Studying the properties of the deconfined medium in heavy-ion collisions with fluctuations

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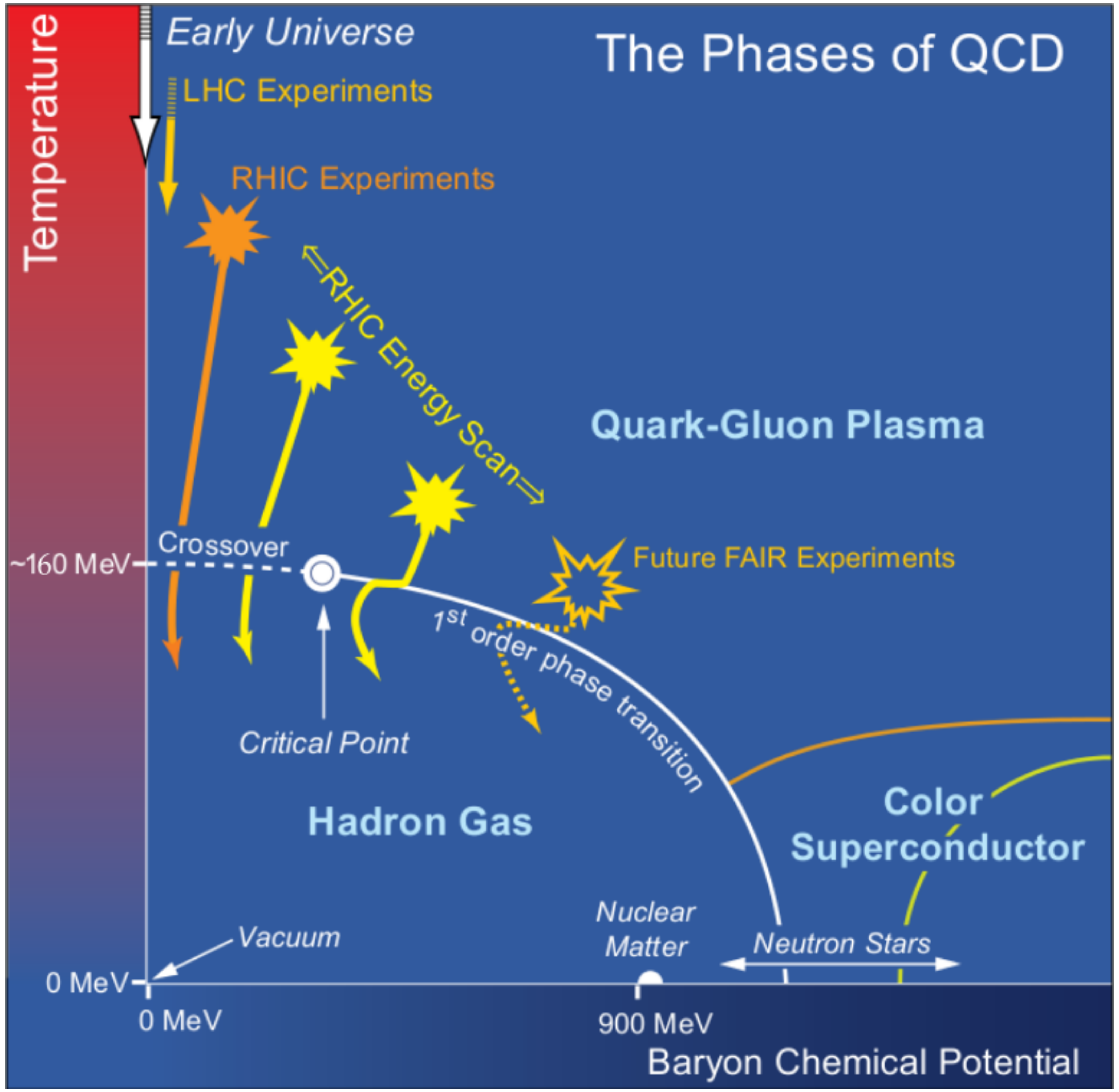
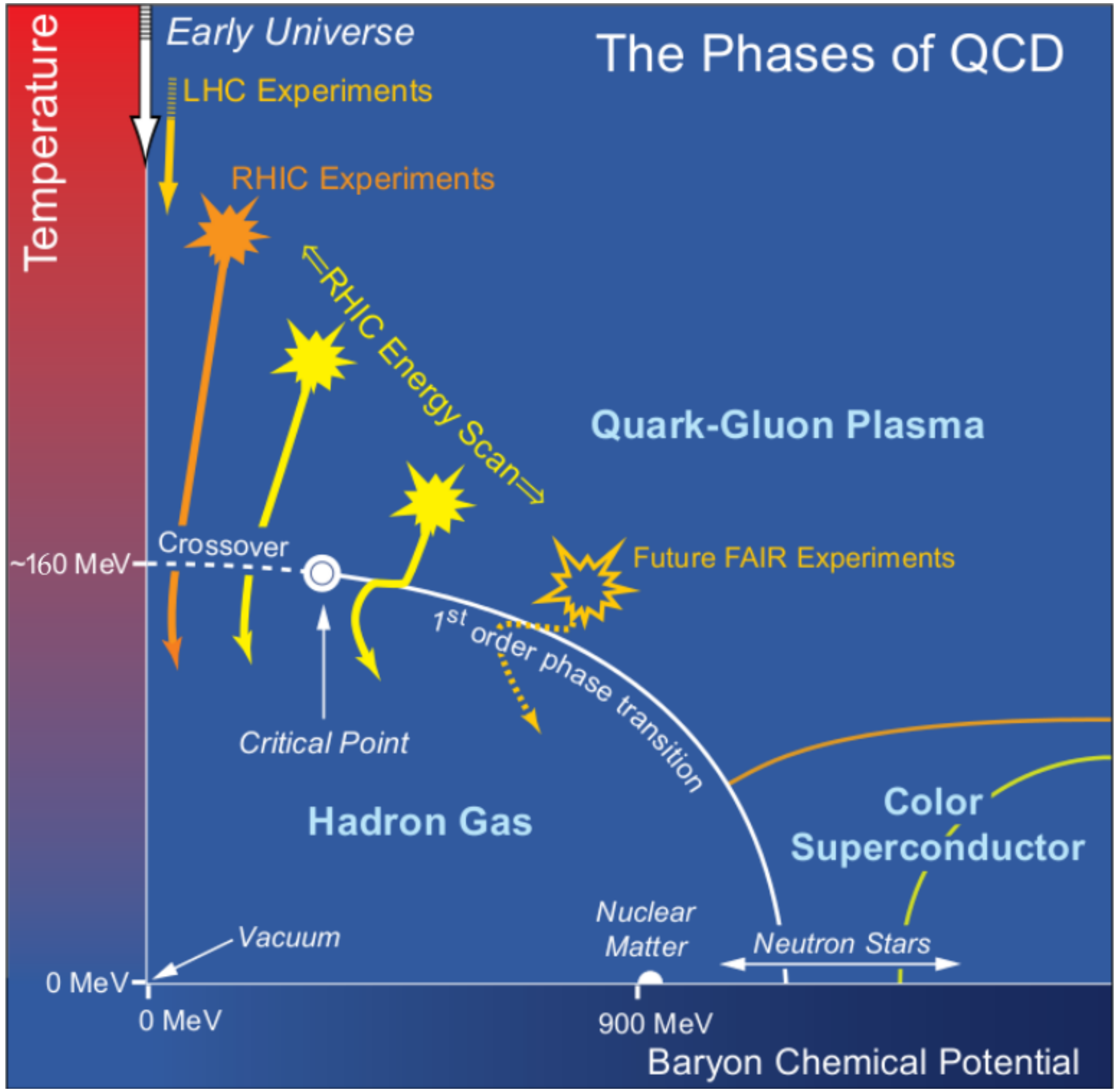
6 August 2021
A Virtual Tribute to Quark Confinement and the Hadron Spectrum

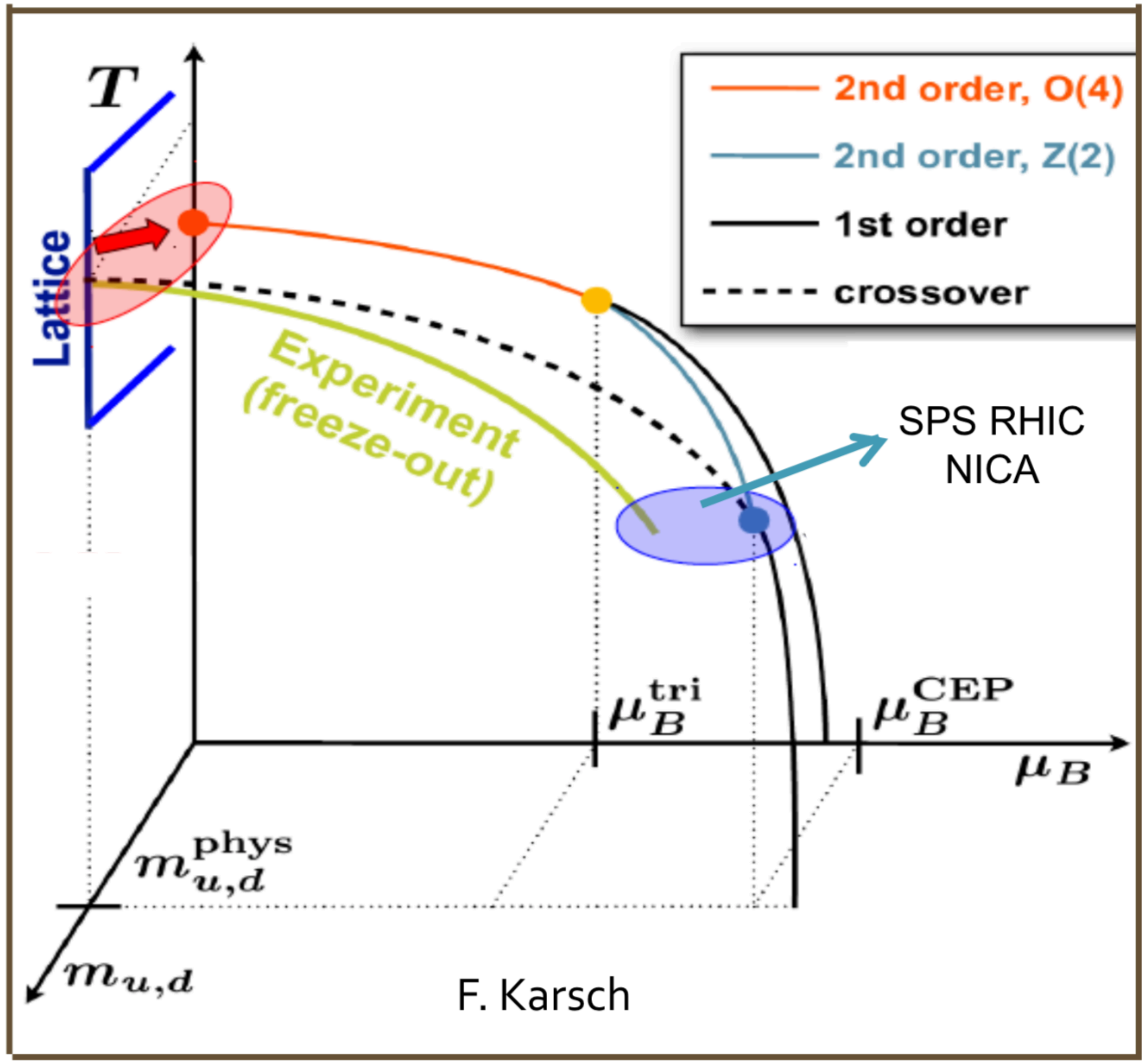
Phase structure of nuclear matter



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

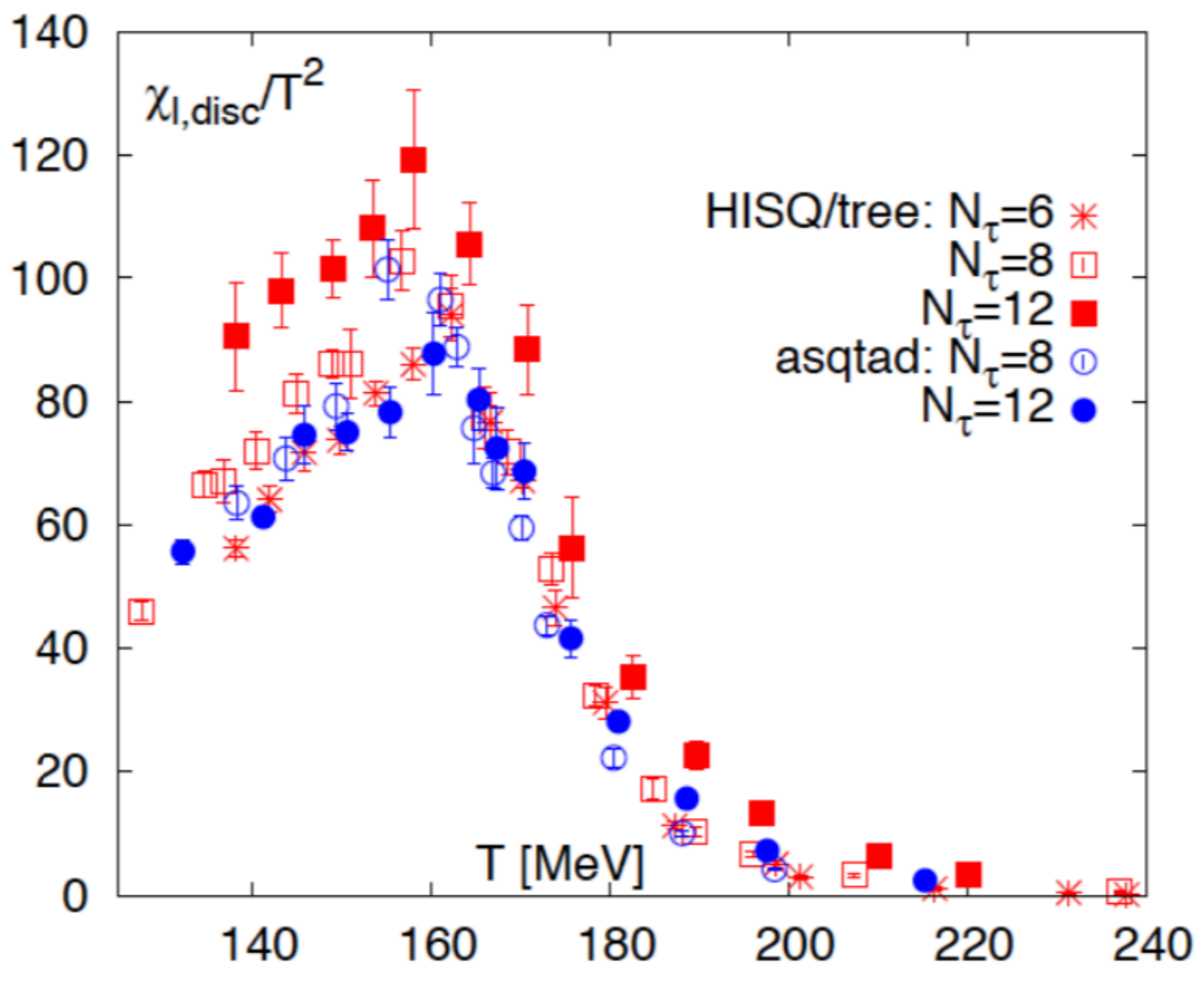
Phase structure of nuclear matter

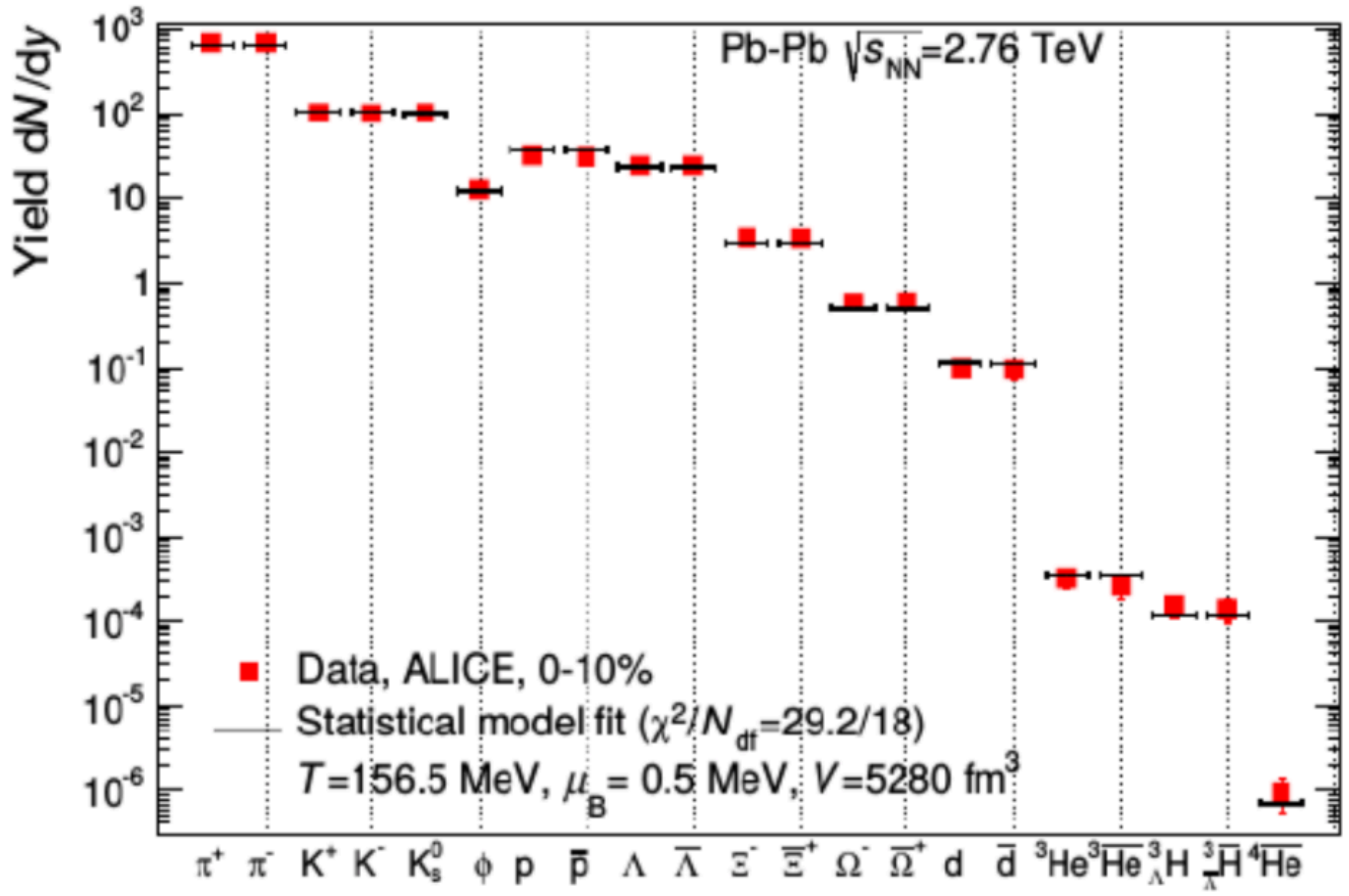




- Small u, d quark masses → proximity to O(4) second order phase transition → pseudocritical features may be observable

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

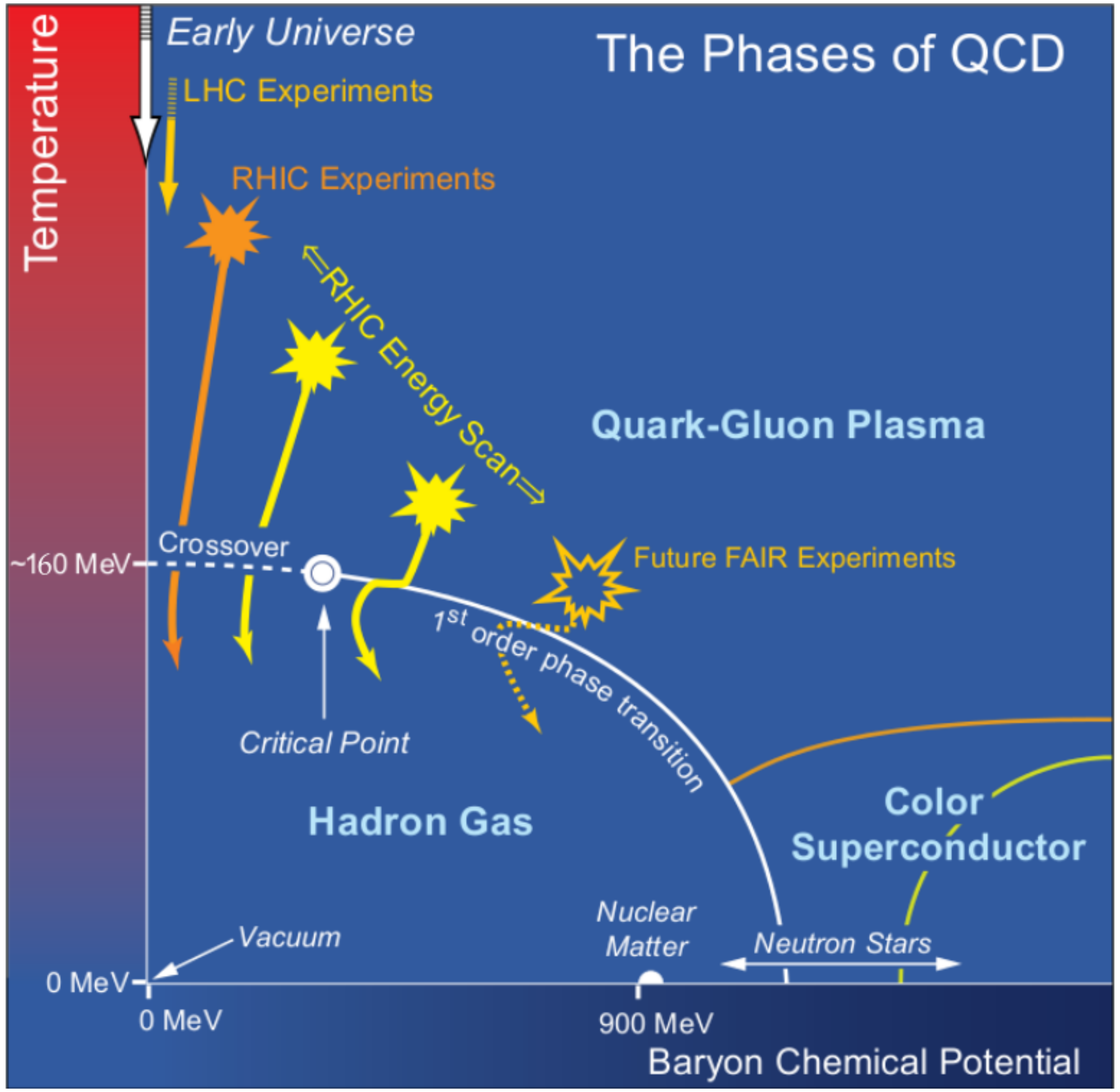
T_{fo} = 156.5 ± 3 MeV

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?

