

# Physics with ATLAS at the High-Luminosity LHC

*New Directions in Accelerator-Based Experiments*

Maximilian Swiatlowski

TRIUMF



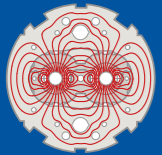
# The LHC Today



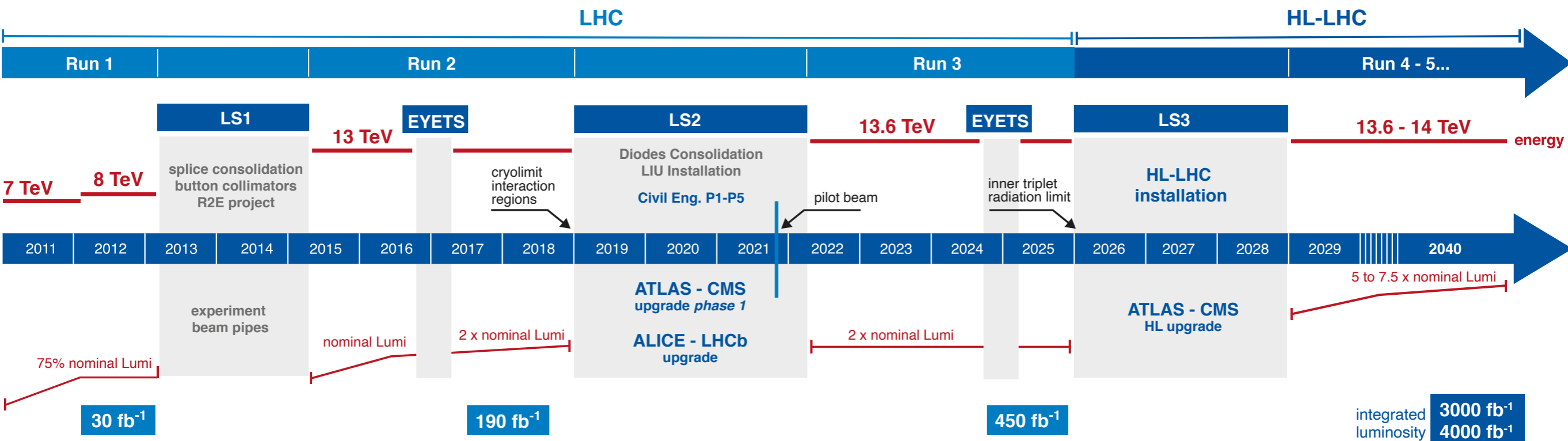
- The **Large Hadron Collider** is a 27 km long accelerator on the French/Swiss border
- Collides protons at **13 TeV**: upgrade to **13.6 TeV** this year for Run3
- Two large general purpose experiments, but I will focus on **ATLAS**



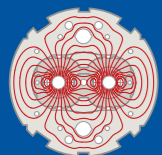
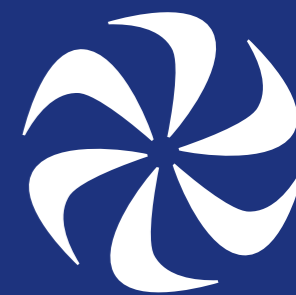
# The HL-LHC, ~Tomorrow



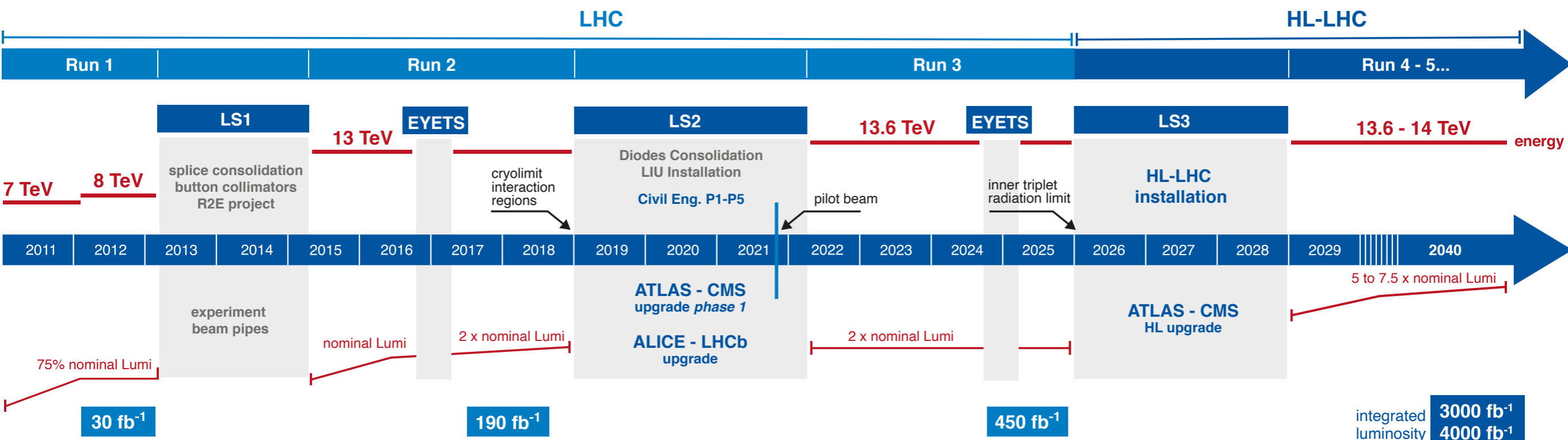
## LHC / HL-LHC Plan



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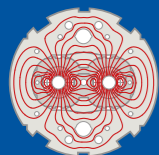
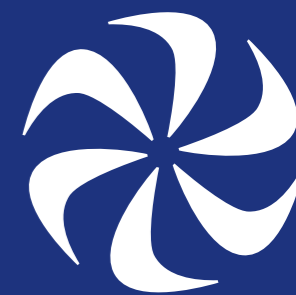


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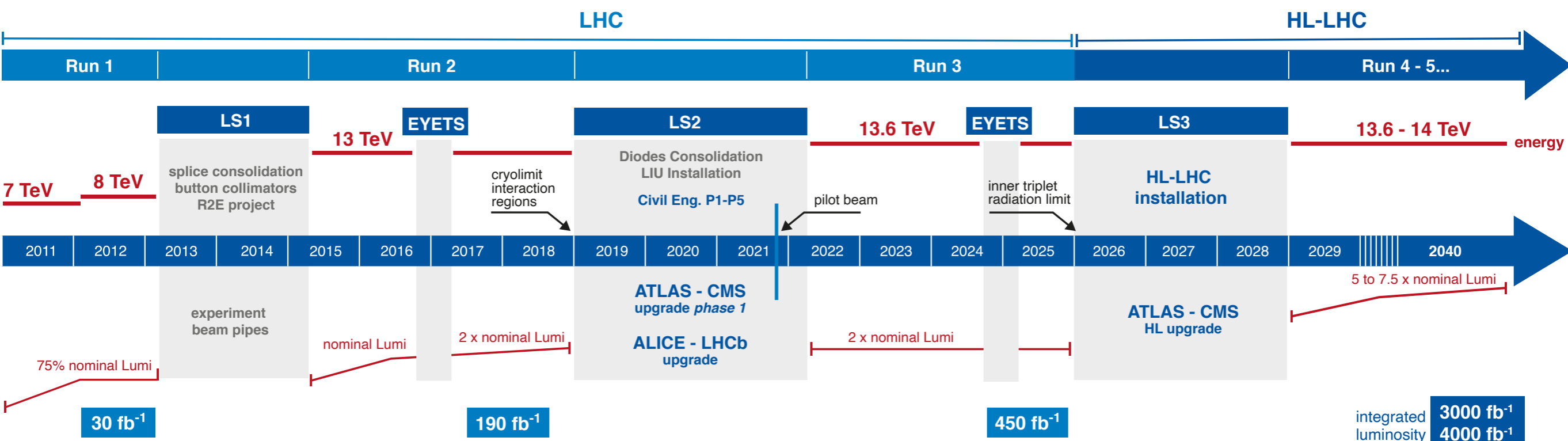


The HL-LHC will be installed 2026-2028, and run in 2029-2035(++)

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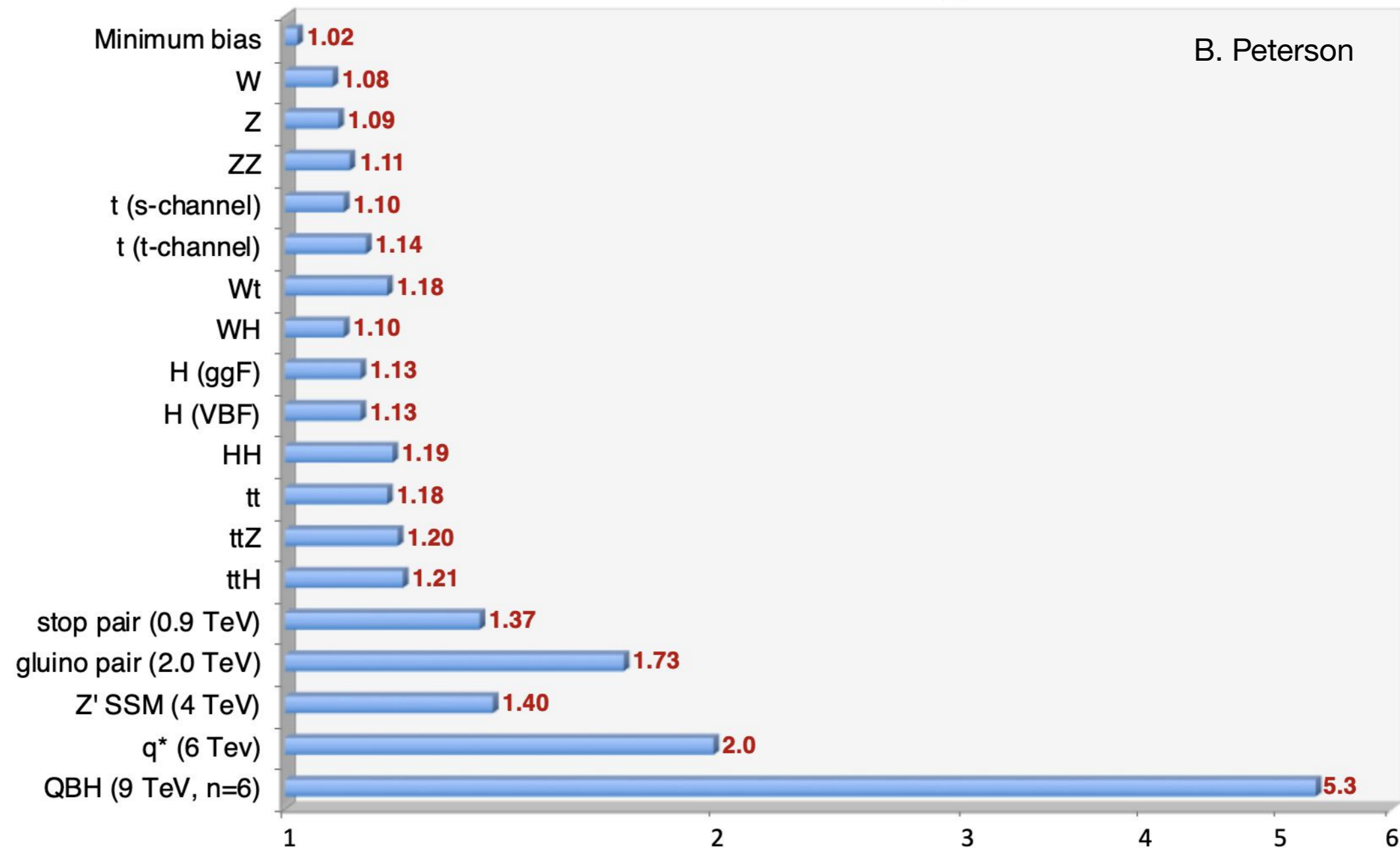
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Increase energy to **14 TeV**,  
and instantaneous luminosity to **5-7x10<sup>34</sup> cm<sup>-2</sup>s<sup>-1</sup>**

# Rising Energy

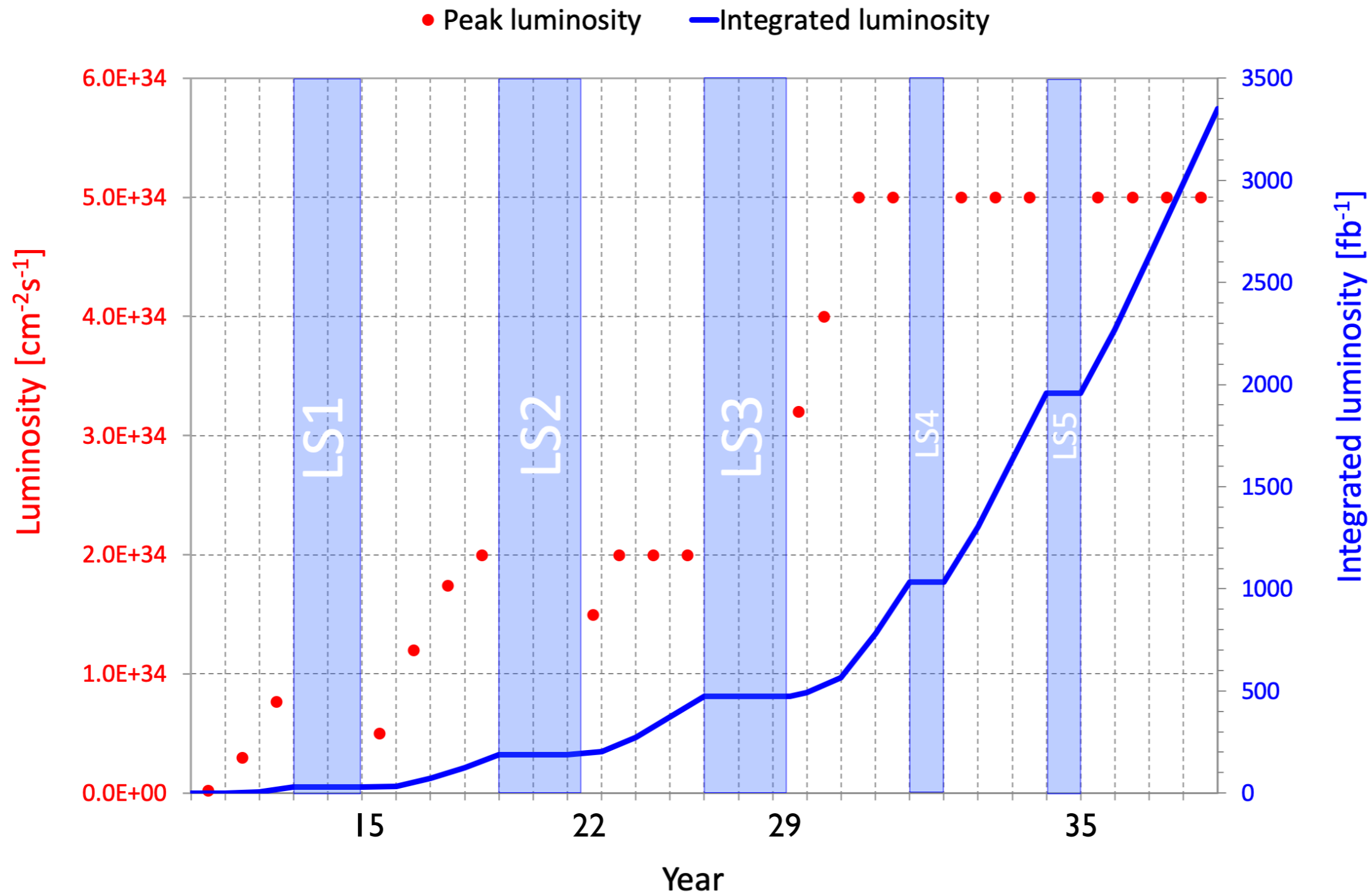


Increase in energy may seem small, but can have a big impact on important physics processes!

# Datasets

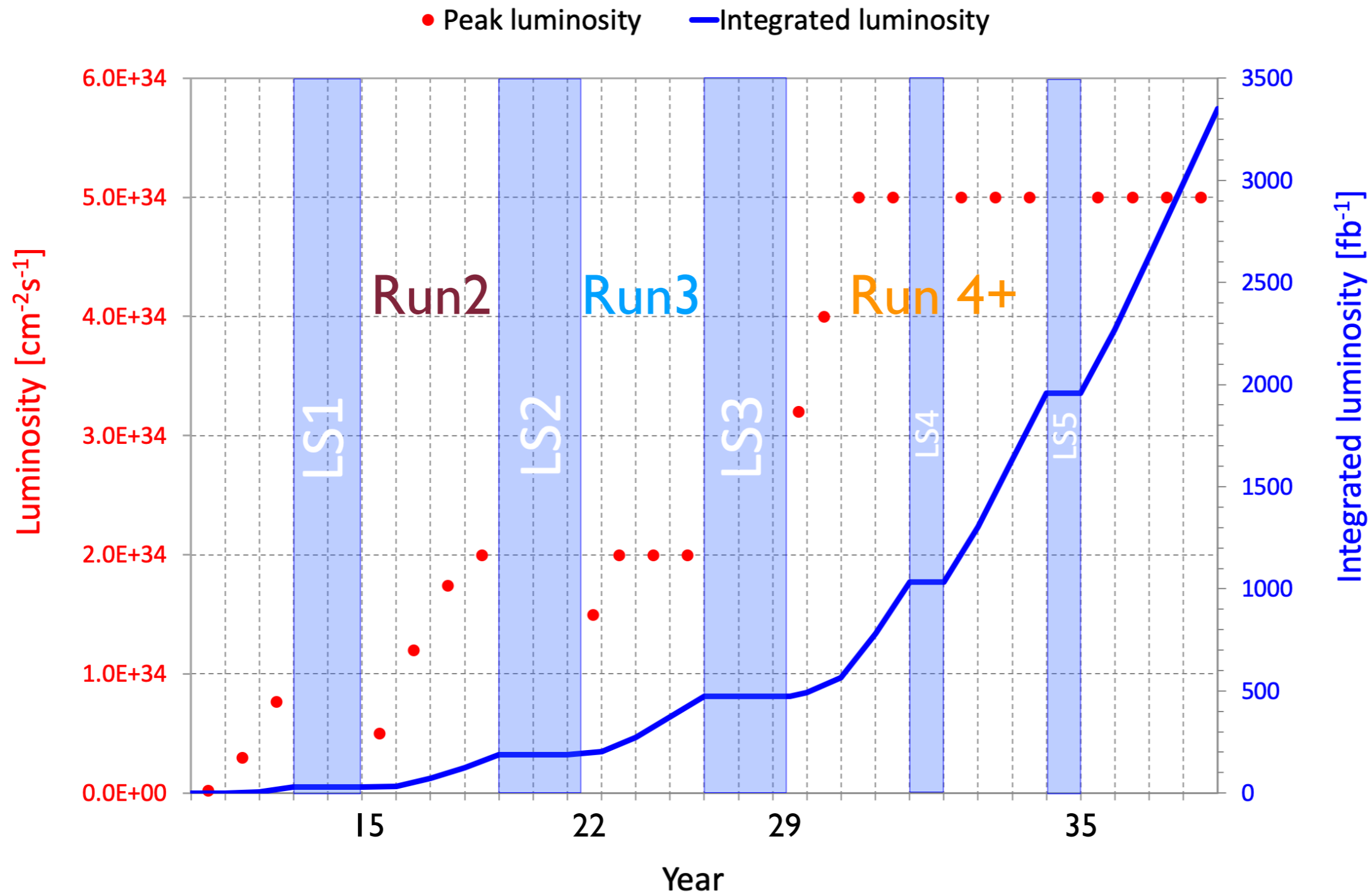


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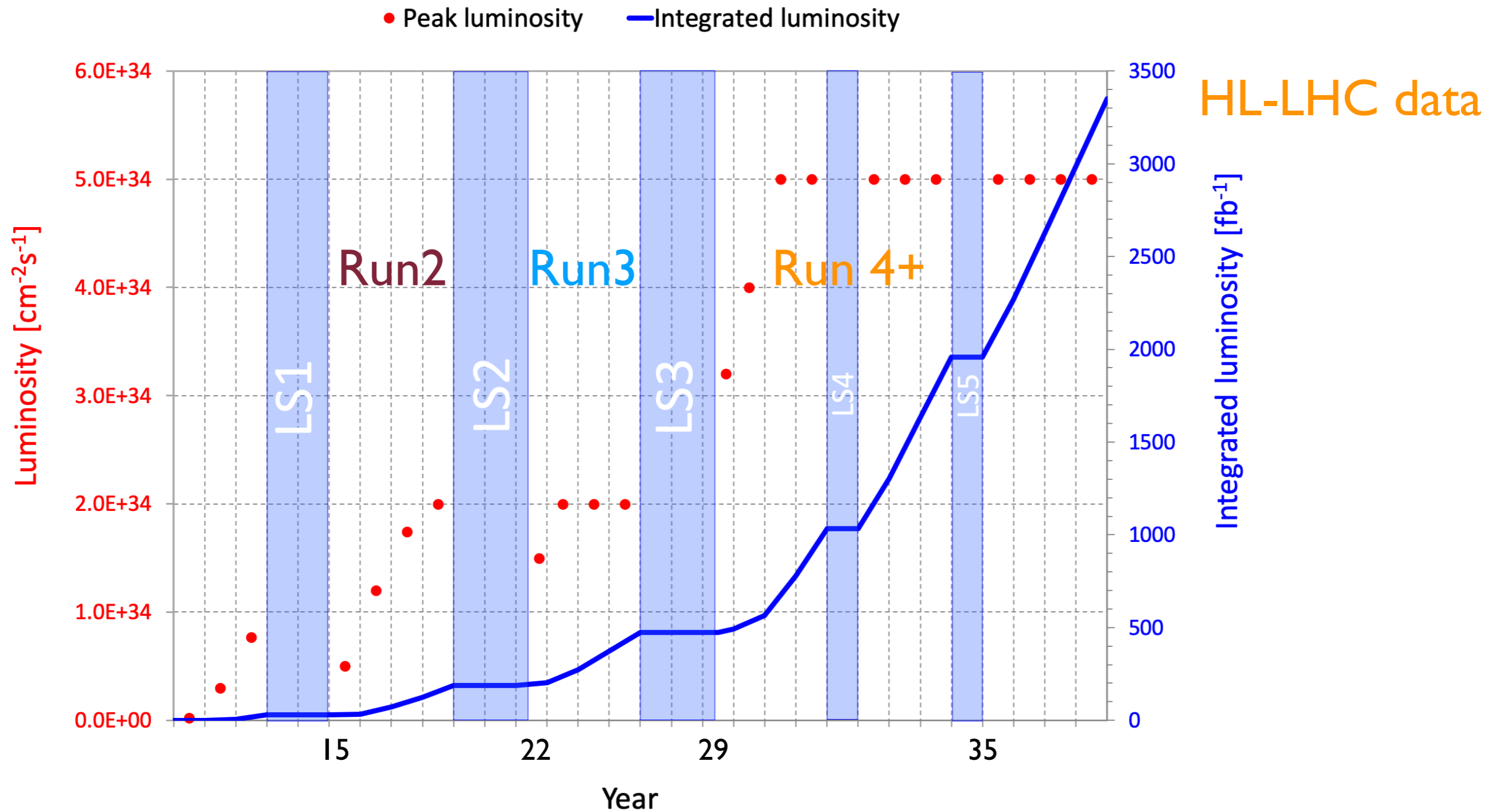




