

Latest Results from ATLAS and Higgs Self- Coupling Measurements

TRIUMF Science Week

Maximilian Swiatlowski

TRIUMF



Physics at the LHC



Physics at the LHC



Protons circulate in bunches around a 27 km ring

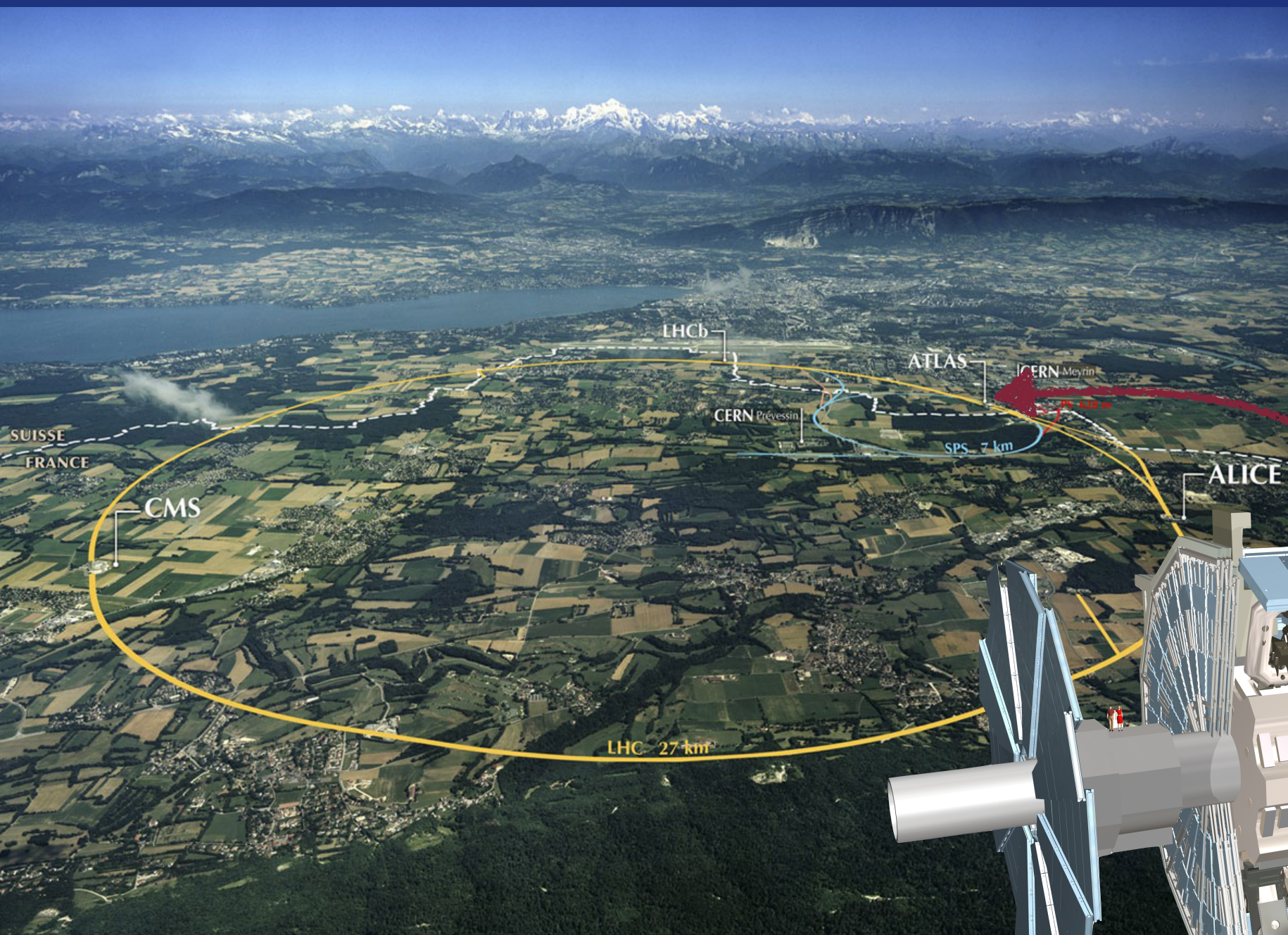
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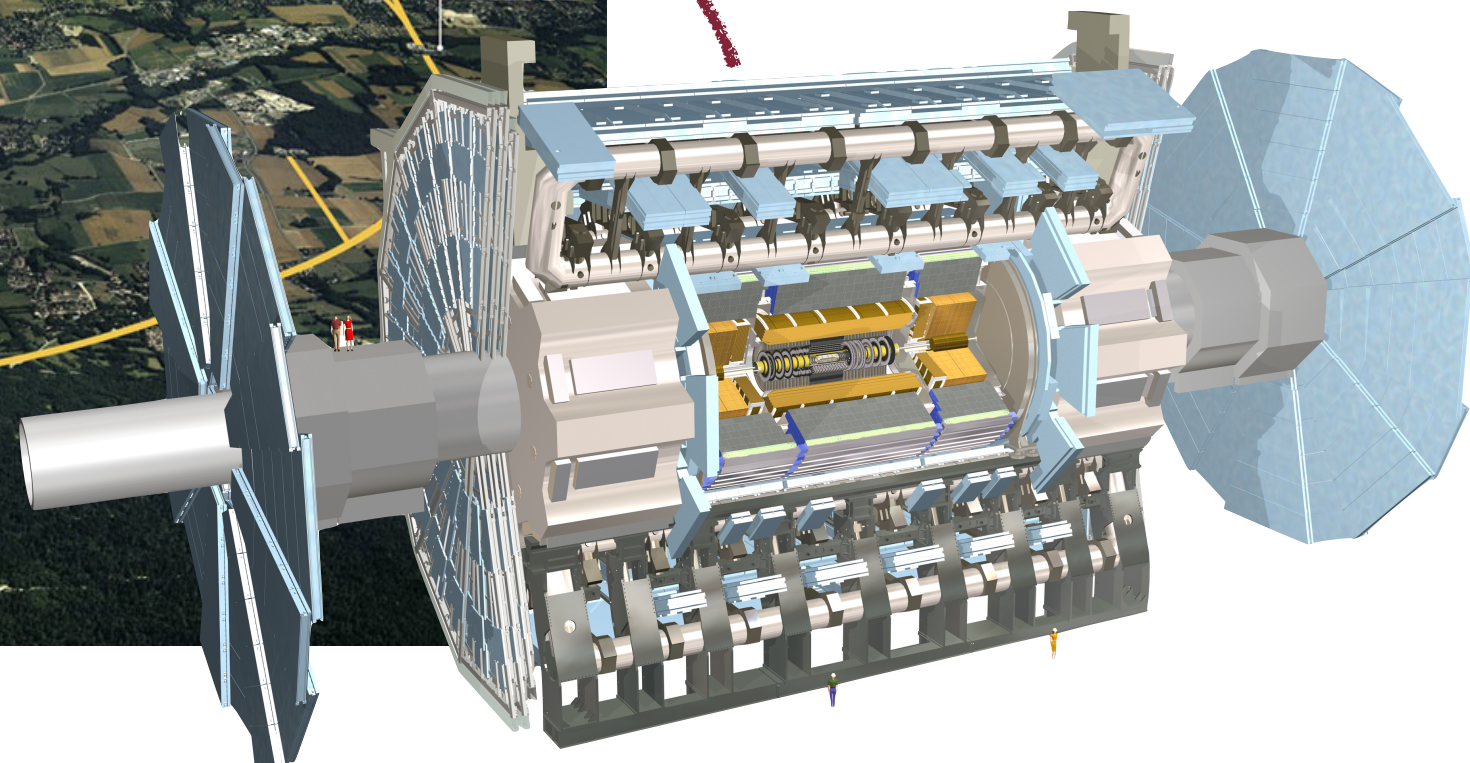
Collide protons at $\sqrt{s} = 13 \text{ TeV}$

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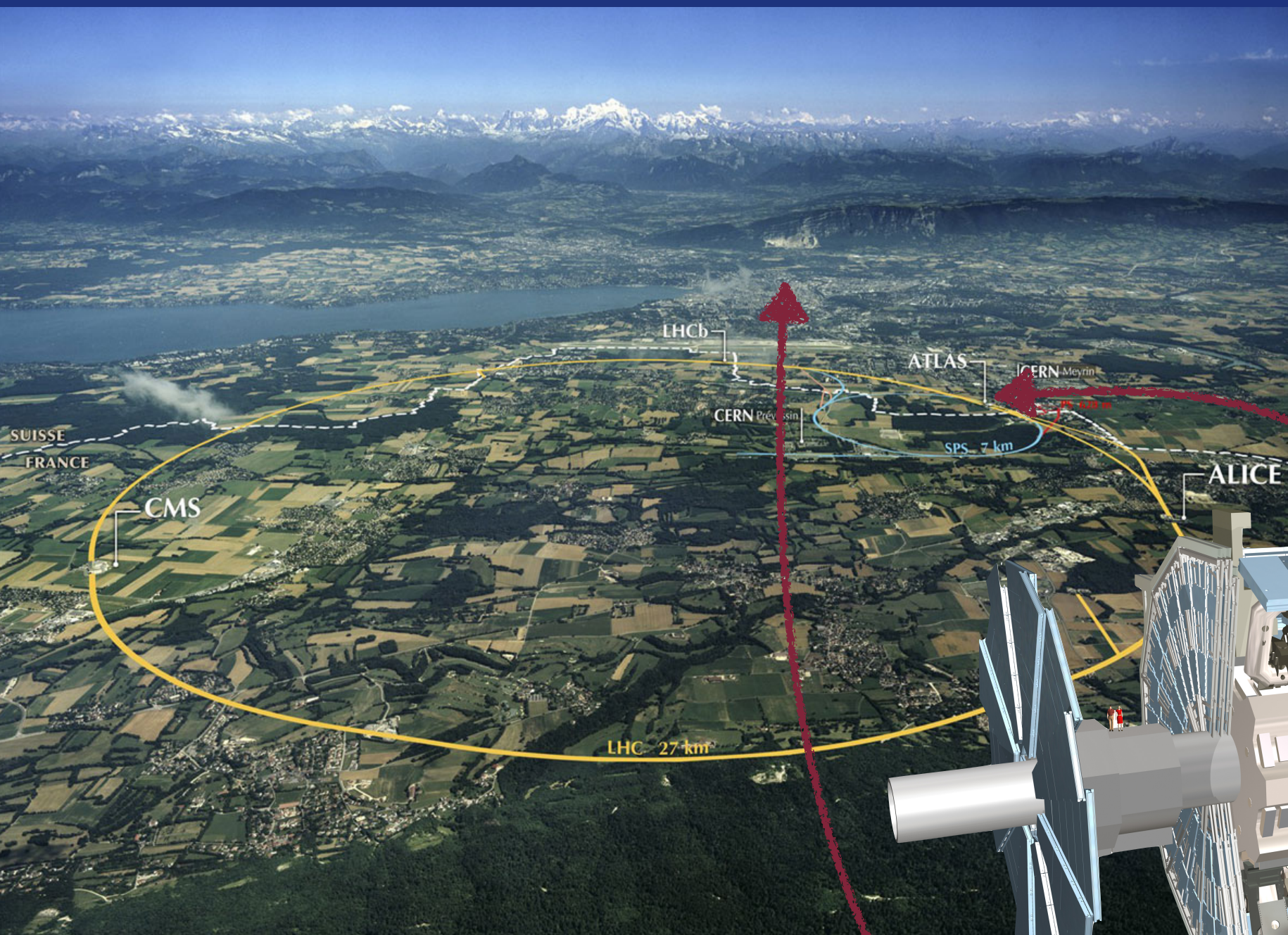
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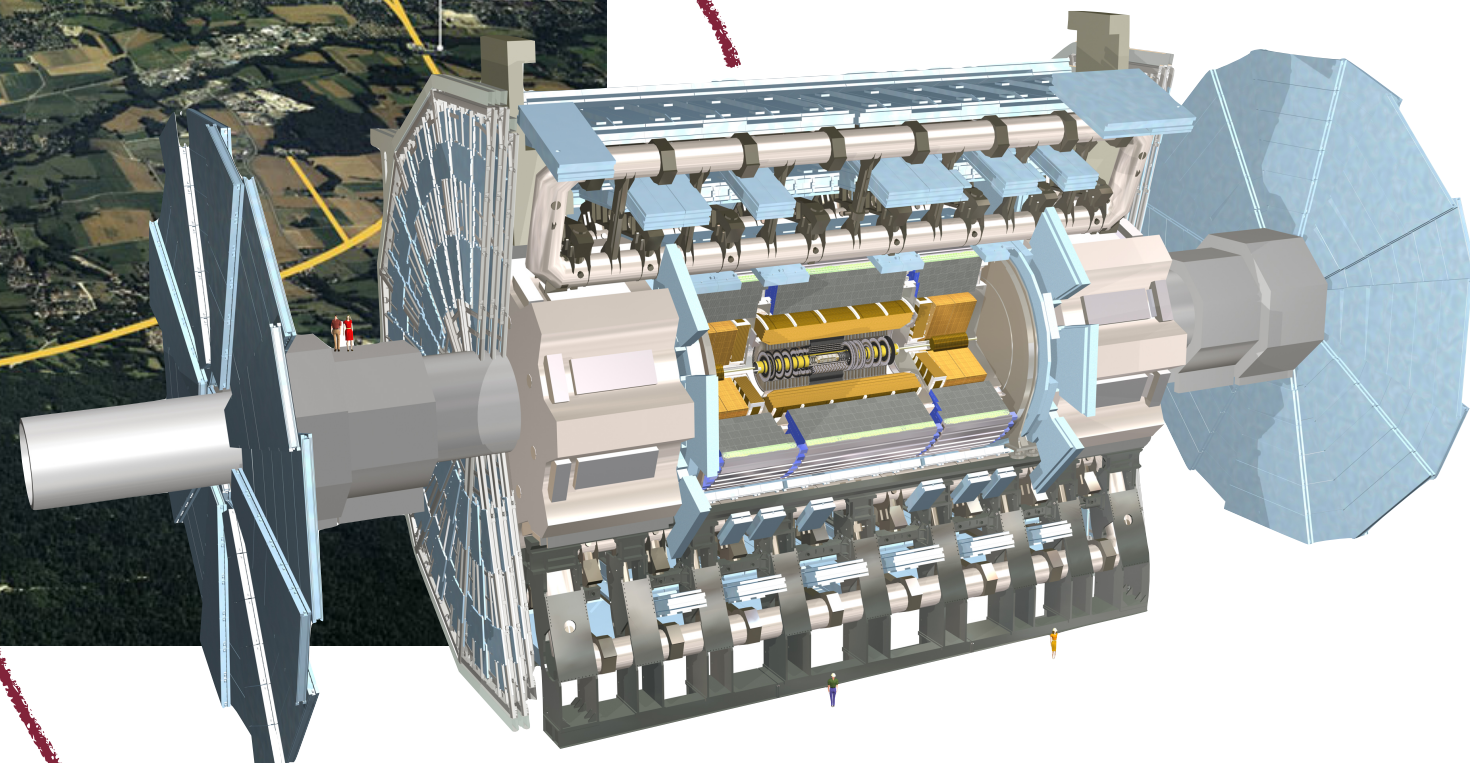
Measure collisions with the **ATLAS detector**

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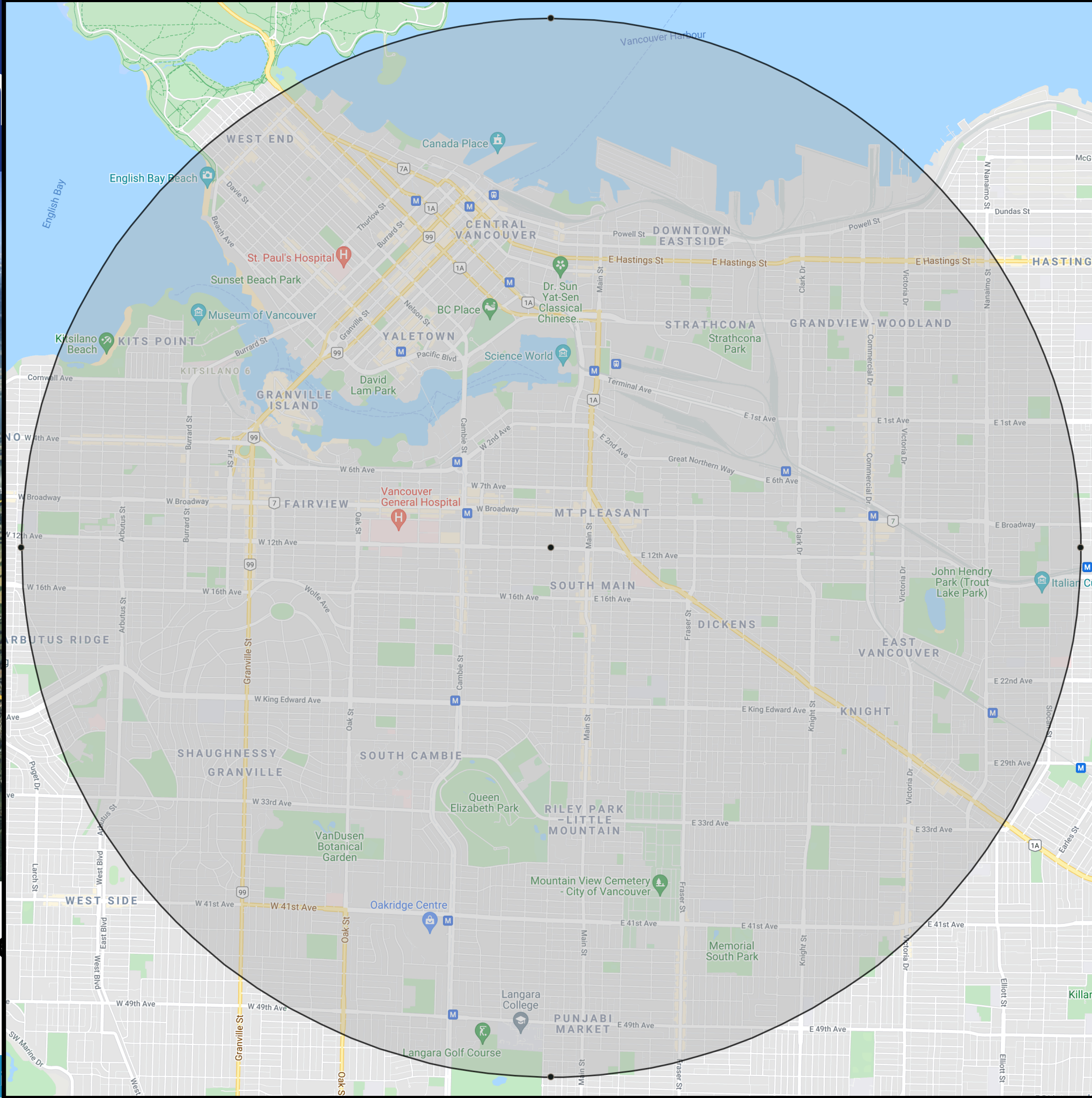
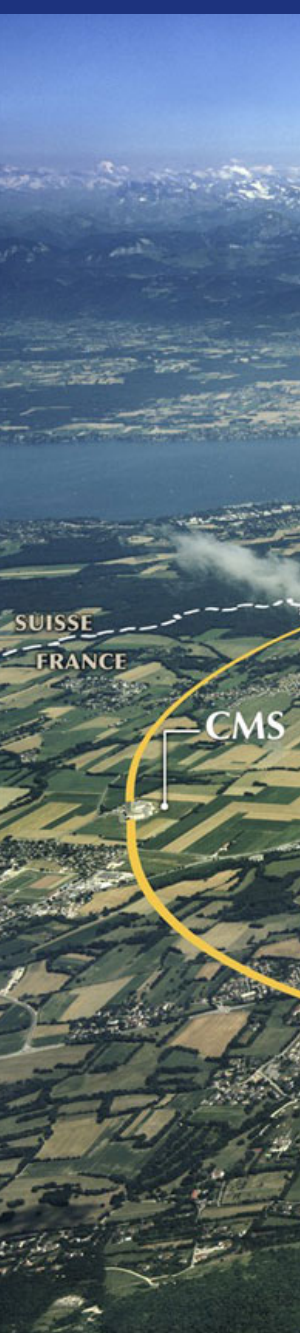
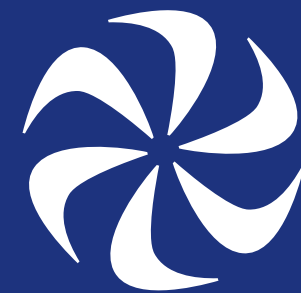
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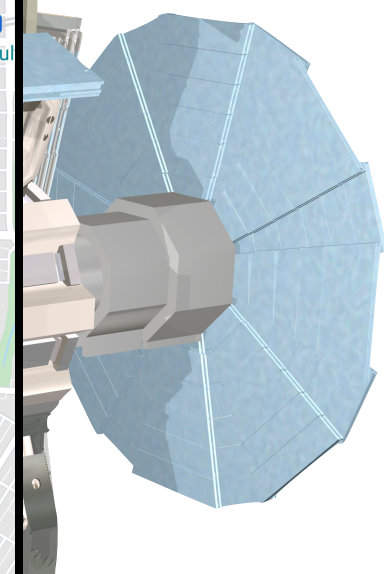
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I live here (moving to Van in one month!)

Ph



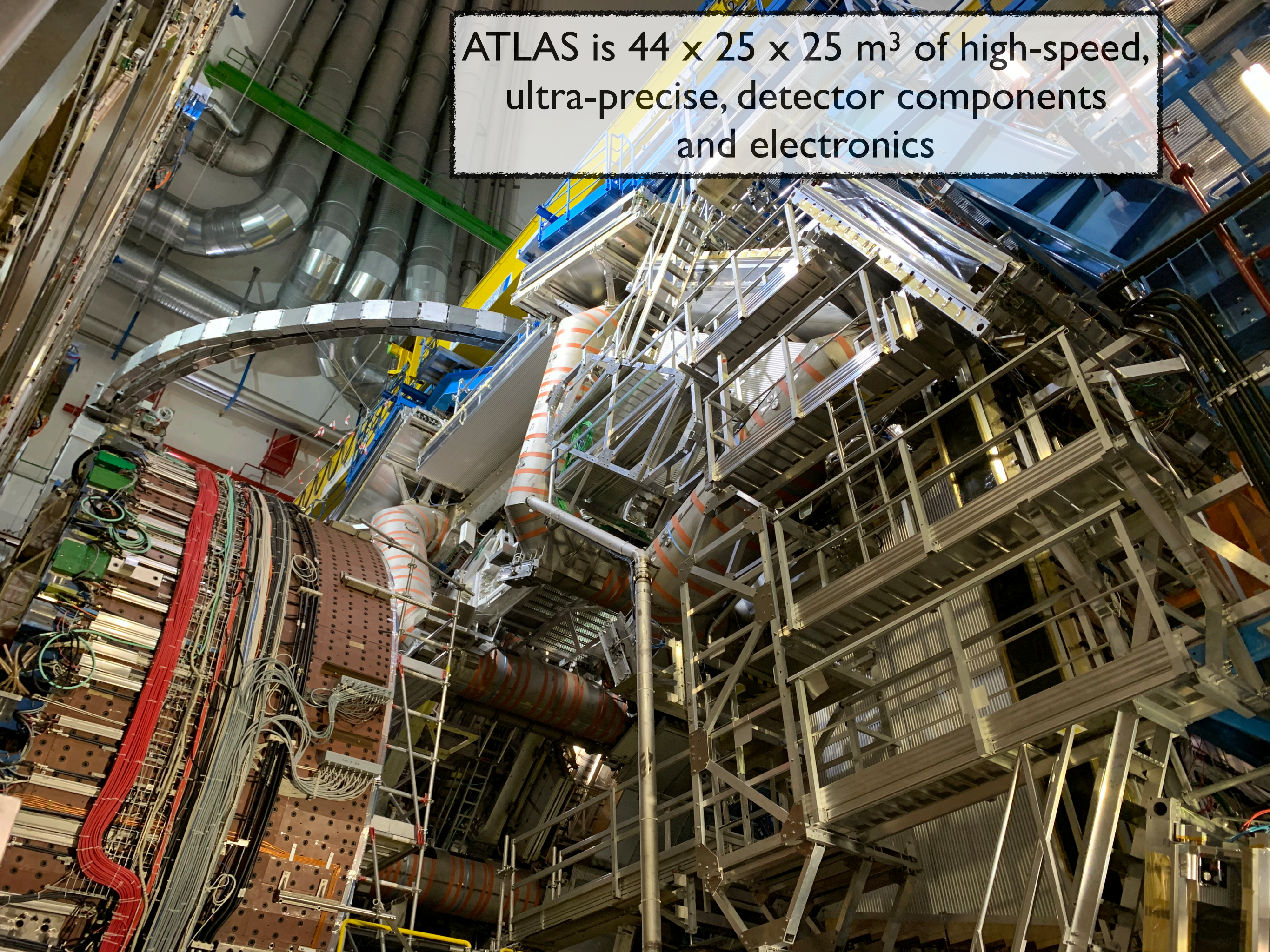
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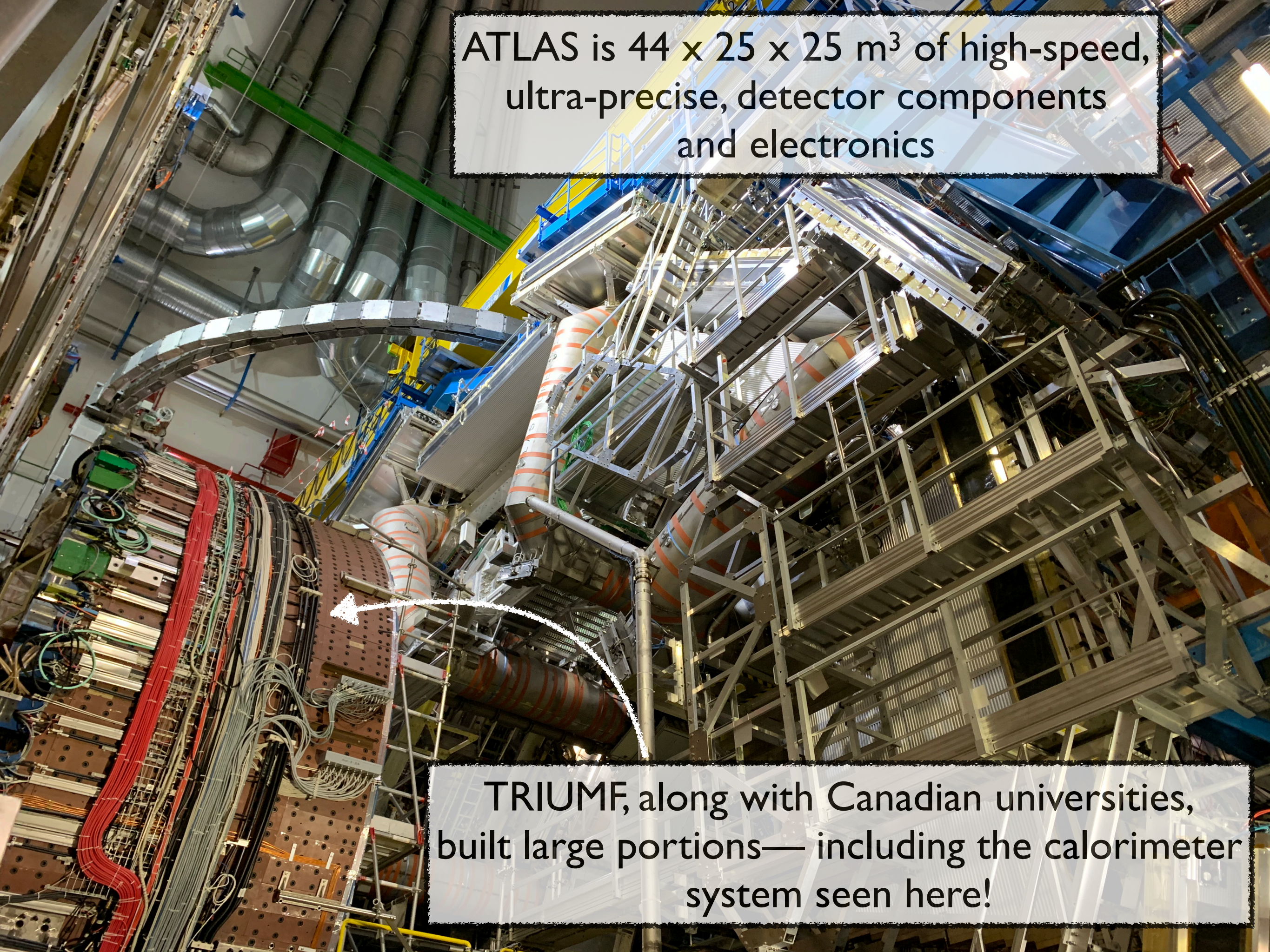


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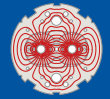
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TRIUMF, along with Canadian universities, built large portions— including the calorimeter system seen here!

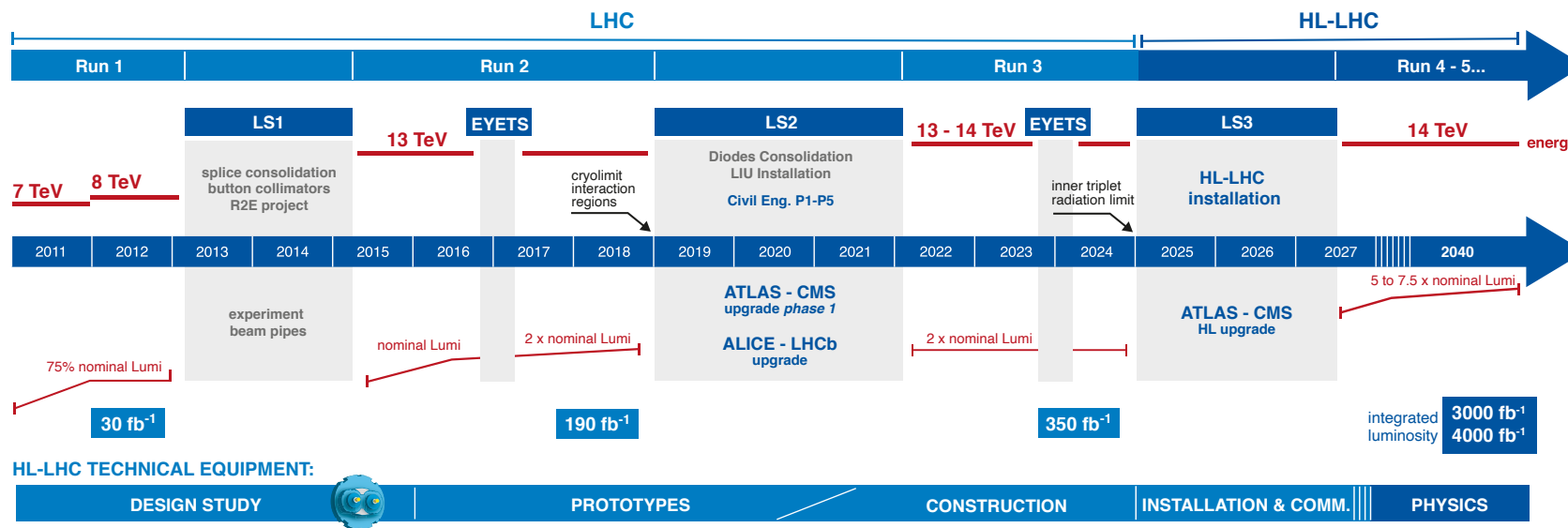
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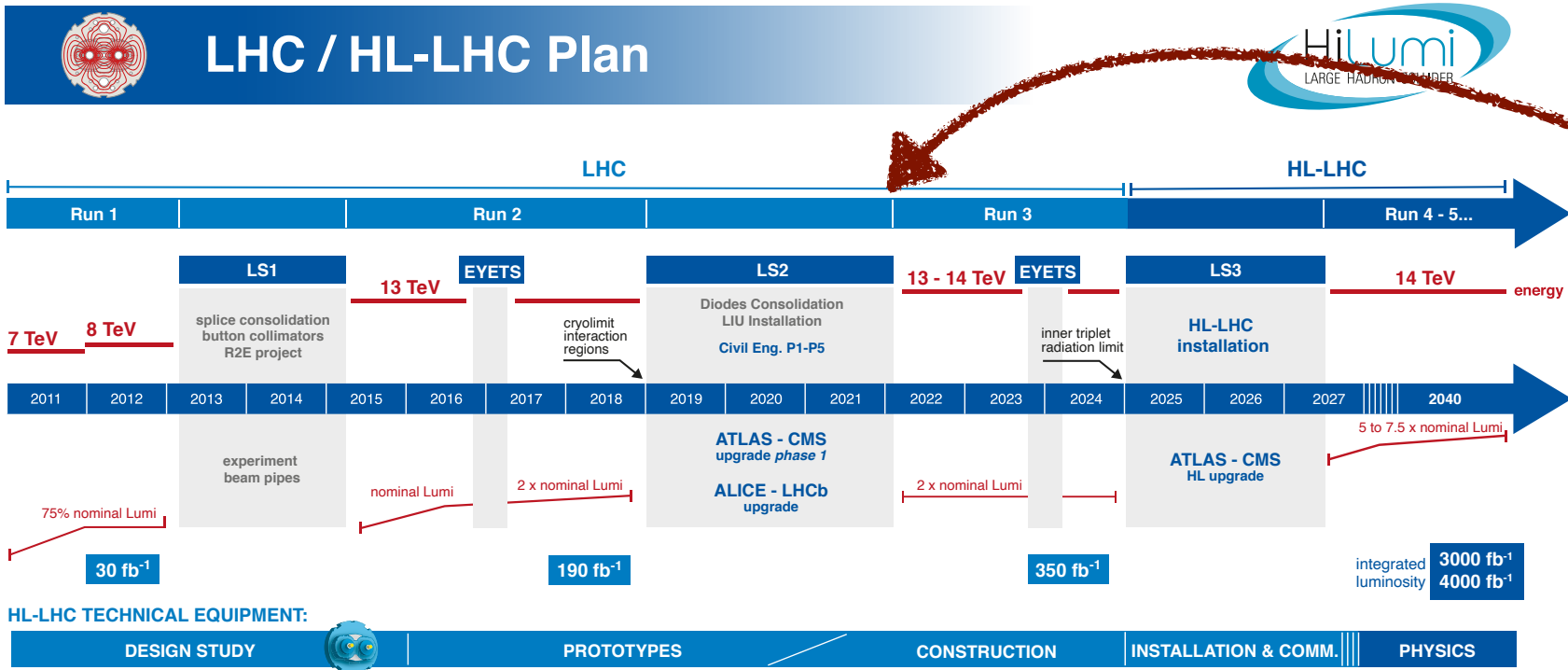
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LHC / HL-LHC Plan

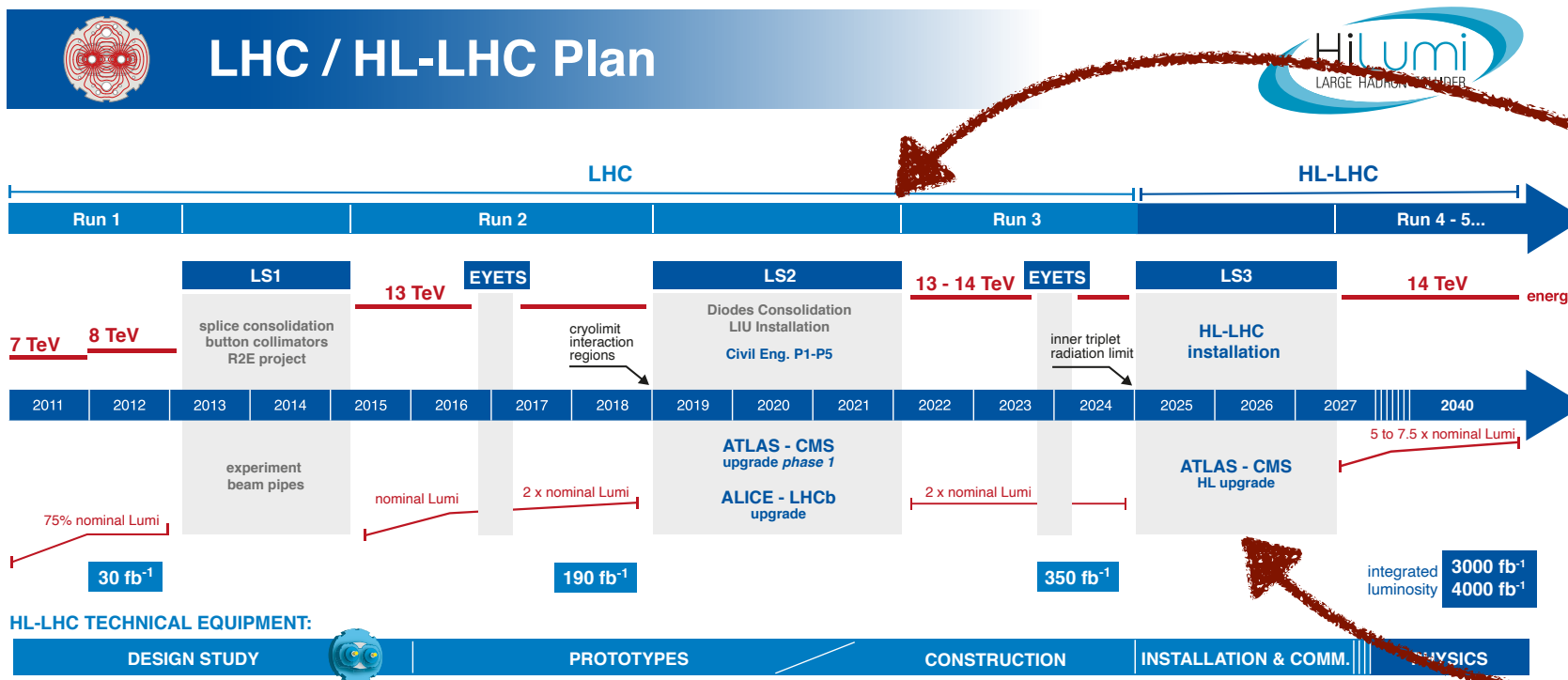
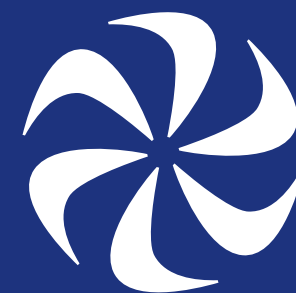


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Run3 about to start!

