SM + Higgs results at the LHC

IOP: APP, HEPP and NP Conference

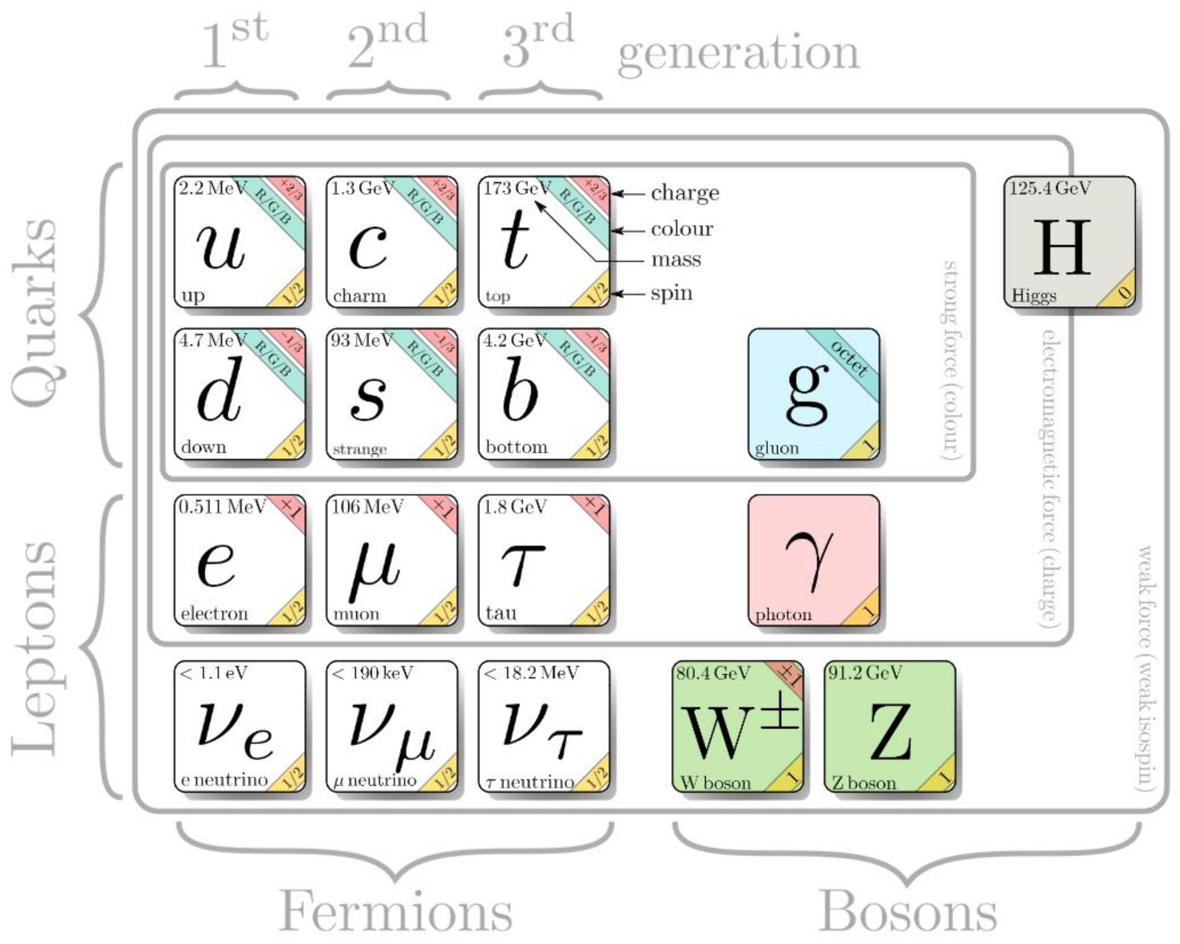
Dr. Jonathon Langford

IMPERIAL

Imperial-X

CMS

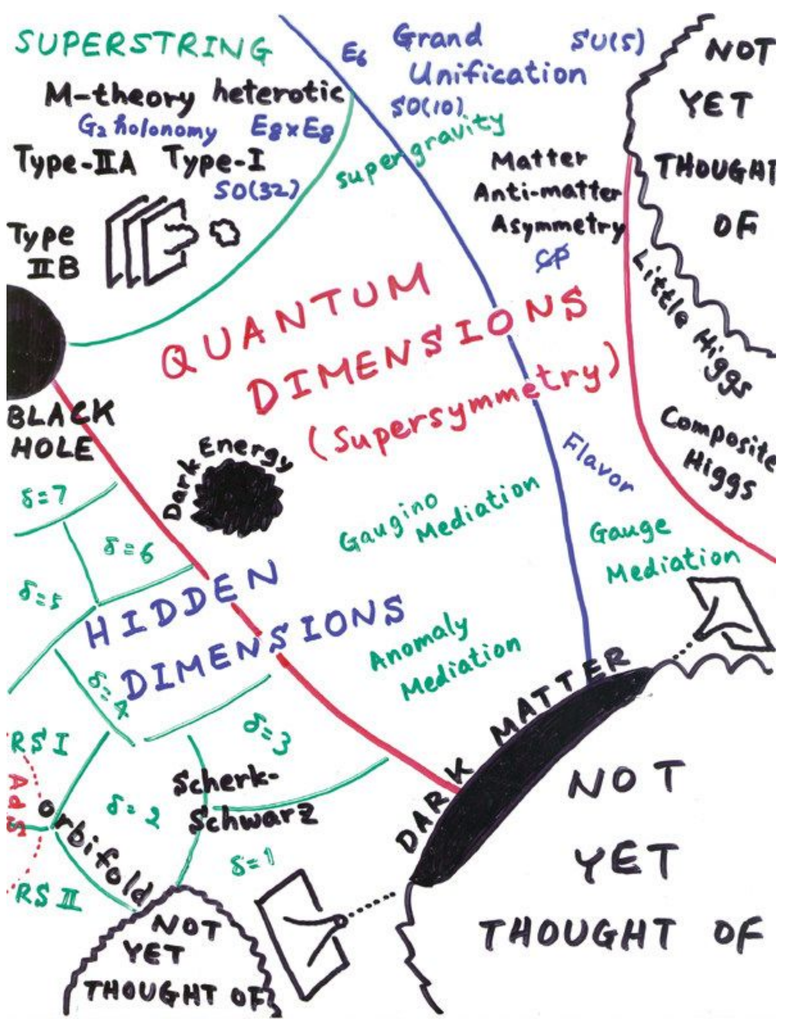
SM & shortcomings



$$
\begin{aligned}
\mathcal{L}_{\mathrm{SM}} =& \mathcal{L}_{\mathrm{gauge}} + \mathcal{L}_{\mathrm{Higgs}} + \mathcal{L}_{\mathrm{int}} + \mathcal{L}_{\mathrm{Yukawa}} \\
=& -\frac{1}{4} G^a_{\mu\nu} G^{a,\mu\nu} - \frac{1}{4} W^i_{\mu\nu} W^{i,\mu\nu} - \frac{1}{4} B_{\mu\nu} B^{\mu\nu} \\
&+ (D^\mu H)^\dagger (D_\mu H) - \mu^2 H^\dagger H - \frac{1}{4}\lambda (H^\dagger H)^2 \\
&+ i(\bar{L}\not{D}L + \bar{\ell}\not{D}\ell + \bar{Q}\not{D}Q + \bar{u}\not{D}u + \bar{d}\not{D}d) \\
&- (\lambda_\ell \bar{L} H \ell + \lambda_d \bar{Q} H d + \lambda_u \bar{Q} \tilde{H} u + \text{h.c.})
\end{aligned}
$$

Unanswered Questions

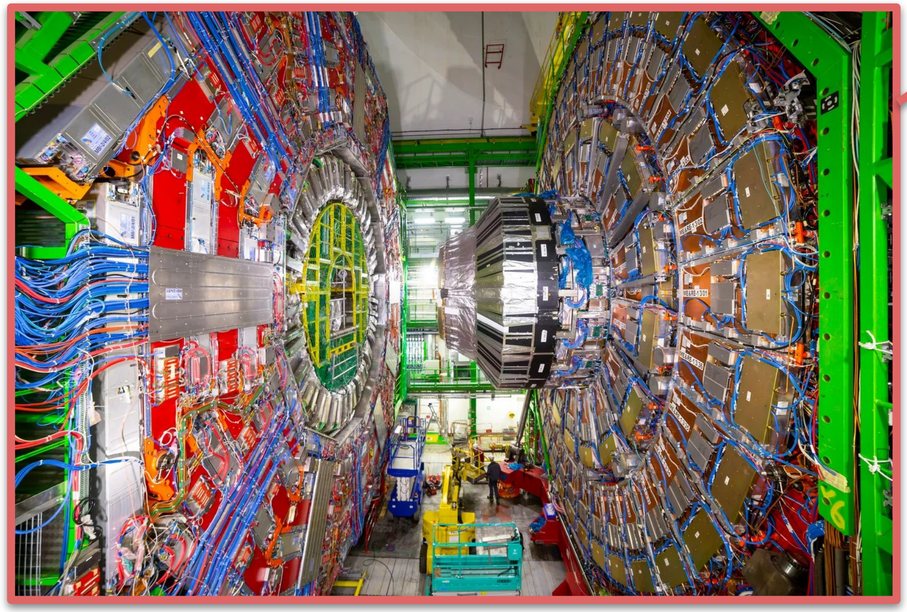
- Gravity (quantum)
- Dark matter
- Dark energy
- Matter-antimatter asymmetry
- Naturalness
- Hierarchy problem
- Neutrino oscillations
- Inflation
- …



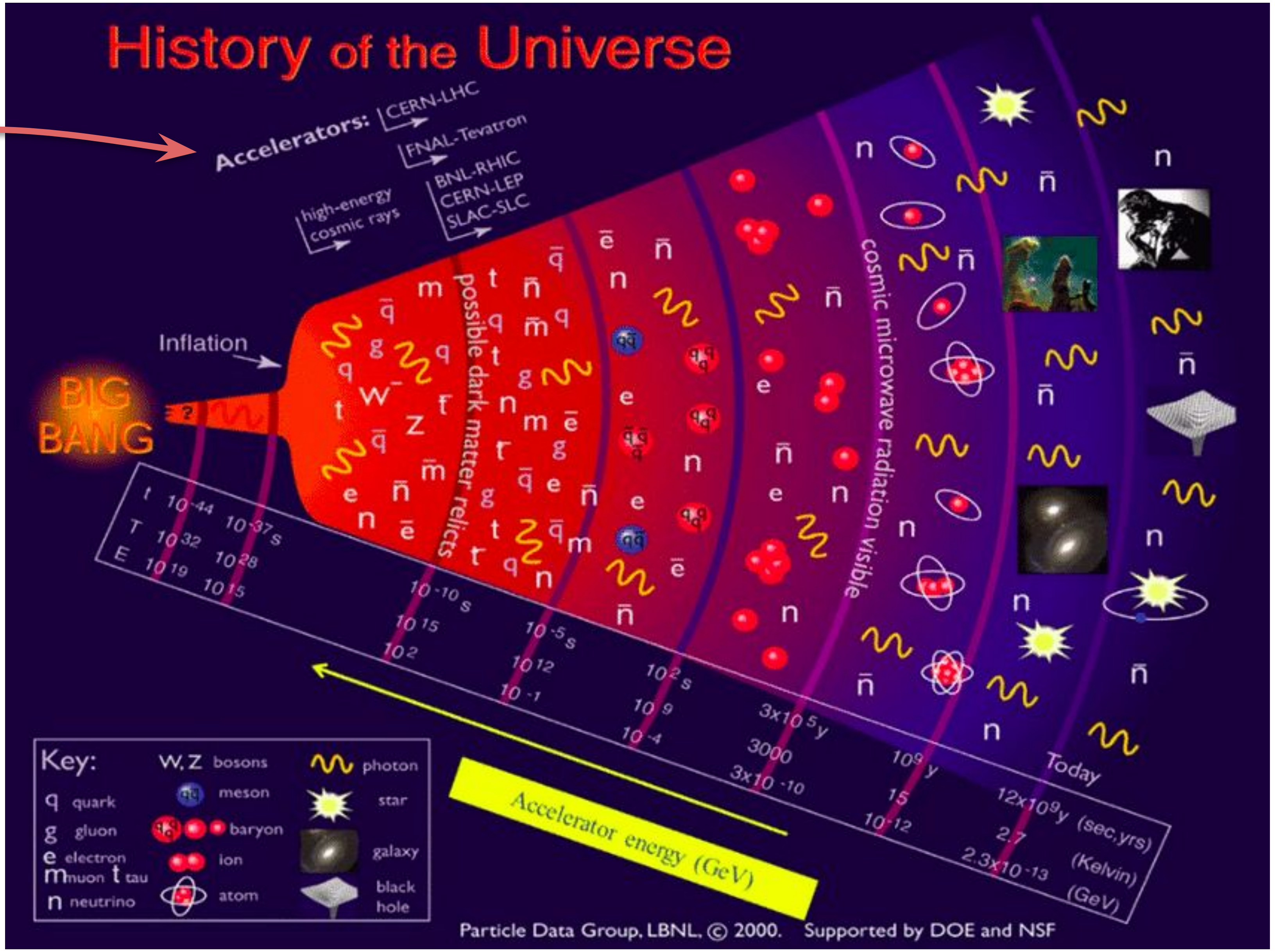
?

Probing the answers

Large Hadron Collider (LHC)



Particle observatories



Two approaches:

1. **Direct searches:** see Sara's talk
2. **Indirect searches:** *imprints of new physics on SM interactions*

Probing the answers

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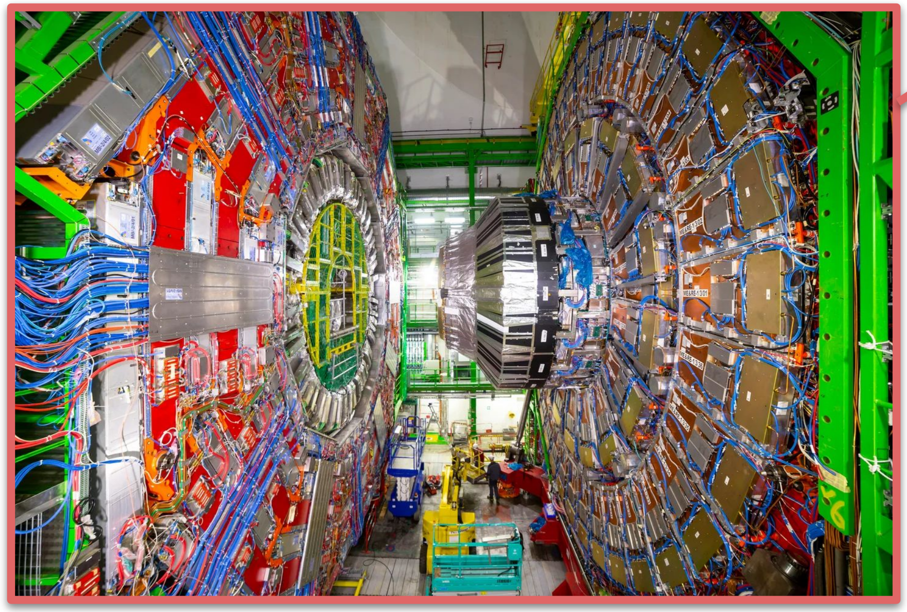
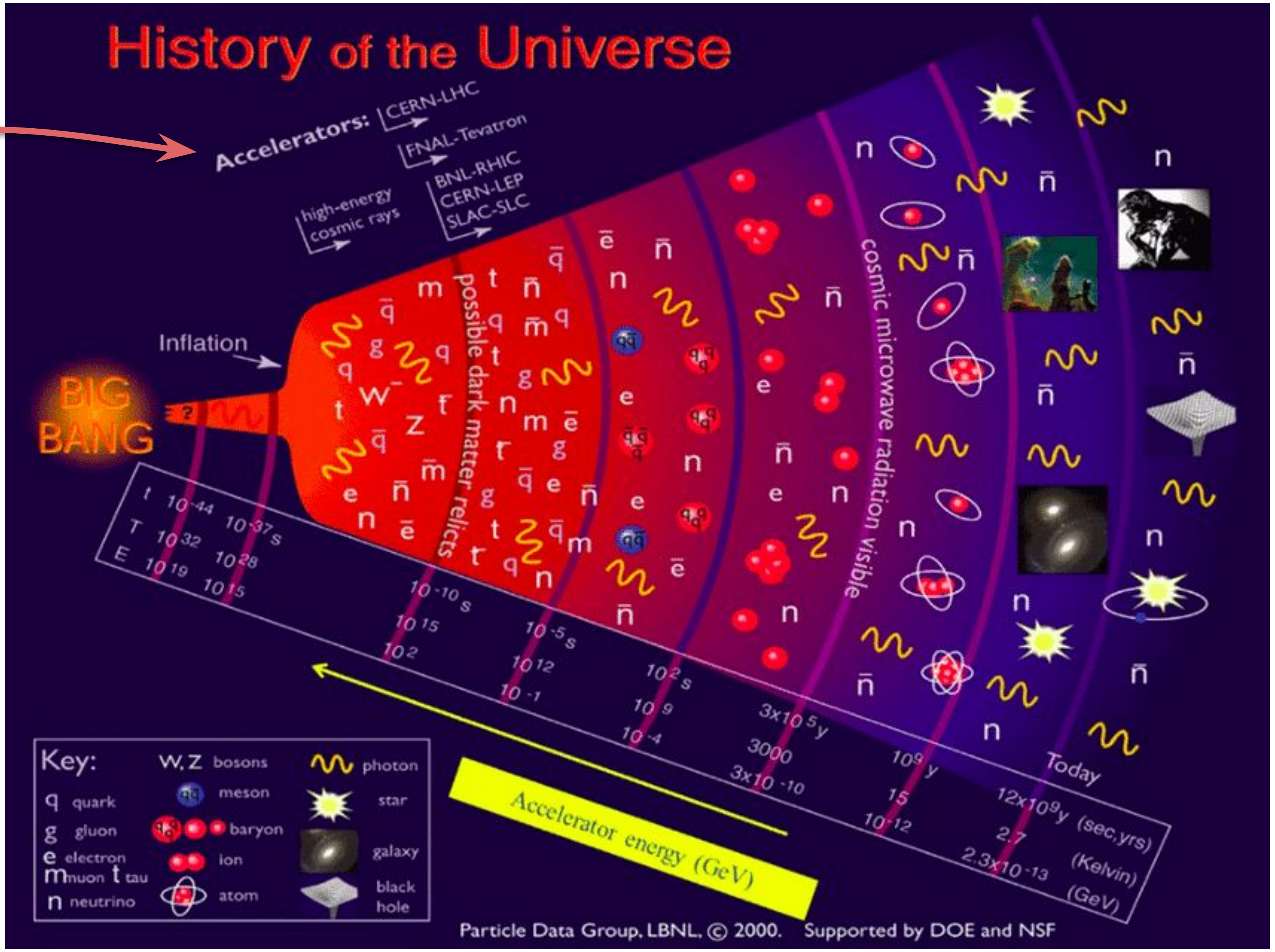


Particle observatories



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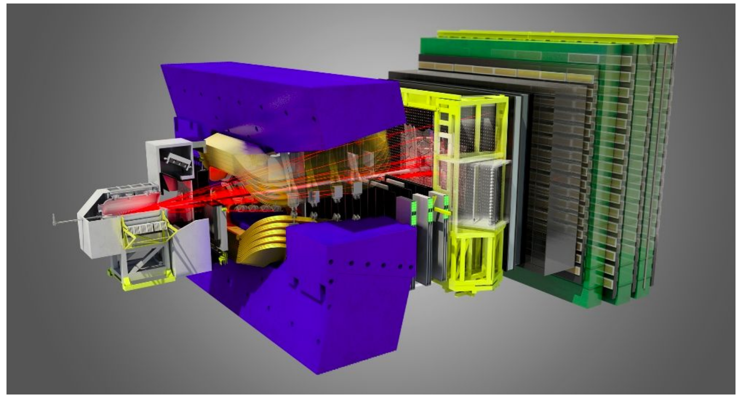
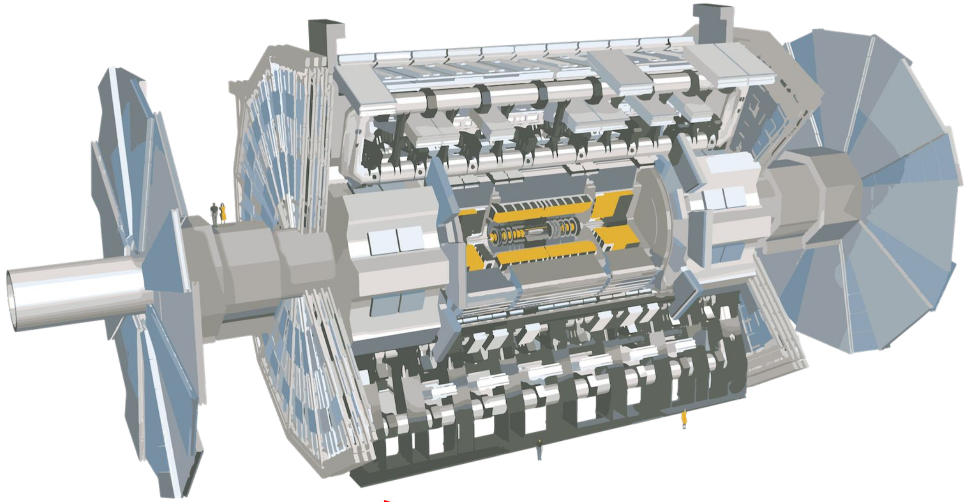
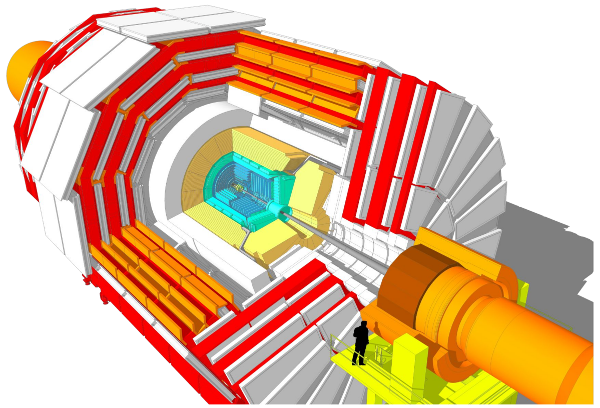
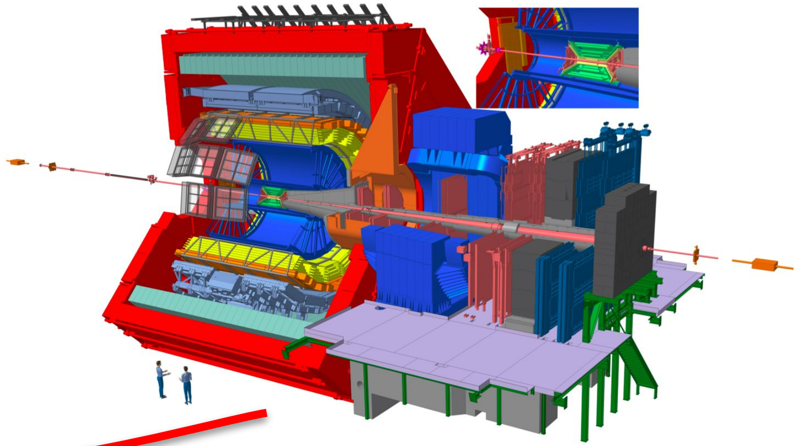
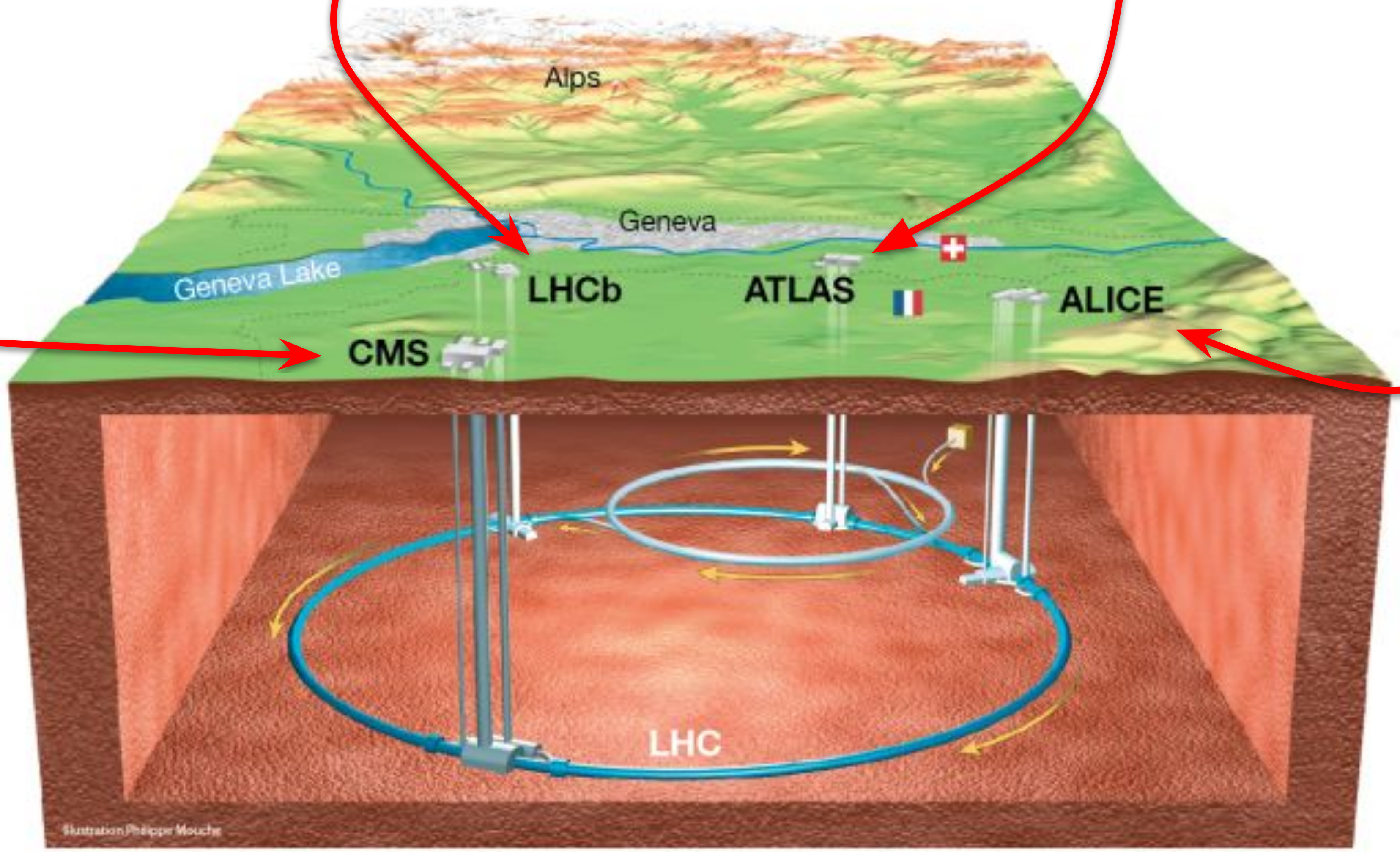
LHC overview





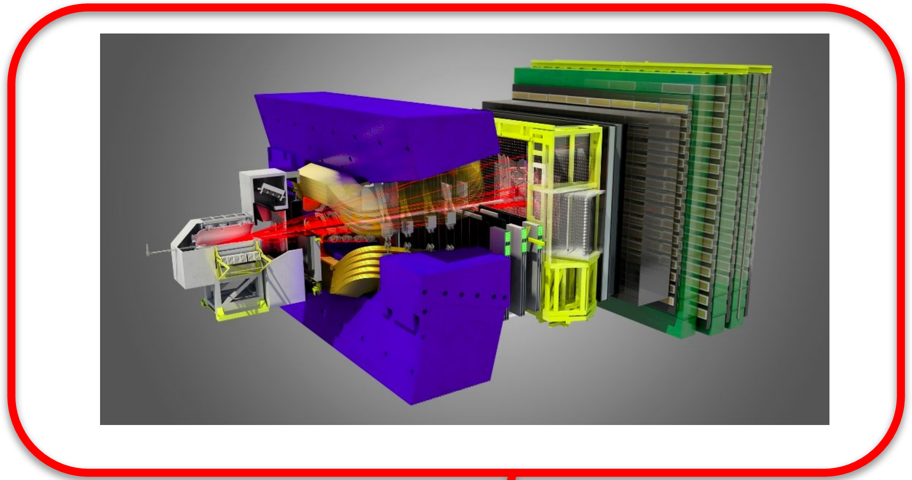


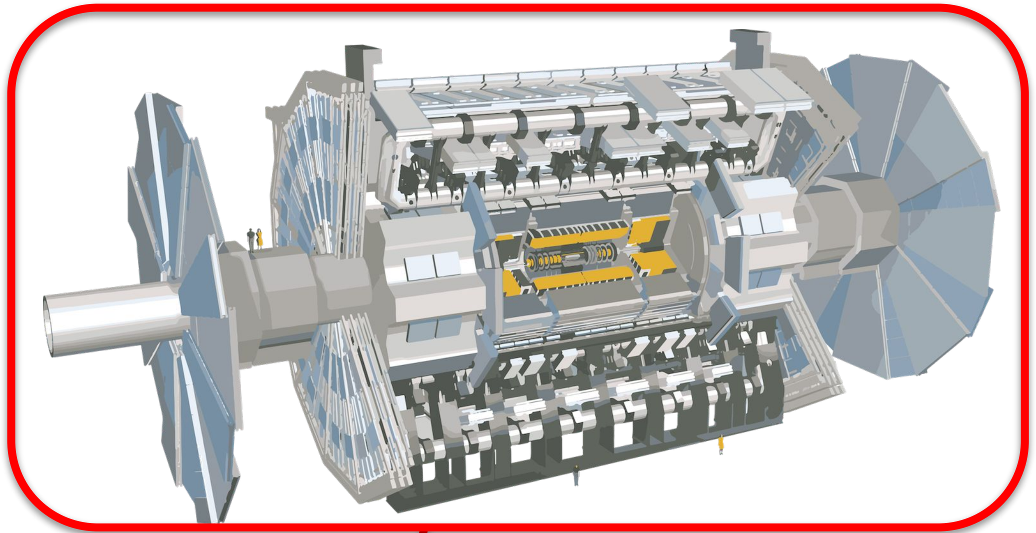


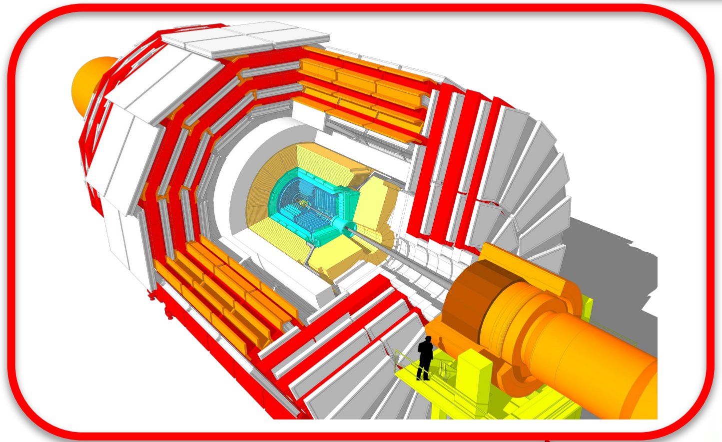


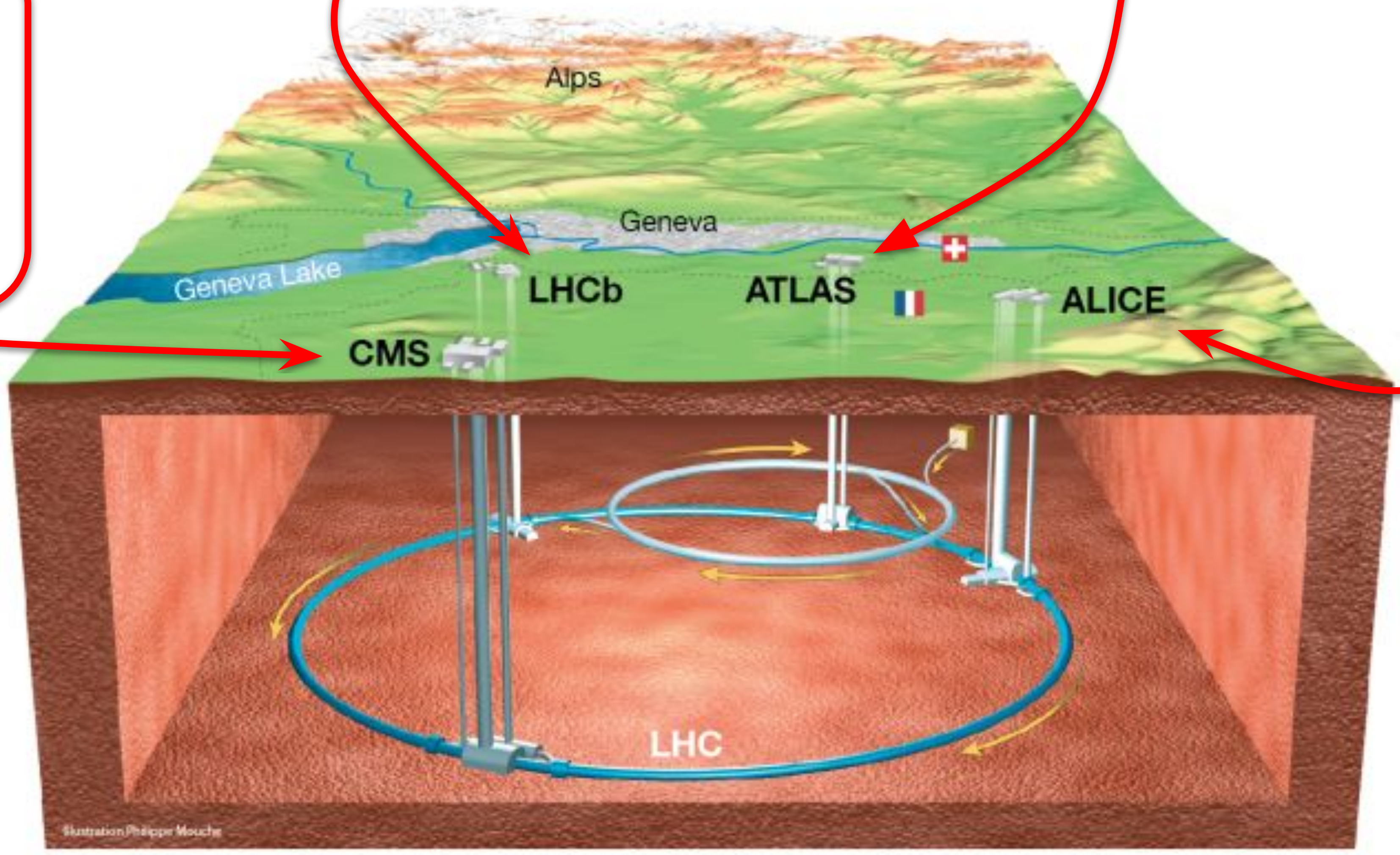
+ Smaller experiments:
  - Totem
  - MilliQan
  - MoEDAL
  - Faser
  - ...

