Stefano Catani Memorial Symposium
GGI, Firenze
9 Gennaio 2025

Hadronic Physics: new frontiers and Stefano's legacy

Michelangelo L. Mangano
Theory Department,
CERN, Geneva

Dedicato alla memoria di Stefano,

un caro amico

Alla fisica, che è pur stata il grande motore della sua vita,

ha sempre anteposto l'amore per Anna e la famiglia,

l'amicizia, il rispetto e l'affetto per tutti quelli che hanno

avuto la fortuna di incontrarlo

- The friendship with Stefano goes back to the Spring of 1984, when we first met in Cortona for the annual meeting of Italian theorists. At the time, we shared the exposure to the teaching of Marcello Ciafaloni, who was his mentor in Florence and whose lectures on QCD I had recently followed in Scuola Normale Superiore

- We were later colleagues for several years at CERN, when the scientific collaboration was accompanied by the buildup of friendship of Anna and Stefano with Paola and myself

- The friends who spoke before me already highlighted facts, anecdotes and appreciation for Stefano's contributions to the progress of physics and of the community at large, from experiments to theory

- In particular, Paolo covered the fraction of Stefano's work that I've been fortunate enough to participate in, together with him an Luca. On the scale of what Stefano has done in his career, this was just a minor event and, as is often the case in collaborations with Stefano, what I have learned far outweighs what I've been able to give in return

- The goal of this tribute to Stefano is to put in perspective the impact that progress in QCD is having on re-shaping the physics programme and goals of the LHC and of future colliders.
- This is clearly a tribute to the work of all of you, and to the whole community, but you will all recognize the imprint of Stefano's vision and the direct impact of his cornerstone contributions, which define Stefano's legacy
- It's fair to say that without this progress physics at the LHC would not be the same…

CERN Workshop on Standard Model Physics (and more) at the LHC May 2000 (with G.Altarelli)

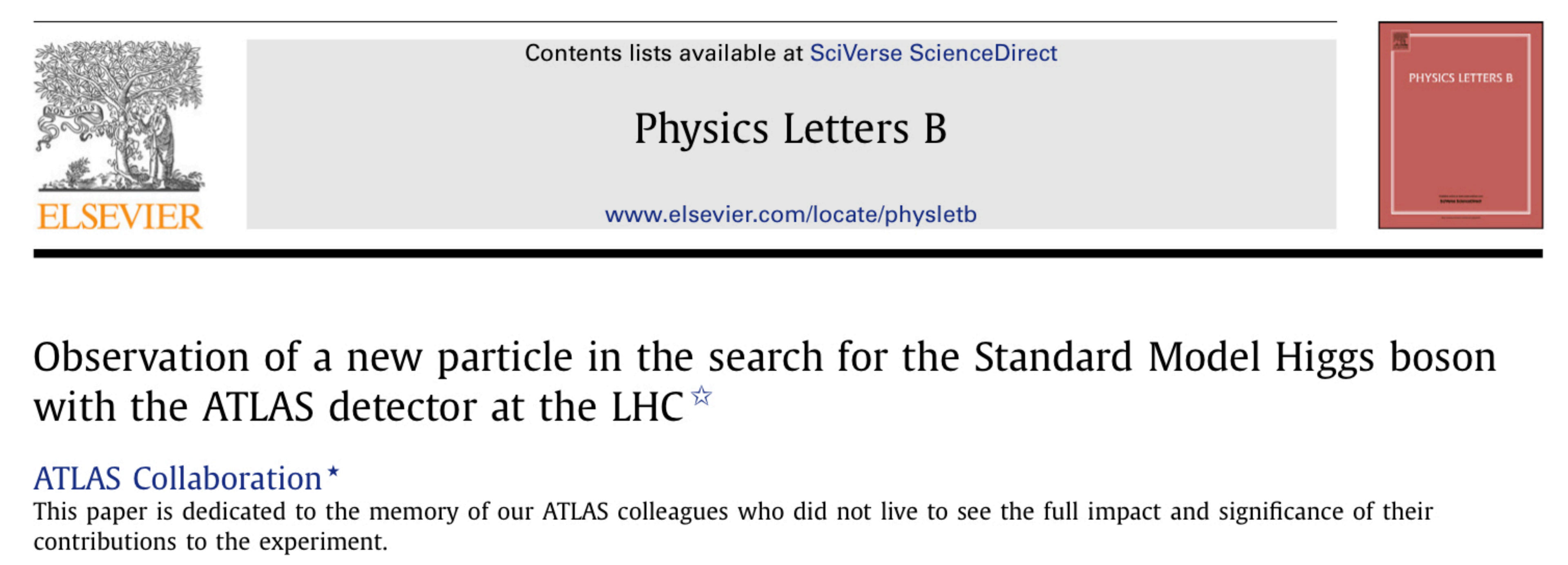
From the Preface of the Yellow Report:

The specific goal of the Workshop, not directly evident from the somewhat mysterious title, was to promote physics studies at the LHC in areas beyond the Higgs and new particles search (especially supersymmetric particles). That is, the purpose was to explore additional possibilities of the experiments beyond the well-studied subjects that are the main focus of the physics programme at the LHC. A strong encouragement to promote this Workshop came from the physicists community, which is very much interested in keeping the discussion on physics alive and focused during the long years of machine and detector construction.

WGs:

- QCD (TH conv: **Catani** Soper Stirling)
- EW physics (TH conv: Hollik Kunszt)
- Bottom quark production (TH conv: Nason Ridolfi)
- Bottom quark decays (TH conv: Ball Fleischer)
- Top quark (TH conv: Beneke MLM)

2012


Contents lists available at SciVerse ScienceDirect

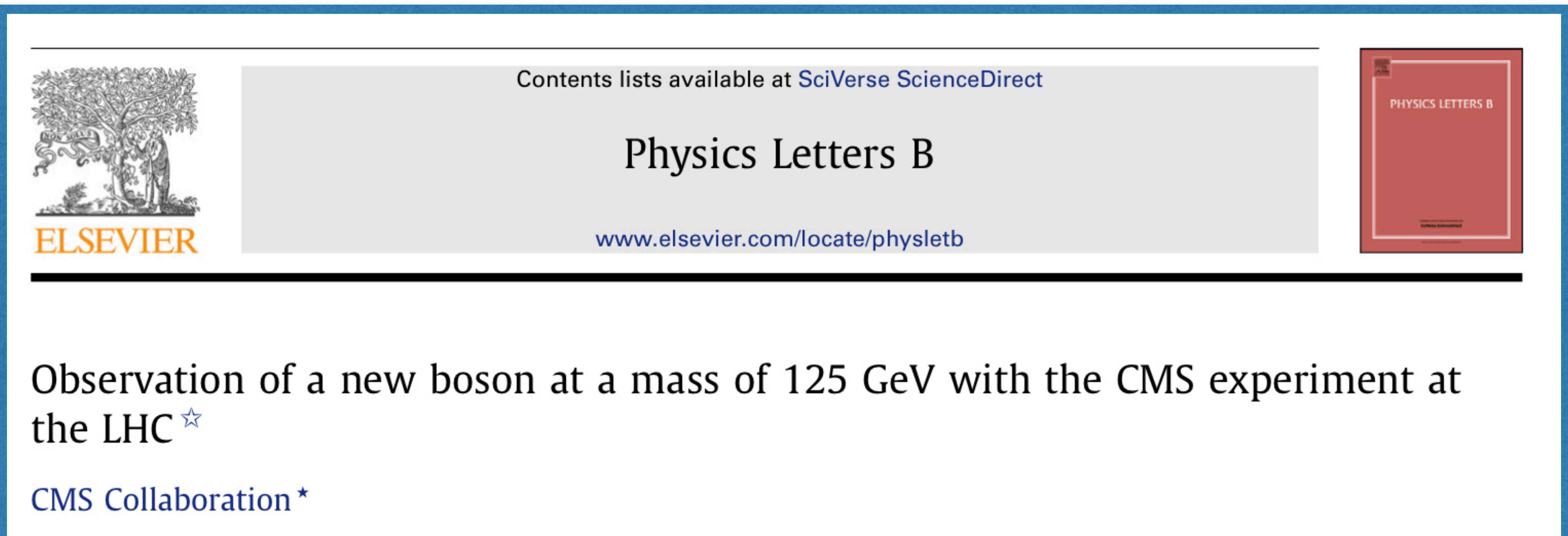
Physics Letters B

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

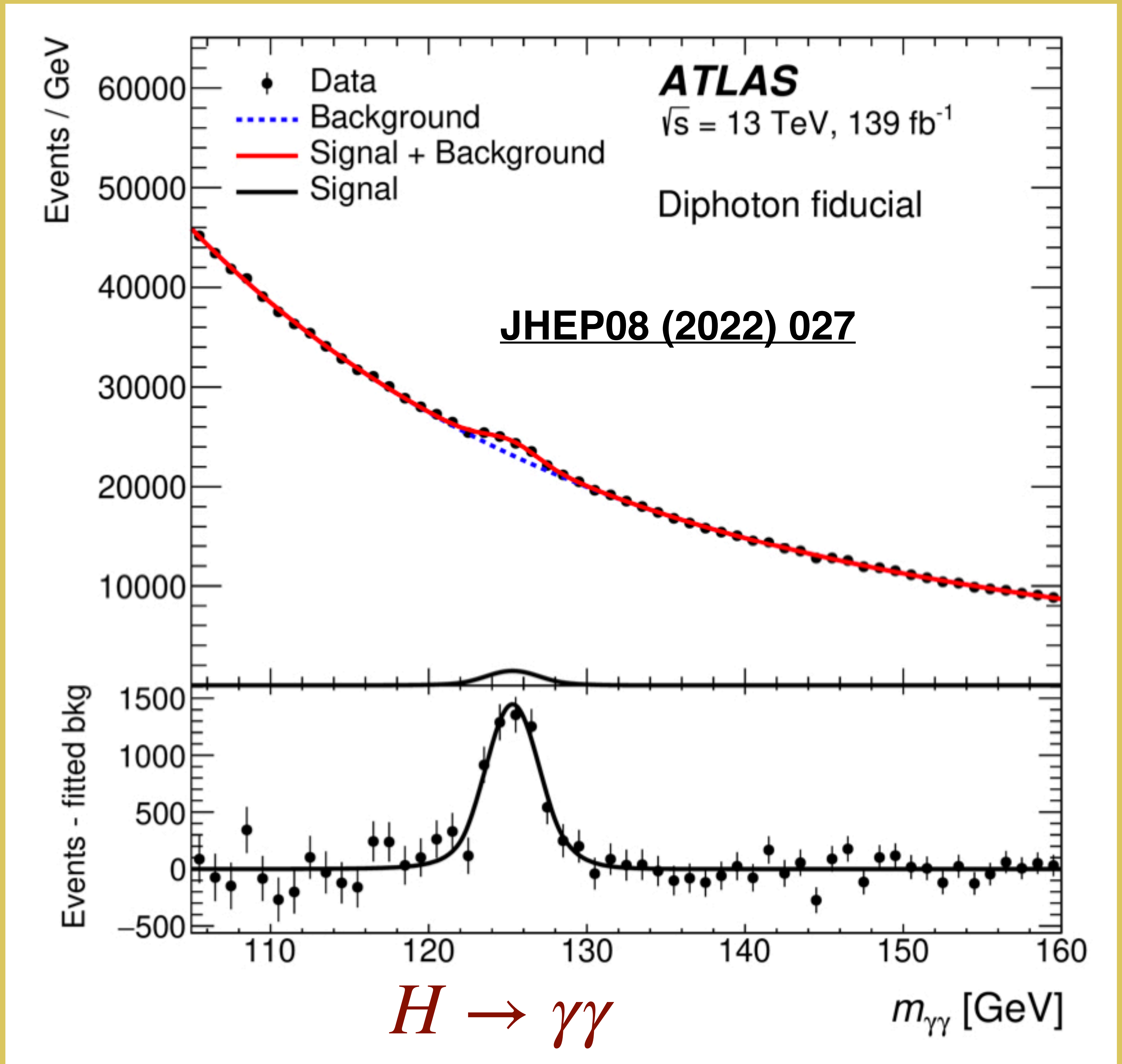
Physics Letters B

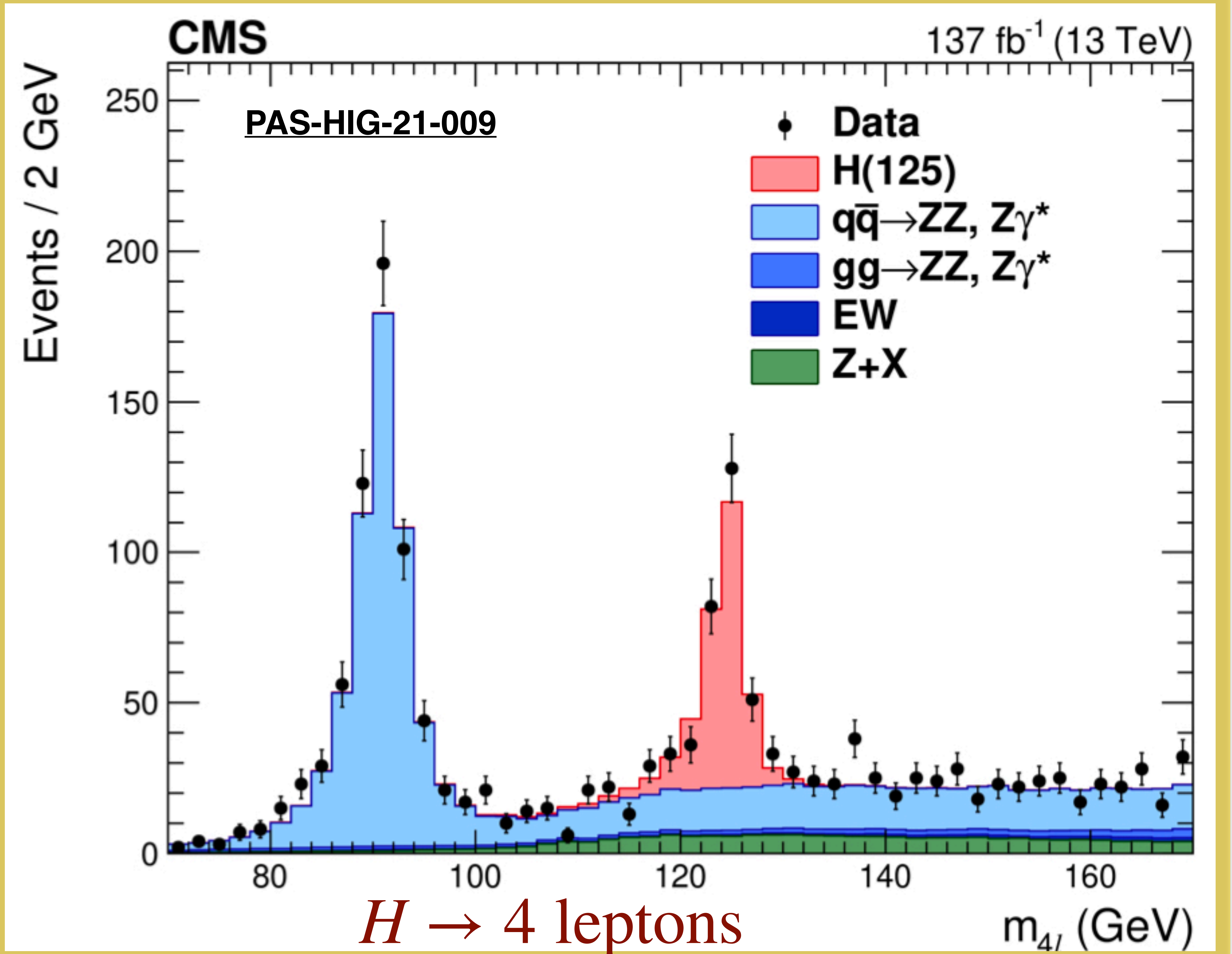
www.elsevier.com/locate/physletb

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

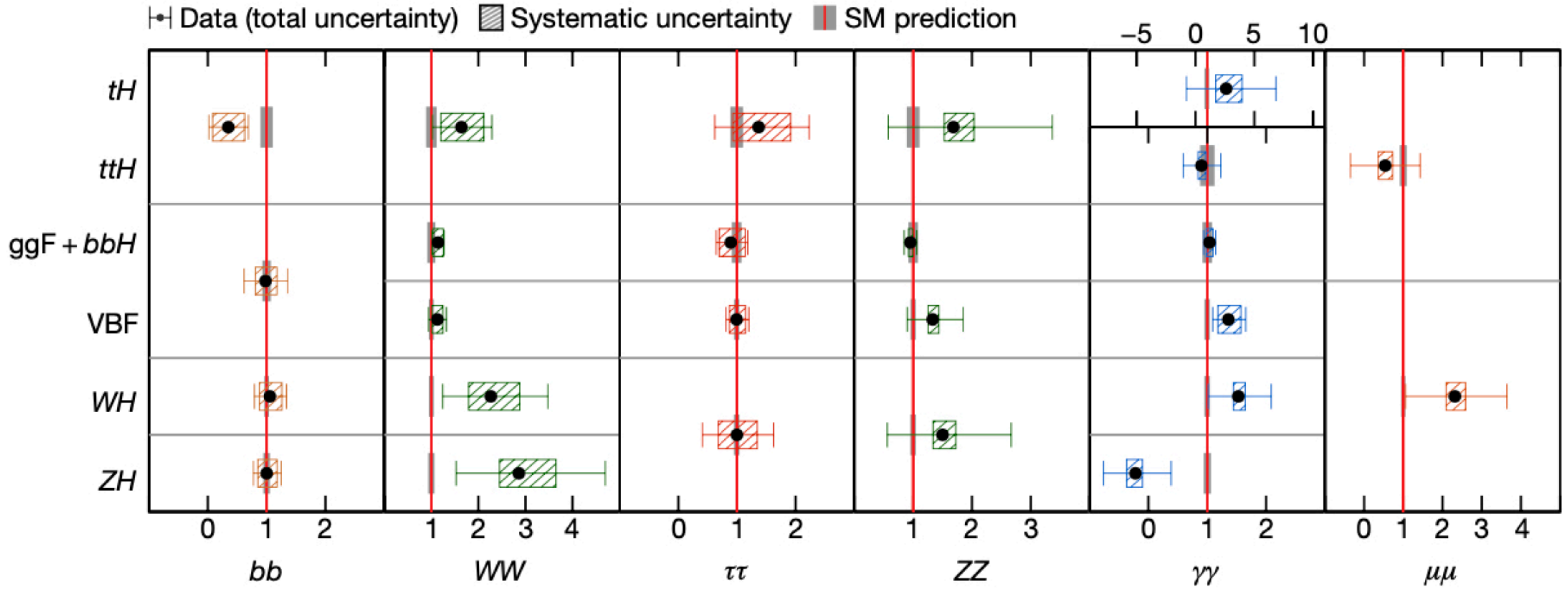
CMS Collaboration *

2023



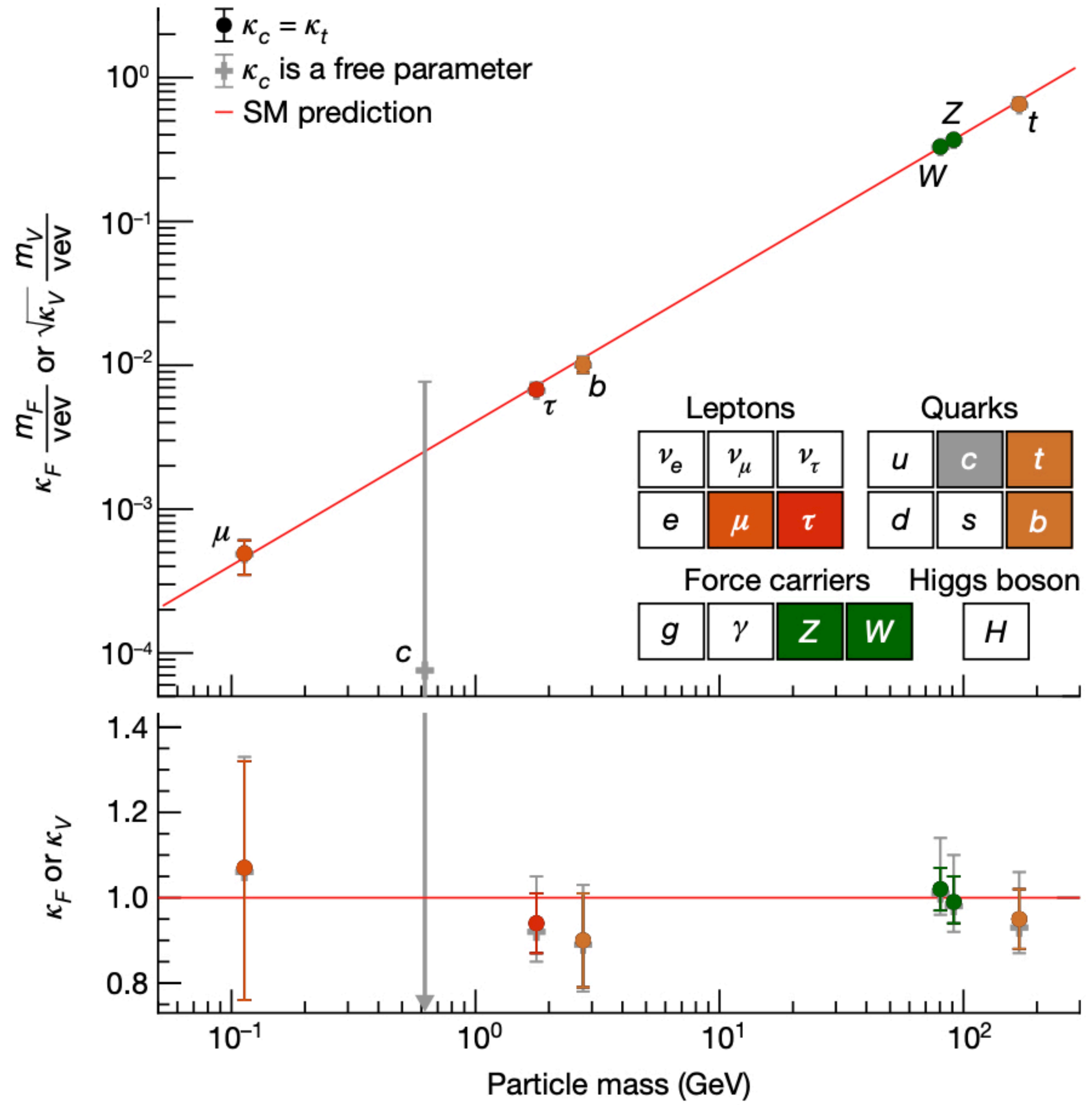


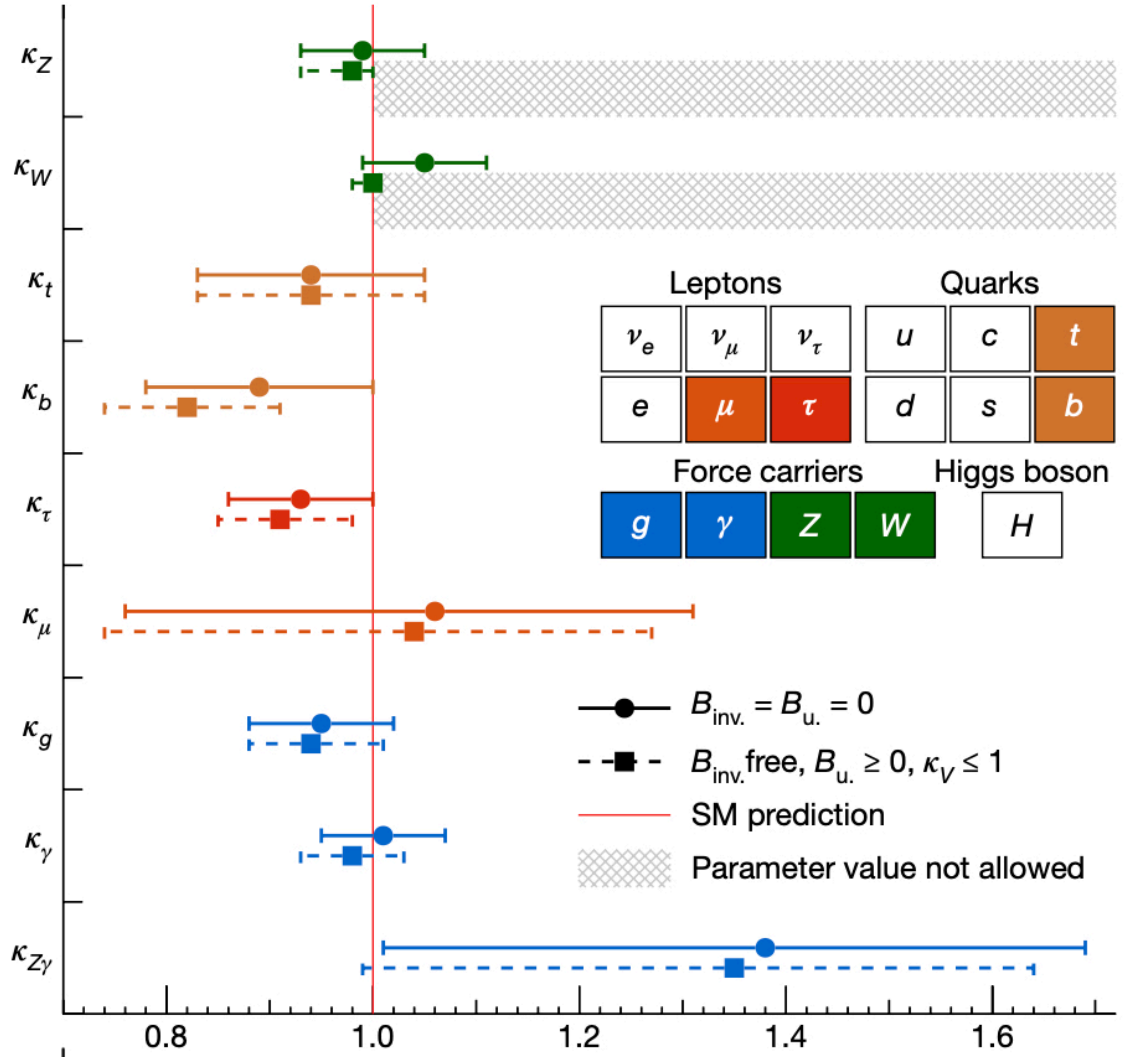
by 2024:
general properties and couplings are OK w. SM



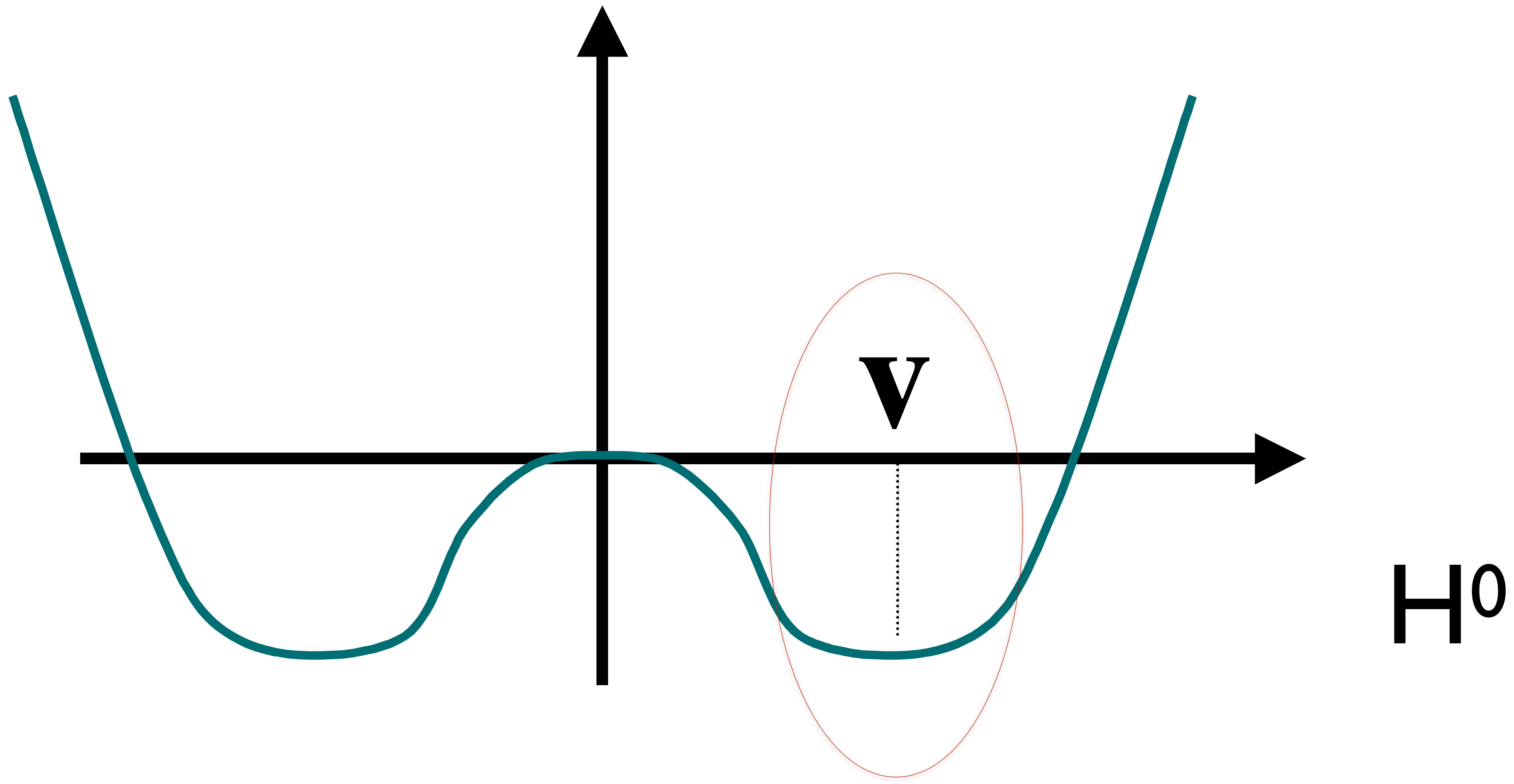
The ATLAS Collaboration
Nature, 607, 52–59 (2022)

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





The ultimate goal of Higgs studies is to address the question



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

Where does this come from?

