High-Density QCD with Proton and Ion beams
— an experimental perspective —

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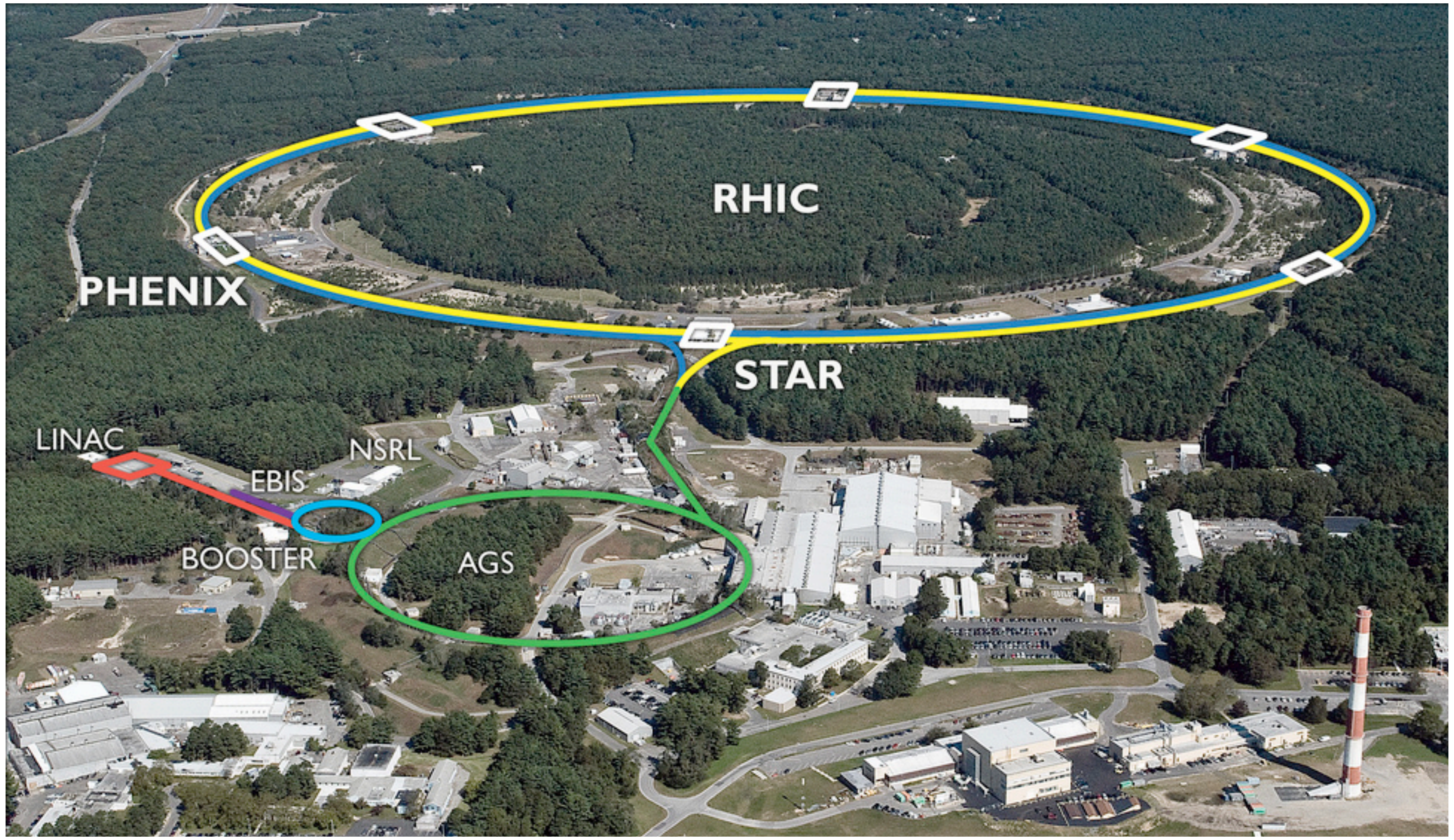
CERN-Fermilab Hadron Collider Physics Summer School

2 September 2021

Heavy-ion colliders



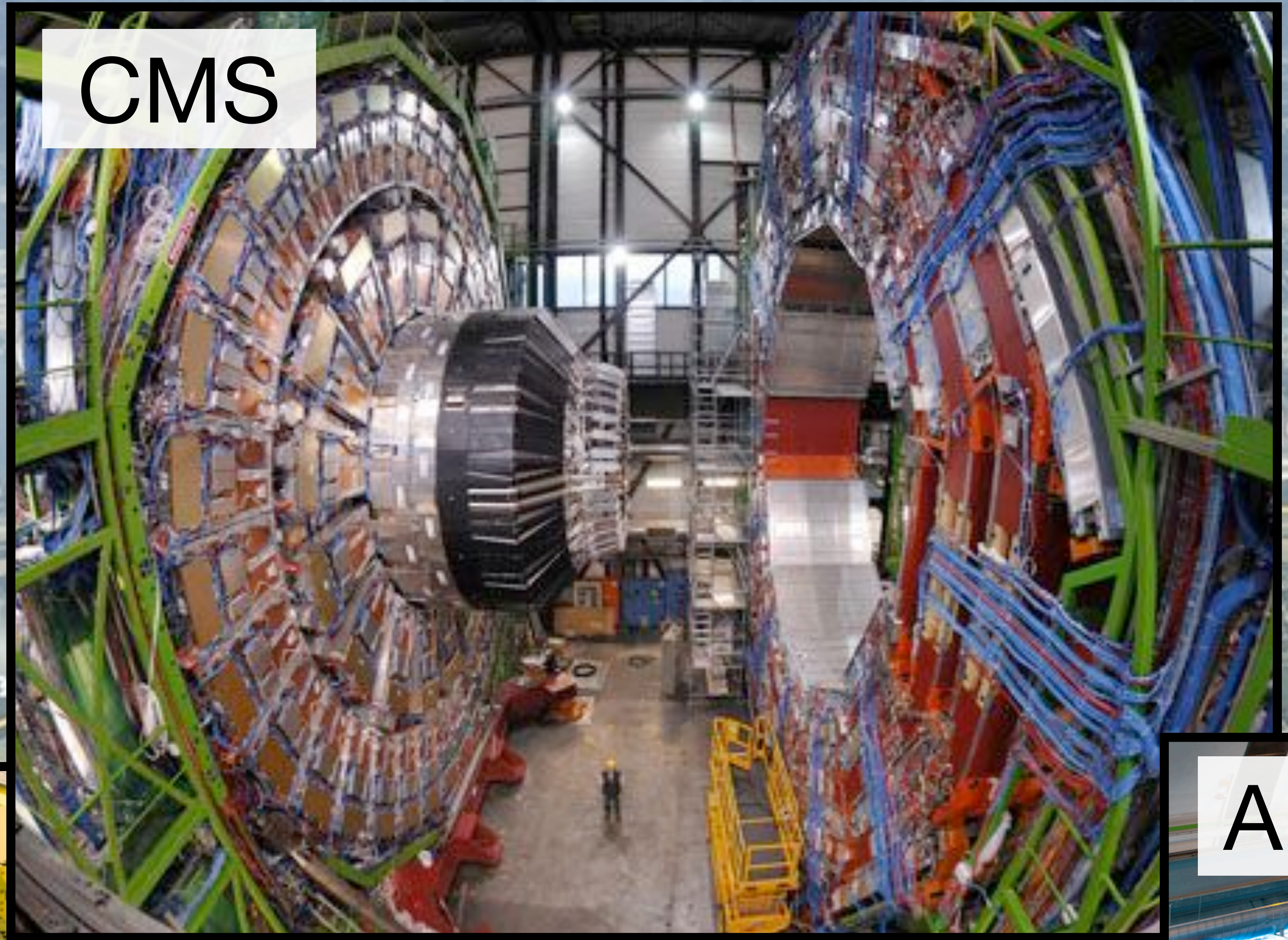
Relativistic Heavy Ion Collider

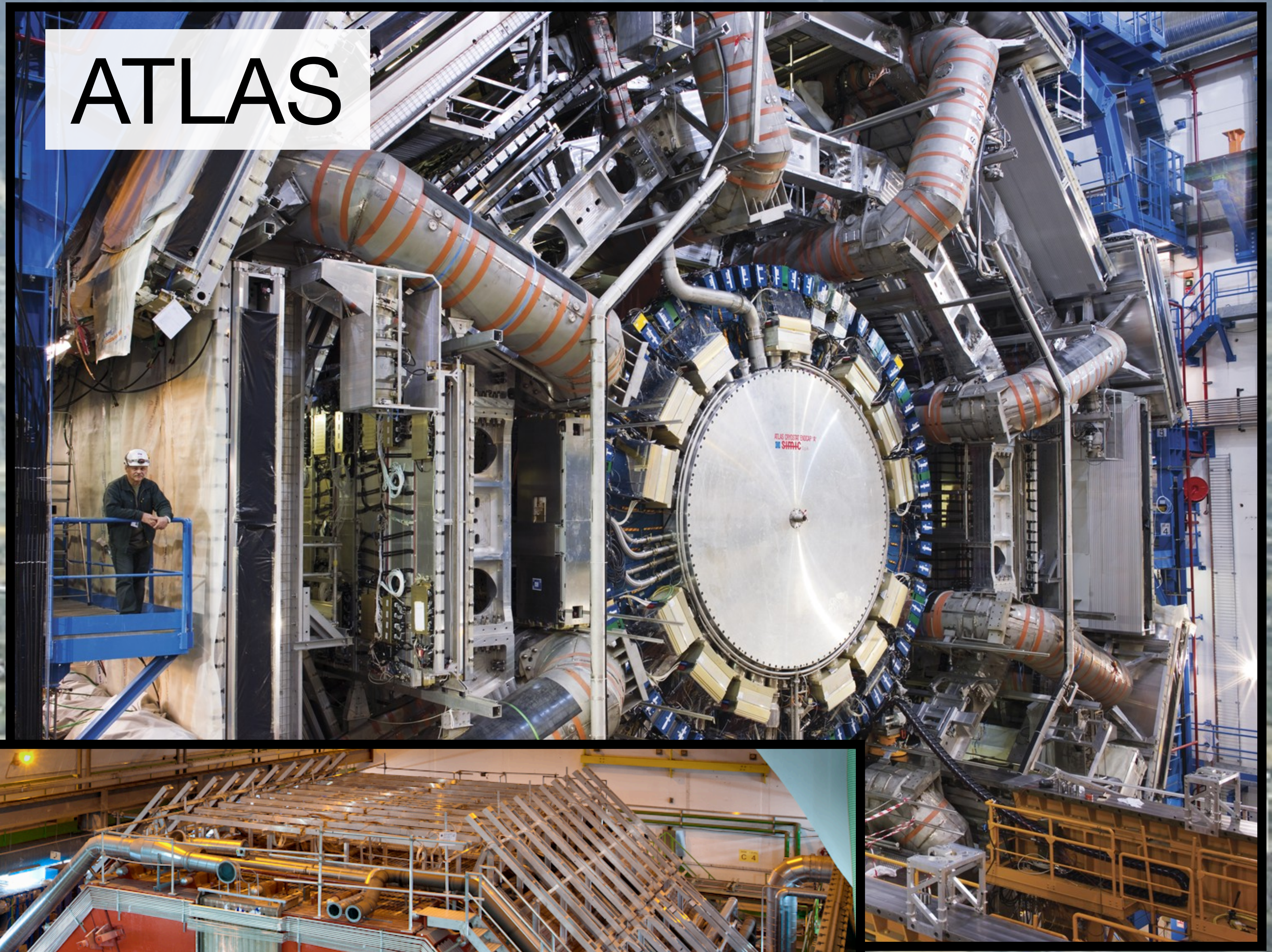
- 3.8 km circumference
- Au+Au collisions @ $\sqrt{s_{NN}}$ = 7.7 – 200 GeV
- also p+p, p+Au, d+Au, ^{3}He+Au, Cu+Cu, Cu+Au, U+U

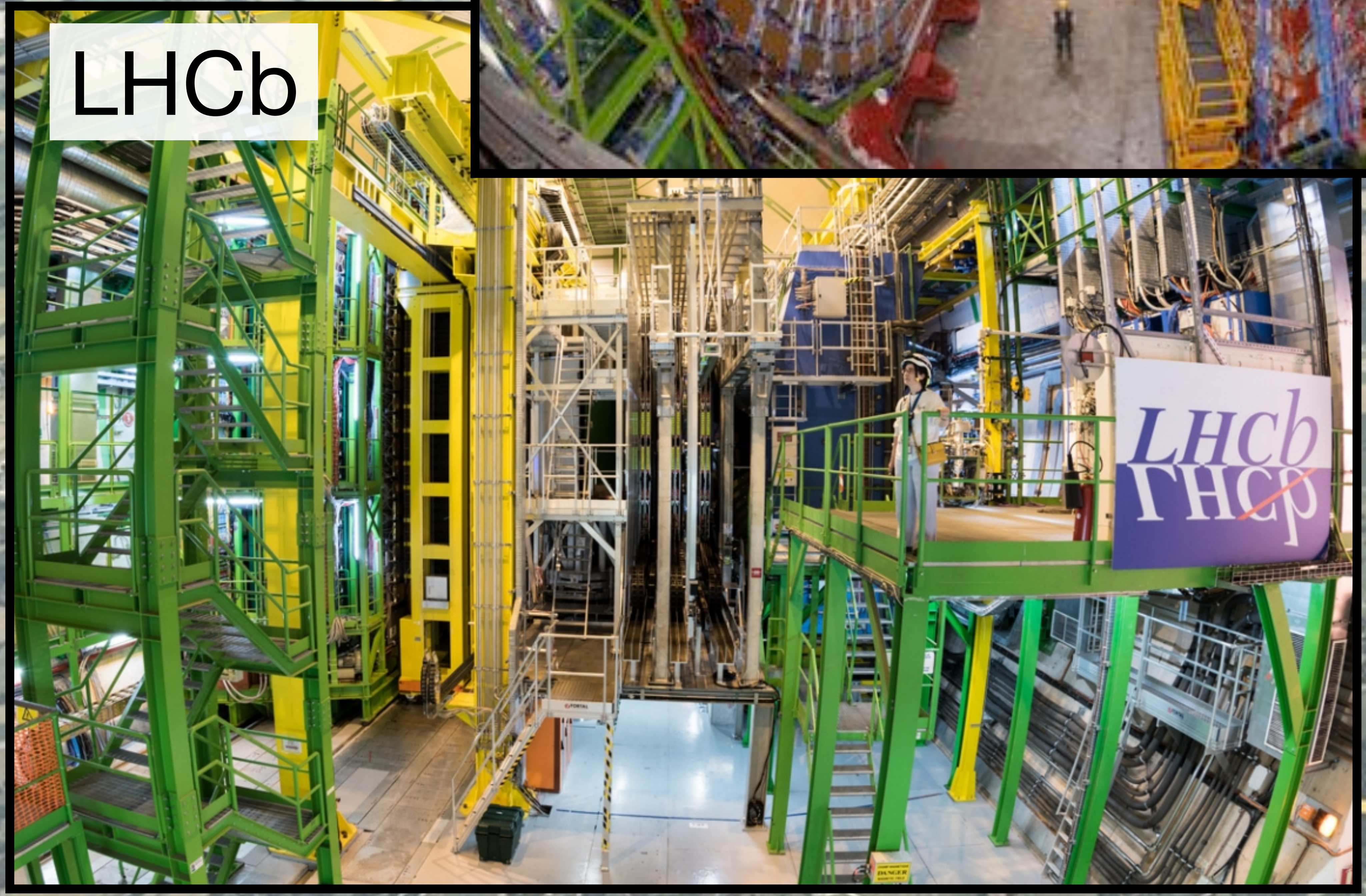
Large Hadron Collider

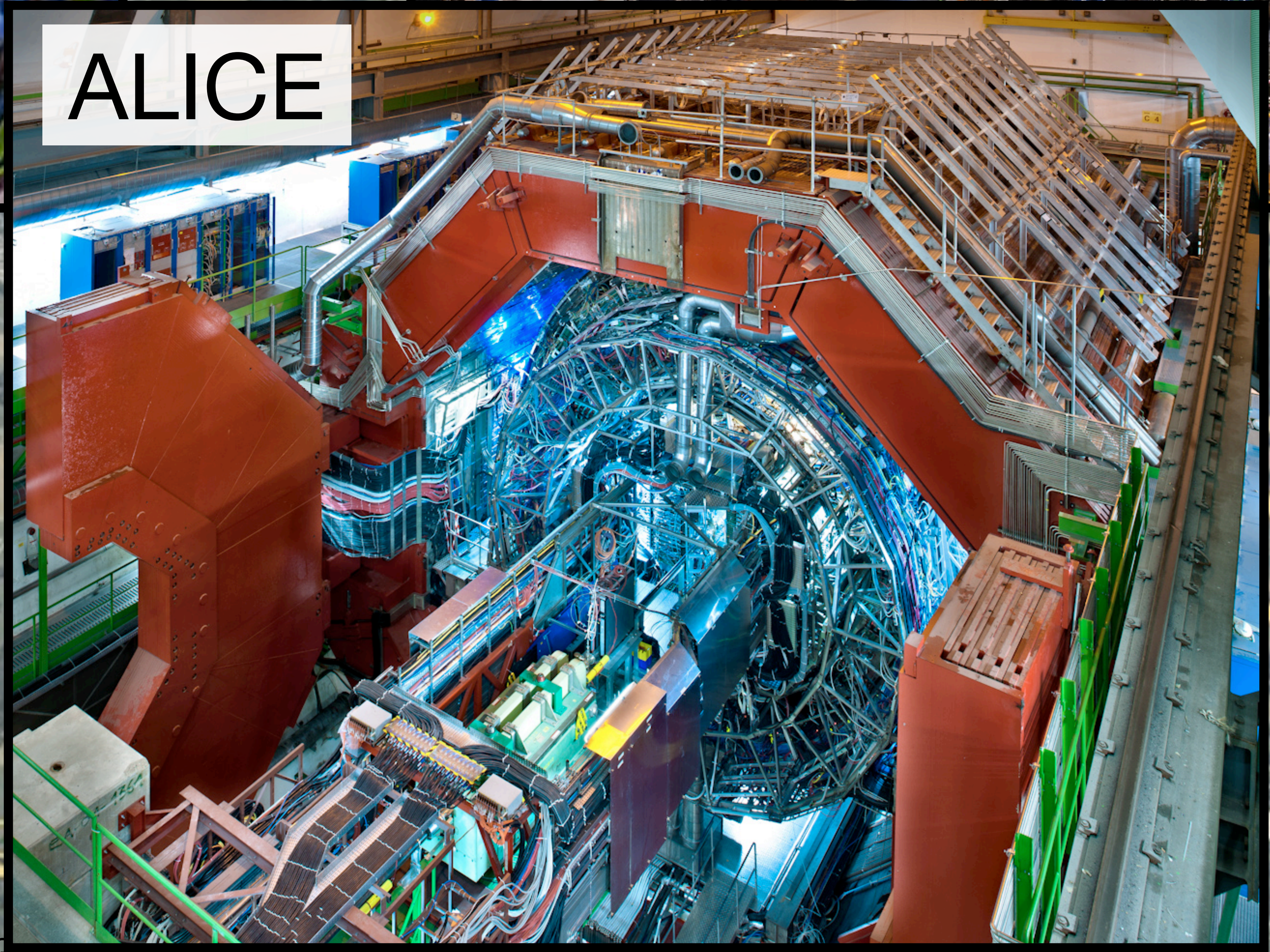
- 27 km circumference
- Pb+Pb collisions @ $\sqrt{s_{NN}}$ = 2.76, 5 TeV
- also p+p, p+Pb, Xe+Xe

Heavy-ion detectors at the LHC









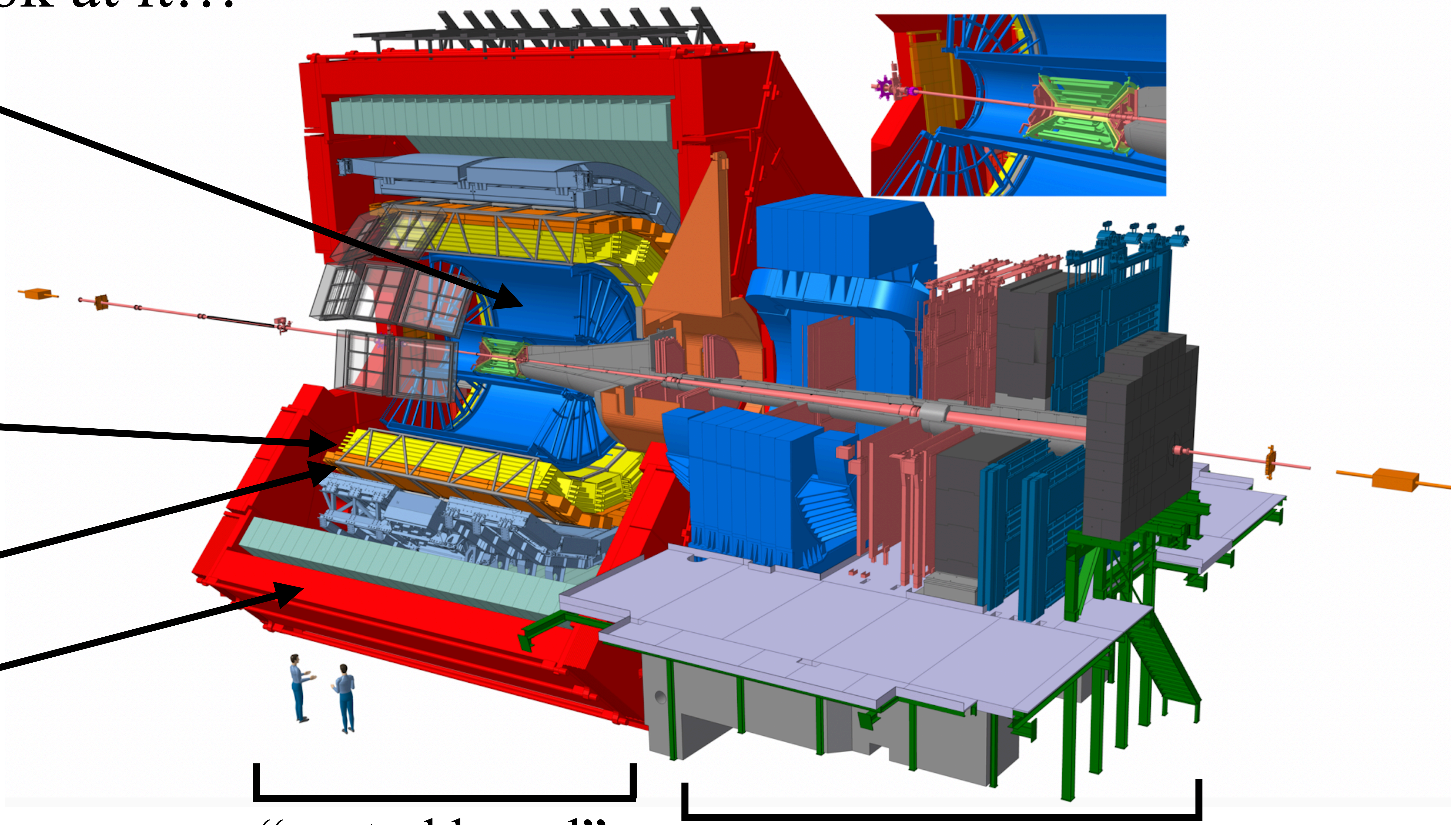
How to build a heavy-ion detector

- Physics goals are different for heavy-ions and high-energy physics
  → different detector priorities (speaking in very broad generalities here…)

HEP (e.g. CMS/ATLAS)	**HIP** (e.g. ALICE)
more emphasis on hard (high-q^2) probes: measure high-p_T jets and single particles	more emphasis on soft (non-perturbative) regime: measure particles down to low p_T
looking for rare probes: need fast triggers with high rejection factors	minimum-bias events are still interesting, also low-p_T signals which are challenging to trigger on
emphasis on distinguishing hadrons, leptons, jets	emphasis on identifying hadron species
want to cover full phase space, detector should be almost hermetic	emphasis on mid-rapidity measurements

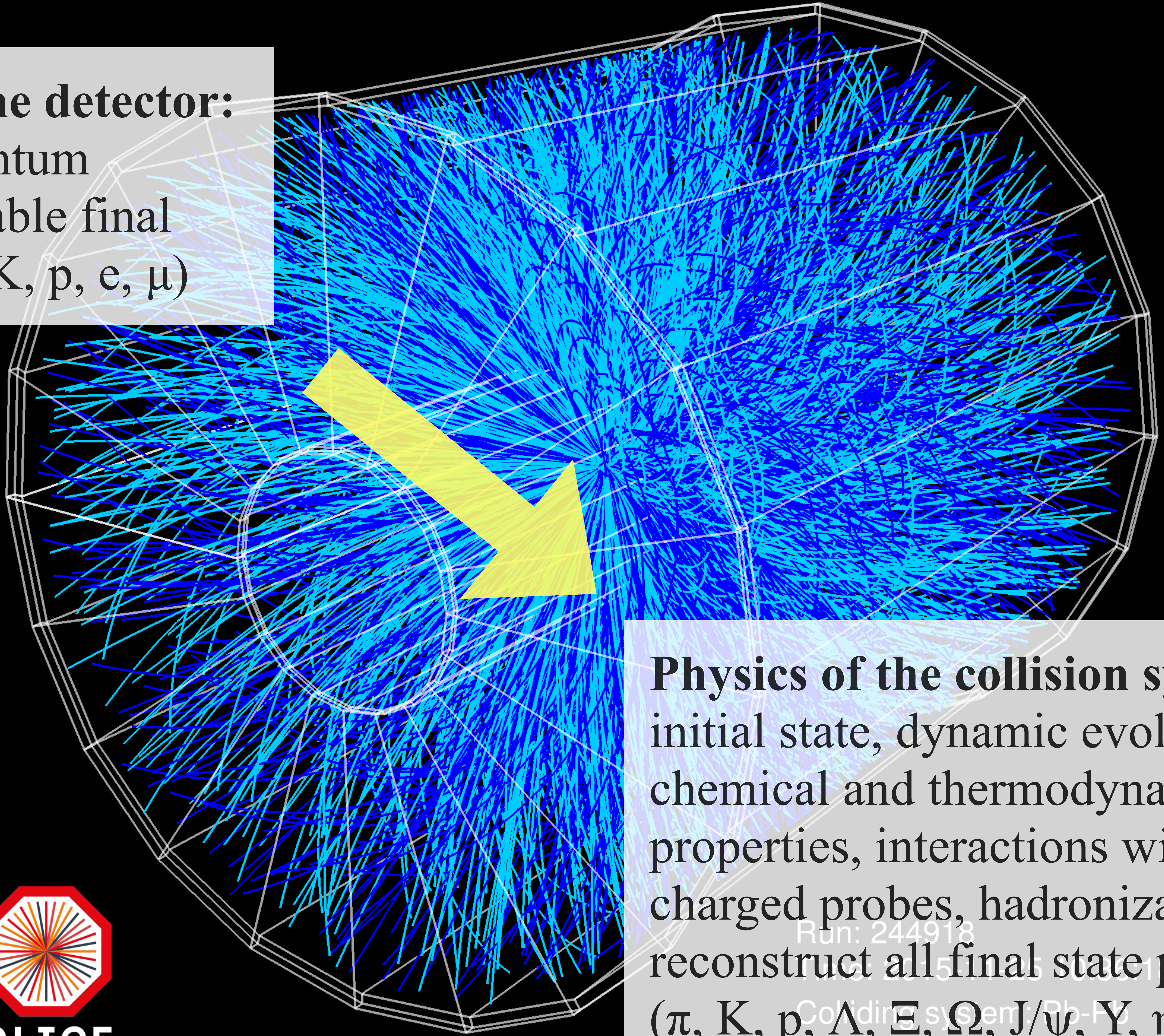
How to build a heavy-ion detector

- ALICE is the dedicated heavy-ion detector at the LHC, built specifically for this purpose, so let's take a closer look at it…



- Reminder: ATLAS/CMS are also excellent detectors for heavy-ion physics, and the different detector capabilities and strengths lead to complementary physics programs!

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

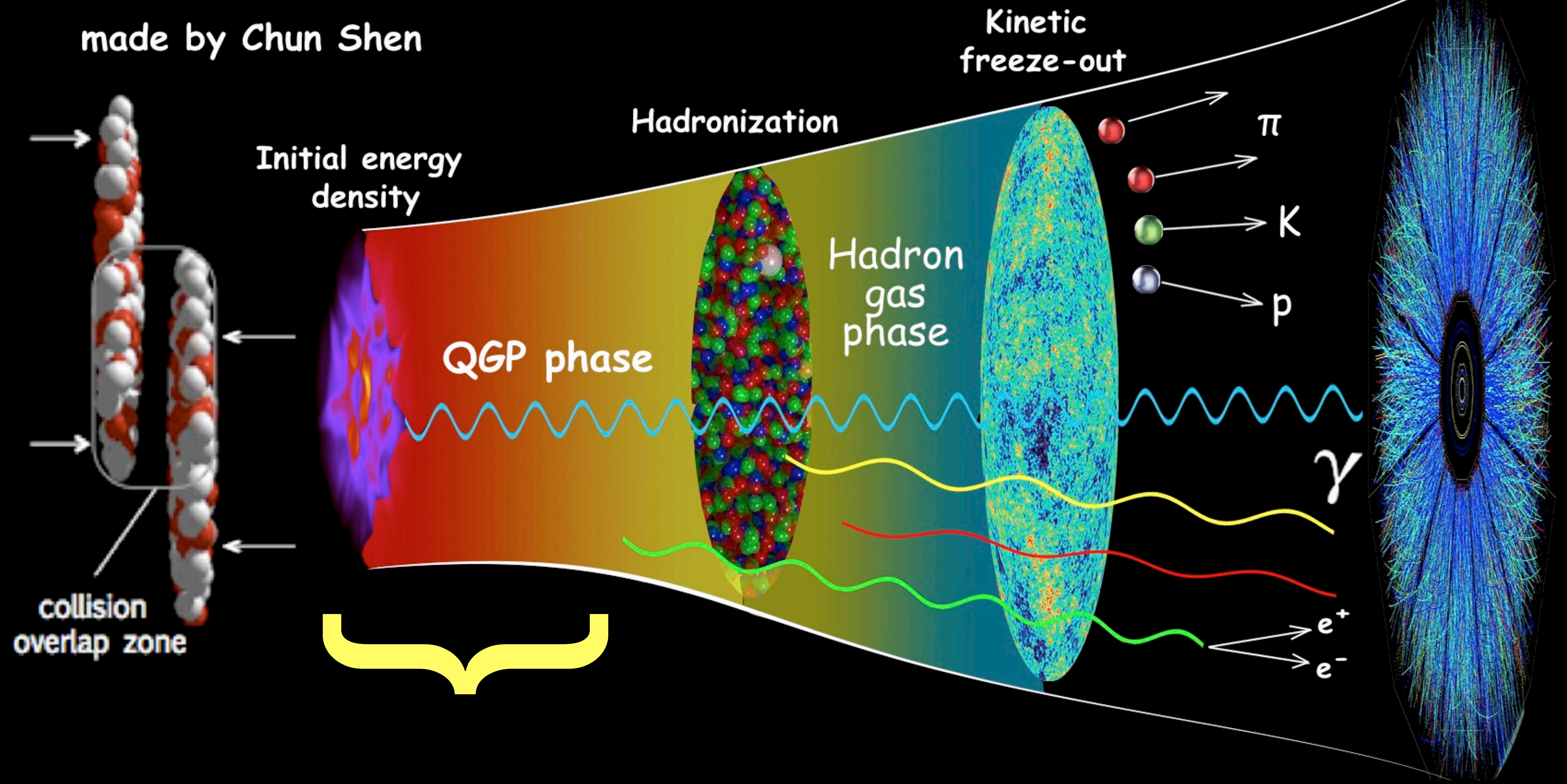


Physics of the collision system:
initial state, dynamic evolution, chemical and thermodynamic properties, interactions with charged probes, hadronization, reconstruct all final state particles (π, K, p, Λ, Ξ, Ω, J/ψ, Υ, η, ρ, γ, e, μ,…)

ALICE


Relativistic Heavy-Ion Collisions
made by Chun Shen
final detected particle distributions
Kinetic freeze-out
Hadronization
Initial energy density
Hadron gas phase
QGP phase
π
K
p
γ
e+
e−
collision overlap zone
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



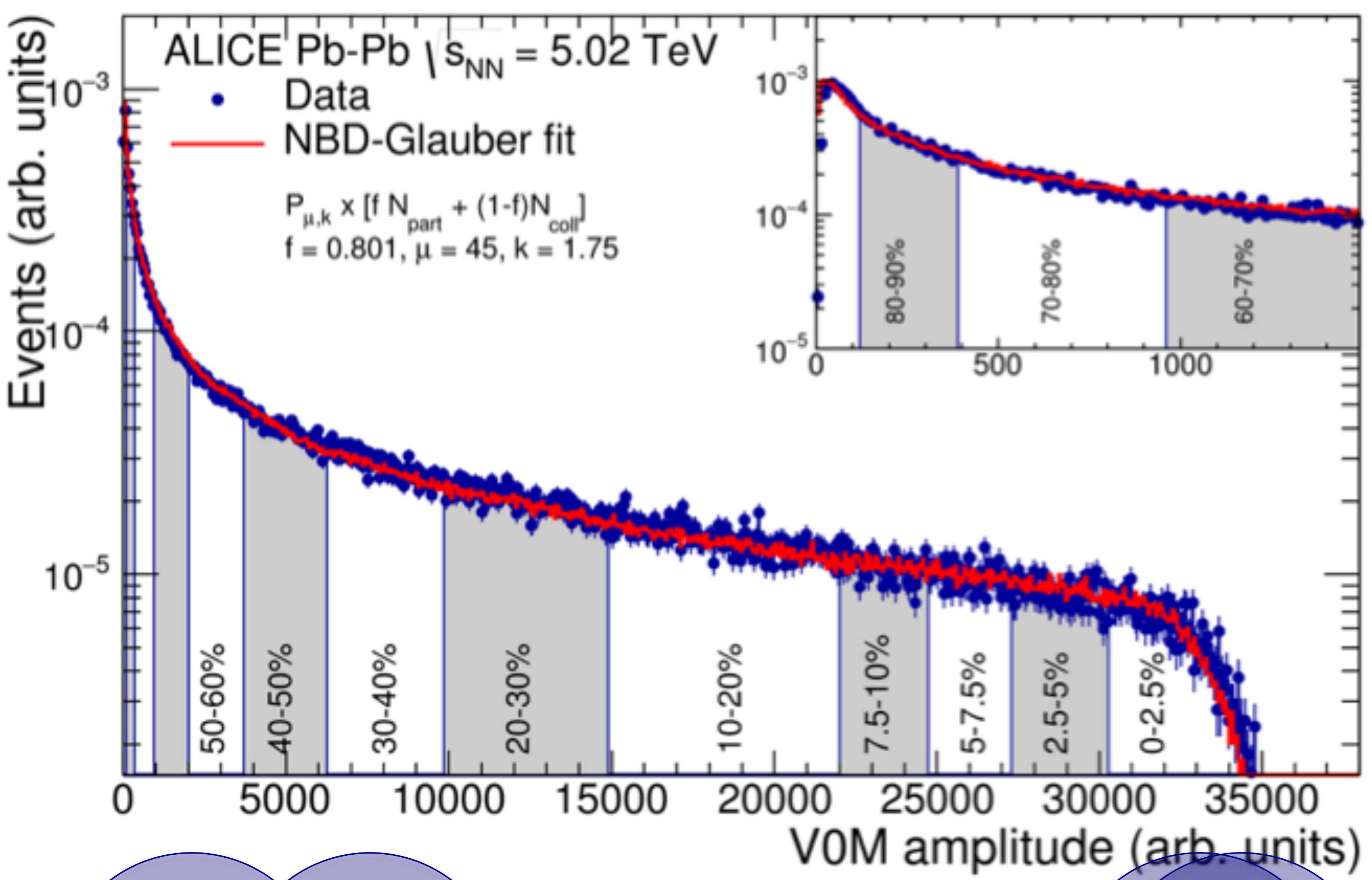
1. The soft sector:
   anisotropic flow coefficients

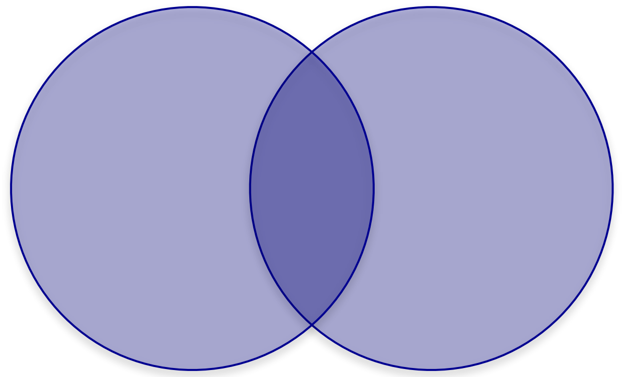
Quick review: geometry of a heavy-ion collision

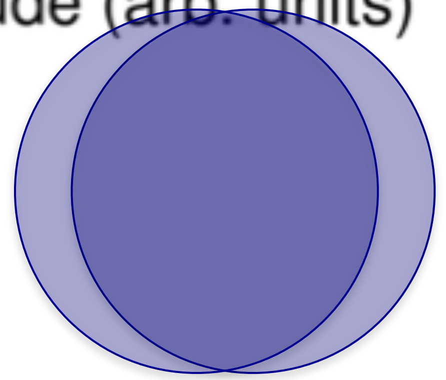
- More "head-on" collision
  → smaller impact parameter
  → larger overlap region
  → more particles produced

- More "glancing" collision
  → larger impact parameter
  → smaller overlap region
  → fewer particles produced

- Centrality is usually quoted as a percentage of the cross-section





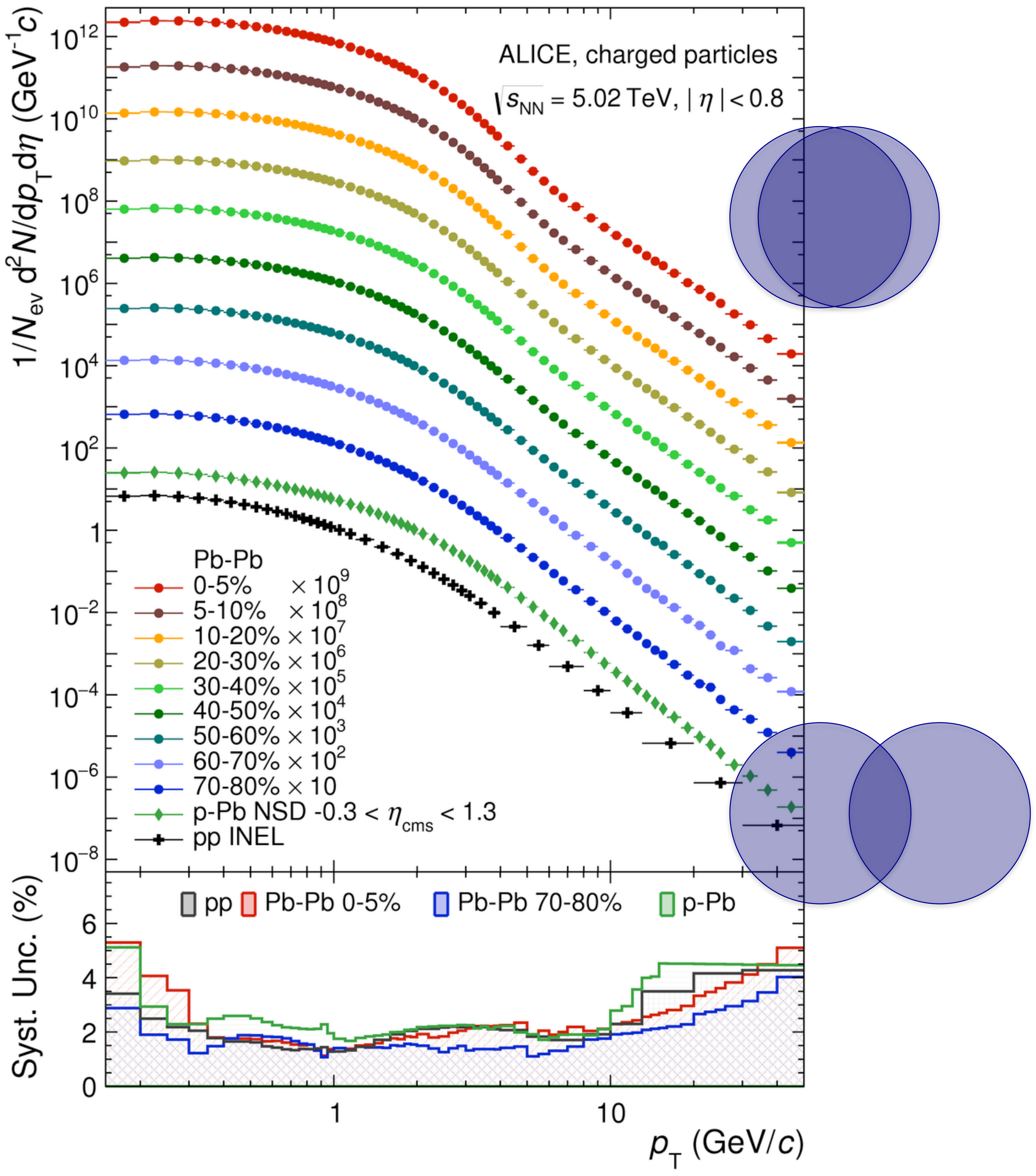


70-90%, "peripheral"   0-5%, "central"