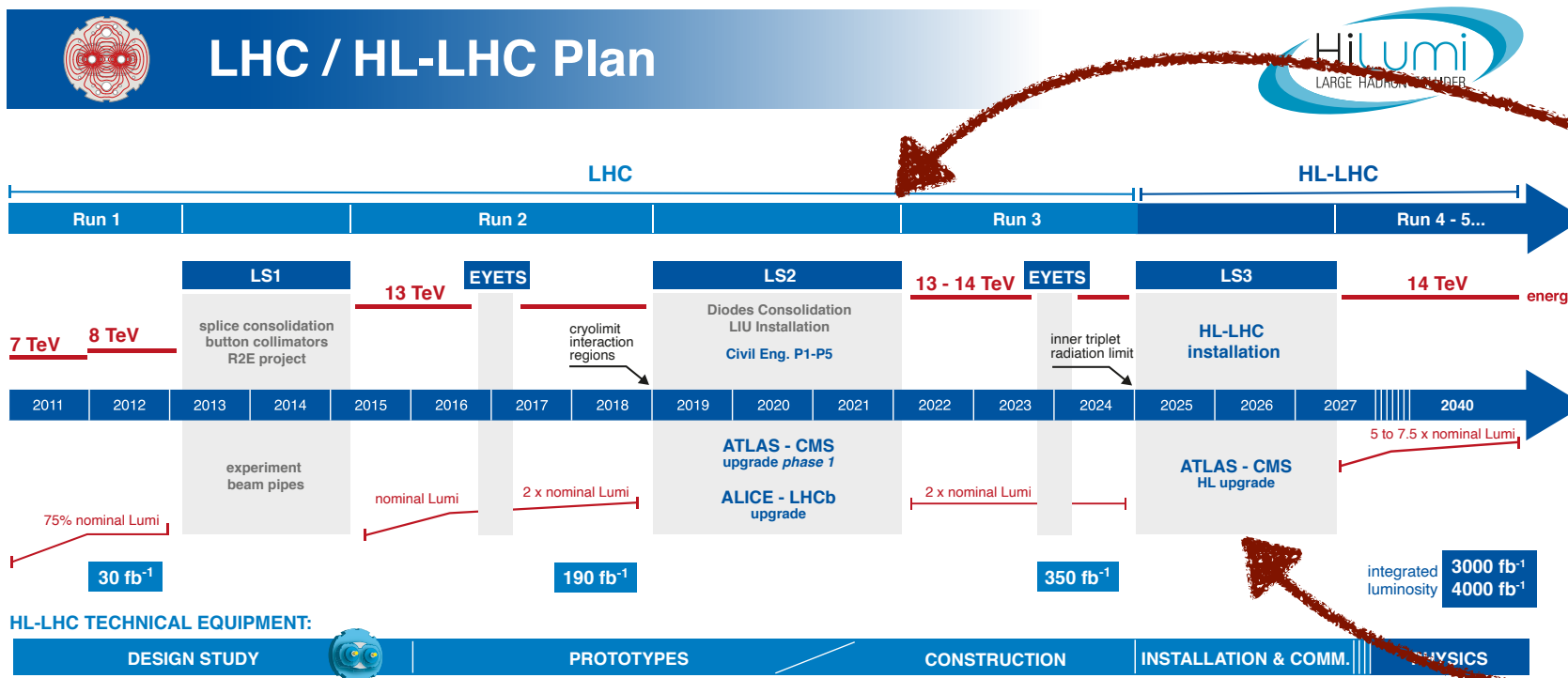
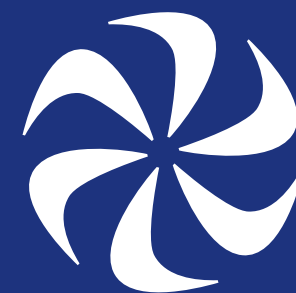
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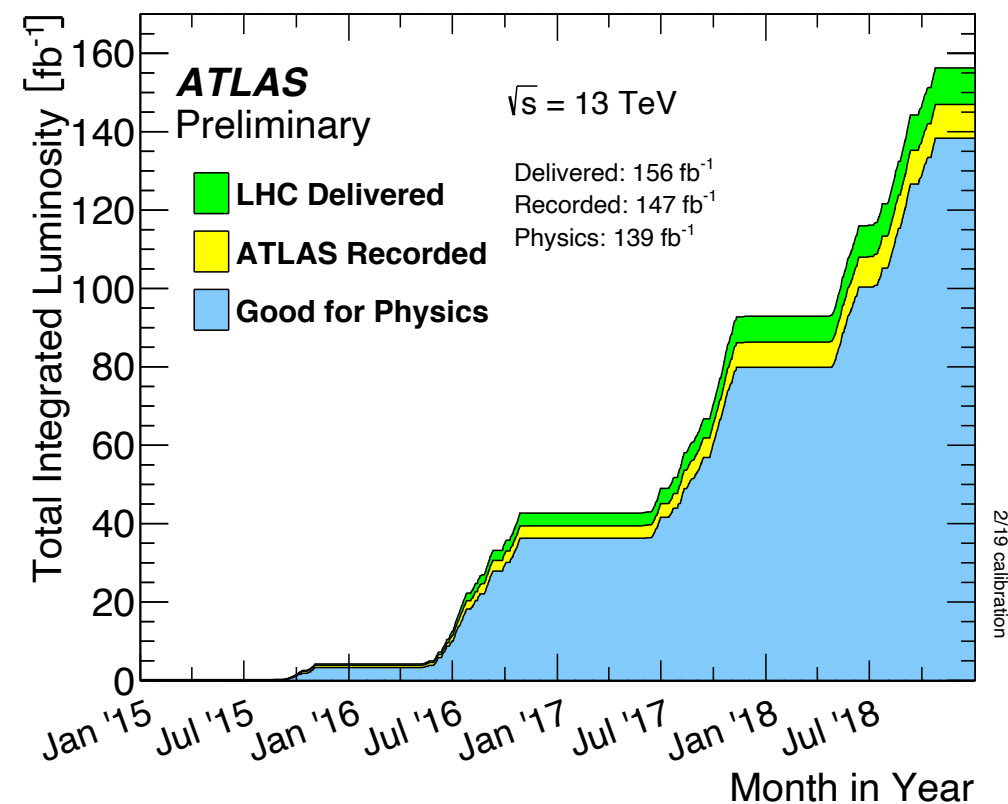
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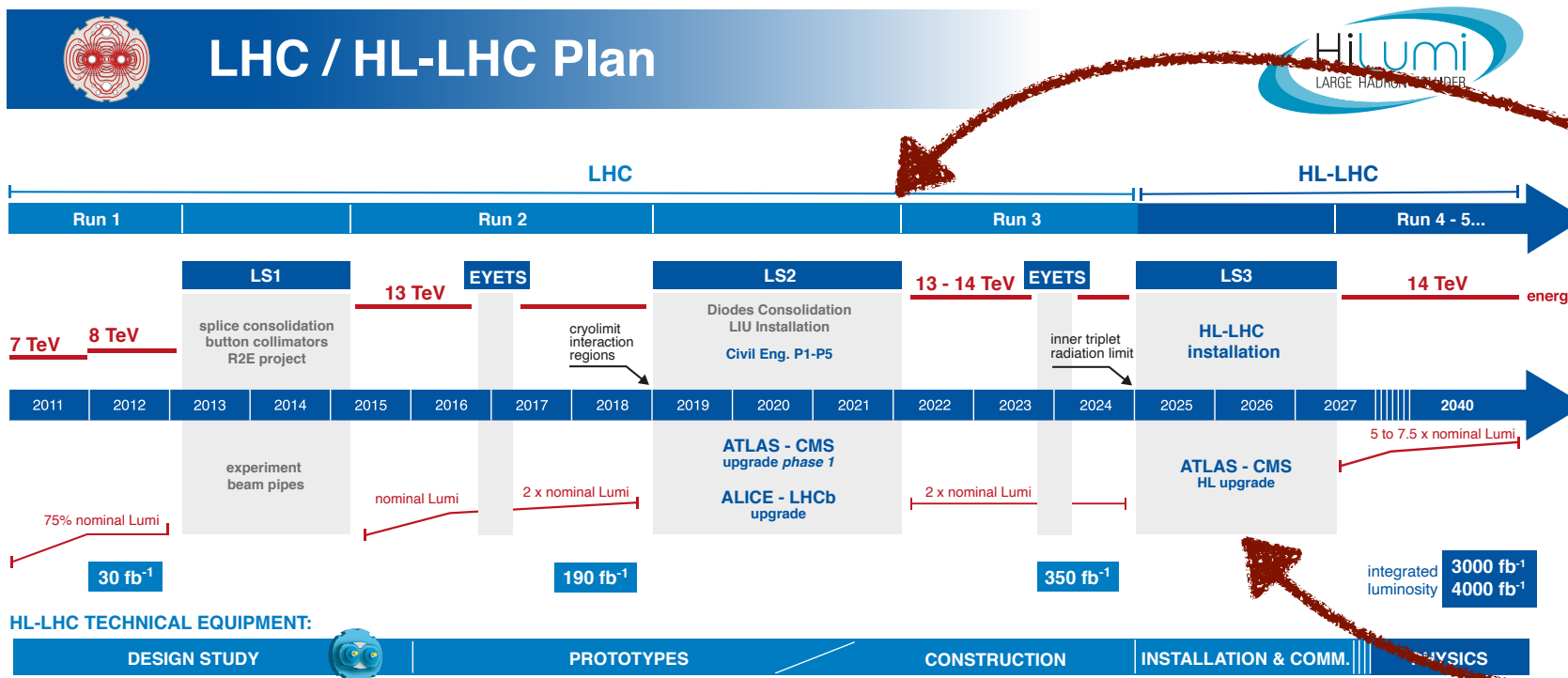
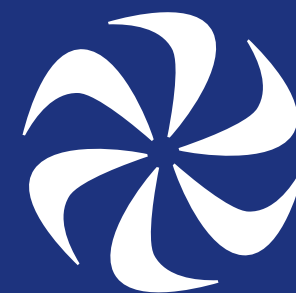
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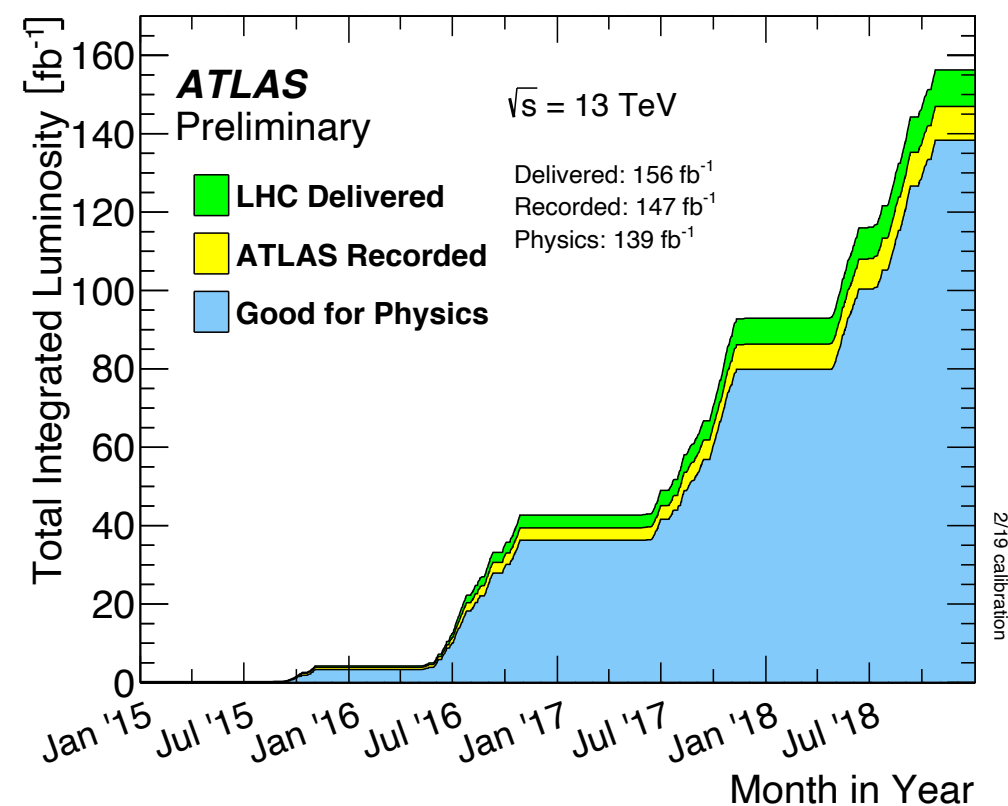


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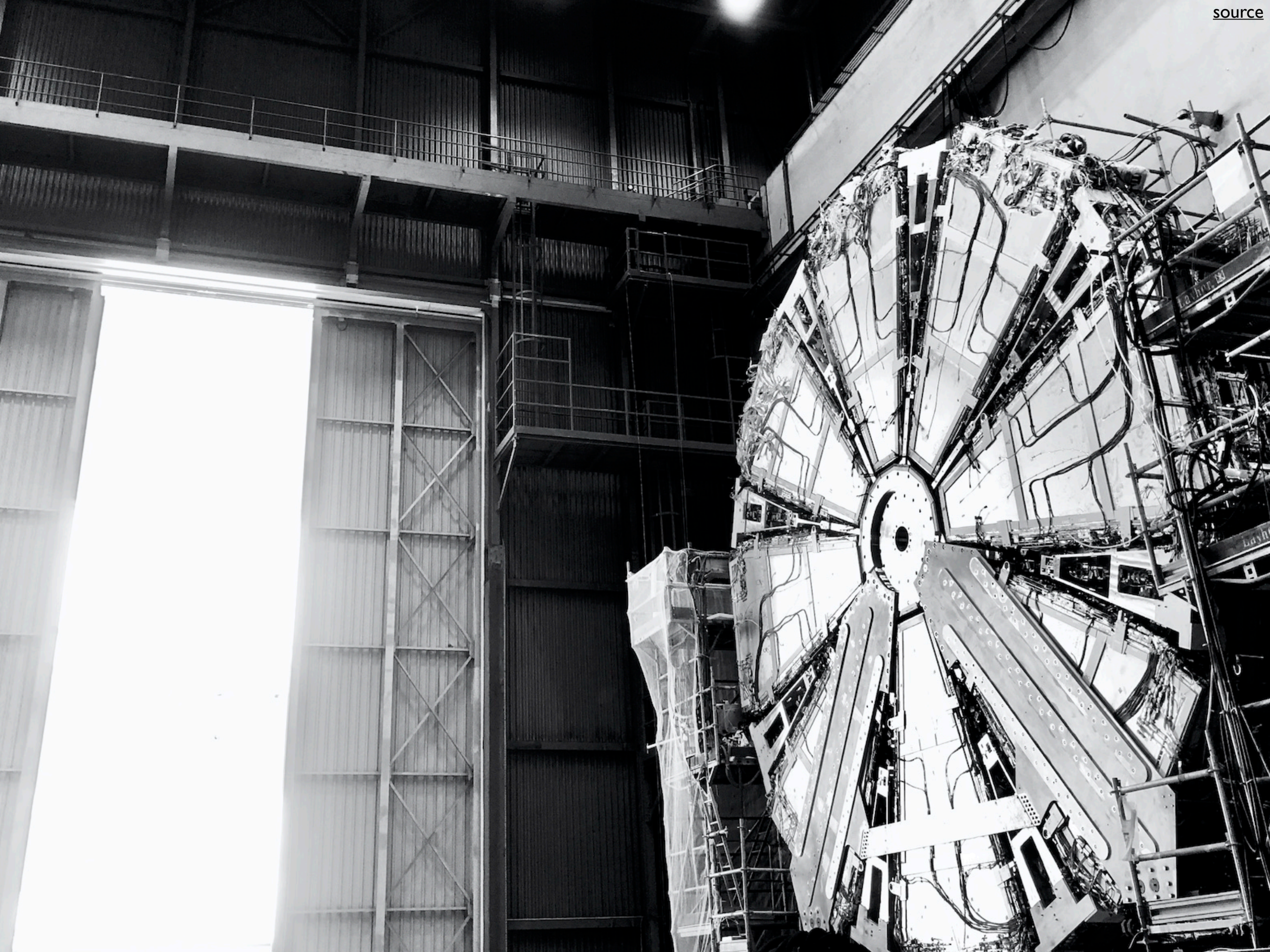
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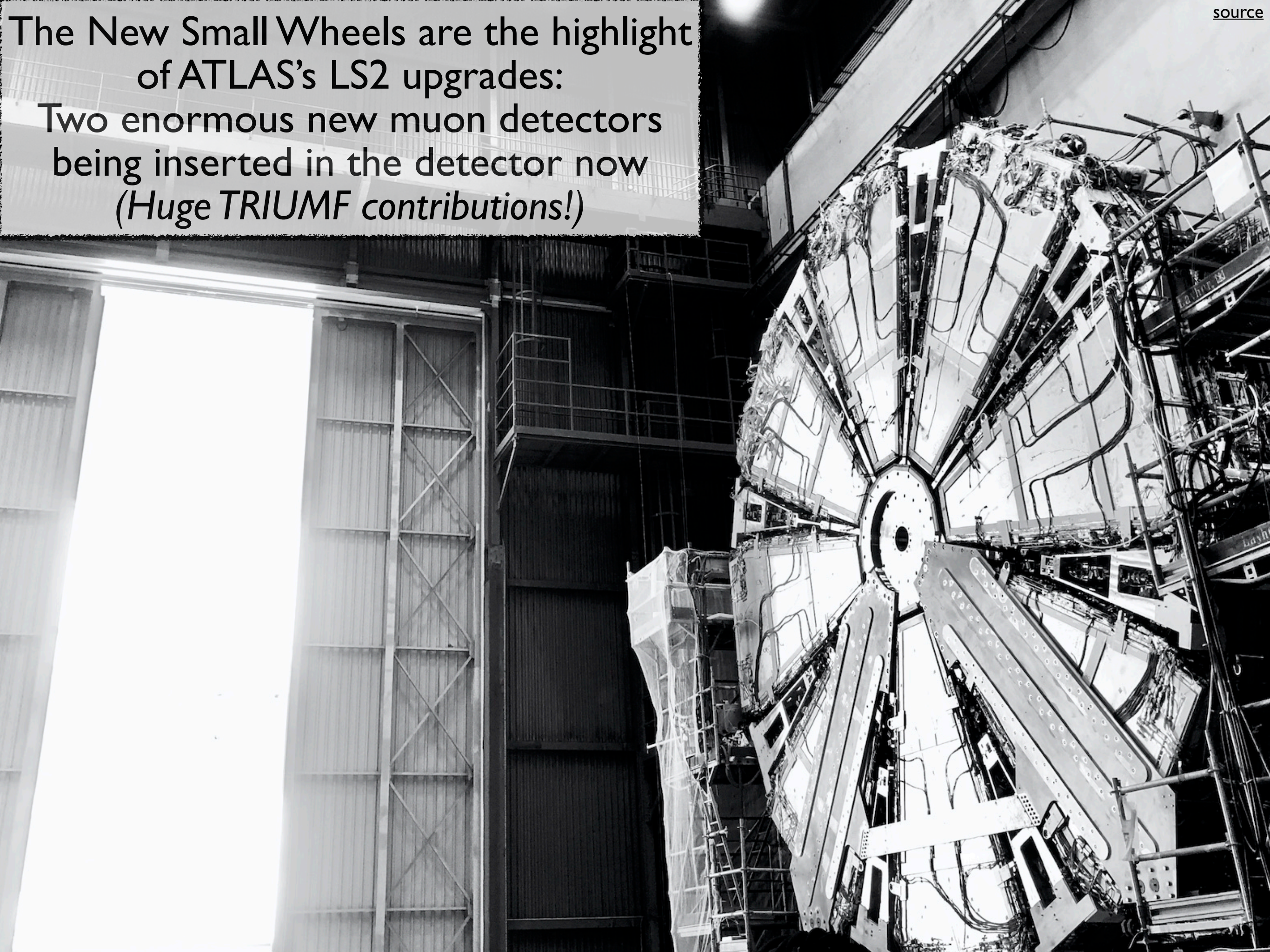
139 fb⁻¹ of data: huge dataset for measurement and discovery



Latest ATLAS Highlights

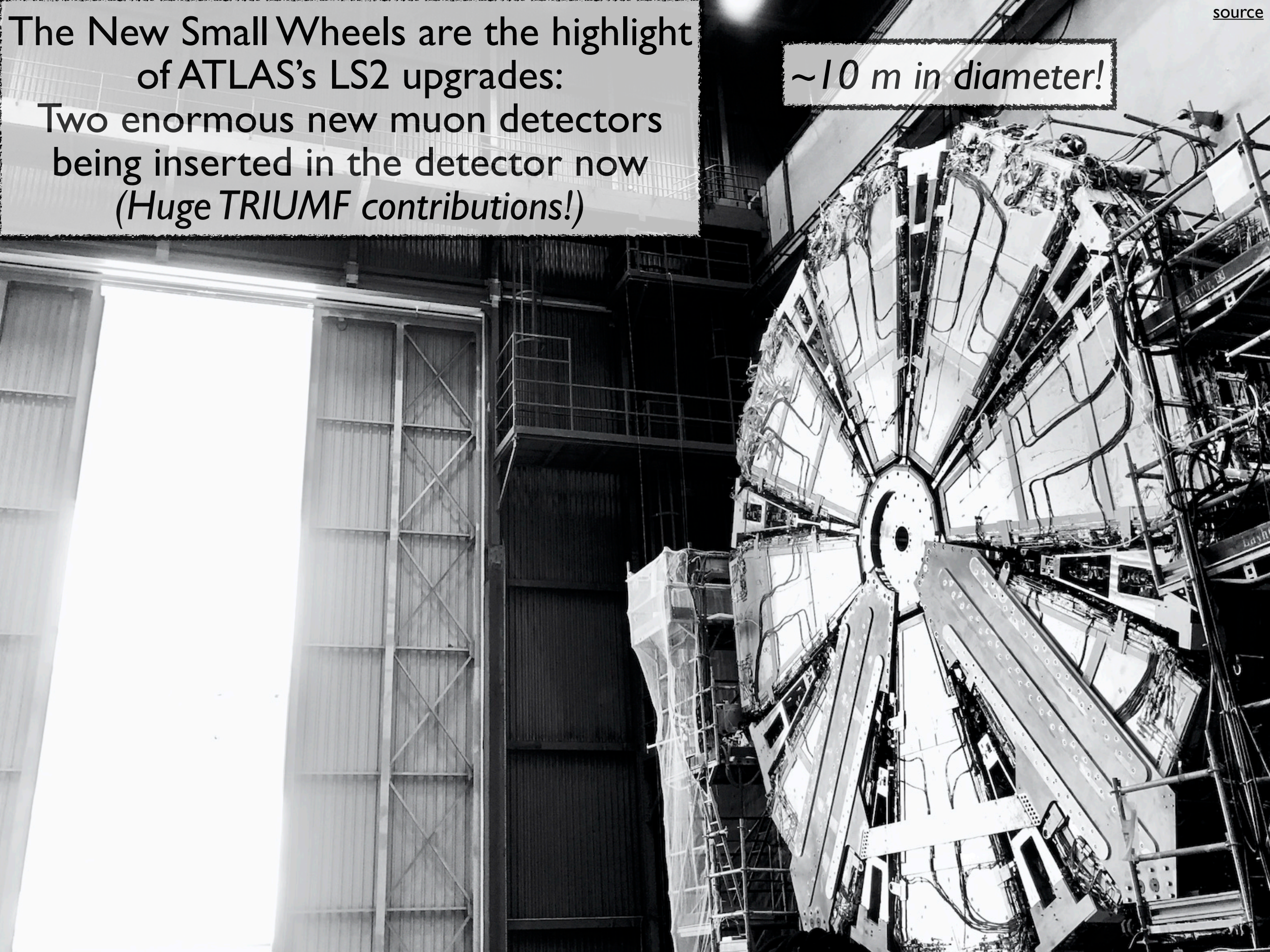


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Two enormous new muon detectors being inserted in the detector now
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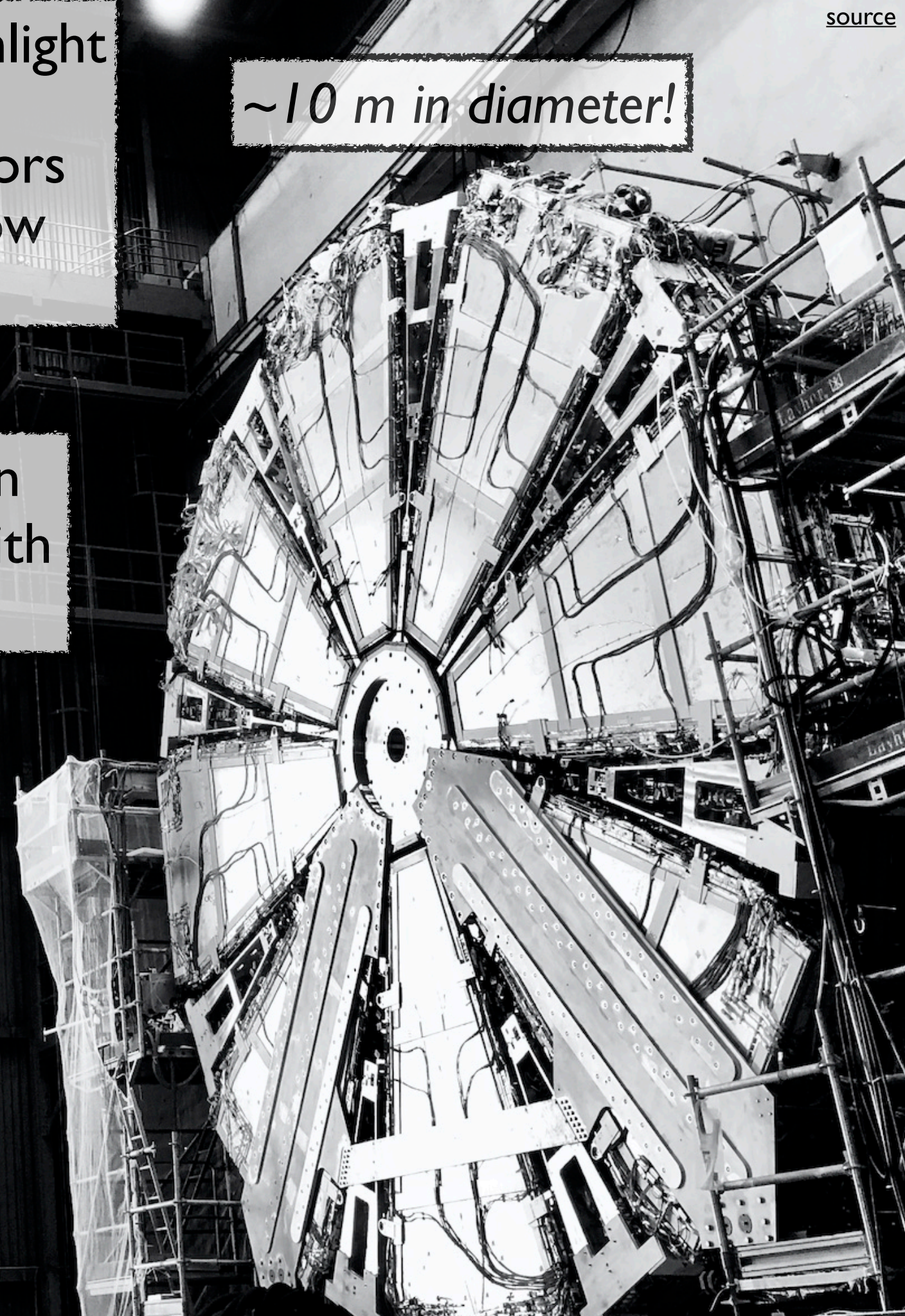
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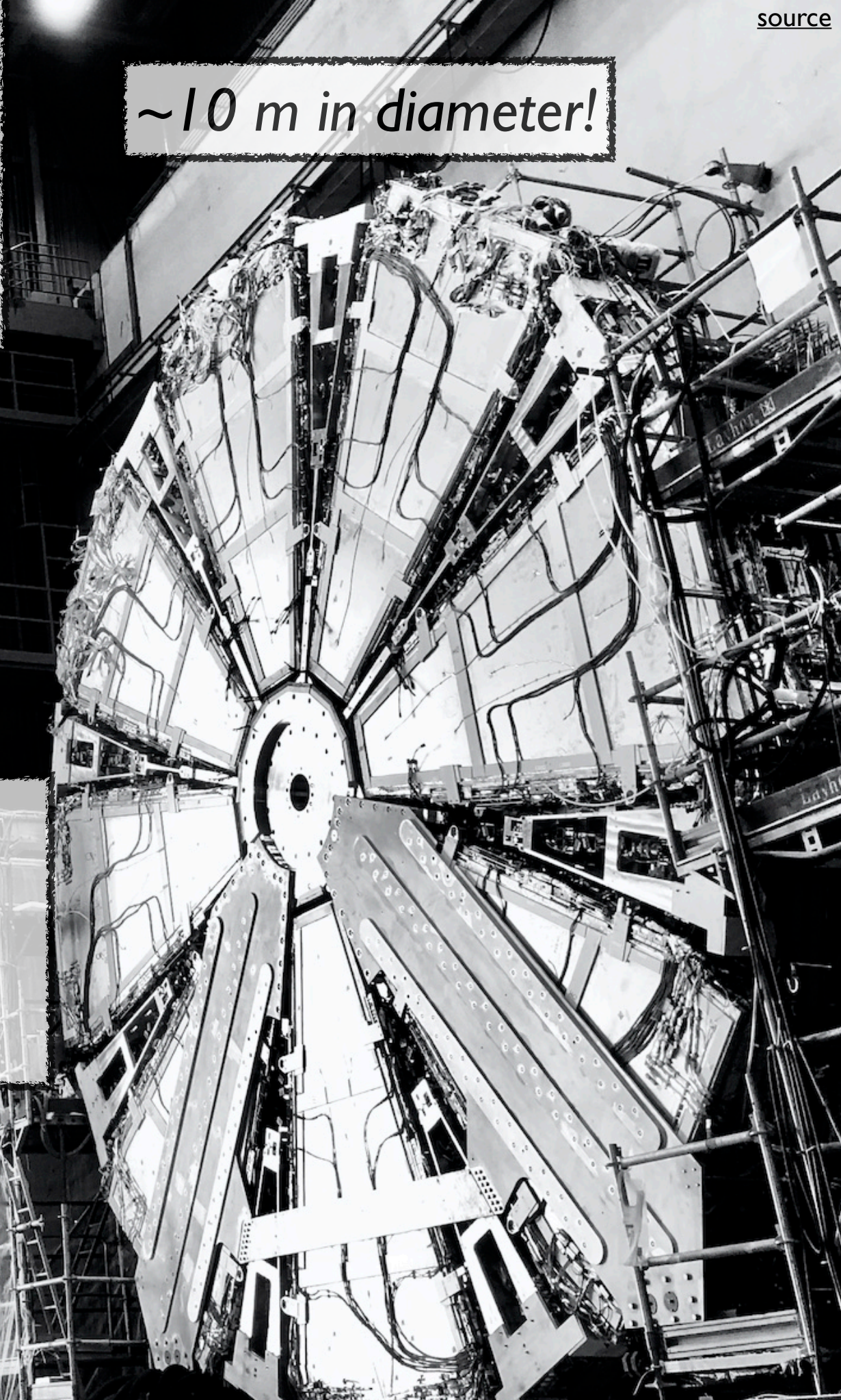
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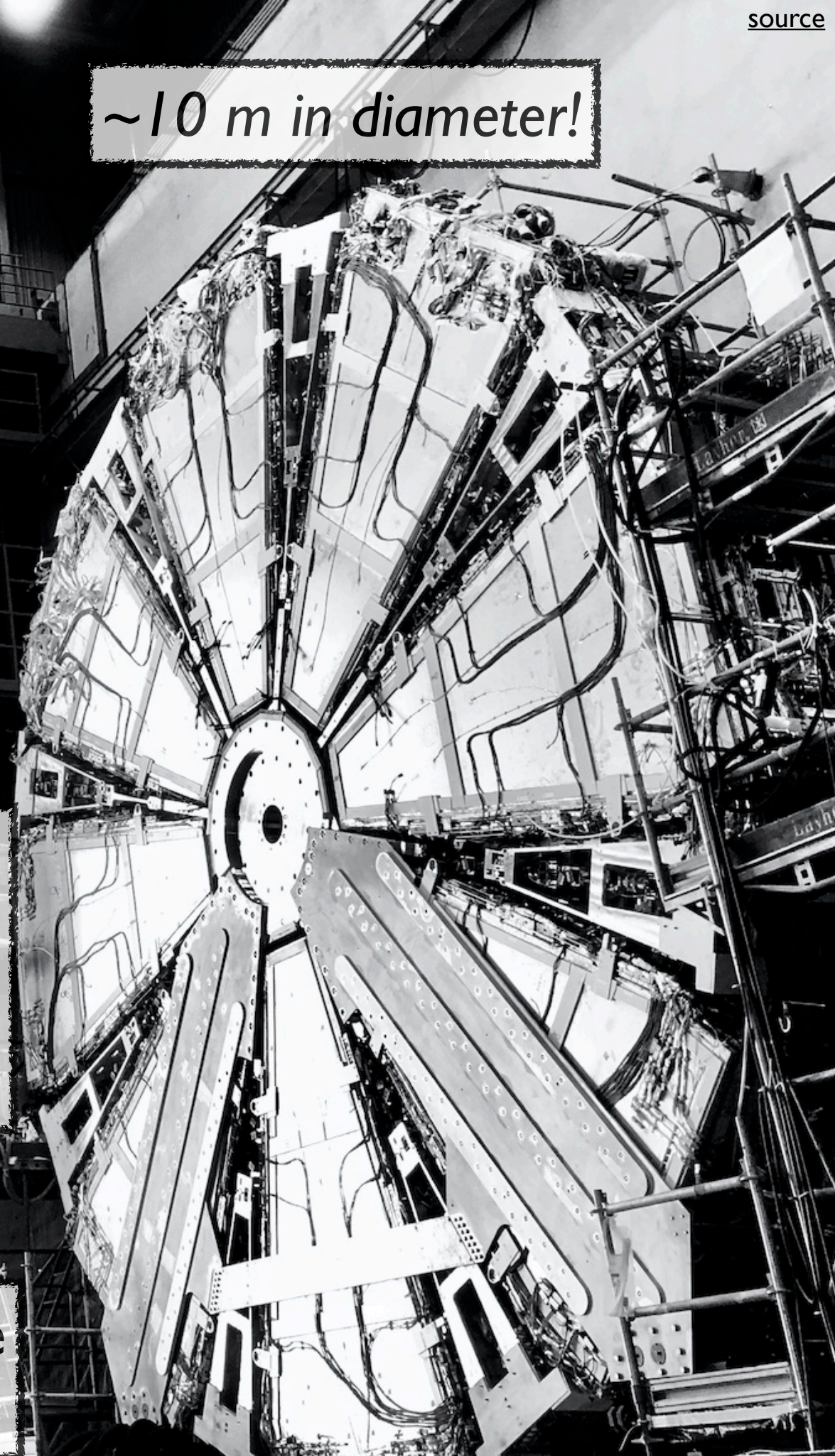
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Dozens of new results this summer: some highlights today!



Higgs Boson Measurements



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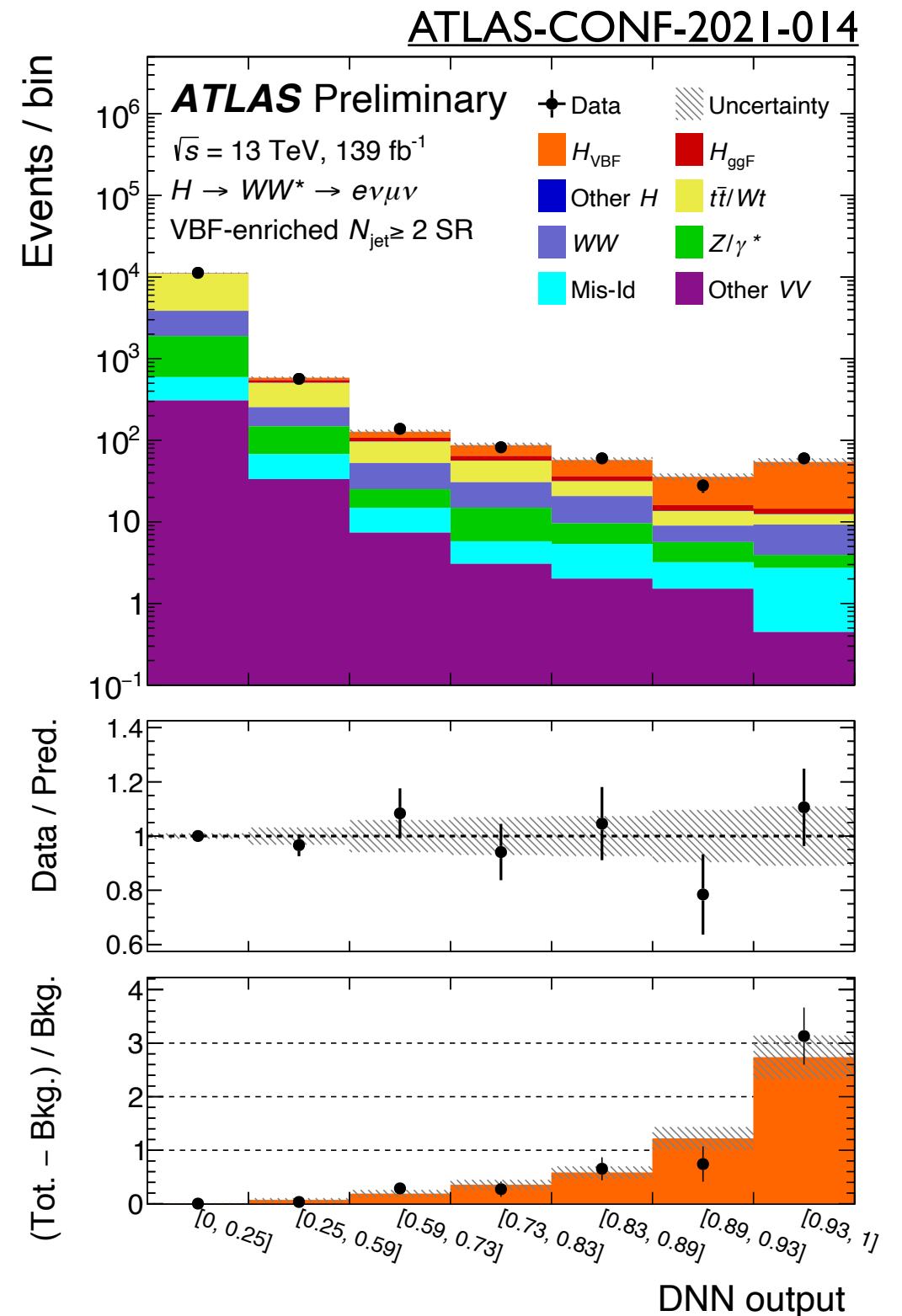


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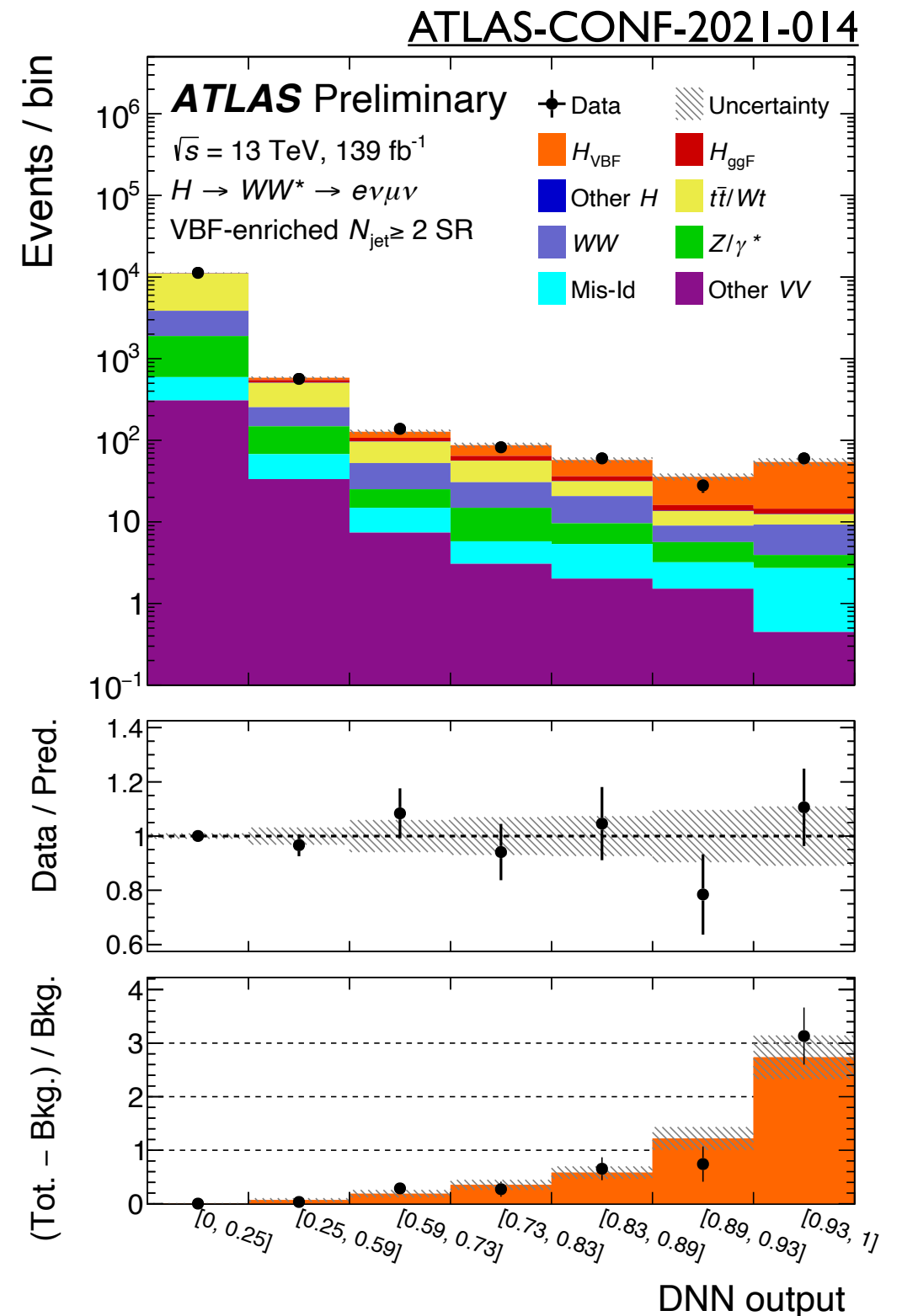