The Higgs mechanism* , as implemented in the SM (*á la Weinberg, 1967*), provides the *minimal* set of *ingredients* required to enable a consistent breaking of the EW symmetry.

* Higgs, Brout, Englert, Guralnik, Hagen, Kibble 1964

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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 …

* Higgs, Brout, Englert, Guralnik, Hagen, Kibble 1964

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Eg, can we calculate m_H from 1^{st} principles?

* Higgs, Brout, Englert, Guralnik, Hagen, Kibble 1964

To address this question, whose answer cannot be found in the SM, the LHC experiments have been exploring a vast multitude of scenarios of physics beyond the Standard Model

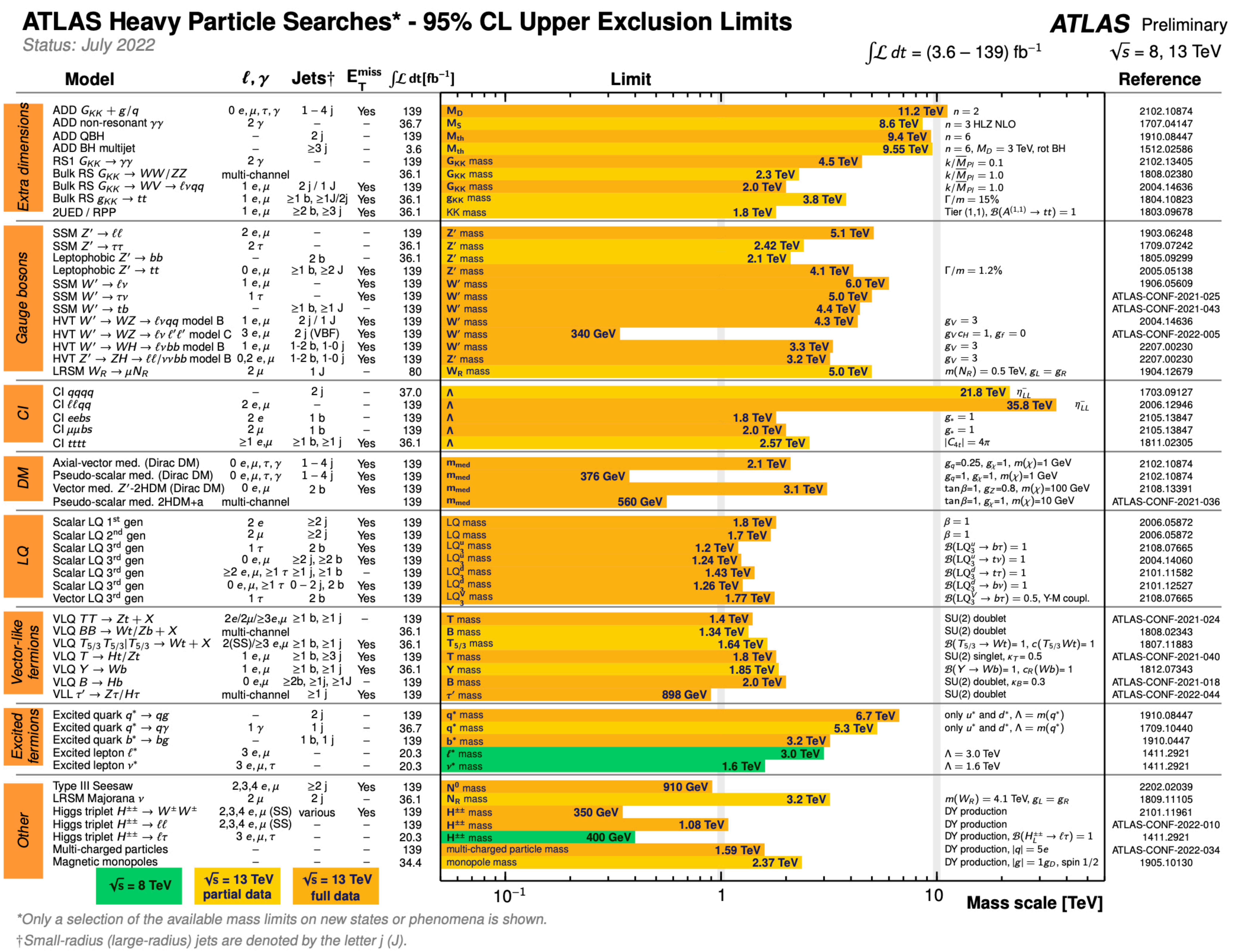
In search of the origin of known departures from the SM

- **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



Given no clear sign of BSM is there,
what else is the LHC good for?

Diversity in the LHC scientific production

Over 4000 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, …)

Beyond Higgs and BSM at the LHC

CERN Workshop on Standard Model Physics (and more) at the LHC May 2000

QCD

Convenors: *S. Catani, M. Dittmar, D. Soper, W.J. Stirling, S. Tapprogge.*
Contributing authors: *S. Alekhin, P. Aurenche, C. Balázs, R.D. Ball, G. Battistoni, E.L. Berger, T. Binoth, R. Brock, D. Casey, G. Corcella, V. Del Duca, A. Del Fabbro, A. De Roeck C. Ewerz, D. de Florian, M. Fontannaz, S. Frixione, W.T. Giele, M. Grazzini, J.P. Guillet, G. Heinrich, J. Huston, J. Kalk, A.L. Kataev, K. Kato, S. Keller, M. Klasen, D.A. Kosower, A. Kulesza, Z. Kunszt, A. Kupco, V.A. Ilyin, L. Magnea, M.L. Mangano, A.D. Martin, K. Mazumdar, Ph. Miné, M. Moretti, W.L. van Neerven, G. Parente, D. Perret-Gallix, E. Pilon, A.E. Pukhov, I. Puljak, J. Pumplin, E. Richter-Was, R.G. Roberts, G.P. Salam, M.H. Seymour, N. Skachkov, A.V. Sidorov, H. Stenzel, D. Stump, R.S. Thorne, D. Treleani, W.K. Tung, A. Vogt, B.R. Webber, M. Werlen, S. Zmouchko.*

An example of the status quo then: the vector boson pt spectrum

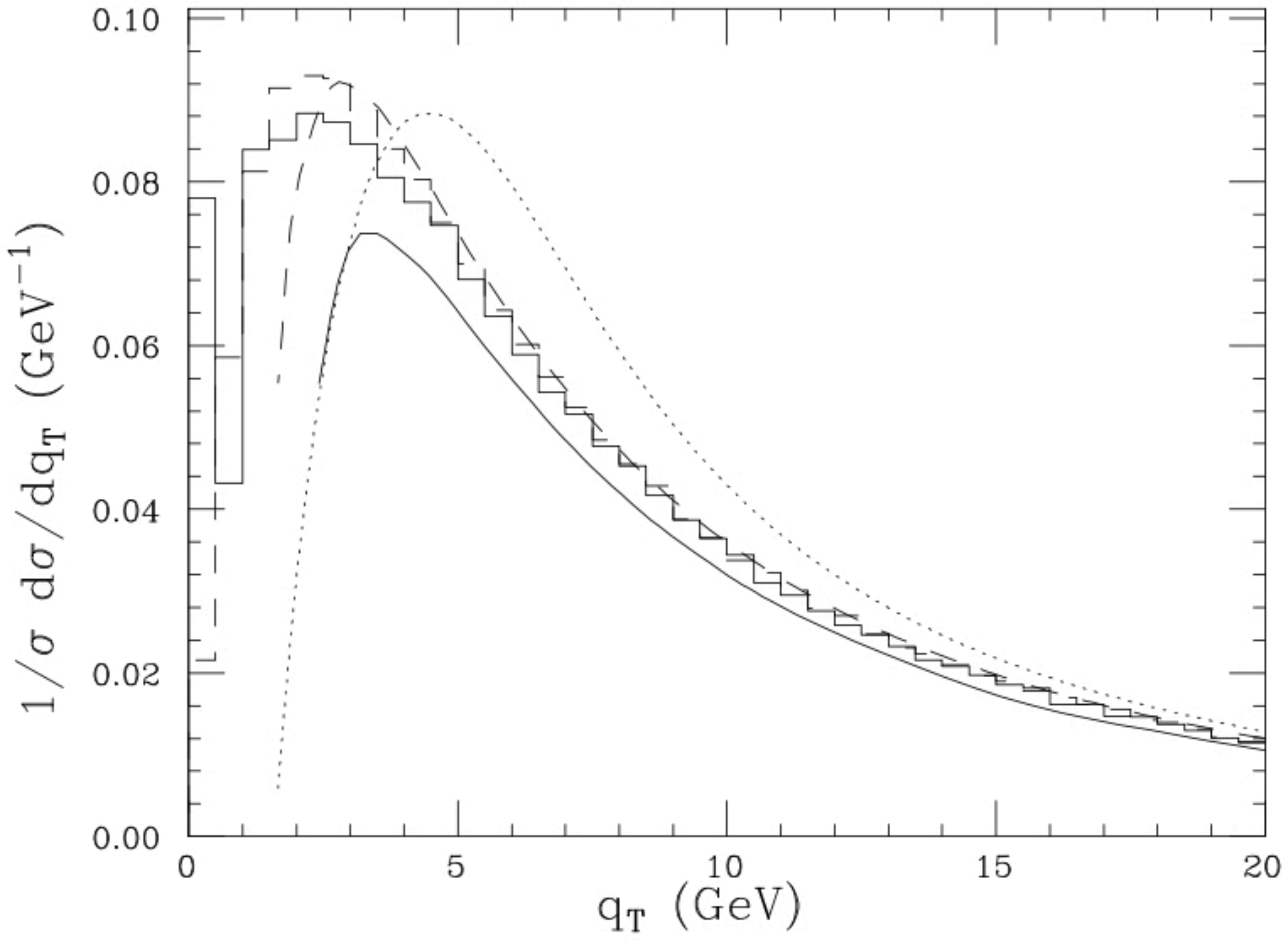


Fig. 26: The W q_T distribution in the low q_T range at the Tevatron, according to HERWIG 6.1, for $q_{T\mathrm{int}} = 0$ (solid histogram) and 1 GeV (dashed histogram), compared with the resummed results of [190] in q_T- (solid line) and b-space (dotted line) and of [191] in the q_T-space.

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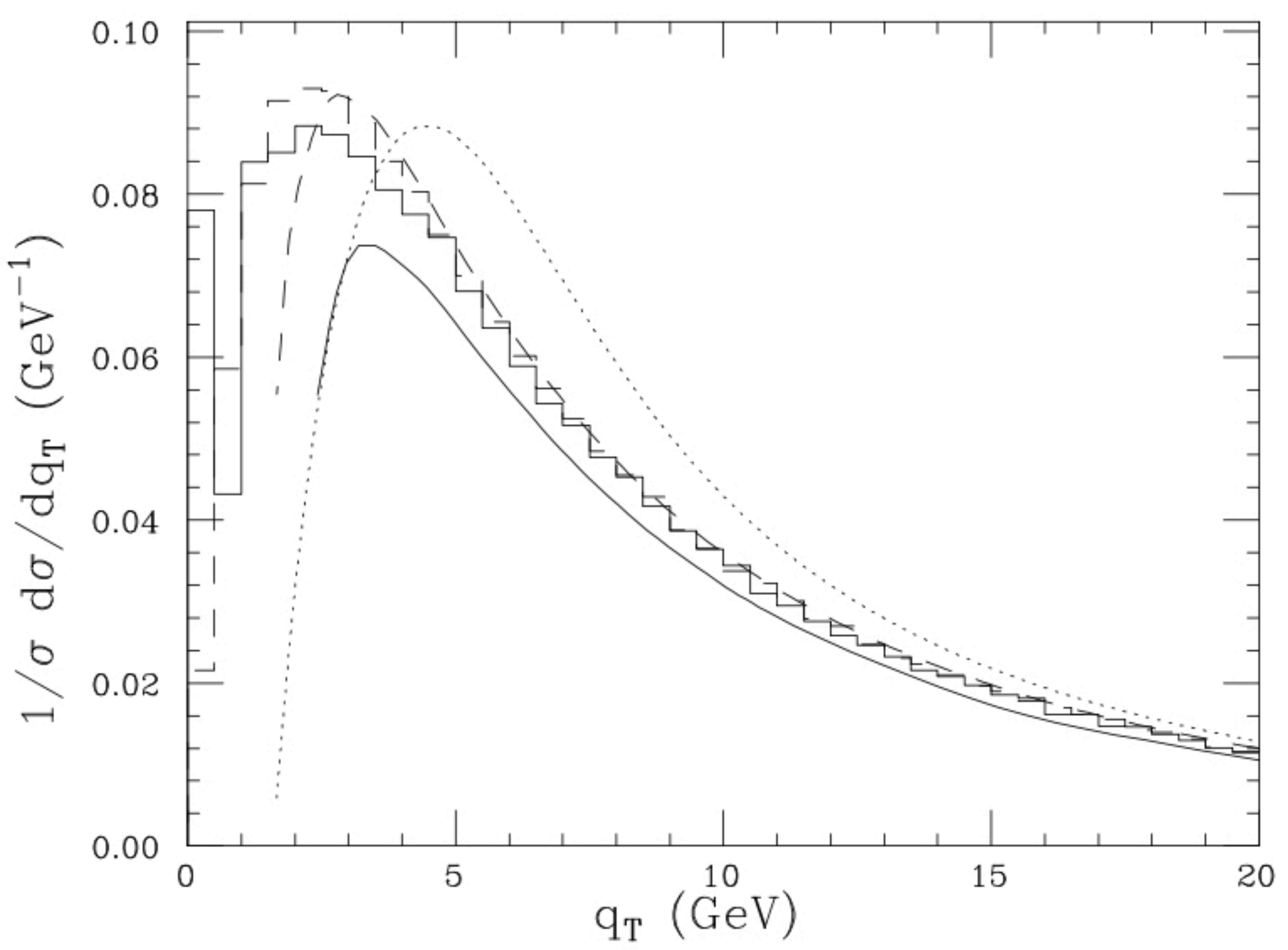

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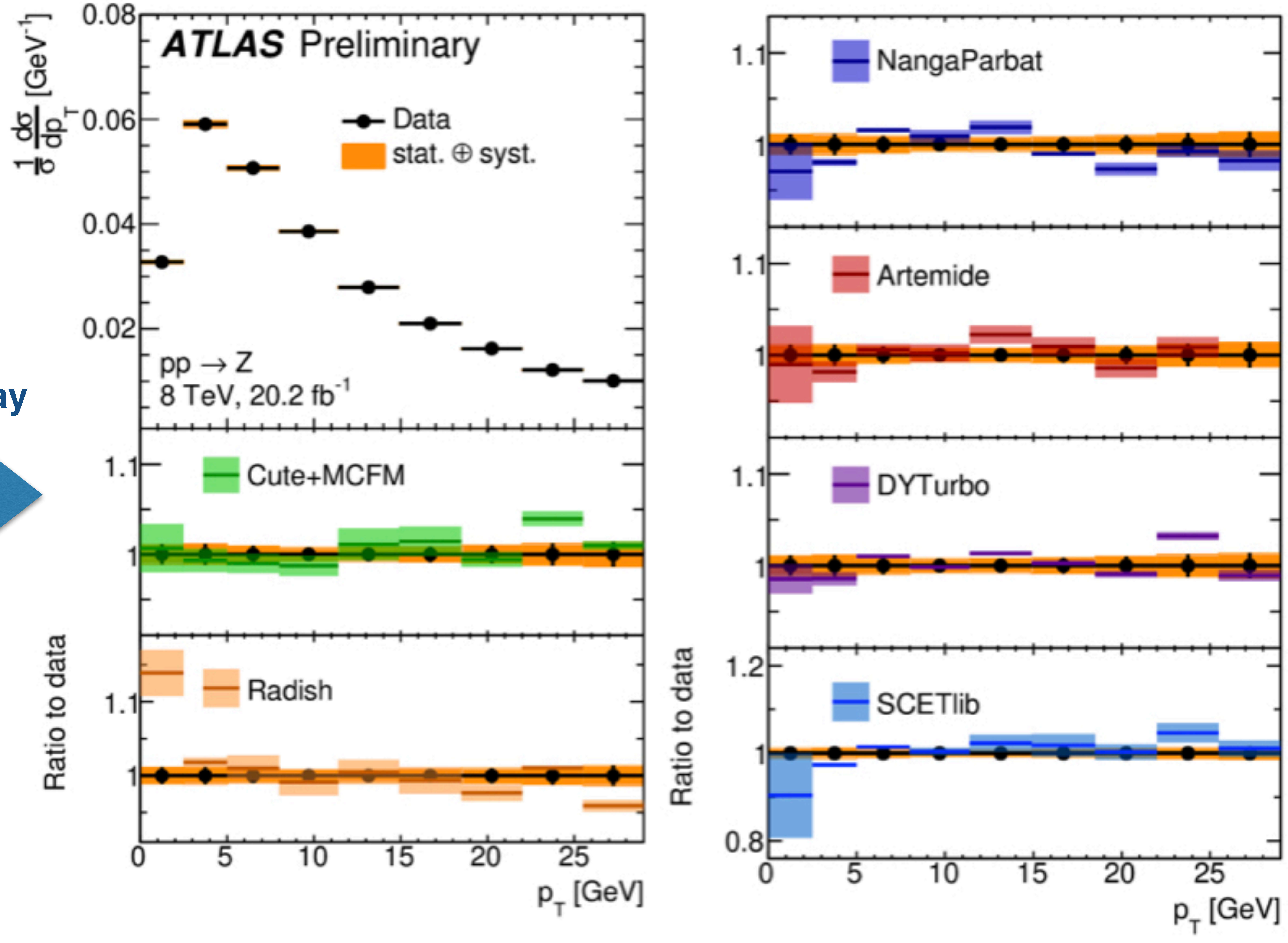
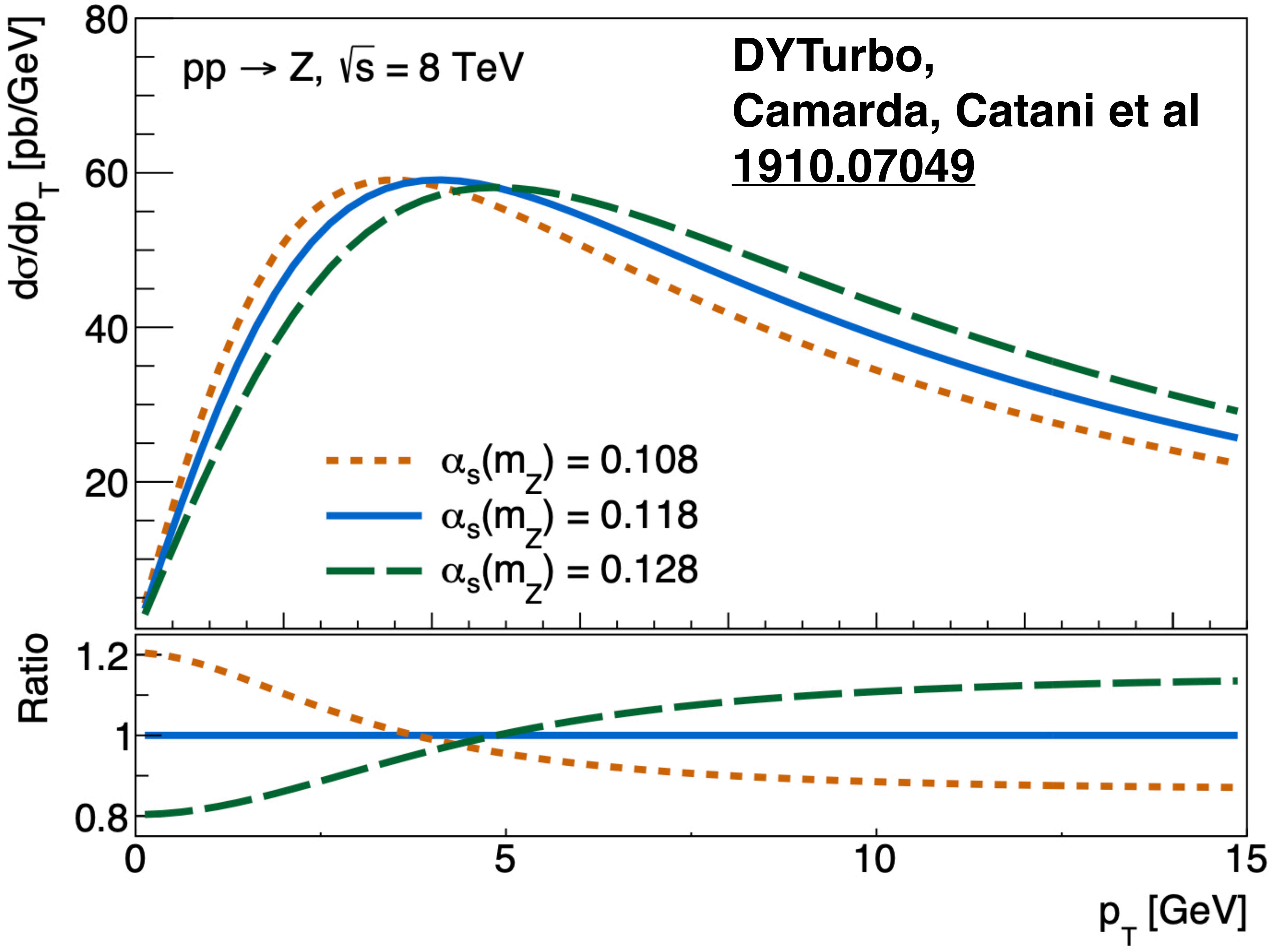
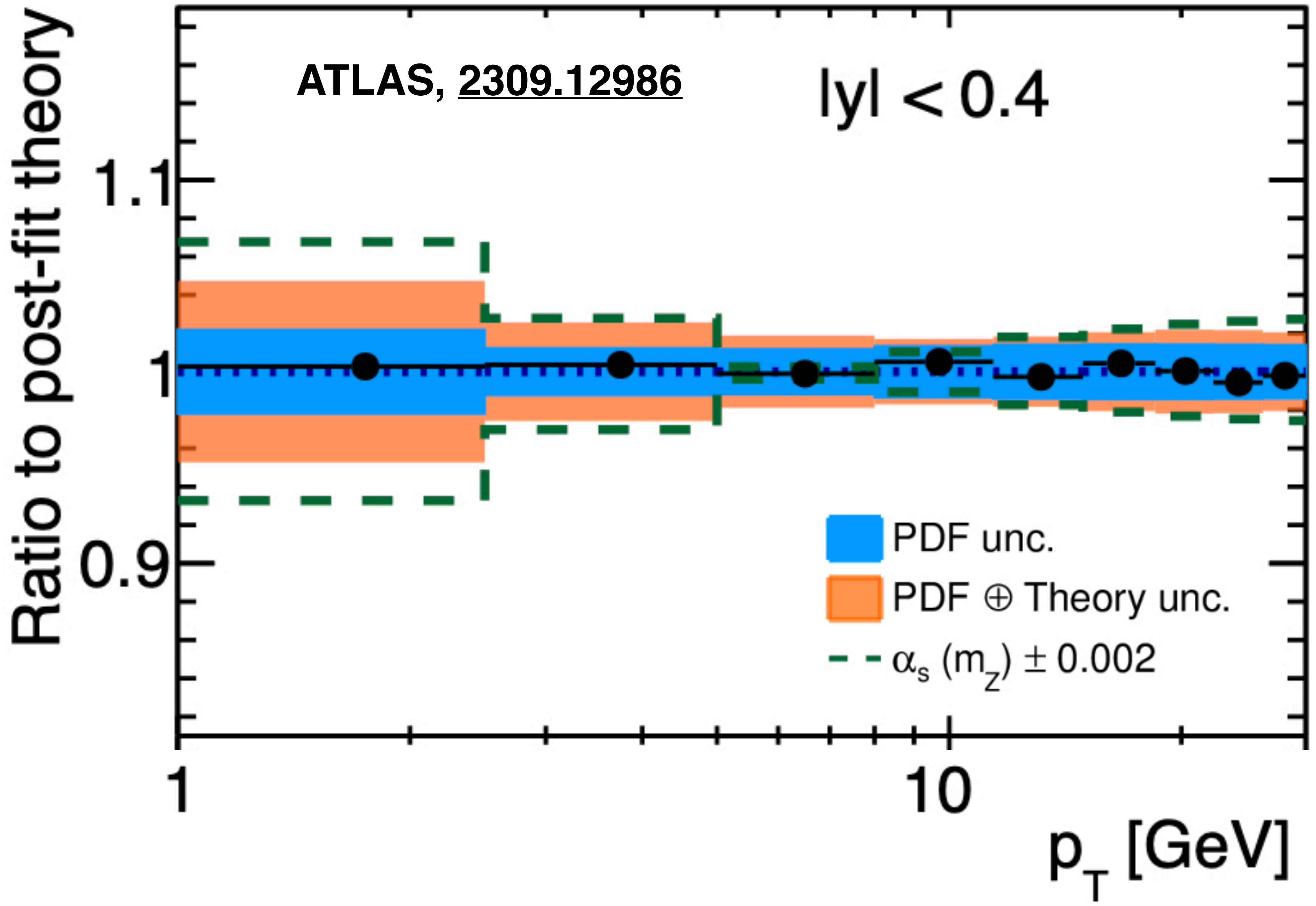
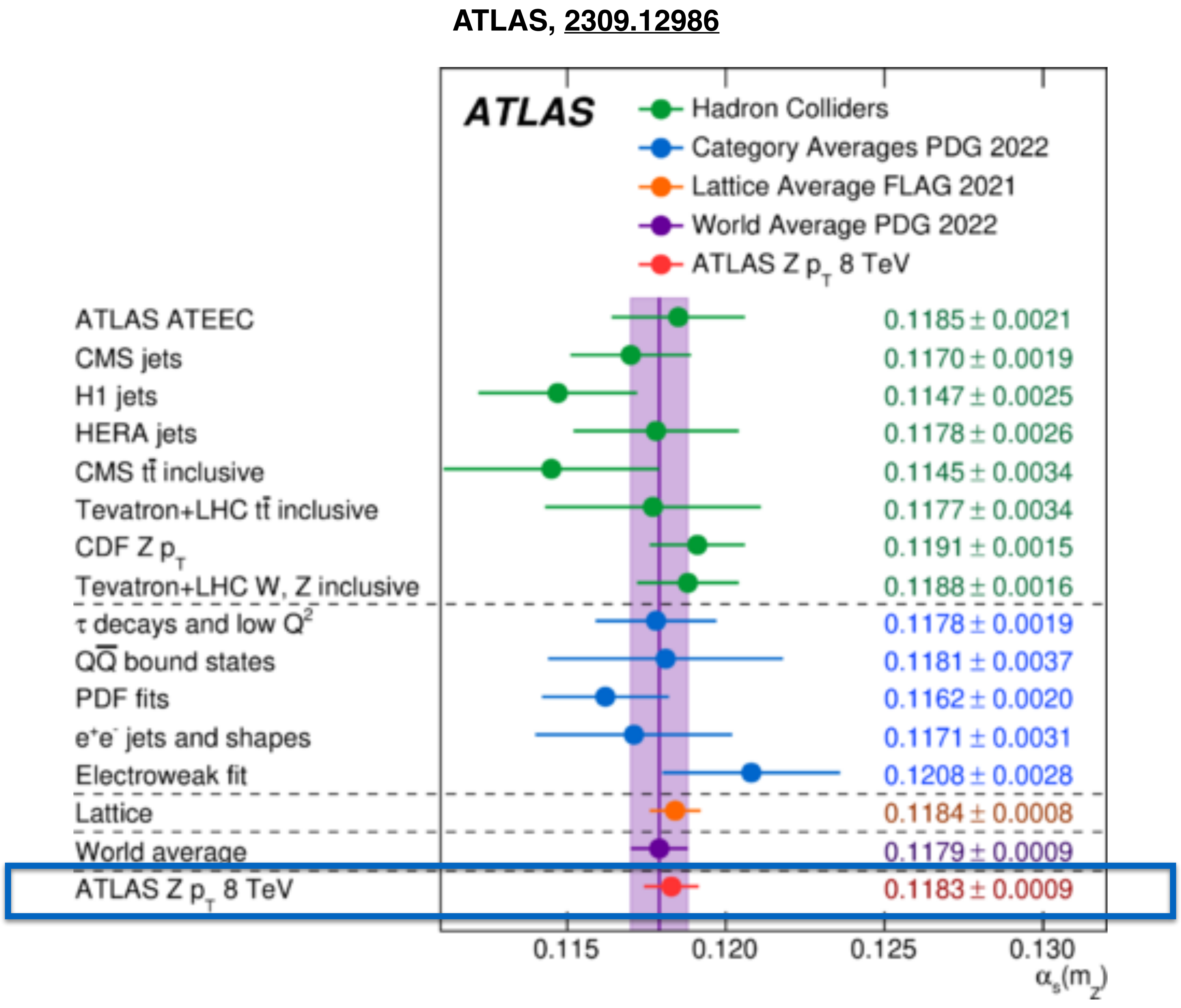
today

