



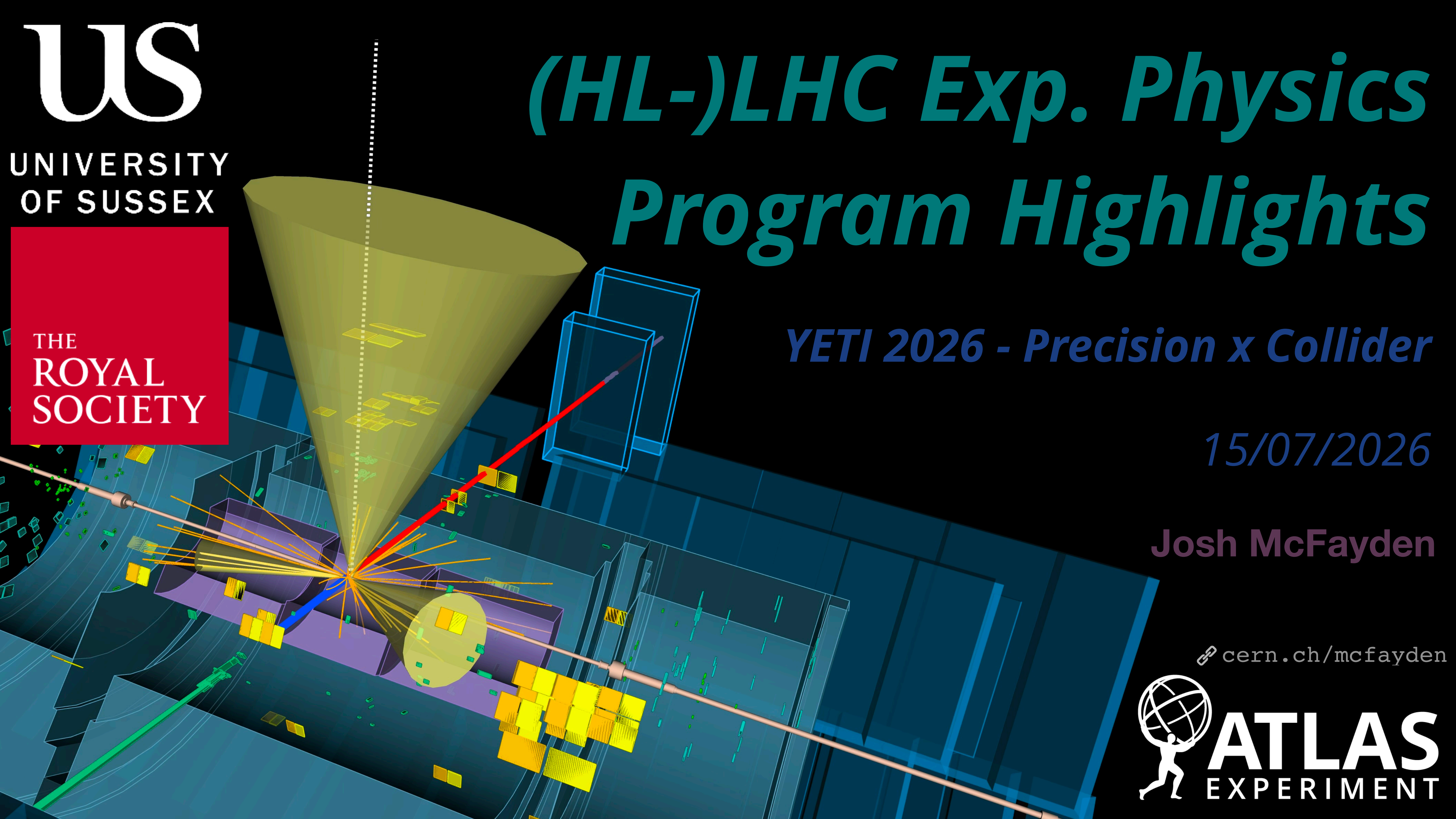
(HL-)LHC Exp. Physics Program Highlights

YETI 2026 - Precision x Collider

15/07/2026

Josh McFayden

cern.ch/mcfayden



Hello! 🖐️

- ▶ I am a Royal Society University Research Fellow at University of Sussex
- ▶ **I have been a member of ATLAS for 15+ years**
 - ▶ Physics analysis on Higgs boson & Top quarks (+ other rare heavy stuff)
 - ▶ Currently ATLAS Top Quark WG convener
- ▶ **Since 2019 I have also worked on the FASER Experiment**
 - ▶ Looking for Dark Matter and measuring the highest energy collider neutrinos



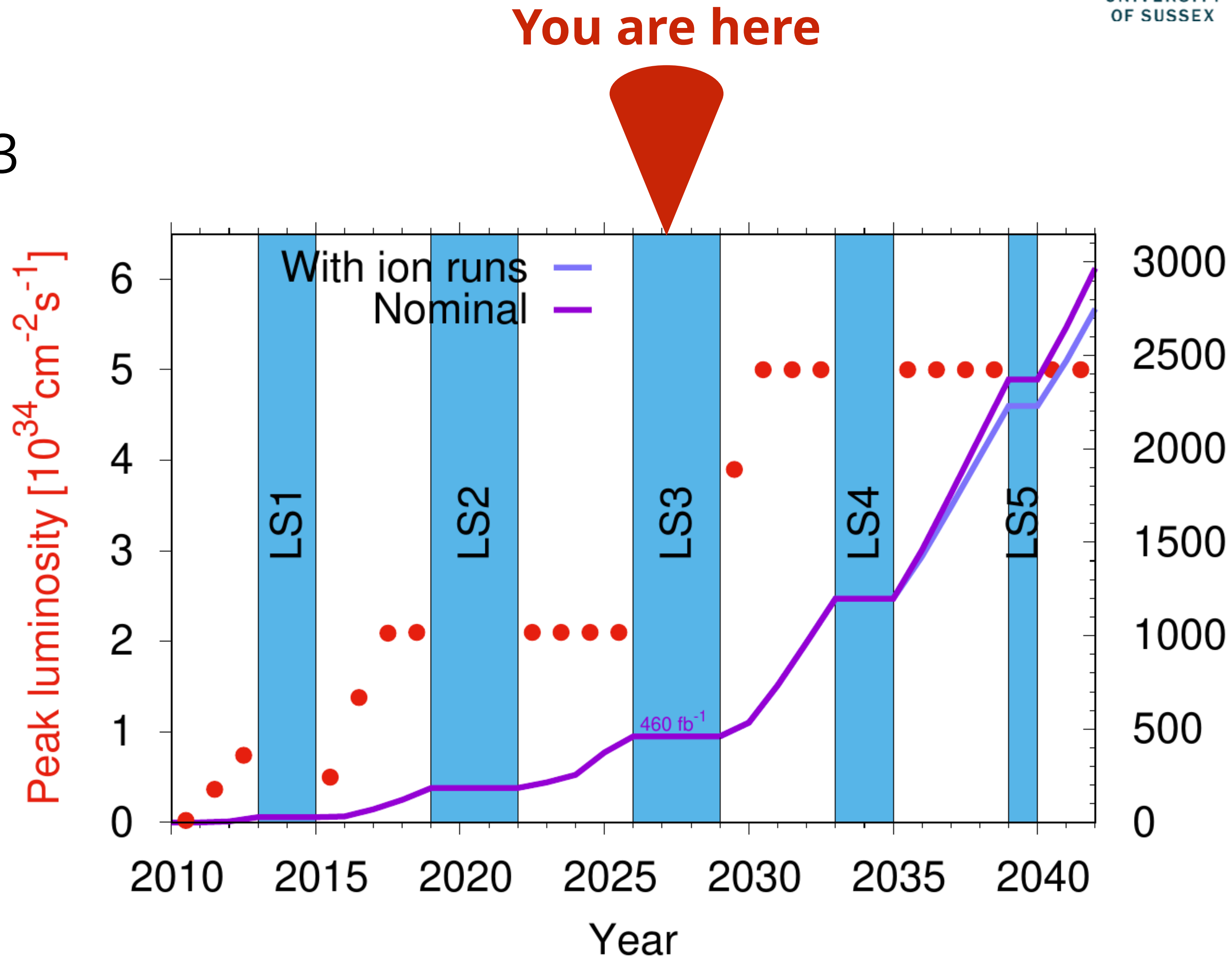
Overview

► Highlights of Run 2 & Run 3

- The price of precision
- Proving the LHC as a precision machine
- The LHC beyond design

► Highlights of the HL-LHC programme

- HL-LHC upgrades
- A physics programme for two decades



Open questions/ key goals of (HL-)LHC



Open questions

Open question	Why it matters	How HL-LHC contributes
Is there physics beyond the Standard Model?	The Standard Model is incomplete!	Precision measurements and direct searches up to several-TeV masses.

Open questions

Open question	Why it matters	How HL-LHC contributes
Is there more to the Higgs boson?	It is the only known elementary scalar particle and not yet precisely measured	Measure Higgs couplings to percent precision & probe self-interactions
What makes the top quark unique?	Largest Yukawa coupling and may be closely connected to electroweak symmetry breaking.	Precision top measurements, rare processes, and EFT constraints.
What is dark matter?	We think about 85% of matter is dark.	Search for dark matter production and dark-sector mediators.
Why more matter than antimatter?	CP violation in the Standard Model is insufficient.	Measure CP-violating interactions at highest yet precision
Is the electroweak vacuum stable?	Determines the long-term fate of our Universe (or hints of high scale NP)	Improve of Higgs & top measurements relevant to vacuum stability.

Open questions

Which questions is the HL-LHC most likely to answer?

Some are realistic targets for the HL-LHC, while others are less likely to be resolved outright:

Question	Chance of major progress
Higgs couplings	★★★★★
Higgs self-coupling	★★★★★
Top quark interactions	★★★★★
Effective Field Theory constraints	★★★★★
Long-lived particles	★★★★☆
Dark matter mediators	★★★★☆
Heavy new particles	★★★☆☆
Electroweak phase transition	★★★☆☆
Origin of neutrino masses	★★☆☆☆
Grand unification	★☆☆☆☆
Quantum gravity	☆☆☆☆☆

Highlights of the Run 3/HL-LHC Experimental Physics Program

Highlights of the Run 2 & 3 $\sqrt{s}=13$ TeV Experimental Physics Program

The price of precision



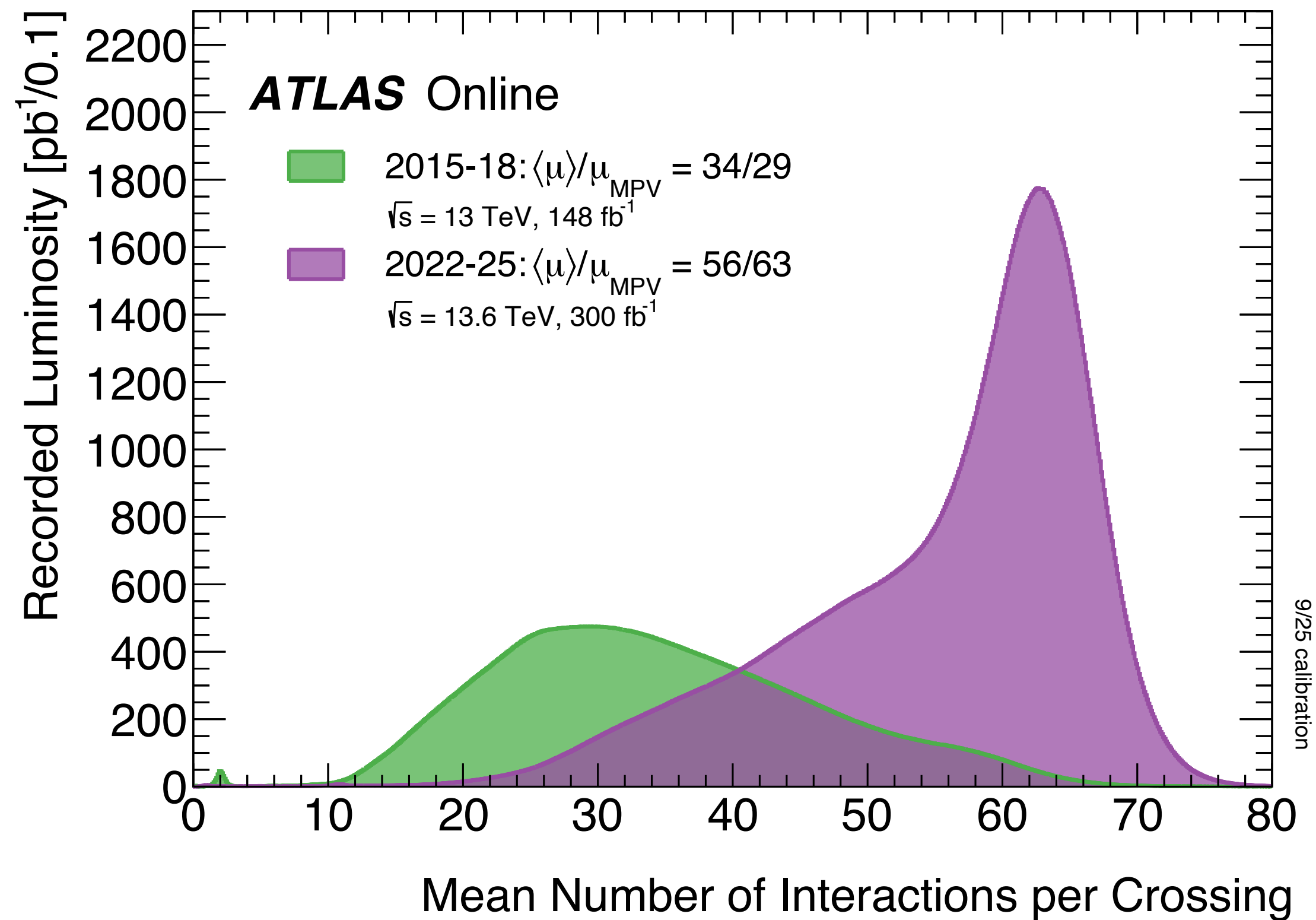
The price of precision

Hydration breaks?

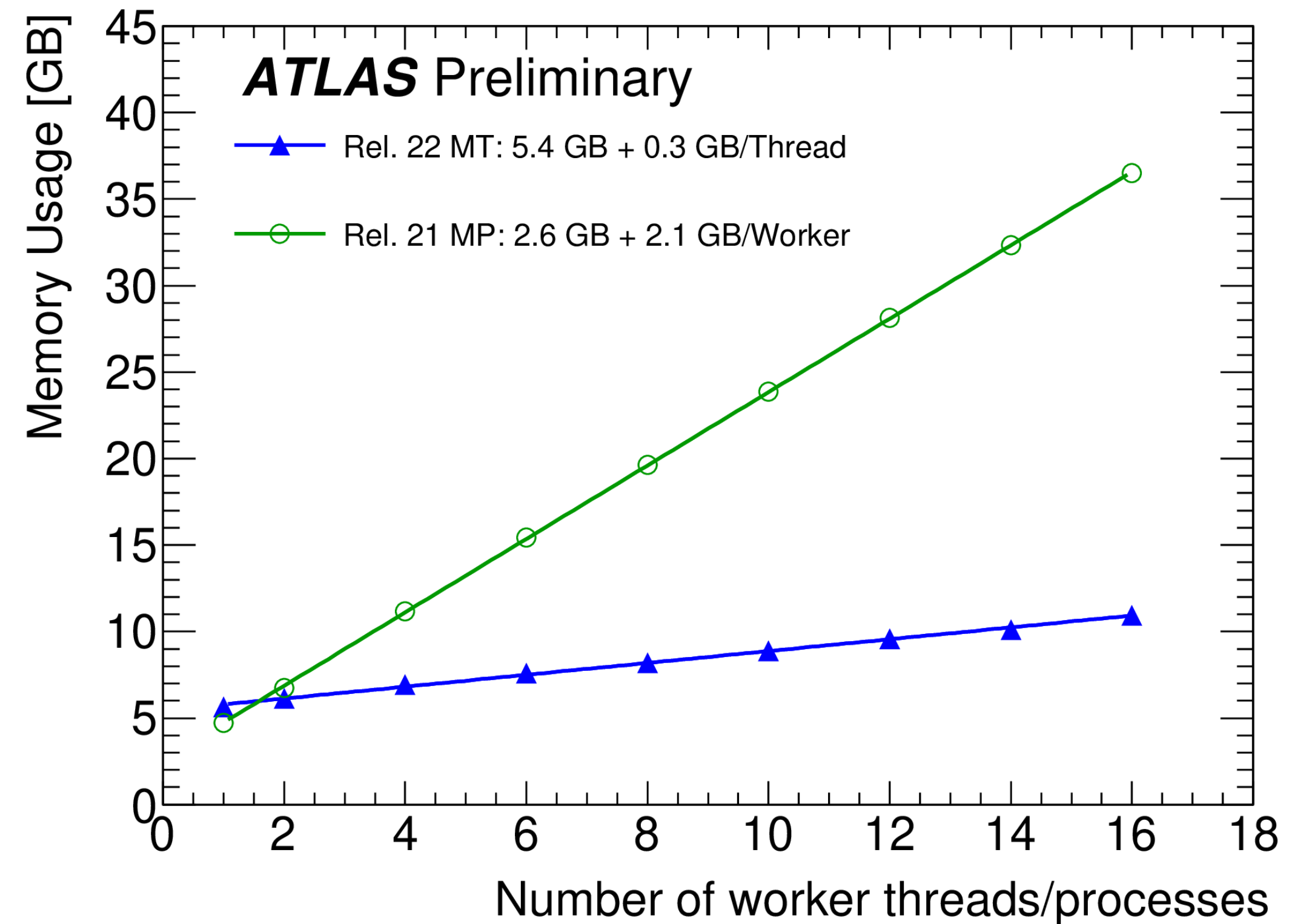


The price of precision

► A challenging environment...



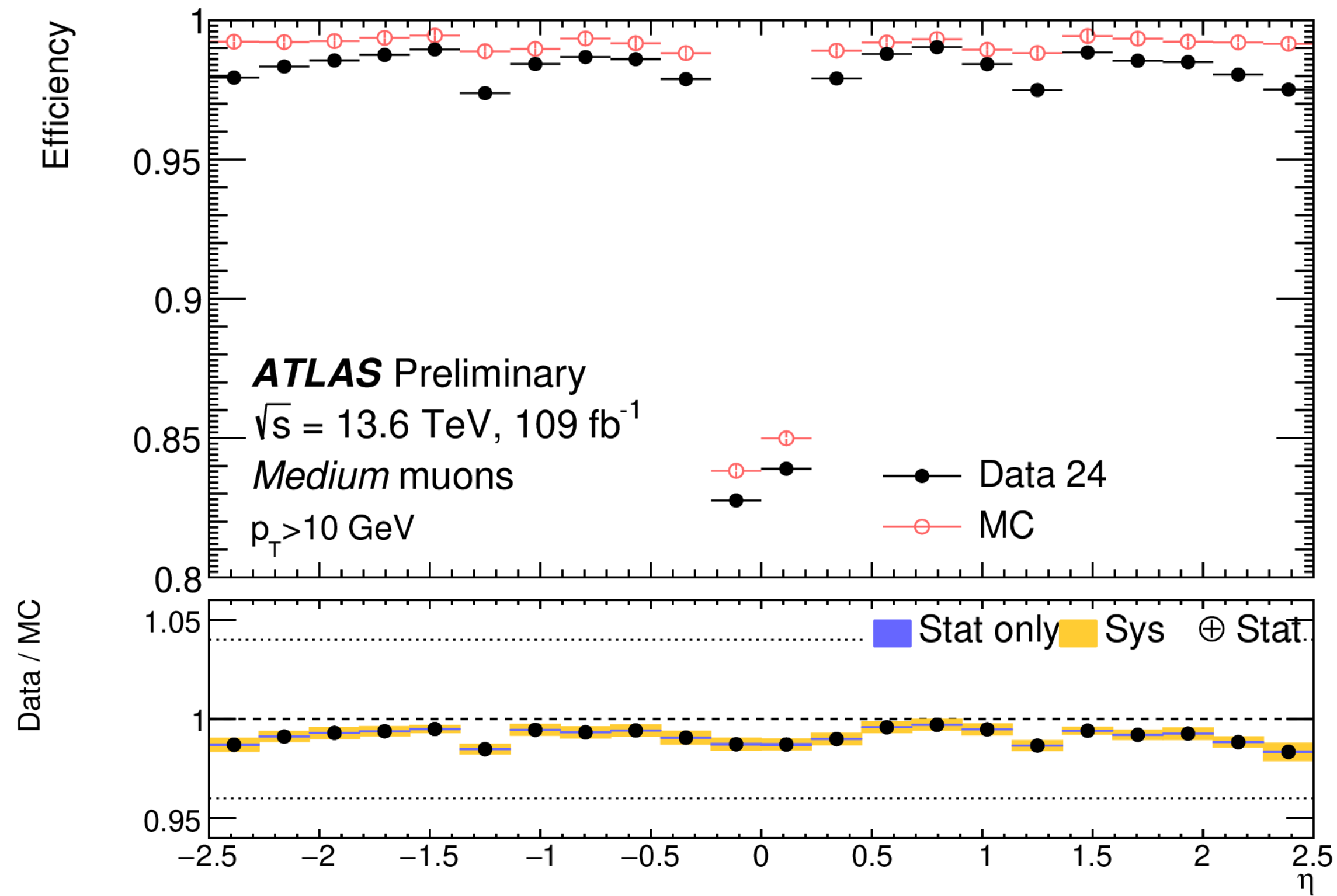
LuminosityPublicResultsRun3



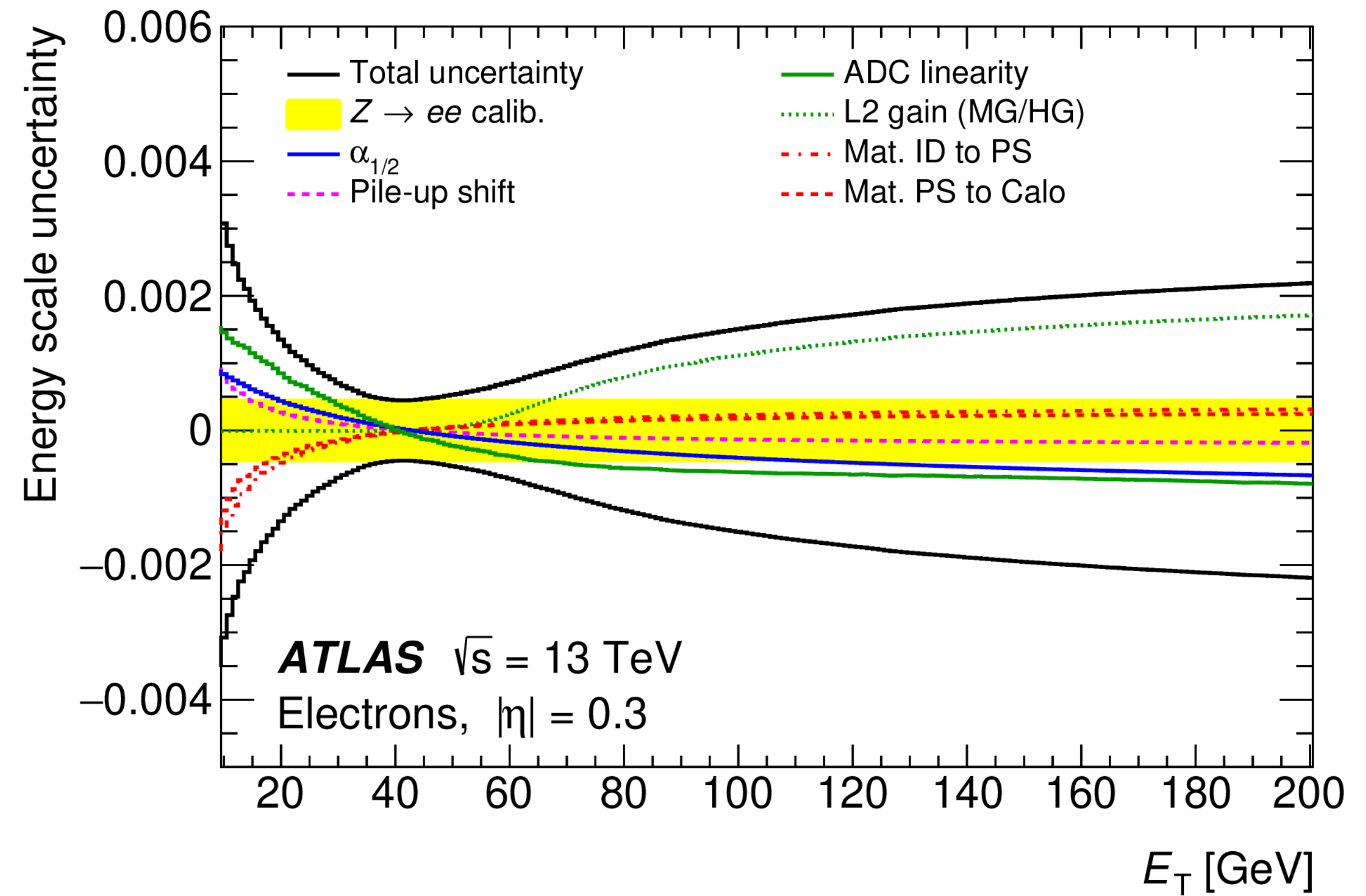
ATL-SOFT-PUB-2021-002

The price of precision

► Precision object calibrations



MUON-2025-03

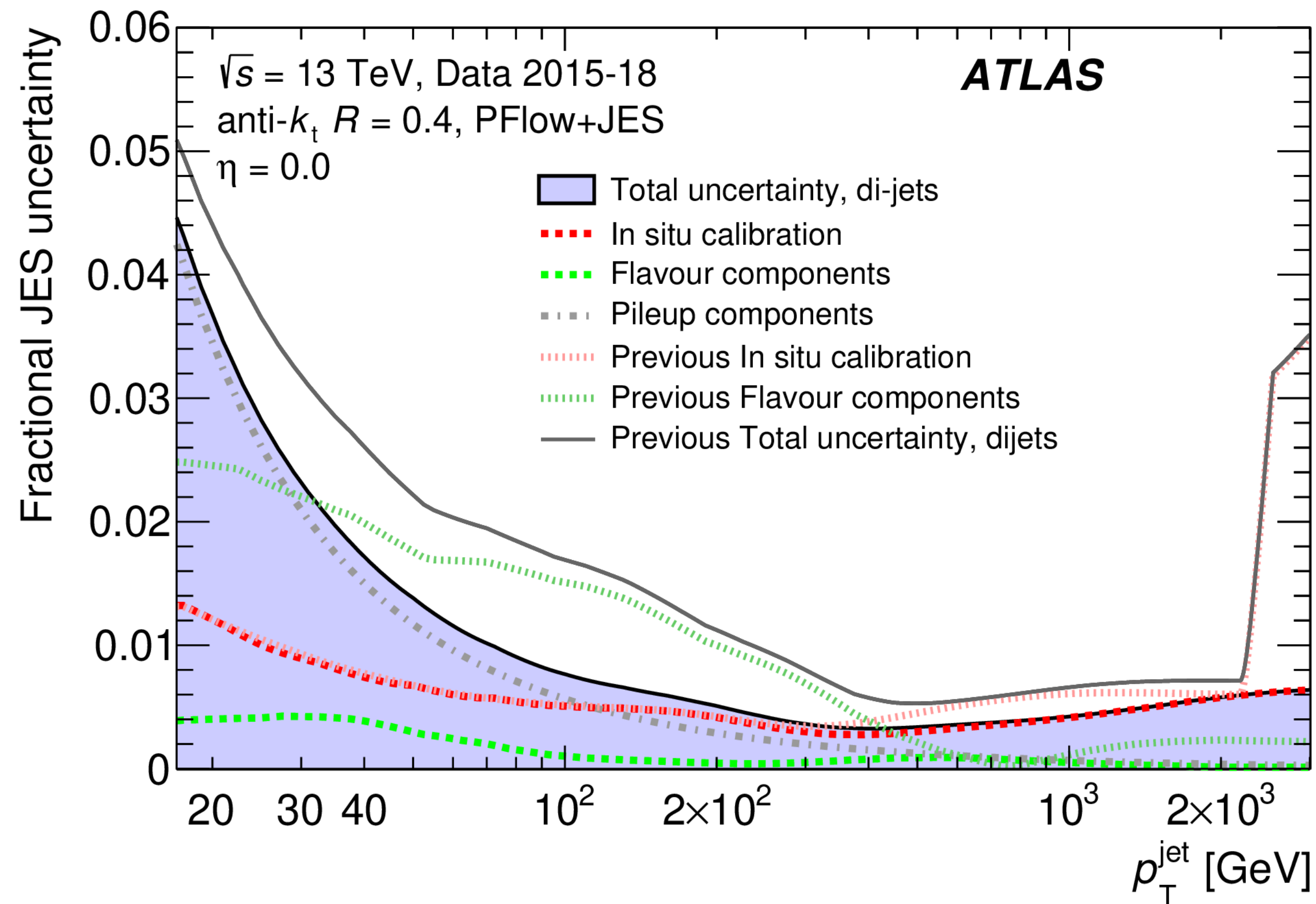


EGAM-2021-02

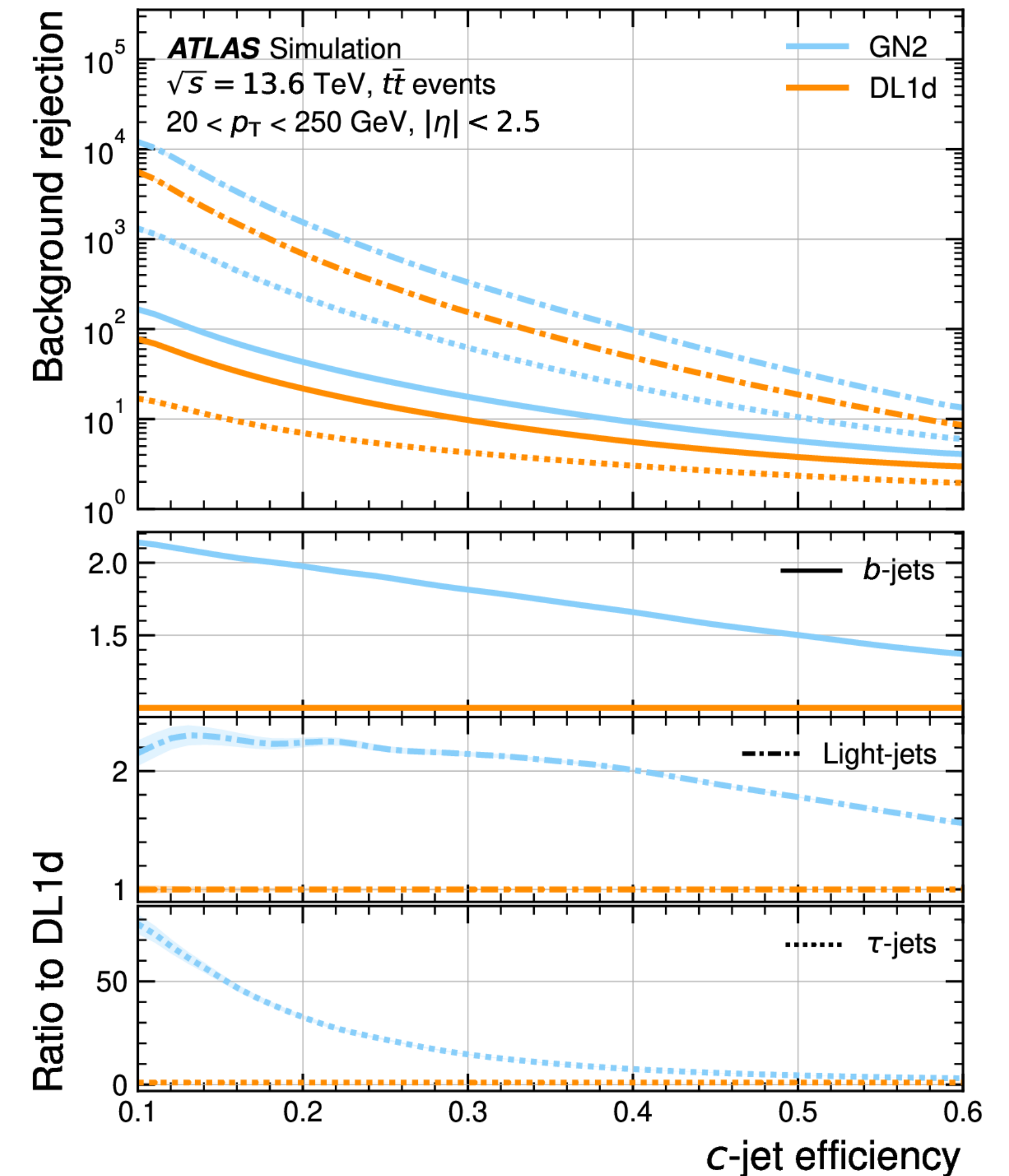
The price of precision

- Many improvements through Run 2 and Run 3

FTAG-2023-05



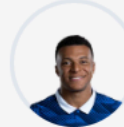
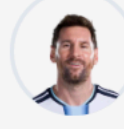
JETM-2022-06



Proving the LHC as a precision machine

Proving the LHC as a precision machine

The power rankings

Rank		Player	
1	0		Kilian MBAPPE  France
2	0		Jude BELLINGHAM  England
3	0		Lionel MESSI  Argentina
4	0		Erling HAALAND  Norway

Proving the LHC as a precision machine

► Run 2 (139 fb^{-1})

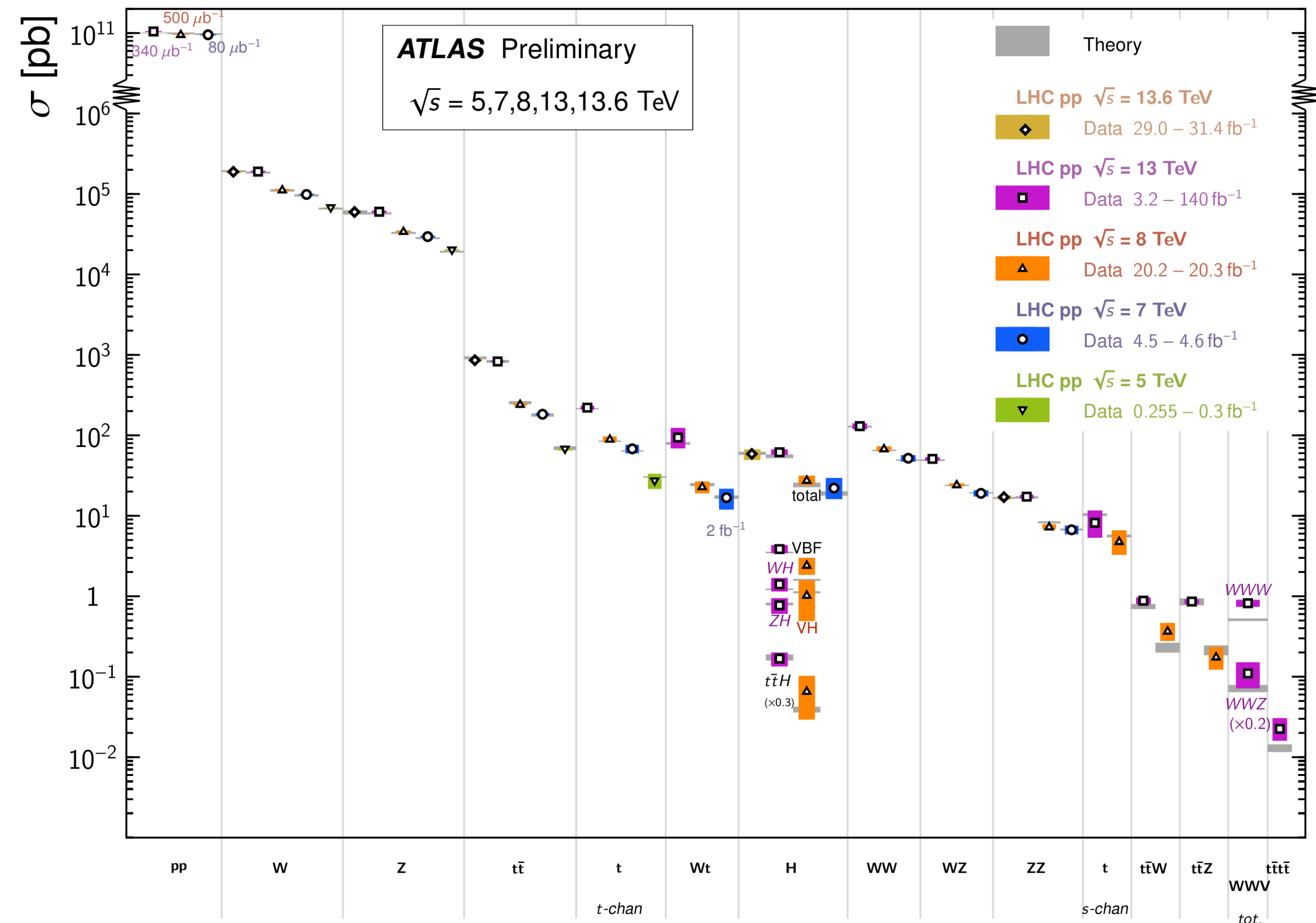
- 8 million Higgs bosons
- 100 million top quark pairs
- 30 trillion W bosons
- 8 trillion Z bosons

► Run 3 ($\sim 300 \text{ fb}^{-1}$)

- 17 million Higgs bosons
- 250 million top quark pairs
- 60 trillion W bosons
- 20 trillion Z bosons

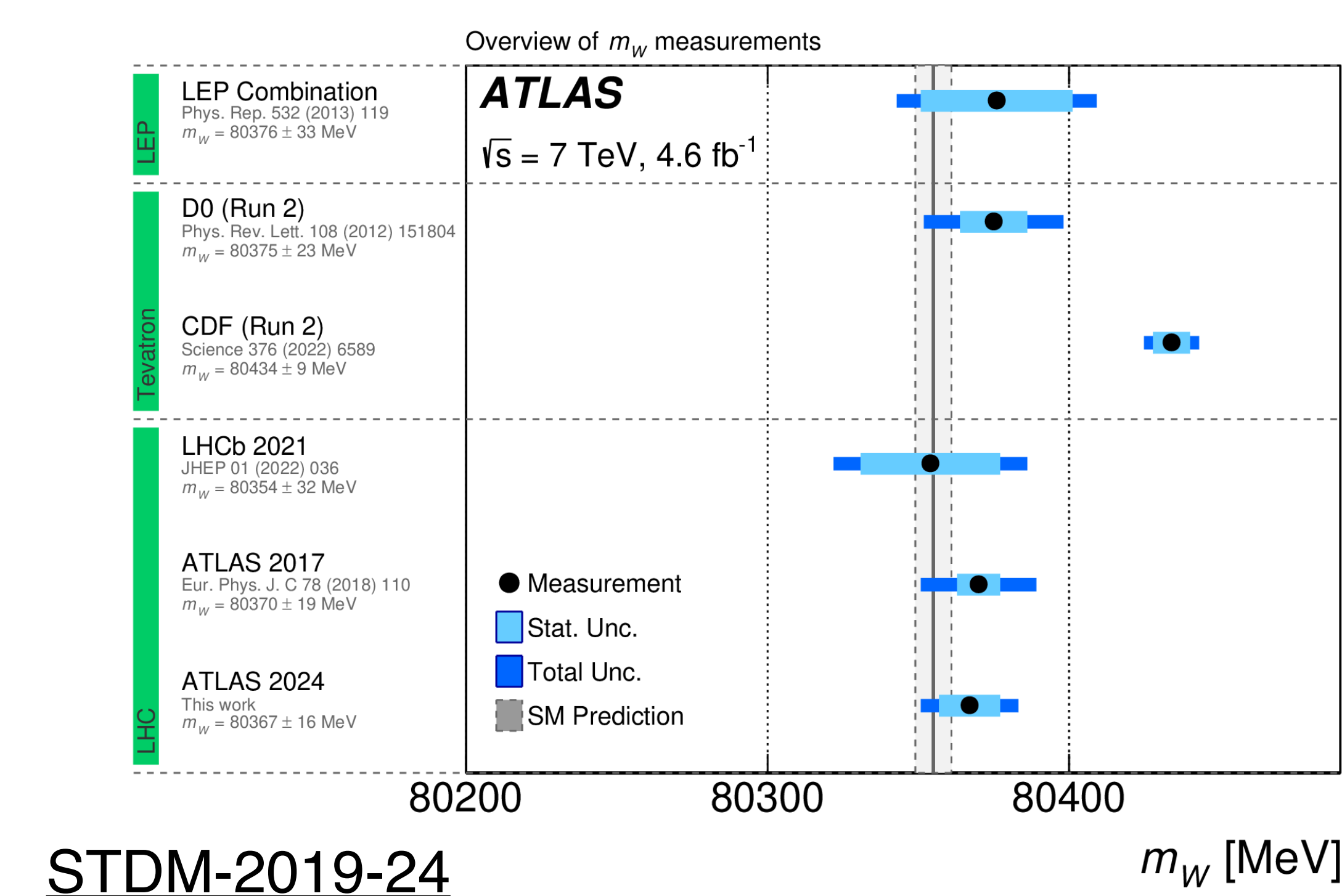
Standard Model Total Production Cross Section Measurements

Status: June 2024

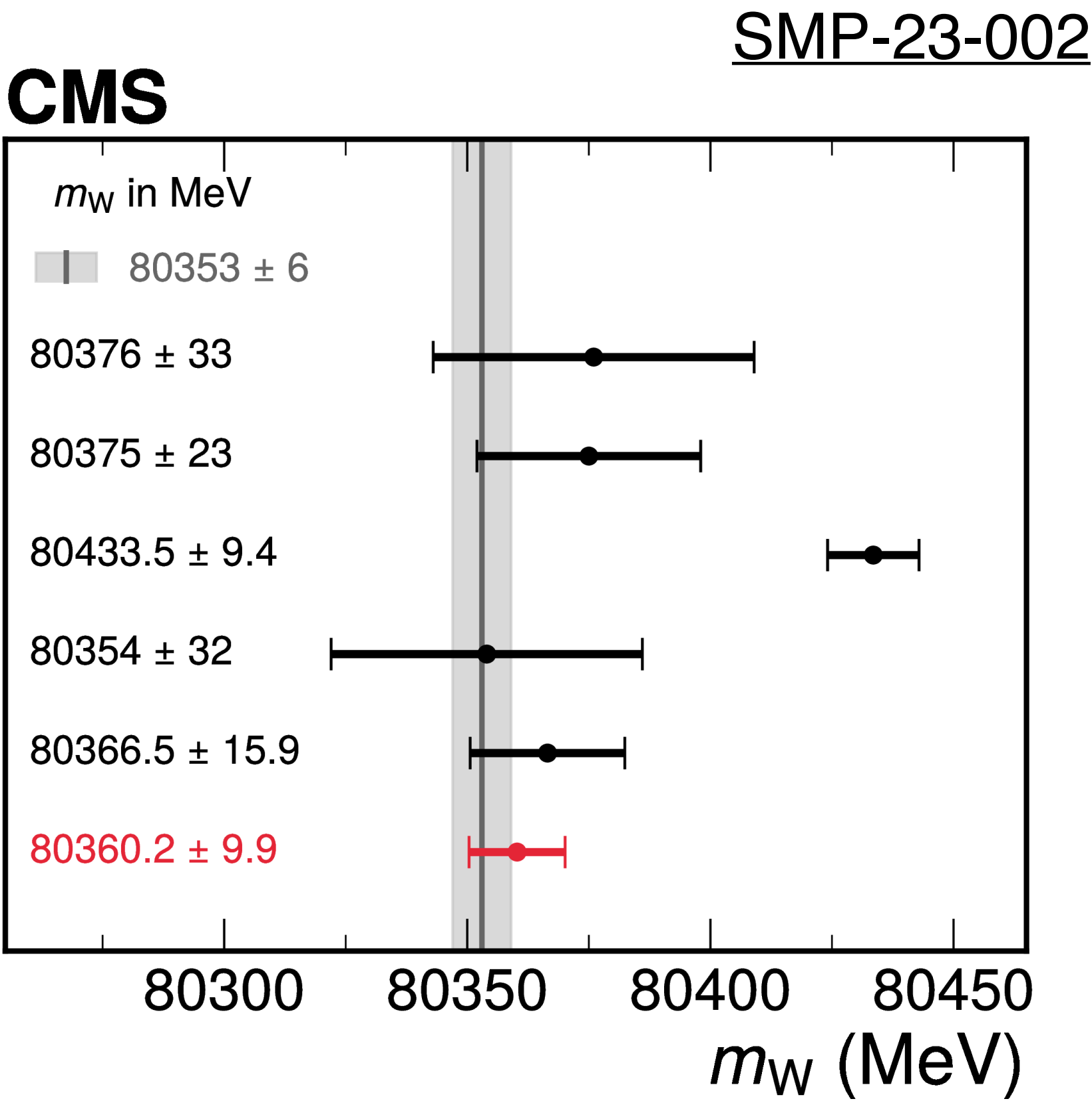


Proving the LHC as a precision machine

► The LHC is now more precise than LEP!



