Collider physics:
LHC prospects and beyond

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2012

Contents lists available at SciVerse ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC ☆

ATLAS Collaboration *

This paper is dedicated to the memory of our ATLAS colleagues who did not live to see the full impact and significance of their contributions to the experiment.

Contents lists available at SciVerse ScienceDirect

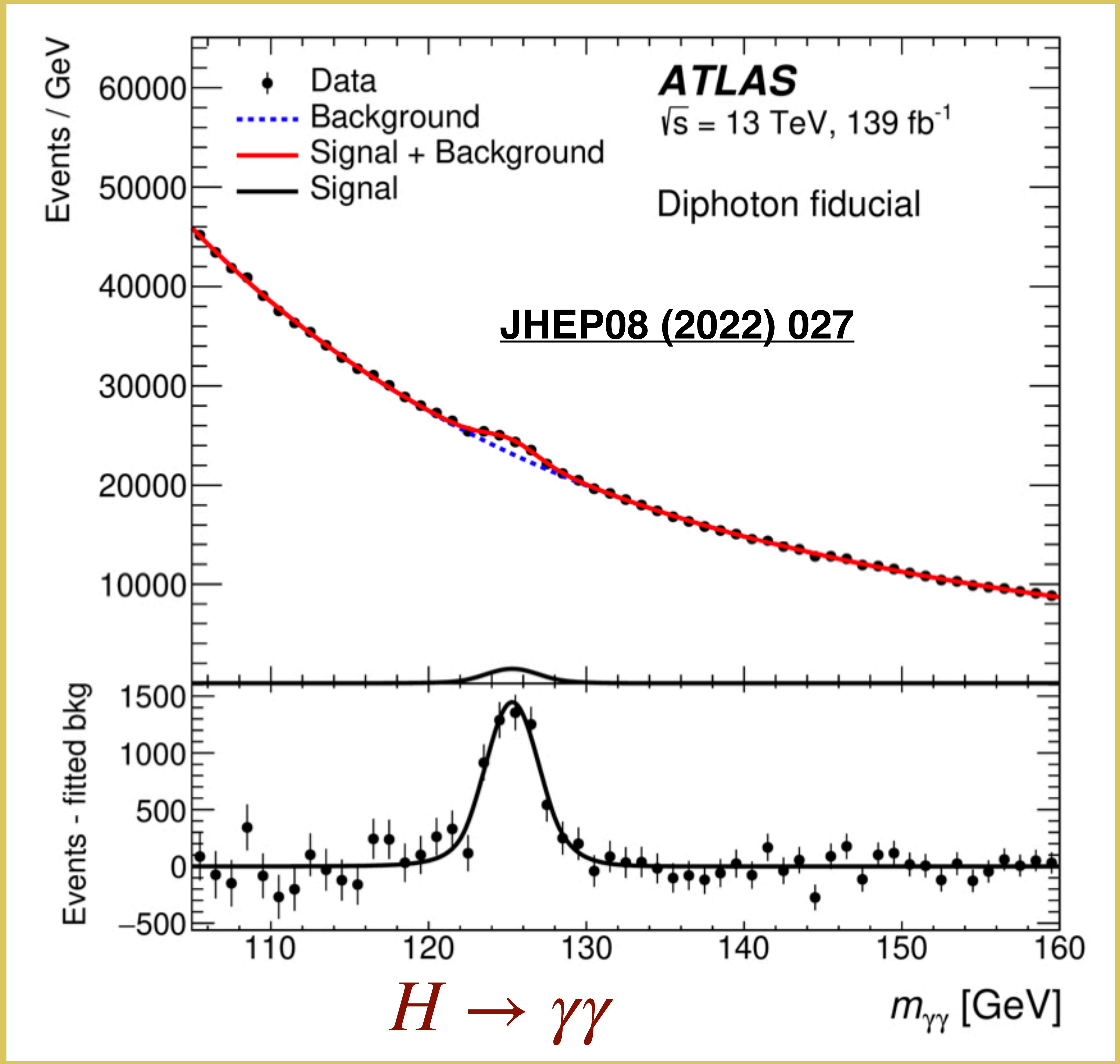
Physics Letters B

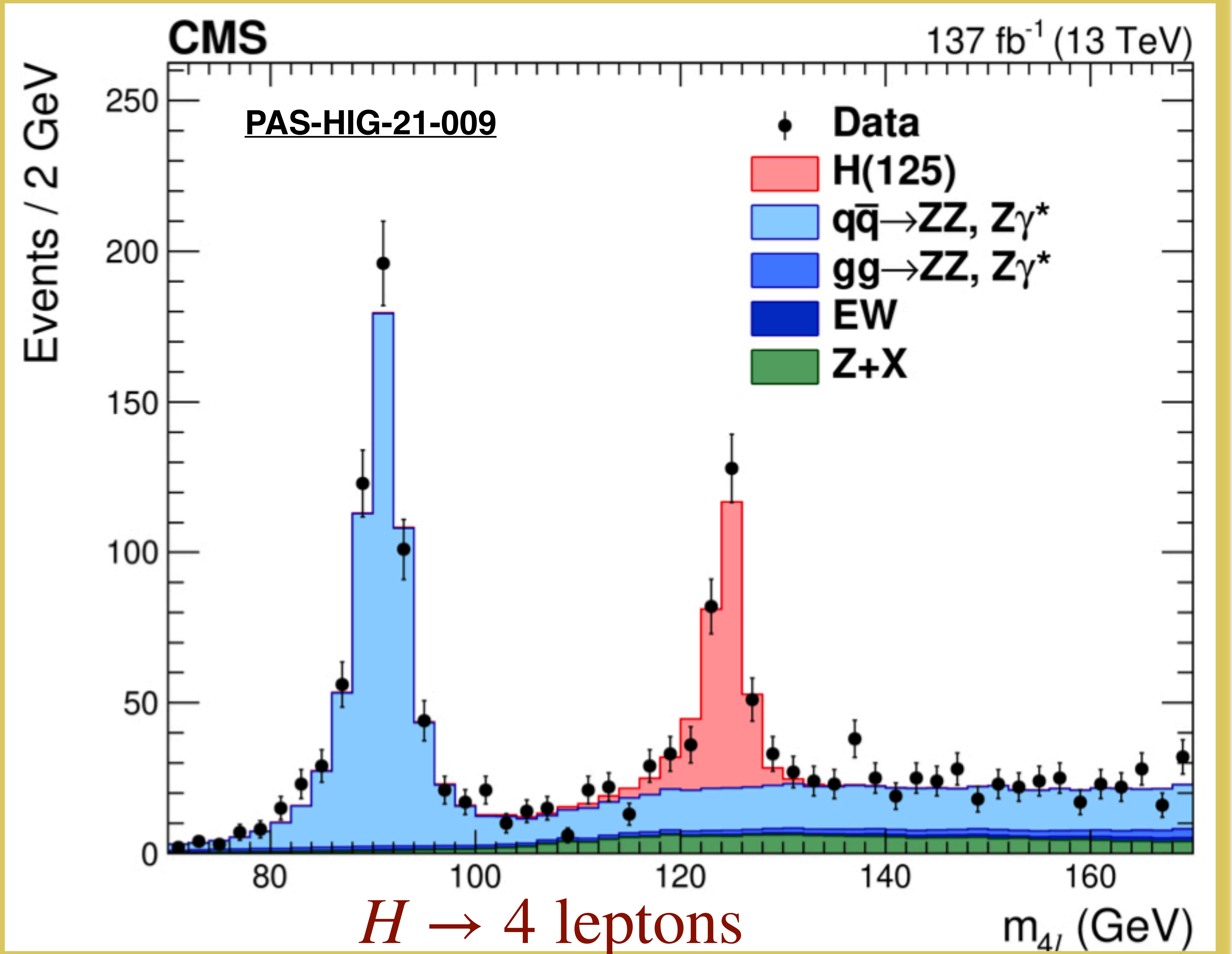
www.elsevier.com/locate/physletb

Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC ☆

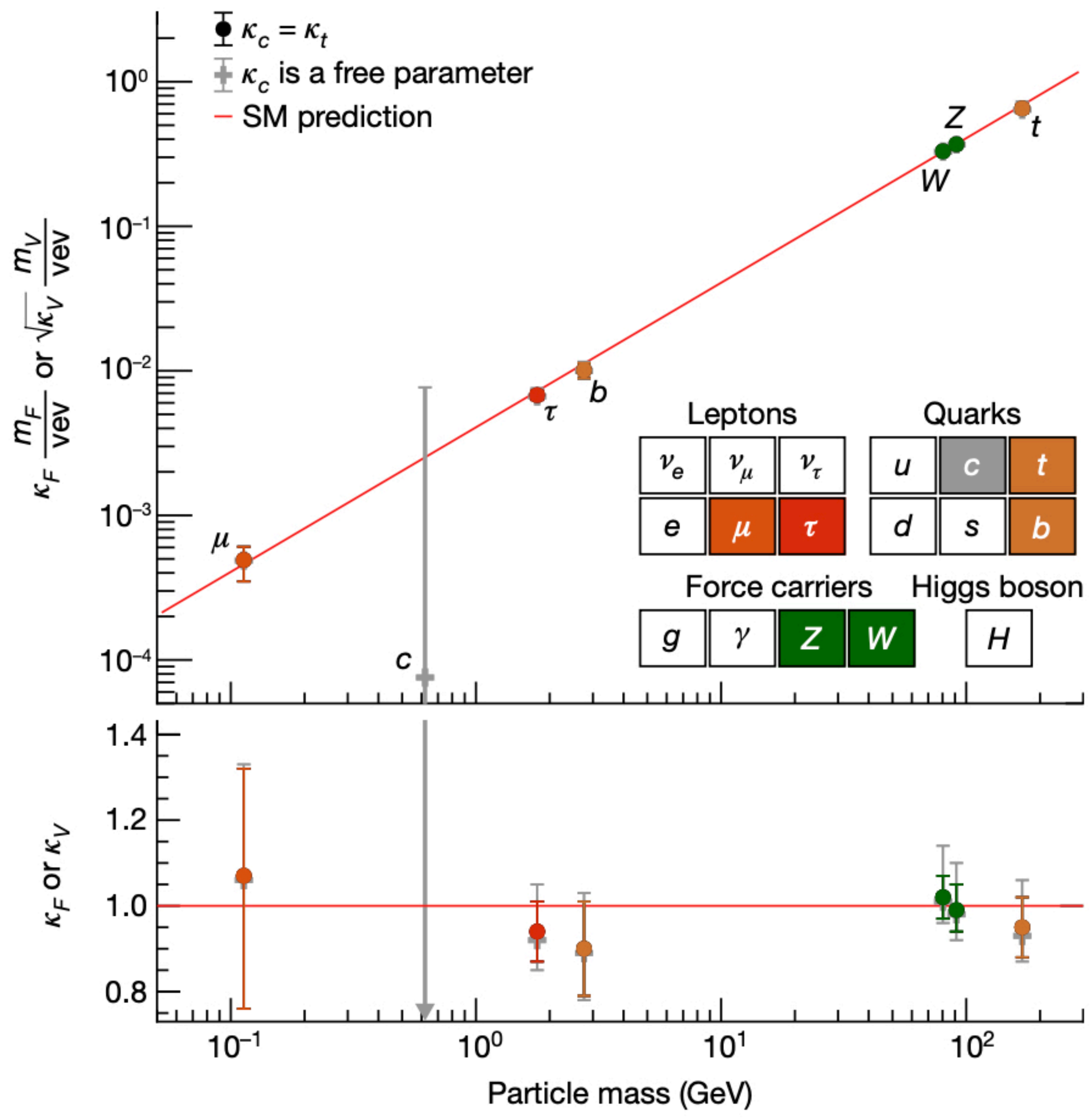
CMS Collaboration *

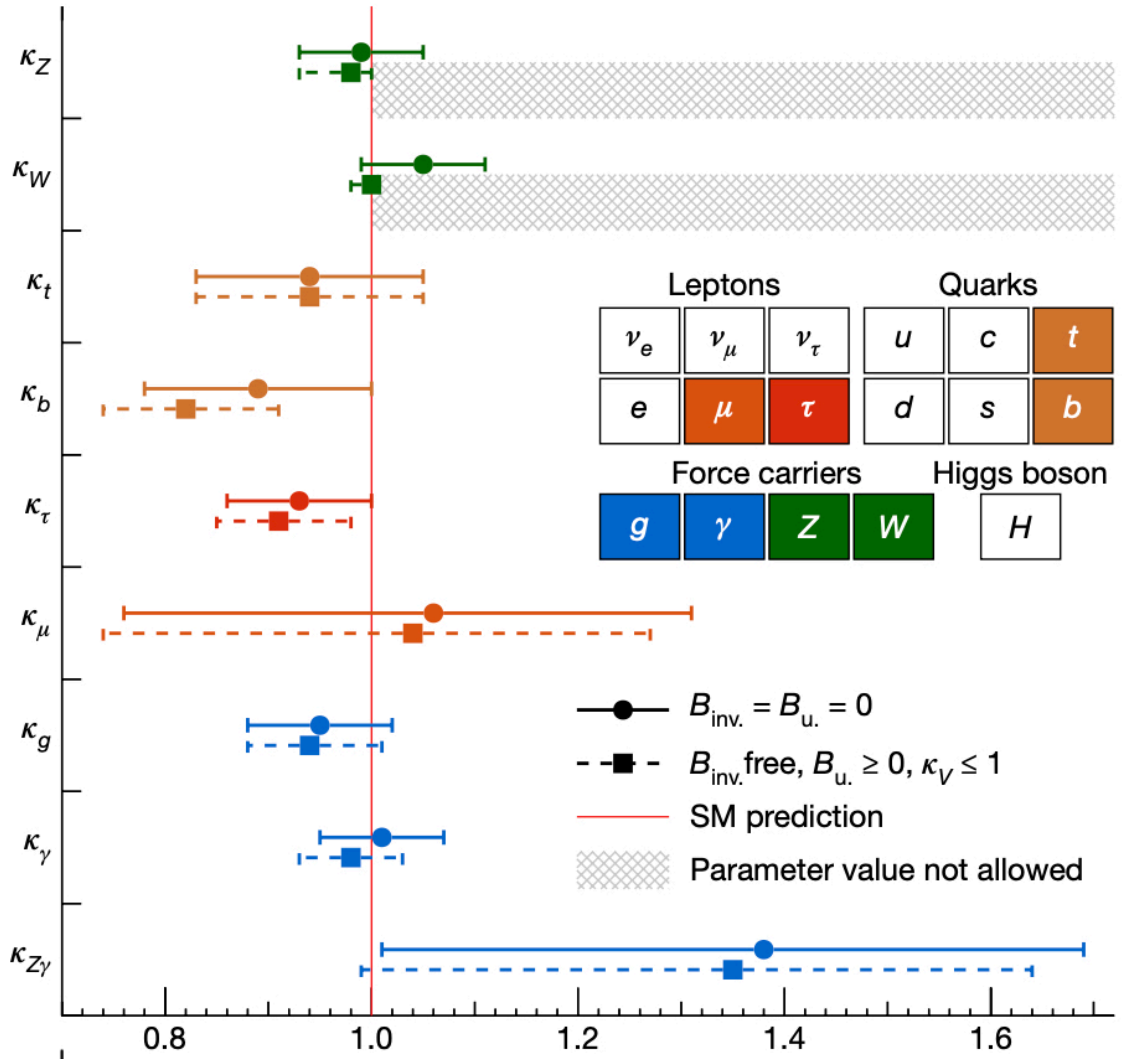
2013





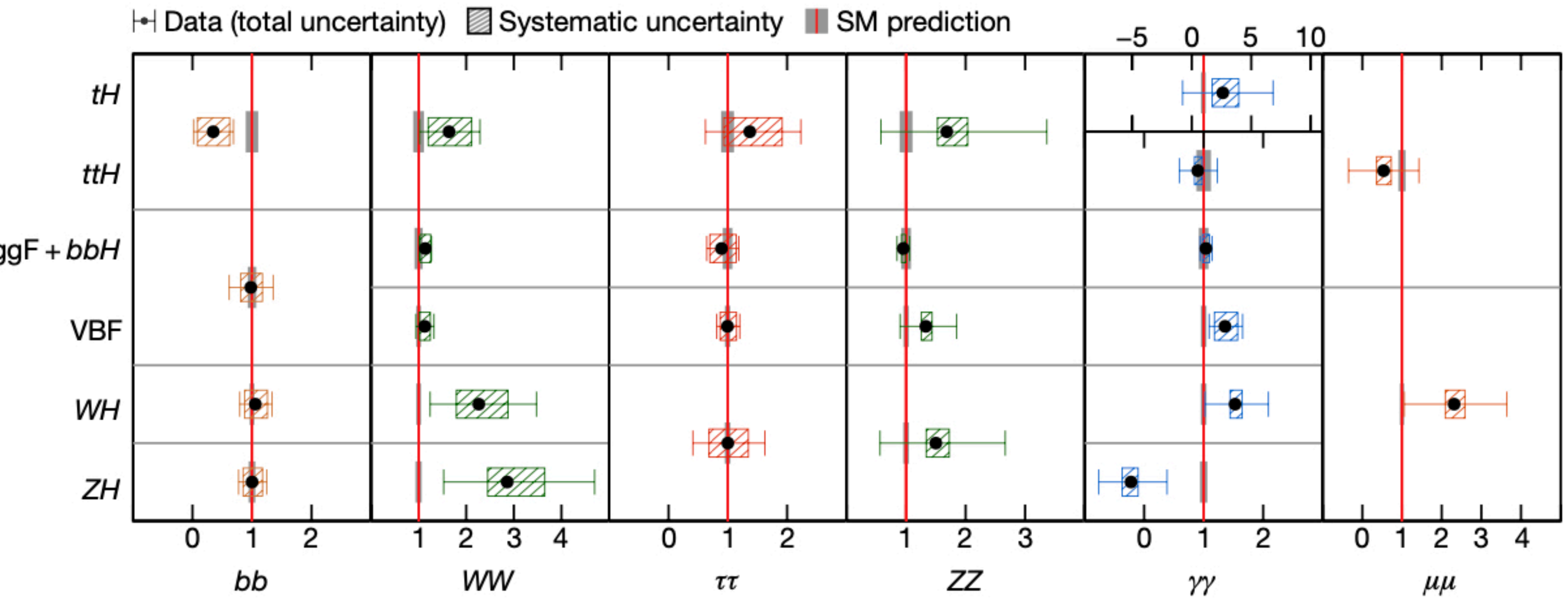
General properties and couplings: OK

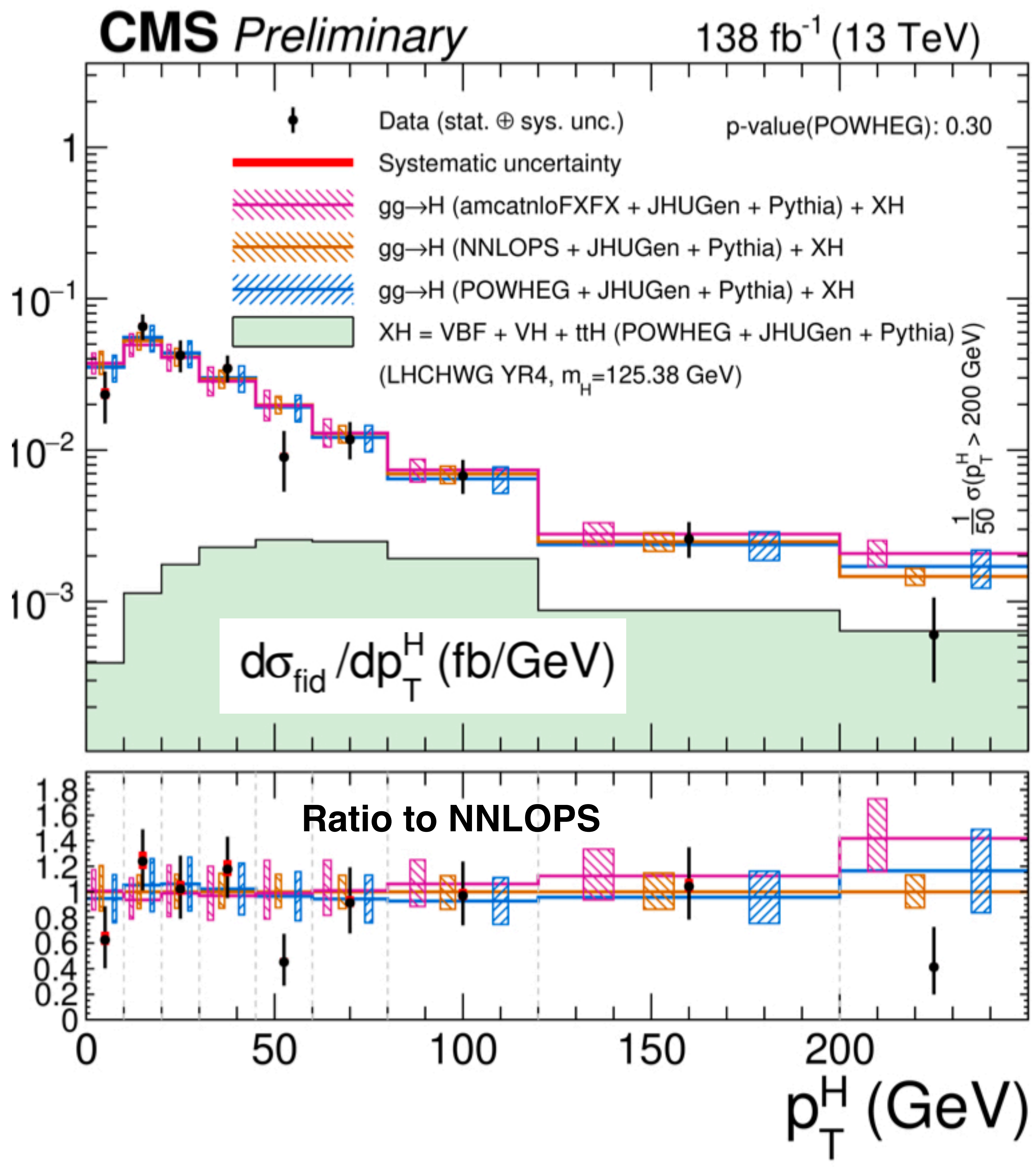




The ATLAS Collaboration Nature, 607, 52–59 (2022) , The CMS Collaboration Nature, 607, 60–68 (2022)

Production properties: OK





The Higgs width (SM: 4.1 MeV) : OK

$$\sigma^{\text{on-shell}}_{gg\to H\to VV} \sim \frac{g^2_{\text{ggH}} g^2_{\text{HZZ}}}{m_H \Gamma_H} \qquad \sigma^{\text{off-shell}}_{gg\to H\to VV} \sim \frac{g^2_{\text{ggH}} g^2_{\text{HZZ}}}{m^2_{ZZ}}$$

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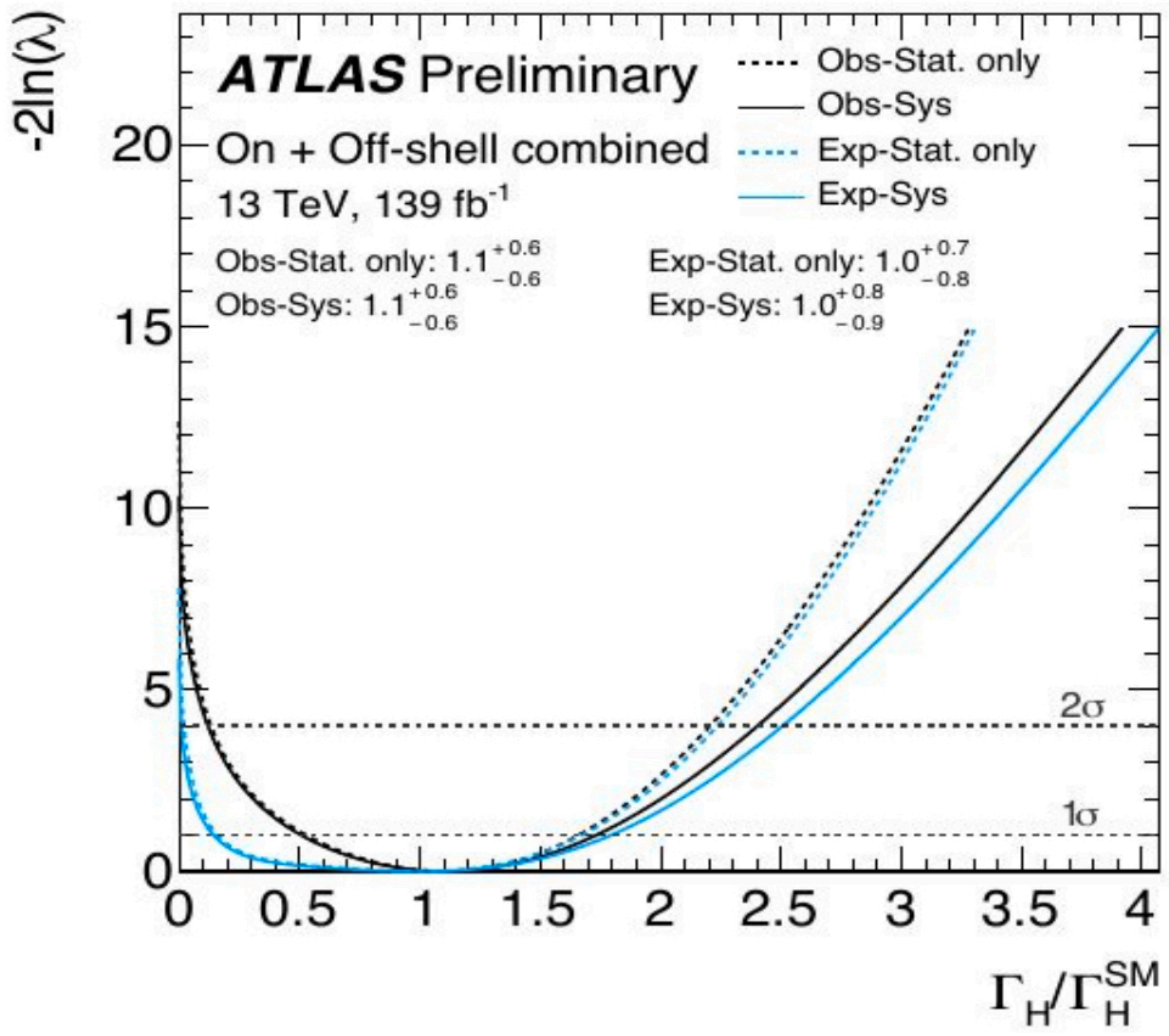
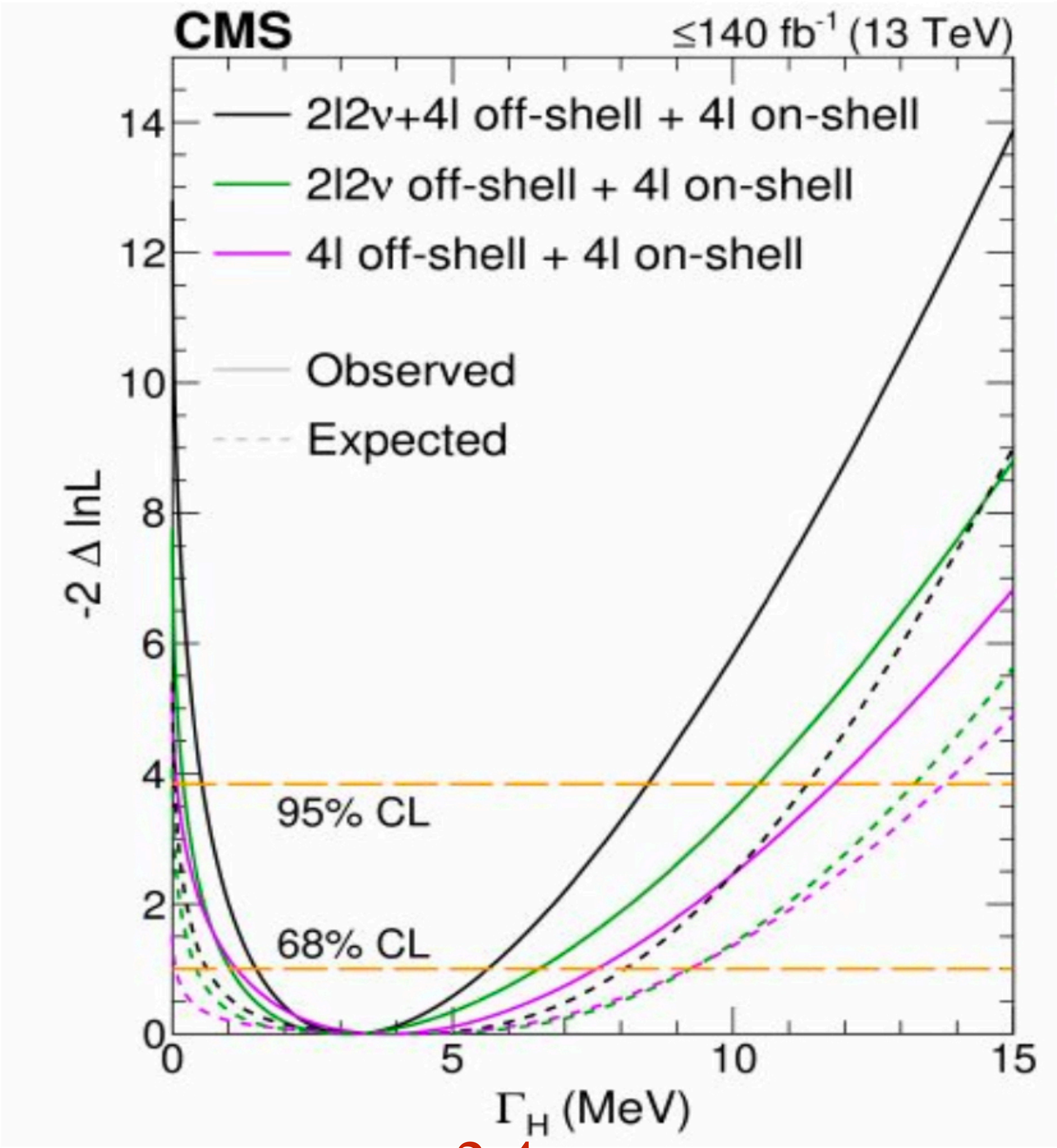


$$\Gamma_H = 4.6^{+2.6}_{-2.5} \text{ MeV at } 68\,\%\, CL$$

Nat. Phys. 18 (2022) 1329



$$\Gamma_H = 3.2^{+2.4}_{-1.7} \text{ MeV at } 68\,\%\, CL$$

The next steps in HEP build on

- having important questions to pursue
- creating opportunities to answer them
- being able to constantly add to our knowledge, while seeking those answers

