A very quick introduction to heavy-ion physics

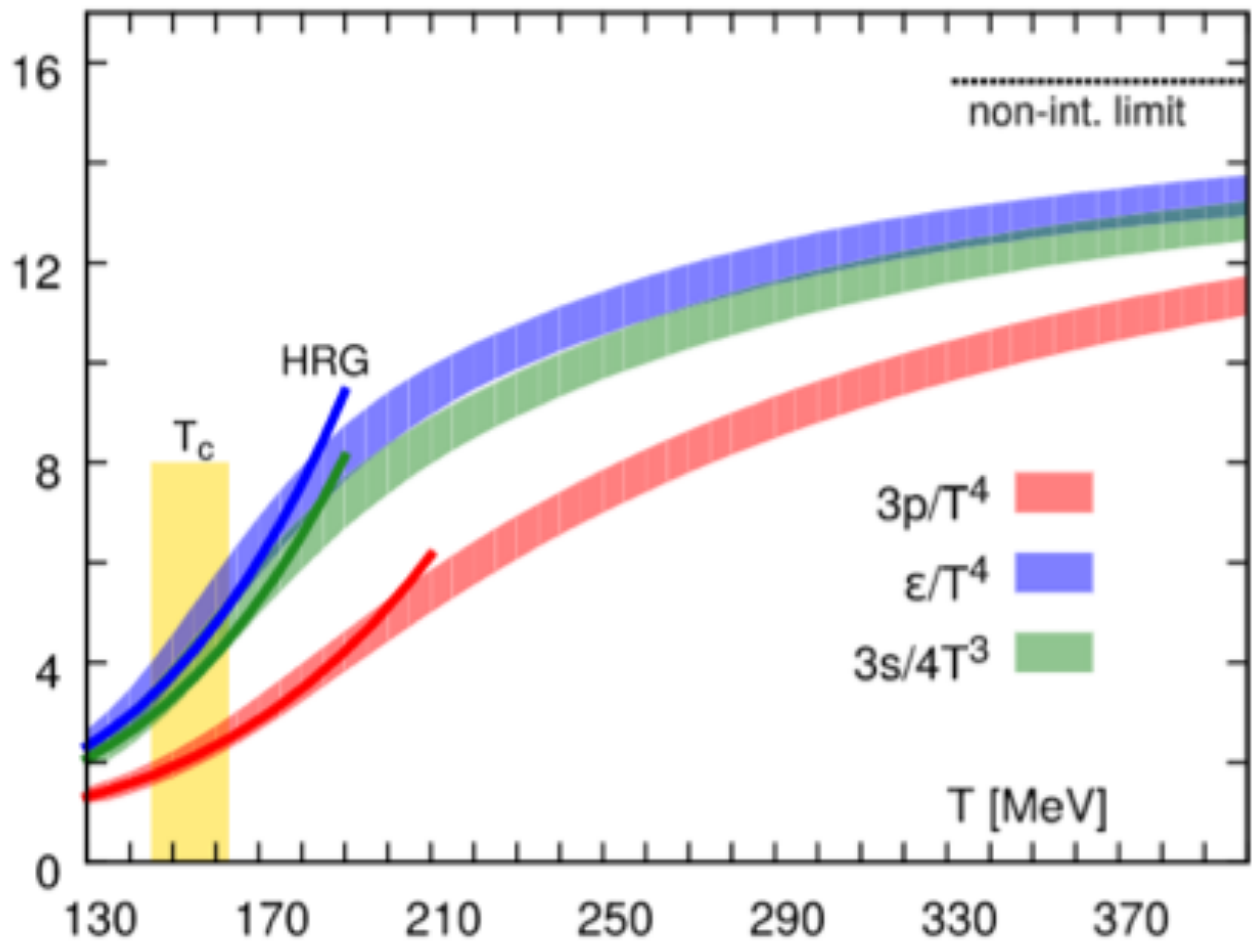
Alice Ohlson
Lund University, Sweden

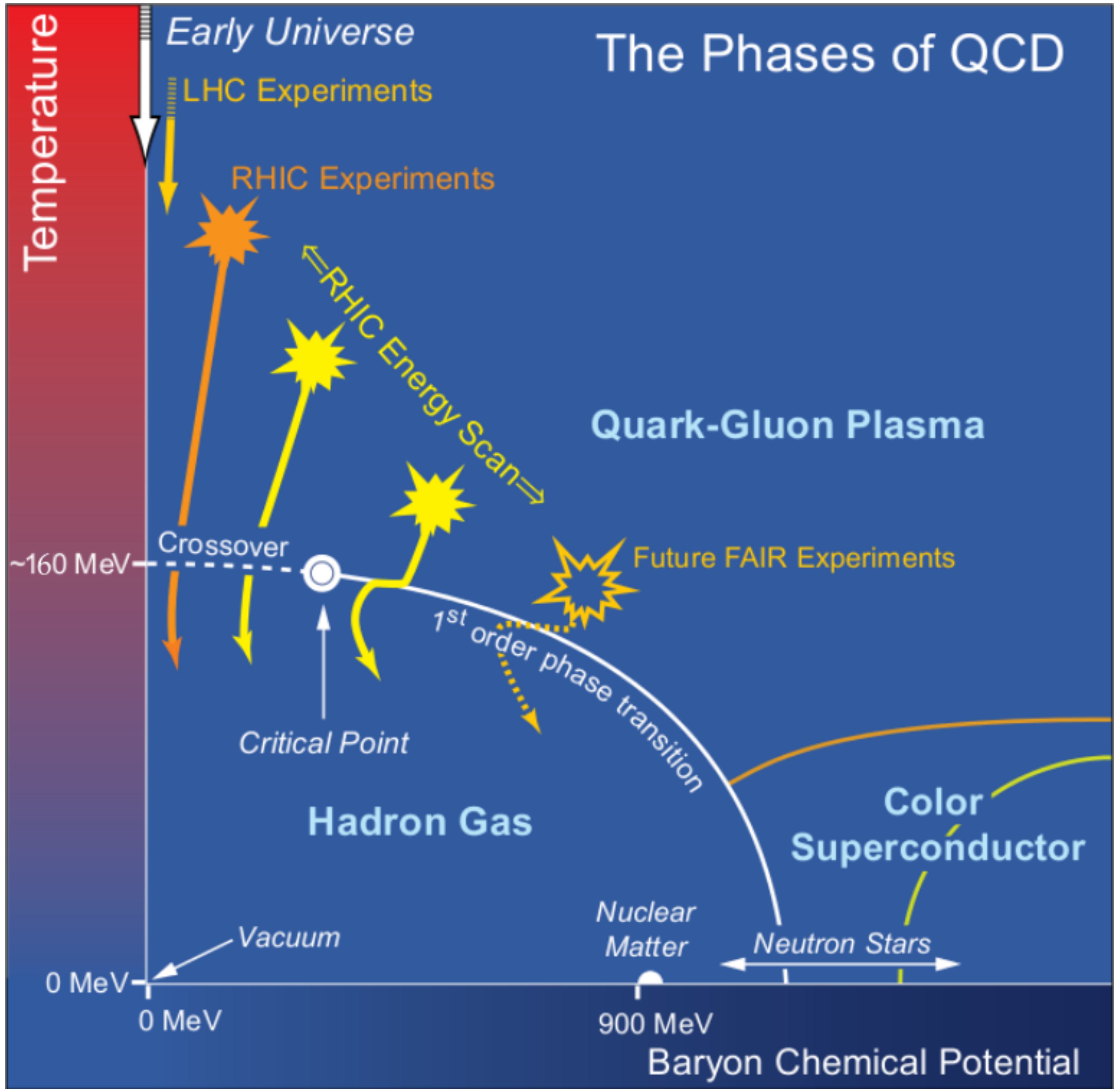
November 30, 2020

High-temperature regime of QCD

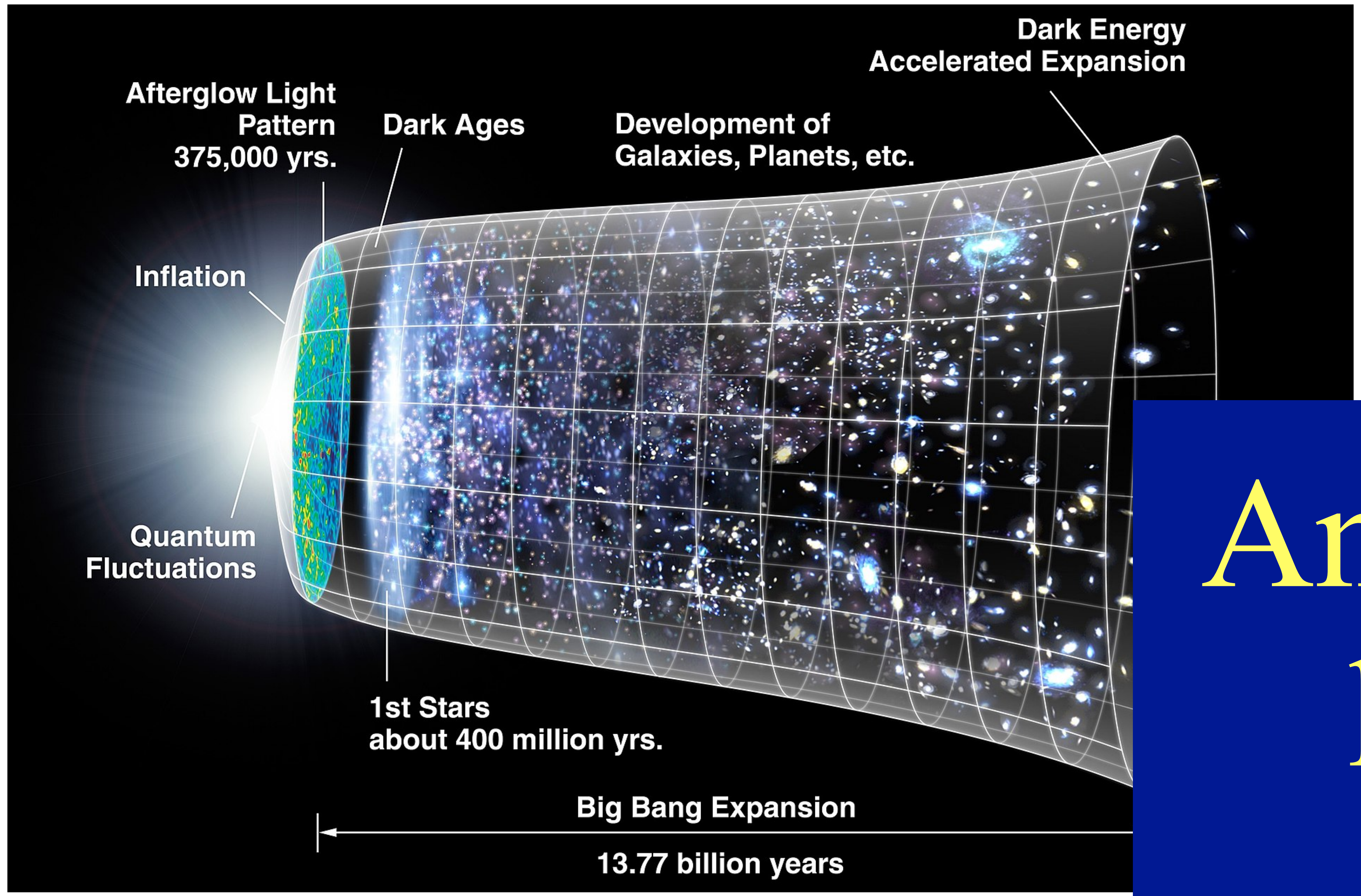
- At high temperatures and densities, quarks and gluons are no longer confined into hadrons but behave quasi-freely
  - Quark-Gluon Plasma (QGP)

[PRD 90 094503 (2014)]





Where do we find deconfined matter?



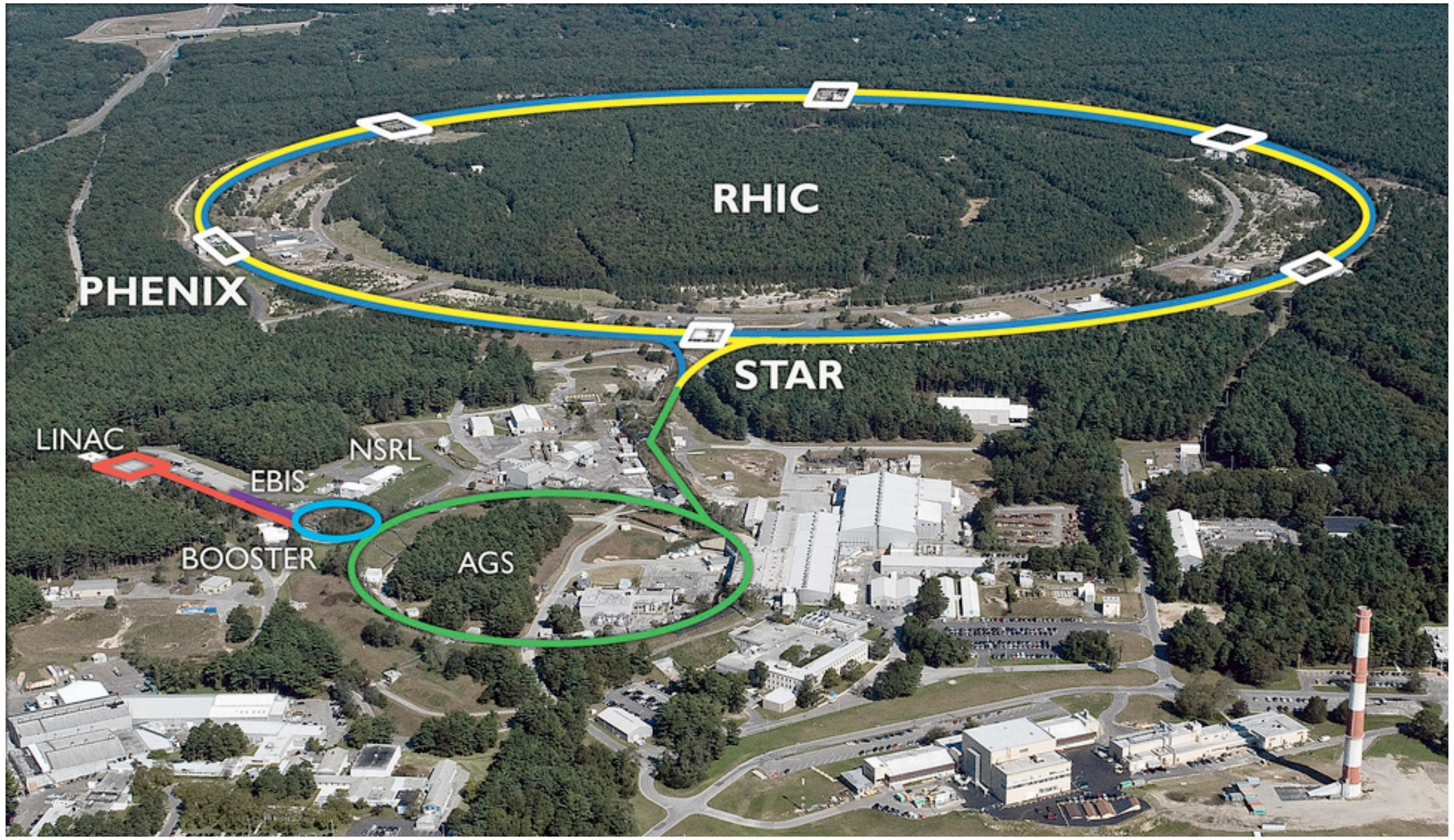
- microseconds after the big bang

And in collisions of heavy nuclei at high energies!

- in the cores of neutron stars

- in numerical simulations on supercomputers

Heavy-ion colliders



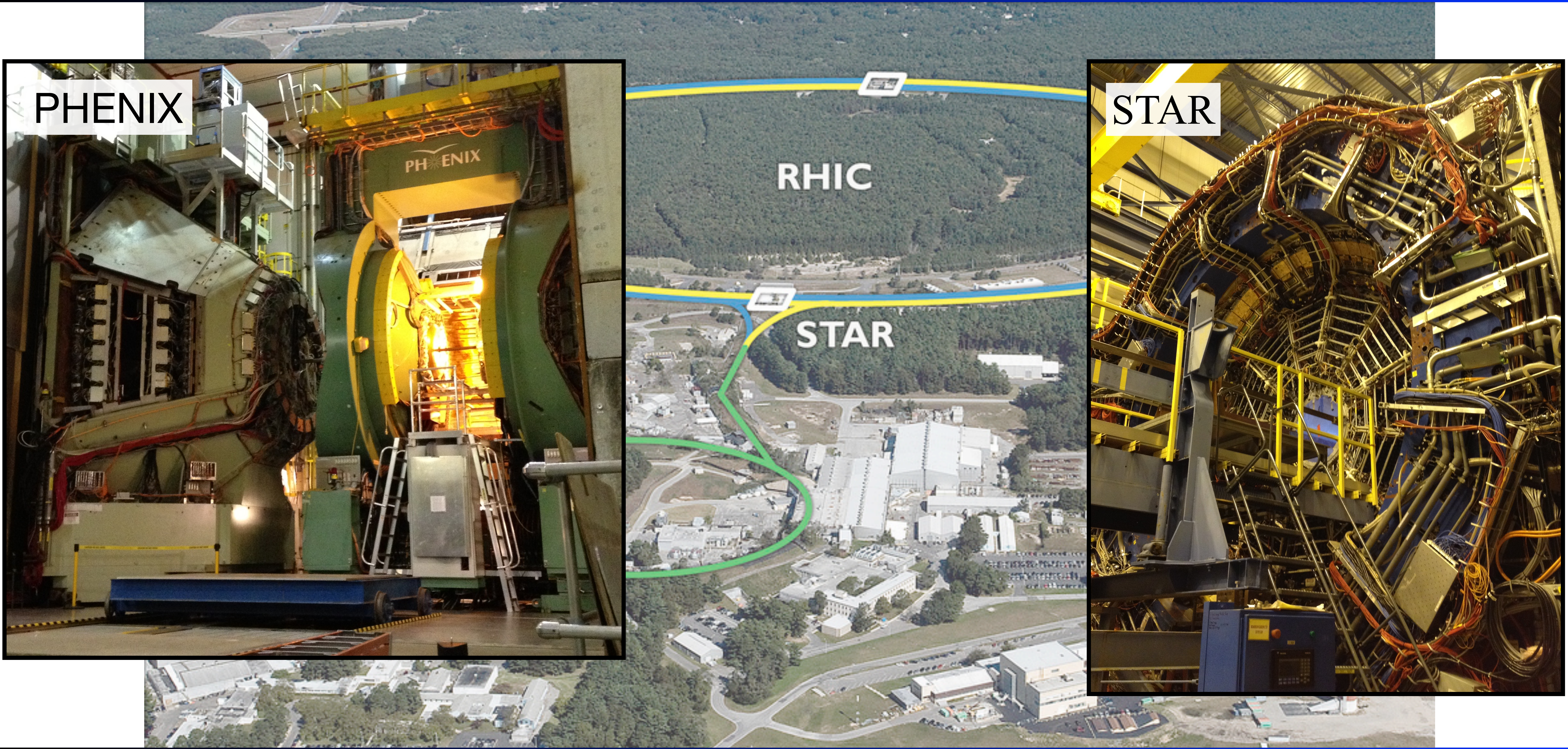
Relativistic Heavy Ion Collider

- 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

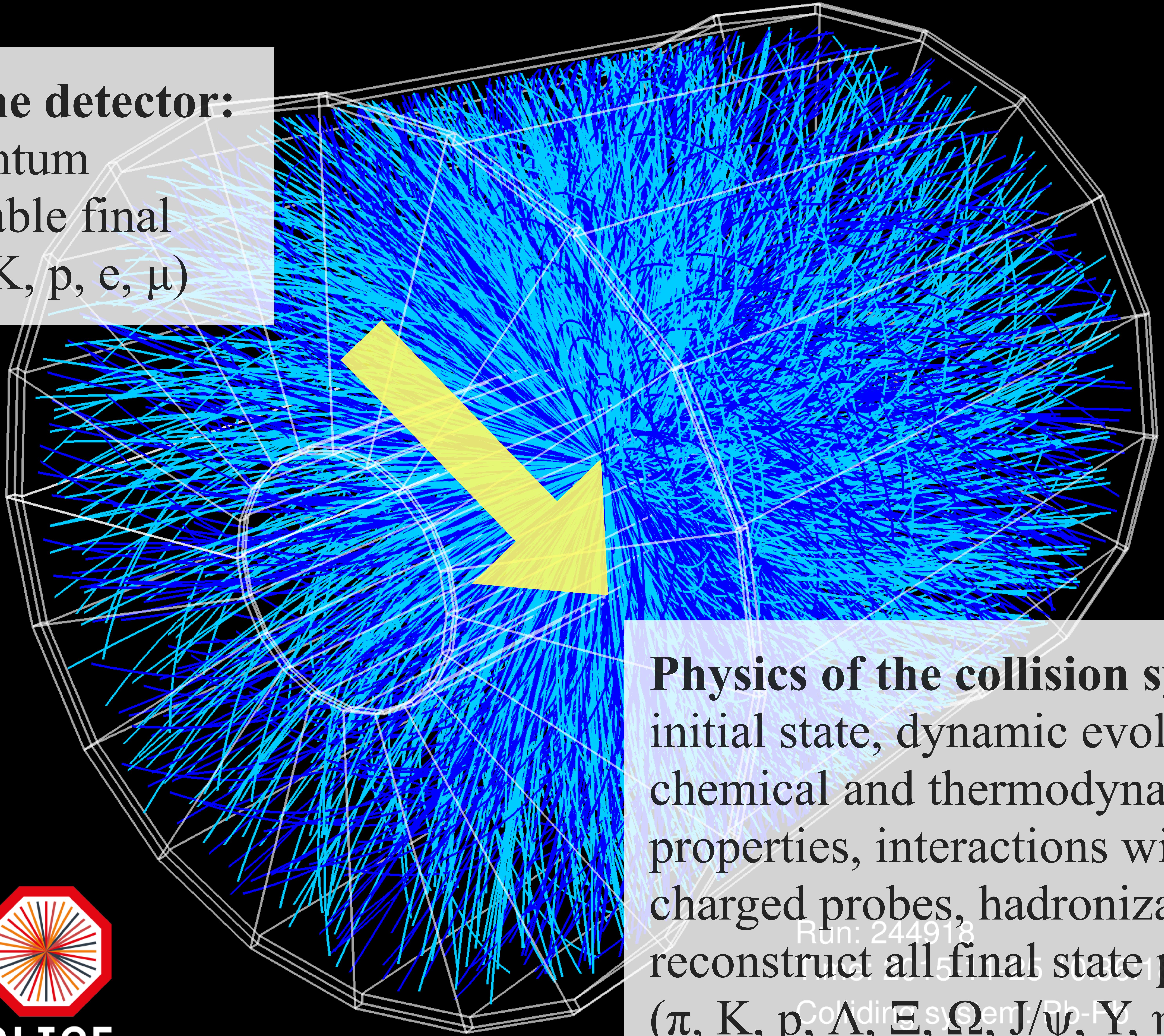
- 27 km circumference
- Pb+Pb collisions @ $\sqrt{s_{NN}}$ = 2.76, 5 TeV
- also p+p, p+Pb, Xe+Xe

Heavy-ion detectors at RHIC



Heavy-ion detectors at the LHC

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,…)

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Relativistic Heavy-Ion Collisions
made by Chun Shen
final detected particle distributions
Kinetic freeze-out
Hadronization
Initial energy density
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QGP phase
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collision overlap zone
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pre-equilibrium dynamics
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τ ~ 0 fm/c
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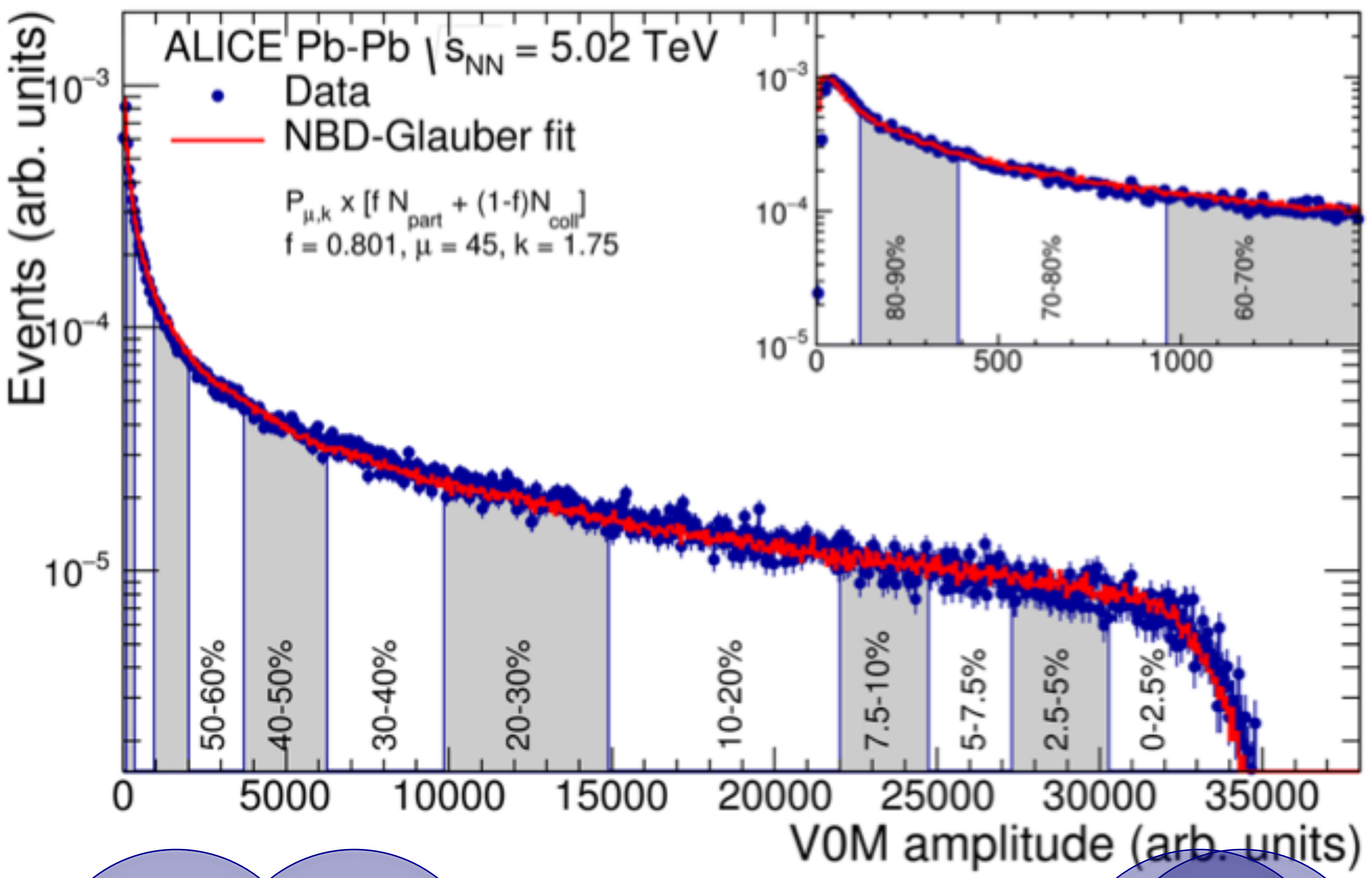
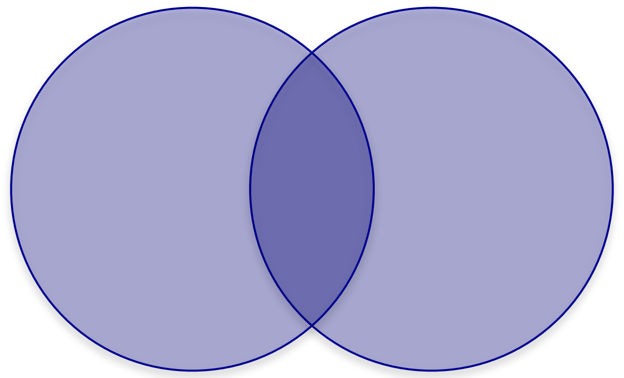
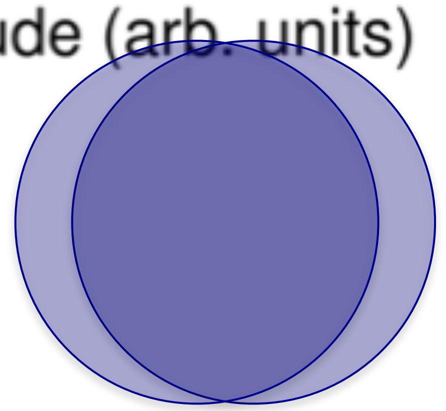
Geometry of a heavy-ion collision

- Centrality: amount of overlap of the colliding nuclei



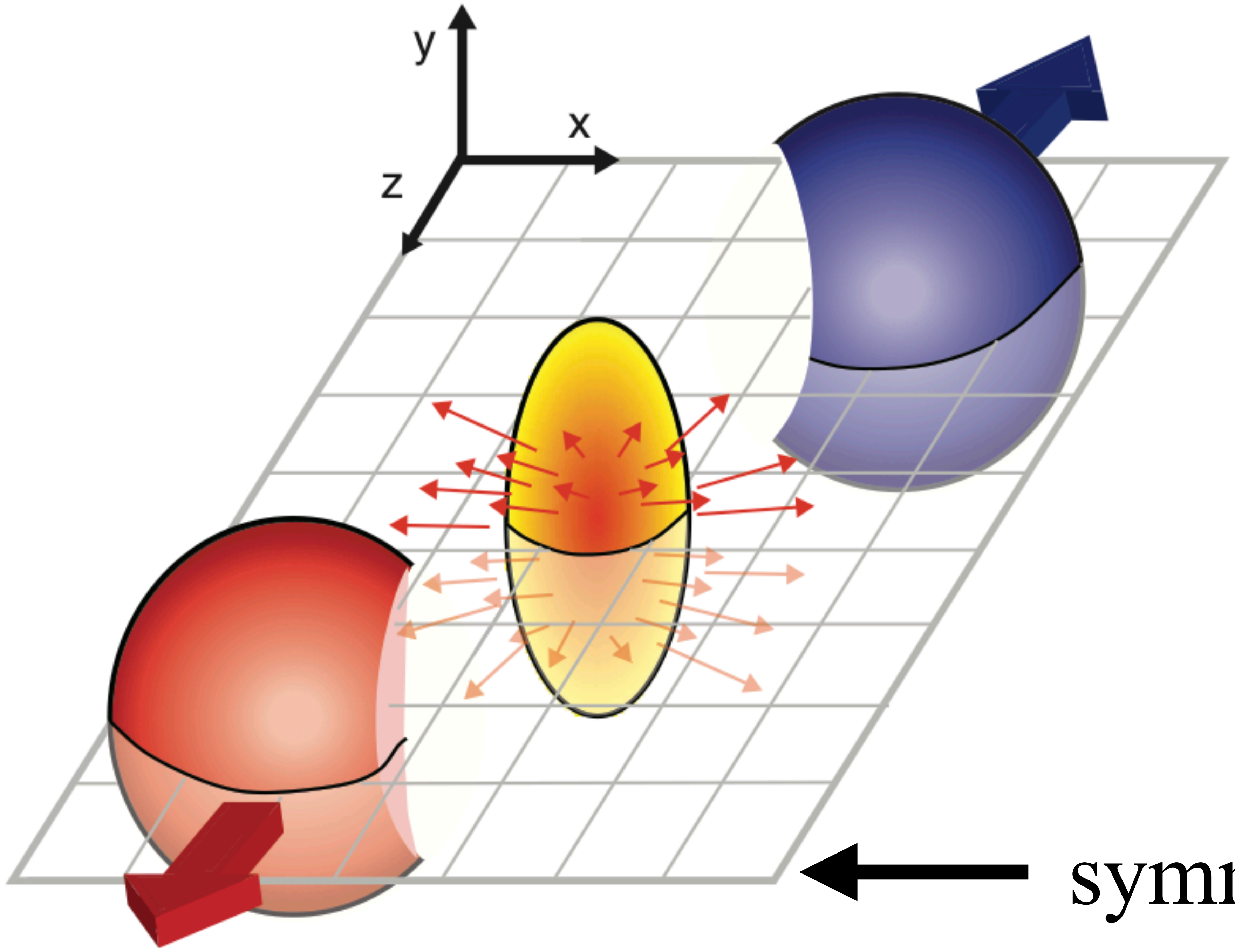


"peripheral"



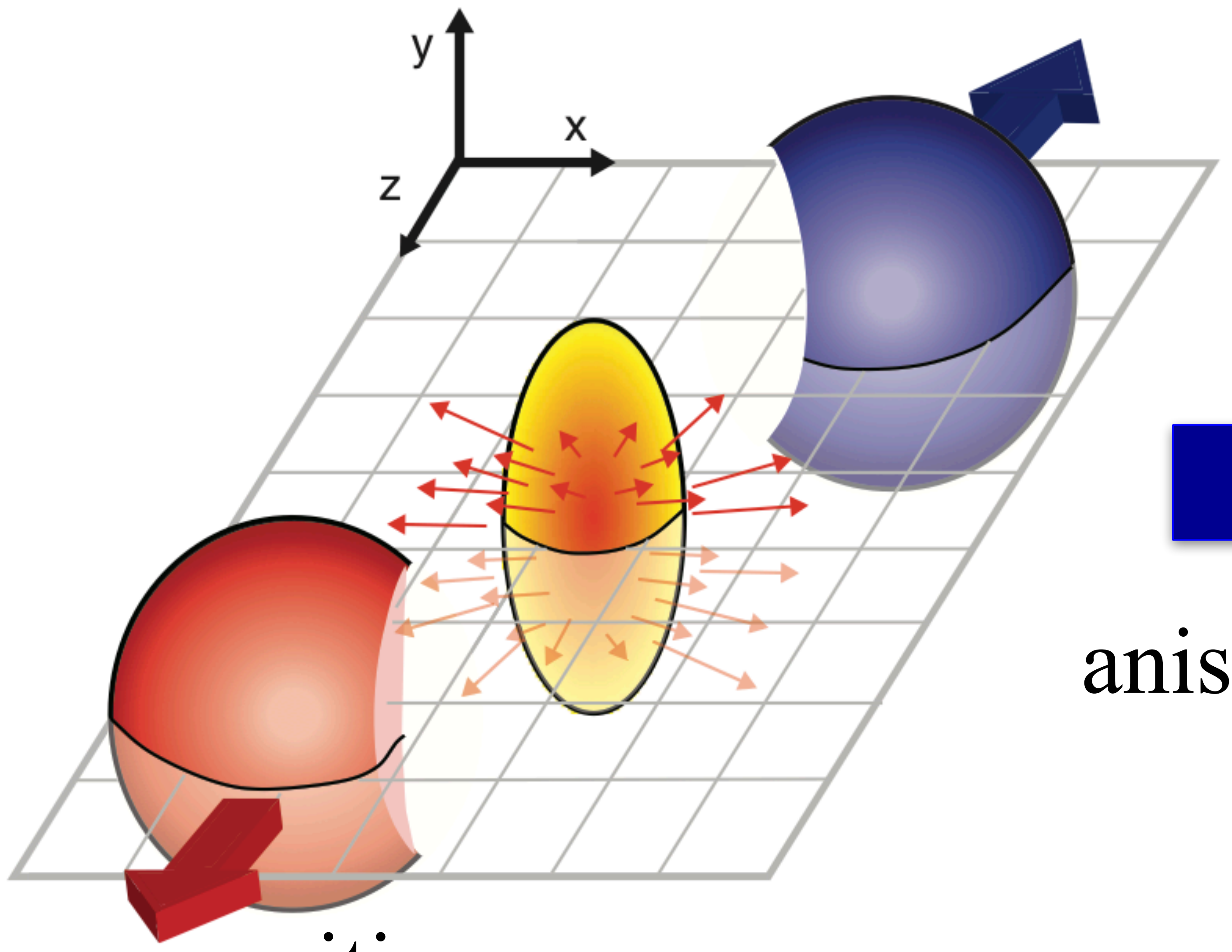
"central"

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



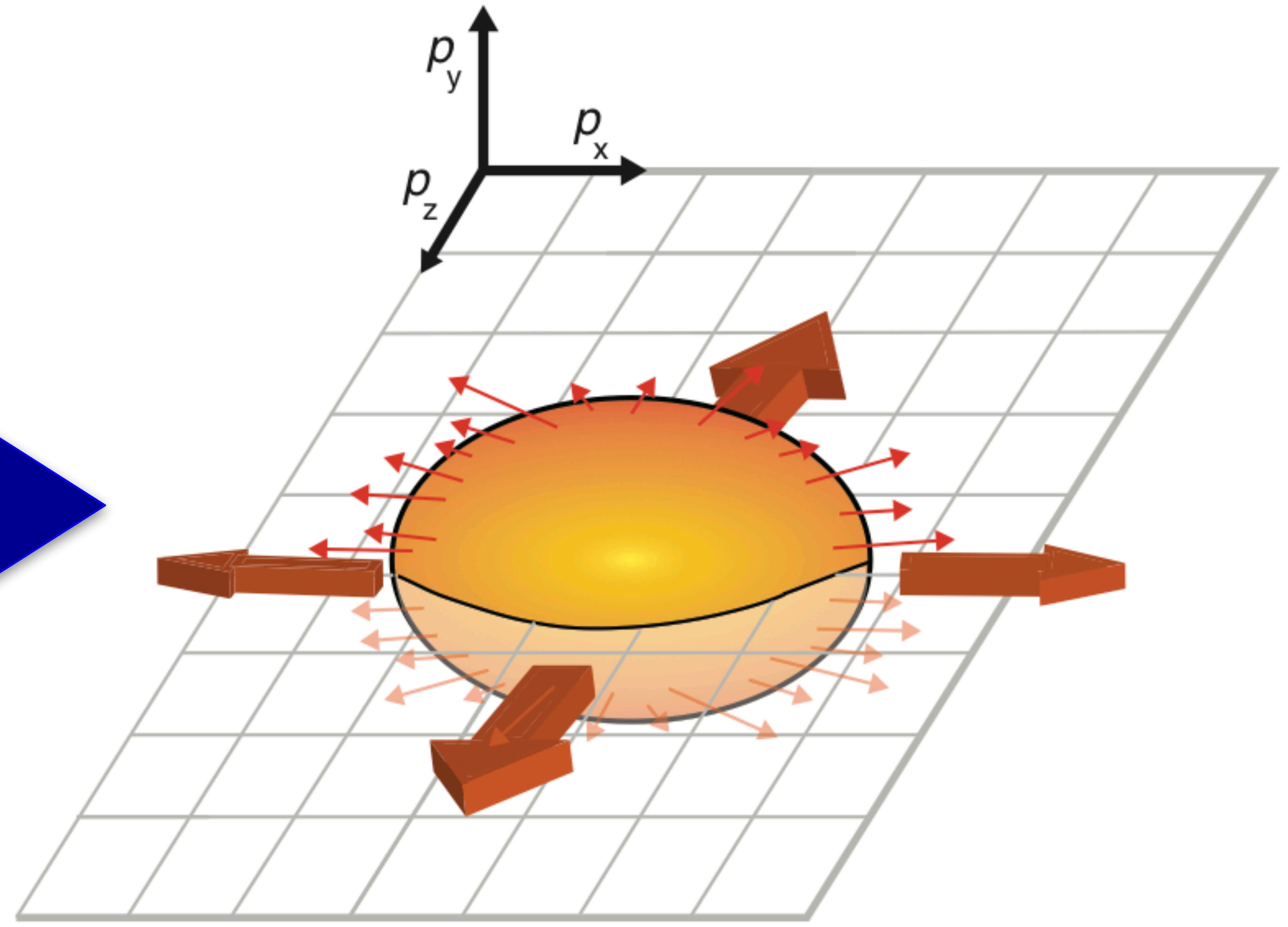
symmetry plane

Anisotropic interaction region



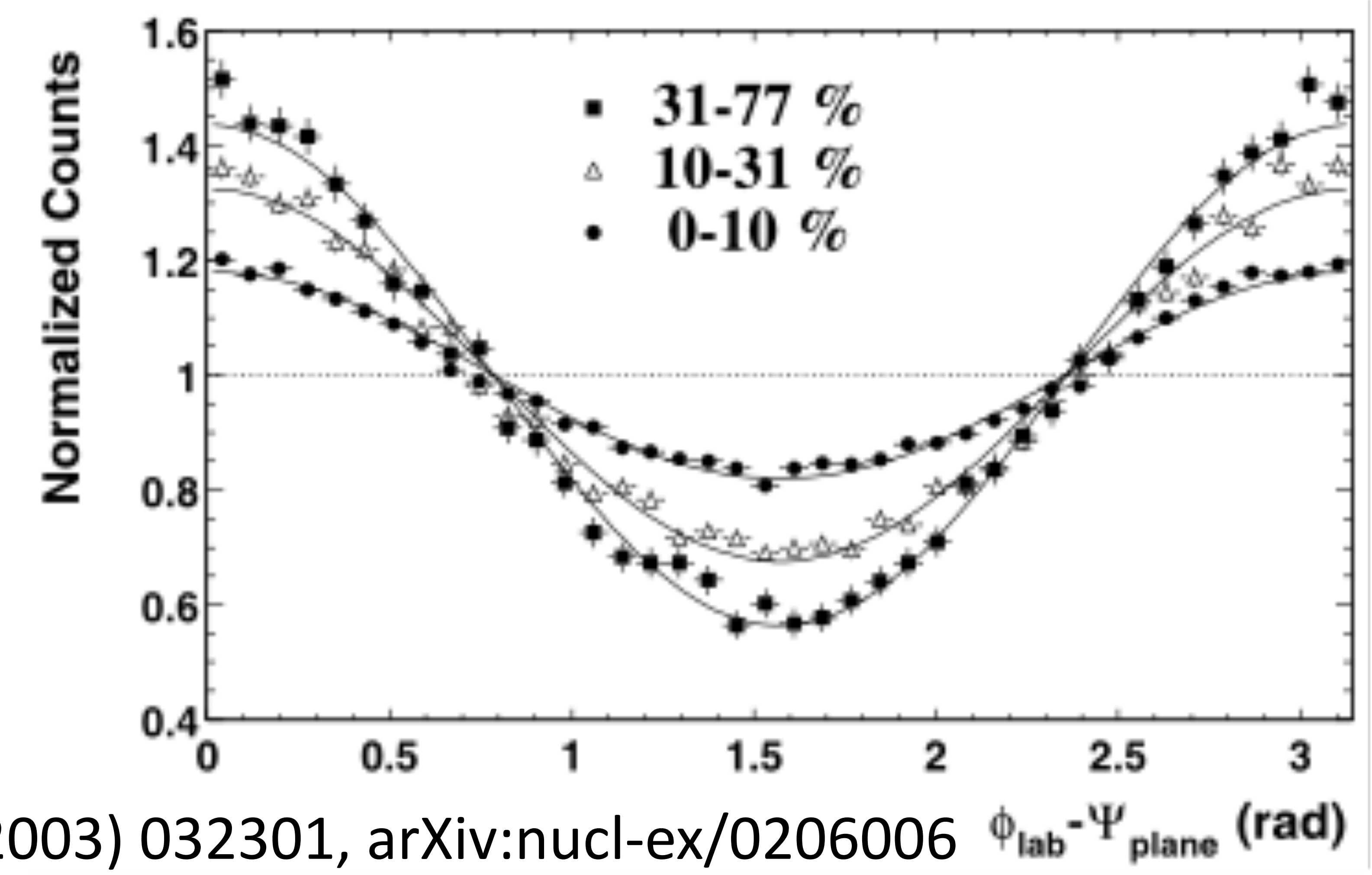
position-space anisotropy

anisotropic pressure gradients

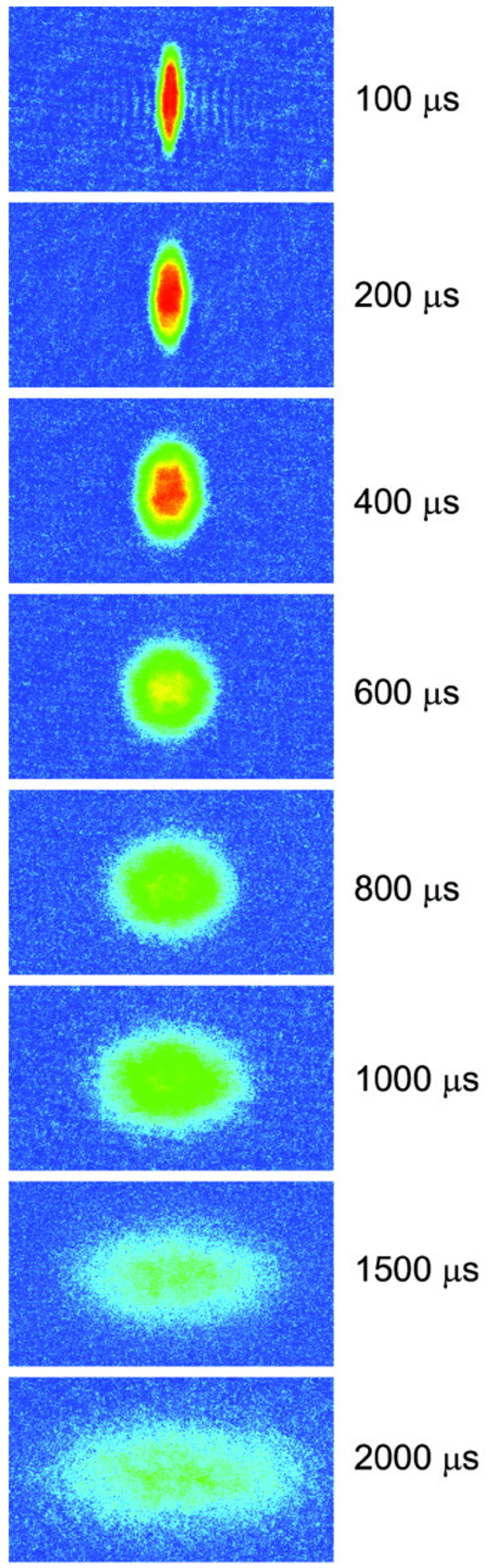


momentum-space anisotropy

- 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

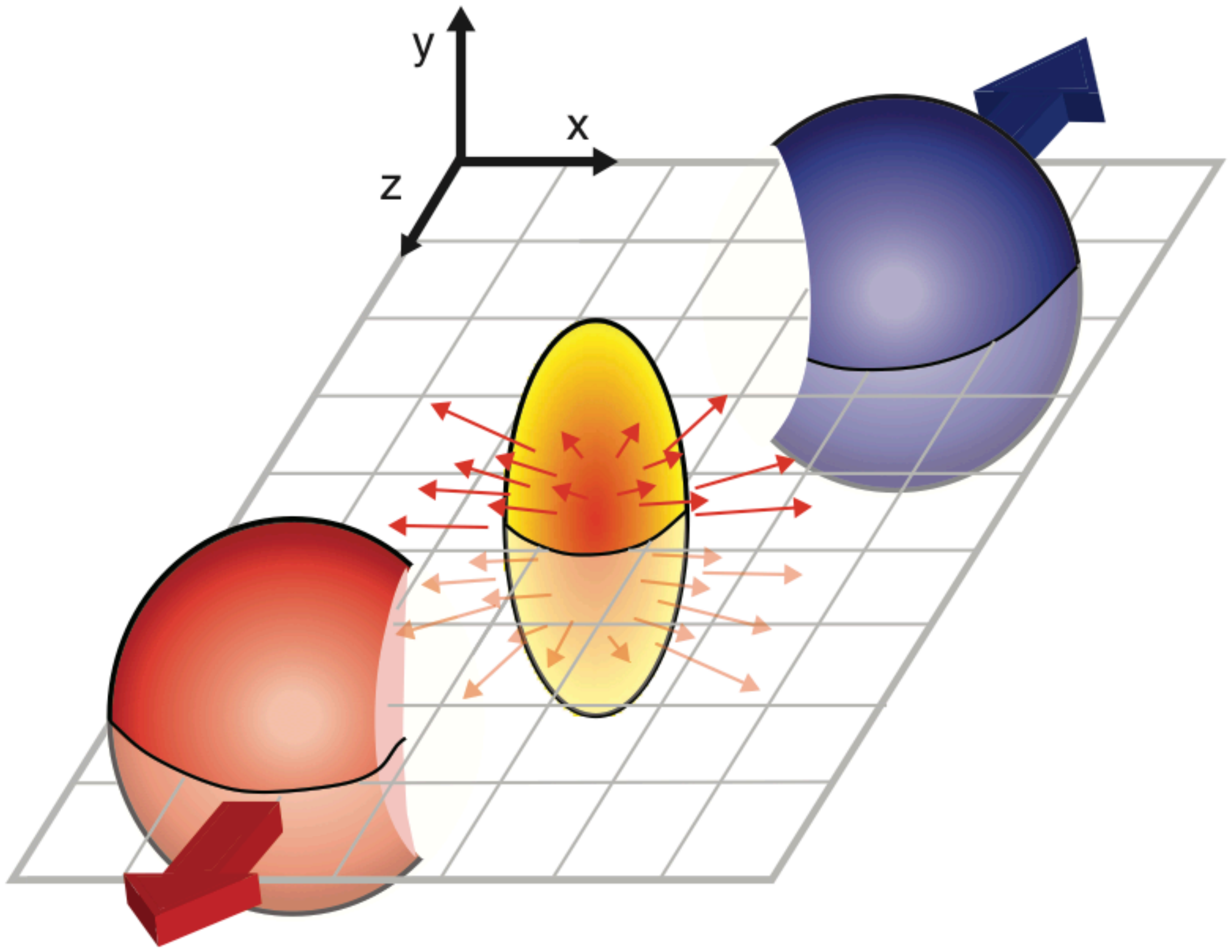
K.M. O'Hara et al., Science, 13 Dec 2002: 2179-2182

