Net-conserved charge fluctuations in ALICE and long-term perspectives

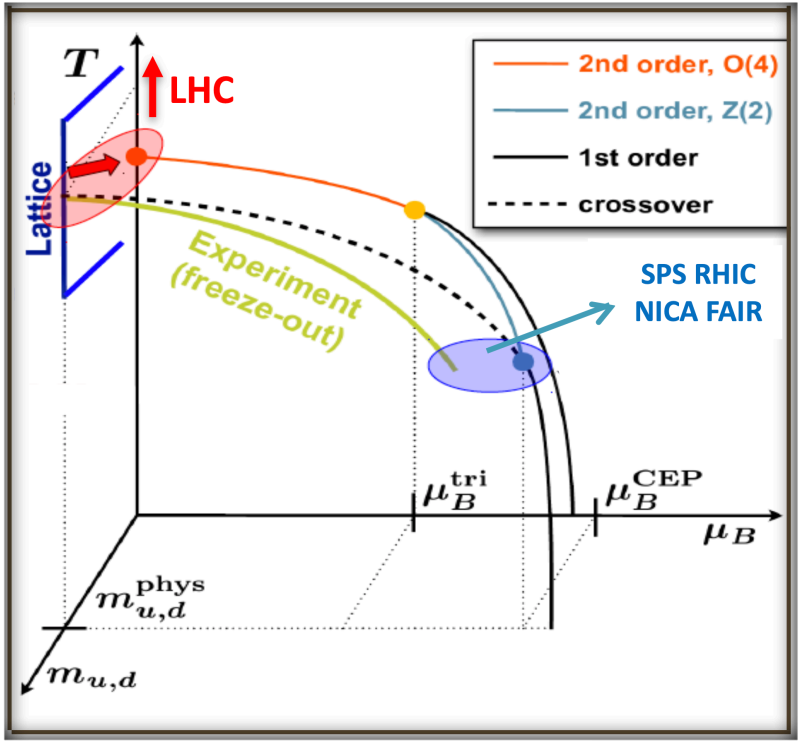
Mesut Arslandok
Yale University / CERN
on behalf of the ALICE Collaboration

The 20th International Conference on Strangeness in Quark Matter
13-17 June 2022, Busan, Republic of Korea

In part supported by

Nature of chiral phase transition

F. Karsch, Schleching 2016



- **Vanishing u, d quark masses:**

  ⟹ vicinity to 2nd order O(4) criticality

  ⟹ pseudocritical features at the crossover due to massless modes

  ⟹ **long range correlations & increased fluctuations**

Nature of chiral phase transition

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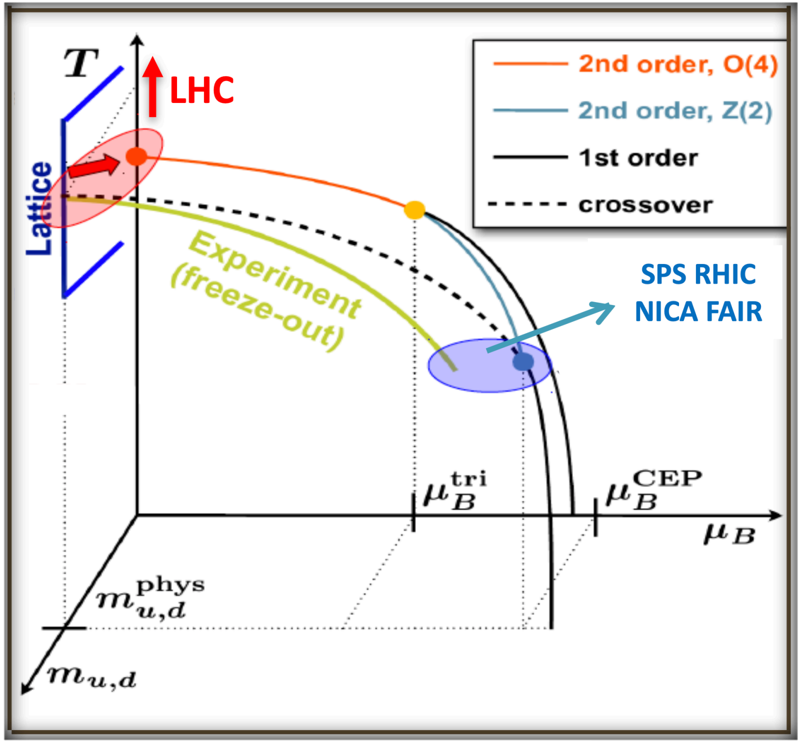

- **Vanishing u, d quark masses:**
  - ⟹ vicinity to 2nd order O(4) criticality
  - ⟹ pseudocritical features at the crossover due to massless modes
  - ⟹ **long range correlations & increased fluctuations**
- **Cross over transition at $\mu_B \approx 0$ MeV**
  - ⟹ no experimental confirmation
  - ⟹ $T_{pc}^{LQCD} \approx T_{fo}^{ALICE} = 156.5 \pm 3$ MeV

A. Andronic et.al. Nature 561 (2018) 321
HotQCD Collaboration, Phys.Lett. B795 (2019) 15
S. Borsanyi et.al. Phys. Rev. Lett. 125, 052001 (2020)

Link to lattice QCD: Cumulants of net-charge distributions

LQCD

Baryon number **(B)**, Strangeness **(S)**, Electric charge **(Q)**, Cham **(C)**

$$\chi^{BQSC}_{klmn} = \left.\frac{\partial^{(k+l+m+n)}[P(\hat{\mu}_B,\hat{\mu}_Q,\hat{\mu}_S,\hat{\mu}_C)/T^4]}{\partial\hat{\mu}_B^k\partial\hat{\mu}_Q^l\hat{\mu}_S^m\partial\hat{\mu}_C^n}\right|_{\vec{\mu}=0}$$

EXPERIMENT

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

κ_n → central moments of X

$$\hat{\chi}_2^B = \frac{\kappa_2(\Delta N_B)}{VT^3} \Rightarrow \frac{\kappa_4(\Delta N_B)}{\kappa_2(\Delta N_B)} = \frac{\hat{\chi}_4^B}{\hat{\chi}_2^B}$$

Effect of volume fluctuations:

P. Braun-Munzinger, A. Rustamov, J. Stachel, Nucl. Phys. A960 (2017) 114

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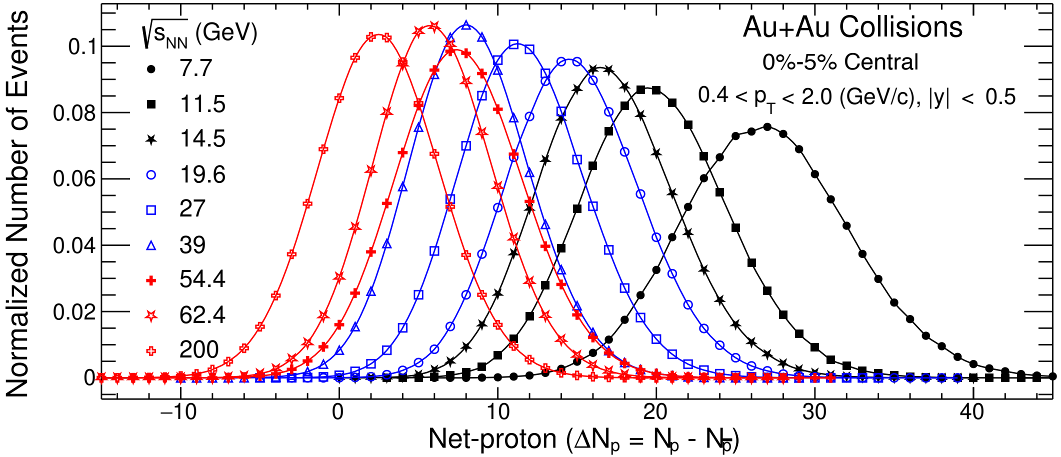
STAR Collaboration, Phys. Rev. Lett. 126, 092301



- Critical signals are hidden in the tails
- Experimentally very challenging

Effect of volume fluctuations:

P. Braun-Munzinger, A. Rustamov, J. Stachel, Nucl. Phys. A960 (2017) 114

What does theory tell us?

1) **Baseline:** Difference between two independent Poissonian distributions (Skellam distr.)
   $\Longrightarrow$ **κ_n/κ_2 is 0 (odd) or 1 (even)**

2) **Up to 3rd order** Hadron Resonance Gas (HRG) model agrees with LQCD at $\mu_B = 0$

3) **Higher order** $\rightarrow$ larger deviation from baseline

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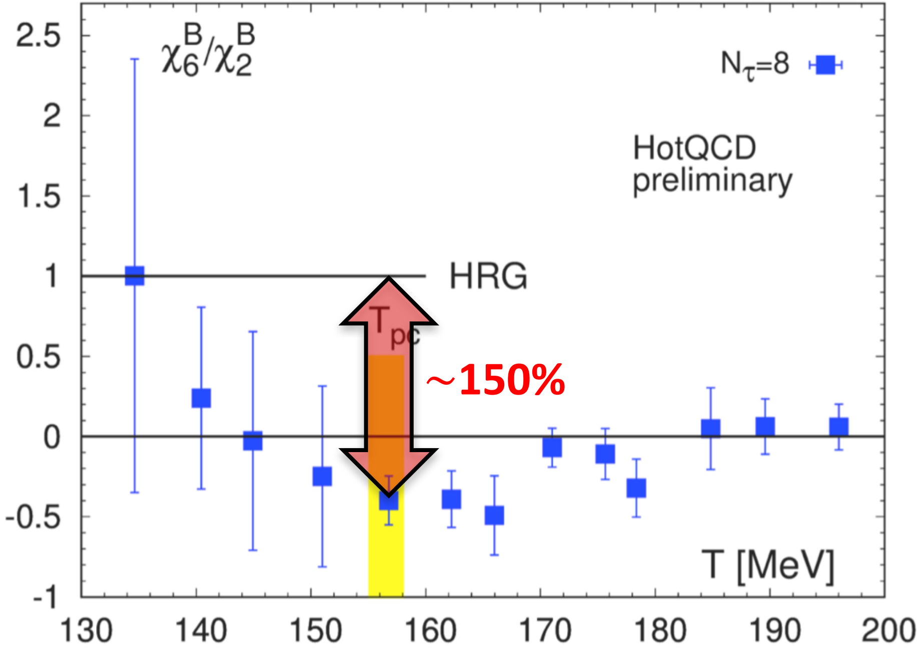
2) **Up to 3rd order** Hadron Resonance Gas (HRG) model agrees with LQCD at $\mu_B = 0$

3) **Higher order** → larger deviation from baseline

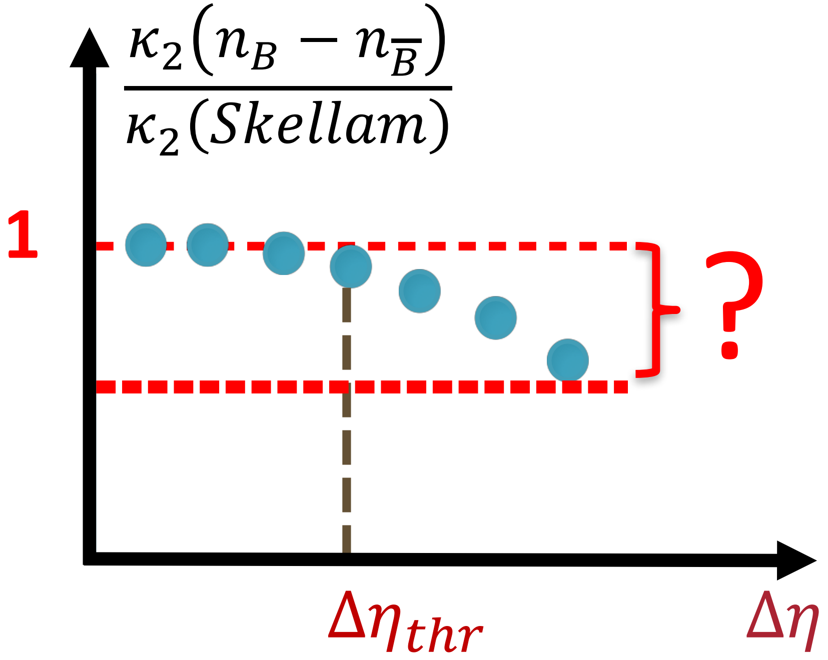
4) **Holy grail:** Critical behavior as from 6th order
   $\Longrightarrow$ 4th order ~30%, **6th order ~150%**

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



What do we expect to see in the data?

- ✓ Fluctuations of conserved charges appear only inside finite acceptance
- ✓ In the limit of very small acceptance → only Poissonian fluctuations

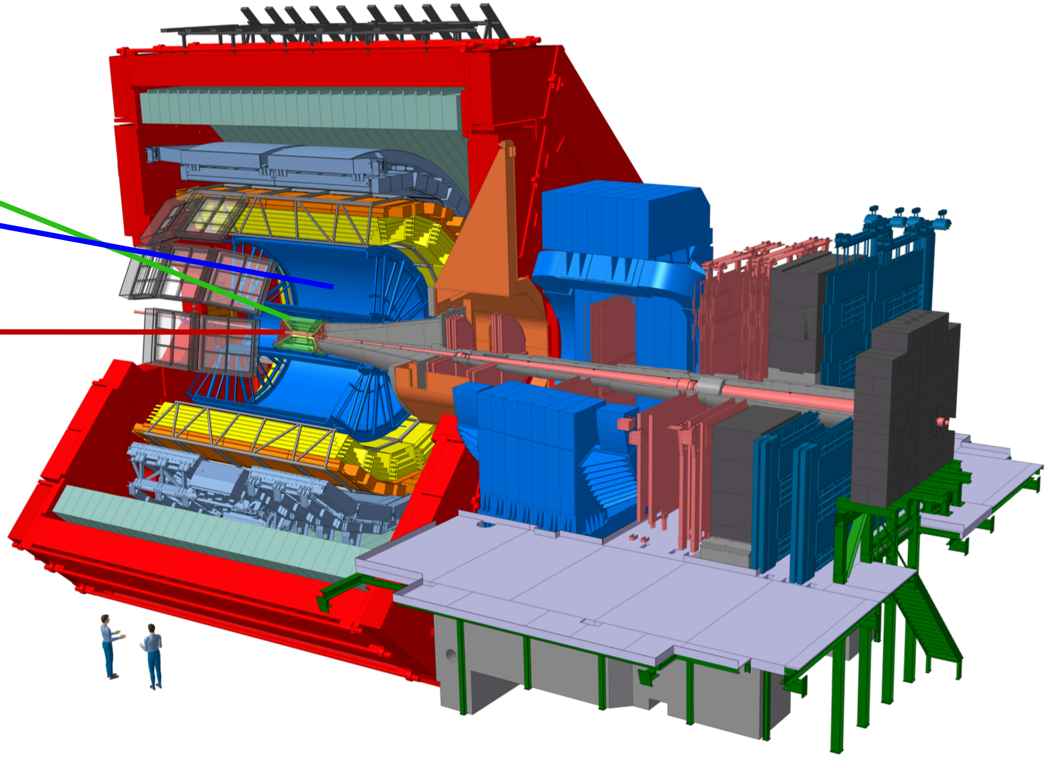


RESULTS

A Large Ion Collider Experiment

Main detectors used:

- **Inner Tracking System (ITS)**
  → Tracking and vertexing
- **Time Projection Chamber (TPC)**
  → Tracking and
  Particle Identification (PID)
- **V0**
  → Centrality determination



Data Set:

- $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV, ~78 M events
- $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV, ~13 M events

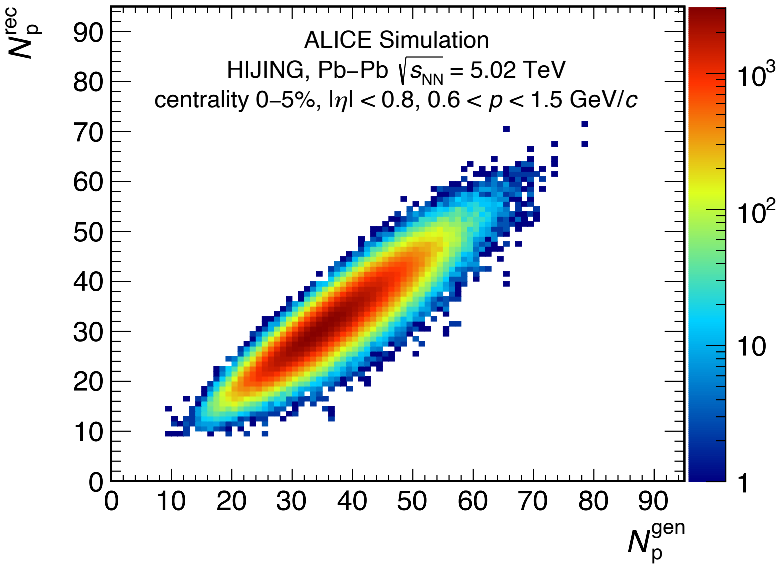
Kinematic acceptance:

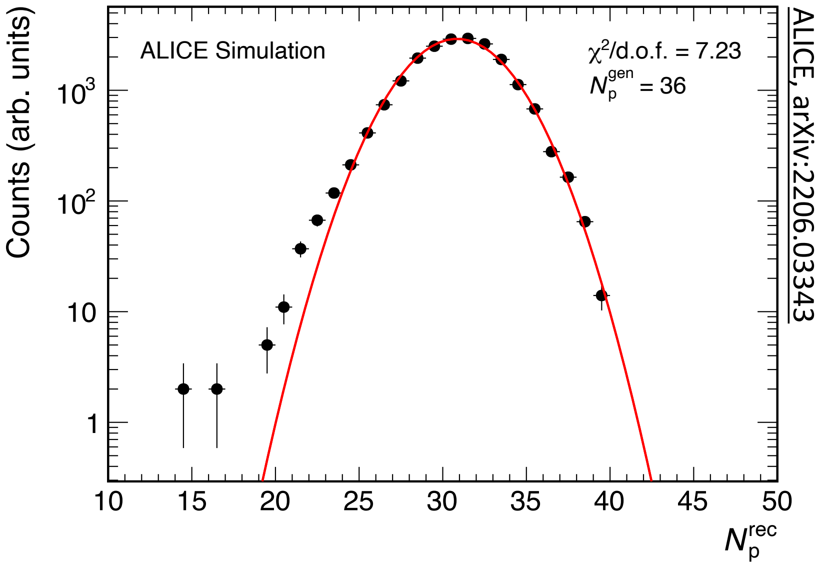
- $0.6 < p < [1.5, 2]$ GeV/c
- $|\eta| < 0.2, 0.4, \ldots, 0.8$

Experimental challenges: E.g. efficiency correction

NEW

Binomiality of the detector response is important for the efficiency correction



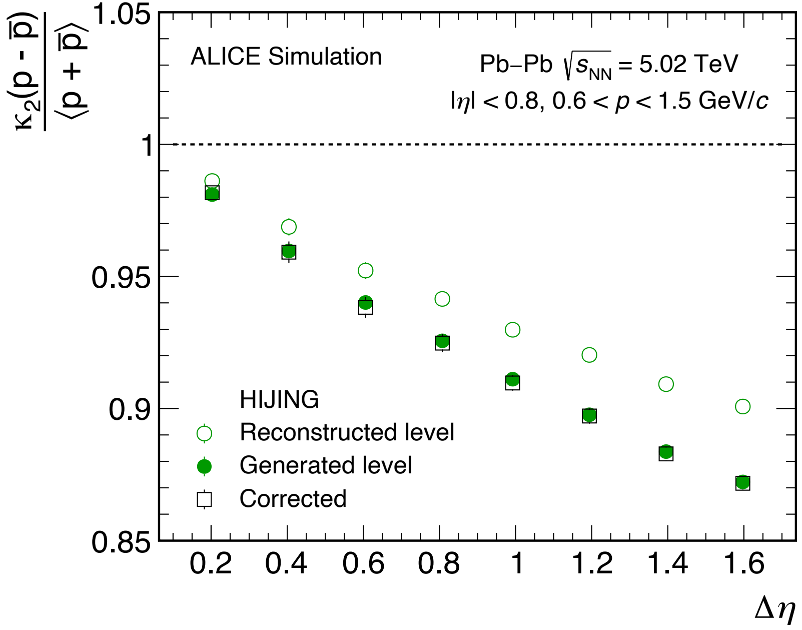


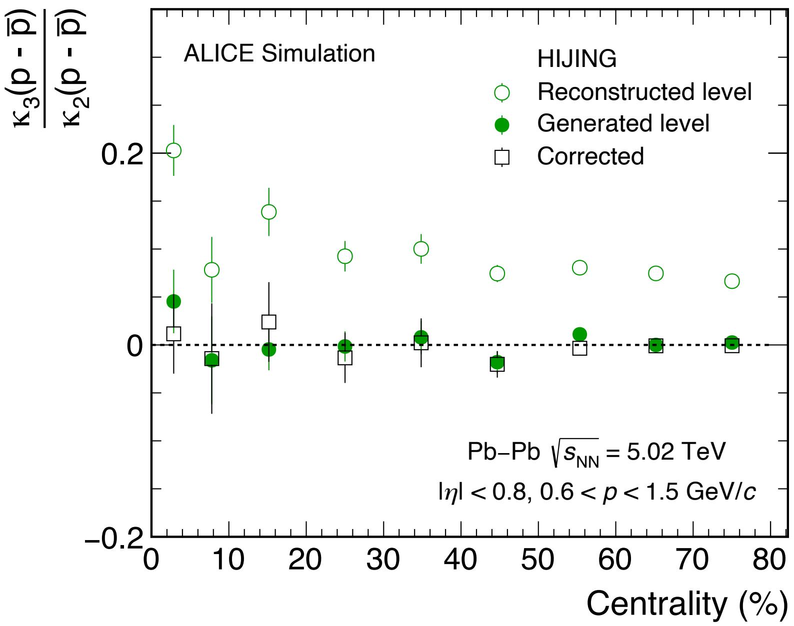
Slight deviation from the binomial efficiency loss

- Event and track selection
- TPC dE/dx calibration in particular for the events with pileup
  M. Arslandok, E. Hellbär, M. Ivanov, R.H. Münzer and J. Wiechula, Particles 2022, 5(1), 84-95
- Realistic detector simulation

Experimental challenges: E.g. efficiency correction

NEW





ALICE, arXiv:2206.03343

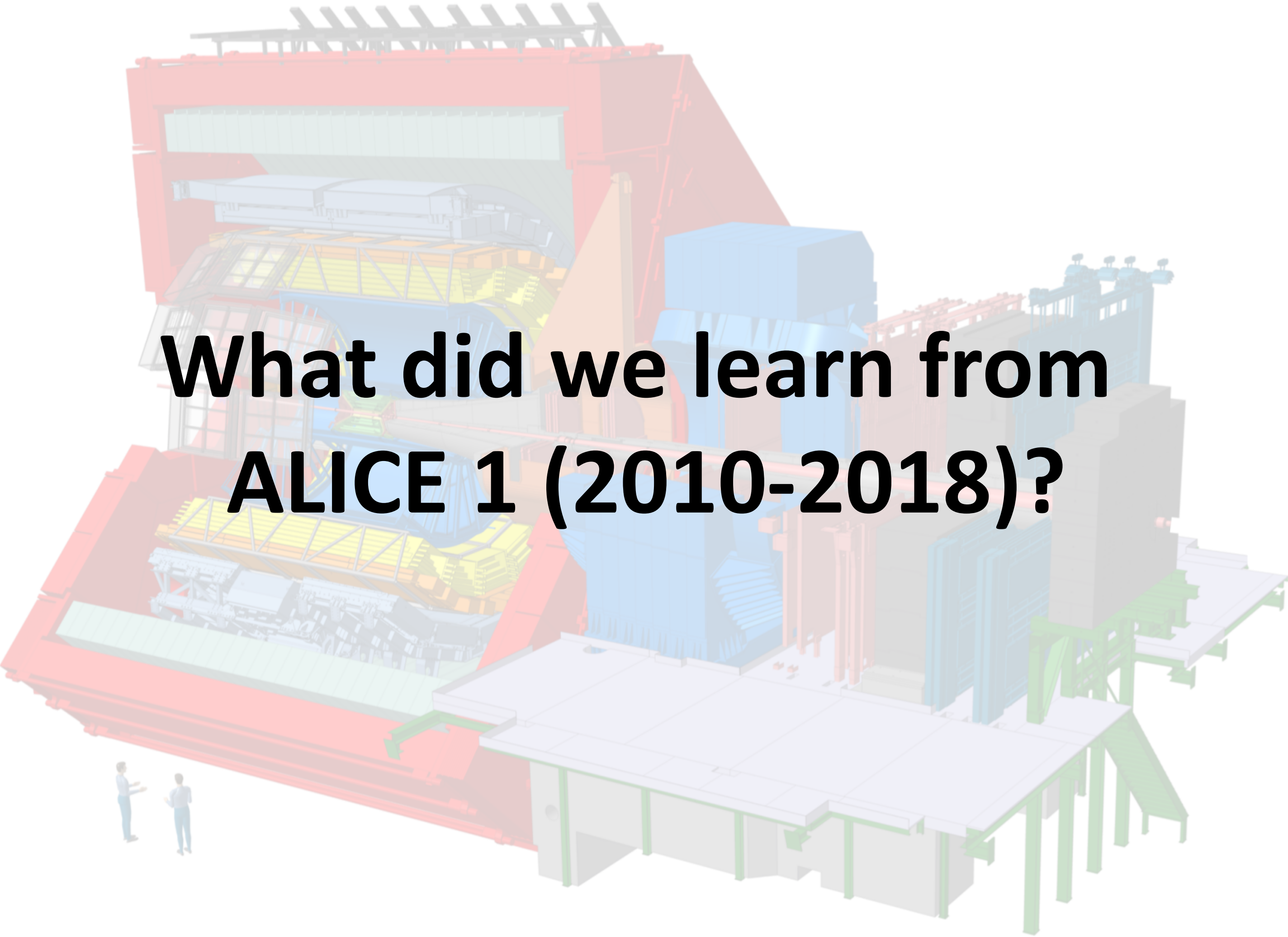
Very good closure despite the slight deviation from binomial loss

Efficiency correction with binomial assumption:

T. Nonaka, M. Kitazawa, S. Esumi, Phys. Rev. C 95, 064912 (2017)

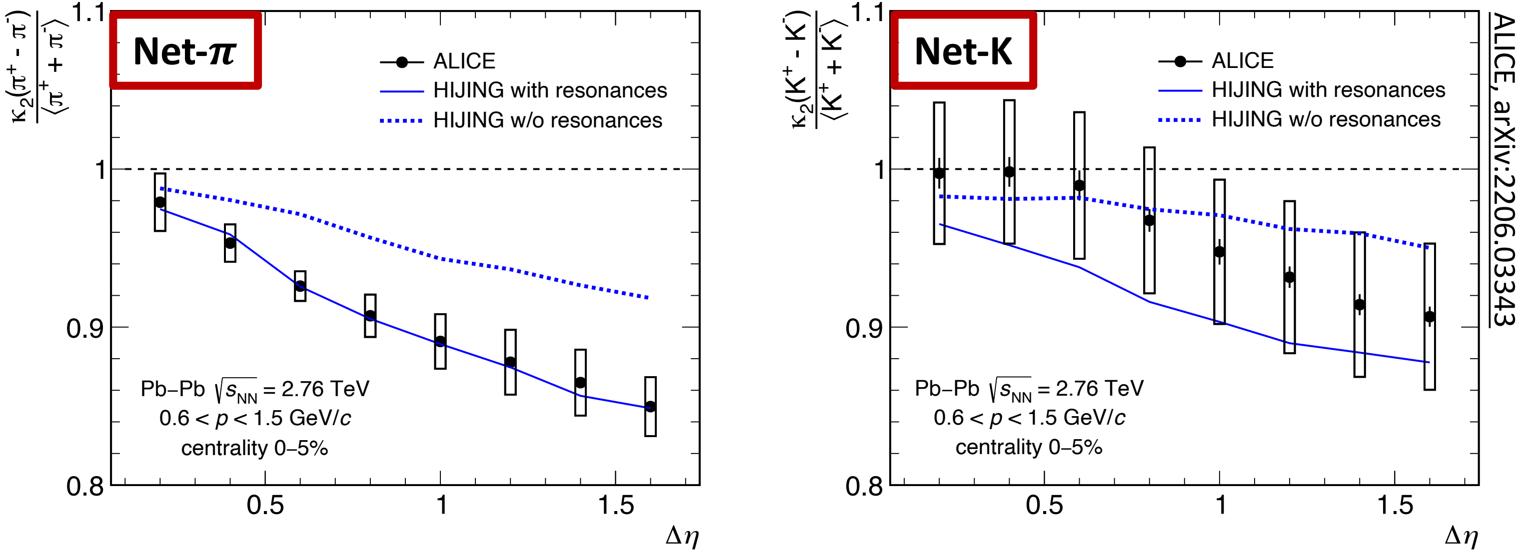
Adam Bzdak, Volker Koch, Phys. Rev. C86, 044904 (2012)

What did we learn from ALICE 1 (2010-2018)?



Net-(global)charge fluctuations

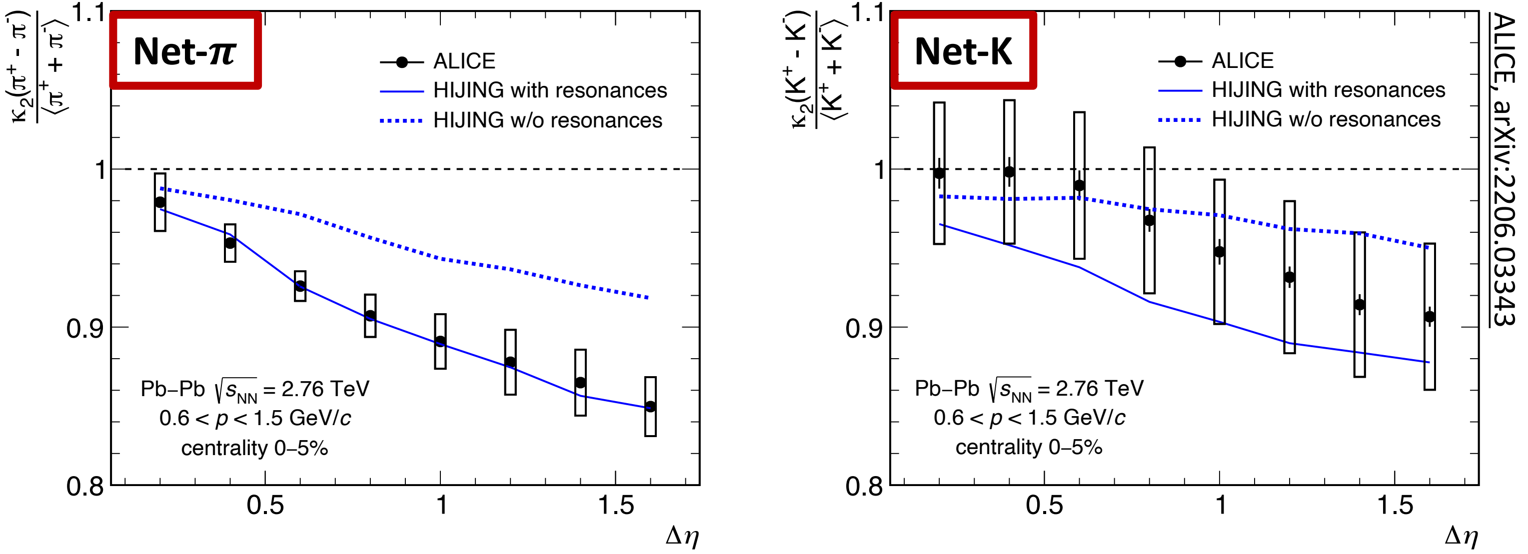
NEW



- **Net-Q,S:** → Strongly dominated by **resonance contributions**
  (V. Vovchenko and V. Koch Phys. Rev. C 103, 044903 (2021))