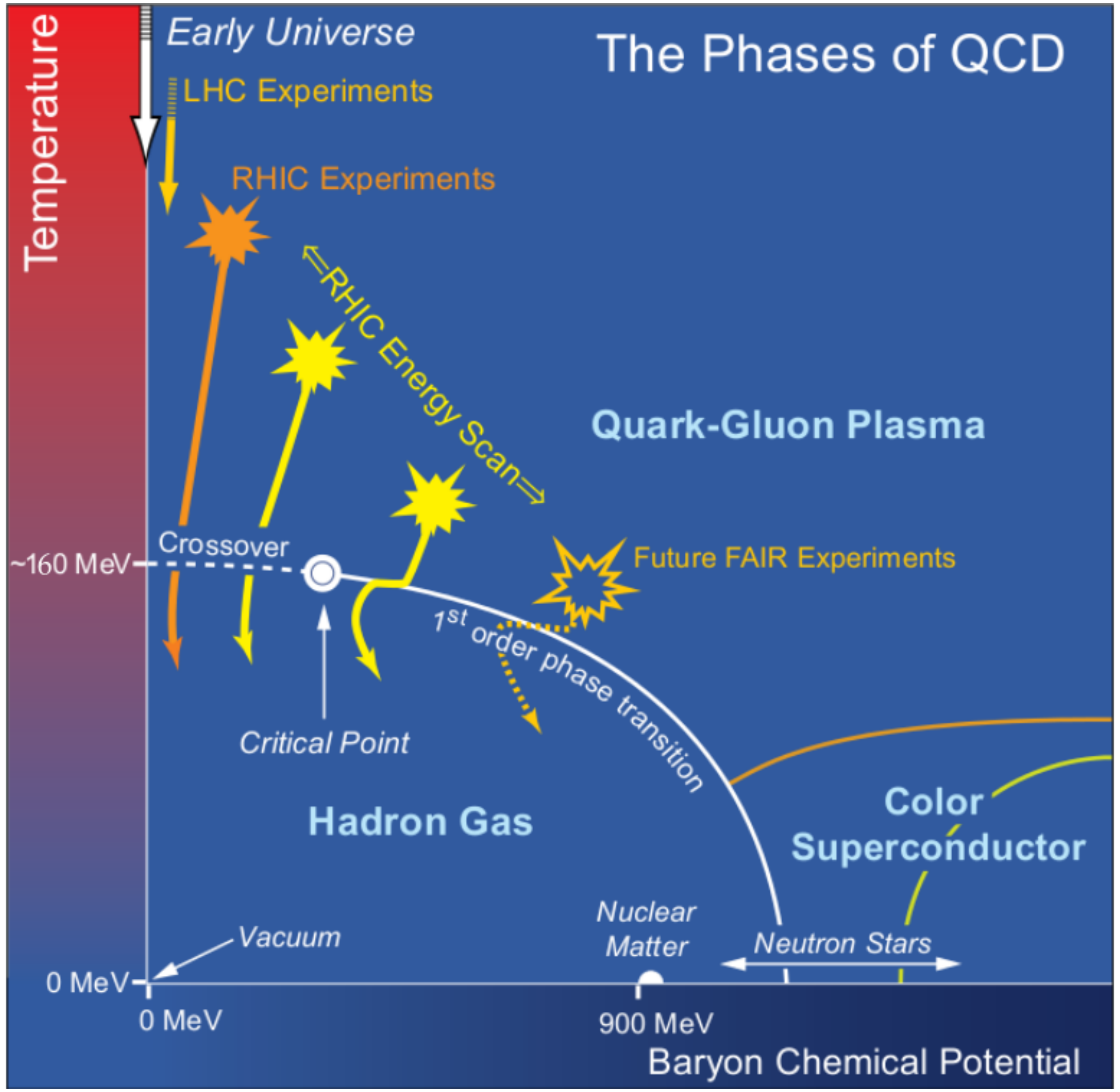
Critical opalescence in CO_2

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

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

Fluctuations in heavy-ion collisions

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



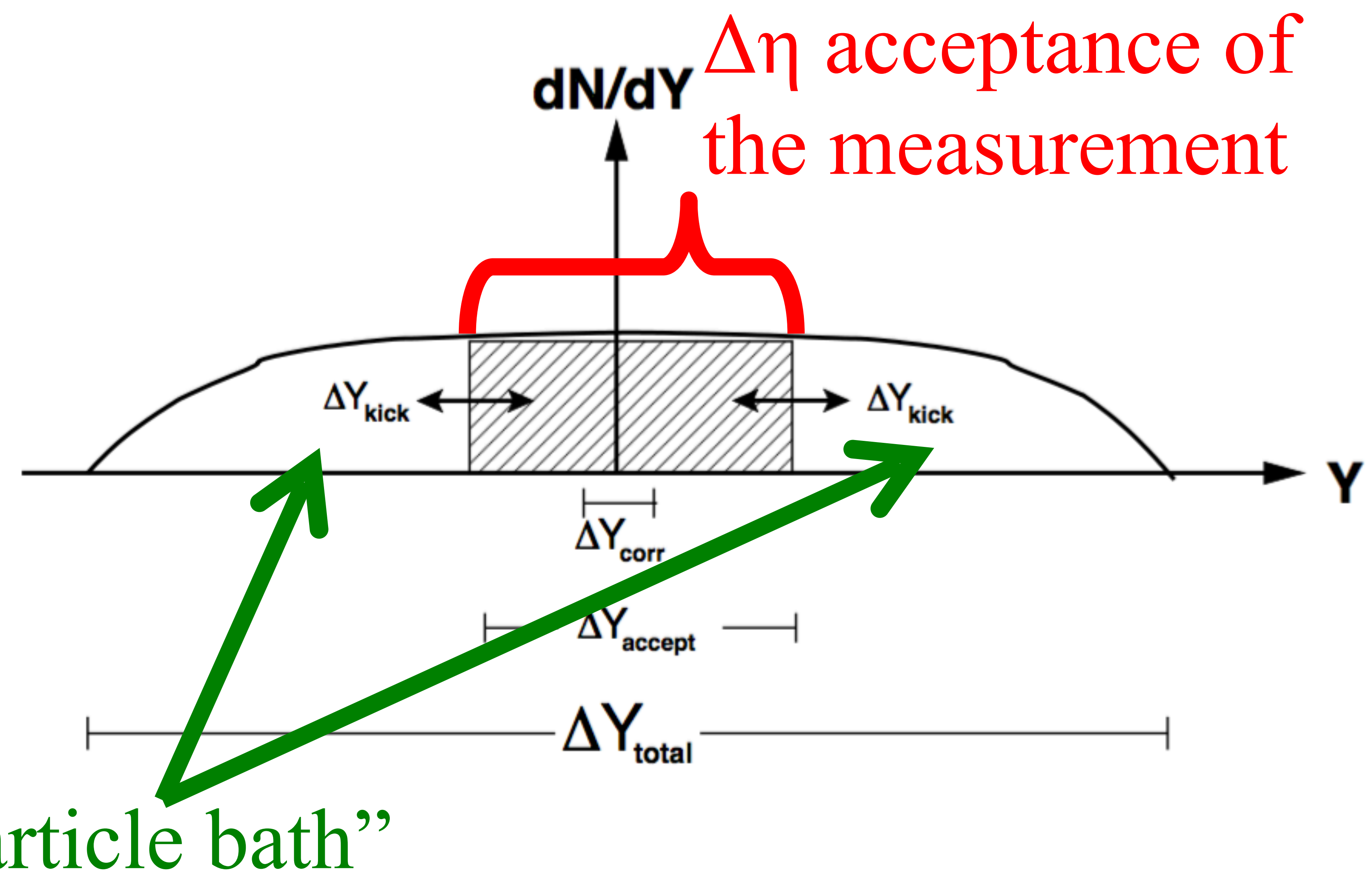
- Fluctuations grow in the region near a phase transition and/or critical point
  - Can we observe signs of criticality?
- Fluctuations of conserved charges can be related to susceptibilities calculable in lattice QCD
  - Precision test of LQCD at $\mu_B \approx 0$

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

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



Experiment: moments of particle multiplicity distributions

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

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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

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

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Theory: susceptibilities

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

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

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

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

$$\boxed{S\sigma = \chi_3^B / \chi_2^B \qquad \kappa\sigma^2 = \chi_4^B / \chi_2^B}$$

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

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

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

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

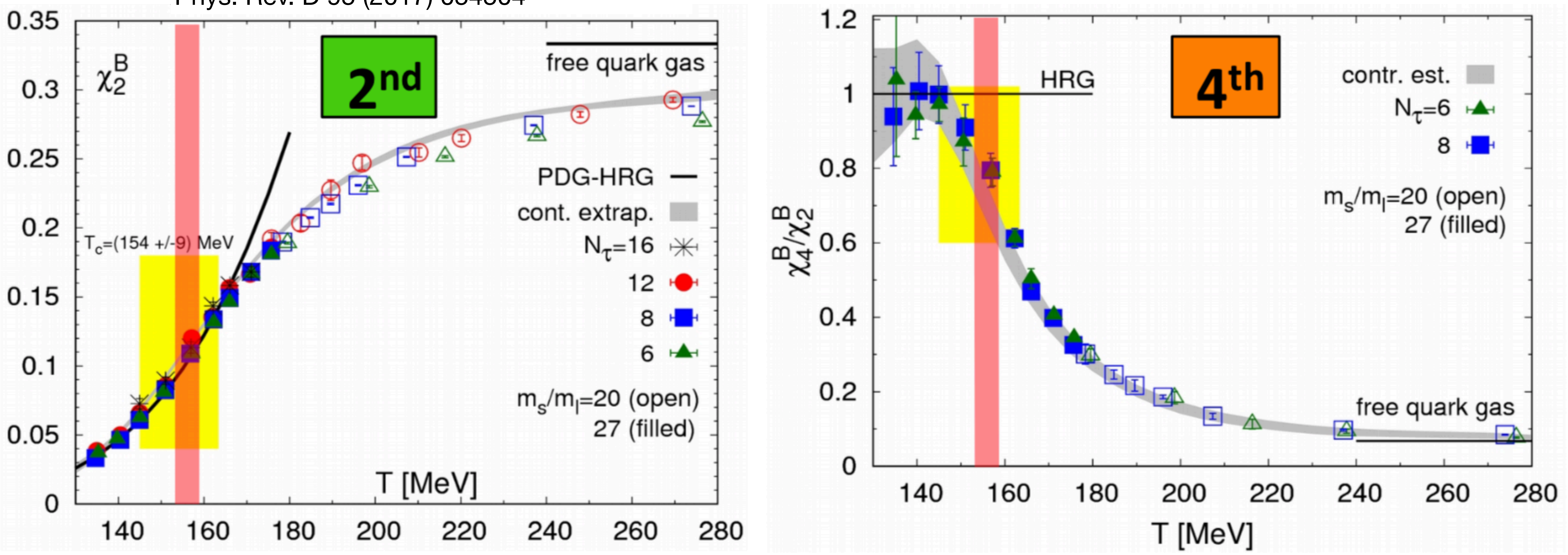
$$\left\langle \left(\Delta N_B - \langle \Delta N_B \rangle \right)^3 \right\rangle / \sigma^3 \approx \frac{VT^3 \chi_3^B}{\left(VT^3 \chi_2^B \right)^{3/2}} = S$$

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

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

Needed: high precision

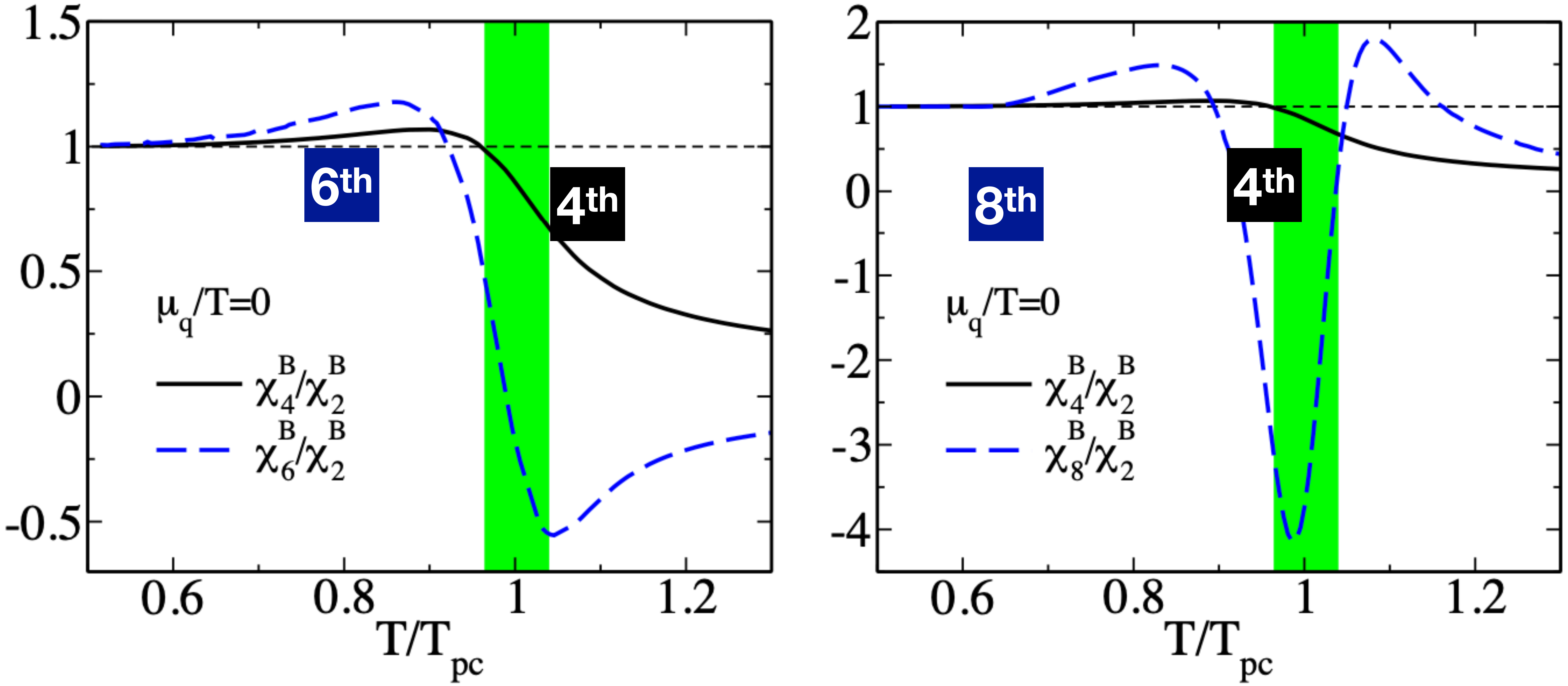
A. Bazavov et al. (HotQCD Collaboration),
Phys. Rev. D 95 (2017) 054504



- 2^{nd} order moments → no deviation between HRG and LQCD expectations
- 4^{th} 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]

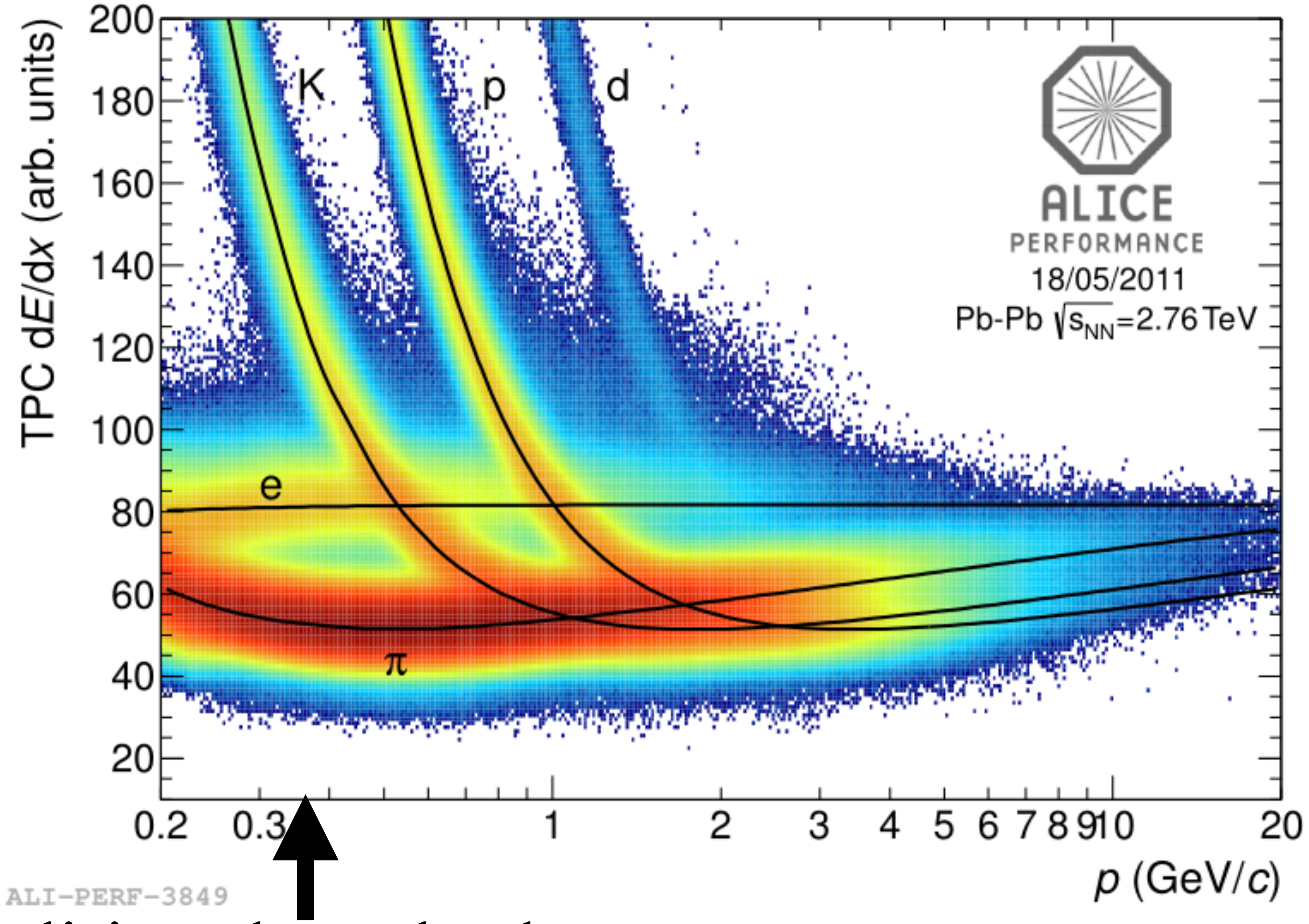
- But huge statistics are needed and experimental effects must be carefully controlled