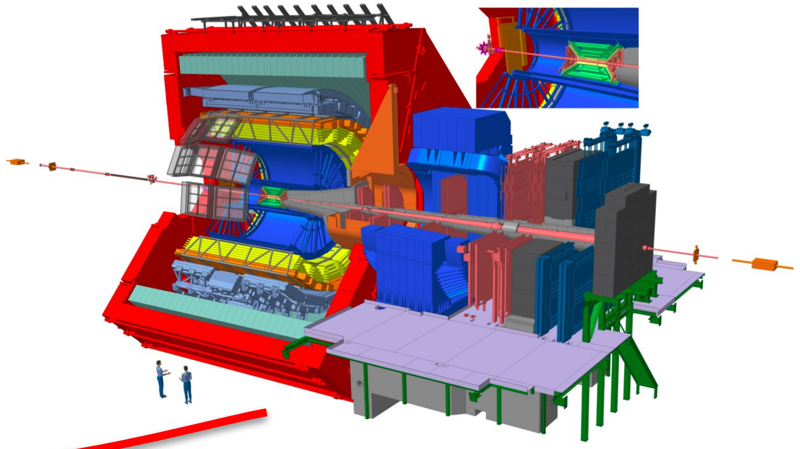
LHC overview











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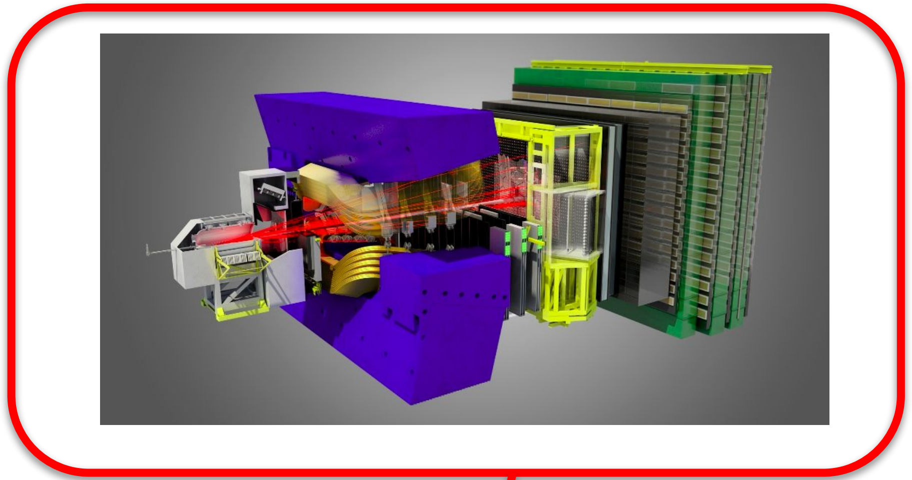
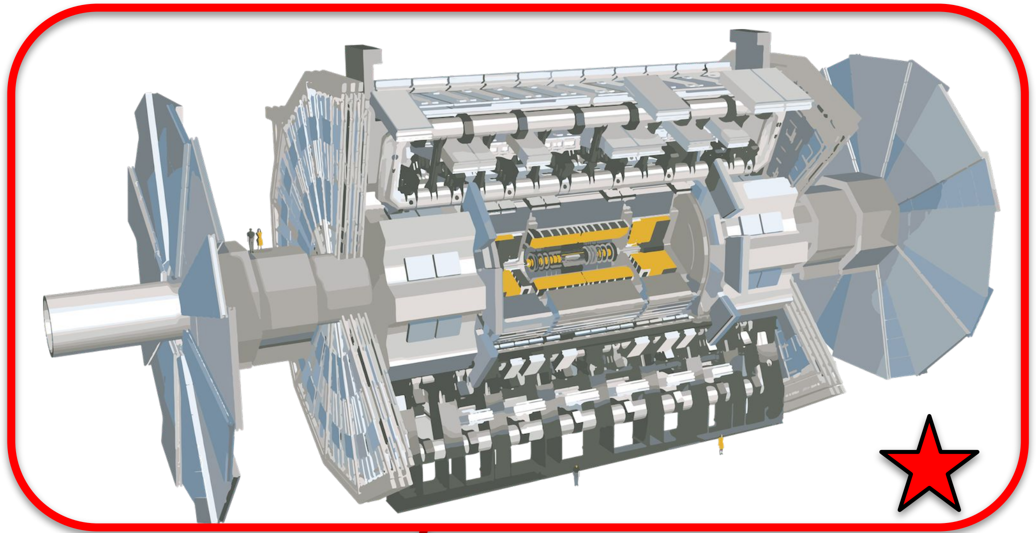
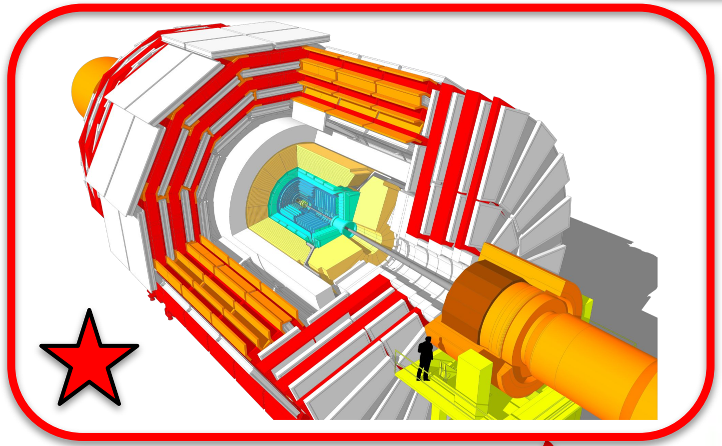
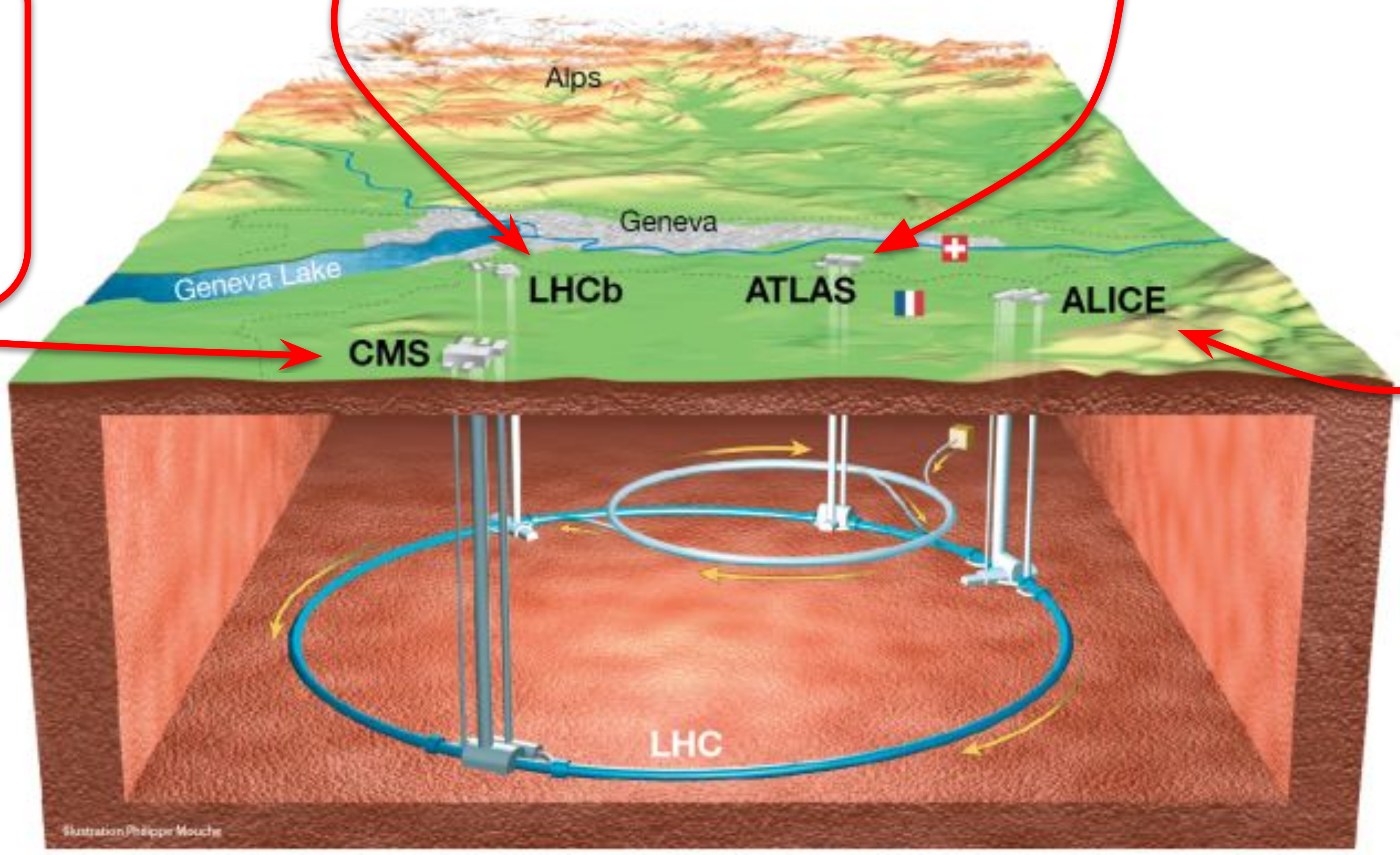
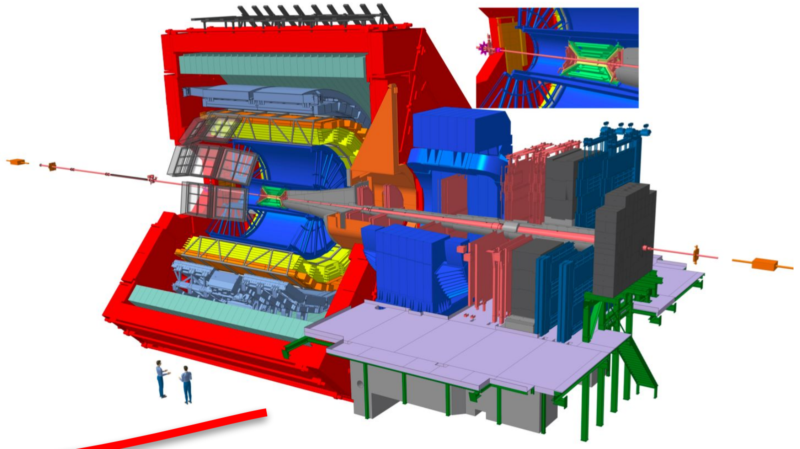
LHC overview











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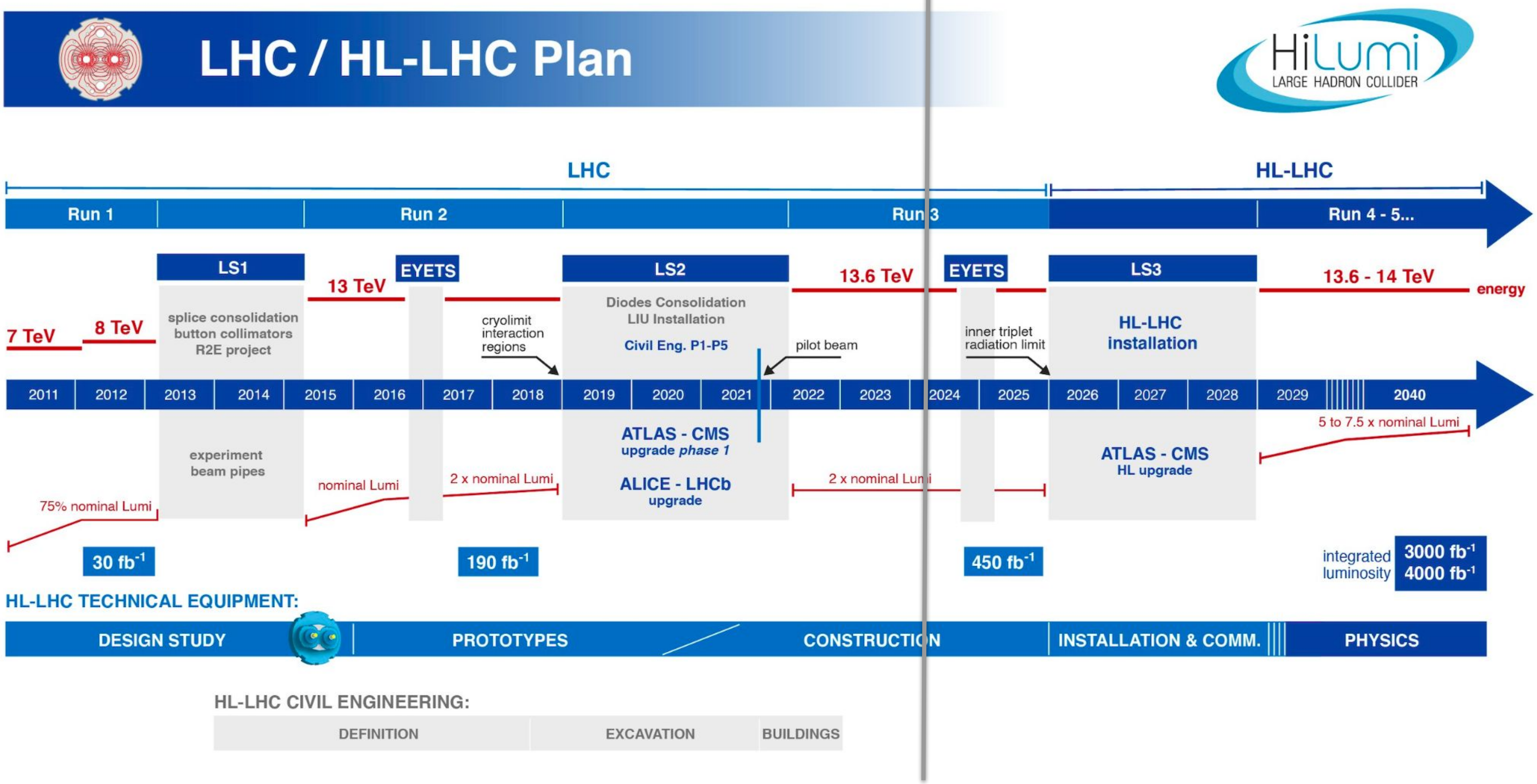
LHC timeline

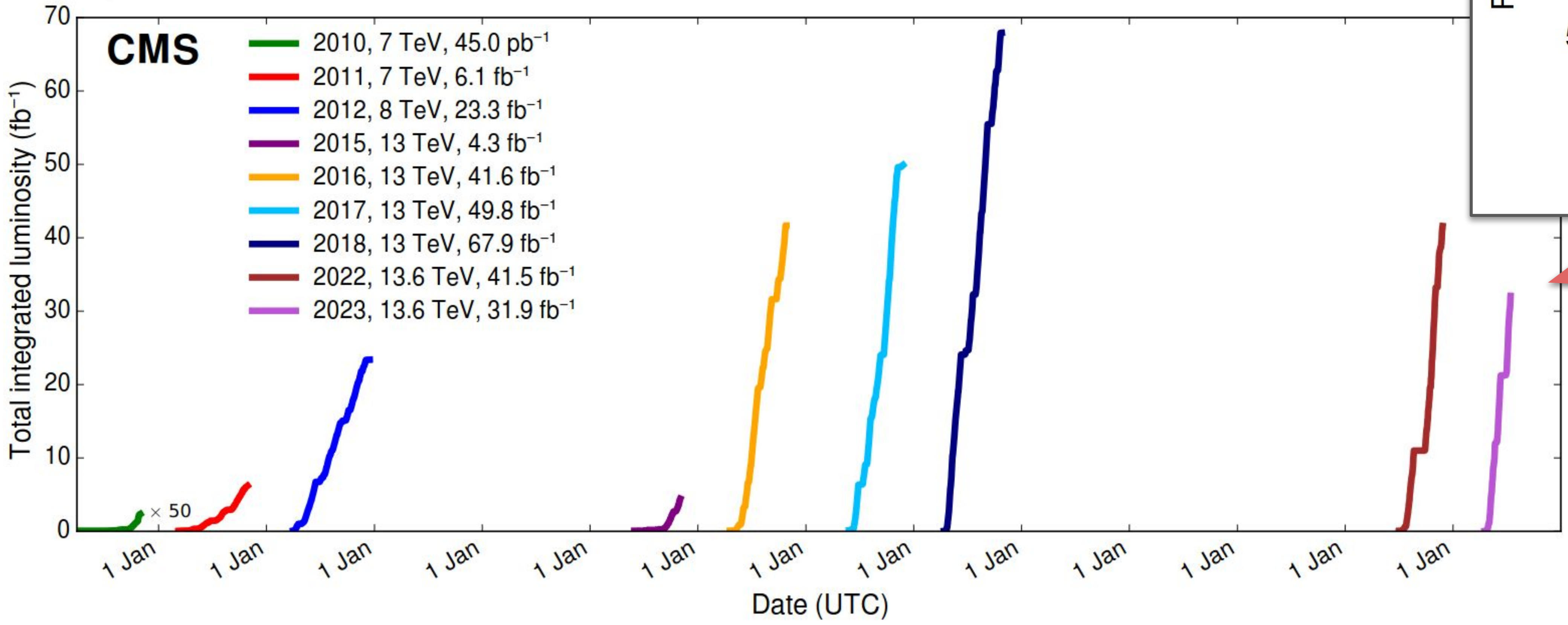
We are here

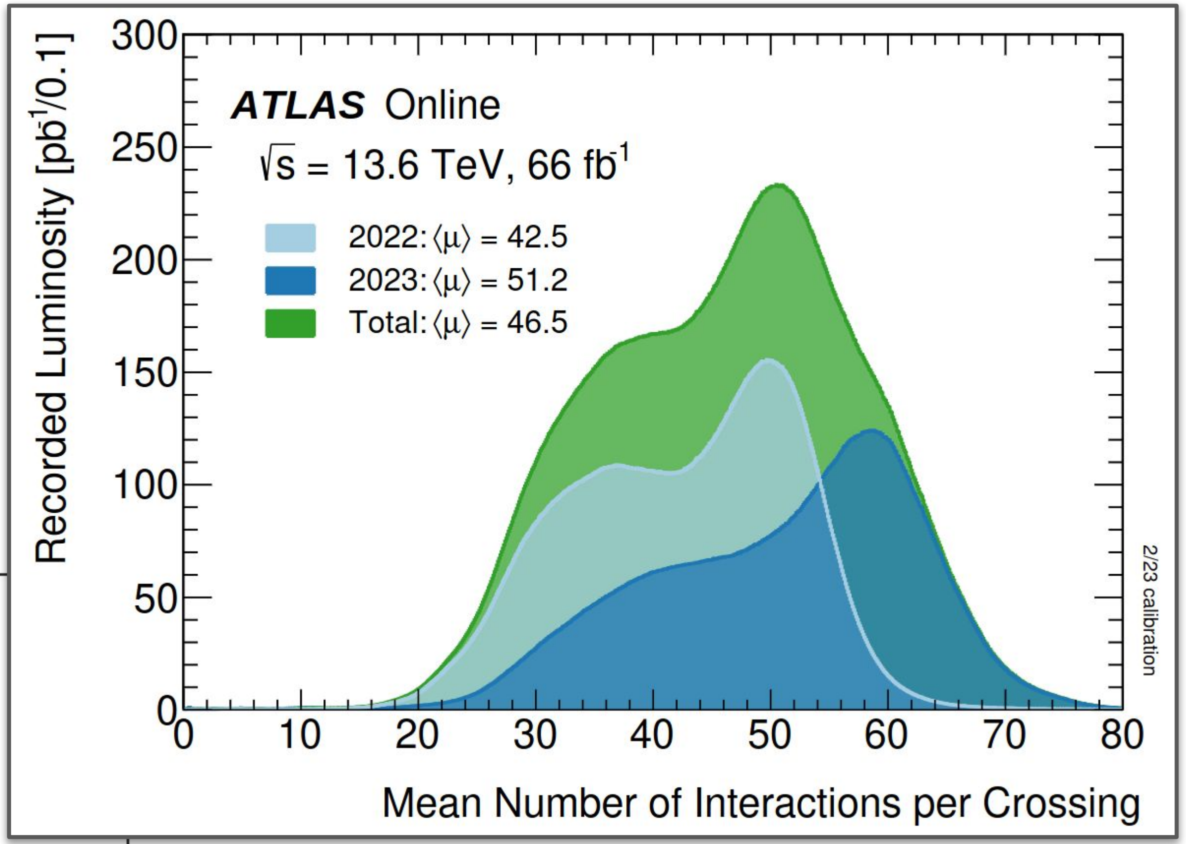


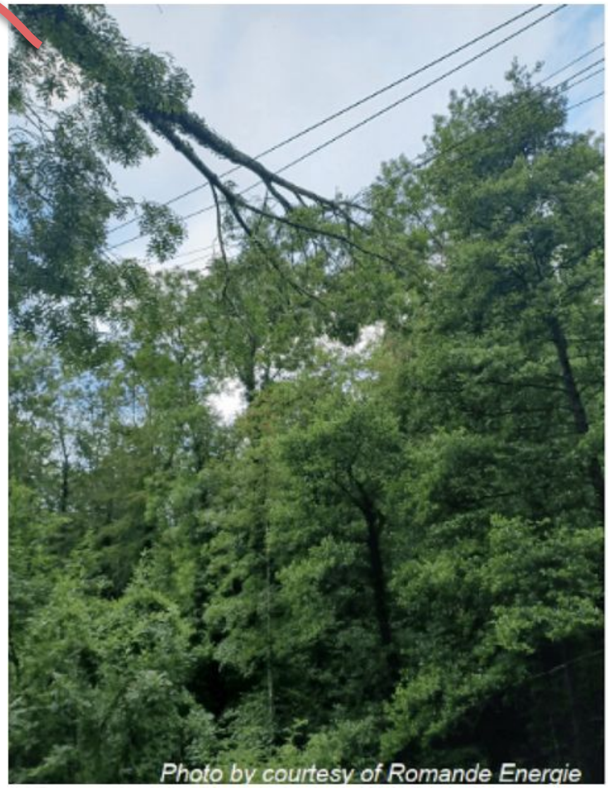
LHC status

- Run 2 (2015–2018) saw the LHC move into its precision era (>140 fb^{-1})
- Start of Run 3 (2022–) has been patchy… but still some incredible highlights

New record for integrated lumi in 24h = 1.2 fb^{-1}





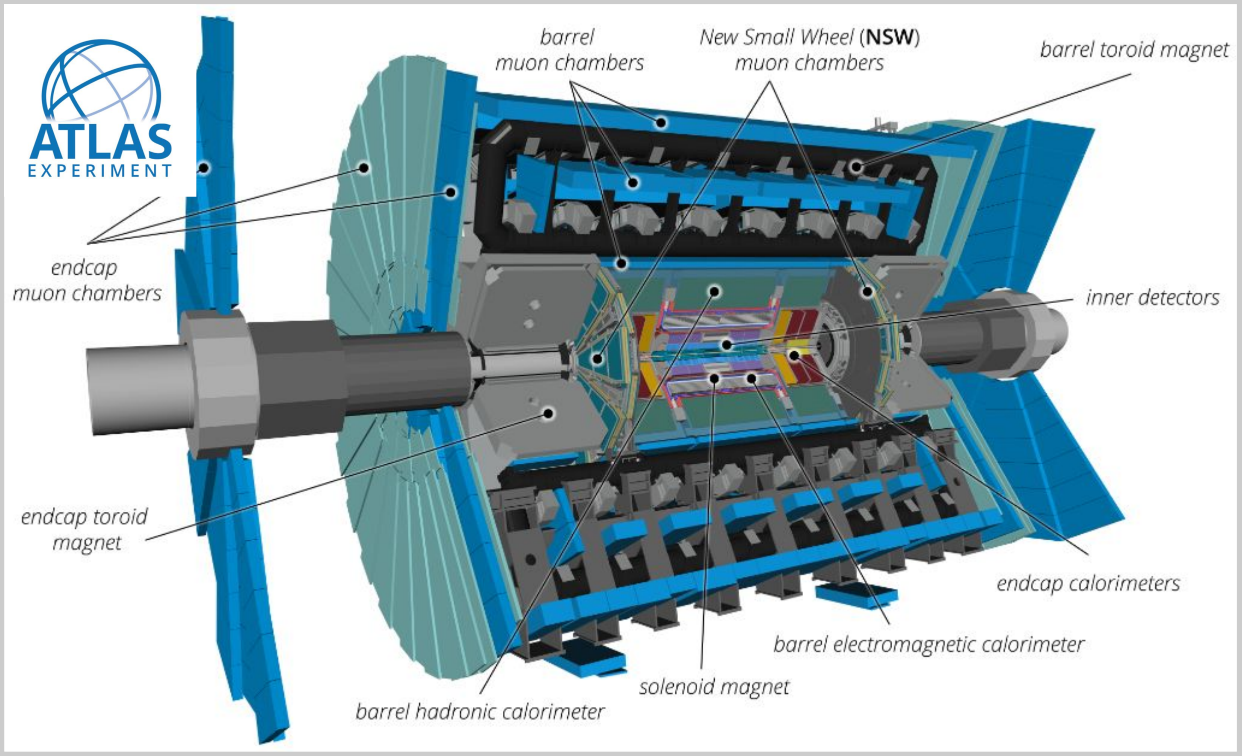


ITL8 quench

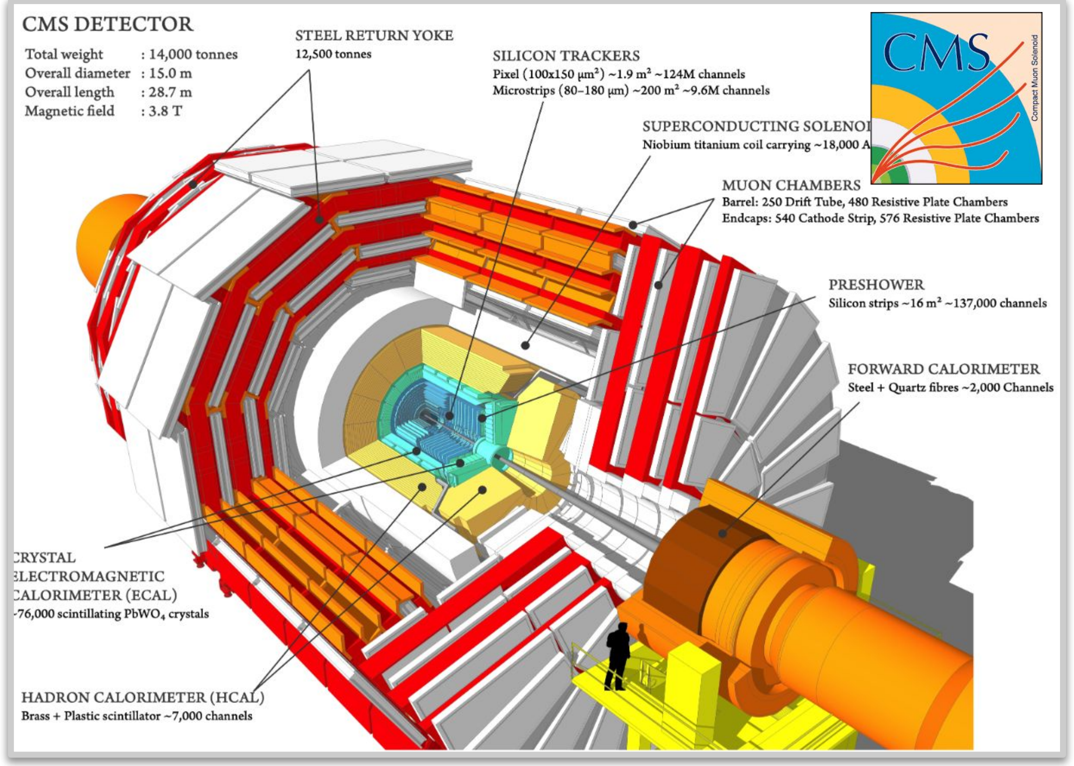
- **2024 promises to be an outstanding year**
  - First collisions at 13.6 TeV on 19/3/24 → Stable beams **this week** → Ending on 25/11/24
  - ~145 days of p-p physics providing >100 fb^{-1} in a single year + ~16 days of Pb-Pb!

Detector status

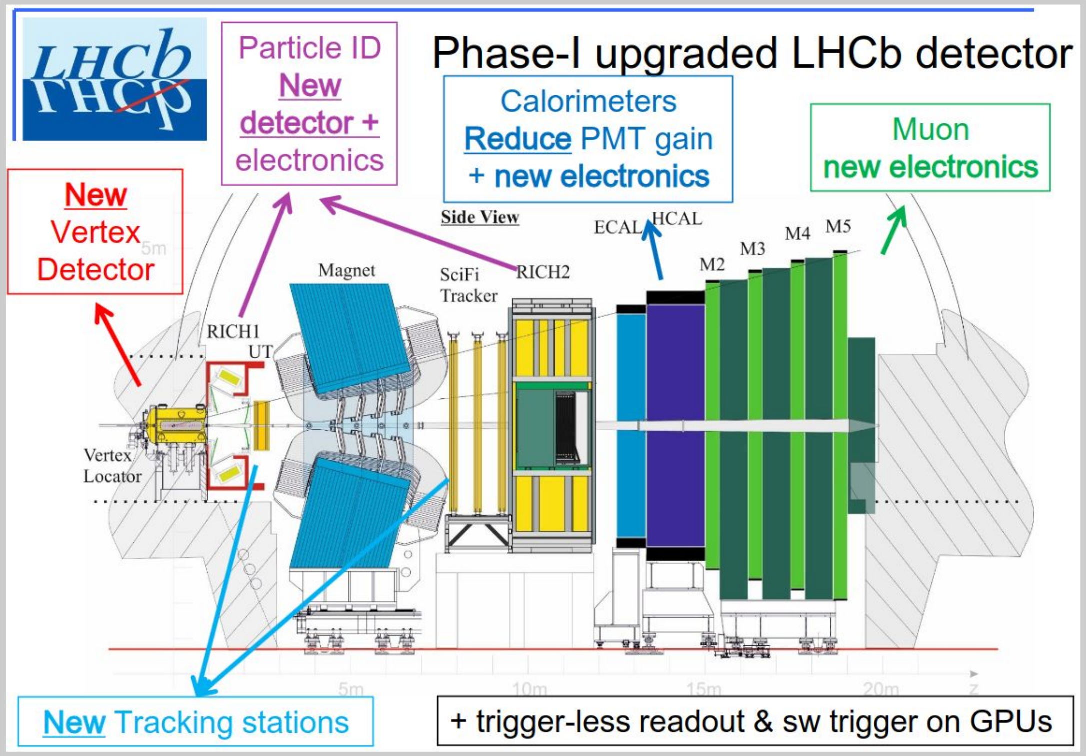
arXiv:2305.16623



arXiv:2309.05466



LHCb news

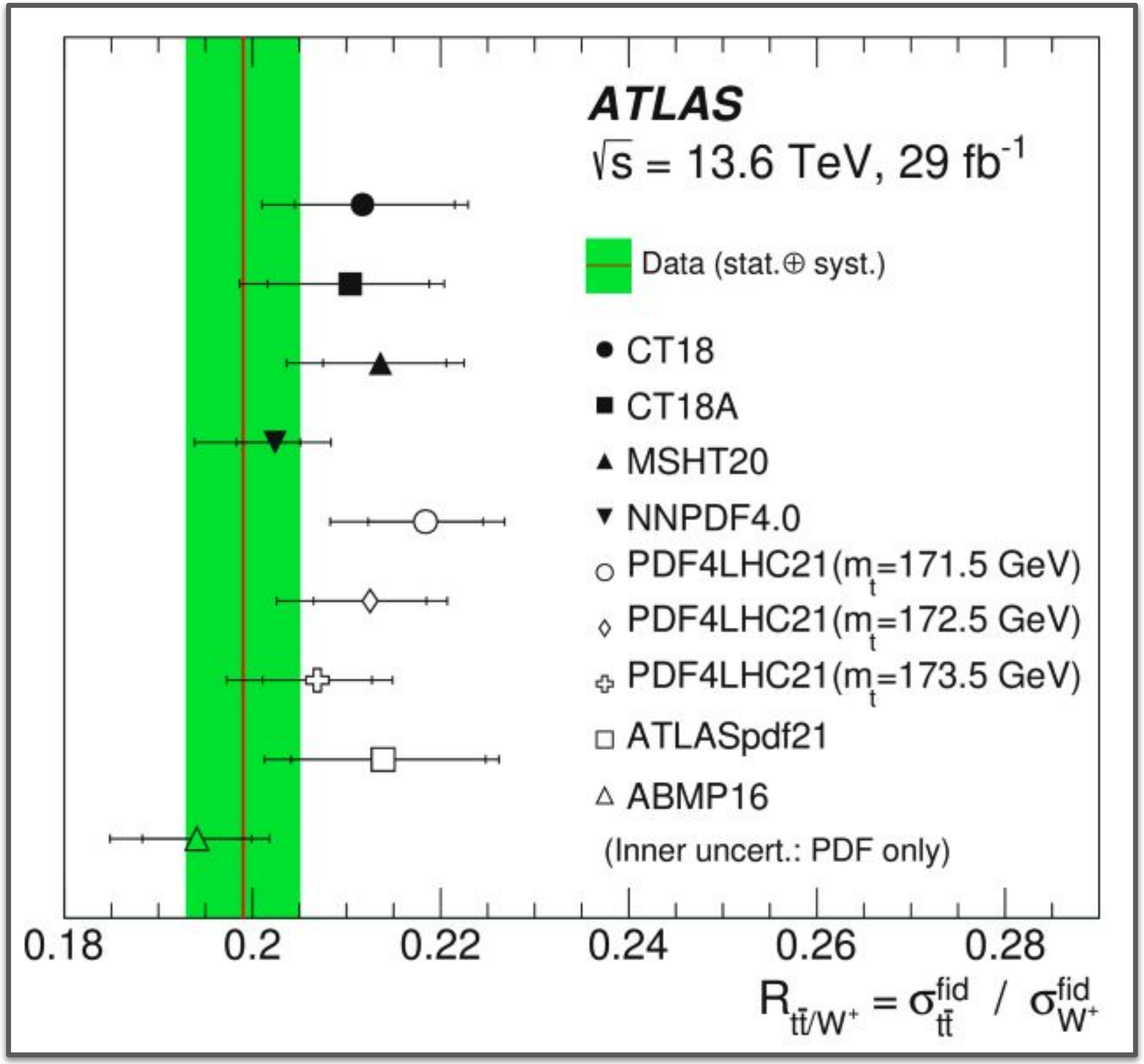


Run 3 upgrades have been a success → stepping stone to HL-LHC

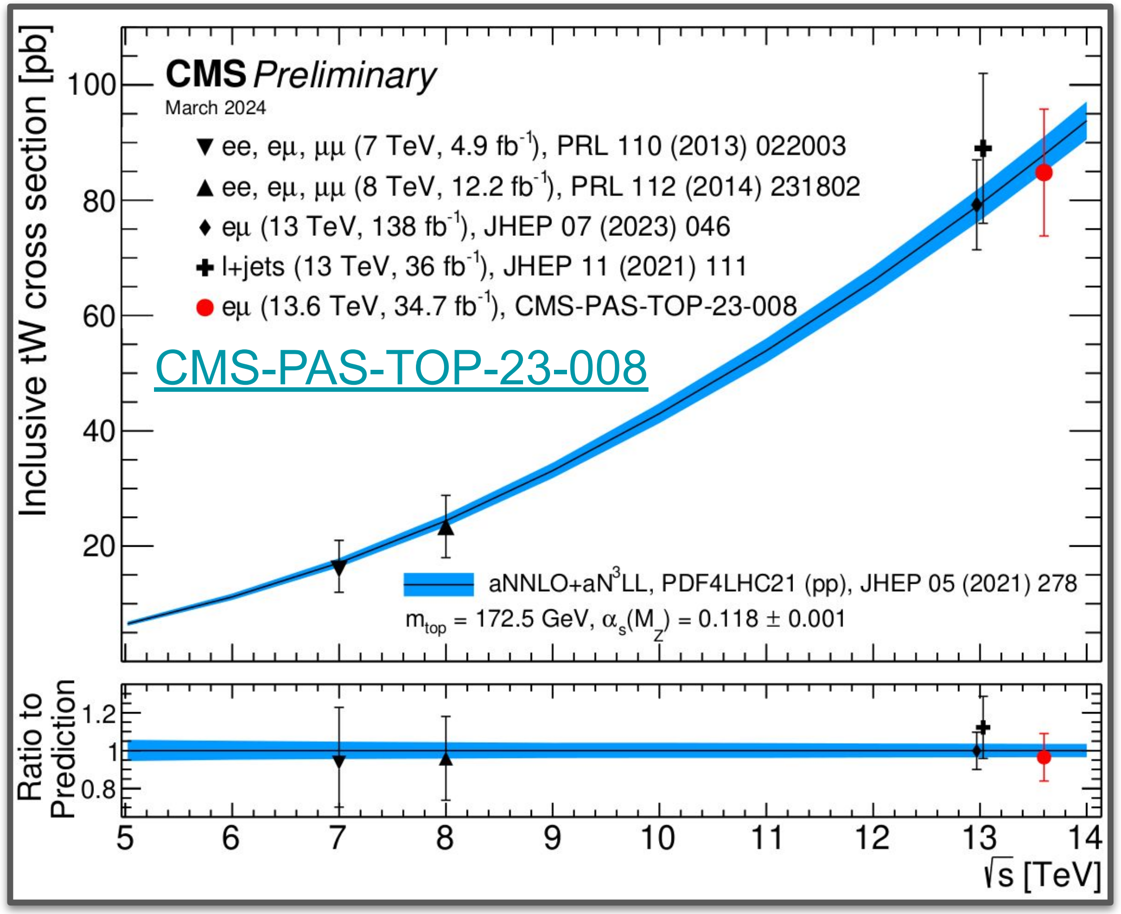
Experiments performing well and starting to turn out physics results…

Early Run 3 analyses

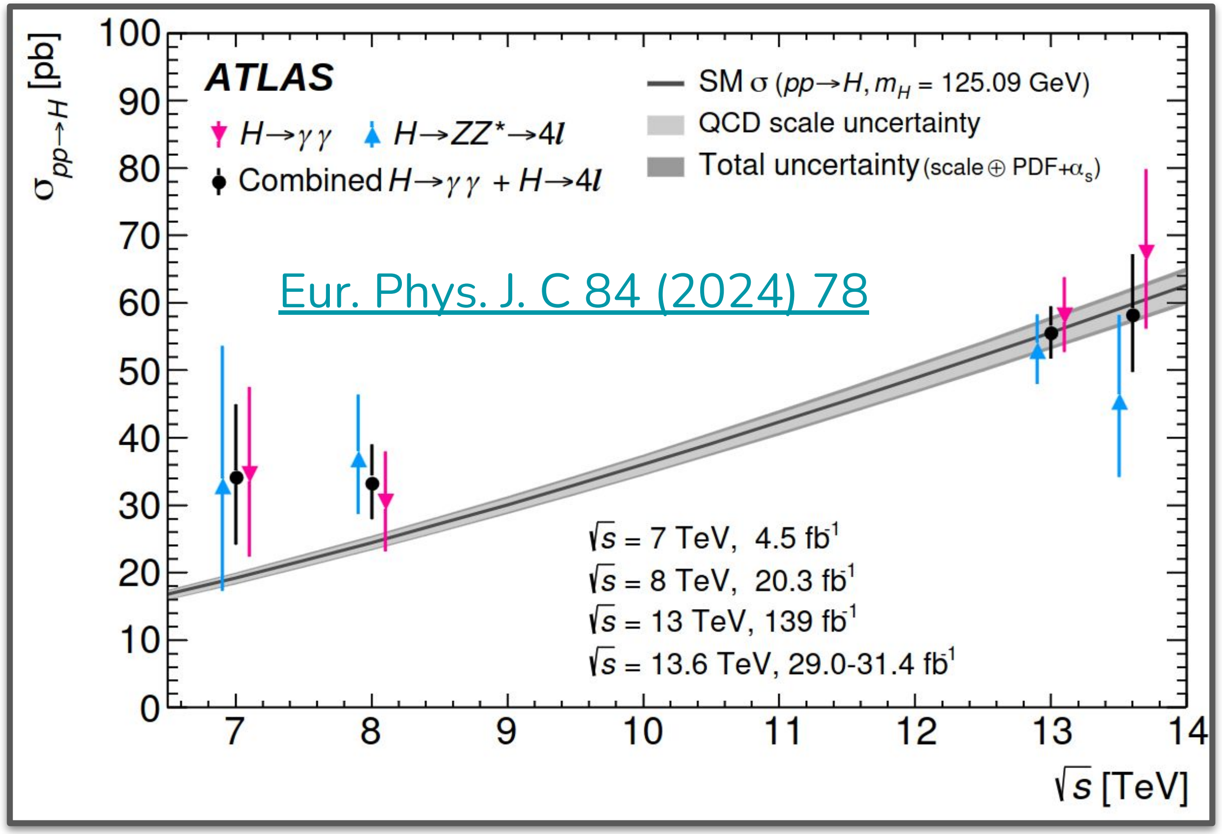
- EW, top, Higgs



[arXiv:2403.12902 (Sub. to Phys. Lett. B)]



[CMS-PAS-TOP-23-008]



[Eur. Phys. J. C 84 (2024) 78]

An exciting time @ LHC

1. **Rapidly growing LHC datasets**

2. **Boom in analysis techniques:** *machine-learning (ML), new triggers/data-taking strategies*

3. **Use experience from the past:** *Run 1 + 2*

4. **Lay foundations for a successful future:** *HL-LHC and beyond*

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1. **Rapidly growing LHC datasets**
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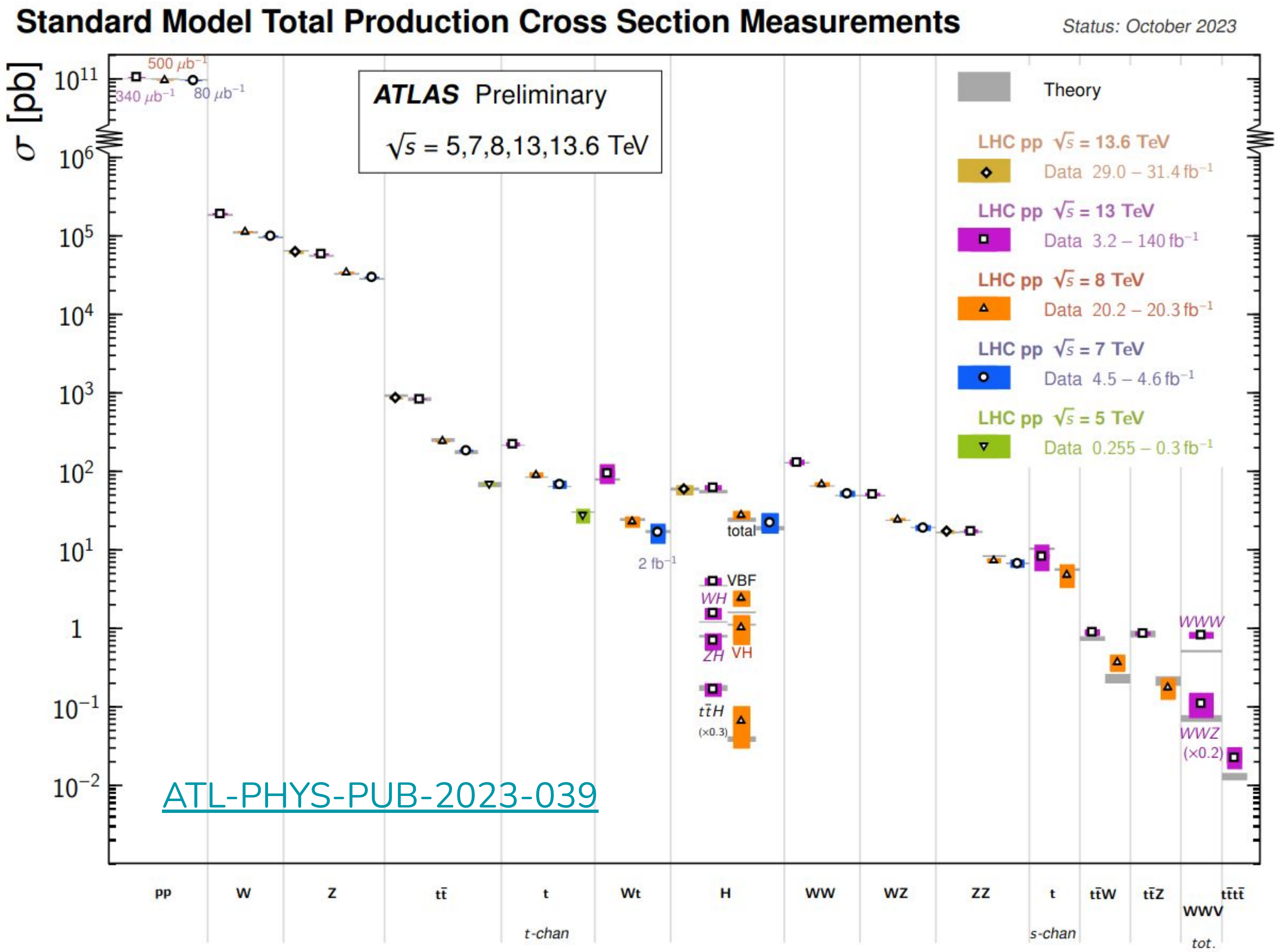
What can we do with the large amount of data...