Net-(global)charge fluctuations

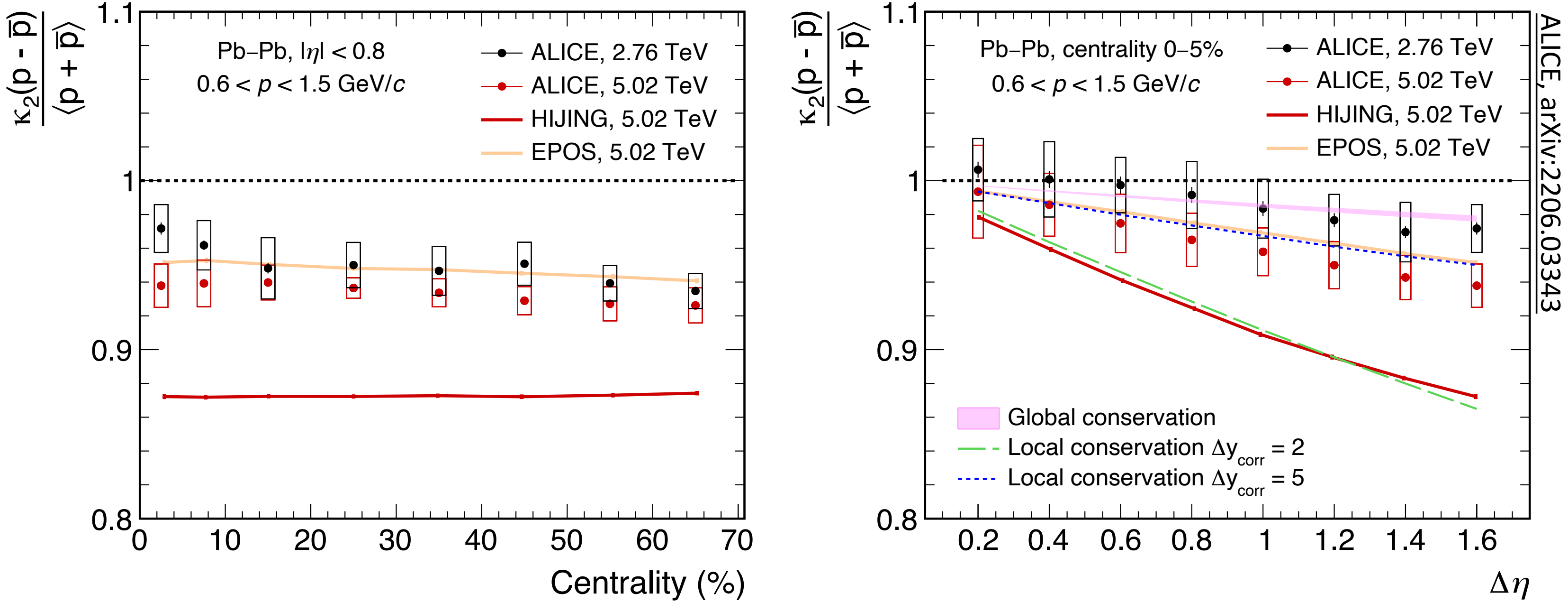
NEW



- **Net-Q,S:** → Strongly dominated by **resonance contributions**
  (V. Vovchenko and V. Koch Phys. Rev. C 103, 044903 (2021))
- **Net-B:**
  → Due to **isospin randomization,** at $\sqrt{s_{NN}}$ > 10 GeV **net-baryon ↔ net-proton**
  (M. Kitazawa, and M. Asakawa, Phys. Rev. C 86, 024904 (2012))
  → No resonance feeding $p + \bar{p}$
  → **Best candidate for measuring charge susceptibilities is net-p**

2^{nd} order cumulants of net-p

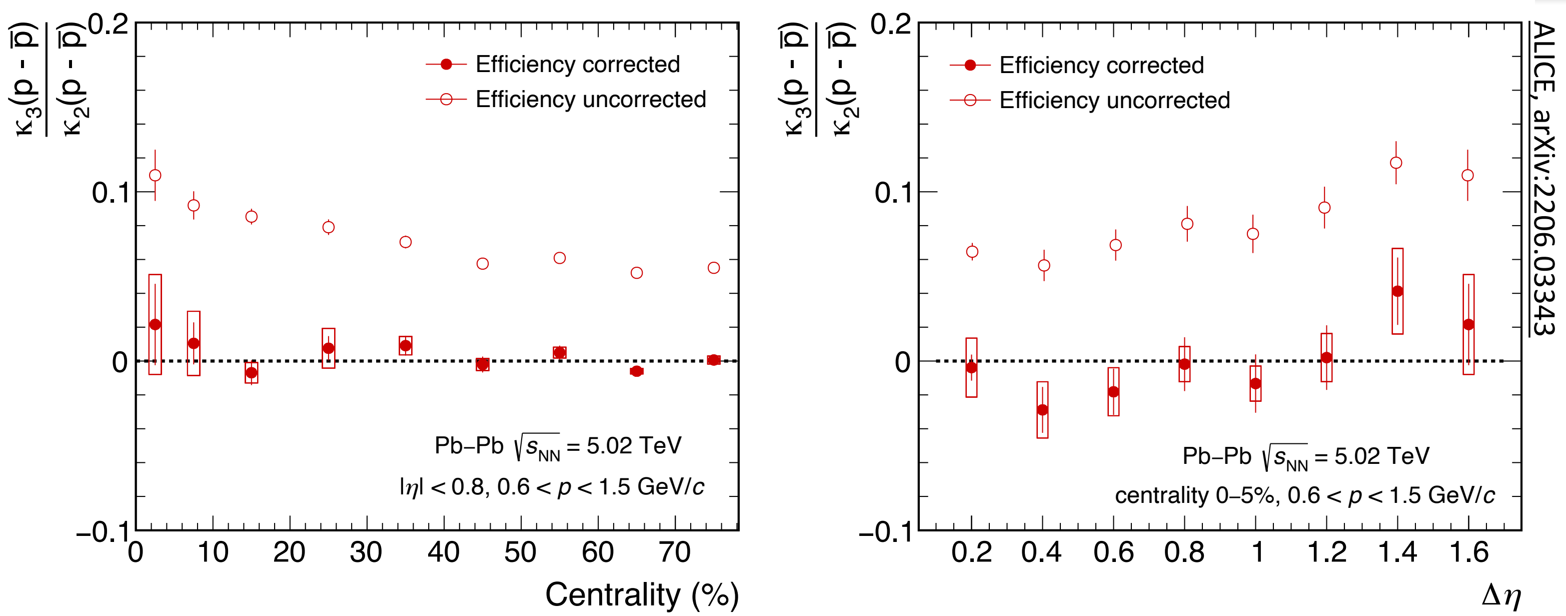
NEW



- Deviation from Skellam baseline is due to **baryon number conservation**
- ALICE data suggest **long range correlations**, $\Delta y = \pm 2.5$ **unit or longer → earlier in time**
  A. Dumitru, F. Gelis, L. McLerran, and R. Venugopalan, *Nucl. Phys. A* 810 (2008) 91
- EPOS agrees with ALICE data but HIJING deviates significantly
  - Event generators based on **string fragmentation (HIJING)** conserve baryon number over $\Delta y = \pm 1$ **unit**

3rd order cumulants of net-p

NEW

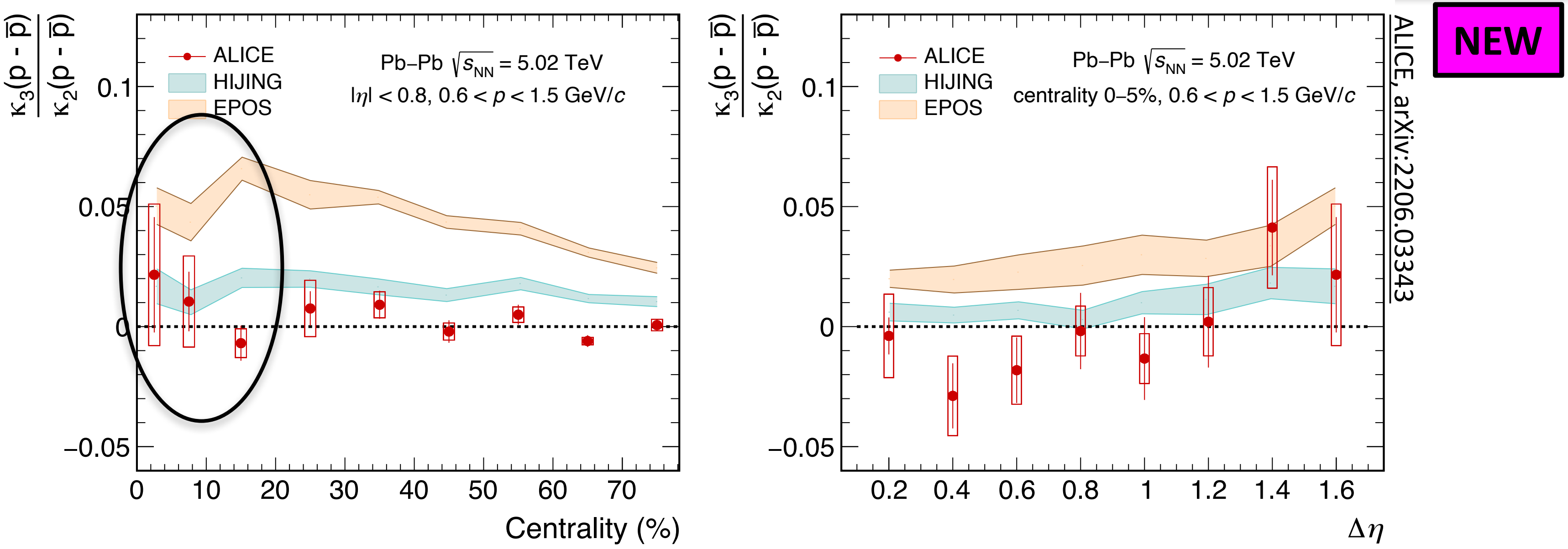


- **Data agree with Skellam baseline "0"** as a function of centrality and pseudorapidity
  - **μ_B is very close to 0** at LHC energies

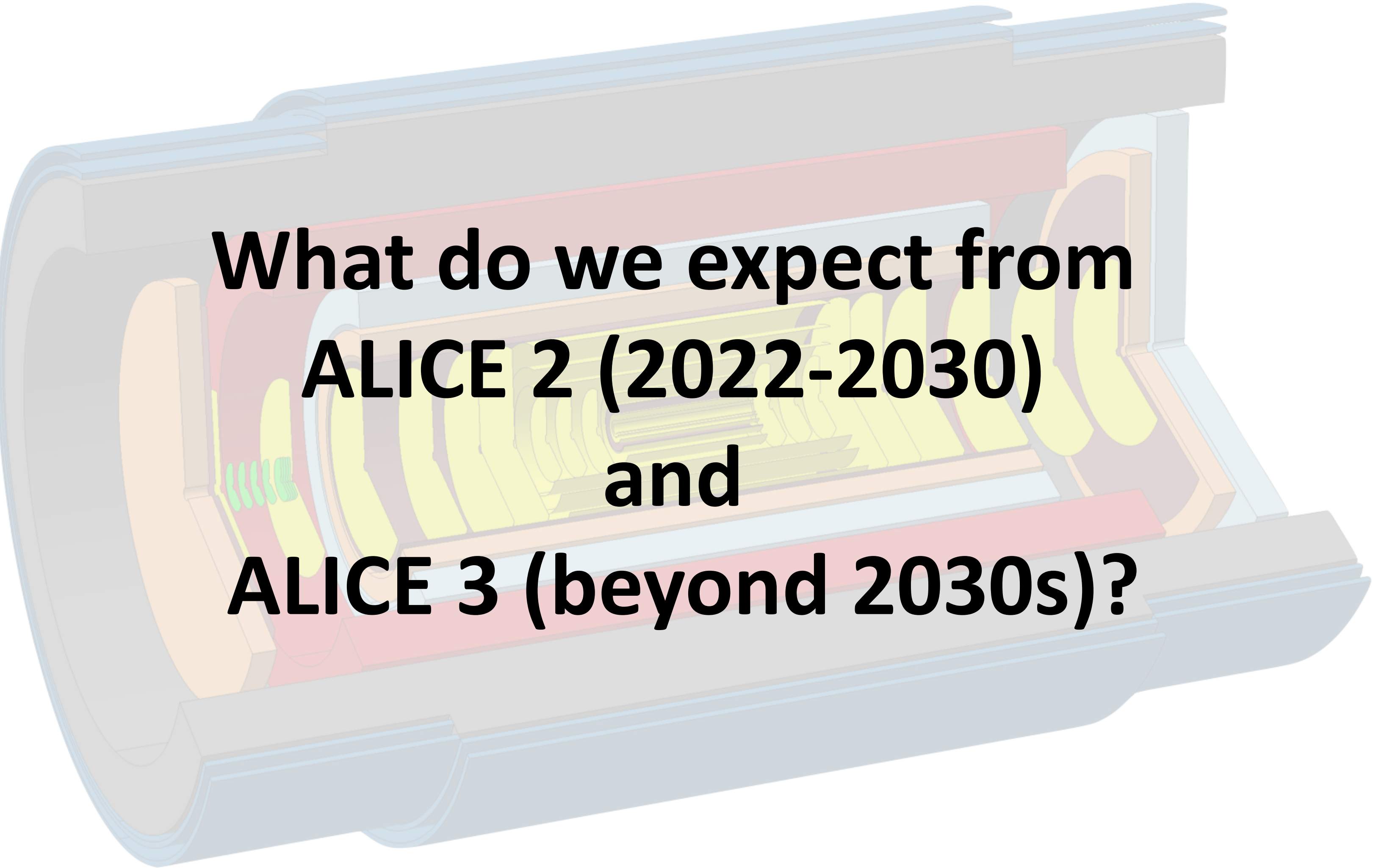
Parallel talk, Mario Ciacco, 14.06

- **Achieved precision of better than 4%**

3rd order cumulants of net-p



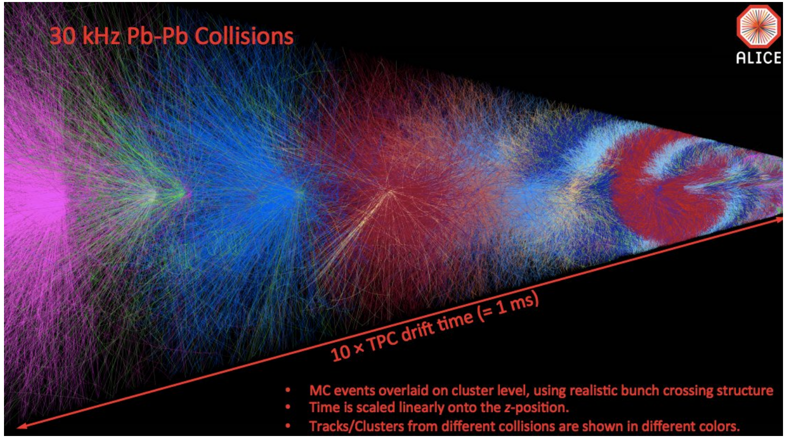
- **Data agree with Skellam baseline "0"** as a function of centrality and pseudorapidity
  - **μ_B is very close to 0** at LHC energies — Parallel talk, Mario Ciacco, 14.06
- **Achieved precision of better than 4%**
- **EPOS and HIJING deviate from "0"**
  - They conserve global charge but $p/\bar{p}$ **deviates from unity**: 1.025±0.004 (EPOS), 1.008±0.002 (HIJING)
  - **Volume fluctuations** for 2nd and 3rd order cumulants are not negligible



What do we expect from ALICE 2 (2022-2030) and ALICE 3 (beyond 2030s)?

Future of conserved charge fluctuations in ALICE

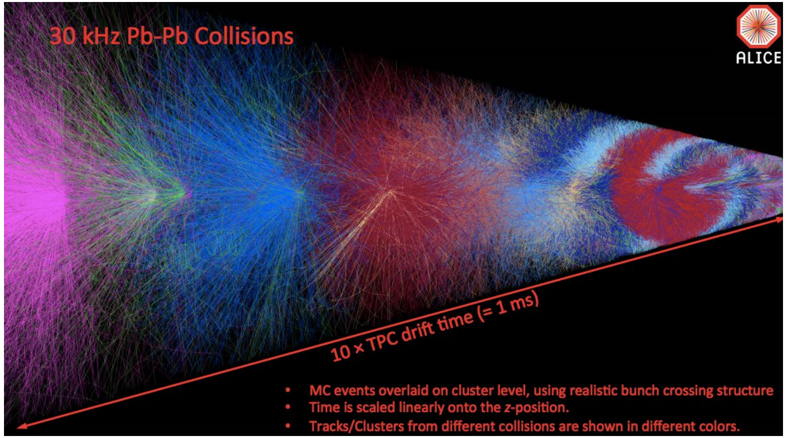
ALICE 2 (2022-2030)



- ✓ **Continuous readout:**
  → ~ 50kHz Pb−Pb min. bias
  → ~ 5 pileup events within the TPC
- ✓ **Improved vertexing**
- ✓ **High tracking efficiency at low p_T**

Future of conserved charge fluctuations in ALICE

ALICE 2 (2022-2030)



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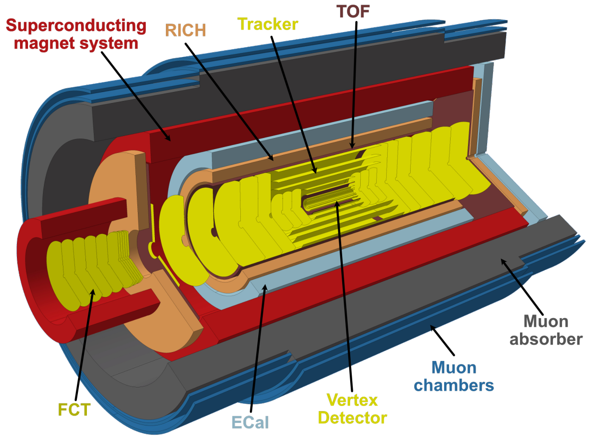
ALICE 3 (beyond early 2030s)