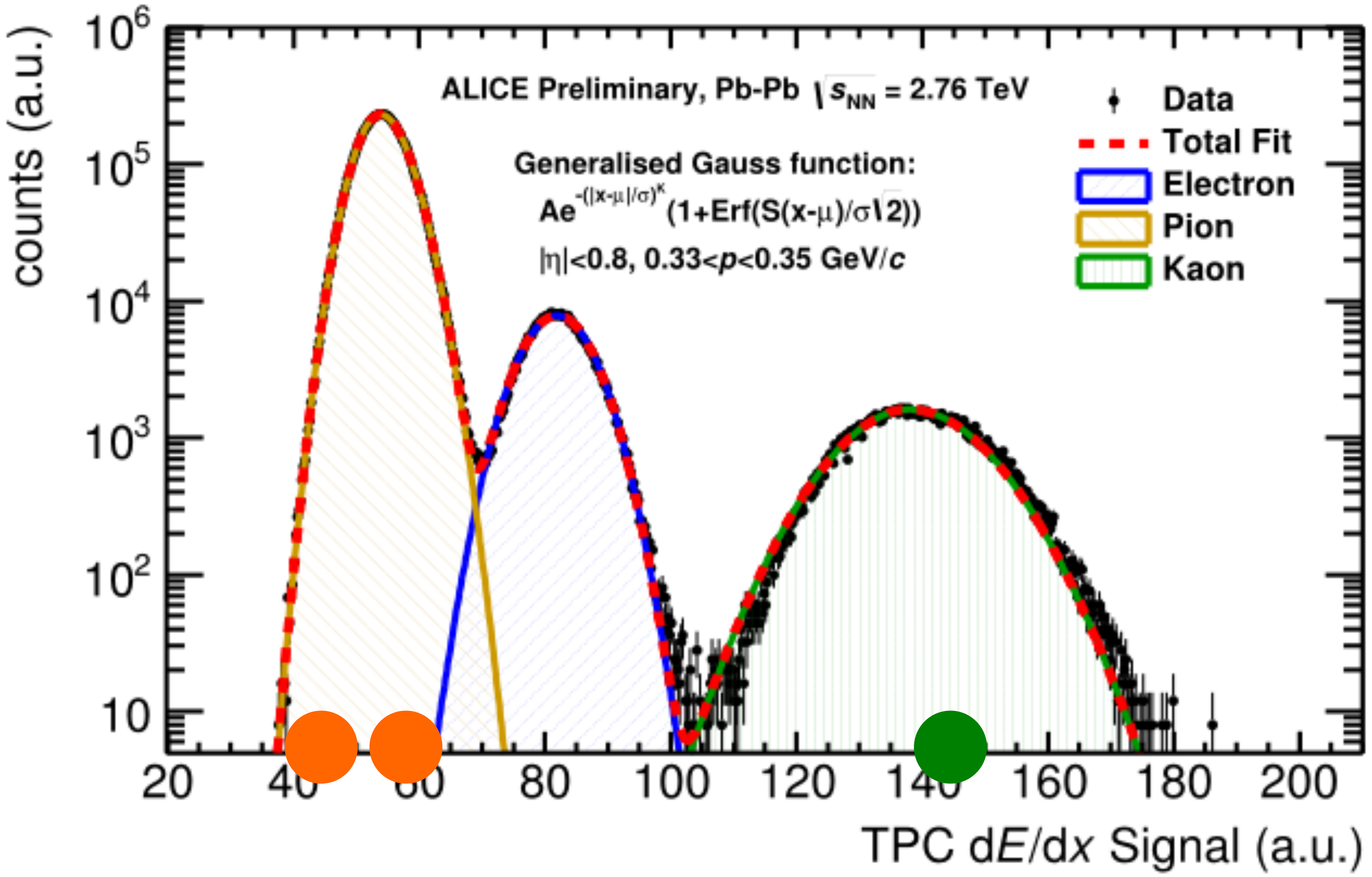
Experimental challenges

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



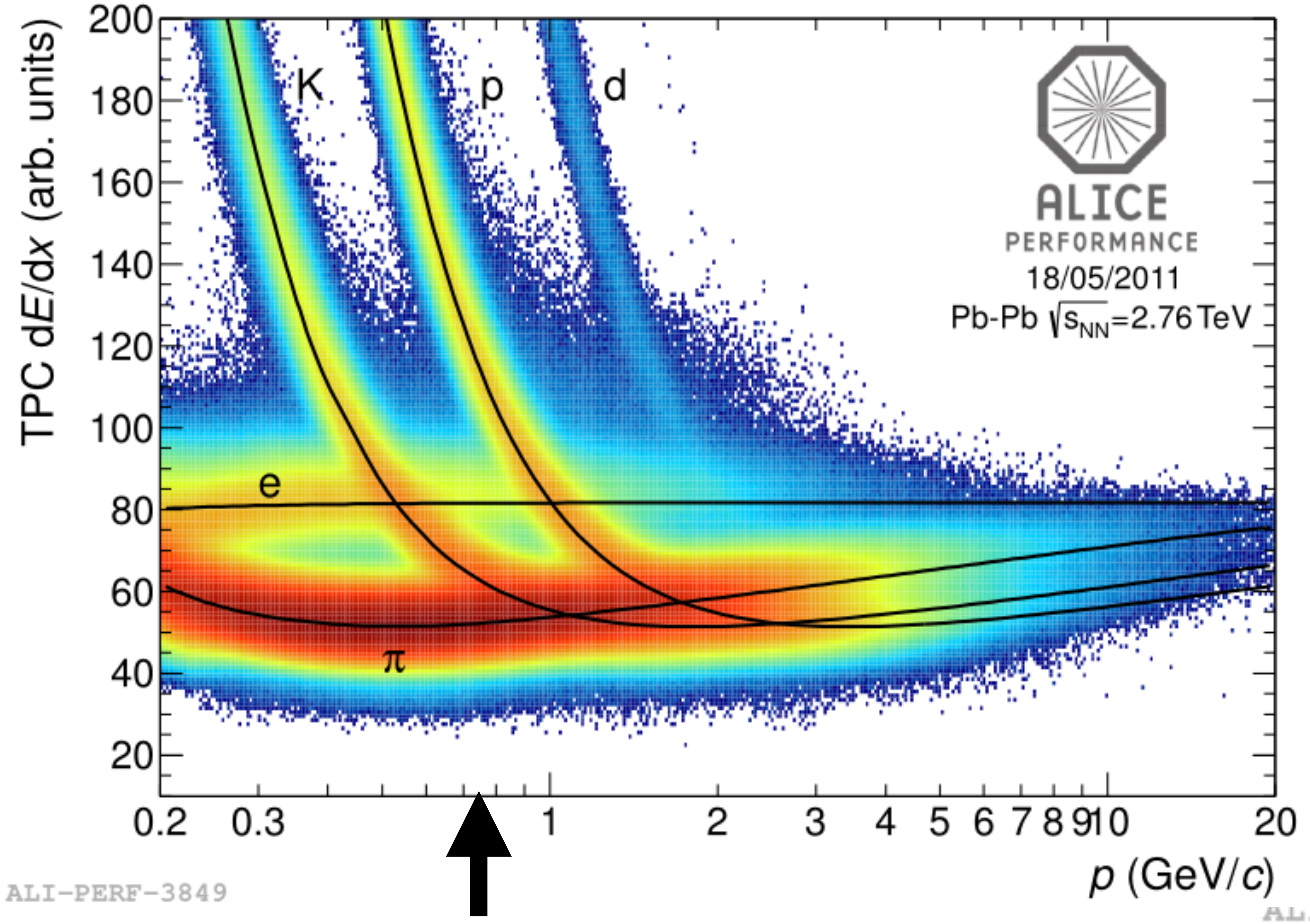


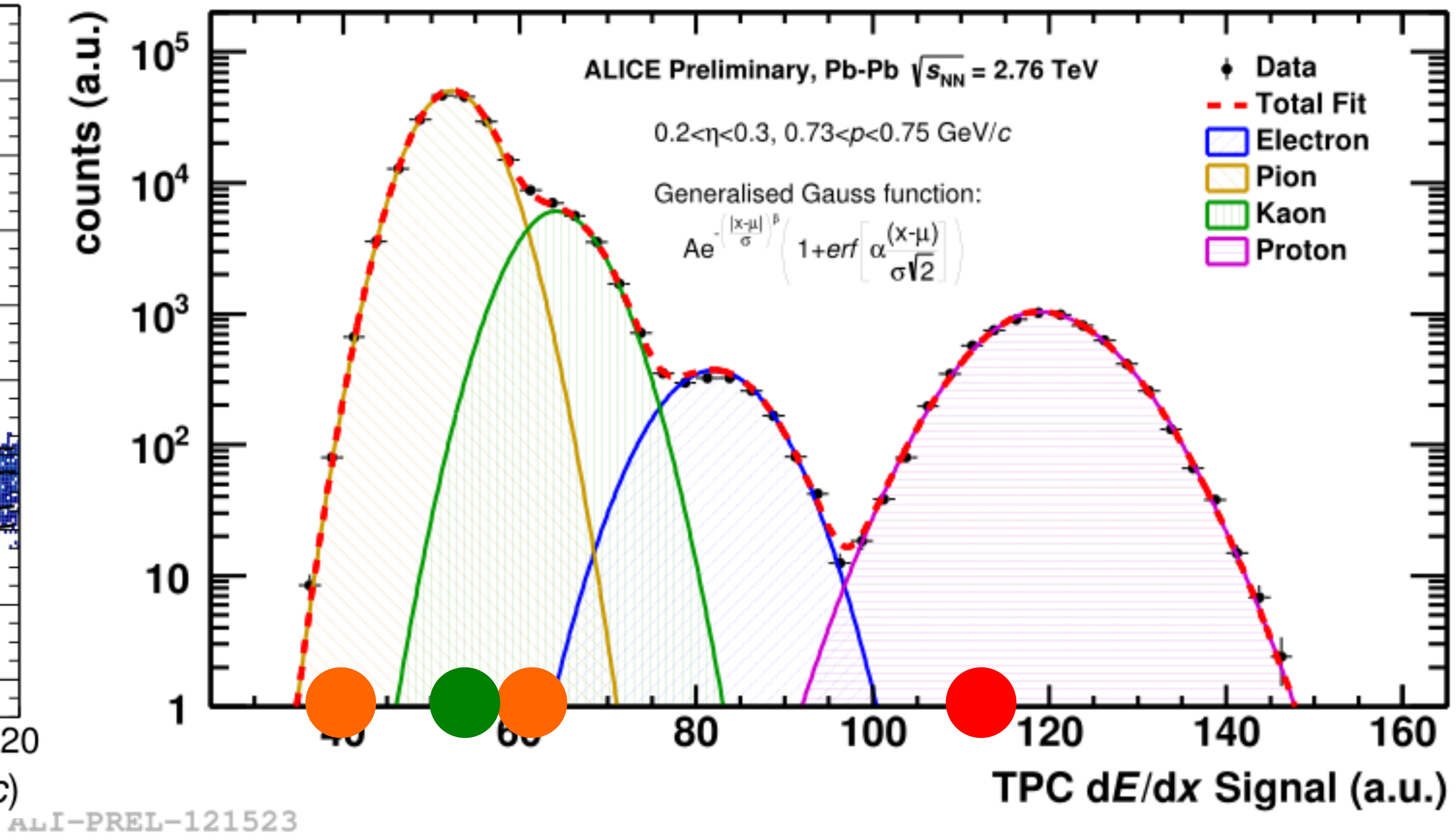
- Traditional method:
  - count number of pions (N_π), kaons (N_K), protons (N_p) in each event

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

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

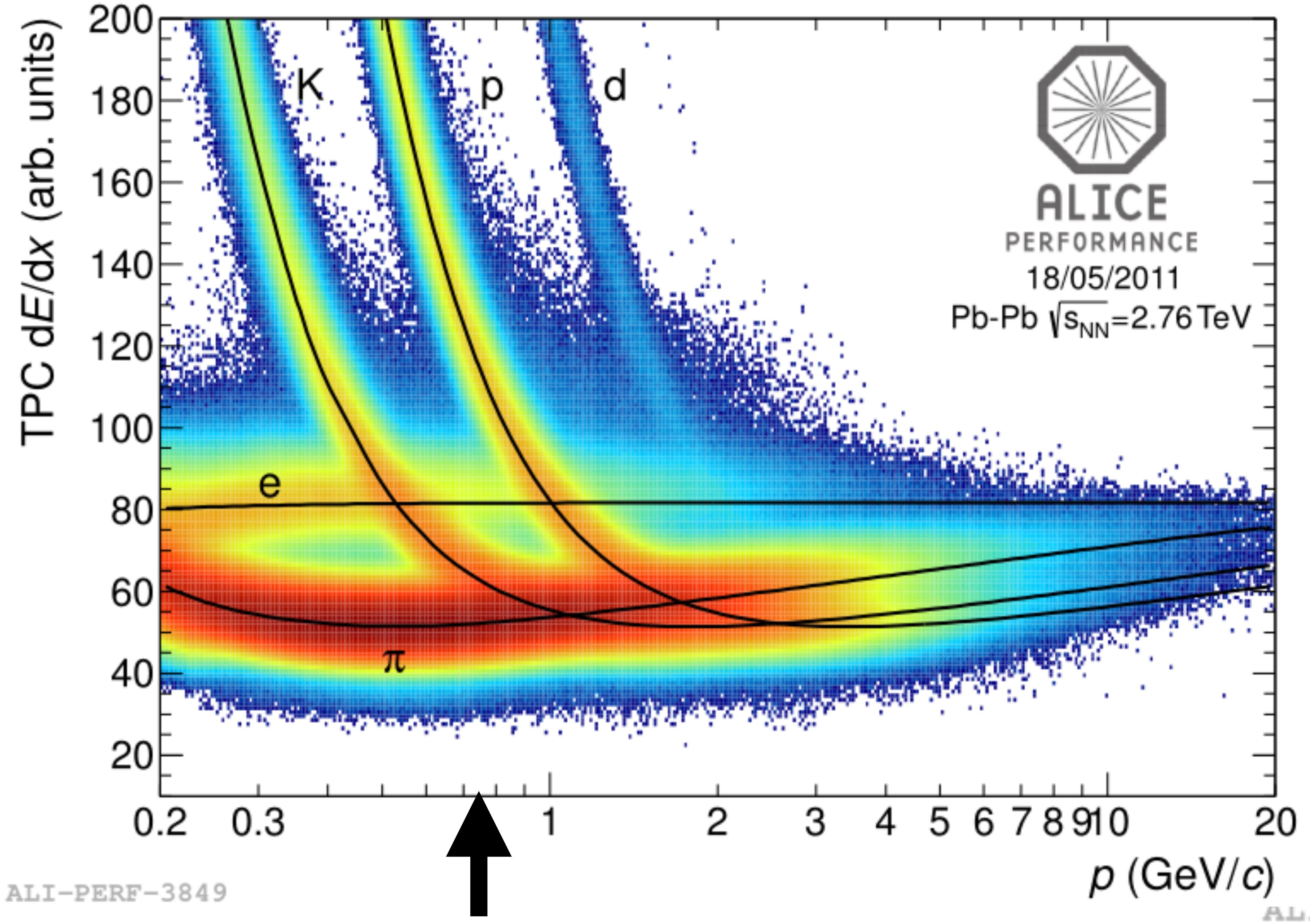
Traditional method

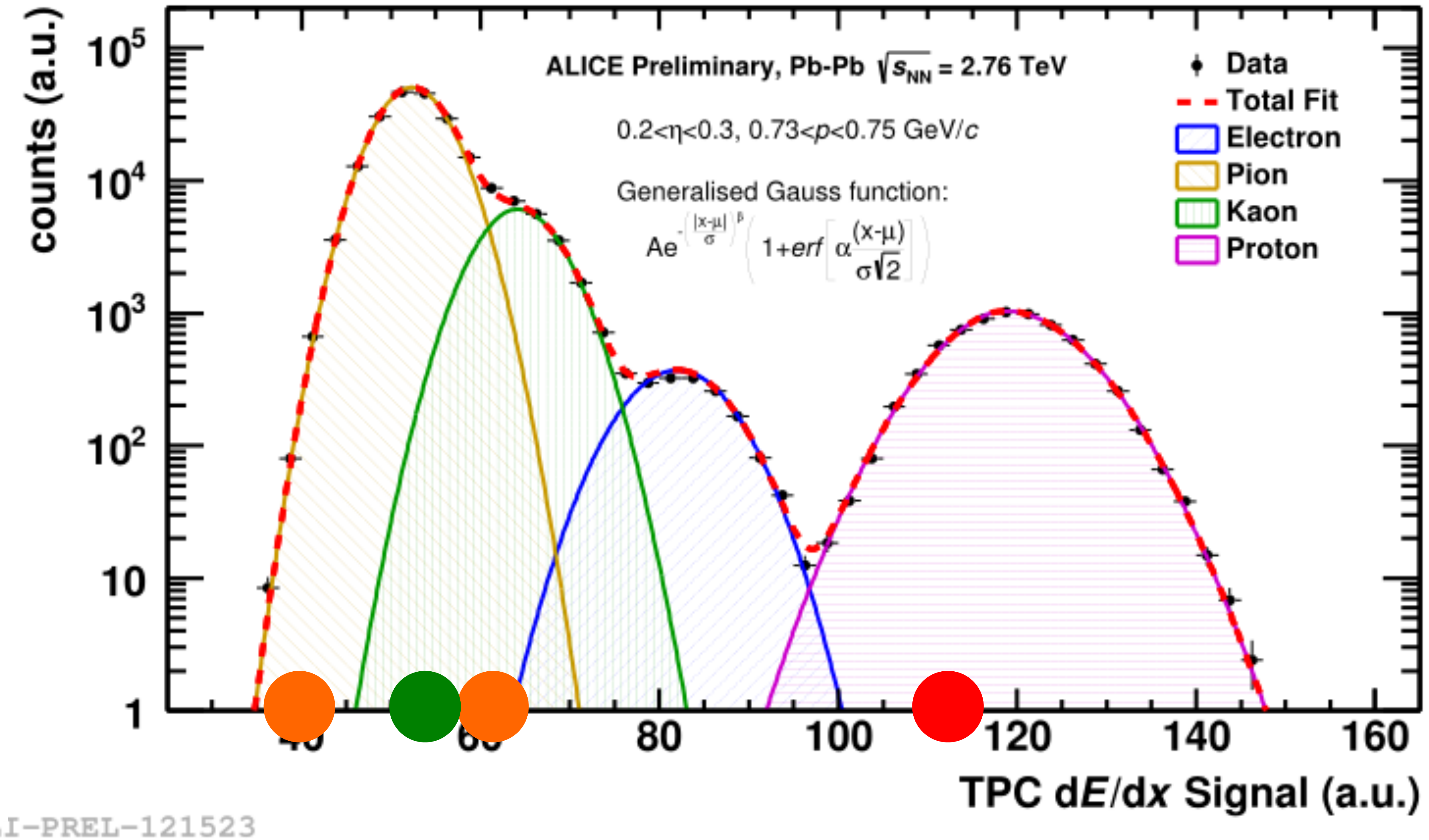




- What if PID is unclear?
  - use other detector information or reject phase space bin
  - results in lower efficiency

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, ...

$$W_p = \sum_{i=1}^{N_{tracks}} w_p(m_i)$$

- 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

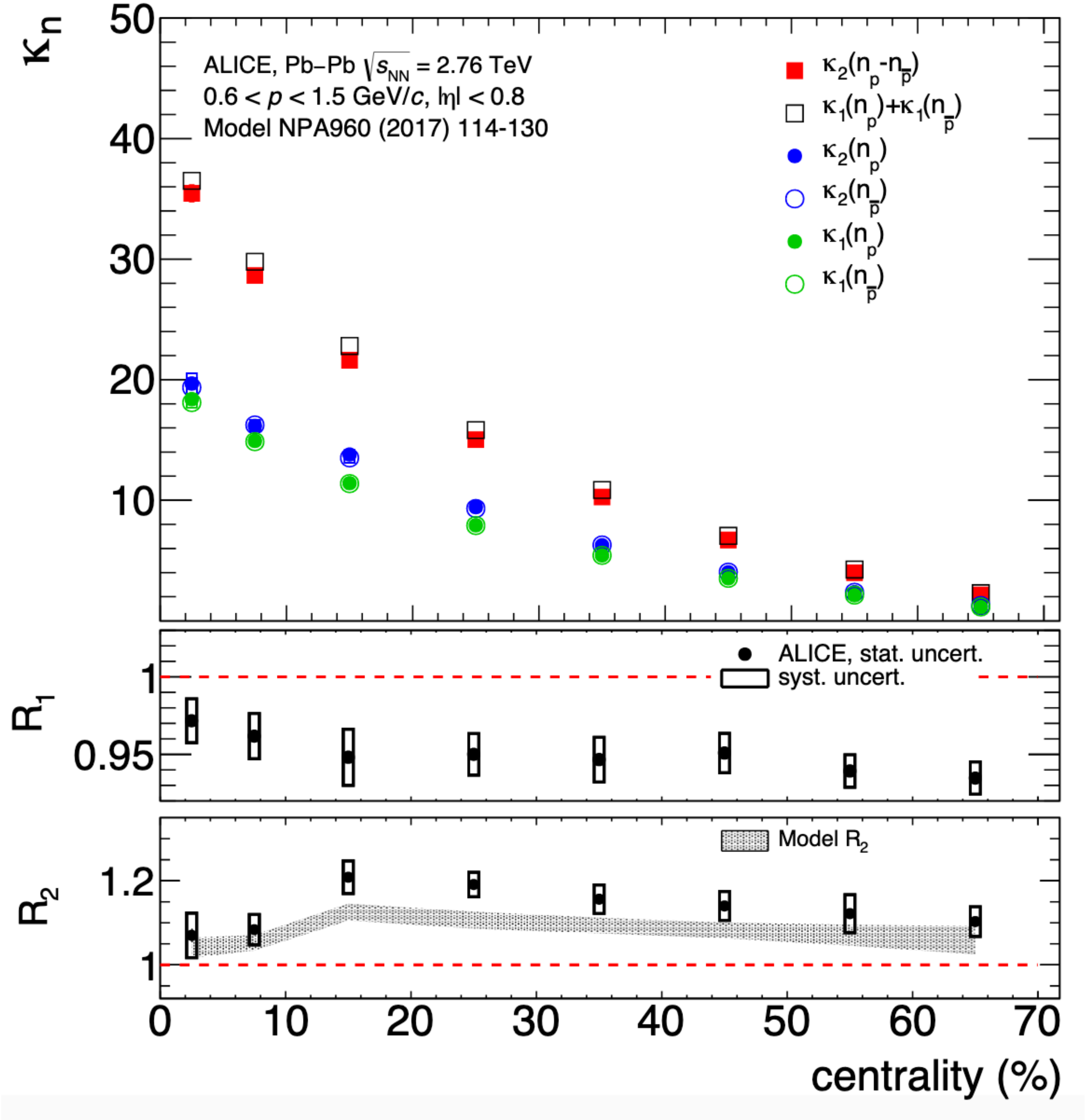
  C. Pruneau, Phys. Rev. C96 (2017) 054902,
  arXiv:1706.01333 [physics.data-an]
- Correction using moments of detector response matrix

