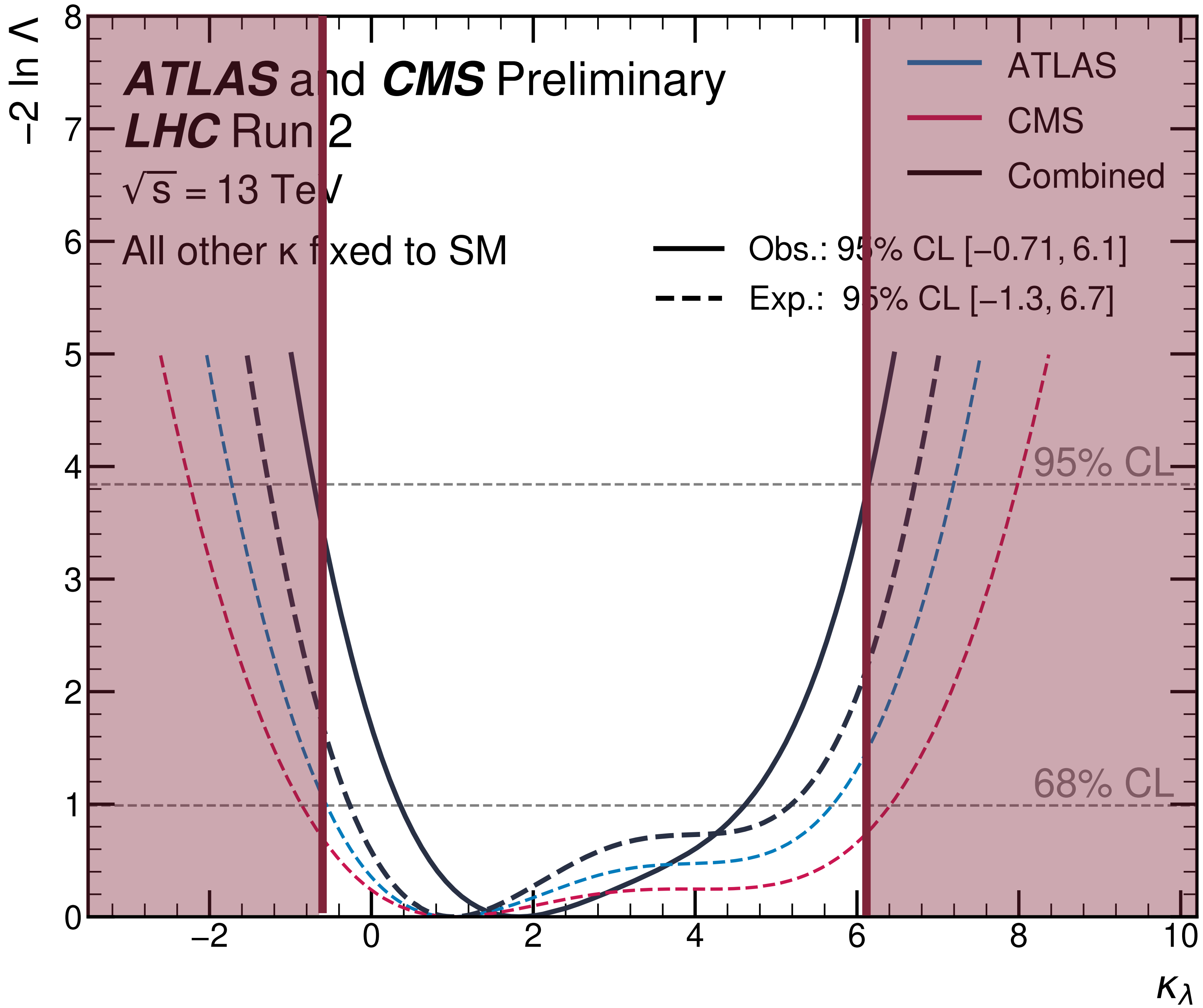
ATLAS and CMS individually exclude ~3xSM signal

Combined, expected limit at 1.7xSM, and observed at 2.5xSM

Corresponds to 1.1σ, observed signal (1.3σ expected)

Not celebrating yet, but coming into view!

κ_λ Sensitivity



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

Combined limits strongly improve over inputs

More data needed to improve measurements: all statistically limited

Looking forward to full Run 3 analysis and beyond!

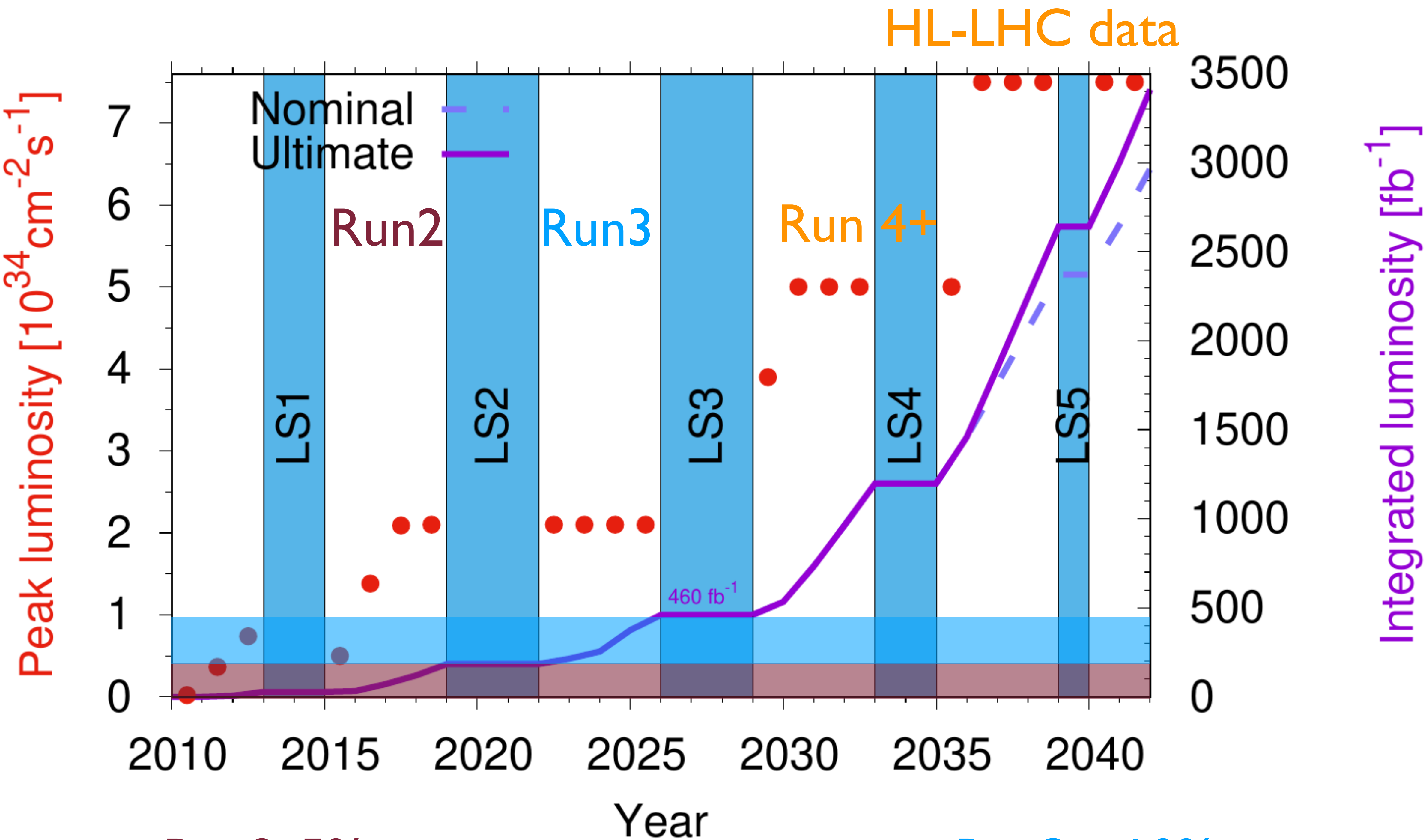
The Higgs Potential Tomorrow

The HL-LHC

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

Increase energy to **14 TeV**,
and instantaneous luminosity to **5-7.5x10^{34} cm^{-2}s^{-1}**