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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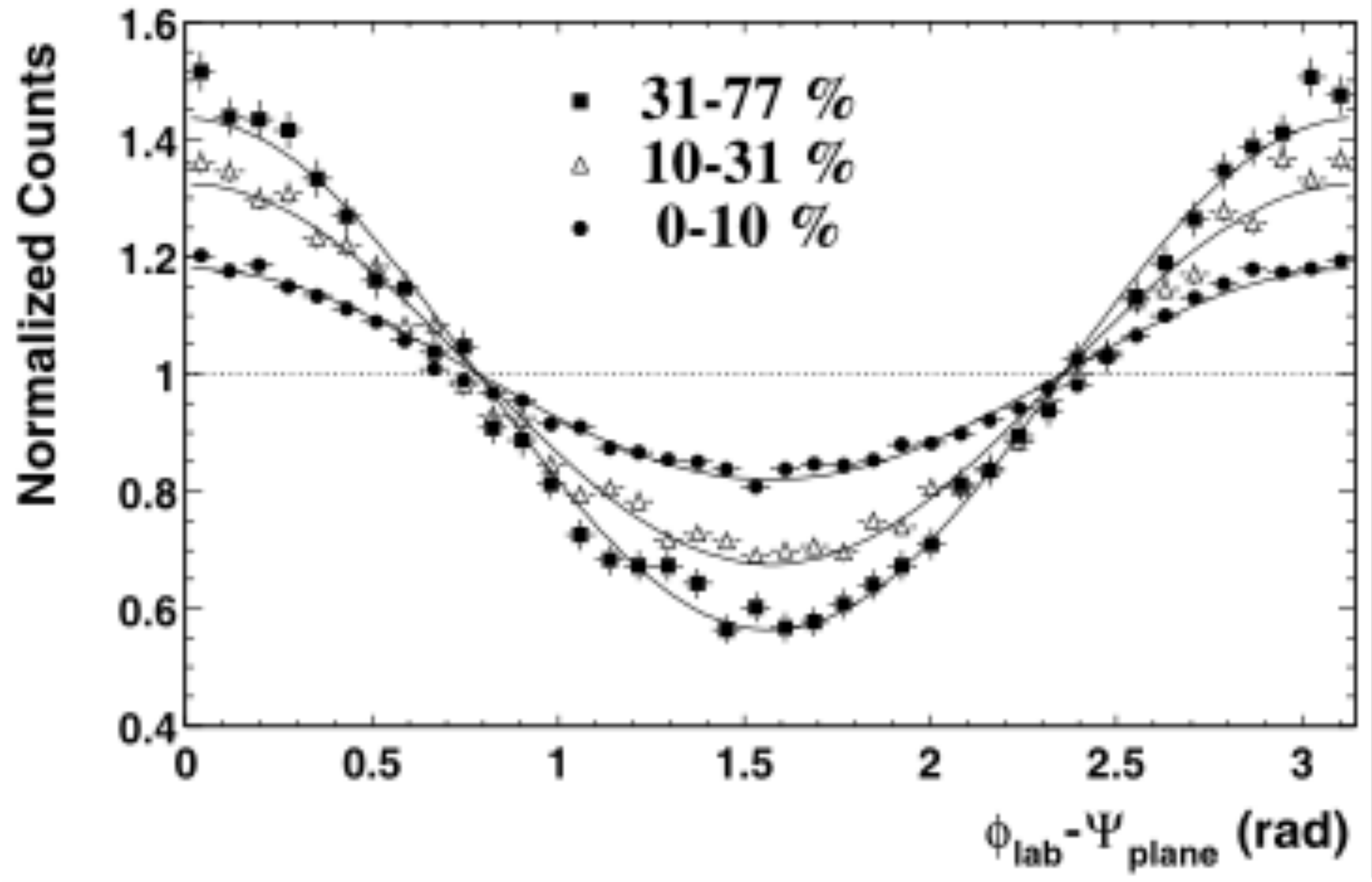


Anisotropic flow coefficients

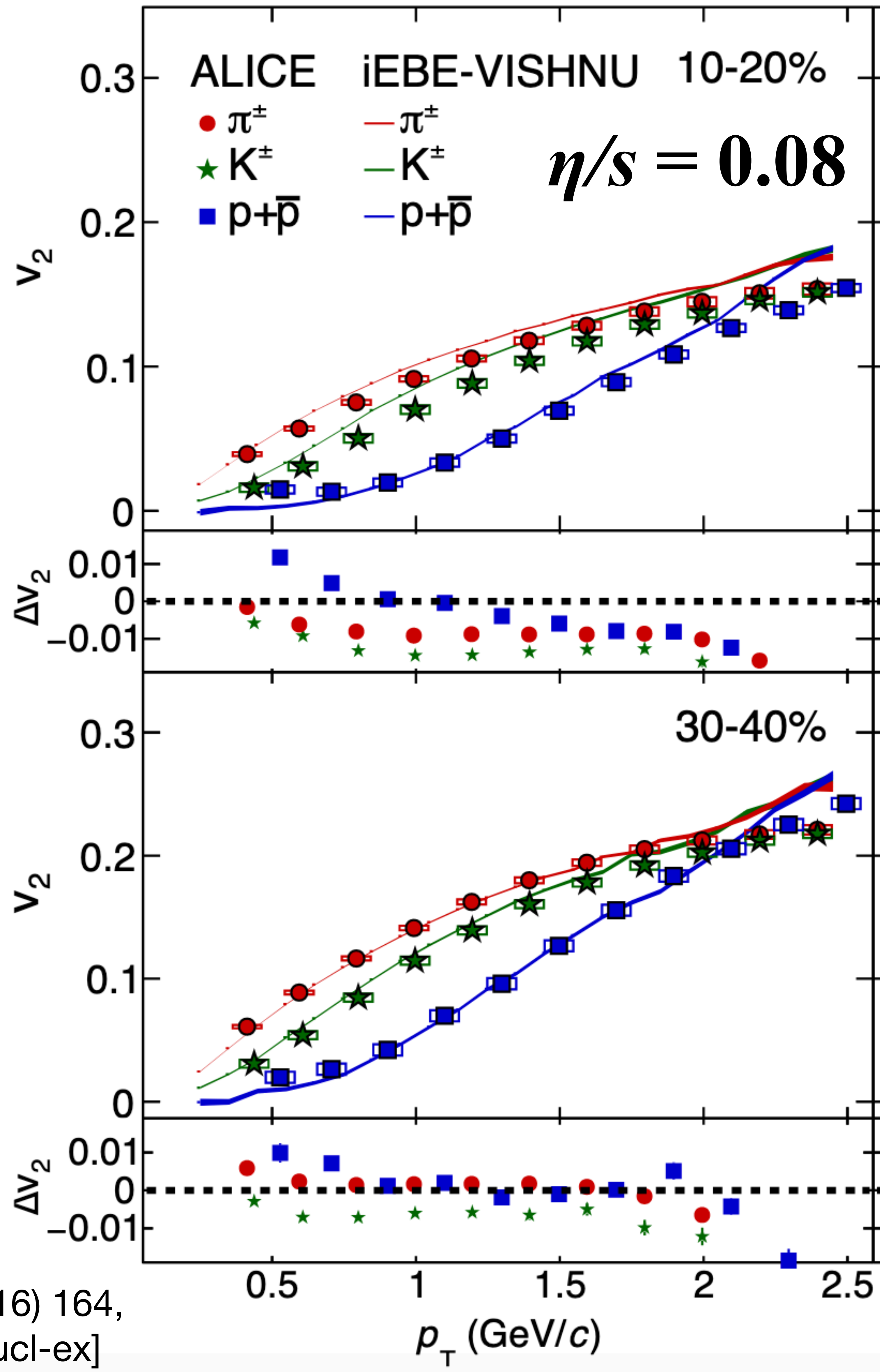
- Particle distribution described by a Fourier cosine series

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

- $v_2 \rightarrow$ "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]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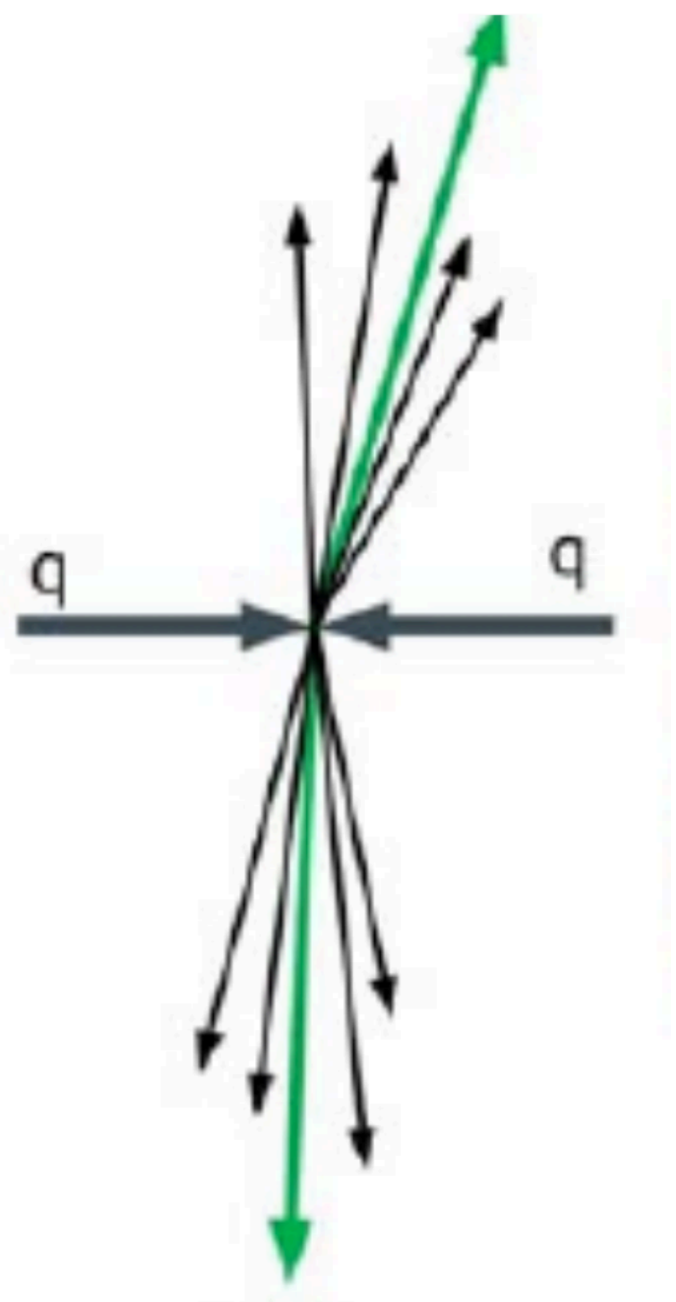
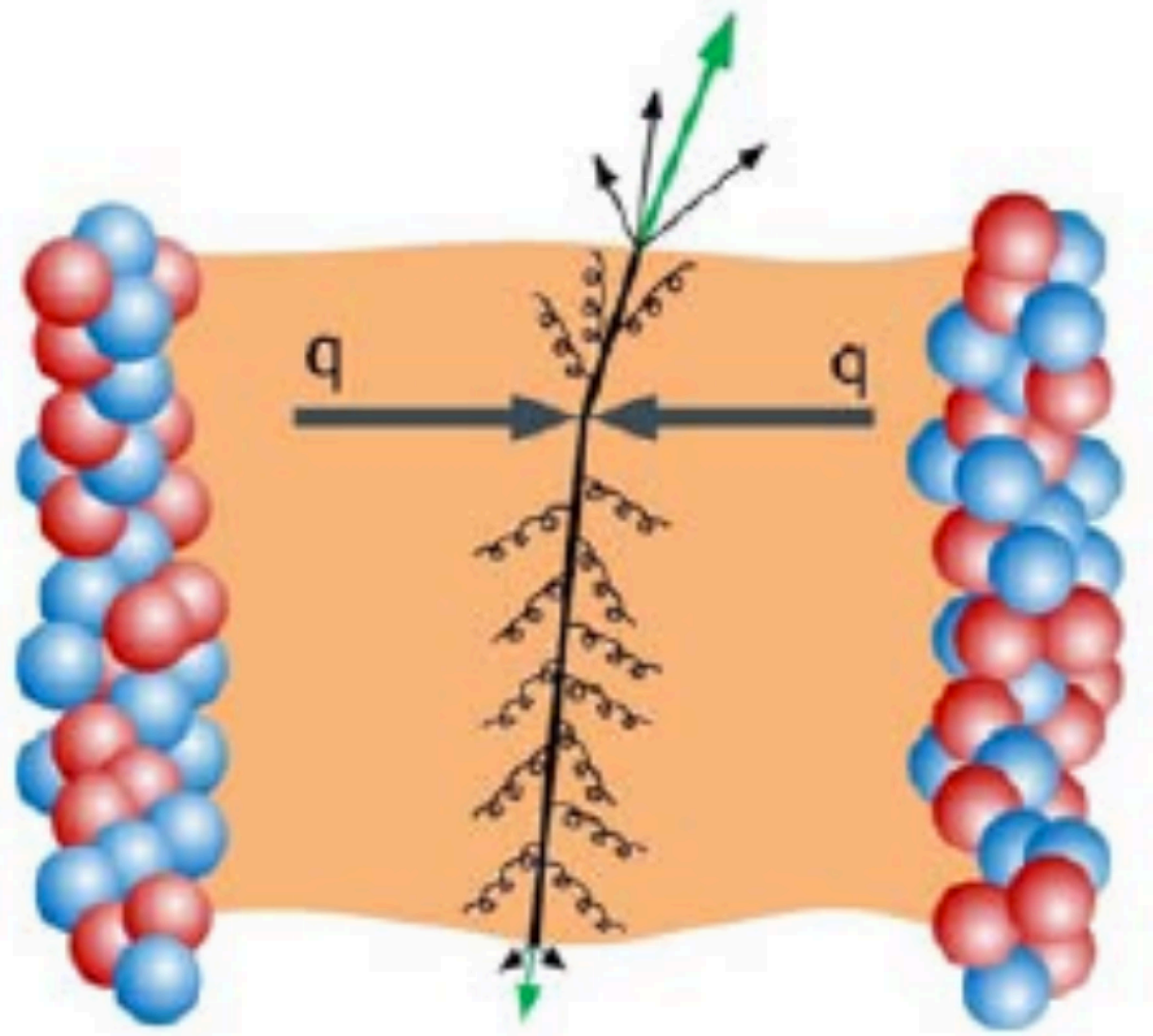
A colored probe in a colored medium

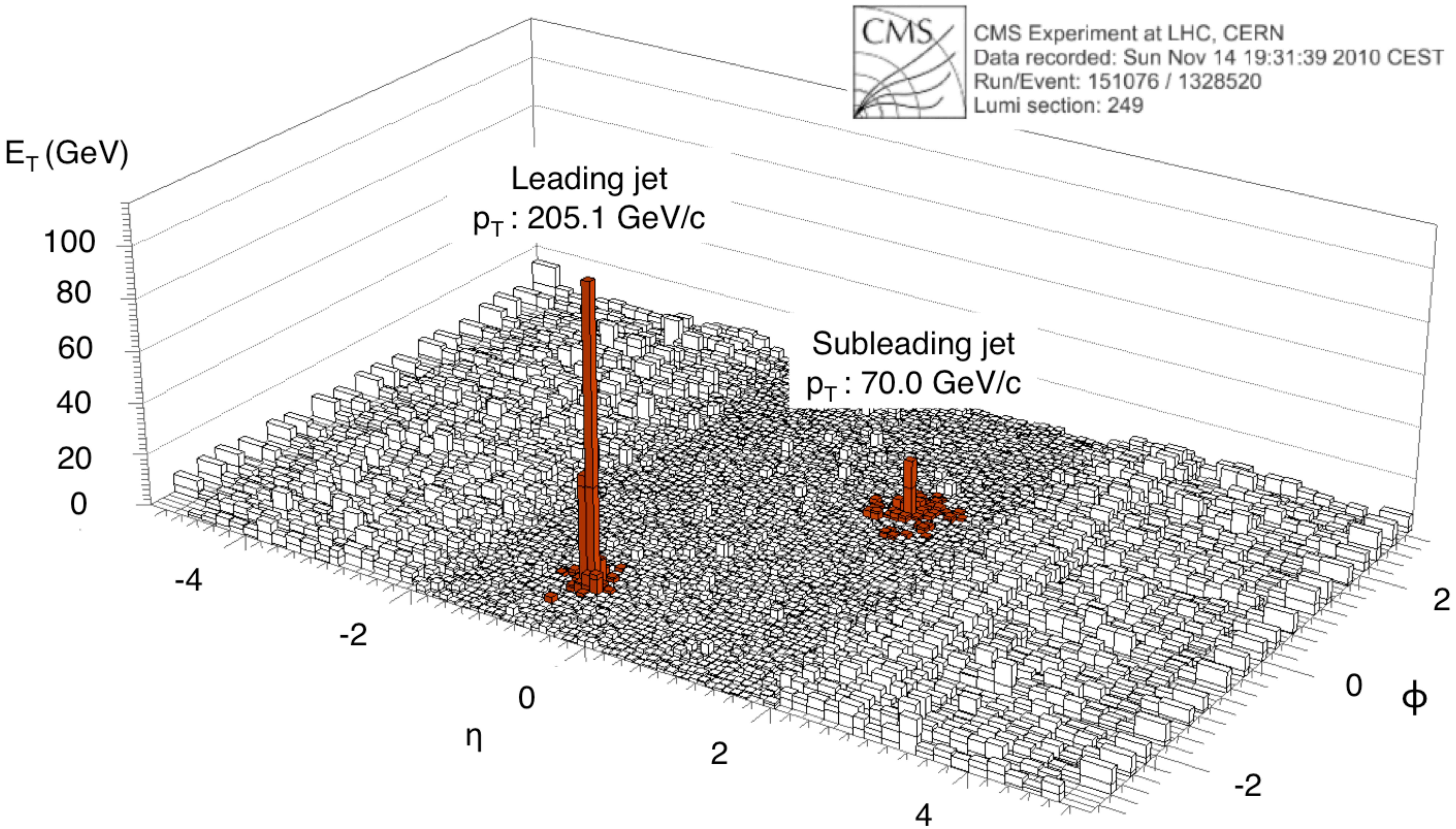
- Hard scatterings in the early stages of the collision produce back-to-back recoiling partons, which fragment into collimated clusters of hadrons



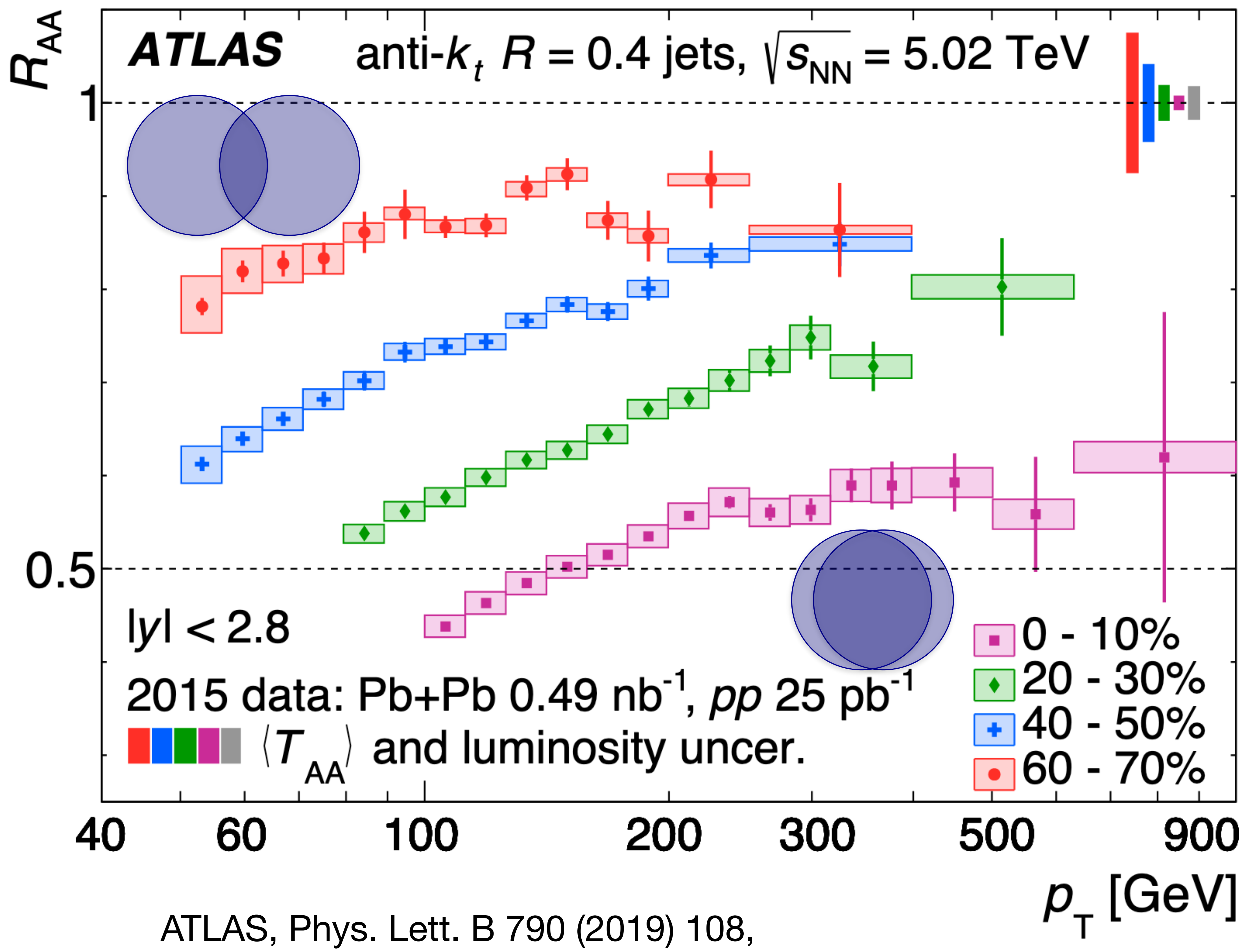
- As they traverse the QGP, partons interact with the medium → "jet quenching"
- Characterize the nature of this energy loss to understand properties of the QGP and the interactions of a colored probe with a colored medium



Jets in heavy-ion collisions



Jet 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!
- By comparing with a wide variety of models, extract the *jet transport coefficient* $\hat{q}$

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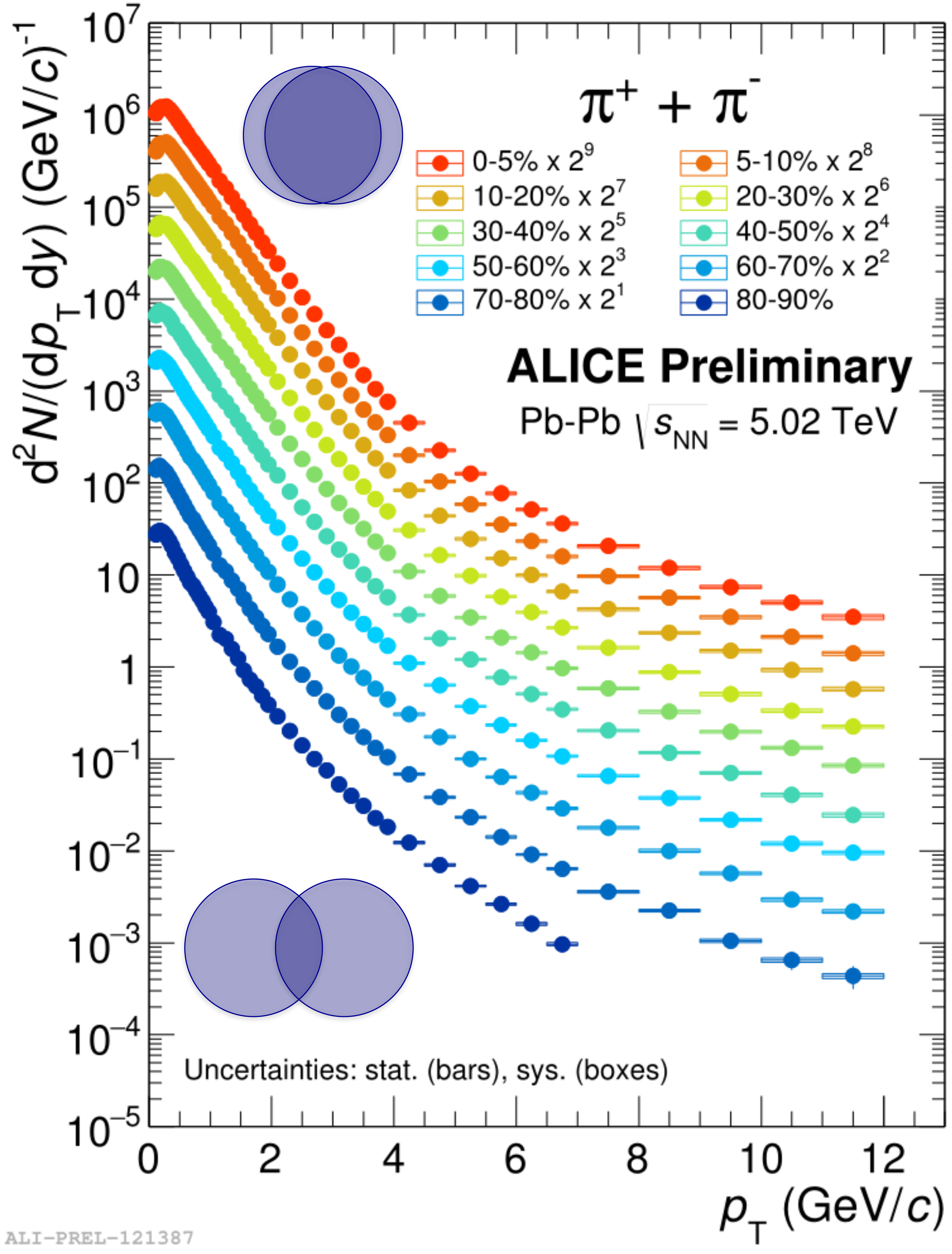
Identified particle spectra



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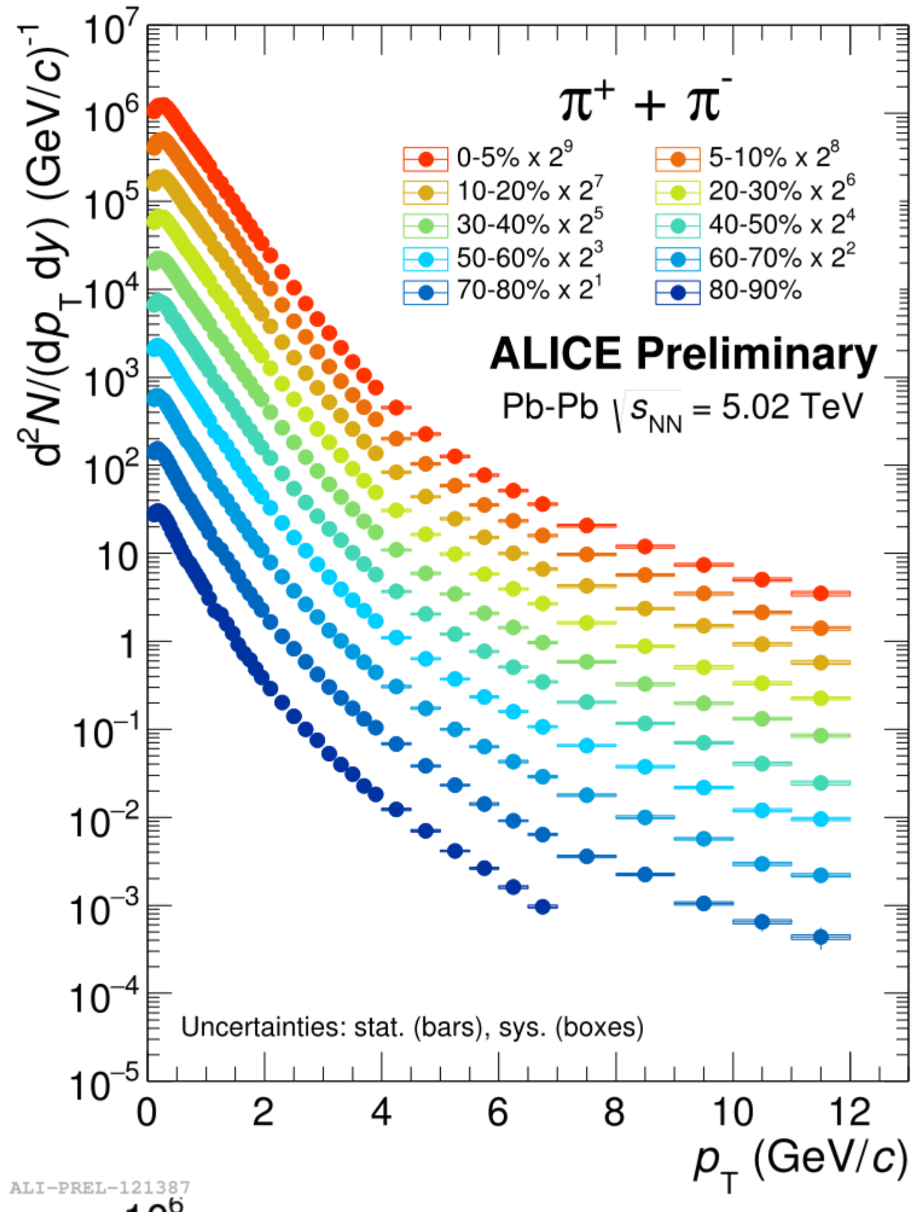