Increased granularity	***Rare processes***	***Precision***	***Outside-of-the-box analyses***

This talk is a **subset** of new LHC SM results using Run 2 data

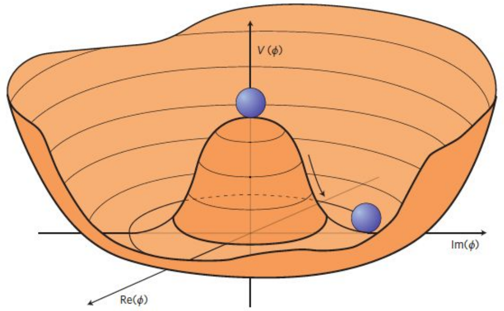
Personally selected

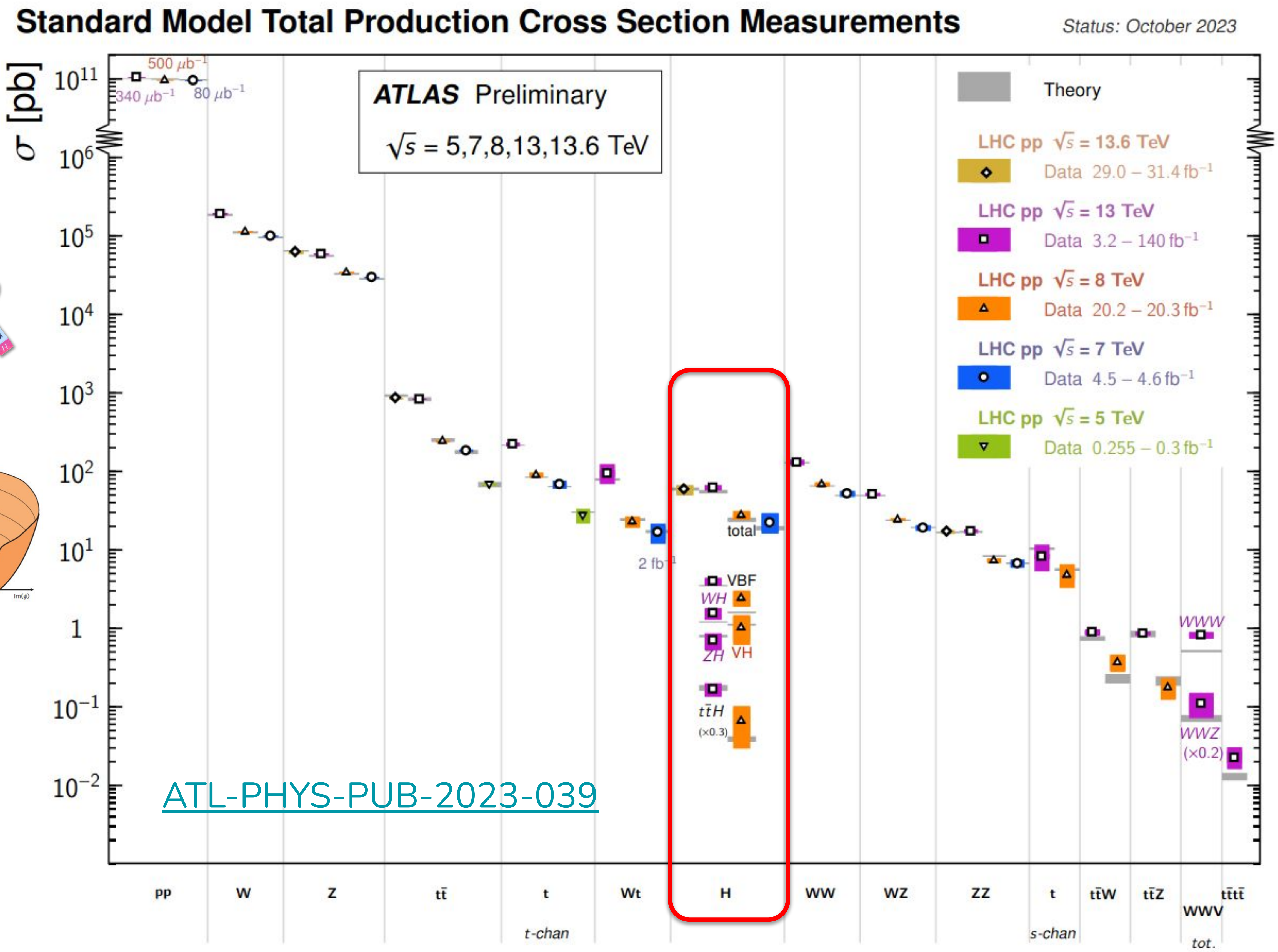
Mostly CMS+ATLAS



13 orders of magnitude!

ATL-PHYS-PUB-2023-039



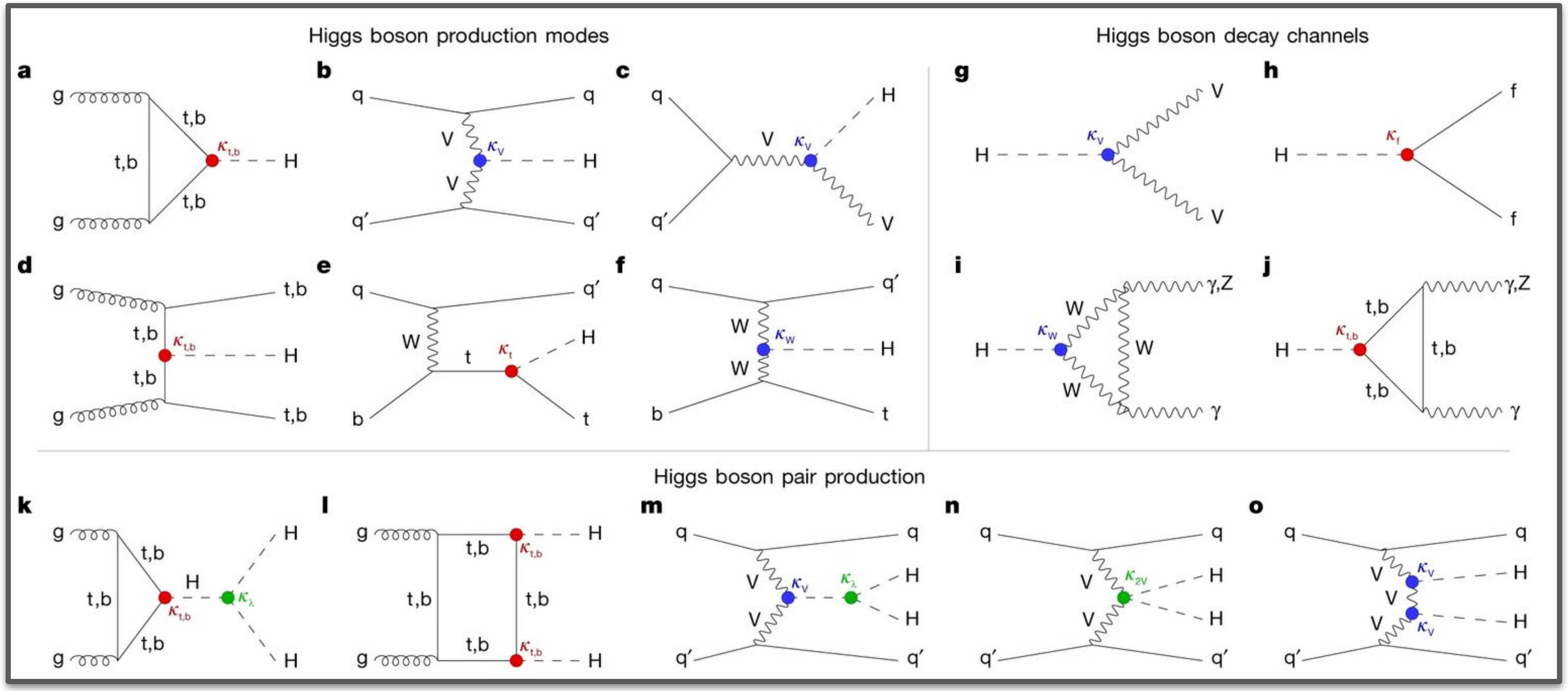


ATL-PHYS-PUB-2023-039

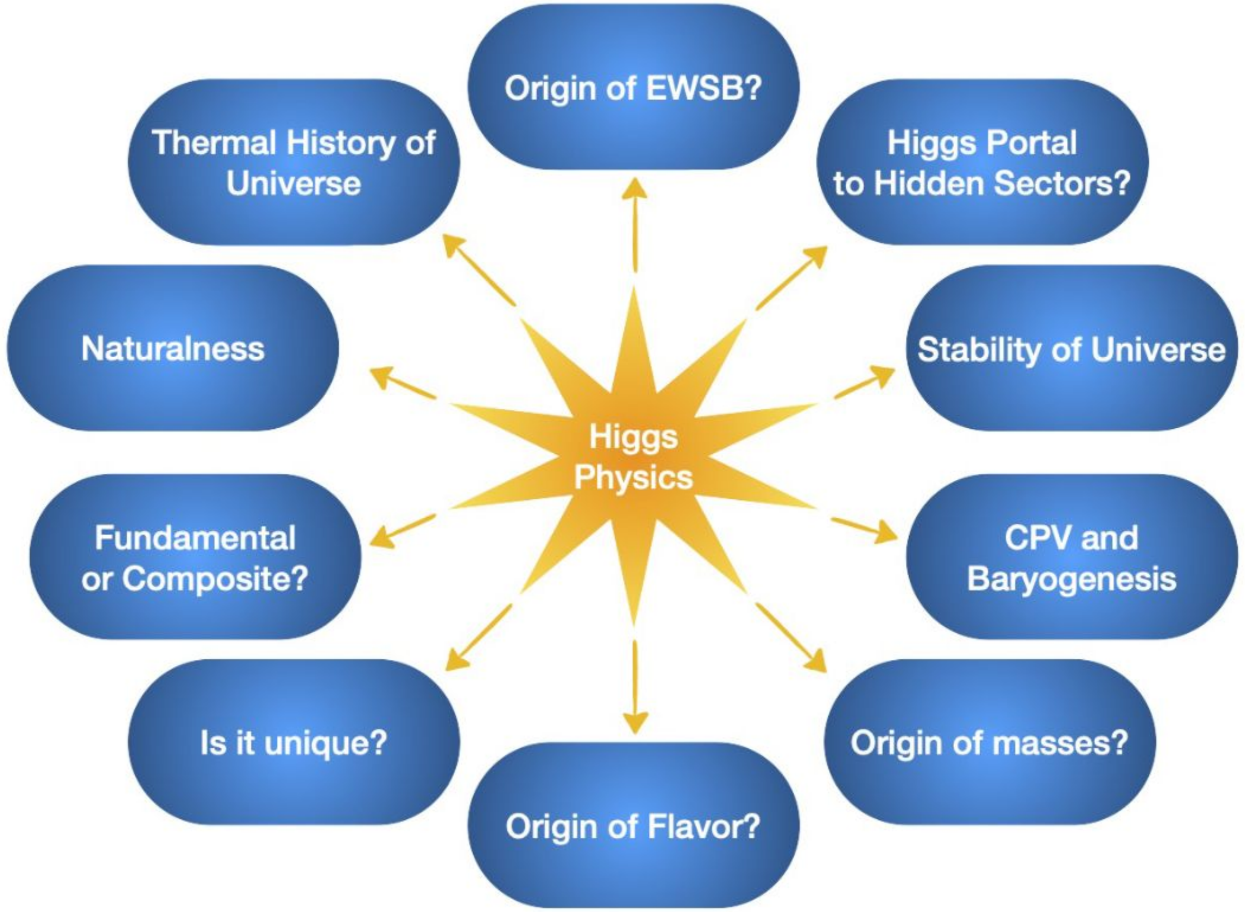
13 orders of magnitude!

Higgs sector

- Since 2012 ATLAS + CMS have undergone a comprehensive research program to **provide detailed map of Higgs sector**
- Unique tool to search for new fundamental physics



"Almost every problem of the Standard Model originates from Higgs interactions"



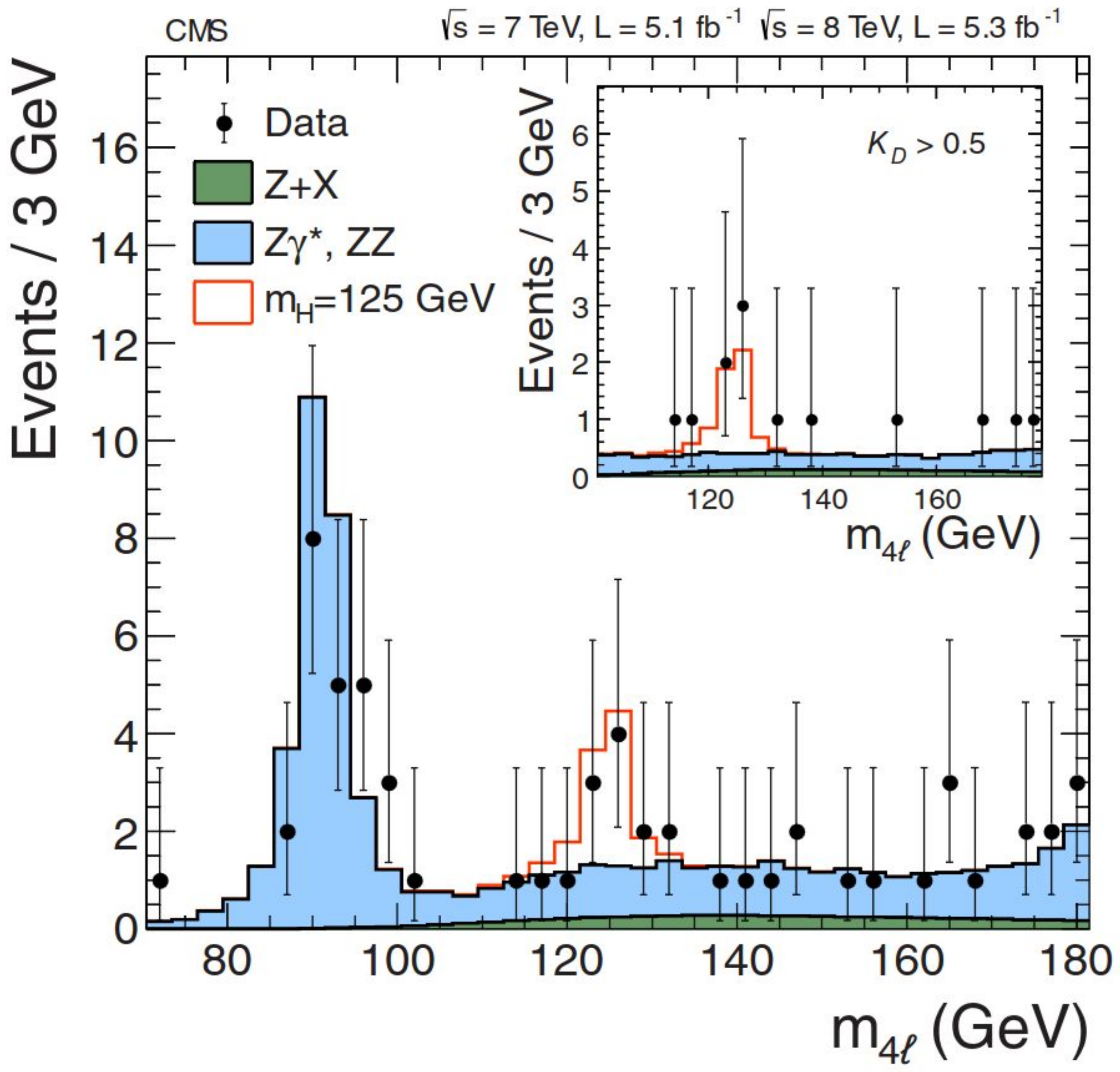
$$\mathscr{L} = y H \psi \bar{\psi} + \mu^2 |H|^2 - \lambda |H|^4 - V_0$$

flavour *naturalness* *stability*

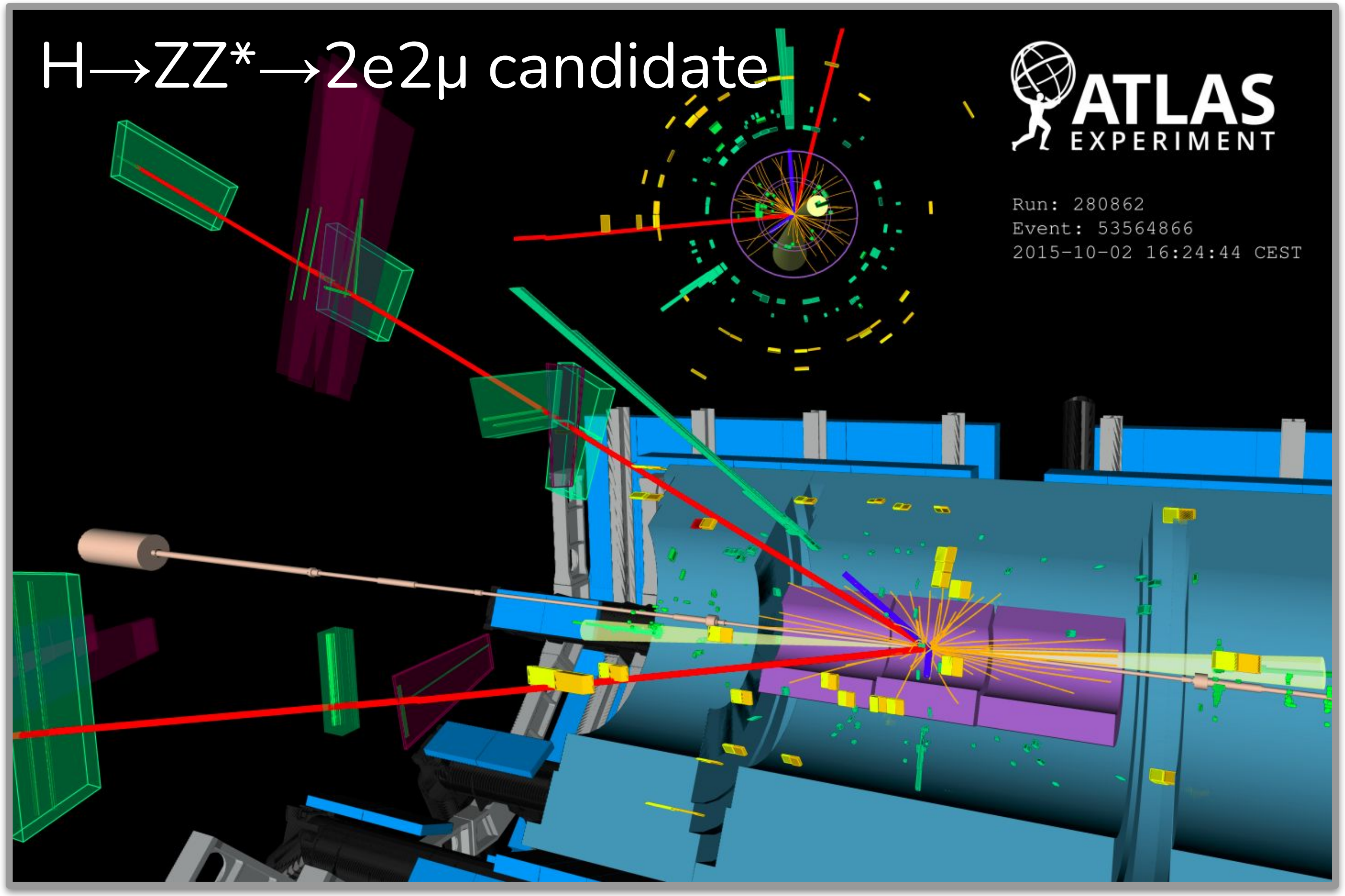
cosmological constant

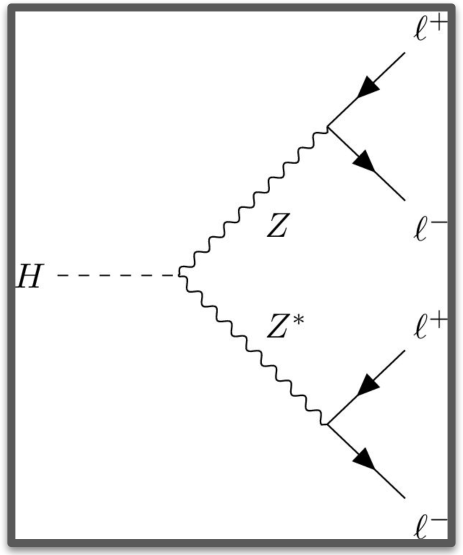
Taken from Gavin Salam slides at FCC week 2023

Higgs @ 10



2012





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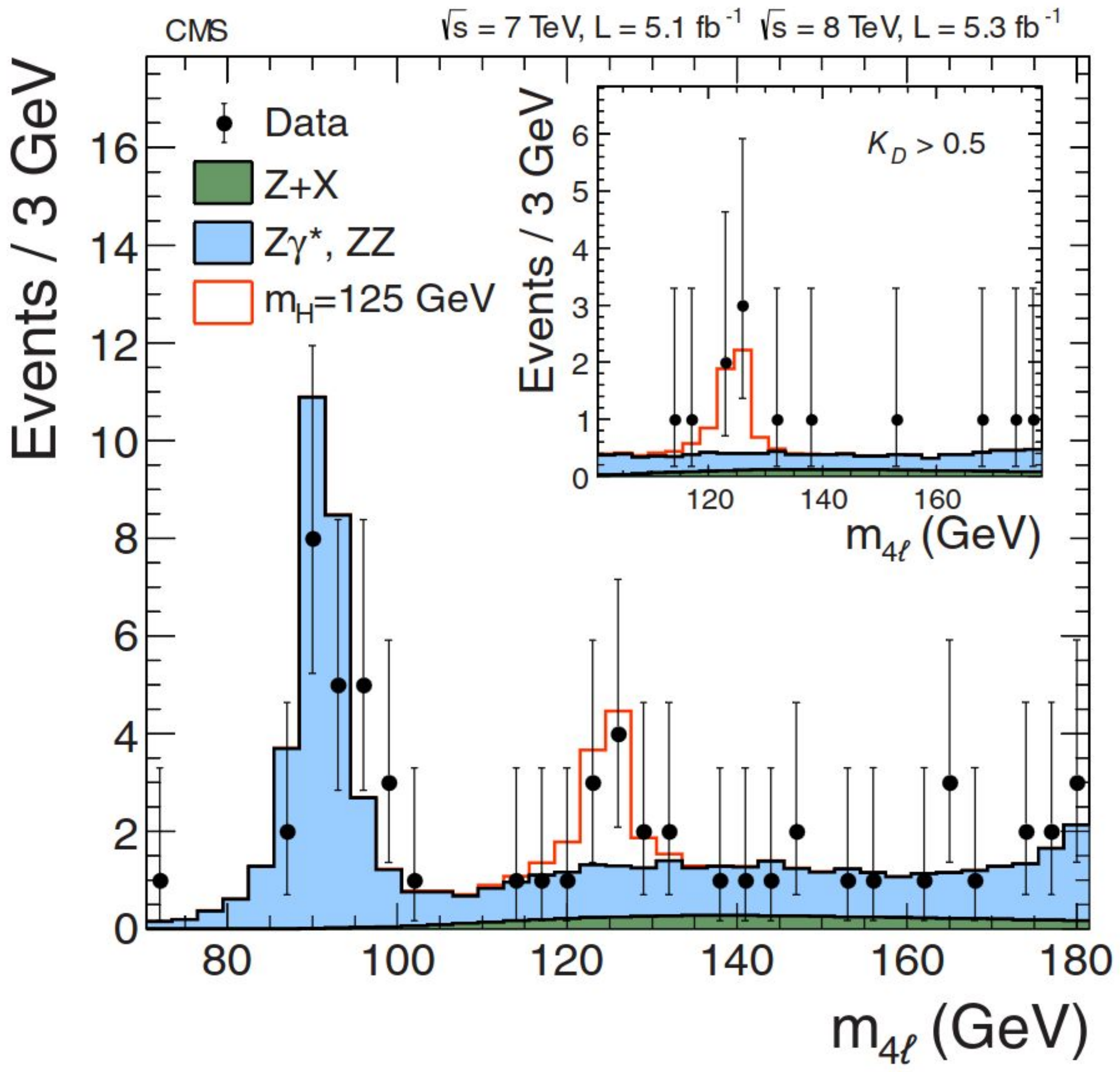
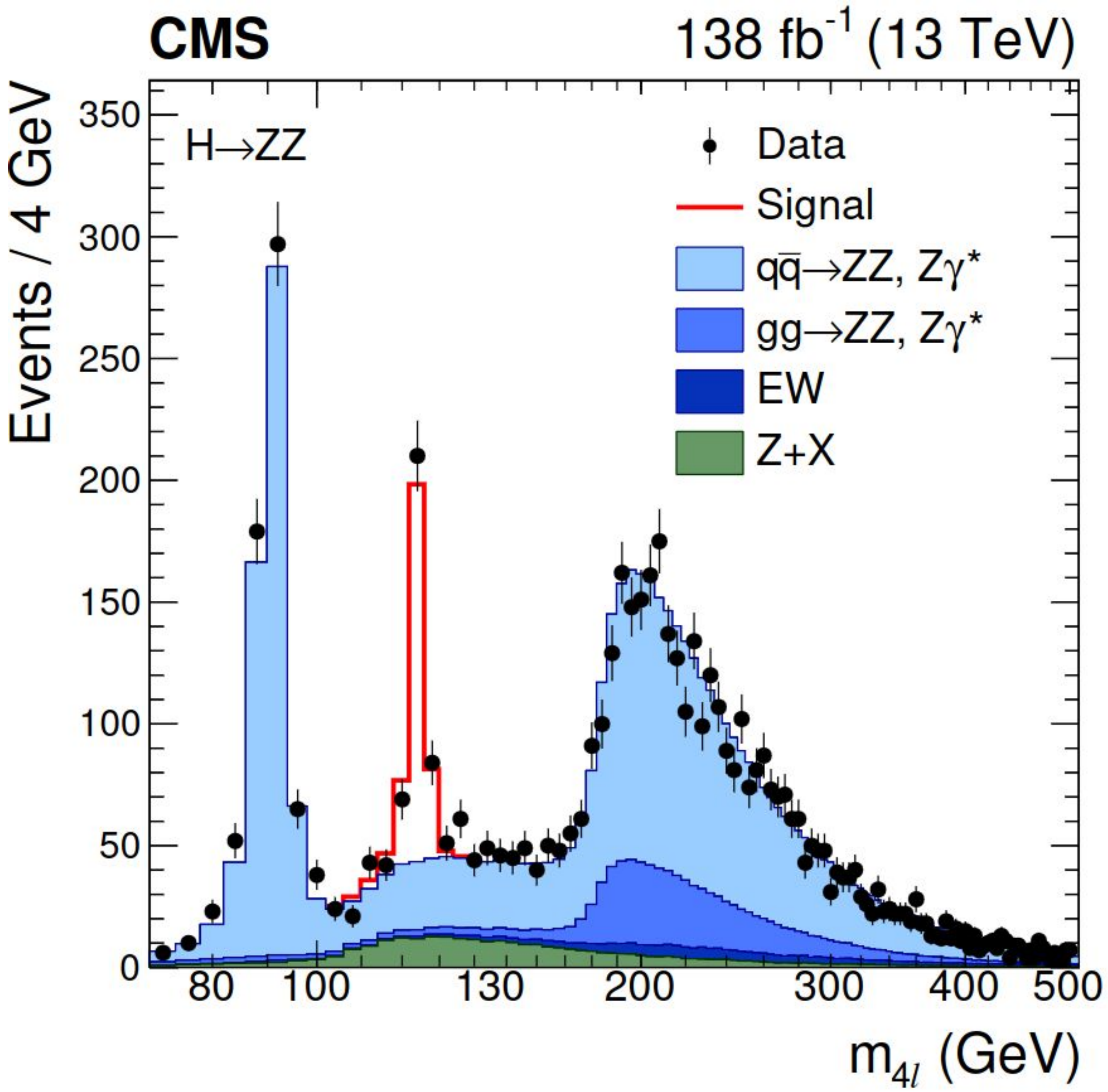
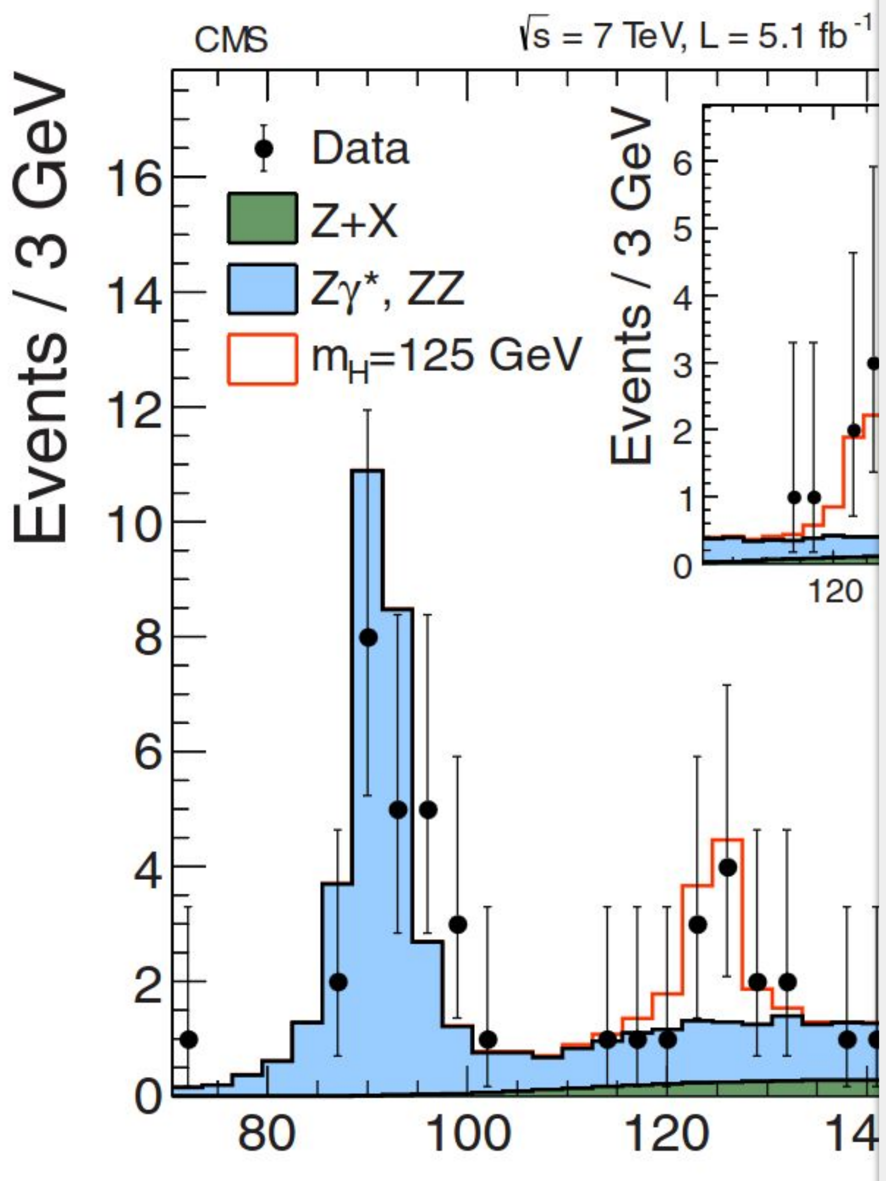


2012



2022

Higgs @ 10



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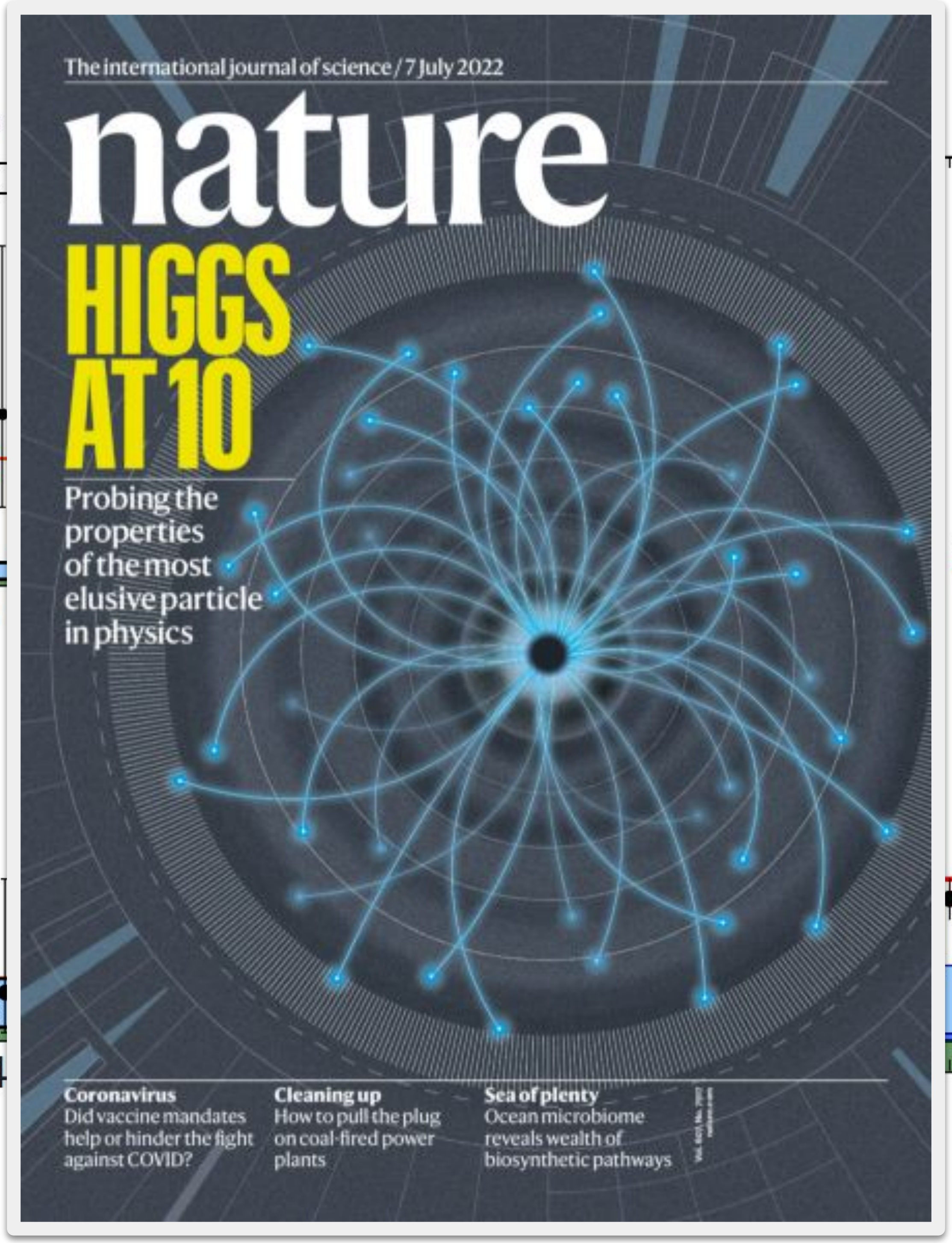
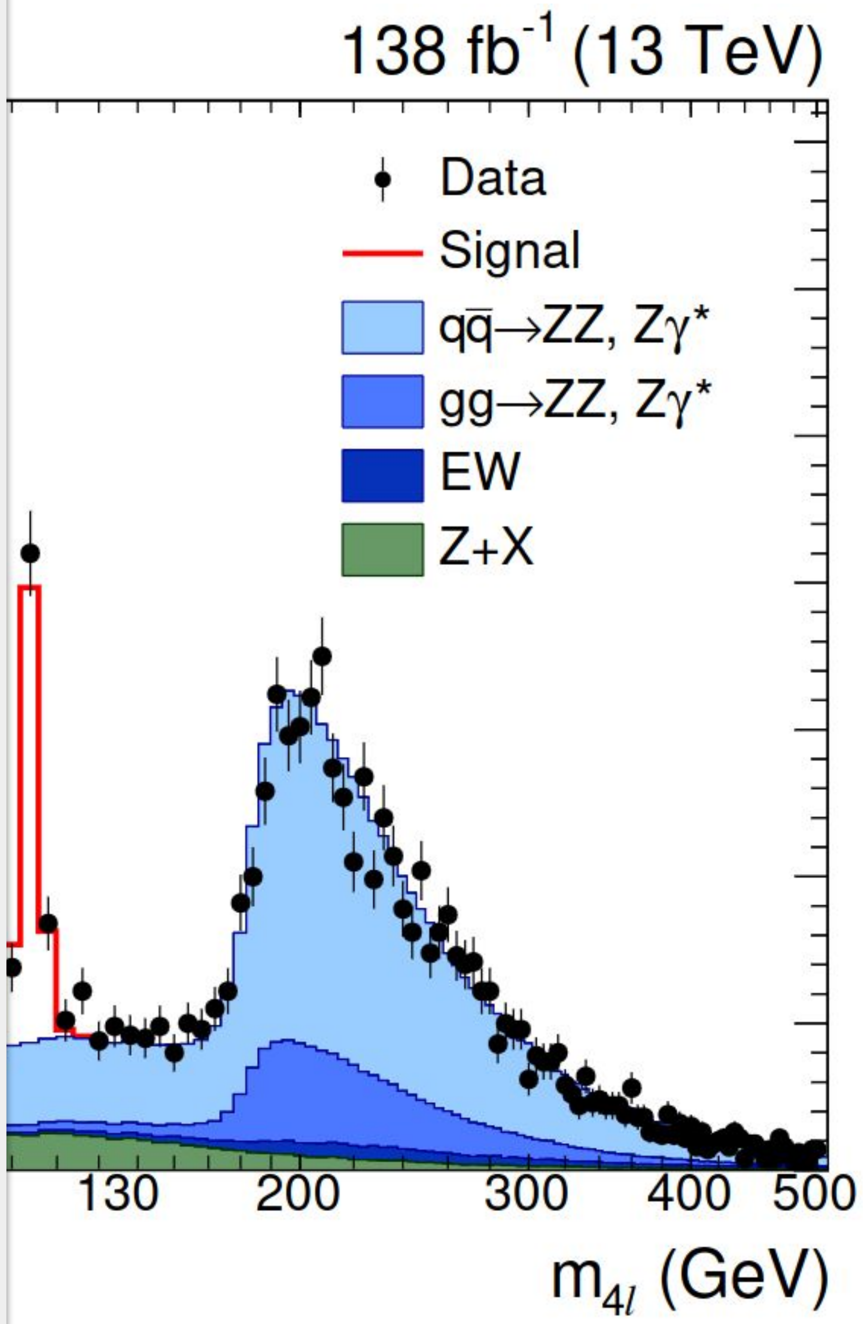
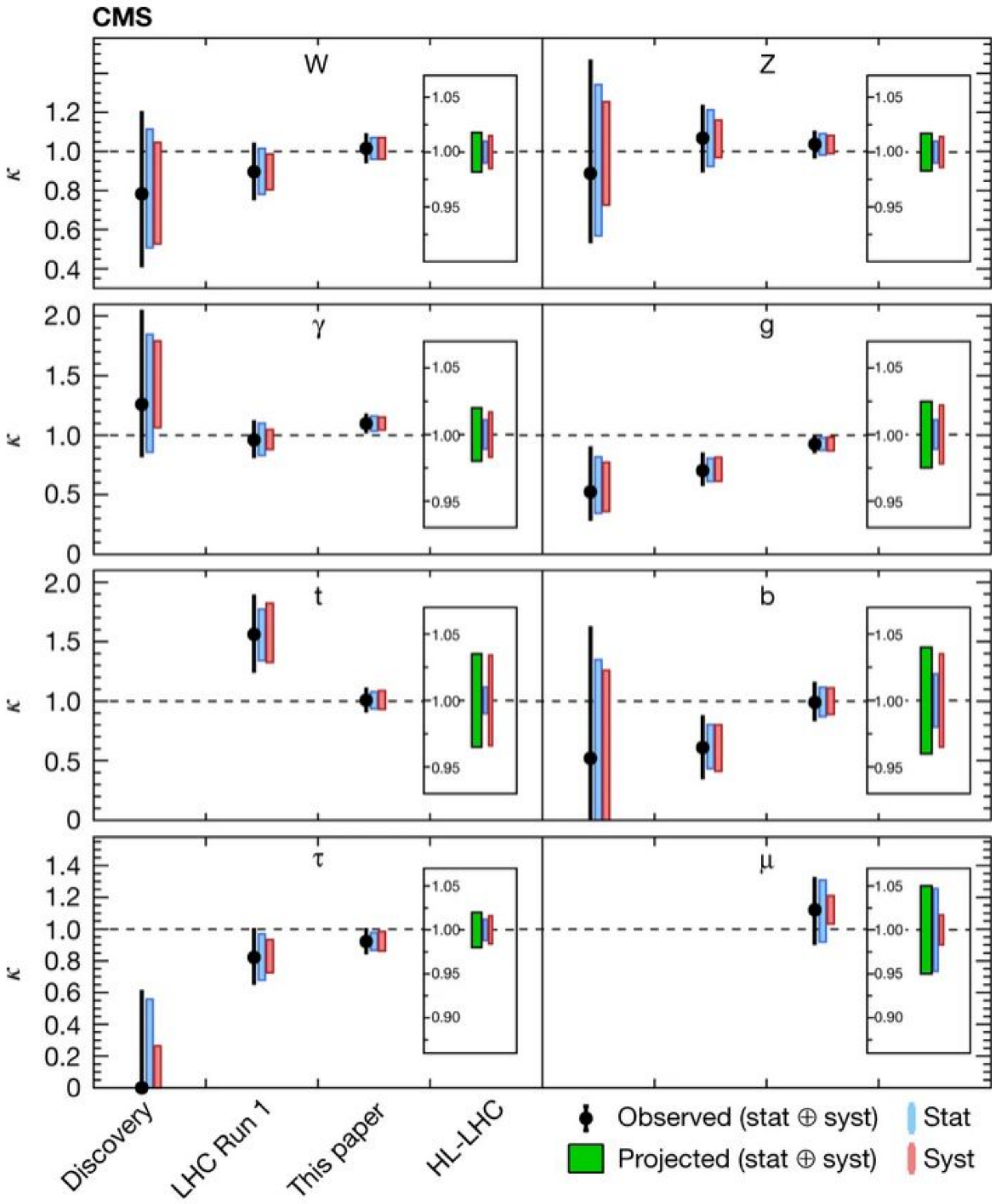