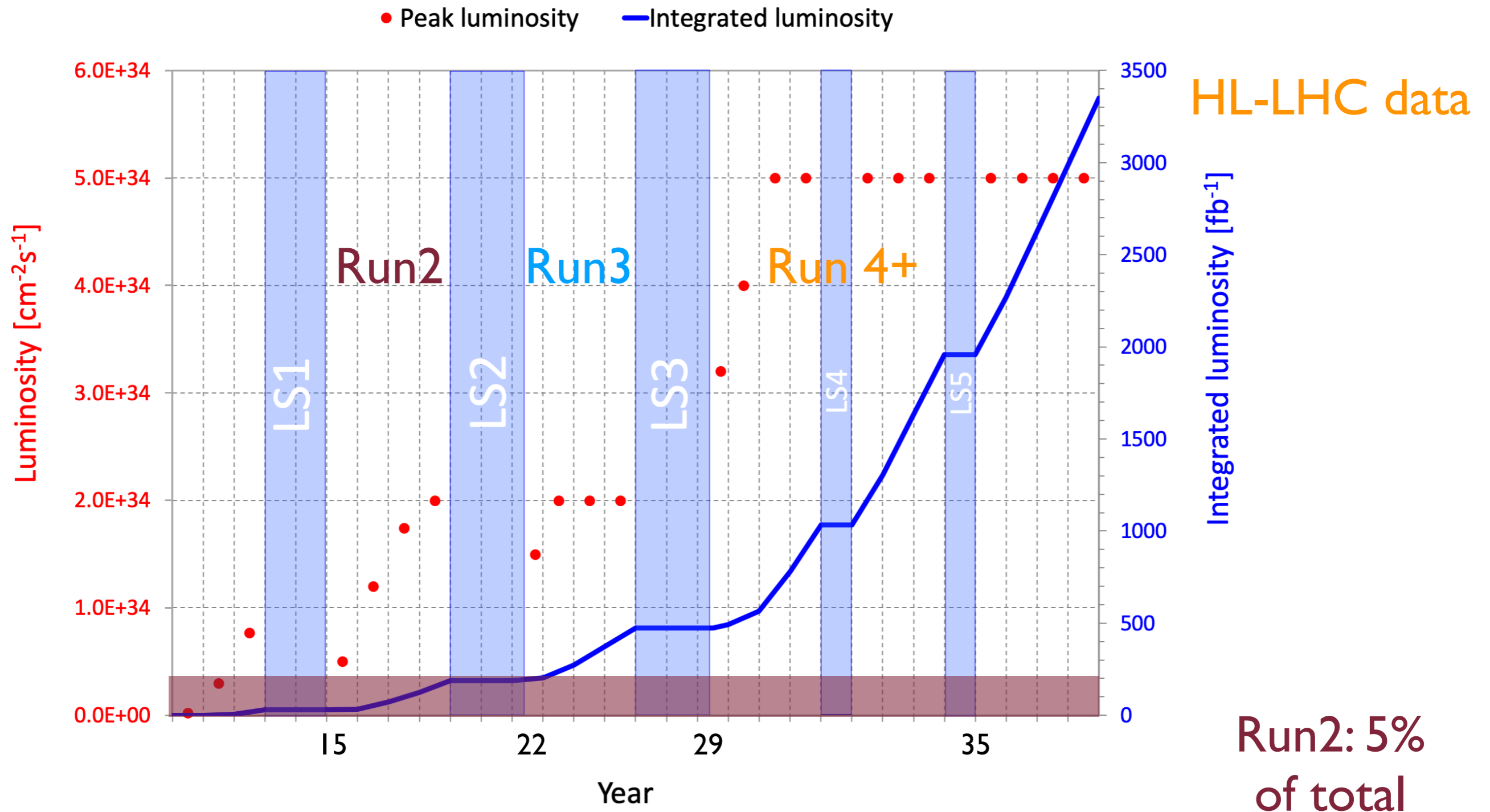
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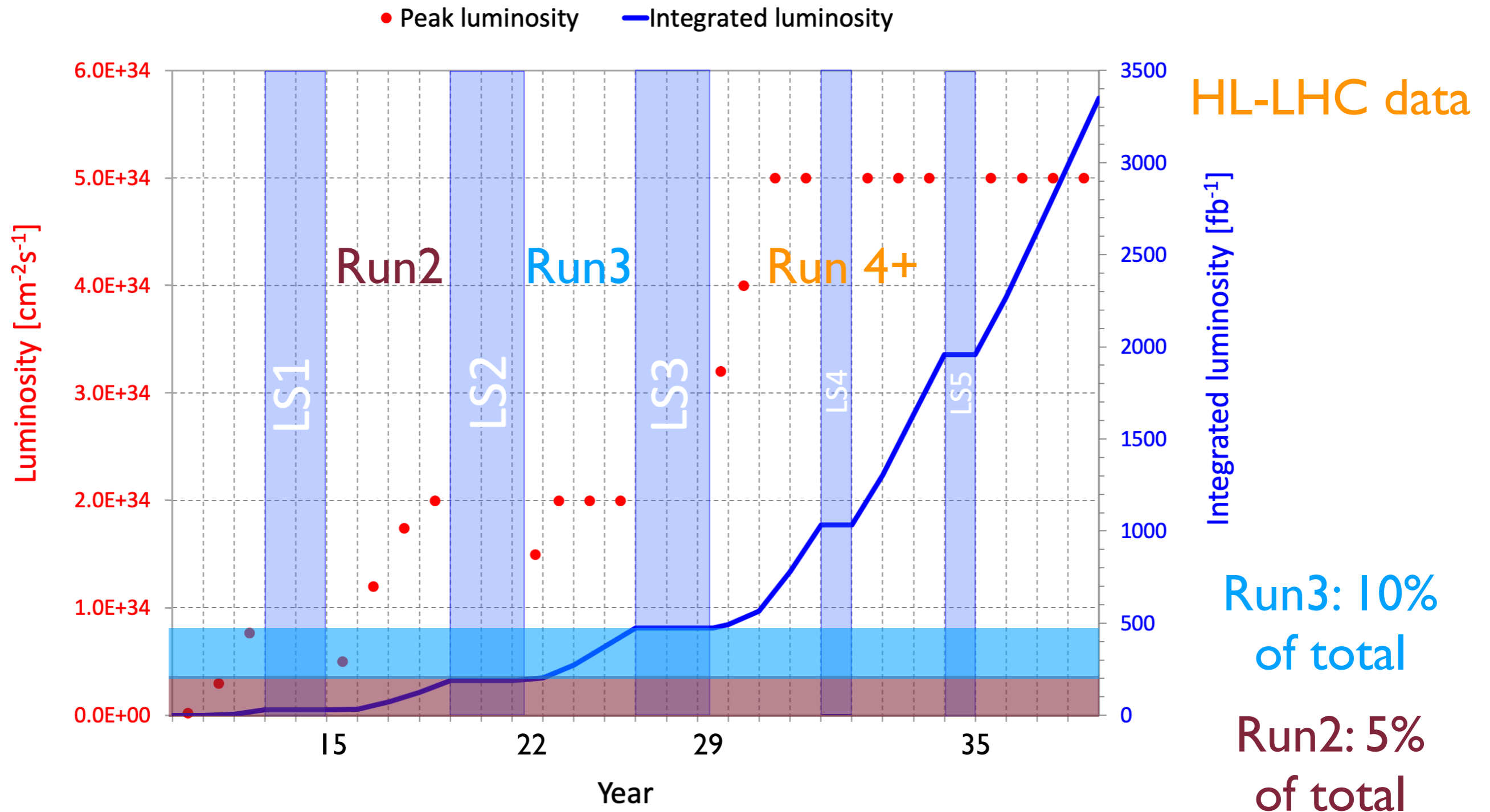
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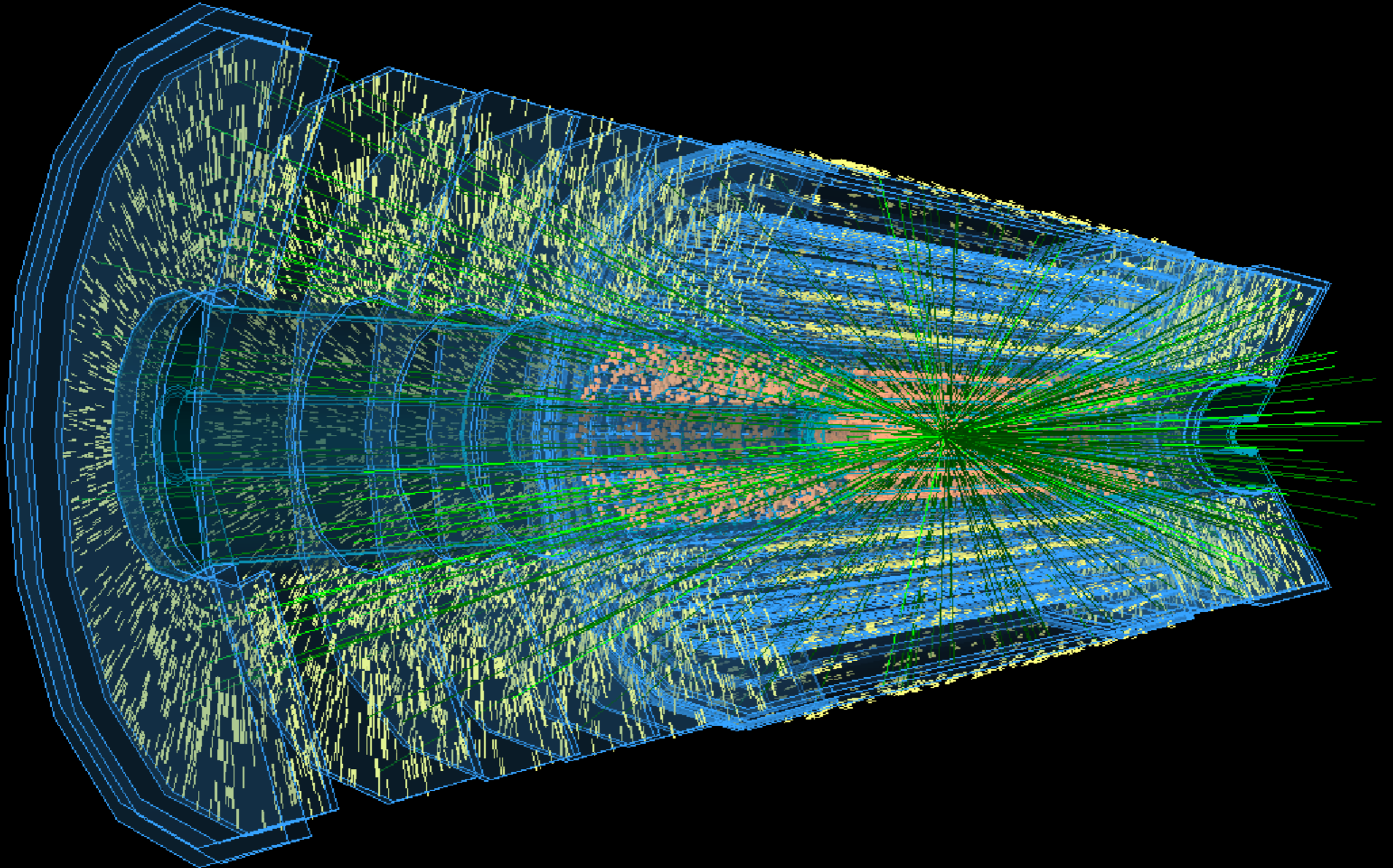
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# The Price of Rate: Pileup



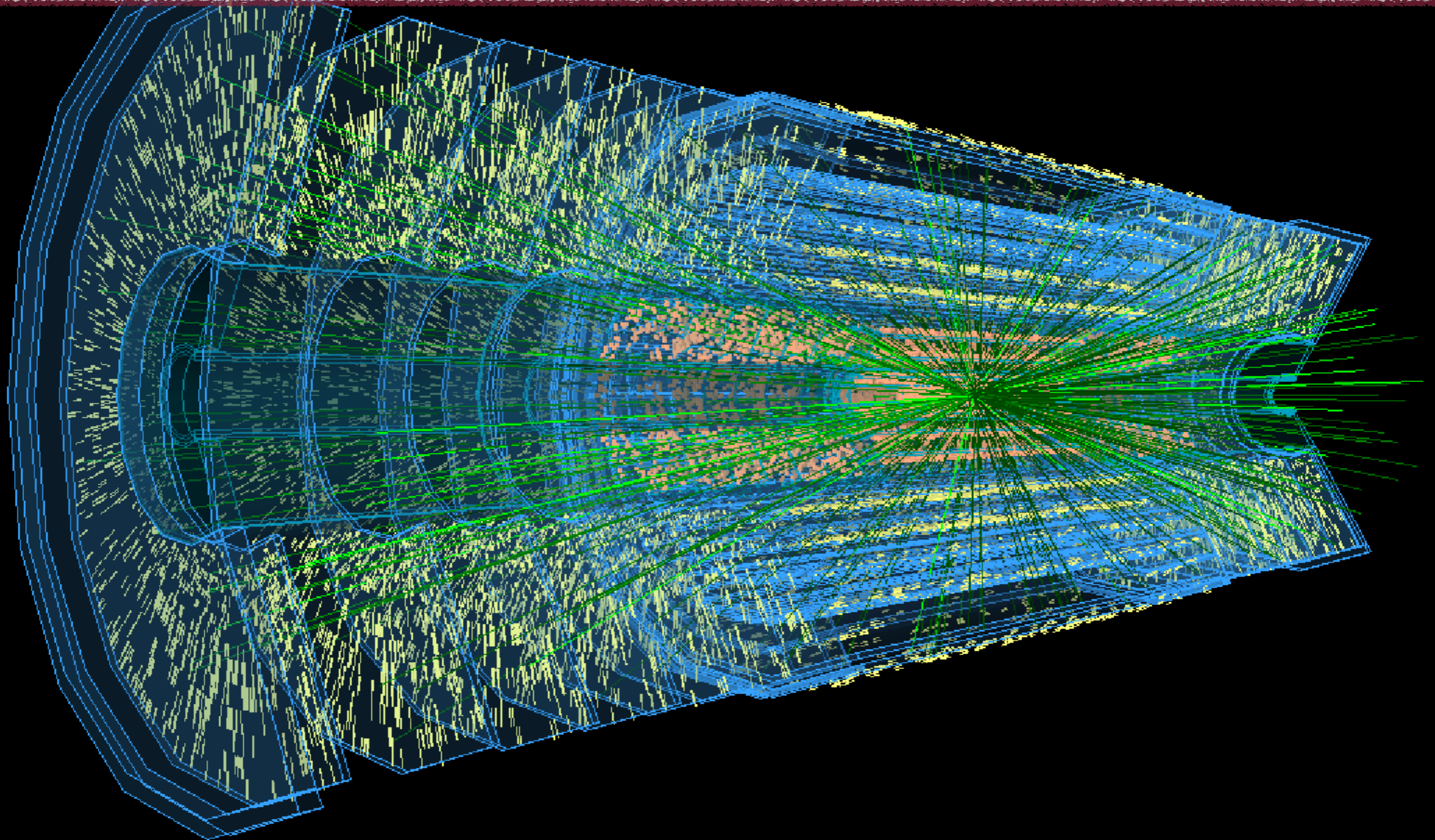
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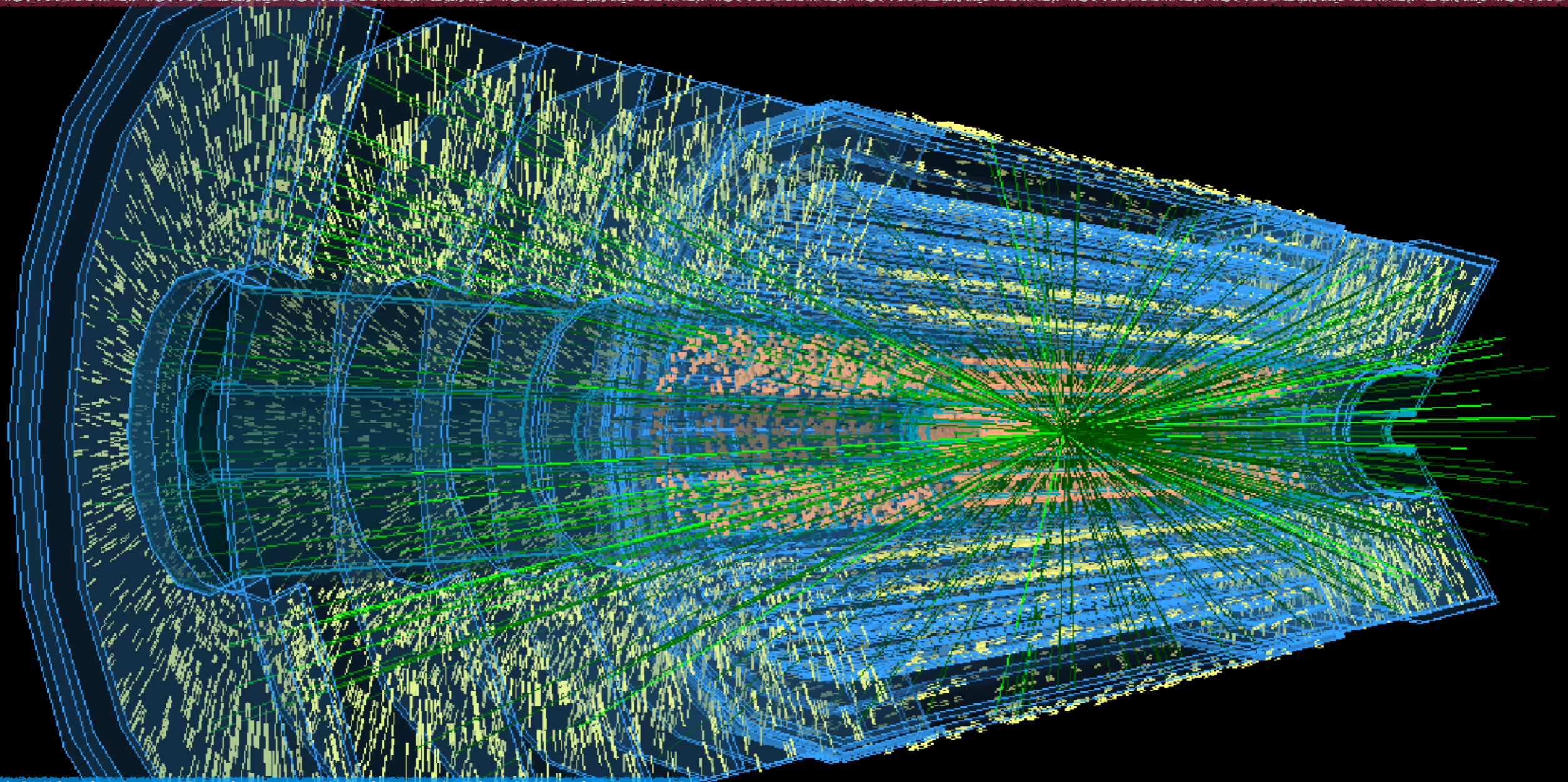
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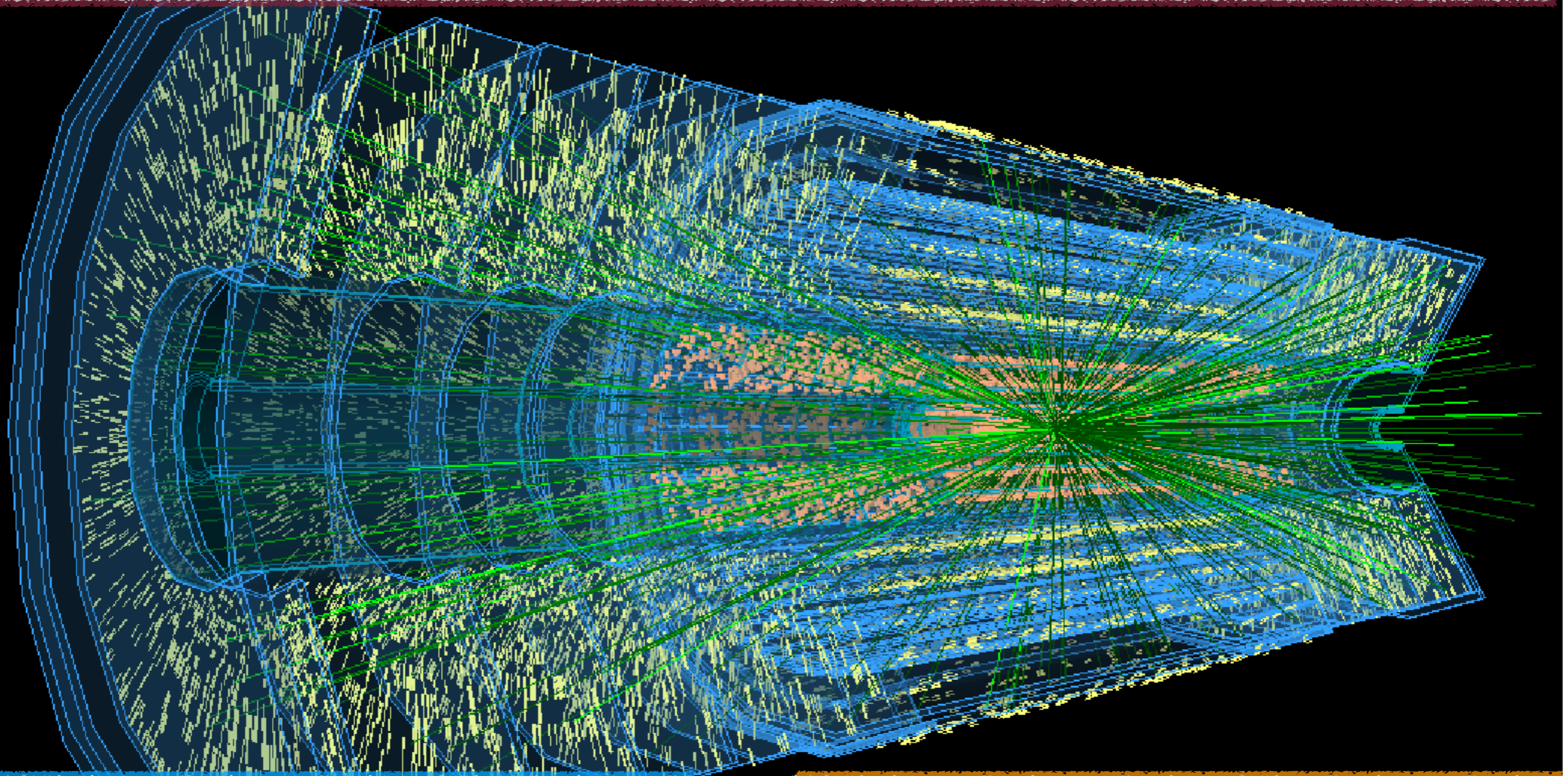
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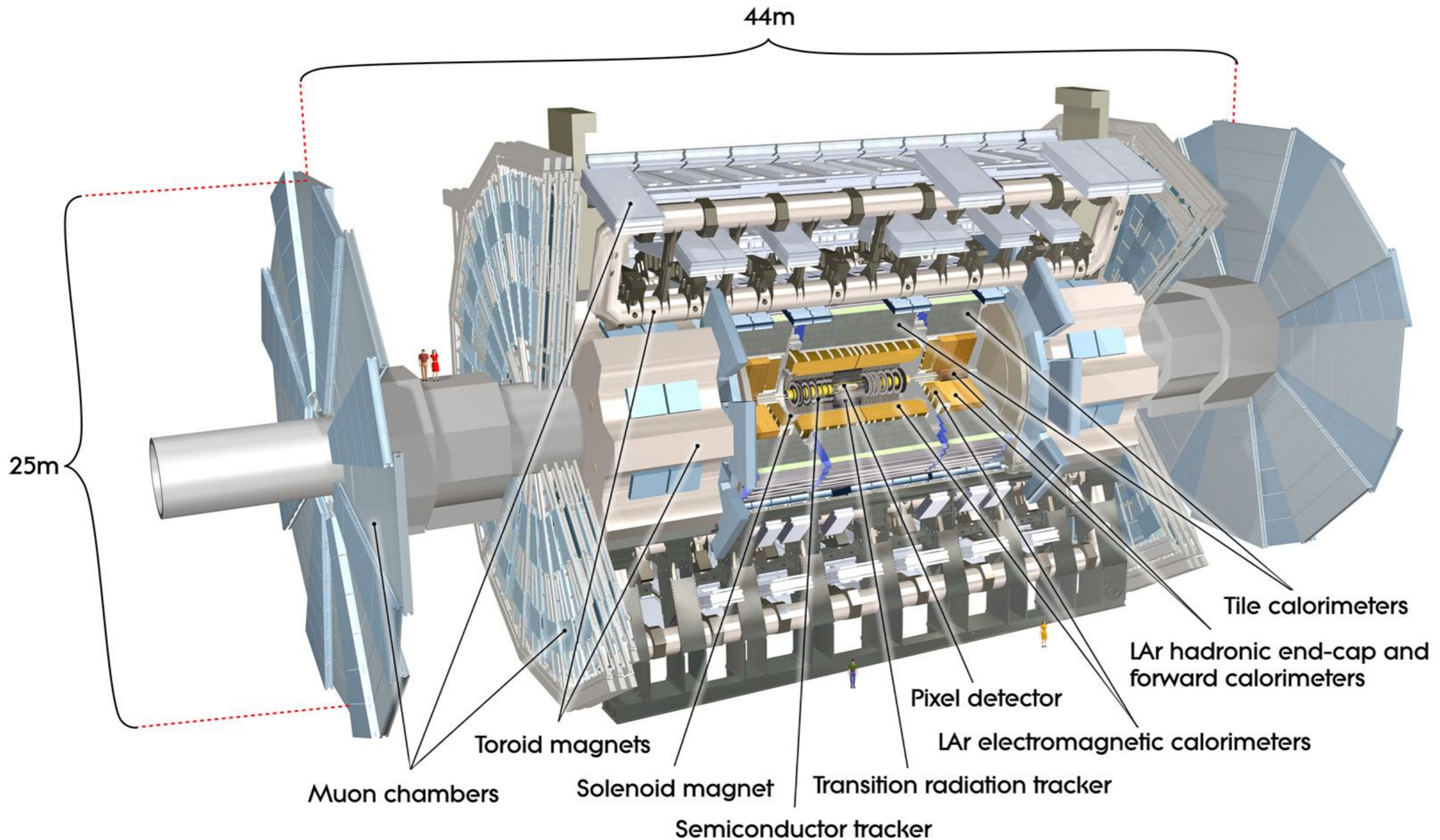
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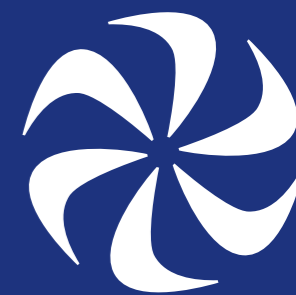
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Expect **200 collisions** per crossing!  
Compare to ~50 today

# Upgrades



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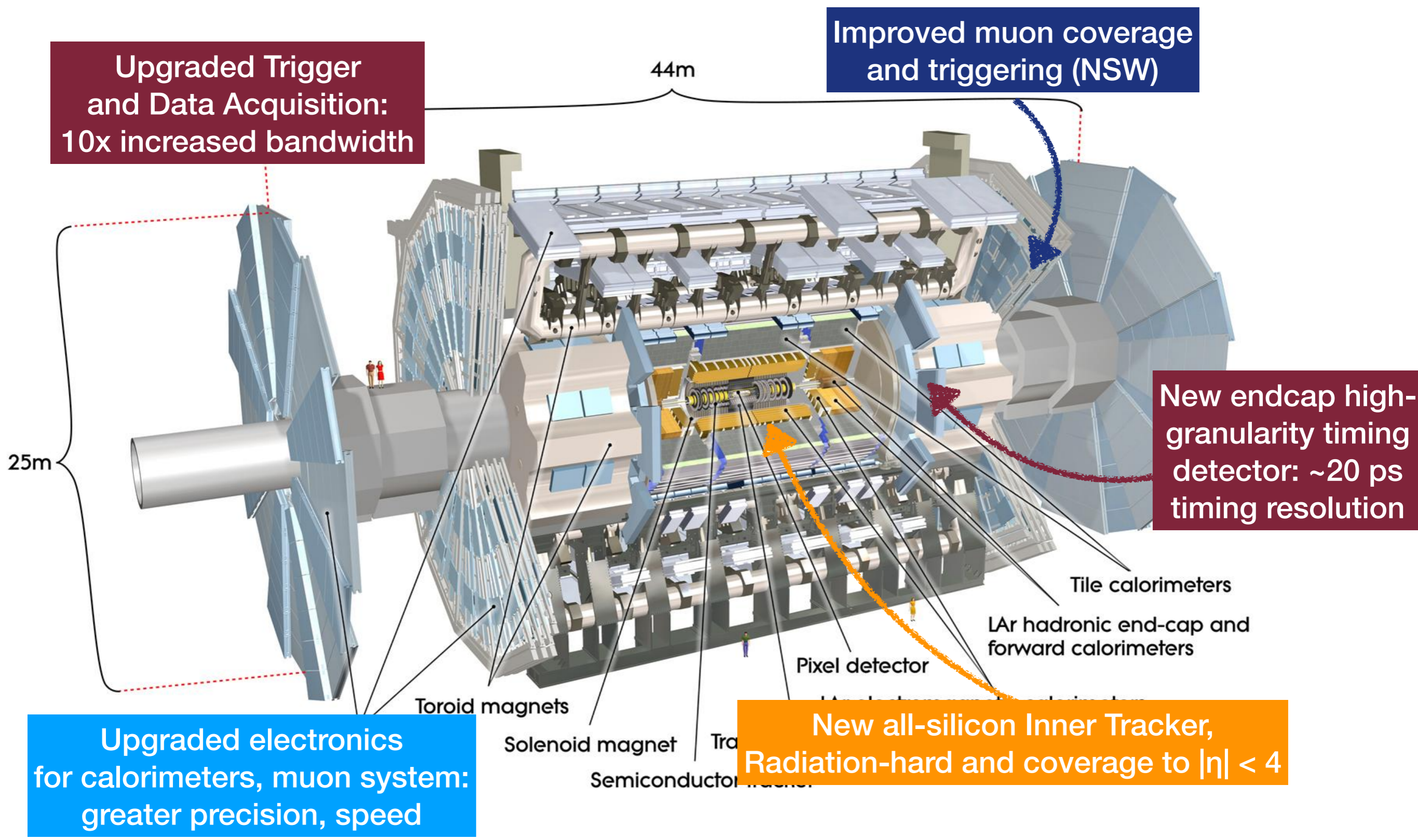
Upgraded Trigger and Data Acquisition: 10x increased bandwidth

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



# Preparing for the Future



- European Strategy Update
- Canadian Long Range Planning
- Snowmass Community Planning Exercise
- The HL-LHC plays a critical role in all of these exercises
  - Important to understand how this device interplays with others!