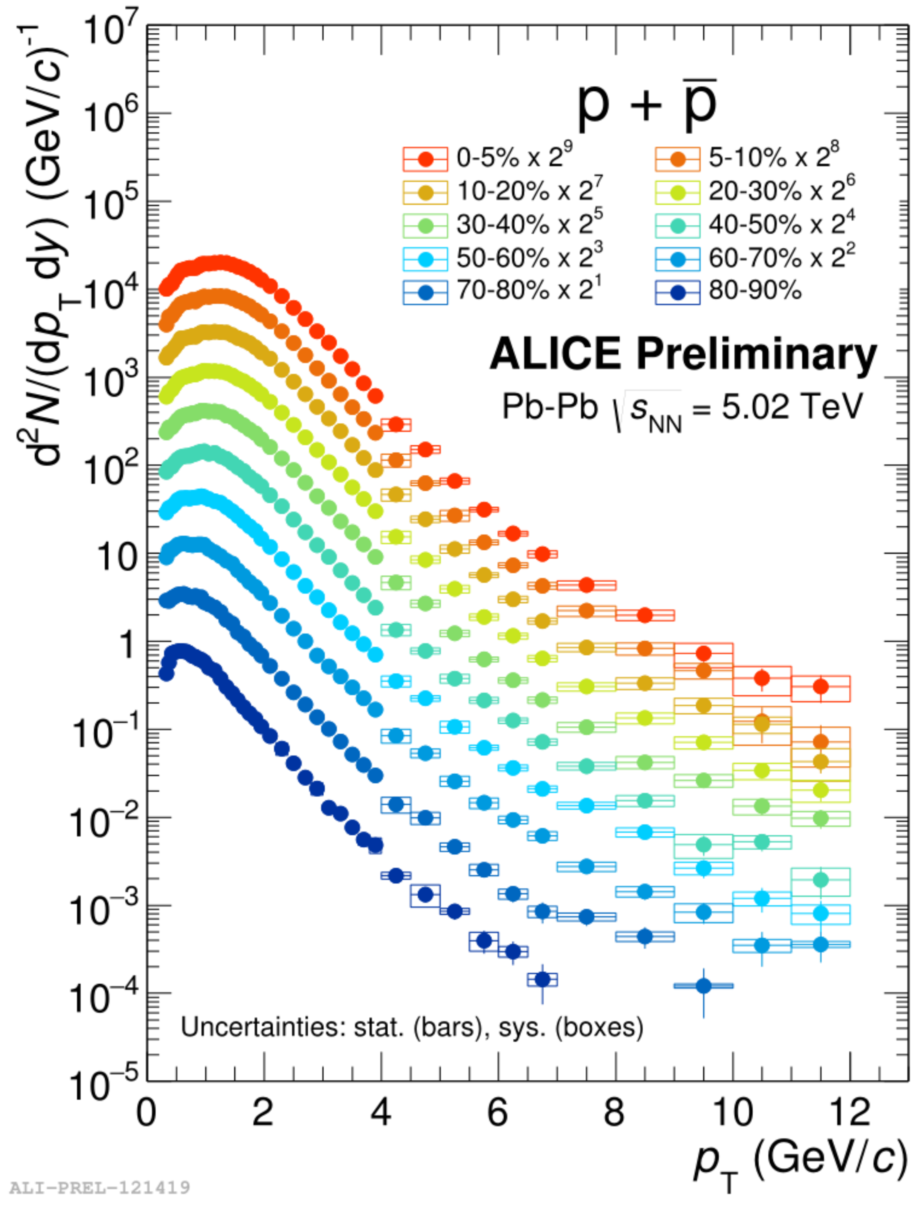

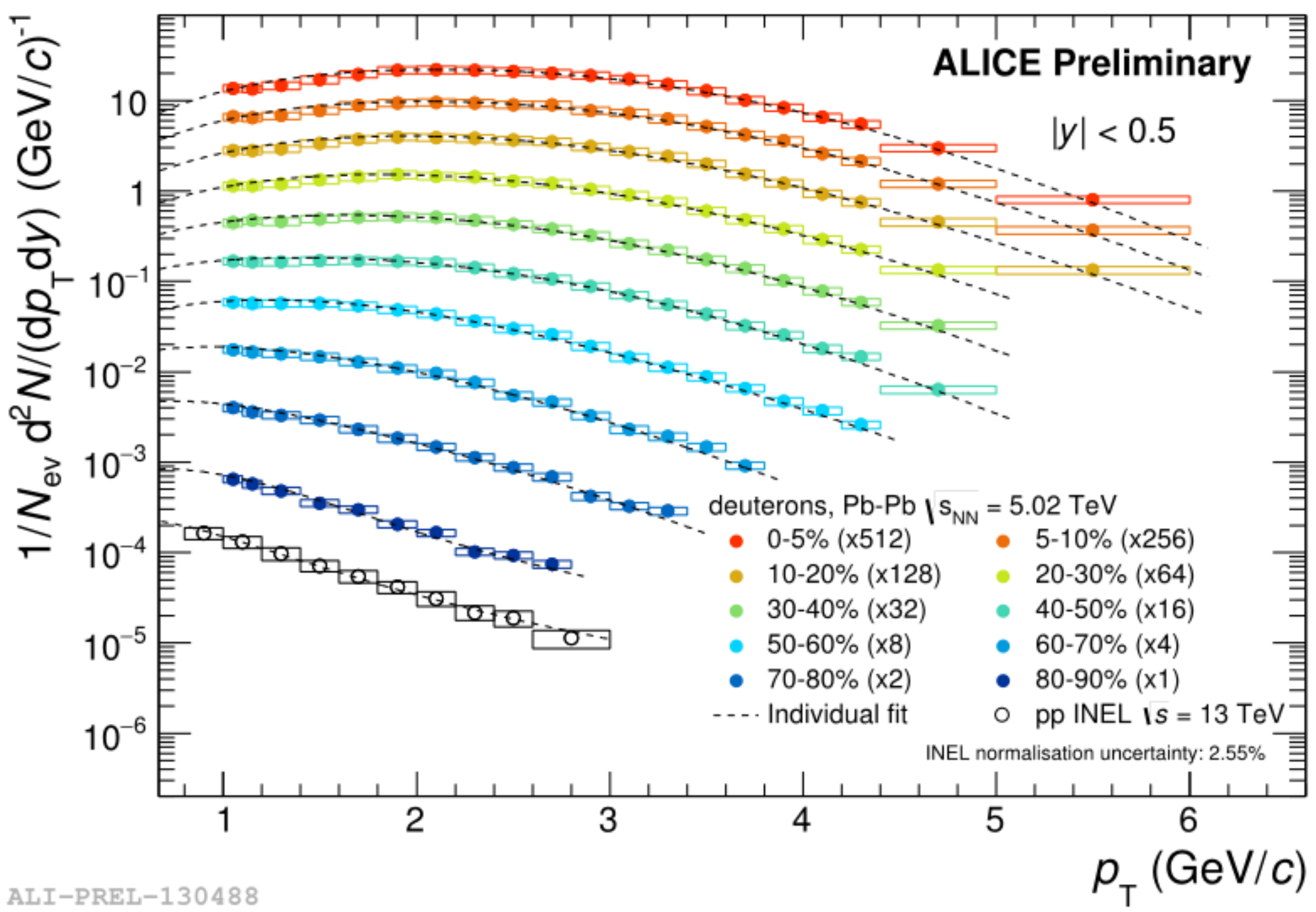

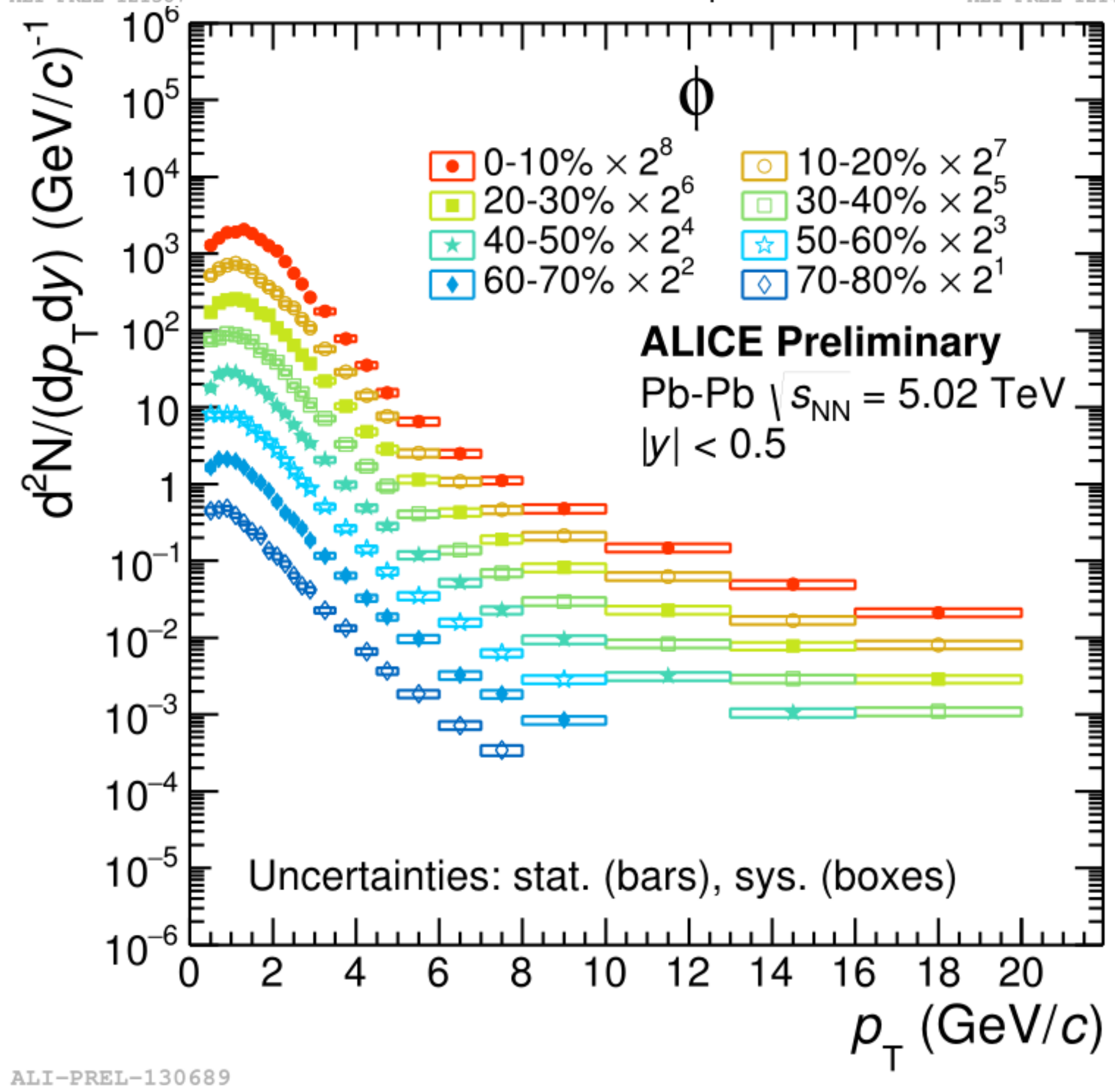

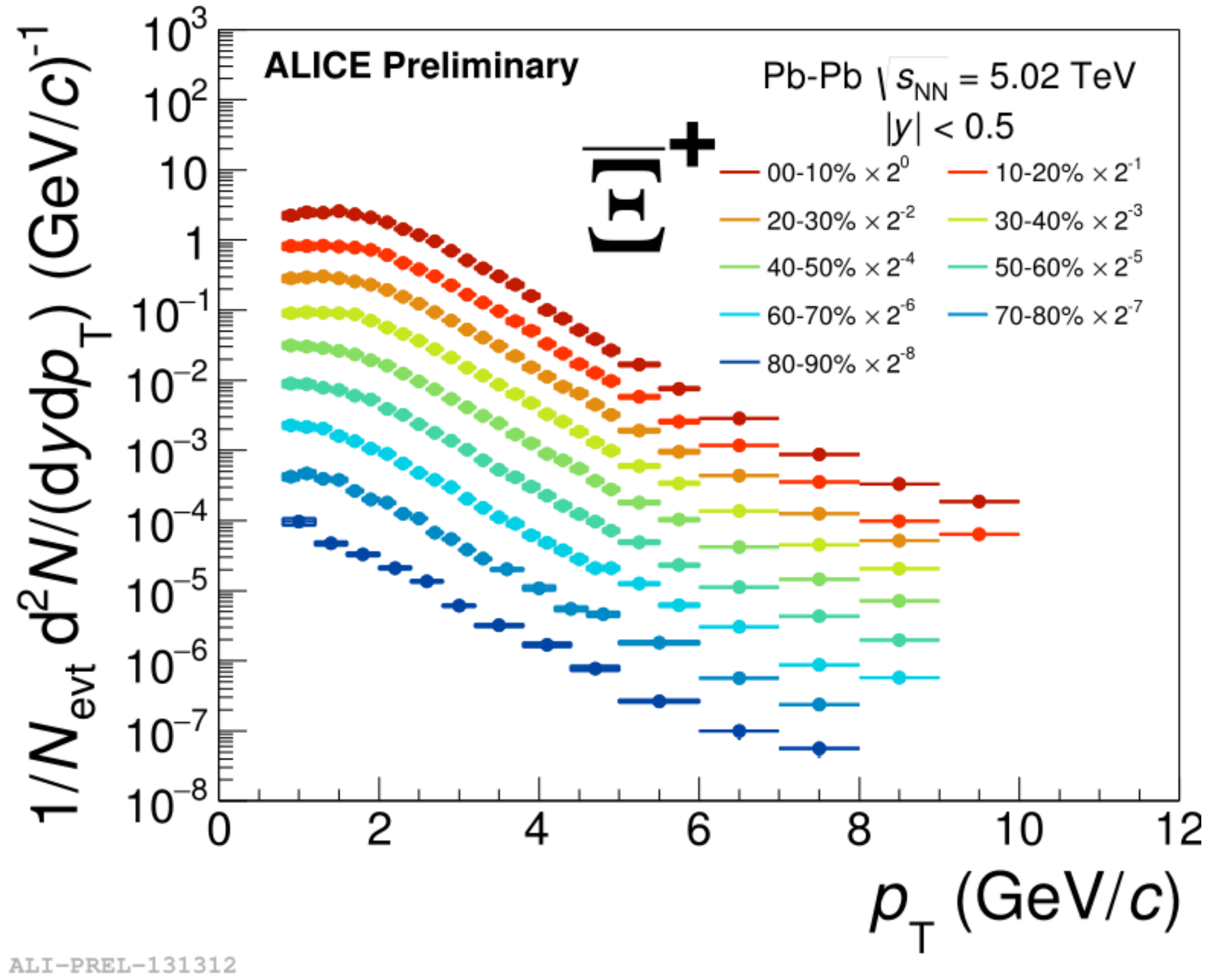

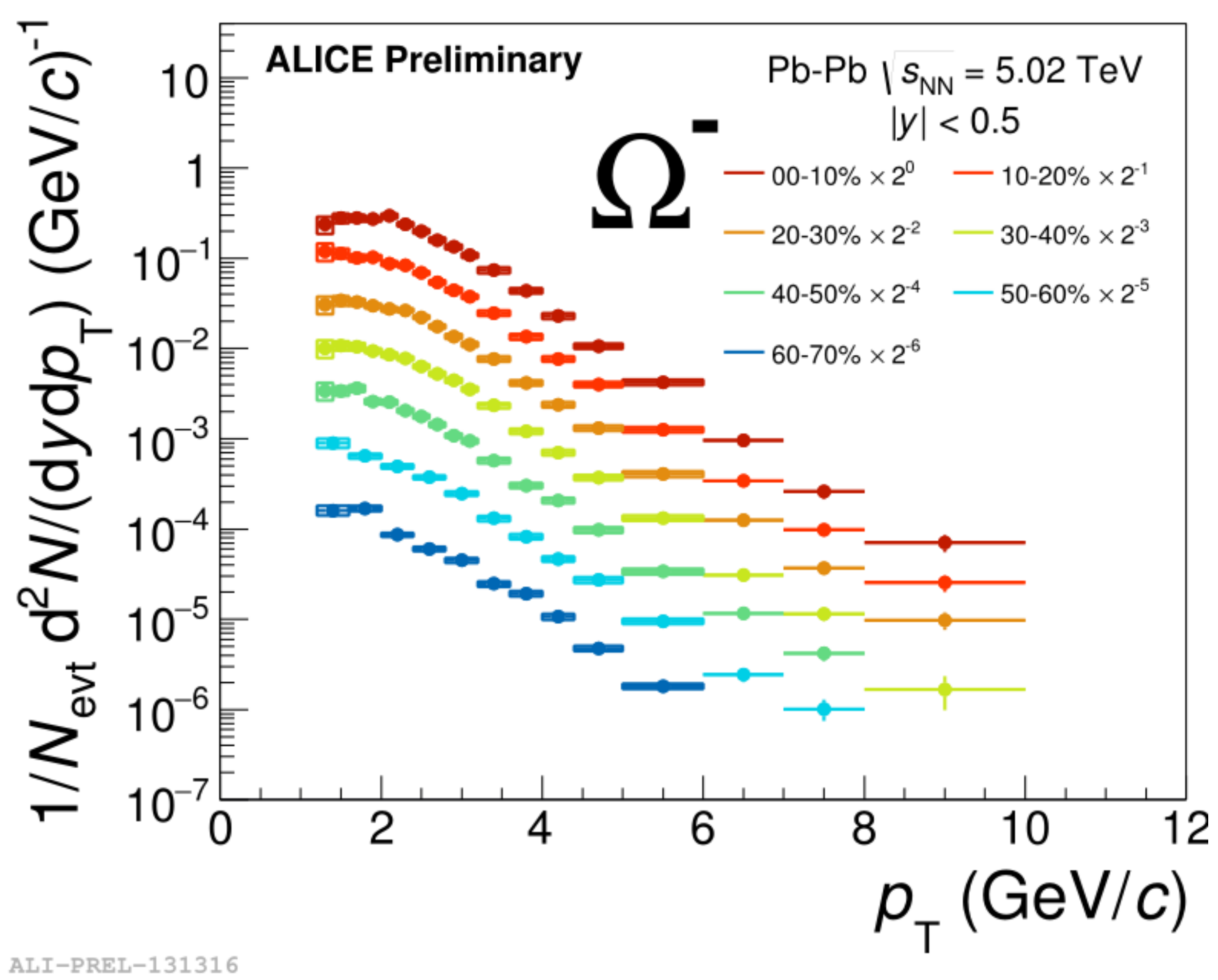

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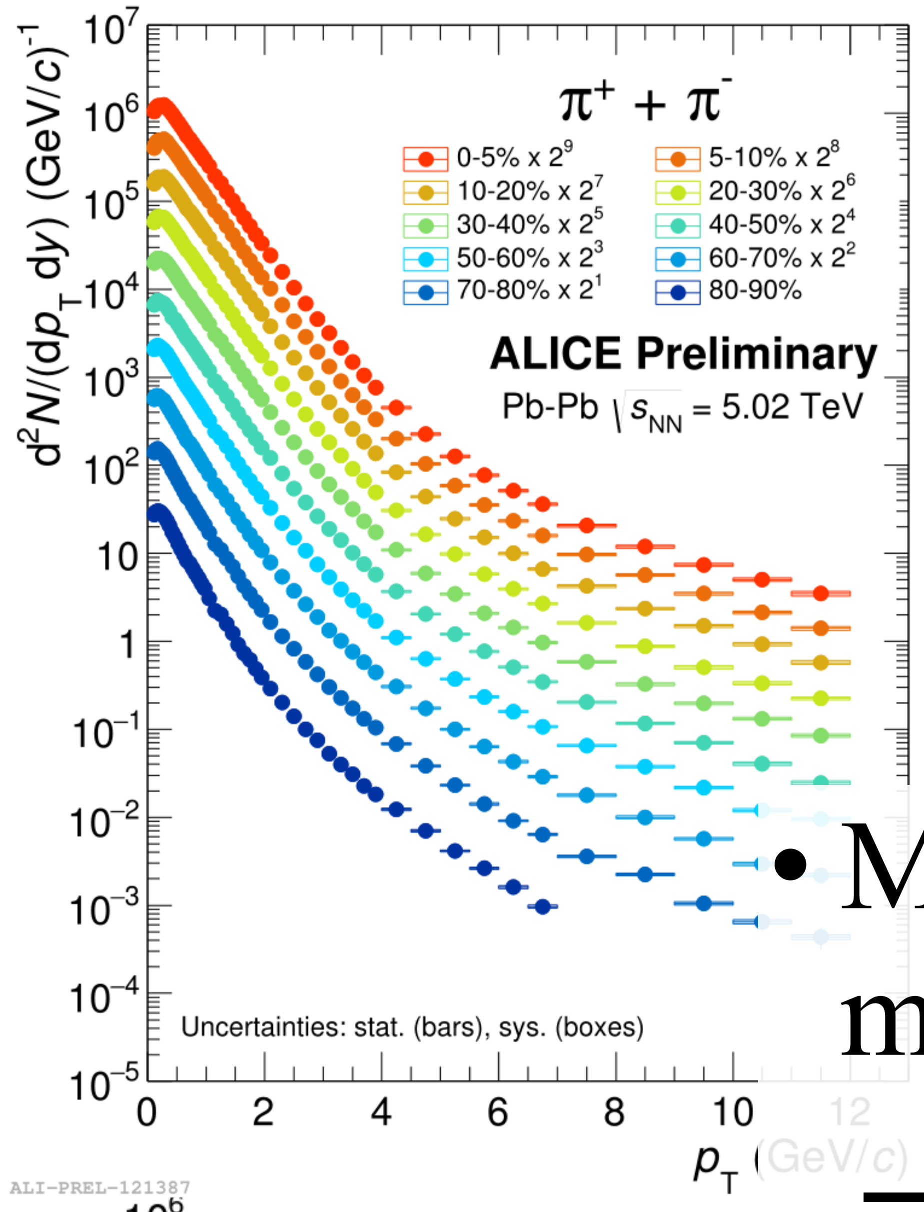
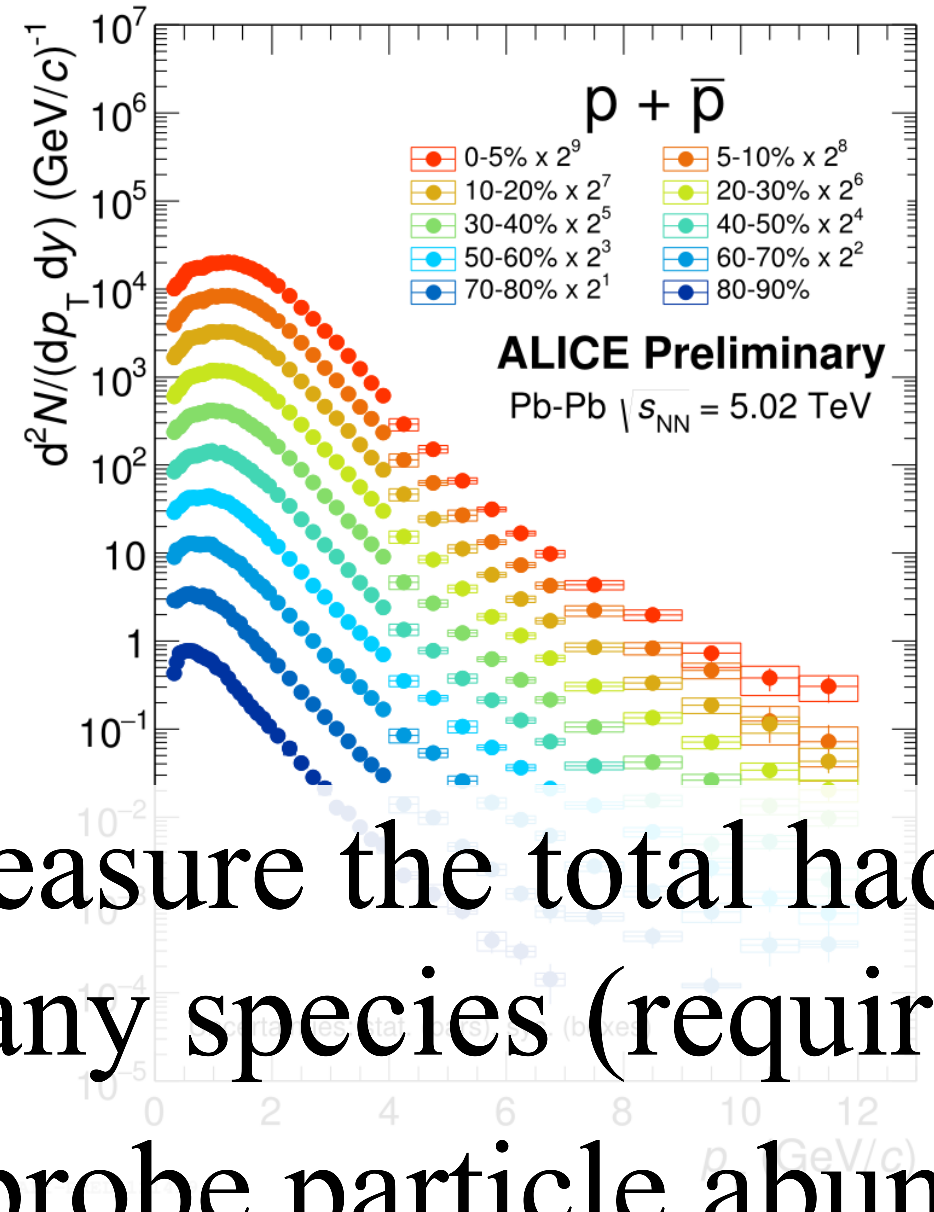
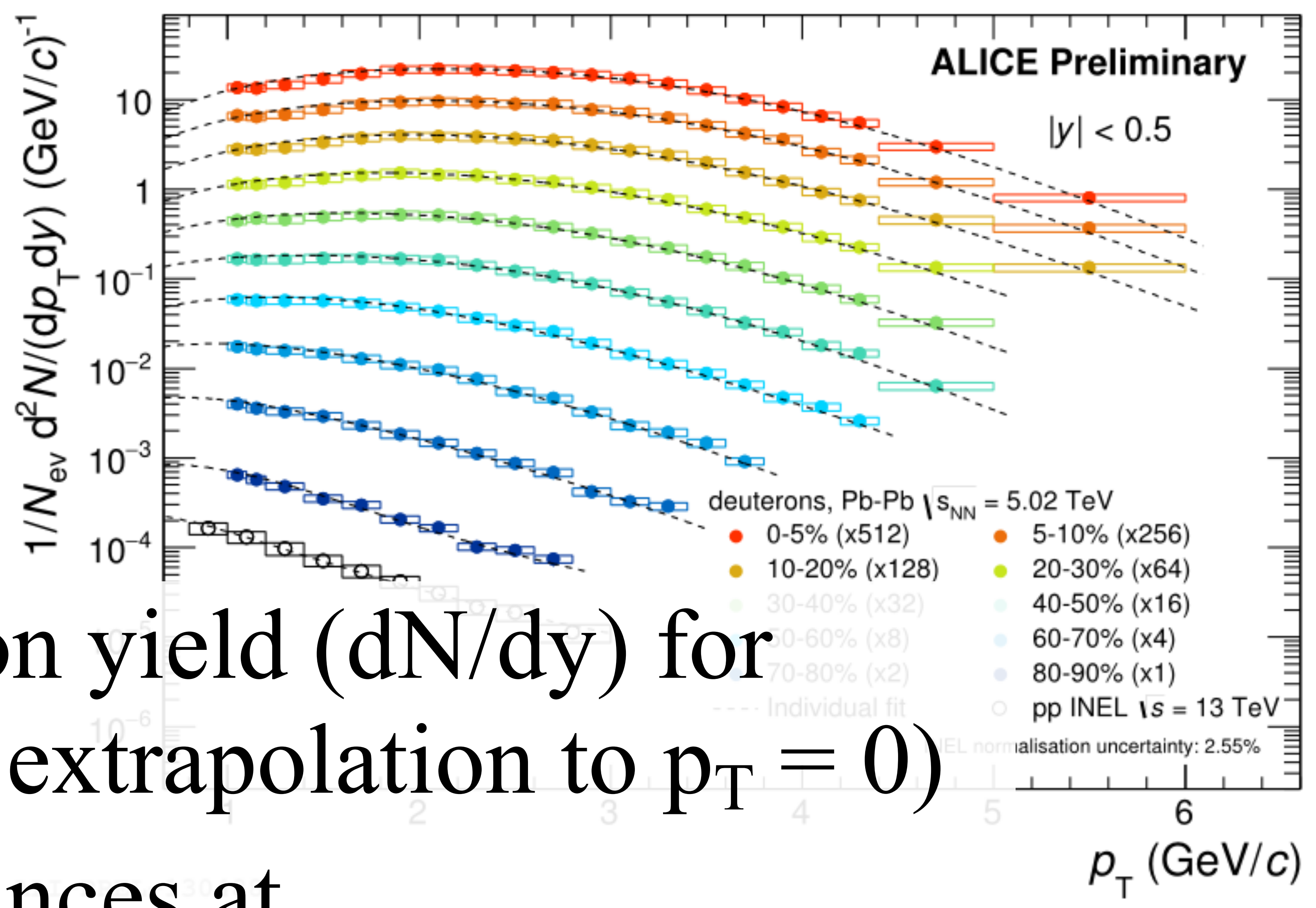
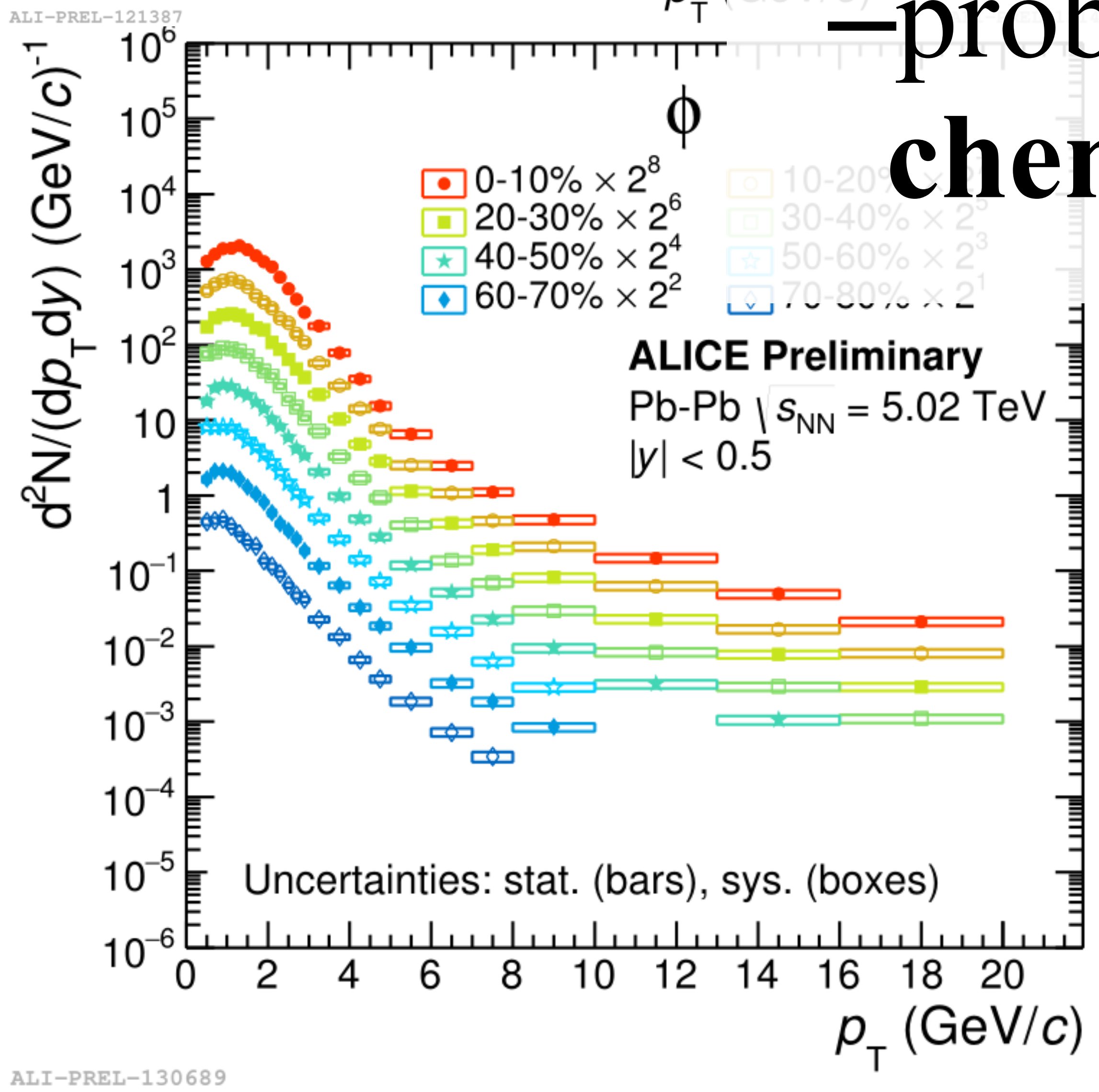
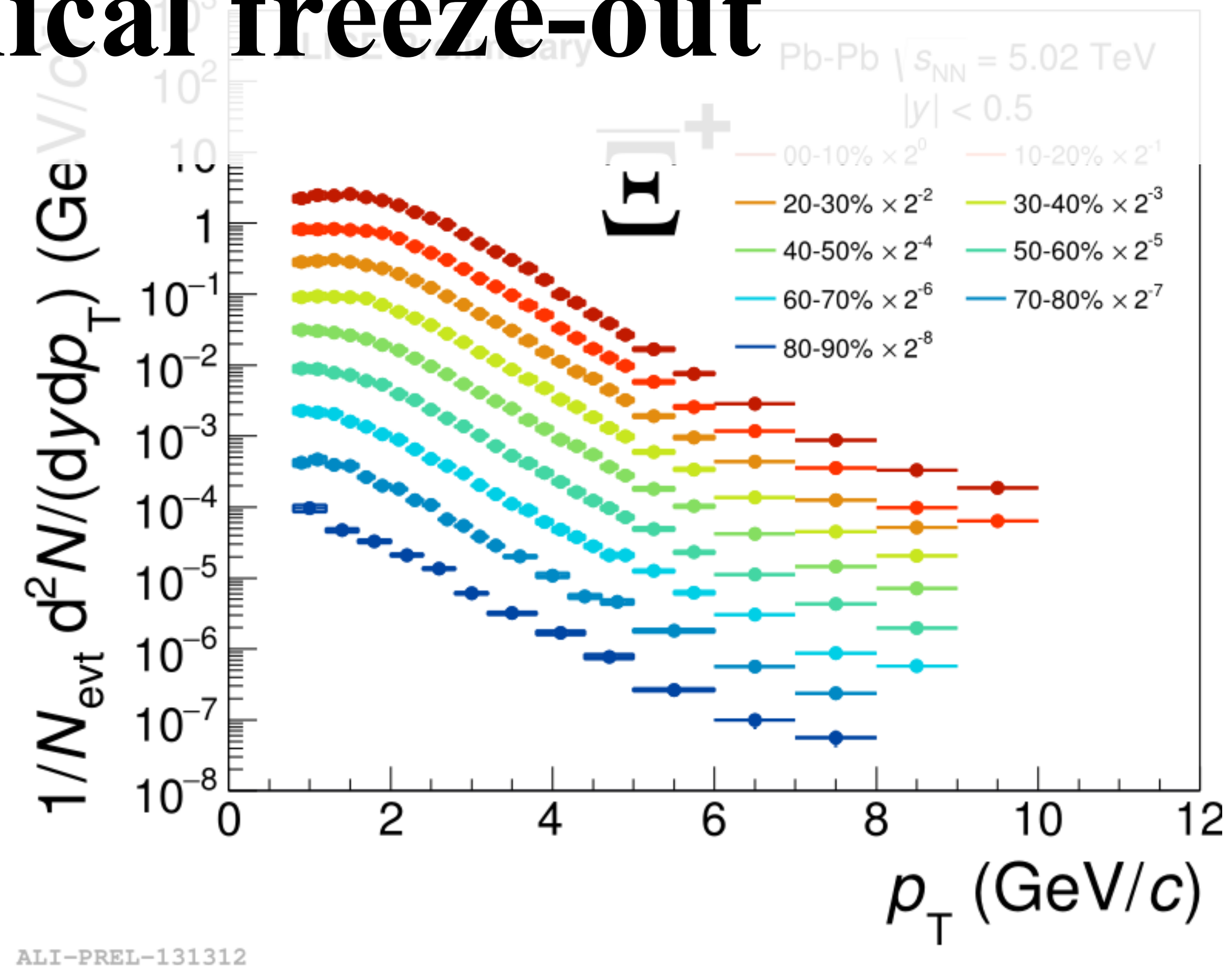


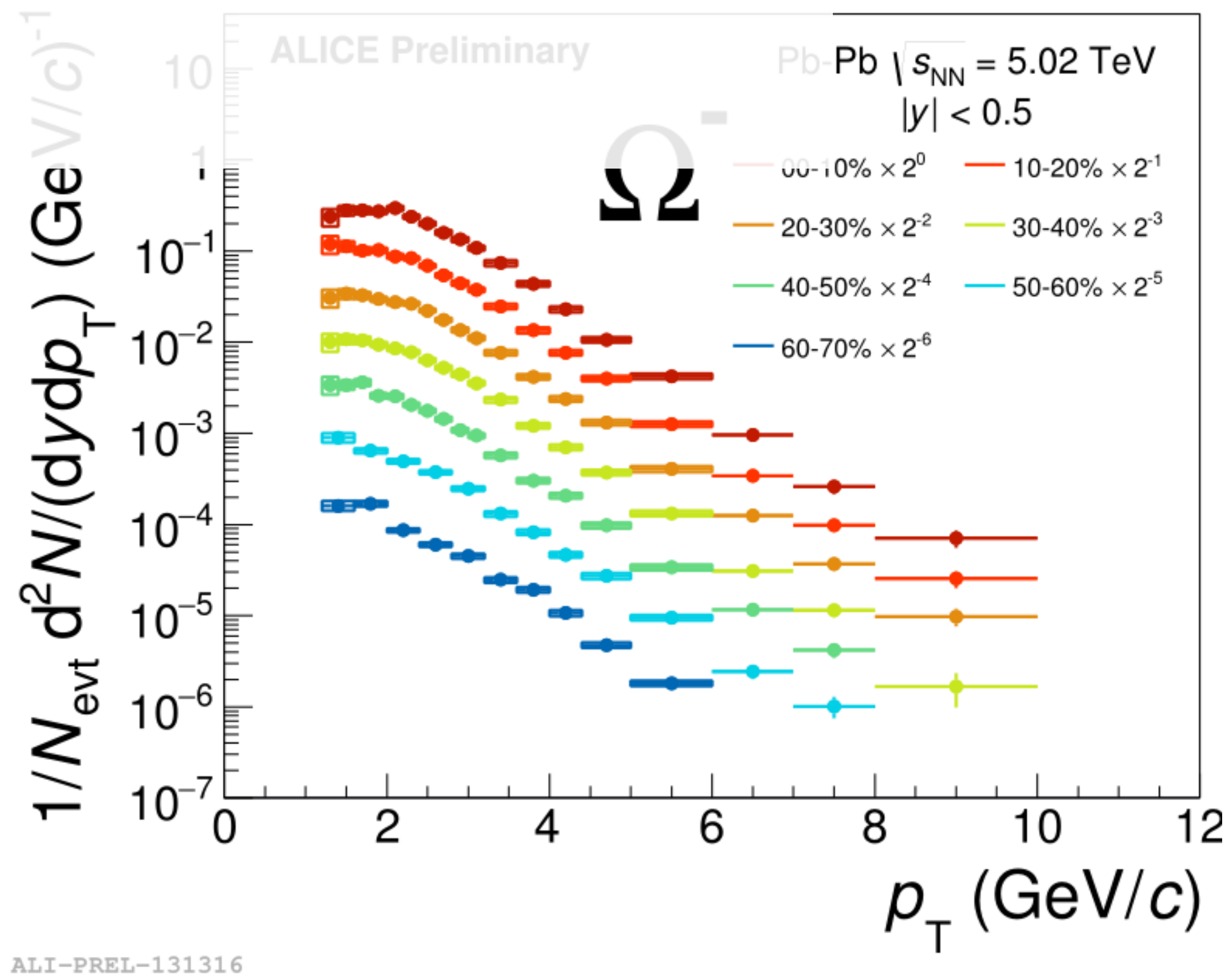




- Measure the total hadron yield (dN/dy) for many species (requires extrapolation to $p_T = 0$)
  - –probe particle abundances at **chemical freeze-out**

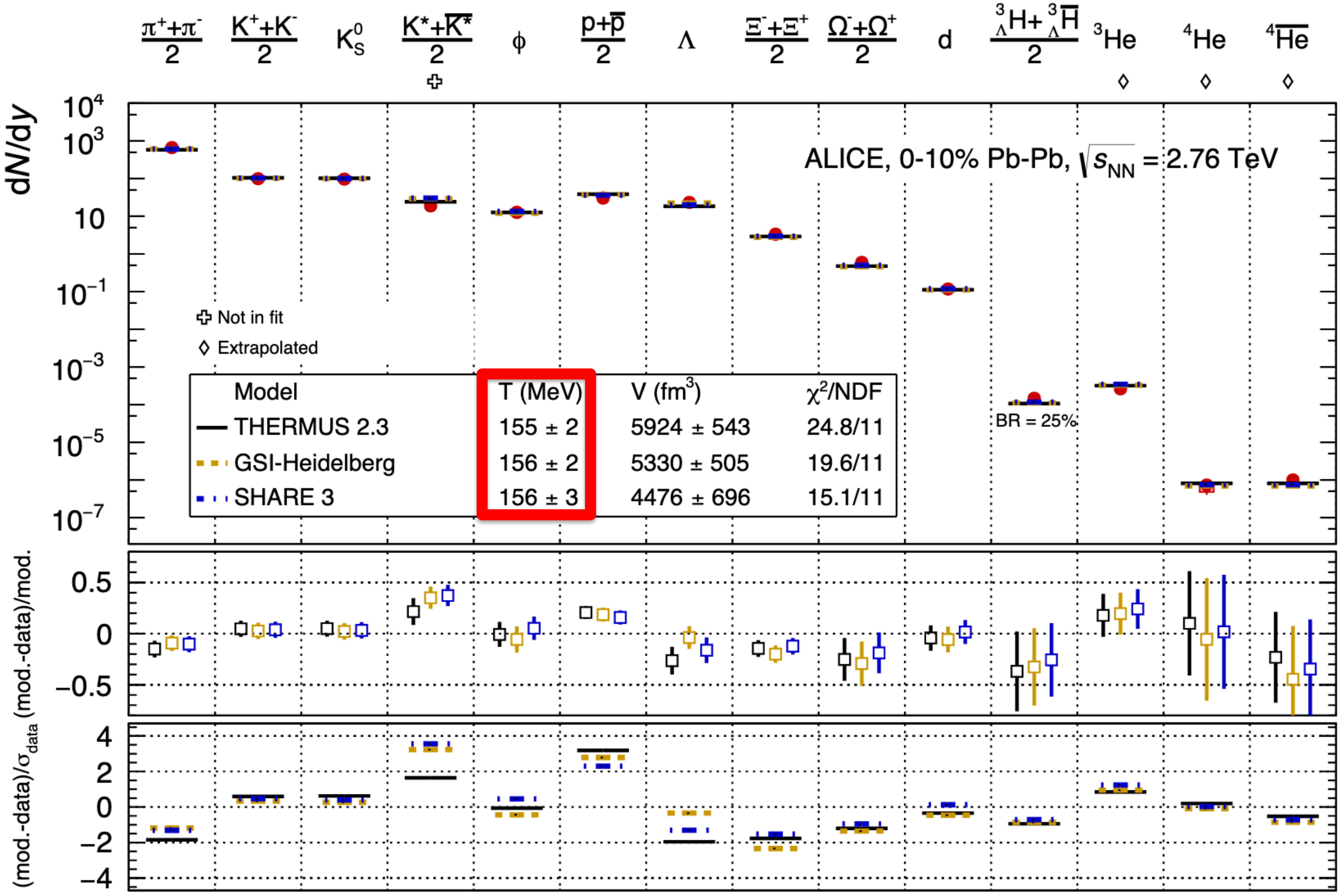






Statistical model of particle production

- 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



ALICE, Nucl. Phys. A 971 (2018) 1, arXiv:1710.07531 [nucl-ex]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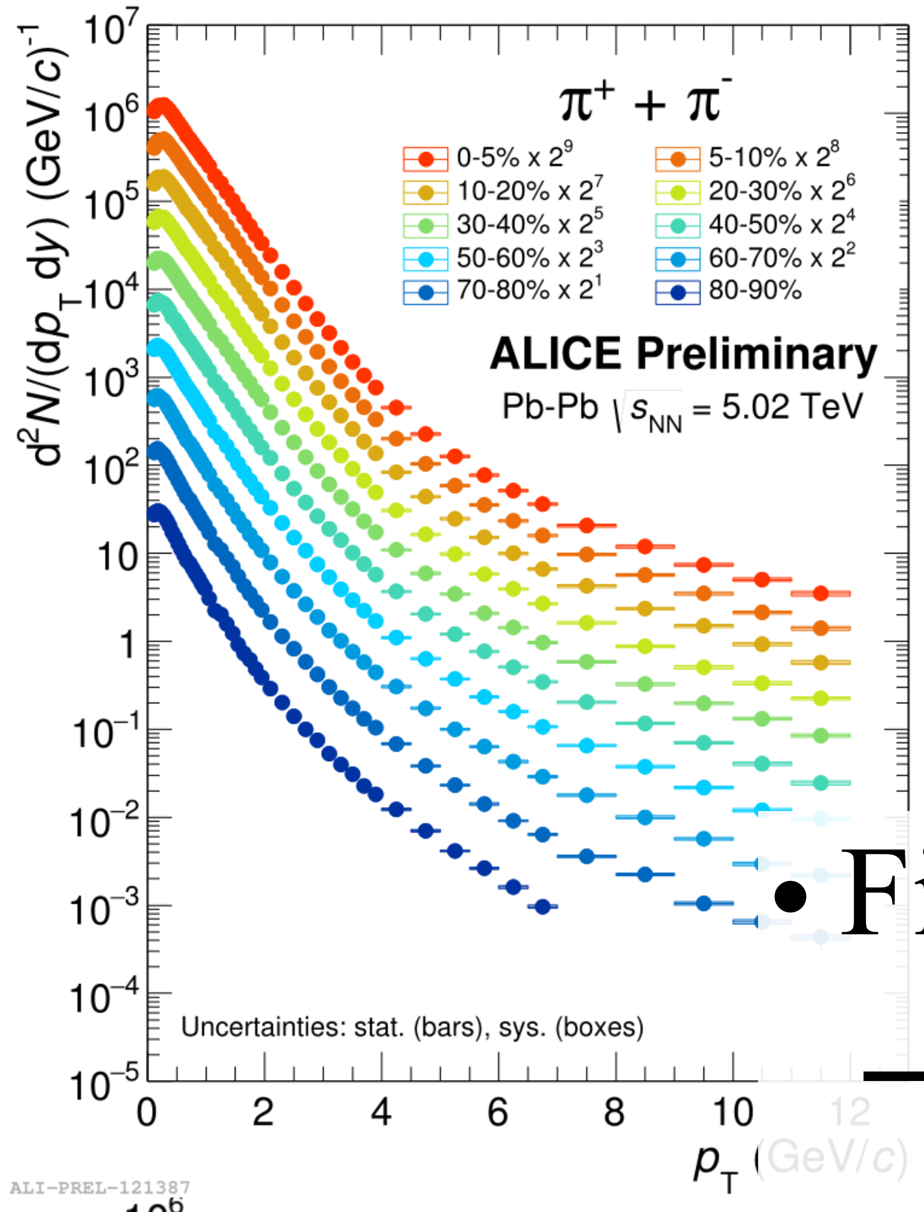
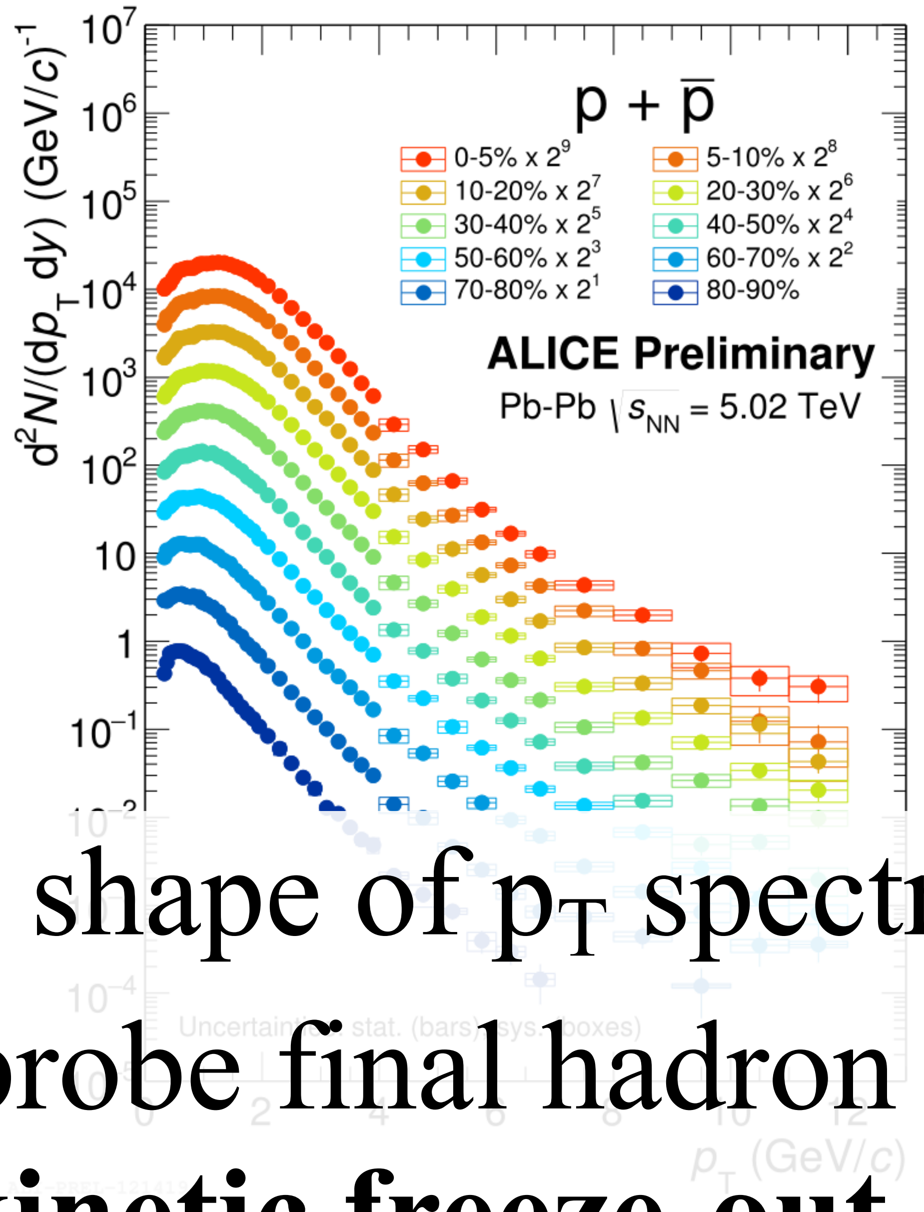
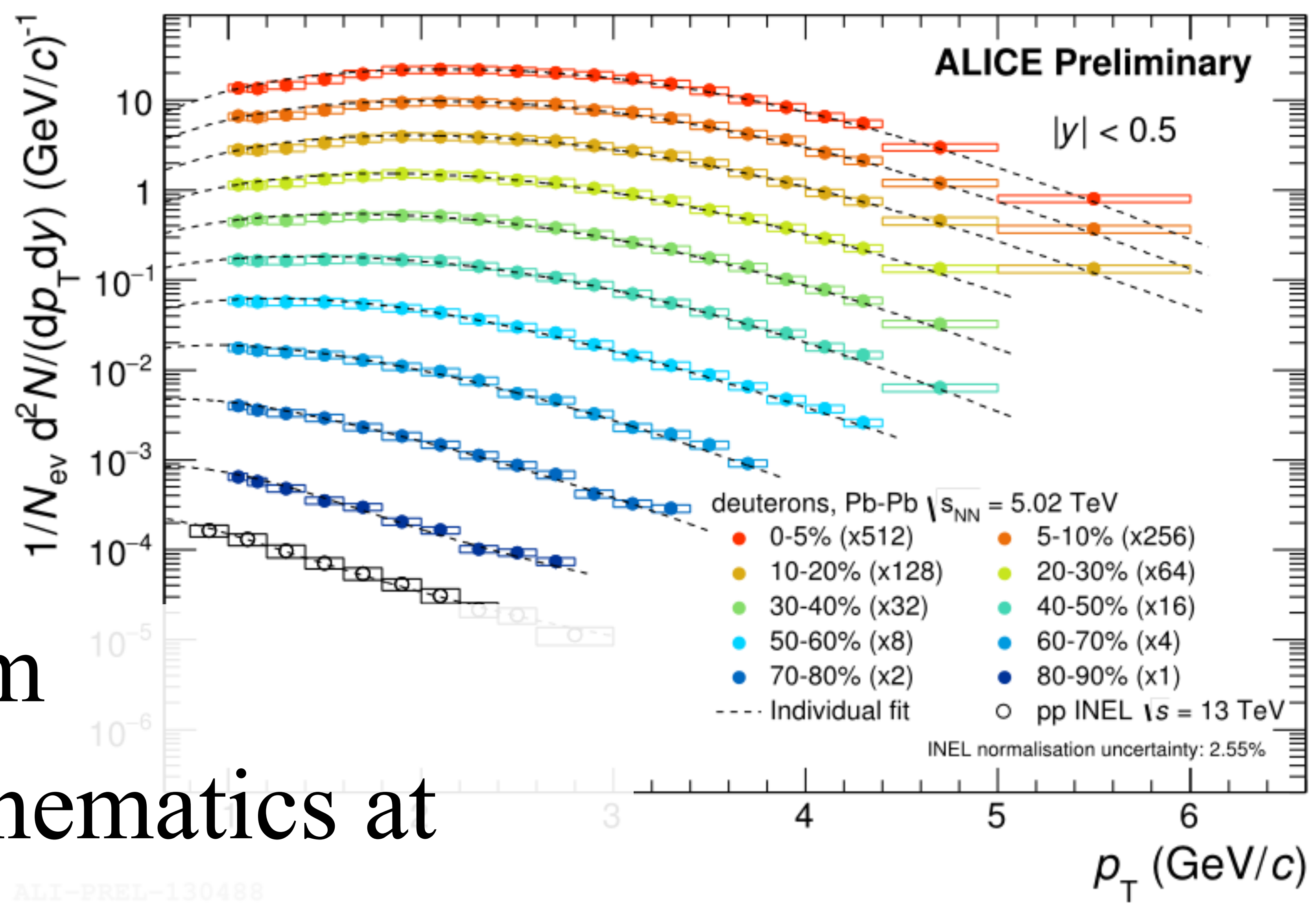
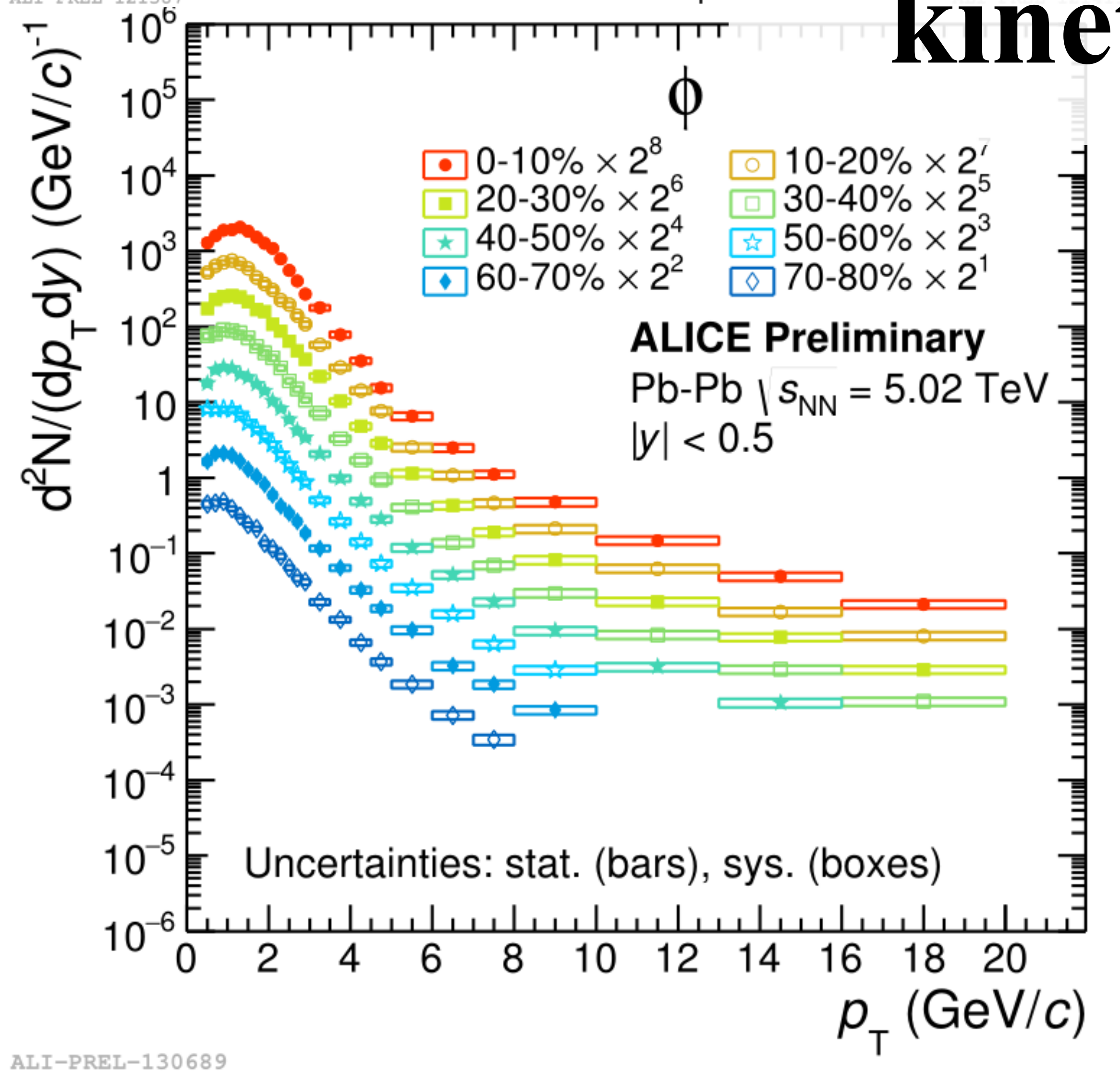
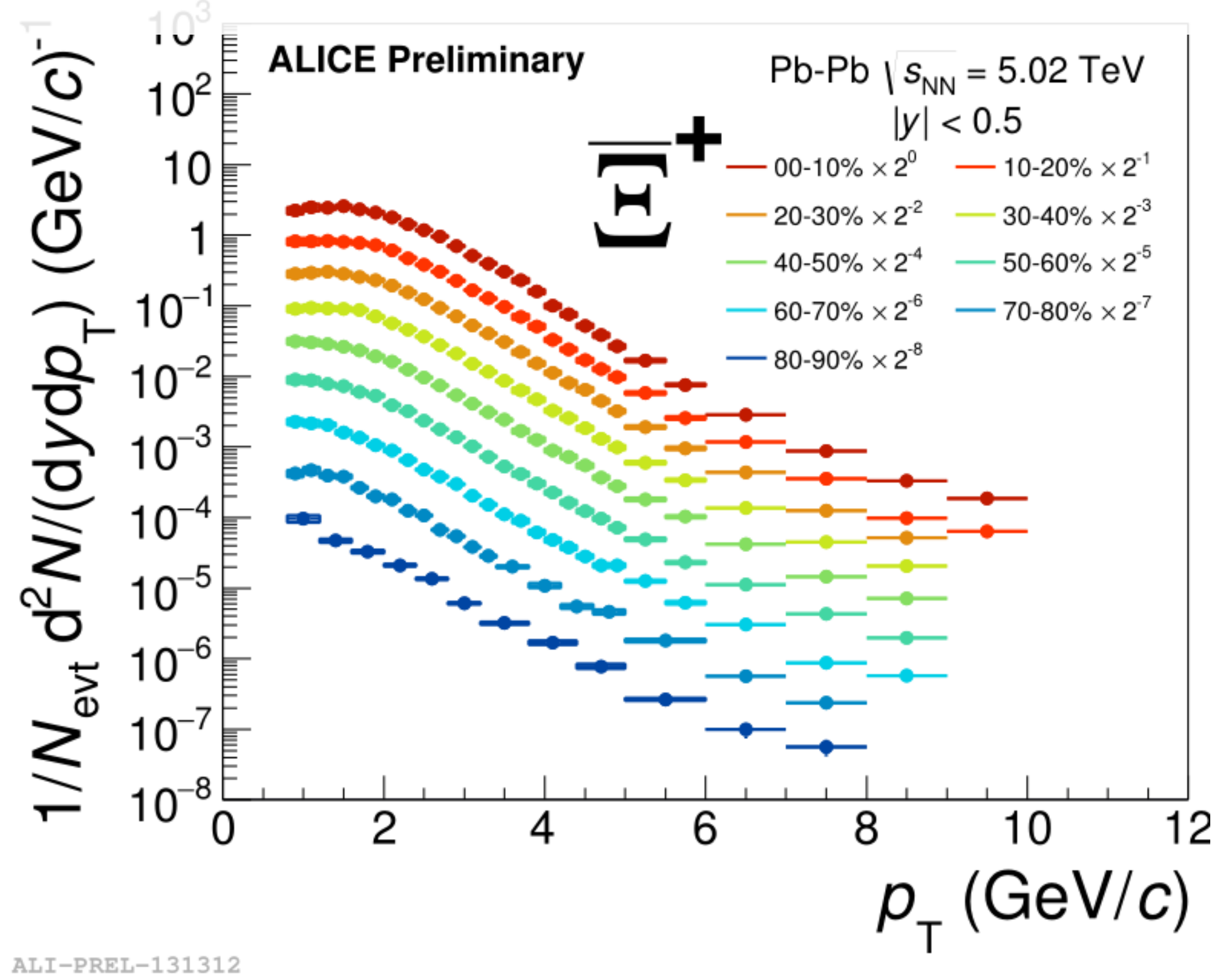


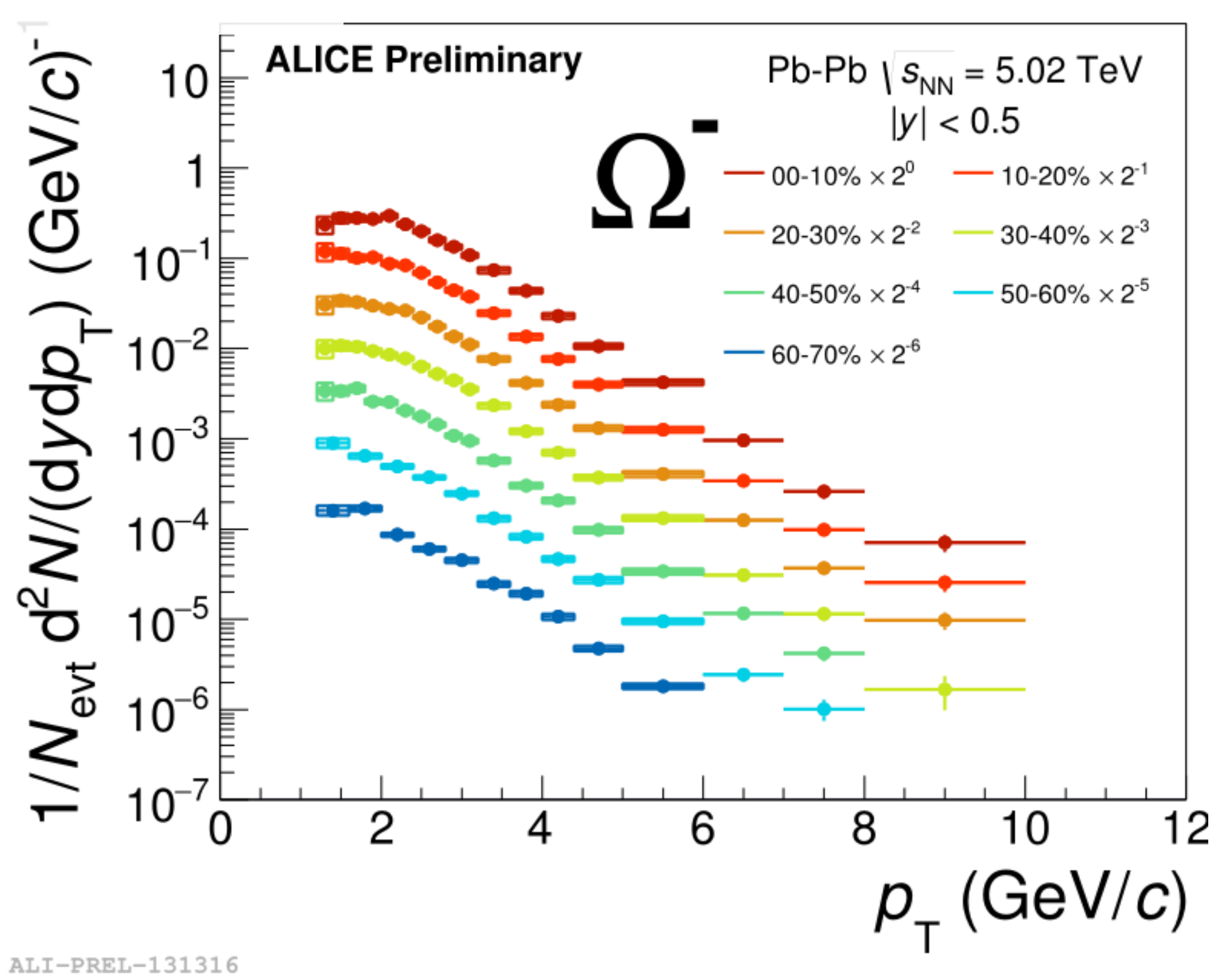




- Fit shape of p_T spectrum
  - –probe final hadron kinematics at **kinetic freeze-out**

