Recent experimental results on 2^{nd} order conserved charge fluctuations

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Yale University

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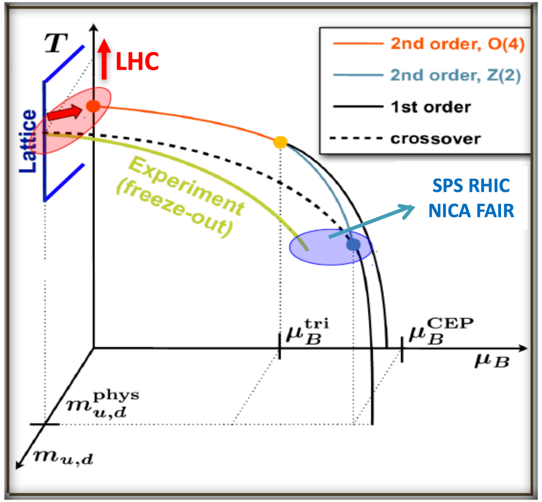
In part supported by

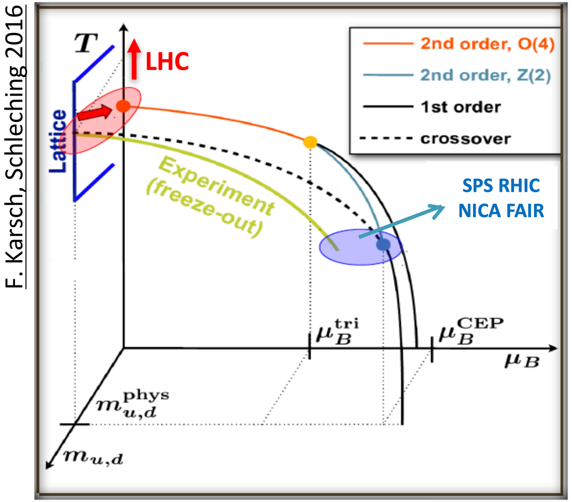
Nature of QCD phase diagram

F. Karsch, Schleching 2016



- **Pseudocritical features** at the crossover due to massless modes
- Long range correlations & **increased fluctuations**
- **Non-monotonic energy dependence**
- …

Nature of QCD phase diagram



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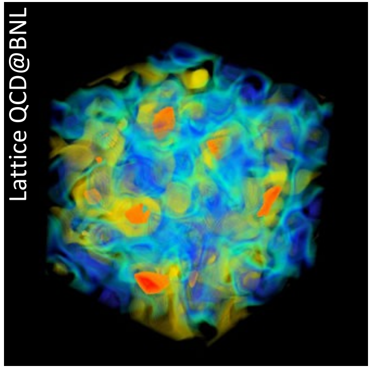
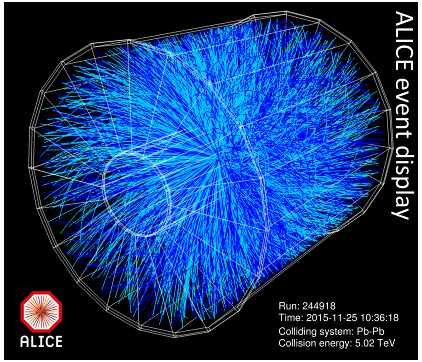
Bridge experimental data to LQCD calculations

Theory



Experiment



Static	Dynamic
Coordinate space	Momentum space
Net-baryon	Net-proton
Fixed V	Fluctuating V
…	…

LQCD $\leftrightarrow$ Experiment

Google Translate

Detect language | English | German | Spanish | **LQCD**

EXPERIMENT | Spanish

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

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

0 / 5,000

Translation

$$\chi_2^B = \frac{\kappa_2(\Delta N_B)}{VT^3} \Rightarrow \frac{\kappa_4(\Delta N_B)}{\kappa_2(\Delta N_B)} = \frac{\chi_4^B}{\chi_2^B}$$

$\kappa_n \rightarrow$ cumulants of $\Delta N_B = N_B - N_{\bar{B}}$

LQCD ↔ Experiment

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0 / 5,000

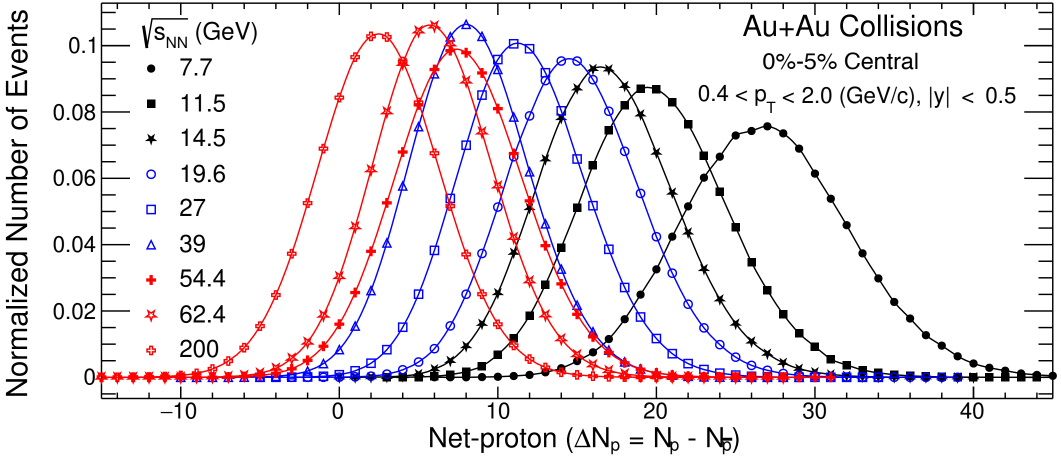
EXPERIMENT Spanish

Translation

$$\chi^B_2 = \frac{\kappa_2(\Delta N_B)}{VT^3} \Rightarrow \frac{\kappa_4(\Delta N_B)}{\kappa_2(\Delta N_B)} = \frac{\chi^B_4}{\chi^B_2}$$

$\kappa_n \rightarrow$ cumulants of $\Delta N_B = N_B - N_{\bar{B}}$

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



LQCD ↔ Experiment

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EXPERIMENT | Spanish

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

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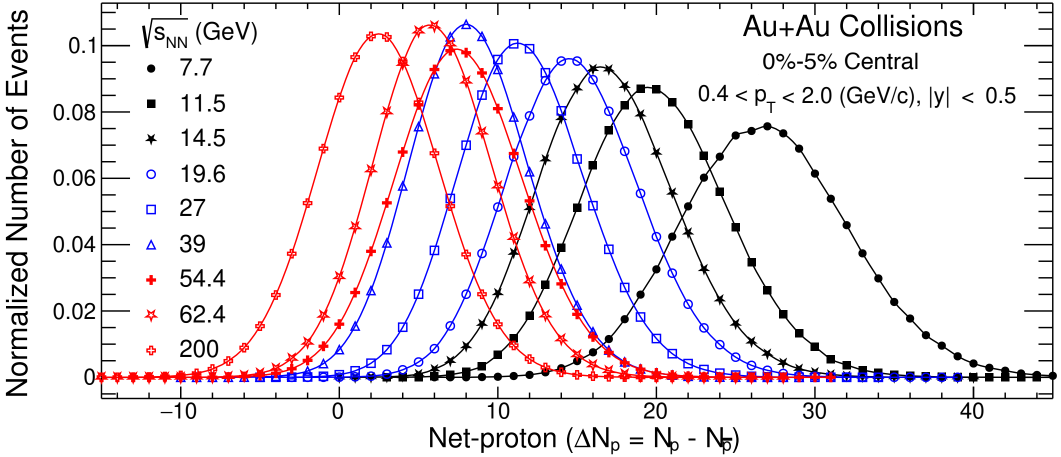

- The devil is in the tails!
- What can we learn from κ_2?

Outline

- **Experimental challenges:** Particle identification, efficiency correction, effect of event pileup, volume fluctuations …
- **Theoretical/phenomenological challenges:** Effect of resonances, charge conservation, effect of magnetic field, cluster formation, baryon annihilation, excluded volume …

Outline

- **Experimental challenges:** Particle identification, efficiency correction, effect of event pileup, volume fluctuations …
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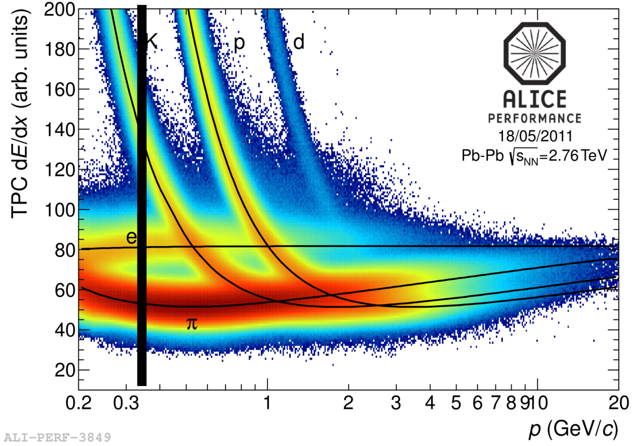
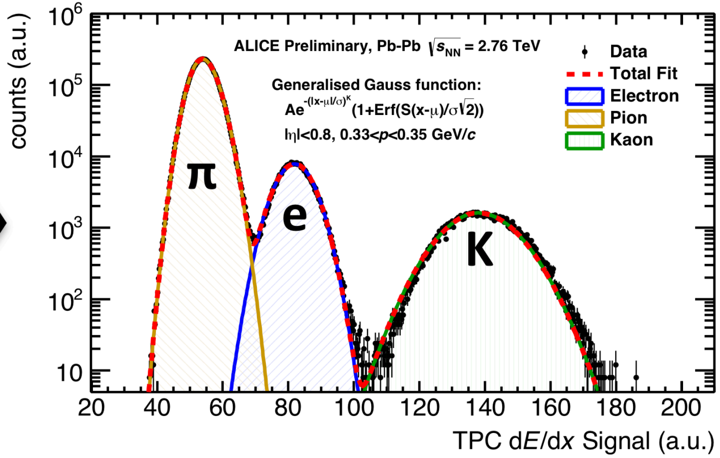
- How do we measure cumulants of conserved charges?
- How do we interpret the results?
- What have we learned so far from 2nd order cumulants?
  - Net-$[\pi, K, p, \Lambda, \Xi]$ and cross-cumulants and correlations
- What to expect from future?

How do we measure cumulants?

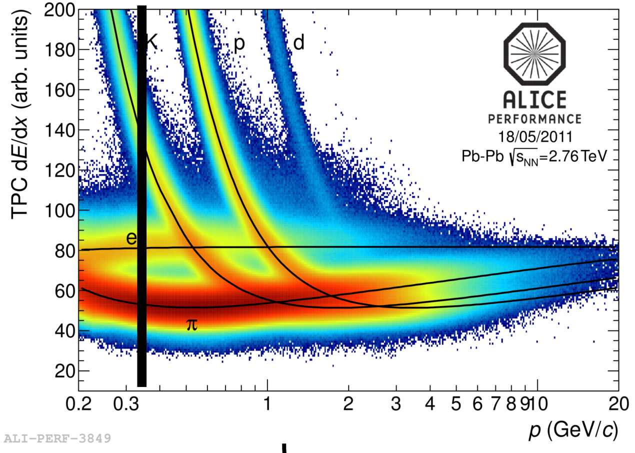
Main challenge: Particle identification (PID)

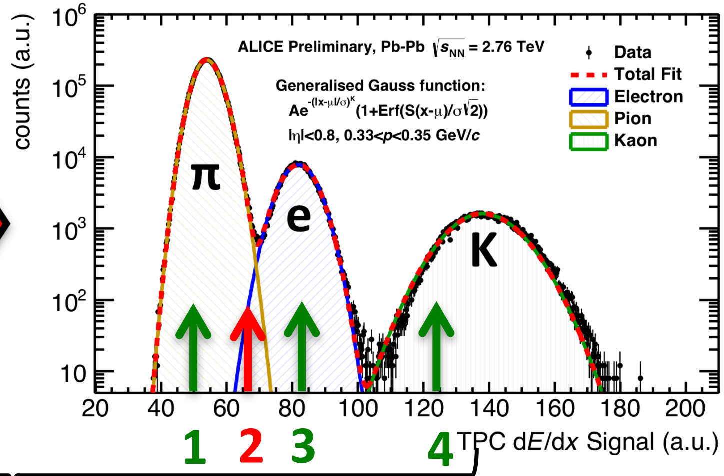
Cut-based approach (track counting) and **Identity method** (probability counting)





Cut-based approach (track counting) and **Identity method** (probability counting)



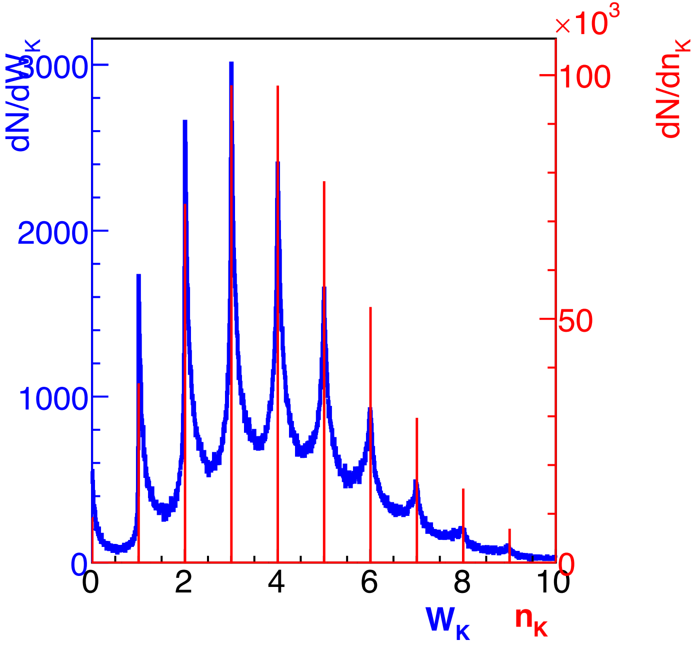


$$\omega_\pi^{(1)} = 1, \quad \omega_\pi^{(2)} \cong 0.6, \quad \omega_\pi^{(3)} = 0, \quad \omega_\pi^{(4)} = 0 \quad \Rightarrow \quad W_\pi = 1.6 \neq N_\pi$$