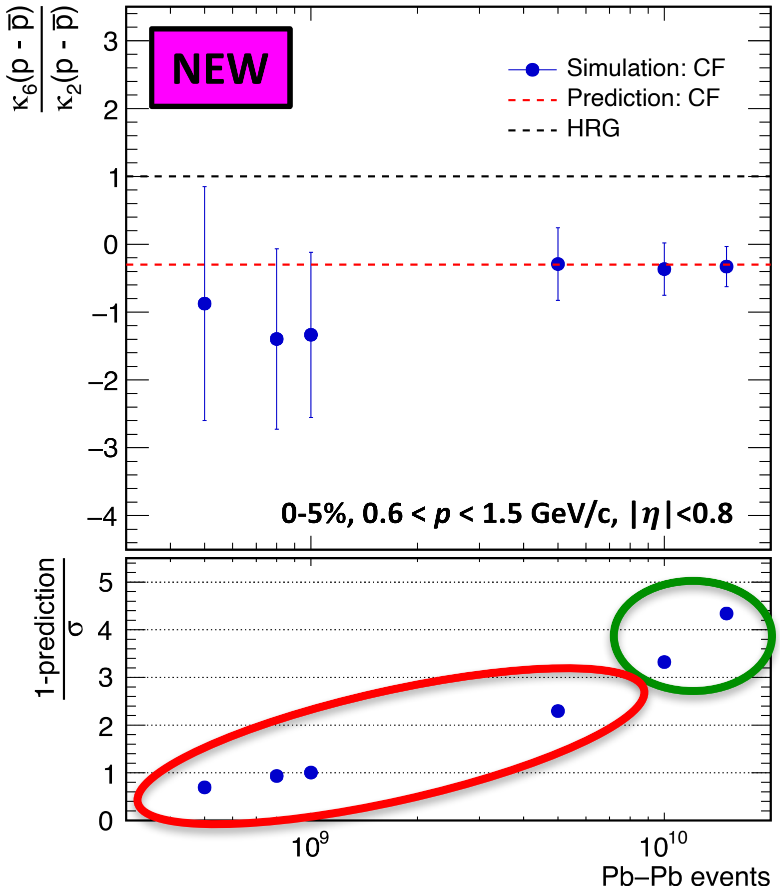


ALICE, CERN-LHCC-2022-009

Plenary talk, Raphaelle Bailhache, 16.06

- ✓ **High statistics** → O (10^9) billion events
- ✓ **Large acceptance** → |η|< 4
- ✓ **High PID purity** → 0.3 < p_T < 7 GeV/c
- ✓ **High efficiency** → ~95%
- ✓ **Excellent vertexing** → O (3μm) resolution

Criticality in ALICE 2 and 3: 6th and higher order cumulants



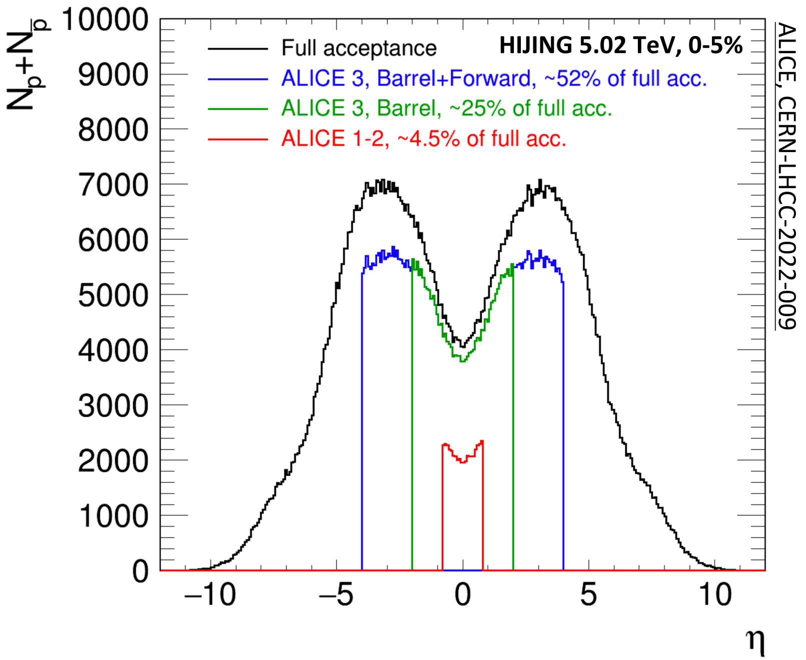
- Simulation of the Critical Fluctuations (CF) is based on PQM model
  G. A. Almasi, B. Friman, and K. Redlich, Phys. Rev.D96 (2017), 014027
- **ALICE 2:**
  → More than 5 billion central Pb-Pb collisions is required
- **ALICE 3:**
  → **x3 larger statistics:** $>4\sigma$ significance with ALICE 2 acceptance

Net baryon and net strangeness fluctuations
for |η| ≤ 4 and for 6th and higher order

ALICE 3: High PID purity in large kinematic acceptance

NEW

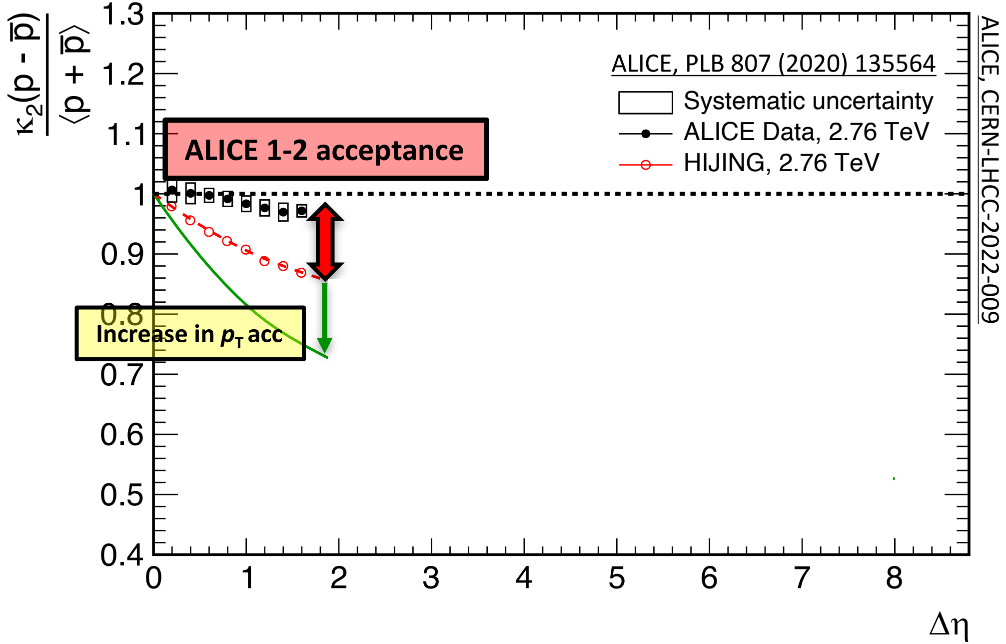
High PID purity and efficiency within a larger acceptance:
0.3 < *p* < 7 GeV/c, |η|<4



High precision & more differential measurements

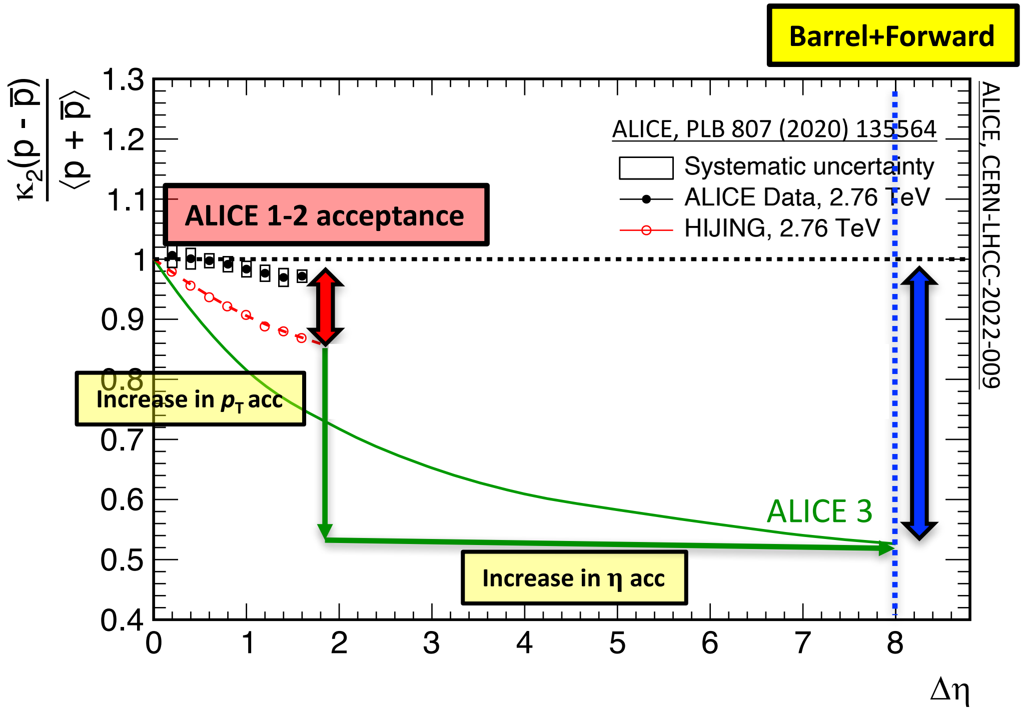
ALICE 3: Correlation length → Baryon number conservation

NEW



ALICE 3: Correlation length → Baryon number conservation

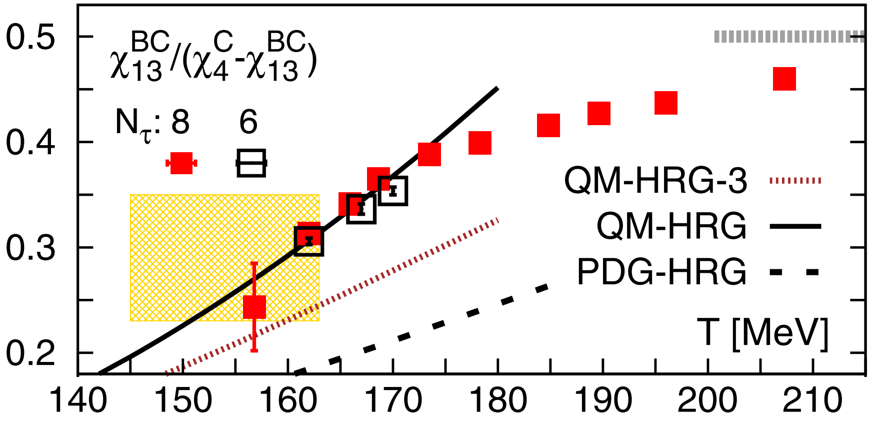
NEW

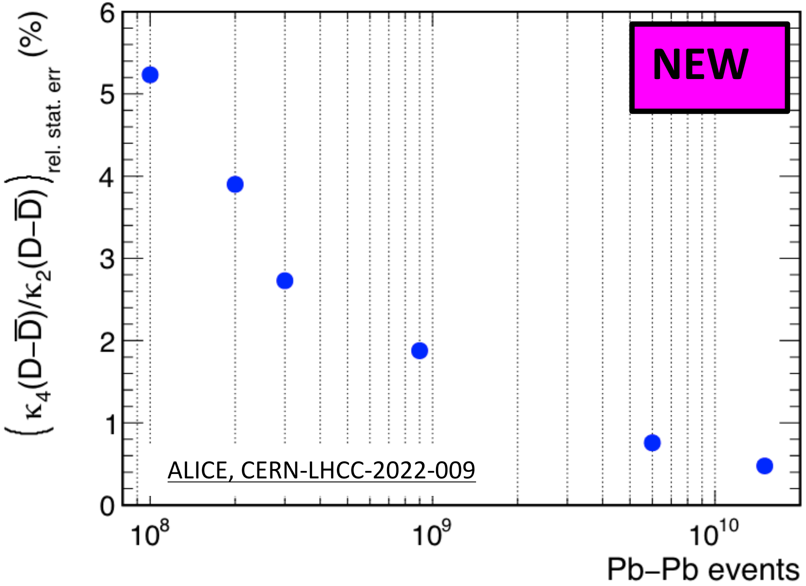


- Precise mapping of **correlation length of conserved charges, B, S, C**
- **Constraining individual dynamic signals** such as volume fluctuations, baryon number conservation, thermal blurring, annihilation, effect of hydrodynamic evolution etc.

ALICE 3: Net-charm fluctuations

A. Bazavov et.al. Phys.Lett.B 737 (2014) 210-215





- **2^{nd} order** → **Correlation length of charm**
- **4^{th} order** → Close to T_{pc} charmed baryon fluctuations are about 50% larger than expected in a HRG based on known charmed baryon resonances (PDG-HRG) → **missing states of QCD**

Summary

What did we learn from ALICE 1?

- **Net-Q,S fluctuations:** → resonance contributions
- **Net-p fluctuations:**
  - ✓ **1st order:** $T_{fo}^{ALICE} \sim T_{pc}^{LQCD}$
  - ✓ **2nd order:** Deviation from Skellam baseline is due to baryon number conservation
    - Long range correlations originating from **early phase of the collision**
  - ✓ **3rd order:** Up to 3rd order ALICE data agree with the LQCD expectations
    - **μ_B is very close to 0** at LHC energies

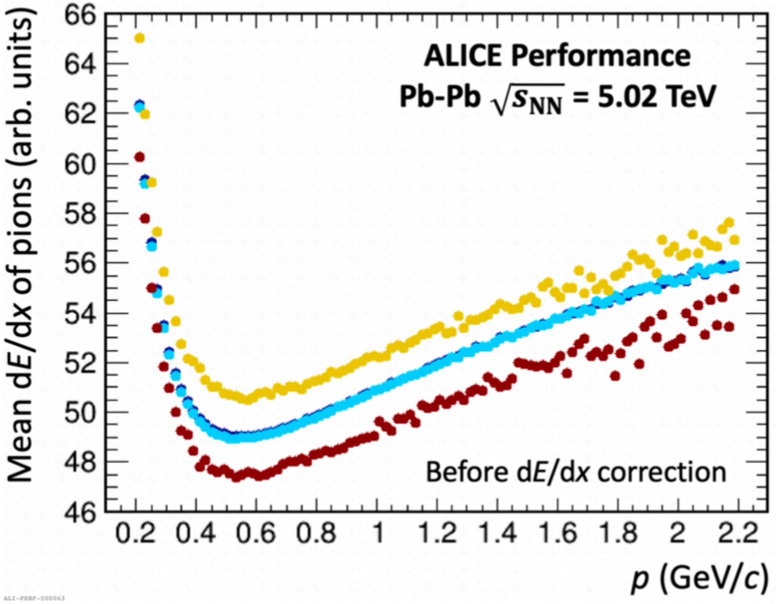
What do we expect from ALICE 2-3?