Datasets

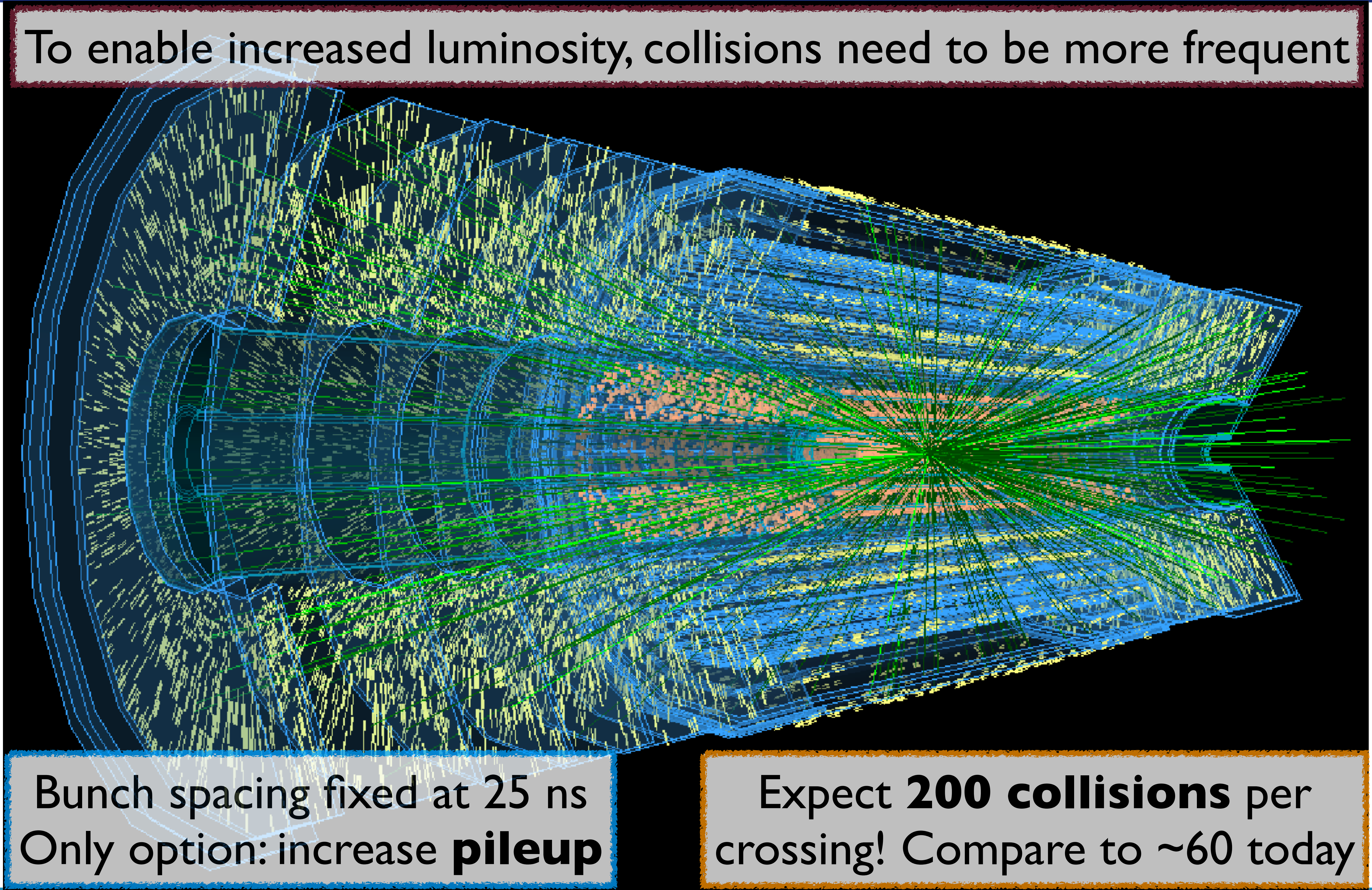


Run2: 5% of total

Run3: ~10% of total

The Price of Rate: Pileup

To enable increased luminosity, collisions need to be more frequent



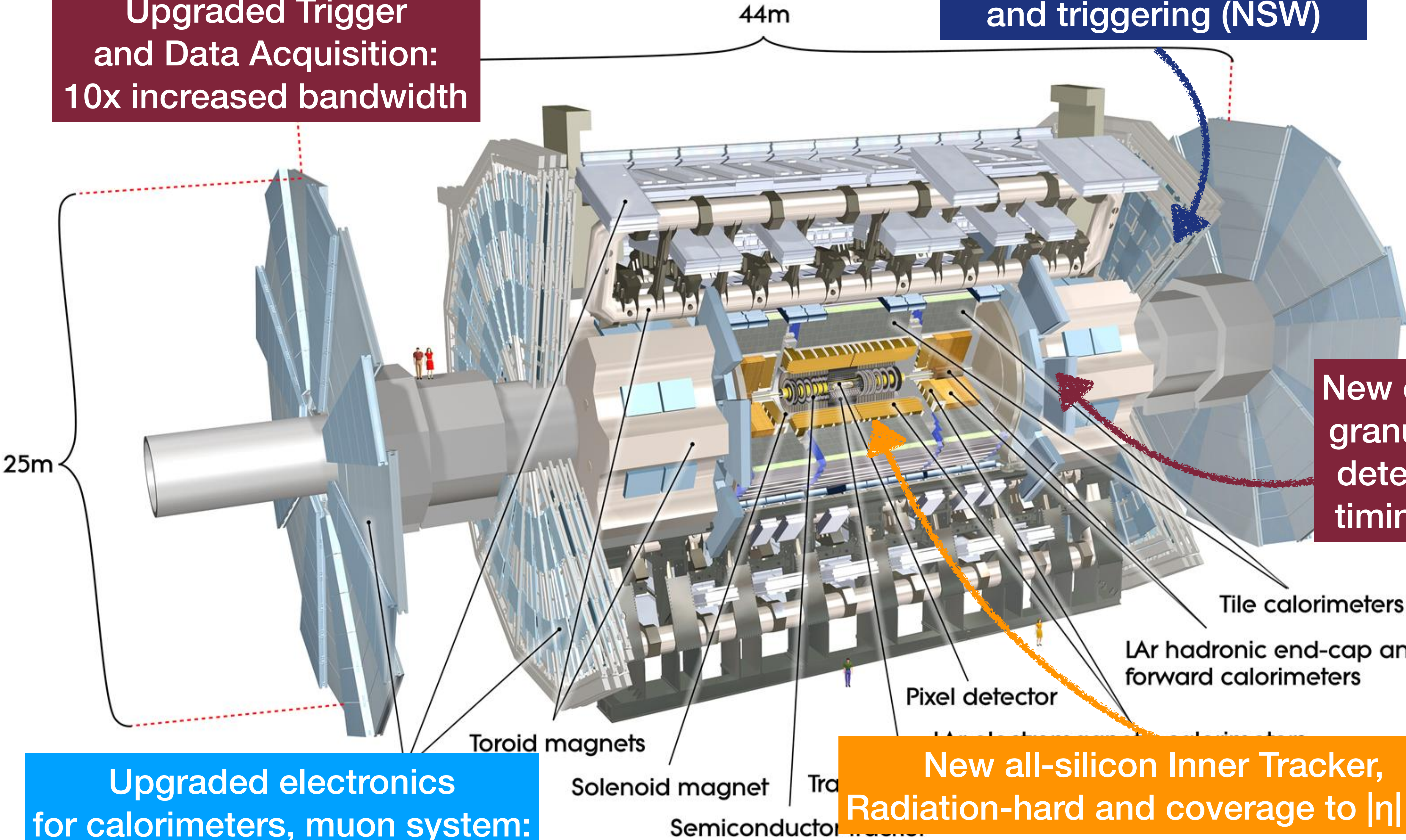
Bunch spacing fixed at 25 ns
Only option: increase **pileup**