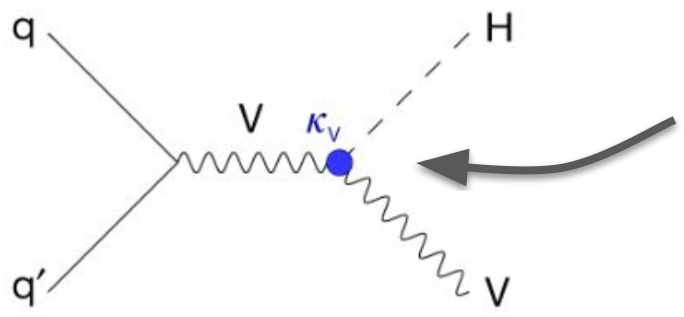


2022

Higgs interactions



[Nature 607, 60-68 (2022)]



Kappa framework

Ultimate precision via Higgs boson **statistical combinations**

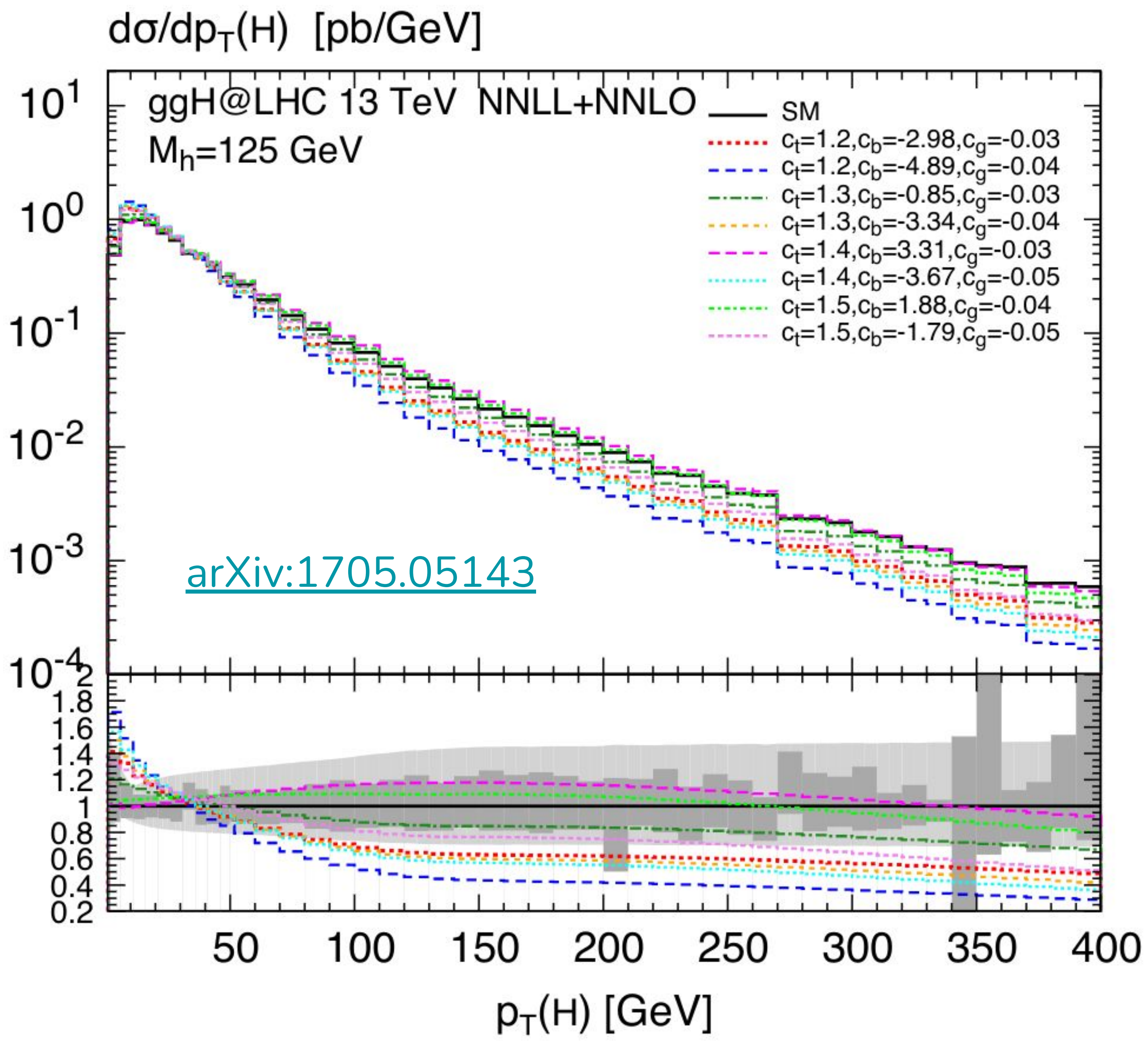
- H→bb, H→WW, H→ZZ, H→ττ, H→γγ, H→μμ, H→Zγ

Table 1-8. *Generic size of Higgs coupling modifications from the Standard Model values when all new particles are $M \sim 1$ TeV and mixing angles satisfy precision electroweak fits. The Decoupling MSSM numbers assume $\tan\beta = 3.2$ and a stop mass of 1 TeV with $X_t = 0$ for the κ_γ prediction.*

Model	κ_V	κ_b	κ_γ
Singlet Mixing	$\sim 6\%$	$\sim 6\%$	$\sim 6\%$
2HDM	$\sim 1\%$	$\sim 10\%$	$\sim 1\%$
Decoupling MSSM	$\sim -0.0013\%$	$\sim 1.6\%$	$\sim -.4\%$
Composite	$\sim -3\%$	$\sim -(3-9)\%$	$\sim -9\%$
Top Partner	$\sim -2\%$	$\sim -2\%$	$\sim +1\%$

[arXiv:1310.8361]

Cannot rule out new physics with current precision (10-20%)



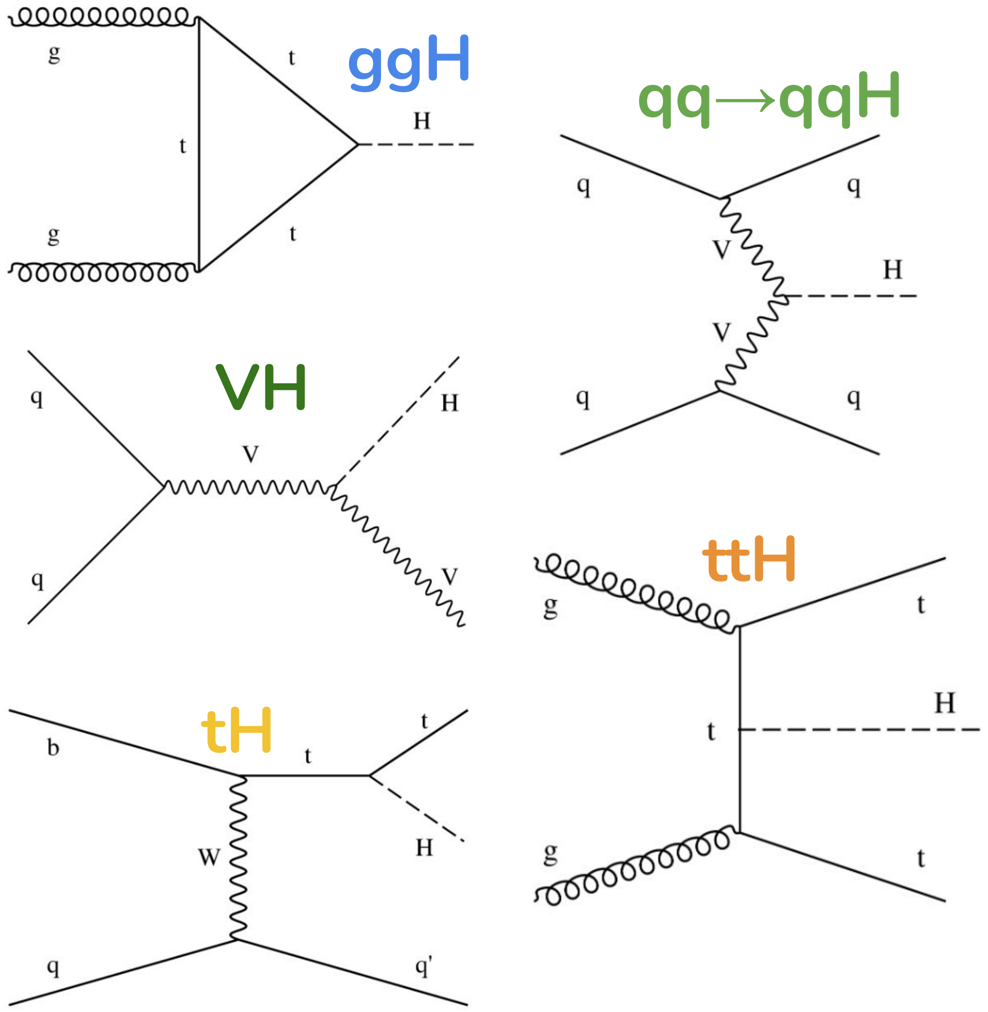
Increased granularity

Rates → Distributions

Going granular

Rates ⟶ Distributions

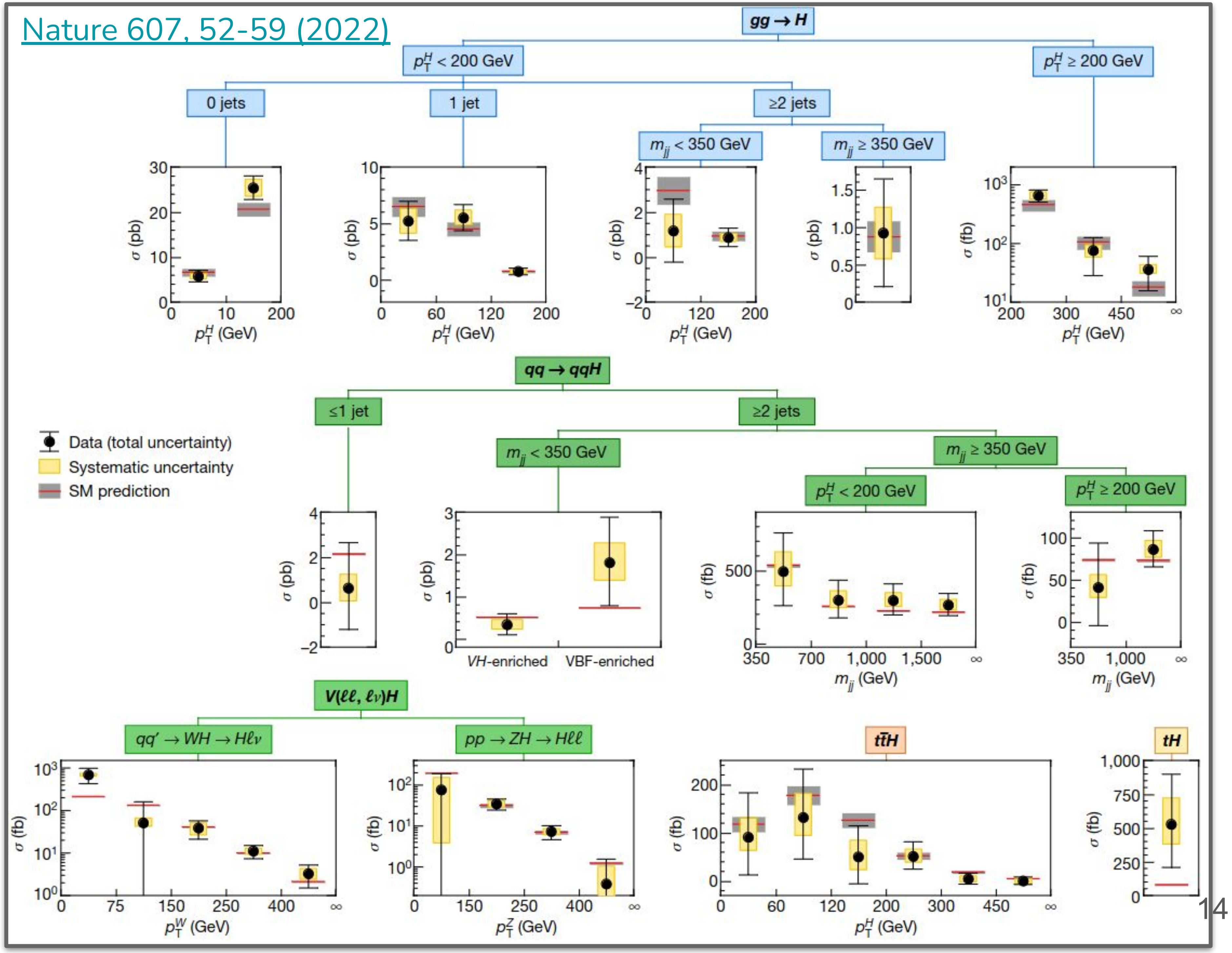
- Measure Higgs boson production **differentially** in the simplified template cross section **(STXS)** framework
  - Good agreement with the SM…
  - Large (stat-dominated) uncertainties!



Great framework for BSM interpretation e.g. SMEFT

[See Back-Up] [arXiv:2304.05742]

Nature 607, 52-59 (2022)

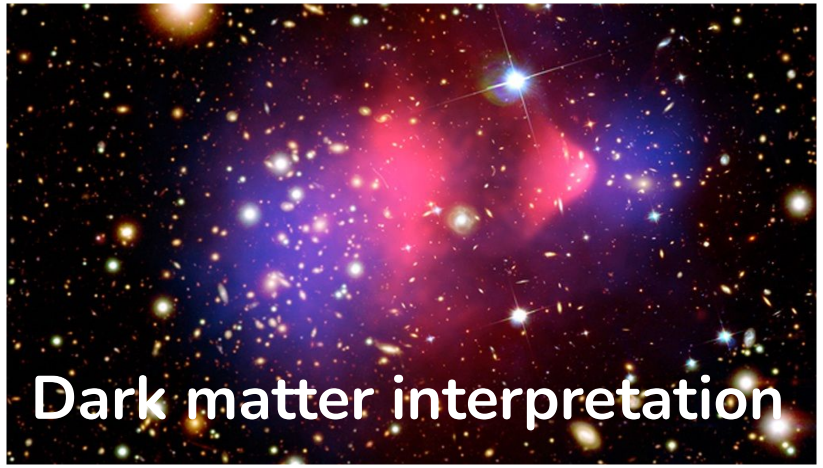


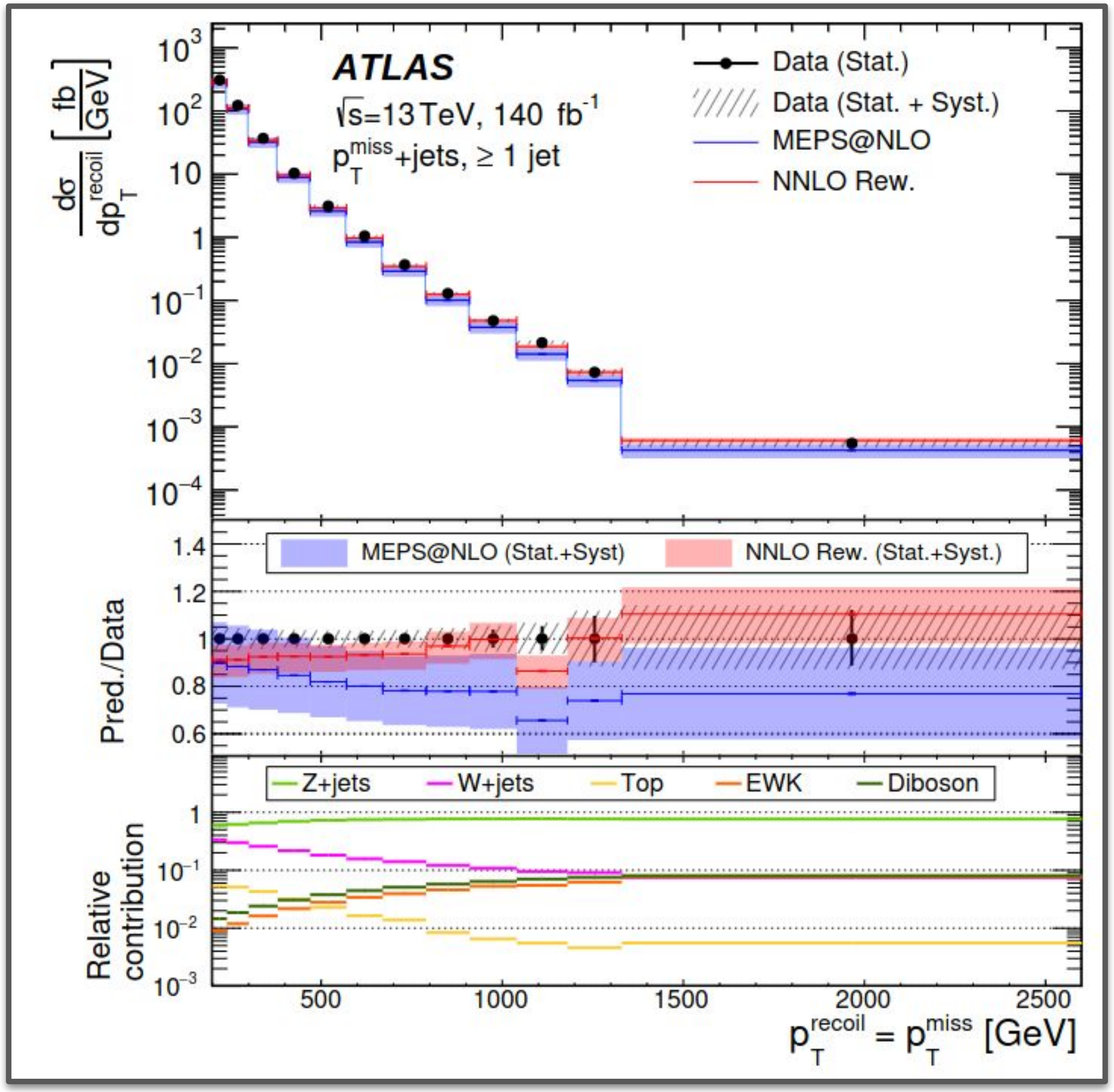
Going granular

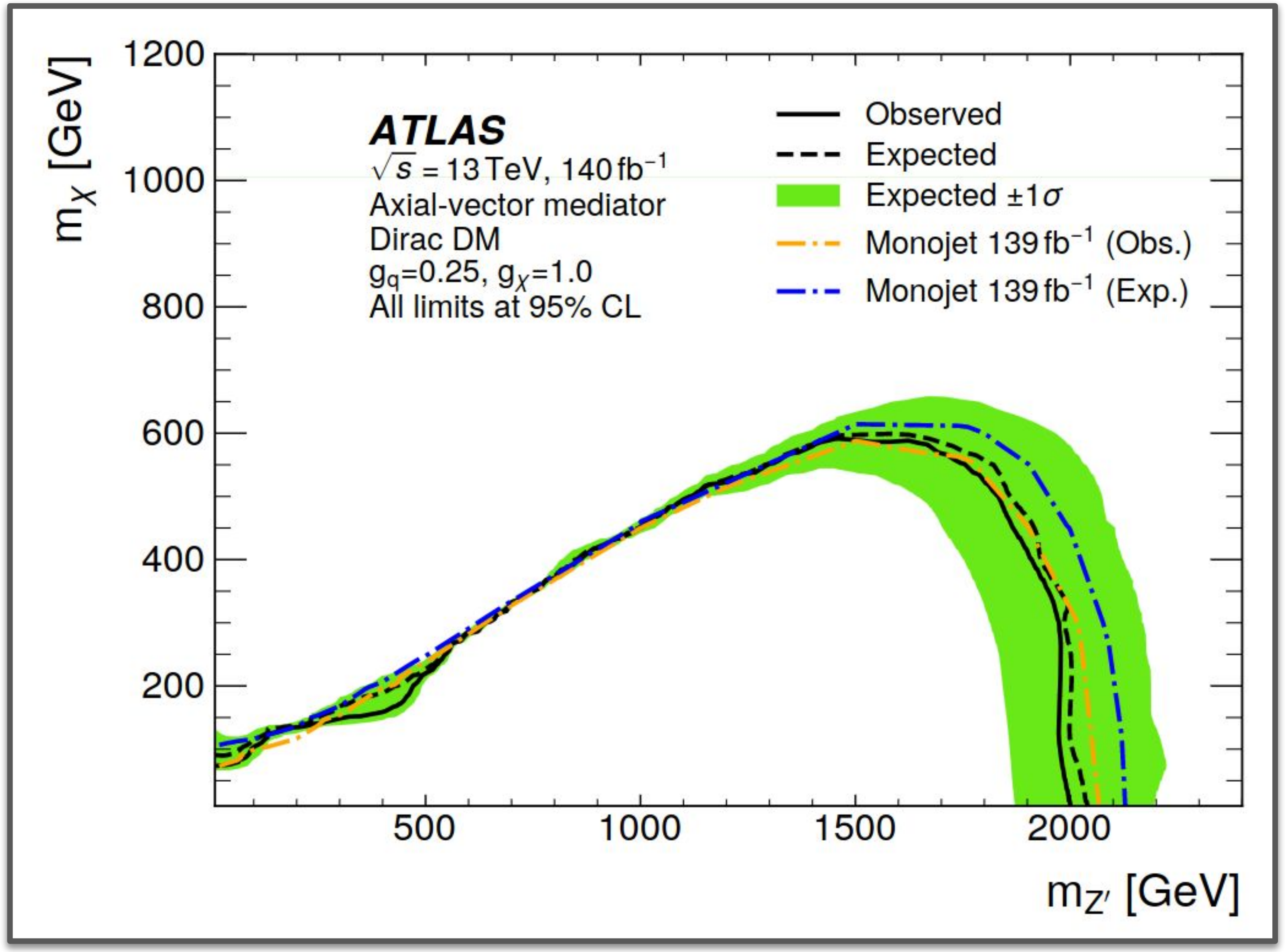
Rates → Distributions

$$\sum_i \vec{p}_{\mathrm{T},i} = 0 \qquad \boxed{\vec{E}_{\mathrm{T}}^{\mathrm{miss}} = - \sum_{\mathrm{observable}} \vec{p}_{\mathrm{T},i}}$$

- [arXiv:2403.02793] Diff. XS measurements for events with MET+jets (ATLAS)
  - Aim to be as inclusive and model-independent as possible
  - BSM interpretation: **excellent focus on reinterpretation** (HEPdata, Rivet)



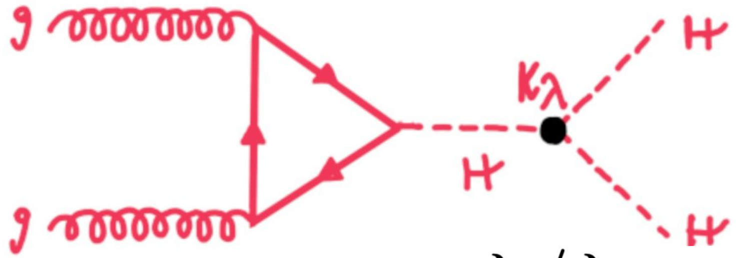




Rare processes

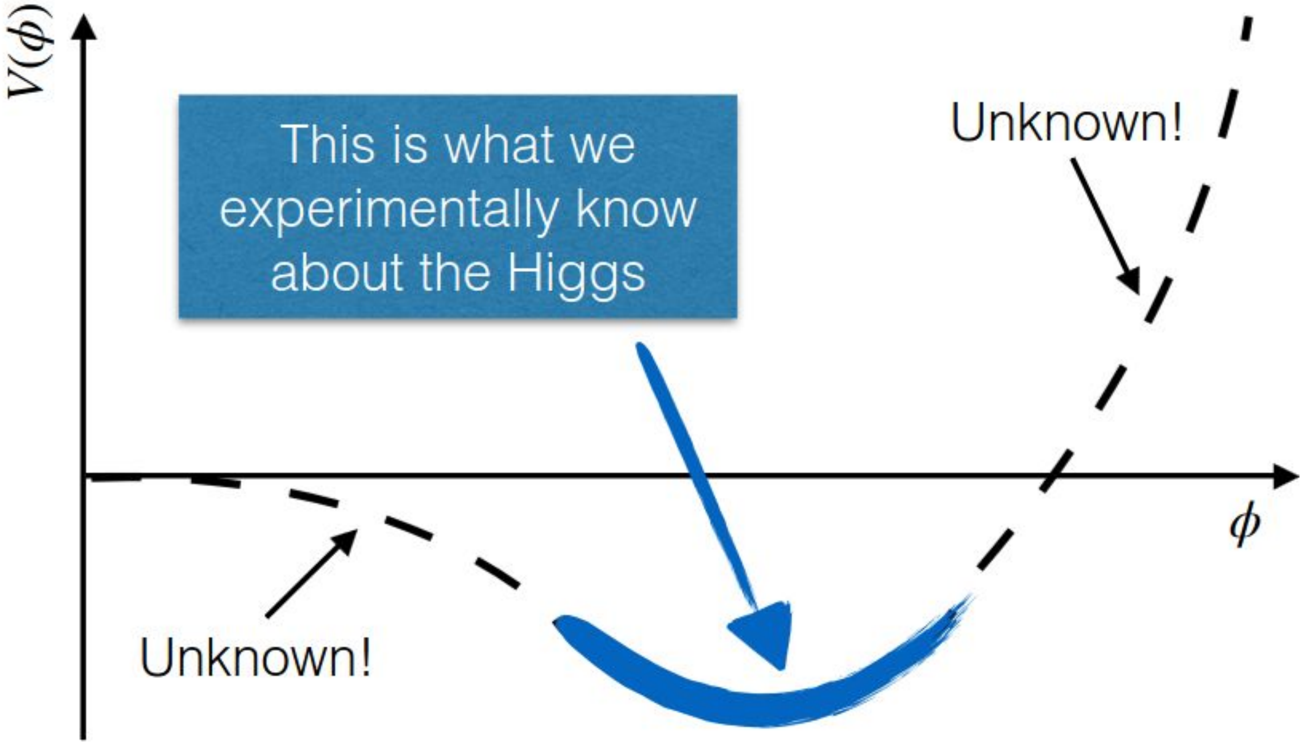
HH production

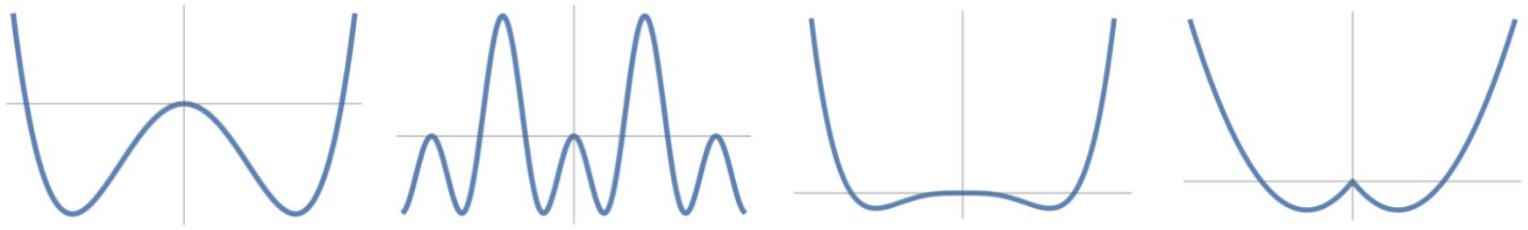
Cross section ~1000x smaller than single Higgs production



Direct probe of Higgs boson self-coupling → strong implications for early Universe dynamics

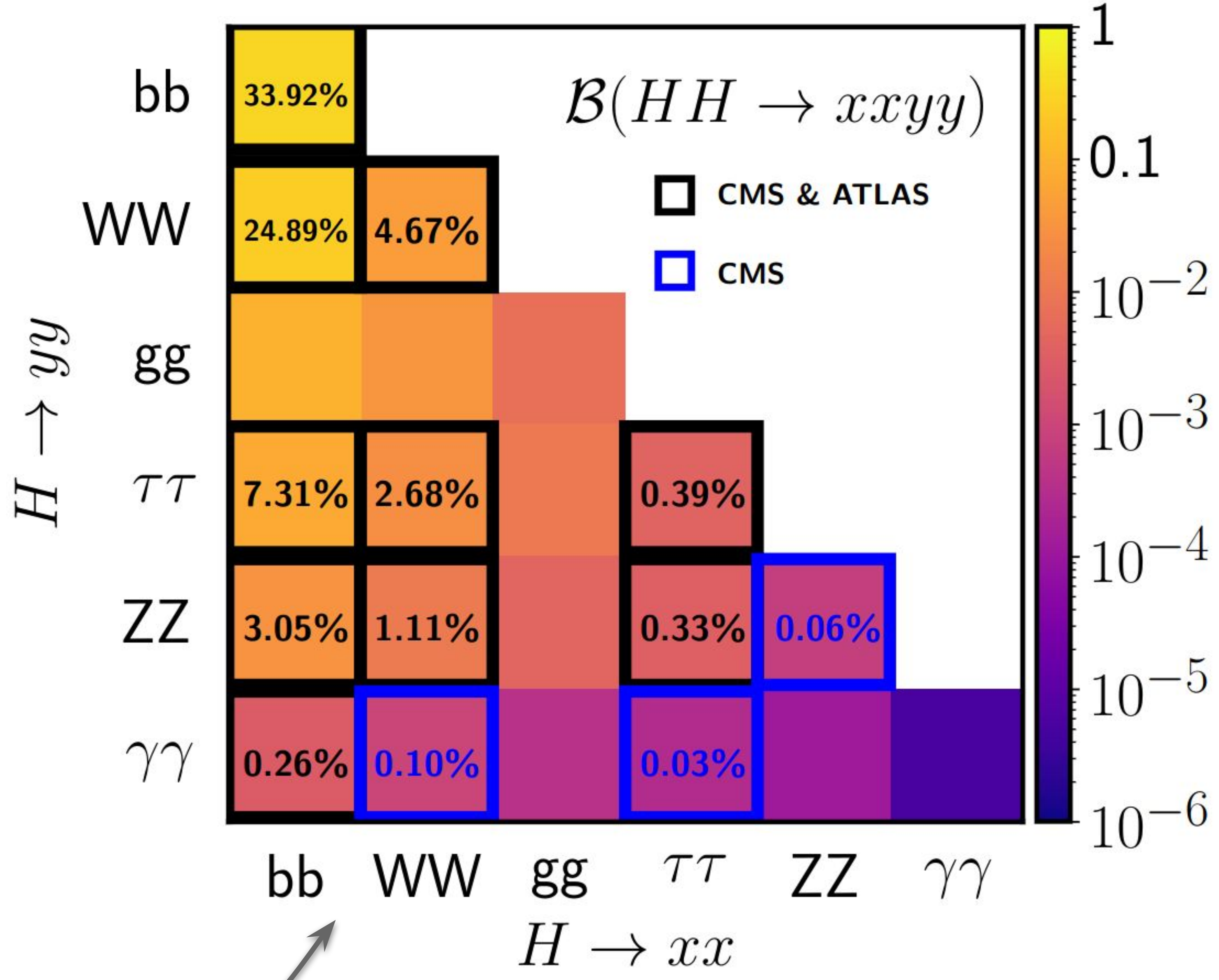
$$\kappa_\lambda = \lambda/\lambda_{SM}$$



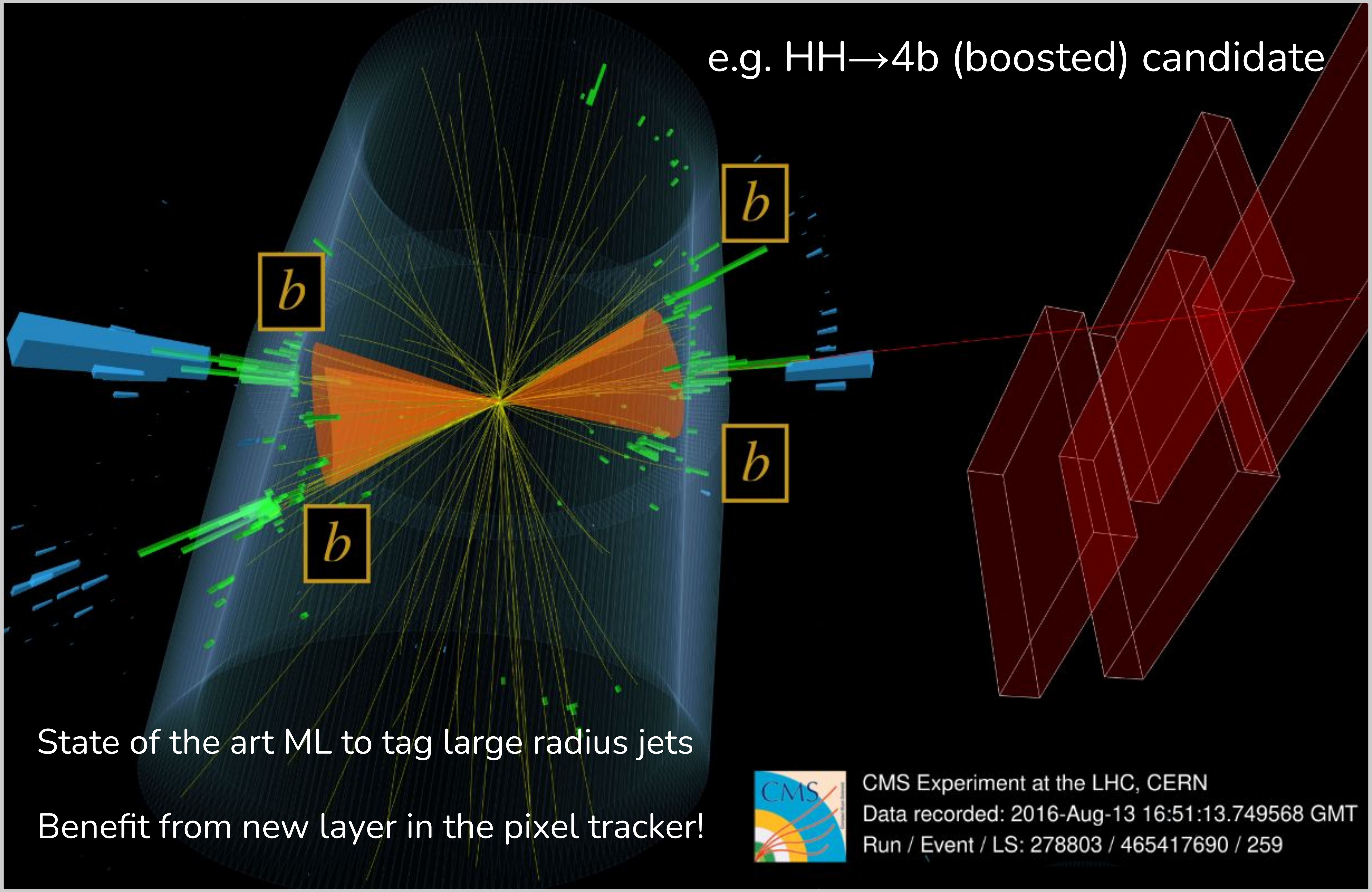


Landau-Ginzburg Higgs | Nambu-Goldstone Higgs | Coleman-Weinberg Higgs | Tadpole-Induced Higgs

