Heavy-ion physics & extreme QCD

— a (biased) experimental overview —

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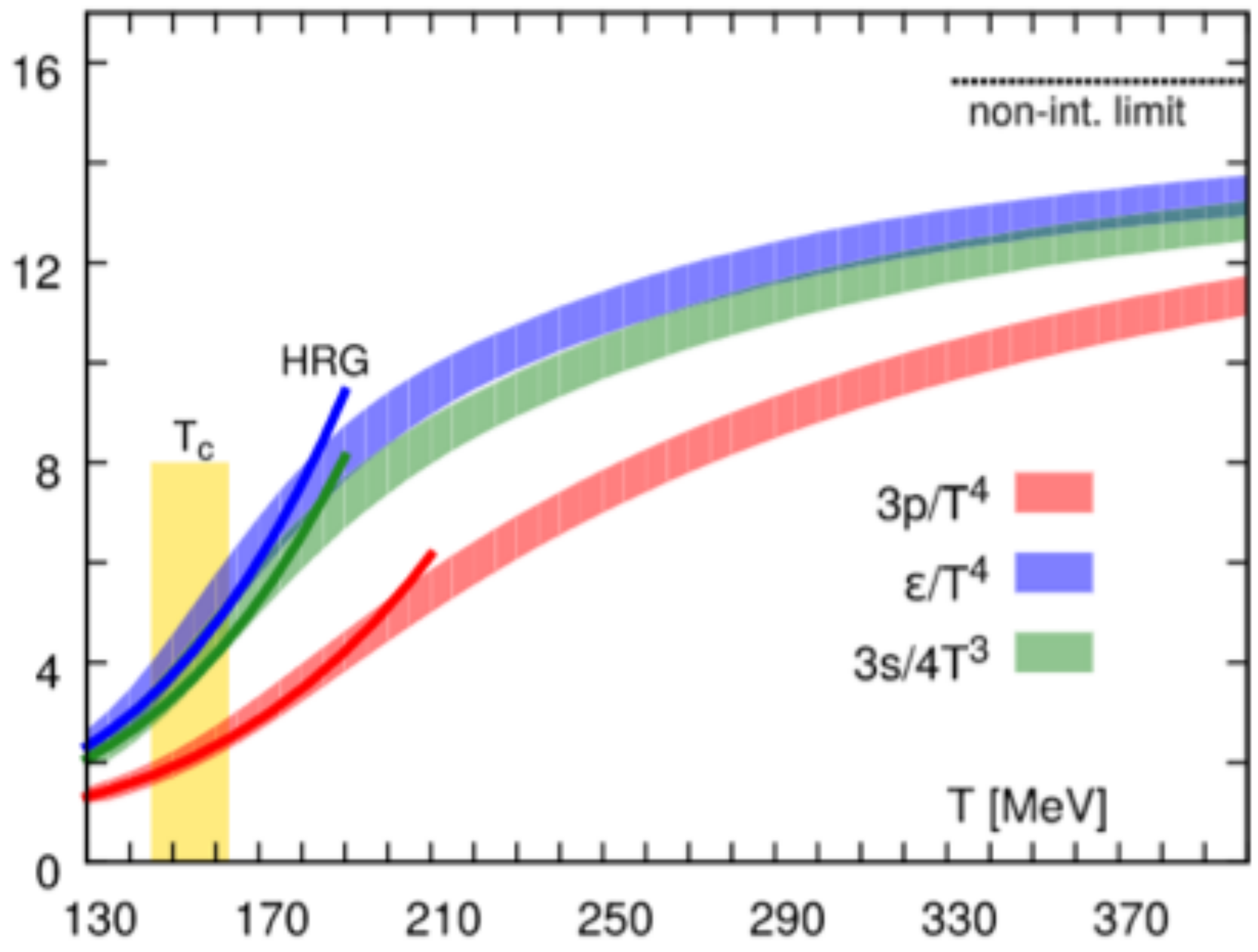
Lund University

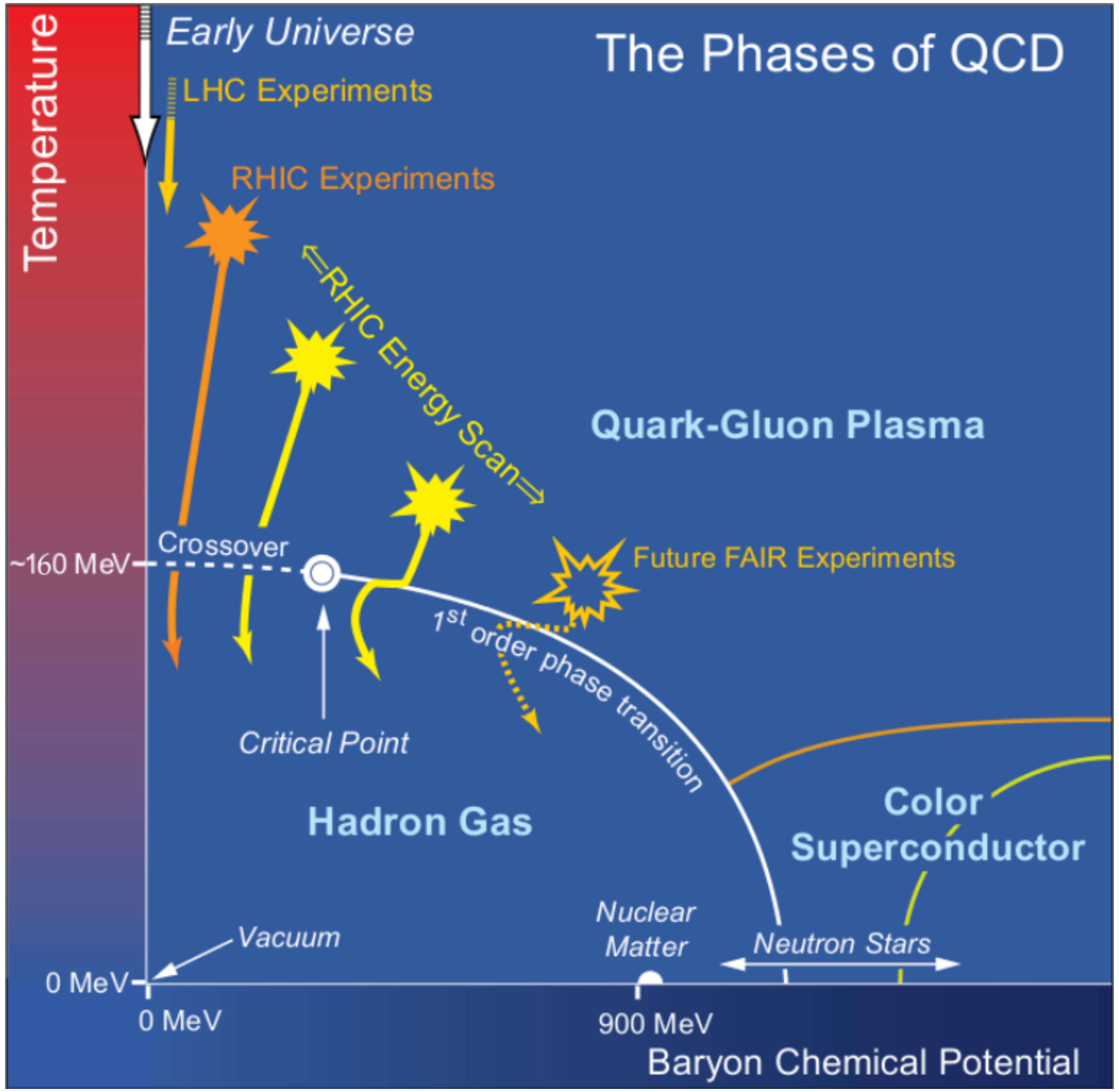
Nordic Conference on Particle Physics
4 January 2023

High-temperature regime of QCD

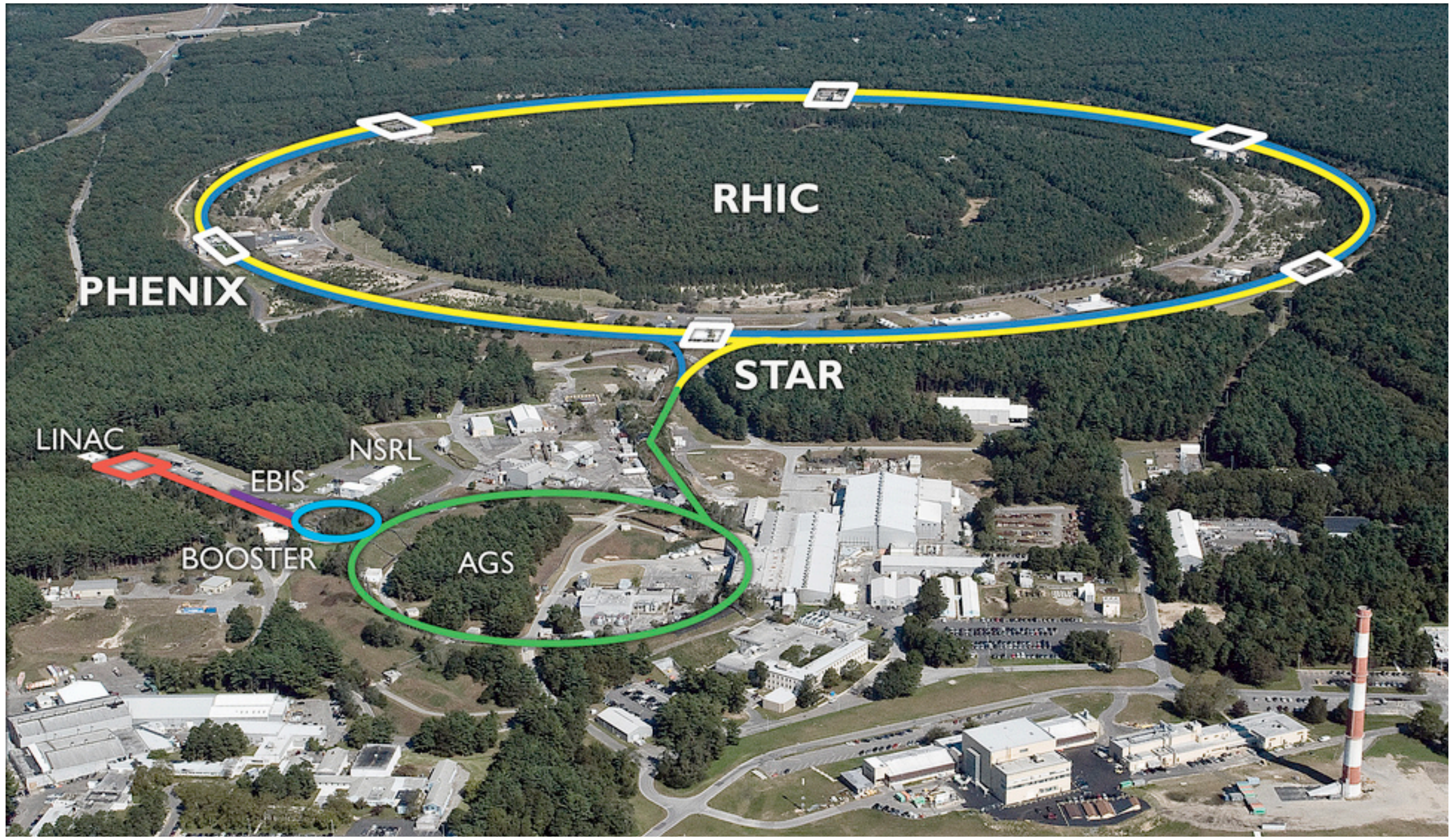
- At high temperatures and densities, quarks and gluons are no longer confined into hadrons but behave quasi-freely
  - Quark-Gluon Plasma (QGP)

[PRD 90 094503 (2014)]





Heavy-ion colliders



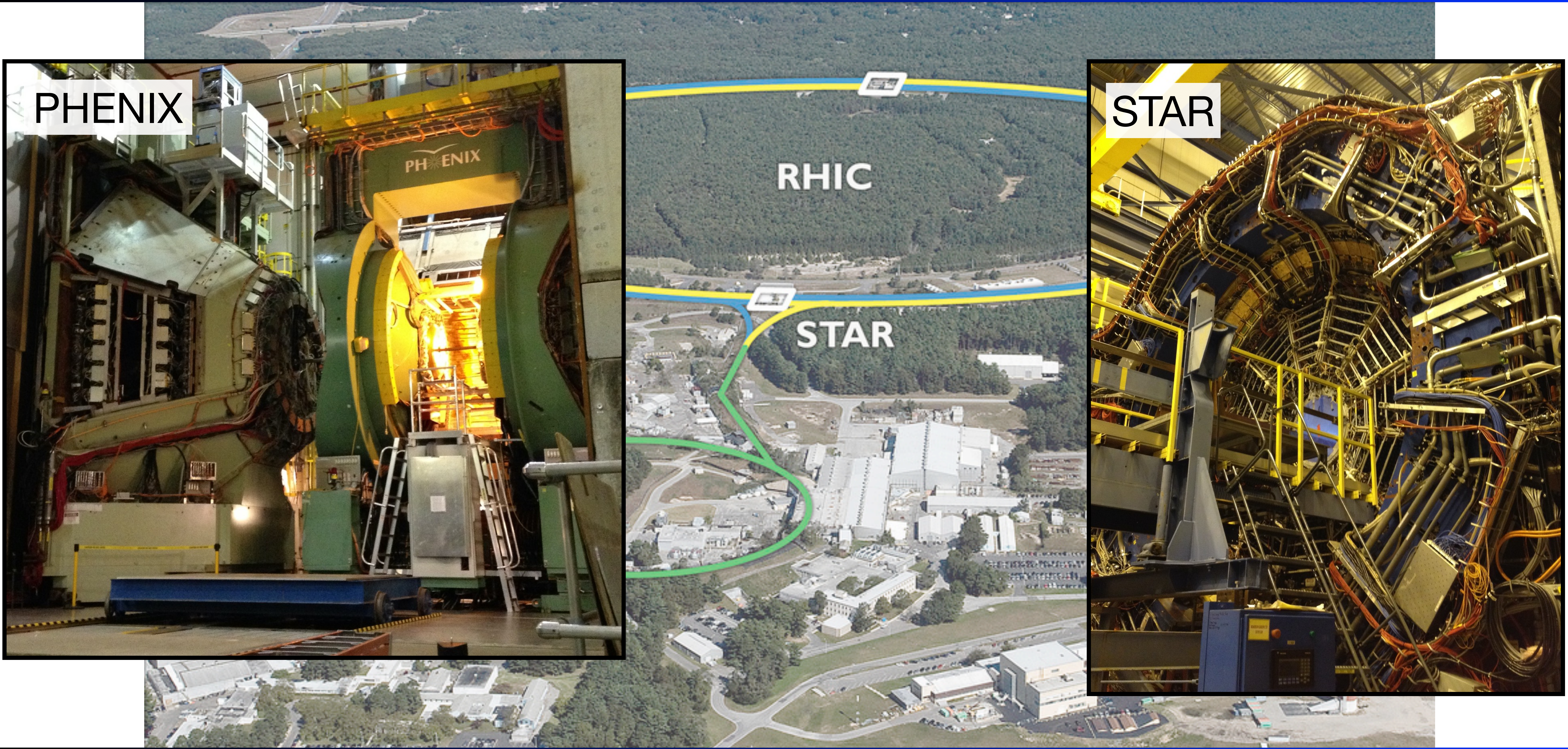
Relativistic Heavy Ion Collider

- 3.8 km circumference
- Au+Au collisions @ $\sqrt{s_{NN}}$ = 7.7 – 200 GeV
- also p+p, p+Au, d+Au, ^{3}He+Au, Cu+Cu, Cu+Au, U+U

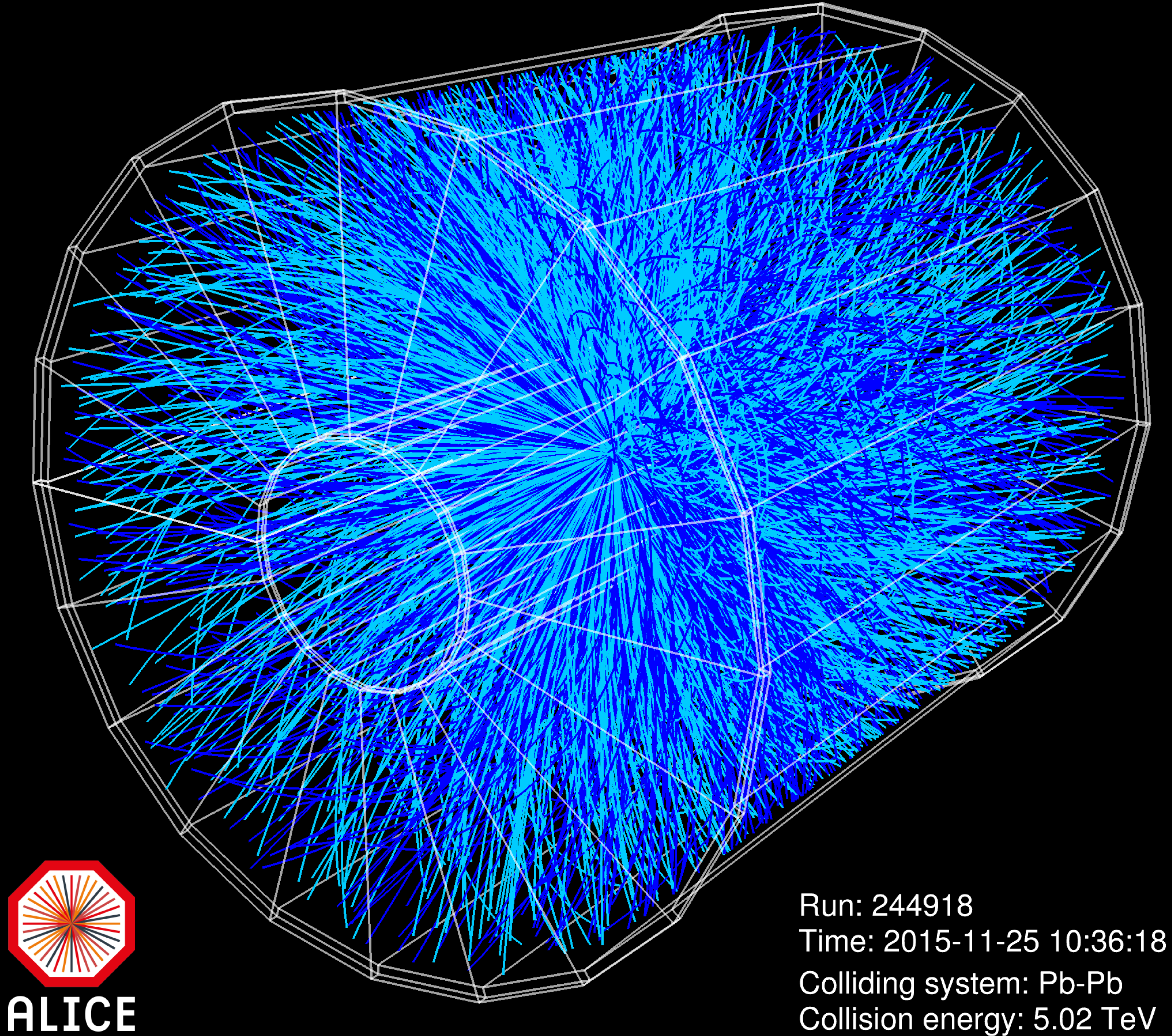
Large Hadron Collider

- 27 km circumference
- Pb+Pb collisions @ $\sqrt{s_{NN}}$ = 2.76, 5 TeV
- also p+p, p+Pb, Xe+Xe

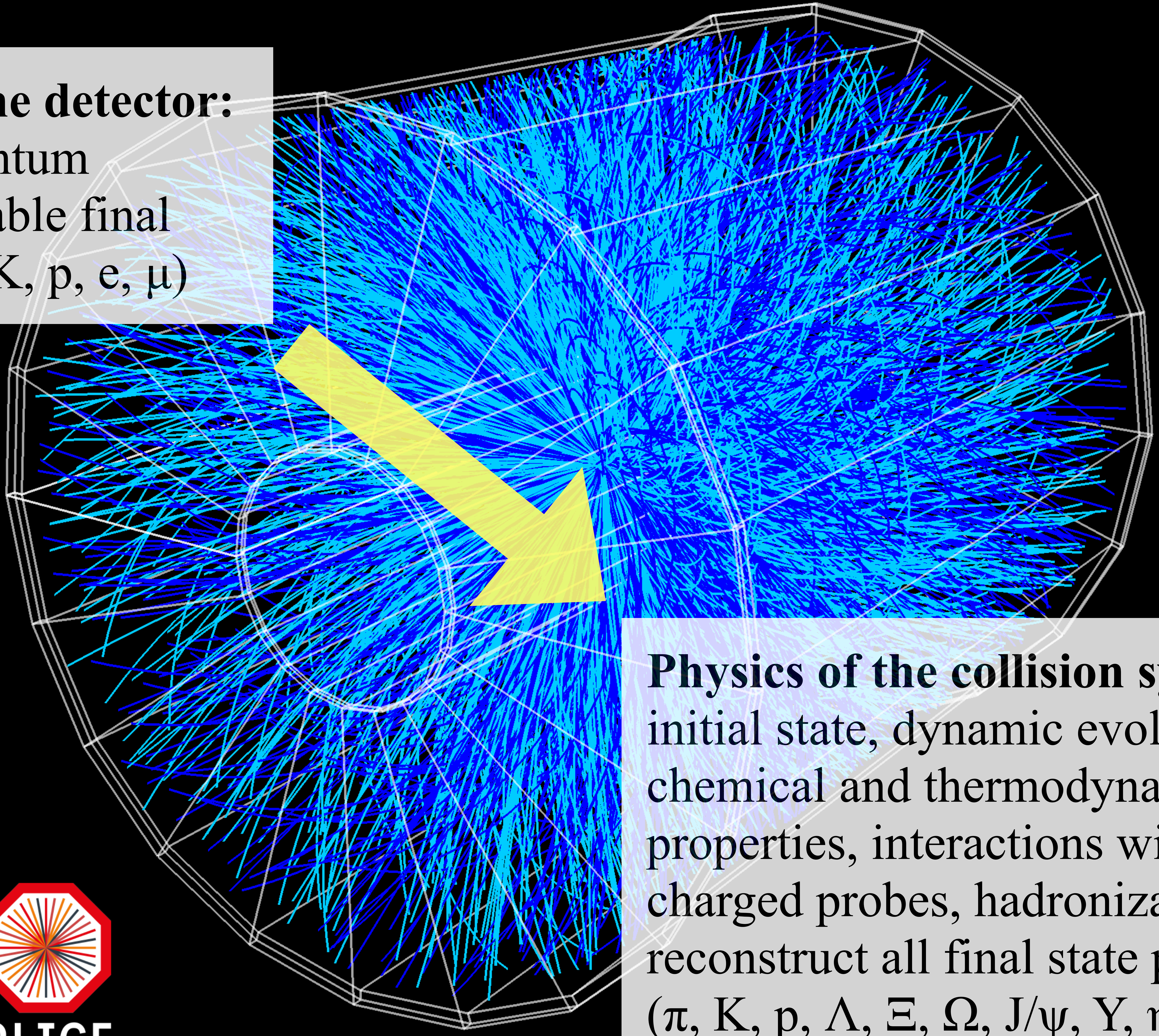
Heavy-ion detectors at RHIC



Heavy-ion detectors at the LHC


ALICE
Run: 244918
Time: 2015-11-25 10:36:18
Colliding system: Pb-Pb
Collision energy: 5.02 TeV

Observables in the detector:
spatial and momentum distributions of stable final state particles (π, K, p, e, μ)



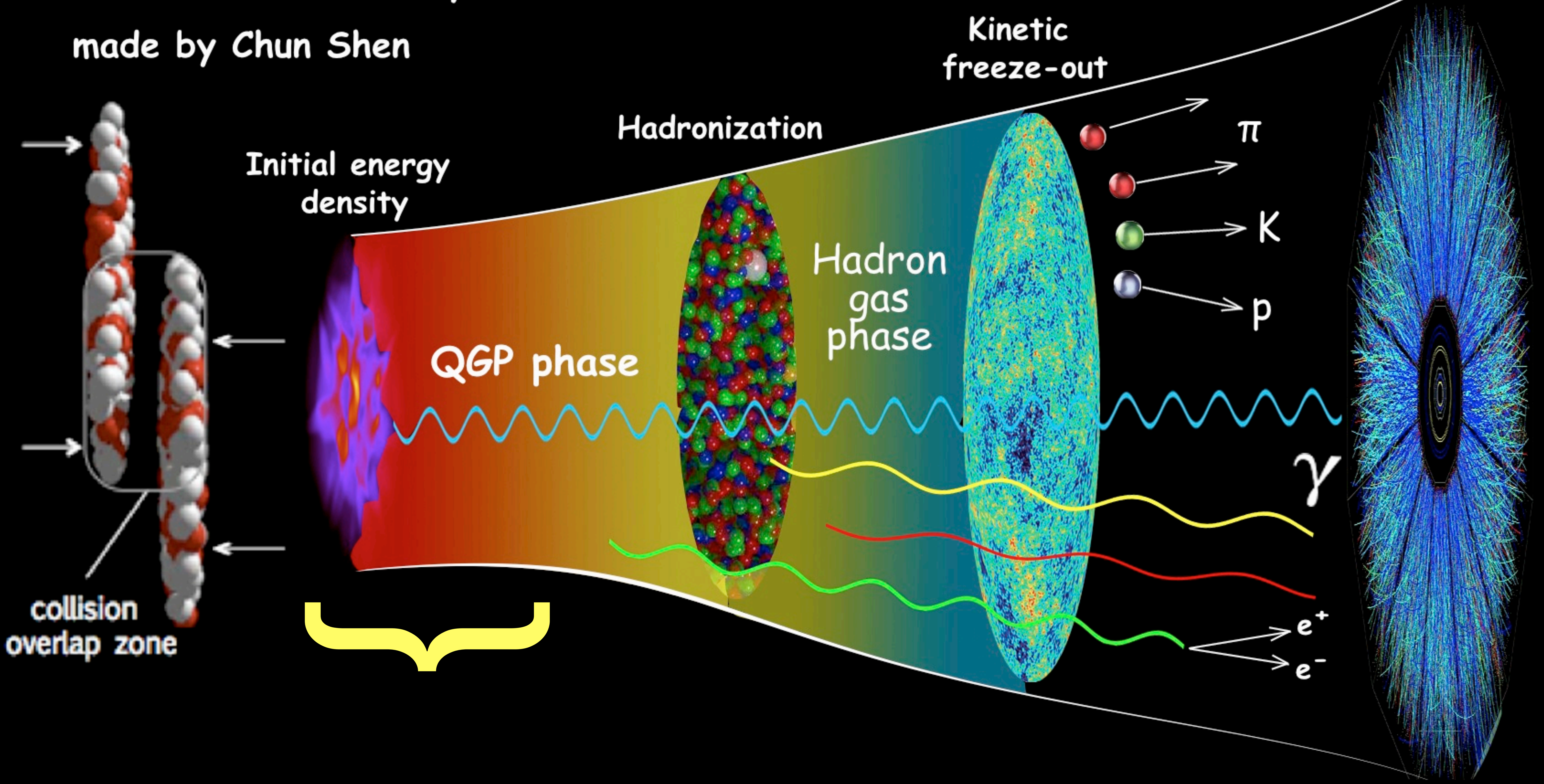
Physics of the collision system:
initial state, dynamic evolution, chemical and thermodynamic properties, interactions with charged probes, hadronization, reconstruct all final state particles (π, K, p, Λ, Ξ, Ω, J/ψ, Υ, η, ρ, γ, e, μ,…)

ALICE


Relativistic Heavy-Ion Collisions
made by Chun Shen
final detected particle distributions
Kinetic freeze-out
Hadronization
Initial energy density
collision overlap zone
QGP phase
Hadron gas phase
π
K
p
γ
e+
e-
pre-equilibrium dynamics
viscous hydrodynamics
free streaming
collision evolution
τ ~ 0 fm/c
τ ~ 1 fm/c
τ ~ 10 fm/c
τ ~ 10^15 fm/c

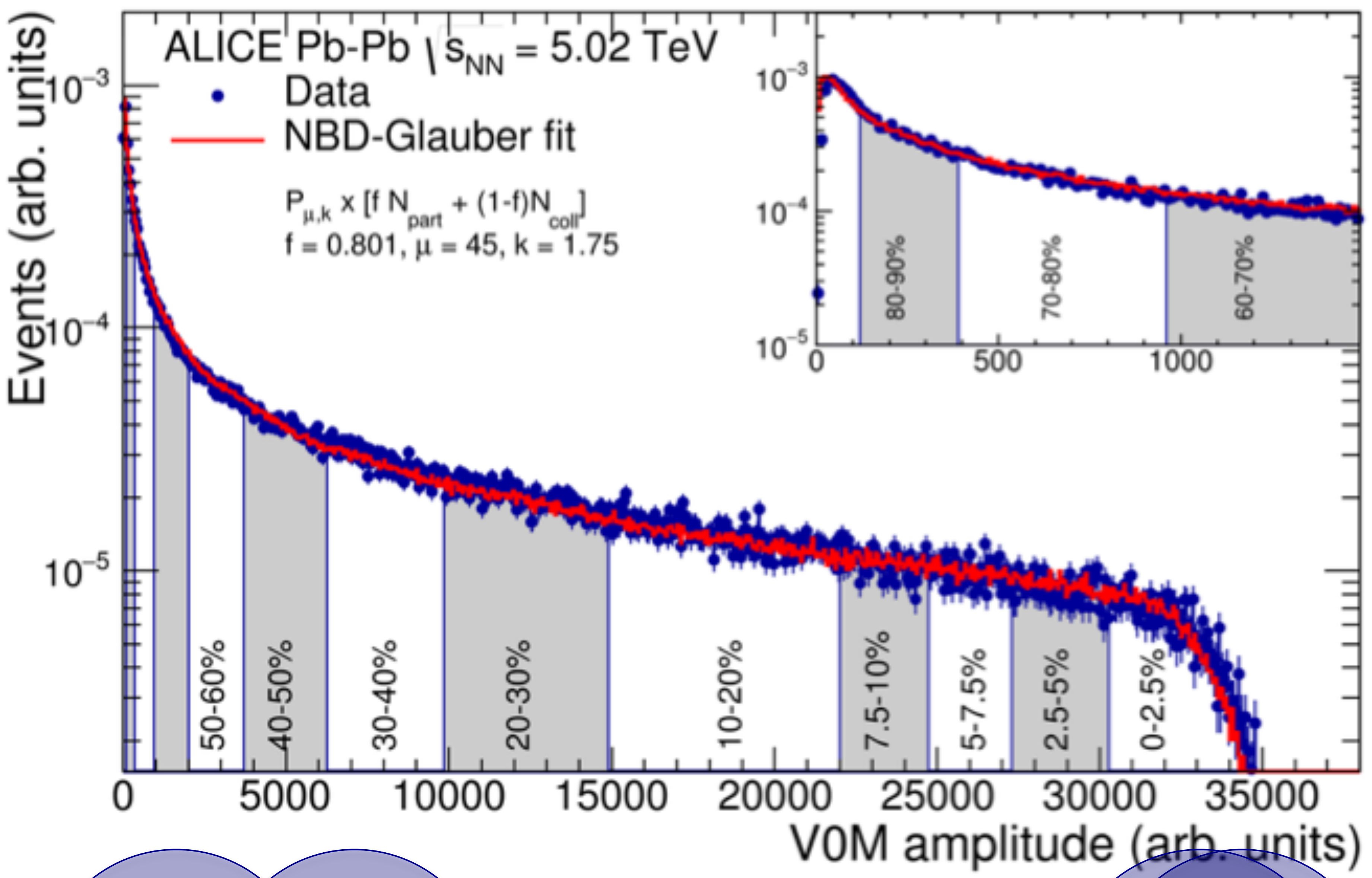
Relativistic Heavy-Ion Collisions

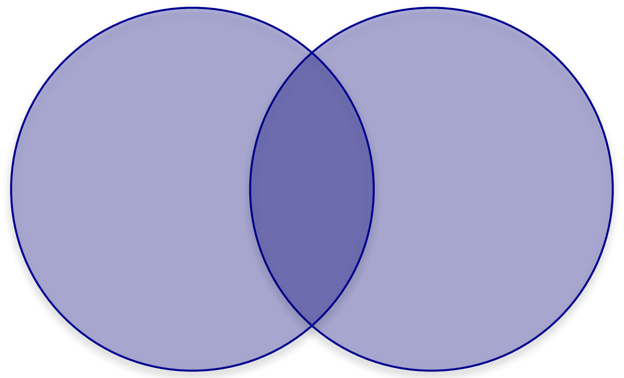
made by Chun Shen



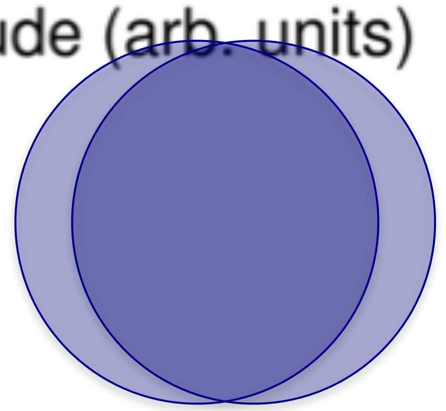
Geometry of a heavy-ion collision

- Centrality: amount of overlap of the colliding nuclei



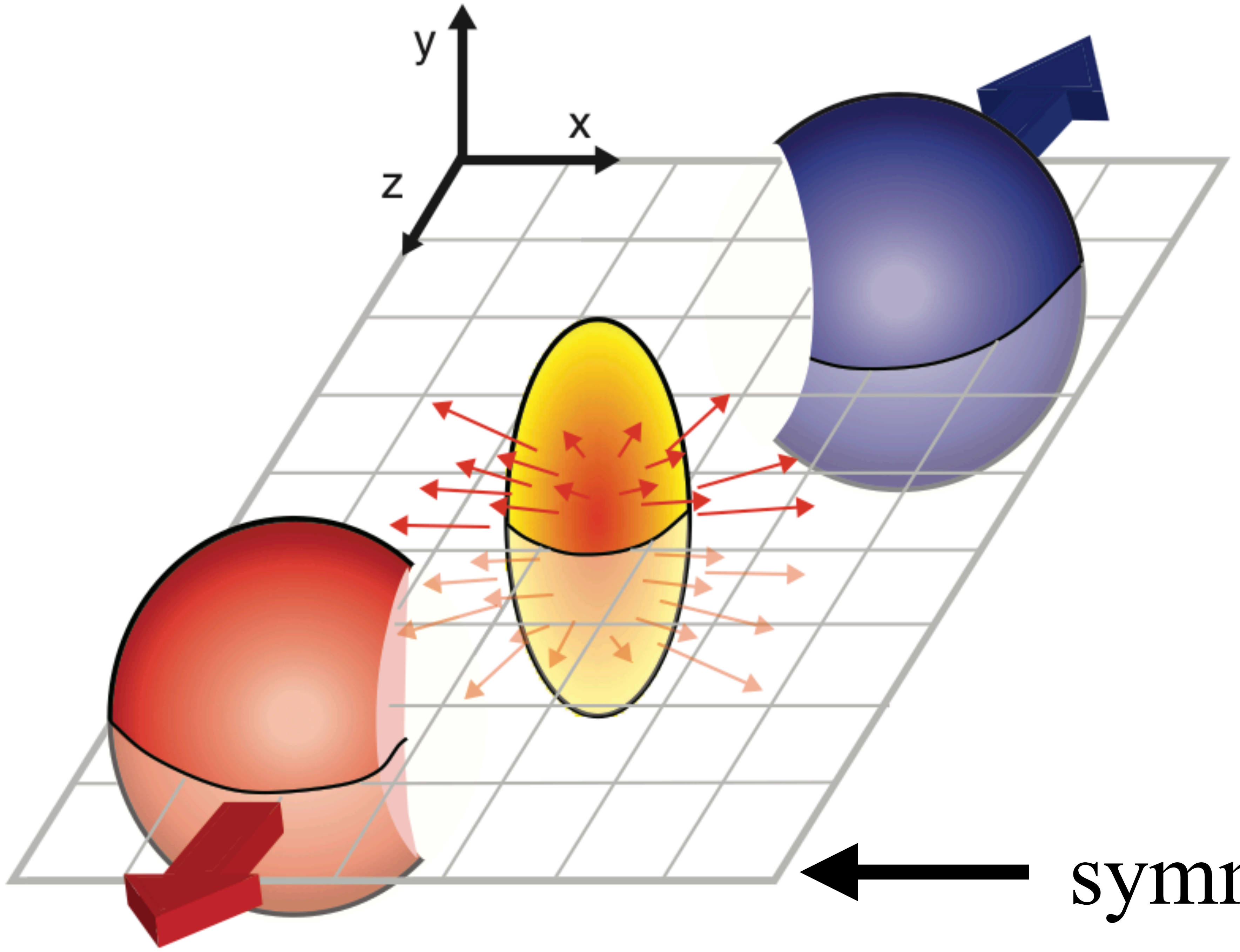


“peripheral”