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

Upgrades

Upgraded Trigger and Data Acquisition: 10x increased bandwidth

Improved muon coverage and triggering (NSW)

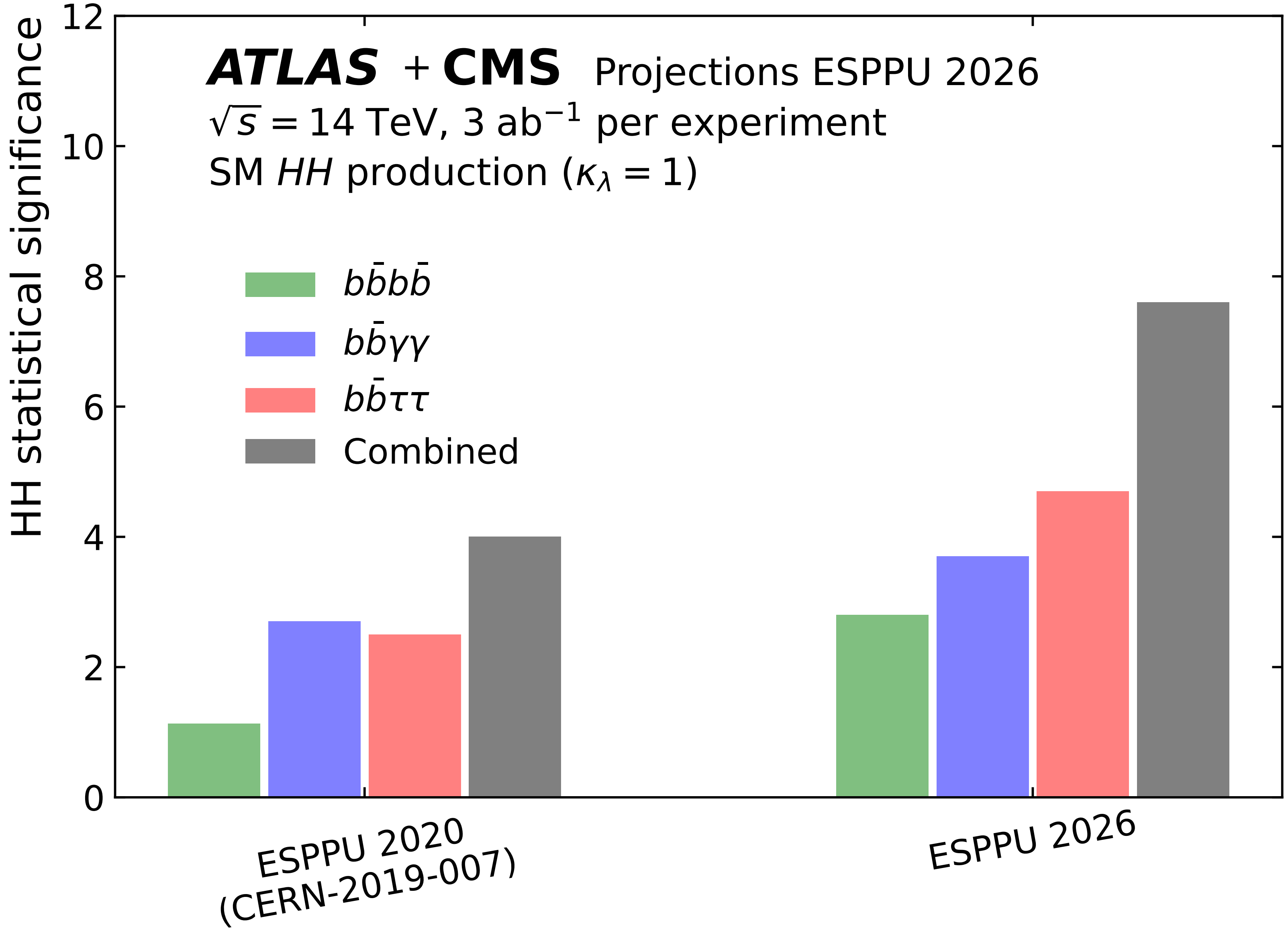


New endcap high-granularity timing detector: ~20 ps timing resolution

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

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

Higgs Pairs Sensitivity

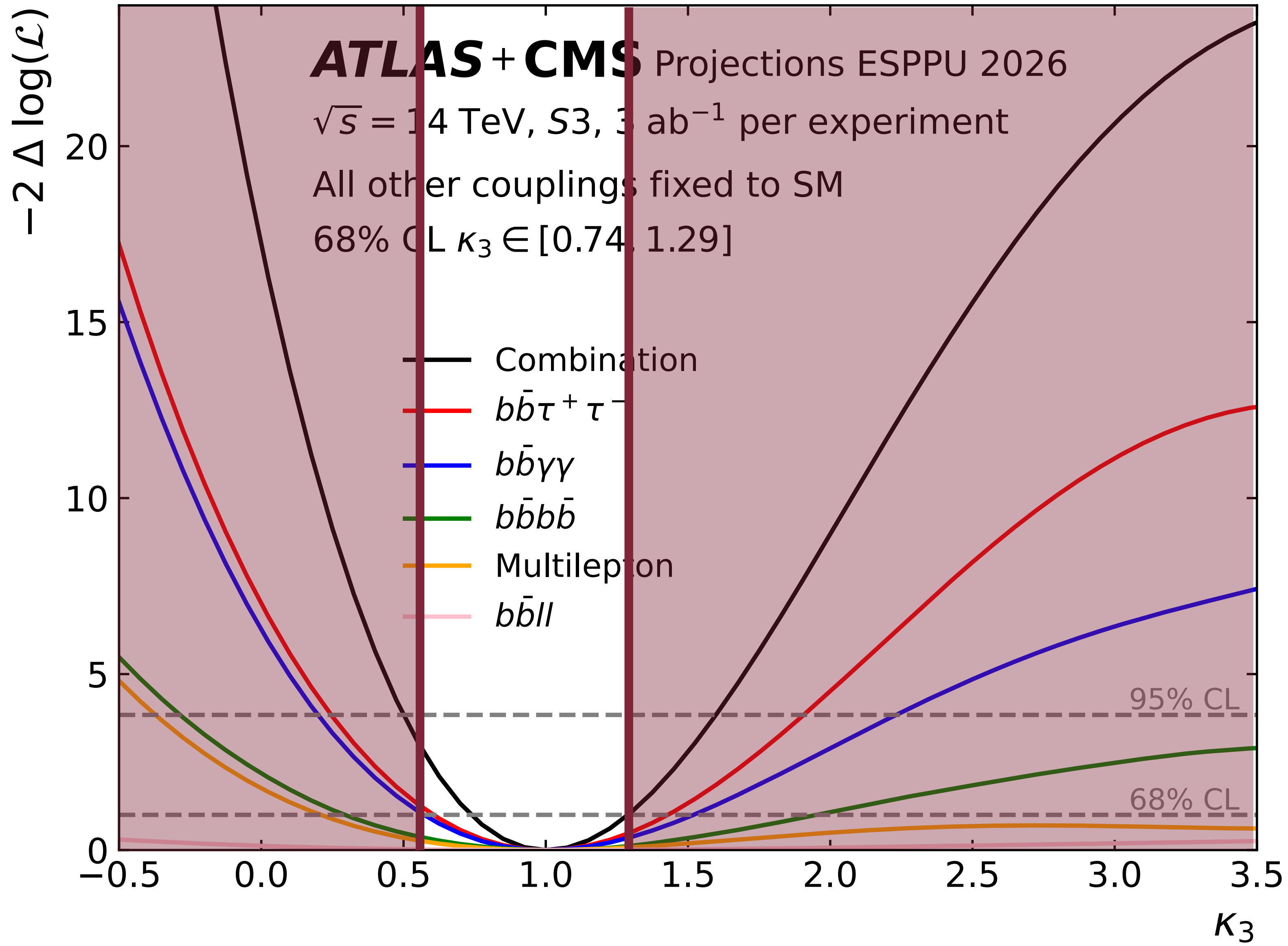


Previous round of projections: 4σ sensitivity

Latest results: **8σ sensitivity**

Likely to keep growing as techniques continue to improve!