ATLAS, 2309.12986




pp → Z, √s = 8 TeV
DYTurbo,
Camarda, Catani et al
1910.07049
dσ/dp_T [pb/GeV]
α_s(m_Z) = 0.108
α_s(m_Z) = 0.118
α_s(m_Z) = 0.128
Ratio
p_T [GeV]


ATLAS, 2309.12986
|y| < 0.4
Ratio to post-fit theory
PDF unc.
PDF ⊕ Theory unc.
α_s (m_Z) ± 0.002
p_T [GeV]

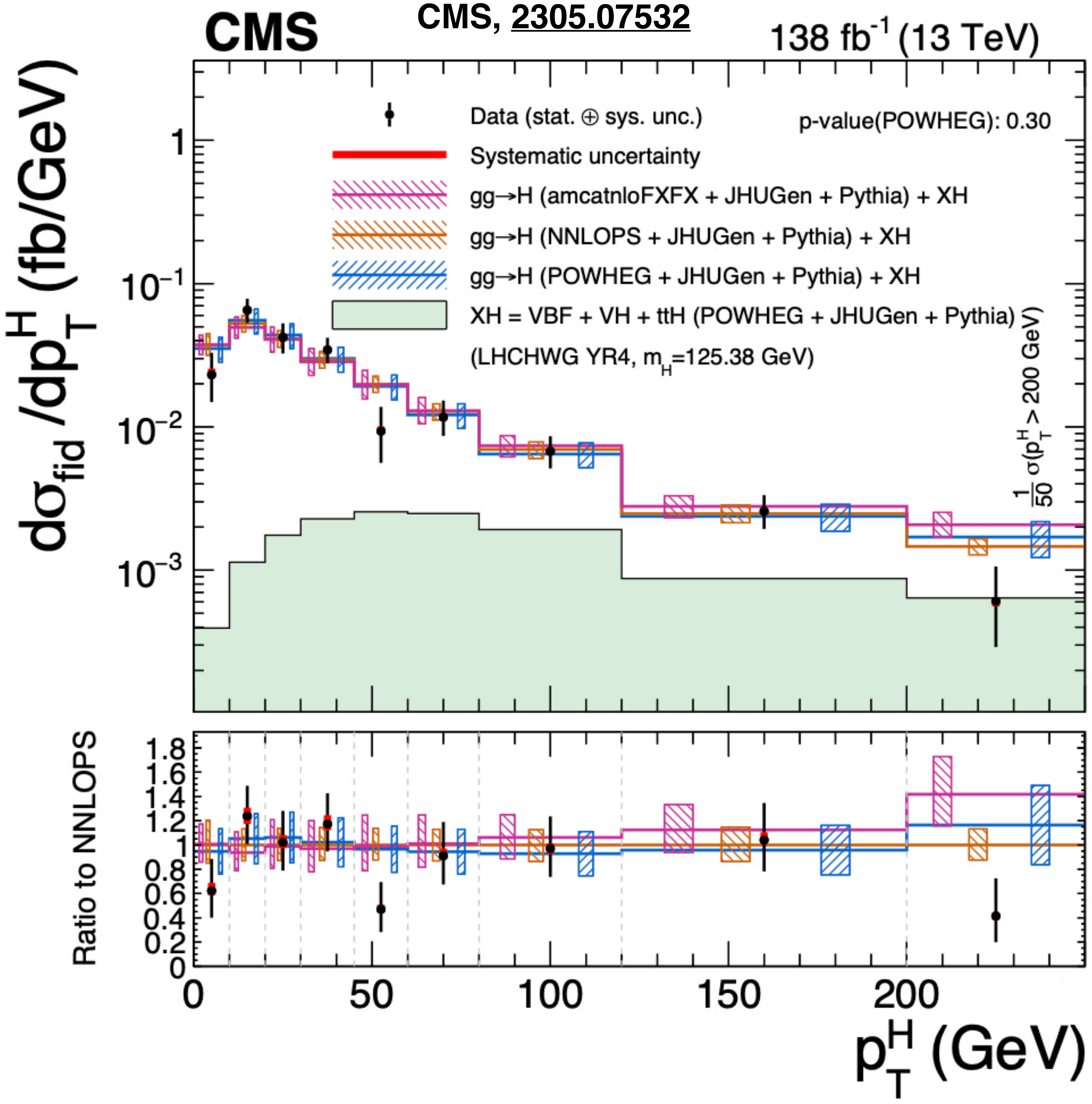

ATLAS, 2309.12986
ATLAS
Hadron Colliders
Category Averages PDG 2022
Lattice Average FLAG 2021
World Average PDG 2022
ATLAS Z p_T 8 TeV
ATLAS ATEEC 0.1185 ± 0.0021
CMS jets 0.1170 ± 0.0019
H1 jets 0.1147 ± 0.0025
HERA jets 0.1178 ± 0.0026
CMS tt̄ inclusive 0.1145 ± 0.0034
Tevatron+LHC tt̄ inclusive 0.1177 ± 0.0034
CDF Z p_T 0.1191 ± 0.0015
Tevatron+LHC W, Z inclusive 0.1188 ± 0.0016
τ decays and low Q² 0.1178 ± 0.0019
QQ̄ bound states 0.1181 ± 0.0037
PDF fits 0.1162 ± 0.0020
e⁺e⁻ jets and shapes 0.1171 ± 0.0031
Electroweak fit 0.1208 ± 0.0028
Lattice 0.1184 ± 0.0008
World average 0.1179 ± 0.0009
ATLAS Z p_T 8 TeV 0.1183 ± 0.0009
α_s(m_Z)

The future: precision measurements of the Higgs pt spectrum

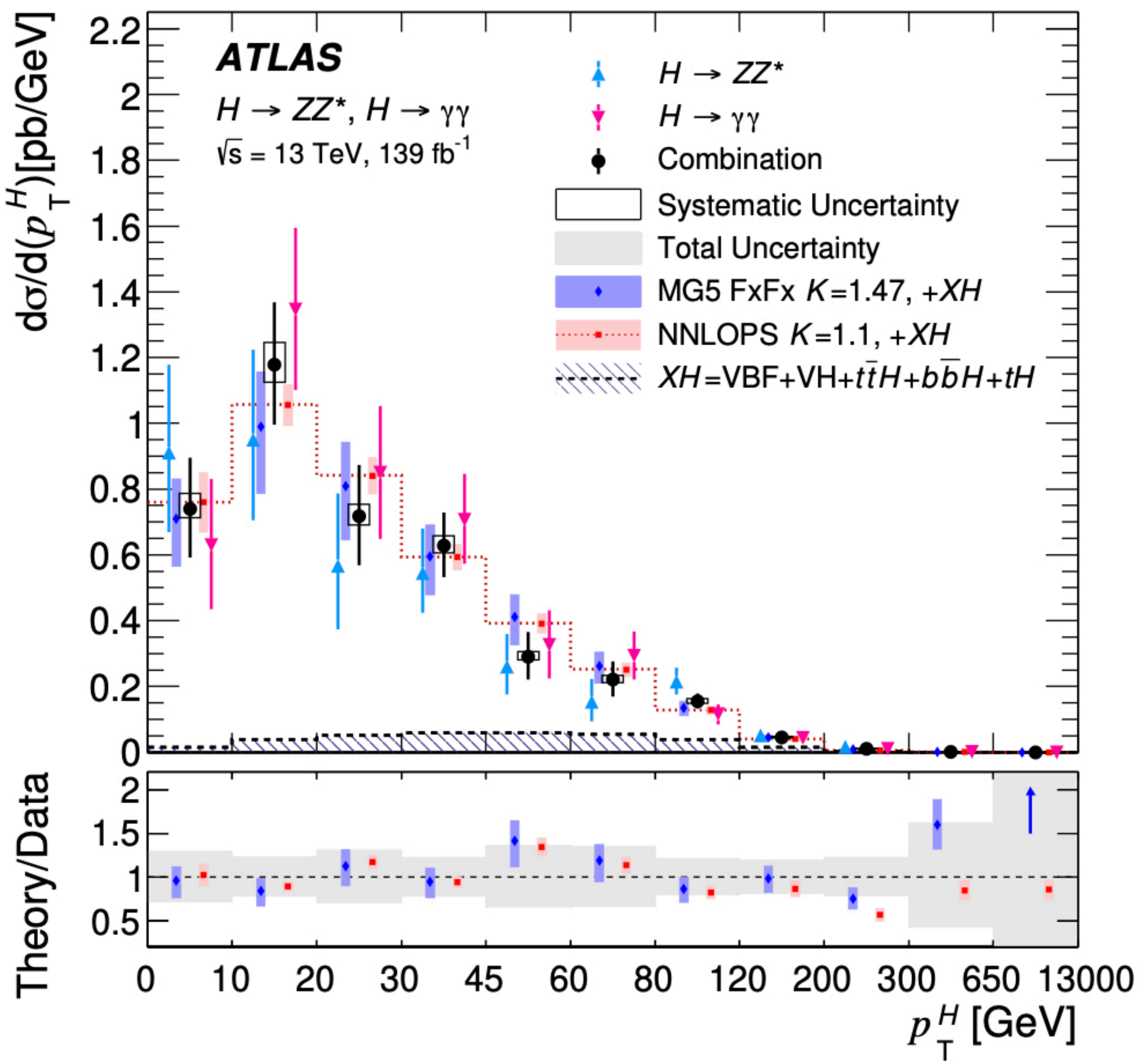
Catani, d'Emilio, Trentadue, The Gluon Form-factor to Higher Orders: Gluon Gluon Annihilation at Small Q_T PLB 211 (1988) 335

> In the foreseeable future, at the energies of the large hadron colliders as LHC (16 TeV) and SSC (40 TeV) the large majority of physical processes will be generated via initial state interactions among gluons [1]. These will give rise to states such as Higgs particles [2], neutral heavy mesons and jets.

CMS, 2305.07532



ATLAS, 2207.08615



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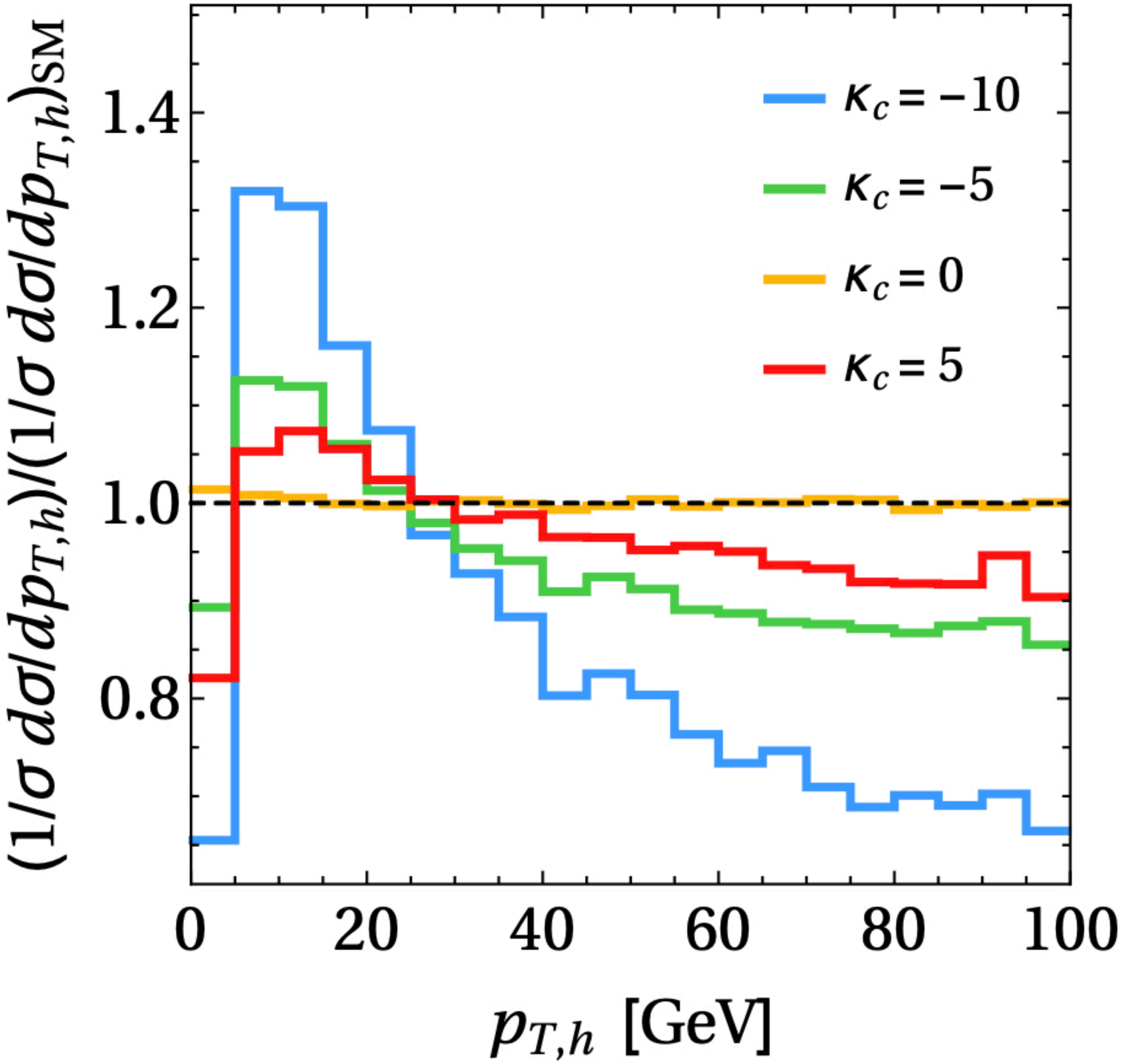
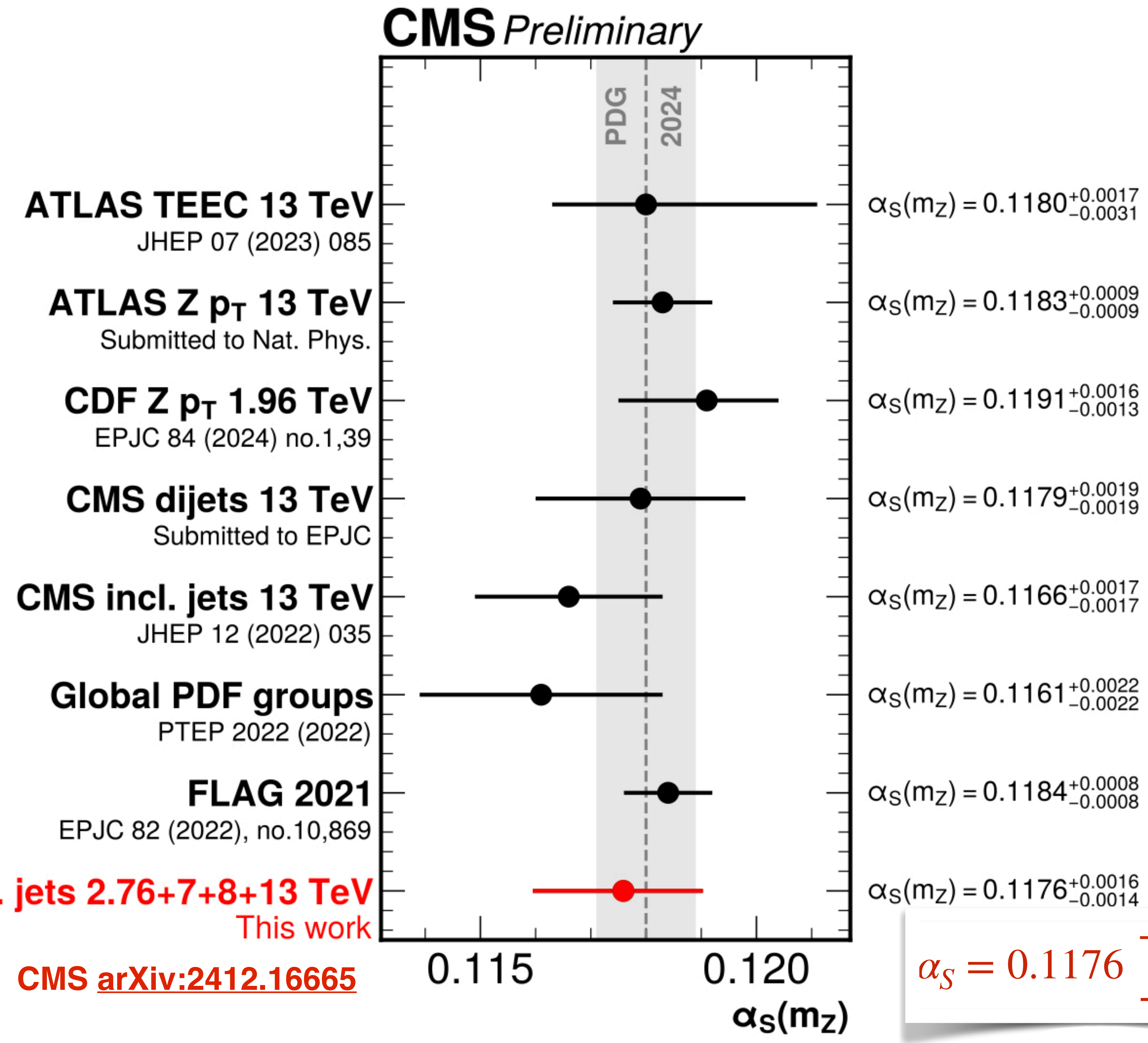
E.g sensitivity to light-quark Higgs Yukawa coupling:
Bishara et al, 1606.09253

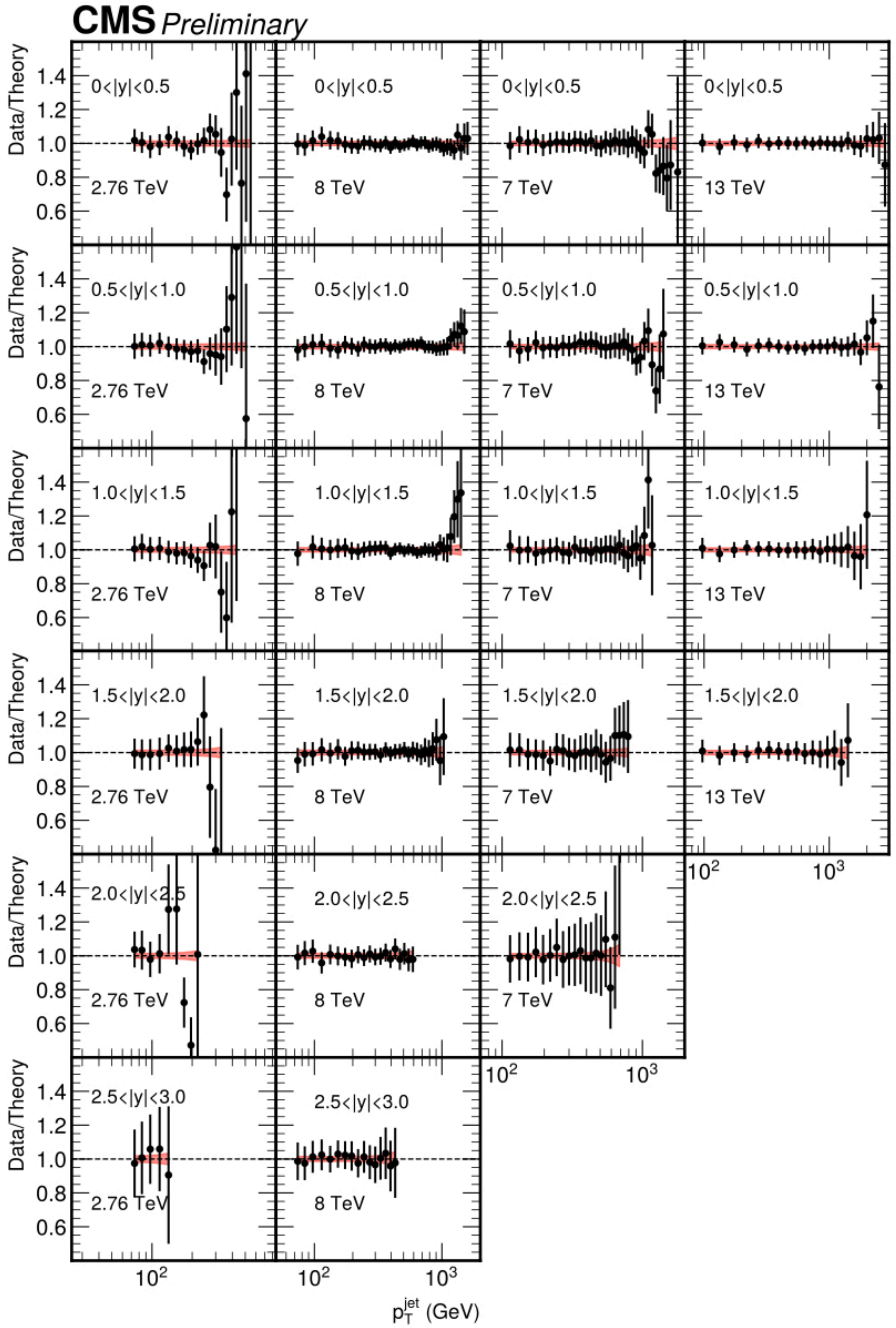


α_S from inclusive jet p_T at $\sqrt{S}$ = 2.76, 7, 8 and 13 TeV

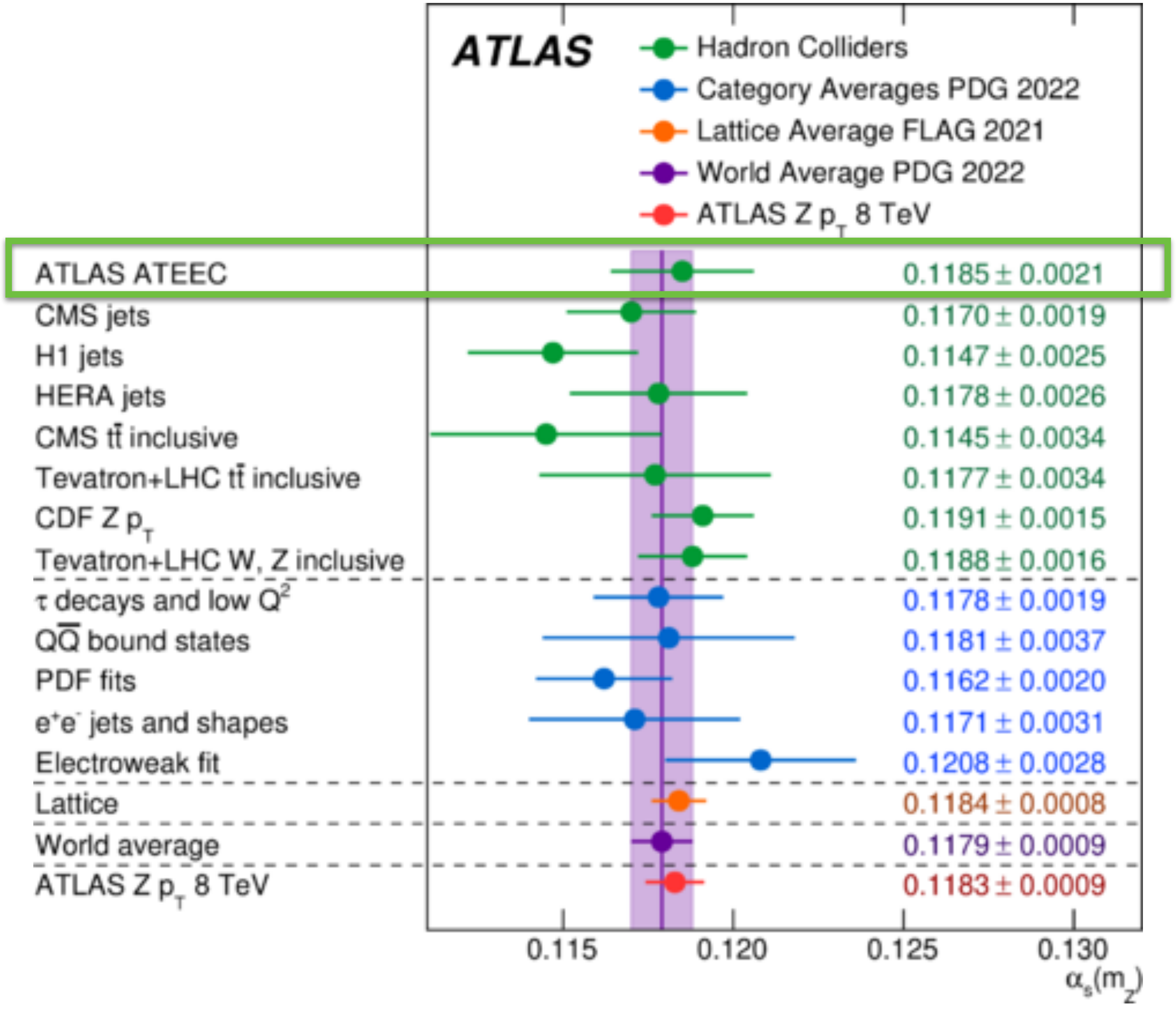


CMS arXiv:2412.16665

$$\alpha_S = 0.1176 \begin{array}{l} +0.0016 \\ -0.0014 \end{array}$$



Improved experimental precision drives new opportunities for precise theoretical interpretations of the results