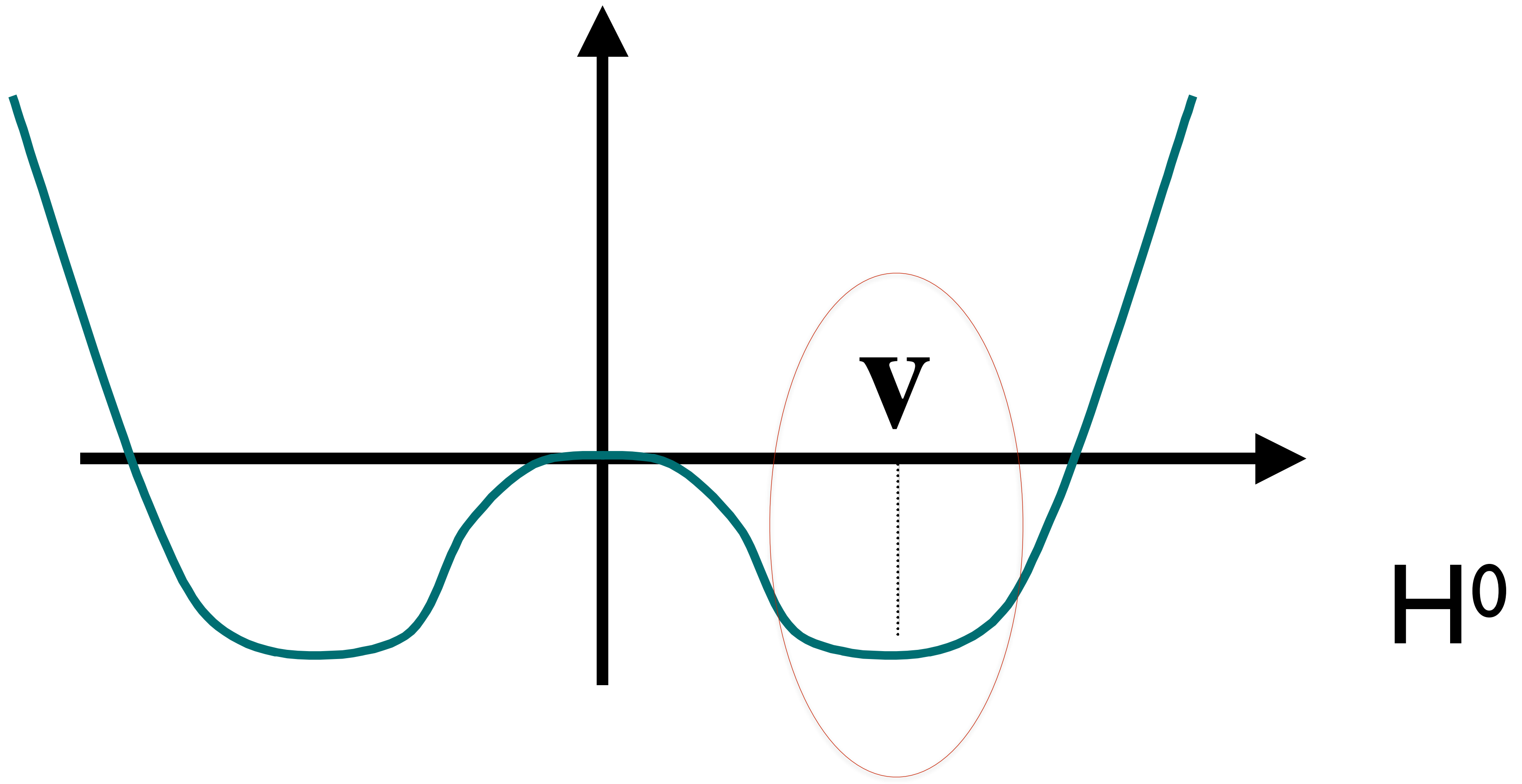
beyond the Higgs:
the important questions

- **Data driven:**
  - DM
  - Neutrino masses
  - Matter vs antimatter asymmetry
  - Dark energy
  - …
- **Theory driven:**
  - The hierarchy problem and naturalness
  - The flavour problem (origin of fermion families, mass/mixing pattern)
  - Origin of inflation
  - …
  - Quantum gravity

The opportunities

- For none of these questions, the path to an answer is unambiguously defined.
- *Two examples:*
  - **DM:** could be anything from fuzzy 10^{-22} eV scalars, to O(TeV) WIMPs, to multi-$M_{\odot}$ primordial BHs, passing through axions and sub-GeV DM
    - *a vast array of expts* is needed, even though most of them will end up empty-handed…
  - **Neutrino masses:** could originate anywhere between the EW and the GUT scale
    - we are still in the process of acquiring basic knowledge about the neutrino sector: mass hierarchy, majorana nature, sterile neutrinos, CP violation, correlation with mixing in the charged-lepton sector ($\mu \to e\gamma$, $H \to \mu\tau$, …): as for DM, *a broad range of options* to explore, to find the right clues
- We cannot objectively establish a hierarchy of relevance among the fundamental questions. The hierarchy evolves with time (think of GUTs and proton decay searches!) and is likely subjective. It is also likely that several of the big questions are tied together and will find their answer in a common context (eg DM and hierarchy problem, flavour and nu masses, quantum gravity/inflation/dark energy, …)

But there is one central question to the progress of HEP, which can only be addressed by colliders



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

Where does this come from?

The SM Higgs mechanism (*á la Weinberg*) provides the *minimal* set of *ingredients* required to enable a consistent breaking of the EW symmetry.

Where these *ingredients* come from, what possible additional infrastructure comes with them, whether their presence is due to purely anthropic or more fundamental reasons, we don't know, the SM doesn't tell us ...

a historical example: superconductivity

- The relation between the Higgs phenomenon and the SM is similar to the relation between superconductivity and the Landau-Ginzburg theory of phase transitions: a quartic potential for a bosonic order parameter, with negative quadratic term, and the ensuing symmetry breaking. If superconductivity had been discovered after Landau-Ginzburg, we would be in a similar situations as we are in today: an experimentally proven phenomenological model. But we would still lack a deep understanding of the relevant dynamics.

- For superconductivity, this came later, with the identification of e^-e^- Cooper pairs as the underlying order parameter, and BCS theory. In particle physics, we still don't know whether the Higgs is built out of some sort of Cooper pairs (composite Higgs) or whether it is elementary, and in both cases we have no clue as to what is the dynamics that generates the Higgs potential. With Cooper pairs it turned out to be just EM and phonon interactions. With the Higgs, none of the SM interactions can do this, and **we must look beyond.**

examples of possible scenarios

- **BCS-like**: the Higgs is a composite object
- **Supersymmetry**: the Higgs is a fundamental field and
  - $\lambda^2 \sim g^2+g'^2$, it is not arbitrary (MSSM, w/out susy breaking, has one parameter less than SM!)
  - potential is fixed by susy & gauge symmetry
  - EW symmetry breaking (and thus m_H and λ) determined by the parameters of SUSY breaking
- …

Other important open issues on the Higgs sector

- Is the Higgs the only (fundamental?) scalar field, or **are there other Higgs-like states** (e.g. $H^{\pm}$, A^0, $H^{\pm\pm}$, ... , EW-singlets, ...) ?
  - Do all SM families get their mass from the **same** Higgs field?
  - Do $I_3=1/2$ fermions (up-type quarks) get their mass from the **same** Higgs field as $I_3=-1/2$ fermions (down-type quarks and charged leptons)?
  - Do **Higgs couplings conserve flavour?** $H\to\mu\tau$? $H\to e\tau$? $t\to Hc$?
- Is there a deep reason for the apparent metastability of the Higgs vacuum?
- Is there a relation among Higgs/EWSB, baryogenesis, Dark Matter, inflation?
- What happens at the EW phase transition (PT) during the Big Bang?
  - what's the order of the phase transition?
  - are the conditions realized to allow EW baryogenesis?

➡ the Higgs discovery does not close the book, it opens a whole new chapter of exploration, based on precise measurements of its properties, *which can only rely on the LHC and on a future generation of colliders*

The LHC experiments have been exploring a vast multitude of scenarios of physics beyond the Standard Model

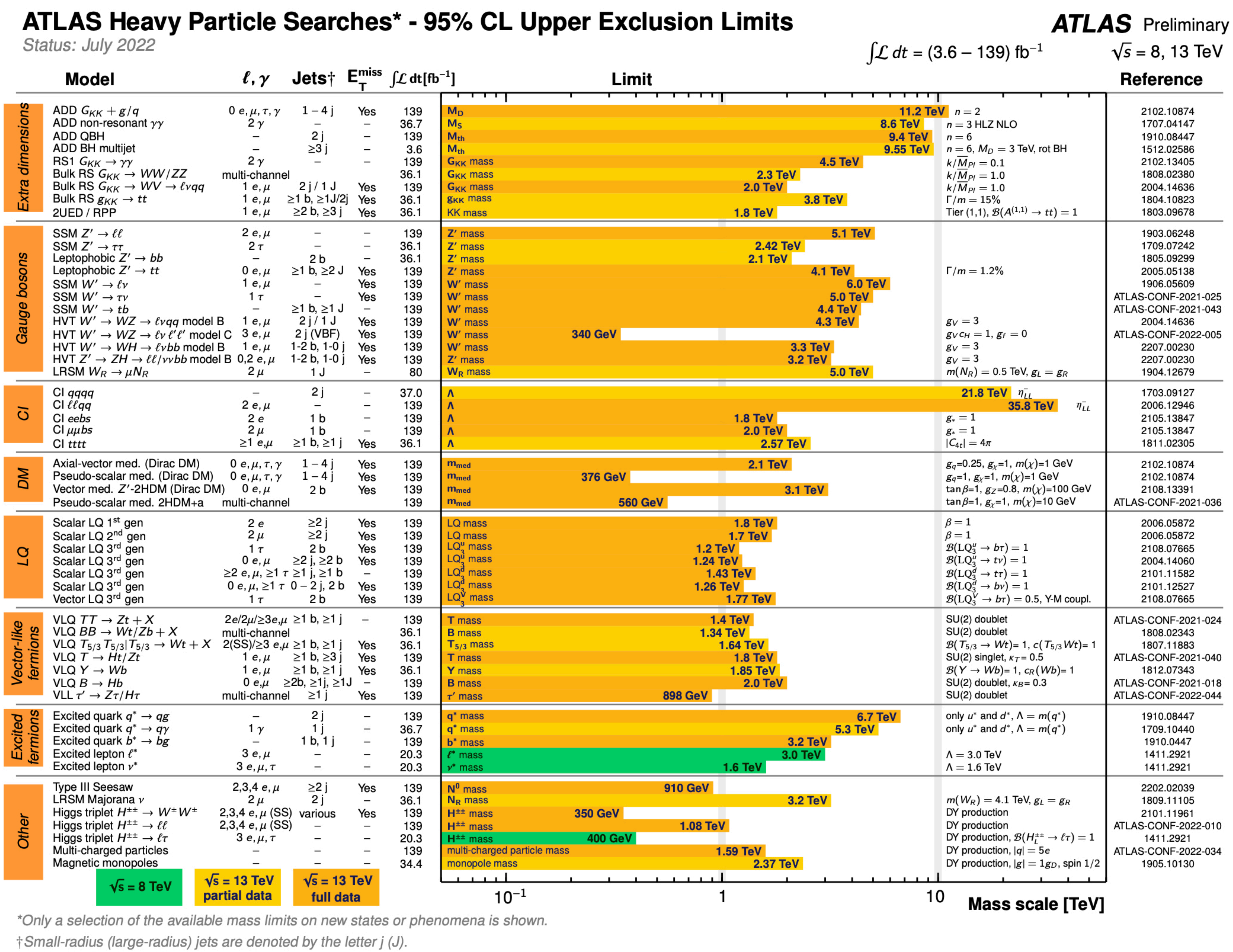
In search of the origin of known departures from the SM

- **Dark matter, long lived particles**
- **Neutrino masses**
- **Matter/antimatter asymmetry of the universe**

To explore alternative extensions of the SM

- **New gauge interactions (Z', W') or extra Higgs bosons**
- **Additional fermionic partners of quarks and leptons, leptoquarks, …**
- **Composite nature of quarks and leptons**
- **Supersymmetry, in a variety of twists (minimal, constrained, natural, RPV, …)**
- **Extra dimensions**
- **New flavour phenomena**
- **unanticipated surprises …**

So far, no *conclusive* signal of physics beyond the SM



The value of diversity in collider physics

LHC scientific production

Over 3000 papers published/submitted to refereed journals by the 7 experiments that operated in Run 1 and 2 (ALICE, ATLAS, CMS, LHCb, LHCf, TOTEM, MoEDAL)… and the first papers are appearing by the new experiments started in Run 3 (FASER, SND@LHC)

Of these:

~10% on Higgs (15% if ATLAS+CMS only)

~30% on searches for new physics (35% if ATLAS+CMS only)

~60% of the papers on SM measurements (jets, EW, top, b, HIs, …)

Not only Higgs and exotic searches !

Flavour physics

- $B_{(s)} \to \mu\mu$
- D mixing and CP violation in the D system
- Measurement of the γ angle, CPV phase ϕ_s, …
- Lepton flavour universality in charge- and neutral-current semileptonic B decays => possible anomalies ?

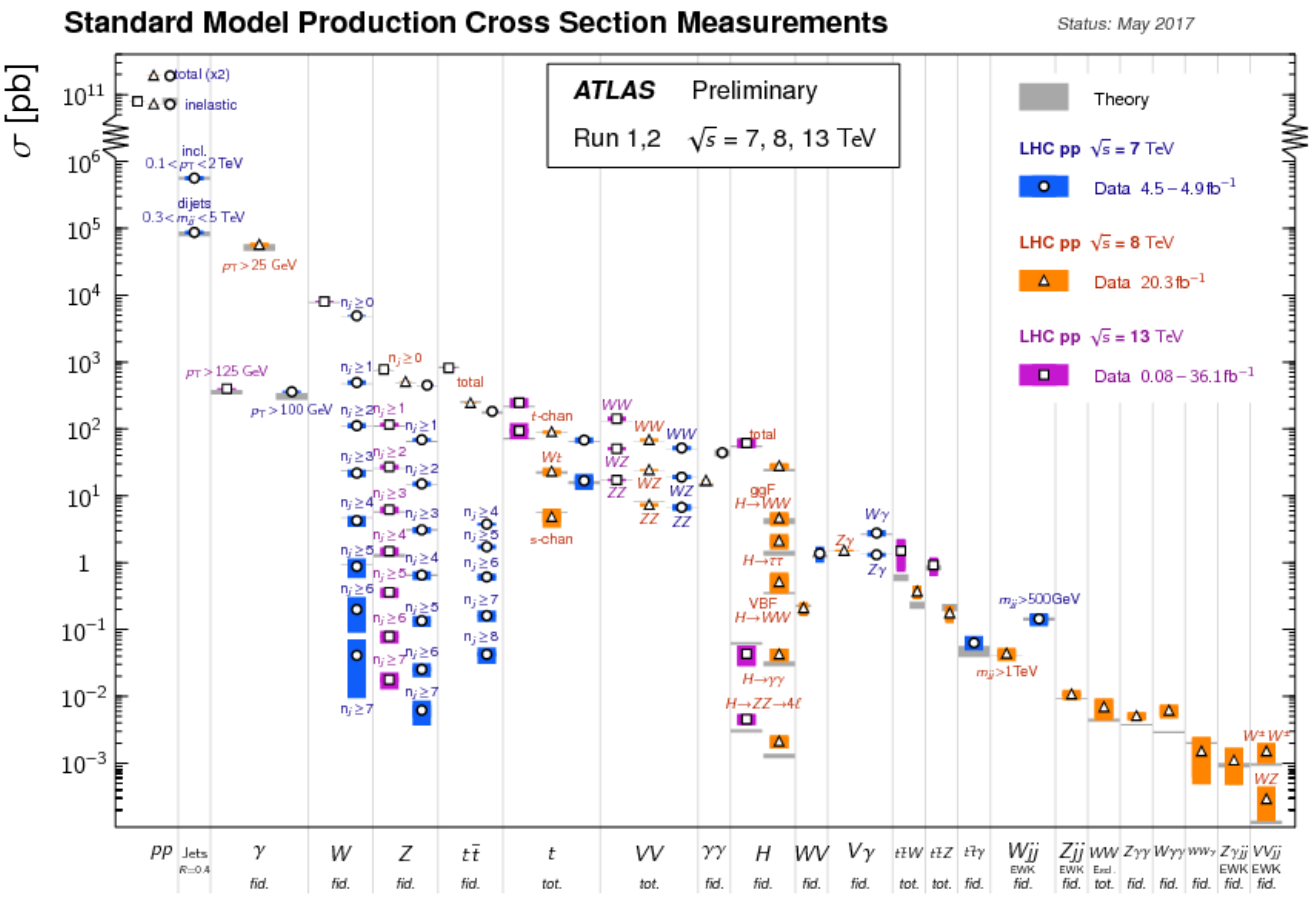
QCD dynamics

- Countless precise measurements of hard cross sections, and improved determinations of the proton PDF
- Measurement of total, elastic, inelastic pp cross sections at different energies, new inputs for the understanding of the dominant reactions in pp collisions
- Exotic spectroscopy: discovery and study of new tetra- and penta-quarks, doubly heavy baryons, expected sensitivity to glueballs
- Discovery of QGP-like collective phenomena (long-range correlations, strange and charm enhancement, …) in "small" systems (pA and pp)

EW param's and dynamics

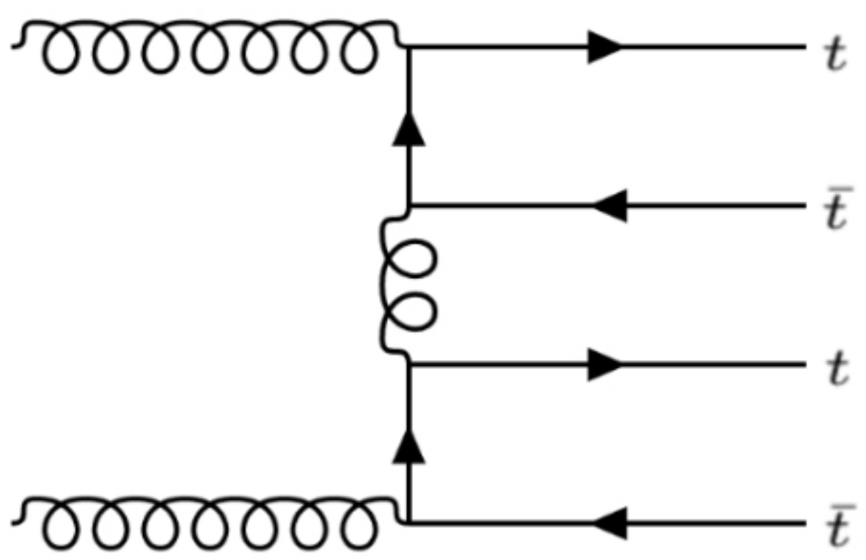
- m_W, m_{top} 171.77 ± 0.37 GeV, (CMS https://arxiv.org/pdf/2302.01967.pdf) $\sin^2\theta_W$
- EW interactions at the TeV scale (DY, VV, VVV, VBS, VBF, Higgs, …)

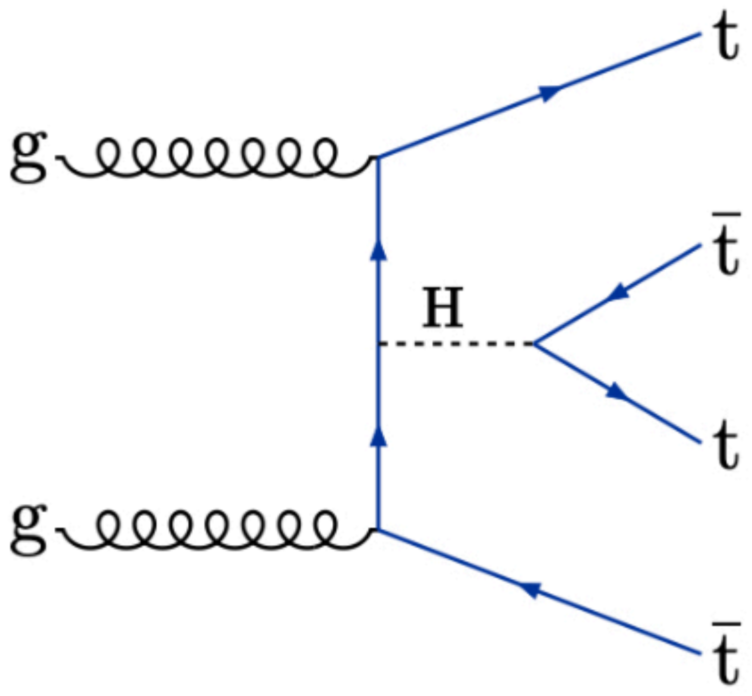
QCD production dynamics

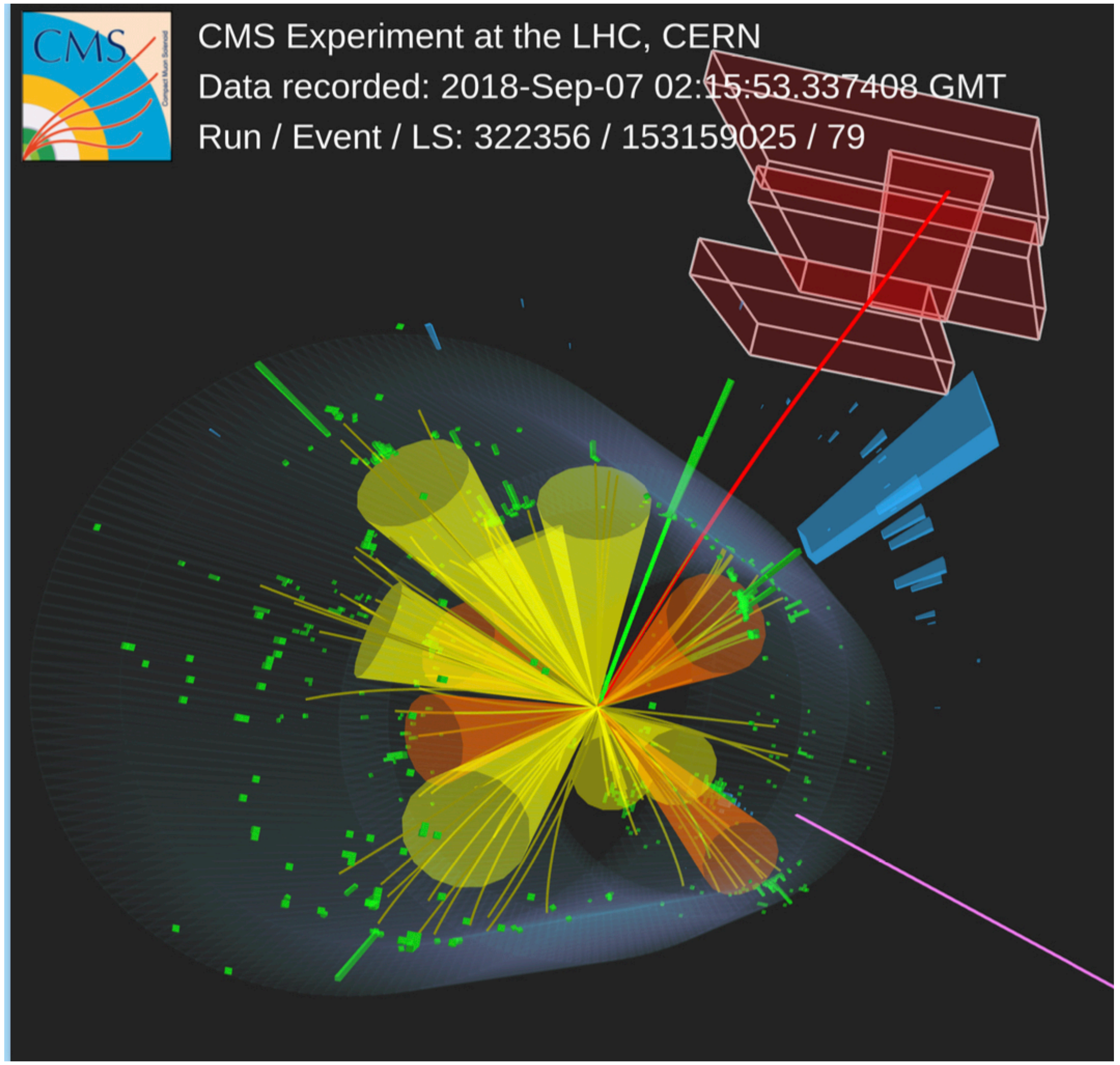


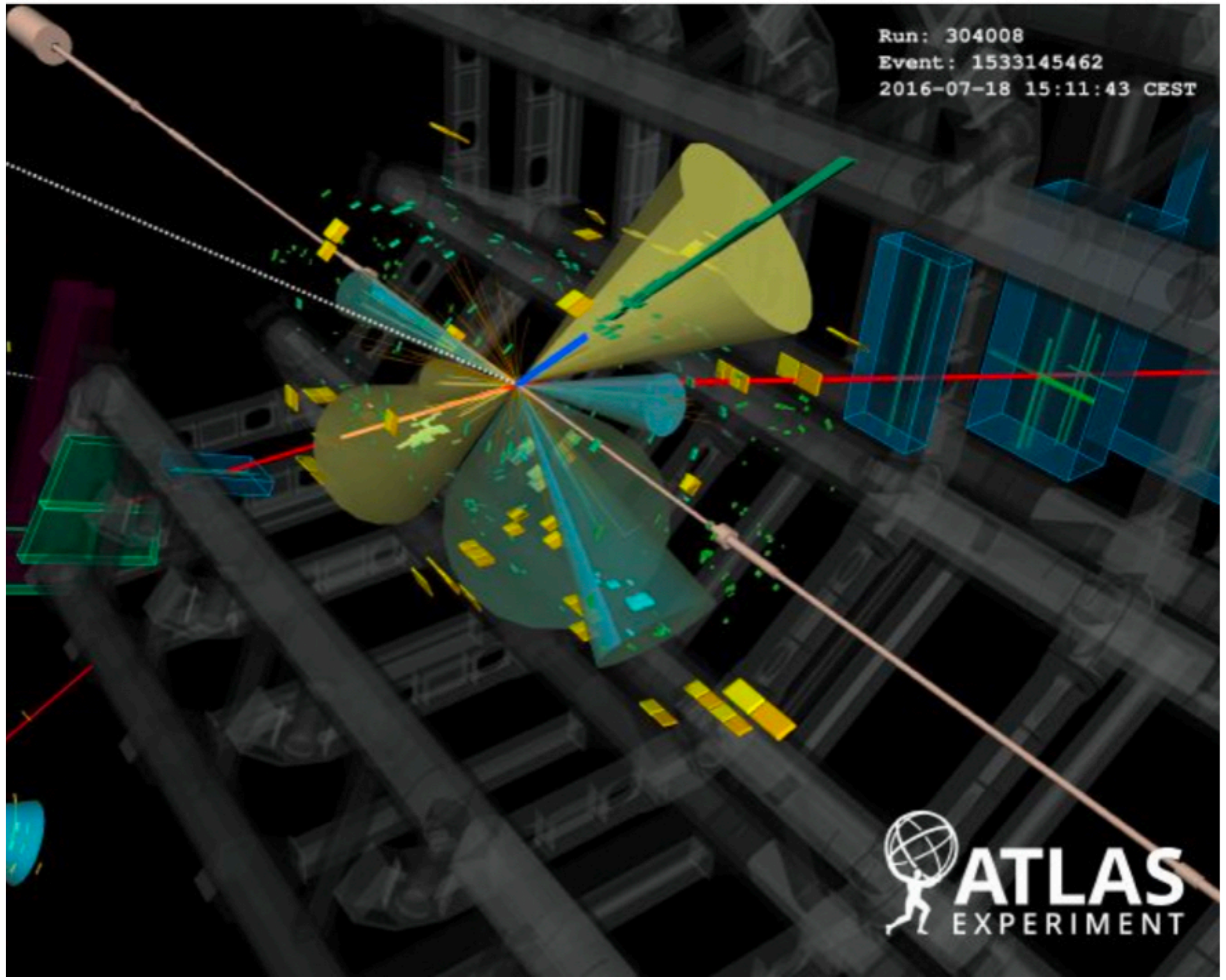
Excellent agreement between data and theoretical predictions, over 10 orders of magnitude, culminating 30 years of progress in higher-order perturbative calculations, which have now reached next-to-leading order as routine, NNLO as benchmark for most processes, and NNNLO available for only some (very important!) cases, but rapidly expanding beyond