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- **These projections may significantly undersell what we can do!**
  - Analysis improvements often significantly outpace luminosity

# Direct Searches for New Physics

# Electroweak SUSY

ATL-PHYS-PUB-2018-048





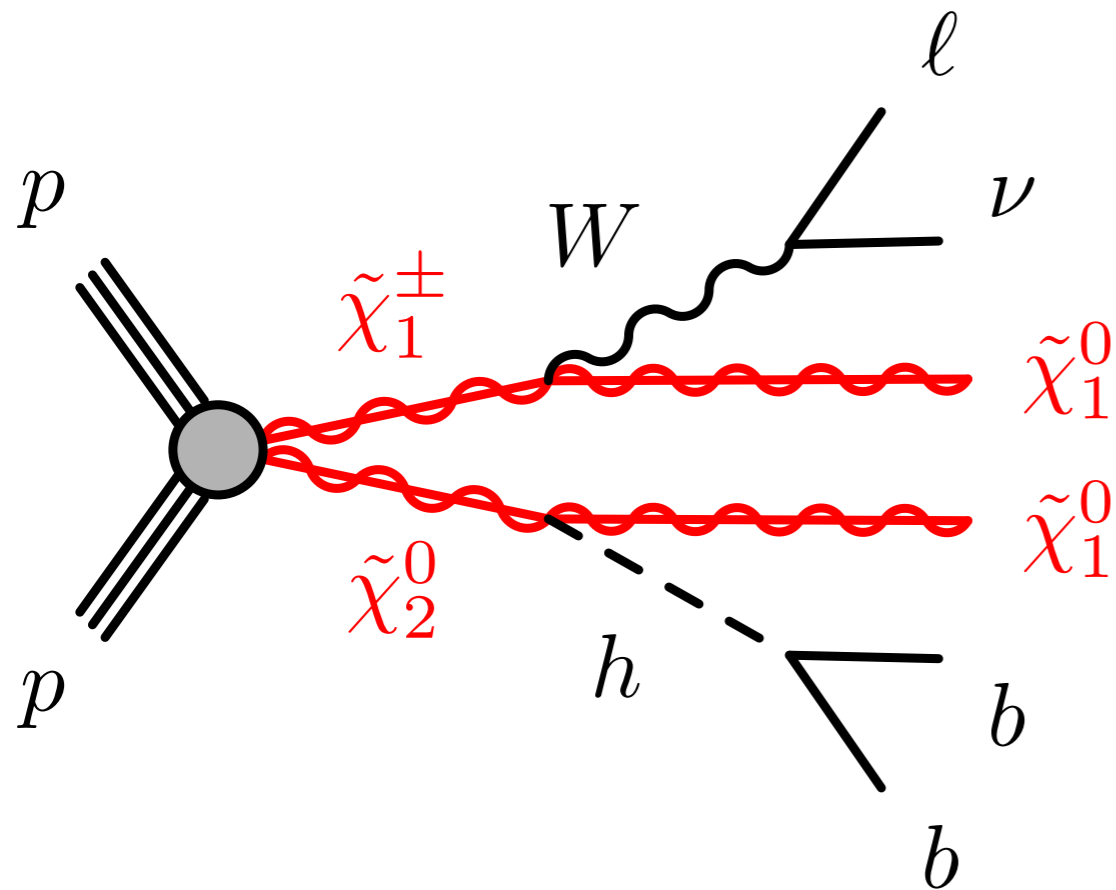
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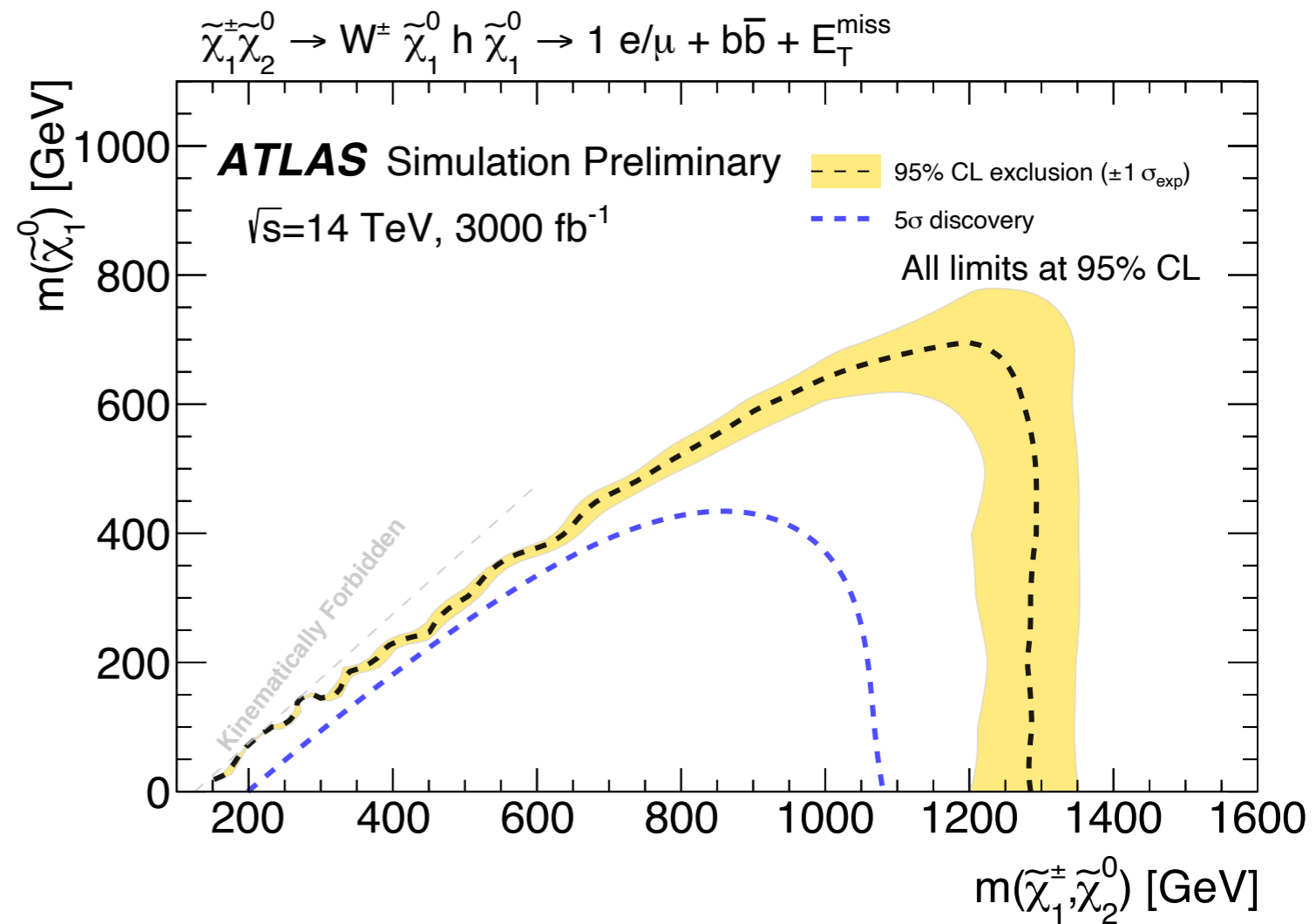
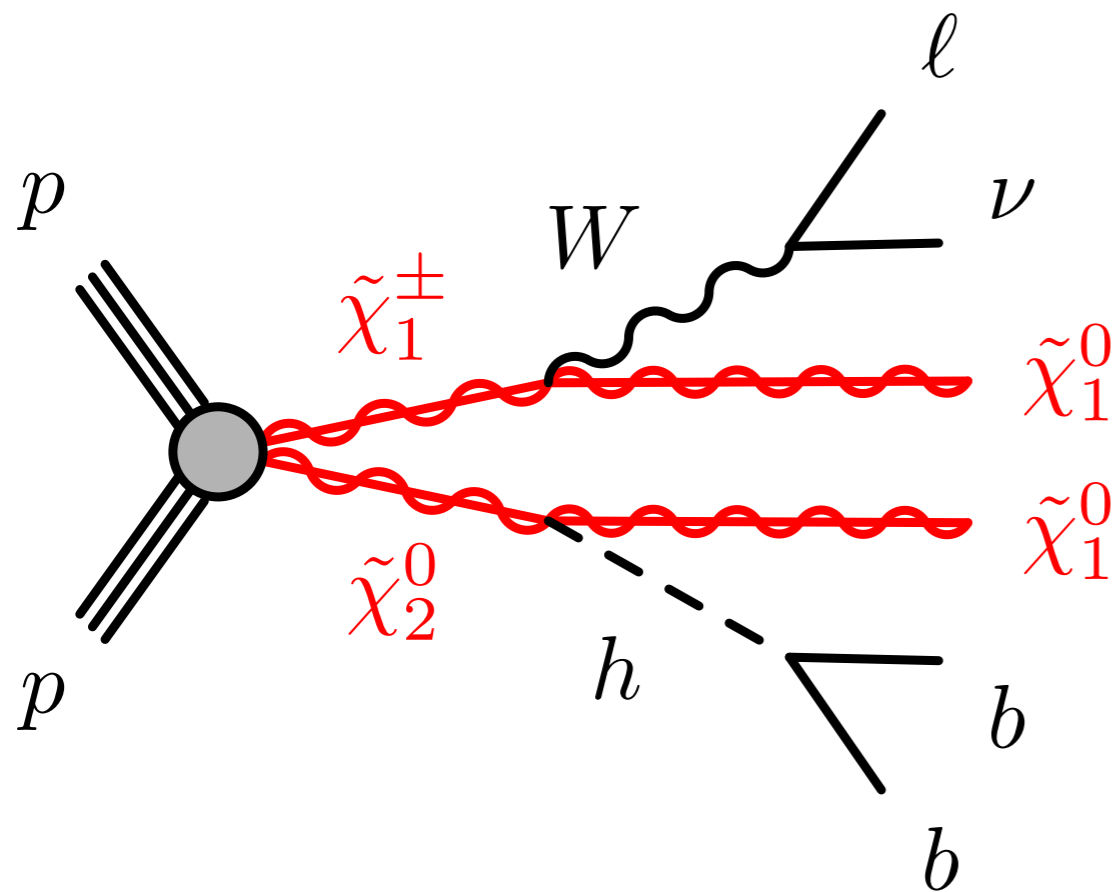






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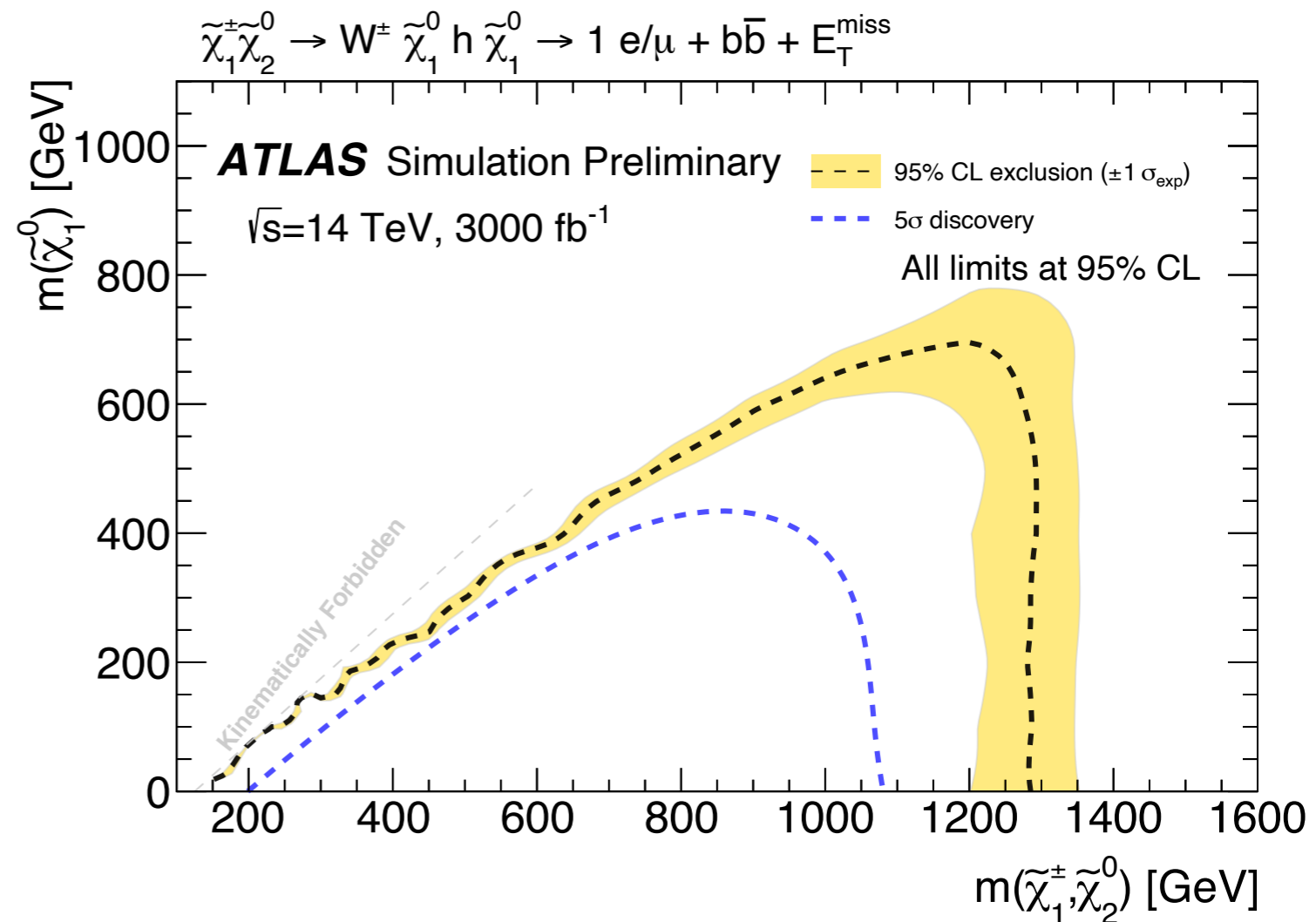
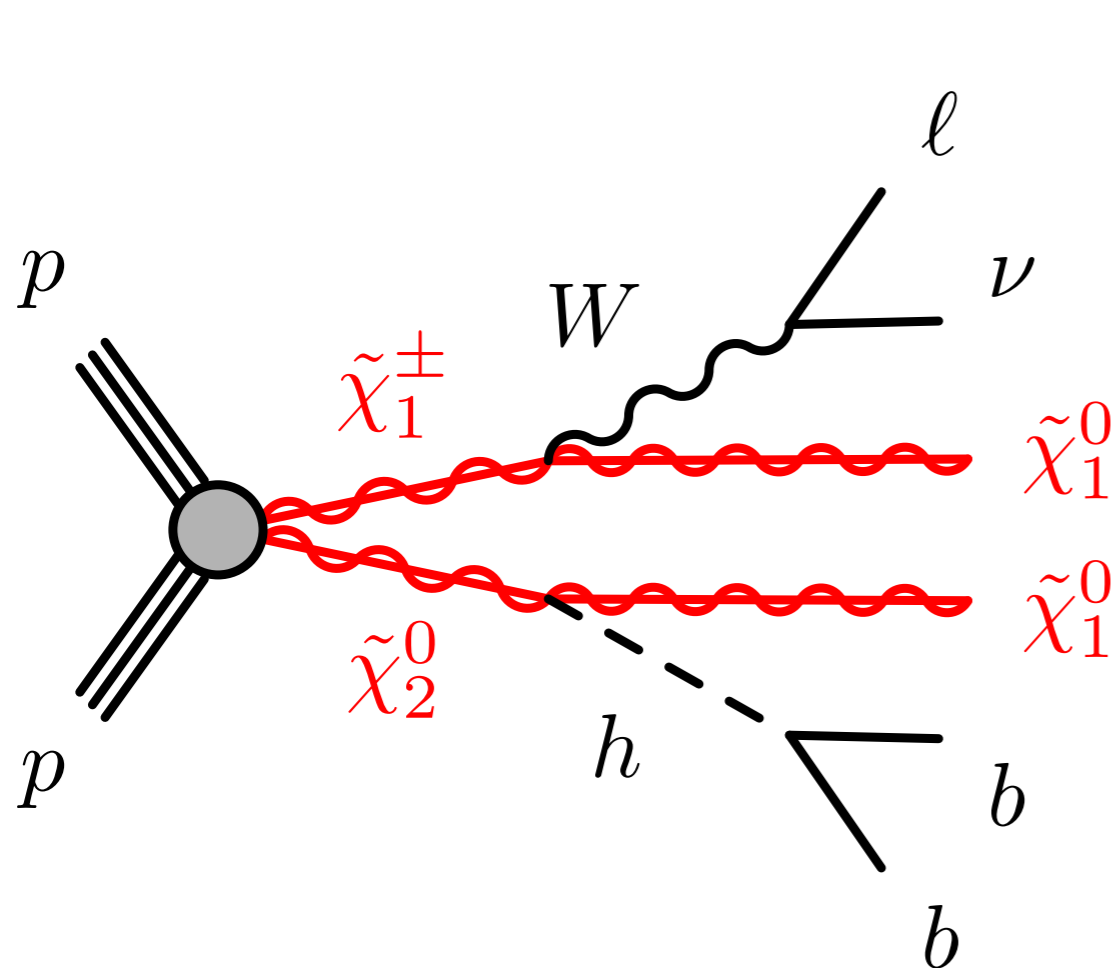
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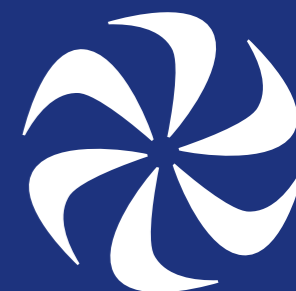


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Wide range of models studied: many sensitive to TeV scale



# Long Lived Particles



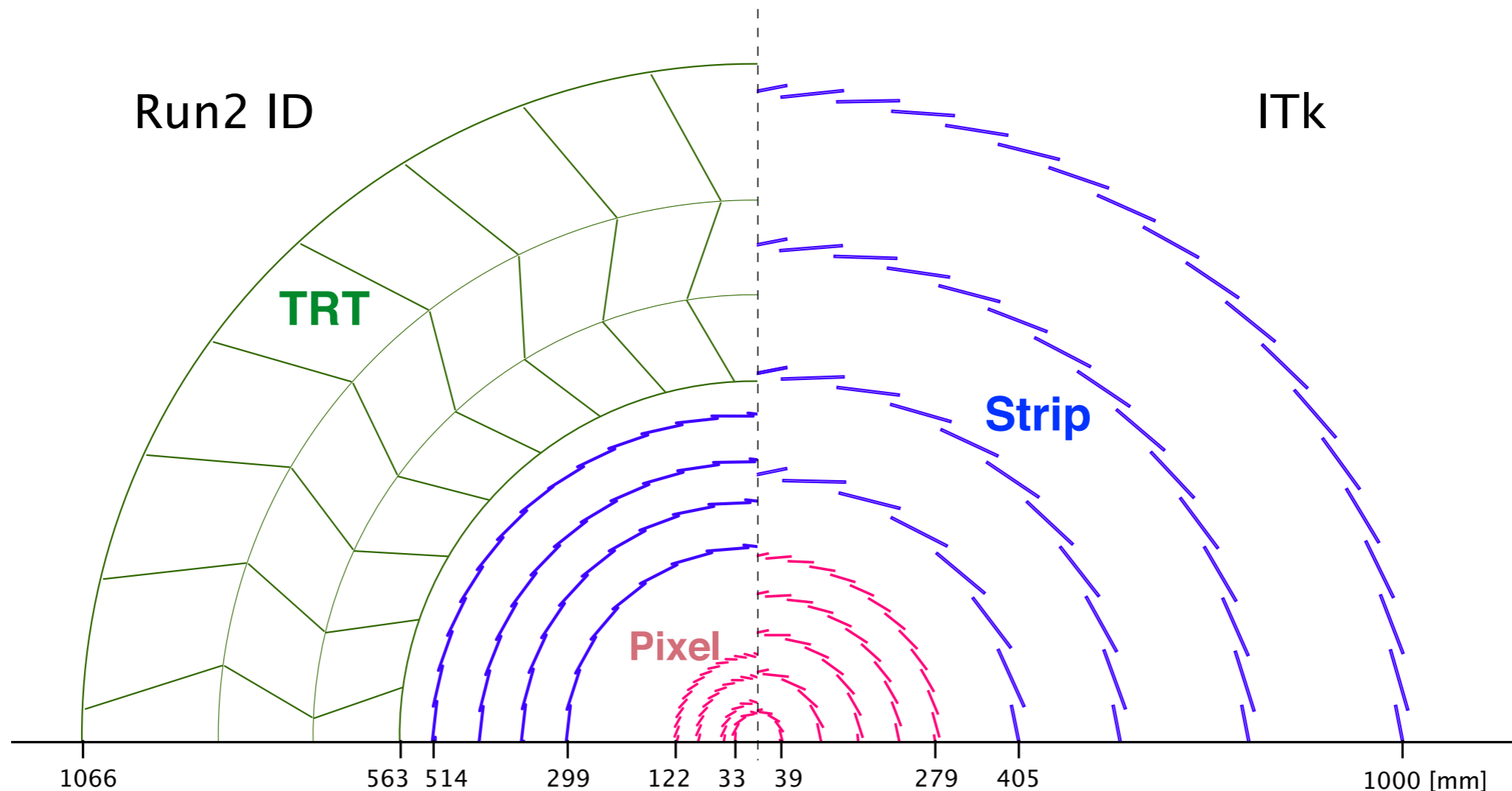
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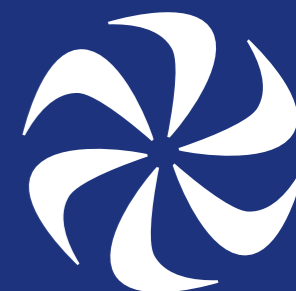


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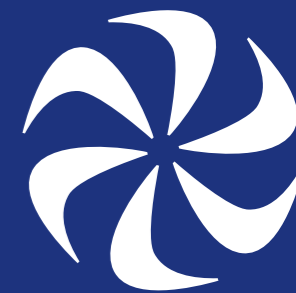
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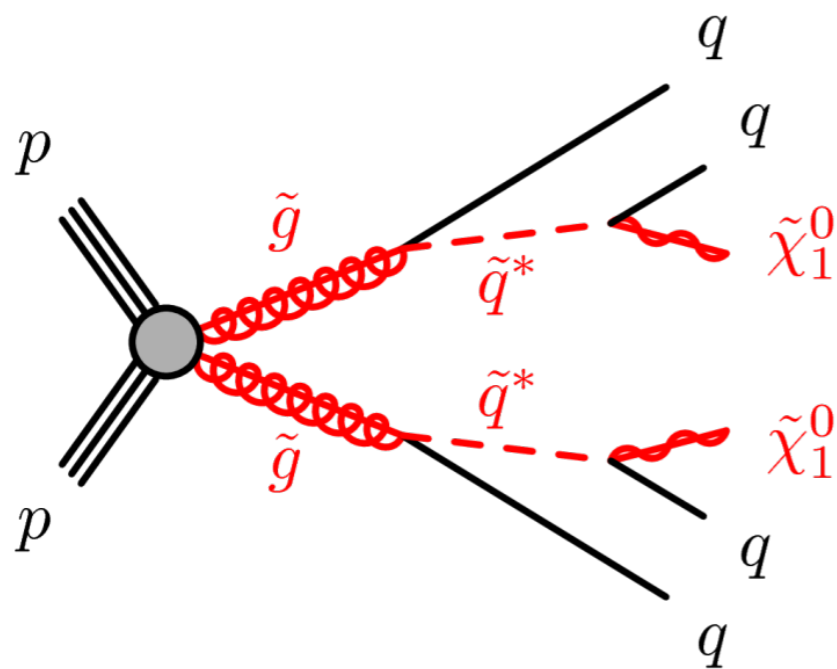
Many searches depend critically on detector design and layout: upgrades provide new opportunity for discovery