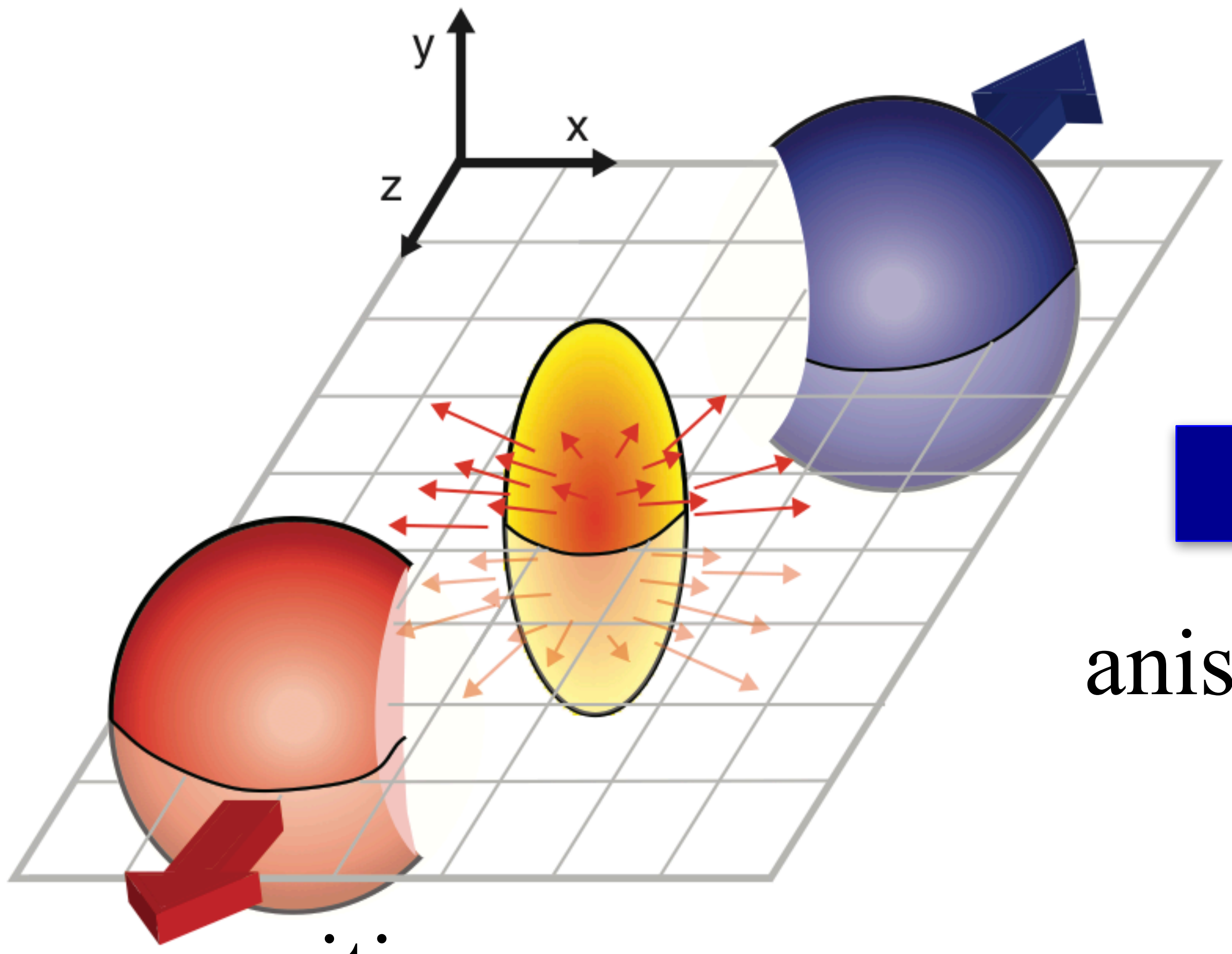
“central”

- Peripheral events are not rotationally-symmetric
- Anisotropic interaction region



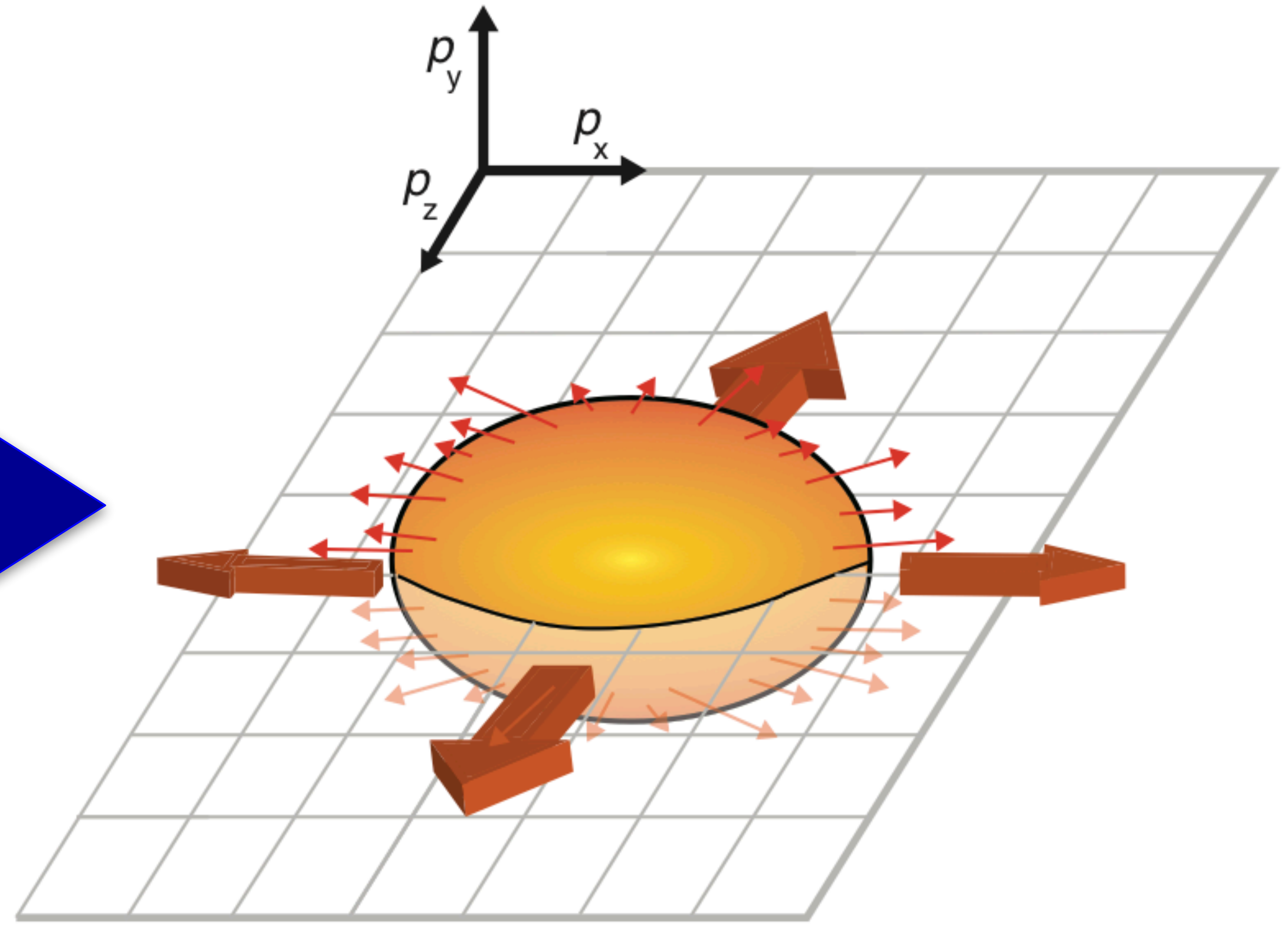
symmetry plane

Anisotropic interaction region



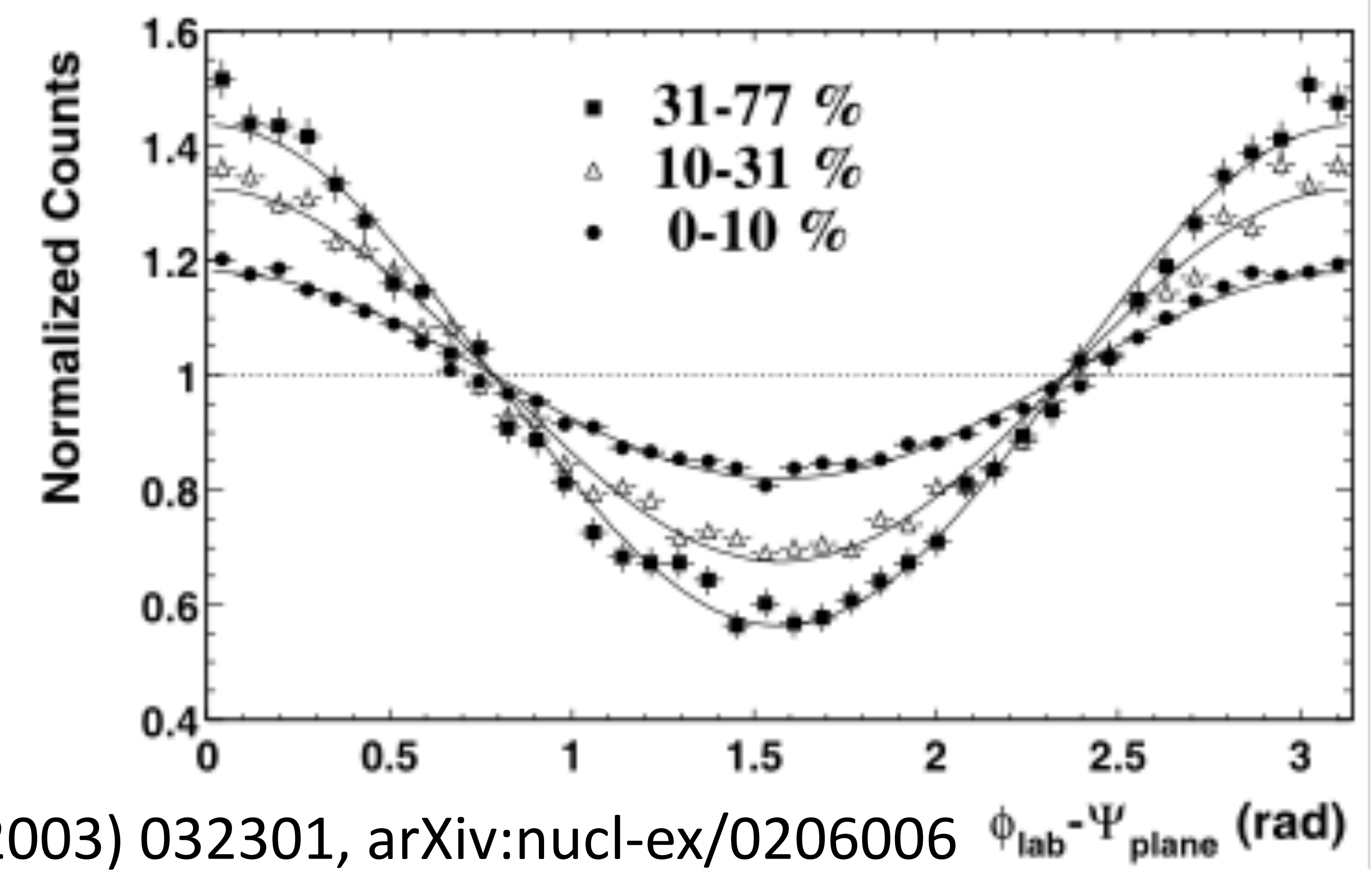
position-space anisotropy

anisotropic pressure gradients

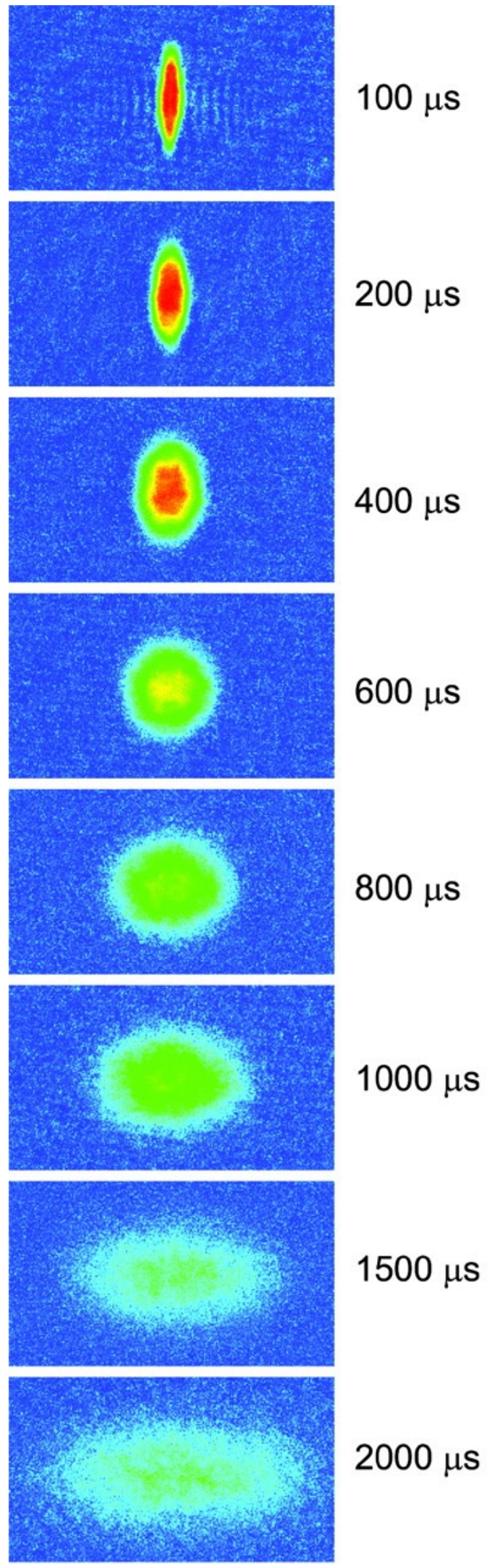


momentum-space anisotropy

- Stronger in-plane pressure gradients
  → particles boosted in-plane more than out-of-plane



STAR, PRL 90 (2003) 032301, arXiv:nucl-ex/0206006



Elliptic Flow in Ultracold Lithium

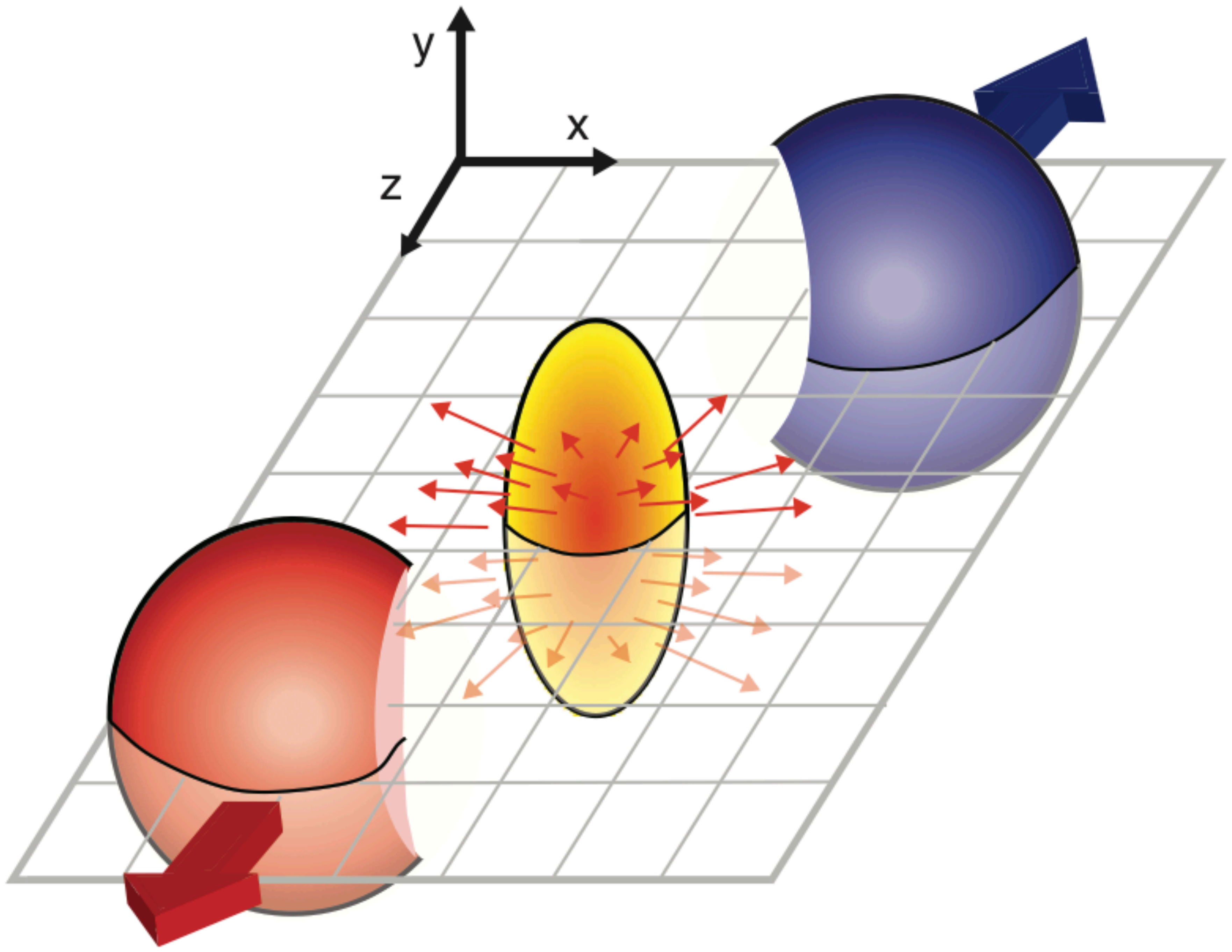
K.M. O'Hara et al., Science, 13 Dec 2002: 2179-2182

Anisotropic flow coefficients

- Particle distribution described by a Fourier cosine series

$$dN/d\varphi \sim 1 + 2v_2\cos(2(\varphi-\Psi_2))$$

- $v_2 \rightarrow$ "elliptic flow"



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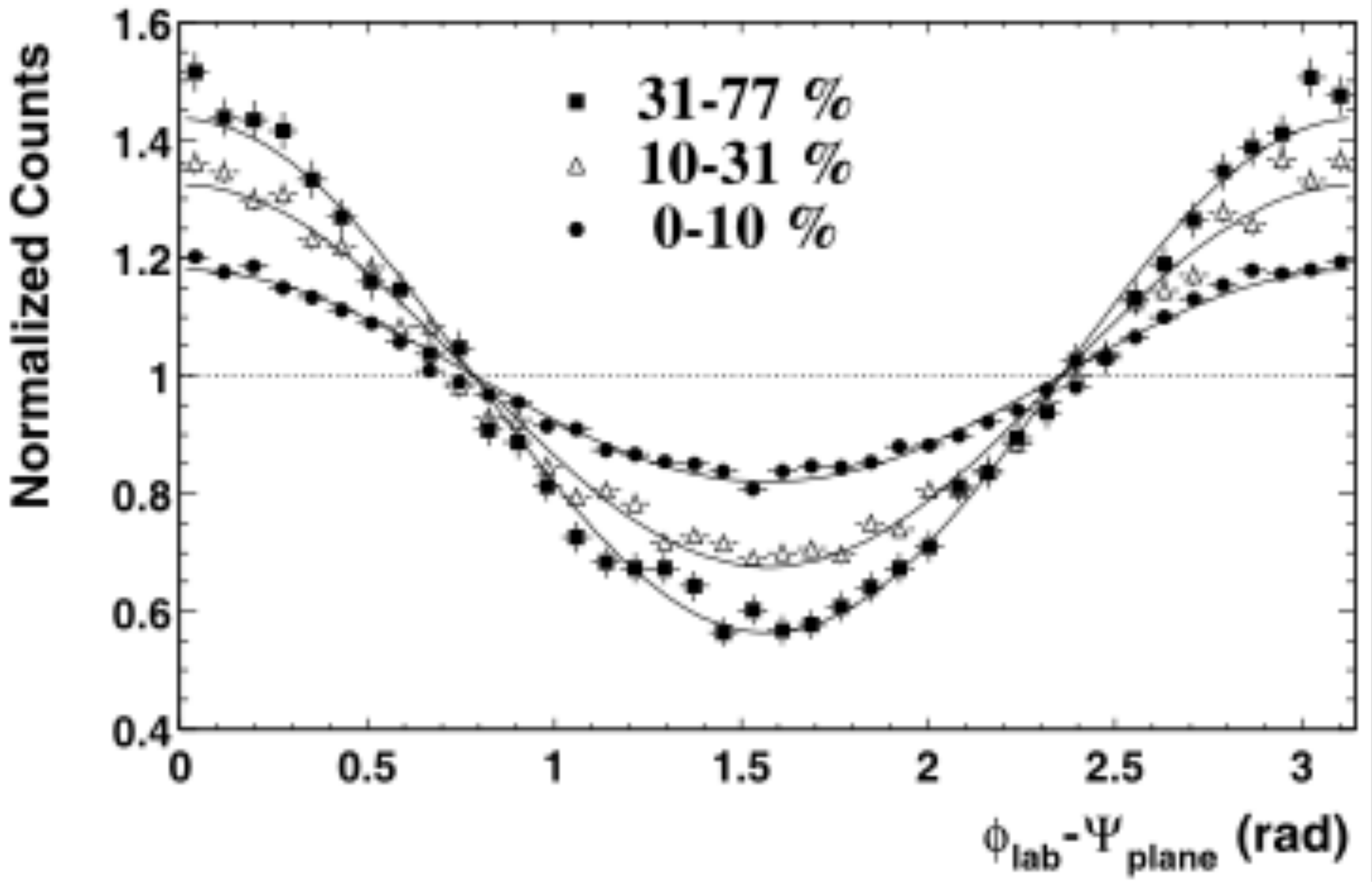


Anisotropic flow coefficients

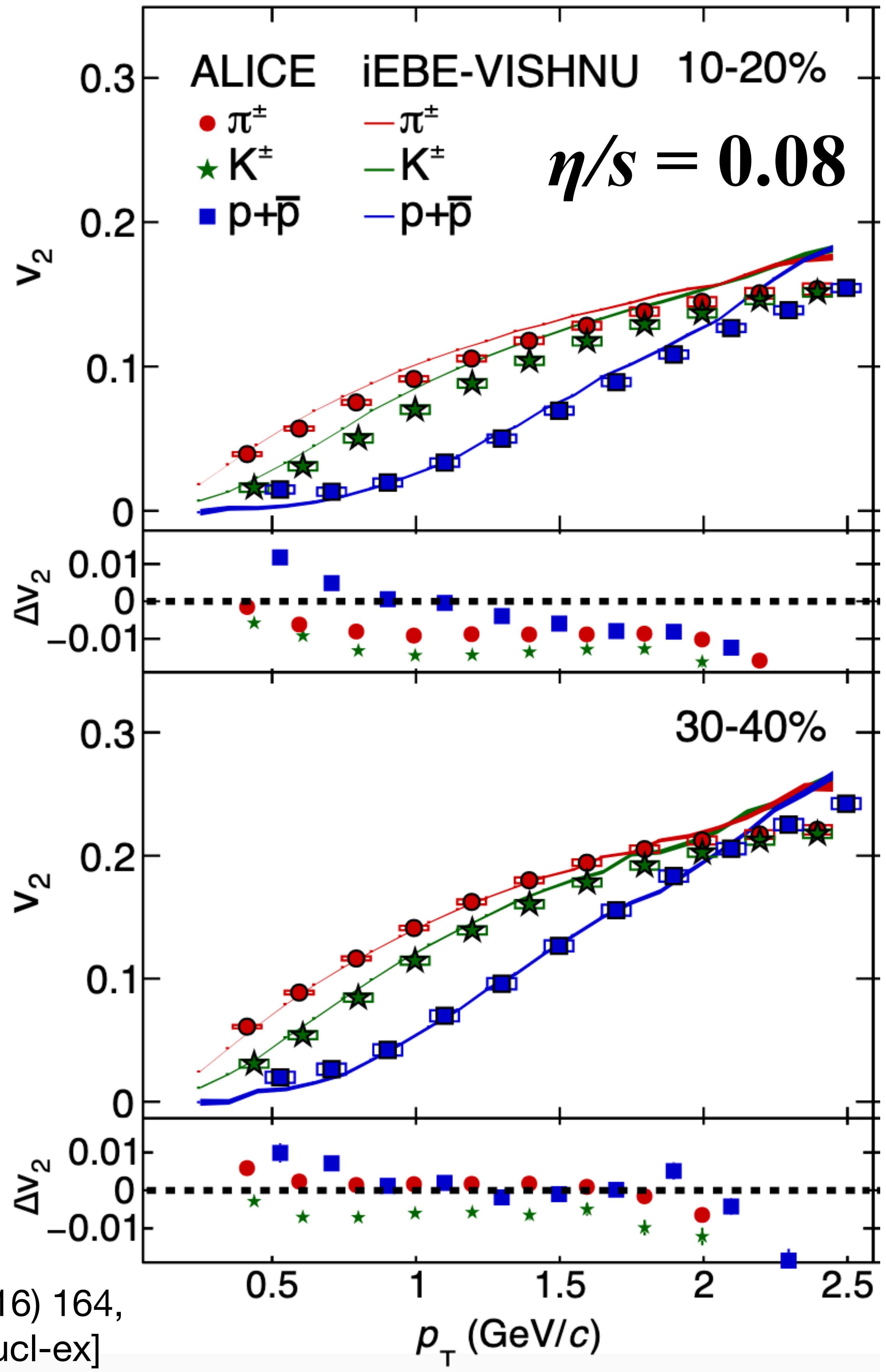
- Particle distribution described by a Fourier cosine series

$$dN/d\varphi \sim 1 + 2v_2\cos(2(\varphi-\Psi_2))$$

- v_2 → "elliptic flow"

- Measurements of v_2 are described very well by hydrodynamic models → QGP behaves as a liquid!

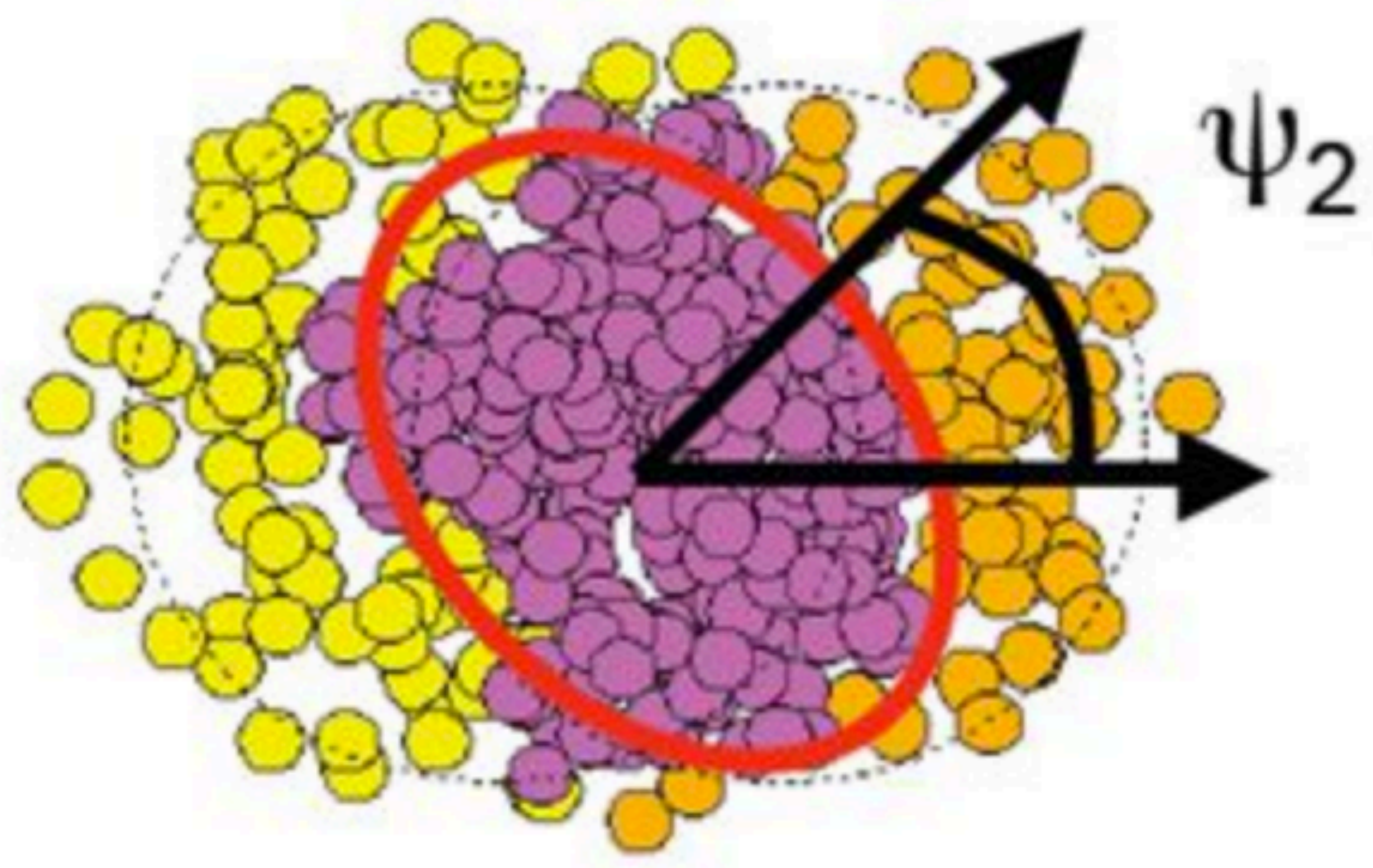
- Viscosity (η/s) is near quantum lower bound → QGP is the "perfect liquid"

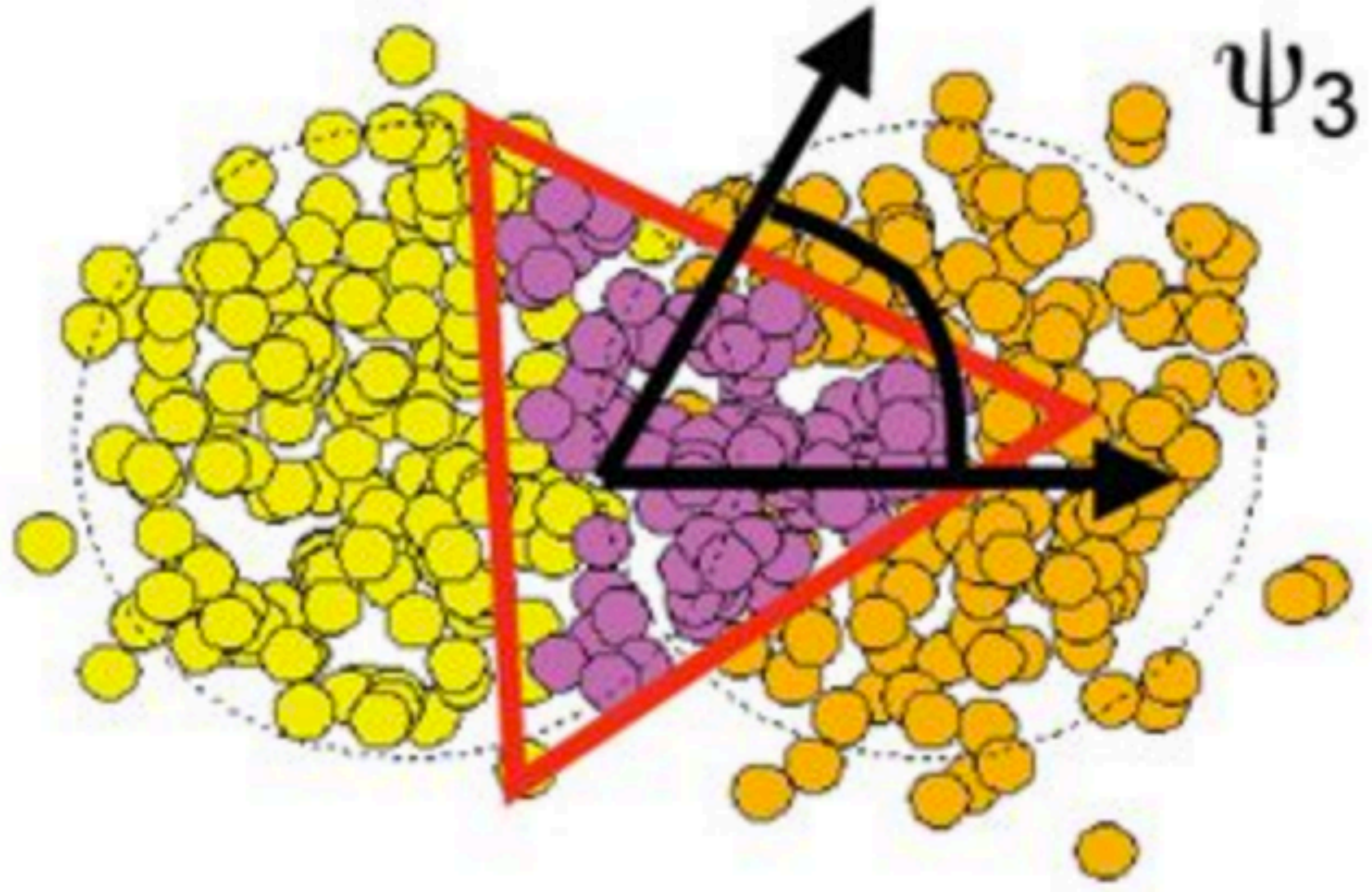


ALICE, JHEP 09 (2016) 164, arXiv:1606.06057 [nucl-ex]

Higher-order flow coefficients

- Due to event-by-event fluctuations of the positions of nucleons, overlap region is not perfectly symmetric
  → development of triangular flow v_3, quadrangular flow v_4,...