κ_λ Sensitivity

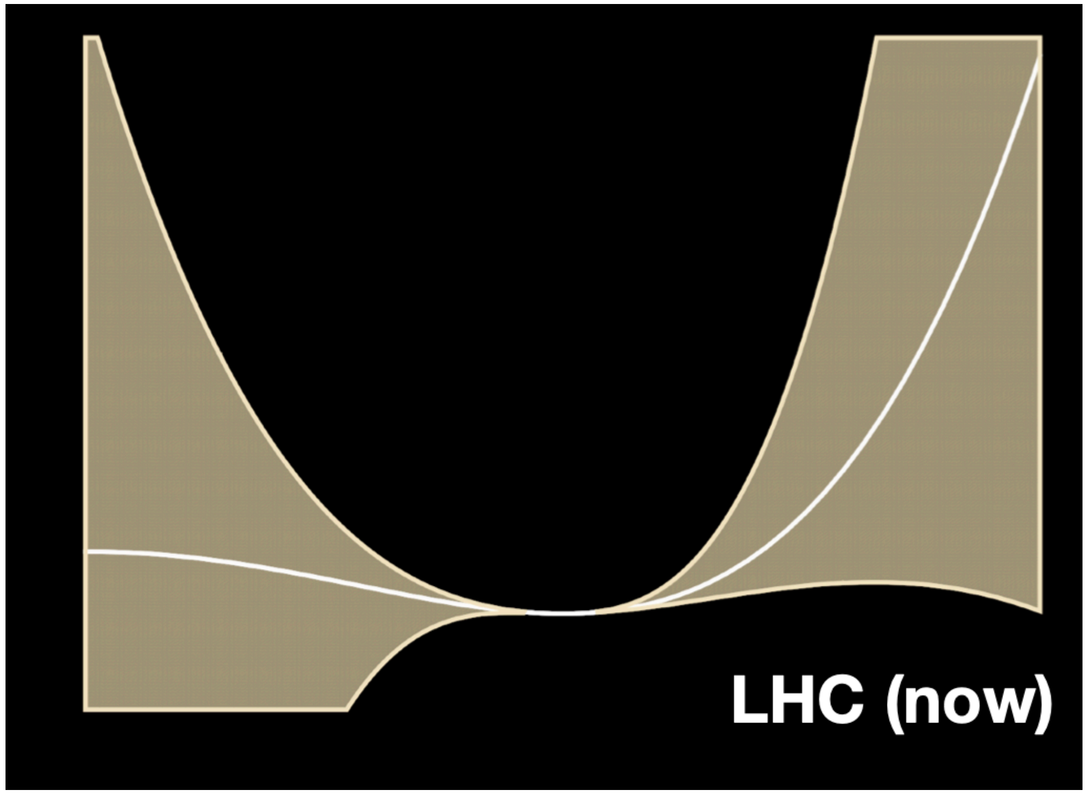


κ_λ sensitivity also significantly improved

Roughly ~30% precision (at 1σ)