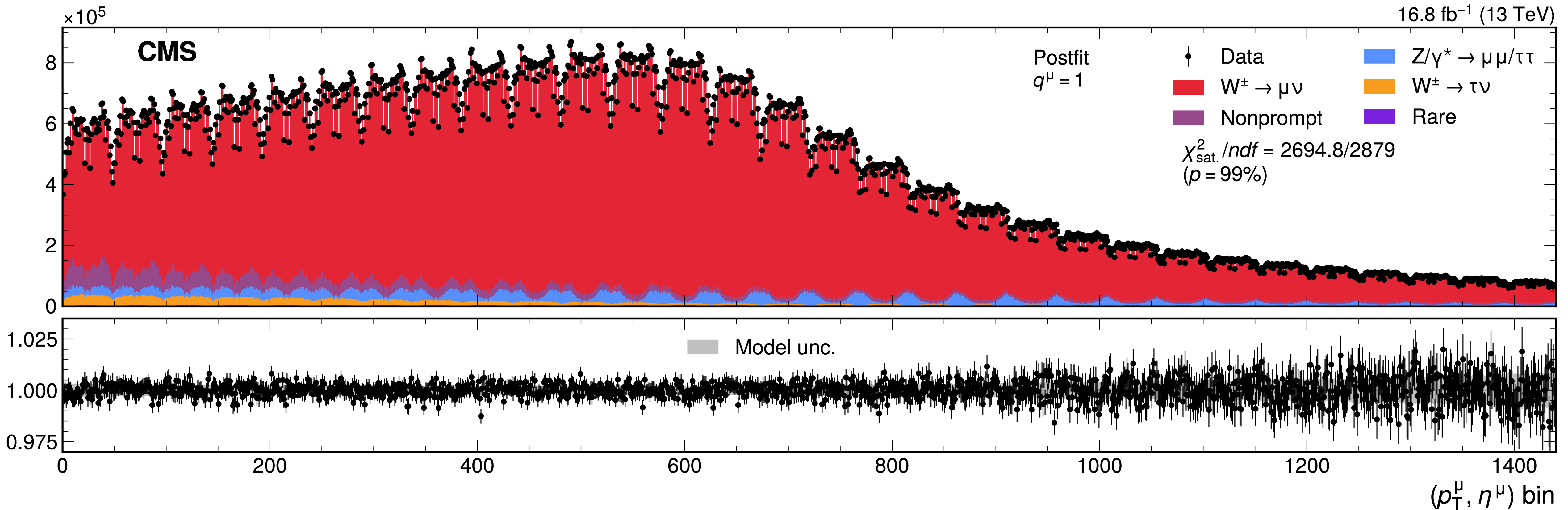
Electroweak fit
PRD 110 (2024) 030001
LEP combination
Phys. Rep. 532 (2013) 119
D0
PRL 108 (2012) 151804
CDF
Science 376 (2022) 6589
LHCb
JHEP 01 (2022) 036
ATLAS
EPJC 84 (2024) 1309
CMS
This work



► But sadly not the EW fits...

Proving the LHC as a precision machine

► Phenomenal precision and complexity

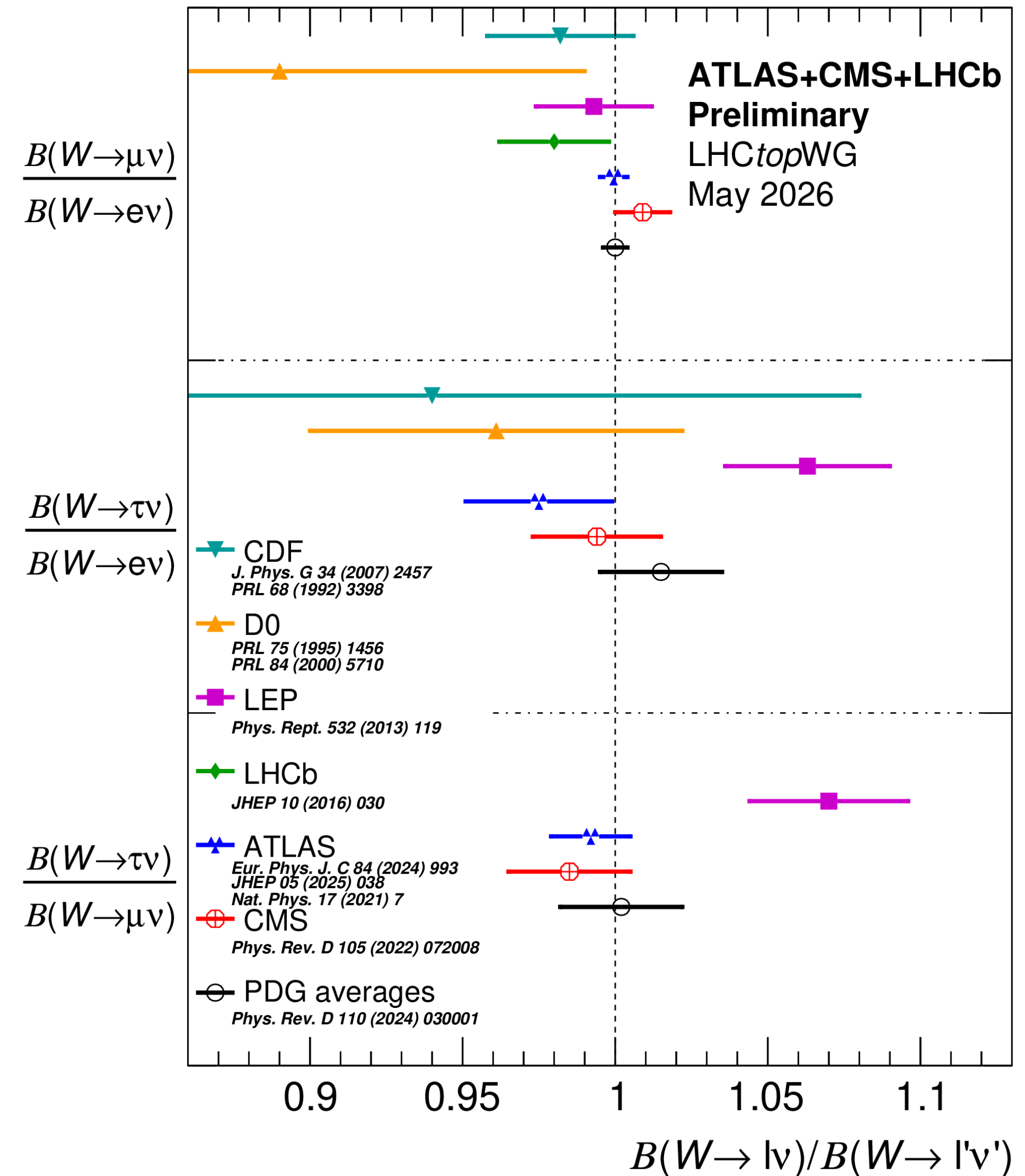


► Approximately 3000 bins and 4000 nuisance parameters!

SMP-23-002

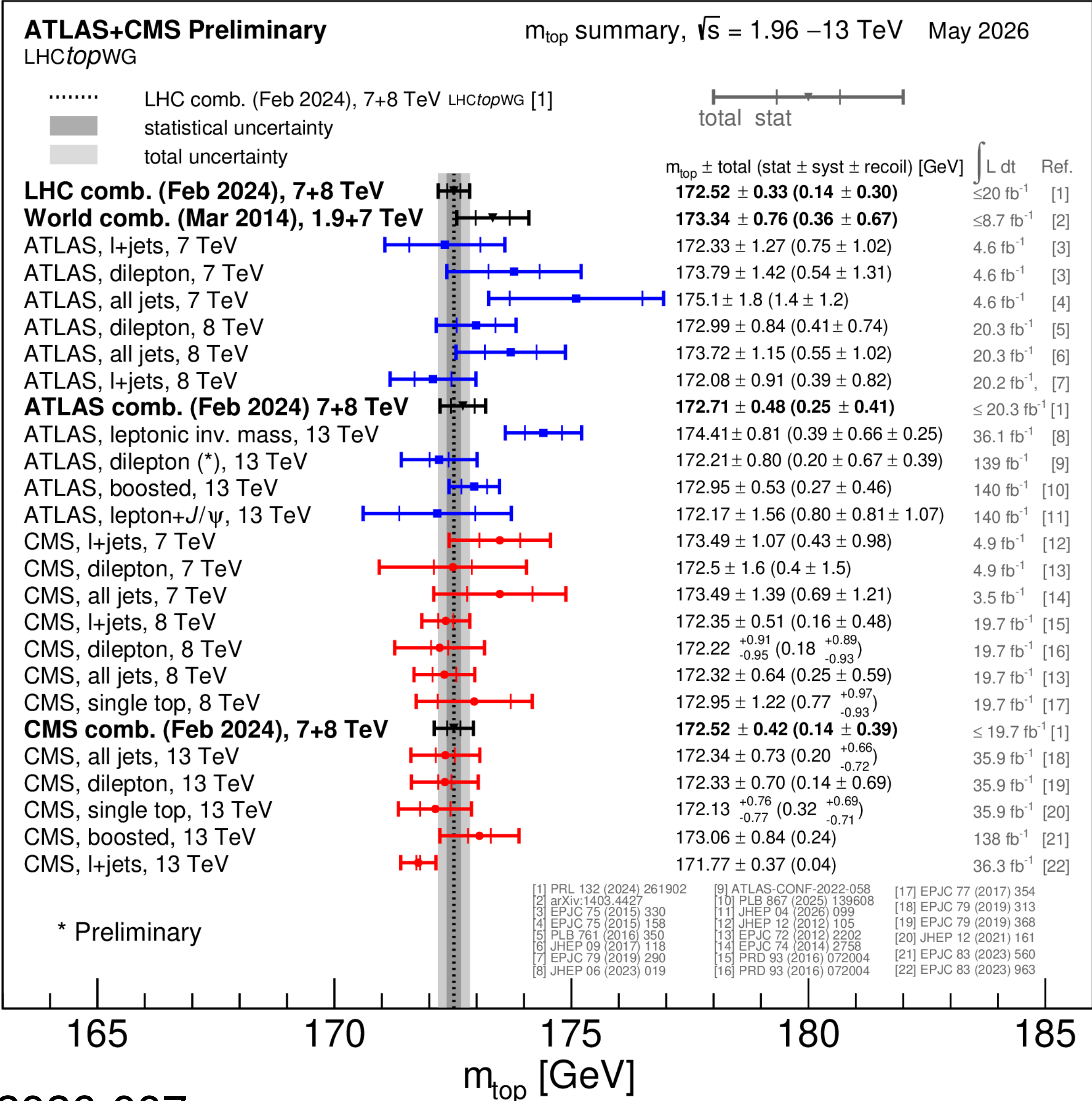
Proving the LHC as a precision machine

- ▶ LHC is a standard candle factory
 - ▶ W-factory
 - ▶ Z-factory
 - ▶ Top-factory (= W-factory)
- ▶ LHC able to probe EW precision in places never expected



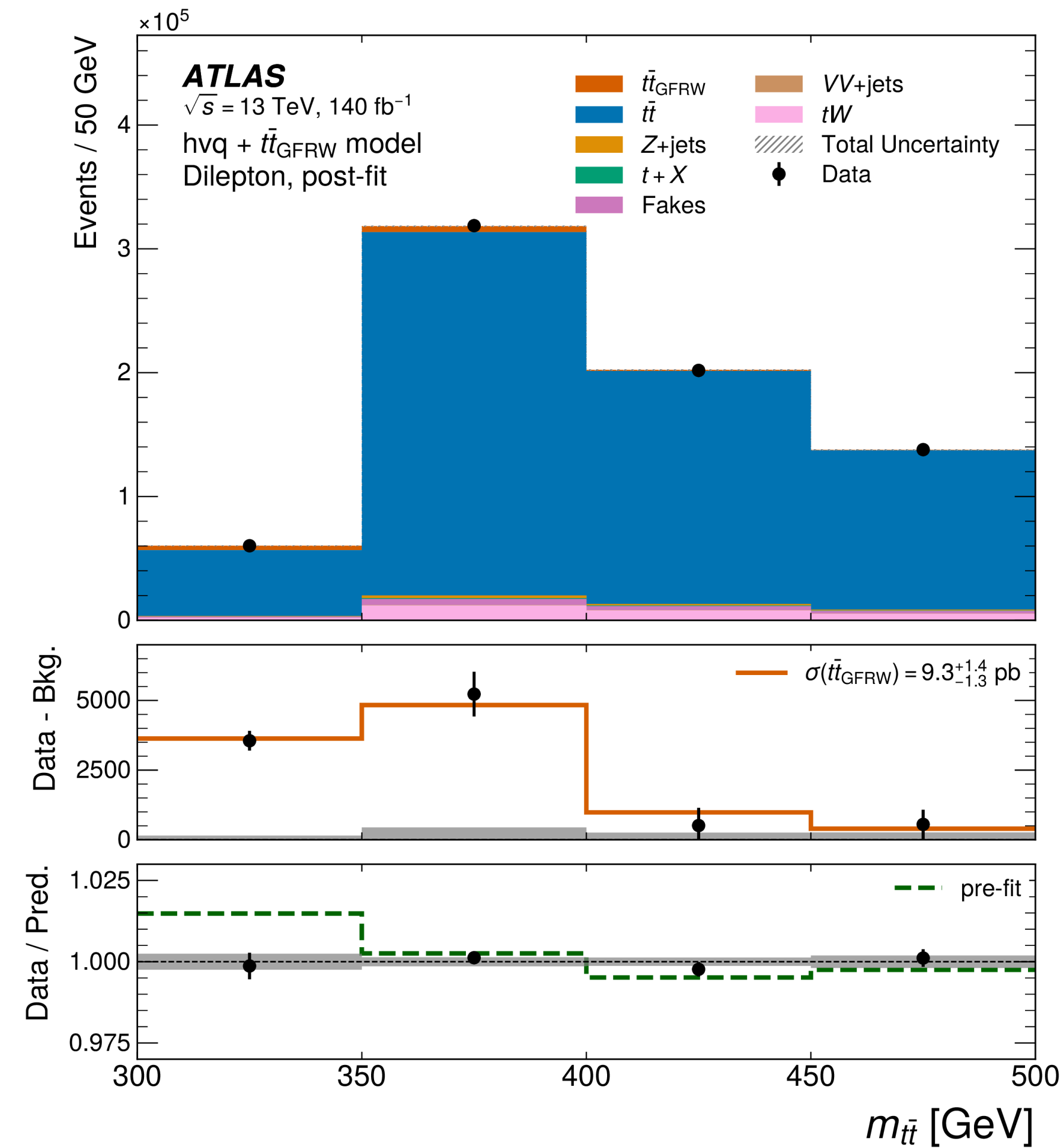
Proving the LHC as a precision machine

- ▶ Top quark factory
 - ▶ Wide-ranging program of top mass measurements
- ▶ LHC Comb - $\Delta m_t=330$ MeV
- ▶ More recent CMS profiled measurement - $\Delta m_t=370$ MeV

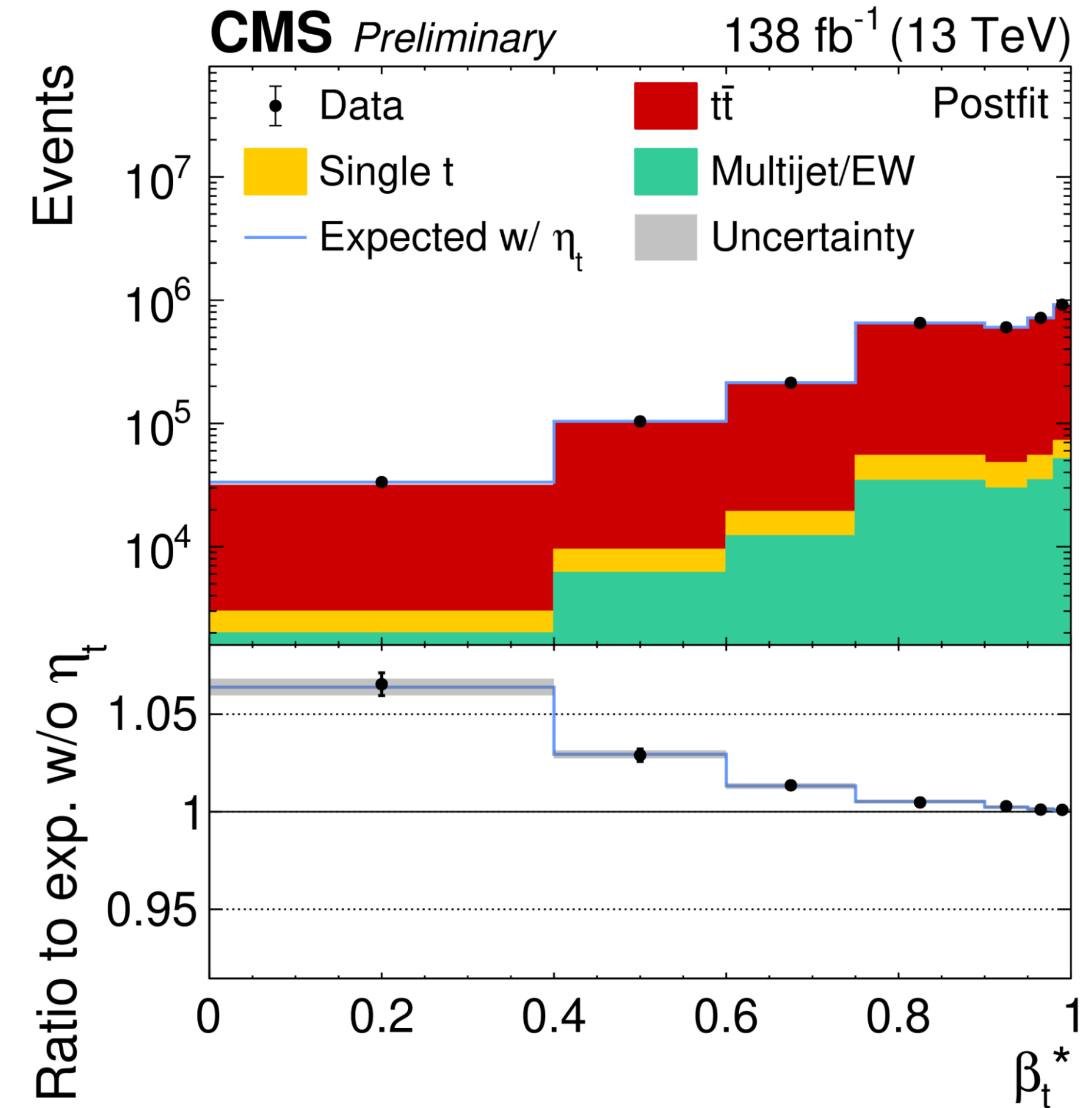


Proving the LHC as a precision machine

- ▶ Even sensitive to “*Elusive romances*”
- ▶ See [link](#)
- ▶ Pseudobound state threshold production aka “*toponium*”
- ▶ A percent-level effect on huge $t\bar{t}$ background



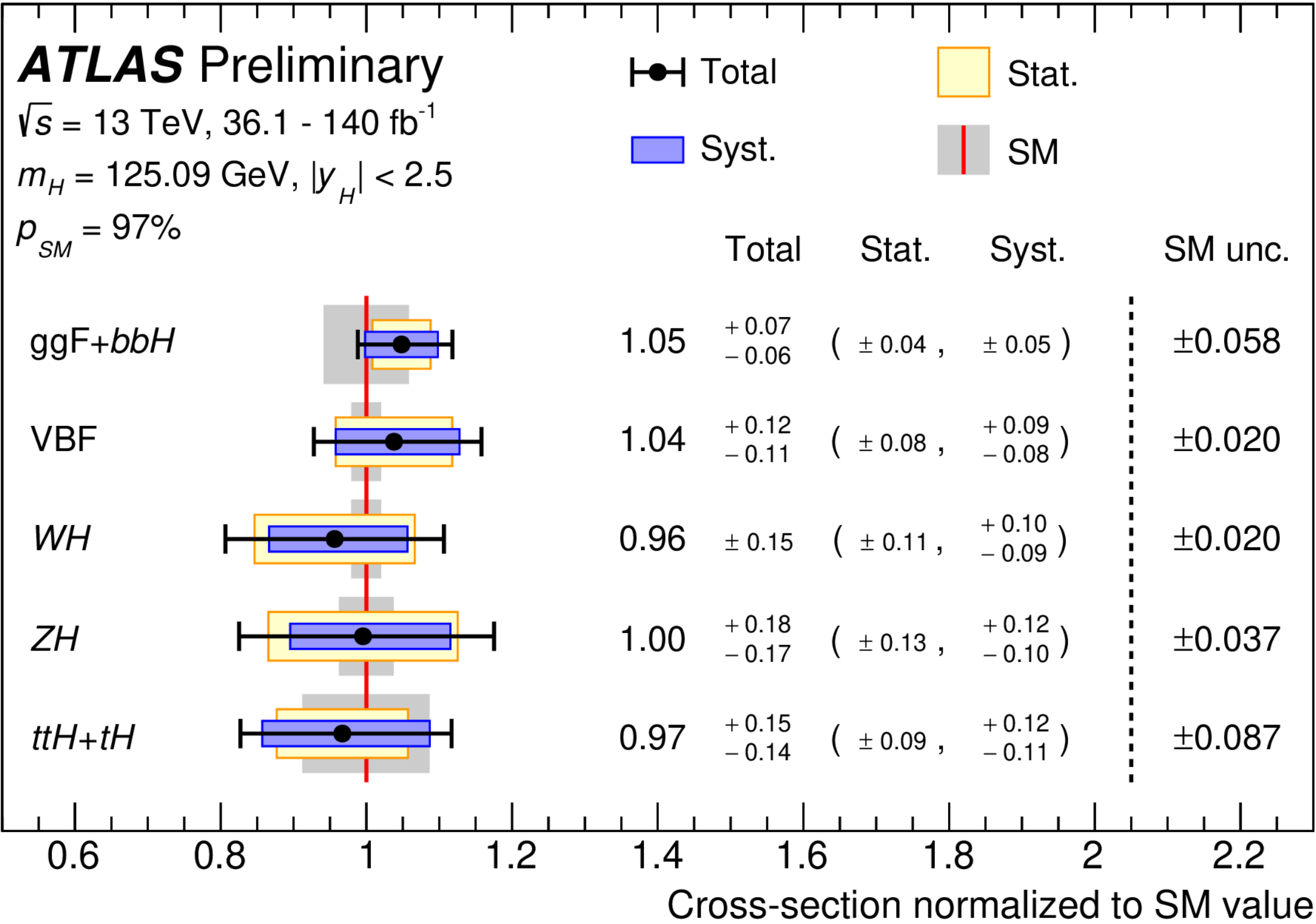
TOPQ-2025-11



TOP-25-002

Proving the LHC as a precision machine

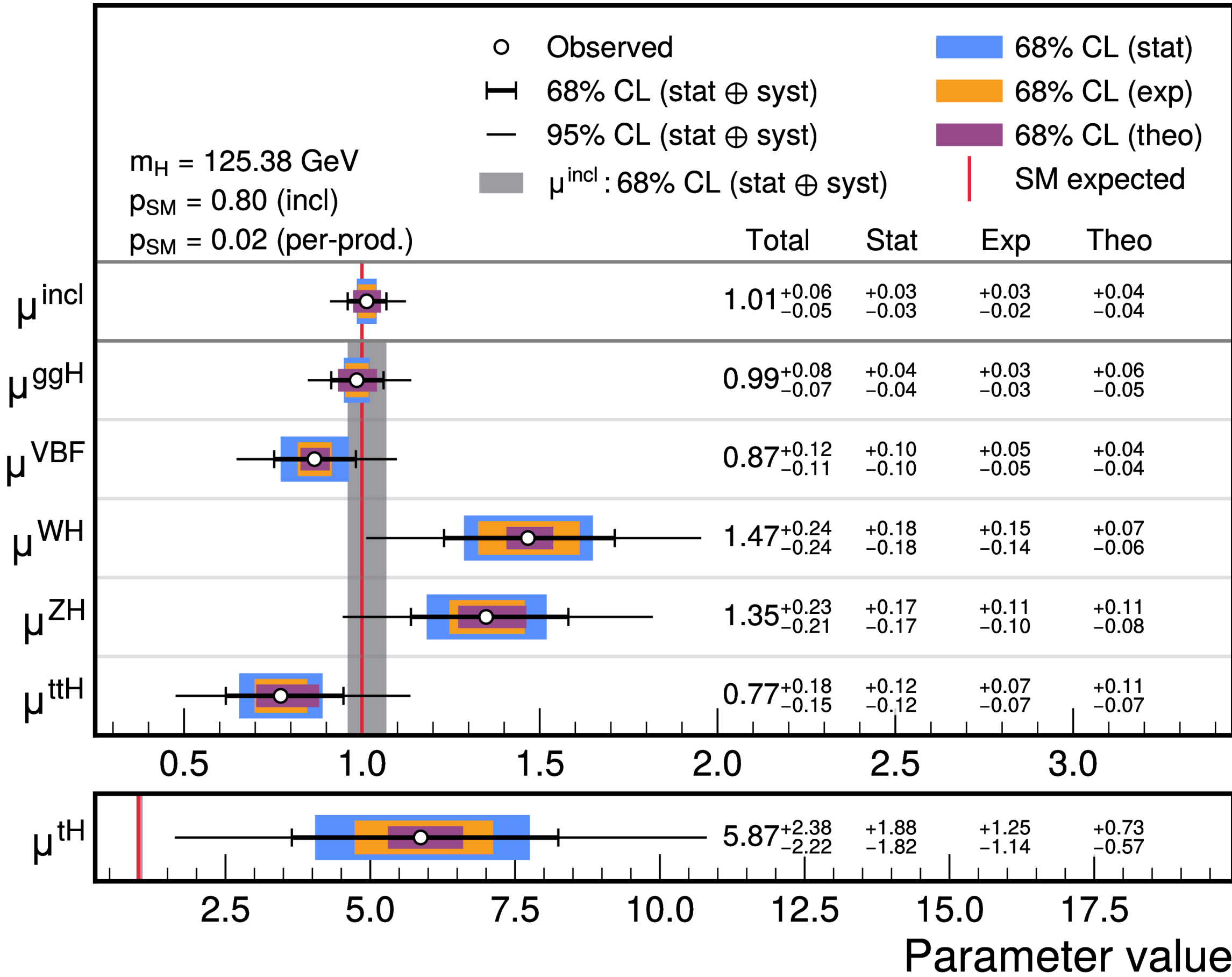
► Higgs combinations give O(10%) precision for most production modes



ATLAS-CONF-2025-006

CMS

138 fb⁻¹ (13 TeV)



HIG-21-018

US
UNIVERSITY
OF SUSSEX

- SMP-24-003**



Proving the LHC as a precision machine

► Multi-messenger particle physics?

► Global EFT

► ATLAS

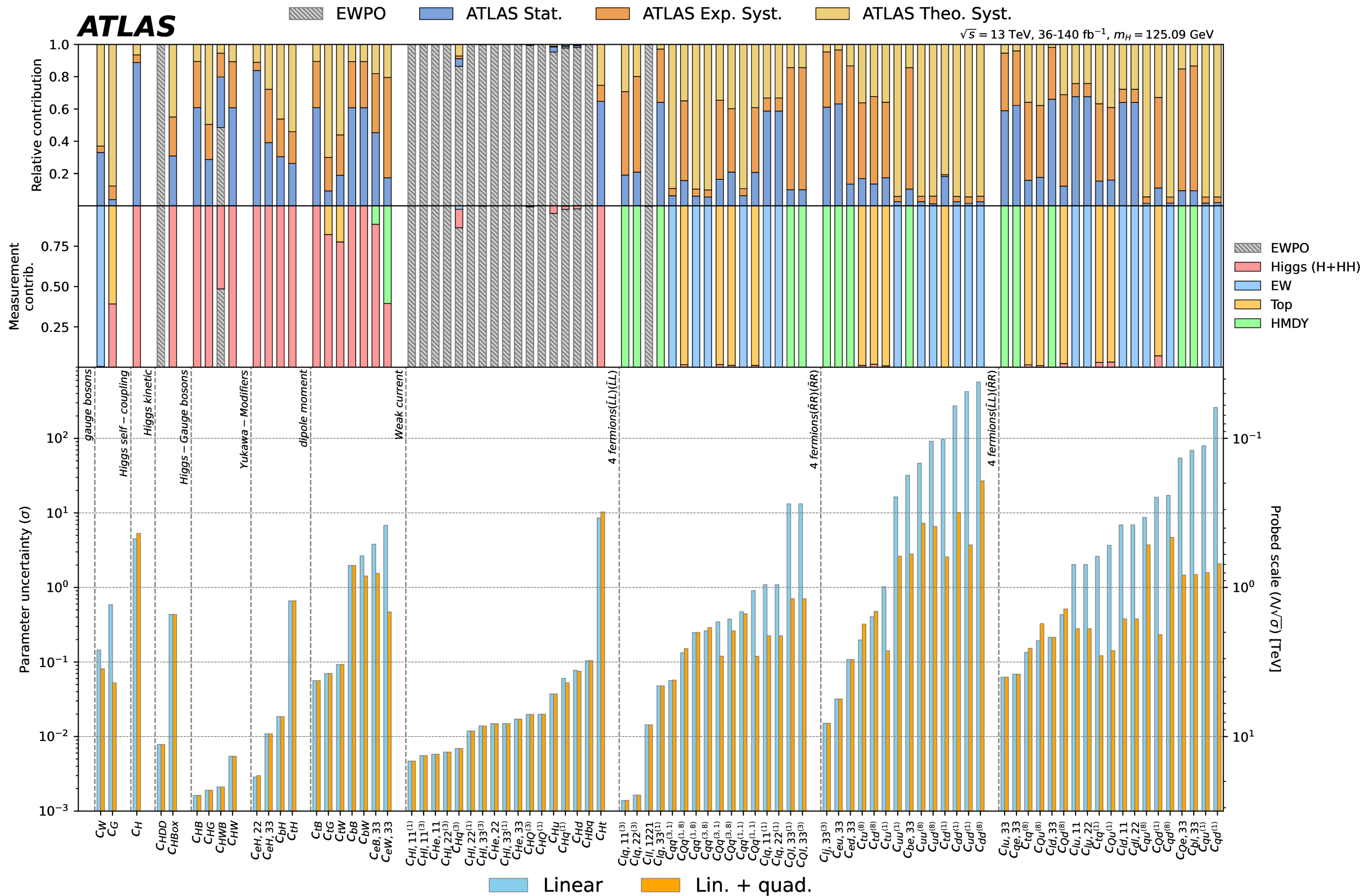
► Individual - 86 ops

► Combined - 48 dirs

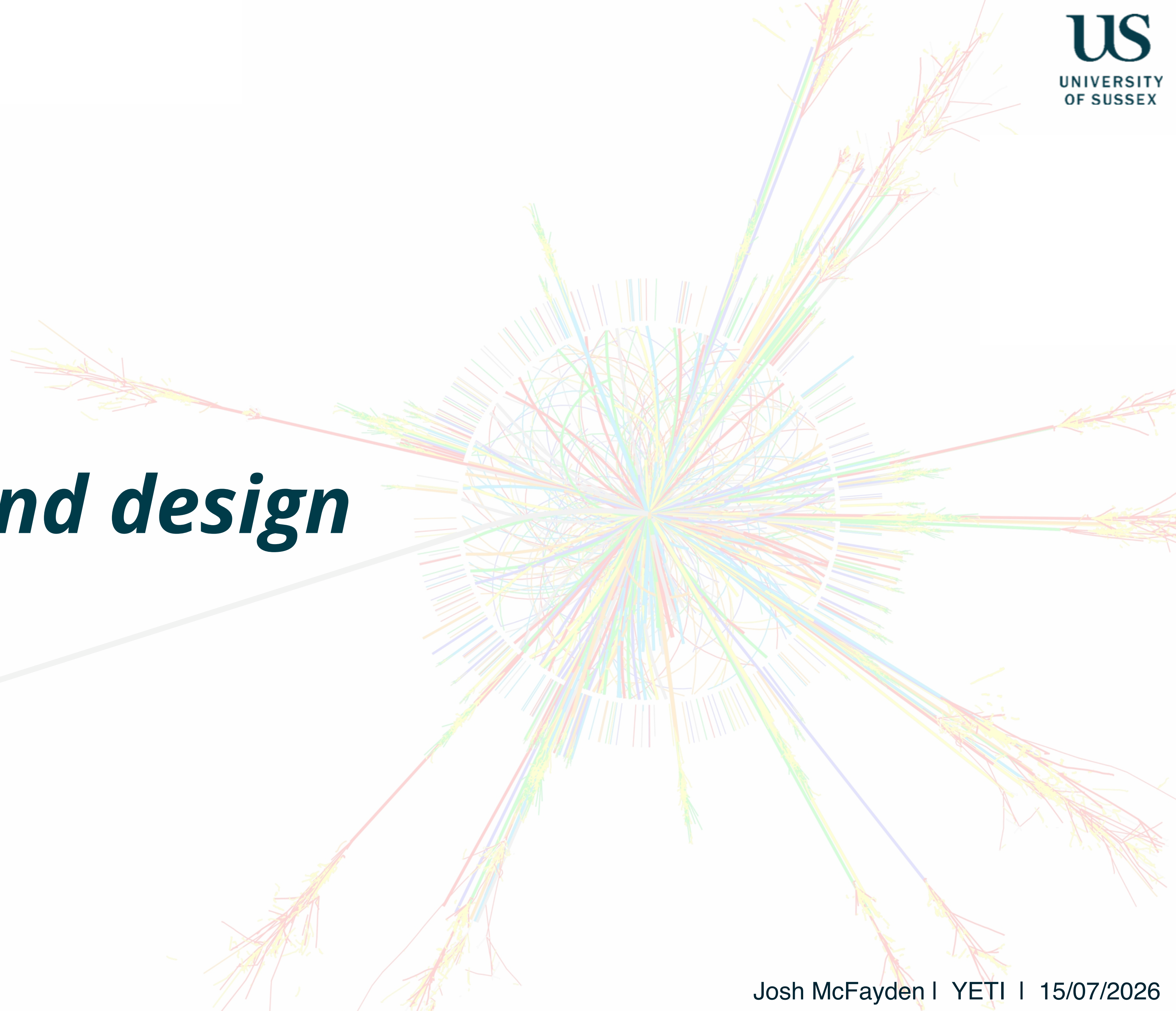
► CMS

► Individual - 64 oprs

► Combined - 43 dirs



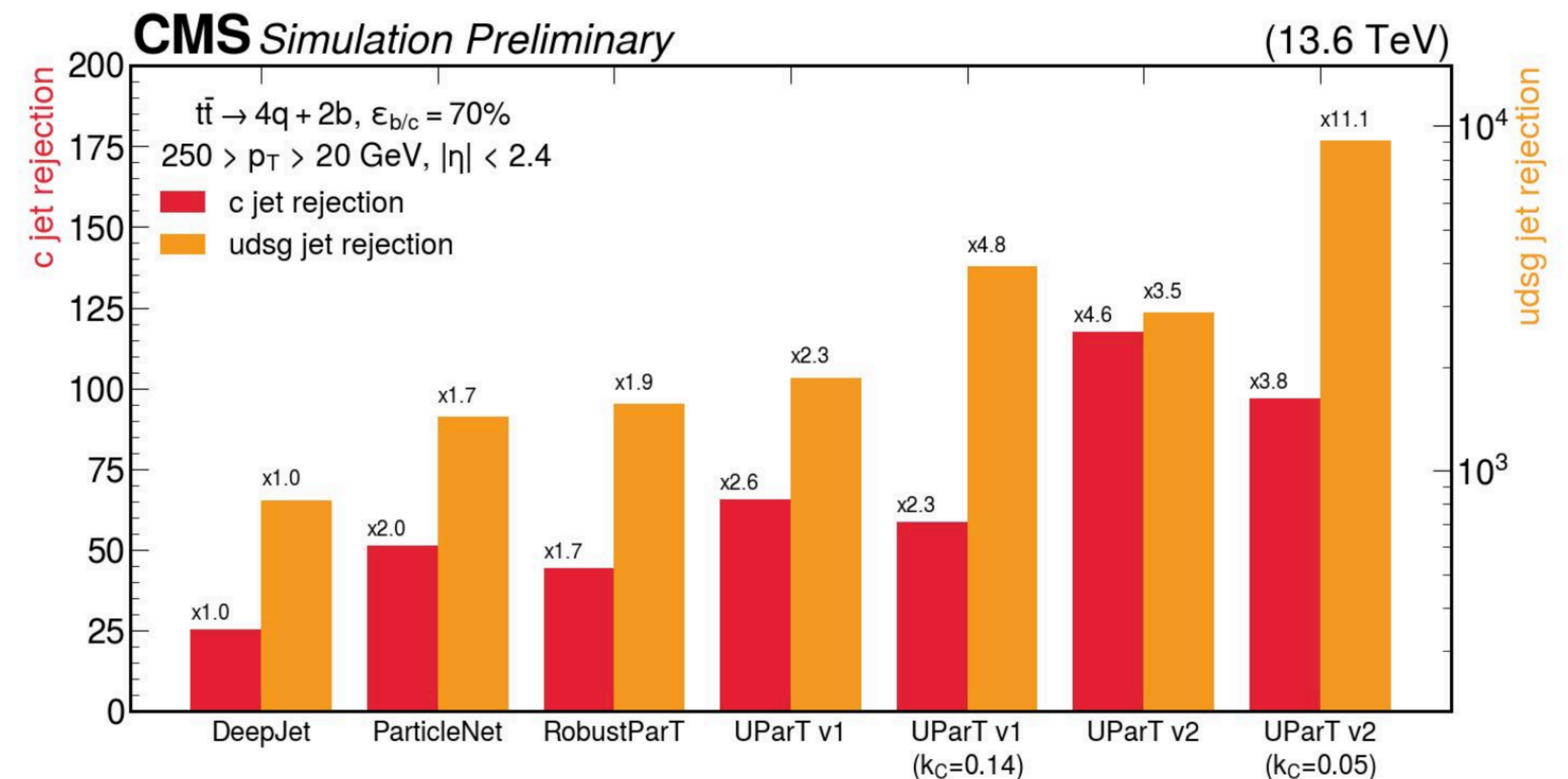
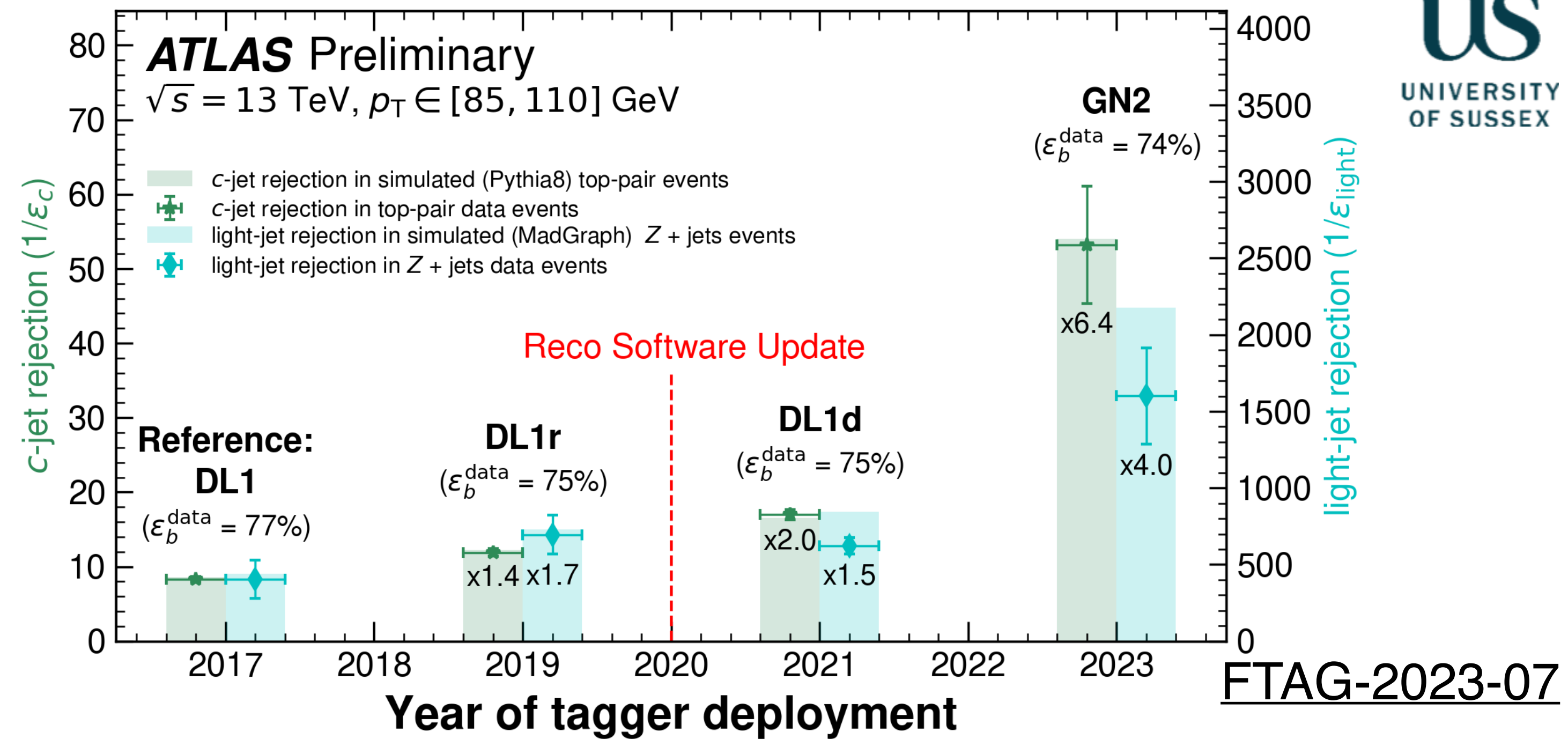
The LHC beyond design



The LHC beyond design aka Norway 🇳🇴 and Morocco 🇲🇷 ?!