Figures taken from M. Valente slides @ Higgs 23



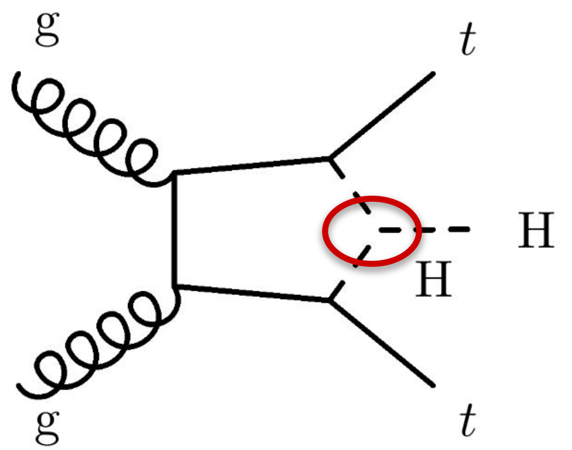
HH provides plethora of final states: a fun experimental challenge!


e.g. HH→4b (boosted) candidate
b
b
b
b
State of the art ML to tag large radius jets
Benefit from new layer in the pixel tracker!
CMS
CMS Experiment at the LHC, CERN
Data recorded: 2016-Aug-13 16:51:13.749568 GMT
Run / Event / LS: 278803 / 465417690 / 259

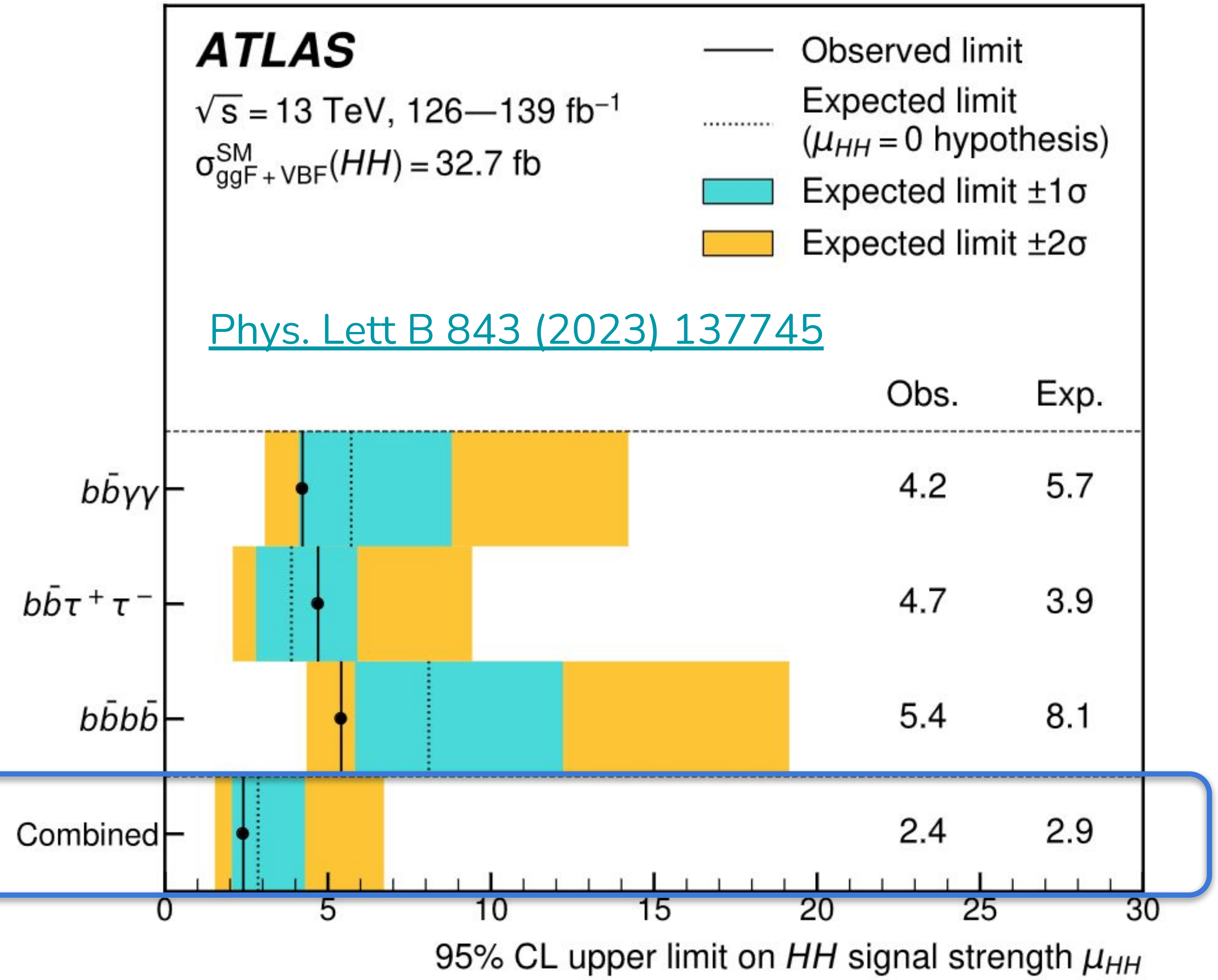
HH combination

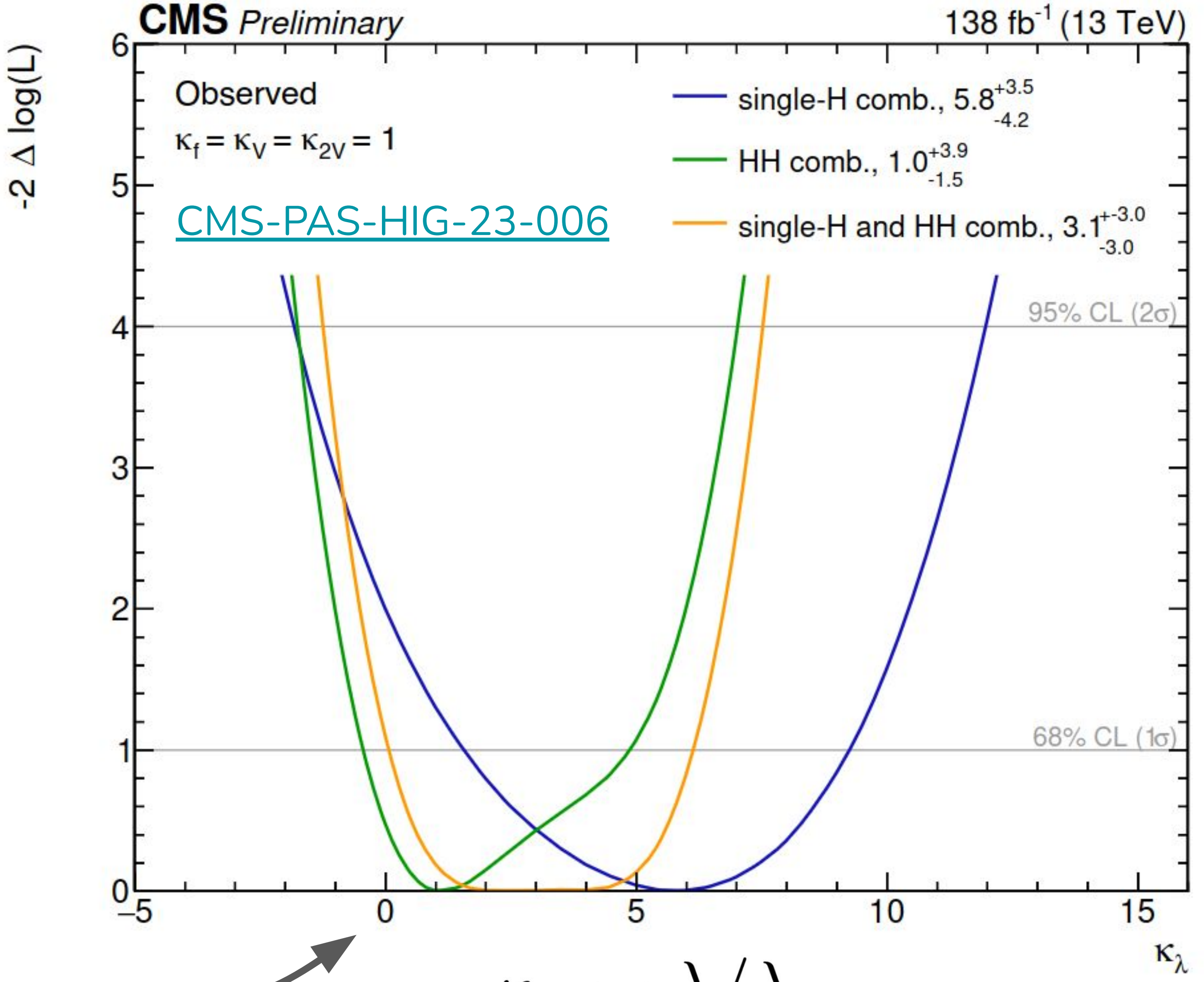
Expected ~2x from increase in statistics alone

NLO corrections to single-Higgs production



- Vast improvements compared to 2016-only results: **~5x better**
  - Driven by advancements in analysis techniques e.g. graph neural networks for b-jet tagging (ML)
- Ultimate κ_λ sensitivity by combining with indirect constraint from single-Higgs analyses



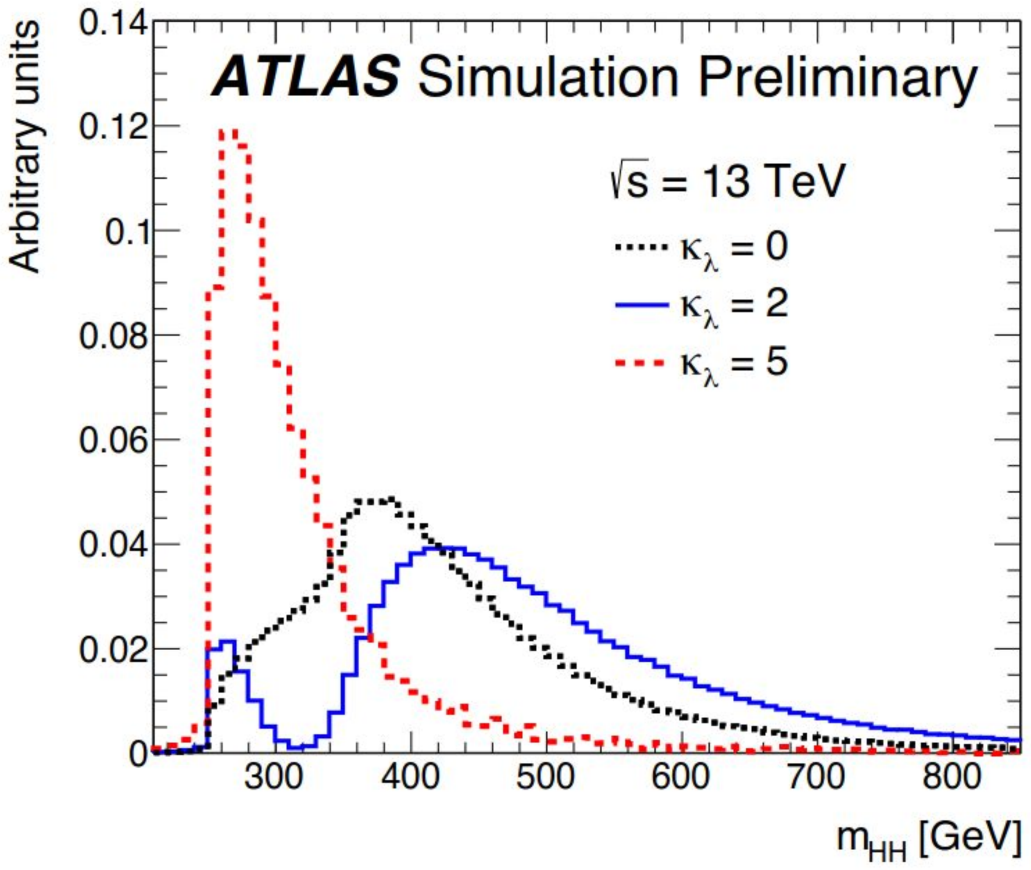


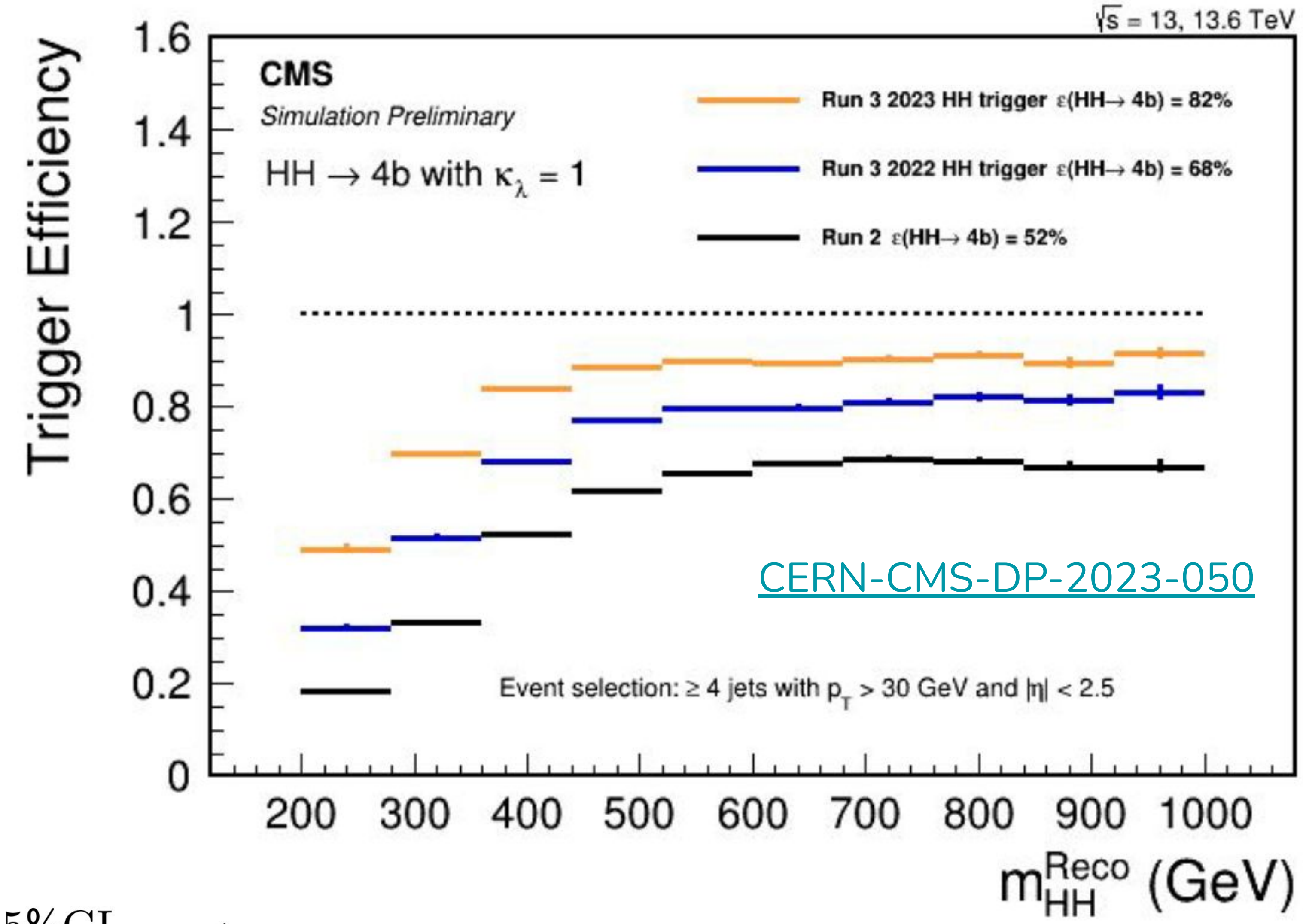
Rapidly approaching exclusion of $\kappa_\lambda = 0$

$$\kappa_\lambda = \lambda/\lambda_{\mathrm{SM}}$$

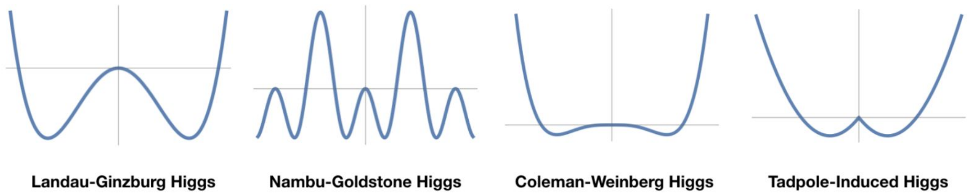
HH @ Run 3

- **More luminosity** (~250 fb^{-1} per experiment), **more energy** (+10% HH cross section at 13.6 TeV)
- Improving analysis techniques e.g. better triggers

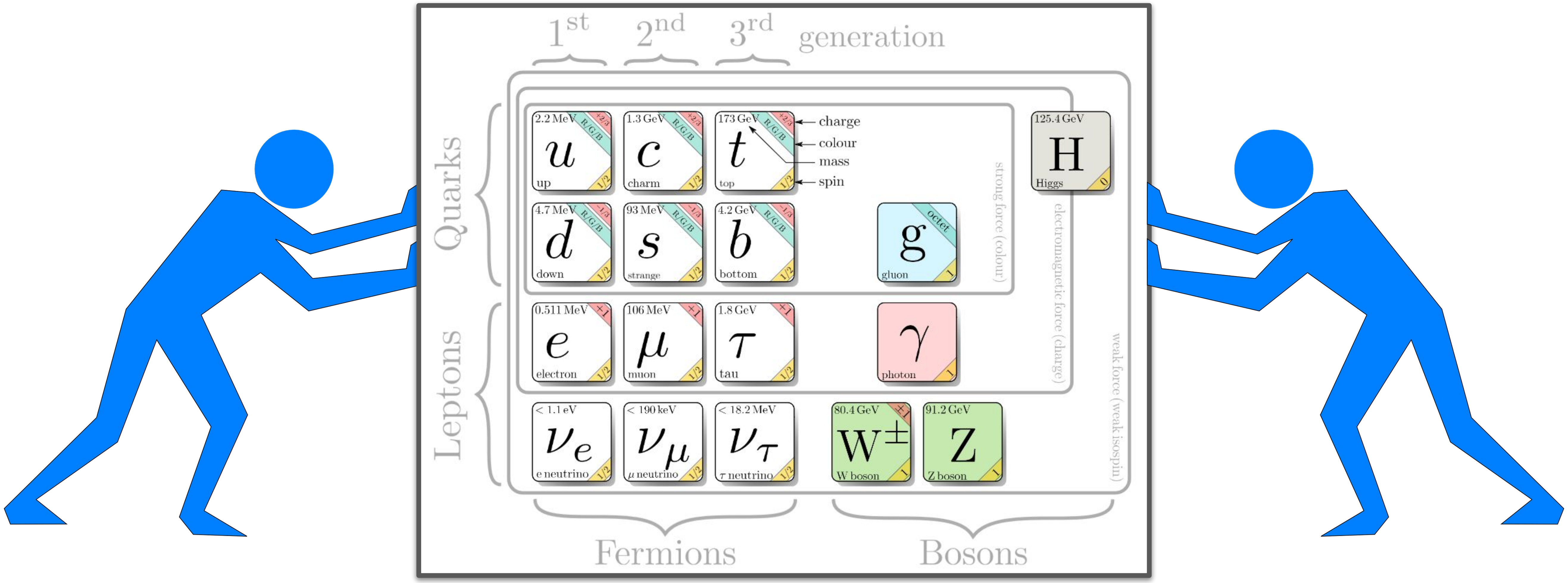




- Higgs self-coupling is within reach during Run 3: $\mu_{\mathrm{SM}}^{95\%\mathrm{CL}} \sim 1$
  - New innovative ideas could bring it even closer!
  - If something is very BSM-like in the Higgs potential → we might see it in Run 3!



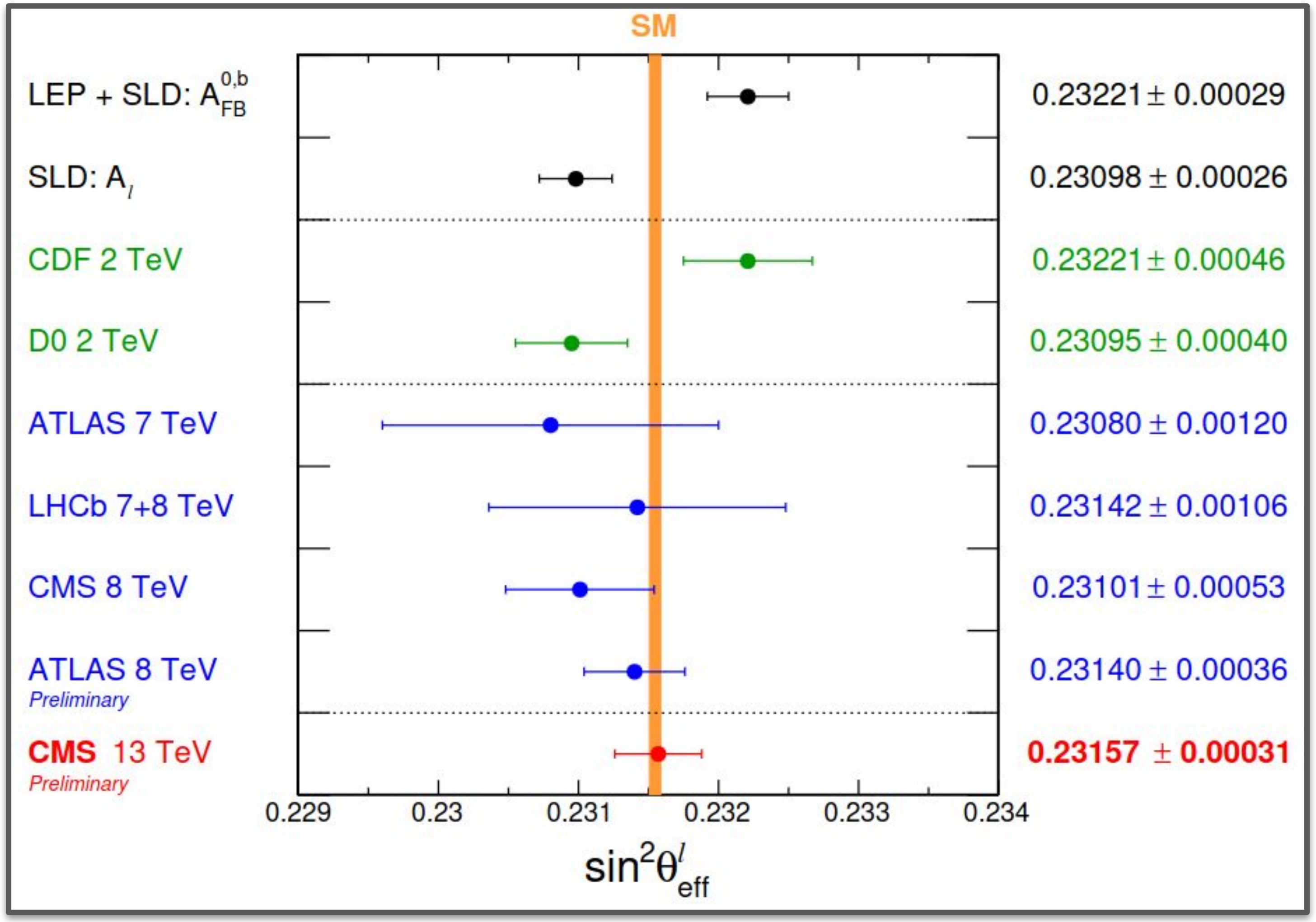
Precision



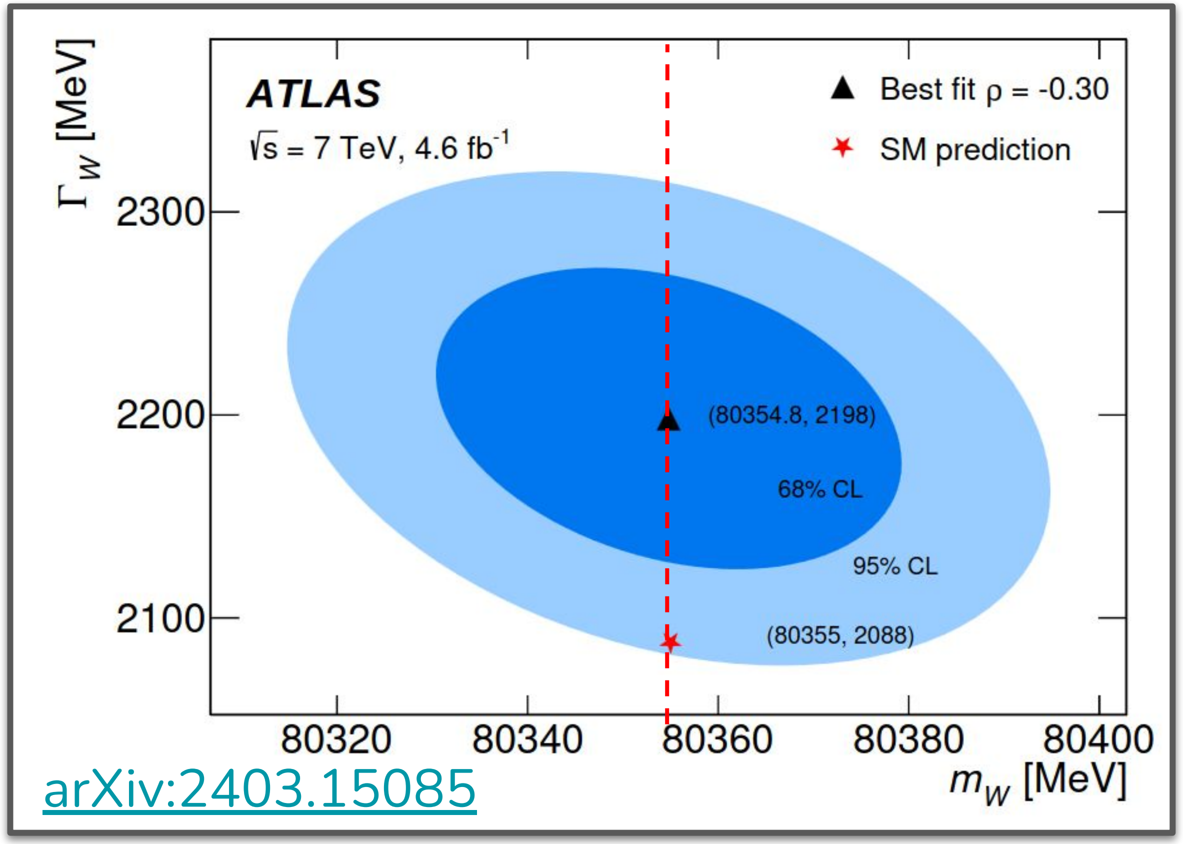
1st 2nd 3rd generation
Quarks
Leptons
2.2 MeV
u
up
1.3 GeV
c
charm
173 GeV
t
top
charge
colour
mass
spin
125.4 GeV
H
Higgs
4.7 MeV
d
down
93 MeV
s
strange
4.2 GeV
b
bottom
g
gluon
octet
0.511 MeV
e
electron
106 MeV
μ
muon
1.8 GeV
τ
tau
γ
photon
< 1.1 eV
ν_e
e neutrino
< 190 keV
ν_μ
μ neutrino
< 18.2 MeV
ν_τ
τ neutrino
80.4 GeV
$W^\pm$
W boson
91.2 GeV
Z
Z boson
strong force (colour)
electromagnetic force (charge)
weak force (weak isospin)
Fermions
Bosons

EW precision tests

CMS-PAS-SMP-22-010

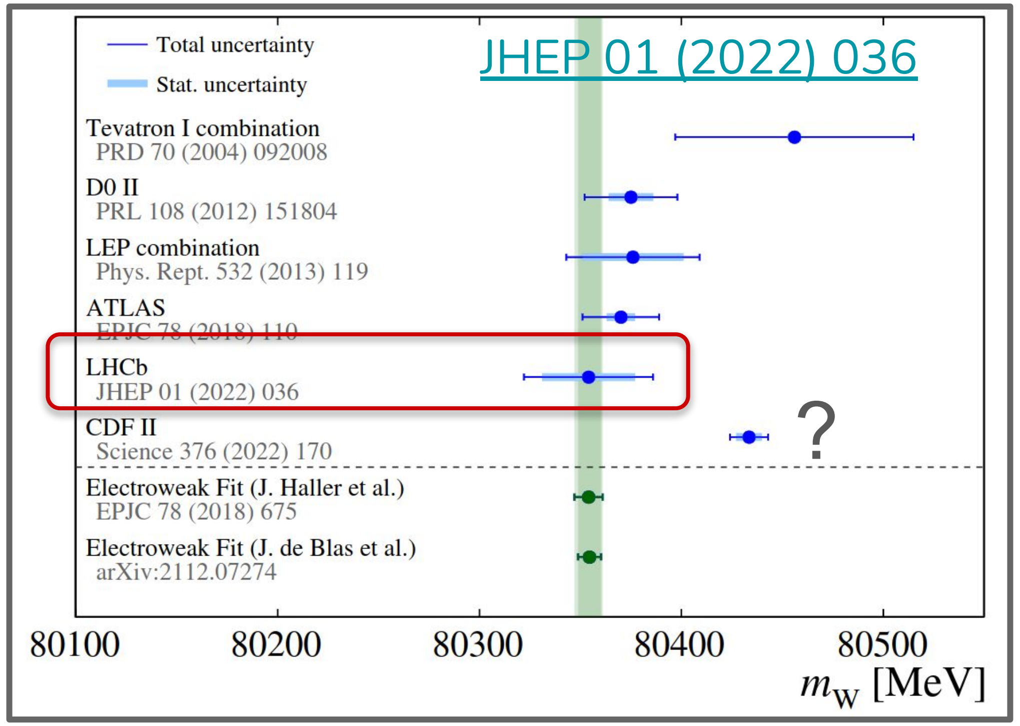


Use $Z/\gamma\to ll$ (Drell-Yan), asymmetry in lepton decay angle



arXiv:2403.15085

Updated result with extended studies of PDF: measured from W boson m_T and p_T distributions



LHCb doing precision physics in the forward region (anti-correlated PDFs)

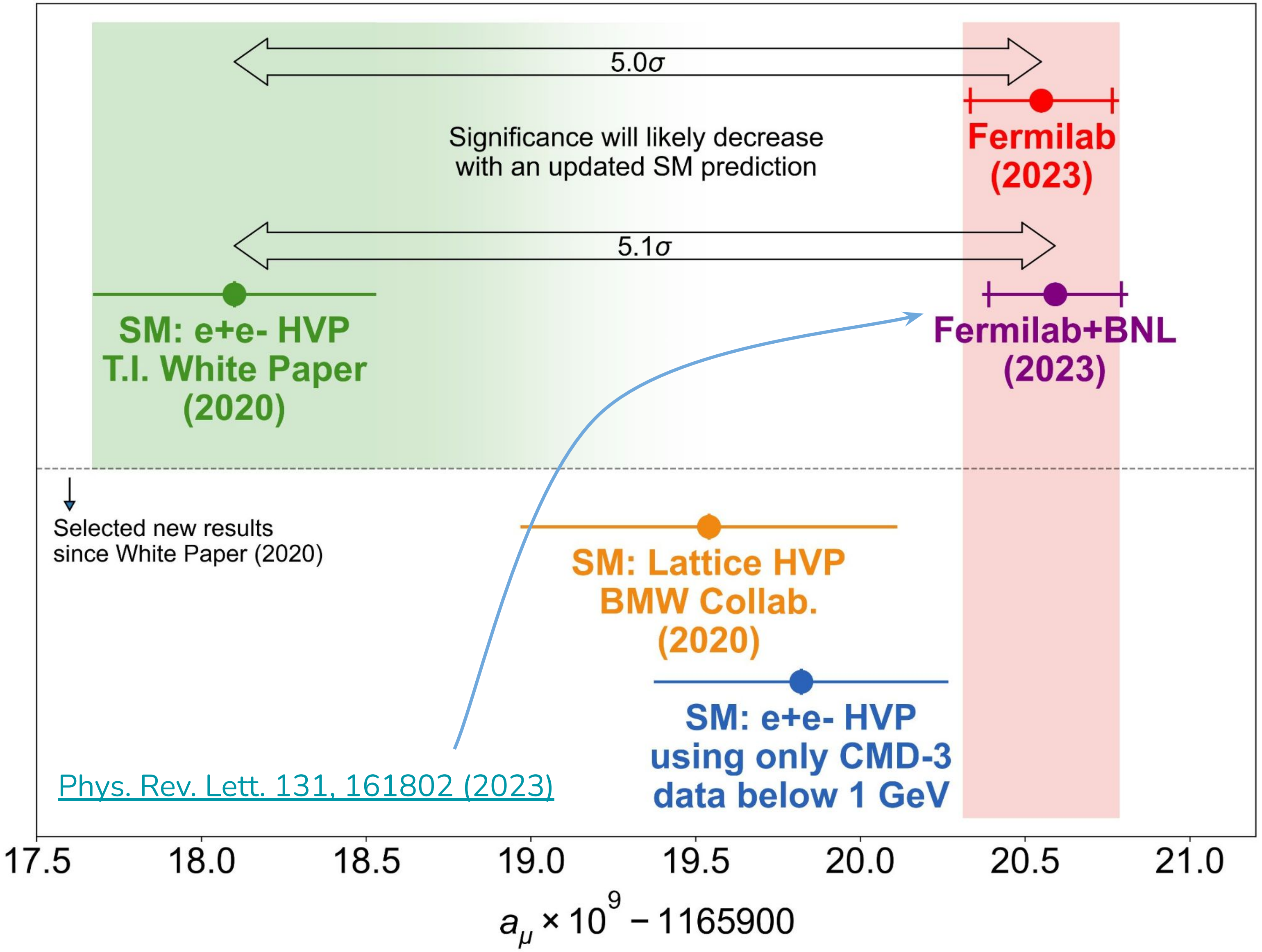
Precision physics can be done at a hadron collider

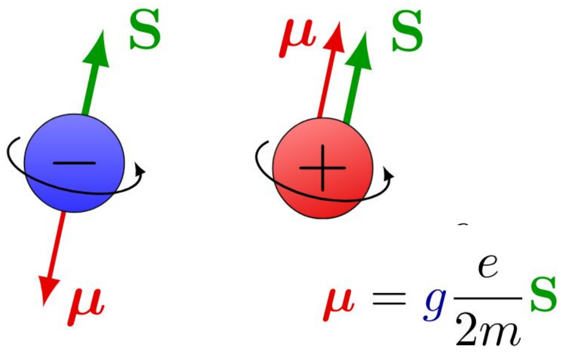
Paves the way for more precision physics at the HL-LHC

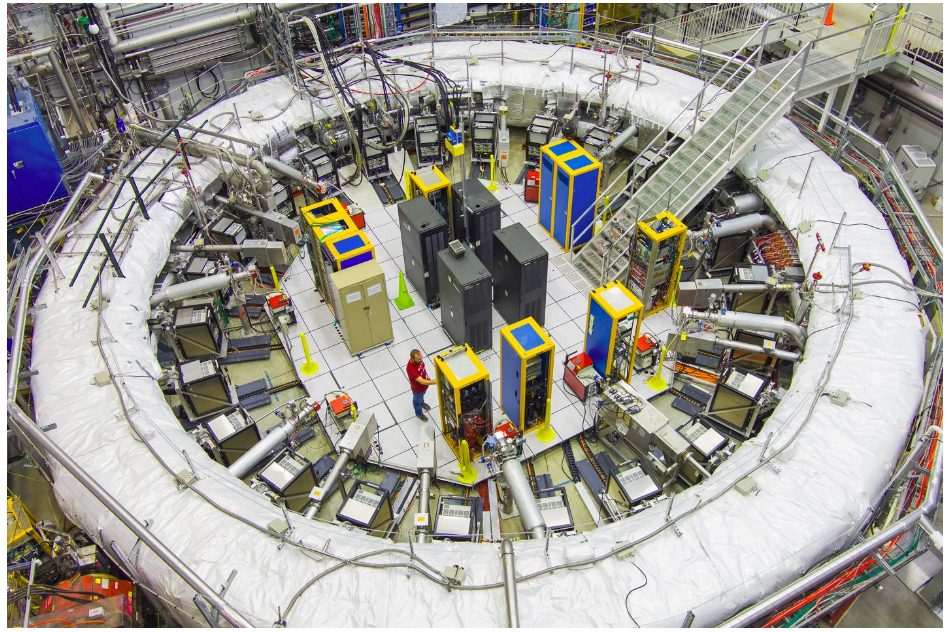
Outside-of-the-box analyses

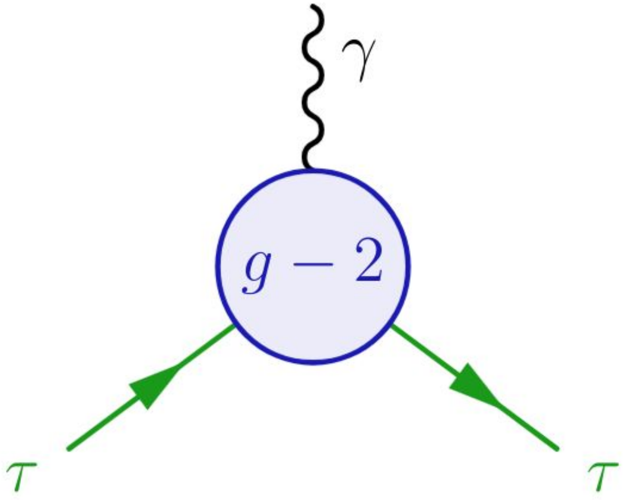
LHC to probe (g-2)

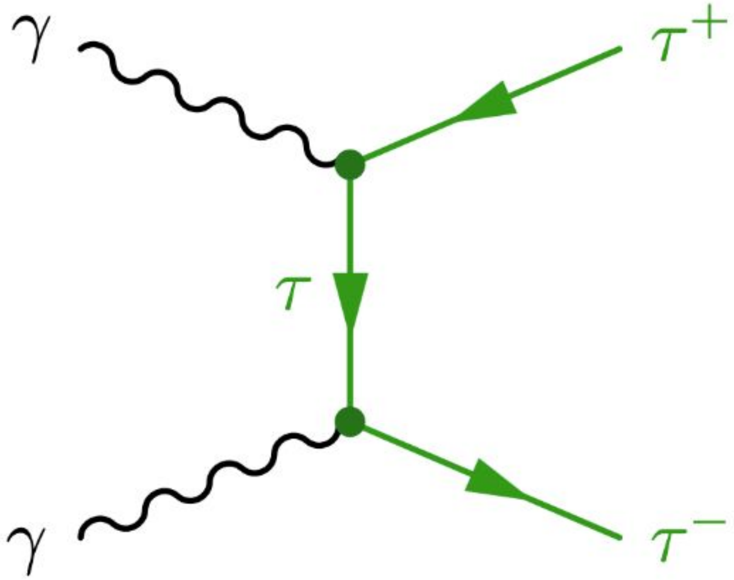
- Quantum corrections give rise to anomalous magnetic moment: $a_\ell = (g-2)/2$
- Persistent discrepancy between experiment & theory at Muon (g-2) experiment
- **What about τ leptons?**