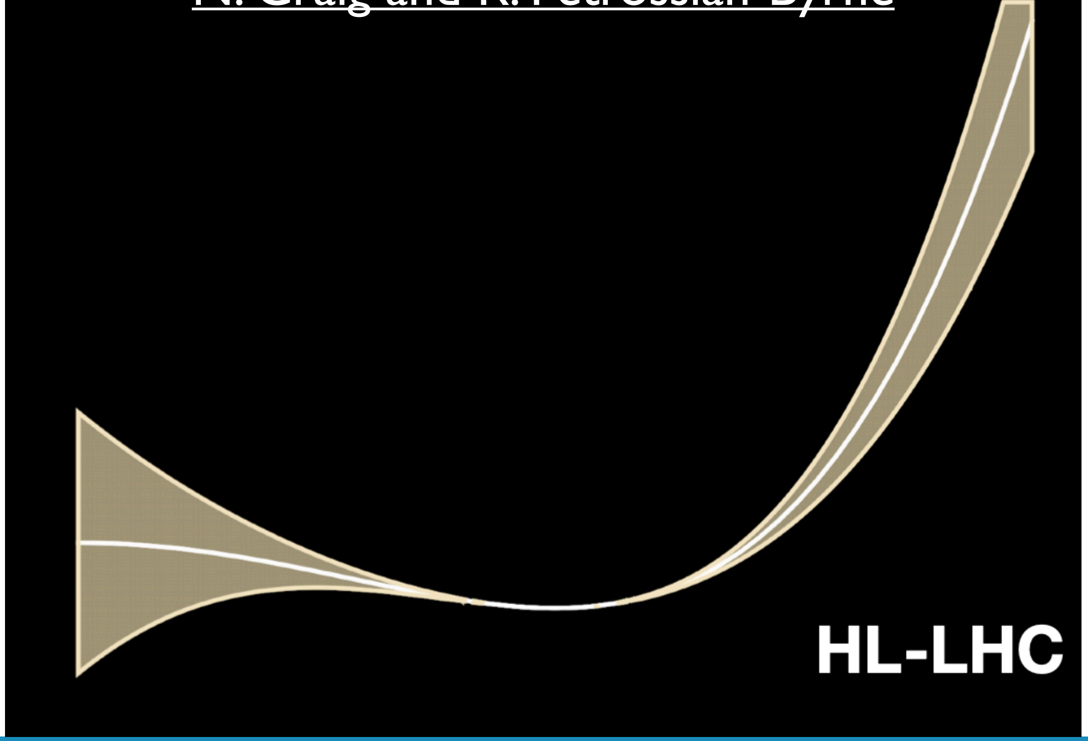
The Nathaniel Sketch

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

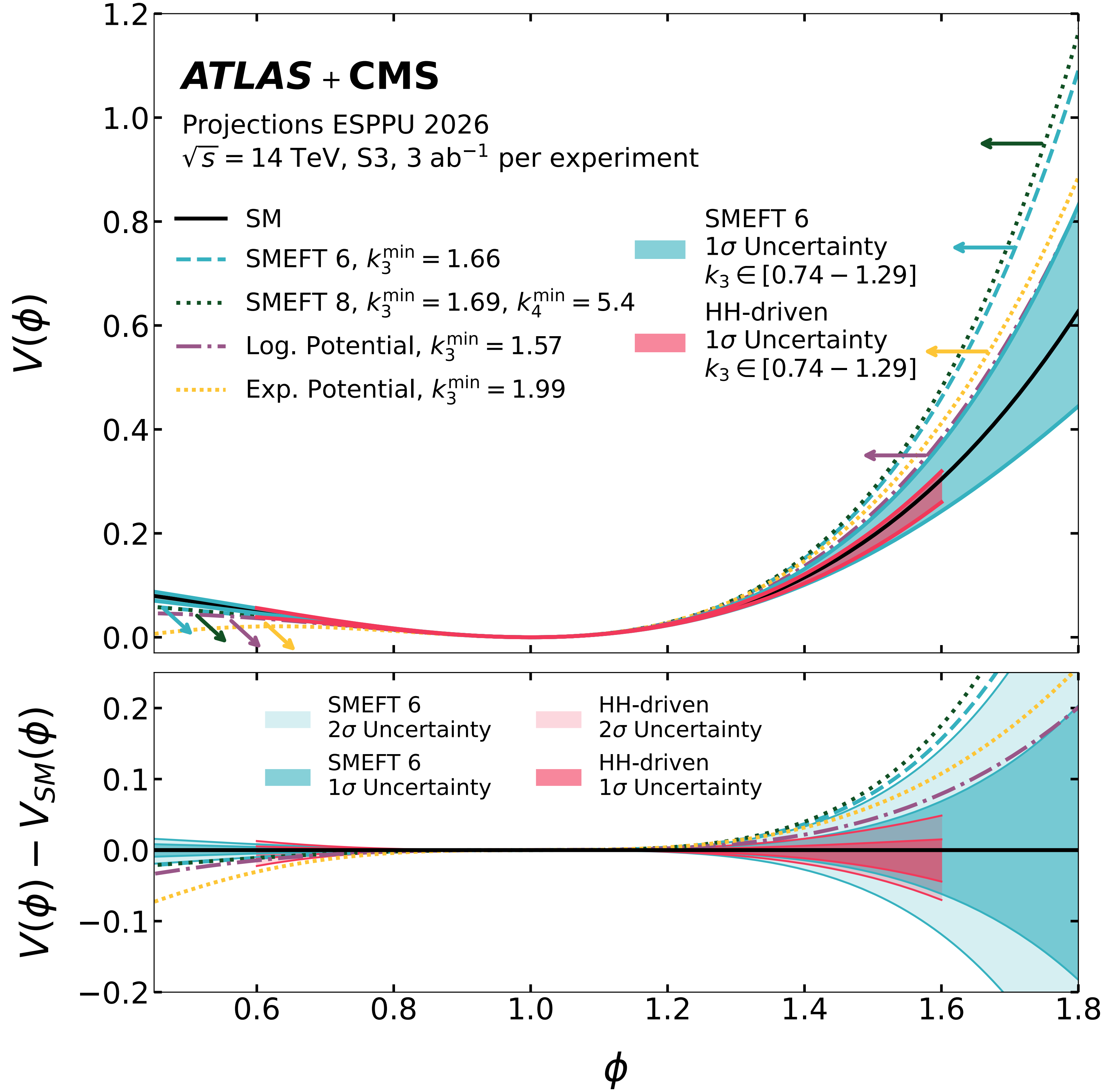


And what's possible at the HL-LHC?

N. Craig and R. Petrossian-Byrne



The Nathaniel Plot



What does this tell us about EWBG?

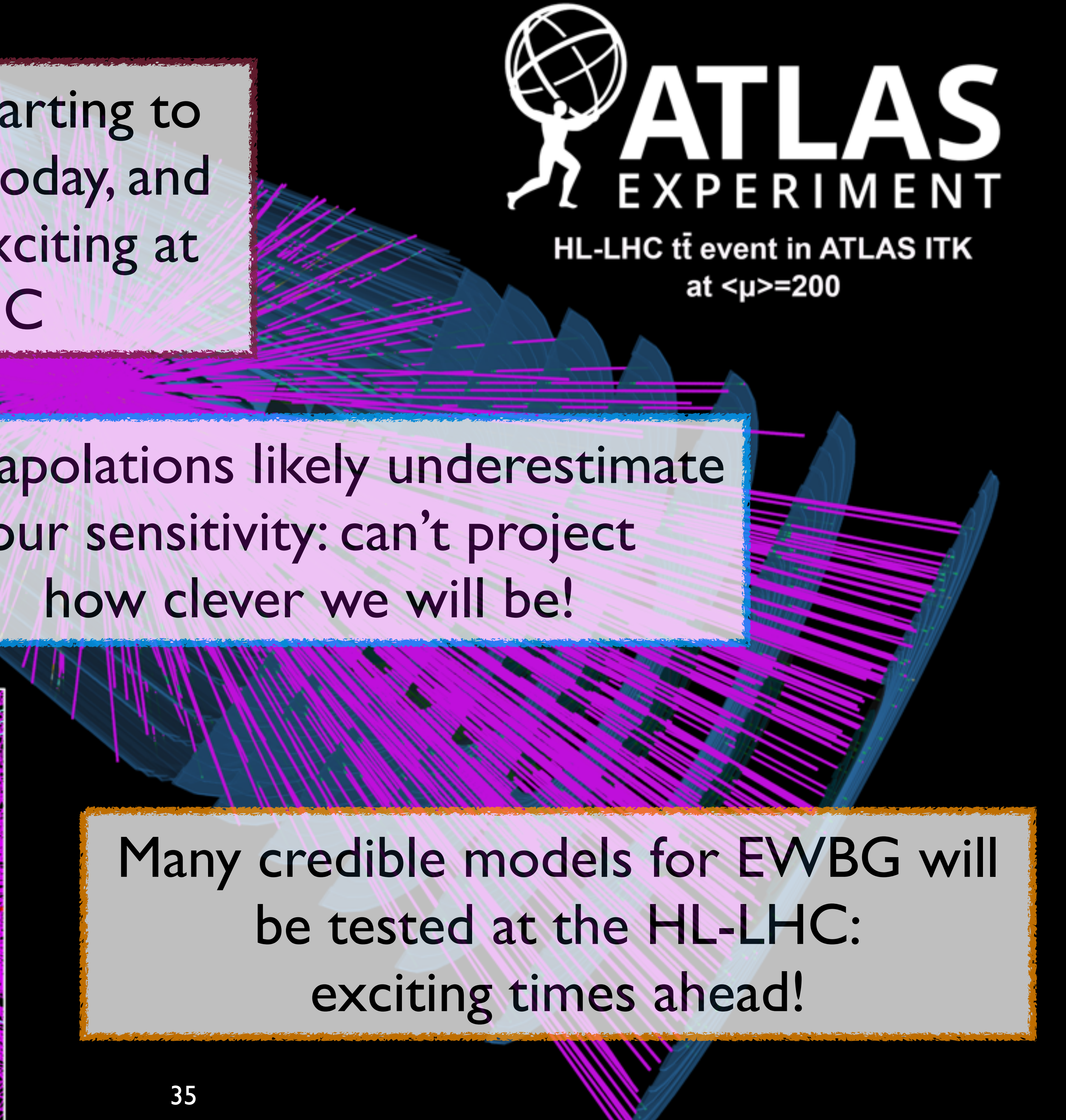
Here, compare precision achievable at LHC under κ_λ-only interpretation and broader SMEFT model

"Realistic" theory models with SFOPT in other lines

We will be probing the electroweak phase transition at HL-LHC!

Conclusions

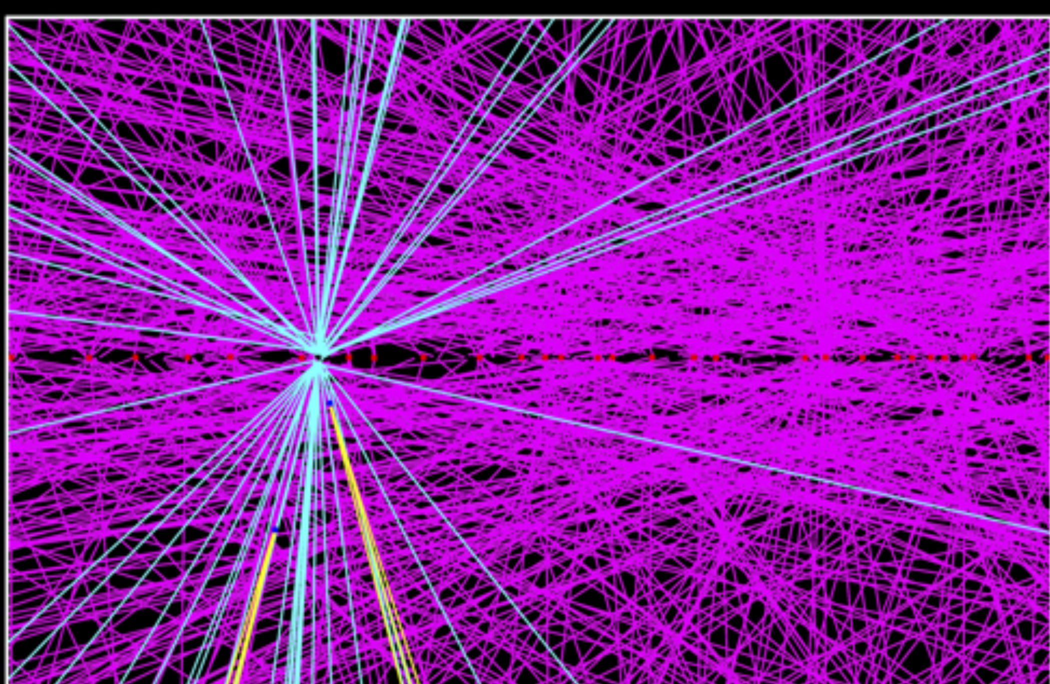
Conclusions



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

Higgs pairs are starting to come into focus today, and are even more exciting at the HL-LHC

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!