- Centrality determination by counting number of particles (multiplicity) or energy deposition in a region of phase space *independent* from the measurement, to avoid biases/autocorrelations in the results

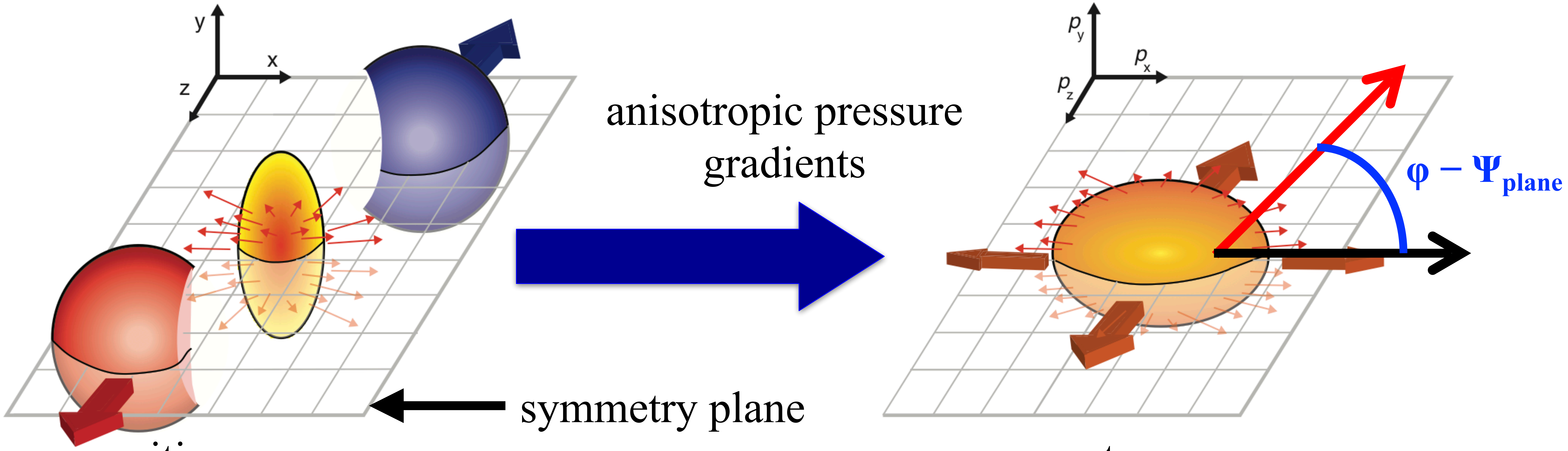
Isotropic expansion of the fireball

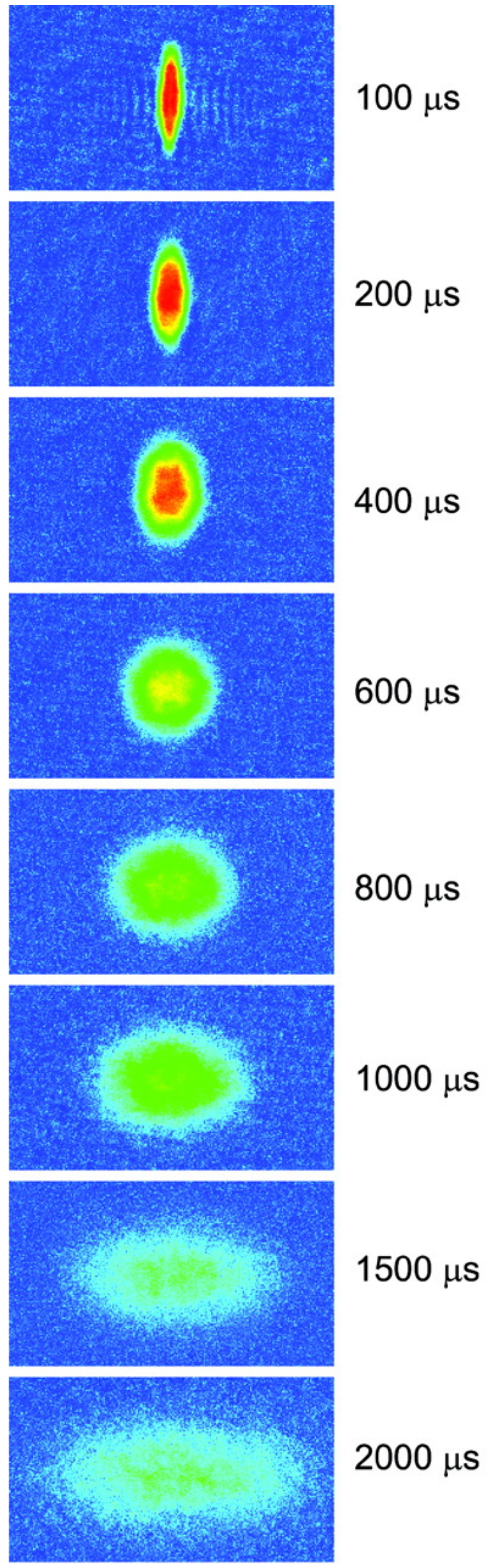
- Pressure gradients build up in the fireball
- Particles boosted in the radial direction
  → "radial flow"
  → higher mean p_T



ALICE, JHEP 11 (2018) 013,
arxiv: 1802.09145 [nucl-ex]

Anisotropic expansion of the fireball

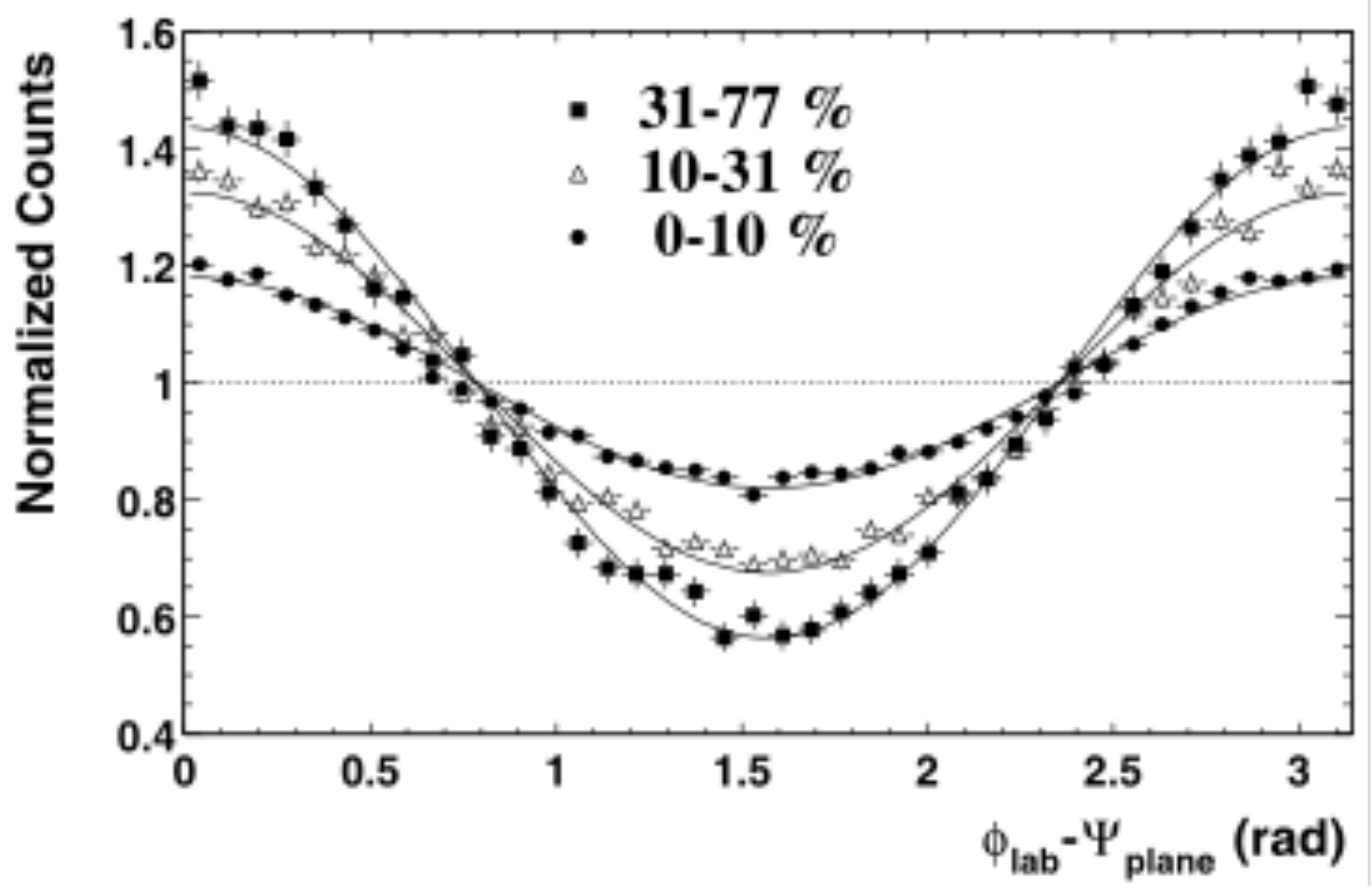




Elliptic Flow in Ultracold Lithium

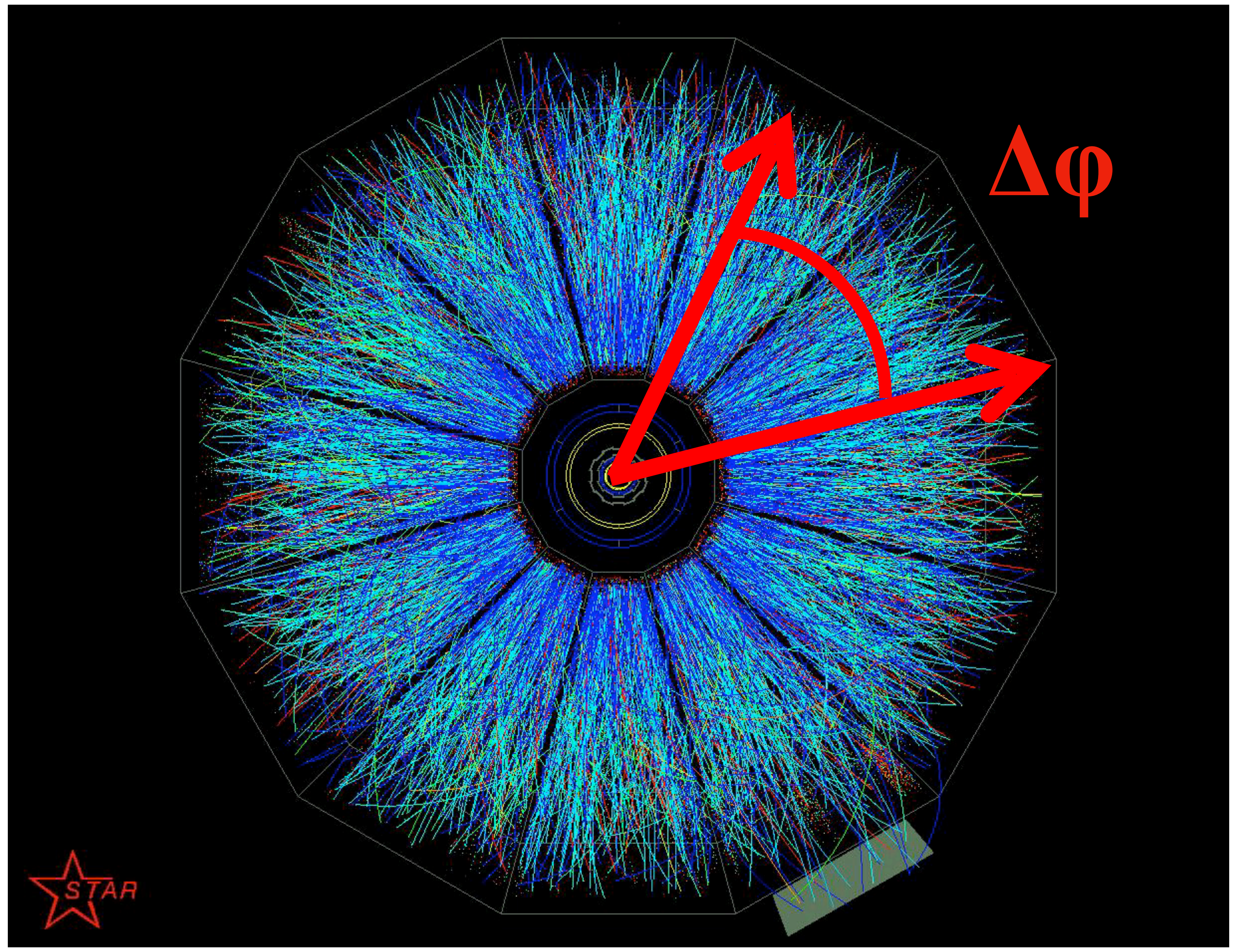
K.M. O'Hara et al., Science, 13 Dec 2002: 2179-2182

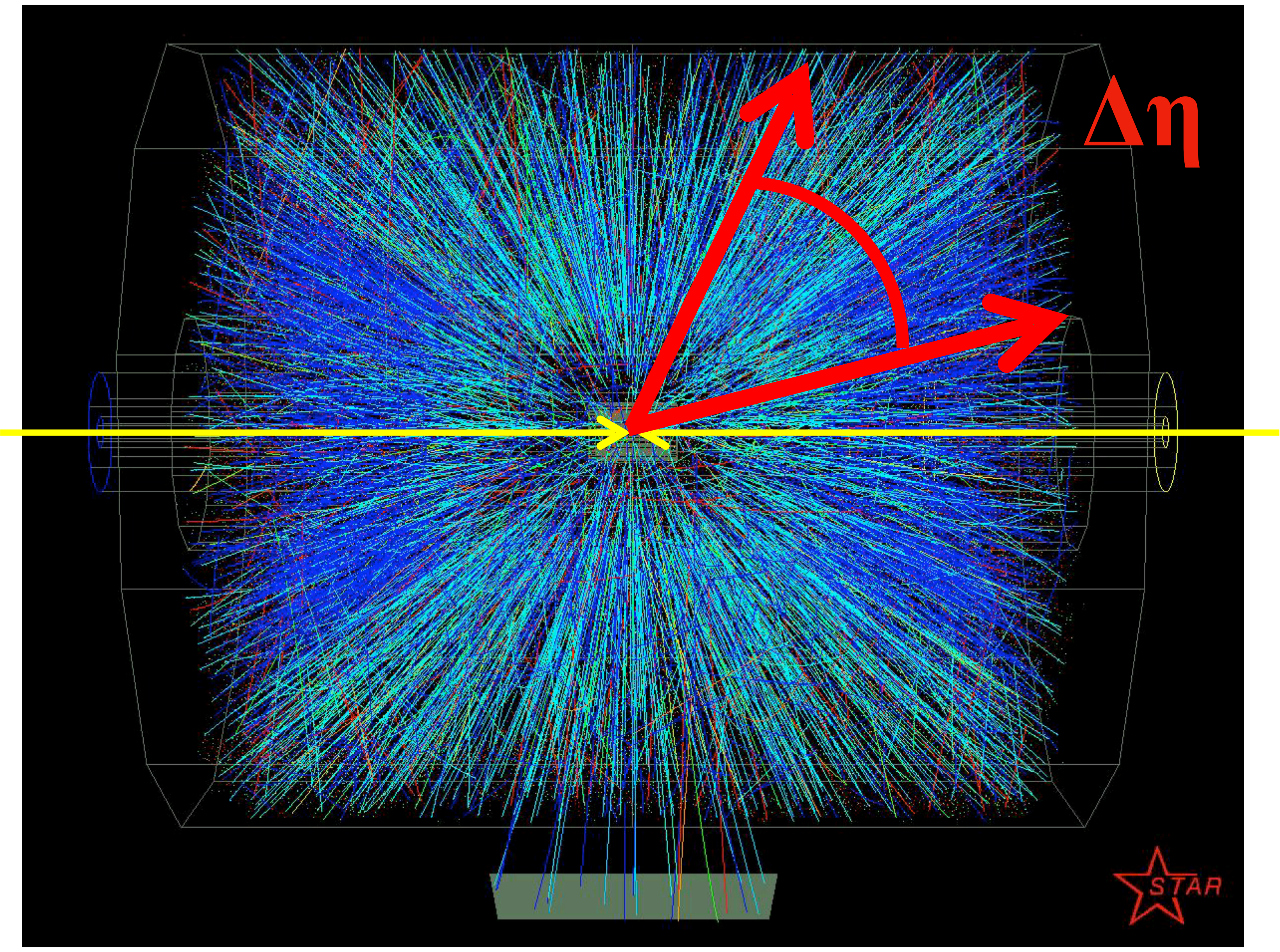
- Stronger in-plane pressure gradients
  → particles boosted in-plane more than out-of-plane
- Particles correlated with a "global" symmetry plane

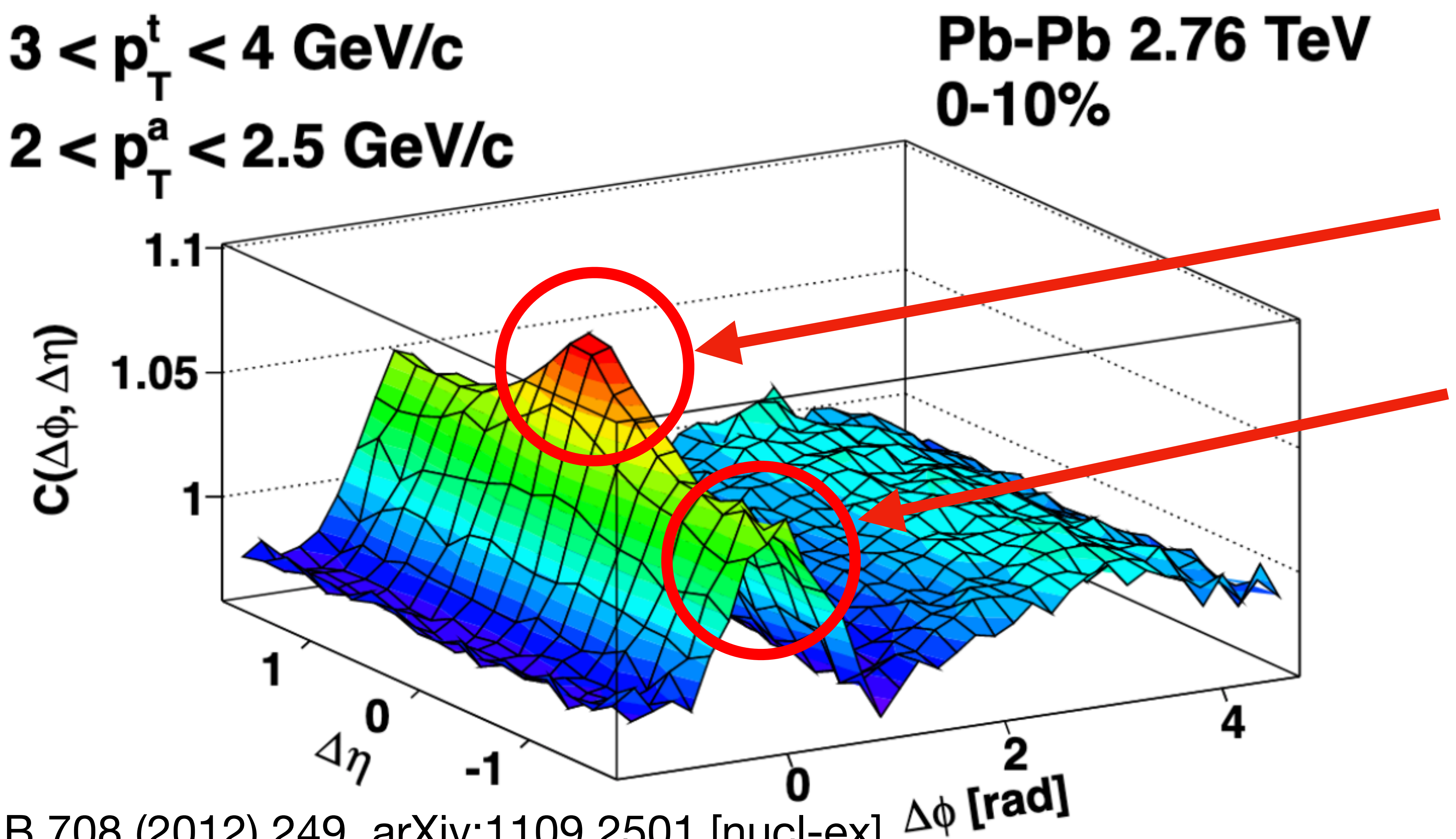


STAR, PRL 90 (2003) 032301, arXiv:nucl-ex/0206006

Two-particle correlations





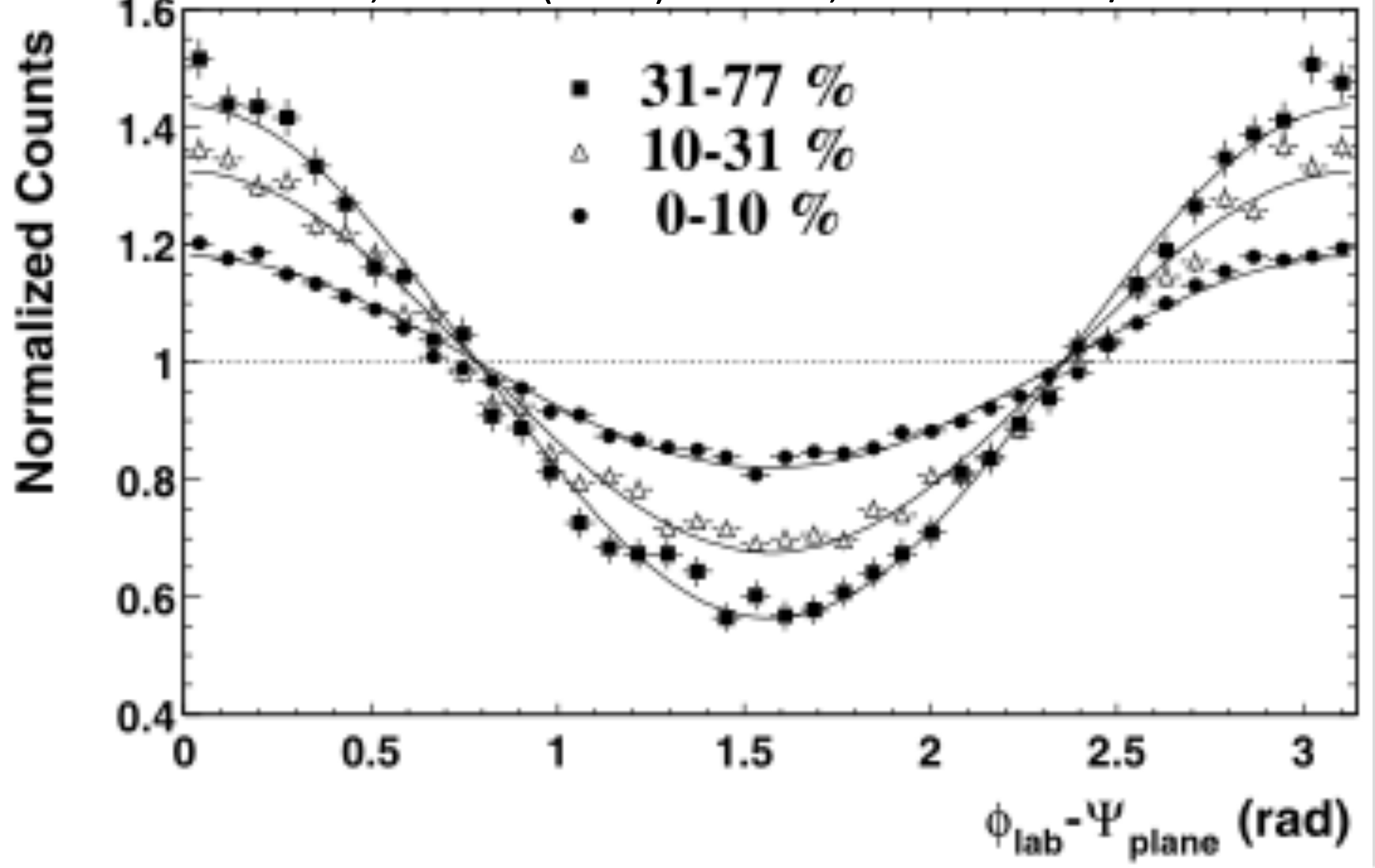


- Short-range correlations → jets (see next slides…)
- Long-range correlations (localized in Δφ, extended in Δη) → anisotropic flow

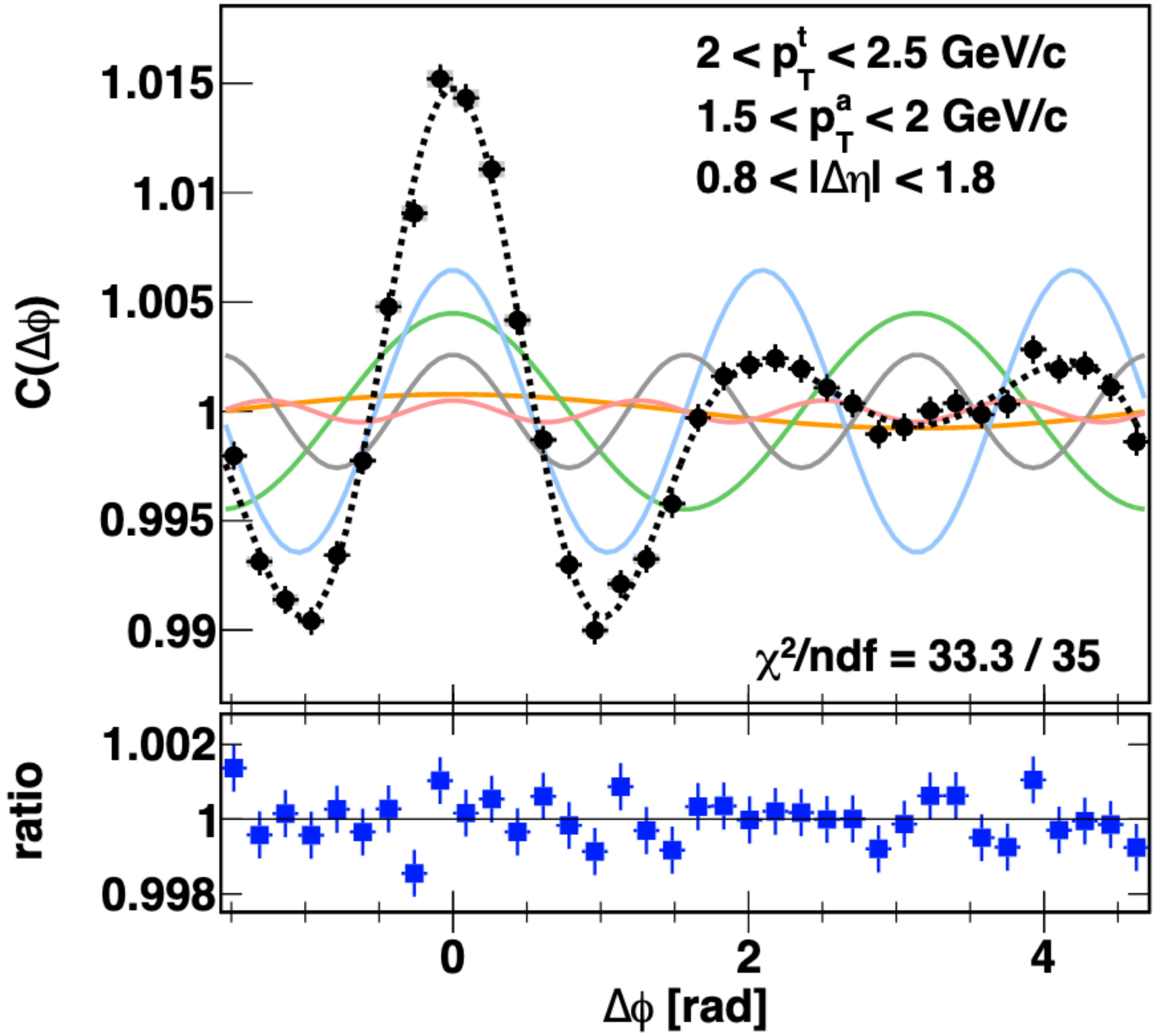
ALICE, PLB 708 (2012) 249, arXiv:1109.2501 [nucl-ex]

Single-particle to Two-particle correlations

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



ALICE, PLB 708 (2012) 249, arXiv:1109.2501 [nucl-ex]



- Particle distribution described by a Fourier cosine series

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

- Two-particle (Δφ) distribution described by Fourier series with coefficients v_n^2

A fun mathematical exercise: show this! → $dN/d\varphi \sim 1 + 2v_2^2\cos(2\Delta\varphi)$

Anisotropic flow coefficients

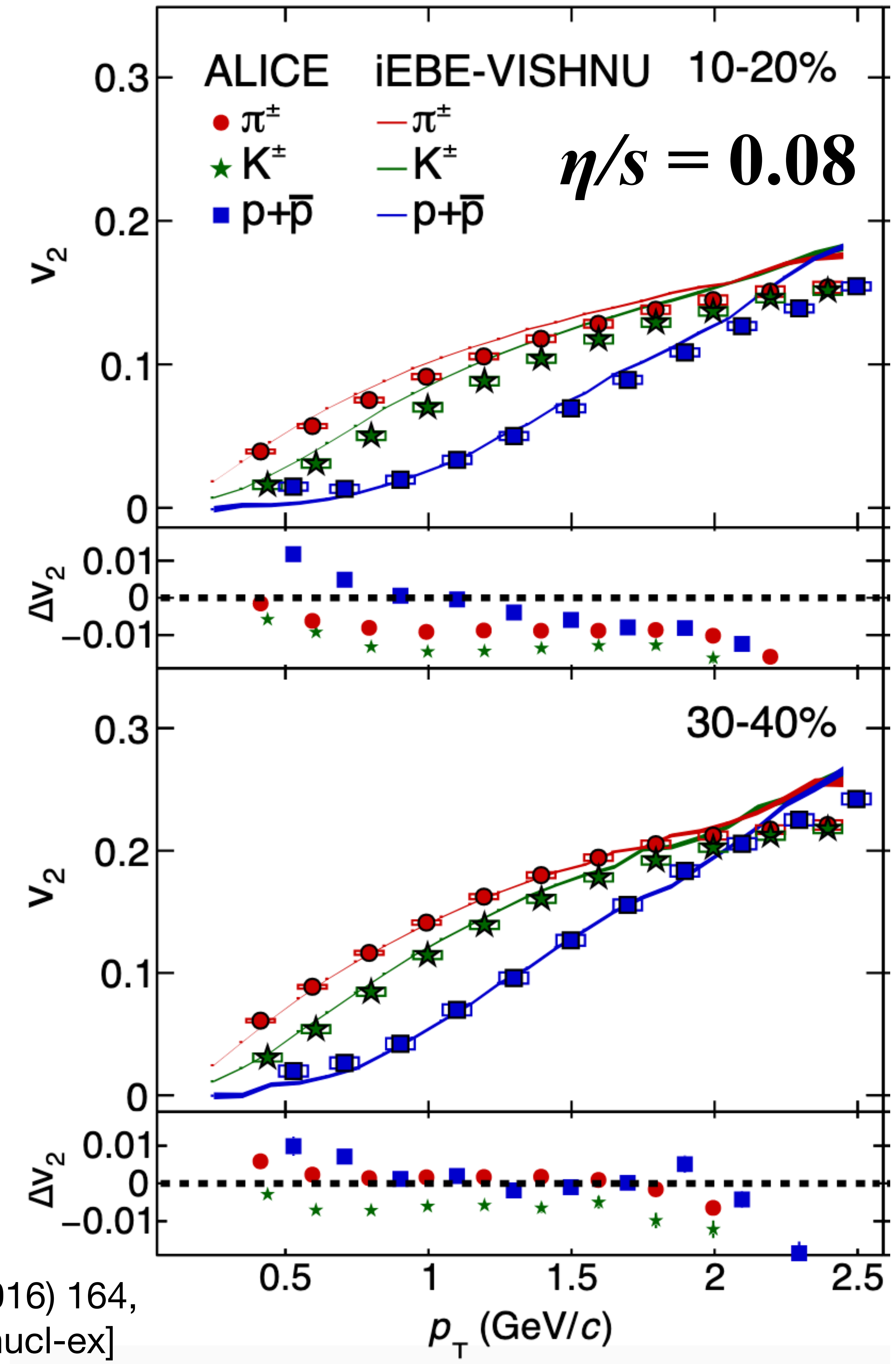
- Particle distribution described by a Fourier cosine series

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

- 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"

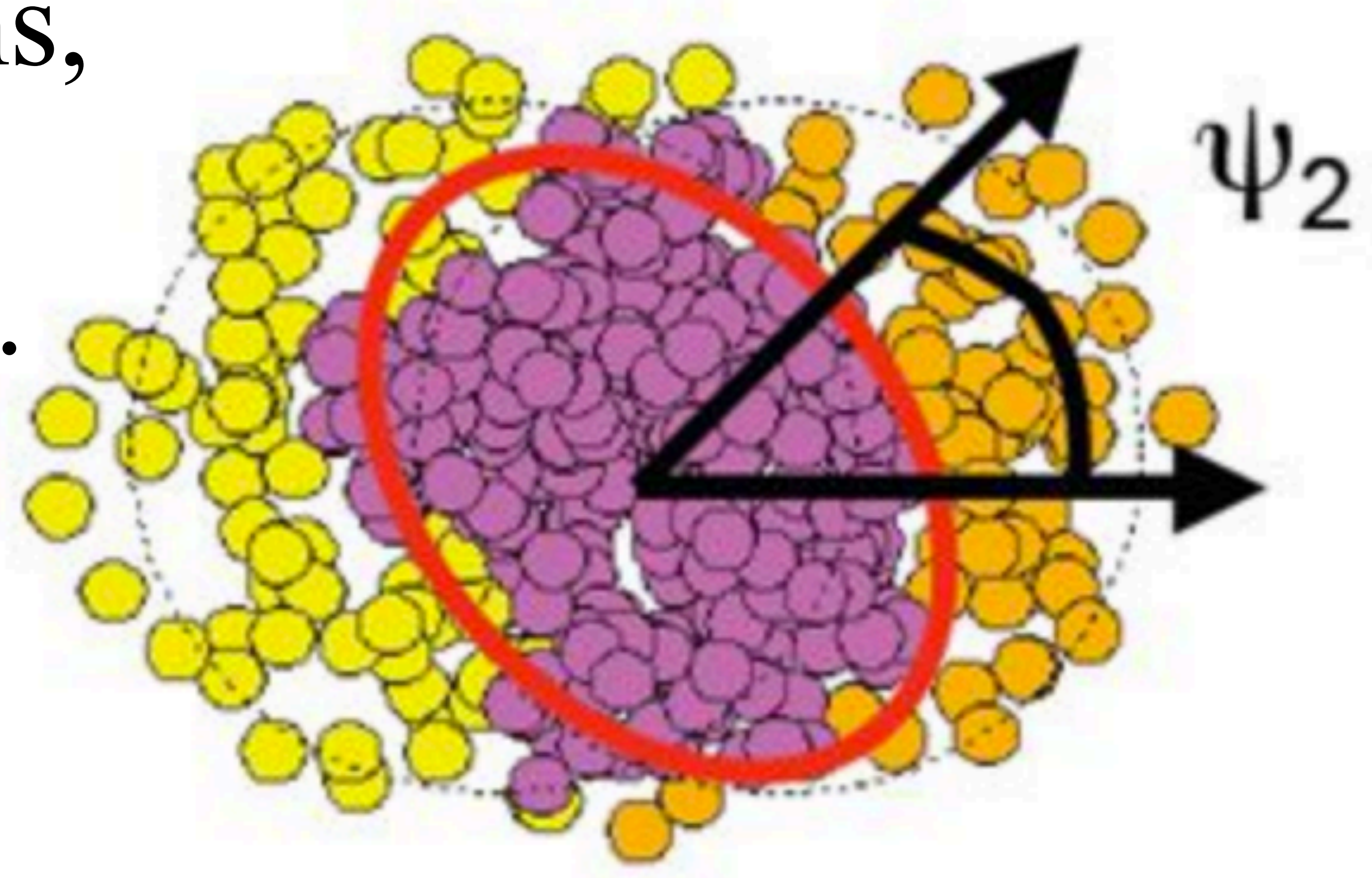


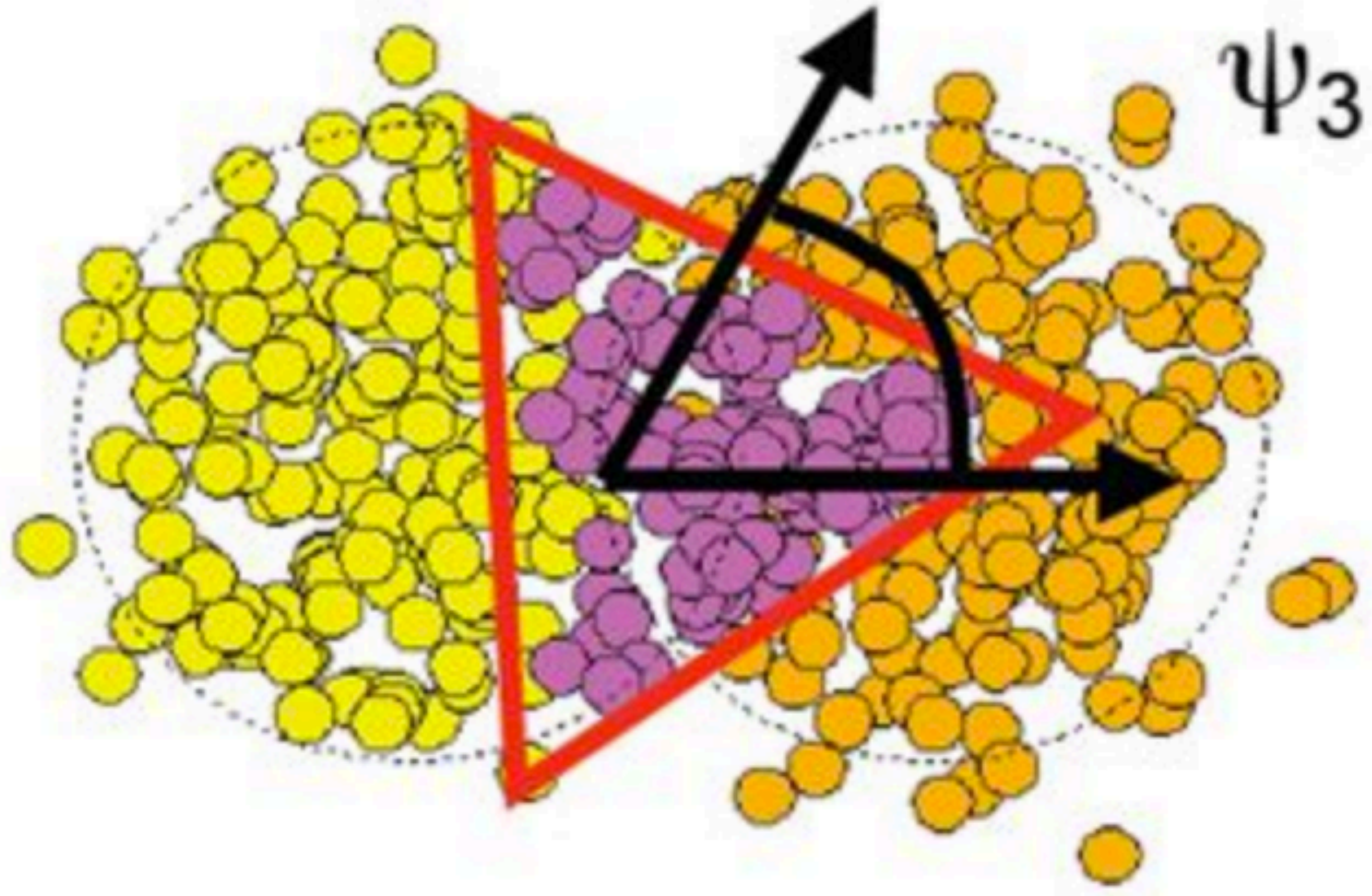
ALICE, JHEP 09 (2016) 164,
arXiv:1606.06057 [nucl-ex]