  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

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

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

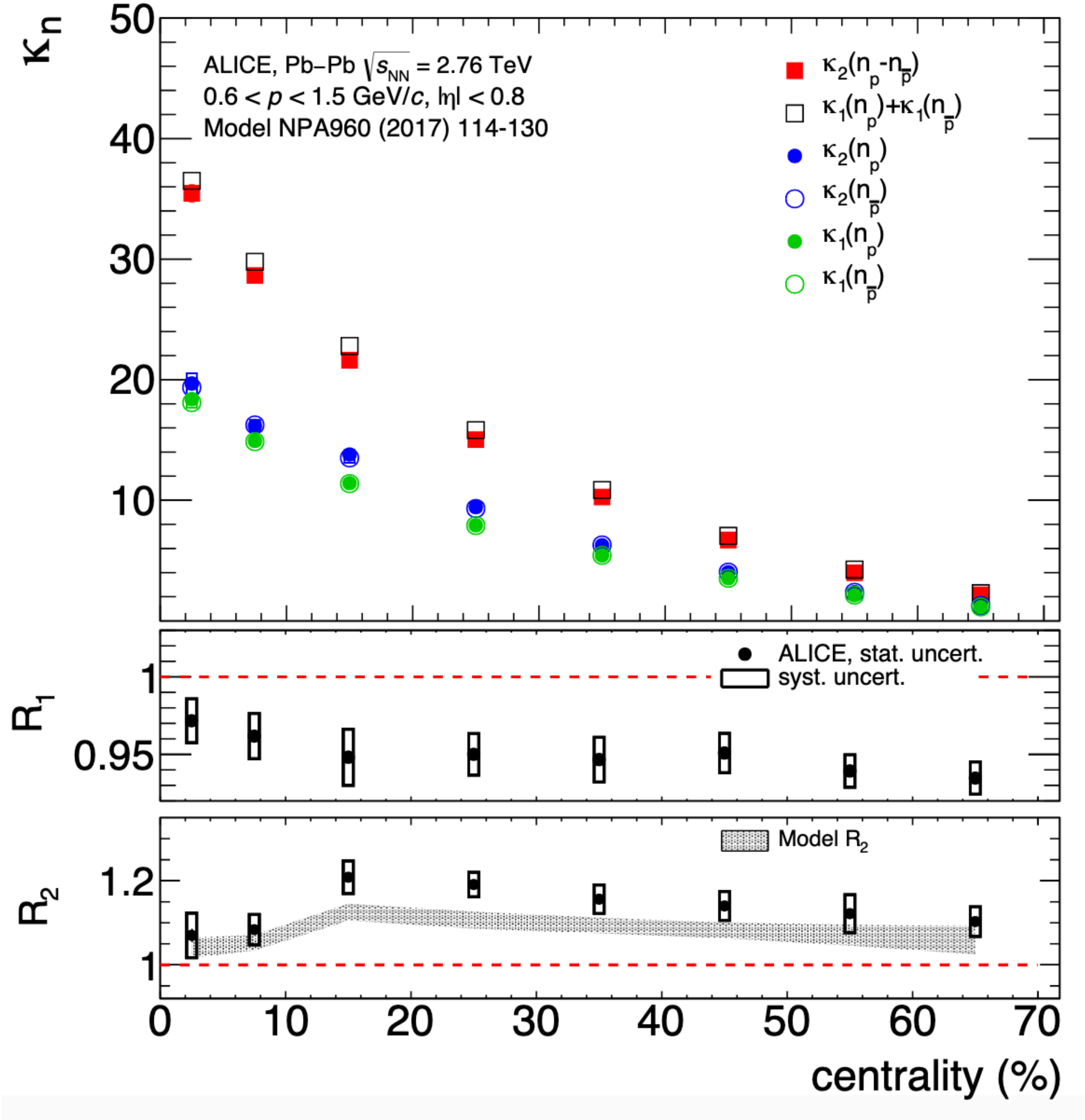
$$= \kappa_2(p) + \kappa_2(\bar{p}) - 2\underbrace{\left(\langle N_p N_{\bar{p}} \rangle - \langle N_p \rangle \langle N_{\bar{p}} \rangle \right)}_{\text{correlation term}}$$

- 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



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

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

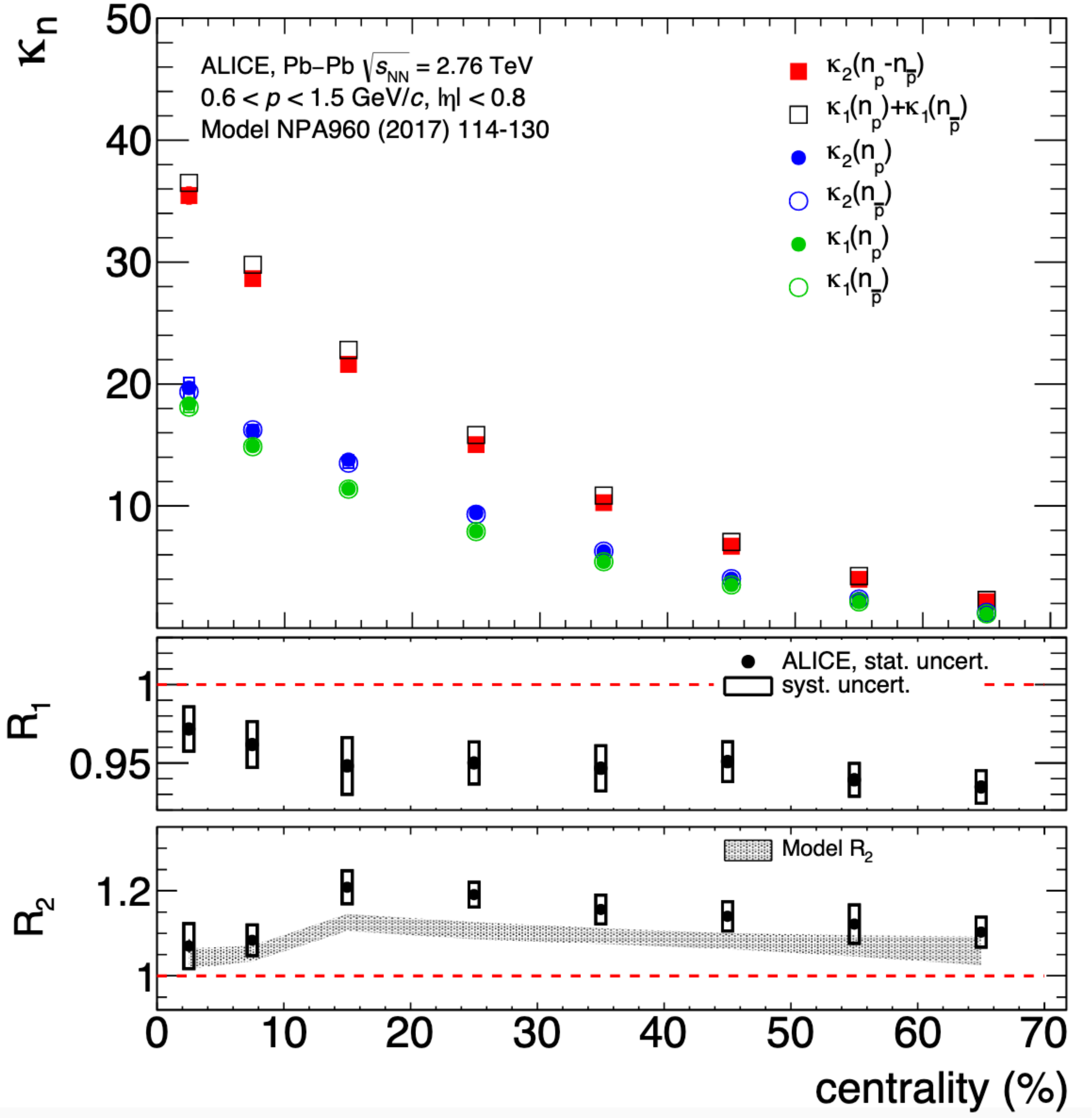
$$= \kappa_2(p) + \kappa_2(\bar{p}) - 2\underbrace{\left(\langle N_p N_{\bar{p}} \rangle - \langle N_p \rangle \langle N_{\bar{p}} \rangle\right)}_{\text{correlation term}}$$

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

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

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

Net-proton second moments at the LHC



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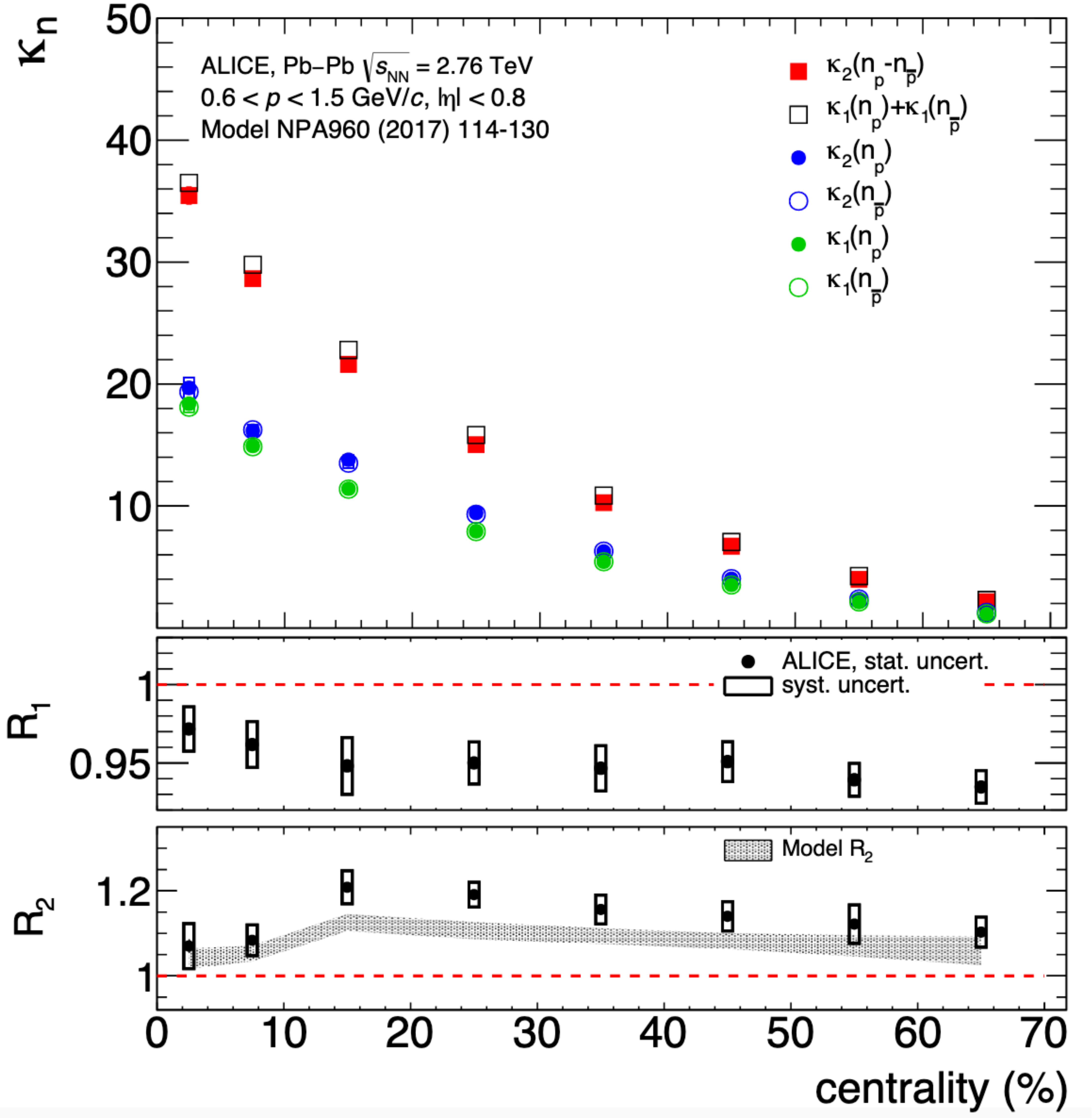
$$\kappa_2(p - \bar{p}) = \left\langle \left(N_p - N_{\bar{p}} - \langle N_p - N_{\bar{p}} \rangle\right)^2 \right\rangle$$

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

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

Net-proton second moments at the LHC



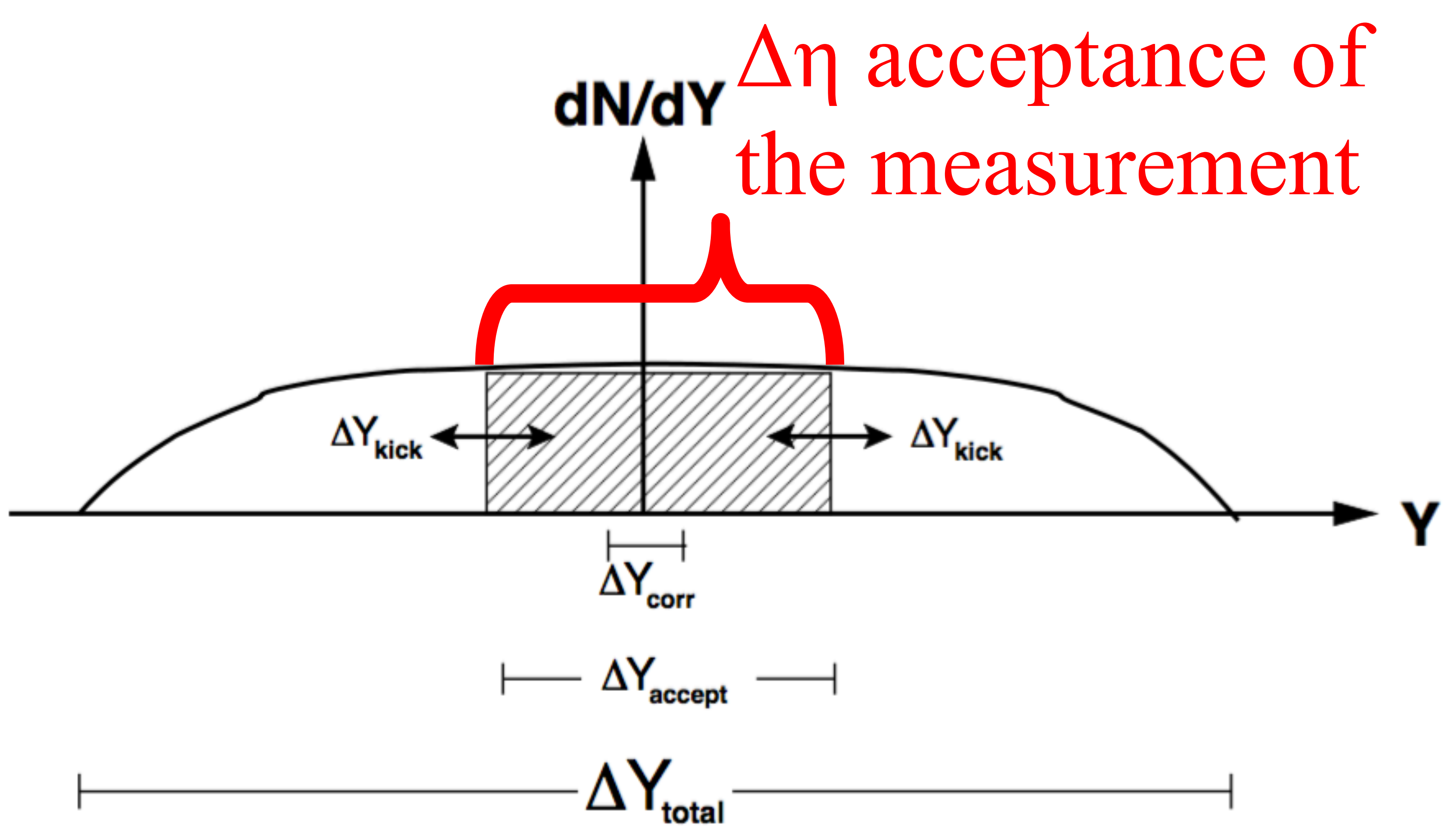
ALICE, PLB 807 (2020) 135564,
arXiv:1910.14396

- 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

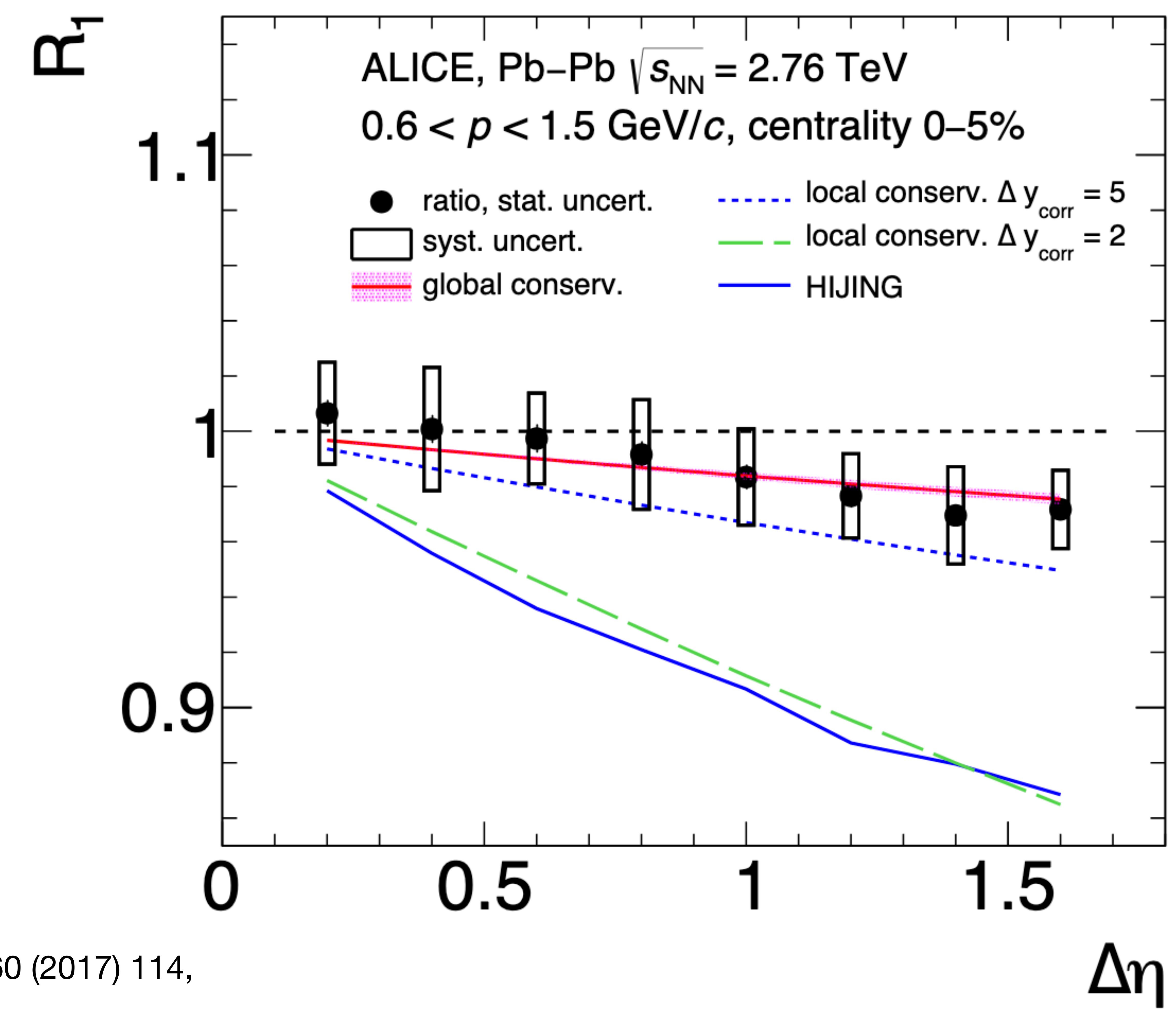
Global conservation laws



- Small Δη → Poissonian fluctuations, ratio to Skellam ~1
- Large Δη → global baryon number conservation effects, ratio to Skellam < 1
- Δη dependence consistent with effects of global baryon number conservation
  - or local conservation over 5 units of pseudorapidity