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

A. Rustamov, M. Arslandok, Nucl. Instrum. A946 (2019) 162622}

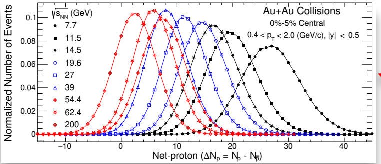
Identity method vs cut-based approach



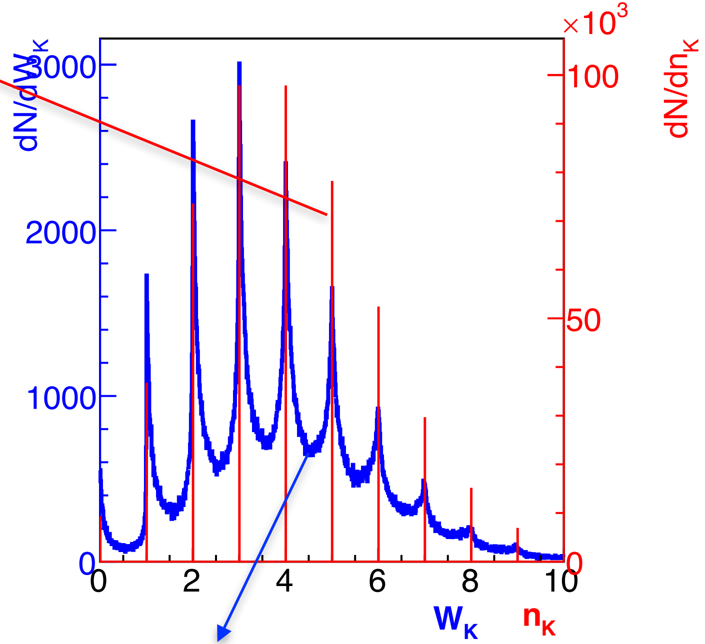
$$\langle N_j^n \rangle = A^{-1} \langle W_j^n \rangle$$

Identity method vs cut-based approach

Cut-based



Cost off efficiency!



Identity method

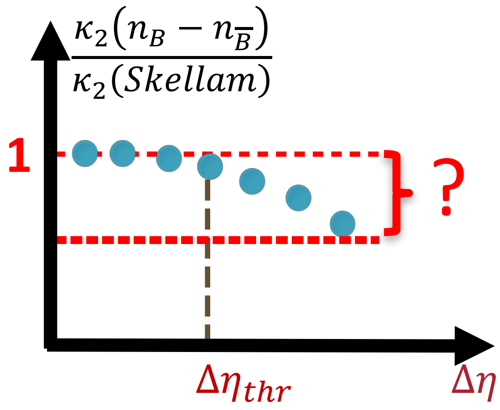
$$\langle N_j^n \rangle$$

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

How do we interpret?

To keep in mind!

Source of the deviation?



- Baryon number conservation
- Volume fluctuations
- Resonance decays
- Initial-state fluctuations
- …

To keep in mind!

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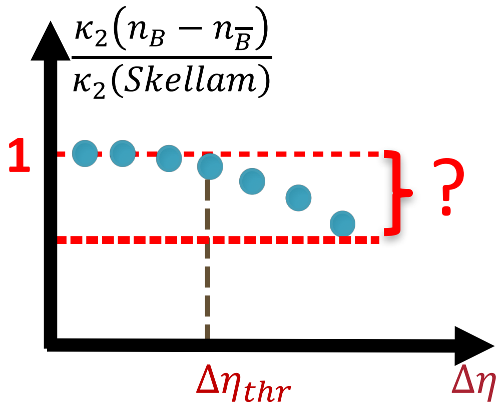

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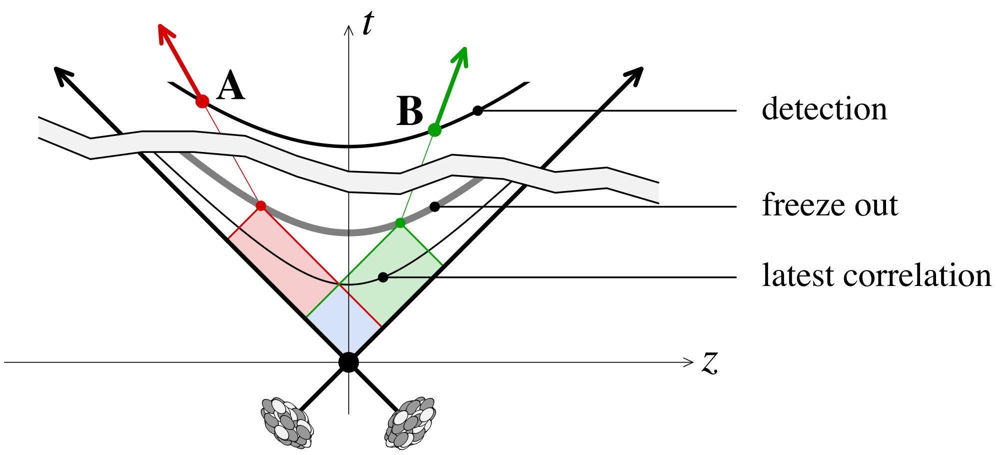
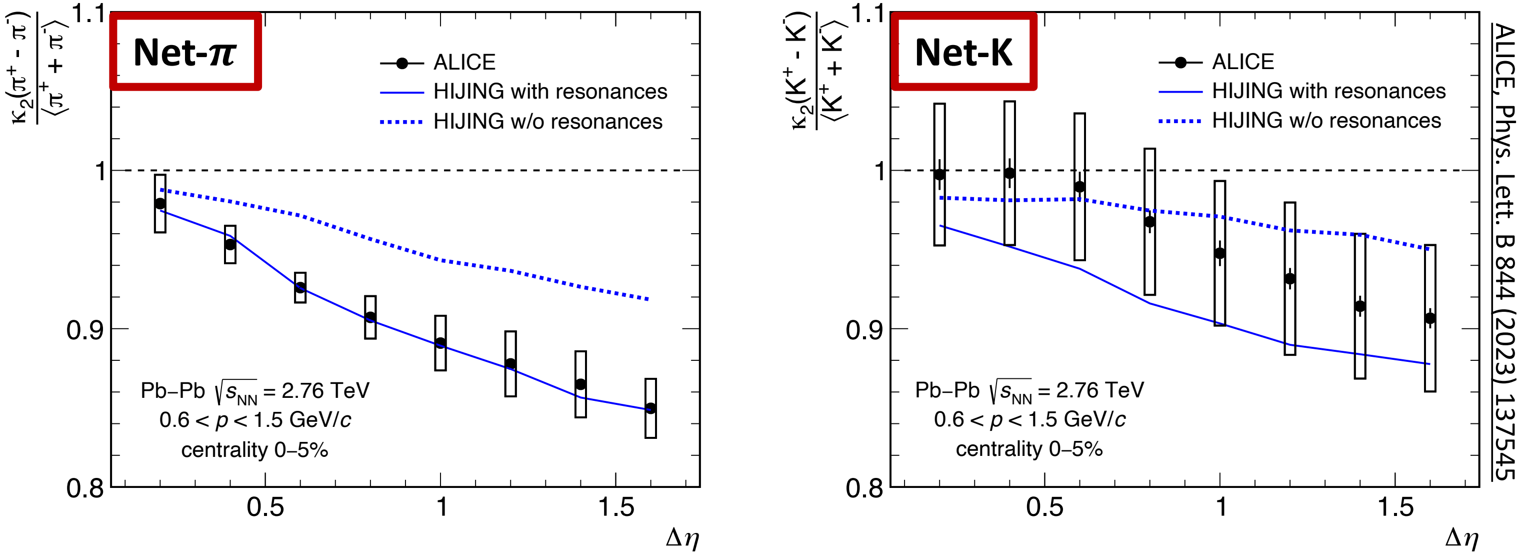
Only **early correlations** can be long range in rapidity



$$\tau \leq \tau_{\text{freeze out}}\, e^{-\frac{1}{2}|y_A - y_B|}$$

A. Dumitru, F. Gelis, L. McLerran, and R. Venugopalan, *Nucl. Phys. A* 810 (2008) 91

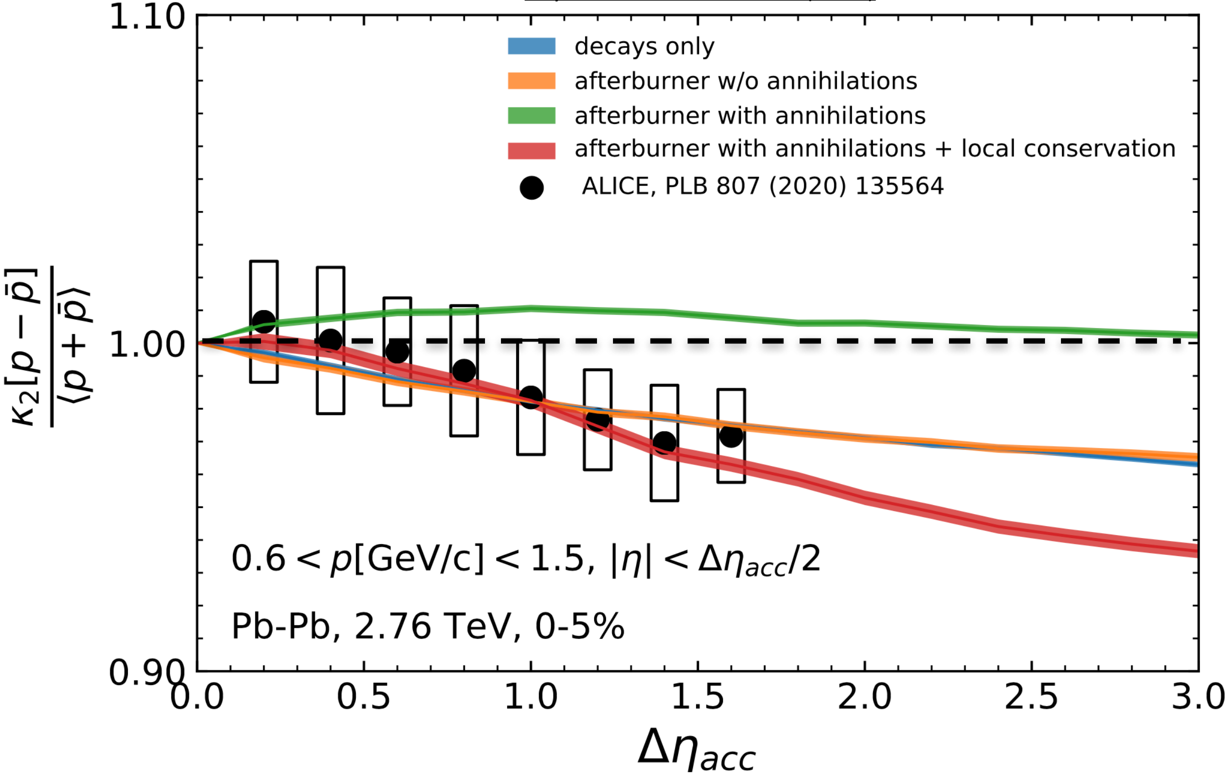
Resonance decays



- **Net-π and net-K are** strongly dominated by resonance contributions
- **Net-[p, Λ, Ξ]** are free from resonance contributions

