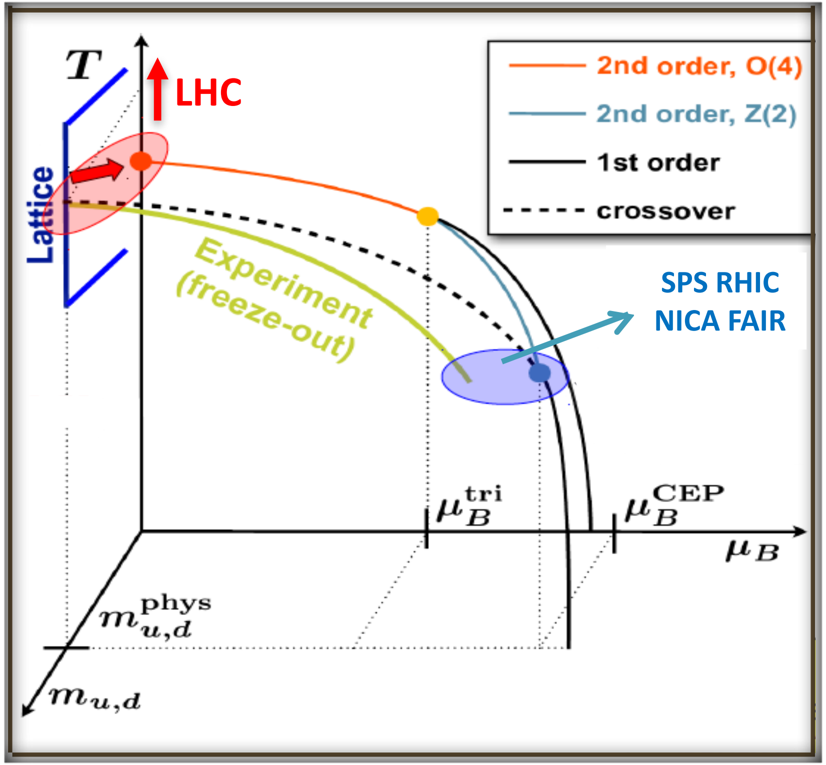
High Moments of Particle Distributions from Heavy-Ion Collisions at LHC

Mesut Arslandok
(Yale University, CERN)

- ✓ Why fluctuations?
- ✓ Results: Conserved charge fluctuations
- ✓ Experimental challenges
- ✓ Future plans

RHIC Beam Energy Scan and Beyond – Online Workshop
Lawrence Berkeley National Laboratory, California, August 16, 2021

Why fluctuations?: Nature of chiral phase transition



F. Karsch, Schleching 2016

small u, d quark masses

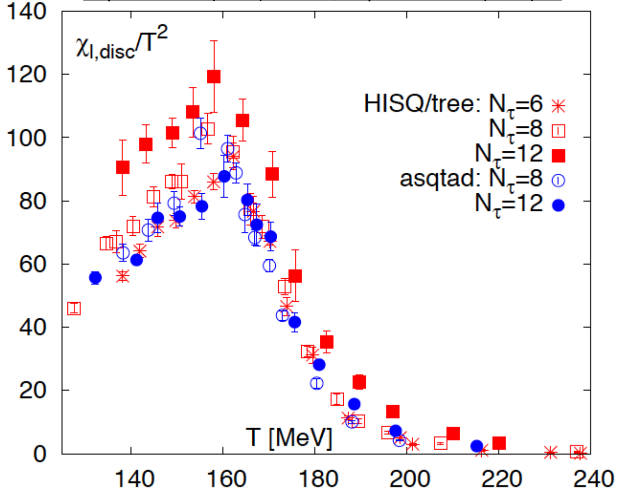
↔

vicinity to 2nd order O(4) criticality

pseudocritical features possible

Criticality at Crossover

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



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

$$\langle \bar{\psi}\psi \rangle_l^{n_f=2} = \frac{T}{V} \frac{\partial \ln Z}{\partial m_l}$$

$$\chi_{m,l} = \frac{\partial}{\partial m_l} \langle \bar{\psi}\psi \rangle_l^{n_f=2}$$

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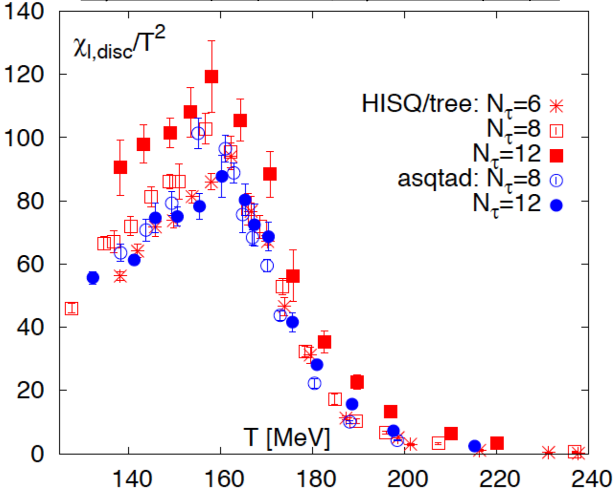

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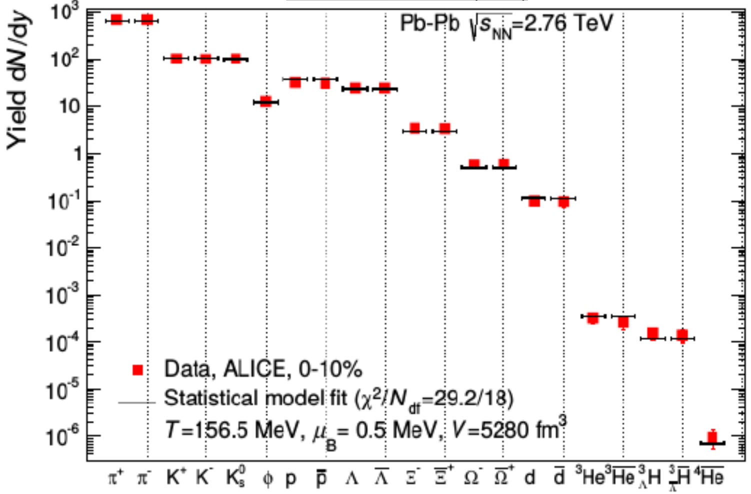
A. Andronic, P. Braun-Munzinger, J. Stachel and K. Redlich
Nature 561, 321–330 (2018)



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

$$\langle N_i \rangle = V\frac{g_i}{2\pi^2}\int_0^\infty \frac{p^2 dp}{\exp\left[(E_i-\mu_i)/T\right]\pm 1}$$

$$\mu_i = \mu_B B_i + \mu_s S_i + \mu_I I_i$$

$$\chi^2 = \sum_{k=1}^{n}\frac{\left(\langle N_k^{\mathrm{exp}}\rangle - \langle N_k^{HRG}\rangle\right)^2}{\sigma_k^2}$$

Criticality at Crossover

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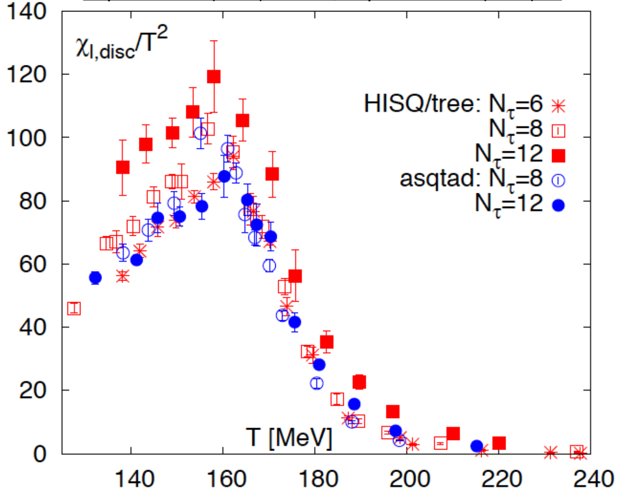

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Chemical freeze-out at the phase boundary!

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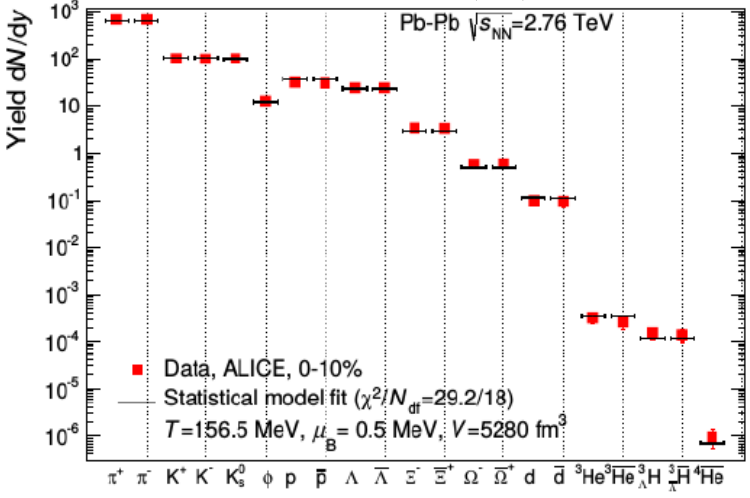

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Chemical freeze-out near T_{pc} → motivation to look for higher order moments

Link to LQCD: Fluctuations of conserved charges

For a thermal system within the **Grand Canonical Ensemble**

$$\frac{P}{T^4} = \frac{1}{VT^3} \ln Z\left(V,T,\mu_{B,Q,S}\right) \Rightarrow \hat{\chi}_n^{N=B,S,Q} = \frac{\partial^n P/T^4}{\partial\left(\mu_N/T\right)^n}$$

Susceptibilities

$$\Rightarrow \quad \hat{\chi}_2^B = \frac{\kappa_2\left(\Delta N_B\right)}{VT^3}$$

Cumulants

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Higher orders

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

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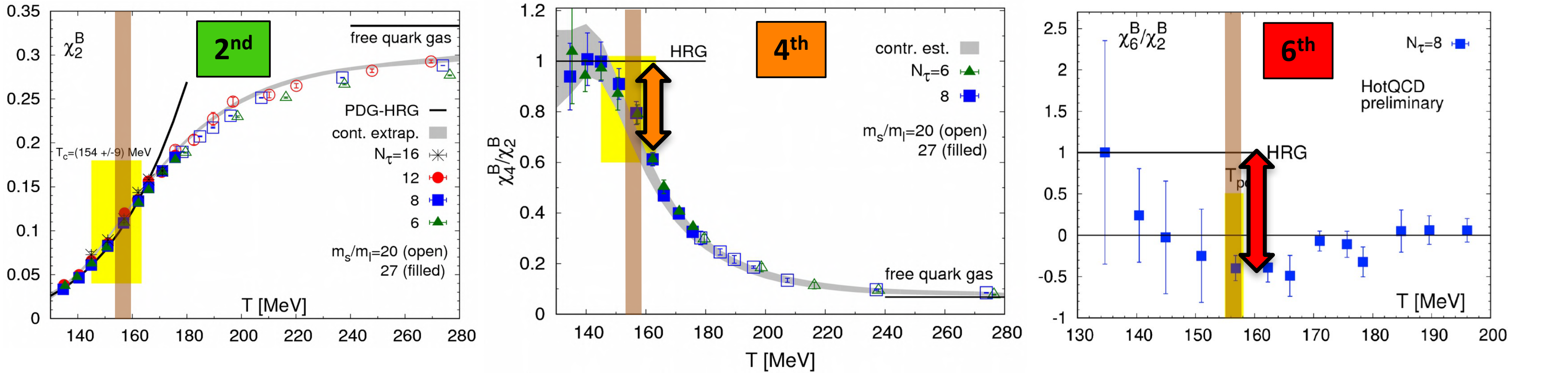

- Up to 3rd order LQCD agrees with Hadron Resonance Gas (HRG)
- At 4th order (~30%) and 6th order (~150%) deviation from HRG

Baseline: Skellam distribution

$$X = N_B - N_{\overline{B}}$$

- **r^th central moment:**

$$\mu_r \equiv \langle (X - \langle X \rangle)^r \rangle = \sum_X (X - \langle X \rangle)^r P(X)$$

- **First four cumulants**

$$\kappa_1 = \langle X \rangle, \quad \kappa_2 = \mu_2,$$
$$\kappa_3 = \mu_3, \quad \kappa_4 = \mu_4 - 3\mu_2^2$$

- **Uncorrelated Poisson limit:**

$$\langle N_B N_{\overline{B}} \rangle = \langle N_B \rangle \langle N_{\overline{B}} \rangle$$

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- **r**

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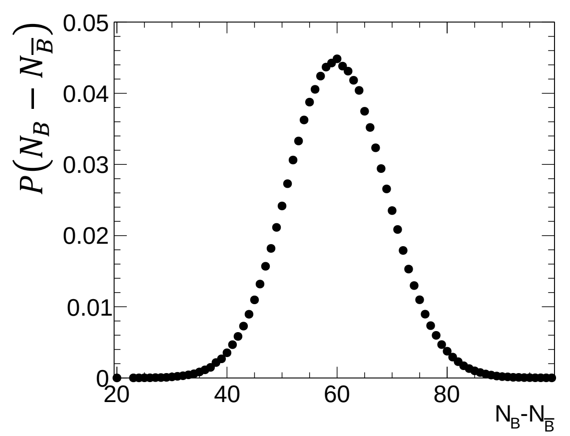


Difference between two independent Poissonian distributions

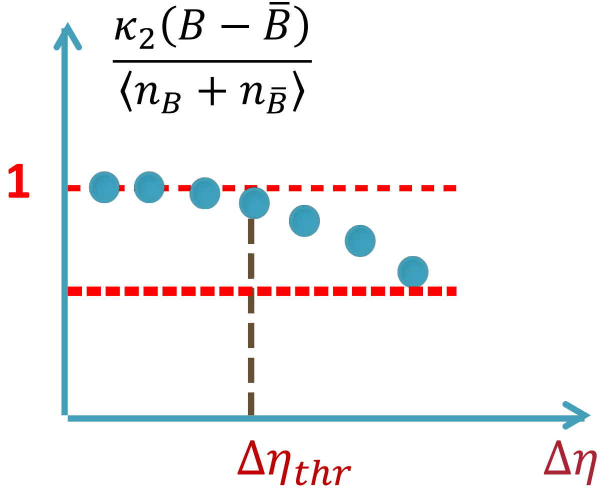
$$\kappa_n = \langle N_B \rangle + (-1)^n \langle N_{\bar{B}} \rangle$$

$$\frac{\kappa_{2n+1}}{\kappa_{2k}} = \frac{\langle n_B \rangle - \langle n_{\bar{B}} \rangle}{\langle n_B \rangle + \langle n_{\bar{B}} \rangle}$$

Odd cumulants vanish for $\langle N_B \rangle = \langle N_{\bar{B}} \rangle$

Importance of acceptance and baryon number conservation

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



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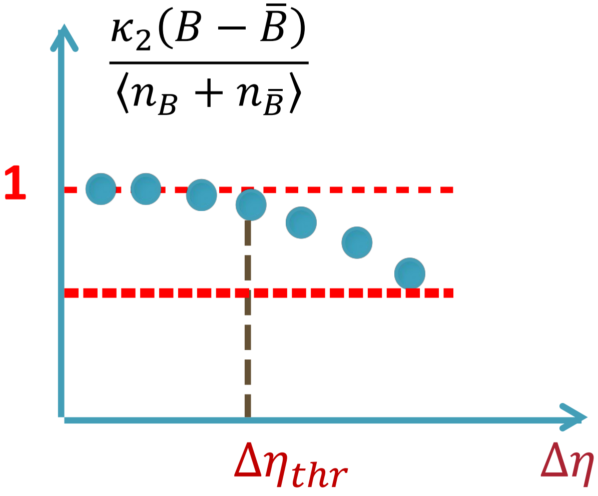
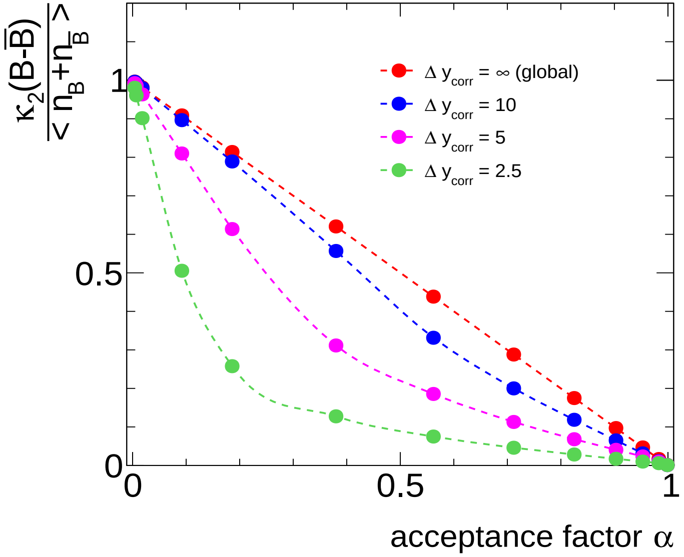


- **Baryon number conservation** imposes subtle correlations

$$\alpha = \frac{\langle N_B^{acc}\rangle}{\langle N_B^{4\pi}\rangle} \qquad |y_{\bar{B}} - y_B| < \frac{\Delta y_{corr}}{2}$$



P. Braun-Munzinger, A. Rustamov, J. Stachel, arXiv:1907.03032
A. Bzdak, V. Koch, V. Skokov, PRC87 (2013) 014901
V. Vovchenko, V. Koch Phys. Rev. C 103, 044903 (2021)

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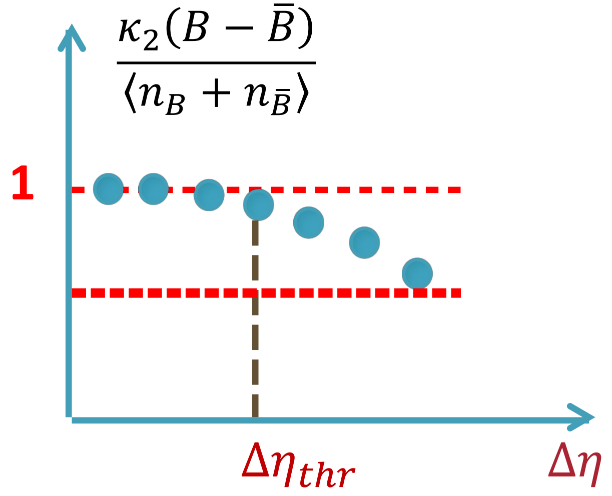