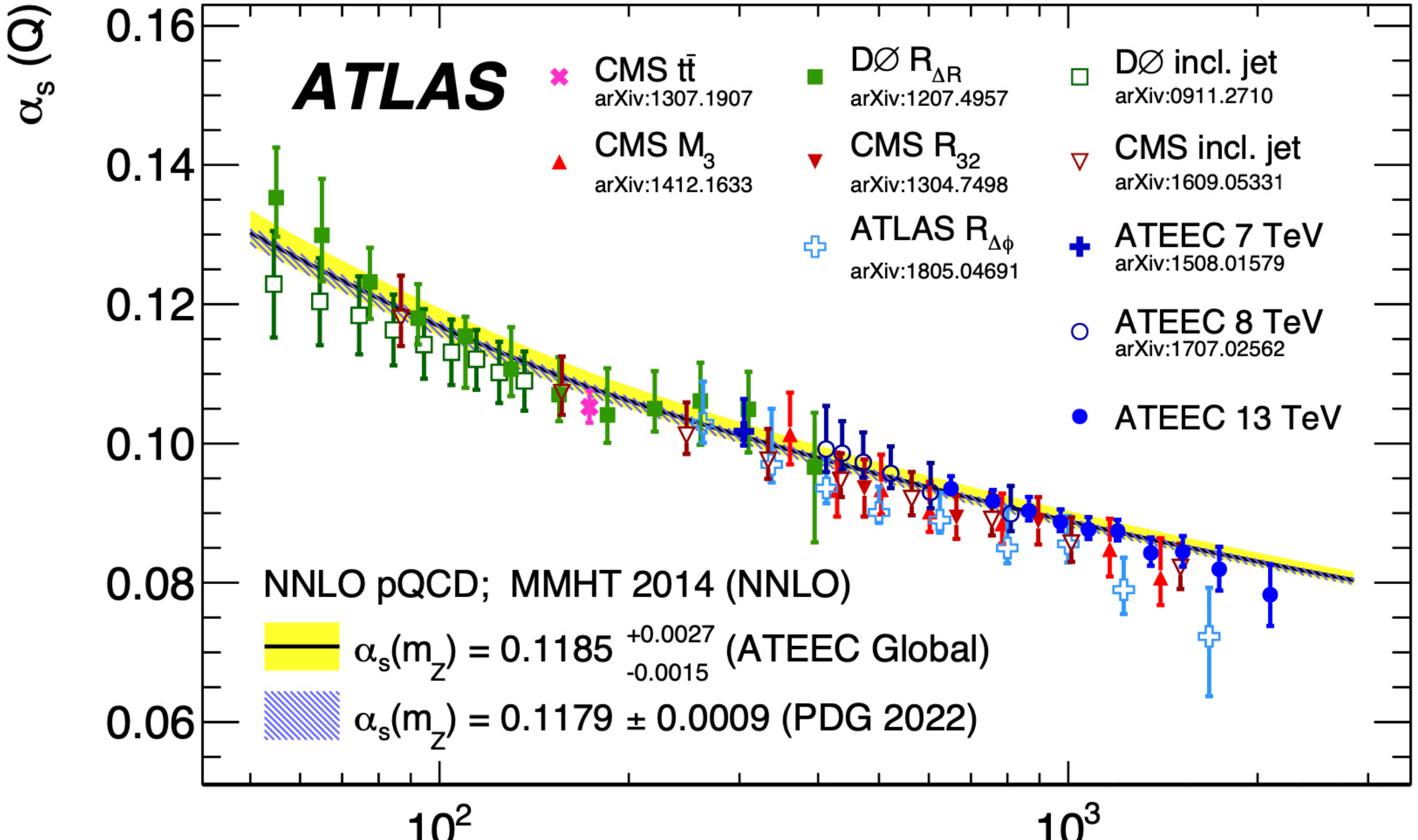


Asymmetric transverse energy-energy correlations

$$\frac{1}{\sigma}\frac{d\Sigma}{d\cos\phi} := \frac{1}{N}\sum_{A=1}^{N}\sum_{ij}\frac{E_{Ti}^{A}E_{Tj}^{A}}{\left(\sum_k E_{Tk}^{A}\right)^2}\delta(\cos\phi - \cos\varphi_{ij}),$$

$$\frac{1}{\sigma}\frac{d\Sigma^{asym}}{d\cos\phi} = \frac{1}{\sigma}\frac{d\Sigma}{d\cos\phi}\bigg|_{\phi} - \frac{1}{\sigma}\frac{d\Sigma}{d\cos\phi}\bigg|_{\pi-\phi}.$$

ATLAS, 2301.09351



- Hot discussions always take place on whether the theoretical systematics are properly accounted for, resulting in over-optimistic estimates of the real uncertainties …
- … but while these discussions back in 2000 dealt with factors of 100% systematics, we are now dealing with factors of few %
- QCD @ hadron colliders has since matured into a powerful, accurate and reliable instrument

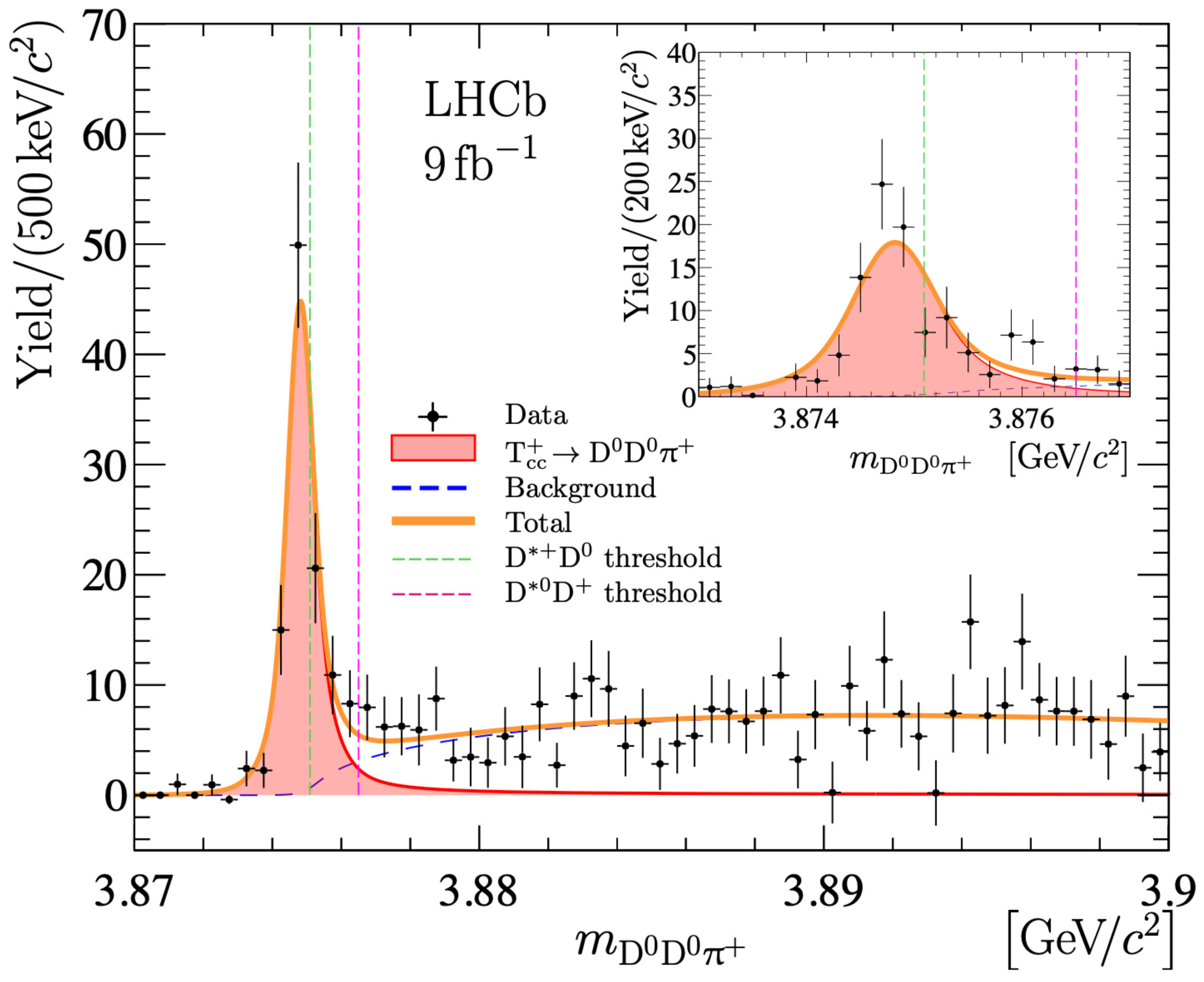
Beyond precision: exploring QCD dynamics with the LHC

- Hadronic spectroscopy, including exotic (anti)nuclei formation
- “Extreme” final states and dynamical regimes:
  - large particle/jet multiplicity,
  - large energy in the partonic system,
  - high density/T …
- Hadronization and fragmentation
- Forward physics:
  - Total cross-sections, elastic scattering, etc.
  - Impact on study of cosmic ray interactions and formation
  - High-E neutrino interactions
- …

Exotic Spectroscopy, nuclear physics and more

Tetraquarks, pentaquarks, double-heavy baryons, exotics, …

$cc\bar{u}\bar{d}$



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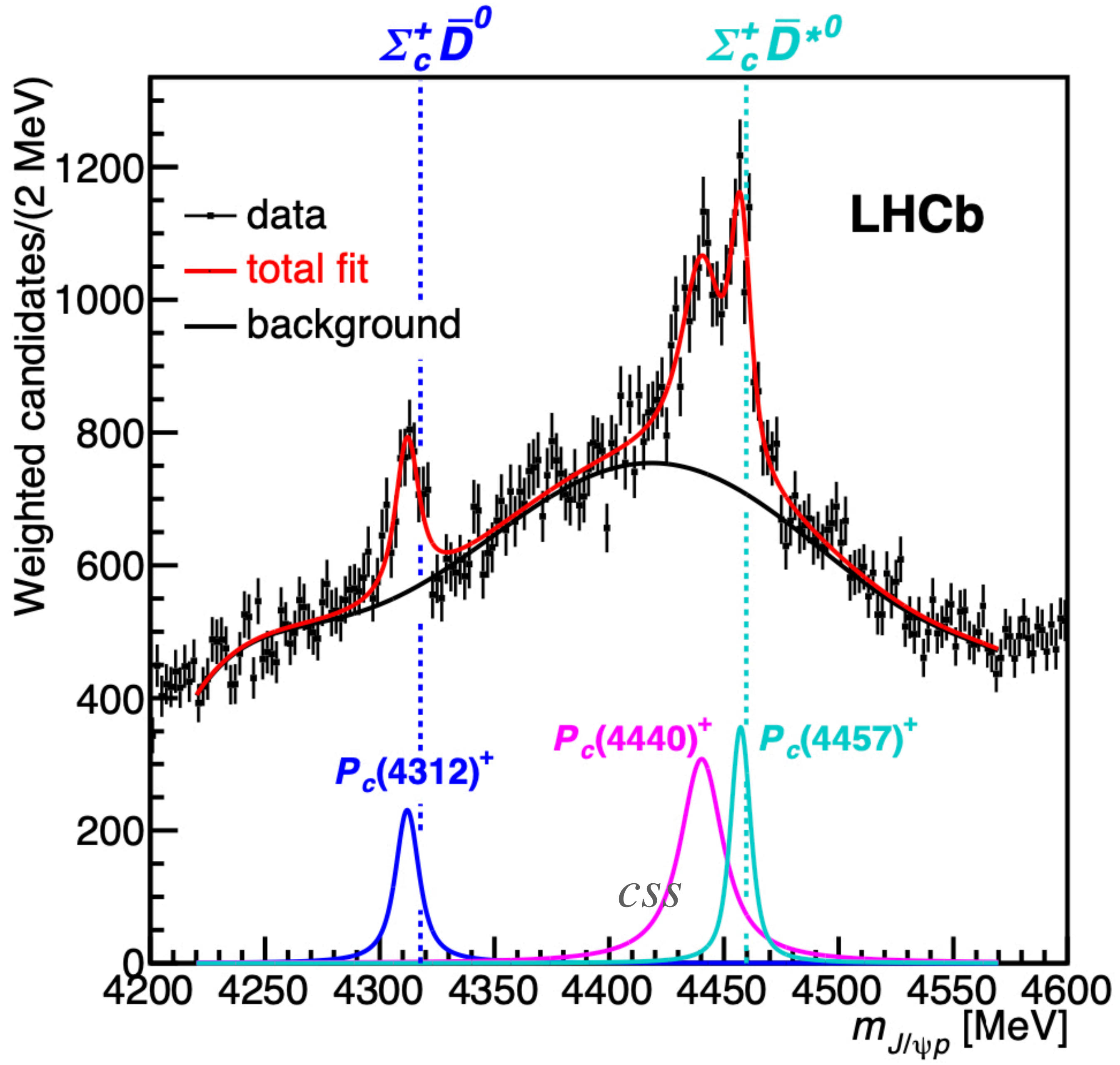

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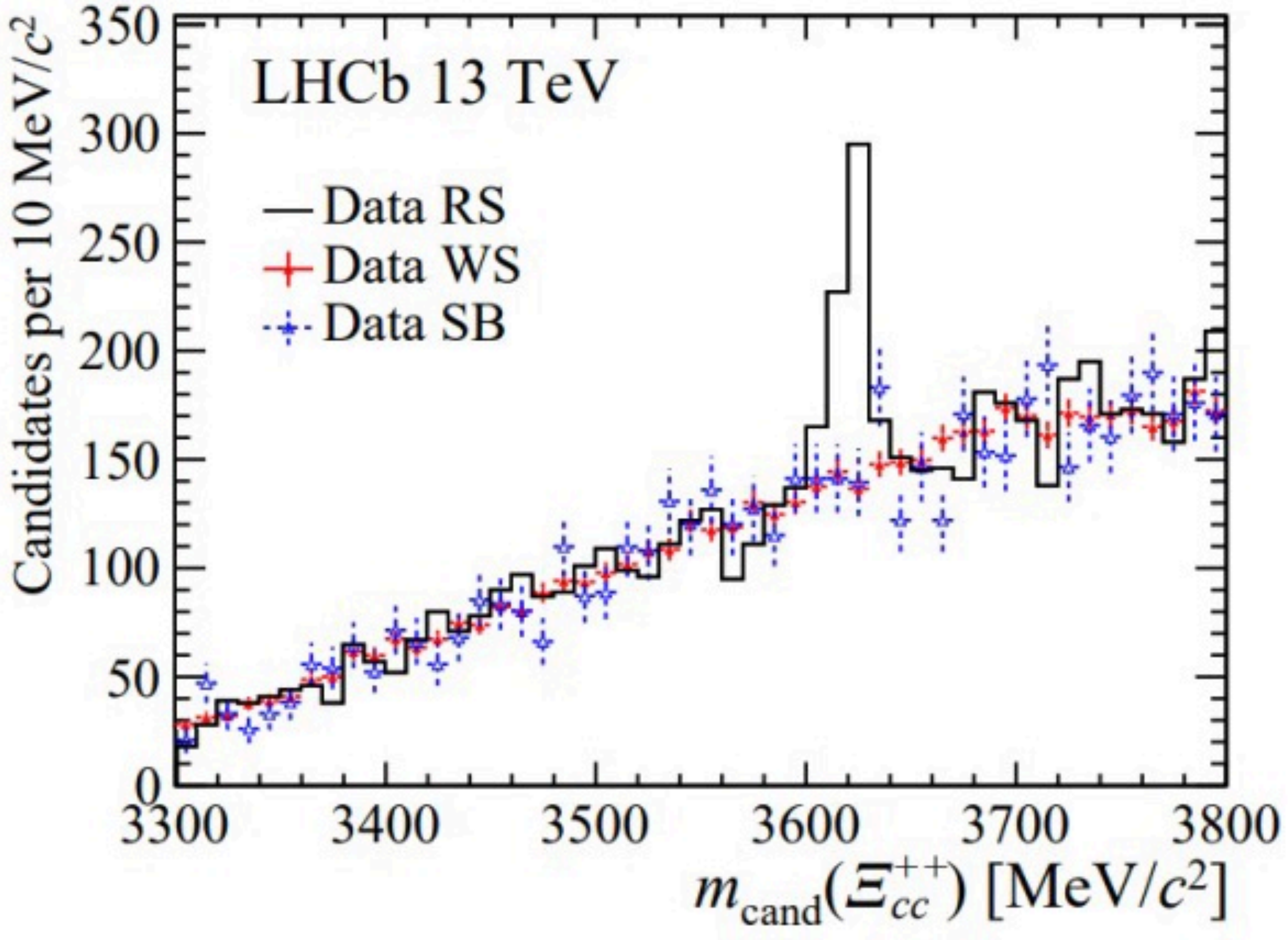
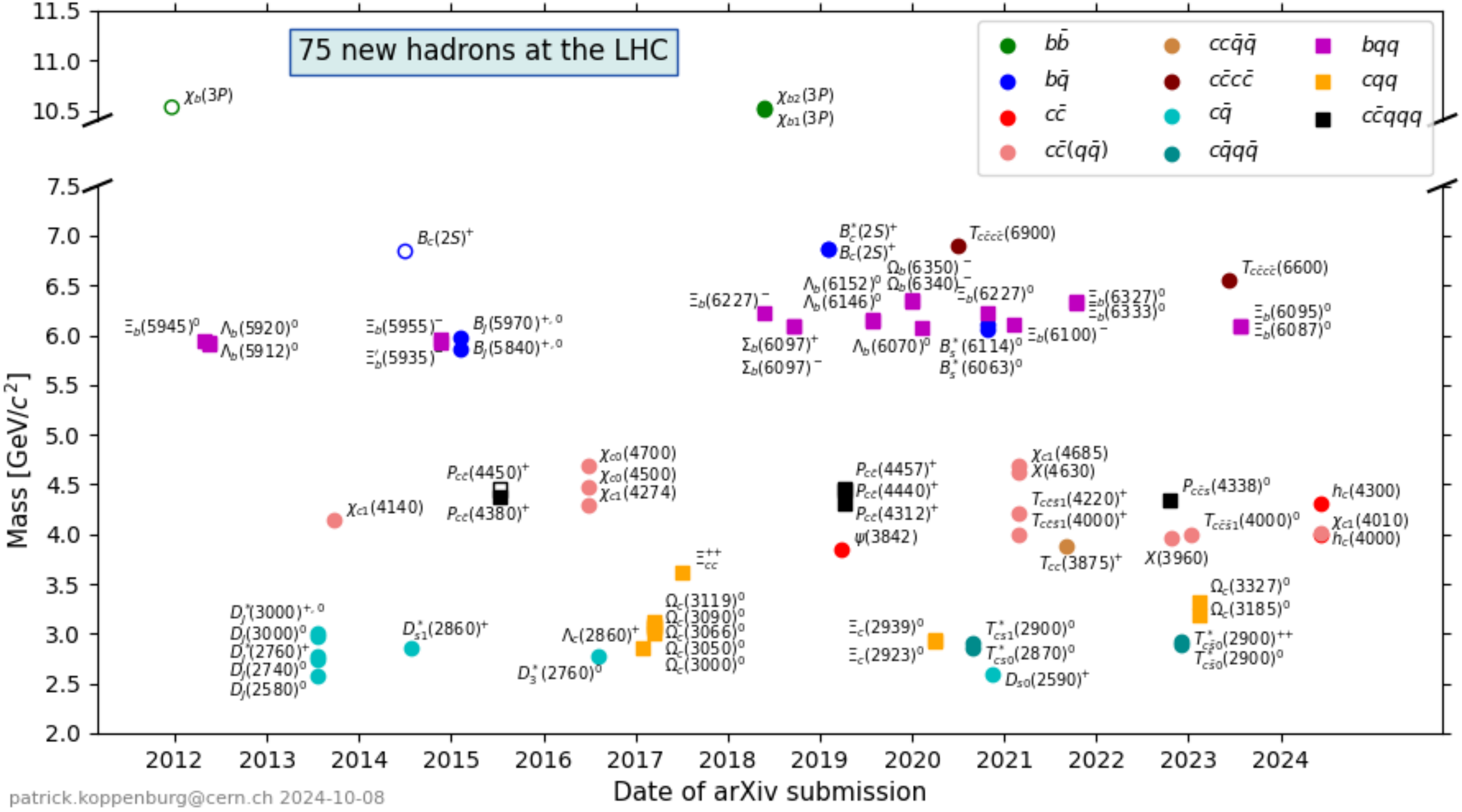


Surprises in quarkonium radiative decays,
Catani Hautmann, 9410394



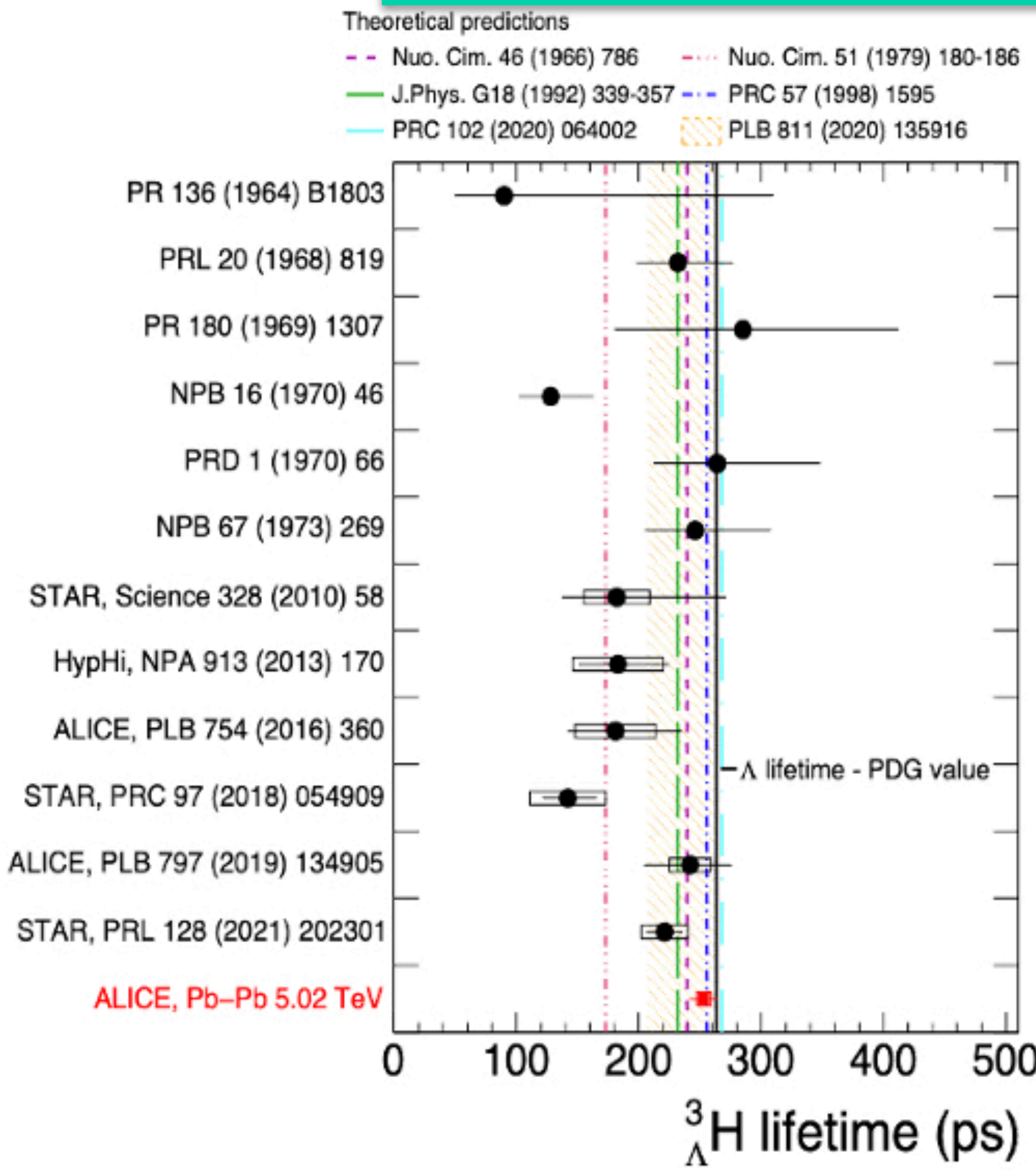
LHCb collaboration, P. Koppenburg, https://www.nikhef.nl/~pkoppenb/particles.html

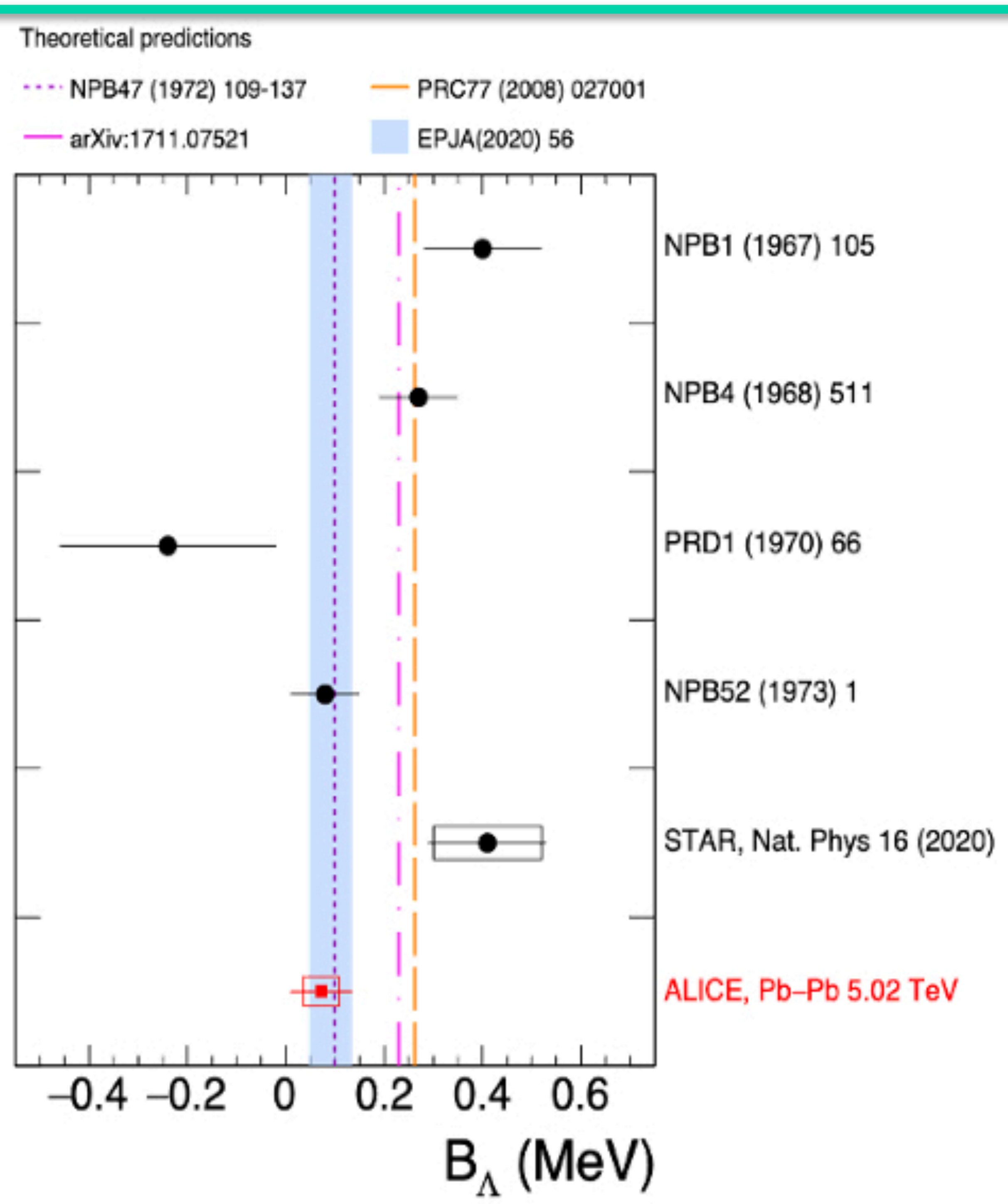
LIFETIME AND BINDING ENERGY OF HYPERTRITON

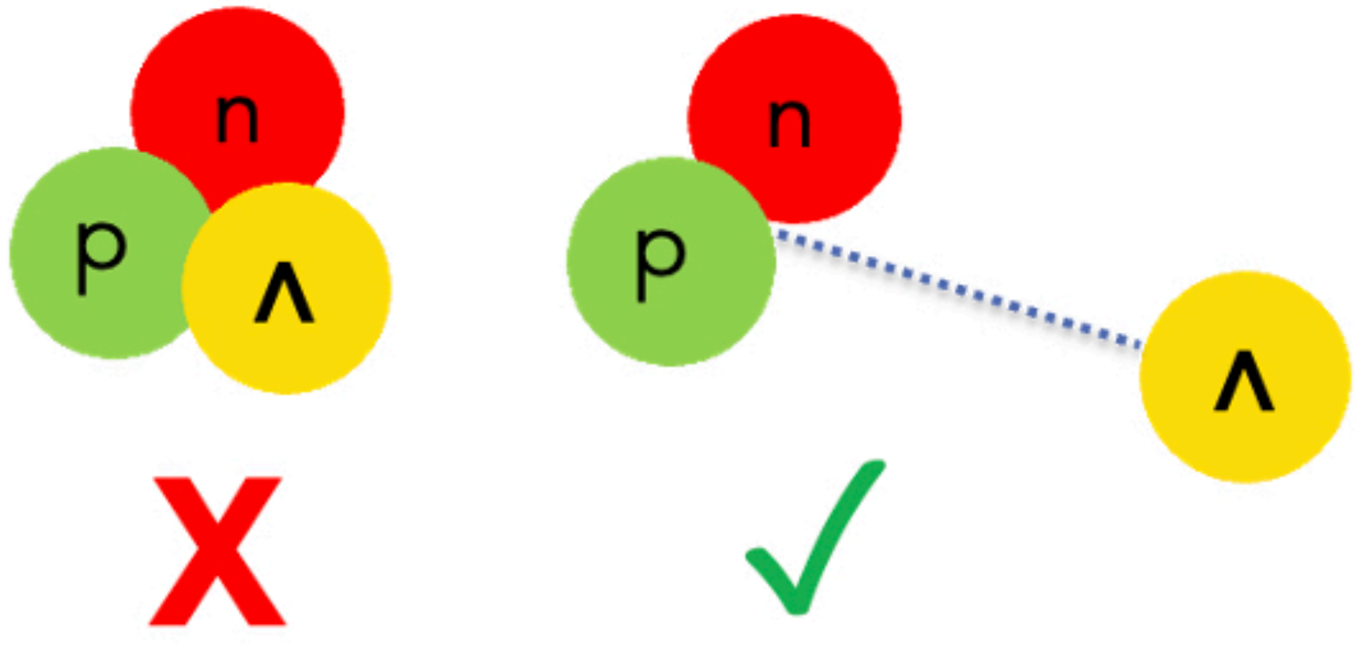
60 years after discovery, its properties were not yet well measured…

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!