4 top production



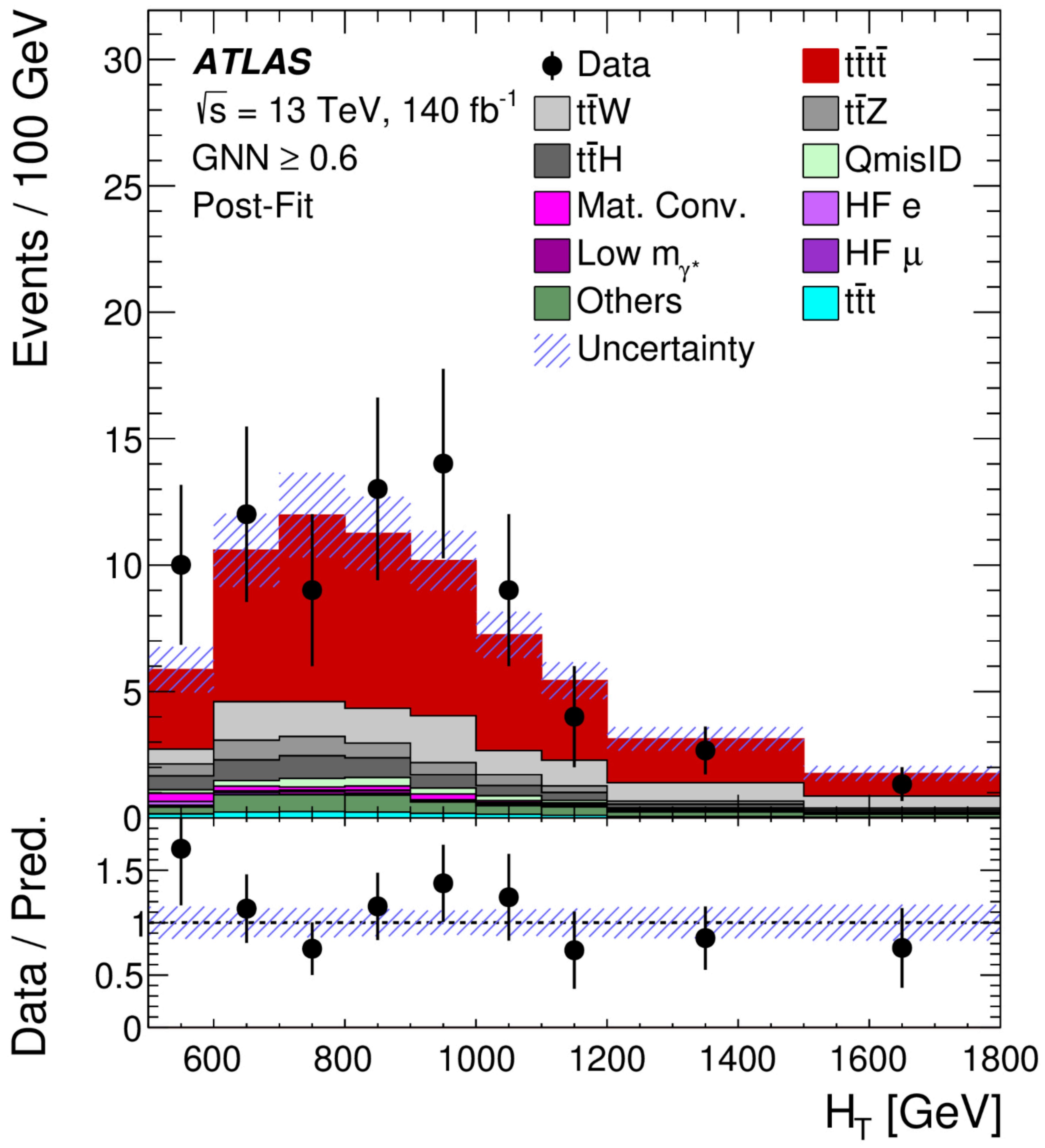


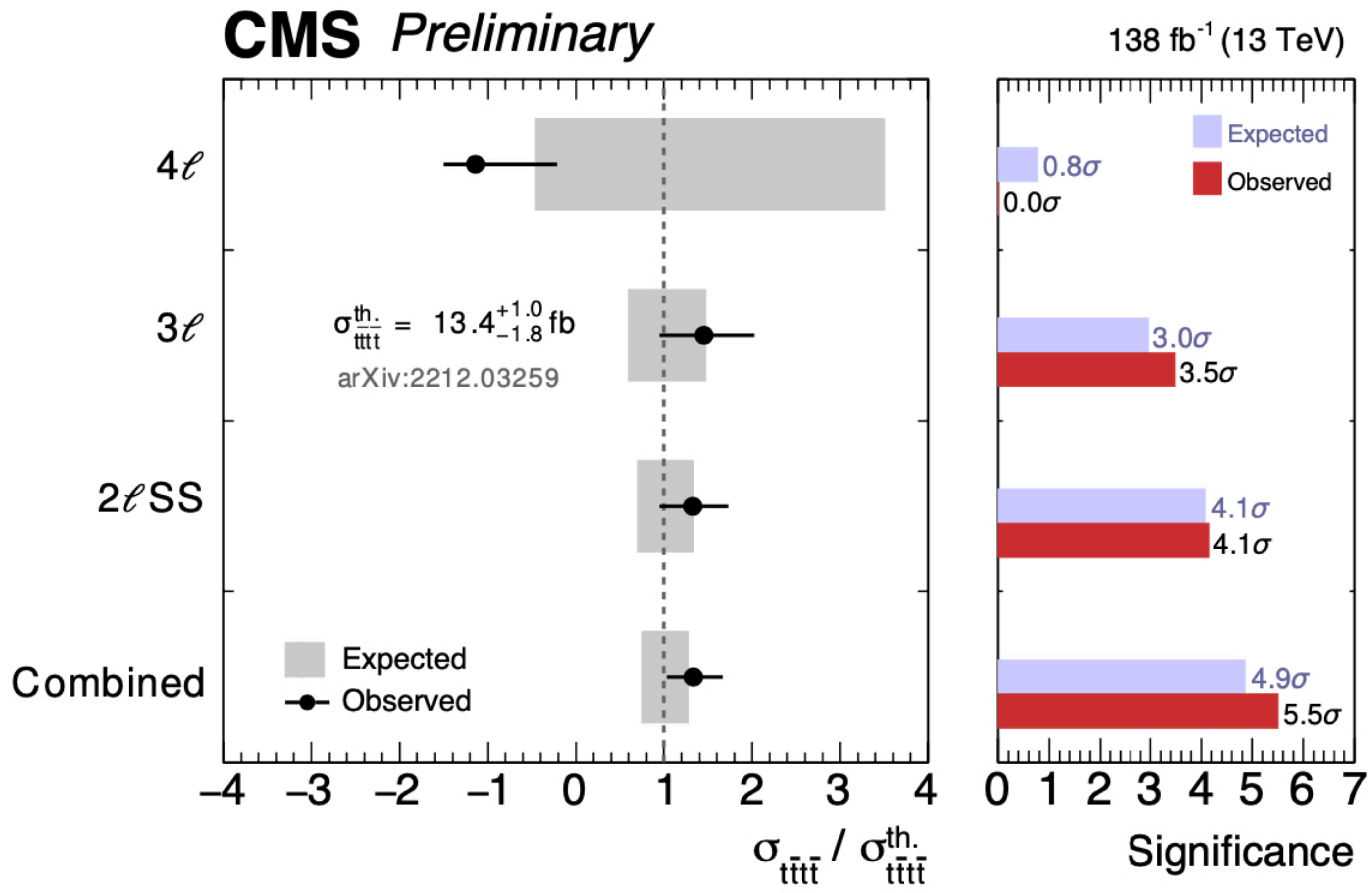




https://arxiv.org/abs/2303.15061

https://cds.cern.ch/record/2853304

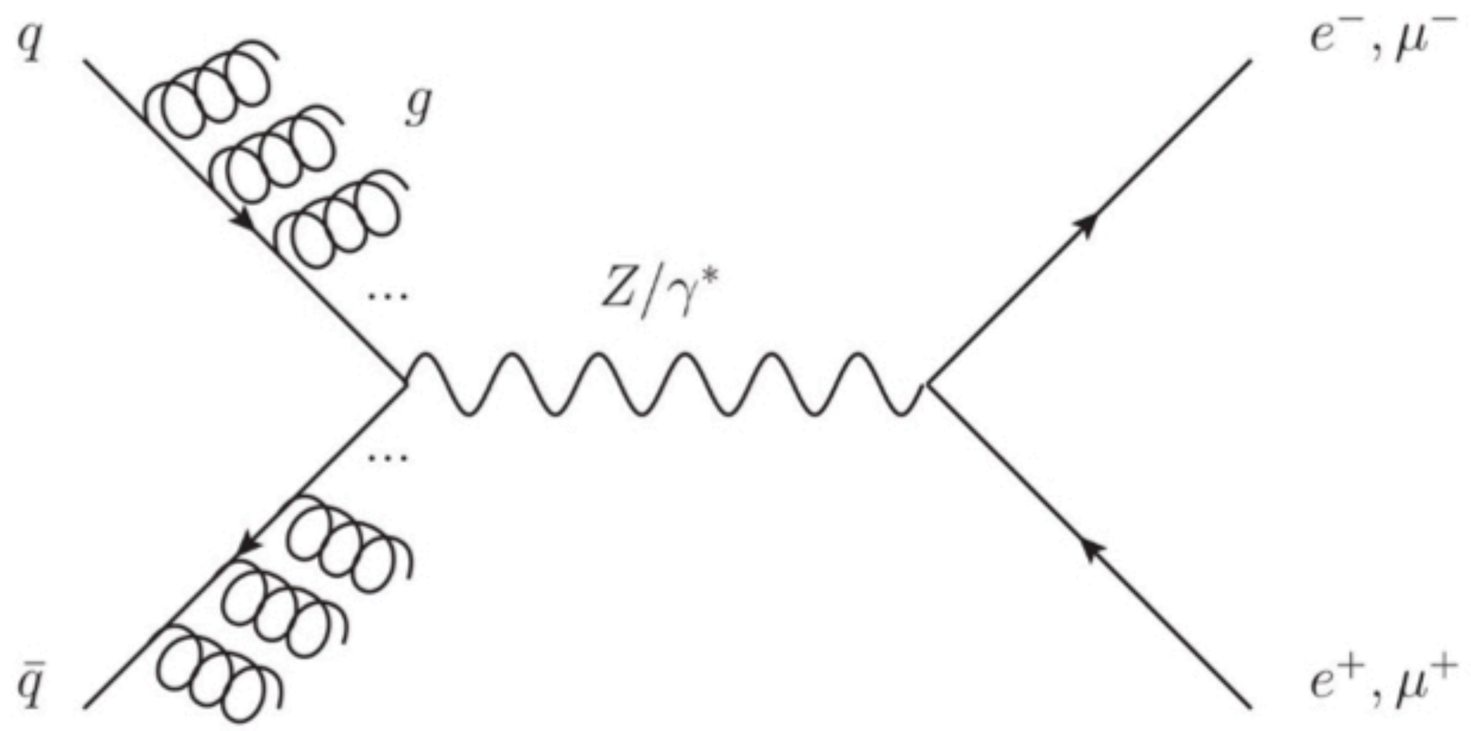


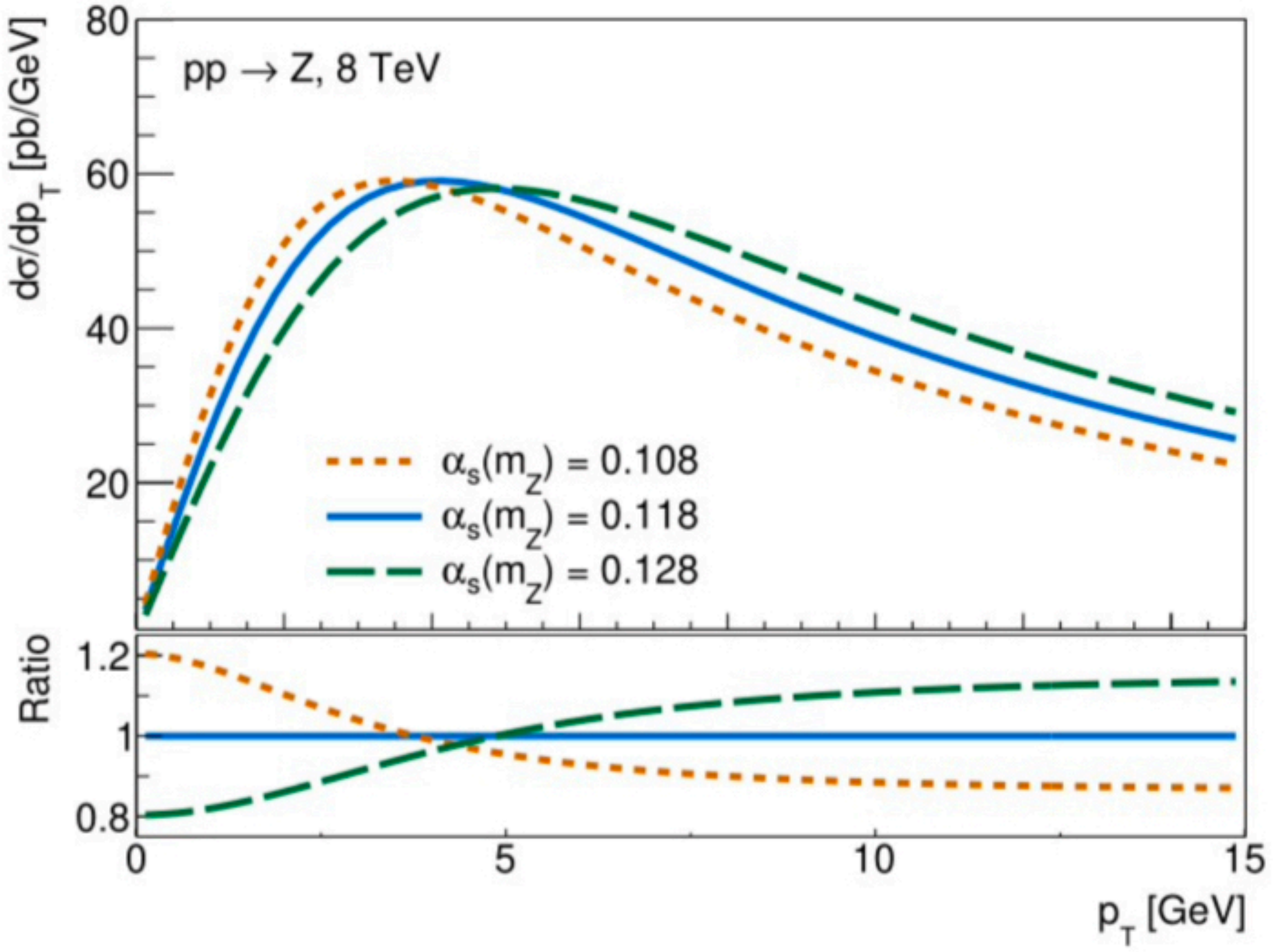


$$\sigma_{exp} = 22.5^{+6.6}_{-5.5} \text{ fb} \quad \text{vs} \quad \sigma_{SM} = 12.0 \pm 2.4 \text{ fb}$$

$$\sigma_{exp} = 17.0^{+3.7}_{-3.5}{}_{stat}{}^{+2.4}_{-2.1}{}_{syst} \text{ fb} \quad \text{vs} \quad \sigma_{SM} = 13.4^{+1.0}_{-1.8} \text{ fb}$$

α_s from Z pt spectrum





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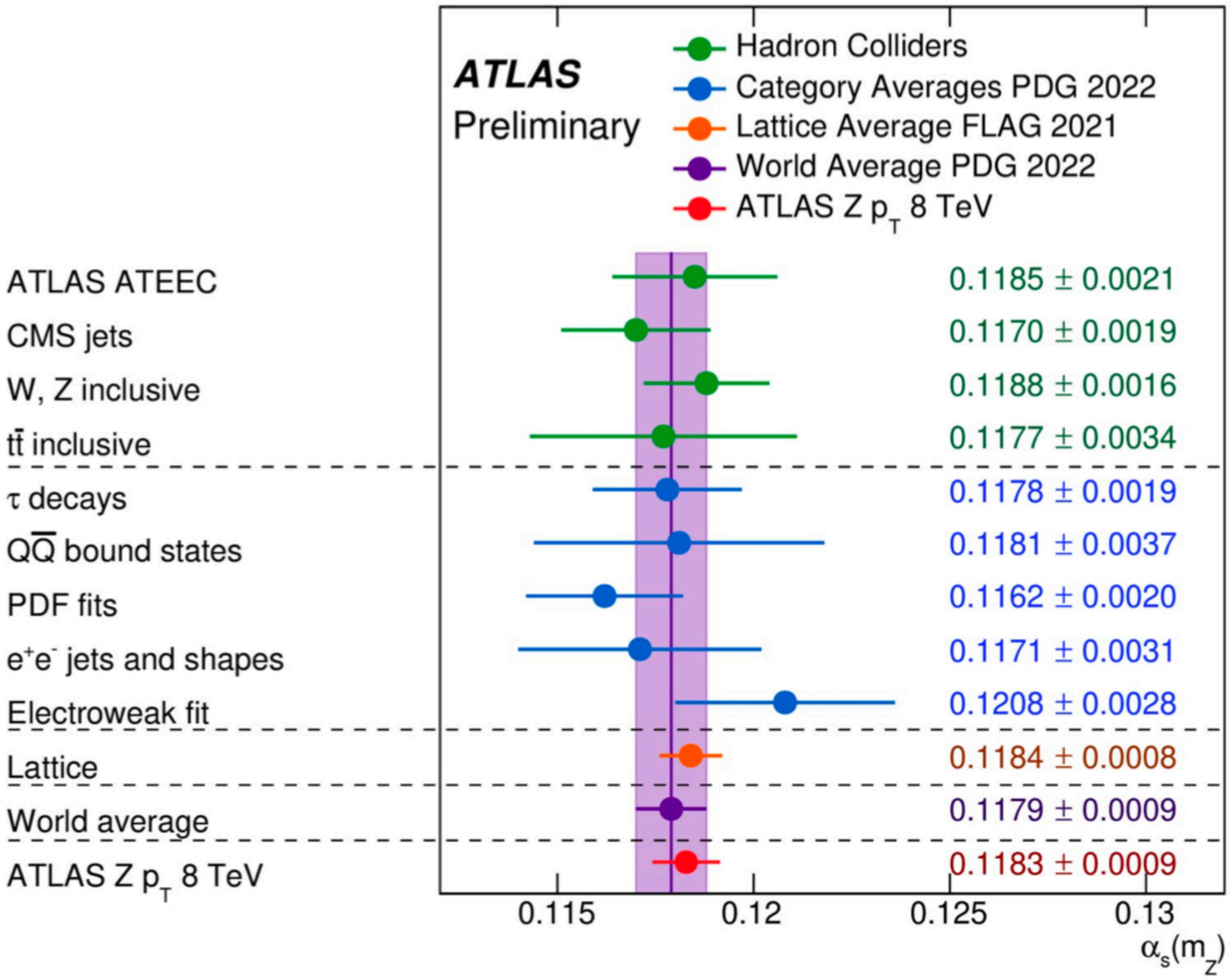
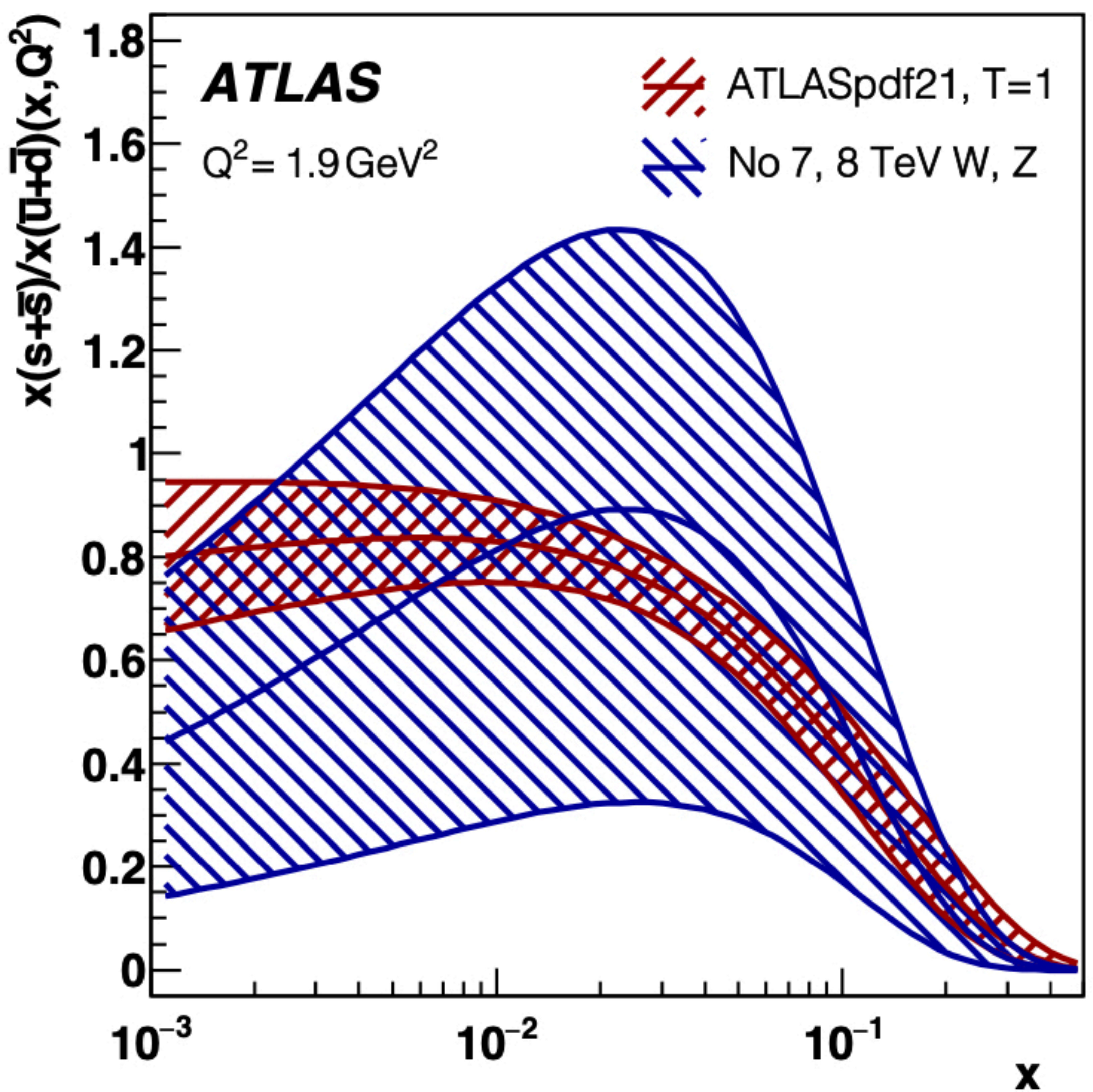


Example: PDF fits from LHC data

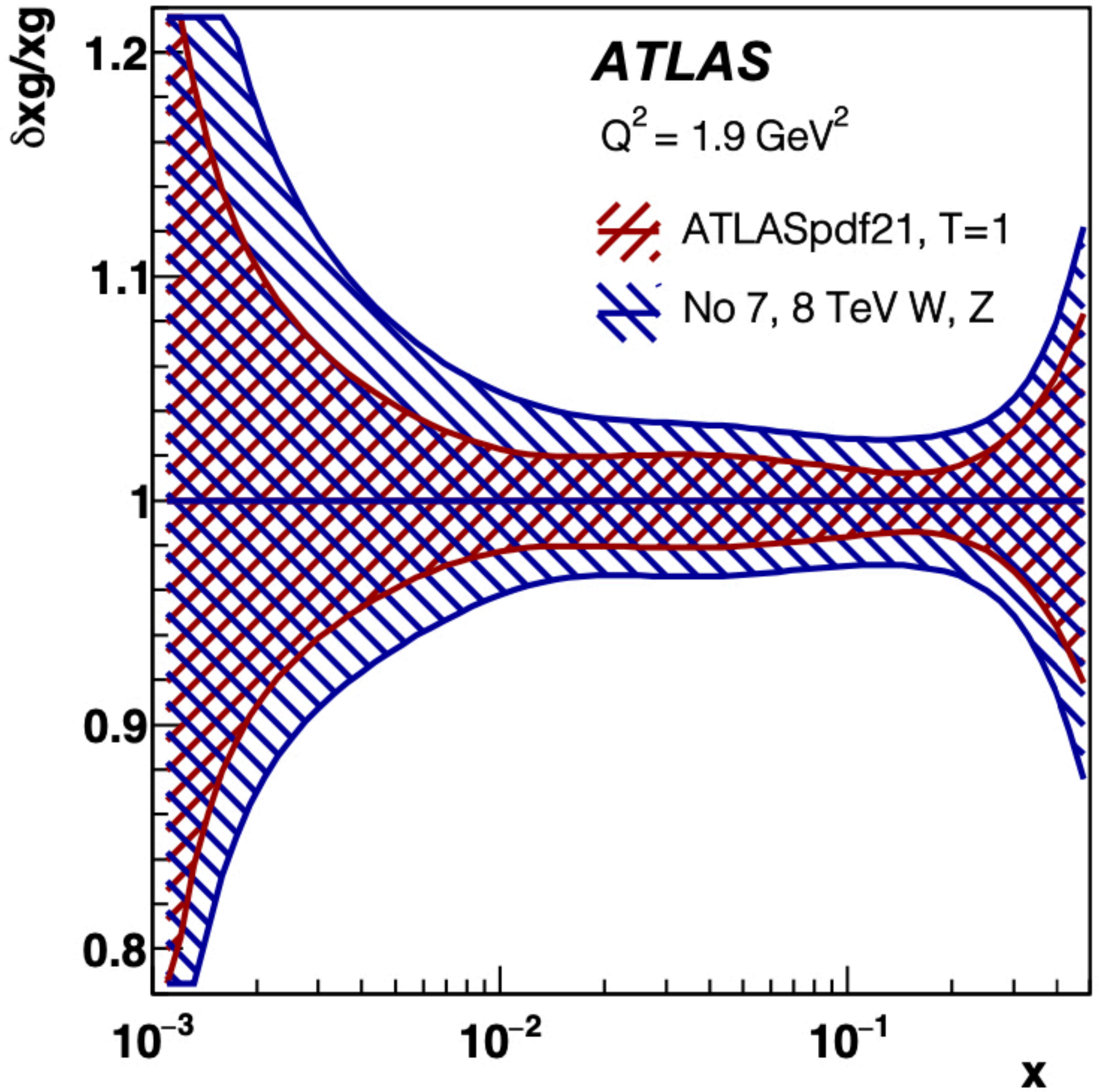
ATLASpdf21 fit, https://arxiv.org/pdf/2112.11266.pdf including HERA and ATLAS data

Data set	$\sqrt{s}$ [TeV]	Luminosity [fb^{-1}]	Decay channel	Observables entering the fit
Inclusive $W, Z/\gamma^*$ [9]	7	4.6	e, μ combined	η_ℓ (W), y_Z (Z)
Inclusive Z/γ^* [13]	8	20.2	e, μ combined	$\cos\theta^*$ in bins of $y_{\ell\ell}$, $m_{\ell\ell}$
Inclusive W [12]	8	20.2	μ	η_μ
$W^\pm$ + jets [24]	8	20.2	e	p_T^W
Z + jets [25]	8	20.2	e	$p_T^{\rm jet}$ in bins of $\|y^{\rm jet}\|$
$t\bar{t}$ [26, 27]	8	20.2	lepton + jets, dilepton	$m_{t\bar{t}}$, p_T^t, $y_{t\bar{t}}$
$t\bar{t}$ [15]	13	36	lepton + jets	$m_{t\bar{t}}$, p_T^t, y_t, $y_{t\bar{t}}^{\rm b}$
Inclusive isolated γ [14]	8, 13	20.2, 3.2	-	E_T^γ in bins of η^γ
Inclusive jets [16–18]	7, 8, 13	4.5, 20.2, 3.2	-	$p_T^{\rm jet}$ in bins of $\|y^{\rm jet}\|$