Higher-order anisotropic 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,…
- Particle distribution described by a Fourier cosine series

$$
\begin{aligned}
dN/d\varphi \sim 1 &+ 2v_1\cos(\varphi-\Psi_1) \\
&+ 2v_2\cos(2(\varphi-\Psi_2)) \\
&+ 2v_3\cos(3(\varphi-\Psi_3)) \\
&+ 2v_4\cos(4(\varphi-\Psi_4)) + \ldots
\end{aligned}
$$





Higher-order anisotropic flow coefficients

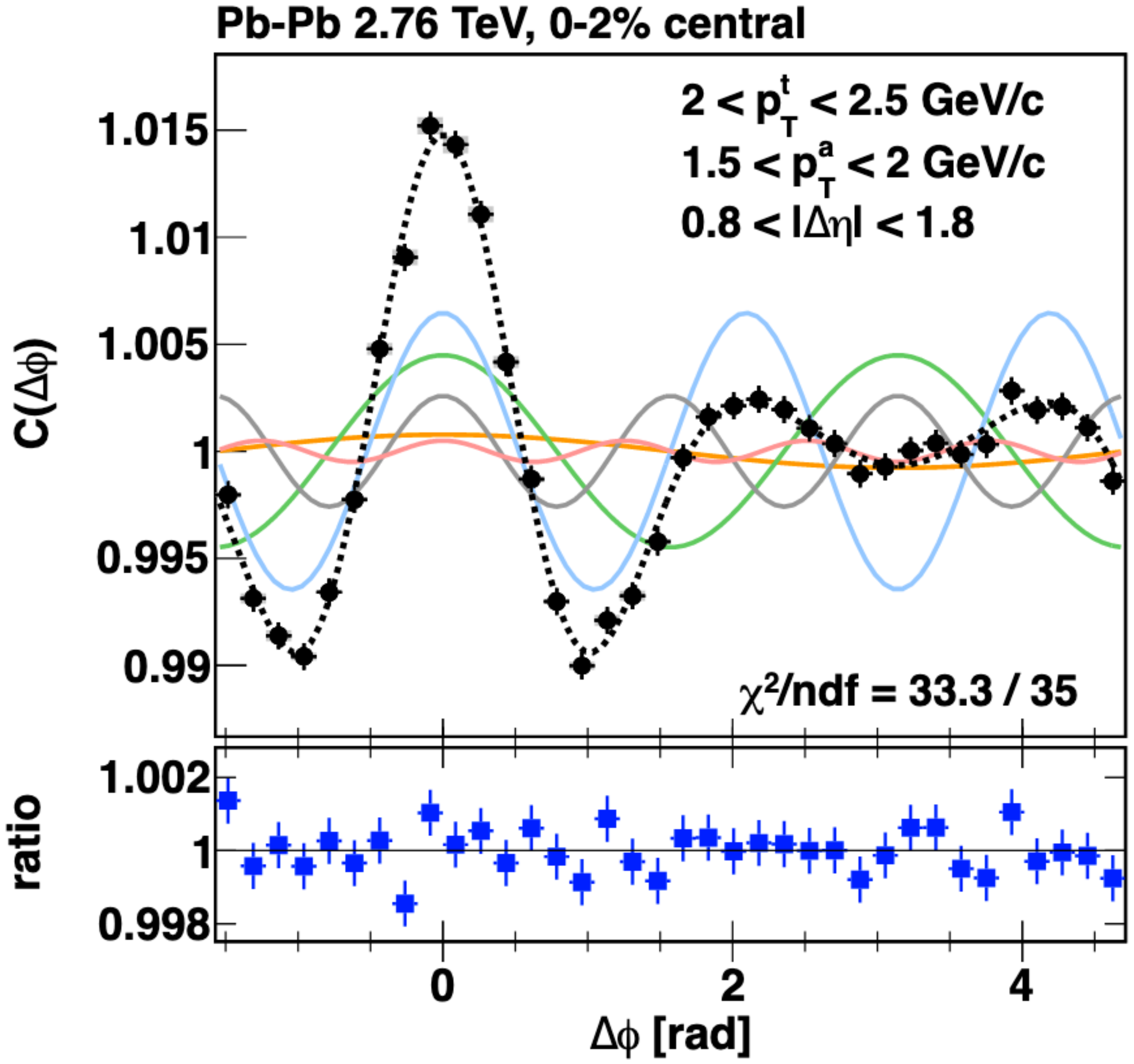
- Due to event-by-event fluctuations of the positions of nucleons, overlap region is not perfectly symmetric
  → development of triangular flow v_3, quadrangular flow v_4,…
- Particle distribution described by a Fourier cosine series

$$dN/d\varphi \sim 1 + 2v_1\cos(\varphi-\Psi_1) + 2v_2\cos(2(\varphi-\Psi_2)) + 2v_3\cos(3(\varphi-\Psi_3)) + 2v_4\cos(4(\varphi-\Psi_4)) + \ldots$$

- Two-particle ($\Delta\varphi$) distribution described by Fourier series with coefficients v_n^2

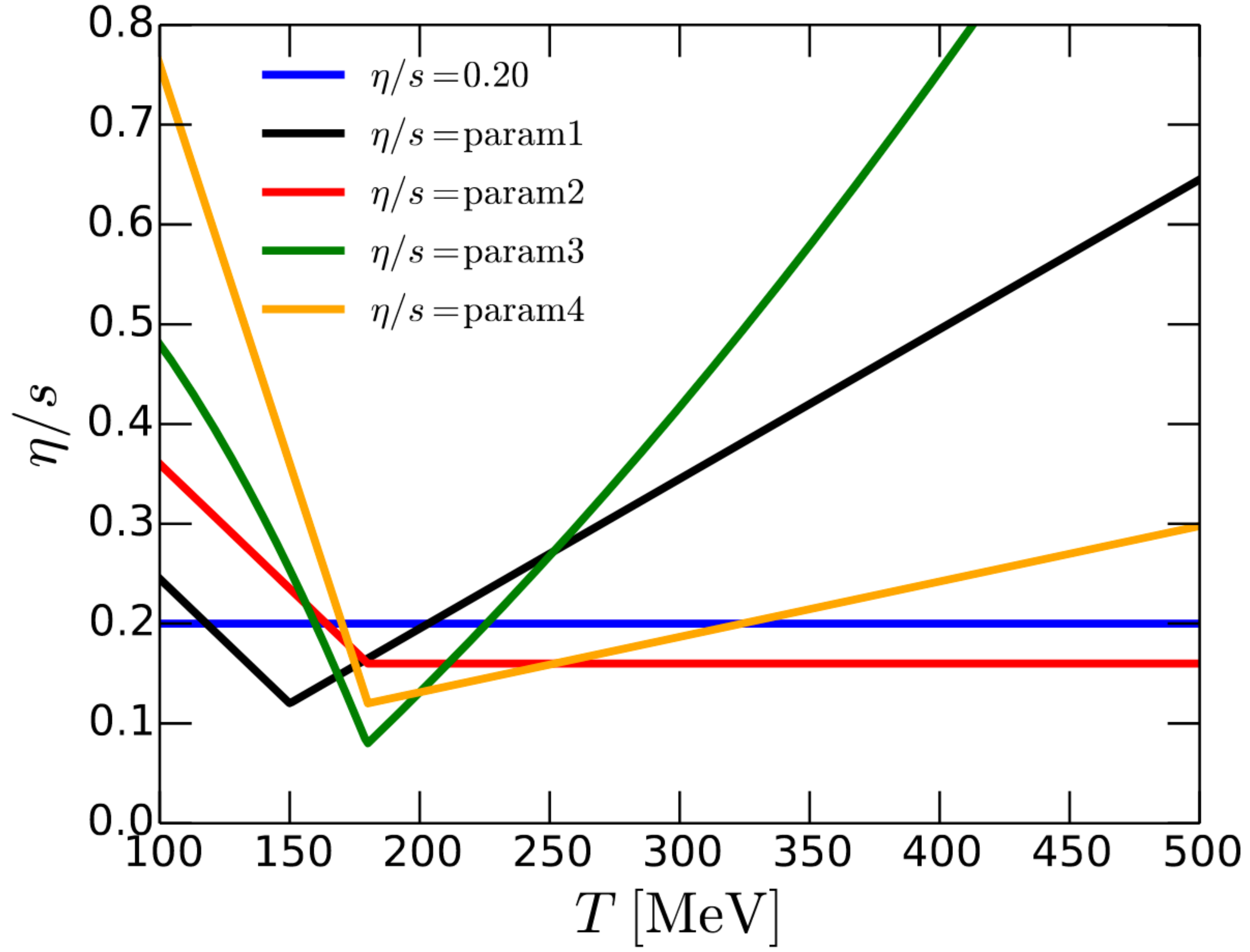
$$dN/d\Delta\varphi \sim 1 + 2v_1^2\cos(\Delta\varphi) + 2v_2^2\cos(2\Delta\varphi) + 2v_3^2\cos(3\Delta\varphi) + 2v_4^2\cos(4\Delta\varphi) + \ldots$$

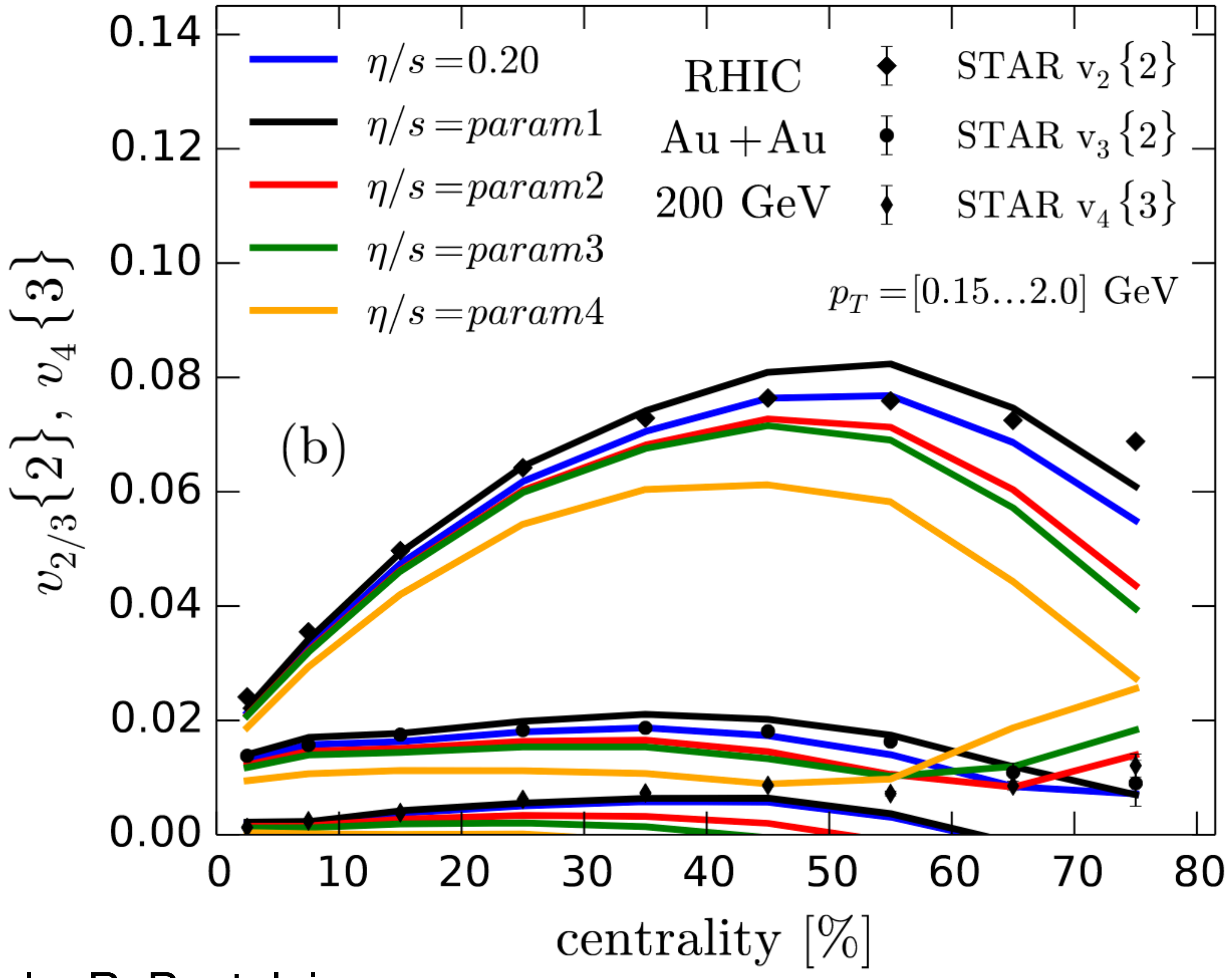
ALICE, PLB 708 (2012) 249, arXiv:1109.2501 [nucl-ex]

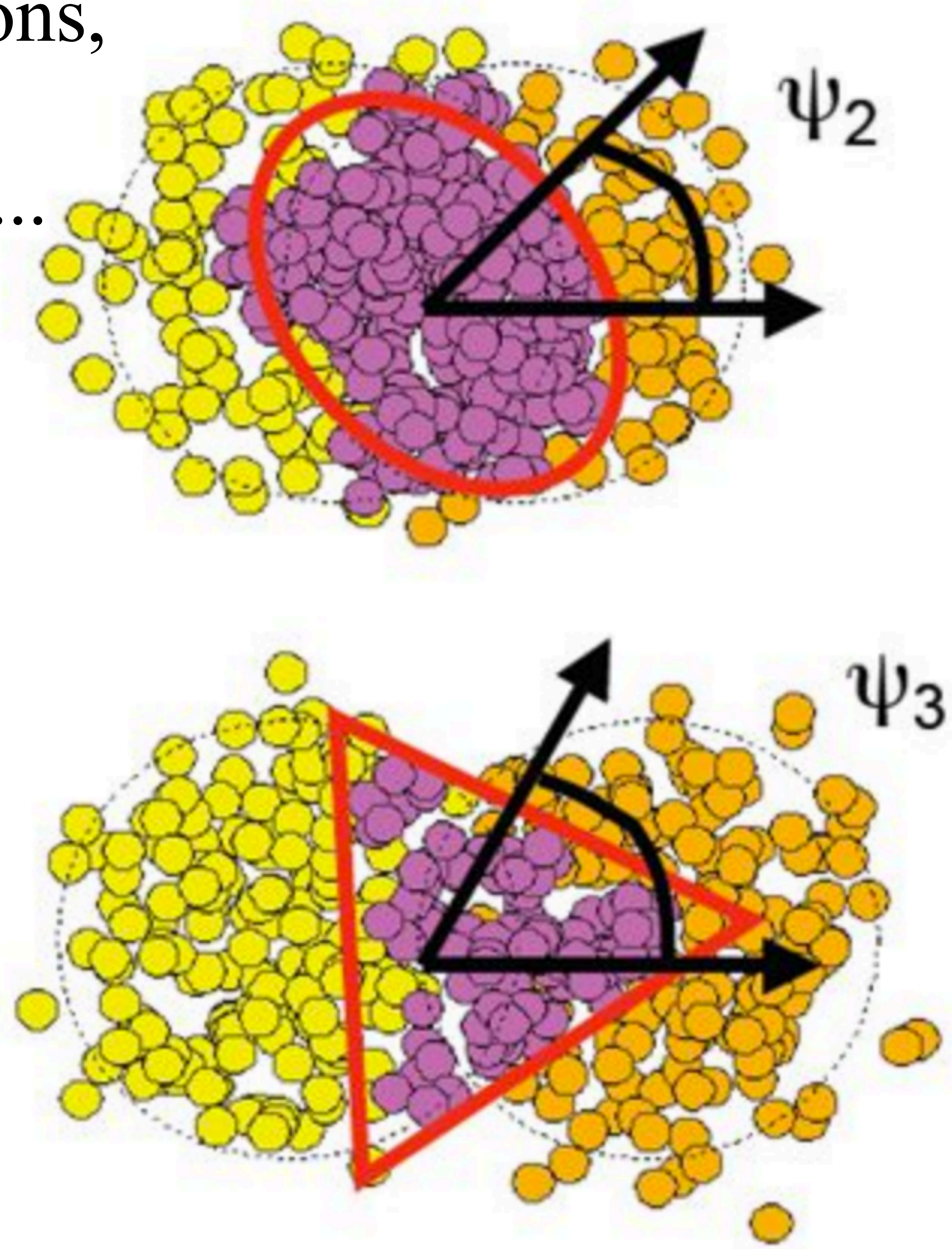


Higher-order anisotropic flow coefficients

- 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 harmonics are sensitive to hydrodynamic properties and dynamics of the QGP



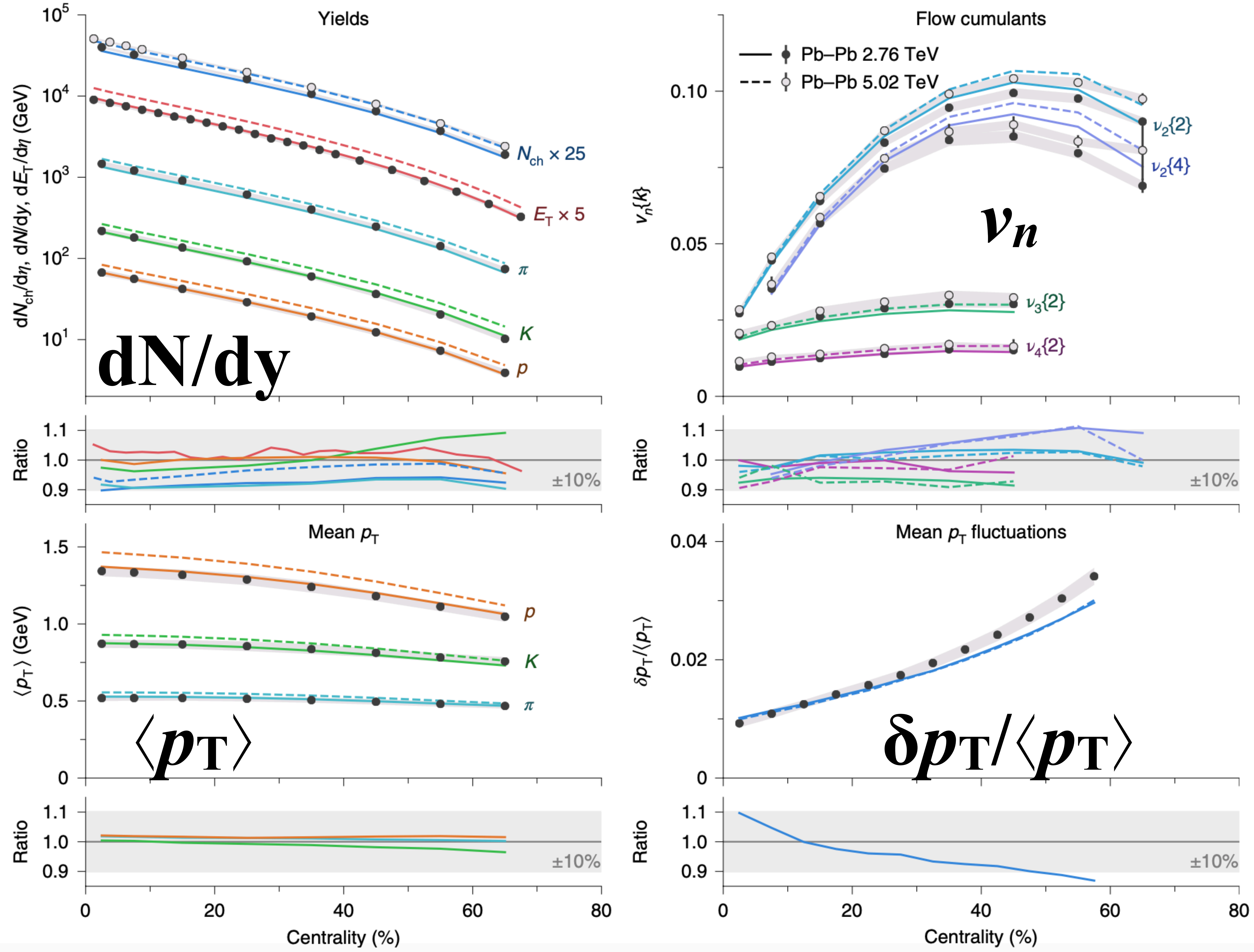




H. Niemi, K.J. Eskola, R. Paatelainen, PRC 93 (2016) 024907, arXiv:1505.02677 [hep-ph]

Extracting QGP properties with flow

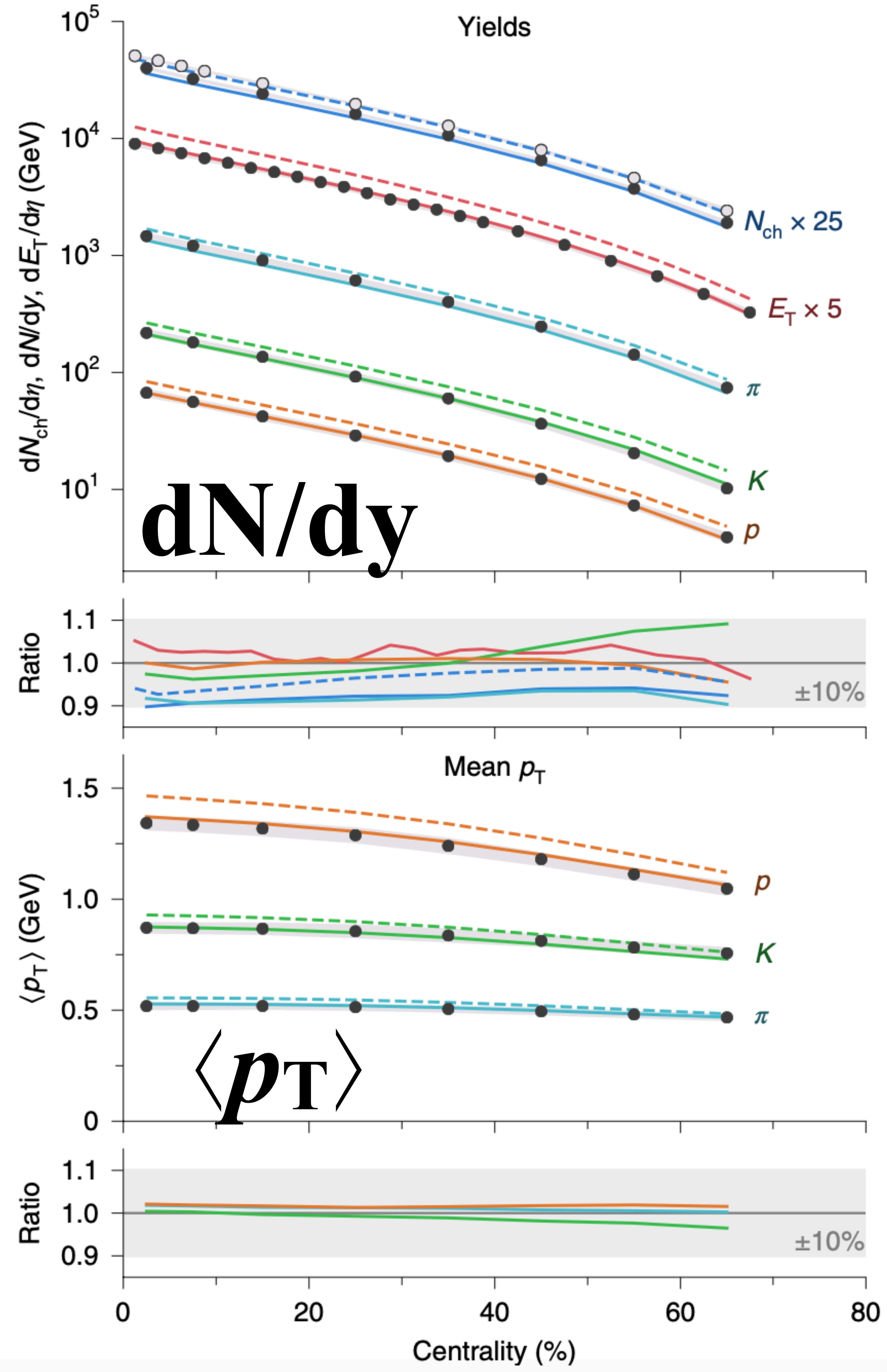
- Bayesian analysis of particle yields, mean p_T, v_2, v_3, v_4 measured by ALICE

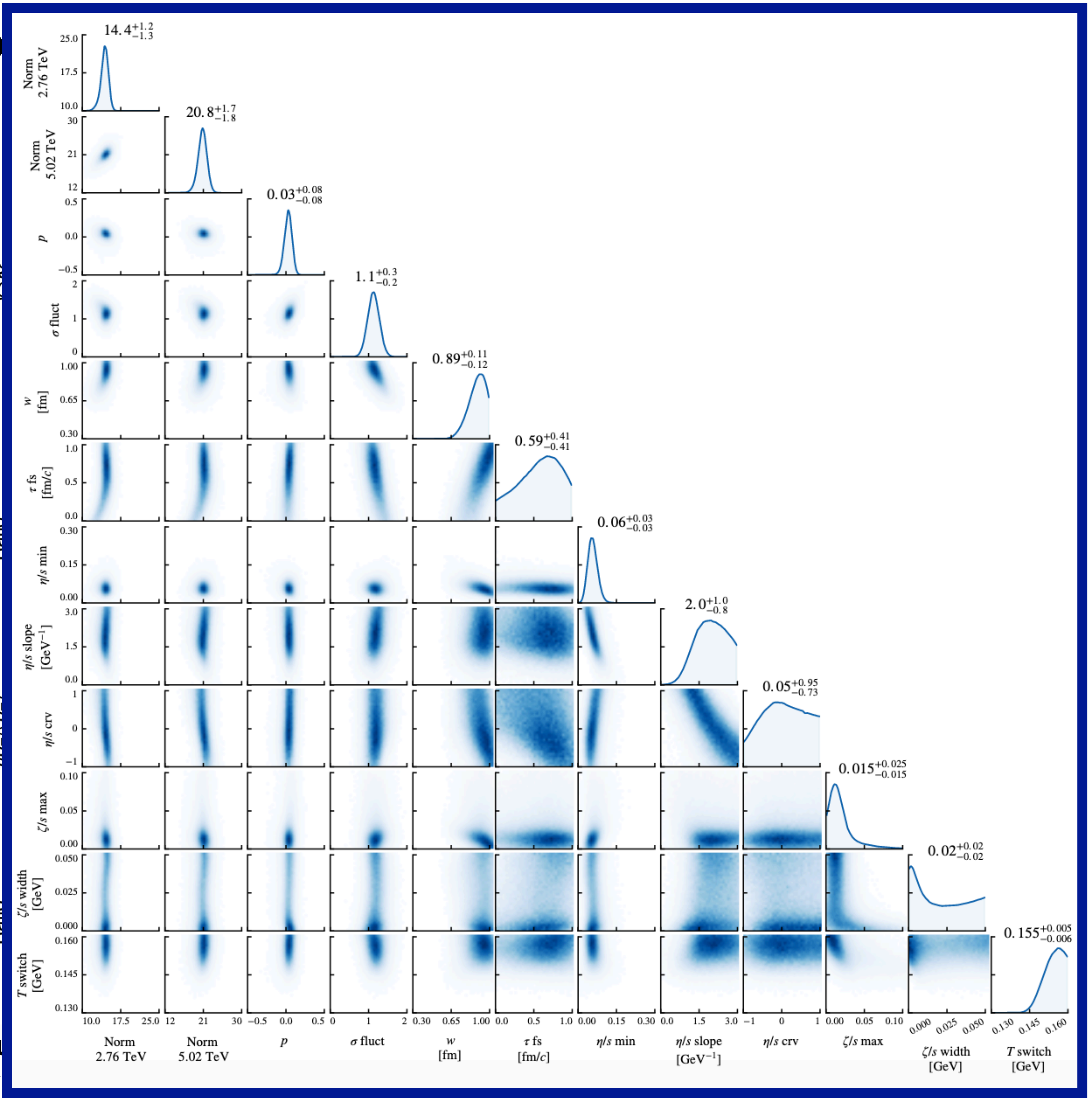


J. E. Bernhard, J. S. Moreland, S. A. Bass, Nature Physics 15 (2019) 1113
J. S. Moreland, J. E. Bernhard, S. A. Bass, Phys. Rev. C 101 (2020) 024911, arXiv:1808.02106 [nucl-th]

Extracting QGP properties with flow

- Bayesian analysis o… by ALICE



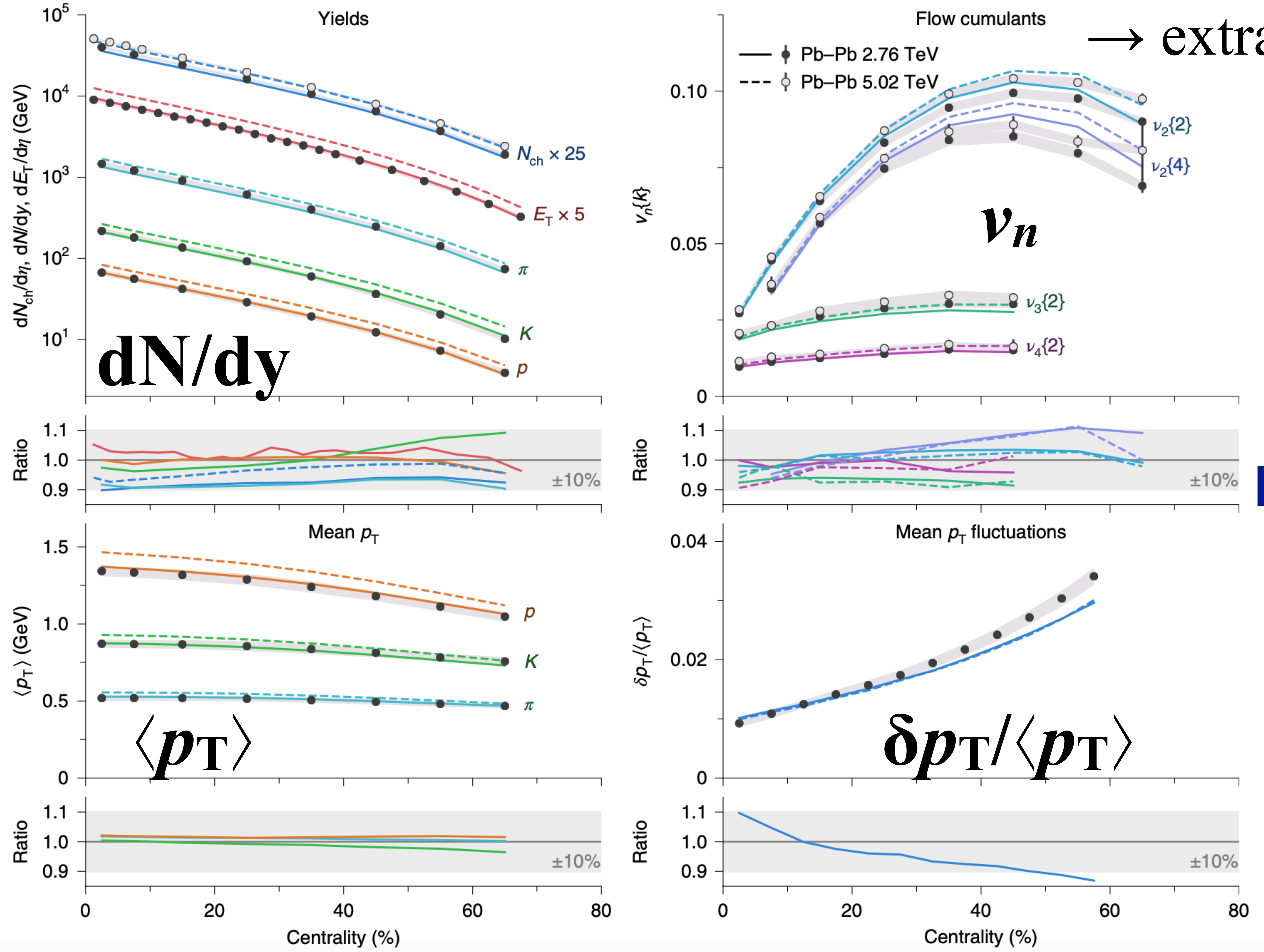


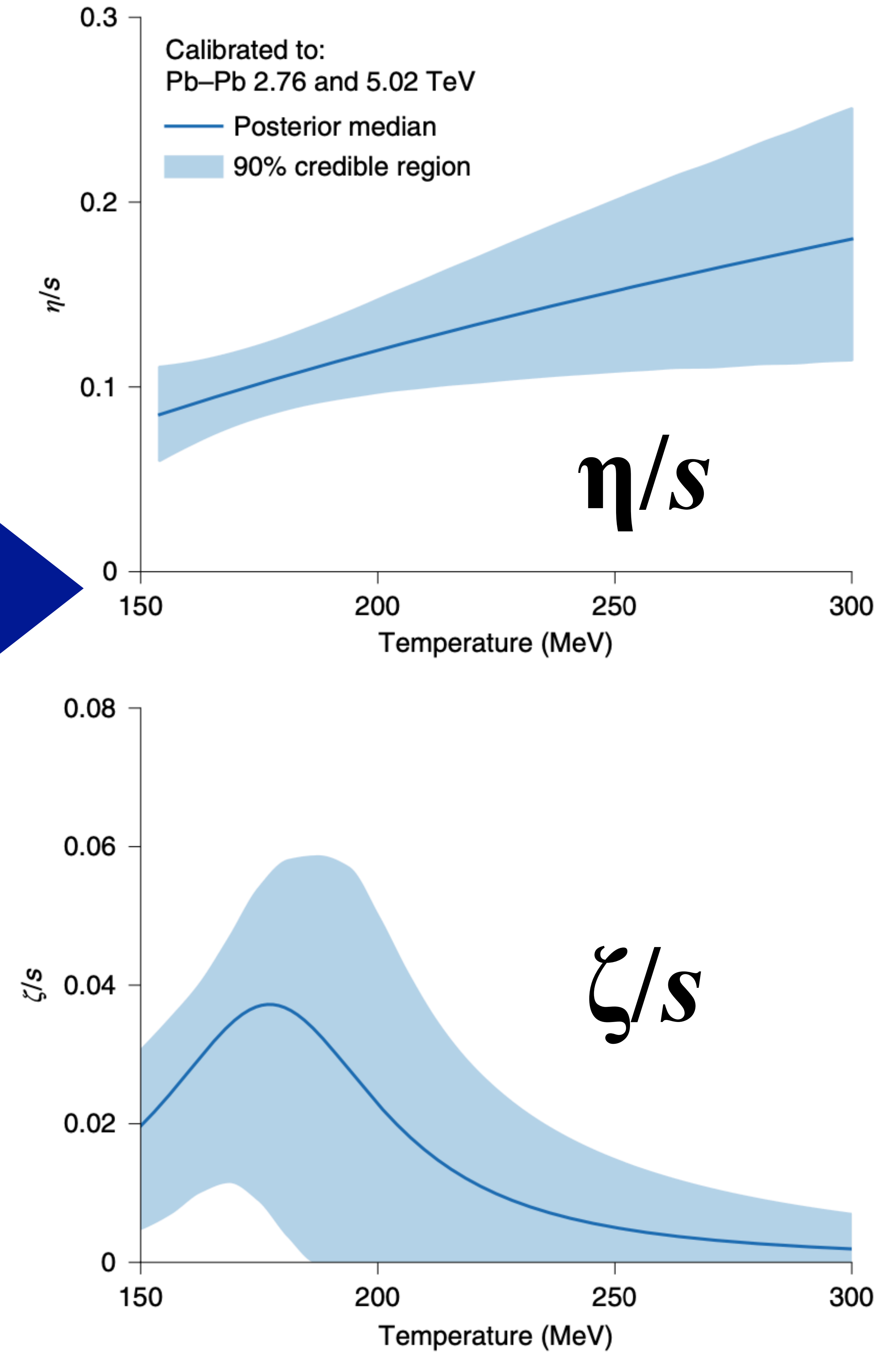
J. E. Bernhard, J. S. Moreland, S. A. Bass, Natu…
J. S. Moreland, J. E. Bernhard, S. A. Bass, Phy…

Extracting QGP properties with flow

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

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





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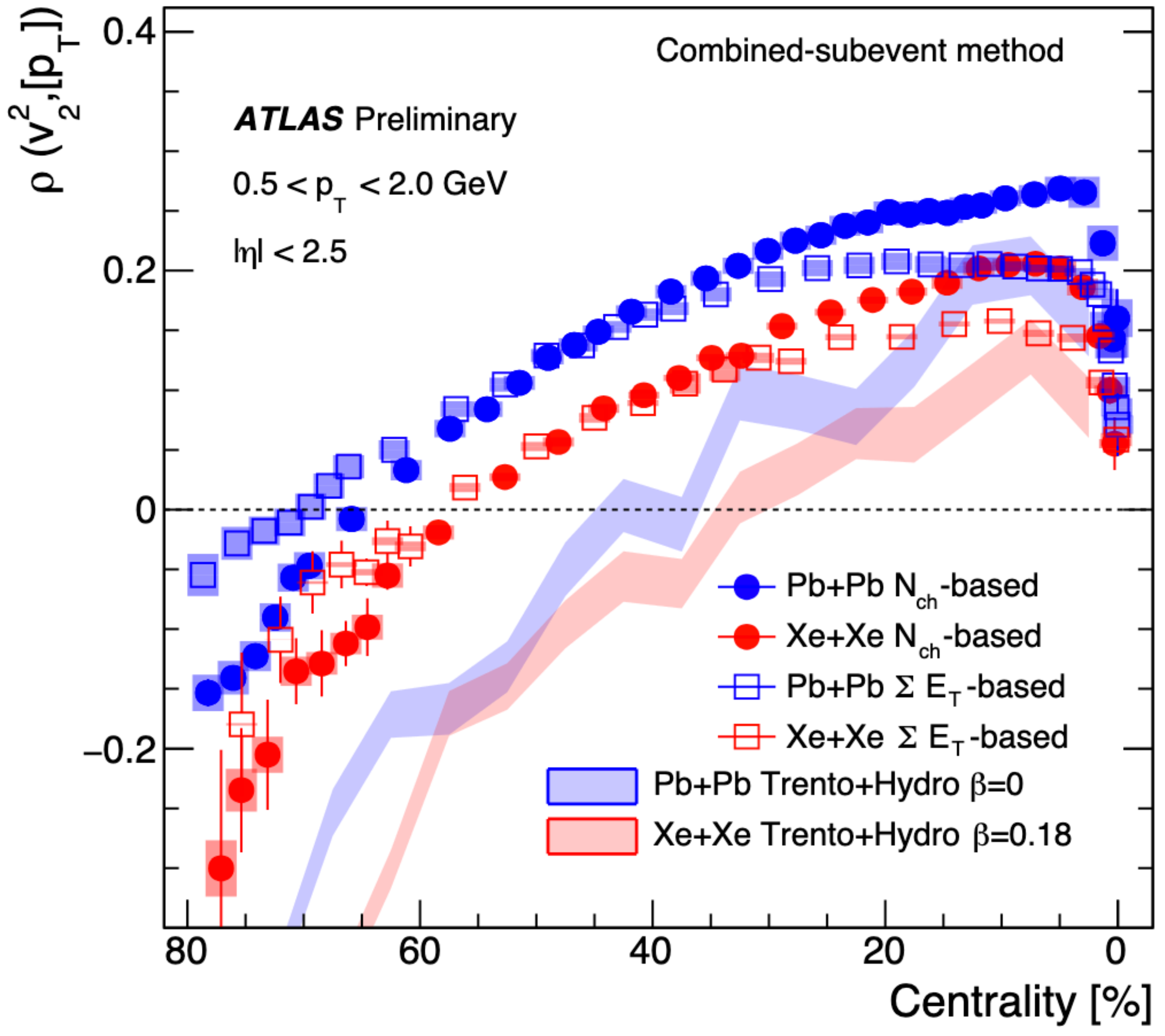
J. S. Moreland, J. E. Bernhard, S. A. Bass, Phys. Rev. C 101 (2020) 024911, arXiv:1808.02106 [nucl-th]