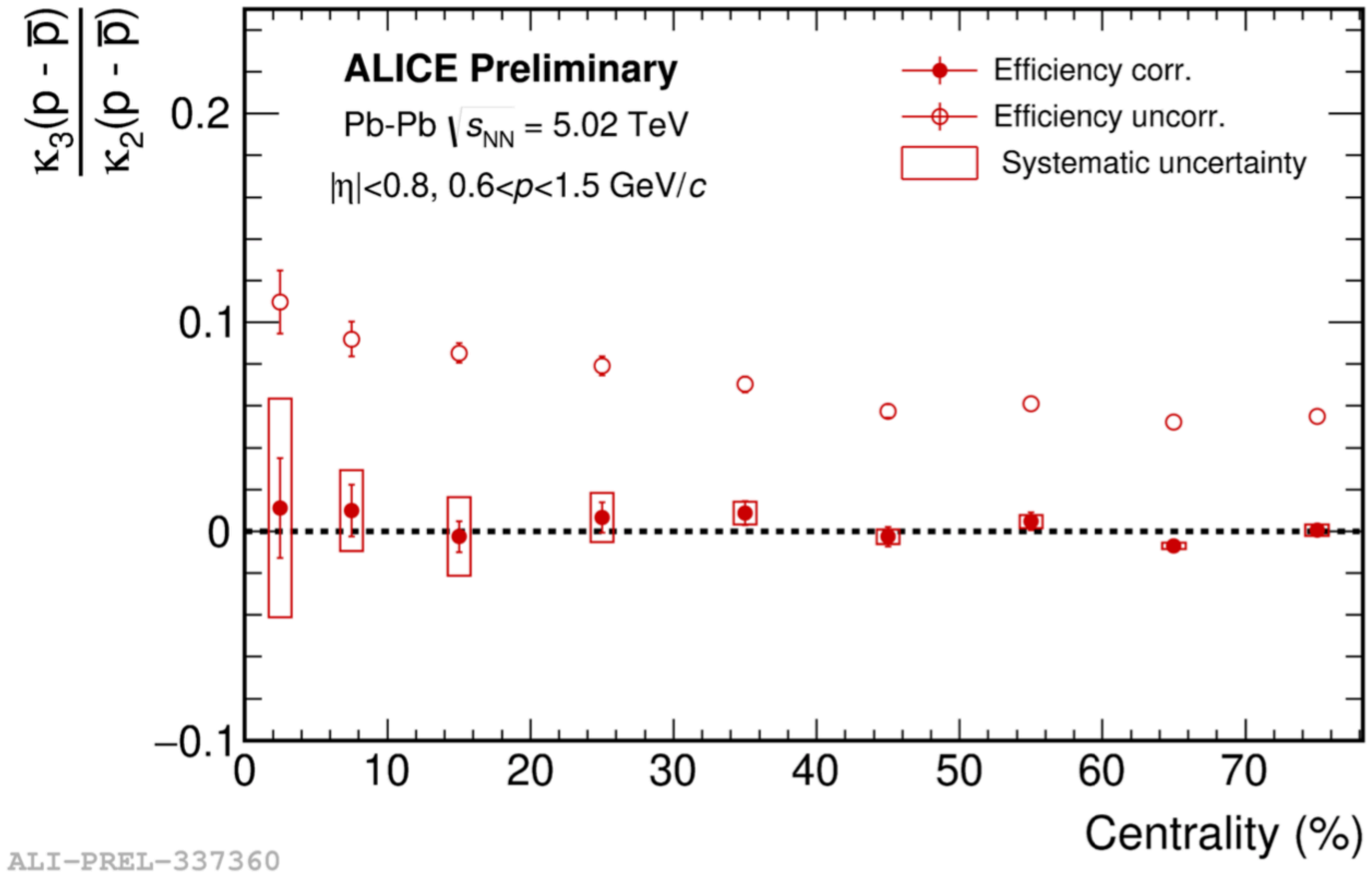
P. Braun-Munzinger et al., NPA 960 (2017) 114, arXiv:1612.00702 [nucl-th]

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



Higher moments at the LHC

Net-proton third moments at the LHC

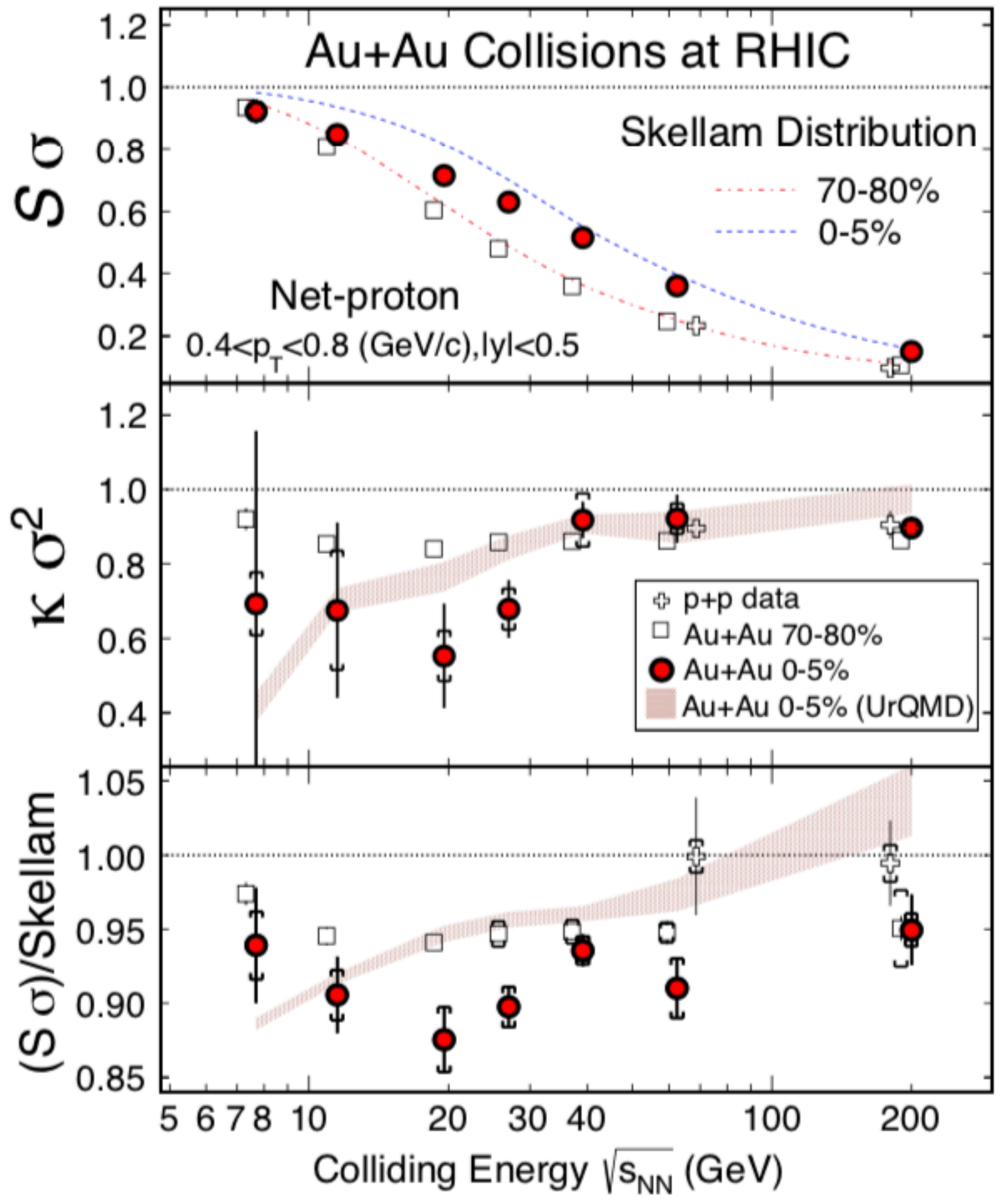


- Third moments agree with Skellam expectation of zero, precision on the order of 5%
- Very sensitive measurements, requires great experimental control over efficiencies, etc
- Fourth moments in progress...

Higher moments at RHIC

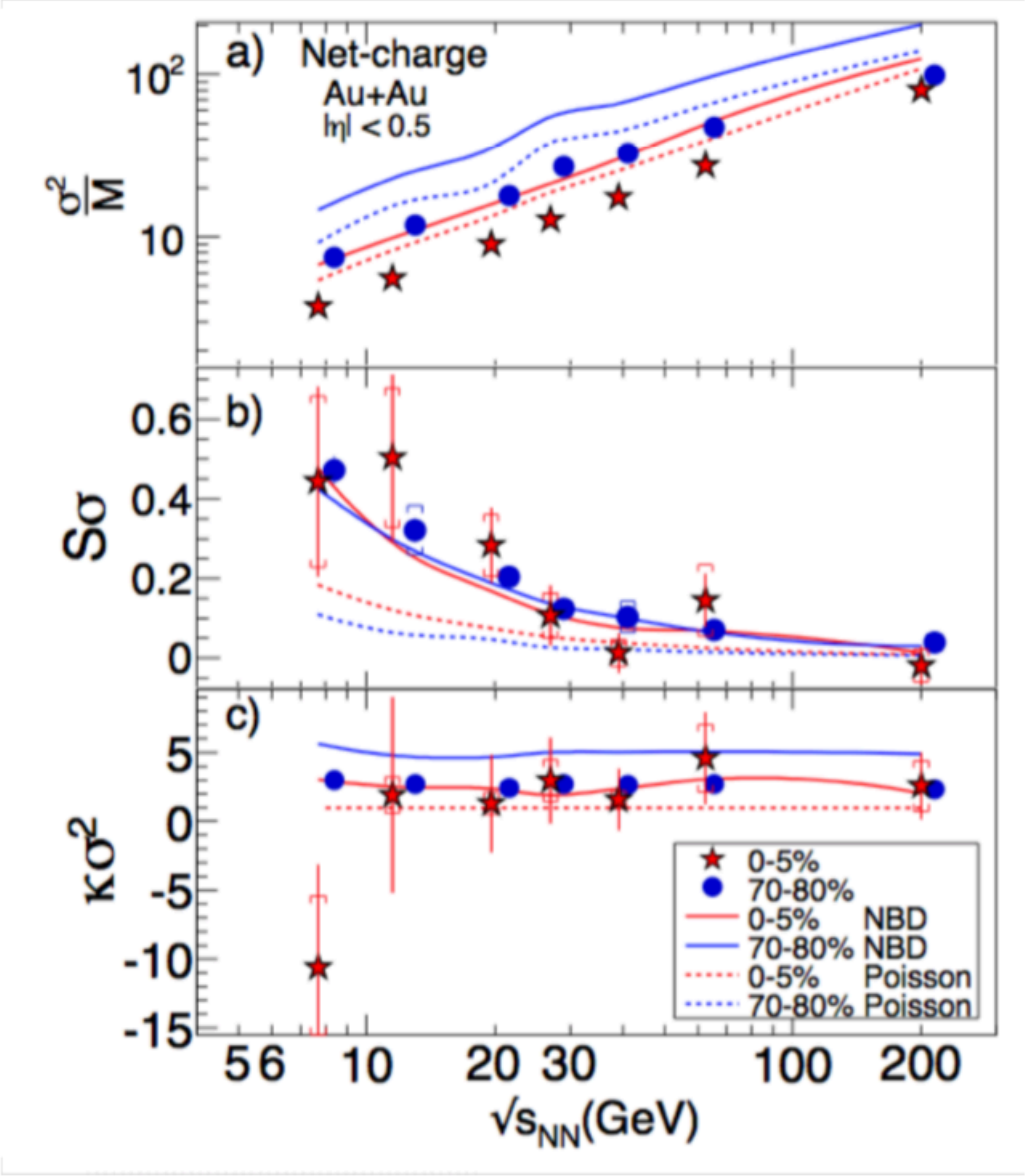
Higher moments at RHIC

Net-Proton



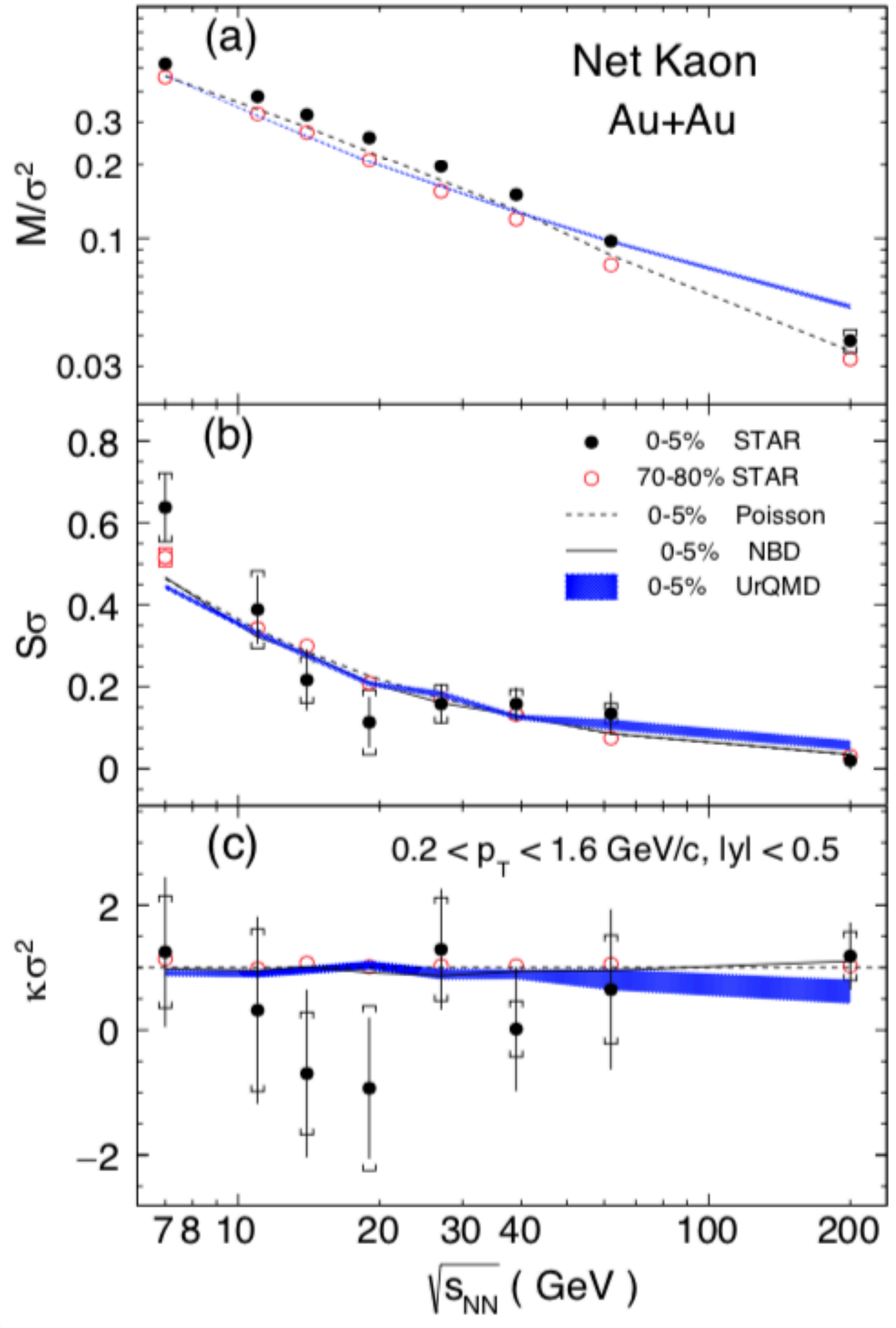
Phys. Rev. Lett. 112, 032302 (2014).

Net-Charge



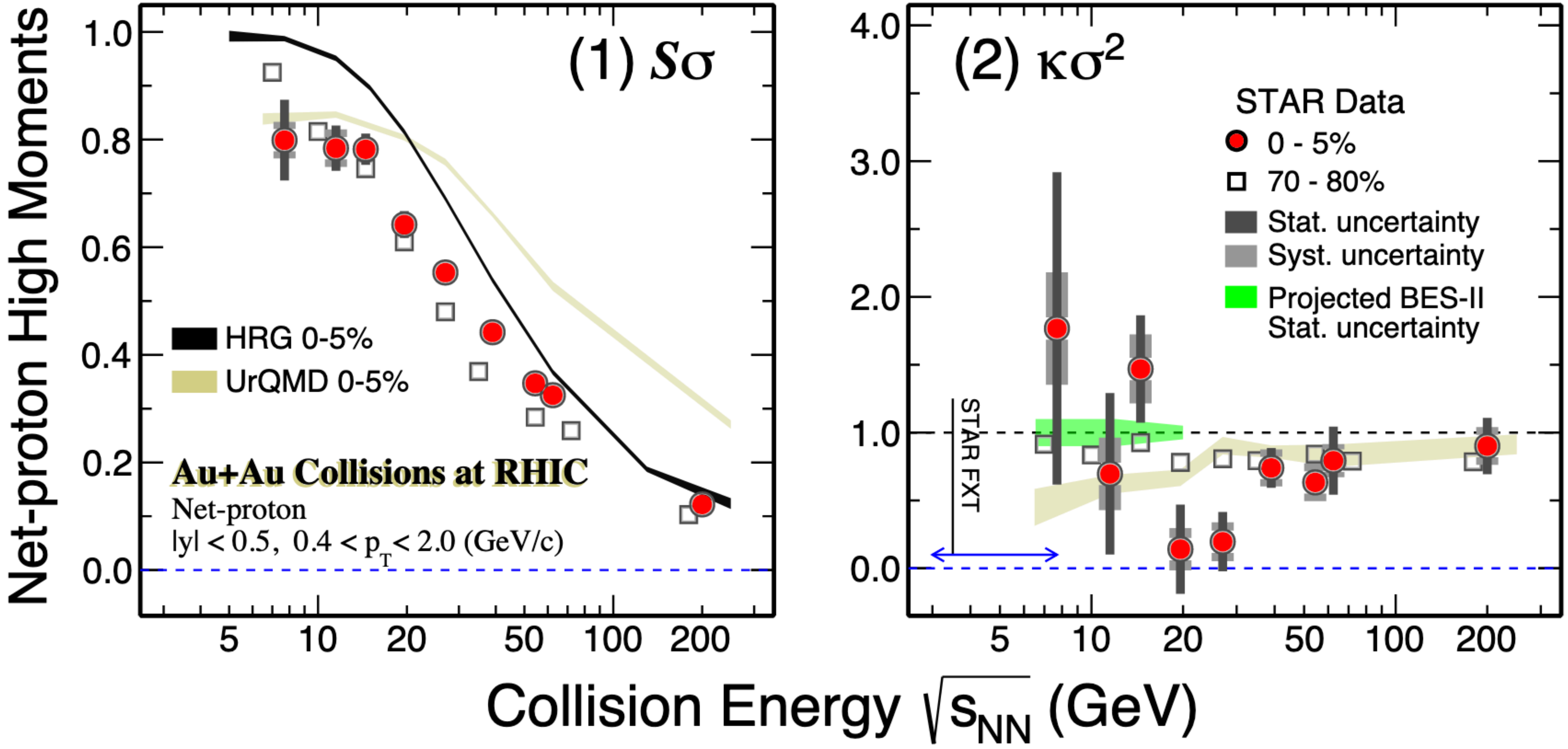
Phys. Rev. Lett. 113 092301 (2014).

Net-Kaon



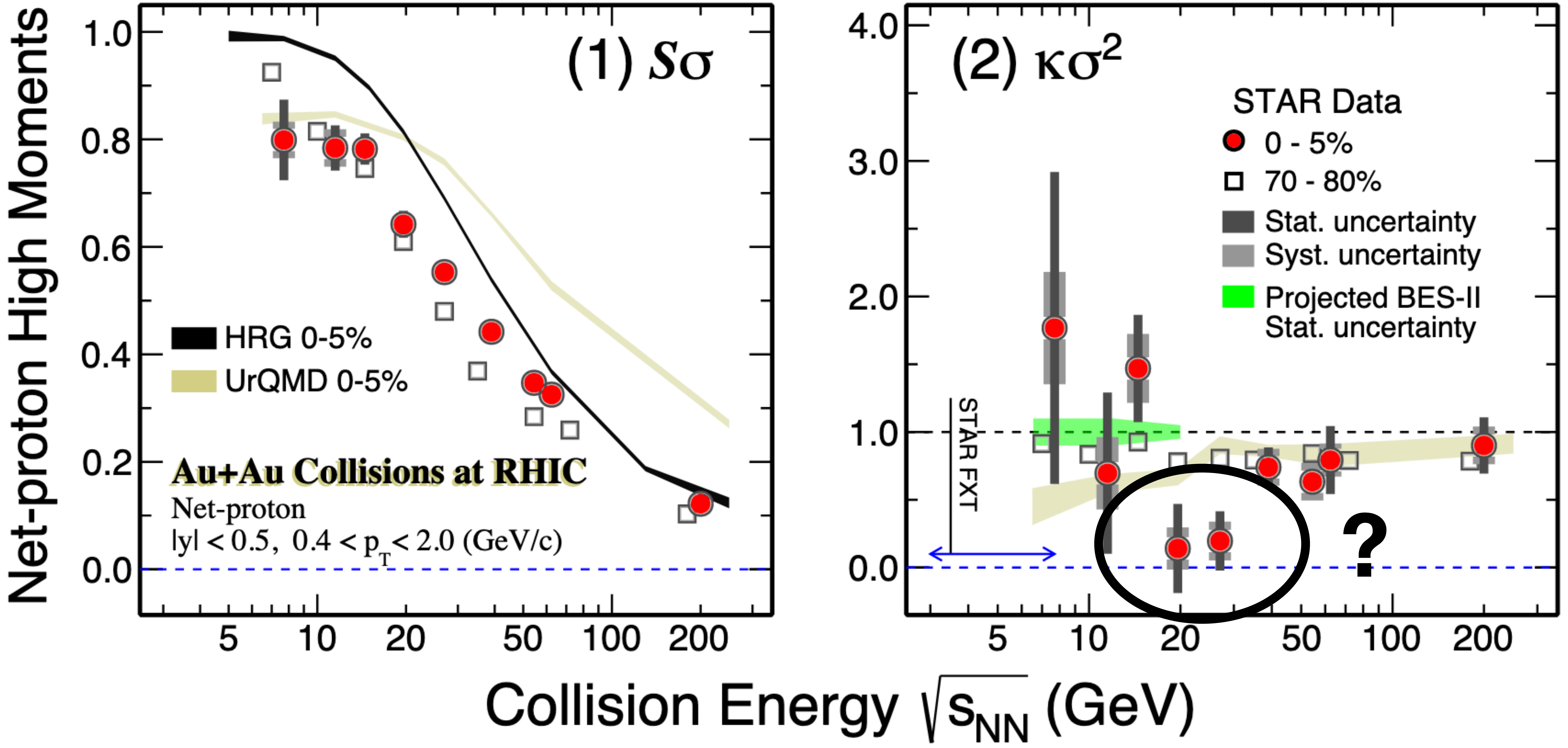
Phys. Lett. B 785, 551 (2018).