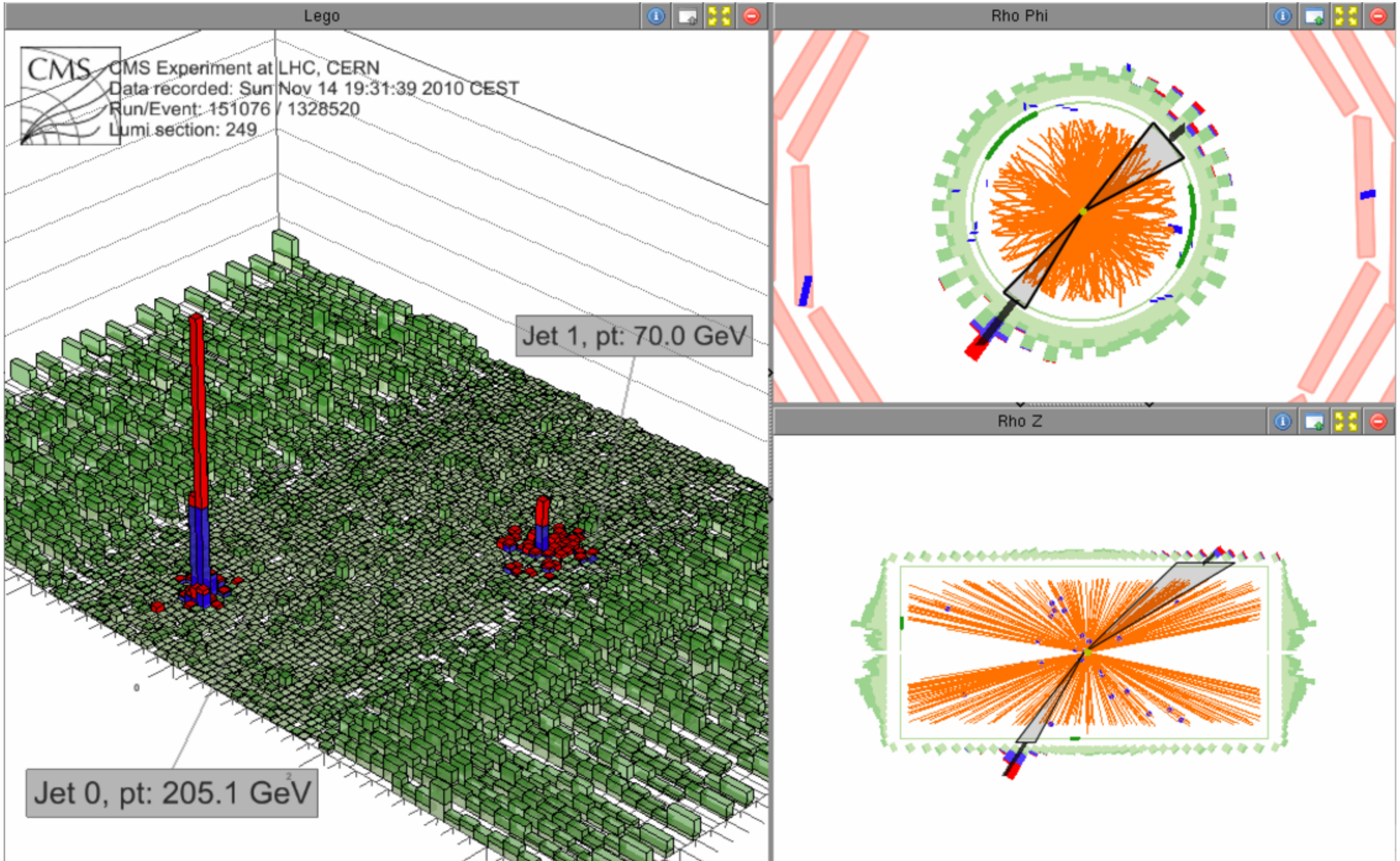
arXiv:2209.07360

Study of QCD in new dynamical regimes

Jet quenching in a quark-gluon plasma

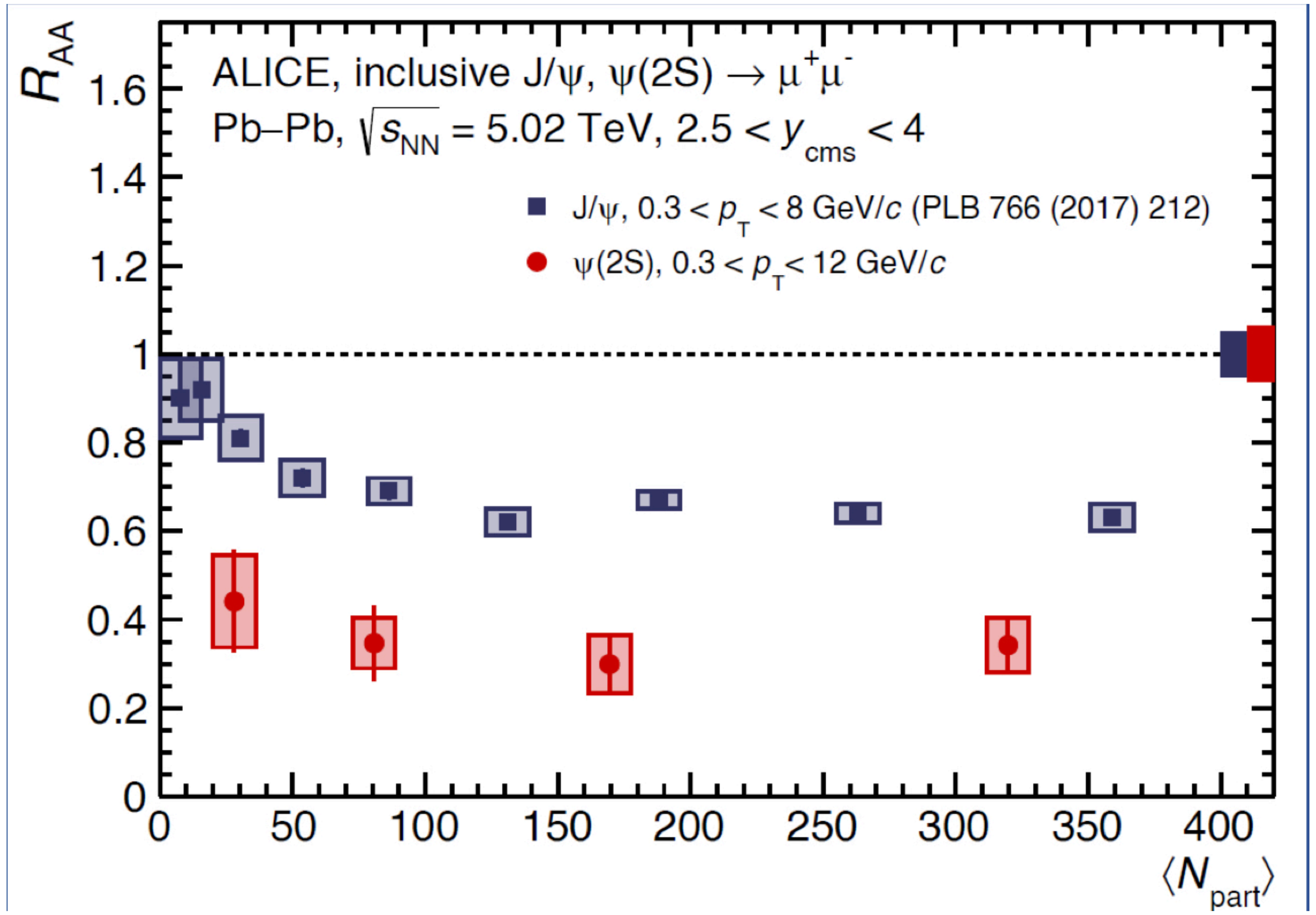
Gauge Invariant Description of the Plasmon in Hot QCD,
Catani d'Emilio PLB 238 (1990) 373

Pb Pb -> jet jet @ 5 TeV



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)



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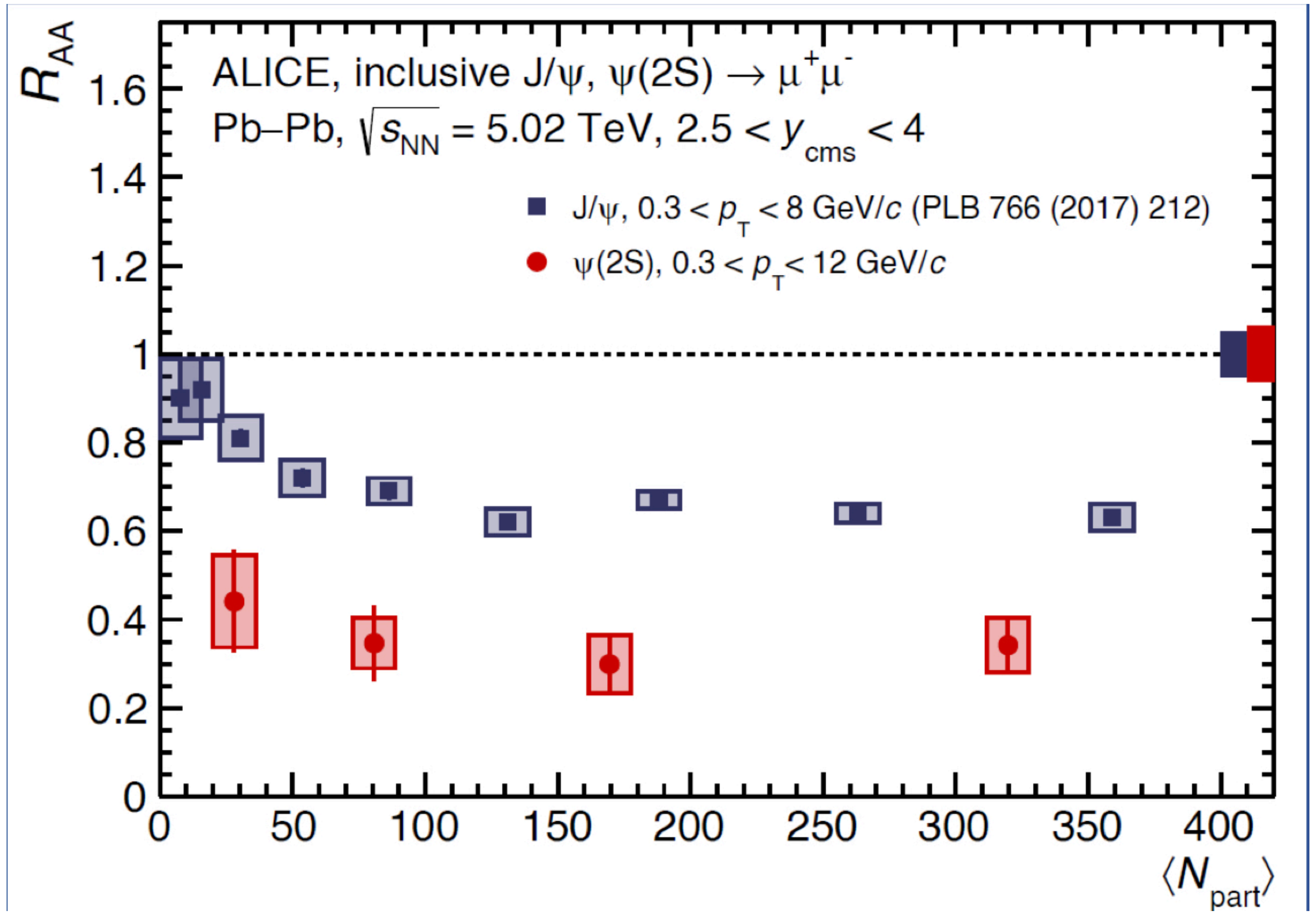
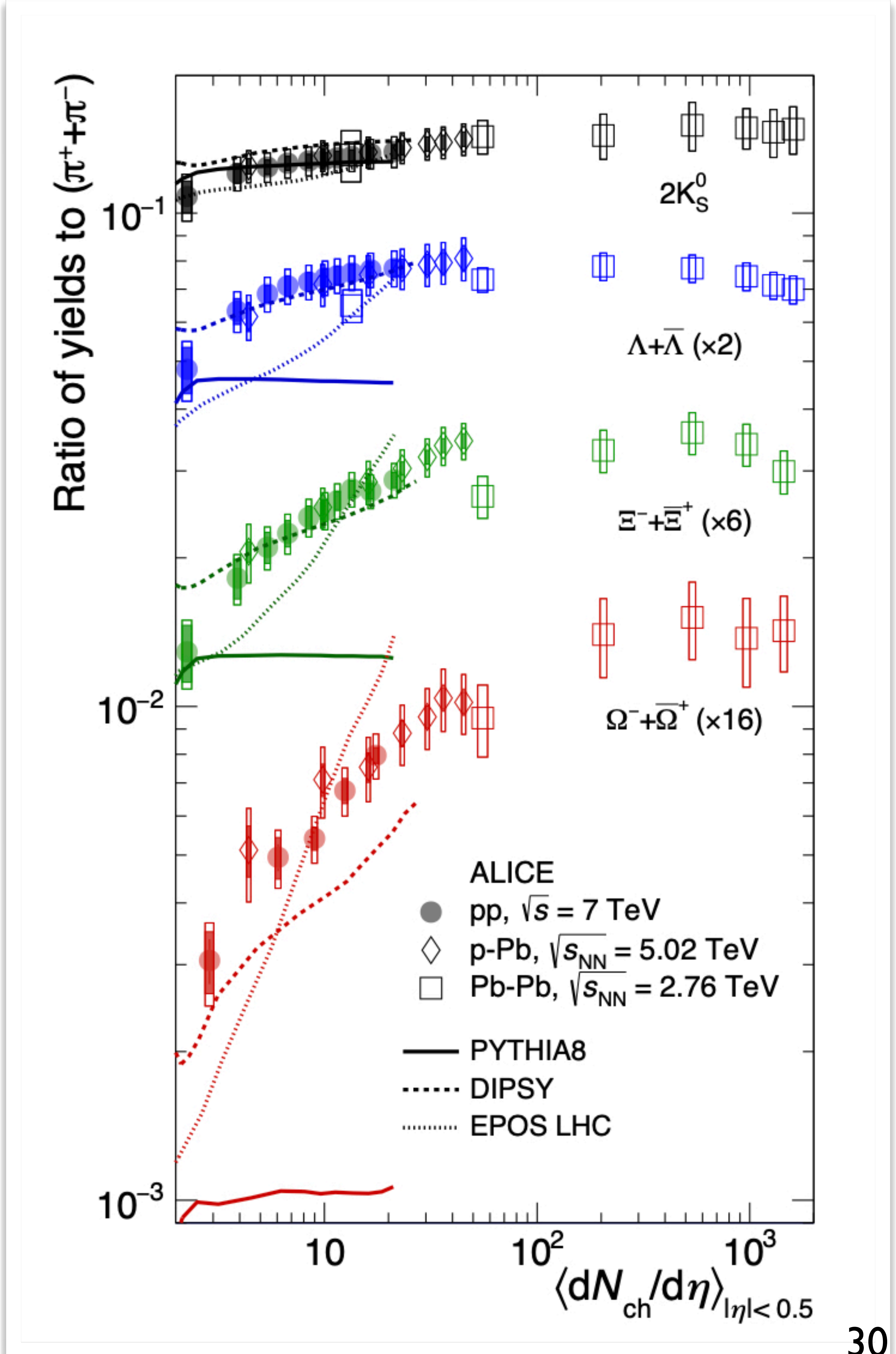


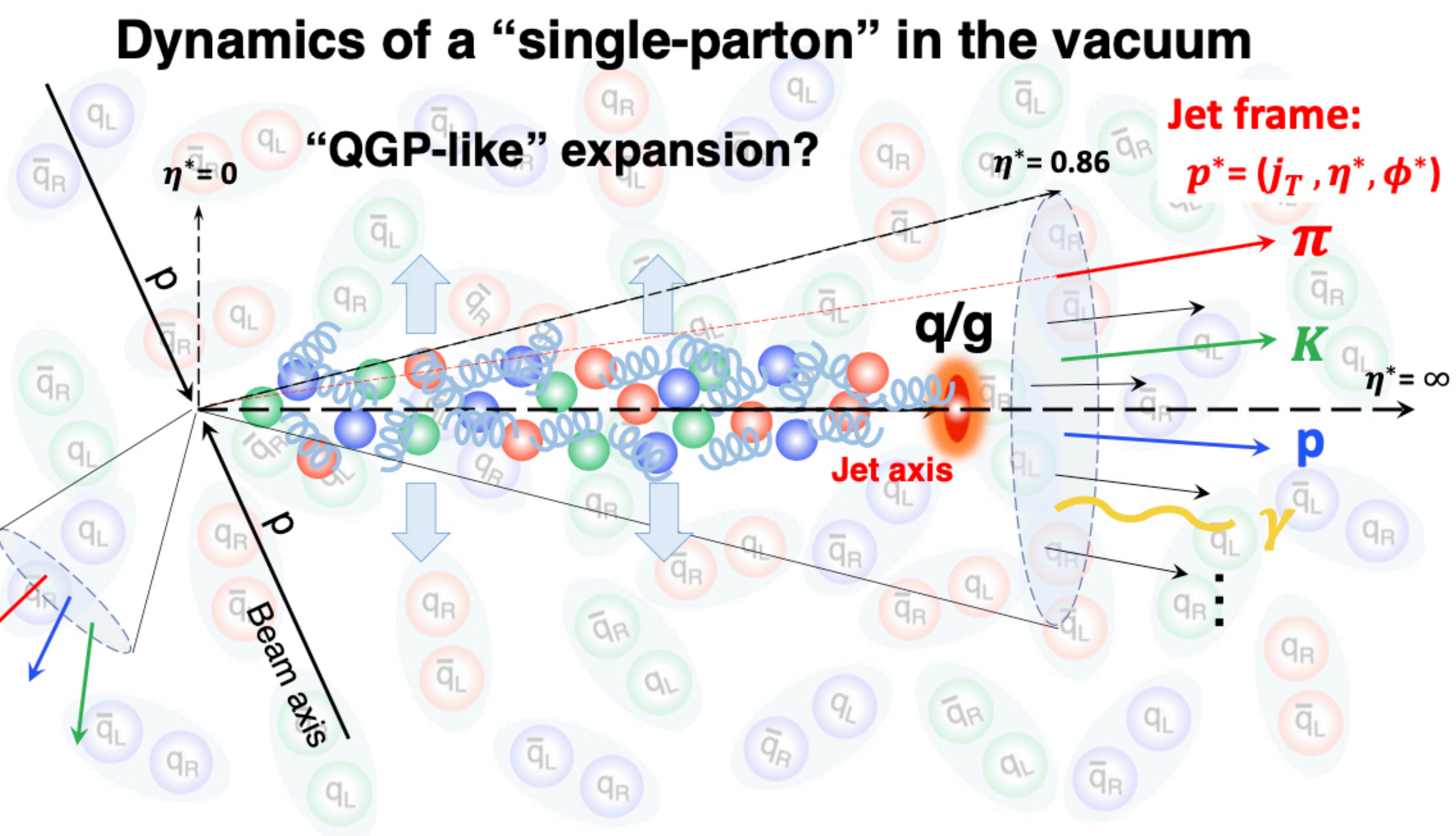
discovery of new dynamical behaviour, with collective phenomena typical of QGP appearing already in high-multiplicity final states of pp and pA



On the inner structure of high-multiplicity jets in pp

CMS, PAS HIN-21-013

Can a high-multiplicity jet lead to correlations/coherent interactions beyond PT?



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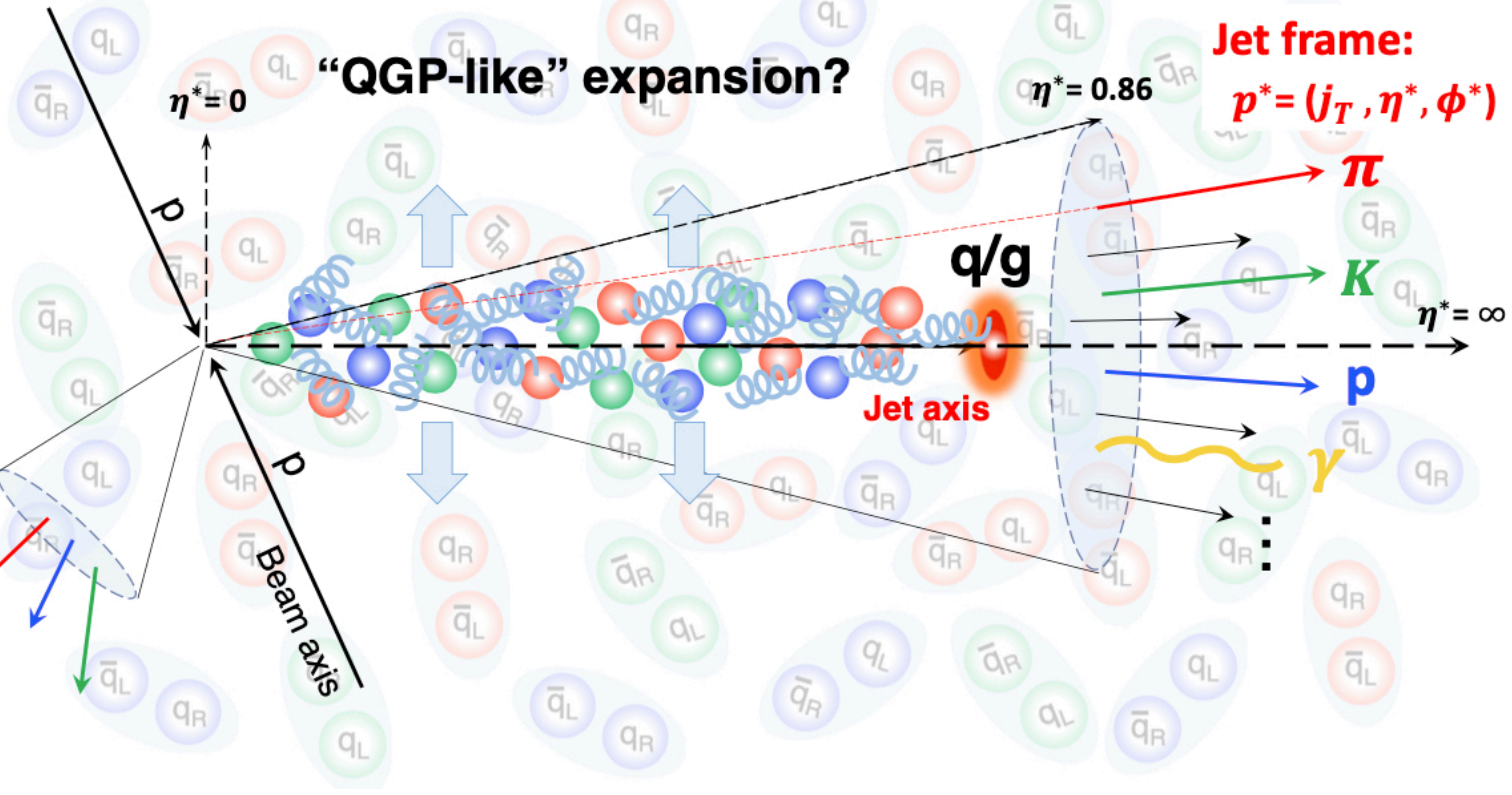
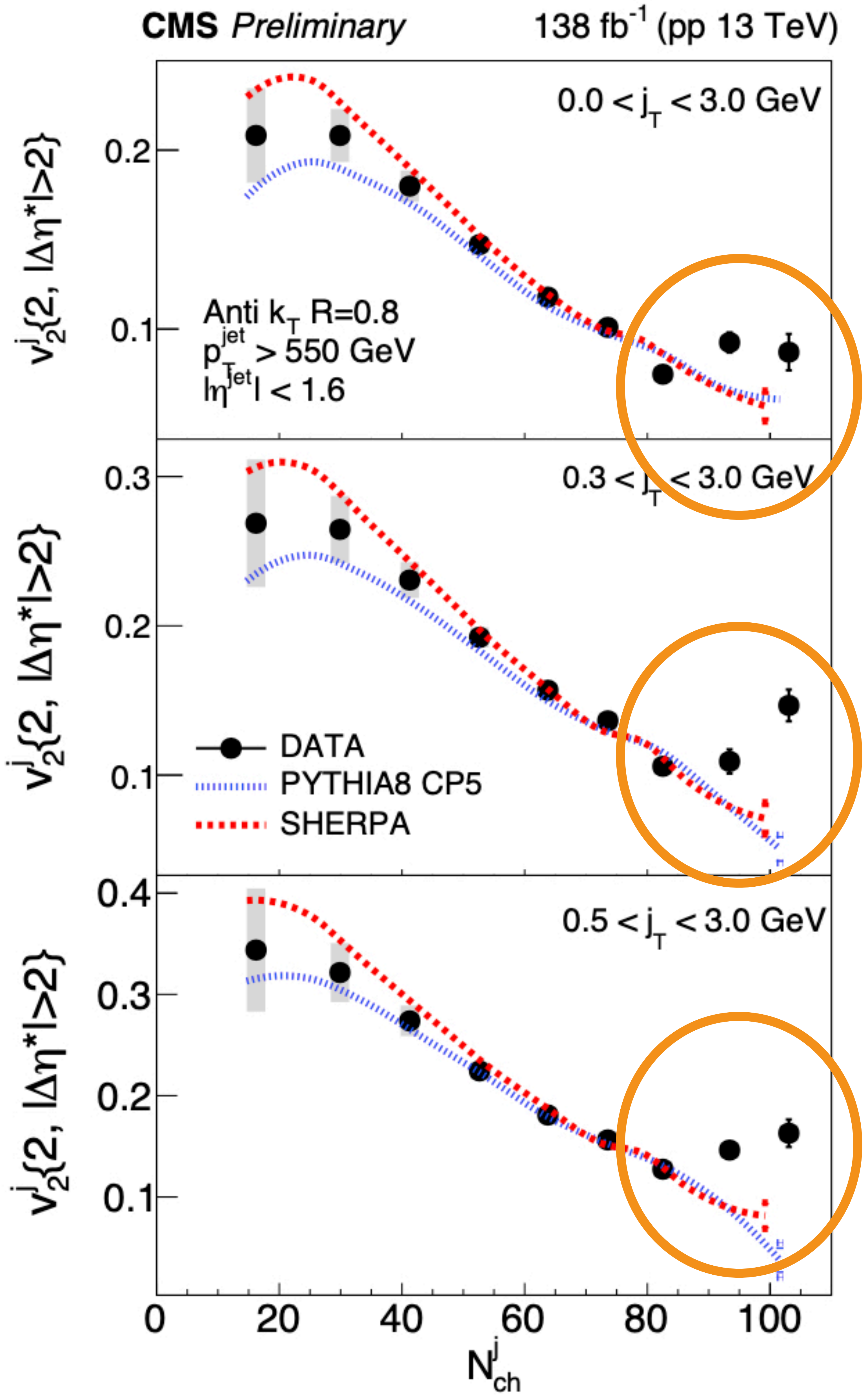
$$\frac{1}{N_{ch}^{trg}}\frac{dN^{pair}}{d\Delta\phi^*} \propto 1 + 2\sum_{n=1}^{\infty} V_{n\Delta}\cos(n\Delta\phi^*),$$