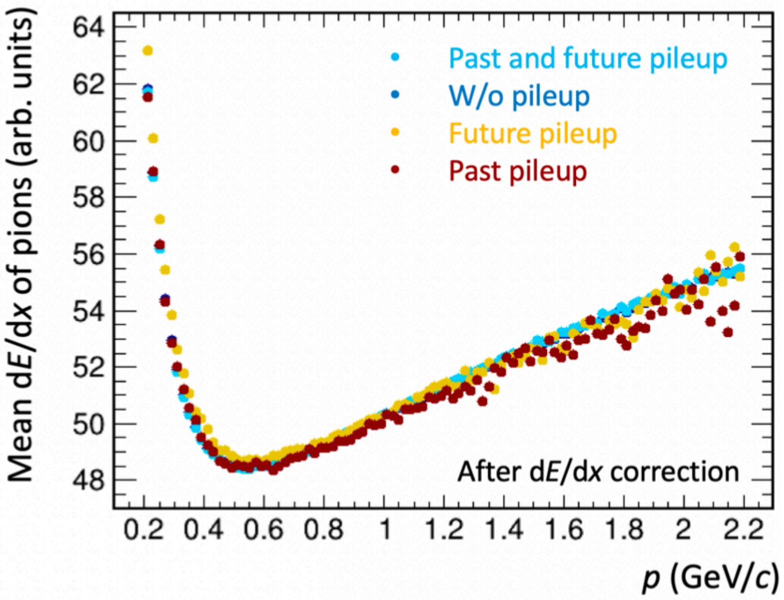
- **Criticality signals at 6th and higher order cumulants for B and S**
- Constraining **individual dynamic signals**
- **Correlation length** of conserved charges: B, S, C
- Net-charm fluctuations up to 4th order → **missing states of QCD**
- …

BACKUP

Experimental challenges: E.g. effect of event pileup

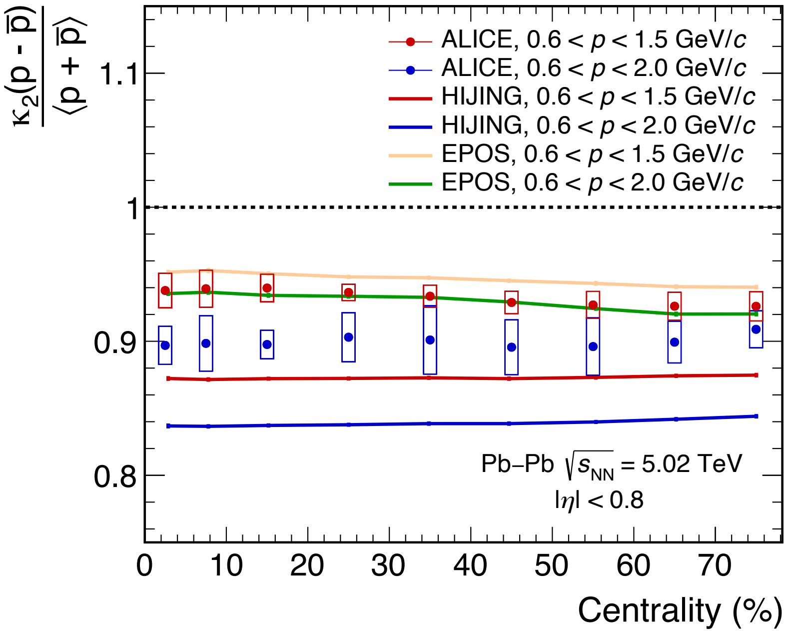
NEW

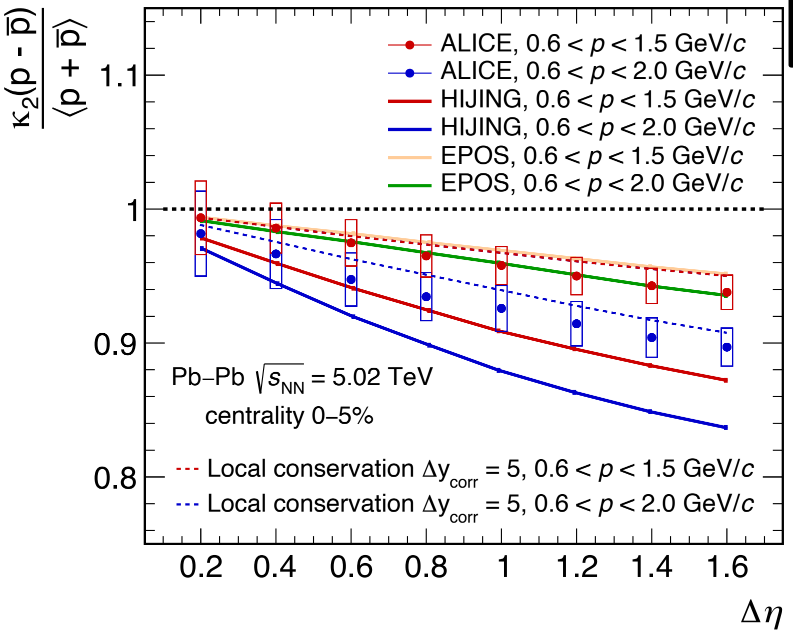




M. Arslandok, E. Hellbär, M. Ivanov, R.H. Münzer and J. Wiechula, Particles 2022, 5(1), 84-95}

2^{nd} order cumulants of net-p: Acceptance dependence



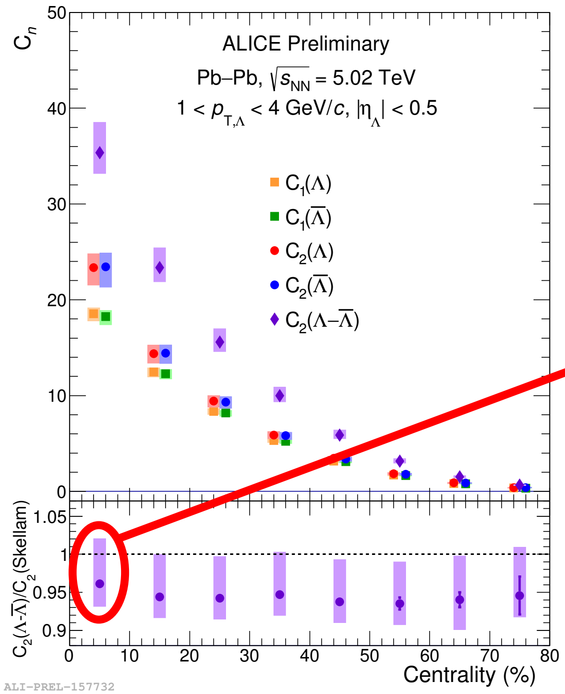


NEW

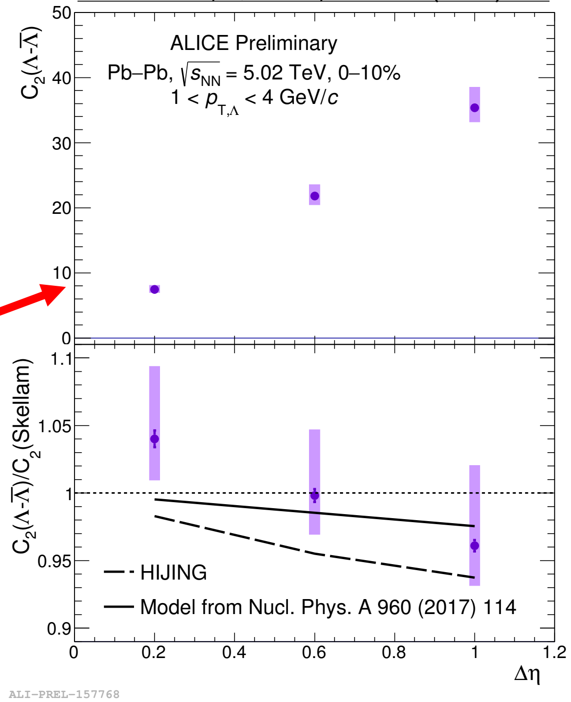
- Consistent with the baryon number conservation picture
  - Increase in fraction of accepted $p, \bar{p}$ -> stronger constraint of fluctuations due to baryon number conservation
- EPOS & HIJING show this drop qualitatively

2^{nd} order Net-Λ cumulants

$$\kappa_2(n-\overline{n}) \equiv C_2(n-\overline{n})$$



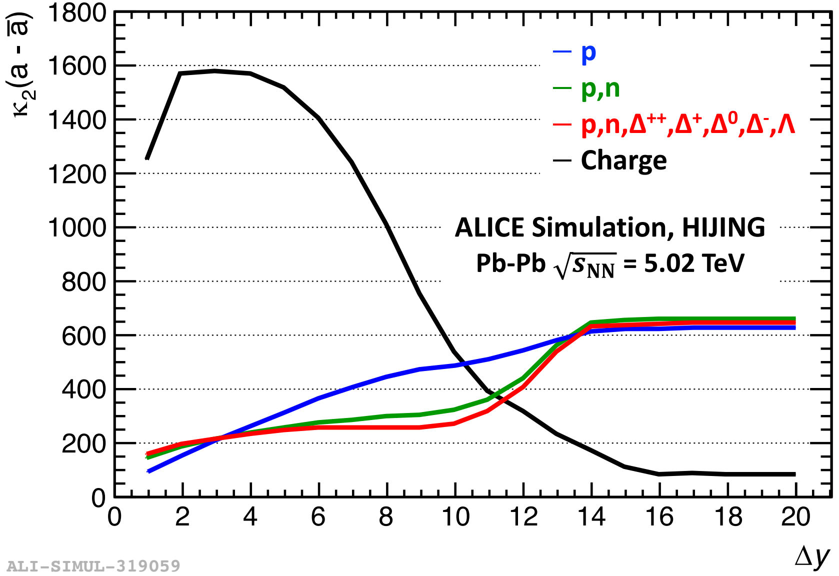
Alice Ohlson, QM2018, NPA 982 (2019) 299

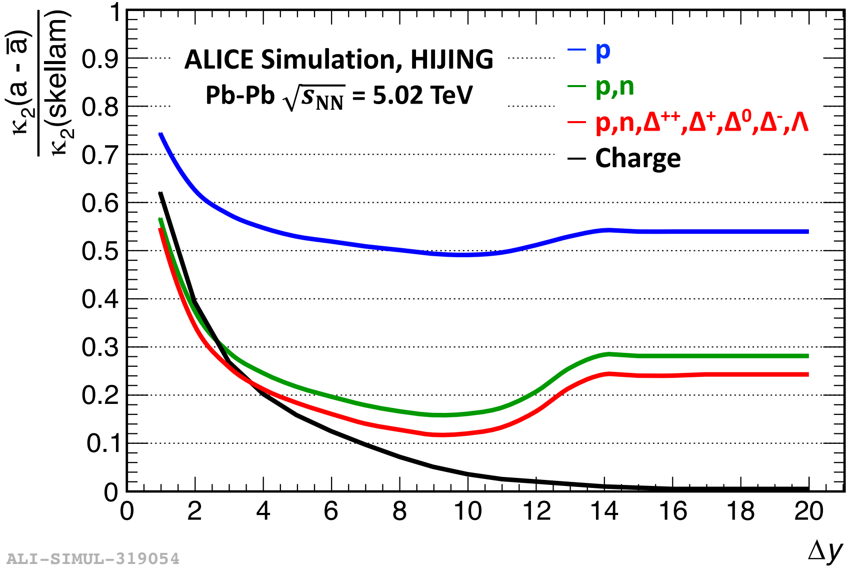


- Similar trend as for **net-p**
- Better precision is needed to disentangle global vs local conservation laws

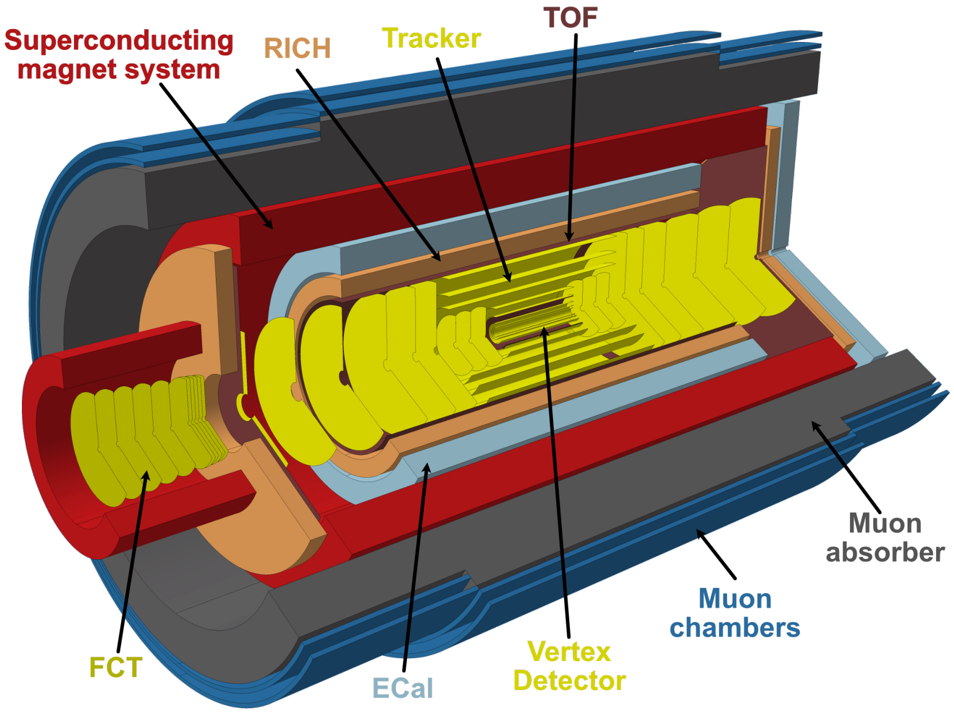
2nd order cumulants in full phase space

NEW





ALICE 3



⟹ **Ultra-low material budget** for low p_T tracking
→ X/X0 ~ 0.05 % / layer

⟹ **Fast** to sample large luminosity
→ 50-100 x Run 3/4 → MHz level

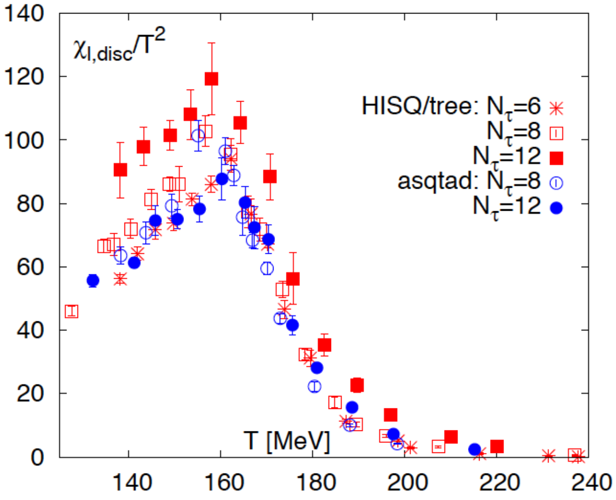
⟹ **Large acceptance**
→ $|\eta|$<1.4 (central barrel), $|\eta|$<4 (total)

⟹ **Excellent spatial resolution** for tracking and vertexing
→ Innermost layers: σ < 3 μm
→ Outer layers: σ ~5 μm

⟹ **Precise time measurements** for PID
→ σ ~ 20 ps

Criticality at Crossover

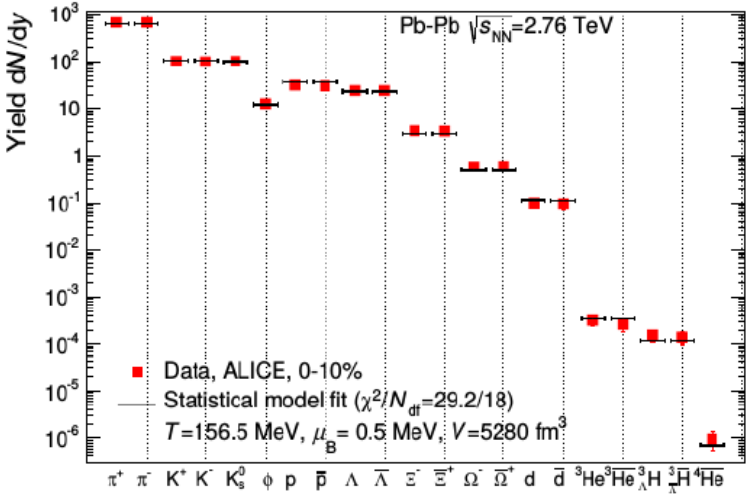
HotQCD Collaboration
Phys.Rev. D85 (2012) 054503, Phys.Lett. B795 (2019) 15



$$T_{\rm pc} = 156.5 \pm 1.5\ \rm MeV$$

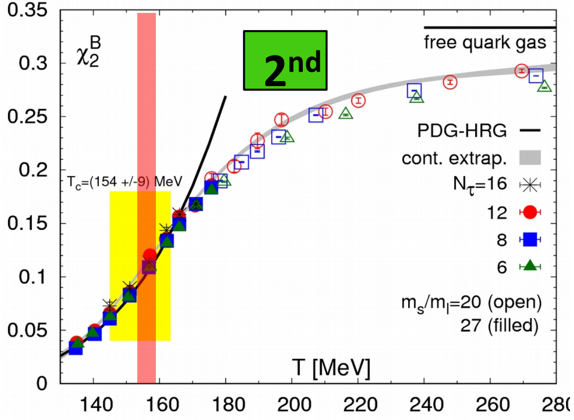
Chemical freeze-out at the phase boundary!