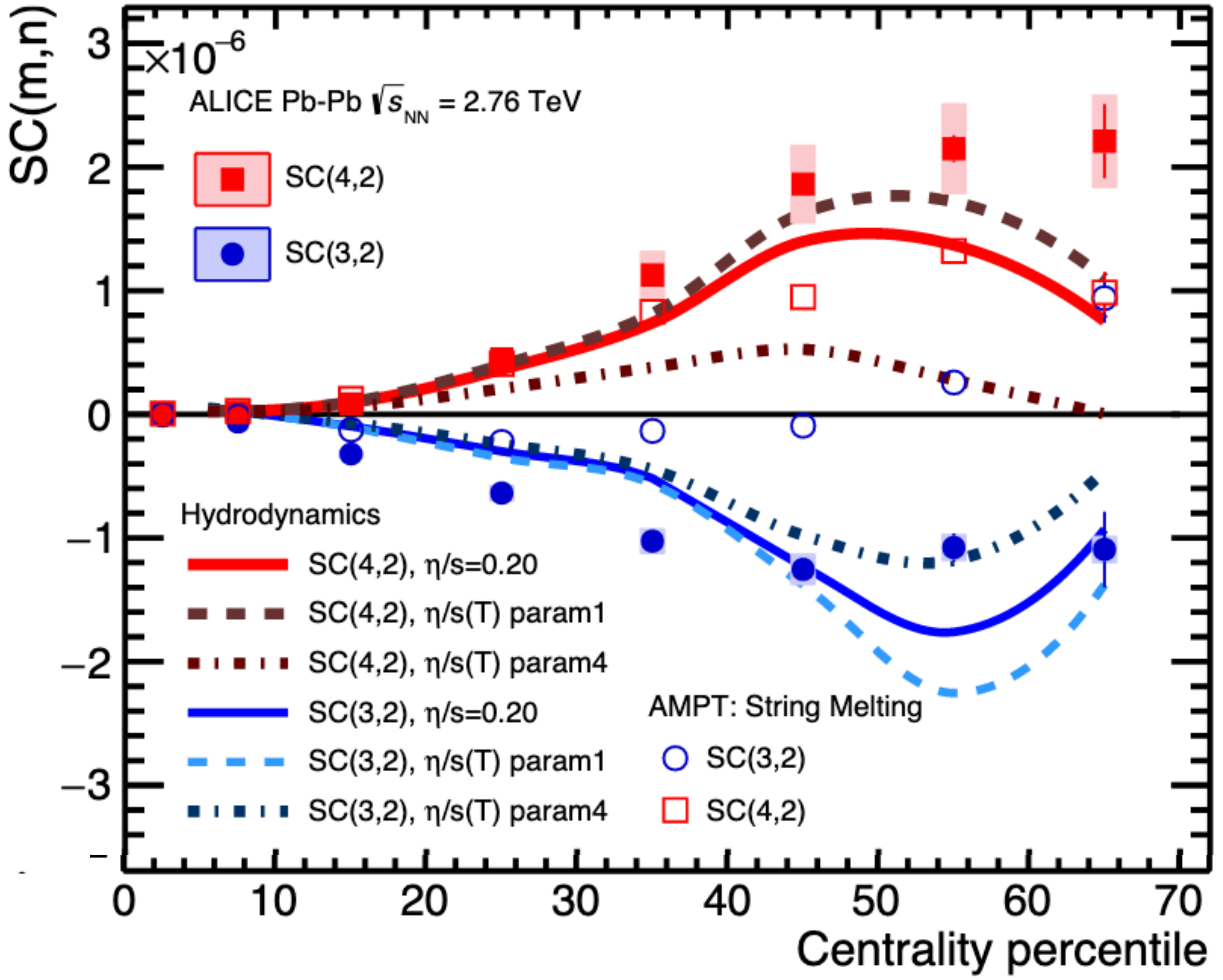
Beyond v_n: flow correlations

- Correlations between radial flow and anisotropic flow
  - sensitive to initial energy deposition, nuclear deformation, and interplay between system expansion and anisotropy

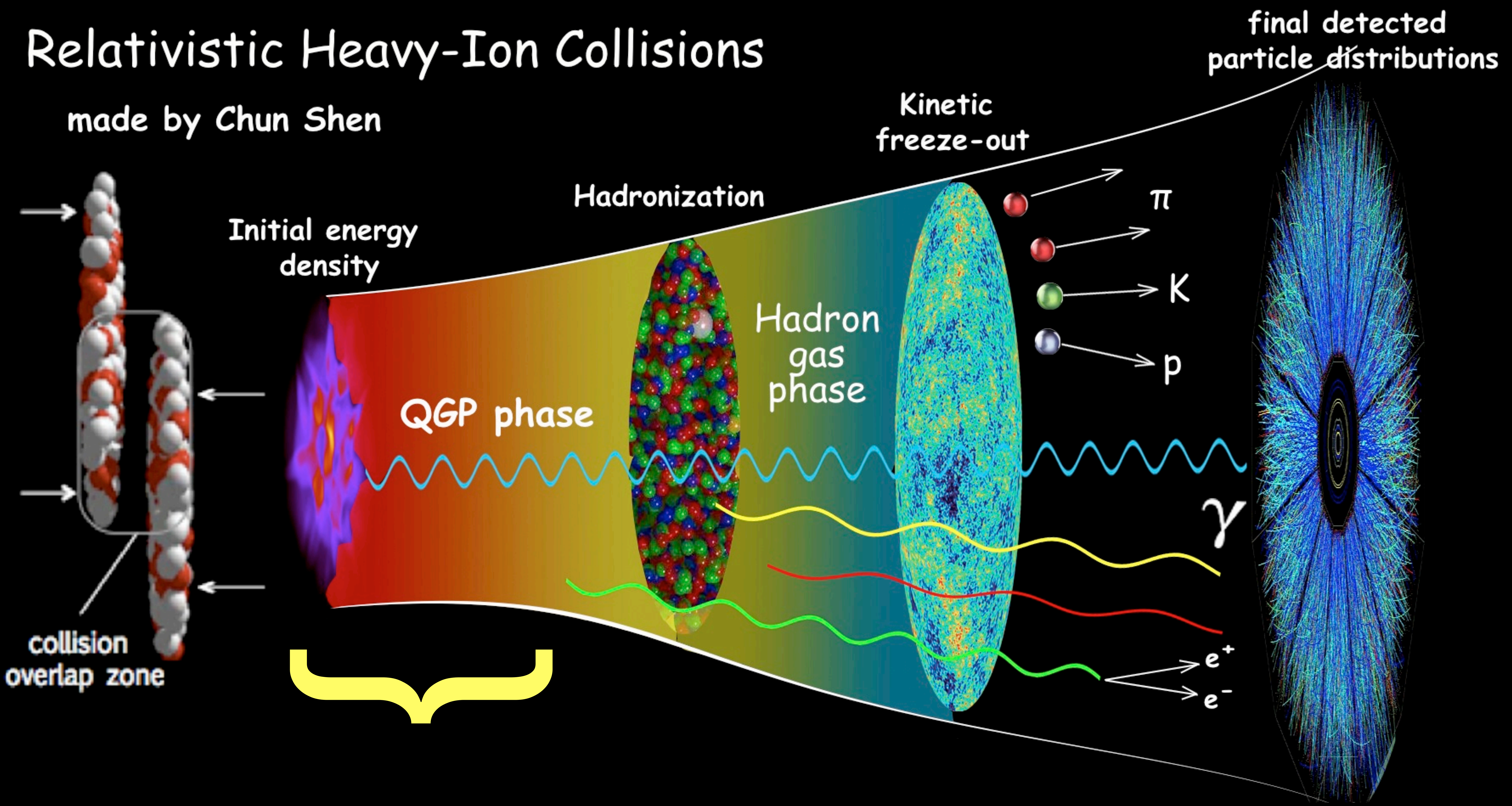
ATLAS-CONF-2021-001



- Correlations between anisotropic flow harmonics of different orders
  - sensitive to initial conditions and final state interactions



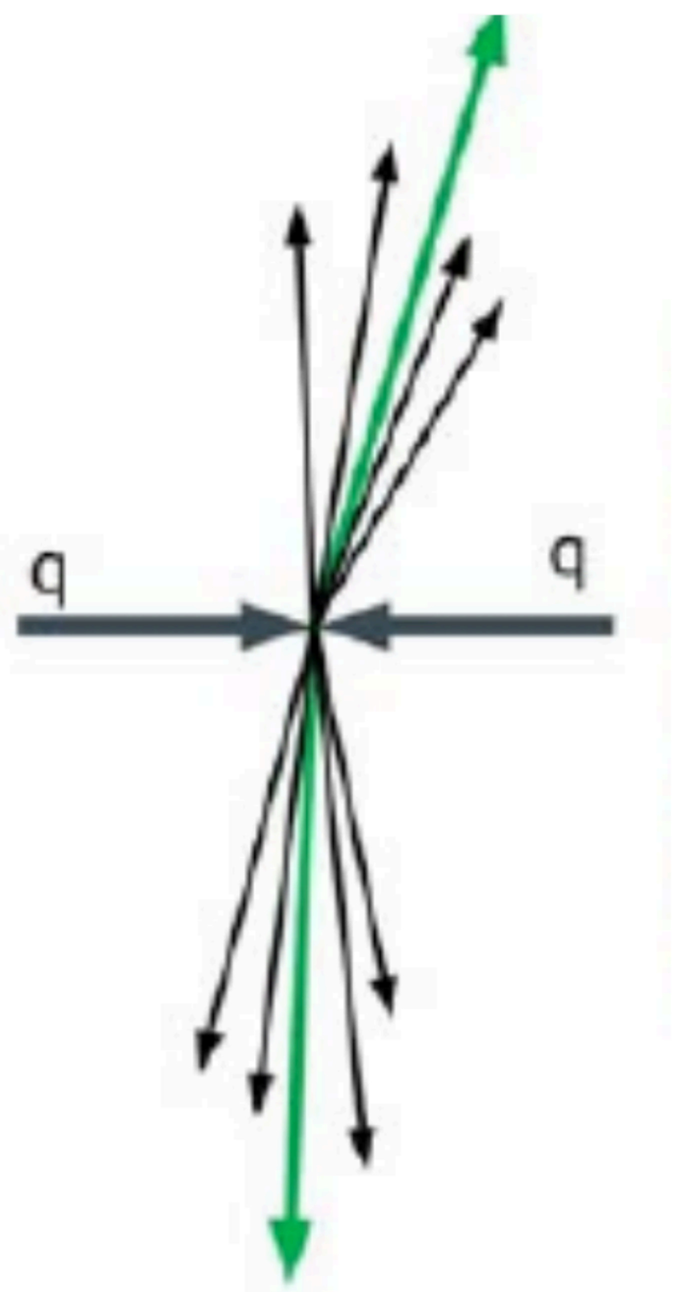
ALICE, PRL 117 (2016) 182301, arXiv:1604.07663 [nucl-ex]



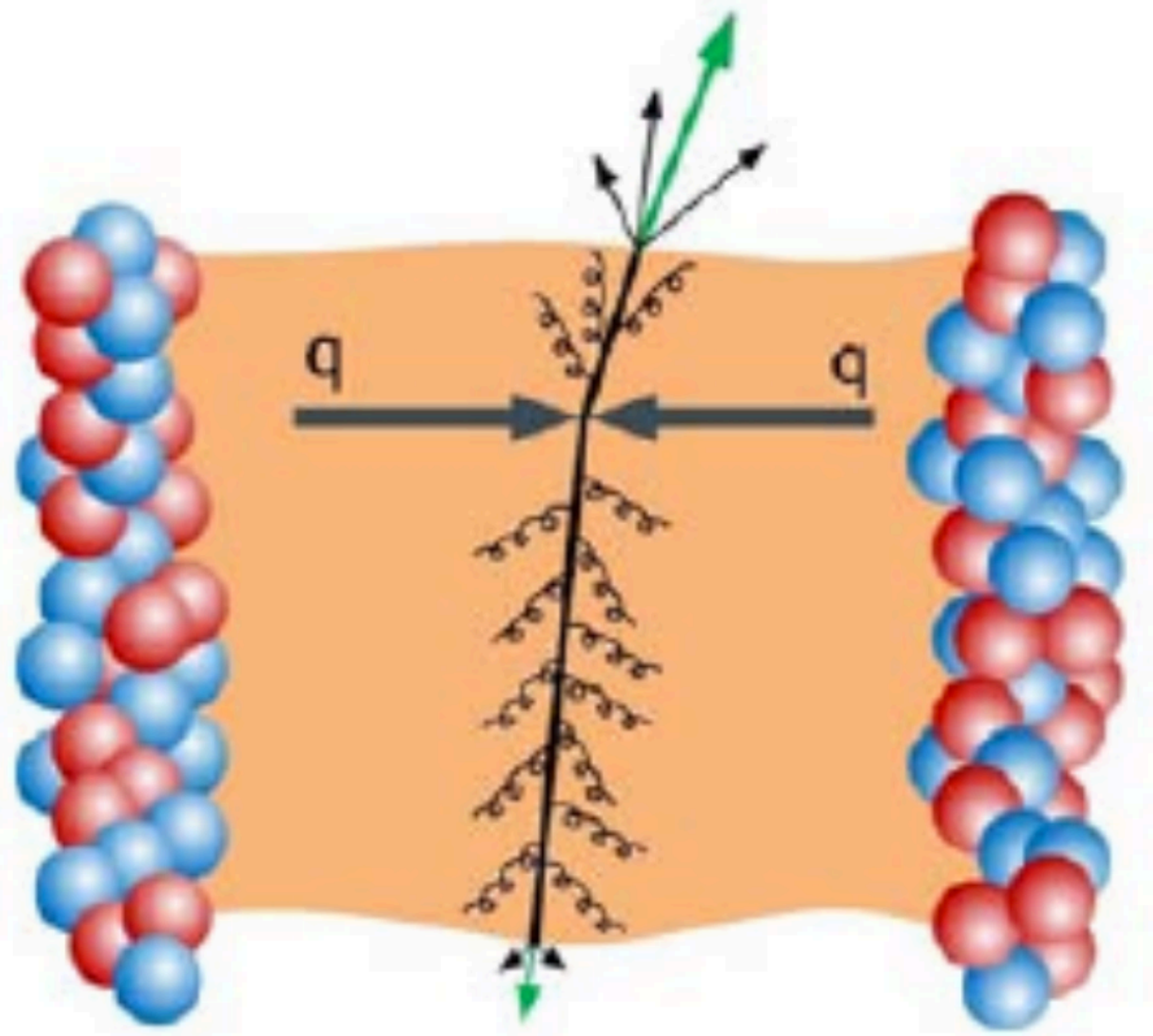
2. The hard sector: jets

A colored probe in a colored medium

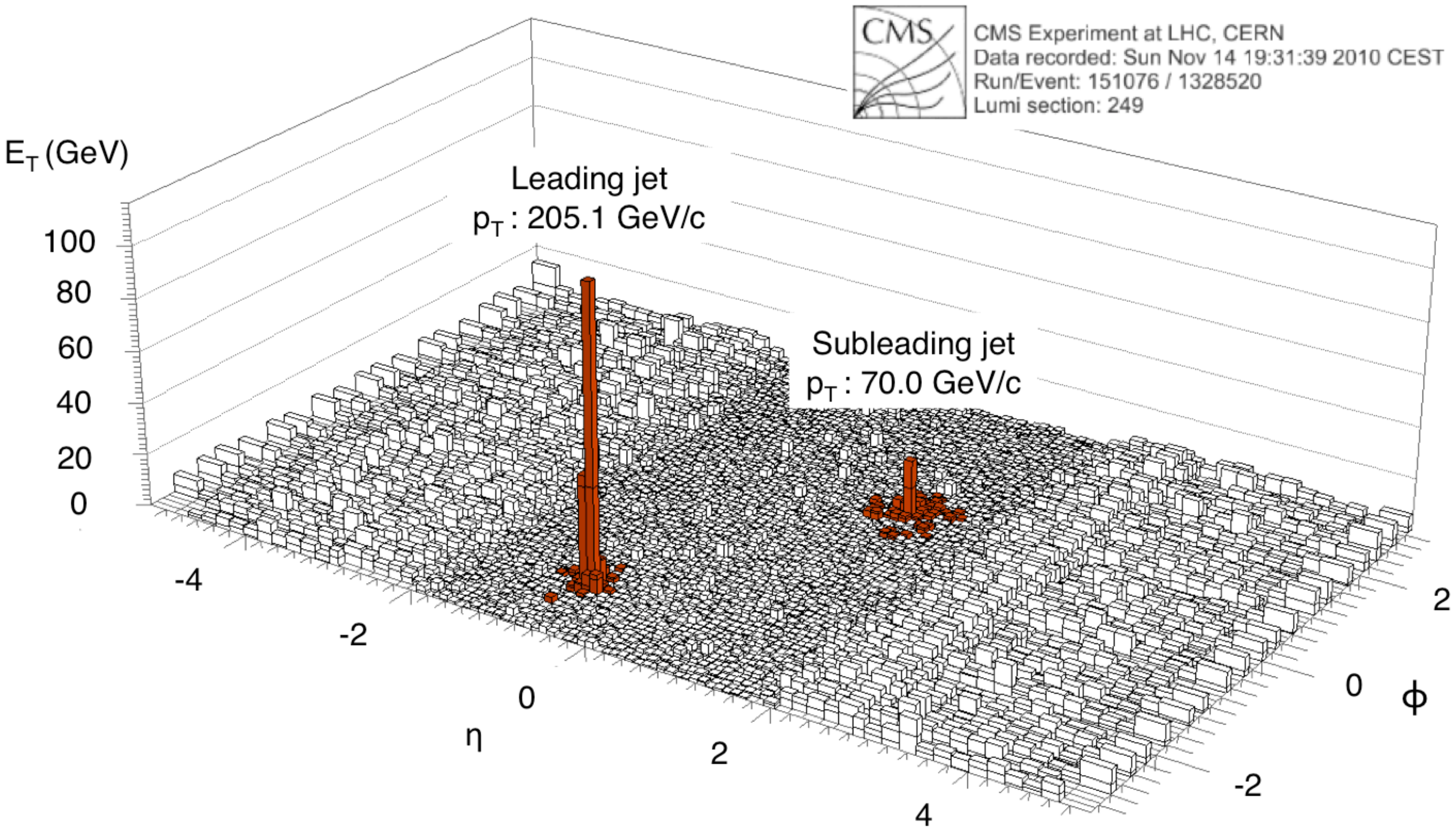
- Hard scatterings in the early stages of the collision produce
back-to-back recoiling partons, which fragment into collimated clusters of hadrons



- As they traverse the QGP, partons interact with the medium
→ "jet quenching"
- Characterize the nature of this energy loss to understand properties of the QGP and the interactions of a colored probe with a colored medium

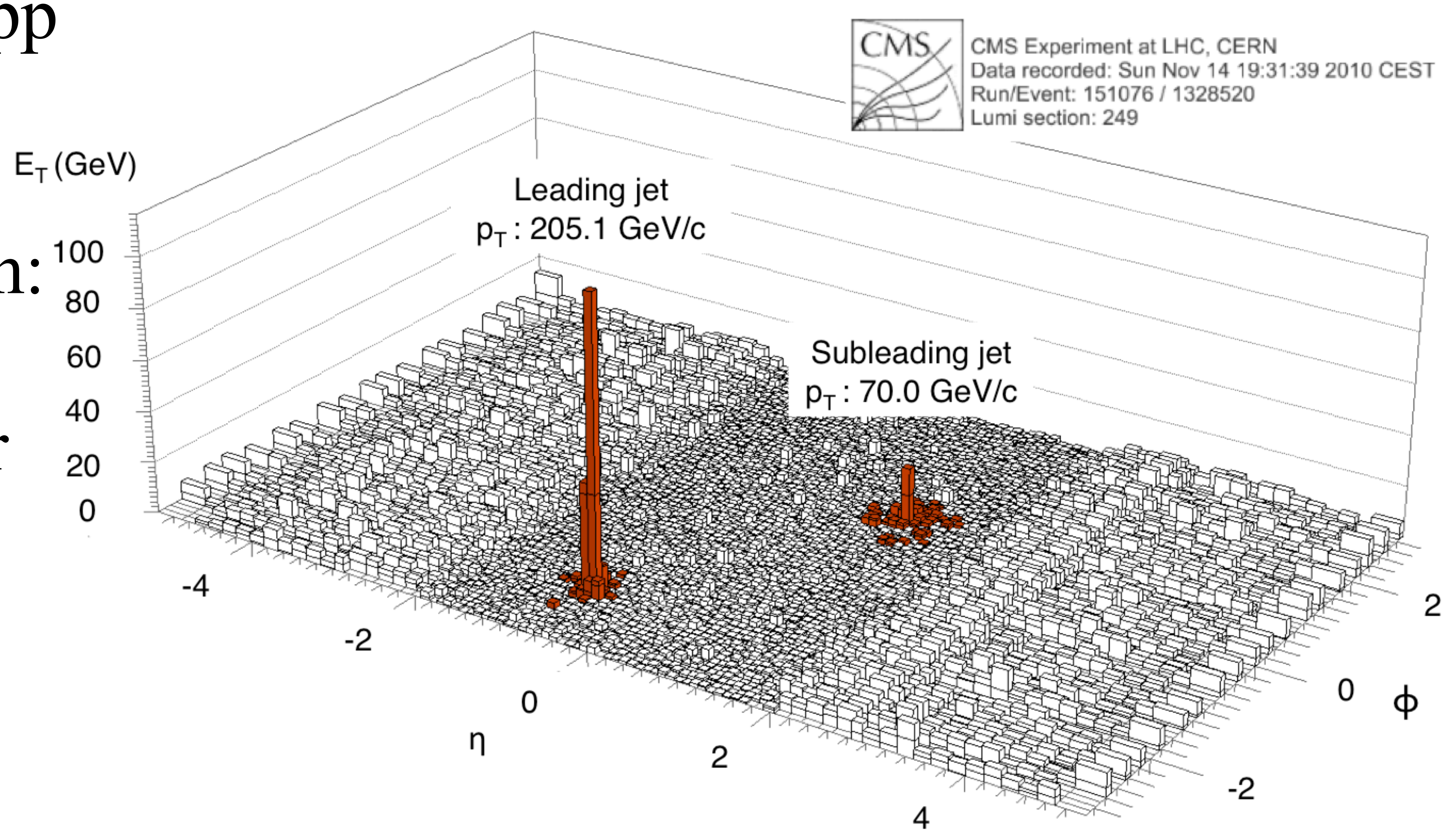


Jets in heavy-ion collisions



Jet finding in heavy-ion collisions

- Use clustering algorithms developed in pp collisions to reconstruct jets from their fragments
  → most common is the anti-k_T algorithm: starting with the high-p_T particles, iteratively cluster hadrons based on their distance $\Delta R = \sqrt{(\Delta\varphi^2+\Delta\eta^2)}$ and p_T
  → common cone sizes in heavy-ion collisions: R = 0.2-0.6



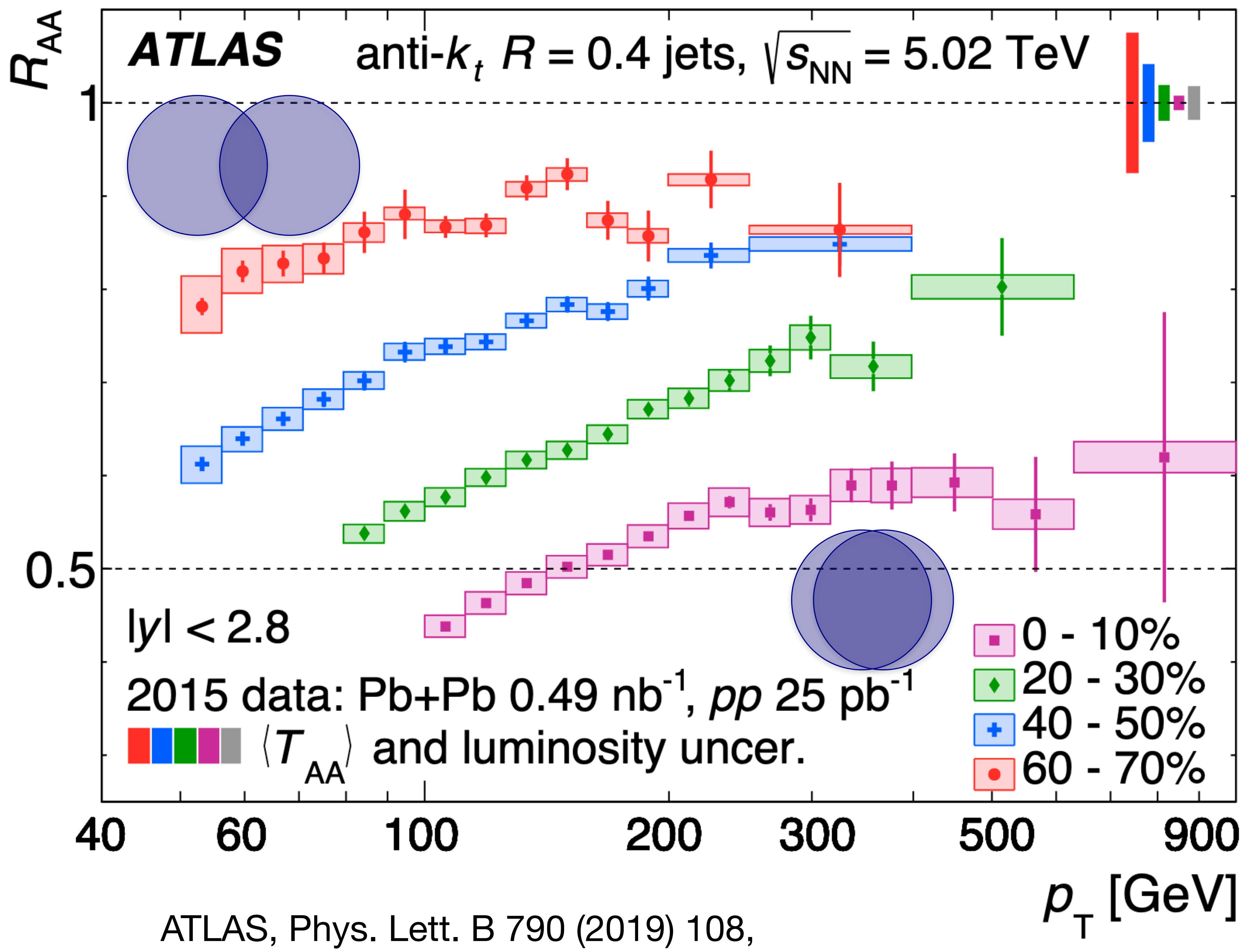
- The challenge: the large and fluctuating background!

In 0-10% central Pb+Pb collisions at 5 TeV:
$\rho = p_T^{bkg}/A \sim 220\text{-}280$ GeV/c
$p_T^{bkg} \sim 110\text{-}140$ GeV/c for R = 0.4
$\sigma[p_T^{bkg}] \sim 16$ GeV/c

← Compare to the energy of the jets we want to measure!
$p_T^{jet} \sim 10\text{-}100$ GeV/c

ALICE, PRC 101 (2020) 034911, arXiv: 1909.09718 [nucl-ex]

Jet quenching



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

Number of jets in a heavy-ion collision

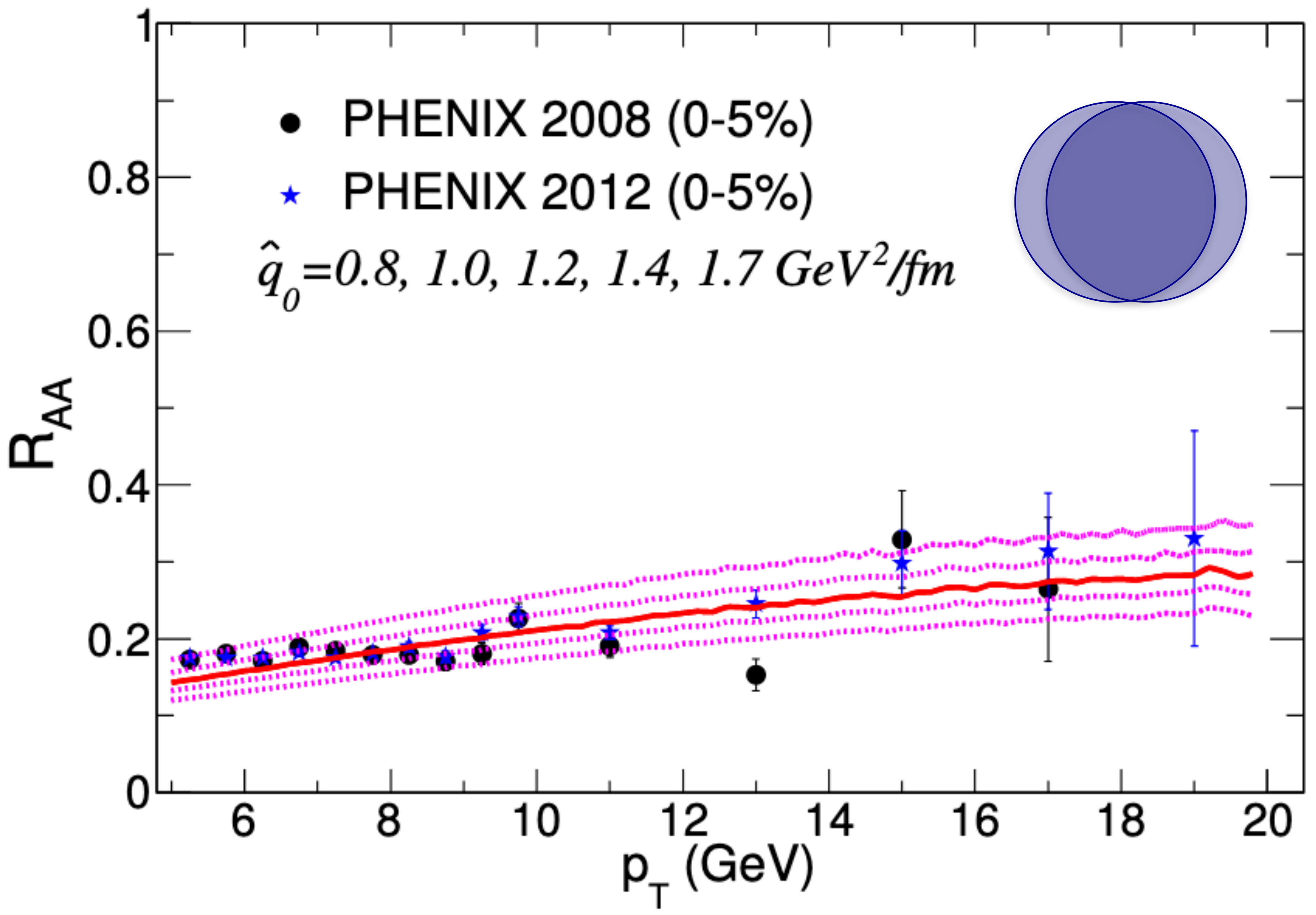
$$R_{AA} = \frac{(1/N_{evt})\ dN_{jet}/dp_T\big|_{AA}}{\langle N_{coll} \rangle\ (1/N_{evt})\ dN_{jet}/dp_T\big|_{pp}}$$

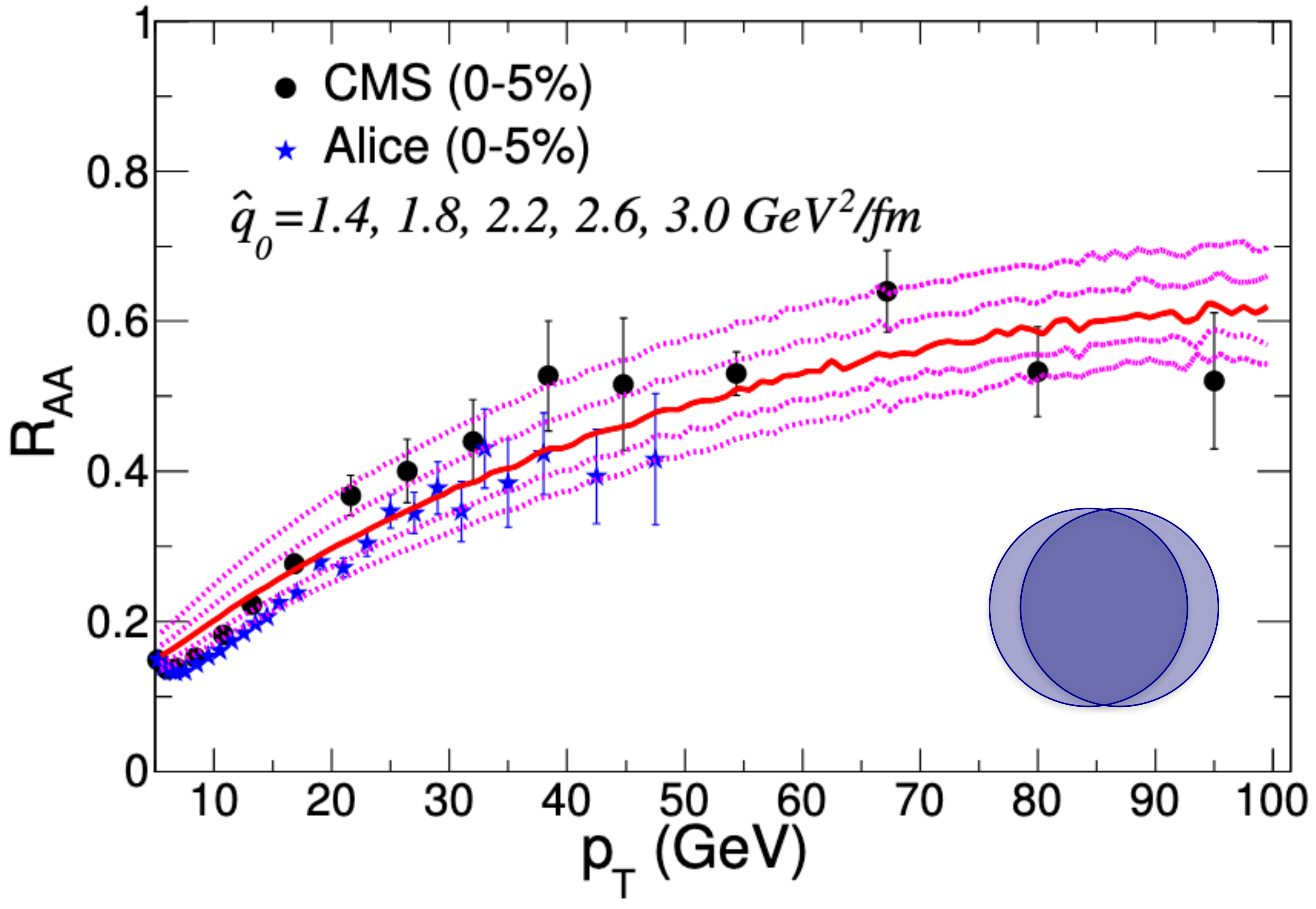
Equivalent number of proton-proton collisions in a heavy-ion event

Number of jets in a proton-proton collision

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

Charged particle R_{AA}





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

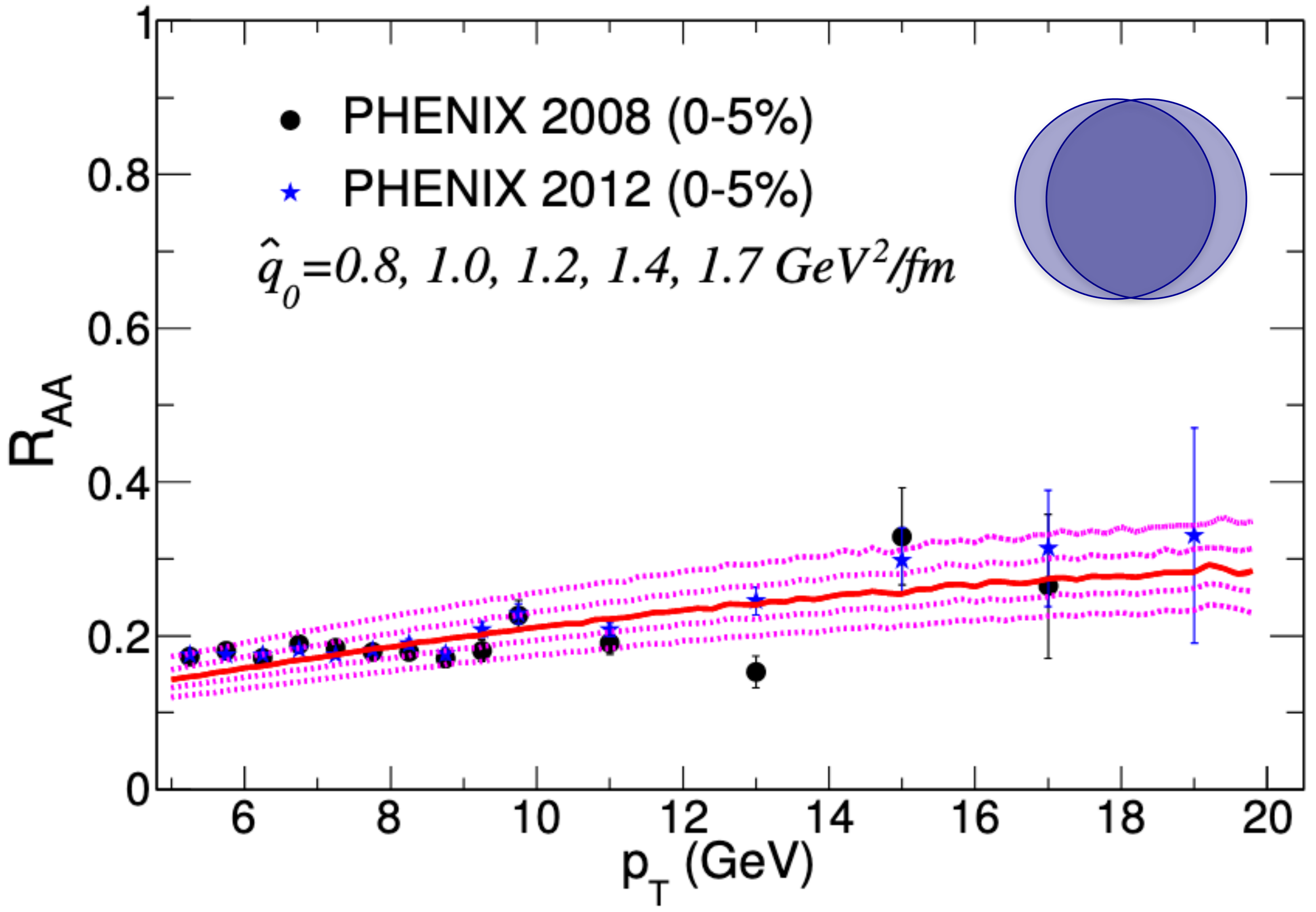
Number of particles in a heavy-ion collision

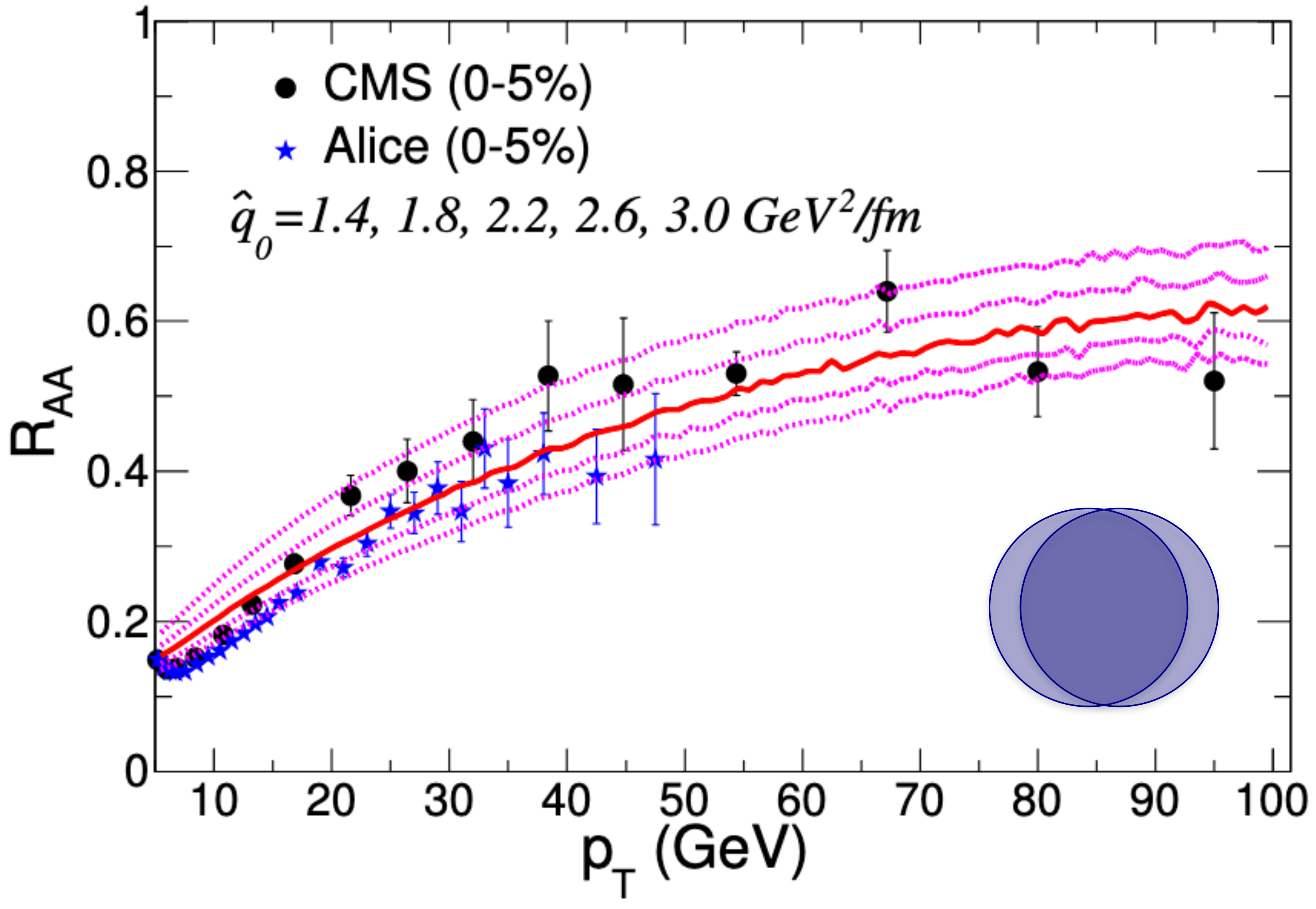
Equivalent number of proton-proton collisions in a heavy-ion event