Net-proton moments at RHIC



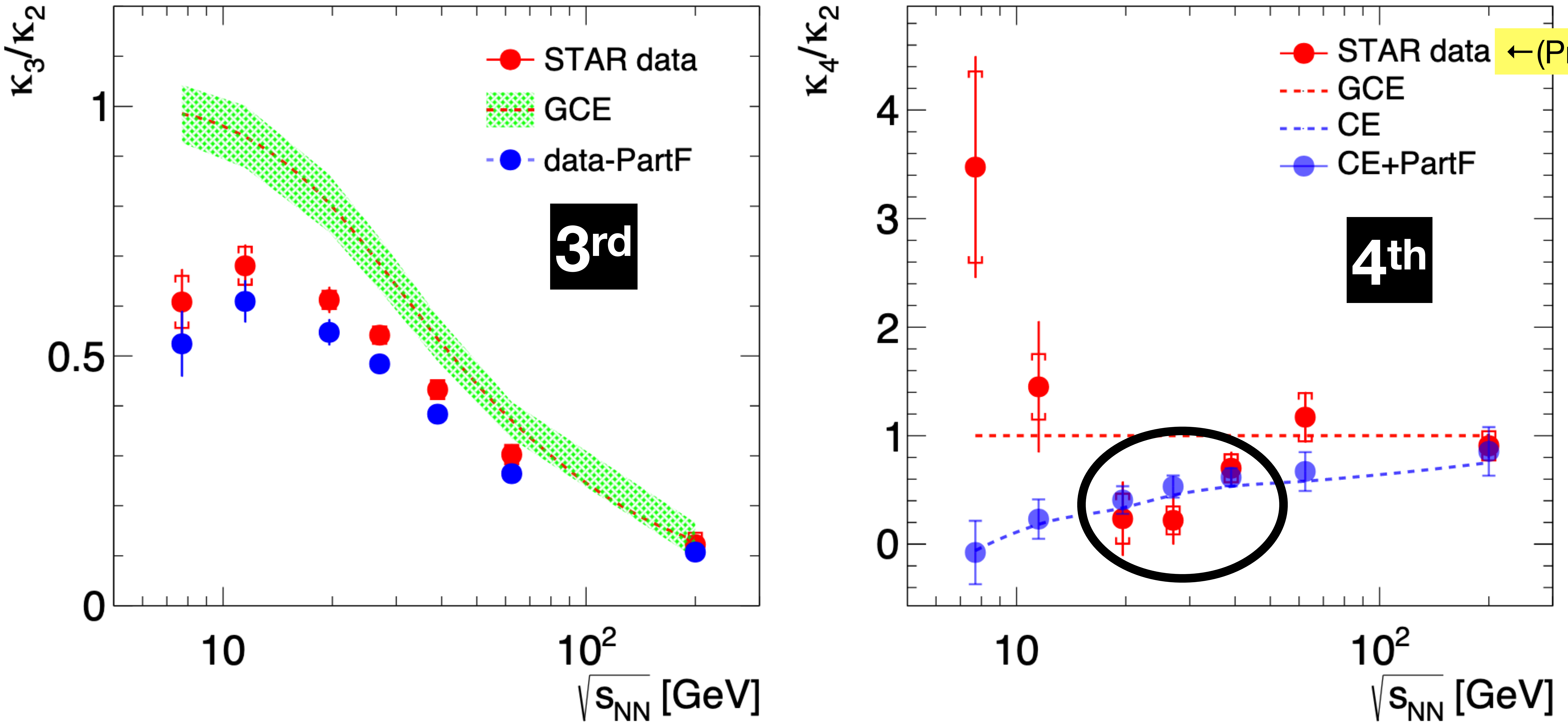
STAR, Phys. Rev. Lett. 126 (2021) 9, 092301
arXiv:2001.02852

Net-proton moments at RHIC



STAR, Phys. Rev. Lett. 126 (2021) 9, 092301
arXiv:2001.02852

Critical behavior? Not yet…



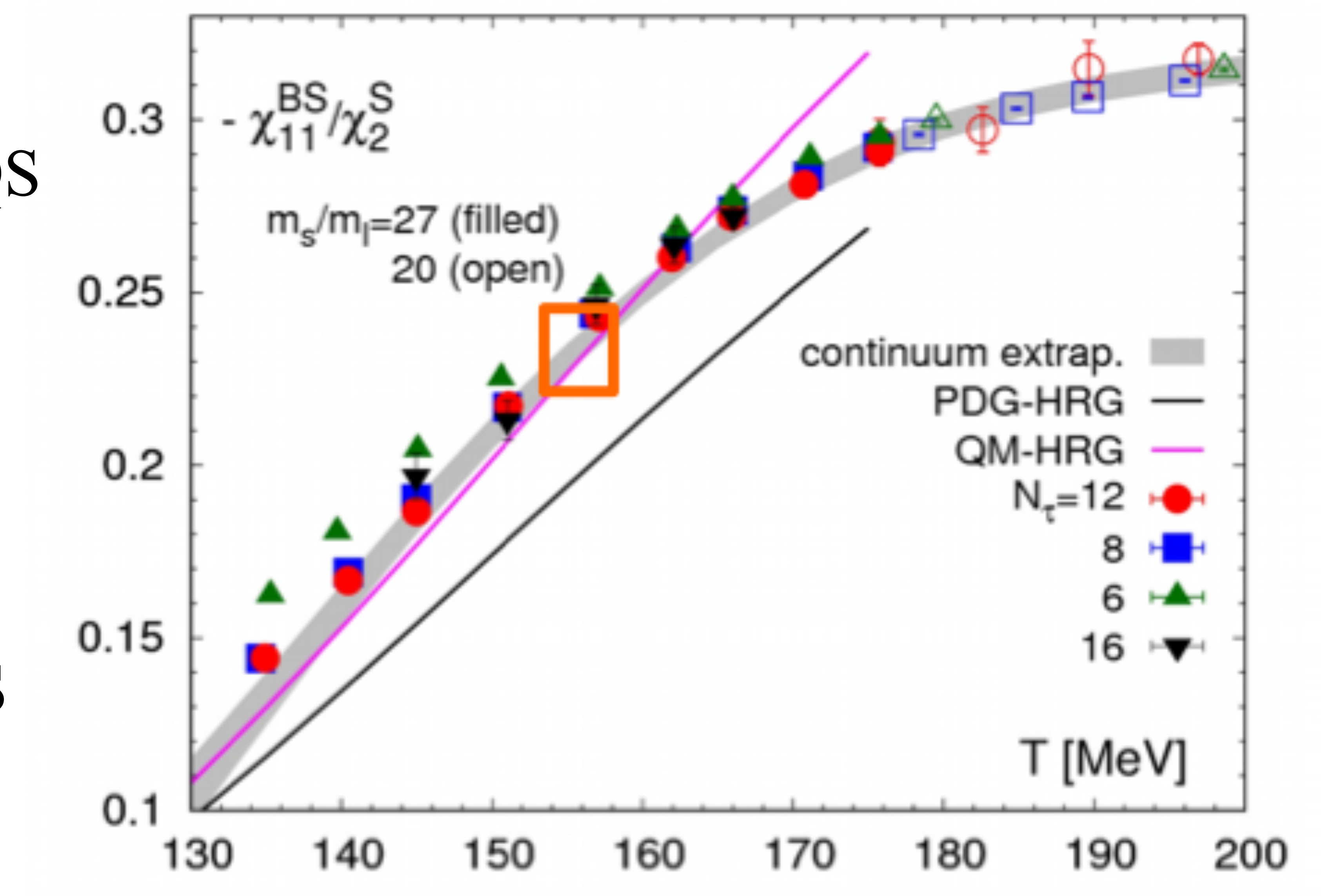
P. Braun-Munzinger, A. Rustamov, J. Stachel, NPA 982 (2019) 307 arXiv:1807.08927 [nucl-th]

- 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

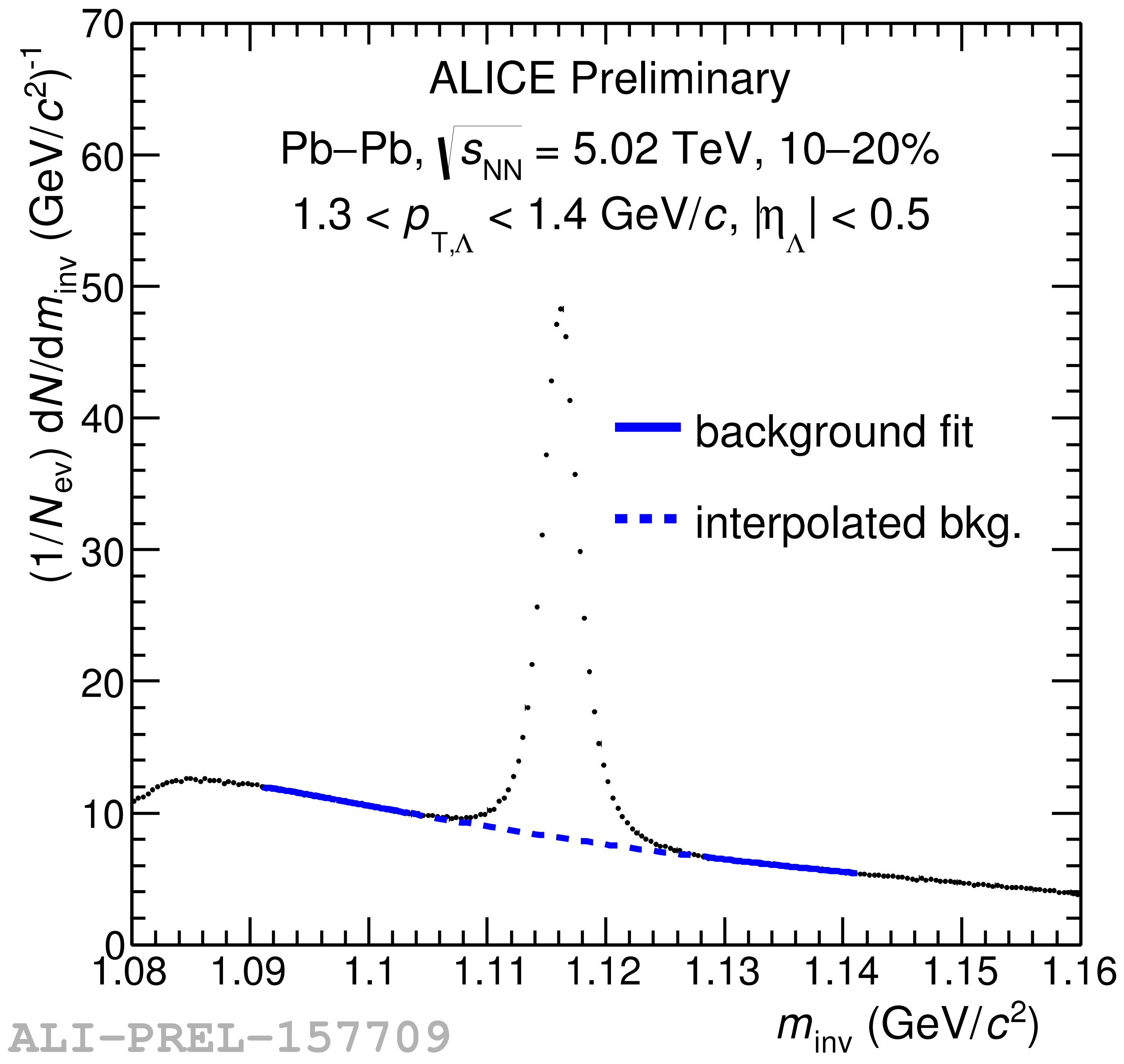
- Moving beyond net-baryon, net-strangeness, net-charge fluctuations to *correlated fluctuations* of net-charge, net-strangeness, net-baryon number
  – Access off-diagonal elements, mixed derivatives χ^{BS}, χ^{BQ}, χ^{QS}
- Net-Λ fluctuations: explore correlated fluctuations of baryon number and strangeness
- 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

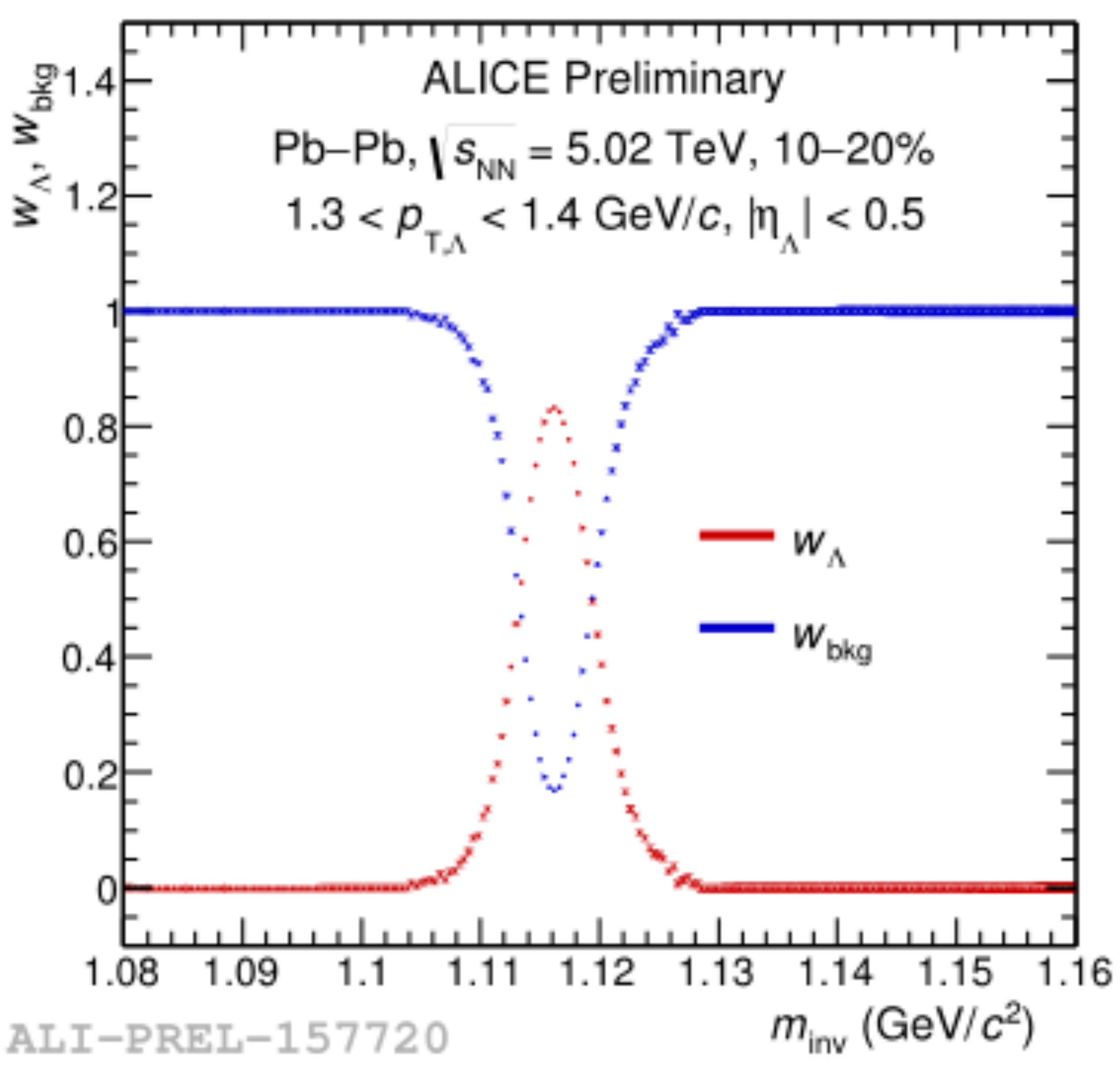


F. Karsch, EMMI Workshop on Fluctuations, Wuhan, October 2017

Identity Method for Λ

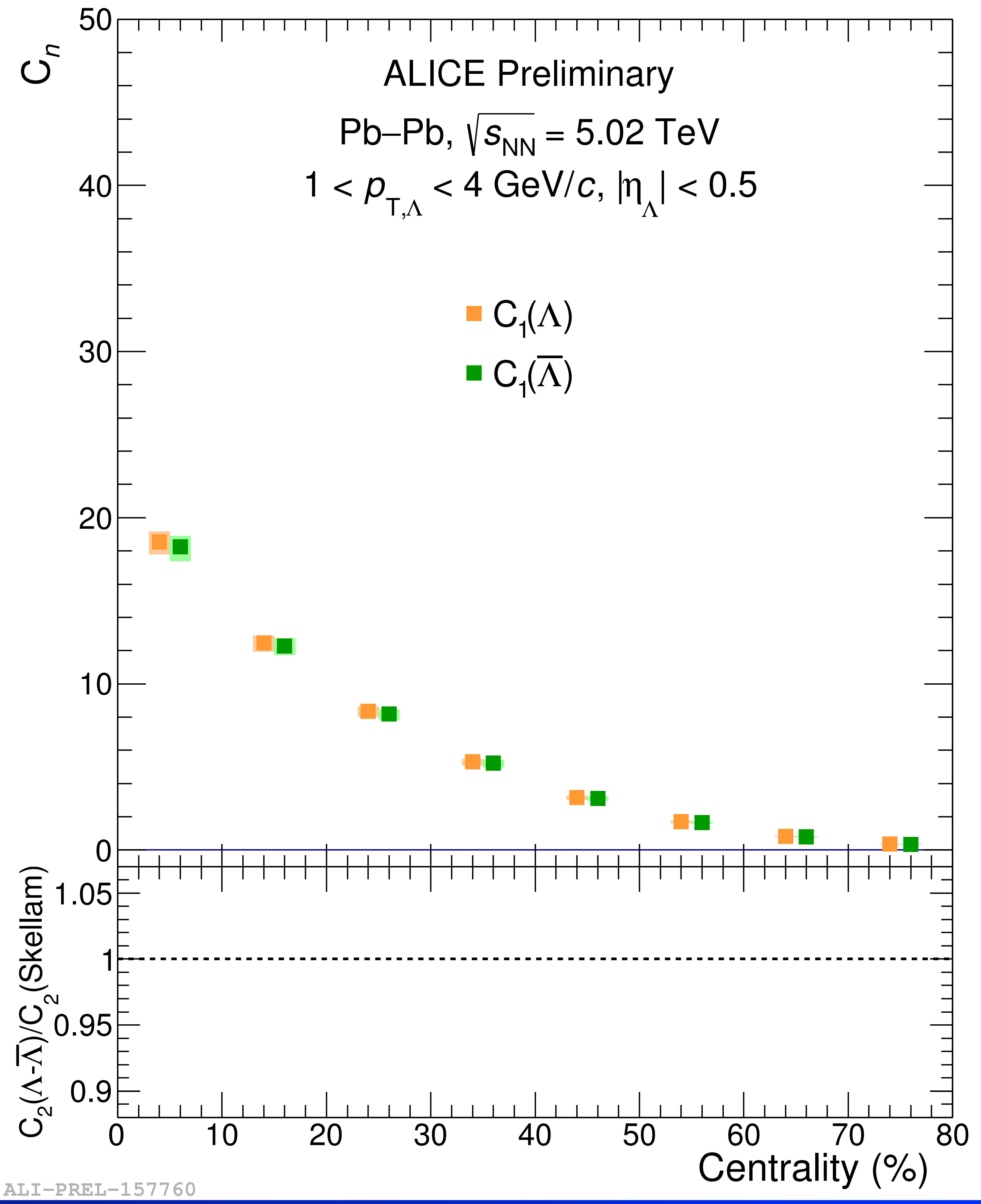
- For any value of m_{inv}, probability that a particle is a Λ or combinatoric pπ pair is known from inclusive distribution
- Identity Method formalism can be applied for four 'species': Λ, $\overline{\Lambda}$, combinatoric $p\pi^-$, combinatoric $\overline{p}\pi^+$
- Identity Method makes it possible 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