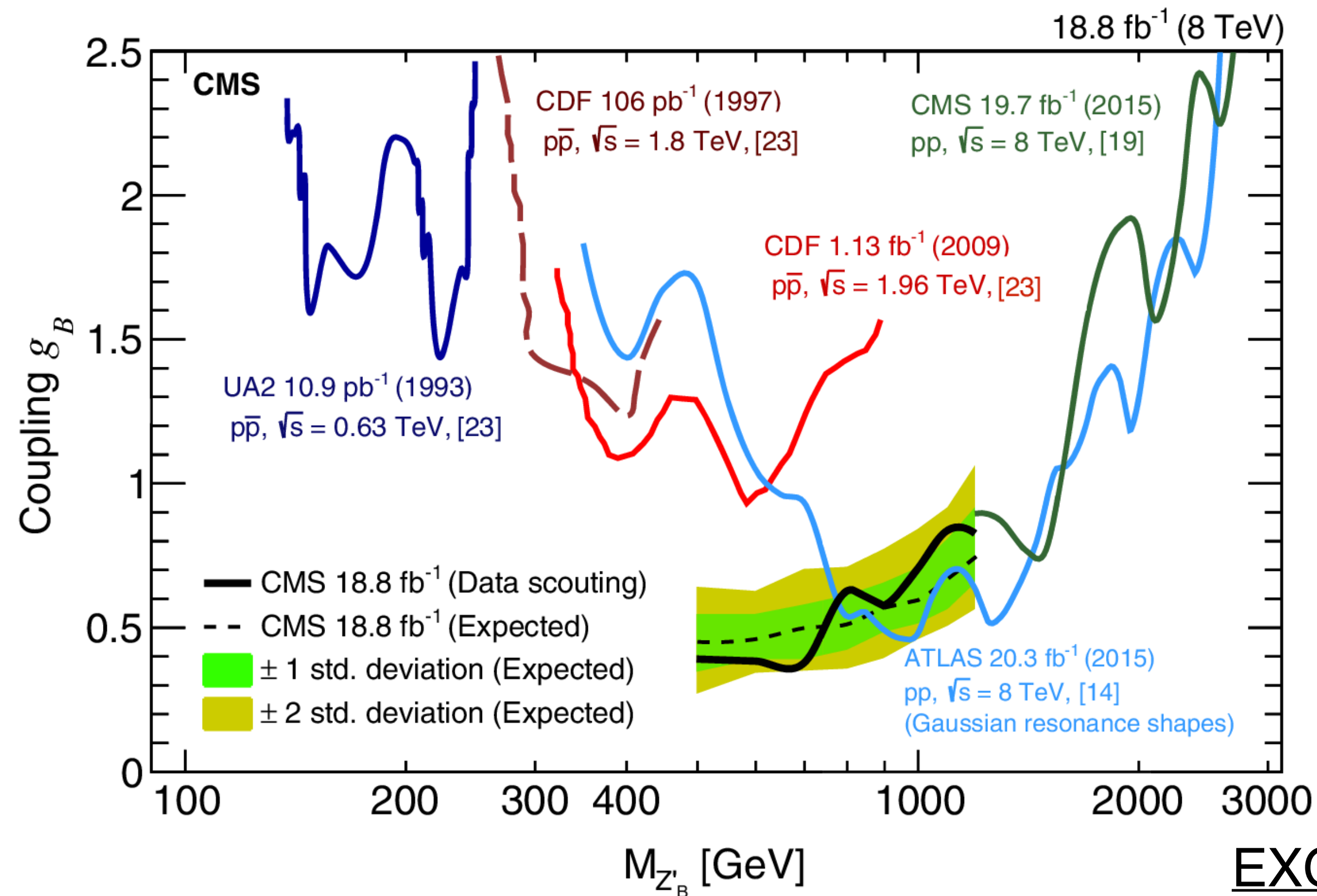
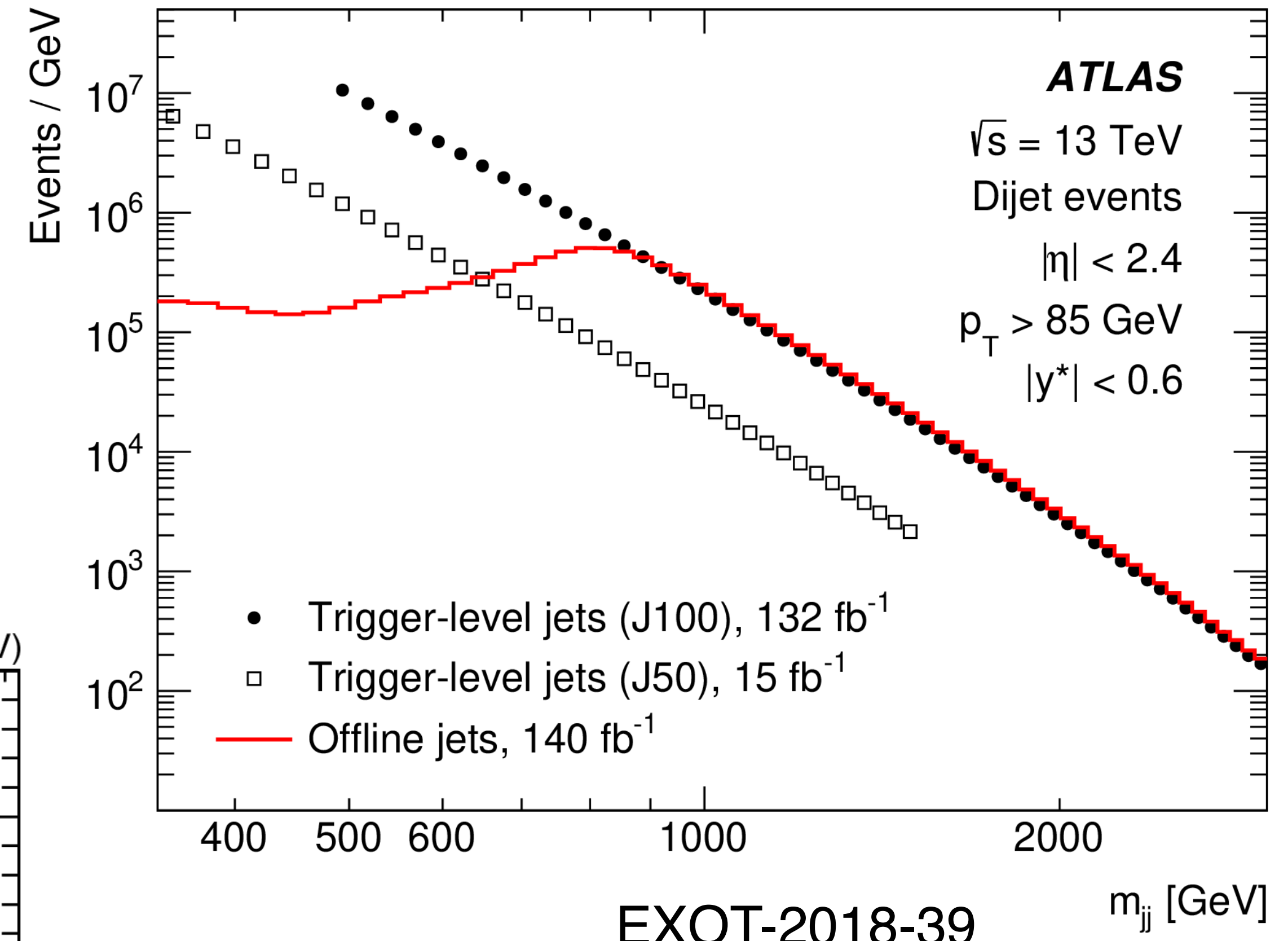
LHC Beyond Design

- Huge advances in Machine Learning applications
- Classification
- Simulation
- Anomaly detection
- etc.



LHC Beyond Design

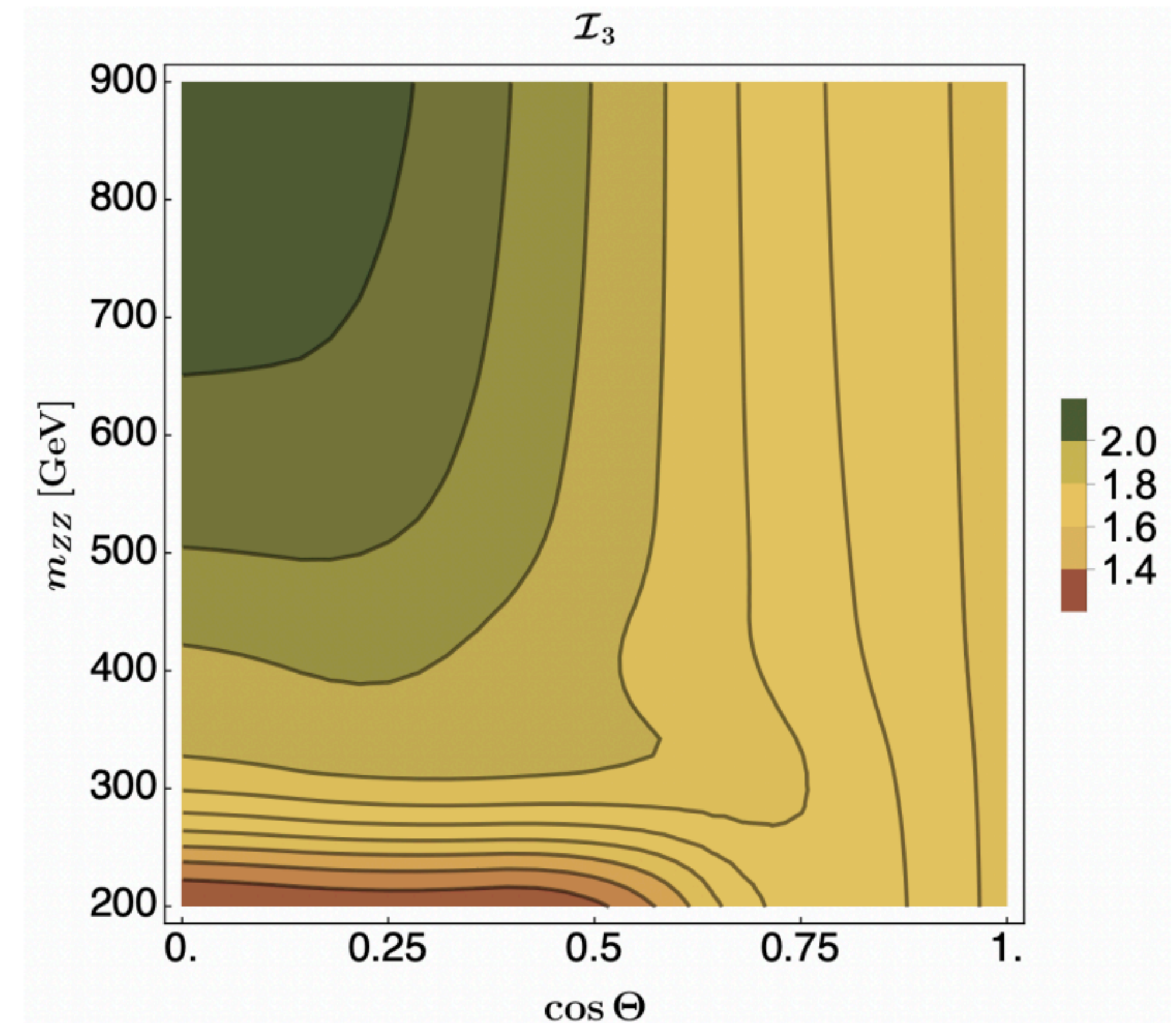
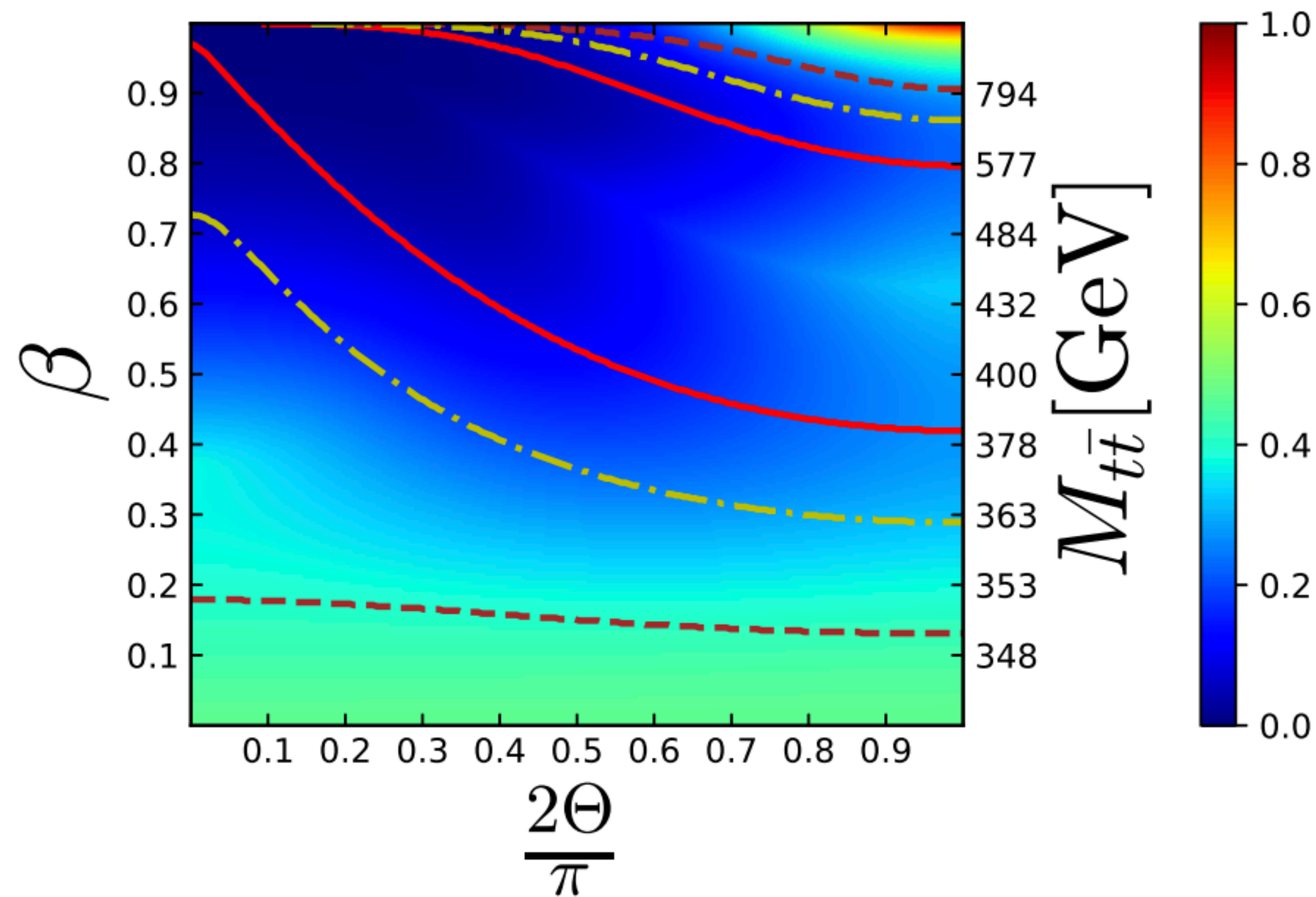
- Online (trigger) analysis
 - ATLAS: Trigger-Level Analysis
 - CMS: Data Scouting
 - LHCb: Turbo Stream



LHC Beyond Design

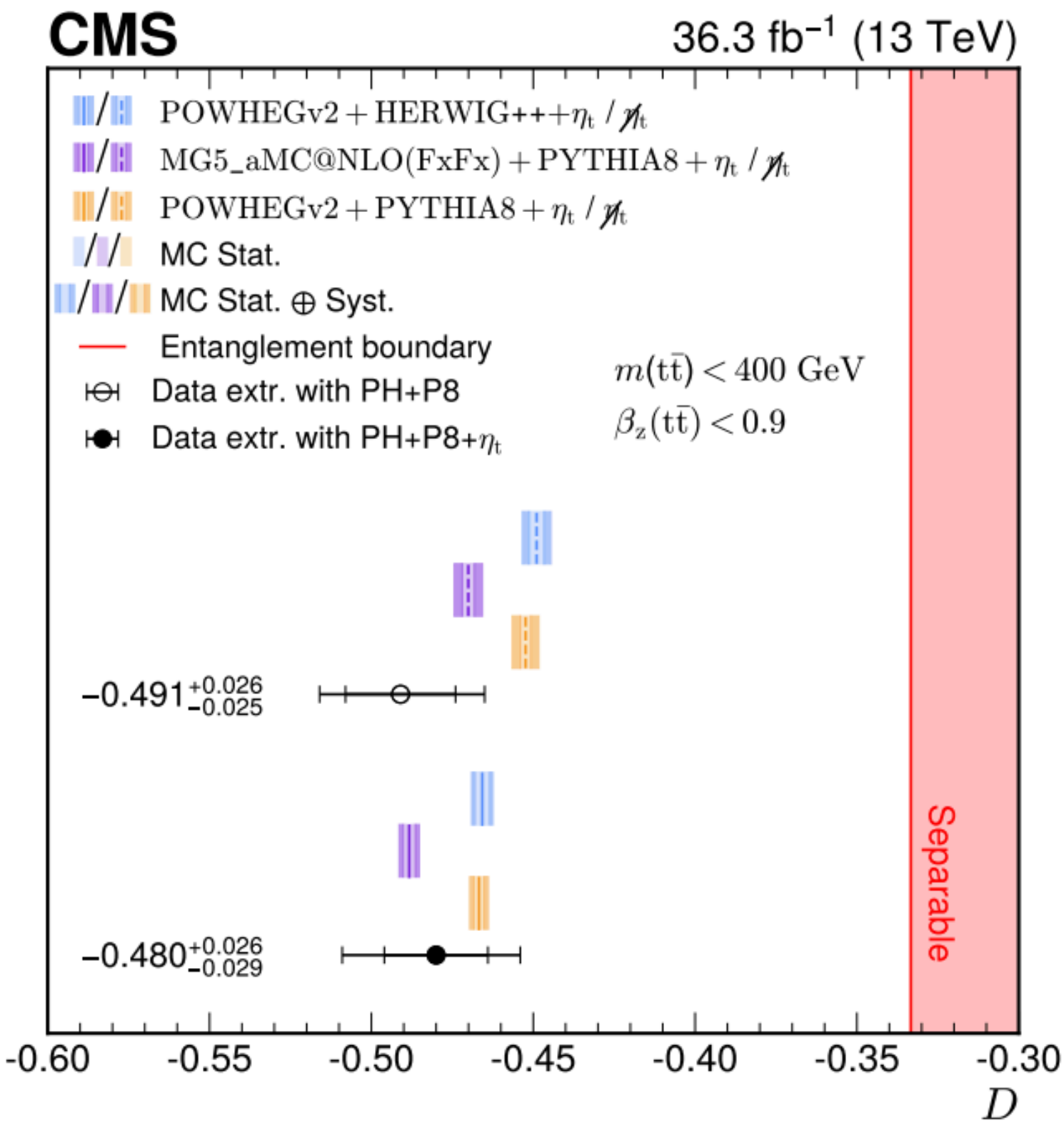
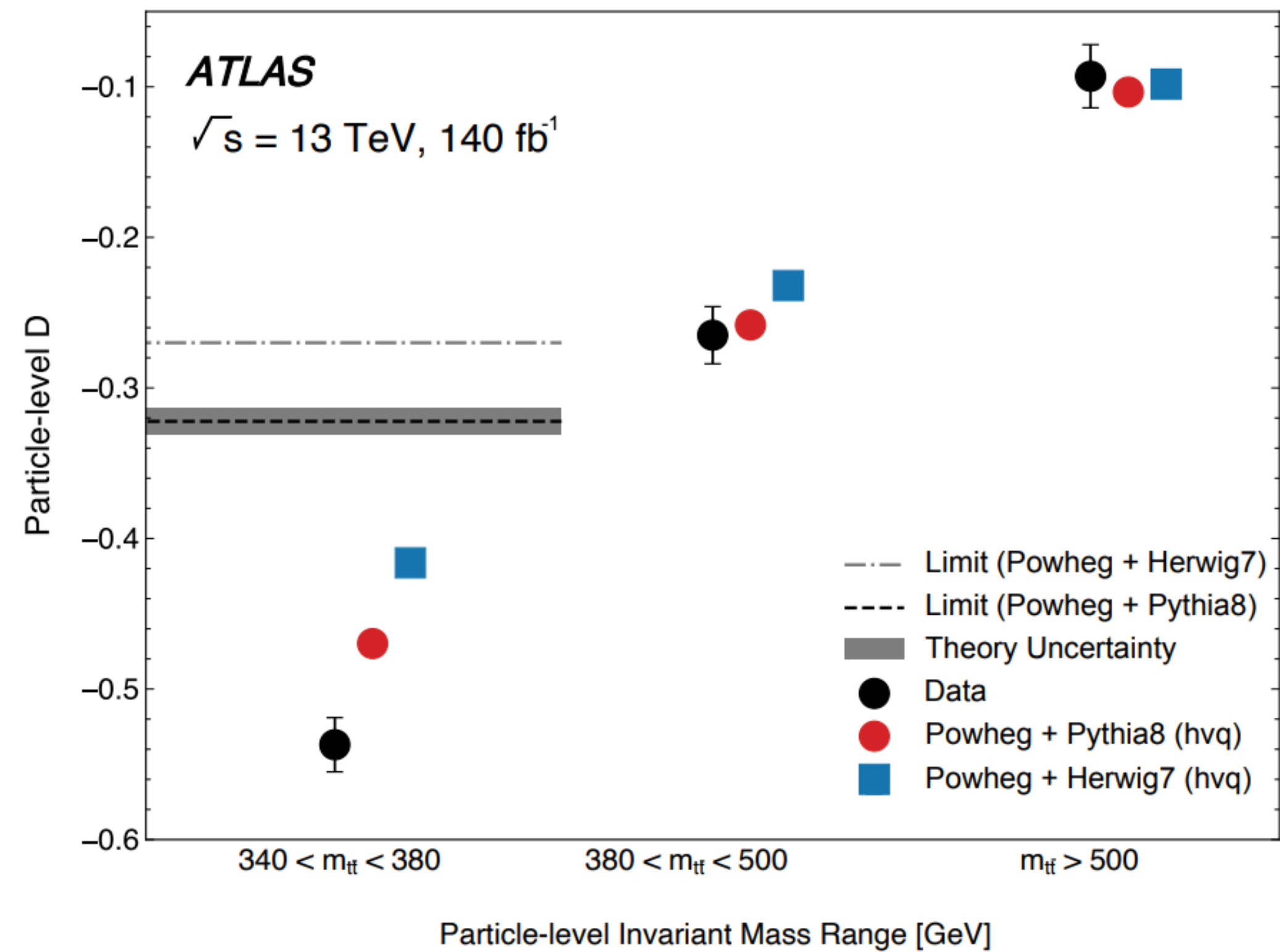
- Quantum Information
 - Entanglement, Discord, Magic and all that!

[arXiv:2504.00086](https://arxiv.org/abs/2504.00086)



LHC Beyond Design

- Quantum Information
 - First observation of entanglement



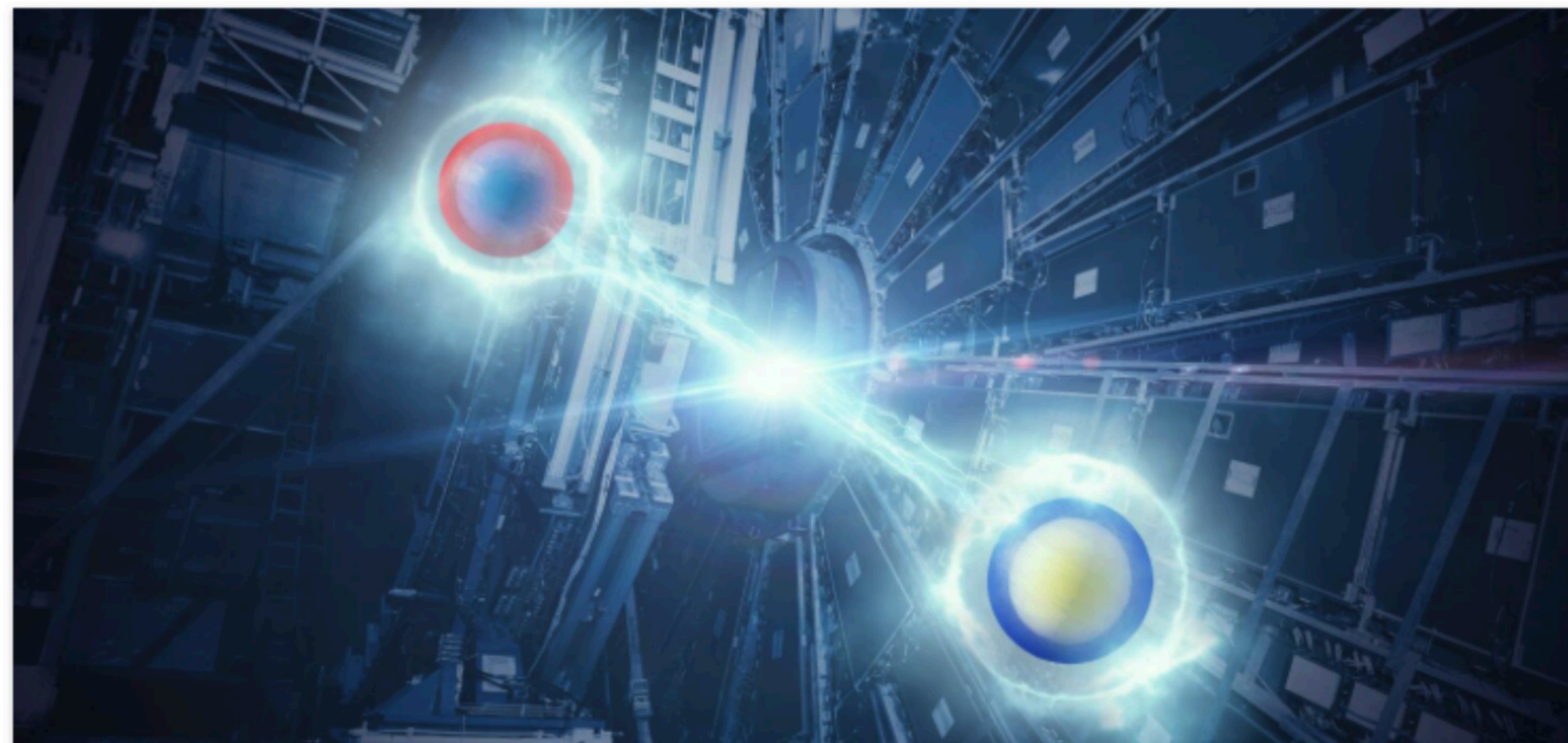
LHC Beyond Design

- Quantum Information
 - First observation of entanglement also in $H \rightarrow ZZ$

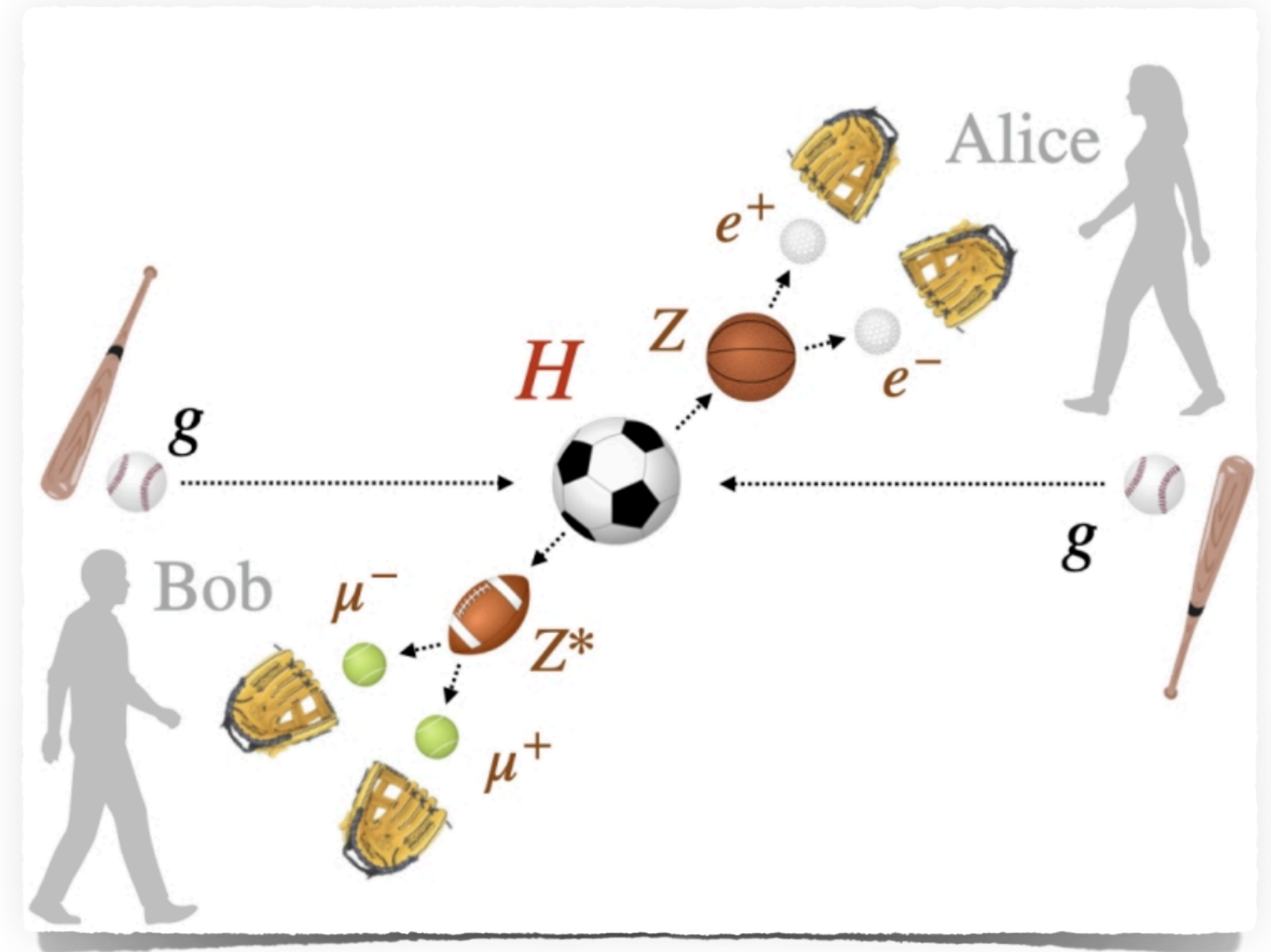
LHC experiments at CERN observe quantum entanglement at the highest energy yet

The results open up a new perspective on the complex world of quantum physics

18 SEPTEMBER, 2024

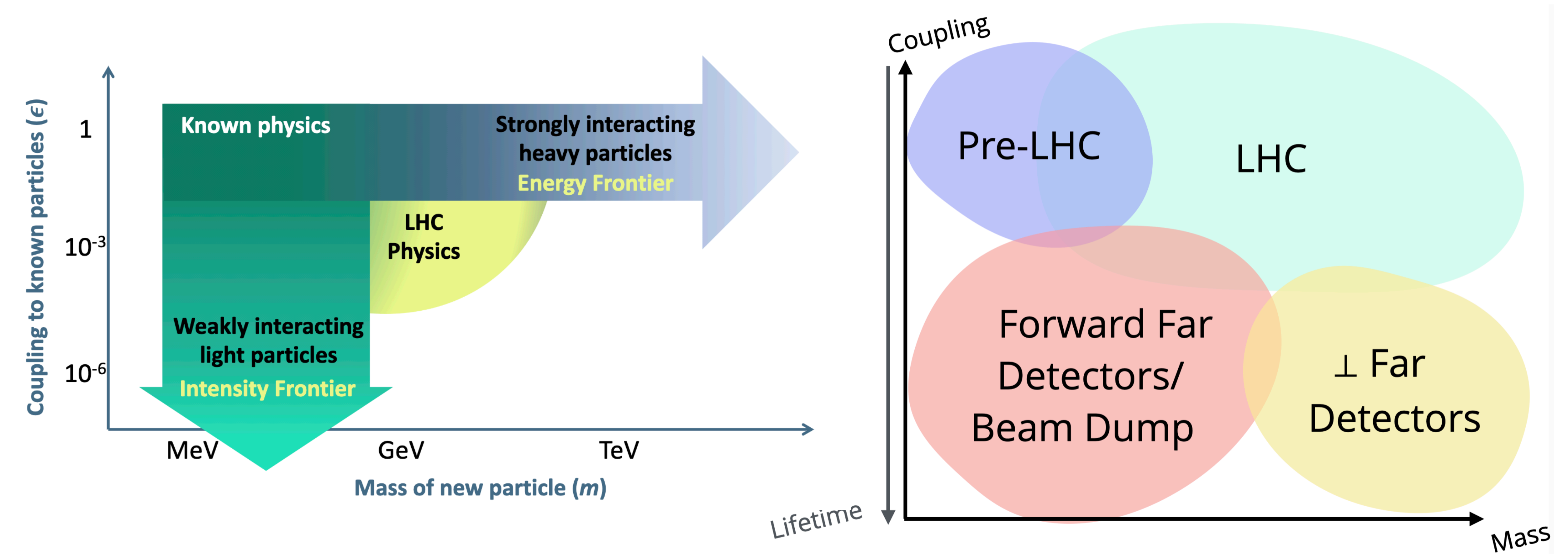


Artist's impression of a quantum-entangled pair of top quarks. (Image: CERN)



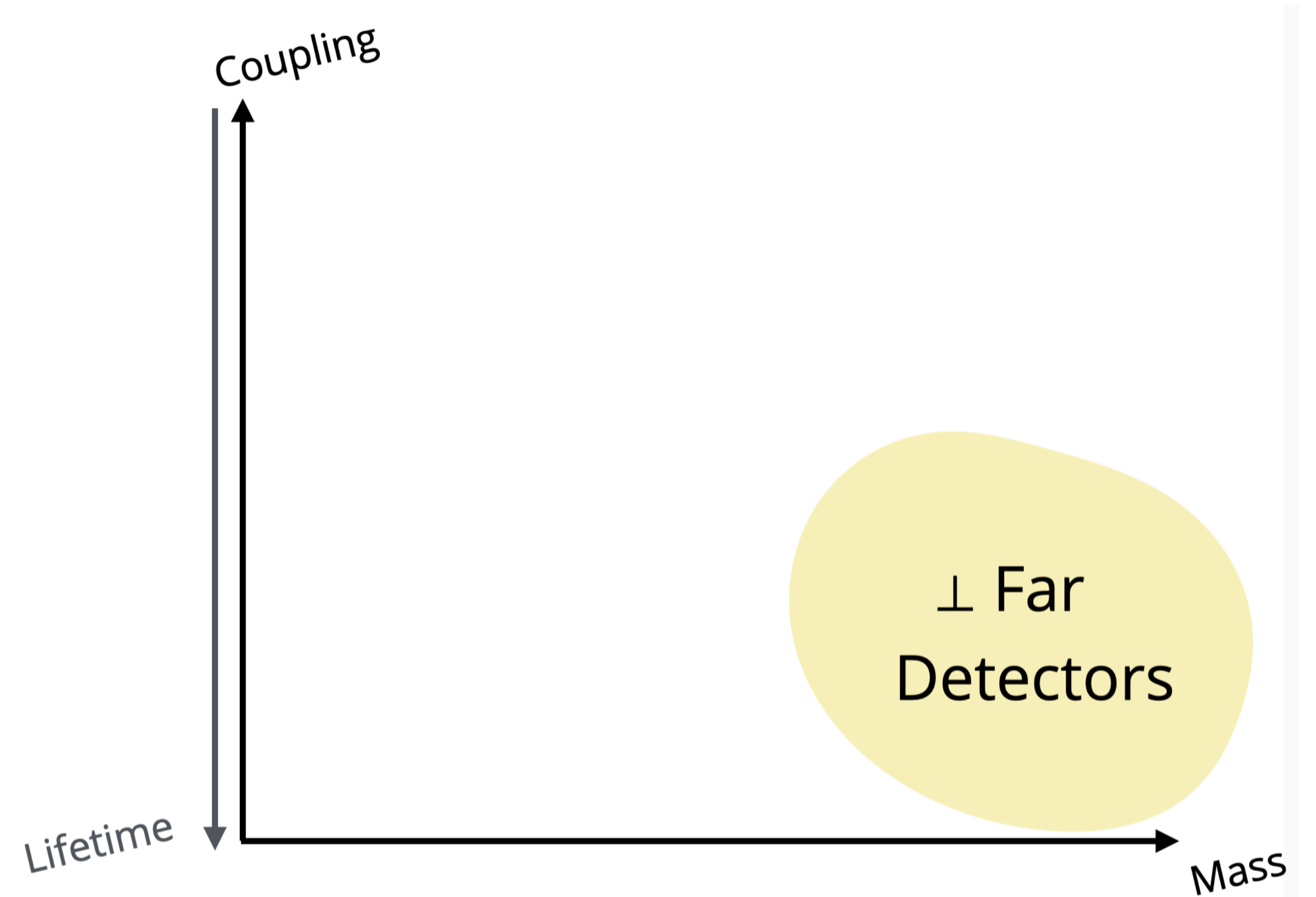
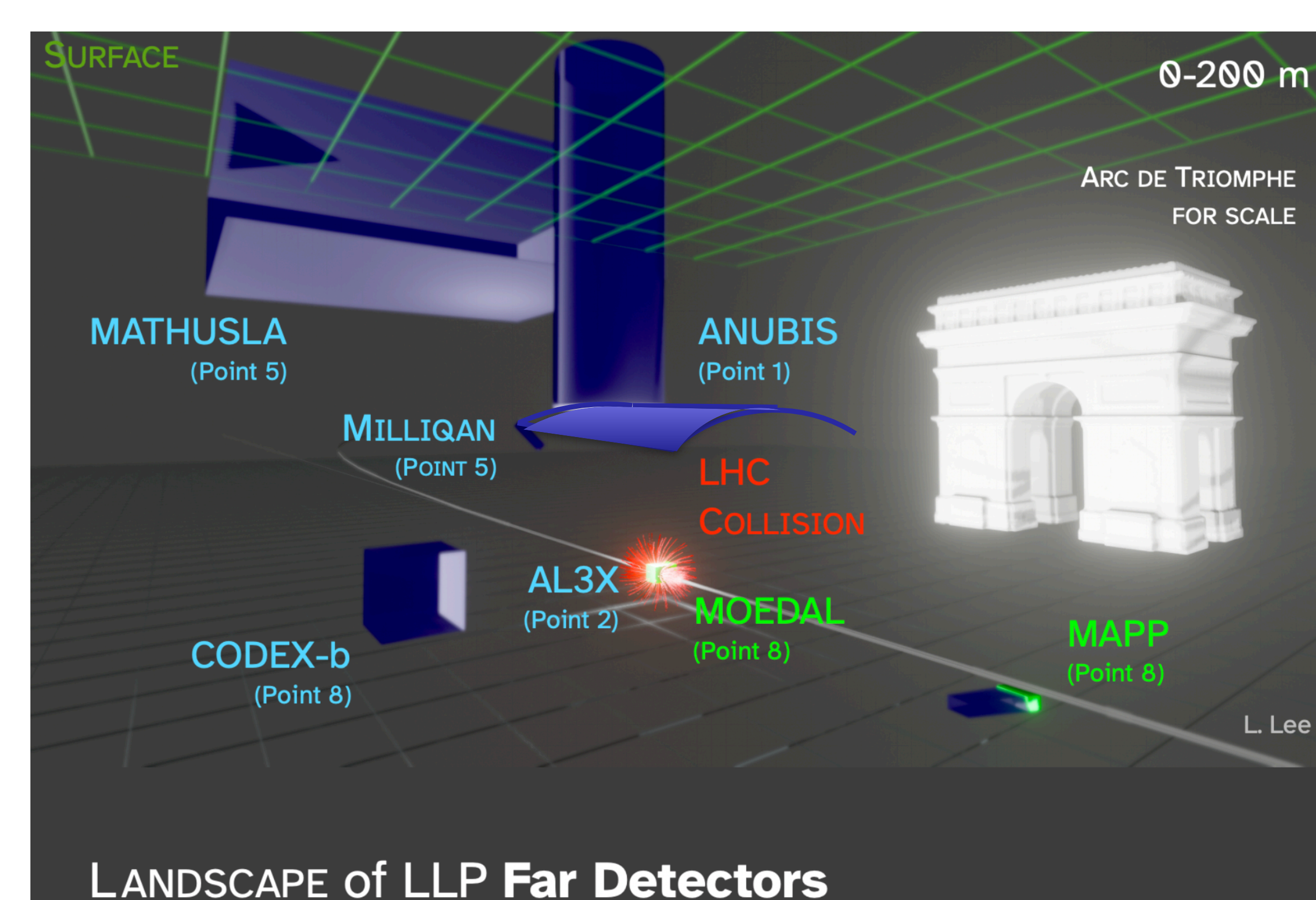
LHC Beyond Design