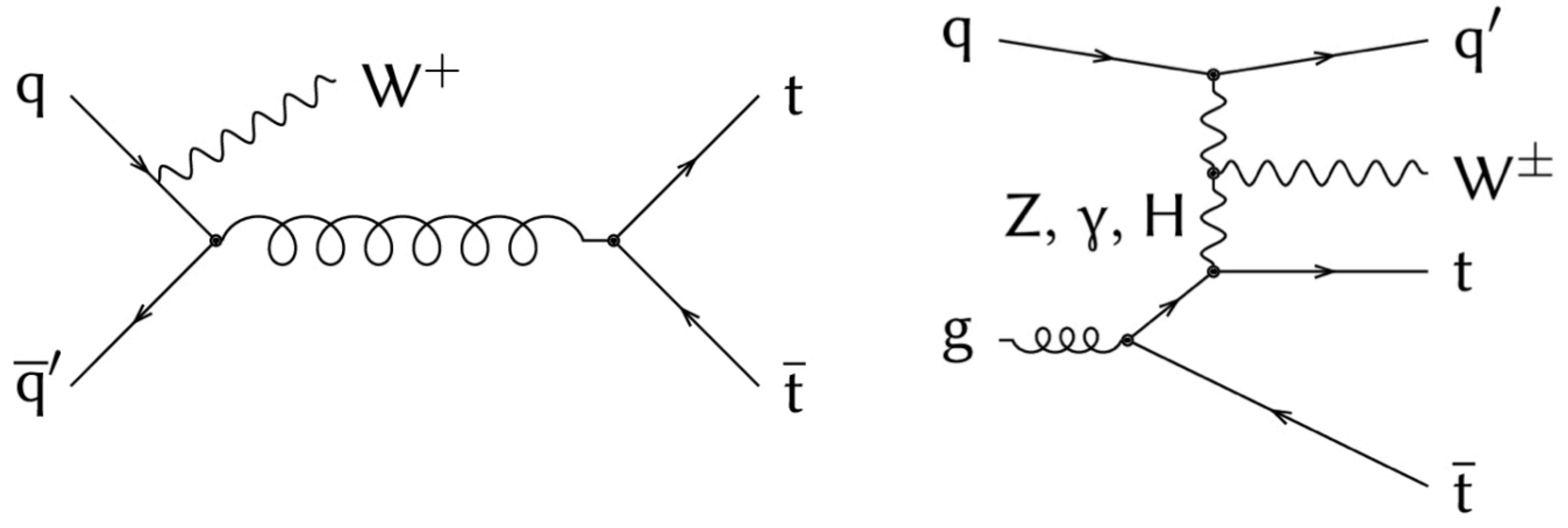
Strange quark / light antiquarks ratio

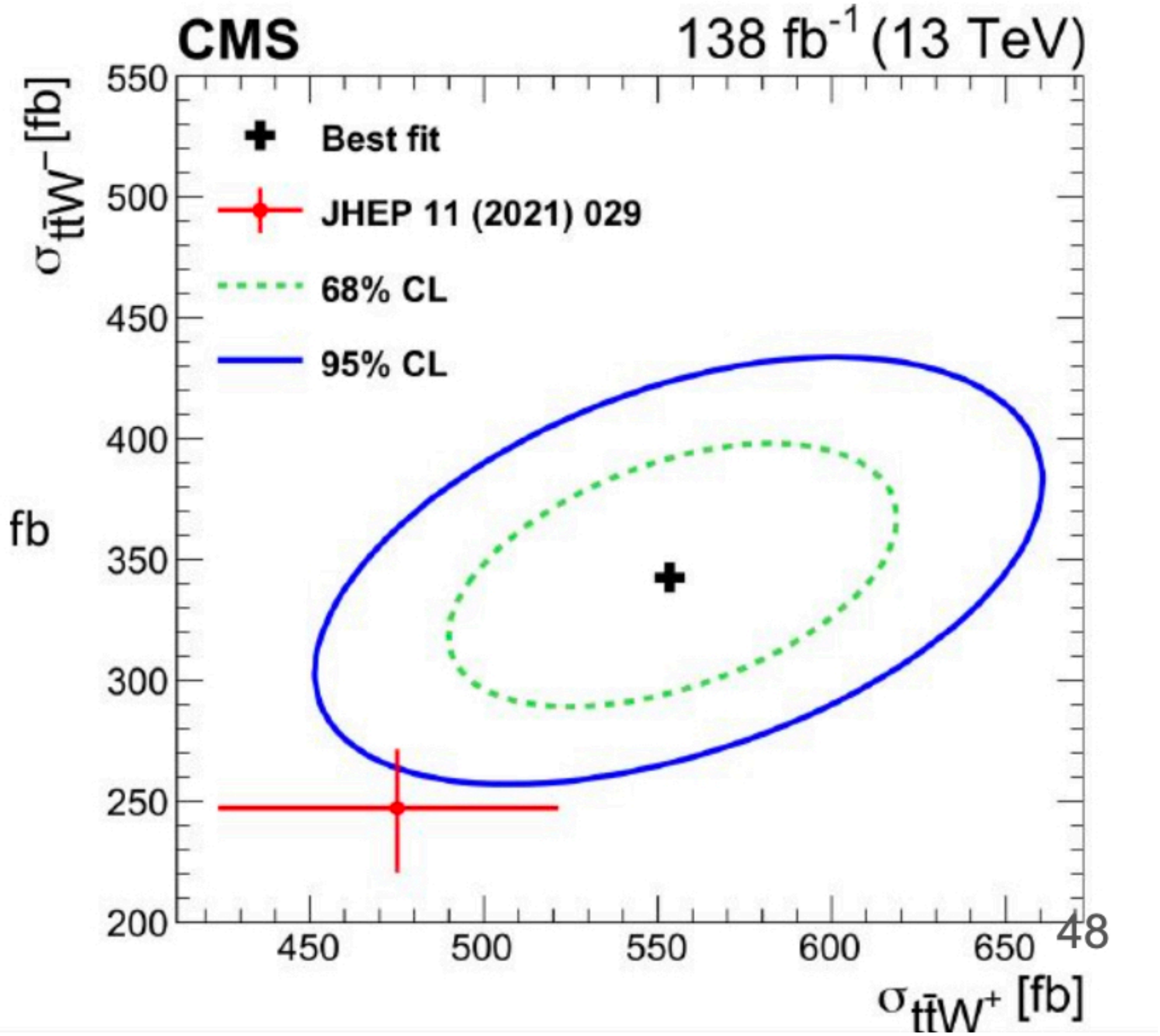


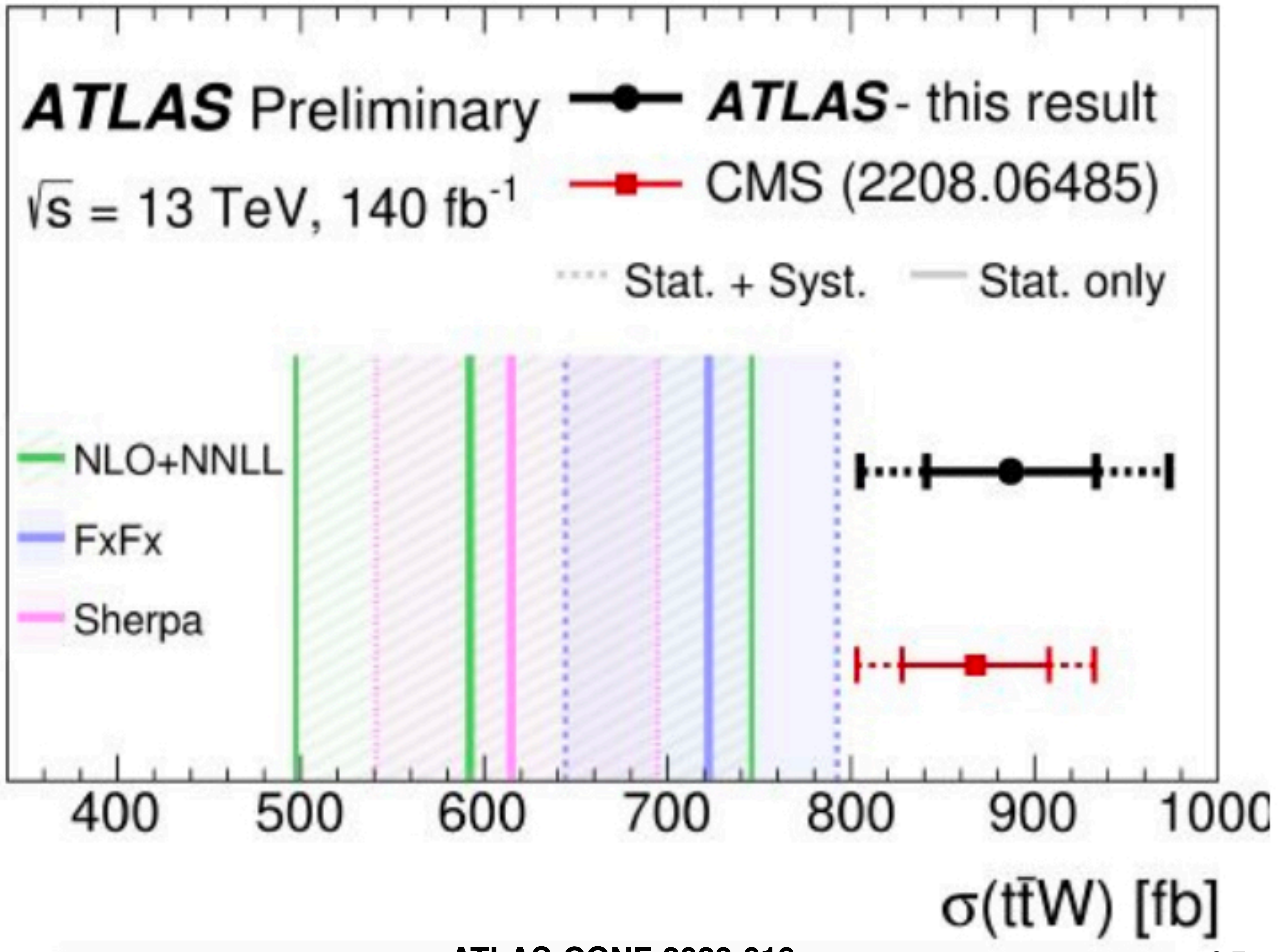
Gluon PDF



Not everything is perfect though!
Ex: ttW cross section….







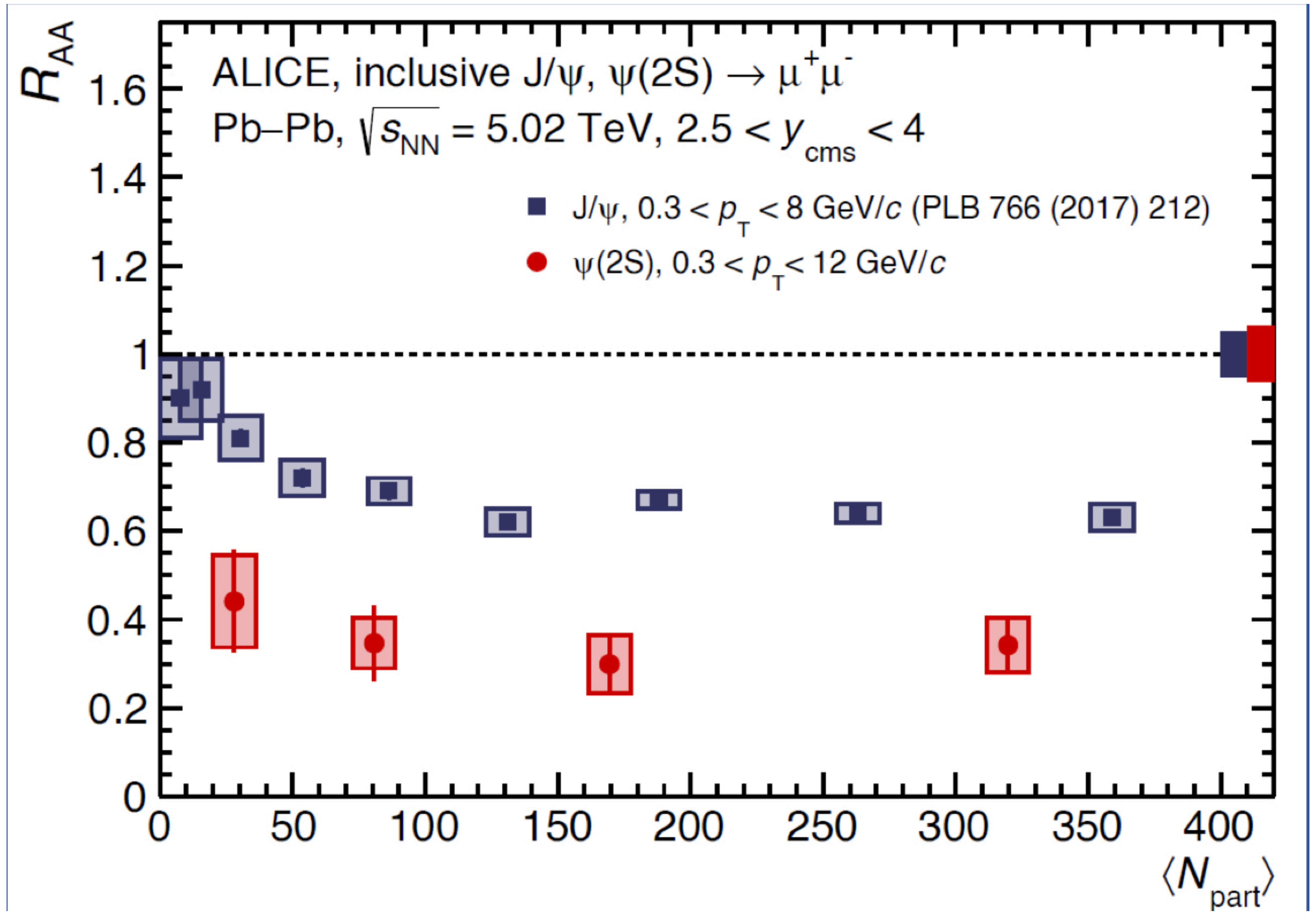
arXiv:2208.06485

ATLAS-CONF-2023-019

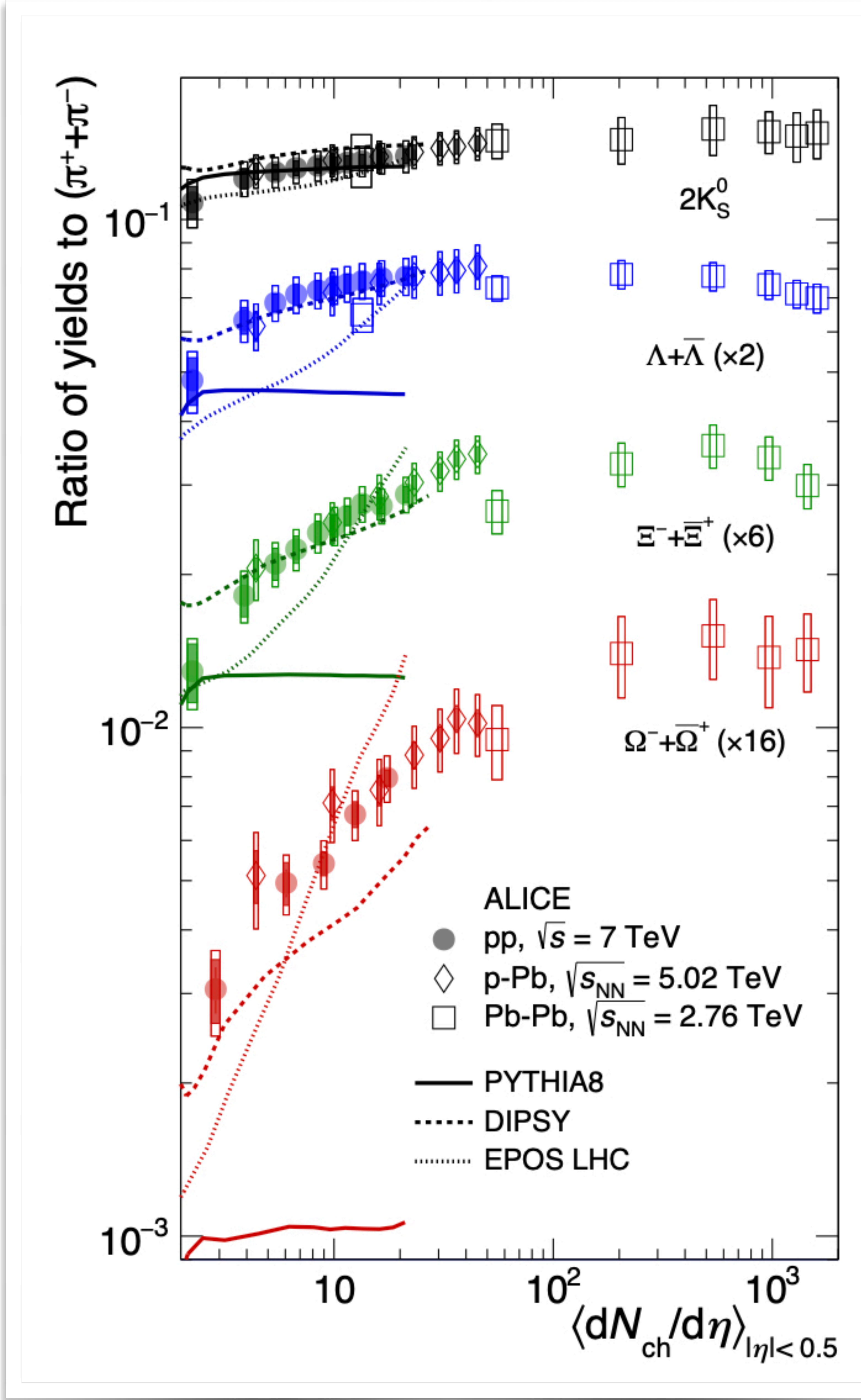
Study of QCD dynamics in previously unexplored dynamical regimes

Collective QCD phenomena in high-T, high-density and other extreme environments

consolidation of known phenomena, with higher precision and broader coverage:
(ALICE, https://inspirehep.net/literature/2165947)



discovery of new dynamical behaviour, with collective phenomena typical of QGP appearing already in high-multiplicity final states of pp and pA

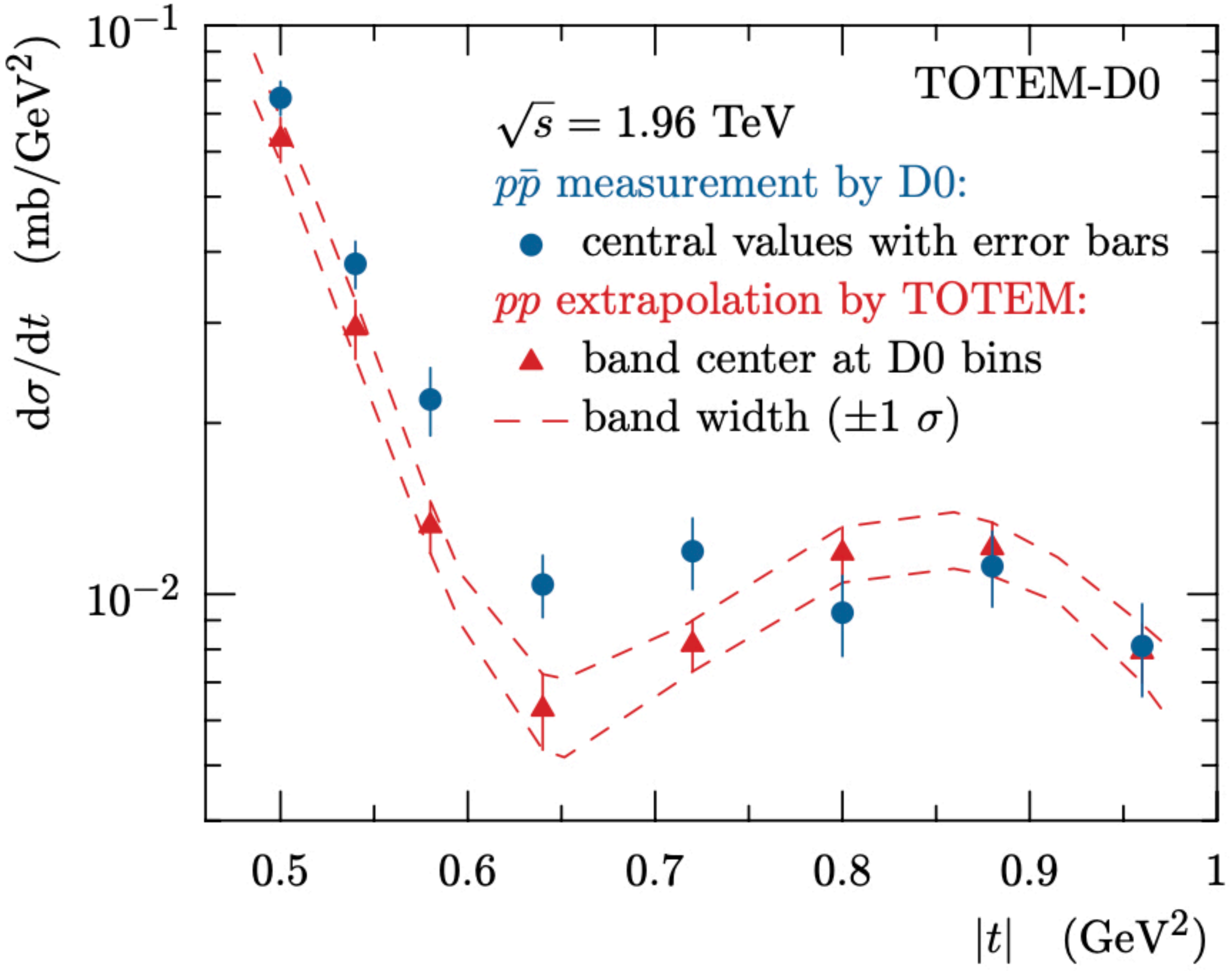


First experimental evidence for odderon exchange made possible by comparison of pp TOTEM data with ppbar D0 data

hh elastic scattering dominated by exchange of leading Regge poles:

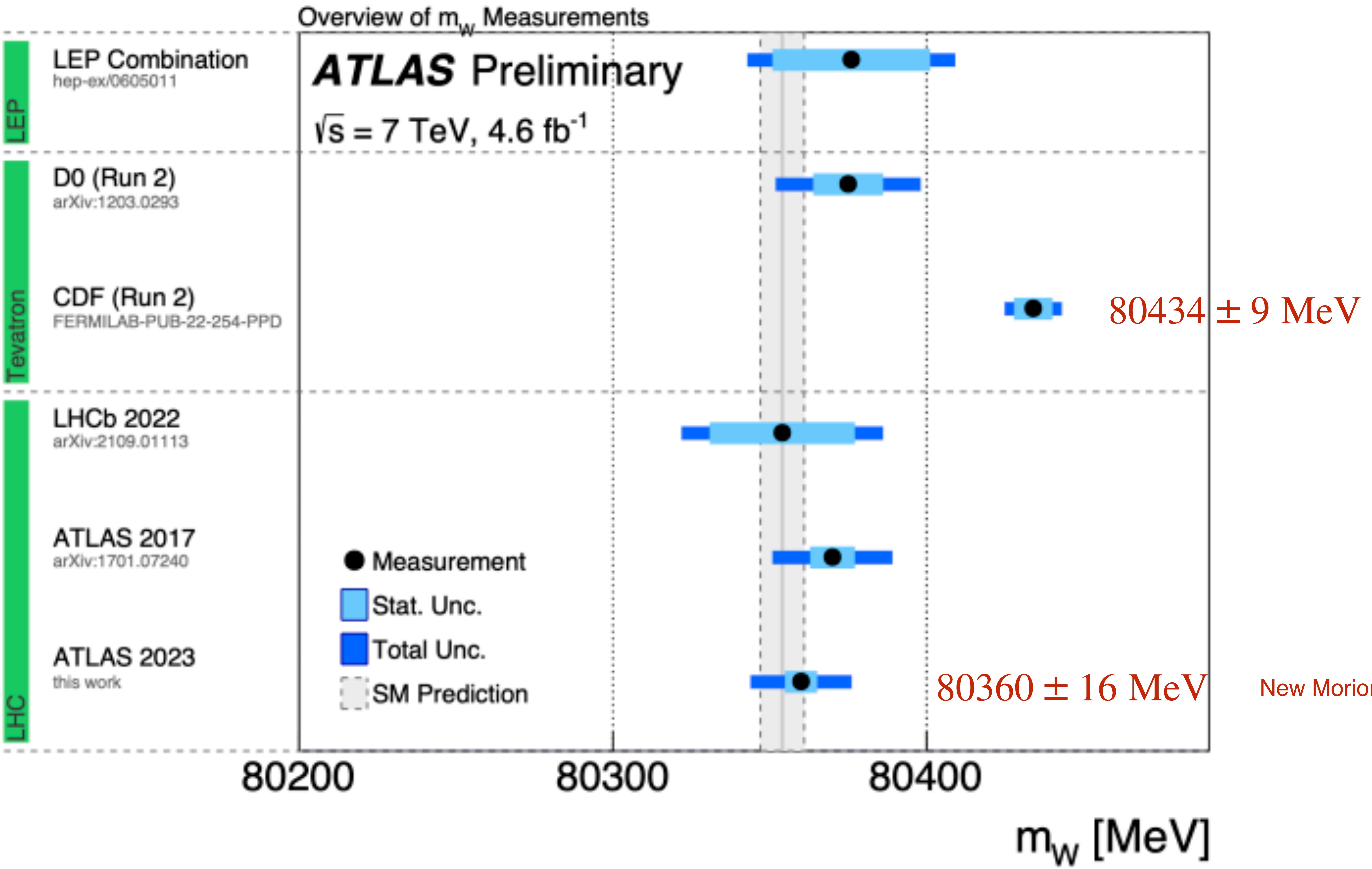
- pomeron (CP even, contributes w. same sign to pp and ppbar amplitudes)
- odderon (CP odd, contribute w. opposite signs to pp and ppbar amplitudes)