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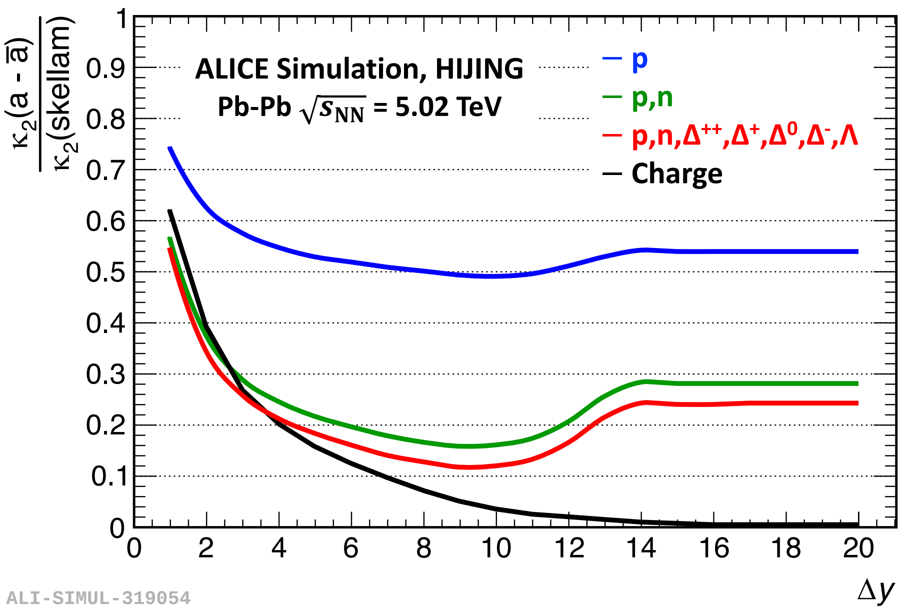
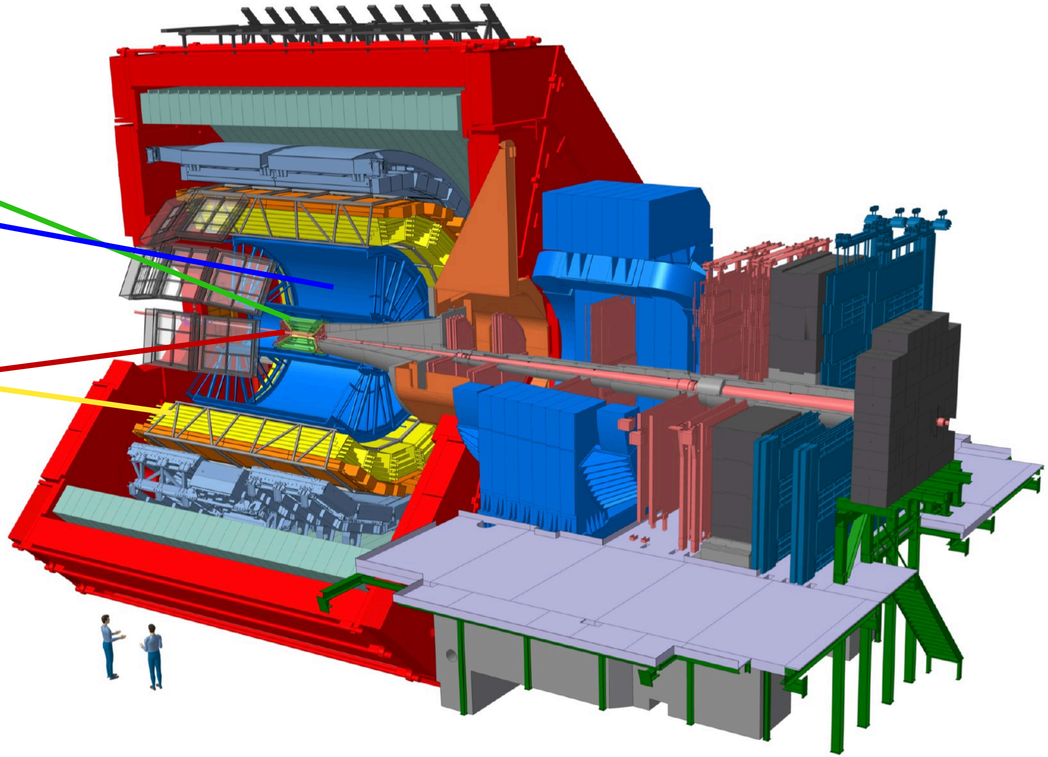


Results

A Large Ion Collider Experiment

Main detectors used:

- **I**nner **T**racking **S**ystem **(ITS)**
  → Tracking and vertexing
- **T**ime **P**rojection **C**hamber **(TPC)**
  → Tracking and
  Particle Identification (PID)
- **T**ime **O**f **F**light **(TOF)**
  → Tracking and PID
- **V**ertex **0** **(V0)**
  → Centrality determination

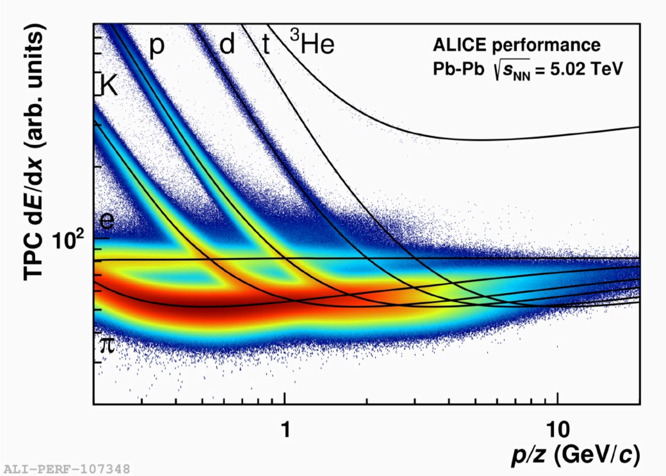


Data Set:

- $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV, ~150 M events
- $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV, ~12 M events

Methods

- **Cut-based approach:**
  - Count tracks of a given particle type
- **Identity method:**
  - Count probabilities to be of a given particle type
  - Gives folded multiplicity distribution
  - Allows for **larger efficiencies**
    → smaller correction needed



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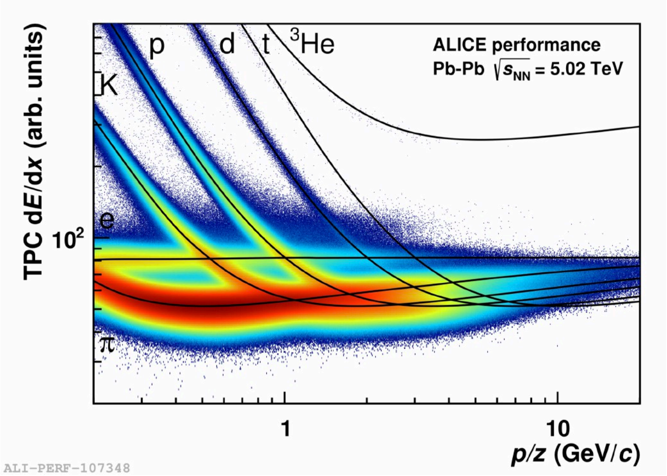

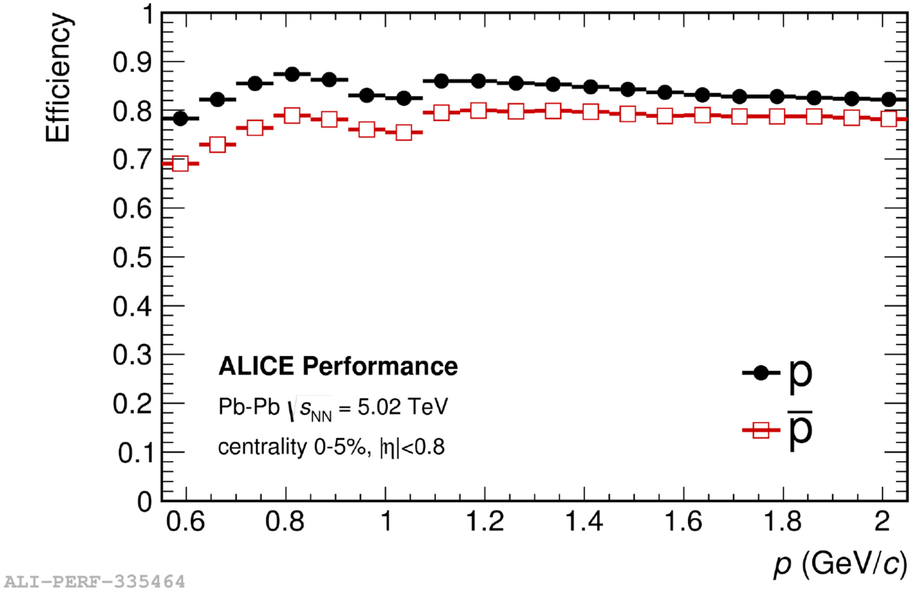

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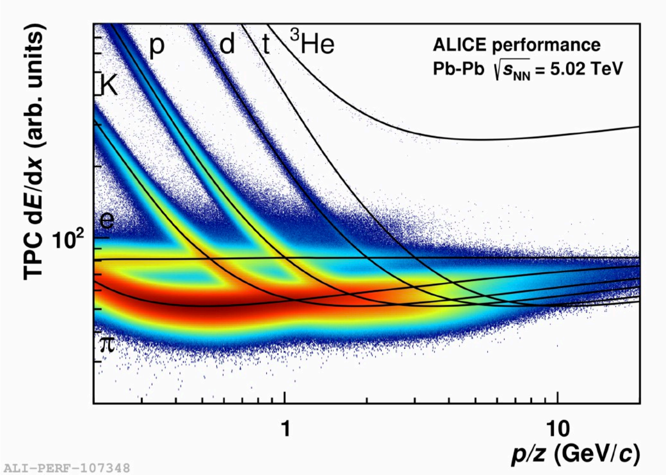

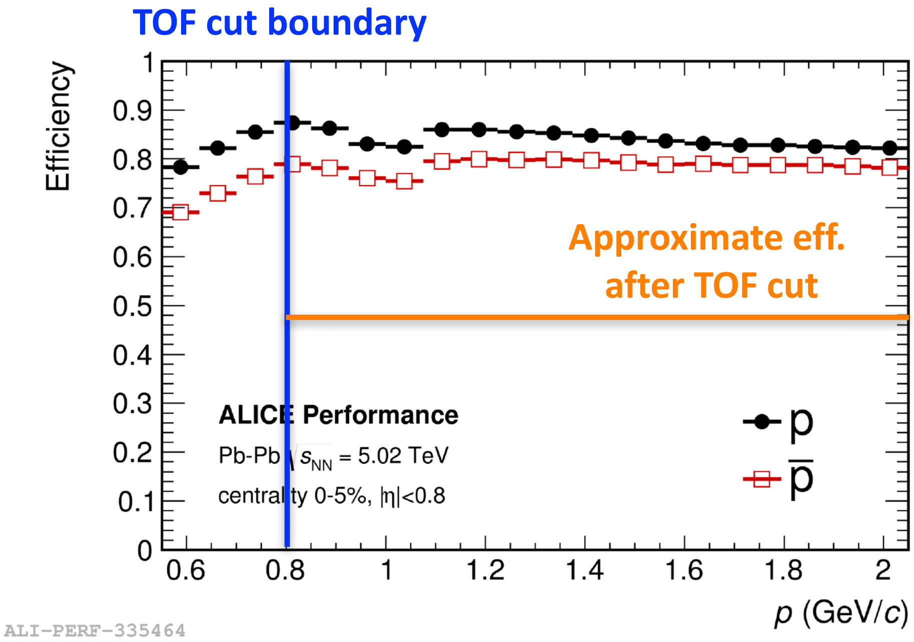

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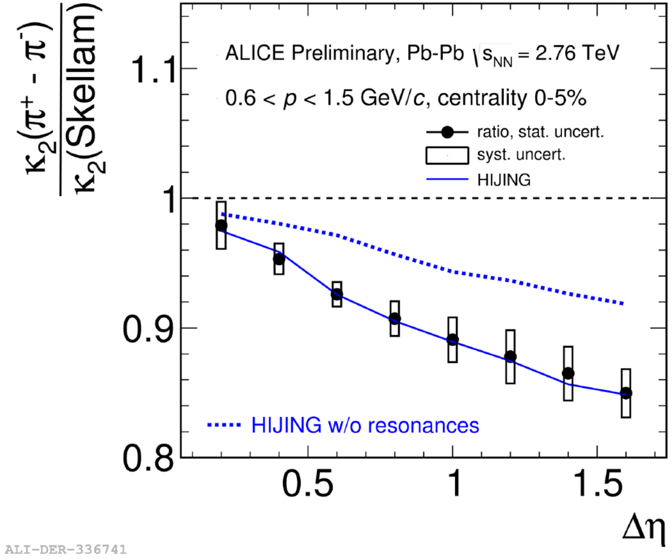
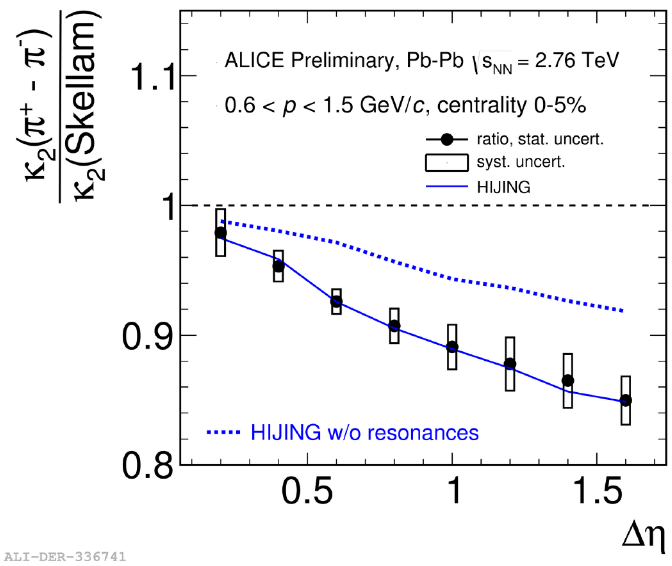
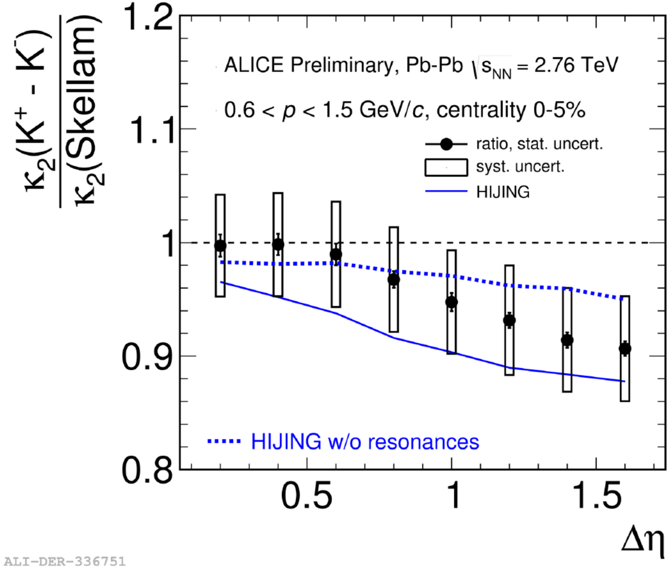
Net-(global)charge fluctuations



➢ **Net-electric-charge:** → Strongly dominated by **resonance contributions**

Net-(global)charge fluctuations





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- **Net-strangeness:** → Kaons are dominated by **ϕ-decay**