► Auxiliary experiments for LLPs



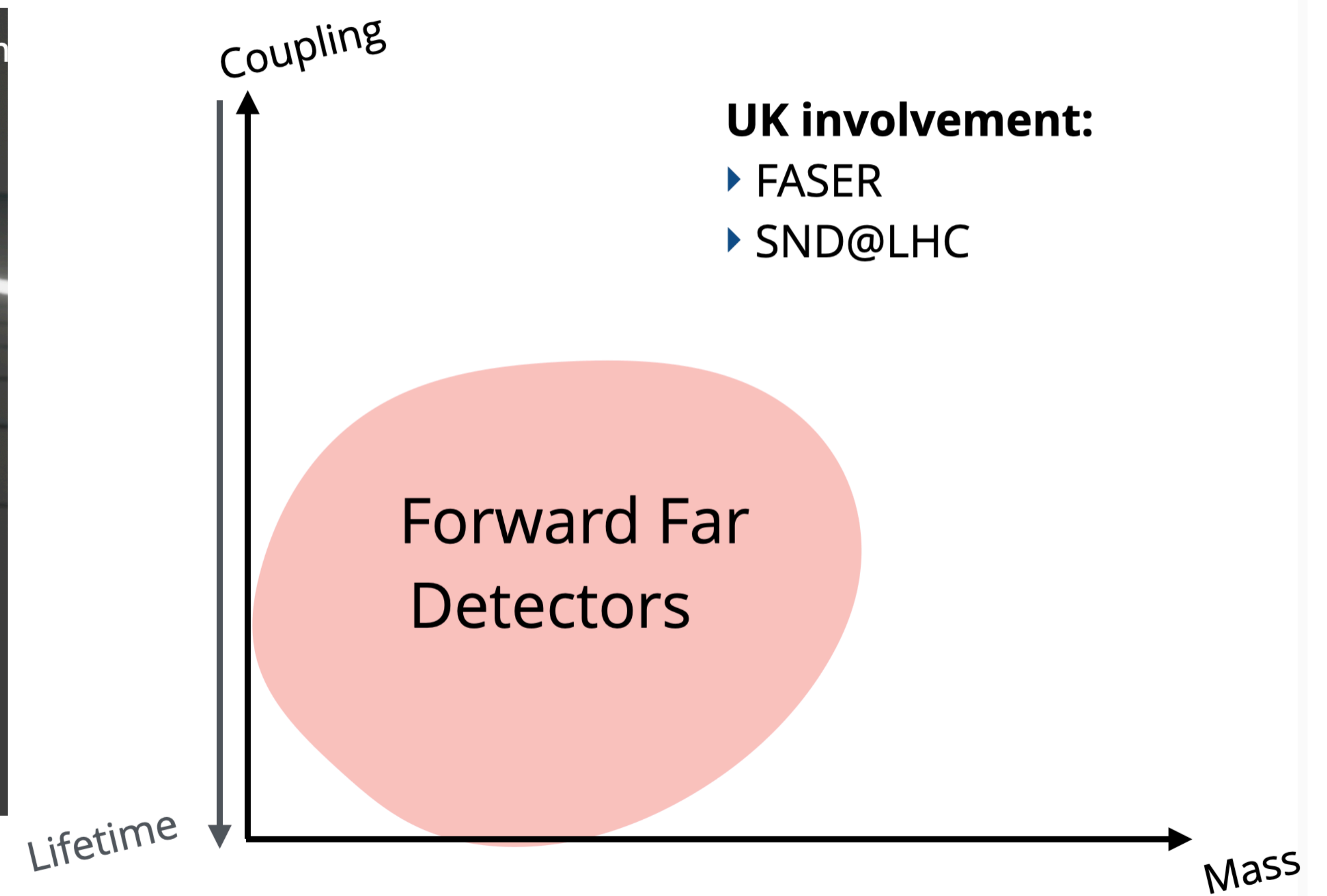
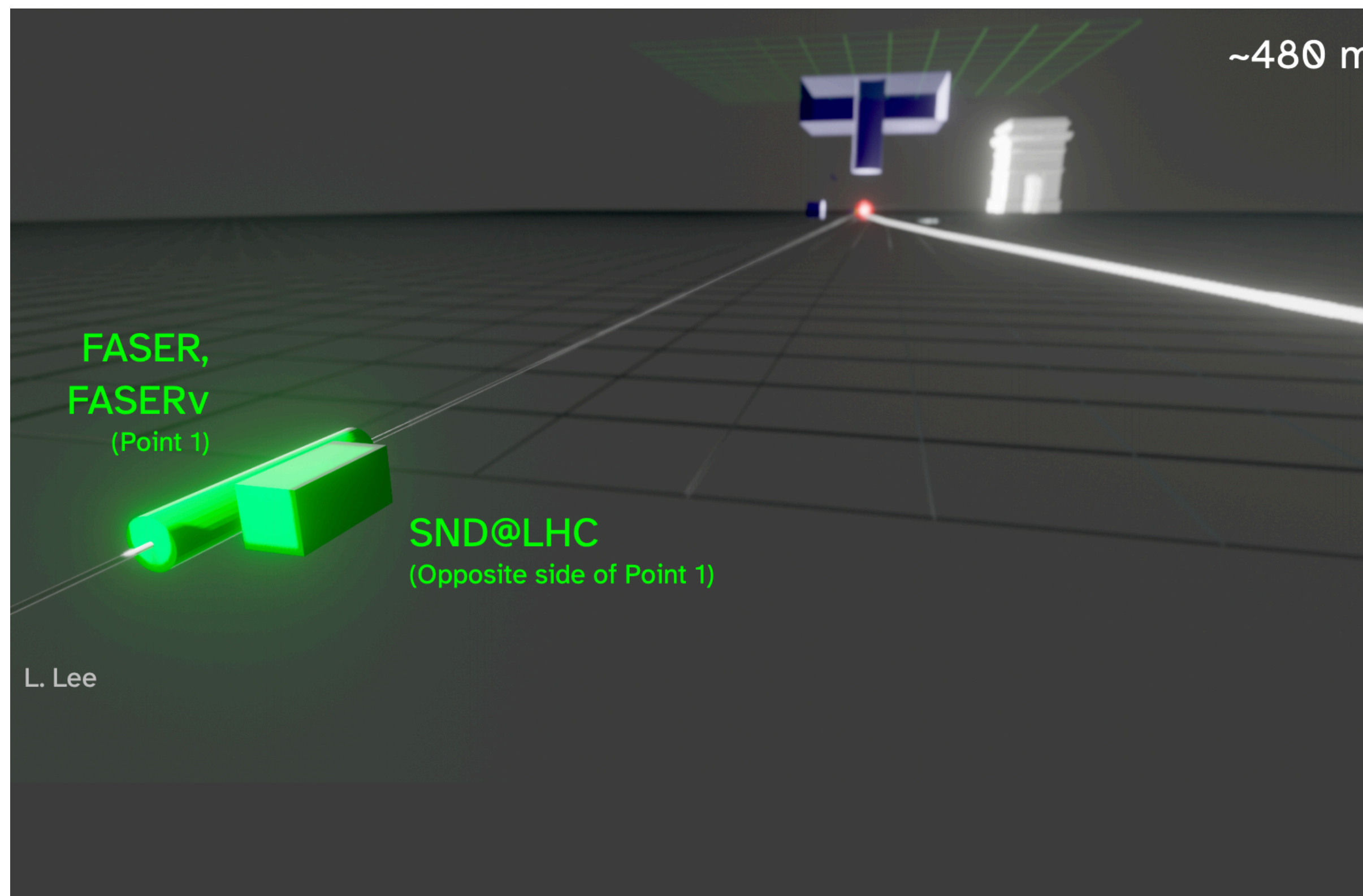
LHC Beyond Design

► Auxiliary experiments for LLPs



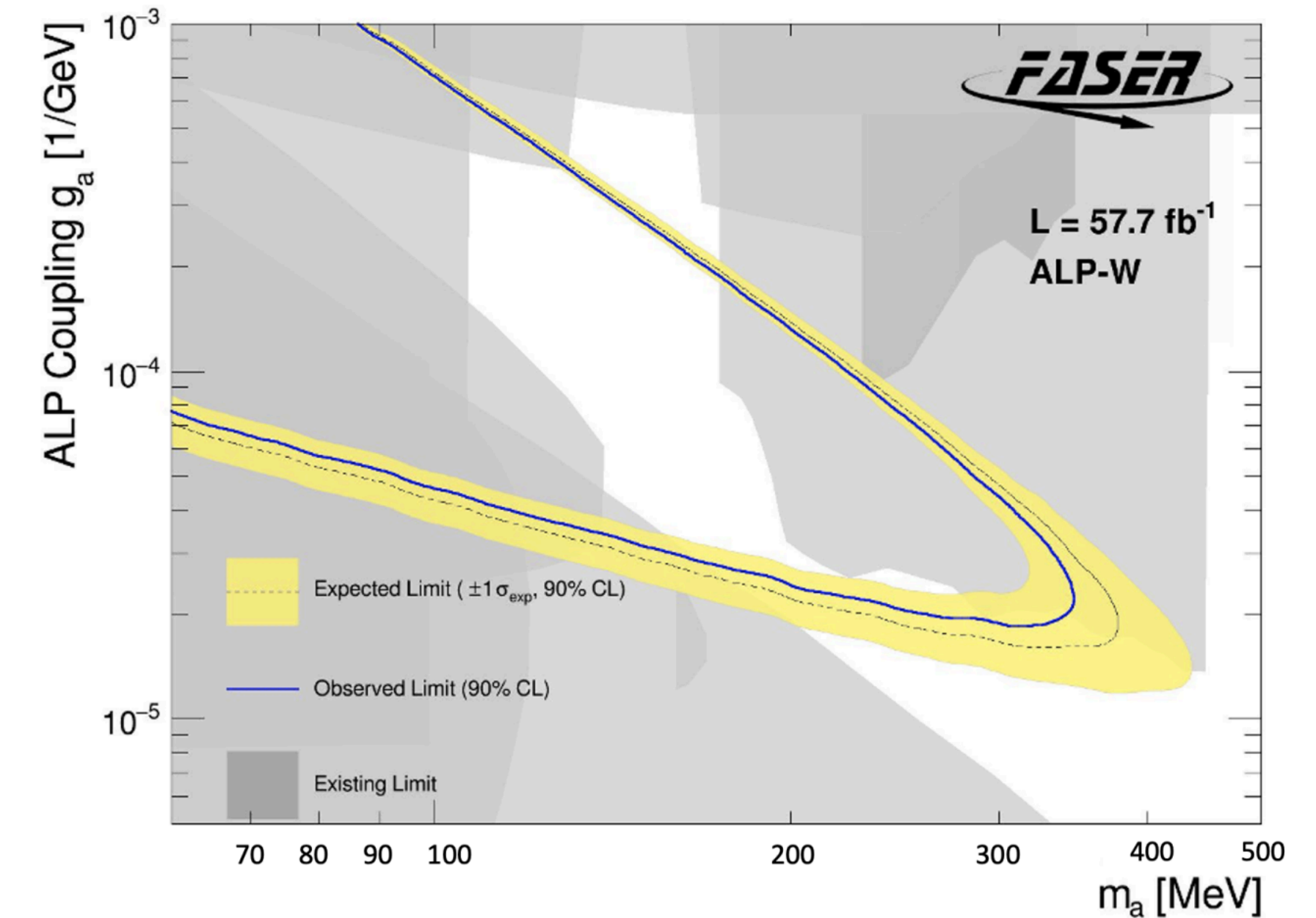
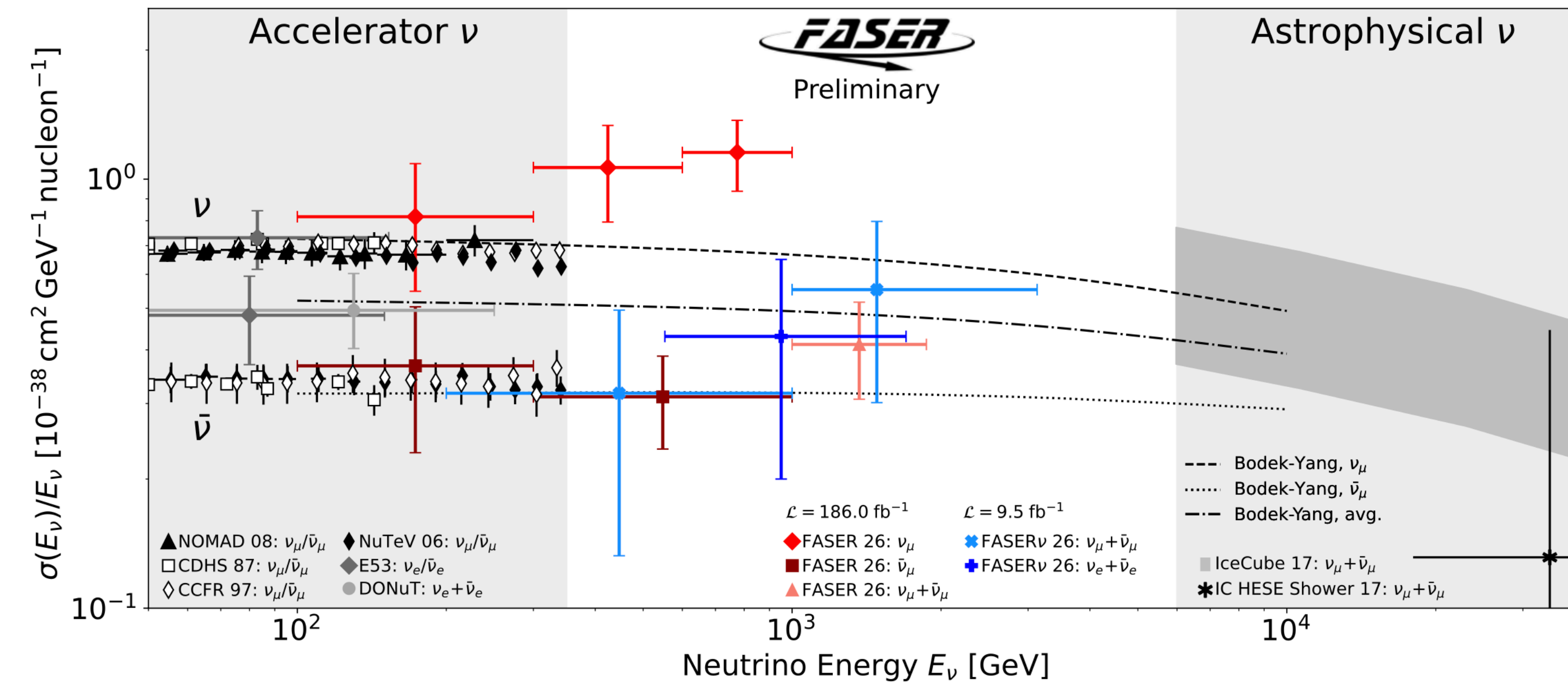
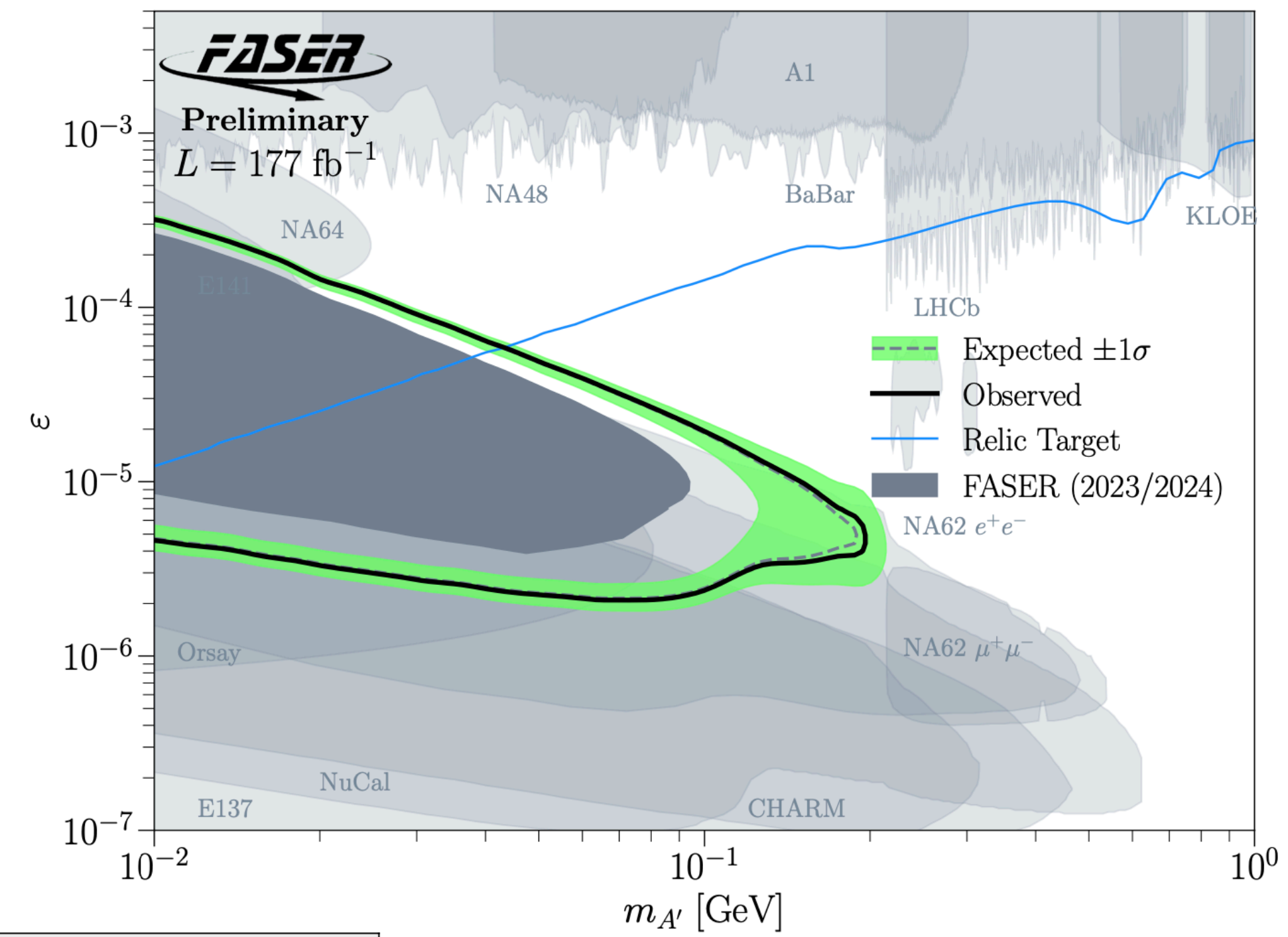
LHC Beyond Design

- ▶ Auxiliary experiments for LLPs and neutrinos!



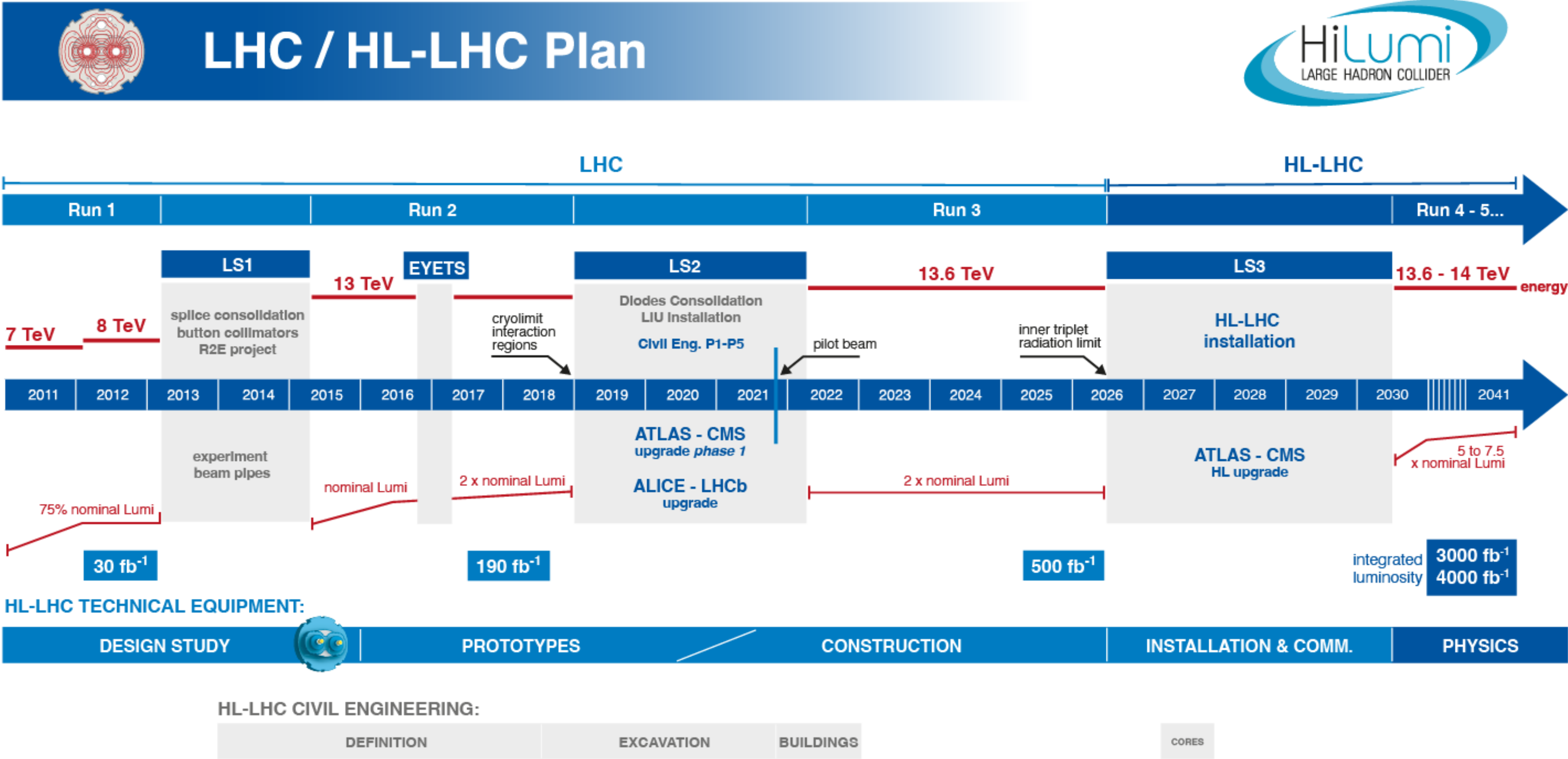
LHC Beyond Design

- Highlights of some FASER results
 - Searches for feebly interacting particles
 - Measurements of neutrinos in previously unexplored energy range

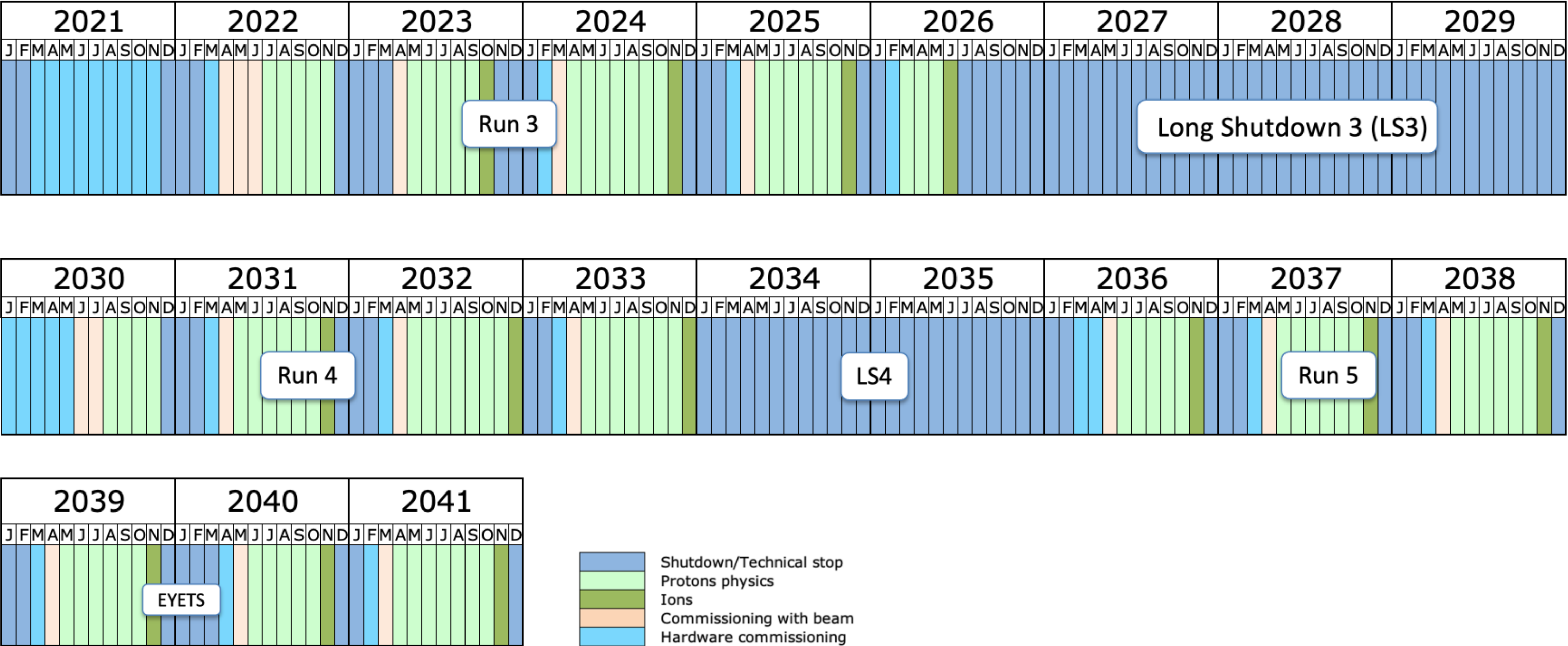


Highlights of the HL-LHC Experimental Physics Program

HL-LHC Timeline

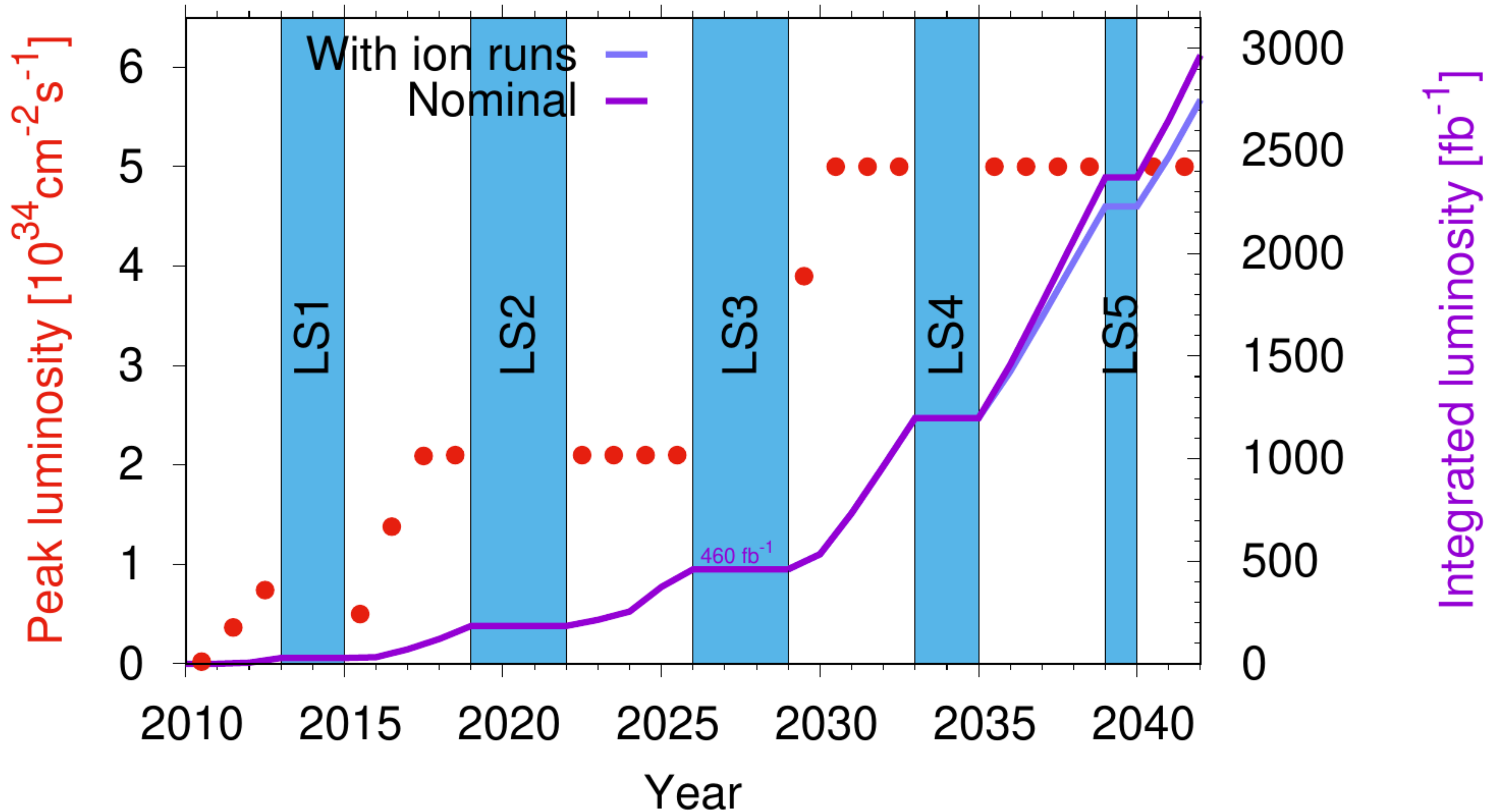


HL-LHC Timeline



Last update: November 24

HL-LHC Timeline



HL-LHC upgrades



***HL-LHC upgrades
48 → 64 teams?***



HL-LHC Upgrades

- ▶ Long Shutdown 3 is the major installation phase for the High-Luminosity LHC (HL-LHC) upgrade



HL-LHC Upgrades

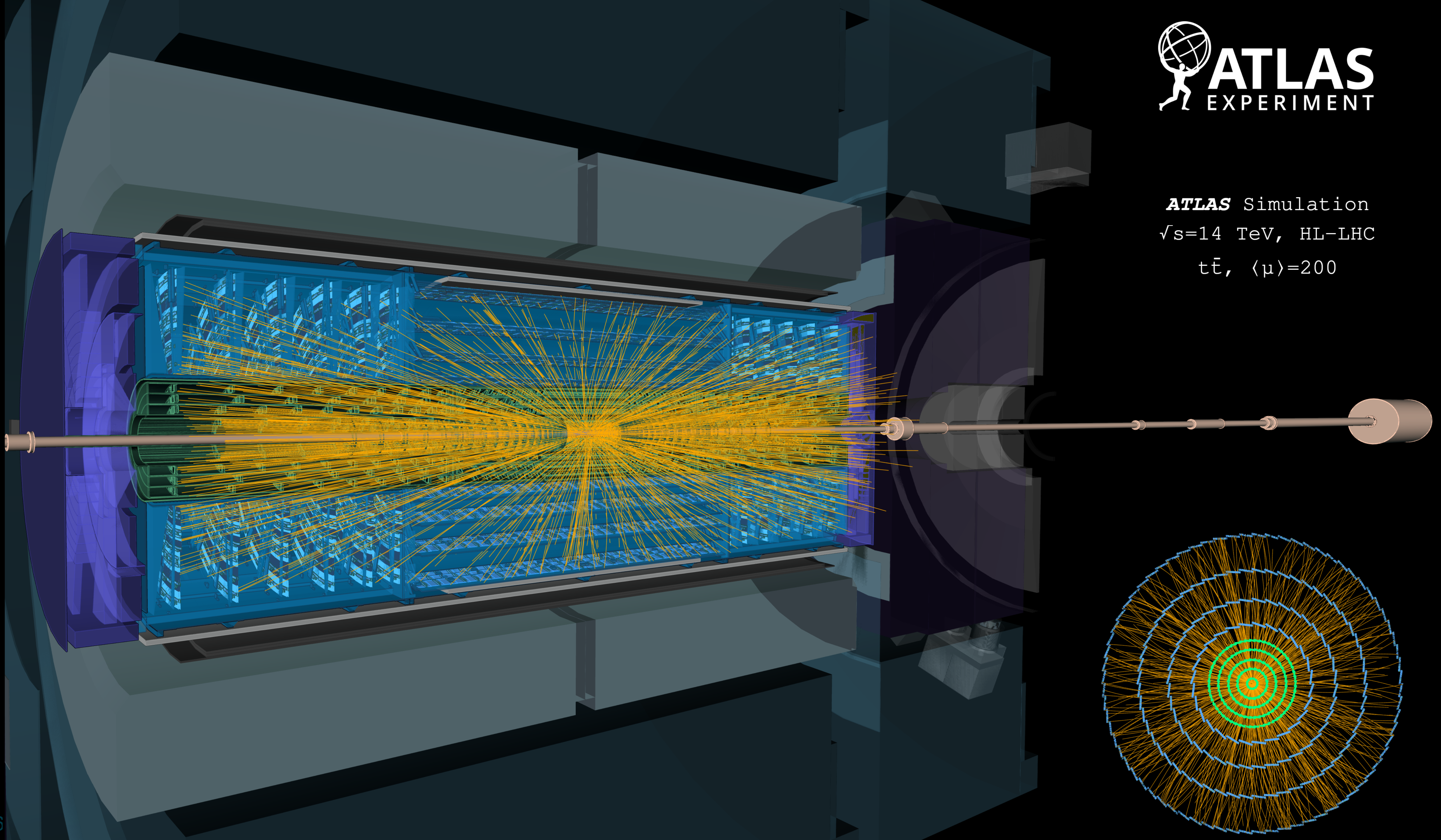
- ▶ Key new technologies include:
 - ▶ Nb_3Sn high-field superconducting magnets
 - ▶ Crab cavities
 - ▶ High-temperature superconducting ($\text{MgB}_2/\text{REBCO}$) powering system
 - ▶ Upgraded collimation and machine protection



HL-LHC Experimental Challenges

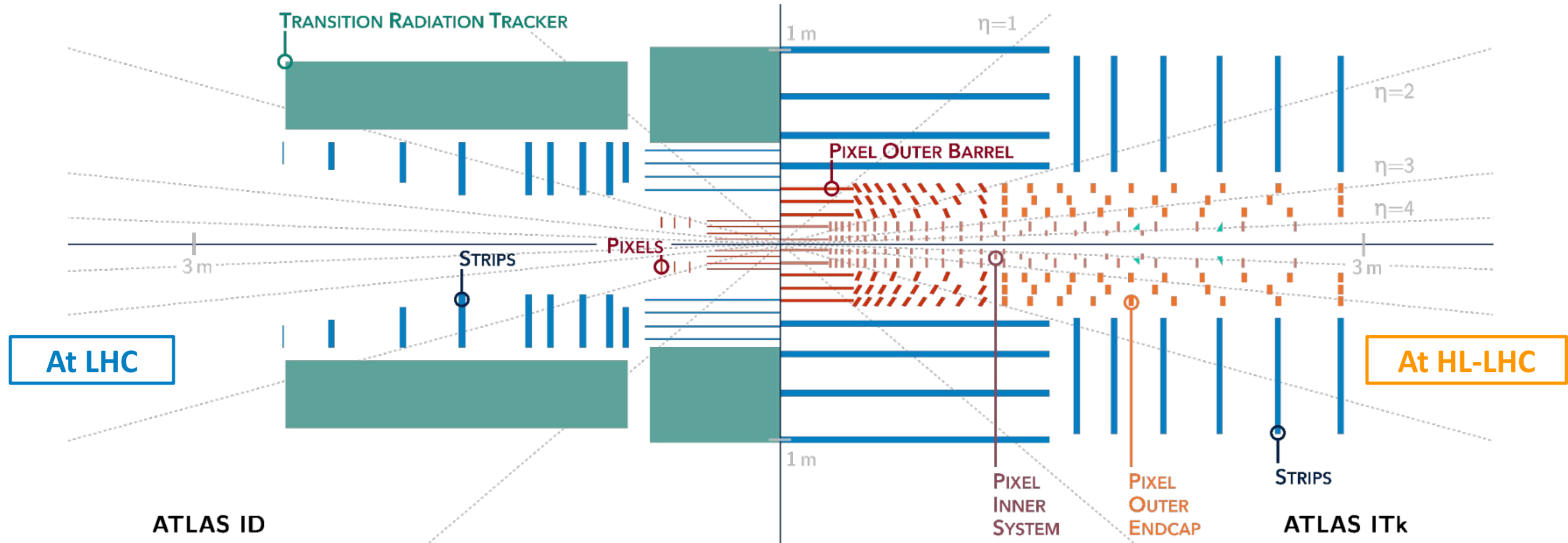
- ▶ Instantaneous luminosity x5-7 and integrated luminosity x10
 - ▶ New radiation hard sensors
 - ▶ completely new trackers
 - ▶ Finer sensor granularity
- ▶ Increase of pile-up from $\langle\mu\rangle \sim 50$ now to $\langle\mu\rangle \sim 200$
 - ▶ Additional energy in calorimeters, accumulation of “pile-up” jets especially in the forward region
 - ▶ High hit rates of up to 3GHz/cm² in tracker center
- ▶ Increase readout rate 10-fold (L0 trigger rate 1 MHz)
 - ▶ Requires new front-end and/or back-end electronics for many sub-detectors

ATLAS Simulation
 $\sqrt{s}=14$ TeV, HL-LHC
 $t\bar{t}$, $\langle\mu\rangle=200$



HL-LHC Detector Upgrades

► ATLAS tracker



ITk will be full silicon detector with extended coverage up to $|\eta|=4.0$:

Pixel layers (Current $\Rightarrow$ ITk):

~2k modules $\Rightarrow$ ~9k modules,
90M channels $\Rightarrow$ 5G channels,
 $1.7 \text{ m}^2 \Rightarrow 13 \text{ m}^2$

Strip layers (Current $\Rightarrow$ ITk):