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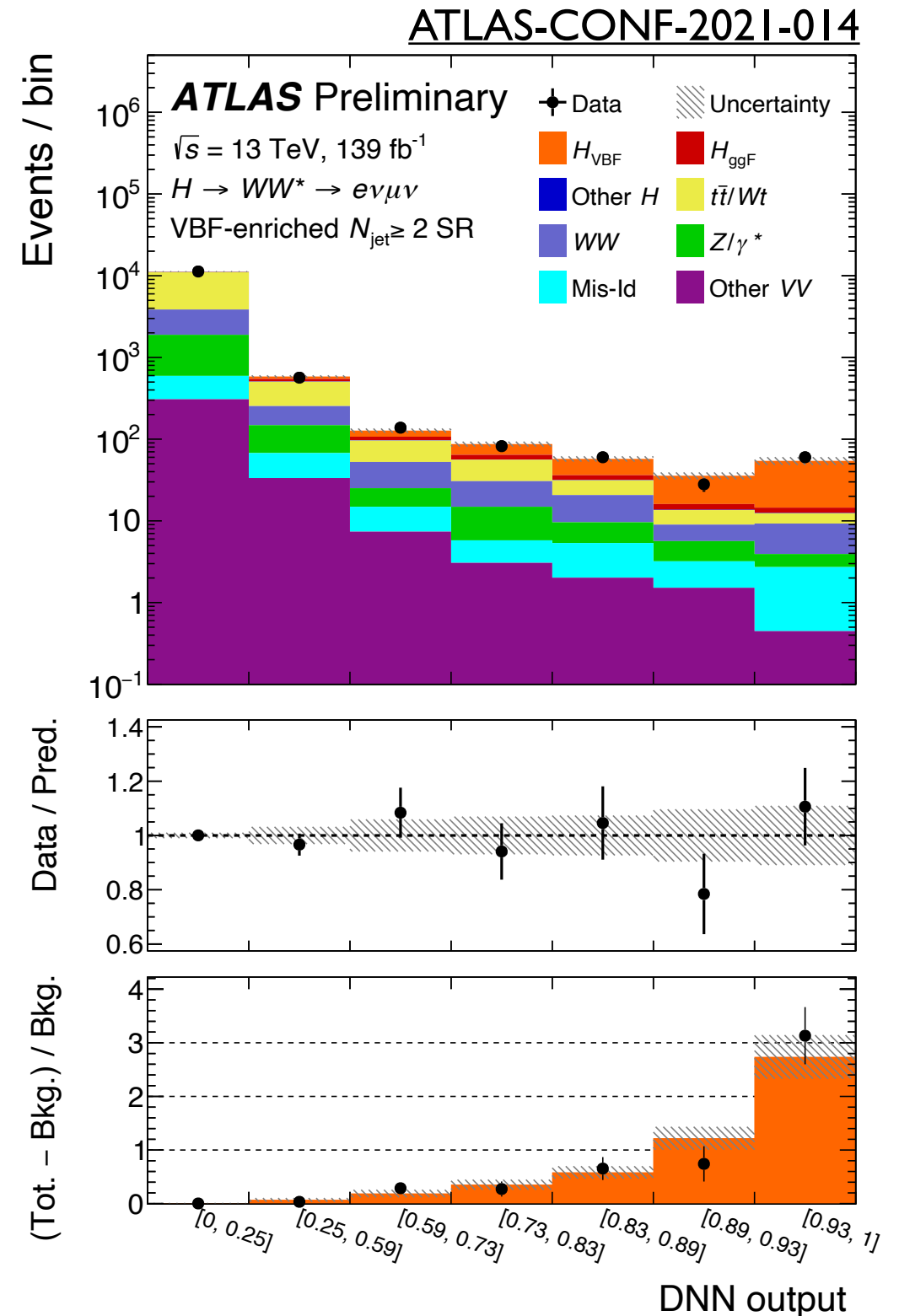
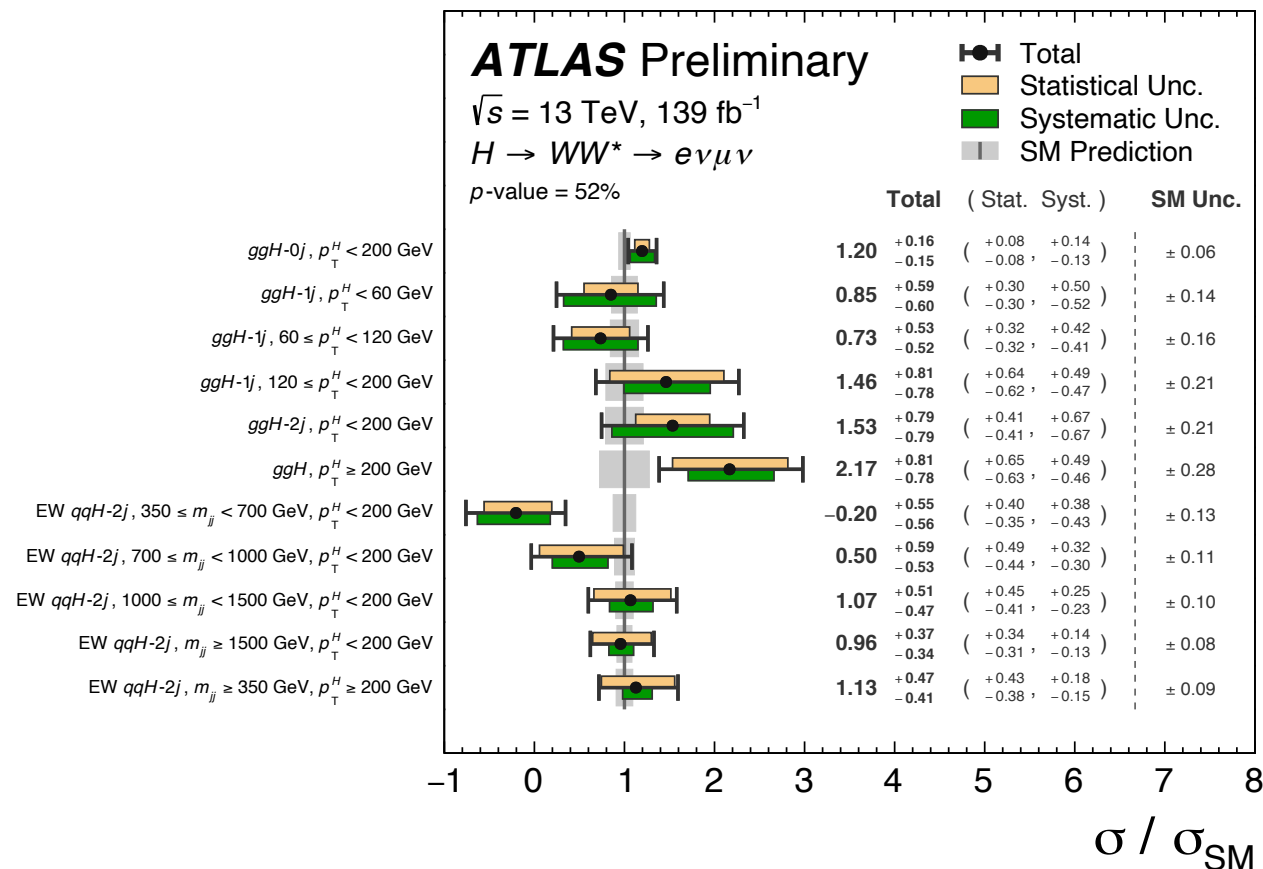
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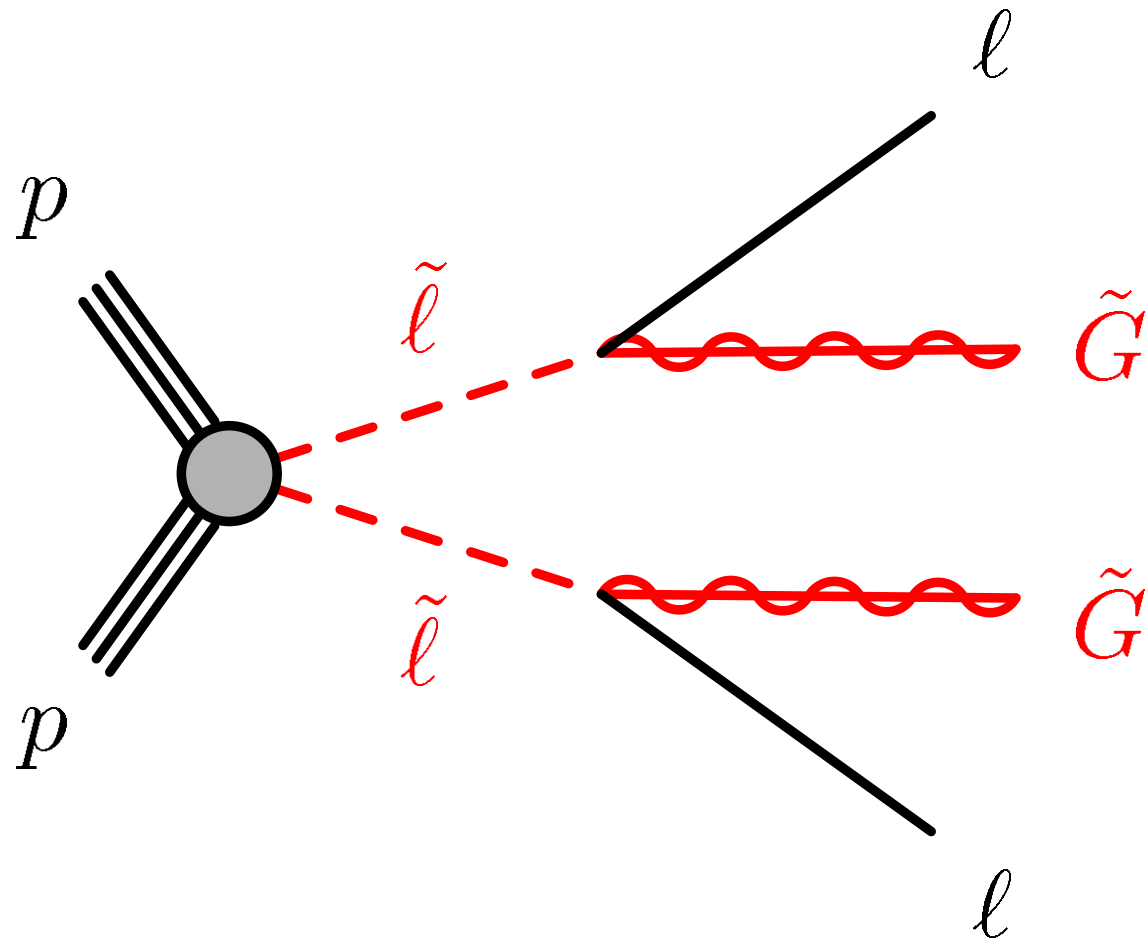
Huge datasets enable hugely differential measurements



Searches for BSM

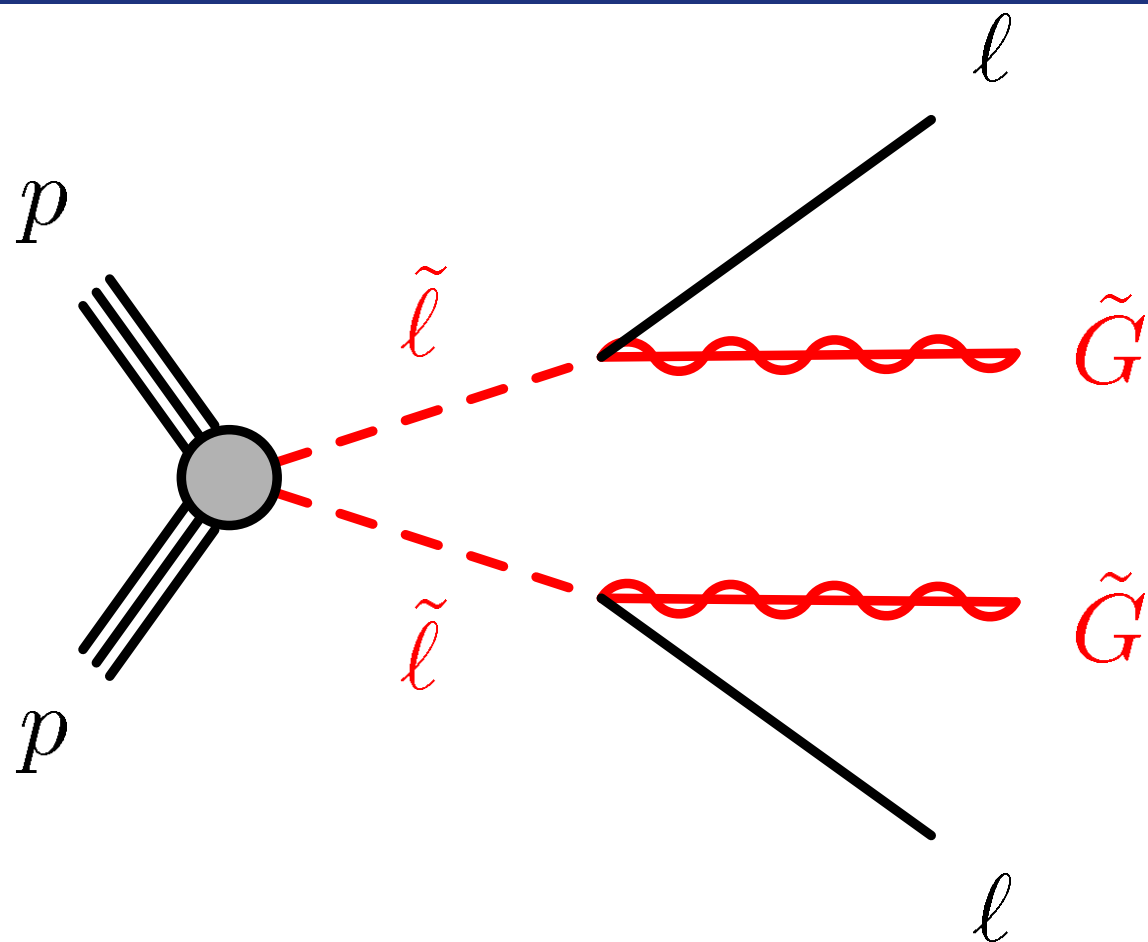
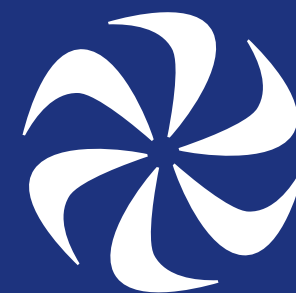


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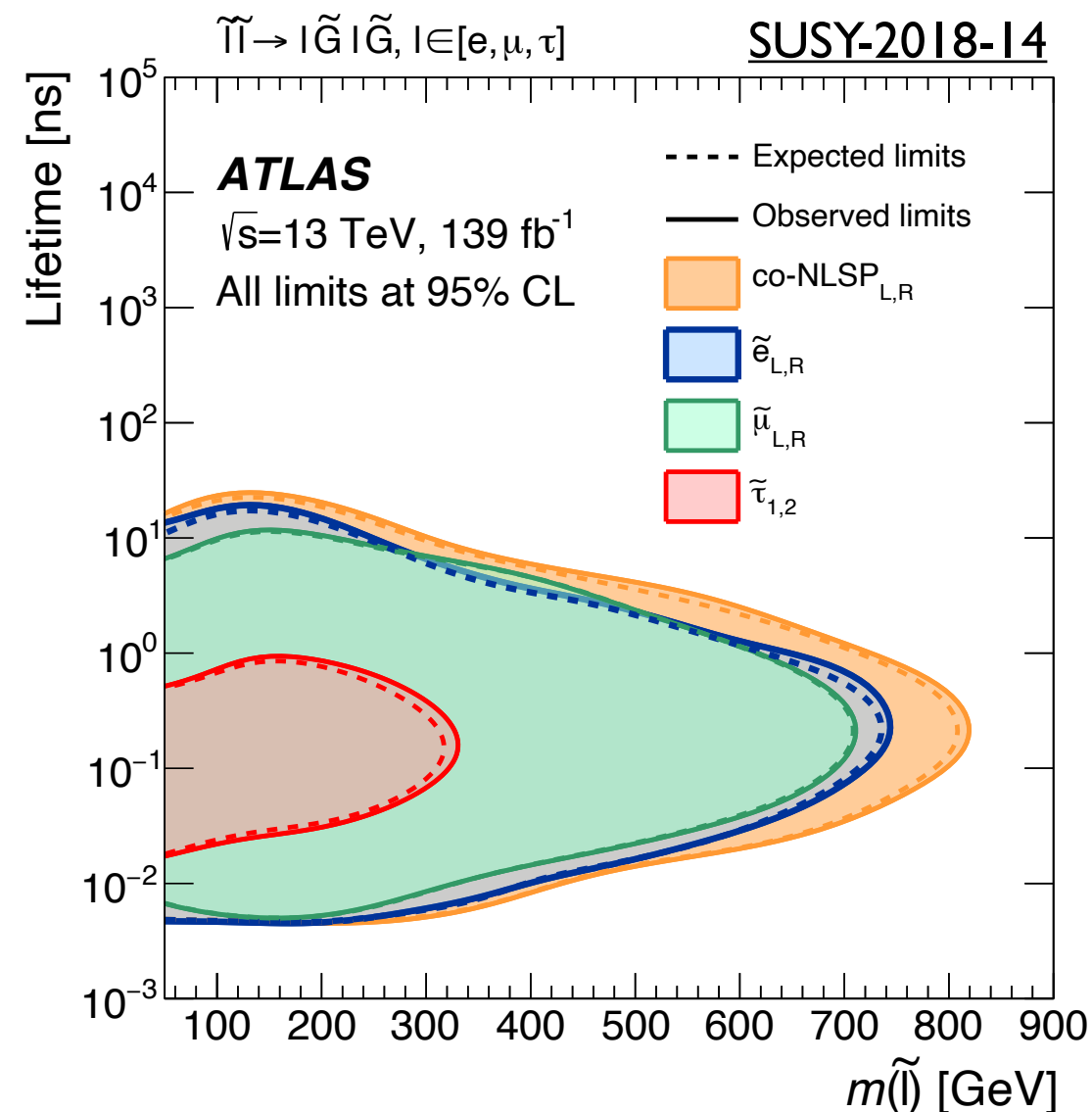
New searches for **long-lived** BSM particles

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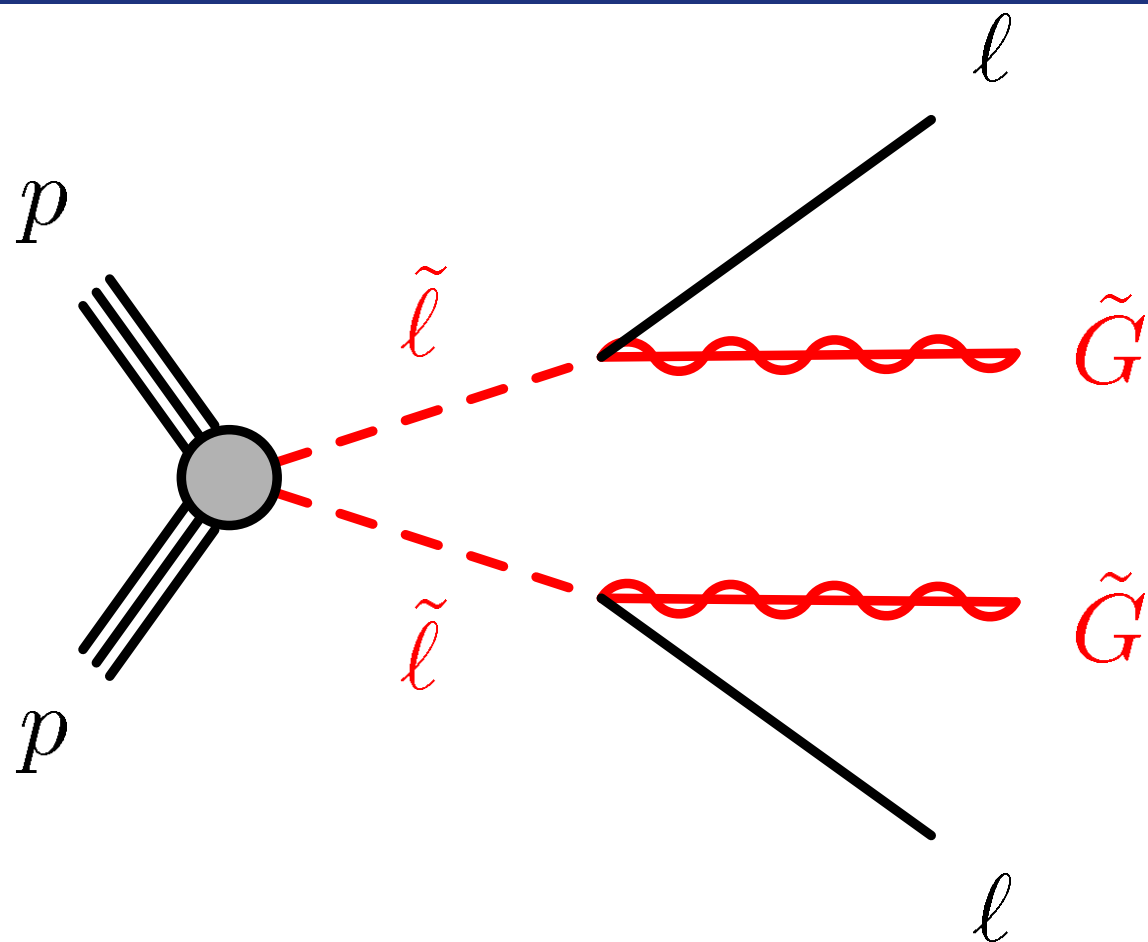
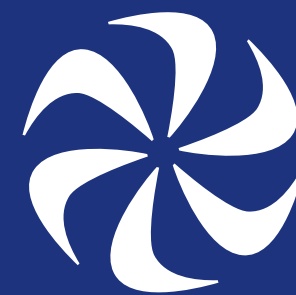


Set limits based on slepton flavor, lifetime, mass

New searches for **long-lived** BSM particles



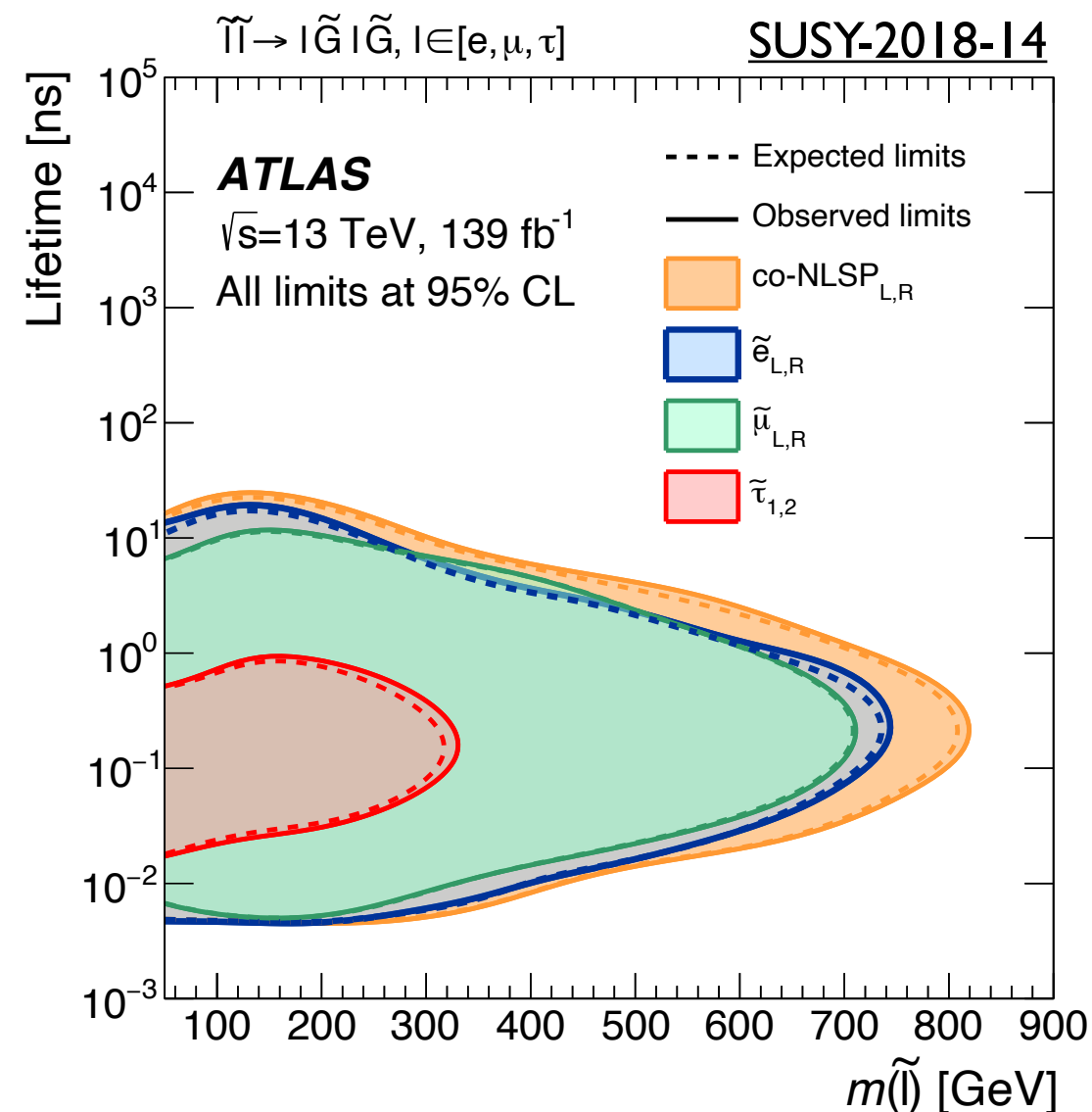
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First limits since LEP on these models!

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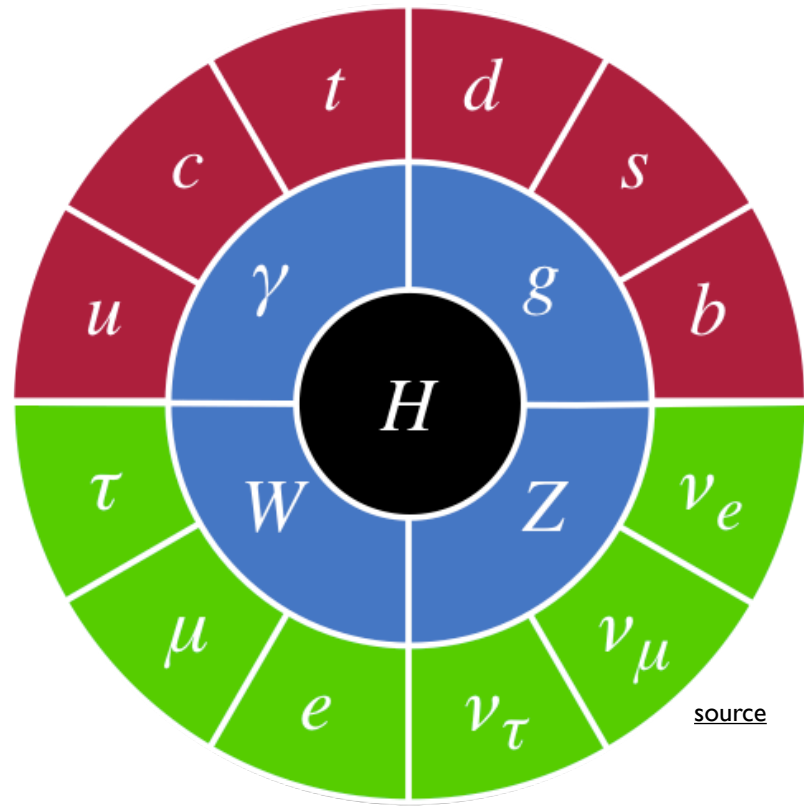


The Higgs Self-Coupling

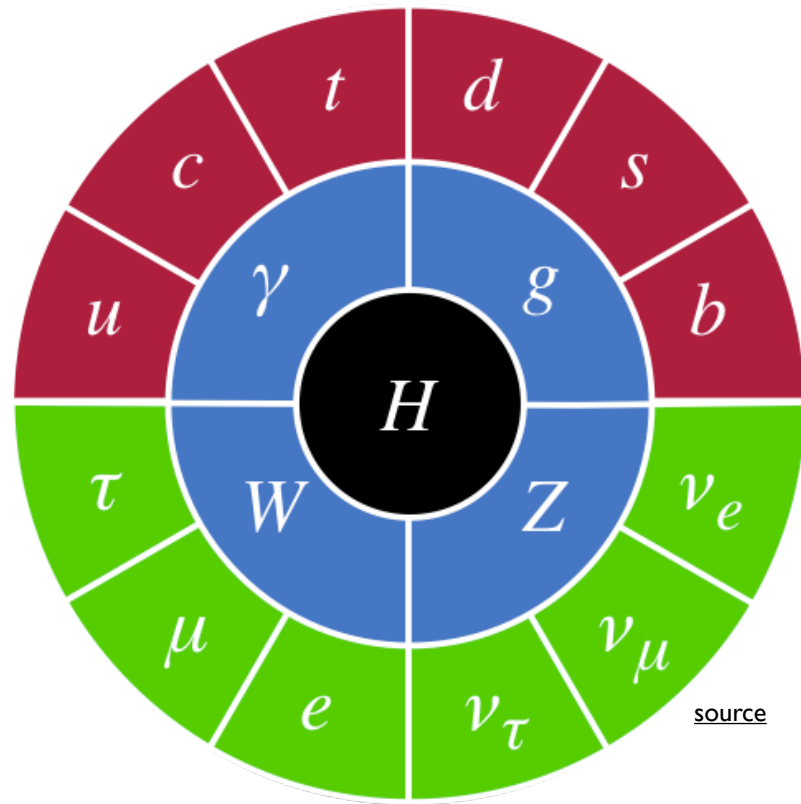
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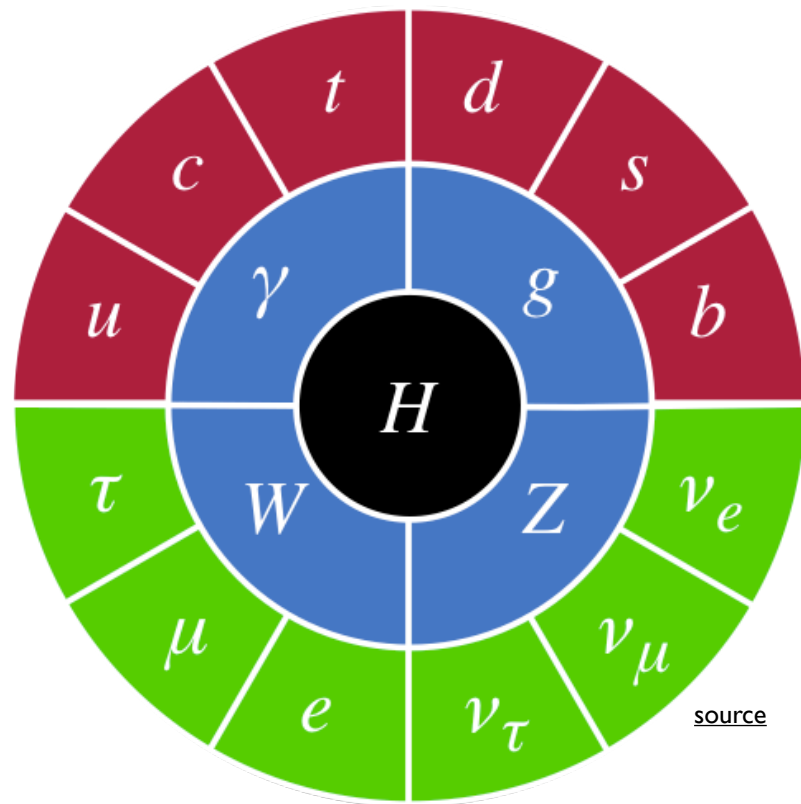


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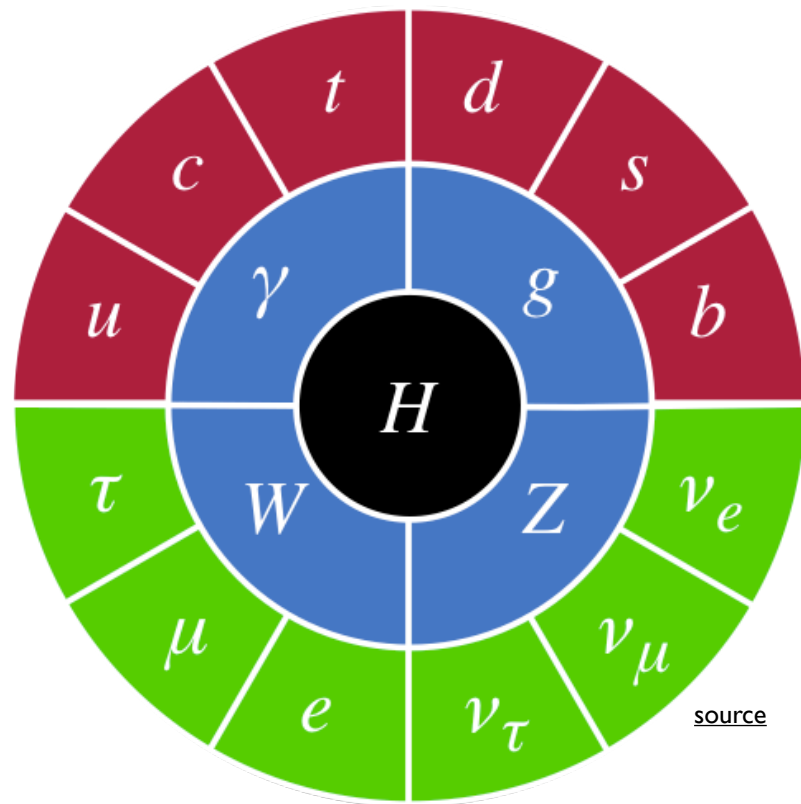
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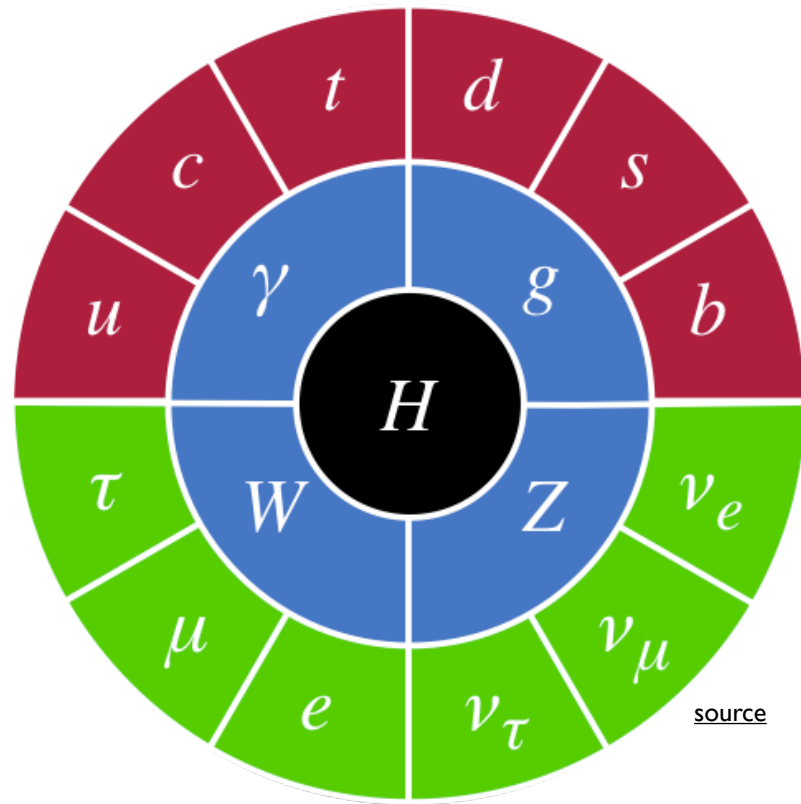