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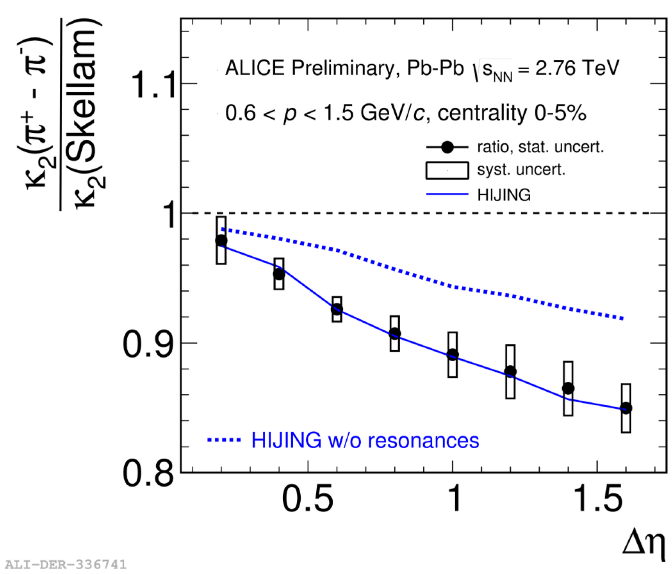
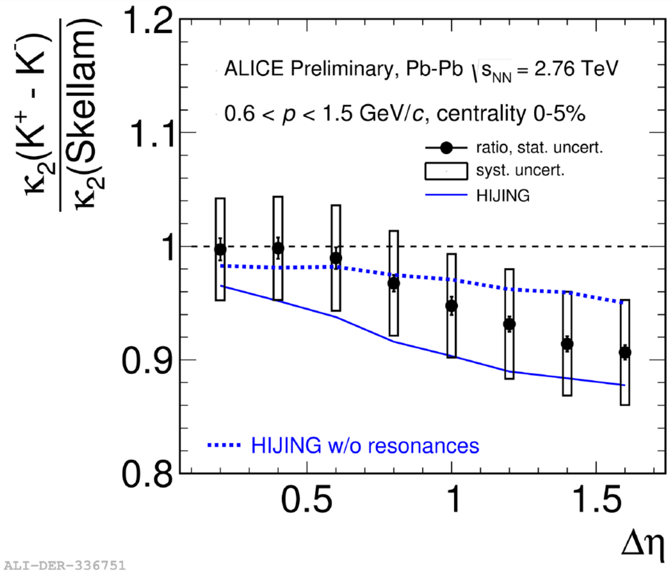
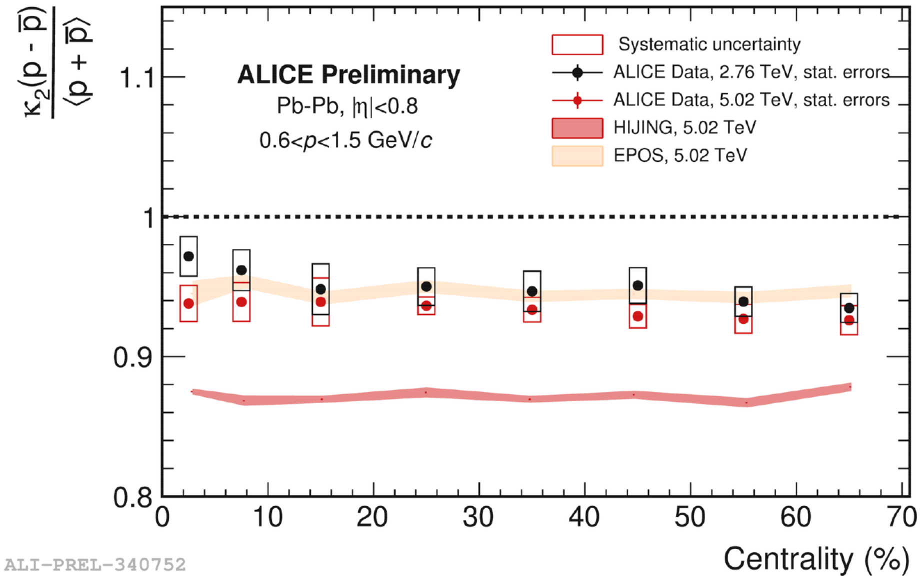
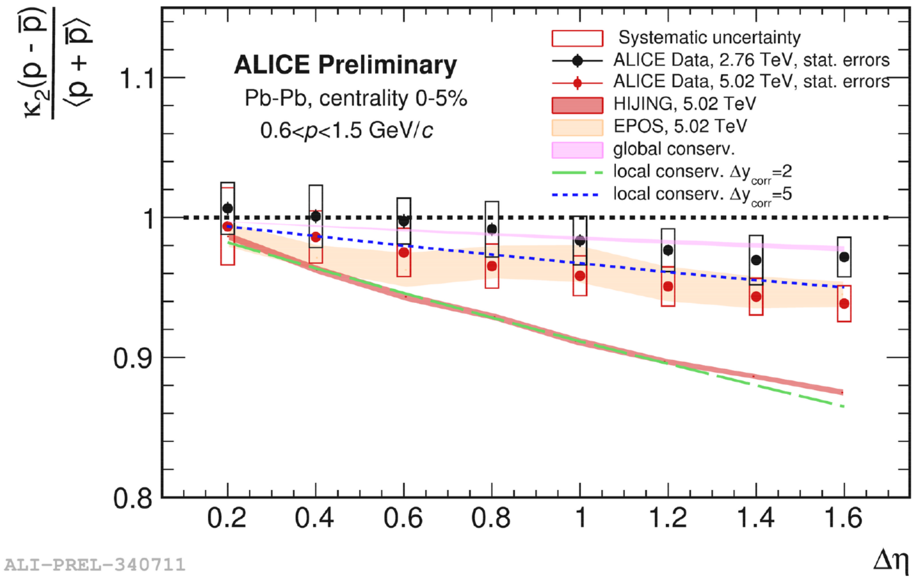




- **Net-electric-charge:** → Strongly dominated by **resonance contributions**
- **Net-strangeness:** → Kaons are dominated by **ϕ-decay**
- **Net-baryon:**
  - → Due to **isospin randomization,** at $\sqrt{s_{\mathrm{NN}}}$ > 10 GeV **net-baryon** fluctuations can be obtained from corresponding **net-proton** measurements (M. Kitazawa, and M. Asakawa, Phys. Rev. C 86, 024904 (2012))
  - → No resonance feeding $\mathrm{p} + \bar{\mathrm{p}}$
  - → **Best candidate for measuring charge susceptibilities**

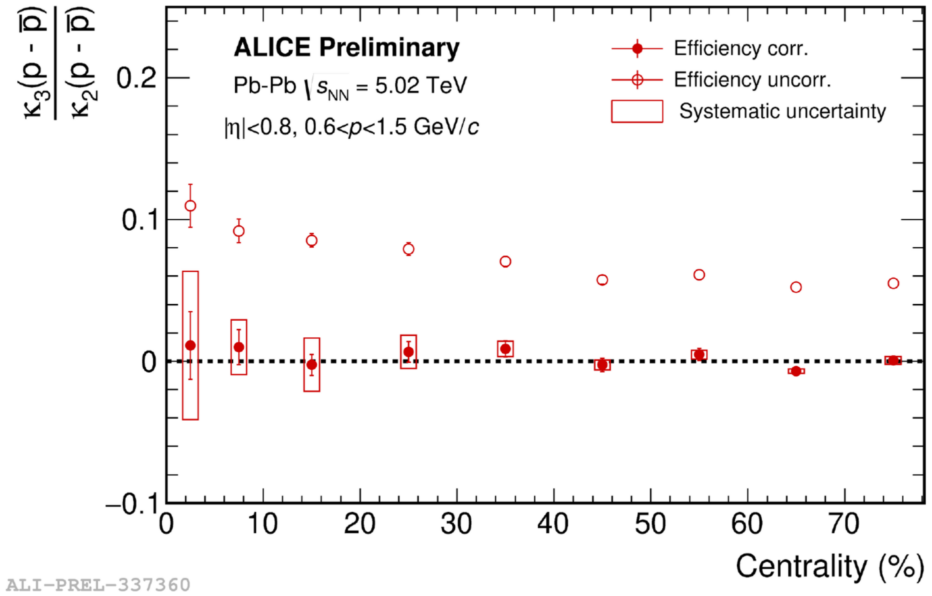
2^{nd} order cumulants of net-p

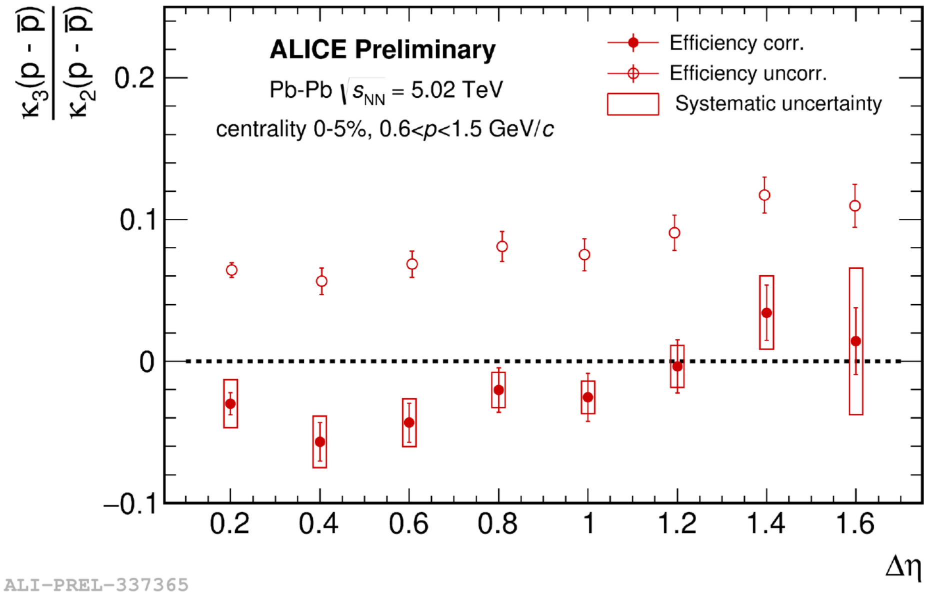




- Deviation from Skellam baseline is due to **baryon number conservation**
- ALICE data suggest **long range correlations,** $\Delta y = \pm 2.5$ unit **or longer**
- EPOS agrees with ALICE data but HIJING deviates significantly
  - Event generators based on string fragmentation (HIJING) conserve baryon number over $\Delta y = \pm 1$ unit

3rd order cumulants of net-p





- **Data** agree with Skellam baseline **“0”** as a function of centrality and pseudorapidity
- Achieved precision of **better than 5%**

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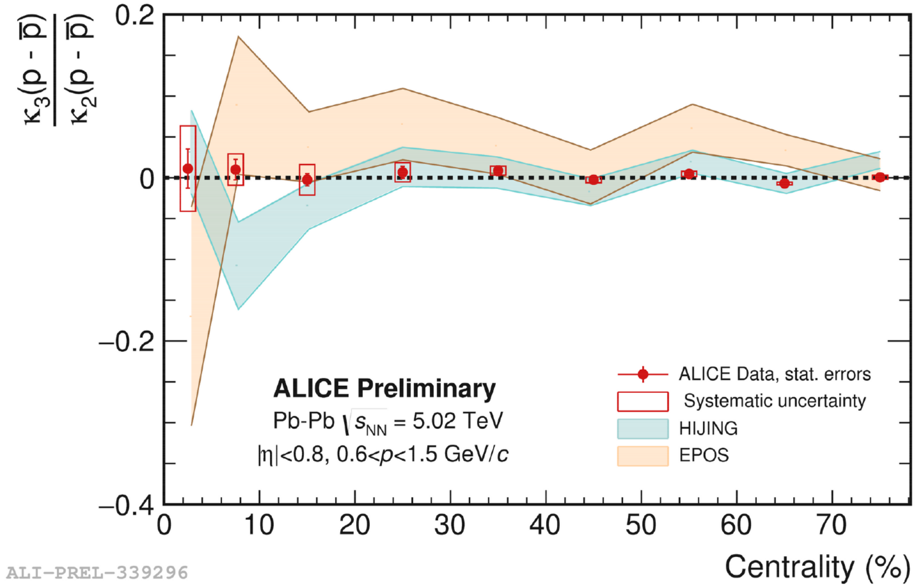
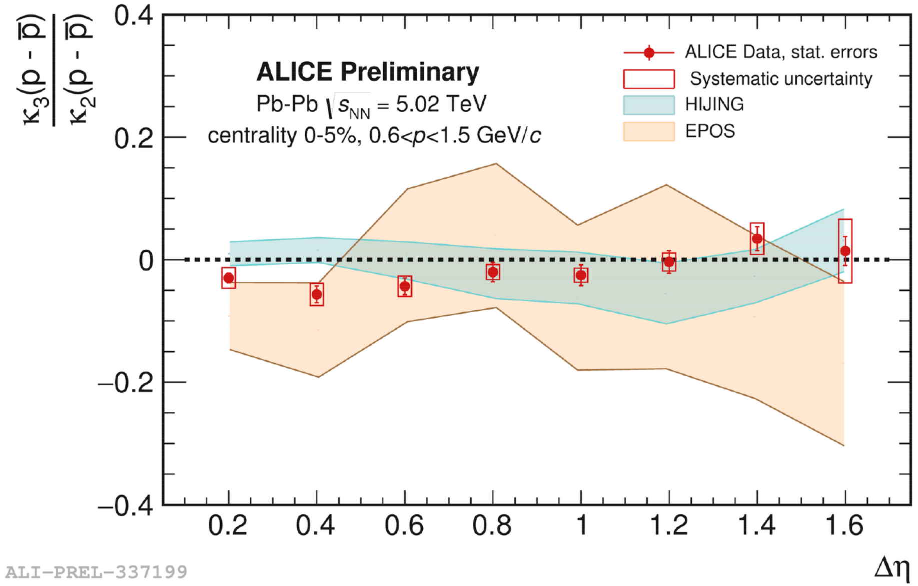
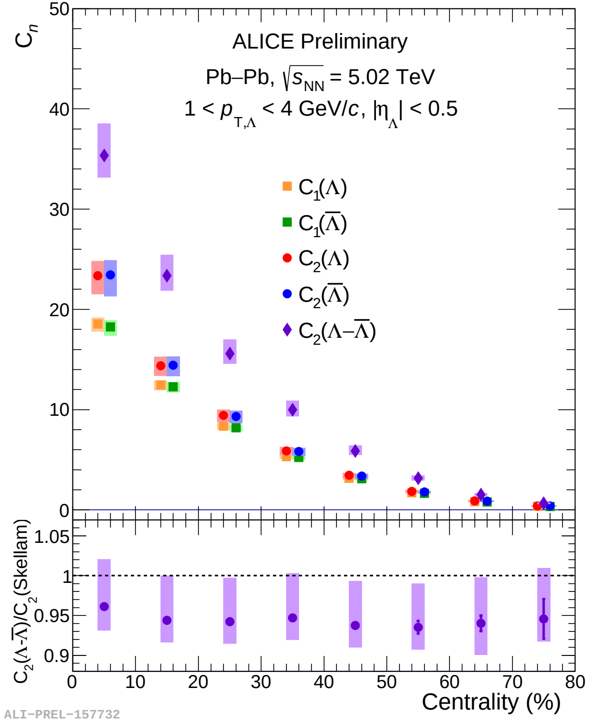




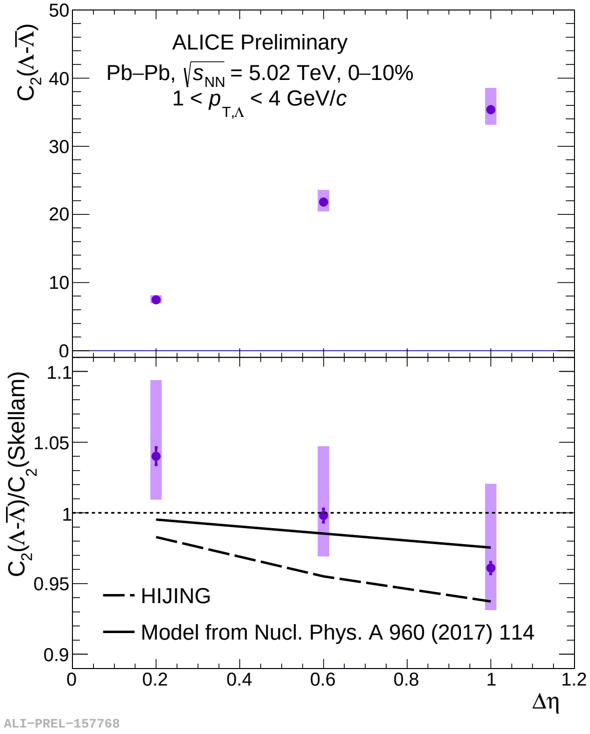
- **Data** agree with Skellam baseline **"0"** as a function of centrality and pseudorapidity
- Achieved precision of **better than 5%**
- **EPOS and HIJING in agreement with data**
  - Both models conserve global charge → net-p within acceptance is ~0

2^{nd} order cumulants of net-Λ

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



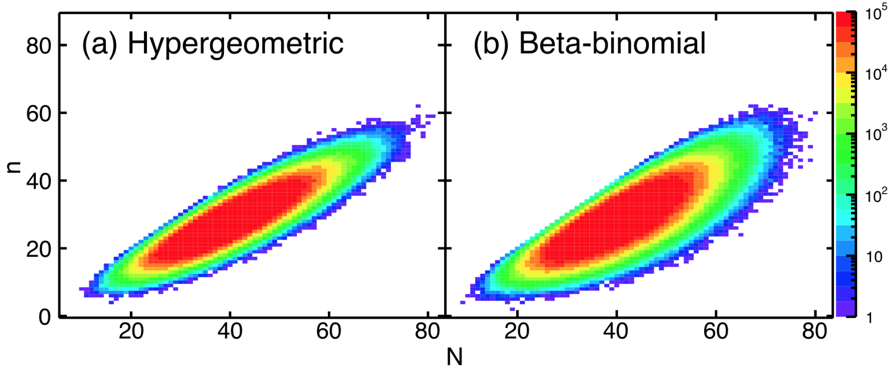
Alice Ohlson, QM2018, NPA 982 (2019) 299



- Similar trend as for **net-p**
- **Better precision** is needed to see the impact of strangeness conservation

Experimental Challenges

What if efficiency loss is not binomial?