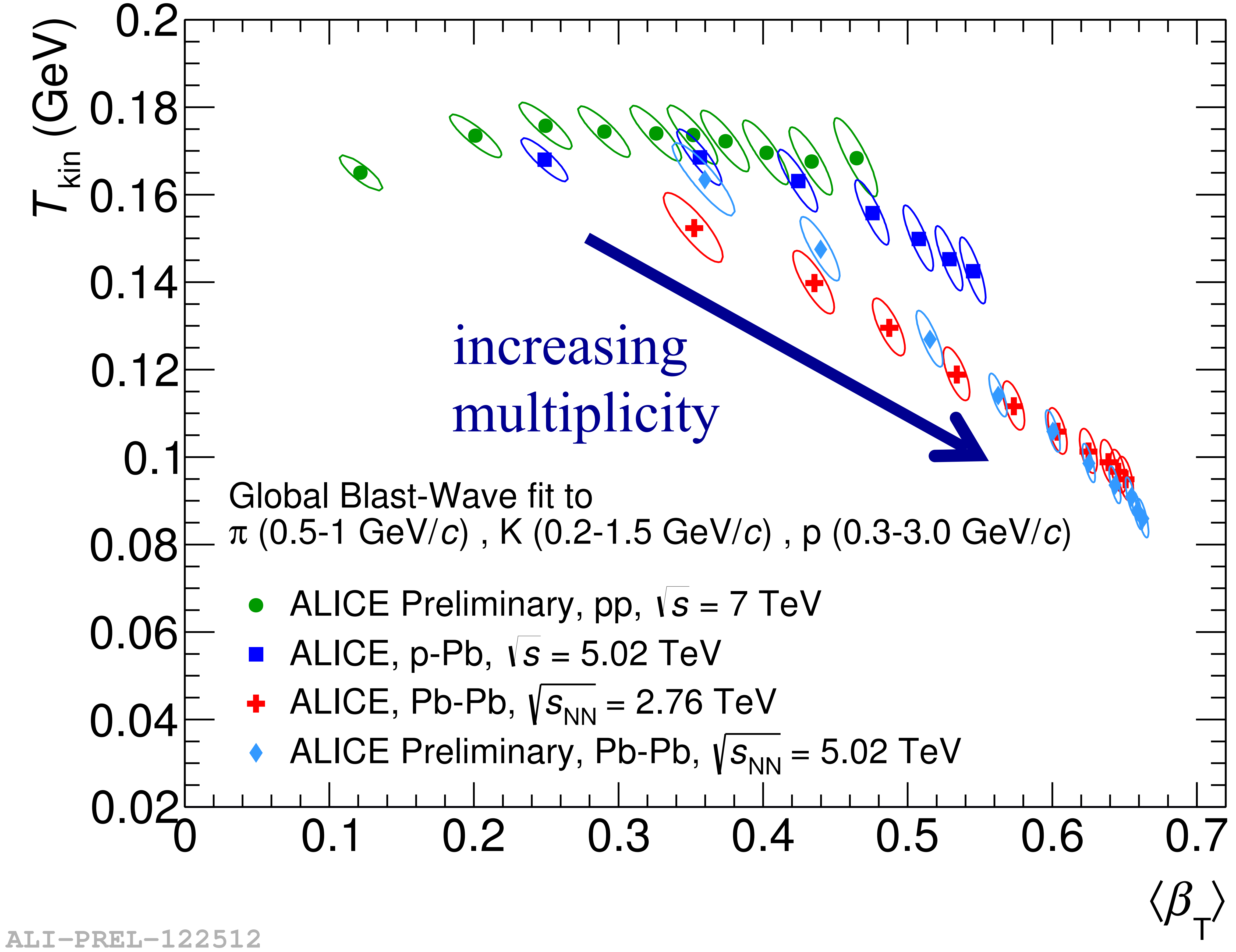






Kinematics – freeze-out parameters

- 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}

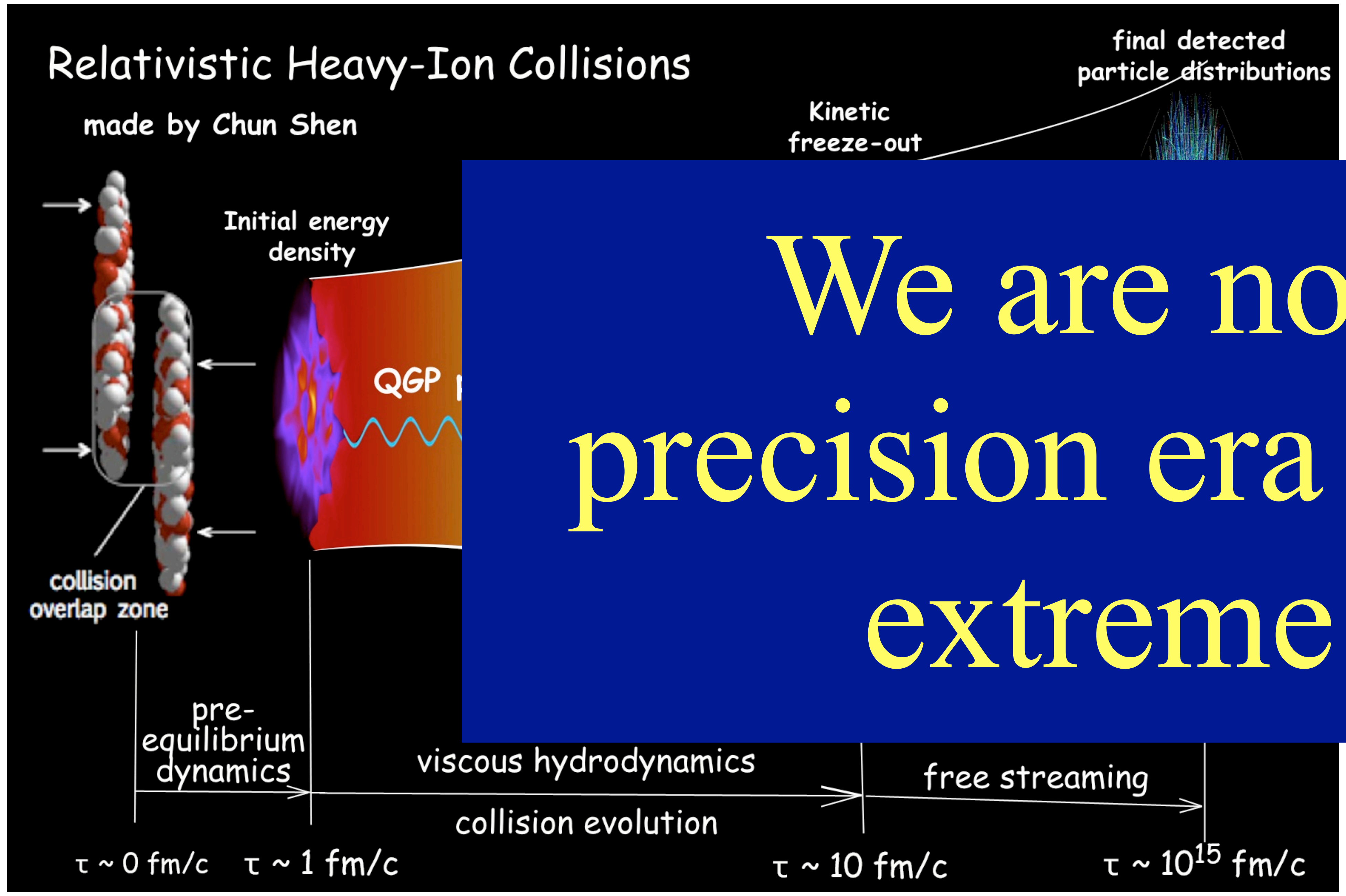


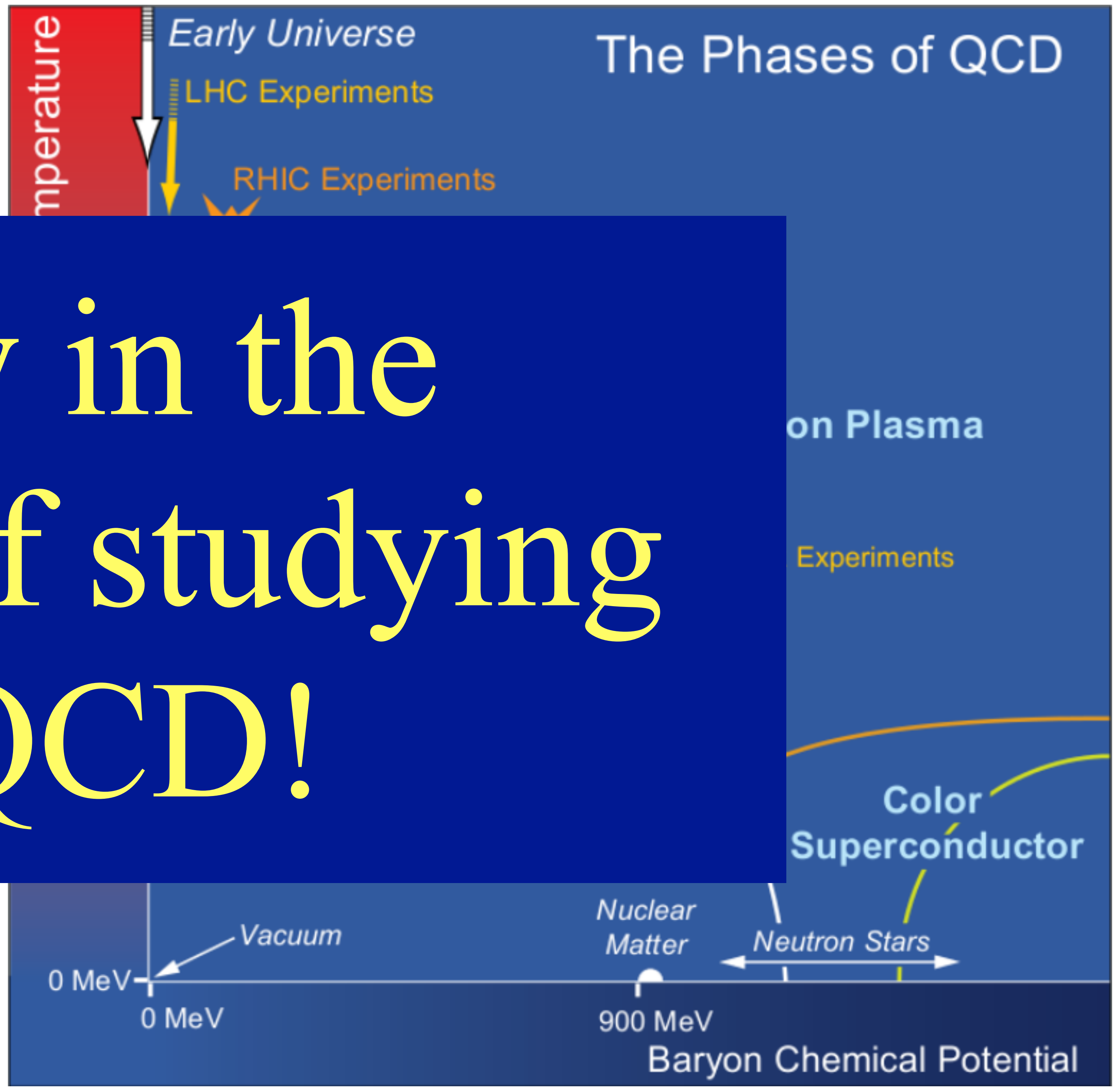
ALI-PREL-122512

- More central (higher multiplicity) events have lower T_{kin} and higher expansion rate

Conclusions

- Properties of the quark-gluon plasma:
  - strong quenching of colored probes ($\hat{q}$)
  - collective behavior with very low shear viscosity (η/s)
  - high temperatures, mostly statistical particle production (T_{chem}, T_{kin})
  - susceptibilities give information about the phase transition (χ)





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

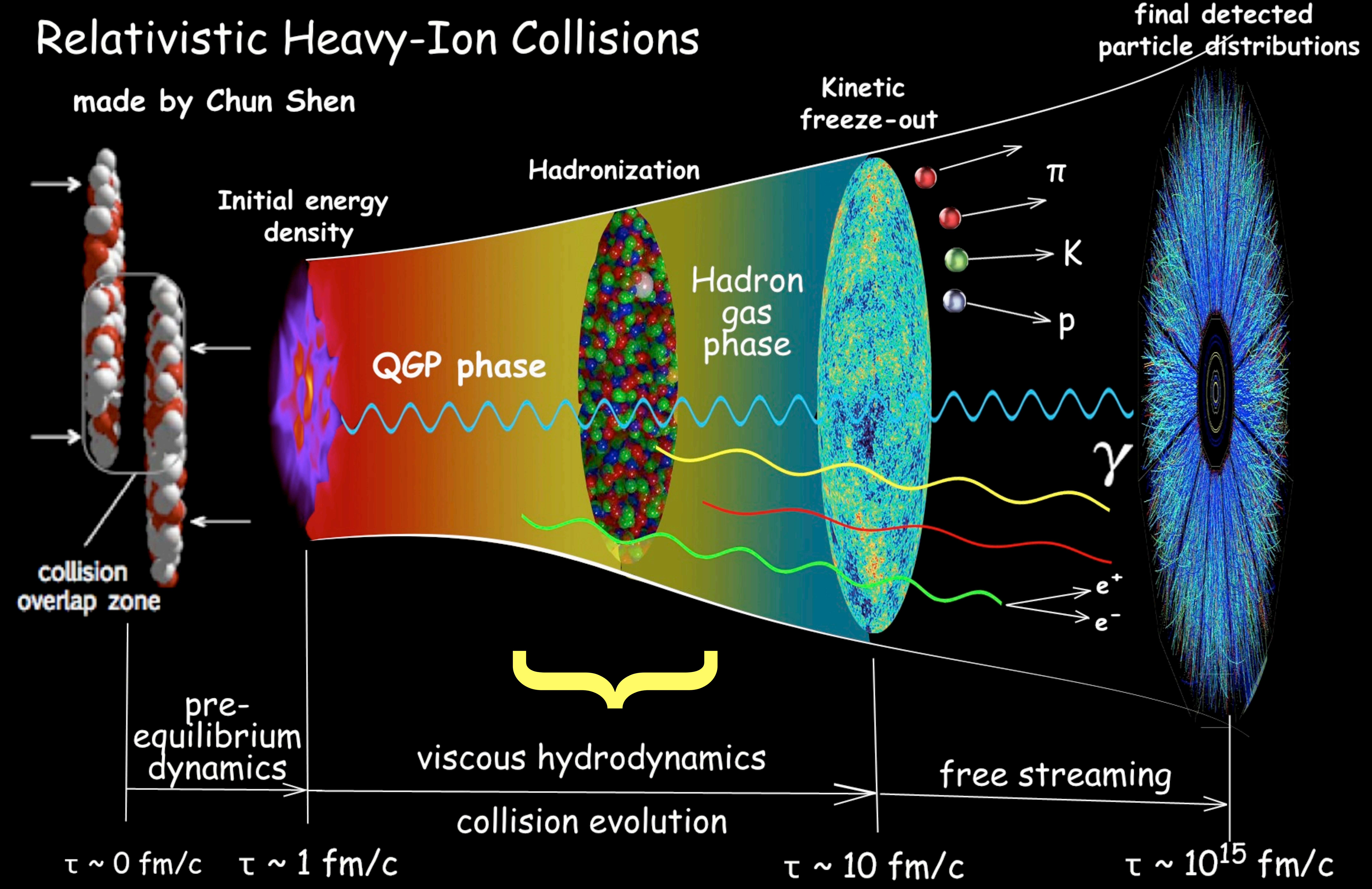
Exploring the phase diagram of nuclear matter with fluctuations in heavy-ion collisions

Alice Ohlson
Lund University, Sweden

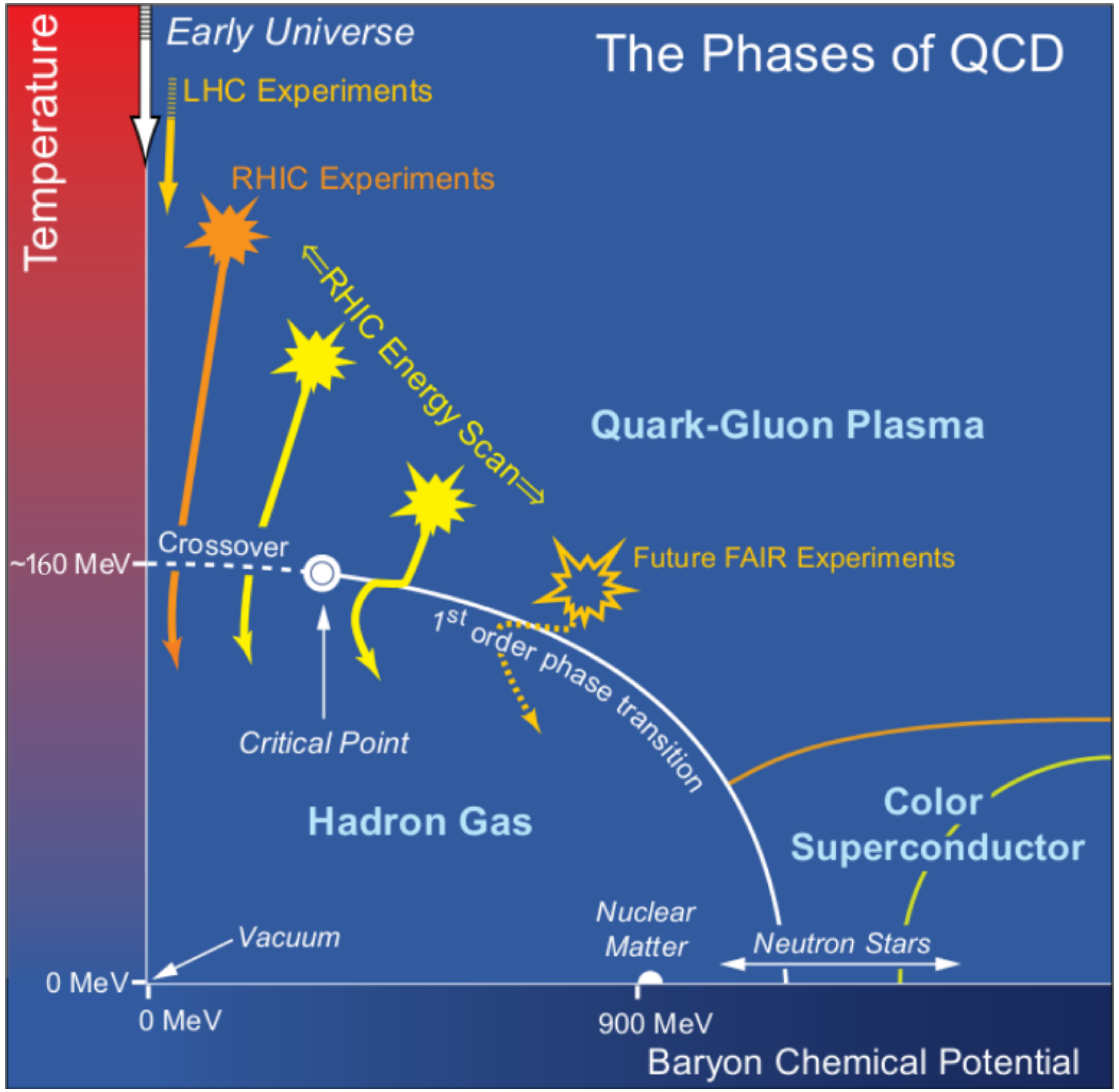
November 30, 2020

Relativistic Heavy-Ion Collisions

made by Chun Shen

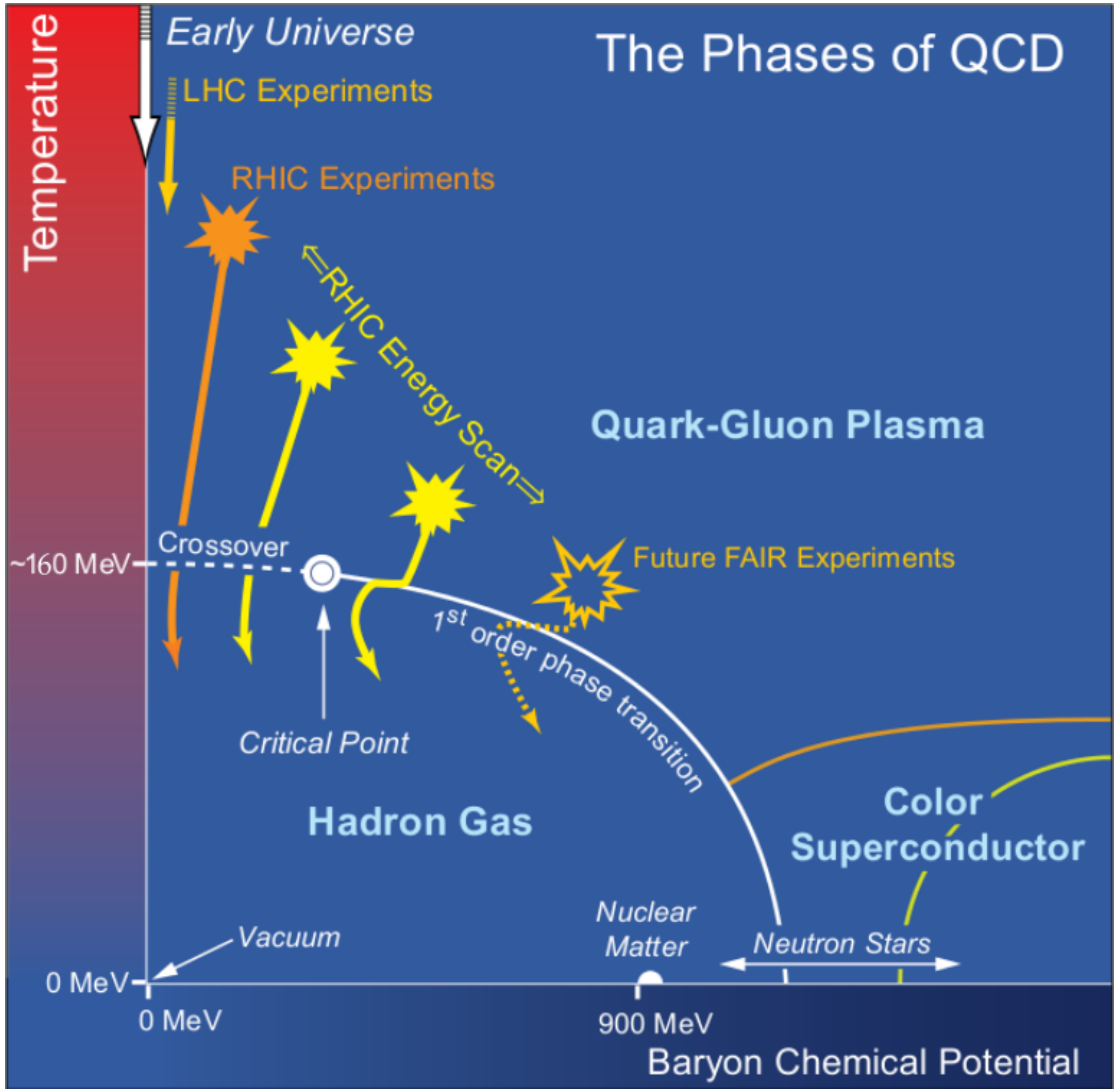


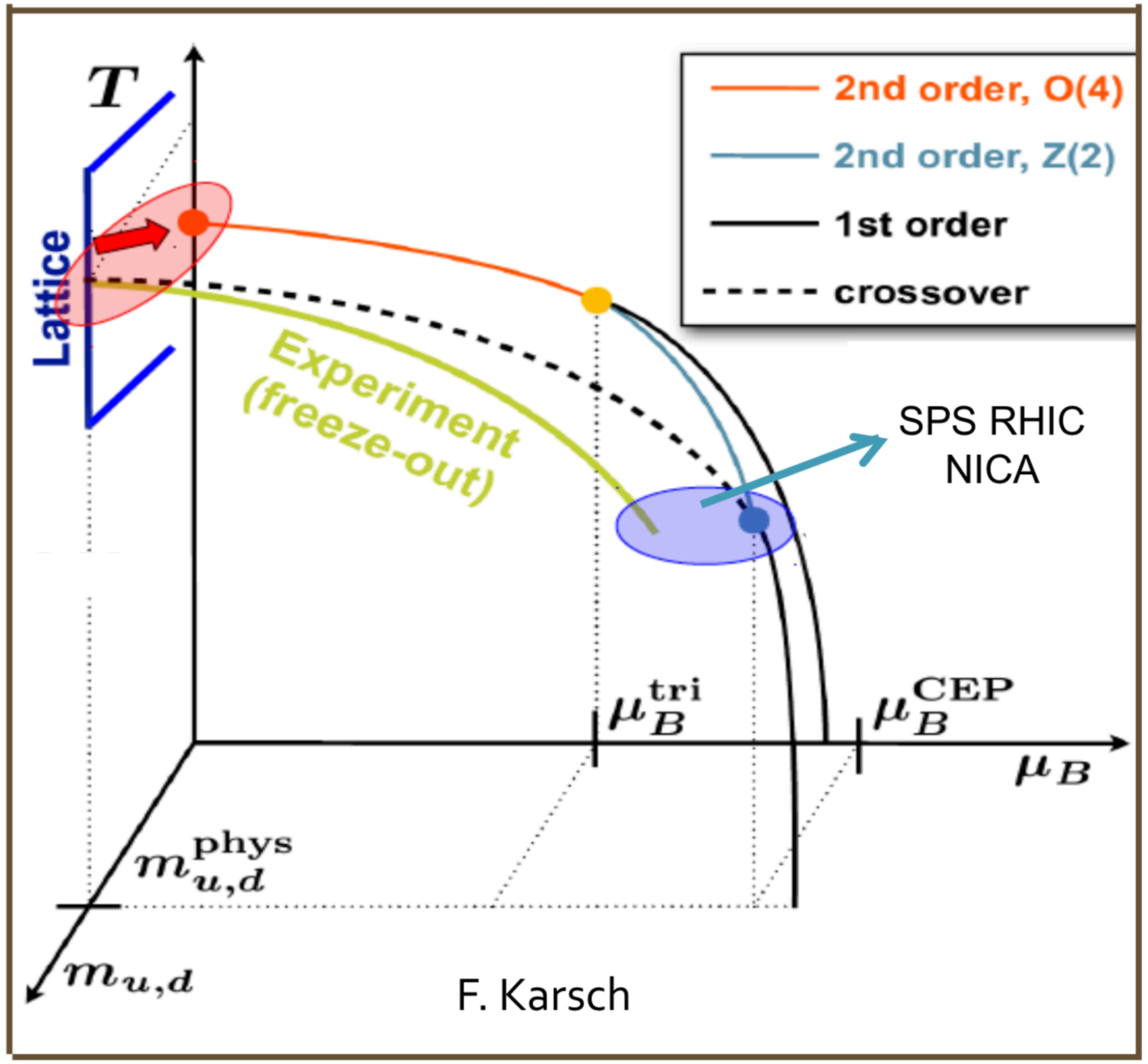
Phase structure of nuclear matter



- At low $\mu_B \rightarrow$ Cross-over transition between deconfined QGP phase and confined hadron gas phase
- At higher $\mu_B \rightarrow 1^{st}$ order phase transition
- In between → critical point?

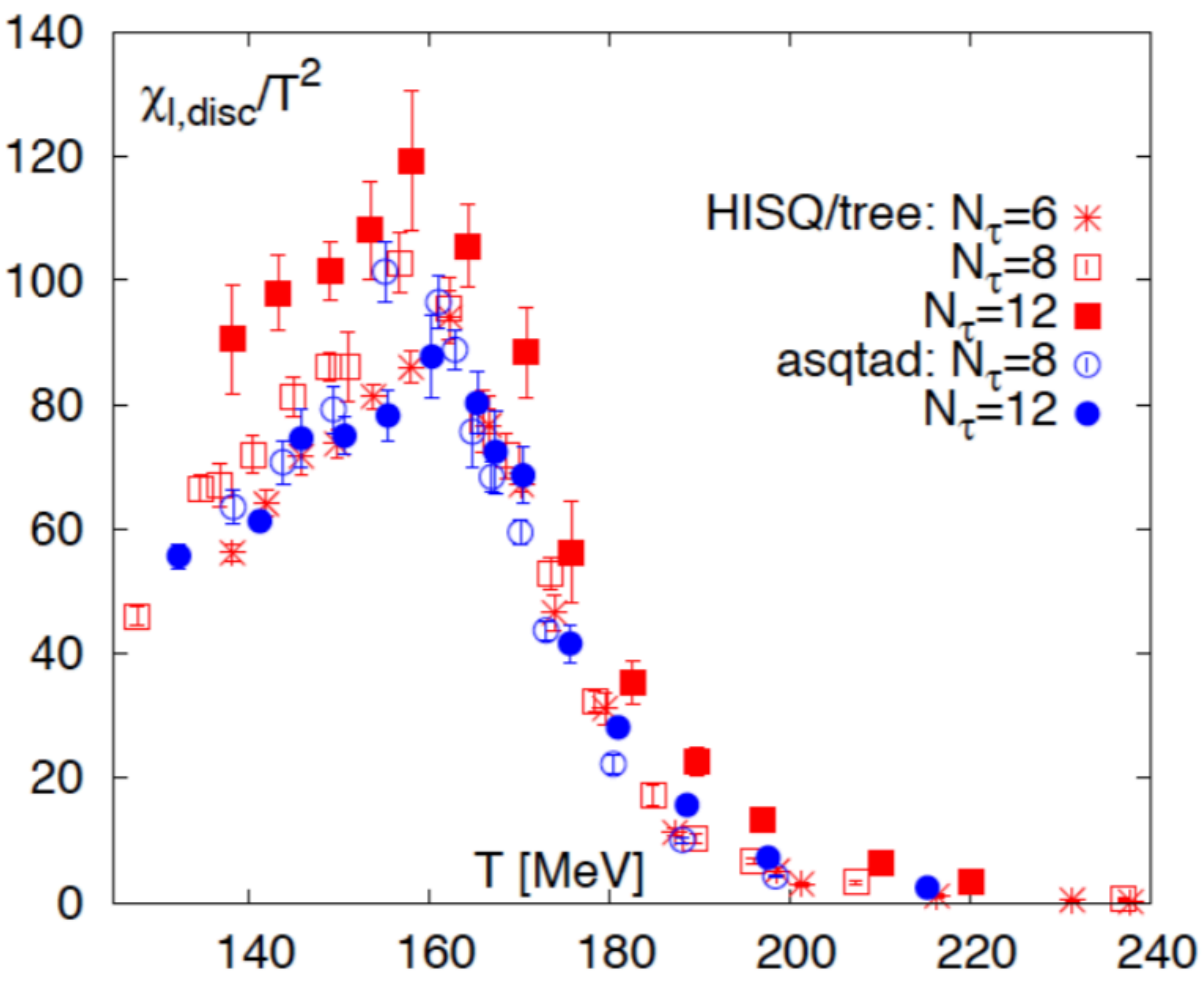
Phase structure of nuclear matter





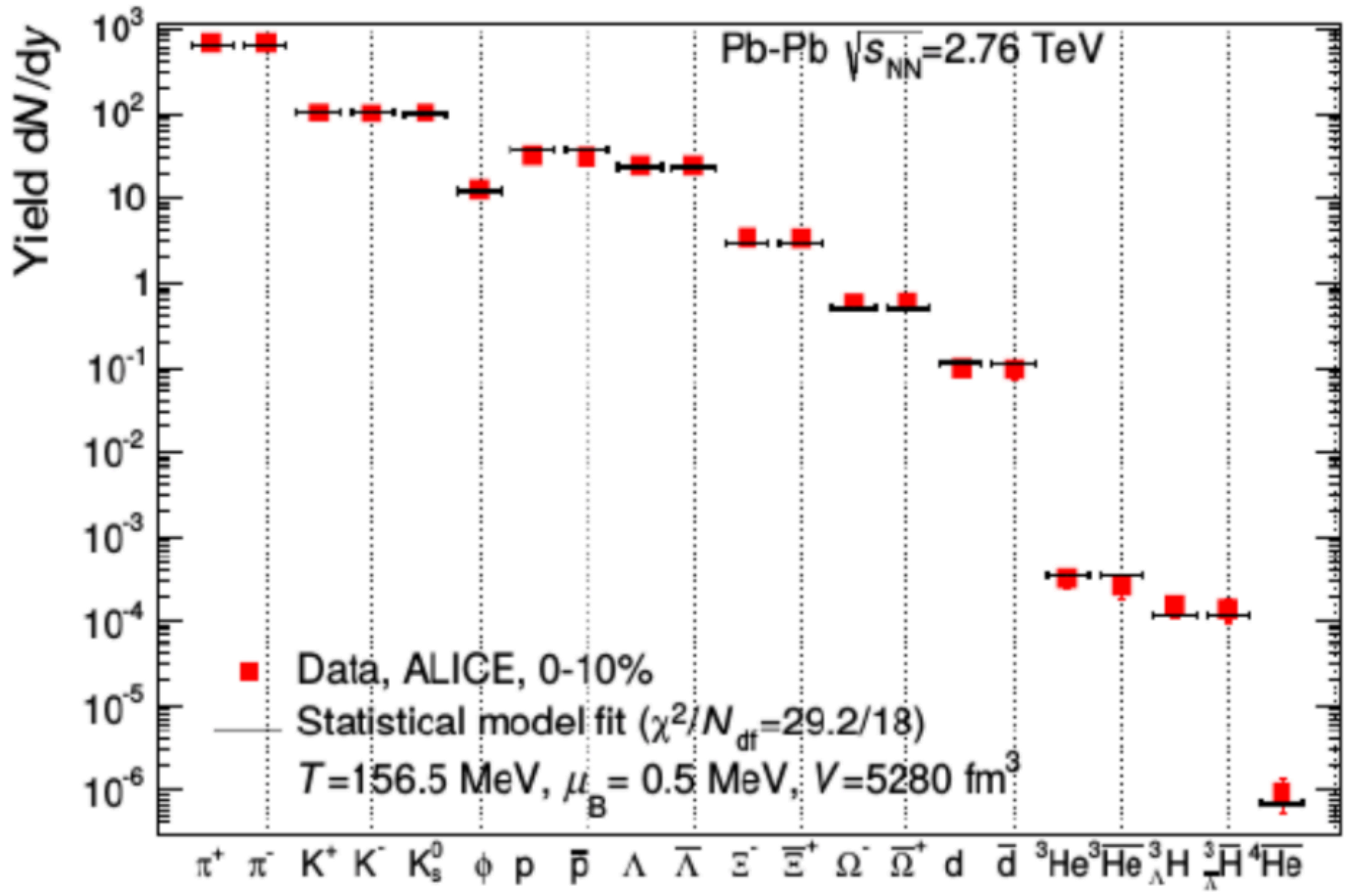
- Small u, d quark masses → proximity to O(4) second order phase transition → pseudocritical features may be observable

Where does the phase transition occur?



A. Bazavov et al. (HotQCD Collaboration), Phys. Rev. D 85 (2012) 054503

T_{pc} = 156.5 ± 1.5 MeV



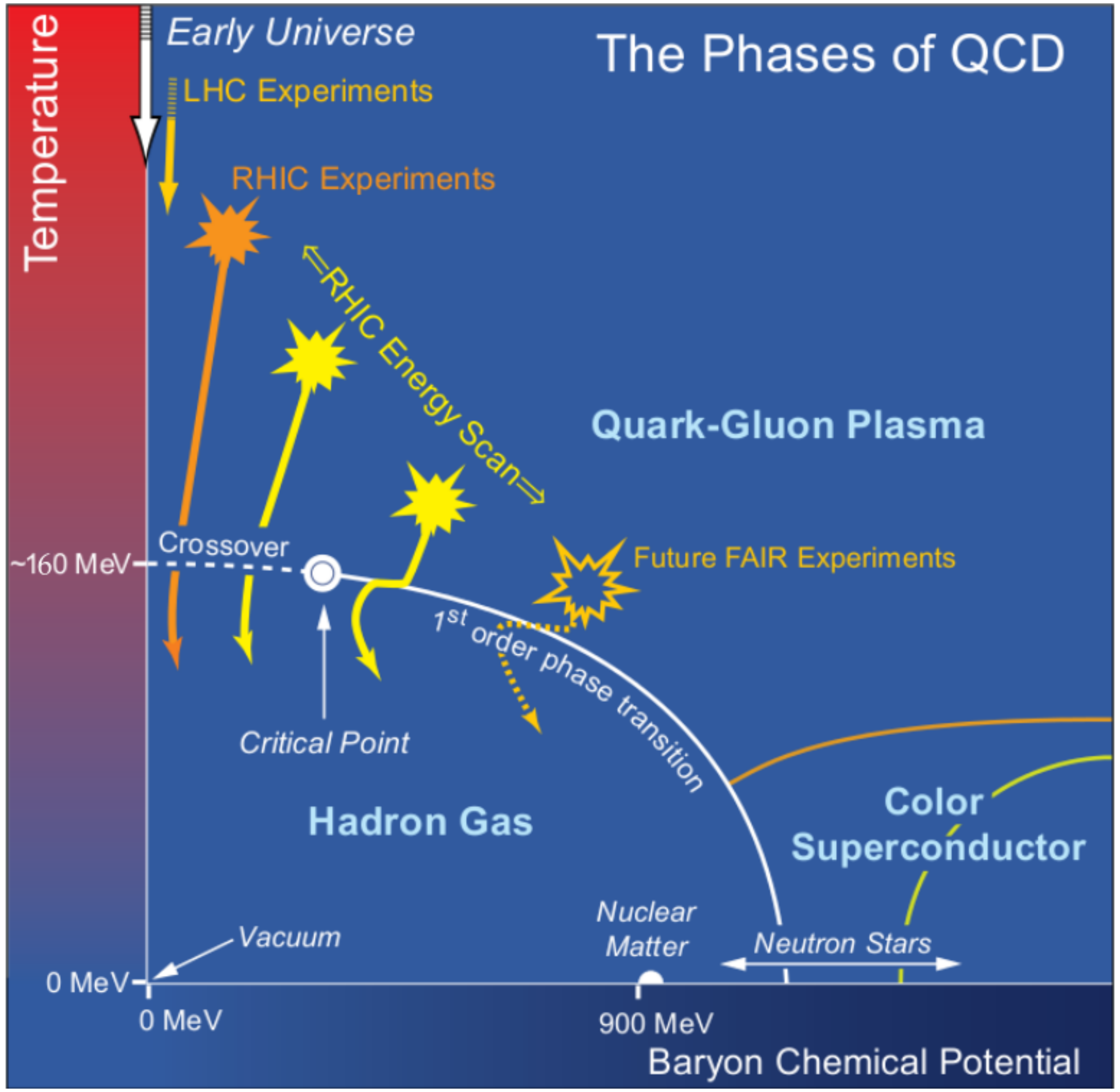
T_{fo} = 156.5 ± 3 MeV

A. Andronic et al. Nature 561 (2018) 321

- Theoretical prediction for the phase boundary temperature coincides with hadronic freeze-out (T_{chem})!
- Look for signatures of the phase transition encoded in the final state hadron yields

Fluctuations in heavy-ion collisions

- Event-by-event fluctuations of particle multiplicities are used to study properties and phase structure of strongly-interacting matter



- Fluctuations grow in the region near a phase transition and/or critical point
  - Can we observe signs of criticality?

Critical opalescence in CO_2

J.V. Sengers, A.L Sengers, Chem. Eng. News, June 10, 104–118, 1968

$T > T_c$ $T >\sim T_c$ $T <\sim T_c$ $T < T_c$

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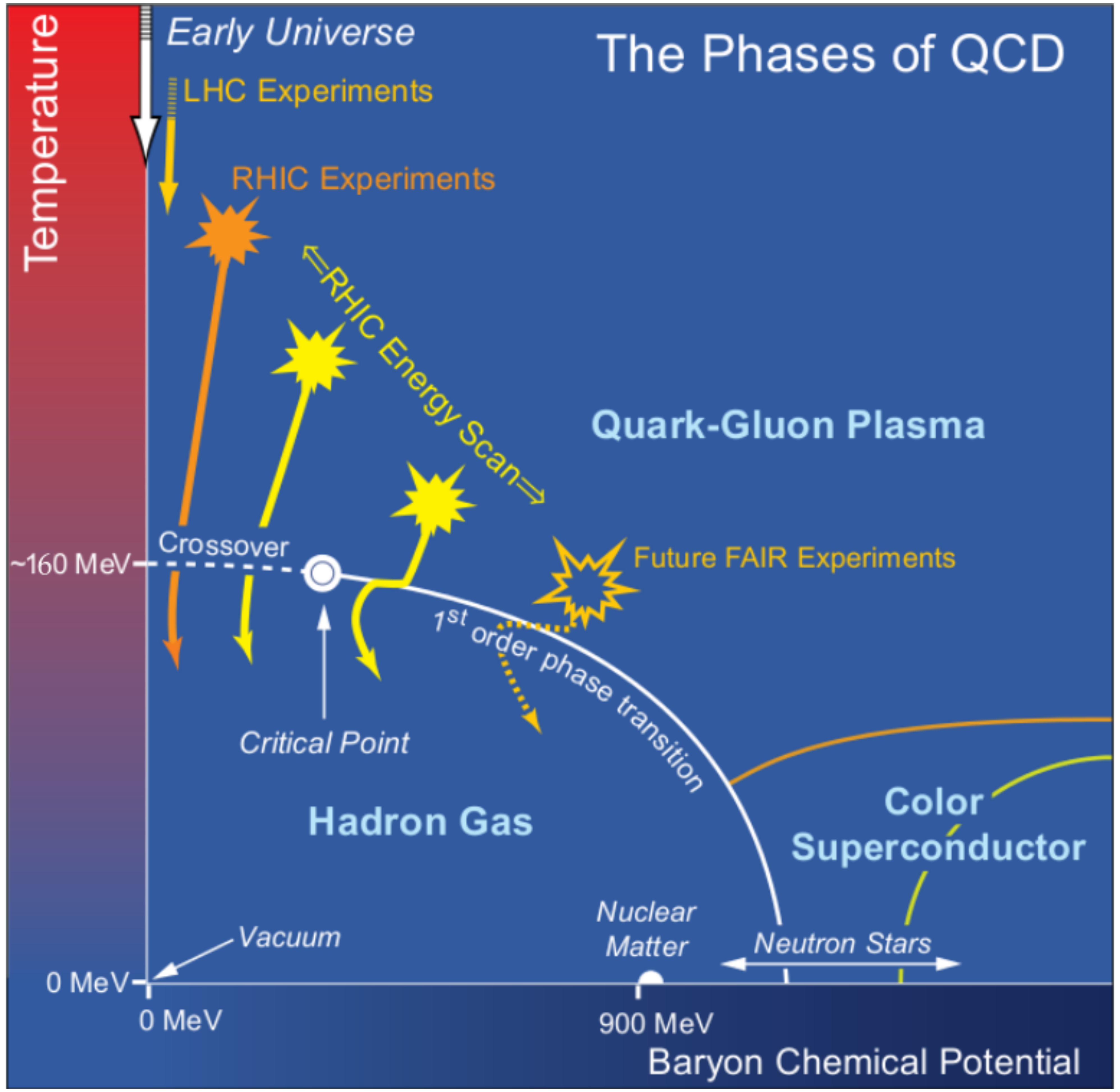


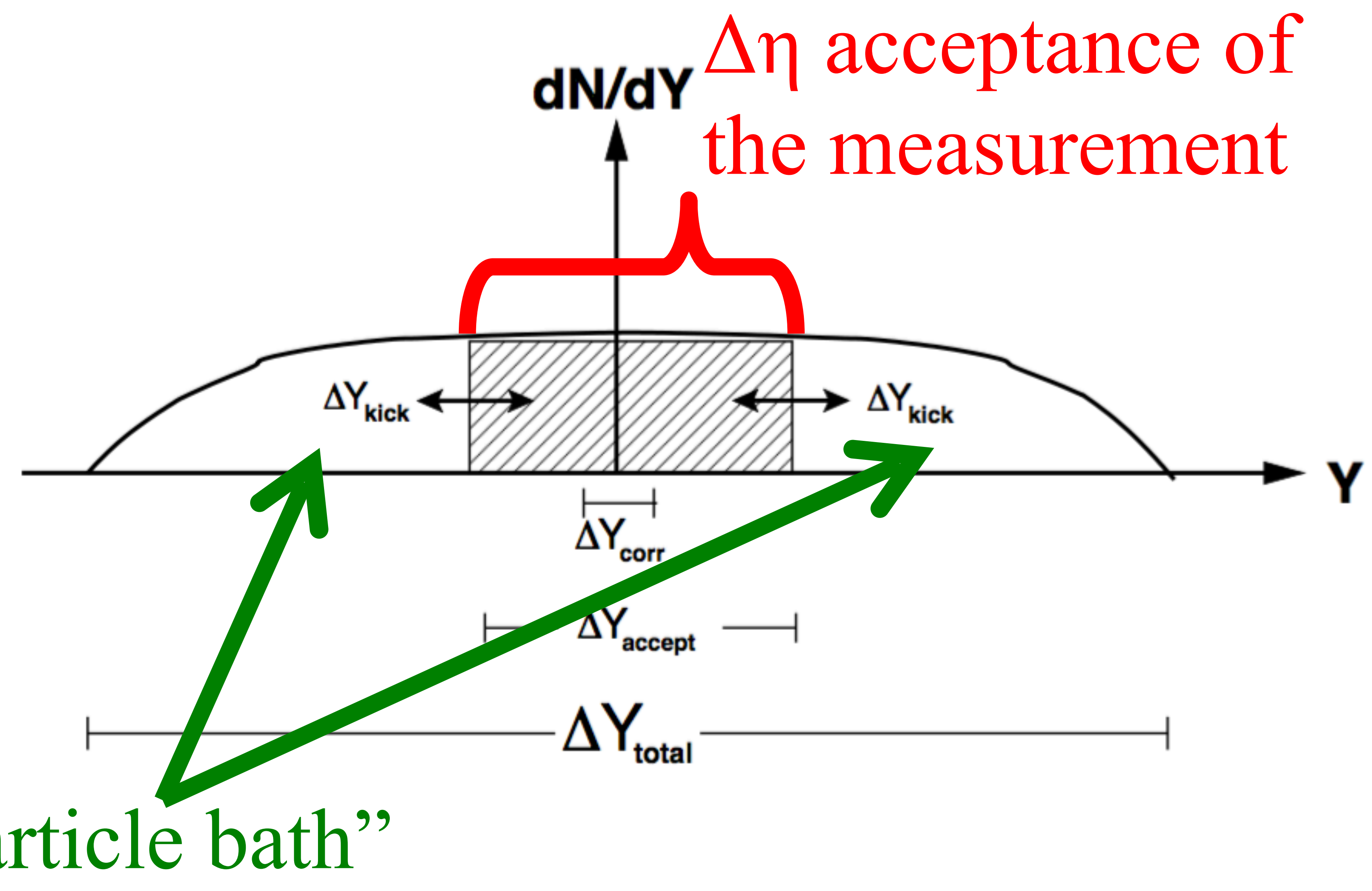
- Fluctuations grow in the region near a phase transition and/or critical point
  - Can we observe signs of criticality?
- Fluctuations of conserved charges can be related to susceptibilities calculable in lattice QCD
  - Precision test of LQCD at $\mu_B \approx 0$

Connecting theory to experiment

- Thermodynamic susceptibilities χ
  - describe the response of a thermalized system to changes in external conditions, fundamental properties of the medium
  - can be calculated within lattice QCD
  - within the Grand Canonical Ensemble, are related to event-by-event fluctuations of the number of conserved charges

Theory: susceptibilities

$$\chi_n^B = \frac{\partial^n (P/T^4)}{\partial(\mu_B/T)^n}$$



Experiment: moments of particle multiplicity distributions

$$\Delta N_B = N_B - N_{\bar{B}}$$

Connecting theory to experiment

- Thermodynamic susceptibilities χ
  - describe the response of a thermalized system to changes in external conditions, fundamental properties of the medium
  - can be calculated within lattice QCD
  - within the Grand Canonical Ensemble, are related to event-by-event fluctuations of the number of conserved charges

Theory: susceptibilities

$$\chi_n^B = \frac{\partial^n \left(P/T^4\right)}{\partial \left(\mu_B/T\right)^n}$$

Charge	Observable
Electric charge	charged particles (proxy: pions)
Strangeness	strange mesons+baryons (proxy: kaons)
Baryon number	baryons (proxy:protons)

Experiment: moments of particle multiplicity distributions

$$\Delta N_B = N_B - N_{\bar{B}}$$

Connecting theory to experiment

- Thermodynamic susceptibilities χ
  - describe the response of a thermalized system to changes in external conditions, fundamental properties of the medium
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Theory: susceptibilities

$$\chi_n^B = \frac{\partial^n (P/T^4)}{\partial(\mu_B/T)^n}$$

$$\langle \Delta N_B \rangle = VT^3 \chi_1^B$$

$$\langle (\Delta N_B \; \ldots \; \chi_2^B = \sigma^2$$

$$\langle (\Delta N_B \; \ldots \; \frac{VT^3\chi_3^B}{\left(VT^3\chi_2^B\right)^{3/2}} = S$$

$$S\sigma = \chi_3^B / \chi_2^B$$

$$\kappa\sigma^2 = \chi_4^B / \chi_2^B$$

$$\left\langle \left(\Delta N_B - \langle \Delta N_B \rangle\right)^4 \right\rangle / \sigma^4 - 3 = \frac{VT^3 \chi_4^B}{\left(VT^3 \chi_2^B\right)^2} = \kappa$$

Experiment: moments of particle multiplicity distributions

$$\Delta N_B = N_B - N_{\bar{B}}$$

Connecting theory to experiment

- Thermodynamic susceptibilities χ
  - describe the response of a thermalized system to changes in external conditions, fundamental properties of the medium
  - can be calculated within lattice QCD
  - within the Grand Canonical Ensemble, are related to event-by-event fluctuations of the number of conserved charges

Theory:
fixed volume,
particle bath in
GCE

$$\langle \Delta N_B \rangle \neq VT^3 \chi_1^B$$

$$\left\langle \left(\Delta N_B - \langle \Delta N_B \rangle \right)^2 \right\rangle \neq VT^3 \chi_2^B = \sigma^2$$

