QCD at high energy density, heavy-ion physics, and the ALICE experiment

Lecture 2/2

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Durham STFC Nuclear Physics Summer School
23/08/2024

Overview

- **ALICE** (**A** **L**arge **I**on **C**ollider **E**xperiment) is the experiment at the LHC dedicated to studying the deconfined state of QCD known as the Quark-Gluon Plasma (QGP)

- In these lectures I want to give an overview of heavy-ion physics

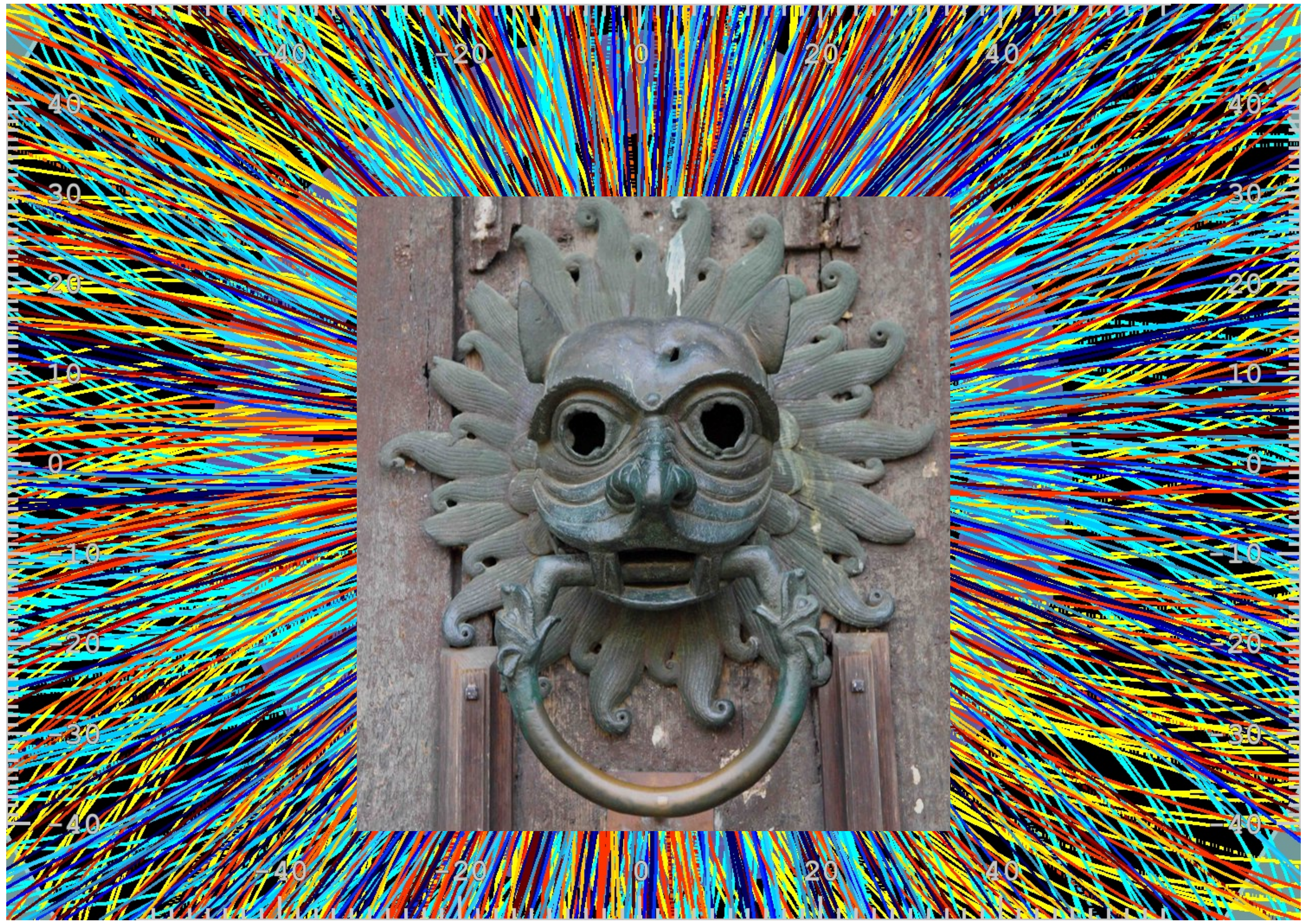
  - Basic concepts of QCD, the QGP and heavy-ion physics (including collider physics)

  - The ALICE experiment

  - **How do we probe the QGP? What have we discovered?**

  - **Future plans of heavy-ion physics at the LHC**

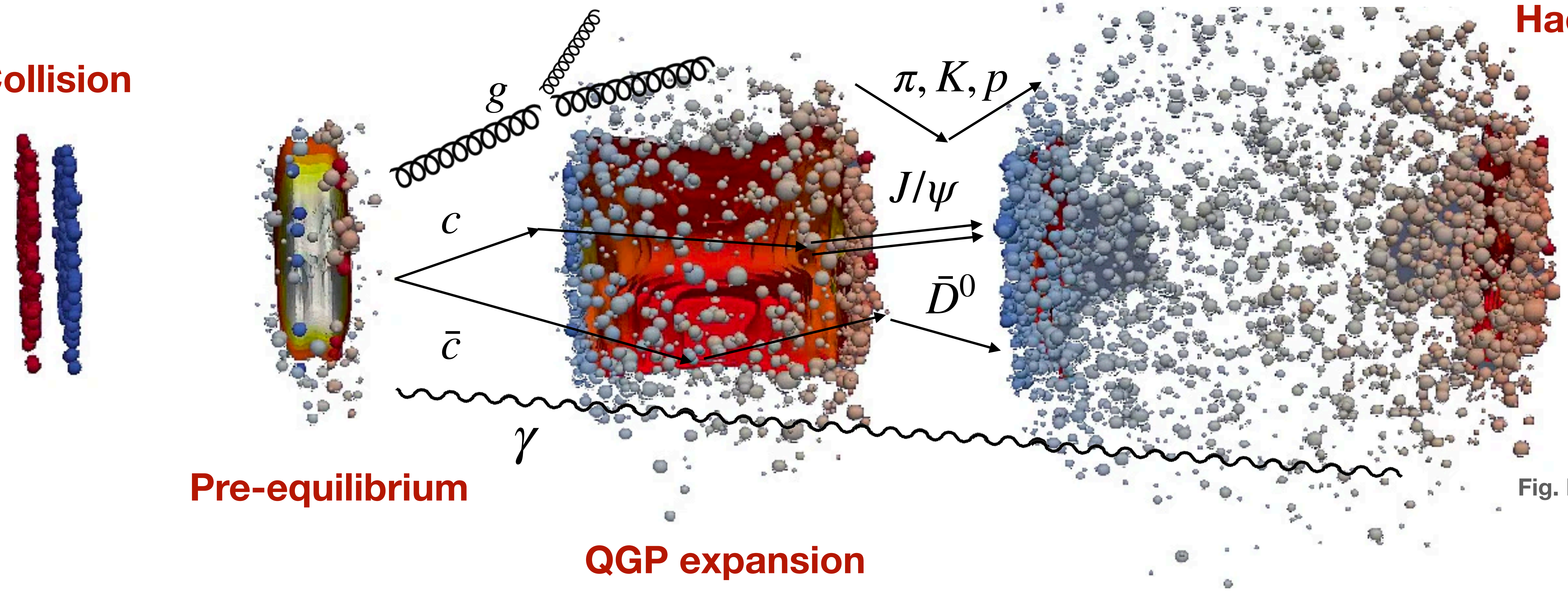
Today!



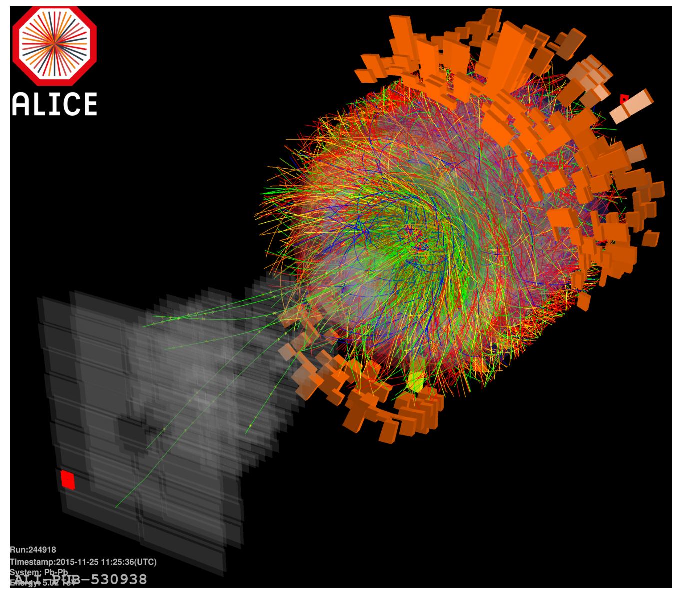
Anatomy of a heavy ion collision

t = 0 → t ~ 0.5 fm/c → t > 15 fm/c (~5x10^{-23} s) t ~ 10^{-6} s

Collision



Hadronisation



Detection

Pre-equilibrium

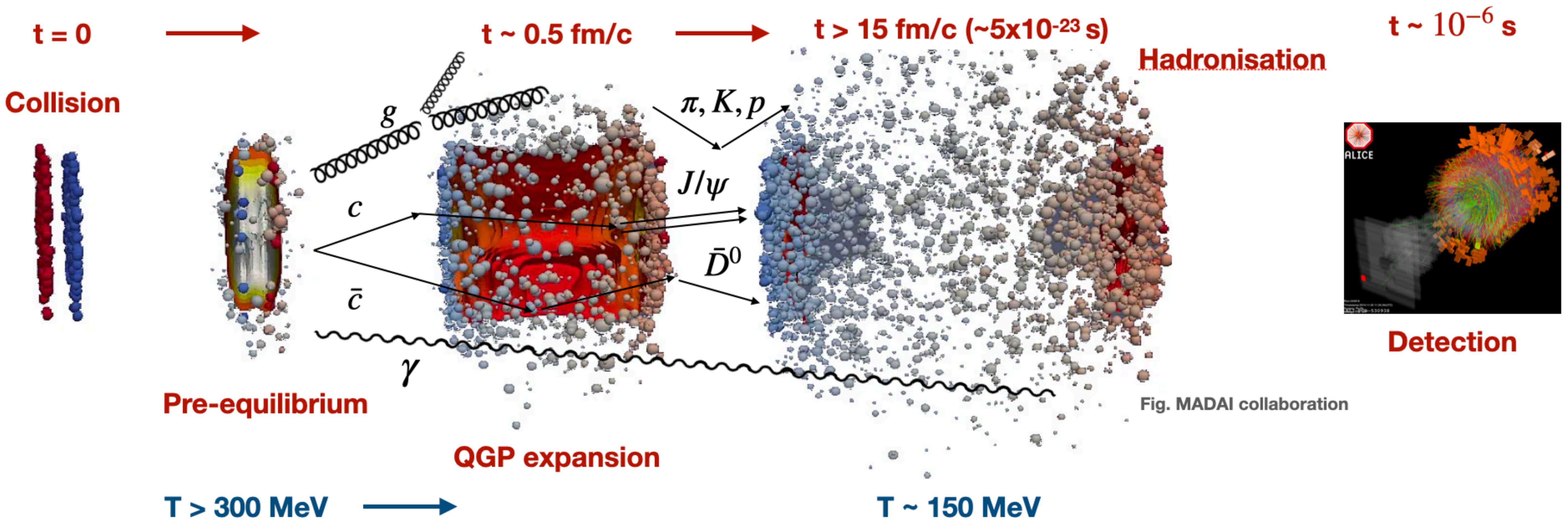
QGP expansion

Fig. MADAI collaboration

T > 300 MeV → T ~ 150 MeV

Many ways to quantitatively characterise the QGP

Characterisation of the QGP created in heavy-ion collisions



Thermodynamics, collectivity, global properties (‘*Macroscopic*’)

- Temperature and energy density (direct photons,
- Collectivity, flow (azimuthal anisotropy, long-range correlations)
- Lifetime, size

Partonic interactions (‘*Microscopic*’)

- Partonic energy loss (jet quenching)
- Heavy-flavour energy loss and diffusion
- Microscopic structure of QGP

Flavour equilibrium, Hadronisation

- Hadron flavour composition/chemistry
- Strangeness enhancement
- Hadronisation mechanisms (Baryon/meson ratios)

Small systems

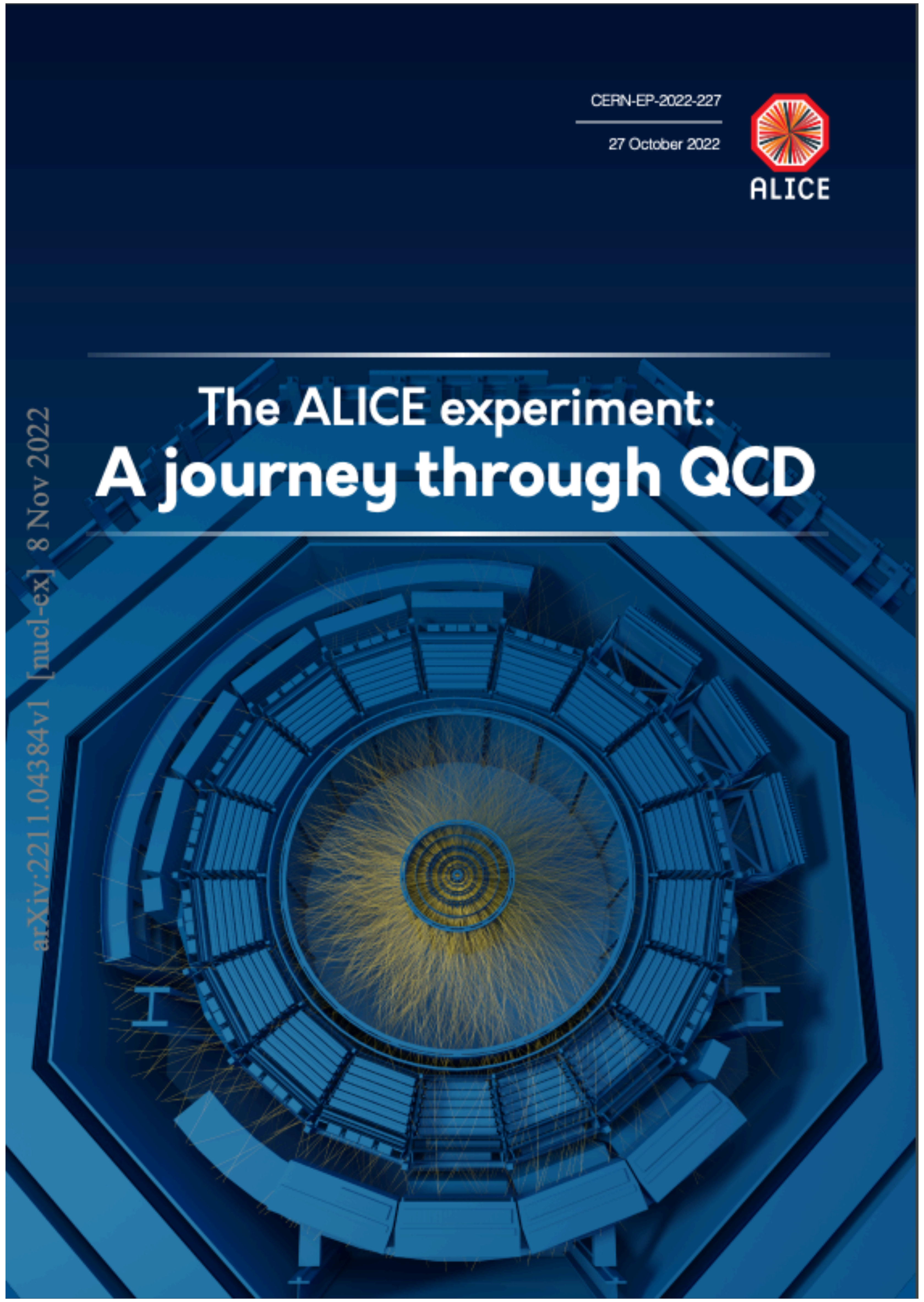
- QCD measurements
- Limit of QGP formation (QGP-like effects)

Further reading

The physics shown here is really just a snapshot of results from ALICE at the LHC!

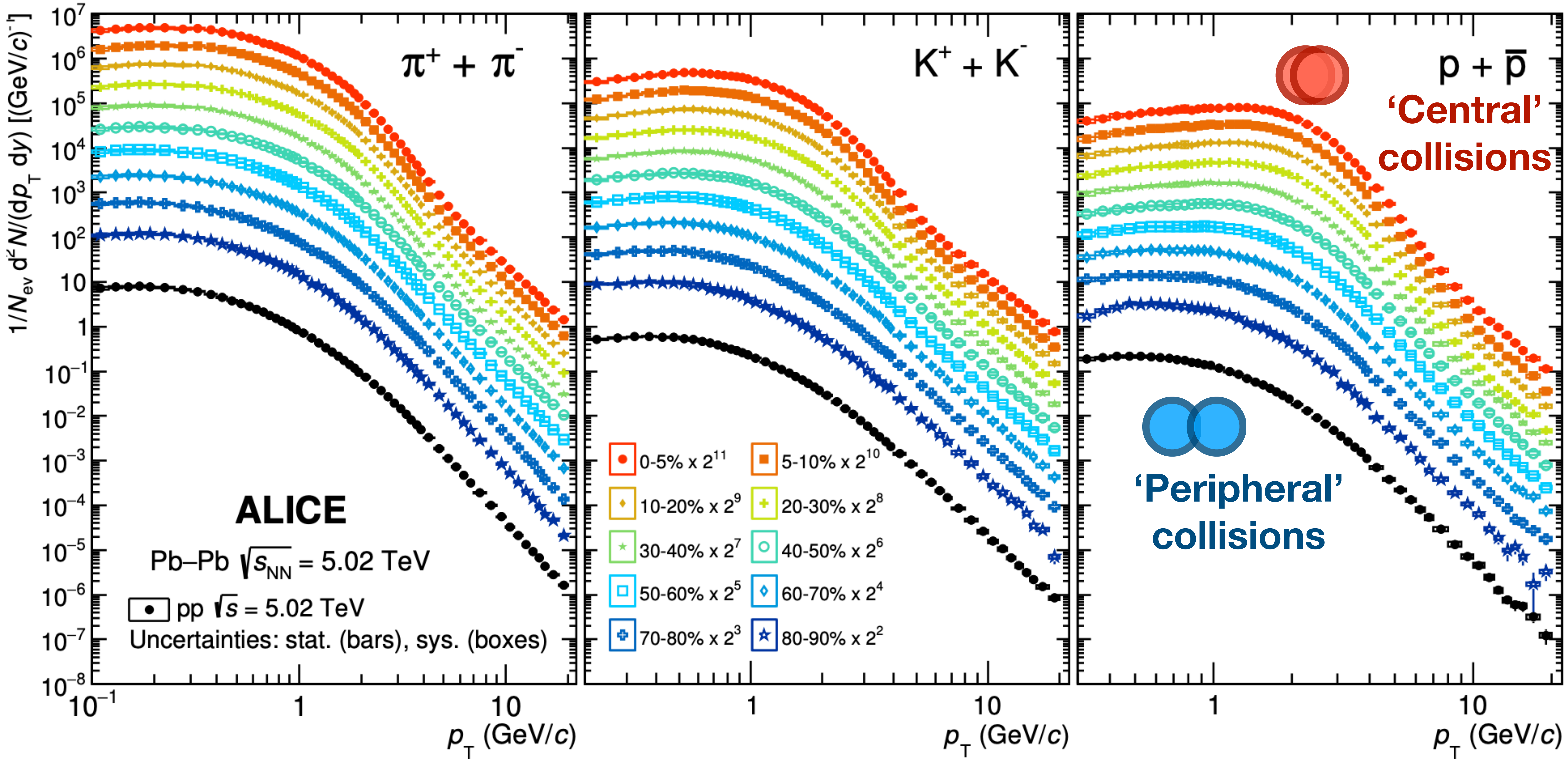
- **> 400 ALICE papers from Run 1 and 2 of the LHC**
- Recent review paper (published last week!) summarises the wealth of physics from this period

Eur.Phys.J.C 84 (2024) 8, 813



Particle spectra

- Measurement of particle spectra ‘starting point’ of many measurements

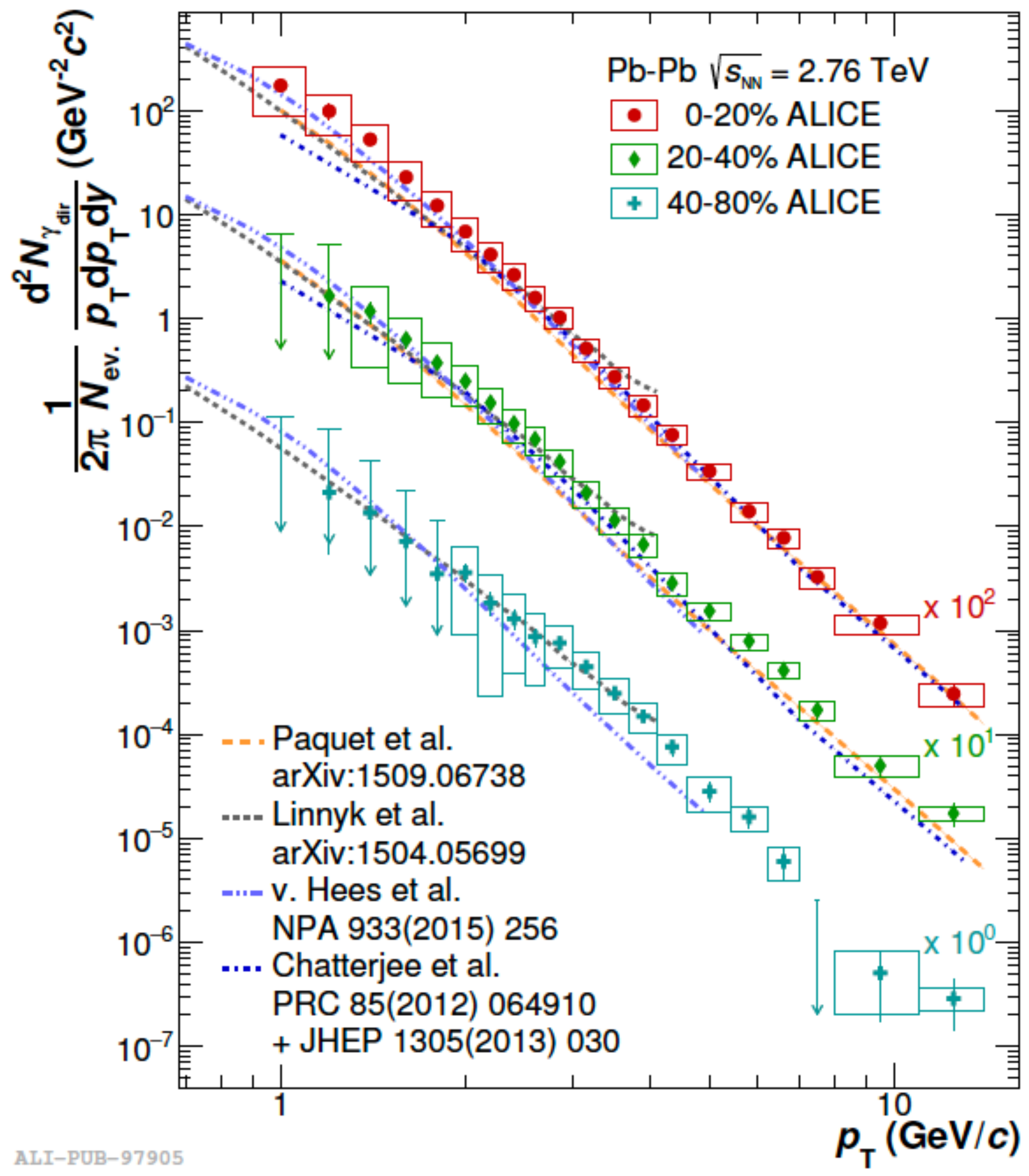


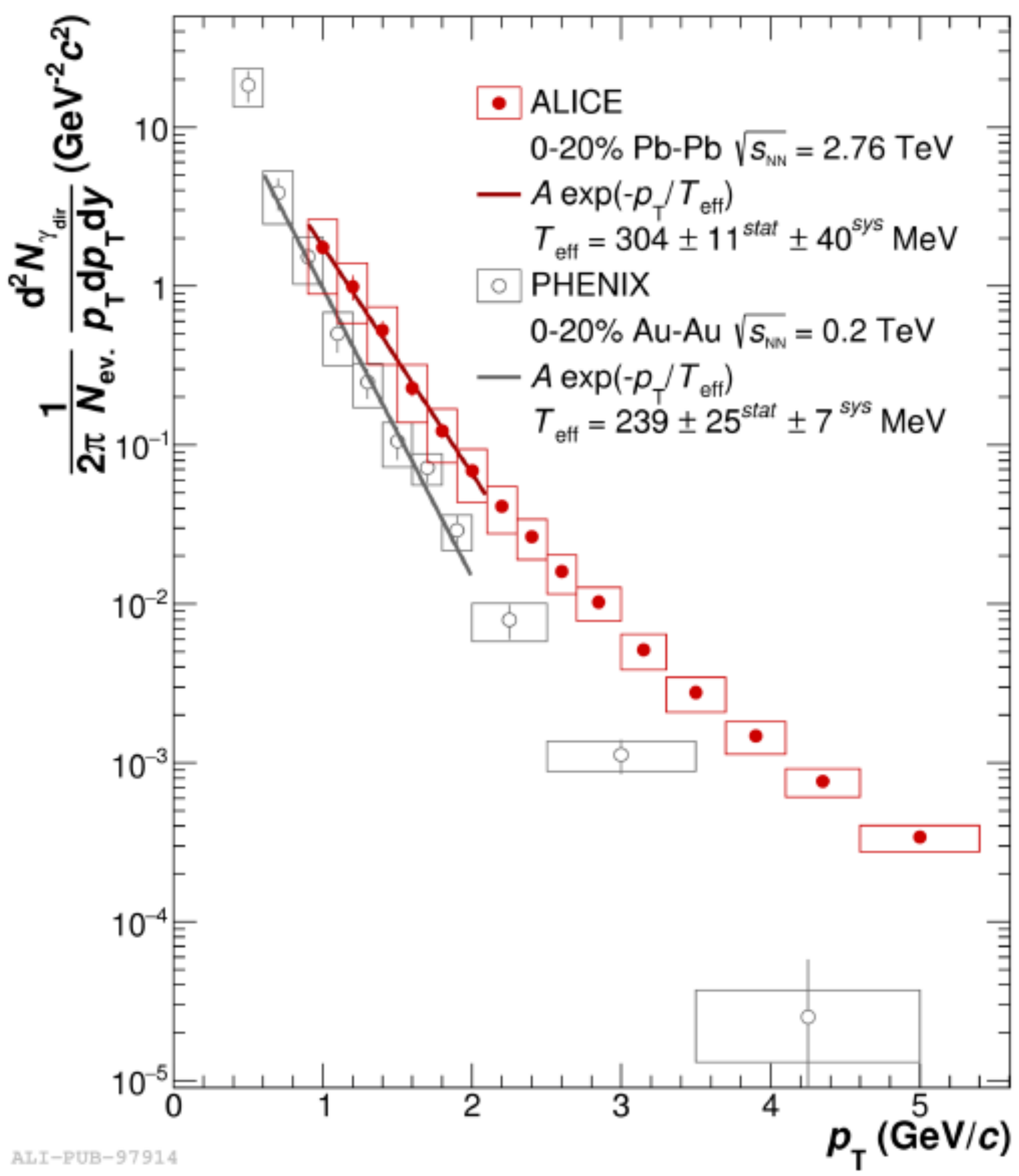
e.g. measure…

- Yields with respect to pp collisions
- Yields vs reaction plane
- Yields vs centrality
- Total ‘integrated’ particle yields
- Ratios of different particle yields
- …

Initial temperature of the QGP

- **Direct photons (not from hadron decays)** emitted at different stages of the collision
  - initial hard scattering produces *prompt photons*, while black body radiation from QGP produces *thermal photons*
- **Thermal photons give access to the initial temperature of the system created in heavy-ion collision.**





[Phys. Lett. B 754 (2016) 235-248]

$$T_{eff} = 304 \pm 11 \pm 40 \text{ MeV}$$

- Temperature higher than critical temperature ~150 MeV
- (Note - effective temperature not exact as radiation 'blue-shifted' due to expansion of system)

Strangeness enhancement

- **pp collisions:** Suppression of strangeness production (locality of strangeness conservation)

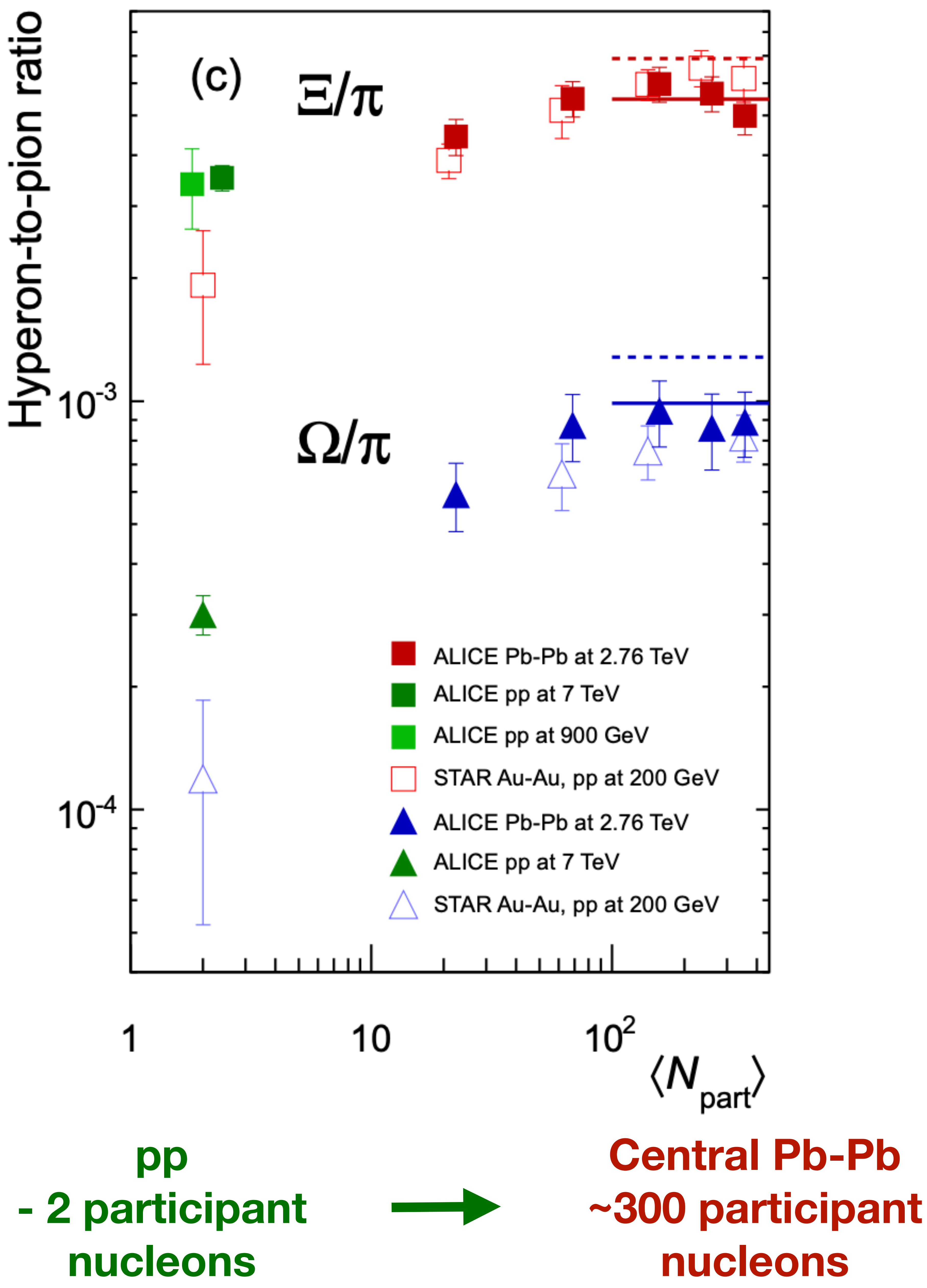
- **Heavy-ion collisions:** abundant thermal production of $s\bar{s}$ quarks due to equilibrated, deconfined phase

  - Production of multi-strange hadrons Ξ (dss) and Ω (sss) most sensitive to strangeness production of a system

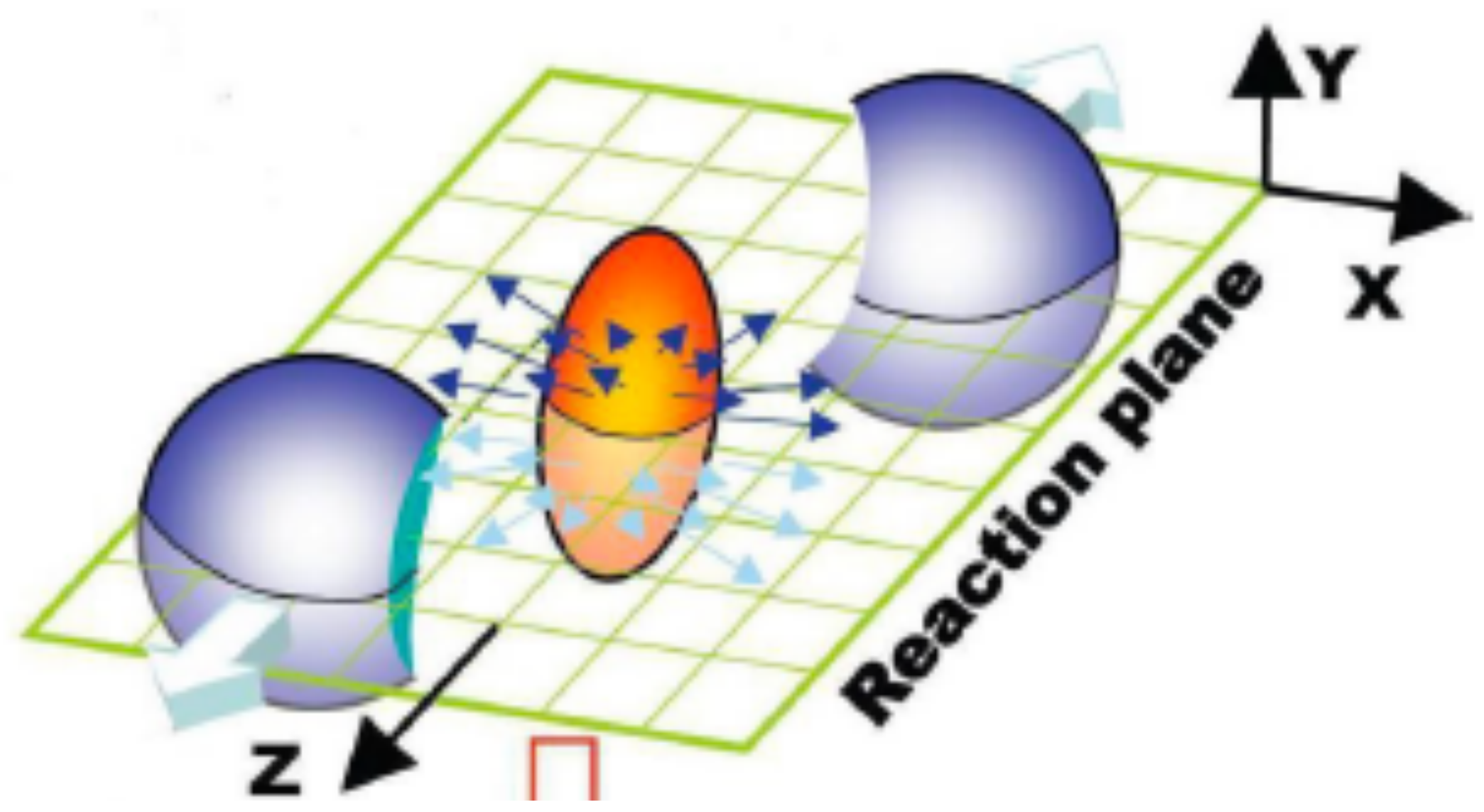
Significant strangeness enhancement seen in heavy-ion collisions → deconfinement!