Higher-order flow coefficients

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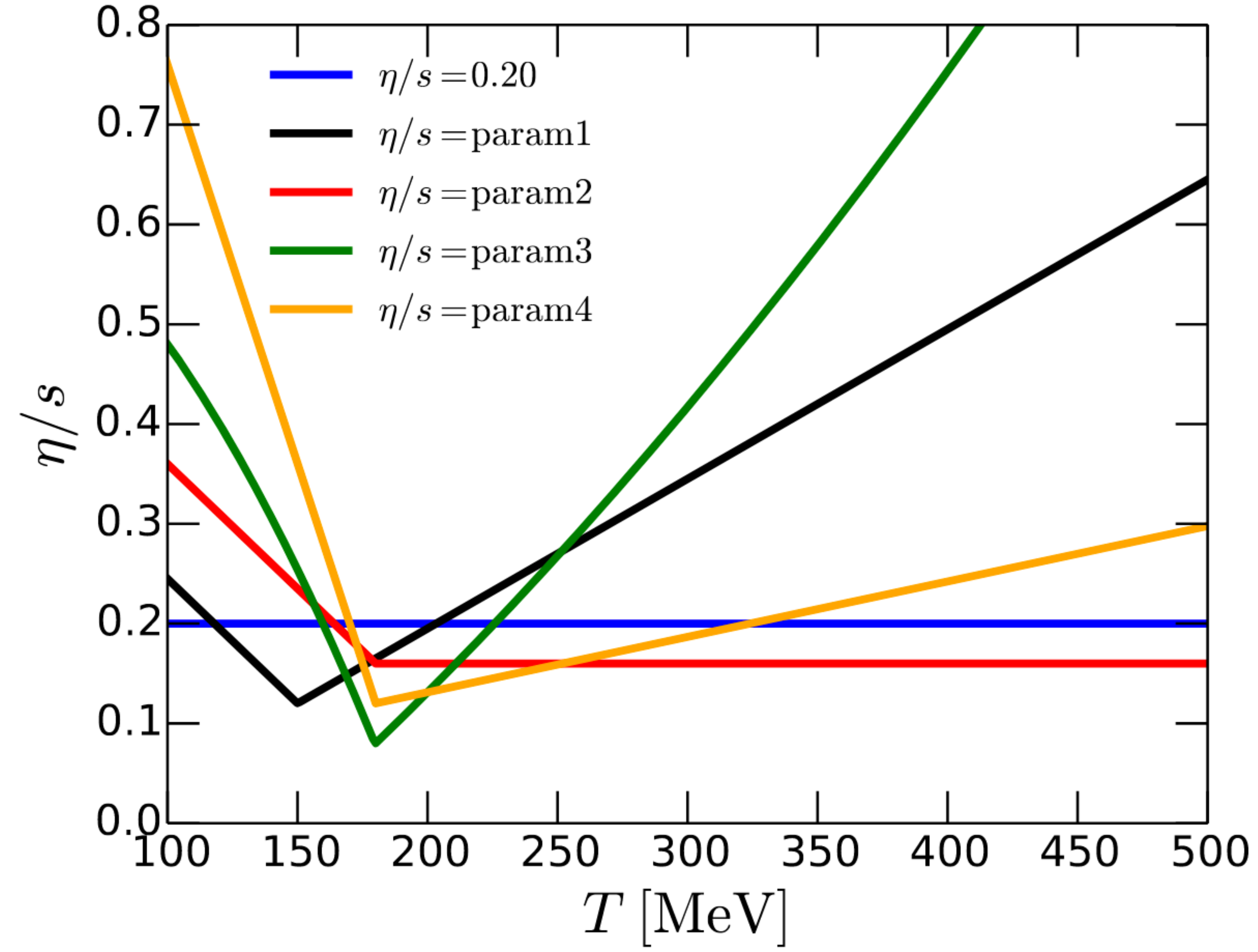
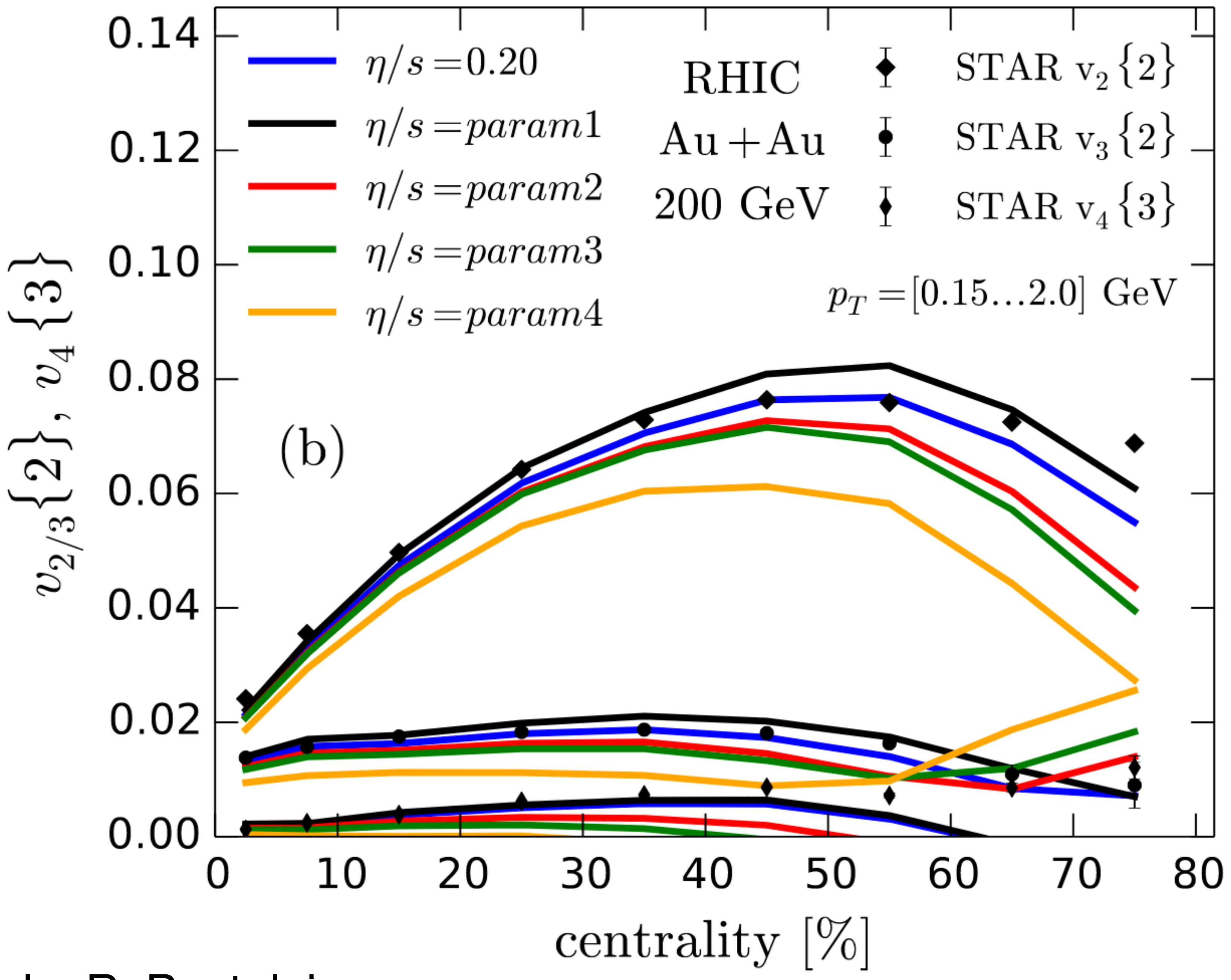
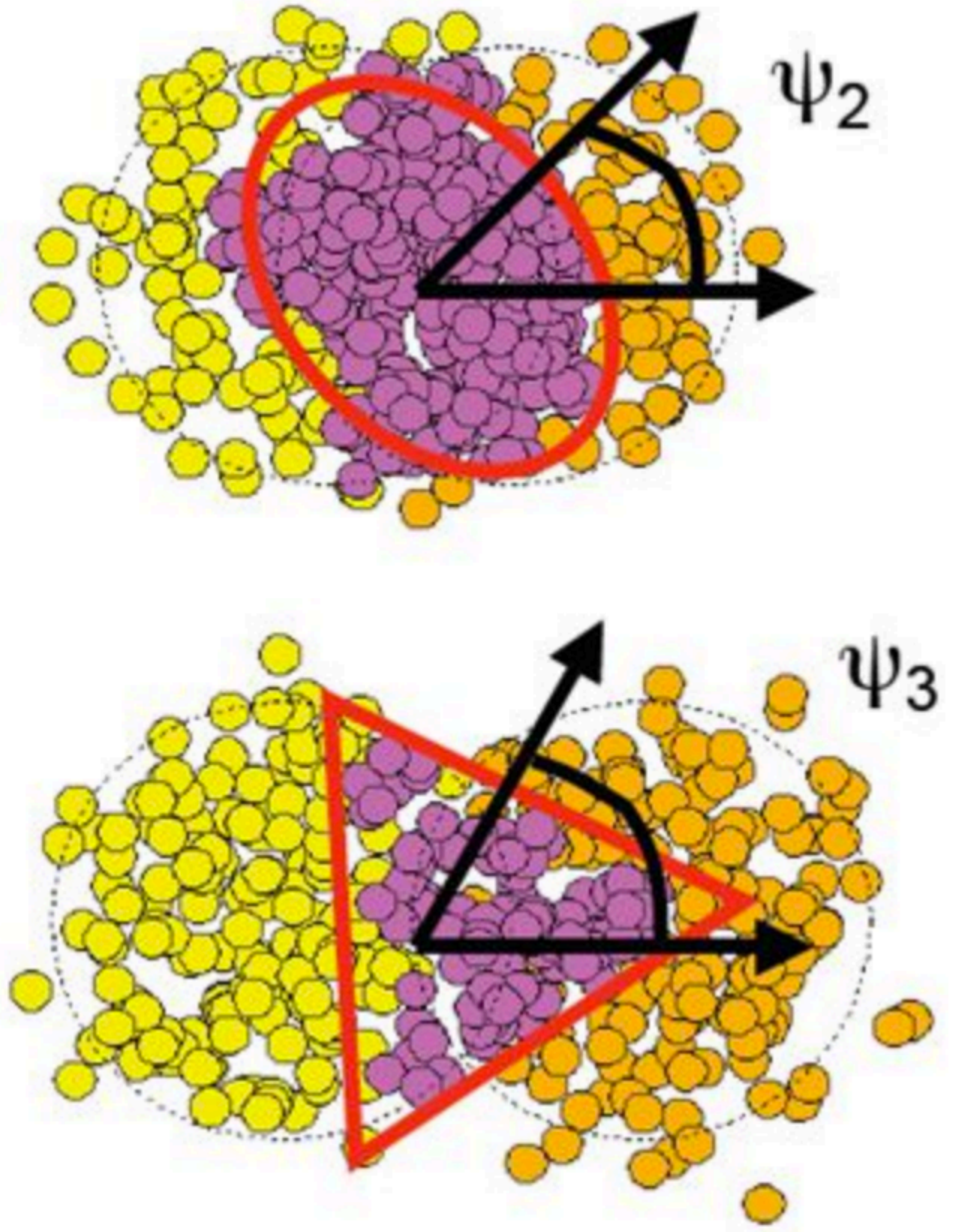
  → development of triangular flow v_3, quadrangular flow v_4,...
- Higher harmonics are sensitive to hydrodynamic properties and dynamics of the QGP



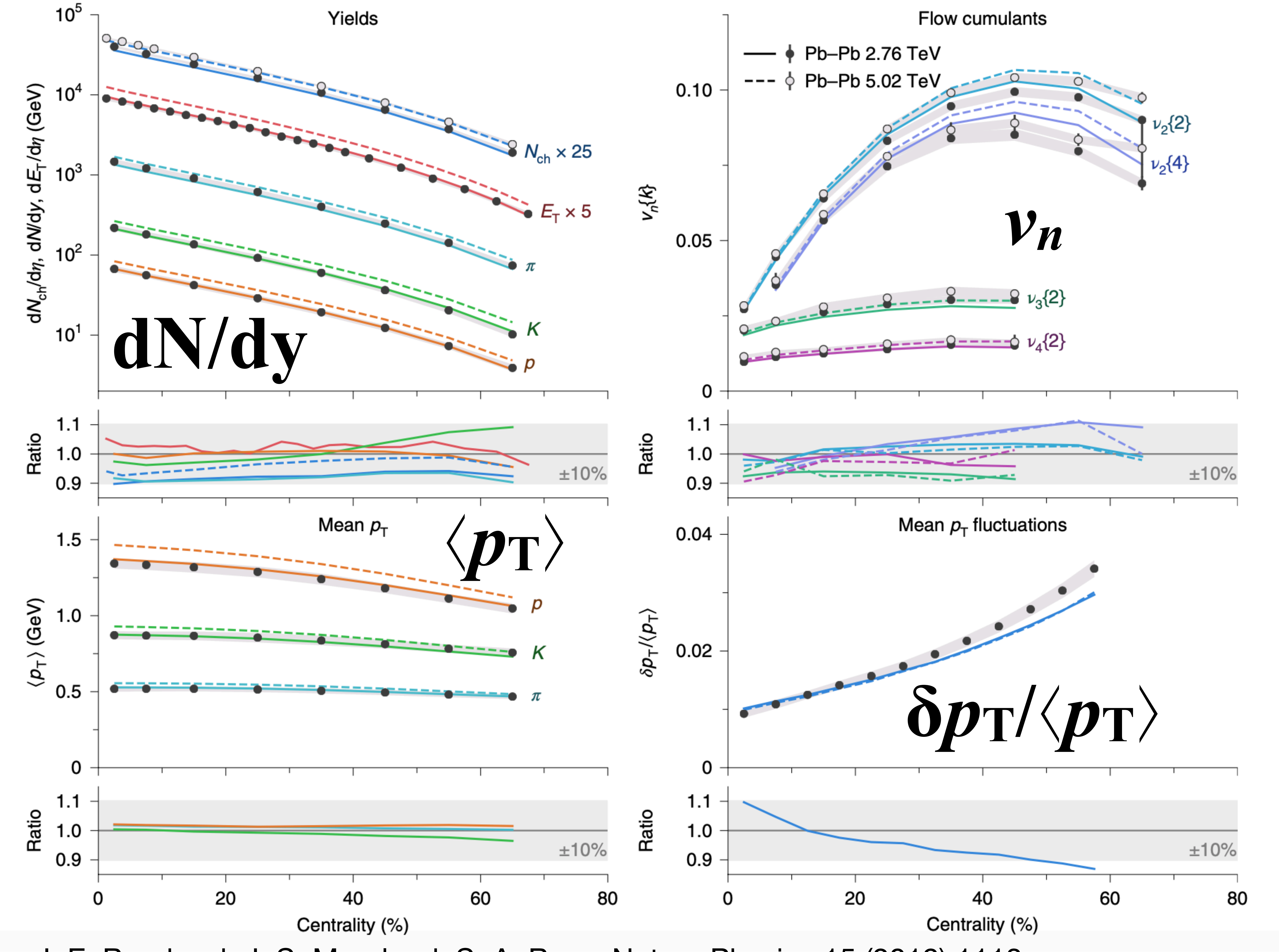




H. Niemi, K.J. Eskola, R. Paatelainen,
PRC 93 (2016) 024907,
arXiv:1505.02677 [hep-ph]

Extracting QGP properties with flow

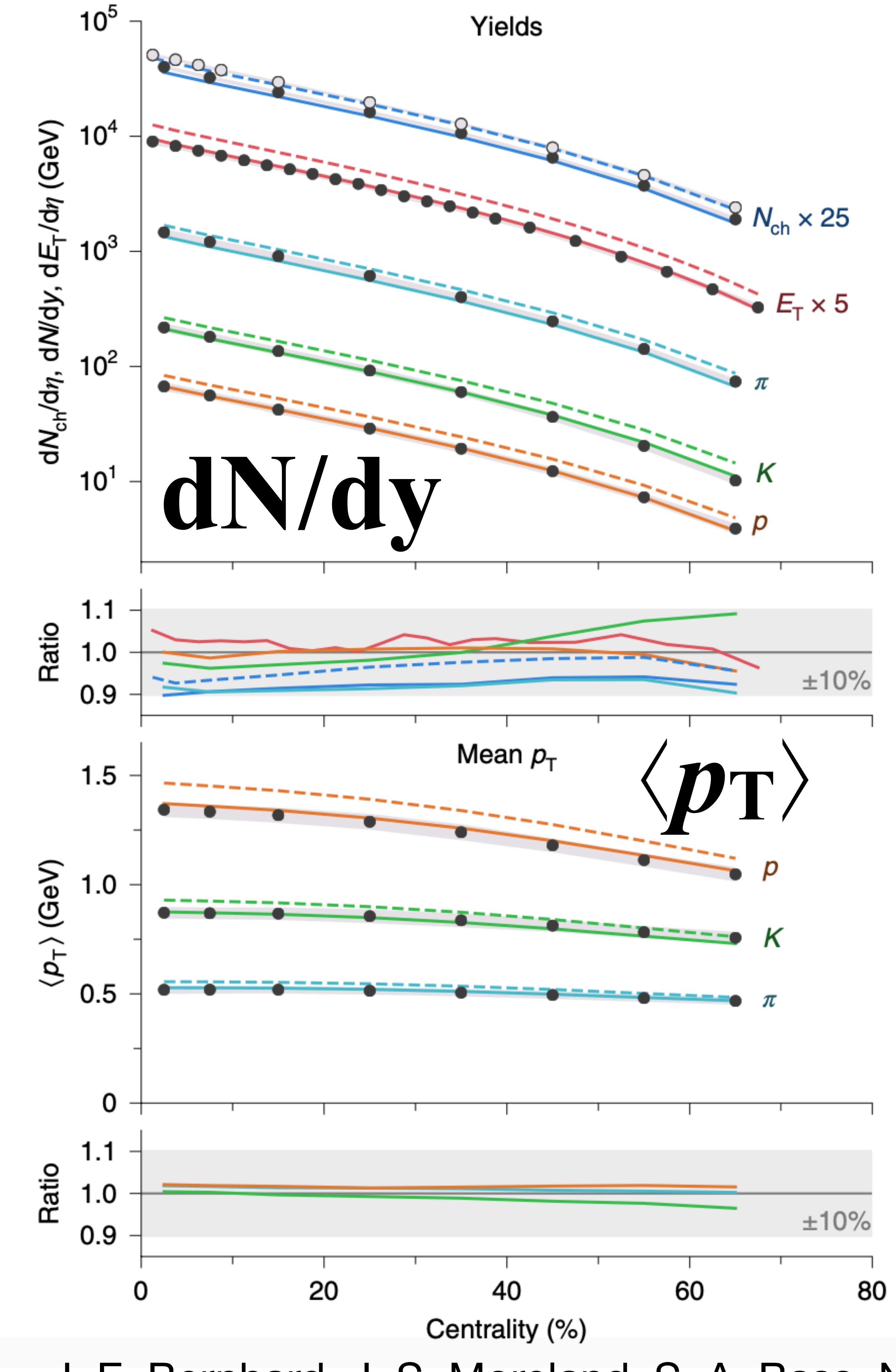
- Bayesian analysis of particle yields, mean p_T, v_2, v_3, v_4 measured by ALICE

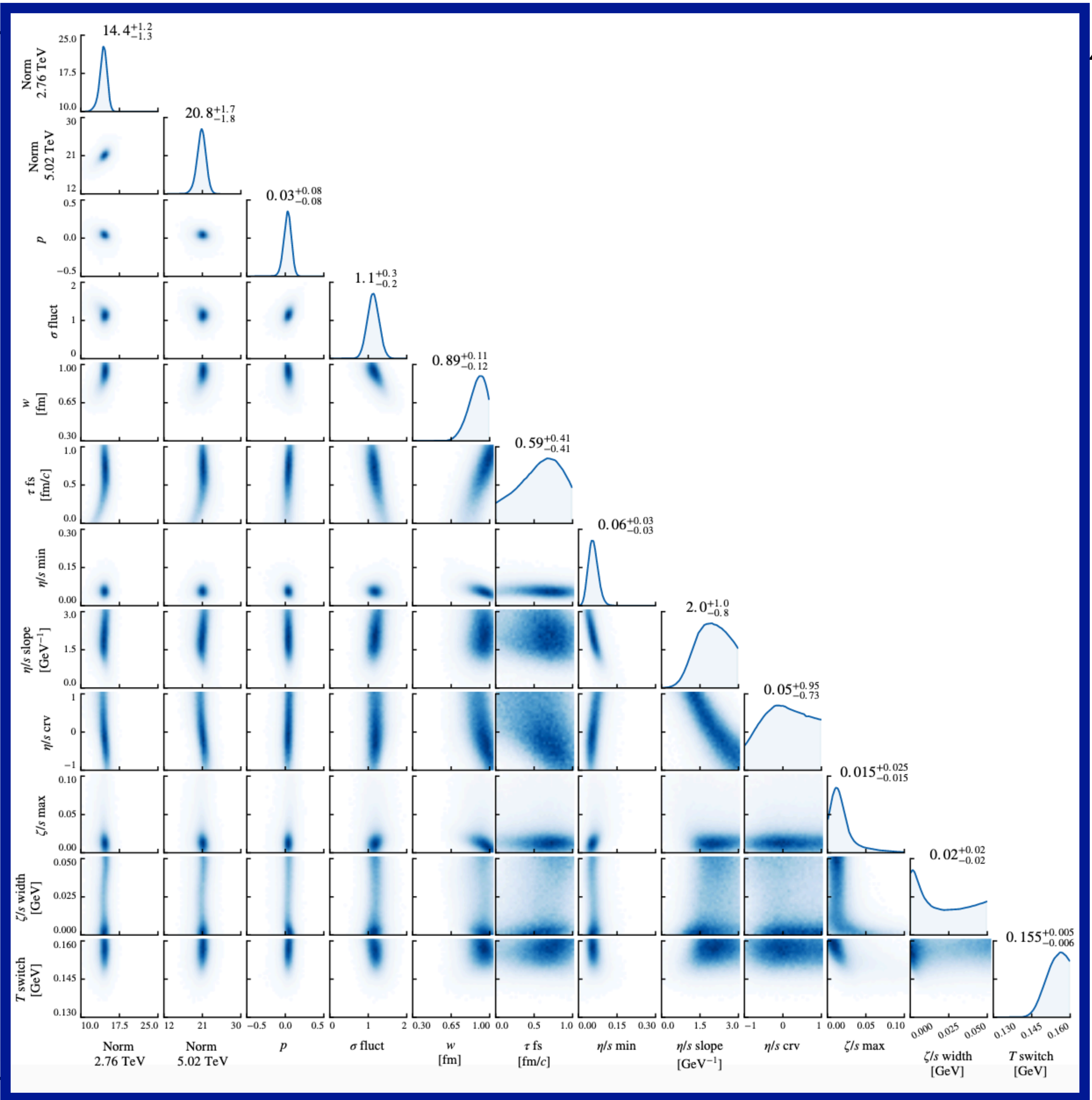


J. E. Bernhard, J. S. Moreland, S. A. Bass, Nature Physics 15 (2019) 1113
J. S. Moreland, J. E. Bernhard, S. A. Bass, Phys. Rev. C 101 (2020) 024911, arXiv:1808.02106 [nucl-th]

Extracting QGP properties with flow

- Bayesian analysis of par … ALICE





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J. S. Moreland, J. E. Bernhard, S. A. Bass, Phys. Rev. C 101 (2020) 024911, arXiv:1808.02106 [nucl-th]

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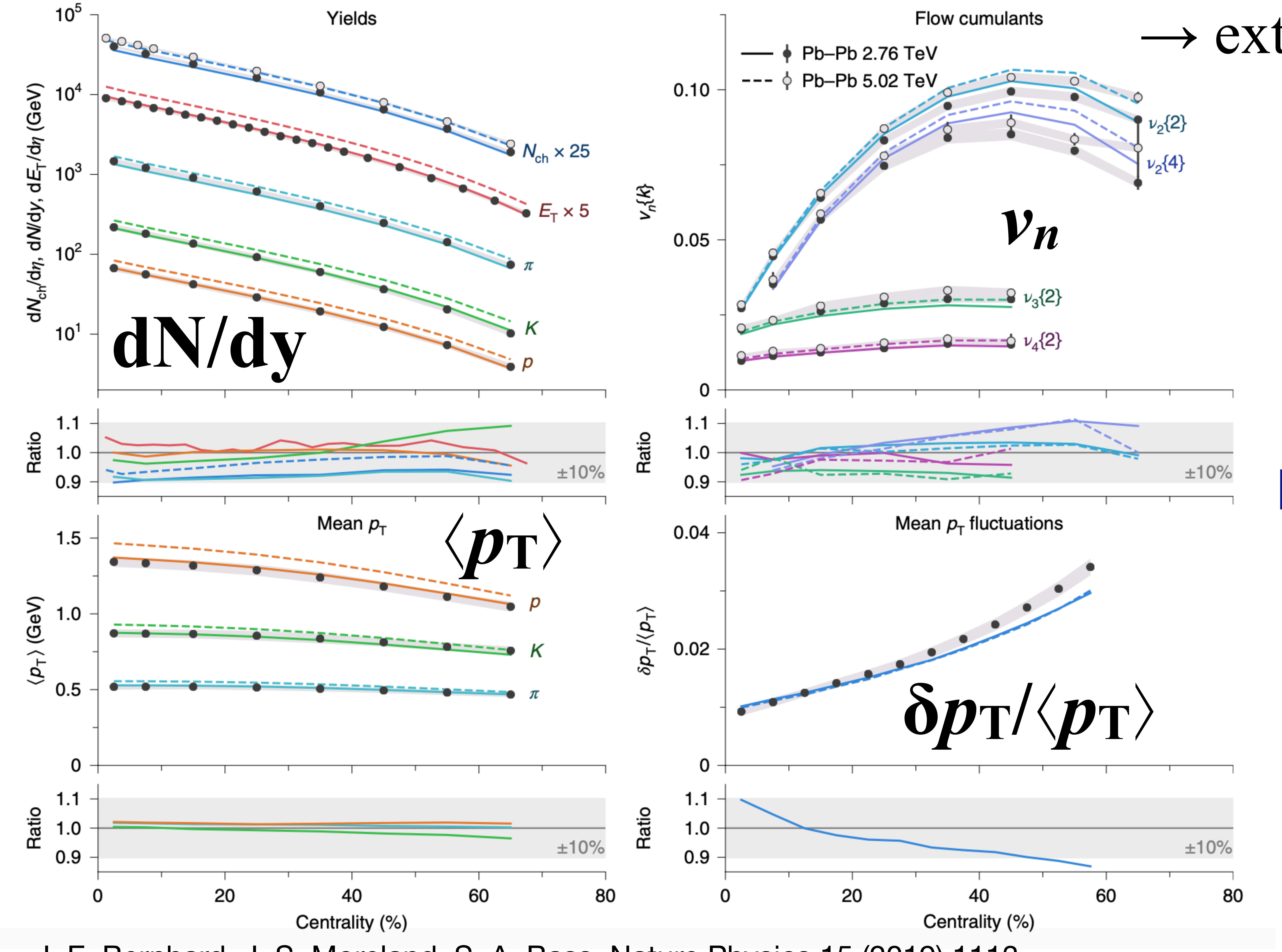
  → extract shear and bulk viscosity $\eta/s(T)$, $\zeta/s(T)$



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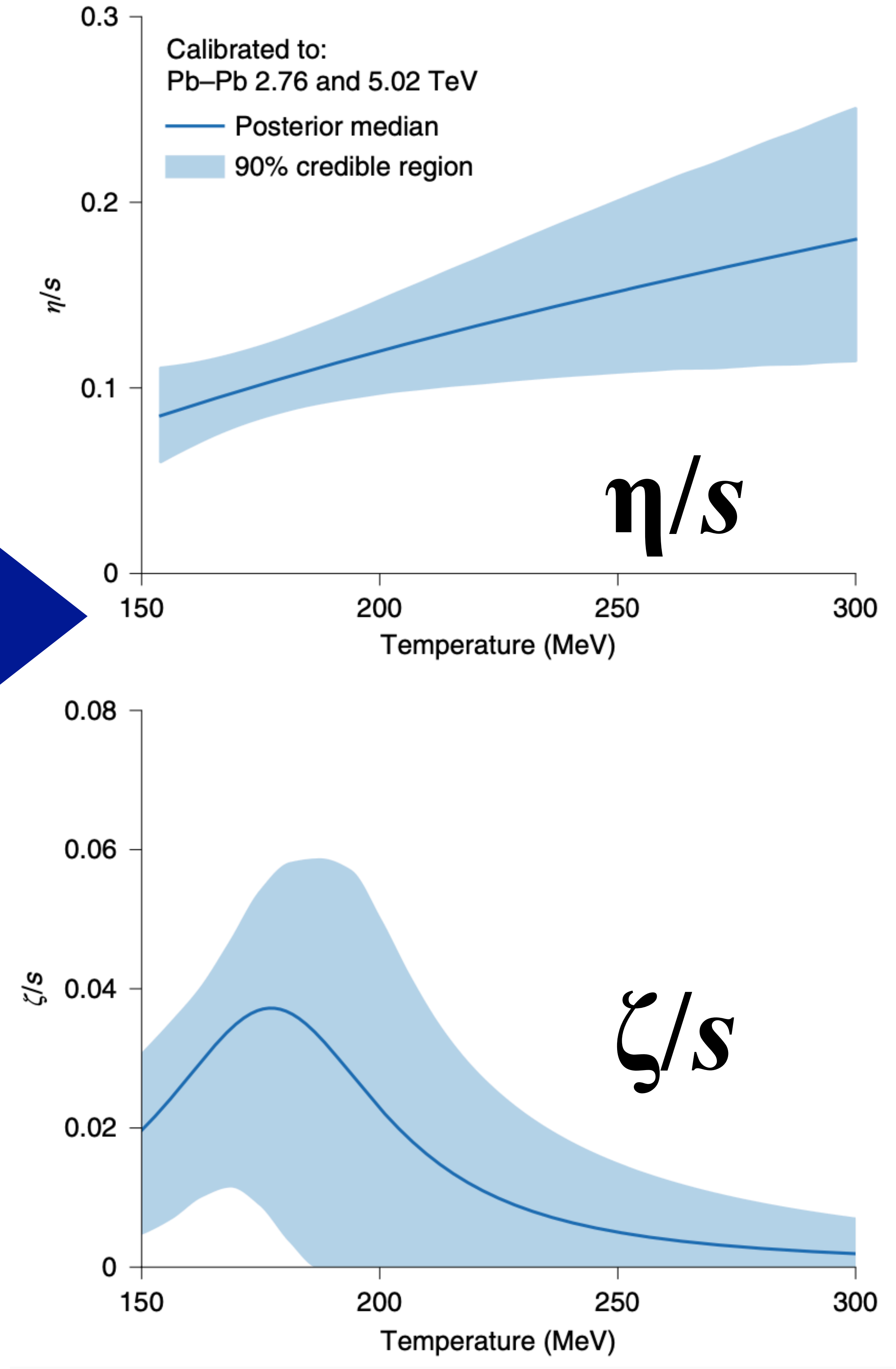

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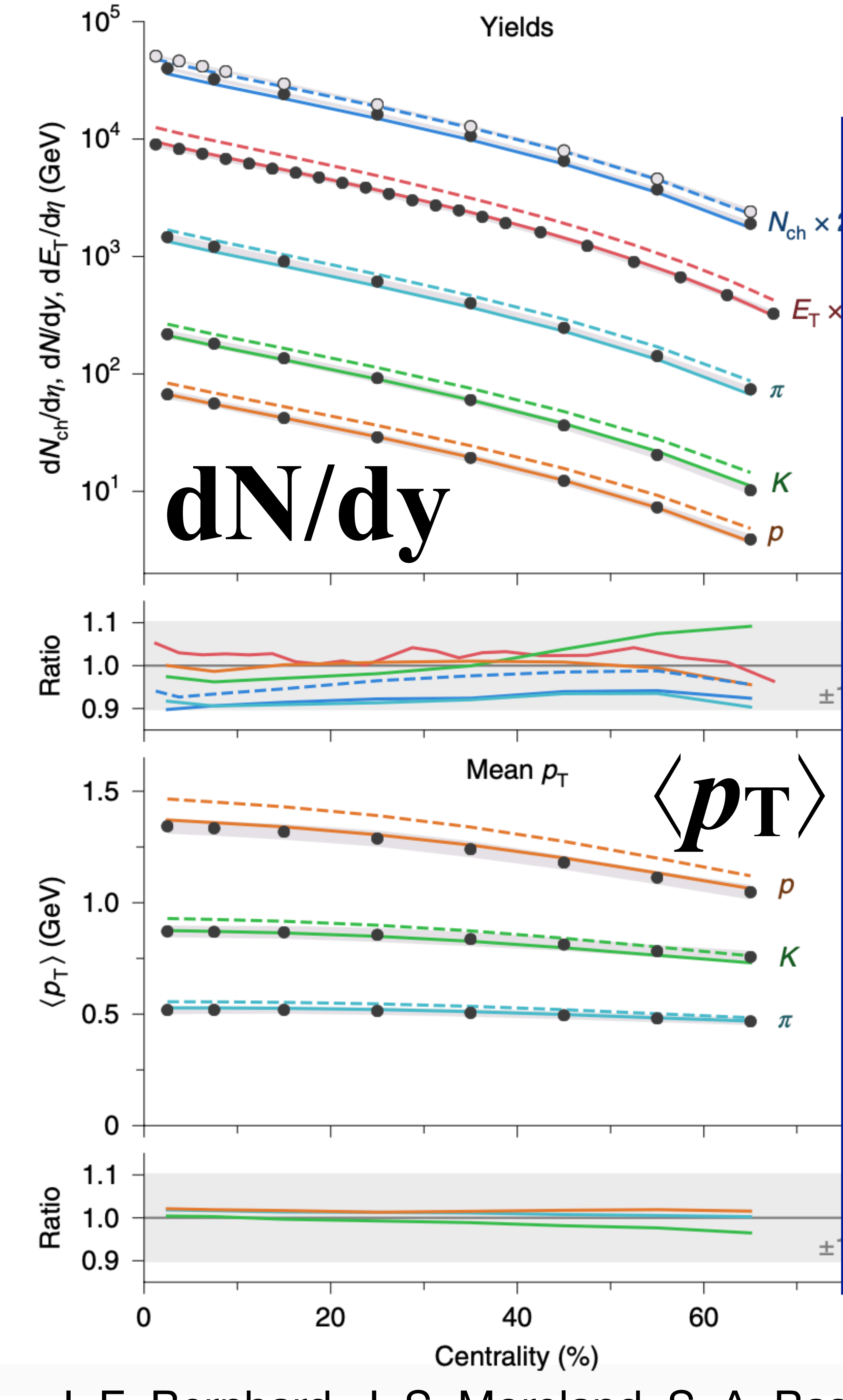