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

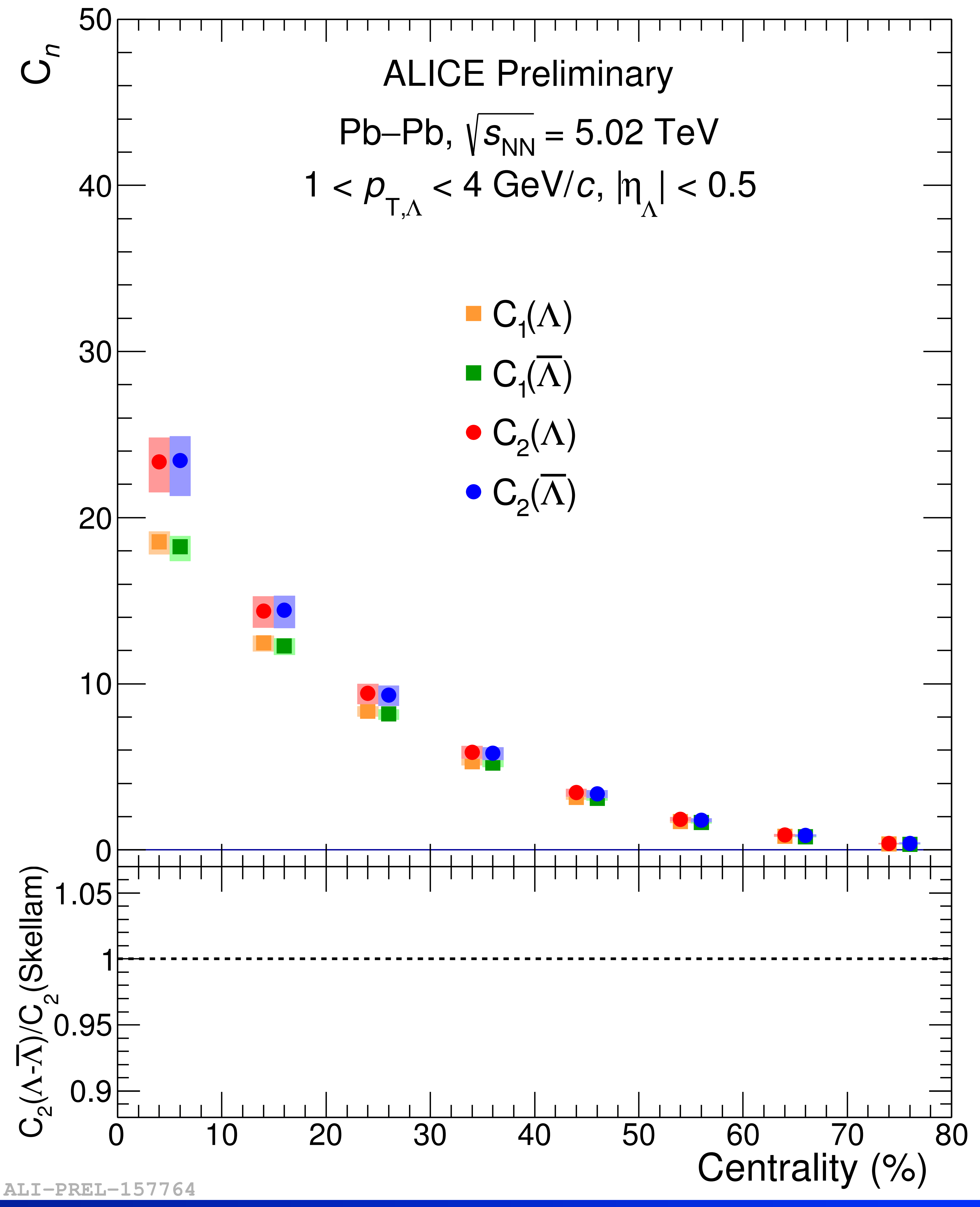


Centrality dependence of 2nd moments

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

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

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



Centrality dependence of net-Λ 2nd moments

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

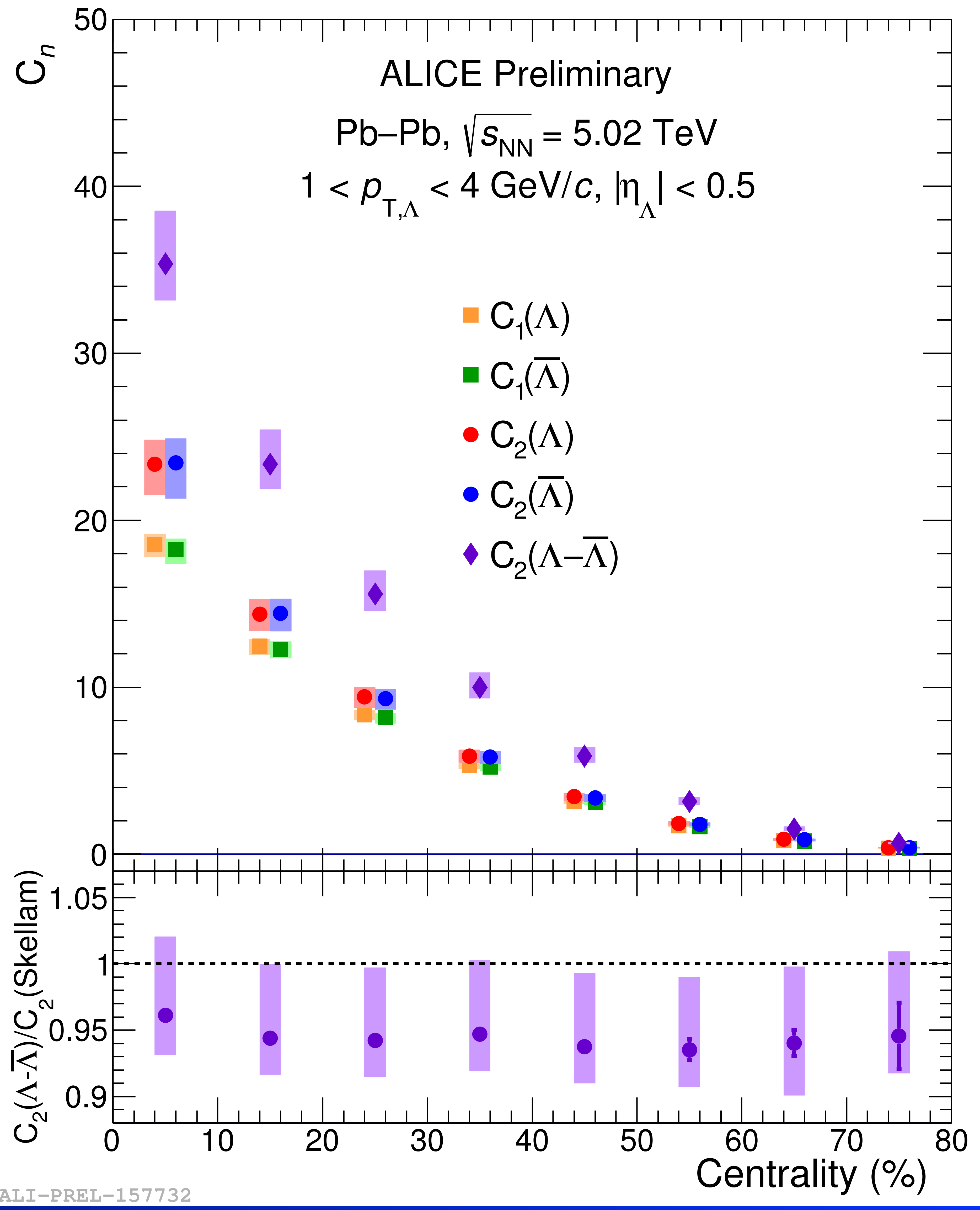
- If multiplicity distributions of Λ and $\overline{\Lambda}$ are Poissonian

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

→ if uncorrelated, Skellam distribution for net-Λ

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

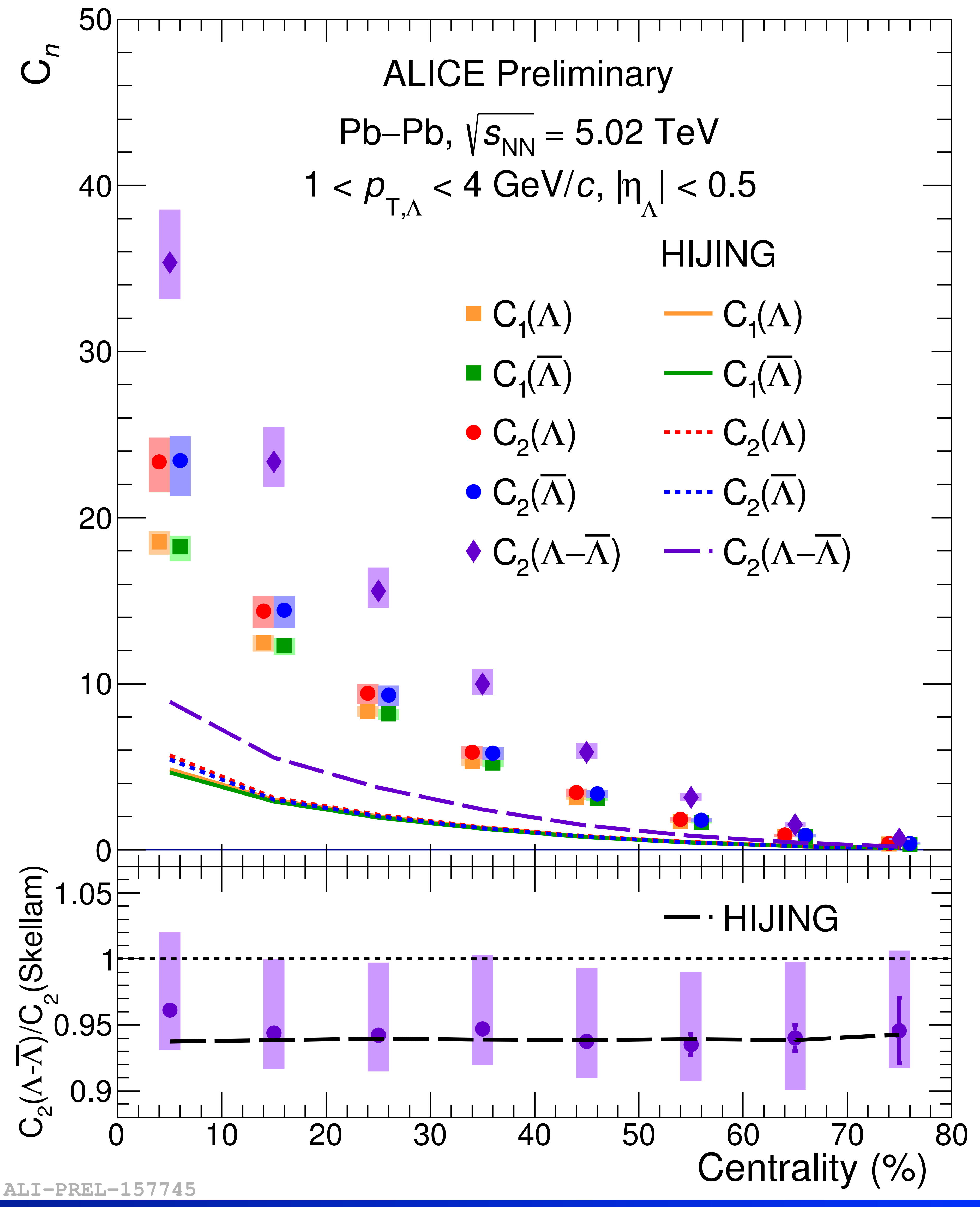
- Small deviations from Skellam baseline
  - correlation term? non-Poissonian Λ or $\overline{\Lambda}$ distributions? critical fluctuations?

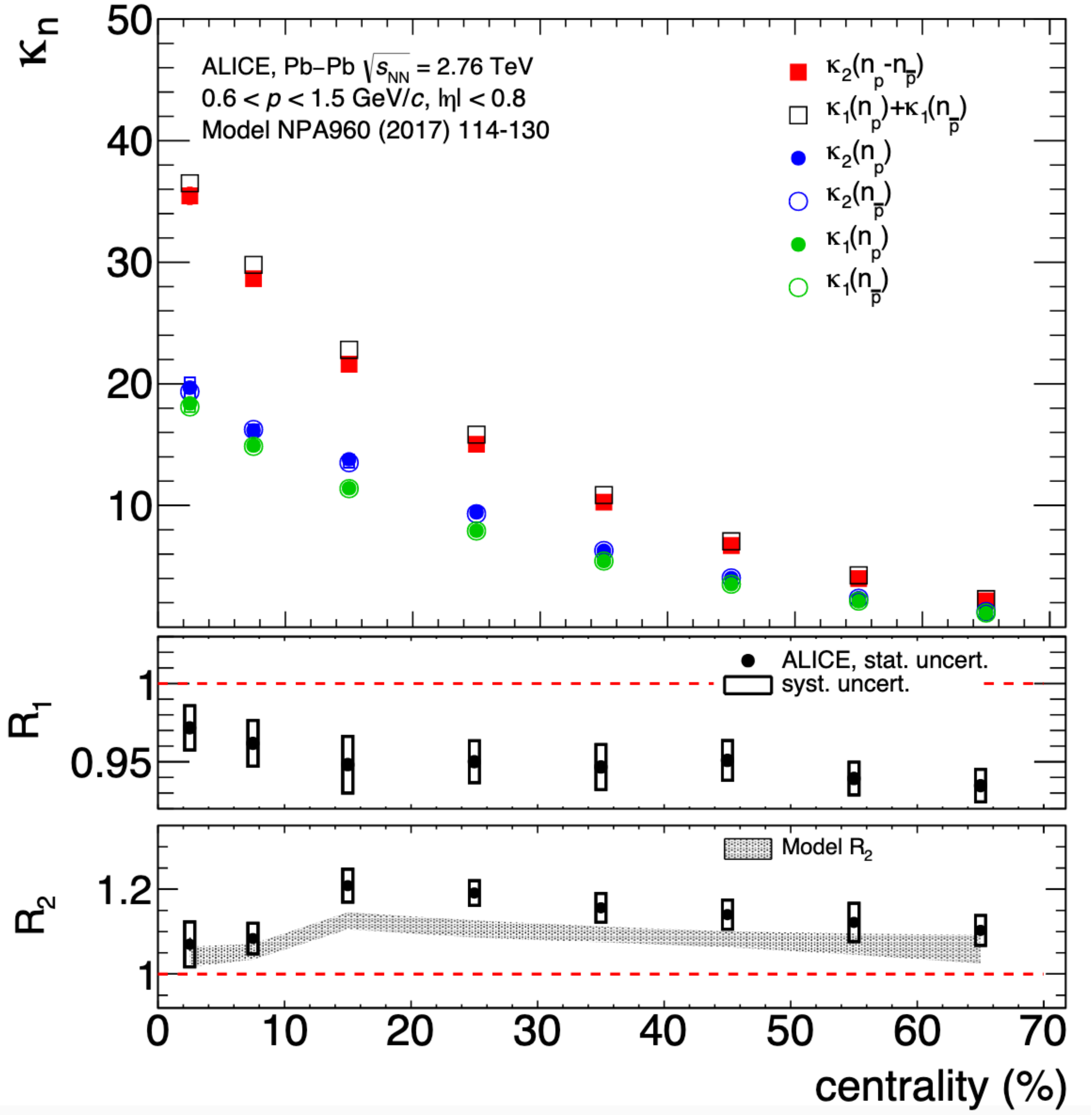


Comparison to HIJING

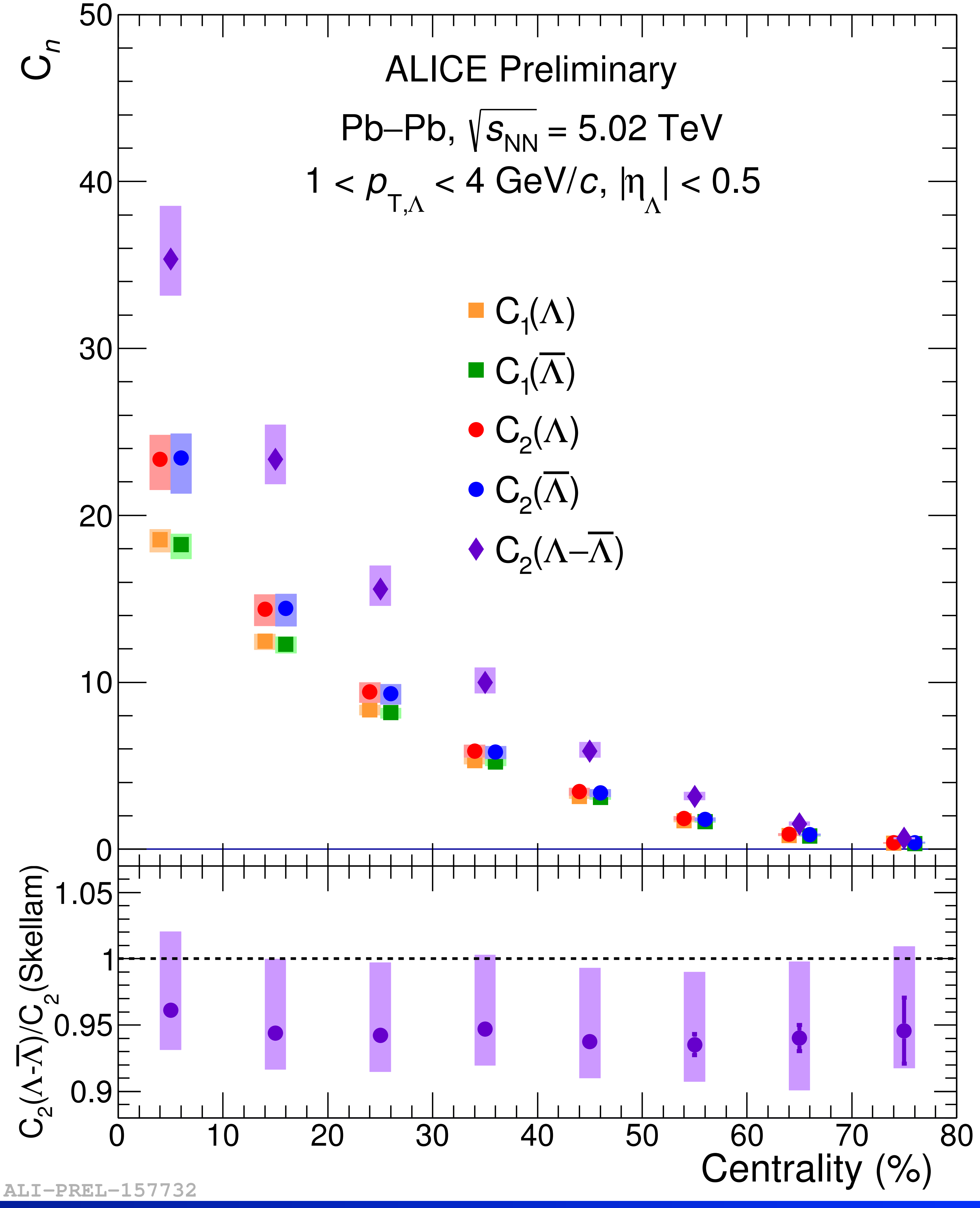
$$C_1(\Lambda) = \langle N_\Lambda \rangle$$
$$C_2(\Lambda) = \langle \left(N_\Lambda - \langle N_\Lambda \rangle\right)^2 \rangle$$
$$C_2(\Lambda - \overline{\Lambda}) = \langle \left(N_\Lambda - N_{\overline{\Lambda}} - \langle N_\Lambda - N_{\overline{\Lambda}} \rangle\right)^2 \rangle$$
$$C_2(\Lambda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

- 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?