Consistent results at low energy (RHIC) and high energy (LHC) → enhancement dependent only on participant nucleons/final state multiplicity

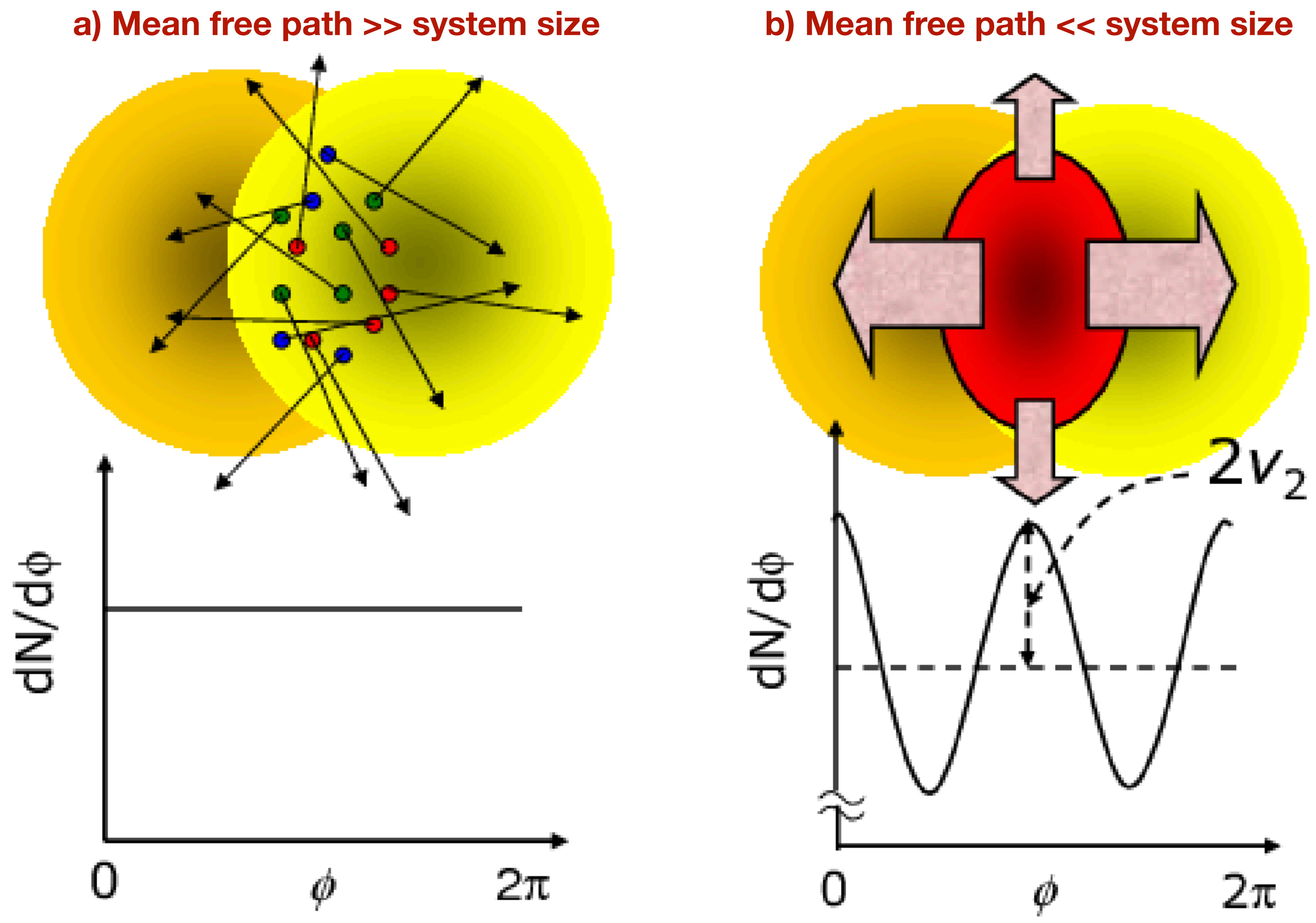
ALICE: Phys. Lett. B 728 (2014) 216



Probing how the QGP 'liquid' flows

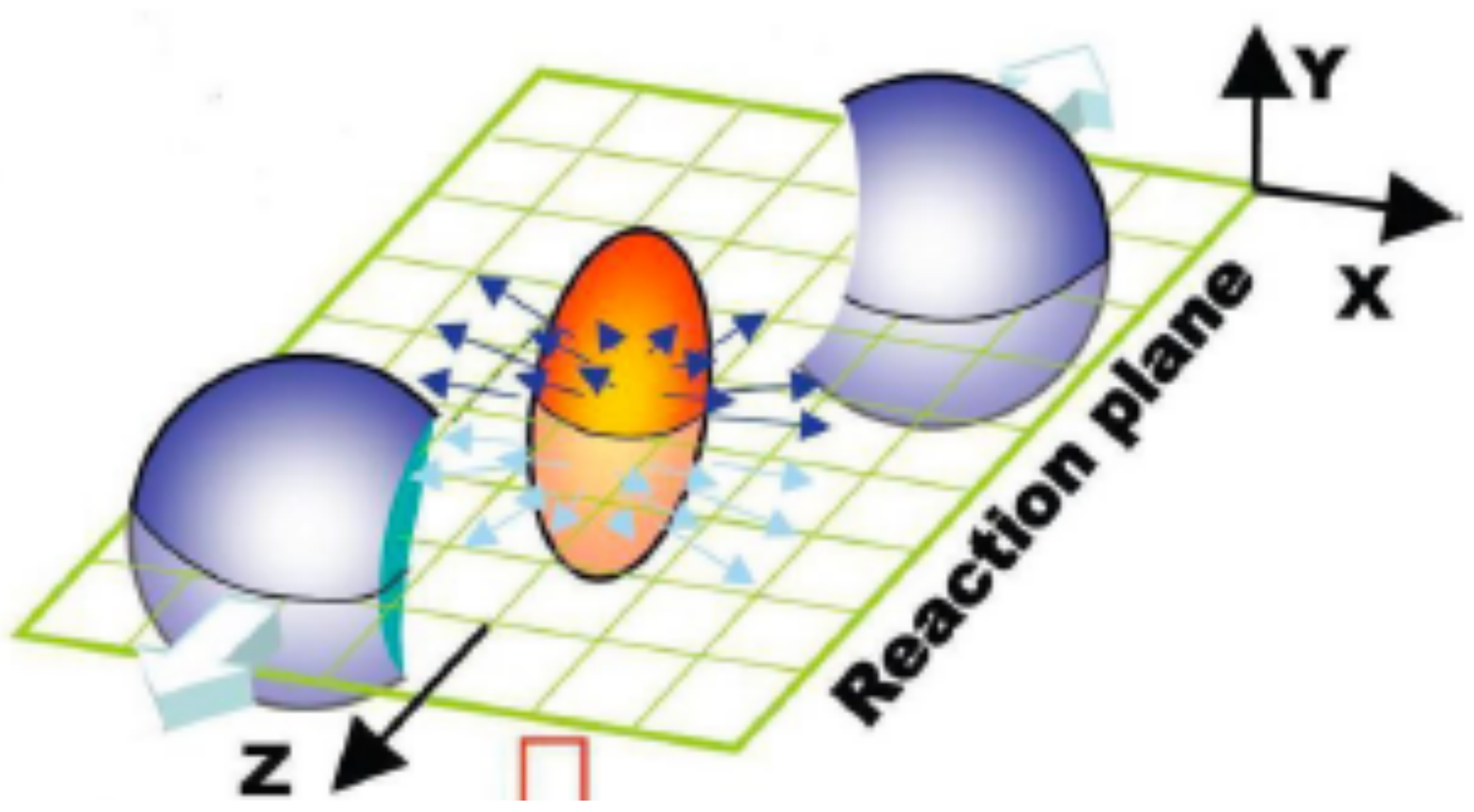


$$\frac{dN}{d\phi} \propto \sum_{n=1}^{\infty} 2v_n(p_T)\ \cos(n(\phi - \Psi_n))$$



- Due to pressure gradients **spatial anisotropy** in collision translates to **momentum anisotropy**
  - Can be characterised by anisotropic flow coefficients v_n - expand azimuthal momentum in a Fourier series
- Magnitude of momentum anisotropy relates relates to how much 'flow' builds up
  - *how are constituents coupled?* Fundamental properties such as viscosity can be determined from data

Probing how the QGP ‘liquid’ flows



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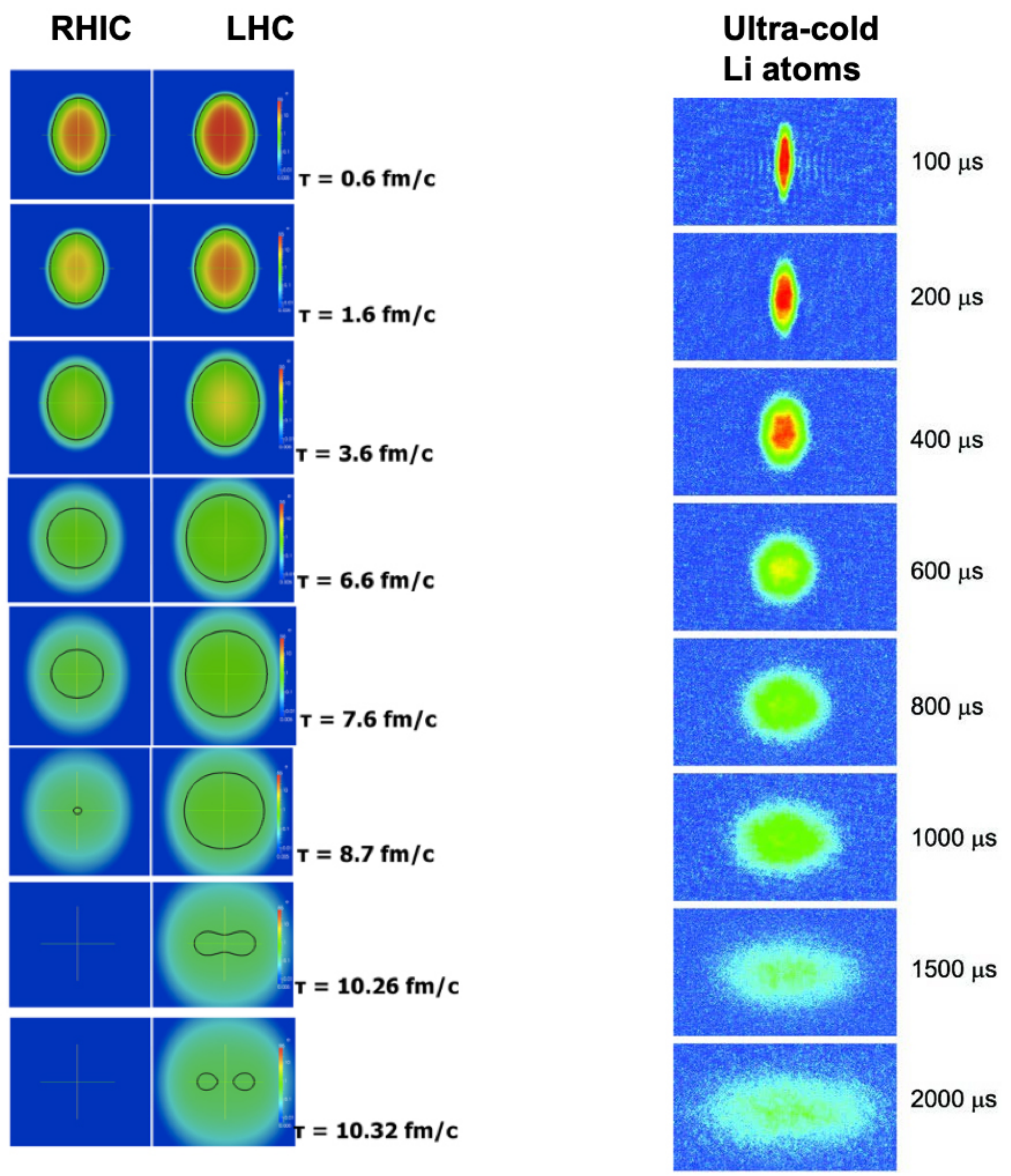

Similar expansion pattern to ultra-cold (~10^{-6} K) lithium atoms

Striking similarity despite factor ~10^{18} difference in temperature!

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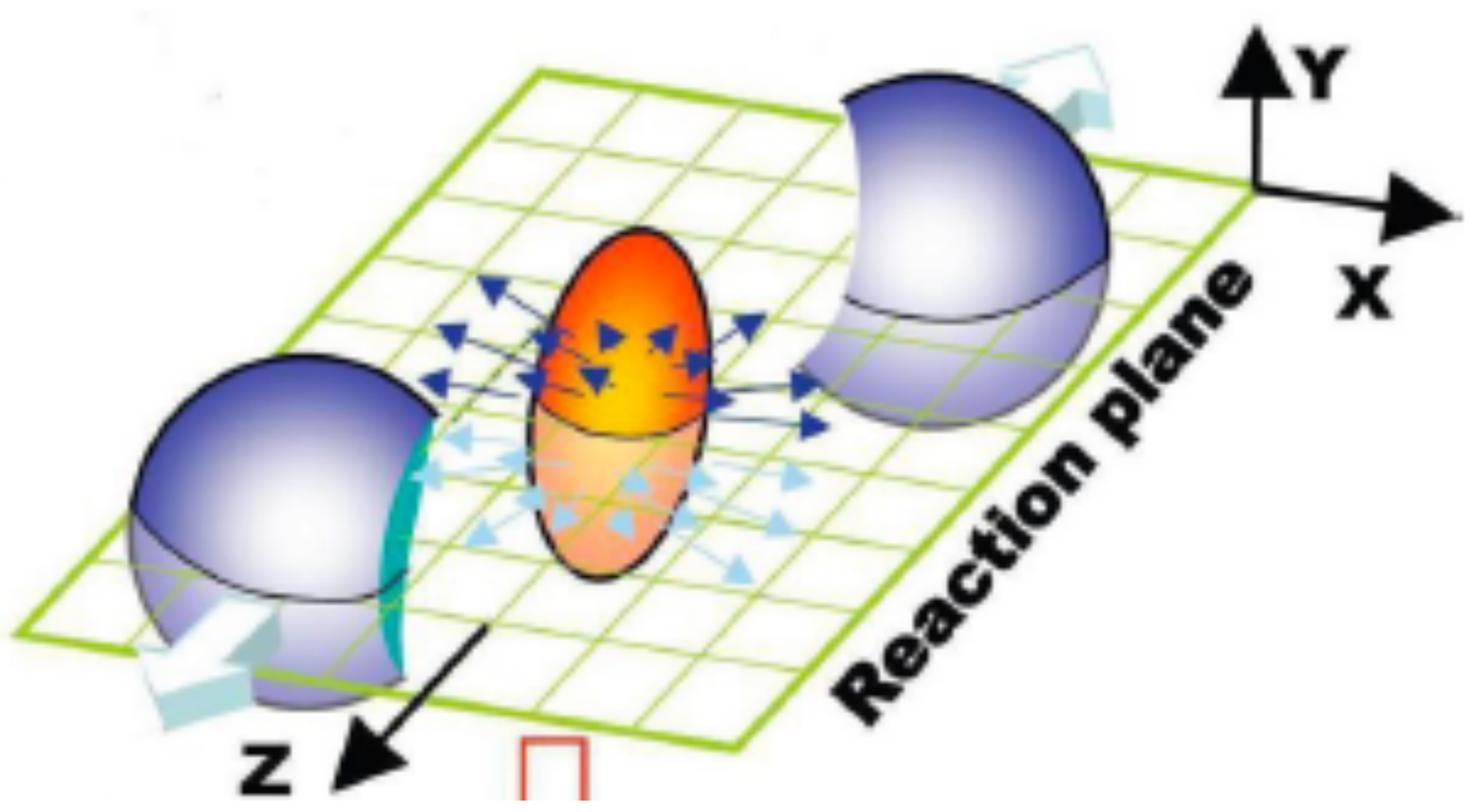

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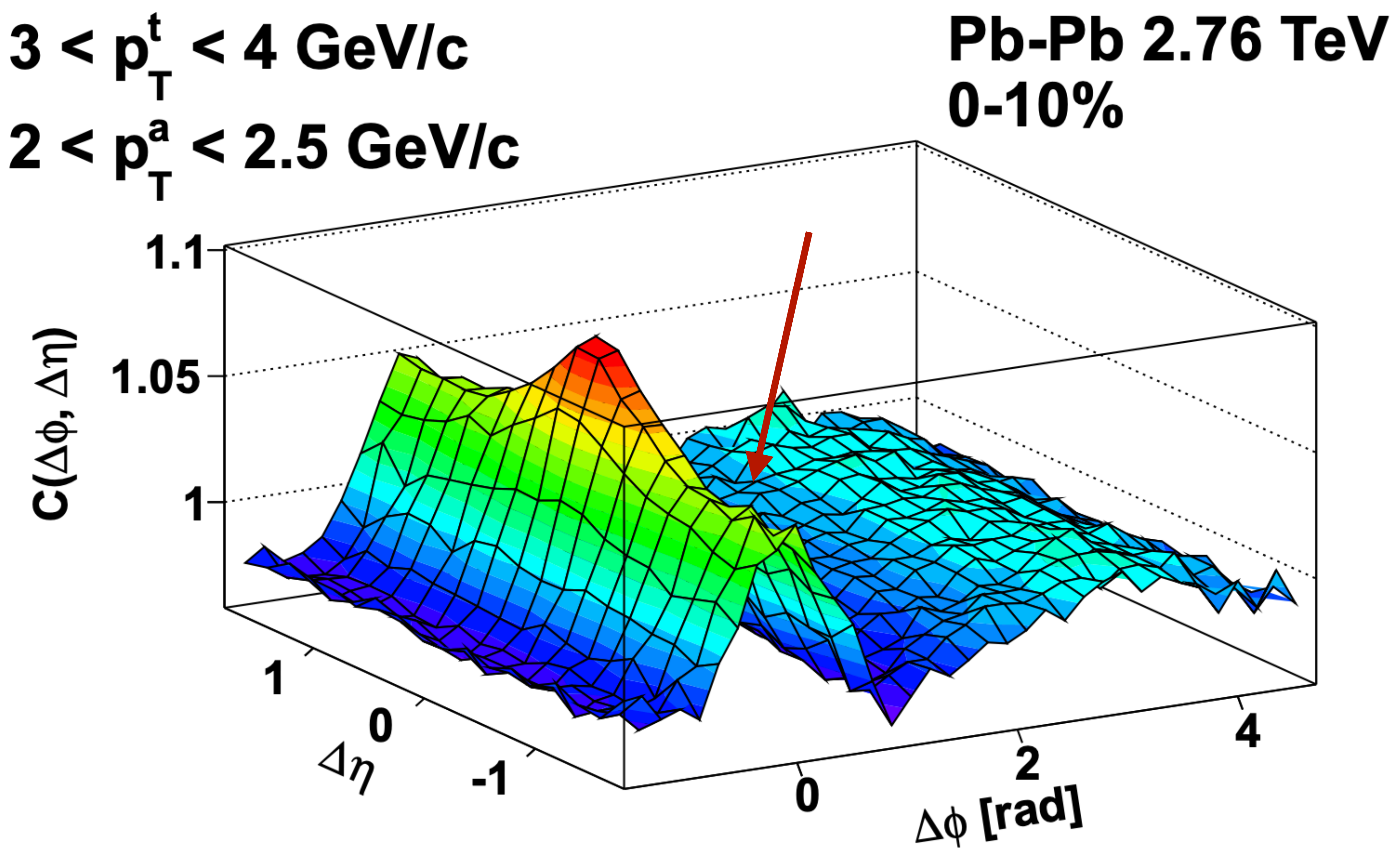
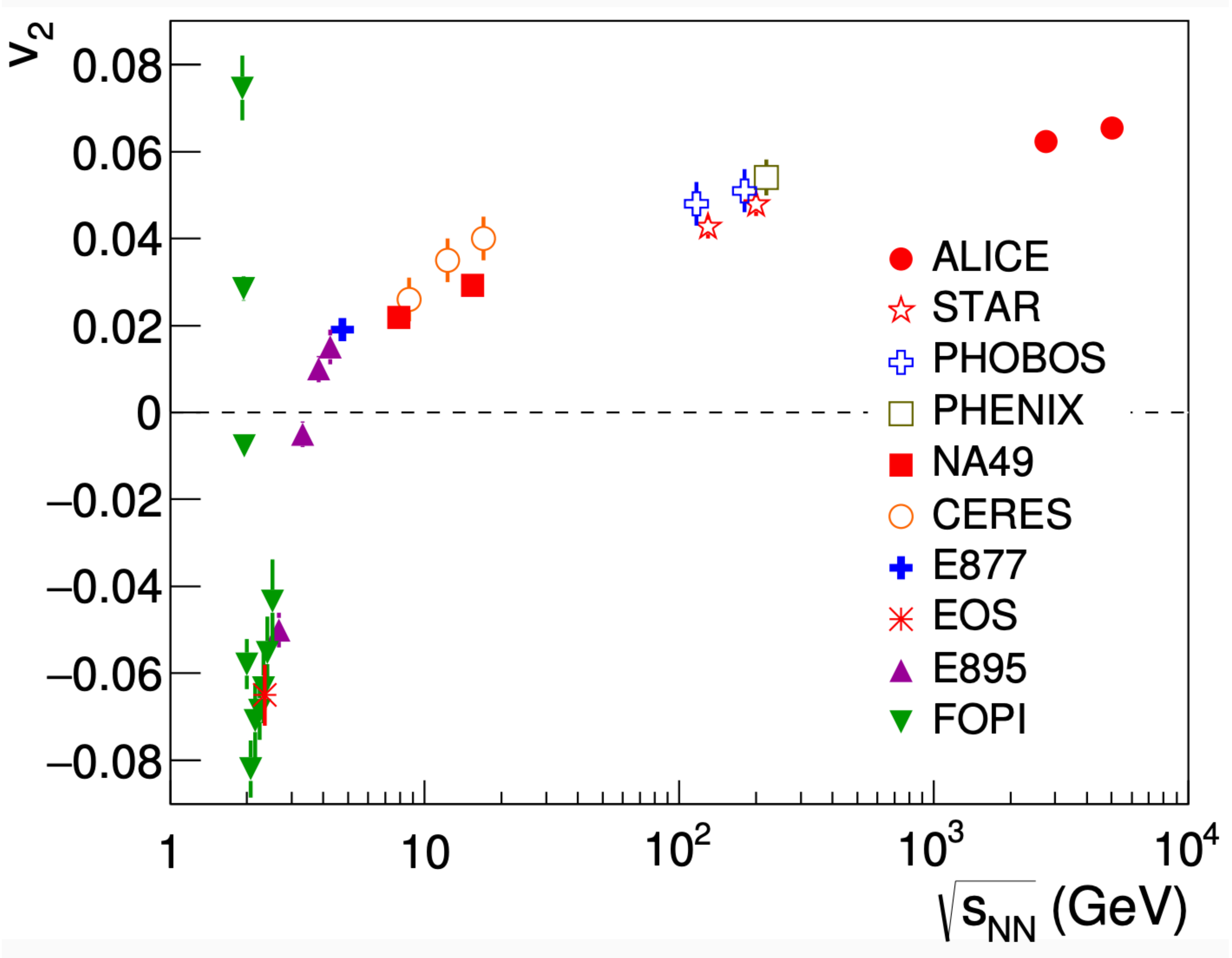


- Can also probe collective effects via two particle correlations (correlation between ‘trigger’ and ‘associated’ particles)
- Long-range correlations over wide η range (‘ridge’) understood to be due to flow of system

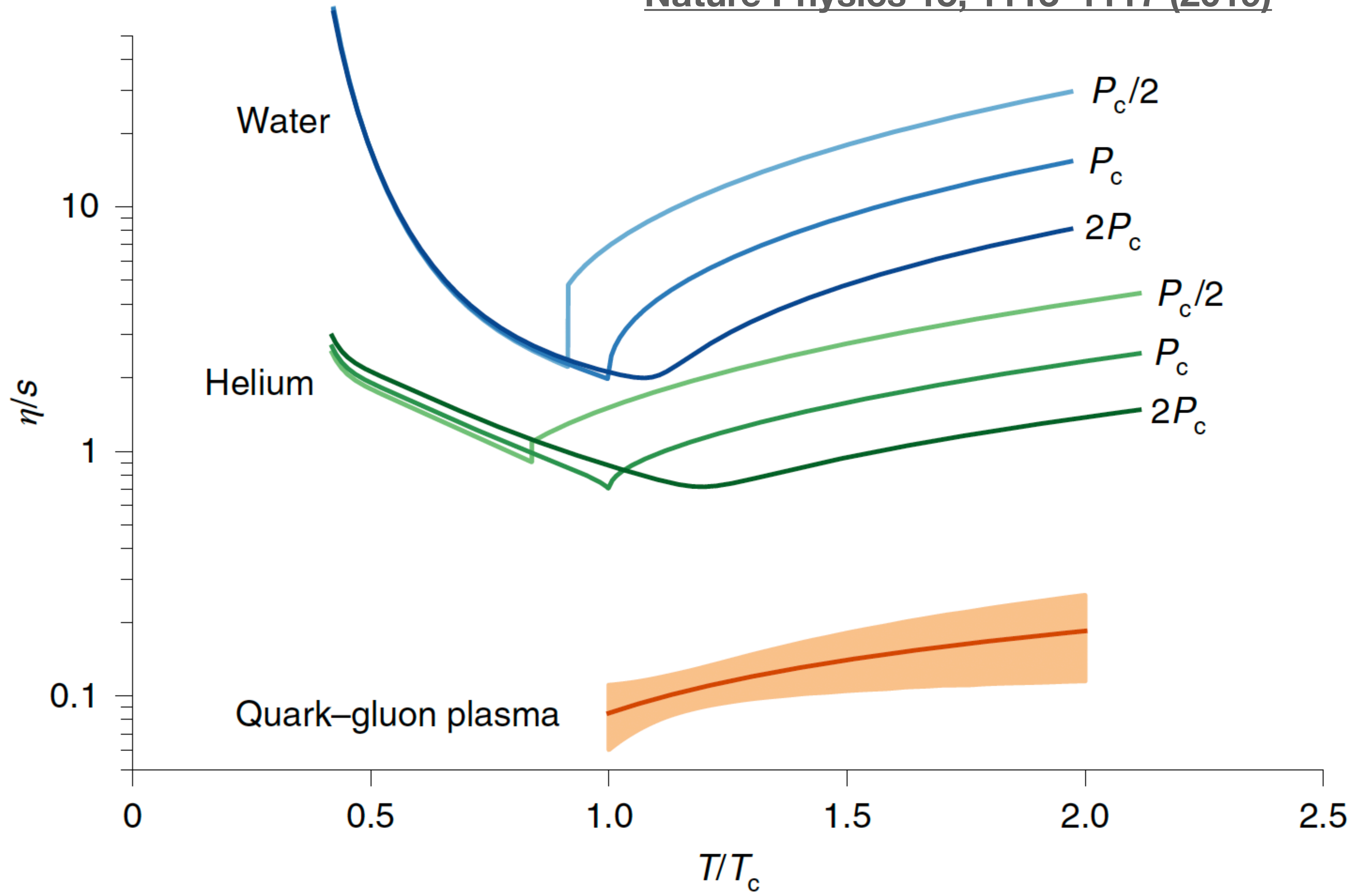
Probing how the QGP 'liquid' flows - elliptic flow v_2

ALICE: Phys. Rev. Lett. 105 (2010) 252302



Bayesian Parameter Estimation

J. Bernhart, J. Moreland, S. Bass
Nature Physics 15, 1113–1117 (2019)



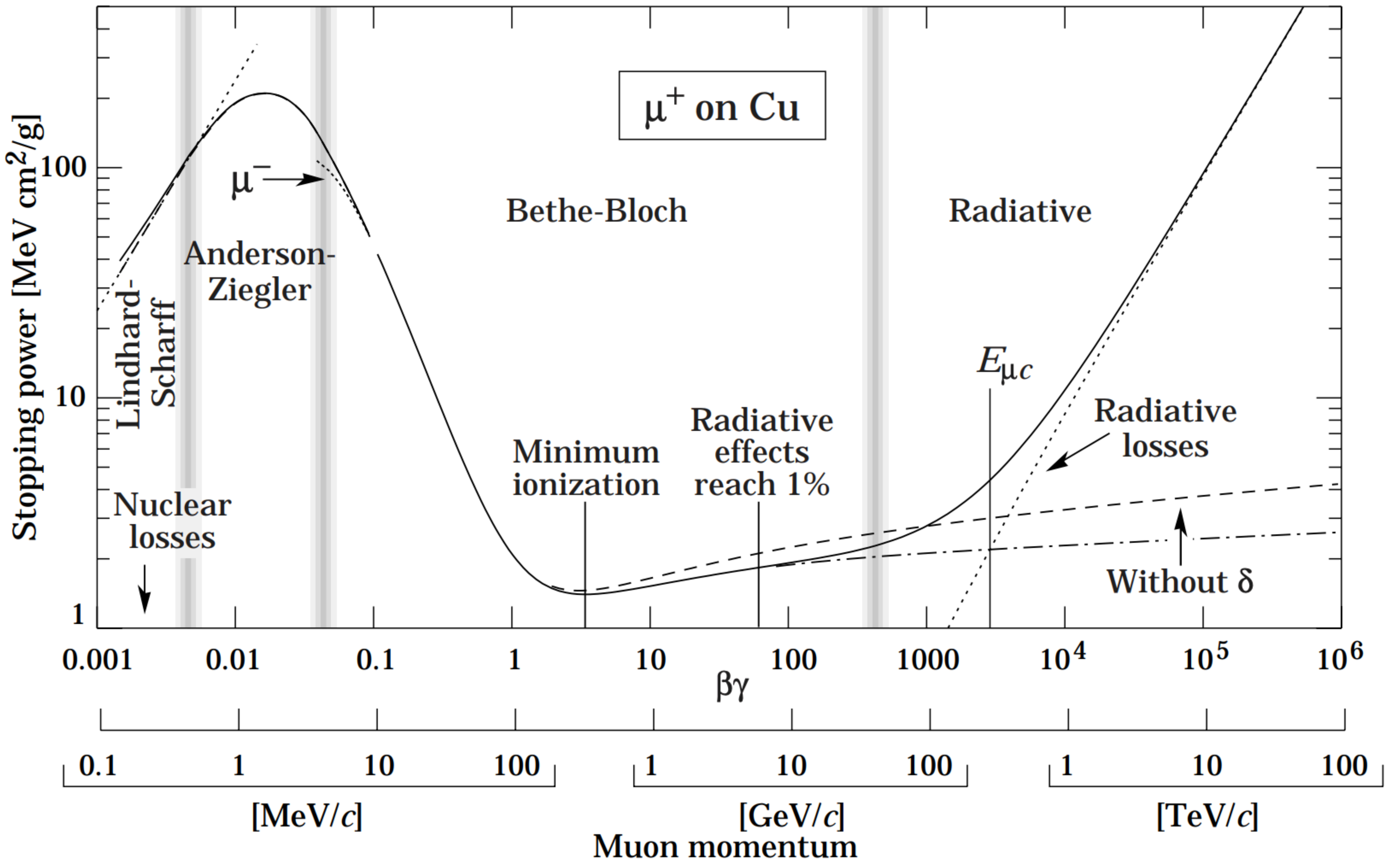
- shear viscosity over entropy density η/s ~ 0.1
  → **smallest viscosity of any known liquid**