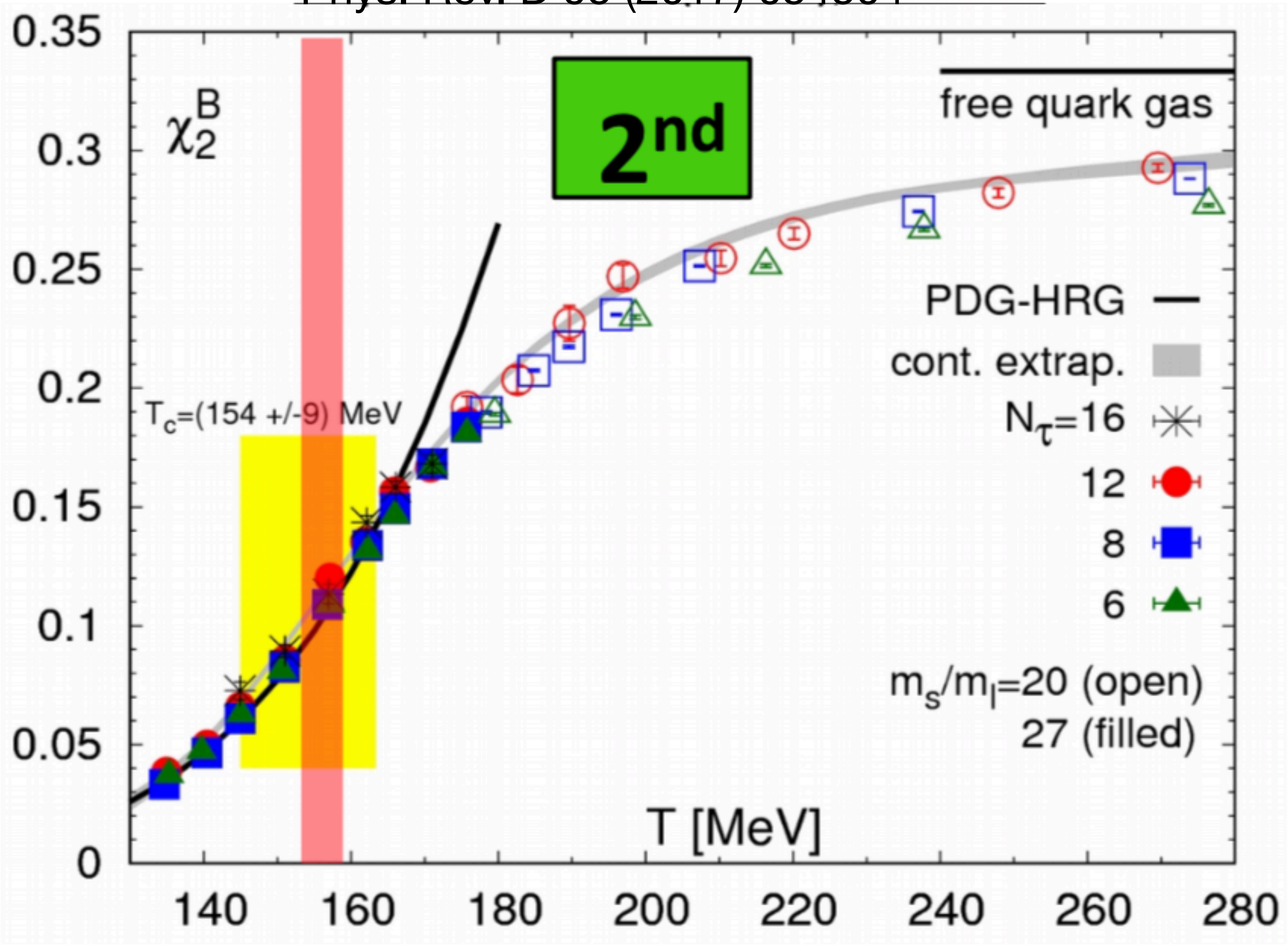
$$\left\langle \left(\Delta N_B - \langle \Delta N_B \rangle \right)^3 \right\rangle / \sigma^3 \neq \frac{VT^3 \chi_3^B}{\left(VT^3 \chi_2^B \right)^{3/2}} = S$$

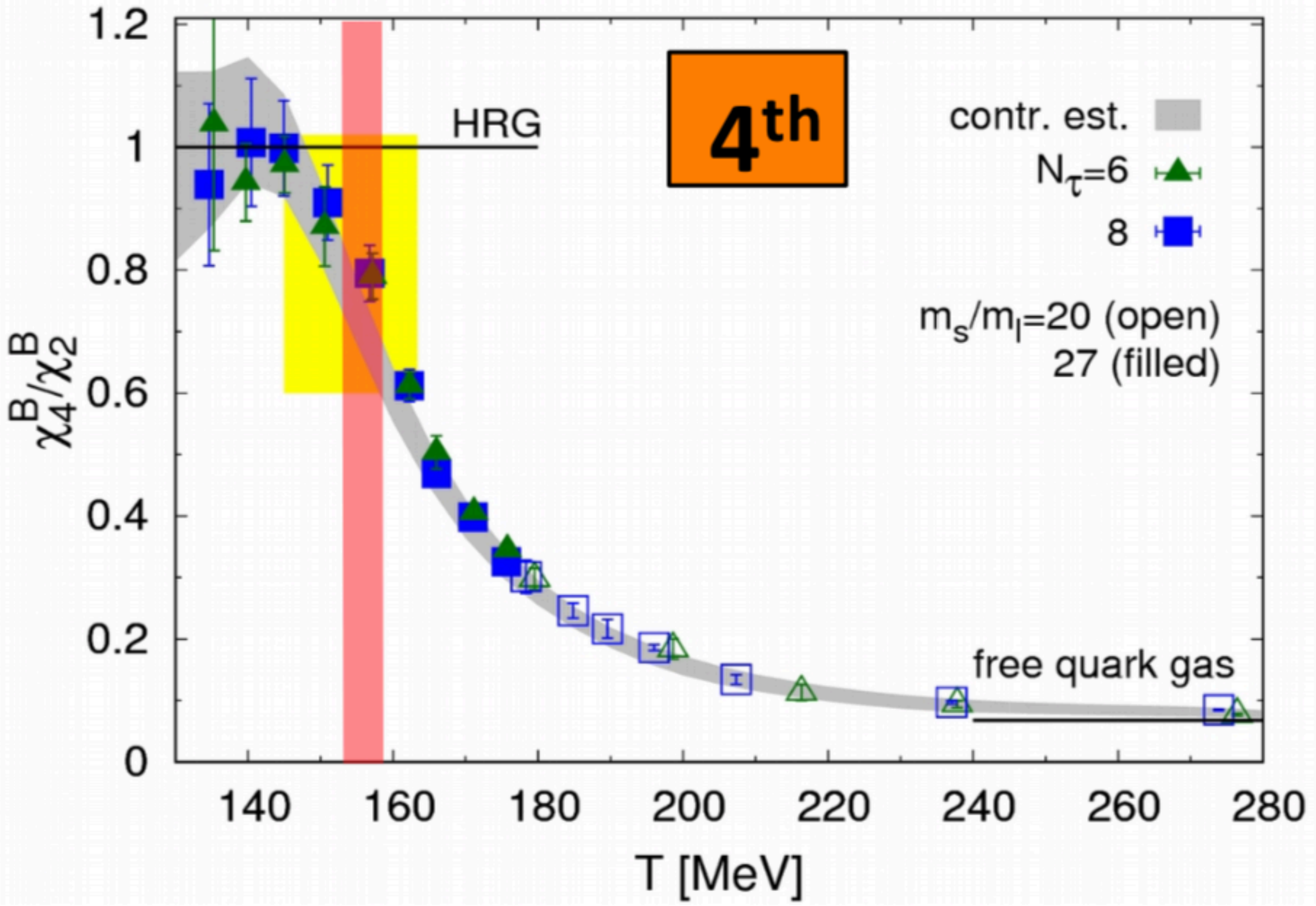
$$\left\langle \left(\Delta N_B - \langle \Delta N_B \rangle \right)^4 \right\rangle / \sigma^4 - 3 \neq \frac{VT^3 \chi_4^B}{\left(VT^3 \chi_2^B \right)^2} = \kappa$$

Experiment:
event-by-event
volume fluctuations,
global conservation
laws

Needed: high precision

A. Bazavov et al. (HotQCD Collaboration),
Phys. Rev. D 95 (2017) 054504

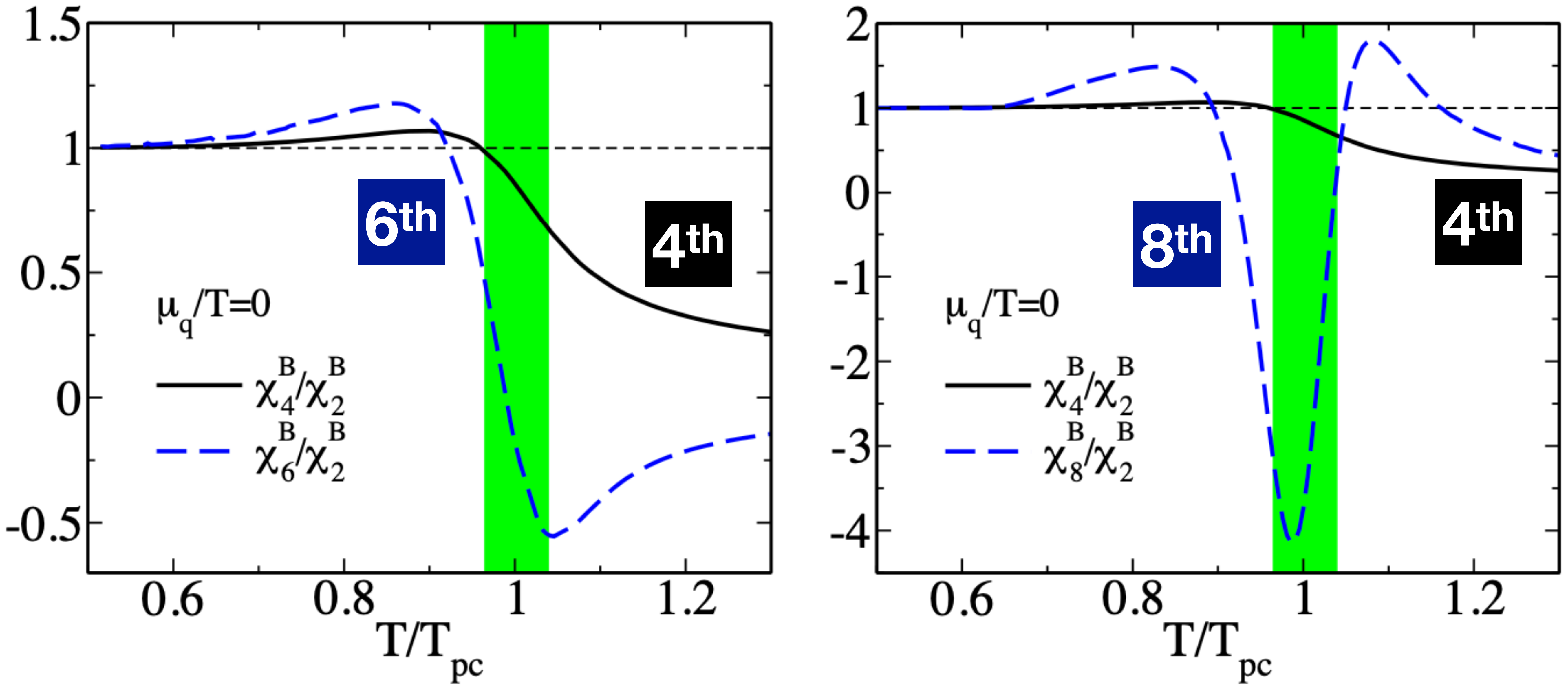




- 2nd order moments → no deviation between HRG and LQCD expectations
- 4th order → 30% deviation from unity expected from LQCD

Needed: higher-order moments

- Deviations from unity and signs of criticality are greatly enhanced for the higher moments (4th, 6th, 8th,…)



Friman, B., et al. Eur. Phys. J. C 71 (2011) 1694, arXiv:1103.3511 [hep-ph]

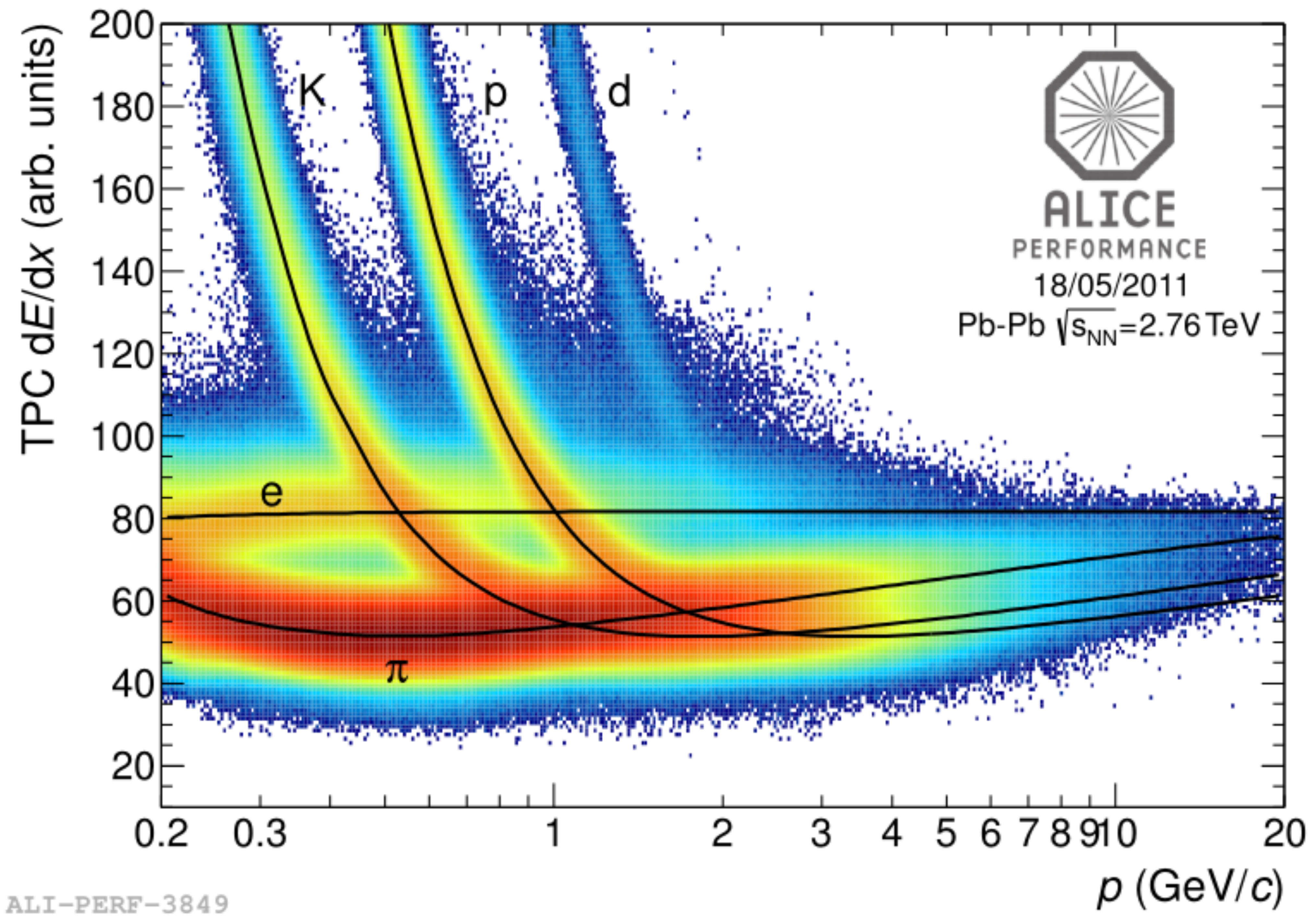
- But huge statistics are needed and experimental effects must be carefully controlled

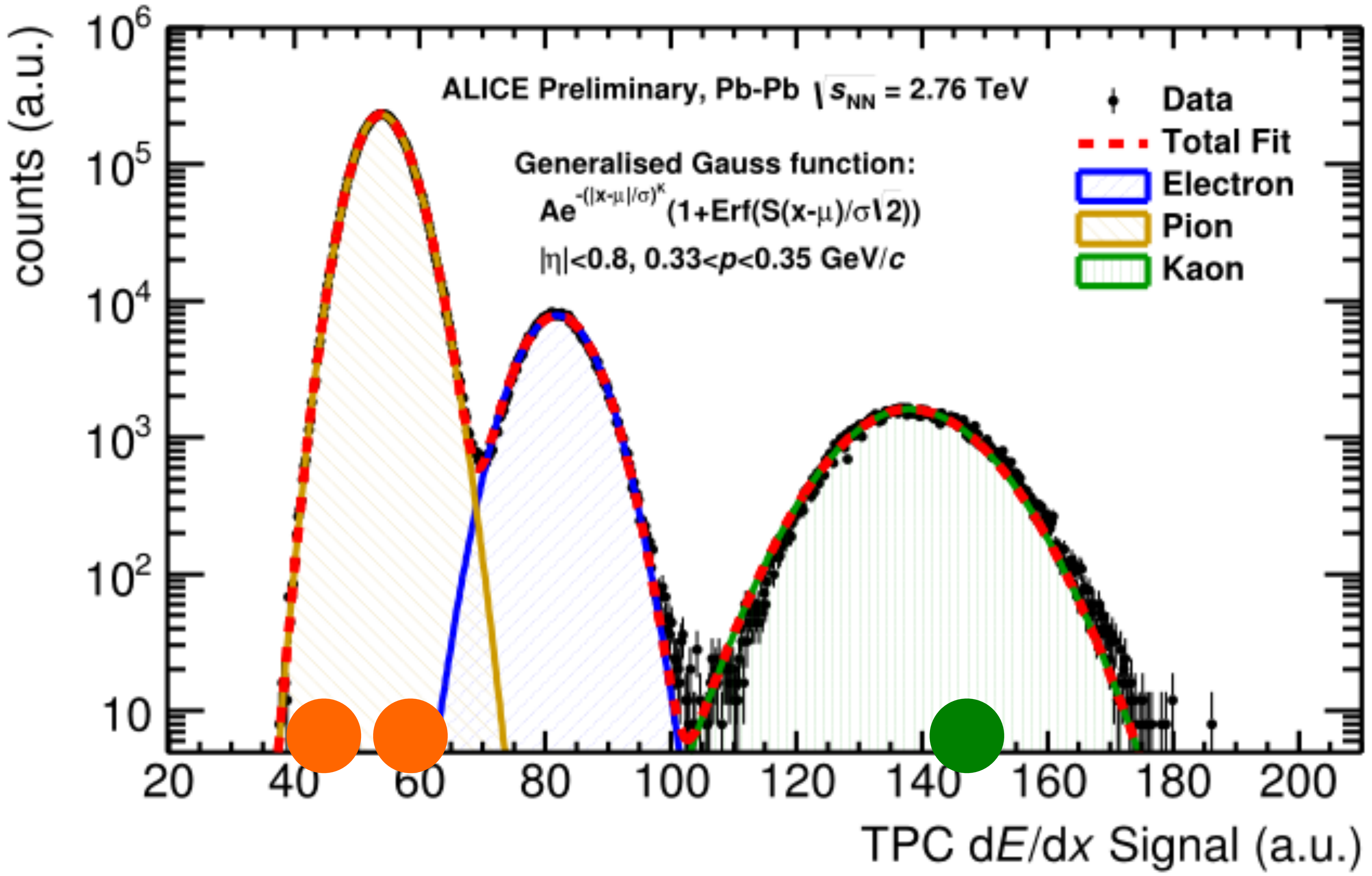
Experimental challenges

1. Event-by-event particle identification
2. Event-by-event efficiency correction

We know how to correct the first moments,
but what about the higher moments?

The challenge: event-by-event PID



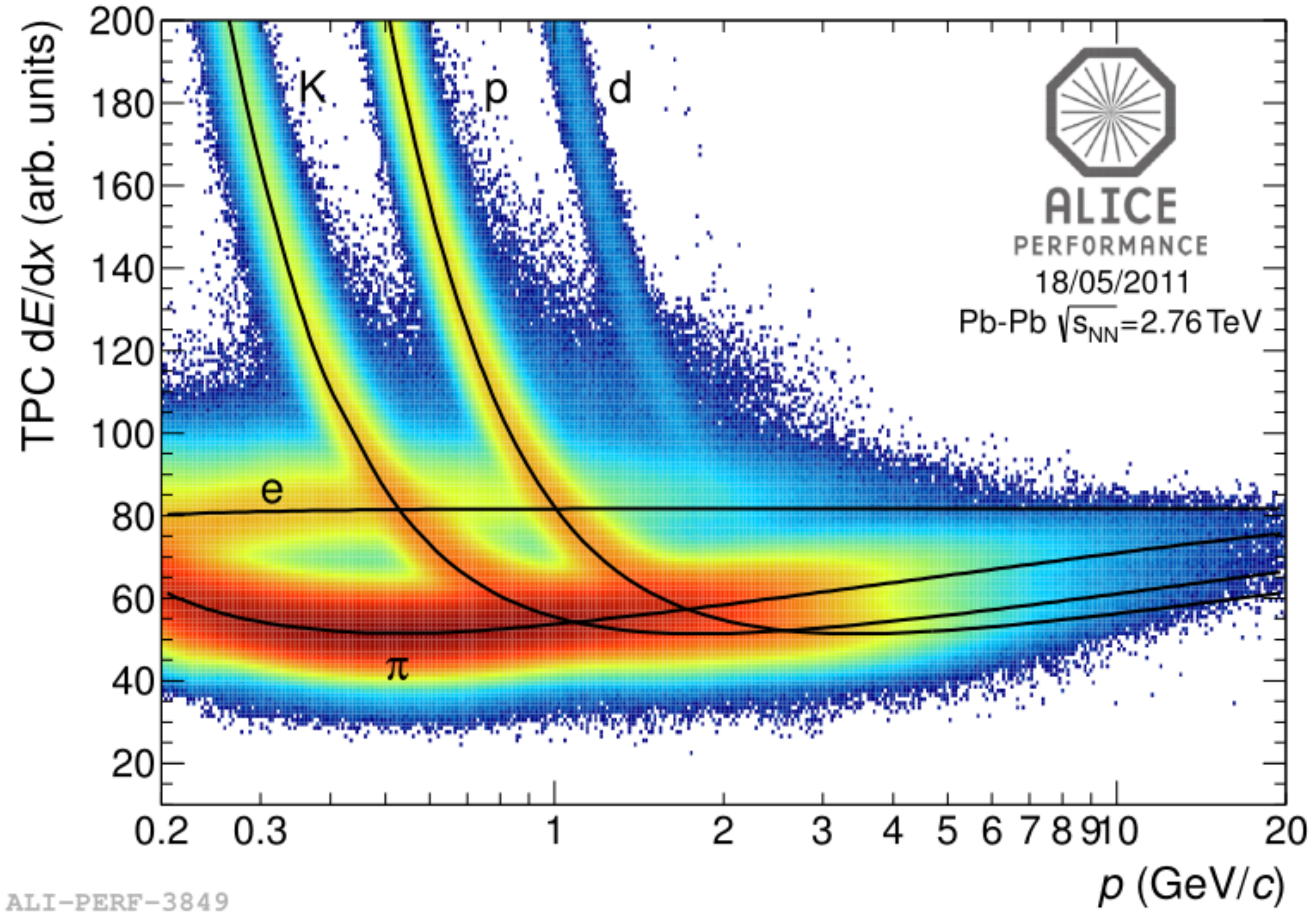


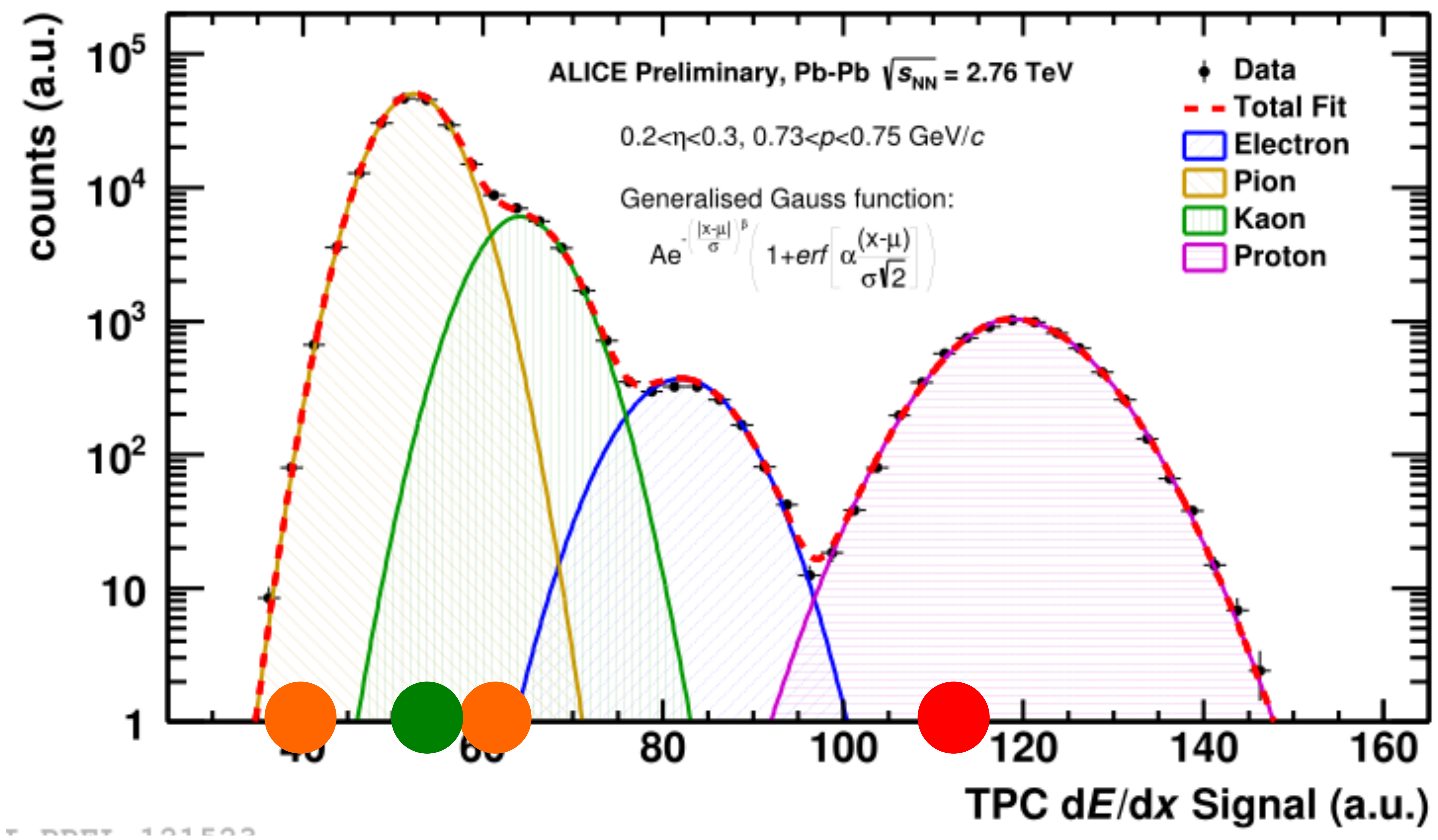
- Traditional method:
  - count number of pions (N_π), kaons (N_K), protons (N_p) in each event

$$N_p = \sum_i^{\#tracks} \begin{cases} 1 & \text{particle } i \text{ is a proton} \\ 0 & \text{particle } i \text{ is not a proton} \end{cases}$$

  - find moments of distributions of N_π, N_K, N_p, ...

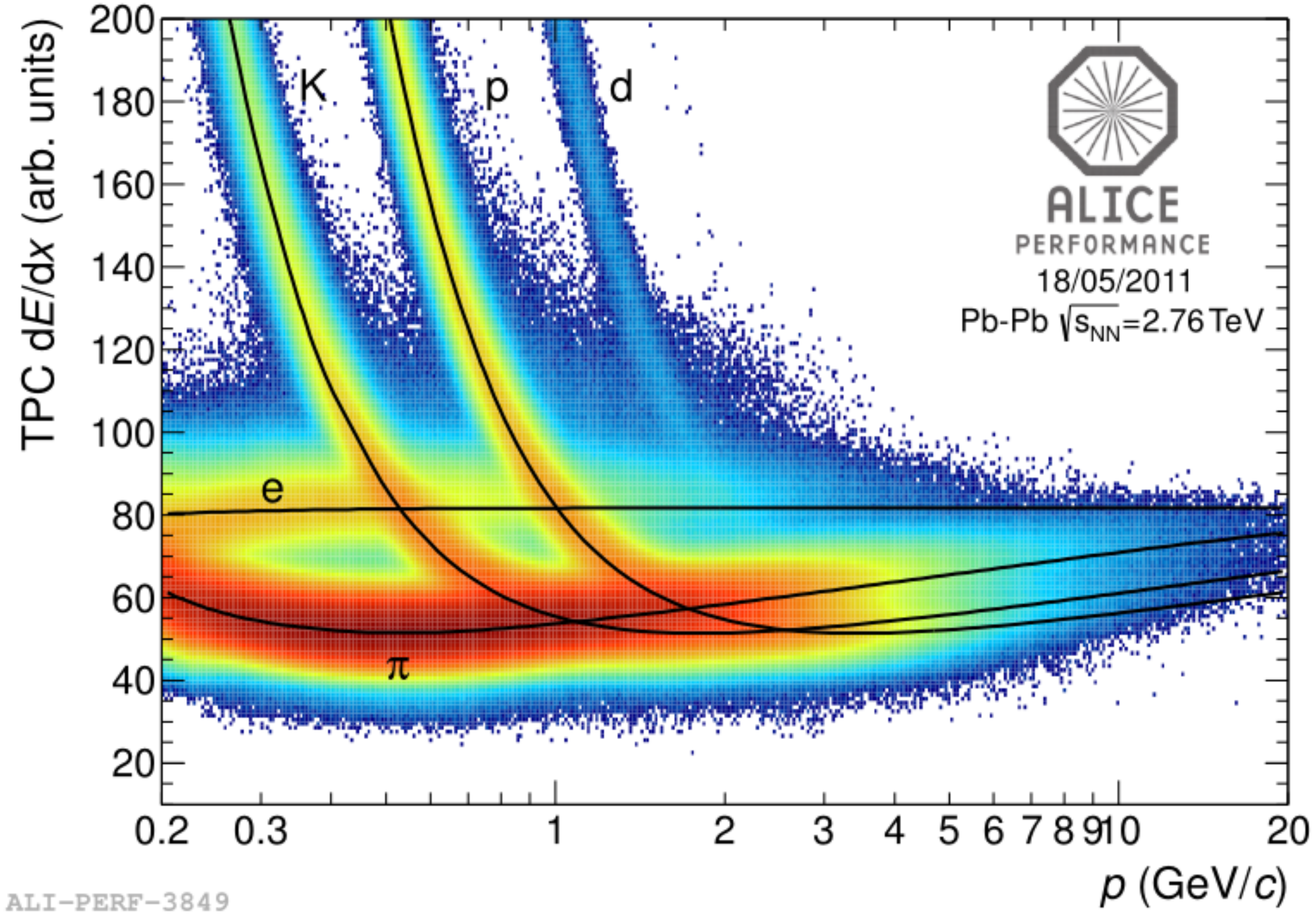
Traditional method

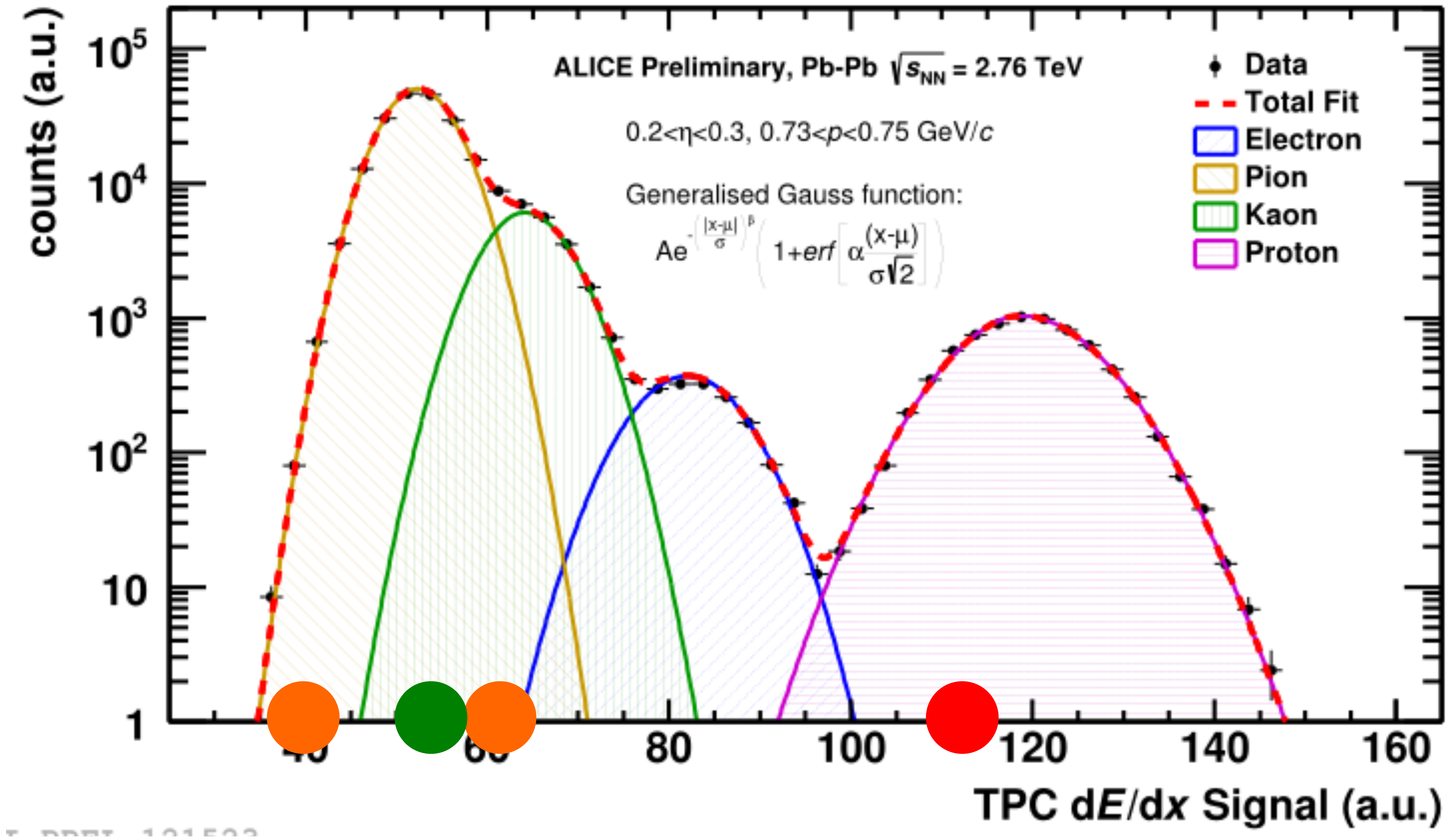




- What if PID is unclear?
  – use other detector information or reject phase space bin
  – results in lower efficiency

Identity Method





- As a function of the PID variable *m*, determine probability *w* that particle is of a given species
- Calculate event-by-event sum of weights W_π, W_K, W_p, ...

$$W_p = \sum_{i}^{\#tracks} w_p(m_i)$$

- Using knowledge of inclusive *m* distributions, unfold moments of W distributions to get moments of N
- Contamination is accounted for, full phase space can be used

A. Rustamov et al., PRC 86 (2012) 044906, arXiv:1204.6632 [nucl-th]

Efficiency correction: several ideas

- Simple scaling of moments using HIJING and/or AMPT
- Correction of factorial moments assuming binomial track loss

A. Bzdak and V. Koch,
Phys. Rev. C86, 044904 (2012),
arXiv:1206.4286 [nucl-th].

A. Bzdak and V. Koch,
Phys. Rev. C91, 027901 (2015),
arXiv:1312.4574 [nucl-th].

  – extension to Identity Method

C. Pruneau, Phys. Rev. C96 (2017) 054902,
arXiv:1706.01333 [physics.data-an]

- Correction using moments of detector response matrix

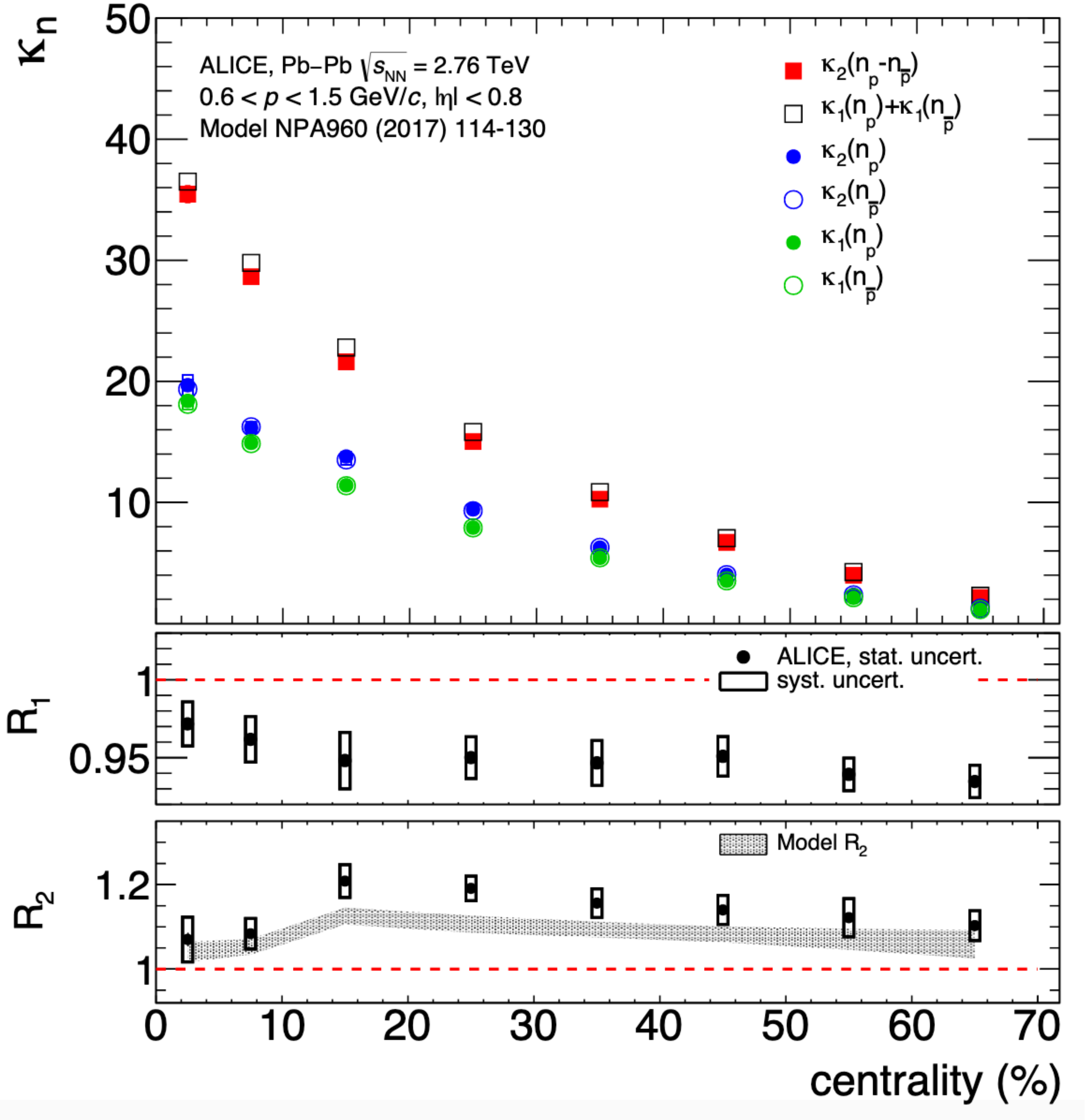
T. Nonaka et al., Nucl. Inst. Meth. A 906 (2018) 10, arXiv:1805.00279
[physics.data-an]

- Full unfolding of moments

All correction methods rely on different assumptions,
which must be assessed and tested carefully!

2nd moments at the LHC

Net-proton second moments at the LHC



ALICE, PLB 807 (2020) 135564,
arXiv:1910.14396

$$\kappa_1(p)=\langle N_p\rangle \qquad \kappa_2(p)=\left\langle\left(N_p-\langle N_p\rangle\right)^2\right\rangle$$

$$\kappa_2(p-\bar{p})=\left\langle\left(N_p-N_{\bar{p}}-\langle N_p-N_{\bar{p}}\rangle\right)^2\right\rangle$$

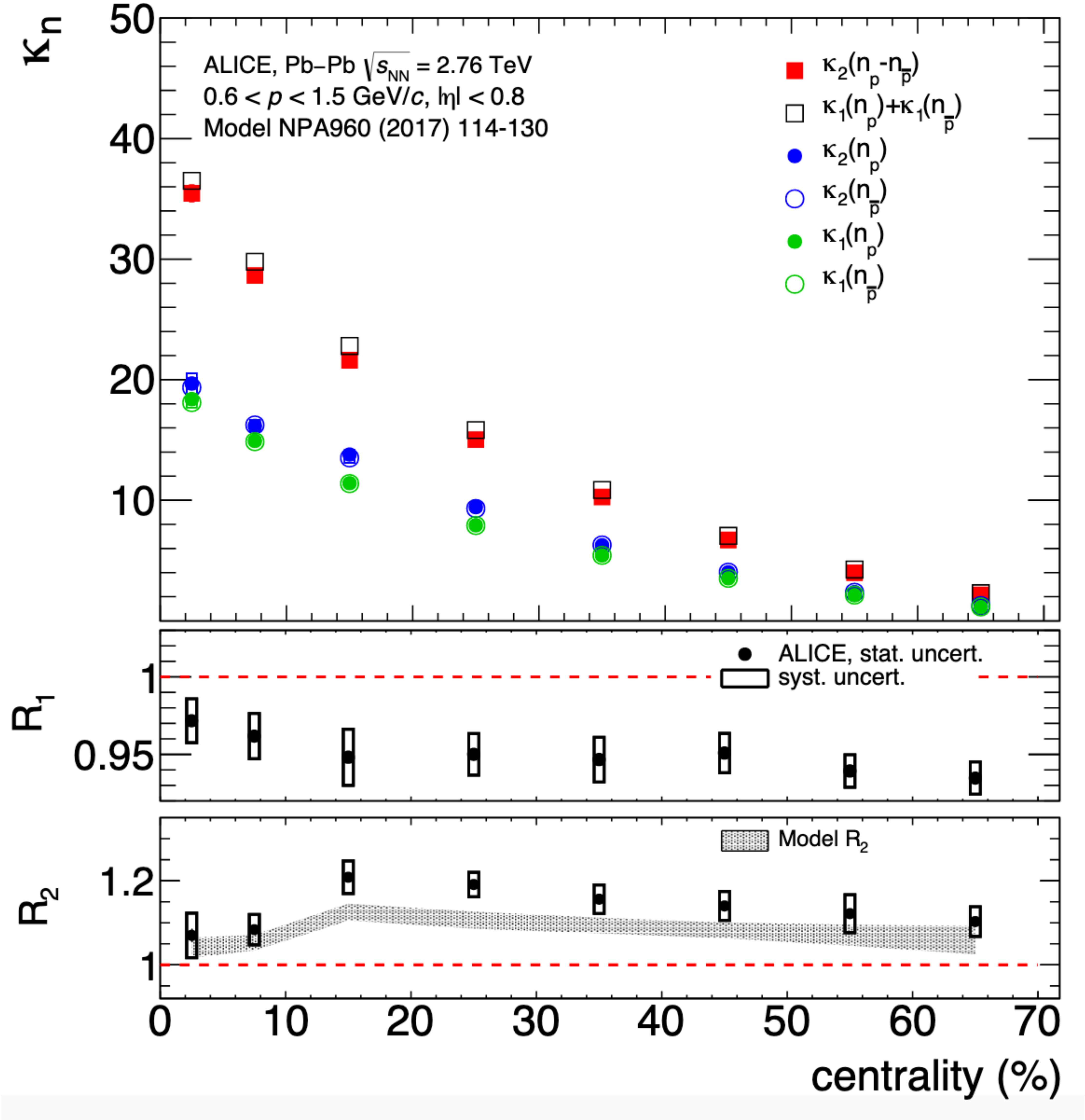
$$=\kappa_2(p)+\kappa_2(\bar{p})-2\underbrace{\left(\langle N_pN_{\bar{p}}\rangle-\langle N_p\rangle\langle N_{\bar{p}}\rangle\right)}_{\text{correlation term}}$$

- If multiplicity distributions of protons and anti-protons are Poissonian and uncorrelated

$$\kappa_2(p) = \kappa_1(p)$$

$$R_1 = \kappa_2(p)/\kappa_1(p) \rightarrow 1$$

Net-proton second moments at the LHC



ALICE, PLB 807 (2020) 135564,
arXiv:1910.14396

$$\kappa_1(p) = \langle N_p \rangle \qquad \kappa_2(p) = \left\langle \left(N_p - \langle N_p \rangle\right)^2 \right\rangle$$

$$\kappa_2(p-\bar{p}) = \left\langle \left(N_p - N_{\bar{p}} - \langle N_p - N_{\bar{p}} \rangle\right)^2 \right\rangle$$

$$= \kappa_2(p) + \kappa_2(\bar{p}) - 2\left(\langle N_p N_{\bar{p}} \rangle - \langle N_p \rangle \langle N_{\bar{p}} \rangle\right)$$

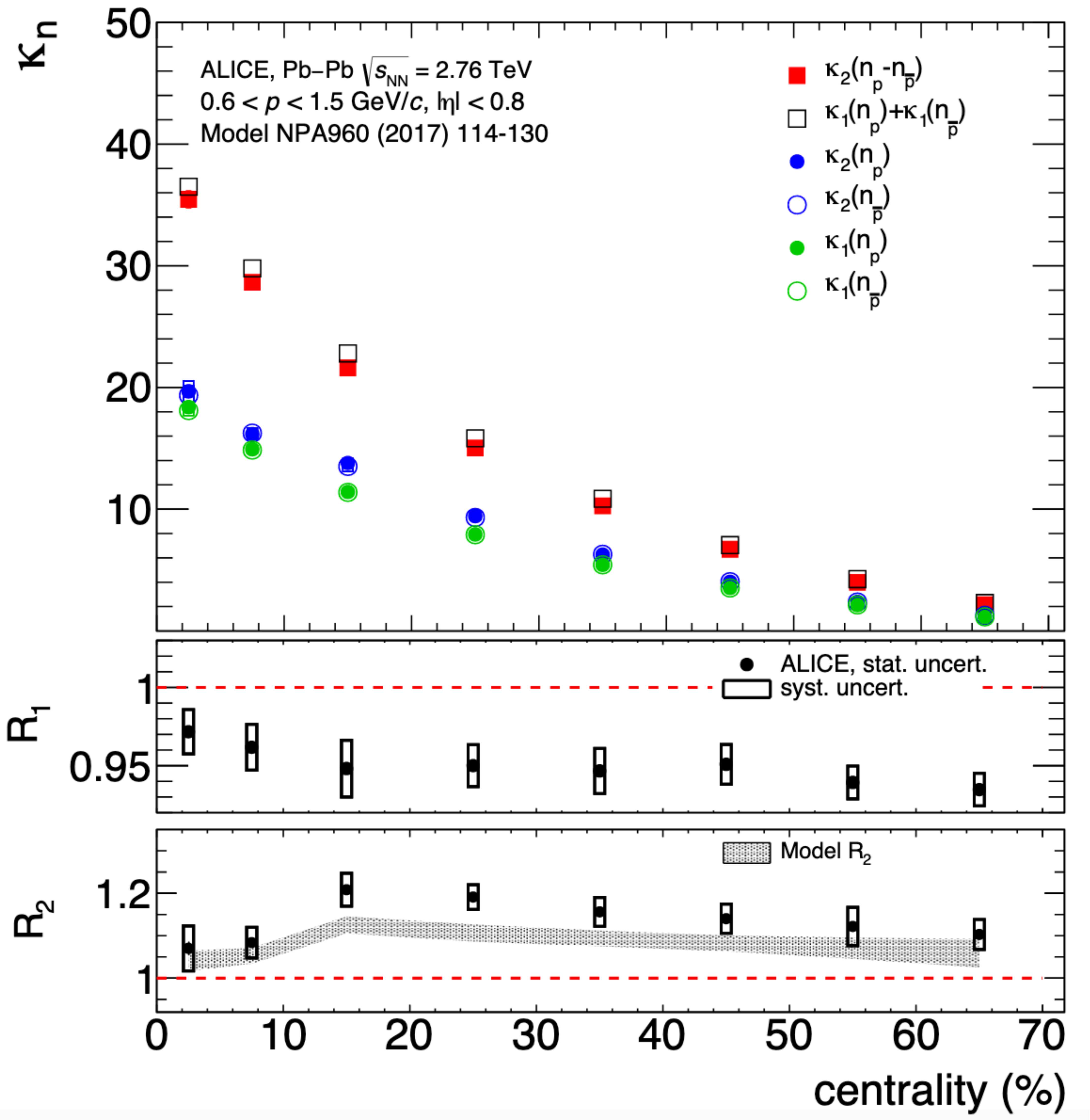
correlation term

- If multiplicity distributions of protons and anti-protons are Poissonian and uncorrelated → Skellam distribution for net-protons

$$\kappa_2(Skellam) = \kappa_1(p) + \kappa_1(\bar{p})$$

$$R_2 = \kappa_2(p-\bar{p})/(\kappa_1(p) + \kappa_1(\bar{p})) \to 1$$

Net-proton second moments



ALICE, PLB 807 (2020) 135564, arXiv:1910.14396

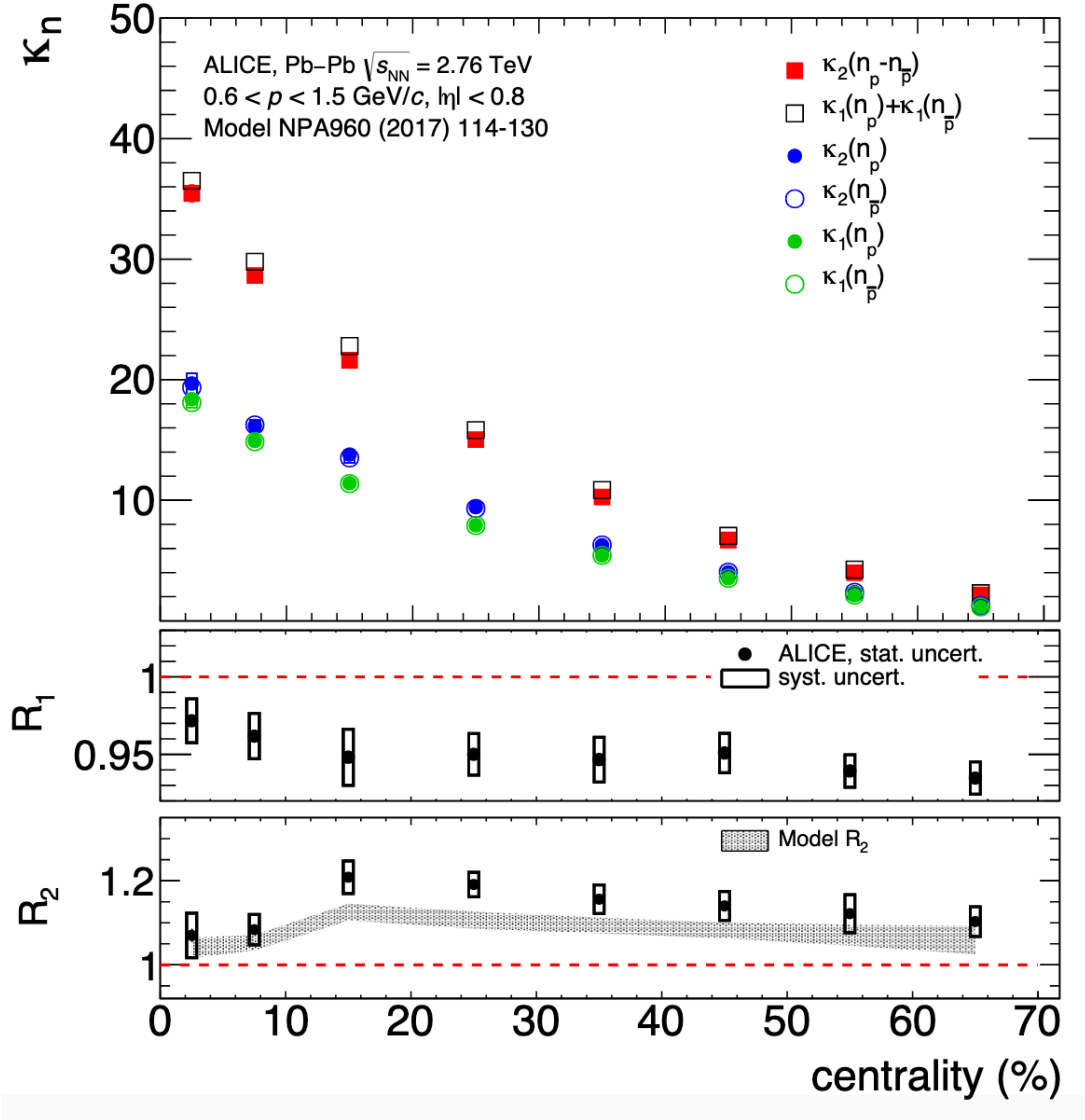
$$\kappa_1(p) = \langle N_p \rangle \qquad \kappa_2(p) = \left\langle \left(N_p - \langle N_p \rangle\right)^2 \right\rangle$$

$$\kappa_2(p-\bar{p}) = \left\langle \left(N_p - N_{\bar{p}} - \langle N_p - N_{\bar{p}} \rangle\right)^2 \right\rangle$$

$$= \kappa_2(p) + \kappa_2(\bar{p}) - 2\underbrace{\left(\langle N_p N_{\bar{p}} \rangle - \langle N_p \rangle \langle N_{\bar{p}} \rangle\right)}_{\text{correlation term}}$$

- κ_2 shows deviation from Skellam prediction
  - due to correlation term?
  - are protons and anti-protons Poissonian?