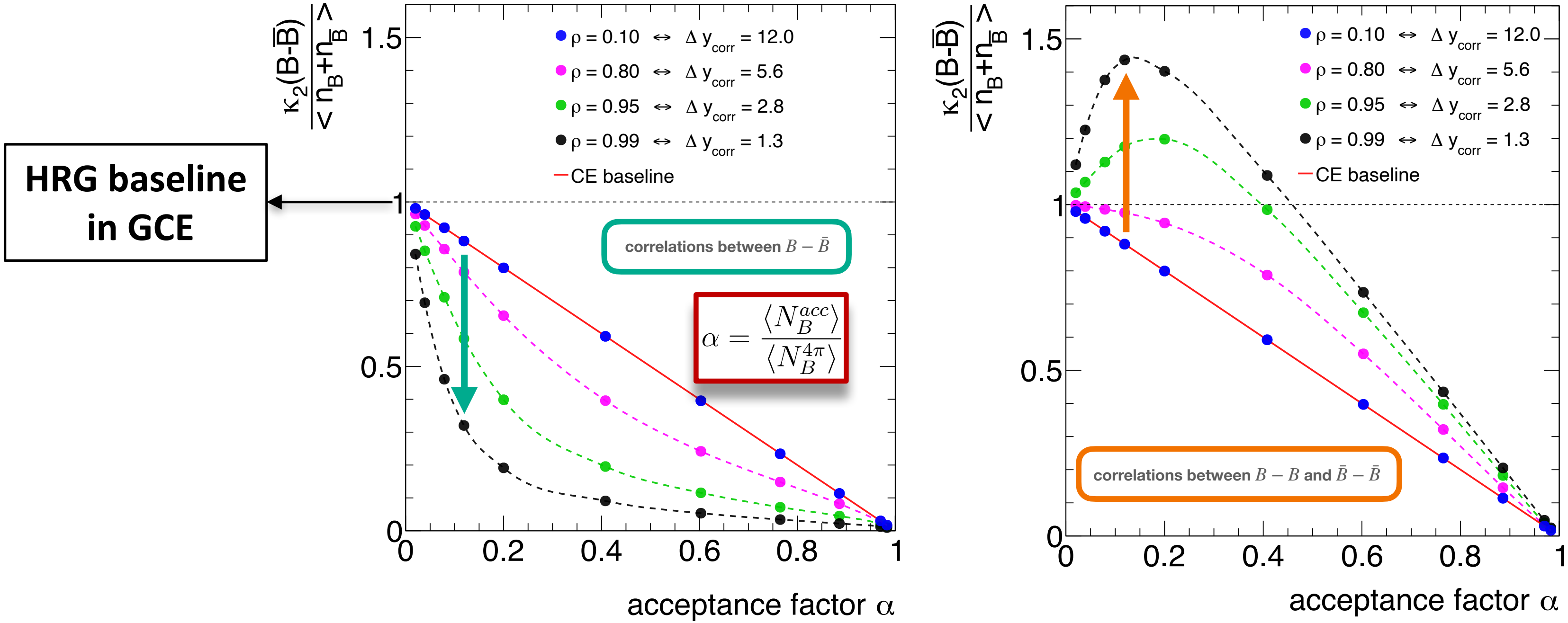
Baryon annihilation

O. Savchuk, V. Vovchenko, V. Koch, J. Steinheimer, H. Stoecker
Phys. Lett. B 827, 136983 (2022)



Baryon number conservation vs "cluster" formation

P. Braun-Munzinger, K. Redlich, A. Rustamov, J. Stachel, arXiv:2312.15534v1



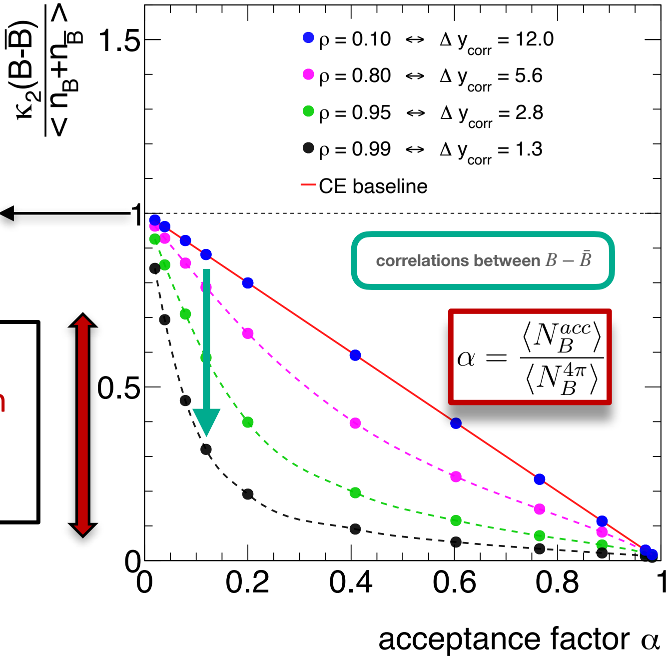
- Measured values depend on the fraction of (anti-)protons in the acceptance
- (Global) local baryon number conservation: **unlike-sign correlations**
- (Anti-)proton clusters: **like-sign correlations**

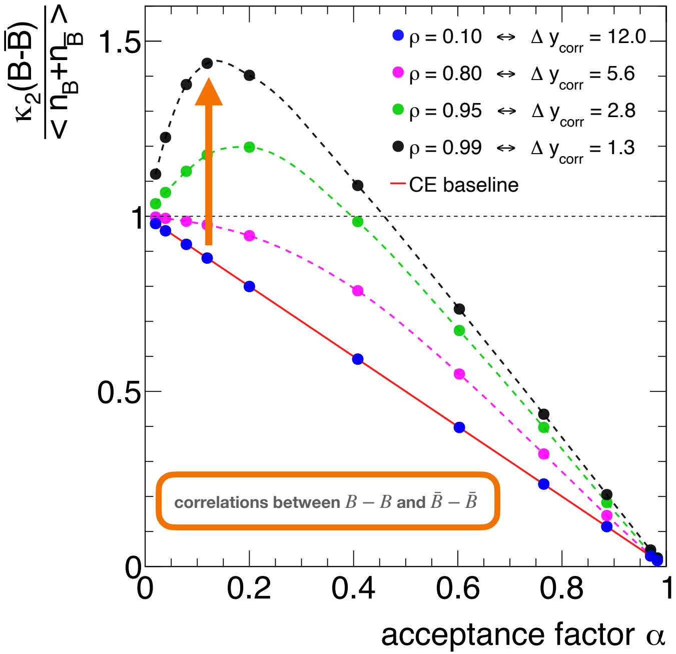
Baryon number conservation vs "cluster" formation

P. Braun-Munzinger, K. Redlich, A. Rustamov, J. Stachel, arXiv:2312.15534v1

HRG baseline in GCE

Larger deviation:
→ Smaller correlation length
→ Late production





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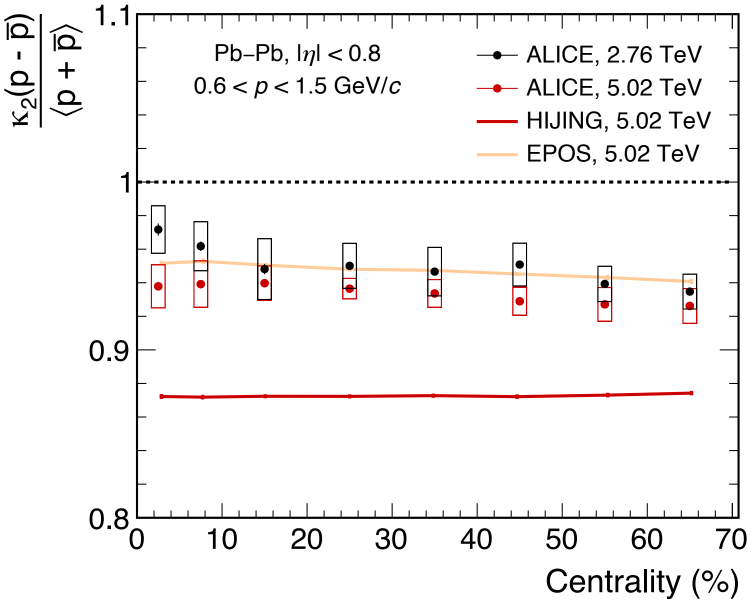
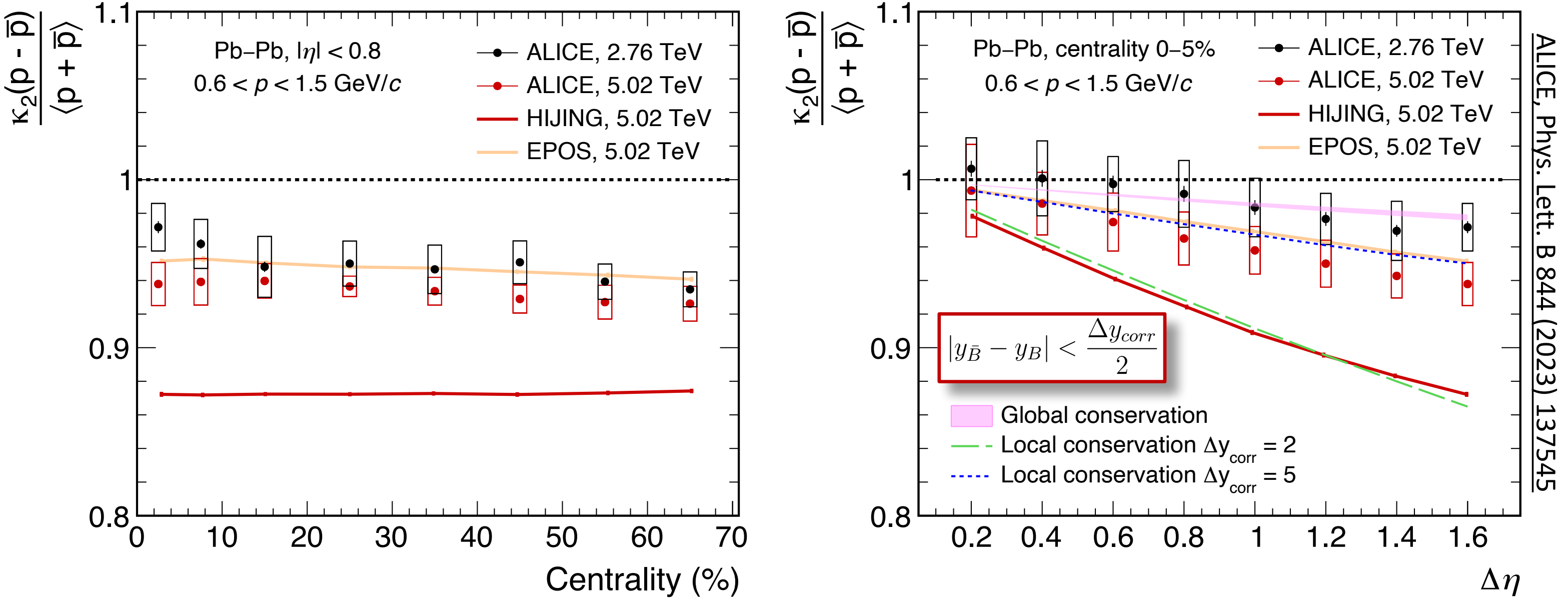
What did we learn?

2^{nd} order cumulants of net-p



- Deviation from Skellam baseline is due to **baryon number conservation**

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 → earlier in time**
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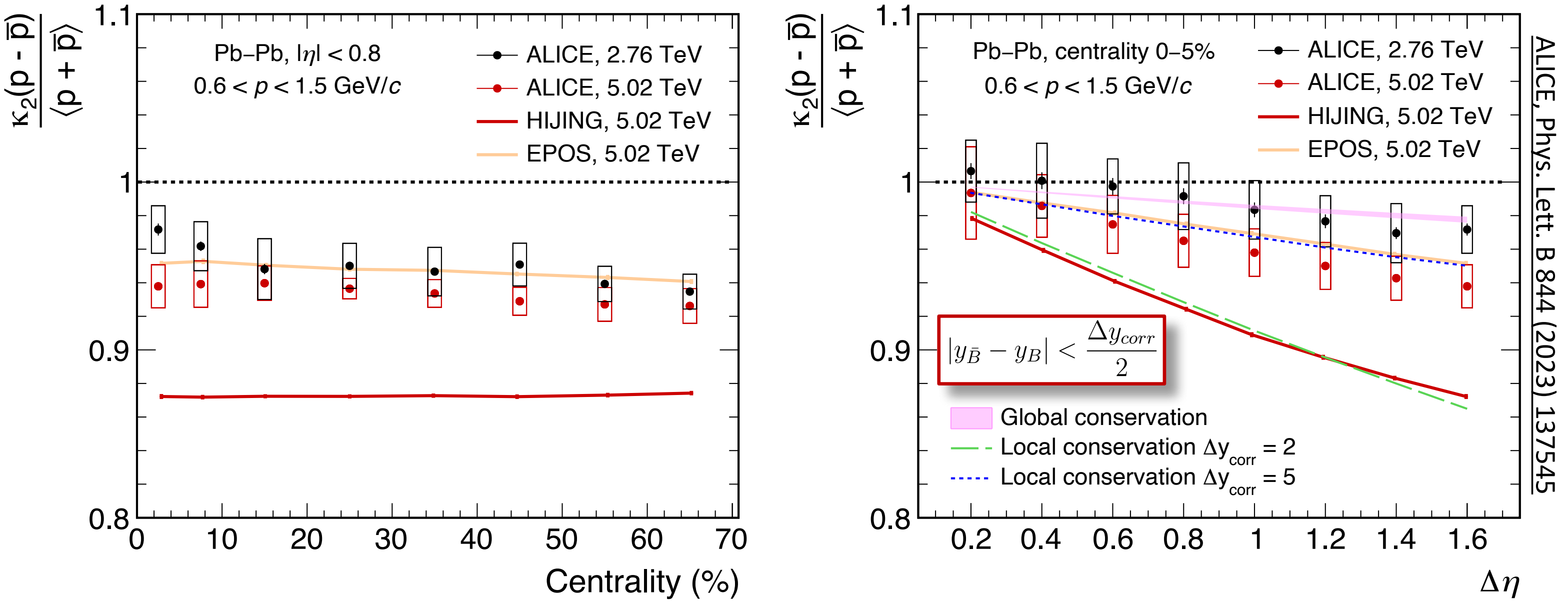
- Event generators based on **string fragmentation (HIJING)** conserve baryon number over **$\Delta y = \pm 1$ unit**

2^{nd} order cumulants of net-p



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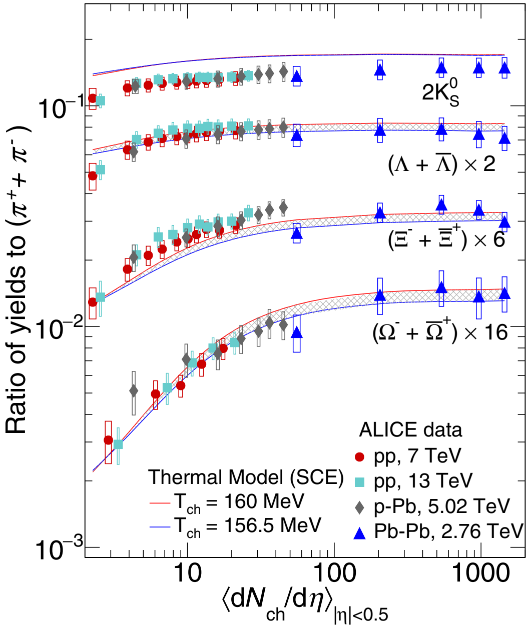
How about strangeness?