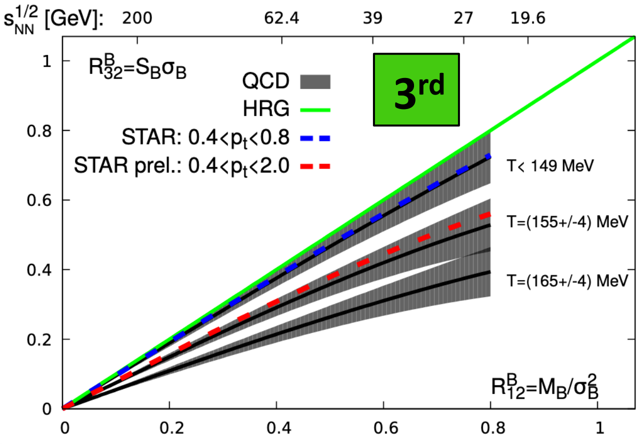
A. Andronic, P. Braun-Munzinger, J. Stachel and K. Redlich
Nature 561, 321–330 (2018)

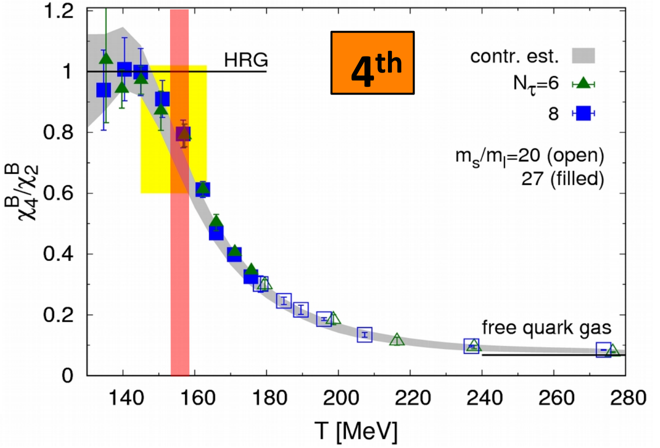


$$T_{\rm fo}^{\rm ALICE} = 156.5 \pm 3\ \rm MeV$$

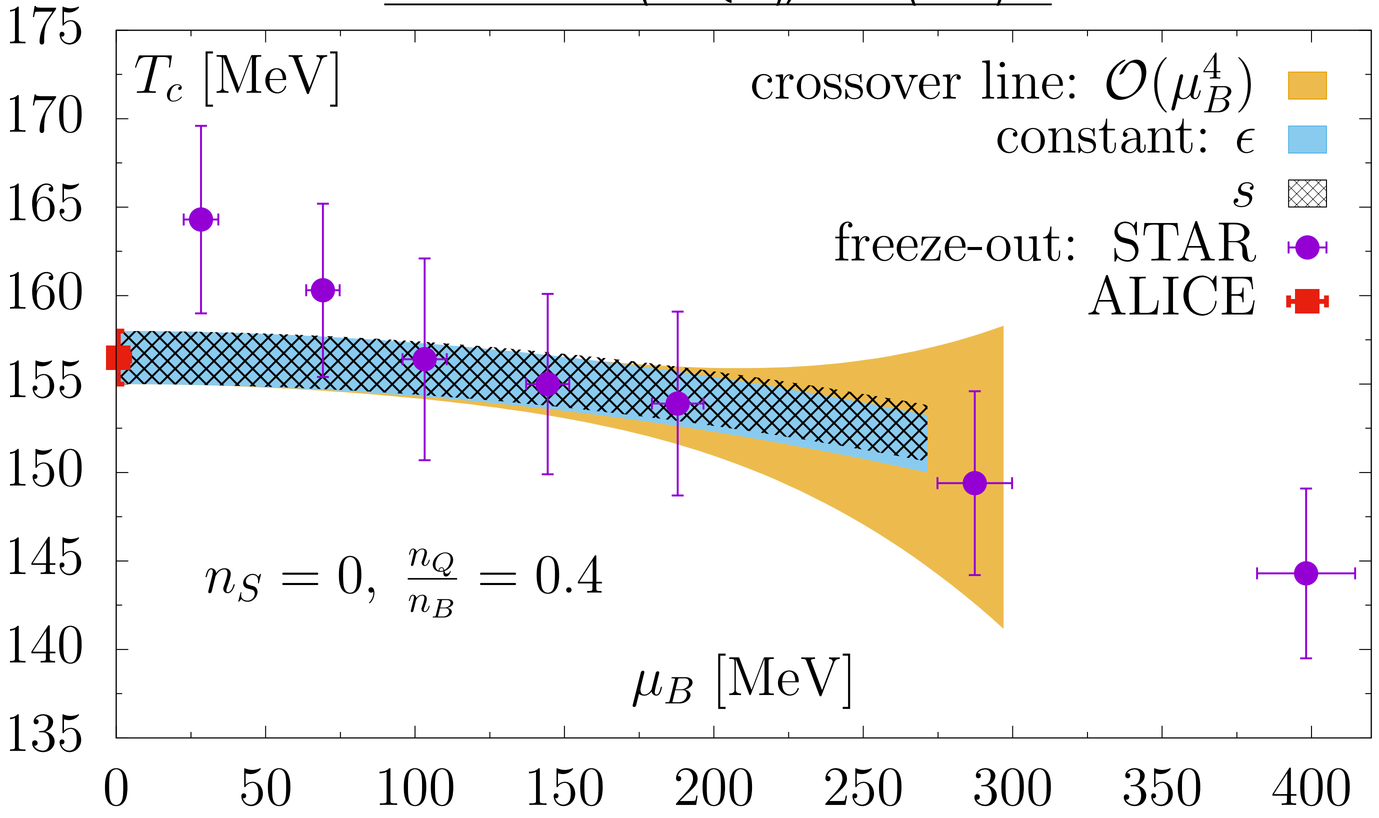
Chemical freeze-out near $T_{\rm pc}$ → motivation to look for higher order moments


2nd
free quark gas
PDG-HRG
cont. extrap.
Nτ=16
12
8
6
ms/ml=20 (open)
27 (filled)
Tc=(154 +/-9) MeV
T [MeV]

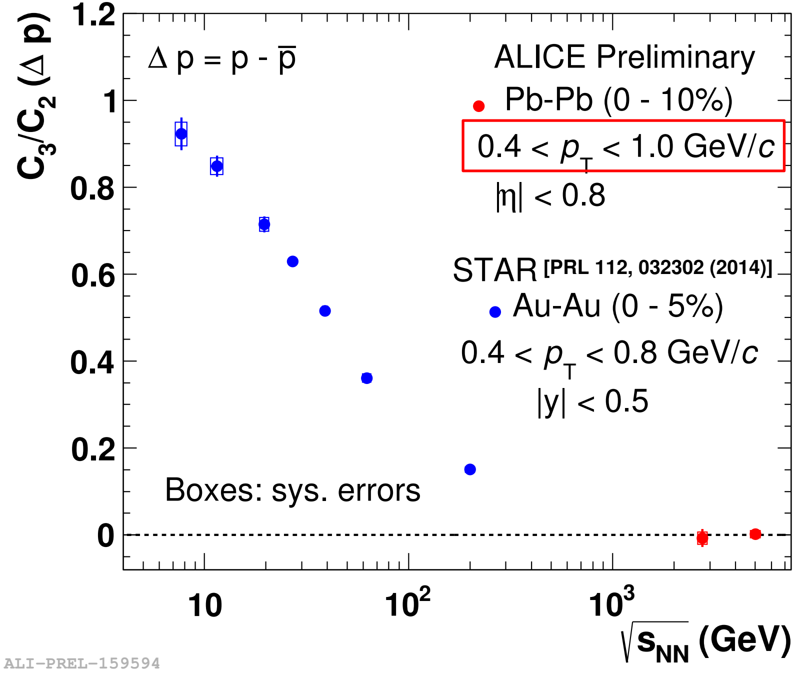

3rd
s_NN^1/2 [GeV]: 200 62.4 39 27 19.6
R^B_32=S_Bσ_B
QCD
HRG
STAR: 0.4<pt<0.8
STAR prel.: 0.4<pt<2.0
T< 149 MeV
T=(155+/-4) MeV
T=(165+/-4) MeV
R^B_12=M_B/σ^2_B

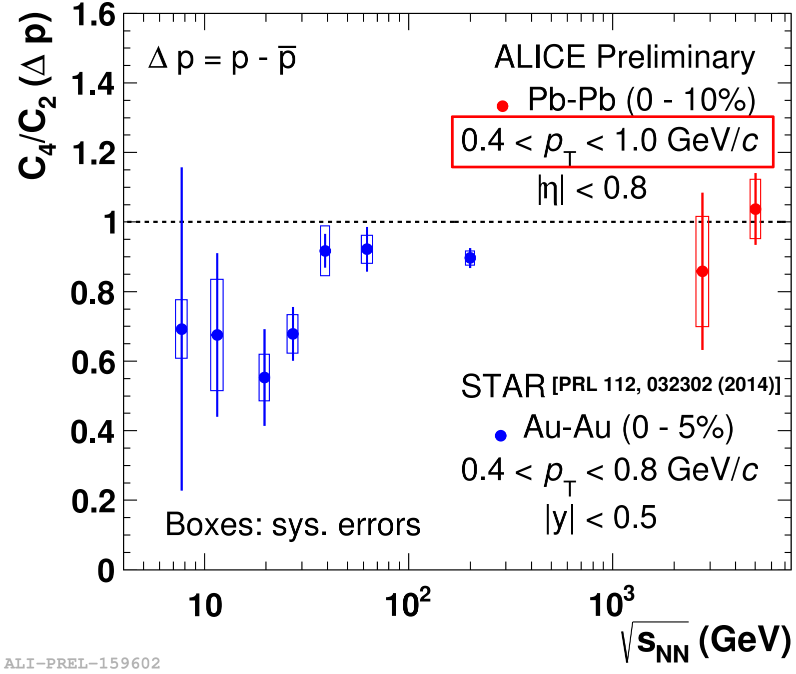

4th
HRG
contr. est.
Nτ=6
8
ms/ml=20 (open)
27 (filled)
free quark gas
T [MeV]

A. Bazavov et al. (HotQCD),PLB795(2019)15



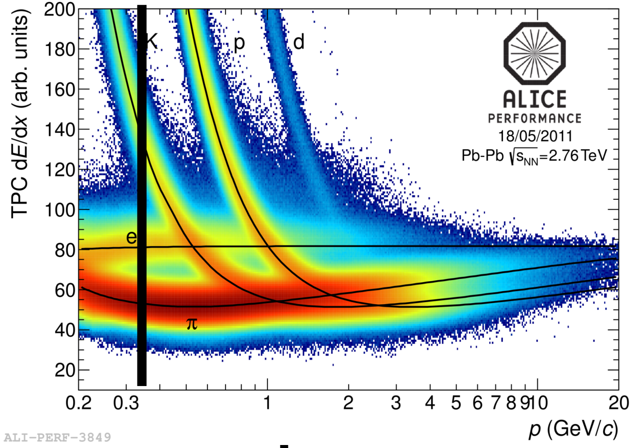
Nirbhay Kubera, QM18, NPA 982 (2019) 851

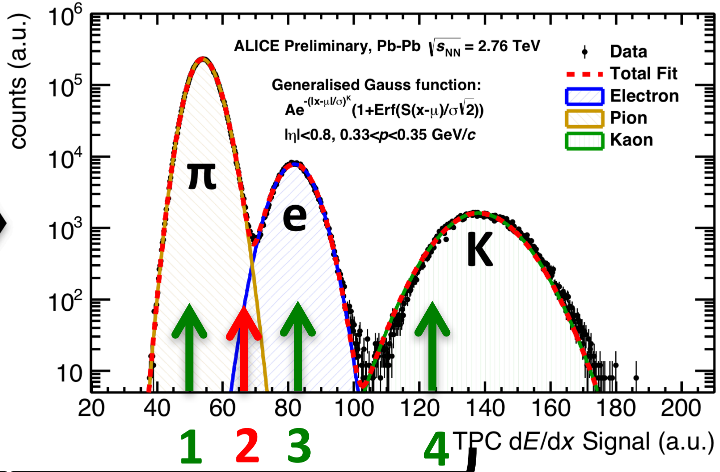




Identity Method

Cut-based approach: count tracks of a given particle type
Identity method: count probabilities to be of a given particle type

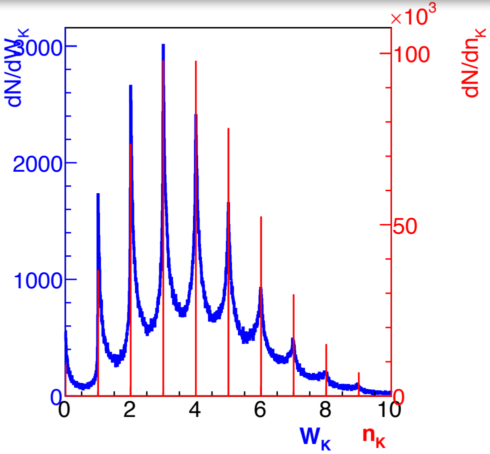




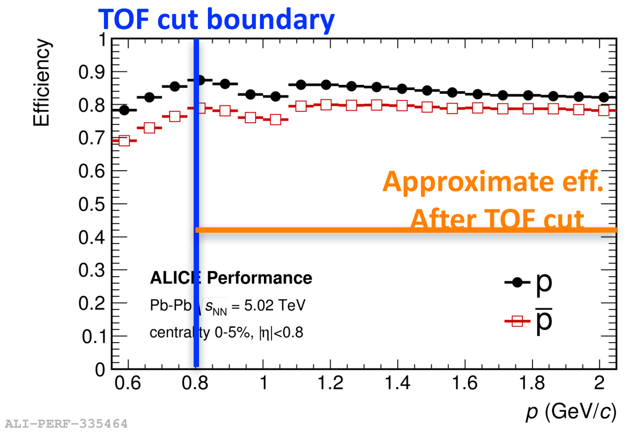
$$\omega_\pi^{(1)} = 1, \quad \omega_\pi^{(2)} \cong 0.6, \quad \omega_\pi^{(3)} = 0, \quad \omega_\pi^{(4)} = 0 \quad \Rightarrow \quad W_\pi = 1.6 \neq N_\pi$$

A. Rustamov, M. Gazdzicki, M. I. Gorenstein, PRC 86, 044906 (2012), PRC 84, 024902 (2011)
A. Rustamov, M. Arslandok, Nucl. Instrum. A946 (2019) 162622}

Identity Method



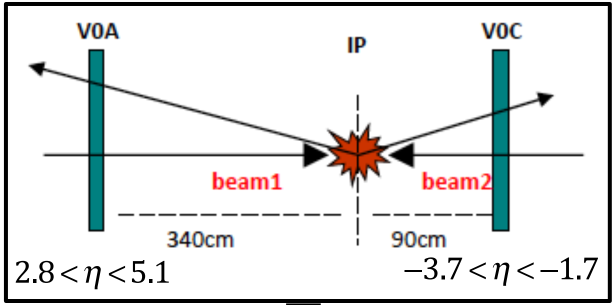
$$\langle N_j^n \rangle = A^{-1} \langle W_j^n \rangle$$

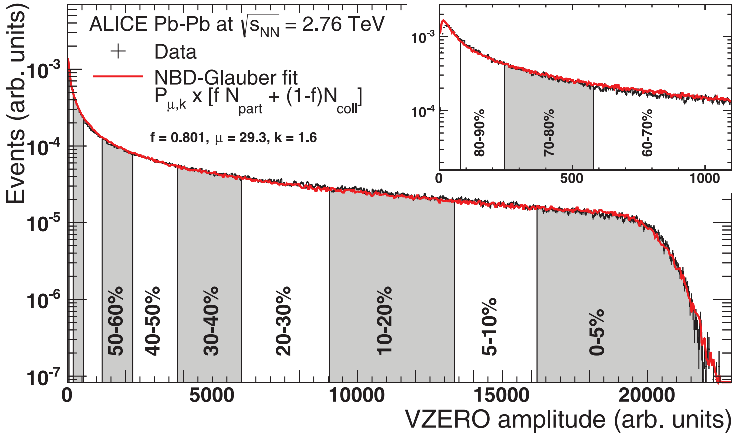


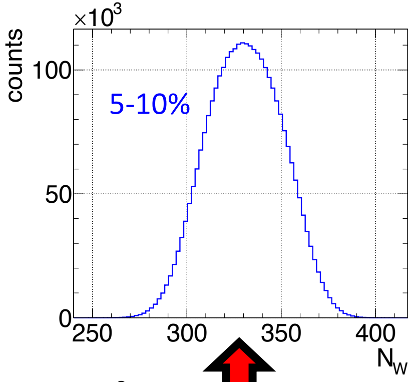
- **Cut based approach**
  - Use additional detector information or reject a given phase space bin
  - Challenge: efficiency correction and contamination
- **Identity Method**
  - Gives folded multiplicity distribution
  - Easier to correct inefficiencies
  - Ideal approach for low momentum (p<2 GeV/c)