Net-proton second moments



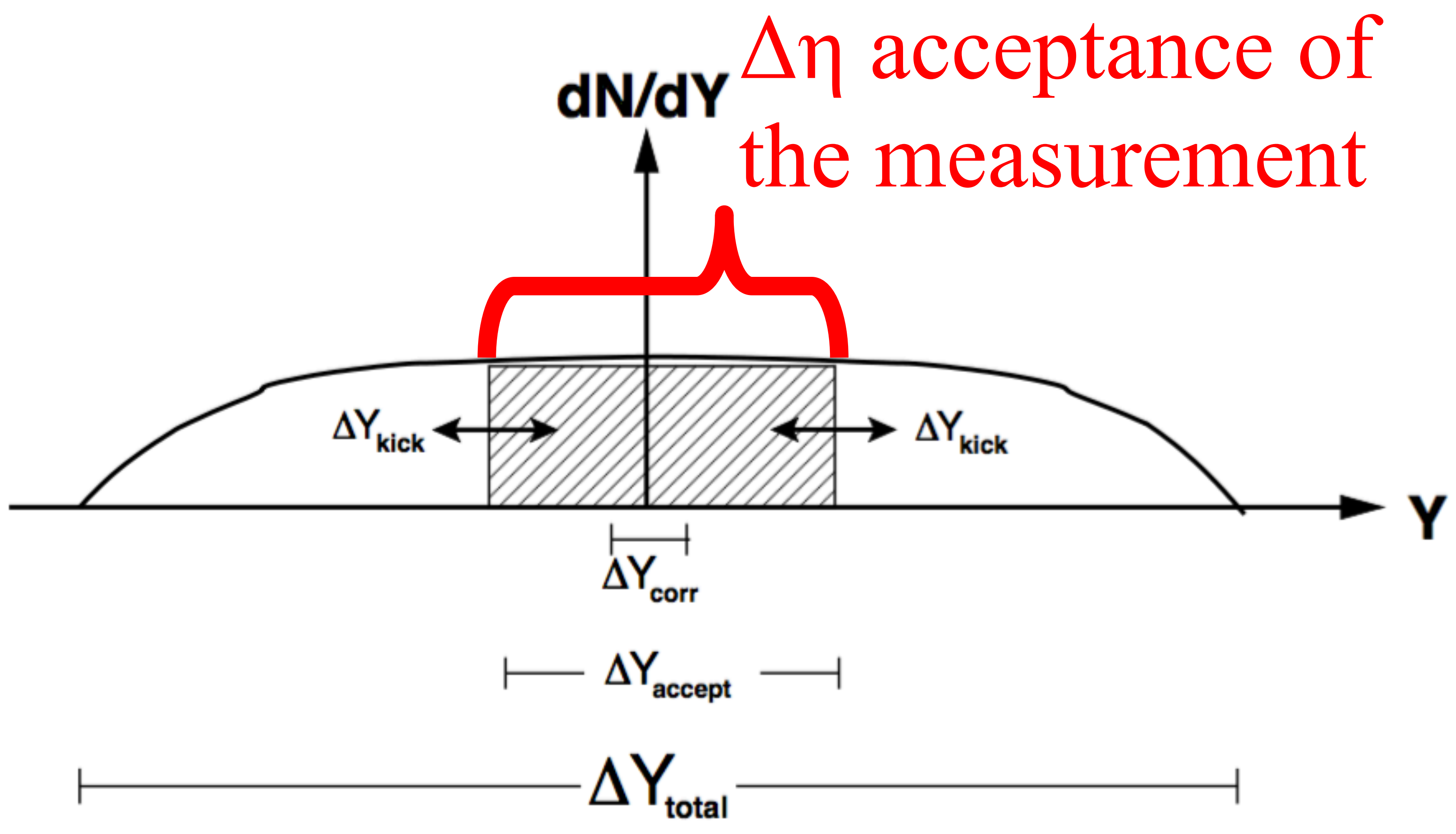
ALICE, PLB 807 (2020) 135564, arXiv:1910.14396

- Modeling the effects of volume fluctuations

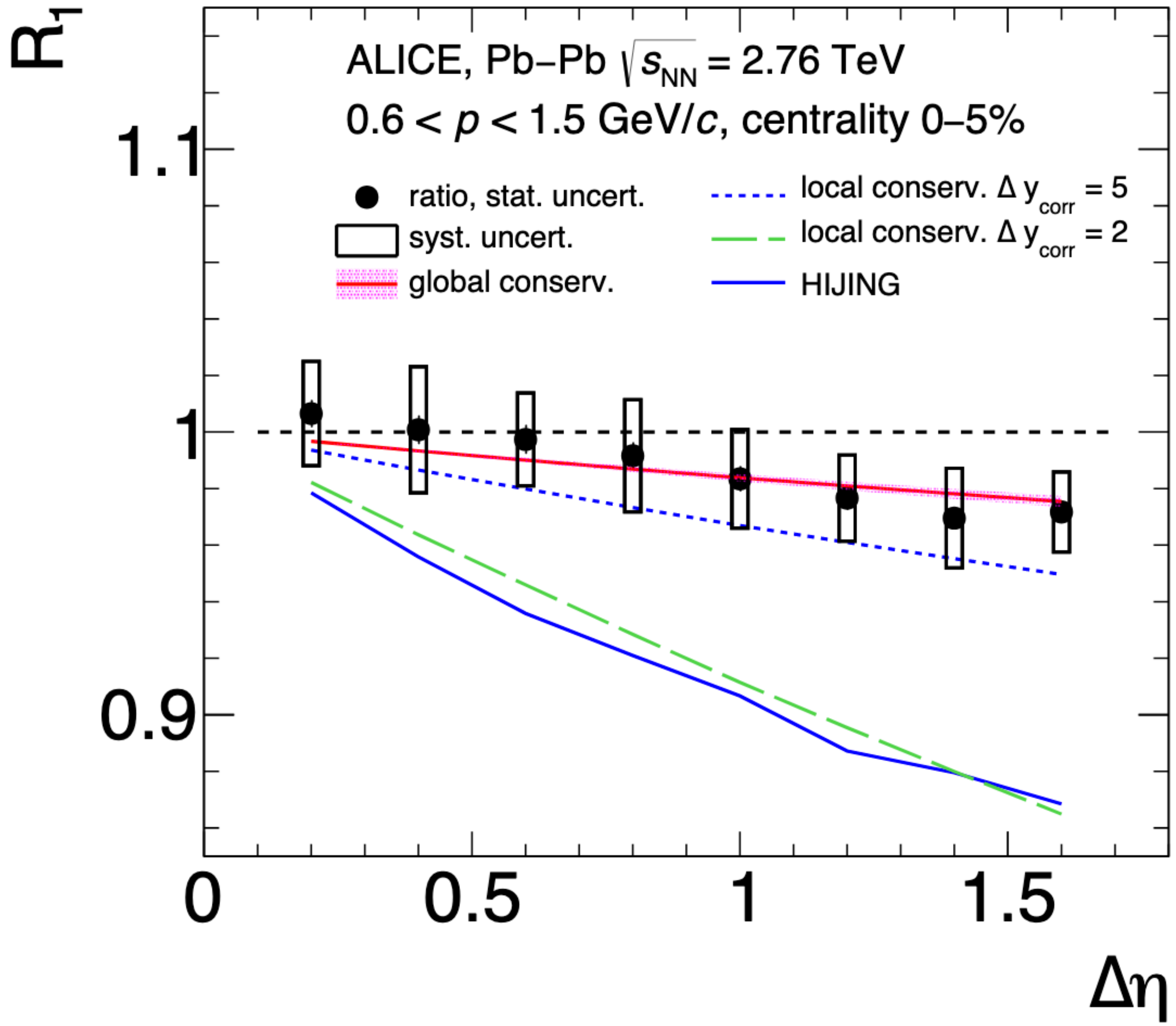
  P. Braun-Munzinger et al., NPA 960 (2017) 114, arXiv:1612.00702 [nucl-th]

- Inputs to the model: $\kappa_1(p)$, $\kappa_1(\bar{p})$, centrality determination procedure
- Model gives a consistent picture of κ_2 without need of correlations or critical fluctuations

Global conservation laws



ALICE, PLB 807 (2020) 135564, arXiv:1910.14396

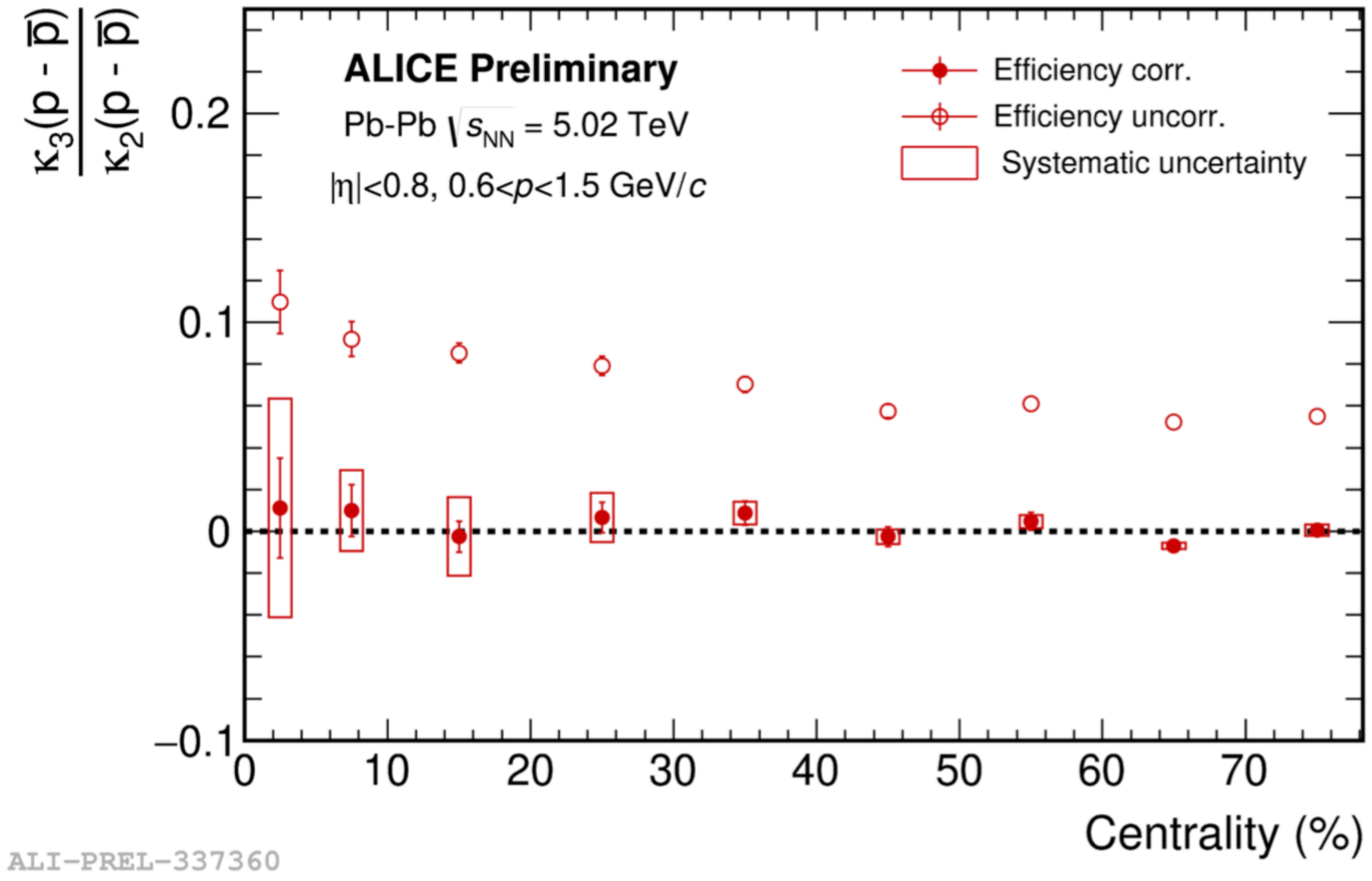


- Small $\Delta\eta \rightarrow$ Poissonian fluctuations, ratio to Skellam ~1
- Large $\Delta\eta \rightarrow$ global baryon number conservation effects, ratio to Skellam < 1
- $\Delta\eta$ dependence consistent with effects of baryon number conservation

P. Braun-Munzinger et al., NPA 960 (2017) 114, arXiv:1612.00702 [nucl-th]

Higher moments at the LHC

Net-proton third moments at the LHC

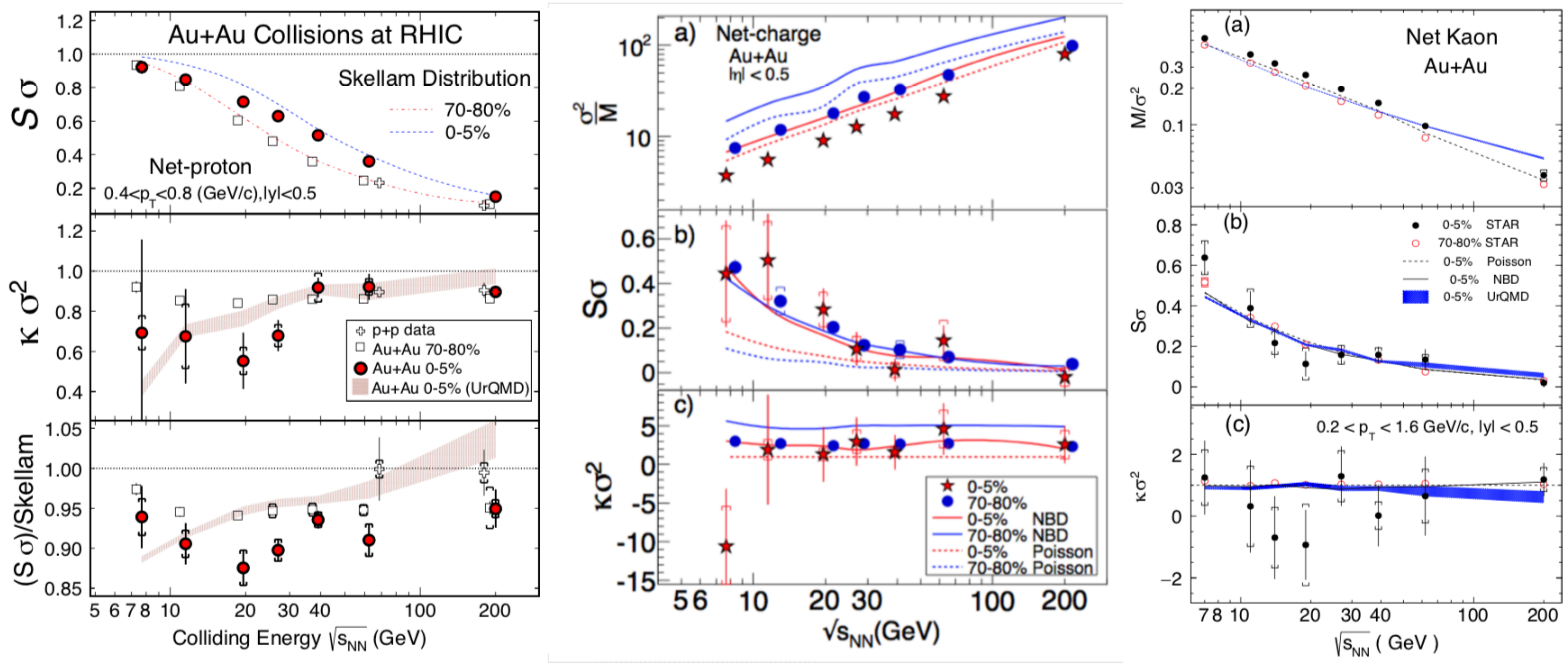


- Third moments agree with Skellam expectation of zero, precision on the order of 5%
- Very sensitive measurements, requires great experimental control over efficiencies, etc
- Fourth moments in progress...

Higher moments at RHIC

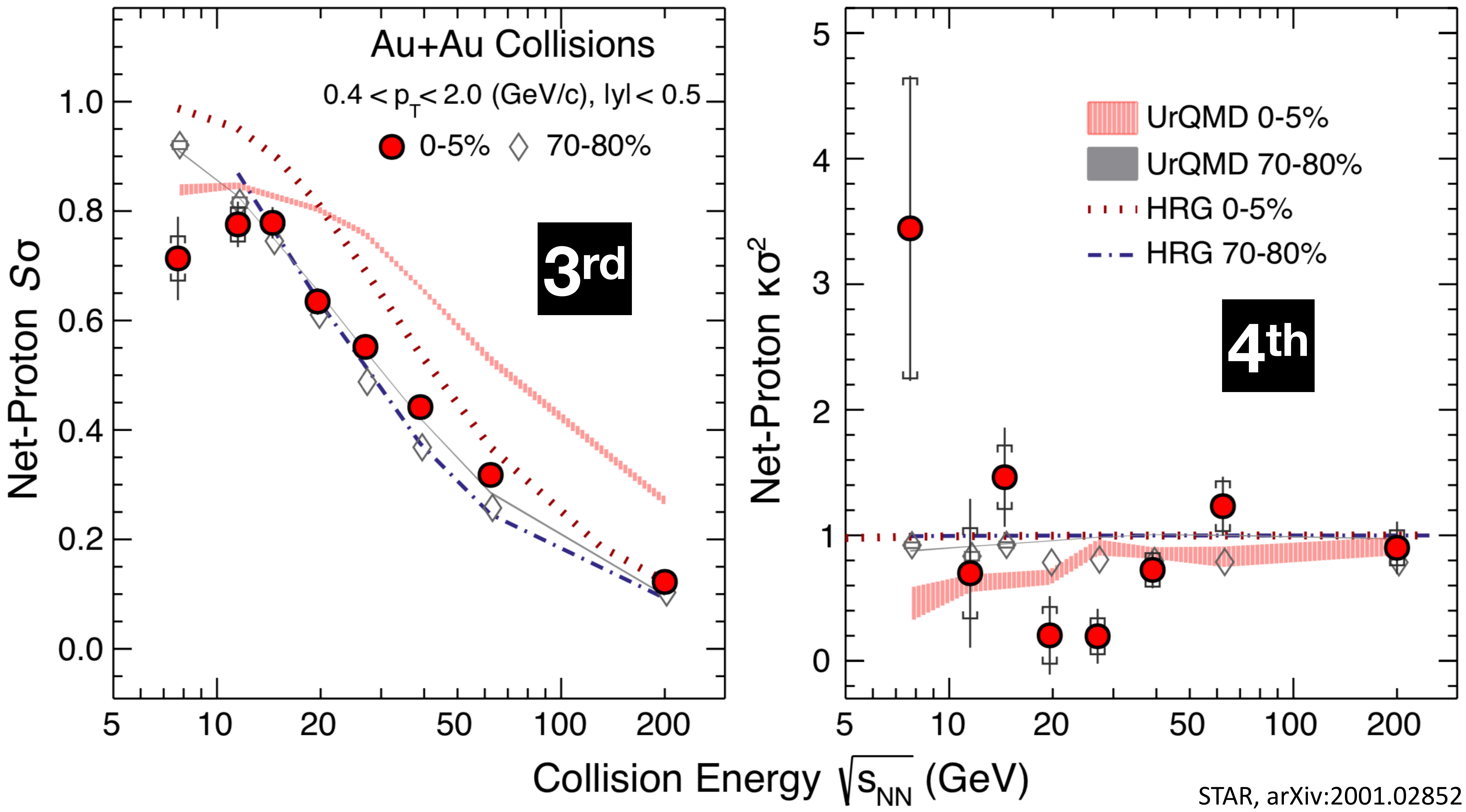
Higher moments at RHIC

Net-Proton | **Net-Charge** | **Net-Kaon**



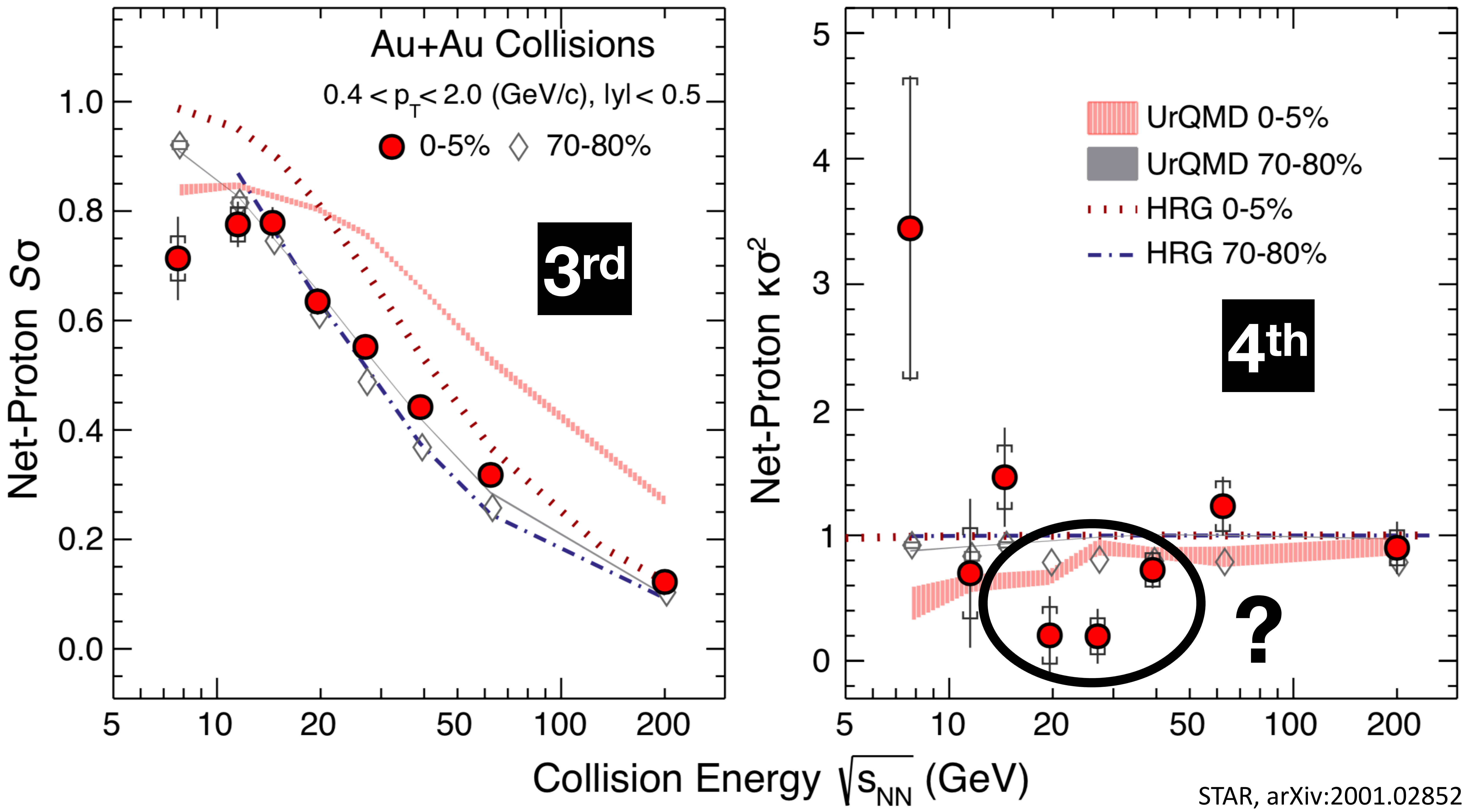
Phys. Rev. Lett. 112, 032302 (2014). **Phys. Rev. Lett. 113 092301 (2014).** **Phys. Lett. B 785, 551 (2018).**

Net-proton moments at RHIC



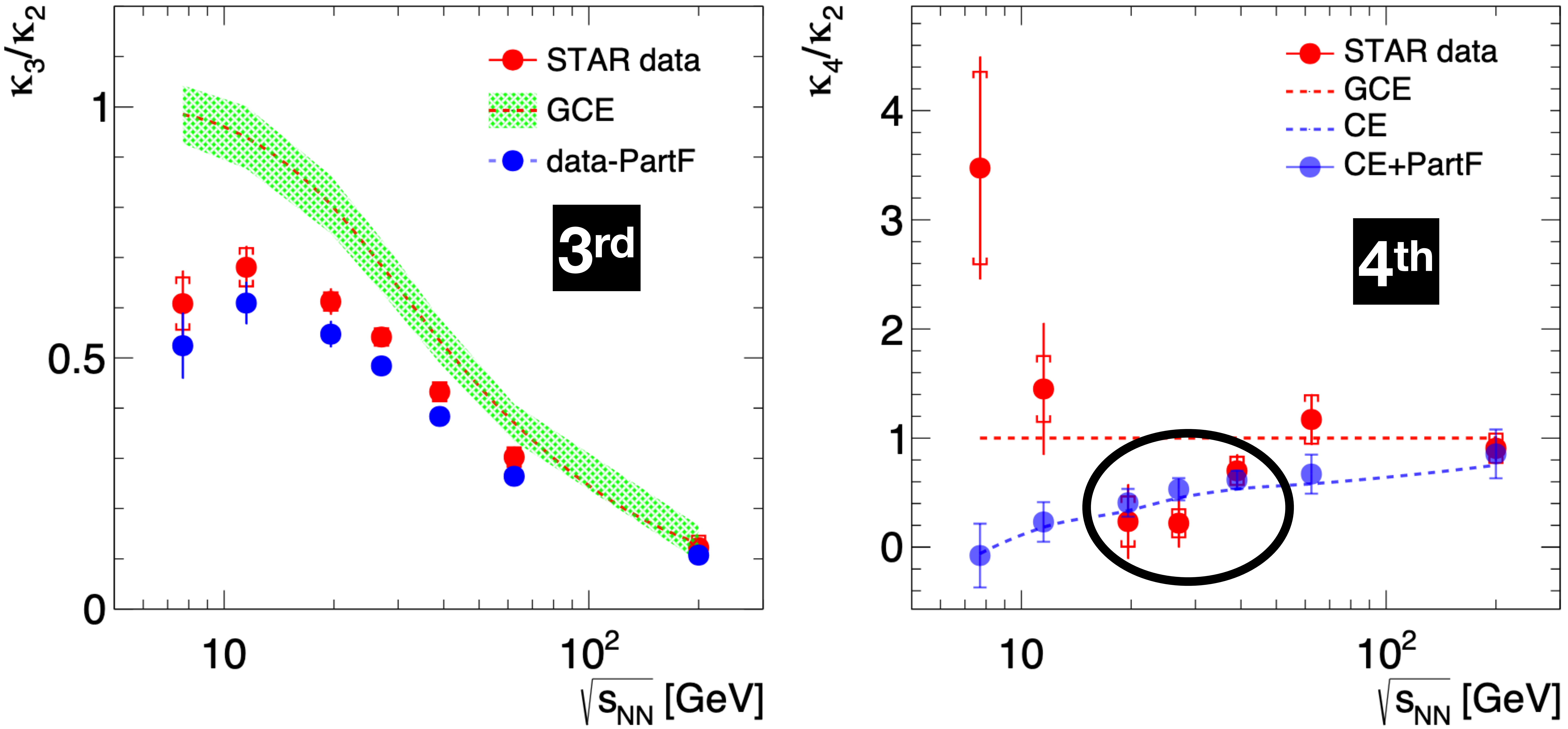
STAR, arXiv:2001.02852

Net-proton moments at RHIC



STAR, arXiv:2001.02852

Critical behavior? Not yet…



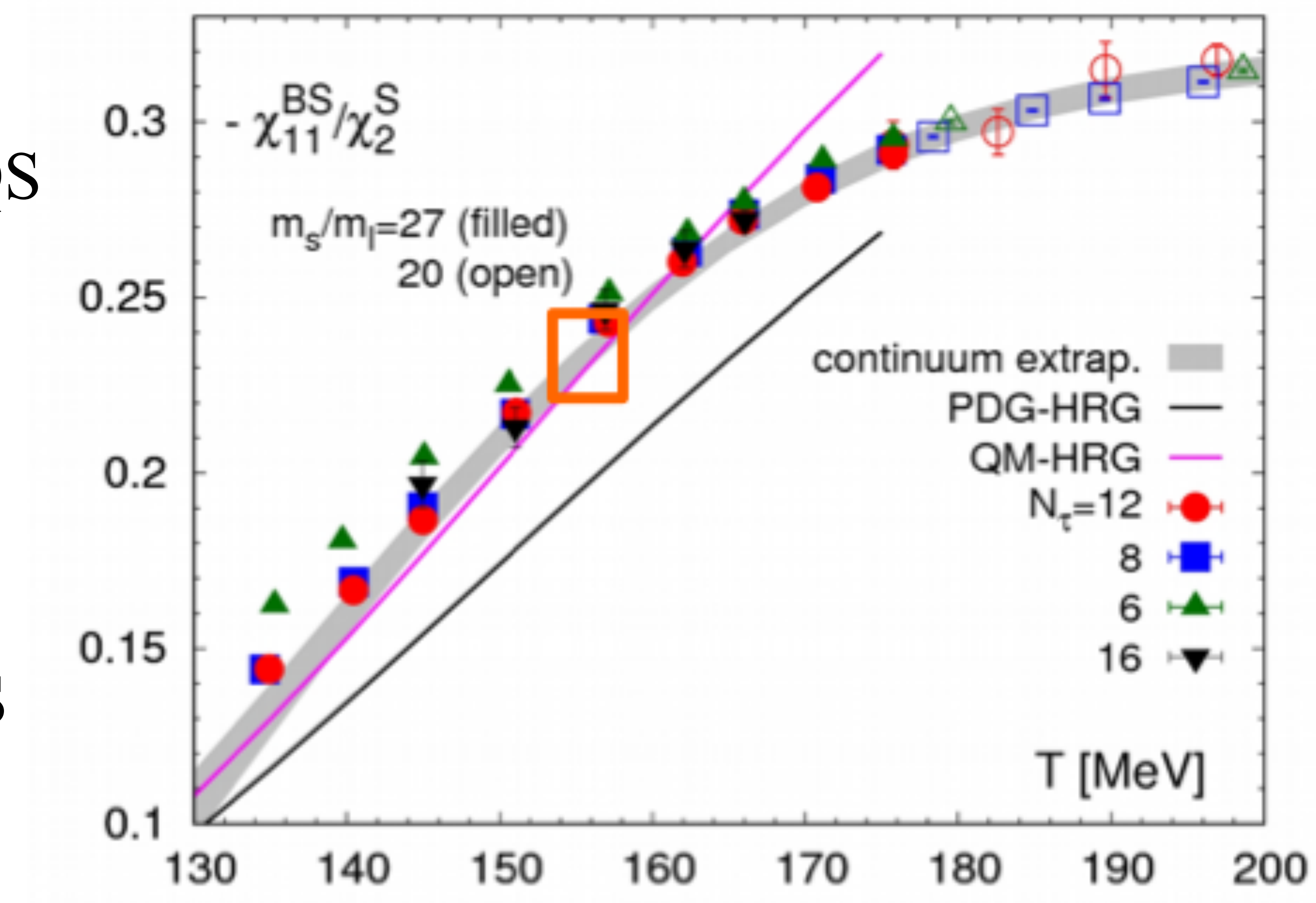
P. Braun-Munzinger, A. Rustamov, J. Stachel, NPA 982 (2019) 307 arXiv:1807.08927 [nucl-th]

- Above $\sqrt{s_{NN}}$ = 11.5 GeV: deviation from unity can be described by global baryon number conservation

Net-Λ fluctuations

From net-π, K, p to net-Λ moments

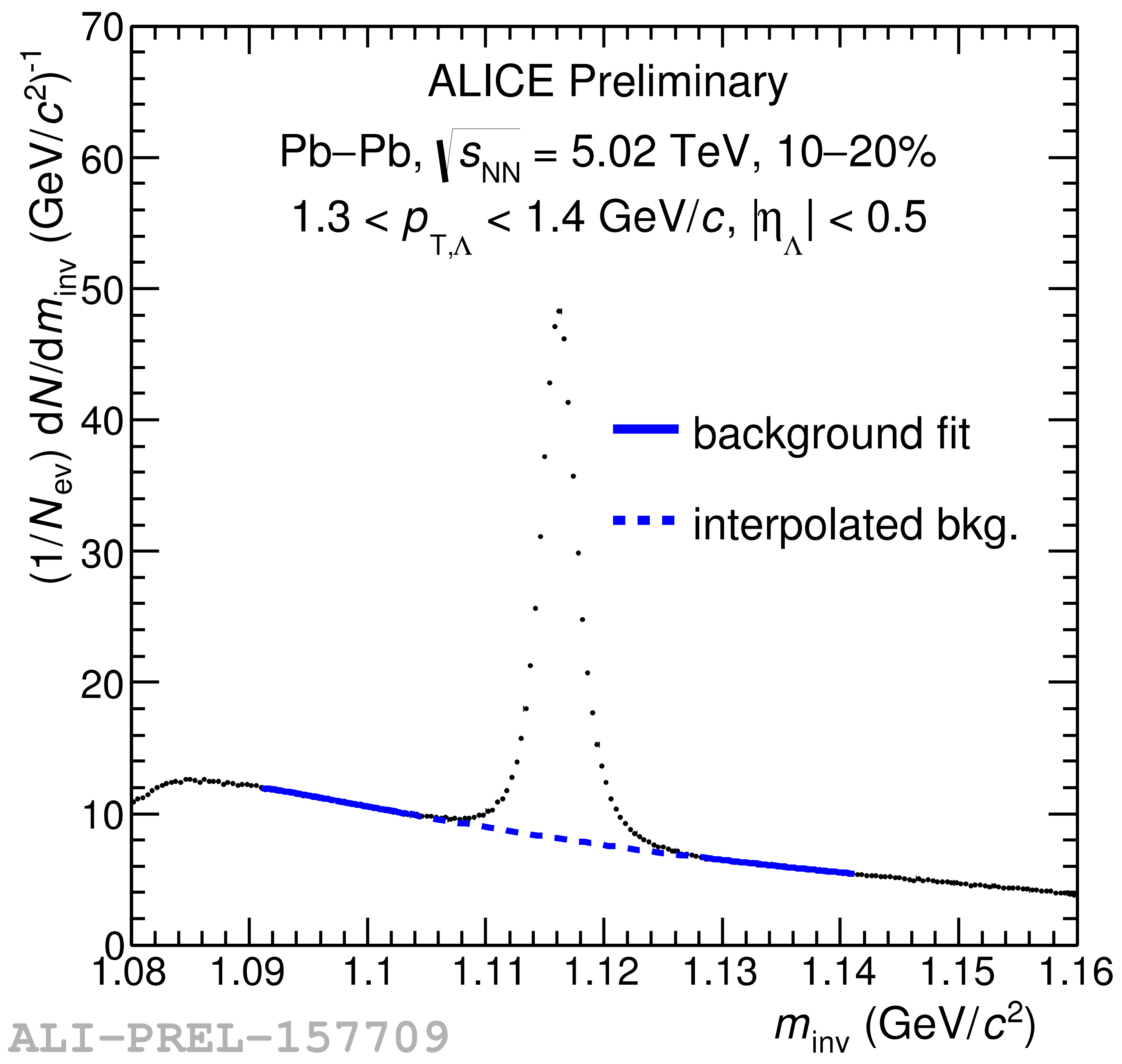
- Moving beyond net-baryon, net-strangeness, net-charge fluctuations to *correlated fluctuations* of net-charge, net-strangeness, net-baryon number
  – Access off-diagonal elements, mixed derivatives χ^{BS}, χ^{BQ}, χ^{QS}
- Net-Λ fluctuations: explore correlated fluctuations of baryon number and strangeness
- Critical fluctuations not expected for second moments, establish baseline for future measurements of higher moments in the strangeness sector
- Improve understanding of net-baryon fluctuations
  - different contributions from resonances, etc, than in net-proton measurement
- Λs can be "added" to net-proton or net-kaon results to get closer to net-baryon and net-strangeness fluctuations

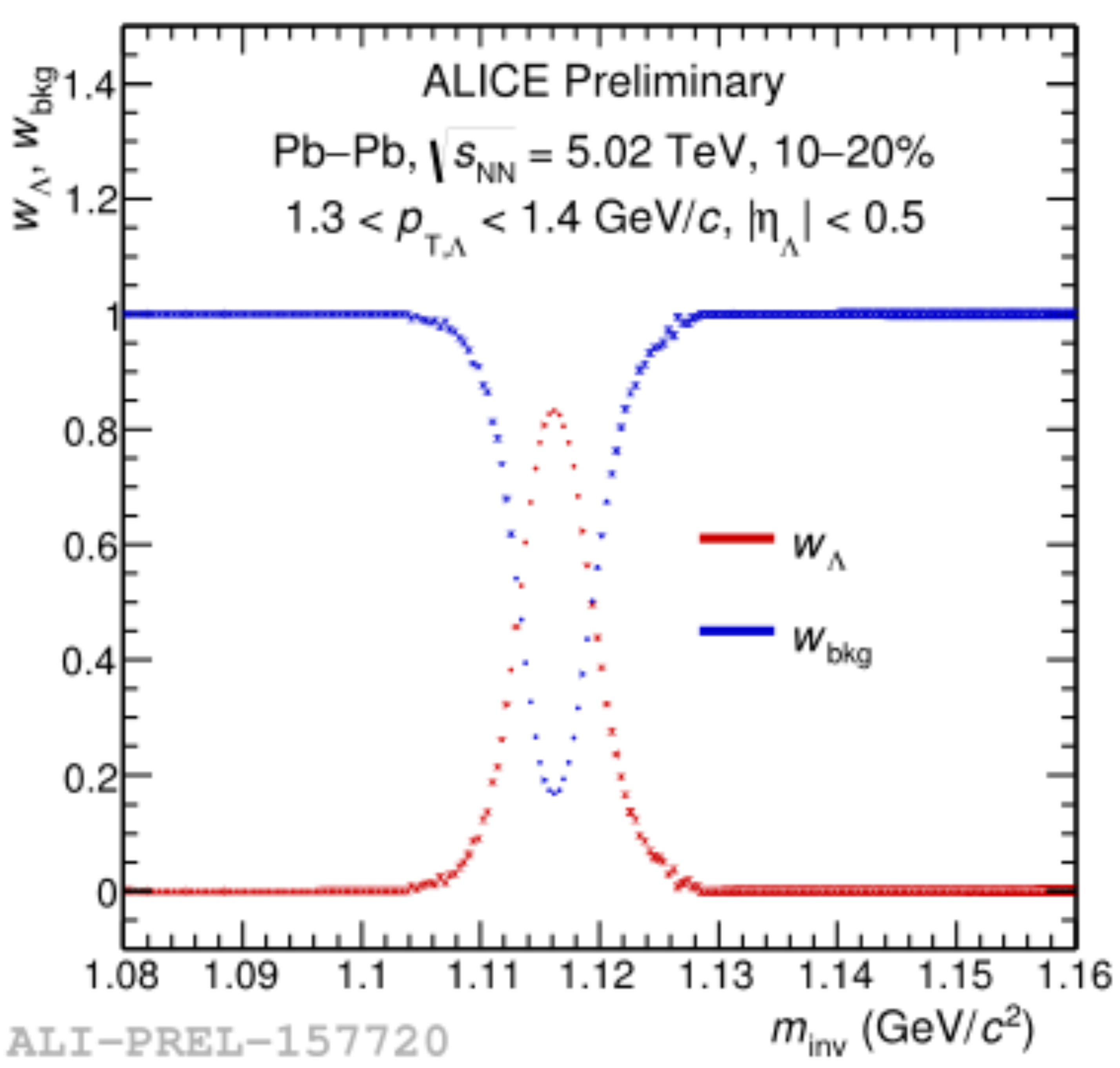


F. Karsch, EMMI Workshop on Fluctuations, Wuhan, October 2017

Identity Method for Λ

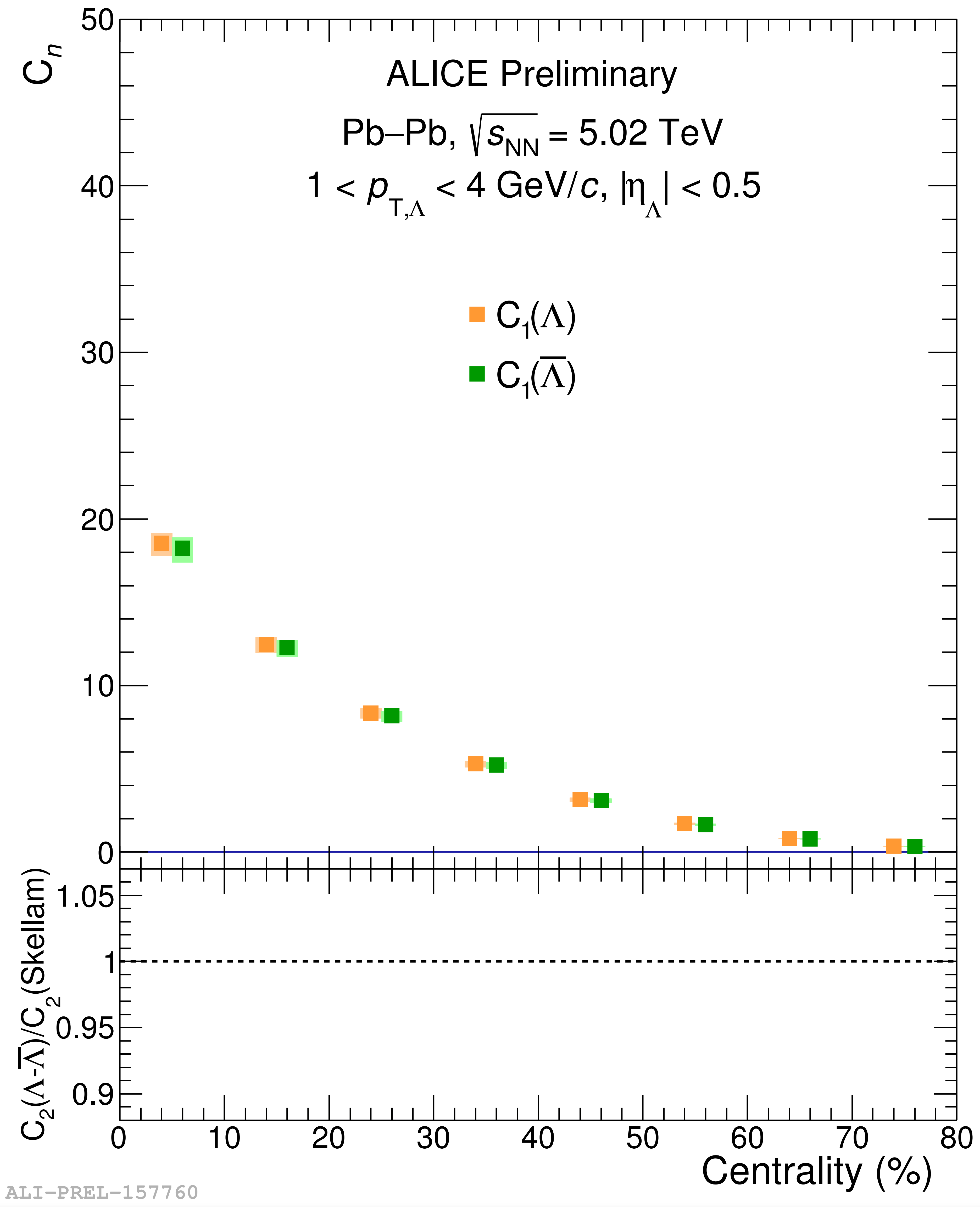
- For any value of m_{inv}, probability that a particle is a Λ or combinatoric pπ pair is known from inclusive distribution
- Identity Method formalism can be applied for four 'species': Λ, $\overline{\Lambda}$, combinatoric $p\pi^-$, combinatoric $\overline{p}\pi^+$
- Identity Method makes it possible to account for large combinatoric background
- Efficiency (ε ~10-30%) and secondary contamination (δ ~ 20-35%) corrections performed under binomial assumption