Phys.Rev.Lett. 127 (2021) 6, 062003



EW physics

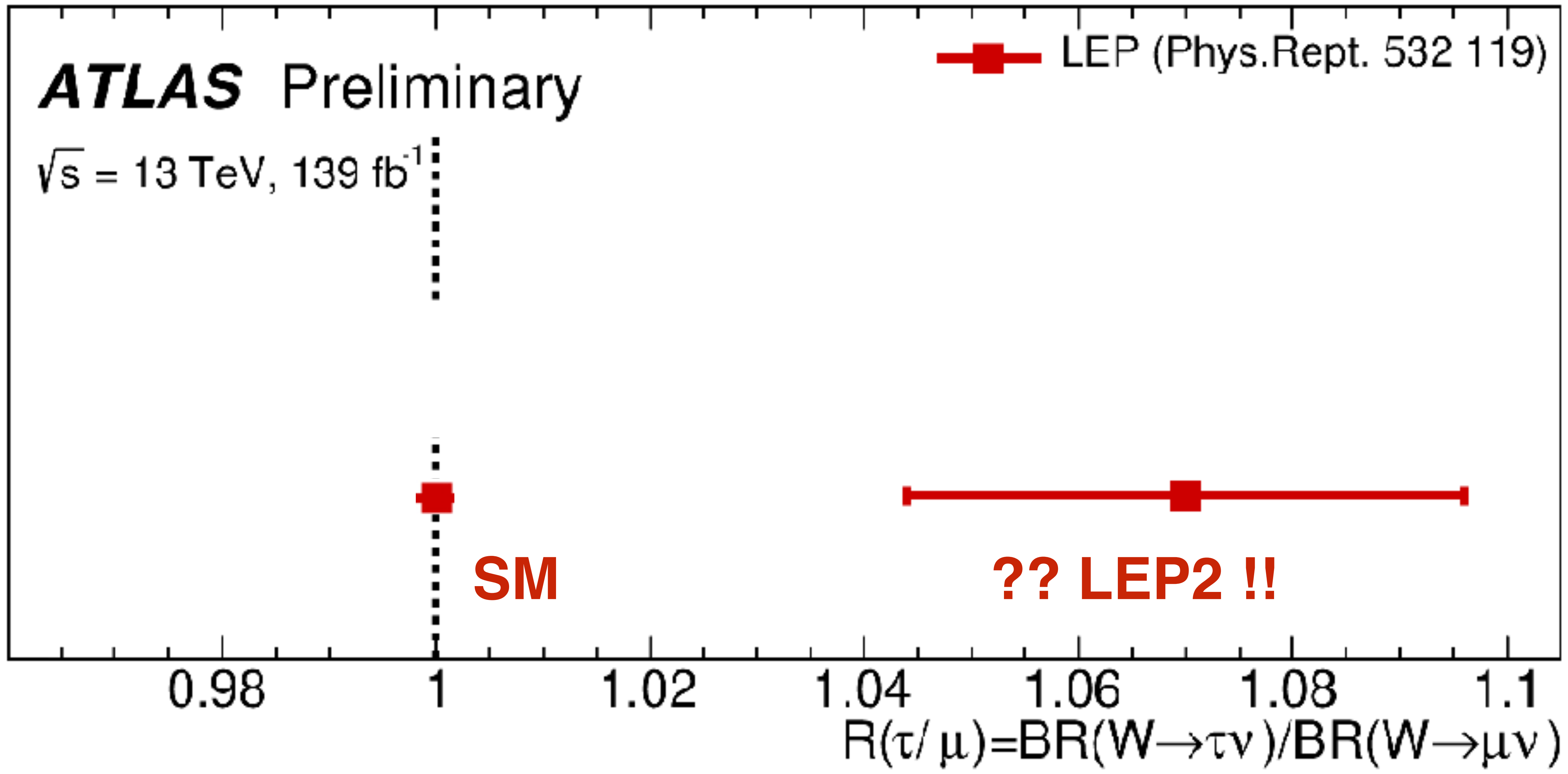
W mass



New Moriond update

Lepton universality of W couplings

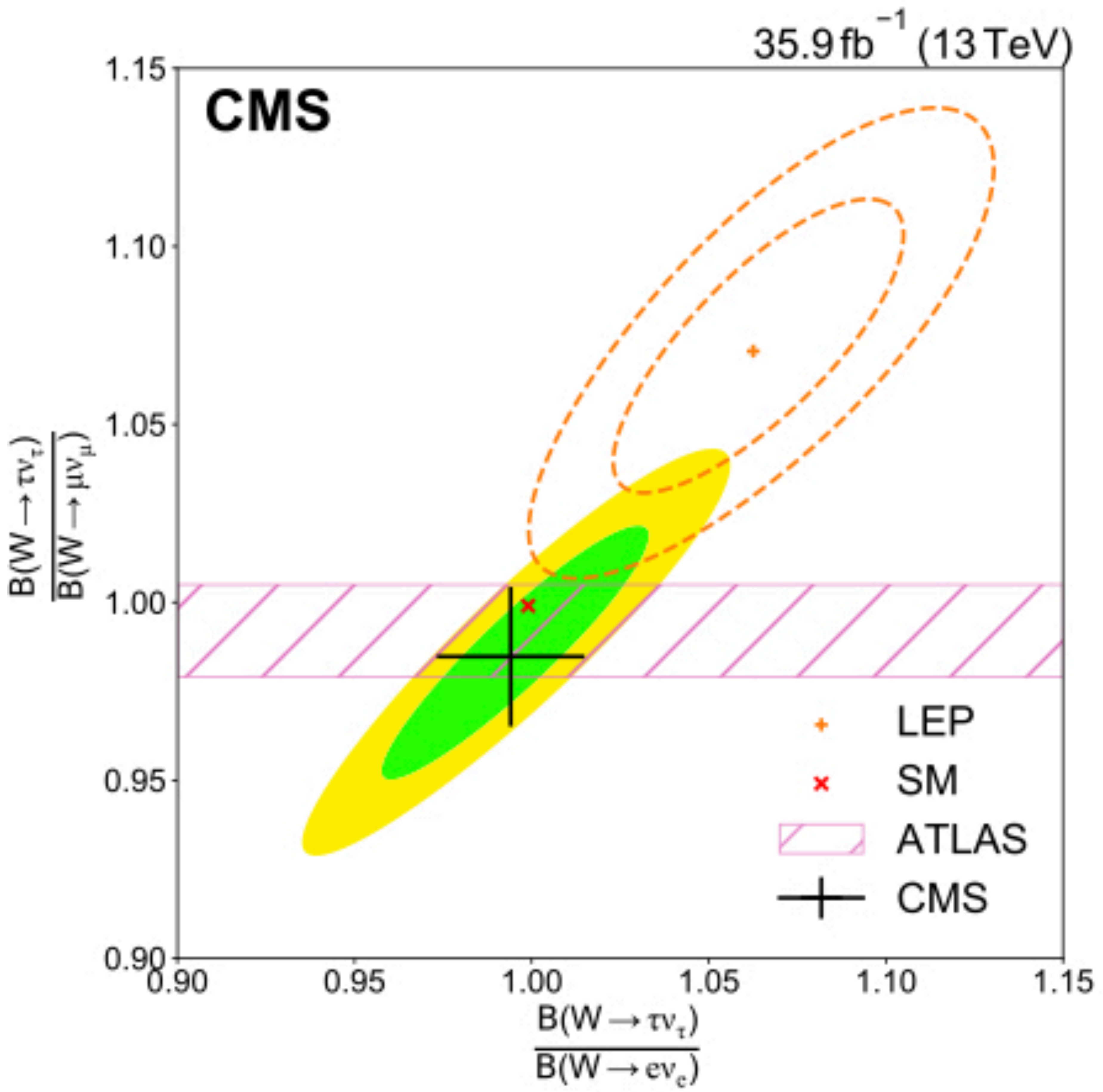
ATLAS 2020: arXiv:2007.14040

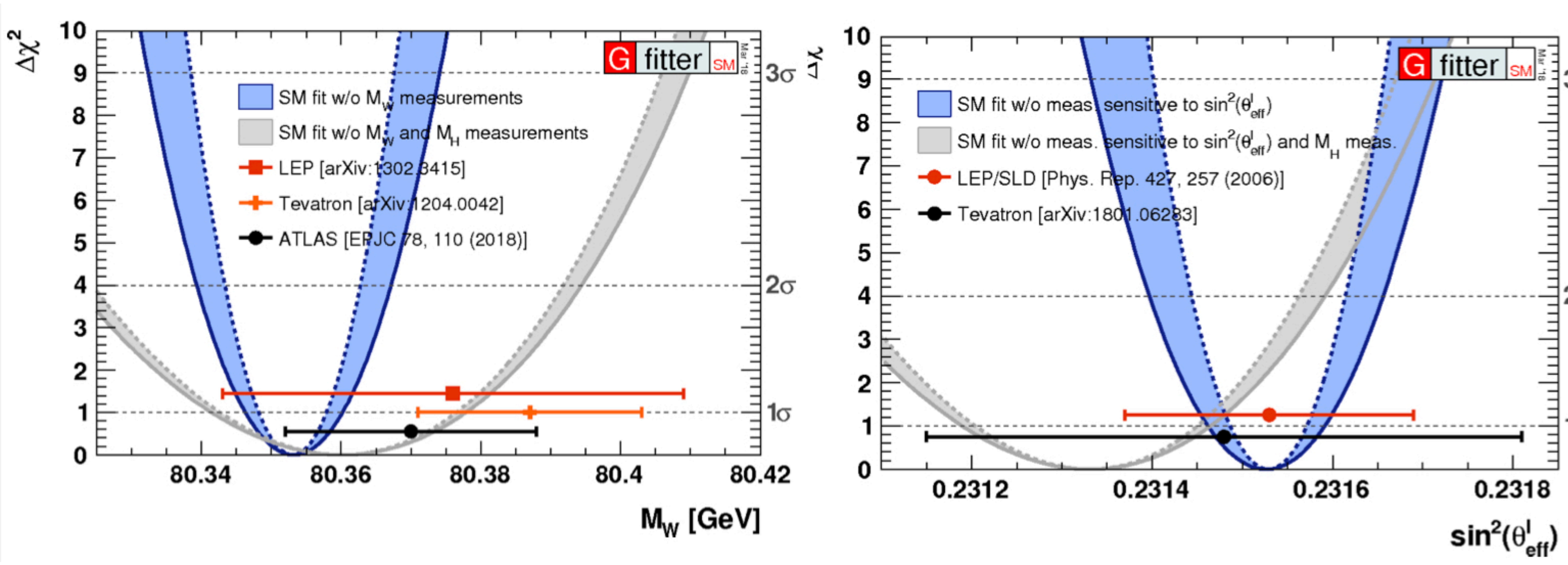


LEP:
BR(W→τν)/*BR*(W→μν) = 1.066 ± 0.025

ATLAS:
BR(W→τν)/*BR*(W→μν) = 0.992 ± 0.013

CMS 2022: arXiv:2201.07861





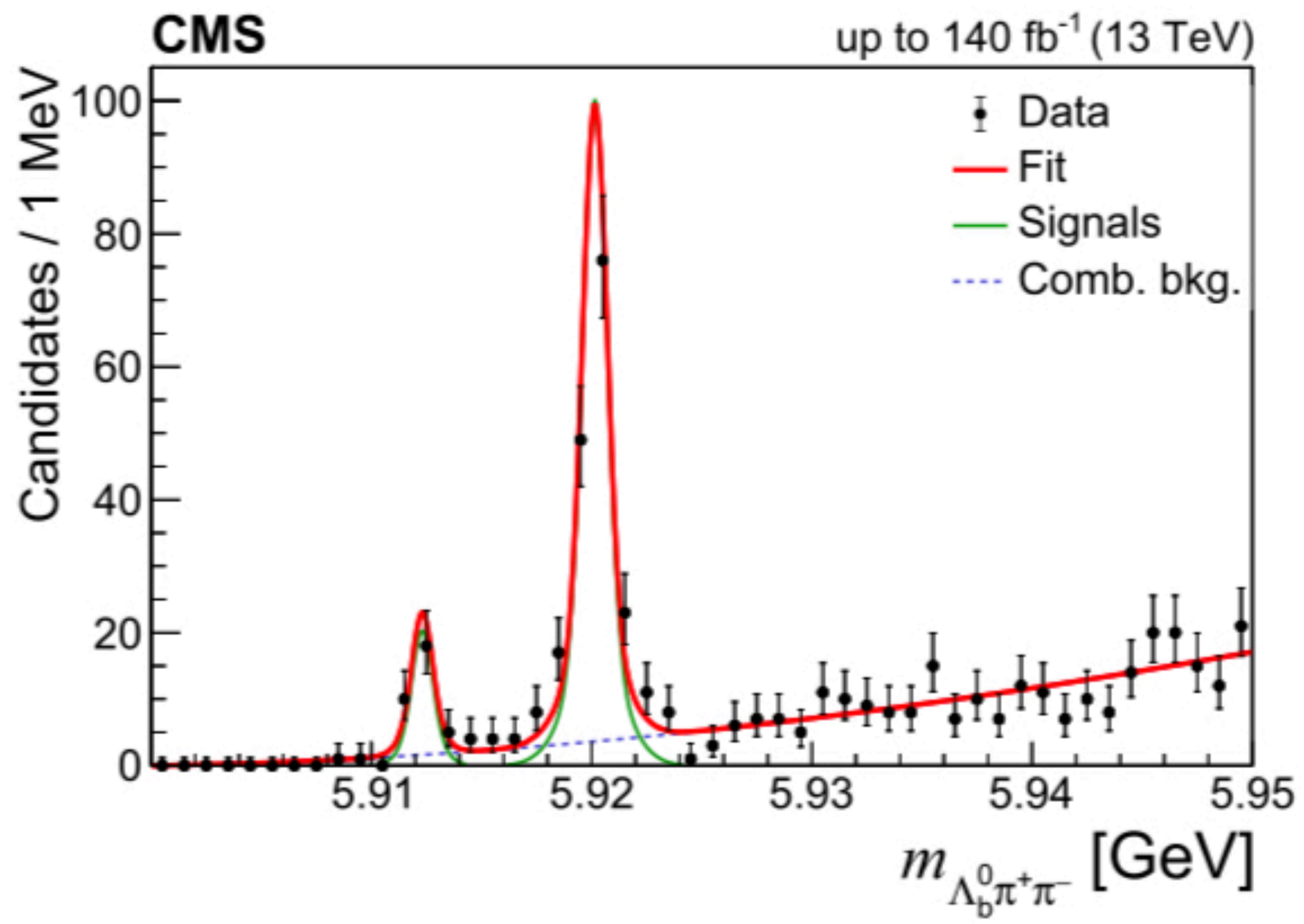
M_W and $\sin^2\theta_W$ precision must still improve to match the accurate SM prediction

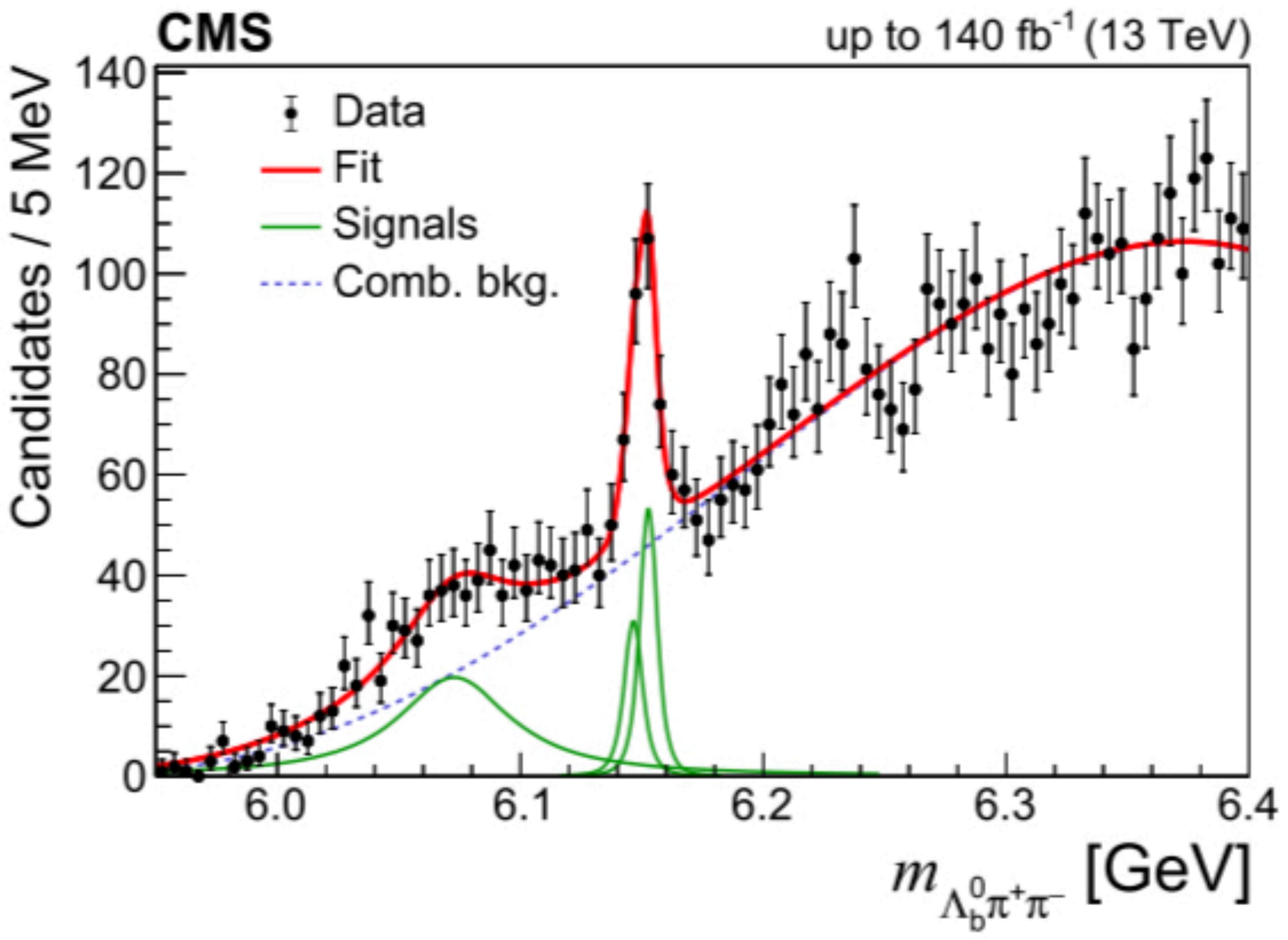
PS: note the big impact in the SM precision due to the knowledge of M_H

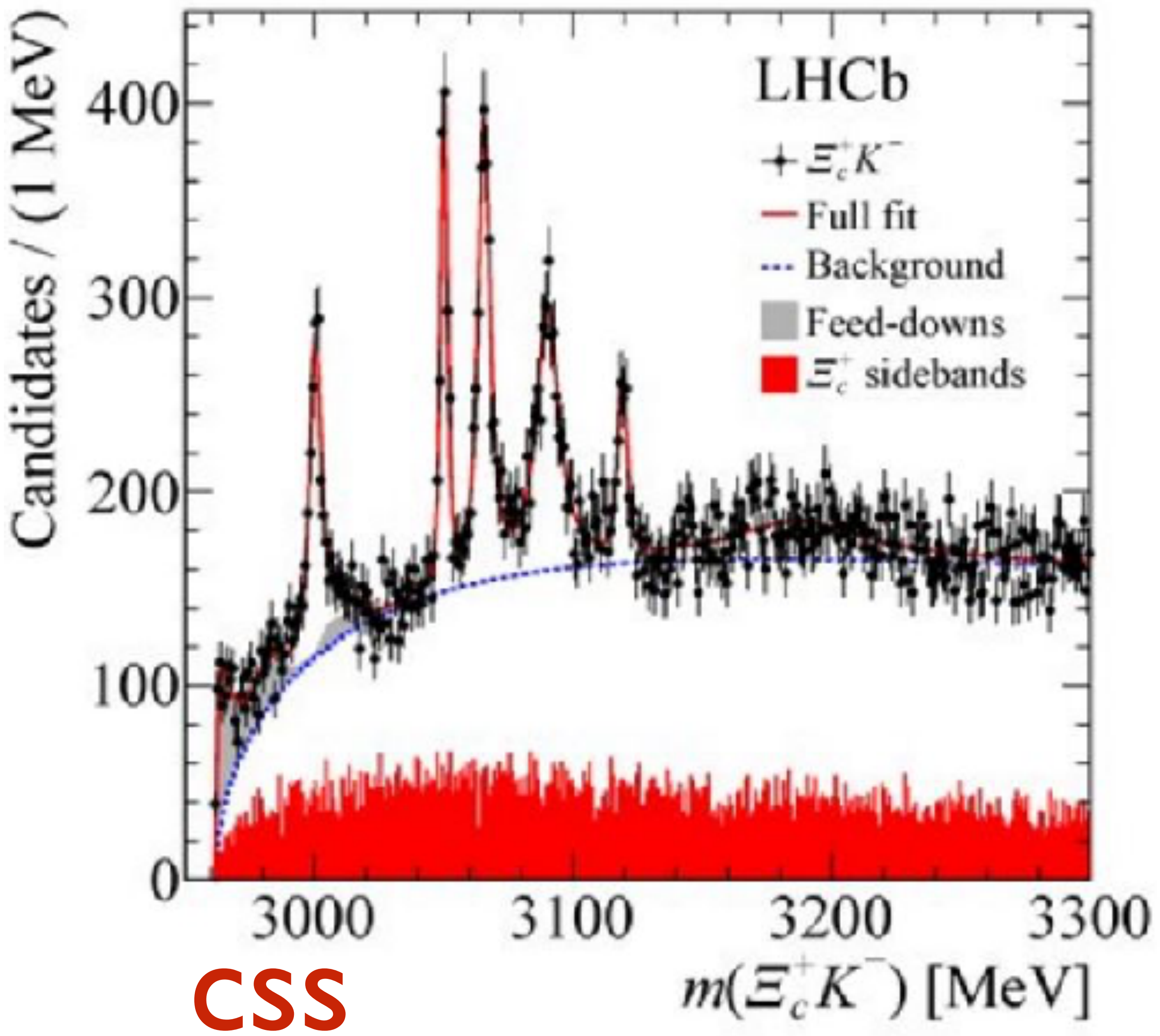
Exotic Spectroscopy, nuclear physics and more

Continued progress, and novelties, in spectroscopy

CMS, Phys. Lett. B 803 (2020) 135345







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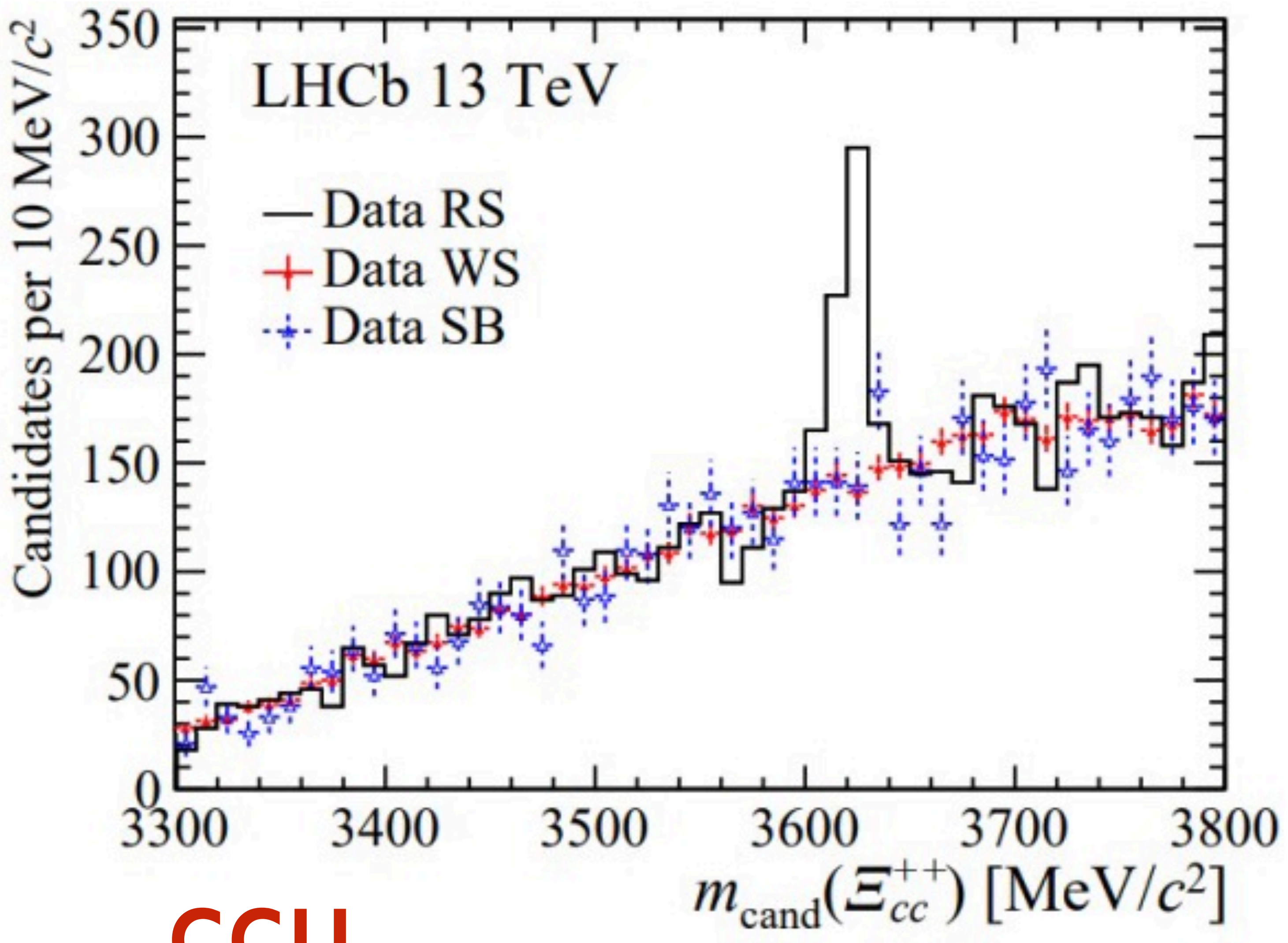
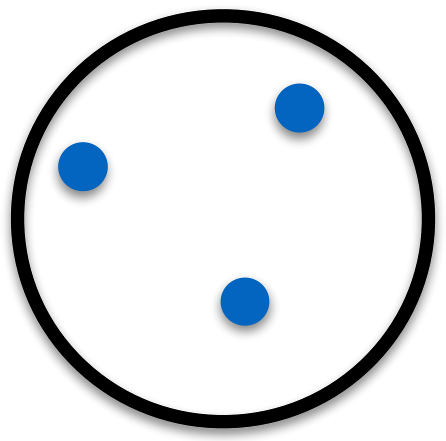
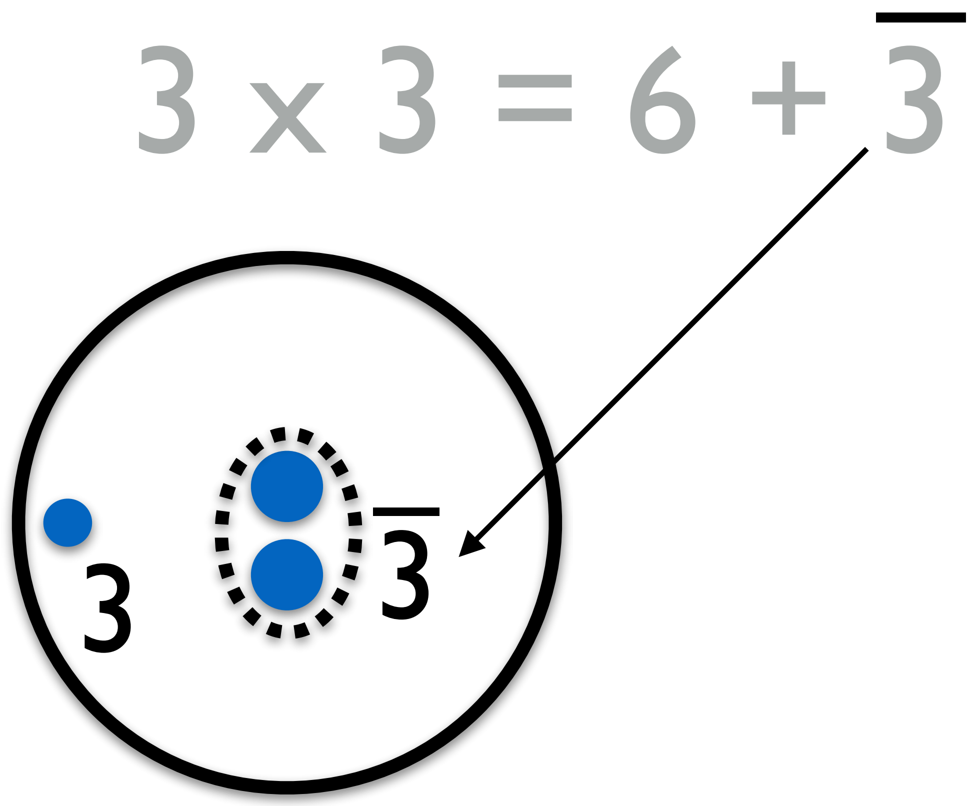


ccu

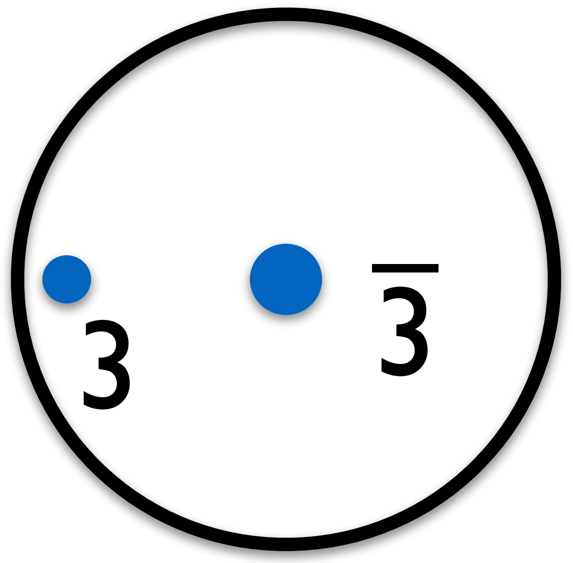
A usual baryon:



A baryon with two heavy q's:



Similar to a heavy meson, eg B_u



but here the core is a fermion, while in a doubly-heavy baryon the core is a boson (different hyperfine splitting structures, etc)

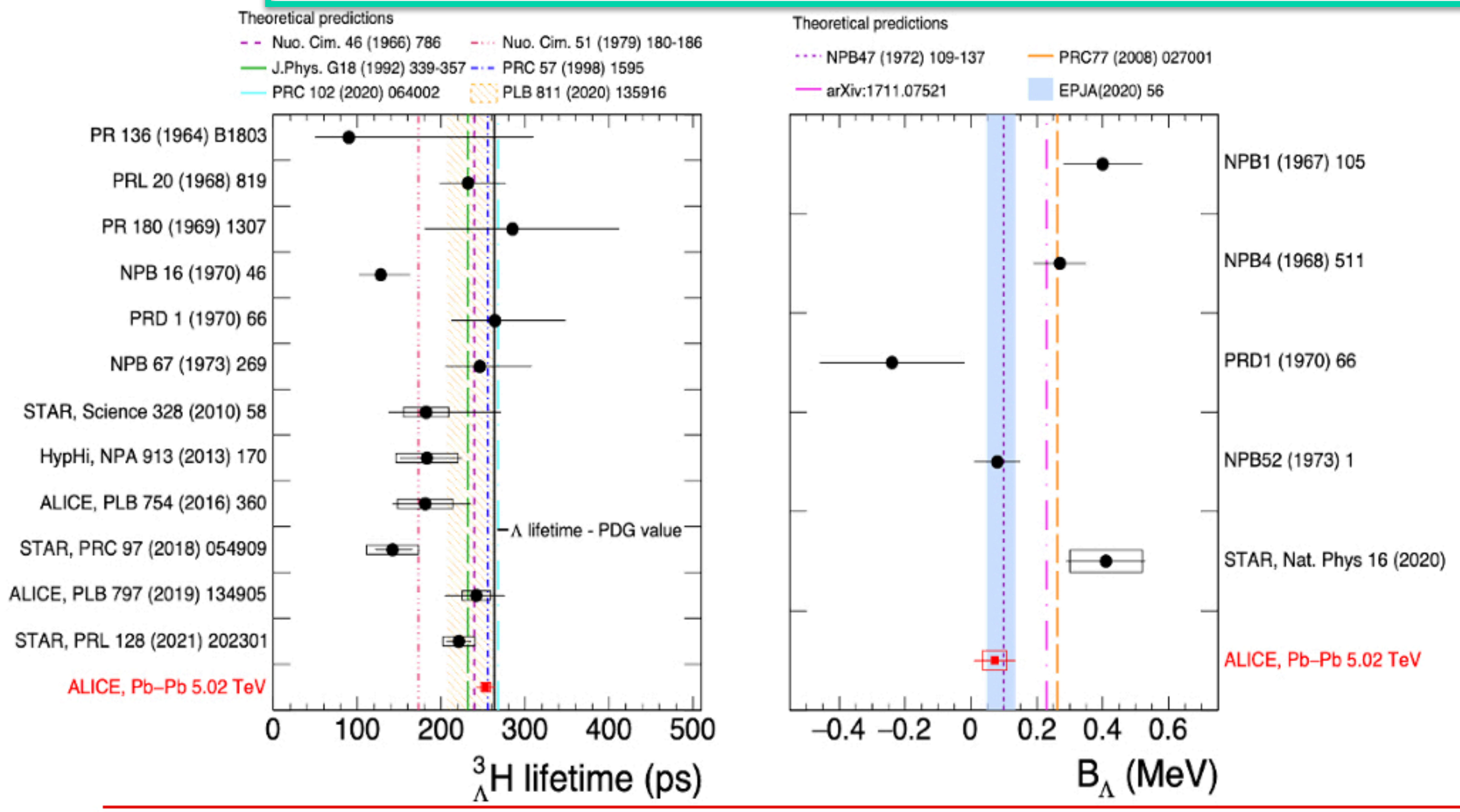
⇒ rewarding for theory and experiment to challenge each other's ability to predict/measure!!