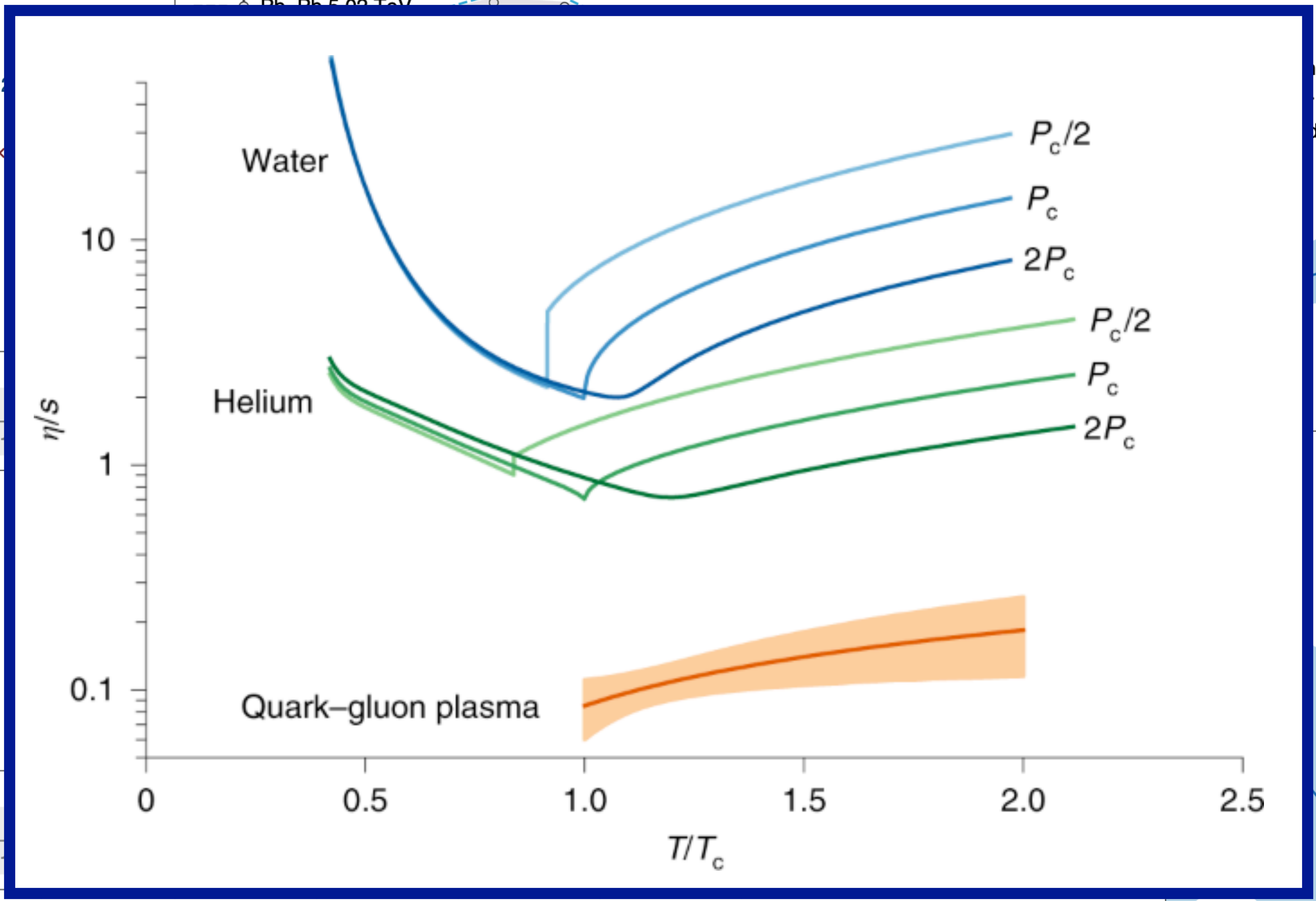

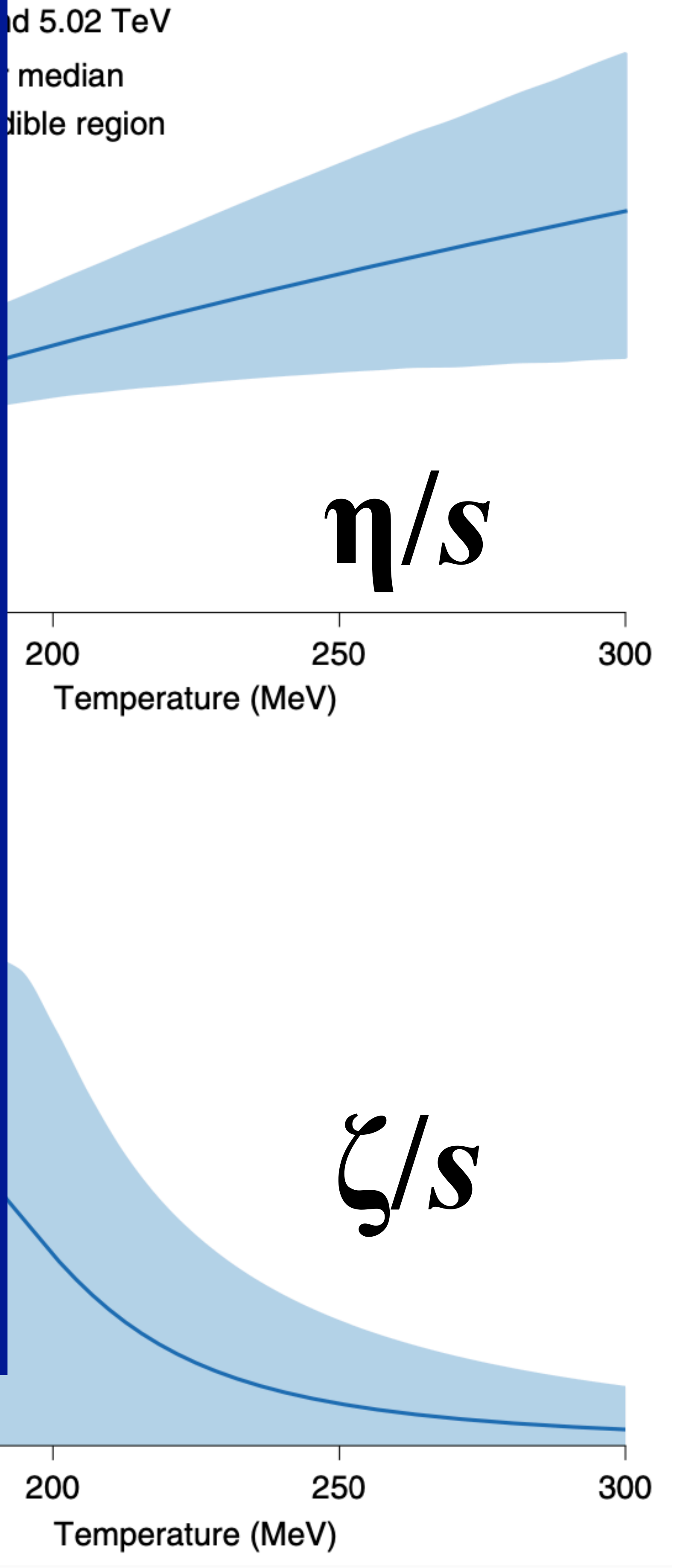

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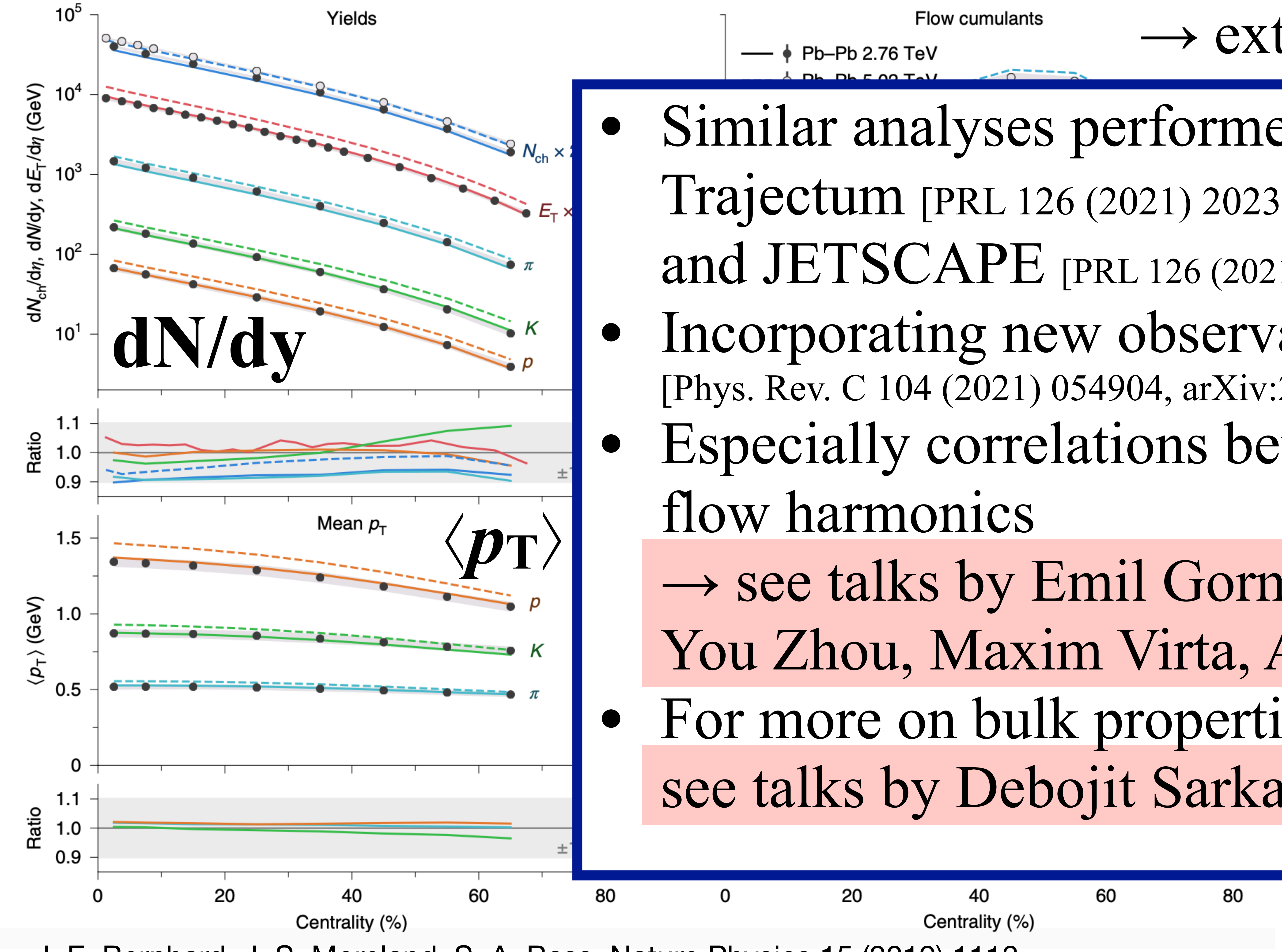
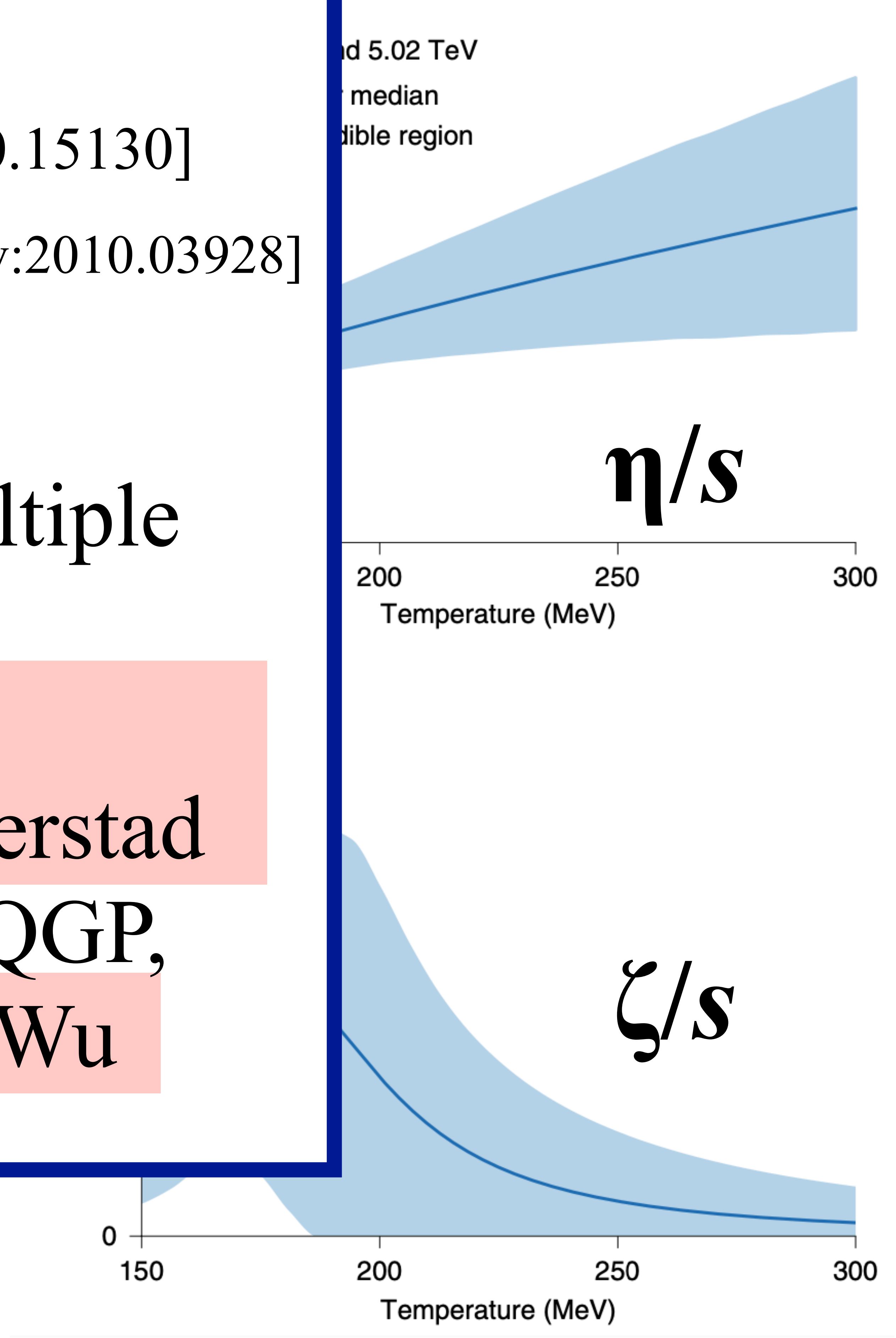


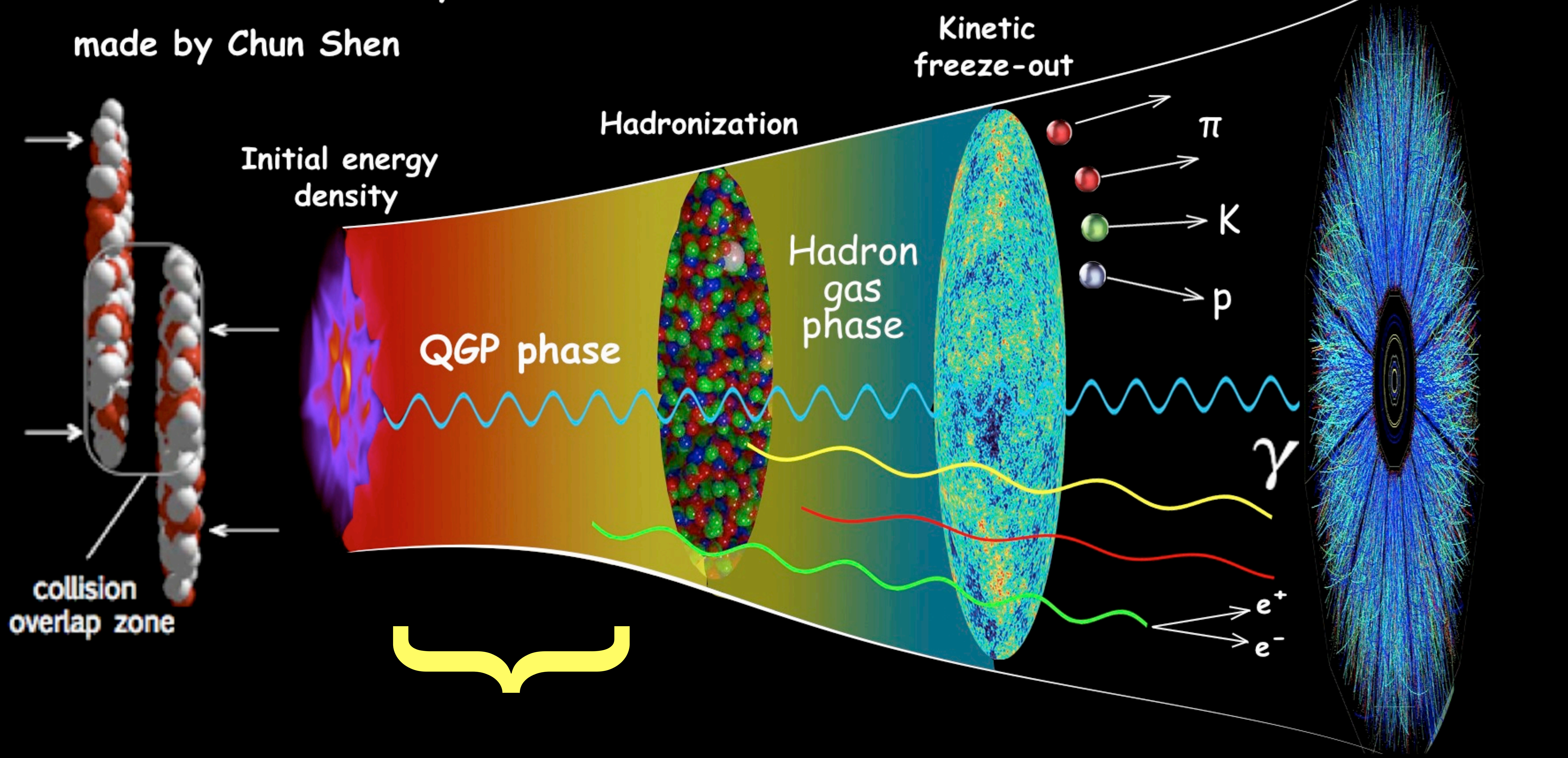


- Similar analyses performed using Trajectum [PRL 126 (2021) 202301, arXiv:2010.15130] and JETSCAPE [PRL 126 (2021) 242301, arXiv:2010.03928]
- Incorporating new observables [Phys. Rev. C 104 (2021) 054904, arXiv:2106.05019]
- Especially correlations between multiple flow harmonics
  → see talks by Emil Gorm Nielsen, You Zhou, Maxim Virta, Anna Önnerstad
- For more on bulk properties of the QGP, see talks by Debojit Sarkar, Wenya Wu

J. E. Bernhard, J. S. Moreland, S. A. Bass, Nature Physics 15 (2019) 1113
J. S. Moreland, J. E. Bernhard, S. A. Bass, Phys. Rev. C 101 (2020) 024911, arXiv:1808.02106 [nucl-th]

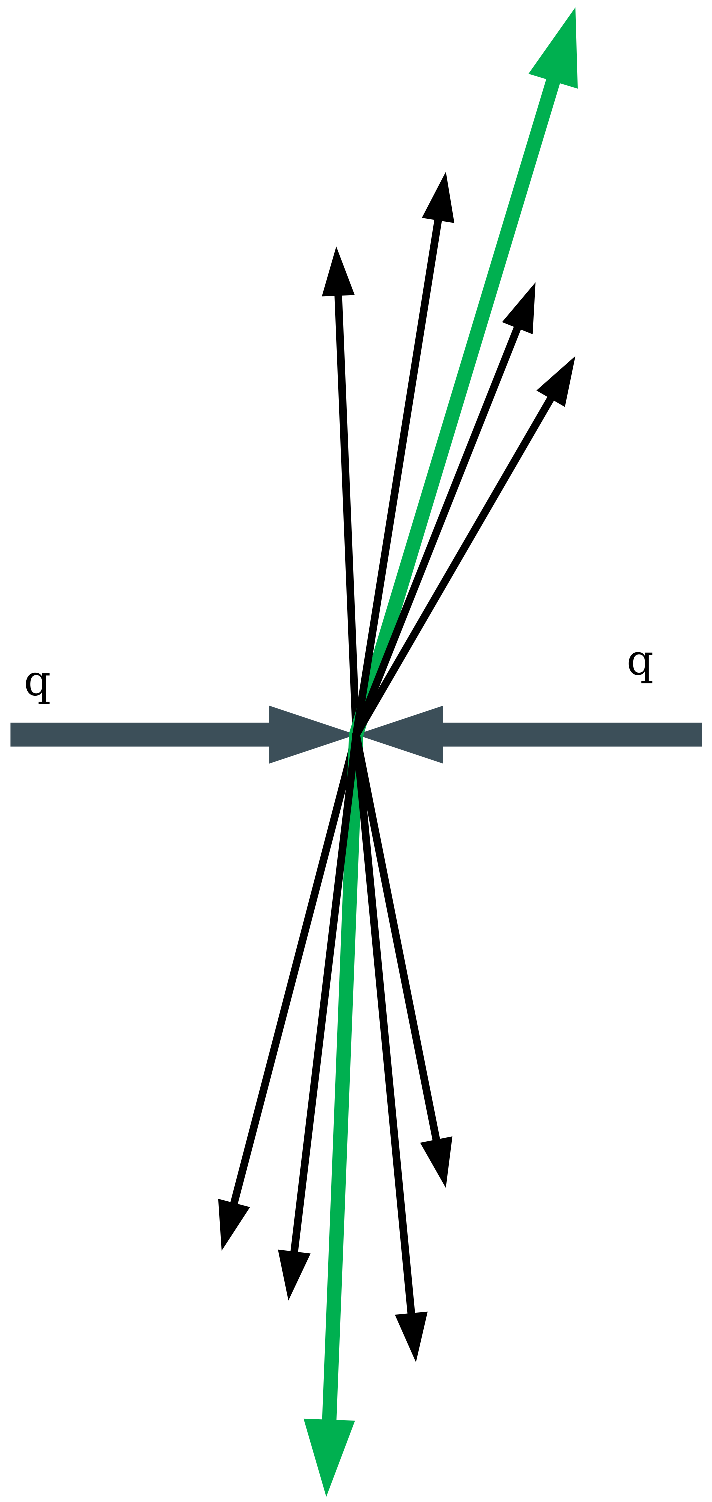
Relativistic Heavy-Ion Collisions

made by Chun Shen

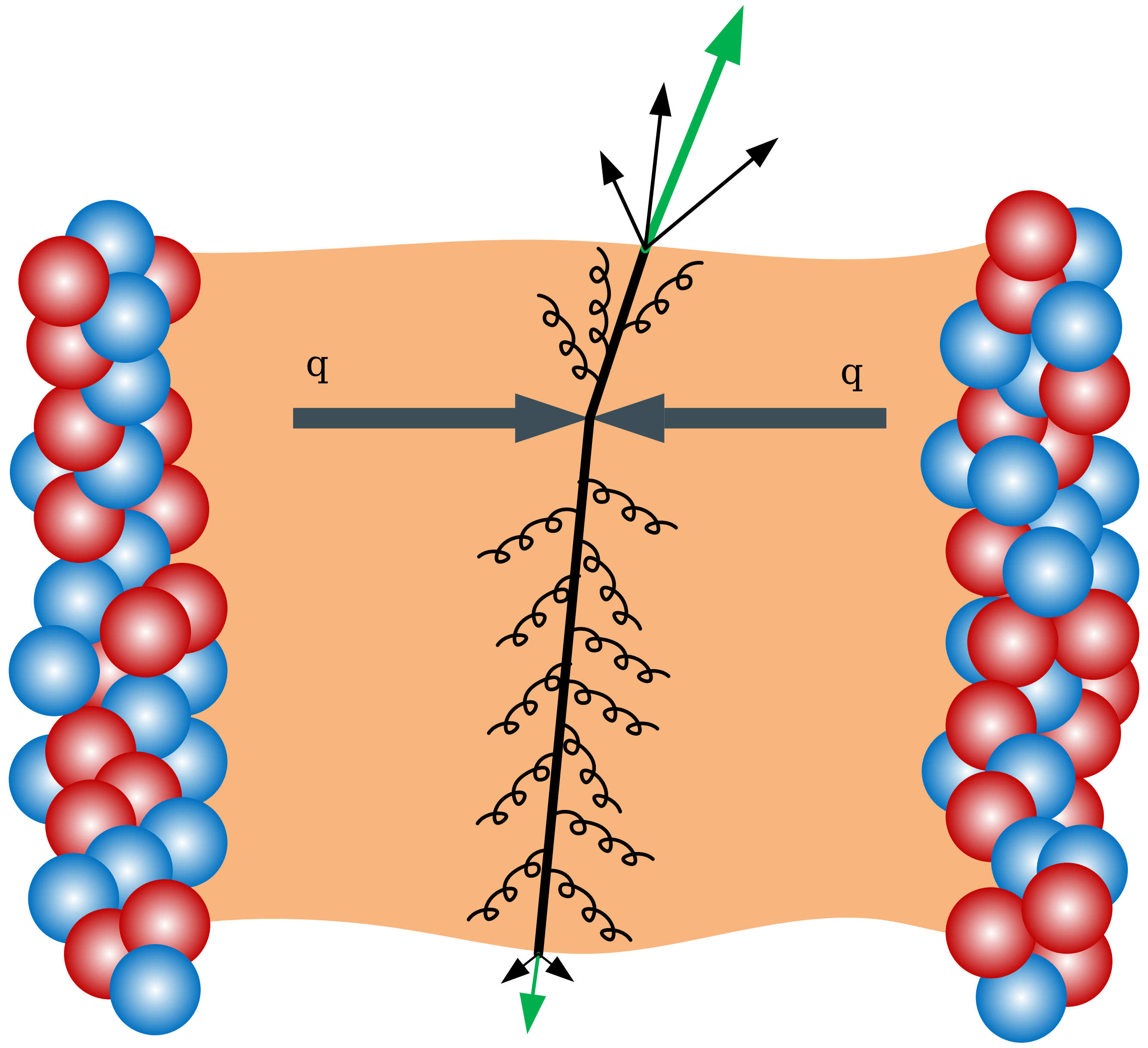


Hard probes: jets

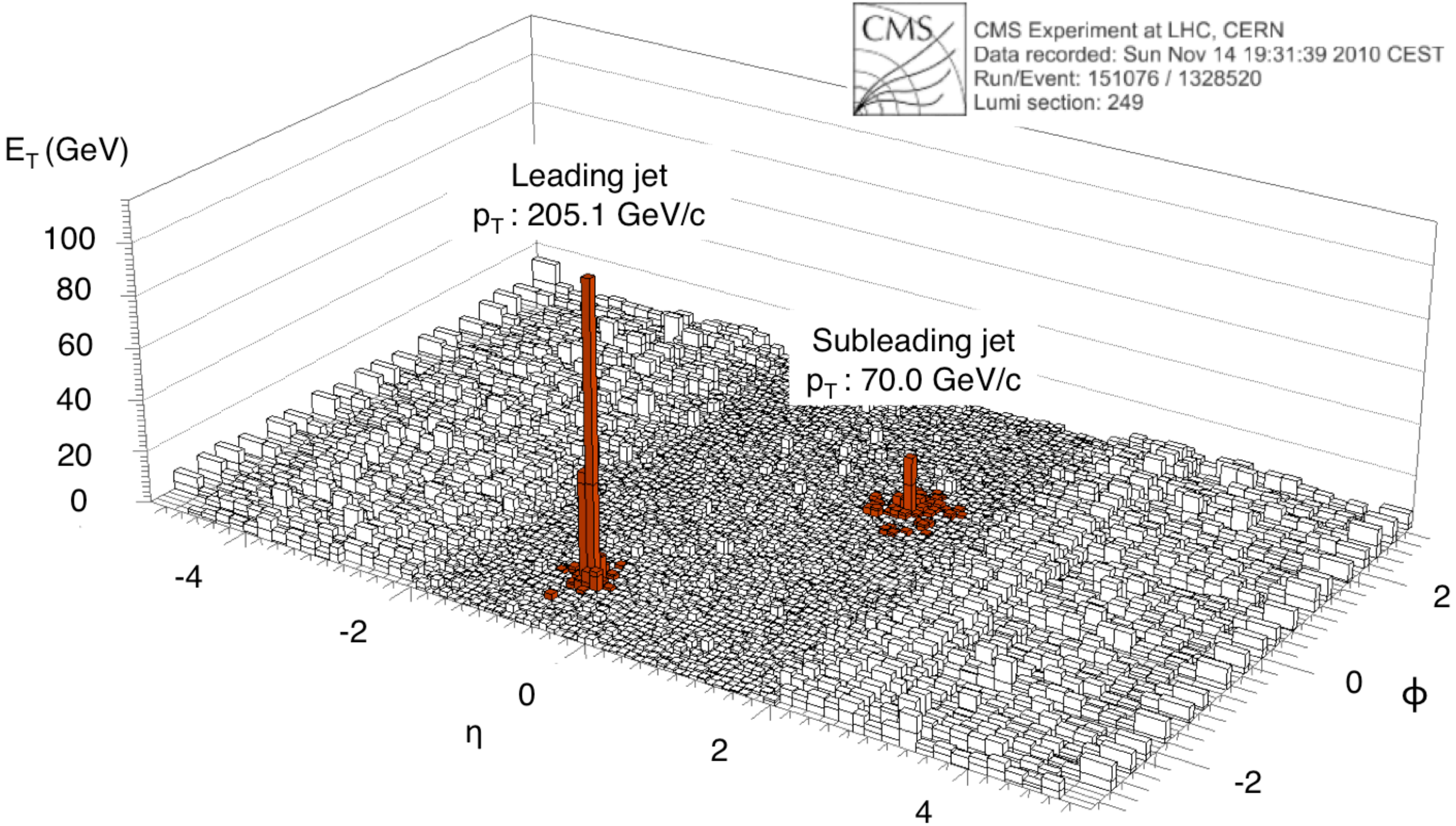
- Hard (high-Q^2) scatterings in the early stages of the collision produce back-to-back recoiling partons, which fragment into collimated clusters of hadrons



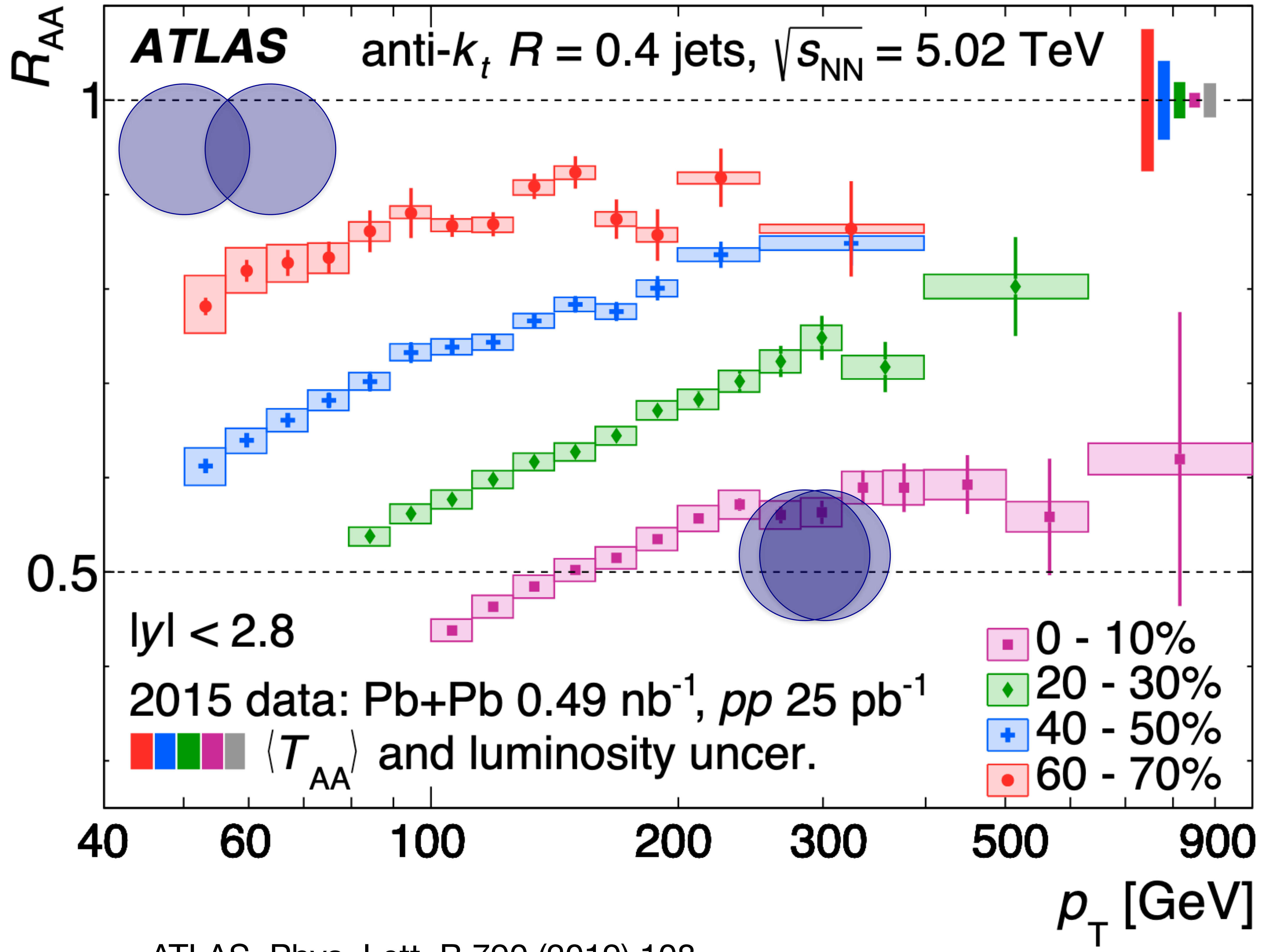
- As they traverse the QGP, partons interact with the medium
→ "jet quenching"
→ gives insight into properties of the QGP and the interactions of a colored probe with a colored medium



Jets in heavy-ion collisions



Jet quenching



ATLAS, Phys. Lett. B 790 (2019) 108, arXiv:1805.05635

Number of jets in a heavy-ion collision

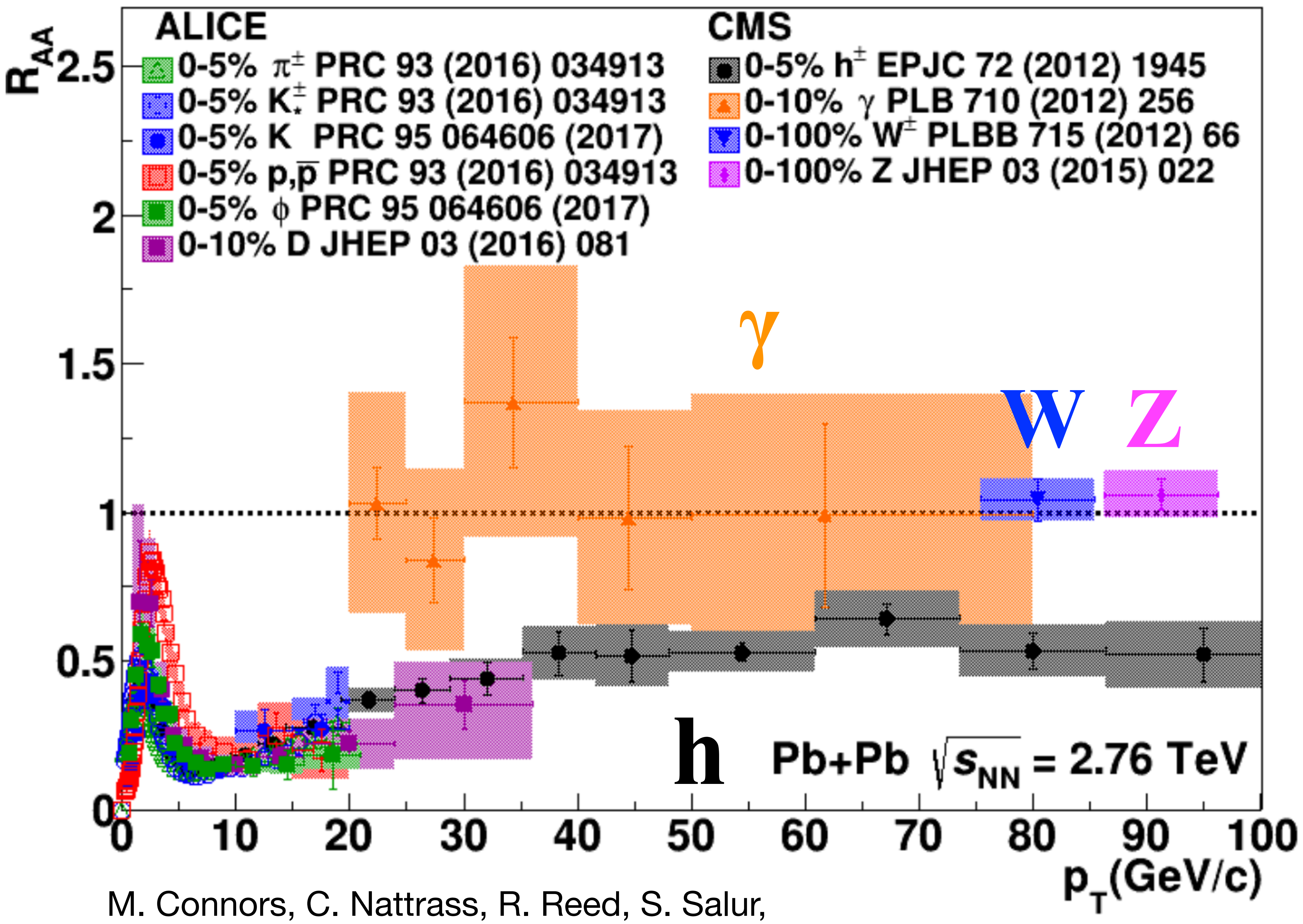
$$R_{AA} = \frac{(1/N_{evt})\ dN_{jet}/dp_T\big|_{AA}}{\langle N_{coll}\rangle\ (1/N_{evt})\ dN_{jet}/dp_T\big|_{pp}}$$

Equivalent number of proton-proton collisions in a heavy-ion event

Number of jets in a proton-proton collision

- Significant suppression of jets in central heavy-ion collisions!