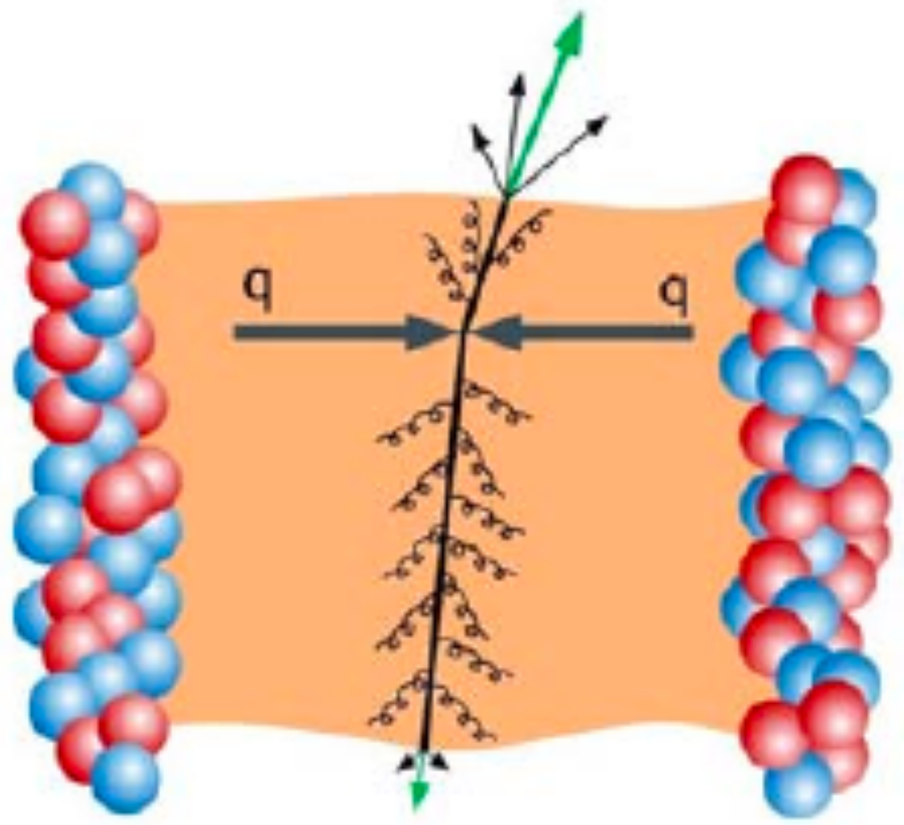
Close to lower limit from AdS/CFT (correspondence between strongly-coupled quantum theories and certain weakly-coupled quantum gravity theories)

$$\eta/s = 1/4\pi \sim 0.08$$

Probing the QGP with jets and heavy-flavour particles

- Out-of equilibrium ‘hard’ probes provide a unique way to probe the medium created
  - ***Jets*** and ***heavy-flavour (charm and beauty) particles*** - created at the start of the collision, and experience full evolution of the system



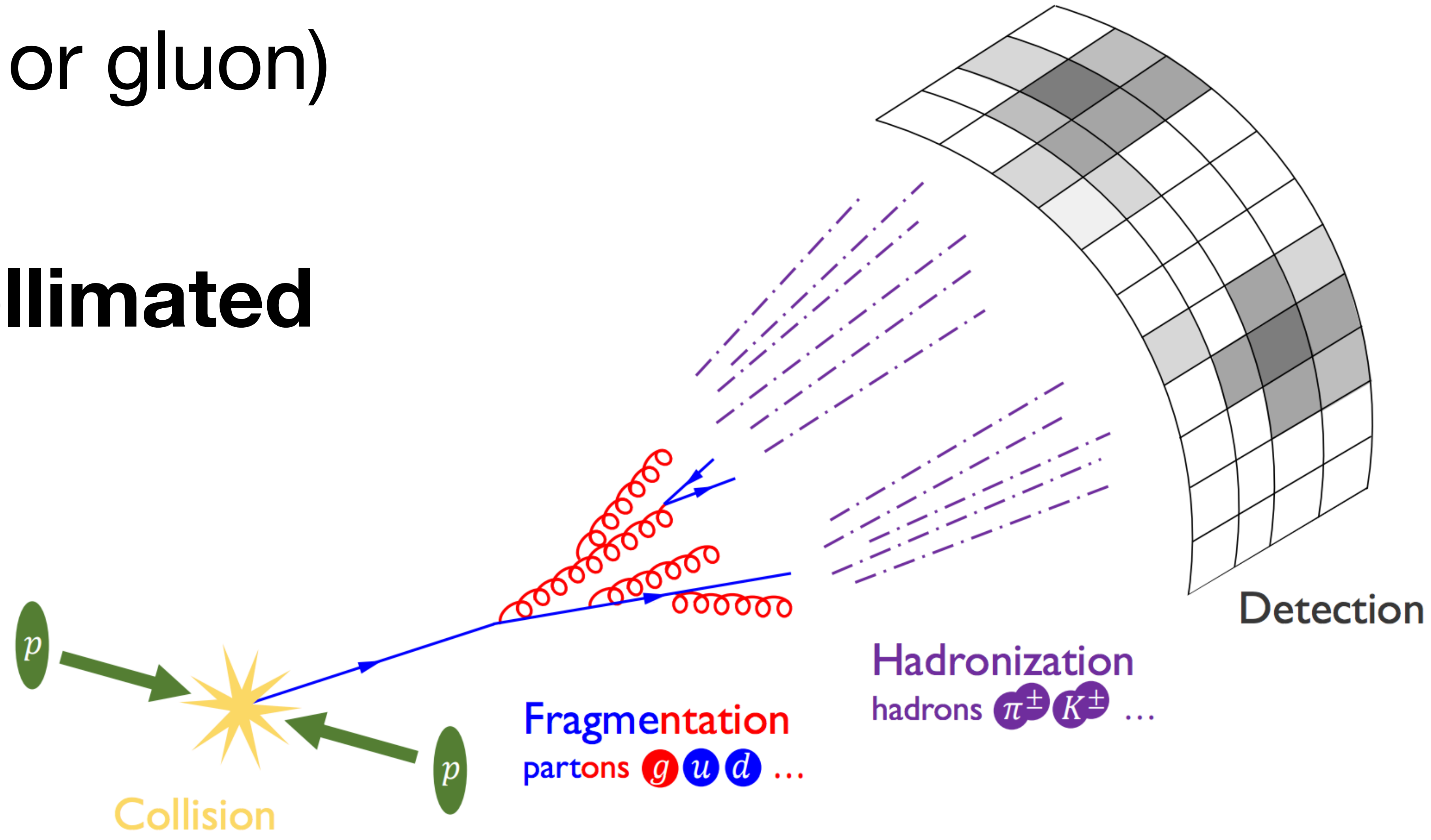


Can we map the ‘Bethe-Bloch curve of QCD matter’?

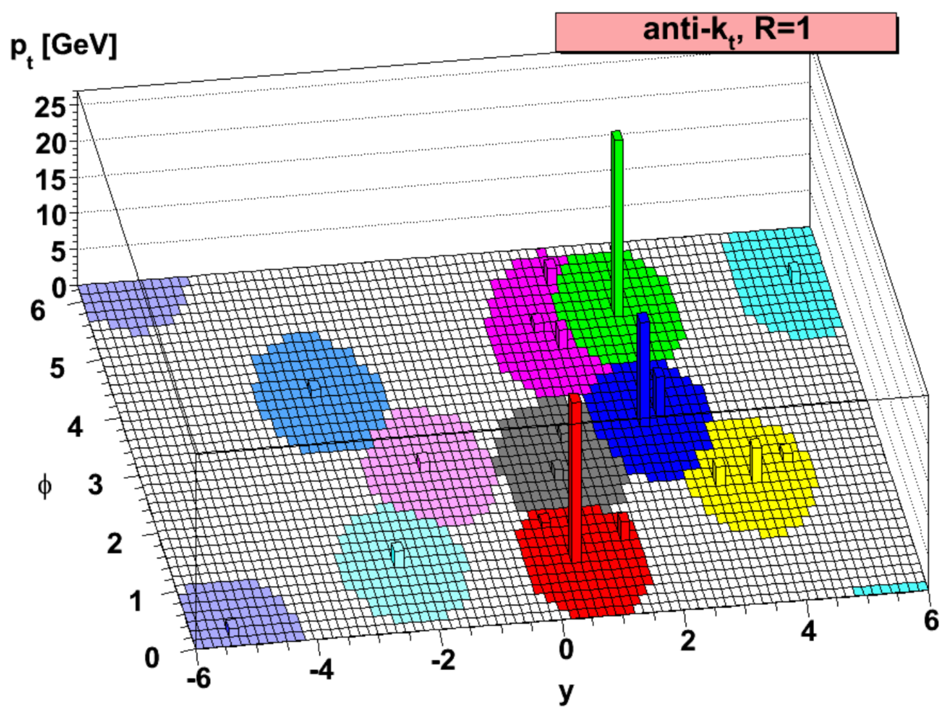
Jets in heavy-ion collisions

- Evolution of hard parton (quark or gluon) → gluon radiation
- Experimentally measured as **collimated spray of hadrons**

Reconstruct jets
→ measure initiating parton



Jet algorithms - precise connection between QCD theory and experiment



e.g. anti-k_T

M. Cacciari, G. Salam, G. Soyez, JHEP 04 (2008) 063

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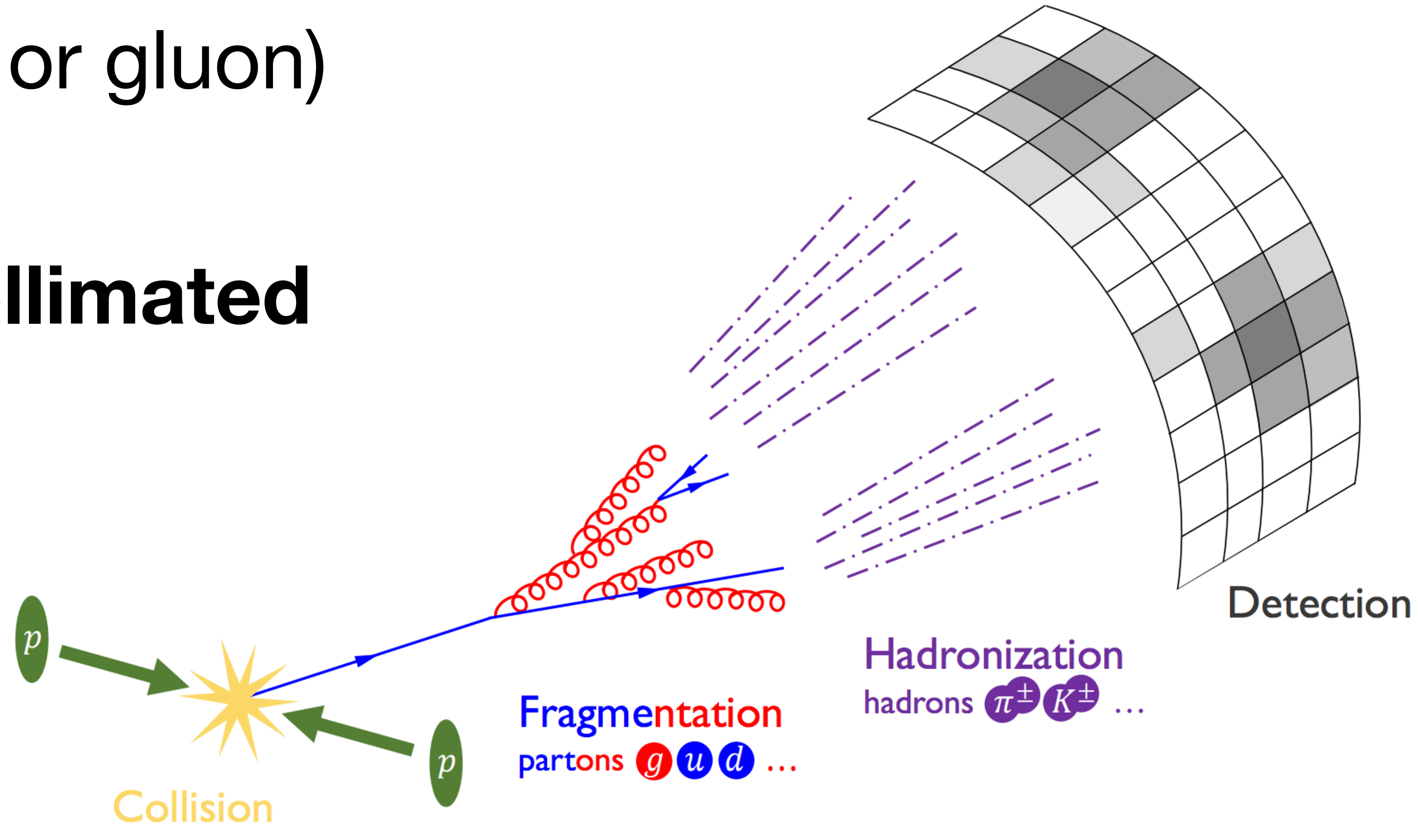

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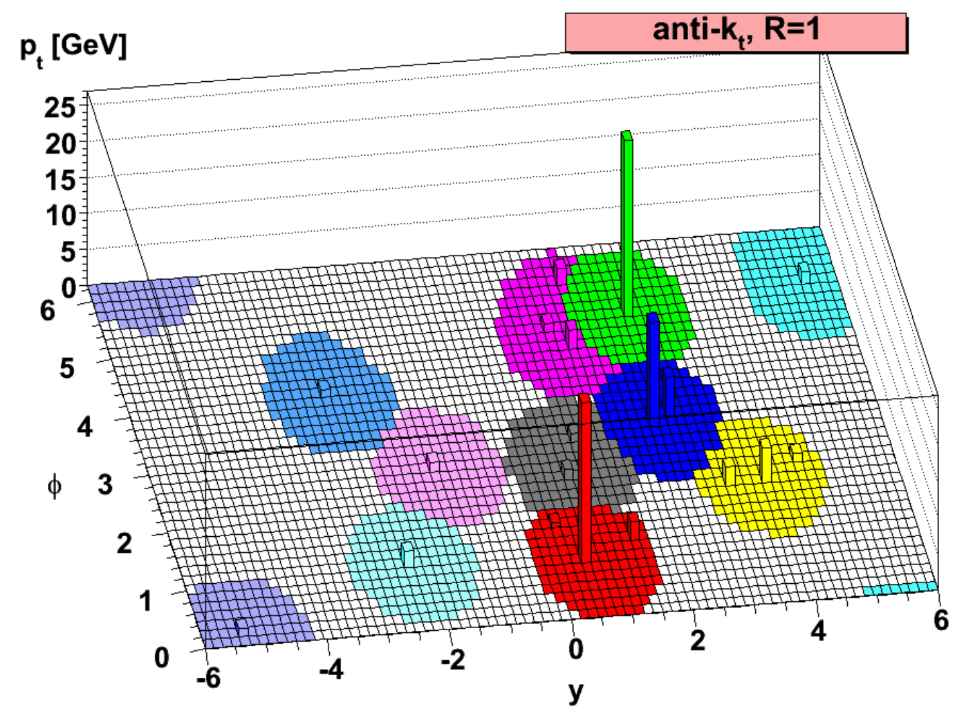

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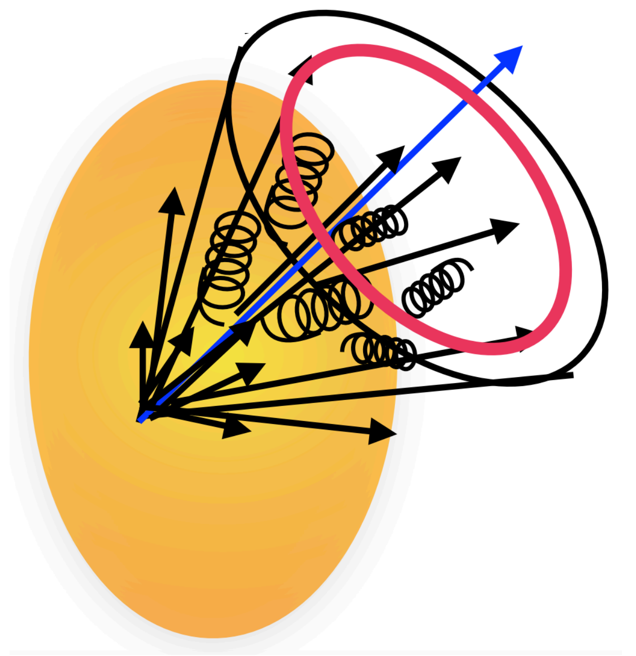
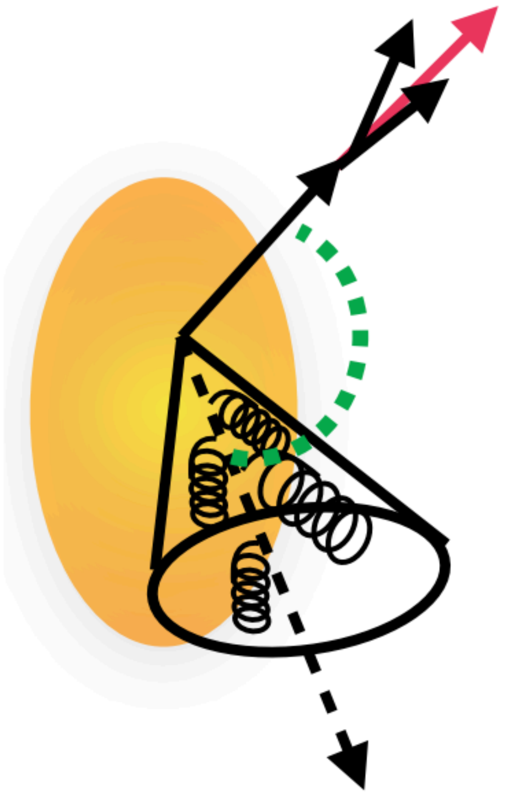
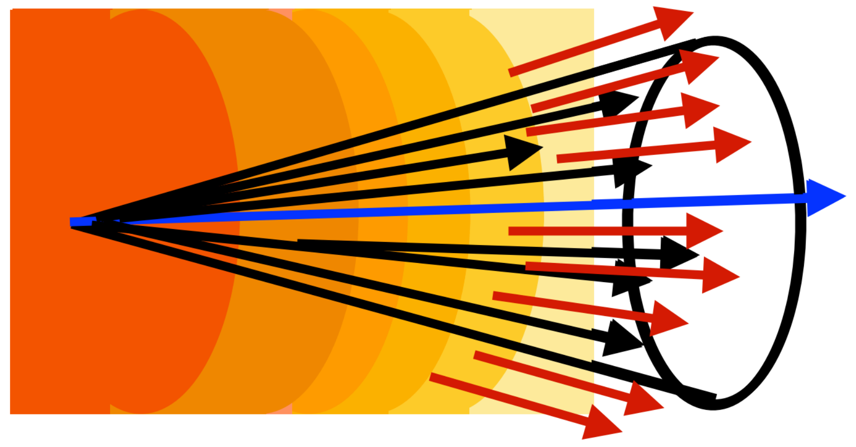
Jets interact with QGP
- manifests in different ways e.g:



Energy loss - *energy transport* outside jet cone



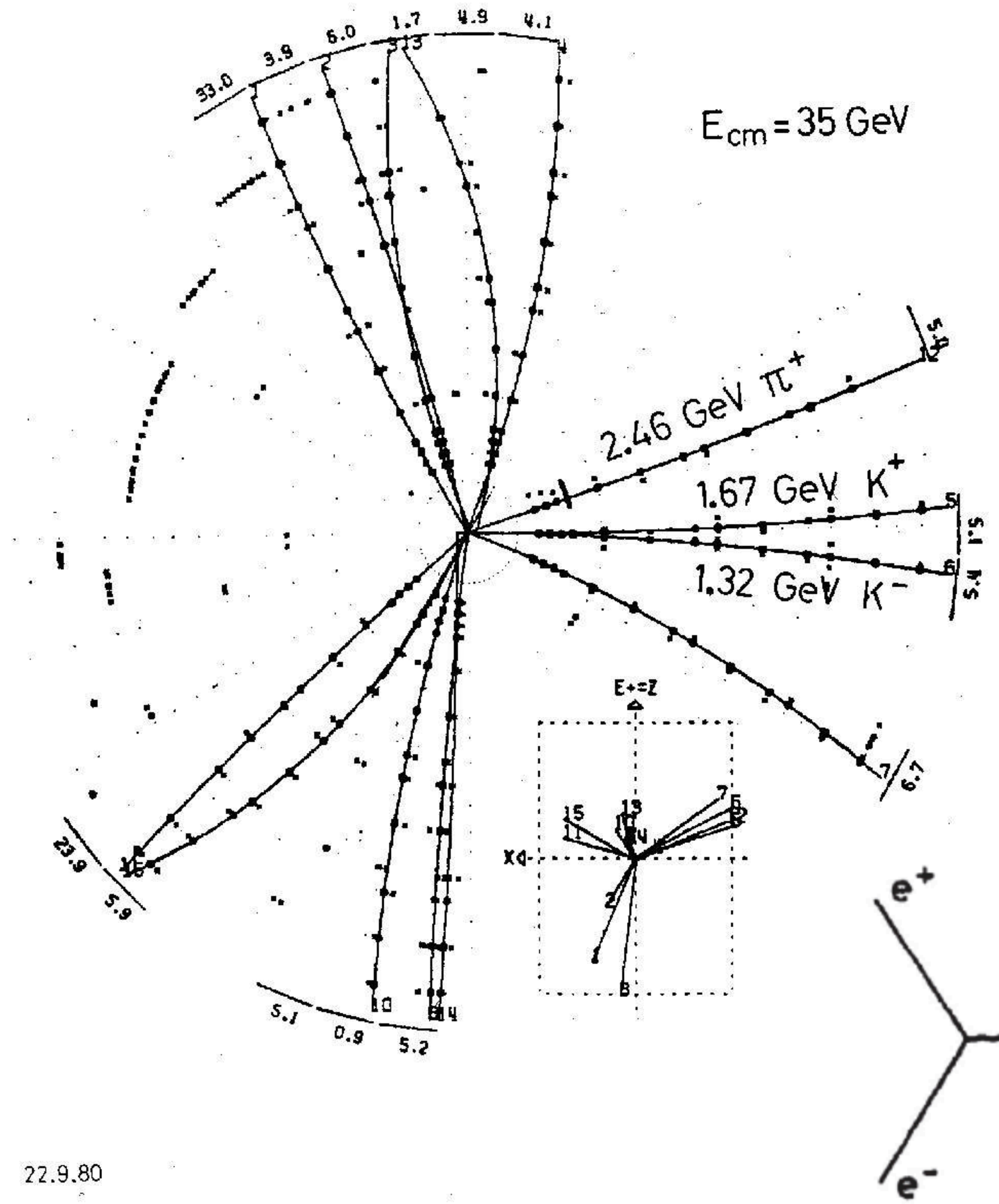
***Jet deflection* via multiple soft scatters or single hard scatters**



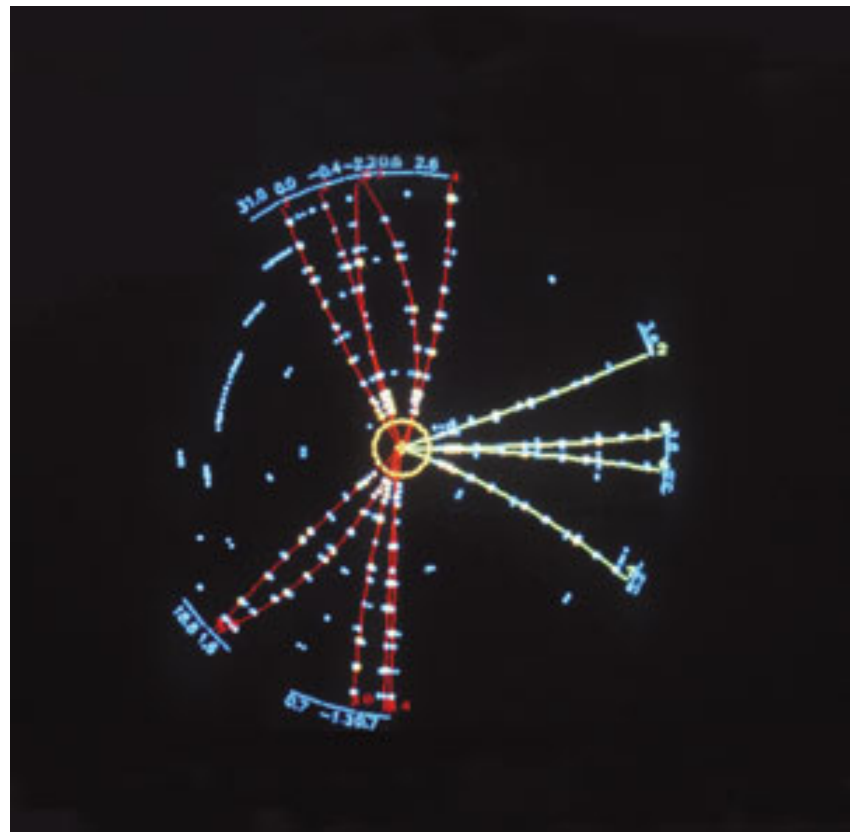
Response of medium to (out-of-equilibrium) jet probe - *wake effects*

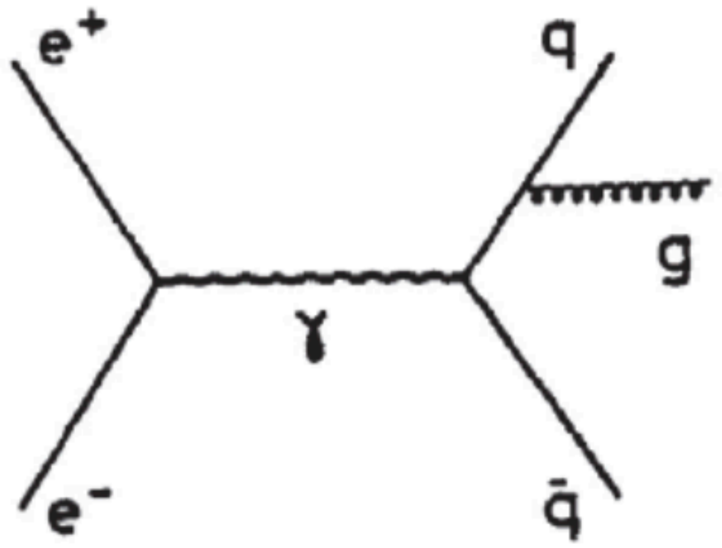
Jets in elementary particle collisions (e+e-, pp)

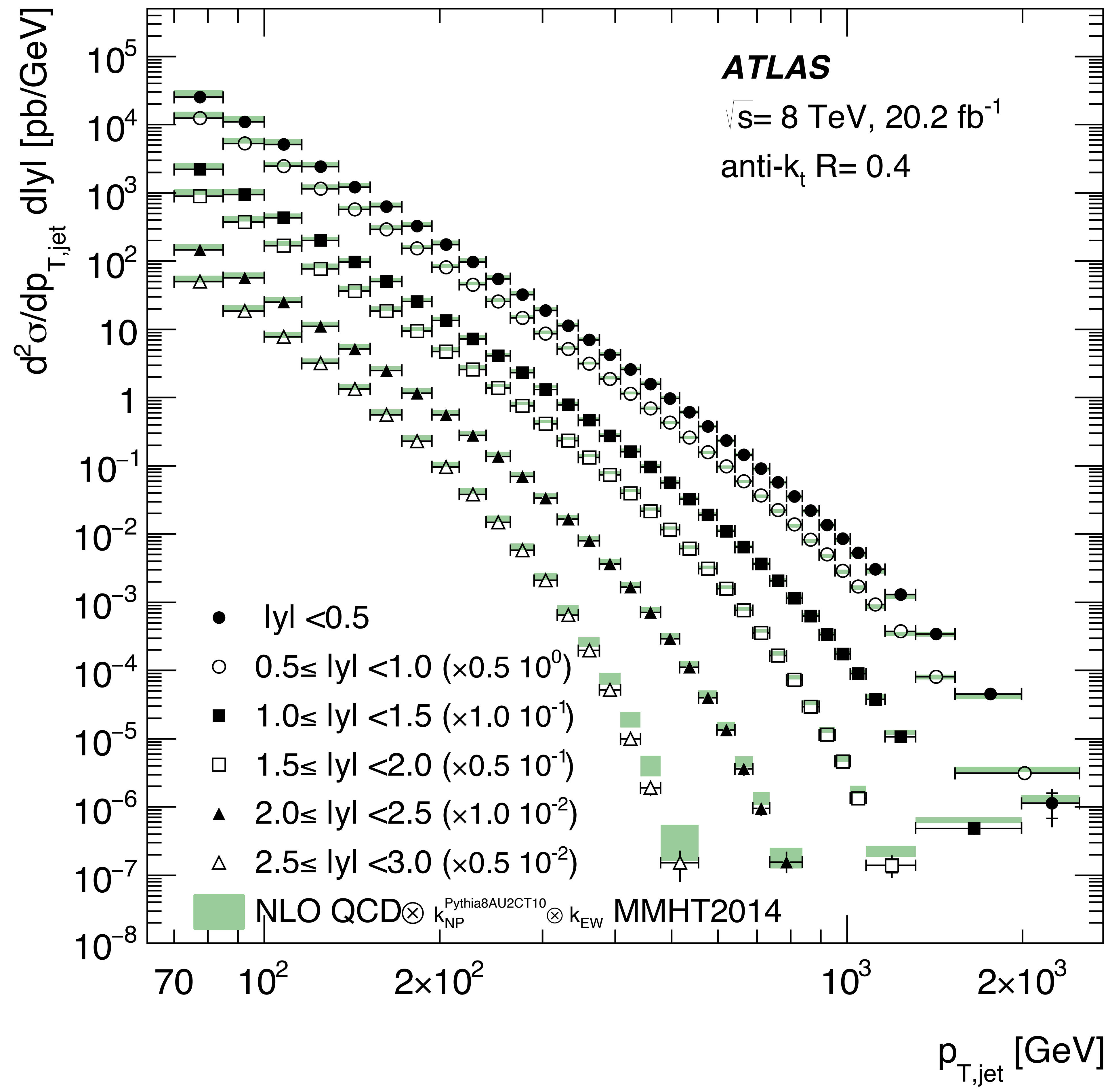
ATLAS: *JHEP* 09 (2017) 020



TASSO experiment







Three-jet event provided first direct evidence for gluons (1979)

At LHC QCD predictions describe data over 14 orders of magnitude of production cross section

https://journals.aps.org/collections/50-years-QCD

Energy loss in the QGP via nuclear modification factor R_{AA}

$$R_{AA}(p_T) = \frac{1}{< N_{coll} >} \frac{dN_{AA}/dp_T}{dN_{pp}/dp_T}$$

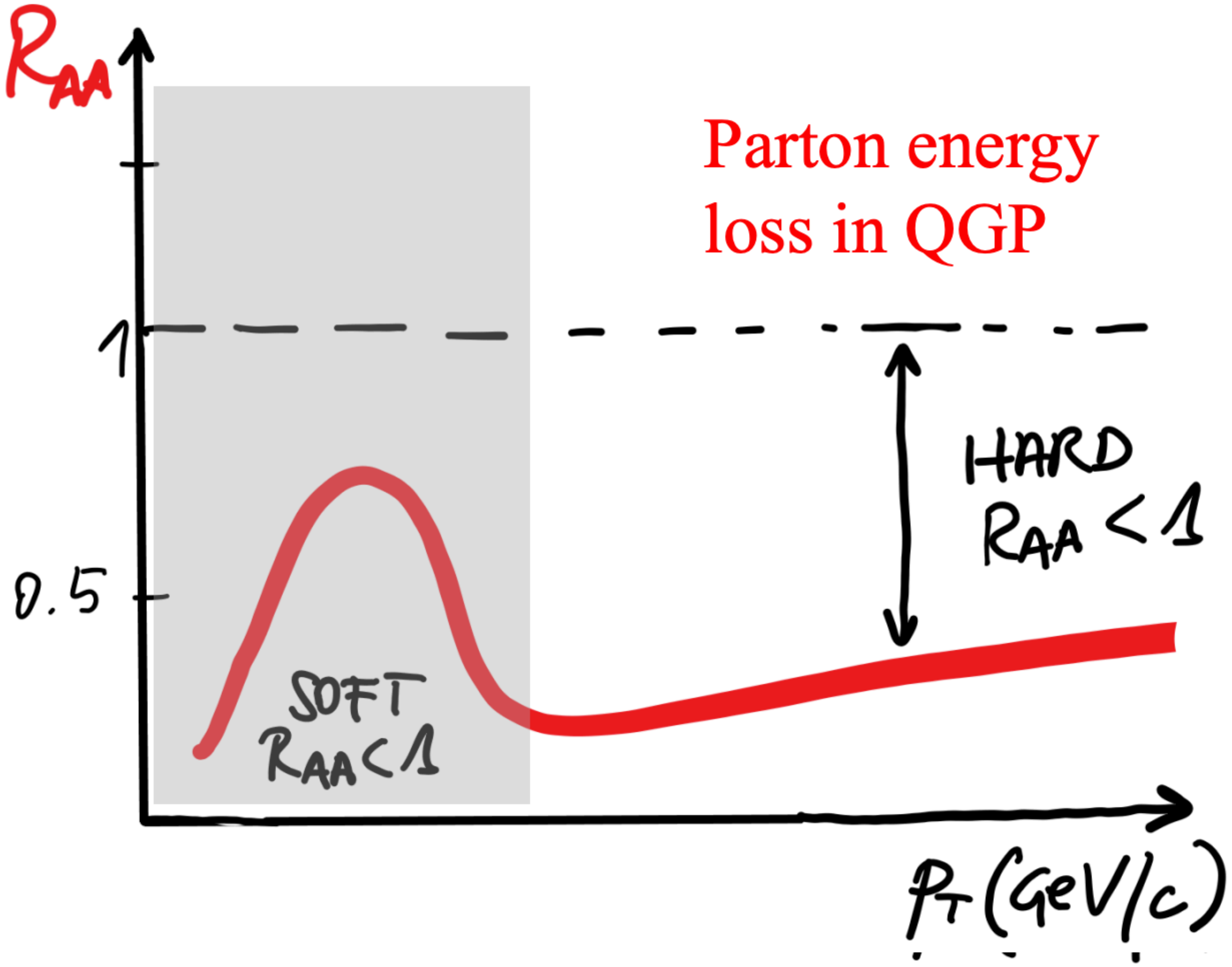


Fig. F. Bellini

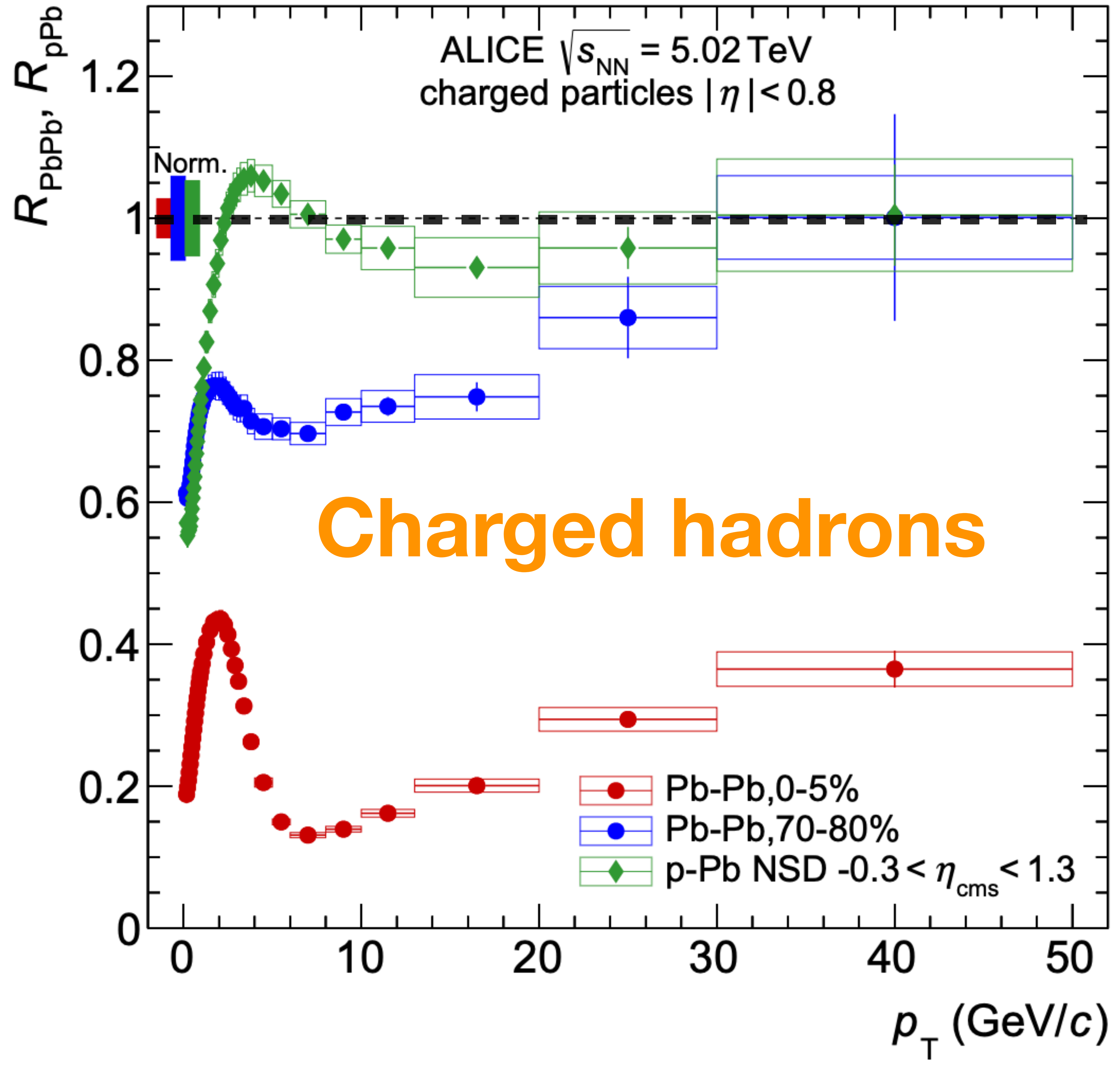
Asks the question:

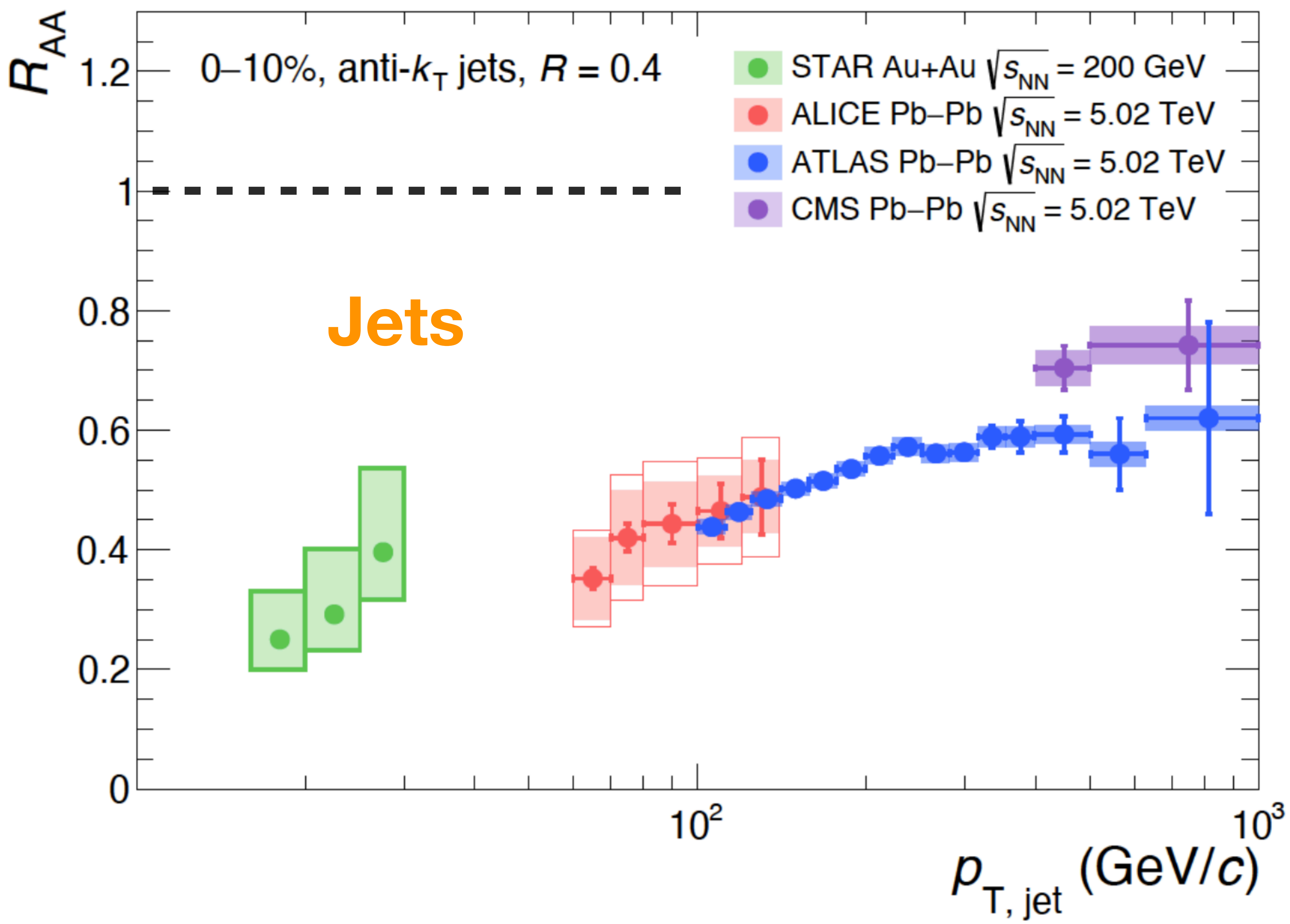
How is the production of 'something' *different* in collisions of protons/neutrons ***within nuclei***, with respect to the ***same number of independent proton-proton collisions***?

- $R_{AA} = 1$: **no modification** due to presence of QGP
- $R_{AA} < 1$ at high p_T : **suppression** due to presence of QGP
  - interpreted as *energy loss* due to partonic interactions

Partonic energy loss in the QGP

J. Harris, B. Müller, arxiv:2308.05743

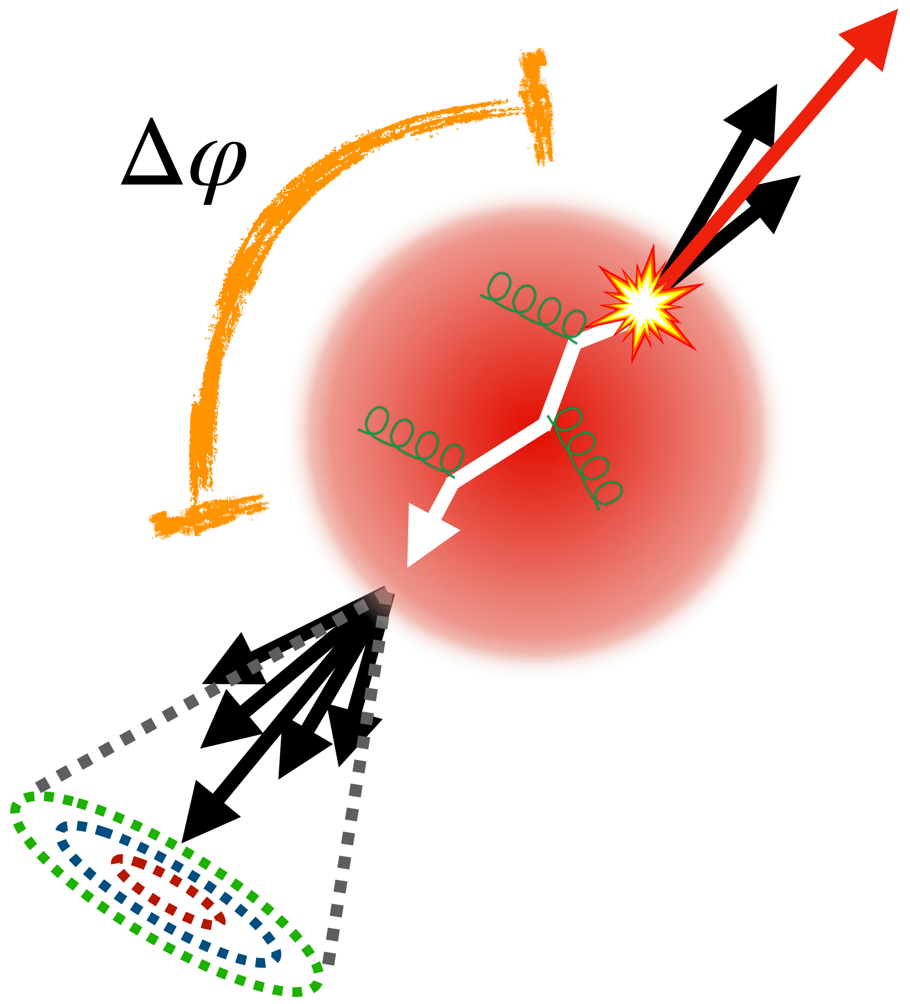




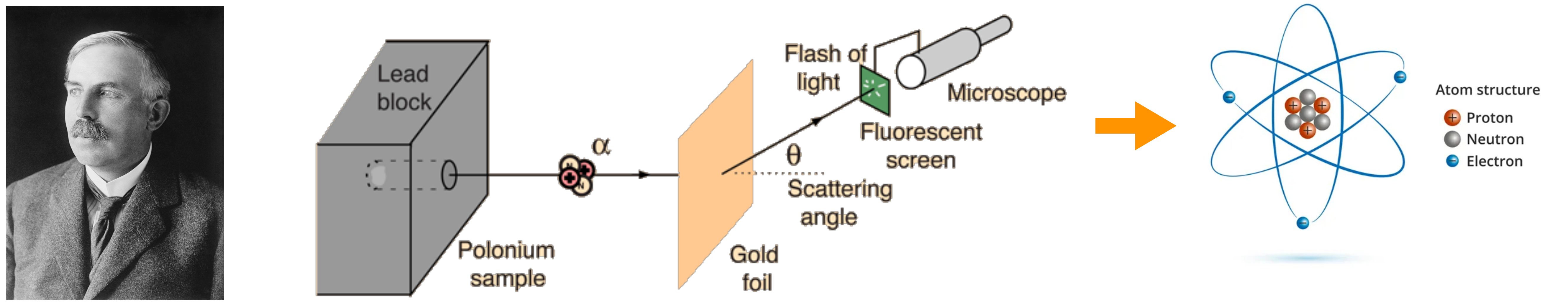
- Significant suppression of high-p_T charged hadrons / jets → medium-induced energy loss

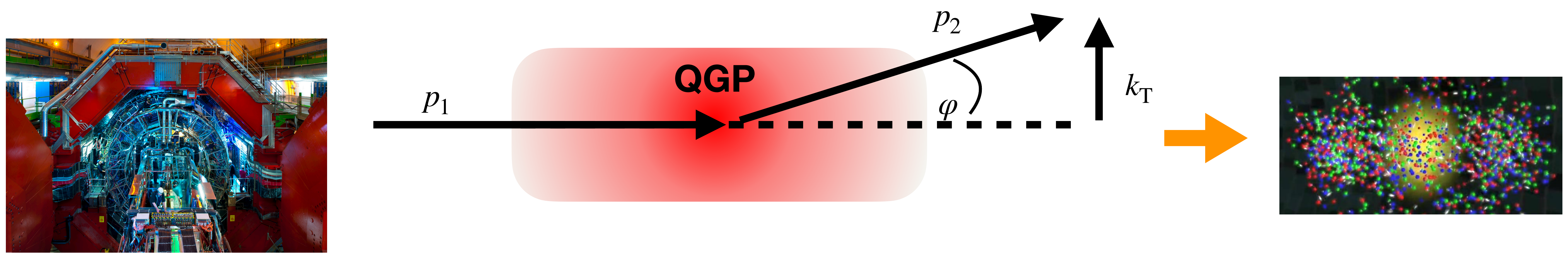
Coincidence measurements of jets

- **Can coincidence measurements** resolve short-distance QGP structure?
  - Transverse broadening of jet also gives fundamental insight into transport properties of QGP
- Example -> hadron+jet correlation - measure azimuthal angle between high-p_T hadron and jet



how does a strongly-coupled liquid emerges from (weakly-coupled) constituent degrees of freedom?
'Rutherford-like' scattering experiment





F. D'eramo, M. Lekaveckas, H. Liu, K. Rajagopal, *JHEP* 05 (2013) 031
F. D'eramo, K. Rajagopal, Y. Yin *JHEP* 01 (2019)

P. Caucal, Y. Mehtar-Tani: *Phys.Rev.D* 106 (2022) 5, L051501
JHEP 09 (2022) 023
Phys.Rev.D 108 (2023) 1, 014008

Coincidence measurements of jets

ALICE: Phys.Rev.Lett. 133 (2024) 2, 022301, Phys.Rev.C 110 (2024) 1, 014906

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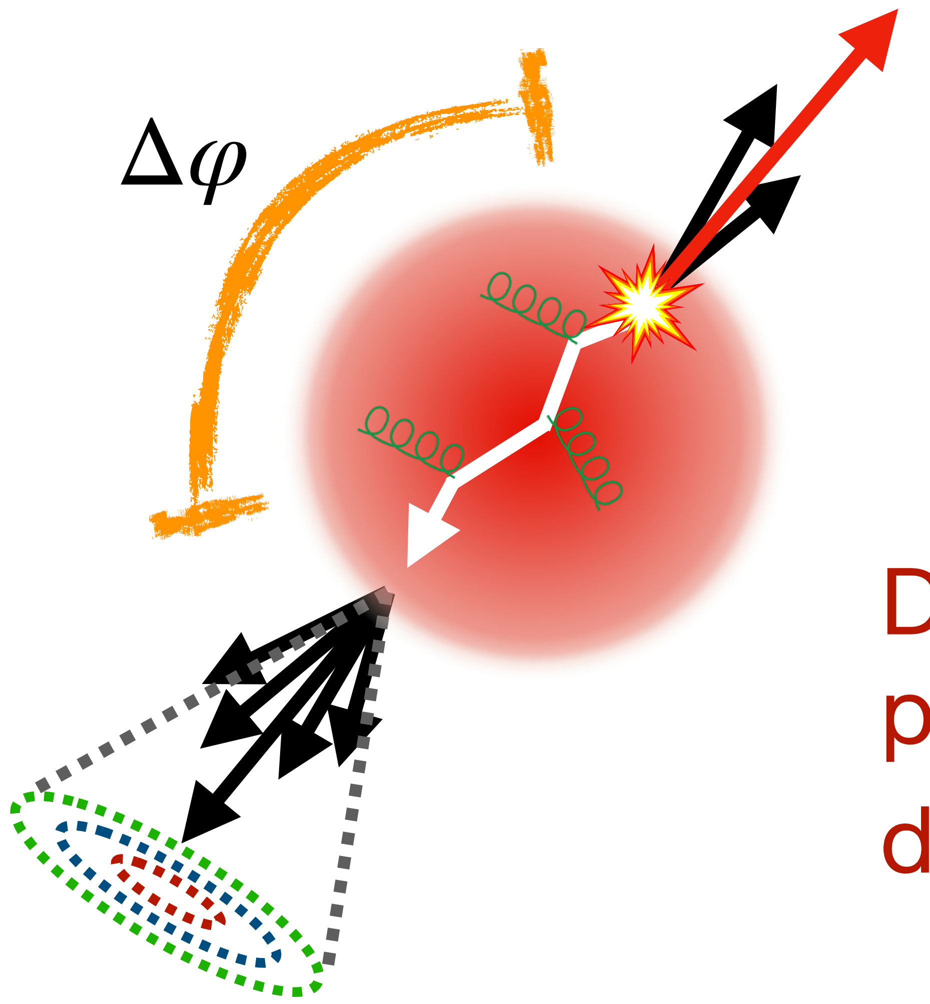
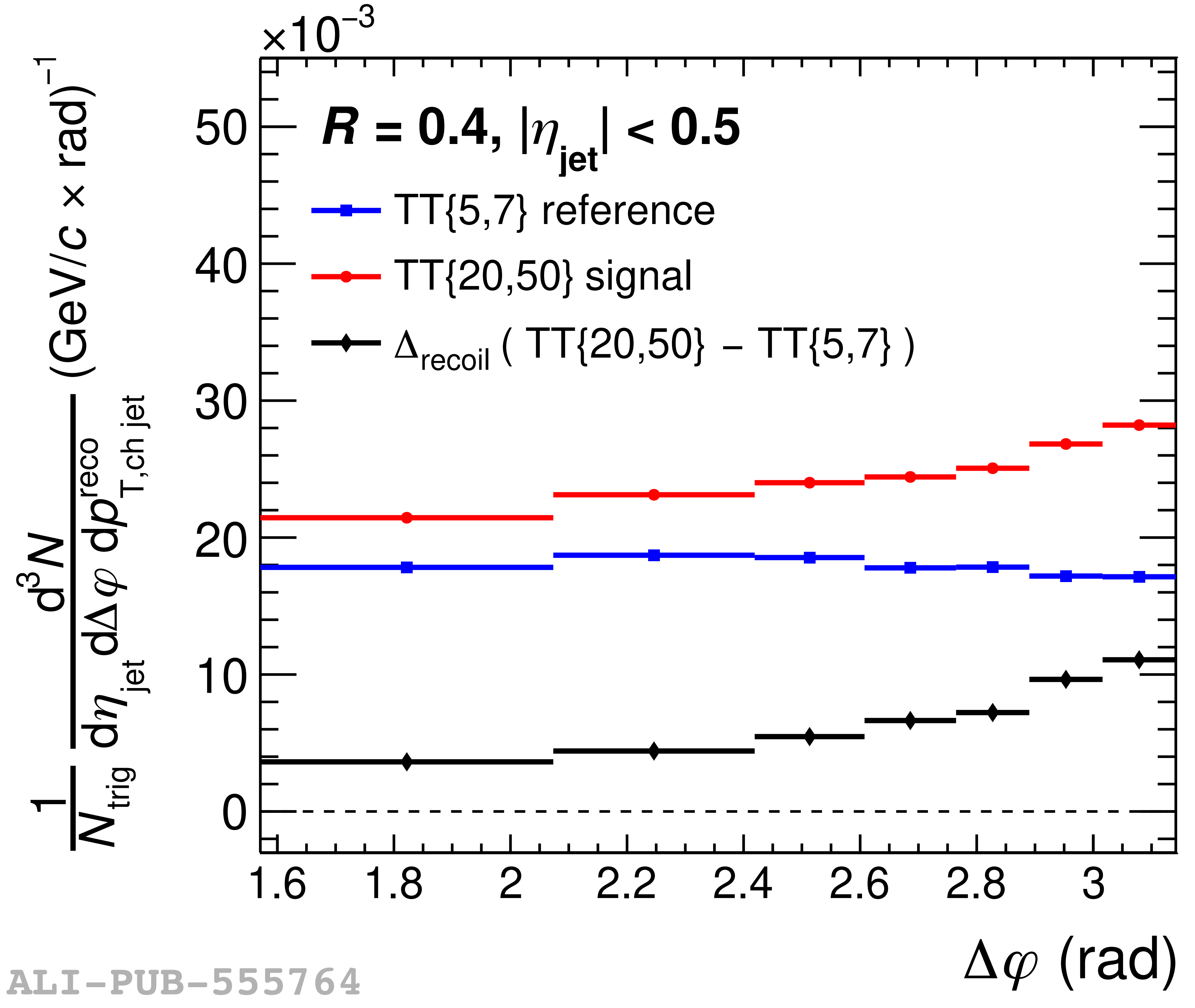


Developed tools to push jet measurements down to low p_T!

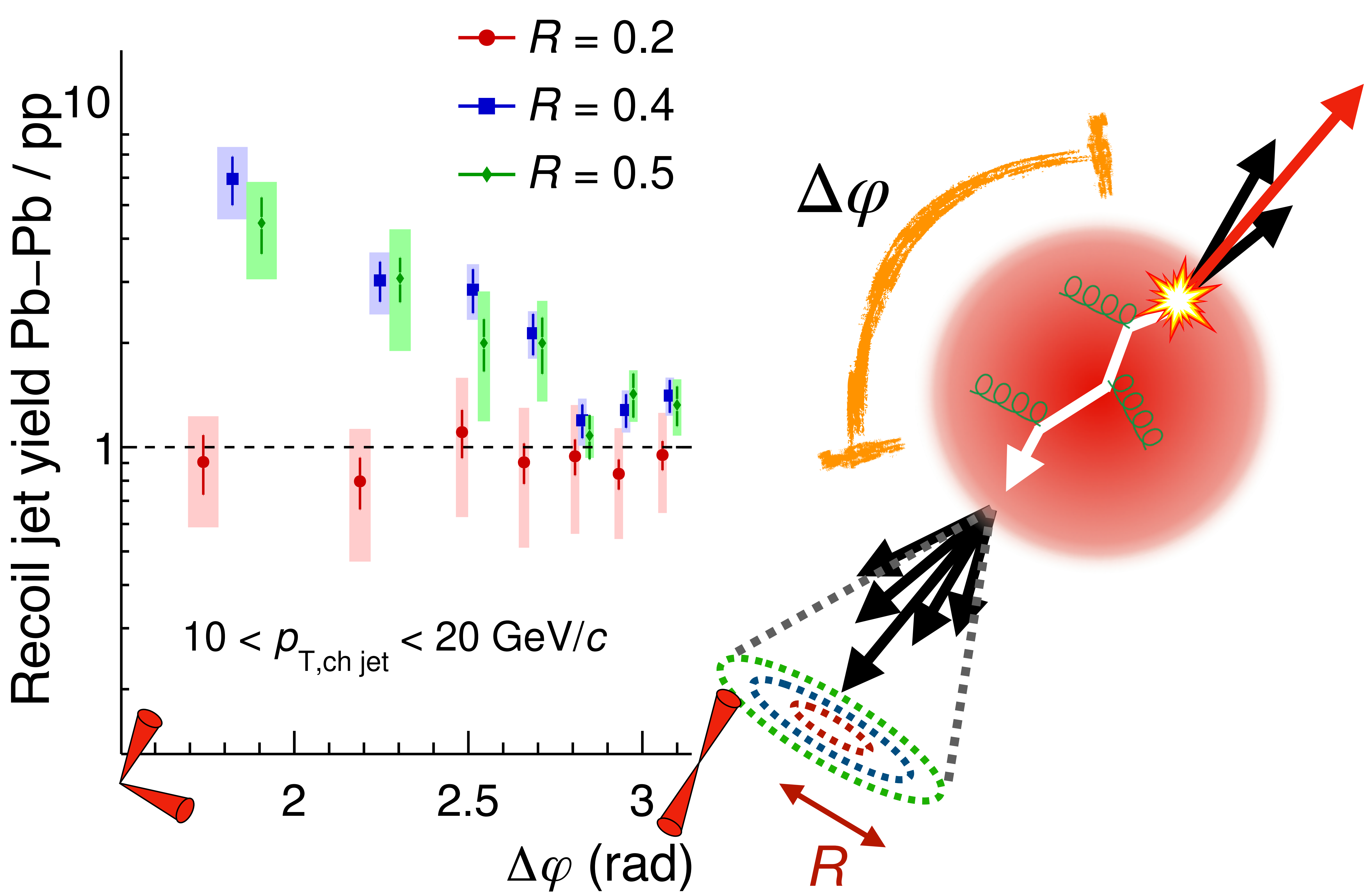


- **Subtract uncorrelated background**: yield difference between two exclusive trigger track-classed distributions: **'signal'** and **'reference'**:

$$\Delta_{recoil} = \frac{1}{N^{AA}_{trig}} \frac{d^3N^{AA}_{jet}}{dp^{ch}_{T,jet}\, d\Delta\varphi\, d\eta_{jet}}\bigg|_{p_{T,trig}\in TT_{Sig}} - c_{Ref} \cdot \frac{1}{N^{AA}_{trig}} \frac{d^3N^{AA}_{jet}}{dp^{ch}_{T,jet}\, d\Delta\varphi\, d\eta_{jet}}\bigg|_{p_{T,trig}\in TT_{Ref}}$$

Coincidence measurements of jets

ALICE: Phys.Rev.Lett. 133 (2024) 2, 022301, Phys.Rev.C 110 (2024) 1, 014906



Significant broadening of $\Delta\varphi$ distribution
R-dependence and model comparisons indicates its due to medium response to jets

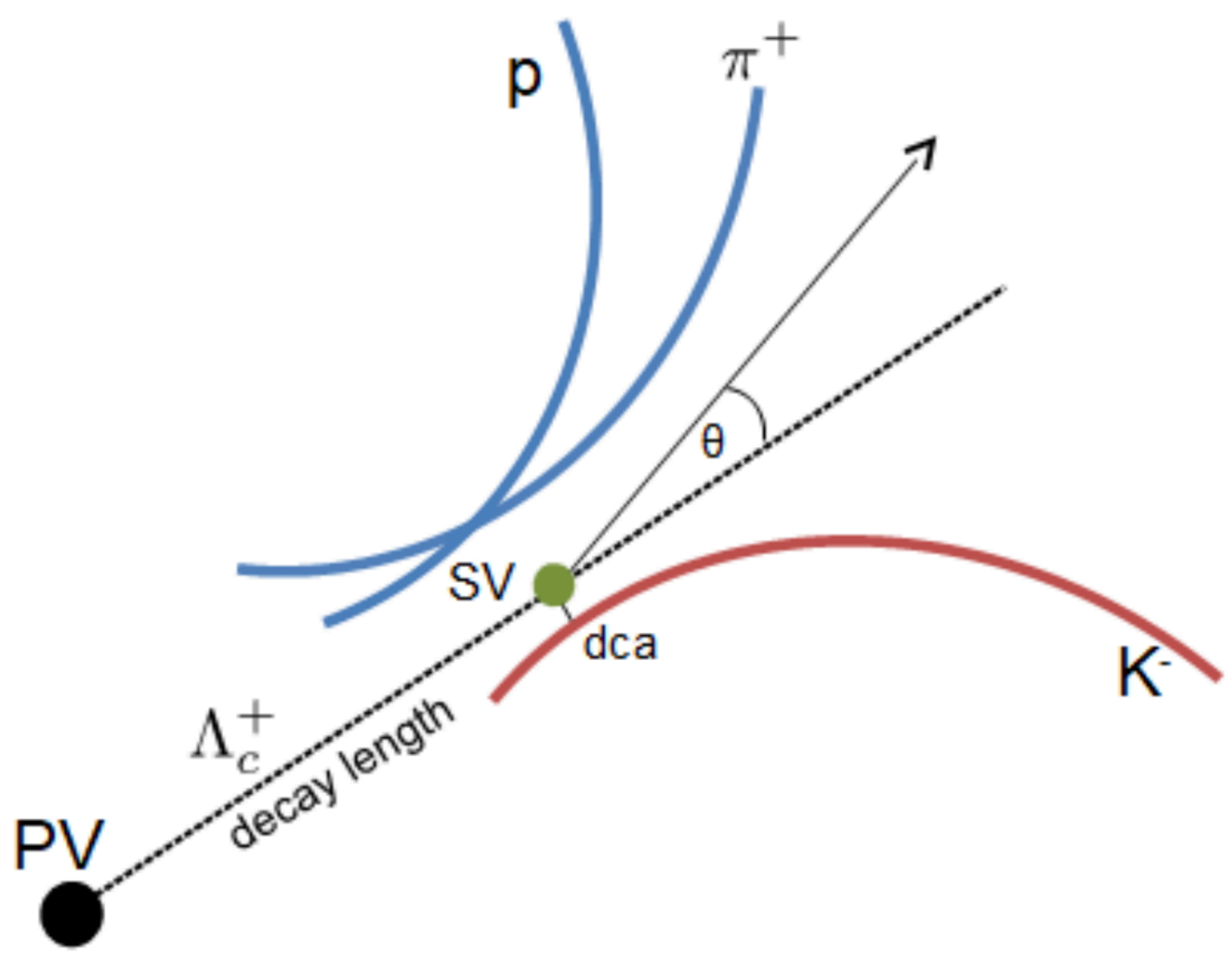
- Theory indicates that internal structure of jets may be most sensitive to large-angle scatterings

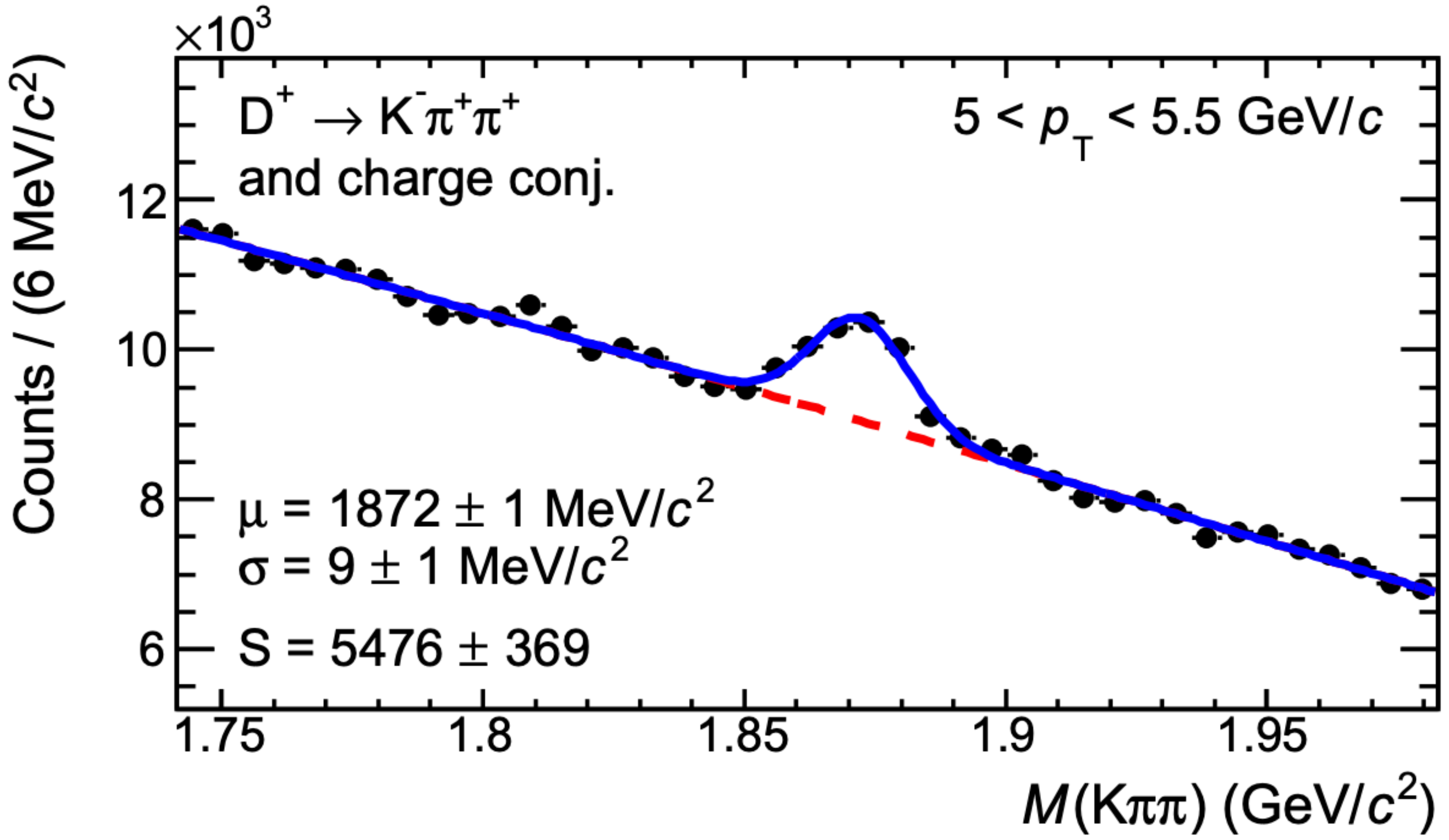
See also e.g:
γ-jet: CMS: PRL 119, 082301 (2017)
CMS: Phys. Lett. B 785 (2018) 14
Z-jet: CMS: Phys. Rev. Lett. 119, 082301 (2017)
D-hadron: ALICE: *Eur.Phys.J.C* 77 (2017) 4, 245