Number of particles in a proton-proton collision

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

Charged particle R_{AA}





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

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

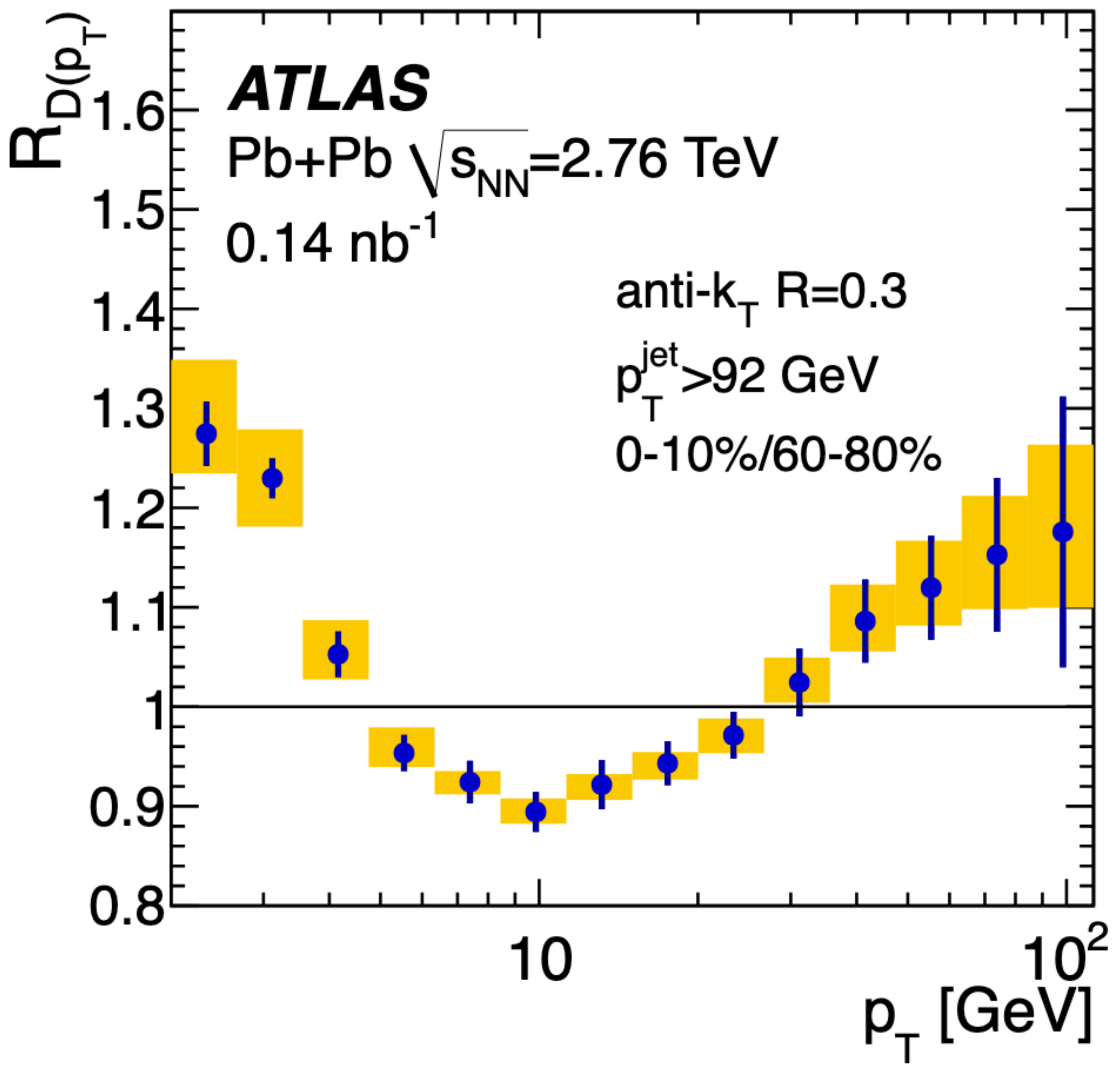
- for a quark jet with E = 10 GeV

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

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

Beyond R_{AA}

- Many detailed studies of the *shape and structure* of jets give insight into the specifics of jet modification mechanisms due to interactions with the medium
  - Fragmentation functions
  - Correlations: jet-hadron (Δφ,Δη) correlations, …
  - Jet shape studies (often pQCD-inspired): jet mass, jet angularities, N-subjettiness, …



ATLAS, PLB 739 (2014) 320, arXiv:1406.2979 [hep-ex]

Beyond R_{AA}

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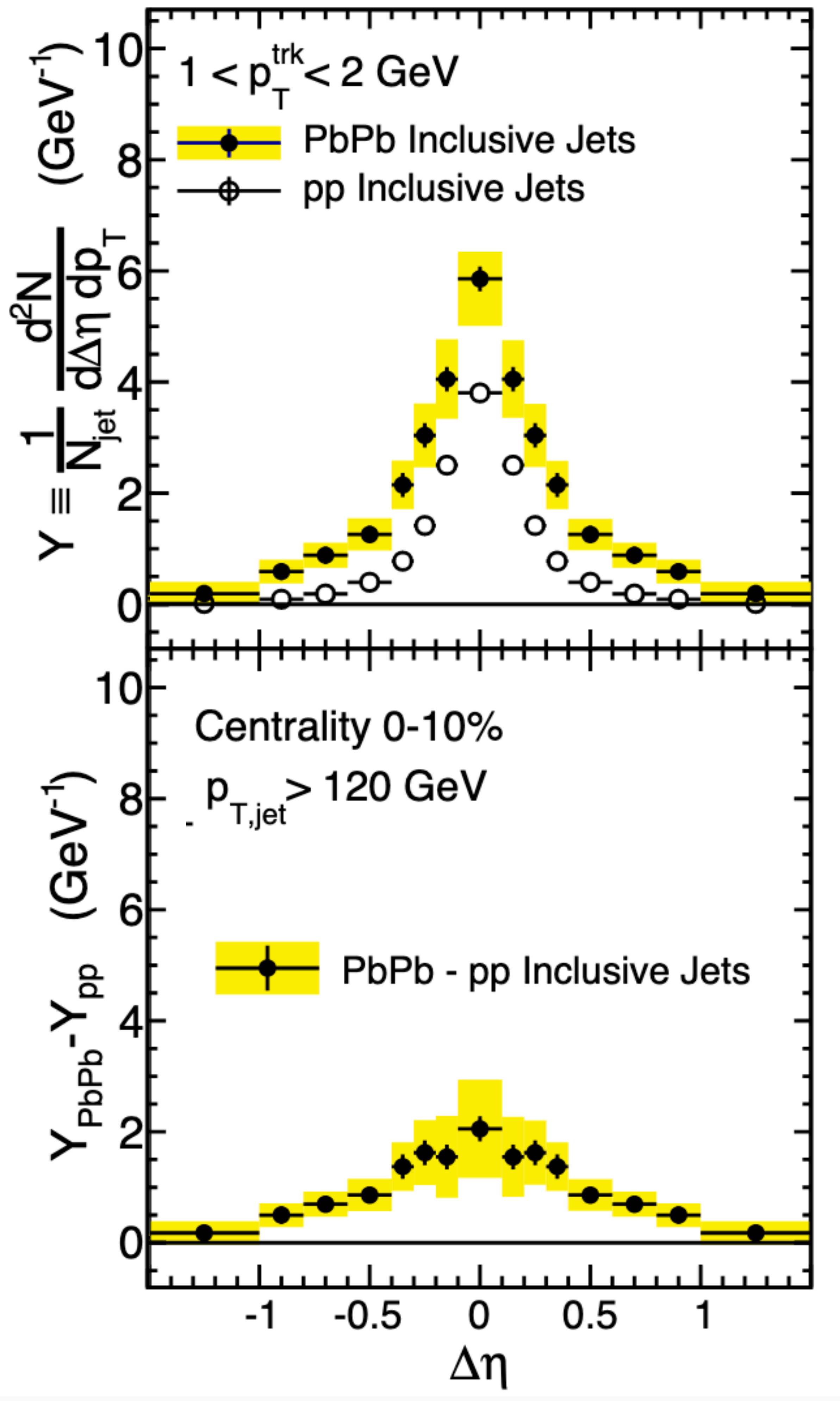
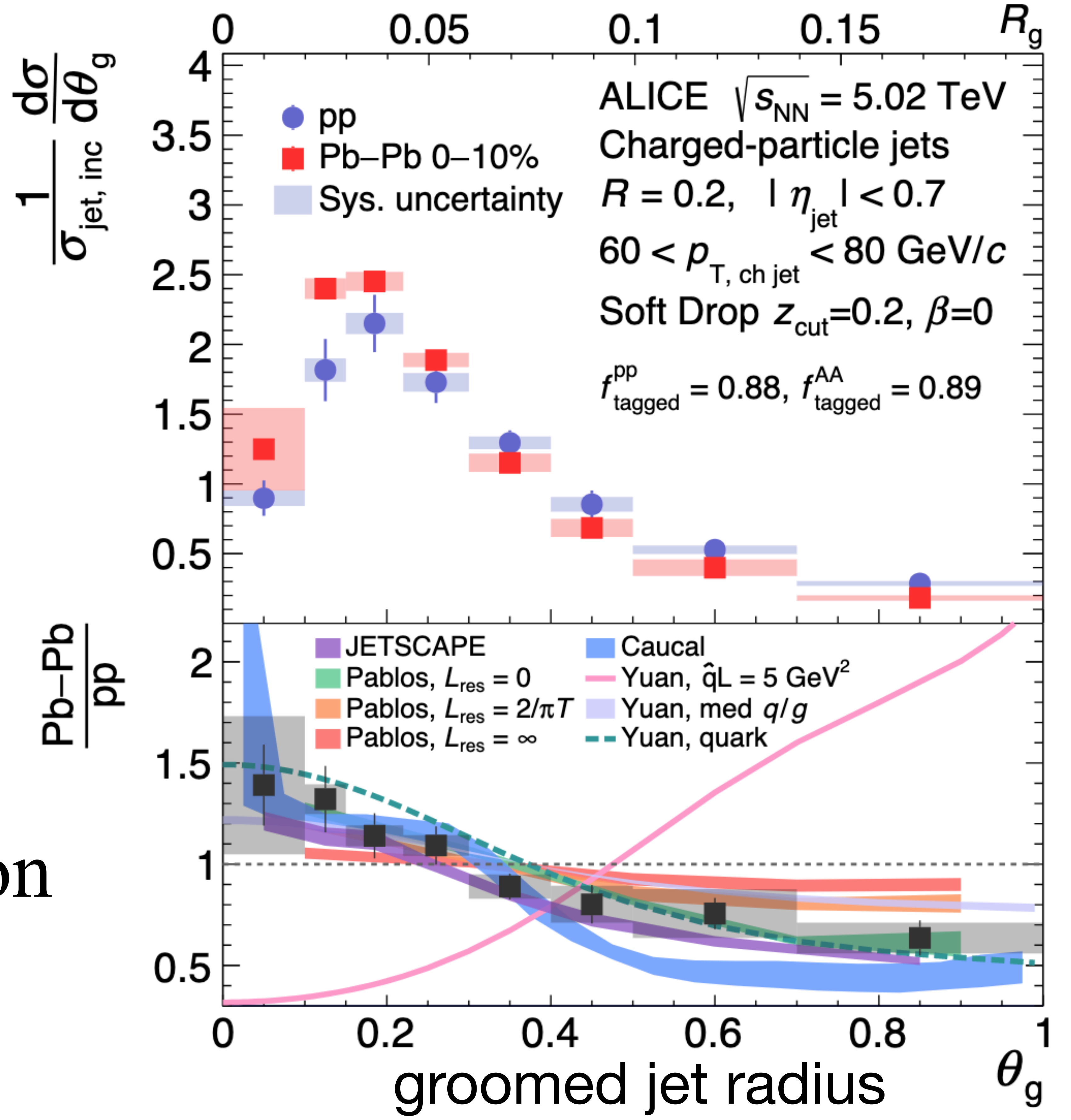
  - Fragmentation functions
  - Correlations: jet-hadron ($\Delta\varphi$,$\Delta\eta$) correlations, …
  - Jet shape studies (often pQCD-inspired): jet mass, jet angularities, N-subjettiness, …



CMS, JHEP 02 (2016) 156,
arXiv:1601.00079 [nucl-ex]

Beyond R_{AA}

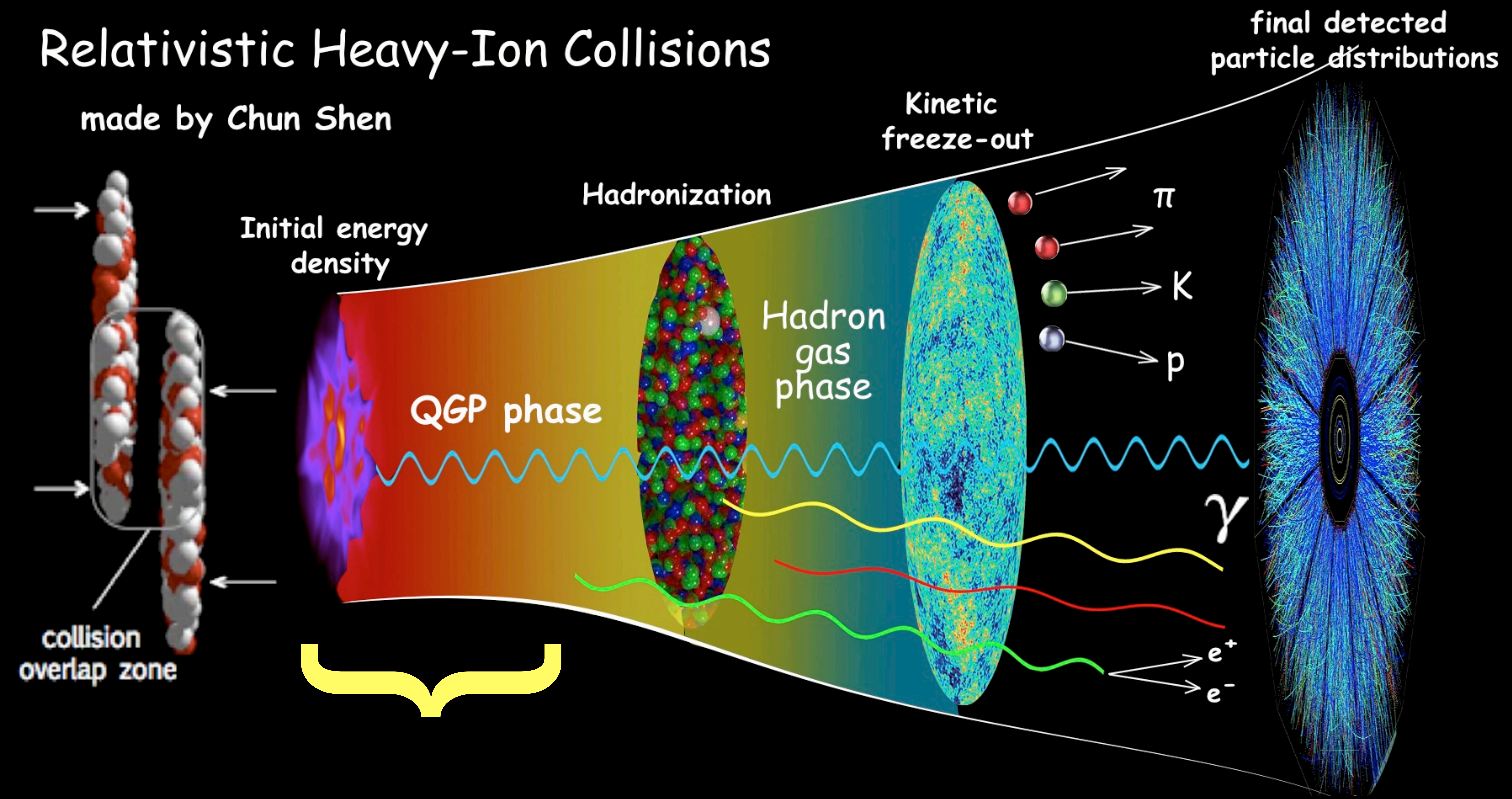
- Many detailed studies of the *shape and structure* of jets give insight into the specifics of jet modification mechanisms due to interactions with the medium
  - Fragmentation functions
  - Correlations: jet-hadron (Δφ,Δη) correlations, …
  - Jet shape studies (often pQCD-inspired): jet mass, jet angularities, N-subjettiness, …



ALICE, submitted to PRL, arXiv:2107.12984 [nucl-ex]

- In general, analyses tend to indicate that jets in heavy-ion collisions are softer and broader than in p+p collisions (caveat: conclusions depend on details of the reconstruction and selection of the jets, and the observable)

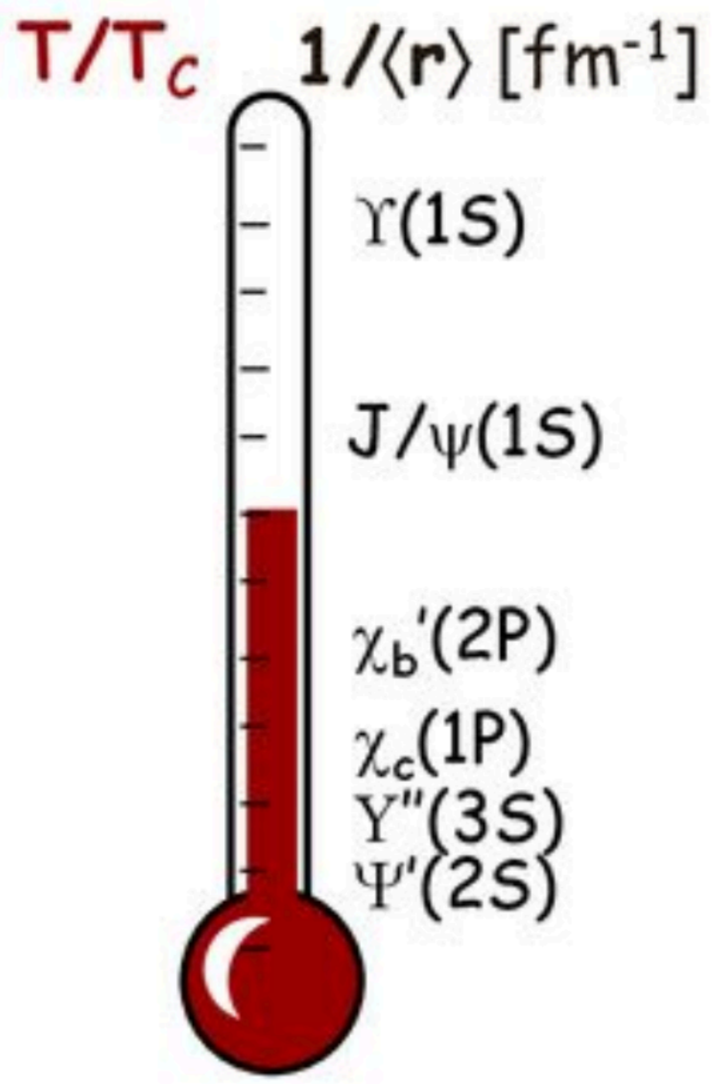
For a comprehensive review of jet measurements in heavy ion physics, see for example M. Connors, C. Nattrass, R. Reed, S. Salur, Rev. Mod. Phys. 90 (2018) 025005, arXiv: 1705.01974 [nucl-ex]

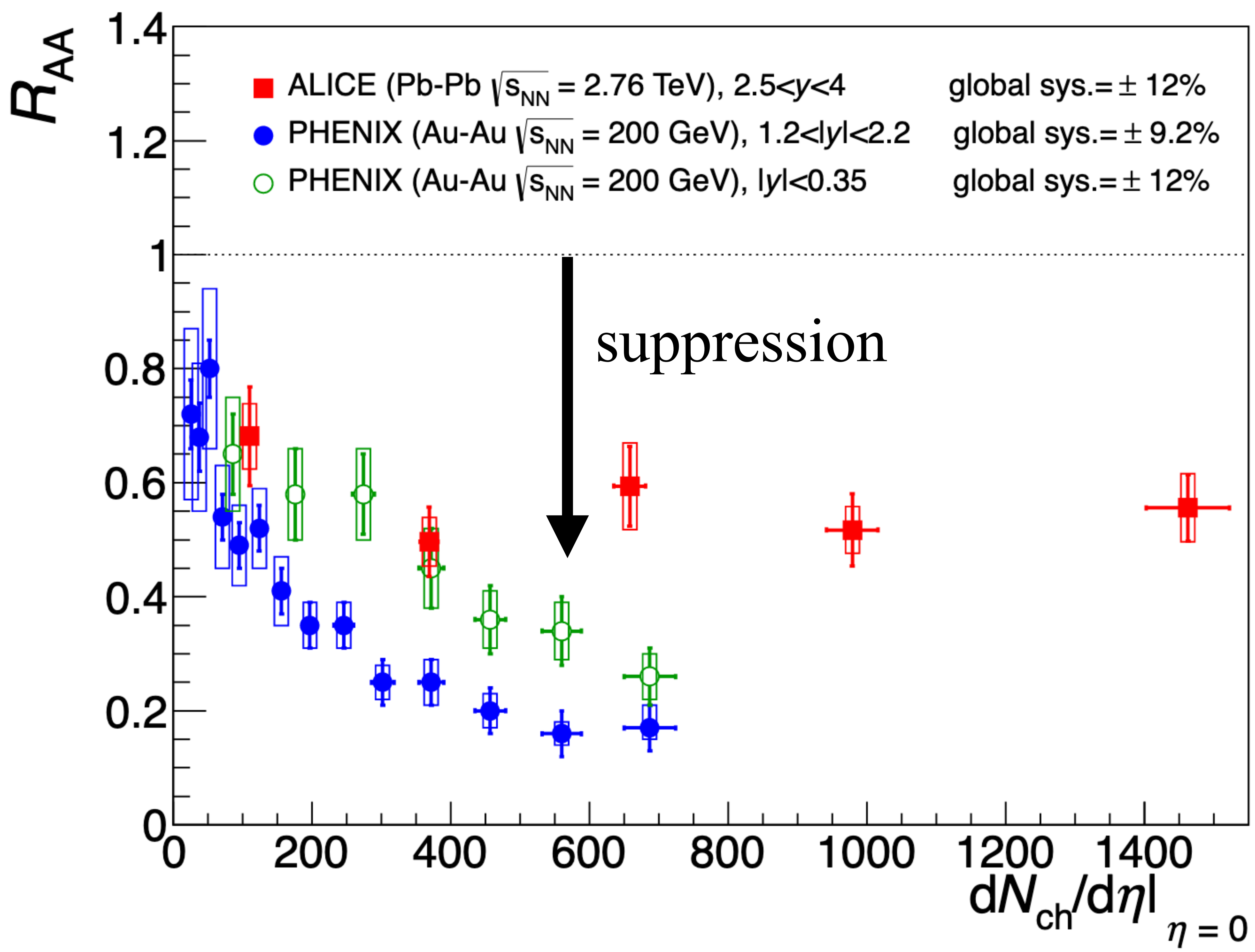


3. The hard sector: heavy flavor

Melting of quarkonia: J/ψ

- Use quarkonia as a “thermometer” of the QGP
- Expect quarkonia to dissociate at high temperatures → suppression

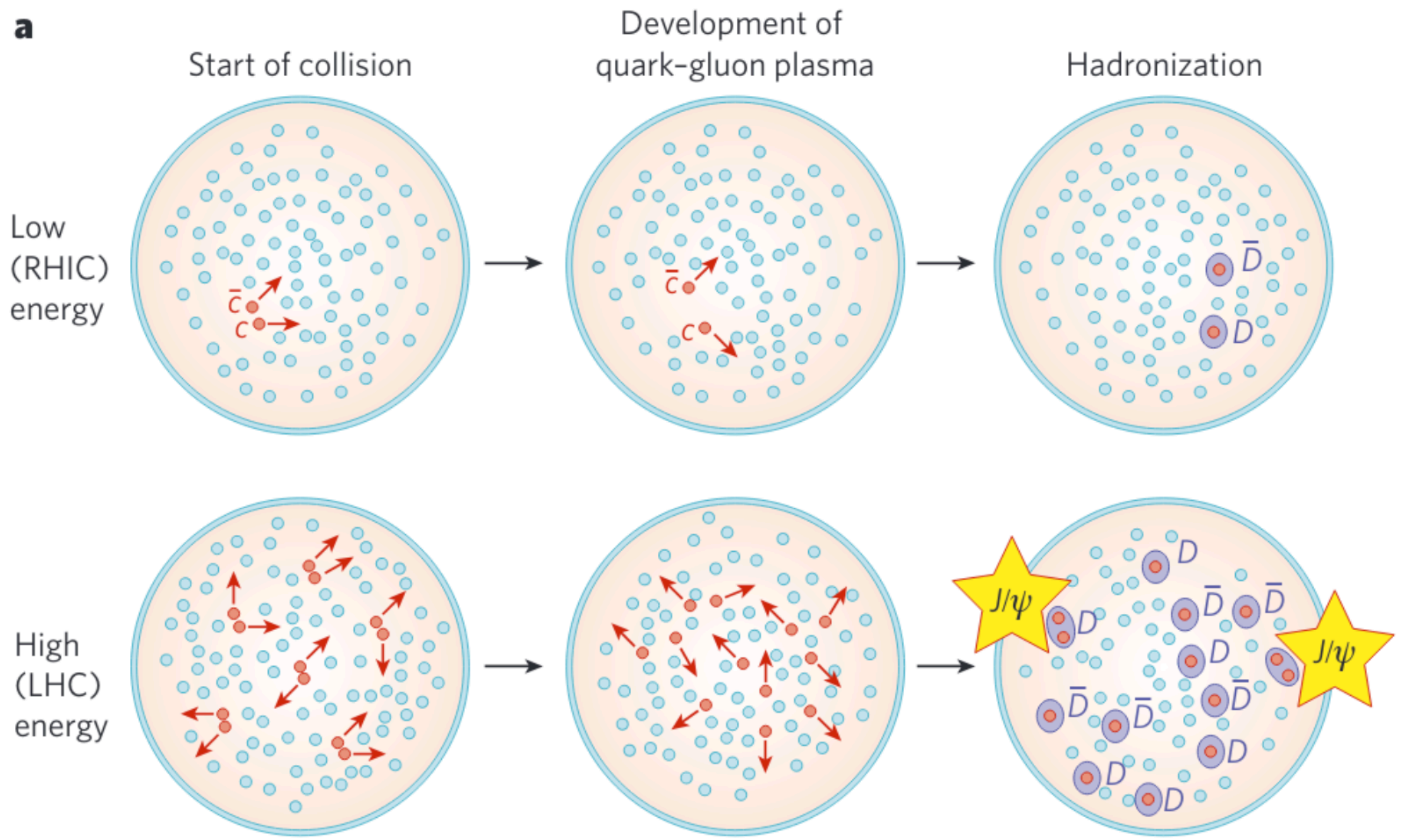




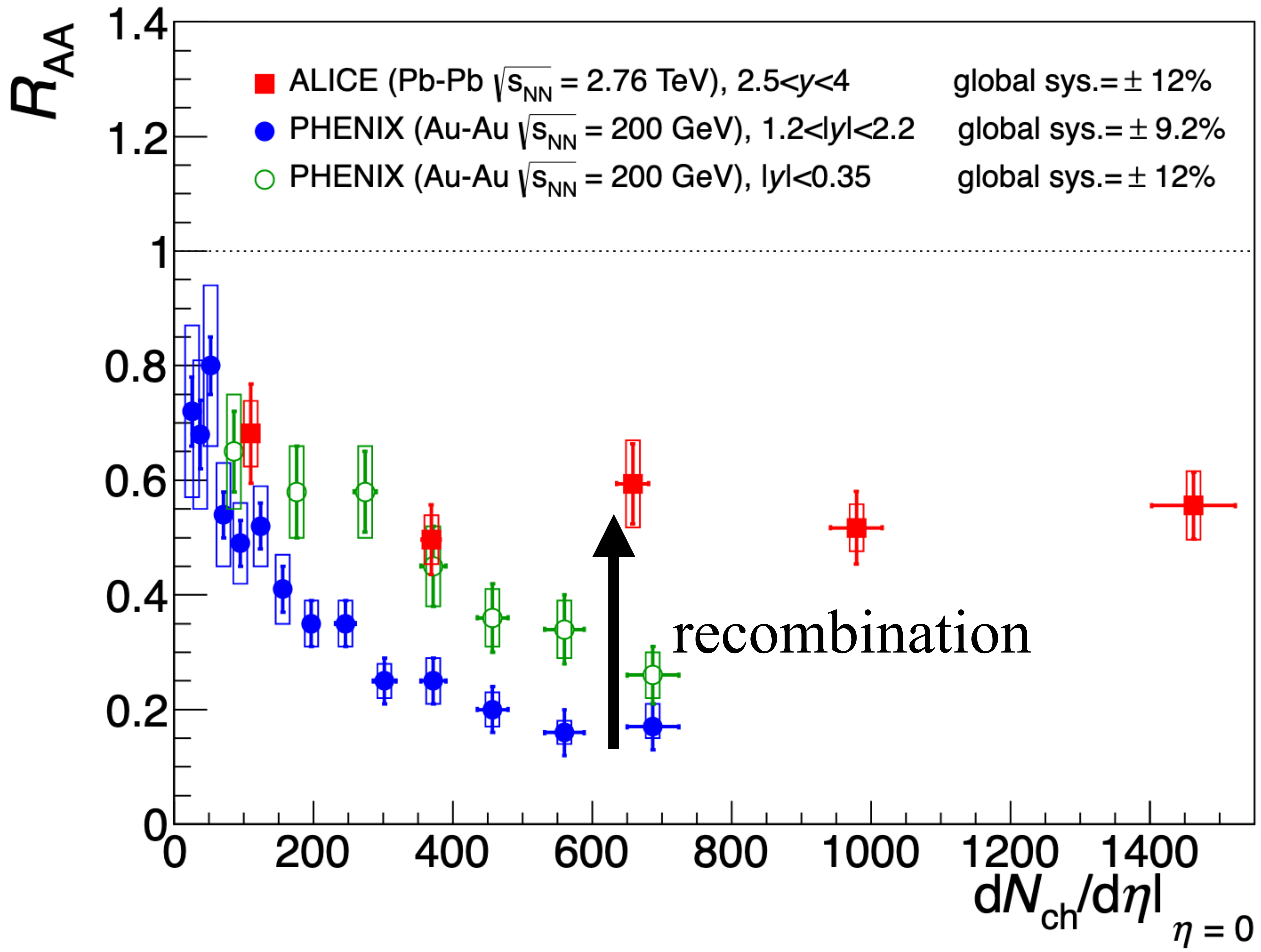
ALICE, PRL 109 (2012) 072301,
arXiv:1202.1383 [hep-ex]

Melting of quarkonia: J/ψ

- Use quarkonia as a “thermometer” of the QGP
- Expect quarkonia to dissociate at high temperatures → suppression
- More charm quarks available to form hadrons at LHC than at RHIC → recombination



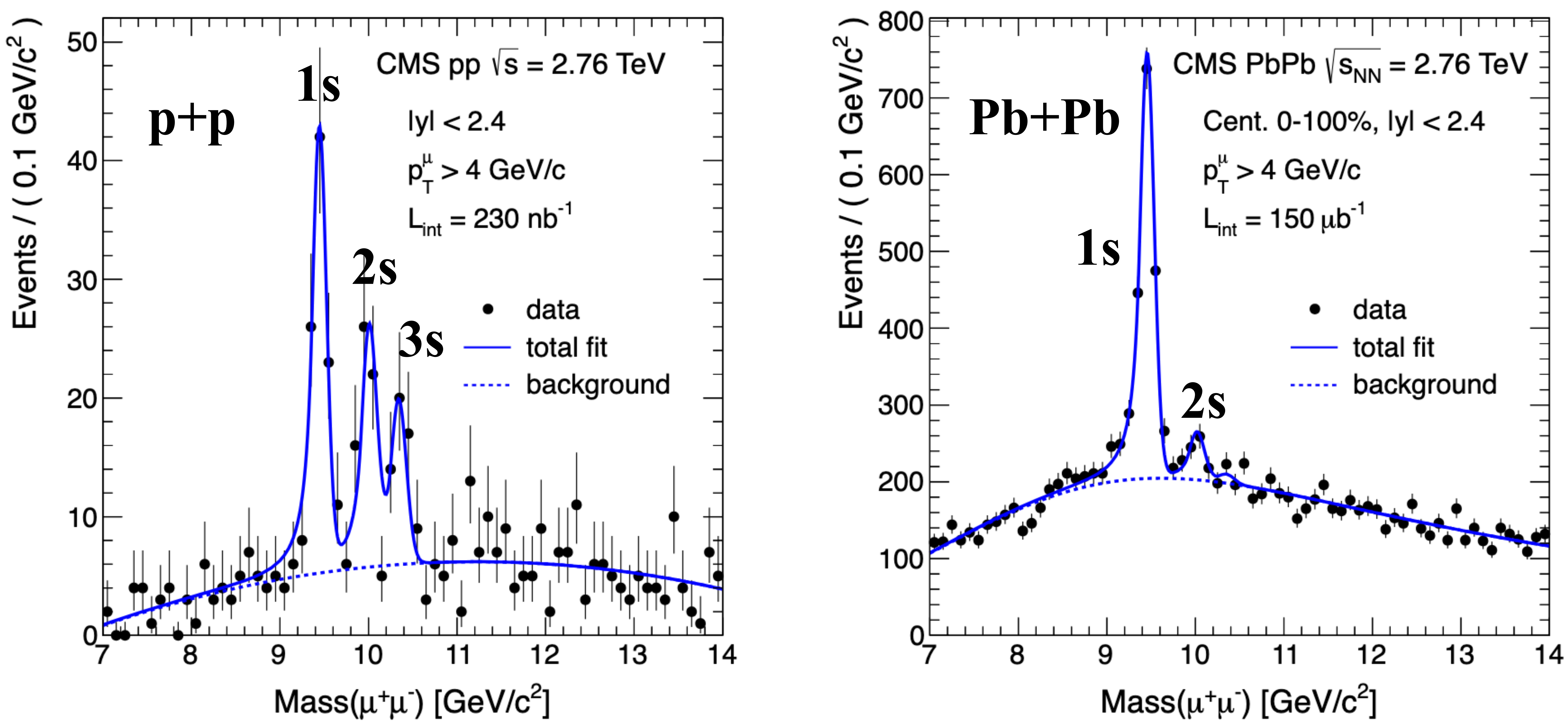
P. Braun-Munzinger and J. Stachel, Nature 448 (2007) 302



ALICE, PRL 109 (2012) 072301, arXiv:1202.1383 [hep-ex]

Melting of quarkonia: Υ

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



CMS, PRL 109 (2012) 222301,
arXiv:1208.2826 [nucl-ex]

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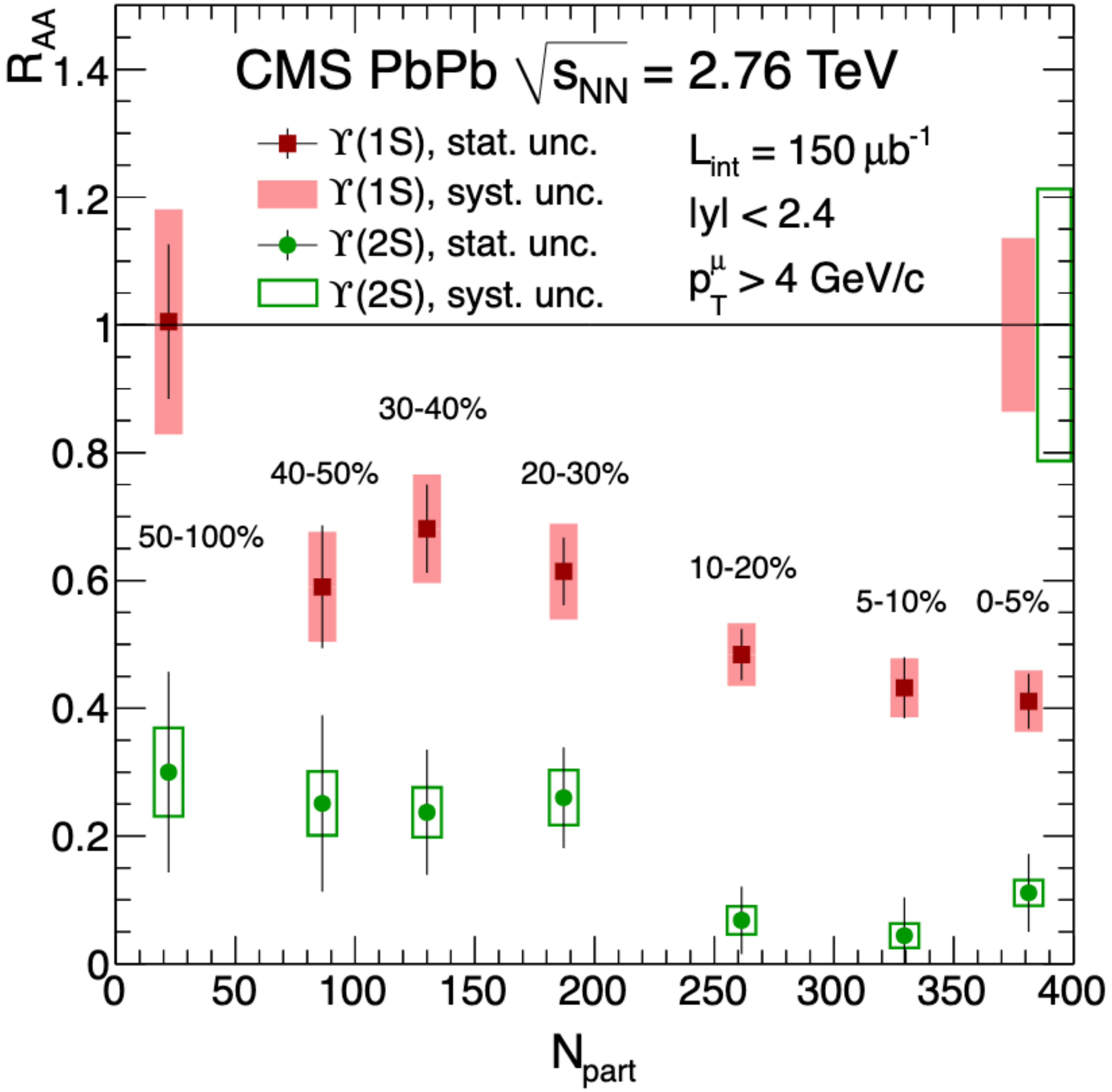
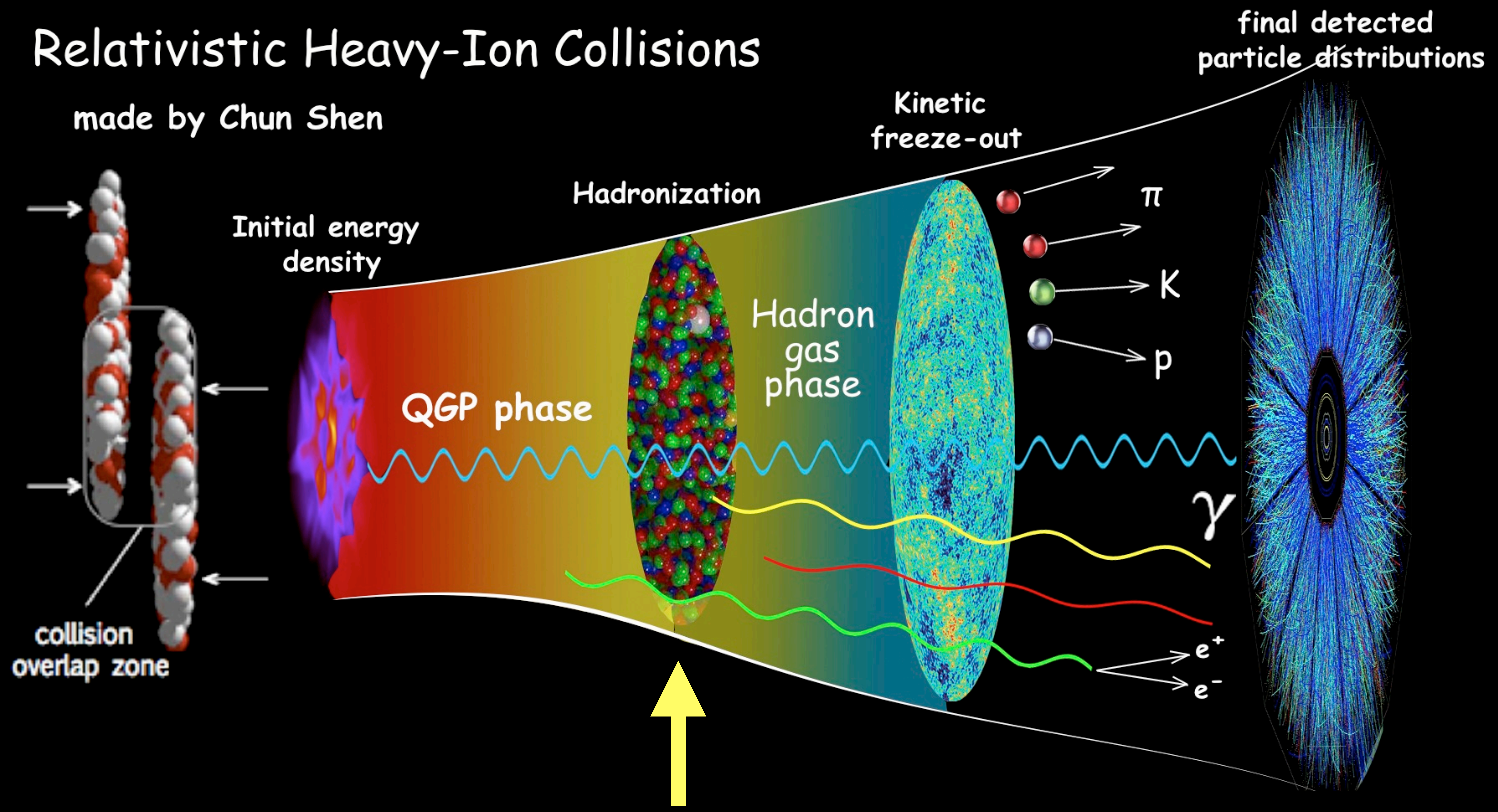