Hadron R_{AA}



M. Connors, C. Nattrass, R. Reed, S. Salur,
Rev. Mod. Phys. 90 (2018) 025005
arXiv:1705.01974 [nucl-ex]

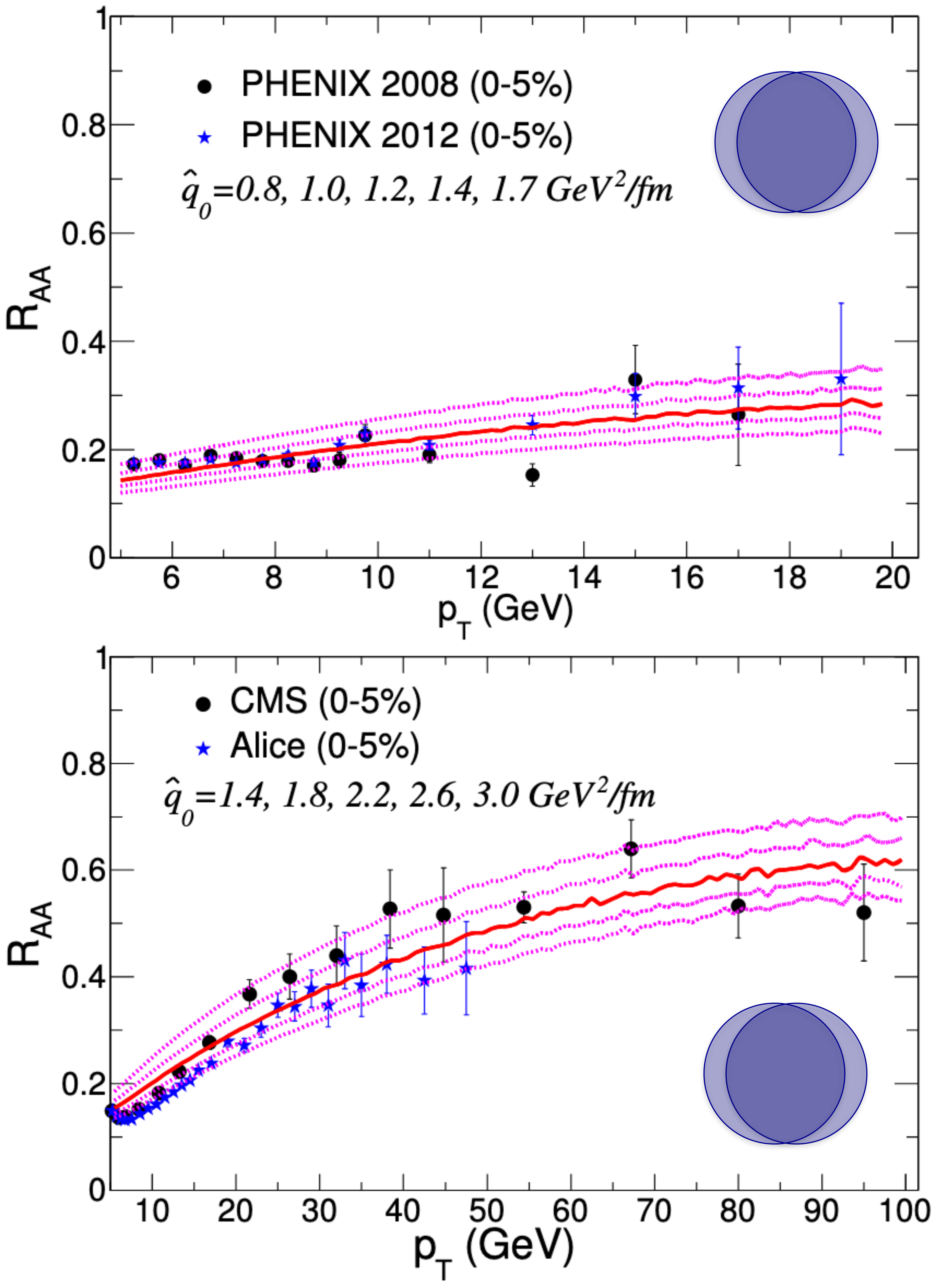
Number of particles in a heavy-ion collision

$$R_{AA} = \frac{(1/N_{evt})\ dN/dp_T\big|_{AA}}{\langle N_{coll}\rangle\ (1/N_{evt})\ dN/dp_T\big|_{pp}}$$

Equivalent number of proton-proton collisions in a heavy-ion event

Number of particles in a proton-proton collision

Charged particle R_{AA}



- By comparing with a wide variety of models, extract the *jet transport coefficient*

$$\frac{\hat{q}}{T^3} \approx \begin{cases} 4.6 \pm 1.2 & \text{at RHIC}, \\ 3.7 \pm 1.4 & \text{at LHC}, \end{cases}$$

- for a quark jet with E = 10 GeV

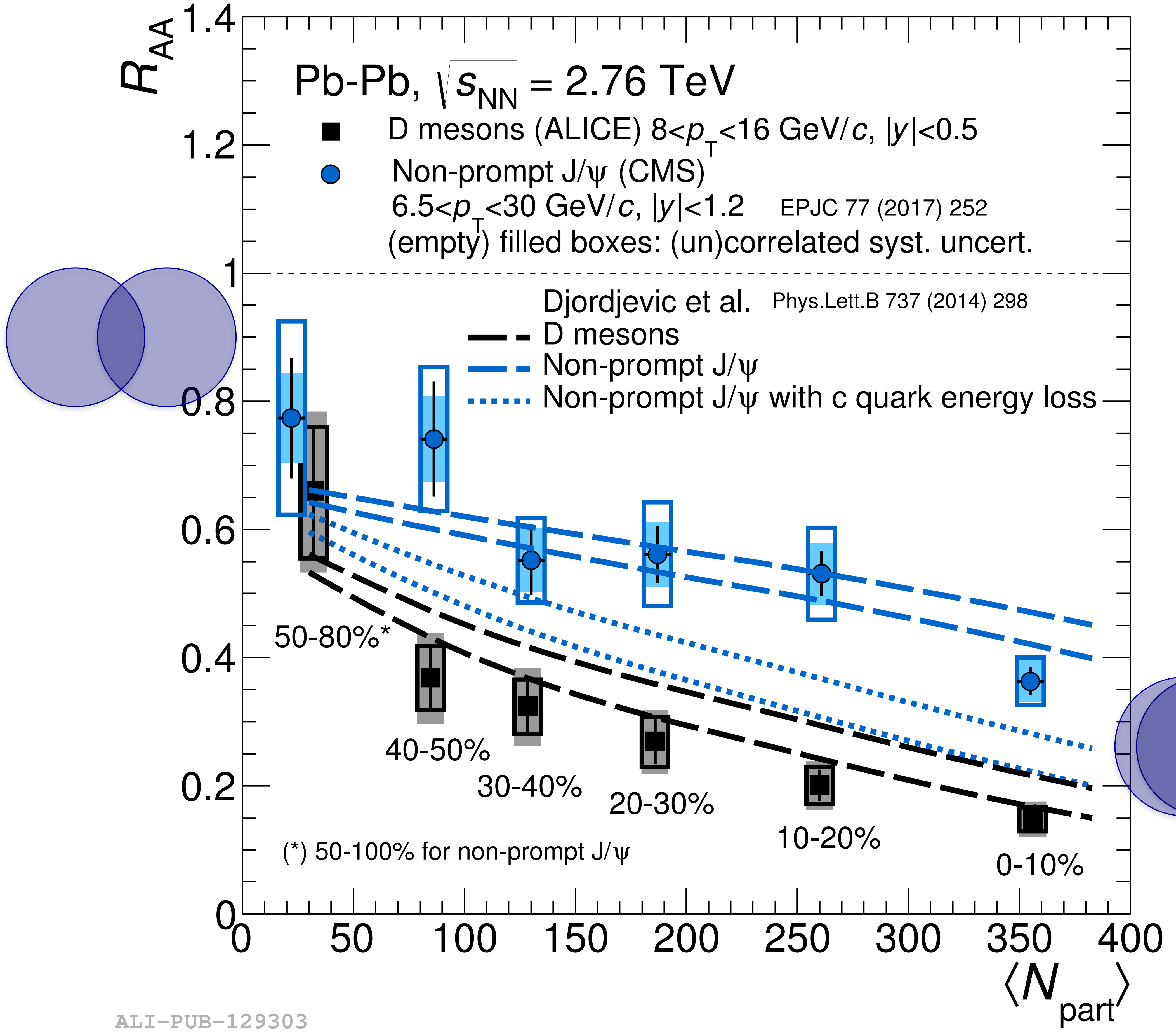
$$\hat{q} \approx \begin{cases} 1.2 \pm 0.3 \\ 1.9 \pm 0.7 \end{cases} \text{GeV}^2/\text{fm at} \begin{matrix} \text{T=370 MeV} \\ \text{T=470 MeV} \end{matrix}$$

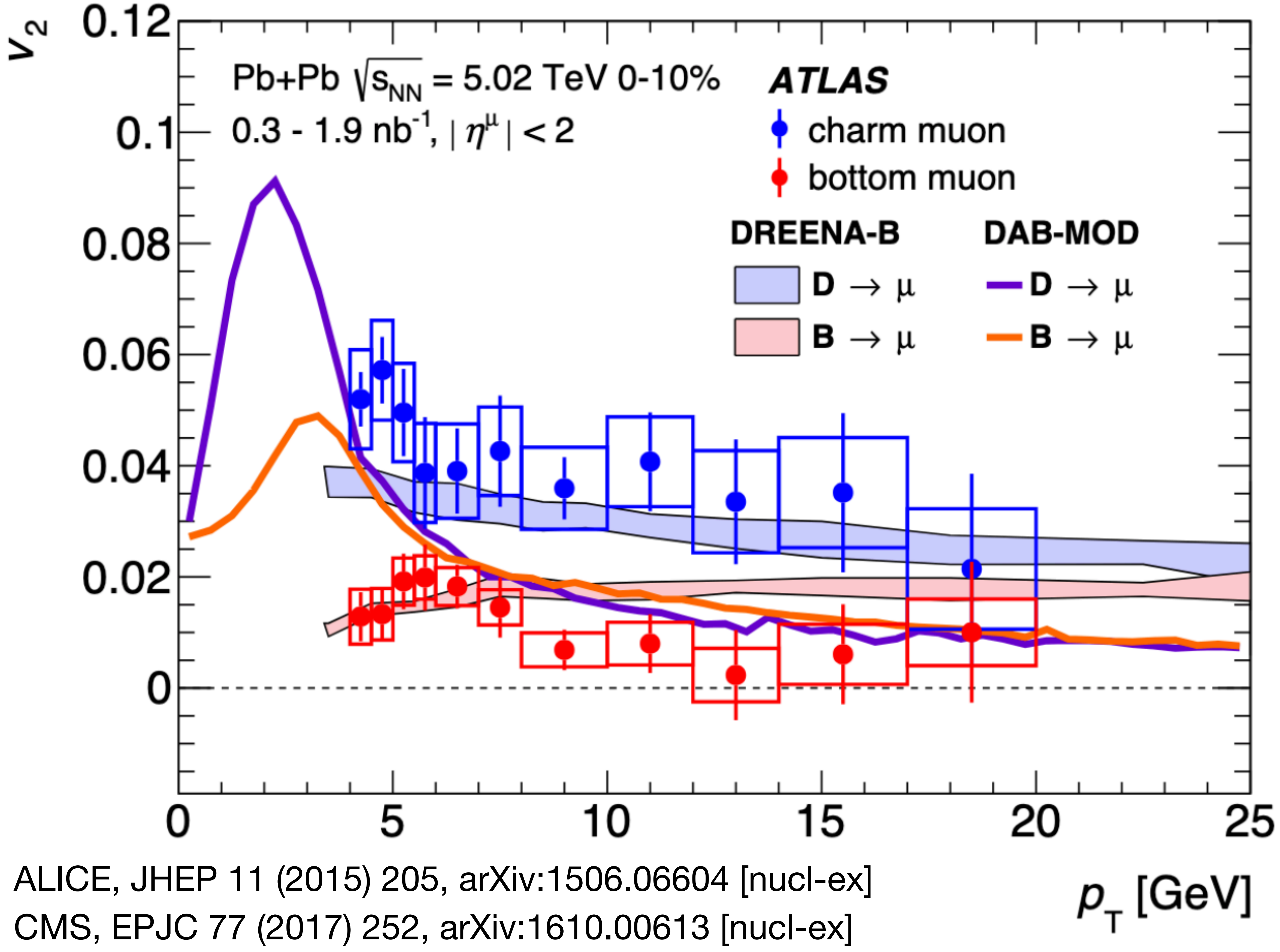
→ for more on jets, see talk by Johannes Hamre Isaksen

JET Collaboration, K.M. Burke et al.,
PRC 90 (2014) 014909, arXiv:1312.5003 [nucl-th]

Hard probes: heavy quarks

- Mass-dependent suppression of D (*c*-hadron) and non-prompt J/ψ (from *b*-hadrons) → dead cone effect
- Hard probes also flow, mass-dependent v_2 of muons from *c* and *b* decays

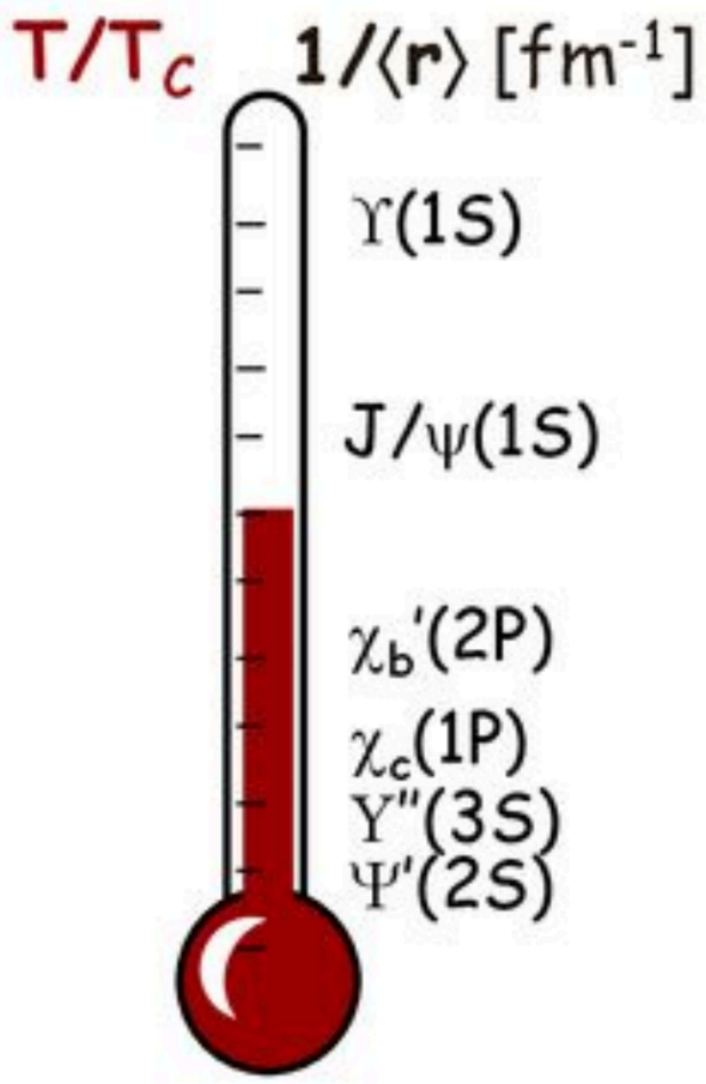




ALICE, JHEP 11 (2015) 205, arXiv:1506.06604 [nucl-ex]
CMS, EPJC 77 (2017) 252, arXiv:1610.00613 [nucl-ex]
ATLAS, PLB 807 (2020) 135595, arXiv:2003.03565 [nucl-ex]

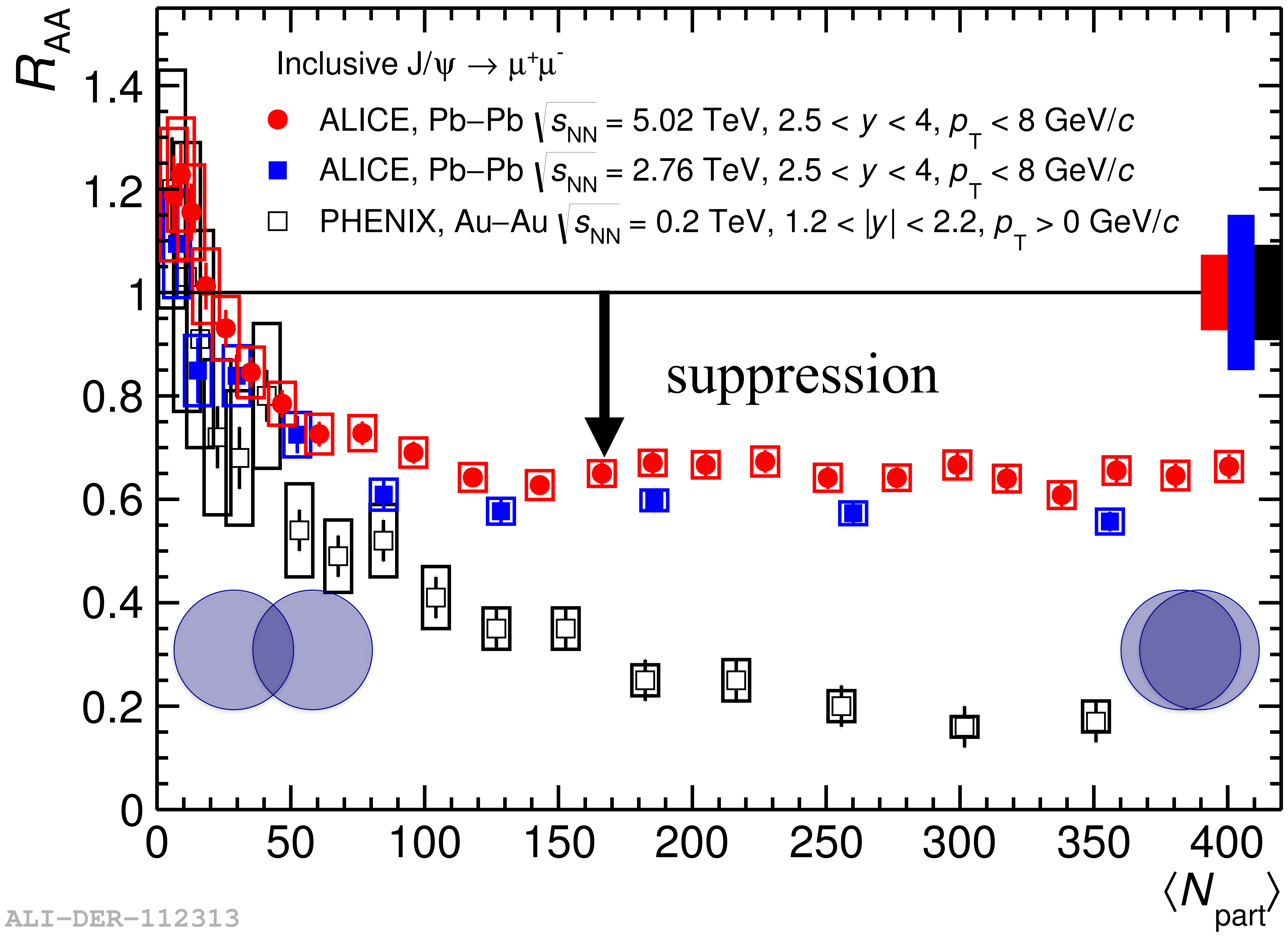
Melting and regeneration of J/ψ

- Quarkonia dissociate at high temperatures → suppression



T. Matsui, H. Satz, PLB 178 (1986) 416

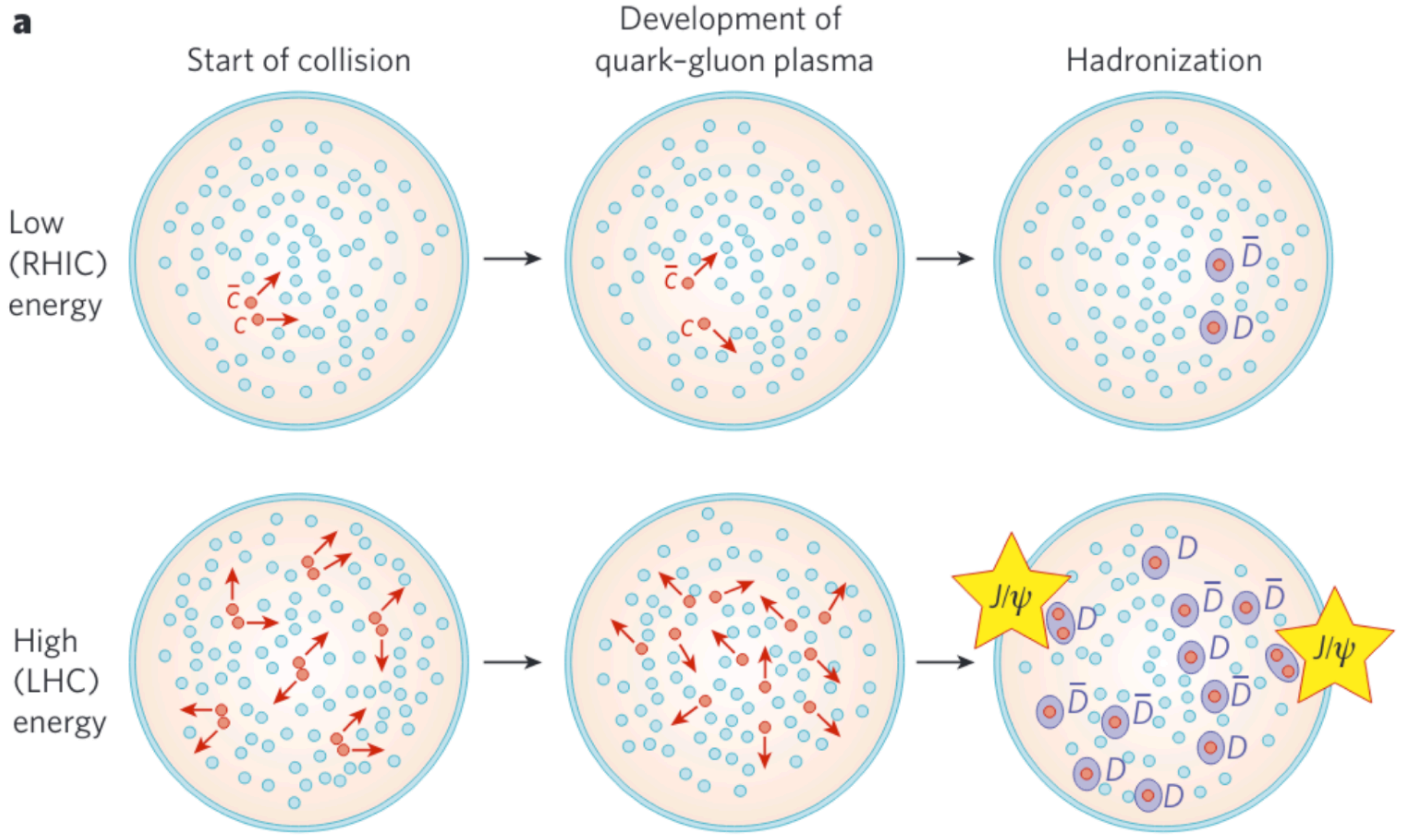
ALICE, PLB 766 (2017) 212, arXiv:1606.08197 [nucl-ex]



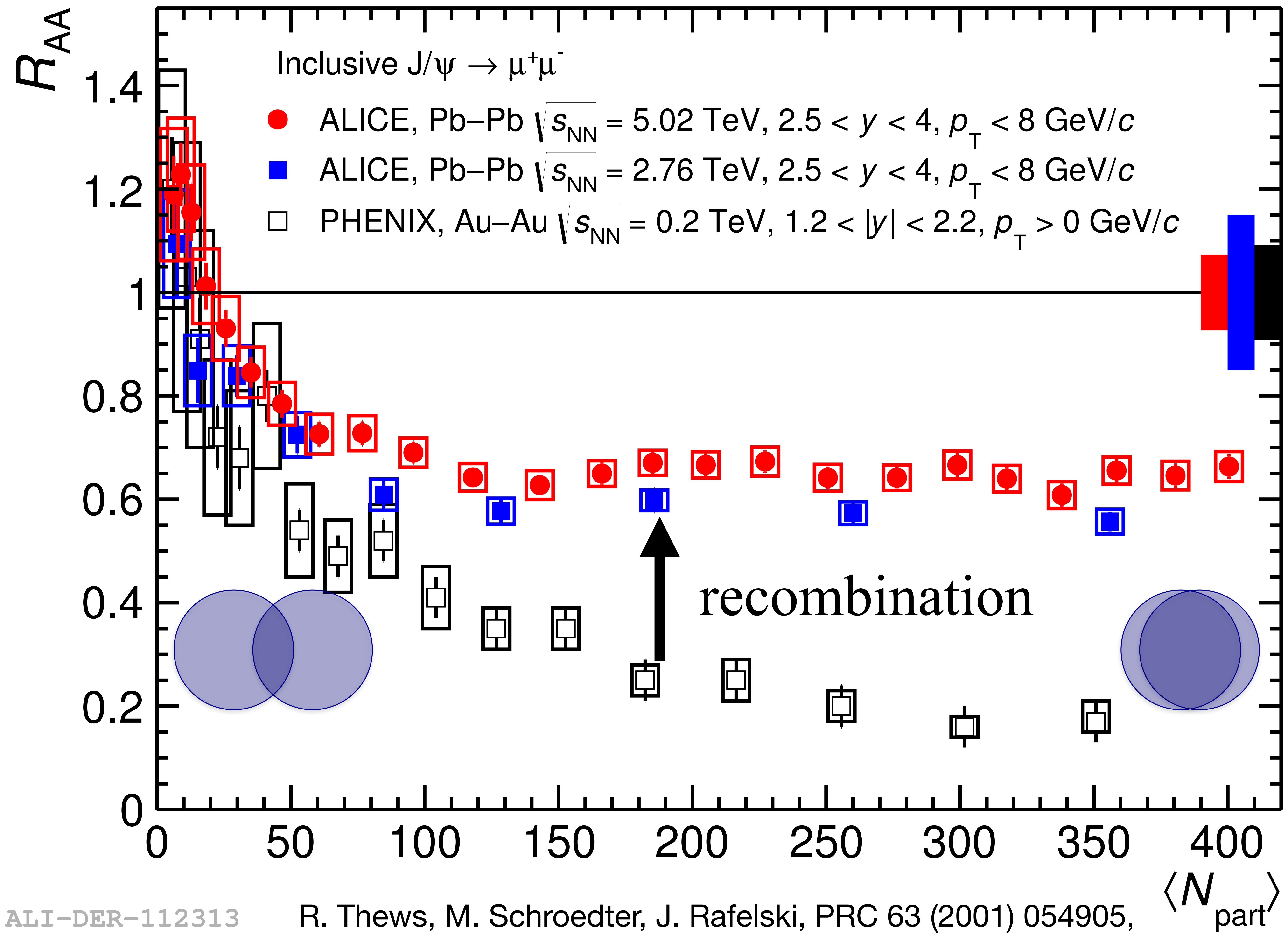
→ see talk by Ida Storehaug

Melting and regeneration of J/ψ

- Quarkonia dissociate at high temperatures → suppression
- More charm quarks available to form hadrons at LHC than at RHIC
  → recombination
  → evidence of deconfinement and thermalization



ALICE, PLB 766 (2017) 212, arXiv:1606.08197 [nucl-ex]

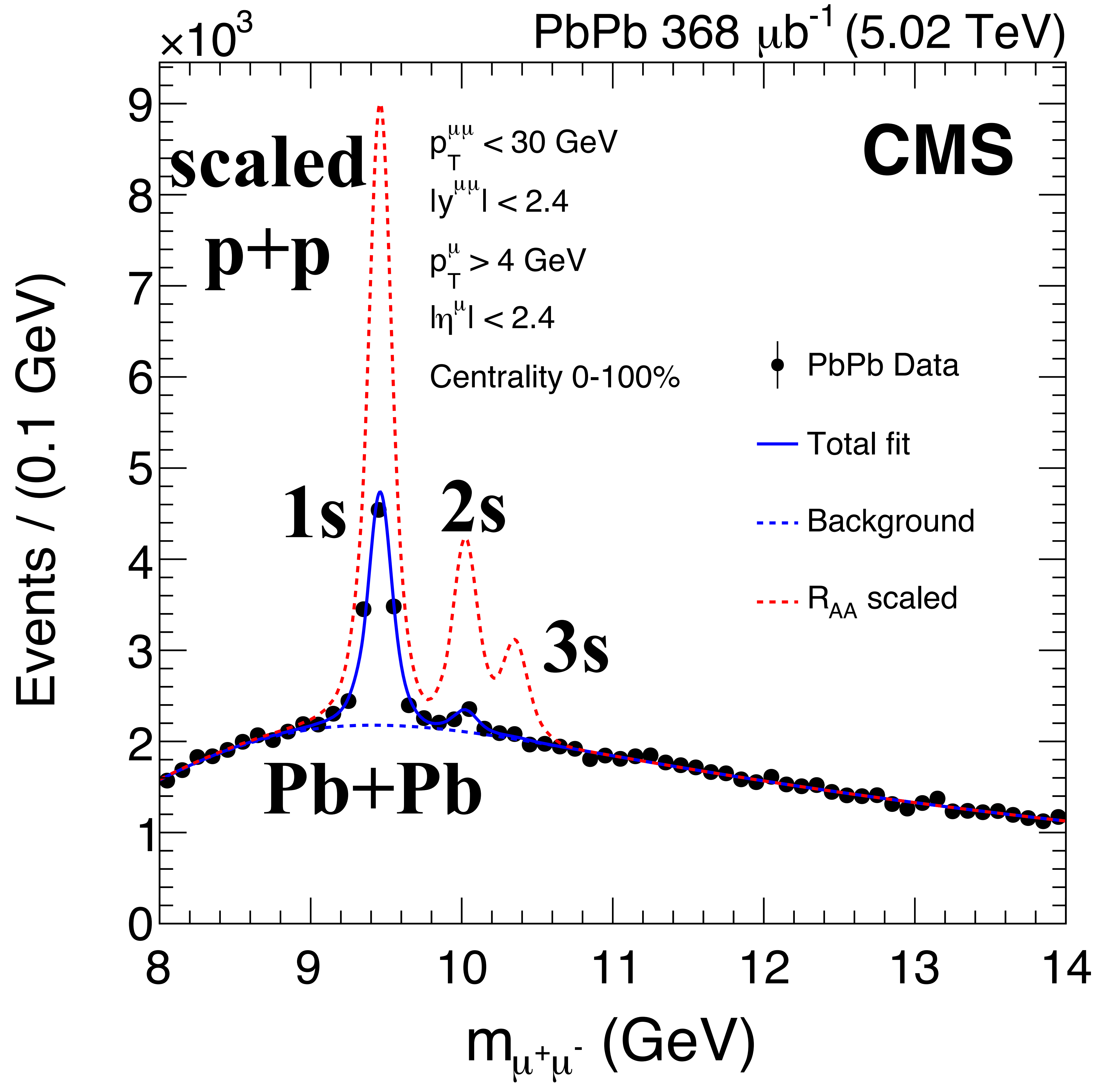


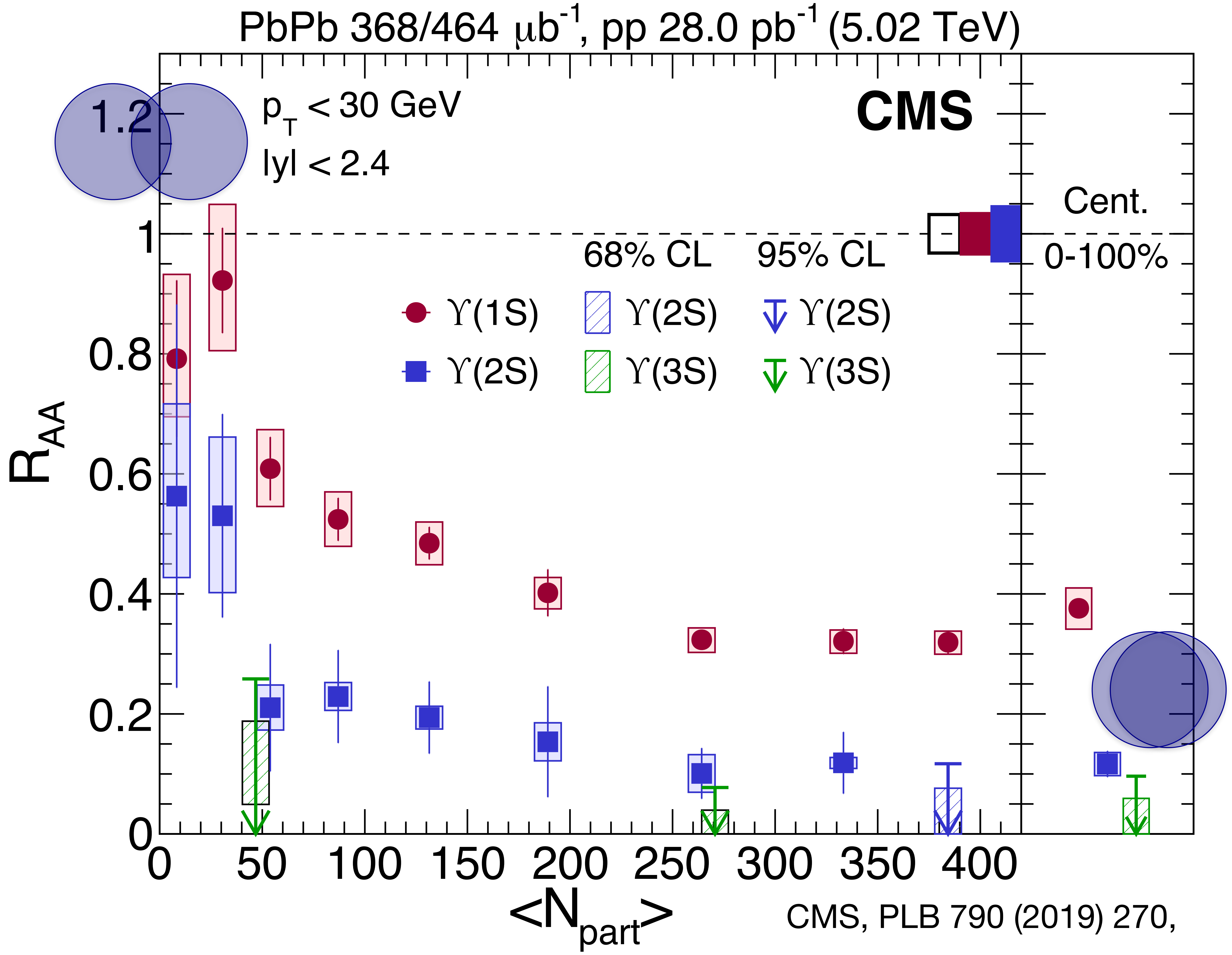
R. Thews, M. Schroedter, J. Rafelski, PRC 63 (2001) 054905, arXiv:hep-ph/0007323

P. Braun-Munzinger and J. Stachel, Nature 448 (2007) 302

Melting of quarkonia: Υ

- Upsilon production is strongly suppressed in Pb+Pb collisions
- Stronger suppression for higher states which are more weakly bound