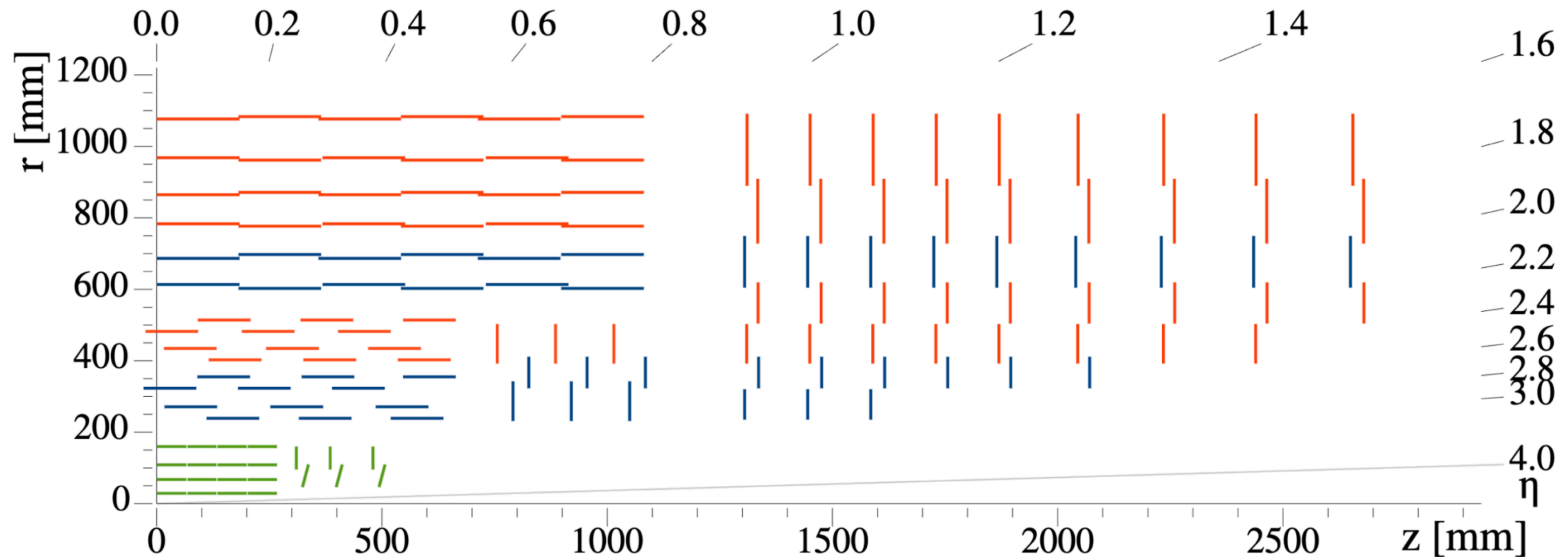
~4k modules $\Rightarrow$ ~18k modules,
6M channels $\Rightarrow$ 60M channels,
 $61 \text{ m}^2 \Rightarrow 165 \text{ m}^2$ (ITk) ²

Courtesy of S.F. Koch

HL-LHC Detector Upgrades

► CMS tracker

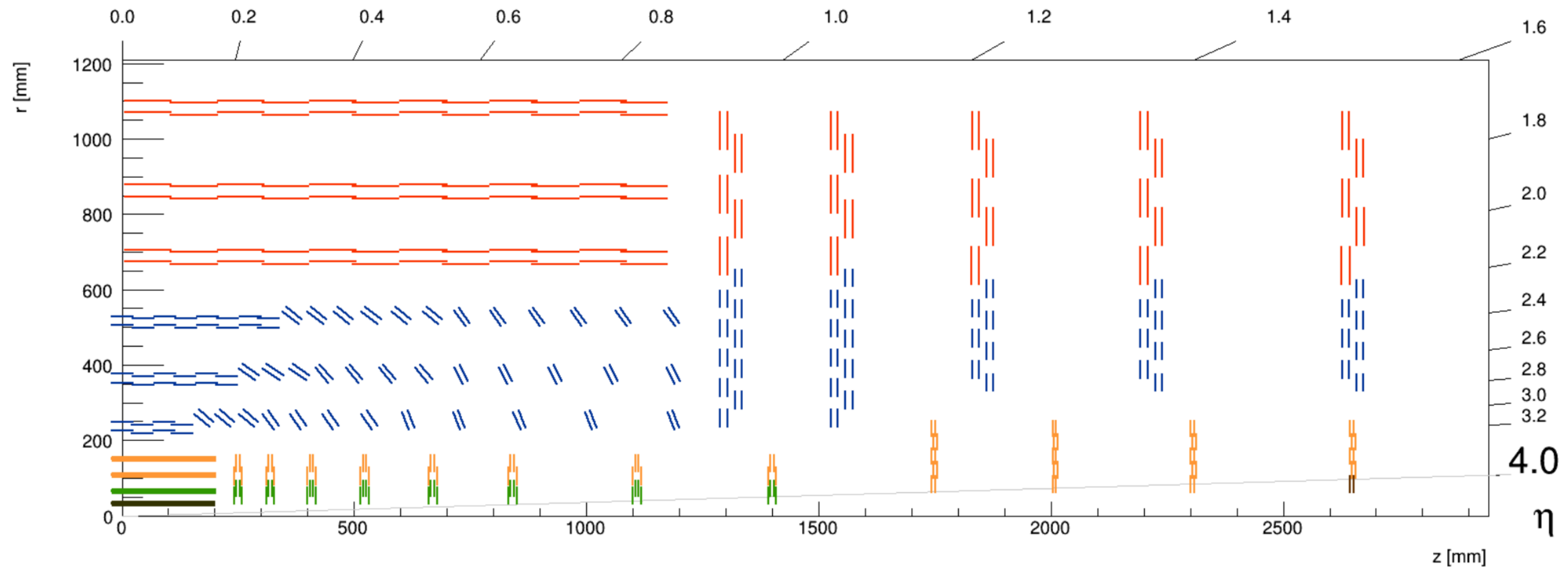
- New silicon pixel modules that feature smaller pixel sizes
- Silicon strips and macropixels. Outer tracker will for the first time feed data directly into the Level-1 trigger



HL-LHC Detector Upgrades

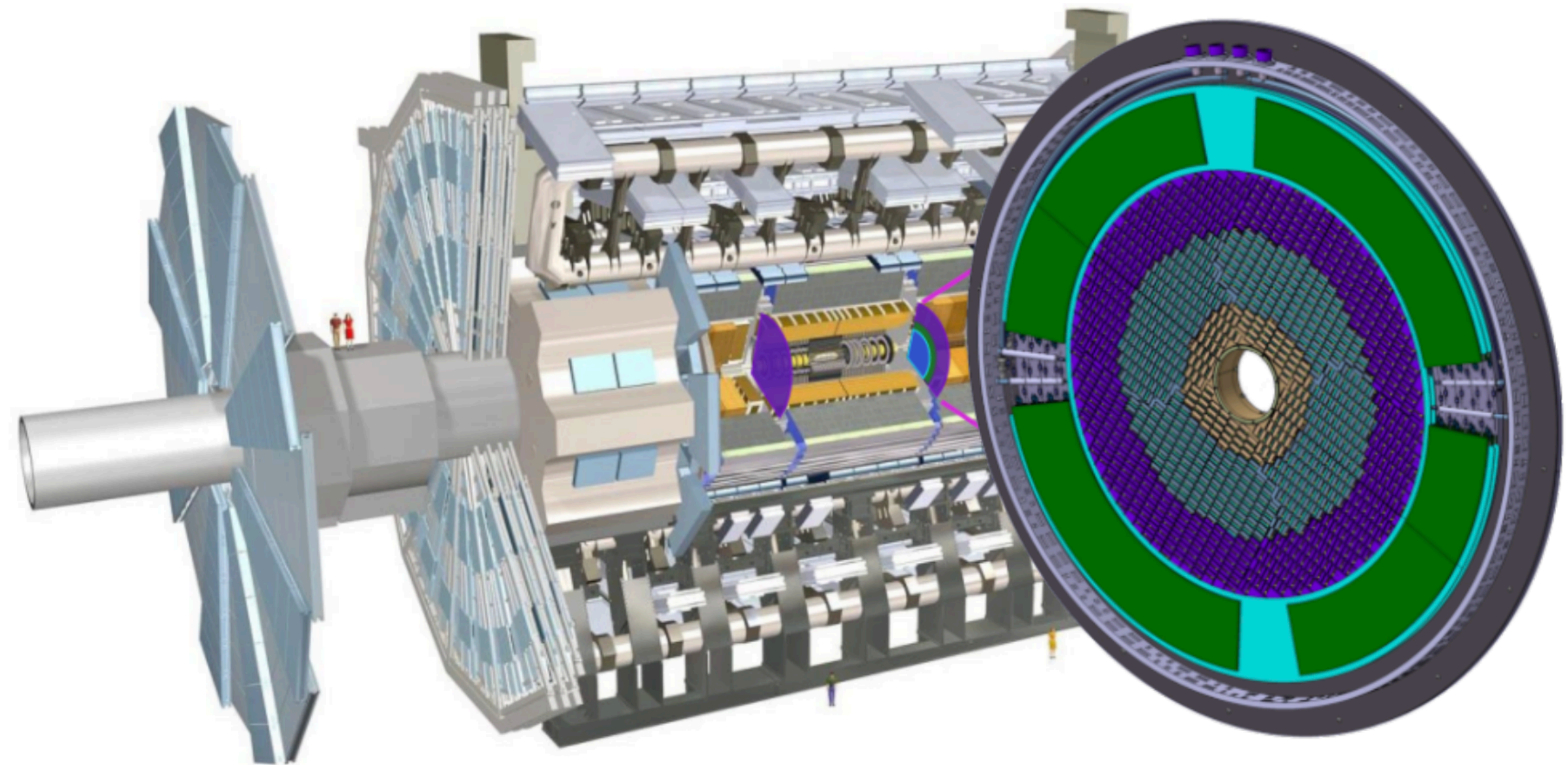
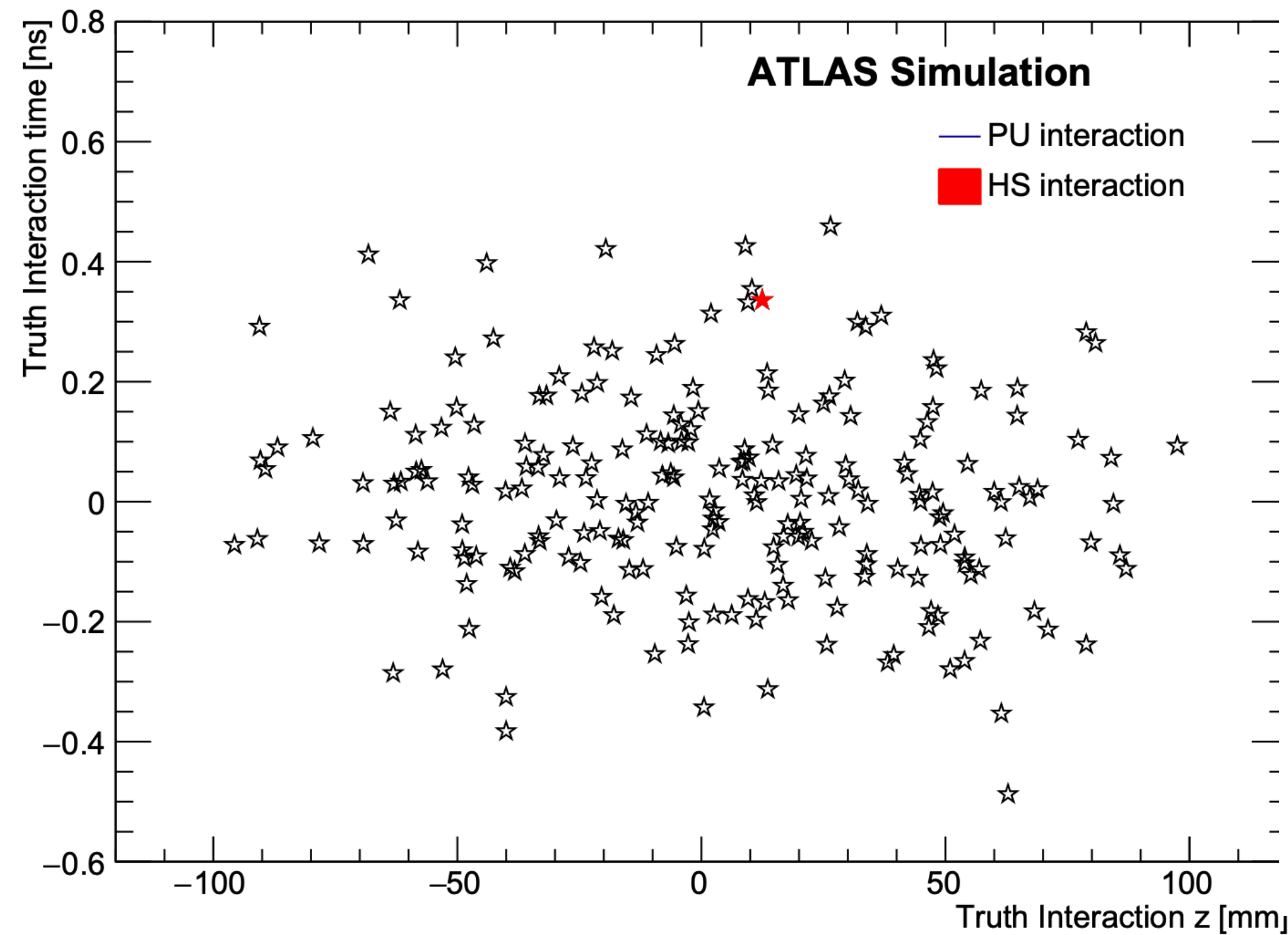
► CMS tracker

- New silicon pixel modules that feature smaller pixel sizes
- Silicon strips and macropixels. Outer tracker will for the first time feed data directly into the Level-1 trigger



HL-LHC Detector Upgrades

- ▶ ATLAS High Granularity Timing Detector
- ▶ 30 ps timing on top of ITk position resolution



HL-LHC Detector Upgrades

- ▶ CMS HGCAL
 - ▶ Replacement for current endcap calorimeters
 - ▶ Will be the largest silicon-based detector ever built
 - ▶ Effectively a 5D calorimeter
 - ▶ Performs 3D spatial & energy reconstruction, and has very high timing resolution



JINST 20 C01031

HL-LHC Detector Upgrades

► Detector upgrades

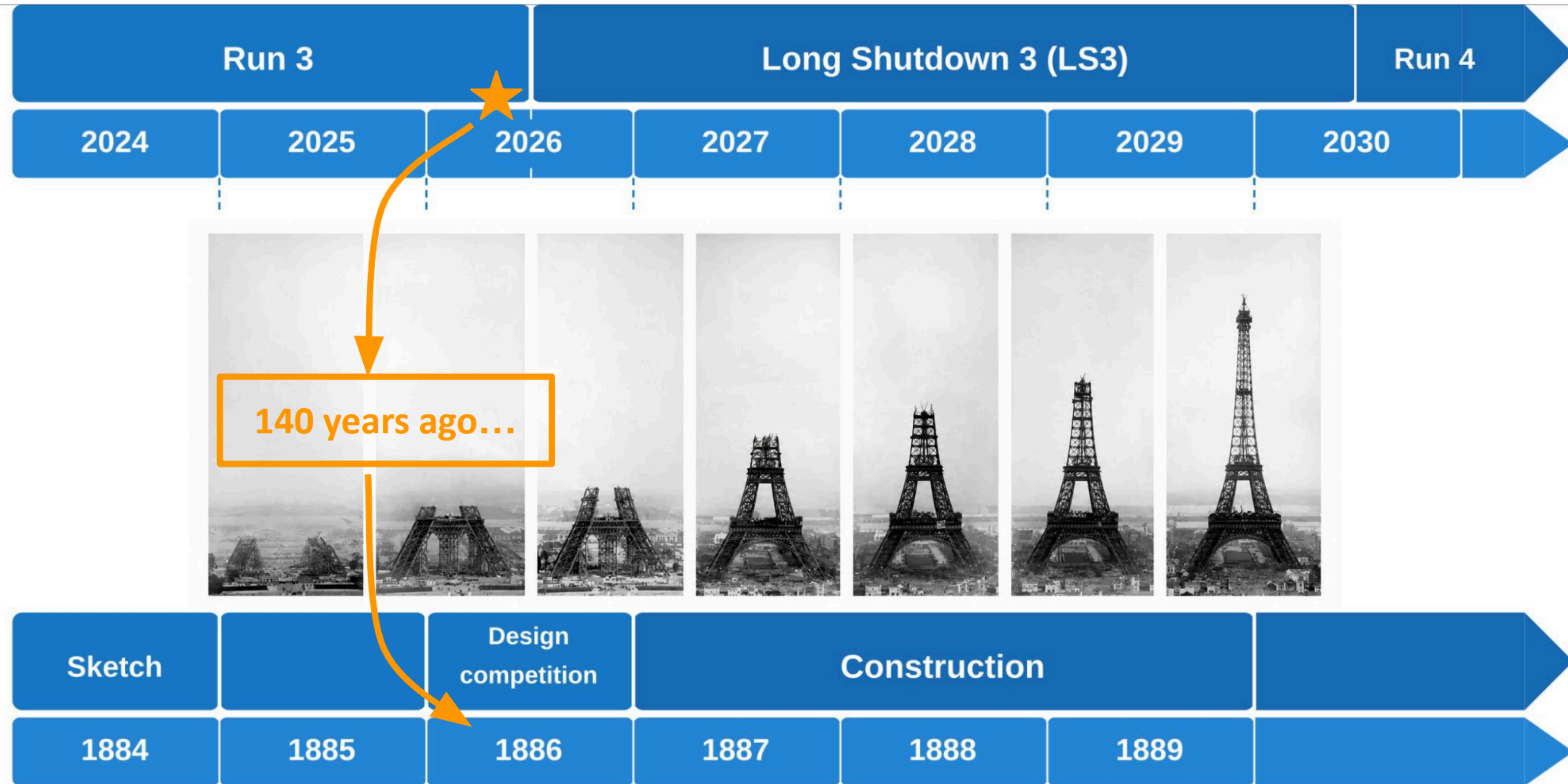


Image from Stefano Manzoni

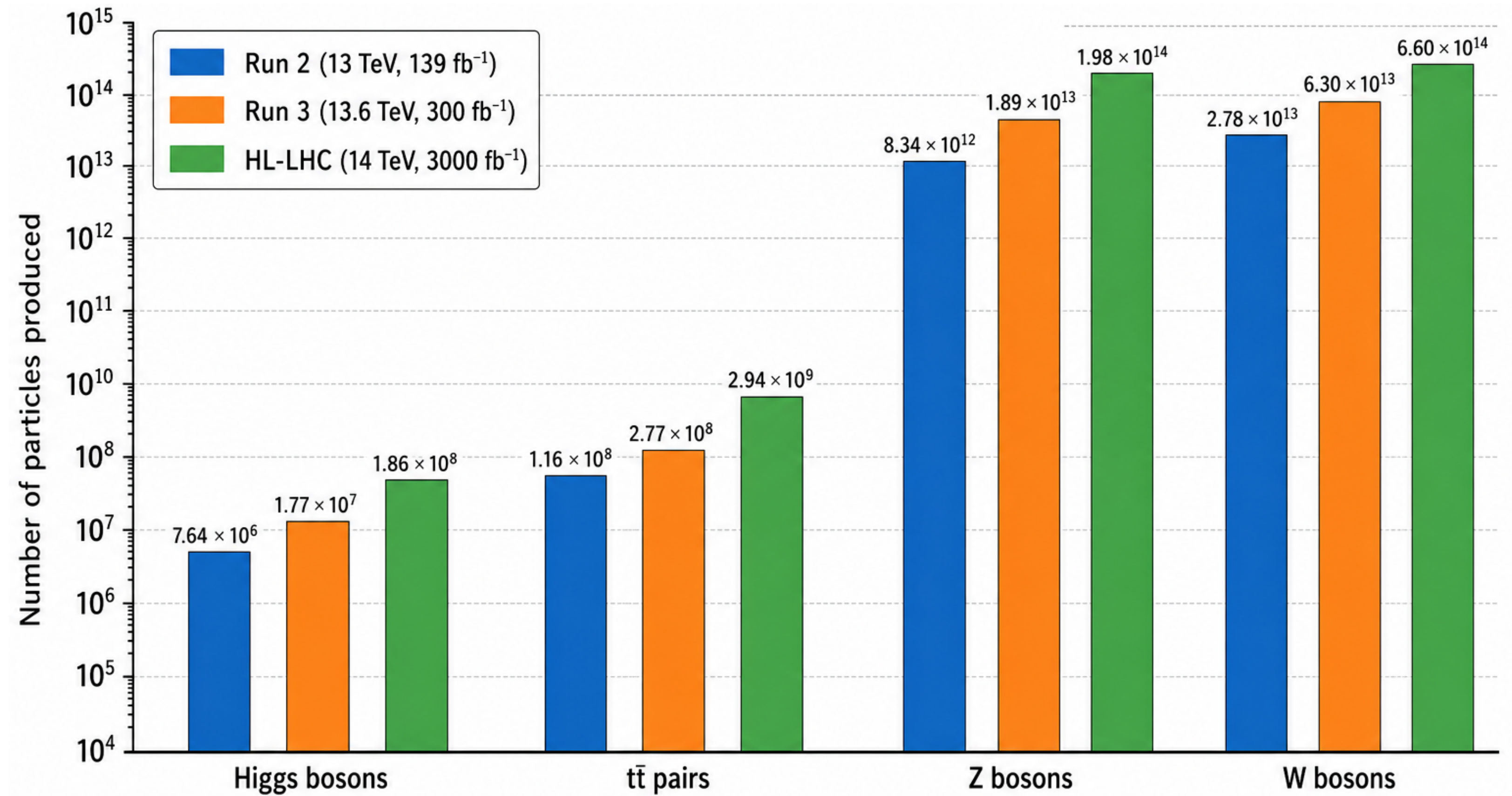
A physics programme for decades

A physics programme for decades 30 years of hurt?!



Scale

- ▶ HL-LHC (3000 fb^{-1})
 - ▶ 190 million Higgs bosons
 - ▶ 3 billion top quark pairs
 - ▶ 600 trillion W bosons
 - ▶ 200 trillion Z bosons

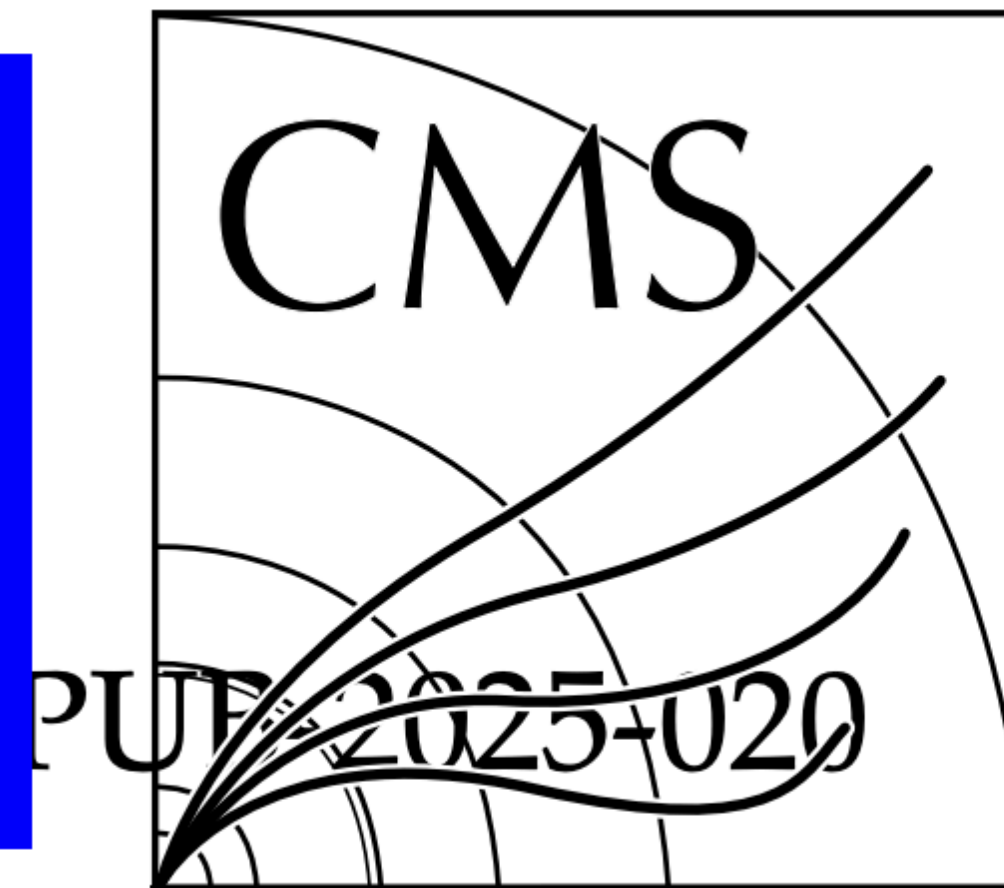


A note about projections

- ▶ S1, S2 and S3 uncertainty scenarios
- ▶ S2
 - ▶ Assumes reduced systematic uncertainties
 - ▶ Theoretical systematic uncertainties halved
 - ▶ Scaling of experimental systematic uncertainties depends on physics object and takes into account the different origin of uncertainties (statistics of the calibration samples, modelling of SM processes in the calibration, etc.)
- ▶ An additional scenario S3
 - ▶ Evaluates impact of recent improvements in object reconstruction relative to S2
 - ▶ Focuses on analyses already demonstrating advancements compared with Run2/3
- ▶ These still represent conservative targets.

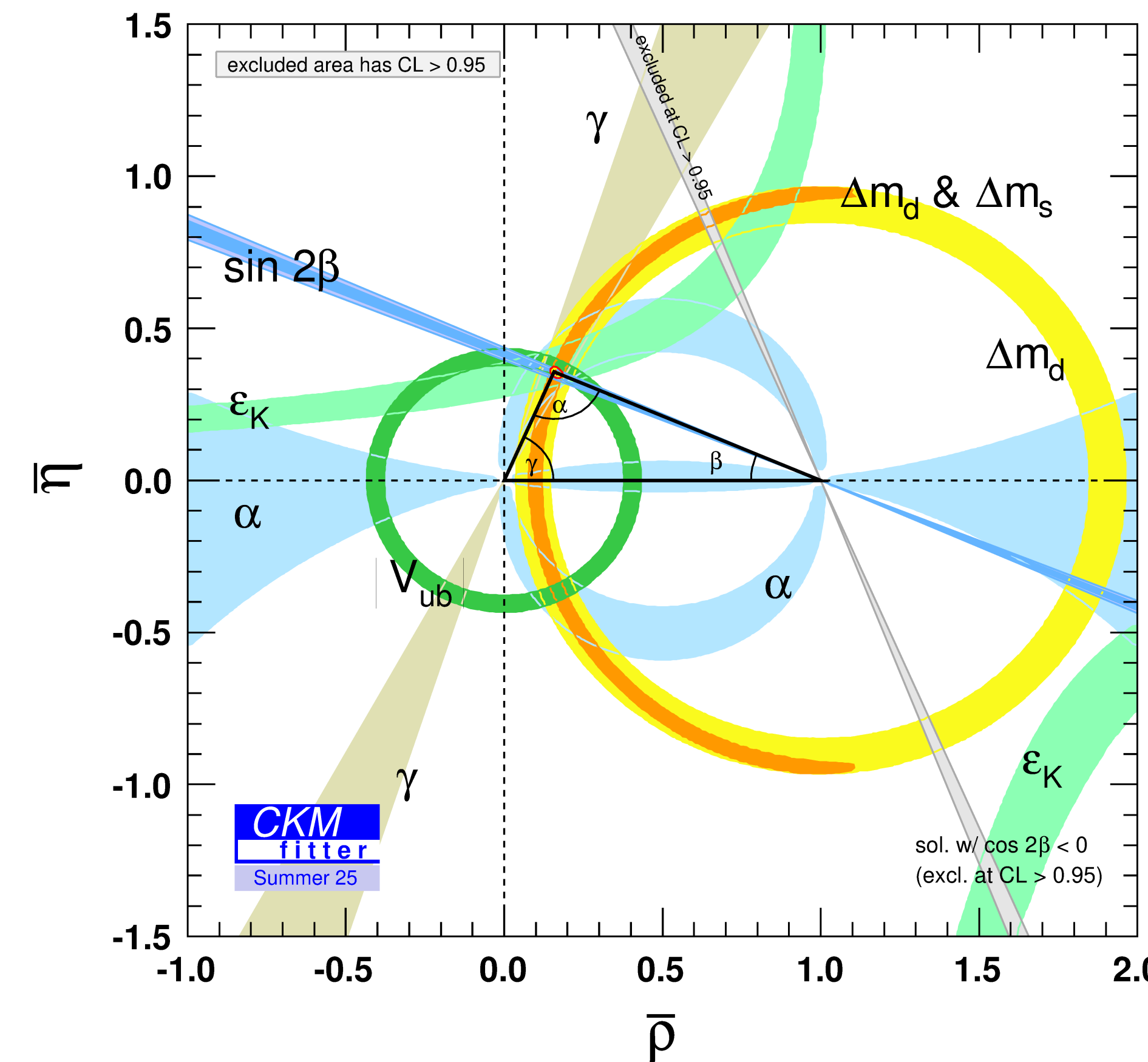
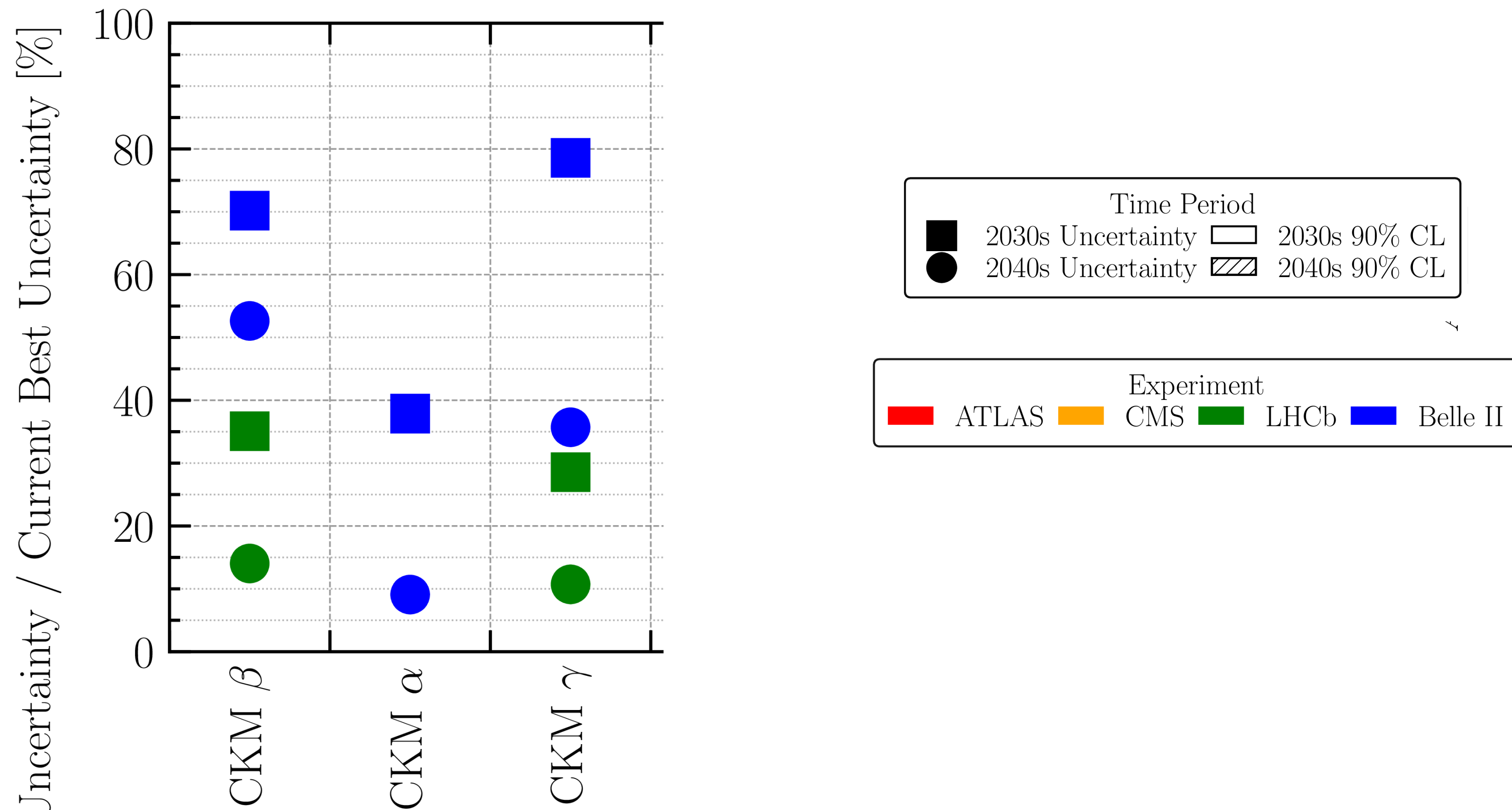
B-sector

- ▶ Some of the most intriguing tensions observed so far at LHC
- ▶ Some of the cleanest searches for new physics



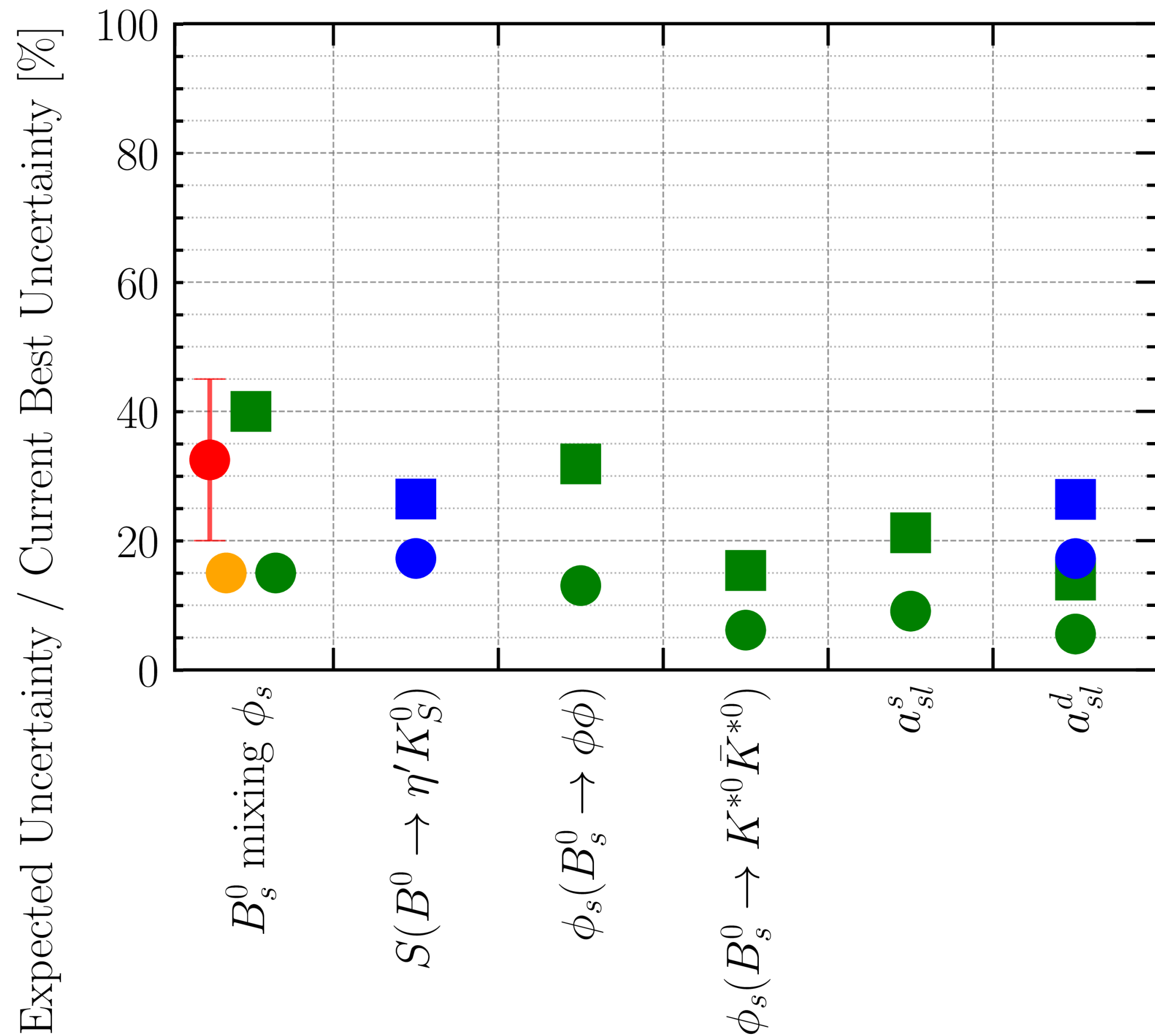
B-sector | CKM angles

- Some of the most intriguing tensions observed so far at LHC
- Some of the cleanest searches for new physics

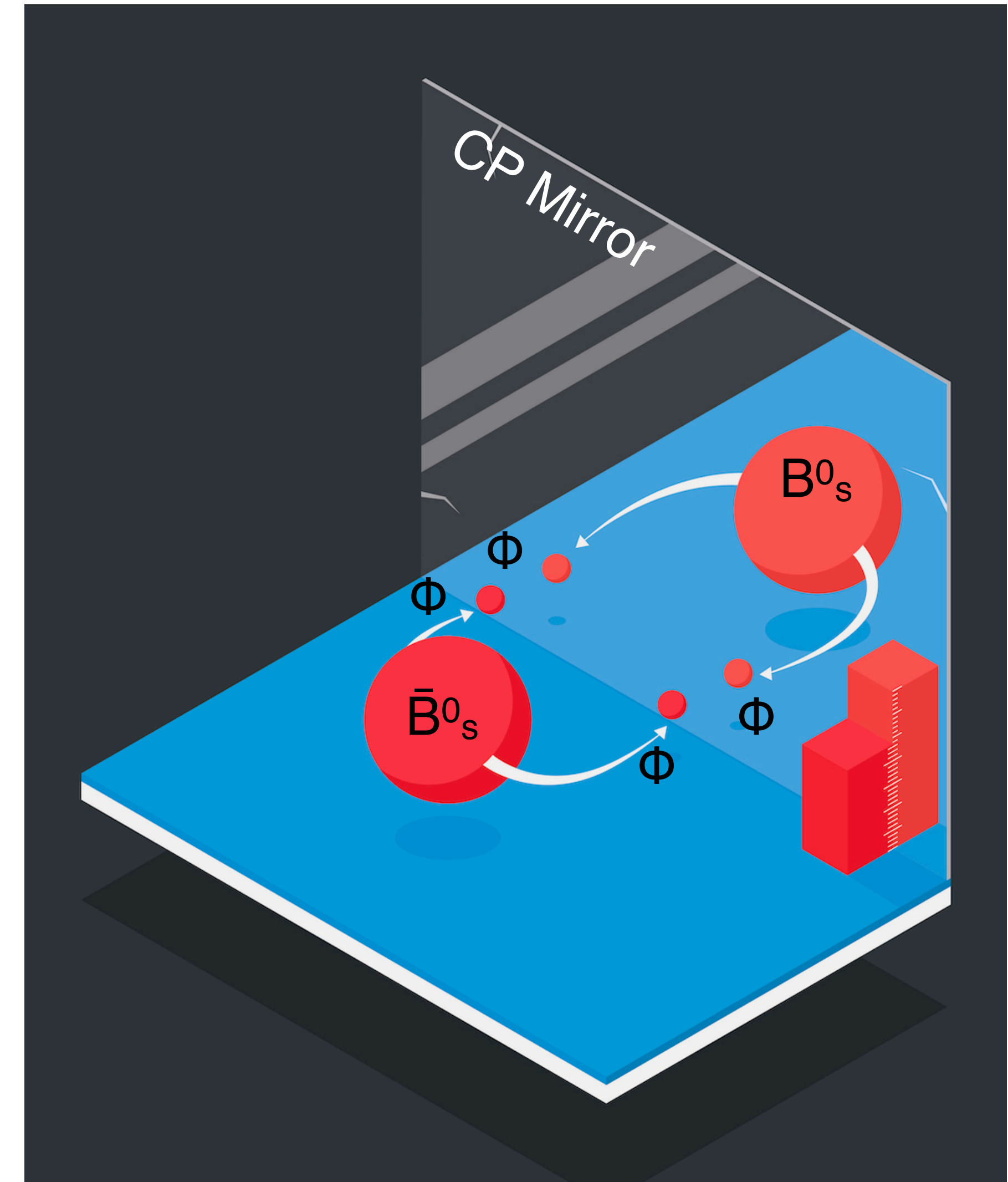


B-sector | CP violation

- ▶ Some of the most intriguing tensions observed so far at LHC
- ▶ Some of the cleanest searches for new physics