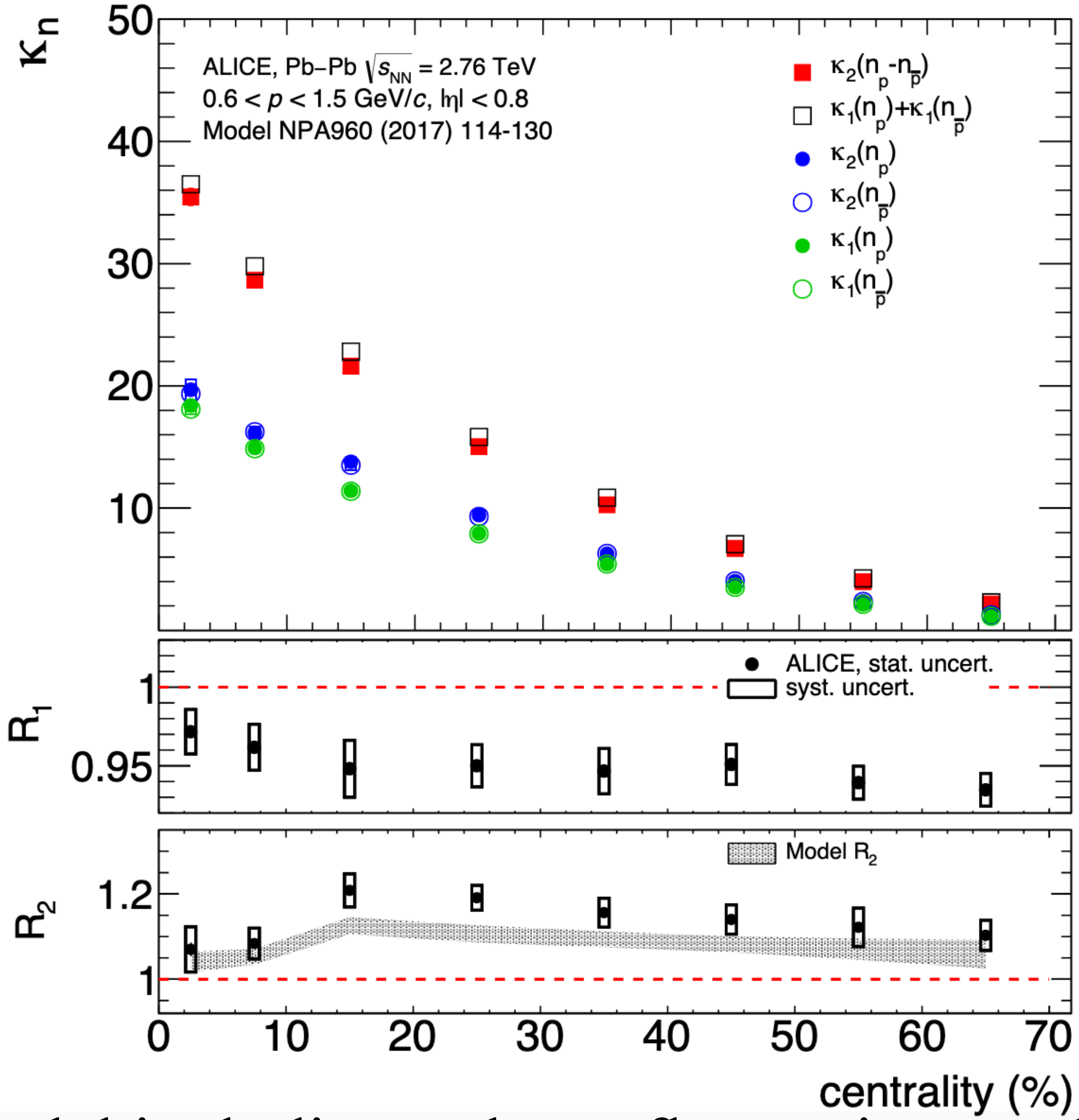


ALICE, PLB 807 (2020) 135564, arXiv:1910.14396

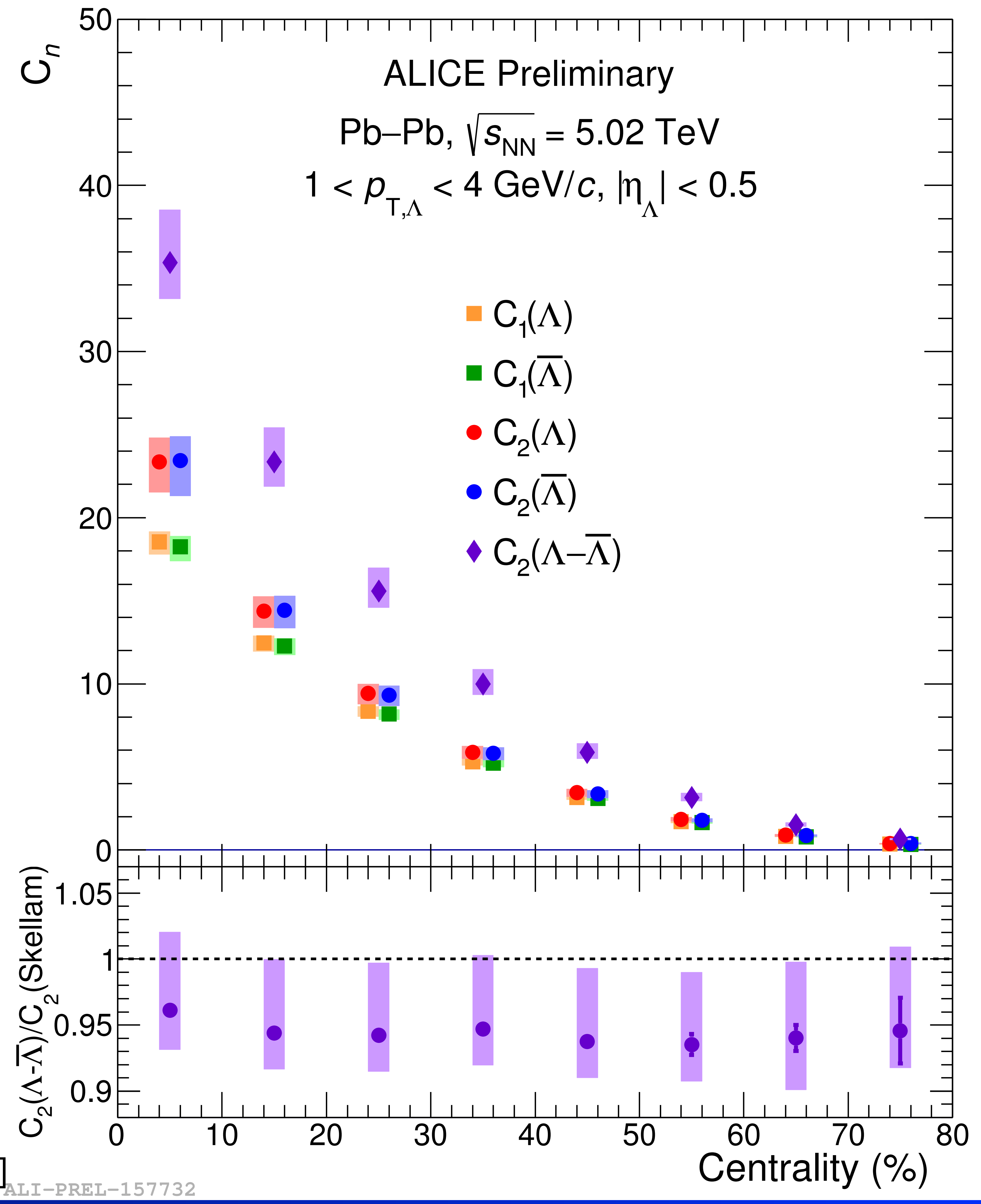


- Qualitatively similar results for net-protons
  - different kinematic range, different contributions from resonance decays

Comparison to net-protons



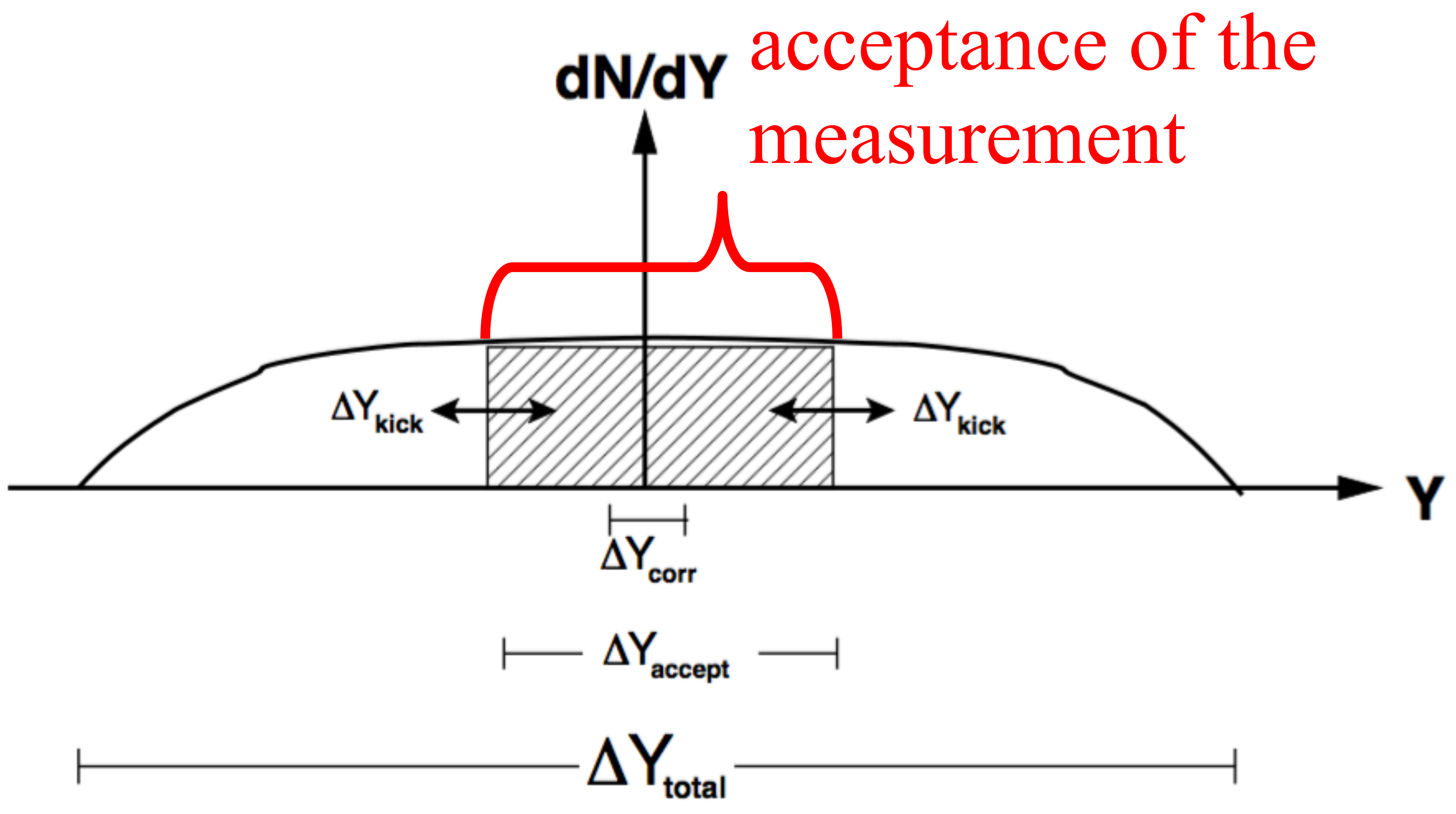
ALICE, PLB 807 (2020) 135564, arXiv:1910.14396

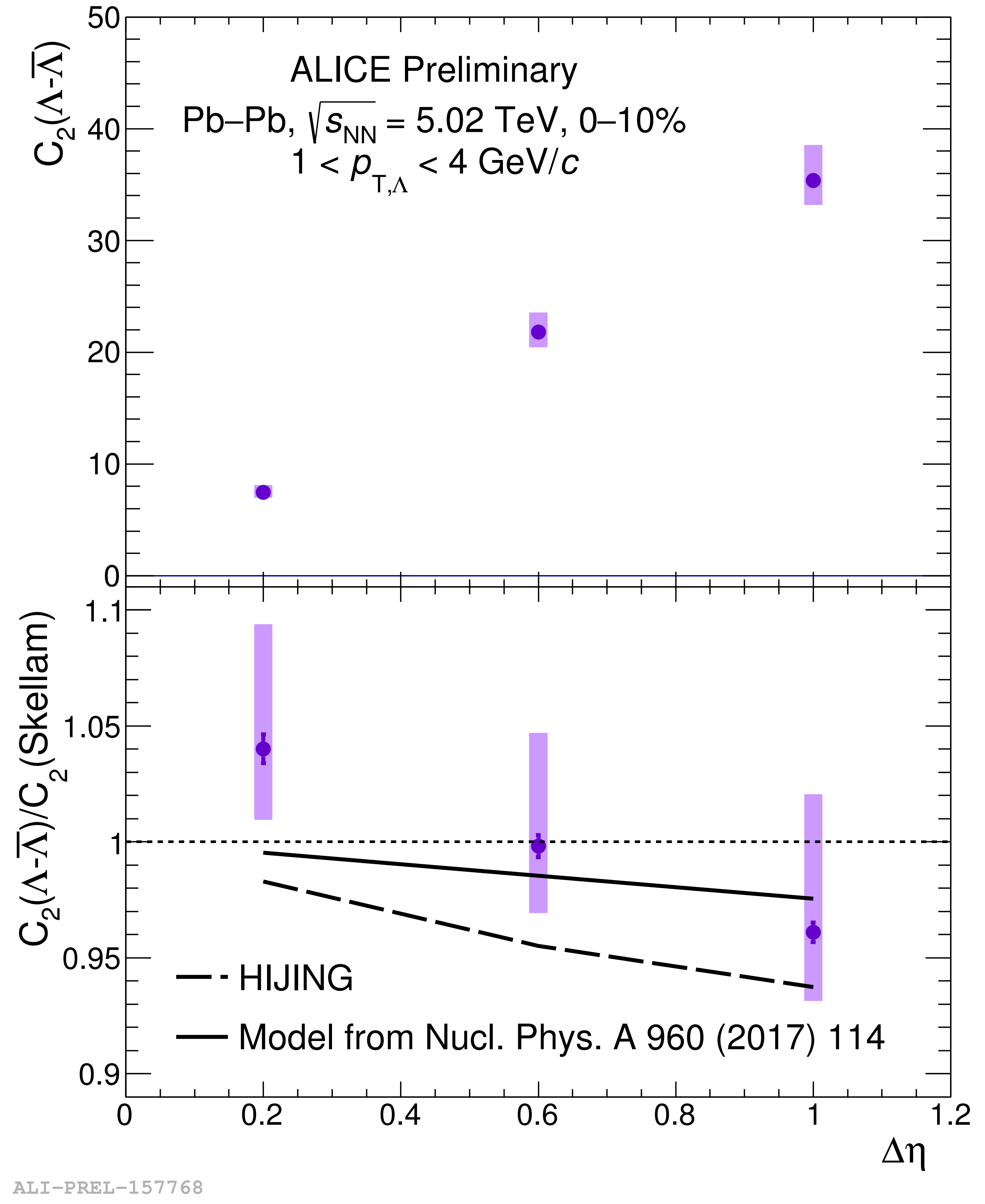


- Model including volume fluctuations and global baryon number conservation fully describes deviations from Poisson/Skellam expectation for net-protons

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

Δη dependence in central collisions





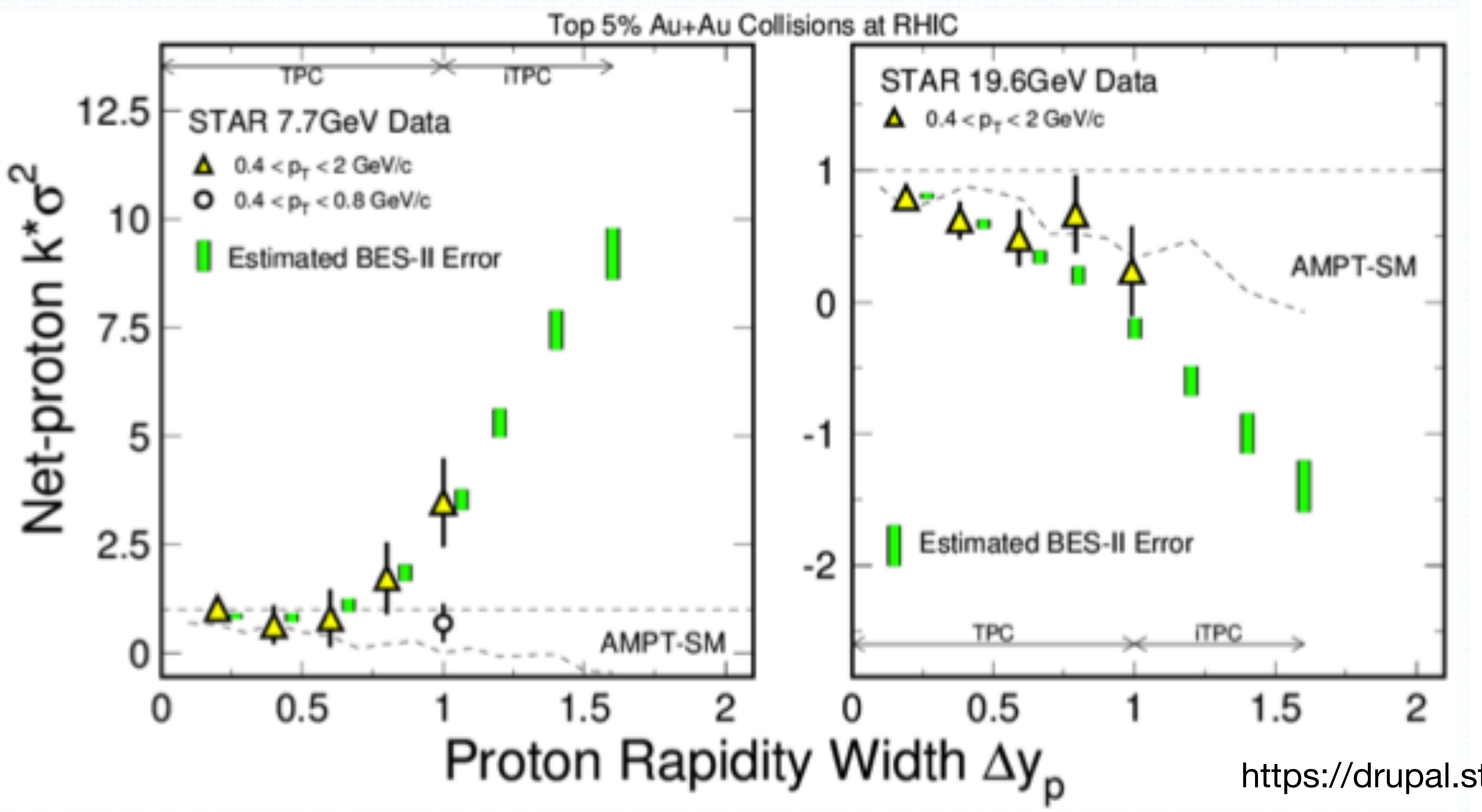
- Small Δη → Poissonian fluctuations, ratio to Skellam ~1
- Large Δη → global baryon number and strangeness conservation effects, ratio to Skellam < 1
- Systematic uncertainties are highly correlated point-to-point
- Δη dependence consistent with effects of baryon number conservation, also strangeness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

Outlook

- Runs 3+4 at the LHC will allow us to measure the fourth and sixth moments of the net-proton distribution with unprecedented precision

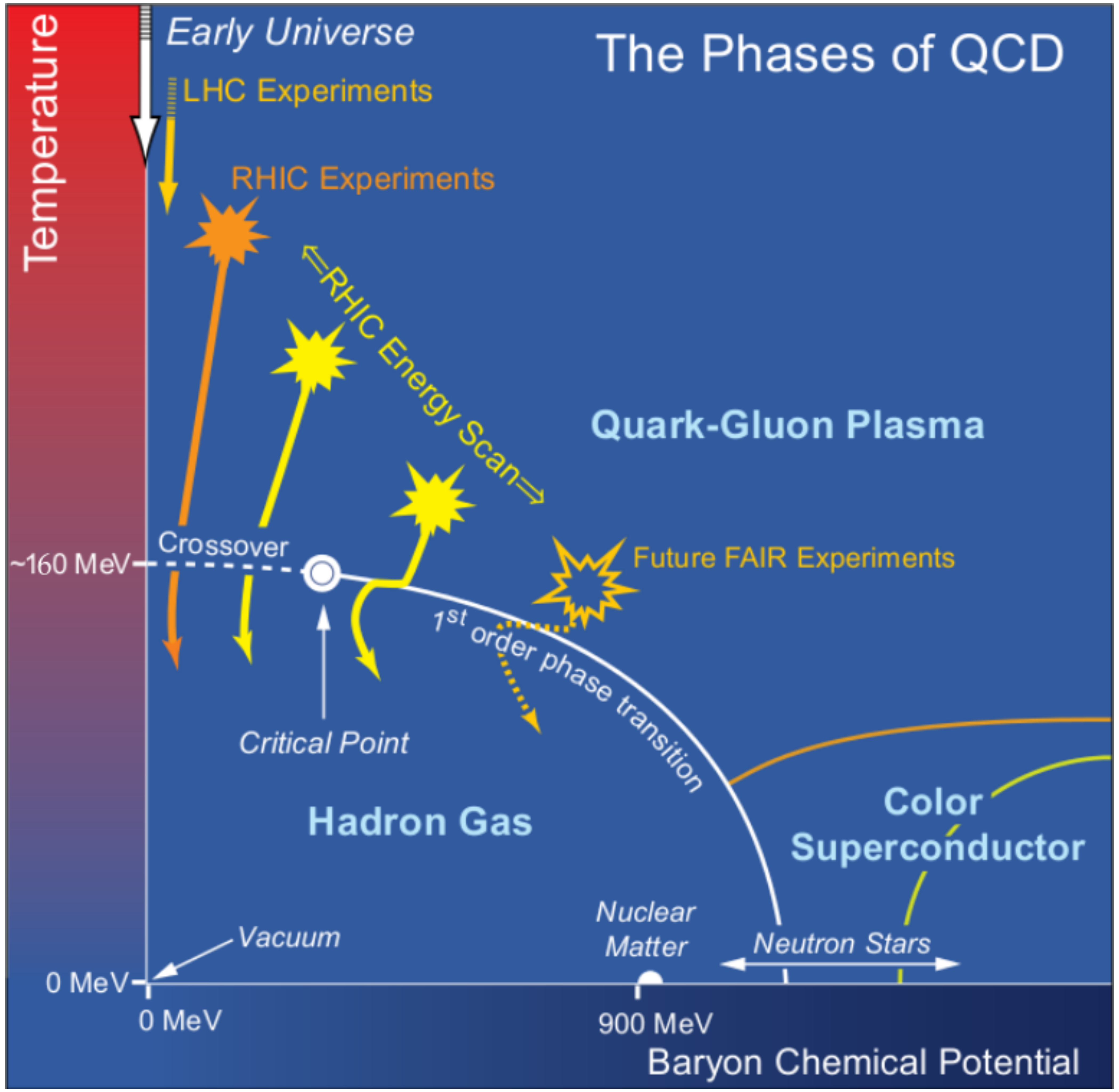
LHC Yellow Report:
arXiv:1812.06772 [hep-ph]

- BES-II + detector upgrades at RHIC will allow us to probe fluctuations across a wide range of the phase diagram



https://drupal.star.bnl.gov/STAR/starnotes/public/sn0619

Conclusions



- 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
- Corrections for detector inefficiency and particle misidentification are being brought under control, effects of volume fluctuations and global baryon number conservation are being assessed
- 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

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

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