Draw N balls from the urn without returning balls to the urn

In each draw, when one draws a white ball, two white balls are returned to the urn

T. Nonaka, M. Kitazawa, S. Esumi, Nucl.Instrum.Meth. A906 (2018) 10-17
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Efficiency correction

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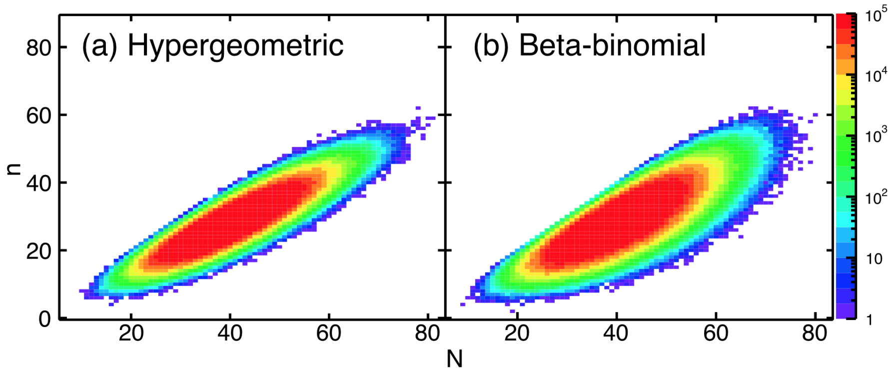

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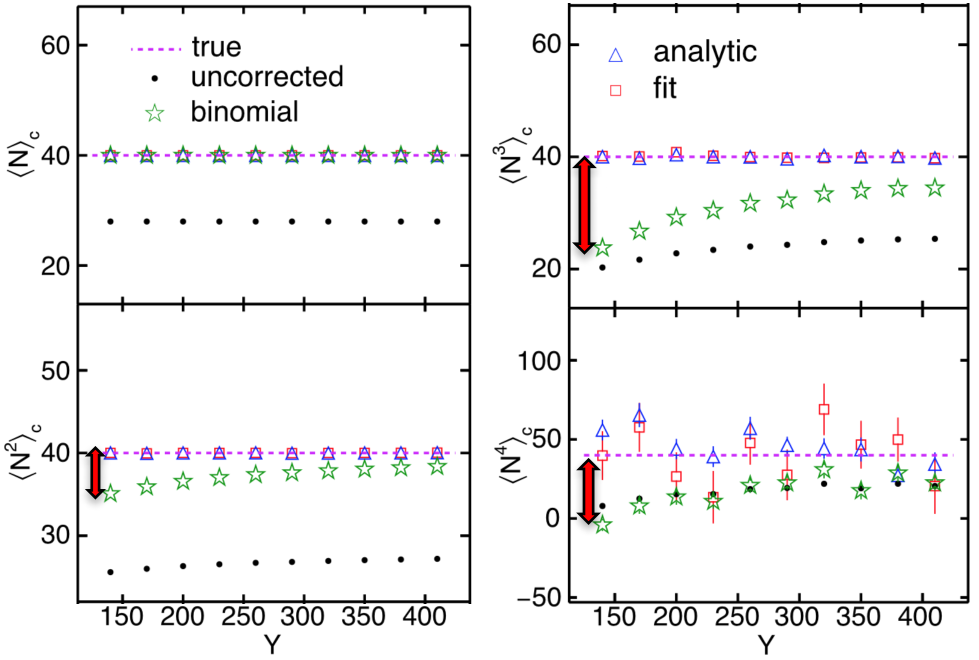
Hypergeometric



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Efficiency correction with binomial assumption:

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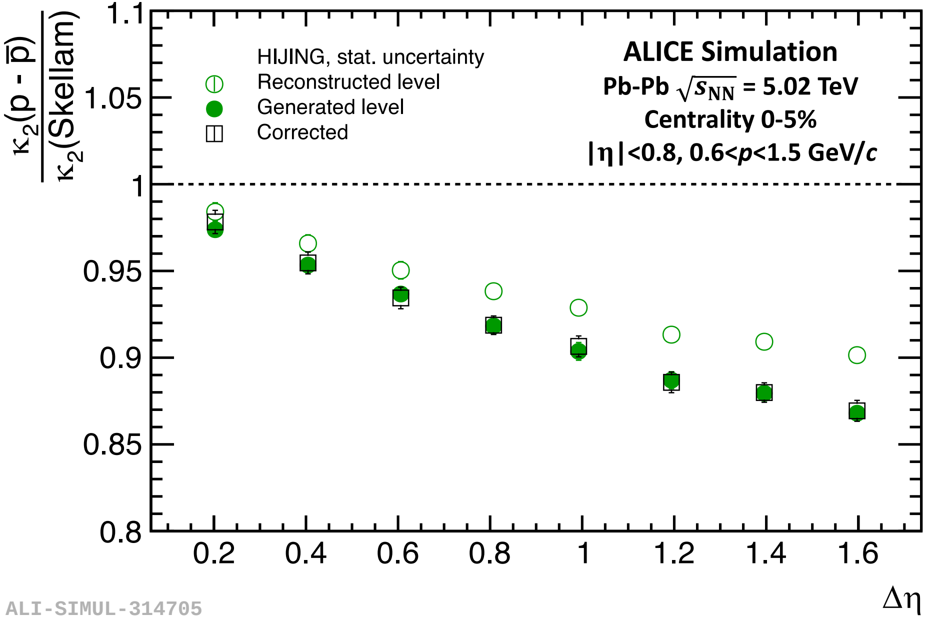
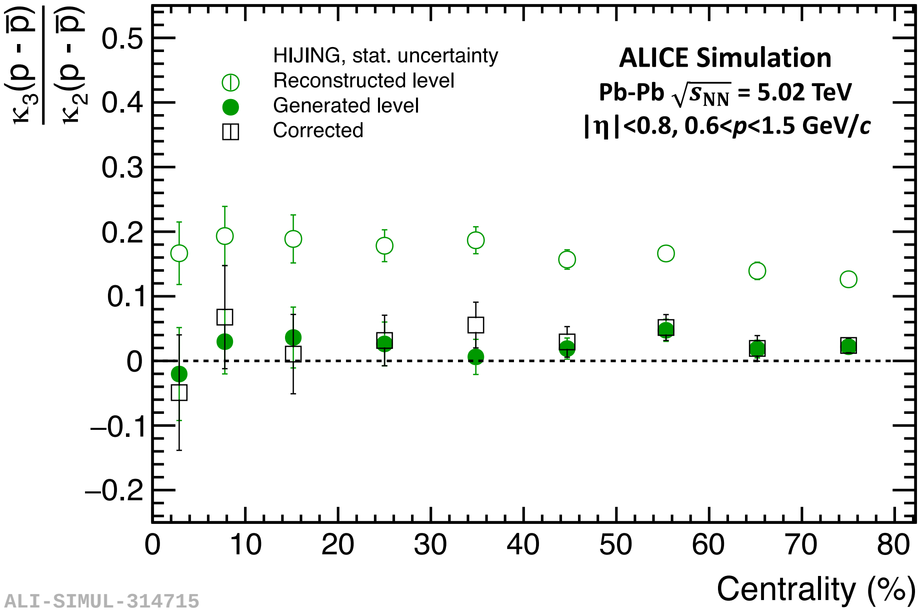
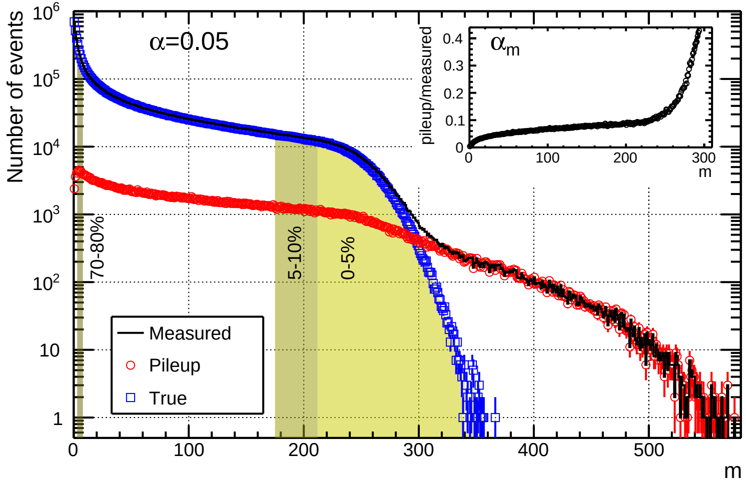




- Monte-Carlo (MC) closure test is successful even though there is slight deviation from binomial detector response
- Realistic MC description and track selection criteria are crucial

Event pileup

- **Event pileup:** When two collision events occur within a small space and time interval, they are identified as a single event
- Significant impact on the higher order cumulants
- Event selection criteria is crucial



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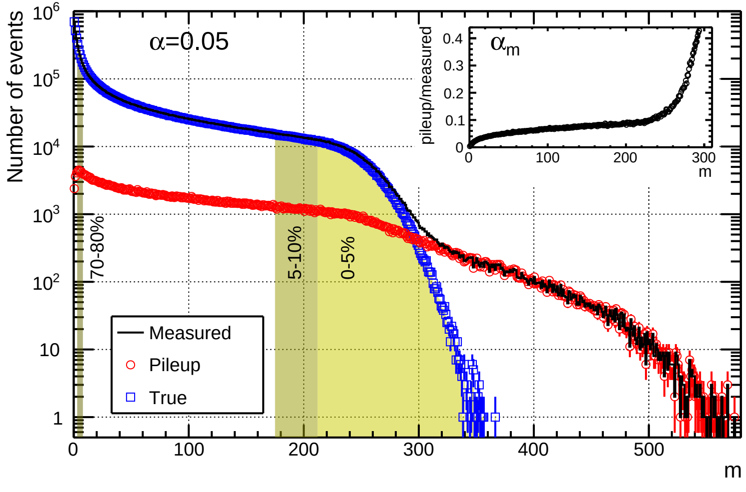
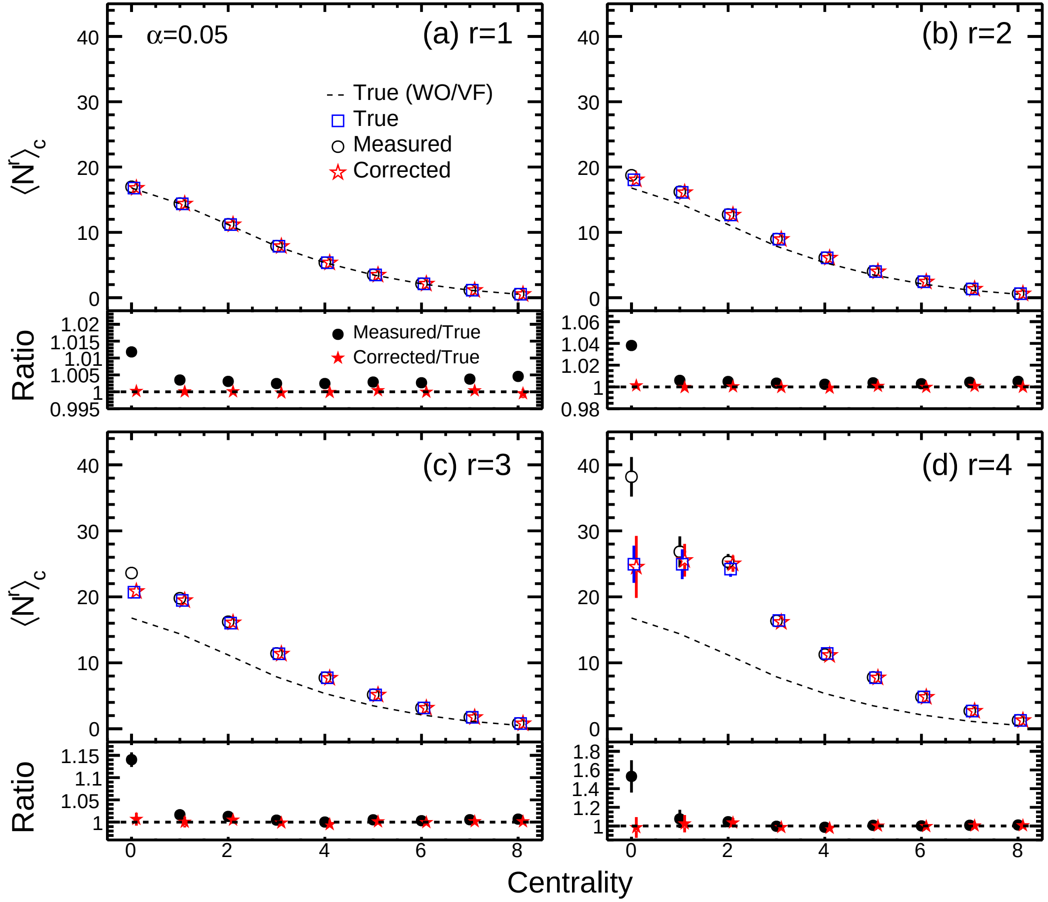
Event pileup

- **Event pileup:** When two collision events occur within a small space and time interval, they are identified as a single event
- Significant impact on the higher order cumulants
- Event selection criteria is crucial





T. Nonaka, M. Kitazawa, S. Esumi, Nucl.Instrum.Meth. A984 (2020)

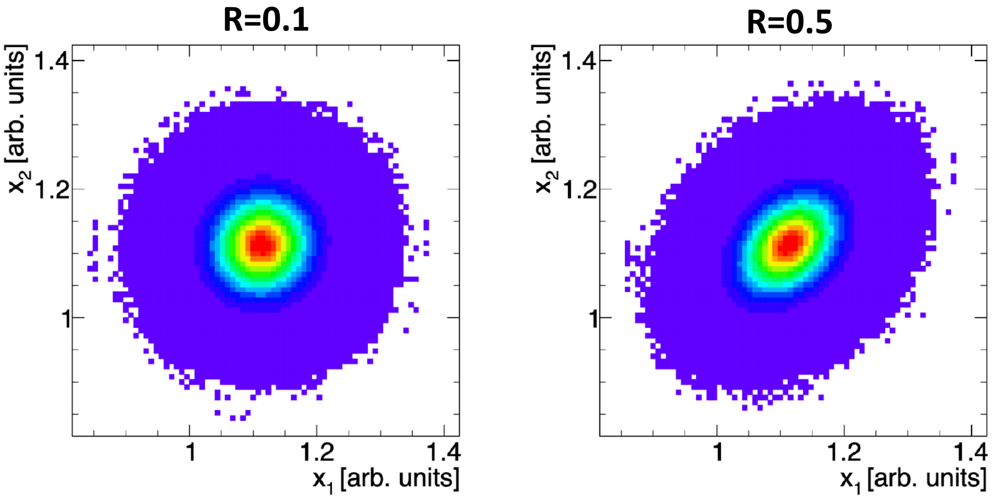
Particle-Set Identification method

Identity Method

+

solution to “**correlations between dE/dx measurements of different particles**”

$$R = \frac{\langle (x_1 - \langle x_1 \rangle)(x_2 - \langle x_2 \rangle) \rangle}{\sigma_{x_1} \sigma_{x_2}}$$



Two-particle distribution $\rho(x_1, x_2)$ for pions ($x \rightarrow dE/dx$)

M.Gazdzicki, M.I.Gorenstein, M.Pawlowska, A.Rustamov, Nuclear Physics A 1001 (2020) 121915

Particle-Set Identification method

Run 1 & Run 2

- **1 nb^{-1}** of Pb−Pb collisions
- ≈**1 kHz** Pb−Pb minimum bias readout rate
- **MWPC** based TPC
- ITS with **6 layers**
- **Offline reconstruction**

LS2 Upgrade

Run 3 & Run 4 (beyond 2021)

- **13 nb^{-1}** of Pb−Pb collisions
- ≈**50 kHz** Pb−Pb minimum bias readout rate
- **GEM** based TPC
- ITS with **7 layers**
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Particle-Set Identification method

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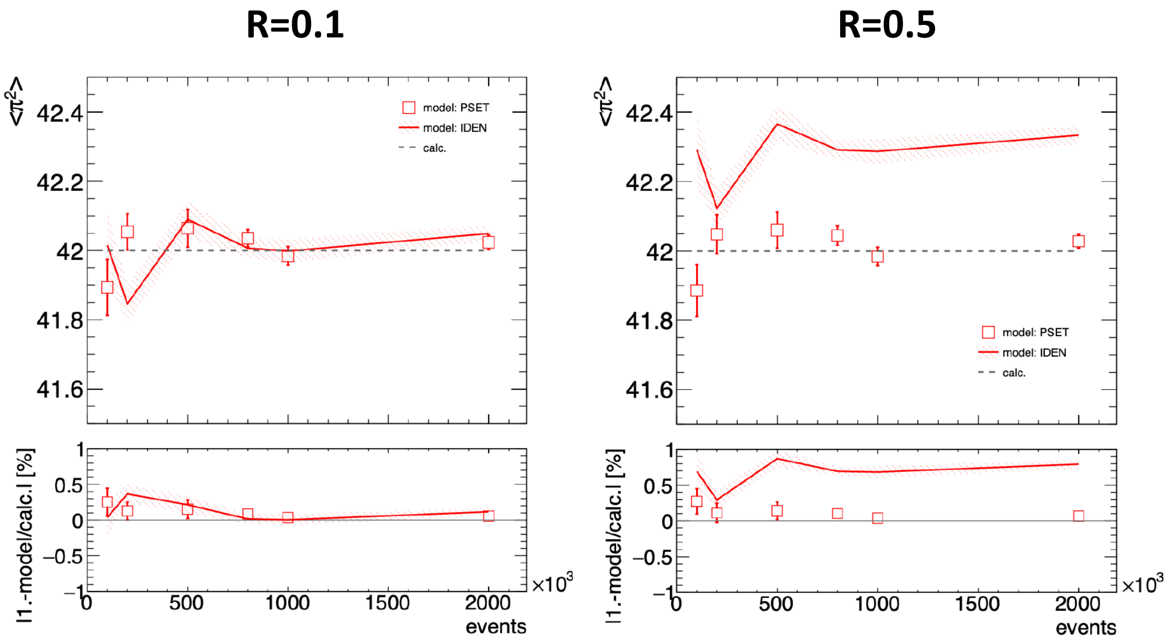

- So far **Identity Method** performs well with **Run 1/2** data
- **PSET** could be and option for **Run 3/4**

M.Gazdzicki, M.I.Gorenstein, M.Pawlowska, A.Rustamov, Nuclear Physics A 1001 (2020) 121915