# LLP Sensitivity

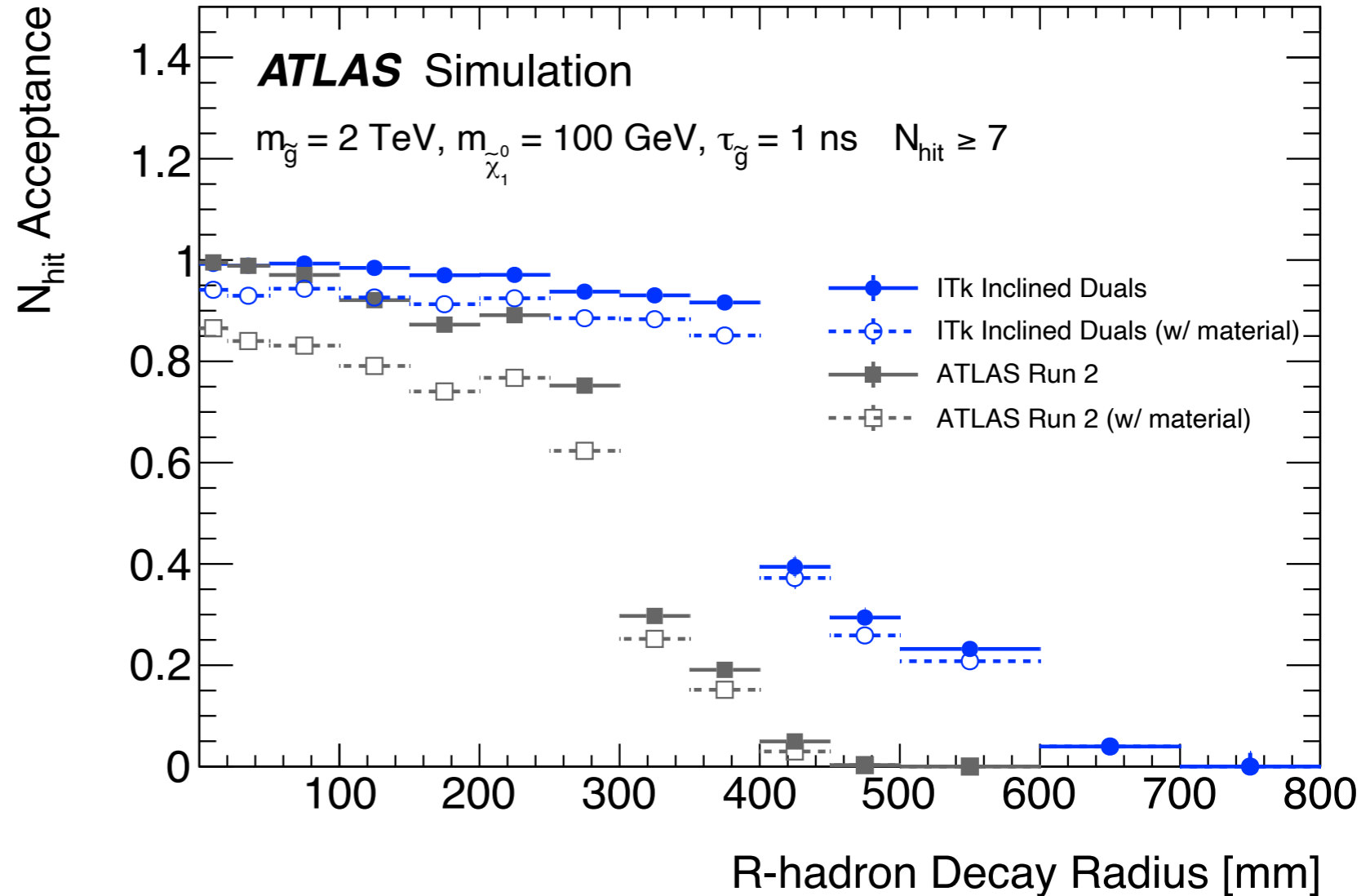
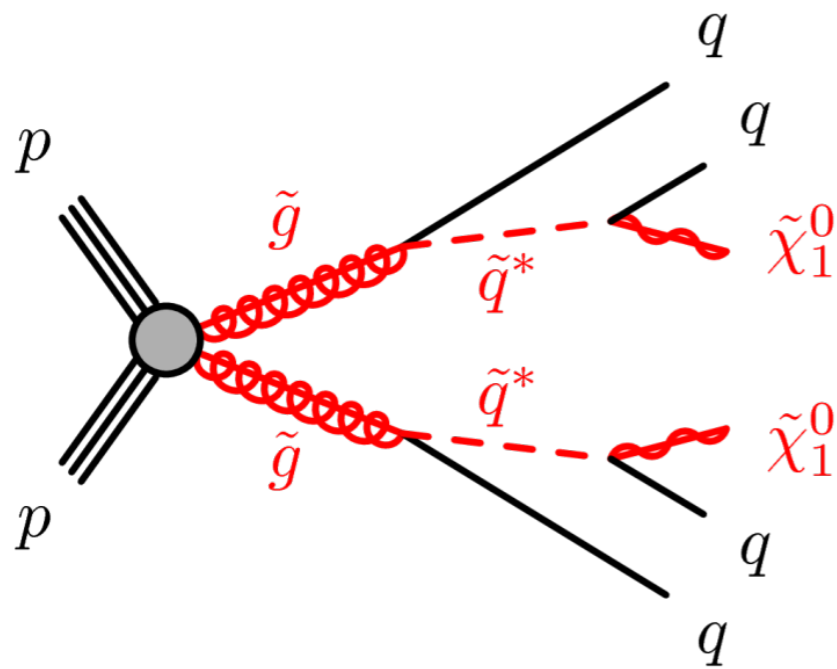


# LLP Sensitivity





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Significantly larger pixel and strip radii enable large increase in acceptance for long-lived particles!



# Precision Measurements of the Standard Model



# Weak Mixing Angle



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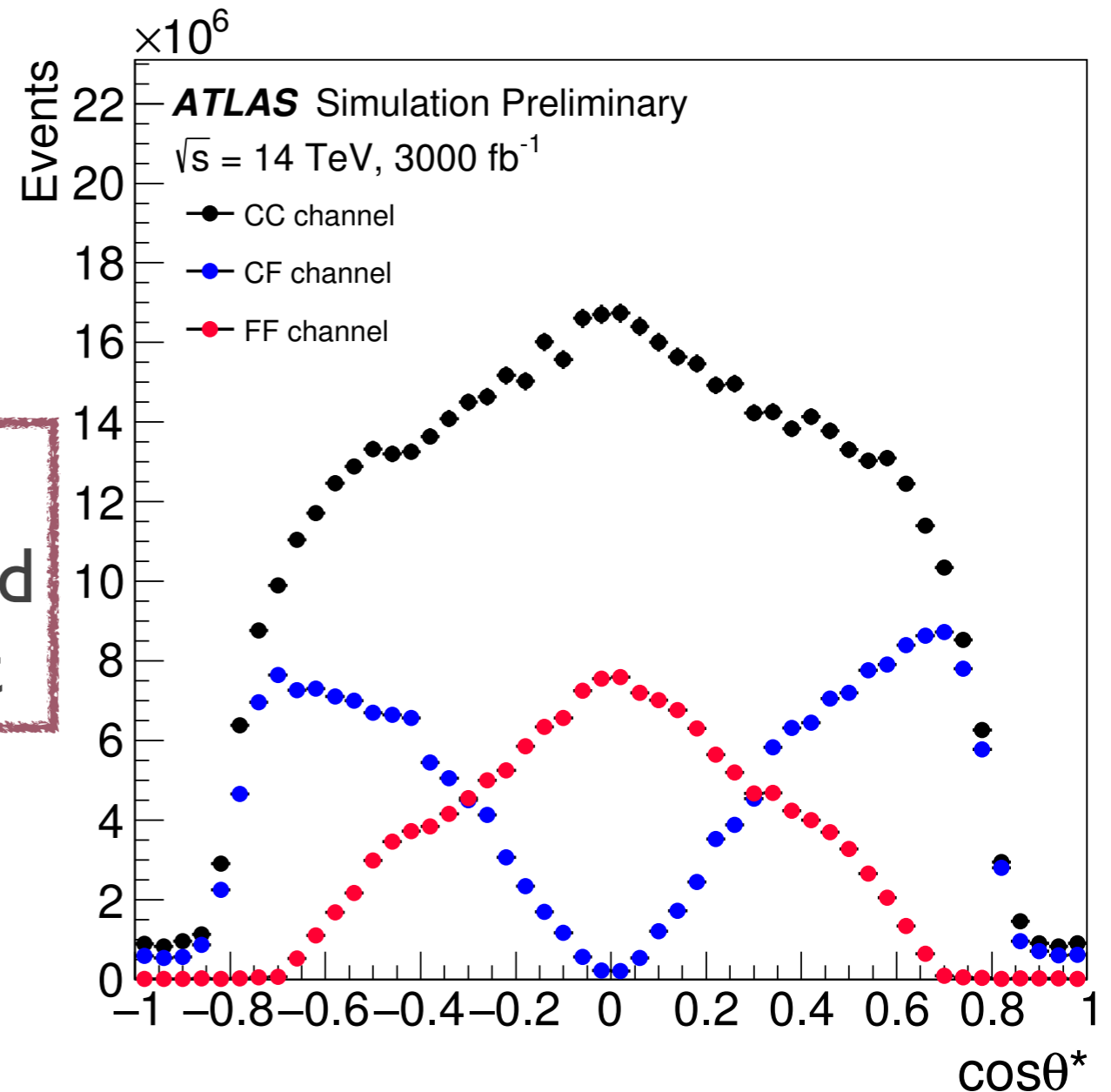
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HL-LHC measurement exploits increased tracker acceptance, improved PDF measurements, and large dataset

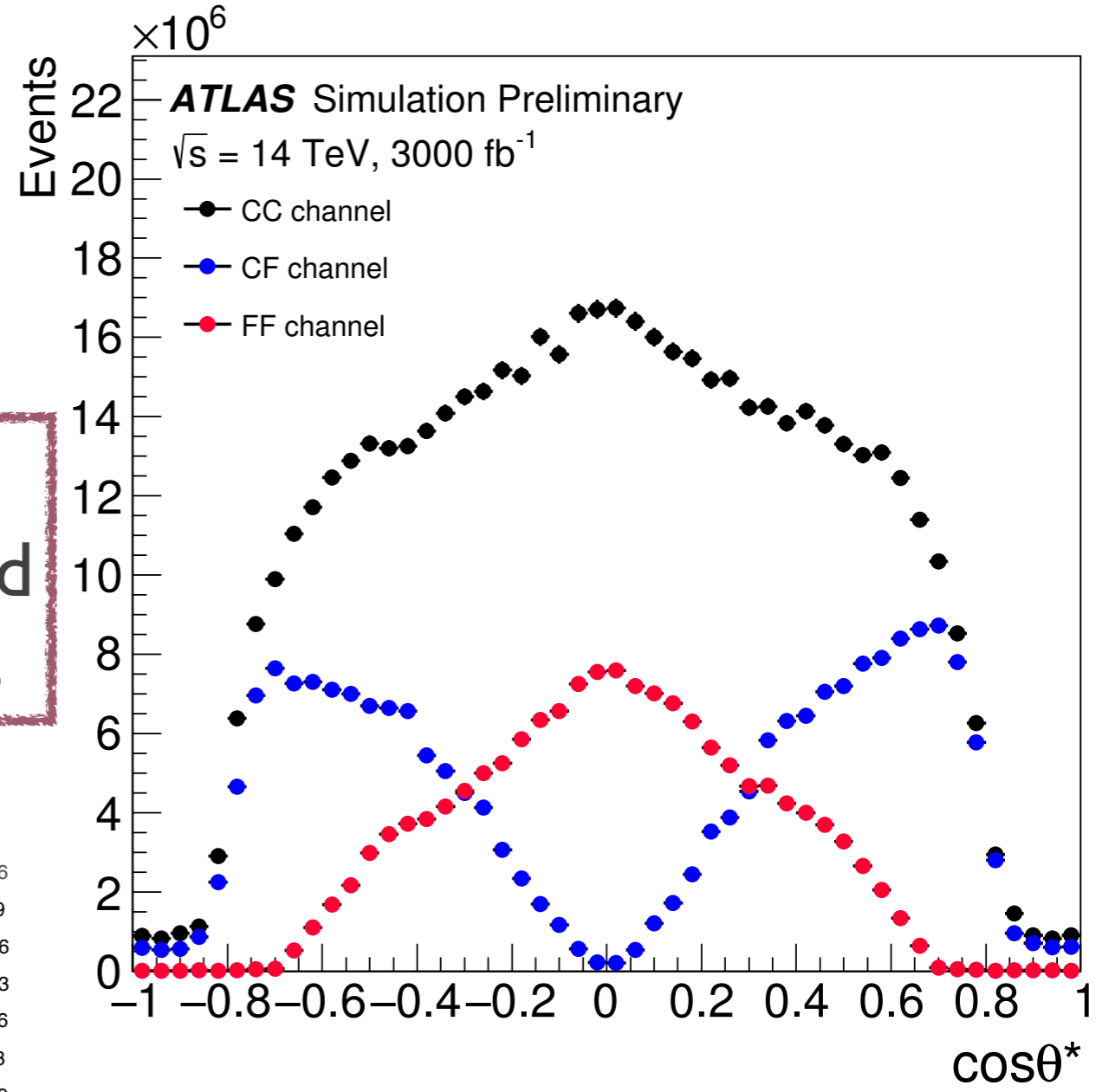




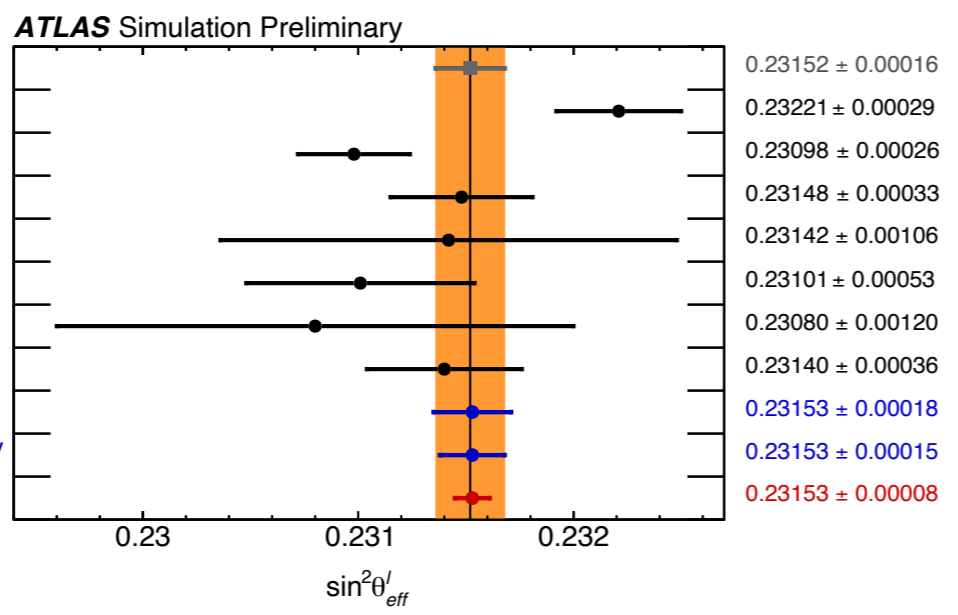
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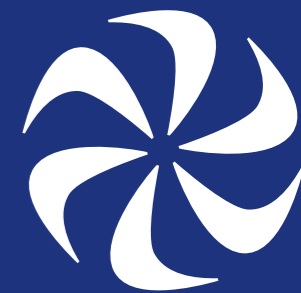
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- LEP-1 and SLD: Z-pole average
- LEP-1 and SLD:  $A_{FB}^{0,b}$
- SLD:  $A_1$
- Tevatron
- LHCb: 7+8 TeV
- CMS: 8 TeV
- ATLAS: 7 TeV
- ATLAS Preliminary: 8 TeV
- HL-LHC ATLAS CT14: 14 TeV
- HL-LHC ATLAS PDF4LHC15<sub>HL-LHC</sub>: 14 TeV
- HL-LHC ATLAS PDFLHeC: 14 TeV



Potential for world's best measurement!



# W Boson Mass



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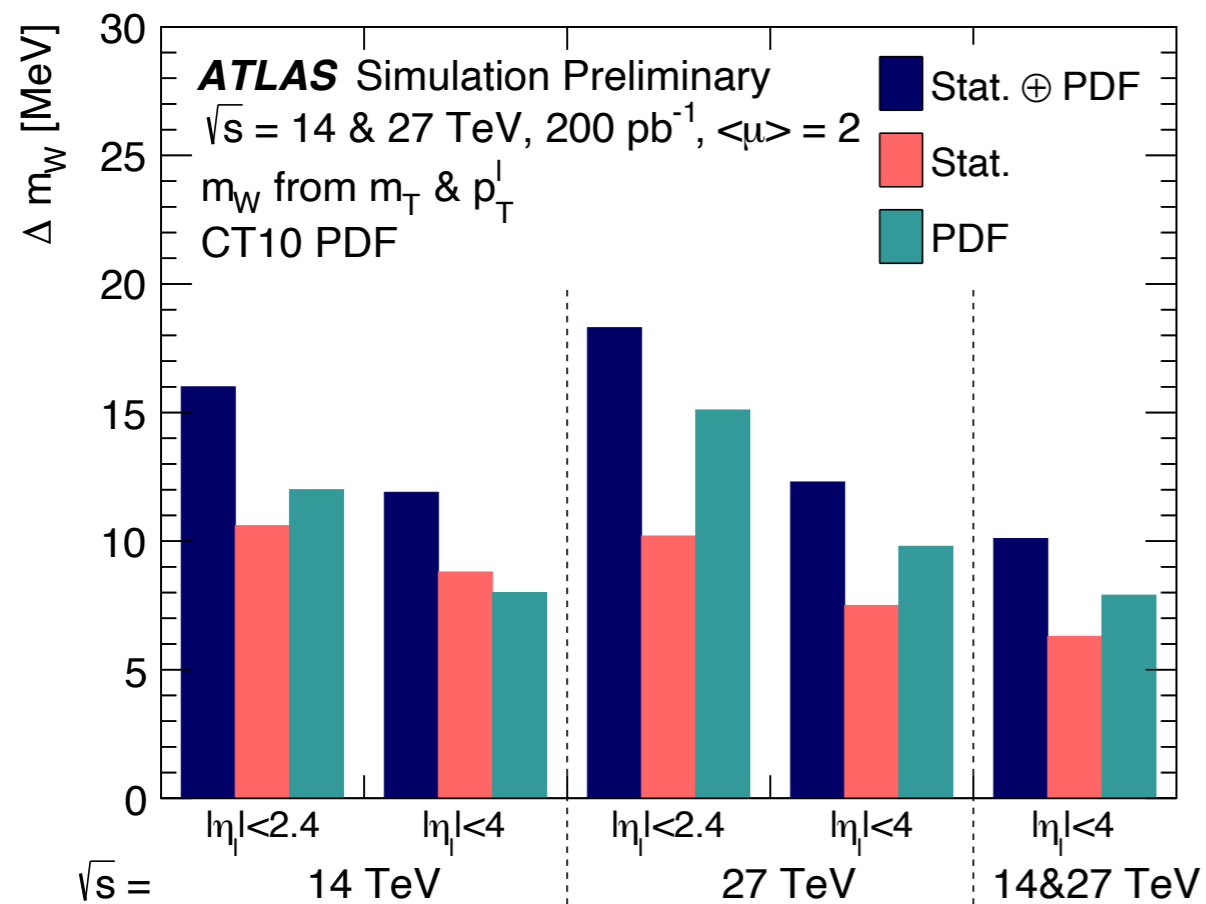
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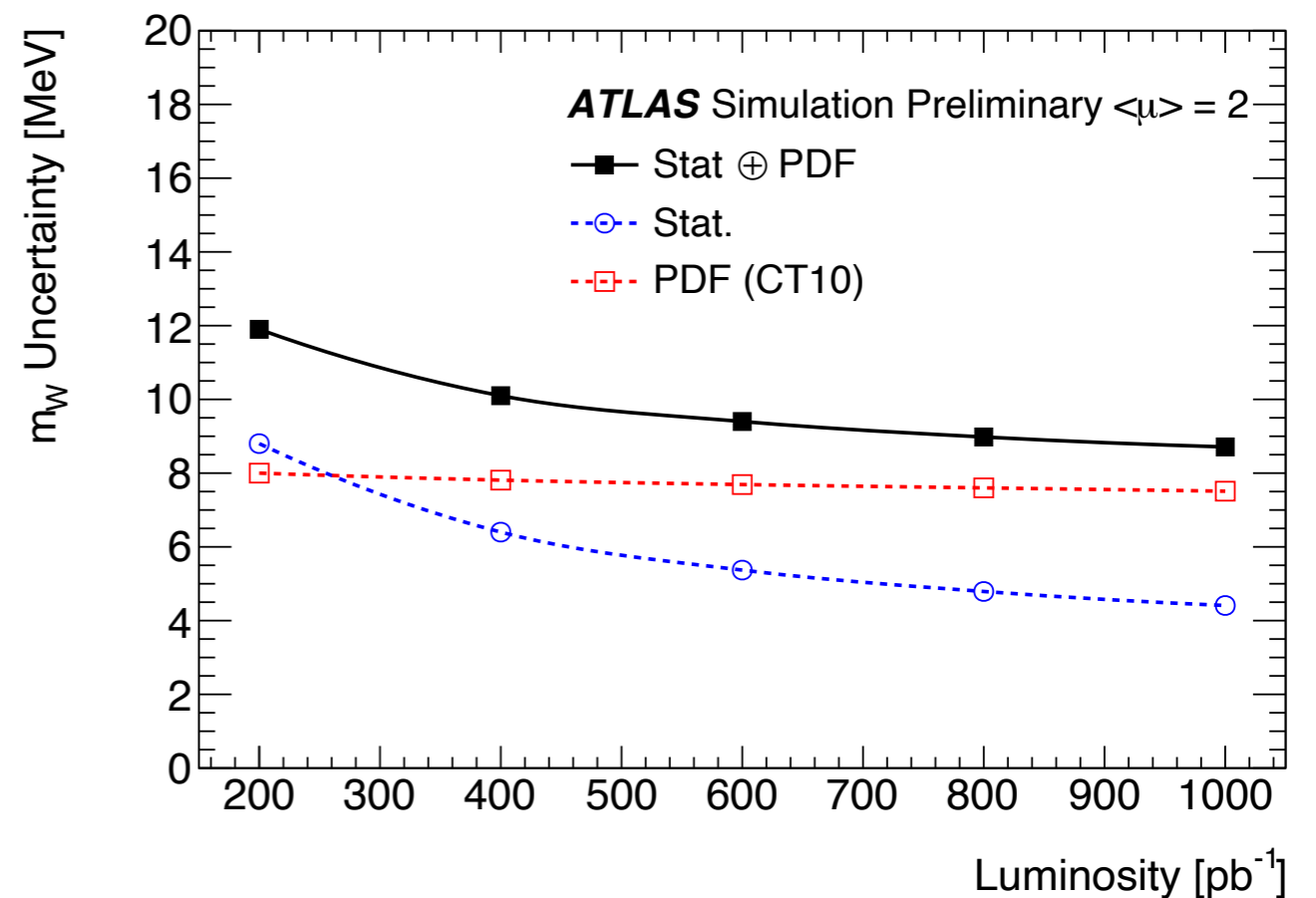
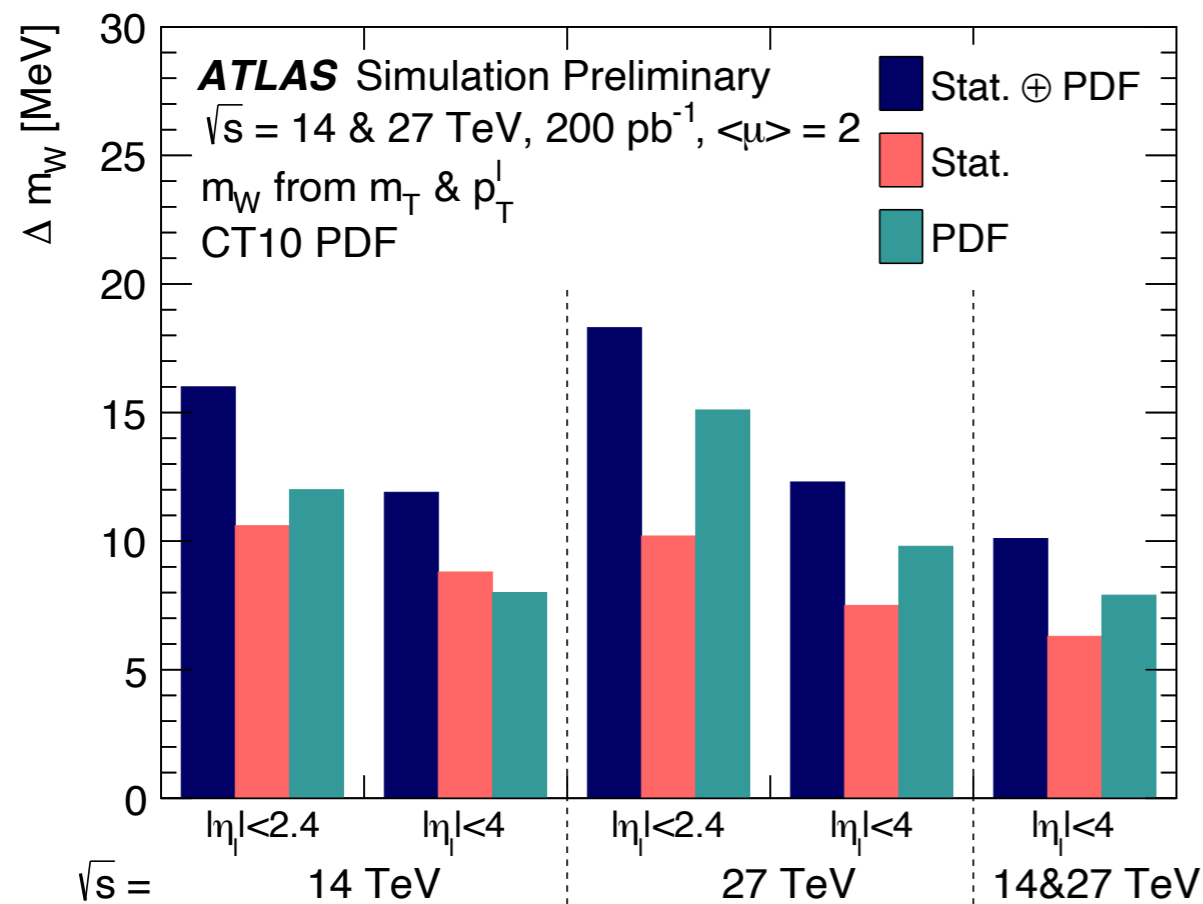


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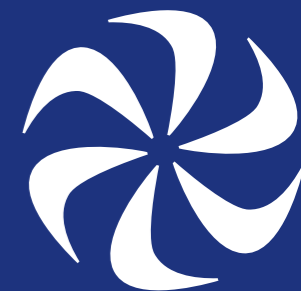
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HL-LHC measurement would exploit upgraded tracker acceptance, improved PDF, larger dataset

Special low-pileup dataset could lead to  $\sim 9$  MeV precision: best cross-check of CDF result?