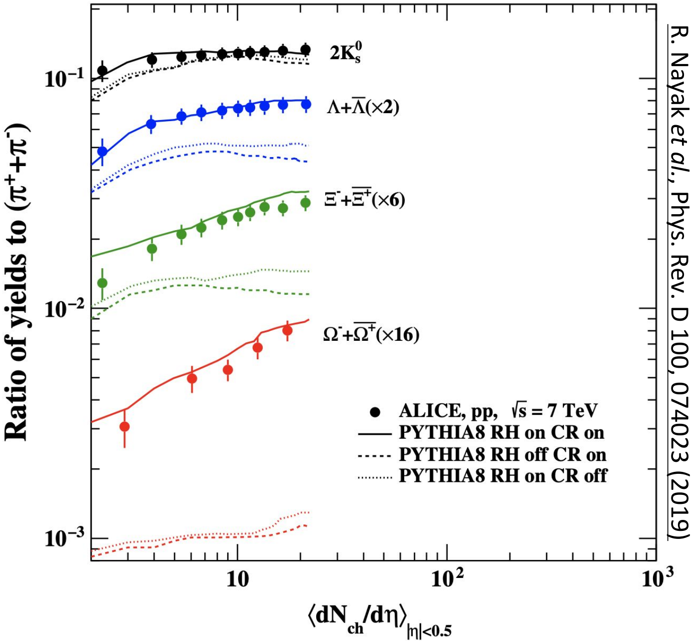
Reminder: Strangeness enhancement/suppression

Canonical statistical model



J. Cleymans, P. M. Lo, K. Redlich, N. Sharma
Phys. Rev. C 103, 014904 (2021)

Lund string fragmentation (PYTHIA)

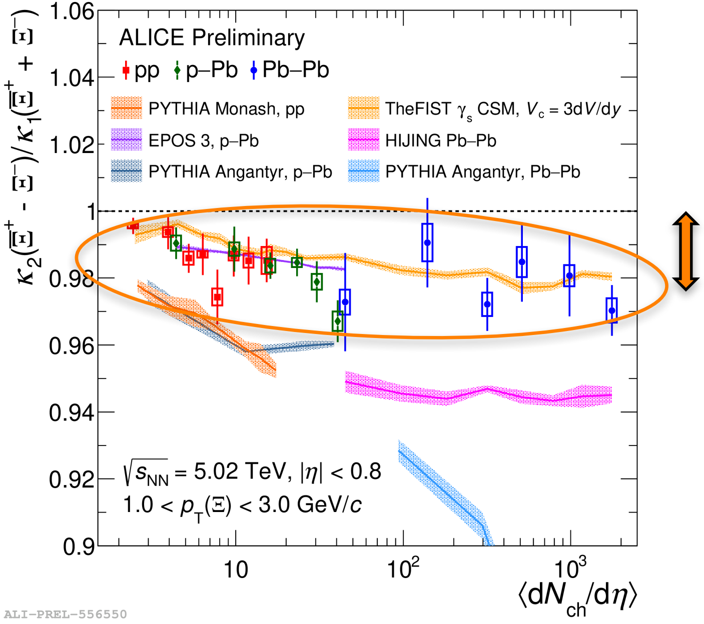


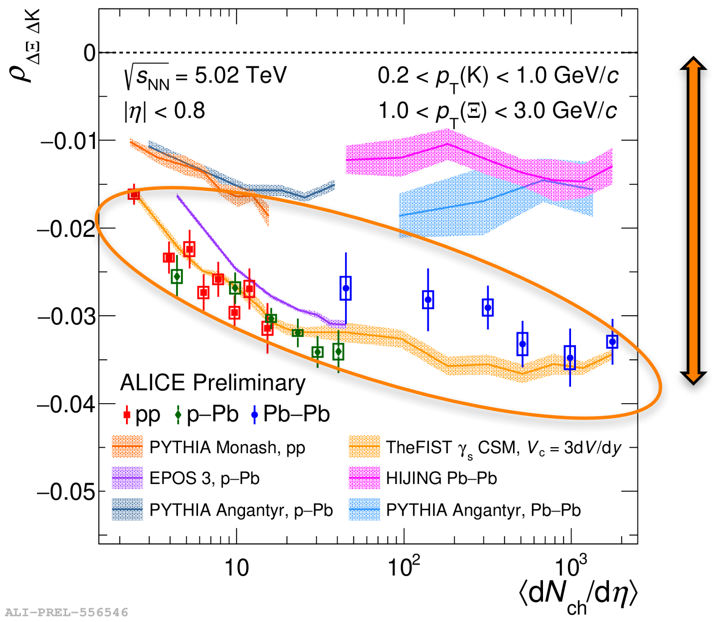
R. Nayak *et al.*, Phys. Rev. D 100, 074023 (2019)

First order moments:

Thermal model with $\mu_B \approx 0$ and $T \approx 150 - 160$ MeV and
PYHTIA with “RH on and CR” on does well at lower multiplicities

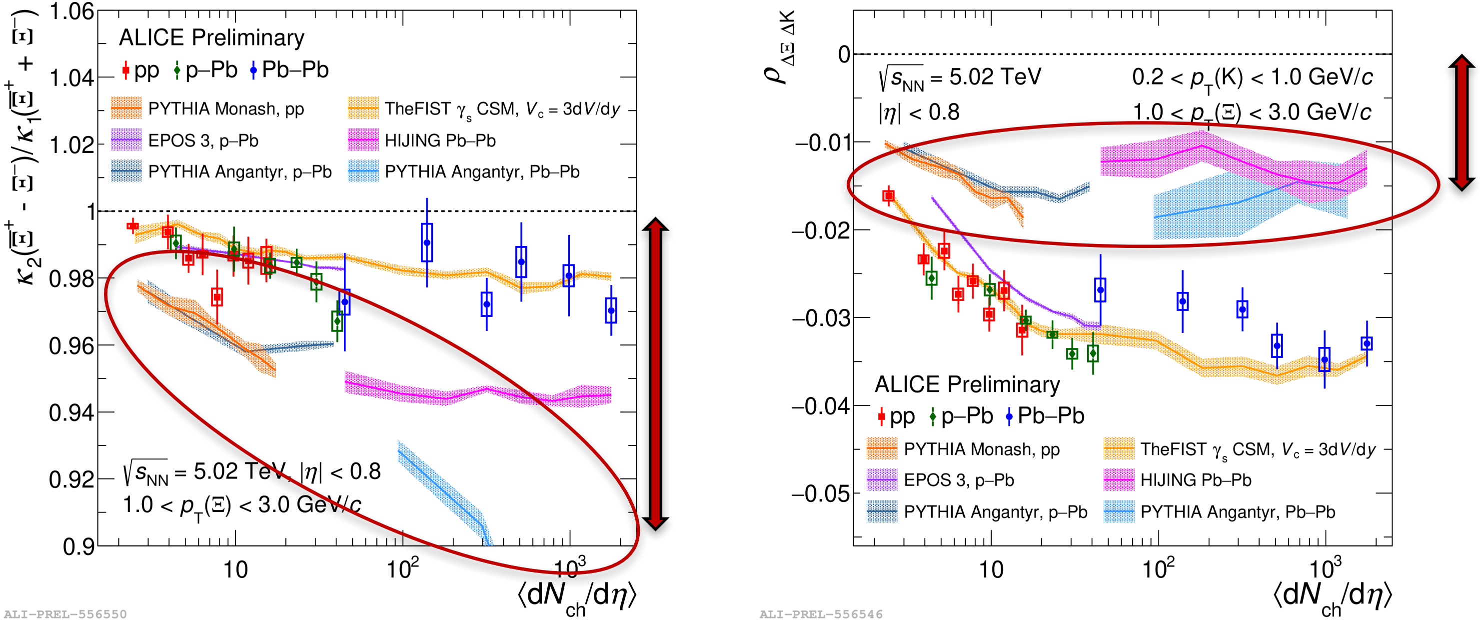
2^{nd} order cumulants of Net-Ξ & Net- Ξ — net-K correlations





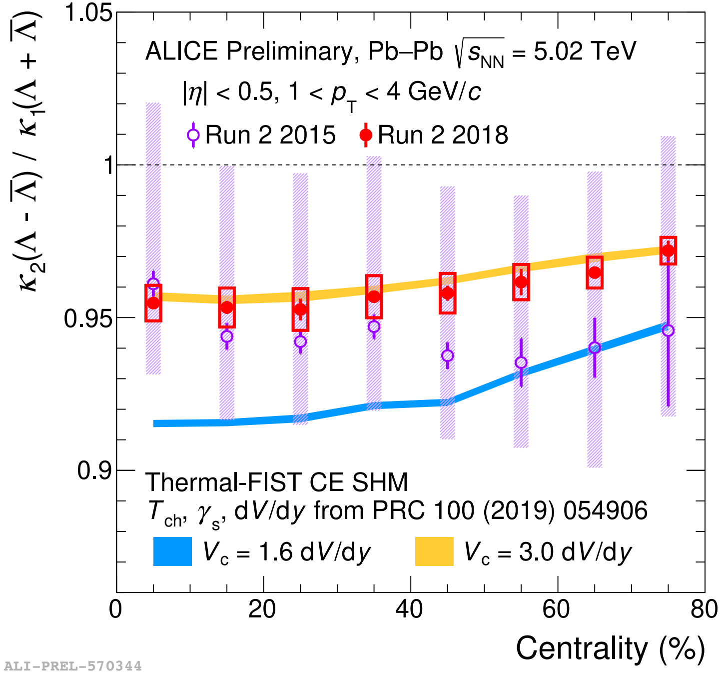
- Canonical picture describes the data with **correlation volume of about 3d*V*/d*y***
  → Indication of large volume (early production) for strangeness (as in case of baryon number)

2^{nd} order cumulants of Net-Ξ & Net- Ξ — net-K correlations



- Canonical picture describes the data with <u>correlation volume of about 3d*V*/dy</u>
  → Indication of large volume (early production) for strangeness (as in case of baryon number)
- Event generators based on <u>**string fragmentation fails for the second order**</u>

2^{nd} order cumulants of Net-Λ



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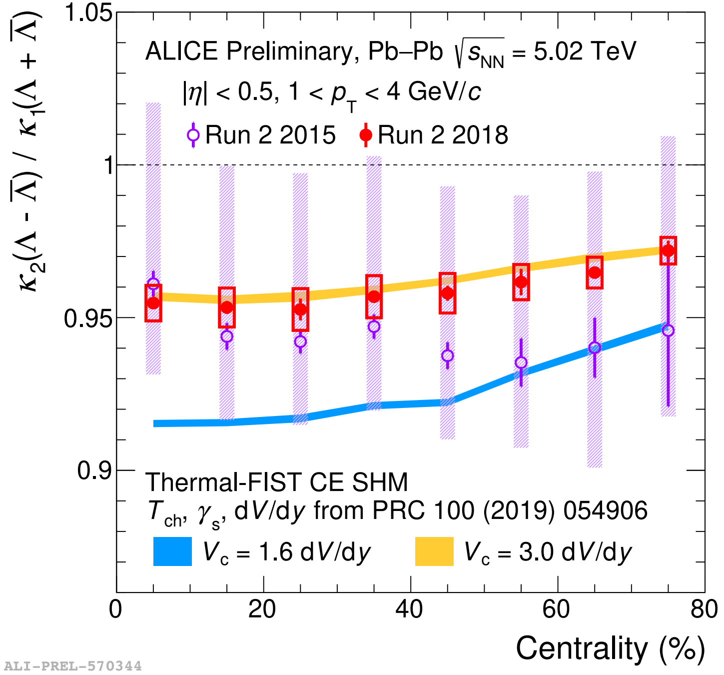
2^{nd} order cumulants of Net-Λ



➢ Canonical picture describes the data with **correlation volume of about 3dV/dy**

How about off-diagonal cumulants?

$$\chi^{lmn}_{\mathrm{B,S,Q}} = \frac{1}{VT^3}\sigma^{lmn}_{\mathrm{B,S,Q}}$$

$$\sigma^{11}_{BS} = \langle BS\rangle - \langle B\rangle\langle S\rangle$$
$$\sigma^{11}_{QS} = \langle QS\rangle - \langle Q\rangle\langle S\rangle$$
$$\sigma^{11}_{QB} = \langle QB\rangle - \langle Q\rangle\langle B\rangle$$