CMS, PRL 109 (2012) 222301,
arXiv:1208.2826 [nucl-ex]

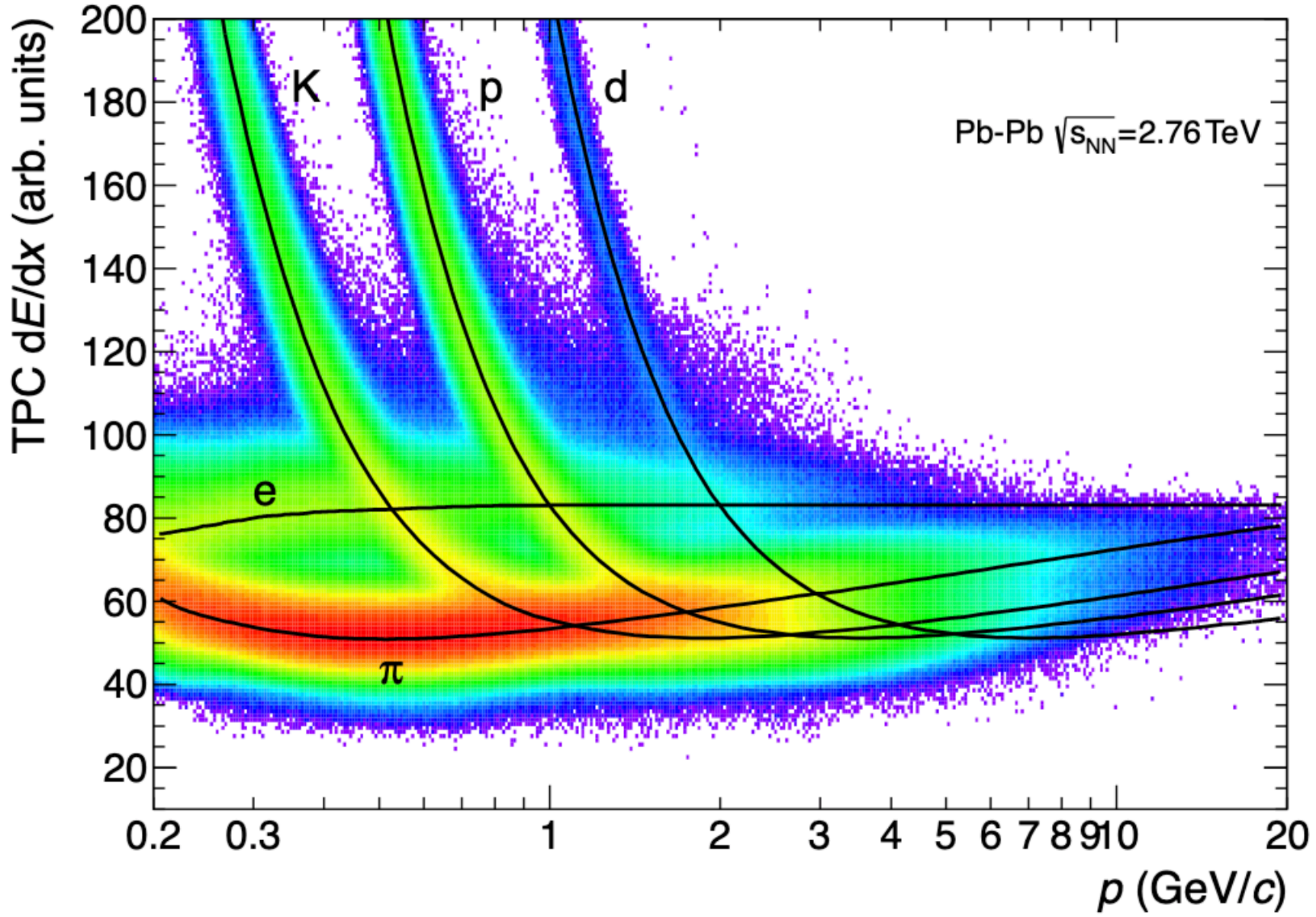


4. Hadronisation: identified particle yields

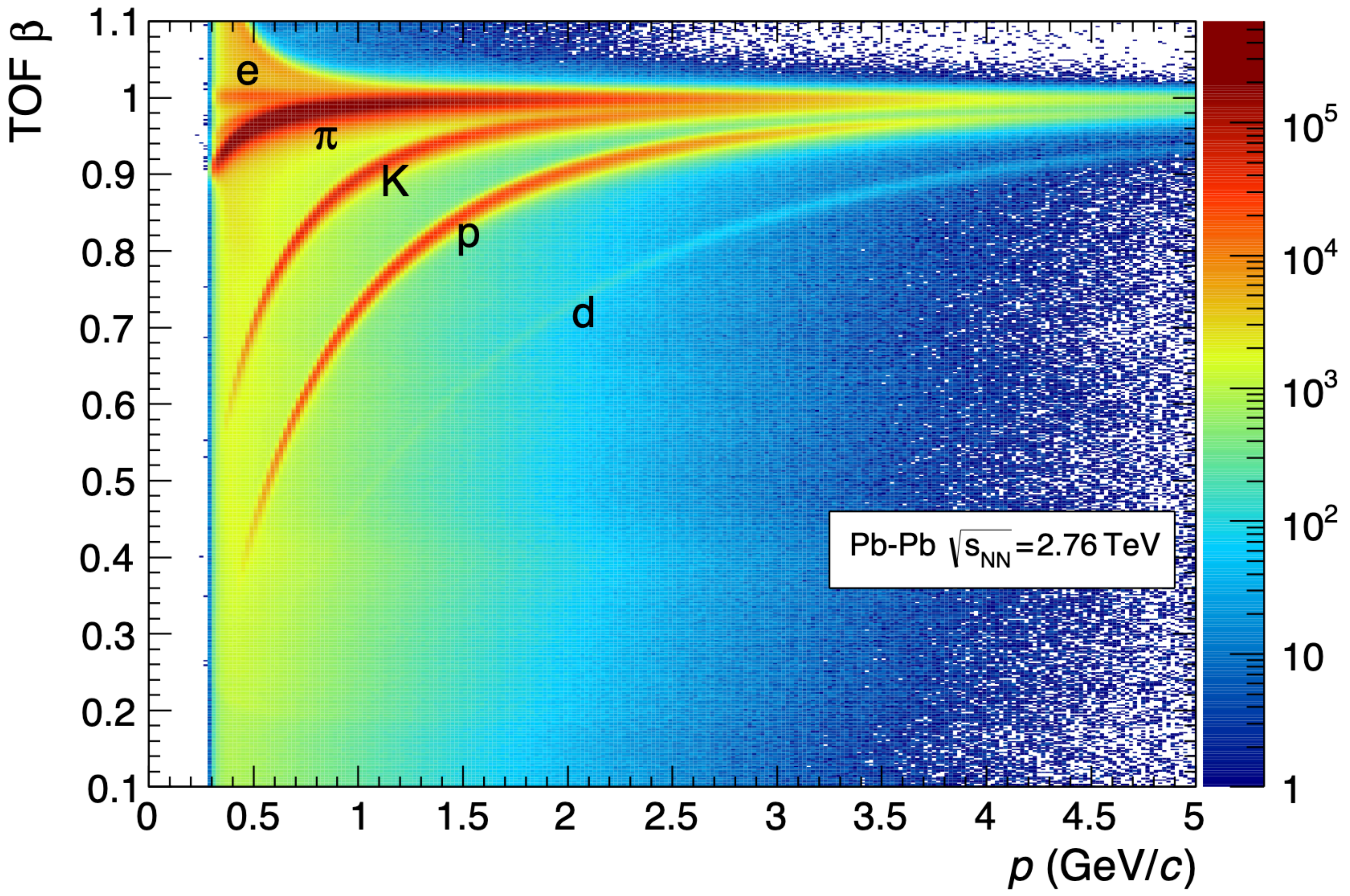
ALICE, Int. J. Mod. Phys. A 29 (2014) 1430044,
arXiv:1402.4476 [nucl-ex]

Particle identification

- Stable particles (e.g. π, K, p) identified via
  - specific energy loss (dE/dx) in the detector (e.g. the Time Projection Chamber in ALICE)
  - time of flight (TOF)



Bethe-Bloch curves describe mean energy loss per unit distance of charged particles through matter



Use velocity (from TOF) and momentum (from TPC) to solve for mass

ALICE, Int. J. Mod. Phys. A 29 (2014) 1430044, arXiv:1402.4476 [nucl-ex]

Particle identification

- Stable particles (e.g. π, K, p) identified via
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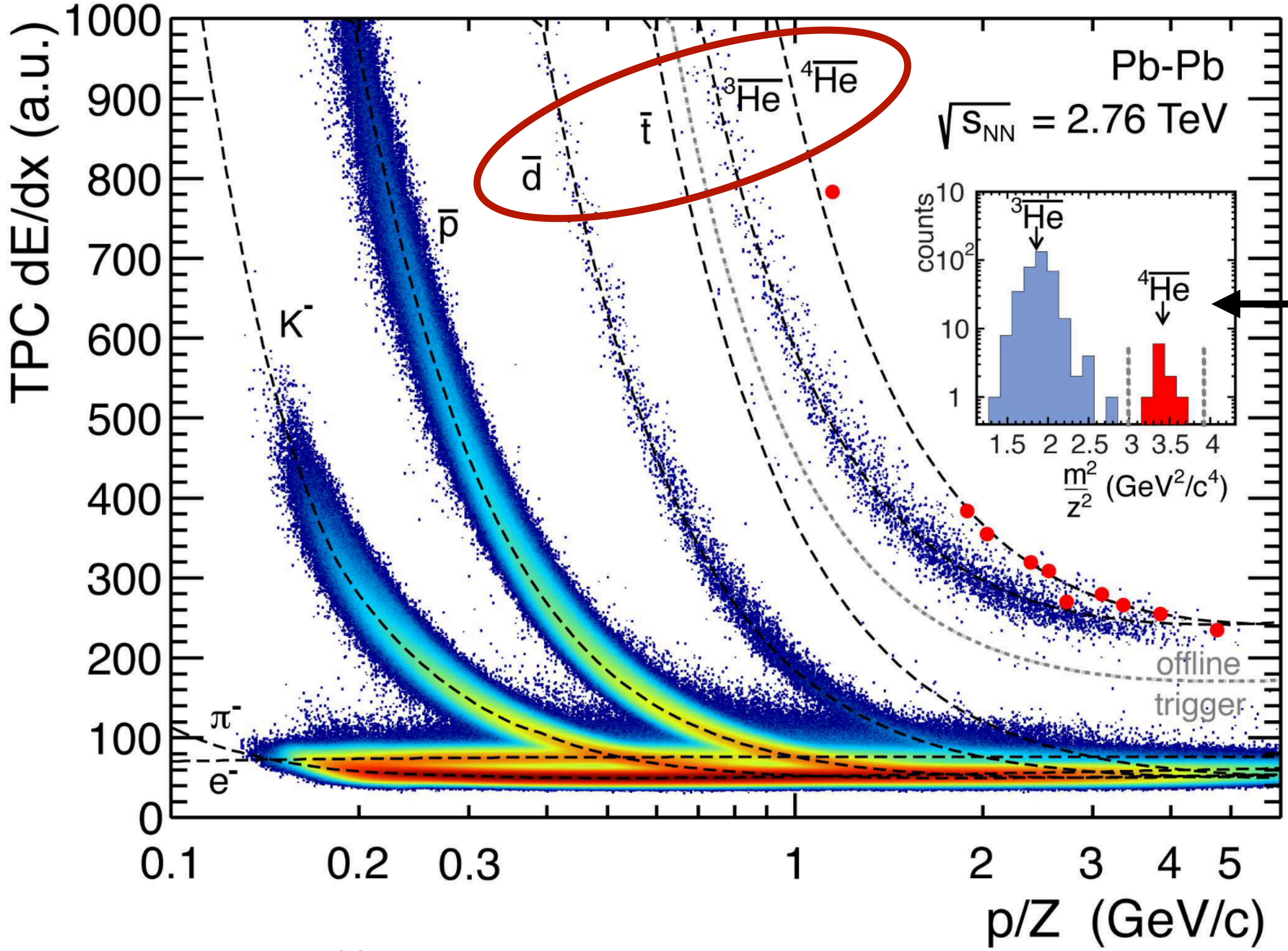
- Also: heavier/rarer nuclei (d, t, ^{3}He, ^{4}He)



complementary TOF measurement

ALICE, Int. J. Mod. Phys. A 29 (2014) 1430044,
arXiv:1402.4476 [nucl-ex]

Particle identification

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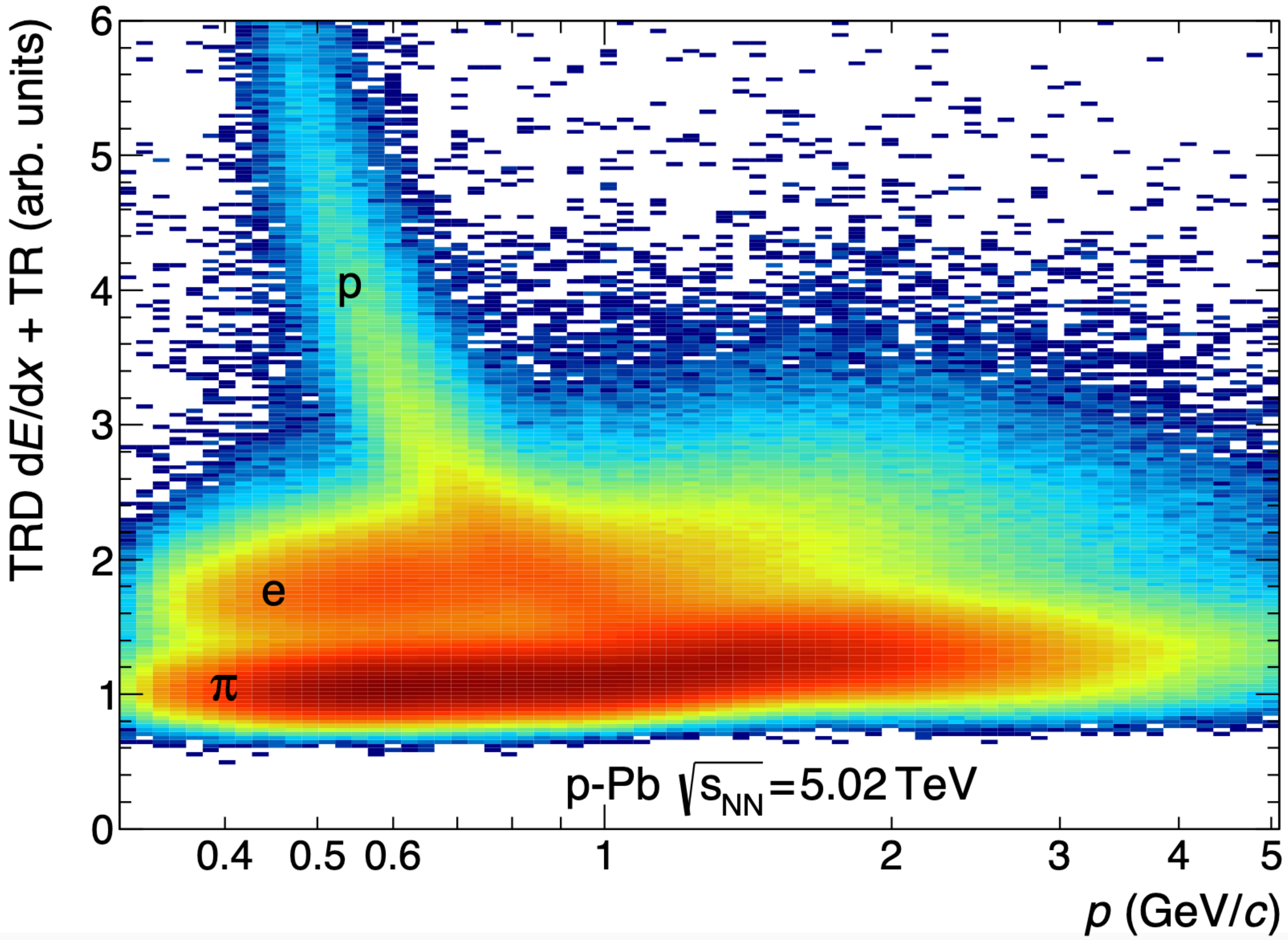
- Electrons identification using calorimeters and transition radiation detectors



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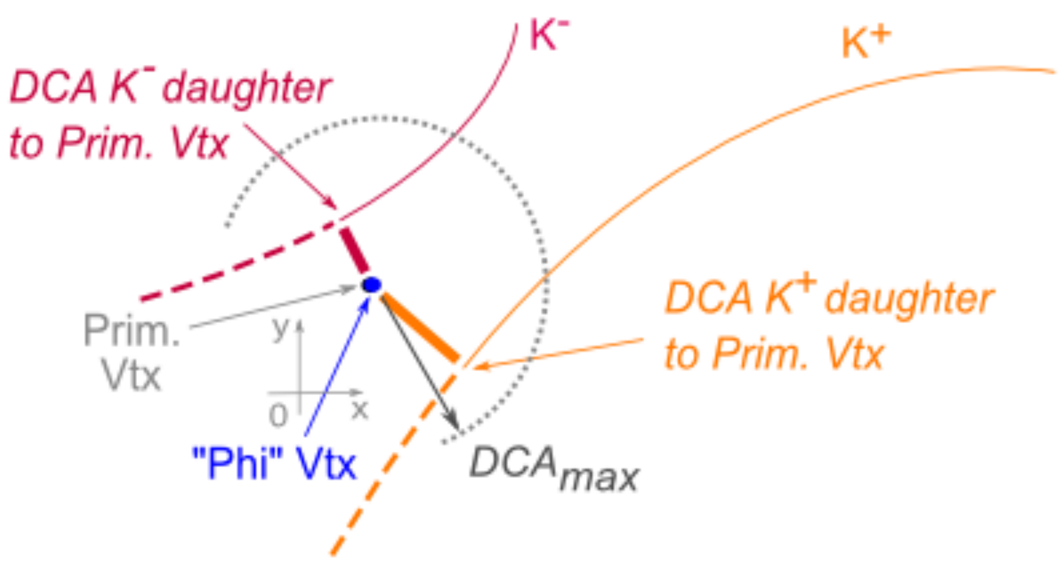
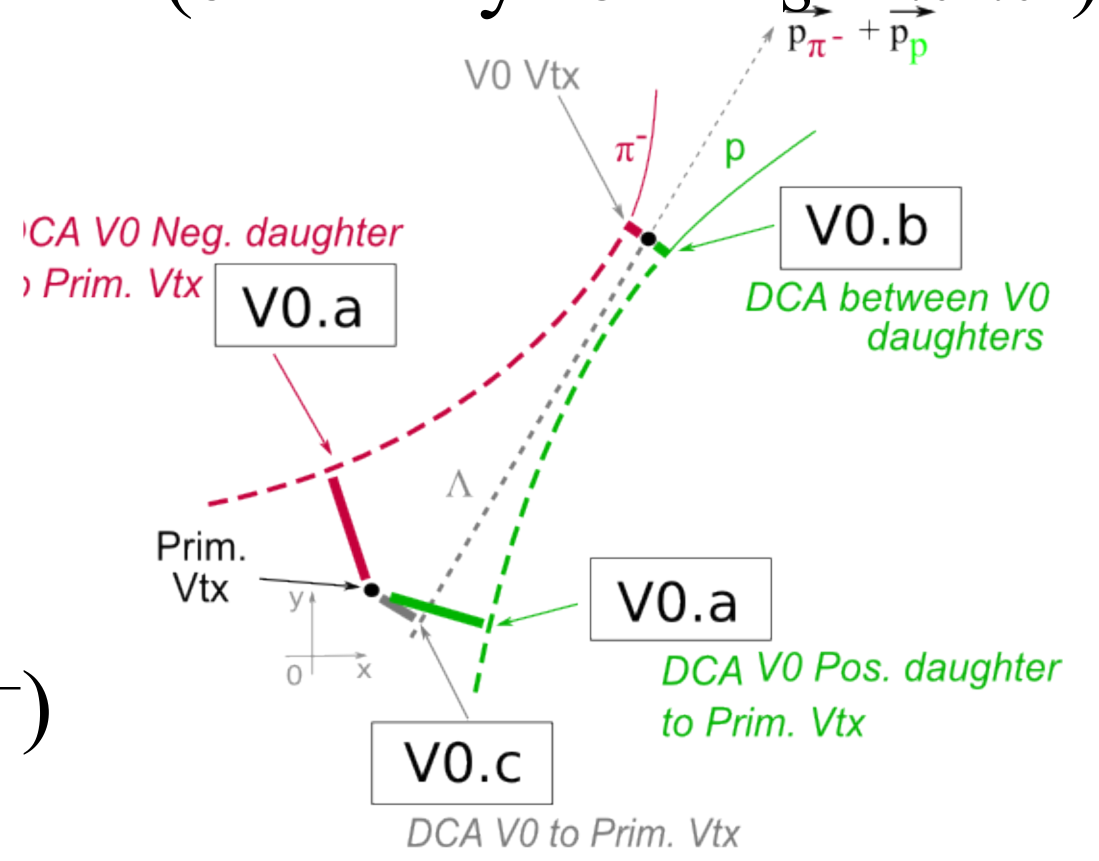
- Also: heavier/rarer nuclei (d, t, ^{3}He, ^{4}He)
- Electrons identification using calorimeters and transition radiation detectors
- Unstable particles (e.g. ϕ, Λ, Ξ, Ω) identified through their decays

$\phi \to K^+K^-$



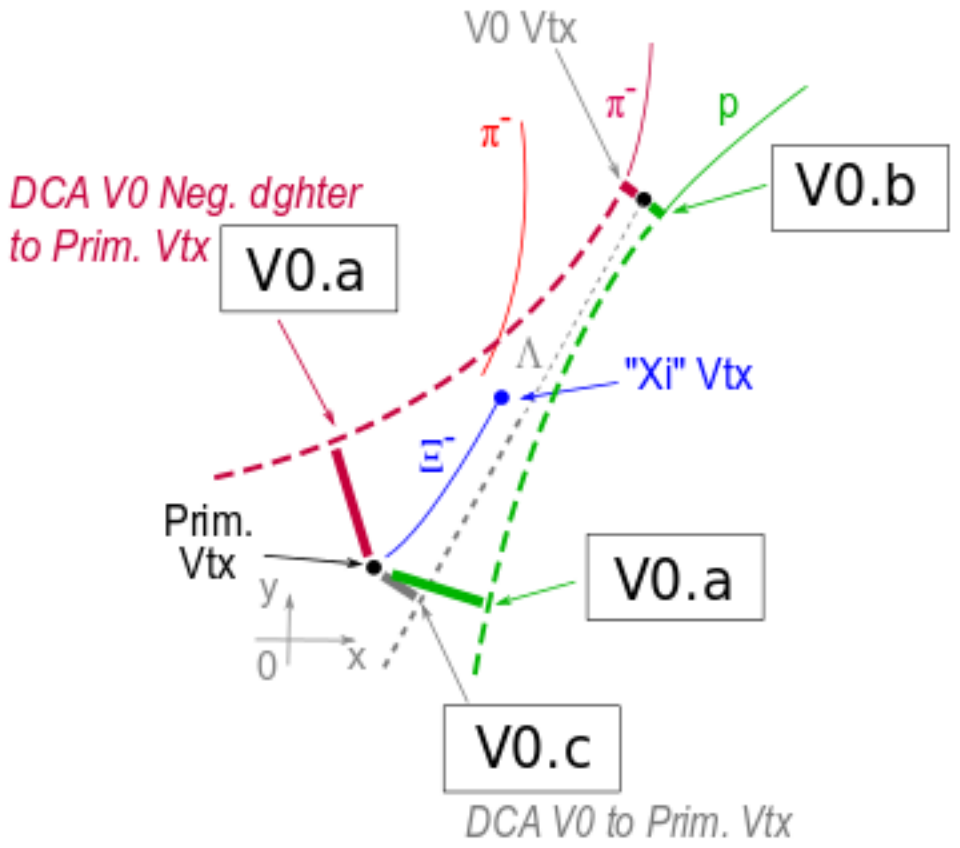
$\Lambda \to p\pi^-$

(similarly for $K^0_S \to \pi^+\pi^-$)



$\Xi \to \Lambda\pi^-$

(similarly for $\Omega \to \Lambda K^-$)



sketches by A. Maire
http://cds.cern.ch/record/2030272/

Particle identification

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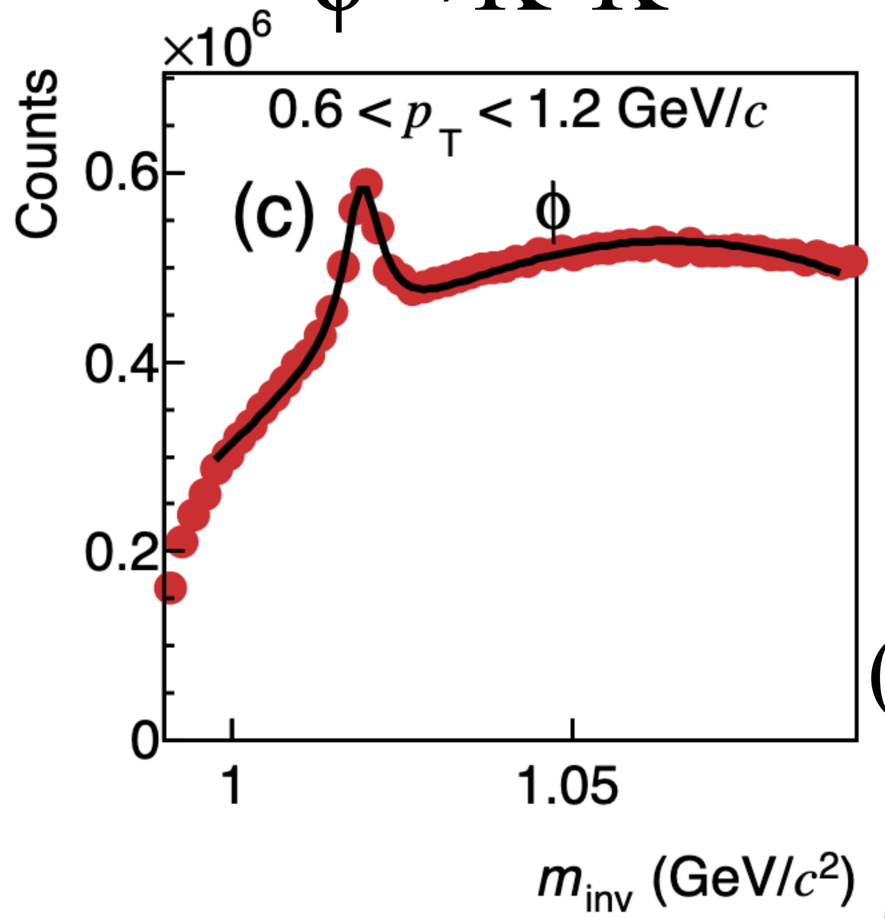

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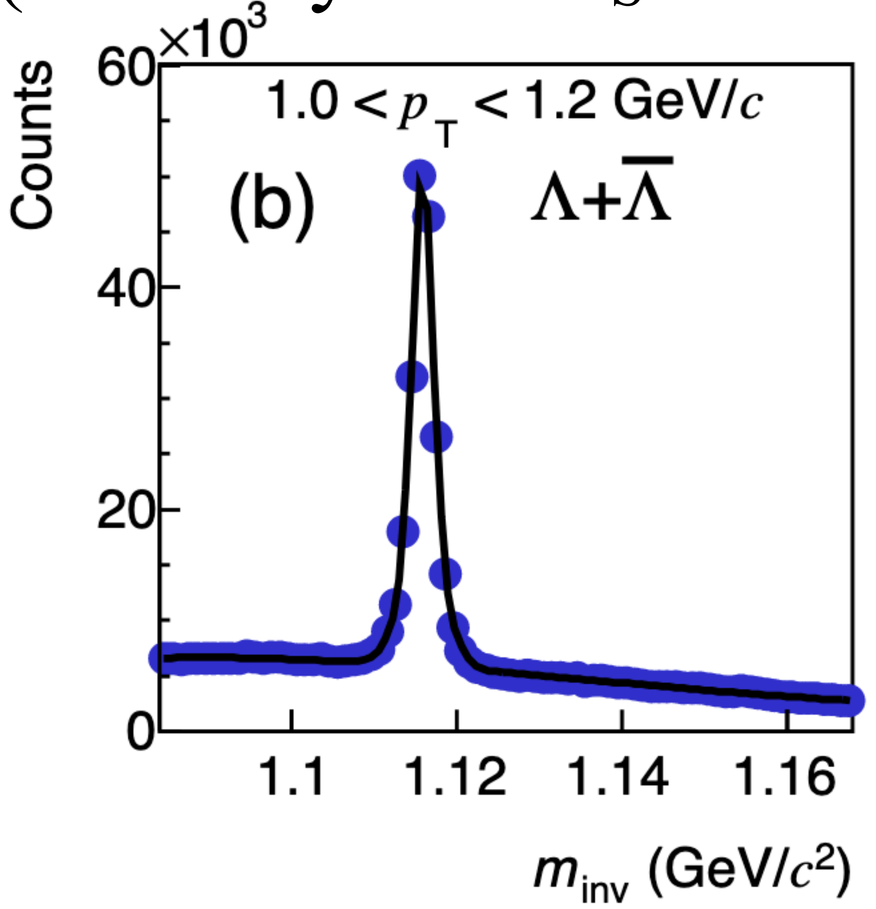

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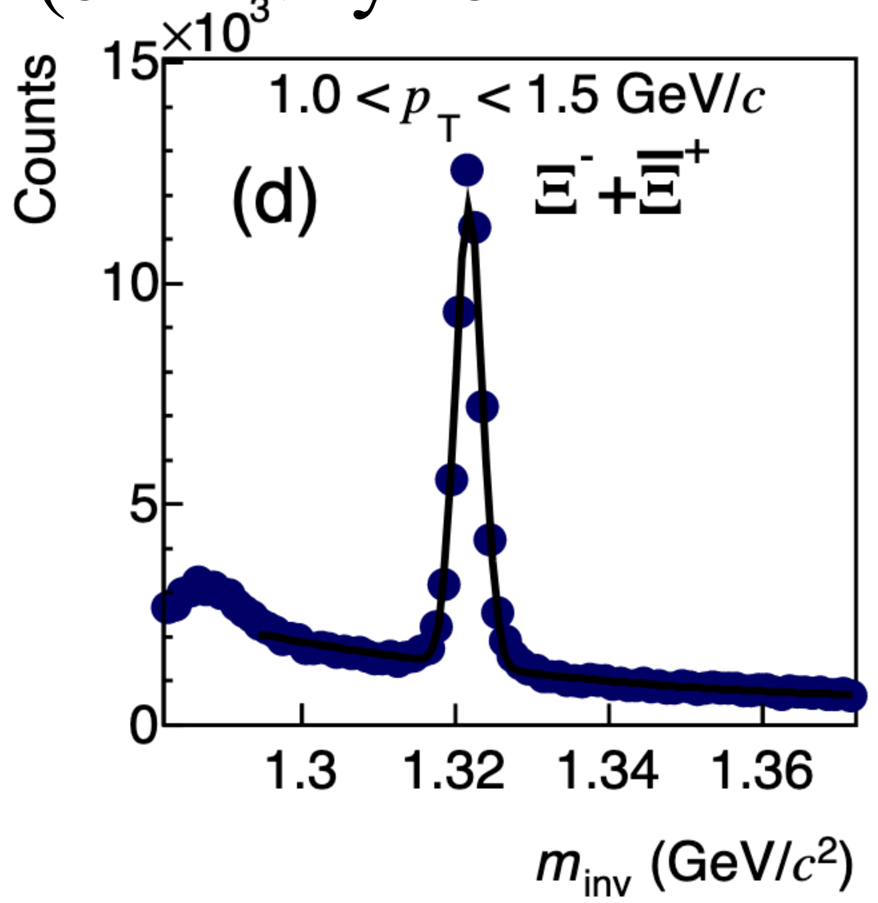

ALICE, JHEP 06 (2015) 190, arXiv:1405.4632 [nucl-ex]

Particle identification

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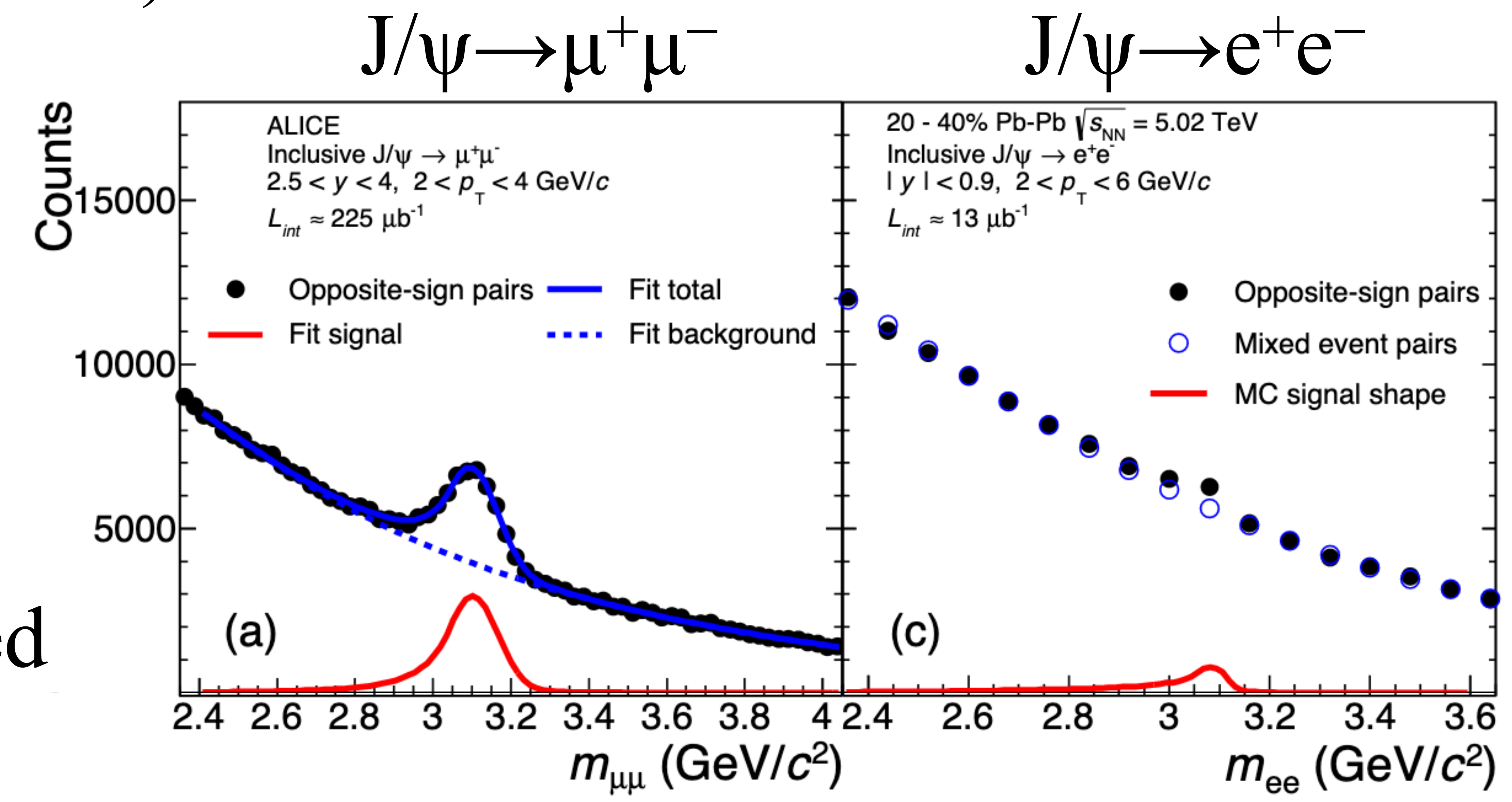
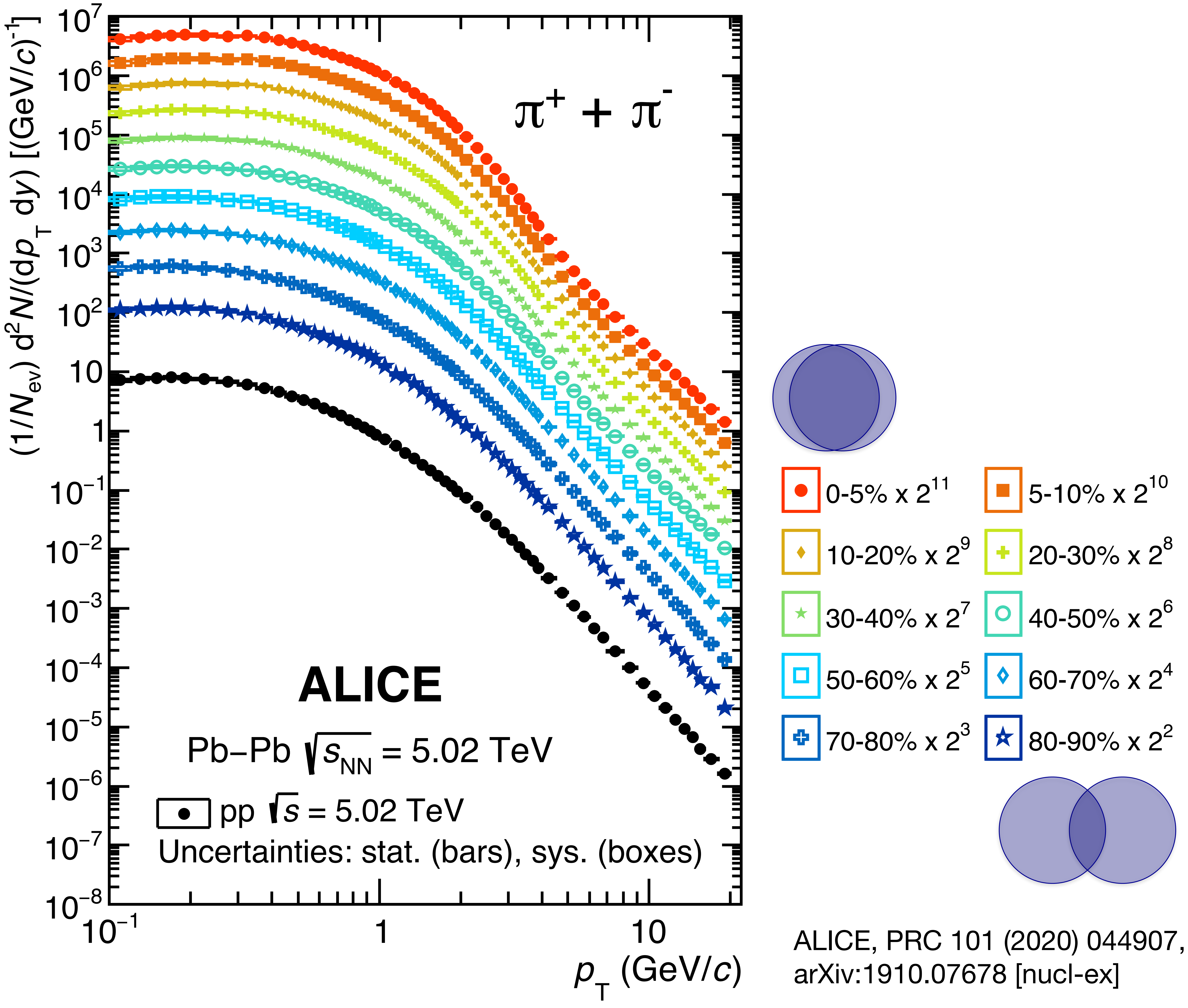
  - time of flight (TOF)
- Also: heavier/rarer nuclei (d, t, ^{3}He, ^{4}He)
- Electrons identification using calorimeters and transition radiation detectors
- Unstable particles (e.g. ϕ, Λ, Ξ, Ω) identified through their decays
- Photons detected in calorimeters and through pair production
- Quarkonia detected through leptonic decays