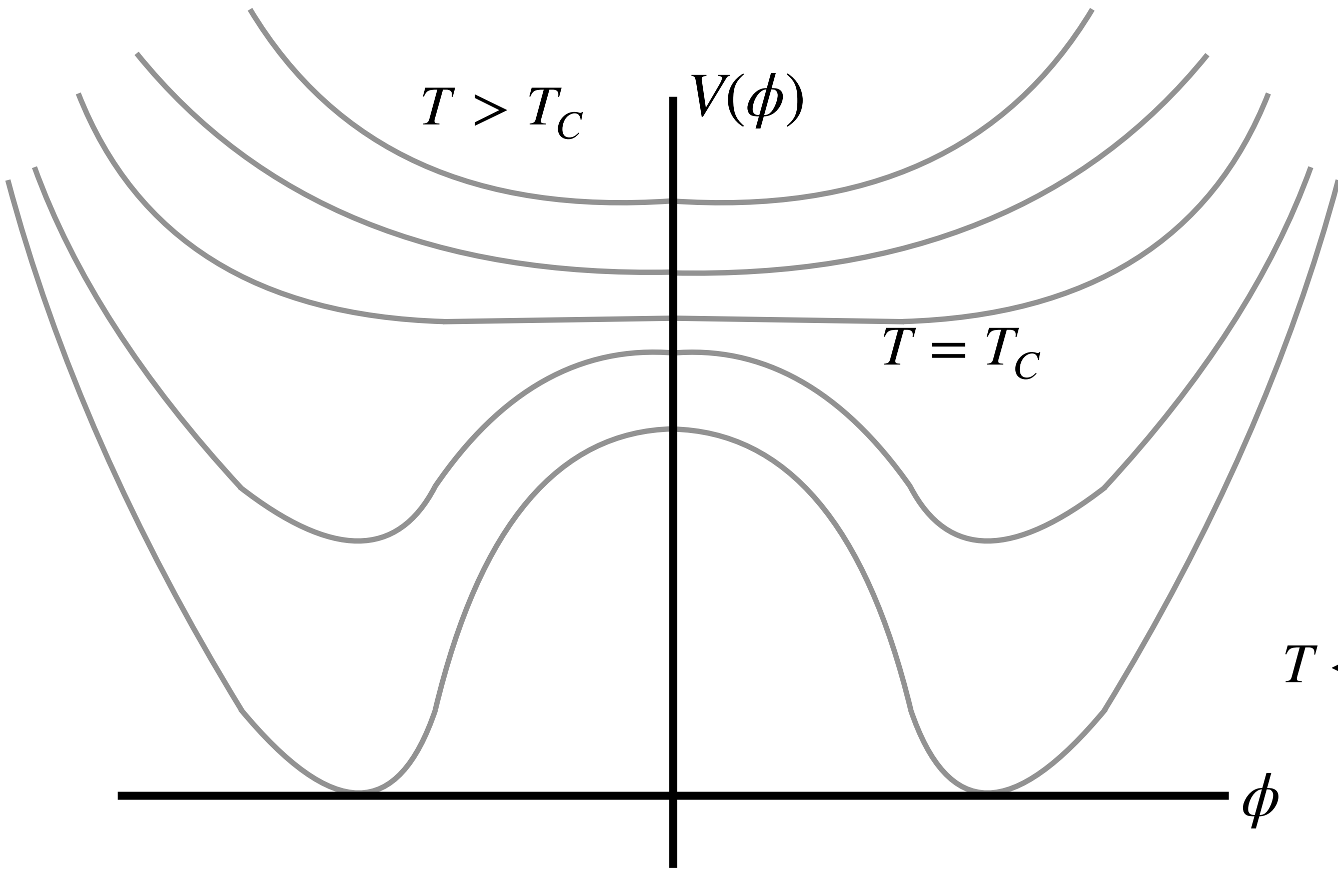
Thank you!