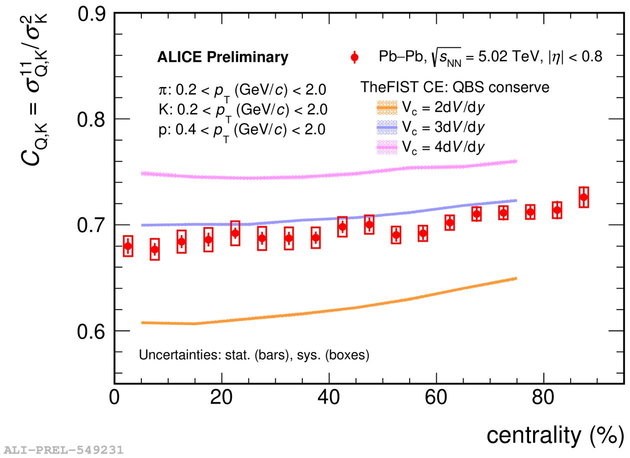
$$\sigma^2_S = \langle S^2\rangle - \langle S\rangle^2$$
$$\sigma^2_B = \langle B^2\rangle - \langle B\rangle^2$$
$$\sigma^2_Q = \langle Q^2\rangle - \langle Q\rangle^2$$

$$\mathrm{C}_{BS} = \sigma^{11}_{BS}/\sigma^2_S$$
$$\mathrm{C}_{QS} = \sigma^{11}_{QS}/\sigma^2_S$$
$$\mathrm{C}_{QB} = \sigma^{11}_{QB}/\sigma^2_B$$

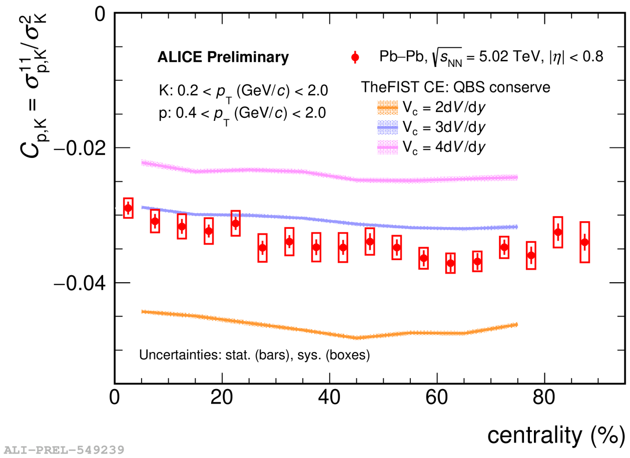
Proxies: Charge: K, π, p | Baryon: p | Strangeness: K

Cross cumulants in view of correlation volume

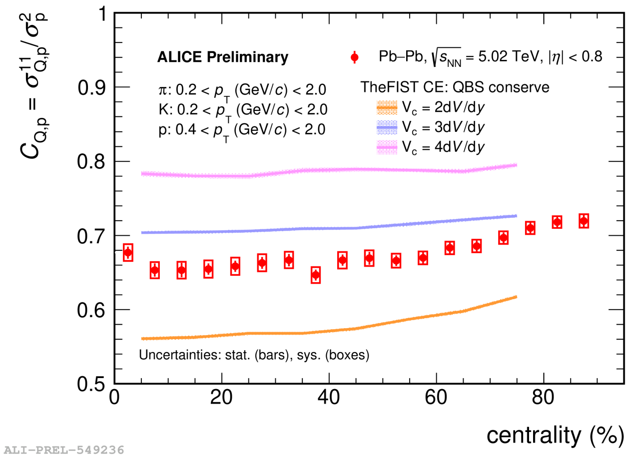
Q – K



p – K



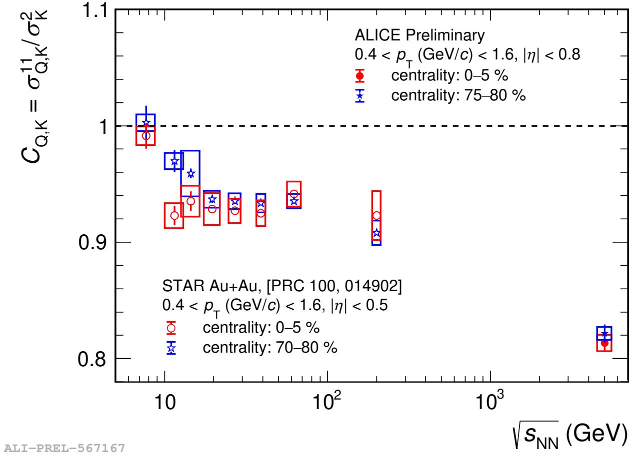
Q – p



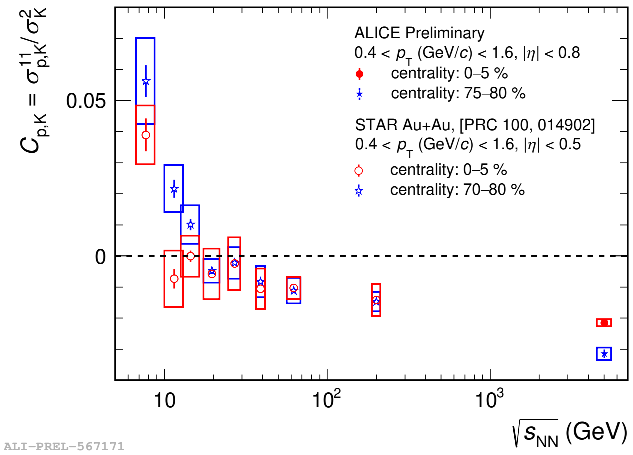
- **Q, B and S conserved** within a correlation volume
  V. Vovchenko *et al.*, Phys. Rev. C 100, 054906 (2019)
- Simultaneous description leads to ***V_c* = ~2.64dV/dy !!!**

Cross cumulants: energy dependence

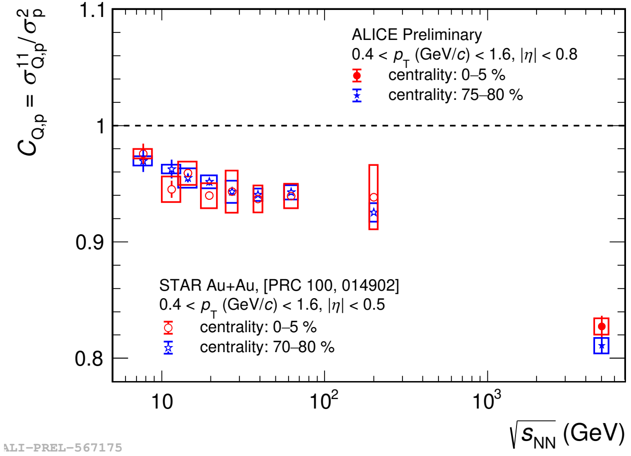
Q – K



p – K

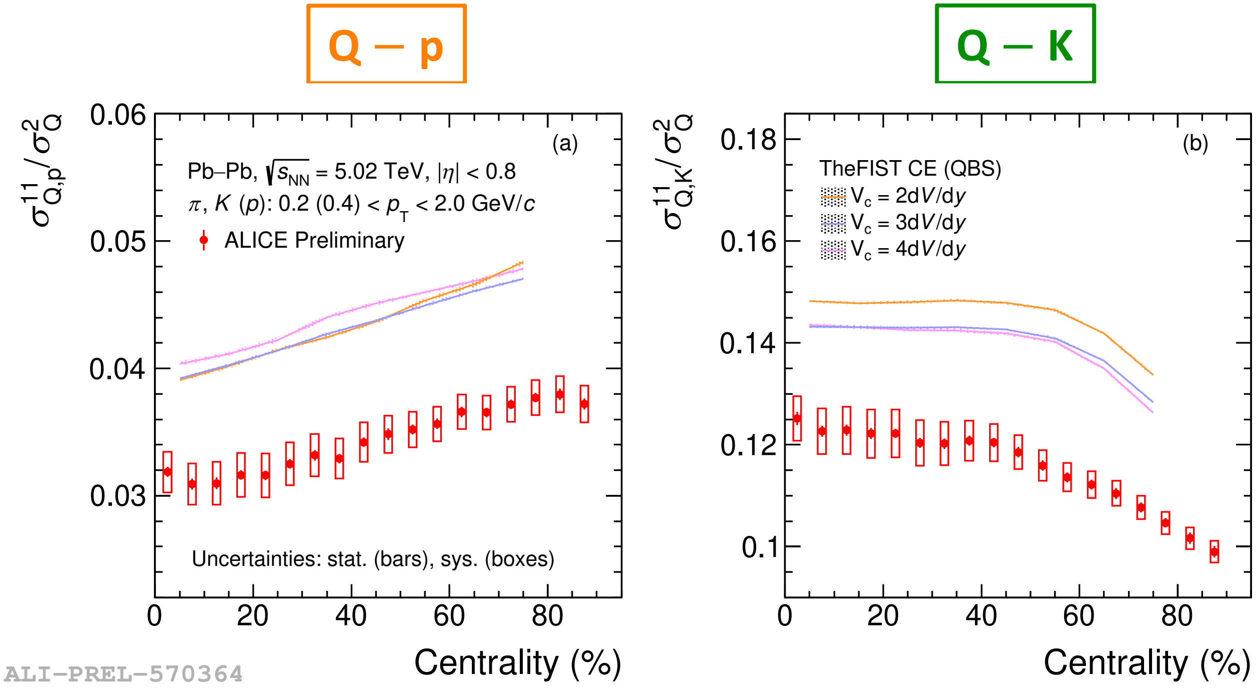


Q – p



- **Monotonic decrease of the correlations with increasing energy**
  - How much of this because of conservation?
  - What are the other possible contributions?

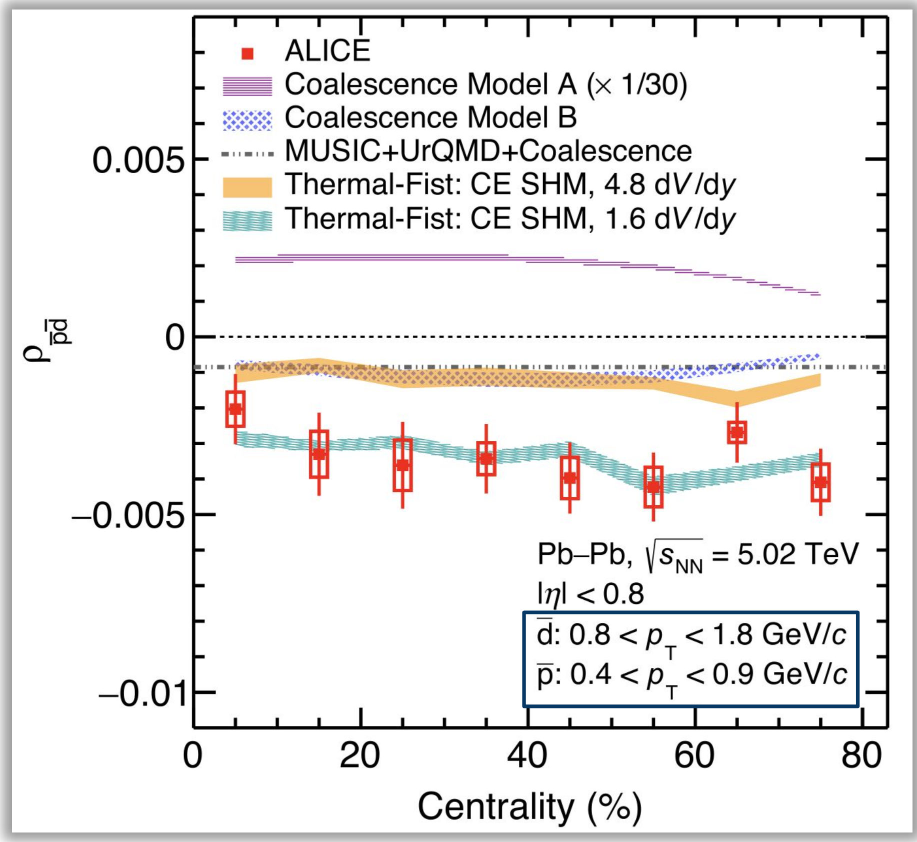
Cross cumulants: Volume independent normalization



- **Sensitivity to V_c is gone but there is a deviation**
  → What is the underlying physics?