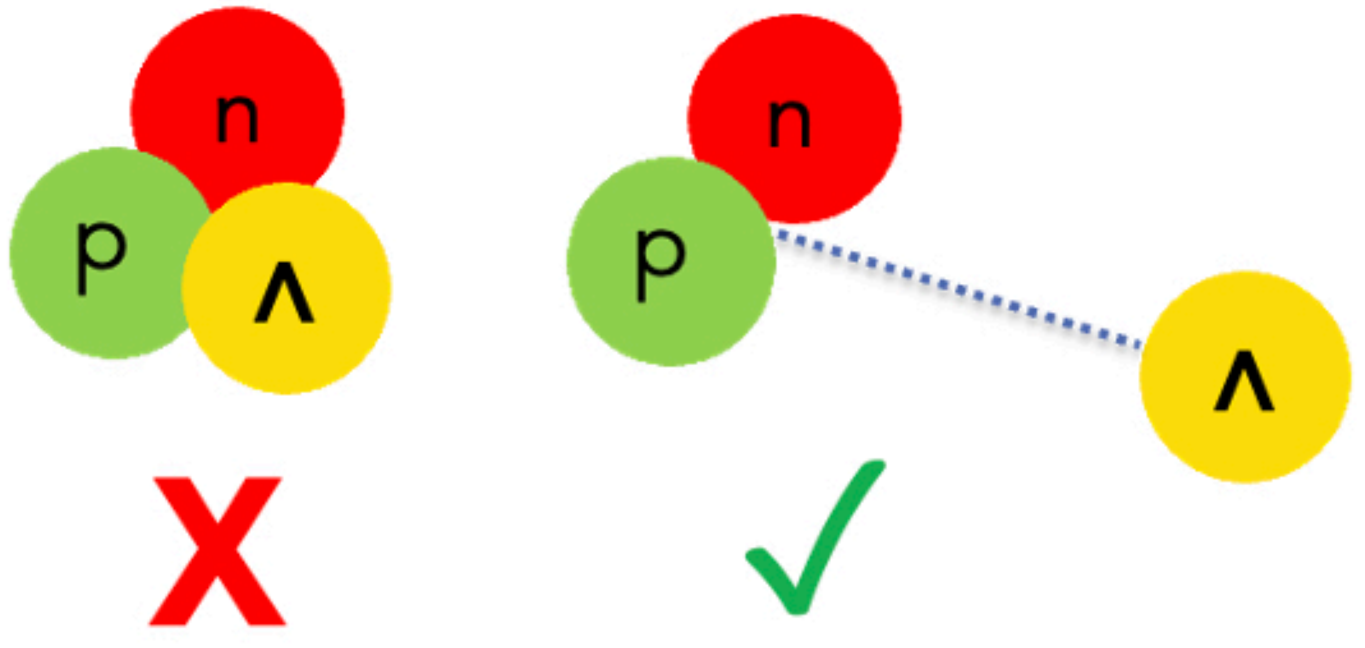
LIFETIME AND BINDING ENERGY OF HYPERTRITON

60 years after discovery, its properties were not yet well measured…

Unprecedented precision with Pb-Pb Run 2 data:

- Lifetime: is there a deviation from the free Λ lifetime? No!
- Binding energy B_Λ: is this really a loosely bound deuteron-Λ molecule? Yes!



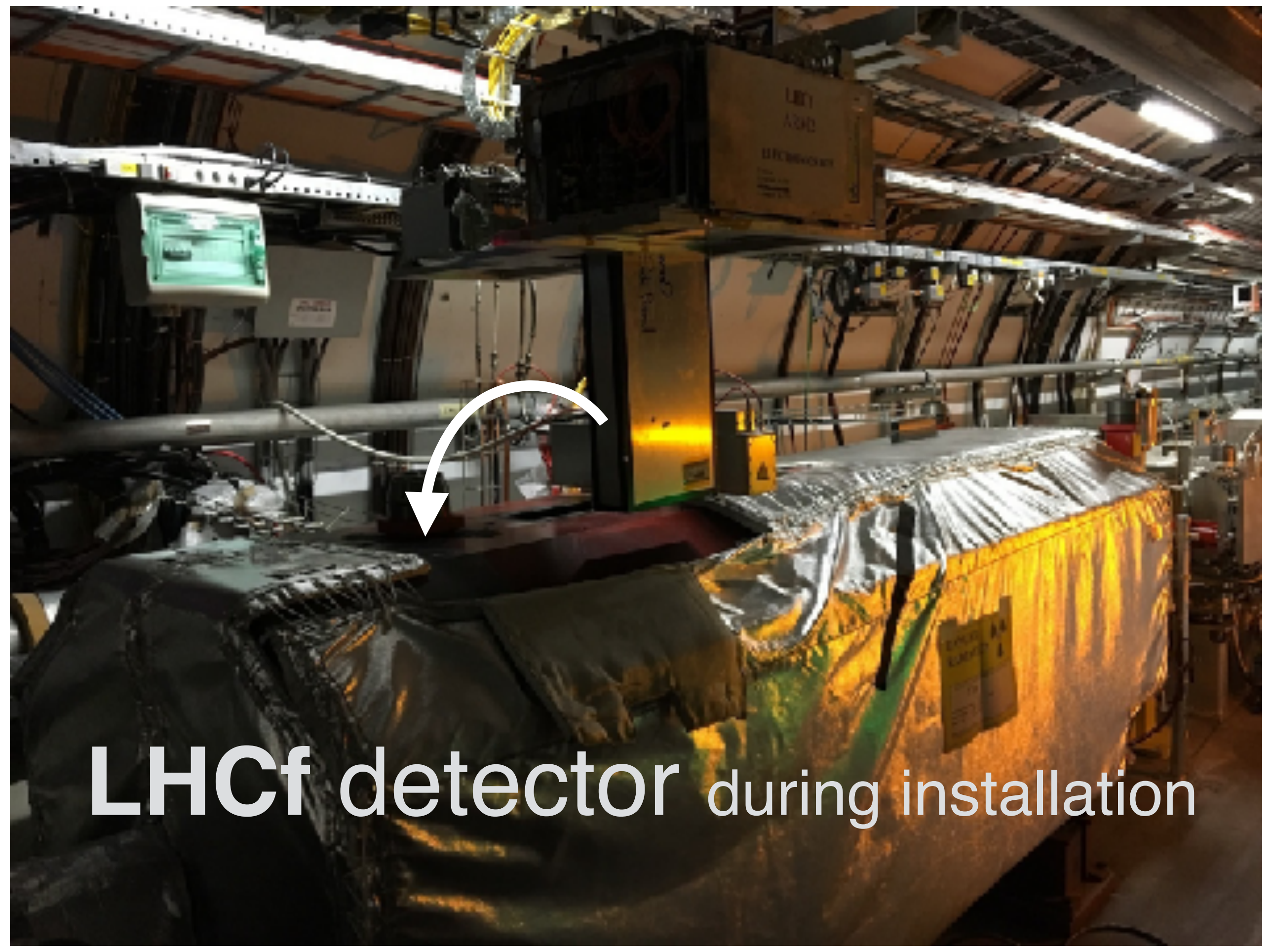


arXiv:2209.07360

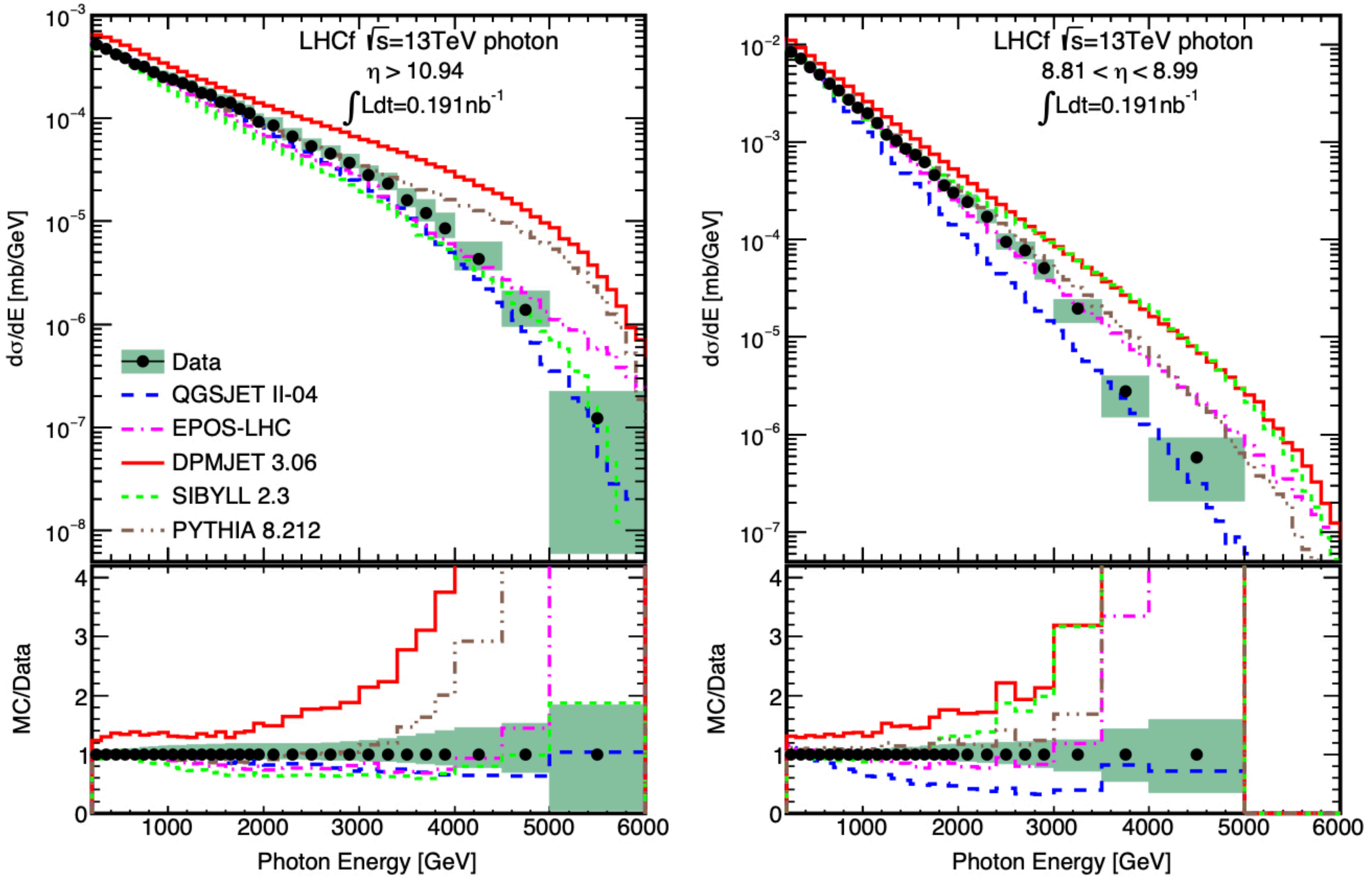
Impact on astroparticle physics

countless searches for dark matter candidates covering a huge domain of plausible model space

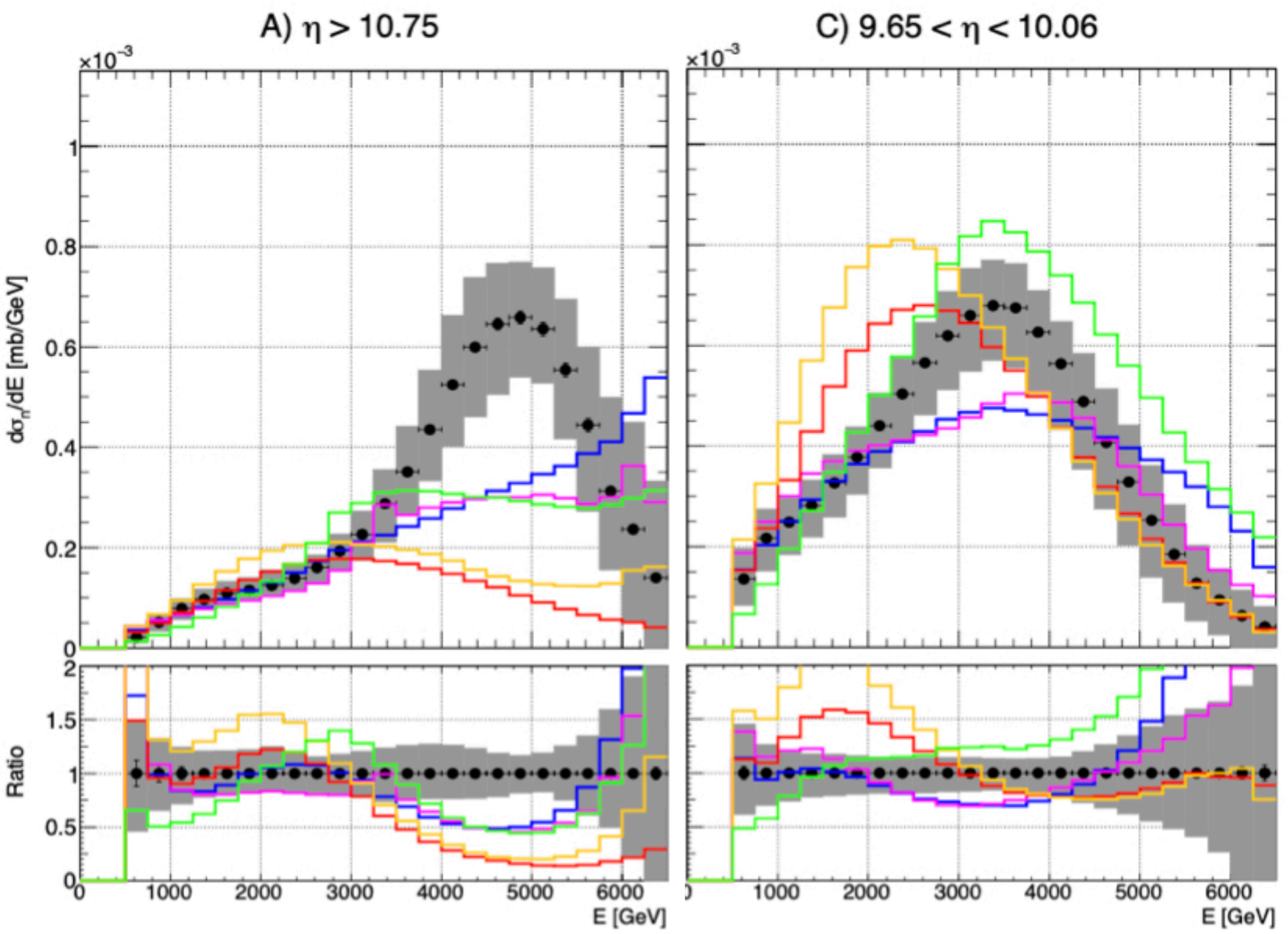
… plus:



Probing the spectrum of most energetic particles forward-produced => model development of highest-energy cosmic ray showers in the atmosphere

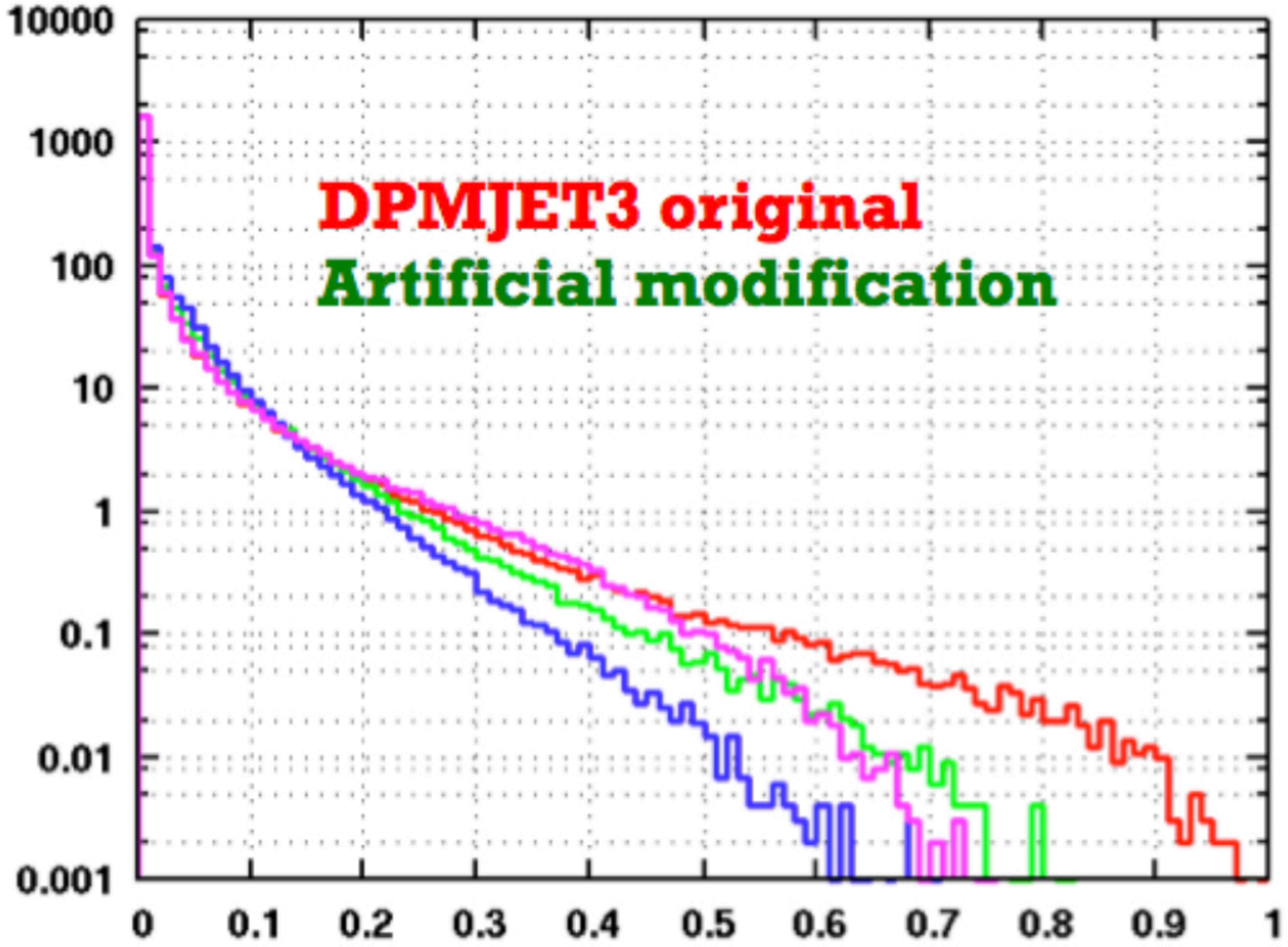


photons~π^0~π^{+-} Phys.Lett.B 780 (2018) 233



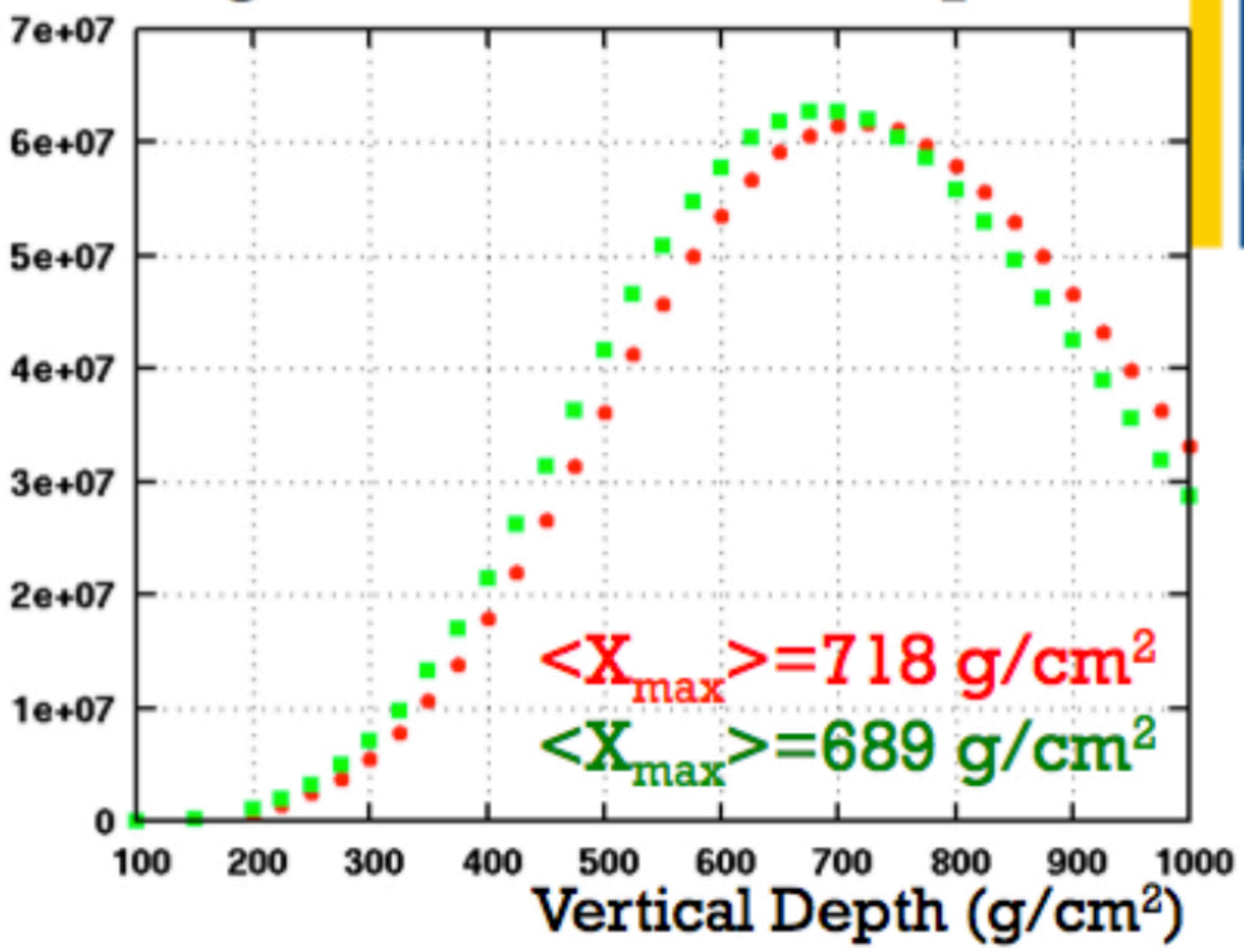
neutrons JHEP 07 (2020) 016

π^0 spectrum and air shower

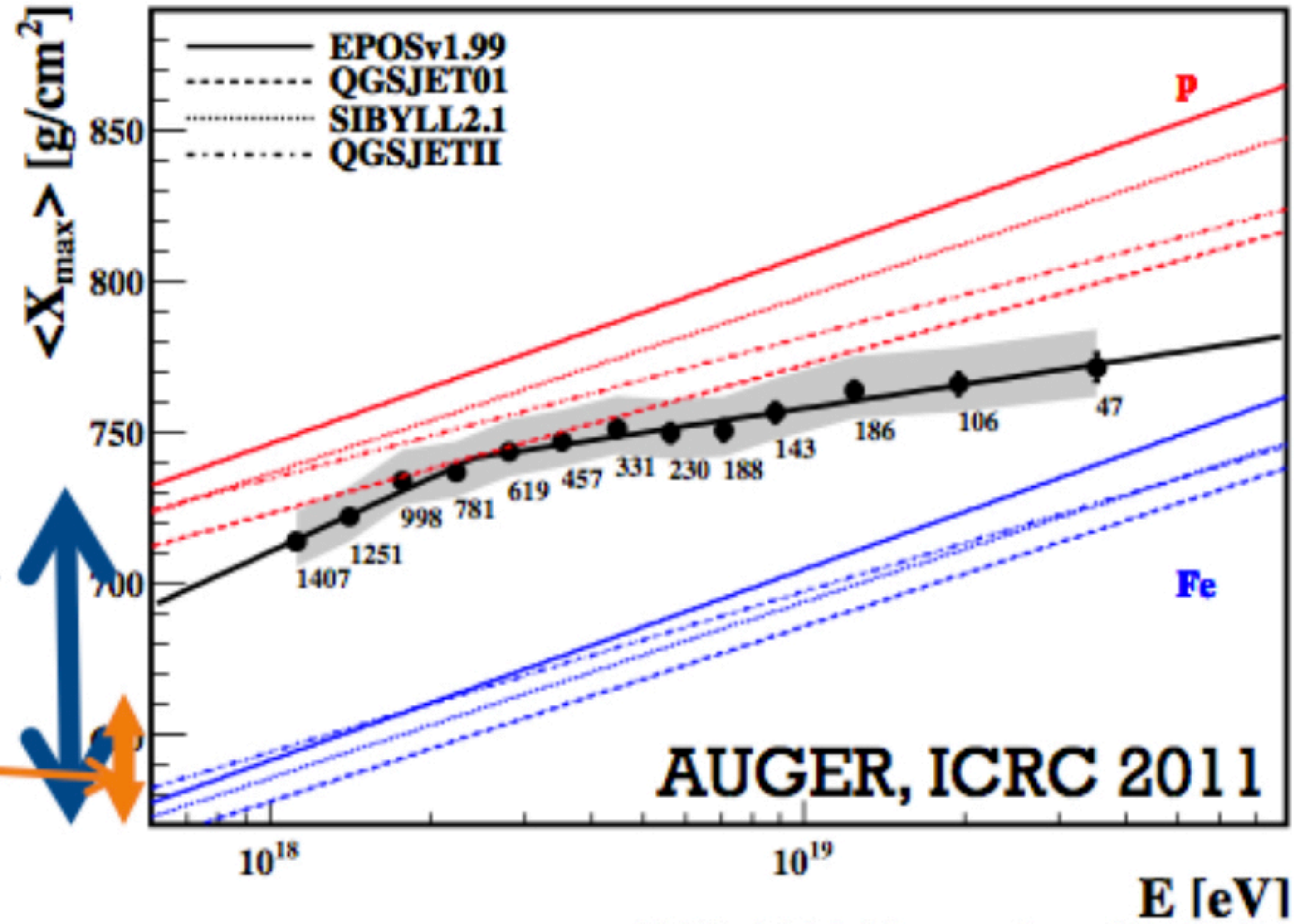


π^0 spectrum at $E_{lab} = 10^{17}$eV

Longitudinal AS development



- ✓ Artificial modification of meson spectra (in agreement with differences between models)
- ✓ $\Delta\langle X_{max}(\text{p-Fe})\rangle \sim$ 100 g/cm²
- ✓ Effect to air shower ~ 30 g/cm²