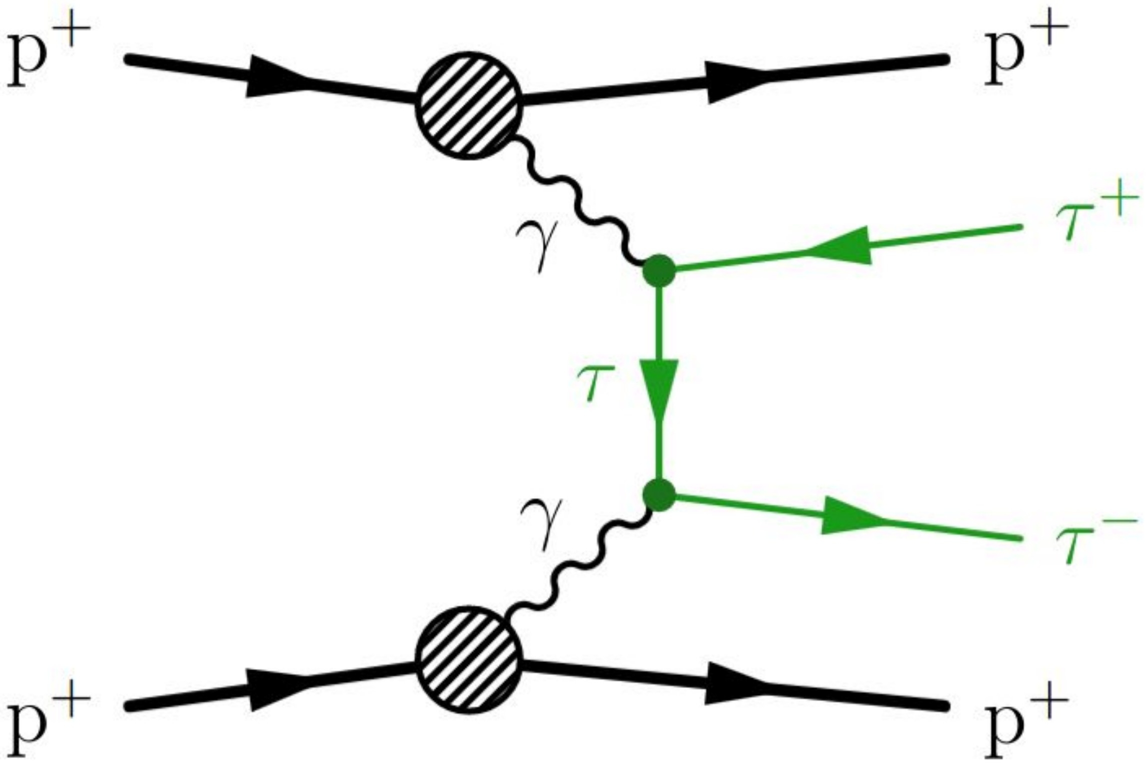


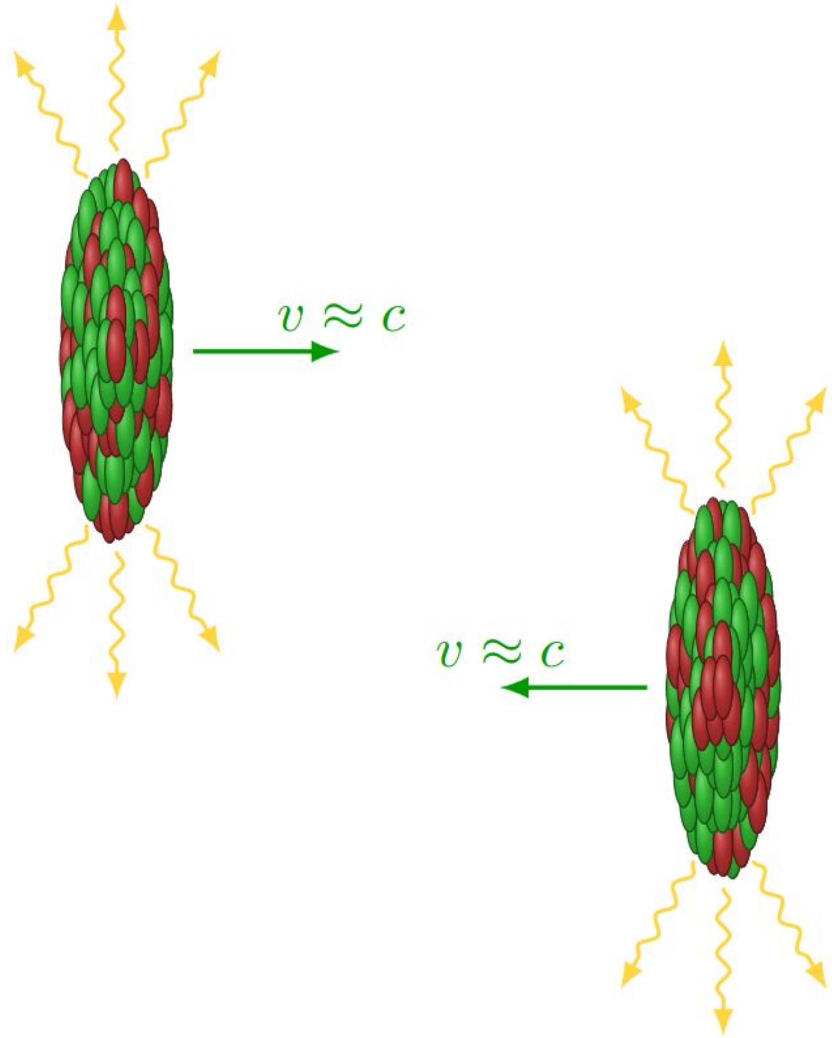


1. Dirac: $a_\tau = 0$
2. Schwinger (NLO): $a_\tau = 0.00116$
3. SM: $a_\tau = 0.00118$

LHC as a photon collider

- Answer lies in **ultraperipheral collisions**





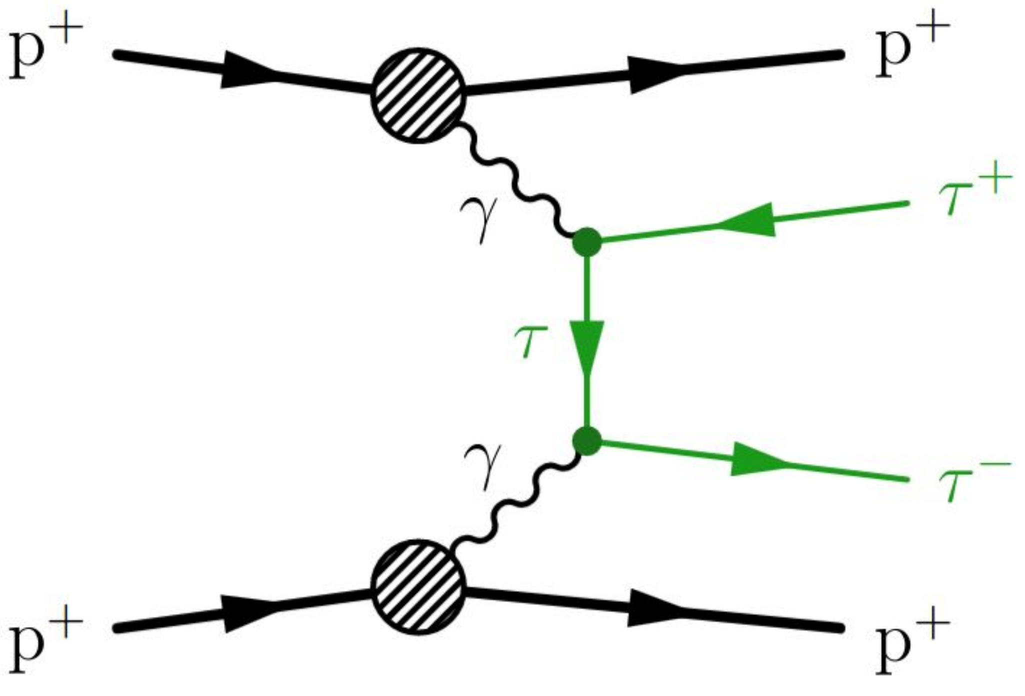
Observed $\gamma\gamma \to \tau\tau$ in Pb-Pb collisions (Z^4 enhancement)

- ATLAS: Phys. Rev. Lett. 131 (2023) 151802, CMS: Phys. Rev. Lett. 131 (2023) 151803
- Probes lower energy domain + small integrated luminosity

Can we benefit from the high integrated luminosity of LHC p-p collisions?

- Challenges: No Z^4 enhancement, low signal acceptance (soft leptons), large backgrounds, high pile-up...

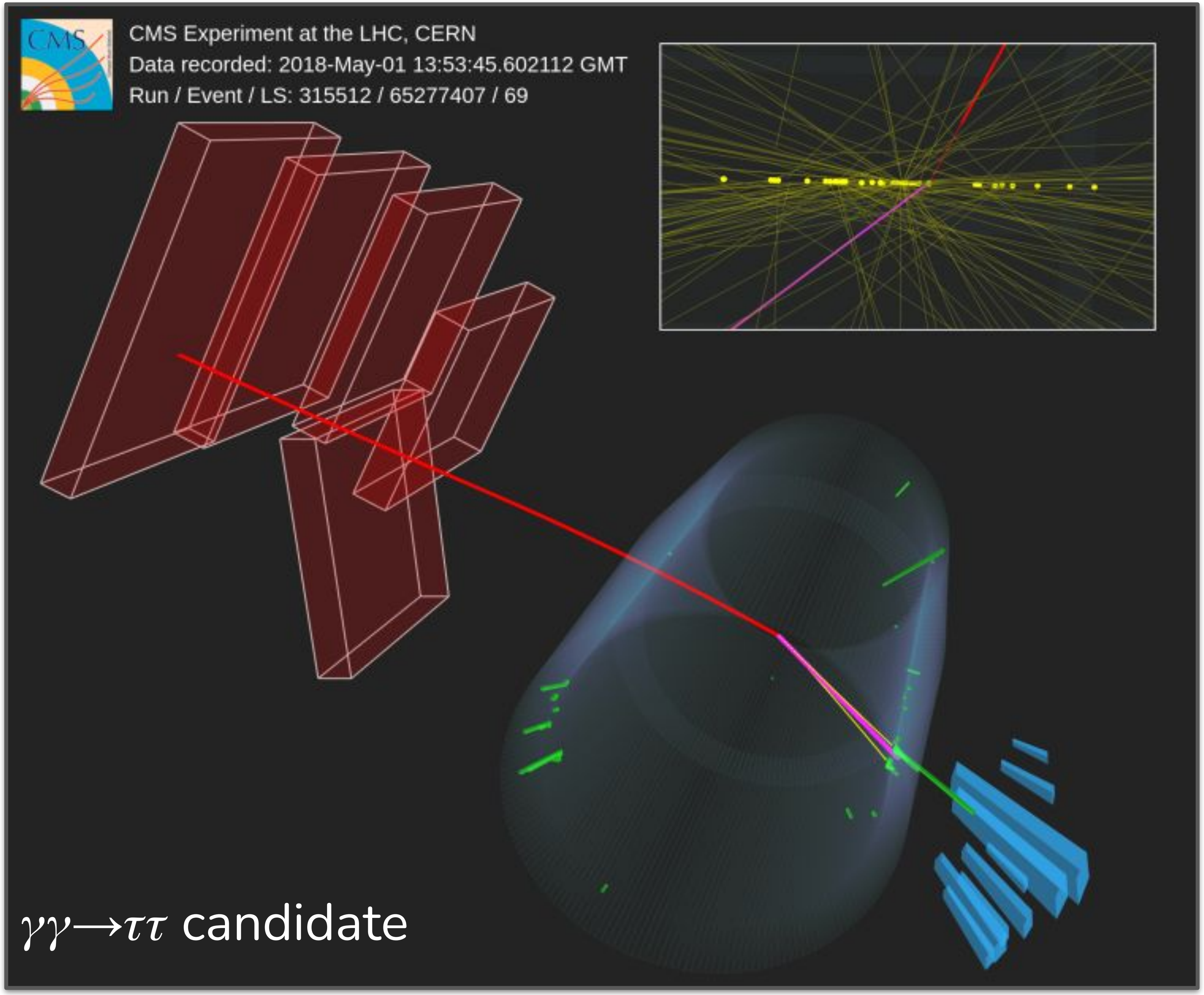
LHC as a photon collider



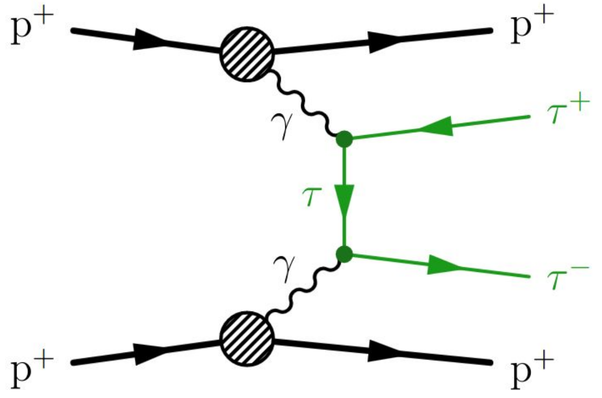
[CMS-PAS-SMP-23-005]

Looking for distinct experimental signature:

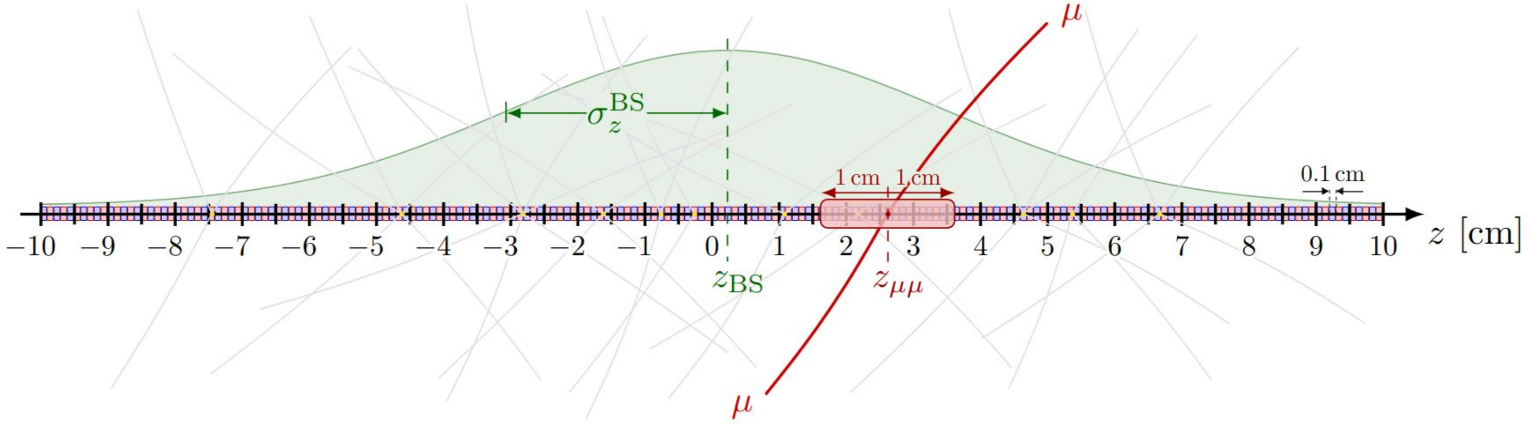
- 2 back-to-back τ leptons
- No hadronic activity close to di-τ vertex: N_{track}=0



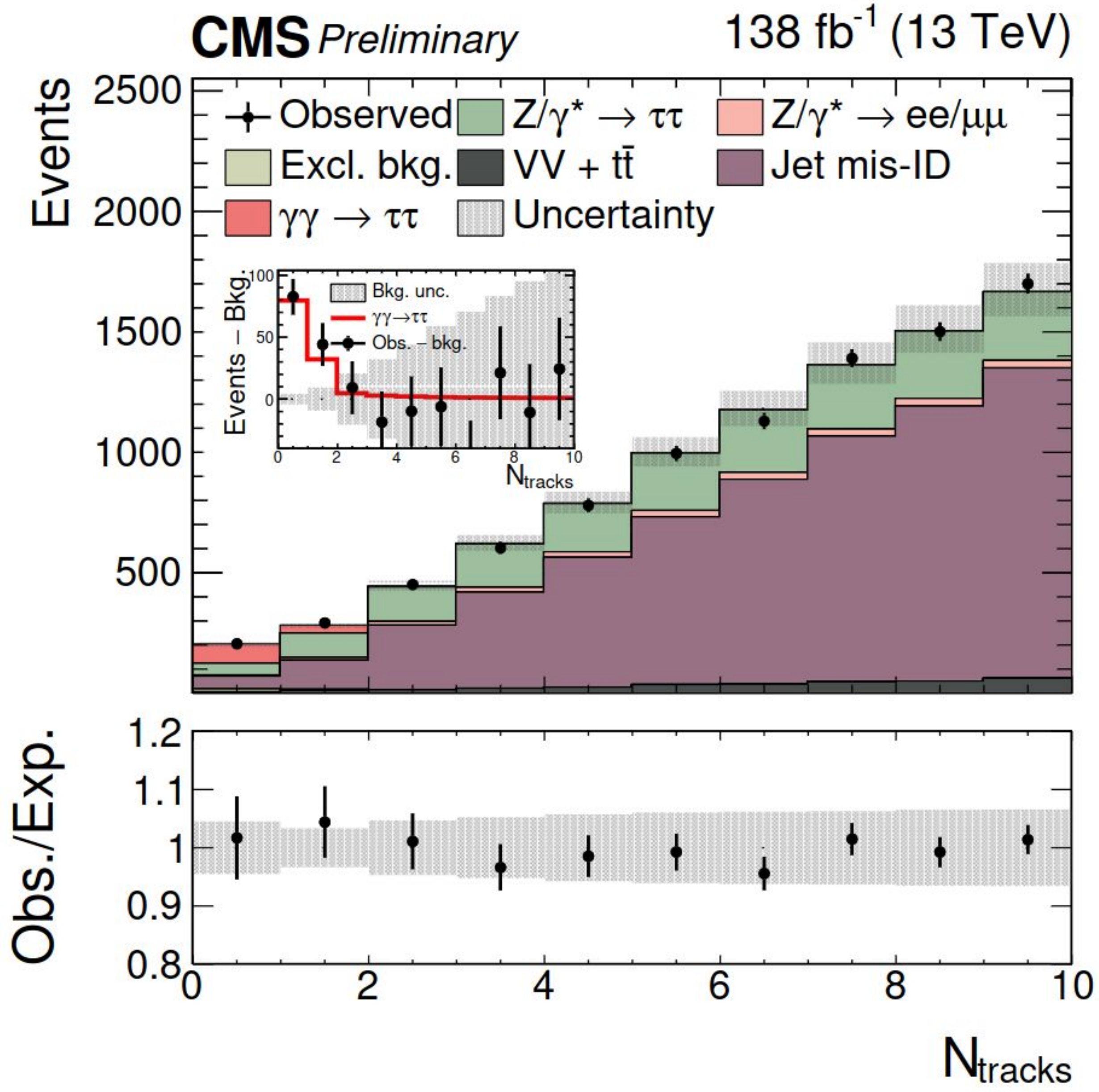
LHC as a photon collider



- N_{track}=0 is an extreme challenge due to pile-up
  - Pushing detector to the max
- Simulated events are corrected for N_{track} + proton dissociation + ...

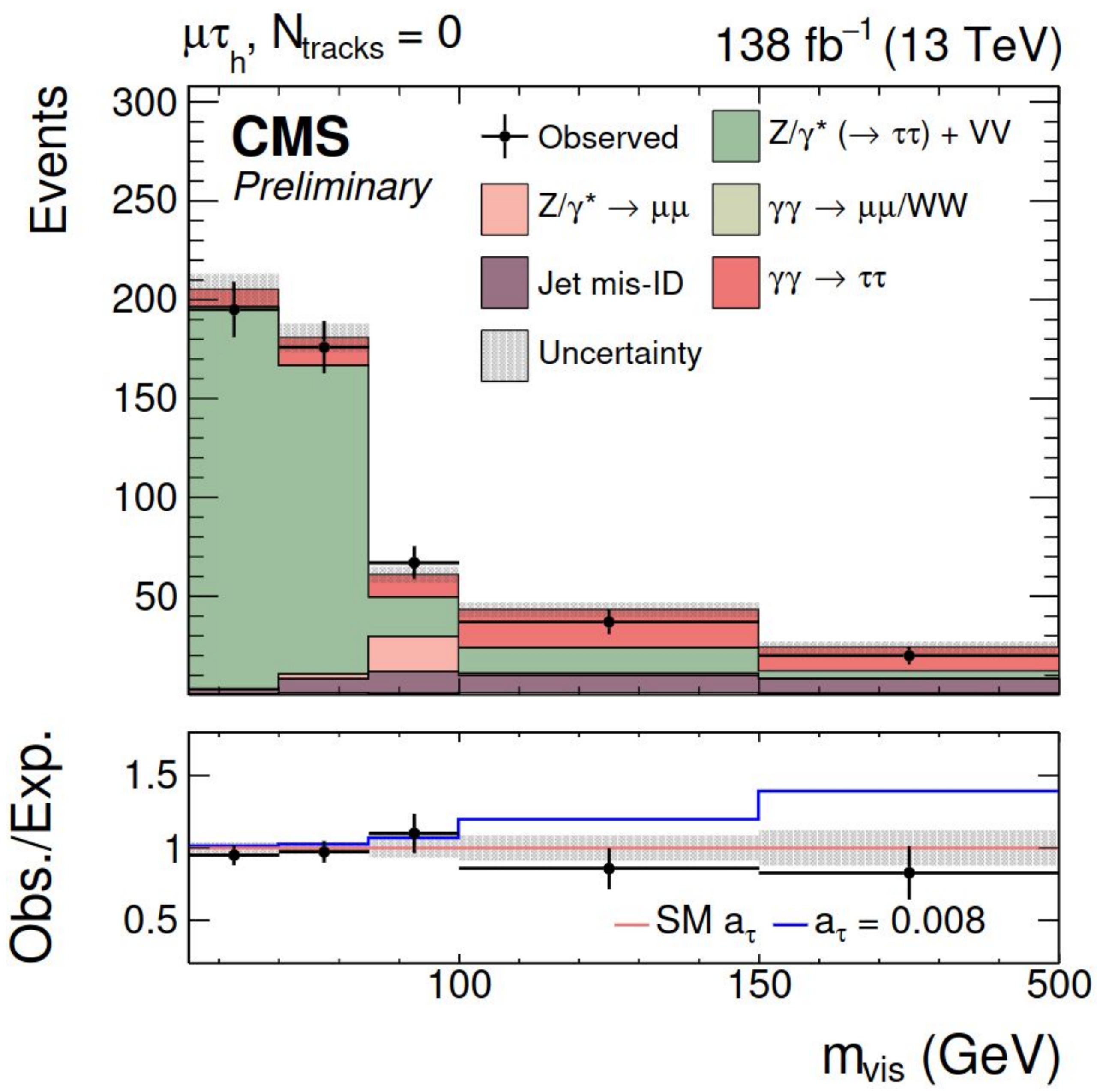


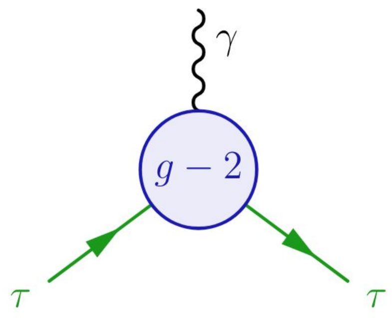
- First observation of $\gamma\gamma\to\tau\tau$ in pp collisions
  - **5.3σ observed, 6.5σ expected**

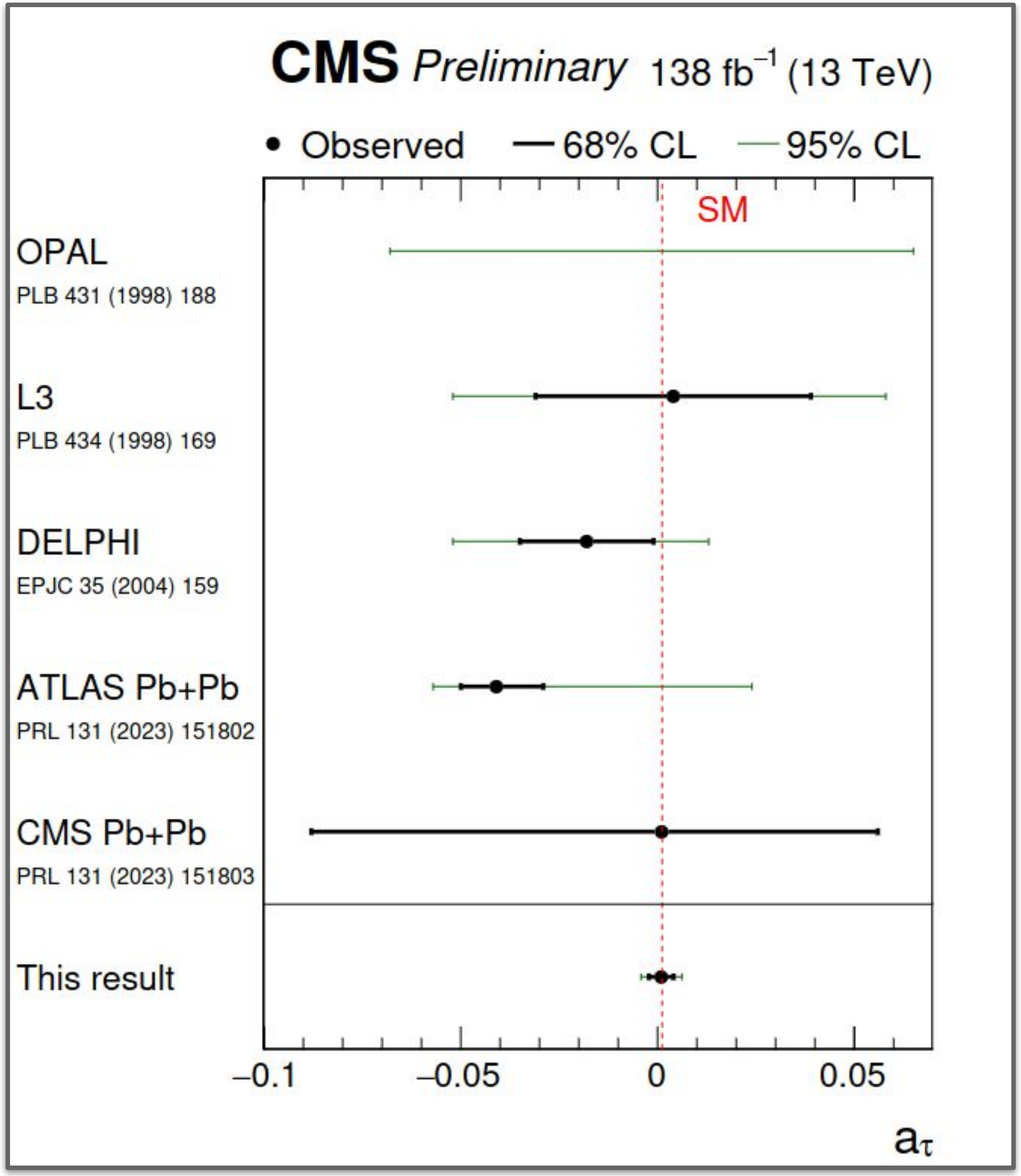


LHC as a photon collider

- Modifying a_τ changes the signal shape and normalisation
  - Maximum likelihood fit to m_{vis} spectra



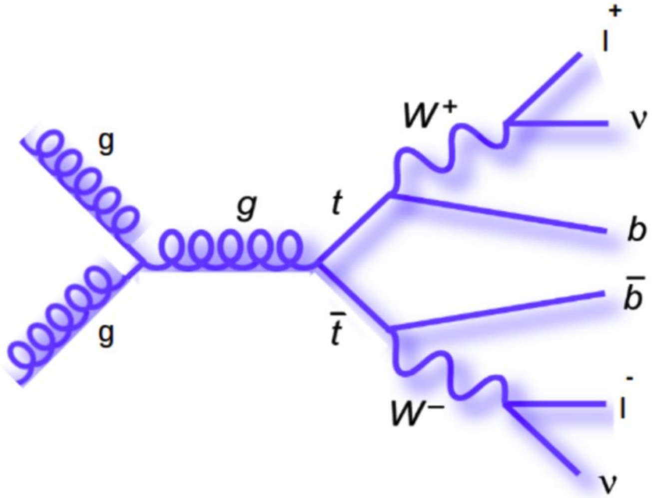


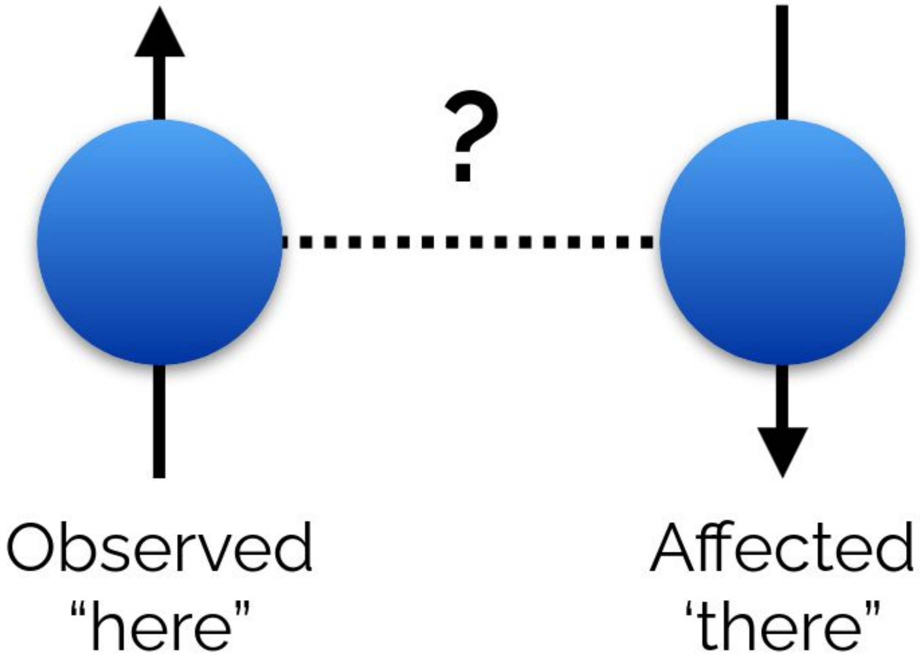


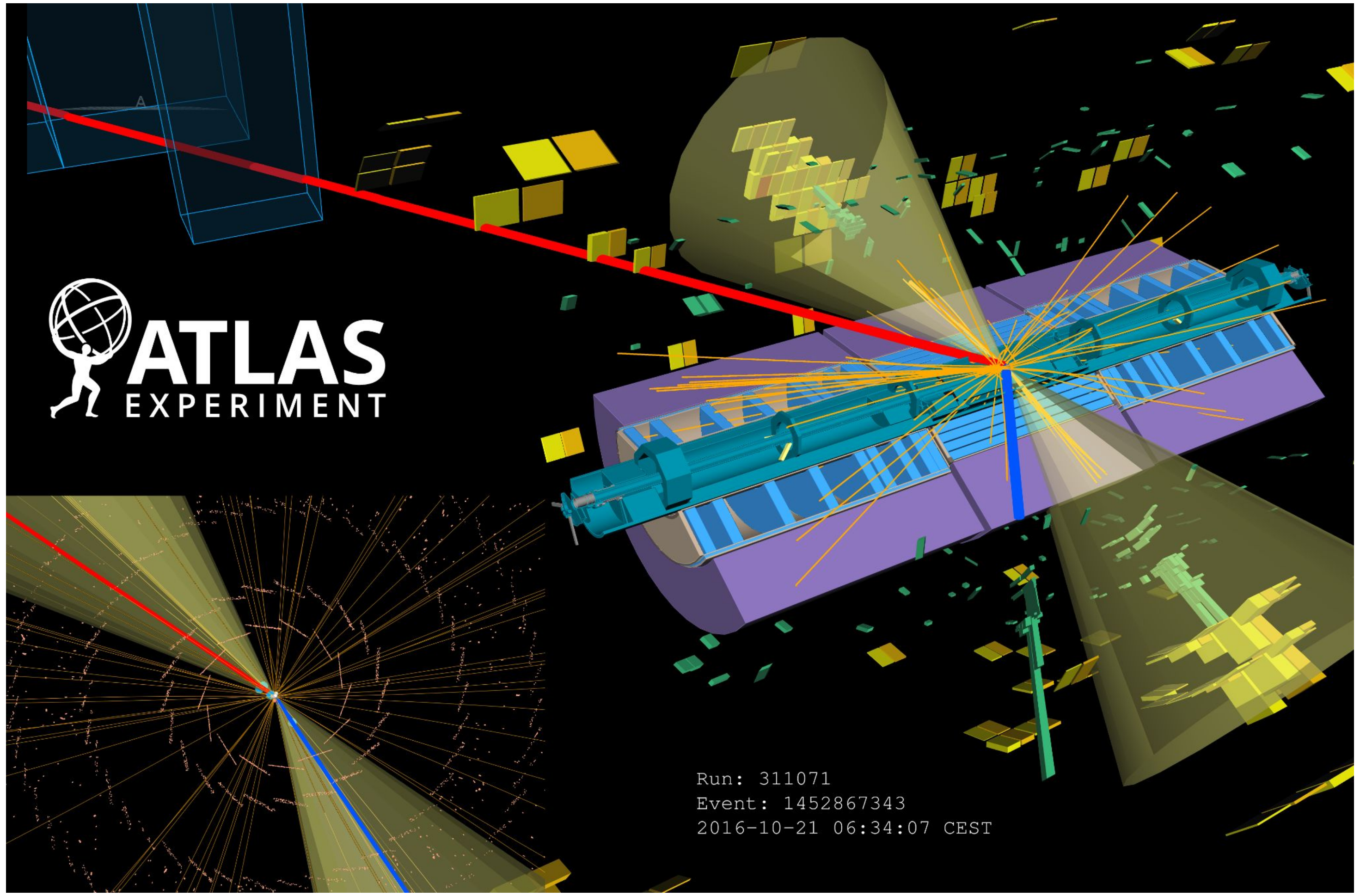
Good agreement with SM, uncertainty is only ~3x Schwinger term!