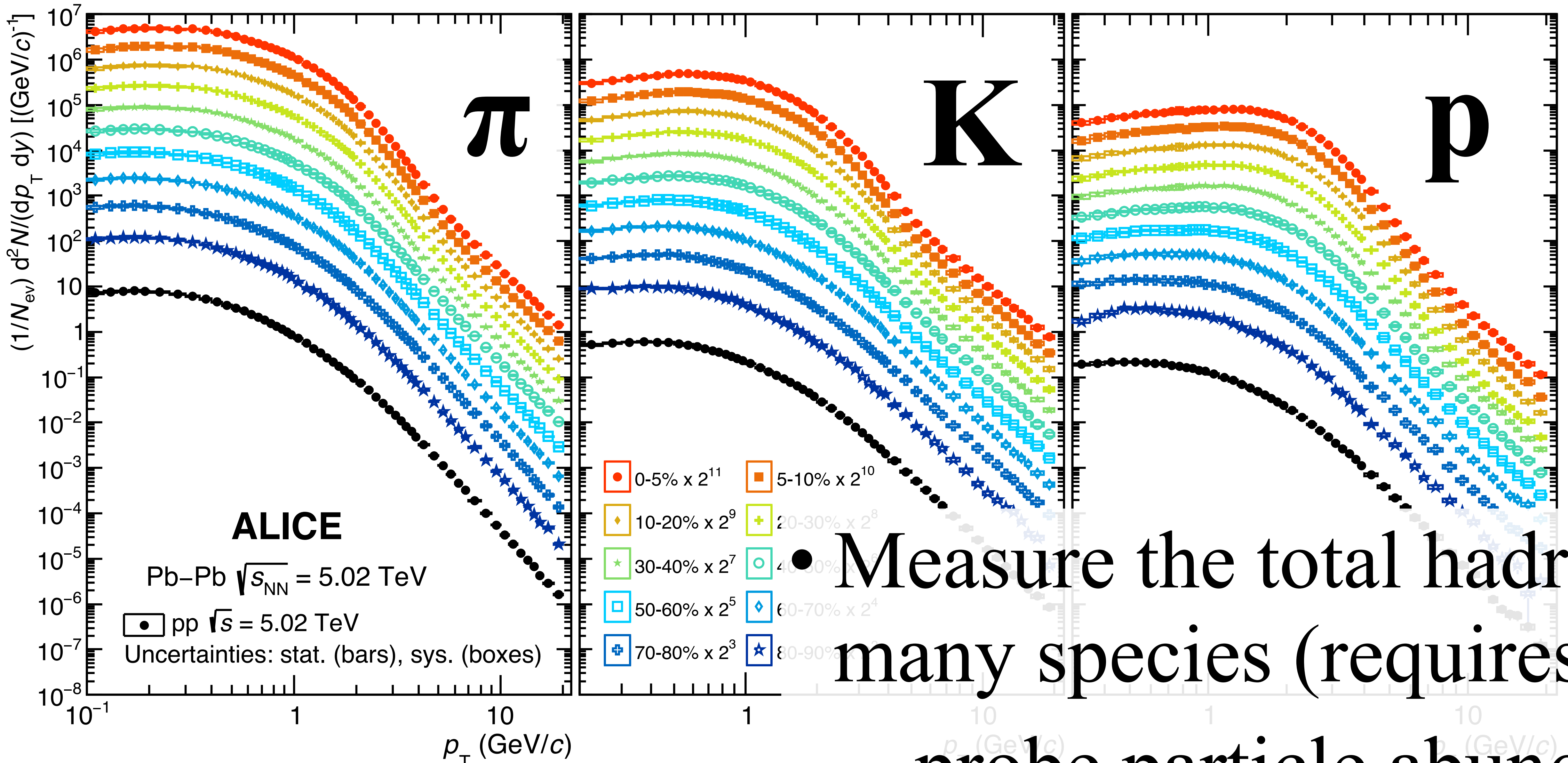
ALICE, PRL 119 (2017) 242301, arXiv:1709.05260 [nucl-ex]

Identified particle spectra

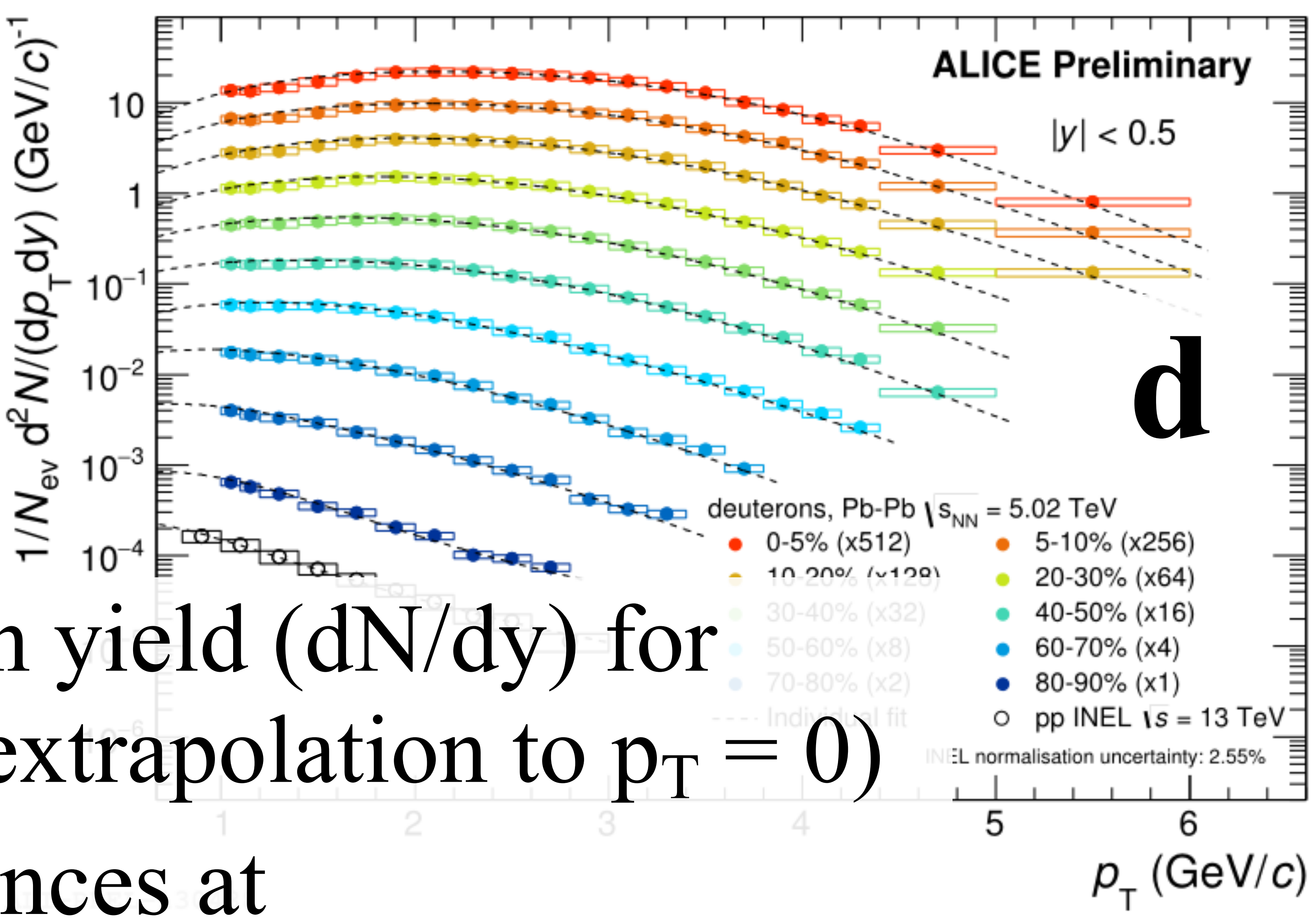


ALICE, PRC 101 (2020) 044907,
arXiv:1910.07678 [nucl-ex]

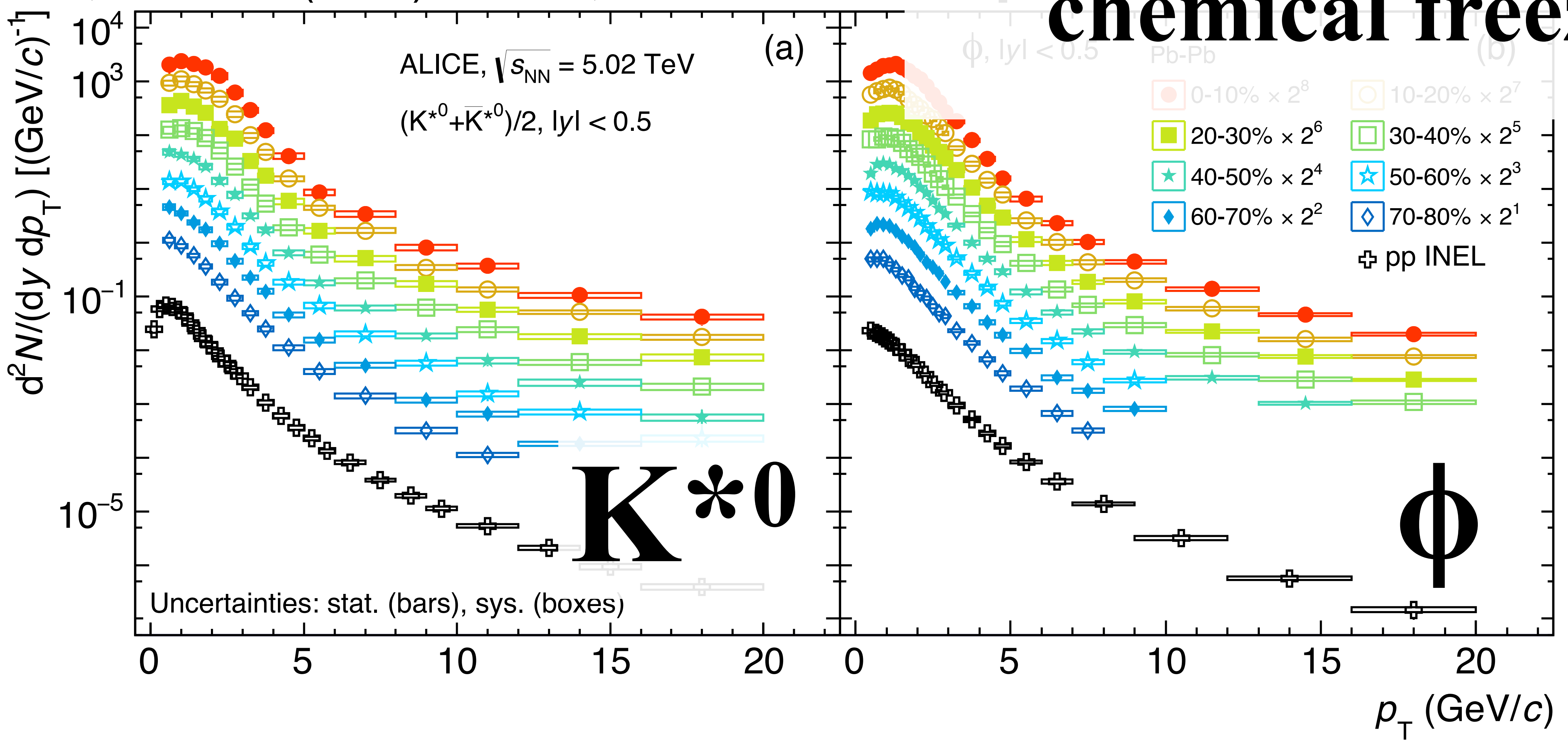
Hadrochemistry at chemical freeze-out

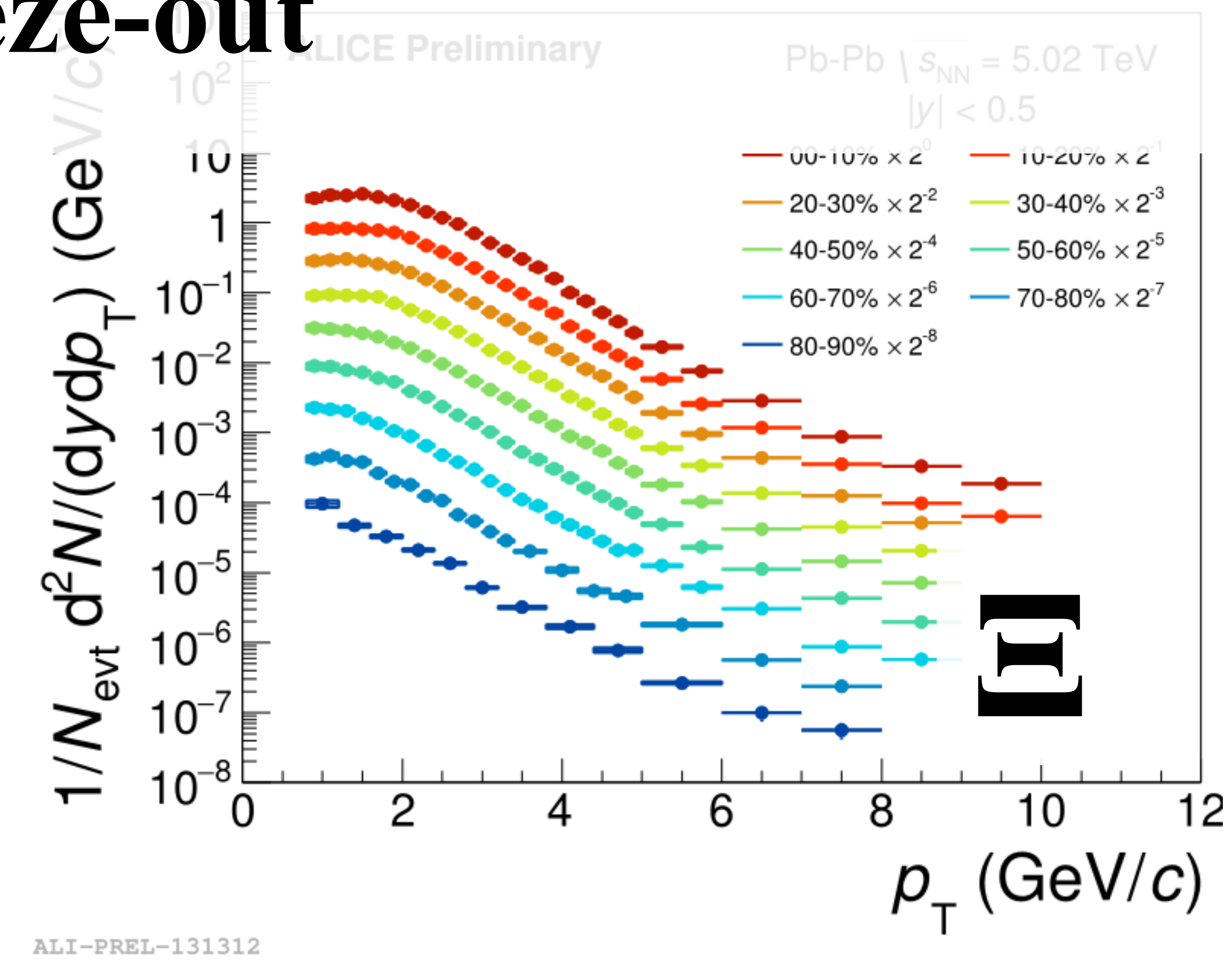


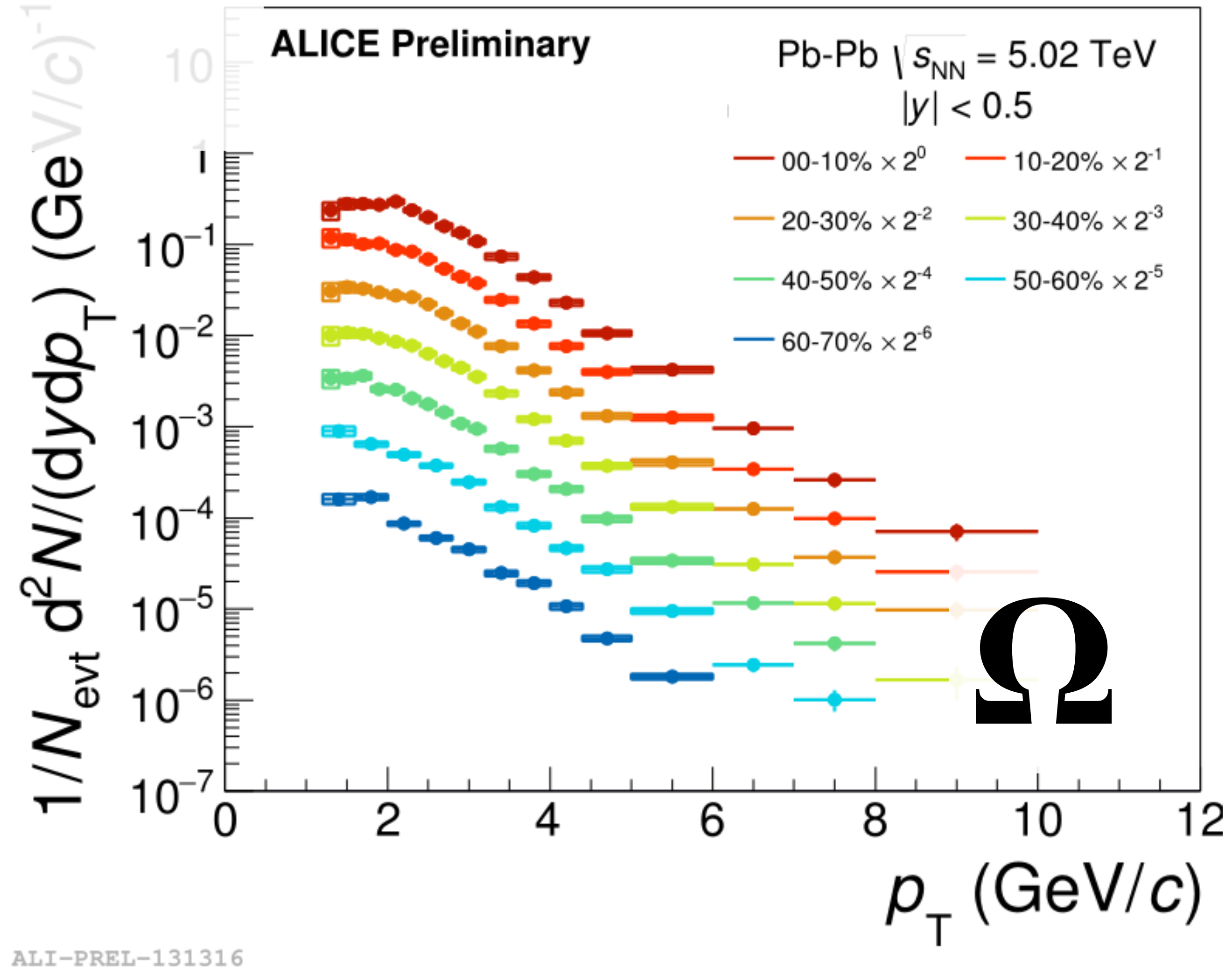
ALICE, PRC 101 (2020) 044907, arXiv: 1910.07678 [nucl-ex]
ALICE, PLB 802 (2020) 135225, arXiv: 1910.14419 [nucl-ex]



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

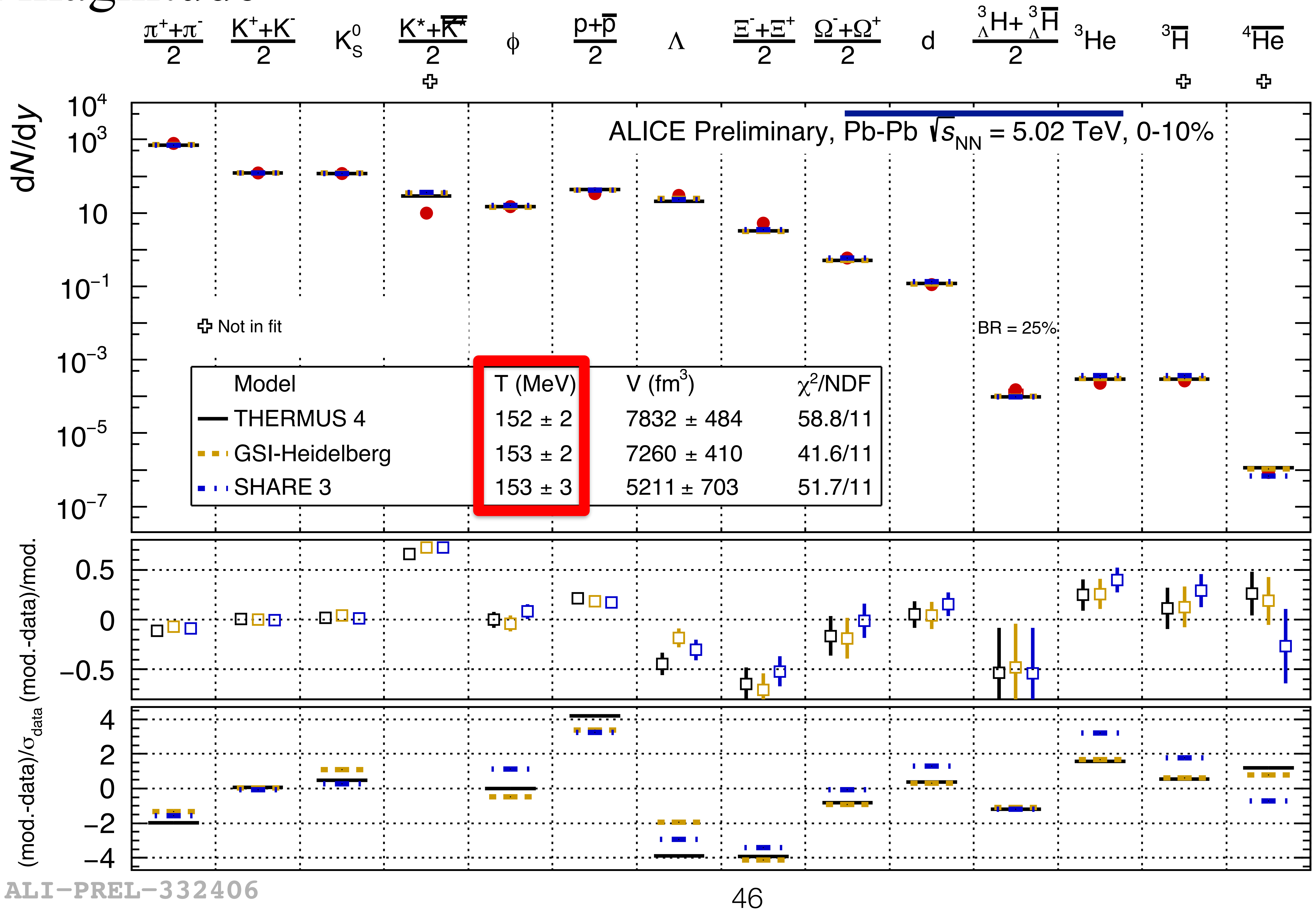




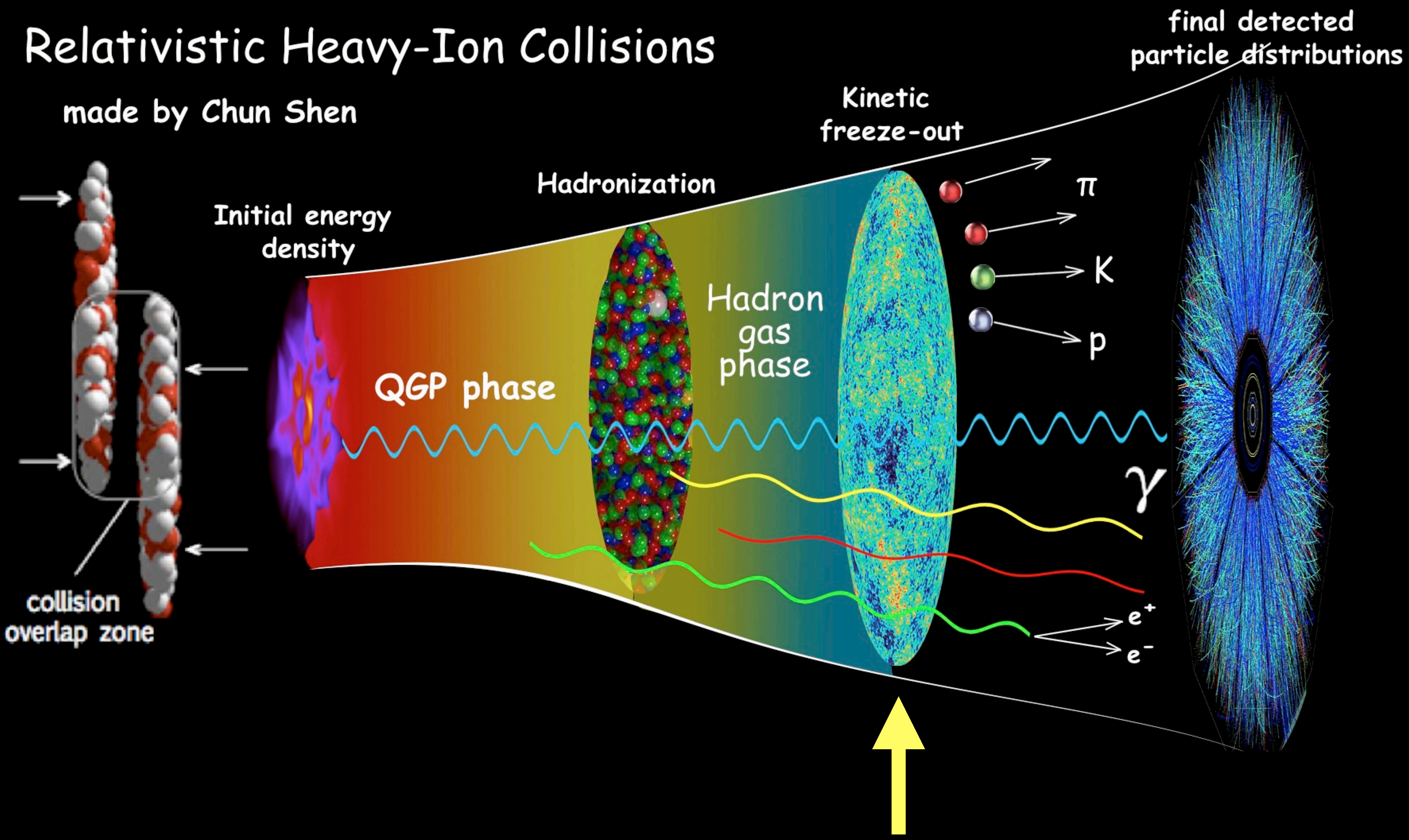


Statistical model of particle production

- 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

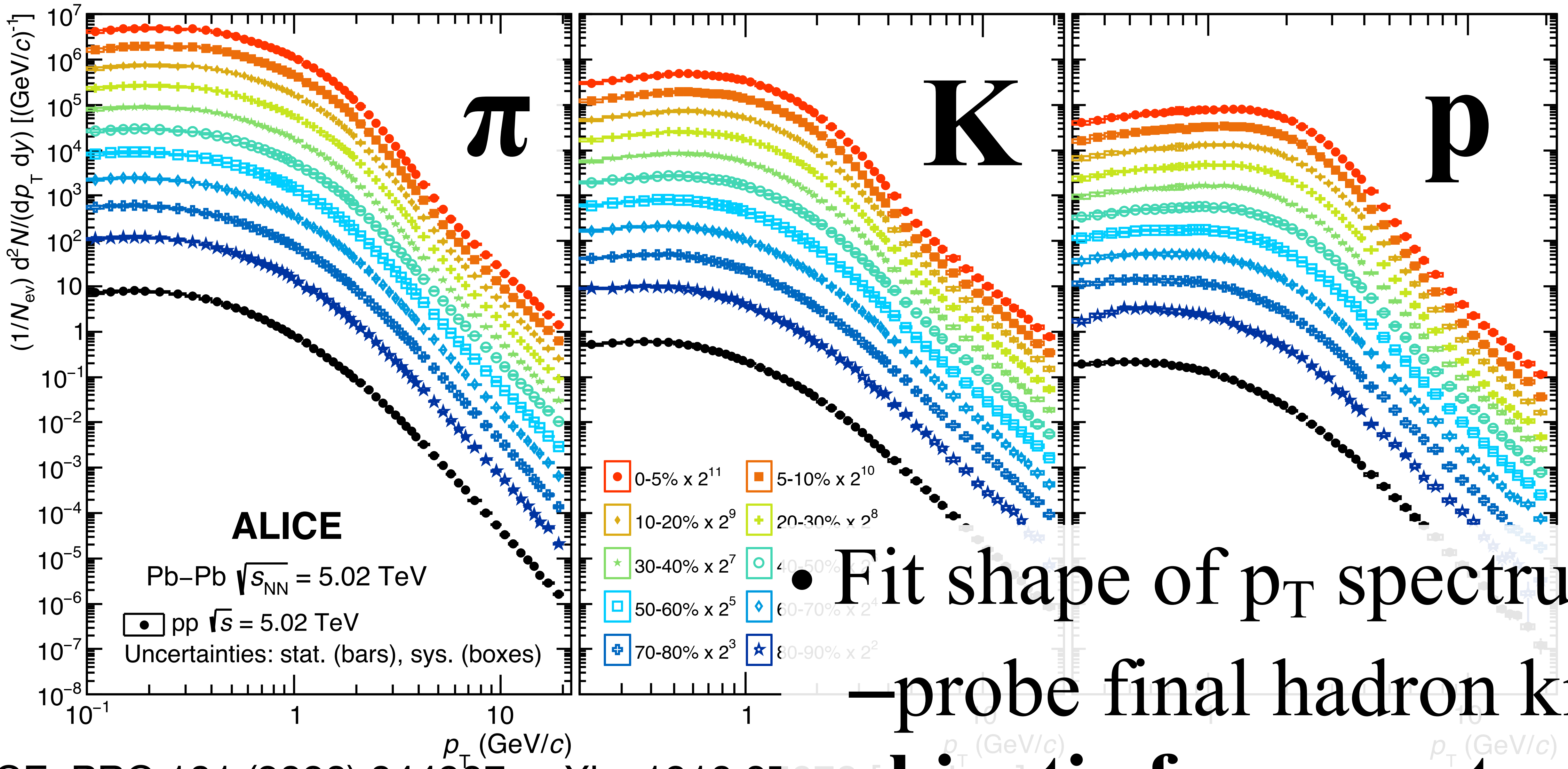


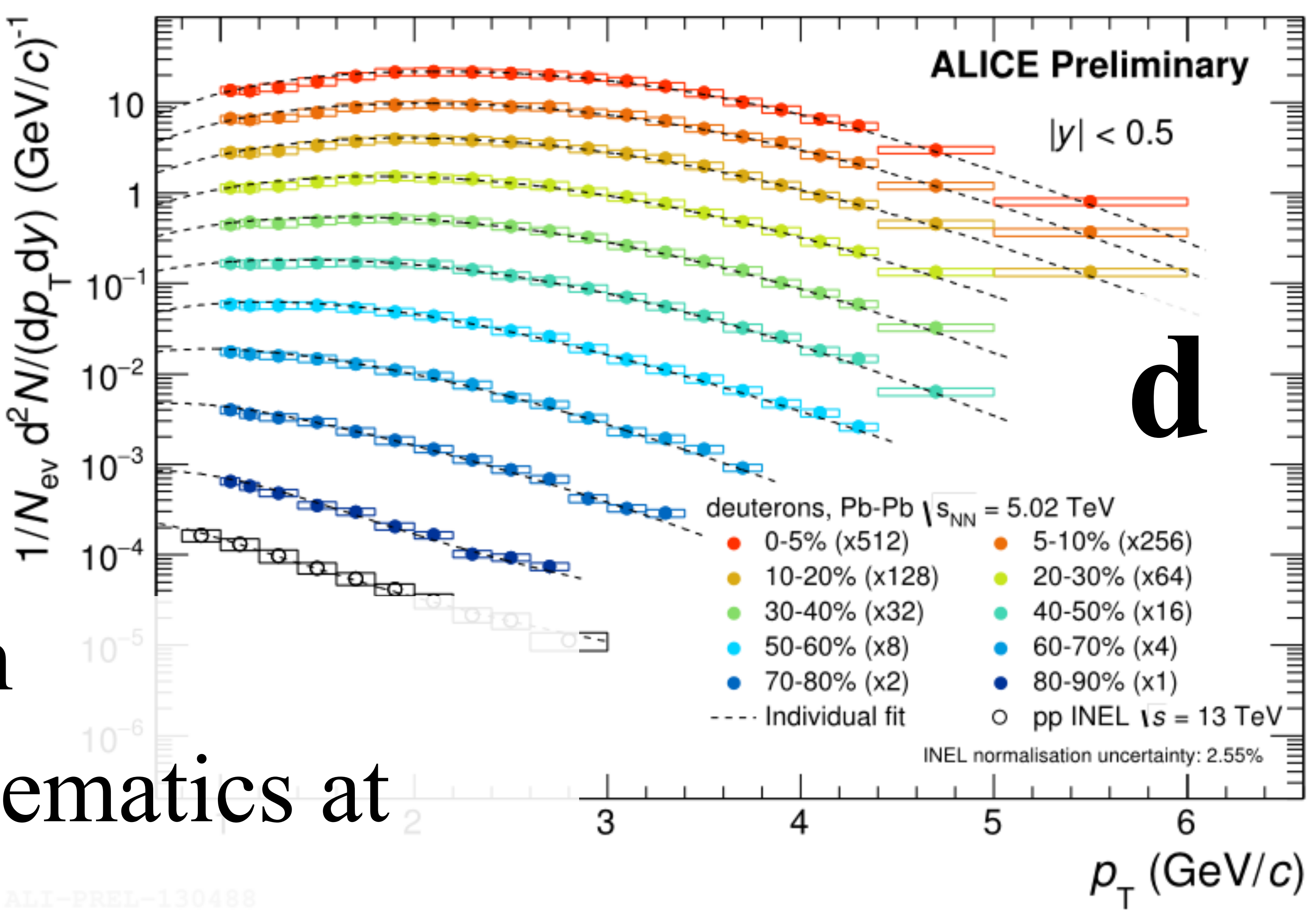
Pb-Pb $\sqrt{s_{NN}}$ = 2.76 TeV:
ALICE, Nucl. Phys. A 971 (2018) 1, arXiv:1710.07531 [nucl-ex]