Light nuclei production in view of correlation volume

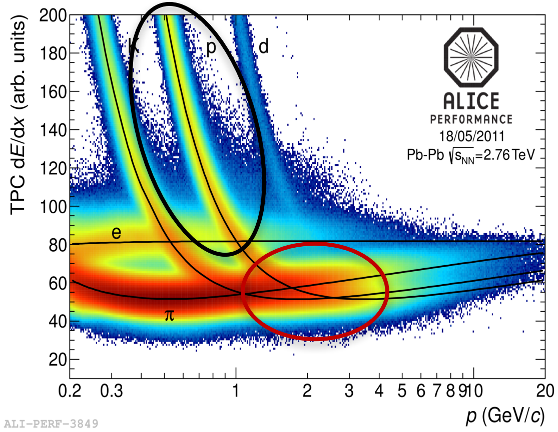
ALICE, PRL 131 (2023) 041901

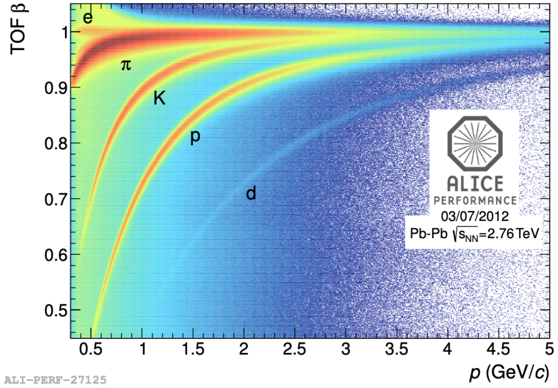


- **Simple coalescence** Z. Fecková *et al.*, PRC 93, 054906 (2016)
  - Model A: correlated nucleons
  - Model B: independent nucleons
- **Improved coalescence** K.-J. Sun *et al.*, PLB, 840, 137864 (2023)
  - MUSIC + UrQMD + Coalescence: No initial correlation between protons and neutrons
- **Canonical Statistical Model** V. Vovchenko *et al.*, PLB 785, (2018) 171
  - Correlation volume, V_c

- **Different correlation volume than for B and S**
- **Stay tuned for SQM** → $\bar{d}\Lambda\Lambda$ correlations

Pushing 2nd net-p to the limits with Identity Method





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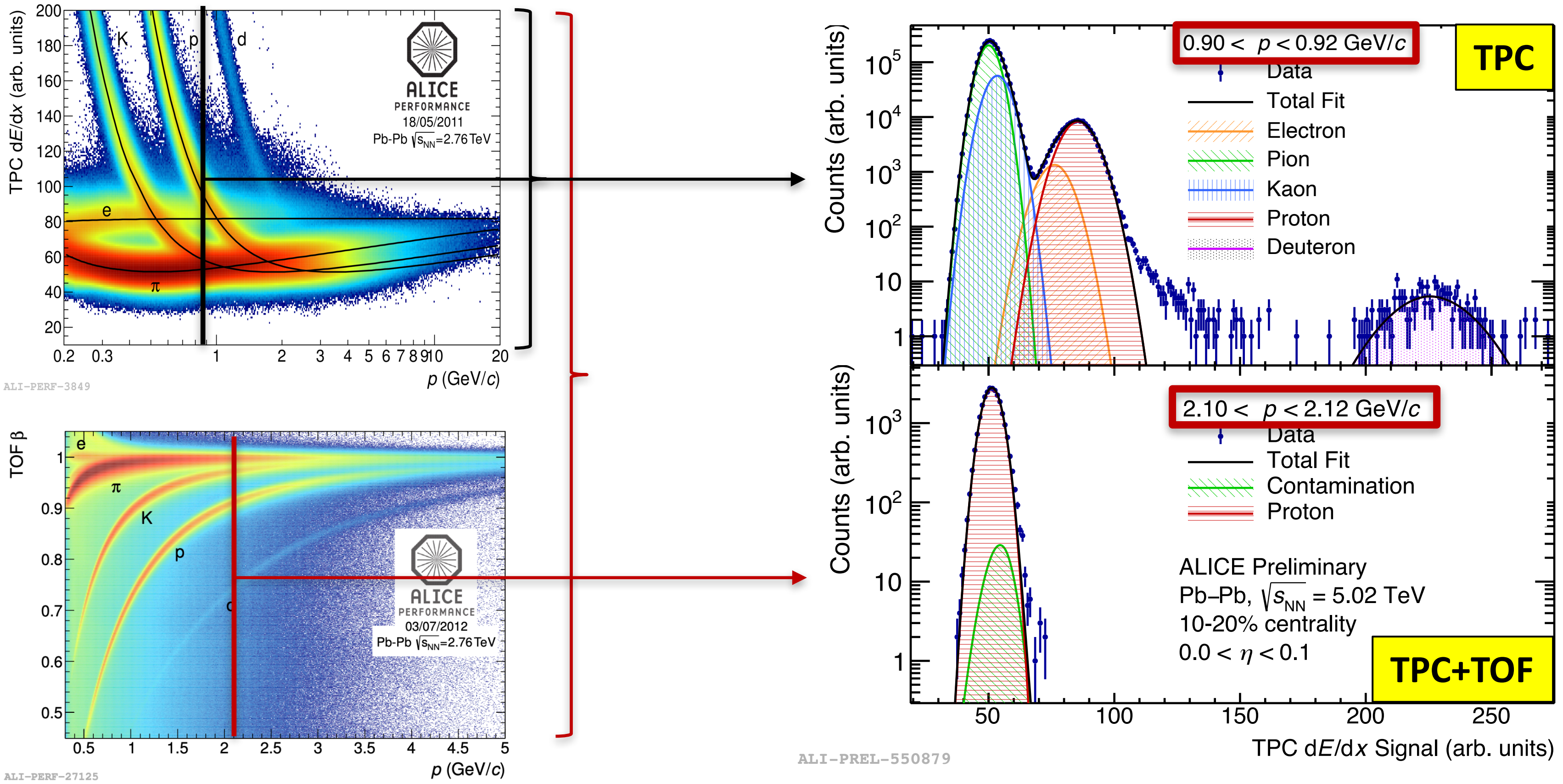

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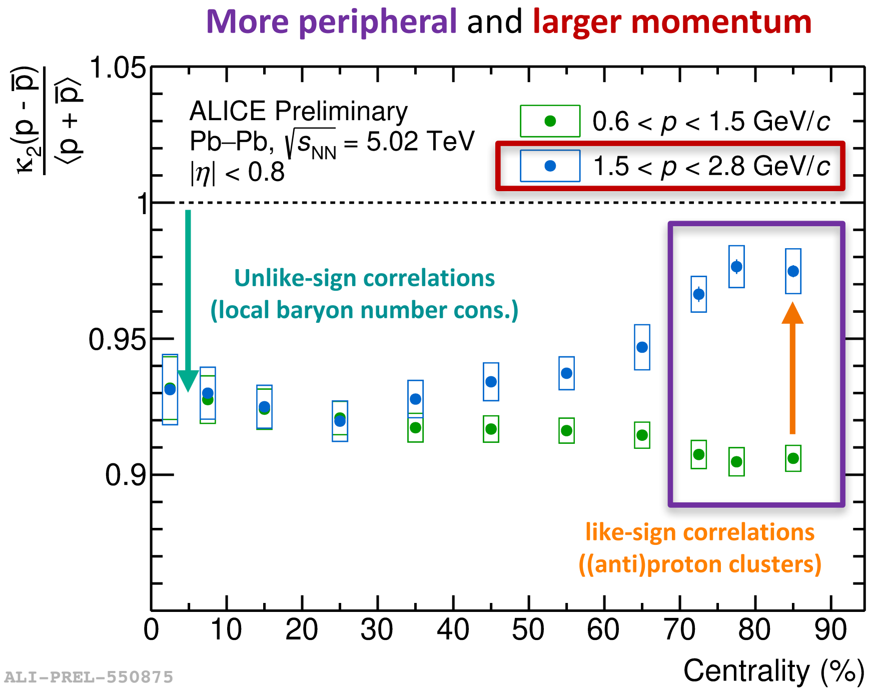
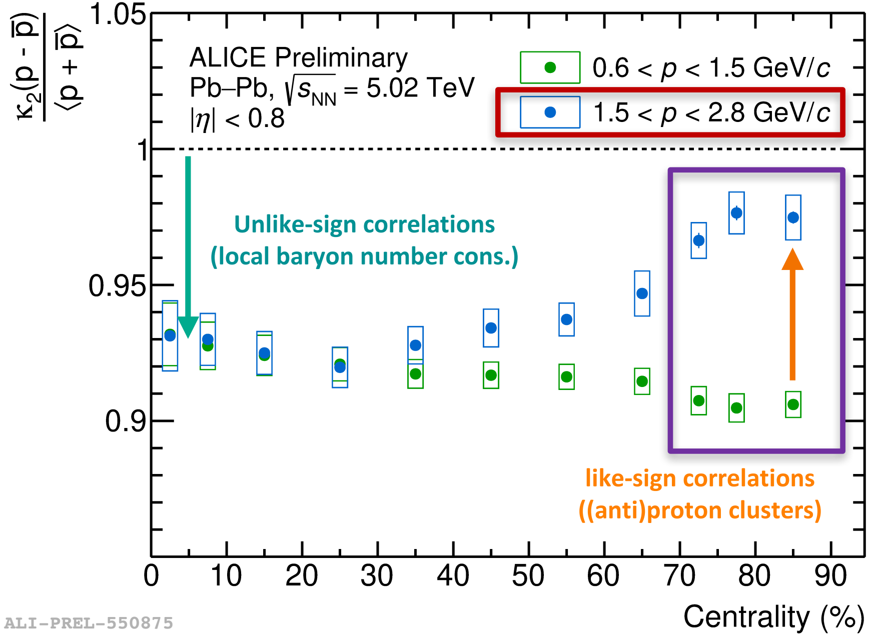
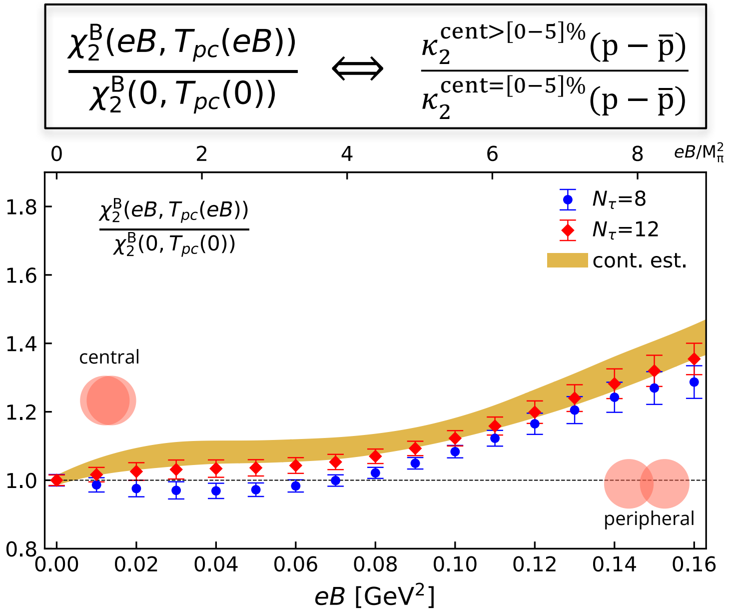