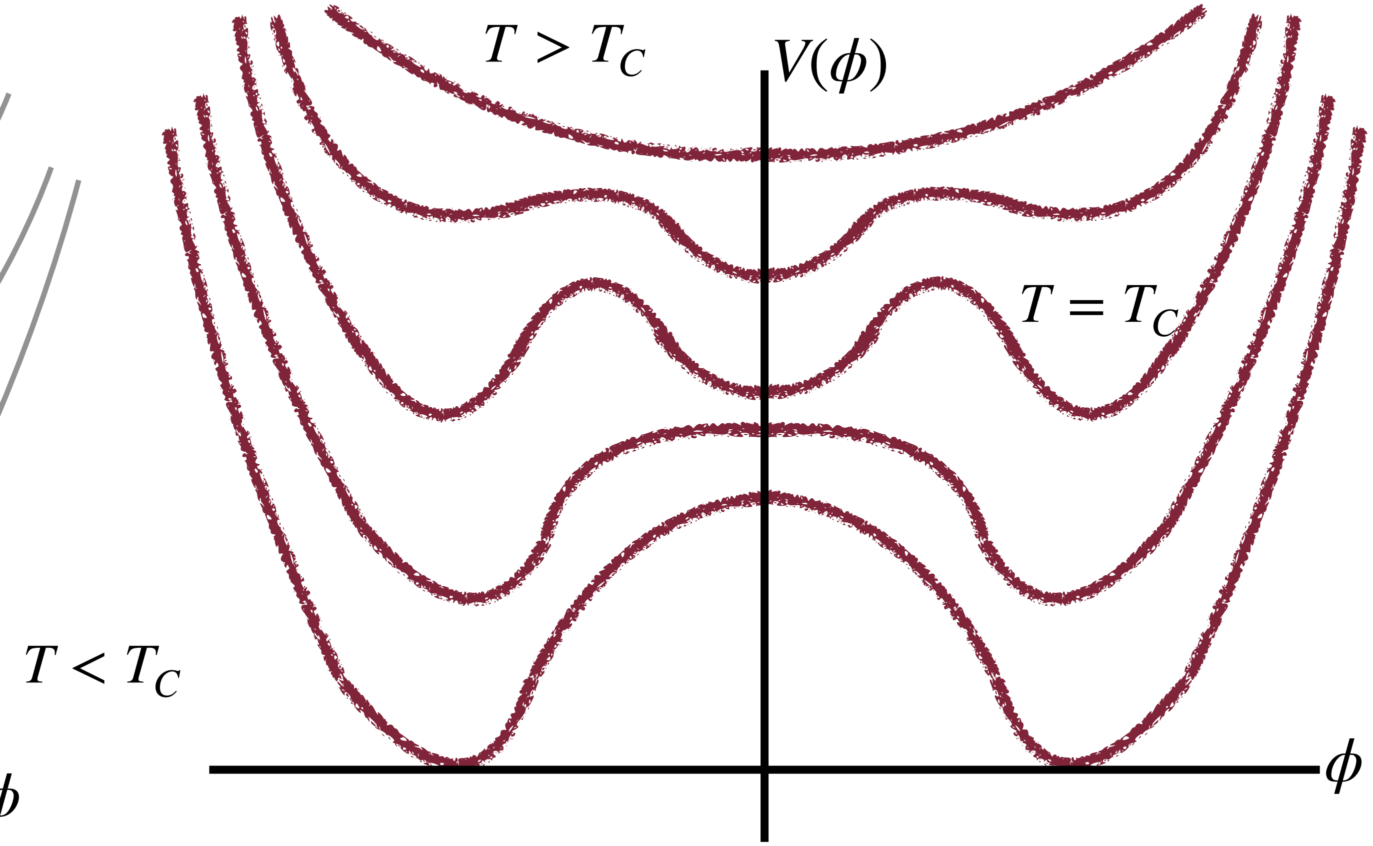
Backup

Very technical warning

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

The Electroweak Phase Transition





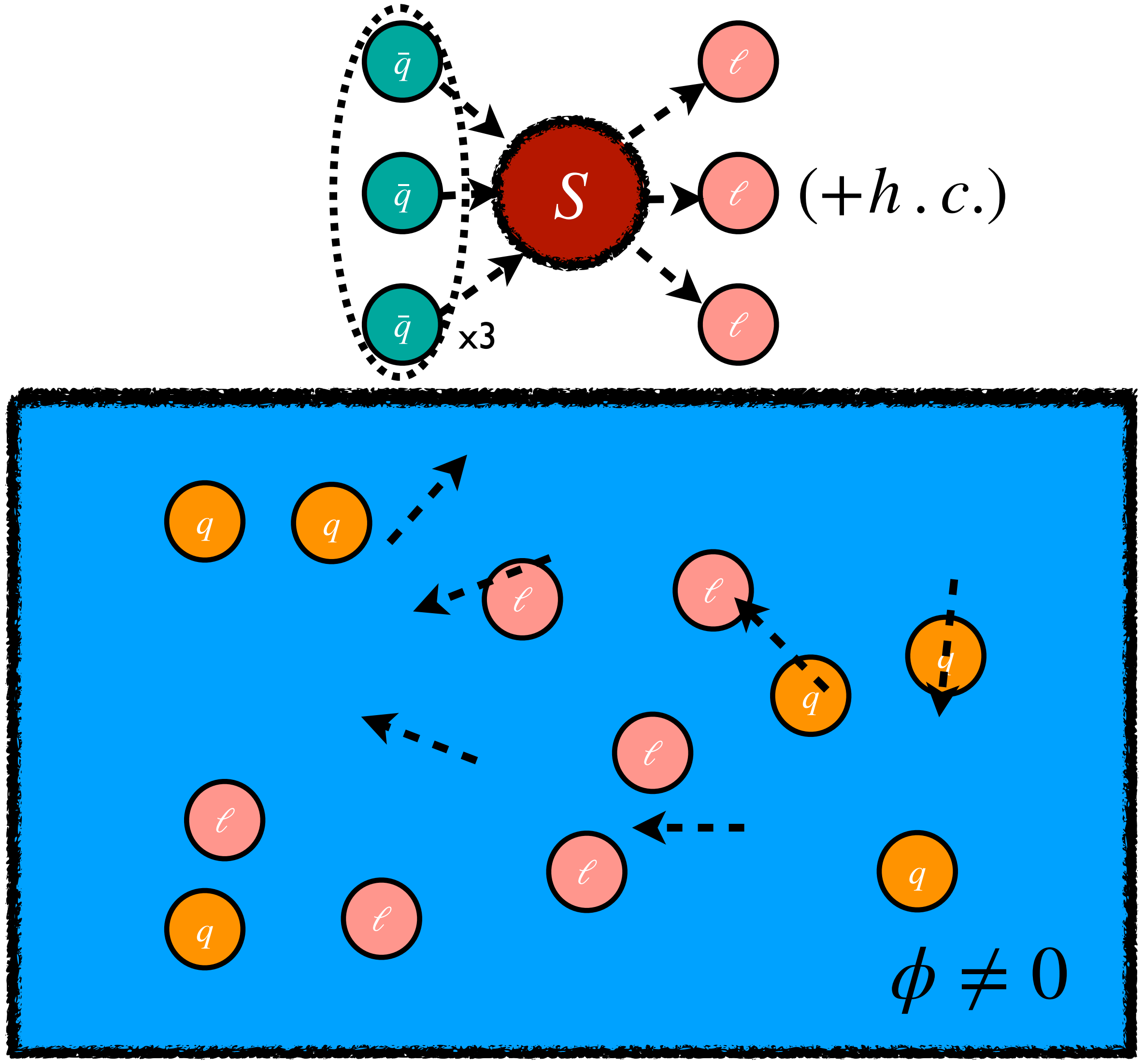
What happens as we increase the temperature:
Go back in time towards the Big Bang

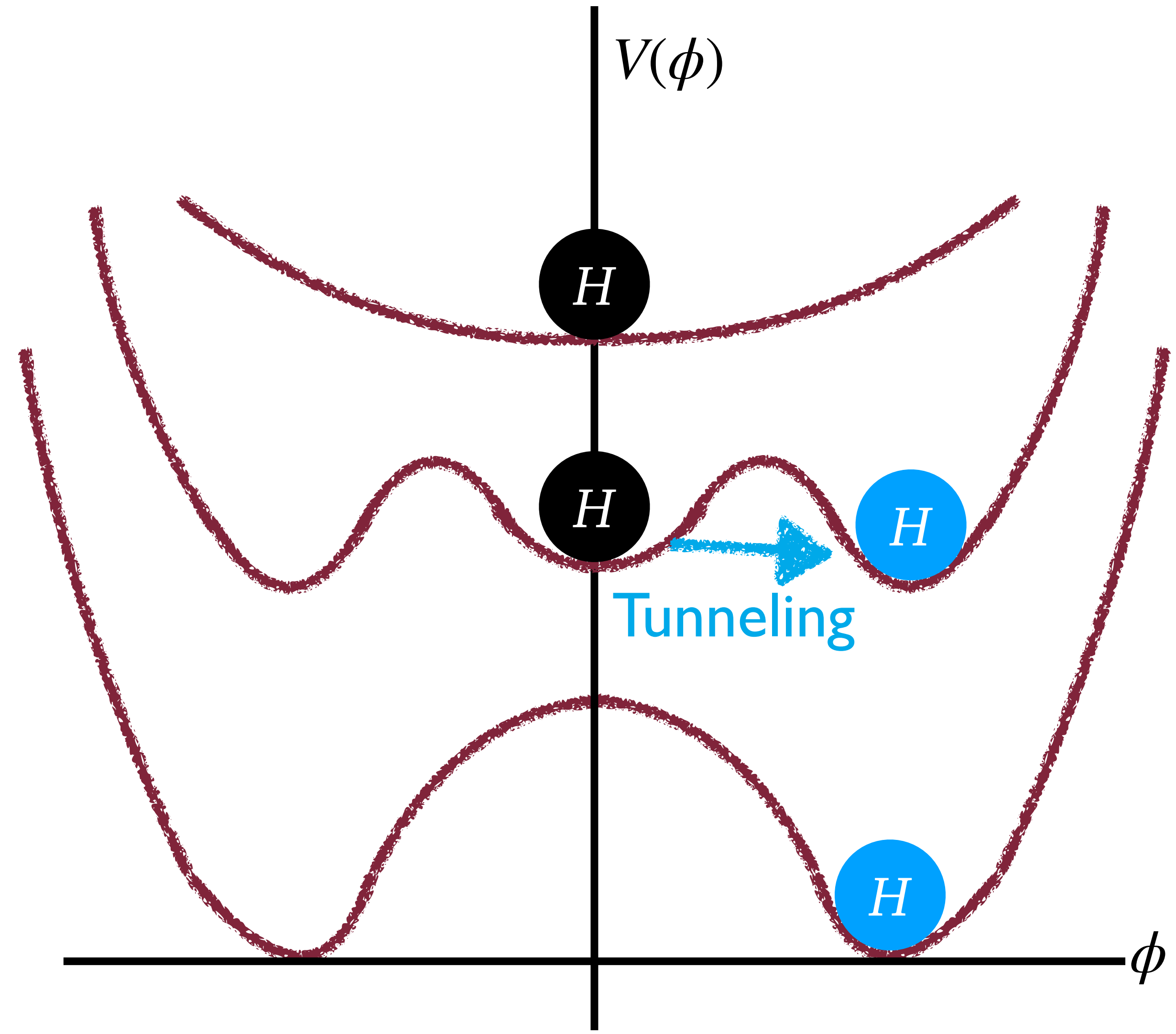
Both the SM, and modified models, undergo a **phase transition**:
Minimum at $\phi = 0$ vs $\phi \neq 0$