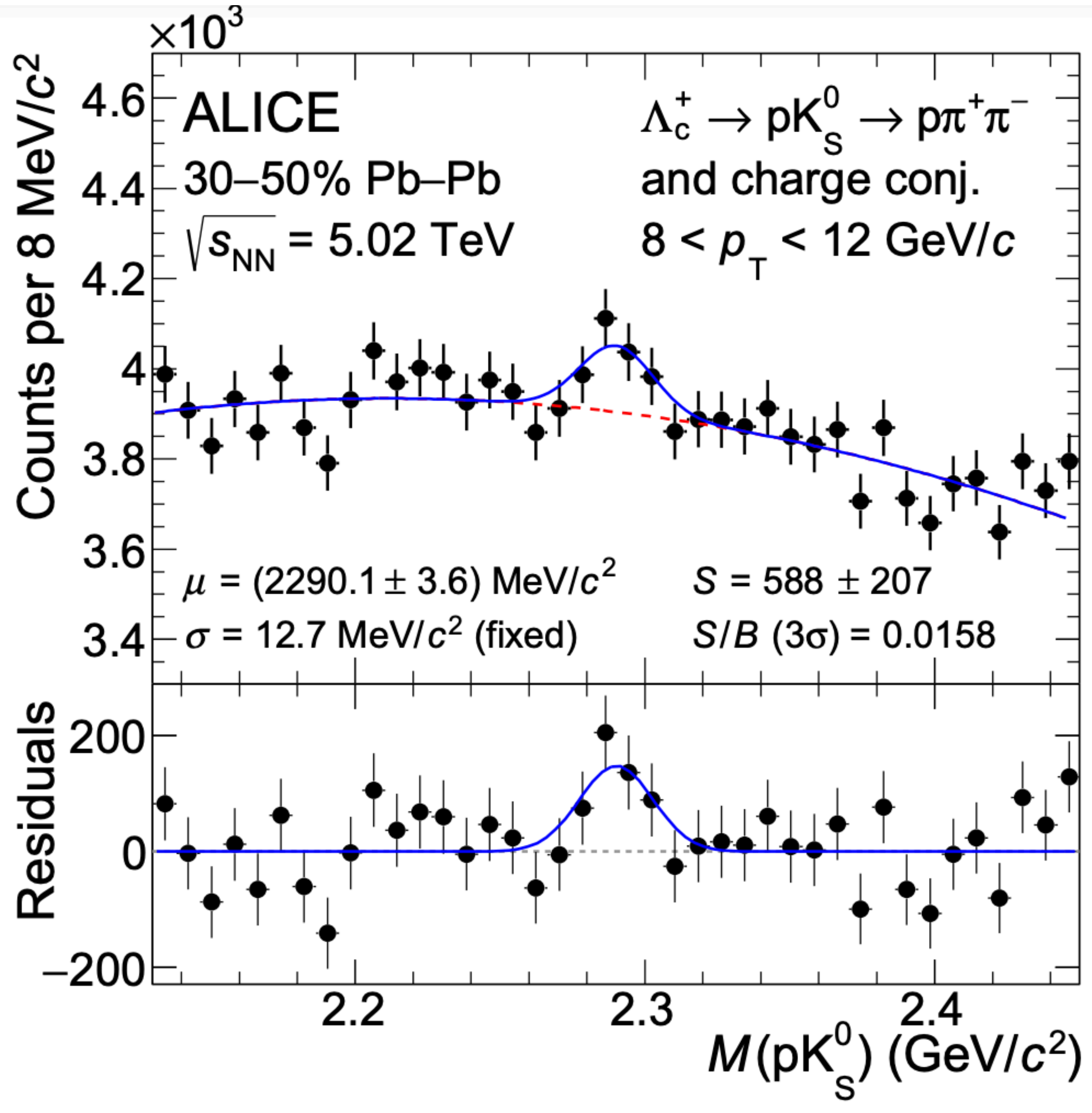
Heavy-flavour measurements

Can reconstruct heavy hadrons via decay products

- Background and charm from decays of B hadrons distinguished from ‘prompt’ charm via displaced vertex
- Signal extracted via fits to invariant mass distribution



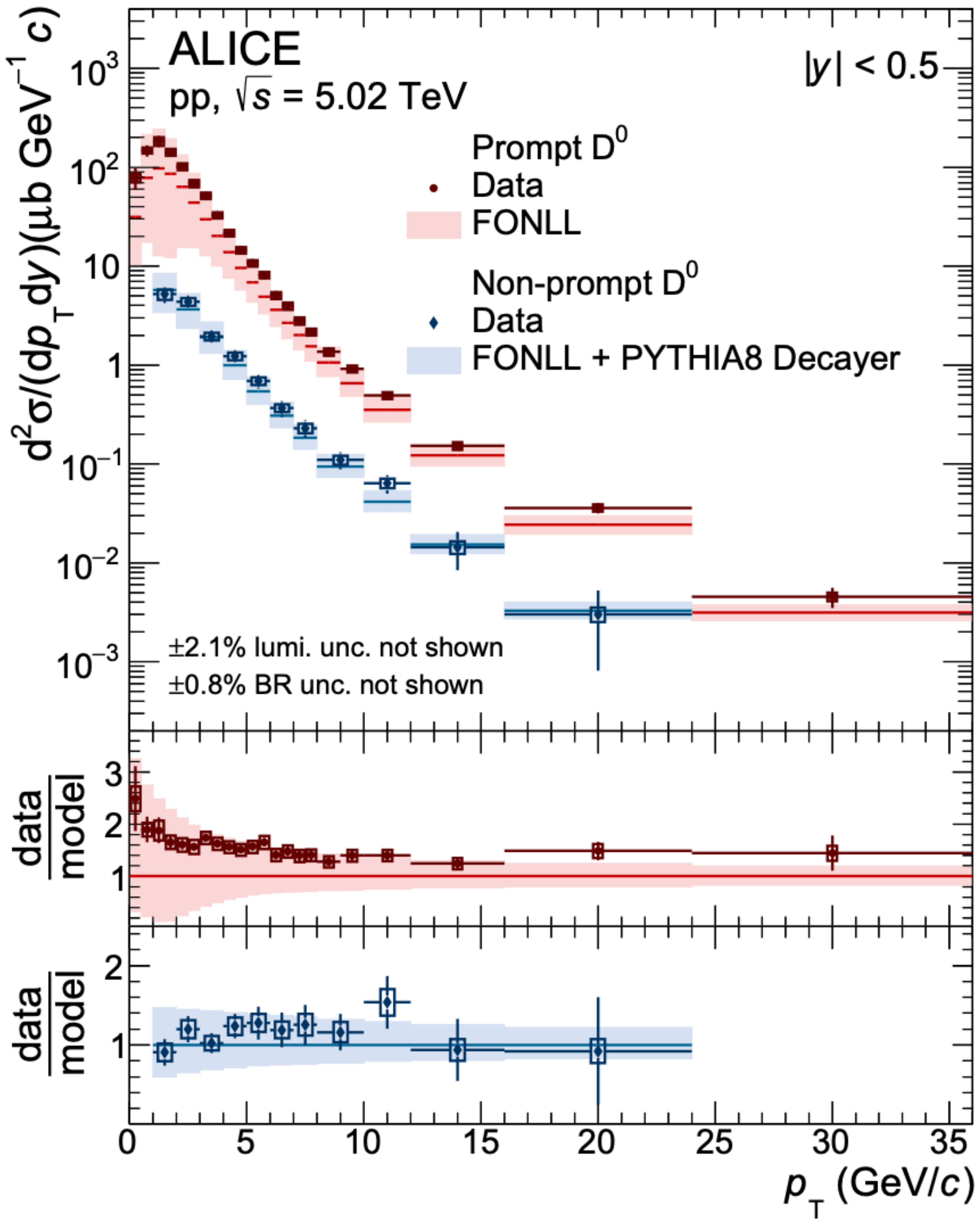




Relatively small production cross sections and branching fractions - Machine learning techniques crucial in many cases to separate signal from huge background present in HI collisions

Heavy-flavour measurements - pp collisions

ALICE: JHEP 05 (2021) 220



Can reconstruct heavy hadrons via decay products

- Background and charm from decays of B hadrons distinguished from ‘prompt’ charm via displaced vertex
- Signal extracted via fits to invariant mass distribution

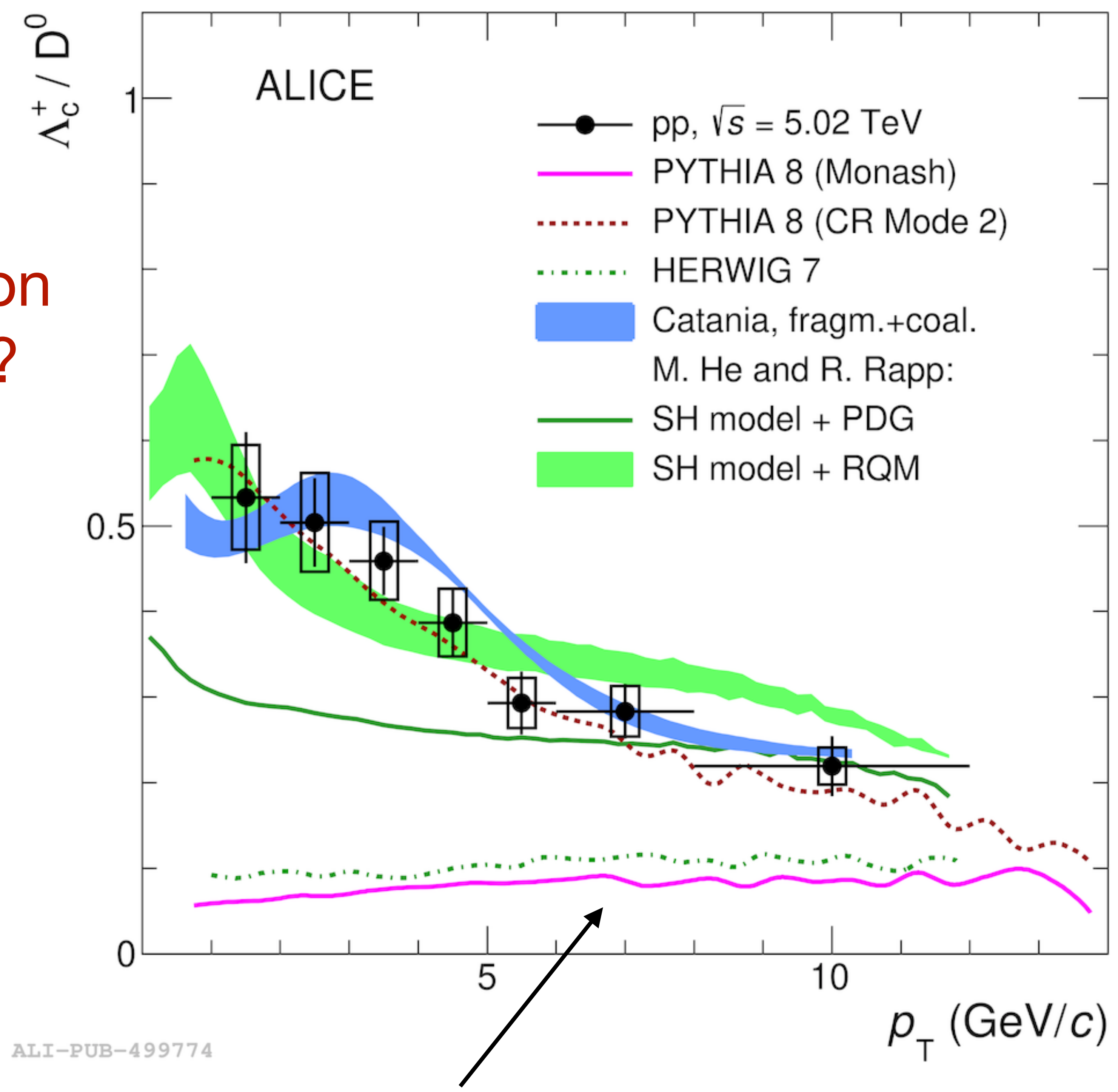
Charm mesons (from c and from beauty decays) described well by pQCD predictions in pp collisions

Heavy-flavour measurements - pp collisions

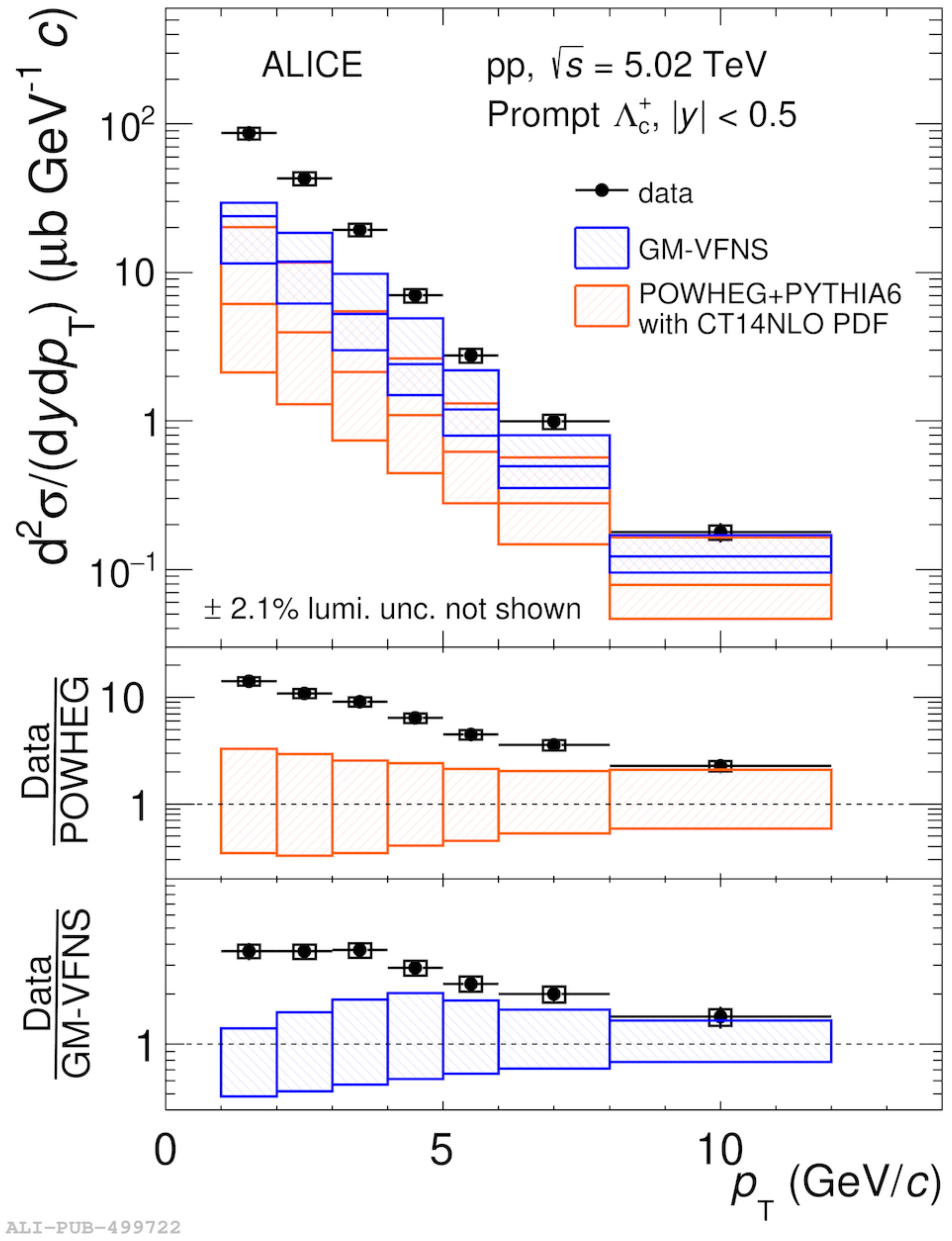
ALICE: JHEP 05 (2021) 220

Modification of hadronisation due to high-density effects?

Additional ‘undiscovered’ baryon states?



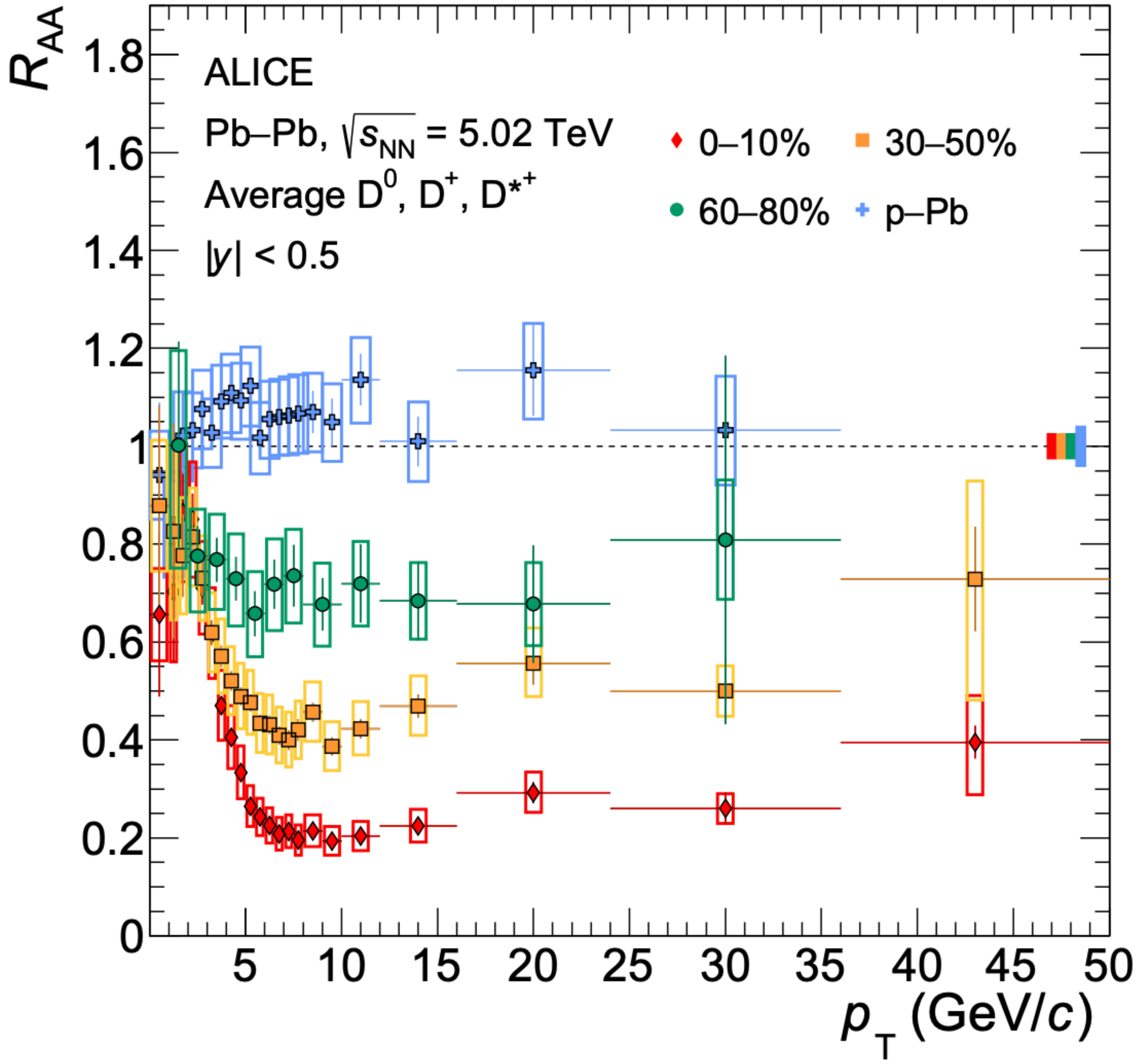
‘Conventional’ models

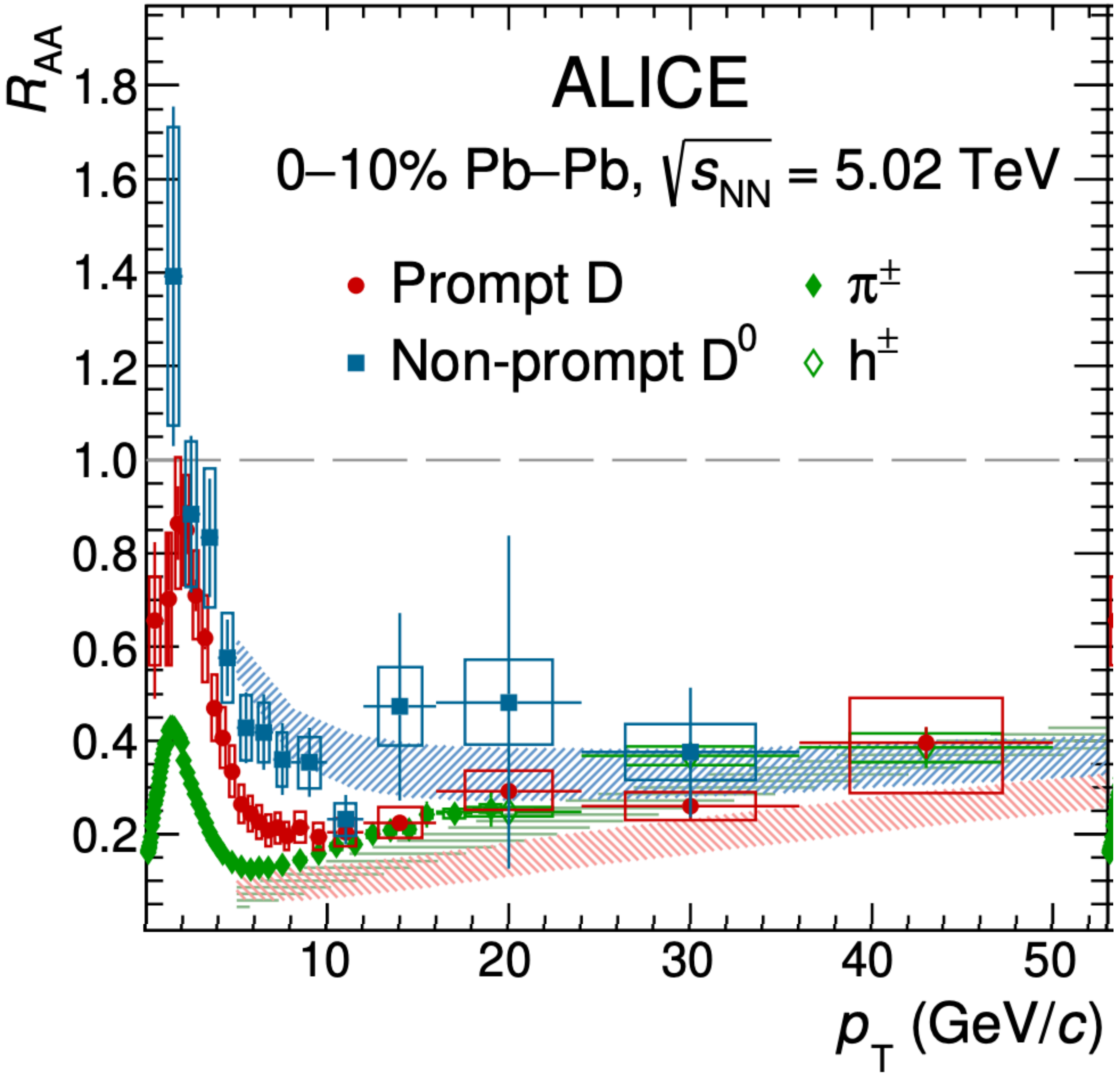


Charm **baryon** production **not described** well by these predictions
→ baryon hadronisation not understood in pp collisions!

Heavy-flavour energy loss in the QGP

$$R_{AA}(p_T) = \frac{1}{< N_{coll} >} \frac{dN_{AA}/dp_T}{dN_{pp}/dp_T}$$





- D-meson energy loss measurements provide tight constraints on transport properties of QGP medium

Thermal production of hadrons

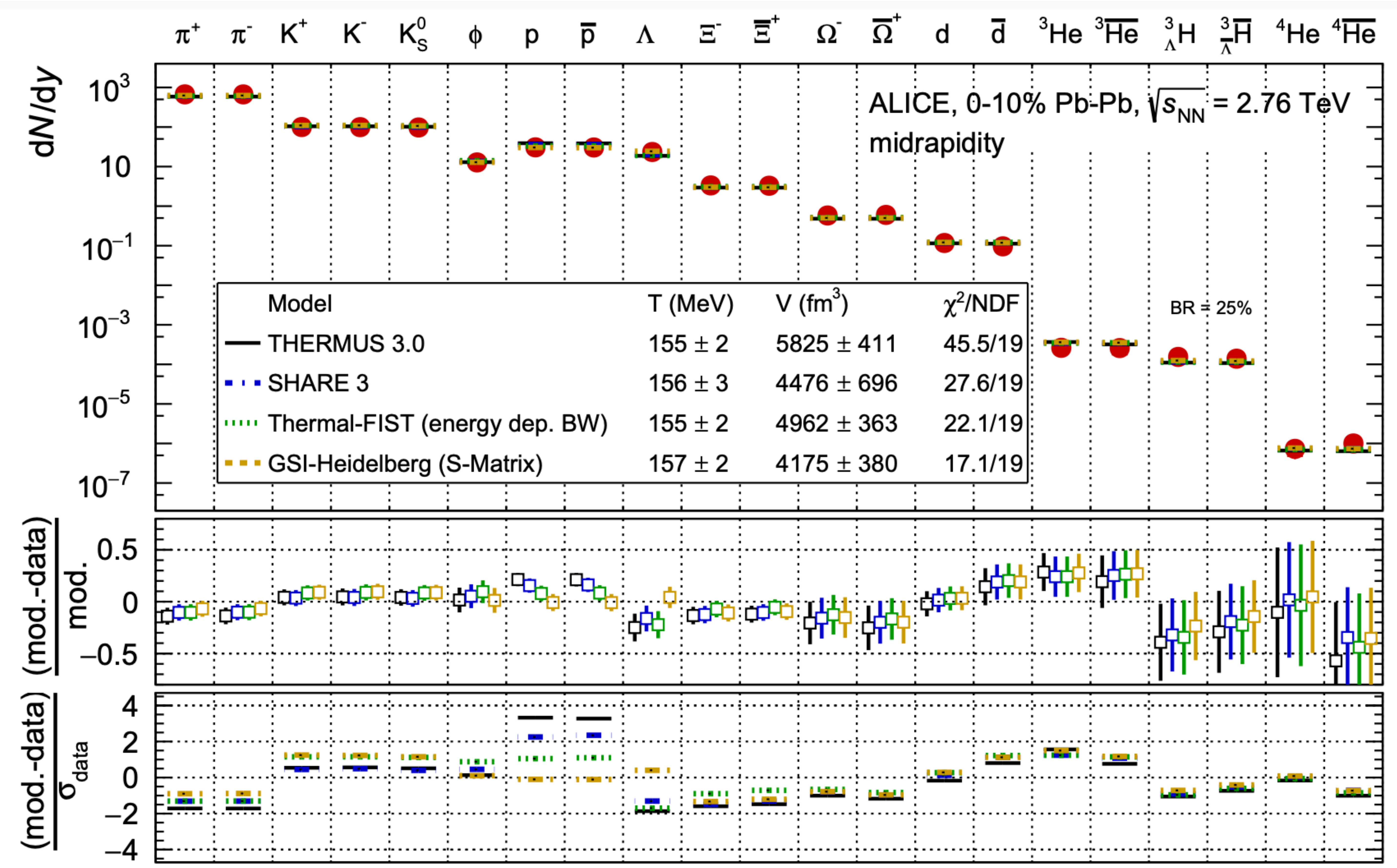
- Bulk of the QGP consists of thermally-equilibrated light quarks (u, d, s)
  - $T_{QGP} > m_{u,d,s}$ - light quarks can be thermally created

ALICE: Eur.Phys.J.C 84 (2024) 8, 813

- **Total production yields of particles** gives **information about system at freeze-out** (temperature, volume, baryochemical potential μ_B)

- Comparison to statistical hadronisation models confirms thermal production of hadrons

From free parameters of models, Chemical freeze-out (hadronisation)
$T_{chem} \approx$ 156 MeV, $\mu_B \approx$ 0
In agreement with lattice QCD calculations shown yesterday



Hadronisation in heavy-ion collisions

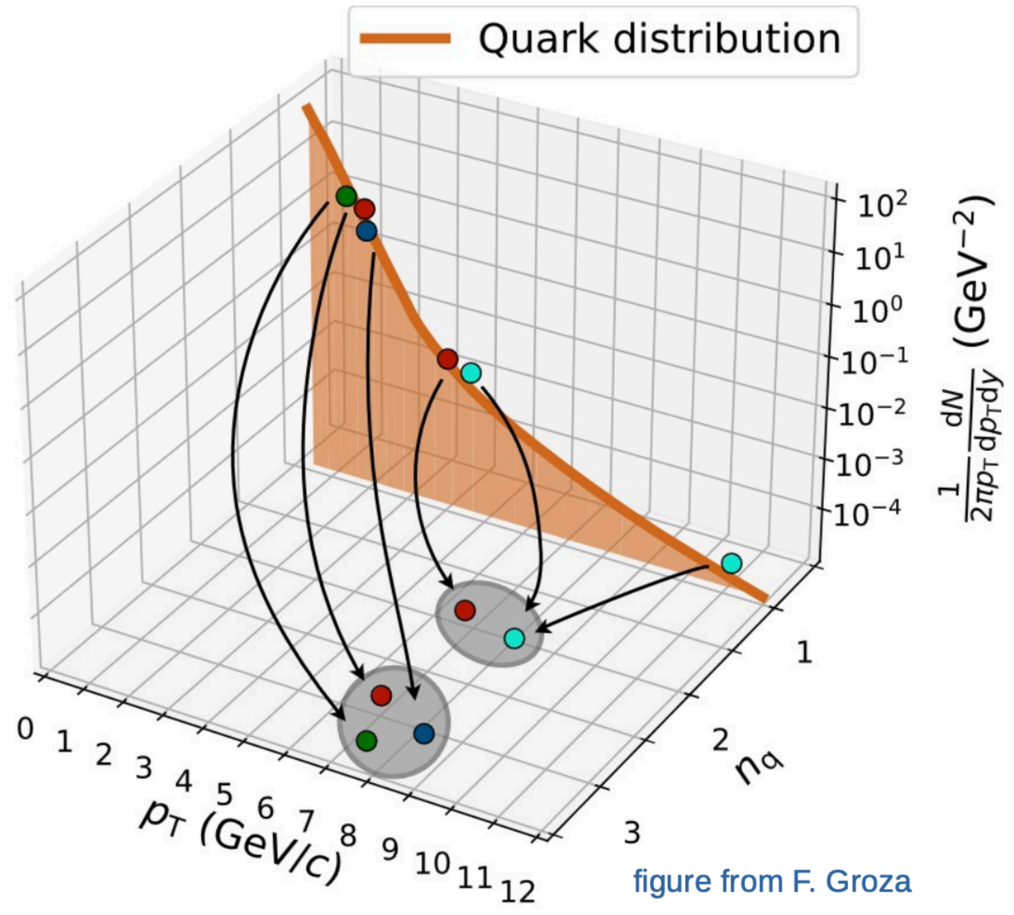
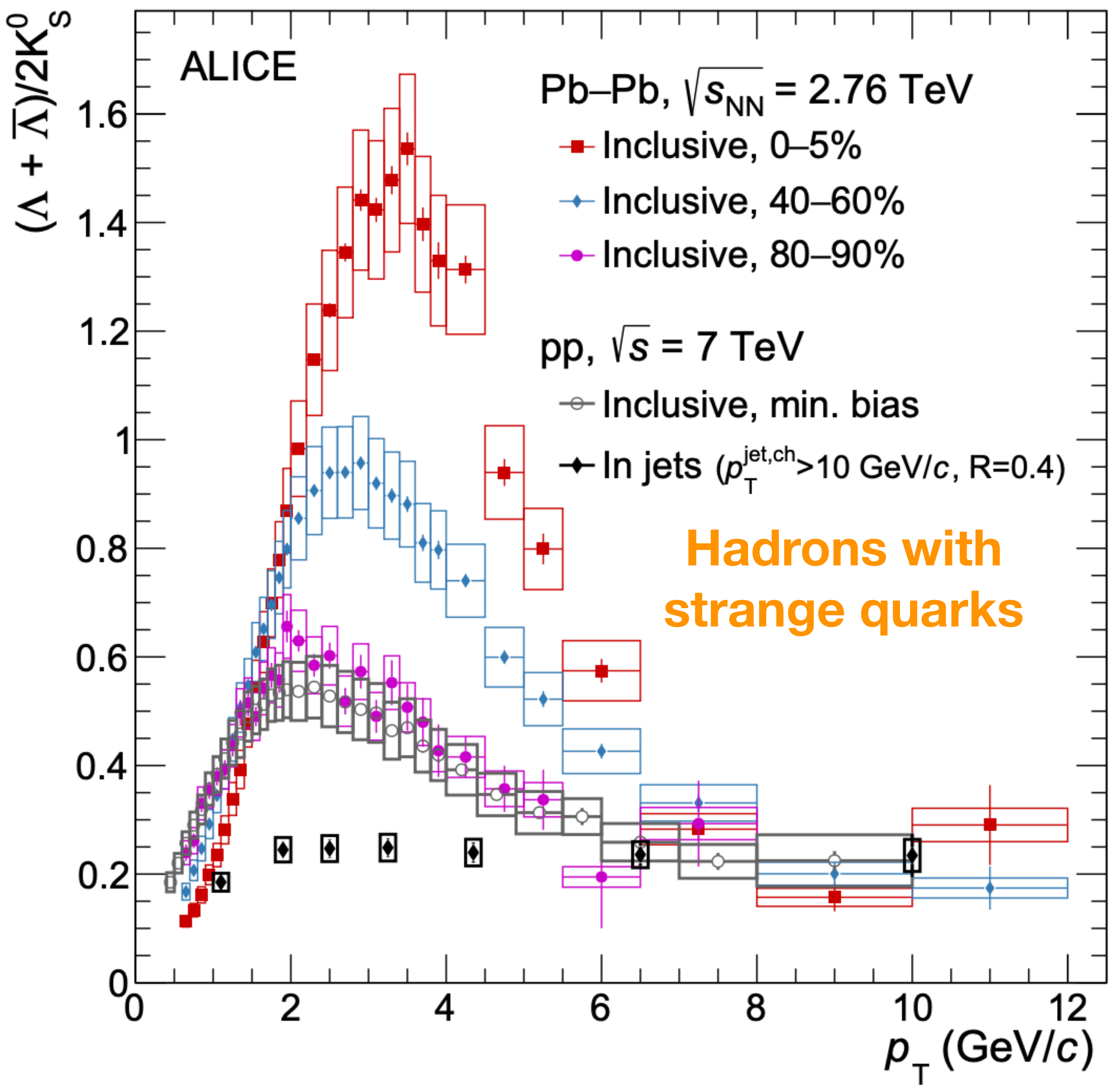
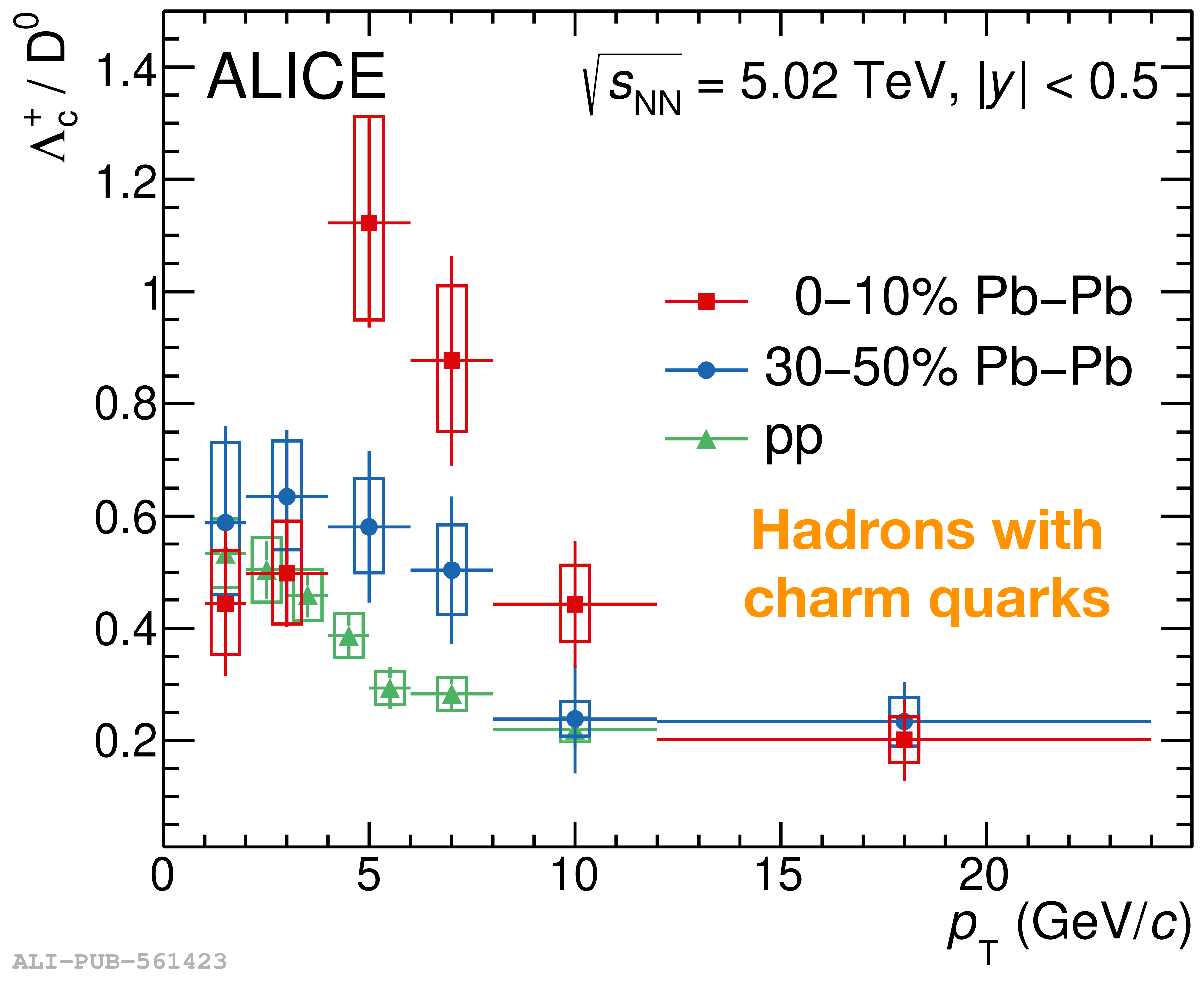