Summary: Current status

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  - ✓ **2nd order:** Deviation from Skellam baseline is due to baryon number conservation
    - ALICE data suggests **long range correlations**
  - ✓ **3rd order:** Agrees with Skellam baseline **"0"** as a function of centrality and pseudorapidity
    - Achieved precision of **better than 5%** for the κ_3/κ_2 results is promising for the higher order cumulants
    - **Up to 3rd order ALICE data agree with the LQCD expectations**
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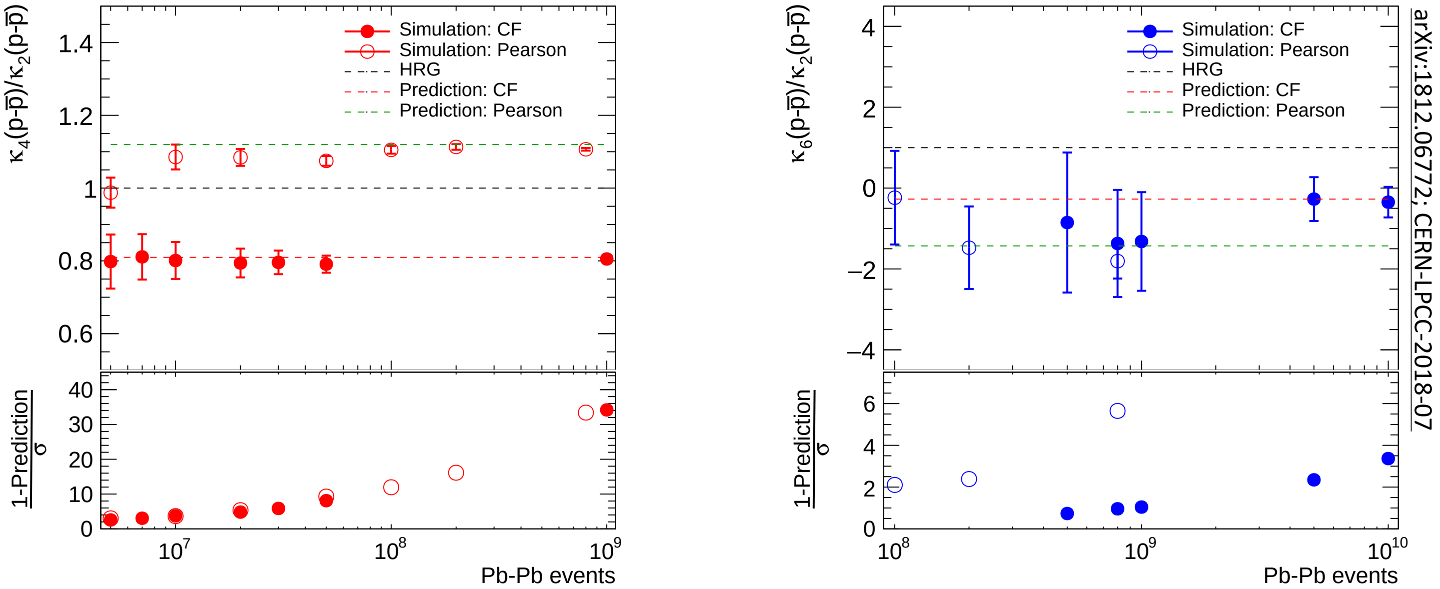
- **Experimental Challenges:**
  - ✓ Efficiency correction
  - ✓ Event pileup
  - ✓ **Correlations between dE/dx measurements of different particles**

→

- ❑ **Event/track selection**
- ❑ **Correction/analysis methods**
- ❑ **Realistic detector simulation**
- ❑ **…**

Outlook: After ALICE upgrade

- **New ITS** (better vertexing) and **TPC** (continuous readout with GEM technology)
- Record minimum-bias Pb-Pb data at 50kHz → Order of magnitude more events

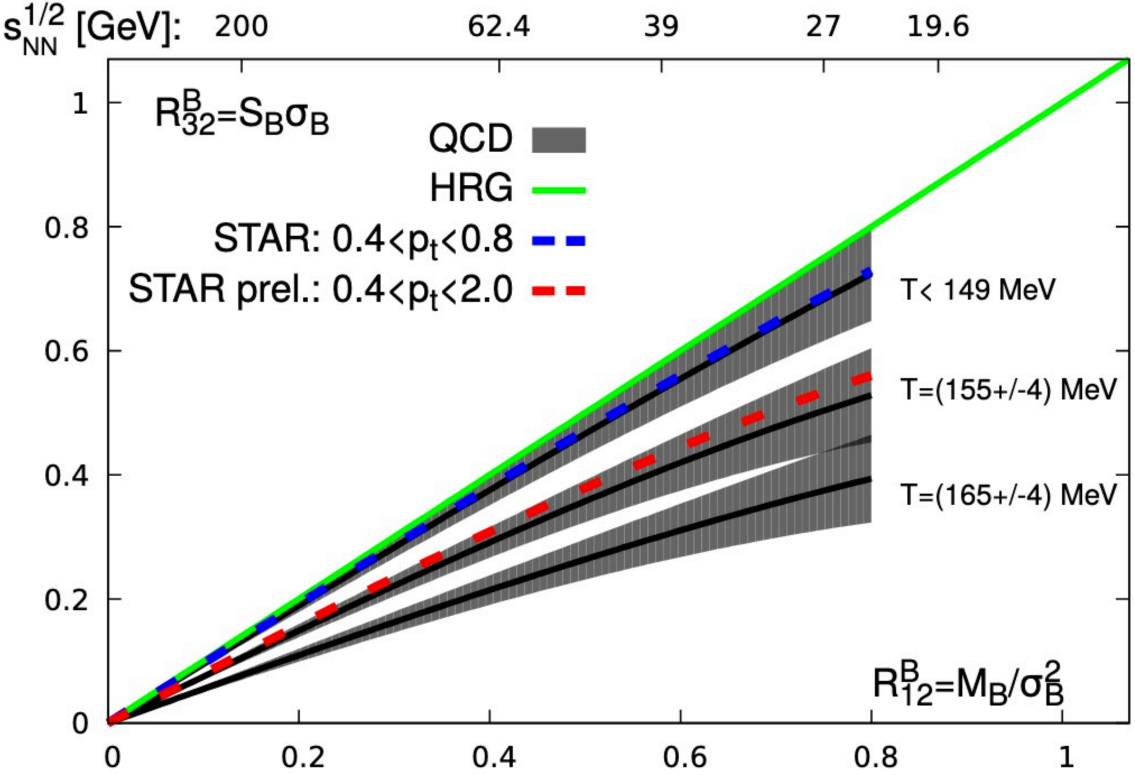


✓ **6^{th} order and maybe beyond**

Polyakov-loop extended Quark- Meson model (PQM), G. A. Almasi, B. Friman, and K. Redlich, Phys. Rev.D96(2017) no. 1, 014027

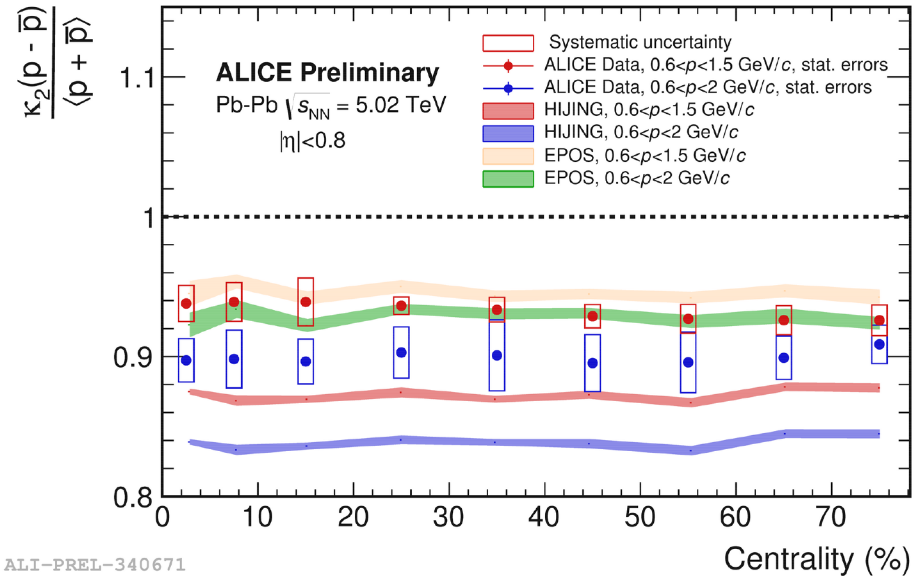
Pearson Curve Method, N. K. Behera, arXiv:1706.06558 [nucl-ex]

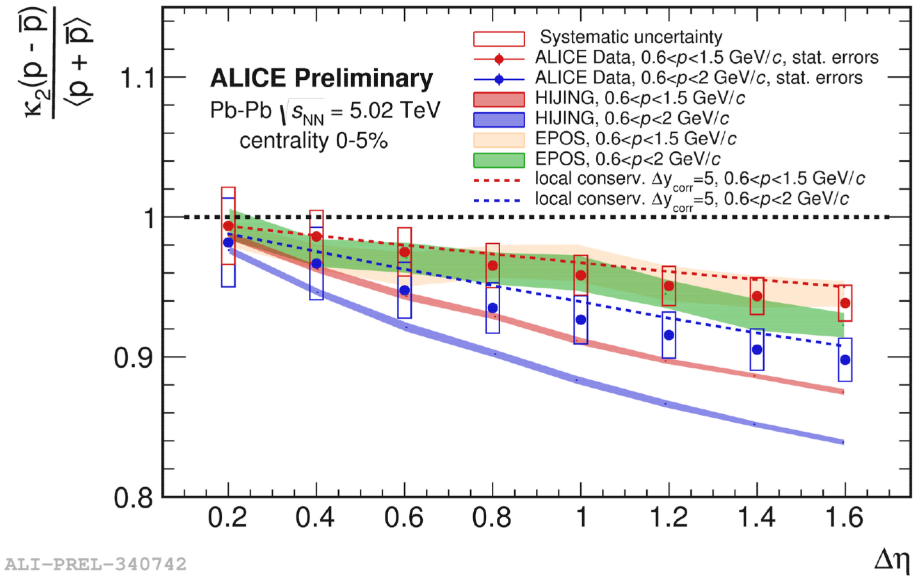
BACKUP



$s_{NN}^{1/2}$ [GeV]: 200 62.4 39 27 19.6
$R_{32}^B = S_B \sigma_B$
QCD
HRG
STAR: $0.4 < p_t < 0.8$
STAR prel.: $0.4 < p_t < 2.0$
T< 149 MeV
T=(155+/-4) MeV
T=(165+/-4) MeV
$R_{12}^B = M_B/\sigma_B^2$
0
0.2
0.4
0.6
0.8
1

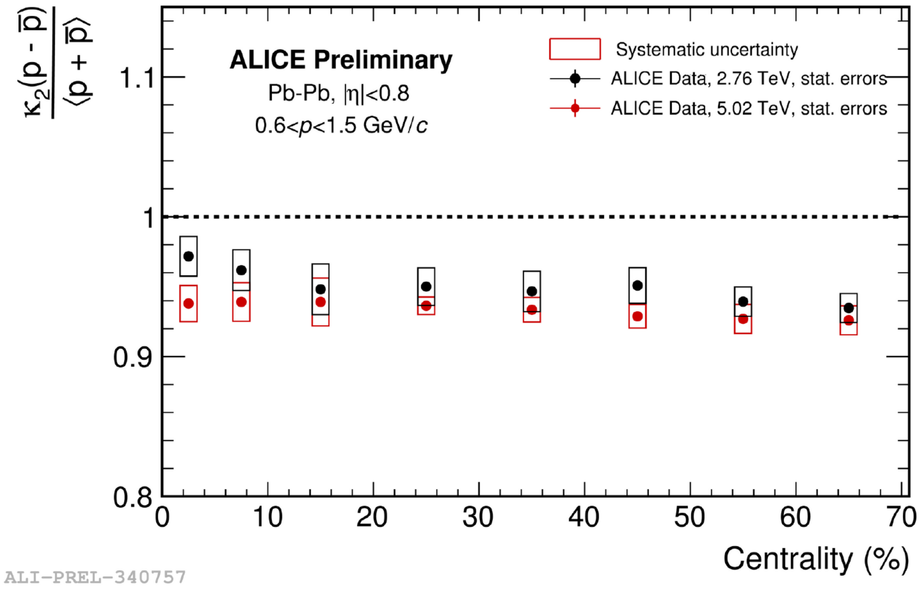
2^{nd} order cumulants of net-p

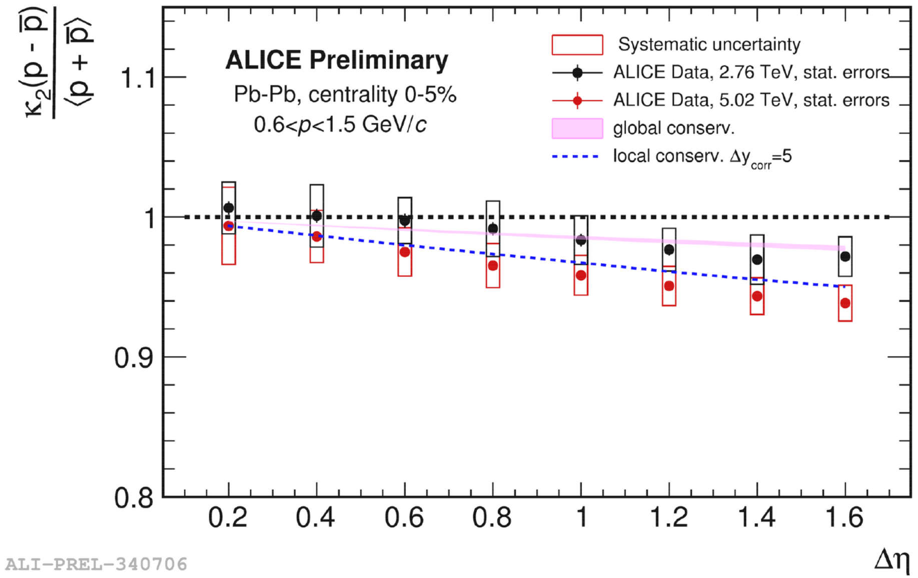




- Consistent with the baryon number conservation picture
  - Increase in fraction of accepted $p, \bar{p}$ -> stronger constraint of fluctuations due to baryon number conservation
- EPOS & HIJING show this drop qualitatively

2^{nd} order cumulants of net-p

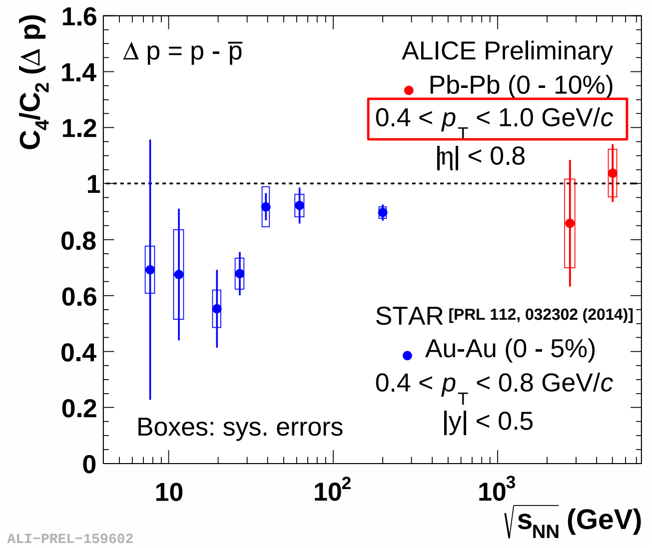


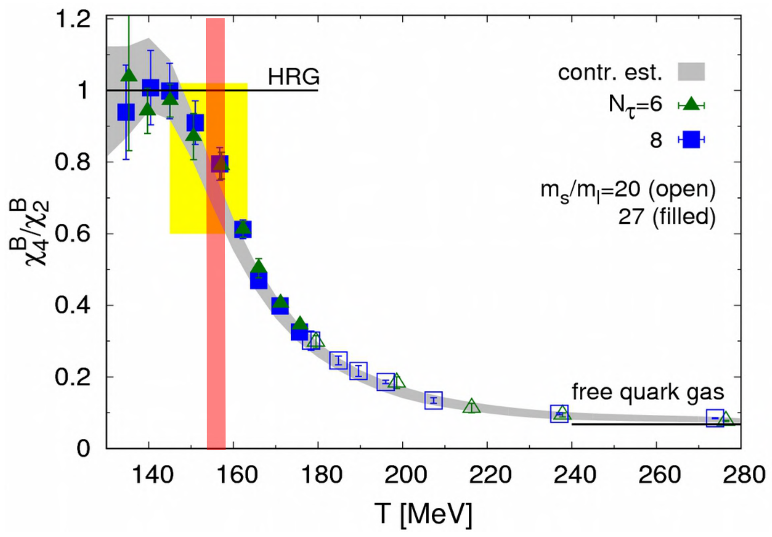


- Deviation from Skellam baseline is due to **baryon number conservation**
- ALICE data suggest **long range correlations,** $\Delta y = \pm 2.5$ unit **or longer**

C_3/C_2 and C_4/C_2 agree with Skellam at LHC energies?