Dynamics of a "single-parton" in the vacuum



j_T = track p_T w.r.t the jet axis



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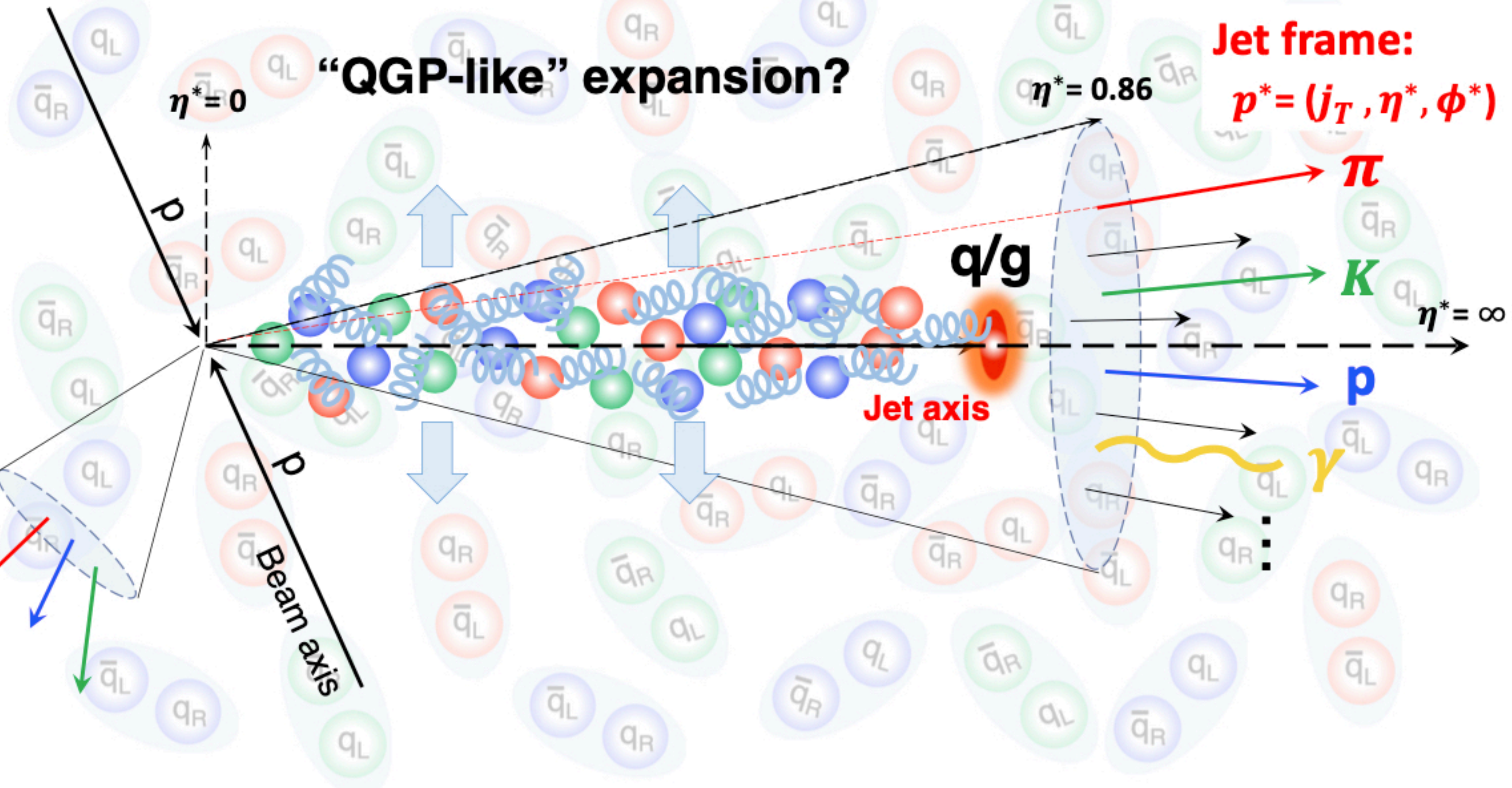
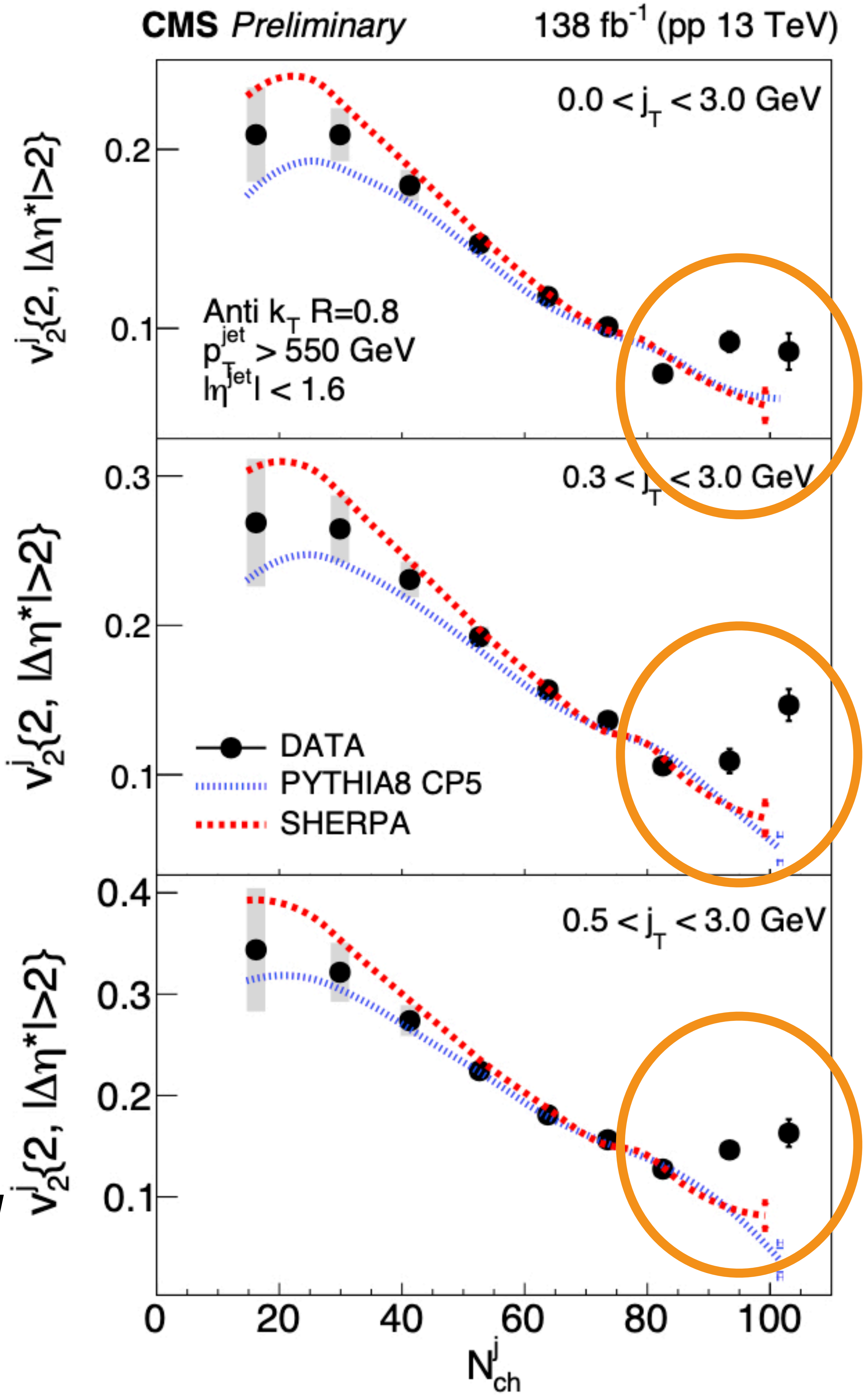
$$\frac{1}{N_{\rm ch}^{\rm trg}}\frac{{\rm d}N^{\rm pair}}{{\rm d}\Delta\phi^*} \propto 1 + 2\sum_{n=1}^{\infty} V_{{\rm n}\Delta}\cos({\rm n}\Delta\phi^*),$$

Dynamics of a “single-parton” in the vacuum

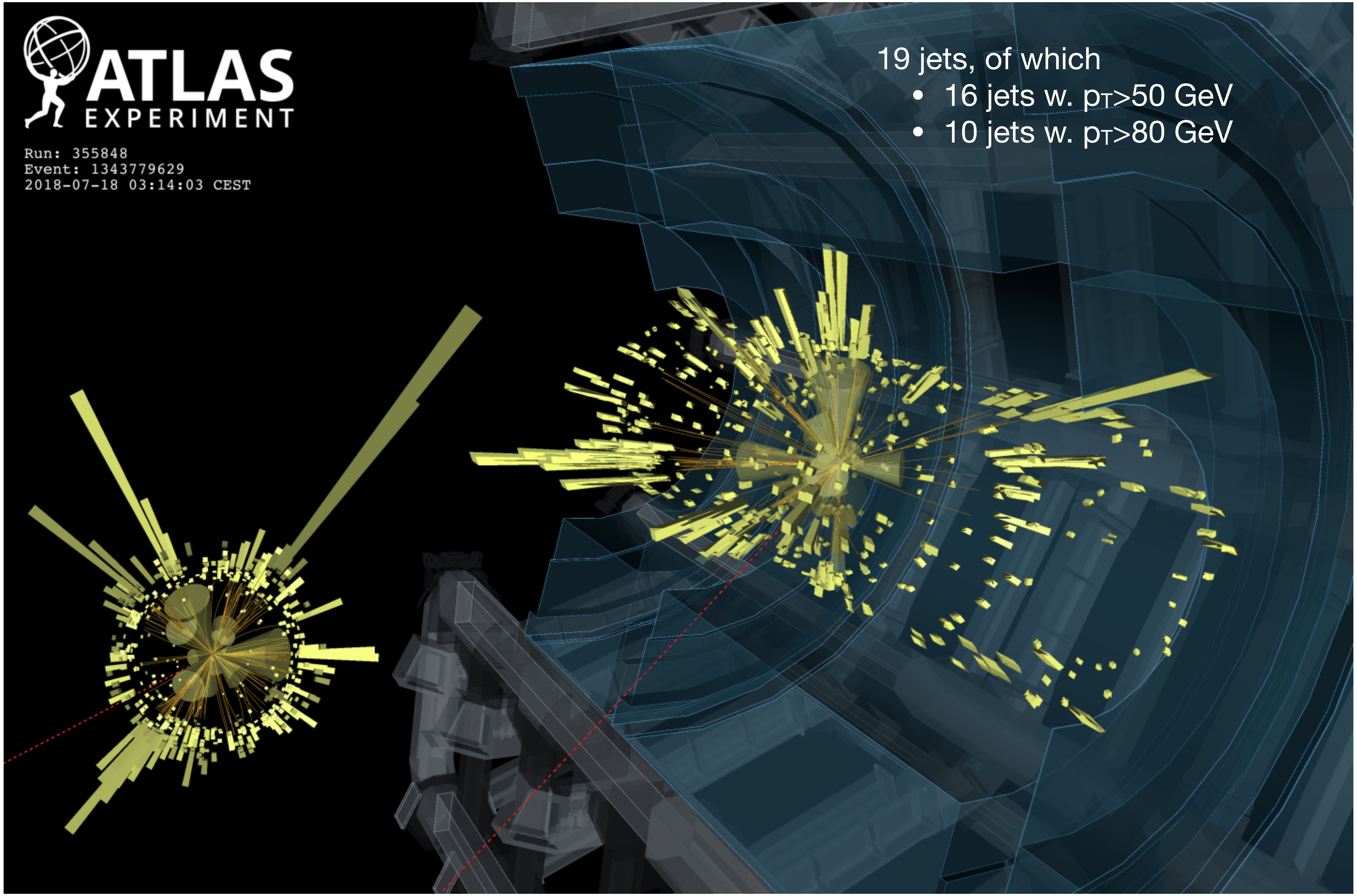


j_T = track p_T w.r.t the jet axis



From the conclusions: *“While data and the MC samples are in good agreement for particle correlations inside low- and mid-Nj ch jets, the extracted long-range elliptic azimuthal anisotropy vj2{2} shows a distinct increase in data for Nj > 80. Such a feature is not observed in any of MC event generators that model the parton fragmentation process. Therefore,* ***results presented in this note may pave a new direction in uncovering novel effects related to nonperturbative QCD dynamics of parton fragmentation in the vacuum****. “*

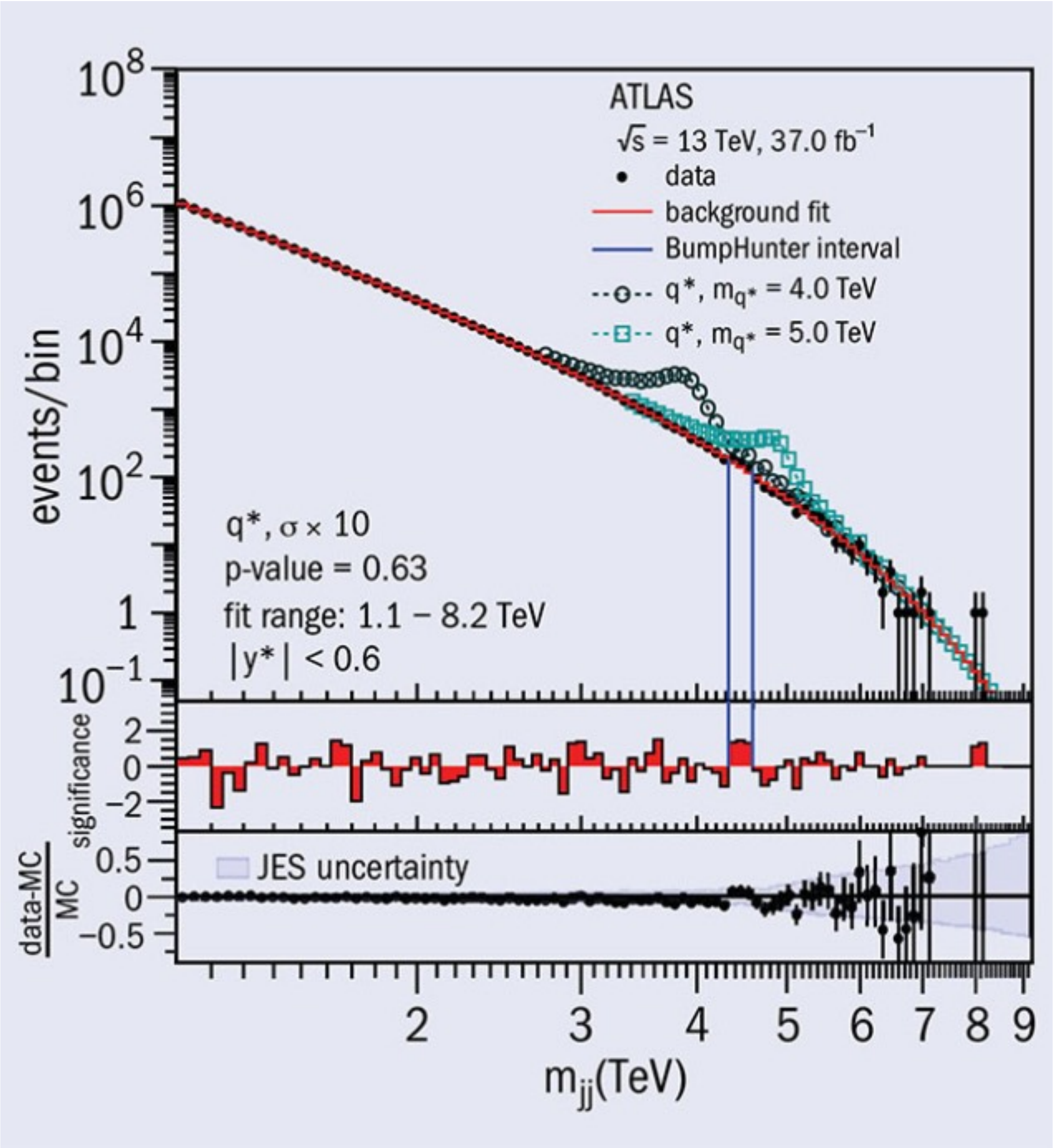
Multijet final states

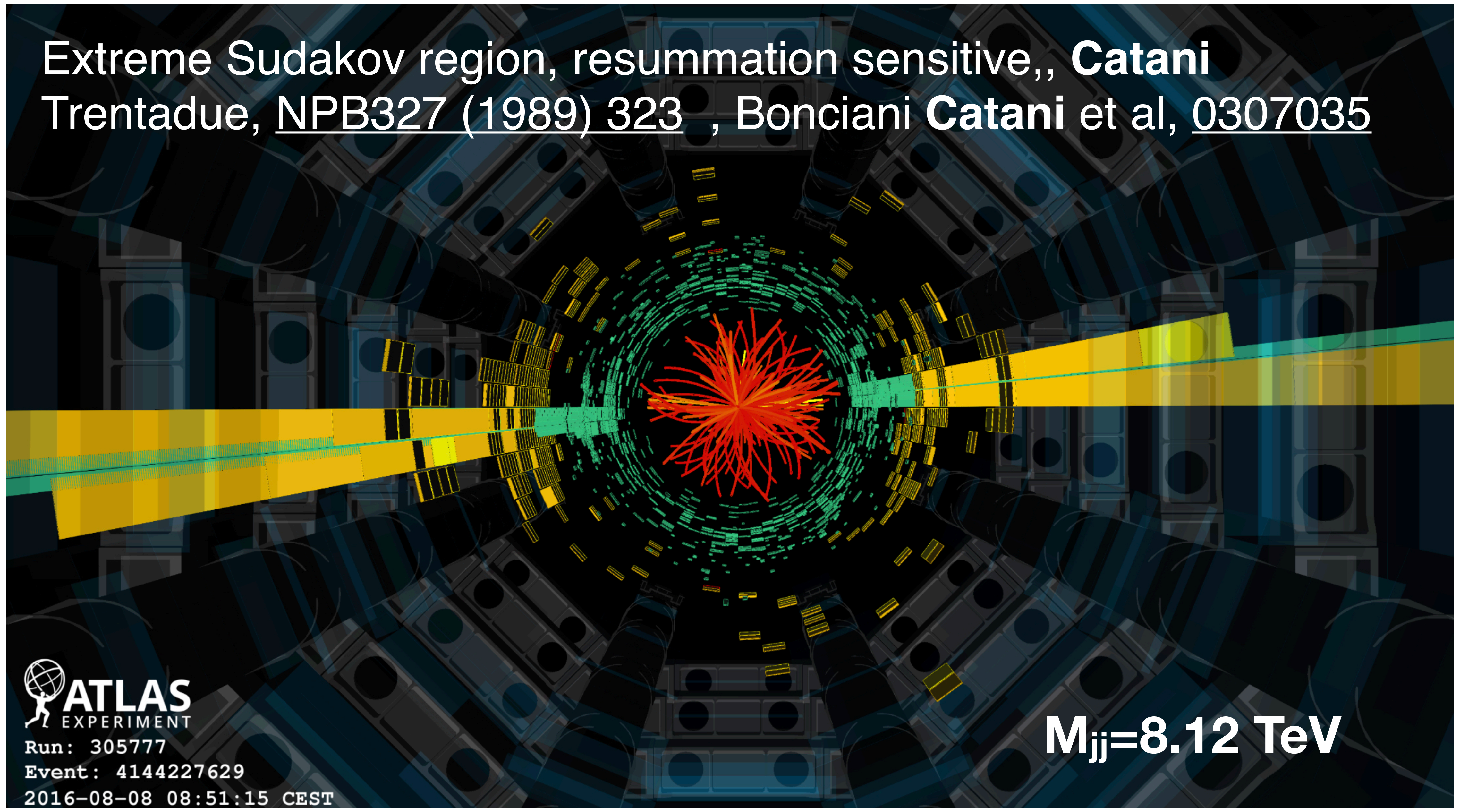


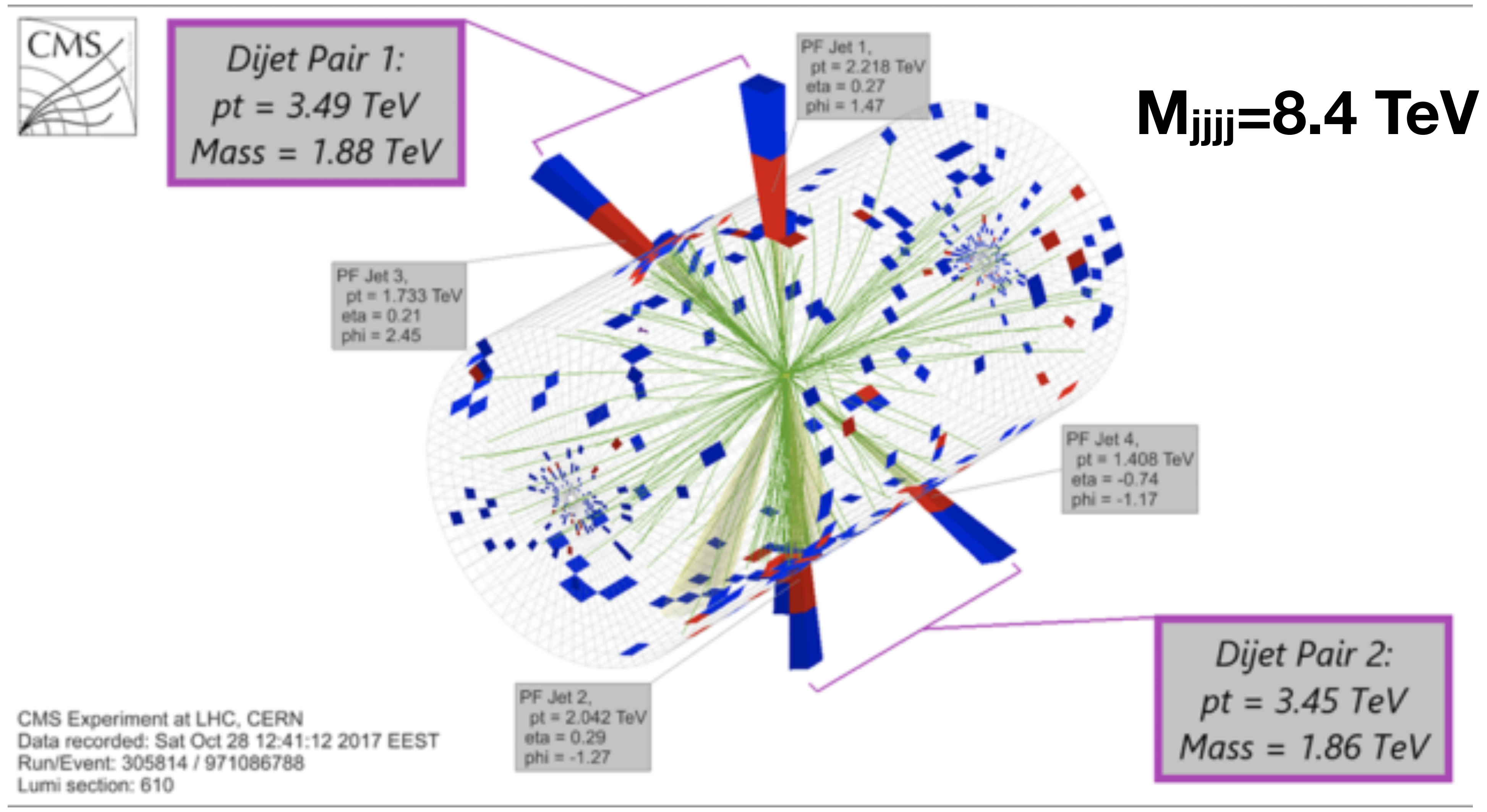
Multiparton MEs and shower evolution matching, CKKW, **Catani** Krauss Kuhn Webber, 0109231

> ***"All options for a 10 TeV pCM collider are new technologies under development and R&D is required before we can embark on building a new collider"***
>
> *P5 Report (2023), p. 17*

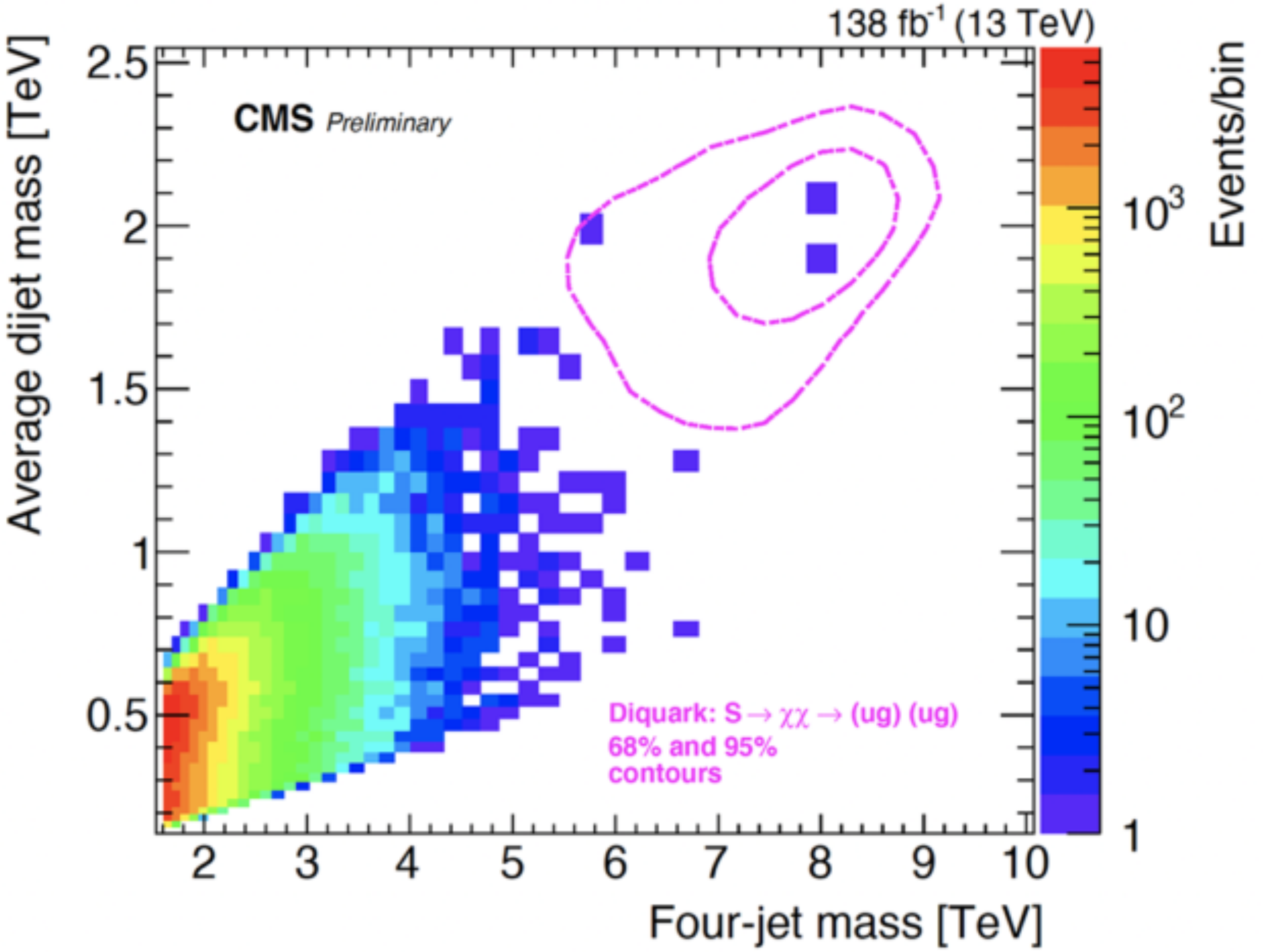
The 10 TeV pCM holy Grail: how far are we from it, really?
not much actually, already at the LHC