figure from F. Groza

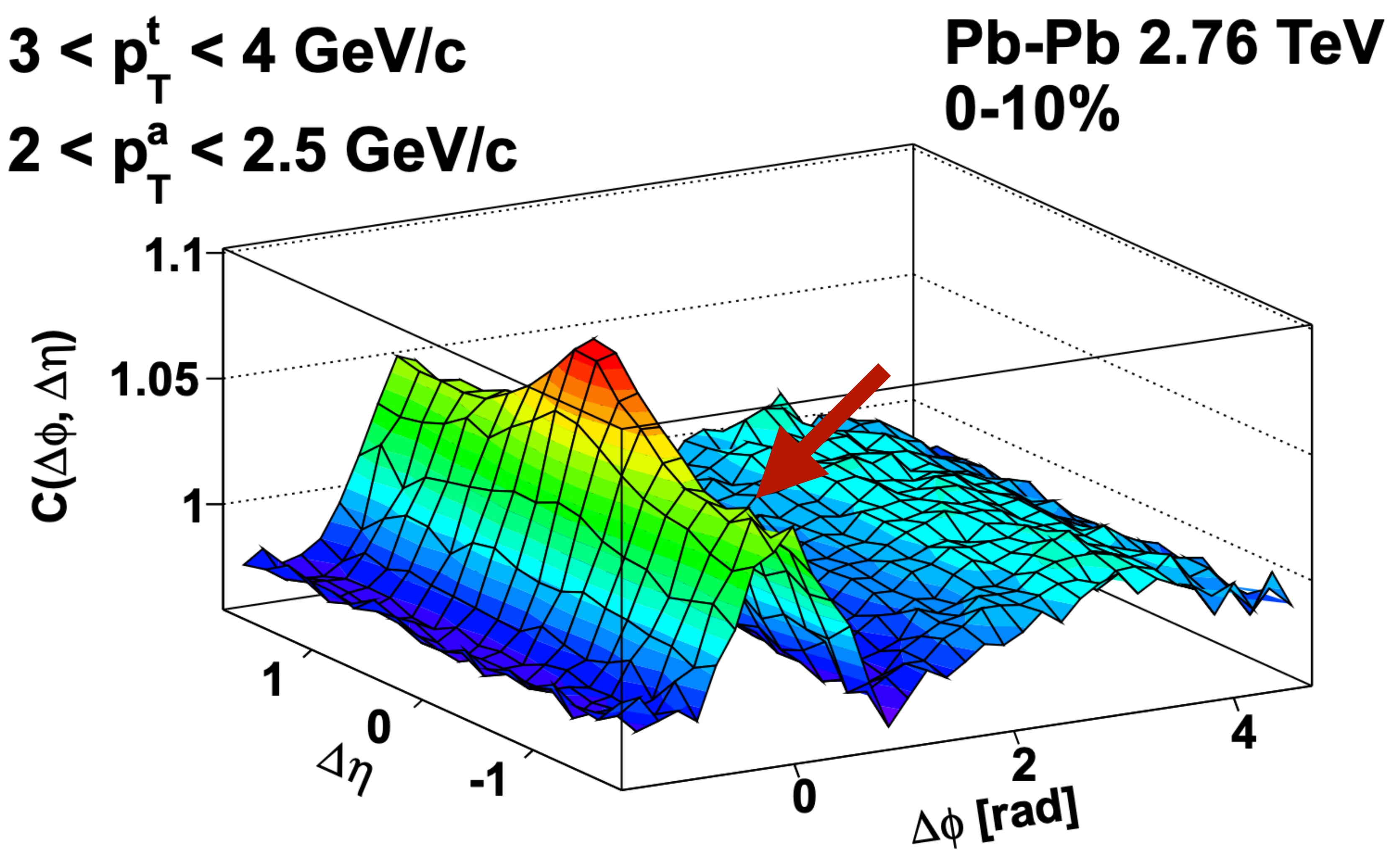




- Measurement of baryon-to-meson ratios probe hadronisation mechanisms
- **Enhancement** of baryons with respect to pp collisions **- coalescence of deconfined quarks rather than usual 'vacuum' fragmentation**

How small can a QGP be?

ALICE: Phys. Lett. B 708 (2012) 249-264



- Long-range correlations over wide η range ('ridge') understood to be due to flow of system

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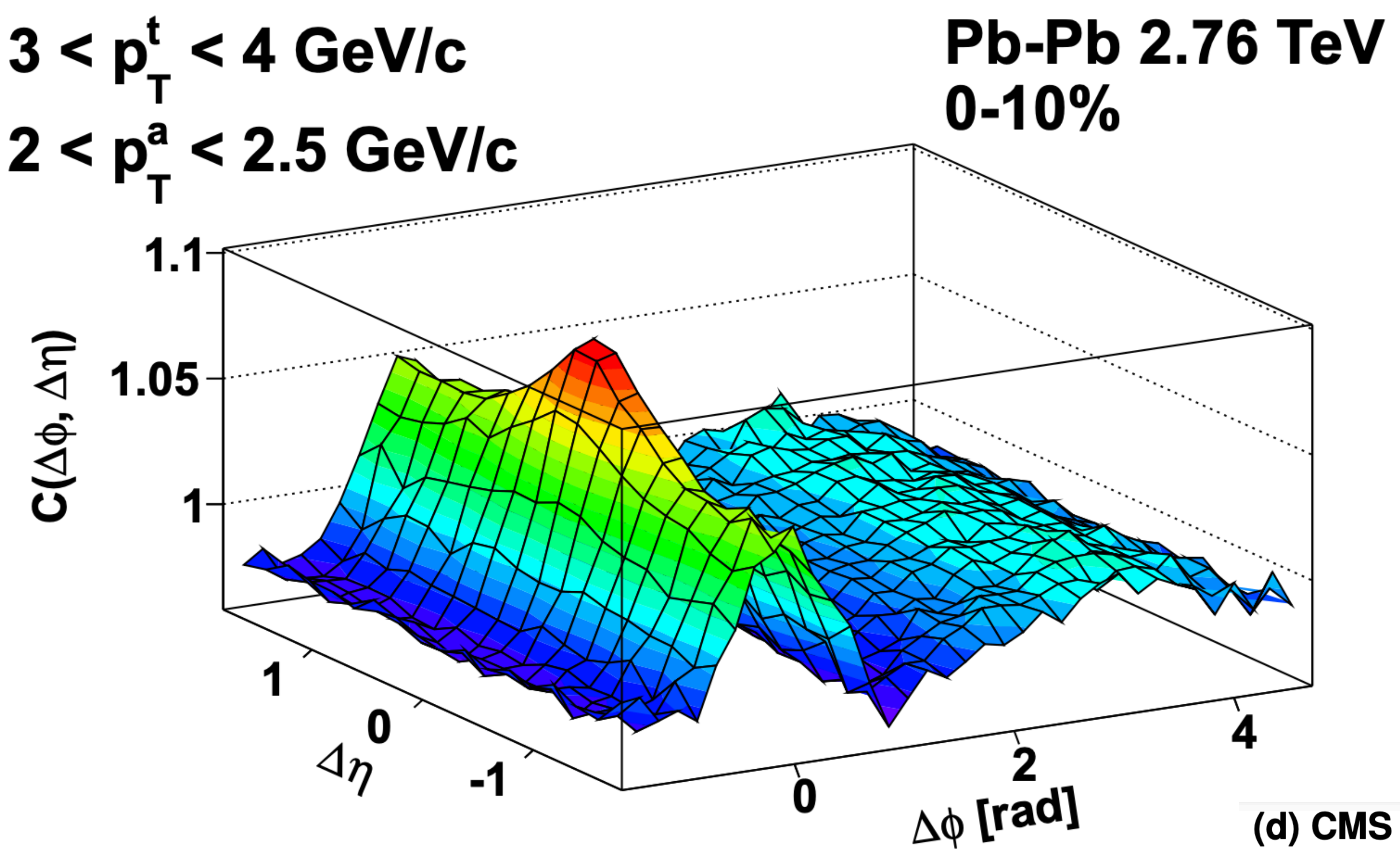
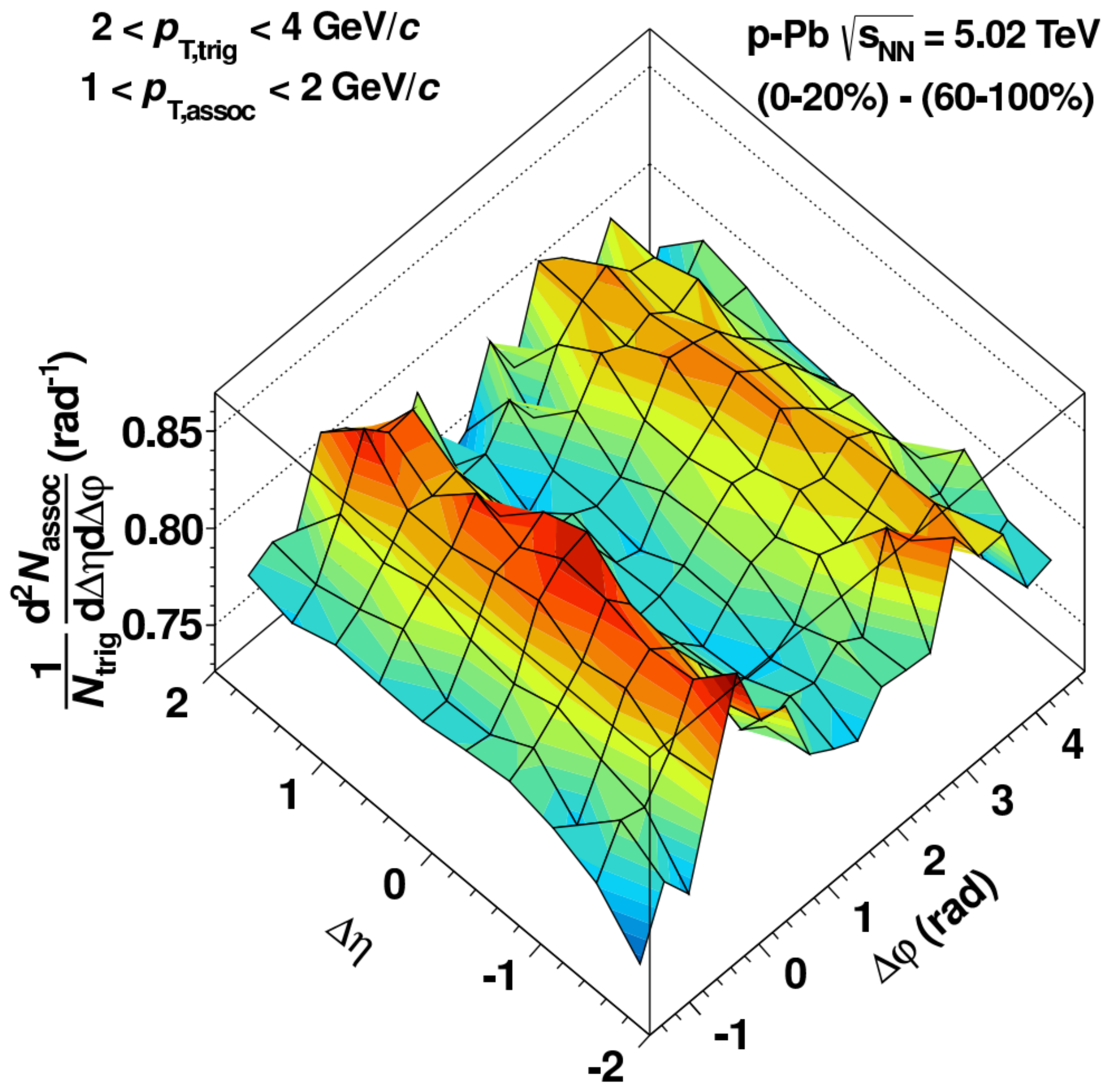
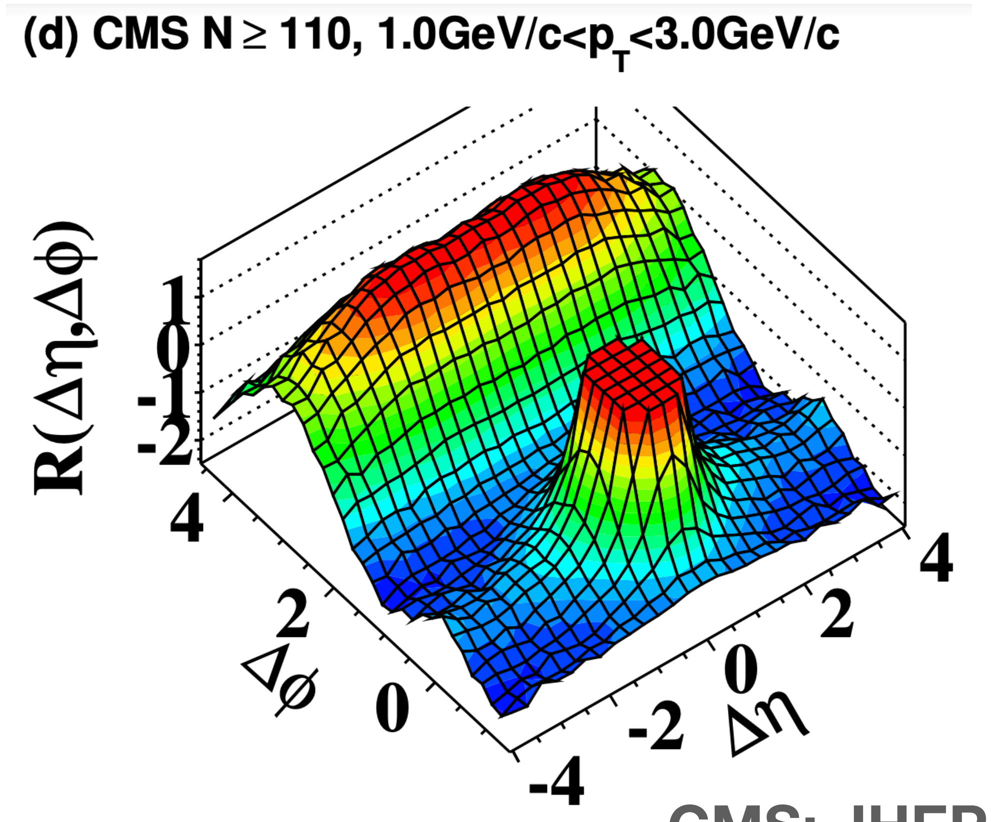


ALICE: Phys.Lett. B719 (2013) 29-41





CMS: JHEP 1009:091,2010

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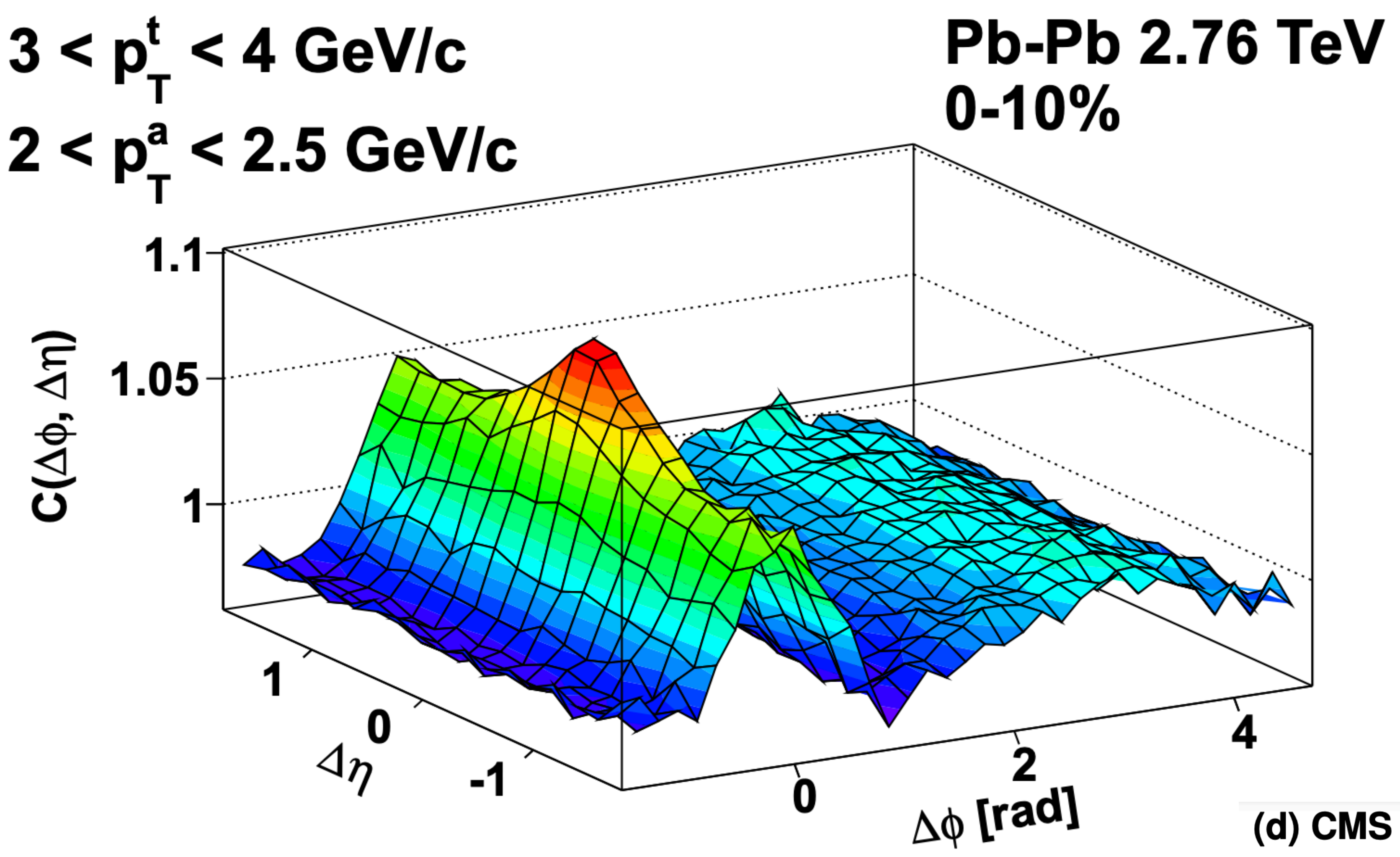

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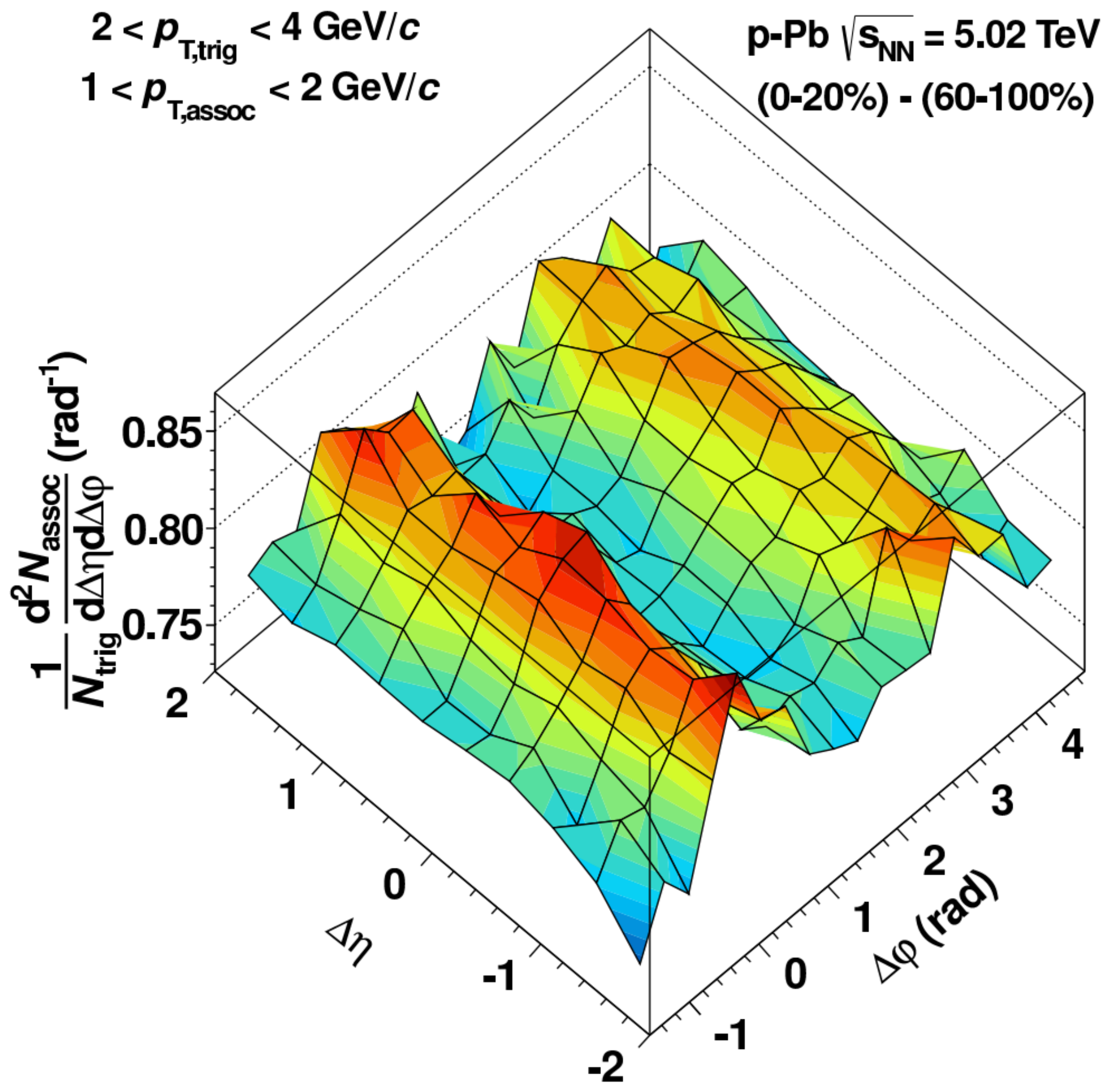

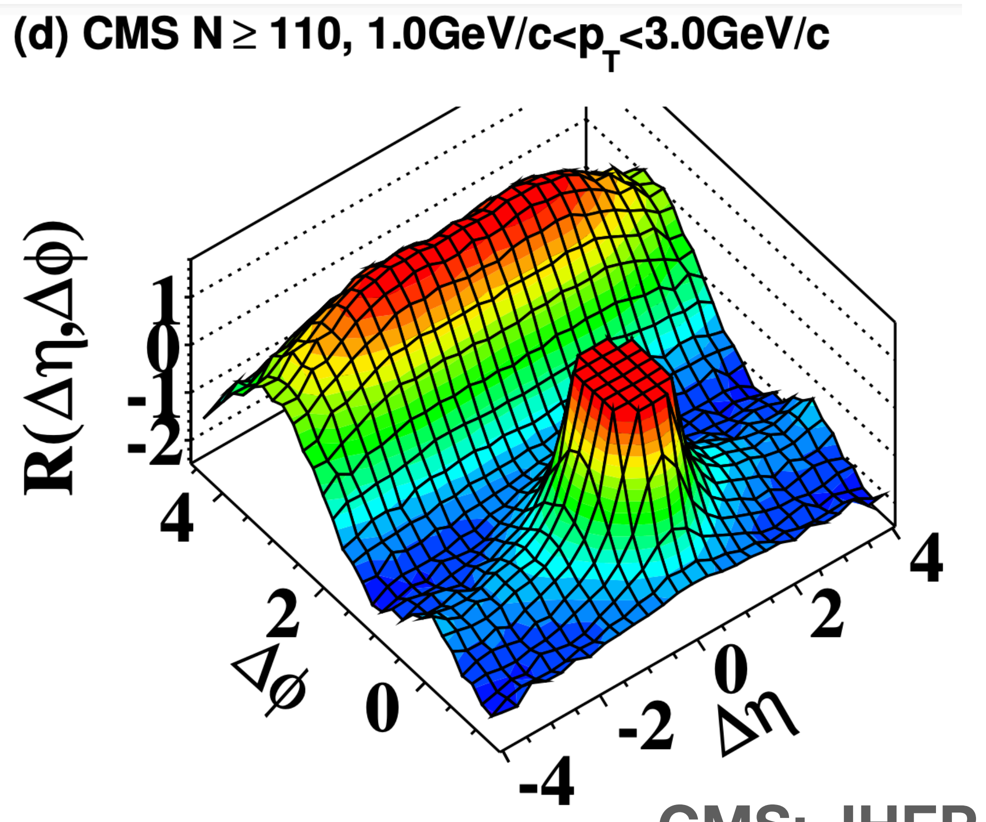

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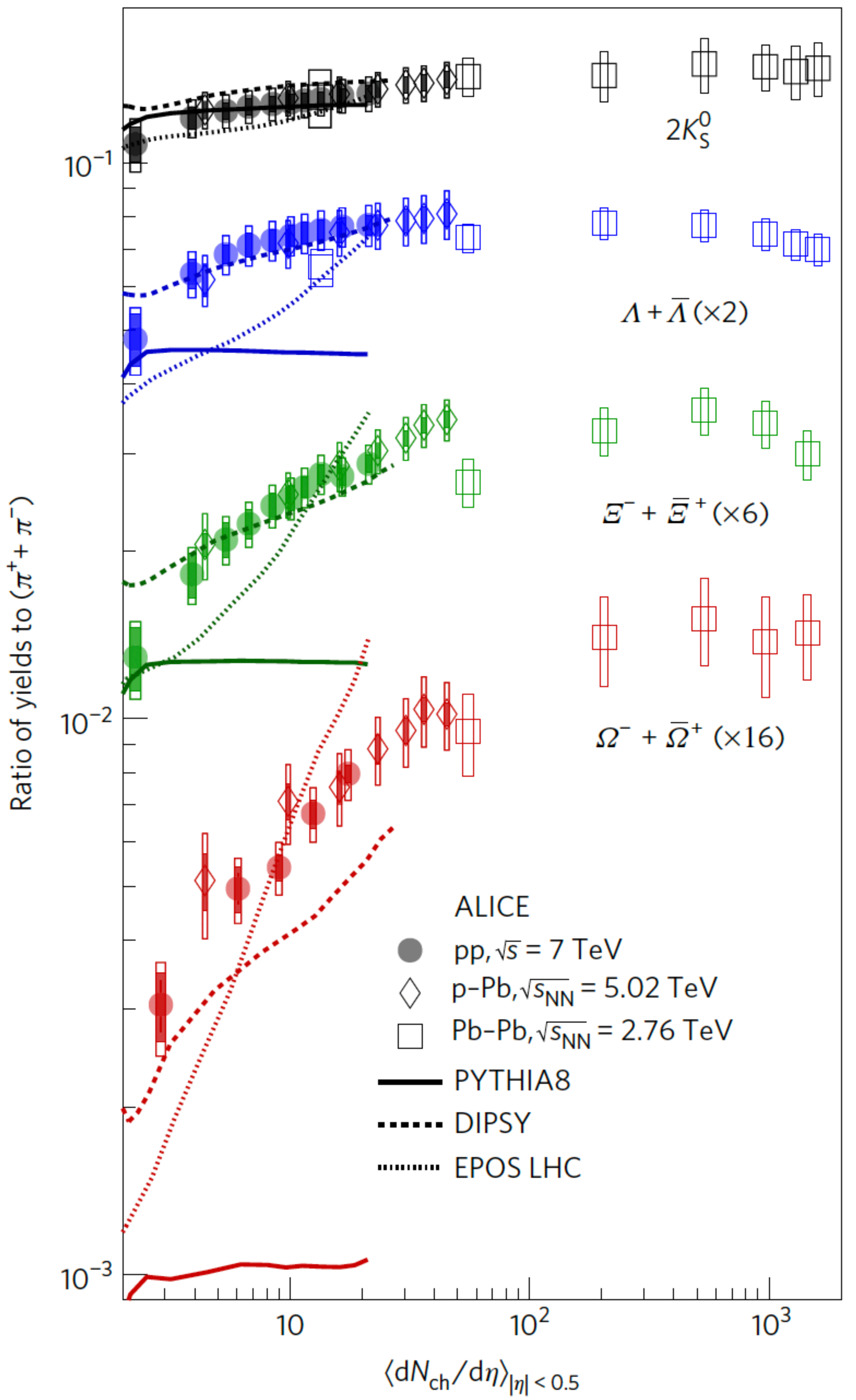
- Many QGP-like effects observed in small system (e.g. strangeness enhancement

ALICE: Nature Physics 13, 535–539 (2017)



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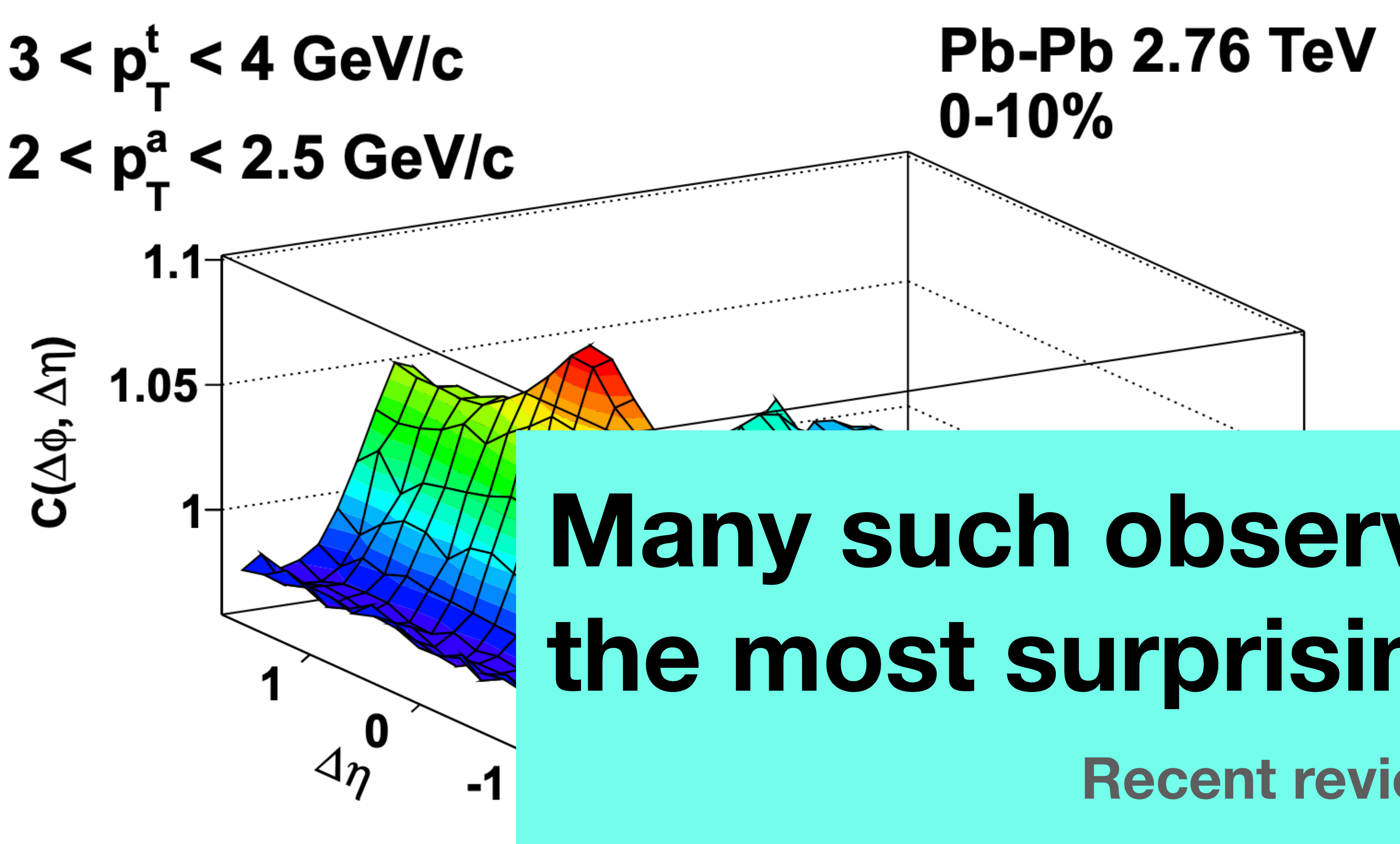