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

Adapted from T. Tait and G. White

Electroweak Baryogenesis





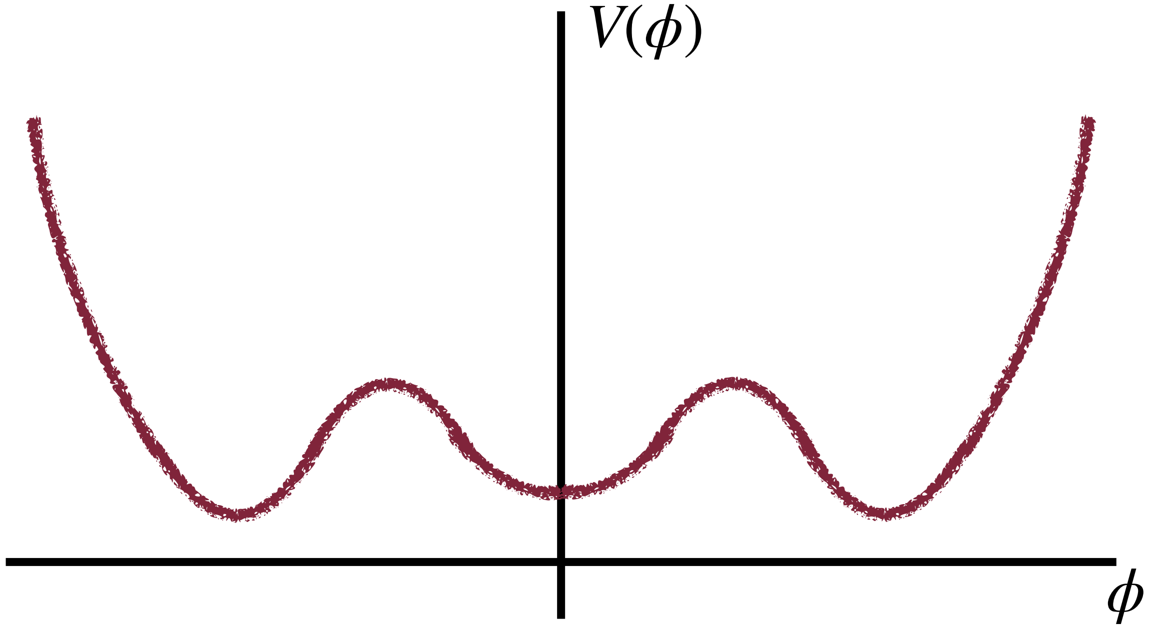
Step 0: ... $= 0$ state

symmetry, but anti-baryons have been removed

These processes ... **electroweak symmetry breaking**

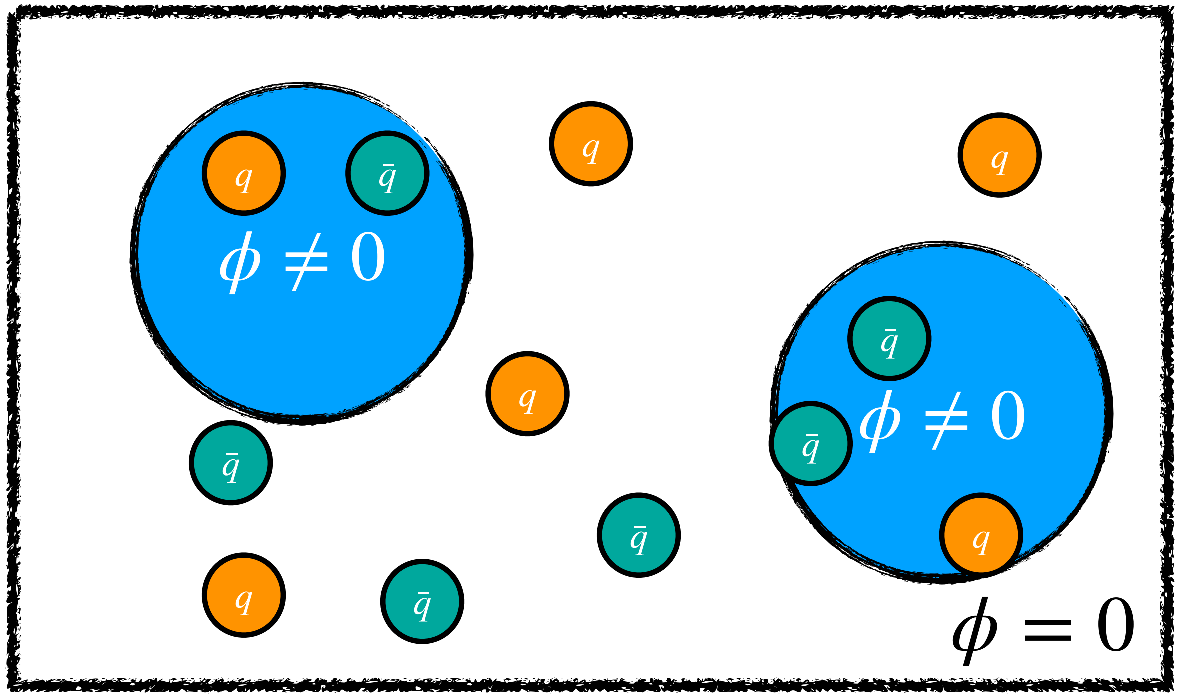
leads to matter symmetry breaking

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



We need a modified Higgs potential to enable this first order transition: κ_λ could be between 1.2 and 6 (very roughly!)

And we could see this at the LHC with di-Higgs!

End very technical warning

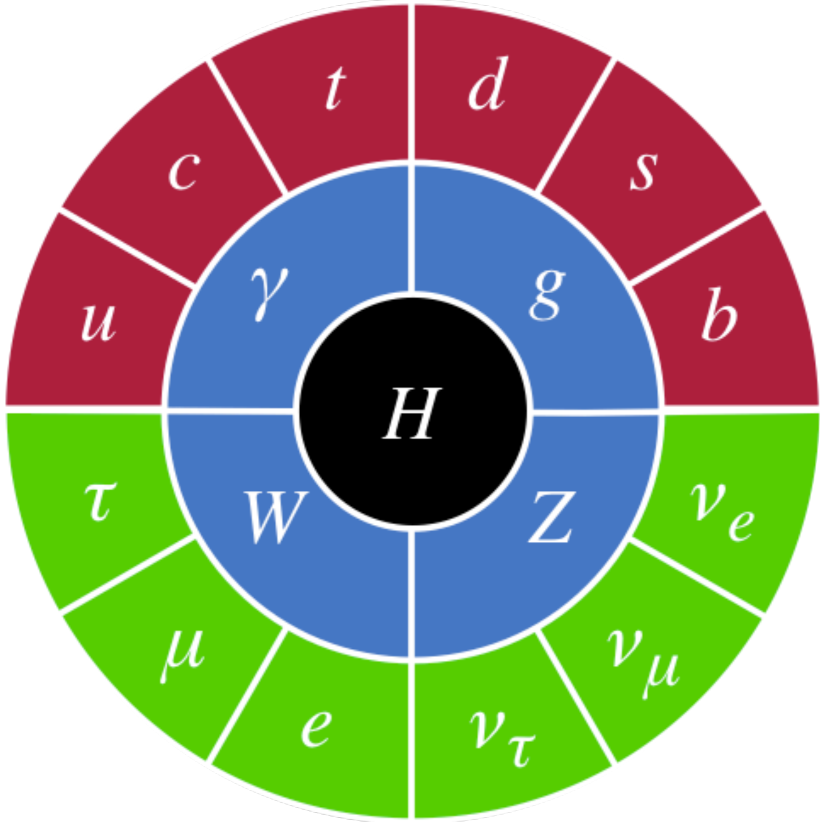
Summary: changes in the Higgs potential can explain matter/anti-matter asymmetry via a process called "**Electroweak Baryogenesis**"

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

The Higgs is still new and not fully explored

What can we learn from this new particle?

We can measure the Higgs potential



The SM leaves huge questions:

Is the universe stable?

Where's the missing anti-matter?

The shape of the Higgs potential may be key to the **birth and death** of the universe

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