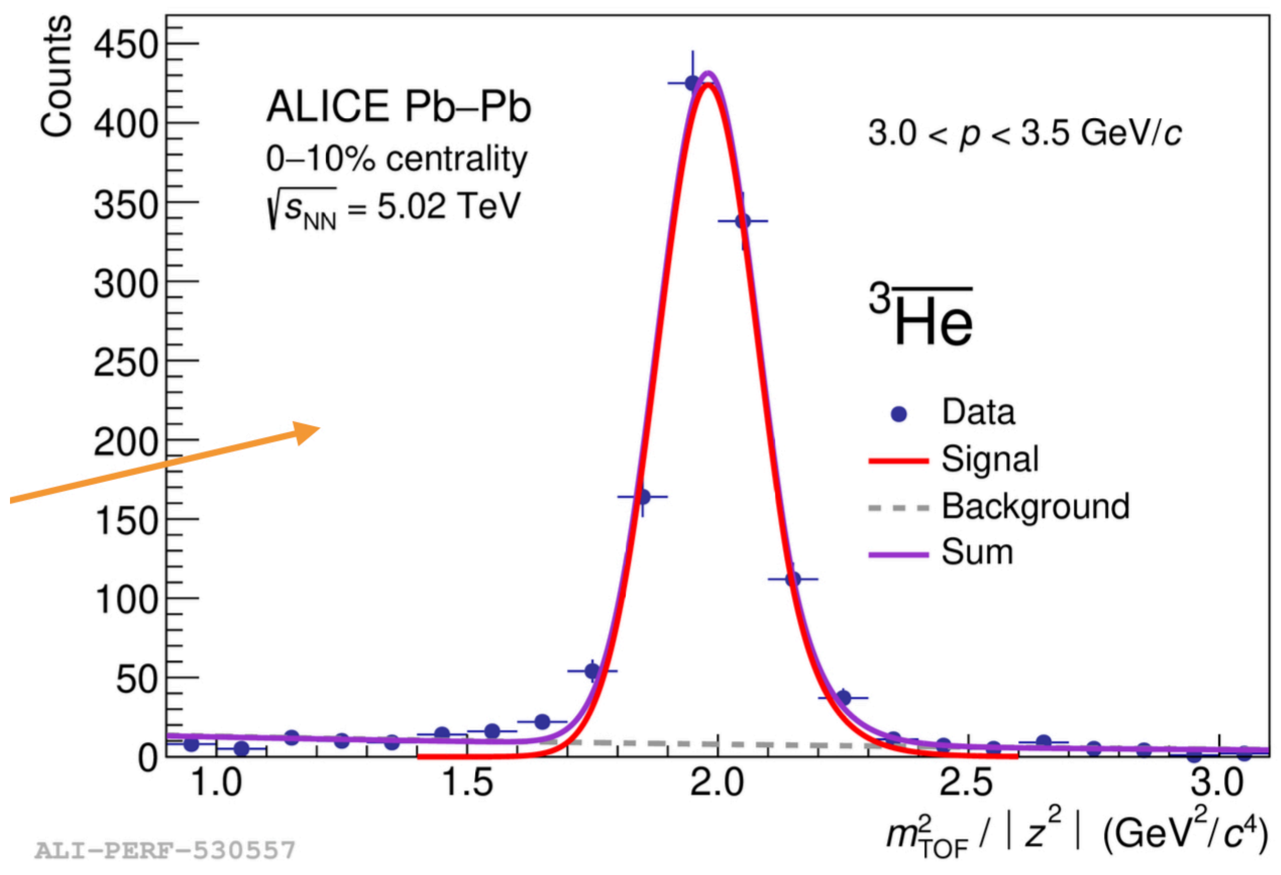


https://doi.org/10.1038/s41567-022-01804-8

Measurement of anti-^{3}He nuclei absorption in matter and impact on their propagation in the Galaxy

ALICE https://doi.org/10.1038/s41567-022-01804-8

Laura Šerkšnytė CERN seminar



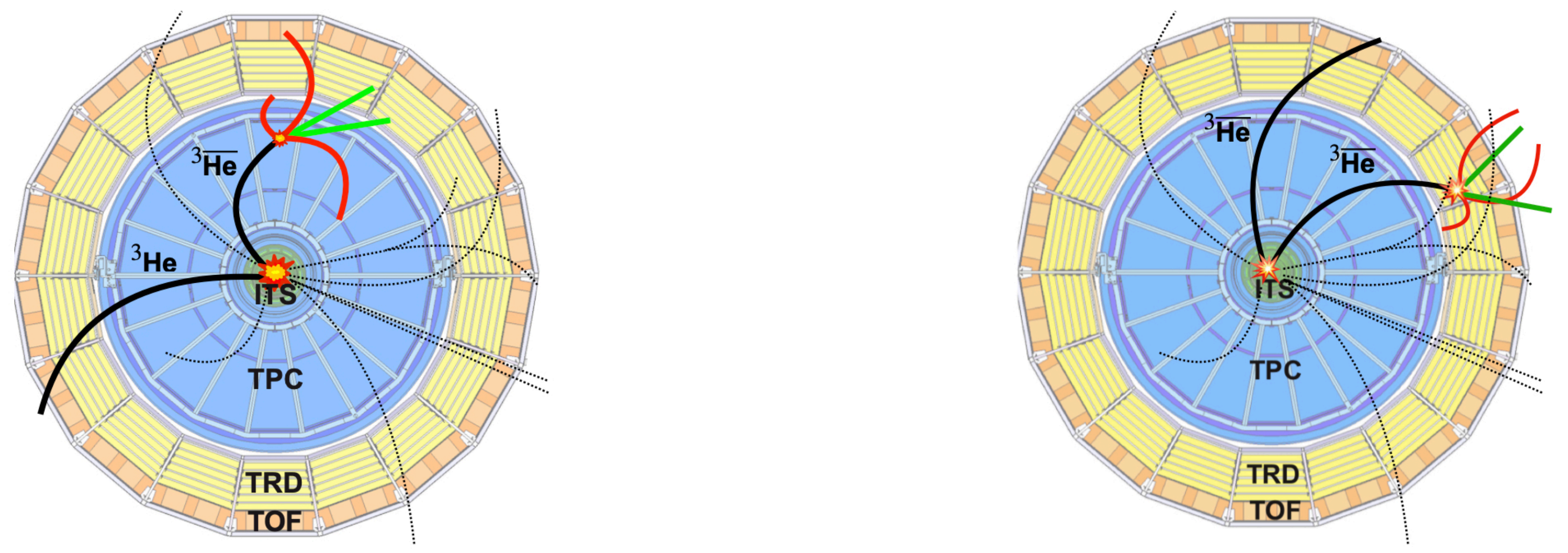
Method: ALICE as a target

Antimatter-to-matter ratio

- Measure reconstructed $^3\overline{He}/^3He$ and compare with MC simulations

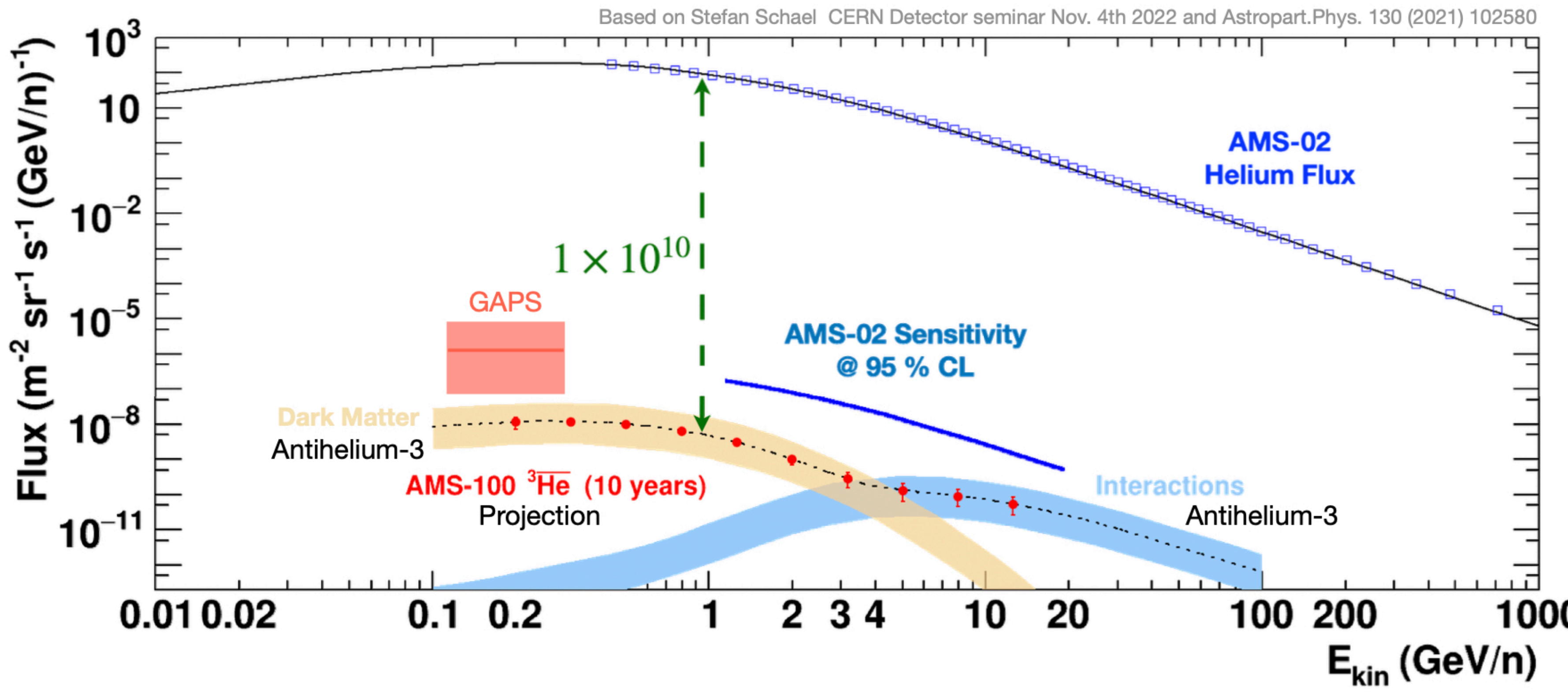
TOF-to-TPC-matching

- Measure reconstructed $^3\overline{He}_{TOF}/^3\overline{He}_{TPC}$ and compare with MC simulations



Measuring antinuclei fluxes

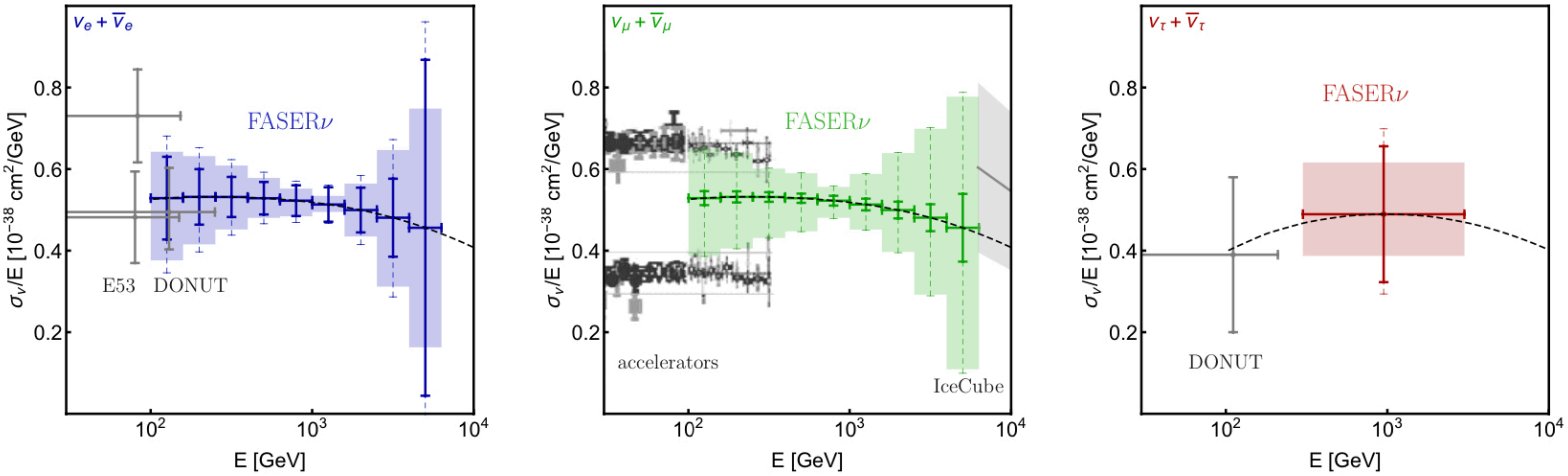
- AMS-02: Magnetic spectrometer on ISS; 9 antihelium candidates; not published yet
- GAPS: Antarctic balloon mission; low energy antinuclei; planned at the end of 2023
- AMS-100: Next generation magnetic spectrometer; x1000 sensitivity; estimated launch 2039



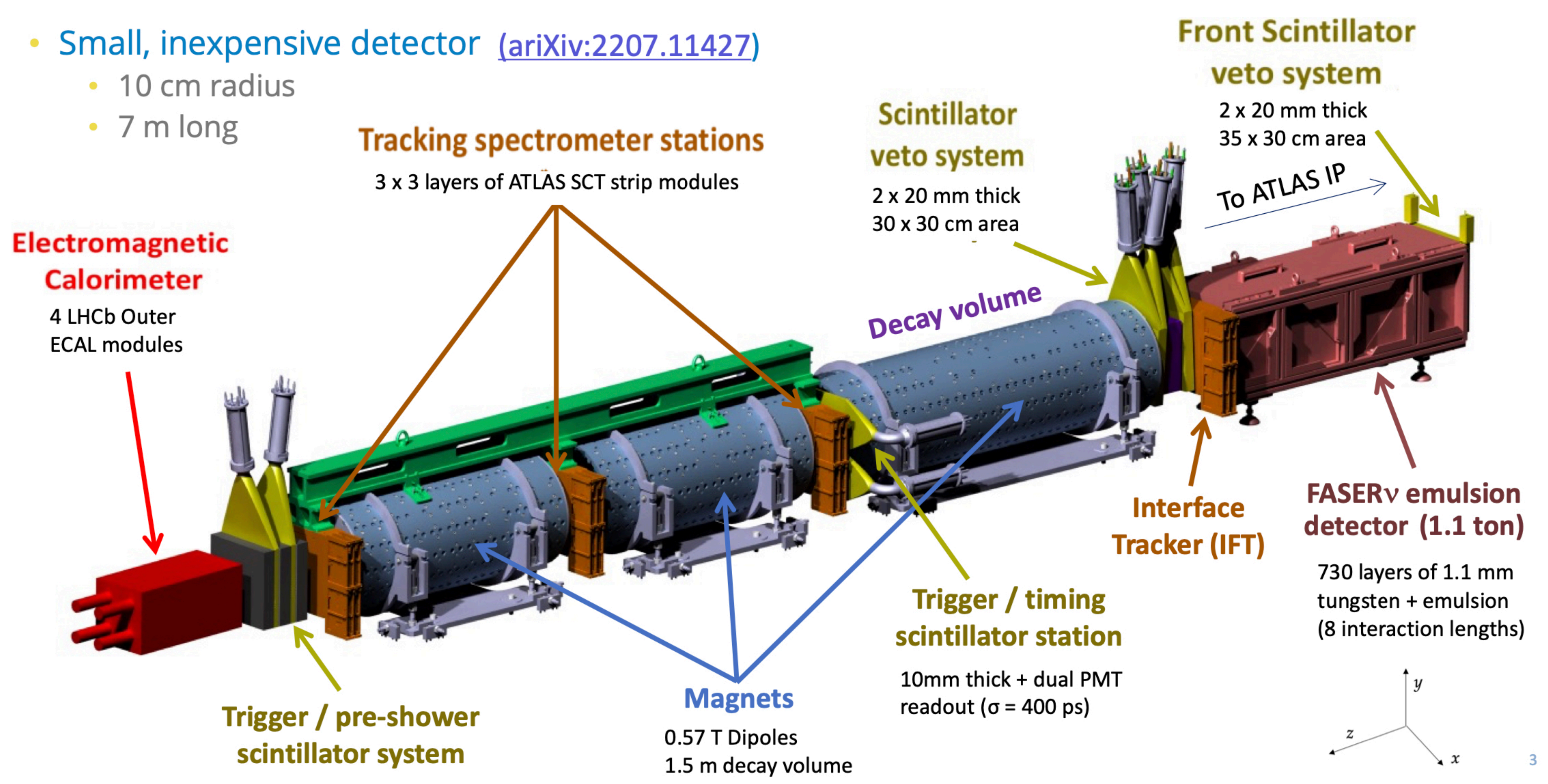
LHC Seminar | laura.serksnyte@cern.ch 3

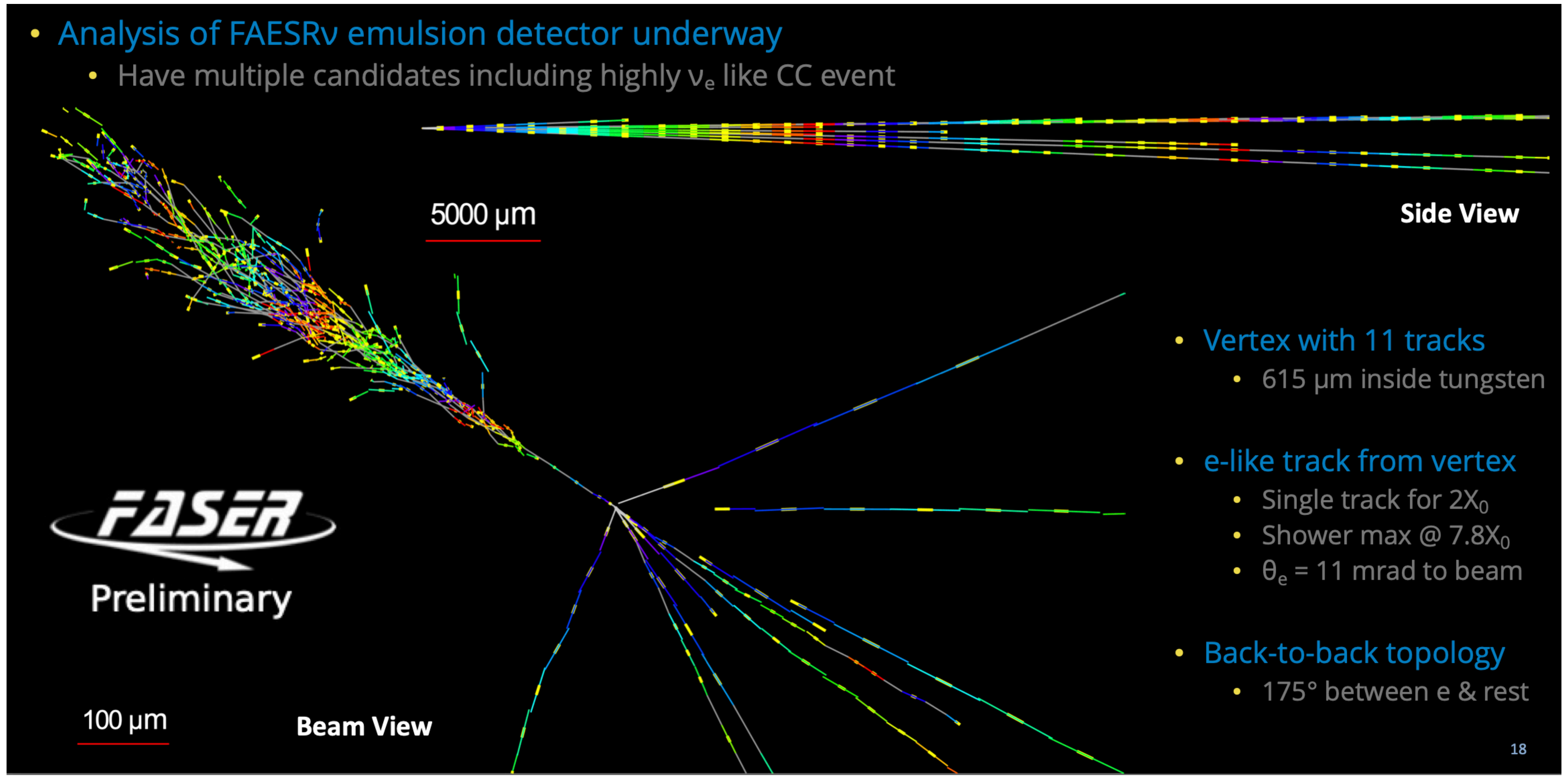
Neutrino Physics: FASERν and SND@LHC

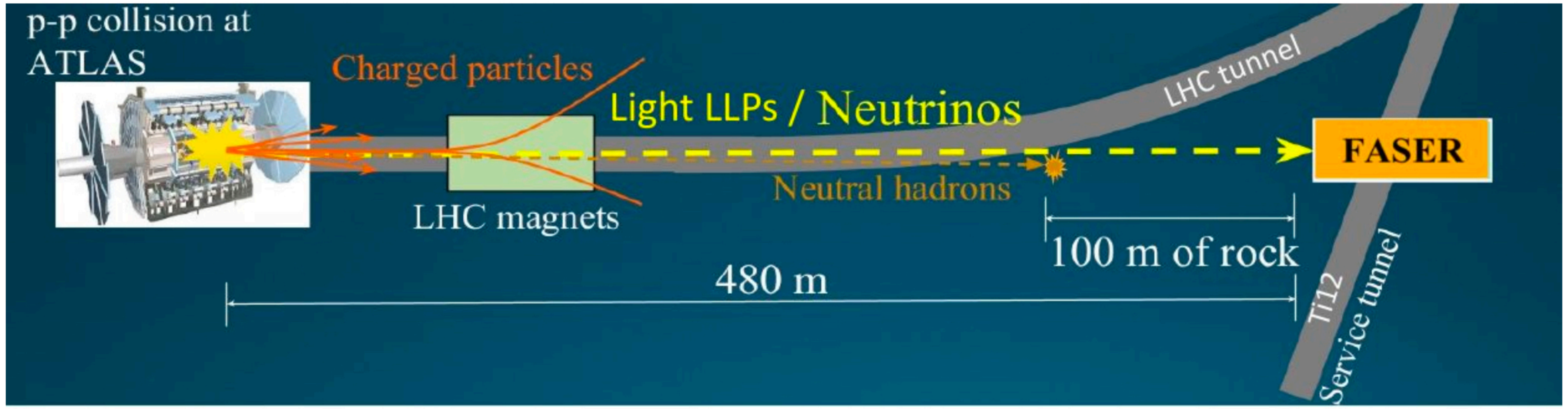
Among other goals:
measure neutrino cross sections in energy ranges never explored before, of relevance to cosmic neutrino studies, and flavour-tagged



FASER/FASERν

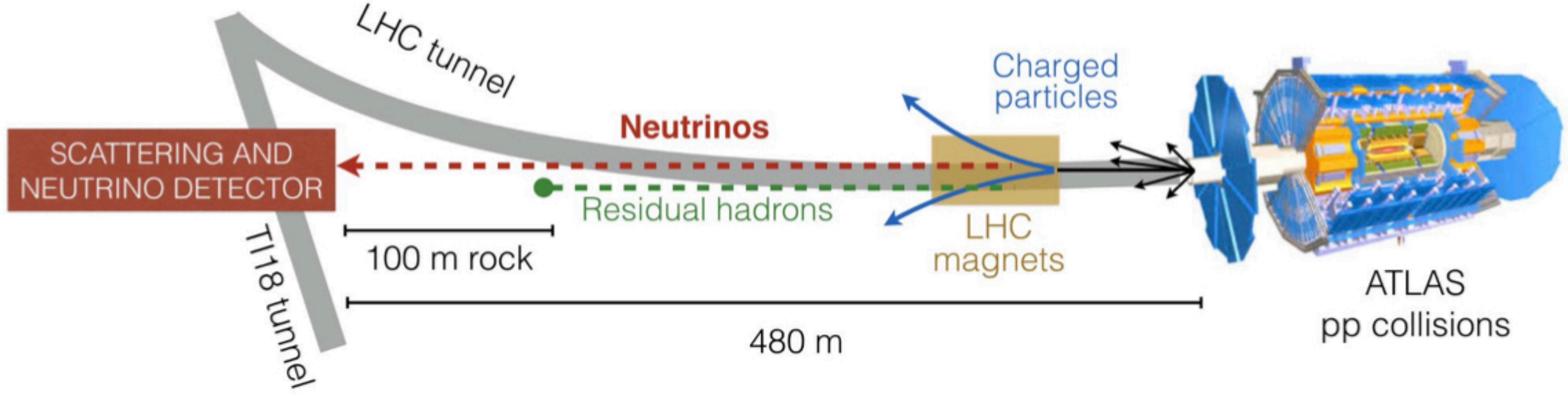






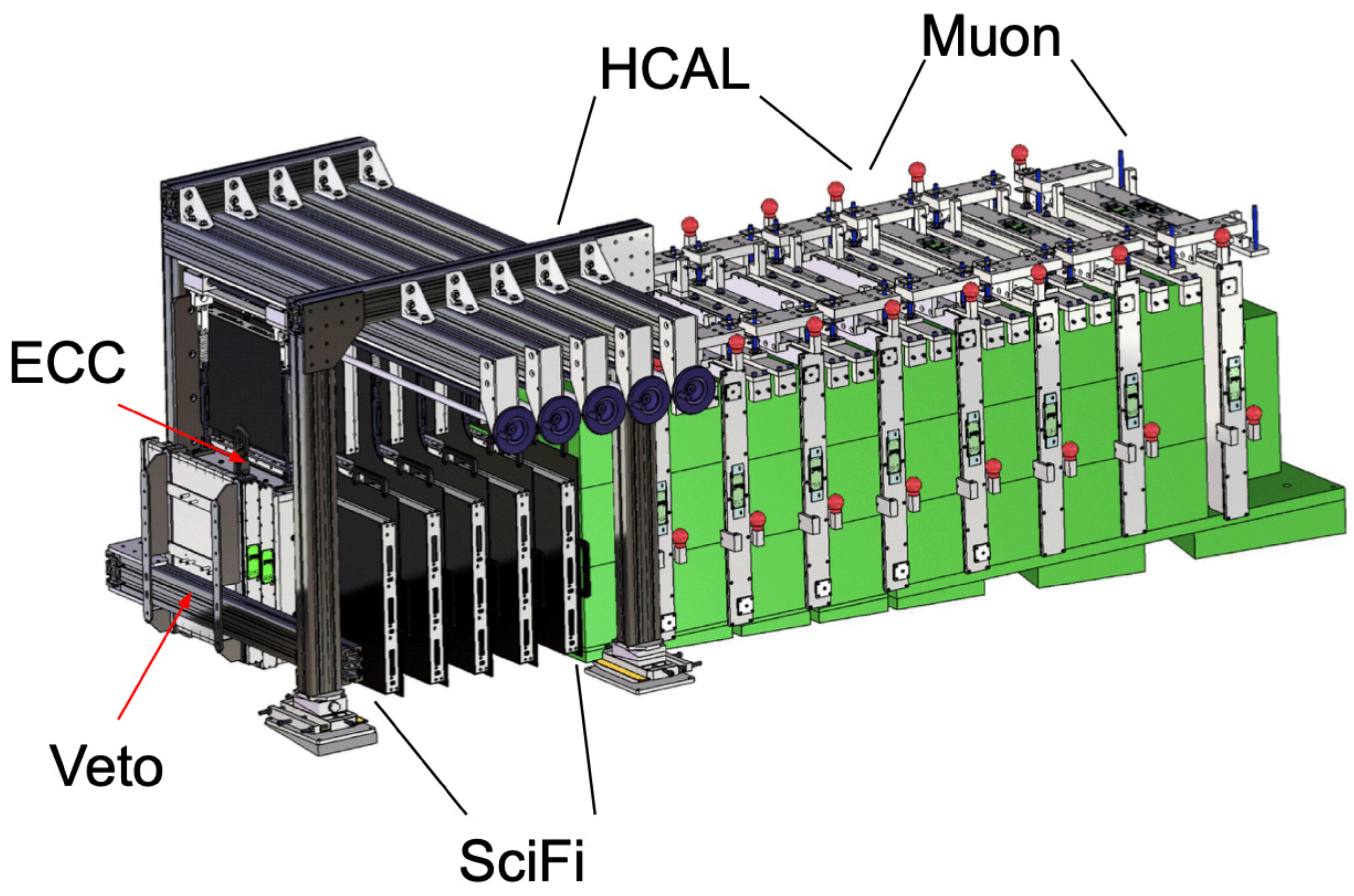
Candidate	Events
n_0	153 (151 ± 41)
n_{10}	4
n_{01}	6
n_2	64014695

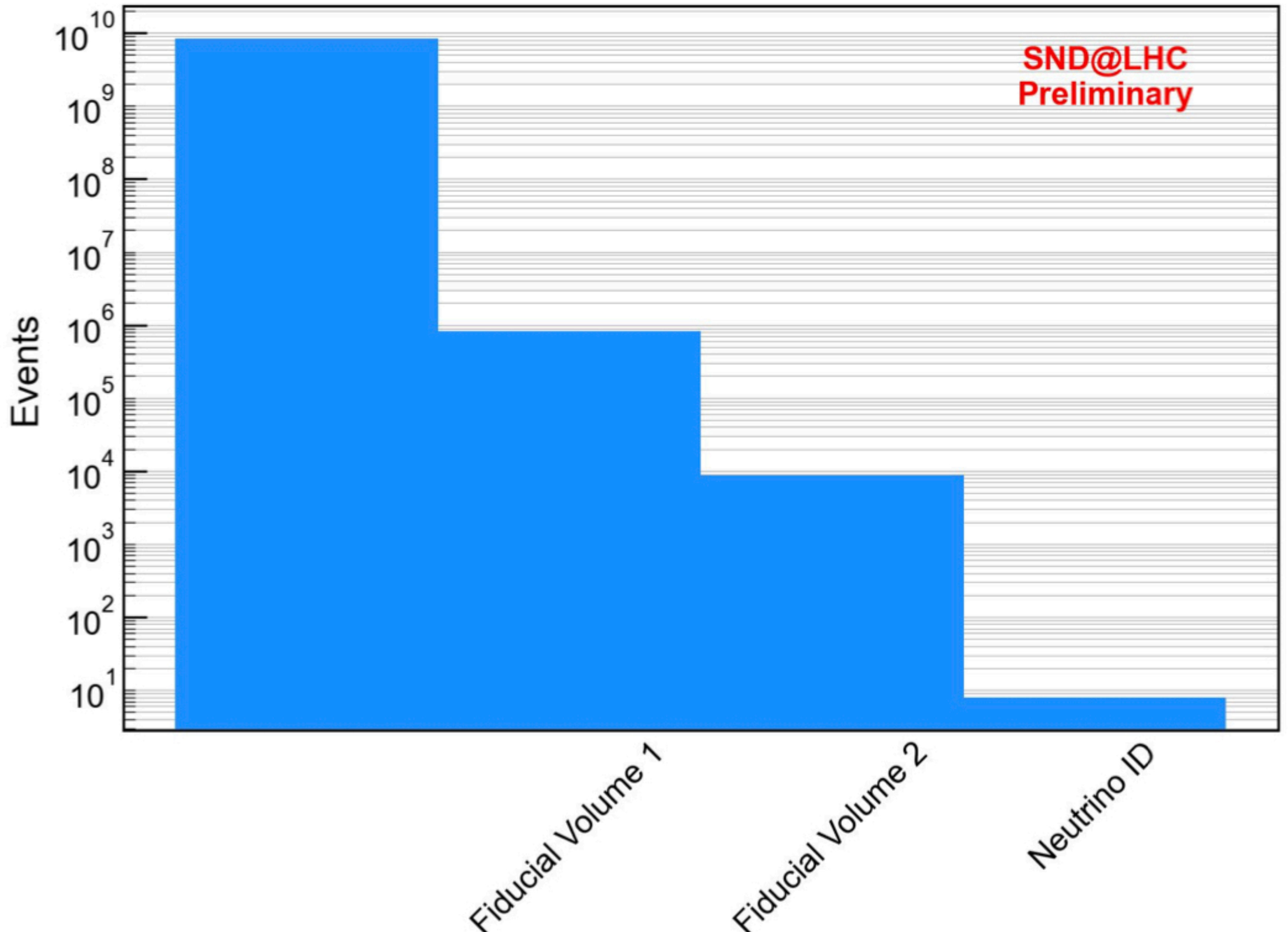
SND@LHC



- About 480 m from ATLAS interaction point
- TI18 tunnel
  - Used in the past as transfer line from SPS to LEP
- Shielded by 100 m of rock and LHC magnet deflection
- Angular acceptance: $7.2 < \eta < 8.4$
- First phase: collect 250 fb^{-1} in Run 3