CMS, PLB 790 (2019) 270,

Relativistic Heavy-Ion Collisions

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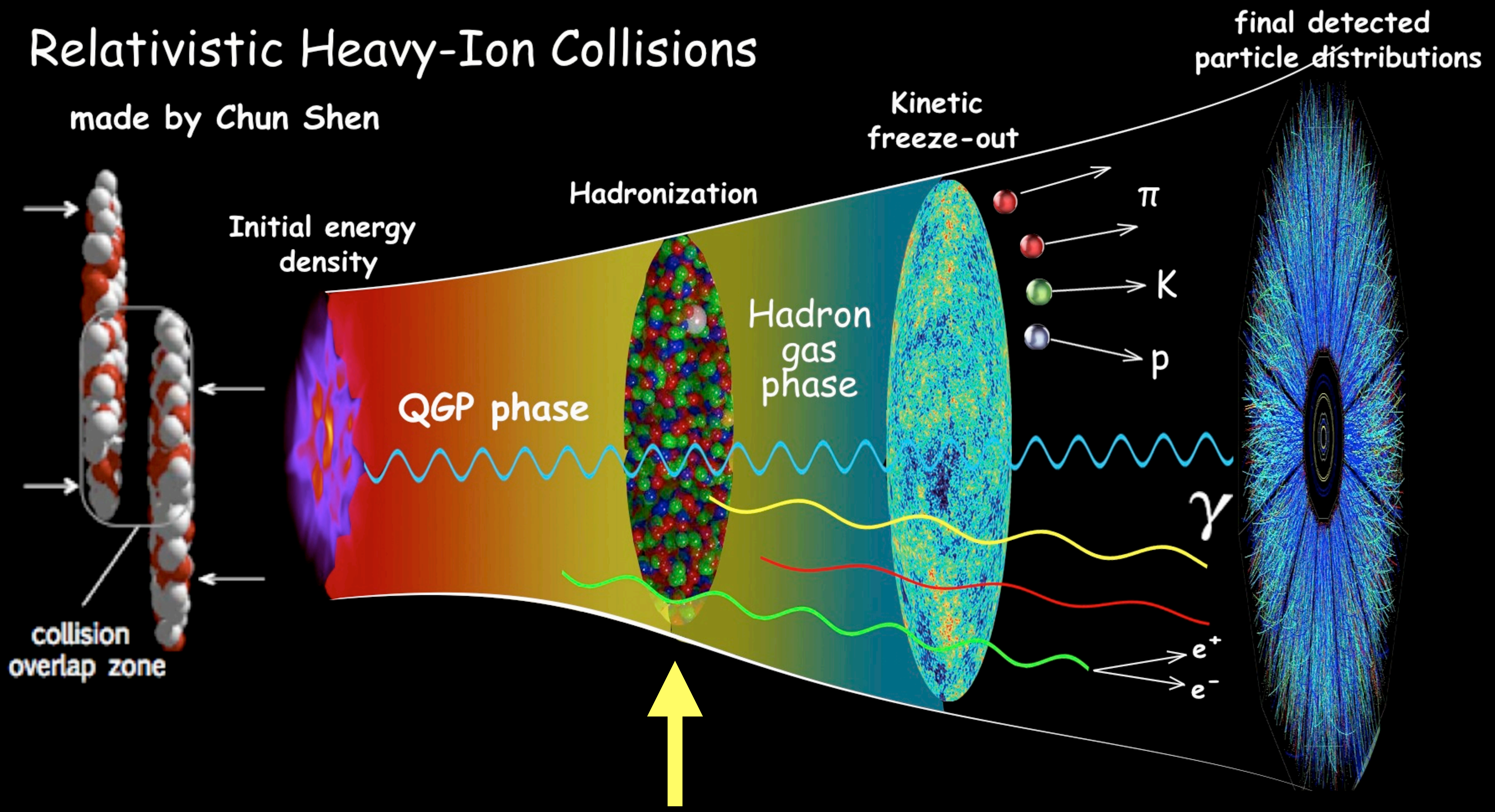
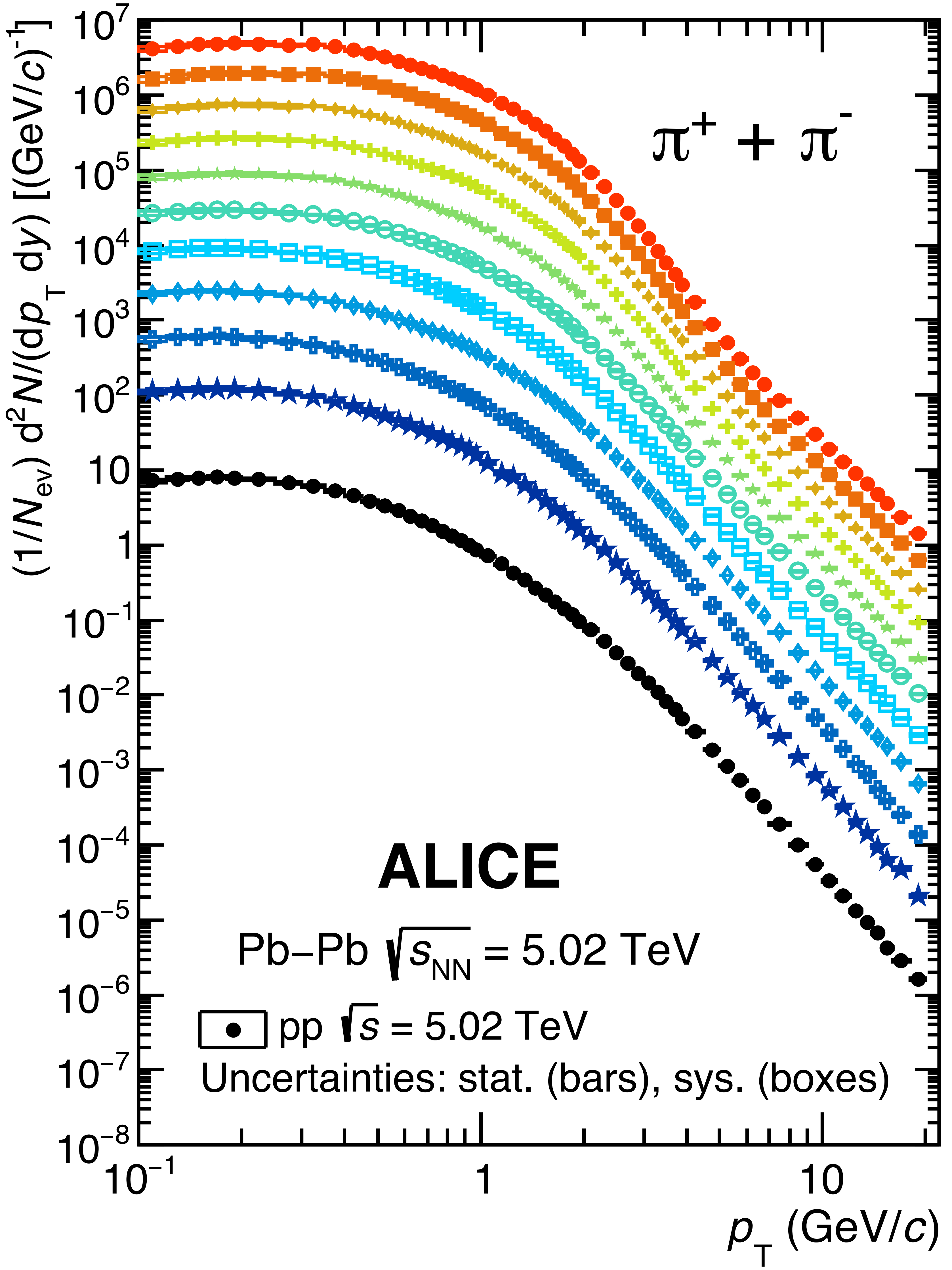
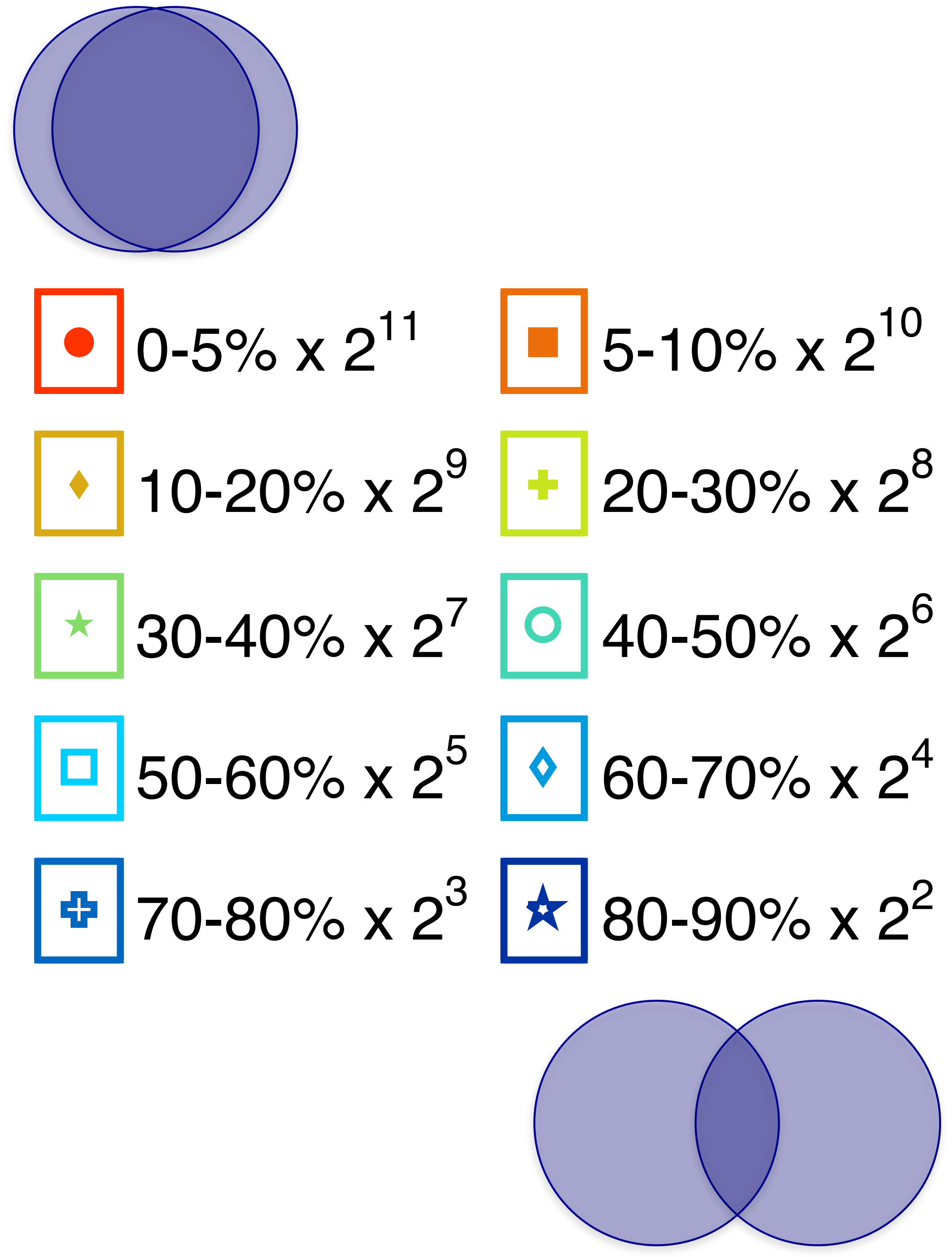


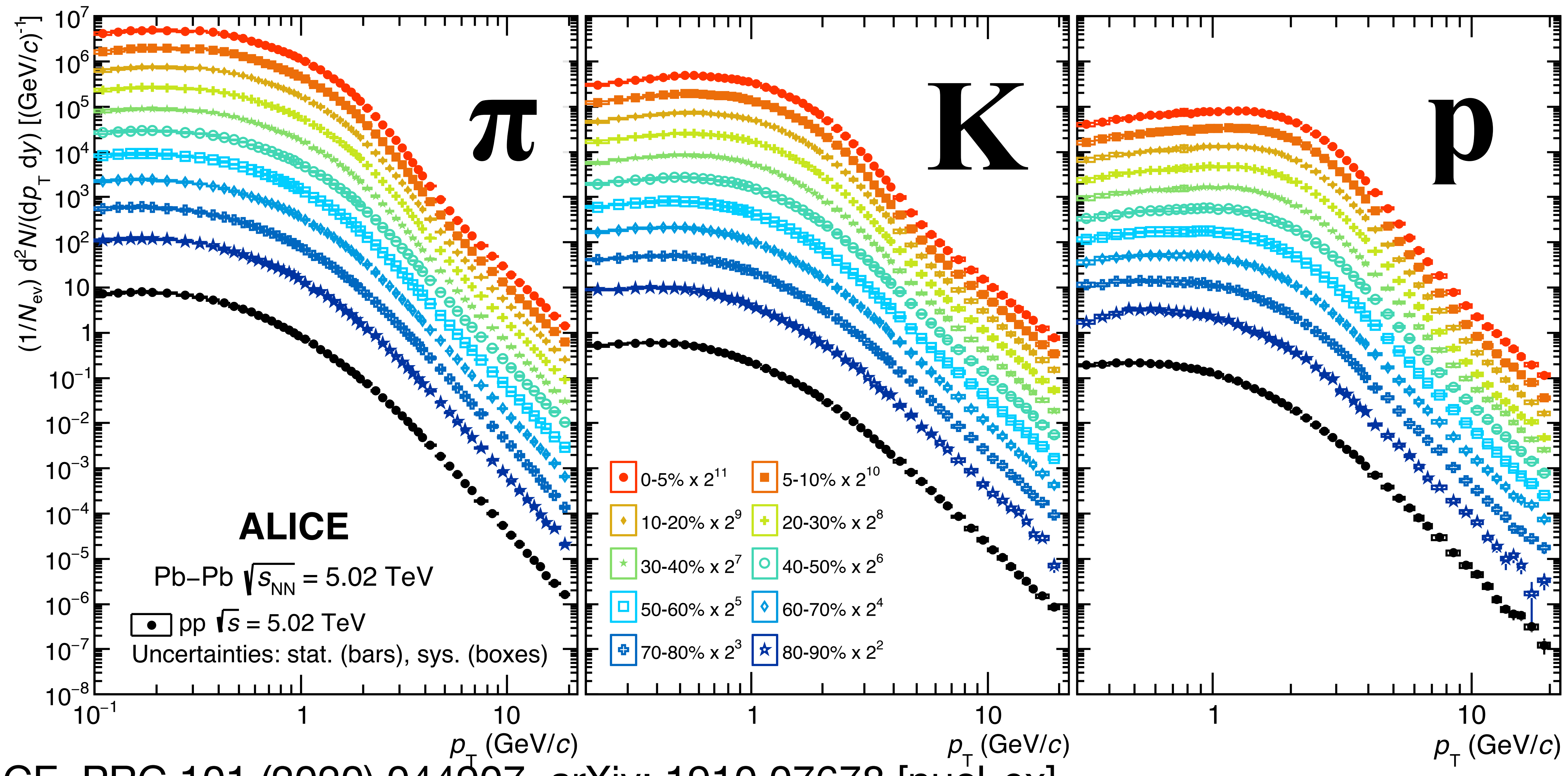
Identified particle spectra

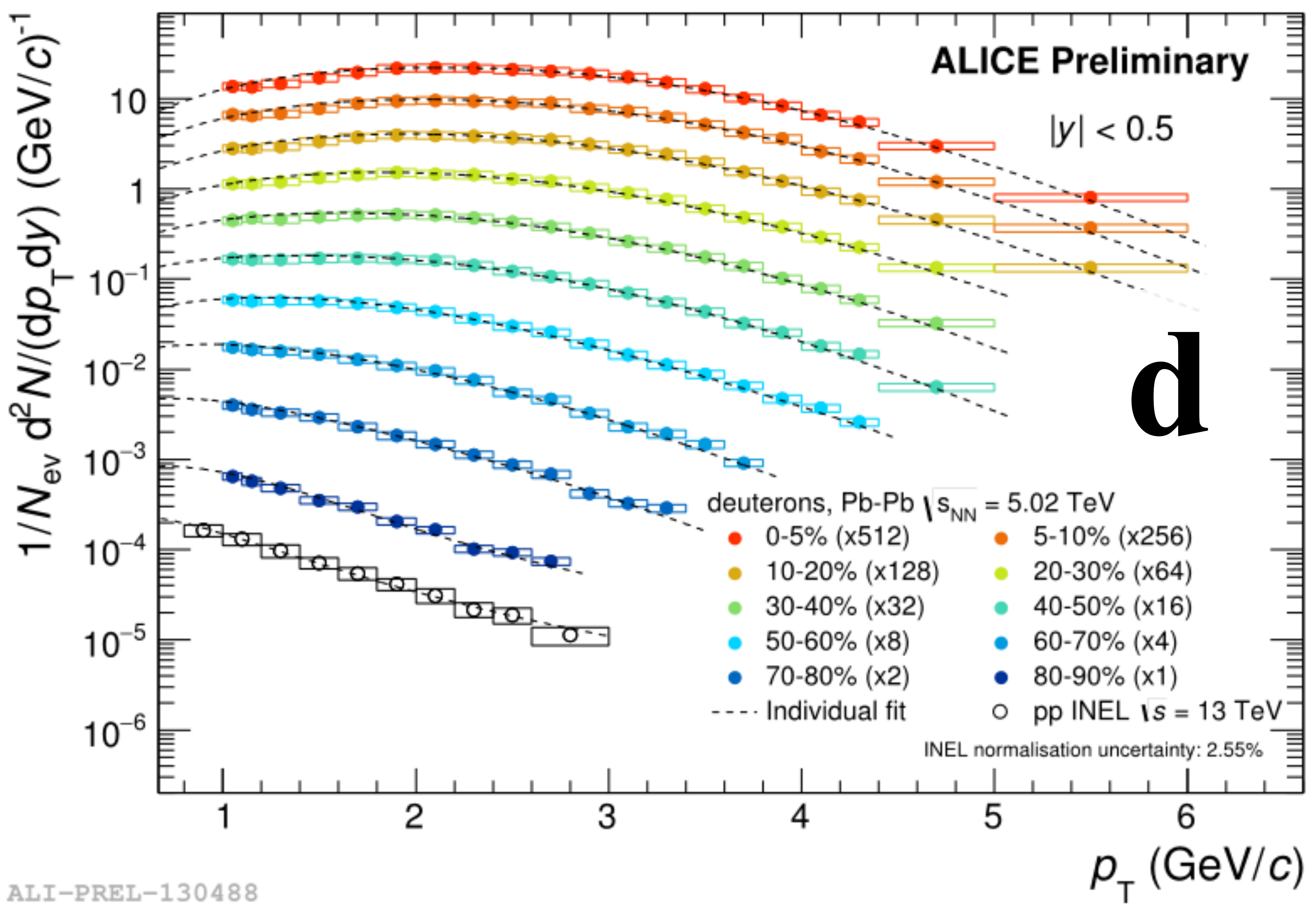




ALICE, PRC 101 (2020) 044907,
arXiv:1910.07678 [nucl-ex]

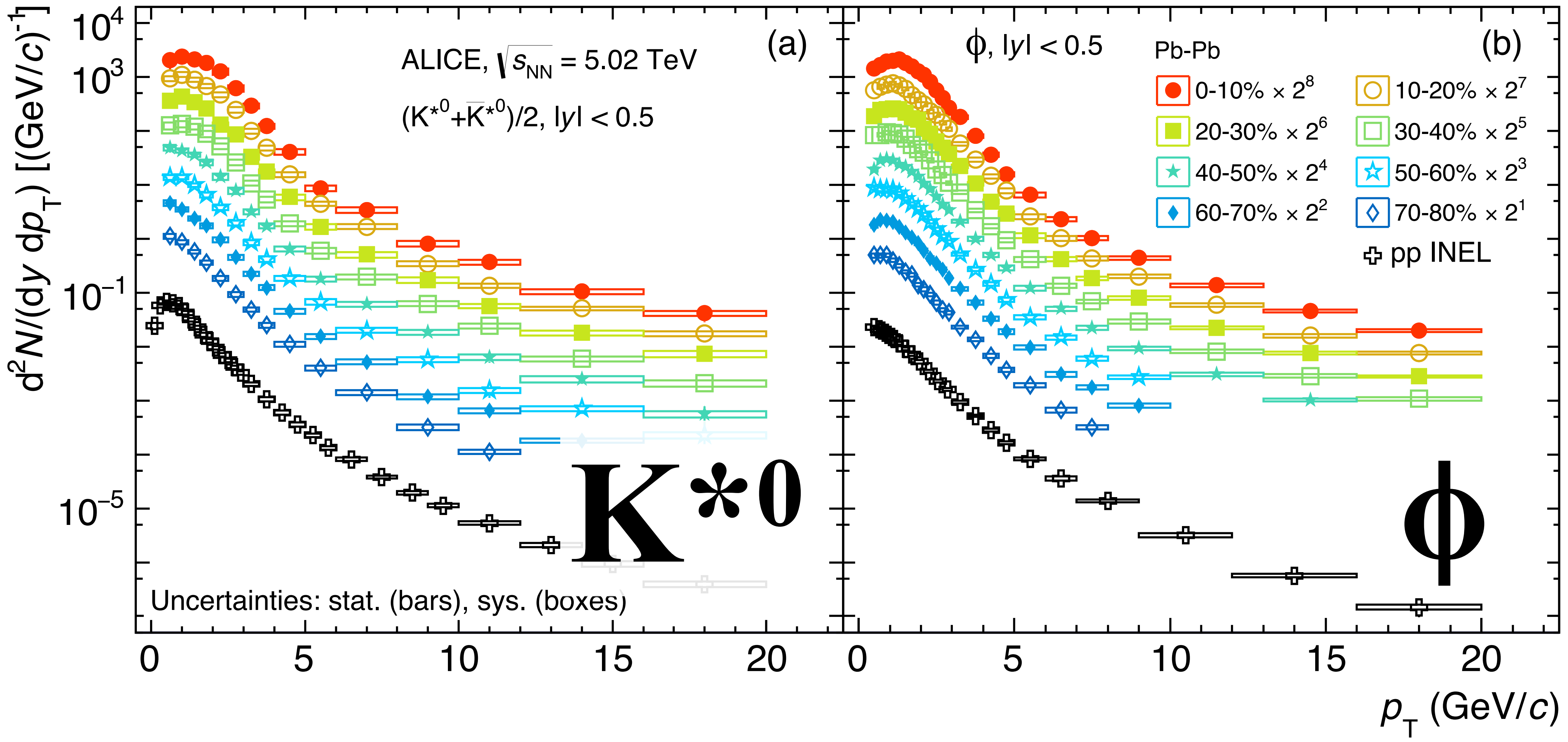
Hadrochemistry at chemical freeze-out

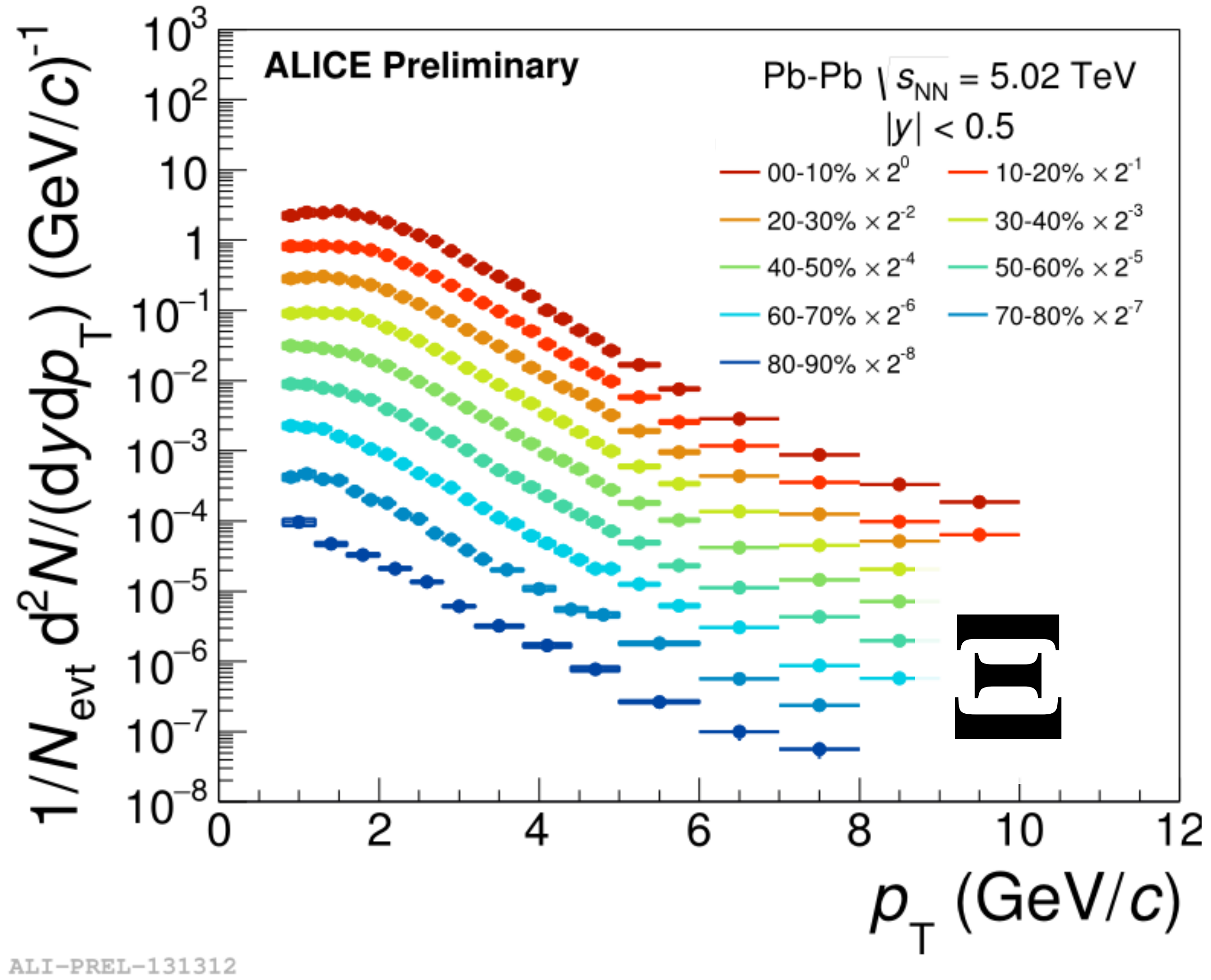


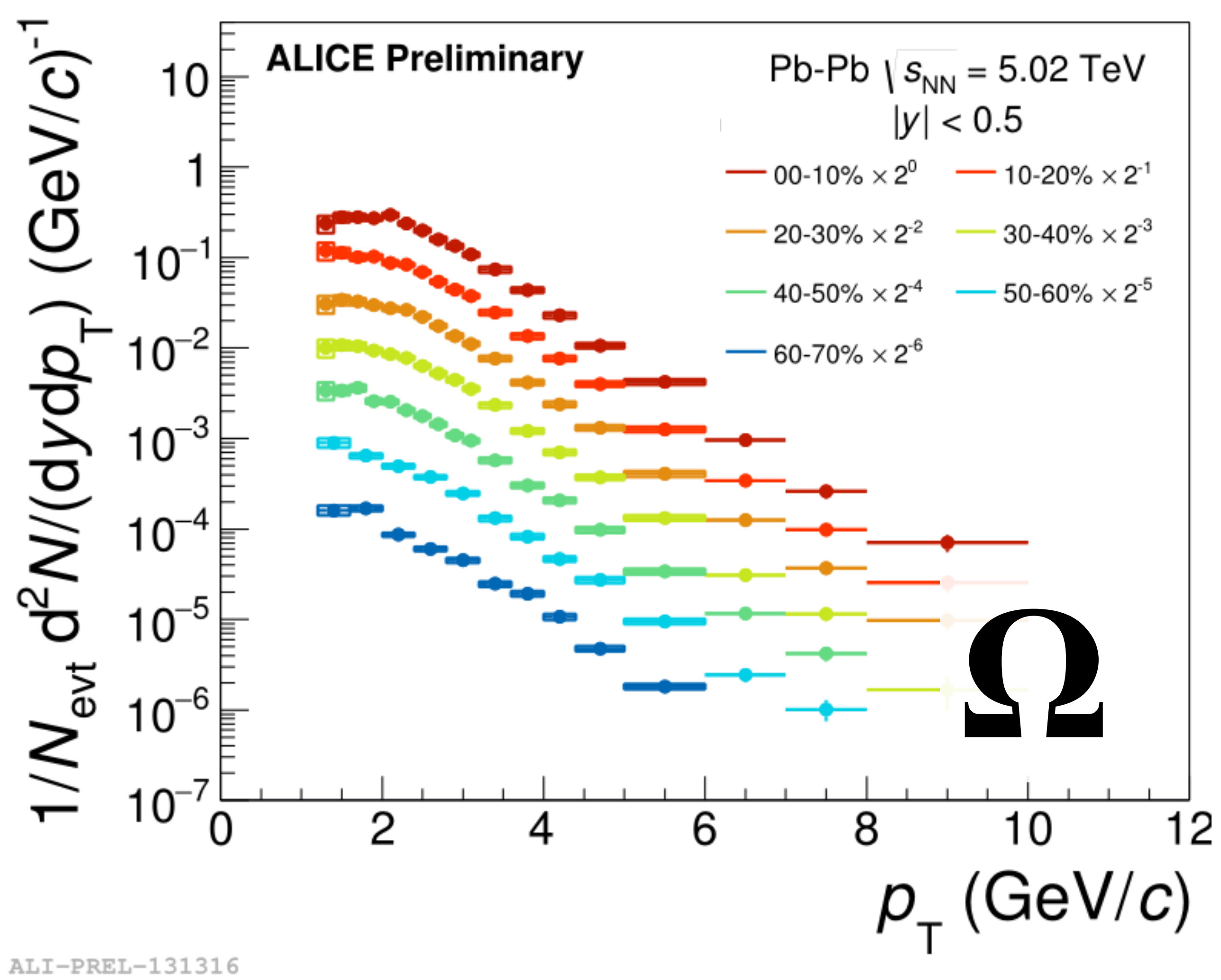


ALICE, PRC 101 (2020) 044907, arXiv: 1910.07678 [nucl-ex]

ALICE, PLB 802 (2020) 135225, arXiv: 1910.14419 [nucl-ex]







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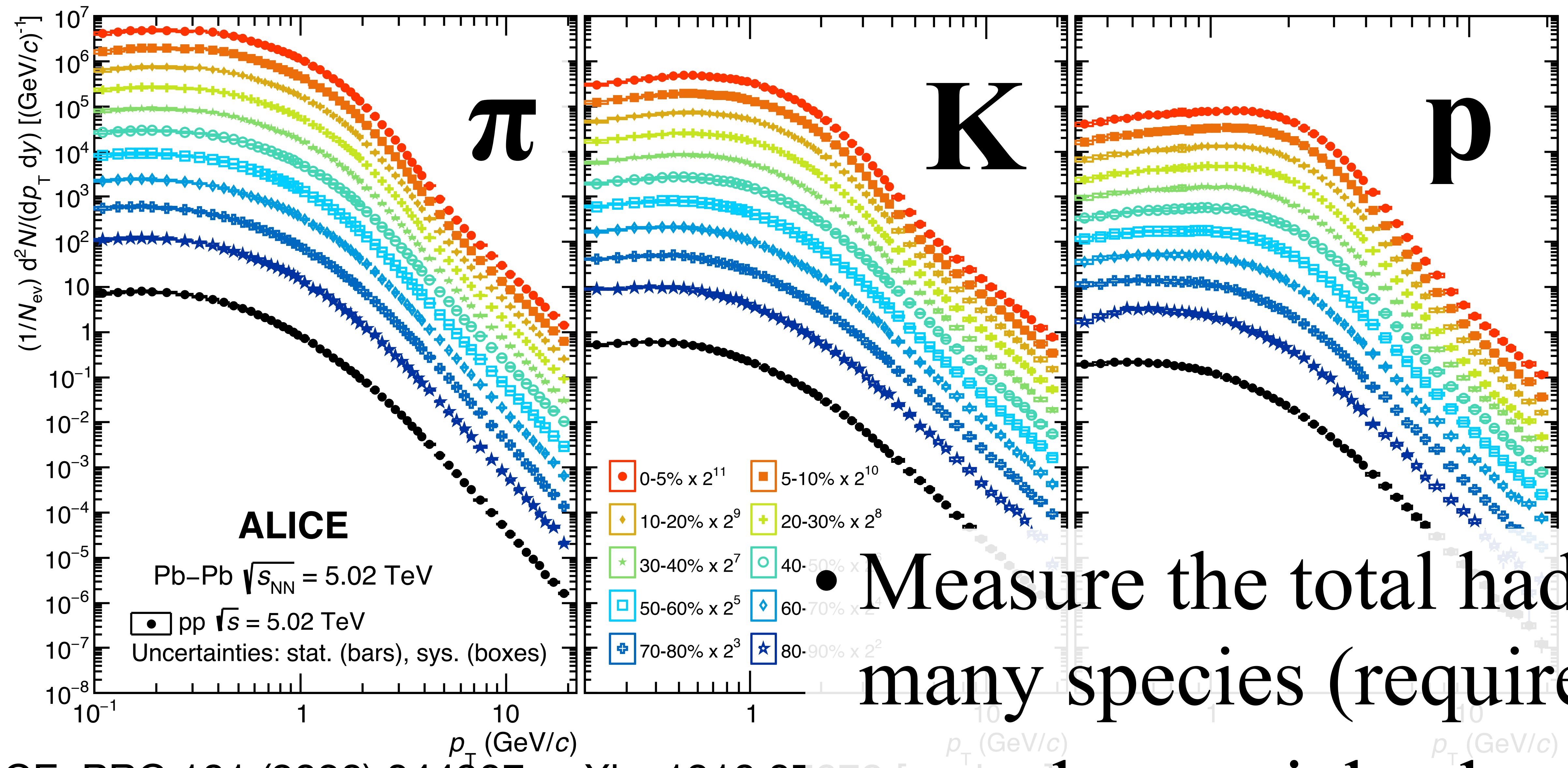
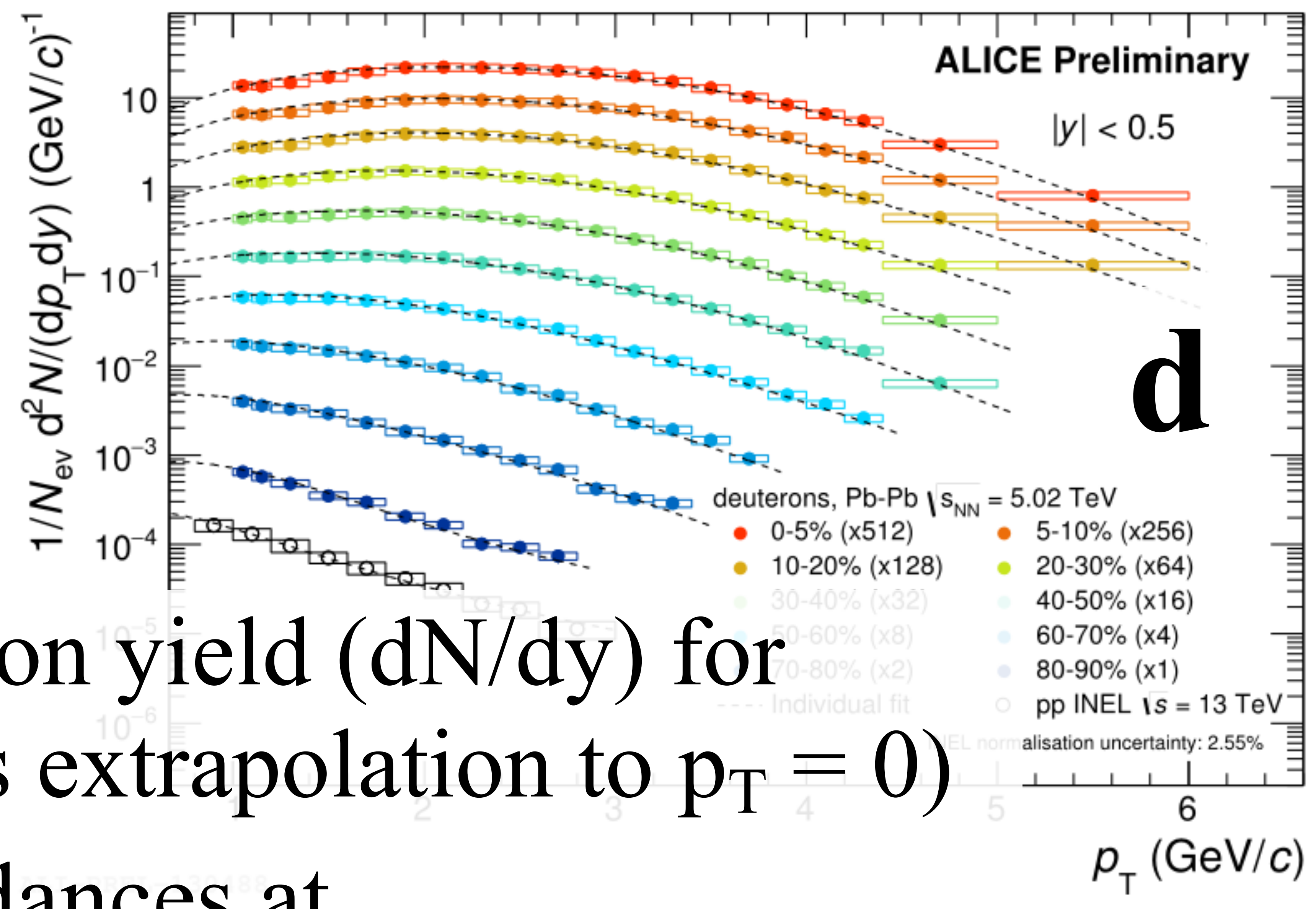
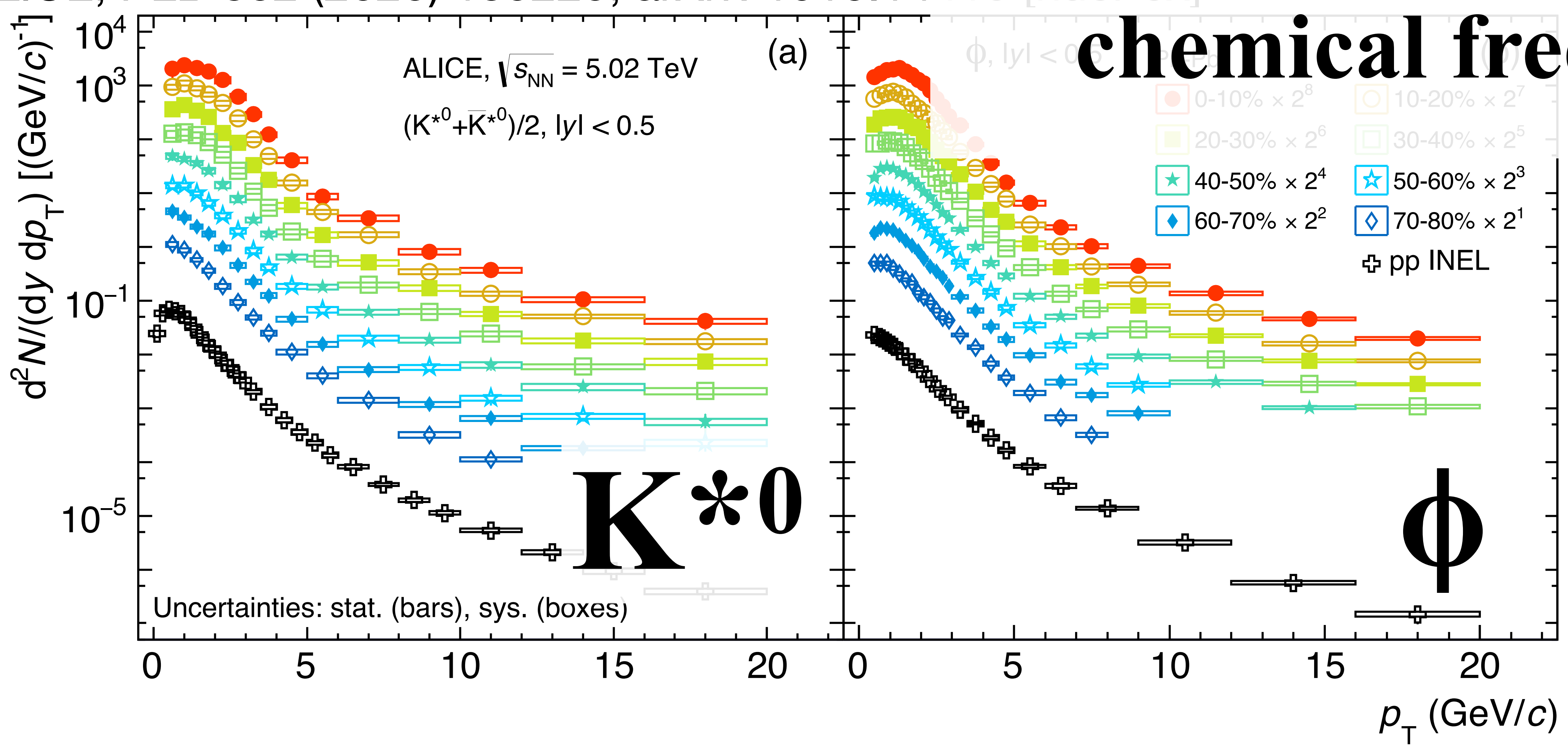
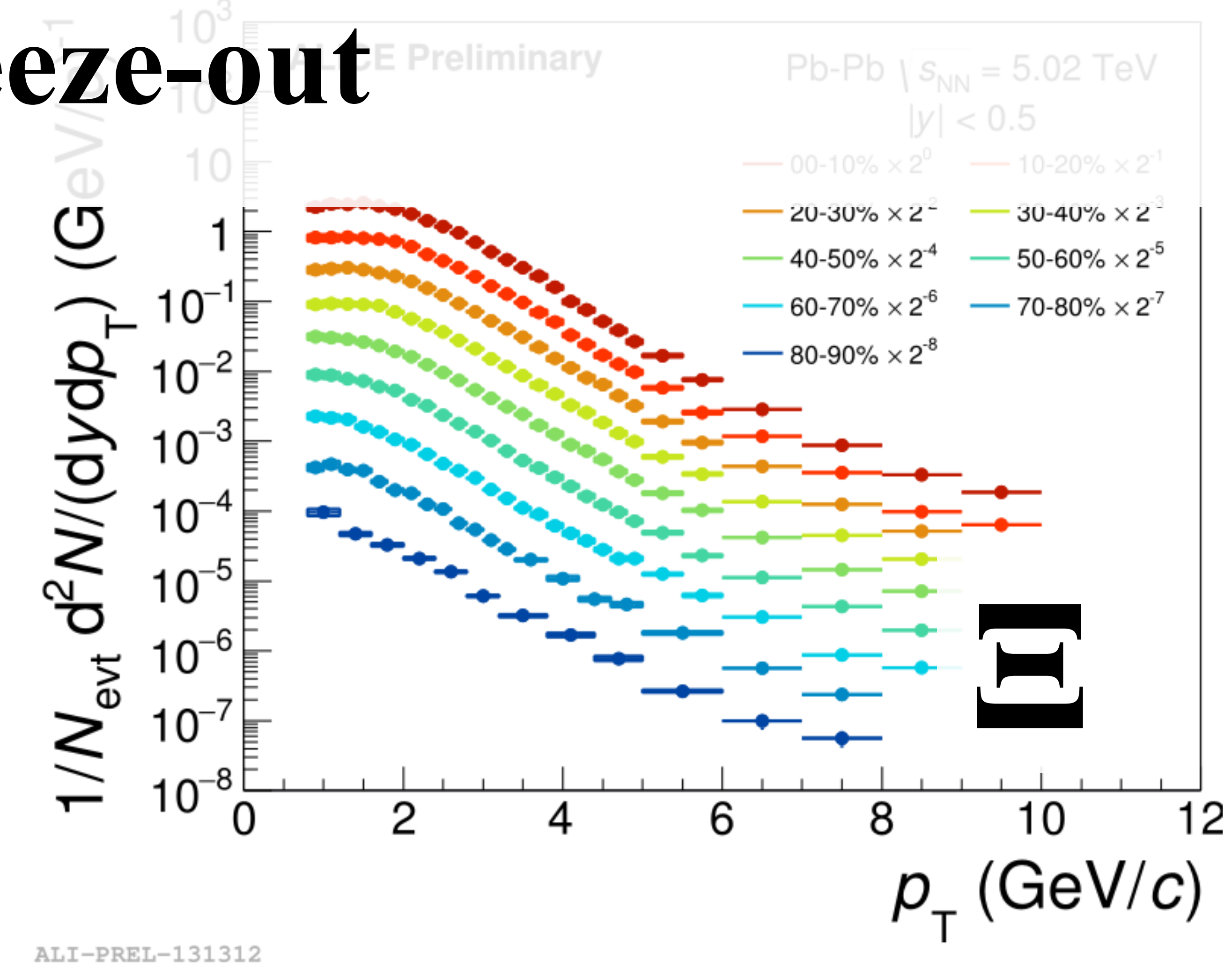