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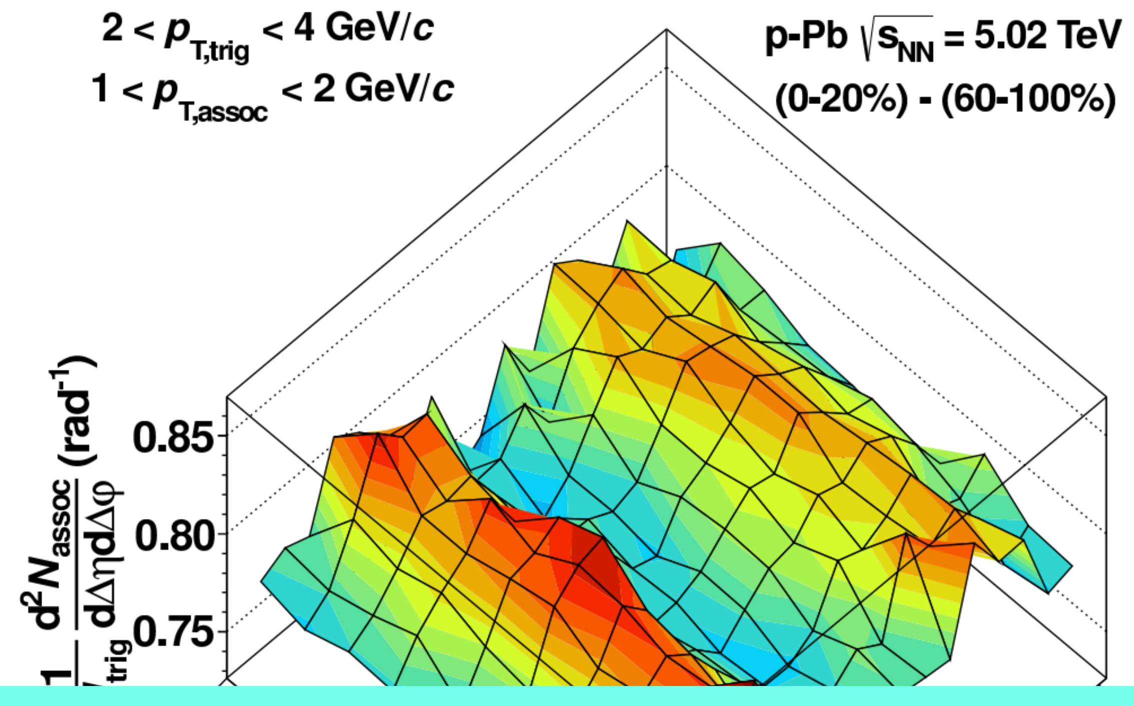

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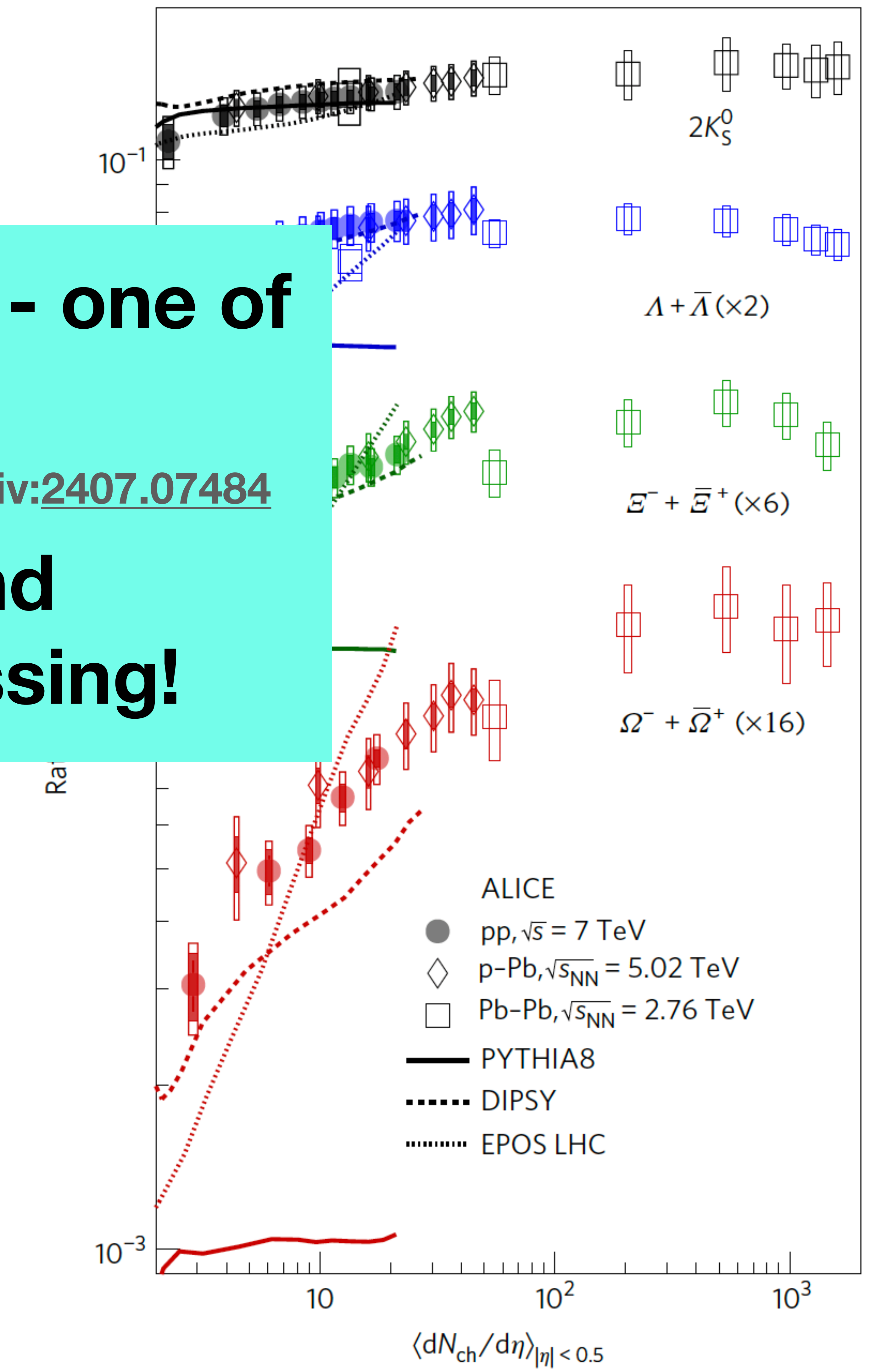
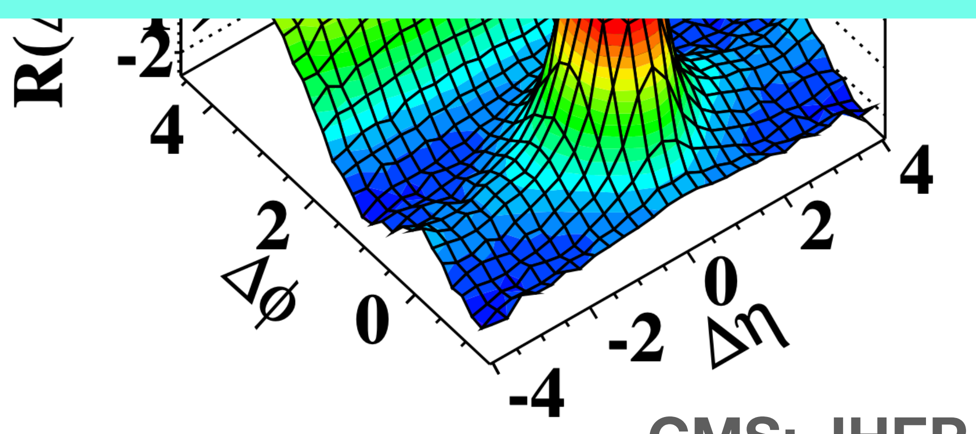


Many such observations over past ~decade - one of the most surprising 'discoveries' at the LHC

Recent review: J. Grosse-Oetringhaus, U. Wiedemann, arxiv:2407.07484

Unified description of particle production and collectivity across collision systems still missing!

- Long-range co[...] over wide η range ('ridge') understood to be due to flow of system



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- Ridge also (unexpectedly) seen in p-Pb and high-multiplicity pp collisions (now even HM e+e-!)

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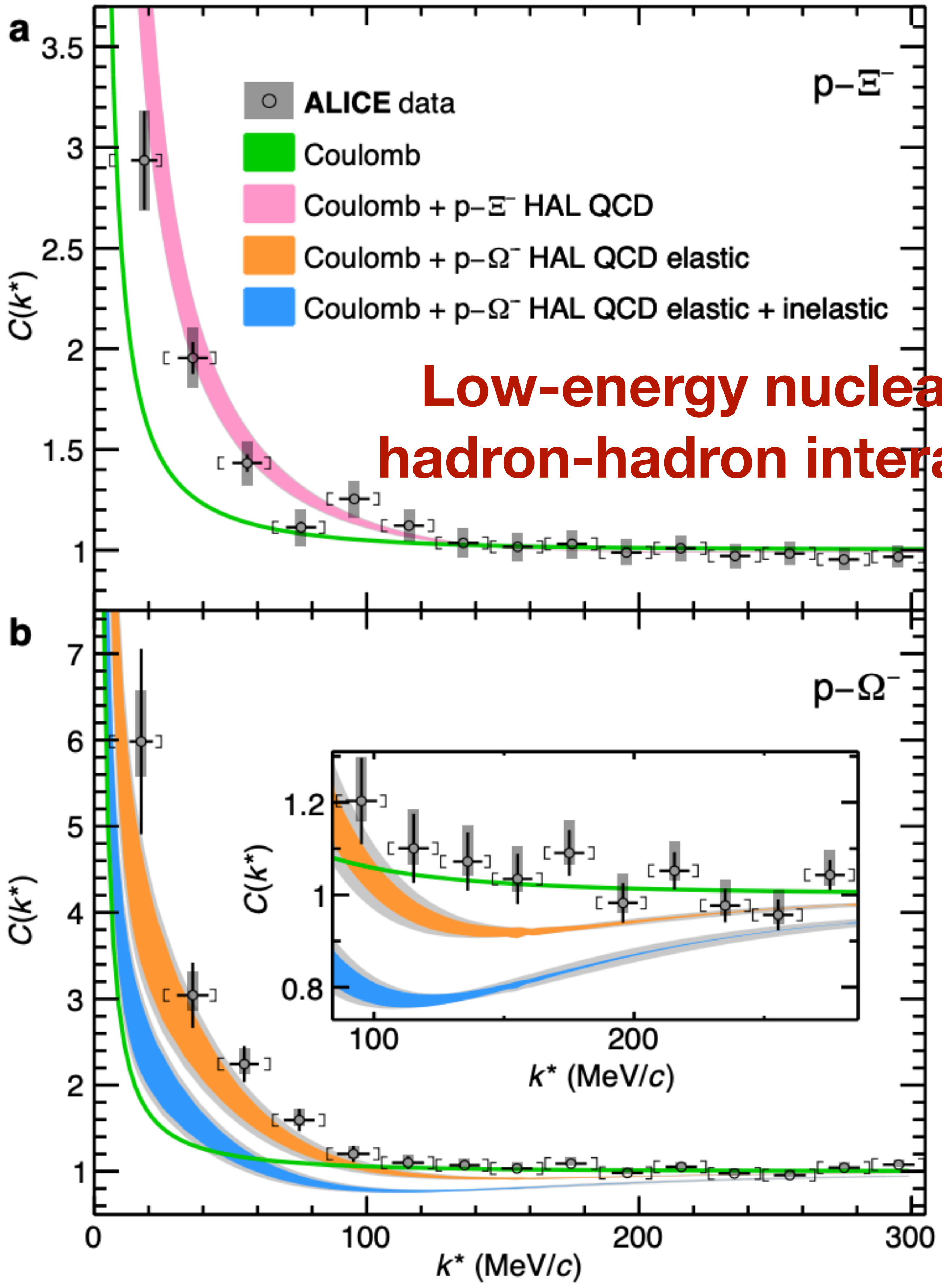
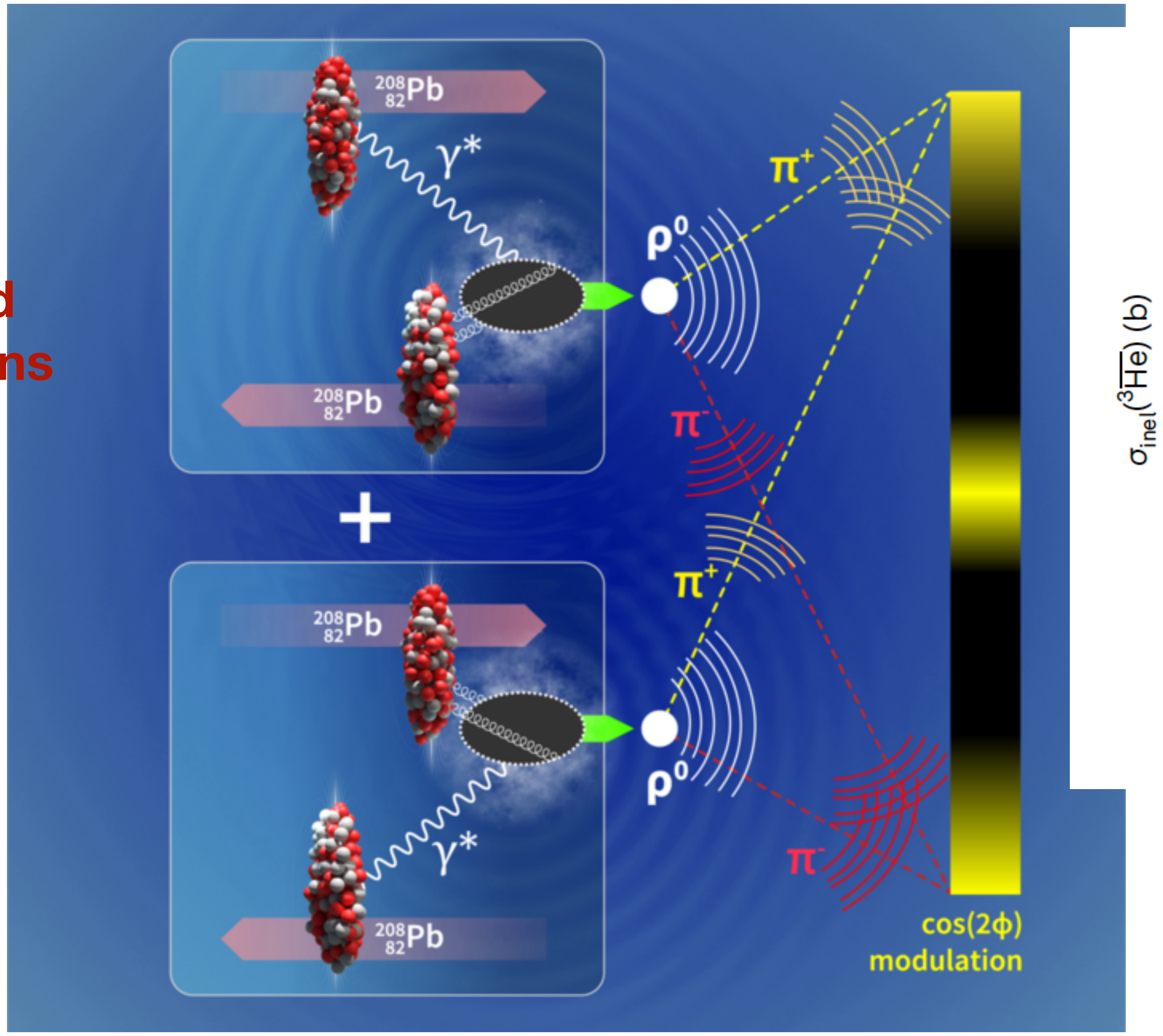
…+ much more…!

ALICE: Nature 588, 232–238 (2020)



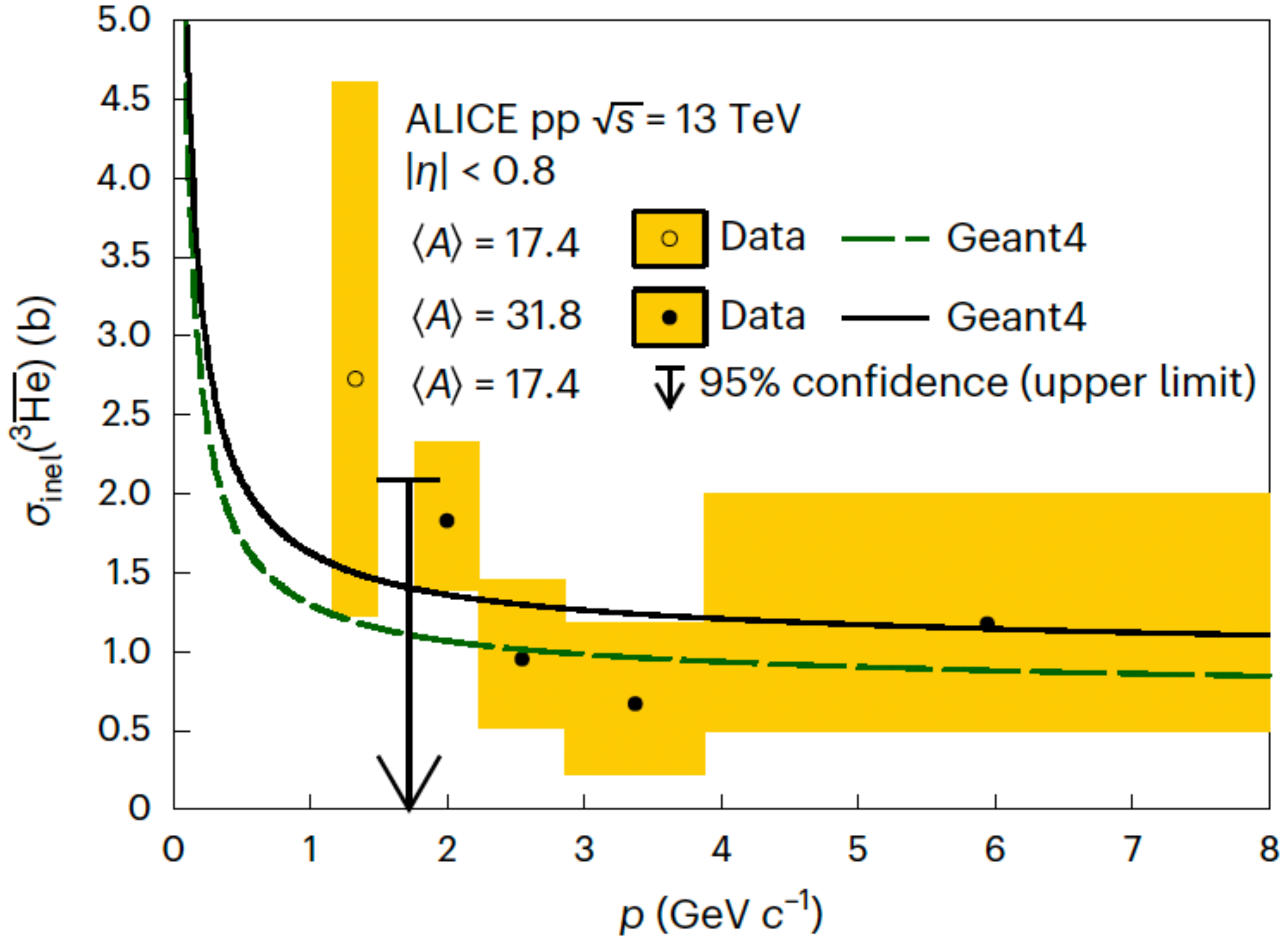
Low-energy nuclear and hadron-hadron interactions



Pb-Pb UPCs as $\gamma-\gamma$ collider

'Double-slit' experiment
- https://home.cern/news/news/physics/alice-does-double-slit

Light nuclei cross section w. matter cosmic ray/dark matter interactions



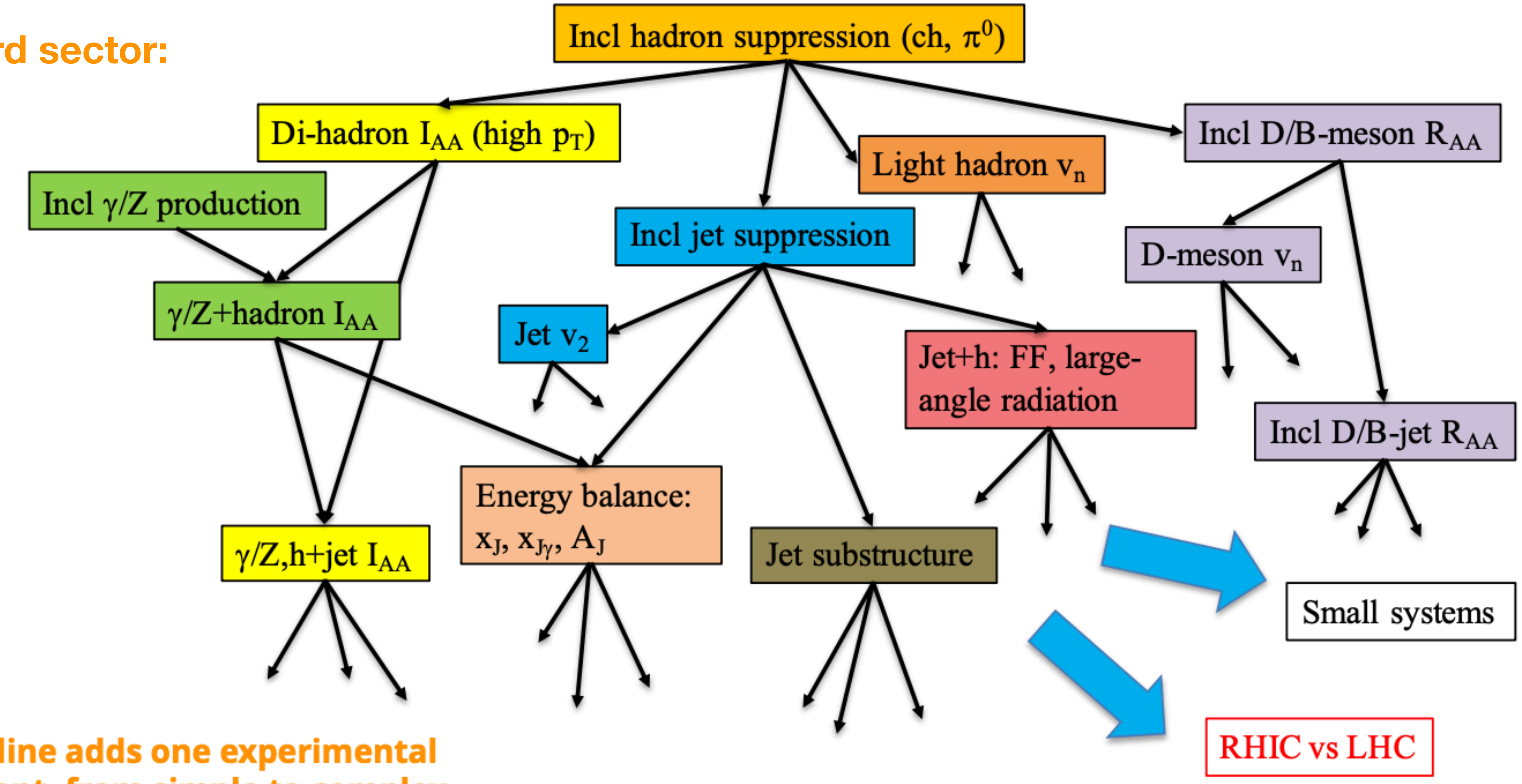
ALICE: Nature Physics 19, 61–71 (2023)

…+ more

Extracting quantitative information from measurements

- **O(100s) of measurements/observables/observations from QGP studies over ~25 years of study at RHIC/LHC**
- 'Multi-messenger', with all measurements sensitive to same underlying physics

e.g. hard sector:



Each line adds one experimental element, from simple to complex

Colors group experimentally related measurements

- How can we optimally utilise these measurements to constrain QGP properties?

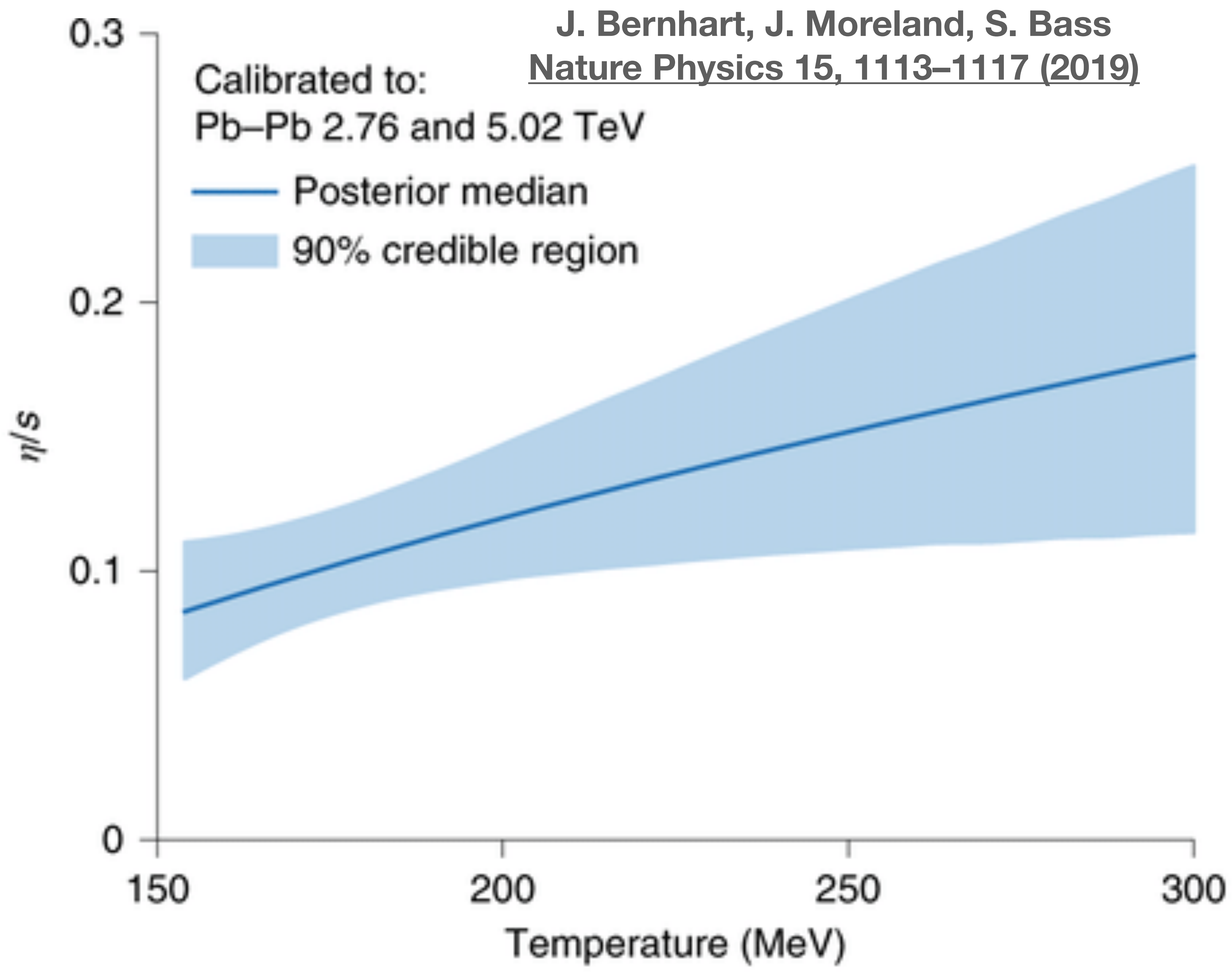
Fig. P. Jacobs

Bayesian parameter estimation

- Bayesian inference parameter estimation to constrain model parameters natural candidate for this task

$$P(x|y) \propto P(y|x)P(x)$$

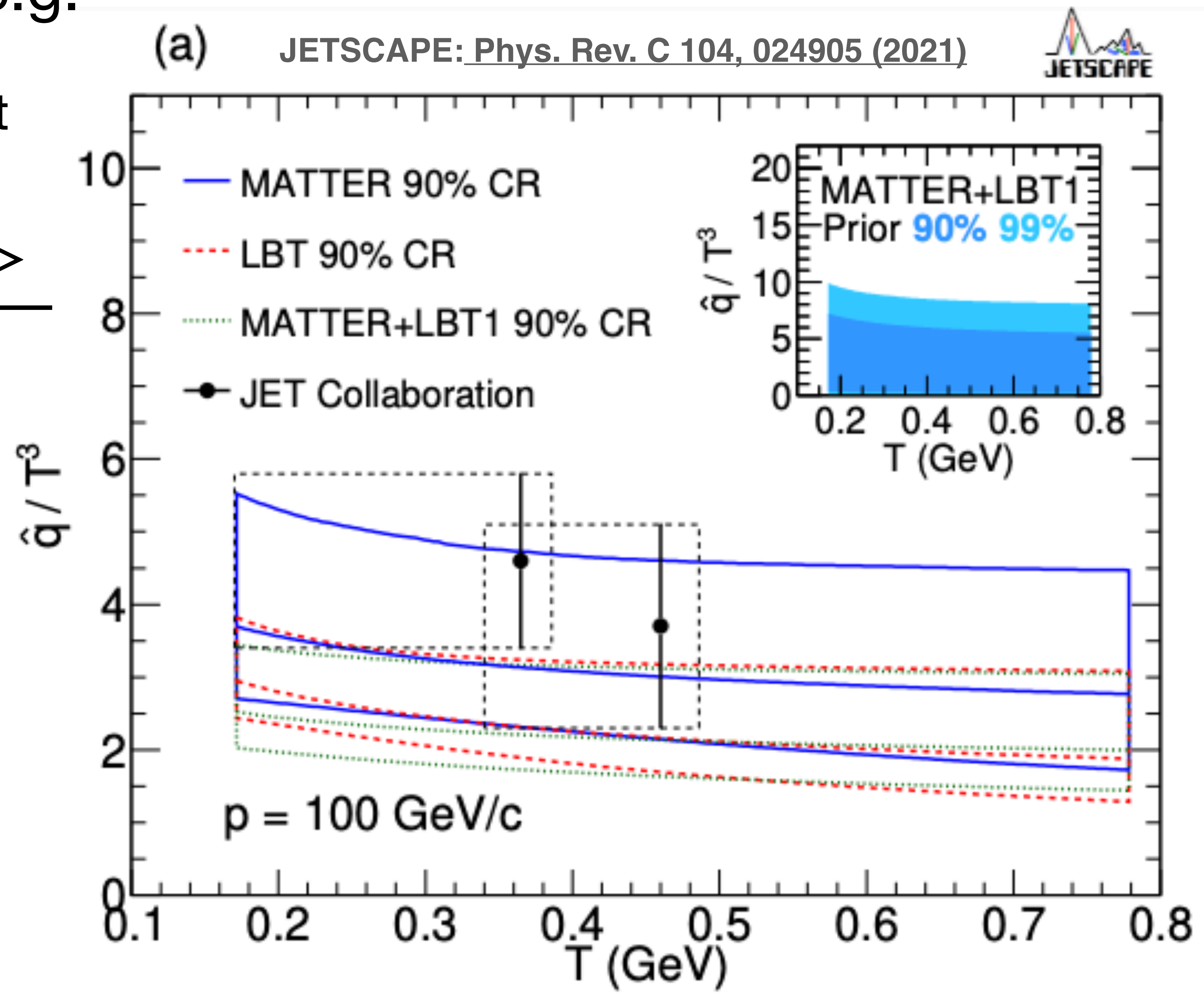
- Last few years have seen many exciting developments, e.g.