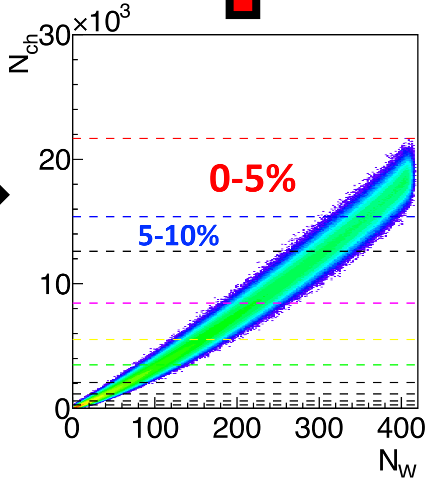
Volume Fluctuations

ALICE: Phys.Rev. C88 (2013) no.4, 044909



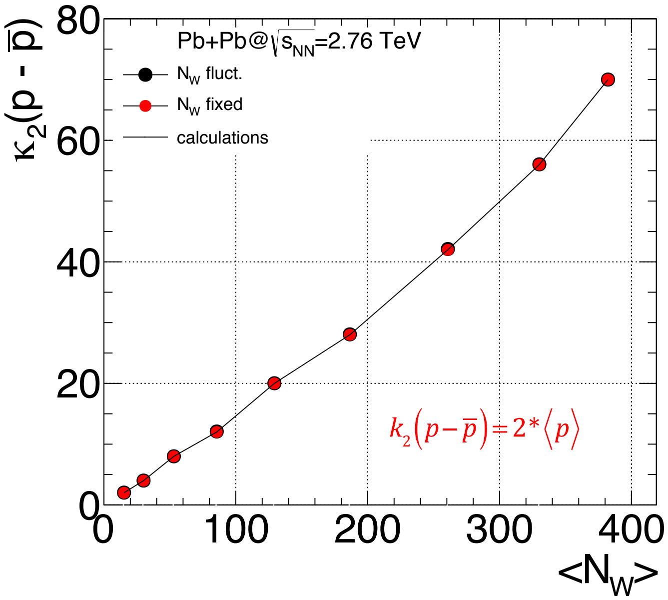


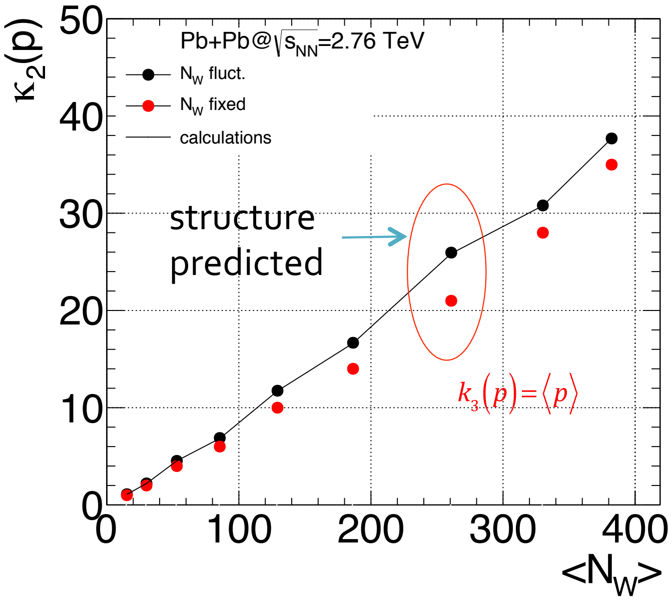




Volume Fluctuations

$150*10^6$ Events





$$k_2(p-\bar{p}) = \langle N_w \rangle k_2(n-\bar{n}) + \langle n-\bar{n} \rangle^2 k_2(N_w)$$

vanishes for ALICE

$$k_2(p) = \langle N_w \rangle k_2(n) + \langle n \rangle^2 k_2(N_w)$$

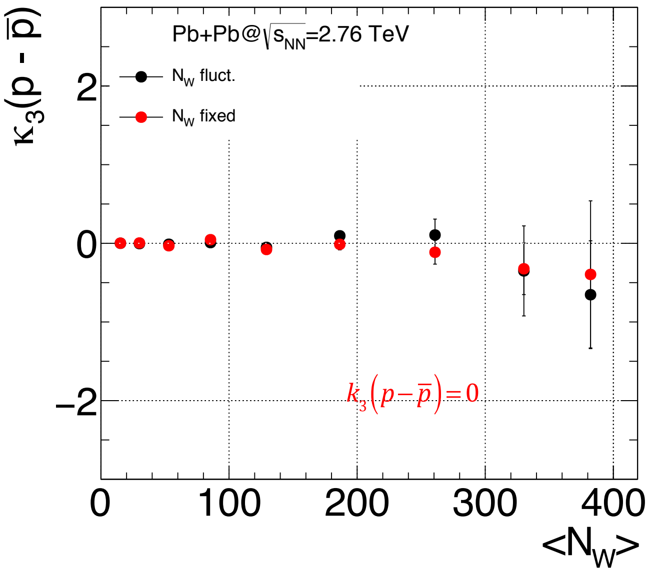
does not vanish

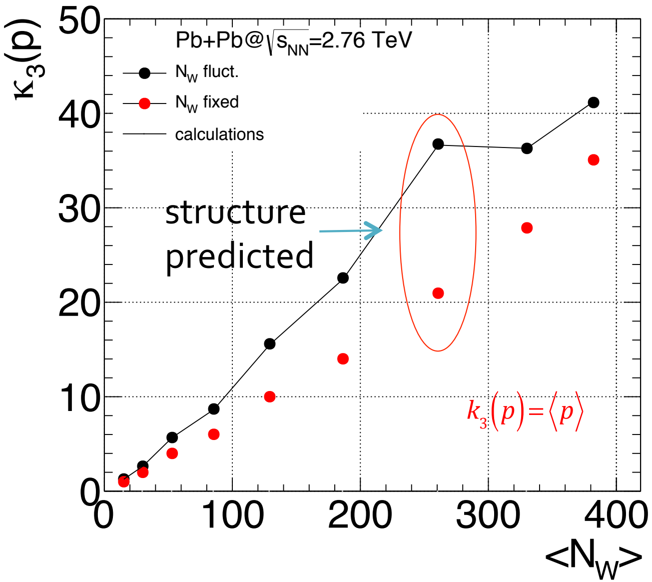
$n, \bar{n}$ from single wounded nucleon

P. Braun-Munzinger, A. Rustamov, J. Stachel, Nuclear Physics A 960 (2017) 114–130

Volume Fluctuations

$150*10^6$ Events





$$k_3(p-\bar{p})=\langle N_w\rangle k_3(n-\bar{n})+\langle n-\bar{n}\rangle(...)$$

vanishes for ALICE

$$k_3(p)=\langle N_w\rangle k_3(n)+\langle n\rangle(...)$$

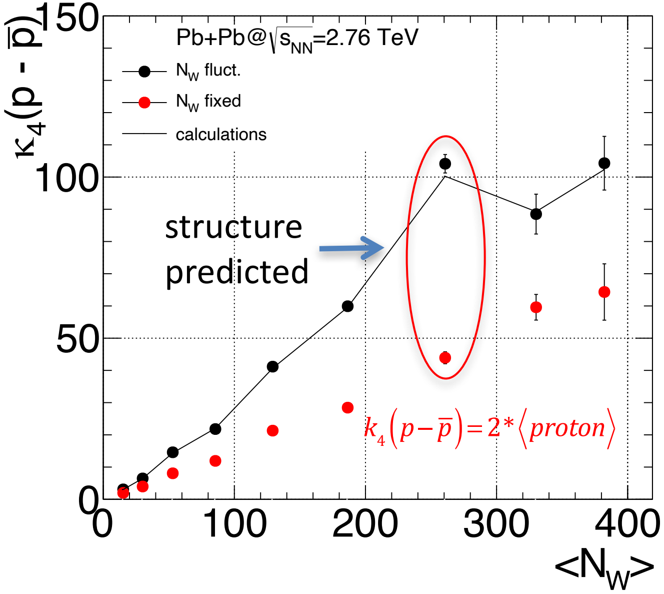
does not vanish

$n,\bar{n}$ from single wounded nucleon

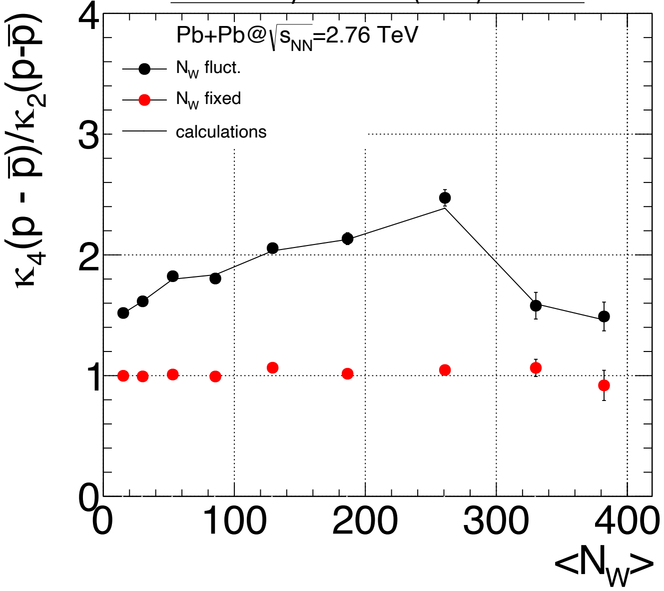
P. Braun-Munzinger, A. Rustamov, J. Stachel, Nuclear Physics A 960 (2017) 114–130

Volume Fluctuations

150*10^6 Events



P. Braun-Munzinger, A. Rustamov, J. Stachel
Nuclear Physics A 960 (2017) 114–130



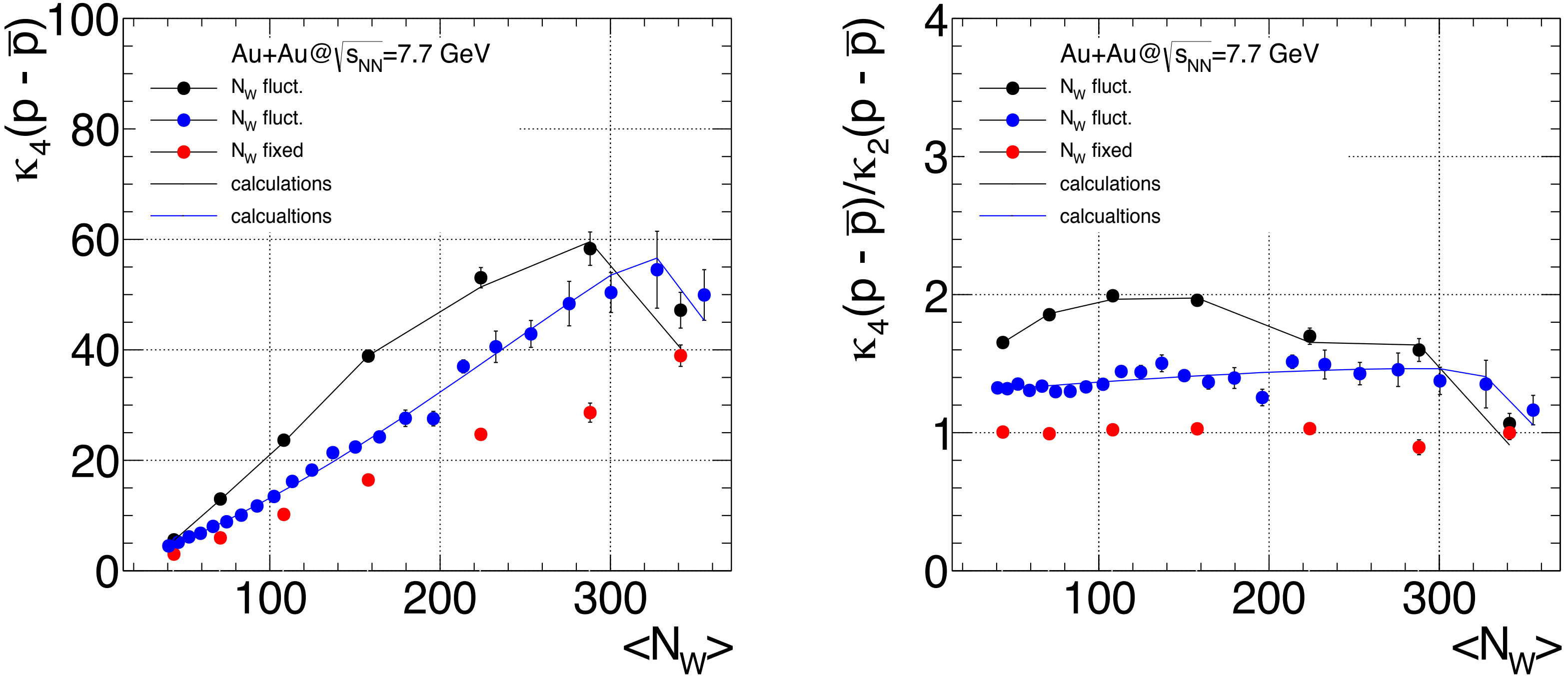
$$k_4(p-\bar{p}) = \langle N_w \rangle k_4(n-\bar{n}) + 3k_2(n-\bar{n})^2 k_2(N_w) + \langle n-\bar{n} \rangle (...)$$

vanishes for ALICE

$n, \bar{n}$ → from single wounded nucleon

P. Braun-Munzinger, A. Rustamov, J. Stachel, Nuclear Physics A 960 (2017) 114–130

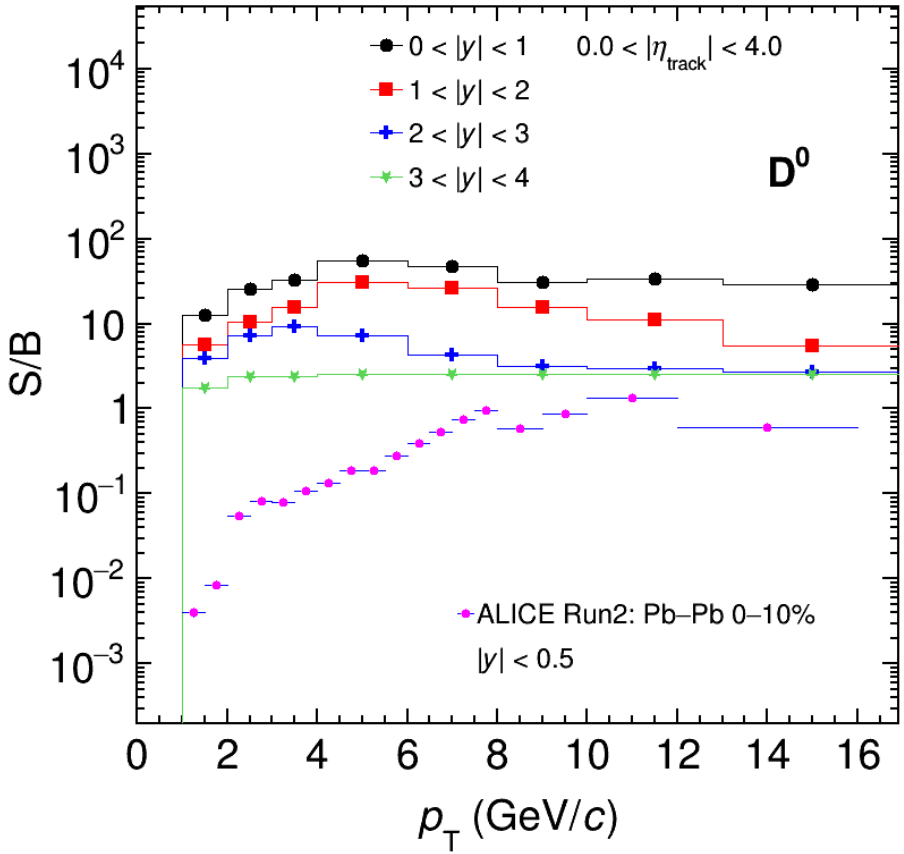
Volume Fluctuations



P. Braun-Munzinger, A. Rustamov, J. Stachel, Nuclear Physics A 960 (2017) 114–130

Excellent vertexing: Charm fluctuations

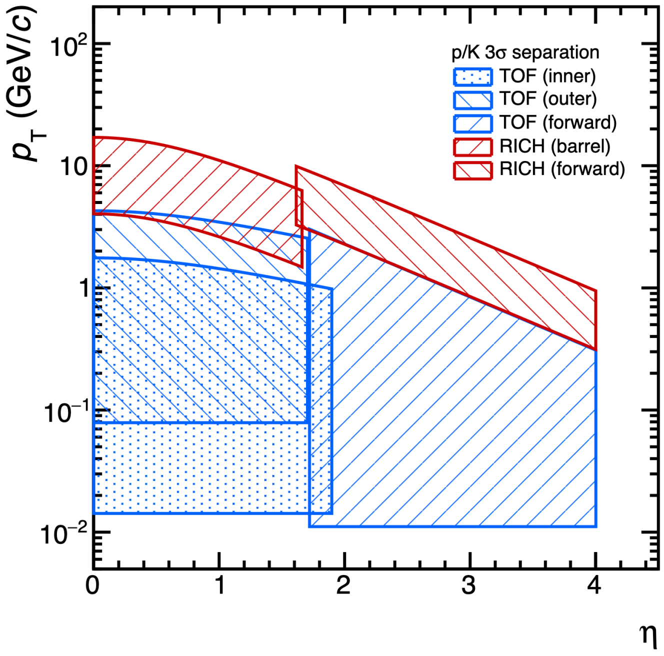
- **Barrel PID improves S/B by a factor ∼10**
  → Close to ‘ideal PID’
  → Much smaller systematic uncertainty
- **Net charm fluctuations for |η| ≤ 4 and up to 4th moments**