Observed ν_μ **candidates**: 8 (expected 5)
Preliminary estimate of background yield: 0.2





2022 run:

8 ν_μ candidates (exp 5)

estimated bg 0.2

Remarks

- These 3000 papers reflect the underlying existence, at the LHC, of 100's of scientifically "independent" experiments, which historically would have required different detectors and facilities, built and operated by different communities
- On each of these topics the LHC expts are advancing the knowledge previously acquired by dedicated facilities
  - HERA→PDFs, B-factories→flavour, RHIC→HIs, LEP/SLC→EWPT, etc
- Even in the perspective of new dedicated facilities, eg SuperKEKB or EIC, LHC maintains a key role of competition and complementarity

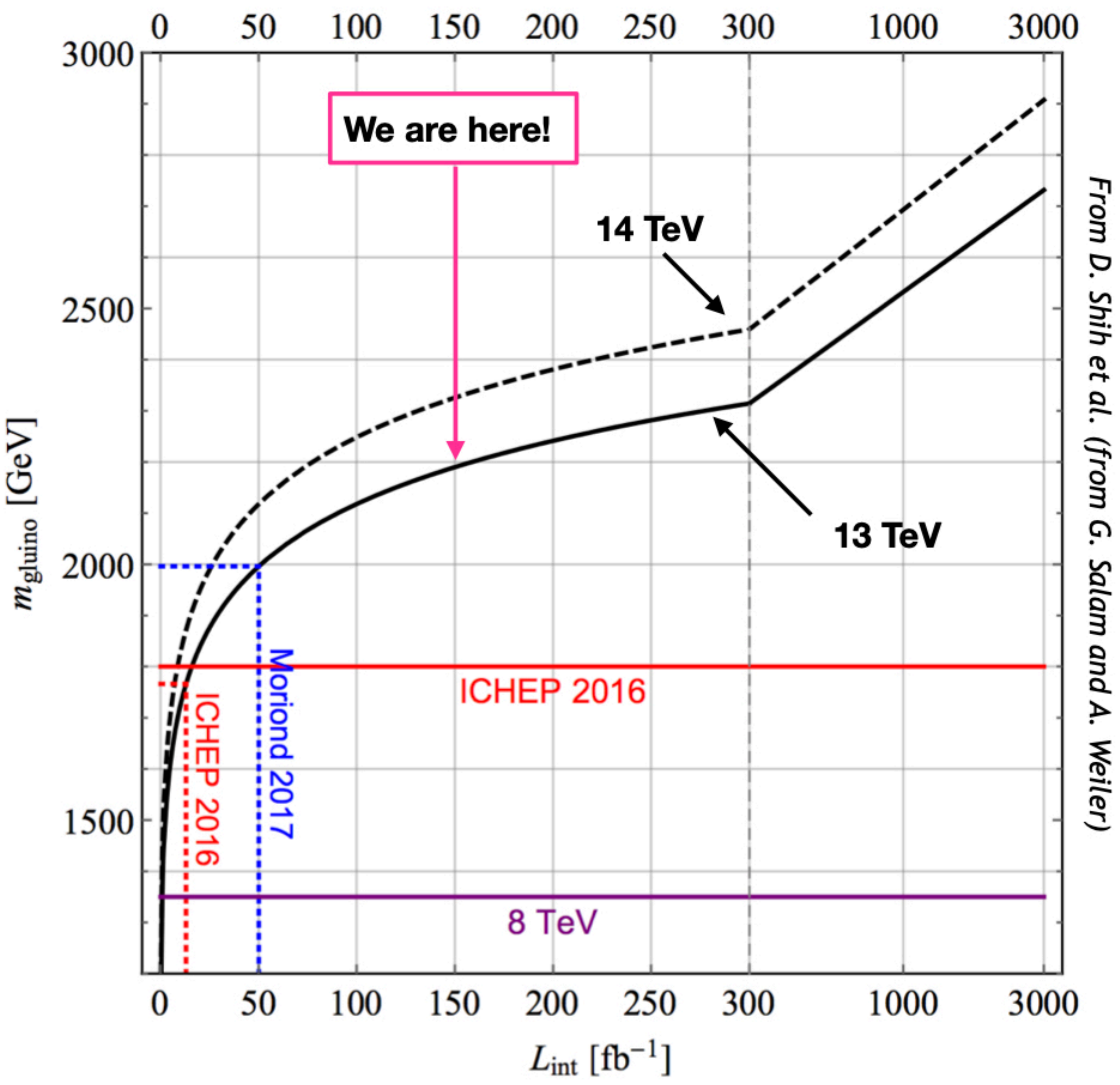
I have a broad concept of "*new physics*", which includes SM phenomena, emerging from the data, that are unexpected, surprising, or simply poorly understood.

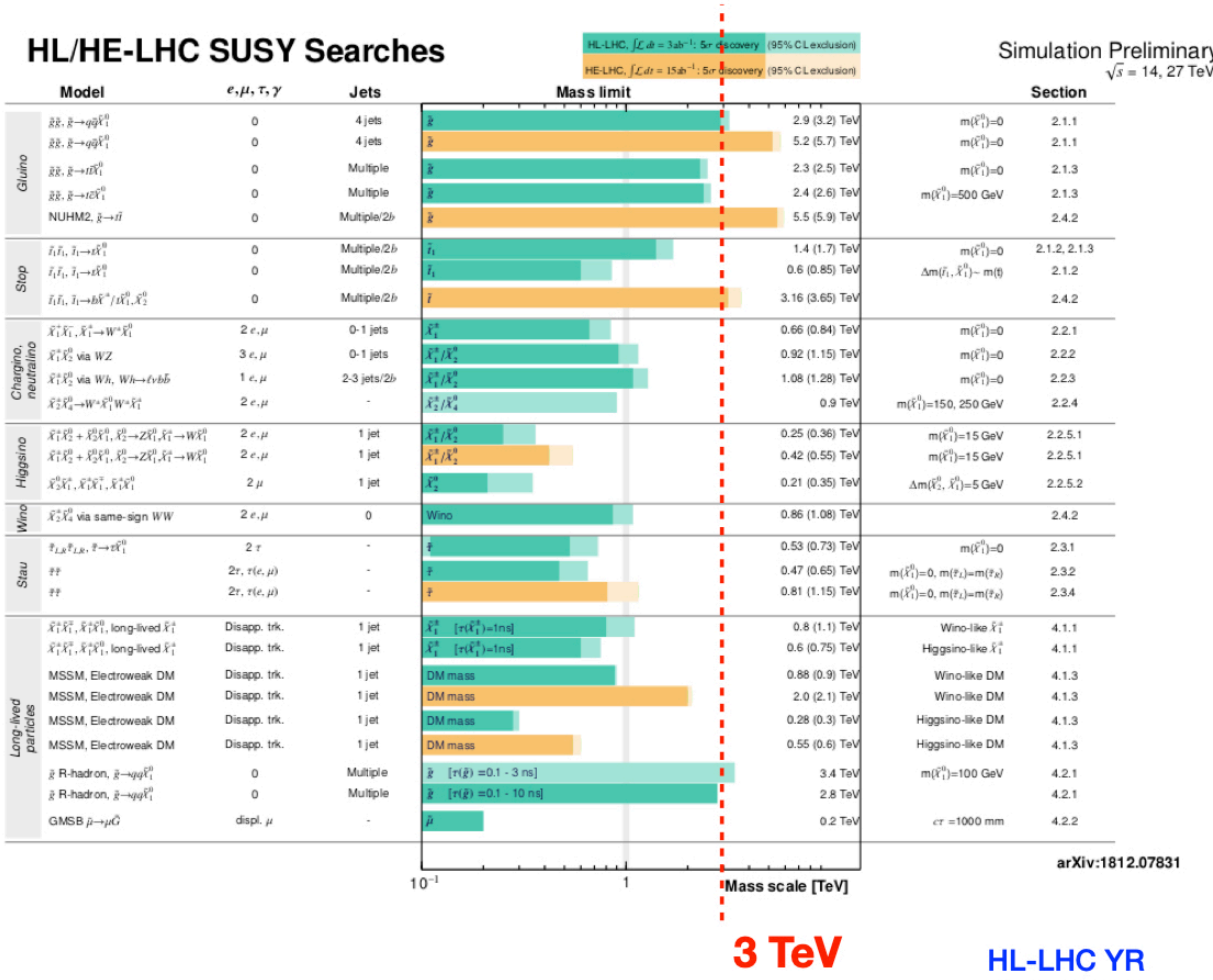
I consider as "new", and as a discovery, everything that is not obviously predictable, or that requires deeper study to be clarified, even if it belongs to the realm of SM phenomena.

"New physics" is emerging every day at the LHC!

The LHC future: High-Luminosity LHC

Gluino mass exclusion search sensitivity, vs luminsoty:
still plenty of room for discovery at HL-LHC!



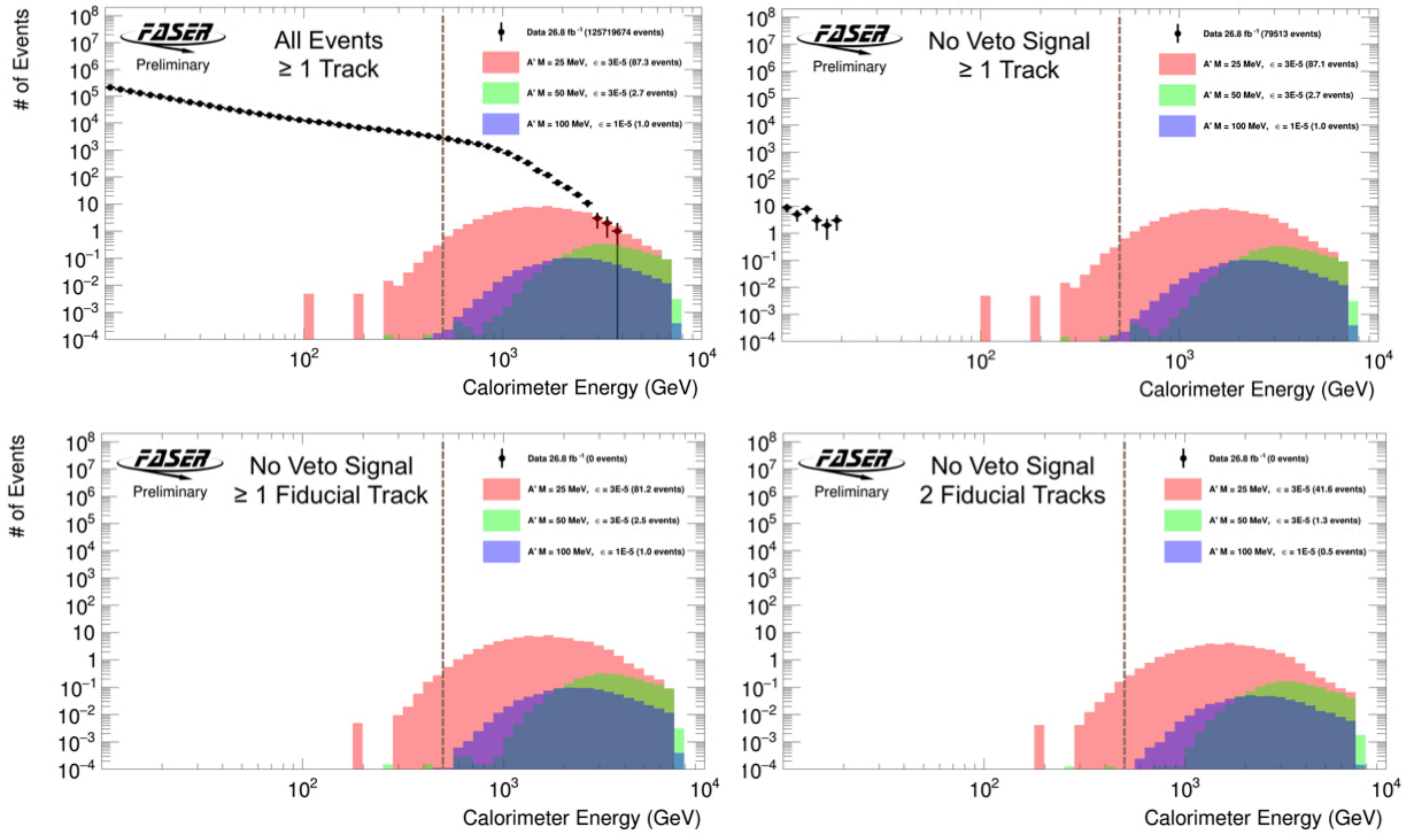


HL-LHC YR
1812.07831

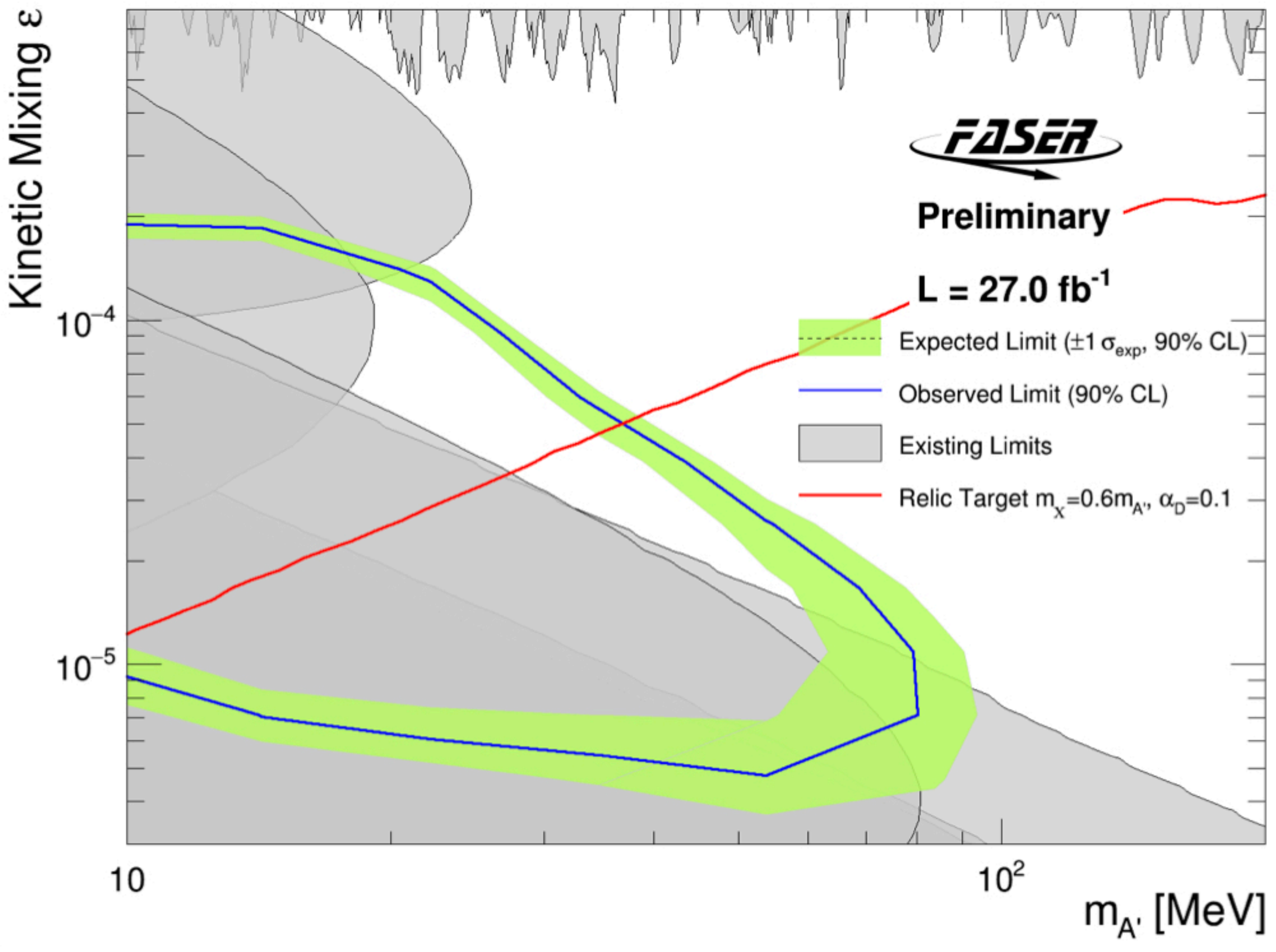
Examples of new opportunities

FASER BSM searches

Dark Photon Results



- No events in unblinded signal region
  - Not even any with ≥1 fiducial track

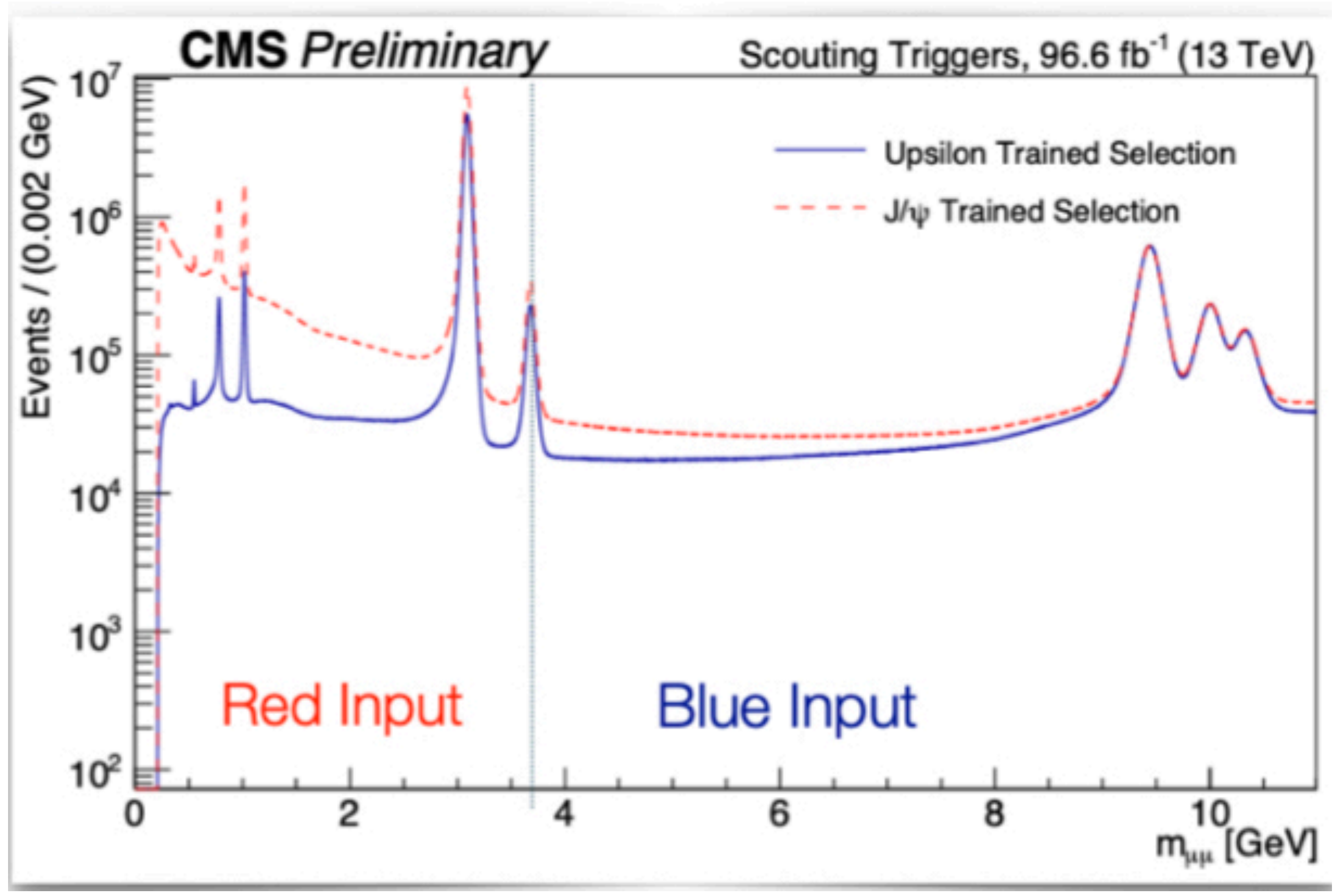


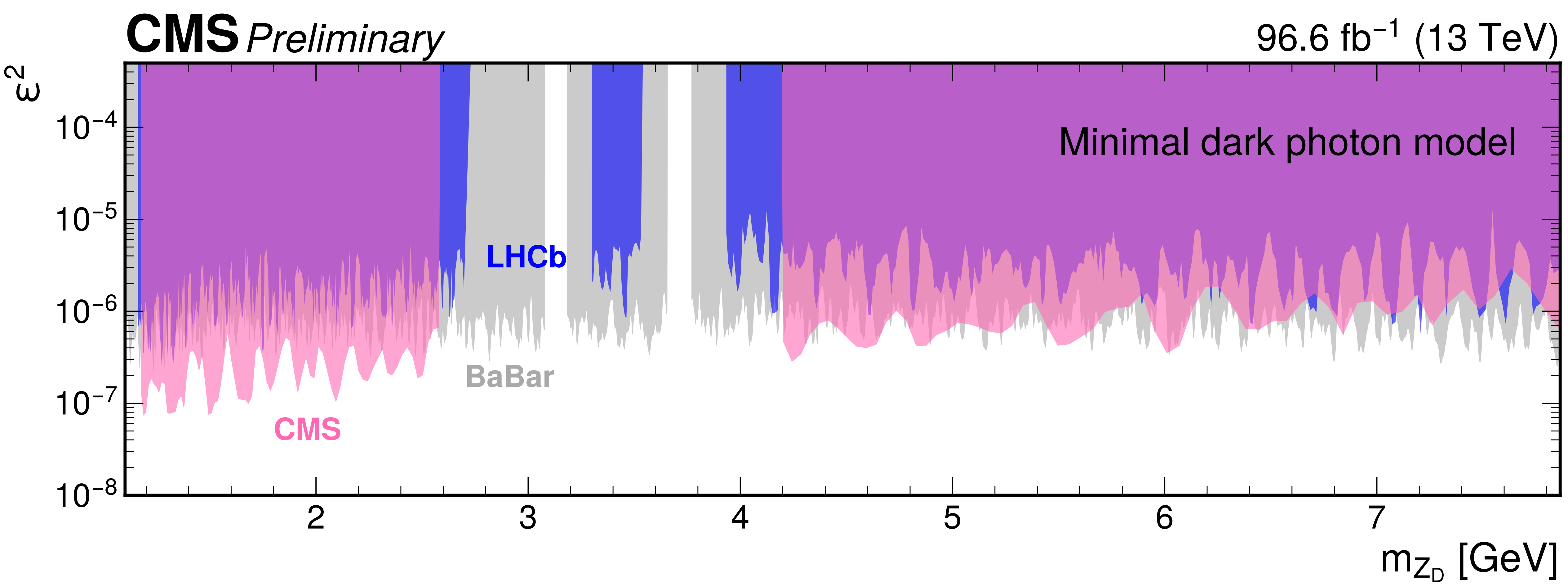
- Based on this null results, FASER sets limits in previously unexplored parameter space!
  - Probing region interesting from thermal relic target
  - Also taking into account new preliminary NA62 result (see backup)

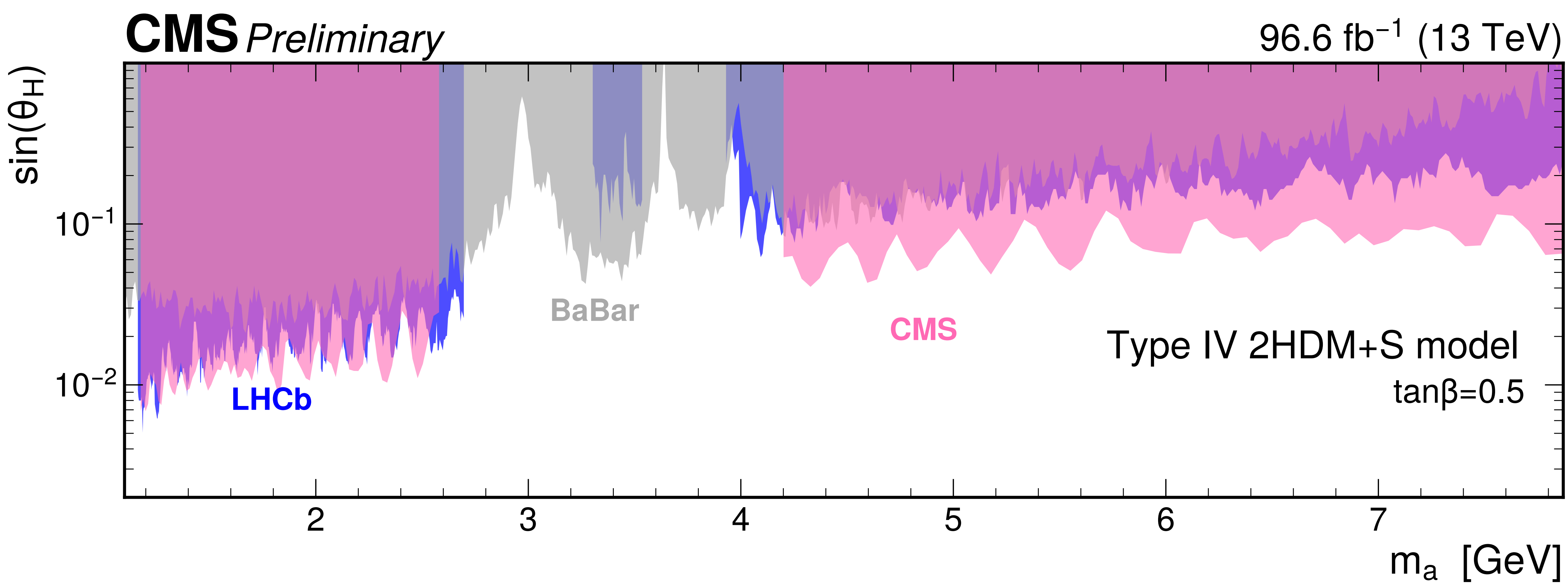
CERN-FASER-CONF-2023-001

CMS light dimuon resonance searches with data scouting

- Mass range 1.1-2.6 GeV and 4.2-7.9 GeV
- Trigger-level reconstruction with low thresholds
- Stores events with 2 μ of pt>3 GeV
- Selects μ+μ– pairs with pt>4 |η|<1.9







Improves on LHCb and Belle/Babar sensitivity

- Plenty of excesses and anomalies exist here and there, which higher luminosity can enhance or evaporate
- focus on development of new analysis strategies, relying on advanced machine-learning techniques, new detector capabilities (eg timing), advences in trigger architectures
- The exploration of the highest mass region (where already now signal eff~O(1) and S/B>>1) is already close to saturation, but plenty of room for significant improvement in sensitivity below the phase-space threshold, especially for rare and/or elusive signatures

Key take-home messages

- The study of the SM will not be complete until we clarify the nature of the Higgs mechanism and exhaust the exploration of phenomena at the TeV scale: many aspects are still obscure, many questions are still open.
- The LHC has proven the immense and unique versatility and precision of a high-energy pp collider.
- The spectrum of observables and diverse phenomena that it has access to, the precision of the measurements, the groundwork for first-principles interpretations in the context of the Standard Model or beyond, have no equals in the history of our field
- The LHC forthcoming upgrades in luminosity and detector performance with expand even more its broad and deep potential, opening the way to possible discoveries, and more surprises