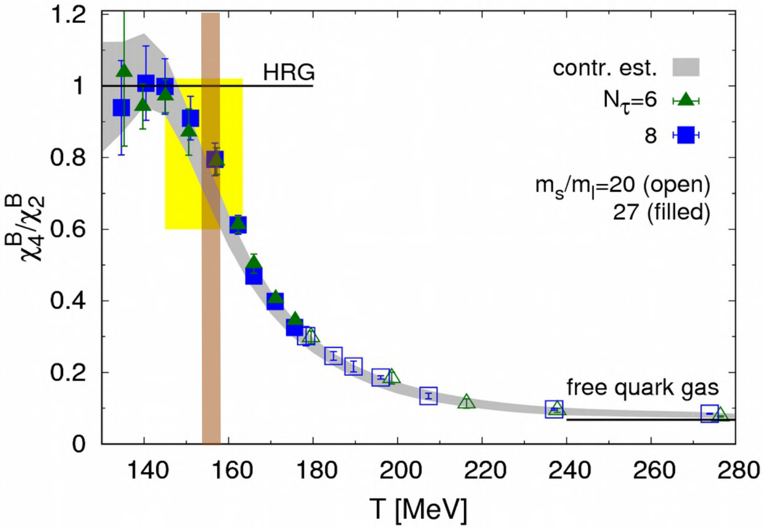
- Small acceptance
- Low statistics
- Cut-based approach for PID

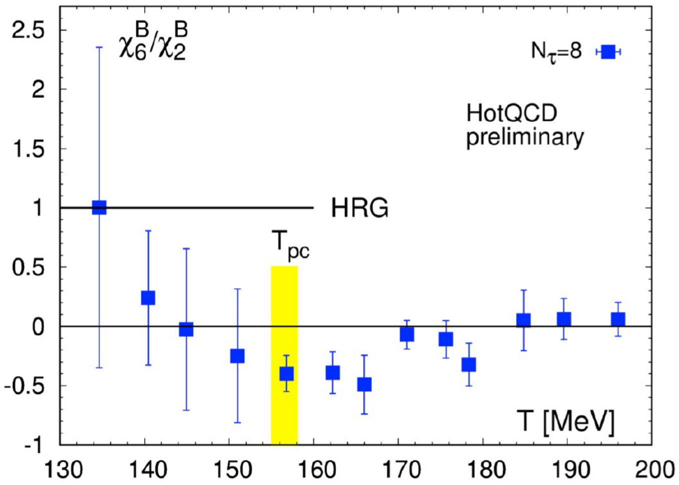




Analysis within a larger kinematic acceptance using Identity Method is in progress

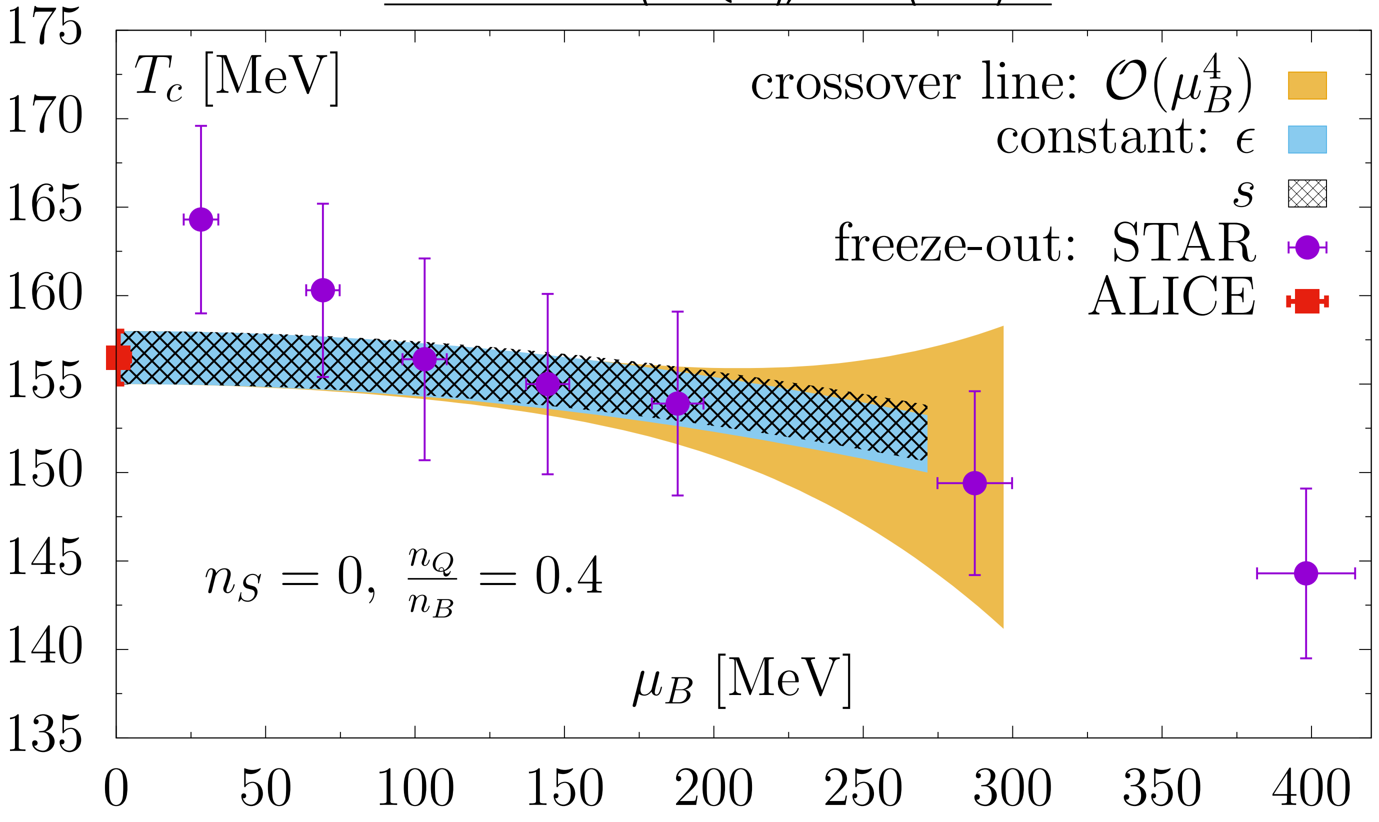
Holy grail: see critical behavior in 6th and higher order cumulants

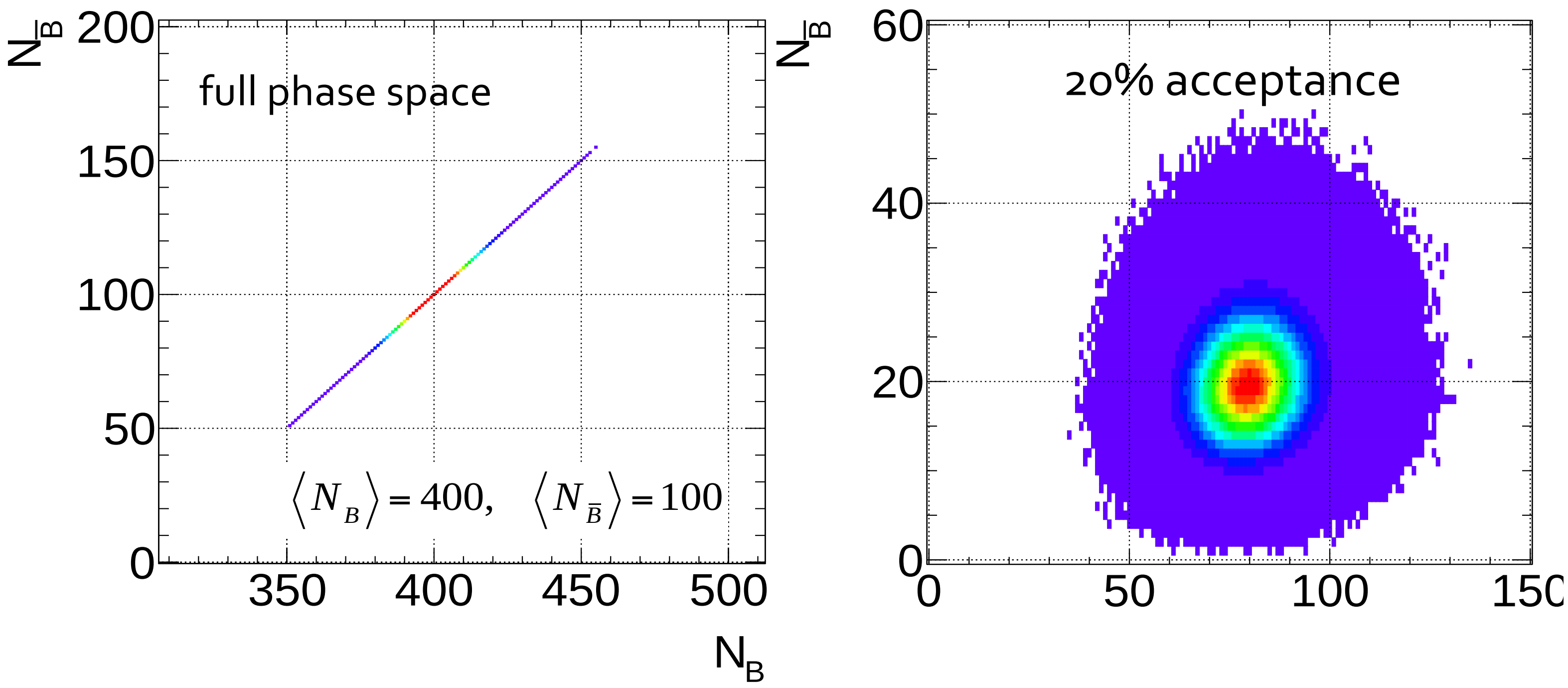




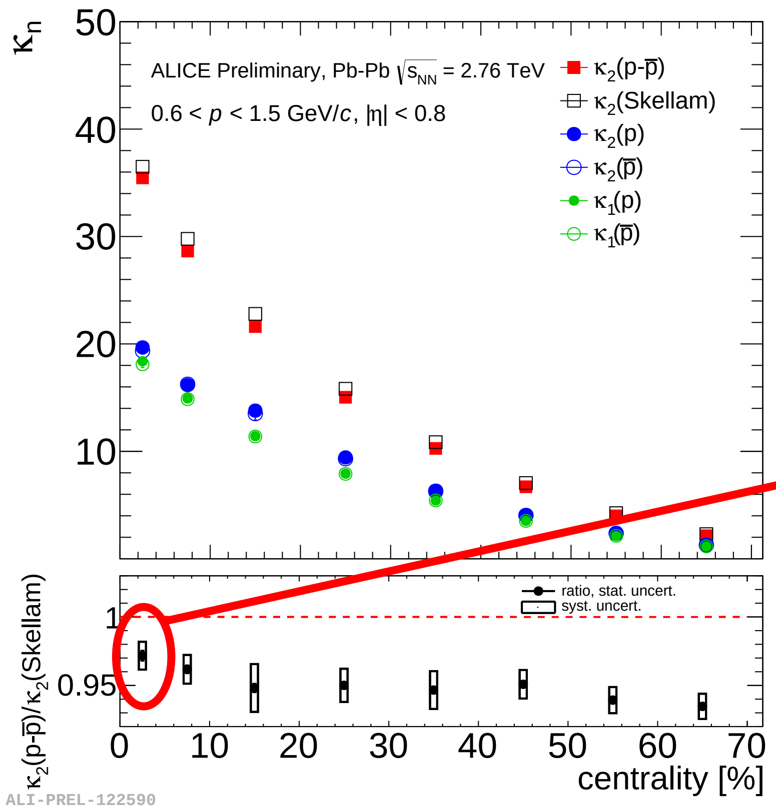
RUN 1: 2nd order (~13M min. bias events)
RUN 2: 4th order (~150M central events)
RUN 3: 6th and higher order? (>1000M central events)

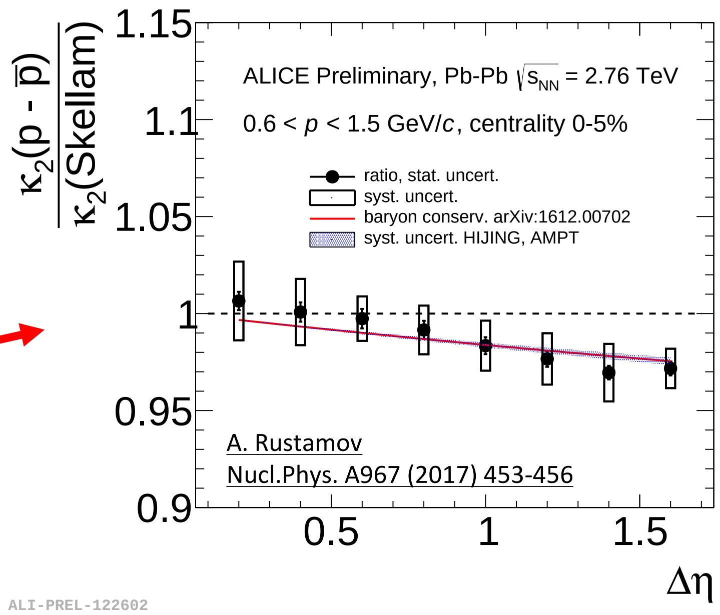
A. Bazavov et al. (HotQCD),PLB795(2019)15



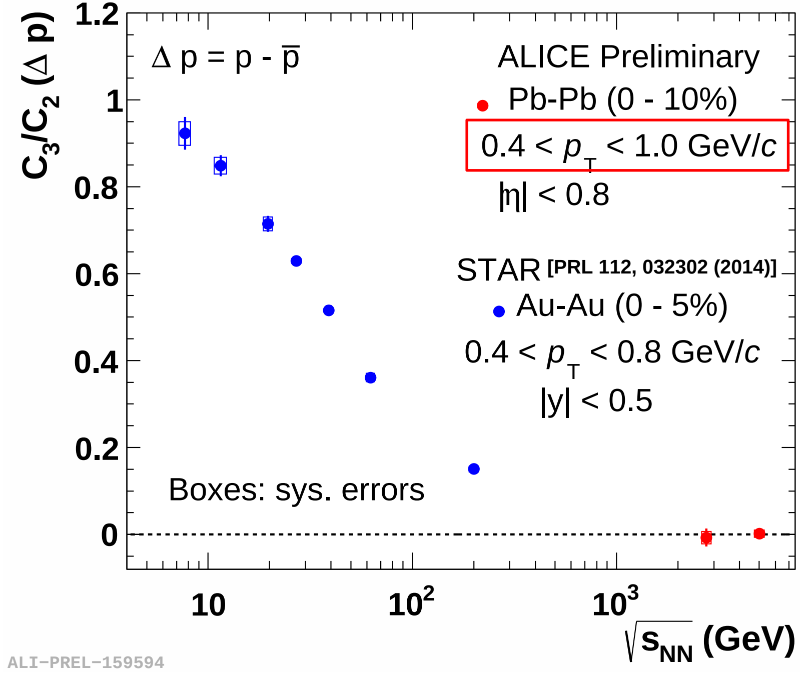


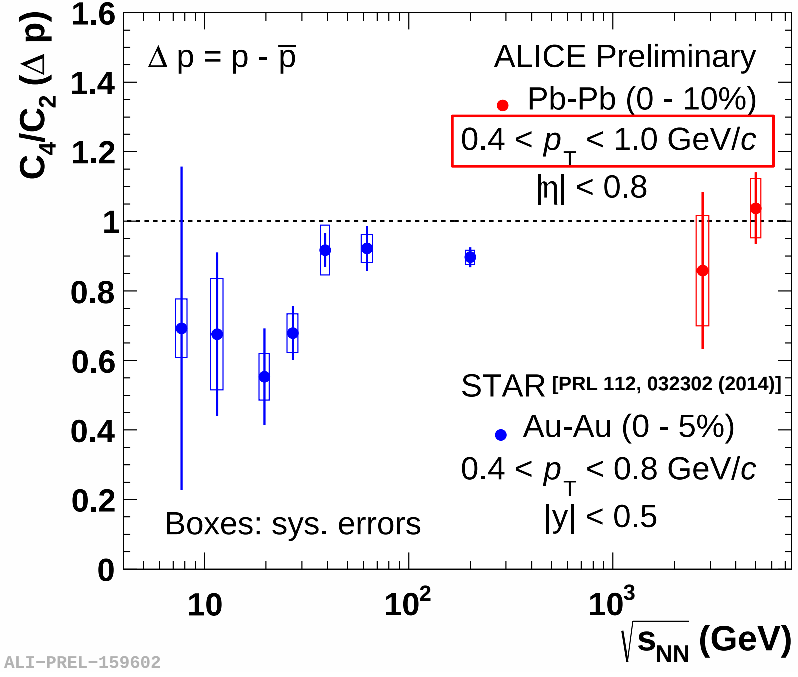
P. Braun-Munzinger, A. Rustamov, J. Stachel, QM18, NPA 982 (2019) 307-310


ALICE Preliminary, Pb-Pb $\sqrt{s_{NN}}$ = 2.76 TeV
0.6 < p < 1.5 GeV/c, |η| < 0.8
$\kappa_2(p-\bar{p})$
κ_2(Skellam)
$\kappa_2(p)$
$\kappa_2(\bar{p})$
$\kappa_1(p)$
$\kappa_1(\bar{p})$
κ_n
ratio, stat. uncert.
syst. uncert.
$\kappa_2(p-\bar{p})/\kappa_2$(Skellam)
centrality [%]
ALI-PREL-122590


ALICE Preliminary, Pb-Pb $\sqrt{s_{NN}}$ = 2.76 TeV
0.6 < p < 1.5 GeV/c, centrality 0-5%
ratio, stat. uncert.
syst. uncert.
baryon conserv. arXiv:1612.00702
syst. uncert. HIJING, AMPT
A. Rustamov
Nucl.Phys. A967 (2017) 453-456
$\frac{\kappa_2(p-\bar{p})}{\kappa_2(\text{Skellam})}$
Δη
ALI-PREL-122602

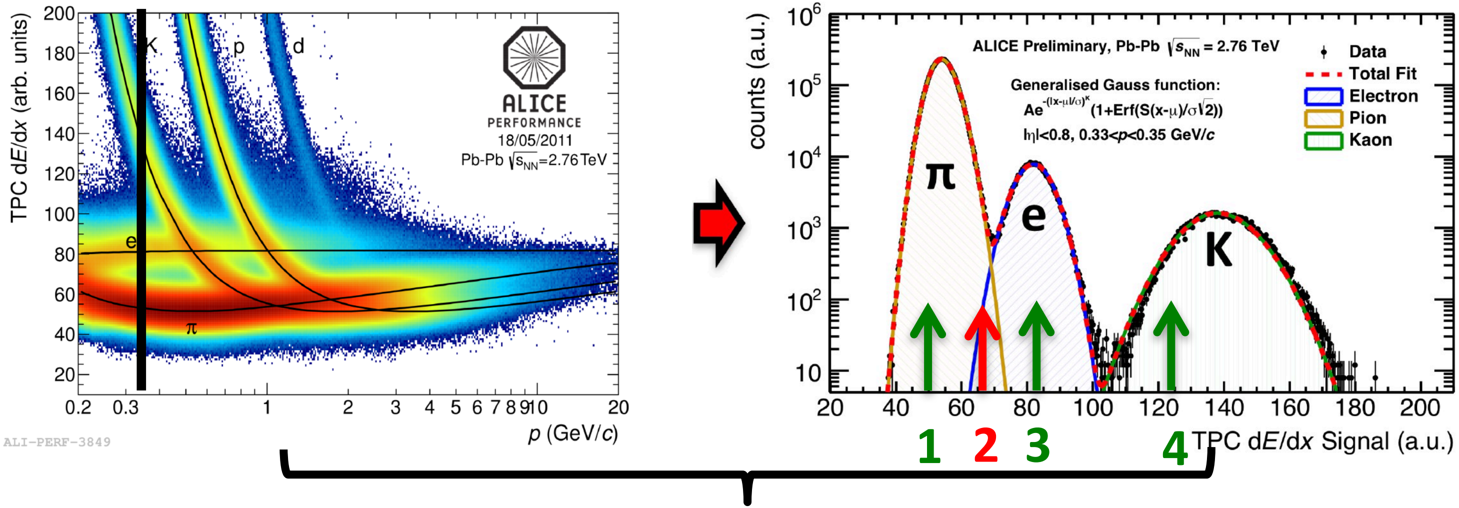
Nirbhay Kubera, QM18, NPA 982 (2019) 851