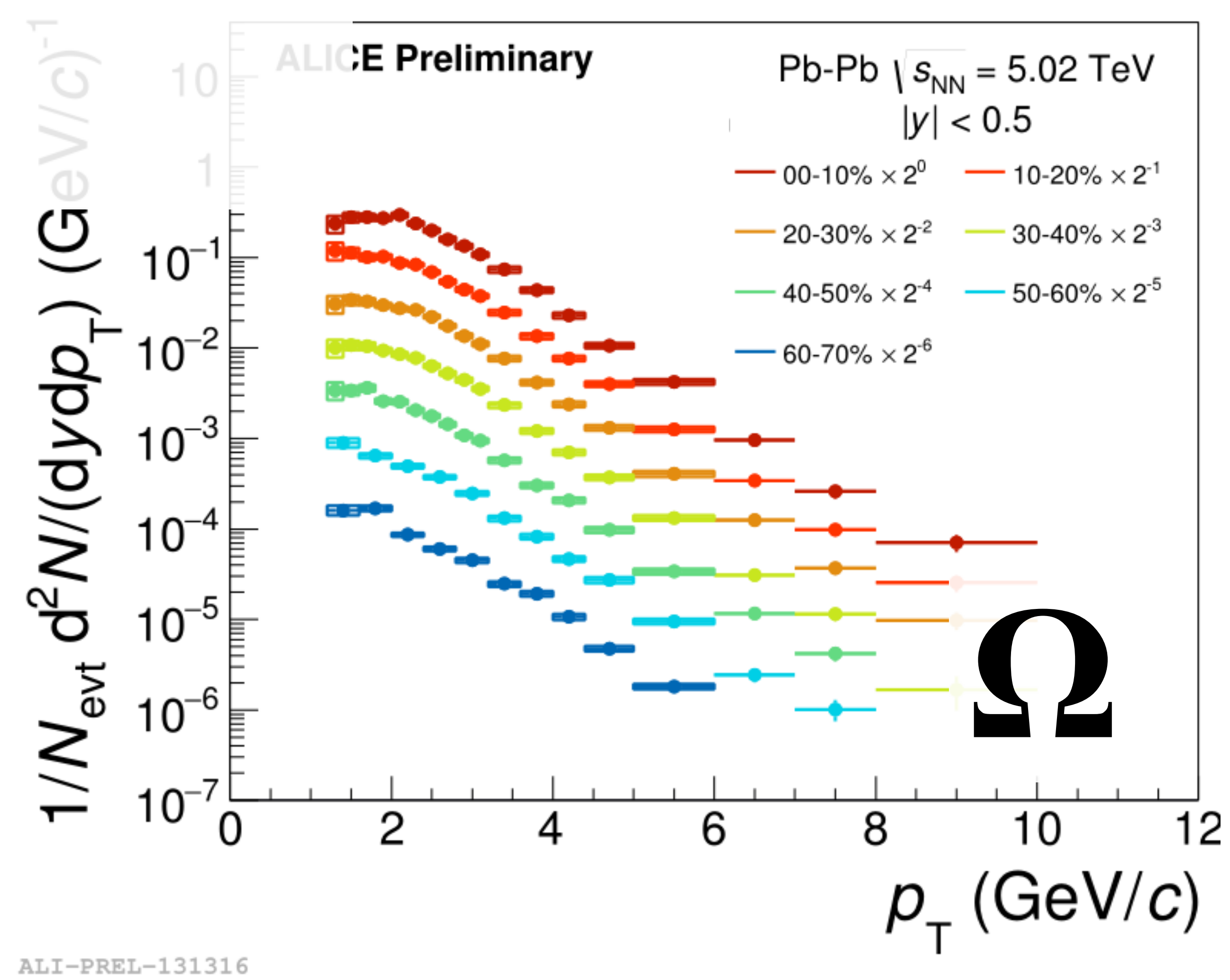


ALICE, PRC 101 (2020) 044907, arXiv: 1910.07678 [nucl-ex]
ALICE, PLB 802 (2020) 135225, arXiv: 1910.14419 [nucl-ex]

- Measure the total hadron yield (dN/dy) for many species (requires extrapolation to $p_T = 0$)
  - probe particle abundances at **chemical freeze-out**

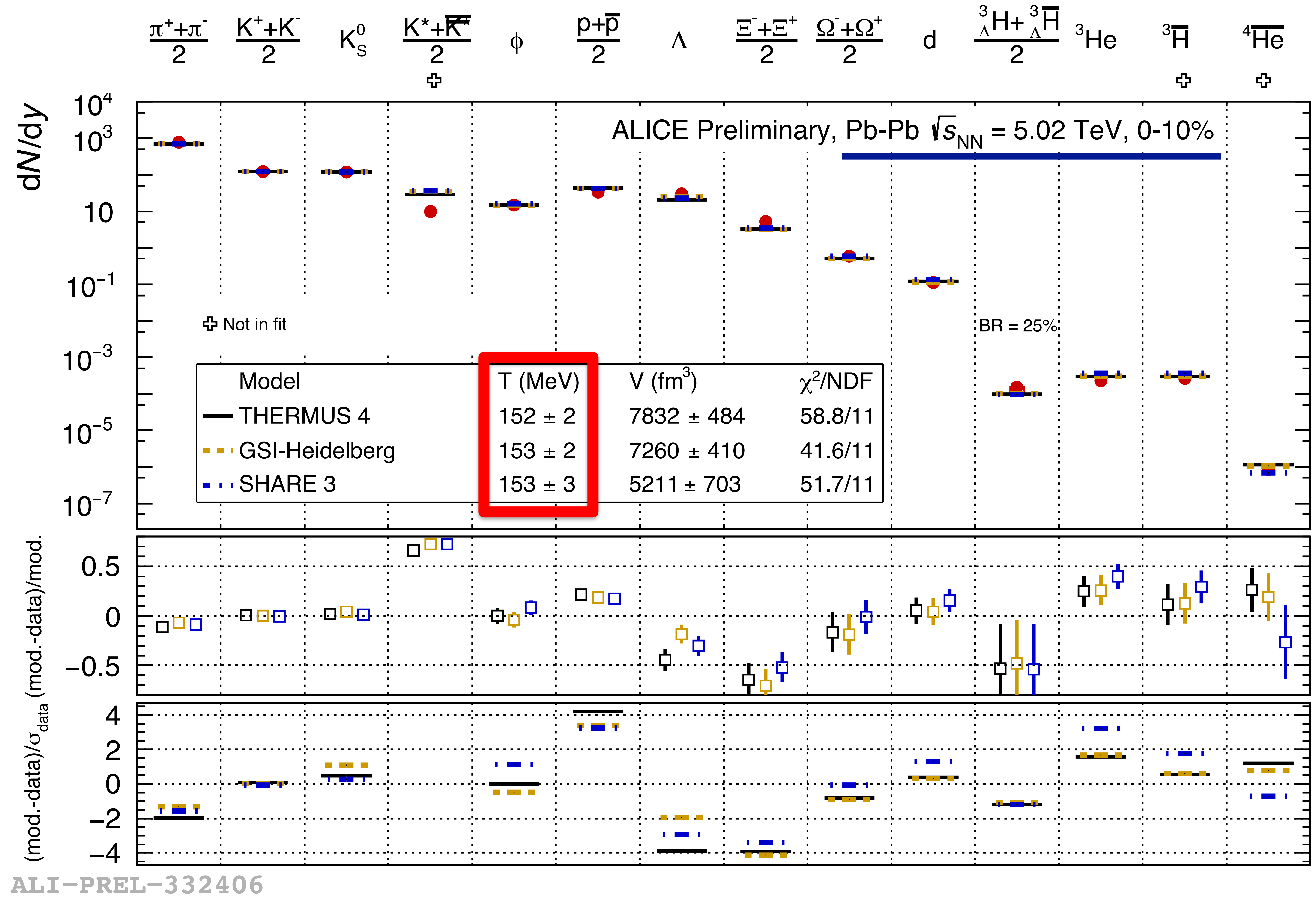






Statistical model of particle production

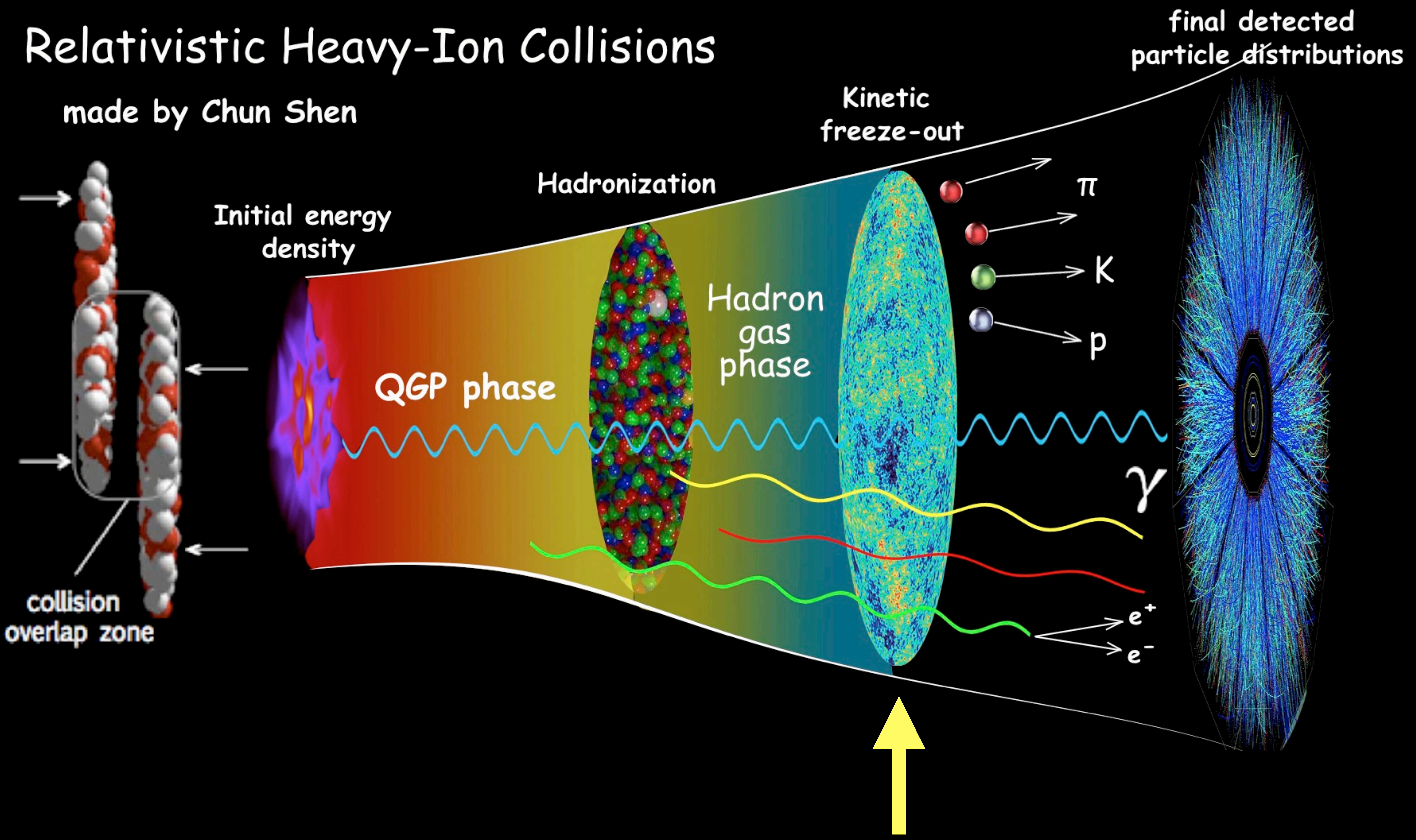
- Calculation of particle yields in thermal equilibrium with a common chemical freeze-out temperature (T_{chem}) shows excellent agreement with the data over seven orders of magnitude



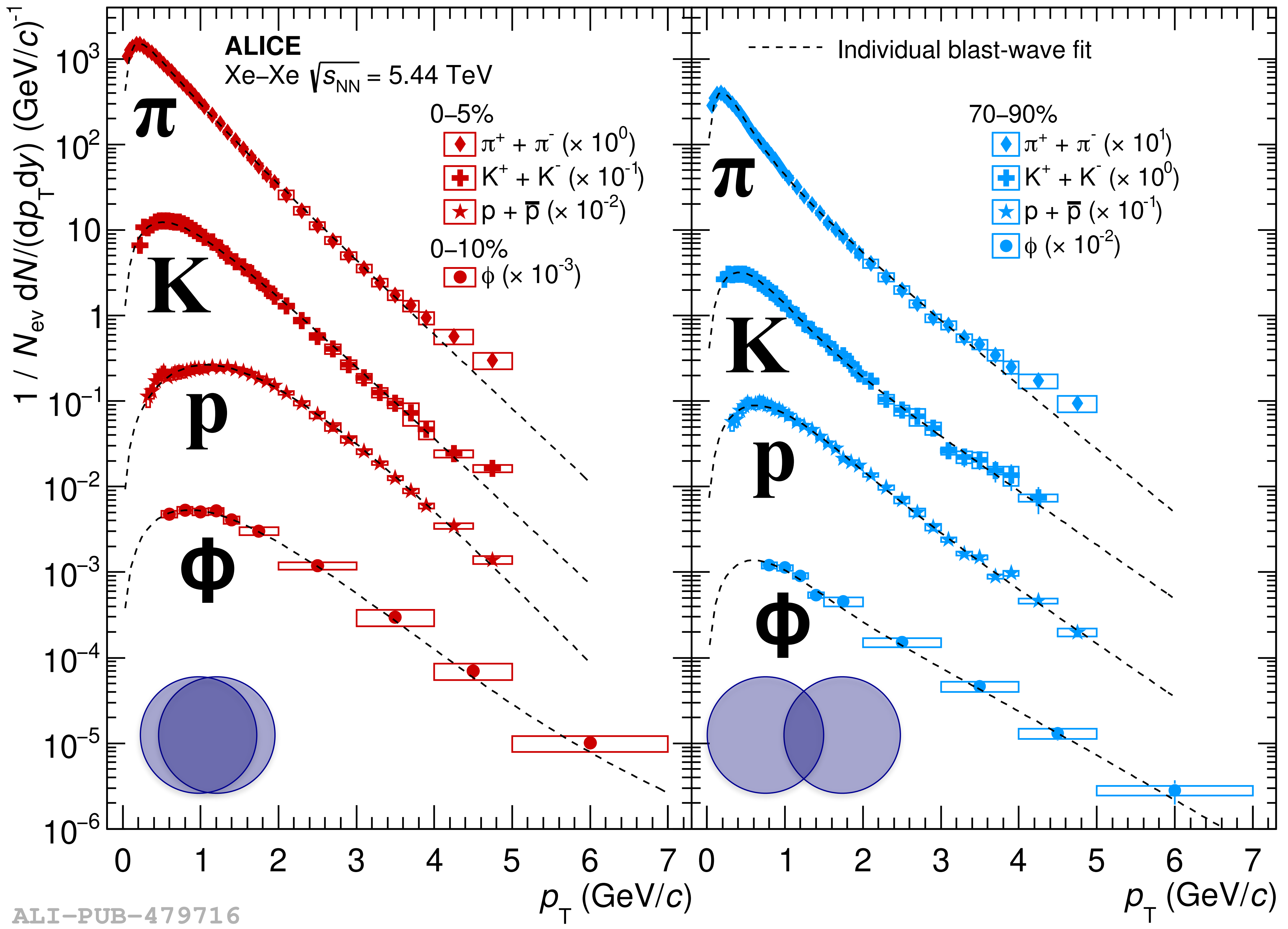
Pb-Pb $\sqrt{s_{NN}}$ = 2.76 TeV:
ALICE, Nucl. Phys. A 971 (2018) 1, arXiv:1710.07531 [nucl-ex]

Relativistic Heavy-Ion Collisions

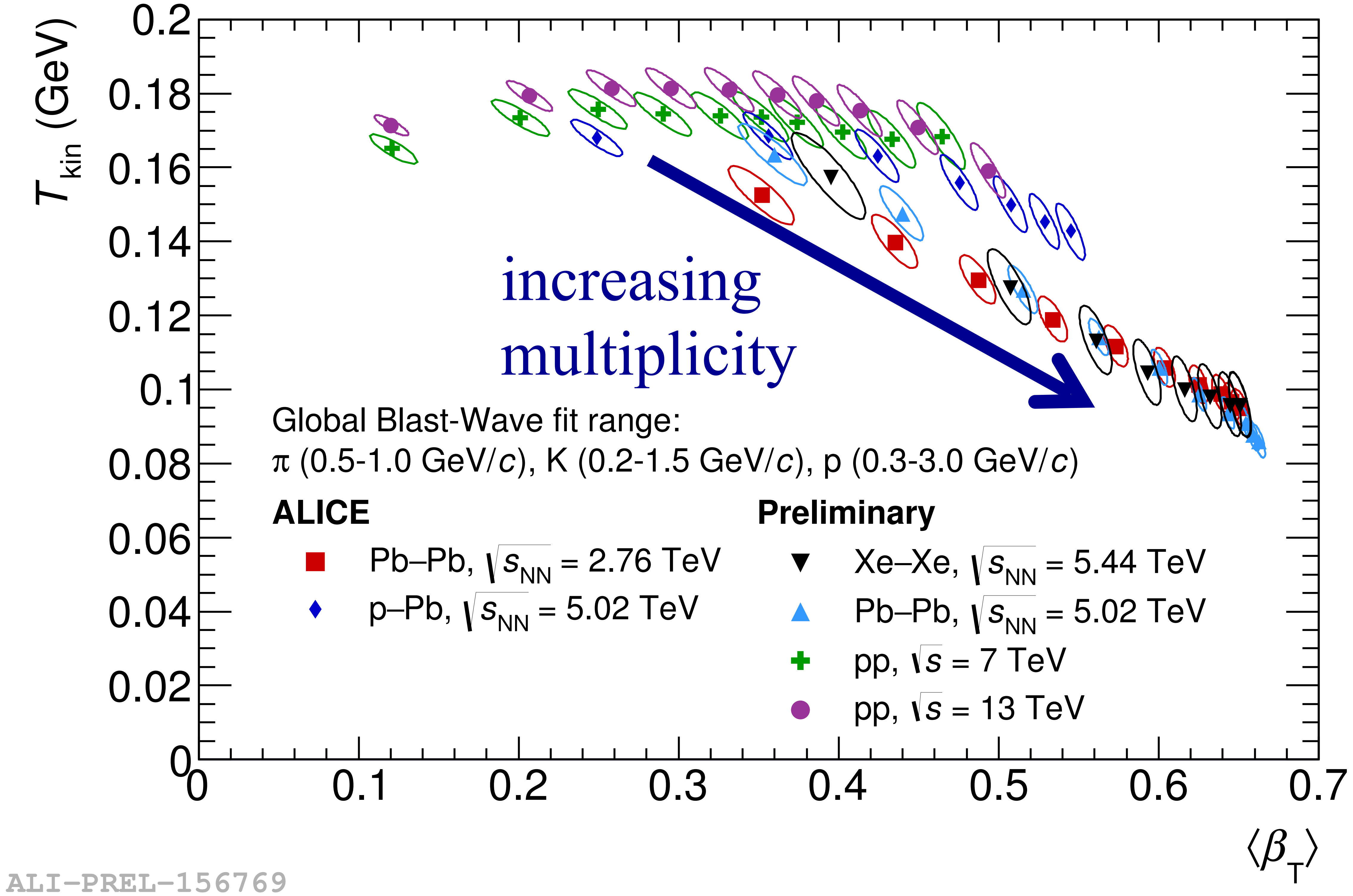
made by Chun Shen



Kinematics at kinetic freeze-out



ALICE, submitted to EPJC,
arXiv: 2101.03100 [nucl-ex]



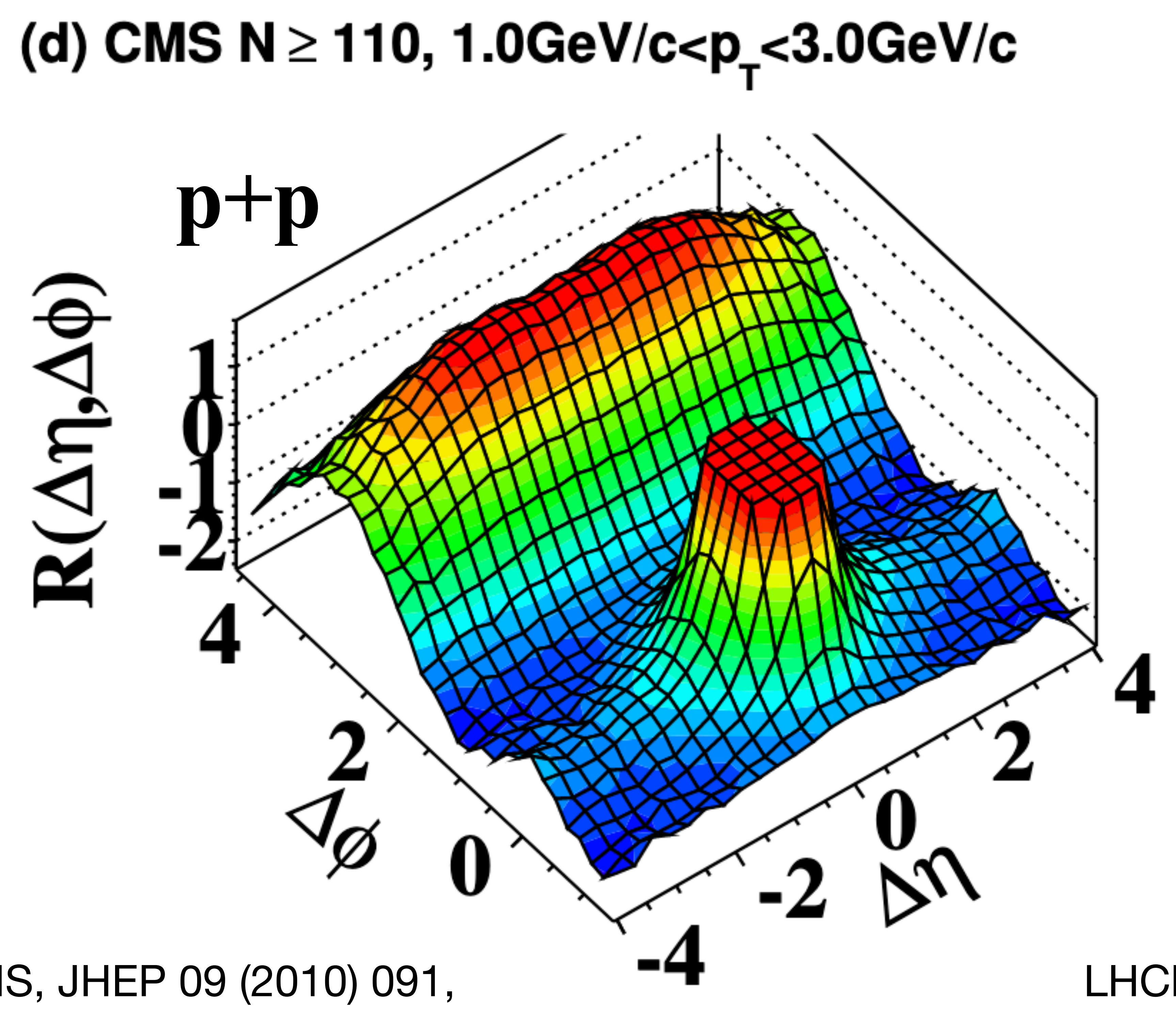
- Fit shape of p_T spectrum → probe final hadron kinematics at **kinetic freeze-out**
- Boltzmann-Gibbs Blast-Wave model: a simplified hydrodynamic model

- Simultaneous fit to π, K, p spectra to obtain
  - radial expansion velocity β_T
  - kinetic freeze-out temperature T_{kin}
- More central (higher multiplicity) events have lower T_{kin} and higher expansion rate

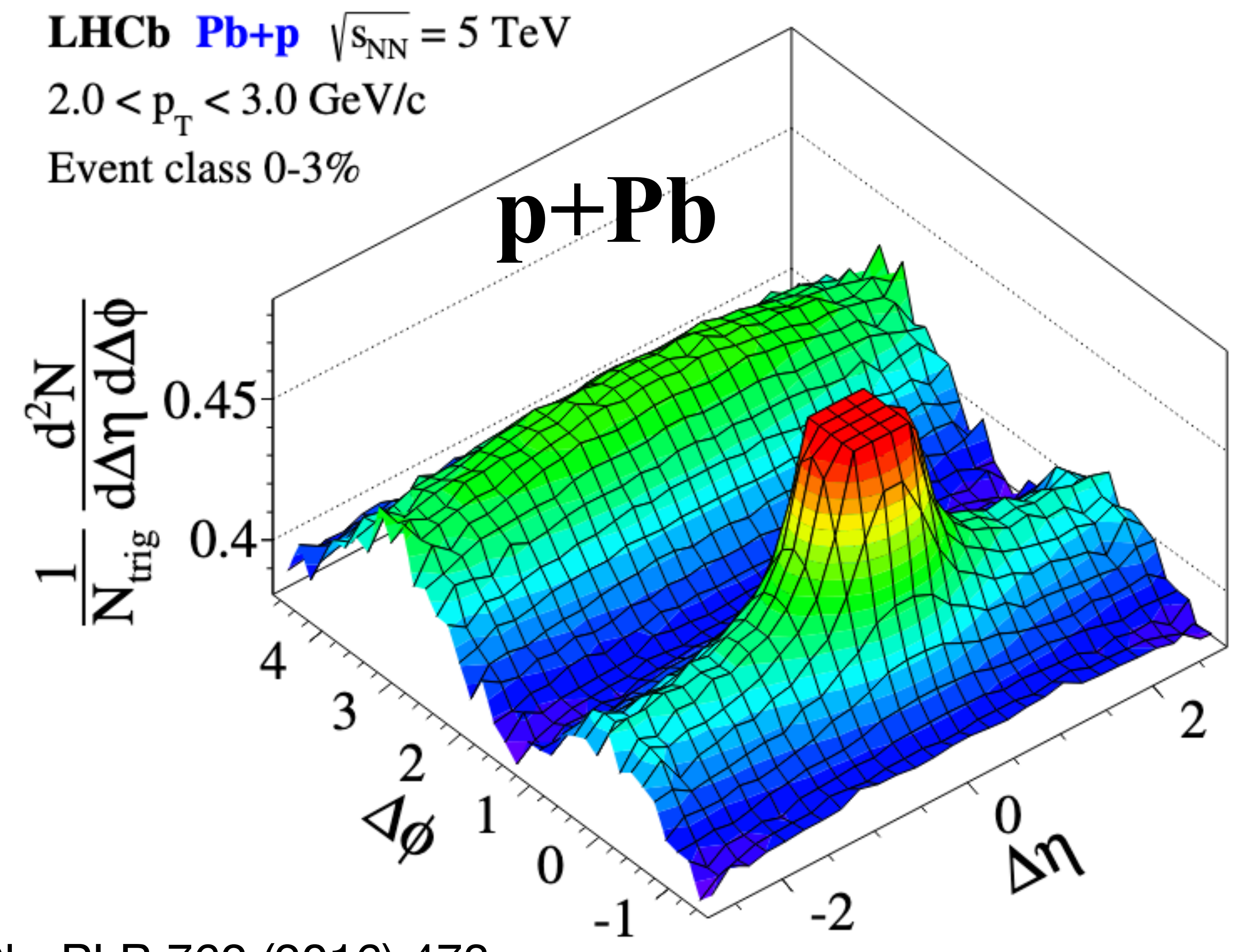
From large to small systems…

… and back again

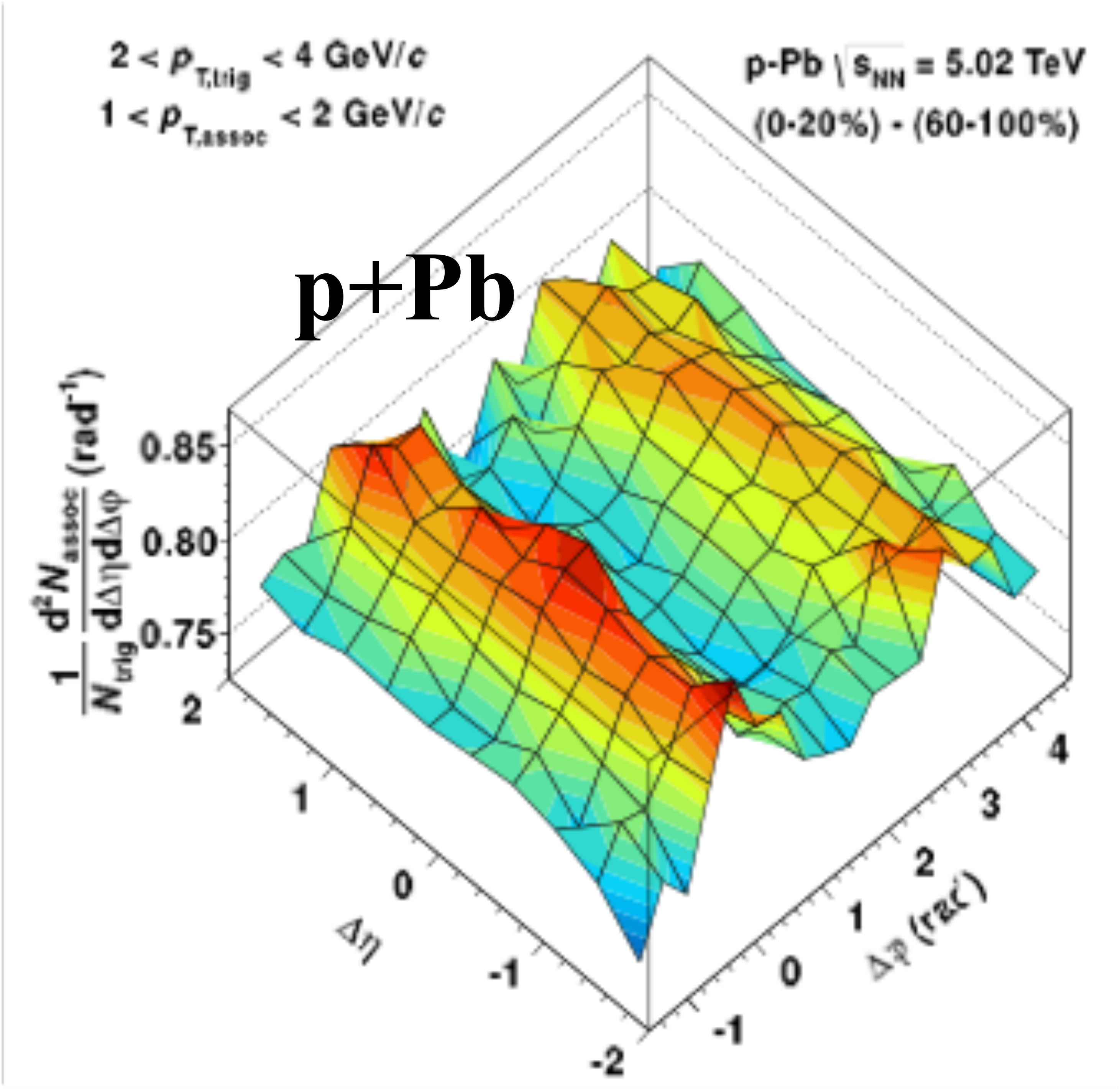
Collective behavior in small systems



CMS, JHEP 09 (2010) 091,
arXiv: 1009.4122 [hep-ex]



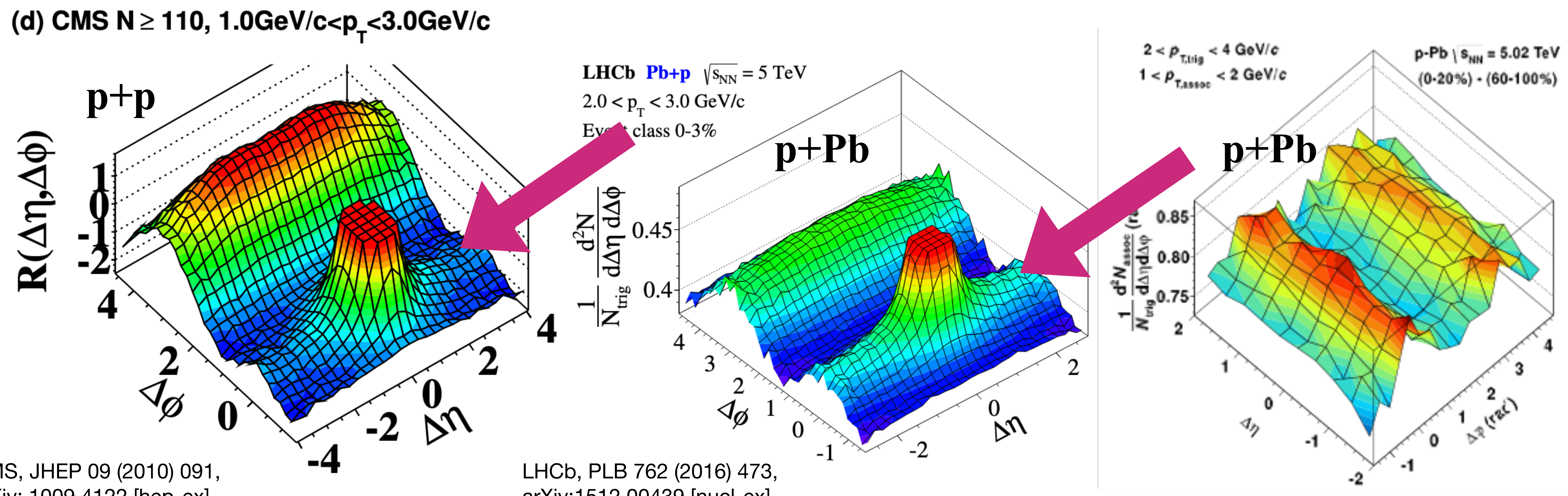
LHCb, PLB 762 (2016) 473,
arXiv:1512.00439 [nucl-ex]



ALICE, PLB 719 (2013) 29,
arXiv: 1212.2001 [nucl-ex]

- Flow-like (v_n) signals observed in high-multiplicity p+p and p+Pb collisions as well!