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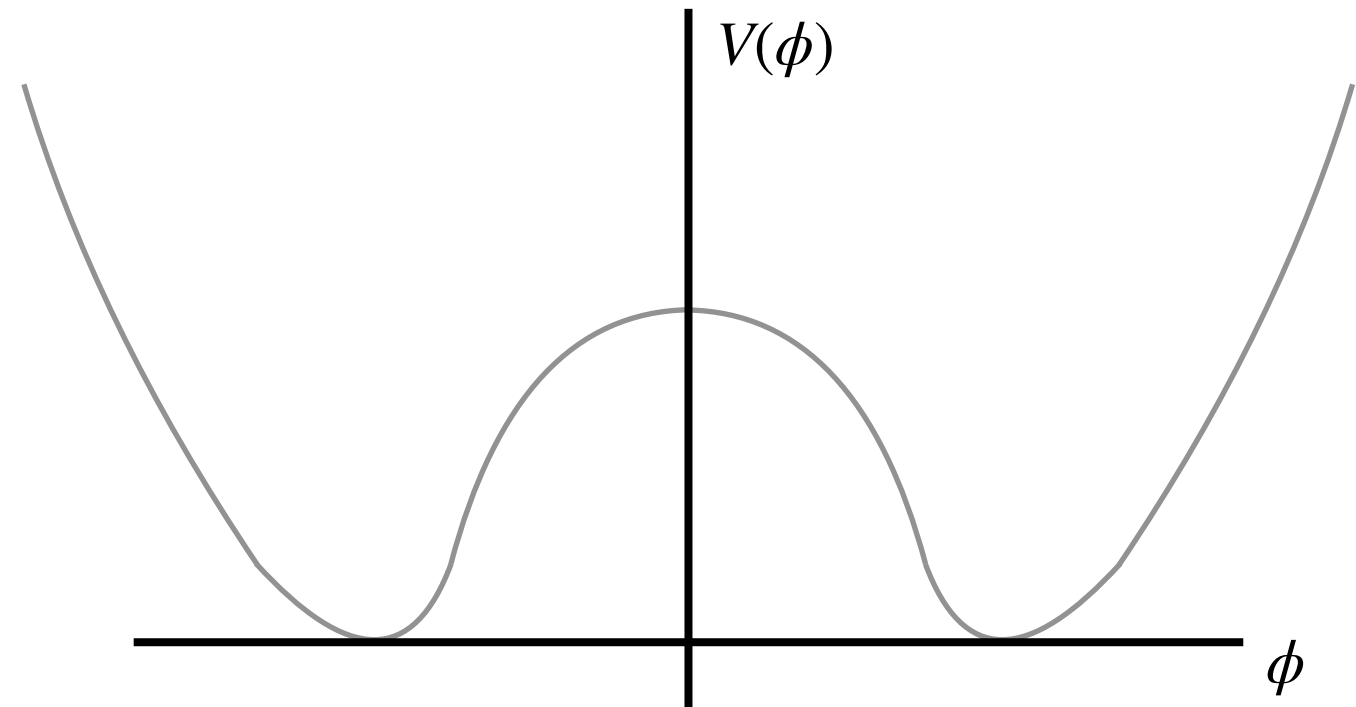
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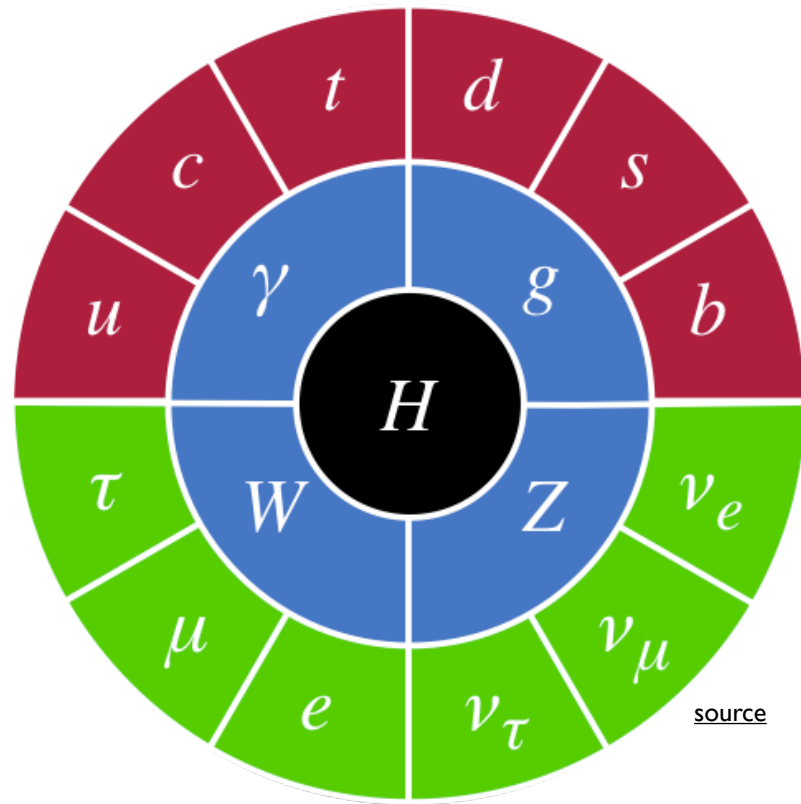
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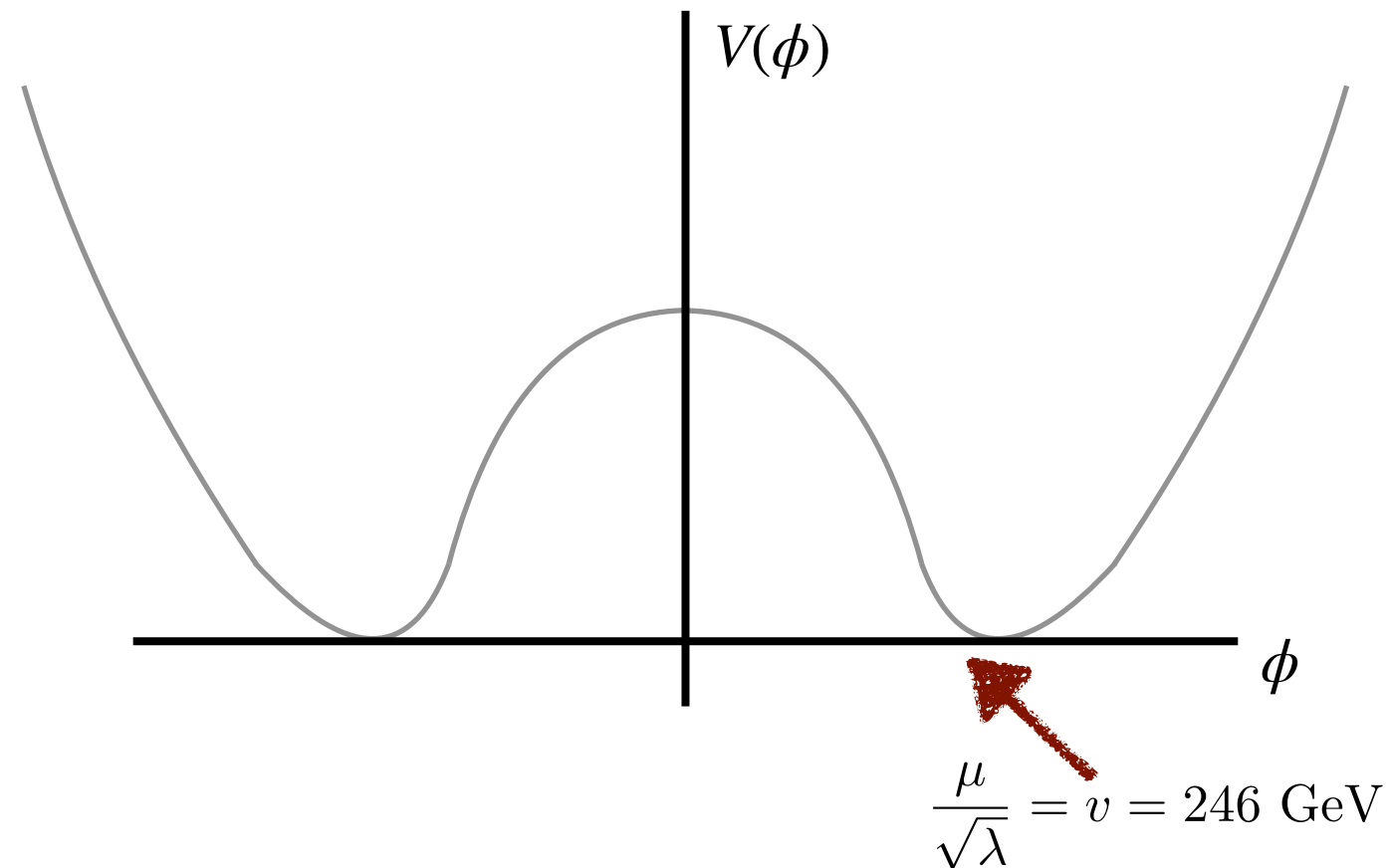
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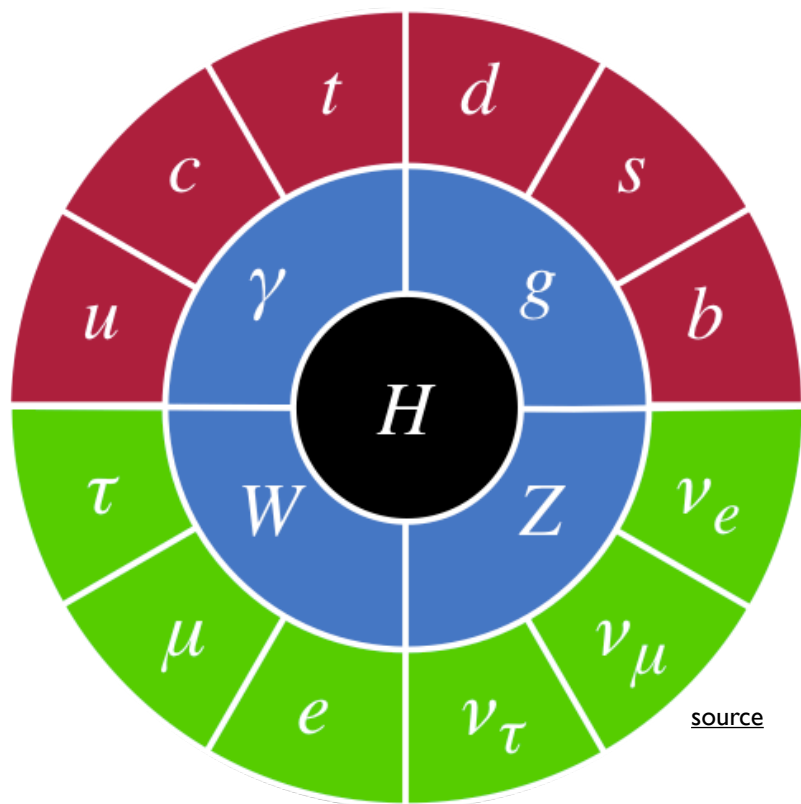
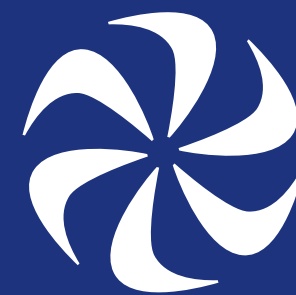
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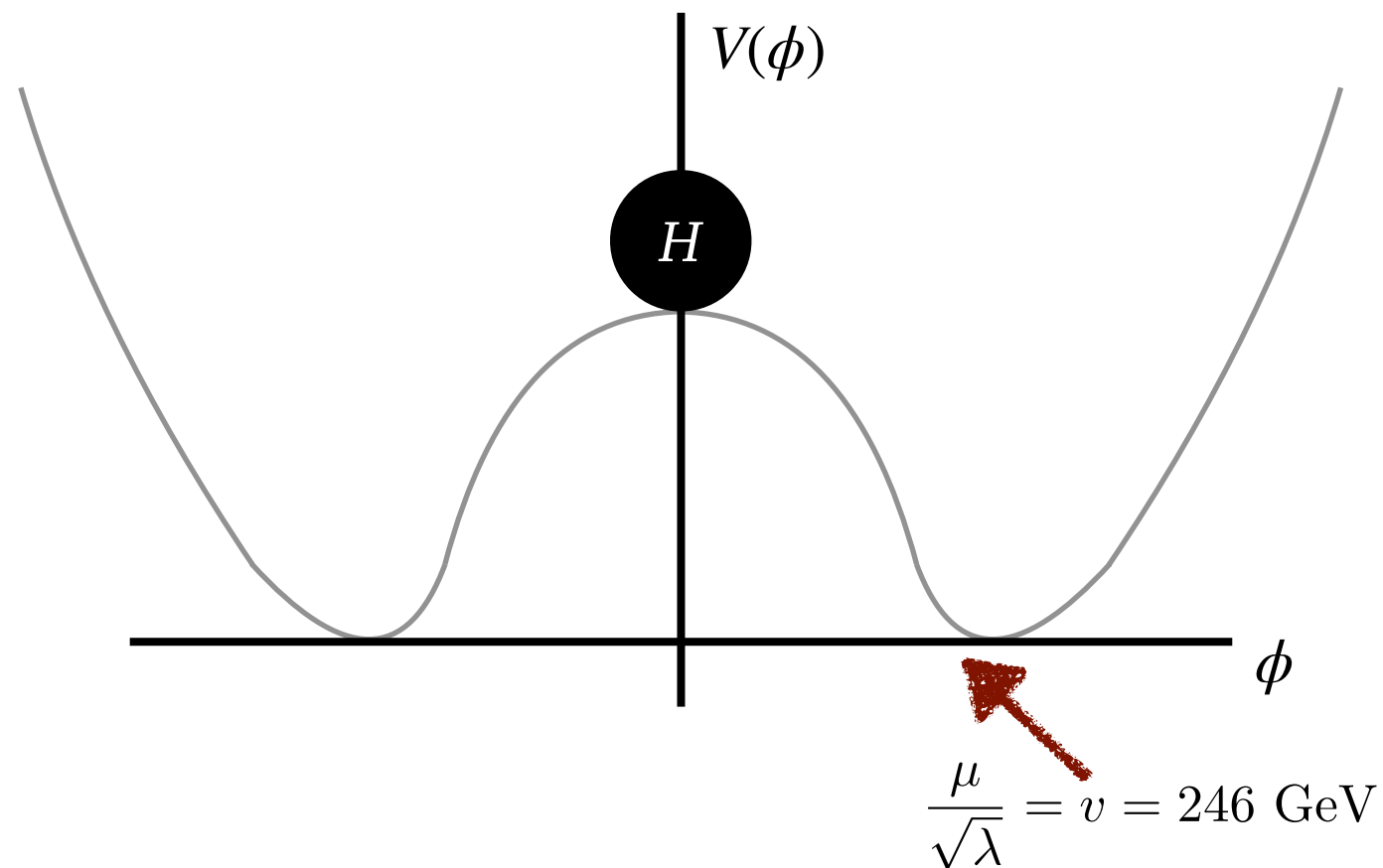
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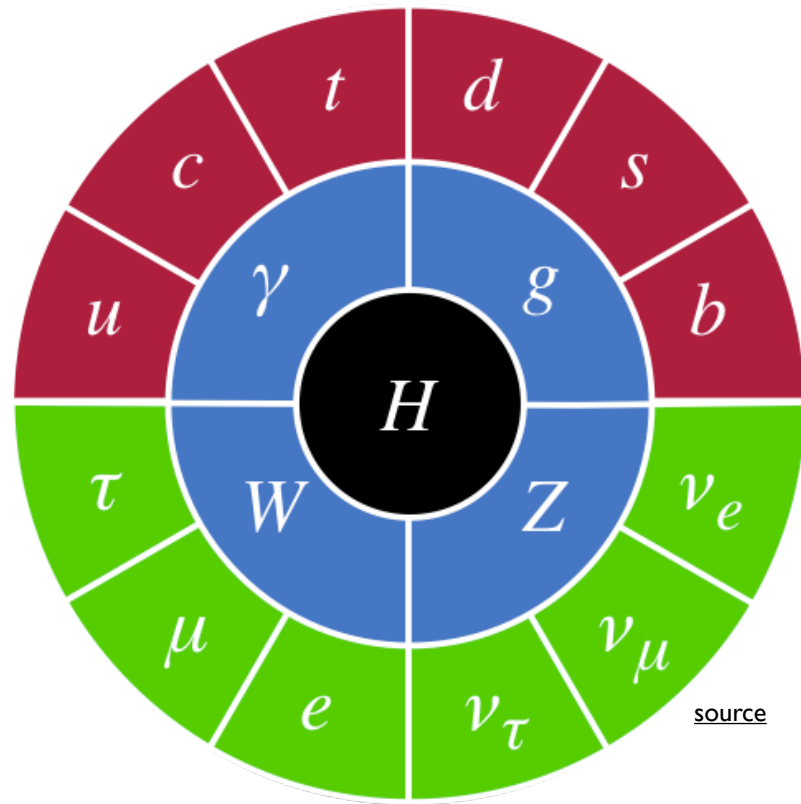
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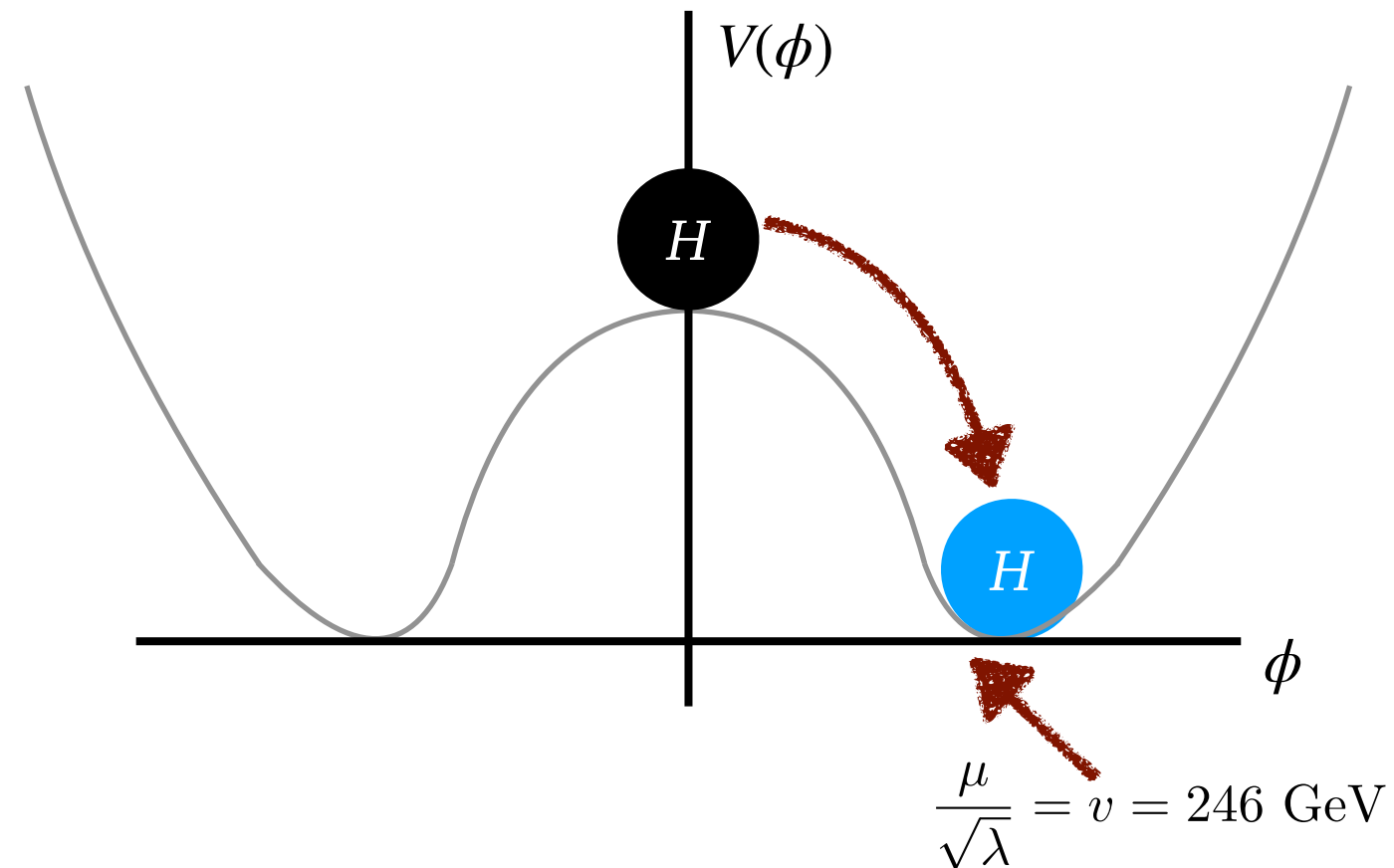
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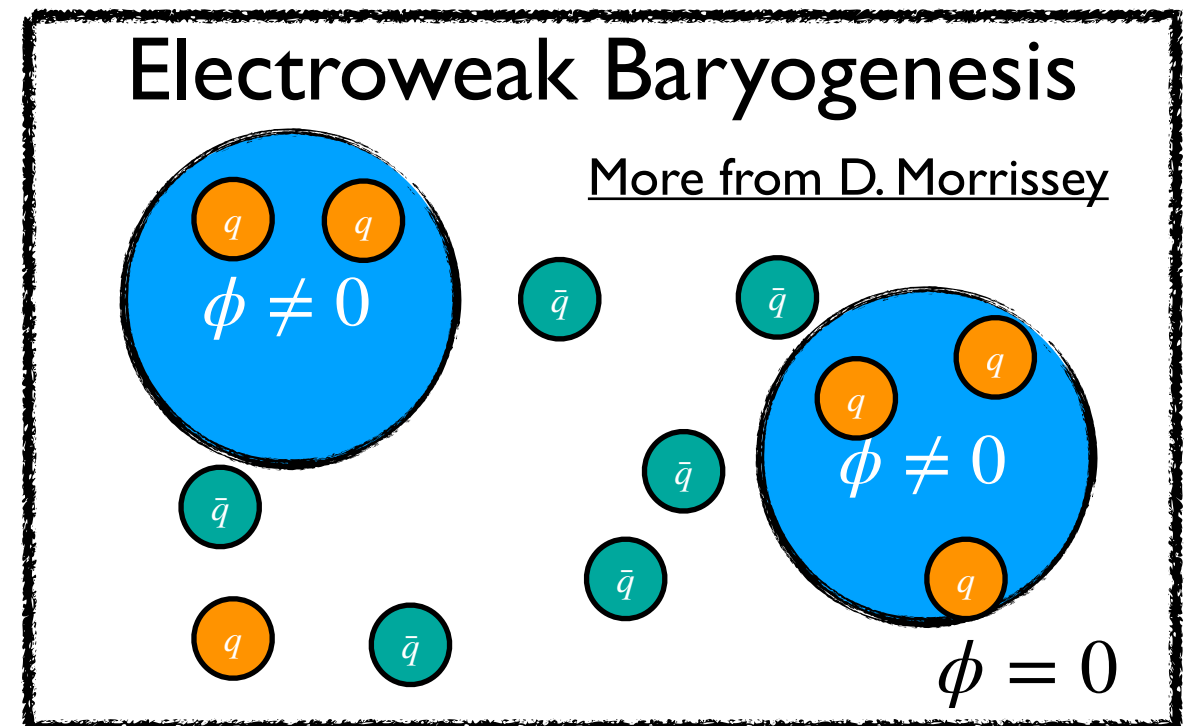
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Why Measure the Potential?



The potential isn't static: it had a different shape in the early universe

If the potential had the *right shape* as it cools after the Big Bang, this phase transition might explain the universe's matter/anti-matter asymmetry!



Measuring the Potential



Measuring the Potential

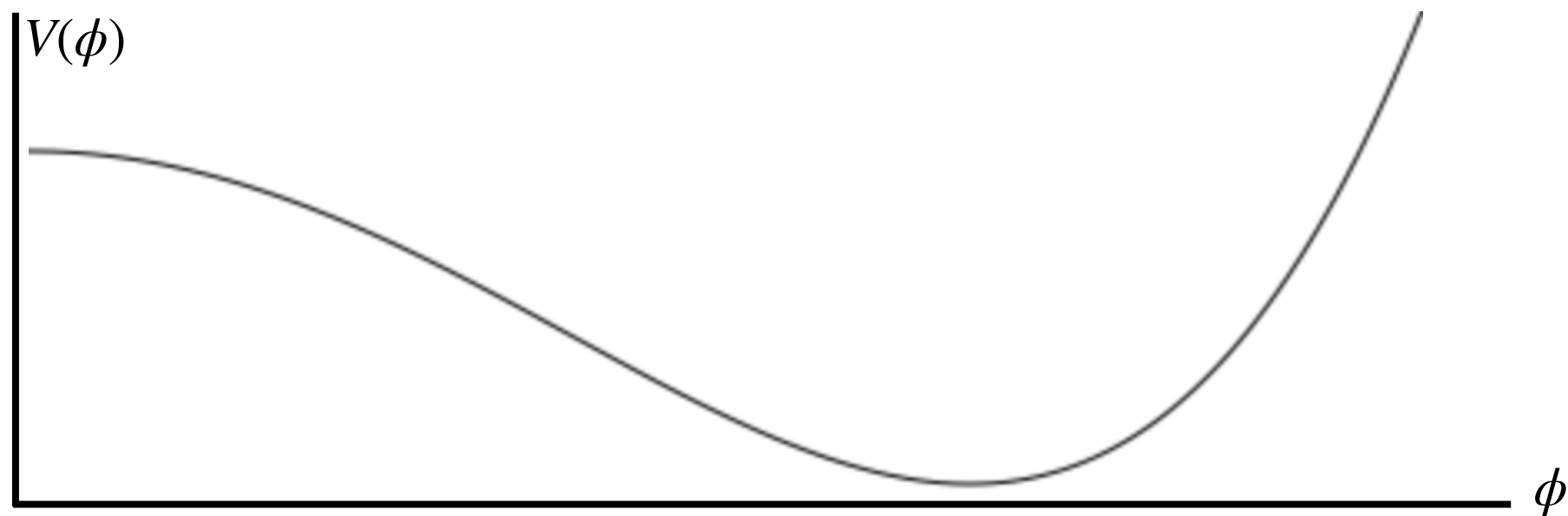


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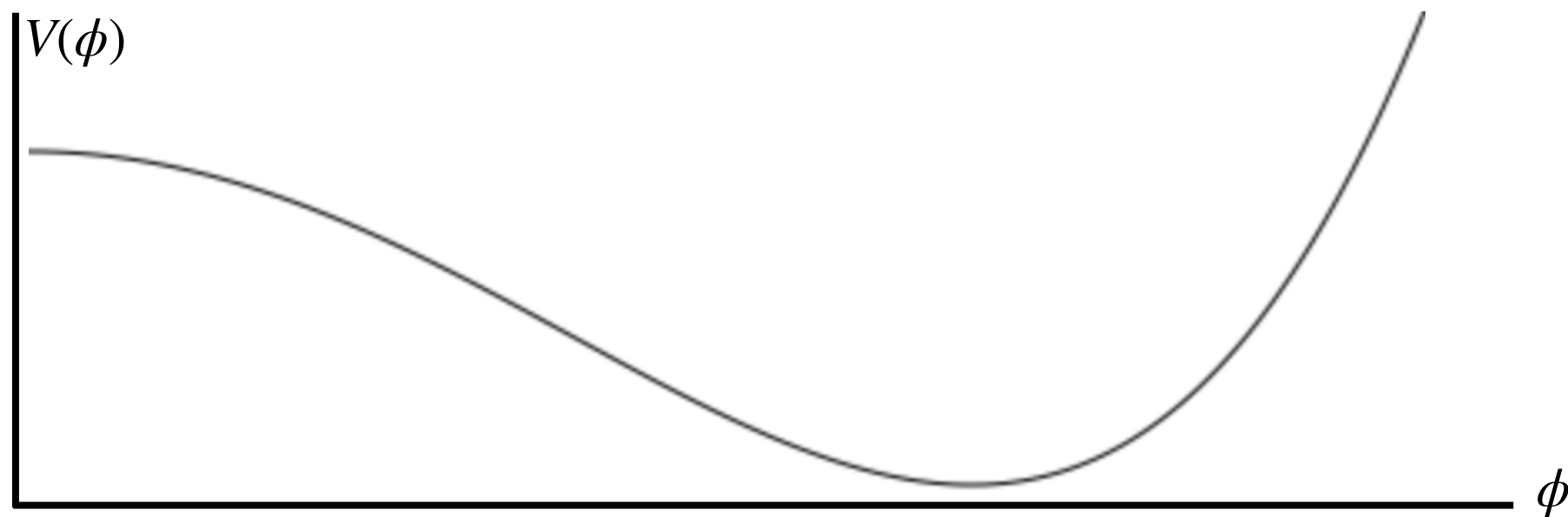


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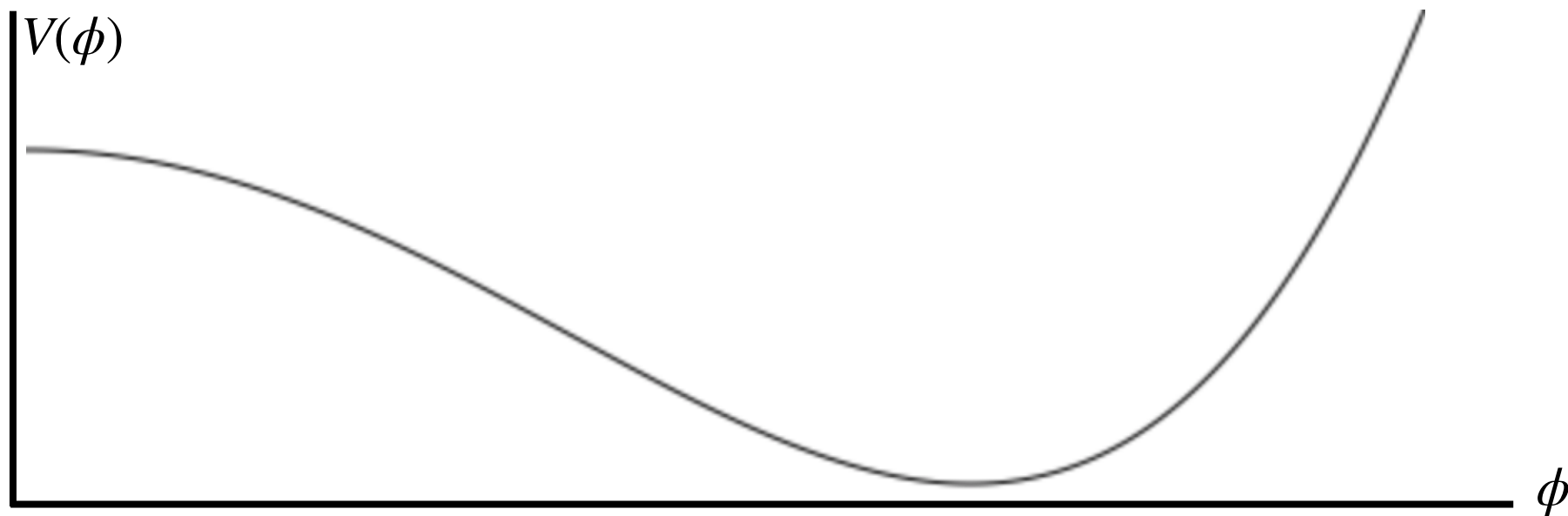
Taylor expand 



Measuring the Potential



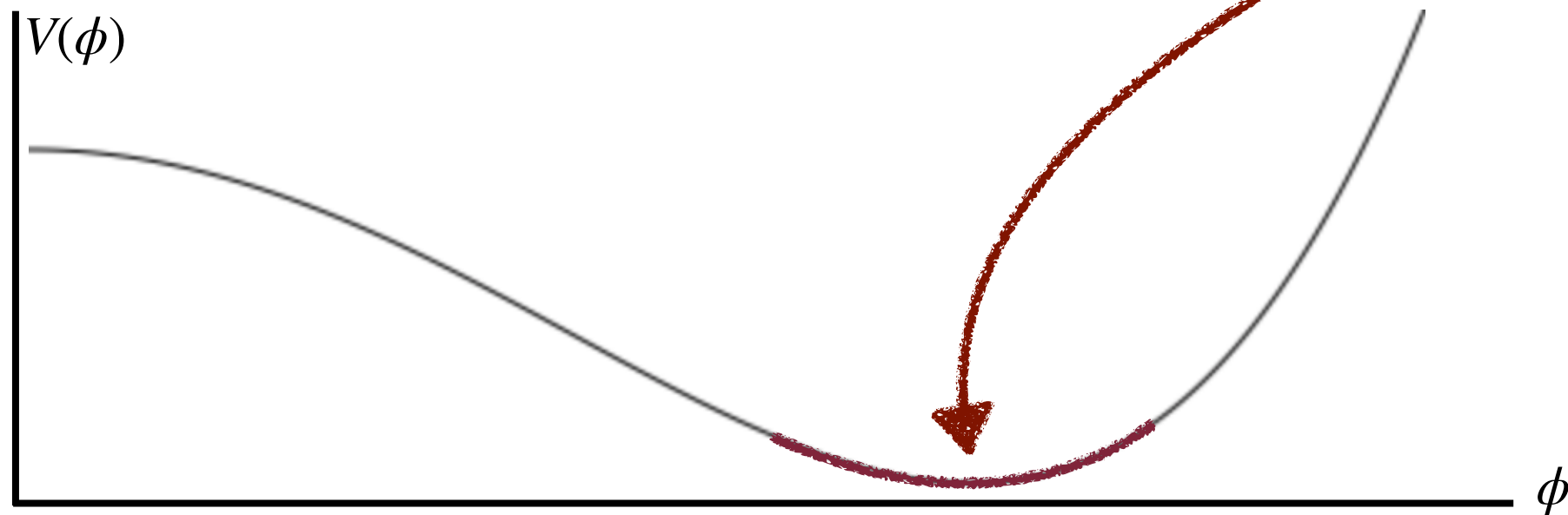
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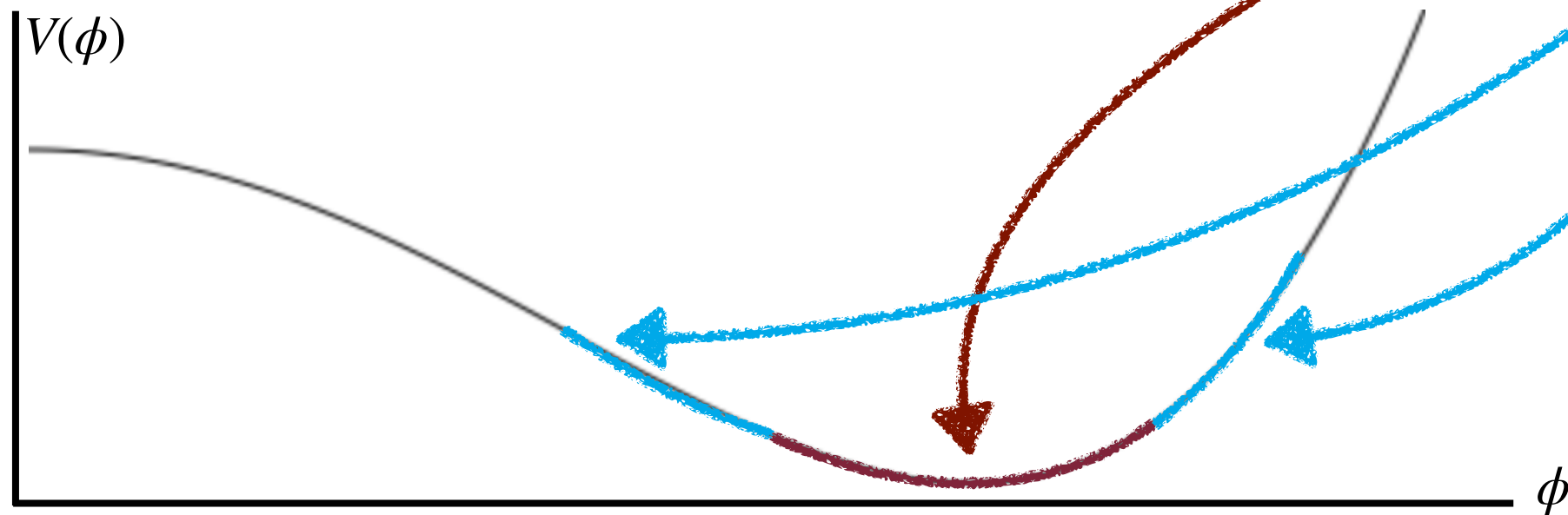
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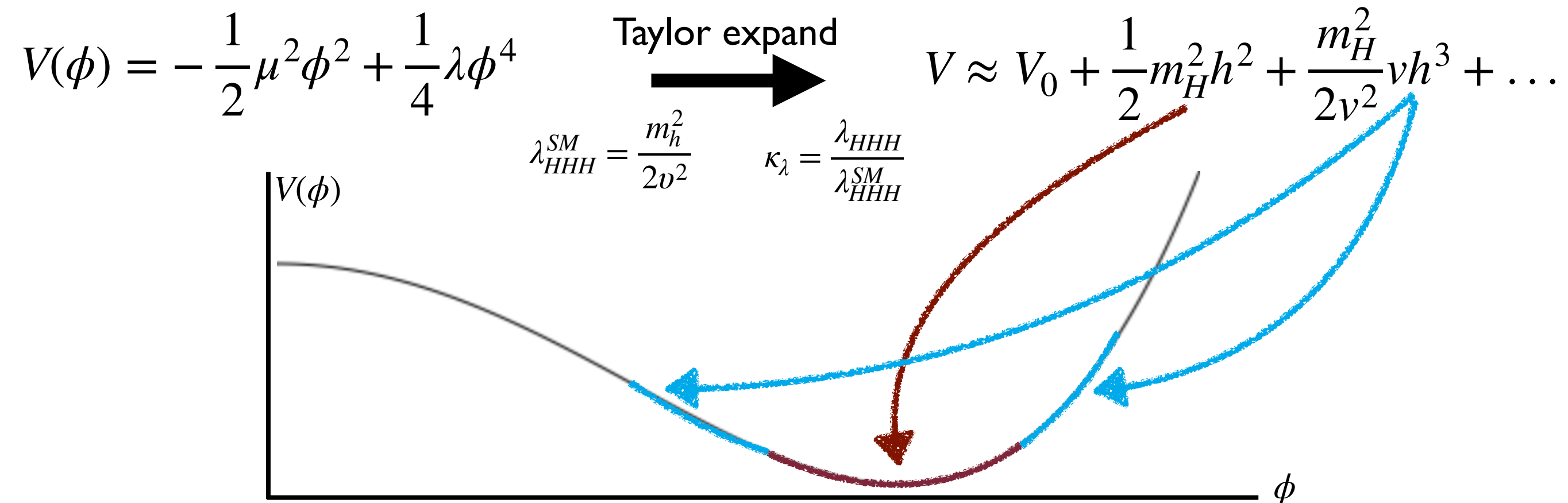
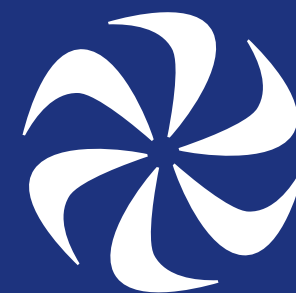
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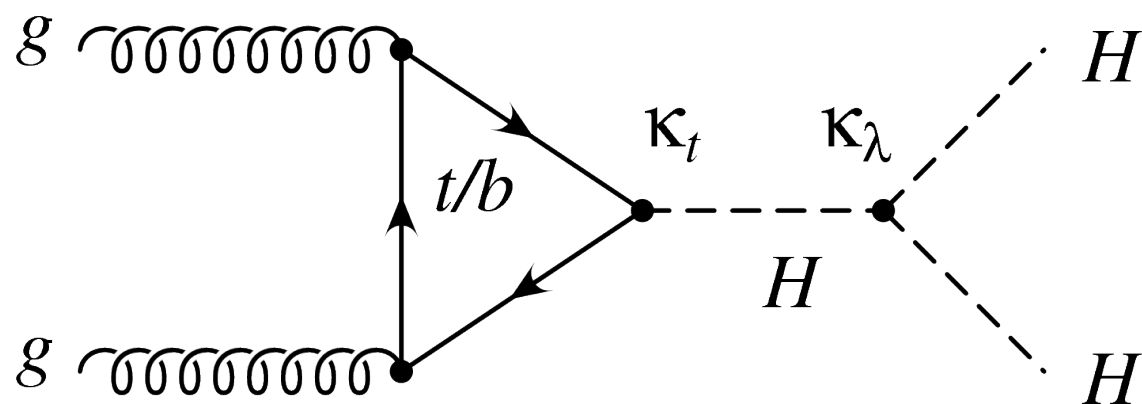
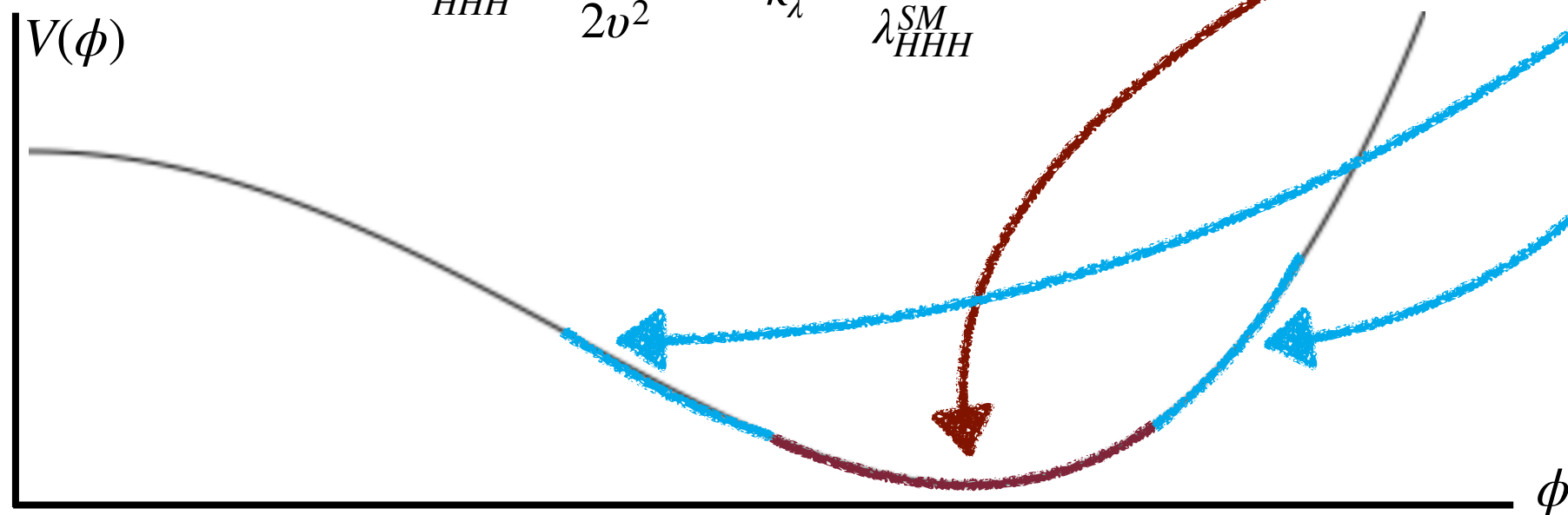
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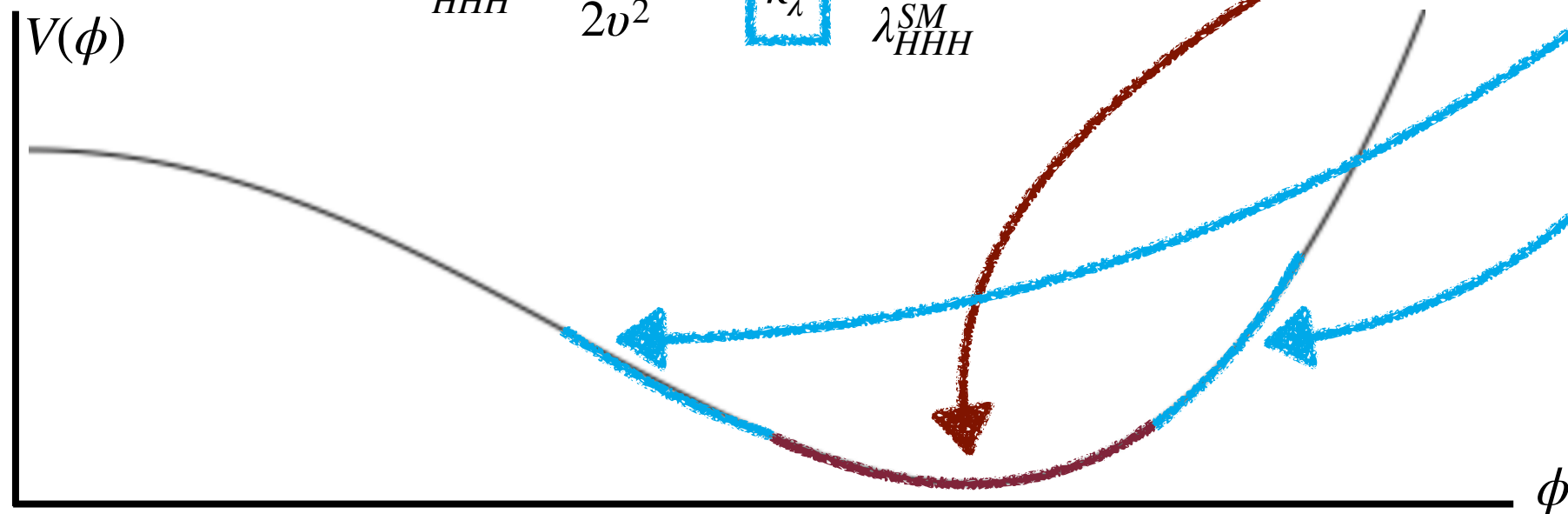
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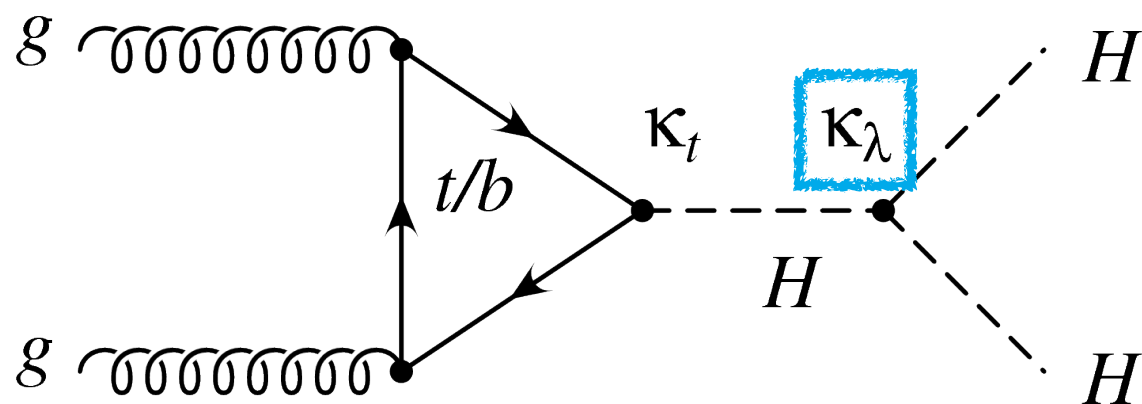
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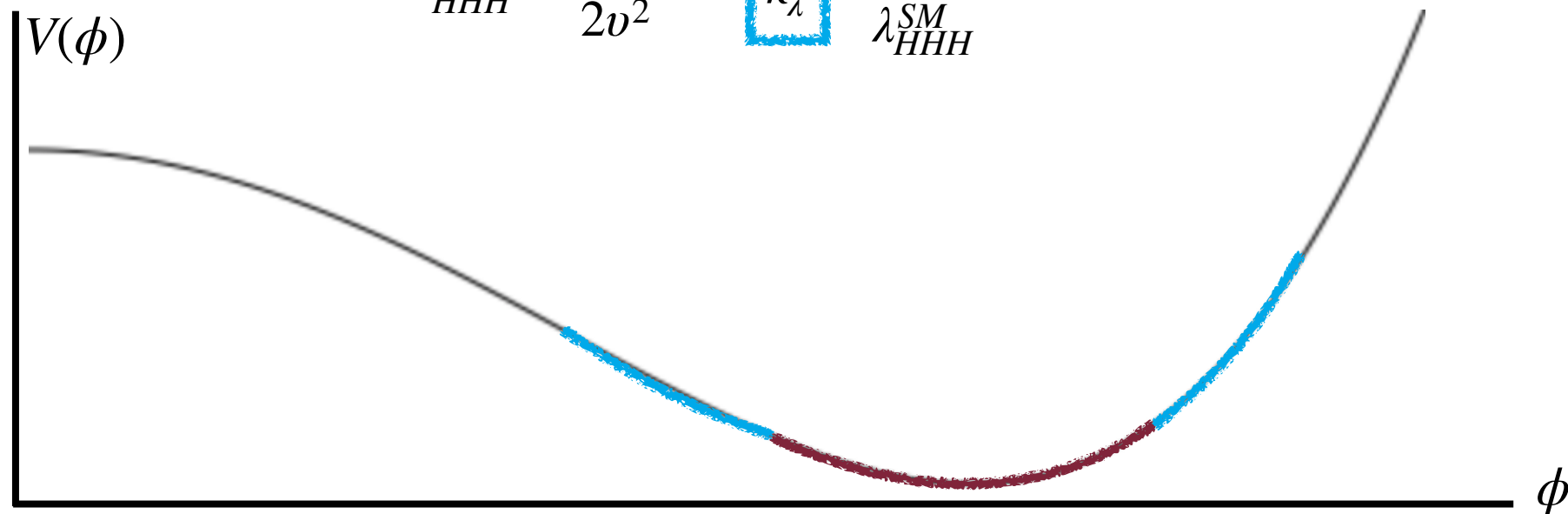
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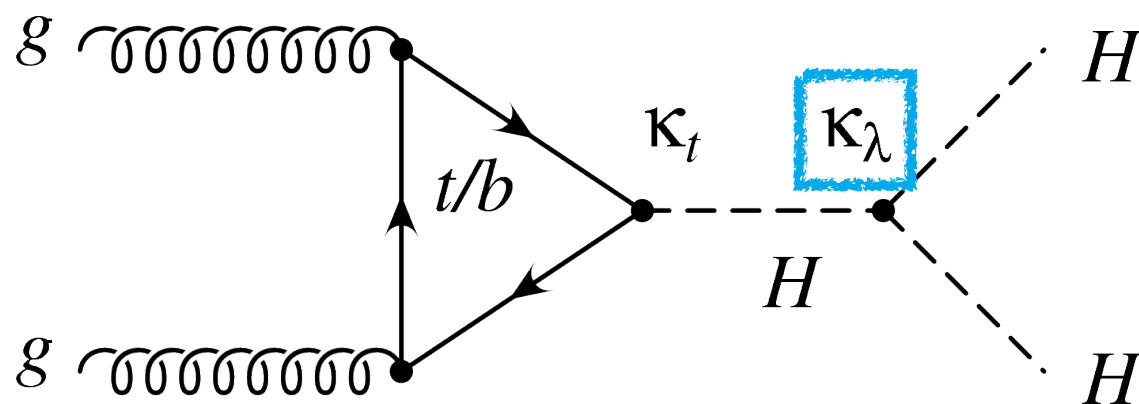
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How often these di-Higgs happen lets us measure the Higgs potential by measuring κ_λ