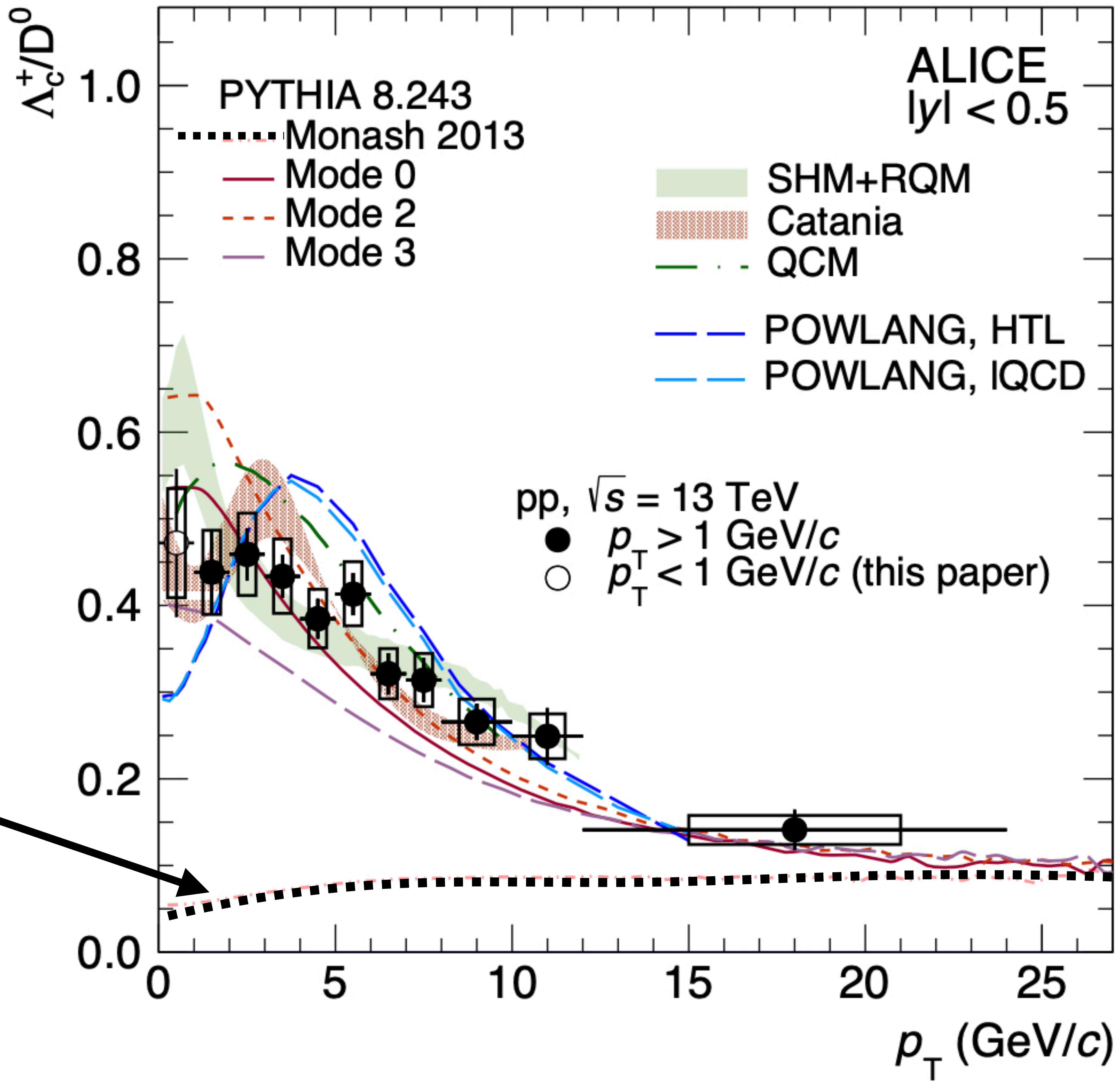


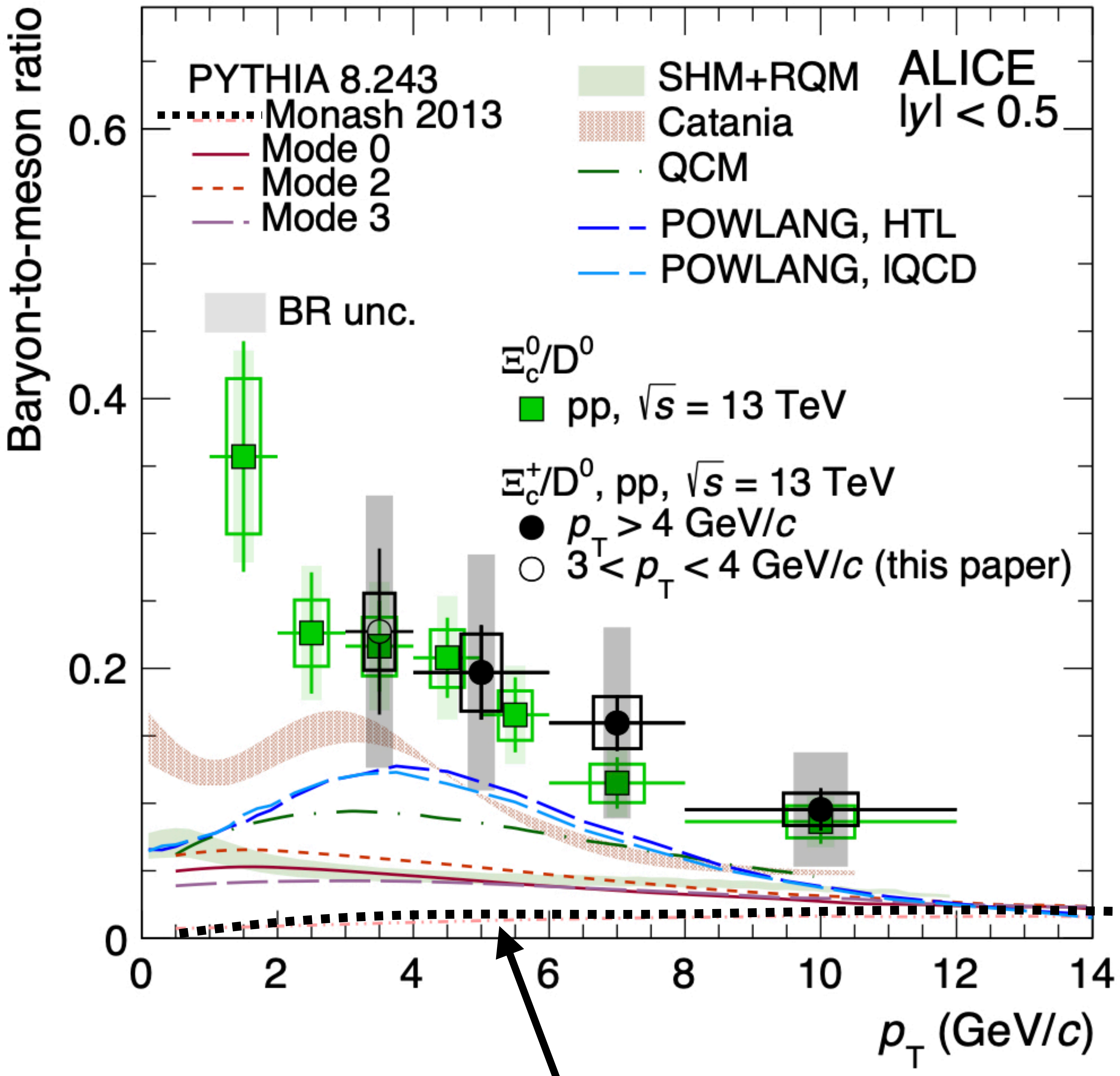
https://arxiv.org/abs/1911.03947



Surprises in heavy quark fragmentation

ALICE, 2308.04877





“Default” PYTHIA prediction

“Default” PYTHIA prediction

PYTHIA Mode 0-3: Christiansen, Skands, 1505.01681

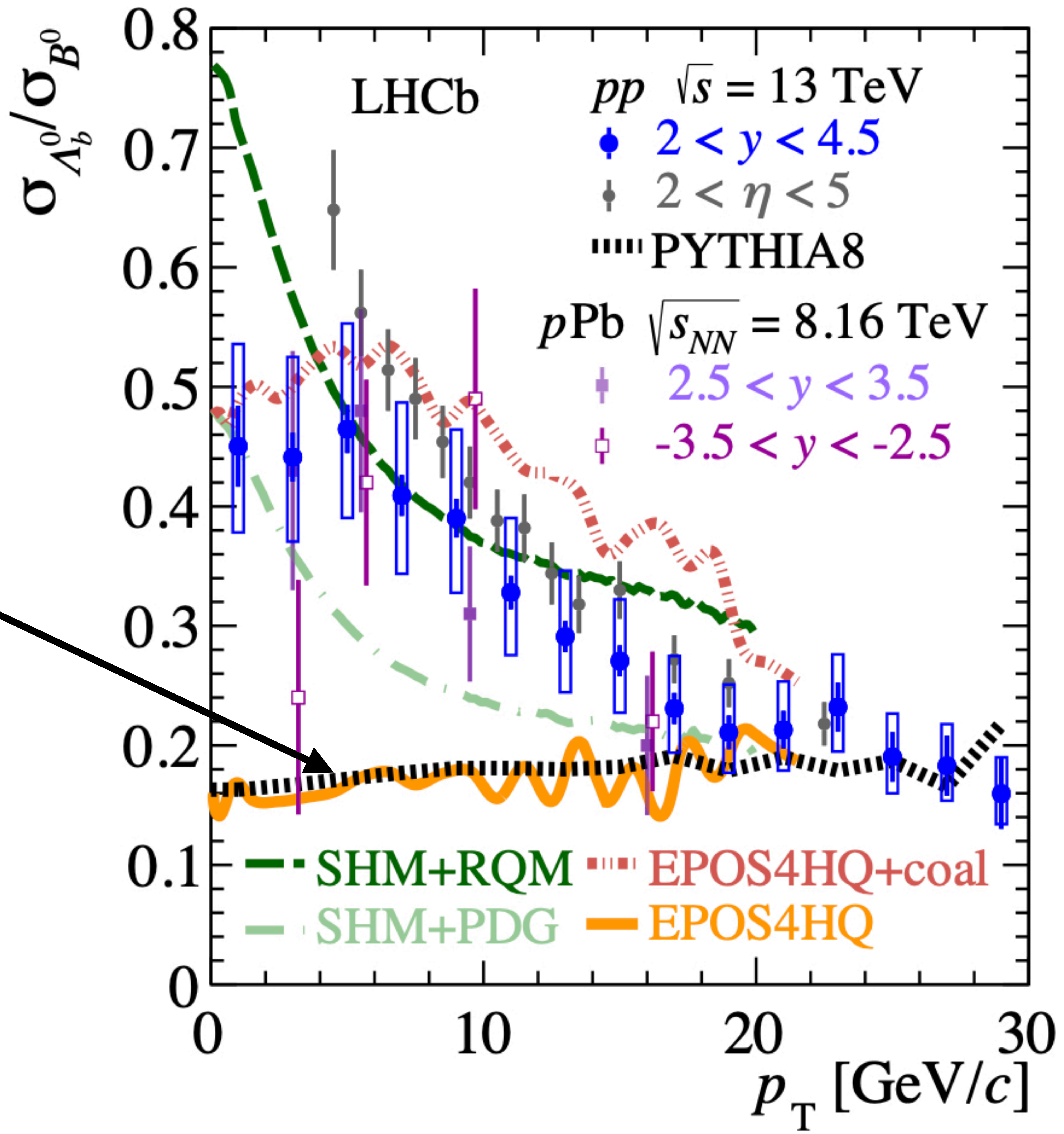
POWLANG: Beraudo et al, 2306.02152

SHM: He, Rapp, 1902.08889

Catania: Minissale et al, 2012.12001

A similar phenomenon is observed in bottom hadrons

LHCb 2310.12278



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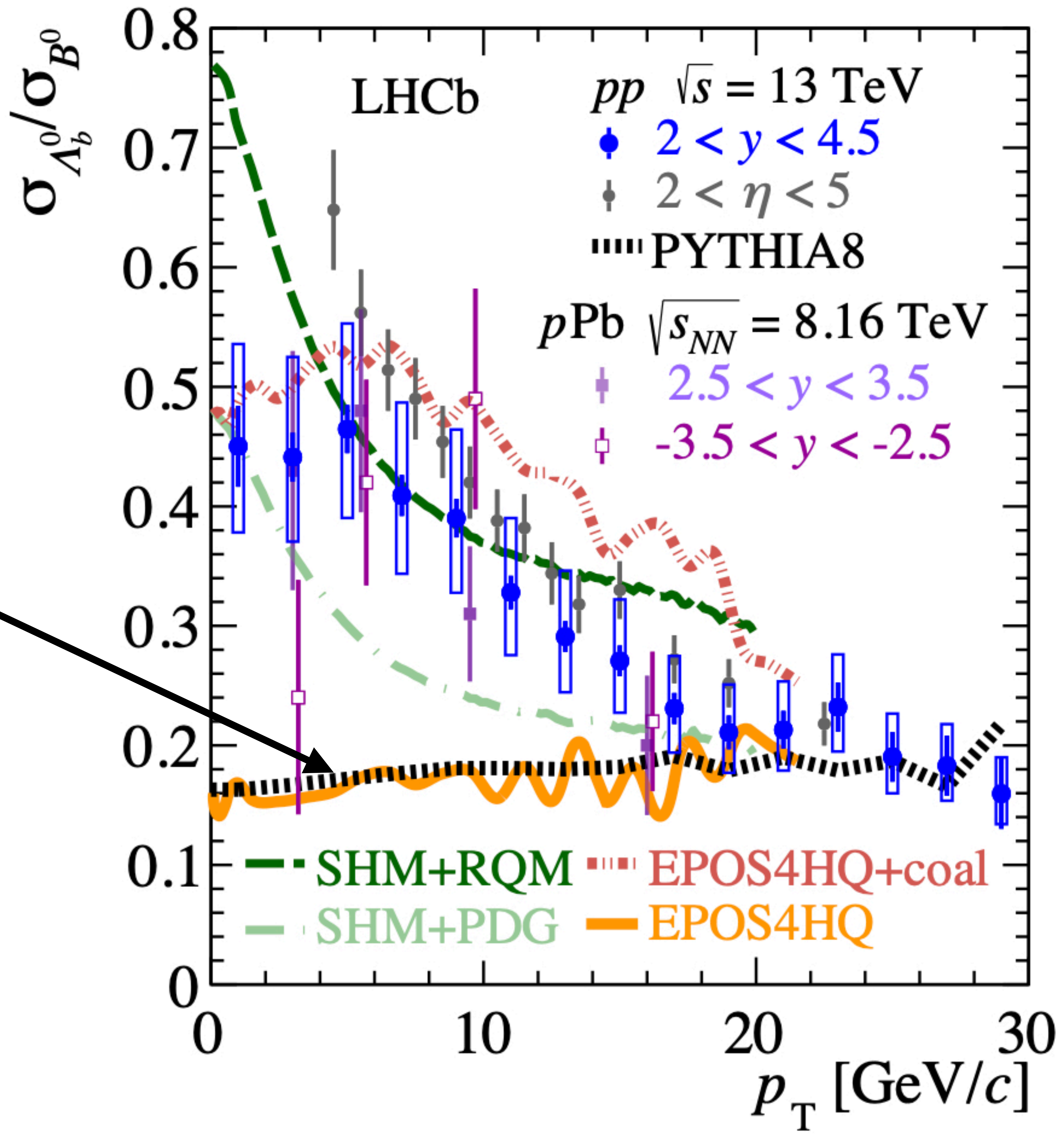
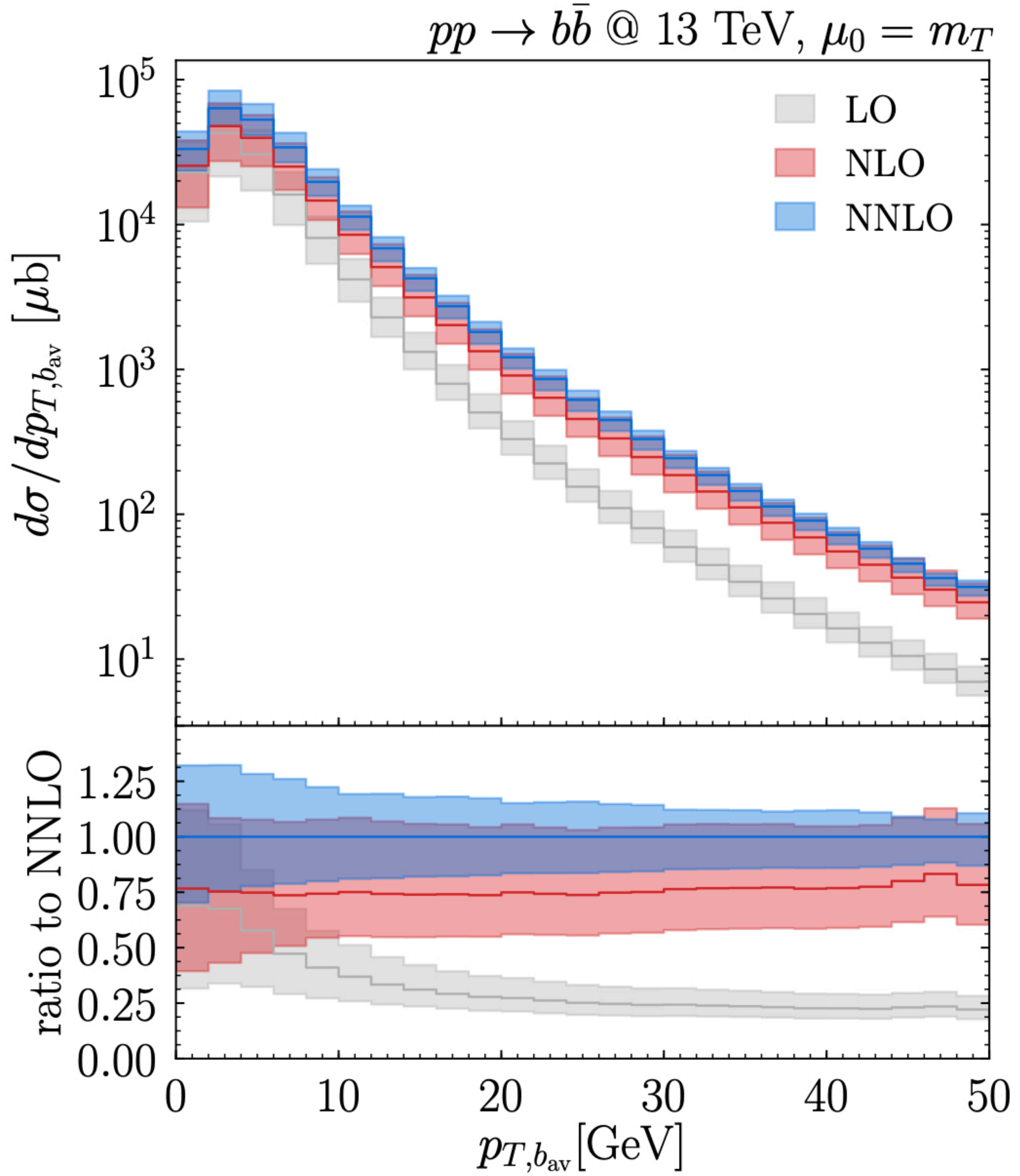


"Default" PYTHIA prediction

Impact on interpretation of B-meson distributions in terms of b-quark theoretical predictions

Catani, Devoto, Grazzini, Kallweit, Mazzitelli, **2010.11906**

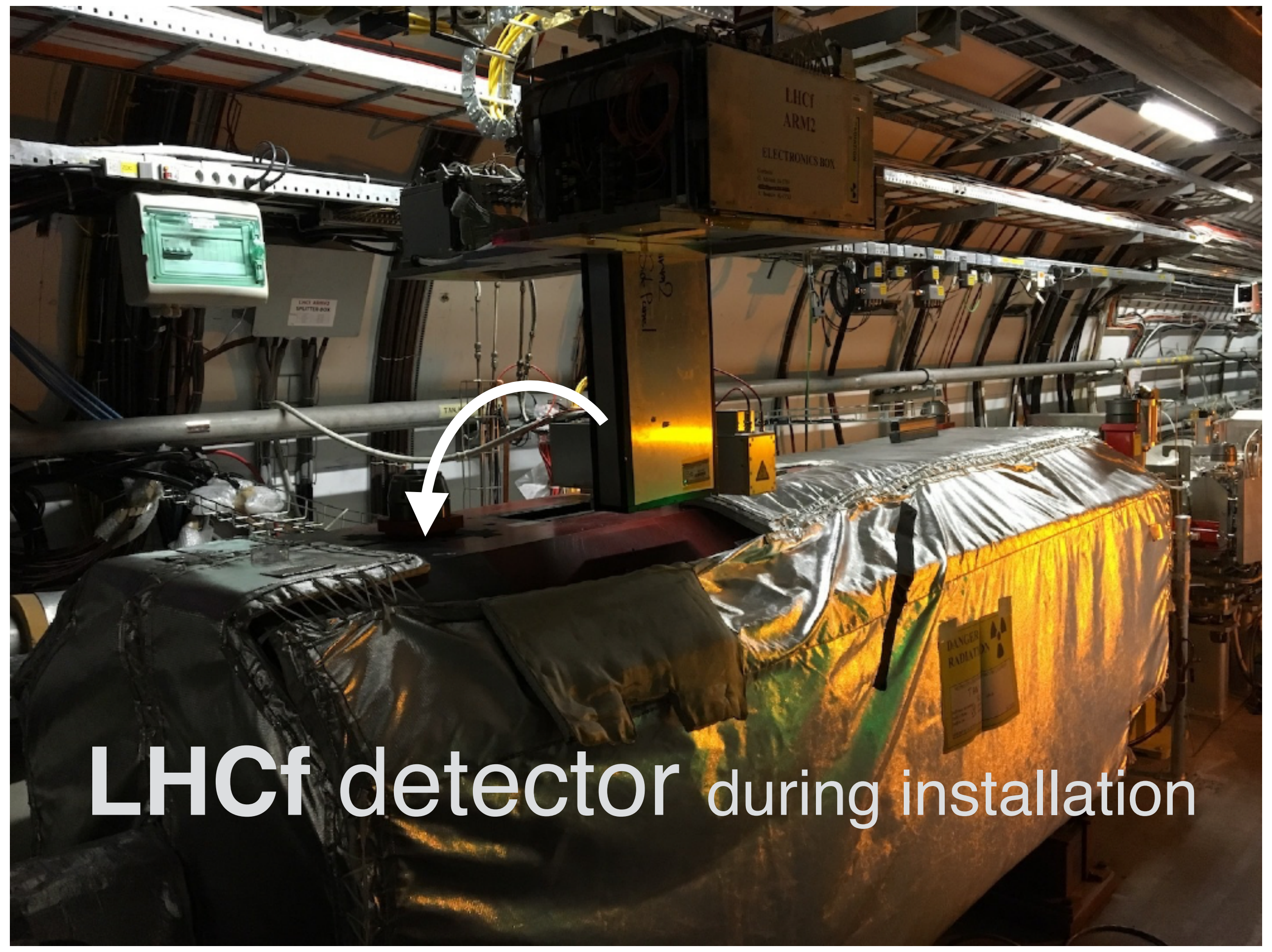


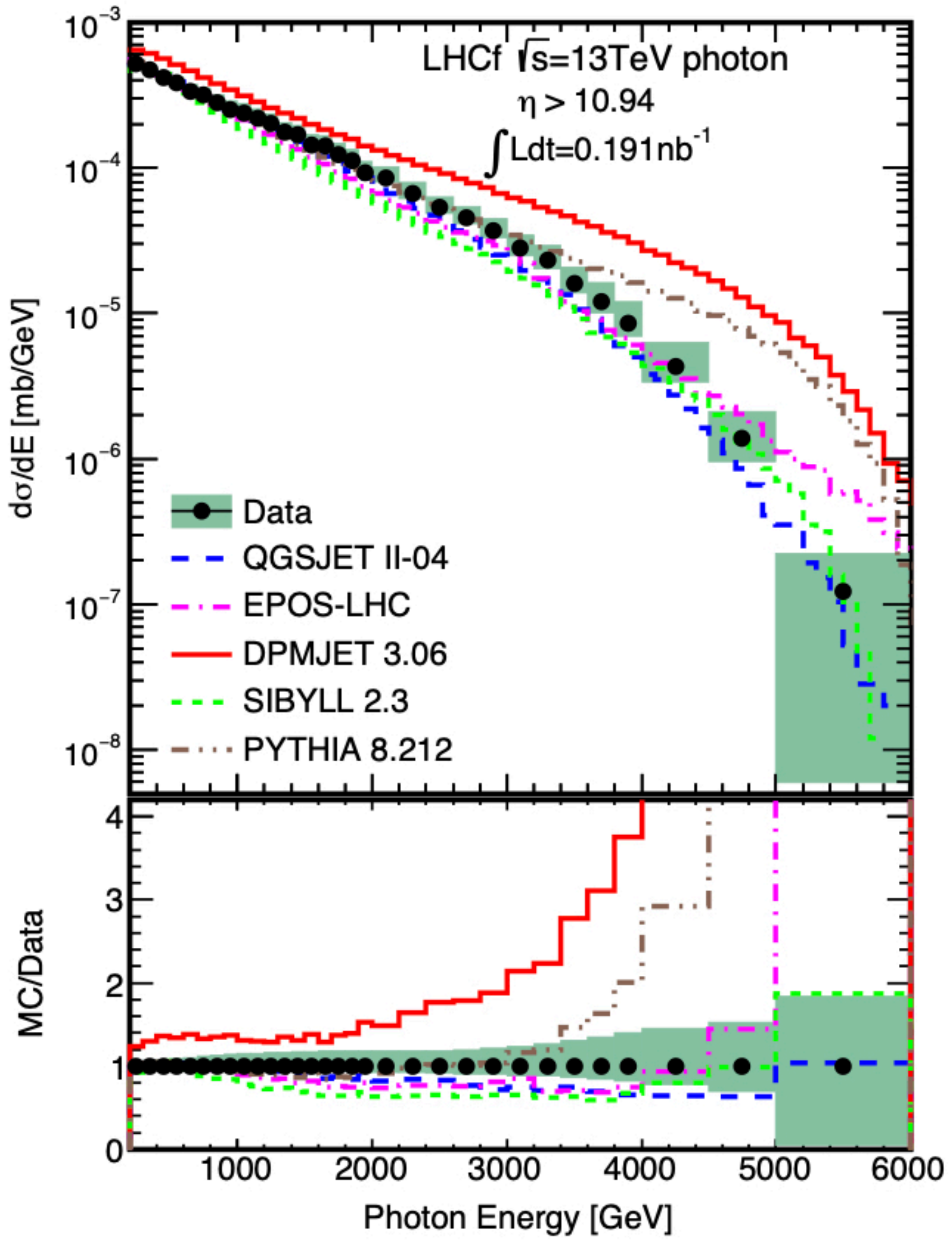
Impact on astroparticle physics

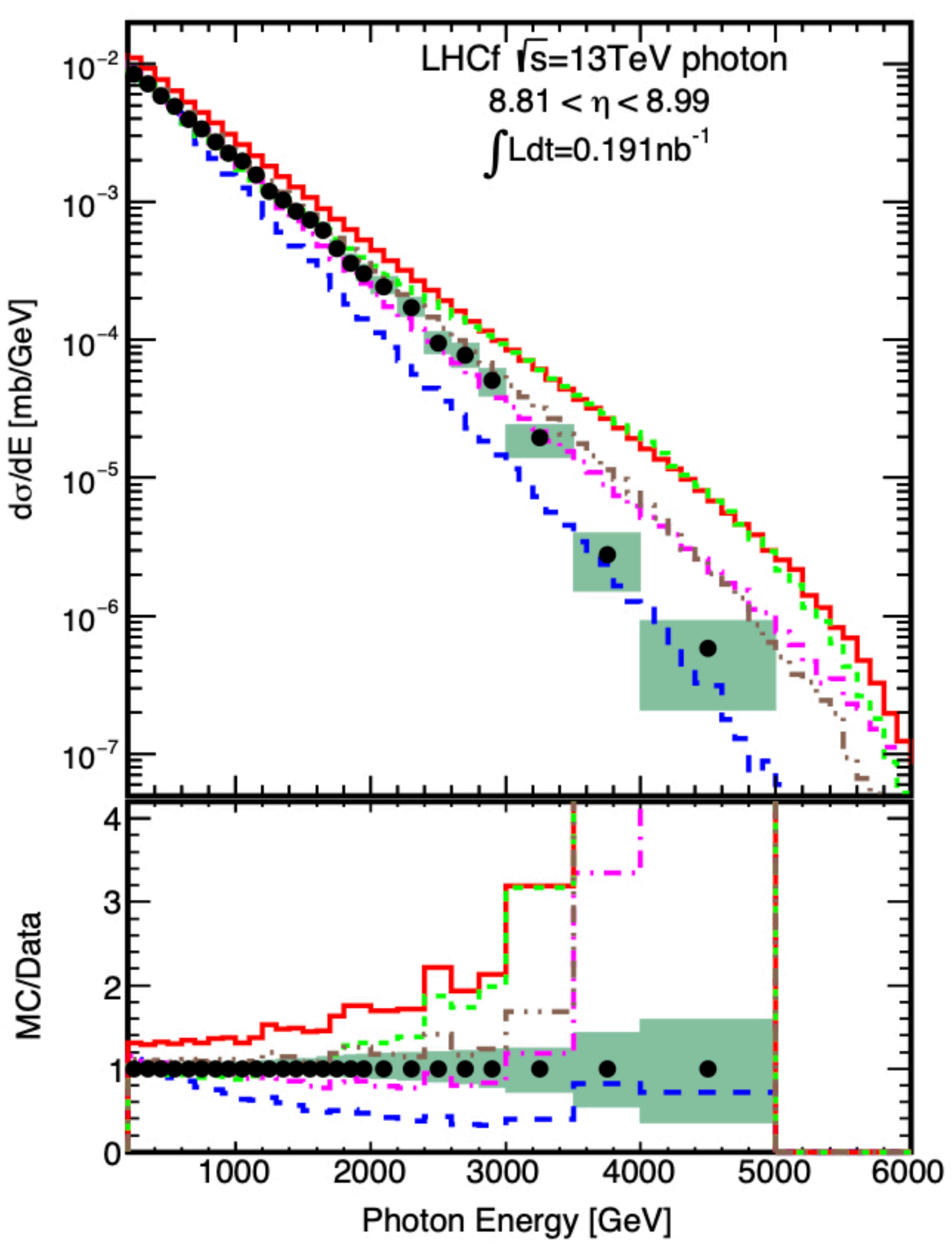
countless searches for dark matter candidates covering a huge domain of plausible model space