Cut-based approach: count tracks of a given particle type

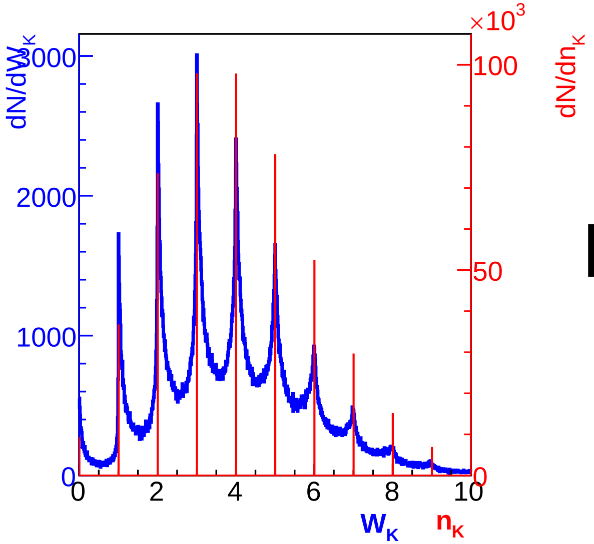
Identity method: count probabilities to be of a given particle type



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

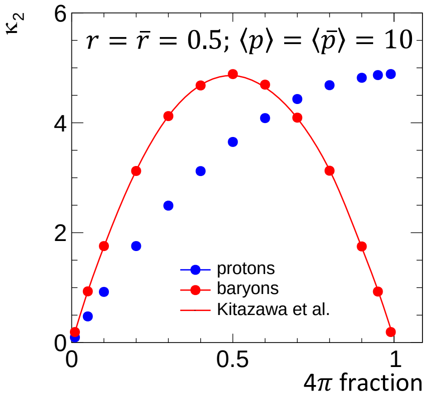
A. Rustamov, M. Gazdzicki, M. I. Gorenstein, PRC 86, 044906 (2012), PRC 84, 024902 (2011)

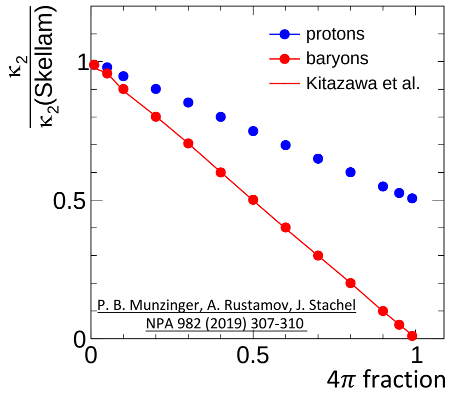
A. Rustamov, M. Arslandok, arXiv:1807.06370, NIM in print

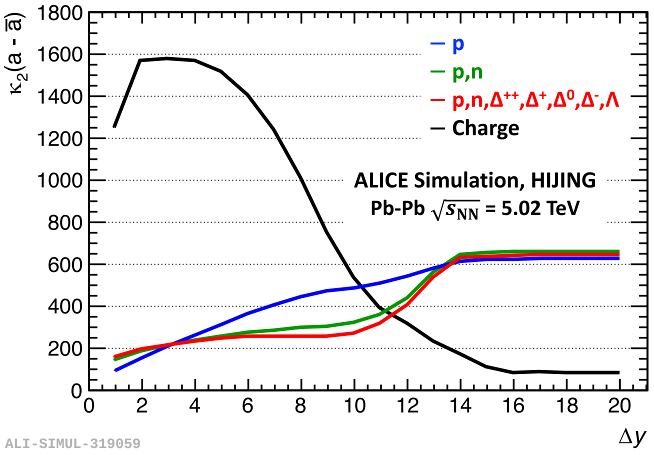


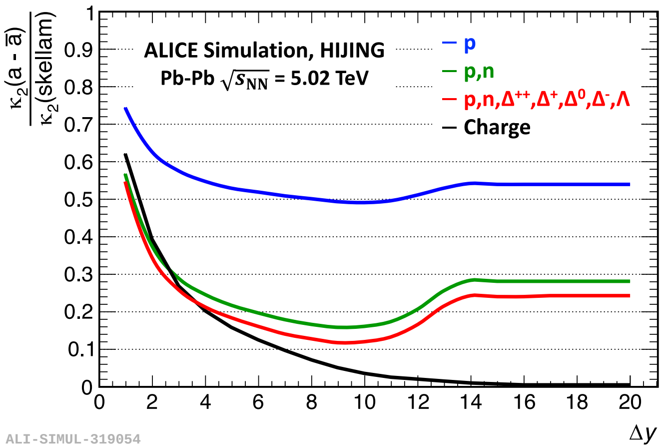
$$\langle N_j^n \rangle = A^{-1} \langle W_j^n \rangle$$

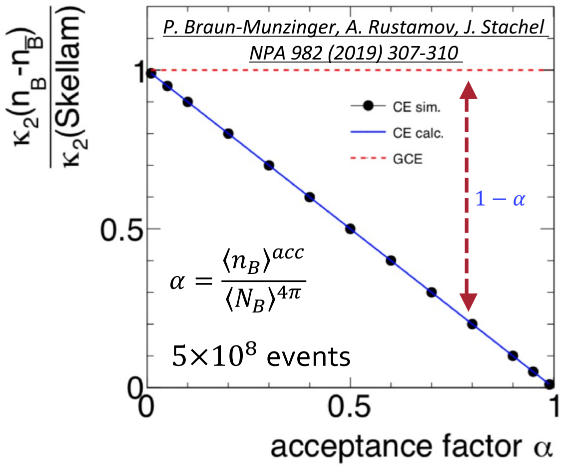
- **Cut-based approach**
  - Uses additional detector information or reject a given phase space bin
  - Challenge: efficiency correction and contamination
- **Identity Method**
  - Gives folded multiplicity distribution
  - Allows for larger efficiencies → smaller correction needed
  - Ideal approach for low momentum (p<2 GeV/c)

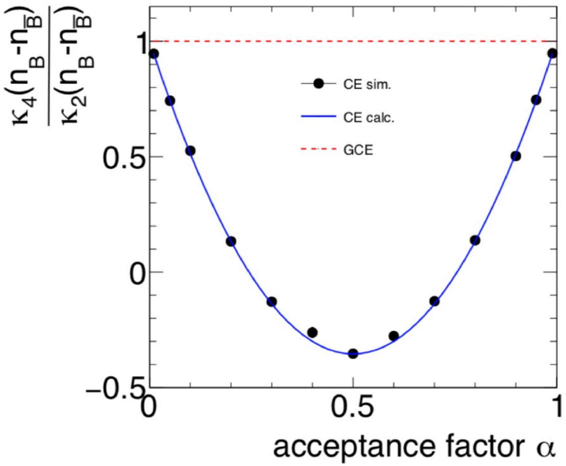

κ_2
$r = \bar{r} = 0.5$; $\langle p \rangle = \langle \bar{p} \rangle = 10$
protons
baryons
Kitazawa et al.
4π fraction


$\frac{\kappa_2}{\kappa_2(\text{Skellam})}$
protons
baryons
Kitazawa et al.
P. B. Munzinger, A. Rustamov, J. Stachel
NPA 982 (2019) 307-310
4π fraction

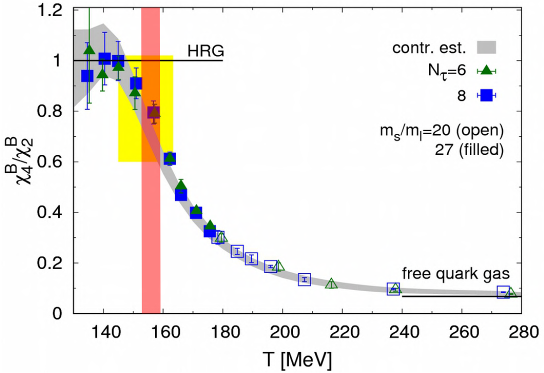

$\kappa_2(a - \bar{a})$
p
p,n
p,n,Δ++,Δ+,Δ0,Δ-,Λ
Charge
ALICE Simulation, HIJING
Pb-Pb $\sqrt{s_{NN}}$ = 5.02 TeV
Δy
ALI-SIMUL-319059


$\frac{\kappa_2(a - \bar{a})}{\kappa_2(\text{skellam})}$
ALICE Simulation, HIJING
Pb-Pb $\sqrt{s_{NN}}$ = 5.02 TeV
p
p,n
p,n,Δ++,Δ+,Δ0,Δ-,Λ
Charge
Δy
ALI-SIMUL-319054



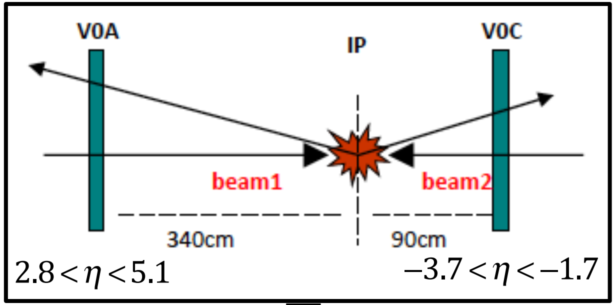


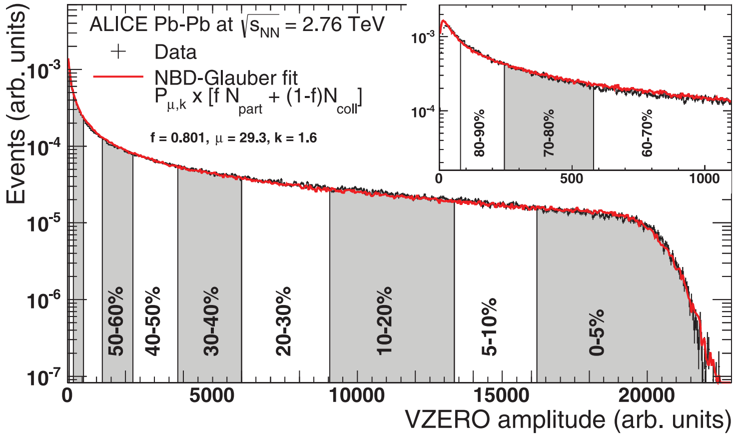
Deviations from unity are driven by different mechanisms

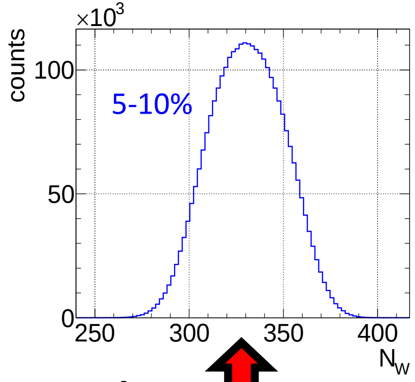


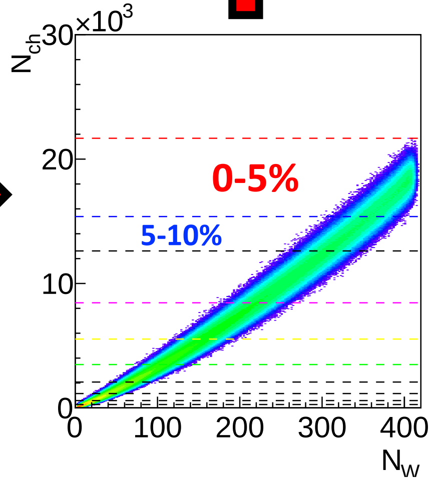
A. Bzdak, V. Koch, V. Skokov, PRC87 (2013) 014901
K. Redlich and L. Turko, Z. Phys. C5 (1980) 201

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

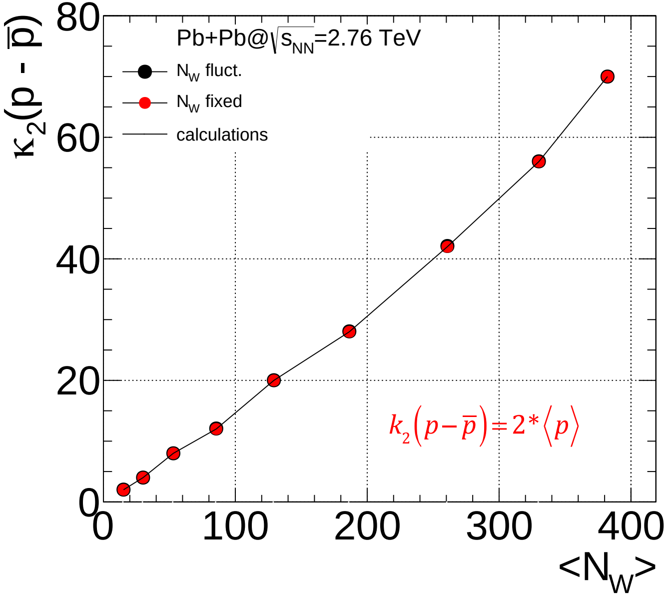




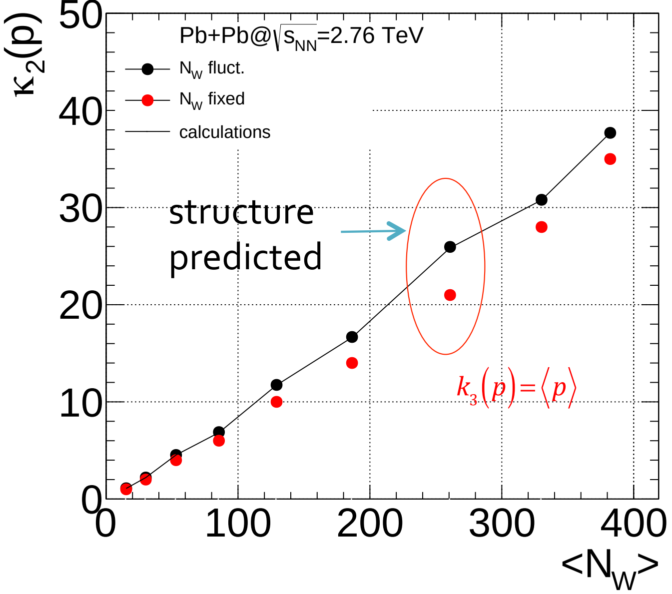




$150*10^6$ Events



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



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

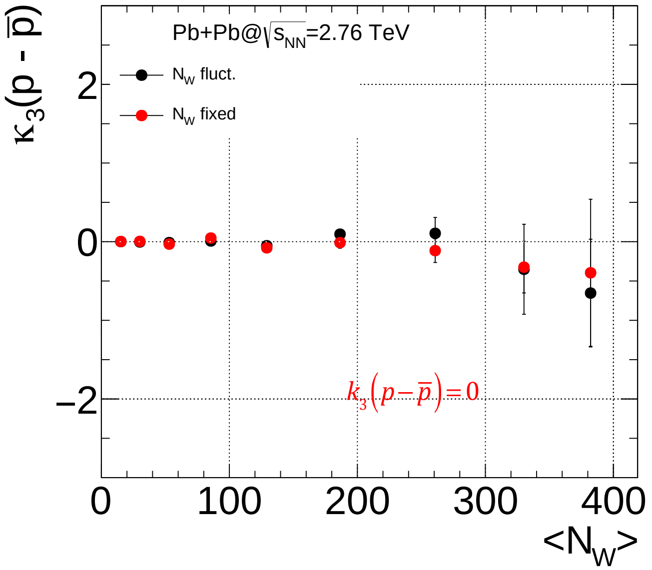
vanishes for ALICE

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

does not vanish

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

150*10^6 Events



P. Braun-Munzinger, A. Rustamov, J. Stachel
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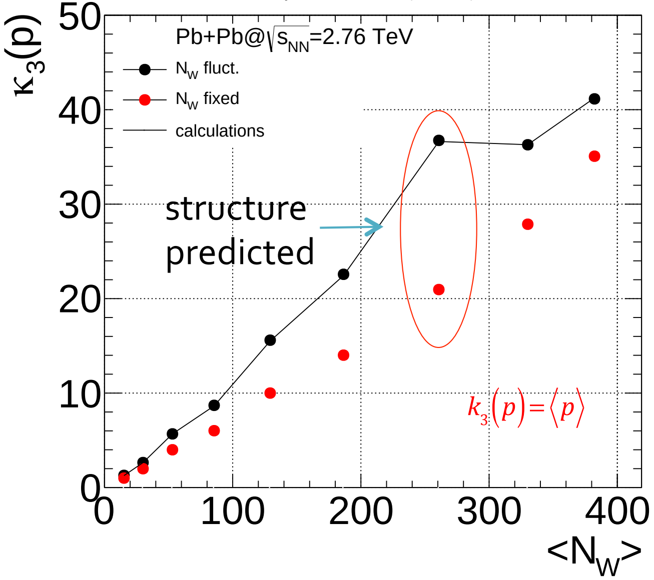


$$k_3(p-\bar{p})=\langle N_w\rangle k_3(n-\bar{n})+\langle n-\bar{n}\rangle(\ldots)$$