5. Kinetic freeze-out: identified particle spectra

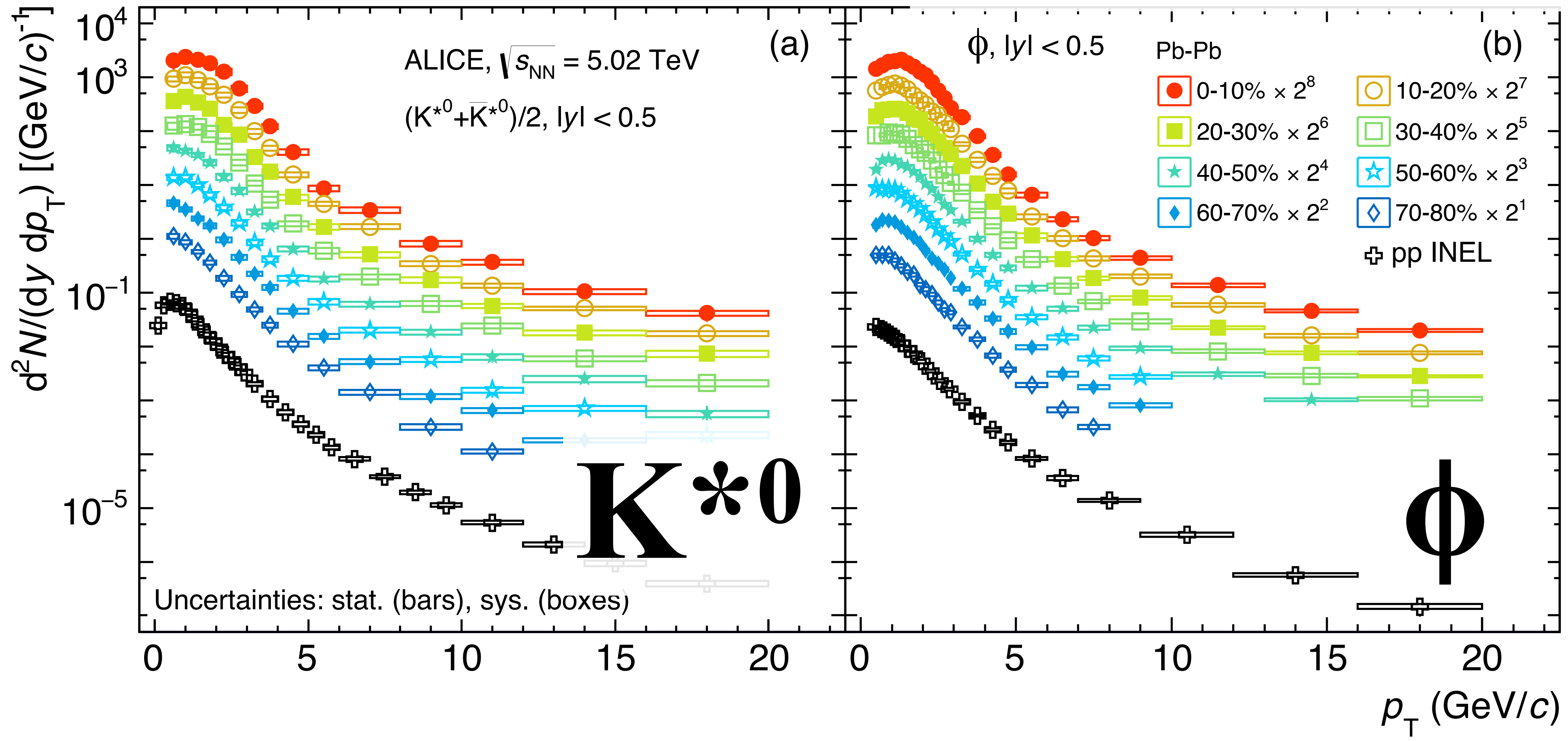
Identified particle kinematics

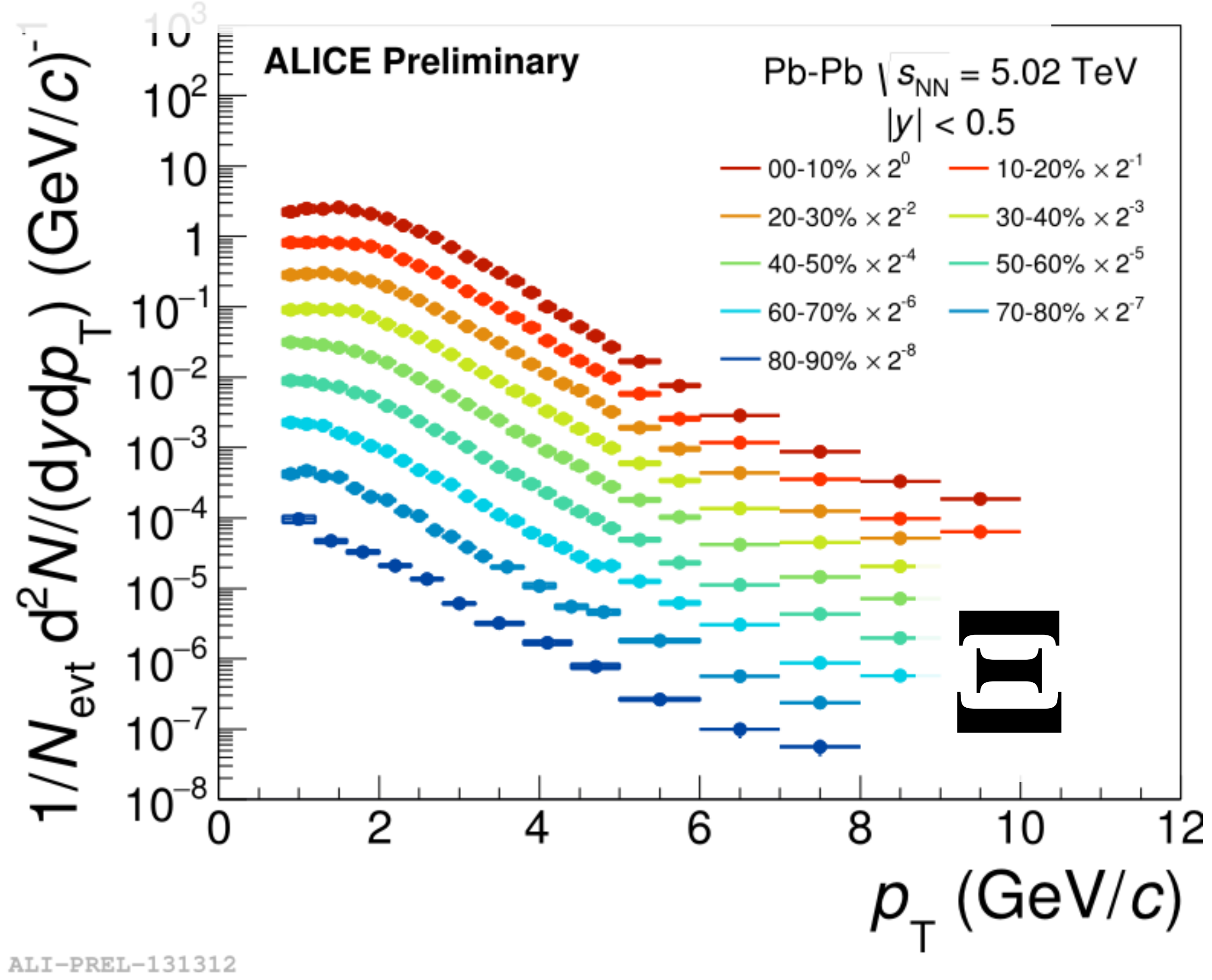


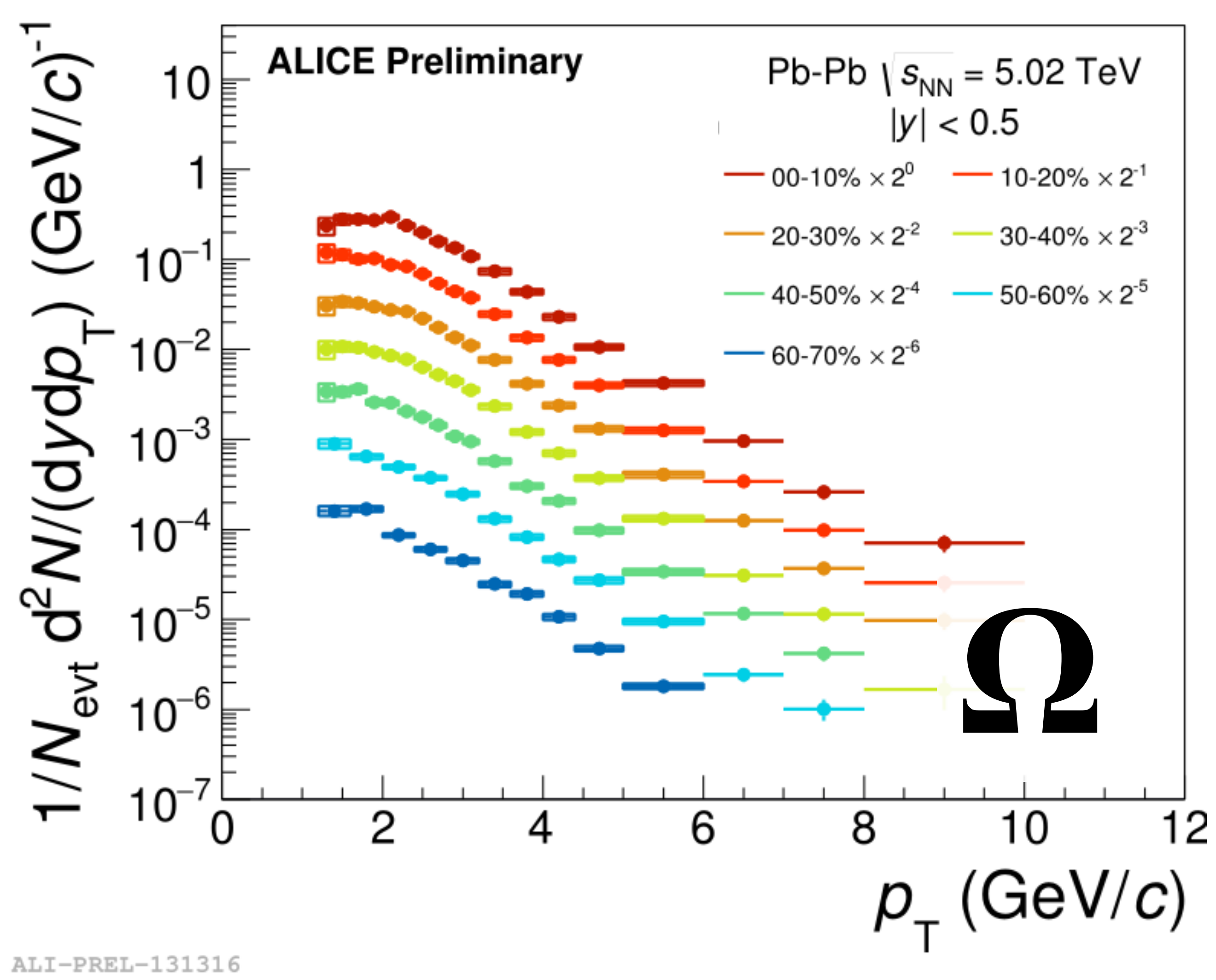


- Fit shape of p_T spectrum
  – probe final hadron kinematics at **kinetic freeze-out**

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

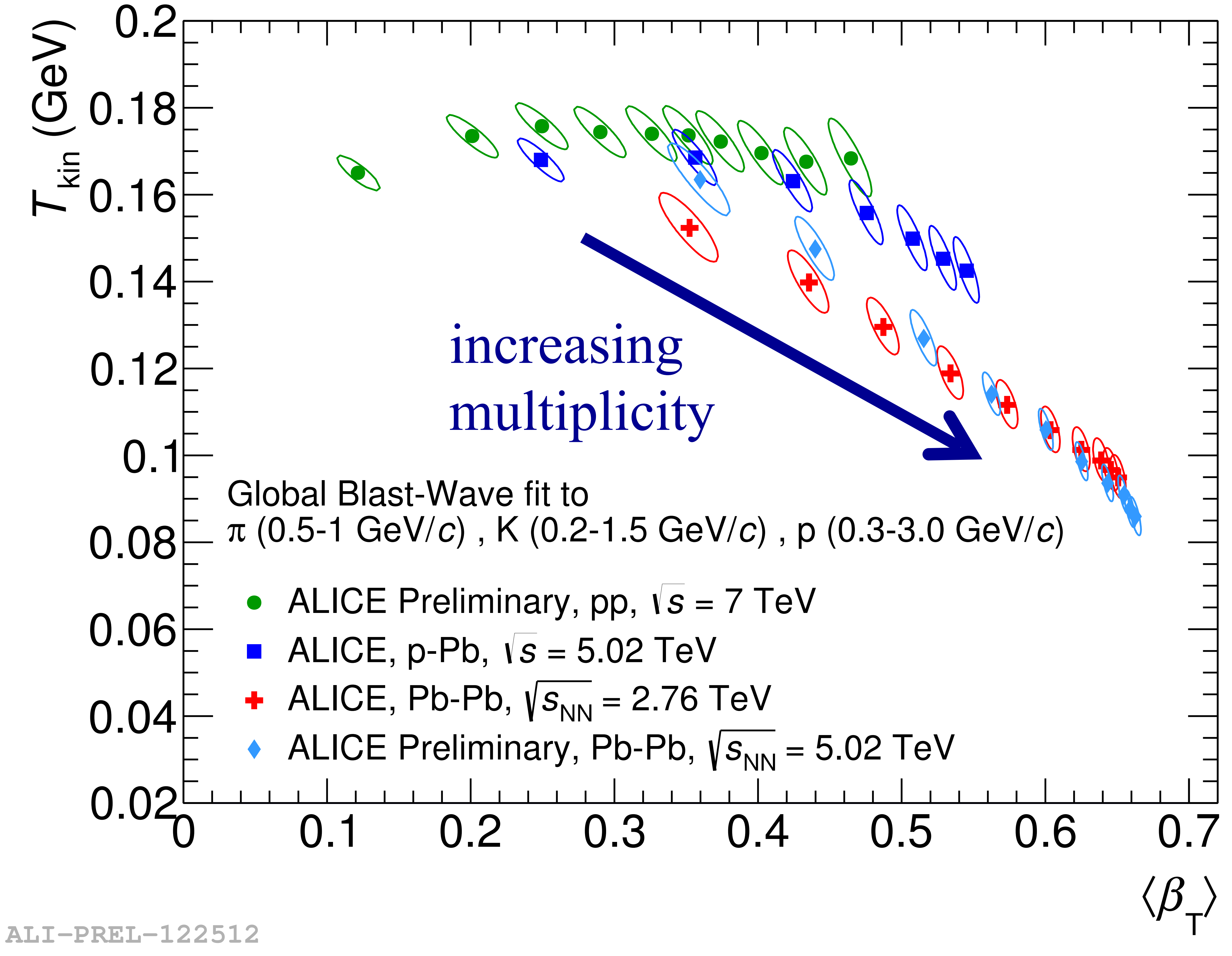






Kinematics – freeze-out parameters

- 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…

pp 13 TeV

p-Pb 5.02 TeV

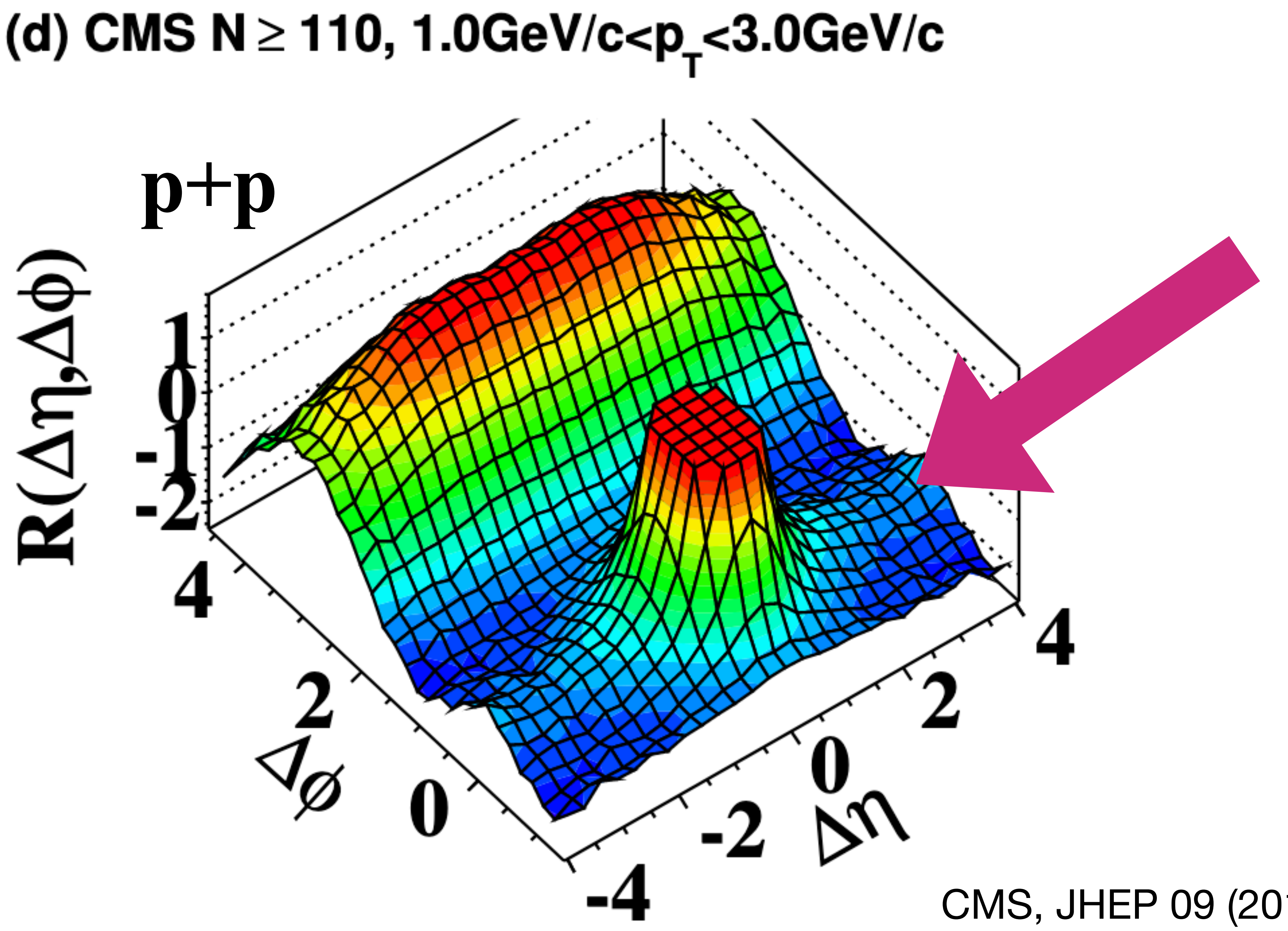
Xe-Xe 5.44 TeV

Pb-Pb 5.02 TeV

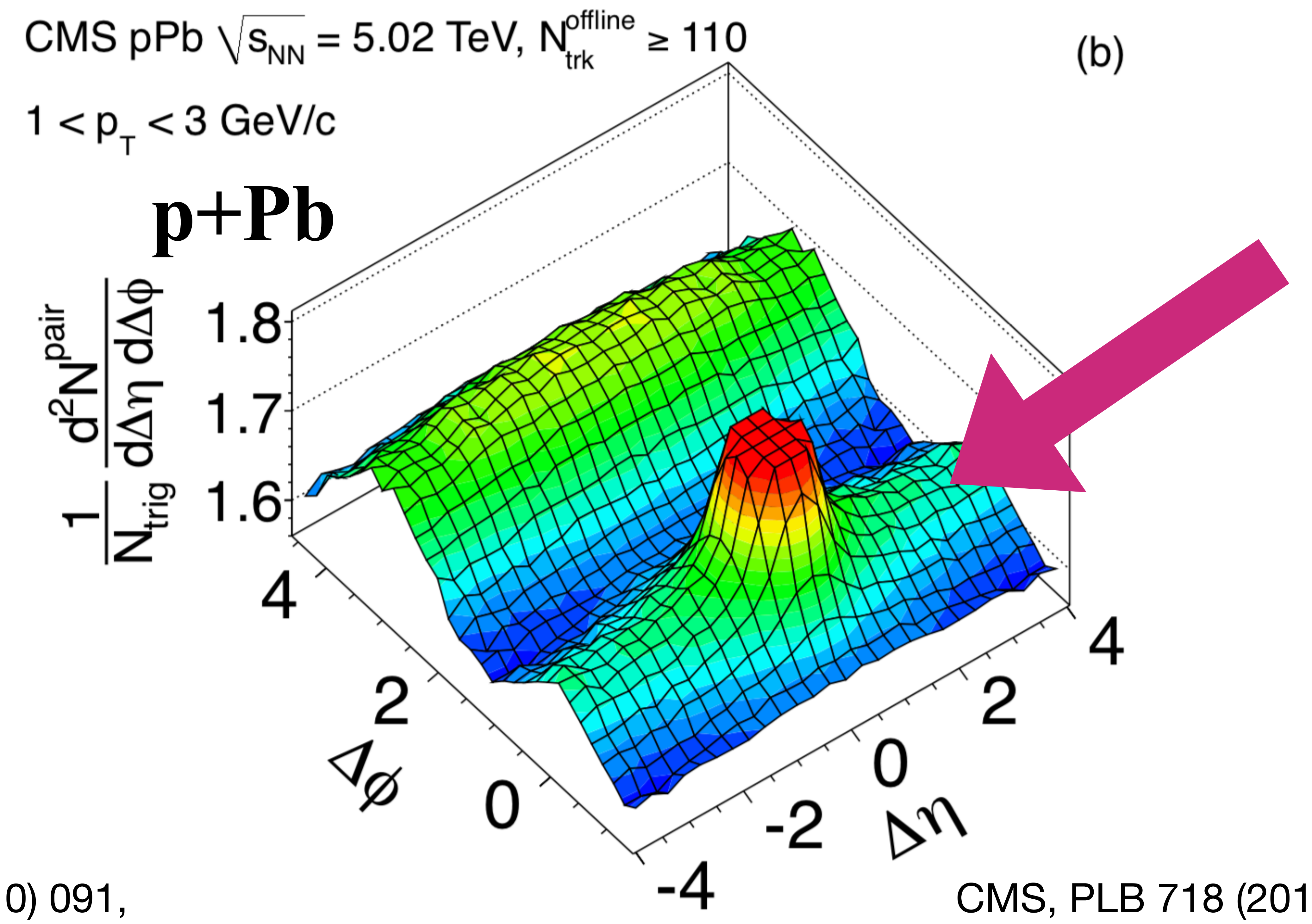
… and back again

Two-particle correlations in small systems

- Similar v_2 signals observed in high-multiplicity p+p and p+Pb collisions as well!



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

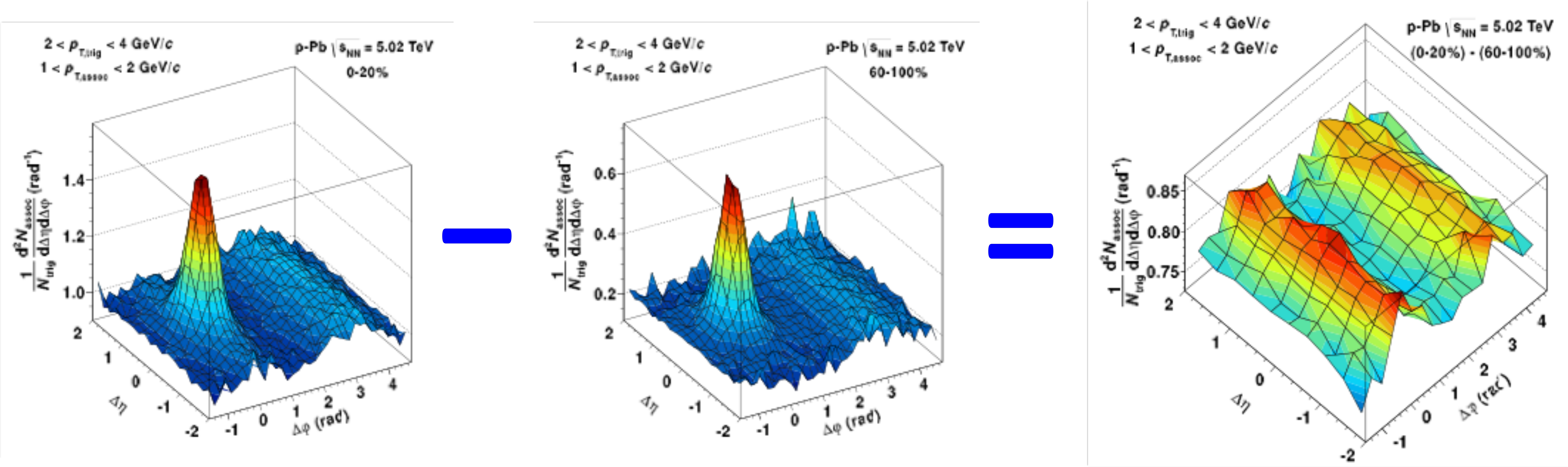


CMS, PLB 718 (2013) 795,
arXiv: 1210.5482 [nucl-ex]

- Long-range correlations had been viewed as a signature of hydrodynamic expansion of a QGP medium. **Surprise!**
- What does this mean for our understanding of heavy-ion collisions?
  What does this mean for our understanding of p+p collisions?

Double ridge structure in p+Pb collisions

- Remove jet structures by subtracting correlations in low-multiplicity collisions from high-multiplicity events



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

- Fit remaining long-range correlations with a Fourier series to extract v_n coefficients

Multi-particle correlations in small systems

- Are these correlations a true “collective” (many-particle) effect, or just between few (~2) particles?
- Measure multi-particle cumulants
  Example: four-particle cumulants

$$c_2\{4\} = \langle\langle \cos 2(\varphi_1 + \varphi_2 - \varphi_3 - \varphi_4)\rangle\rangle$$ ← four-particle correlation

$$- \langle\langle \cos 2(\varphi_1 - \varphi_3)\rangle\rangle \langle\langle \cos 2(\varphi_2 - \varphi_4)\rangle\rangle$$ ← subtract two-particle correlations

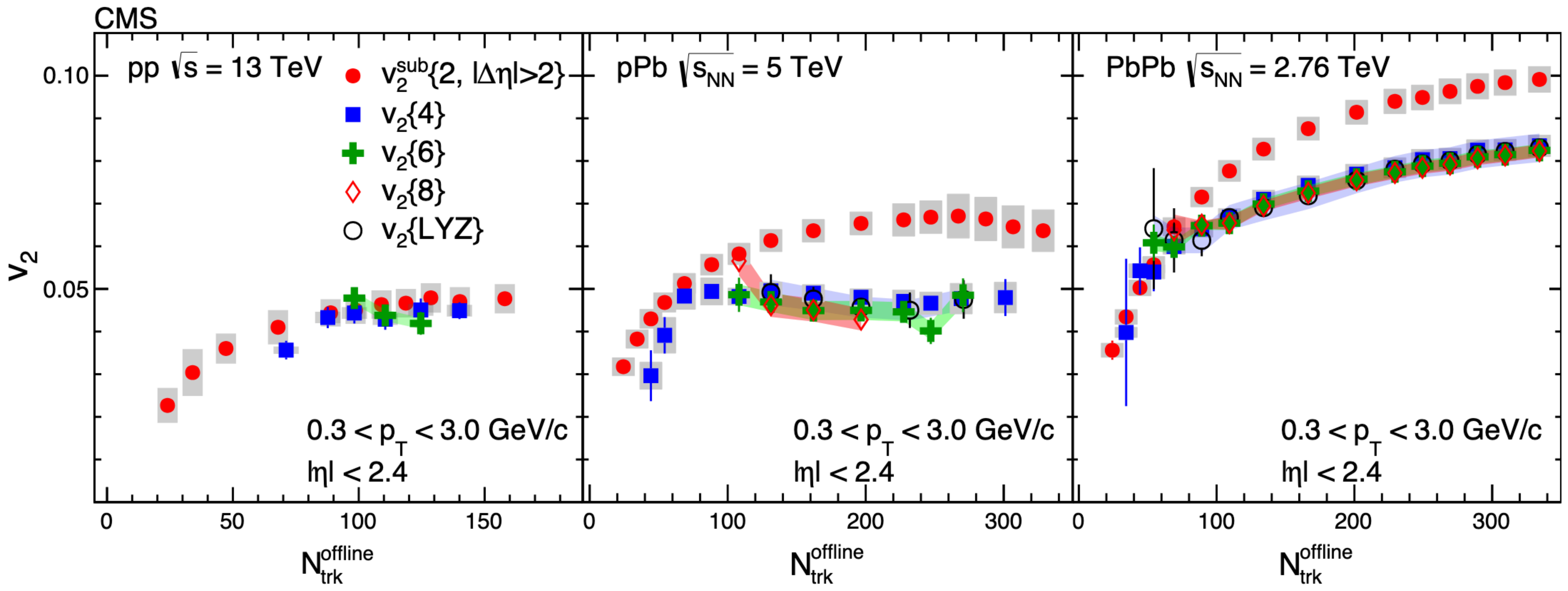
$$- \langle\langle \cos 2(\varphi_1 - \varphi_4)\rangle\rangle \langle\langle \cos 2(\varphi_2 - \varphi_3)\rangle\rangle$$

$$v_n\{4\} = \sqrt[4]{-c_n\{4\}}$$

- Similarly for six-particle, eight-particle cumulants

v_n coefficients in p+p and p+Pb collisions

- Higher-order cumulants are non-zero! →True multi-particle correlation effect!

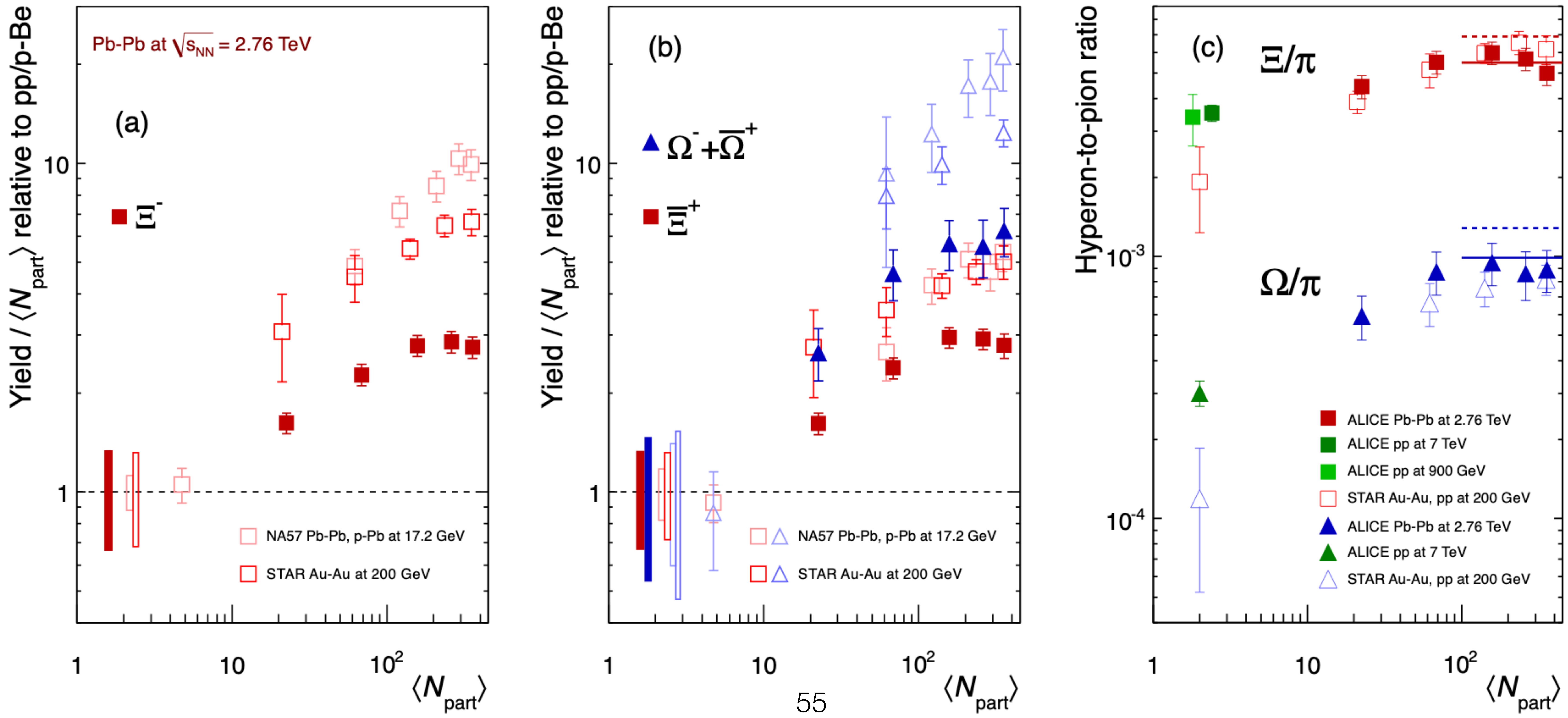


CMS, PLB 765 (2017) 193,
arXiv: 1606.06198 [nucl-ex]

Strangeness enhancement

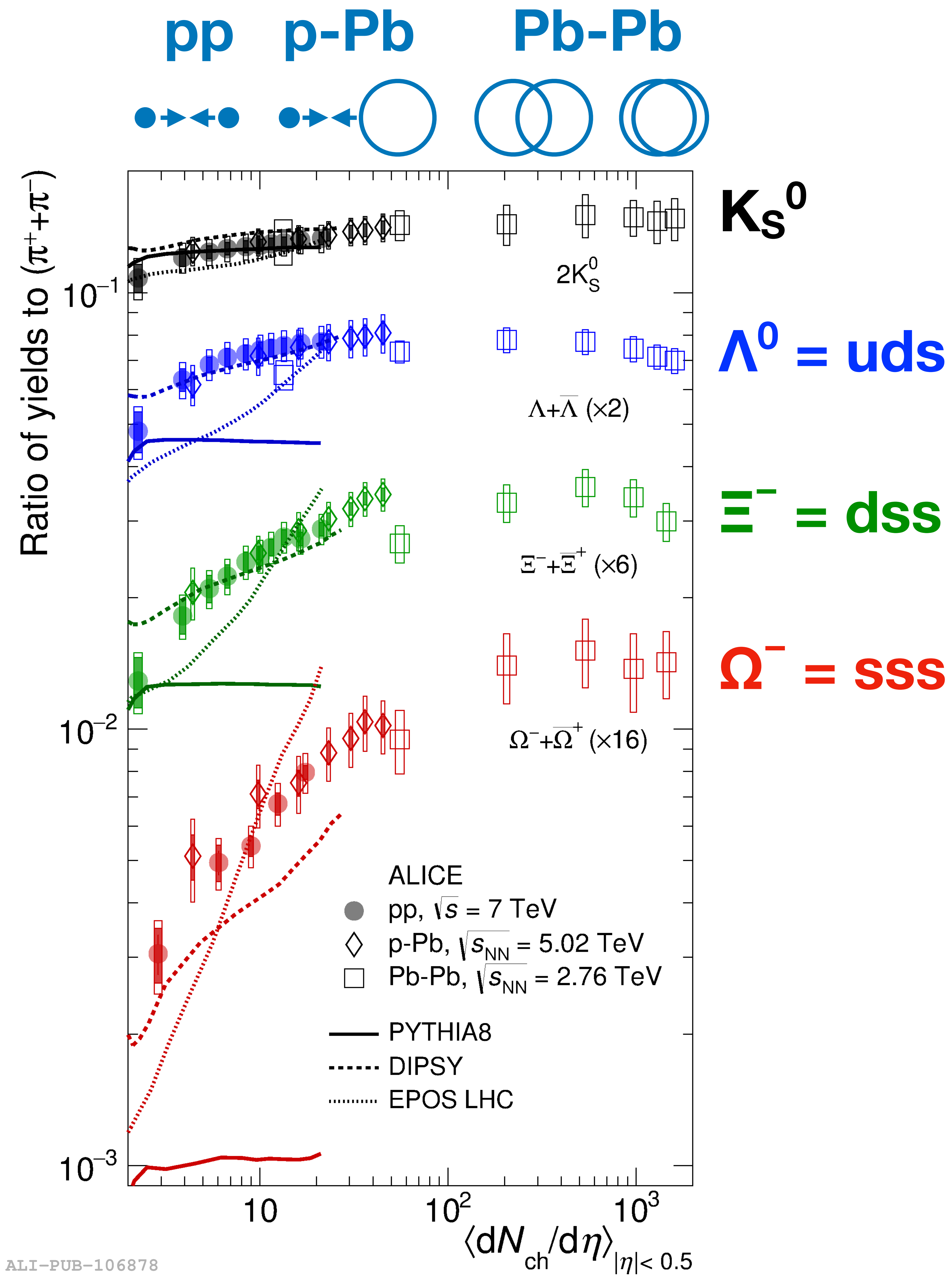
- The enhancement of strange particle yields in heavy-ion collisions (compared to p+p) had long been viewed as a signature of QGP formation
- Although now it is viewed as a suppression of strangeness in p+p collisions due to their small size

ALICE, PLB 728 (2014) 216, arXiv: 1307.5543 [nucl-ex]



Strangeness enhancement

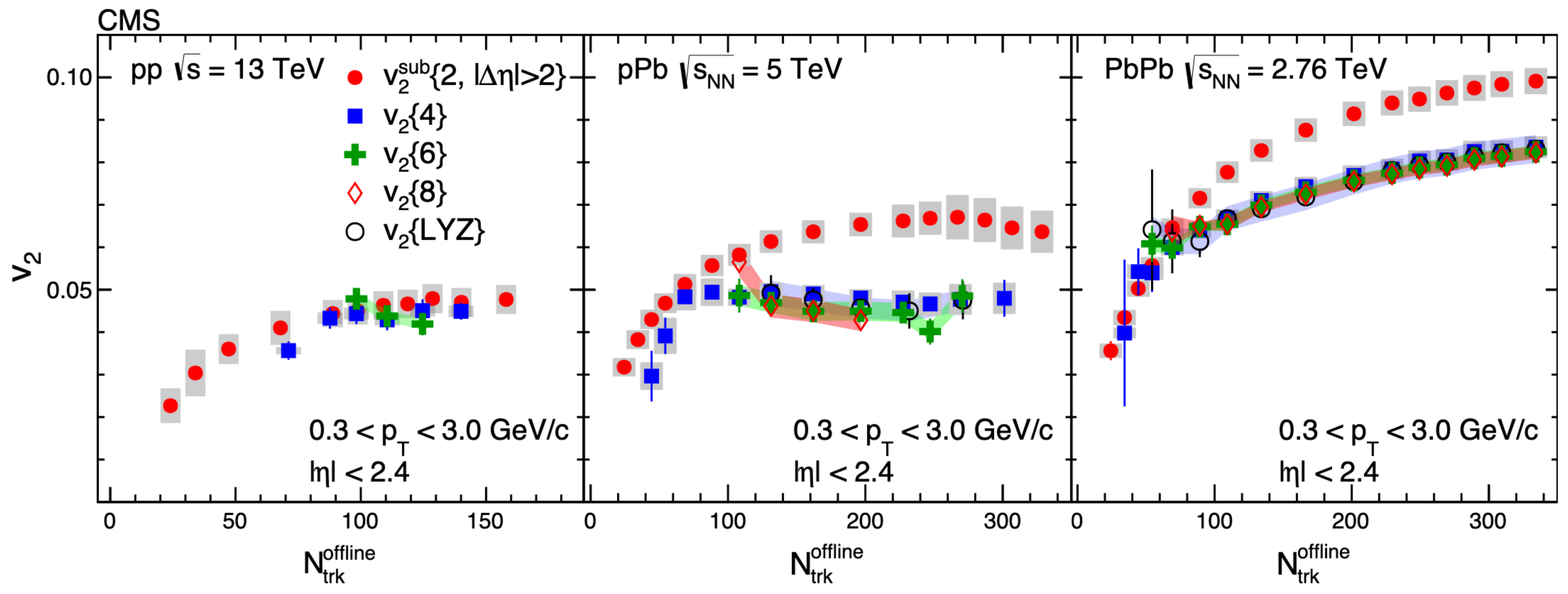
- The enhancement of strange particle yields in heavy-ion collisions (compared to p+p) had long been viewed as a signature of QGP formation
- Although now it is viewed as a suppression of strangeness in p+p collisions due to their small size
- But the smooth increase of strange particle yields (w.r.t. pions) as a function of multiplicity was observed from p+p to p+Pb to Pb+Pb!



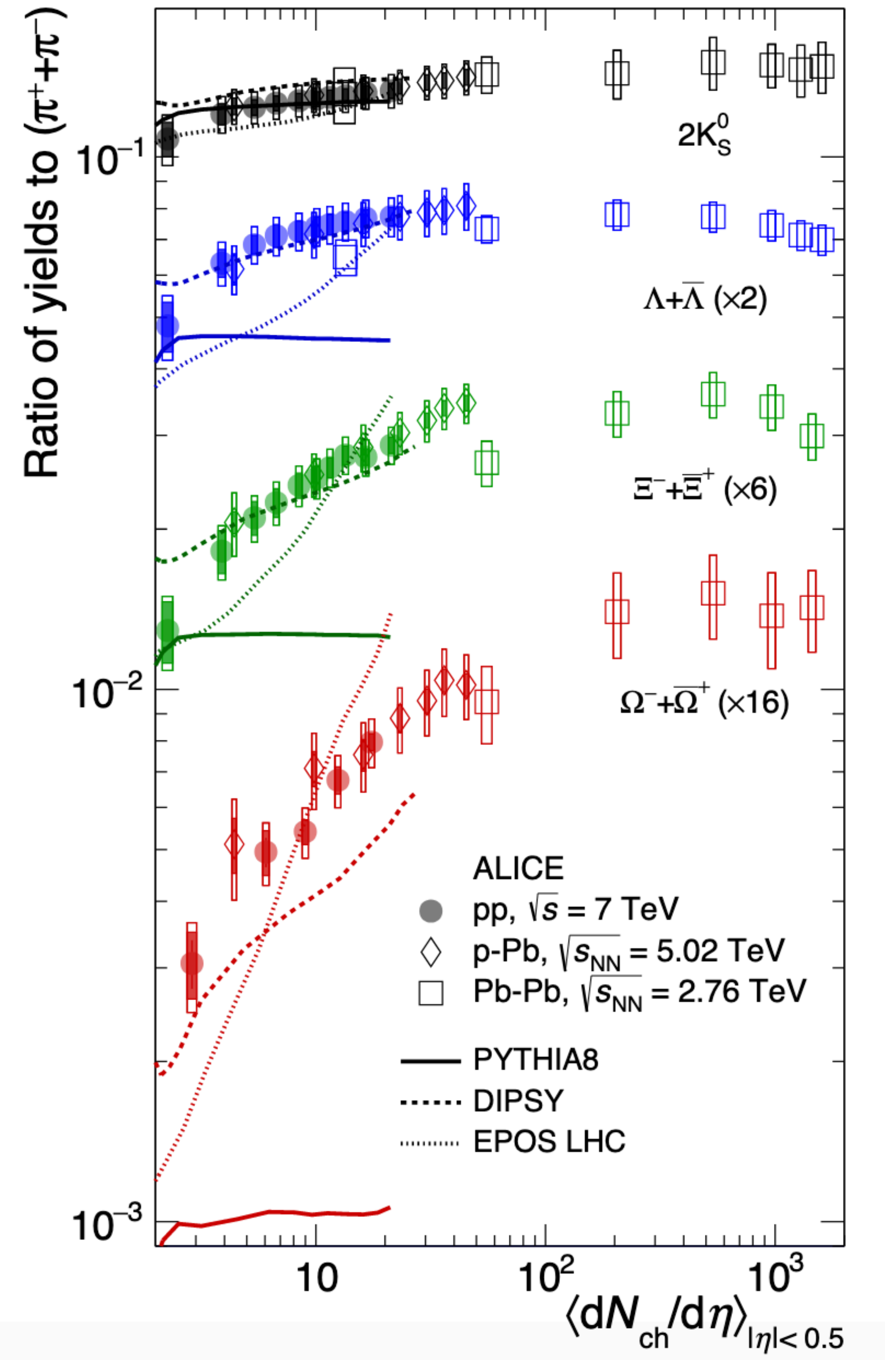
ALICE, Nature Physics 13 (2017) 535,
arXiv: 1606.07424 [nucl-ex]

Heavy-ion-like effects in small systems

- Collective effects and strangeness enhancement were observed in p+p and p+Pb collisions



- 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?)



Summary

- Experimental probes of the properties, dynamics, and evolution of the quark-gluon plasma:
  - Jets → Strong quenching and medium-induced modification
  - Flow coefficients → Collective behavior with very low shear viscosity (η/s),
    Precise descriptions of initial state and geometrical evolution
  - Quarkonium suppression → Melting of states as a function of temperature,
    Recombination
  - Identified particle spectra → High temperatures, mostly statistical particle production (T_{chem}, T_{kin})

- Collective effects and strangeness enhancement, typically viewed as signatures of a deconfined QGP, are also observed in small collision systems

Lots of exciting experimental results!
But many open questions remain to be answered in the future!

Aleksas and I will also join the discussion sessions after this to answer any questions or chat further.

ALICE