# Vector Boson Scattering

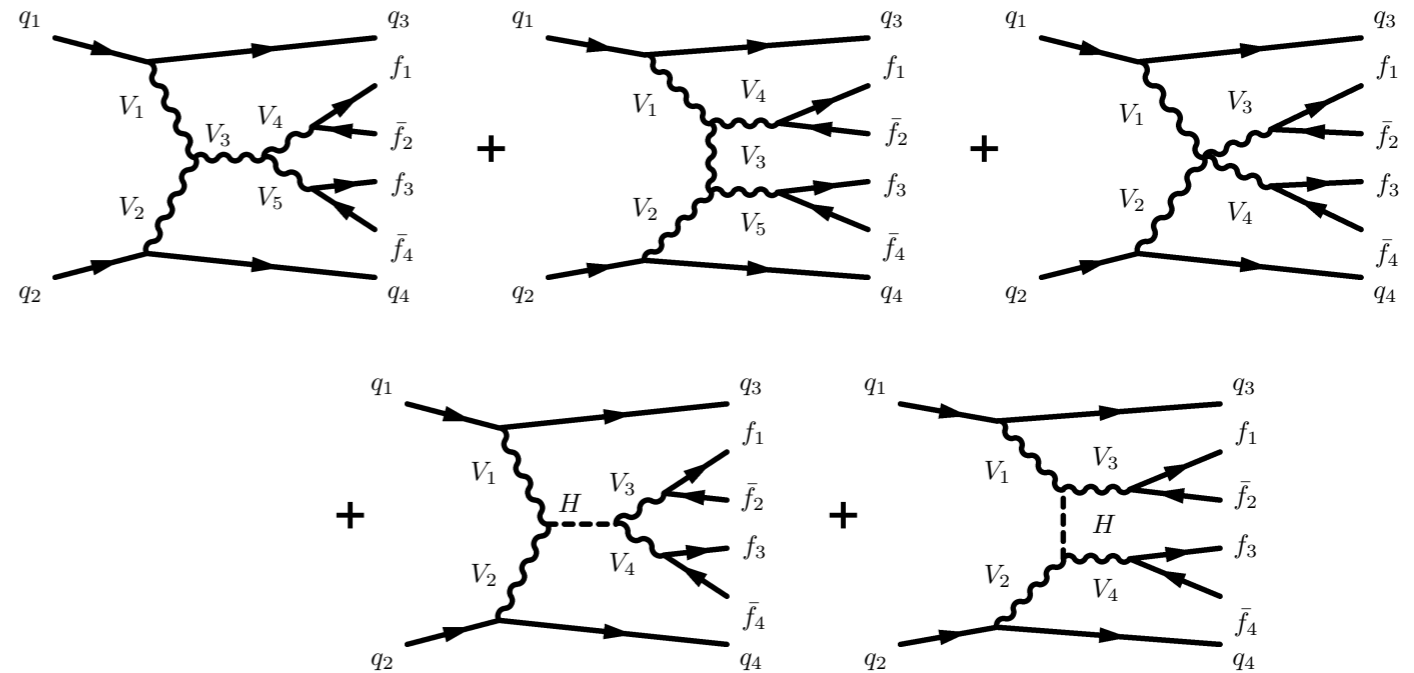




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Vector boson scattering  
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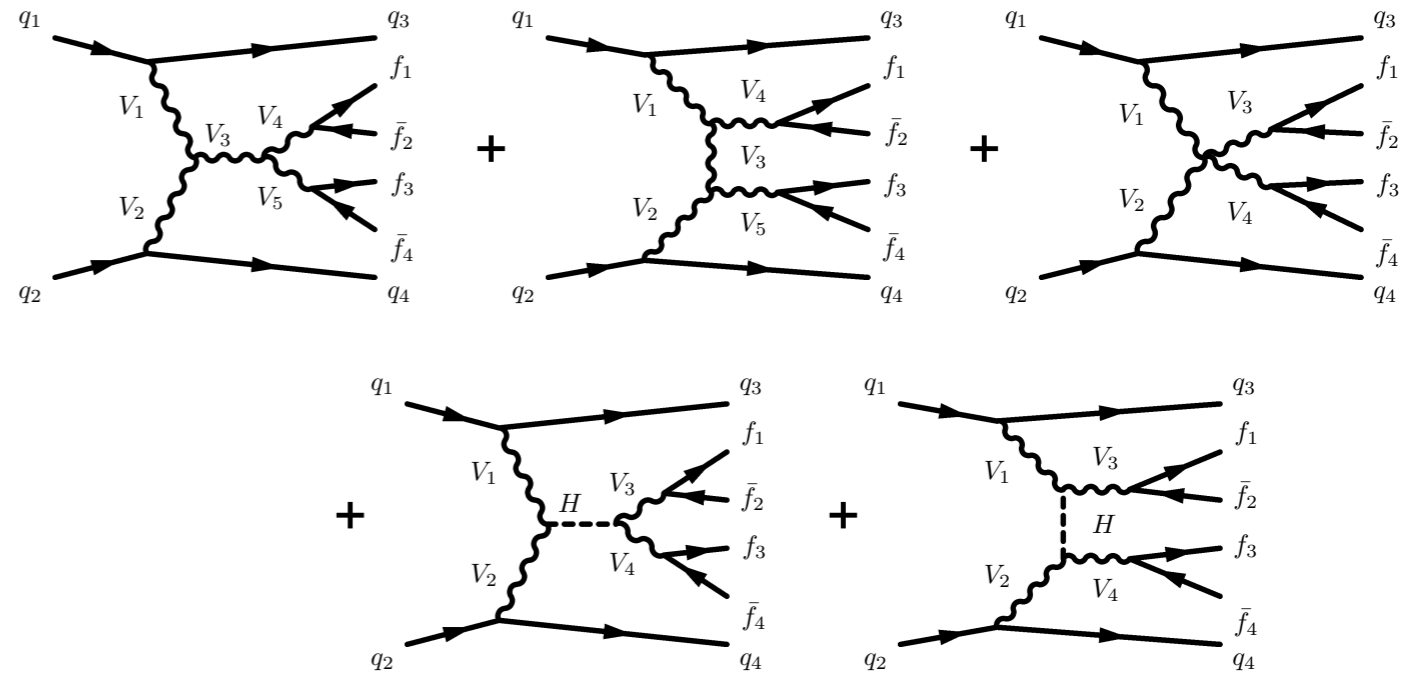


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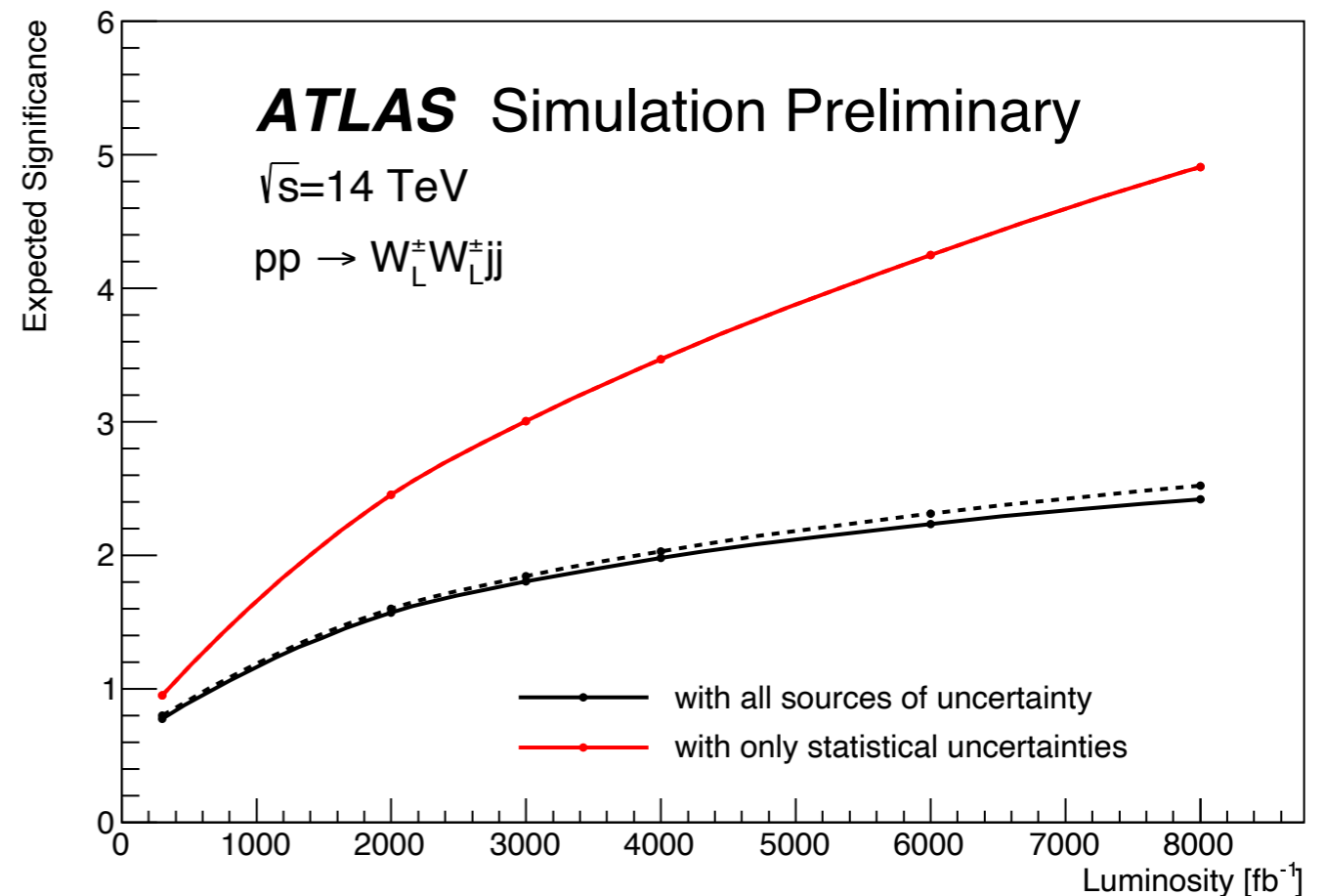
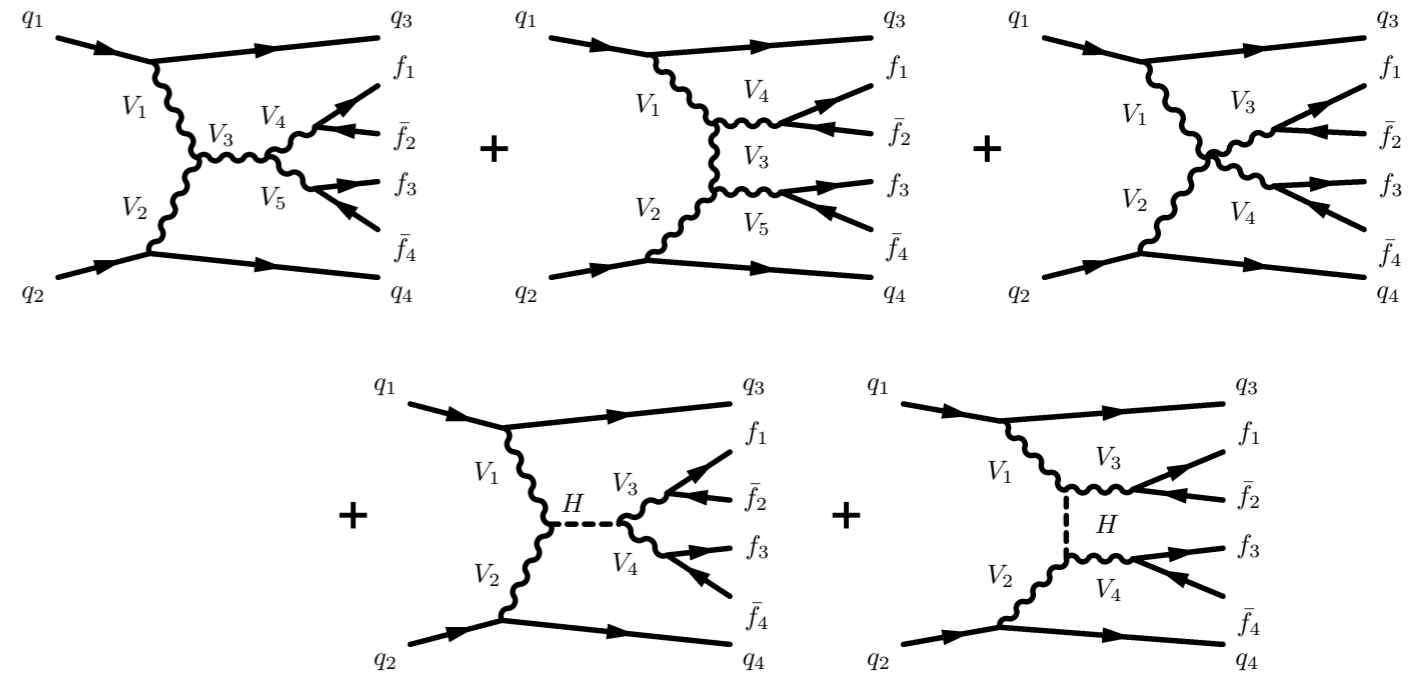


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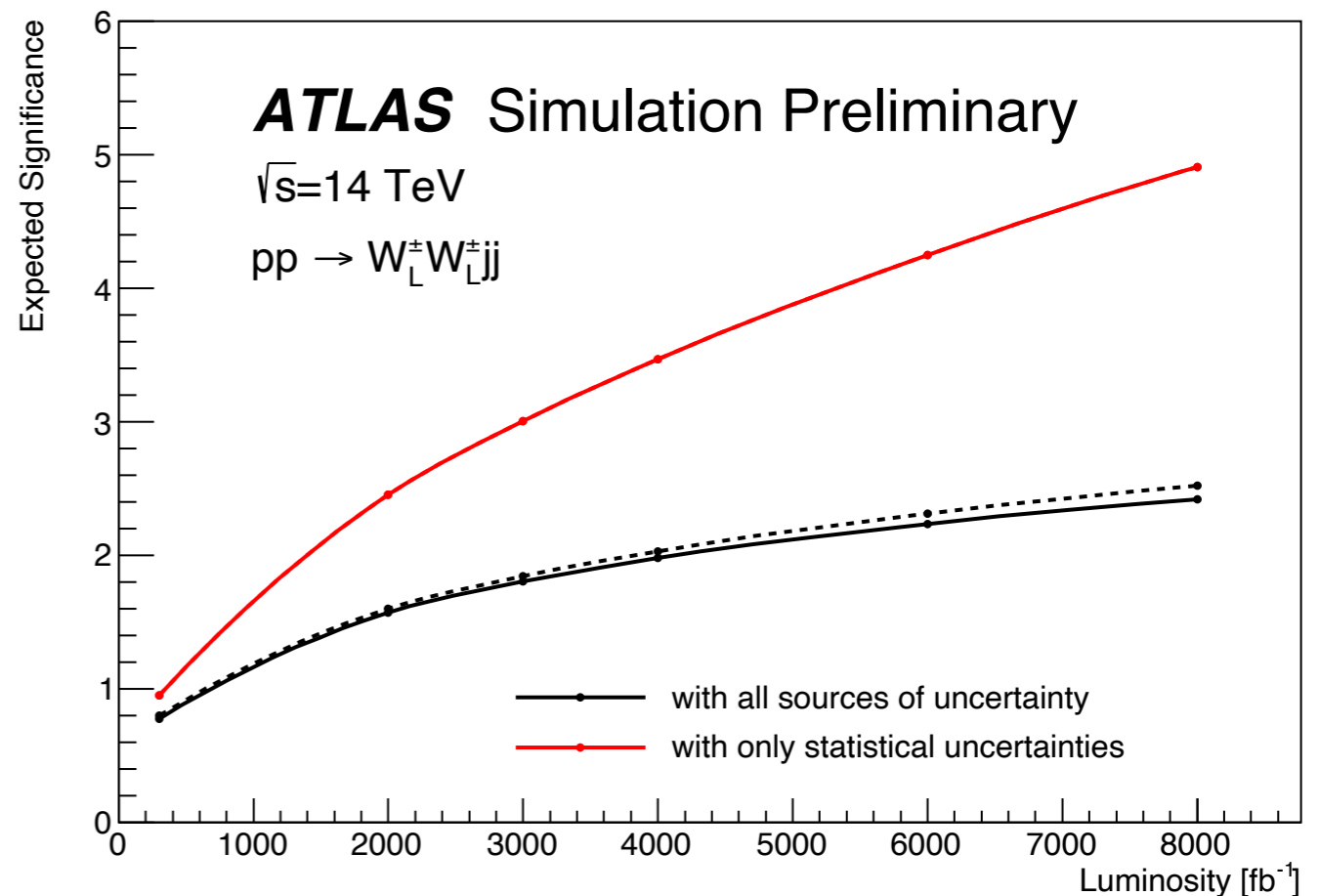
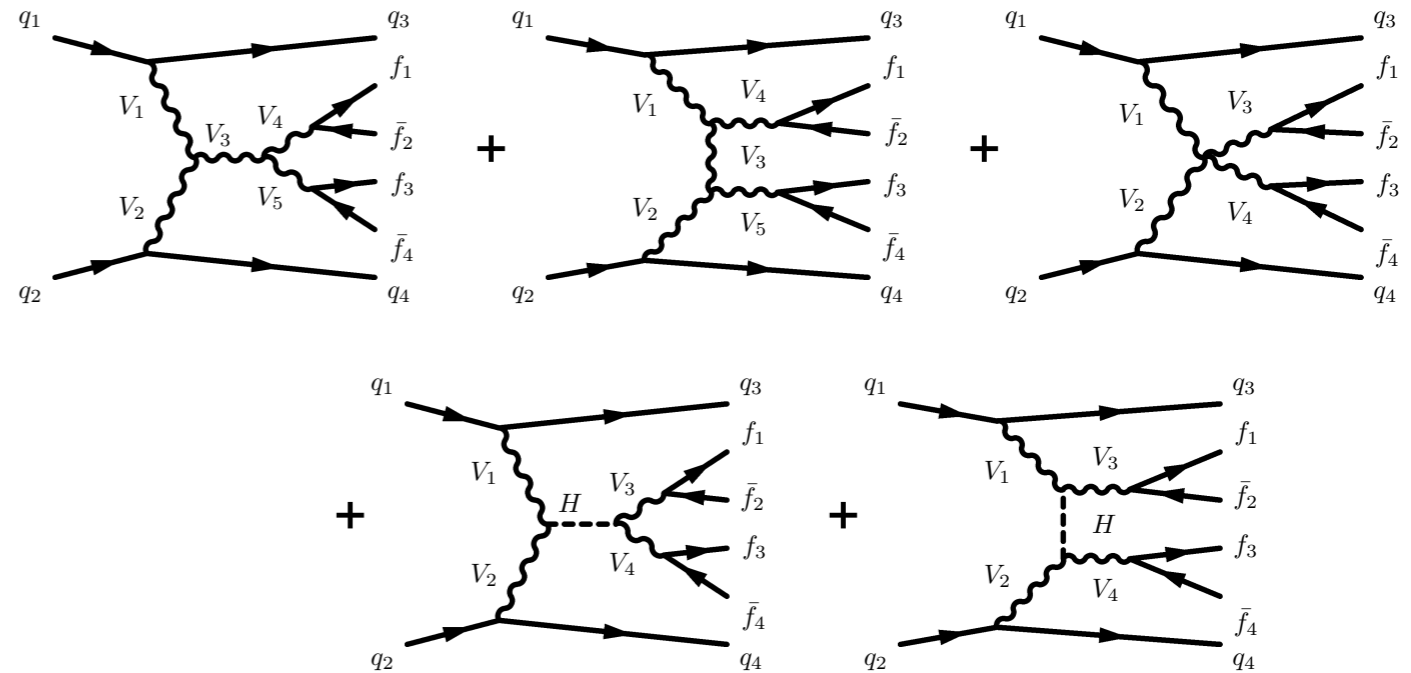
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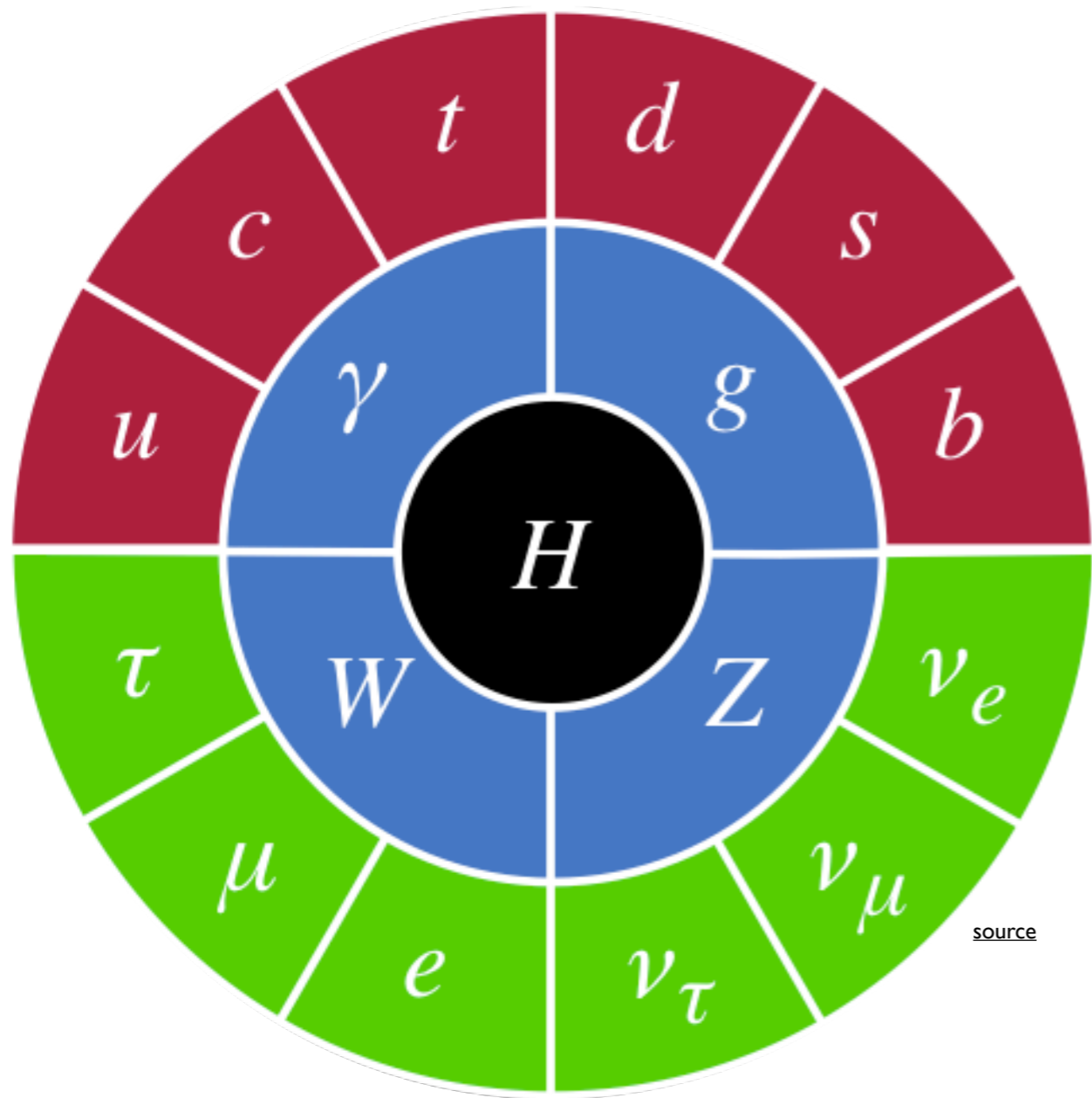
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Challenging to observe:  
systematic and analysis  
improvements needed for  
evidence