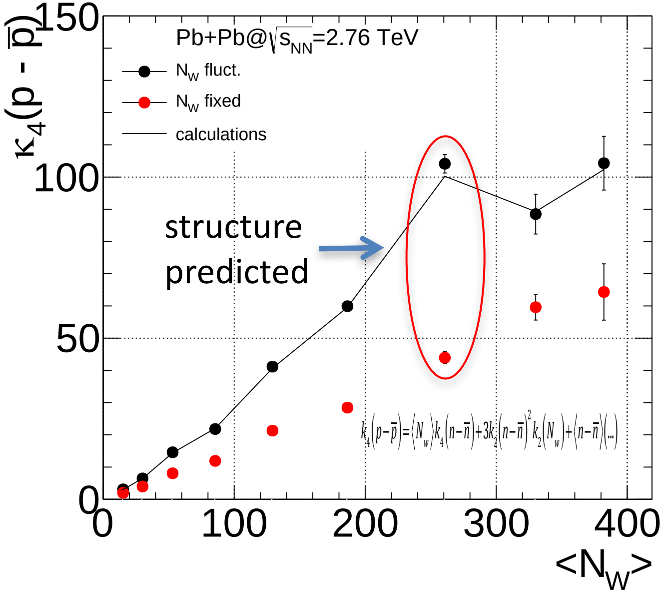
↓ vanishes for ALICE

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

↓ does not vanish

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

150*10^6 Events



P. Braun-Munzinger, A. Rustamov, J. Stachel
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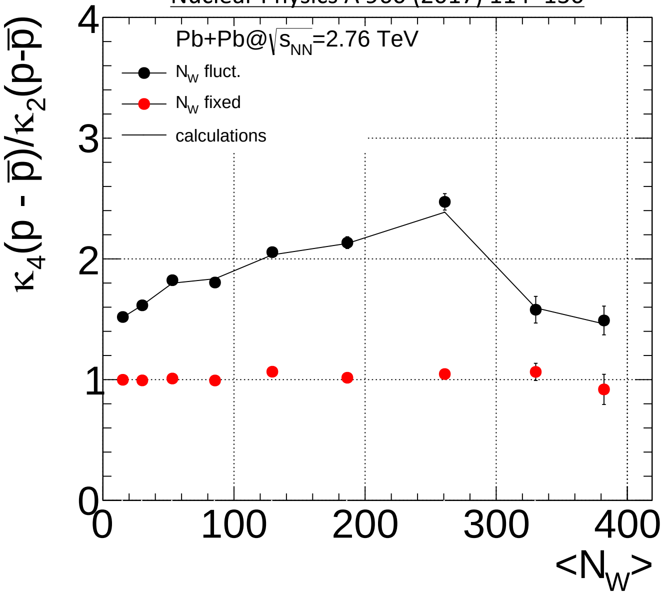
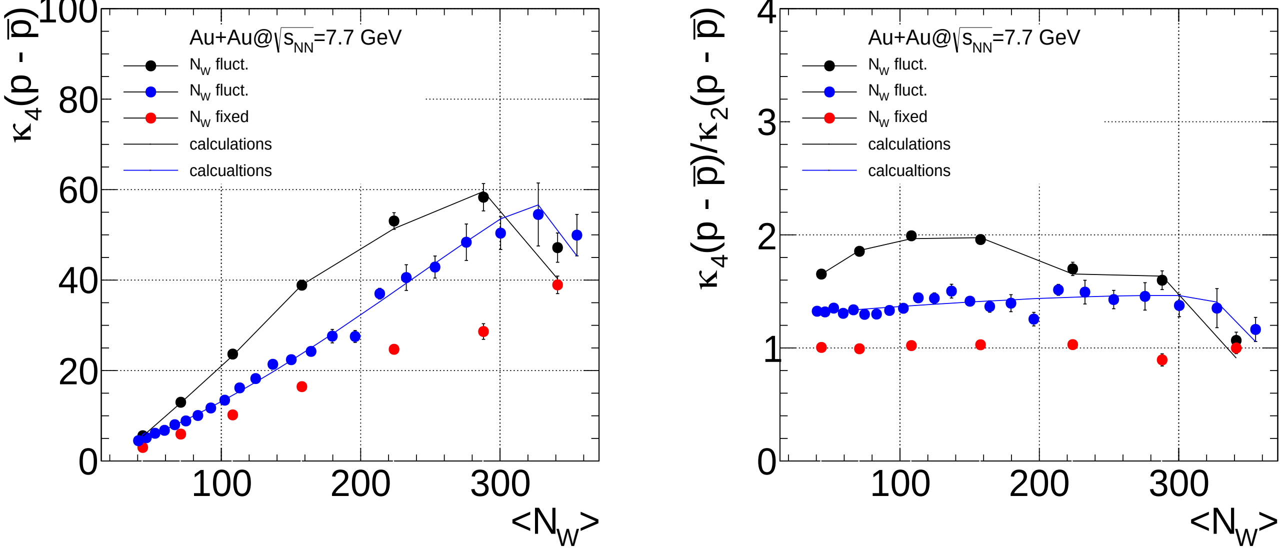


$$k_4(p-\bar{p}) = \langle N_w \rangle k_4(n-\bar{n}) + 3k_2(n-\bar{n})^2 k_2(N_w) + \langle n-\bar{n} \rangle (\ldots)$$

vanishes for ALICE

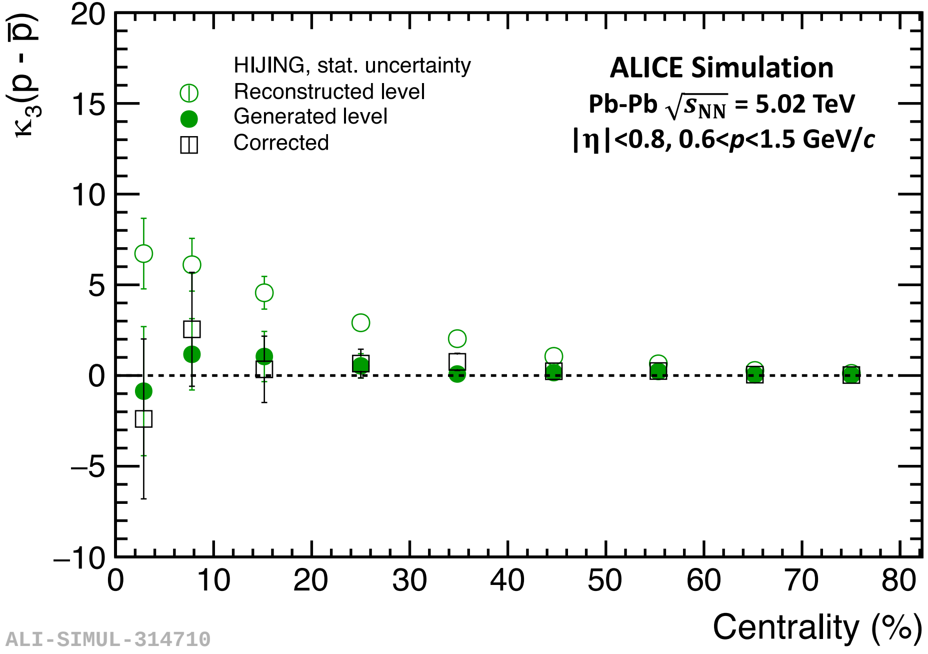
$n, \bar{n}$ → from single wounded nucleon

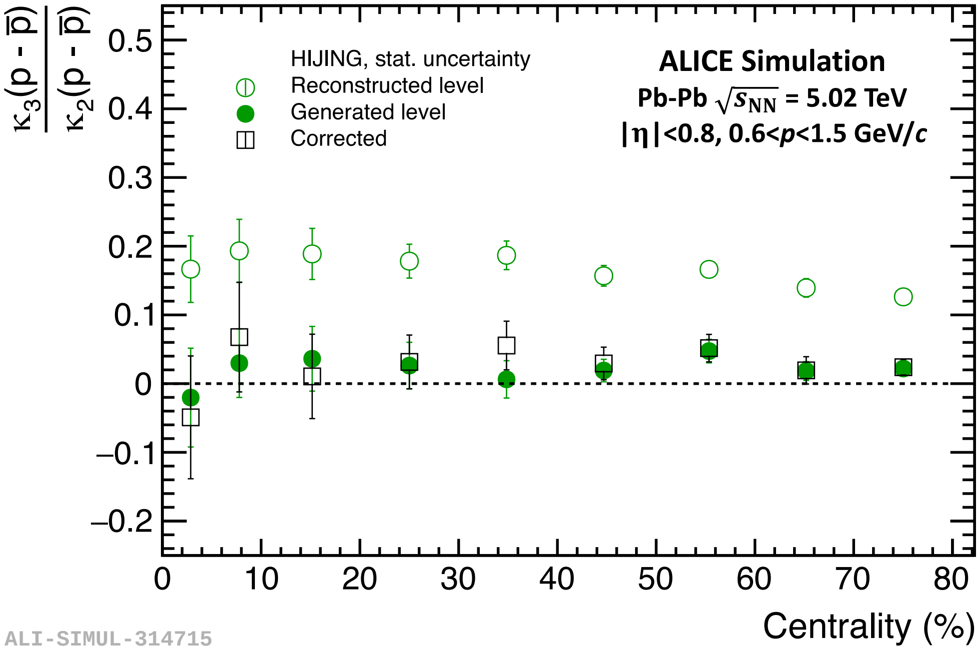
P. Braun-Munzinger, A. Rustamov, J. Stachel, Nuclear Physics A 960 (2017) 114–130



- Subdividing a given centrality bin into smaller ones and then merging them together incoherently.
- Incoherent addition of data from intervals with very small centrality bin width will eliminate true dynamical fluctuations.

Better publish uncorrected results



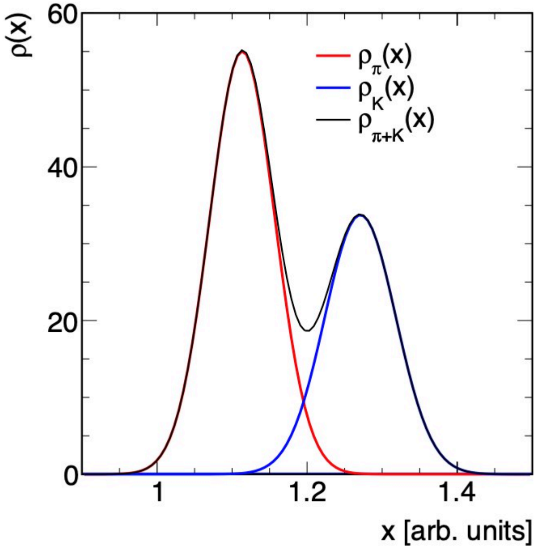


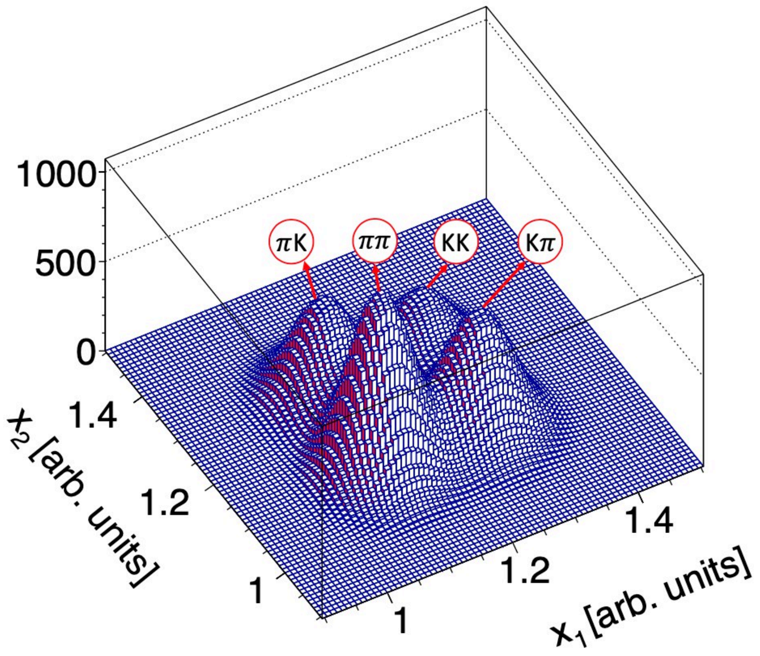
Efficiency correction with binomial assumption:

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

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

Particle-Set Identification method





$\rho(x_1, x_2)$

Particle-Set Identification method

Probability density function of the bi-variate normal distribution

$$f(x_1, x_2) = \frac{1}{2\pi\sqrt{|\Sigma|}} e^{-0.5(\mathbf{x}-\langle\mathbf{x}\rangle)^T\Sigma^{-1}(\mathbf{x}-\langle\mathbf{x}\rangle)}$$

$$\mathbf{x} = \begin{pmatrix} x_1 \\ x_2 \end{pmatrix}, \langle\mathbf{x}\rangle = \begin{pmatrix} \langle x_1\rangle \\ \langle x_2\rangle \end{pmatrix}, \Sigma = \begin{pmatrix} \sigma_{x_1}^2 & R\sigma_{x_1}\sigma_{x_2} \\ R\sigma_{x_1}\sigma_{x_2} & \sigma_{x_2}^2 \end{pmatrix}$$

$$R = \frac{\langle(x_1 - \langle x_1\rangle)(x_2 - \langle x_2\rangle)\rangle}{\sigma_{x_1}\sigma_{x_2}}$$

Correlations between x_1 and x_2 are introduced only if they belong to the same particle, otherwise they are generated independently, i.e., R is set to 0 in this case

Particle-Set Identification method

$$\rho(x_1,x_2) \equiv \rho_{\pi\pi}(x_1,x_2) + \rho_{KK}(x_1,x_2) + \rho_{\pi K}(x_1,x_2) + \rho_{K\pi}(x_1,x_2)$$
$$\equiv \langle N_{\pi\pi}\rangle \cdot f_{\pi\pi}(x_1,x_2) + \langle N_{KK}\rangle \cdot f_{KK}(x_1,x_2) + \langle N_{\pi K}\rangle \cdot f_{\pi K}(x_1,x_2) + \langle N_{K\pi}\rangle \cdot f_{K\pi}(x_1,x_2)$$
$$\equiv \langle N^{(2)}\rangle \left(r_{\pi\pi} \cdot f_{\pi\pi}(x_1,x_2) + r_{KK} \cdot f_{KK}(x_1,x_2) + r_{\pi K} \cdot f_{\pi K}(x_1,x_2) + r_{\pi K} \cdot f_{K\pi}(x_1,x_2)\right),$$

$$F(x_1,x_2|r_{\pi\pi},r_{KK}) = r_{\pi\pi} \cdot f_{\pi\pi}(x_1,x_2) + r_{KK} \cdot f_{KK}(x_1,x_2) + r_{\pi K} \cdot f_{\pi K}(x_1,x_2) + r_{\pi K} \cdot f_{K\pi}(x_1,x_2)$$

$$l(\mathcal{X}^{(2)} \mid r_{\pi\pi}, r_{KK}) = -\sum_{j=1}^{\mathcal{N}^{(2)}} \ln\left(F\left((x_1,x_2)_j \mid r_{\pi\pi}, r_{KK}\right)\right)$$

$$r_{\pi\pi} + r_{KK} + 2 \cdot r_{\pi K} = 1$$

Maximum Likelihood minimization

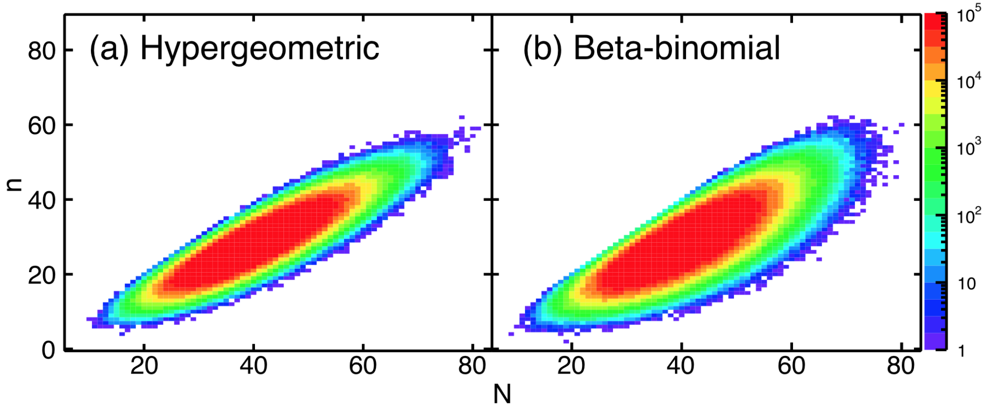
$$\langle N_{\pi\pi}\rangle = \frac{1}{2}\langle N_\pi (N_\pi - 1)\rangle = \frac{\langle N_\pi^2\rangle - \langle N_\pi\rangle}{2}$$

Calculated from 1D dE/dx distribution

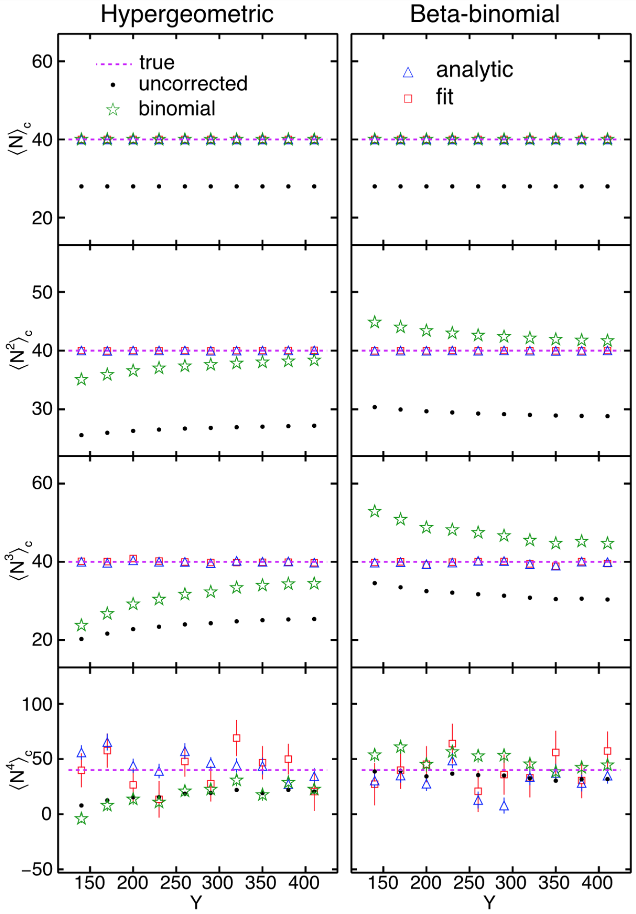
Calculated from 2D dE/dx distribution

Efficiency correction

What if efficiency loss is not binomial?



Draw N balls from the urn without returning balls to the urn	In each draw, when one draws a white ball, two white balls are returned to the urn



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