Pushing 2nd net-p to the limits

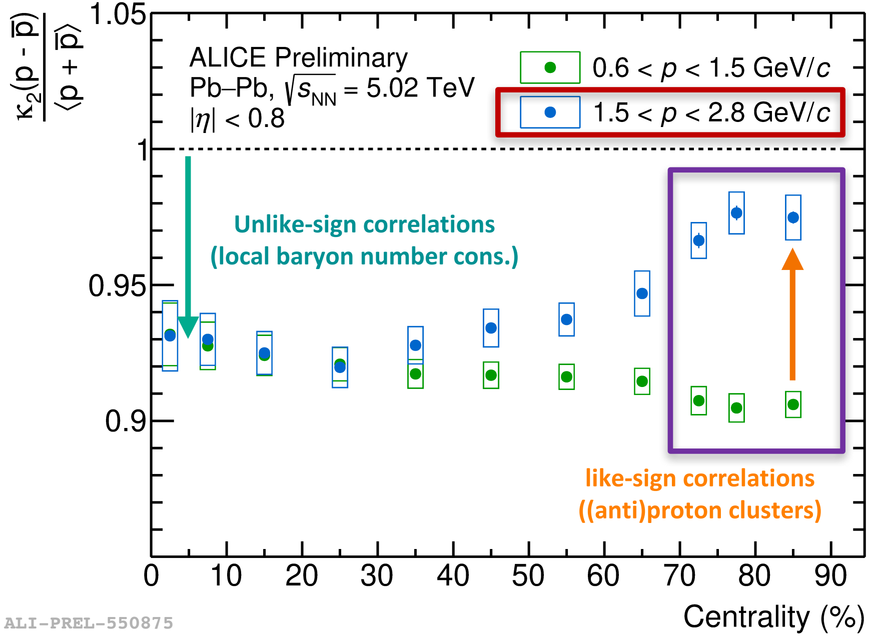
More peripheral and **larger momentum**



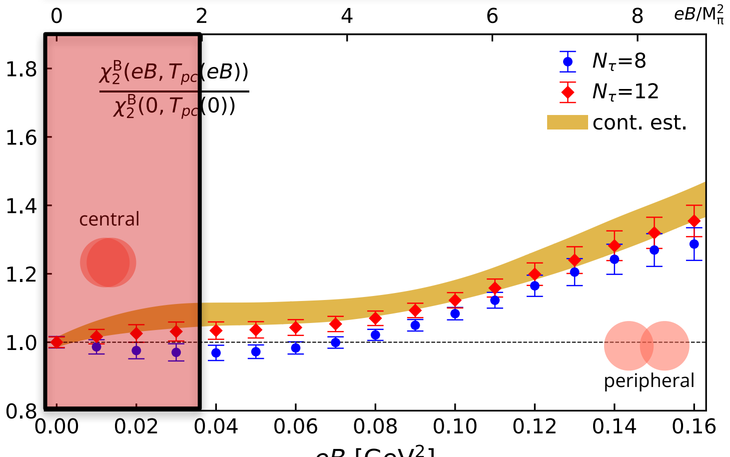


Pushing 2nd net-p to the limits

More peripheral and **larger momentum**

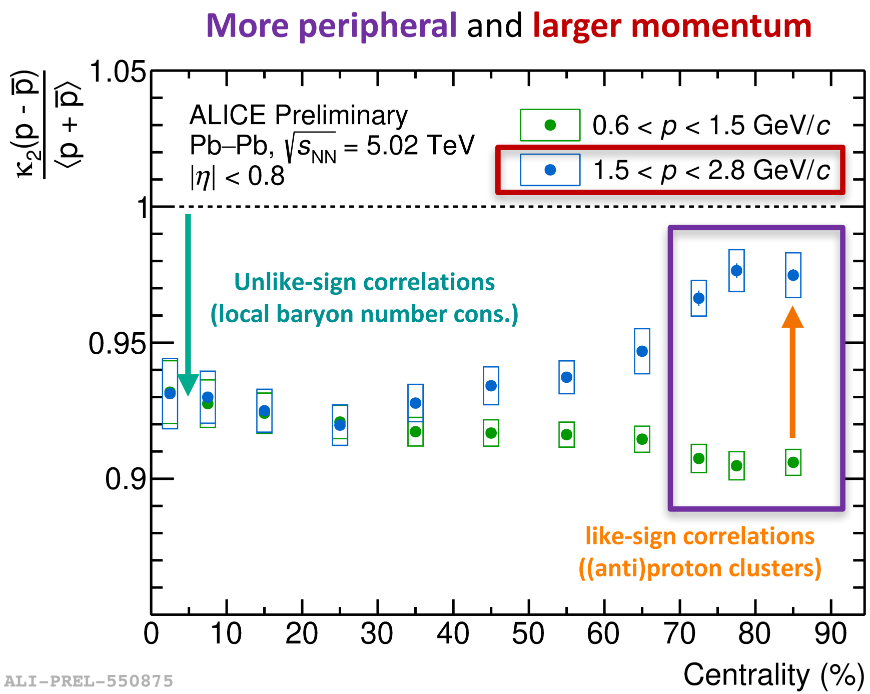


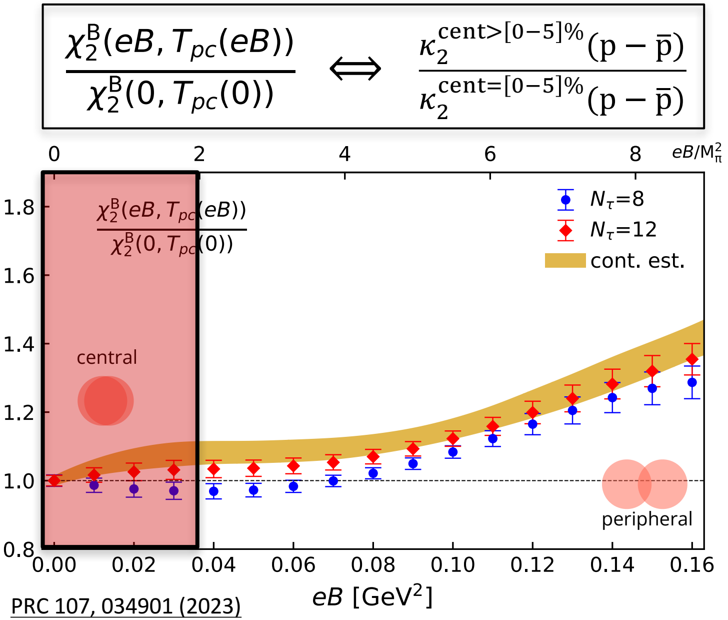
$$\frac{\chi_2^B(eB, T_{pc}(eB))}{\chi_2^B(0, T_{pc}(0))} \Longleftrightarrow \frac{\kappa_2^{\mathrm{cent}>[0-5]\%}(p - \bar{p})}{\kappa_2^{\mathrm{cent}=[0-5]\%}(p - \bar{p})}$$



PRC 107, 034901 (2023)

Pushing 2nd net-p to the limits





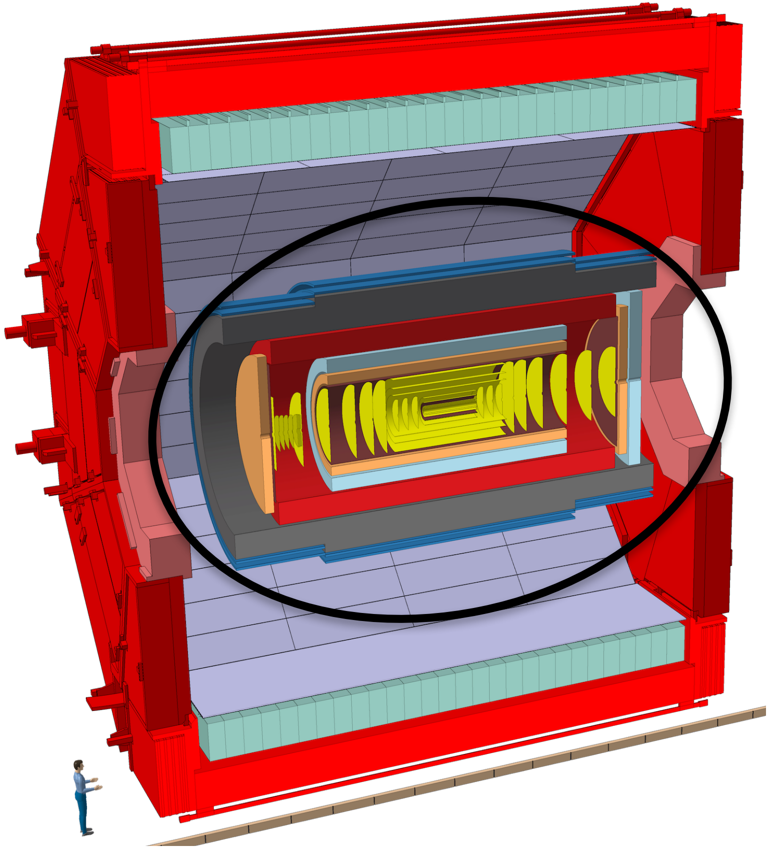
Cluster formation, magnetic field effect or ...?

What can we learn?

(ALICE 3)

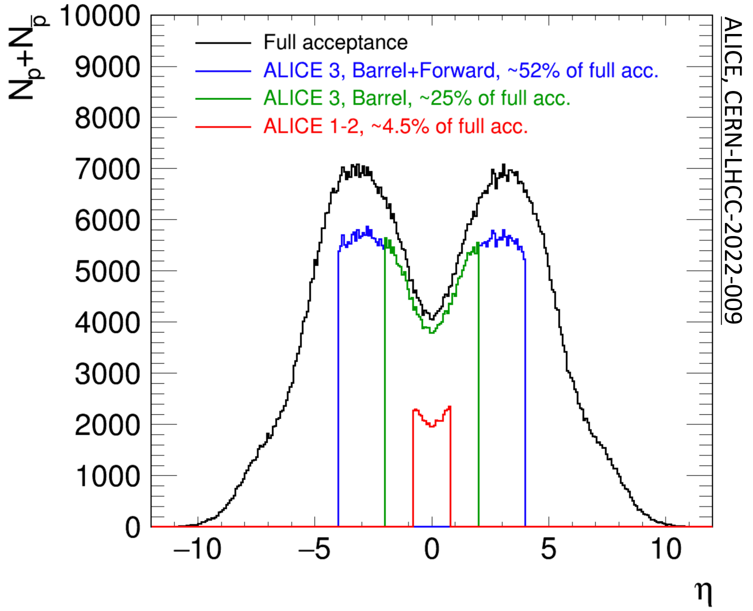
Future beyond early 2030s: ALICE 3

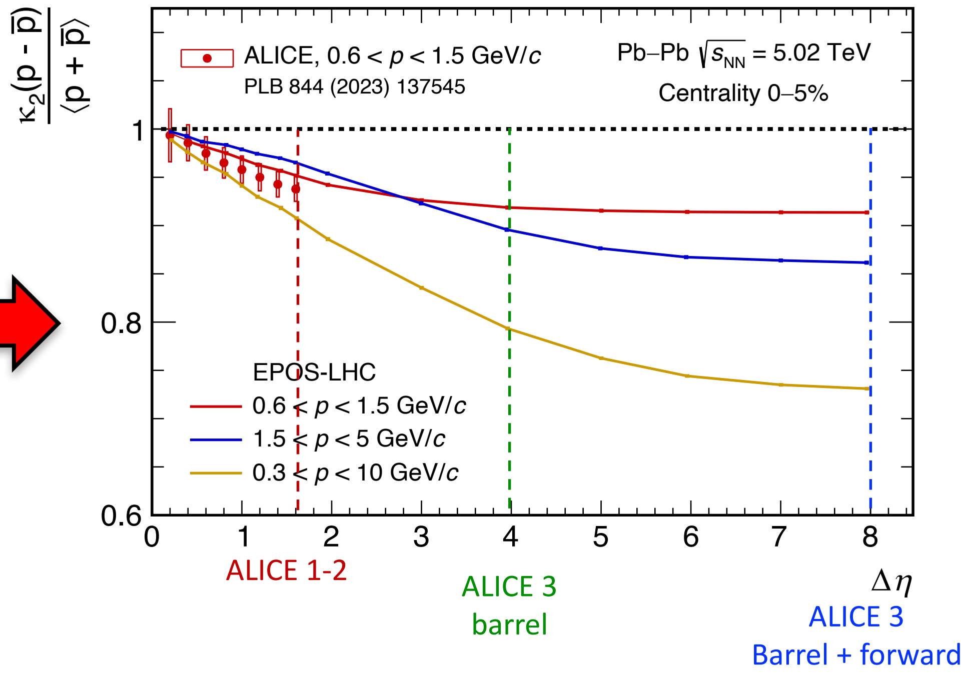
ALICE, CERN-LHCC-2022-009



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

2nd order cumulants of net-p in ALICE 3



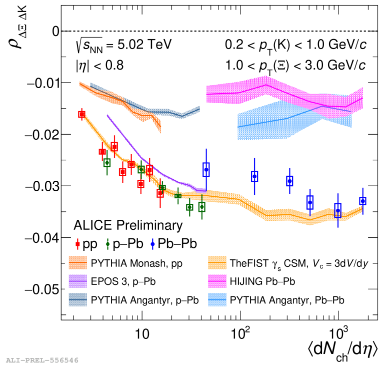


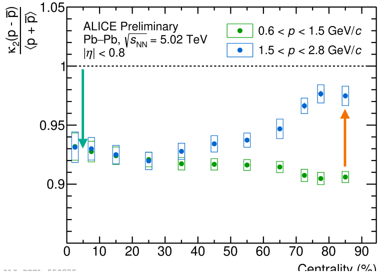
- **High PID purity and efficiency within a larger acceptance**
  (0.3 < *p* < 10 GeV/c, |*η*|<4)

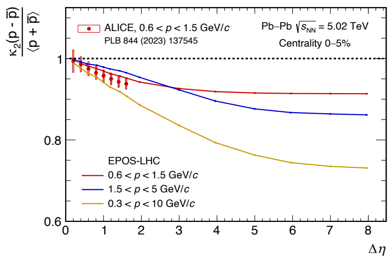
- **More differential and high precision to disentangle:**
  Thermal blurring, Initial-state fluctuations, baryon annihilation, excluded volume effects, baryon number conservation …

Summary

- **String fragmentation fails** at the second order net-[p,Λ,Ξ]
- **Large V_c (≈ <u>3 dV/dy</u>)** but still not fully global
  - What is the source of “locality”?
  - How large is the contribution from annihilation etc.?
- **Slightly smaller V_c for net-Q than net-[p,Λ,Ξ]**
  - Assumption in the implementation of the V_c and/or unprecise description of resonances in FIST?
  - Contribution from other hadronisation mechanisms? Hard vs soft? Coalescence? …
- **Larger momentum range** → interesting centrality dependence
  - Magnetic field? What do pp collisions say?
  - Cluster formation?
- **What impact do these effects have on the higher-order cumulants?**







Summary

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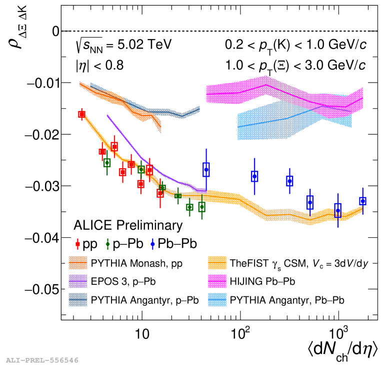
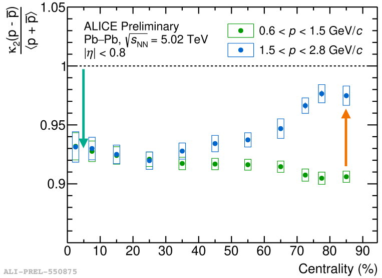
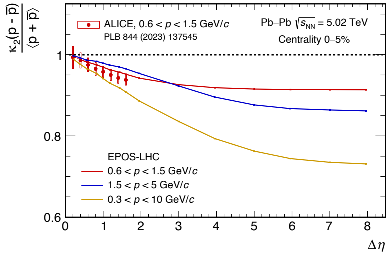
  - Cluster formation?
- **What impact do these effects have on the higher-order cumulants?**

A lot to do but future is very bright!