Centrality dependence of 1st moments

$C_1(\Lambda) = \langle N_\Lambda \rangle$

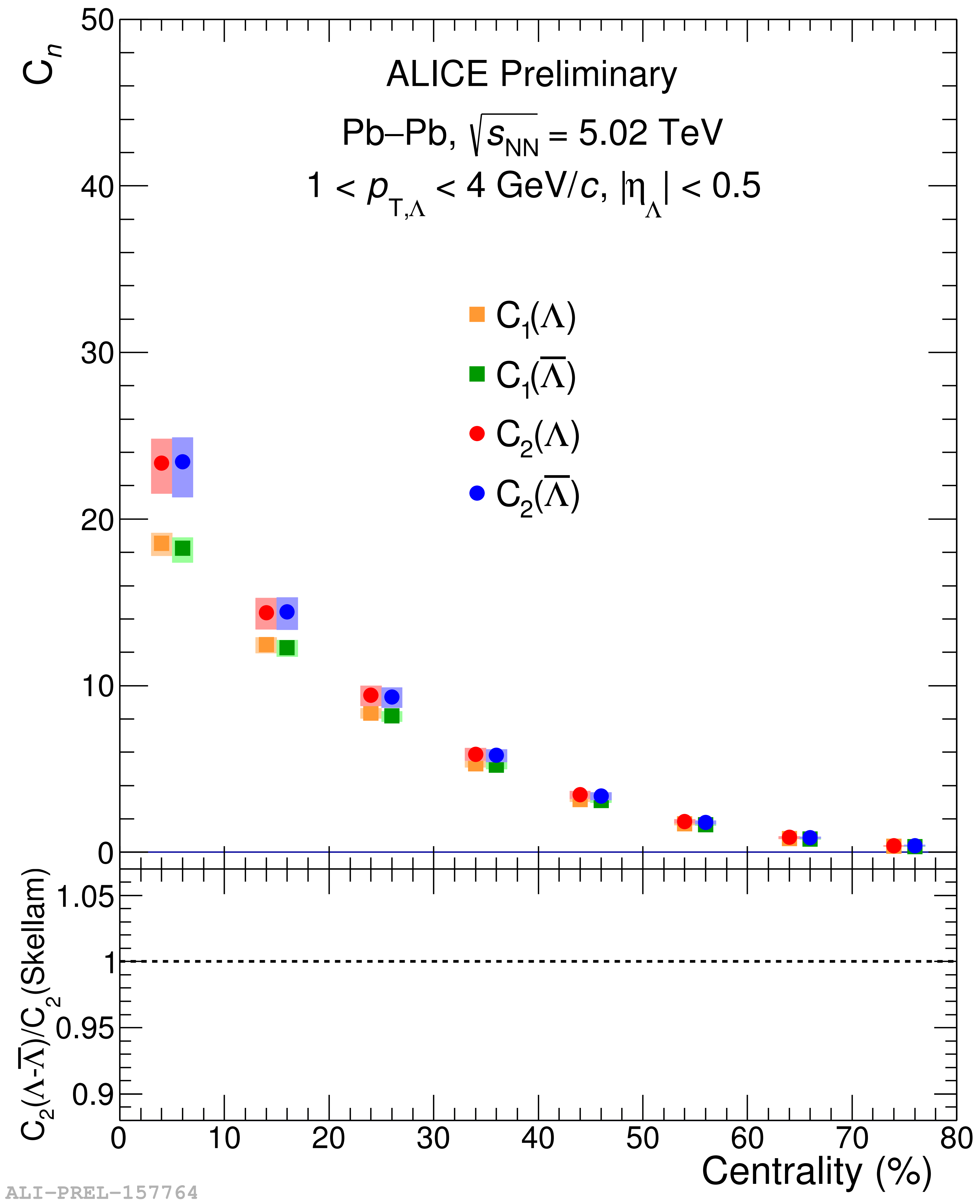


Centrality dependence of 2nd moments

$$C_1(\Lambda) = \langle N_\Lambda \rangle$$
$$C_2(\Lambda) = \langle (N_\Lambda - \langle N_\Lambda \rangle)^2 \rangle$$

- If multiplicity distributions of Λ and $\overline{\Lambda}$ are Poissonian

$$C_2(\Lambda) = C_1(\Lambda)$$



Centrality dependence of net-Λ 2nd moments

$$C_1(\Lambda) = \langle N_\Lambda \rangle$$

$$C_2(\Lambda) = \langle \left(N_\Lambda - \langle N_\Lambda \rangle\right)^2 \rangle$$

$$C_2(\Lambda - \overline{\Lambda}) = \langle \left(N_\Lambda - N_{\overline{\Lambda}} - \langle N_\Lambda - N_{\overline{\Lambda}} \rangle\right)^2 \rangle$$

$$C_2(\Lambda - \overline{\Lambda}) = C_2(\Lambda) + C_2(\overline{\Lambda}) - 2\left(\langle N_\Lambda N_{\overline{\Lambda}} \rangle - \langle N_\Lambda \rangle \langle N_{\overline{\Lambda}} \rangle\right)$$

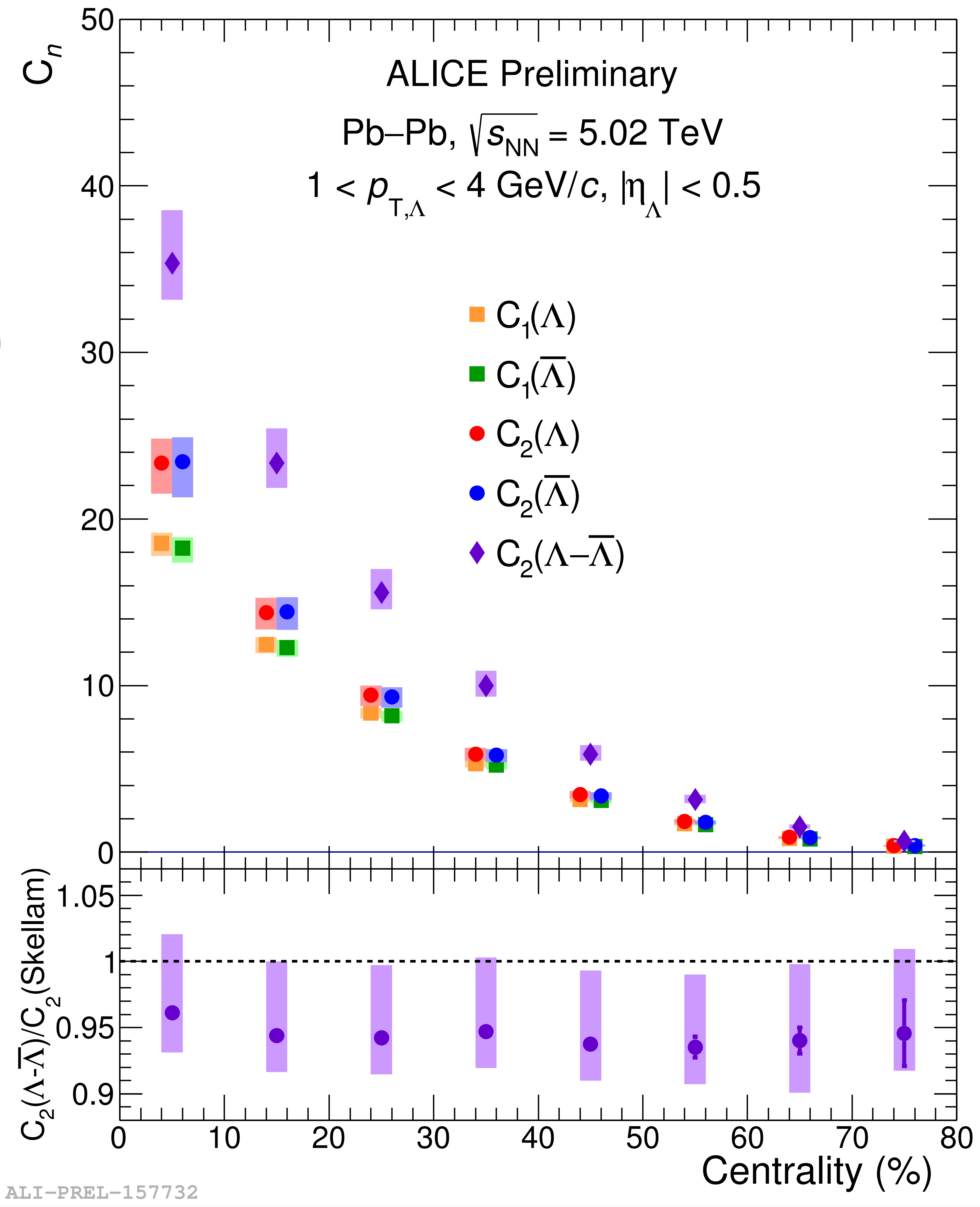
- If multiplicity distributions of Λ and $\overline{\Lambda}$ are Poissonian

$$C_2(\Lambda) = C_1(\Lambda)$$

→ if uncorrelated, Skellam distribution for net-Λ

$$C_2(Skellam) = C_1(\Lambda) + C_1(\overline{\Lambda})$$

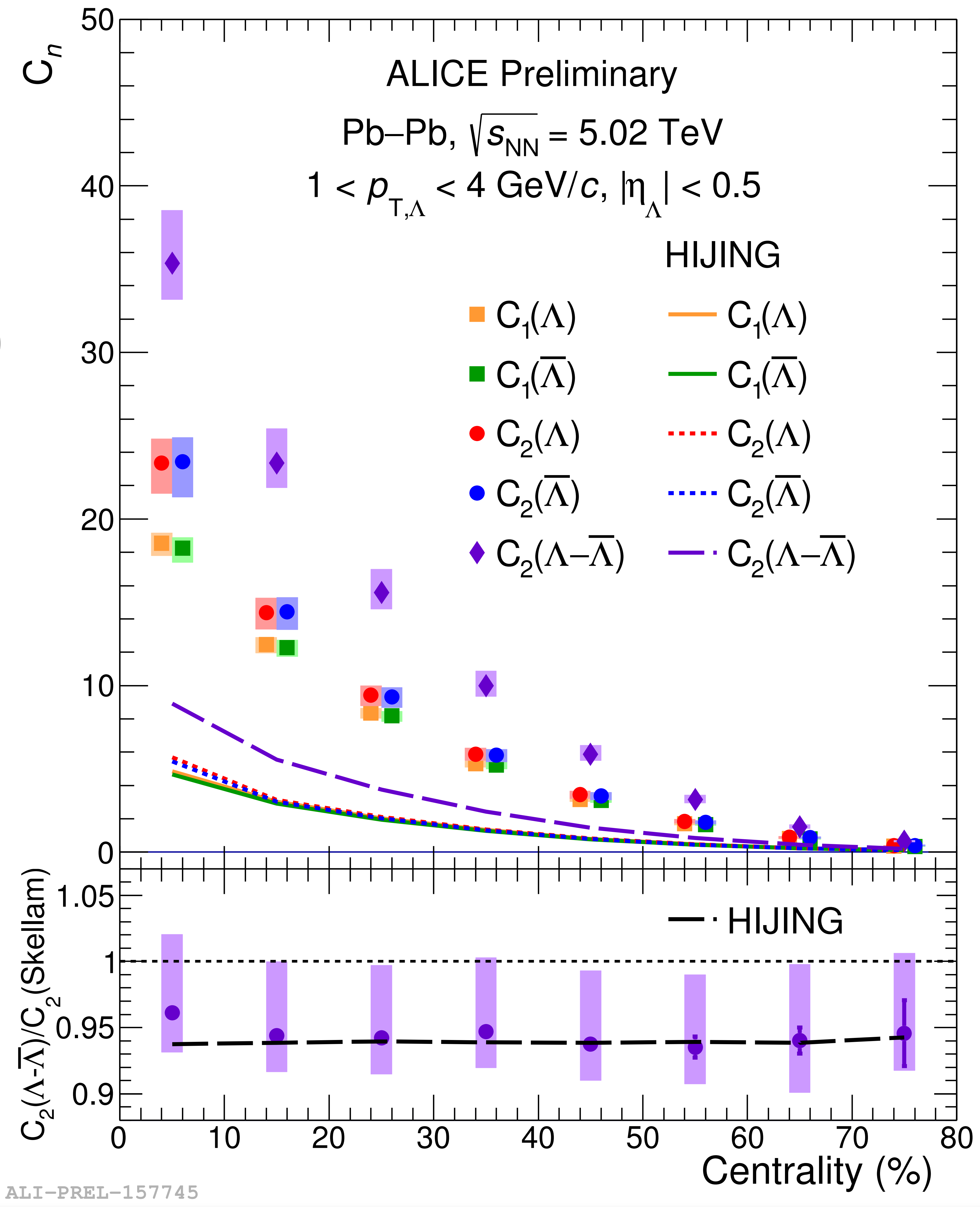
- Small deviations from Skellam baseline
  - correlation term? non-Poissonian Λ or $\overline{\Lambda}$ distributions? critical fluctuations?



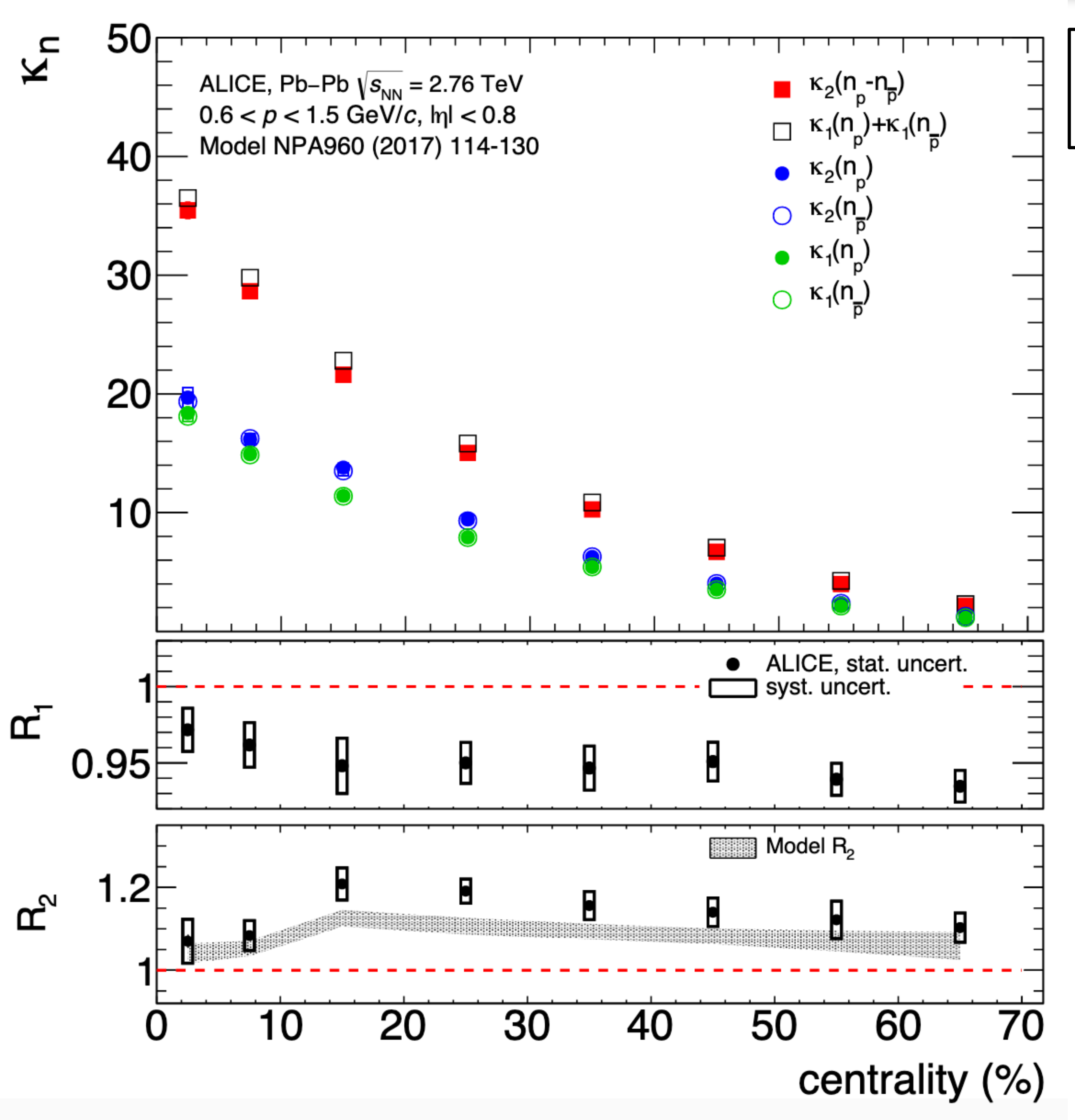
Comparison to HIJING

$$C_1(\Lambda) = \langle N_\Lambda \rangle$$
$$C_2(\Lambda) = \langle \left(N_\Lambda - \langle N_\Lambda \rangle\right)^2 \rangle$$
$$C_2(\Lambda - \overline{\Lambda}) = \langle \left(N_\Lambda - N_{\overline{\Lambda}} - \langle N_\Lambda - N_{\overline{\Lambda}} \rangle\right)^2 \rangle$$
$$C_2(\Lambda - \overline{\Lambda}) = C_2(\Lambda) + C_2(\overline{\Lambda}) - 2\left(\langle N_\Lambda N_{\overline{\Lambda}} \rangle - \langle N_\Lambda \rangle \langle N_{\overline{\Lambda}} \rangle\right)$$

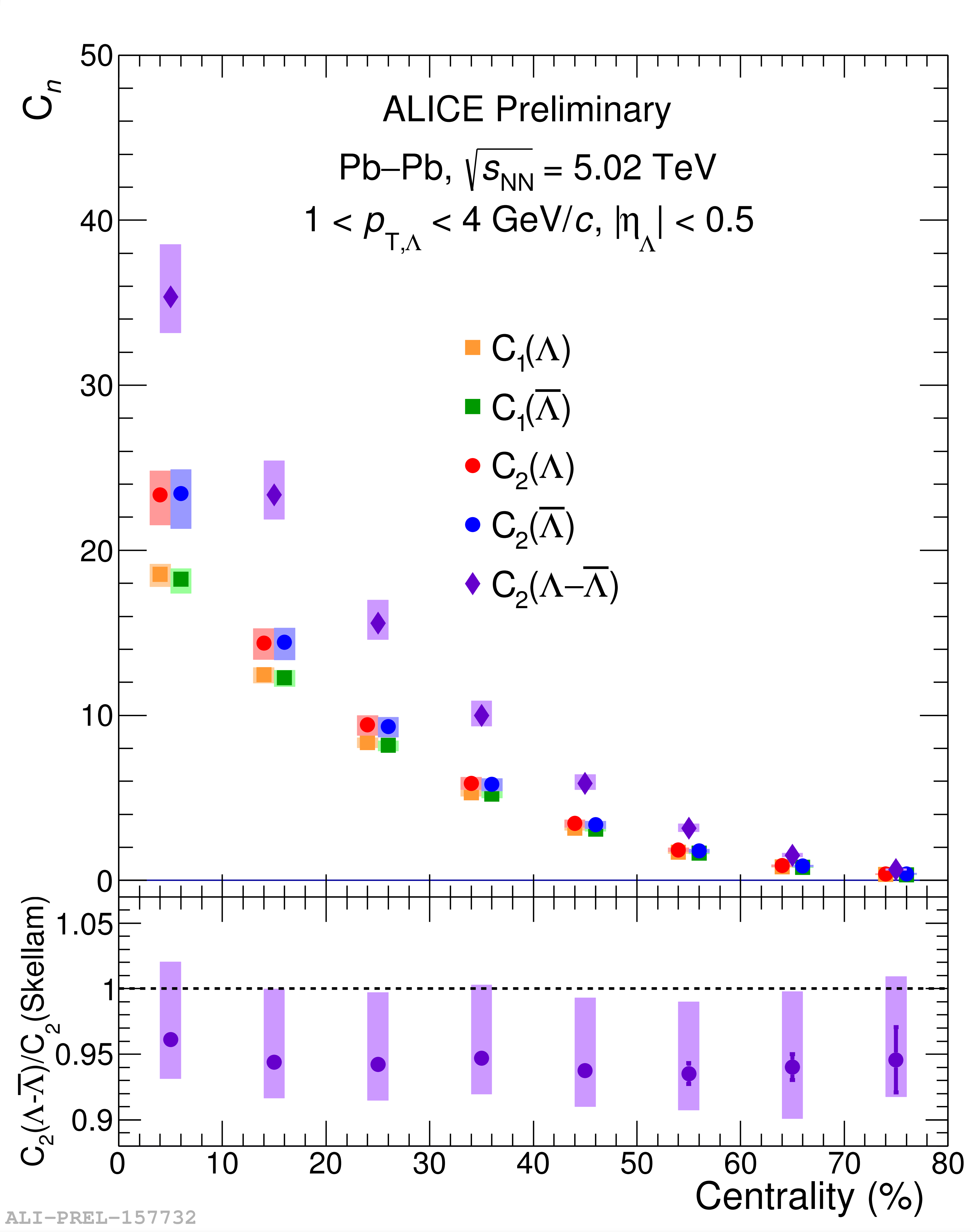
- HIJING does not describe strangeness production well
  - underestimates C_1 and C_2 by factor ~4
- $C_2(\Lambda\text{-}\overline{\Lambda})/C_2(\text{Skellam})$ ratio agrees with data
  - coincidence? or due to description of fluctuations and resonance contributions in HIJING?



Comparison to net-protons

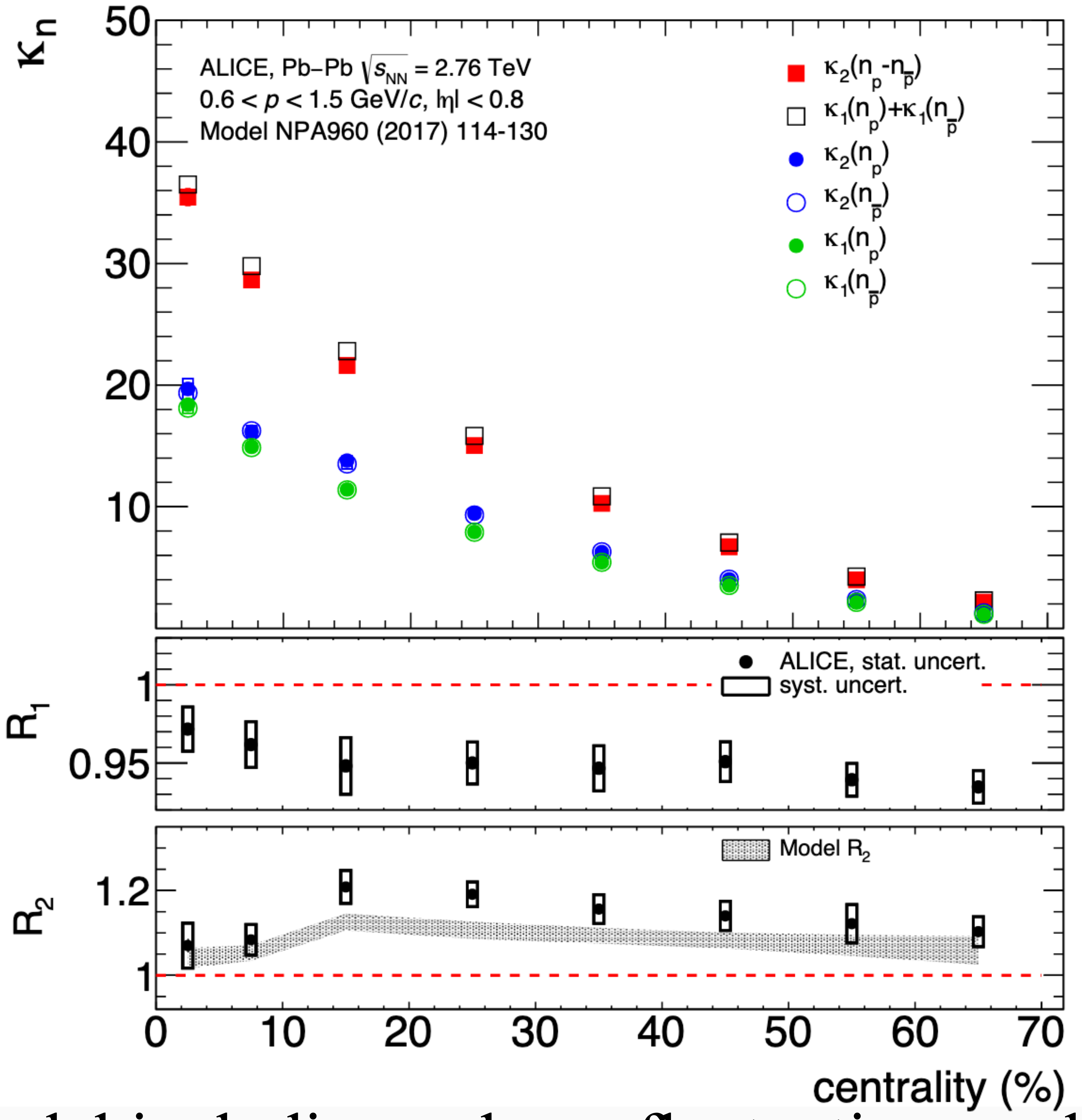


PLB 807 (2020) 135564,
arXiv:1910.14396

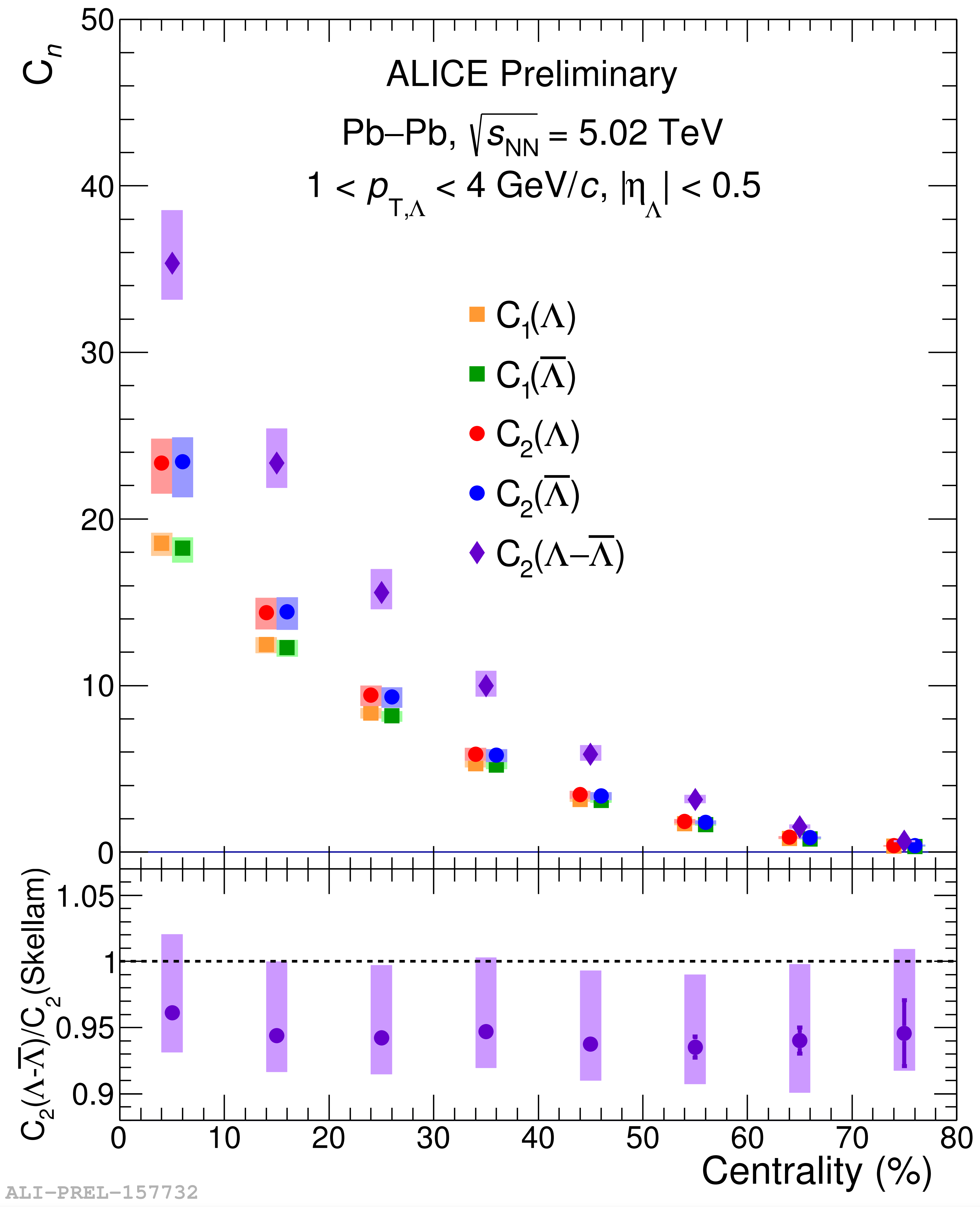


- Qualitatively similar results for net-protons
  - note different kinematic range
  - different contributions from resonance decays

Comparison to net-protons



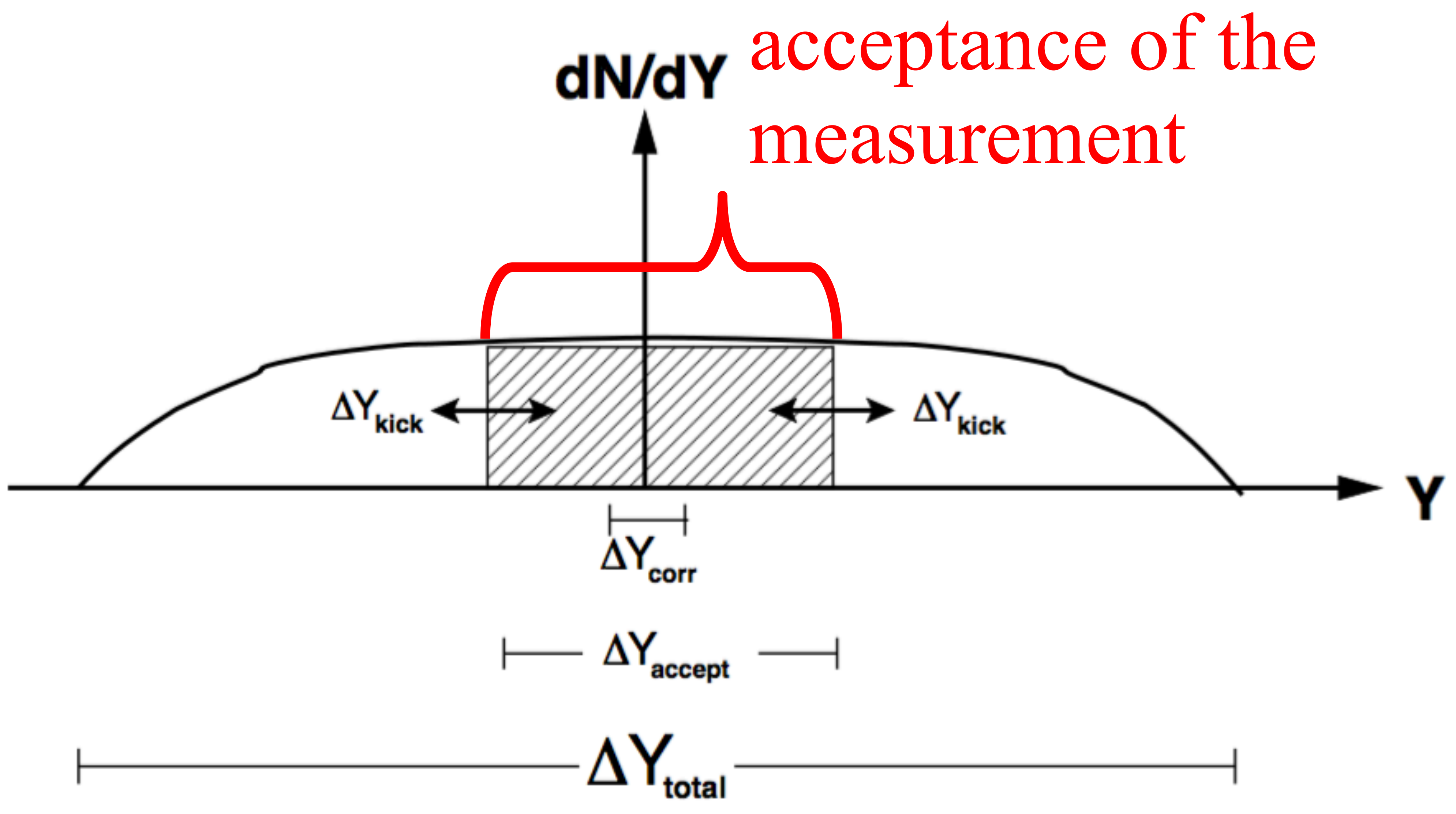
PLB 807 (2020) 135564, arXiv:1910.14396



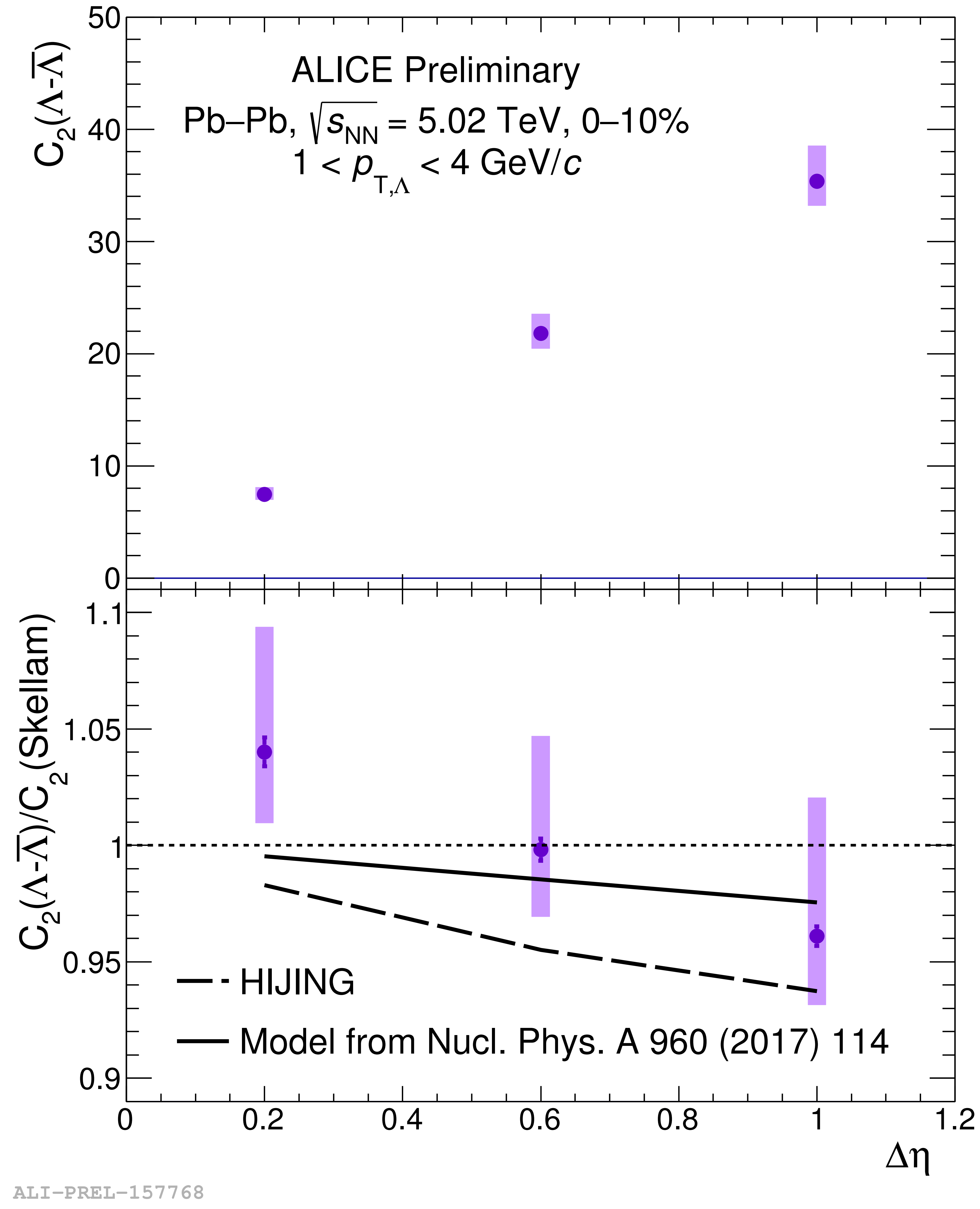
- Model including volume fluctuations and global baryon number conservation fully describes deviations from Poisson/Skellam expectation for net-protons

P. Braun-Munzinger, A. Rustamov, J. Stachel, NPA 960 (2017) 114, arXiv:1612.00702 [nucl-th]

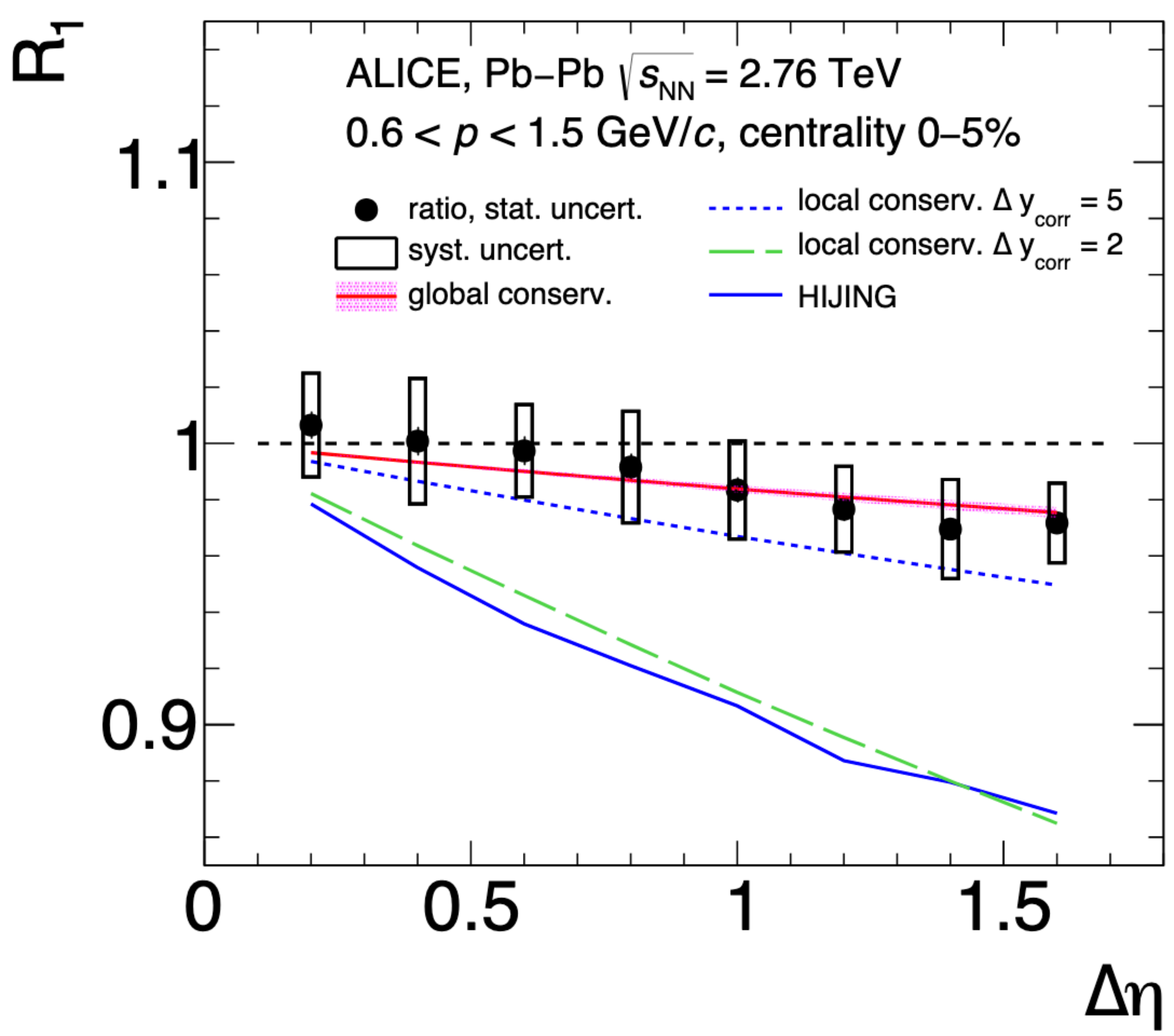
Δη dependence in central collisions



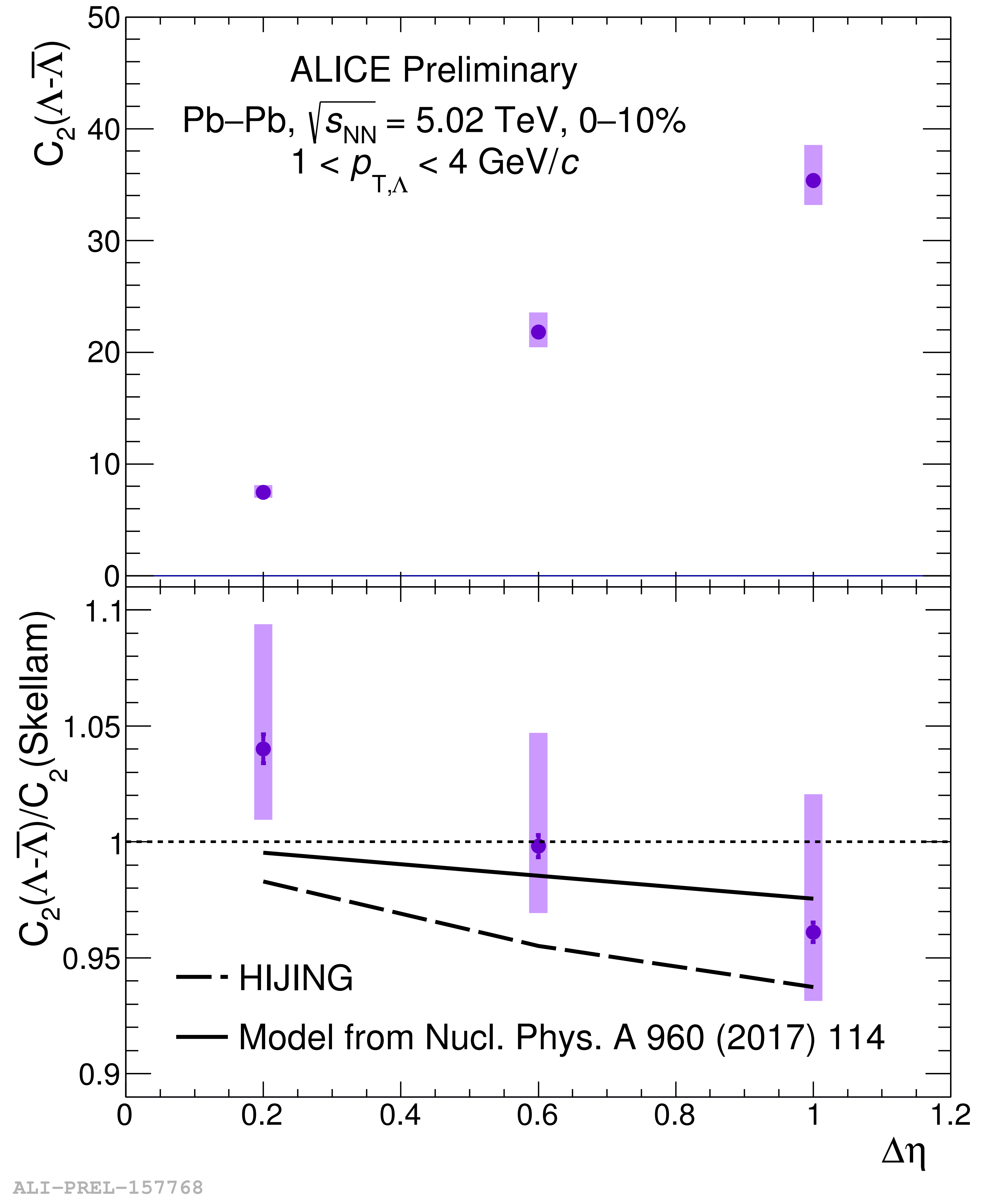
- Small Δη → Poissonian fluctuations, ratio to Skellam ~1
- Large Δη → global baryon number and strangeness conservation effects, ratio to Skellam < 1
- Systematic uncertainties are highly correlated point-to-point
- Δη dependence consistent with effects of baryon number conservation



Δη dependence, comparison to net-protons

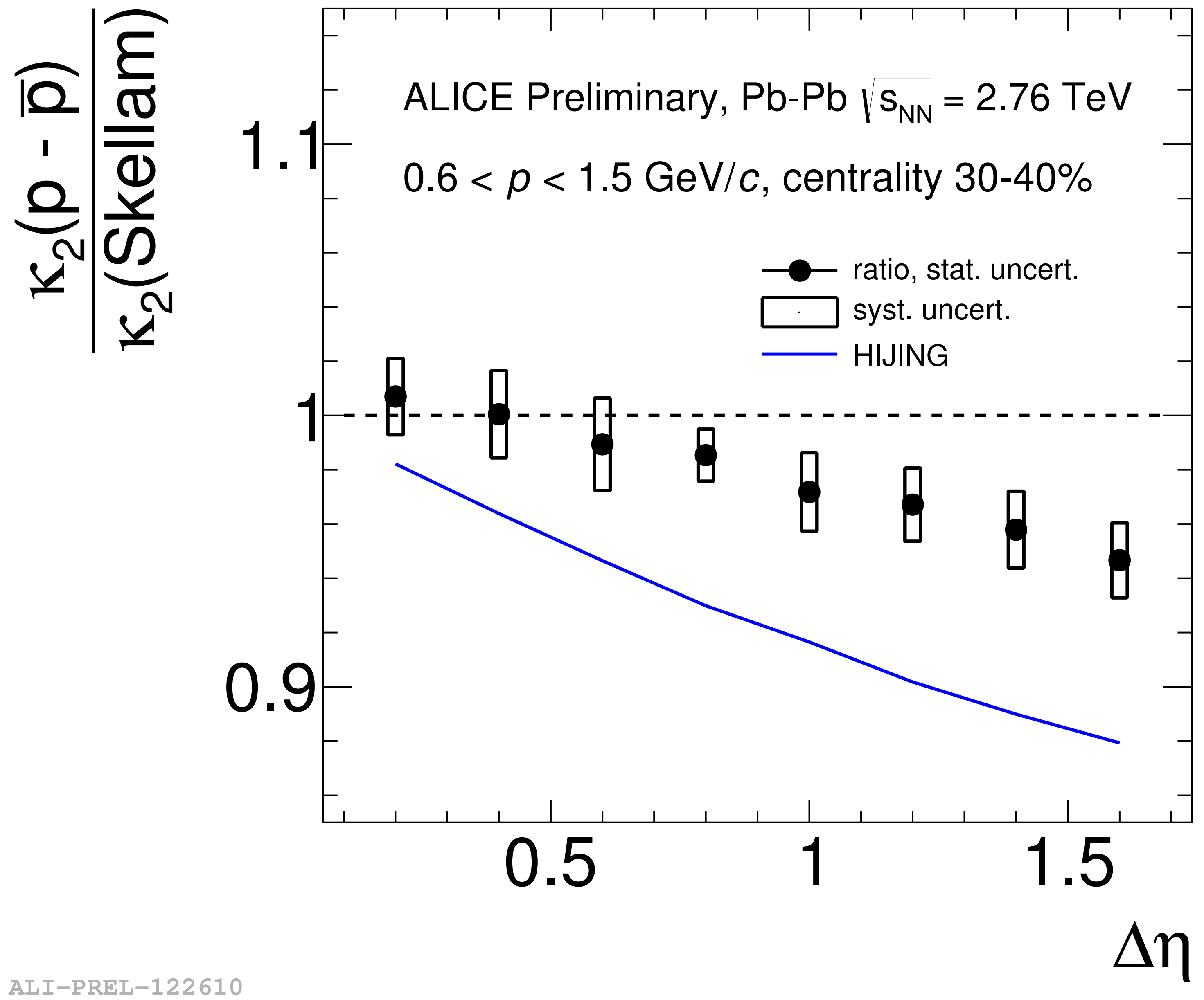


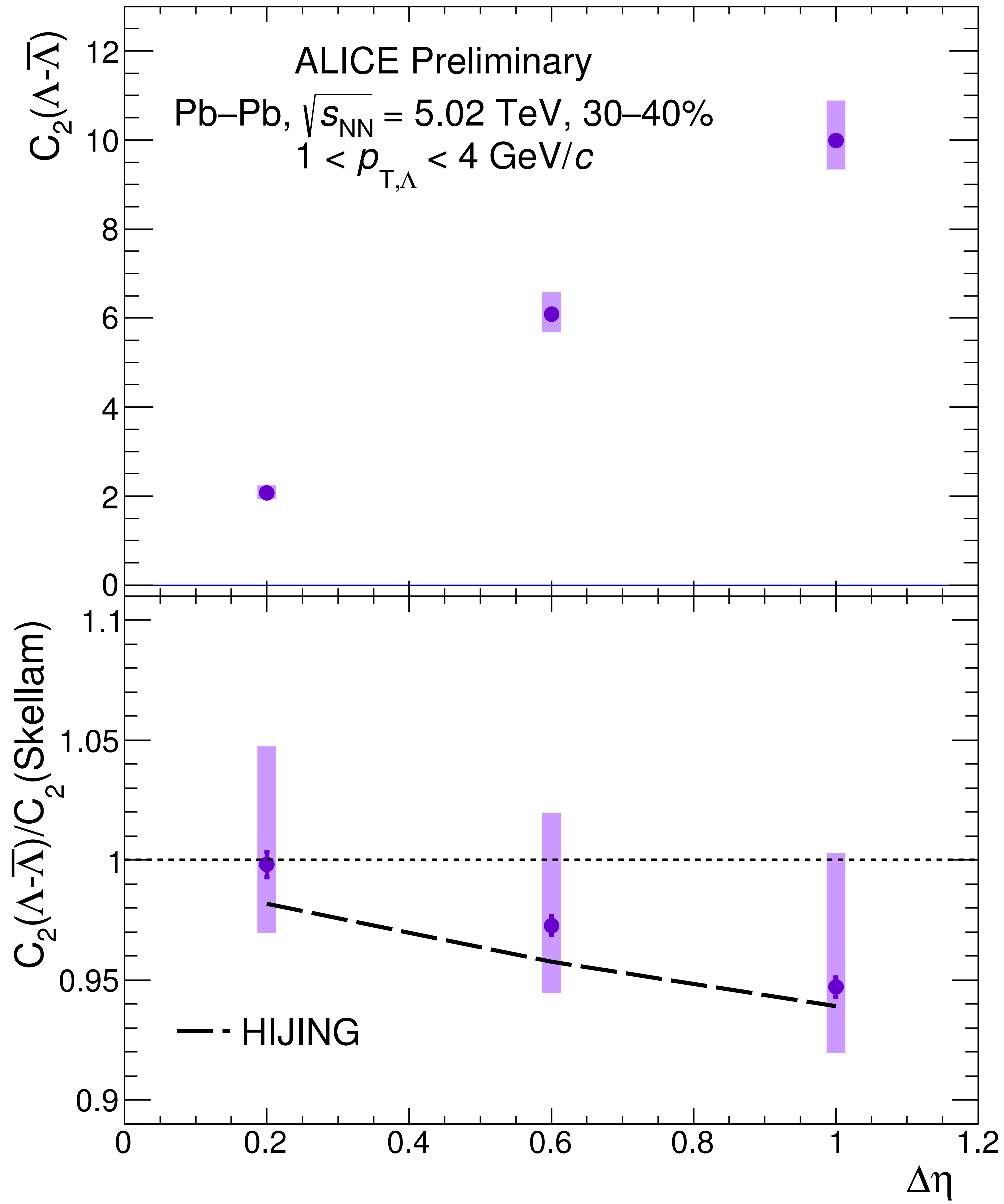
PLB 807 (2020) 135564, arXiv:1910.14396



- $C_2(p-\bar{p})$ fully consistent with Skellam baseline after accounting for global baryon number conservation
- Similar trends for net-Λ
  - also strangeness conservation effects should be considered