Measuring the Potential



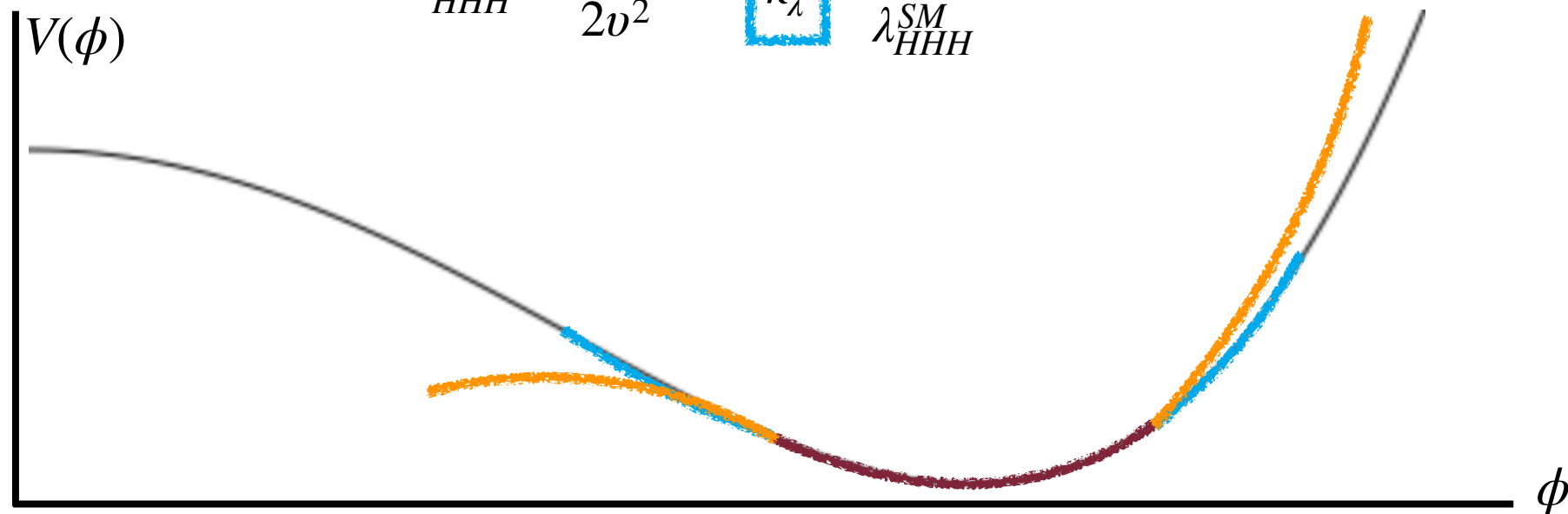
$$V(\phi) = -\frac{1}{2}\mu^2\phi^2 + \frac{1}{4}\lambda\phi^4$$

Taylor expand

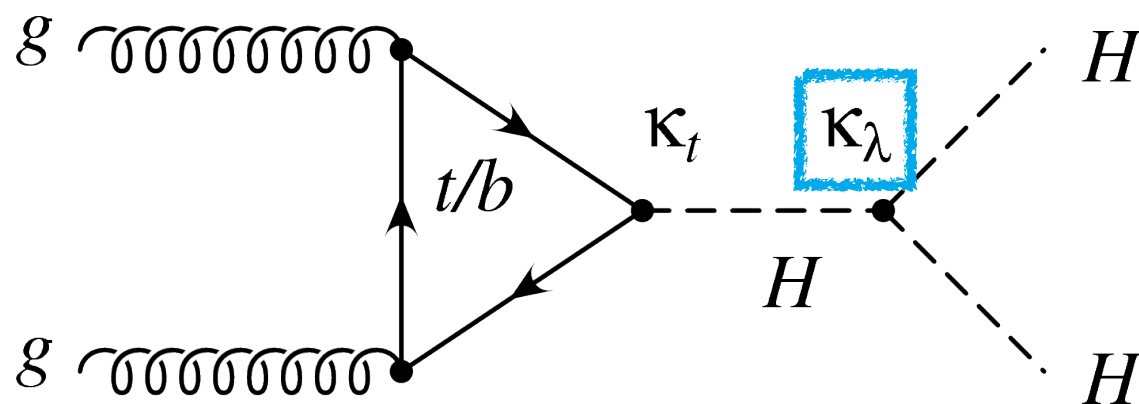


$$V \approx V_0 + \frac{1}{2}m_H^2 h^2 + \frac{m_H^2}{2v^2} v h^3 + \dots$$

$$\lambda_{HHH}^{SM} = \frac{m_h^2}{2v^2} \quad \boxed{\kappa_\lambda} = \frac{\lambda_{HHH}}{\lambda_{HHH}^{SM}}$$



We can measure these **di-Higgs events** at the LHC!



How often these di-Higgs happen lets us measure the Higgs potential by measuring κ_λ

If we see something **completely different** from the SM prediction, we know $\kappa_\lambda \neq 1$!

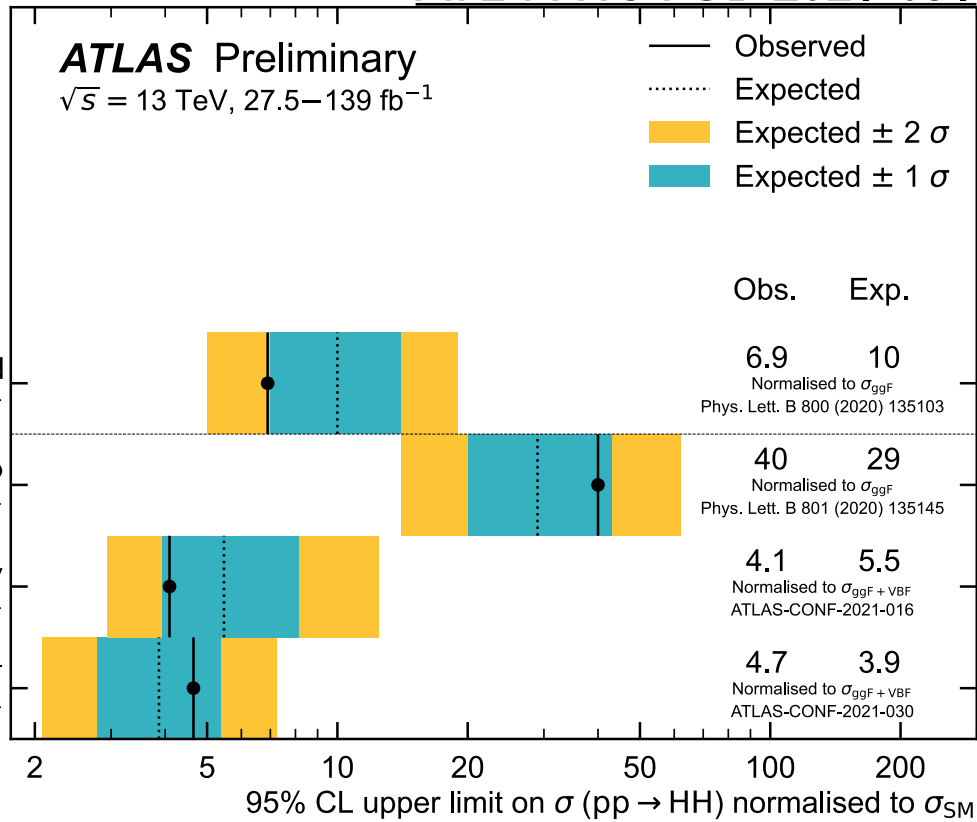
Searching for Higgs Pairs



Searching for Higgs Pairs



ATL-PHYS-PUB-2021-031

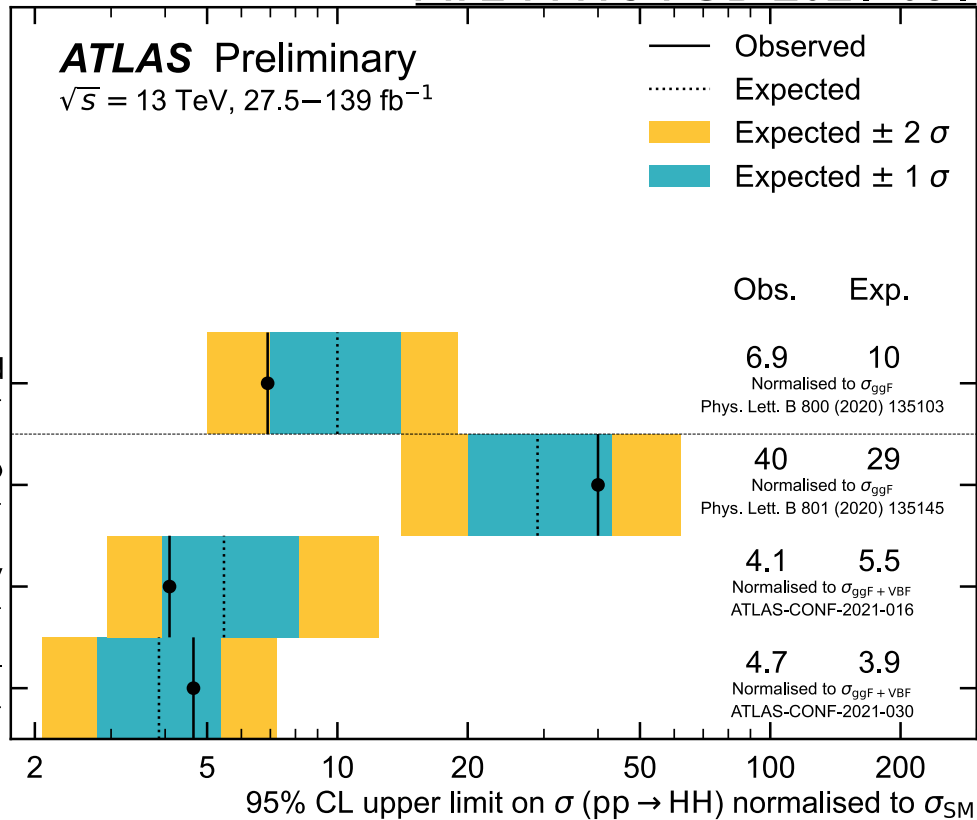


Here, show what factor of the SM x-sec we can exclude

Searching for Higgs Pairs



ATL-PHYS-PUB-2021-031



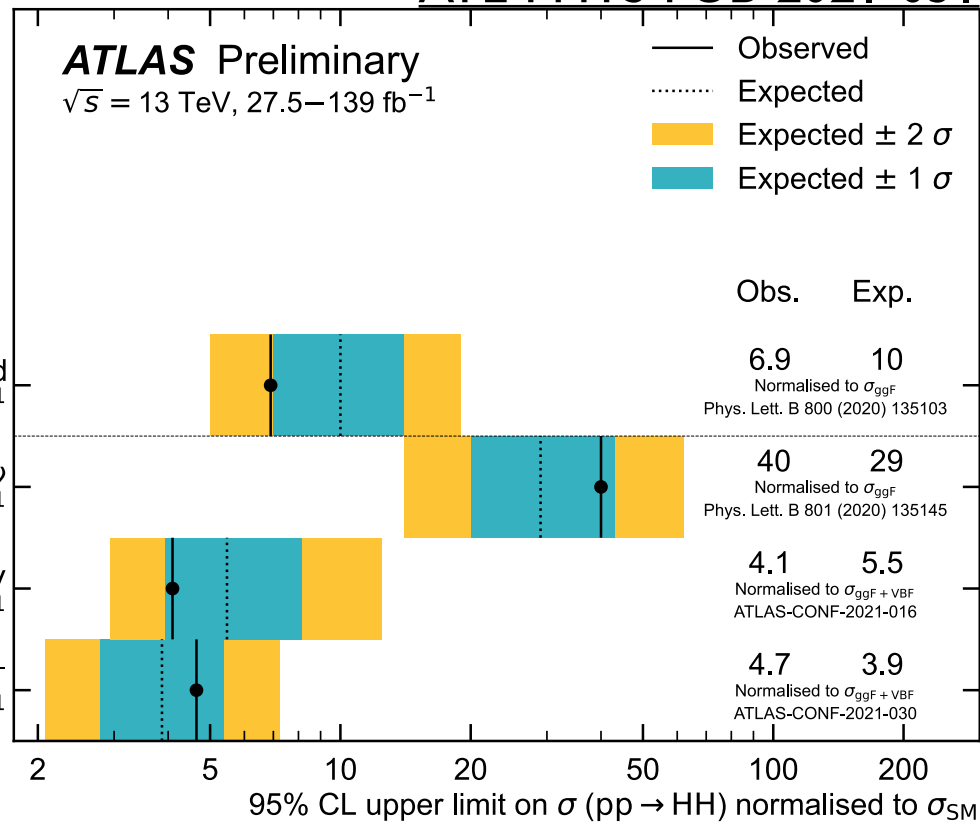
Here, show what factor of the SM
x-sec we can exclude

Two Higgs bosons means two decays:
 $b\bar{b}\gamma\gamma$ and $b\bar{b}\tau\tau$ channels each
exclude around 4x the SM

Searching for Higgs Pairs



ATL-PHYS-PUB-2021-031



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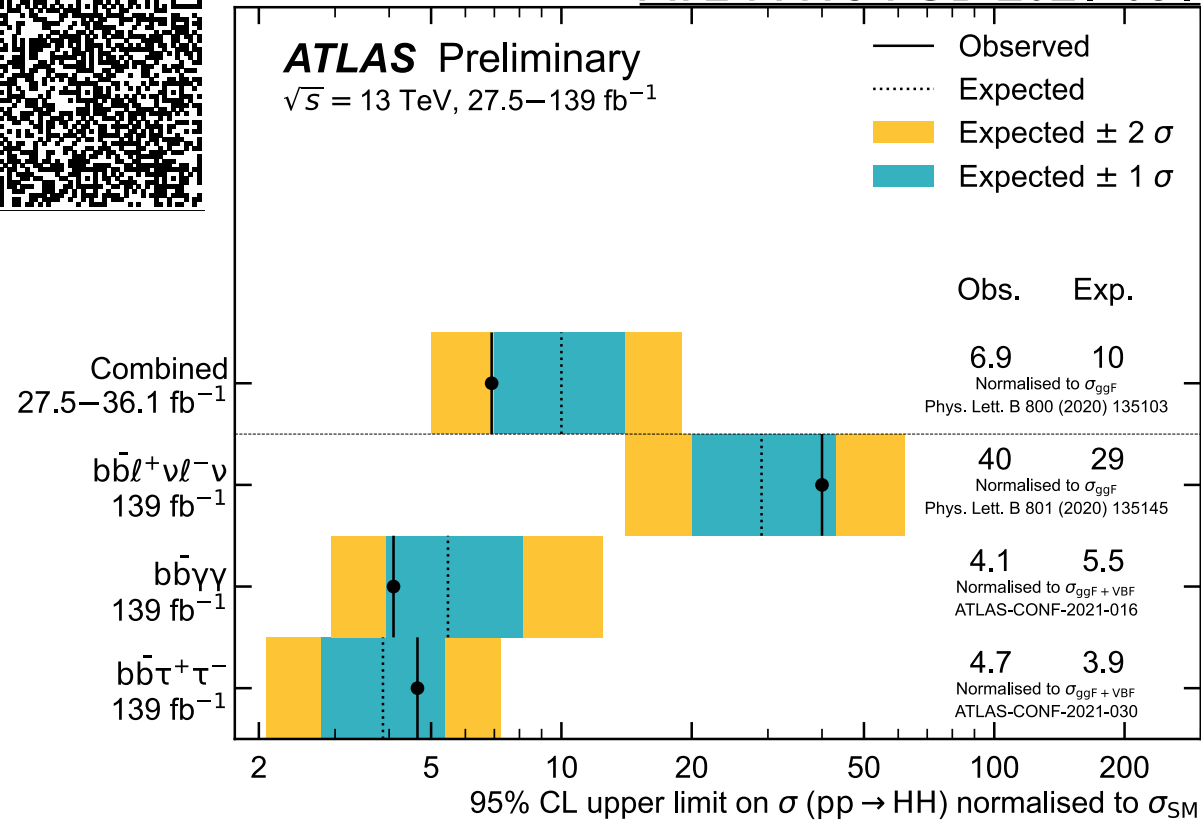
$b\bar{b}\gamma\gamma$ and $b\bar{b}\tau\tau$ channels each
exclude around 4x the SM

More channels and more data mean
the SM x-sec is in sight!

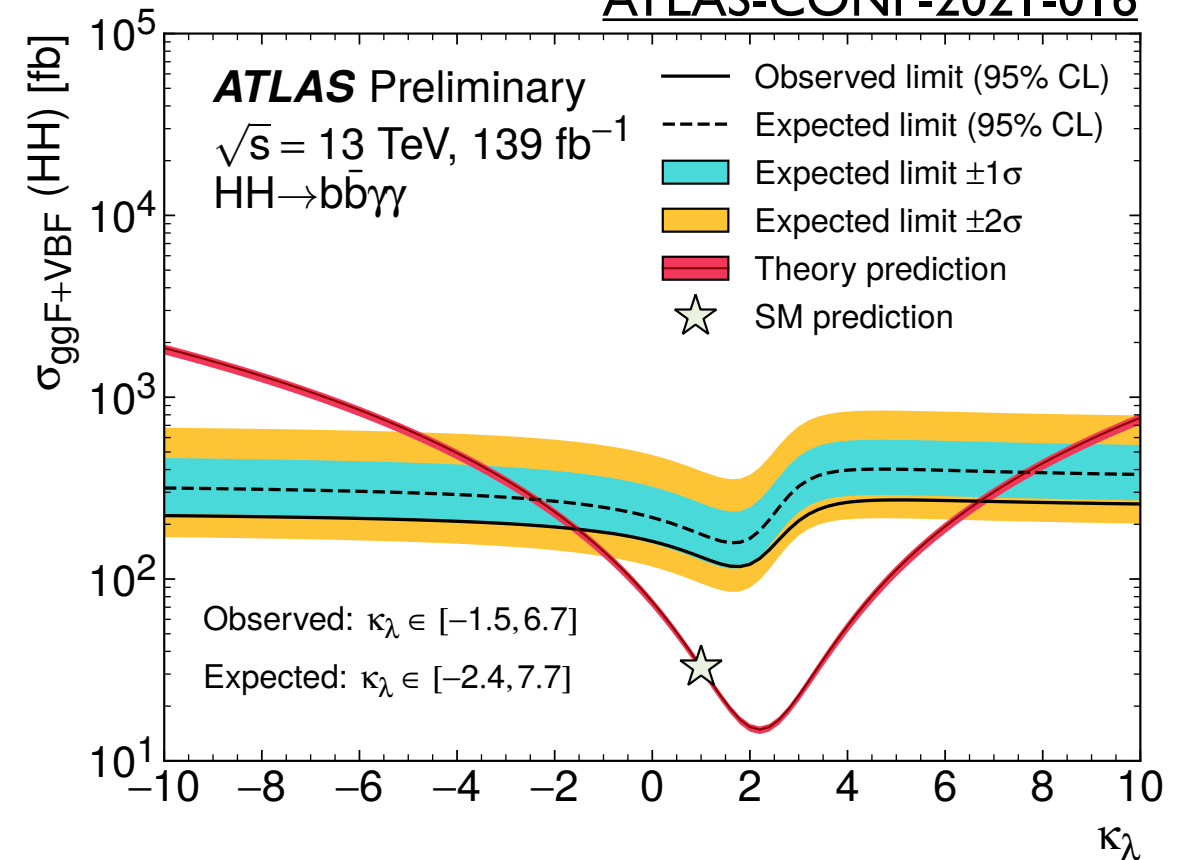
Searching for Higgs Pairs



ATL-PHYS-PUB-2021-031



ATLAS-CONF-2021-016



Here, show what factor of the SM x-sec we can exclude

Here, show sensitivity to κ_λ :
 the actual deviation in the Higgs self-coupling

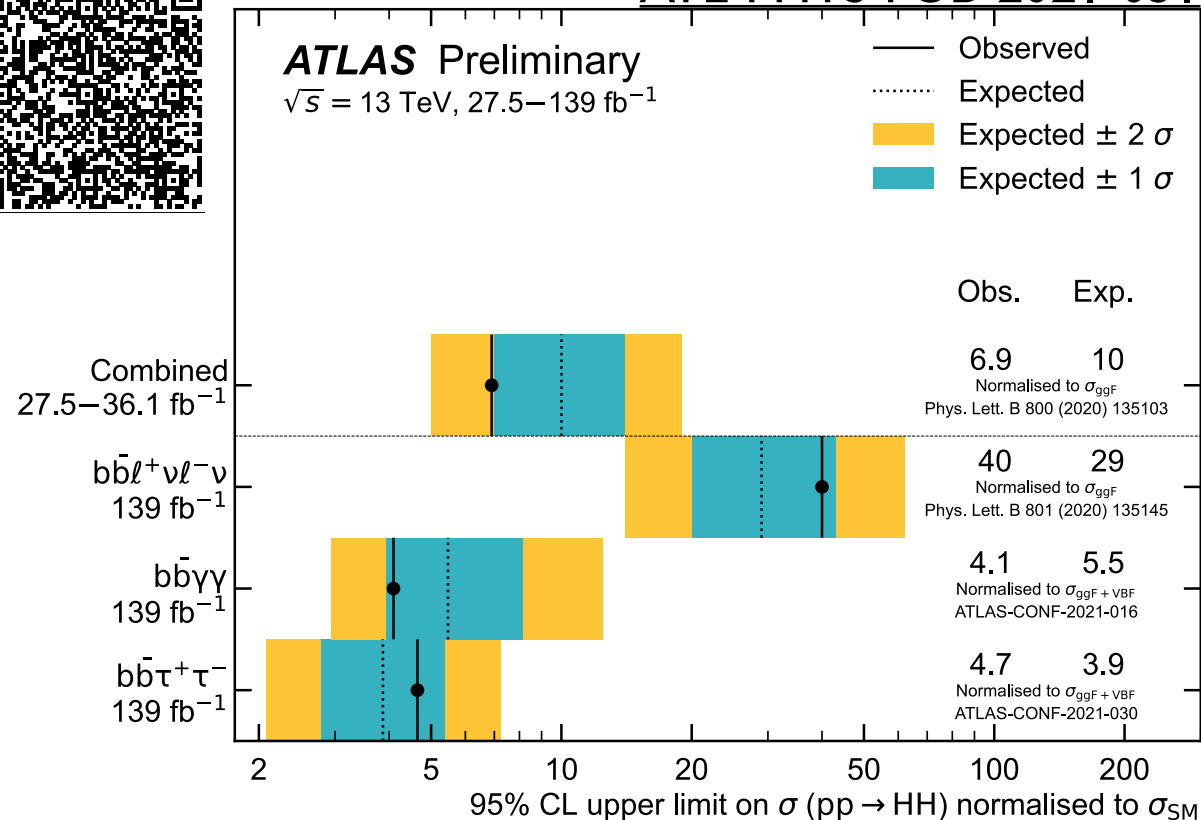
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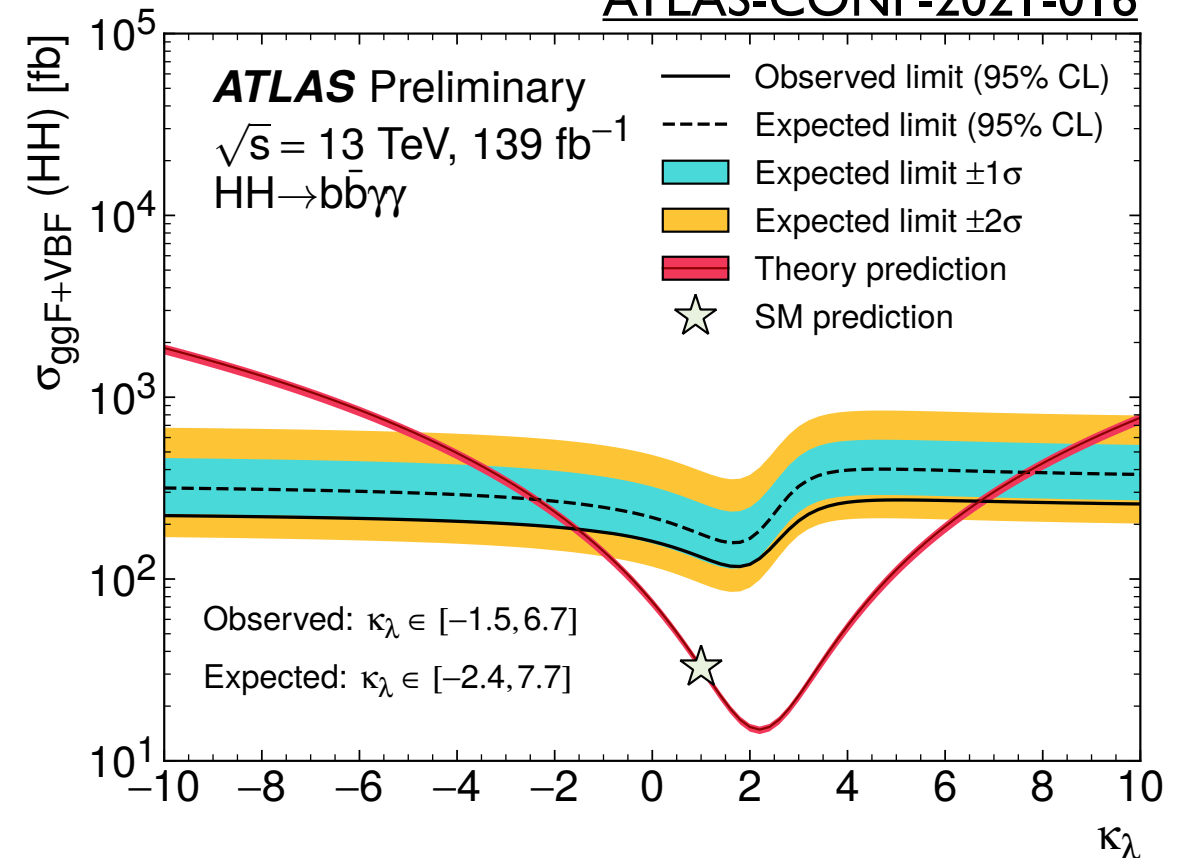
Searching for Higgs Pairs



ATL-PHYS-PUB-2021-031



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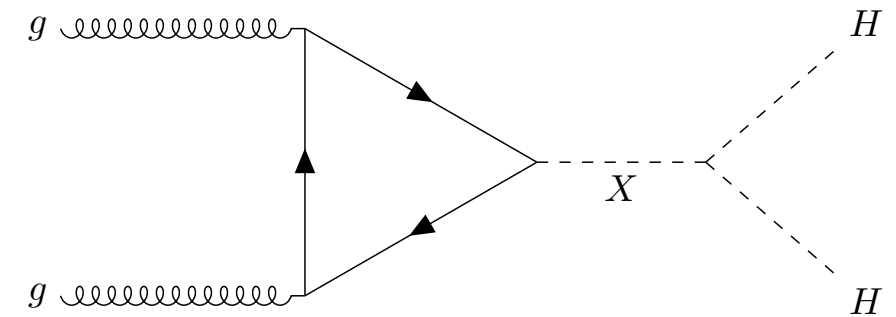
$b\bar{b}\gamma\gamma$ and $b\bar{b}\tau\tau$ channels each exclude around 4x the SM

Values below -1.5 and above 6.7 excluded: even full HL-LHC dataset will be critical to tighten this!