Combination of elliptic flow measurements @ ALICE

Jet transport coefficient

$$\hat{q} = \frac{d < k_\perp^2 >}{dL}$$



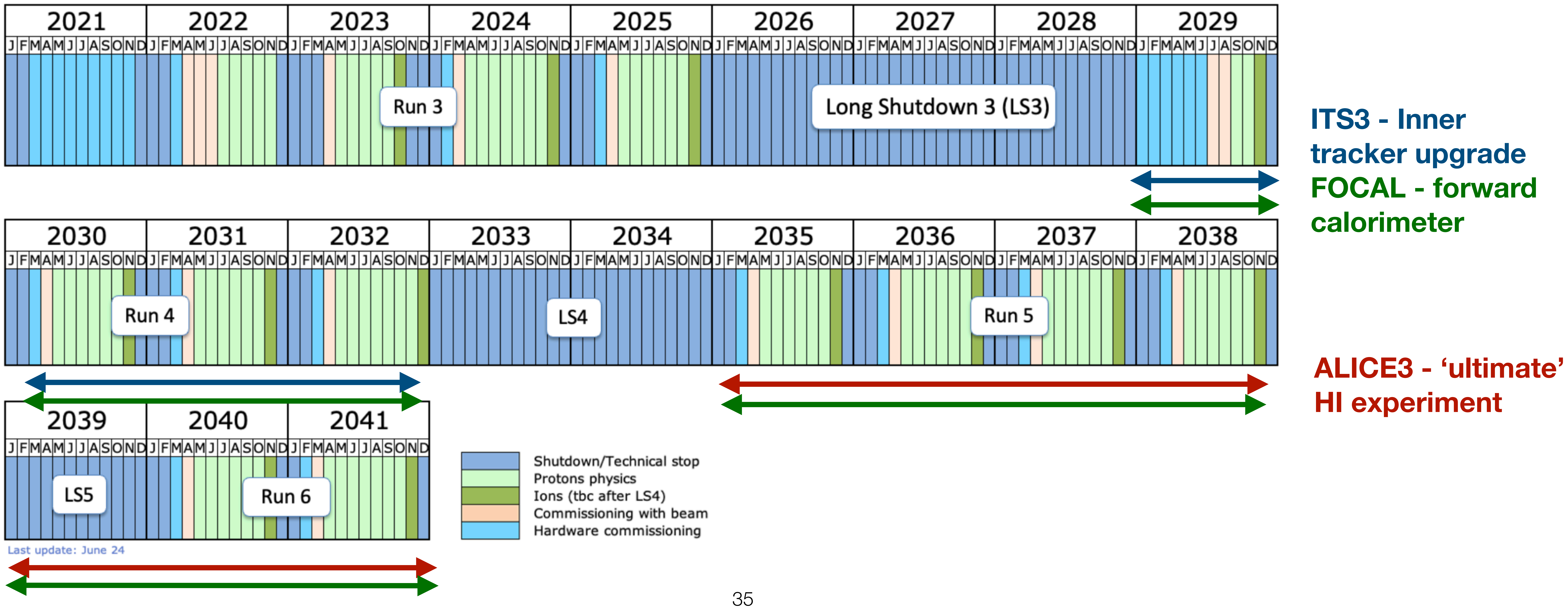
Combination of hadron RAA measurements @ LHC + RHIC

Future upgrades at the LHC

- Current ALICE setup scheduled to run until the end of Run 4 (2032), LHC scheduled to run with heavy-ions until 2041

Longer term LHC schedule

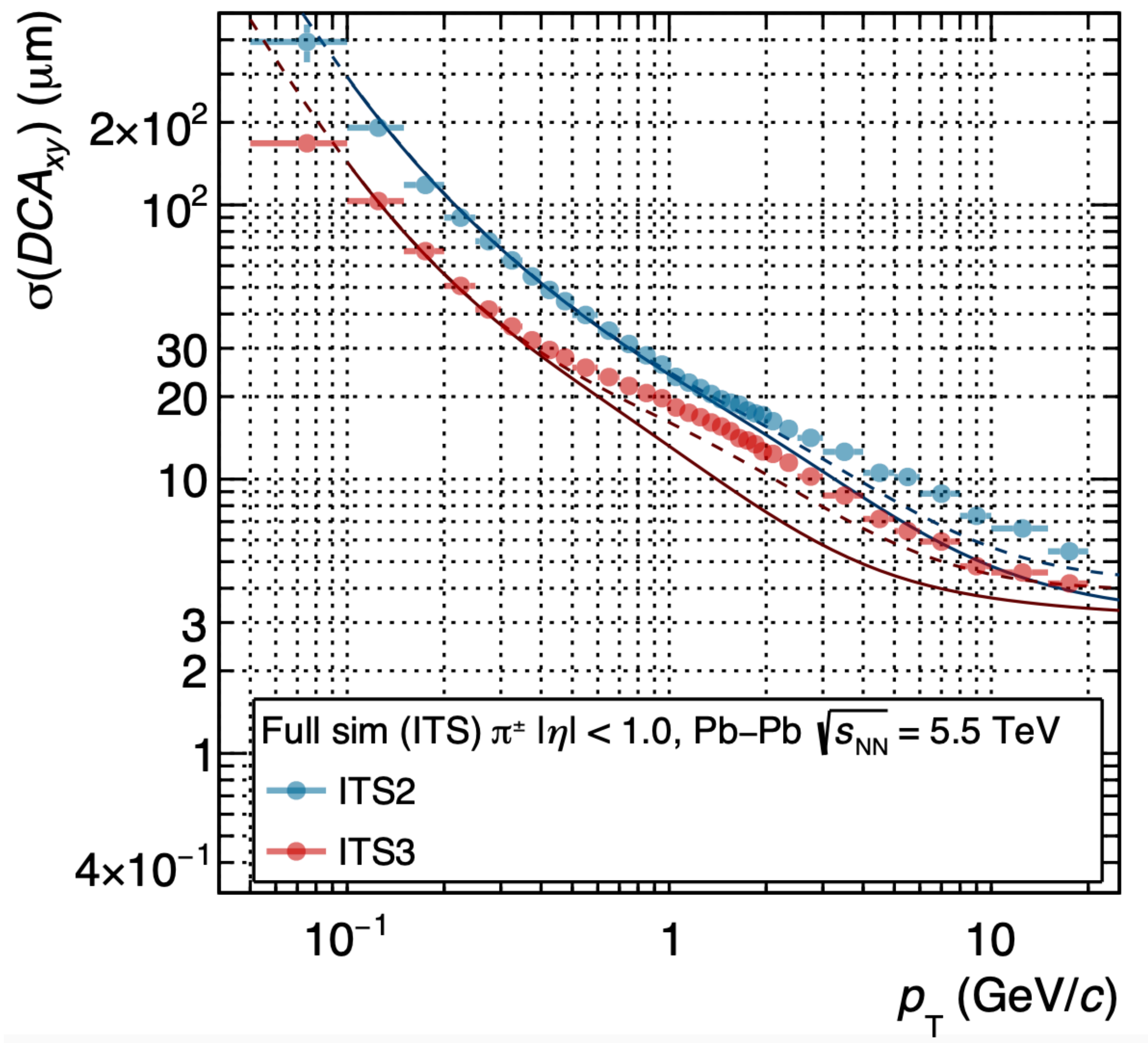
In January 2022, the schedule was updated with long shutdown 3 (LS3) to start in 2026 and to last for 3 years. HL-LHC operations now foreseen out to end 2041.



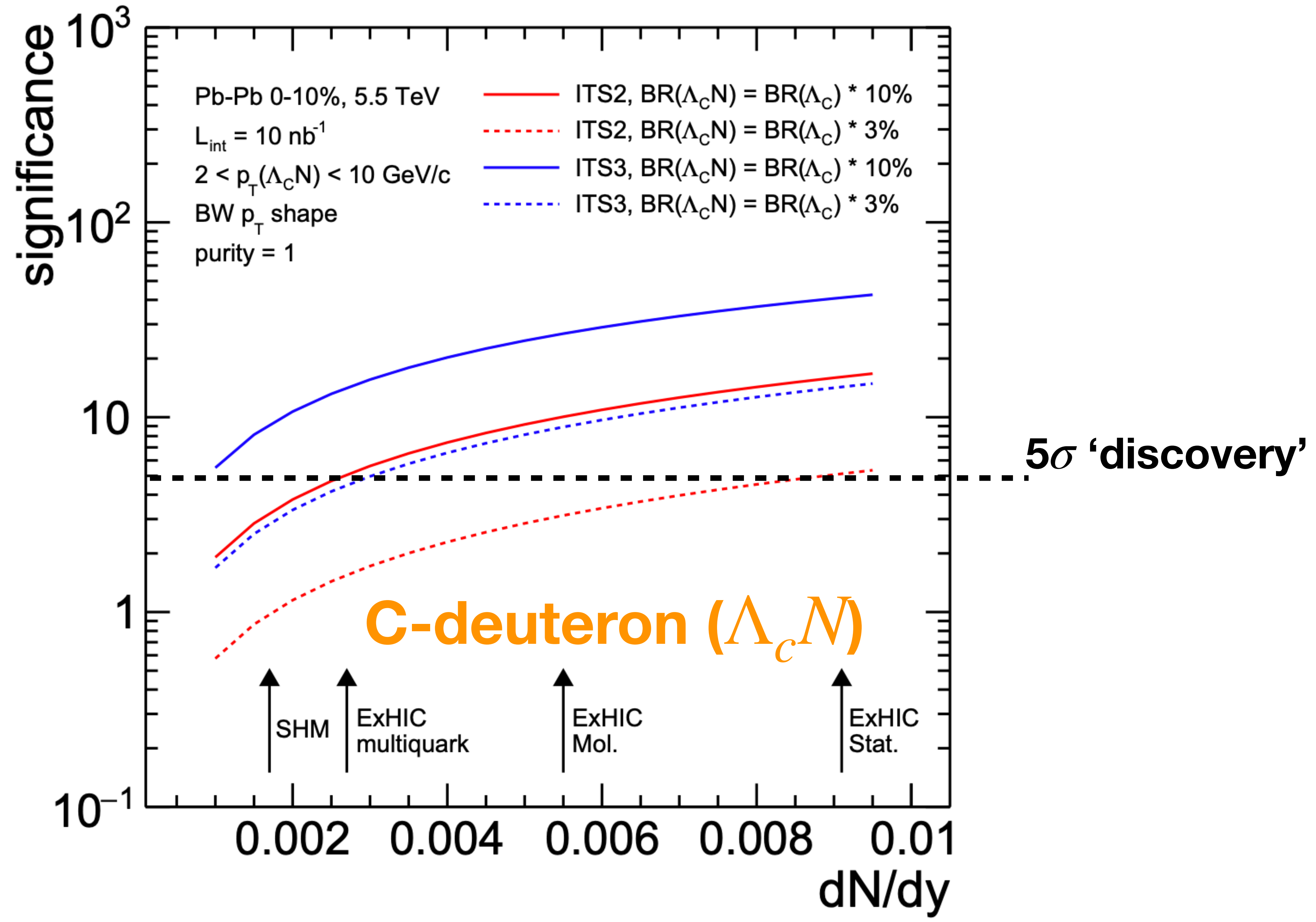
Inner tracker upgrade ‘ITS3’

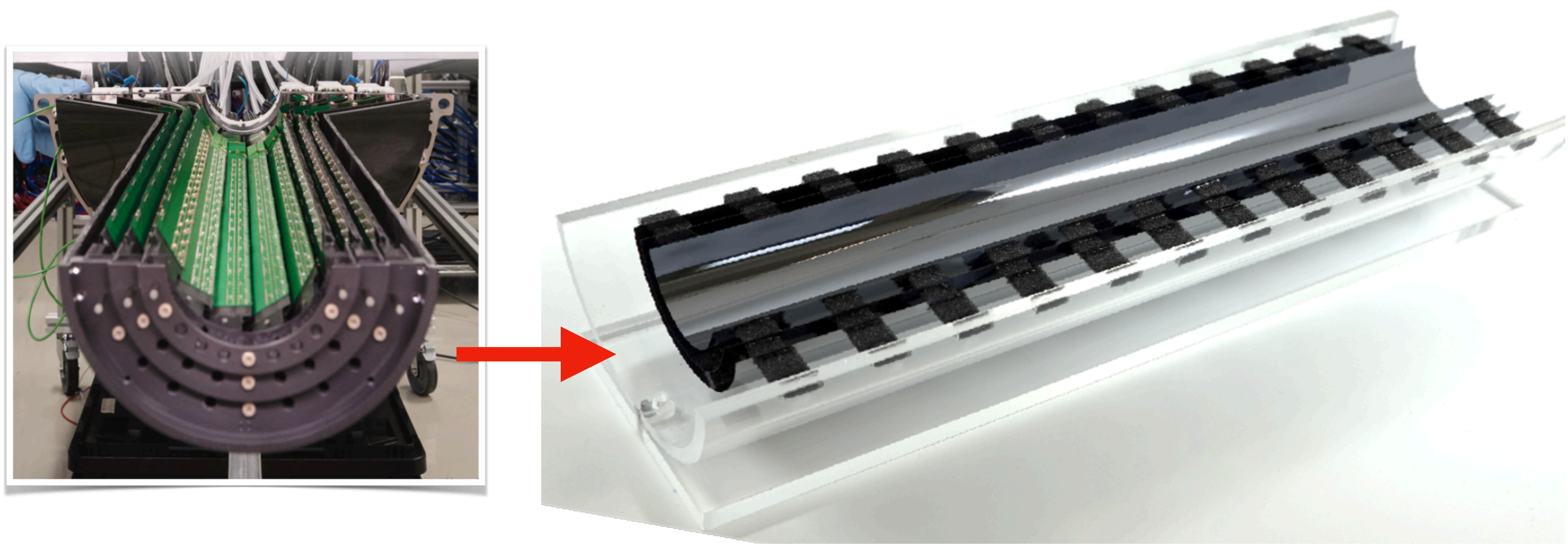
Replacing the ITS2 inner barrel for Run 4 (2029-2032)

- **bent, wafer-scale CMOS (MAPS) sensors**
  - Extremely low material budget 0.02-0.04% X_0
  - Homogeneous material distribution
- x2 improvement in pointing resolution, large improvement in tracking efficiency at low p_T



Significant improvements in measurements of charm+beauty hadrons, plus discovery potential for exotic nuclei

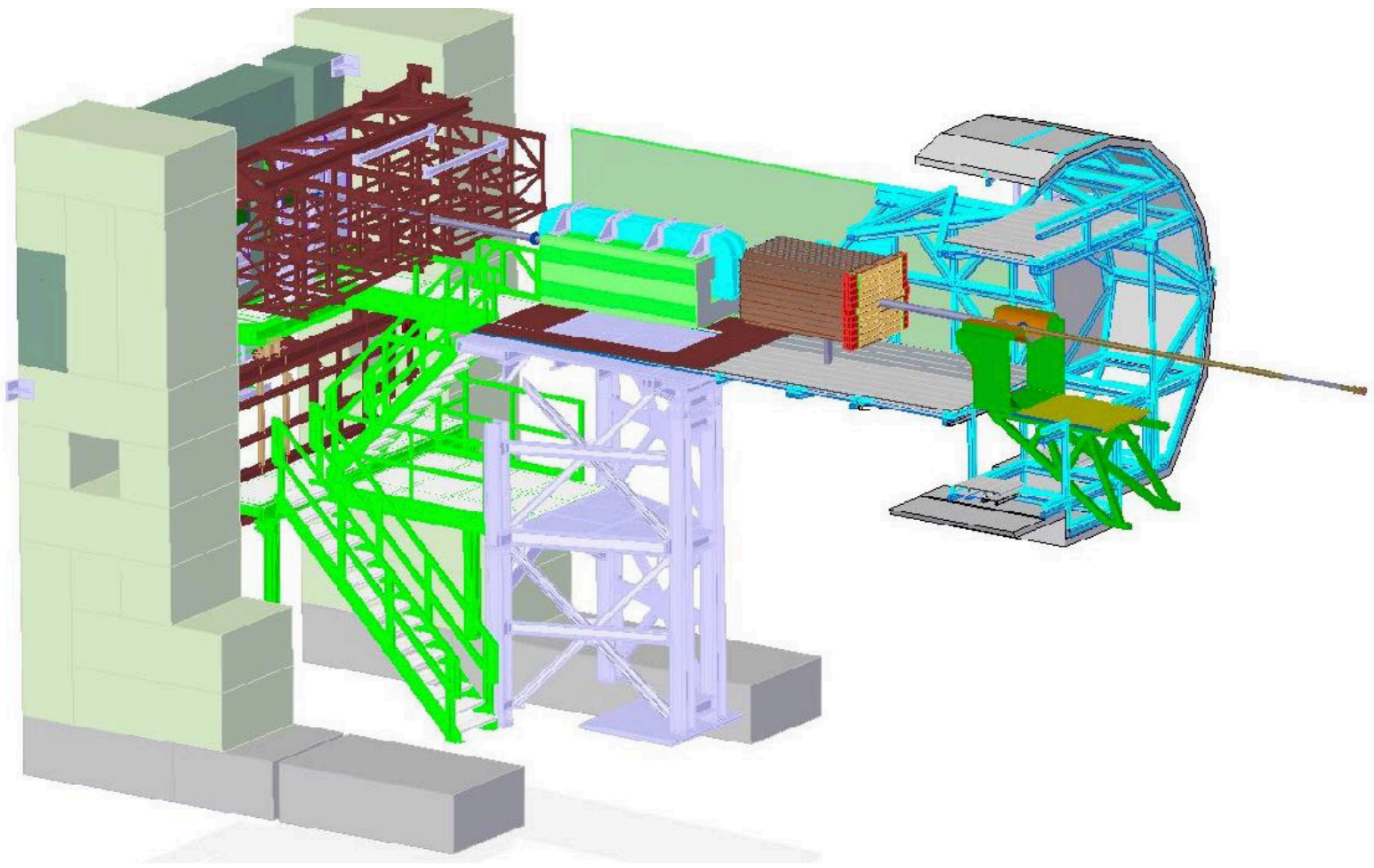


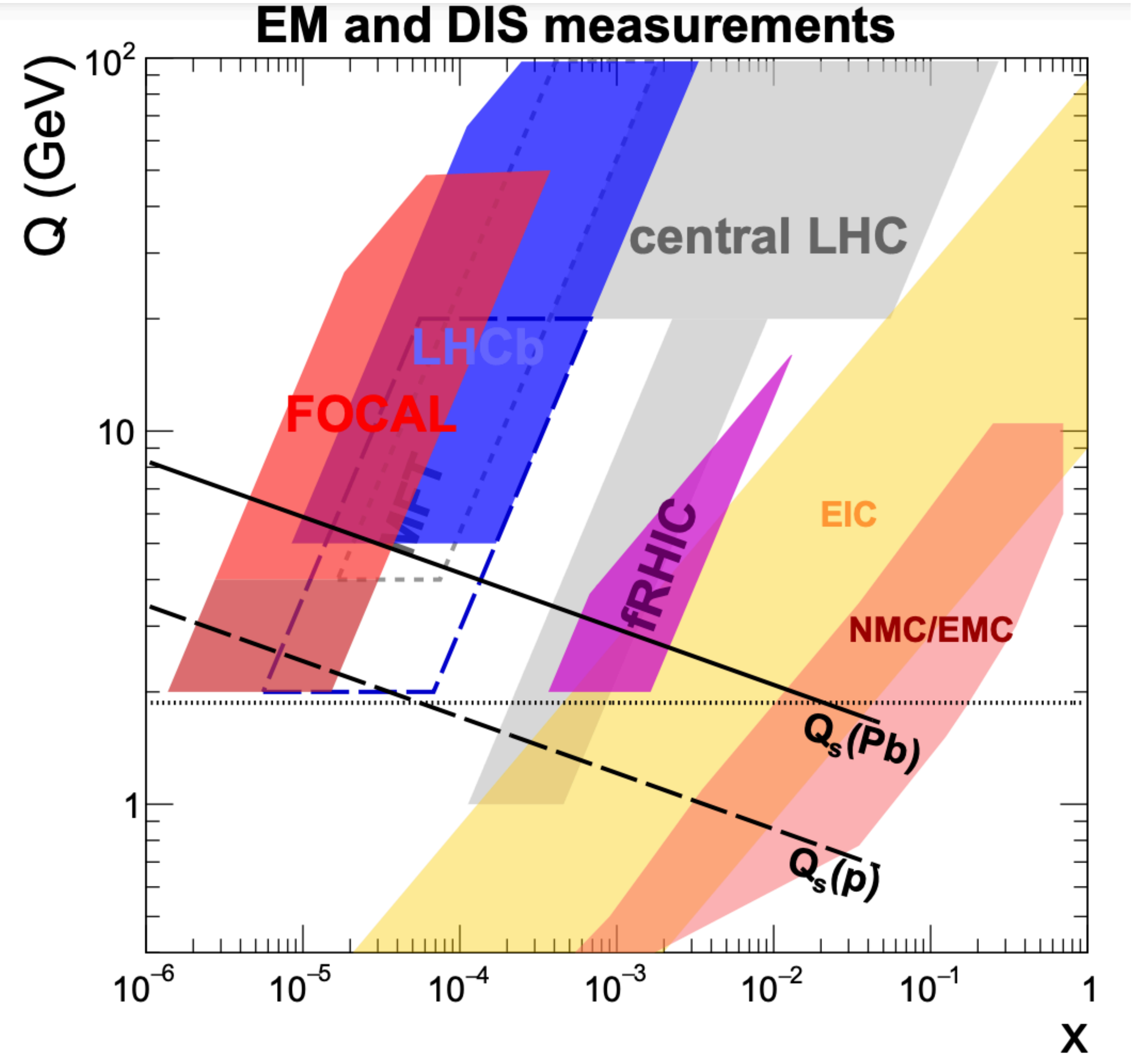


ITS3 LOI: CERN-LHCC-2019-018

Forward Calorimeter 'FOCAL'

- **Forward (3.4<η<5.8) EM calorimeter + hadronic calorimeter to be installed for Run 4**
- Exciting low-x hadron physics program, complimentary to EIC





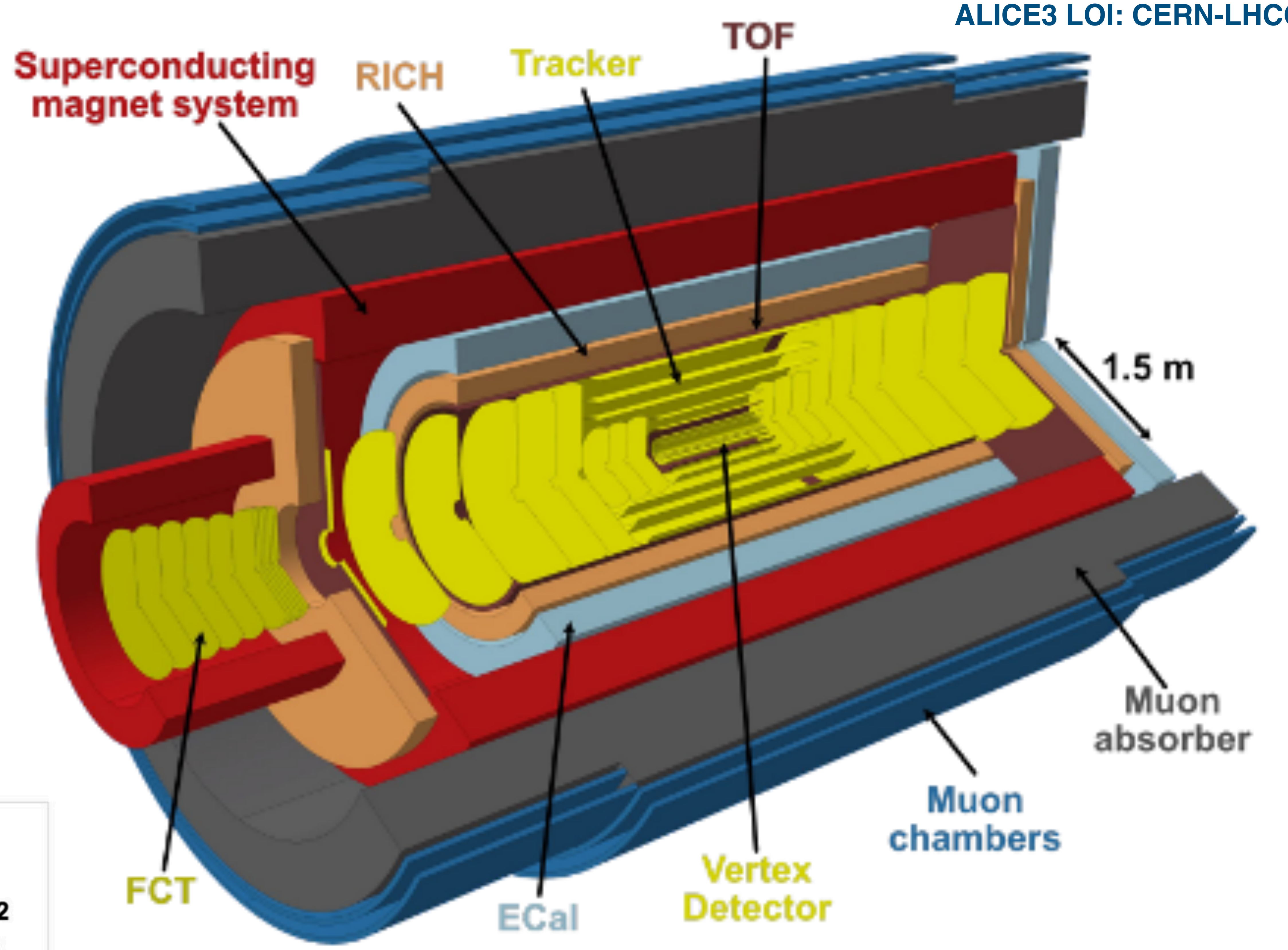
TDR: CERN-LHCC-2024-004
Physics: ALICE-PUBLIC-2023-001

The ultimate heavy-ion experiment - ALICE3

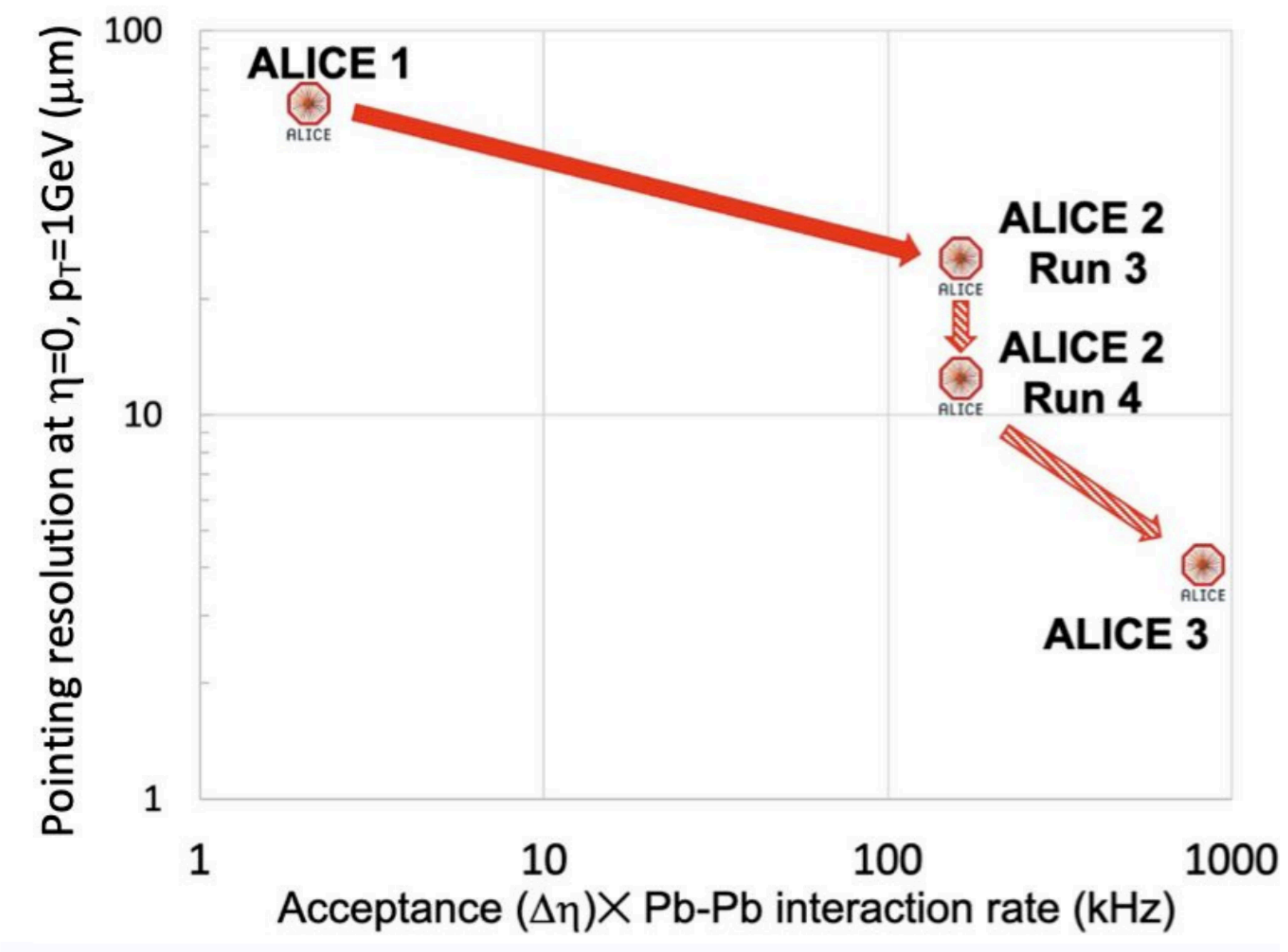
The next-generation heavy-ion experiment for LHC Run 5 and 6 (2035 onwards)

- Novel and innovative detector concept
  - Compact and lightweight all-silicon tracker
  - Retractable vertex detector
  - Extensive particle identification
  - Large acceptance
  - Superconducting magnet system
  - Continuous read-out and online processing

ALICE3 LOI: CERN-LHCC-2022-009



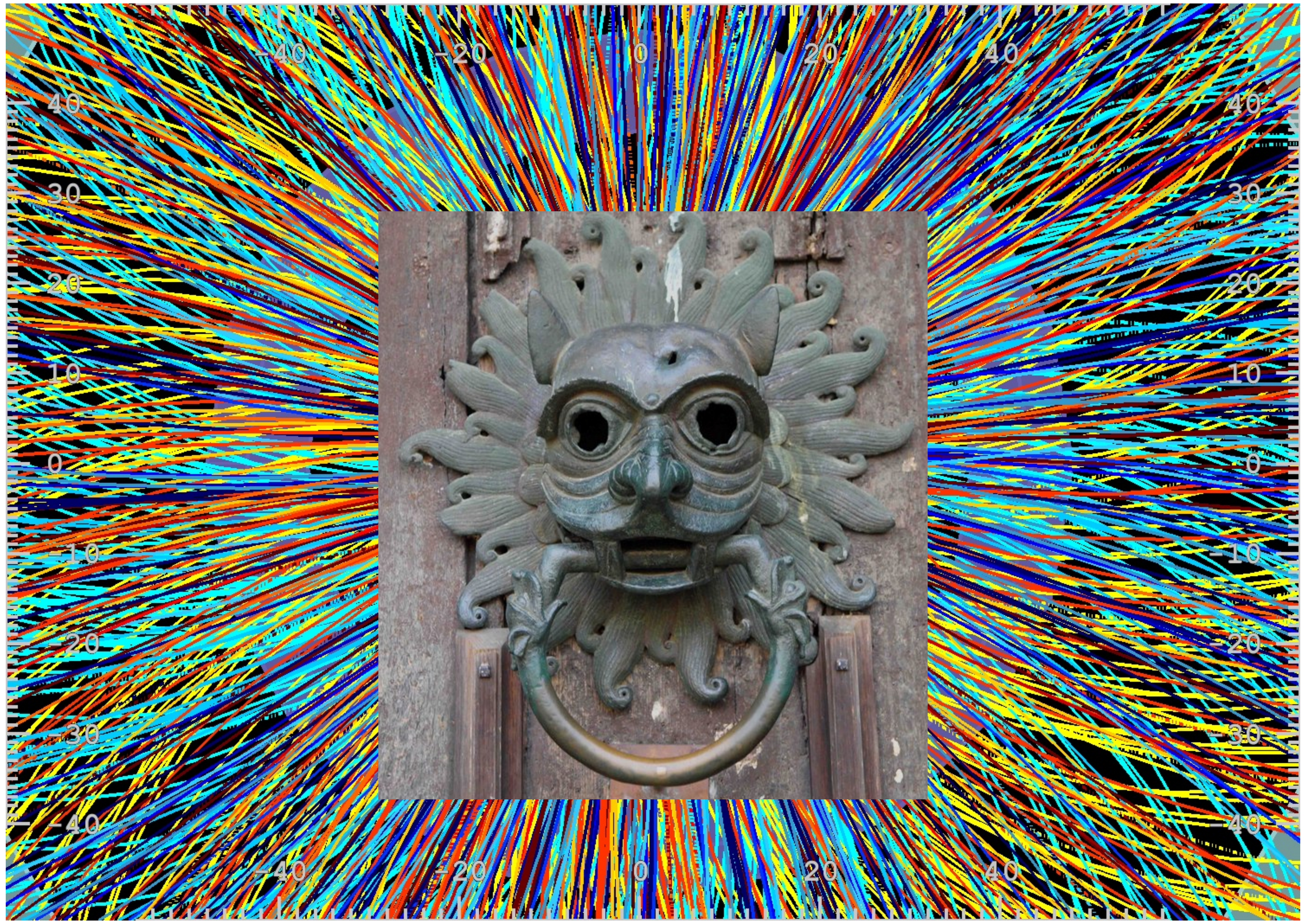
Ultimate performance in terms of acceptance, interaction rate and tracking precision



Precision beauty, charm correlations, exotic charm states and nuclei, dileptons, collectivity…

Summary

- **ALICE** (**A** **L**arge **I**on **C**ollider **E**xperiment) is the experiment at the LHC dedicated to studying the deconfined state of QCD known as the Quark-Gluon Plasma (QGP)
- ALICE has a rich and diverse physics programme and is probing the properties of the QGP with unprecedented accuracy, as well as addressing many topics in QCD and beyond
- **There is a bright (and hot!) future ahead of us**



Further reading:

- [review] ALICE Collaboration, The ALICE experiment - - A journey through QCD, arXiv:2211.04384
- [future] CERN Yellow Report on QCD with heavy-ion beams at the HL-LHC, arXiv:1812.06772
- [future] Letter of intent for ALICE 3: A next generation heavy-ion experiment at the LHC, arXiv:2211.02491

Contact: jknorman@liverpool.ac.uk

Backup

Jet asymmetry due to the QGP

- Measurement of two high p_T jets in Pb-Pb collisions shows significant asymmetry
  - When one jet has a large amount of QGP to travel through, lots of energy lost