Δη dependence in mid-central collisions

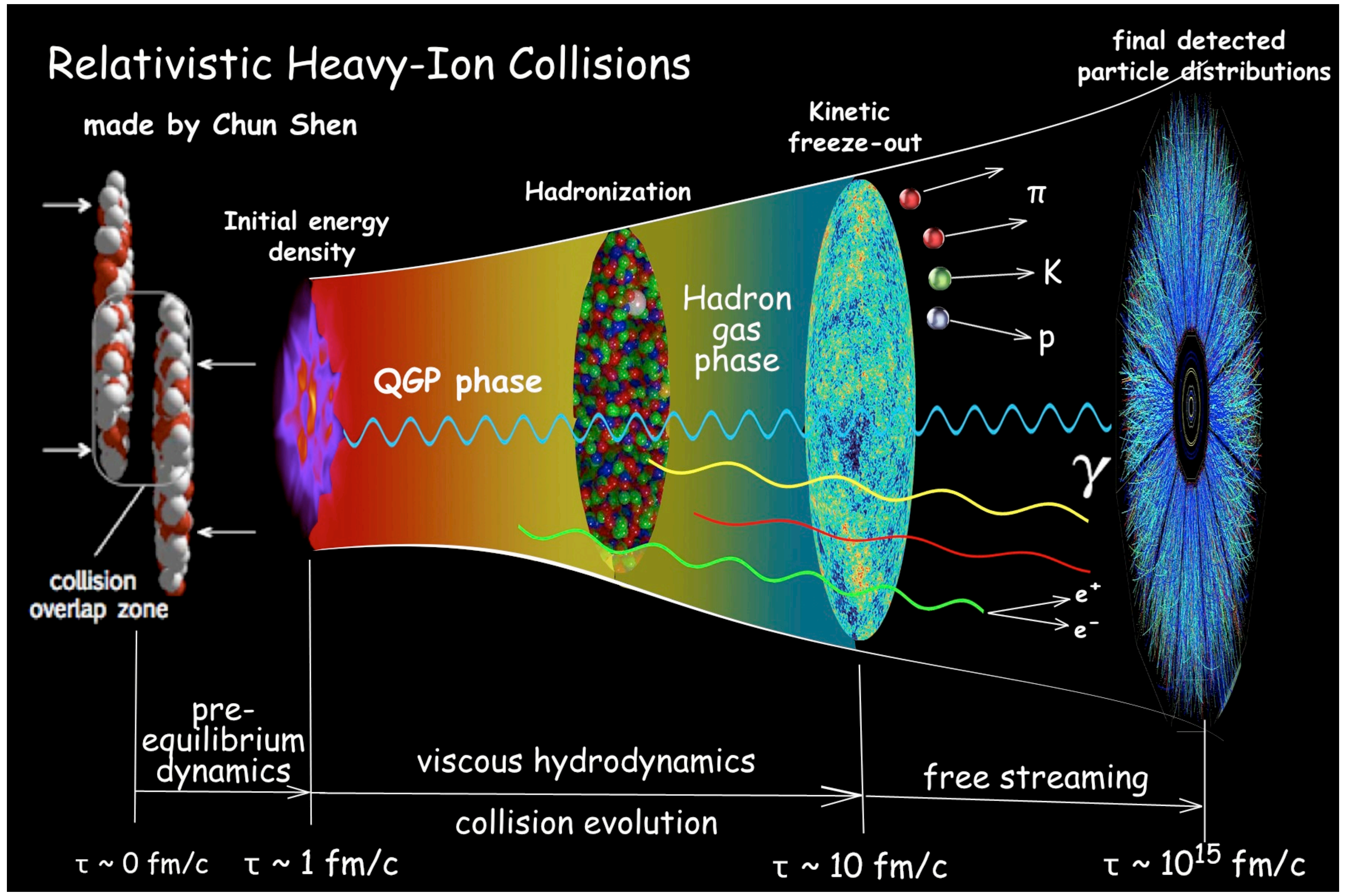


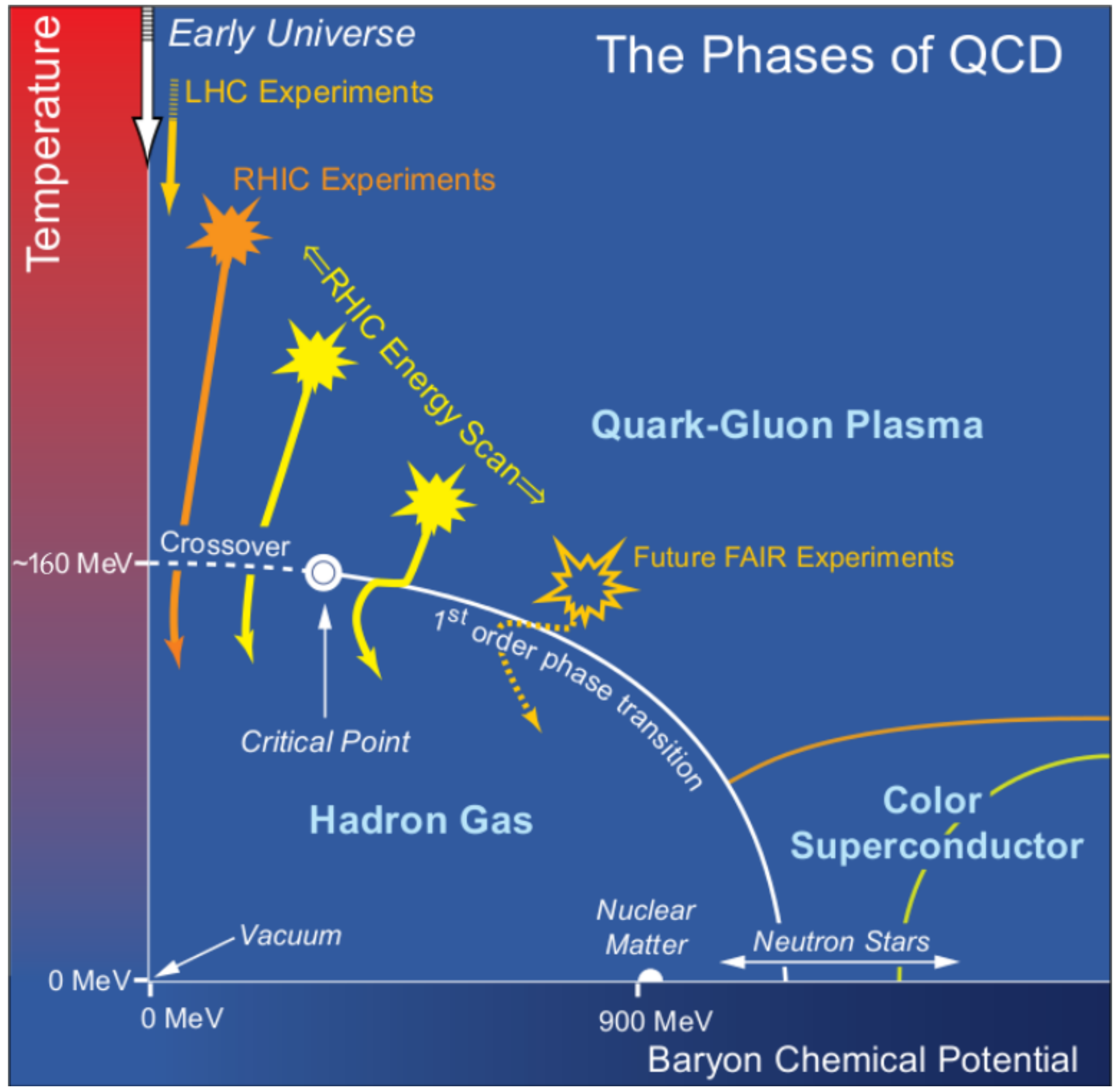


- Net-protons results not described by HIJING, but net-Λ results are consistent

Conclusions

- Properties of the quark-gluon plasma:
  - strong quenching of colored probes ($\hat{q}$)
  - collective behavior with very low shear viscosity (η/s)
  - high temperatures, mostly statistical particle production (T_{chem}, T_{kin})
  - susceptibilities give information about the phase transition (χ)





Conclusions

- Properties of the quark-gluon plasma:
  - strong quenching of colored probes ($\hat{q}$)
  - collective behavior with very low shear viscosity (η/s)
  - high temperatures, mostly statistical particle production (T_{chem}, T_{kin})
  - susceptibilities give information about the phase transition (χ)
- Event-by-event fluctuations of identified particles
  - yield information on properties of the QGP medium
  - test lattice QCD predictions at $\mu_B = 0$
  - allow us to look for effects of criticality
- Net-proton and net-Λ fluctuations at LHC energies: no deviations from Skellam baseline observed after accounting for baryon number conservation, agreement with LQCD predictions
- Net-proton fluctuations at RHIC energies: can be described above $\sqrt{s_{NN}} = 11.5$ GeV by baryon number conservation

Thank you for your attention!

Any questions?

ALICE

Global conservation laws

- Contribution from global baryon number conservation calculated as

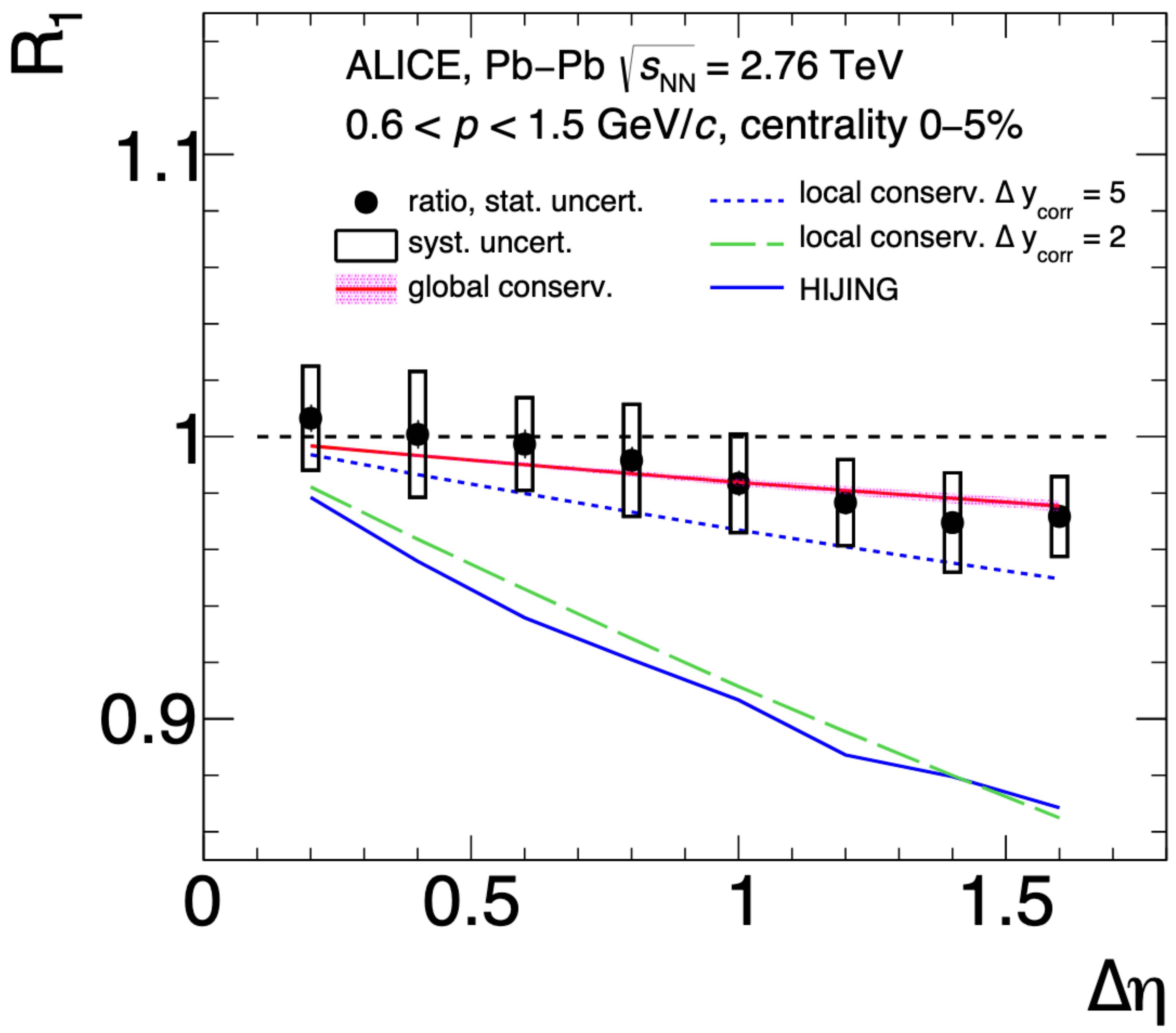
$$\frac{\kappa_2(p-\bar{p})}{\kappa_2(Skellam)} = 1 - \frac{\langle N_p^{meas} \rangle}{\langle N_B^{4\pi} \rangle} = 1 - \alpha$$

- Inputs for $\langle N_B^{acc} \rangle$ from

  P. Braun-Munzinger et al., PLB 747 (2015) 292, arXiv:1412.8614 [hep-ph]

  Extrapolation from $\langle N_B^{acc} \rangle$ to $\langle N_B^{4\pi} \rangle$ using AMPT and HIJING
- Deviation from Skellam baseline accounted for by global baryon number conservation
  - or local conservation over 5 units of pseudorapidity

ALICE, PLB 807 (2020) 135564, arXiv:1910.14396



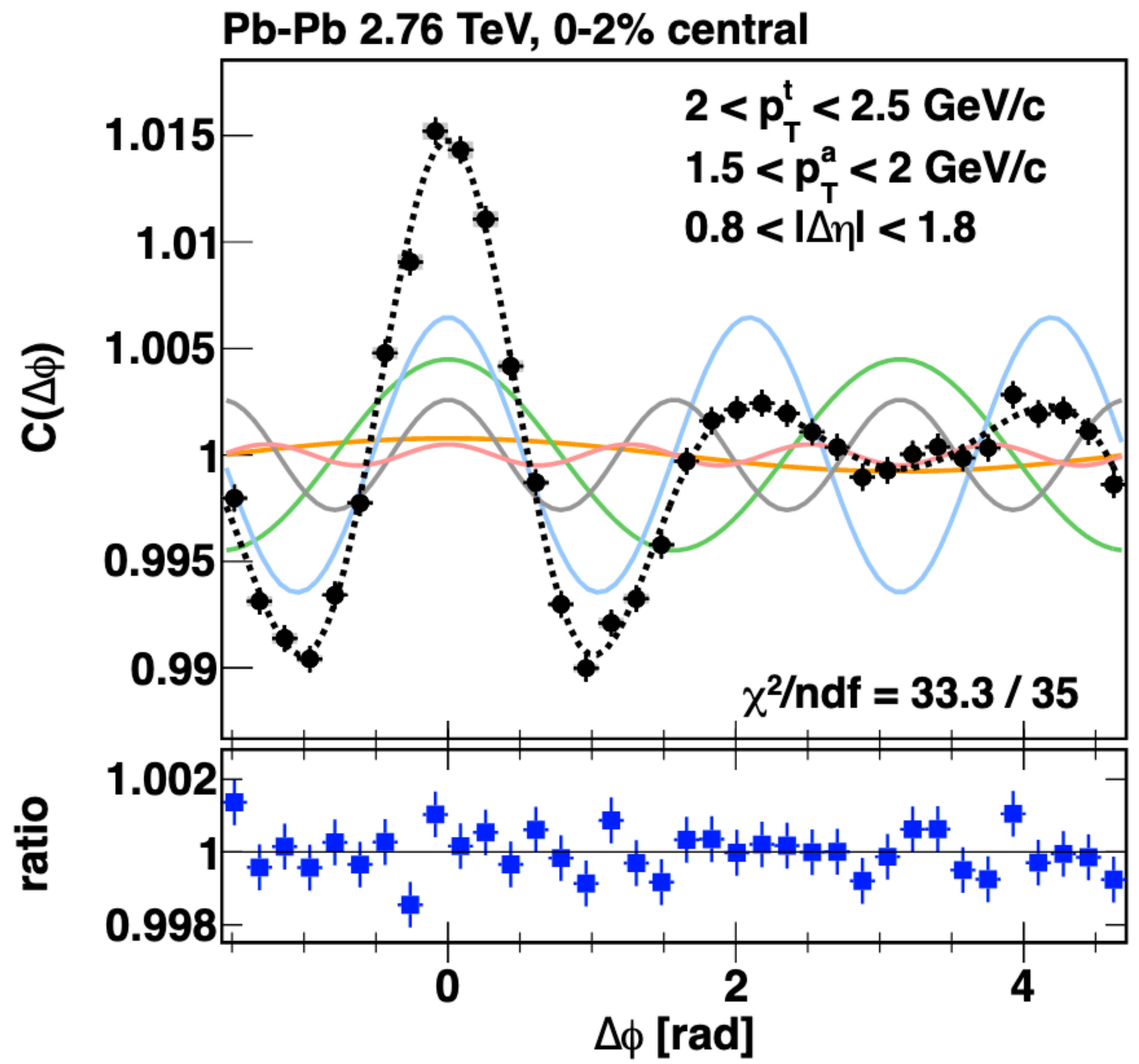
Anisotropic flow coefficients

- Particle distribution described by a Fourier cosine series

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

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

$$dN/d\varphi \sim 1 + 2v_2^2\cos(2\Delta\varphi)$$



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

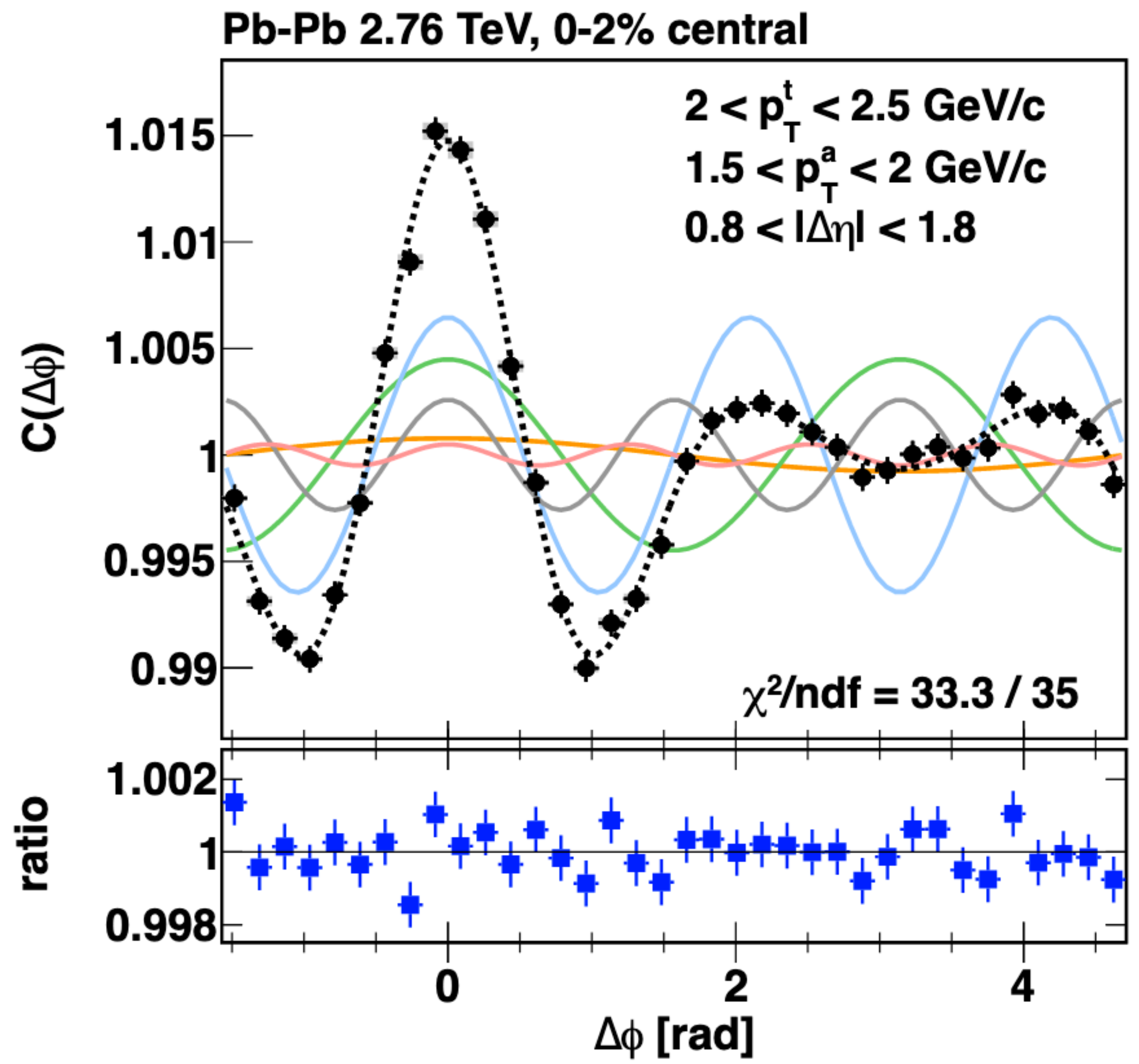
Anisotropic flow coefficients

- Particle distribution described by a Fourier cosine series

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

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

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



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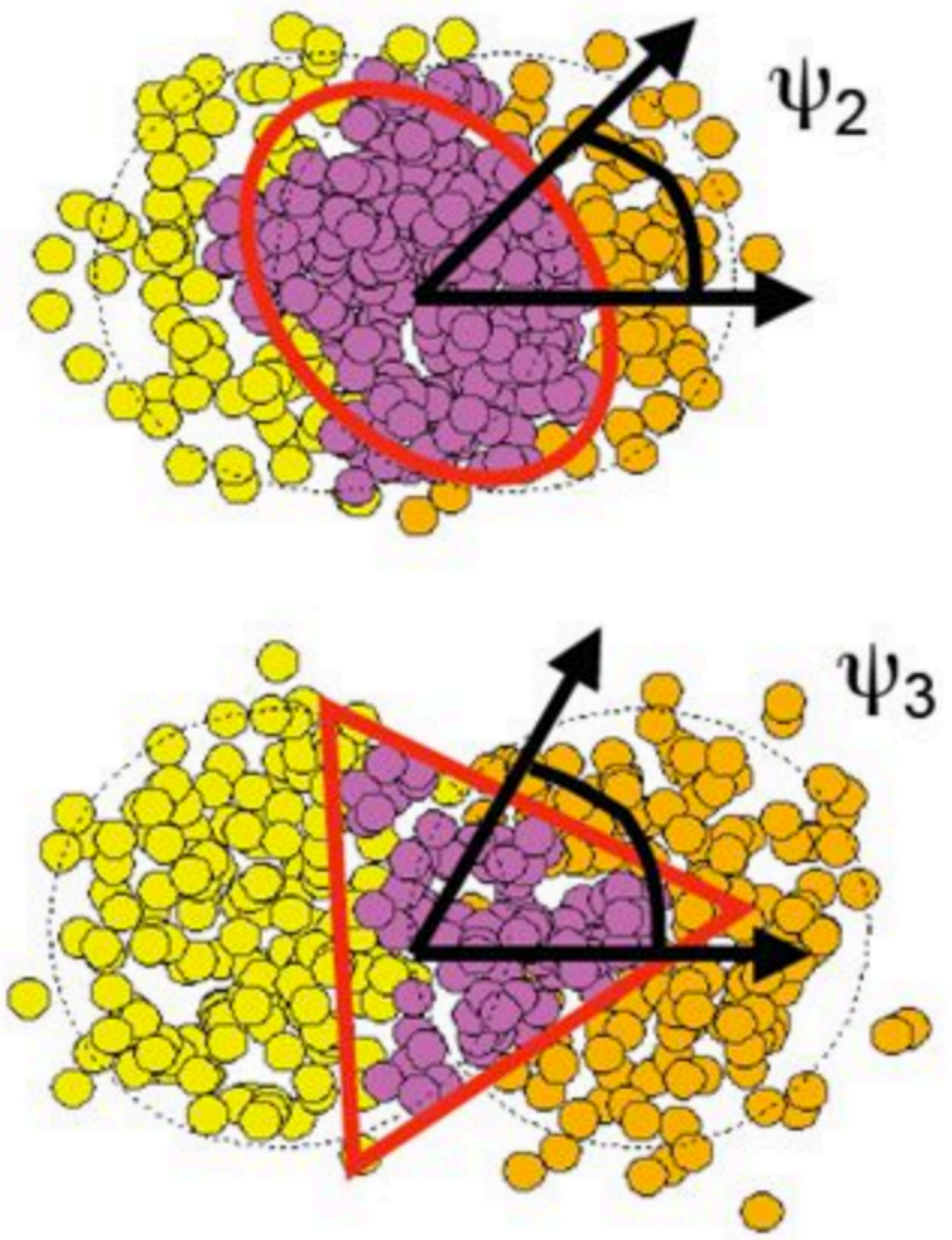
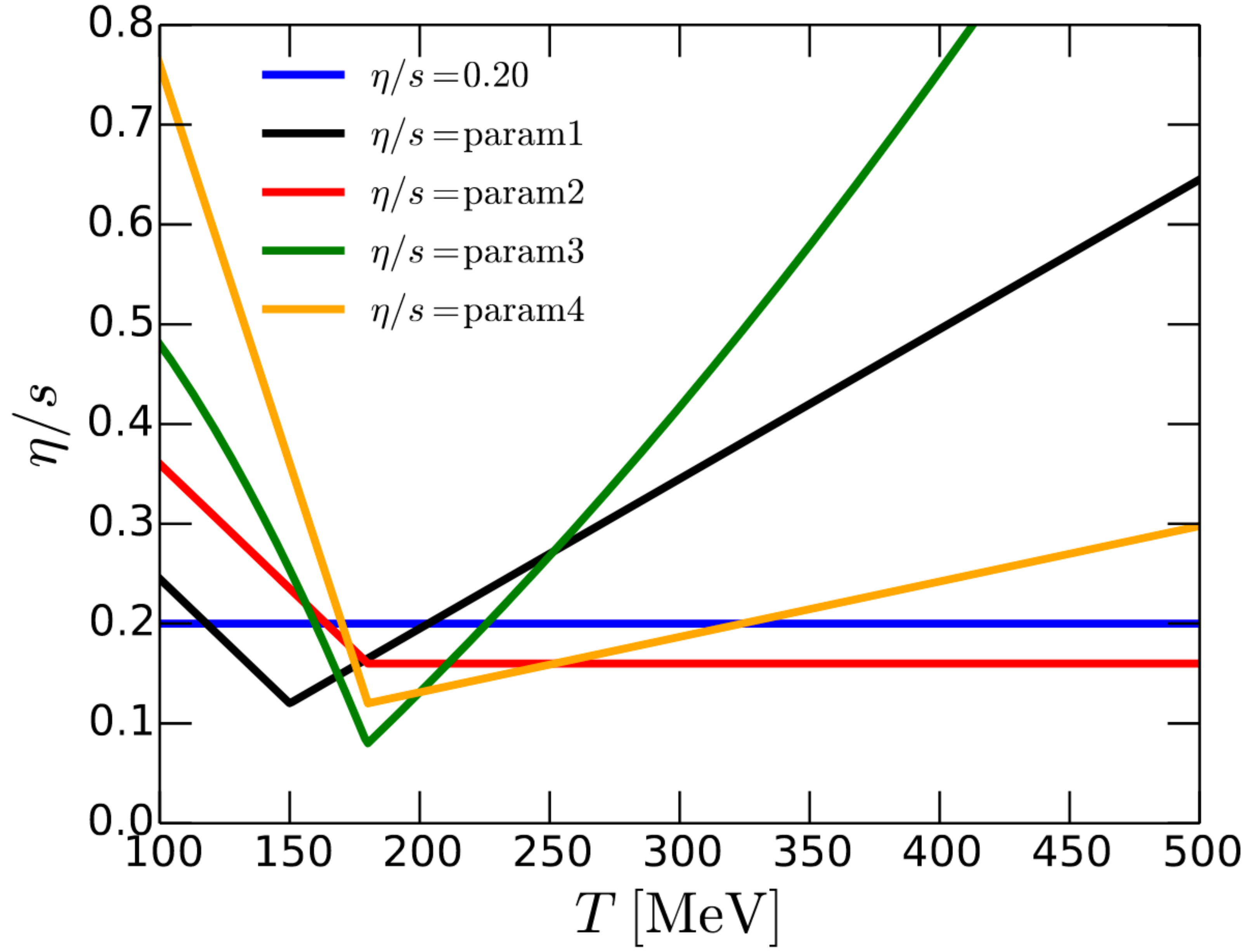
Higher-order flow coefficients

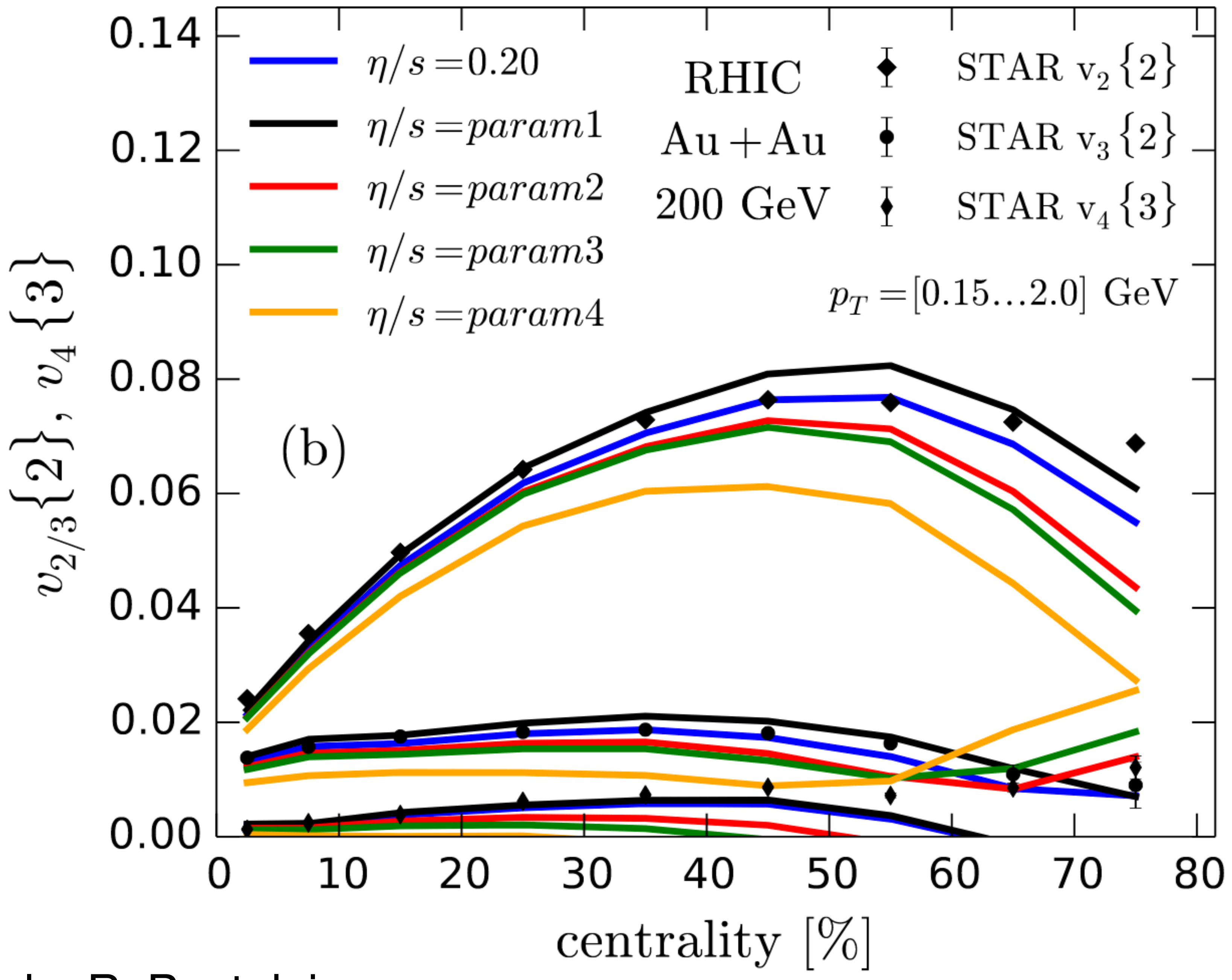
- Due to event-by-event fluctuations of the positions of nucleons, overlap region is not perfectly symmetric
  → development of triangular flow v_3, quadrangular flow v_4,...



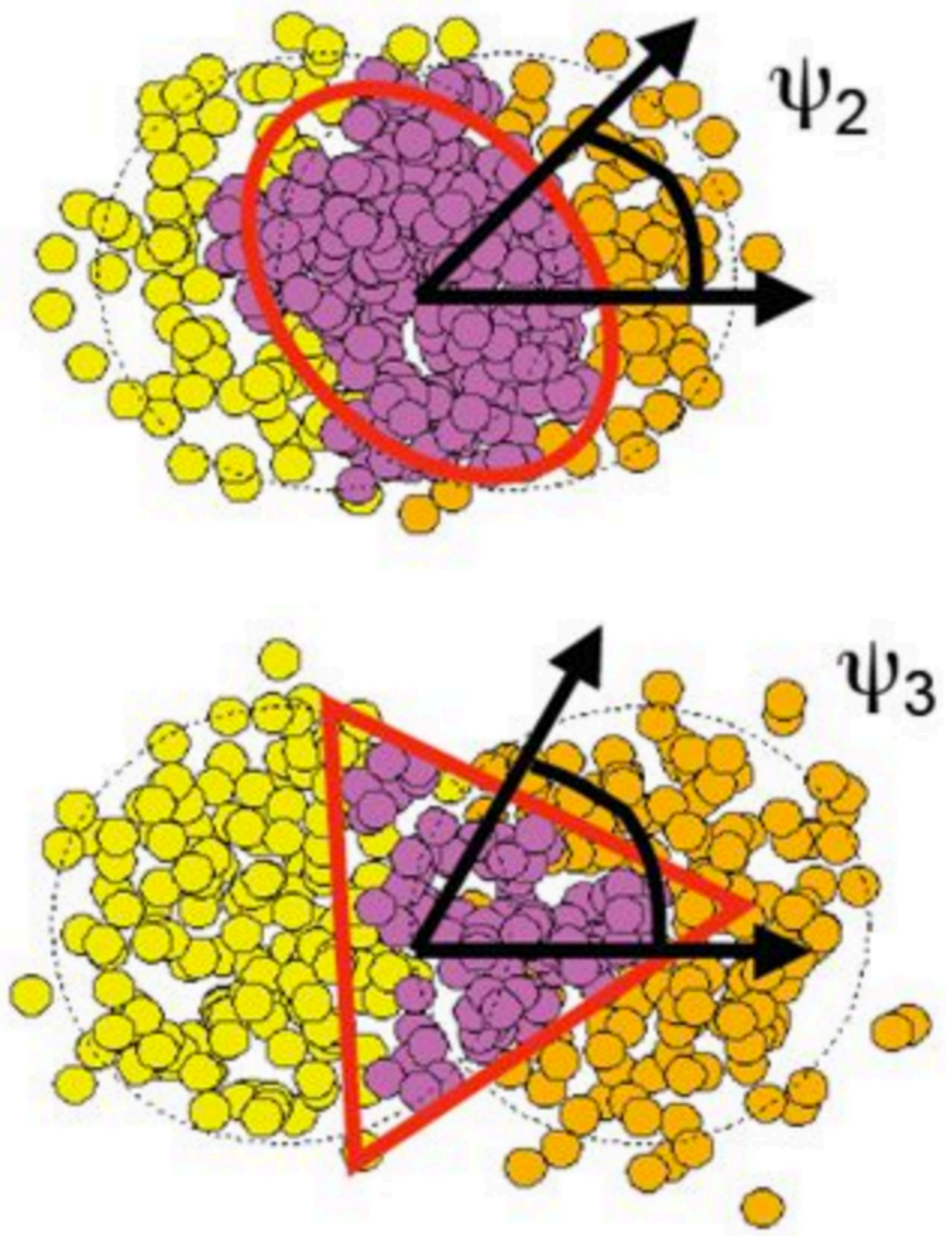
Higher-order flow coefficients

- 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

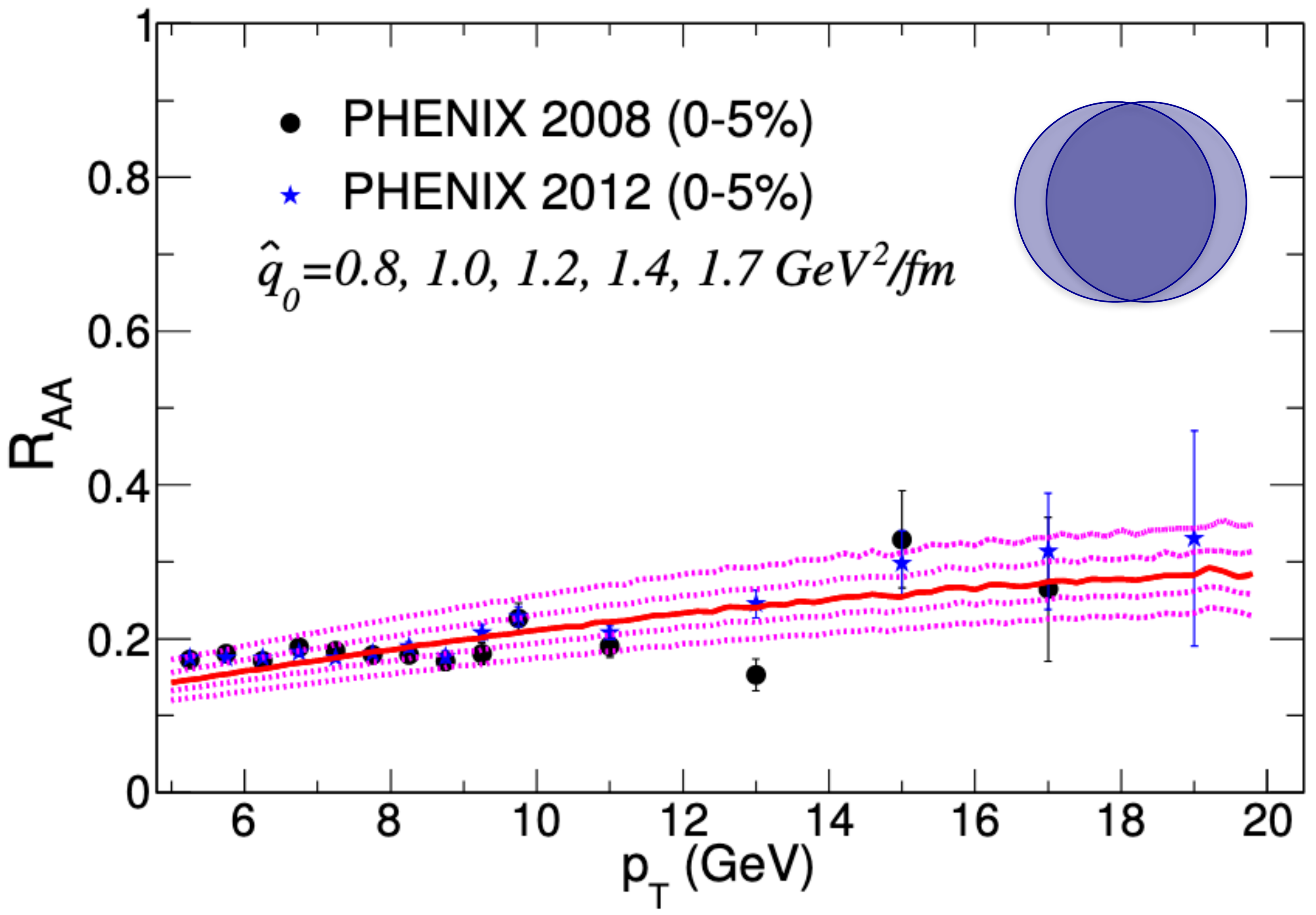


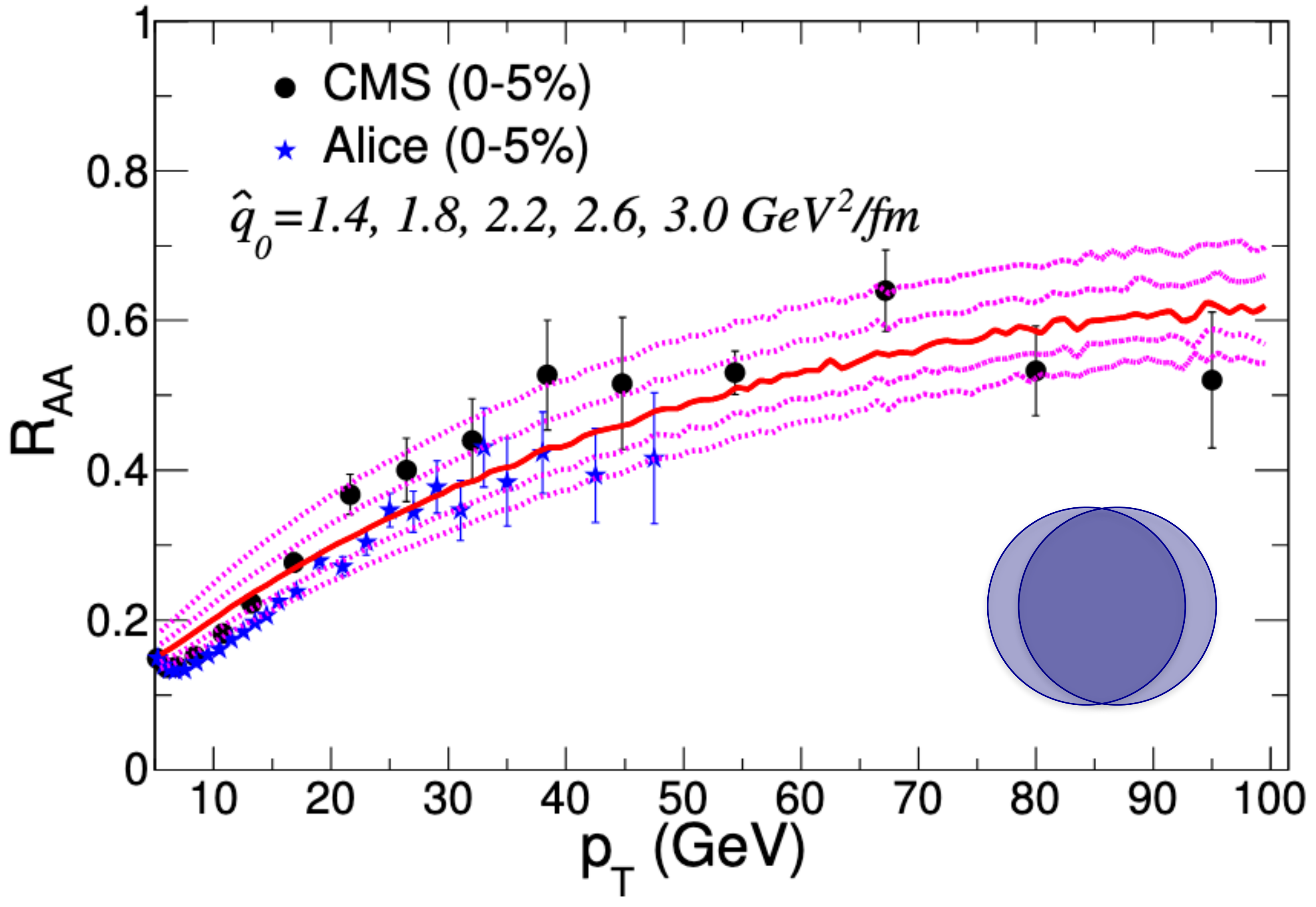


H. Niemi, K.J. Eskola, R. Paatelainen, PRC 93 (2016) 024907, arXiv:1505.02677 [hep-ph]



Charged particle R_{AA}





Number of particles in a heavy-ion collision

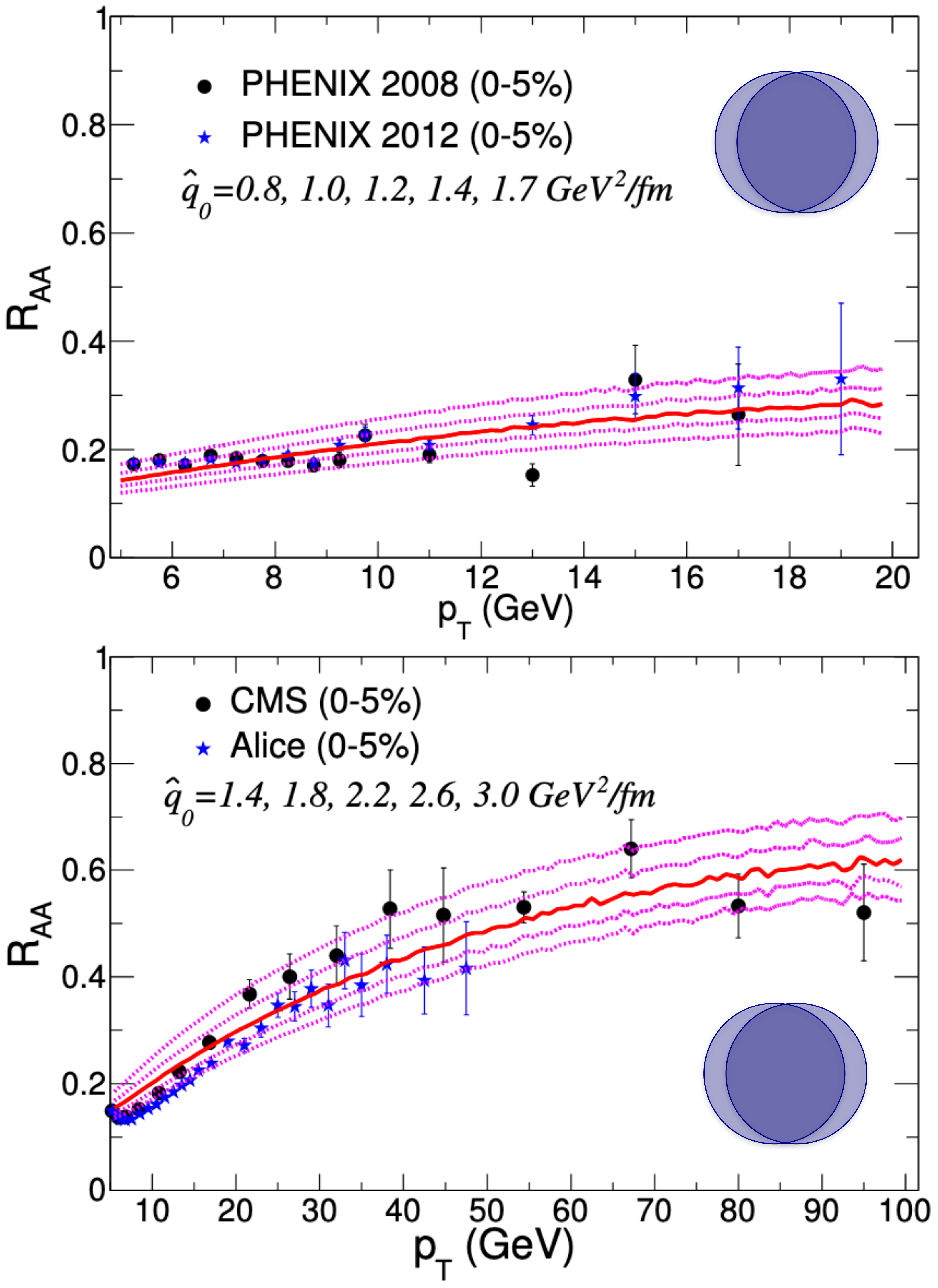
$$R_{AA} = \frac{(1/N_{evt})\ dN_{ch}/dp_T\big|_{AA}}{\langle N_{coll}\rangle\ (1/N_{evt})\ dN_{ch}/dp_T\big|_{pp}}$$

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

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

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