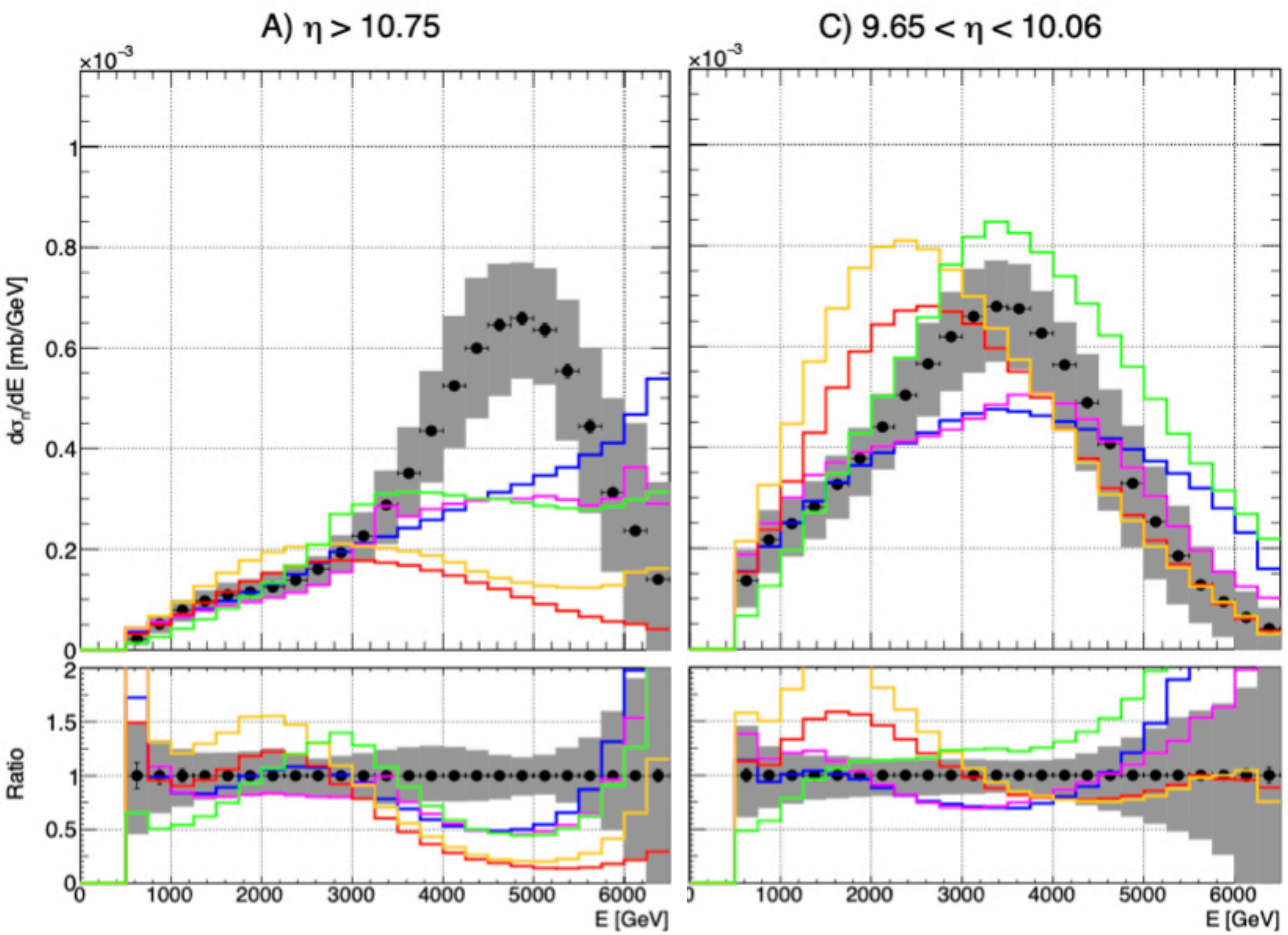
… plus:

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





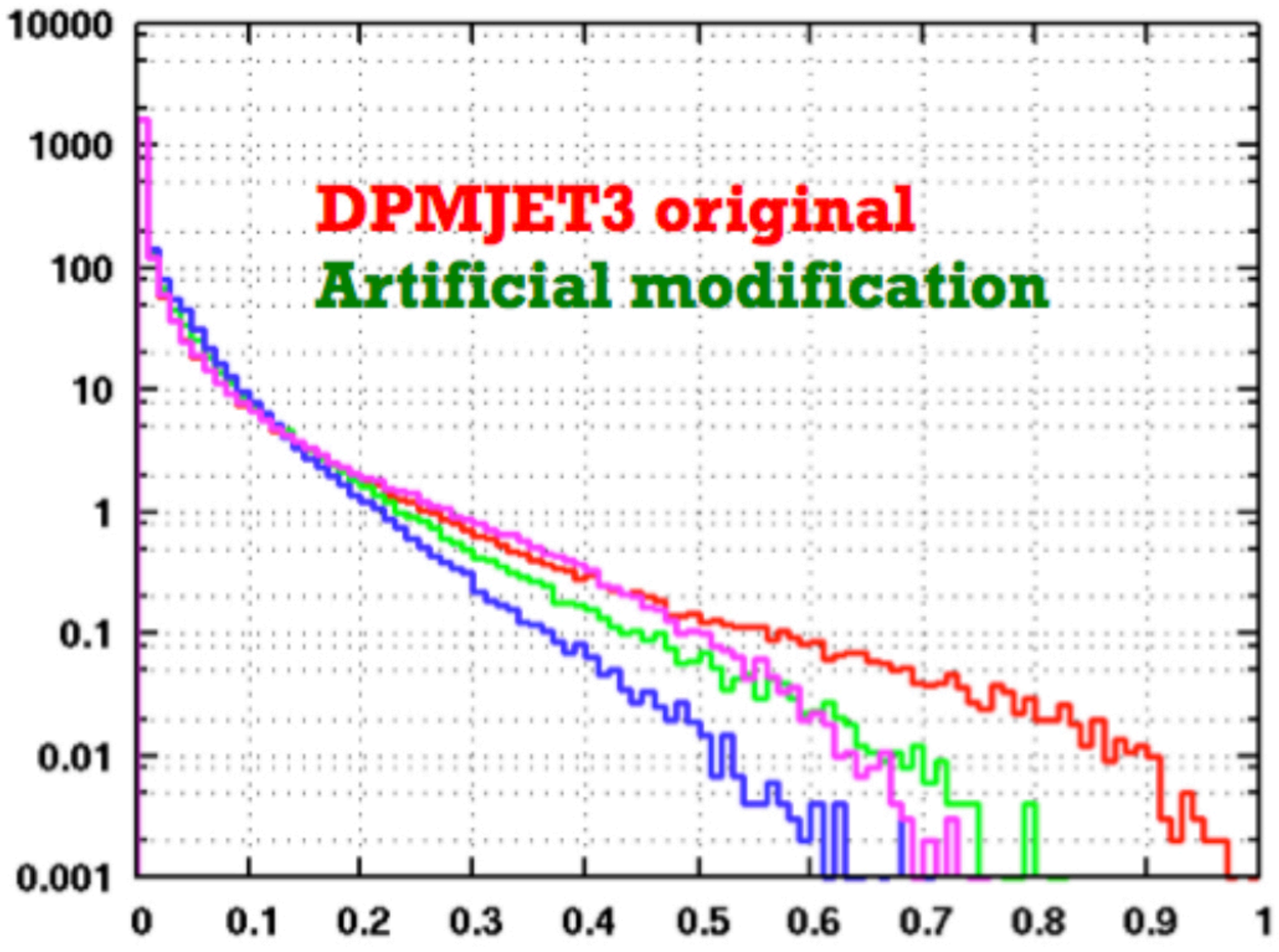




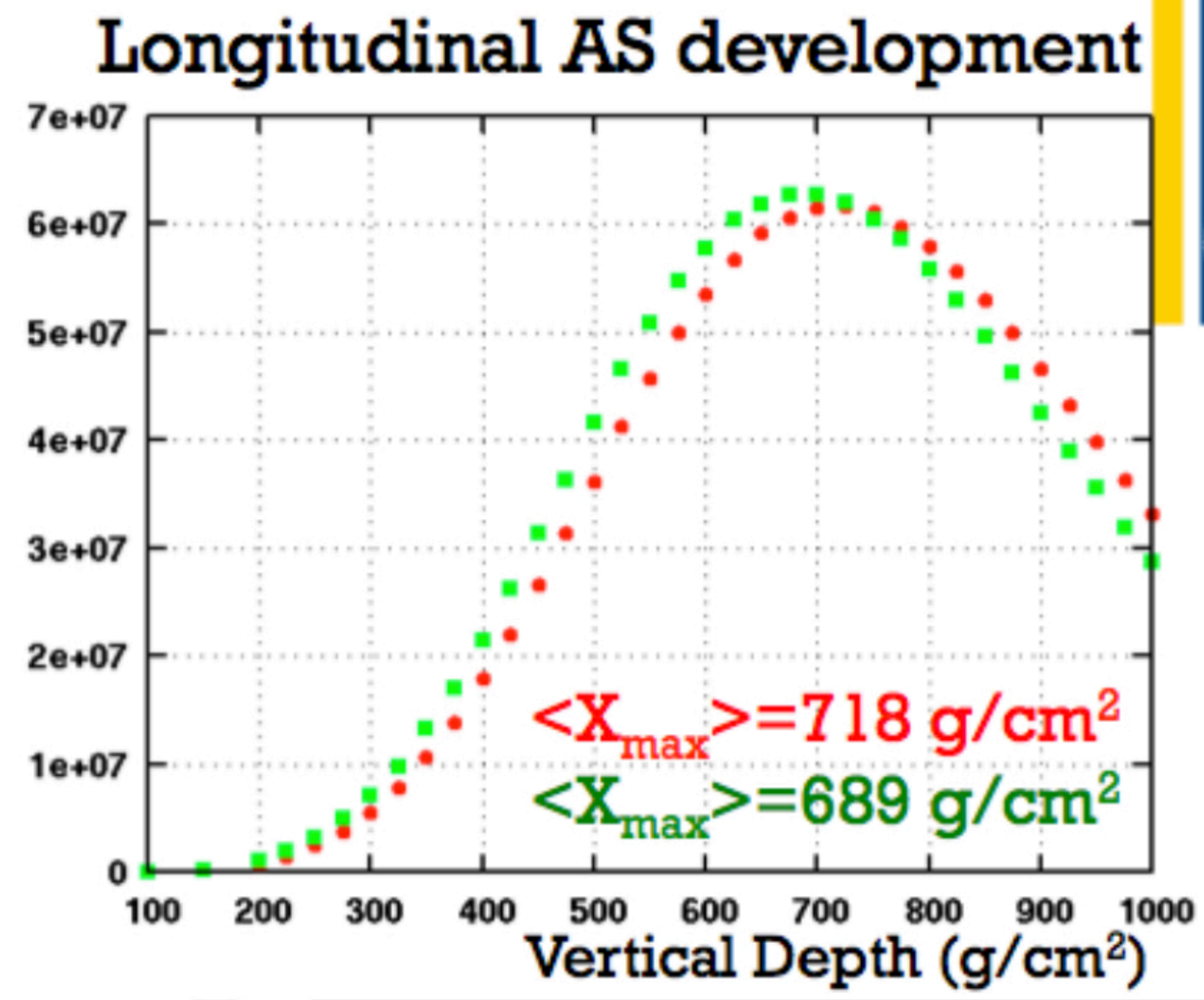
photons~π^0~π^{+-} **Phys.Lett.B 780 (2018) 233**

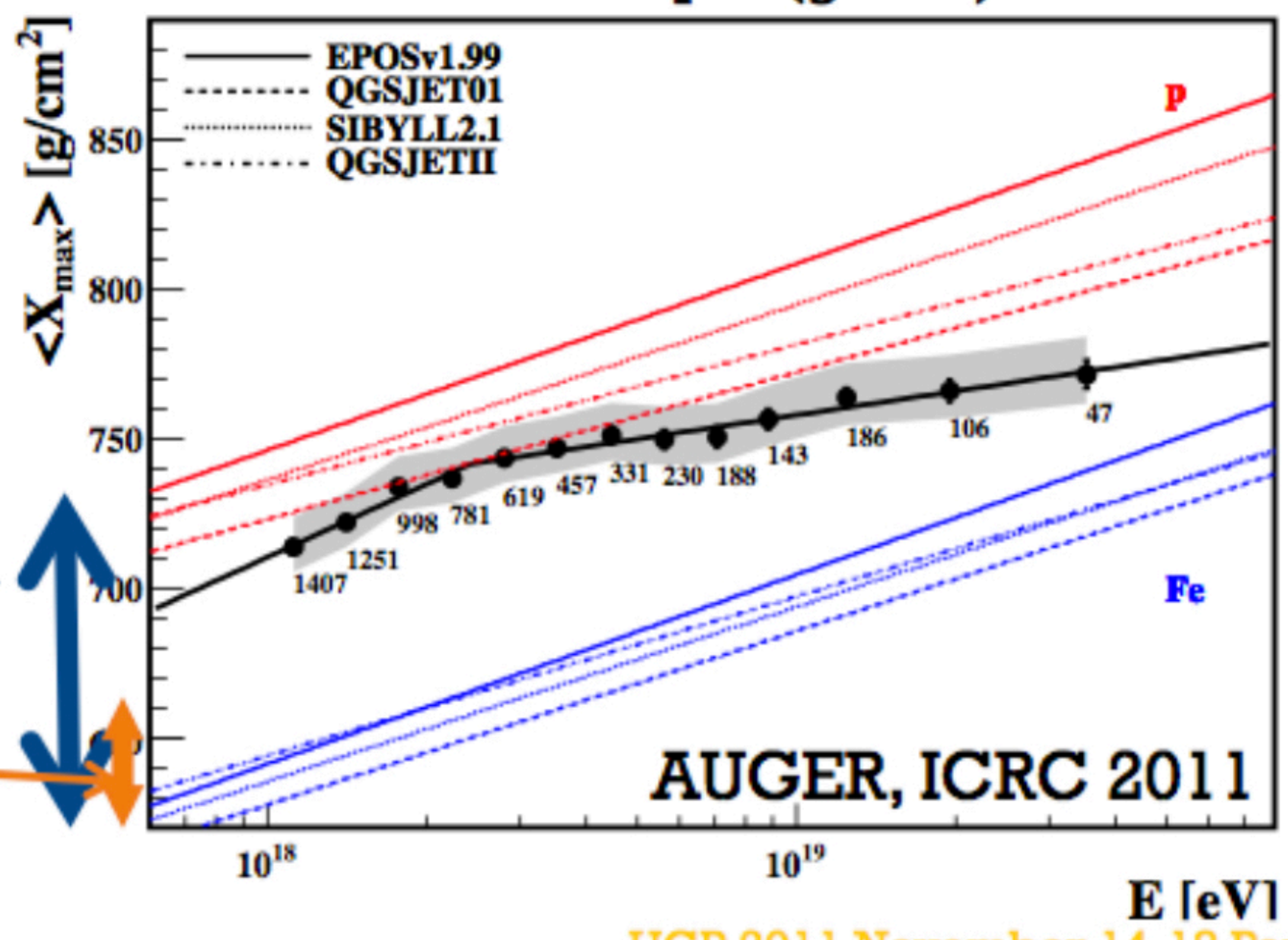
neutrons **JHEP 07 (2020) 016**

π^0 spectrum and air shower



π^0 spectrum at $E_{lab} = 10^{17}$eV



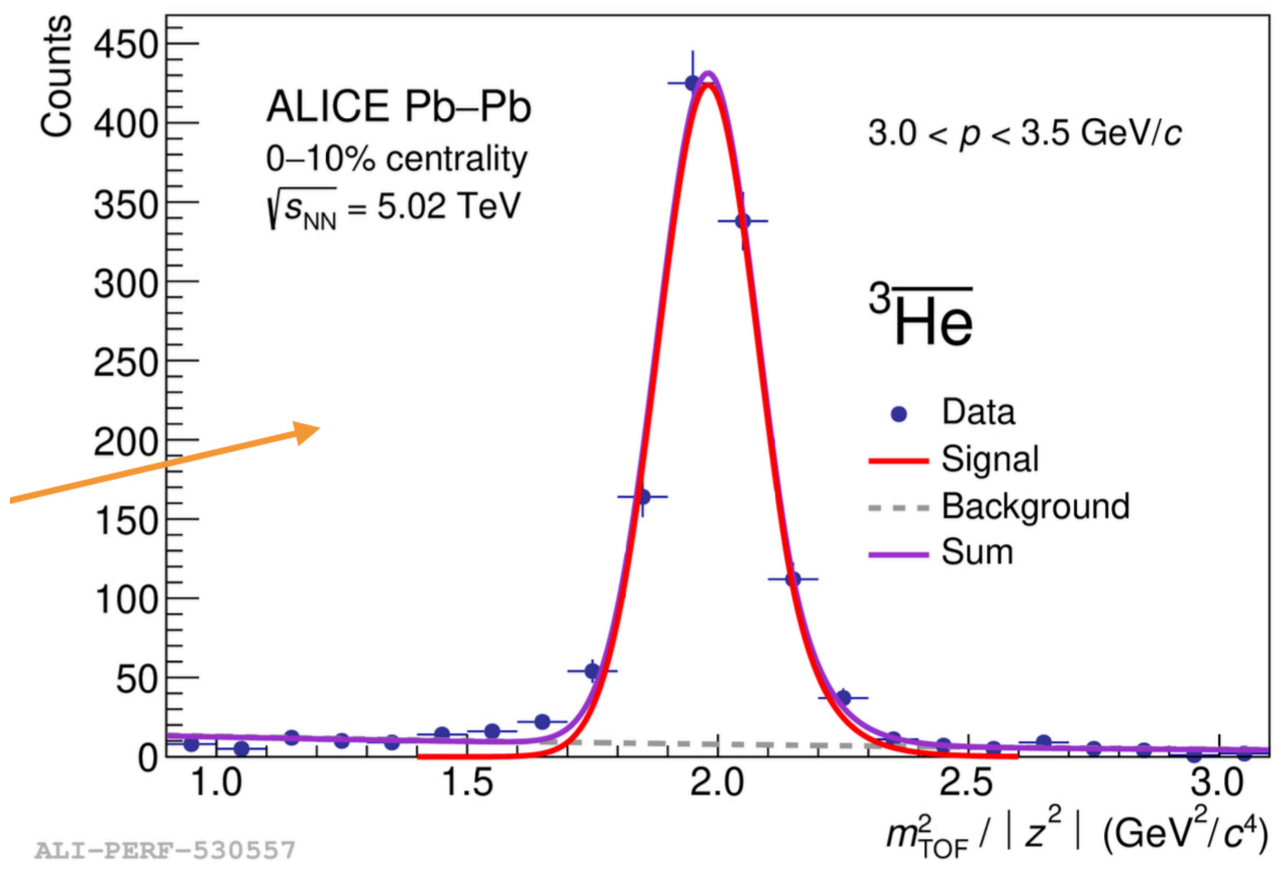


- ✓ Artificial modification of meson spectra (in agreement with differences between models)
- ✓ $\Delta\langle X_{max}(p\text{-}Fe)\rangle \sim$ 100 g/cm^2
- ✓ Effect to air shower ~ 30 g/cm^2

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

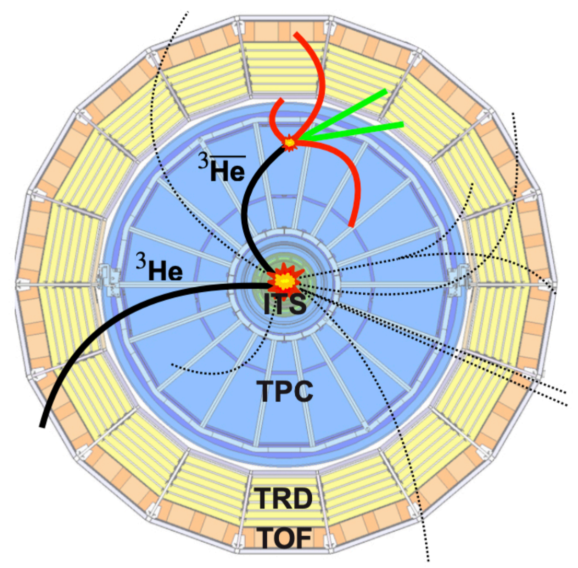
Laura Šerkšnytė CERN seminar



Method: ALICE as a target

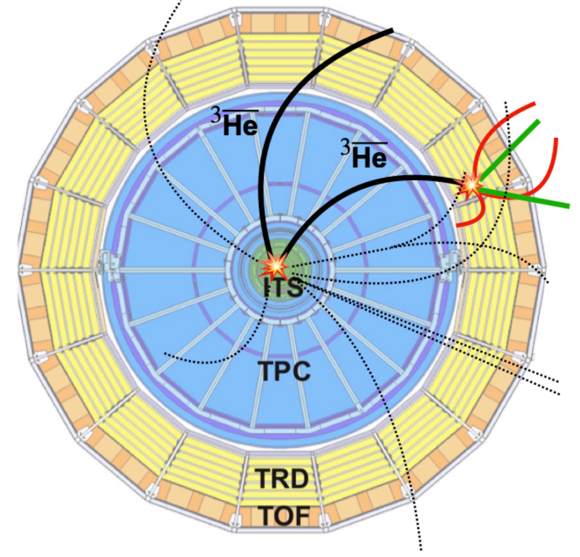
Antimatter-to-matter ratio

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



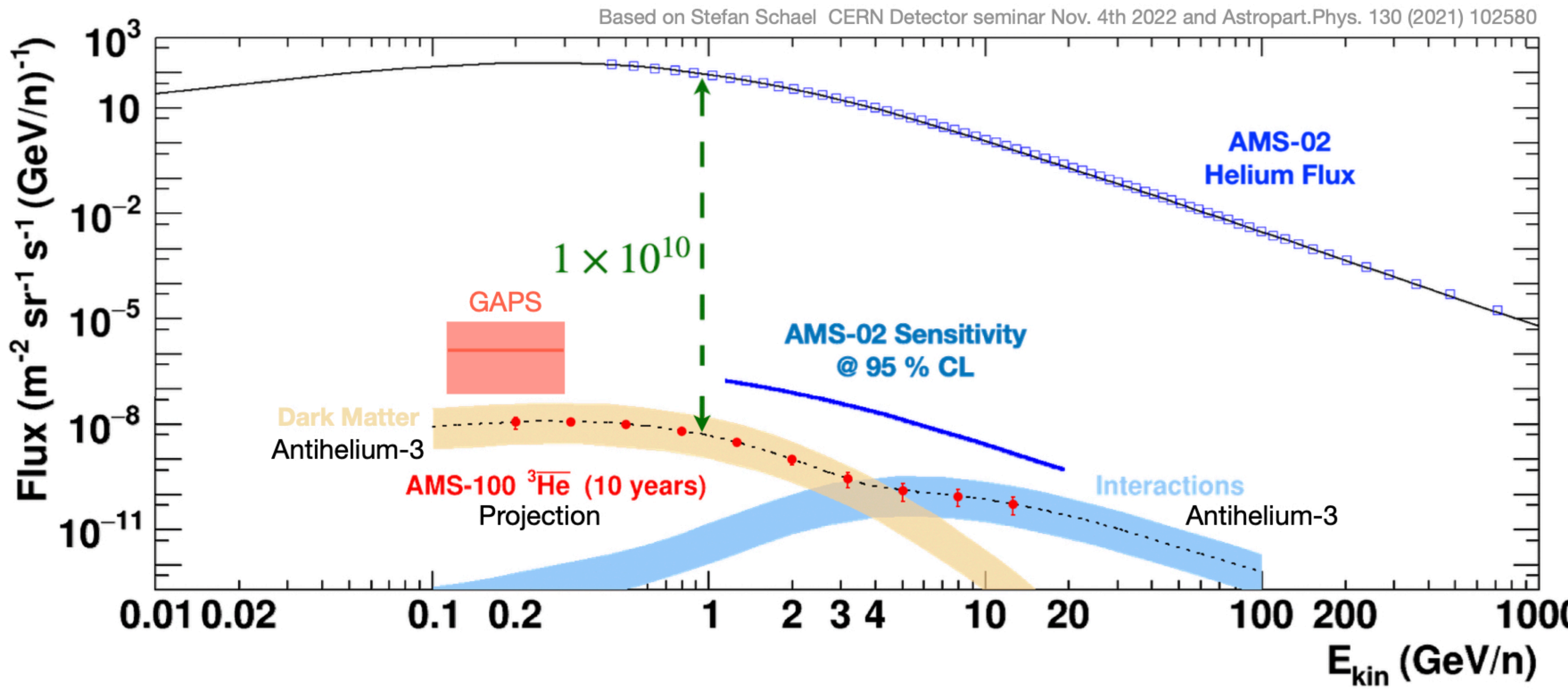
TOF-to-TPC-matching

- 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



Remarks

- The 4000 papers mentioned before 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

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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 and contributes to our deeper understanding of QCD

Final words

- Progress with QCD is critical to exploit the excellent performance of the LHC:
  - *On one side, in absence of direct and unambiguous BSM signals, the only challenges to the SM and the only probes of the origin of EWSB will come from the reliable theoretical interpretation of precision measurements*
  - *On the other side, strong interactions remain the least understood and most challenging aspect of the SM dynamics, with a broad set of implications ranging from spectroscopy to astrophysical domains.*

- The diverse collider phenomenology —particularly the hadronic one —probes a huge dynamical range of phenomena, challenging the theoretical understanding, both at the level of fundamental understanding and of computational complexity.

- The goal of measuring and theoretically describing " SM data " goes hand in hand with the search for BSM physics, whether directly or via precision SM tests:

  It provides the motivational challenge and the intellectual reward to ensure the continued progress of collider physics for the next decades