Quantum entanglement @ LHC

- arXiv: 2311.07288 (sub. to Nature) and CMS-PAS-TOP-23-001
  - Probe entanglement in ttbar leptonic final states
  - Tops decay before hadronisation → transfer spin-state to decay products







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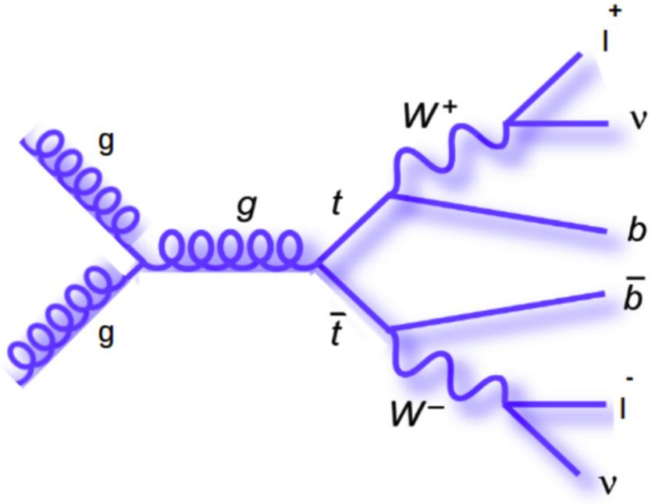
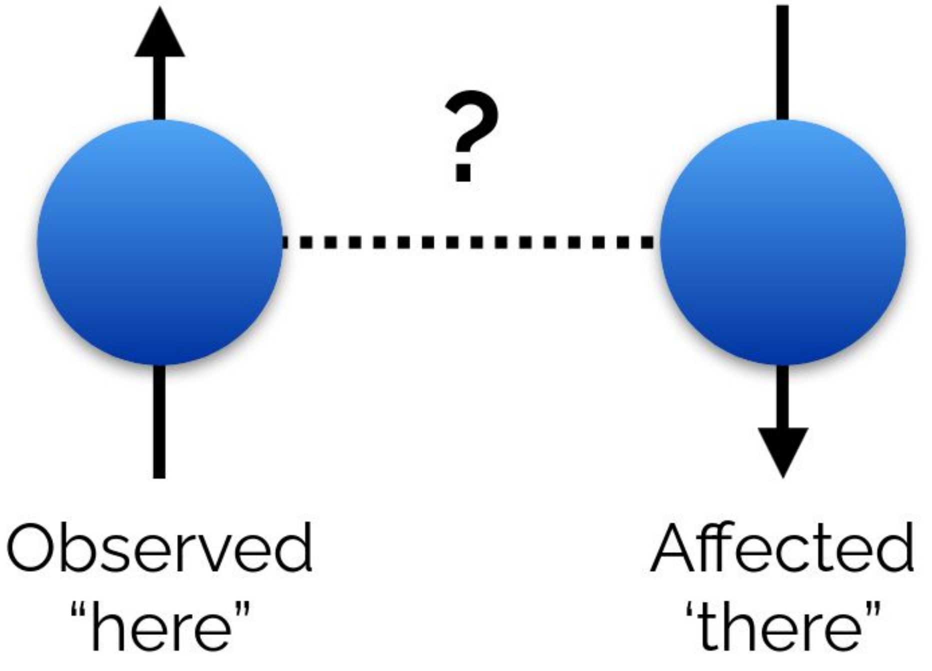




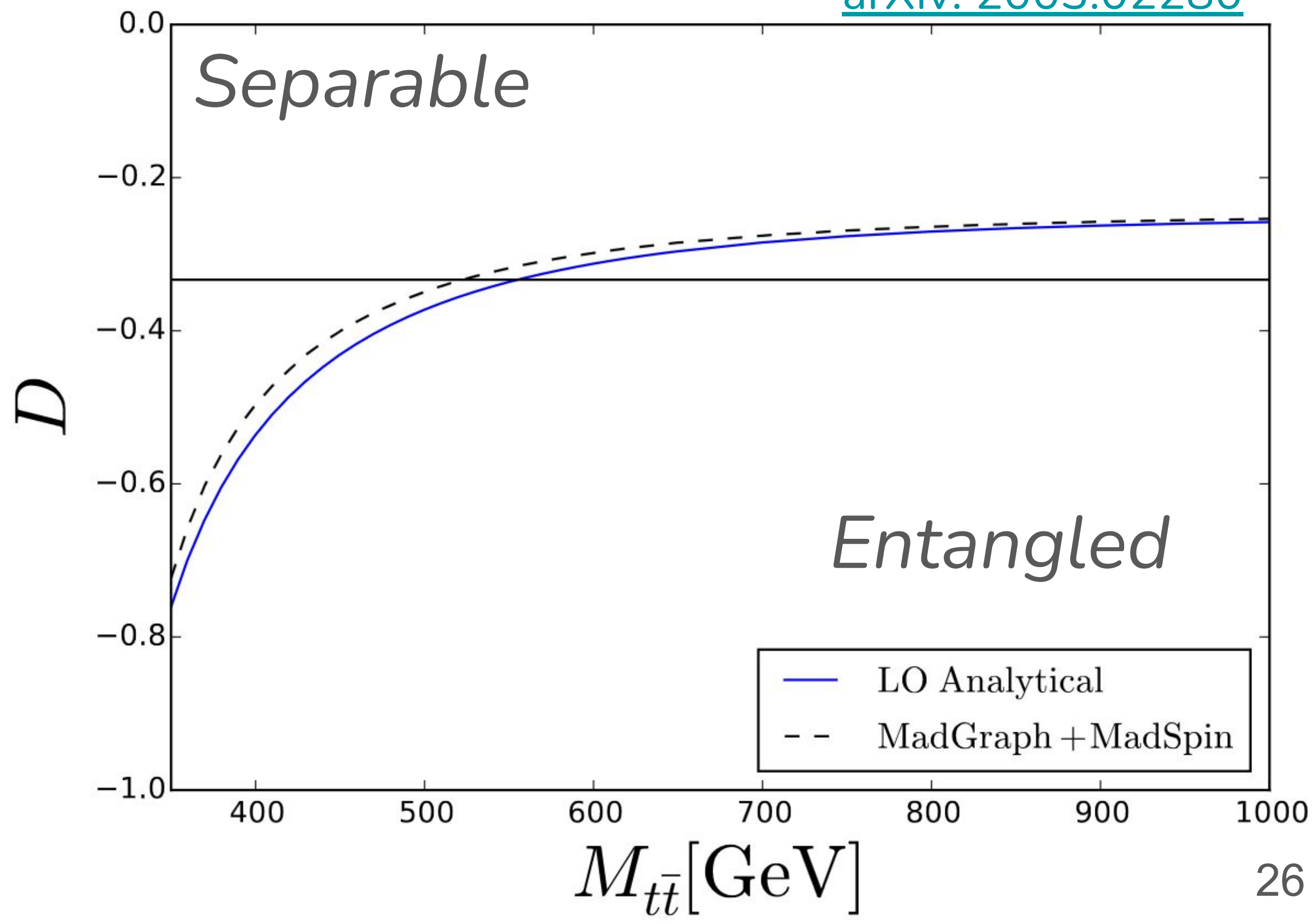
- Differential cross section depends on decay-lepton properties:

$$\frac{1}{\sigma}\frac{d\sigma}{d\Omega_+ d\Omega_-} = \frac{1 + \mathbf{B}^+ \cdot \hat{\mathbf{q}}_+ - \mathbf{B}^- \cdot \hat{\mathbf{q}}_- - \hat{\mathbf{q}}_+ \cdot \mathbf{C} \cdot \hat{\mathbf{q}}_-}{(4\pi)^2}$$

Spin correlation matrix

- Criterium for entanglement: tr[C] + 1 < 0
- Define: D = tr[C] / 3 → $\boxed{\text{D < -1/3}}$

arXiv: 2003.02280



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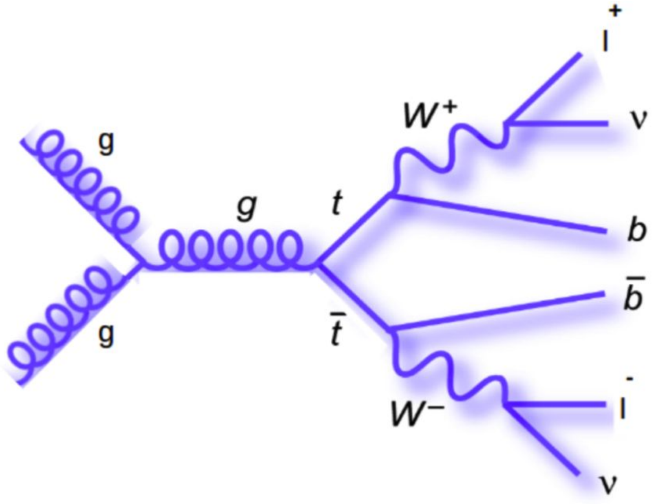

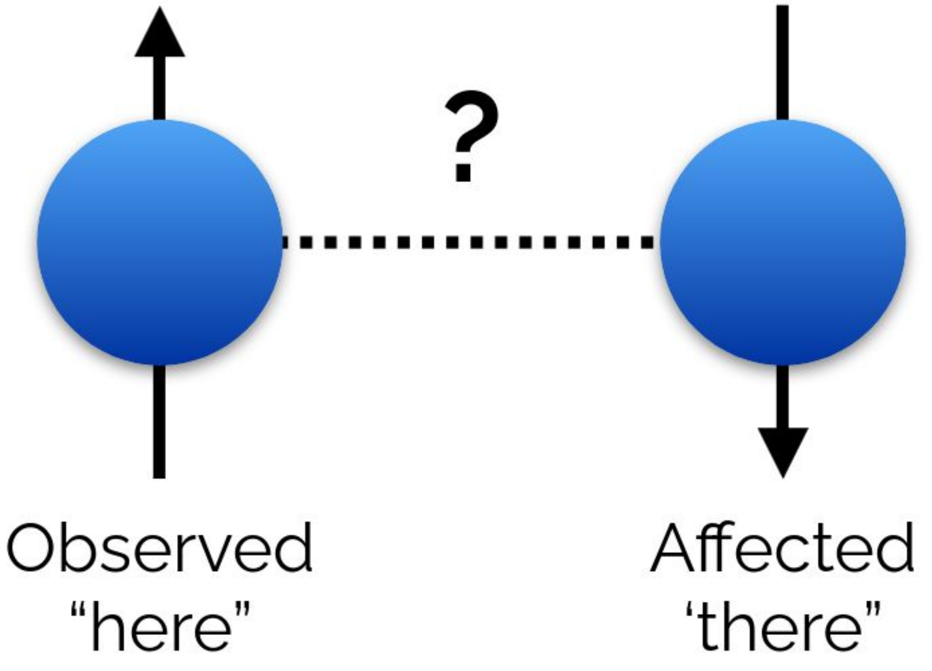

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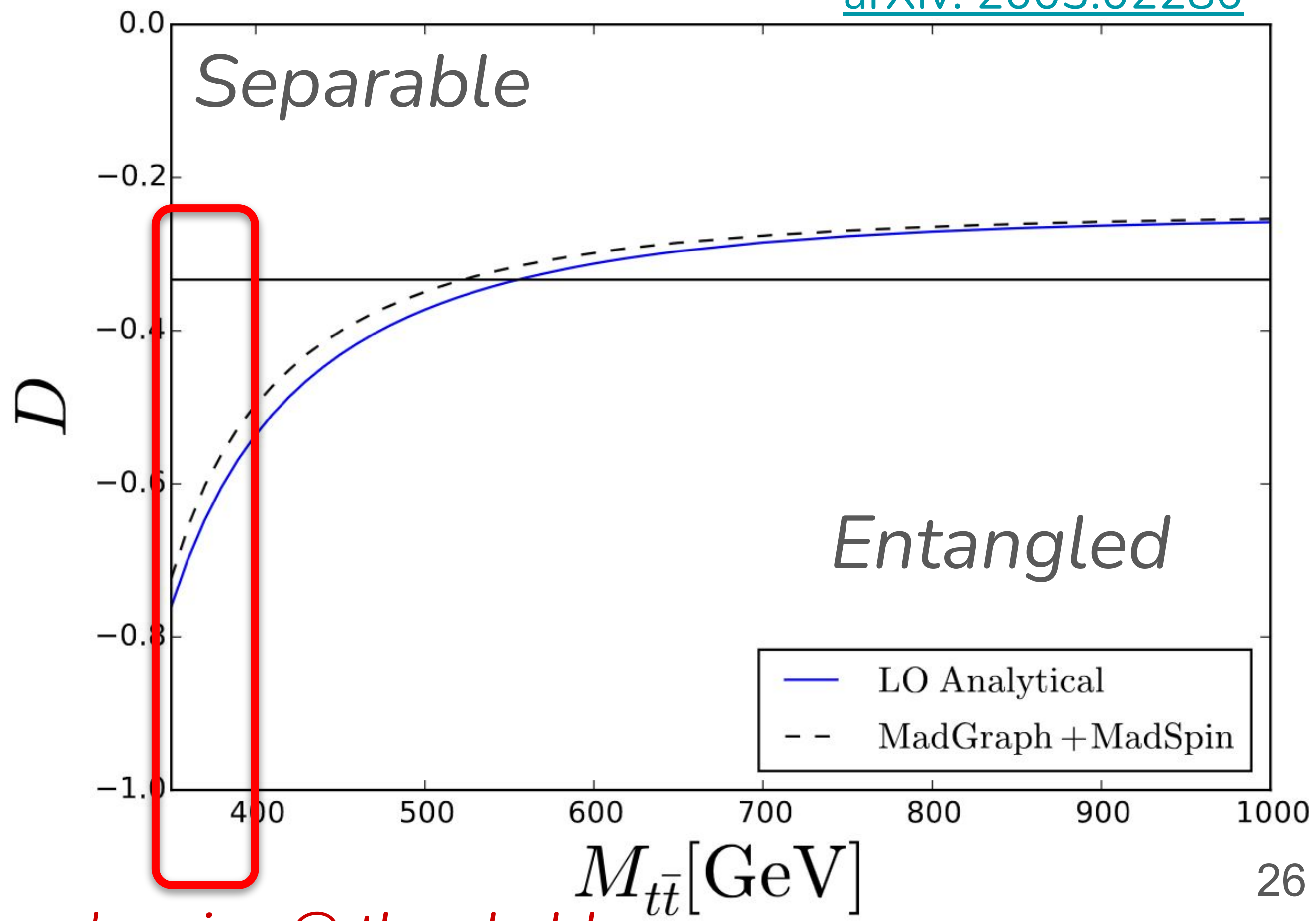
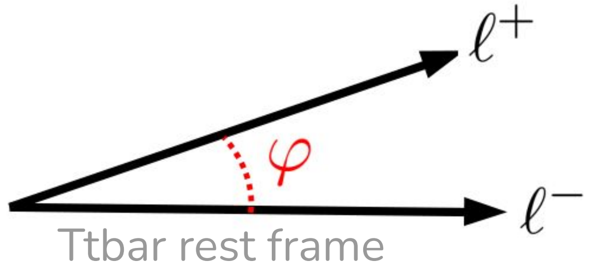


Signal region @ threshold

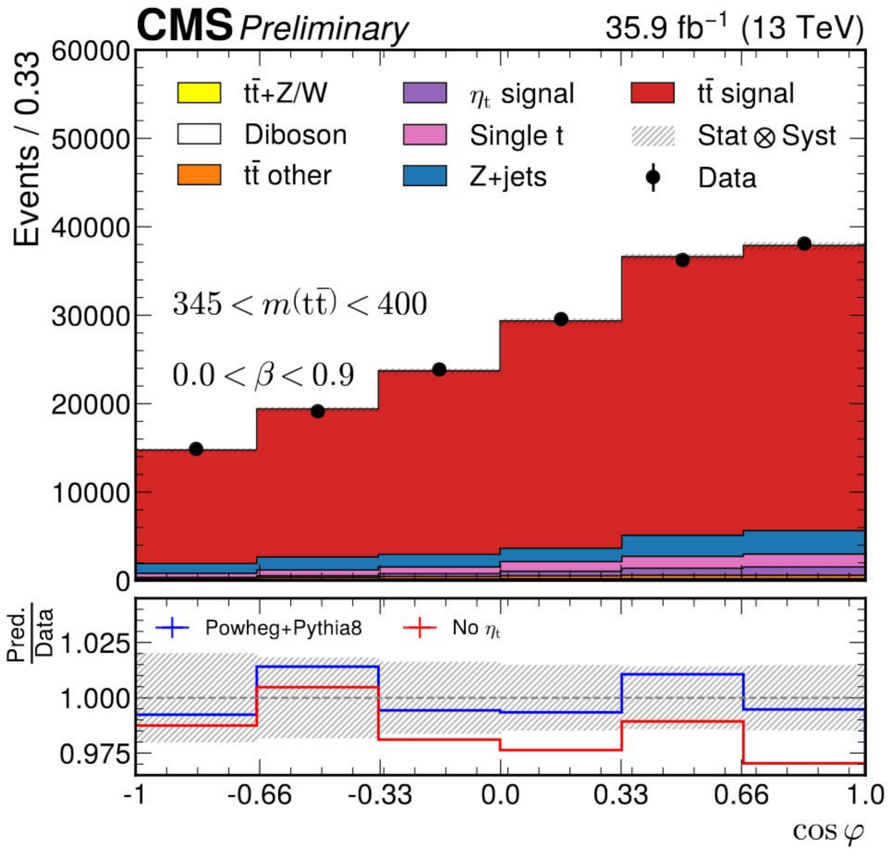
Quantum entanglement @ LHC

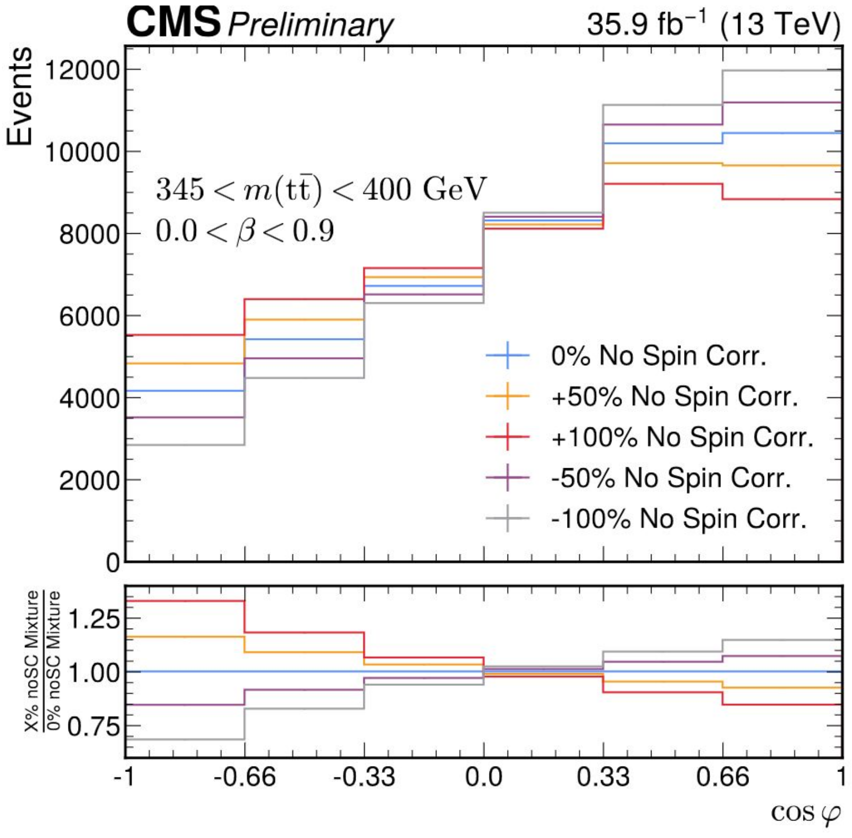
$\cos\varphi$ = Angle between leptons in ttbar rest frame

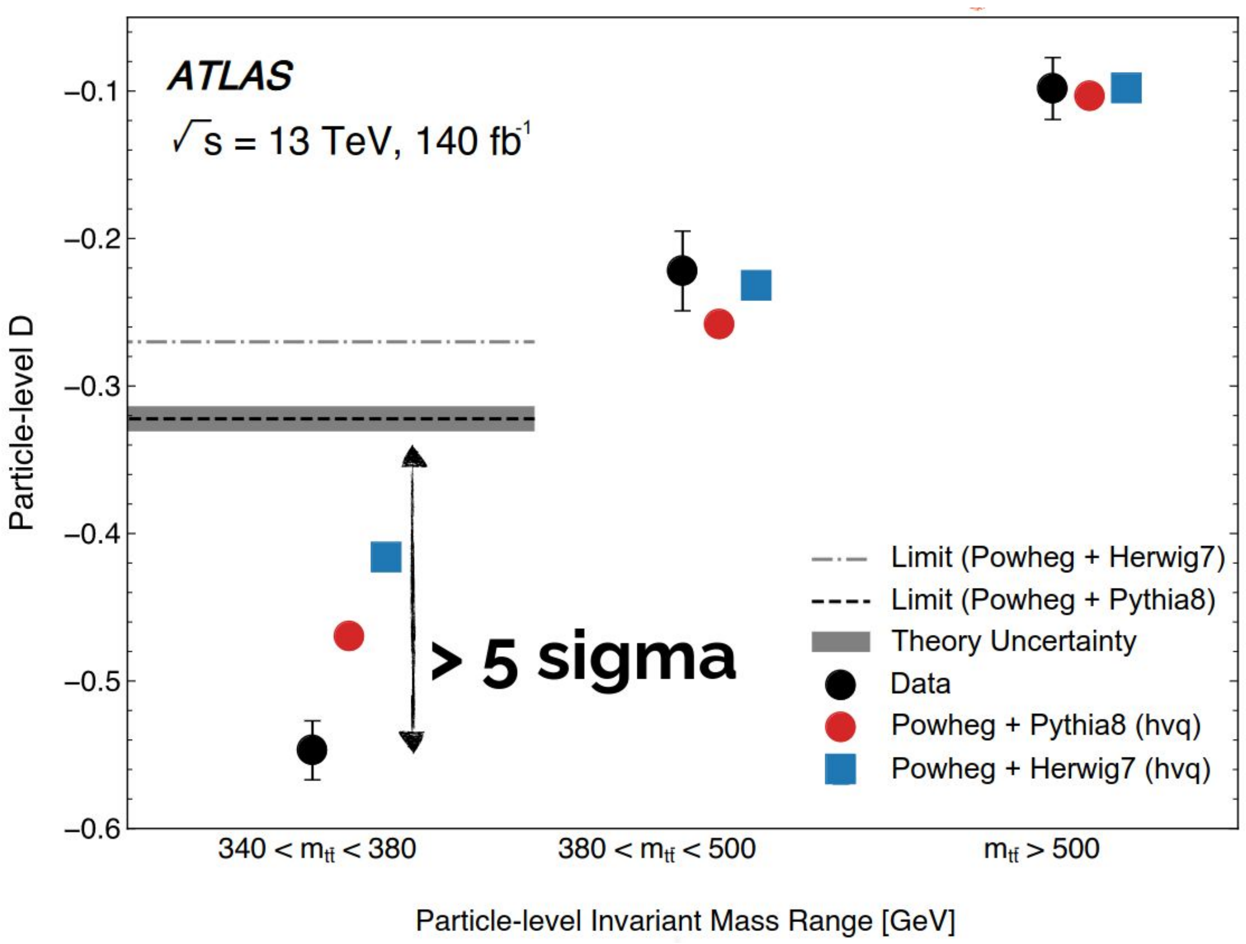


- So how do we measure *D* experimentally:

$$\boxed{\frac{1}{\sigma}\frac{d\sigma}{d\cos\varphi} = \frac{1}{2}(1 - D\cos\varphi)}$$





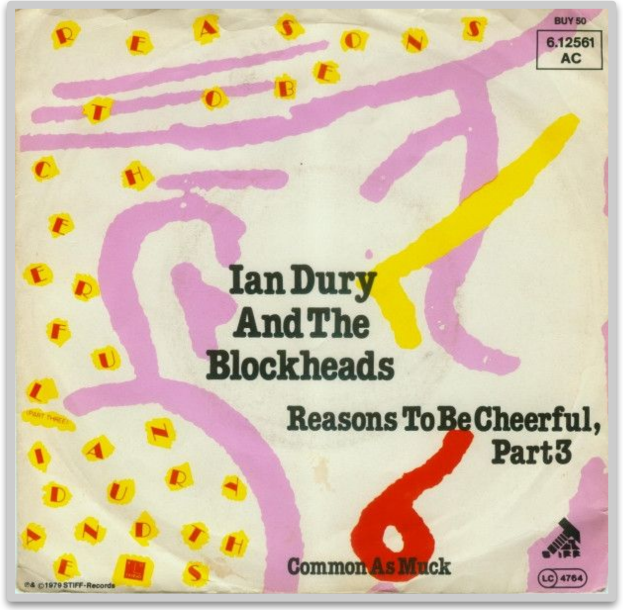


Both experiments have observed entanglement of top quarks at ttbar threshold

Probing fundamental quantum mechanics at the largest accelerator in the world!

Reasons to be cheerful

- Only ~5% of final (HL-)LHC dataset analysed



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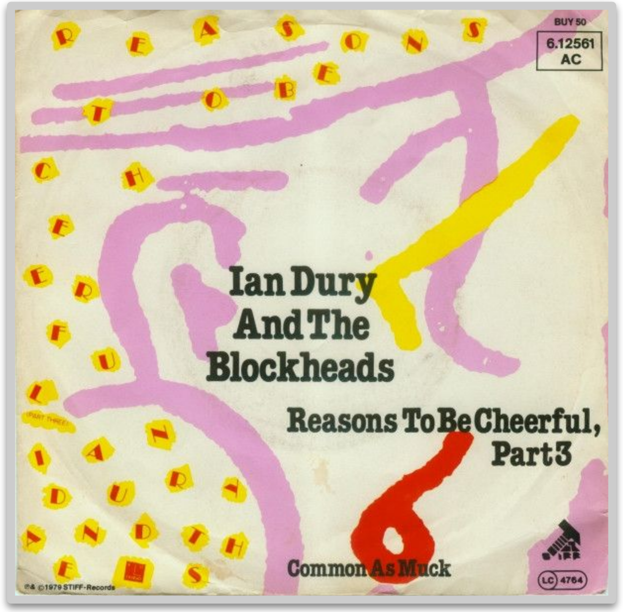
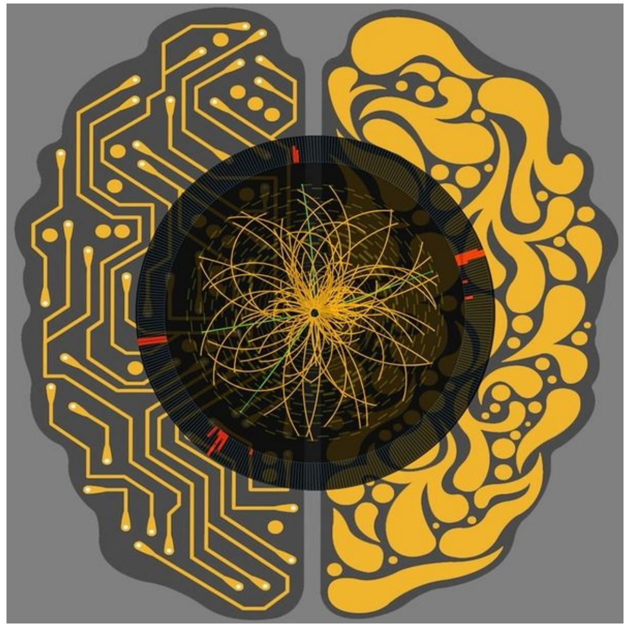
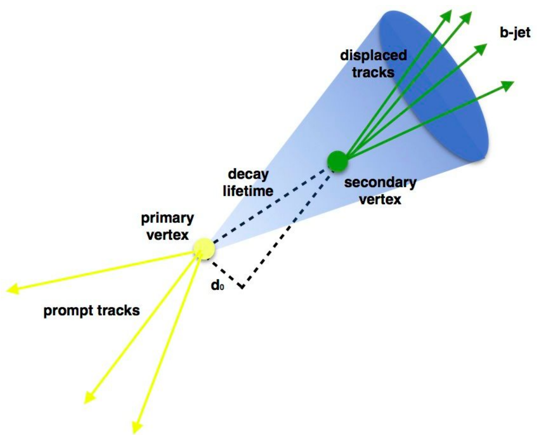


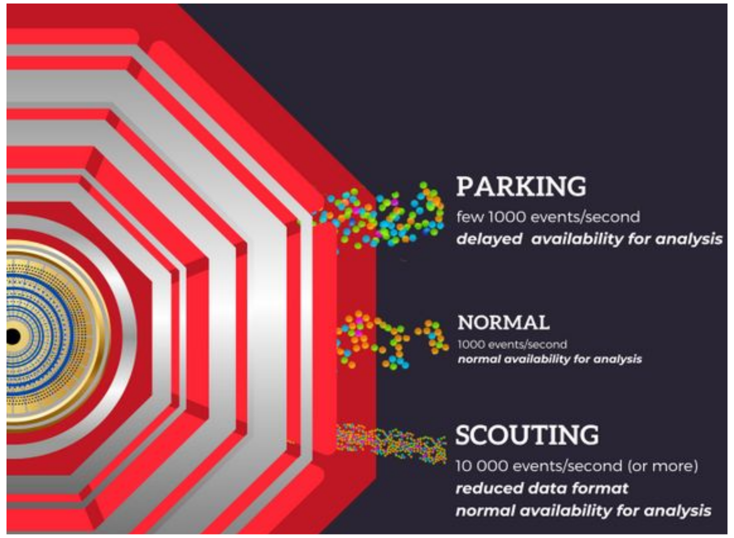
<u>LHC is an exploration machine:</u> we are only now understanding its true potential

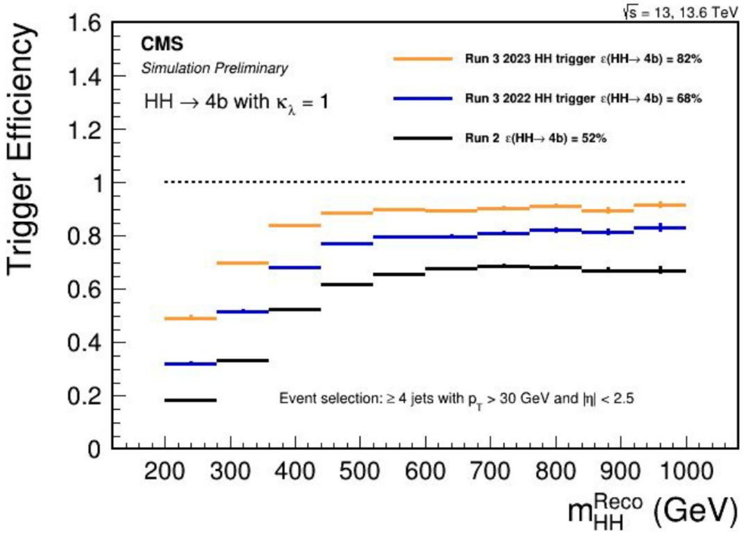
Making the most of Run 3

- Plenty of interesting physics to explore in Run 3

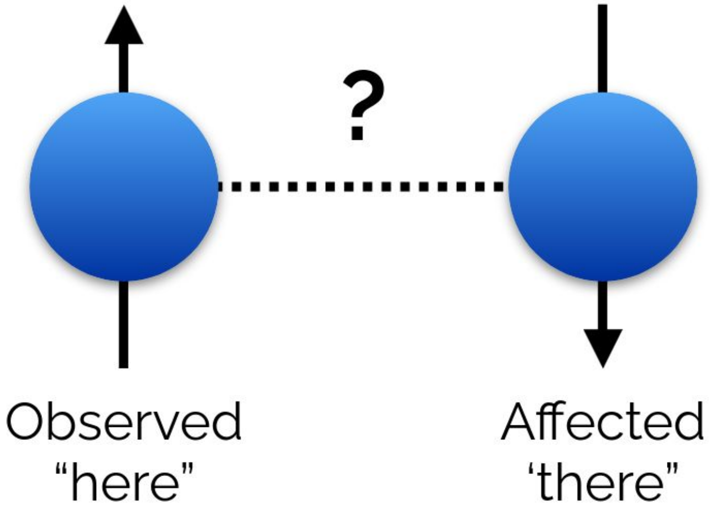



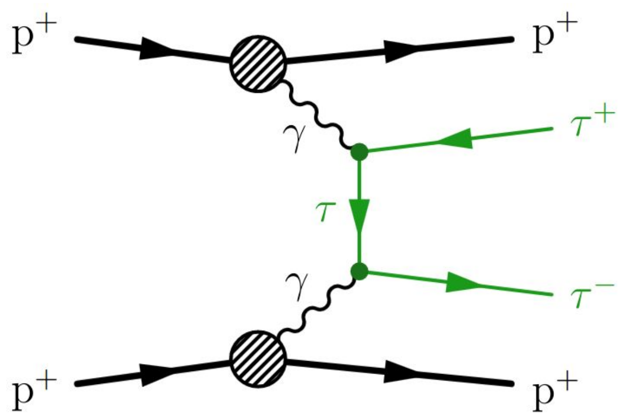
Machine Learning / AI





Unique data-taking efforts



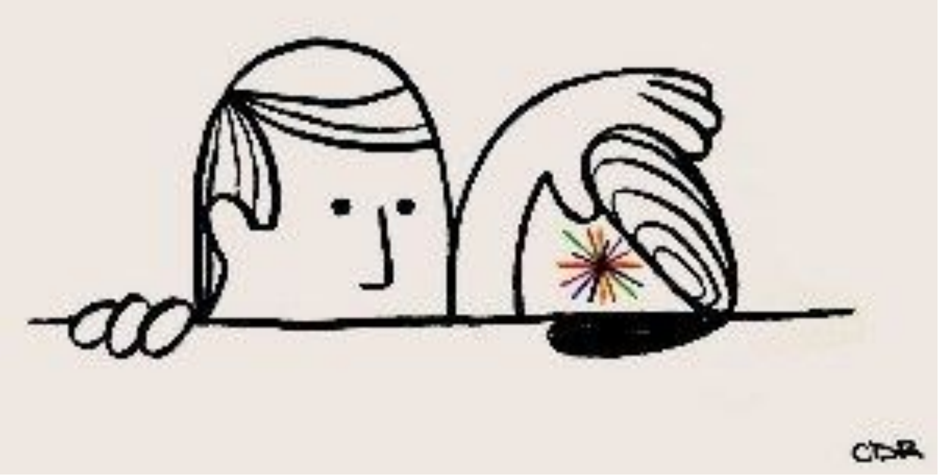


Thinking outside the box

- Experimental techniques developed now will lay foundations for HL-LHC

Summary

- Standard Model holds strong… but not for the lack of trying!
- With our ever-growing toolset these are exciting times @ the LHC
- Presented a **subset** of recent SM results. For a more complete overview see Moriond 24 highlights: CMS, ATLAS
  - Higgs (STXS)
  - Differential cross sections for MET+jets
  - Status of di-Higgs production
  - Precision physics
  - LHC as a photon collider
  - Quantum entanglement in tops



- Progress in Run 3 will lay foundations for a successful HL-LHC era
  - (Personal) high importance items: *EFT understanding and implications, (valid) application of ML, data-taking strategies, analysis preservation, reinterpretation …*

Thanks!

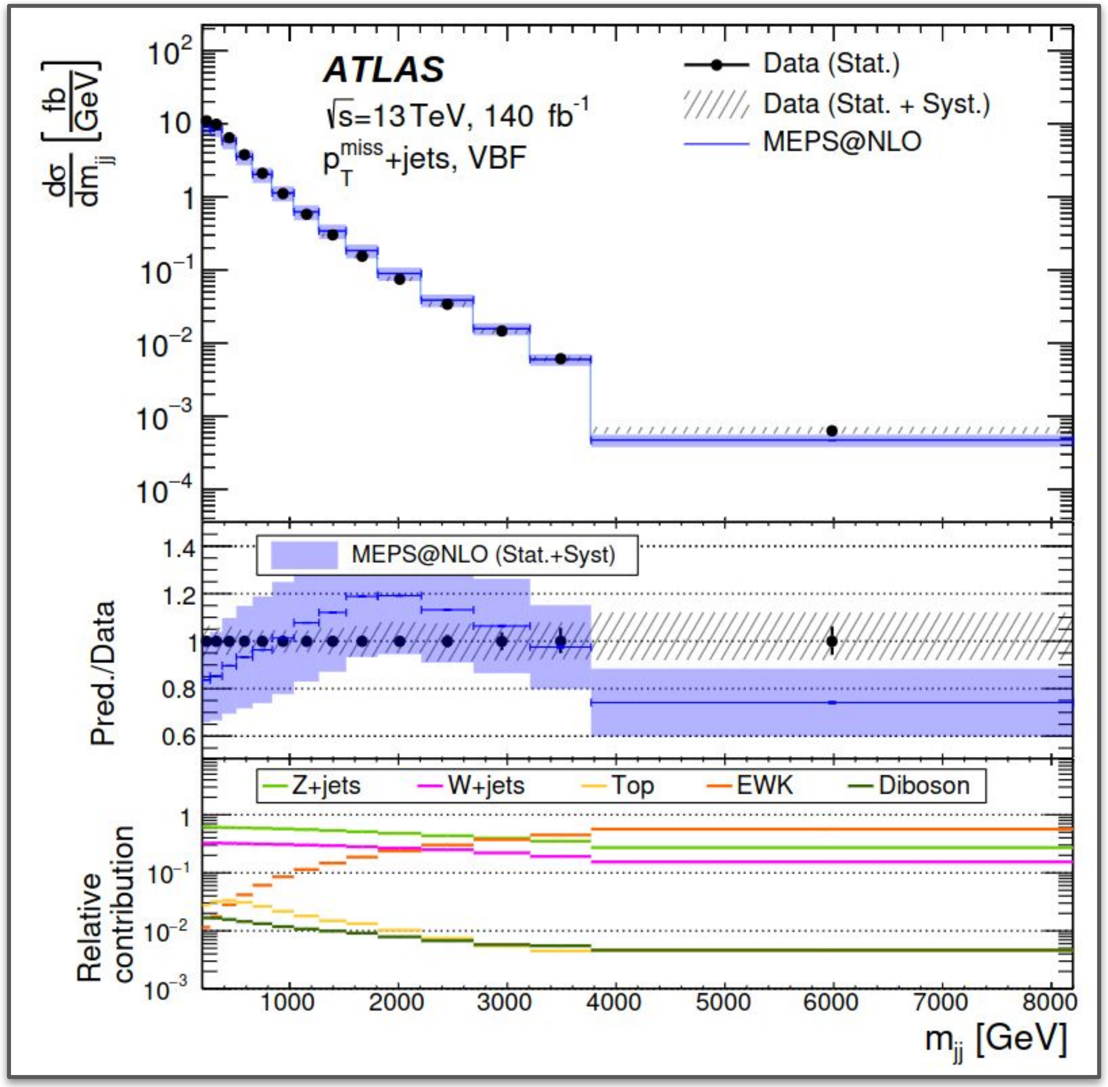
Back-Up

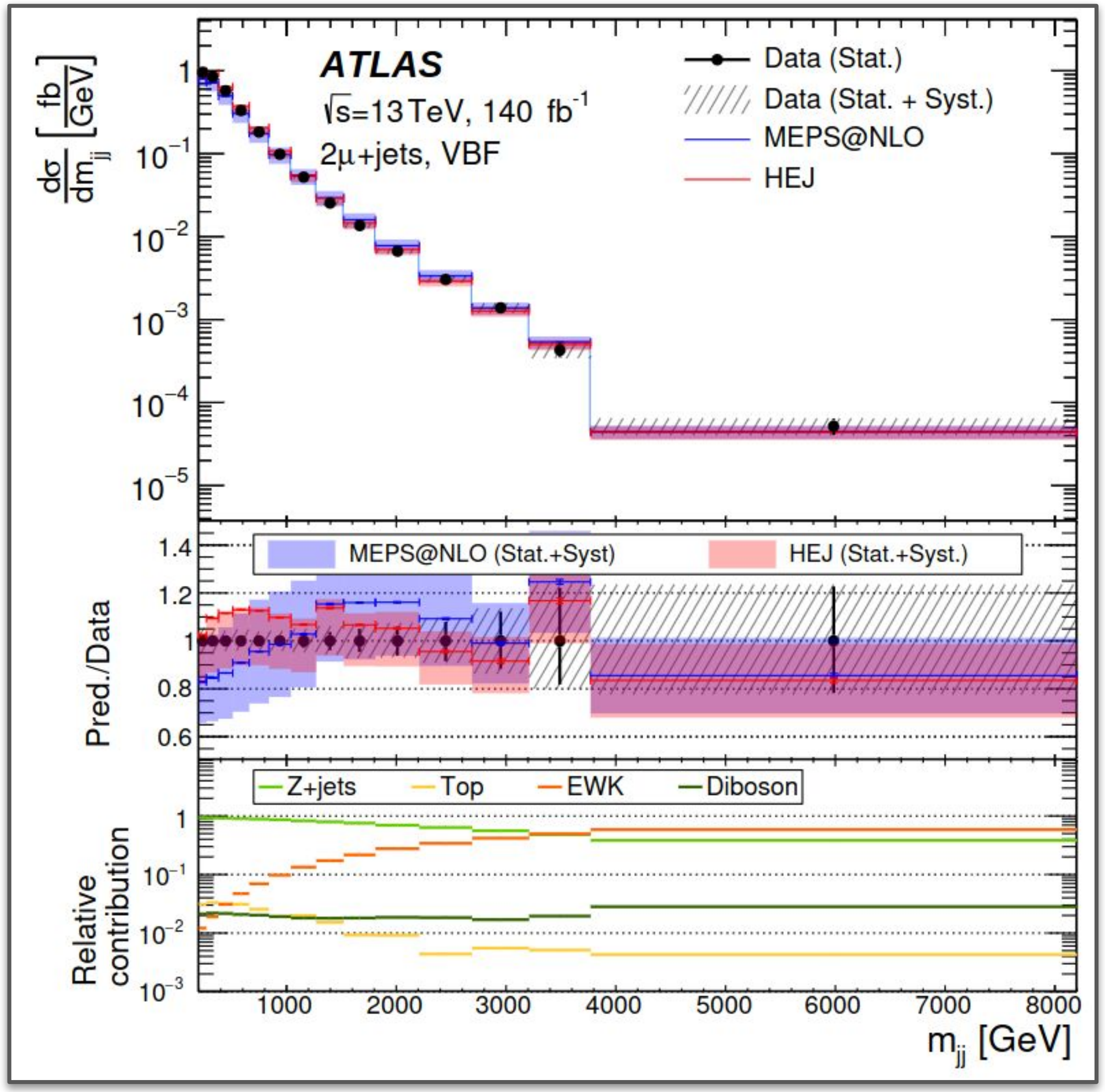
Going granular

Rates → Distributions

$$\sum_i \vec{p}_{\mathrm{T},i} = 0 \qquad \boxed{\vec{E}_\mathrm{T}^\mathrm{miss} = -\sum_{\mathrm{observable}} \vec{p}_{\mathrm{T},i}}$$

- [arXiv:2403.02793] Diff. XS measurements for events with MET+jets (ATLAS)
  - Aim to be as inclusive and model-independent as possible
  - Simultaneous measurements in MET+jets and charged-lepton+jets final states