Searching for Higgs Pairs



Searching for Higgs Pairs

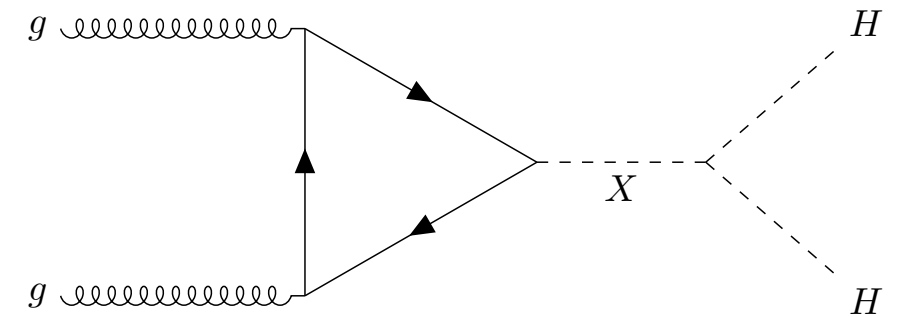
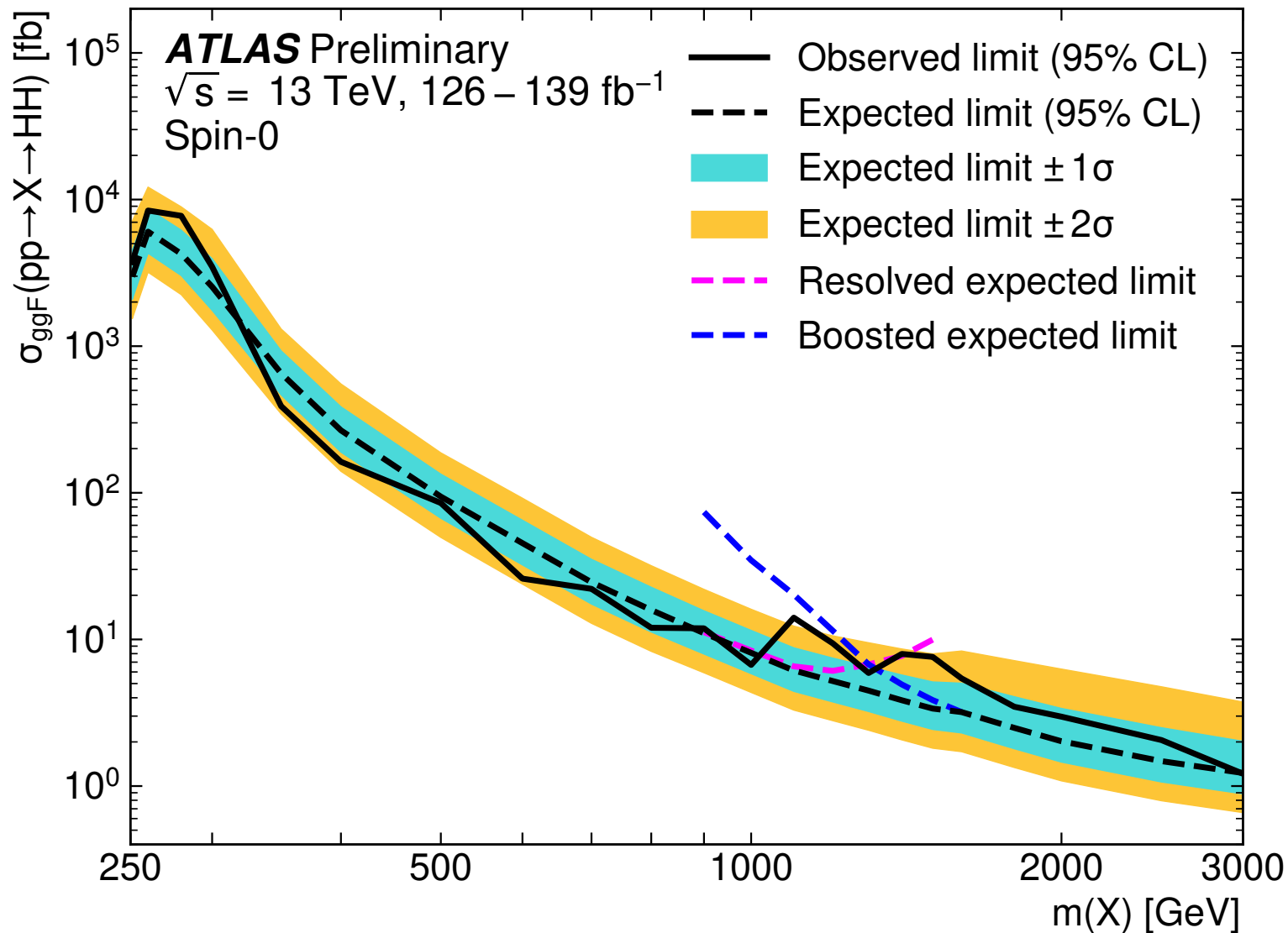


Also important to search for resonances, which actually *cause* the change in the potential

Searching for Higgs Pairs

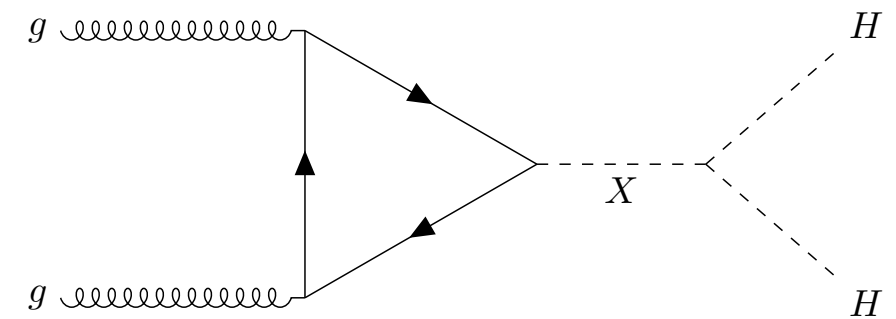
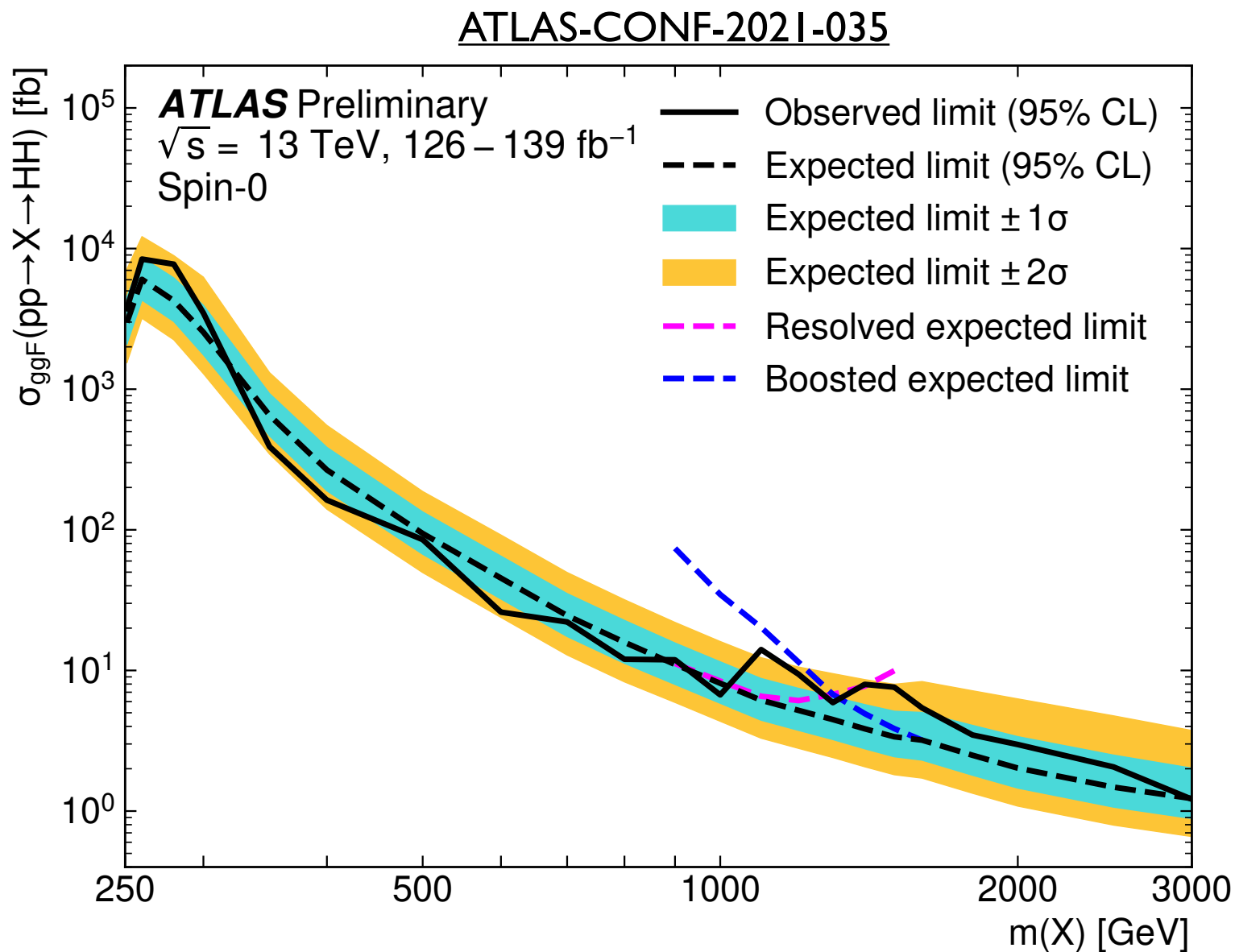


ATLAS-CONF-2021-035



Also important to search for resonances, which actually *cause* the change in the potential

Searching for Higgs Pairs

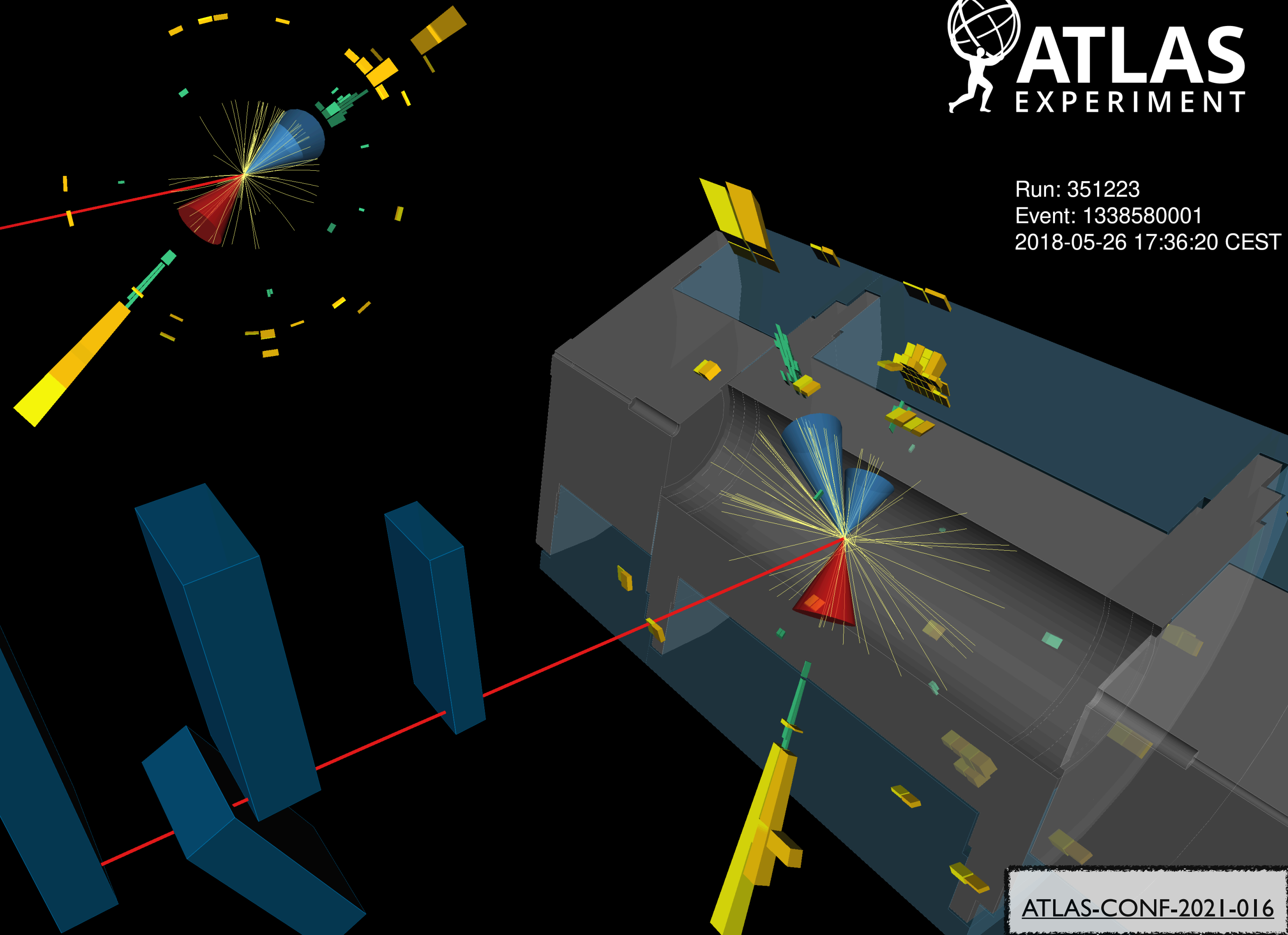


Also important to search for resonances, which actually *cause* the change in the potential

Here, search in the *bbbb* channel: most common decay mode

Conclusions

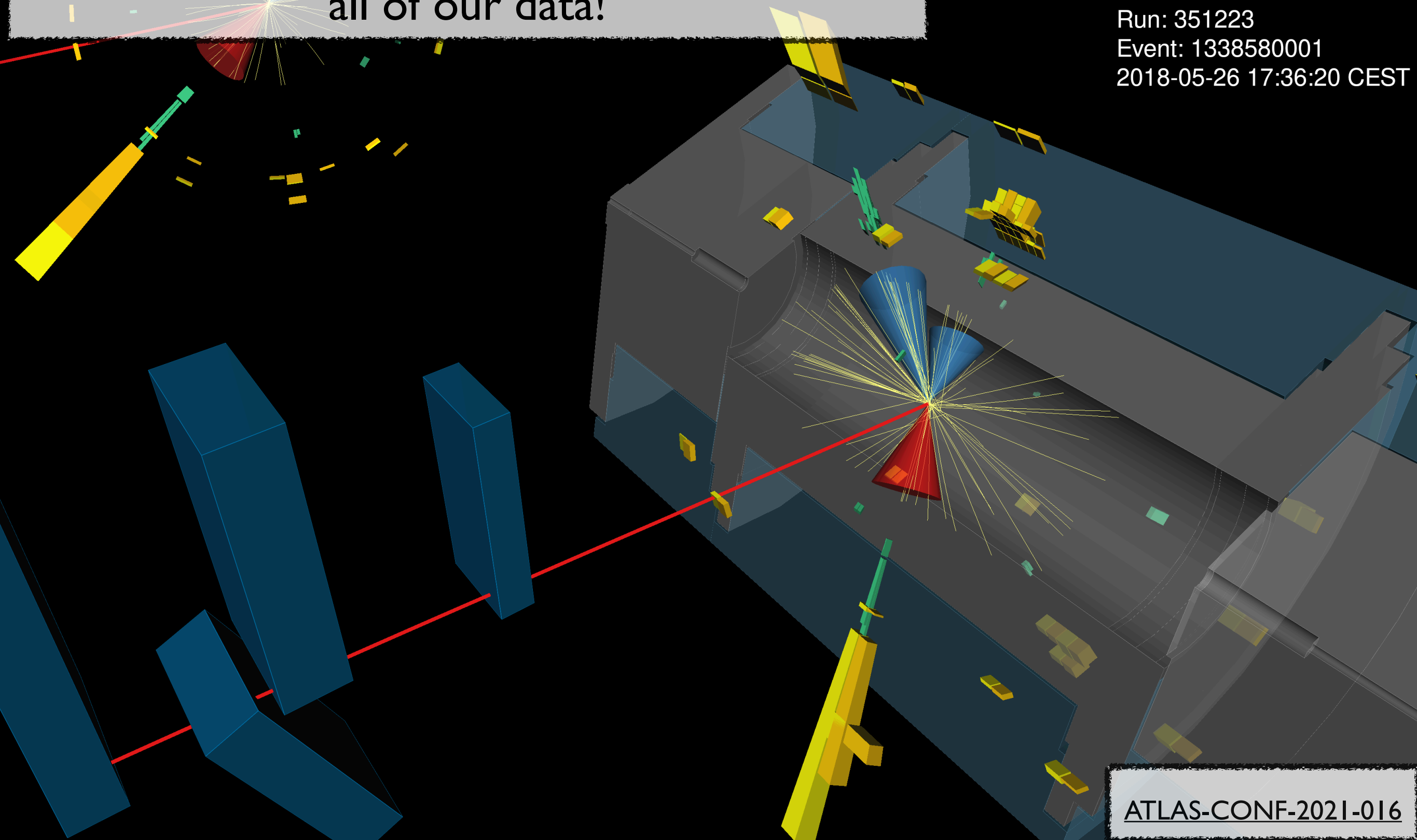
Run: 351223
Event: 1338580001
2018-05-26 17:36:20 CEST



ATLAS was hugely productive in the past years:
preparing for run 3, installing upgrades,
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all of our data!



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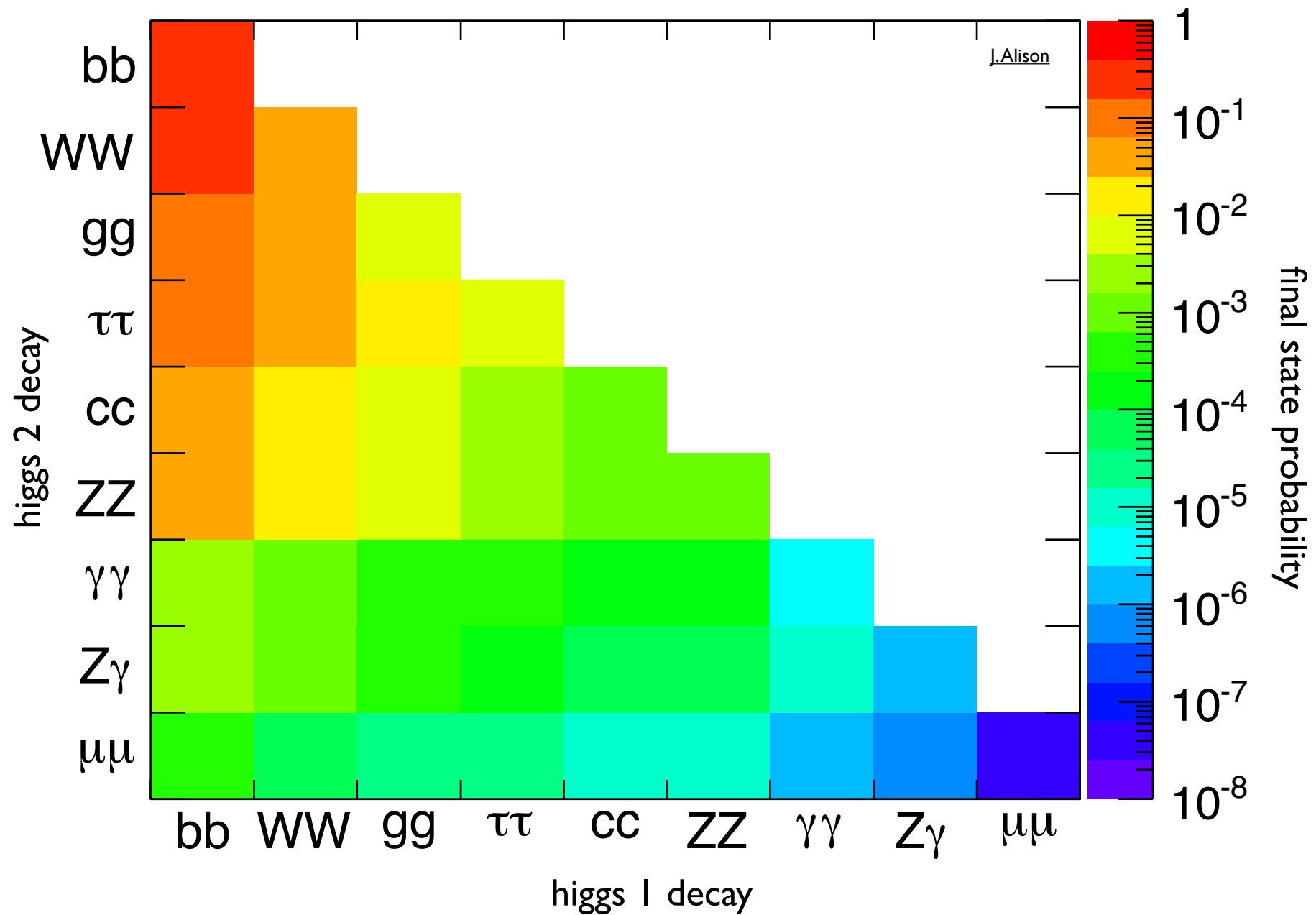
Stay tuned for more upgrades, more data,
and more measurements that elucidate
our biggest questions!

Backup

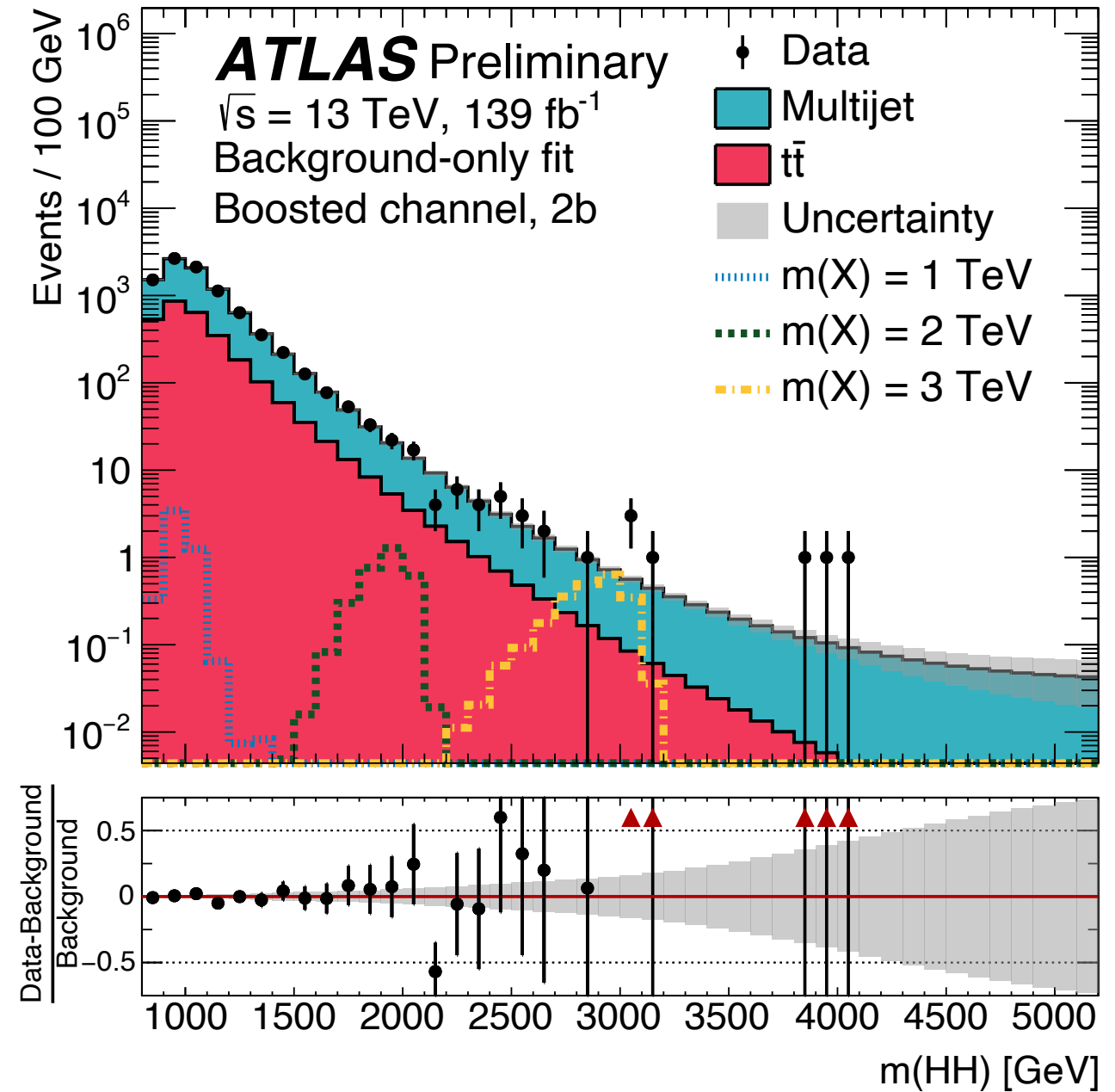
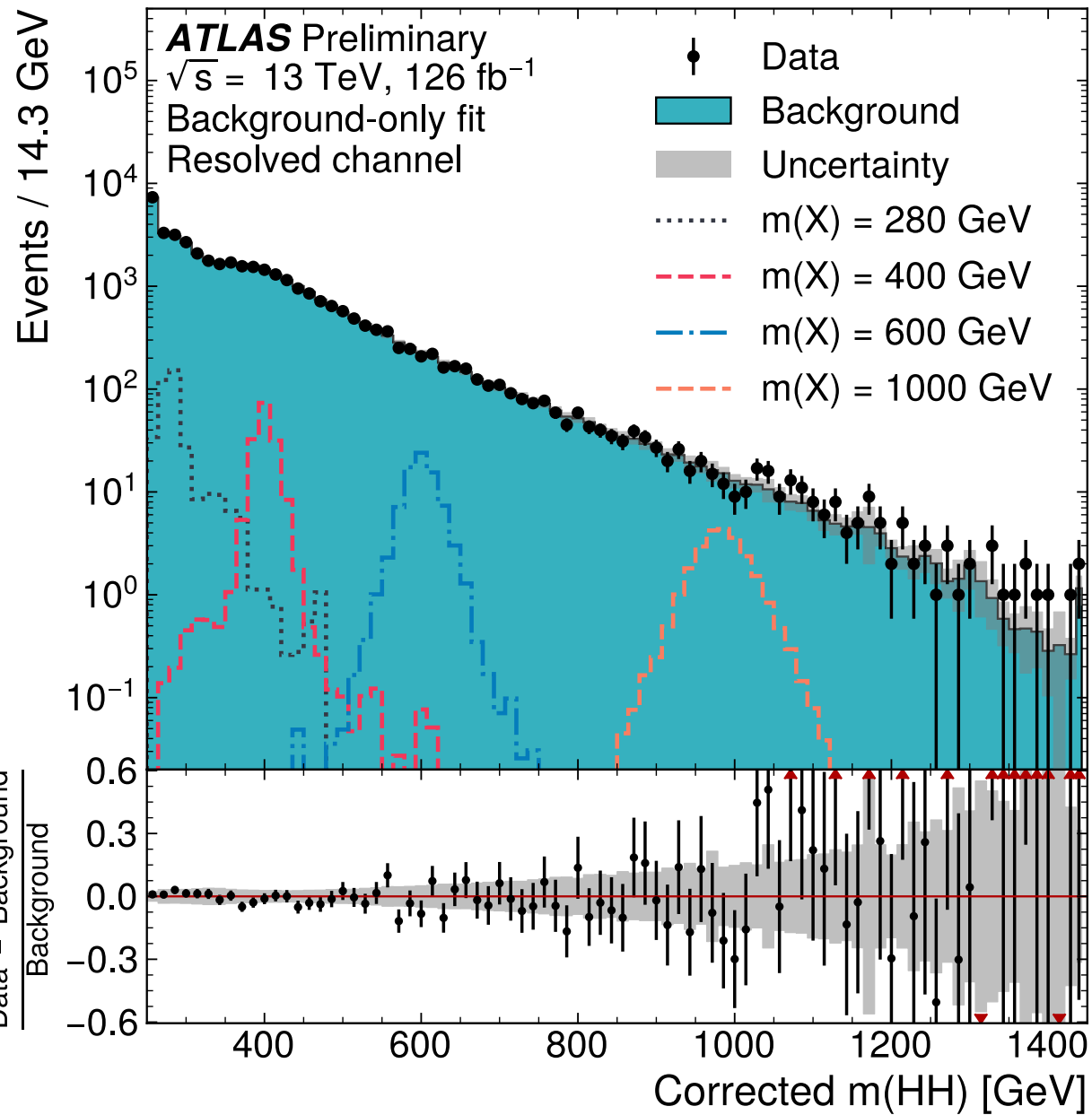
Di-Higgs Decay Modes



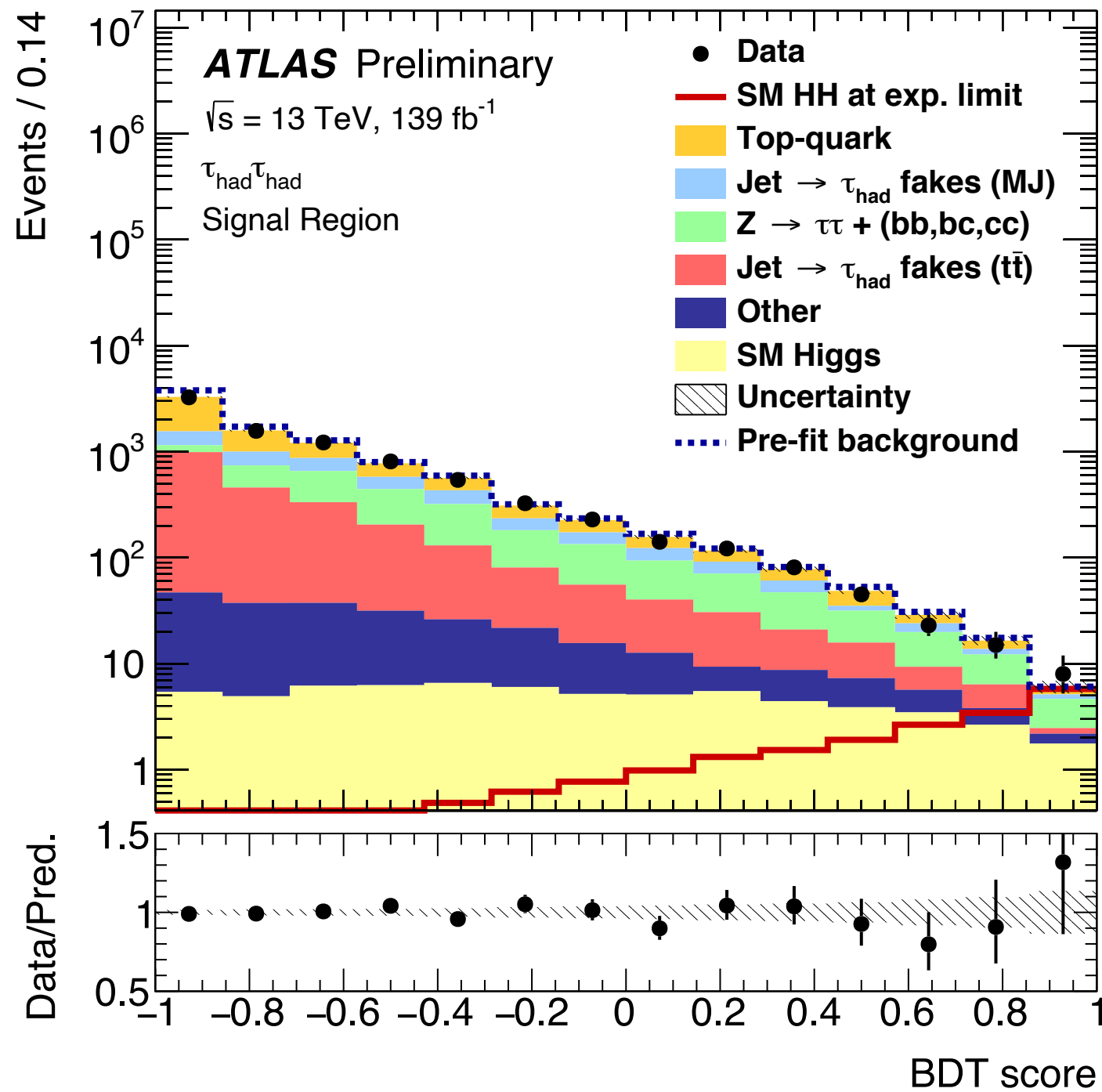
Di-Higgs Decay Modes



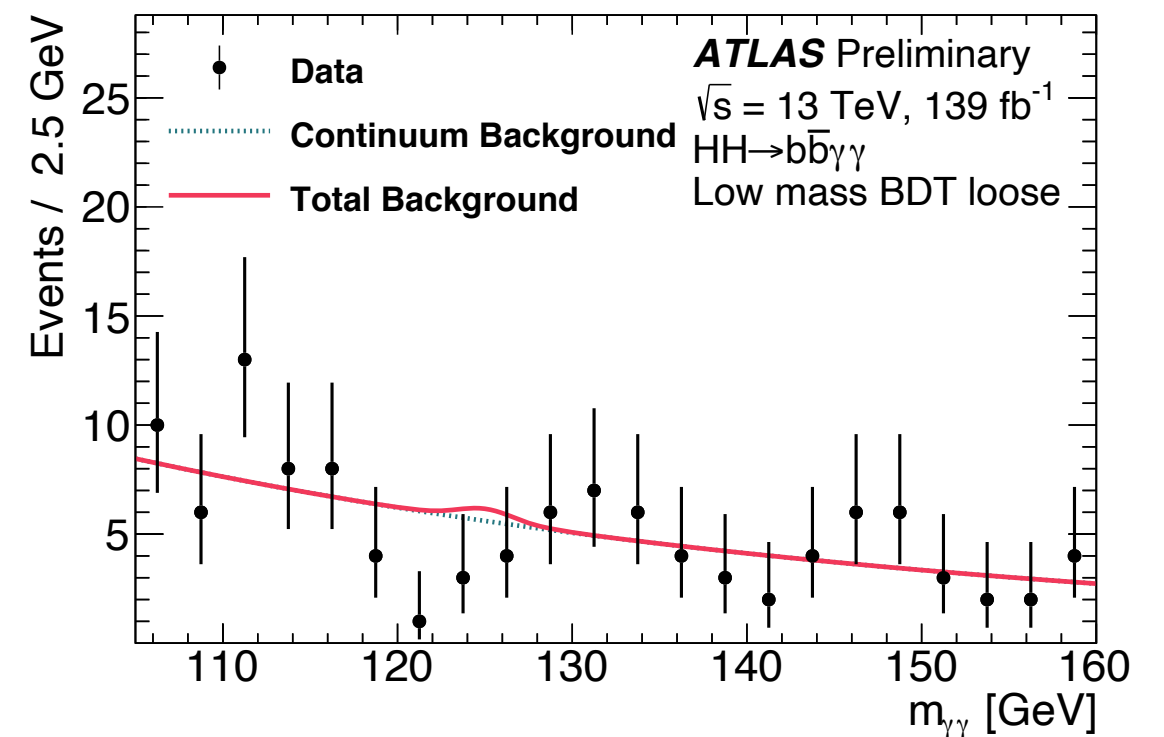
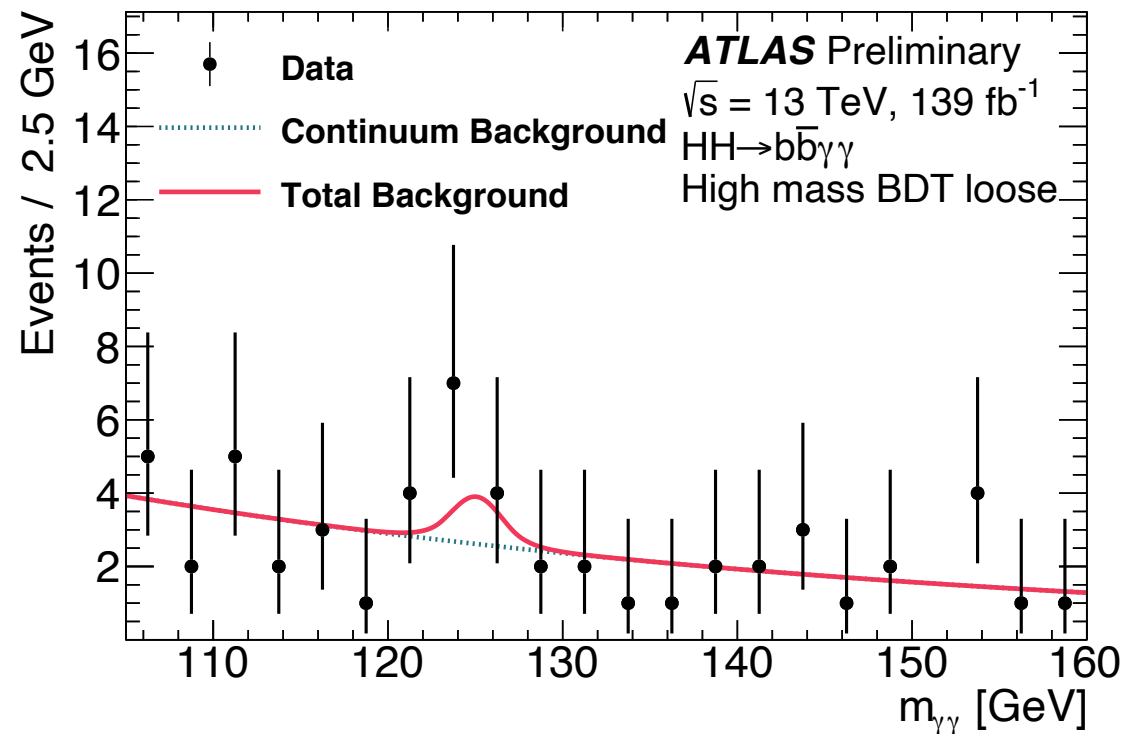
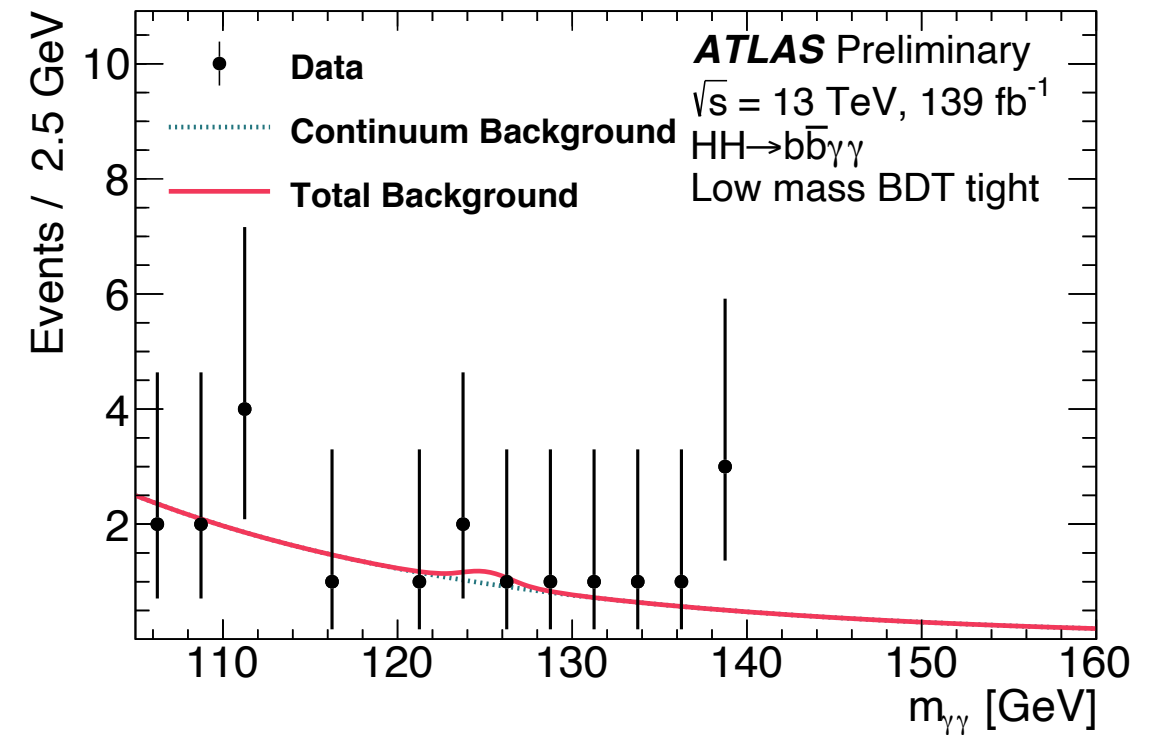
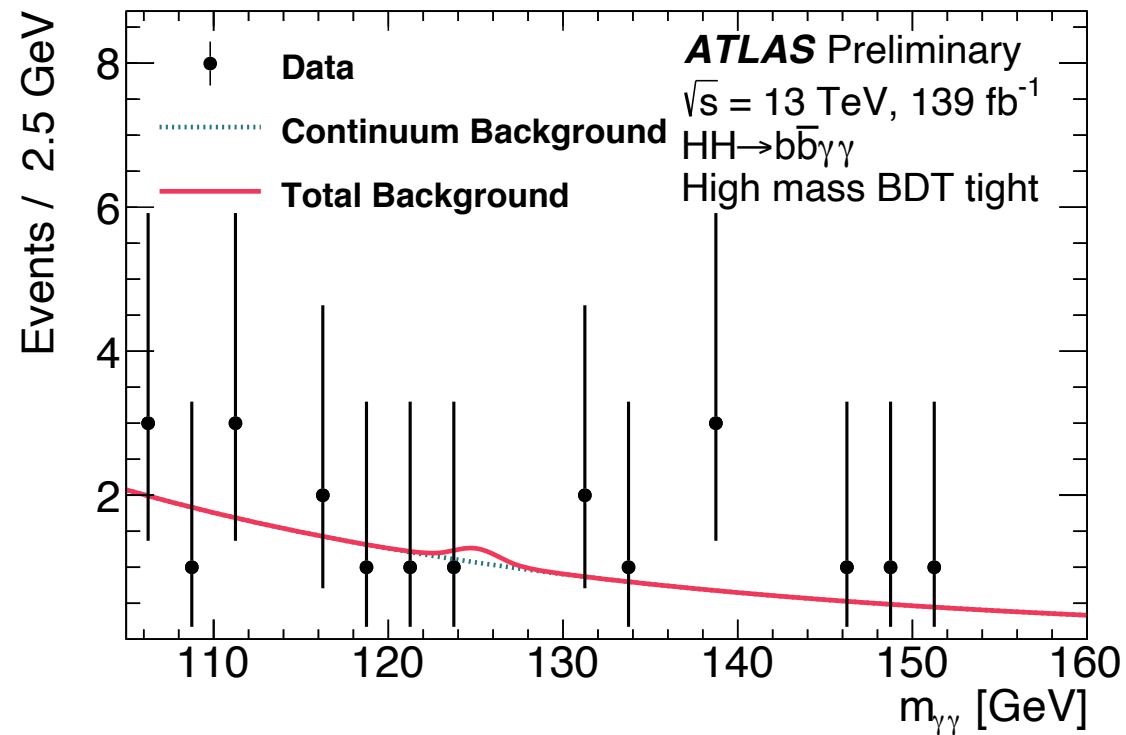
HH4b Results



HHbb $\tau\tau$ Results



HHbbγγ Results



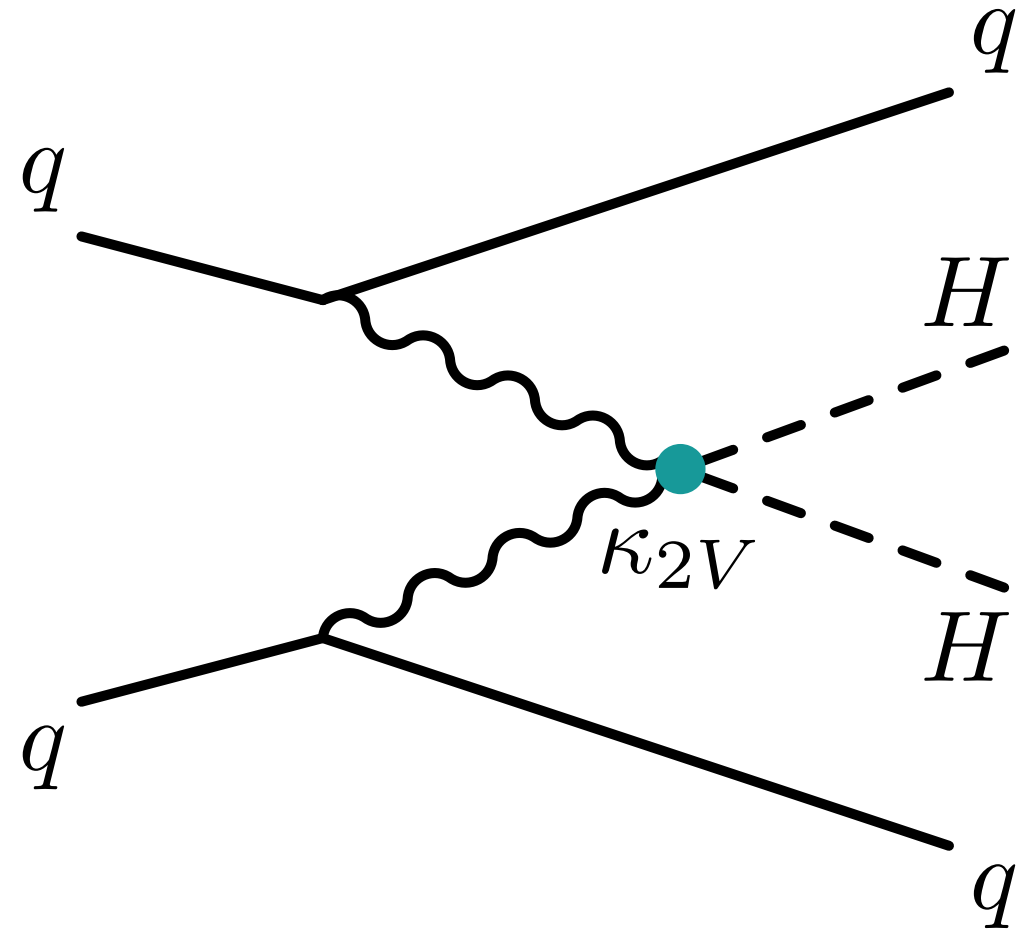
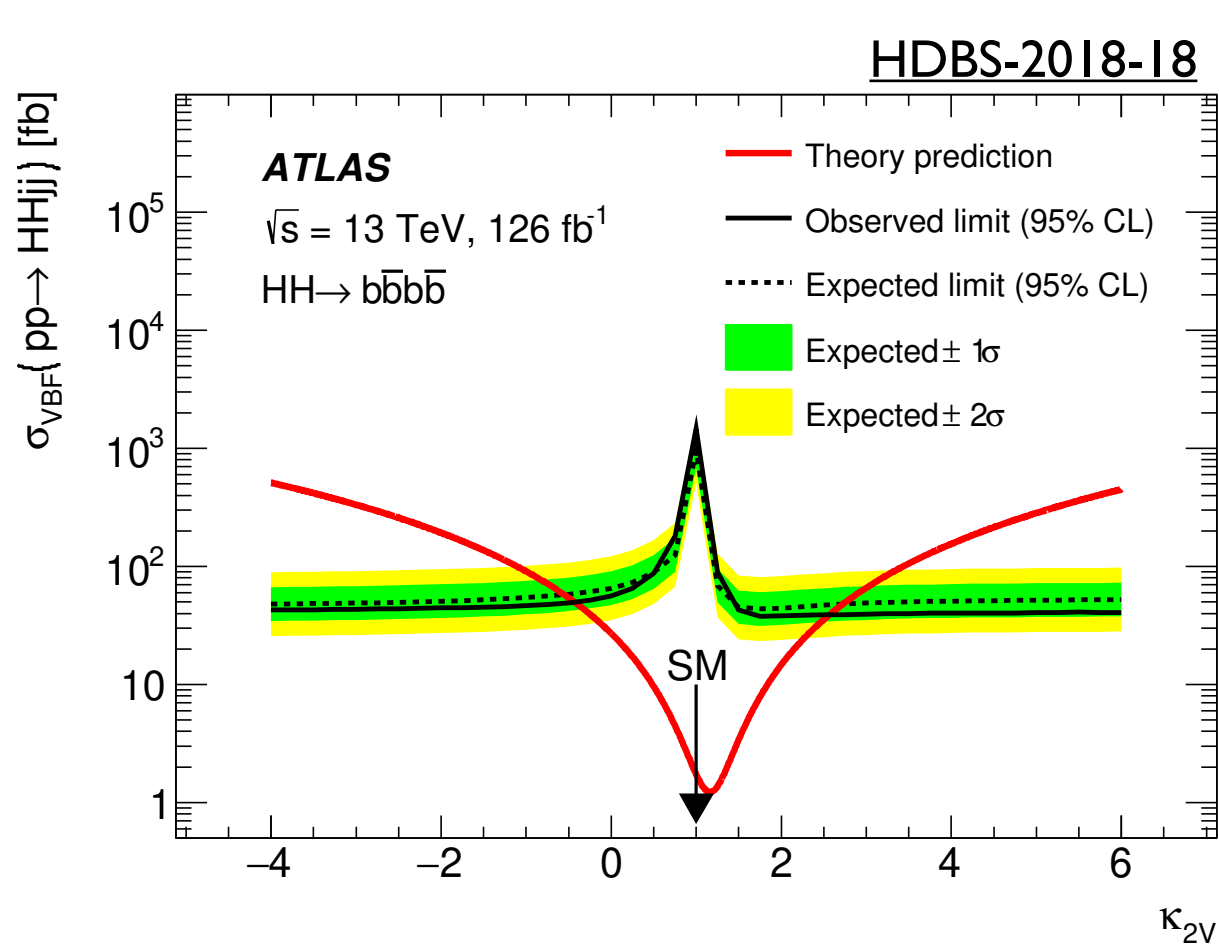
HH4b VBF





Can also measure
other effects!