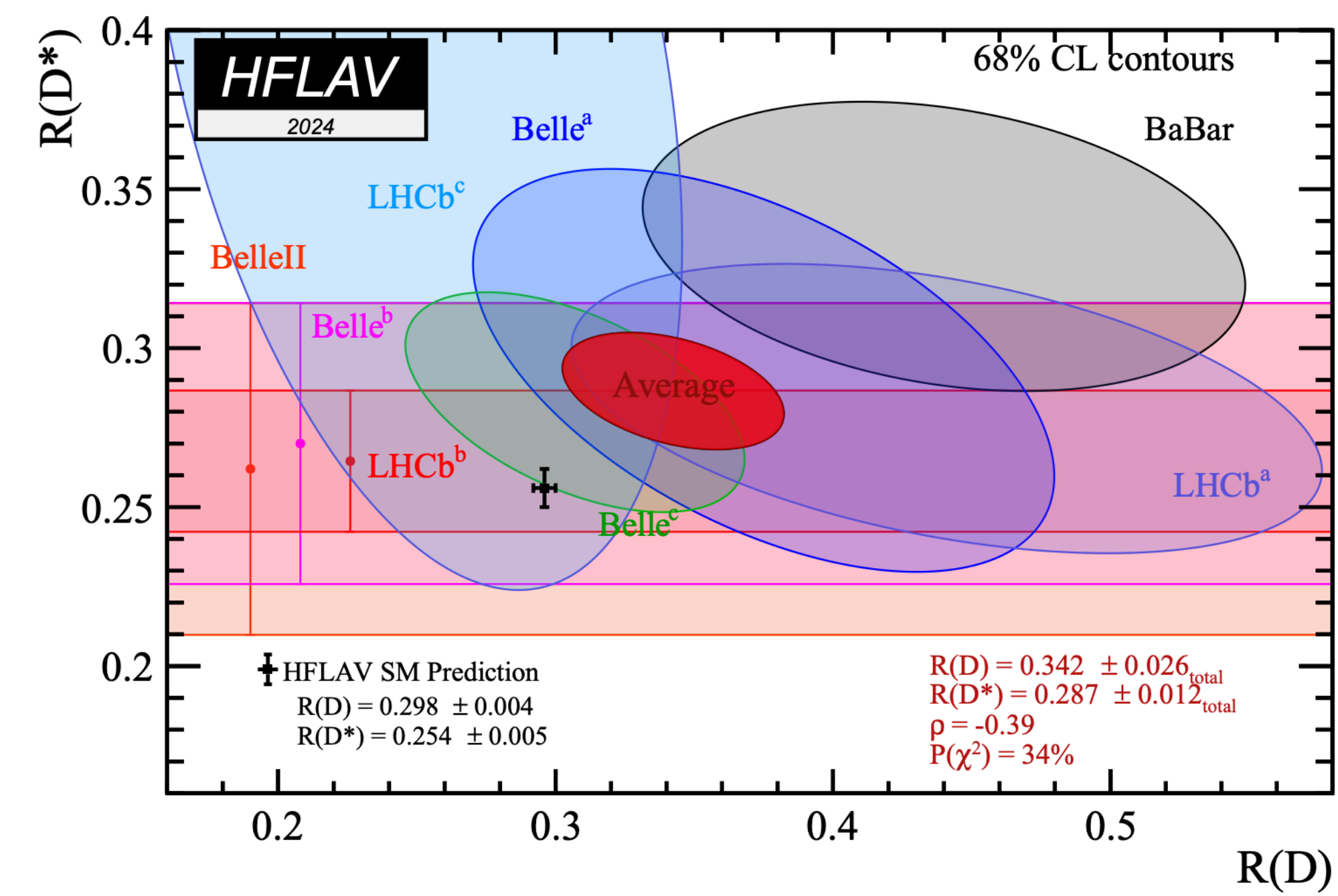
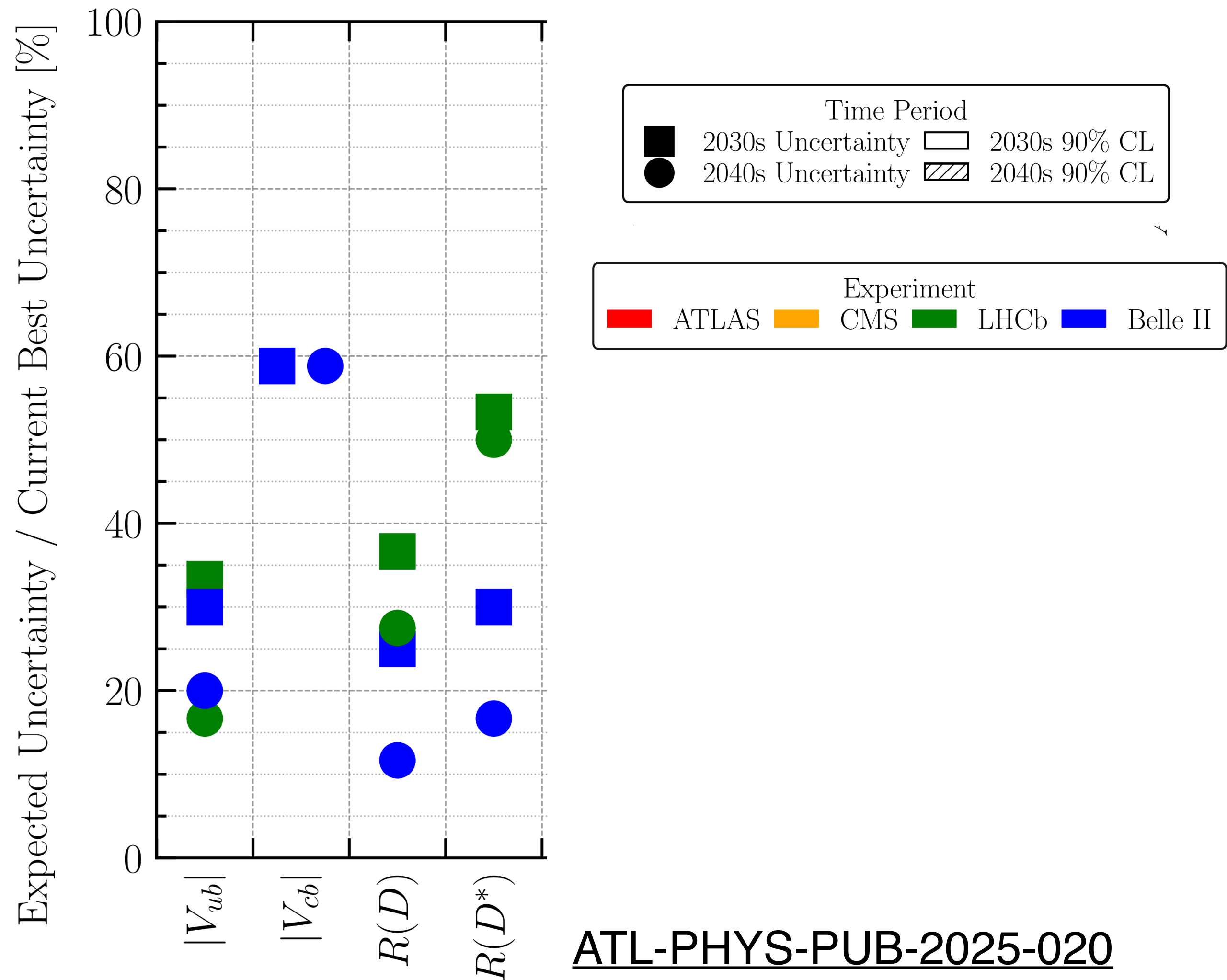


ATL-PHYS-PUB-2025-020



B-sector | Semileptonic decays

- ▶ Some of the most intriguing tensions observed so far at LHC
- ▶ Some of the cleanest searches for new physics



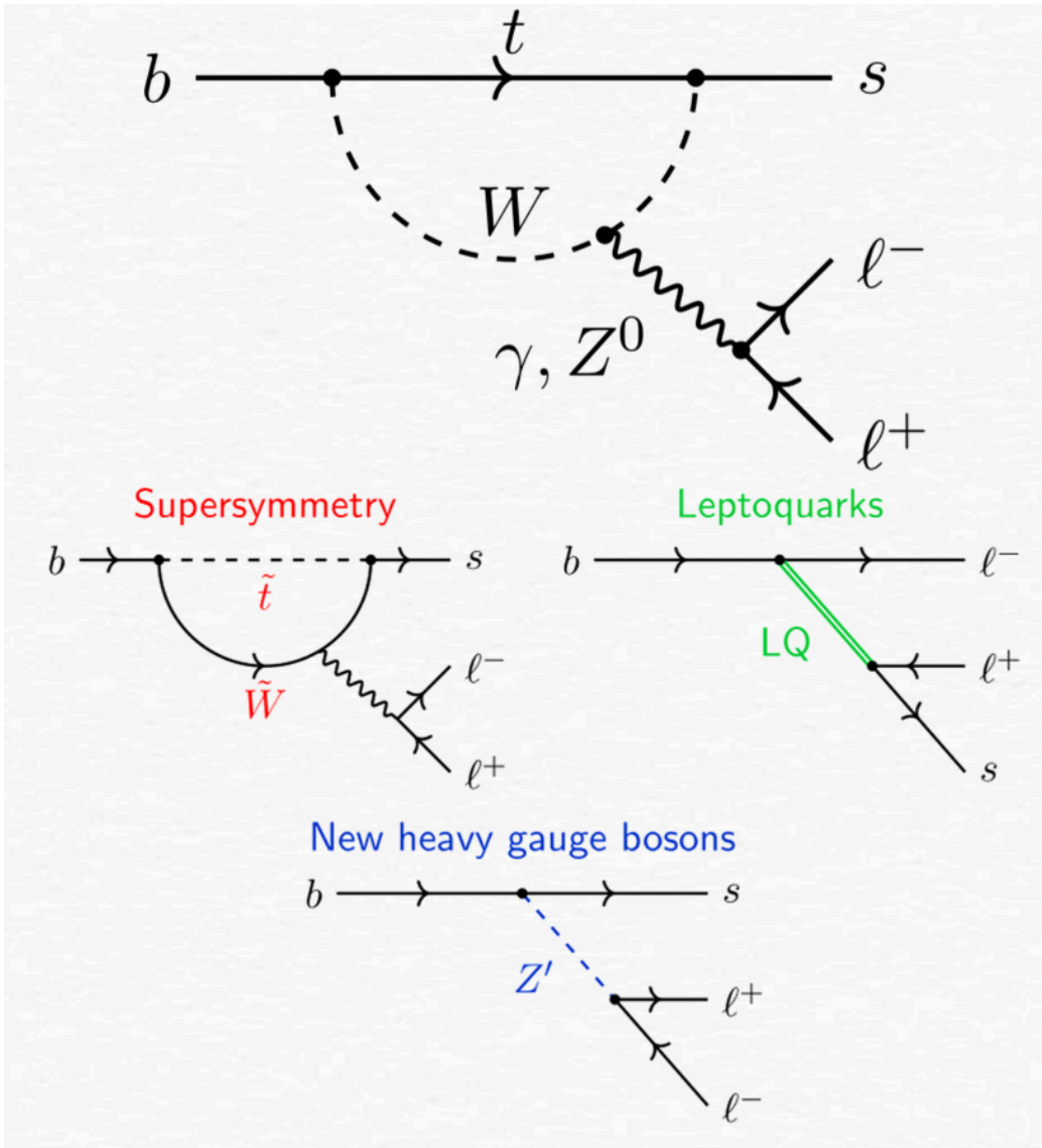
ATL-PHYS-PUB-2025-020

B-sector | $b \rightarrow s$ transitions

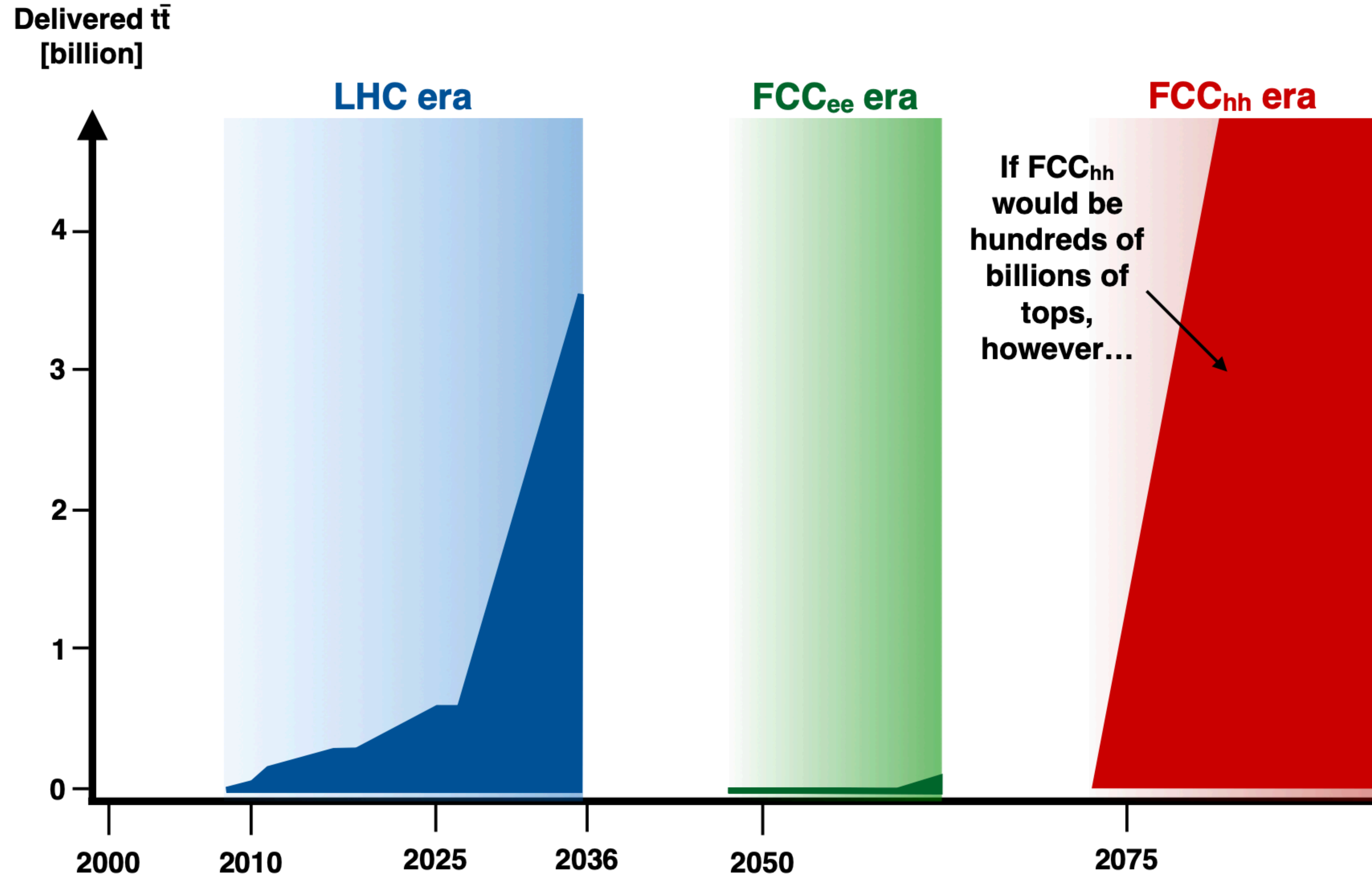
- ▶ Some of the most intriguing tensions observed so far at LHC
- ▶ Some of the cleanest searches for new physics

Experiment Assumed data sample	ATLAS 20.3-99.7 fb ⁻¹	CMS 116-140 fb ⁻¹	LHCb 2-9 fb ⁻¹	Belle II 364-1075 fb ⁻¹
Flavour-changing neutral current $b \rightarrow s \ell \ell$ decays				
$P'_5(B^0 \rightarrow K^{*0} \mu^+ \mu^-) [10^{-3}]^\dagger$	390 [41]	100 [42]	111 [43]	—
$\mathcal{B}(B^{+,0} \rightarrow K^{+,*0} \nu \bar{\nu})$	—	—	—	57%, 110% [17]
$\mathcal{B}(B^{+,0} \rightarrow K^{+,*0} \tau^+ \tau^-) [10^{-4}]$	—	—	—	< 10, < 18 [44]

Experiment Assumed data sample	ATLAS 3000 fb ⁻¹	CMS 3000 fb ⁻¹	LHCb 300 fb ⁻¹	Belle II 50 ab ⁻¹
Flavour-changing neutral current $b \rightarrow s \ell \ell$ decays				
$P'_5(B^0 \rightarrow K^{*0} \mu^+ \mu^-) [10^{-3}]^\dagger$	(47 – 82)	23	12	—
$\mathcal{B}(B^{+,0} \rightarrow K^{+,*0} \nu \bar{\nu})$	—	—	—	8%, 23%
$\mathcal{B}(B^{+,0} \rightarrow K^{+,*0} \tau^+ \tau^-) [10^{-4}]$	—	—	—	< 0.9, < 1.5

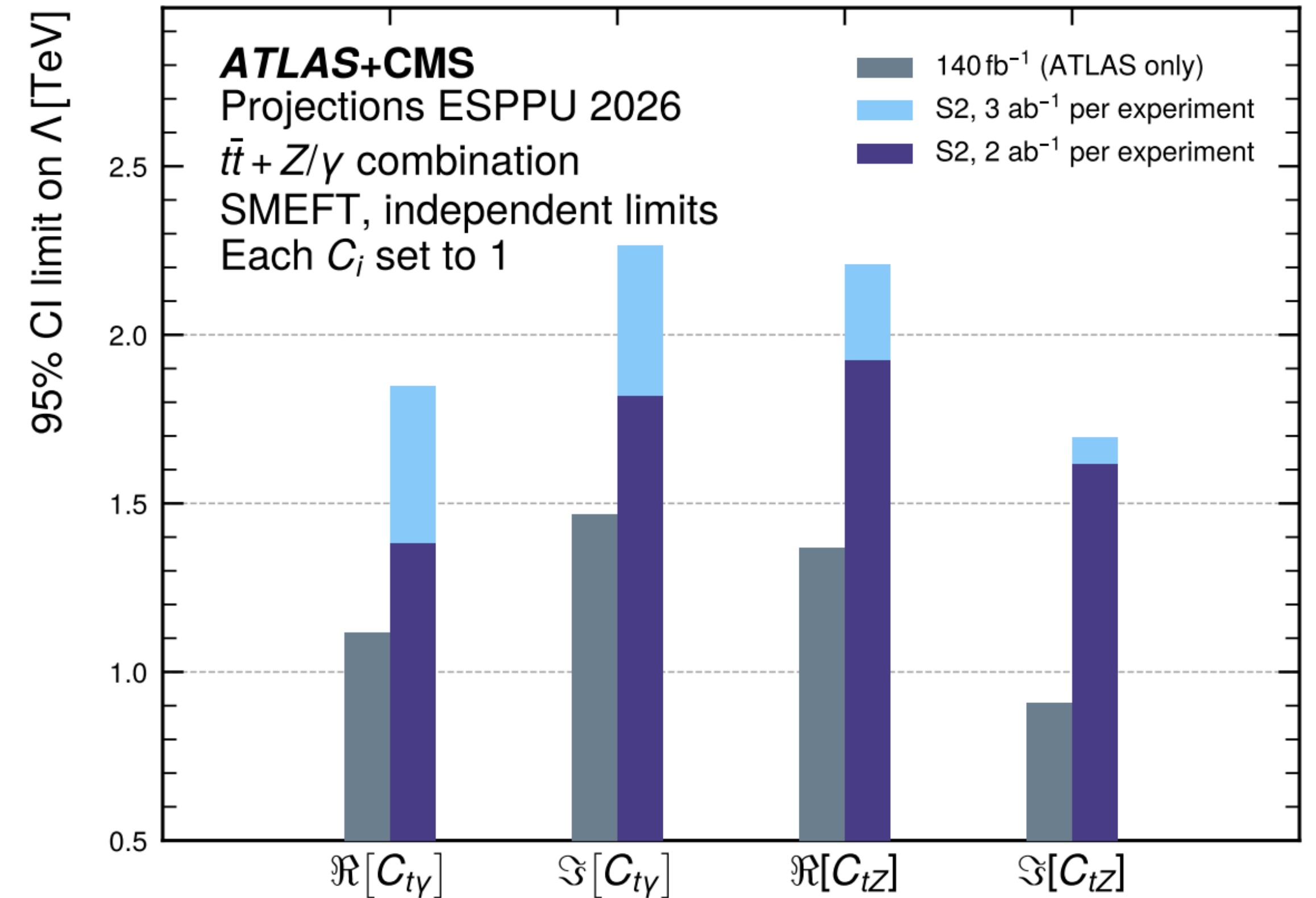
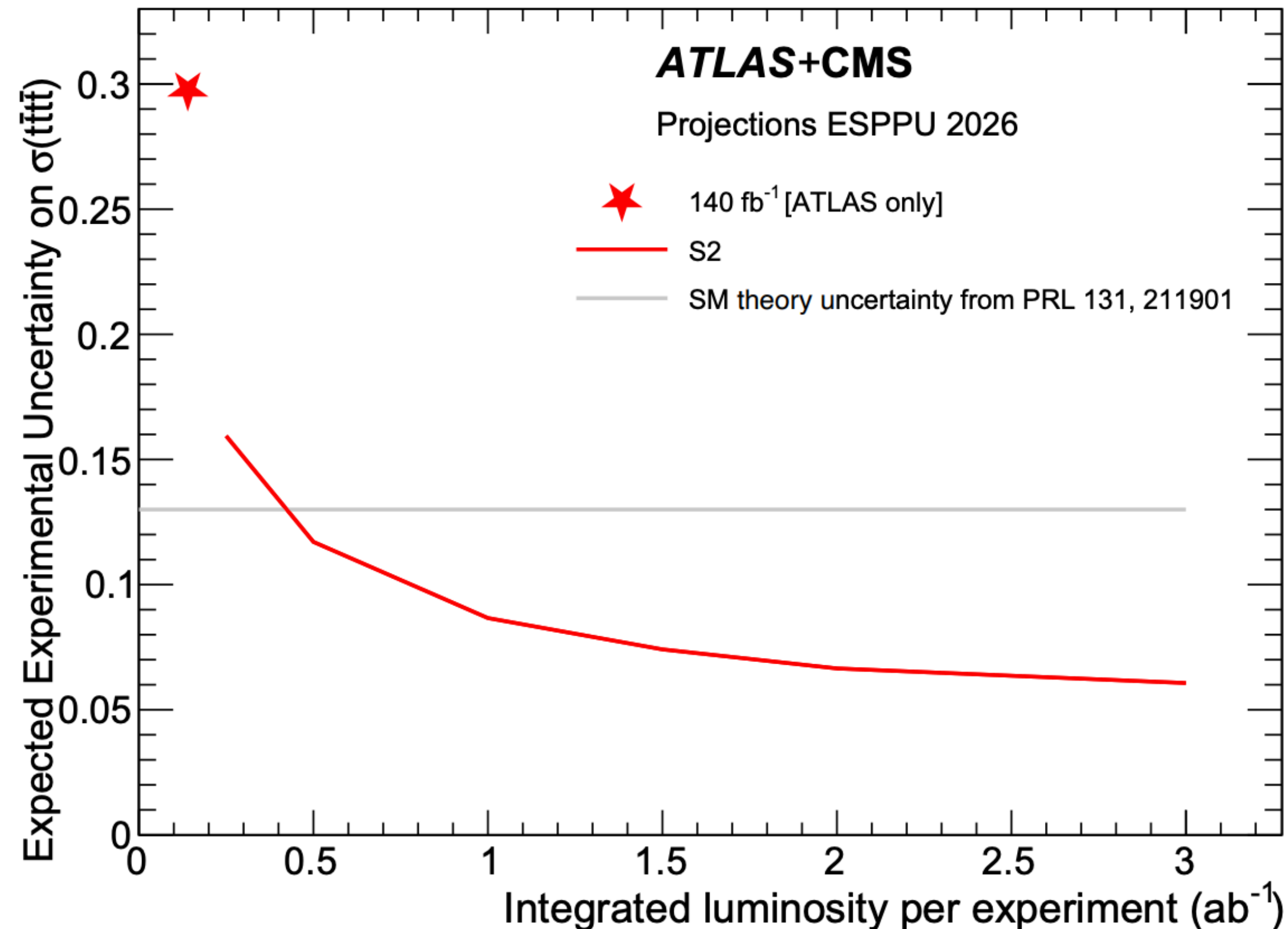


Top sector

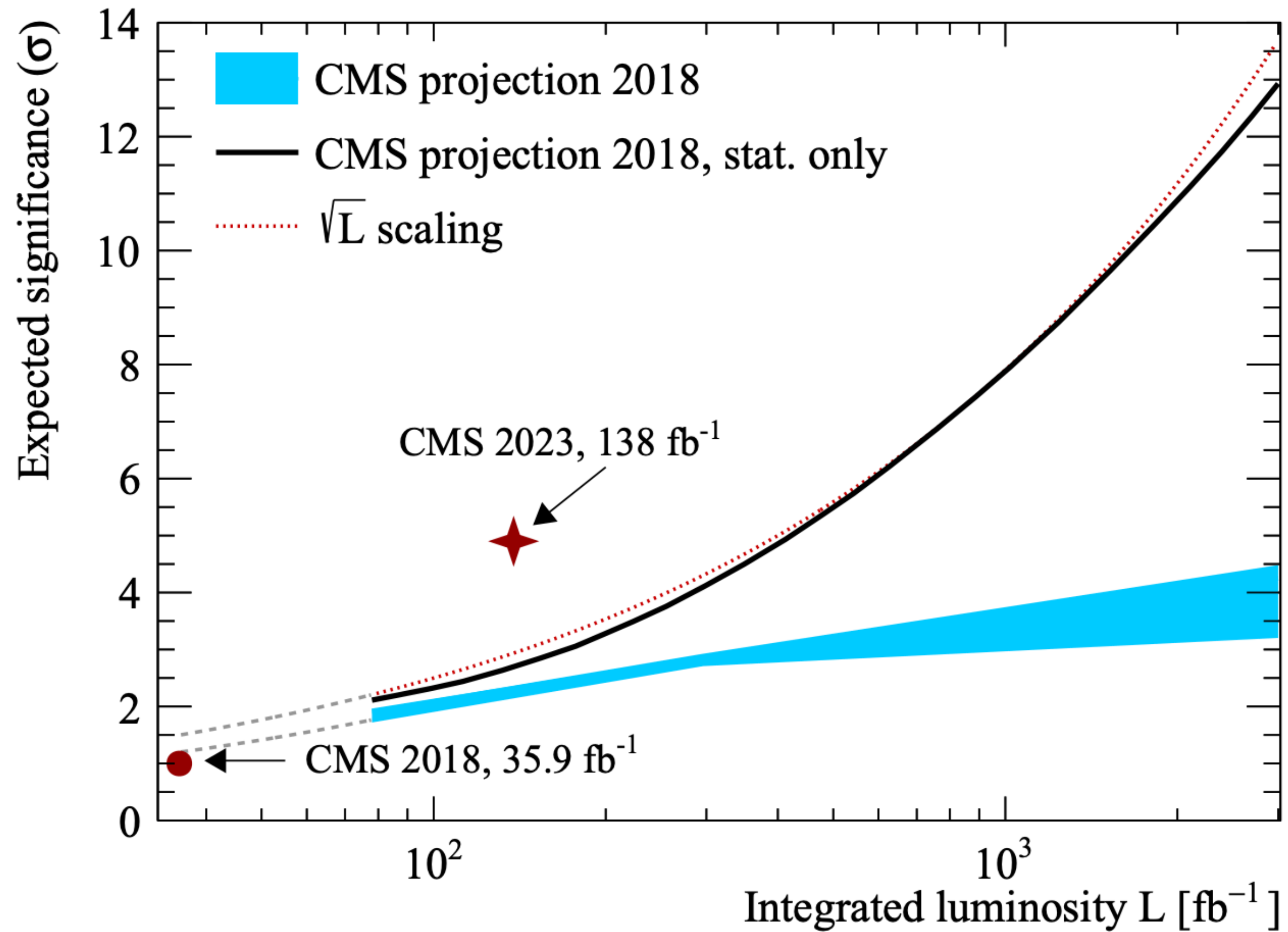


Top sector

- ▶ Ability to measure extremely rare processes
 - ▶ e.g. four-top-quark production with precision of 6%
 - ▶ Constraints on anomalous t-Z interactions probing new physics up to 2 TeV

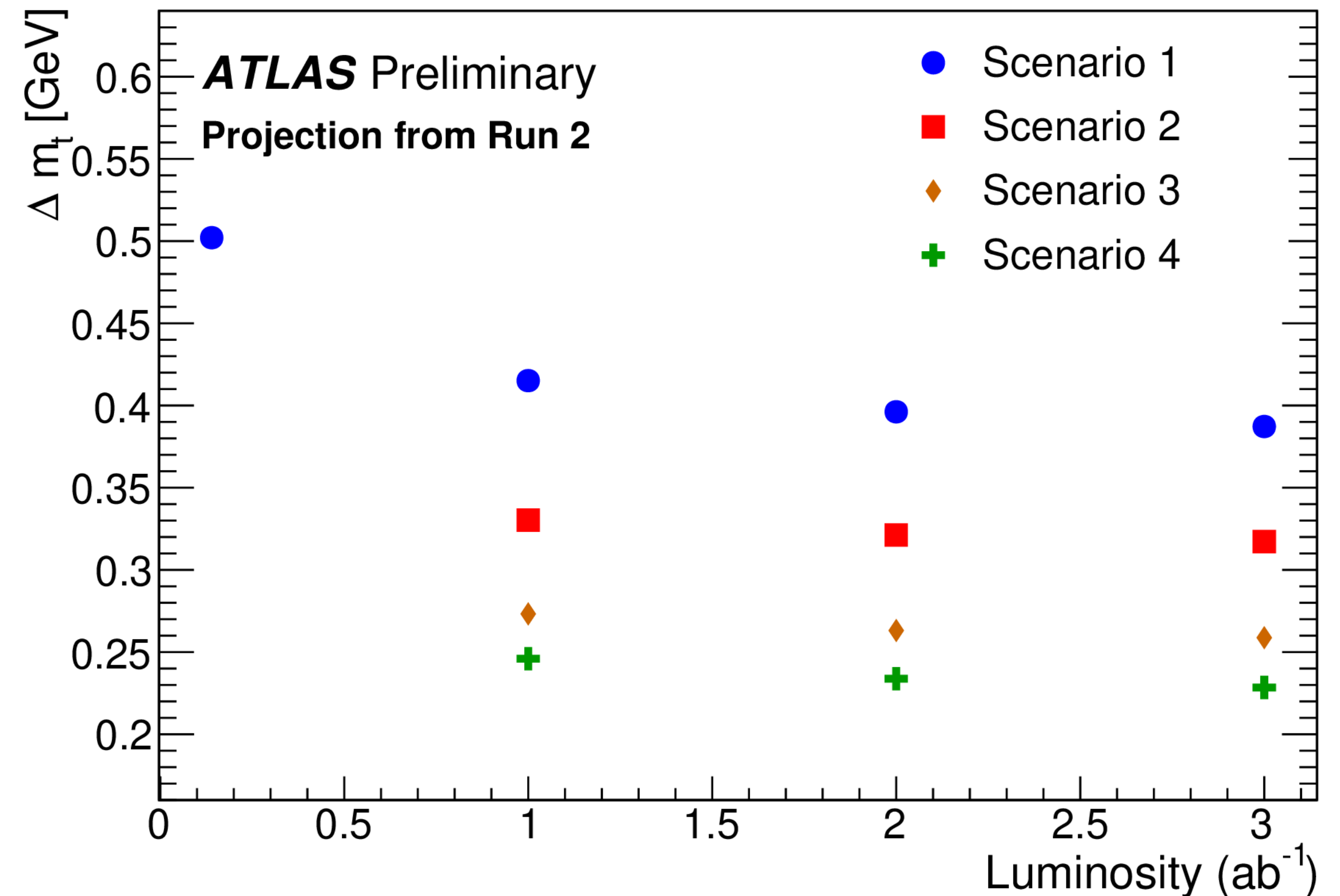


An aside...



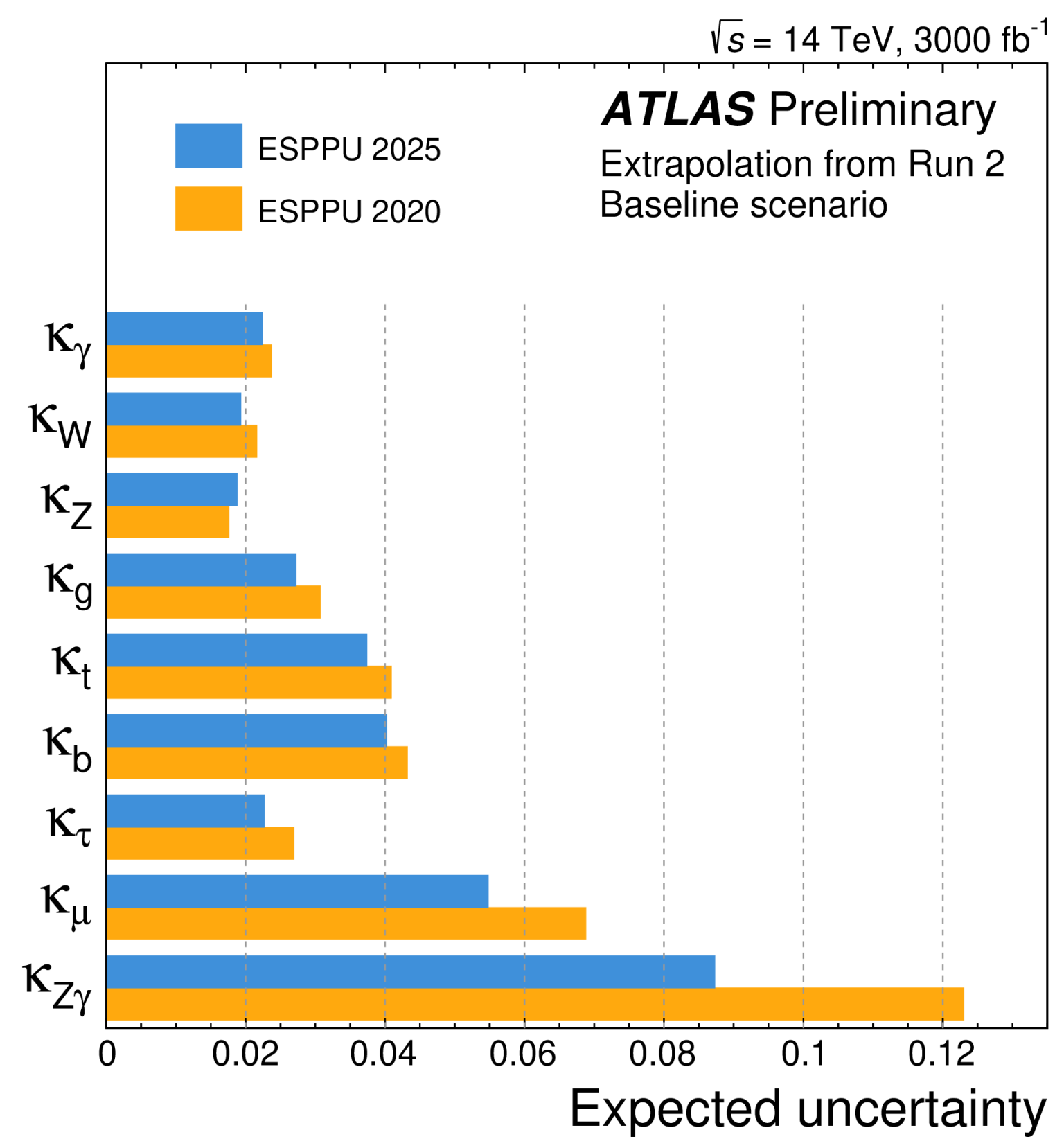
Top sector

- ▶ Ability to measure precision observables in extreme phase spaces
 - ▶ e.g. top mass from boosted tops

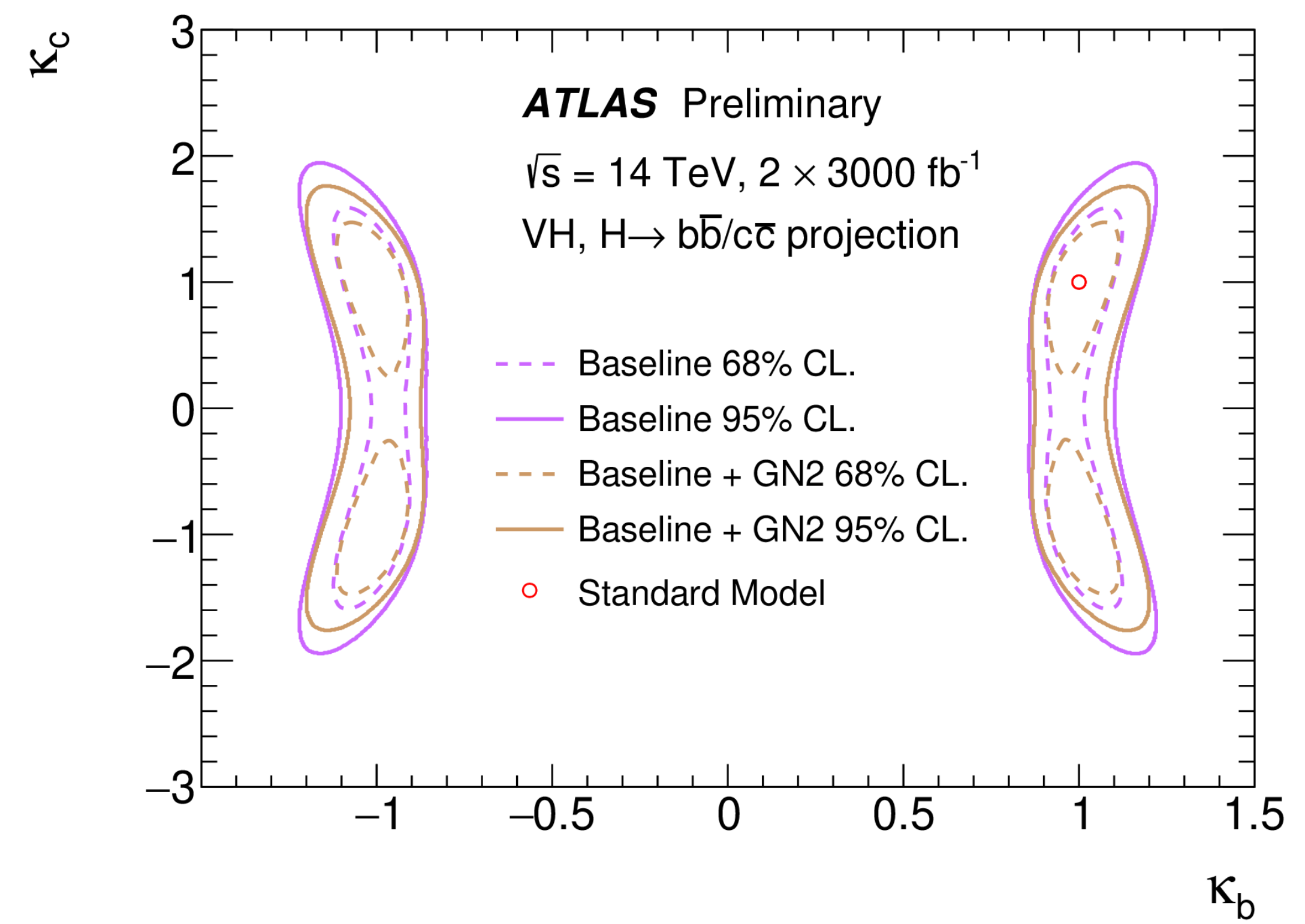


Higgs sector

- Rare Higgs decays and couplings
 - Observation of the $H \rightarrow \mu\mu$ and $H \rightarrow Z\gamma$ rare processes with a precision of 3% and 7%
 - κ_c can be constrained to < 1.5 at 95% CL, improvement of 30%