Collective behavior in small systems



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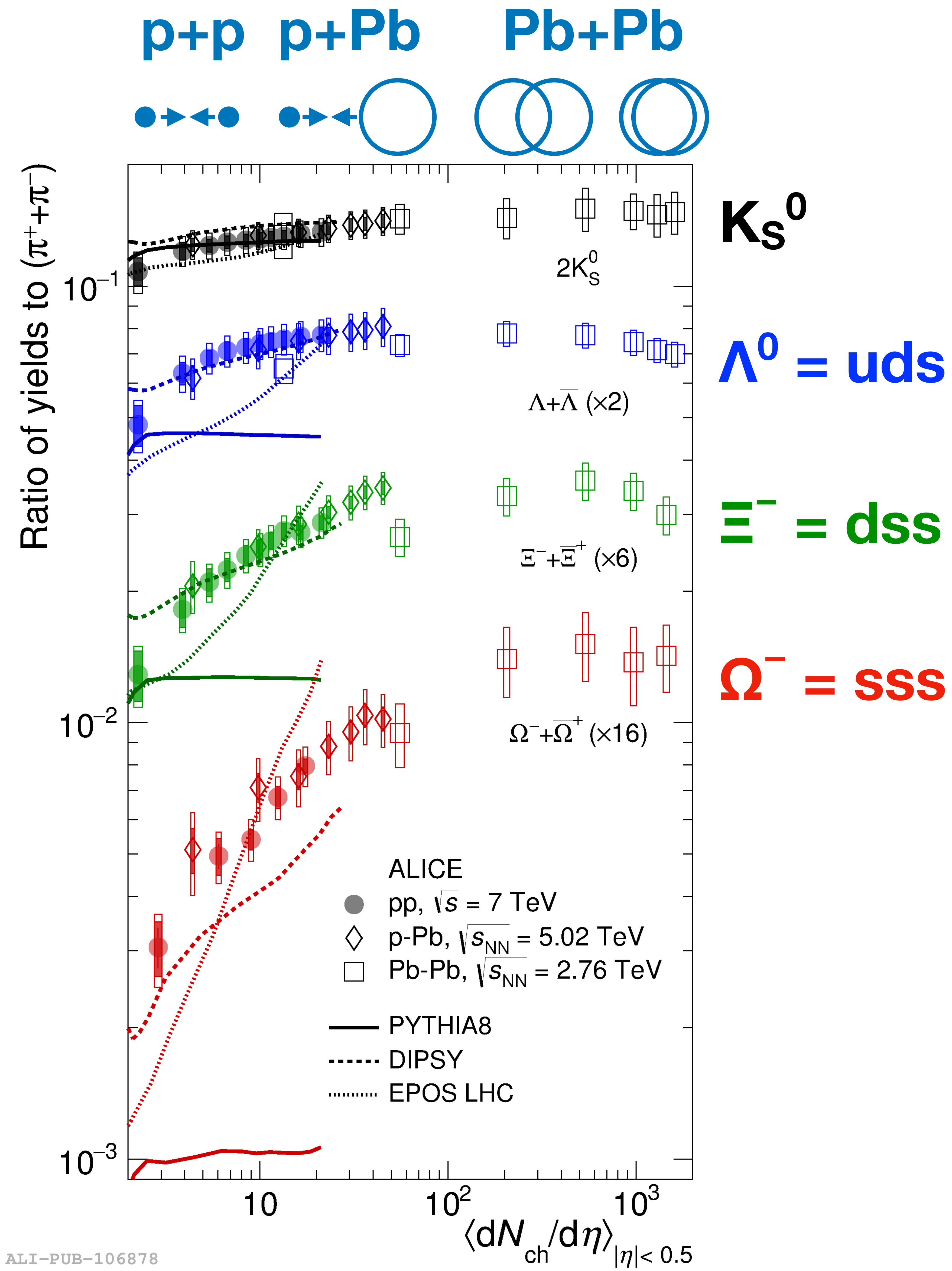
Strangeness enhancement in small systems

- Enhancement of strange particle yields in heavy-ion collisions (compared to p+p) viewed as a signature of QGP formation
  - (Now understood as a suppression of strangeness in p+p collisions due to their small size)
- The smooth increase of strange particle yields (w.r.t. pions) as a function of multiplicity was observed from p+p to p+Pb to Pb+Pb!



ALICE, Nature Physics 13 (2017) 535, arXiv: 1606.07424 [nucl-ex]

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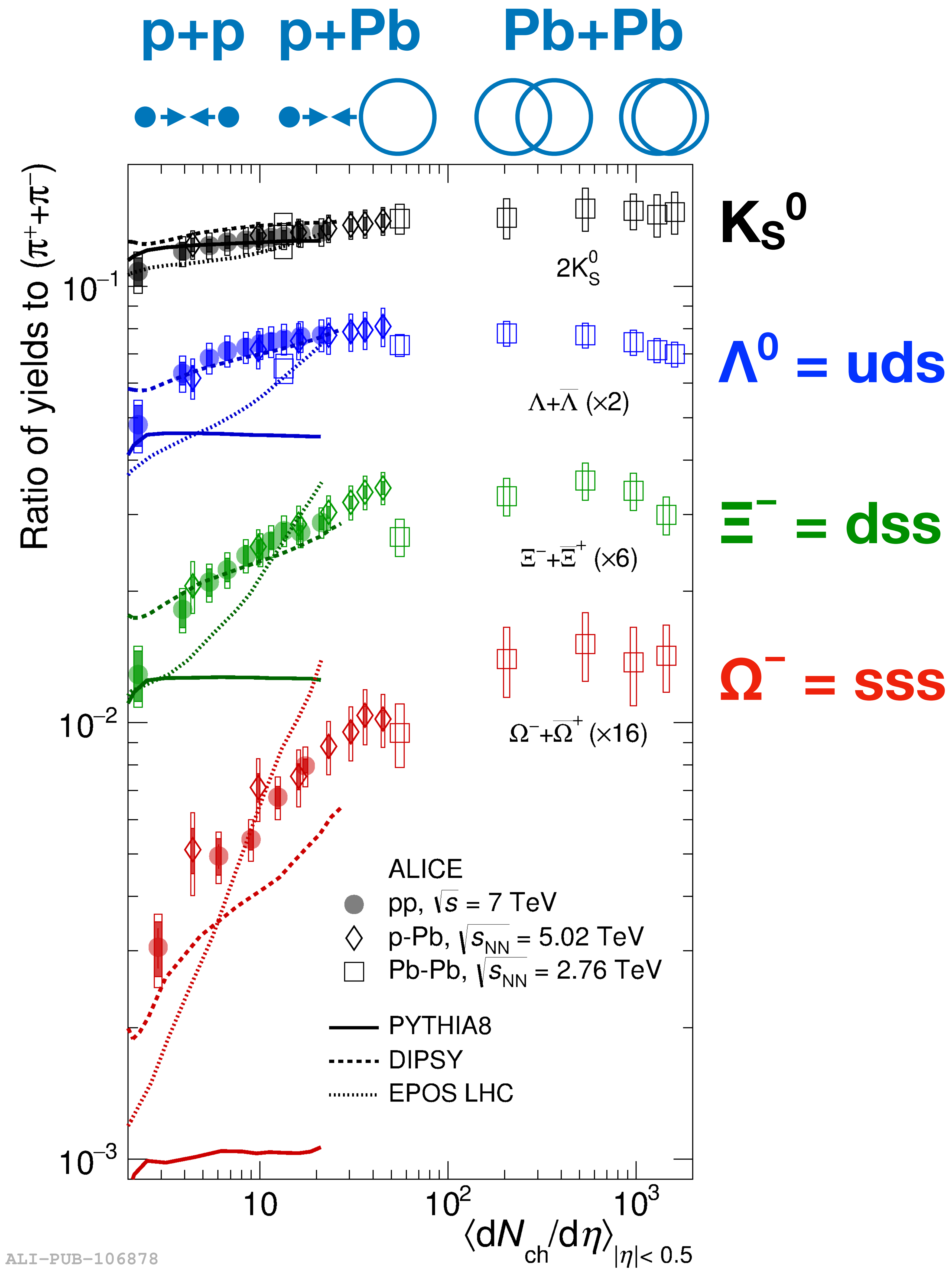
- Is there a non-hydrodynamic explanation for these signatures? (Is there an alternative description of heavy-ion collisions?)
- Is there QGP in small systems? (Is our understanding of p+p collisions incomplete?)



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How can our knowledge of heavy-ion collisions improve our understanding of p+p physics, and vice versa?

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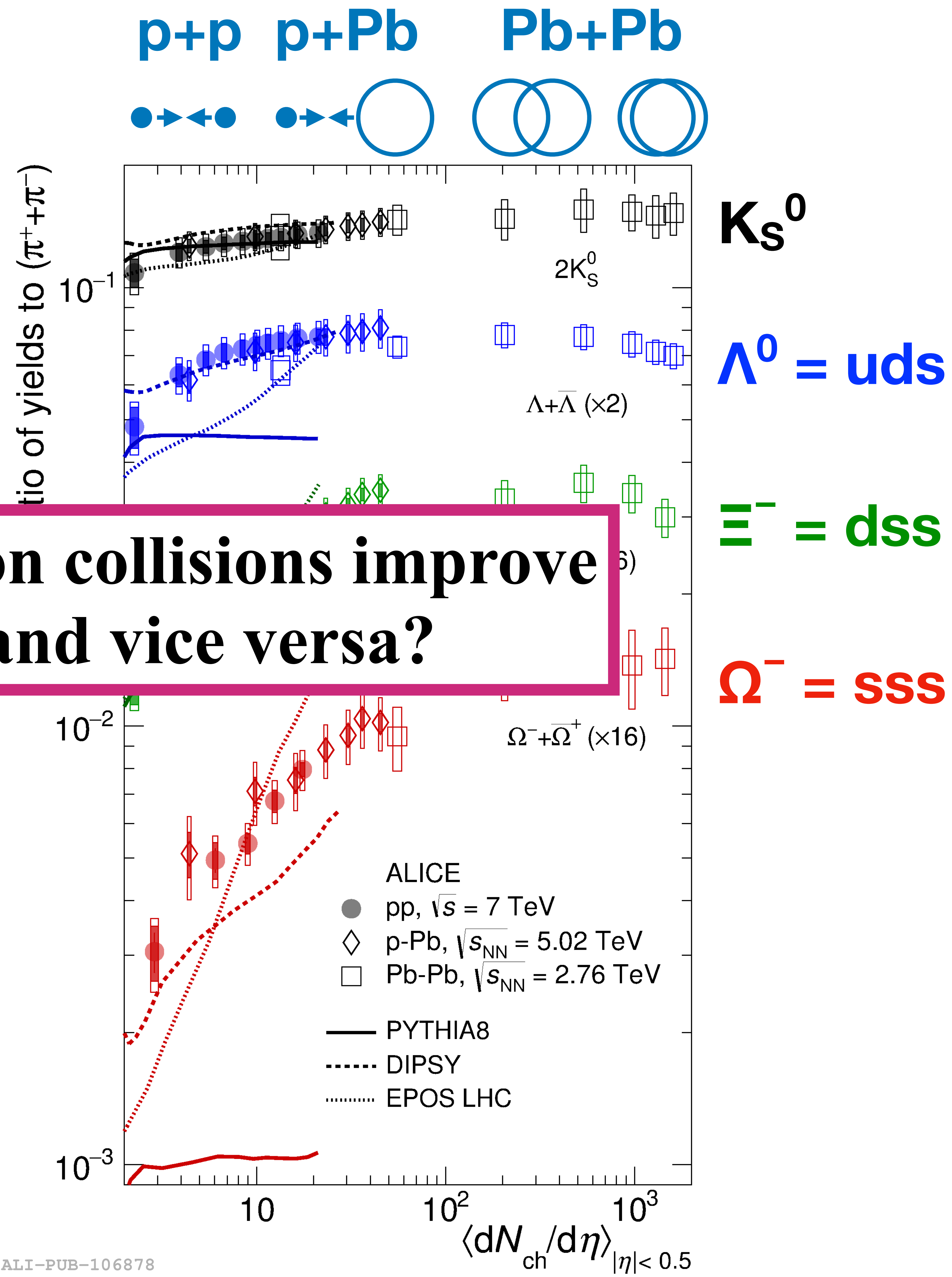

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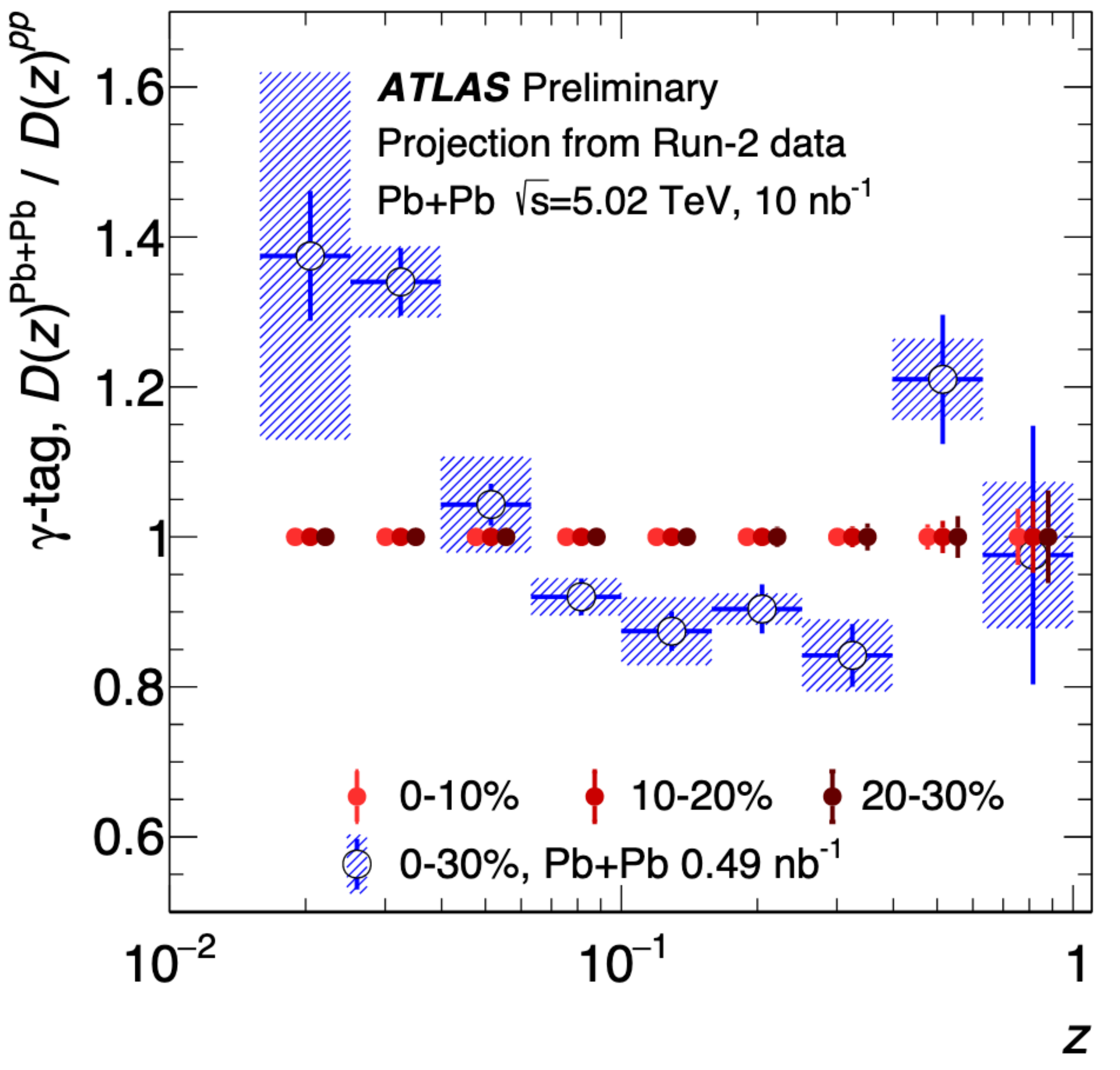
Heavy-ion physics in Run 3 and beyond

- 10x increase in luminosity in Runs 3+4 will enable us to make precision measurements of
  - jets → energy loss and modification
  - heavy-flavor hadrons → hard probe interactions with the medium, hadronization
  - correlations and fluctuations → explore the phase diagram
  - electromagnetic probes
  - and much more!

CERN Yellow Reports: Monographs 7 (2019) 1159, arXiv:1812.06772 [hep-ph]

- Small systems: collectivity/energy loss in p+p, p+Pb, O+O
- Major detector upgrades in order to take high-luminosity heavy-ion data and expand experimental reach
- Goal: unified description of the QGP from the macroscopic level to the fundamentals of QCD at the microscopic level



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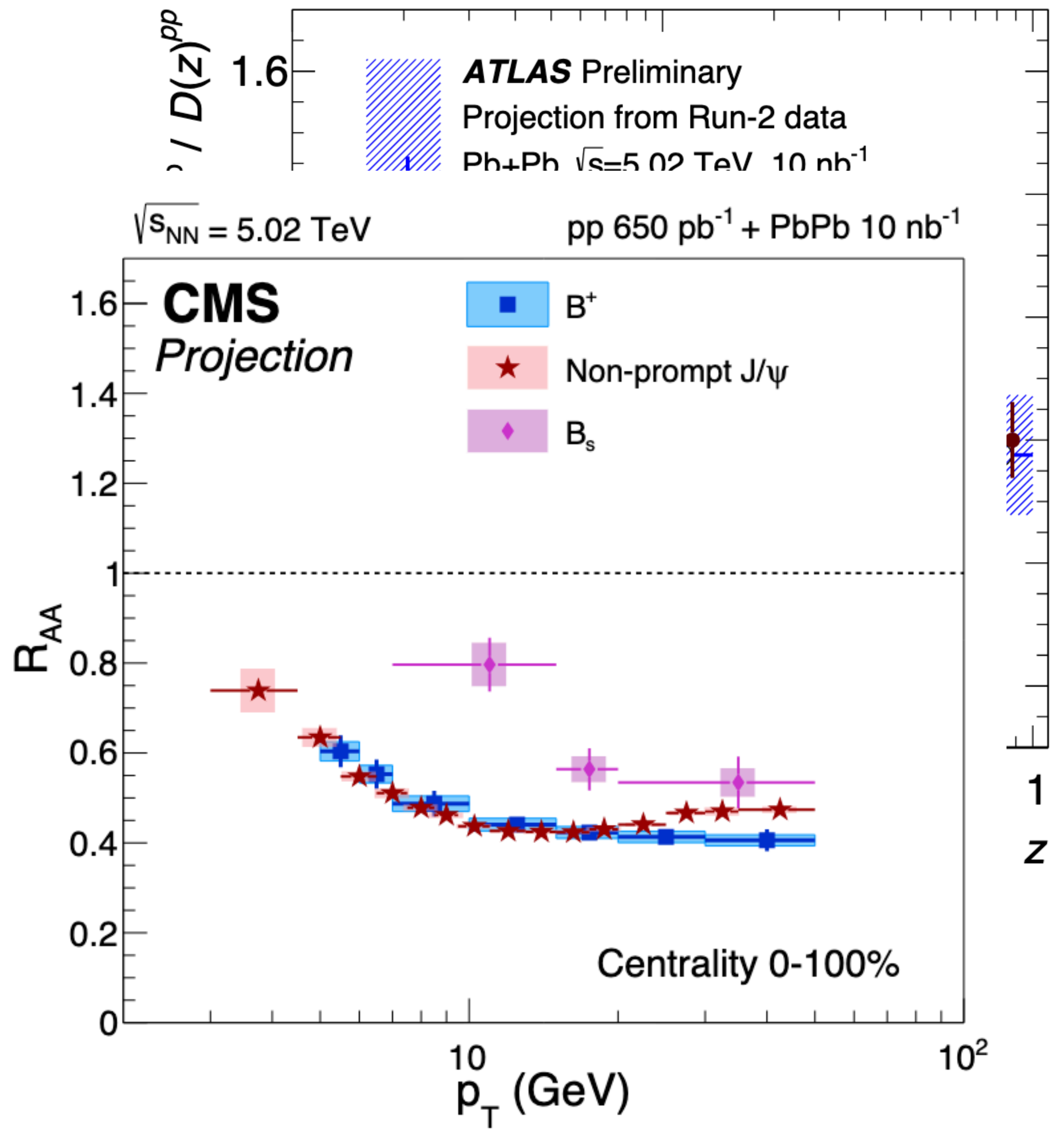

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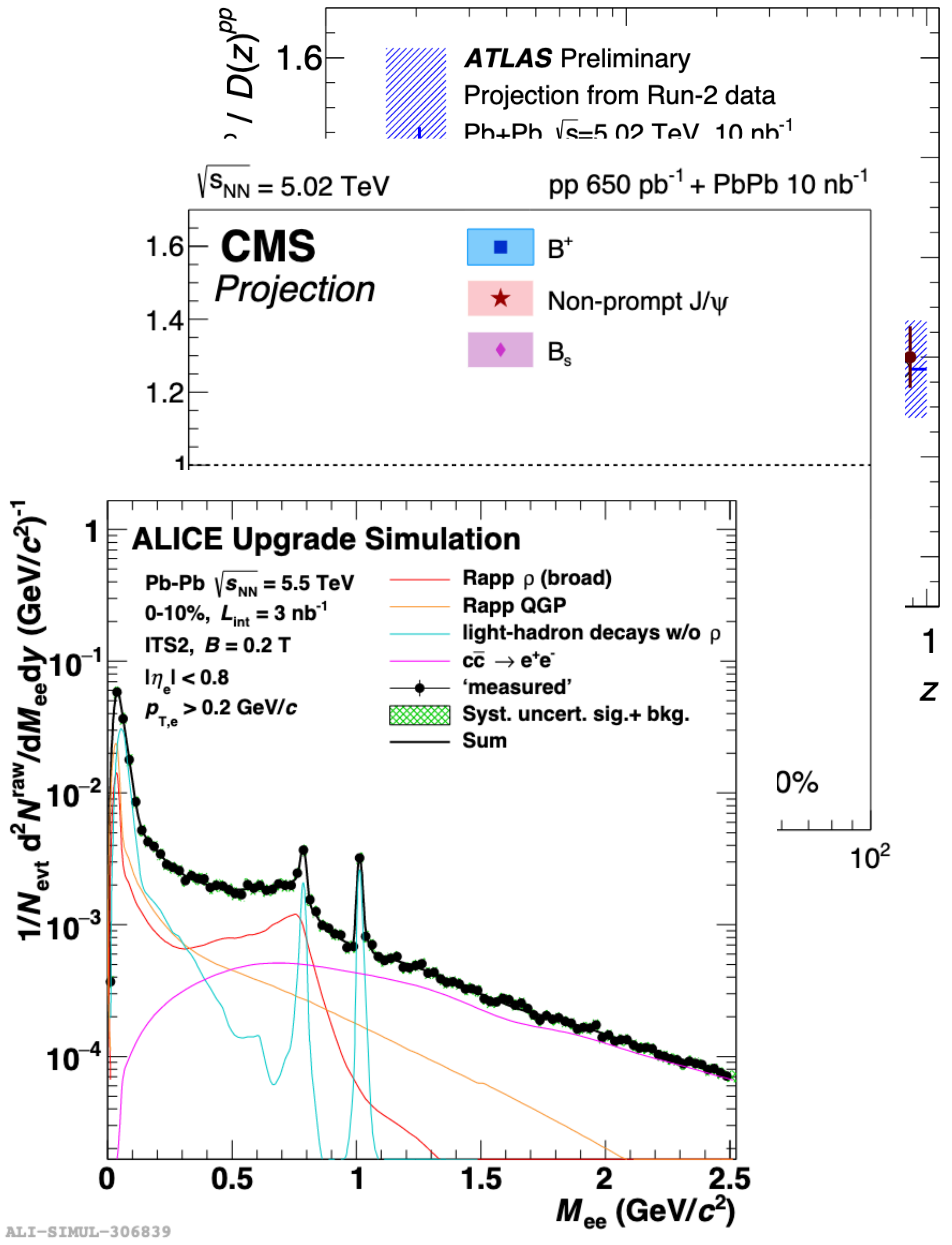

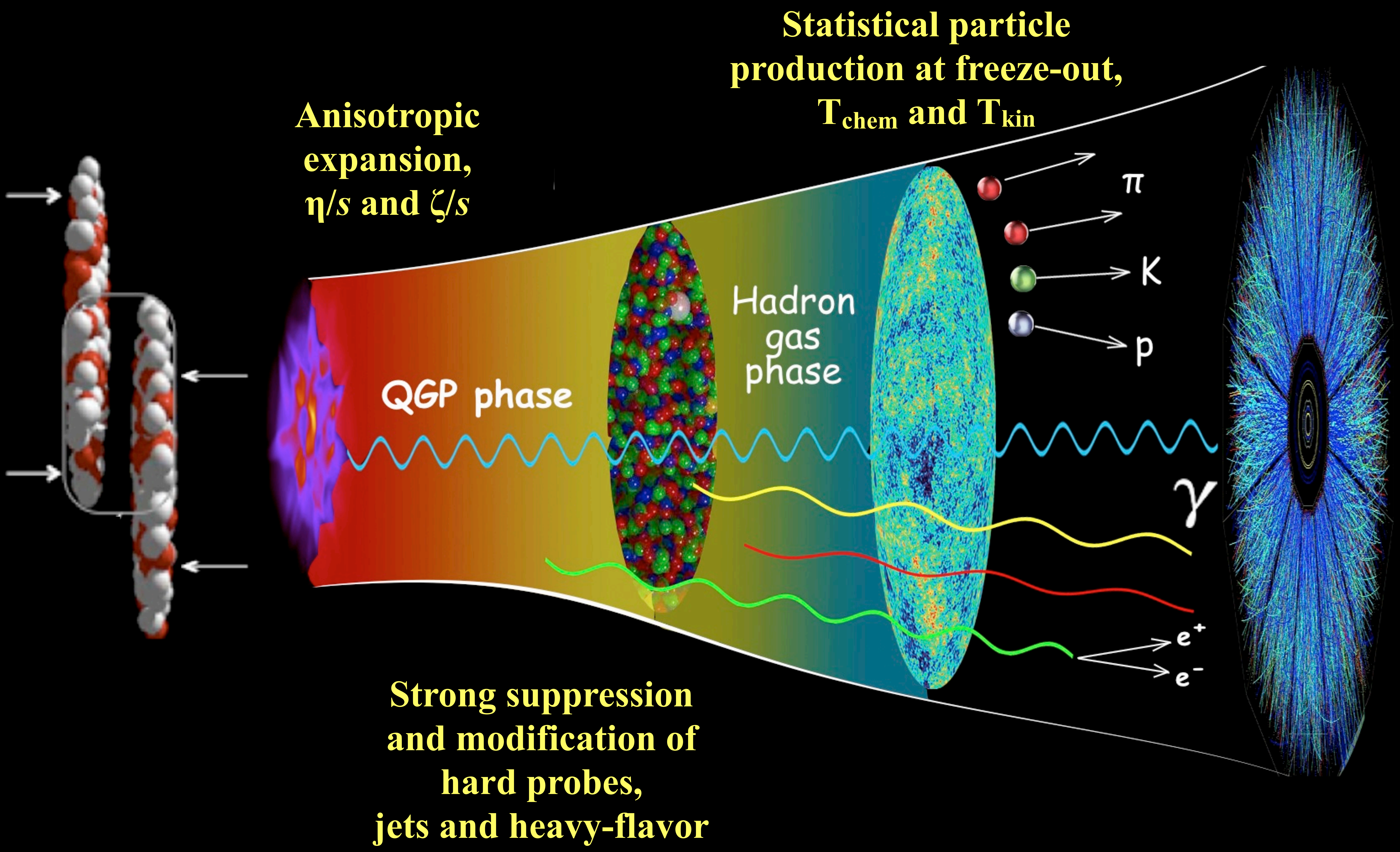
Statistical particle
production at freeze-out,
T_{chem} and T_{kin}
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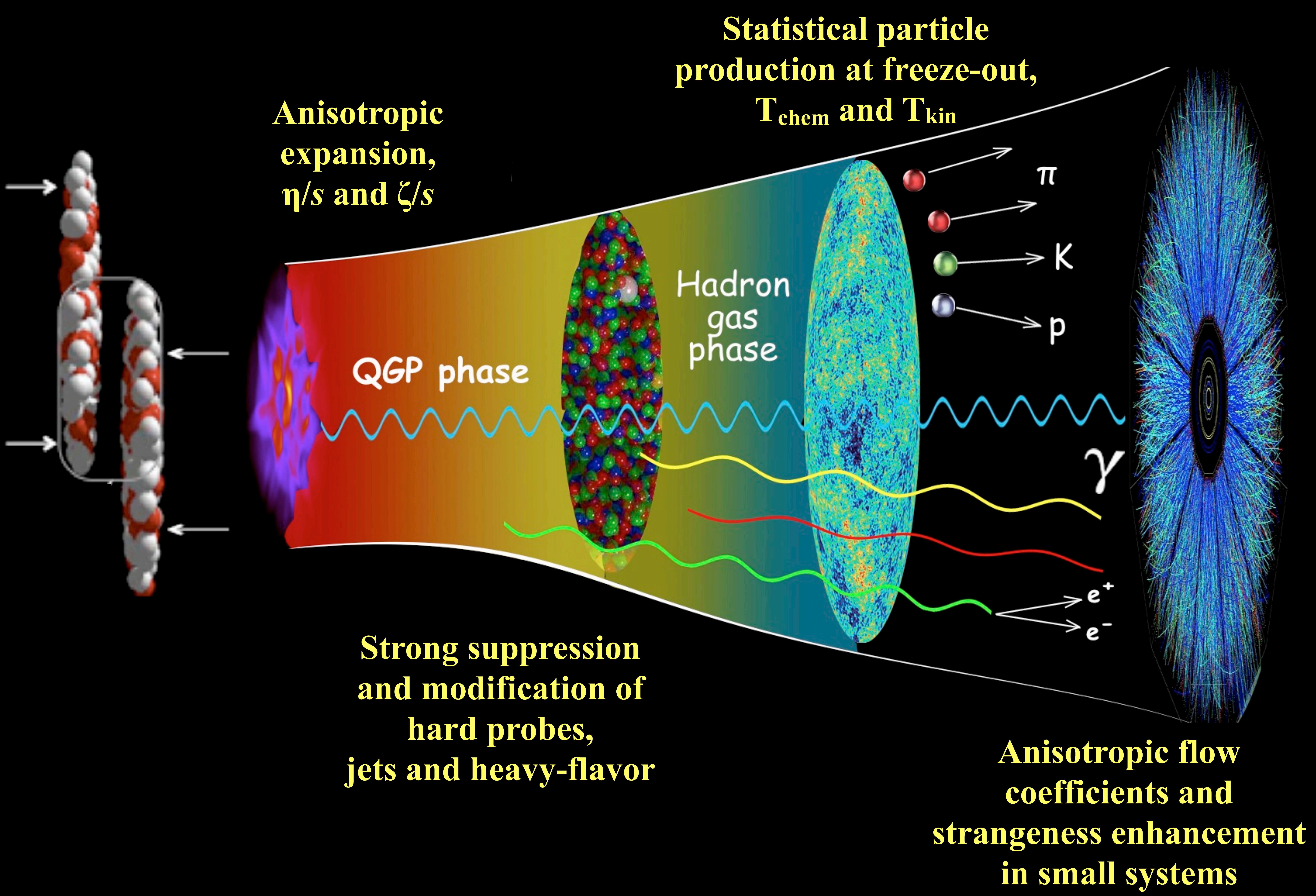
Anisotropic expansion, η/s and ζ/s
Statistical particle production at freeze-out, T_{chem} and T_{kin}
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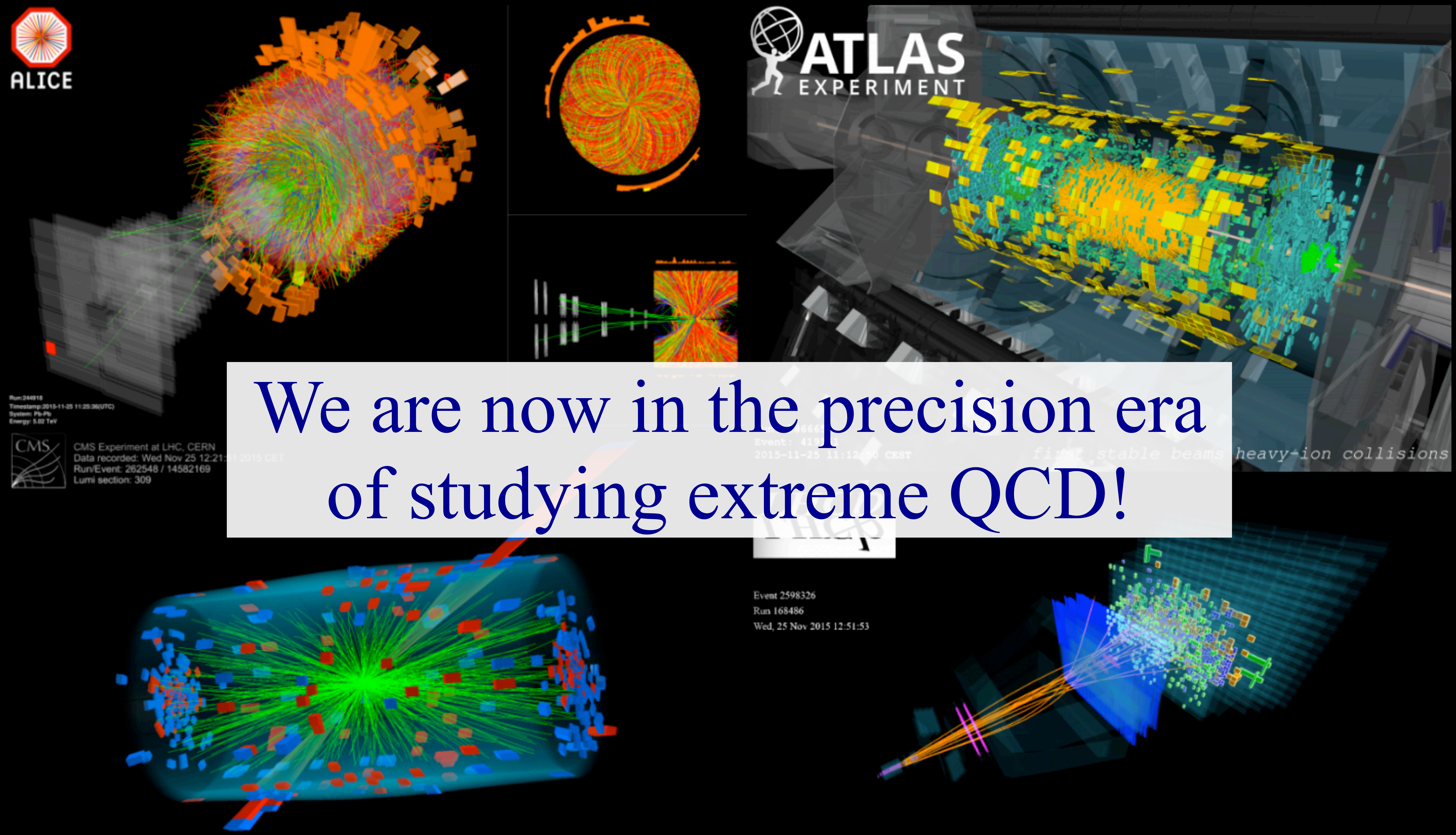

We are now in the precision era of studying extreme QCD!