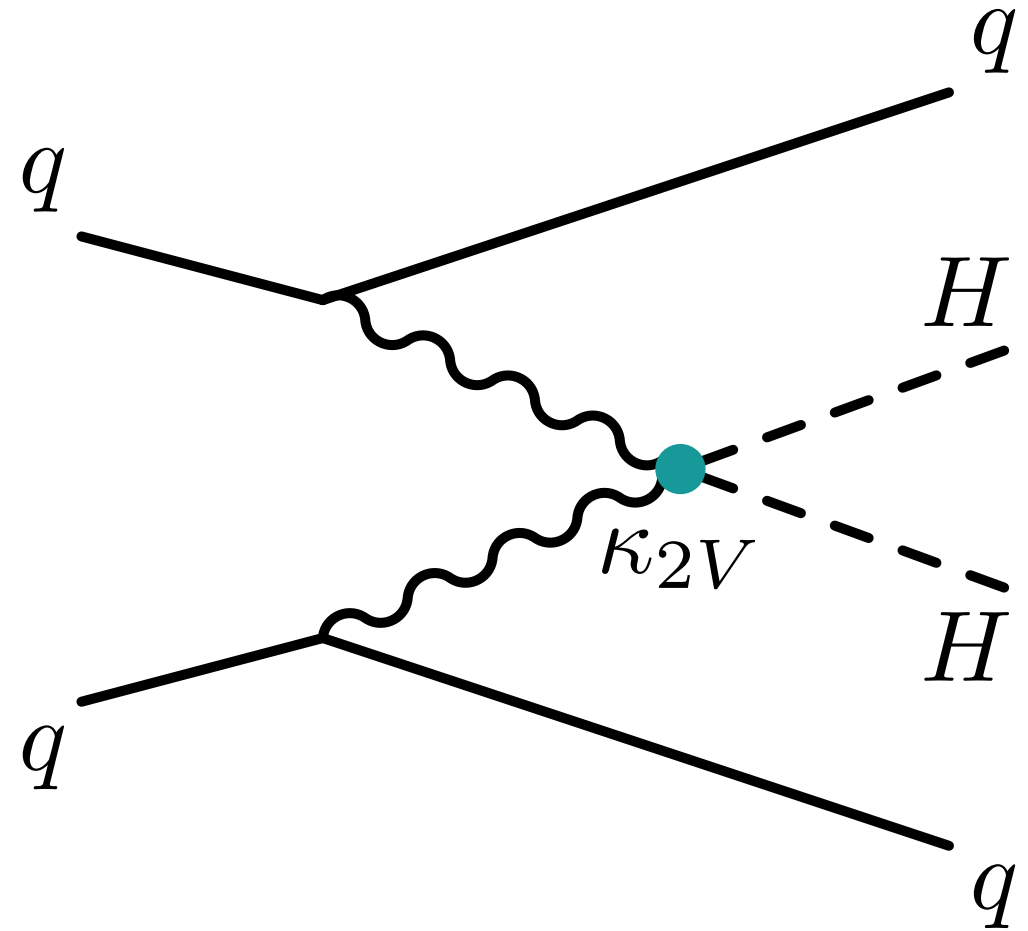
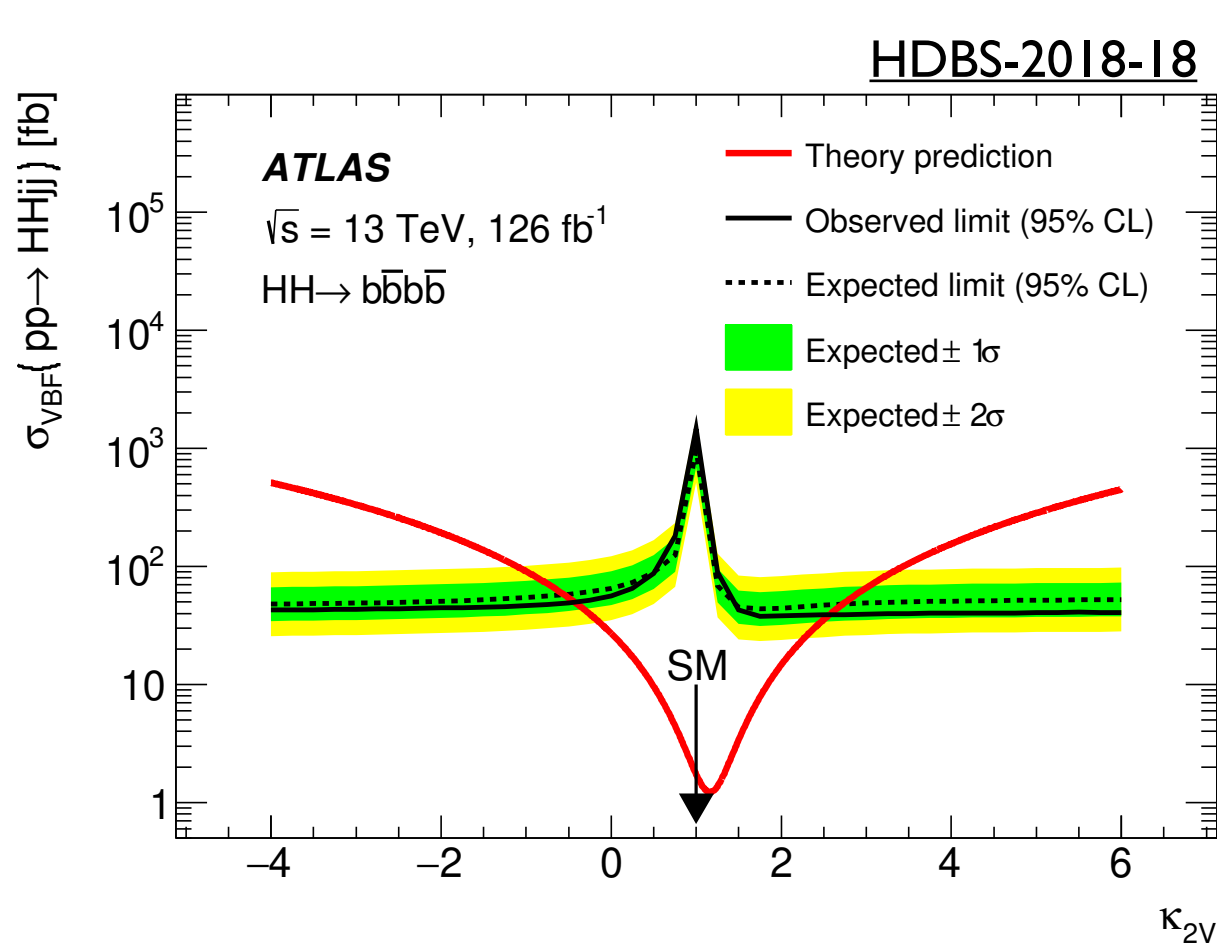
HH4b VBF



Can also measure other effects!

Here, search for 4-point VVhh coupling

HH4b VBF



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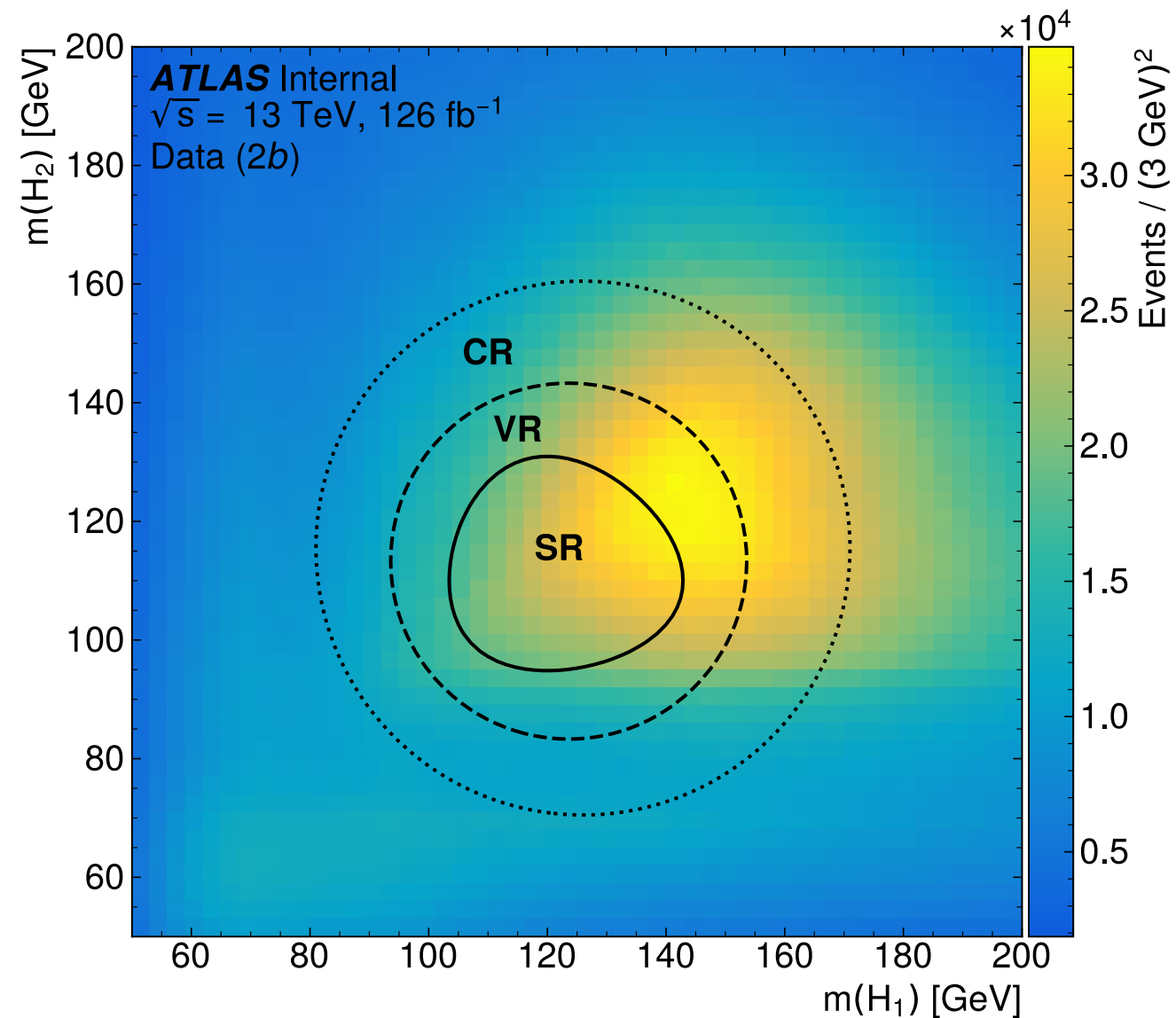
Here, search for 4-point VVhh coupling

First world limits!

HH4b Background



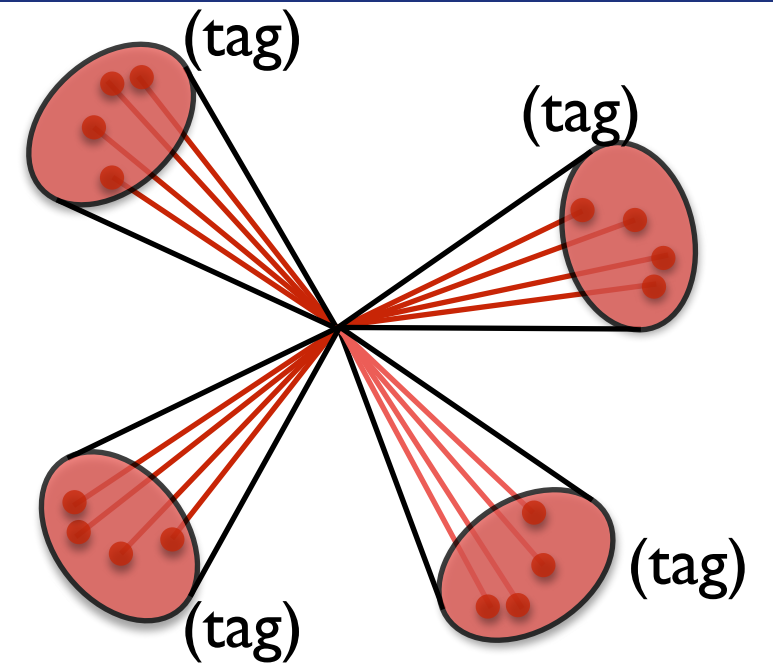
- Background estimate uses 2b events to model 4b events
- Learn correction factors from 2b to 4b using CR, and derive systematics in the VR



Estimating Backgrounds



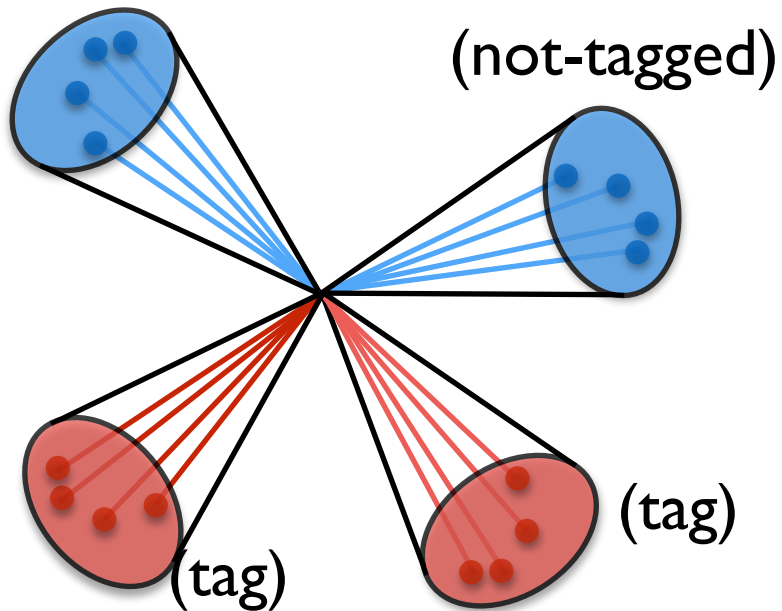
Estimating Backgrounds



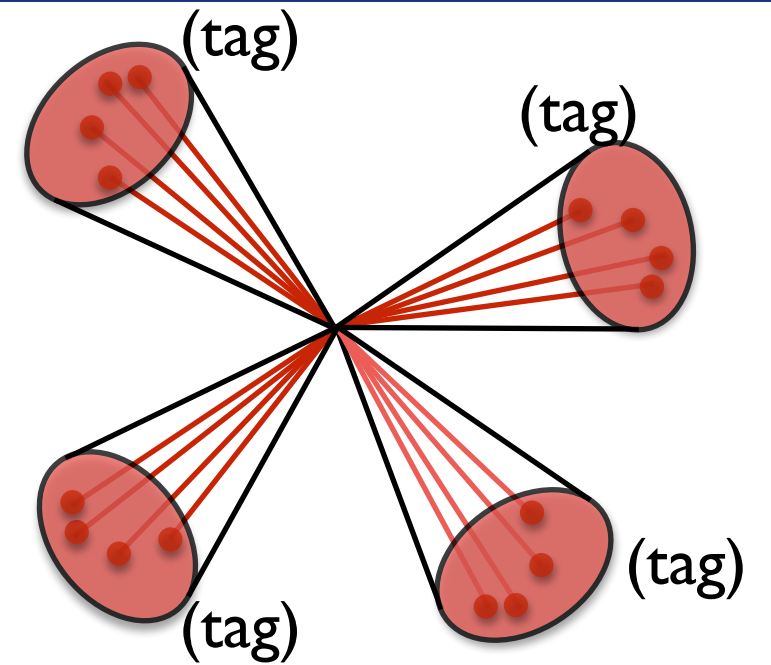
Estimating Backgrounds



(not-tagged)



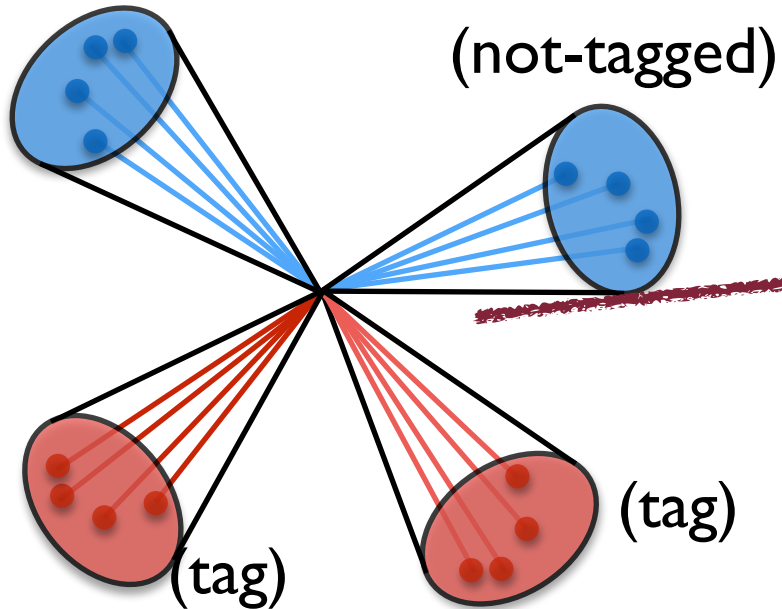
2 b-tag events are
background enhanced,
signal depleted



Estimating Backgrounds

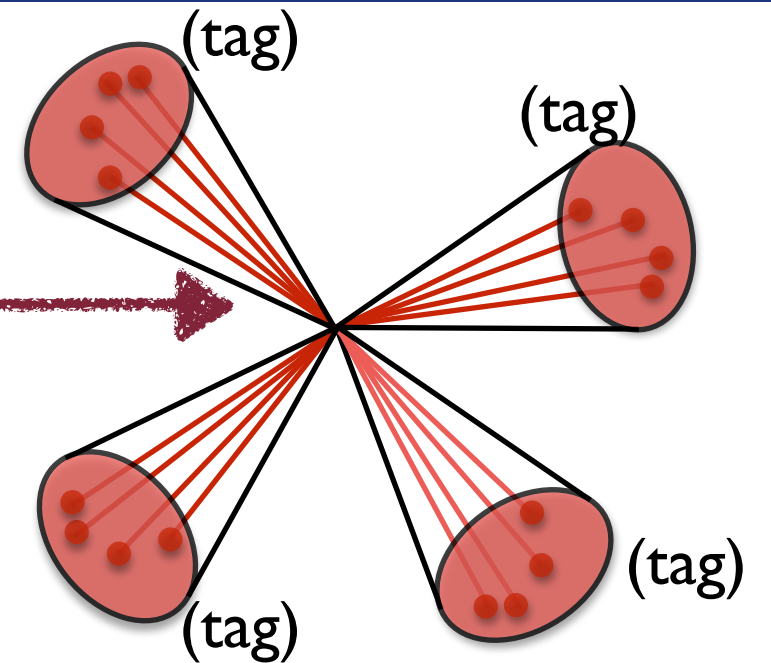


(not-tagged)

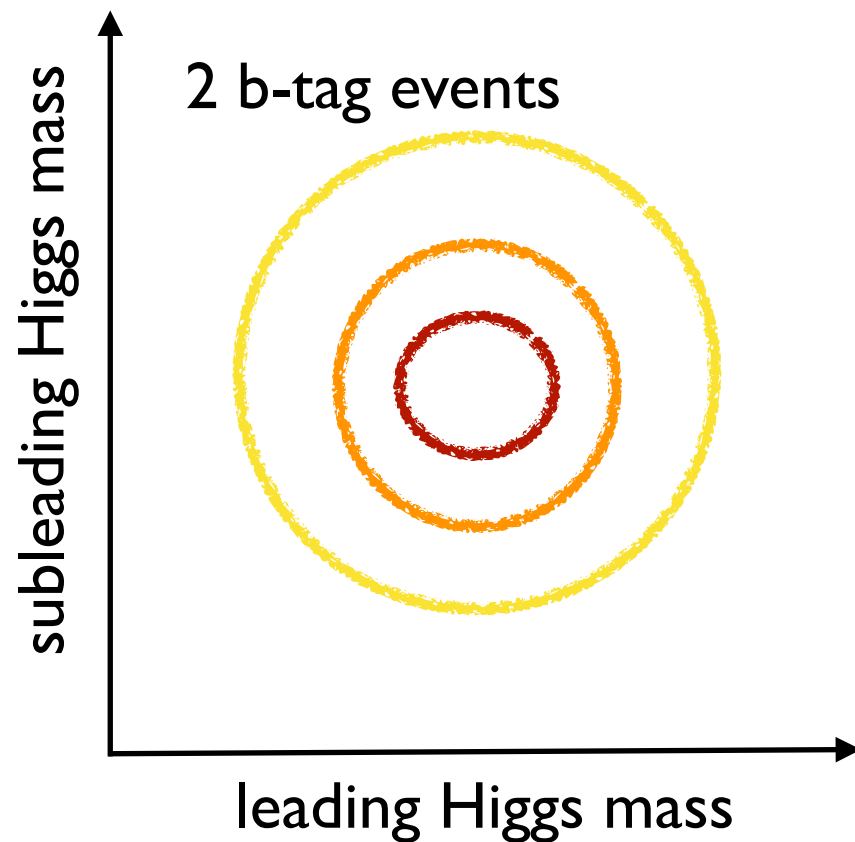
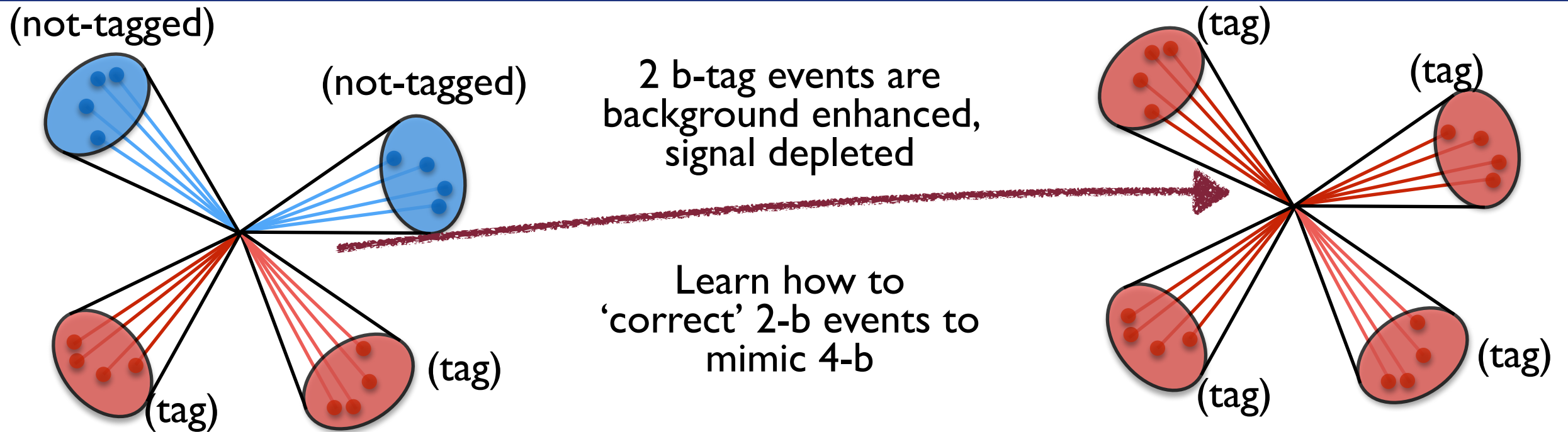


2 b-tag events are background enhanced, signal depleted

Learn how to 'correct' 2-b events to mimic 4-b



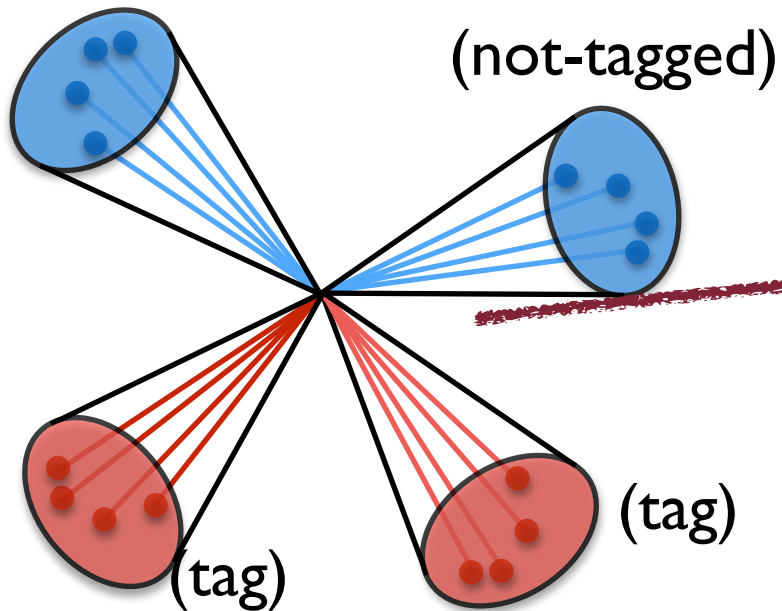
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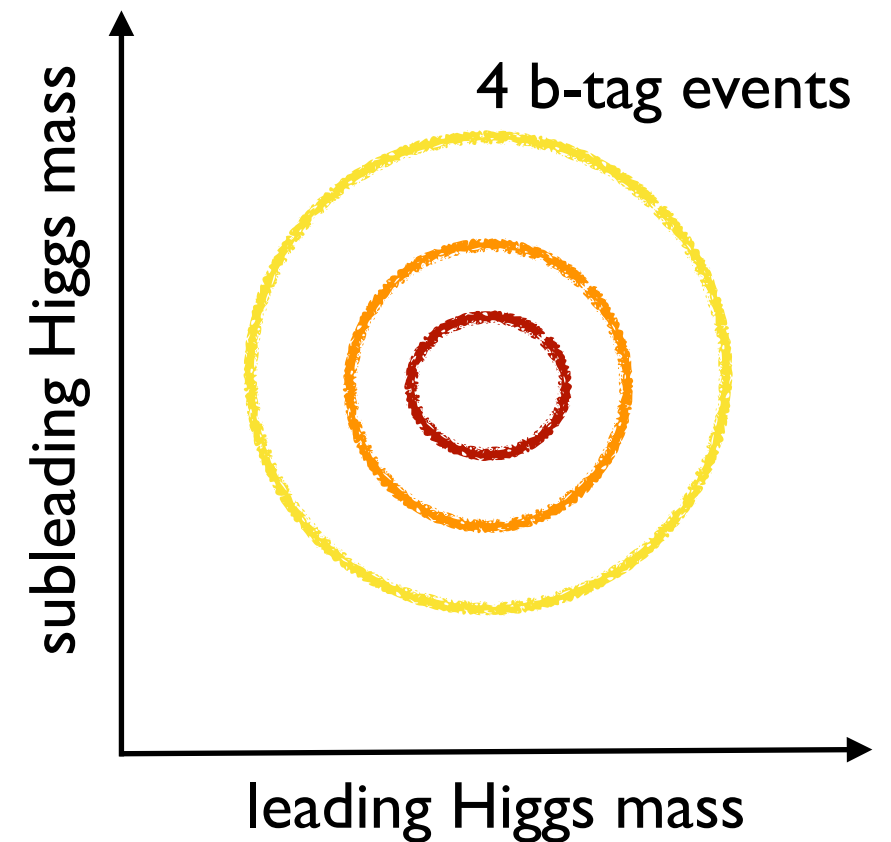
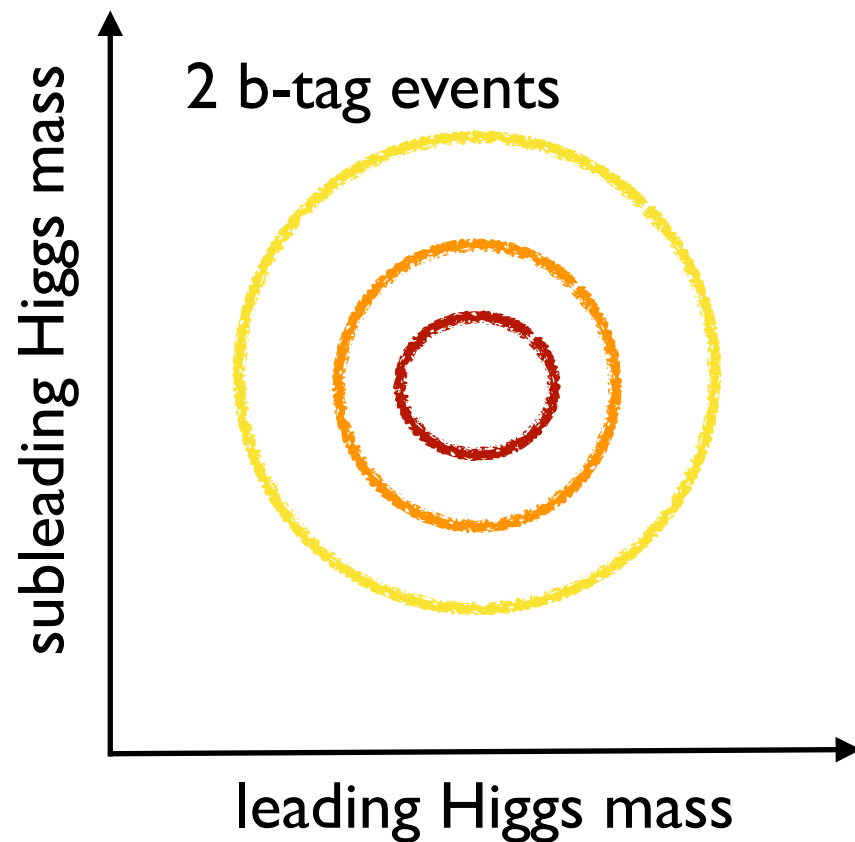
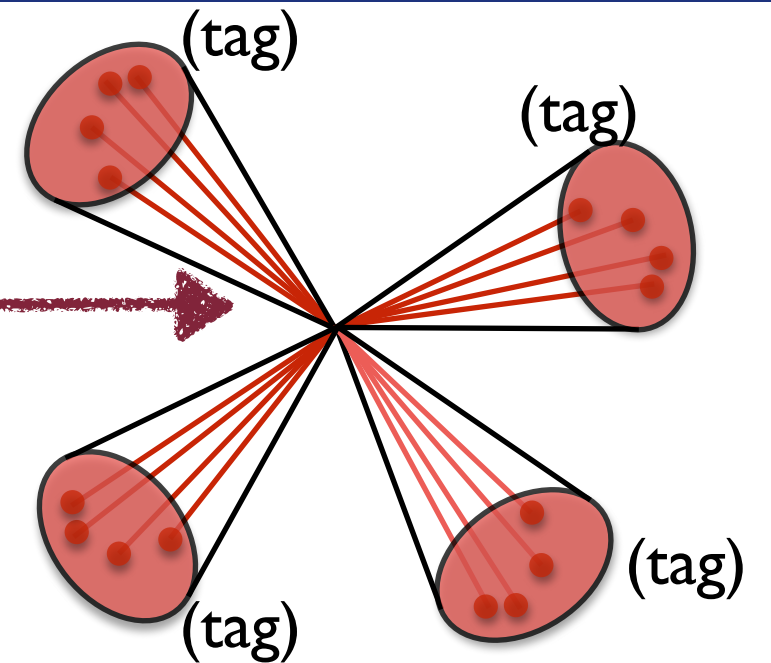


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2 b-tag events are background enhanced, signal depleted

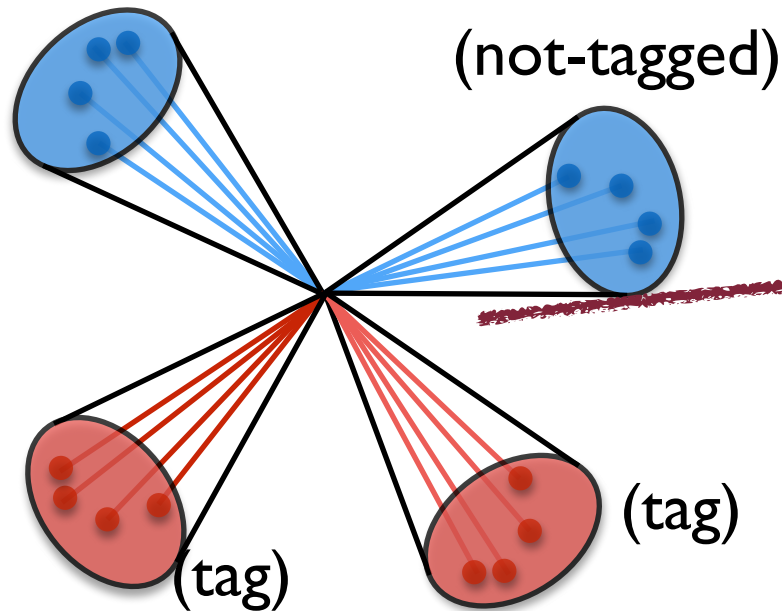
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Estimating Backgrounds

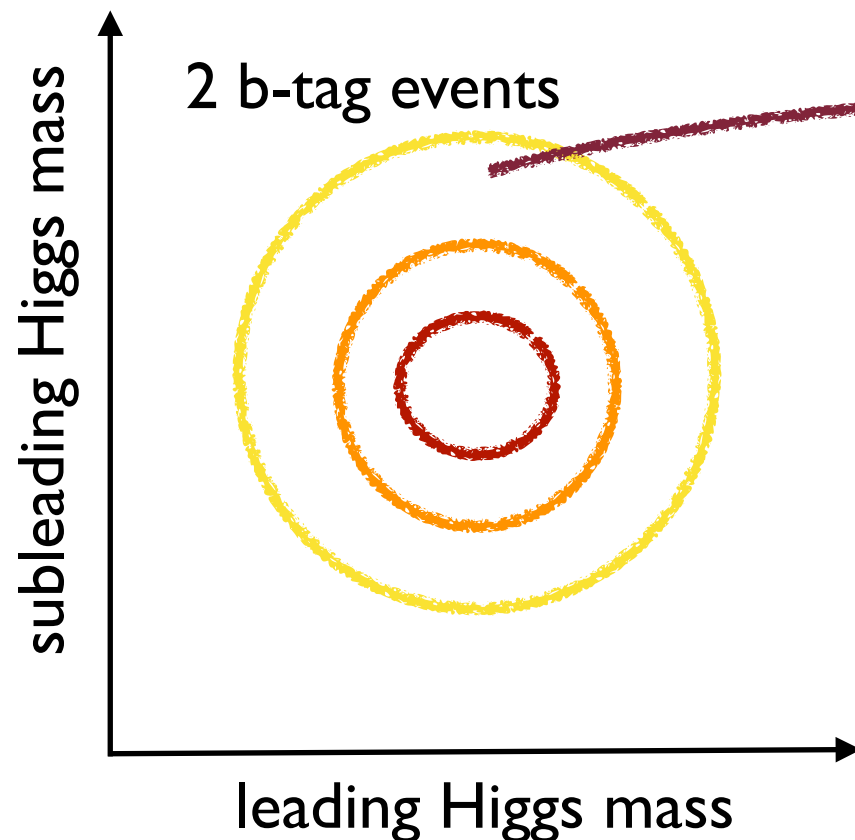
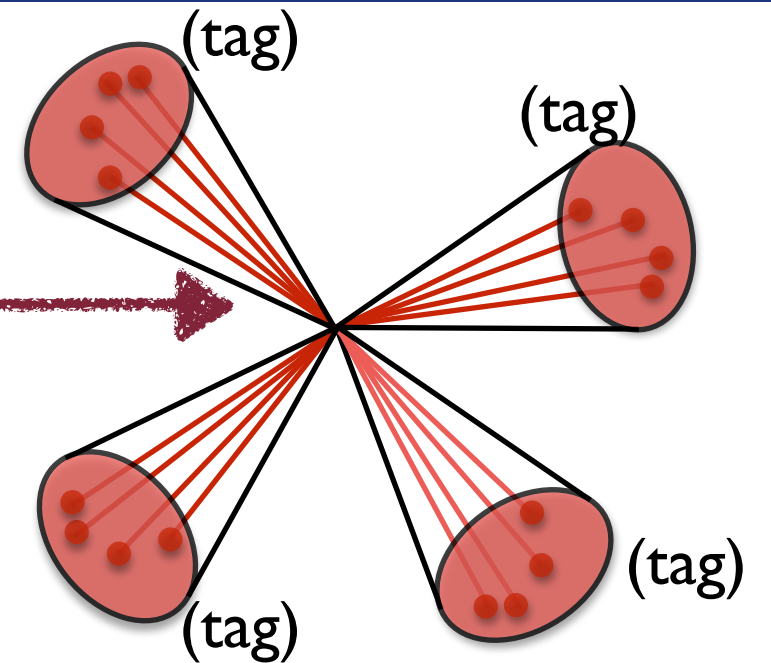