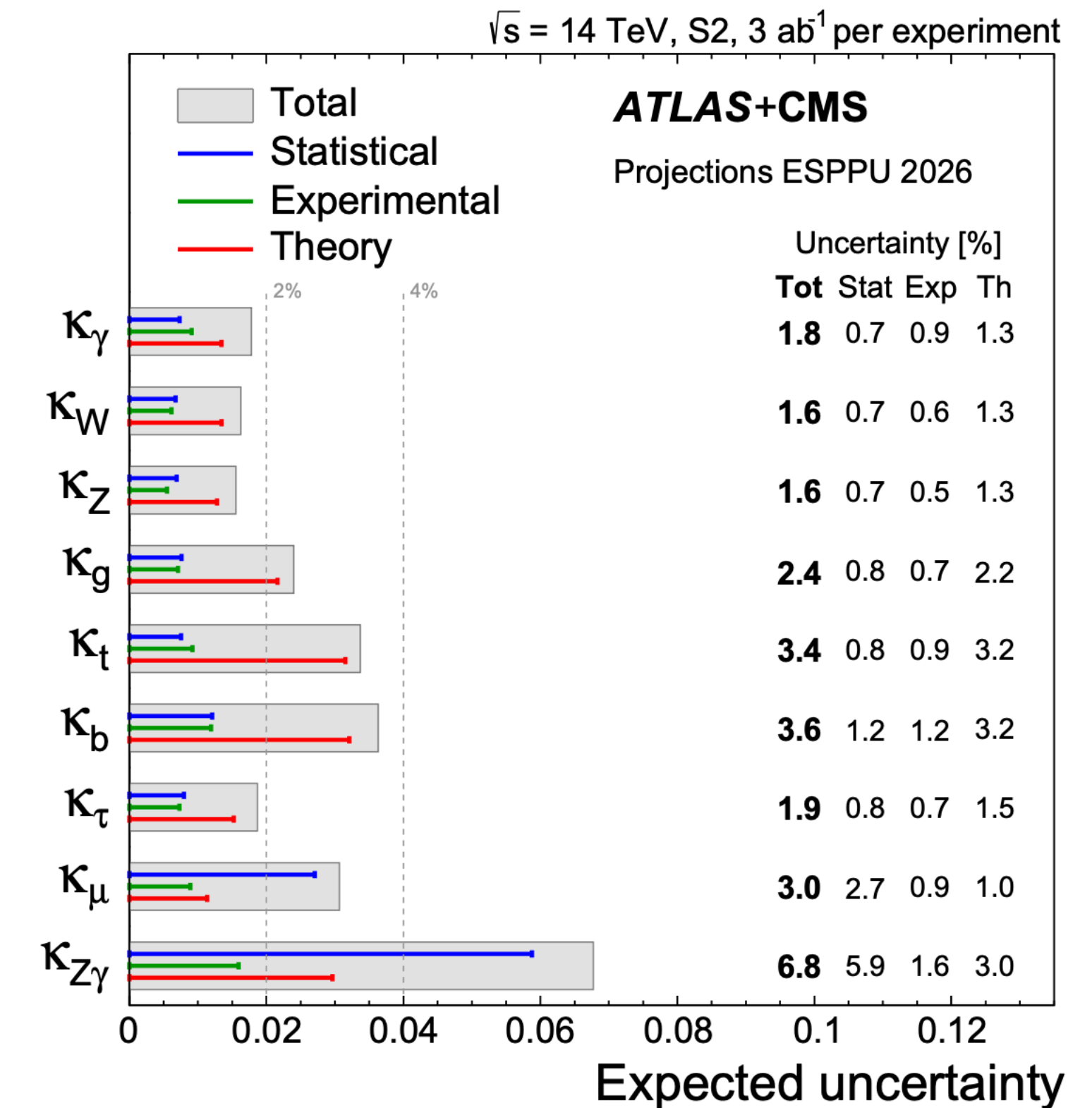
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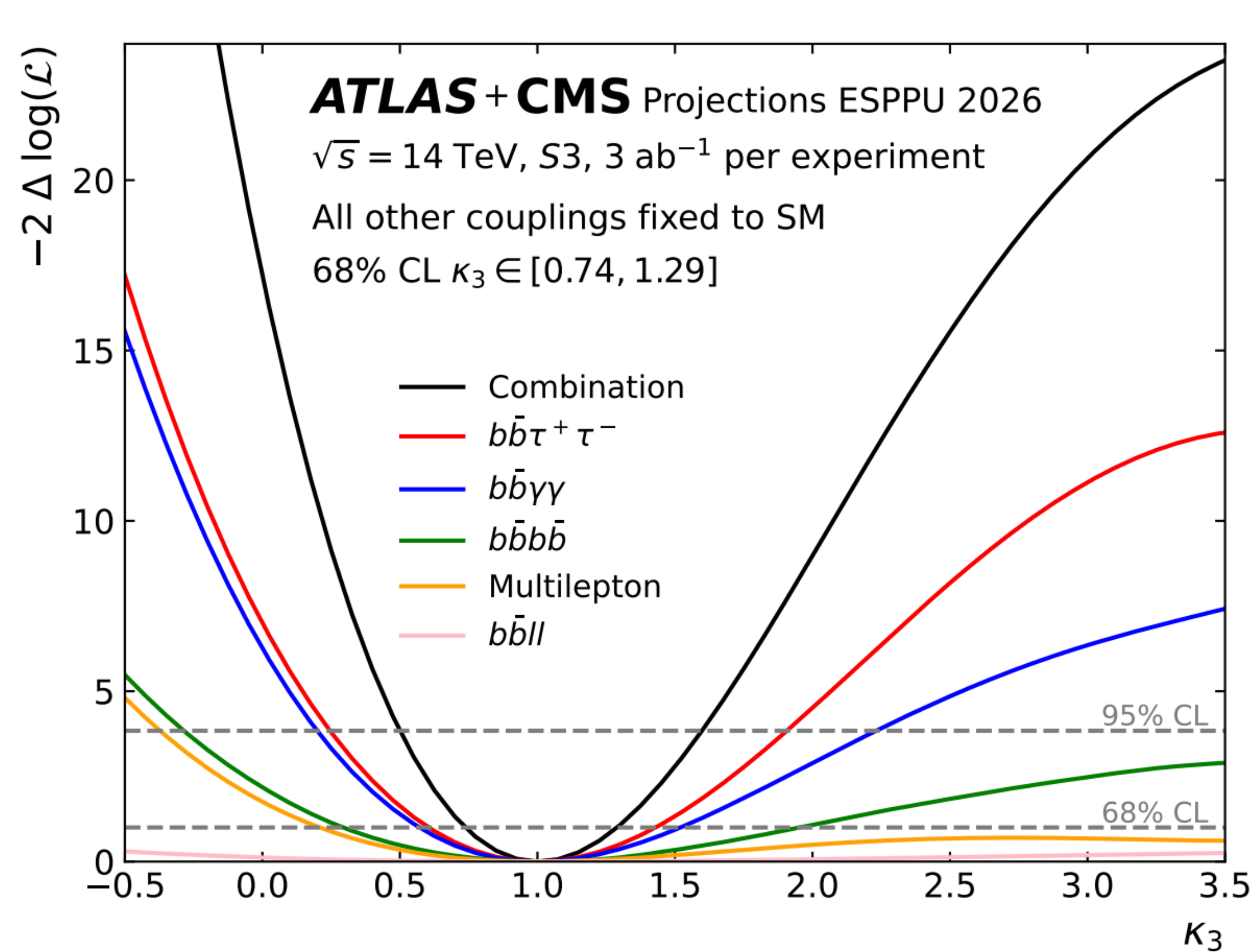
Higgs sector

- ▶ Measurement of the other main Higgs boson couplings with a precision between 1.6 and 3.6%
- ▶ Reducing theoretical uncertainties would significantly enhance the precision of most measurements
- ▶ Combination of the $H \rightarrow ZZ$ off-shell cross section can constrain the Higgs width with an uncertainty of 0.7 MeV with 3 ab^{-1}

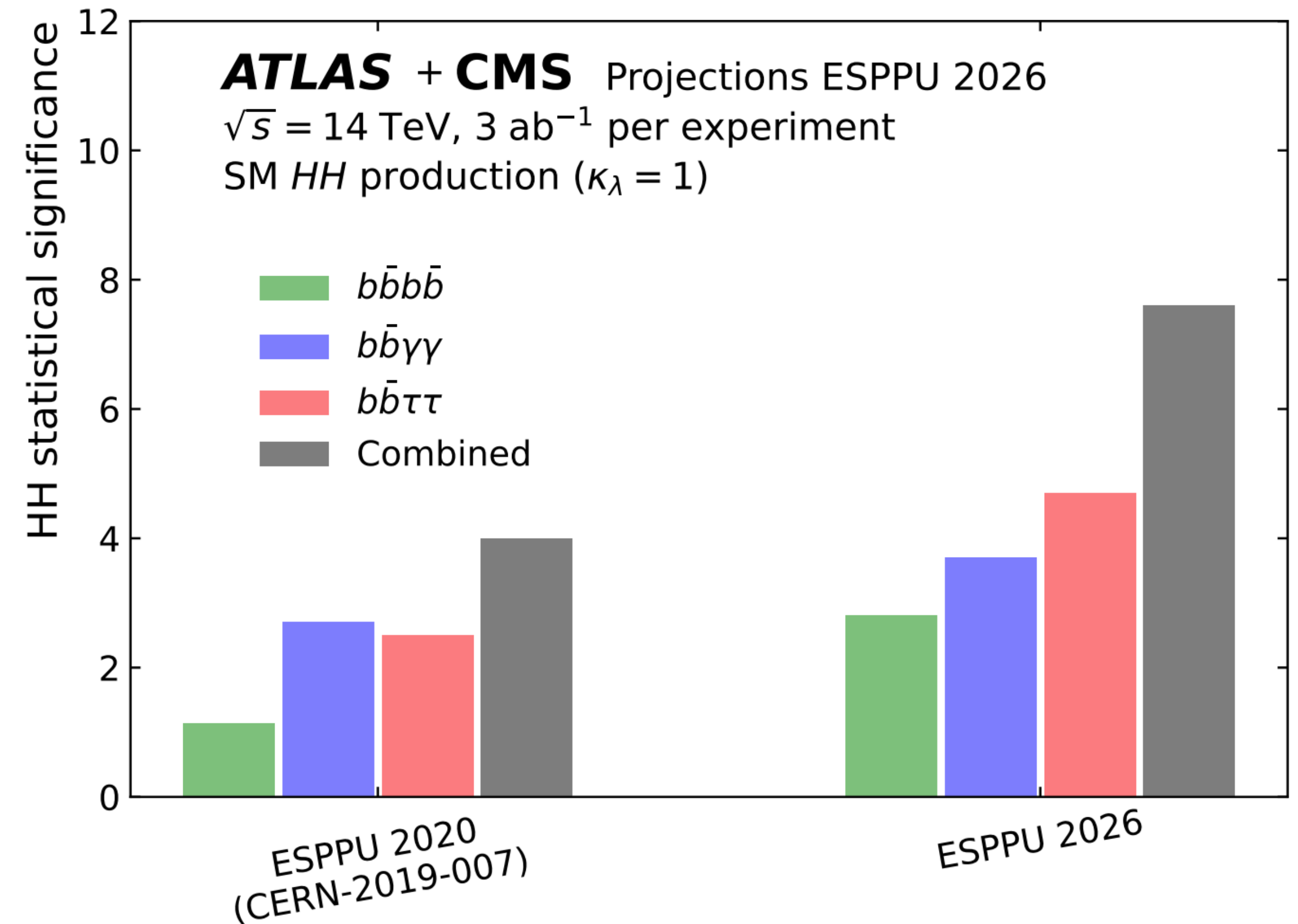


Higgs sector

- Observation of SM di-Higgs at $>7\sigma$;
- Measurement of trilinear self-coupling λ_3 with precision better than 30%
- Analysis techniques improvements strengthen precision even w/o detector upgrades

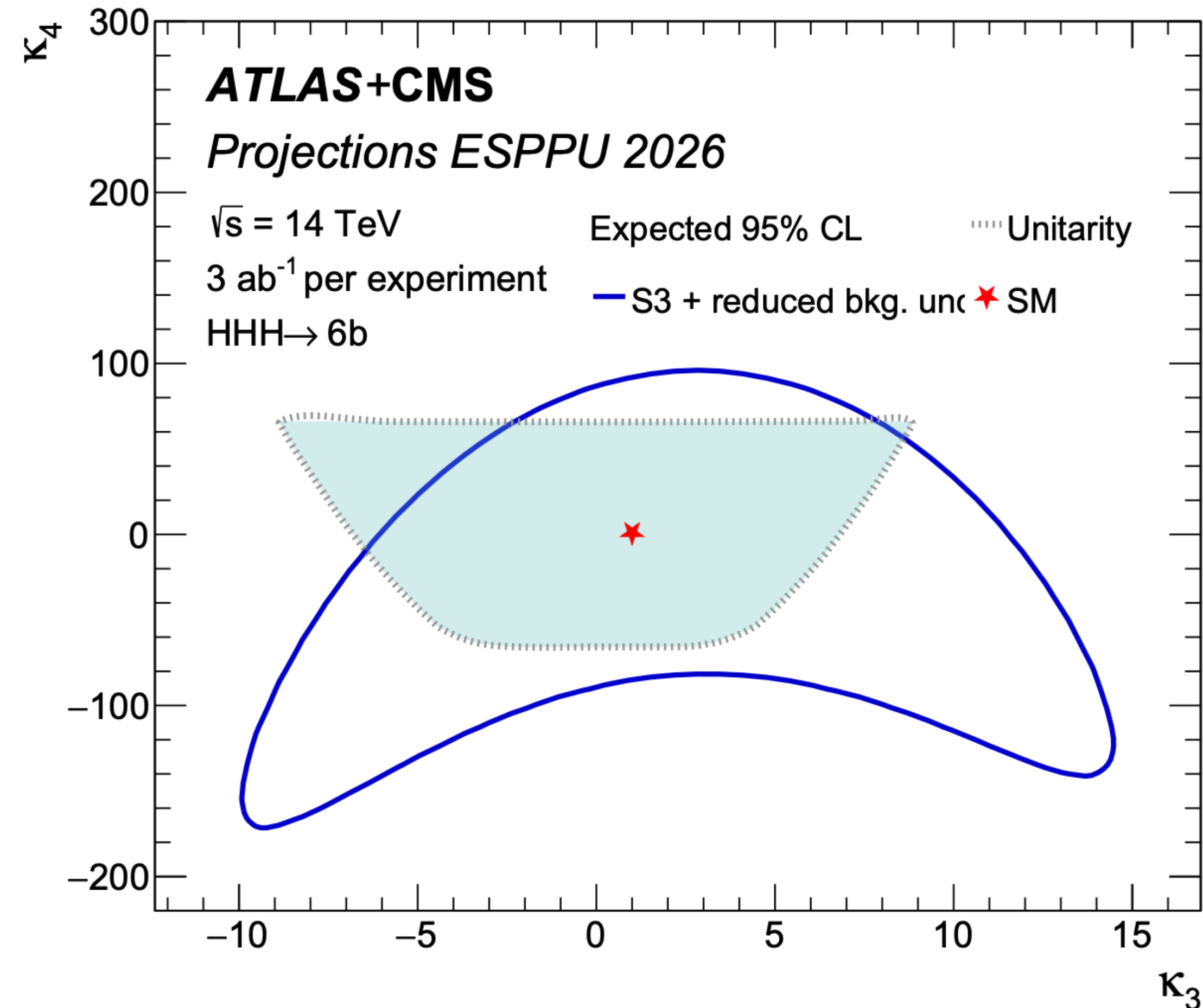
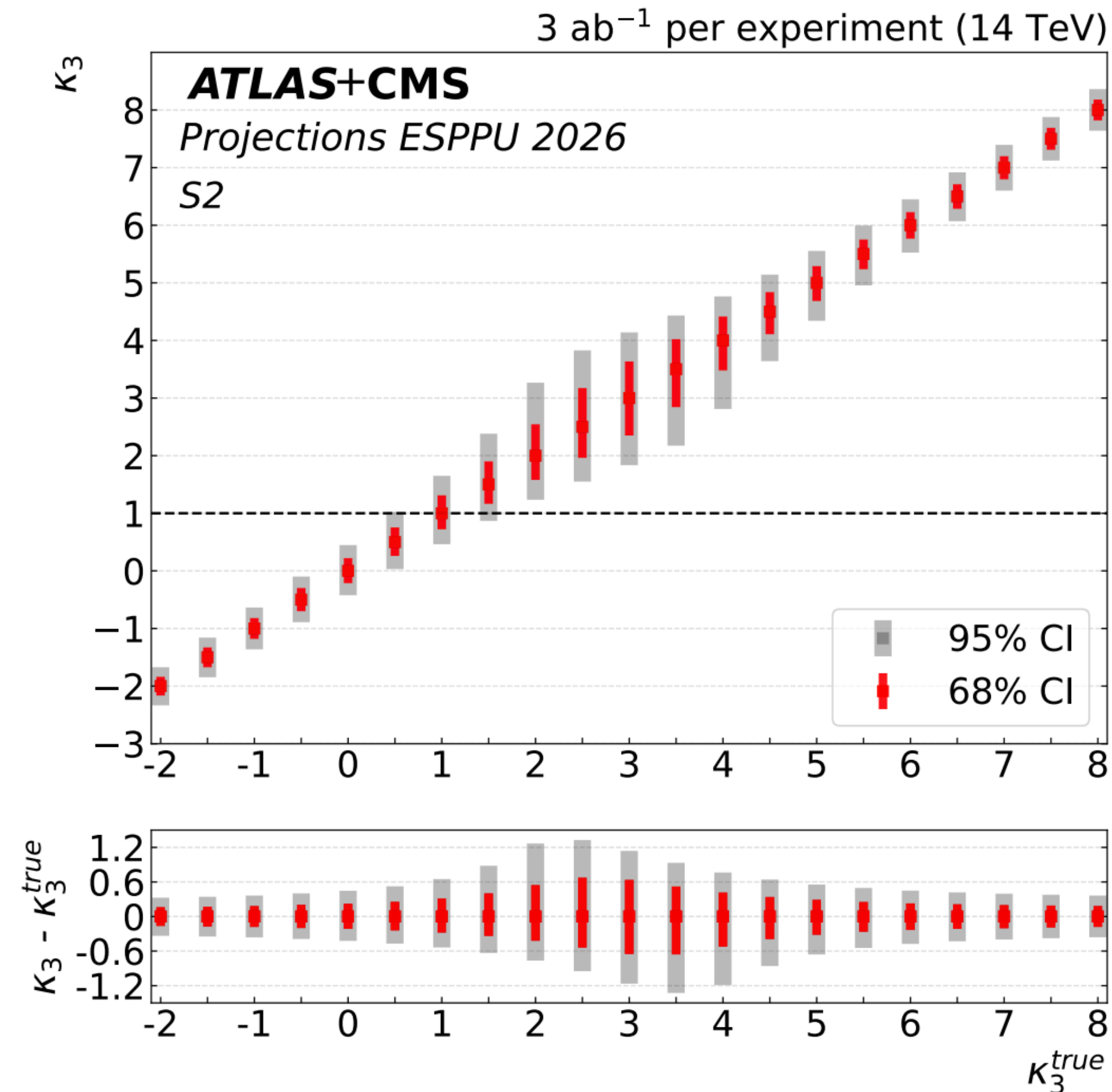


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Higgs sector

- σ_{HH} is minimal when true value of $\kappa_3 \sim 2.5$ - still good sensitivity
- Start excluding region bounded by the unitarity limit in κ_3 vs κ_4



The shape of the Higgs potential

- Low energy Higgs potential:

$$V^{\text{low}}(H) = \frac{1}{2}m_H^2 H^2 + \lambda_3 v H^3 + \frac{\lambda_4}{4} H^4 + \frac{\lambda_5}{v} H^5 + \frac{\lambda_6}{v^2} H^6 + \dots$$

- In the SM:

$$\lambda_3^{\text{SM}} = \lambda_4^{\text{SM}} = \lambda = \frac{m_H^2}{2v^2}$$

$$\text{and} \quad \lambda_i = 0 \quad \text{for} \quad i \geq 5,$$

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$$\text{and } \lambda_i = 0 \text{ for } i \geq 5,$$

- In SMEFT:

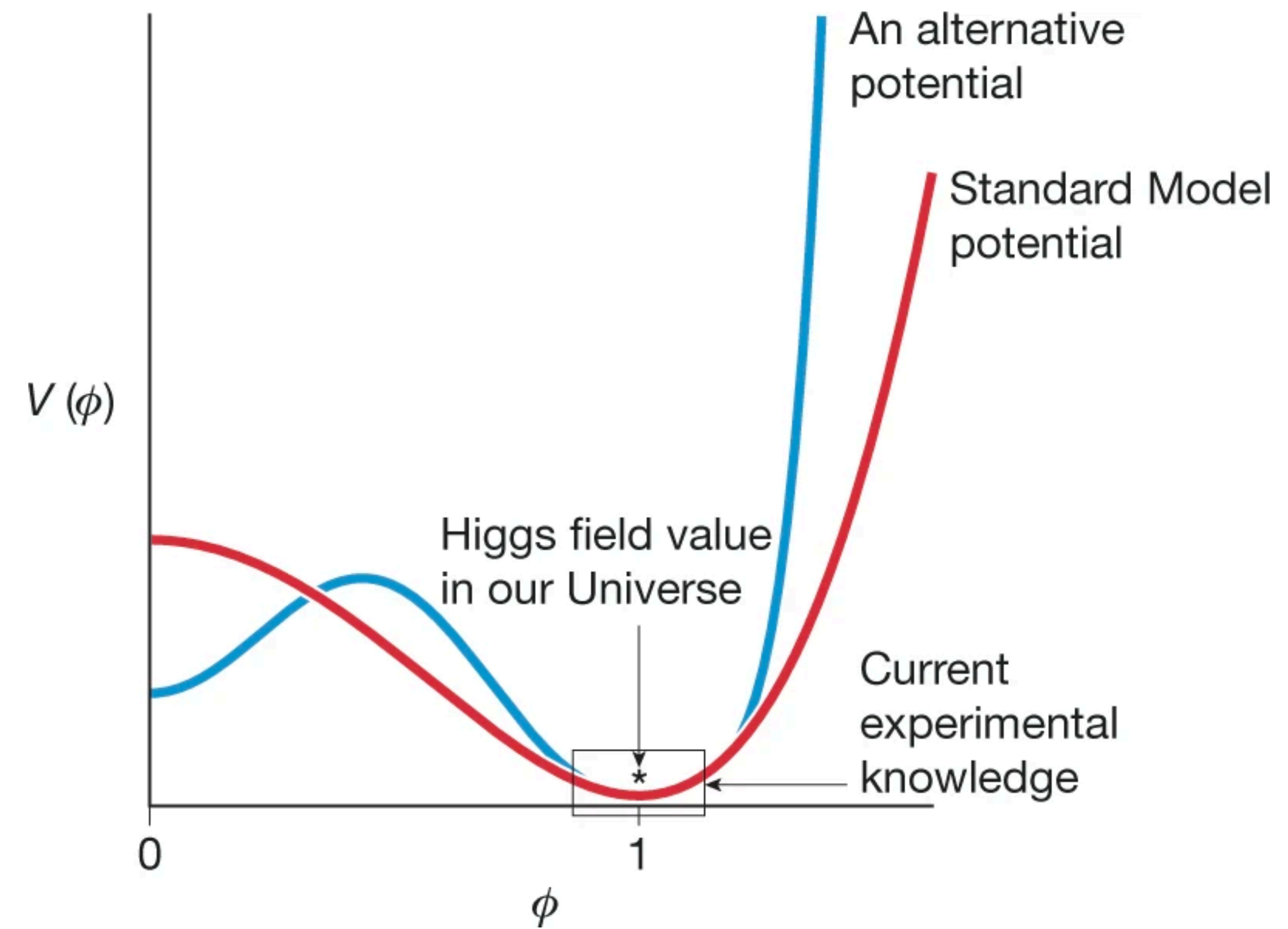
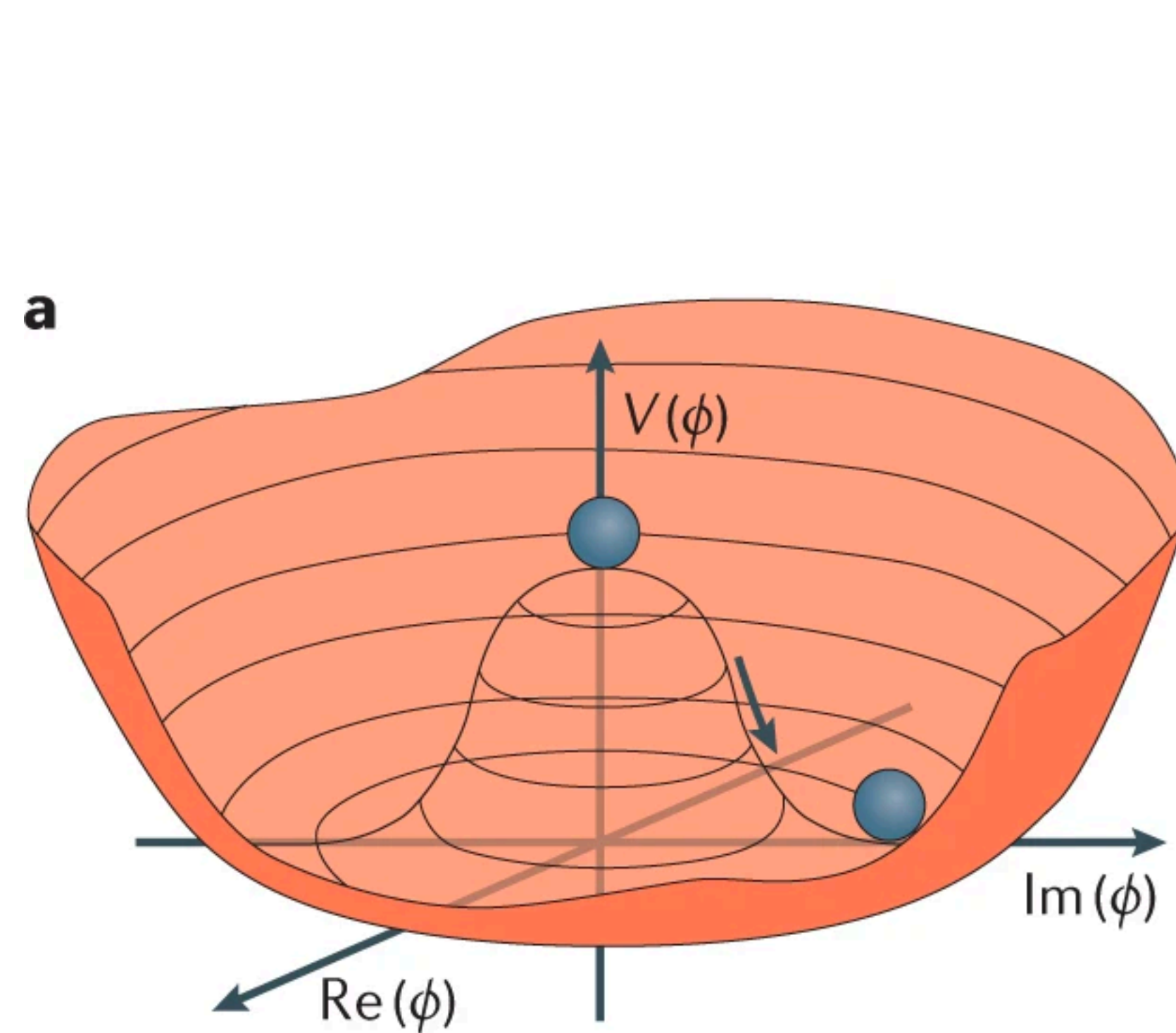
$$\lambda_3 = \lambda(1 + \bar{c}_6)$$

$$\lambda_4 = \lambda(1 + 6\bar{c}_6 + \bar{c}_8)$$

...

$$\lambda_8 = \lambda \frac{1}{64} \bar{c}_8$$

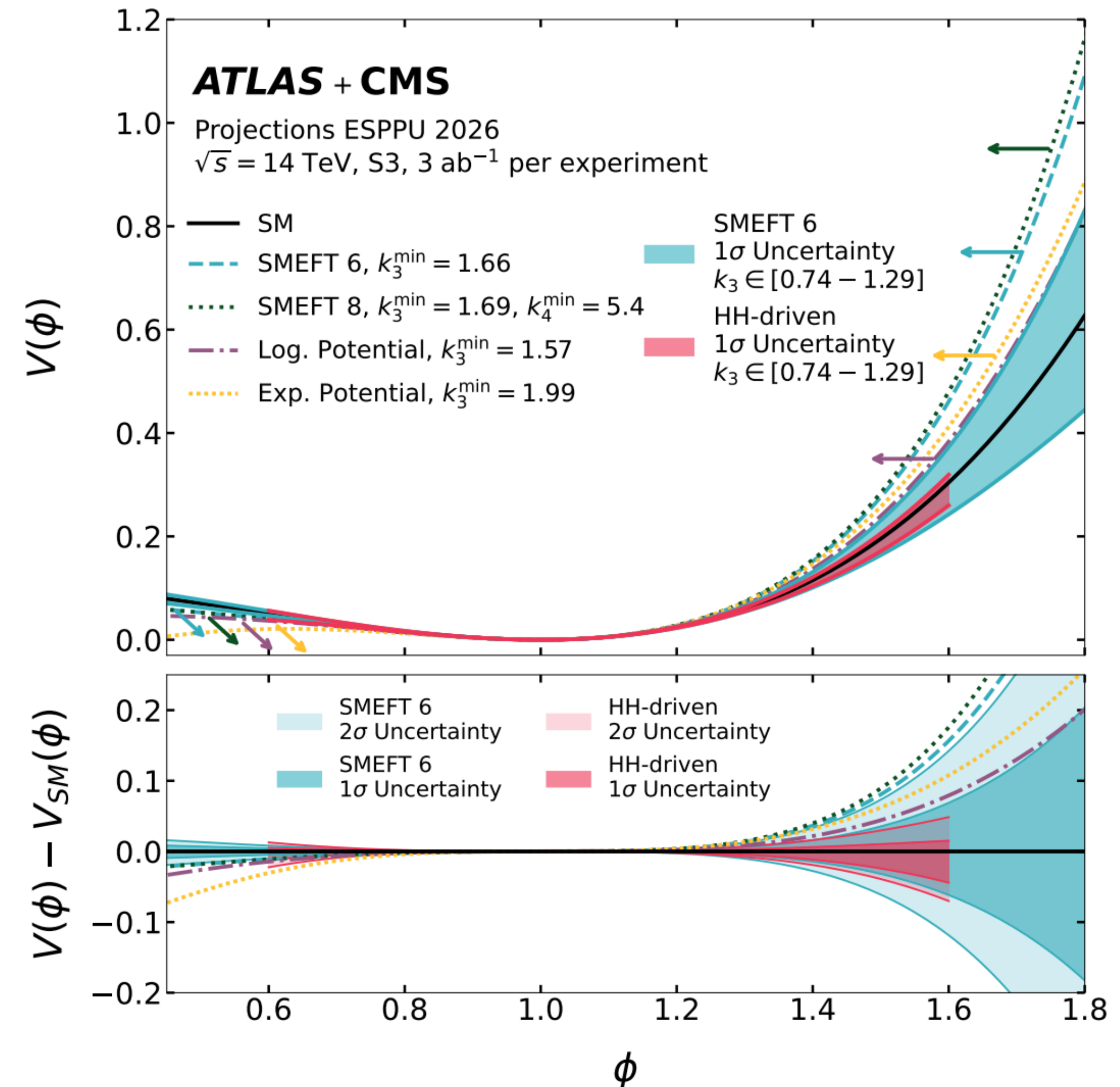
The shape of the Higgs potential



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The shape of the Higgs potential

- ▶ Alternative scenarios predict a strong first-order phase transition in the early universe (does not occur in SM)
- ▶ Sensitivity to fully exclude at 95% CL generic, high-scale new physics models that predict such phenomenology
- ▶ Would be a very strong statement of extreme importance and a unique result for decades to come.



Top+Higgs mass - Vacuum Stability

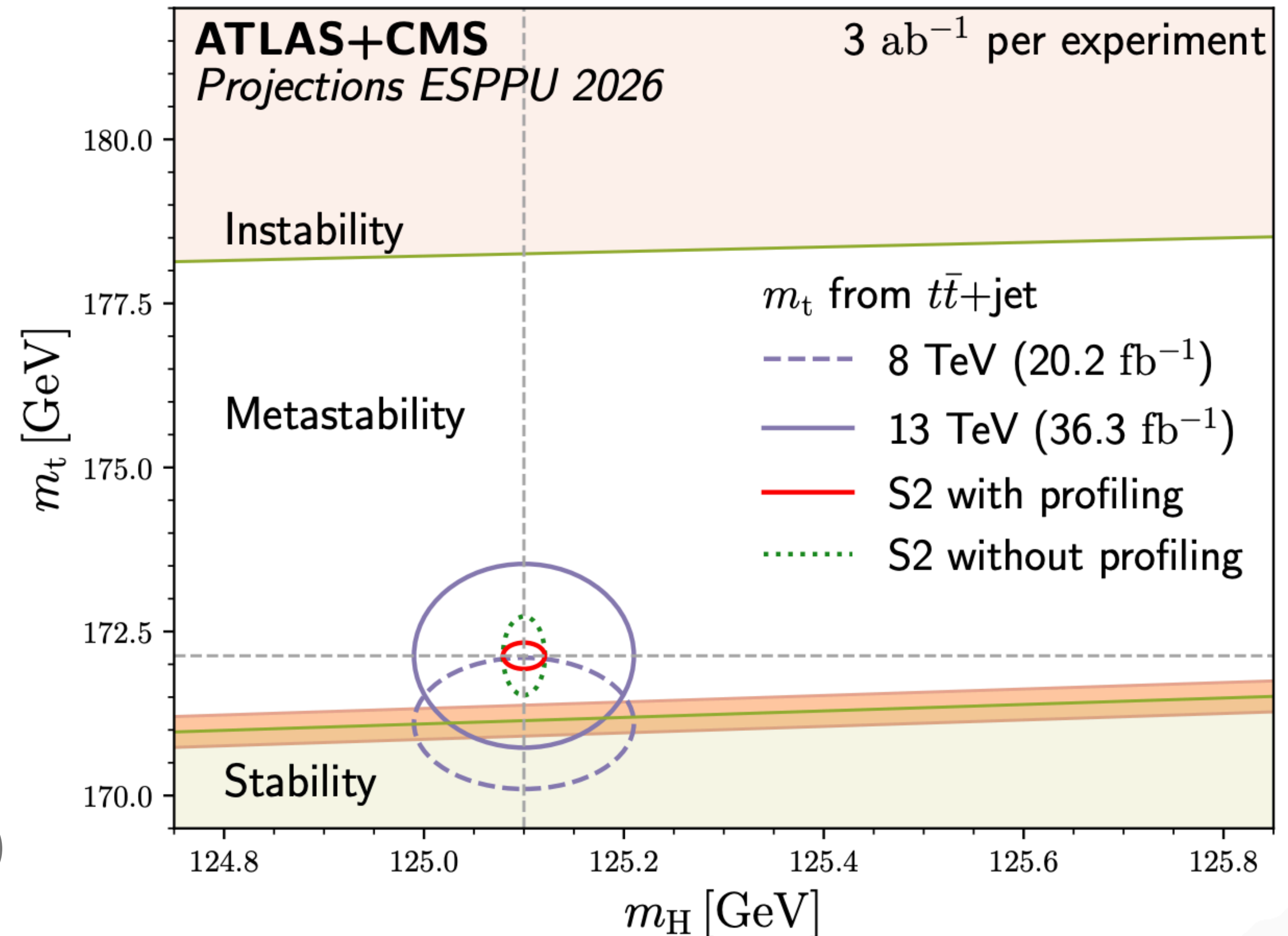
► $H \rightarrow ZZ \rightarrow 4l$ combination gives $\Delta m_H = 21$ MeV

► Top pole mass measurements project $\Delta m_t = 200$ -600 MeV

► improvements in MC generator modeling are required for this.

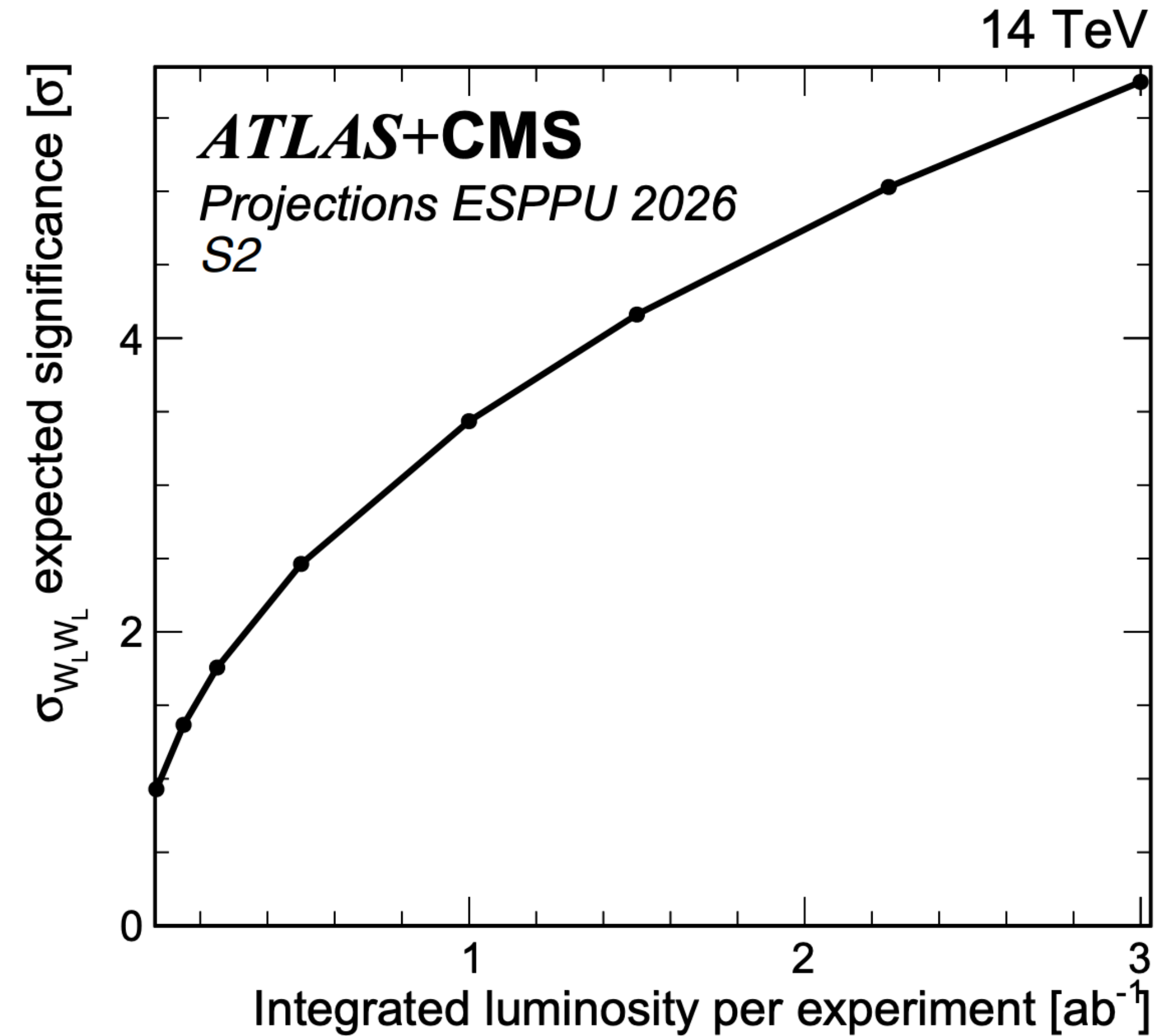
► Full HL-LHC dataset may be able to make a conclusive statement on the stability of the vacuum

► (assuming SM valid to Planck scale)



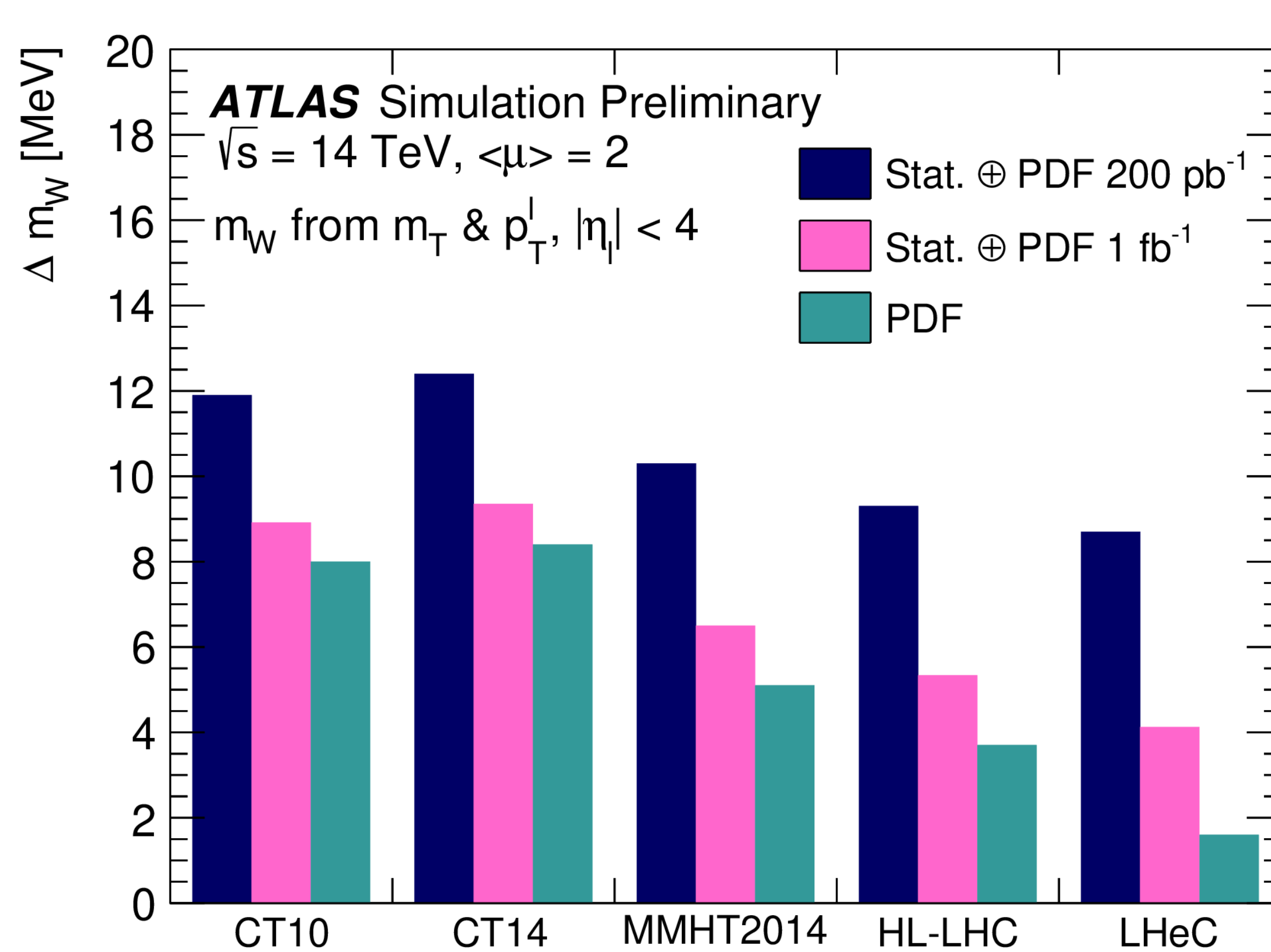
EWSB and $W_L W_L$

- ▶ Measurement of longitudinally polarised vector boson scattering
- ▶ An independent check of spontaneous electroweak symmetry breaking
- ▶ Expect 5σ observation with full 3ab^{-1} HL-LHC dataset
- ▶ Measurement with better than 20% precision