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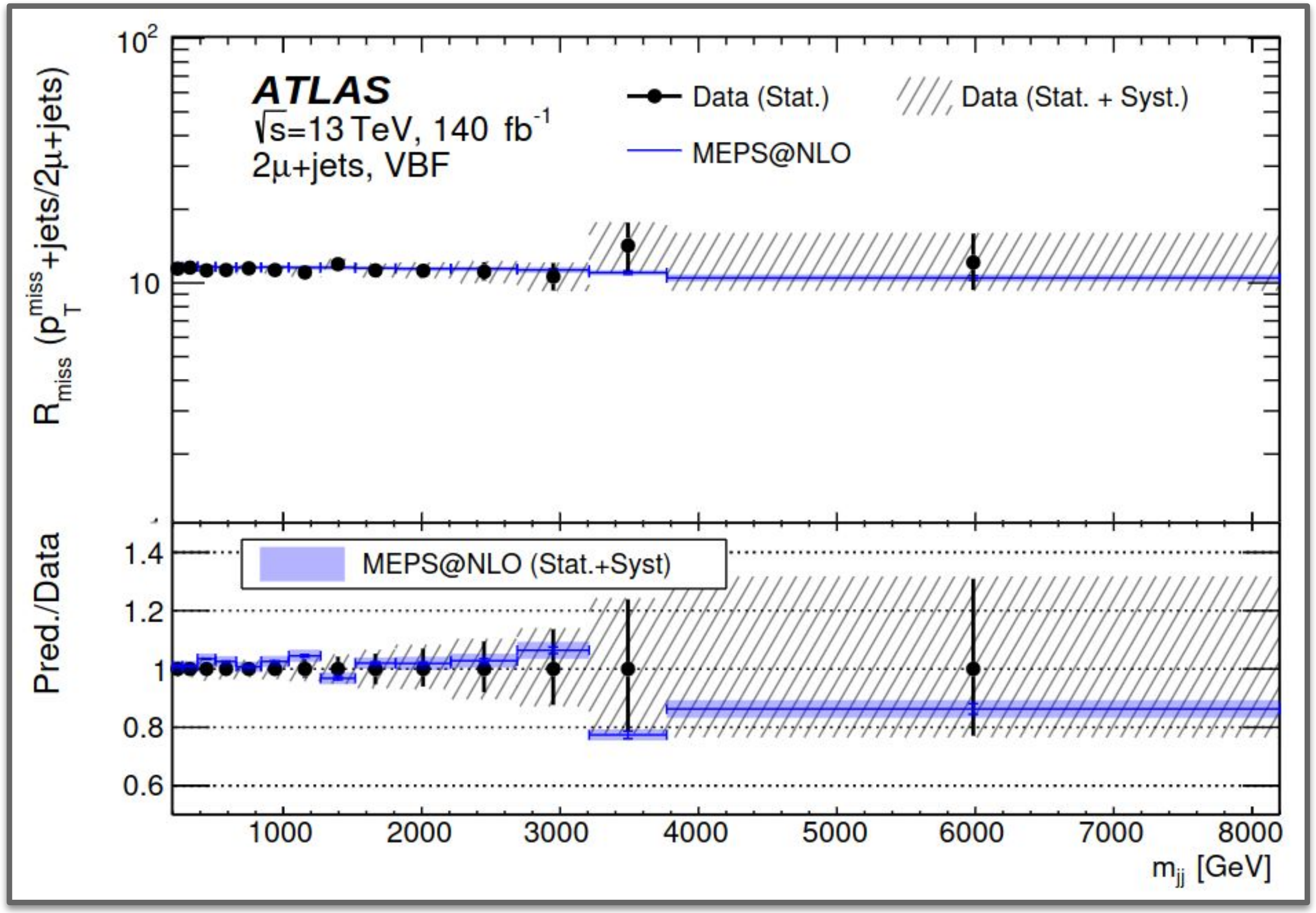
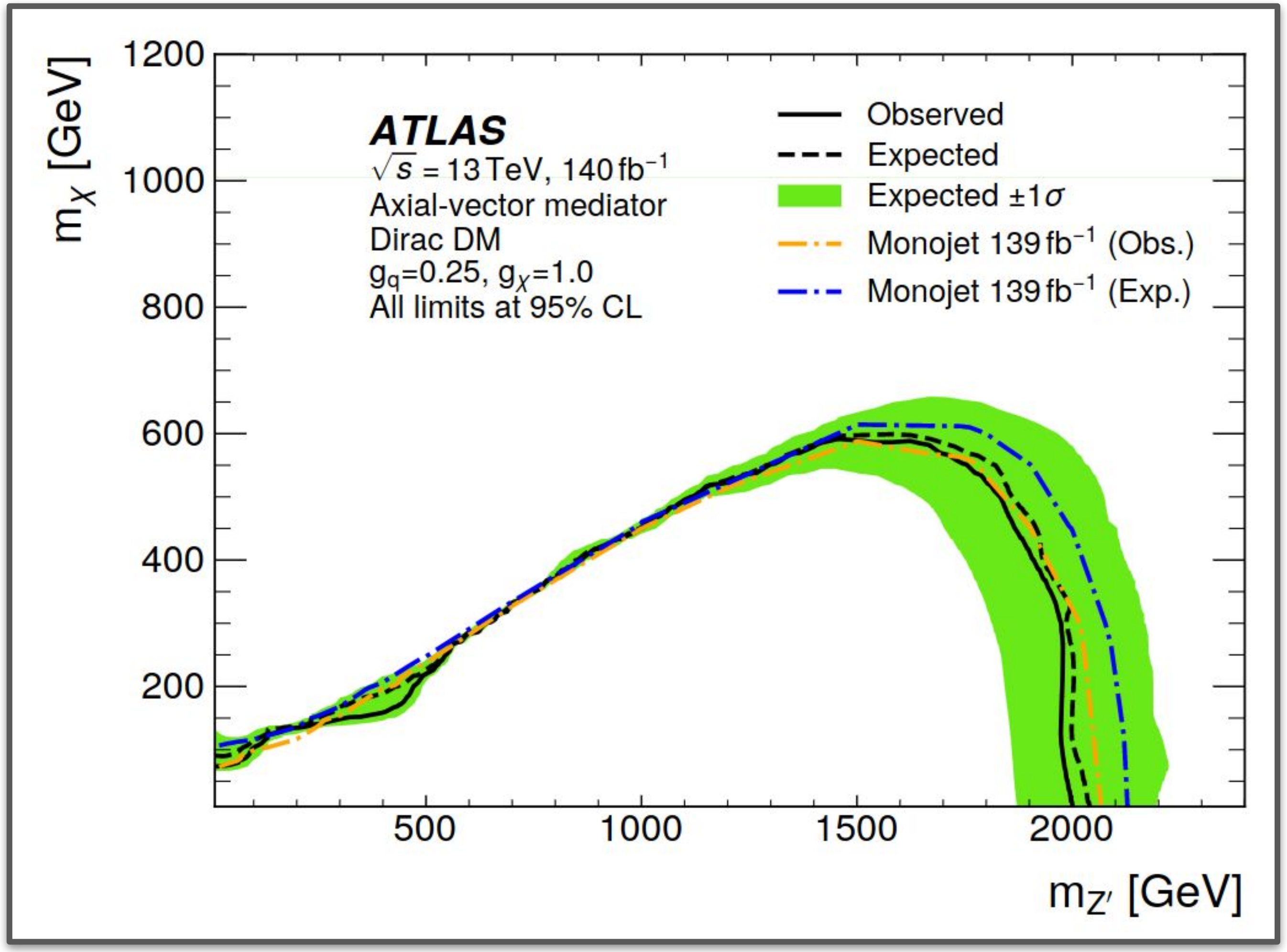
  - Aim to be as inclusive and model-independent as possible
  - Simultaneous measurements in MET+jets and charged-lepton+jets final states
  - Ratios used to search for BSM





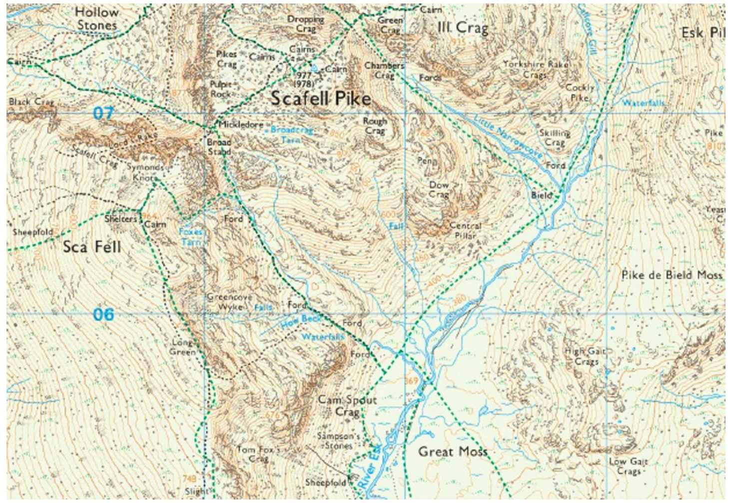
Excellent focus on **reinterpretation**! (HEPdata, Rivet)

Effective field theory (EFT)

Complete theory: map of mountain range with details of cracks in the rocks

Hiker does not need this level of detail

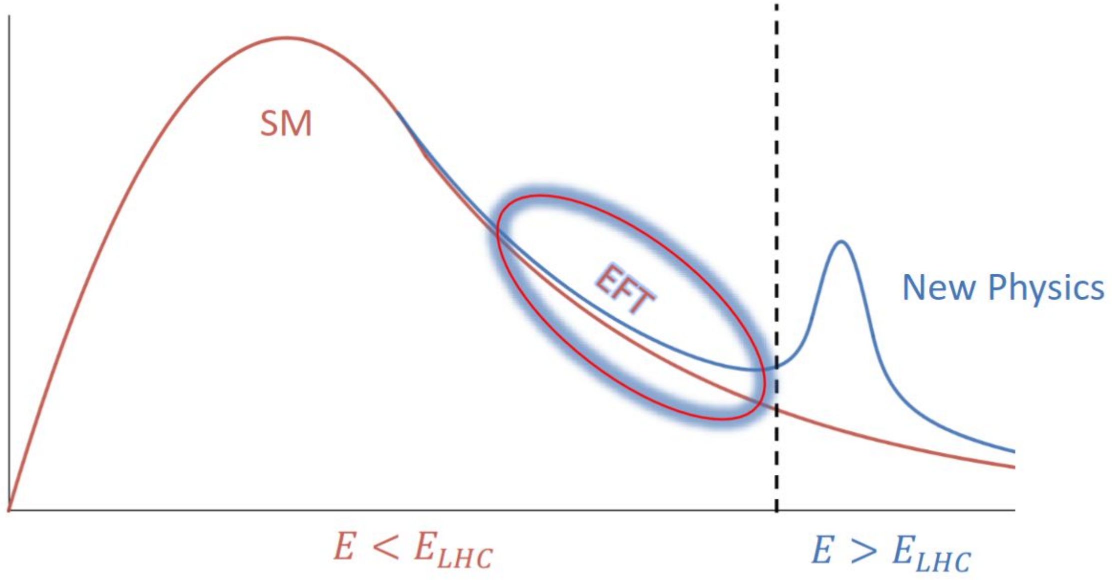
- Introduce 10m grid on terrain and use average values for each square



Effective theory: discard information with length scale below some cut-off

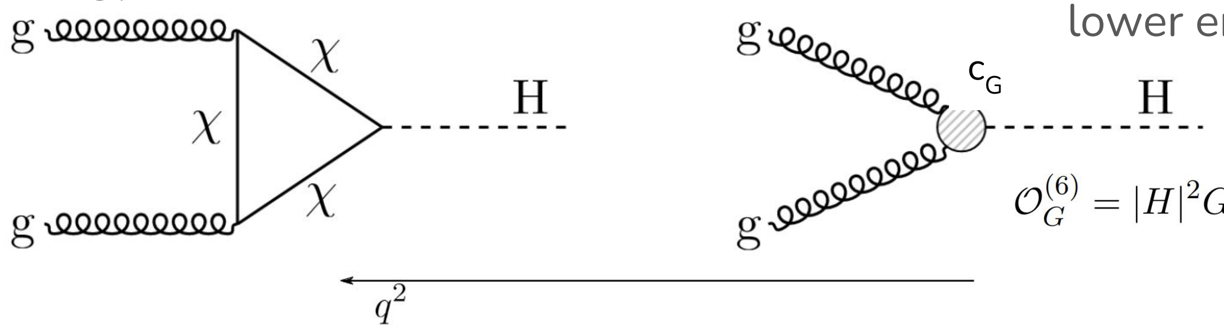
- But capture relevant physics

Same principle applied to particle physics



Short-distance, high-energy

Contact interaction, lower energy



$\mathcal{O}_G^{(6)} = |H|^2 G^a_{\mu\nu} G^{a,\mu\nu}$

SMEFT: (almost) model-independent way to probe BSM physics

$$\mathcal{L}_{\rm EFT} = \mathcal{L}_{\rm SM} + \sum_i \frac{c_i^{(5)}}{\Lambda}\mathcal{O}_i^{(5)} + \sum_i \frac{c_i^{(6)}}{\Lambda^2}\mathcal{O}_i^{(6)} + \sum_i \frac{c_i^{(7)}}{\Lambda^3}\mathcal{O}_i^{(7)} + \sum_i \frac{c_i^{(8)}}{\Lambda^4}\mathcal{O}_i^{(8)} + \dots$$

Measure Wilson coefficients, c_i

- Deviations from zero are smoking gun for BSM → And tell us where to look!

SMEFT interpretation of STXS

[arXiv:2304.05742] (Sub. to JHEP) Interpretations of combined Higgs measurements by ATLAS, including SMEFT

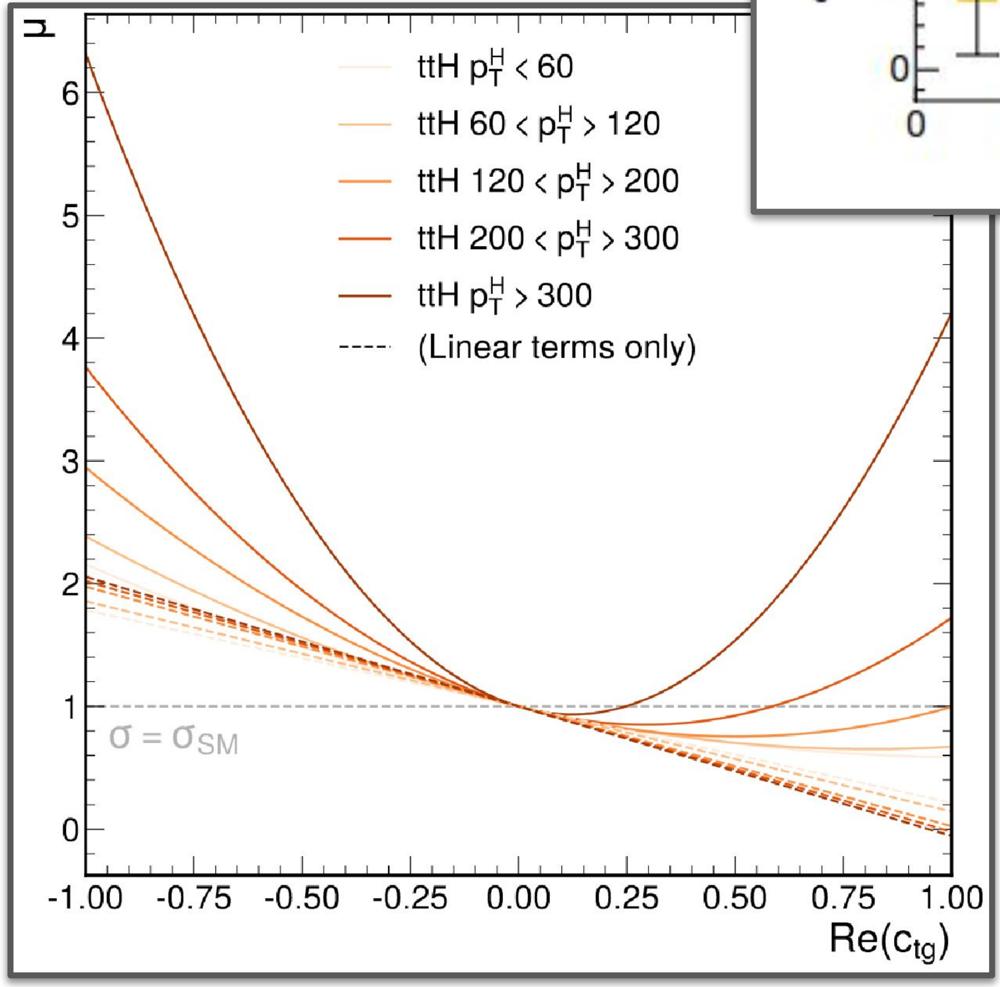
- EFT operators affect event kinematics as well as rates → STXS provides good framework to constrain Wilson coefficients

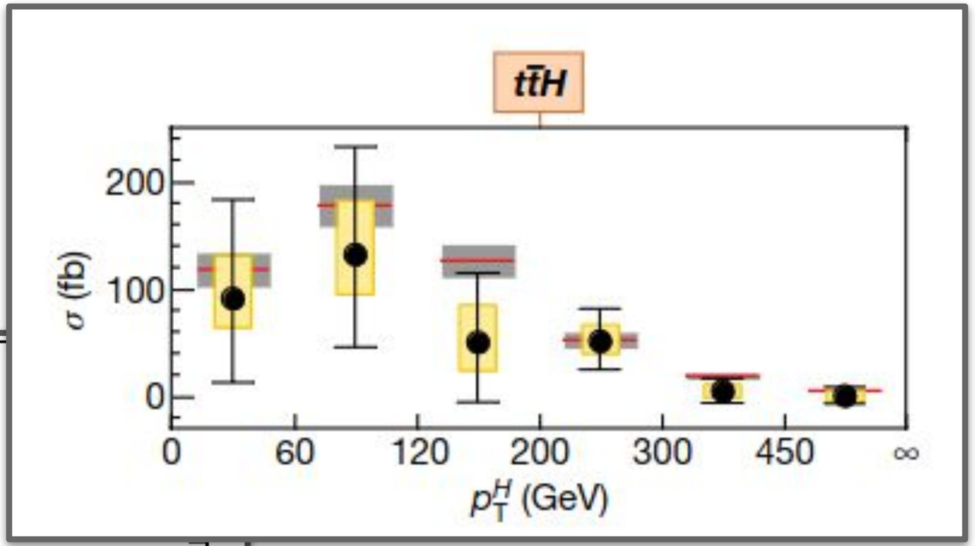
$$\mathcal{L}_{\mathrm{EFT}} = \mathcal{L}_{\mathrm{SM}} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i^{(6)}$$

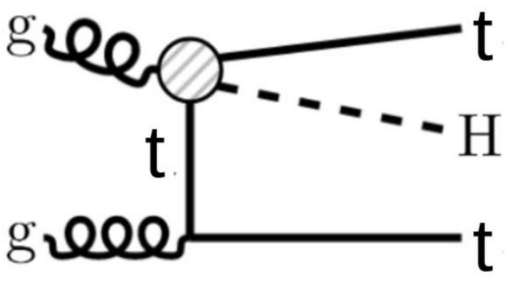
Impact on observables...

$$\boldsymbol{\mu} = \frac{\sigma}{\sigma_{SM}} = \underbrace{1}_{\text{SM}^2} + \underbrace{\underbrace{\sum_j A_j \frac{C_j}{\Lambda^2}}_{\substack{\text{SM-EFT}\\ \text{Interference}}}}_{\textbf{Linear in } C_j} + \underbrace{\underbrace{\sum_{j,k} B_{jk}\frac{C_j C_k}{\Lambda^4}}_{\substack{\text{EFT-EFT}\\ \text{Interference}\\ +\ \text{EFT}^2}}}_{\textbf{Quadratic in } C_j}$$

Derive using Monte-Carlo simulation (+ analytic results)







Add contributions from $\mathcal{O}_{tG}^{(6)}$

$$(\bar{Q}\sigma^{\mu\nu}T^a t)\tilde{H}G^a_{\mu\nu}$$

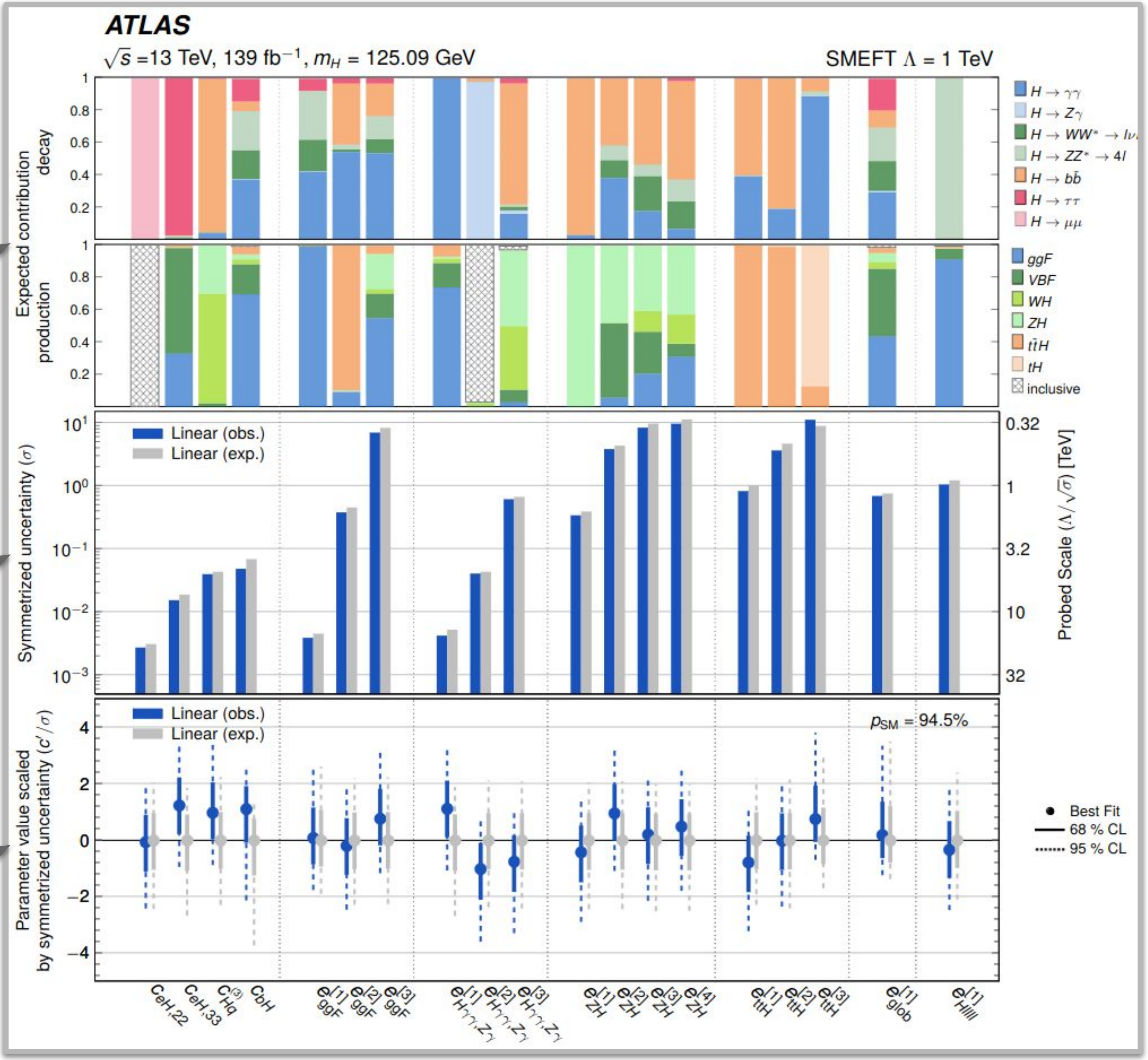
SMEFT interpretation of STXS (ATLAS)

[arXiv:2304.05742]

Contributions from different channels

Probed energy scale

Wilson coefficient confidence intervals



$$\mathcal{L}_{\mathrm{EFT}} = \mathcal{L}_{\mathrm{SM}} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i^{(6)}$$

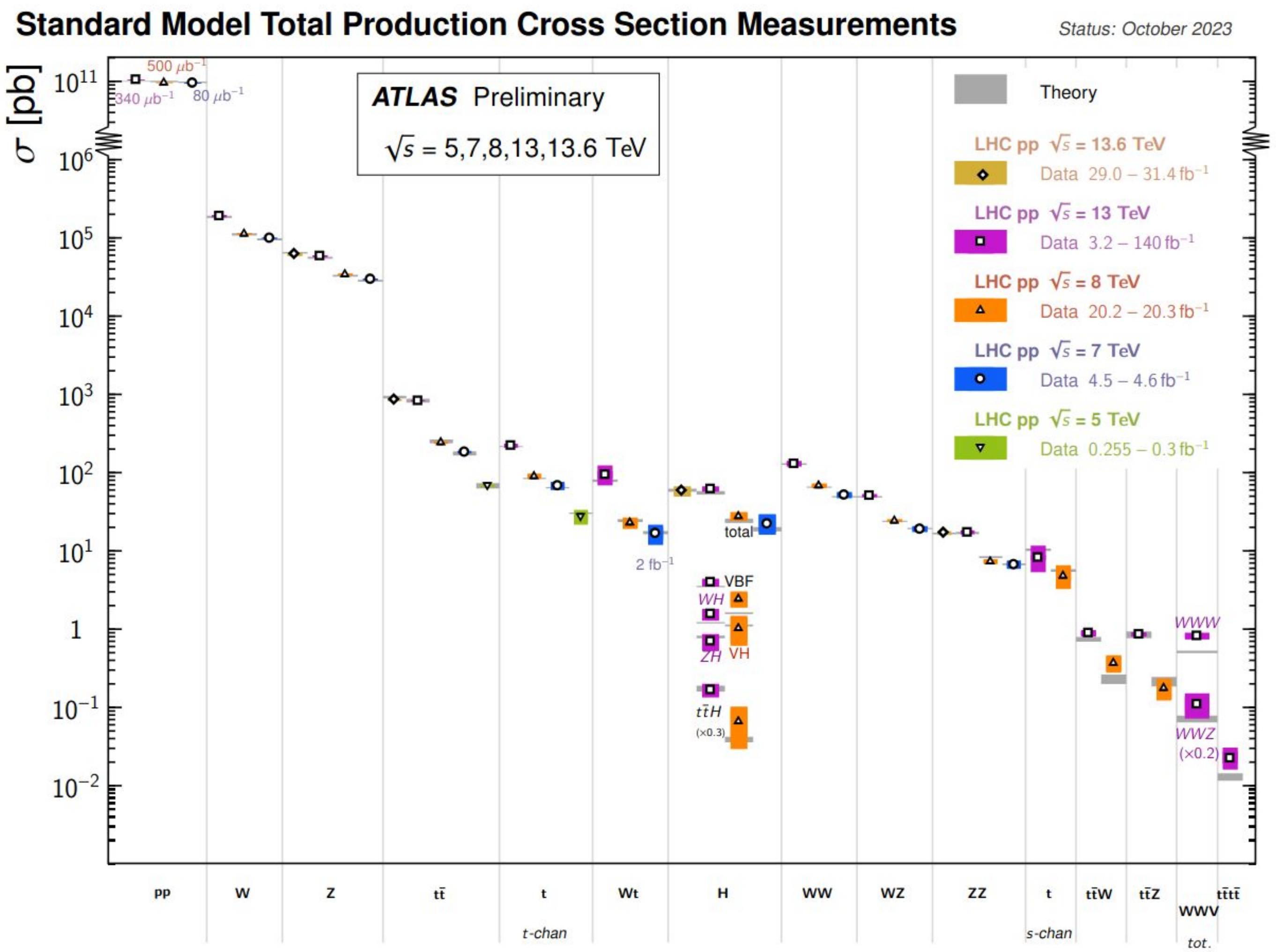
EFT affects distributions as well as rates!

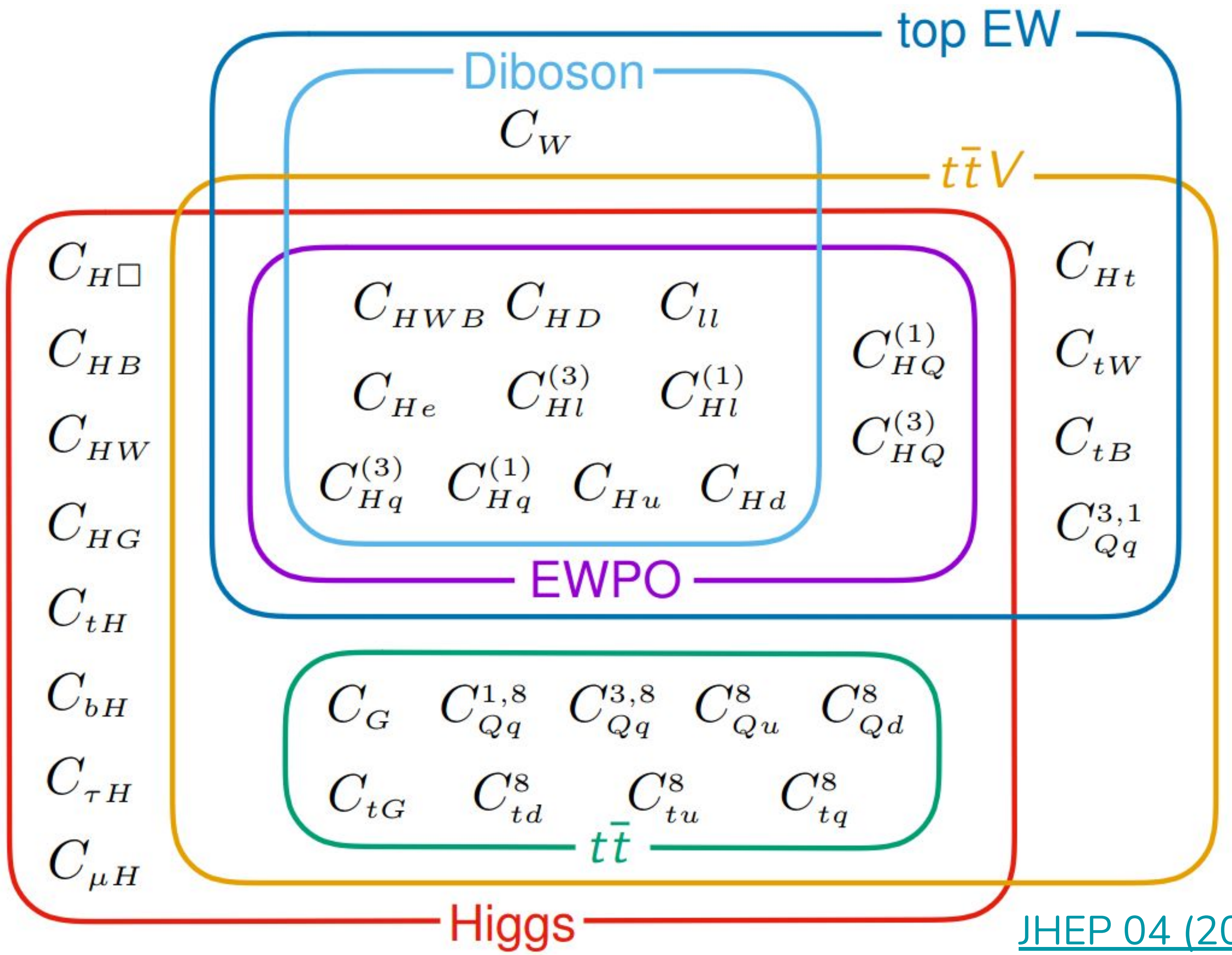
- Extends upon Kappa framework
- Use kinematic information in STXS

Simultaneously constrain 19 types/directions of BSM physics!

Putting everything together

SMEFT is a fully consistent expansion of the SM → correlated effects between different processes



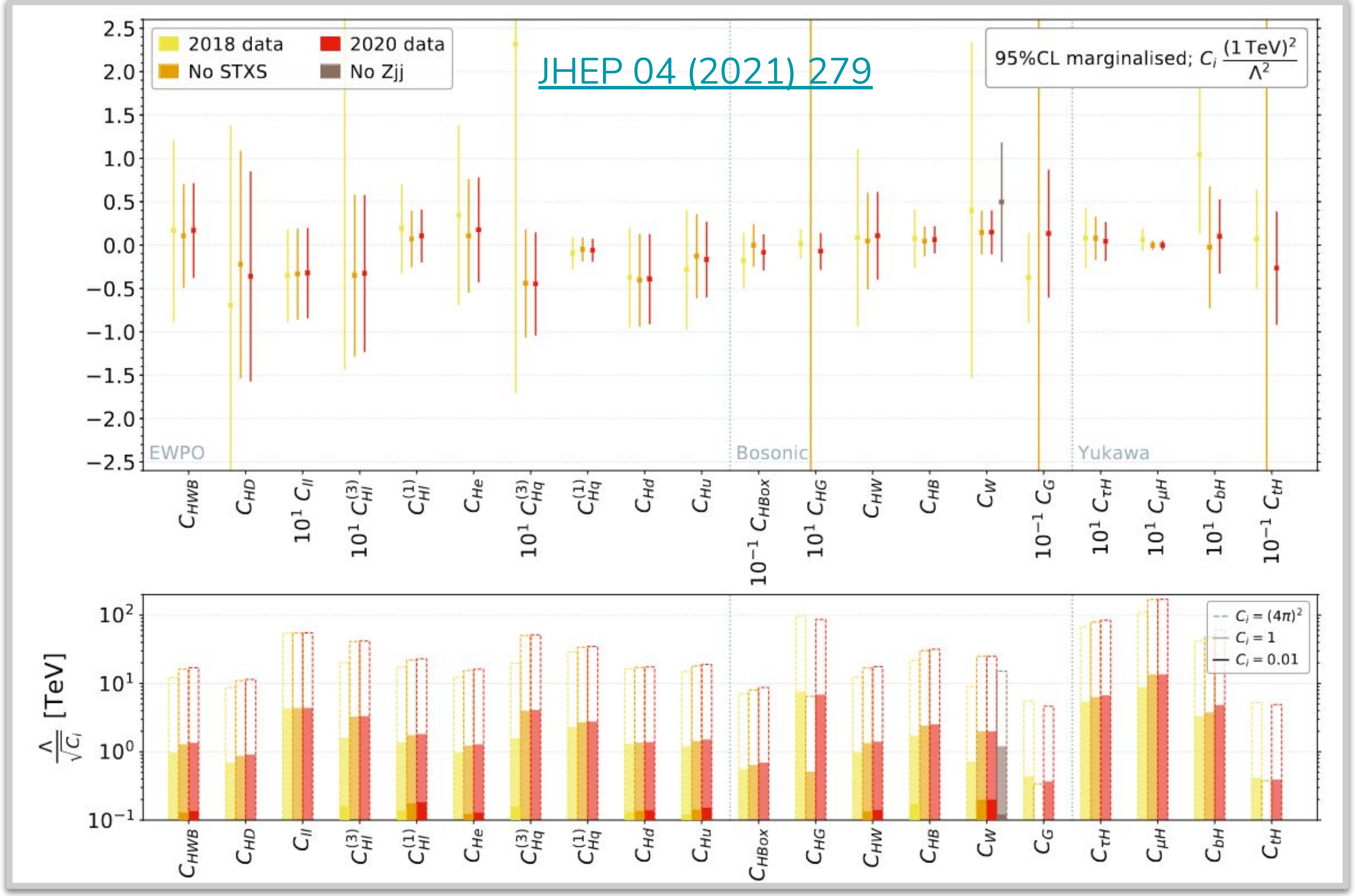


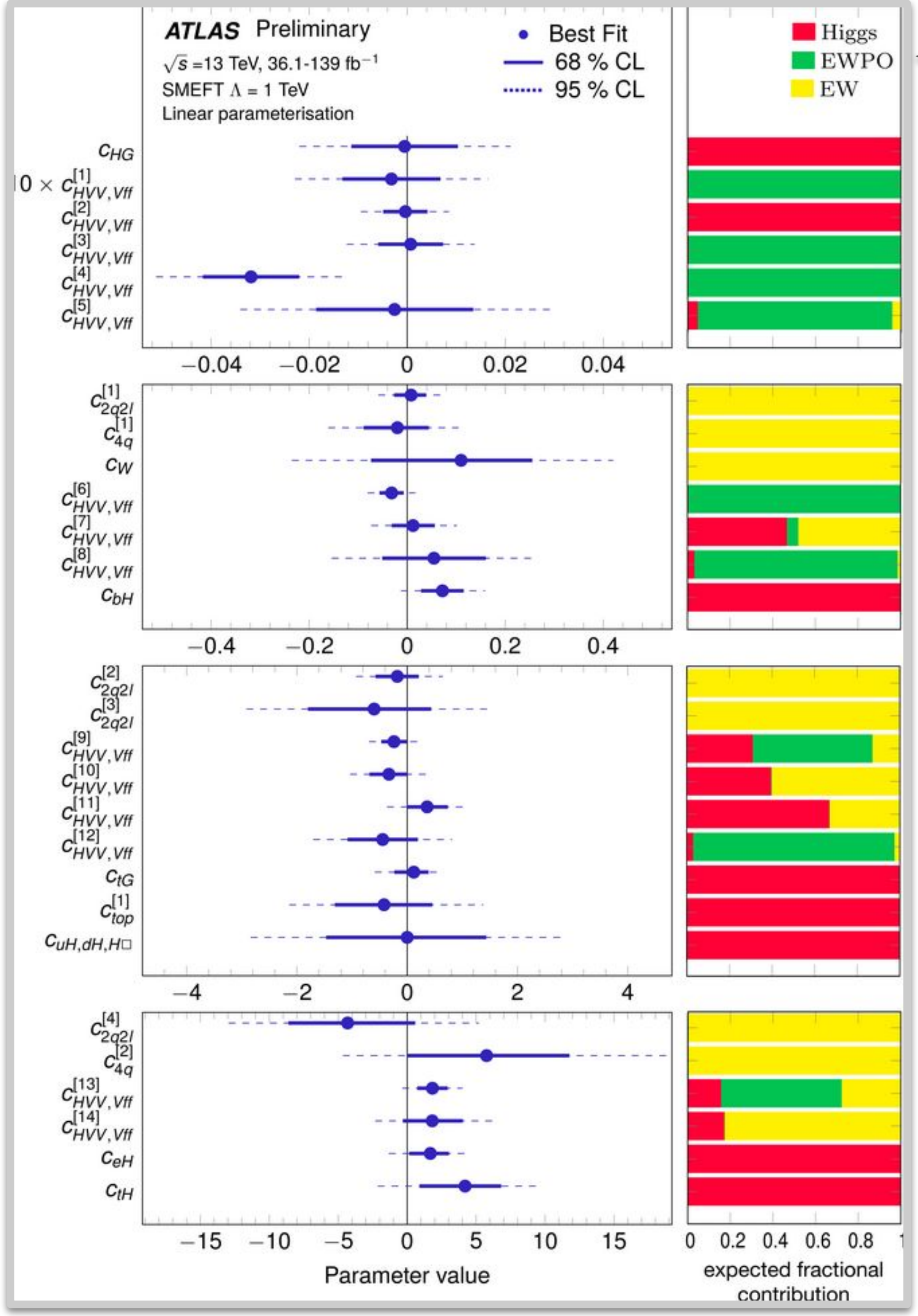
[JHEP 04 (2021) 279]

Legacy LHC result: ultimate SM consistency test is likely to be a global EFT fit

Global EFT fits

- And efforts have started…





We must understand the limitations + implications of this approach on both theory/experimental sides: LHC EFT WG