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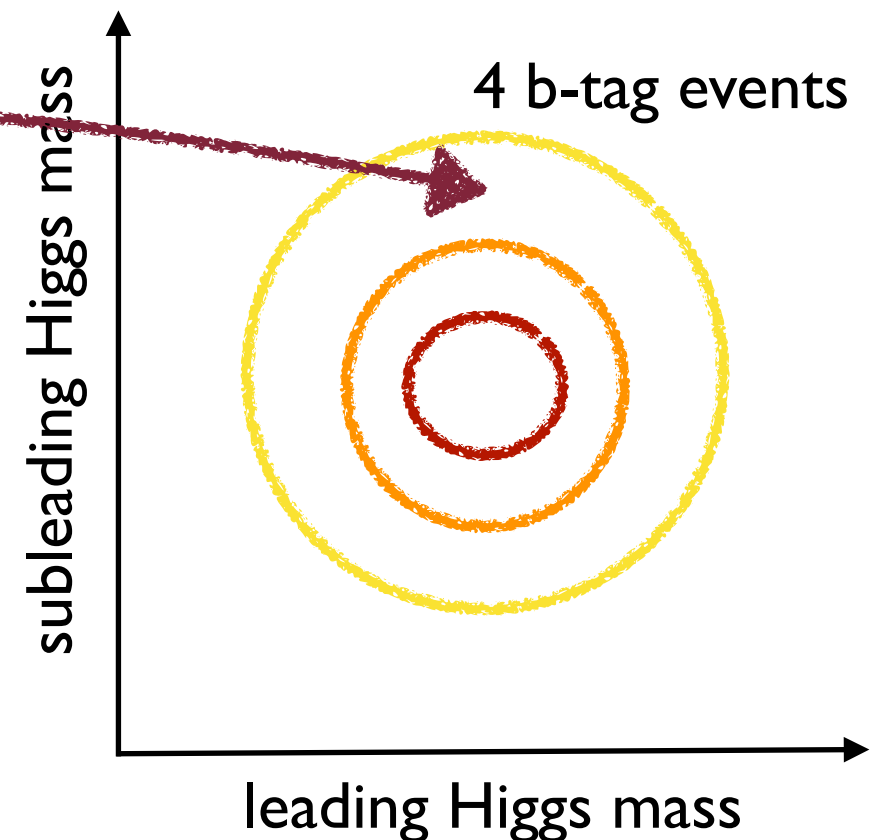


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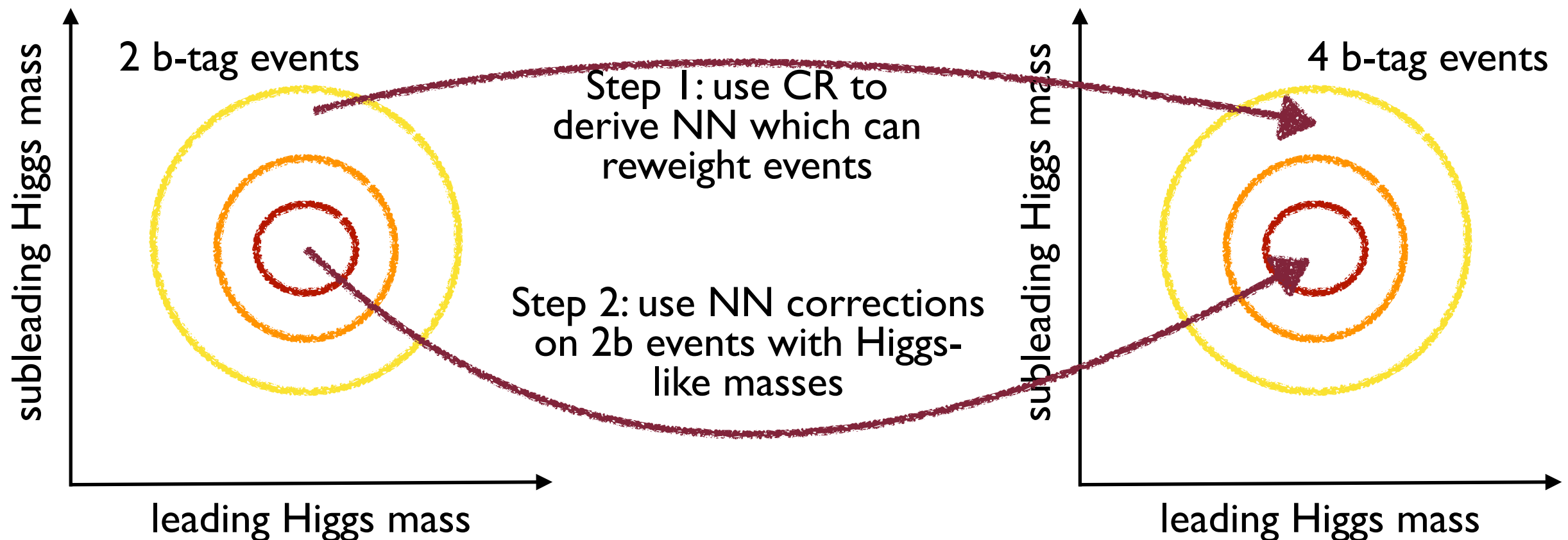
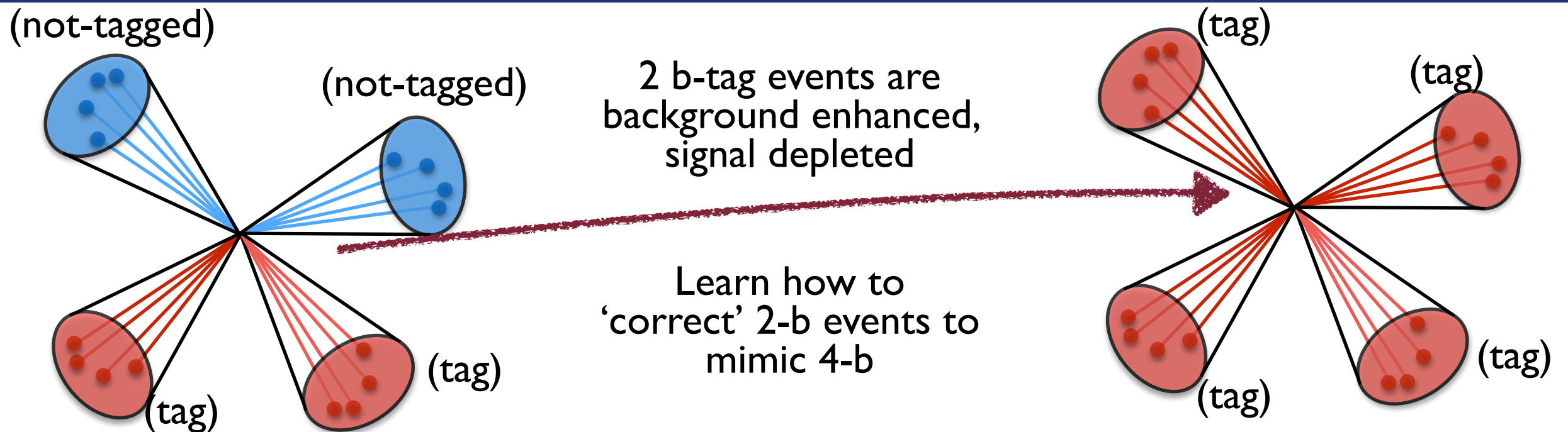
Learn how to 'correct' 2-b events to mimic 4-b



Step 1: use CR to derive NN which can reweight events



Estimating Backgrounds



HH4b NN

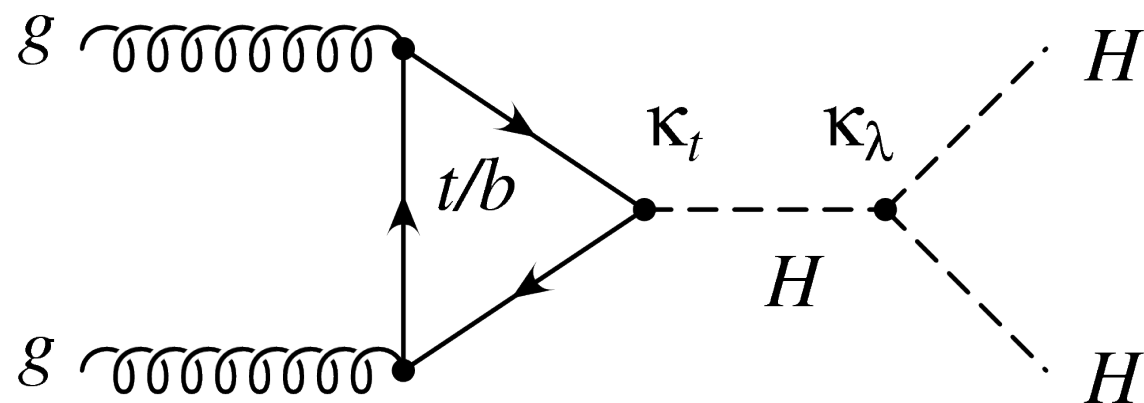
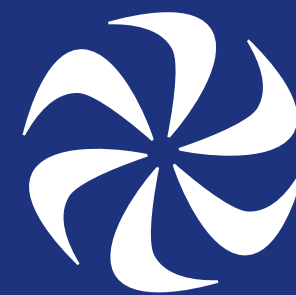


1. $\log(p_T)$ of the selected jet with the 2nd-highest p_T ,
2. $\log(p_T)$ of the selected jet with the 4th-highest p_T ,
3. $\log(\Delta R)$ between the two selected jets with the smallest ΔR ,
4. $\log(\Delta R)$ between the other two selected jets,
5. the average $|\eta|$ of selected jets,
6. $\log(p_T)$ of the HH system,
7. ΔR between the two H candidates,
8. $\Delta\phi$ between the jets making up H_1 ,
9. $\Delta\phi$ between the jets making up H_2 ,
10. $\log(\min(X_{W_t}))$, and
11. the number of jets in the event with $p_T > 40$ GeV and $|\eta| < 2.5$, including jets that are not selected.

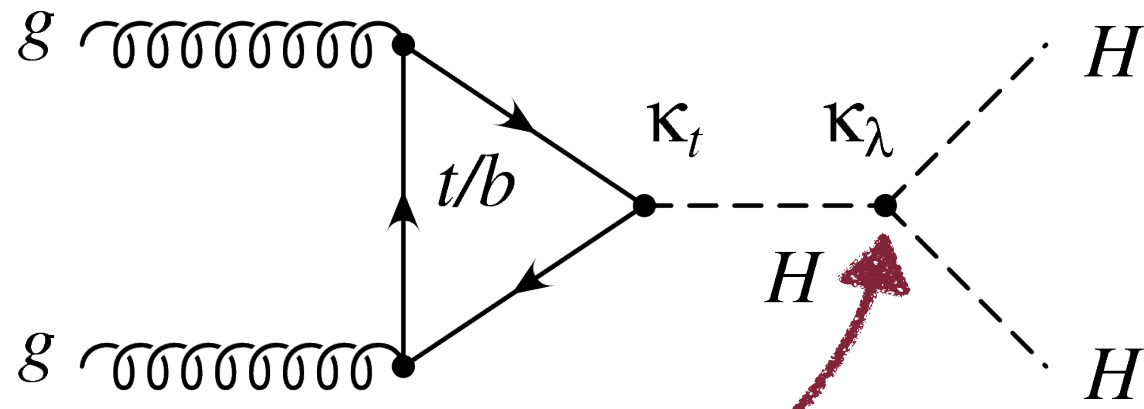
Interference



Interference

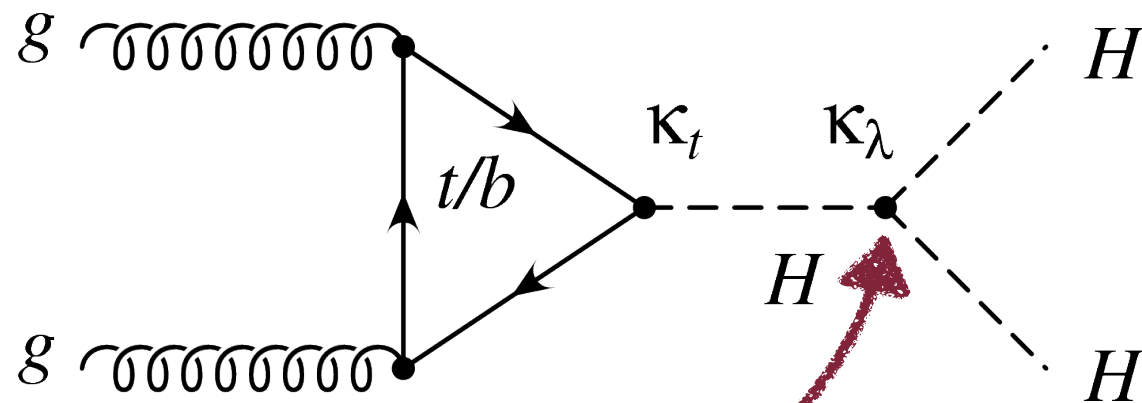


Interference



This coupling is what we want to measure

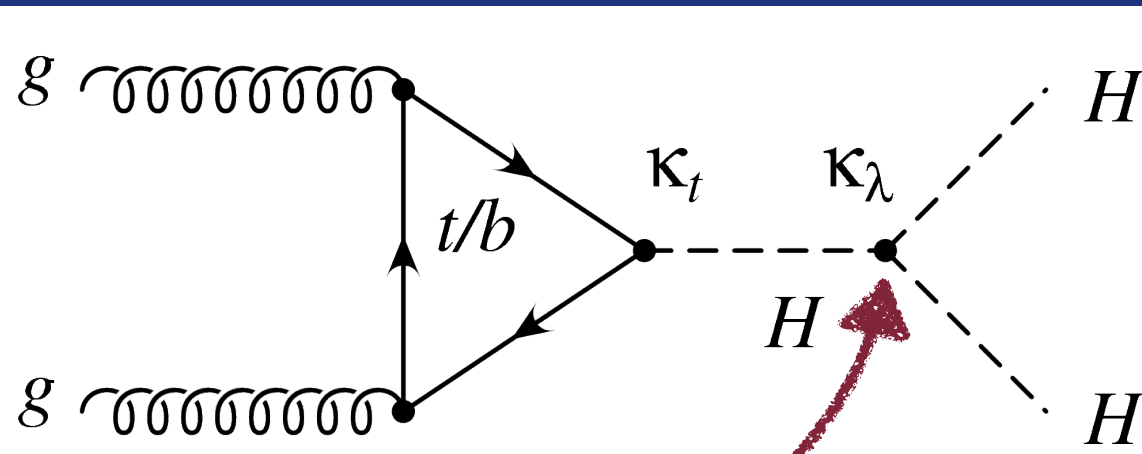
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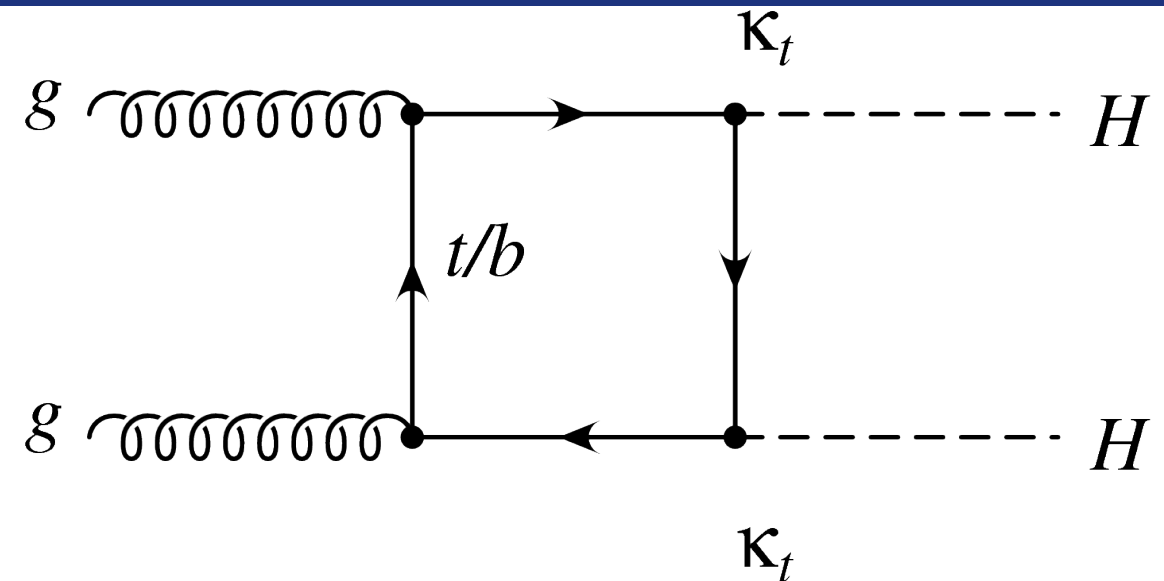
This tells us about the shape of the Higgs potential

Interference



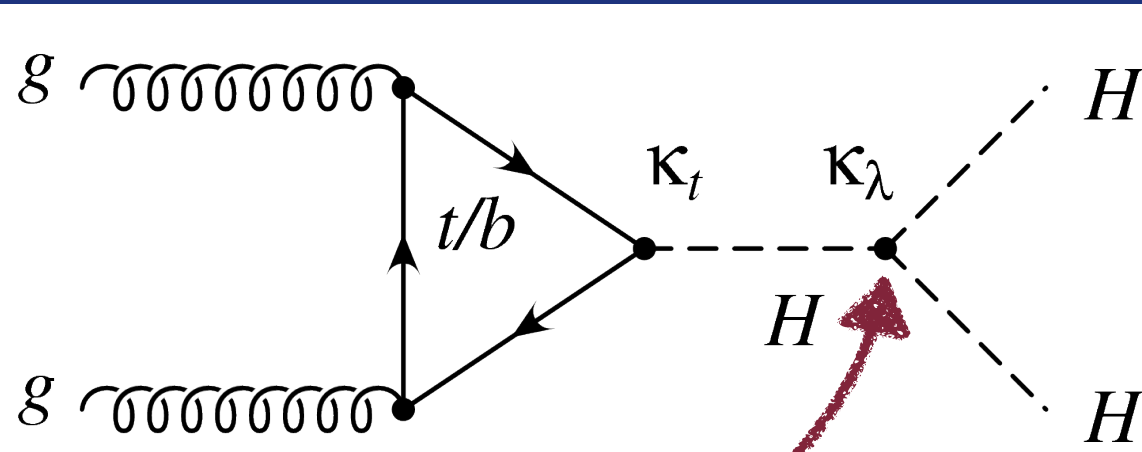
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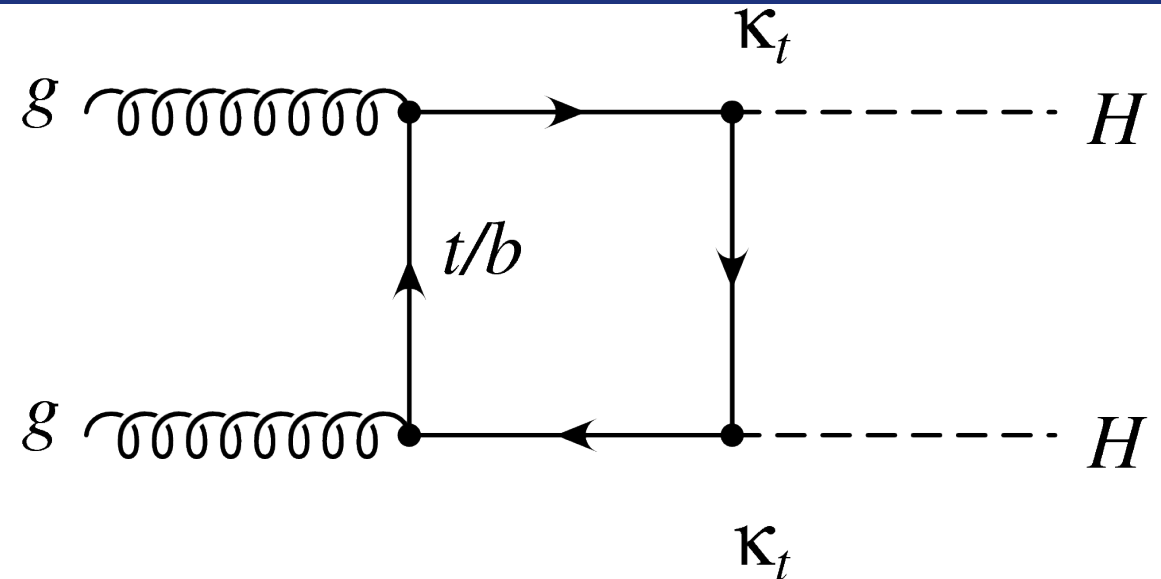
This process has the same final state, but κ_λ doesn't appear: no information about the Higgs potential

Interference



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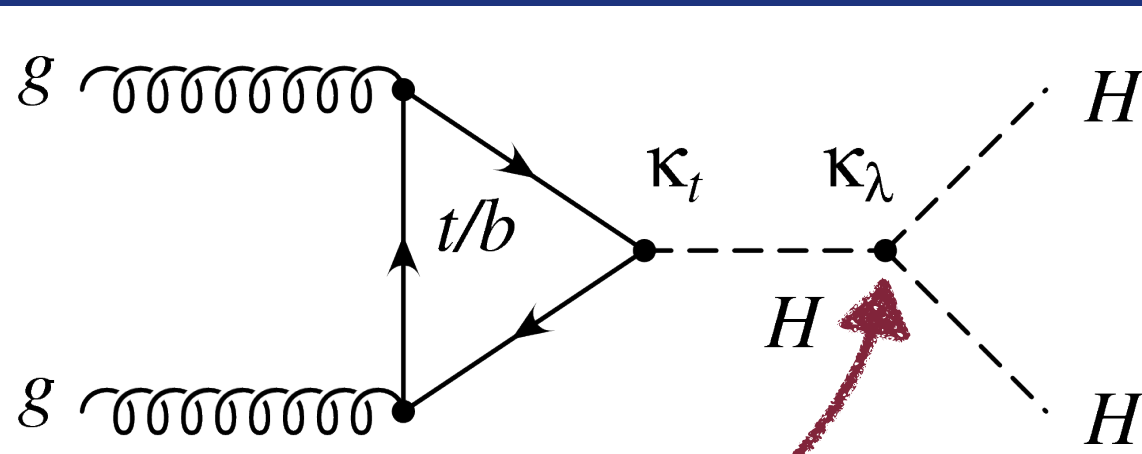
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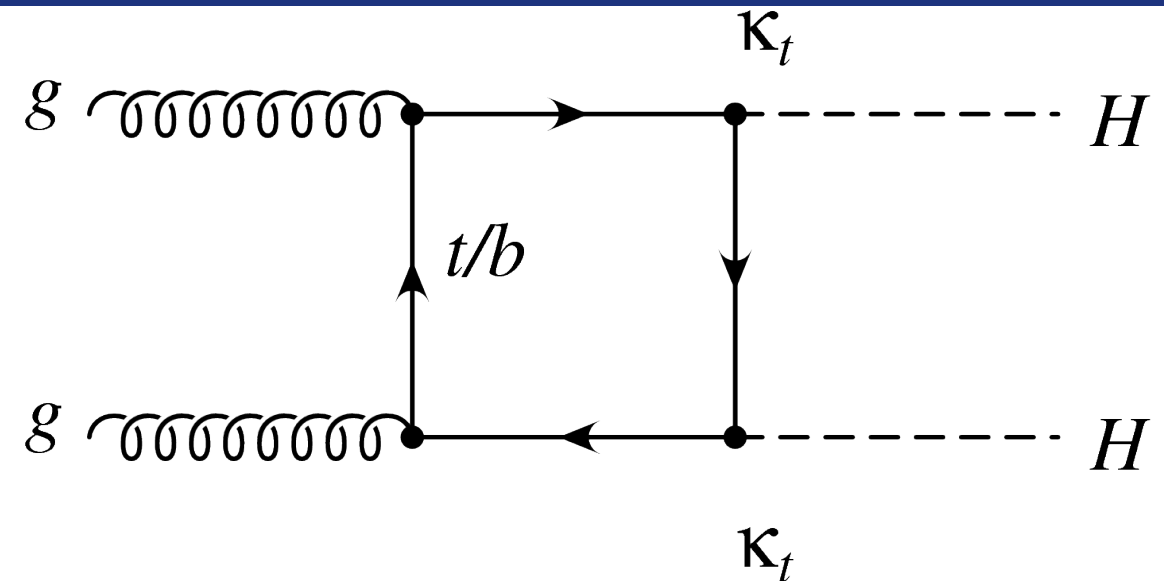
These two processes destructively interfere in the SM, leading to **very low cross section**: 500x rarer than single Higgs

Interference



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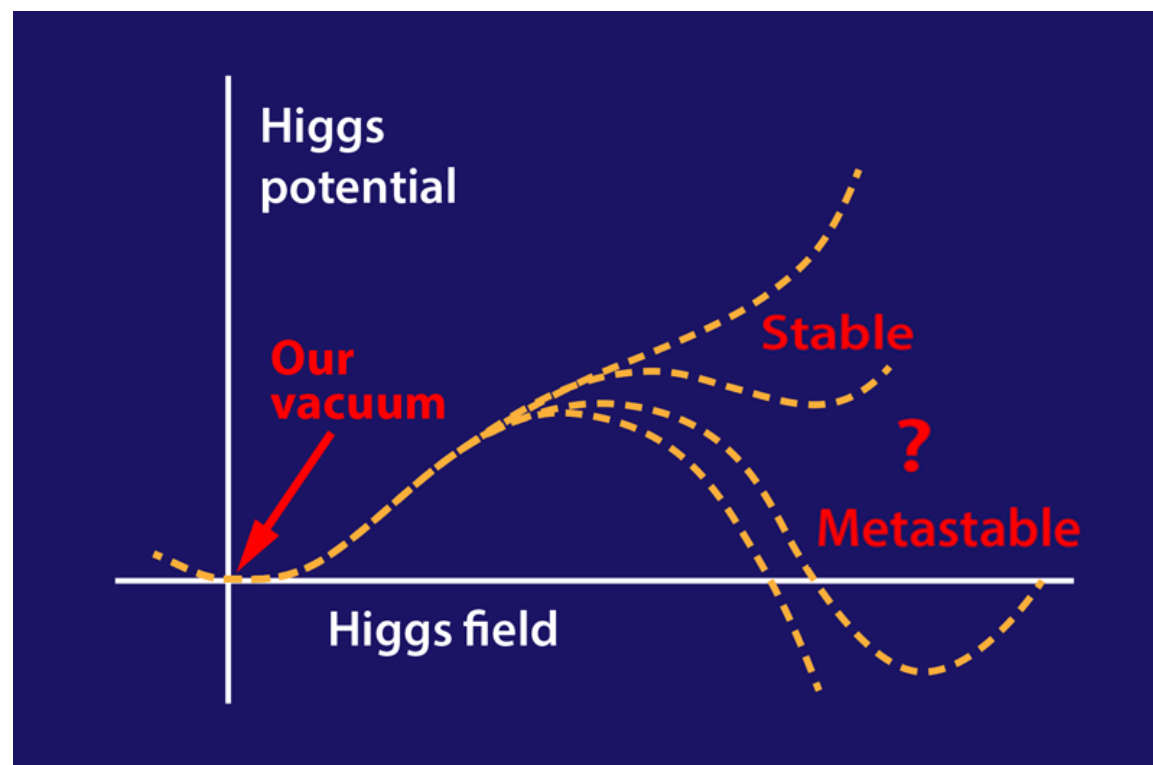
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Di-Higgs production is a **rare process**

Higgs Stability



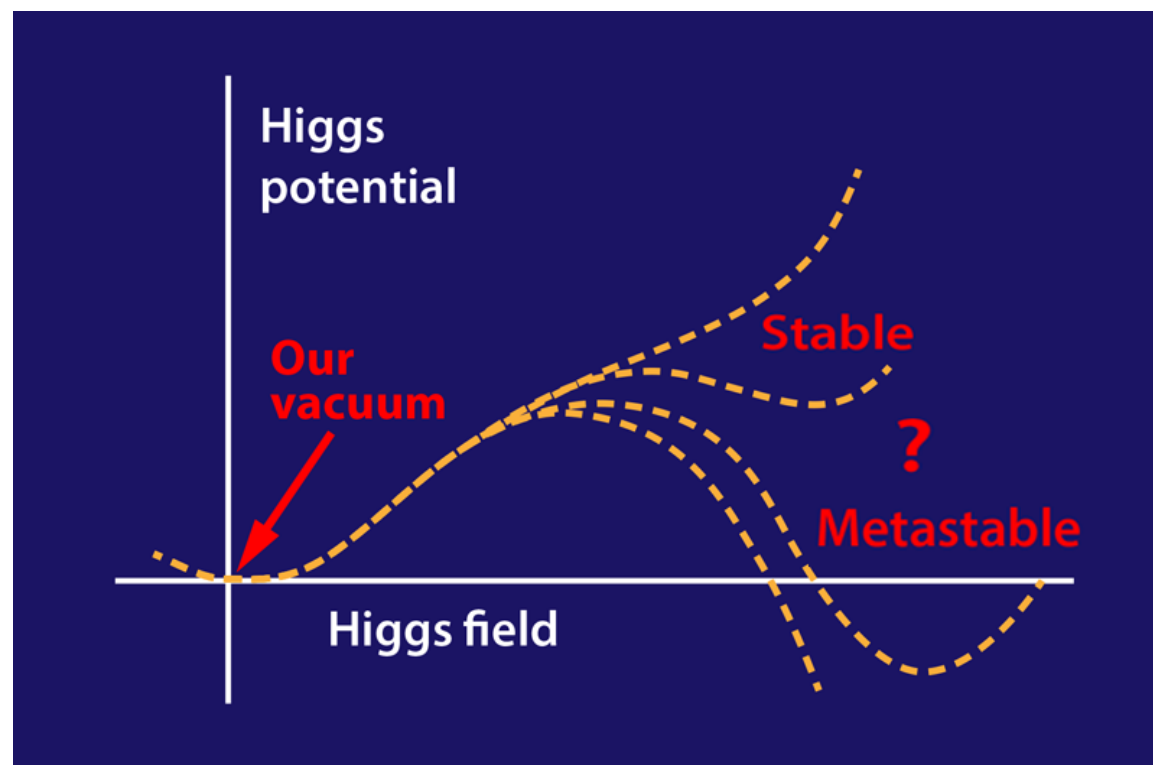
Higgs Stability



source

More simply: we do not know if the Higgs potential, and our vacuum, is stable!

Higgs Stability



source

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Measuring the potential can tell us about the fate of the universe

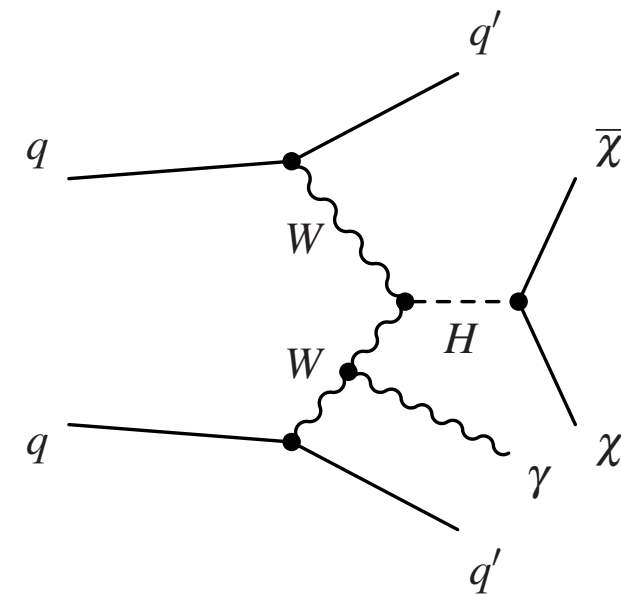
Dark Matter via Higgs



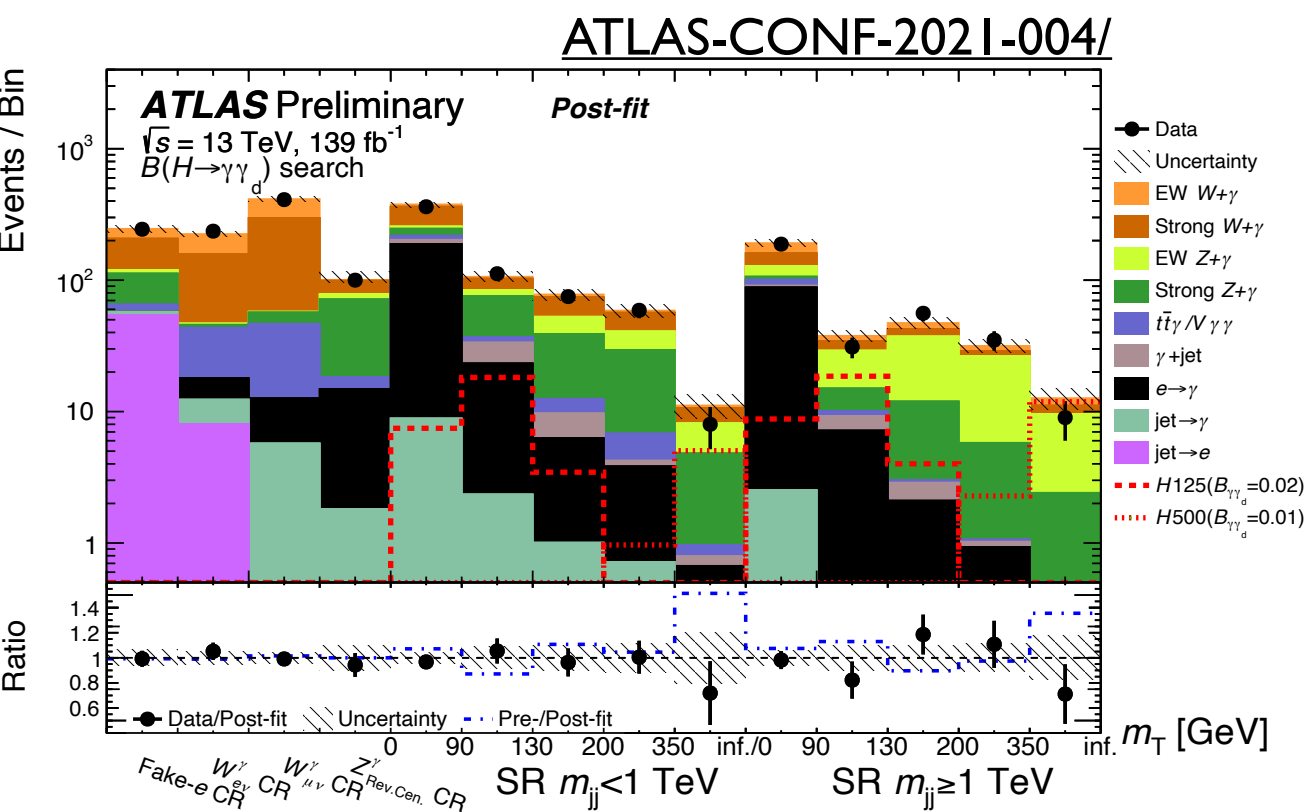
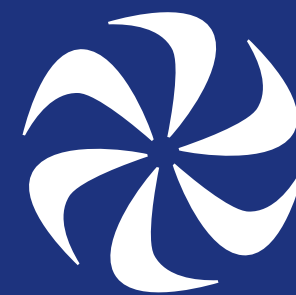
Dark Matter via Higgs



New searches
for Higgs decaying
to Dark Matter

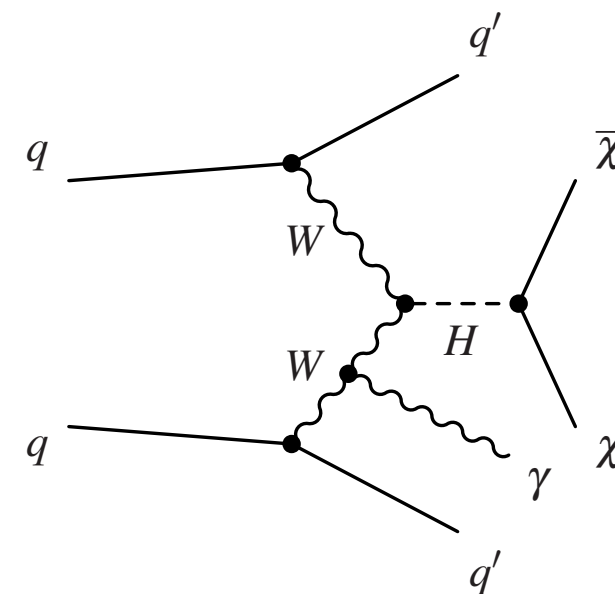


Dark Matter via Higgs



New searches
for Higgs decaying
to Dark Matter

New methods push
sensitivity to strongest
levels yet!



DNN for HWW



	Variable	VBF	V(had)H	ttH vs $t\bar{t}$	ttH vs $Z \rightarrow \tau\tau$
Jet properties	Invariant mass of 2 leading jets	•	•		
	$p_T(jj)$	•	•		
	Product of η of 2 leading jets	•			
	Sub-leading jet p_T	•			
	Leading jet η				•
	Sub-leading jet η				•
	Scalar sum of all jets p_T			•	•
	Scalar sum of all b -tagged jets p_T				•
	Best W -candidate dijet invariant mass			•	•
	Best t -quark-candidate three-jet invariant mass			•	•
Angular distances	$\Delta\phi(\text{jet 0, jet 1})$	•			
	$ \Delta\eta(\text{jet 0, jet 1}) $	•	•		
	$\Delta R(\text{jet 0, jet 1})$		•		
	$\Delta R(\tau\tau, jj)$		•		
	$\Delta R(\tau, \tau)$		•	•	
	Smallest ΔR (any 2 jets)			•	
	$ \Delta\eta(\tau, \tau) $			•	•
τ prop.	$p_T(\tau\tau)$			•	
	Sub-leading τp_T				•
	Sub-leading $\tau \eta$				•
H cand.	$p_T(Hjj)$	•	•		
	$p_T(H)/p_T(jj)$		•		
\vec{E}_T^{miss}	Missing transverse energy E_T^{miss}		•	•	•
	Smallest $\Delta\phi(\tau, \vec{E}_T^{\text{miss}})$				•

HHbb $\tau\tau$ BDT



Variable	$\tau_{\text{had}}\tau_{\text{had}}$	$\tau_{\text{lep}}\tau_{\text{had}}$	SLT	$\tau_{\text{lep}}\tau_{\text{had}}$	LTT
m_{HH}	✓			✓	✓
$m_{\text{MMC}}^{\tau\tau}$	✓			✓	✓
m_{bb}	✓			✓	✓
$\Delta R(\tau, \tau)$	✓			✓	✓
$\Delta R(b, b)$	✓			✓	
$\Delta p_{\text{T}}(\ell, \tau)$				✓	✓
Sub-leading b -tagged jet p_{T}				✓	
m_{T}^W				✓	
$E_{\text{T}}^{\text{miss}}$				✓	
$\mathbf{p}_{\text{T}}^{\text{miss}}$ ϕ centrality				✓	
$\Delta\phi(\tau\tau, bb)$				✓	
$\Delta\phi(\ell, \mathbf{p}_{\text{T}}^{\text{miss}})$					✓
$\Delta\phi(\ell\tau, \mathbf{p}_{\text{T}}^{\text{miss}})$					✓
S_{T}					✓

HHbbγγ BDT



Variable	Definition
Photon-related kinematic variables	
$p_T/m_{\gamma\gamma}$	Transverse momentum of the two photons scaled by their invariant mass $m_{\gamma\gamma}$
η and ϕ	Pseudo-rapidity and azimuthal angle of the leading and sub-leading photon
Jet-related kinematic variables	
b -tag status	Highest fixed b -tag working point that the jet passes
p_T, η and ϕ	Transverse momentum, pseudo-rapidity and azimuthal angle of the two jets with the highest b -tagging score
$p_T^{b\bar{b}}, \eta_{b\bar{b}}$ and $\phi_{b\bar{b}}$	Transverse momentum, pseudo-rapidity and azimuthal angle of b -tagged jets system
$m_{b\bar{b}}$	Invariant mass built with the two jets with the highest b -tagging score
H_T	Scalar sum of the p_T of the jets in the event
Single topness	For the definition, see Eq. (1)
Missing transverse momentum-related variables	
E_T^{miss} and ϕ^{miss}	Missing transverse momentum and its azimuthal angle

Large Radius Tracking