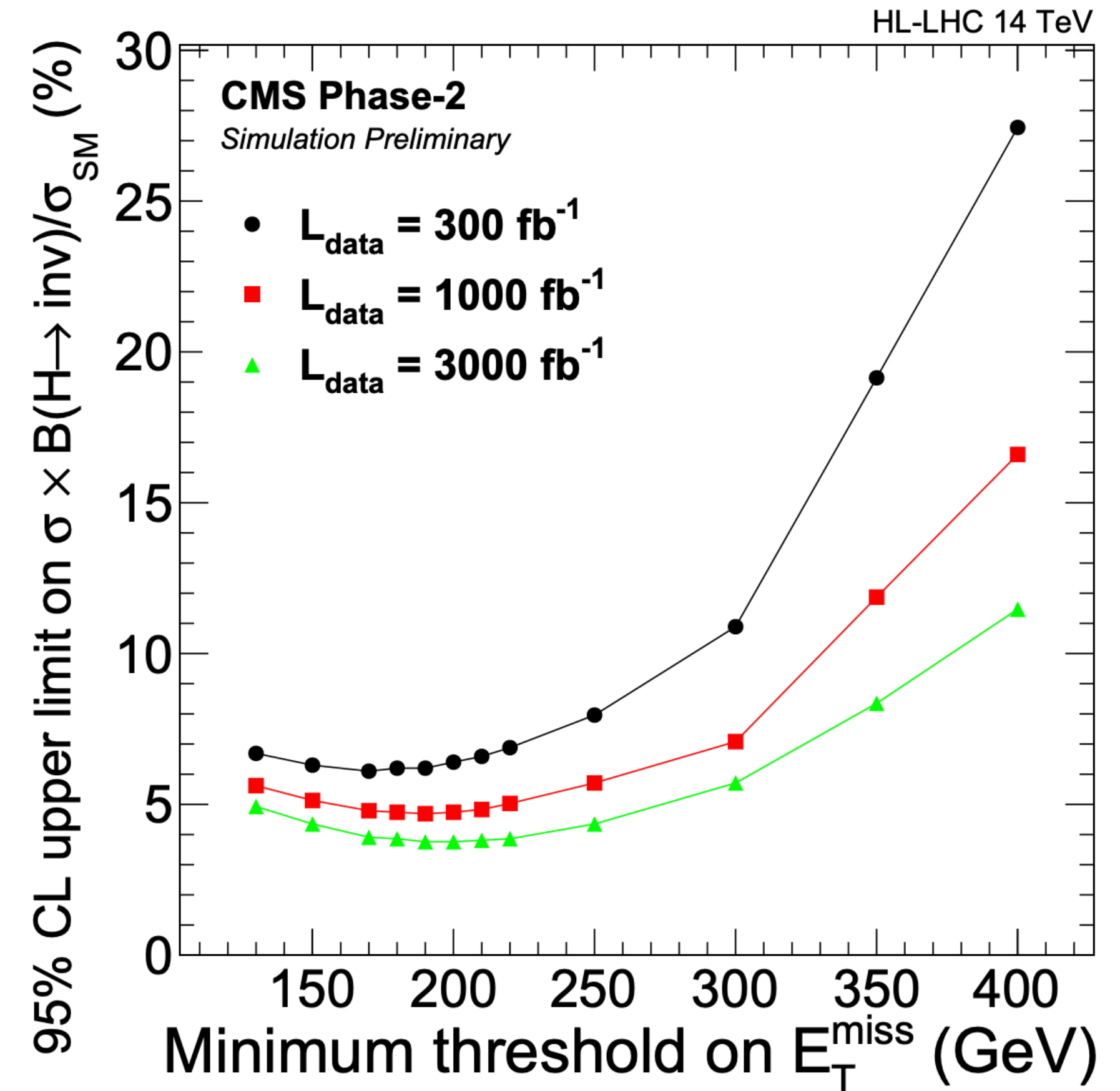


Other highlights | m_W and $H \rightarrow \text{inv}$

- ▶ An uncertainty of ~ 5 MeV on m_W
- ▶ An upper limit of 2.5% on the $H \rightarrow \text{invisible}$ branching fraction

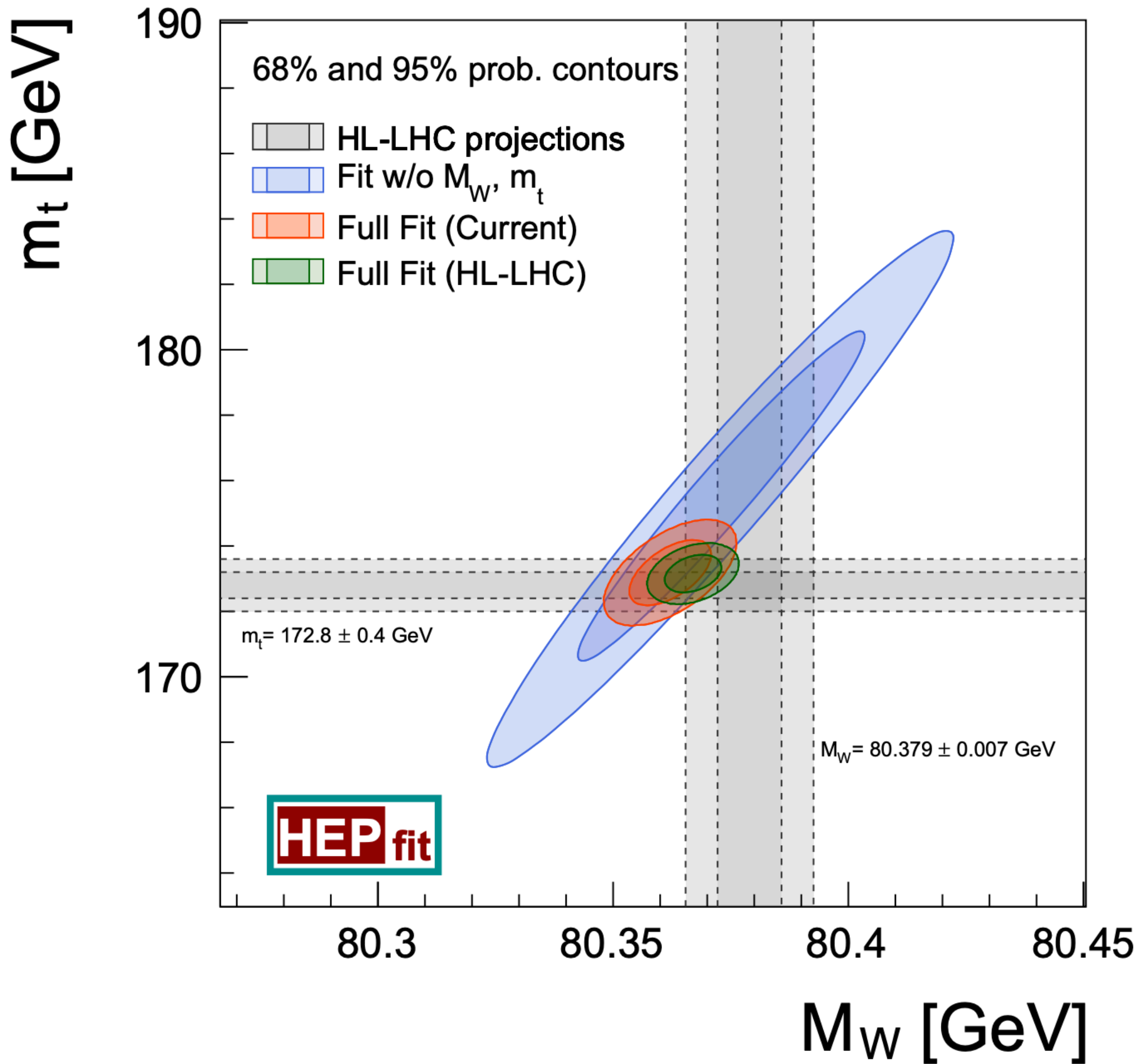


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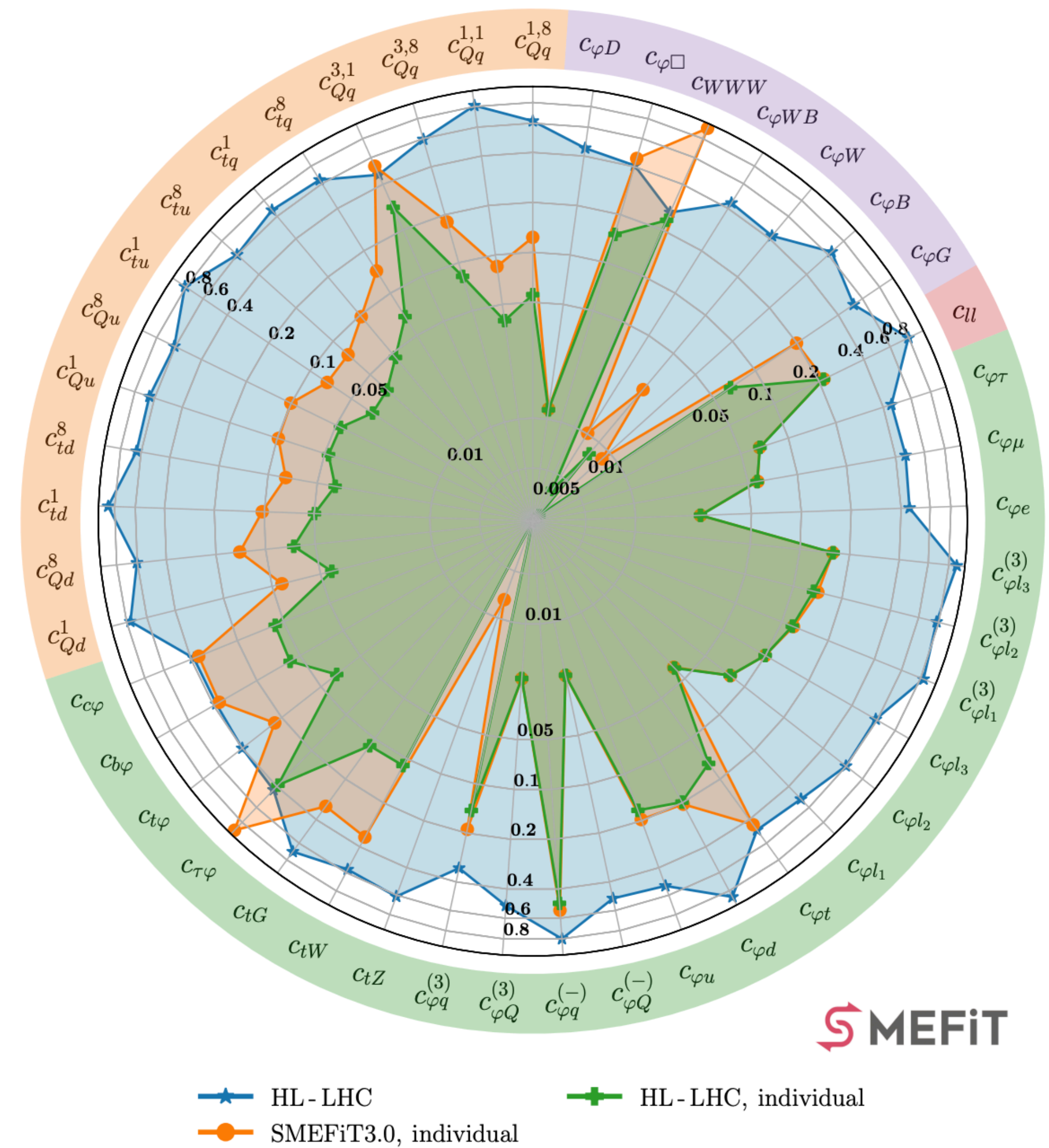


arXiv:1902.00134

Global fits

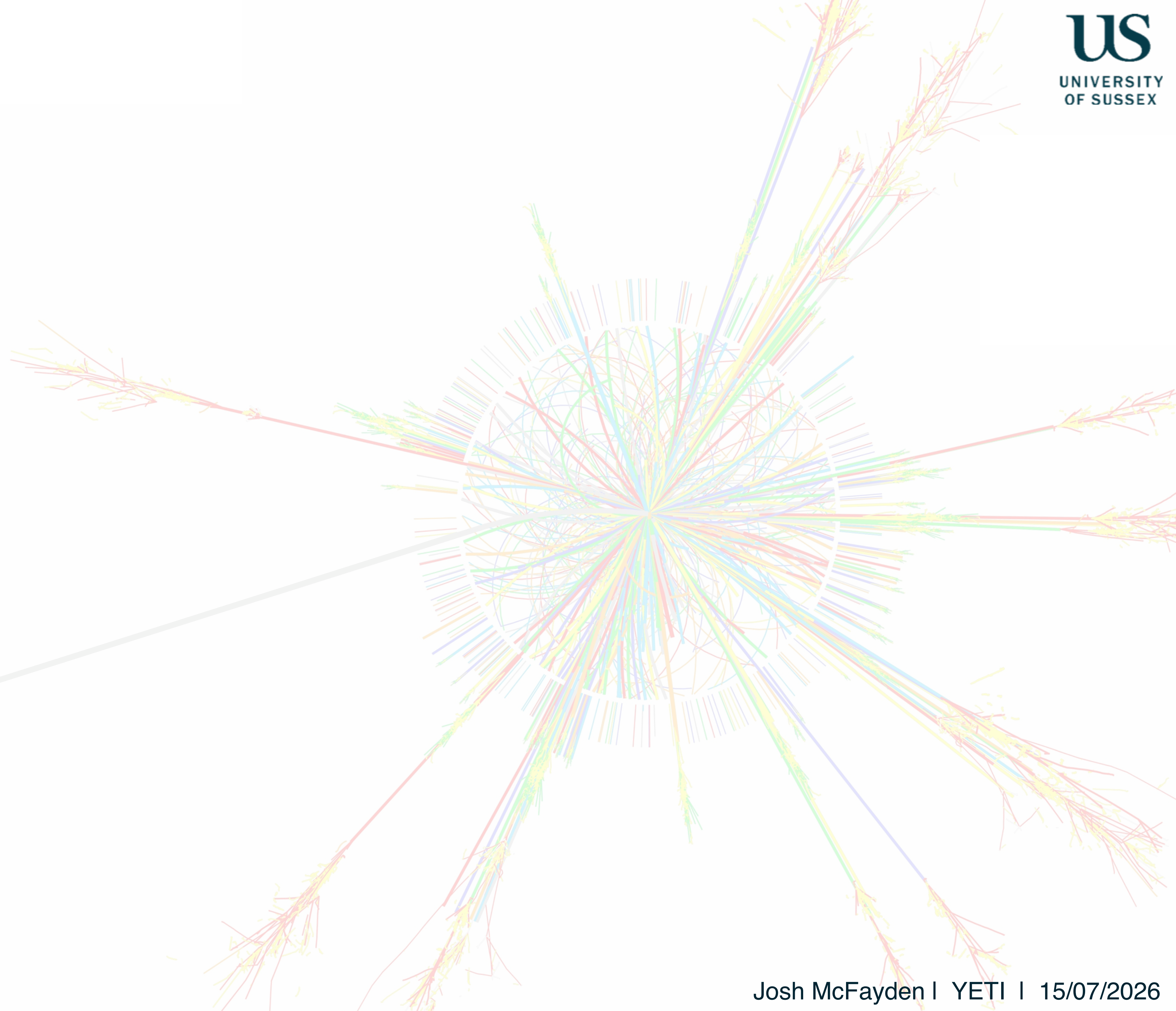


[arXiv:1902.04070](https://arxiv.org/abs/1902.04070)



[arXiv:2404.12809](https://arxiv.org/abs/2404.12809)

Summary



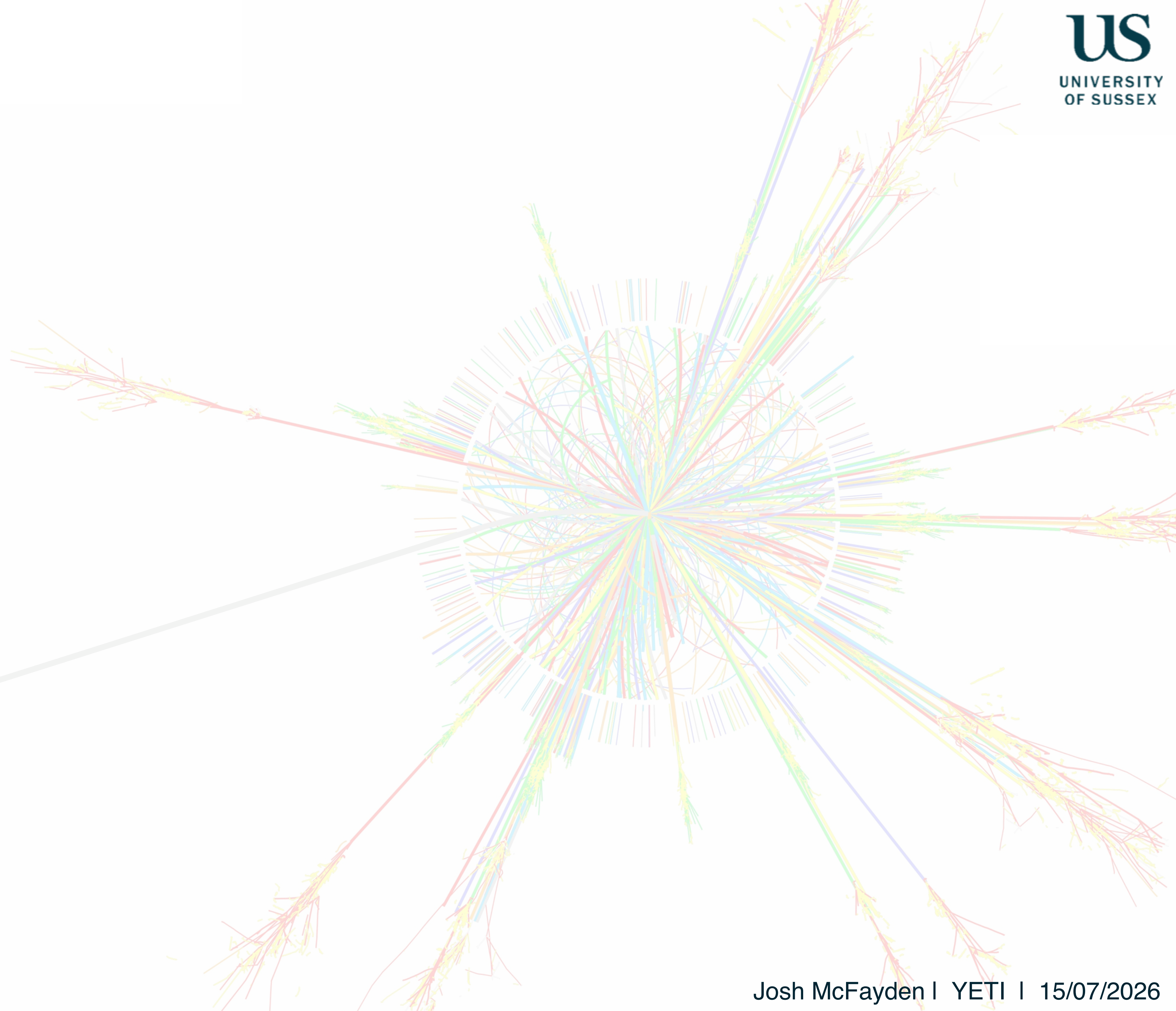
- ▶ Run 2 and Run 3 of the LHC have already been wildly successful
 - ▶ Both as hoped and far beyond
- ▶ The HL-LHC legacy measurements of many SM parameters are expected to remain relevant for decades
 - ▶ Even during the operation of a next future collider.
- ▶ The precision which the HL-LHC will reach for many rare SM processes will not be superseded for many decades, until the next generation hadron or muon collider operation.

Thanks!

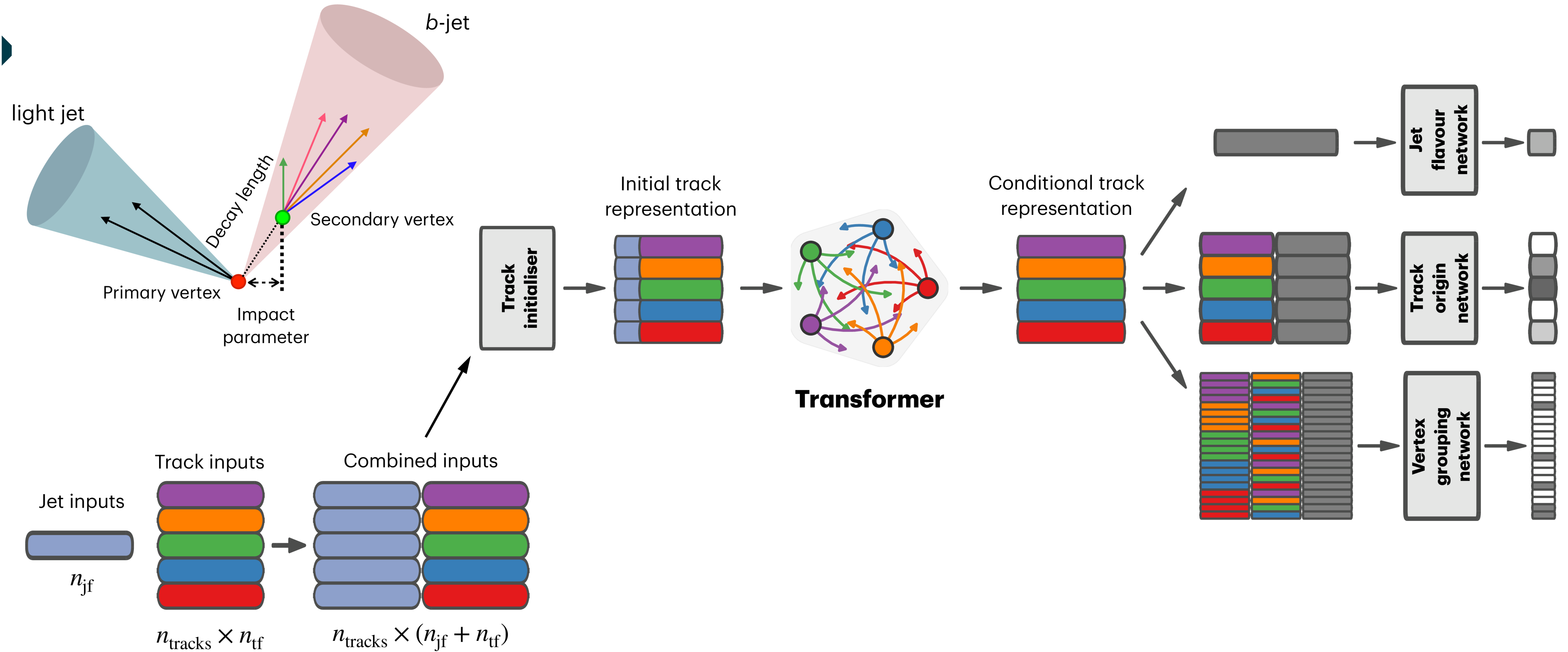


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Event: 3038977
2022-07-05 17:02:31 CEST

Back-ups

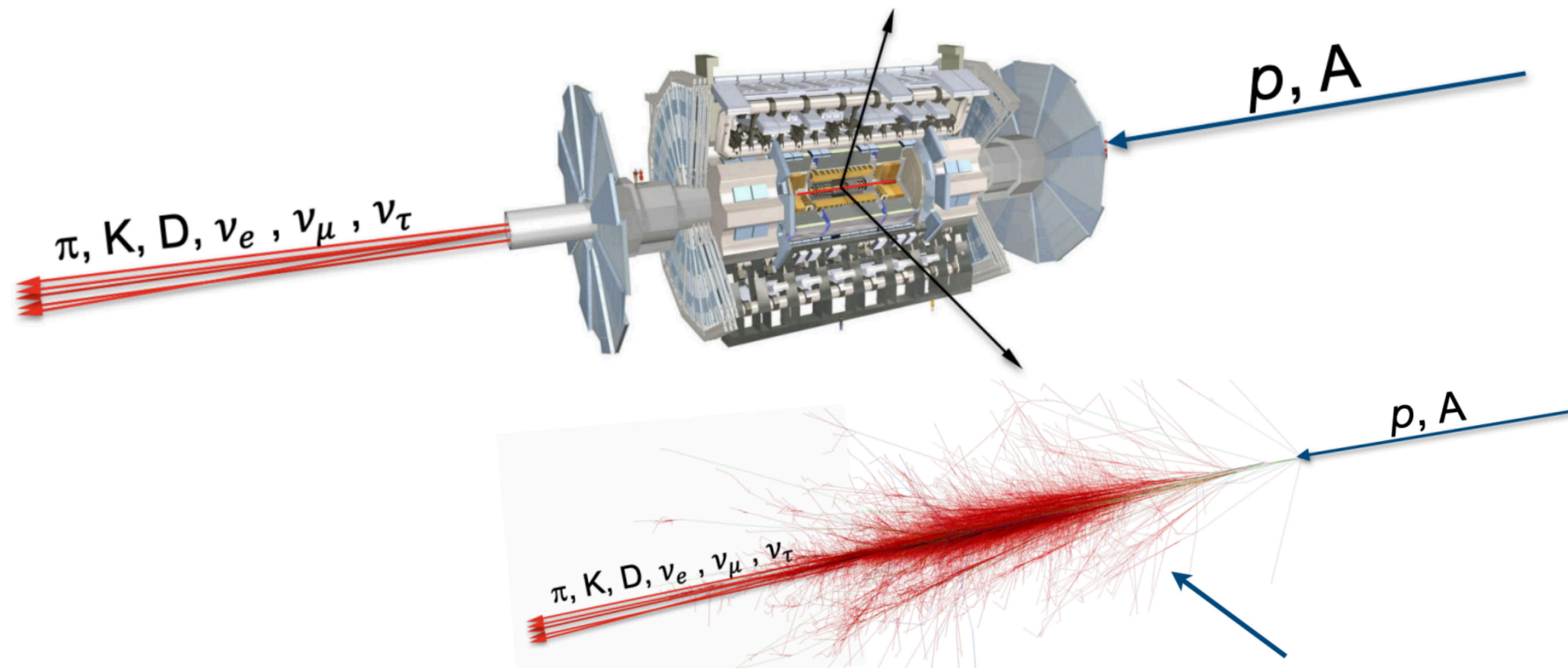
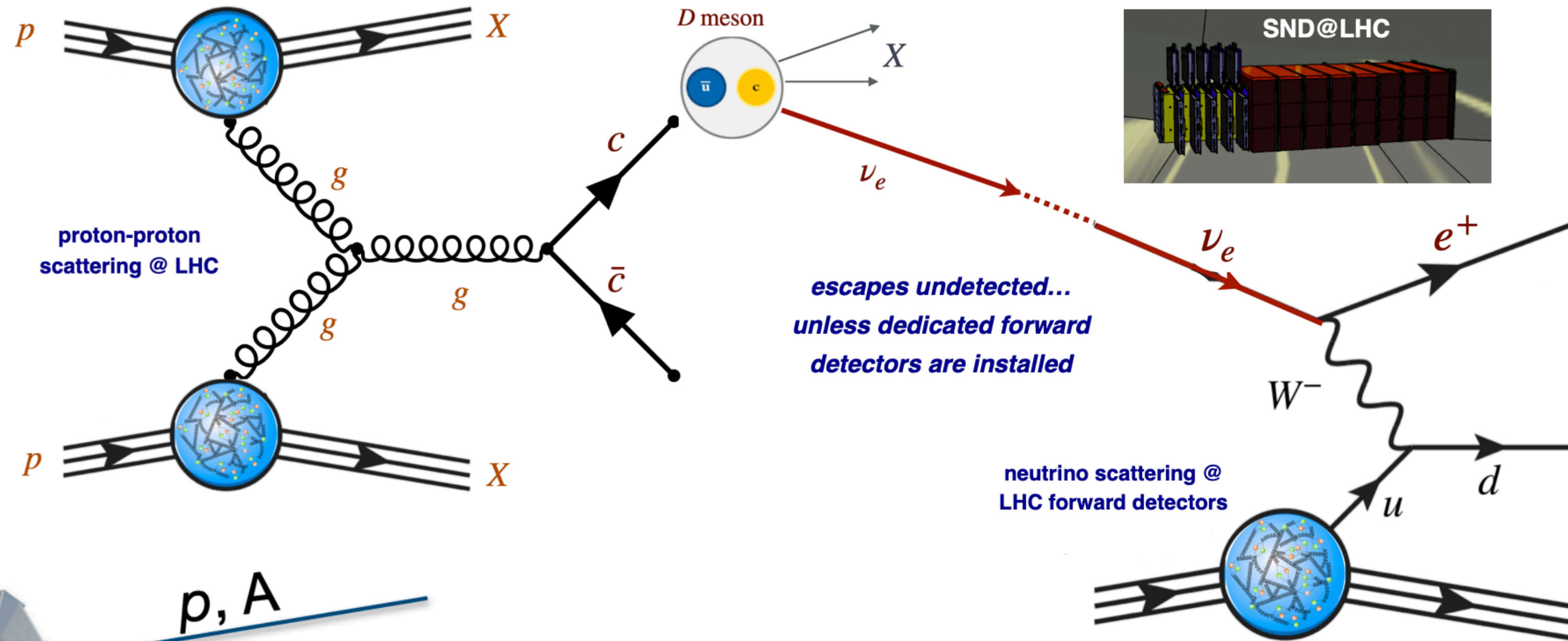


Transformers are all you need

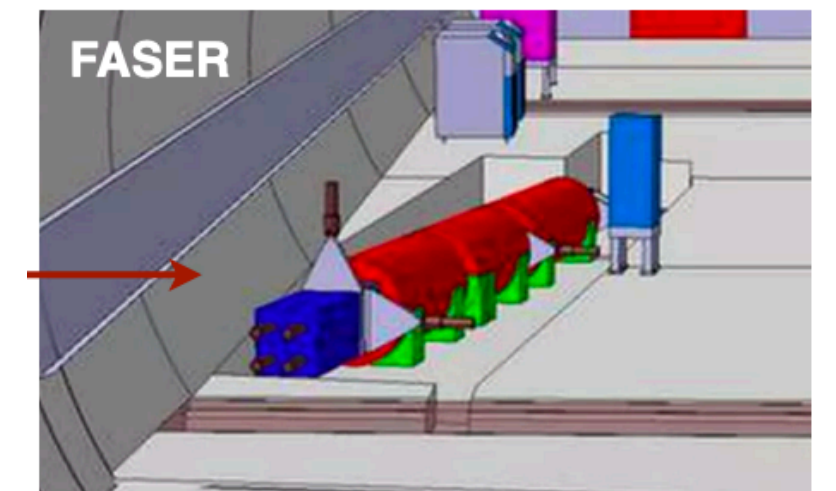


LHC Beyond Design

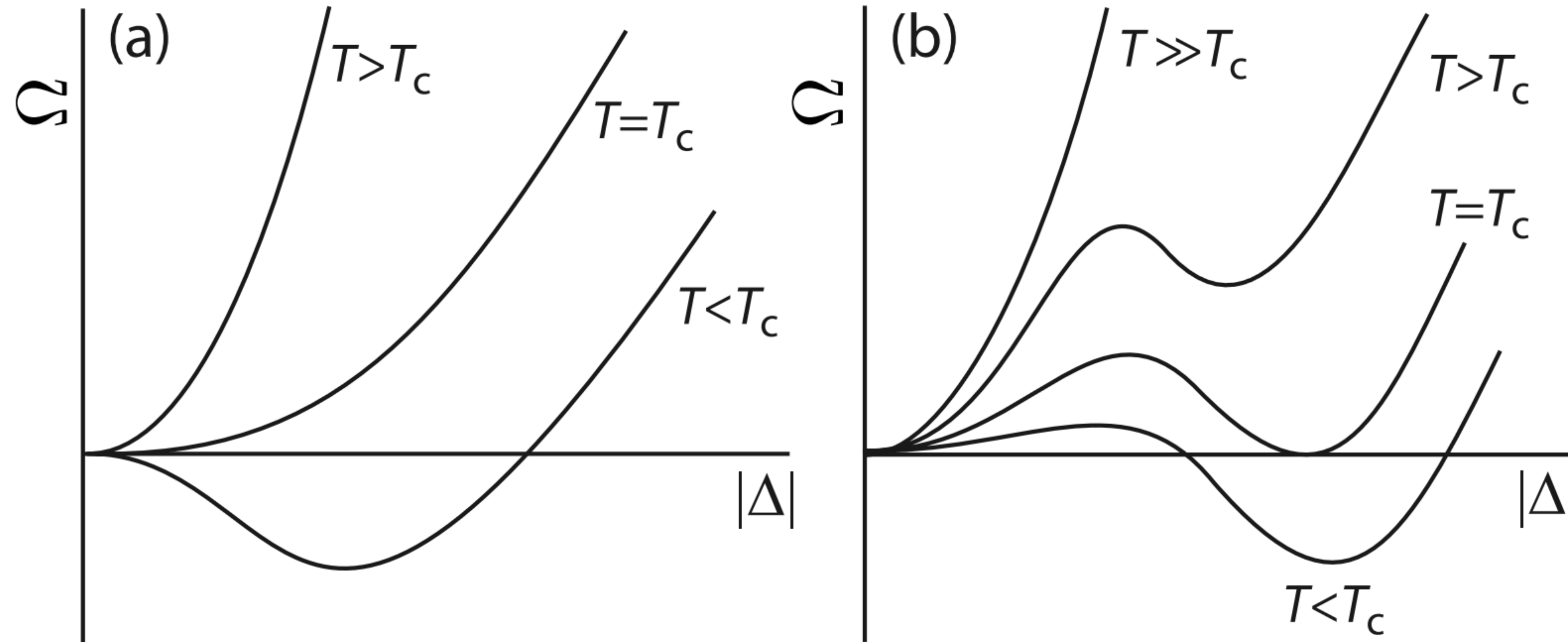
► FASER



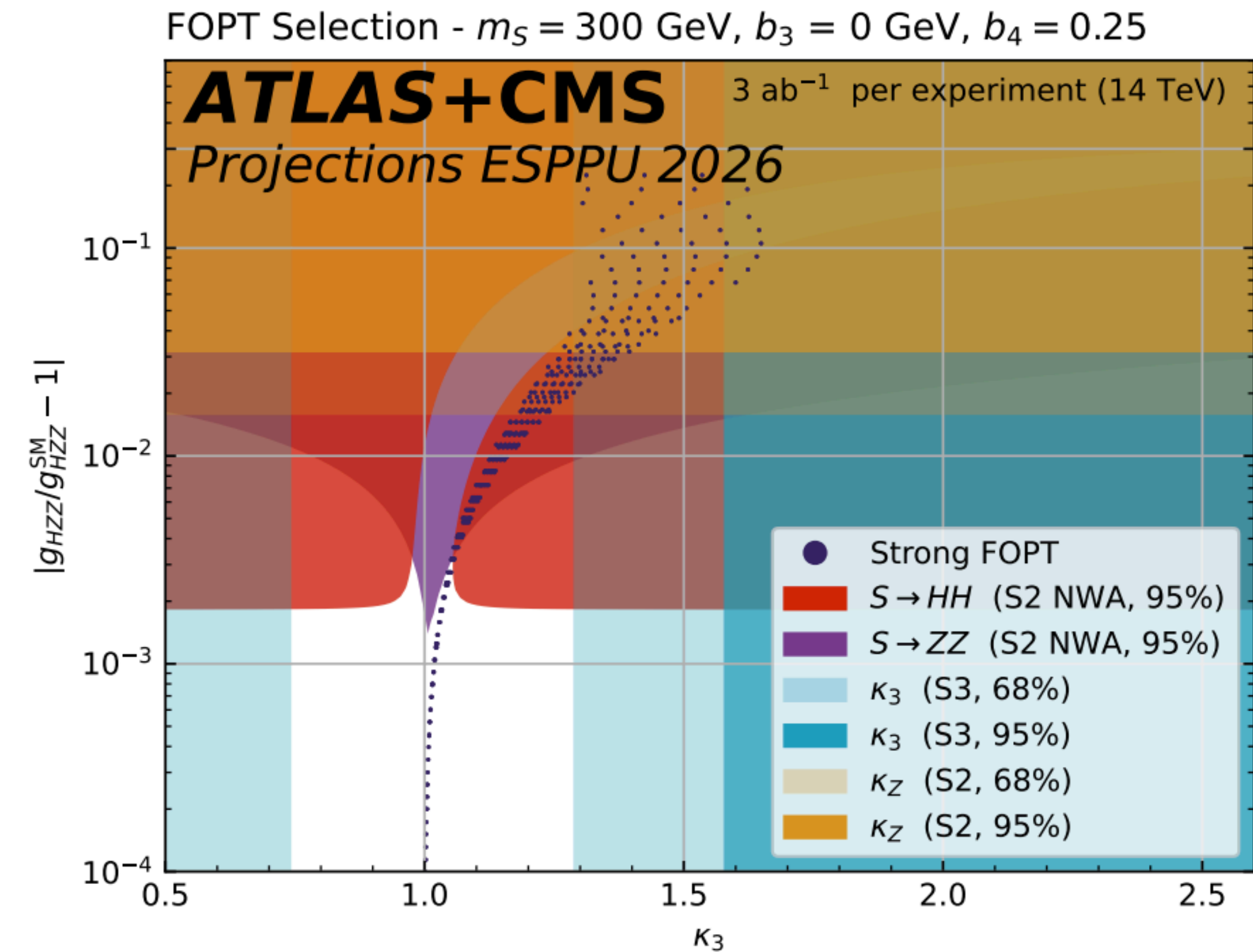
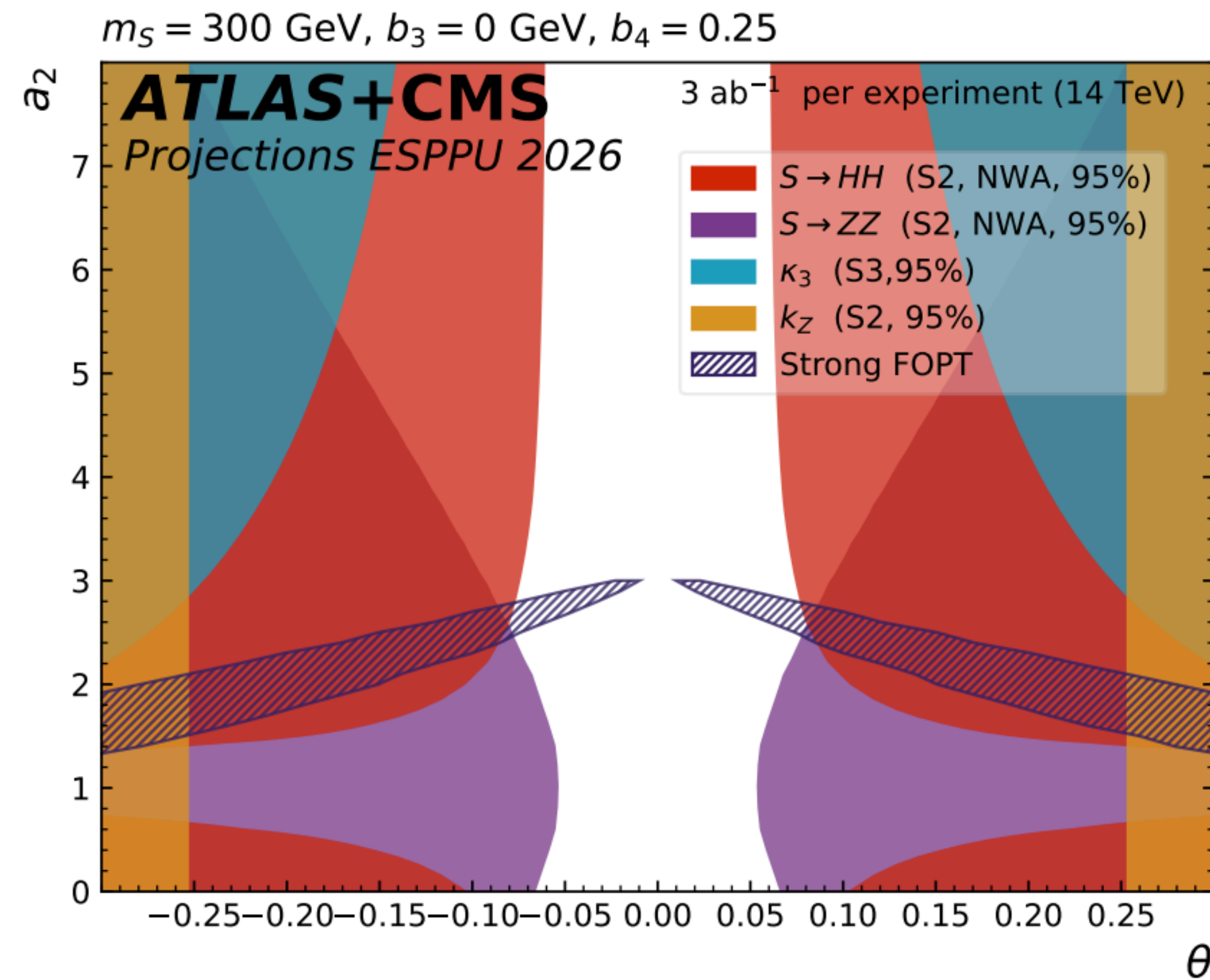
Collider counterpart of high-energy cosmic rays interactions, including prompt neutrino flux



Phase transitions



Higgs vs a heavy scalar singlet



Higgs vs a heavy scalar singlet