# The Higgs Boson

# Why Higgs?



- The Higgs is the **center of the Standard Model**: related to all the particles, so critically important to understand
- The Higgs is the **newest particle**: we know the least about it
- The Higgs is **incredibly rich**: many different ways to study it



# Rare Higgs Processes

ATL-PHYS-PUB-2018-006

ATL-PHYS-PUB-2021-039



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ATL-PHYS-PUB-2021-039

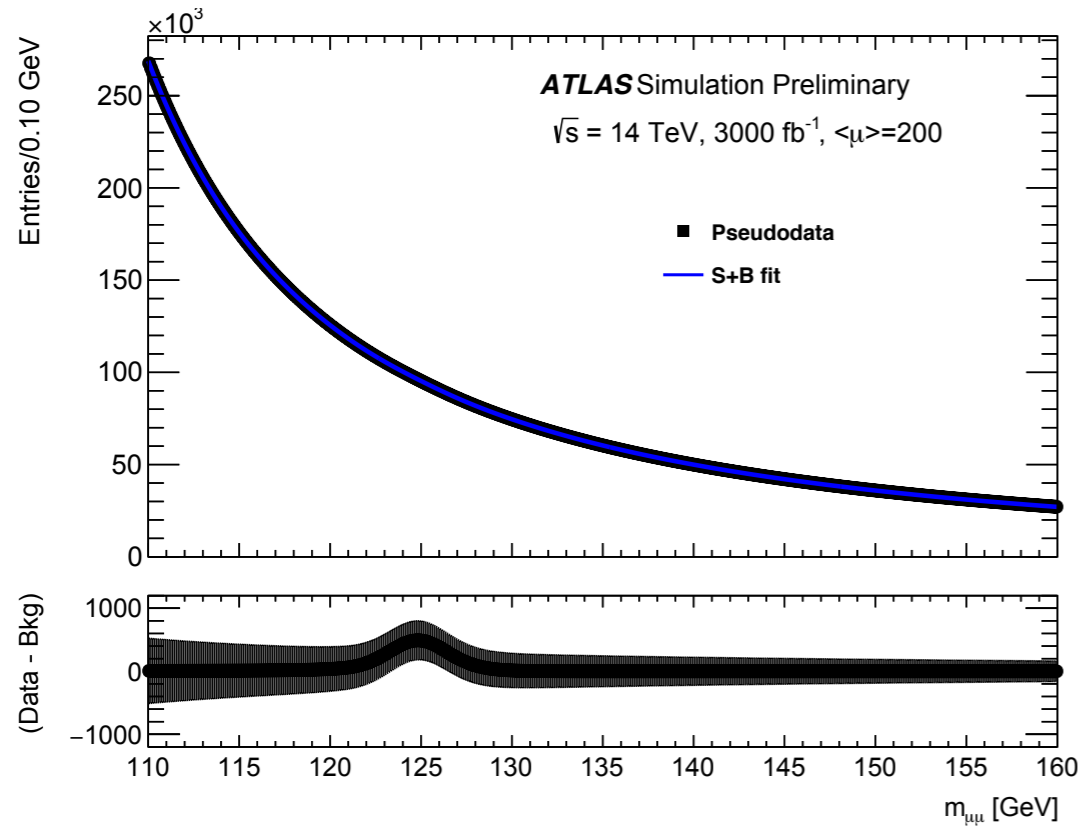


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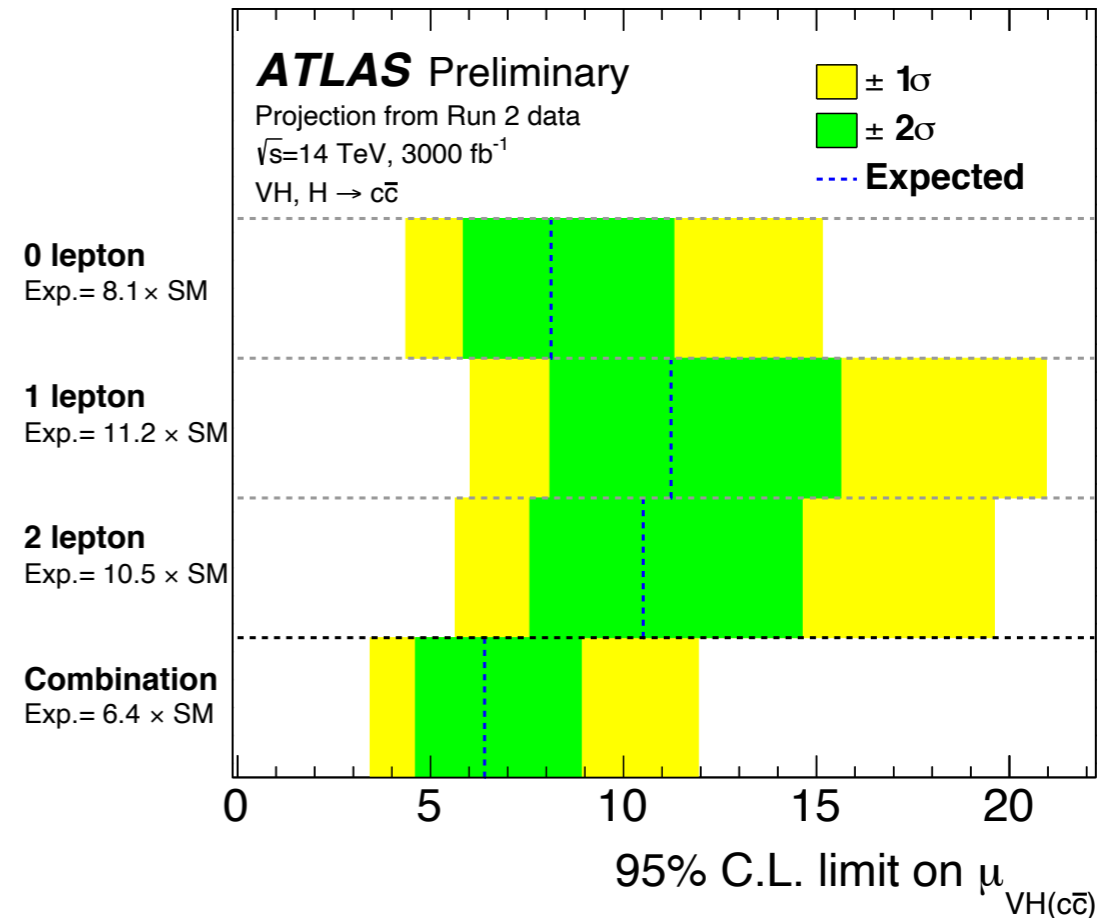
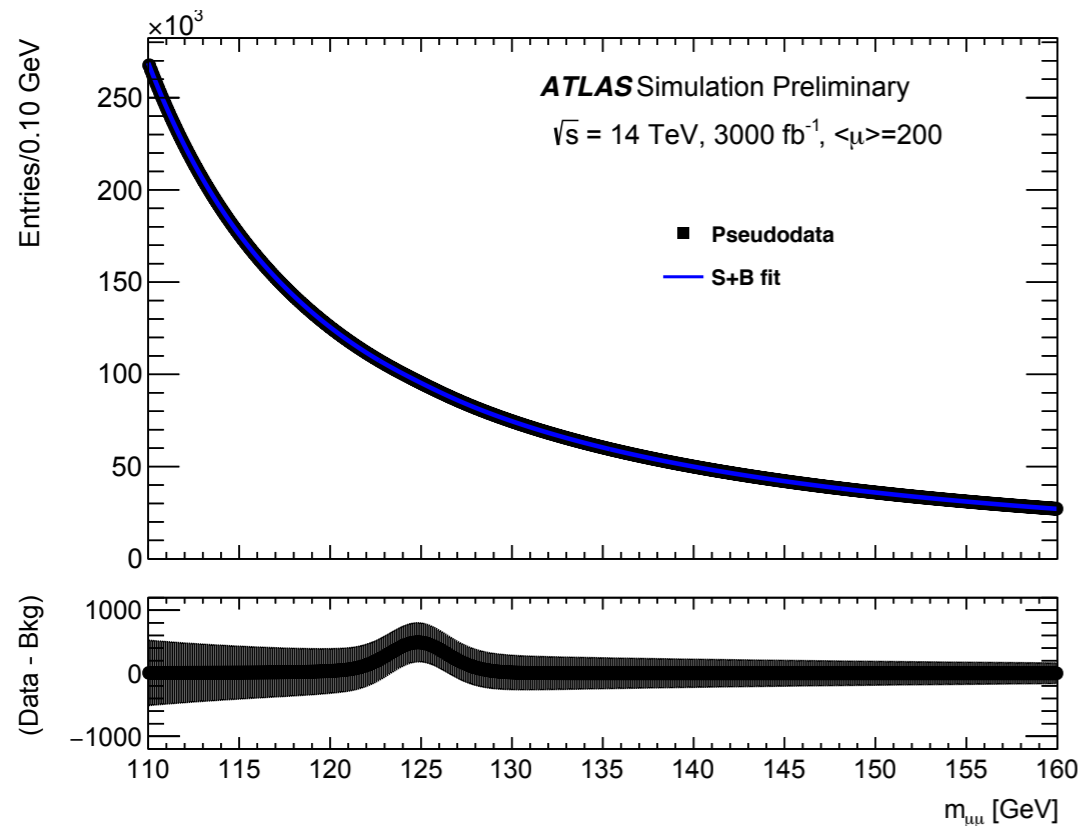
Scoping Scenario	$\langle \mu \rangle$	Overall significance	$\Delta\mu$	
			w/ syst. errors	w/o syst. errors
reference	200	9.5	$\pm 0.13$	$\pm 0.12$
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Expected  $H \rightarrow c\bar{c}$  sensitivity at  $\sim 6x$  SM: improvements in charm tagging and analysis can improve this further

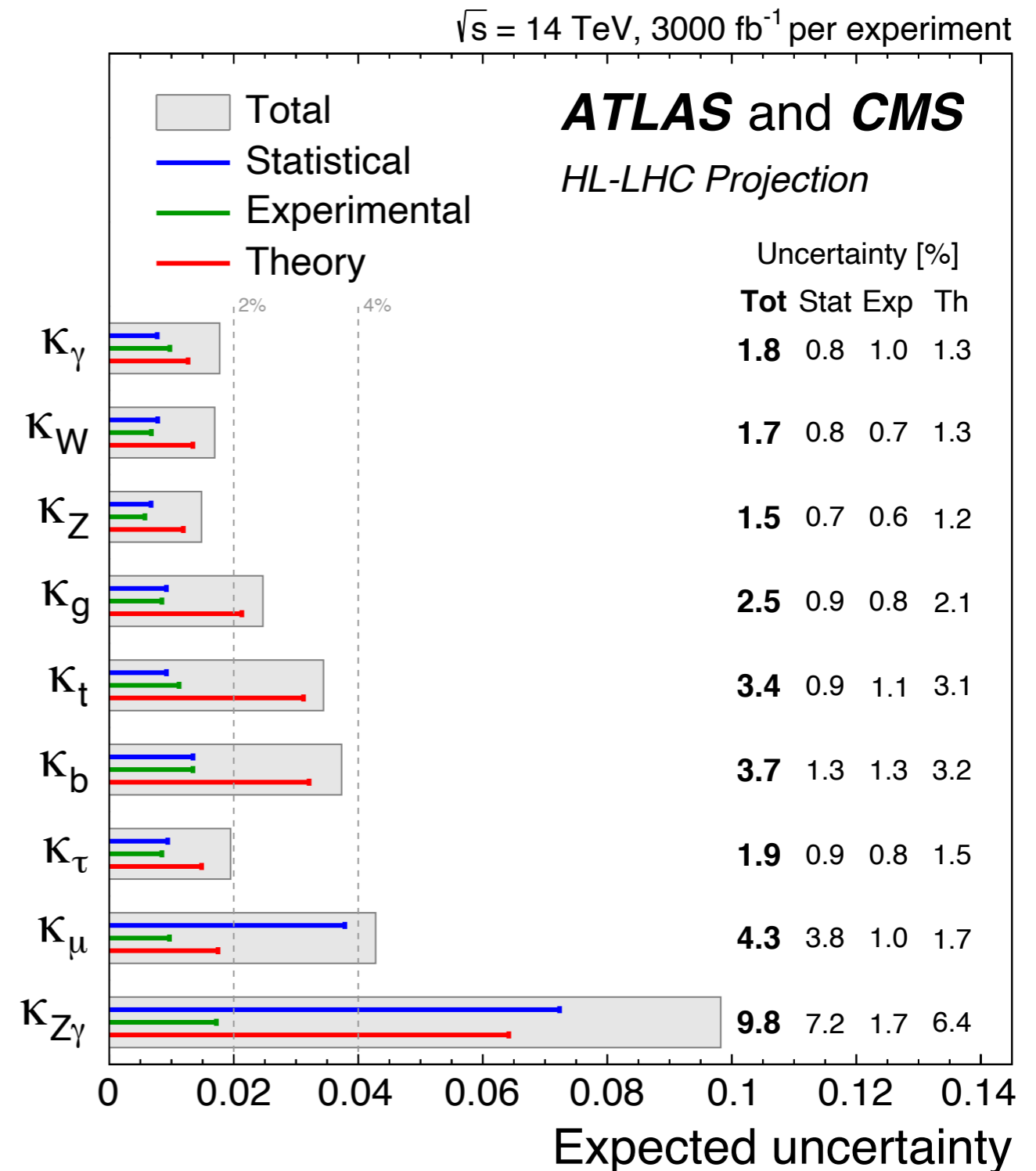


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Huge number of detailed analyses summarized here in one plot: expected uncertainty on Higgs couplings to particles

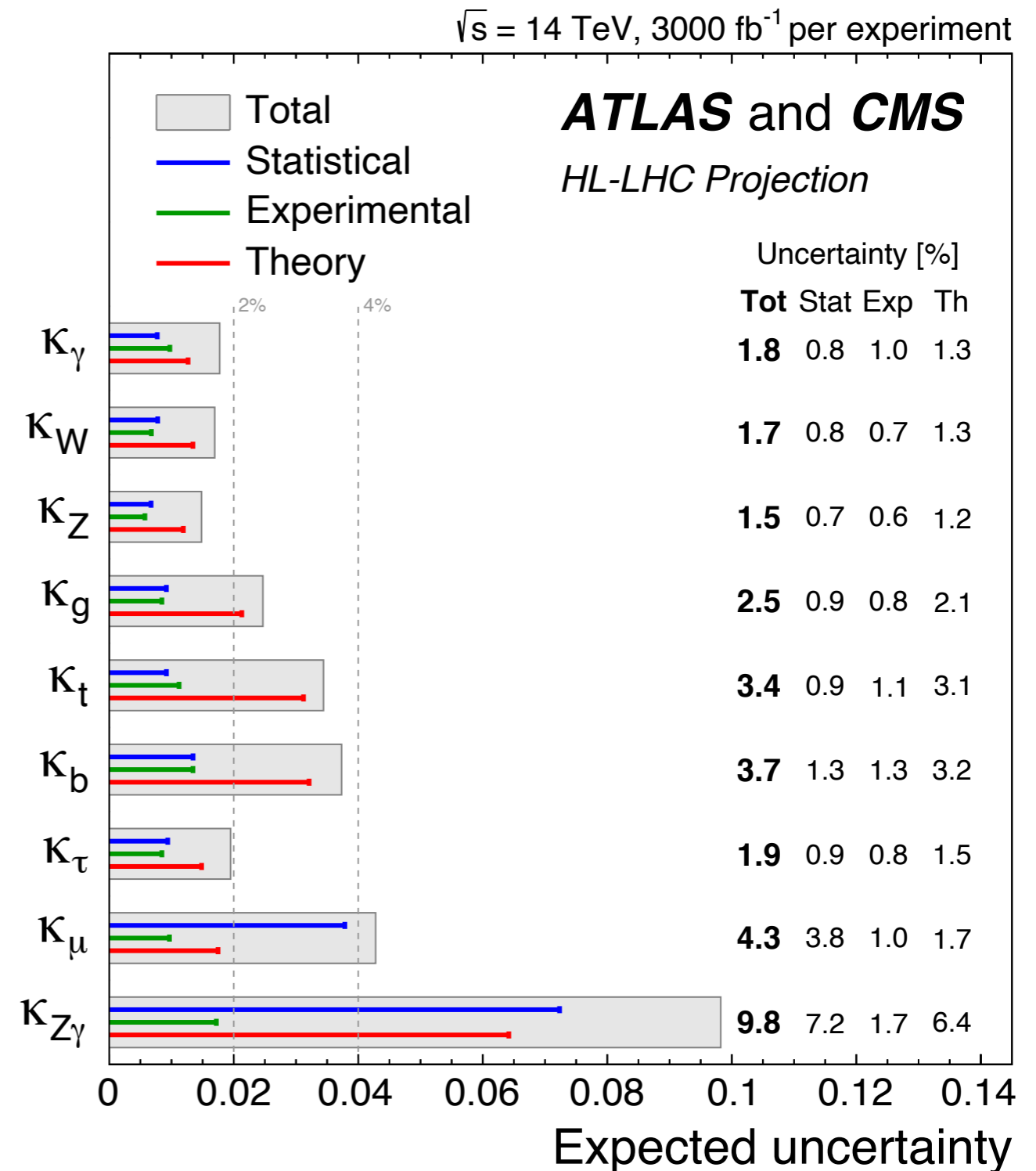




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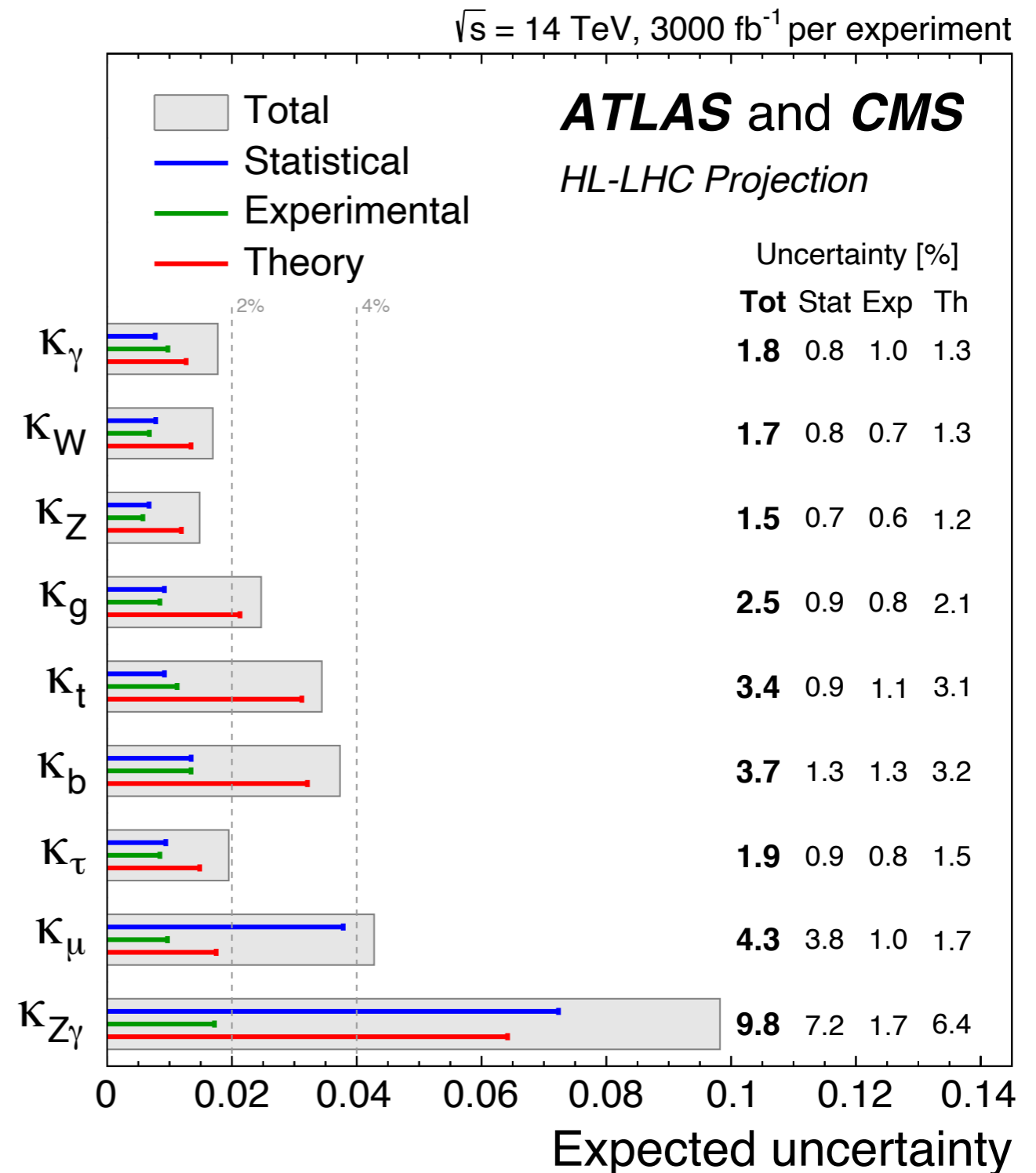


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Many of these measurements expected to be complementary to Higgs Factories (especially rarer decays)





# Understanding EWSB

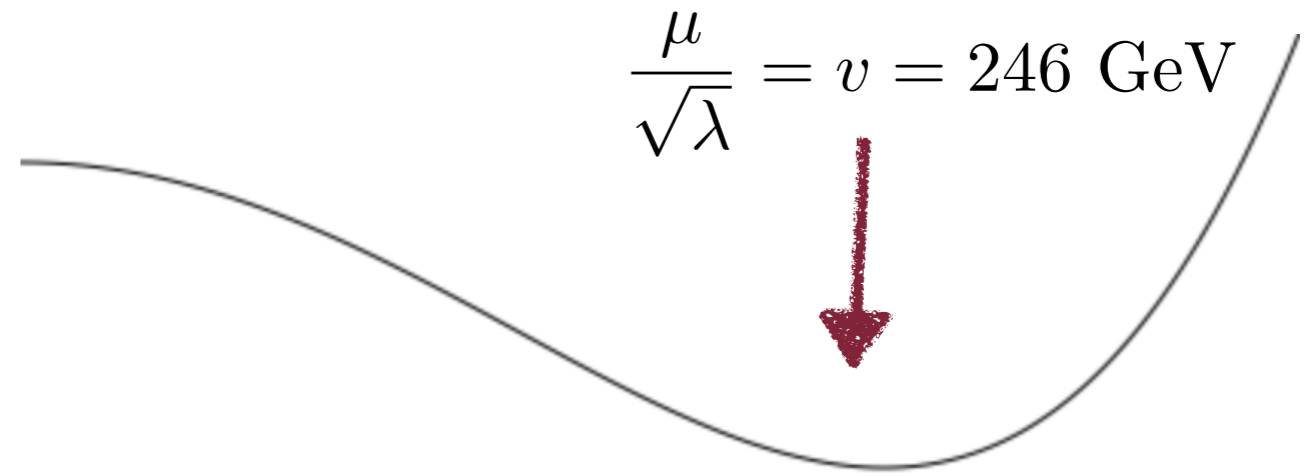


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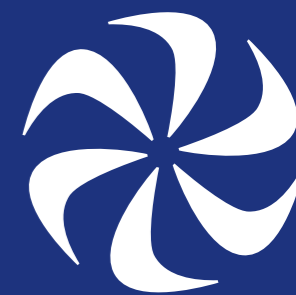


The SM Higgs potential is:

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



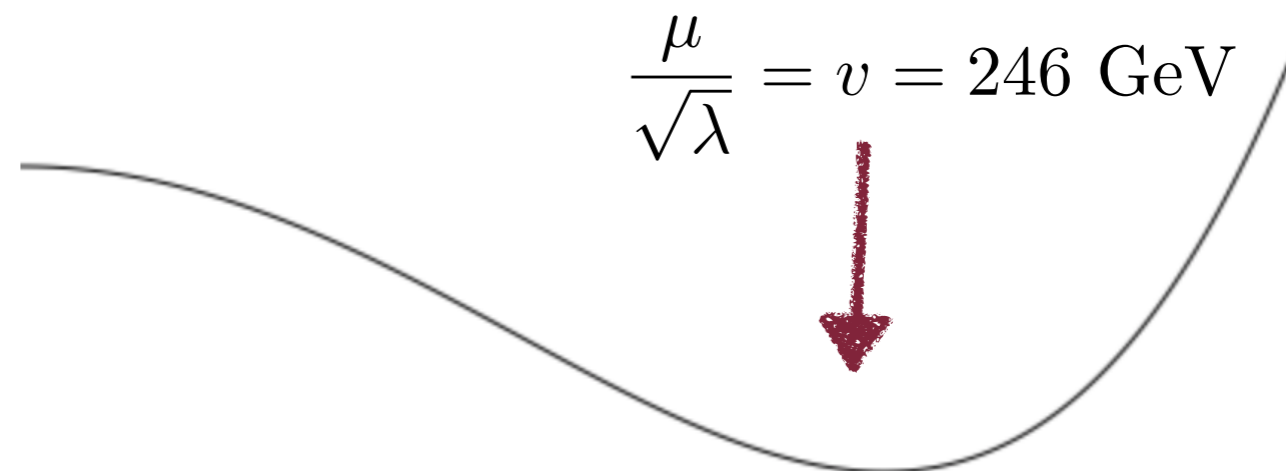
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We live in the minimum:



# Understanding EWSB



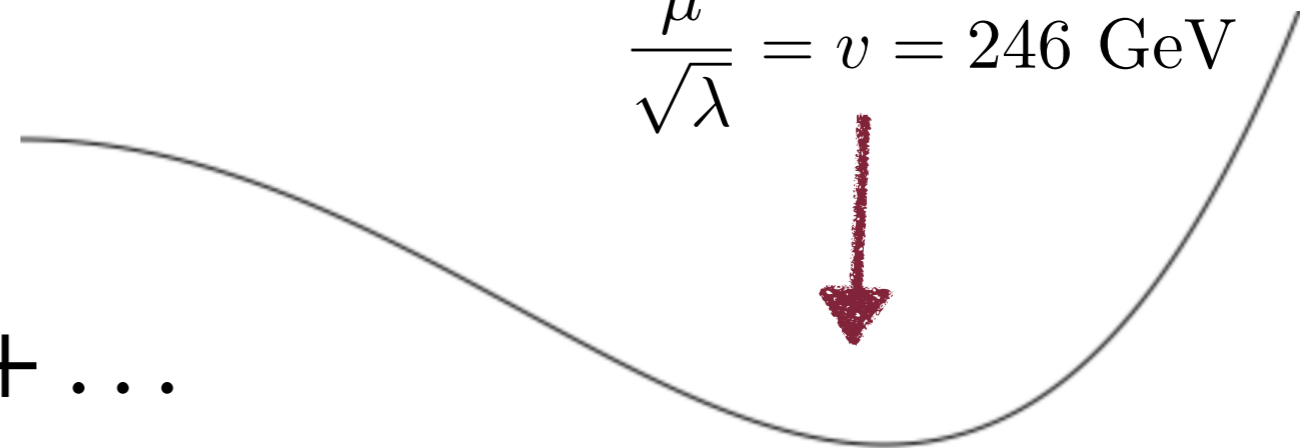
The SM Higgs potential is:

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

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$$V(\phi) = V_0 + \lambda v^2 h^2 + \lambda v h^3 + \dots$$

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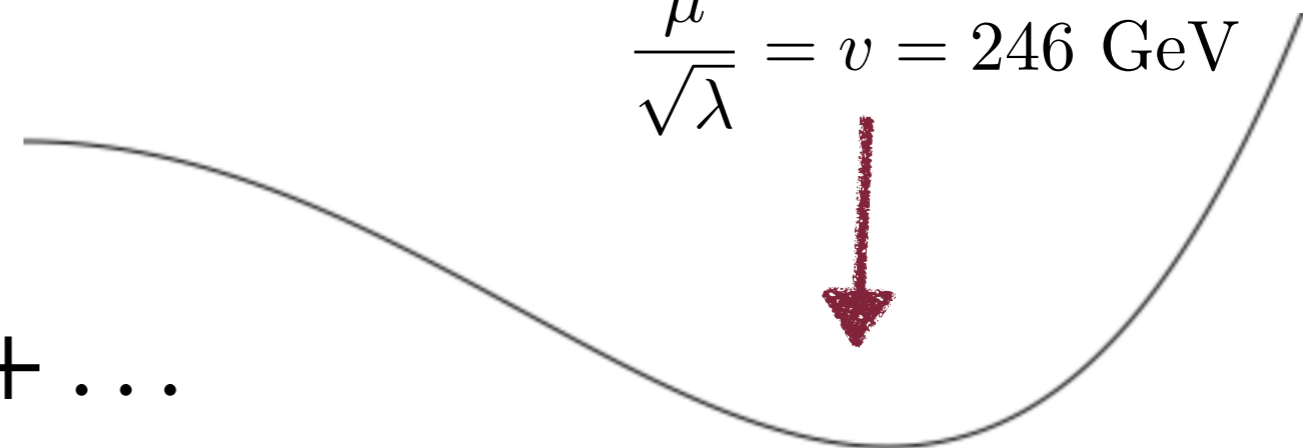
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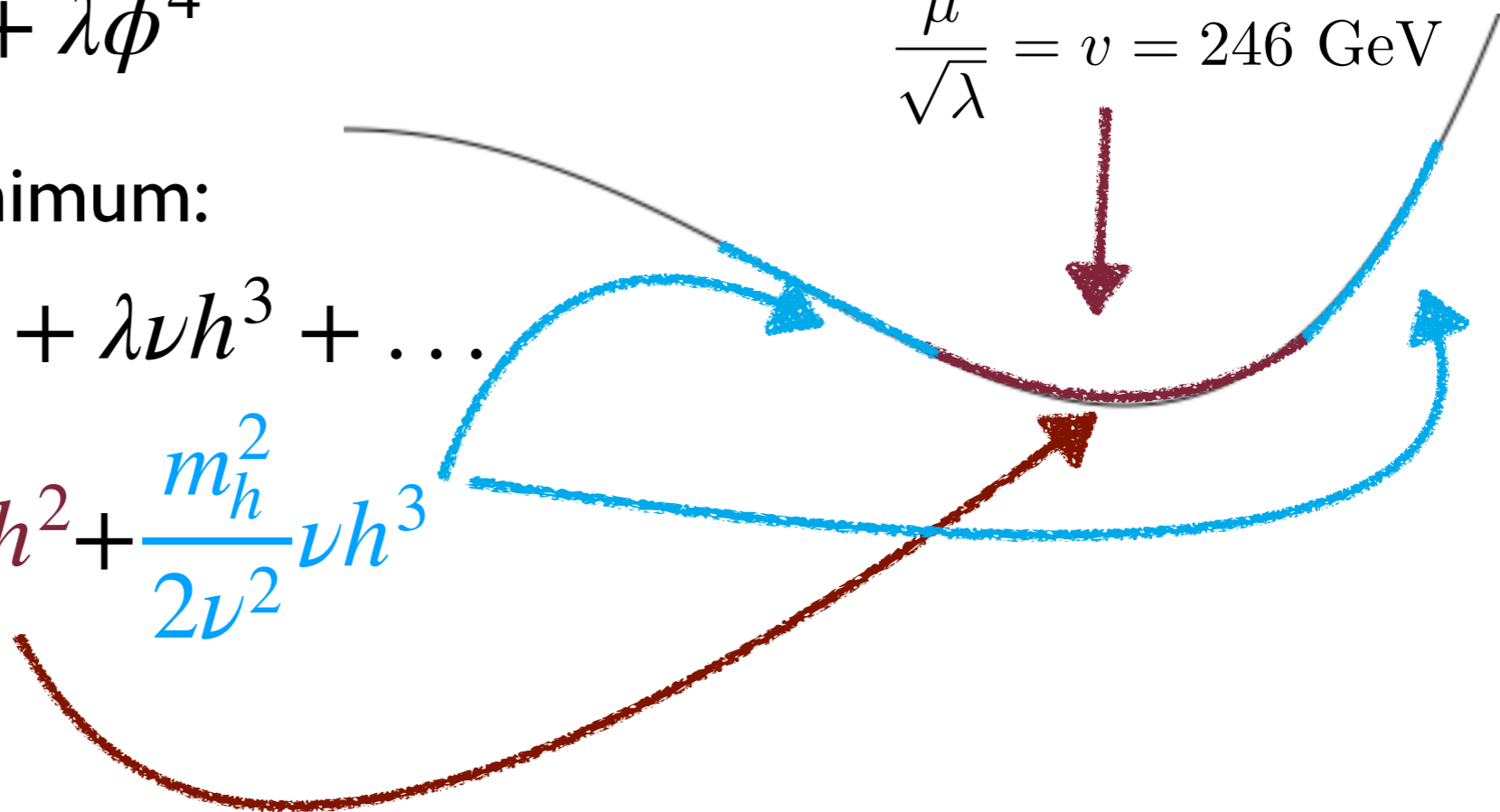
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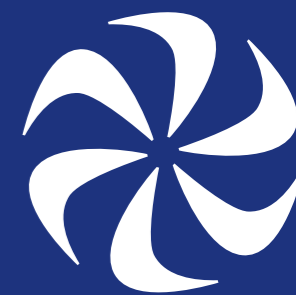
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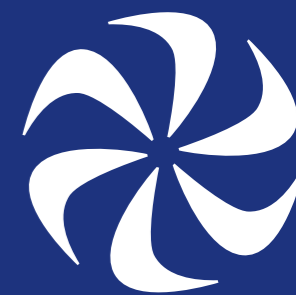
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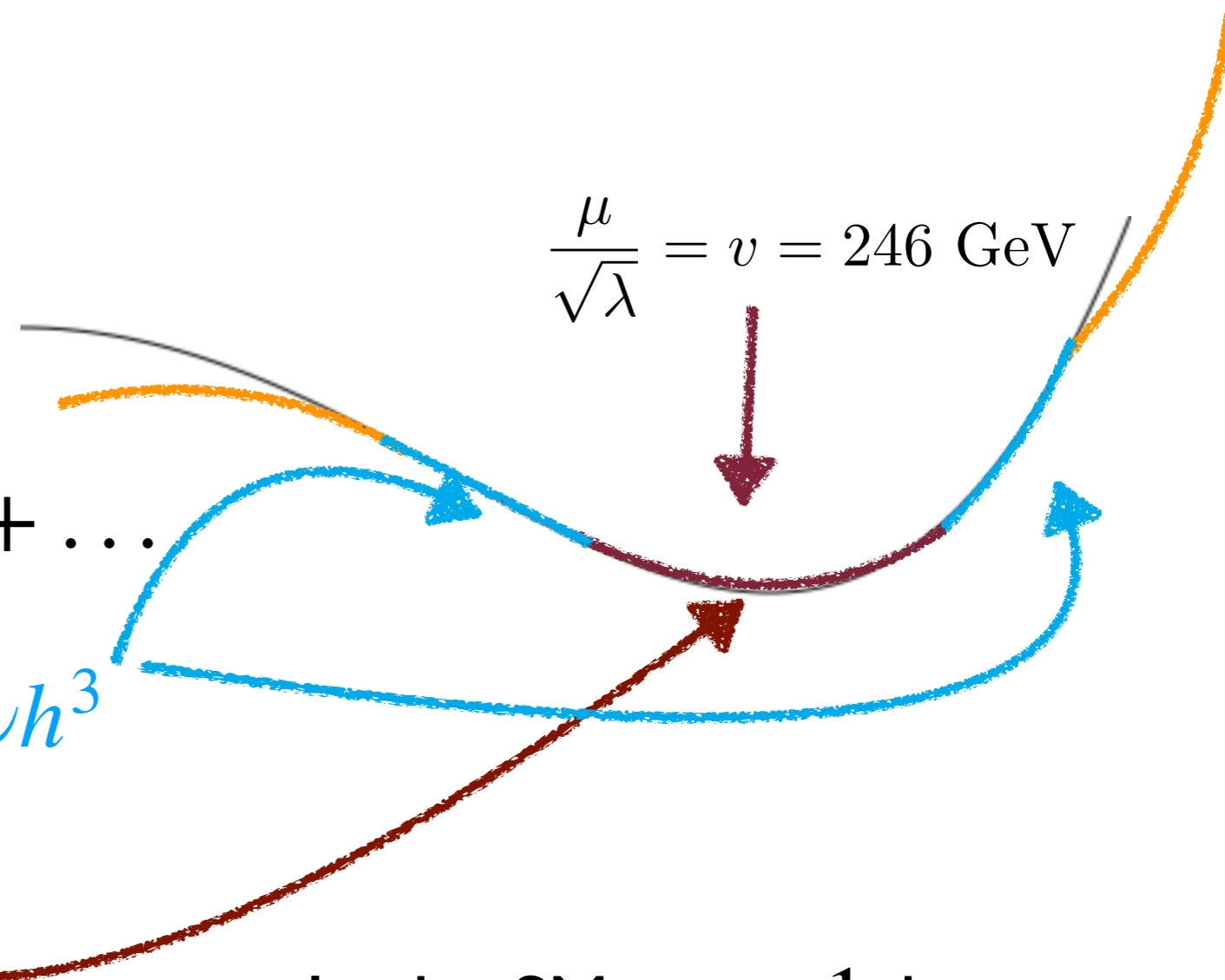
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But what if we see something **completely different**? Could be hints of new physics, related to baryogenesis or vacuum stability!



# Higgs Pairs



# Higgs Pairs



Two diagrams produce  
HH at the LHC...

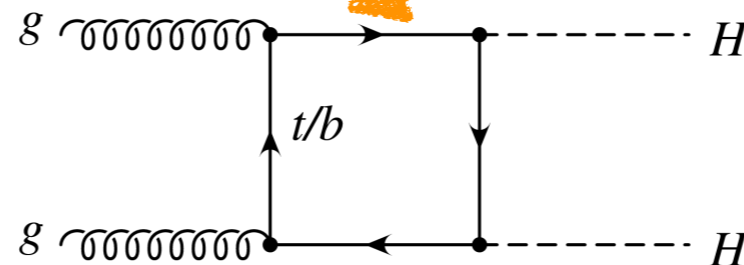
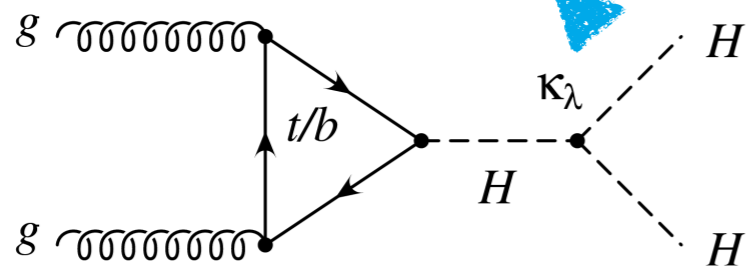
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One diagram involves  $\kappa_\lambda$ :  
What we want to measure

The other is just proportional  
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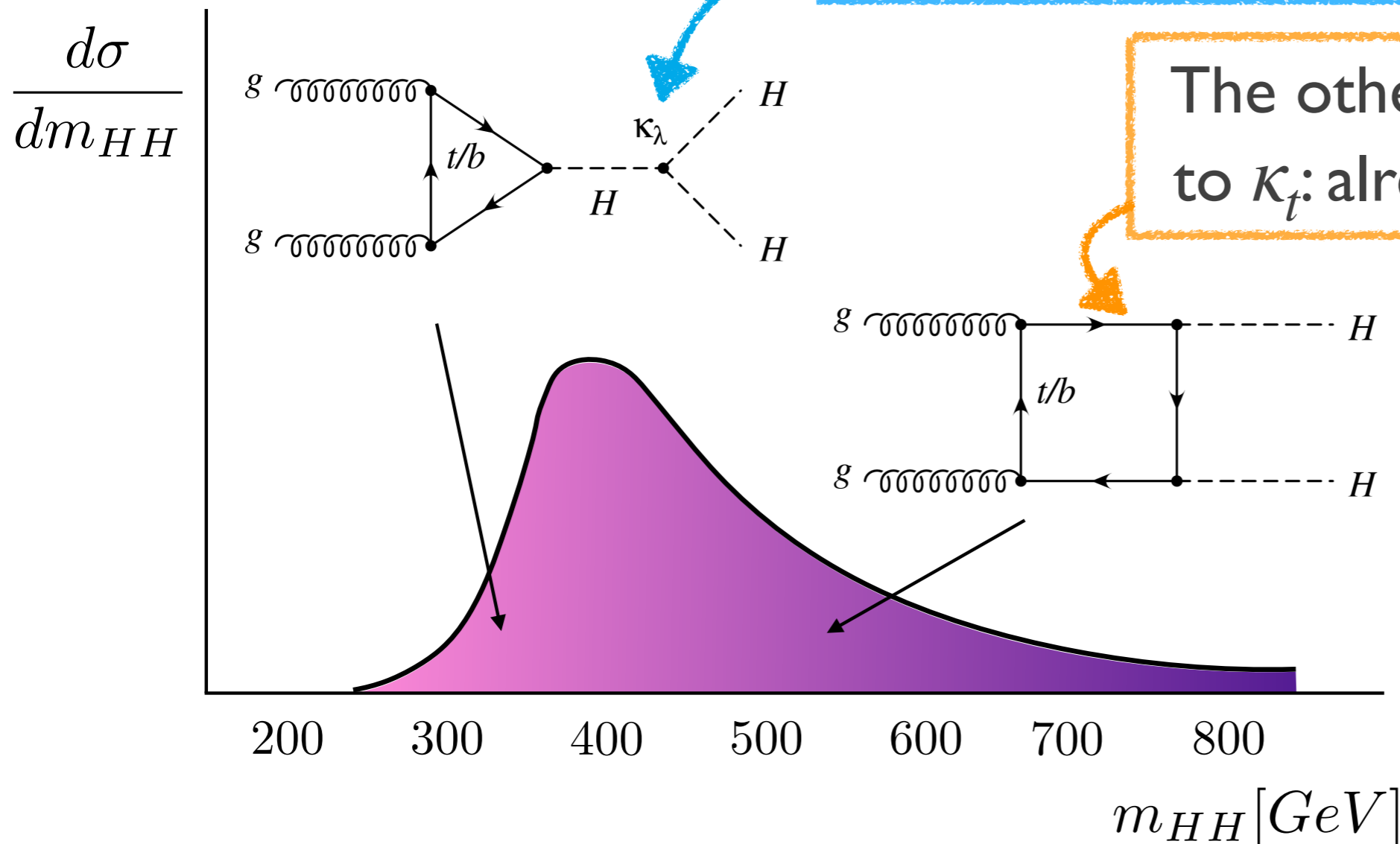


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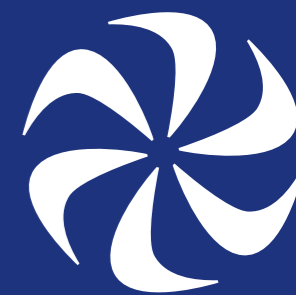
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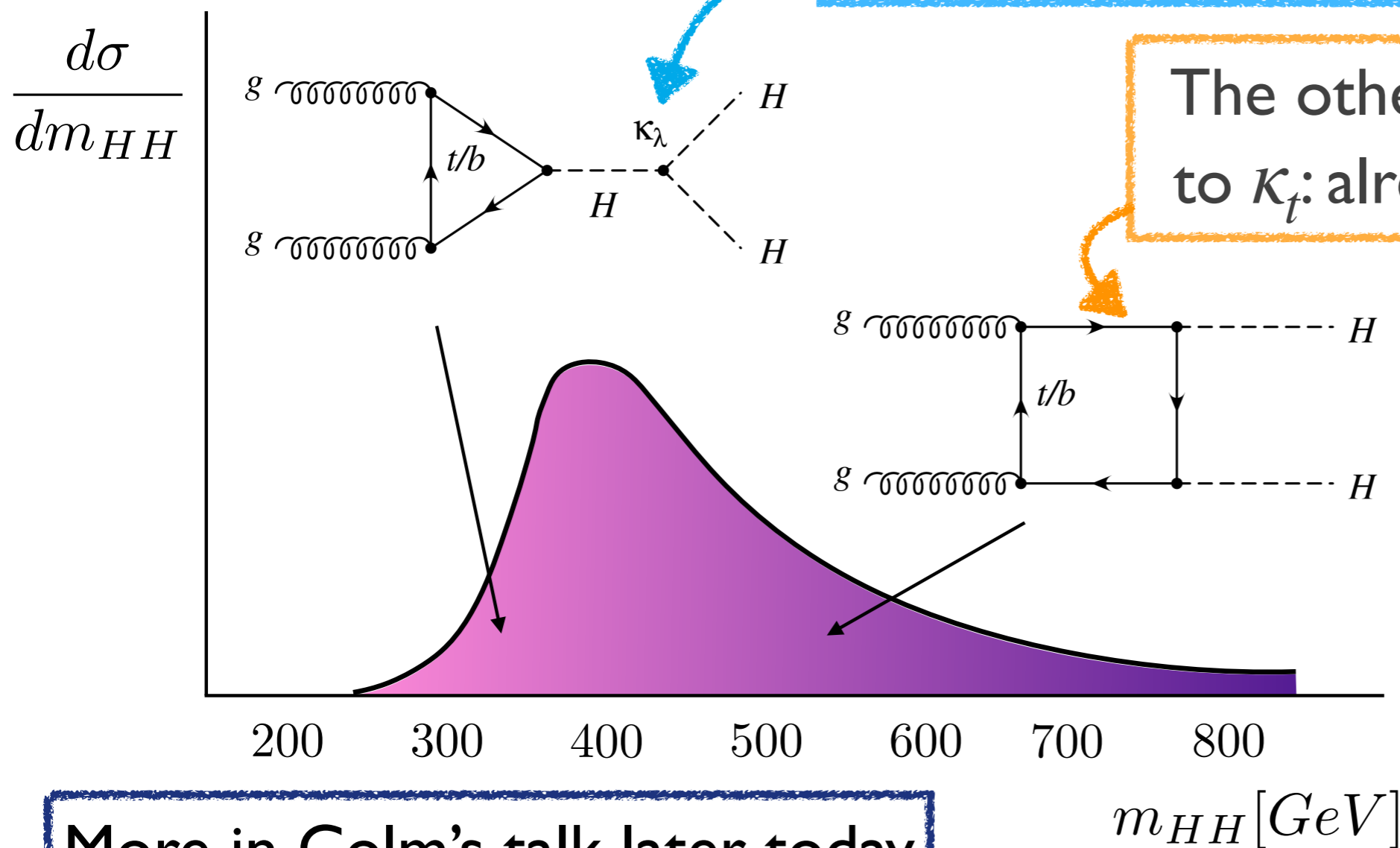


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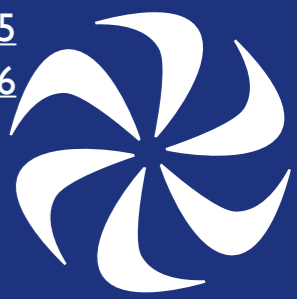
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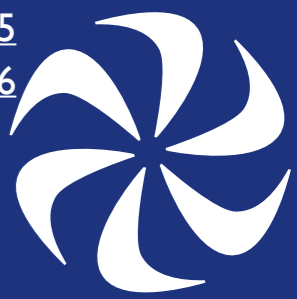
More in Colm's talk later today

# Self Coupling Projections

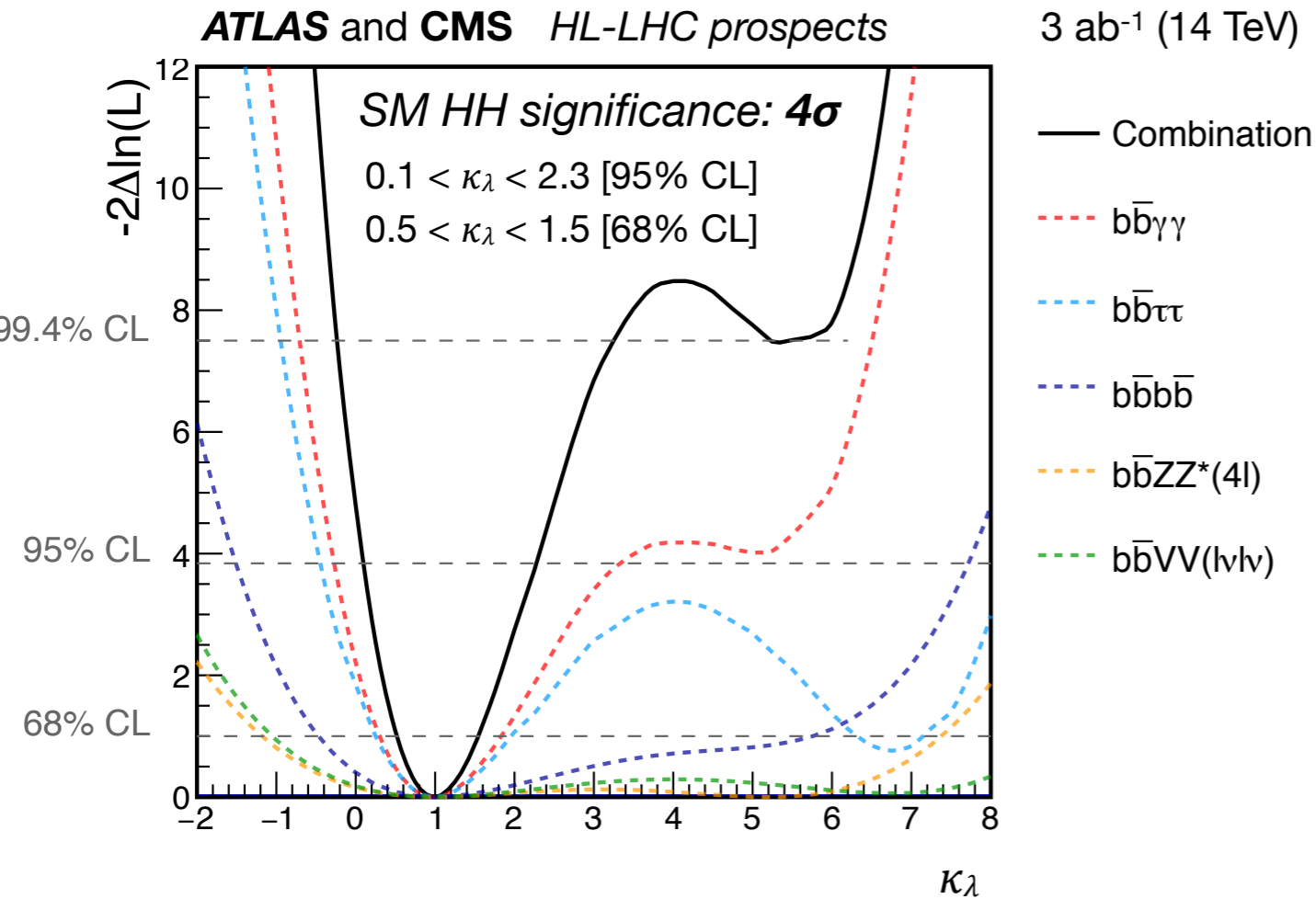
ATL-PHYS-PUB-2022-005  
ATL-PHYS-PUB-2019-006