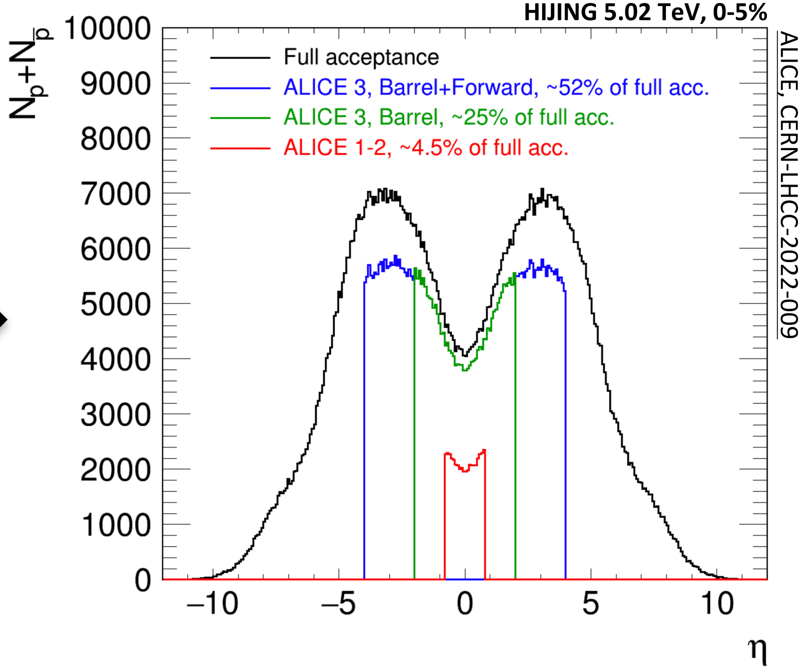


ALICE 3: High PID purity in large kinematic acceptance

NEW

- ✓ **Significant increase in the number of measured protons**
- ✓ **Larger acceptance:** in p_T and η: (0.3 < p < 7 GeV/c, $|\eta|$<4)
- ✓ **Smaller systematics:** high PID purity and efficiency

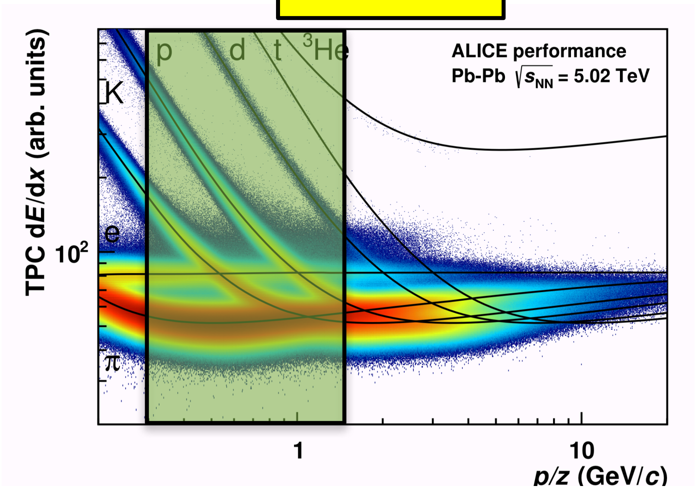


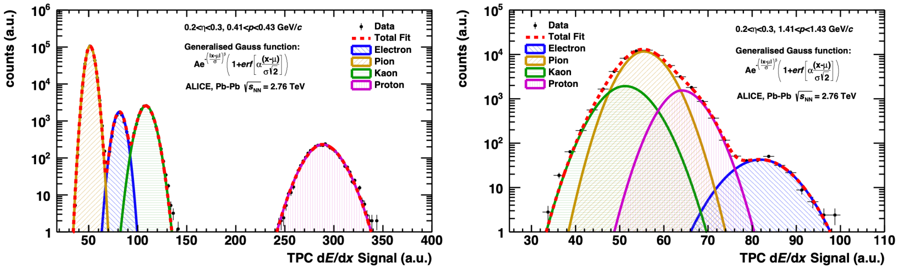


High precision & more differential measurements

Identity Method in ALICE 3: Purity in PID

ALICE 1-2

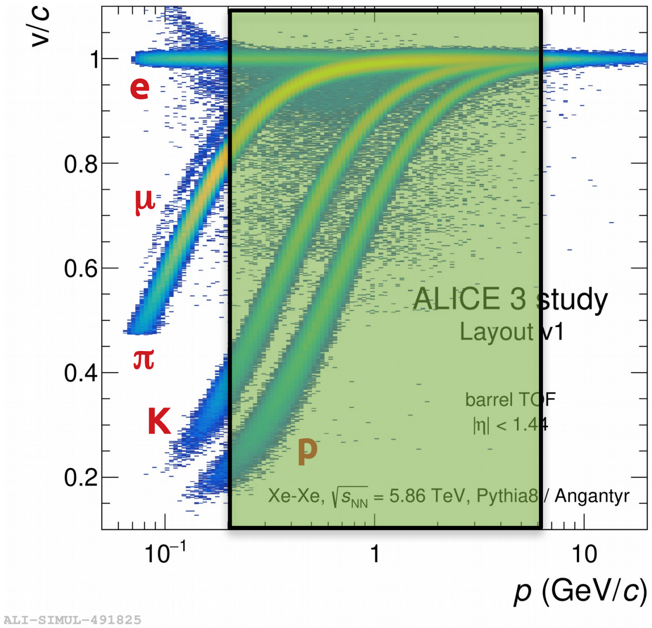




- 0.6 < *p* < 1.5 GeV/*c*
- *p* > 0.8 GeV/*c* → less than one sigma separation

ALICE 3

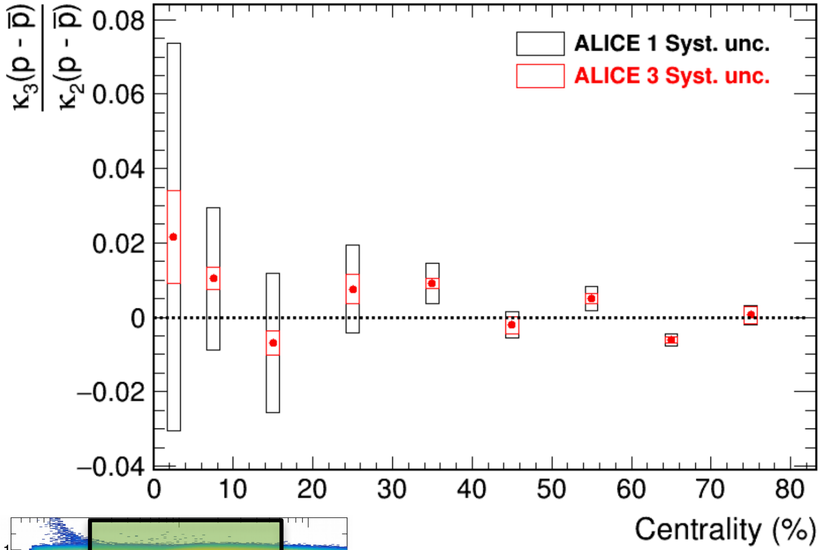
Significant improvement in the purity + IM

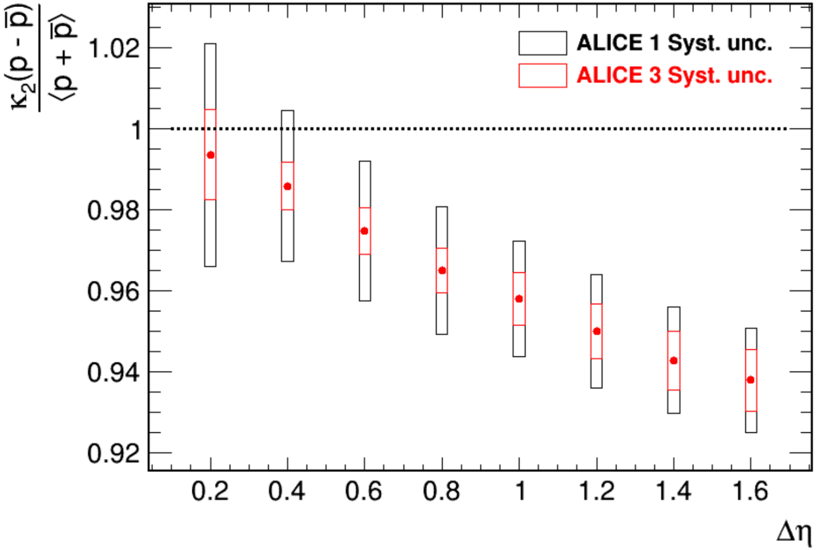


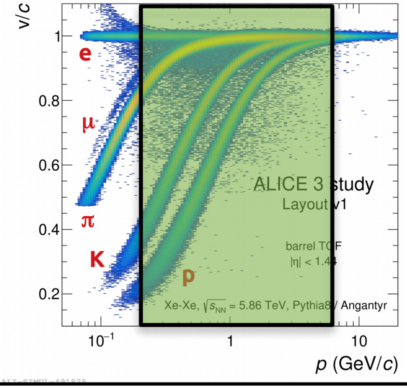
- 0.3 < *p* < ~7 GeV/*c*
- No full overlap of the TOF signal

ALICE 3: Systematic uncertainties

NEW



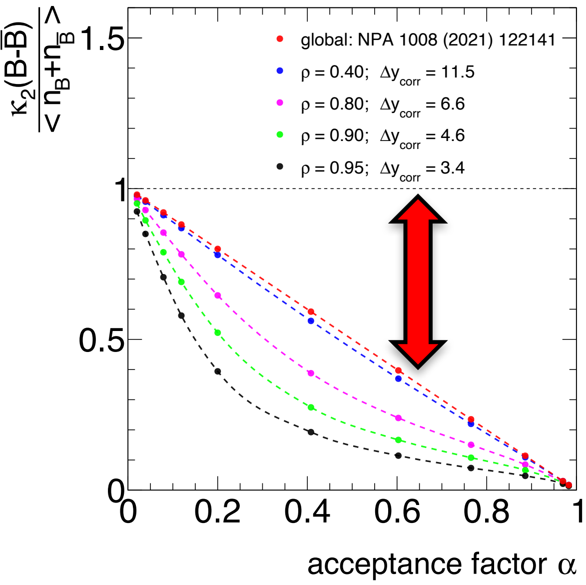


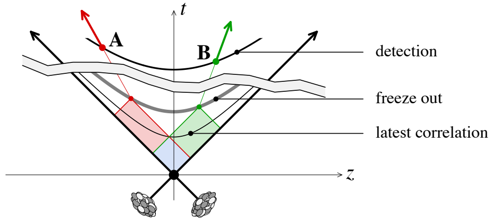


❖ **Main uncertainty is from the dE/dx fits, which will vanish in ALICE 3 (thanks to Identity Method (IM) and improved PID)**

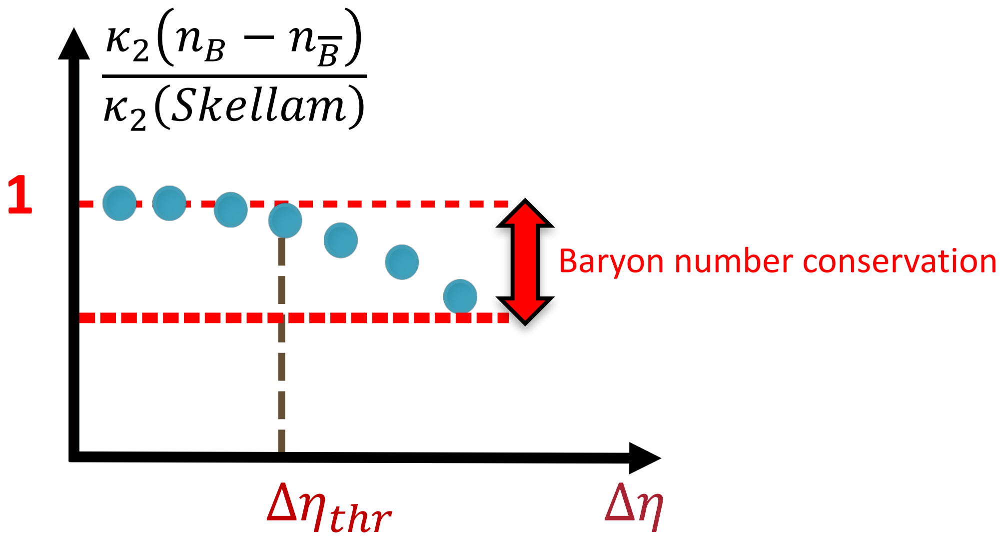
2^{nd} order cumulants of net-p: Correlation length

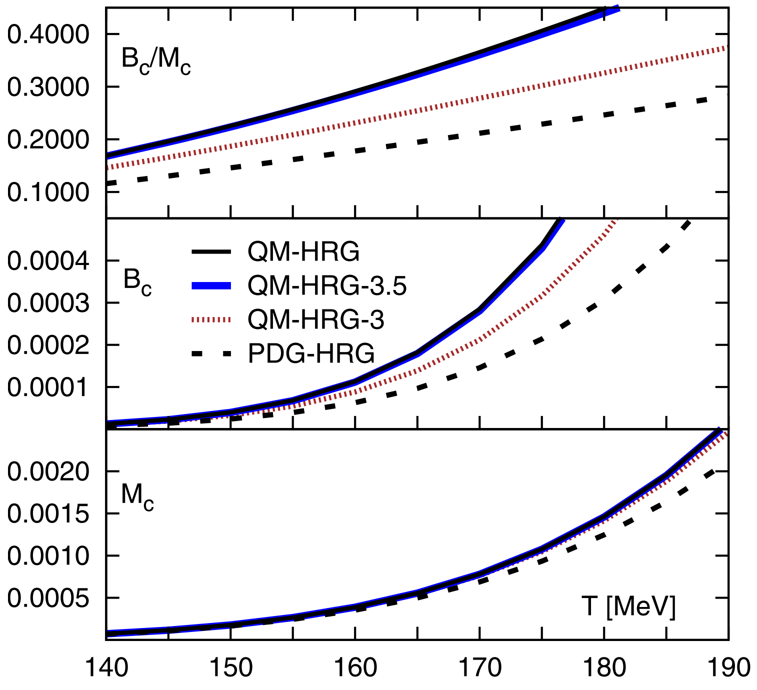
P. Braun-Munzinger, A. Rustamov, J. Stachel, to be published





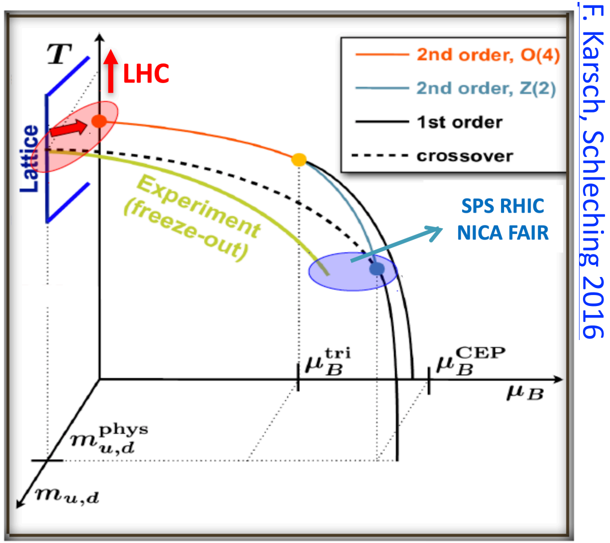
Early correlations → long range in rapidity

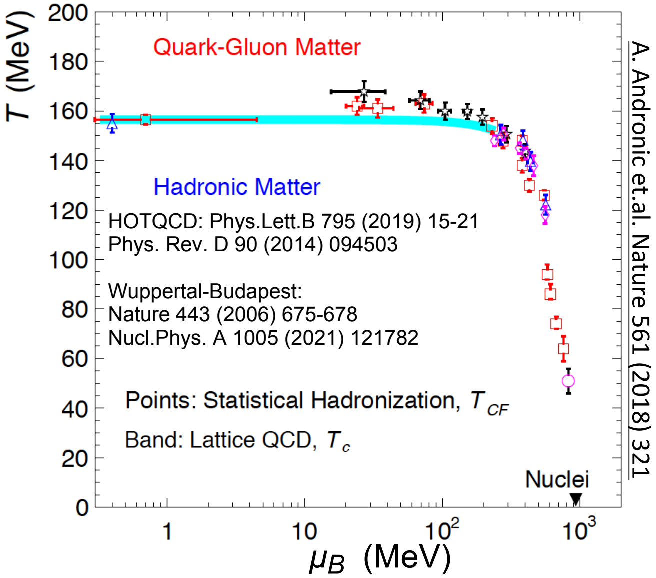




- Partial pressure of open charm mesons (M_c) and baryons (B_c) in a gas of uncorrelated hadrons,
  - **PDG-HRG**: All open charm resonances in PDG
  - **QM-HRG:** Relativistic quark model.
  - **QM-HRG-X:** open charm resonance spectrum is cut off at mass X GeV
- Below 160 MeV the latter coincides with the complete QM-HRG model results to better than 1 %.

Motivation: Nature of the chiral phase transition





- **Cross over** transition at μ_B = 0 MeV
  ⟹ no experimental confirmation
- **Vanishing u, d quark masses**
  ⟹ Vicinity to 2nd order O(4) criticality
  ⟹ Pseudocritical features at the crossover due to massless modes
  ⟹ Long range correlations & increased fluctuations

- Quantitative **agreement** of chemical freeze-out parameters **with most recent LQCD predictions** for μ_B < 300 MeV

$$\Rightarrow T_{pc}^{LQCD} \approx T_{fo}^{ALICE} = 156.5 \pm 3\ \mathrm{MeV}$$

HotQCD Collaboration, Phys.Lett. B795 (2019) 15
S. Borsanyi et.al. Phys. Rev. Lett. 125, 052001 (2020)