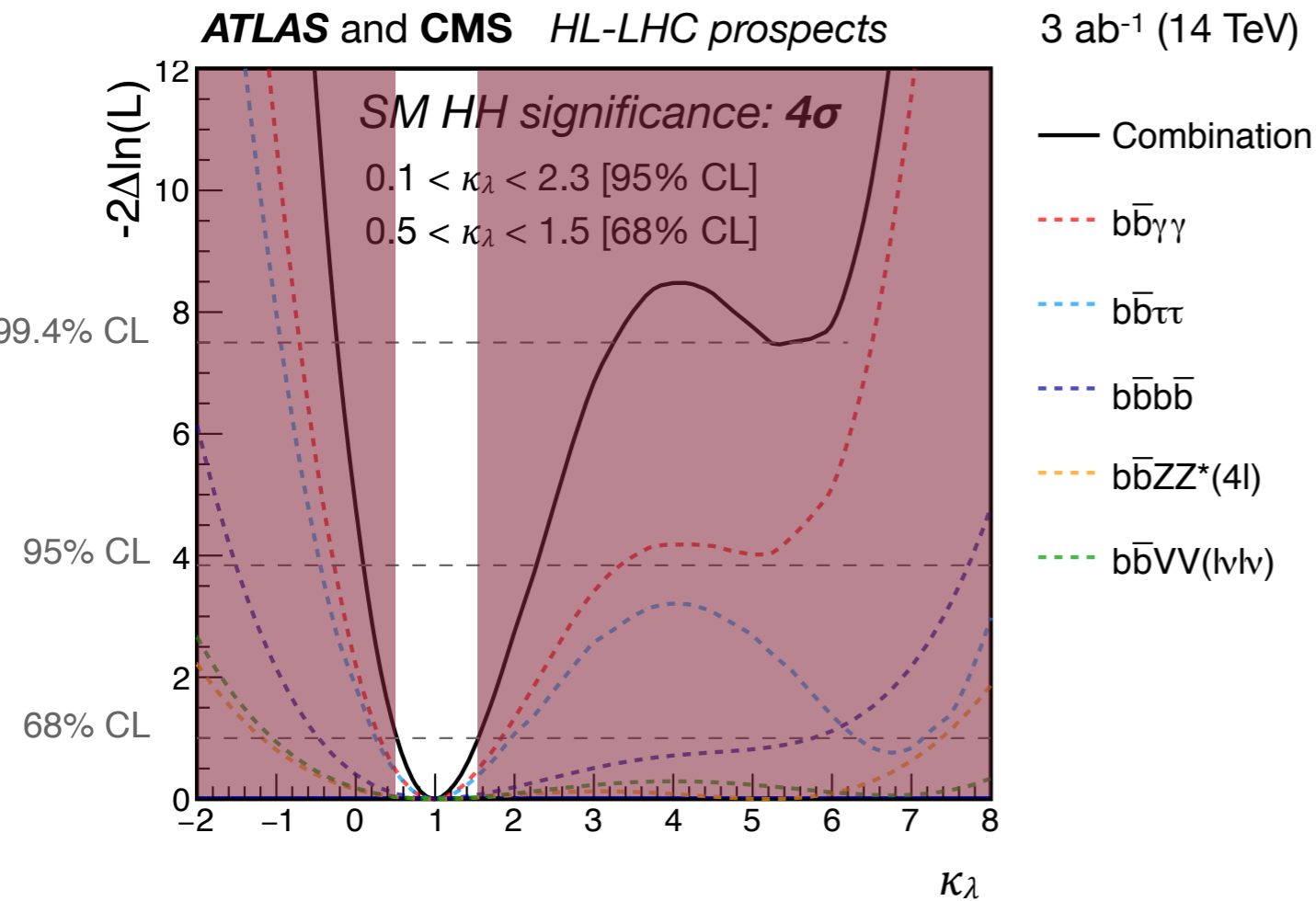


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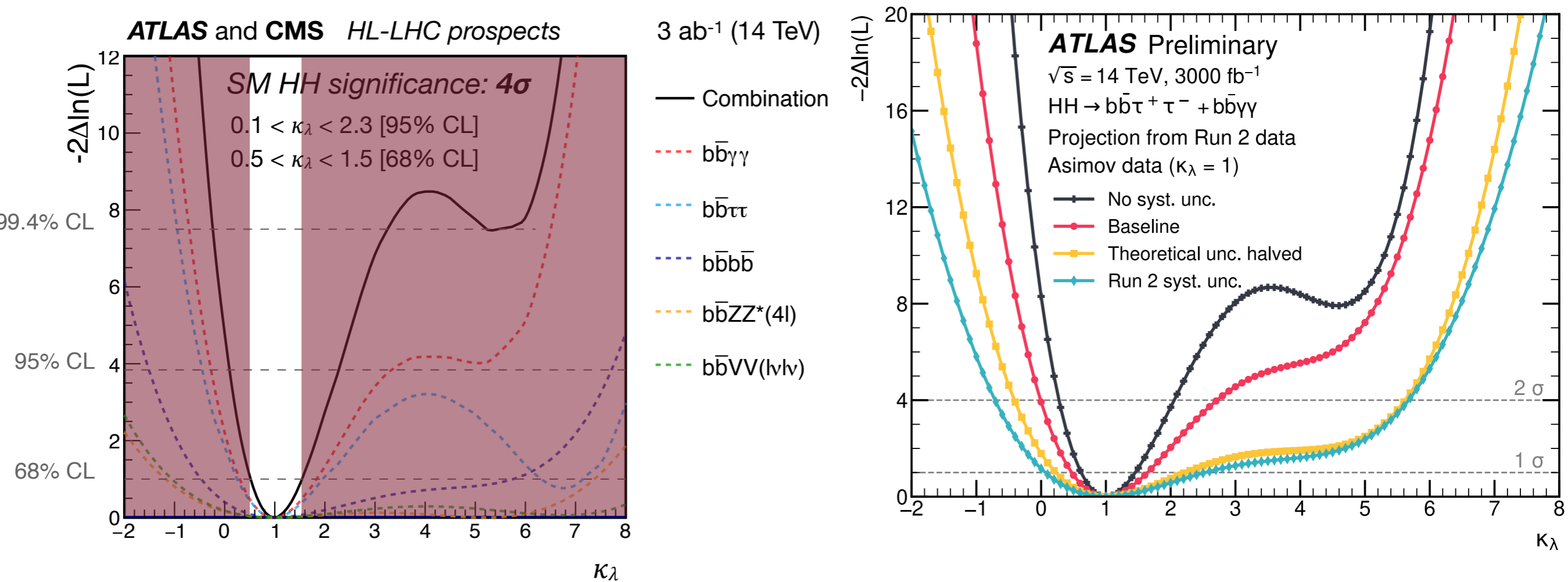
# Self Coupling Projections



Combination of all  
 ATLAS+CMS measurements:  
 $0.5 < \kappa_\lambda < 1.5$  at  $1\sigma$

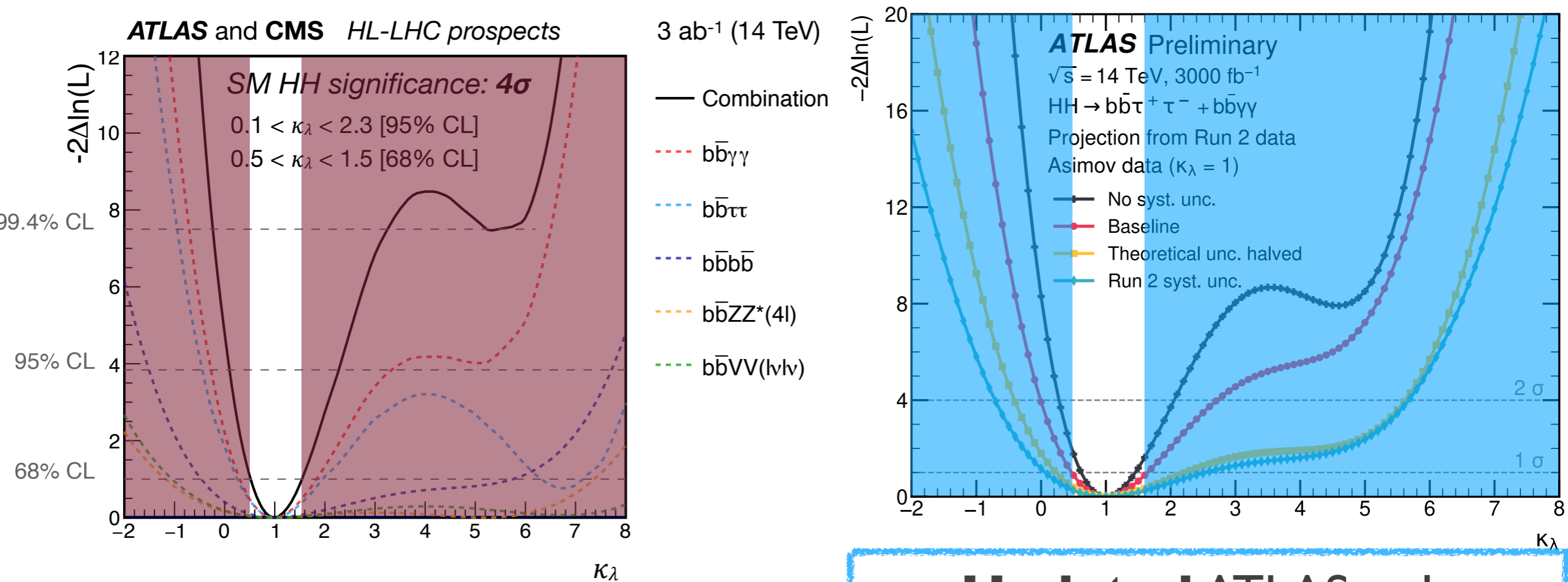


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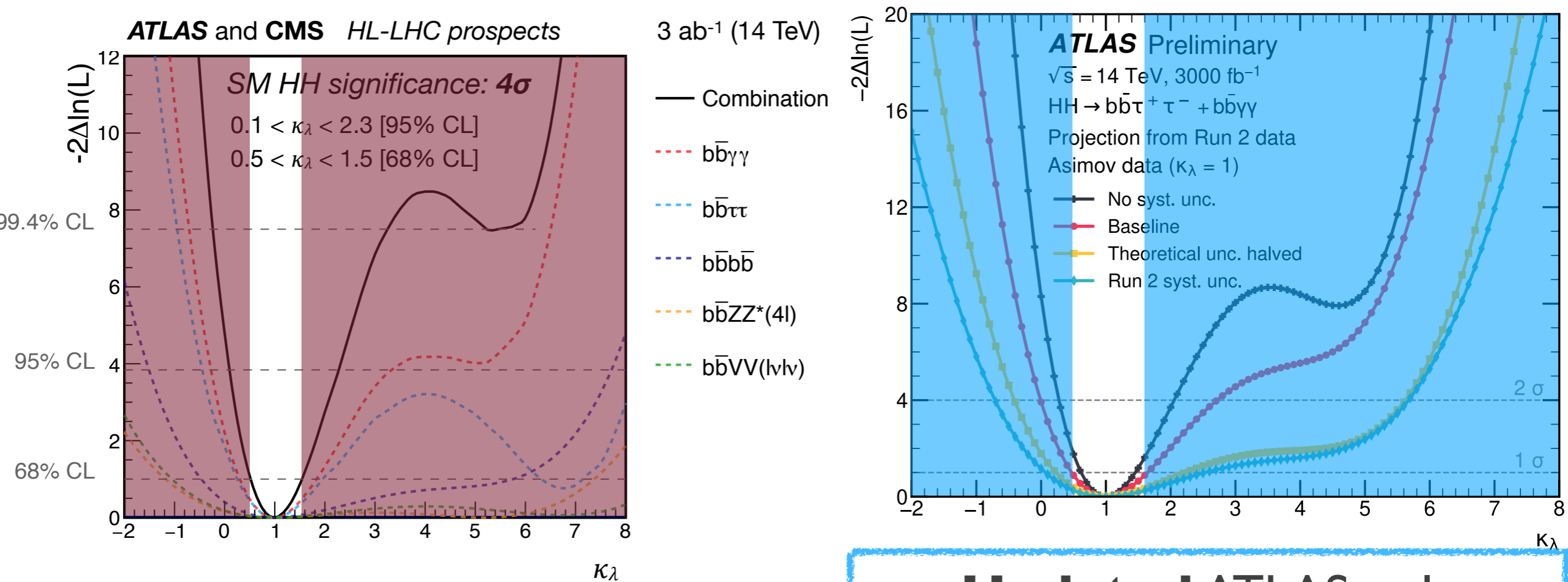


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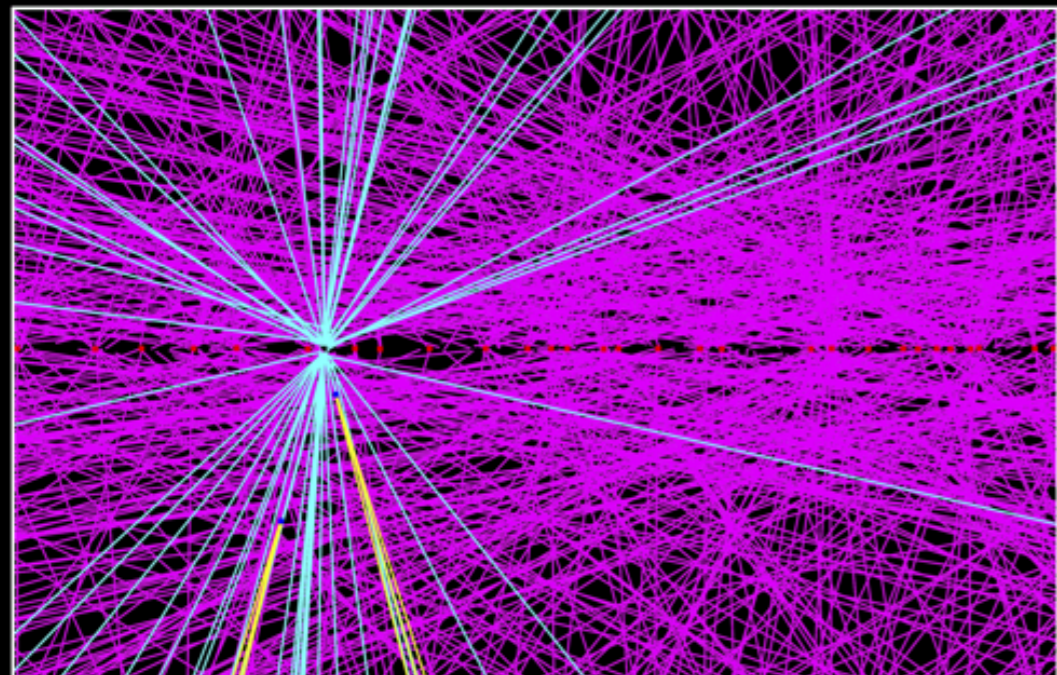
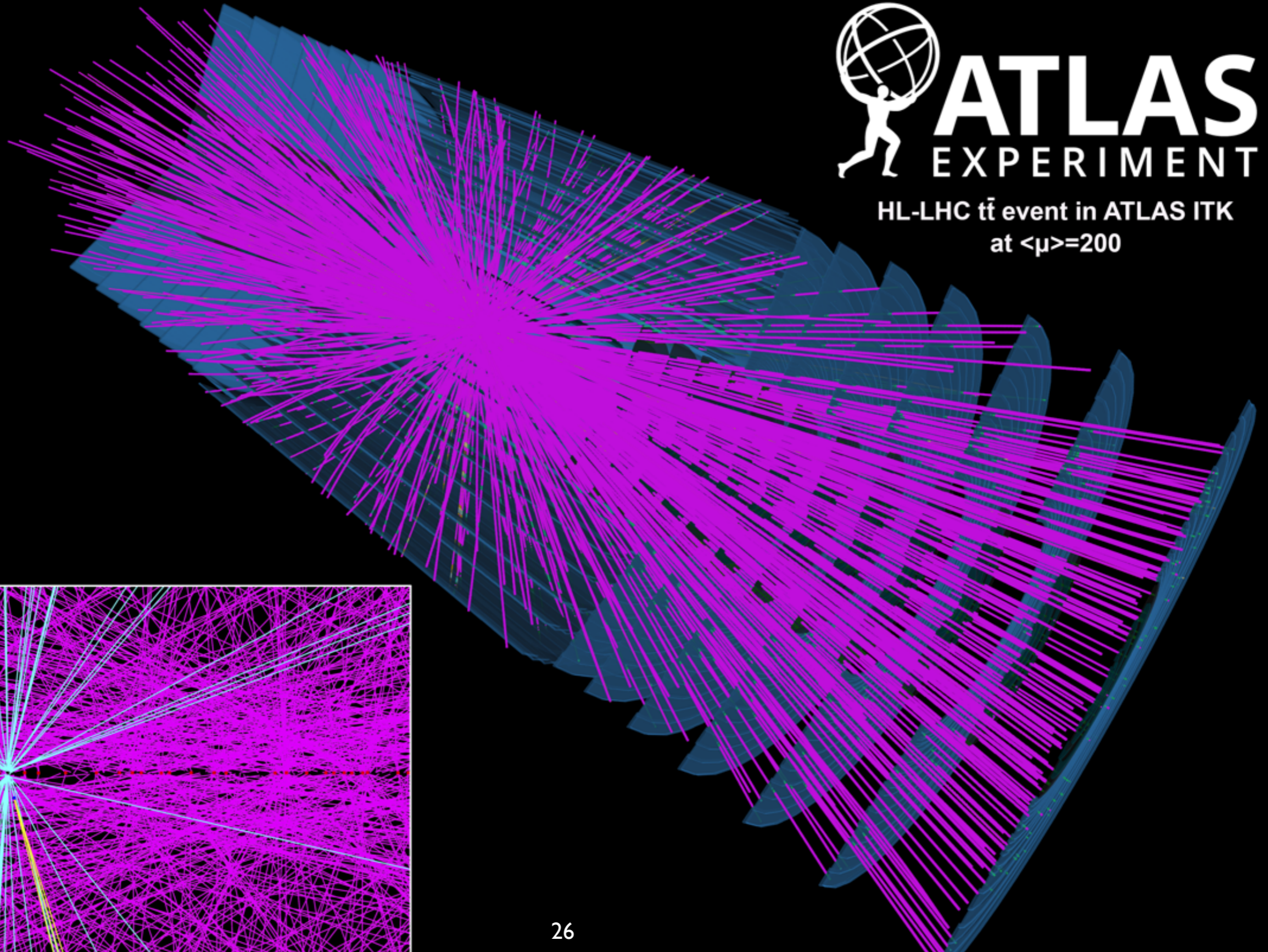
High hopes for even more significant improvements in the future

# Conclusions

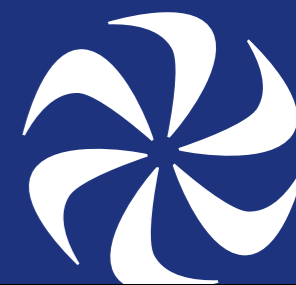
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EXPERIMENT  
HL-LHC  $t\bar{t}$  event in ATLAS ITK  
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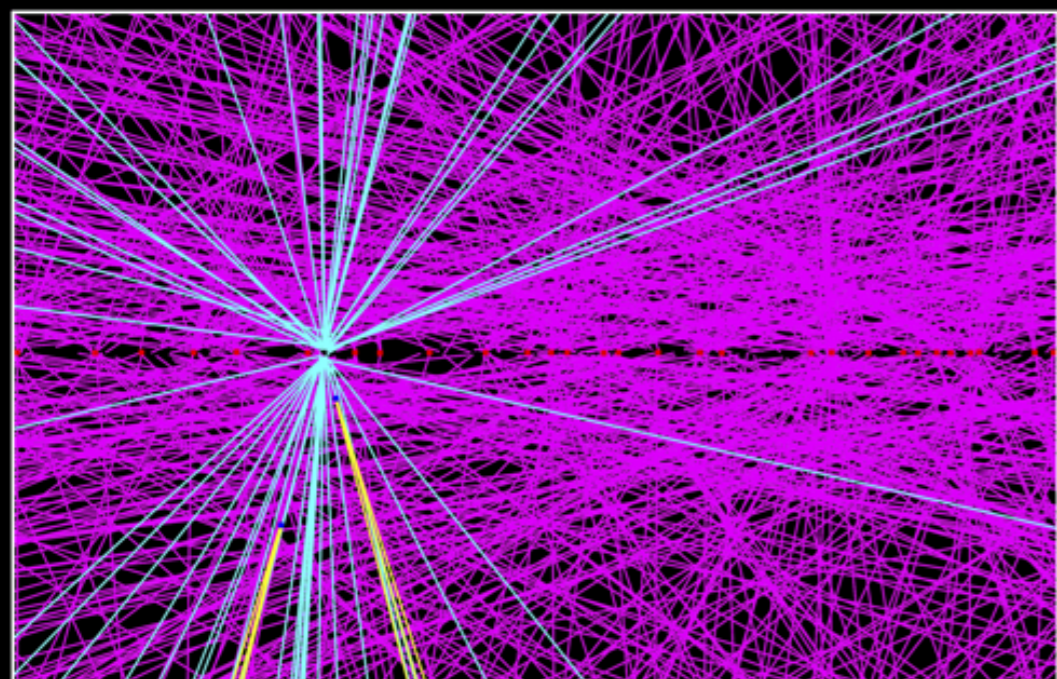


The physics potential of the HL-LHC is enormous!



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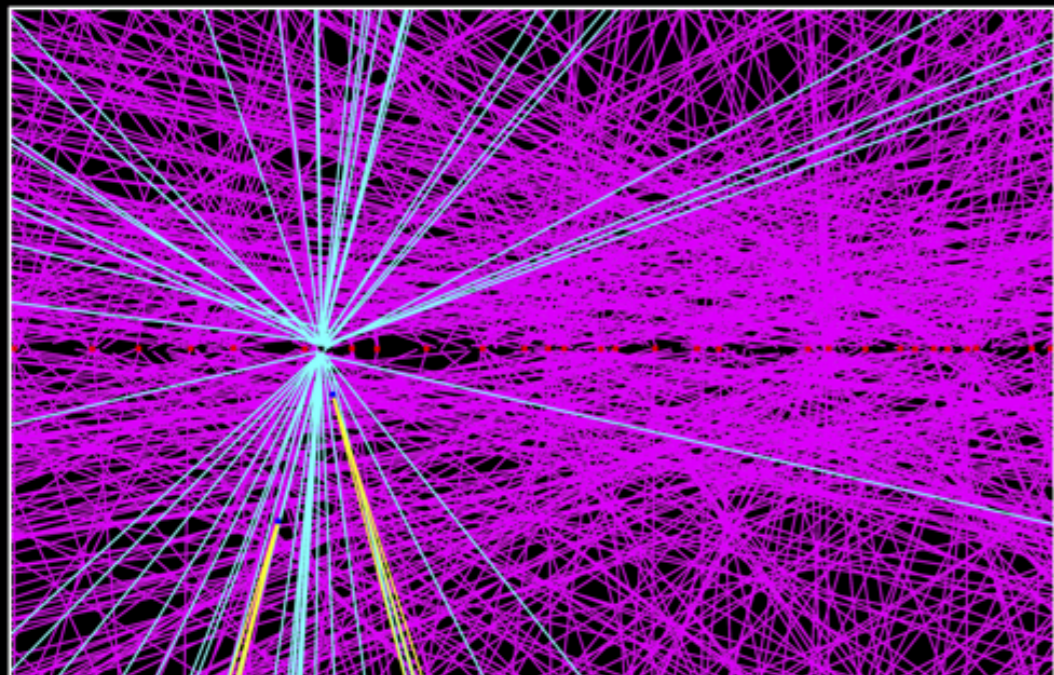
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Upcoming energy increases are small, but huge datasets enable impactful measurements that will be state-of-the-art for many years



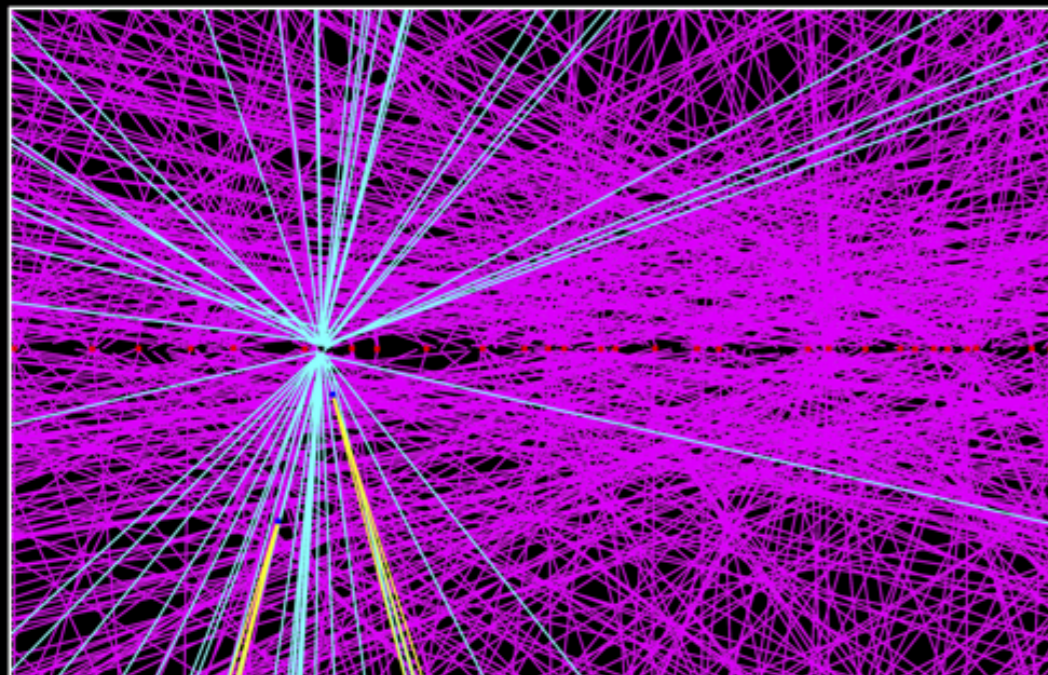
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Creativity has enabled measurements we never thought possible at the LHC already: what else will 20 years bring?

Thank you!