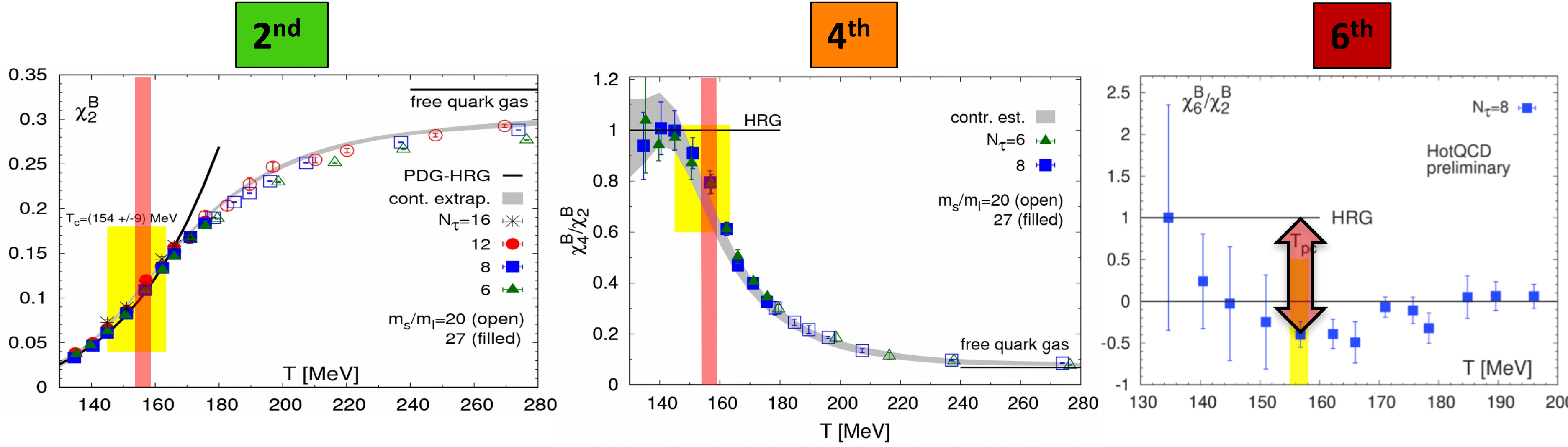




BACKUP

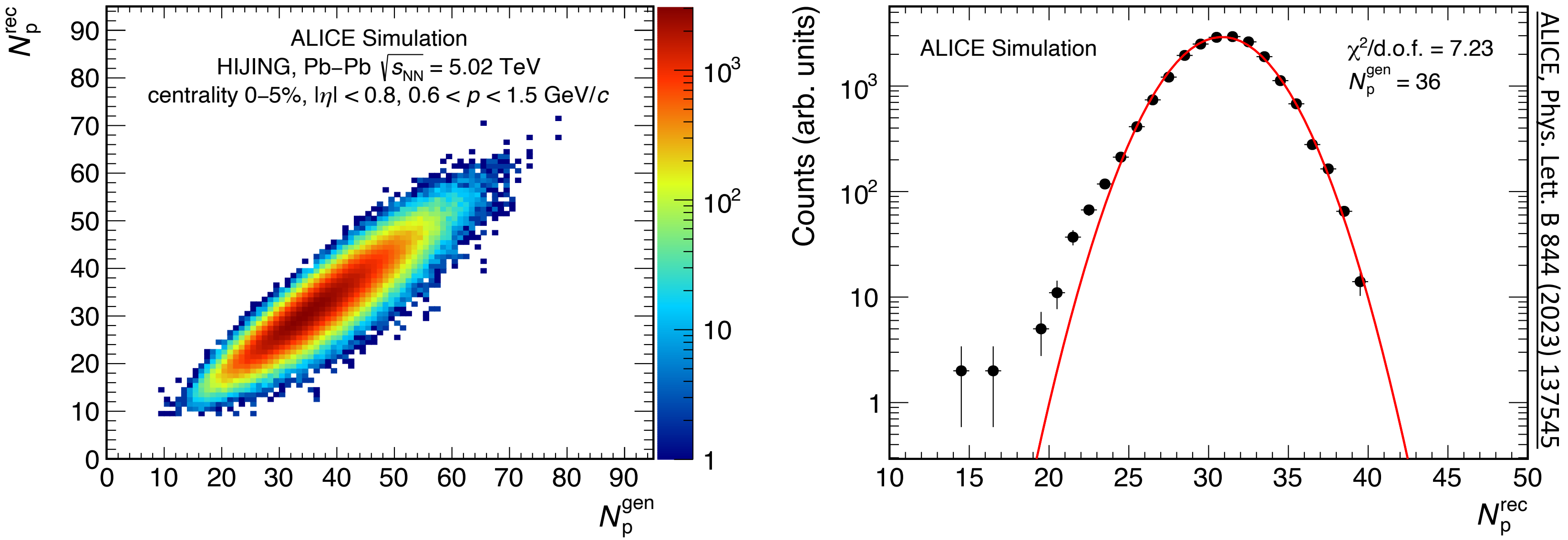
Example case: $\mu_B \approx 0$

- **Baseline:** Difference between two independent Poissonian distributions (Skellam distr.)
  $\Longrightarrow$ **κ_n/κ_2 is 0 (n odd) or 1 (n even)**
- **Holy grail:** Critical behavior as from 6th order
  $\Longrightarrow$ **4th order ~30%, 6th order ~150%**



Efficiency correction

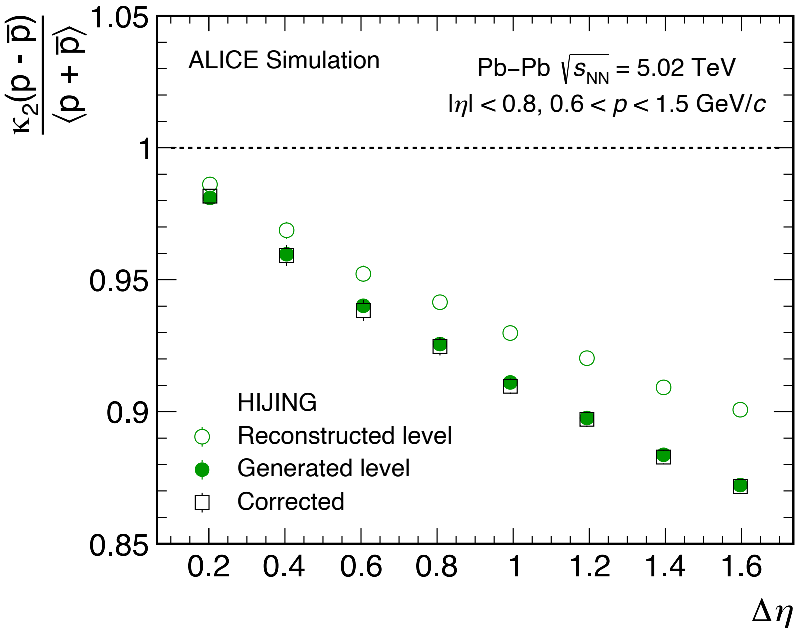
Binomiality of the detector response is important for the efficiency correction

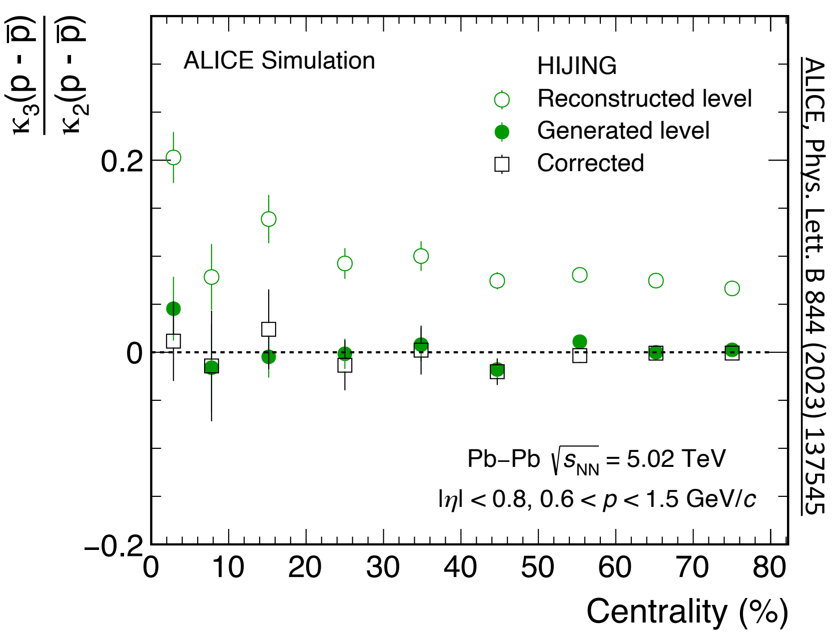


Slight deviation from the binomial efficiency loss

- Event and track selection
- TPC d*E*/d*x* 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

Efficiency correction





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)

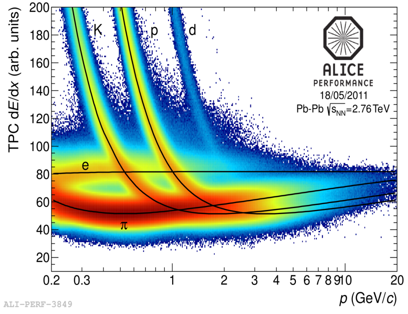
A Large Ion Collider Experiment

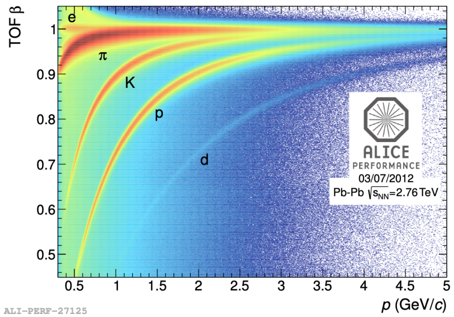
Main detectors used:

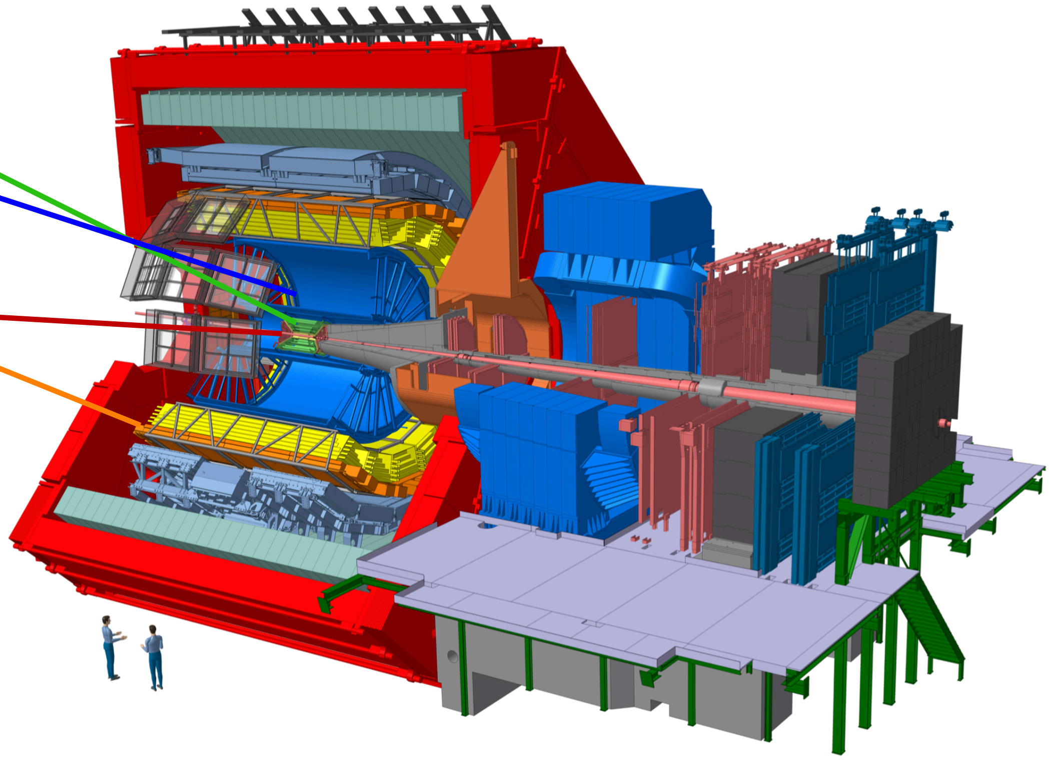
- Inner Tracking System **(ITS)**
  - → Tracking and vertexing
- Time Projection Chamber **(TPC)**
  - → Tracking and Particle Identification (PID)
- Time Of Flight **(TOF)**
  - → Tracking and PID
- **V0**
  - → Centrality determination

Data Set:

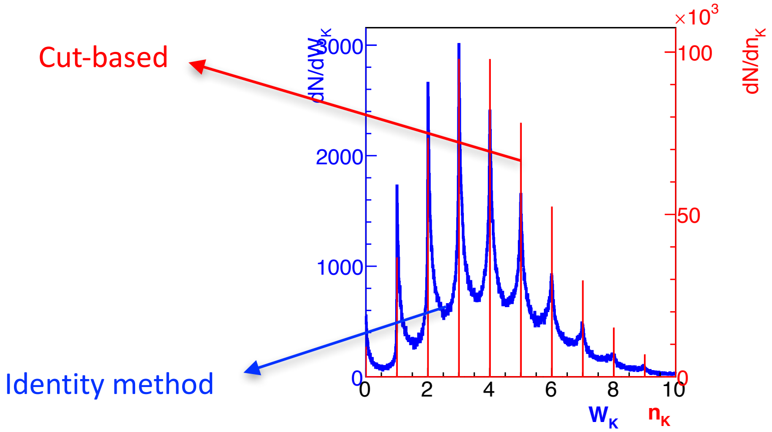
- $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV, ~78 M events
- $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV, ~13 M events





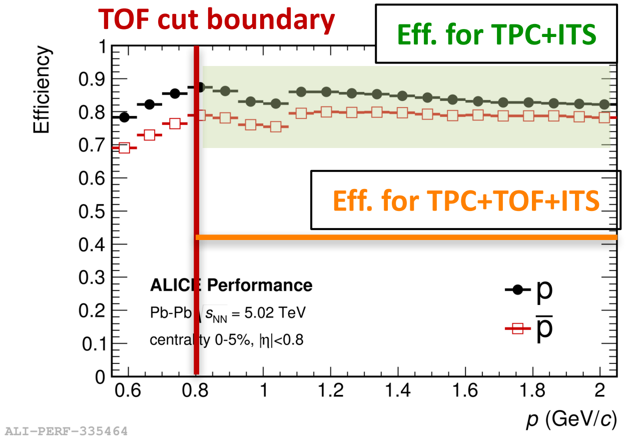


Identity method vs cut-based approach

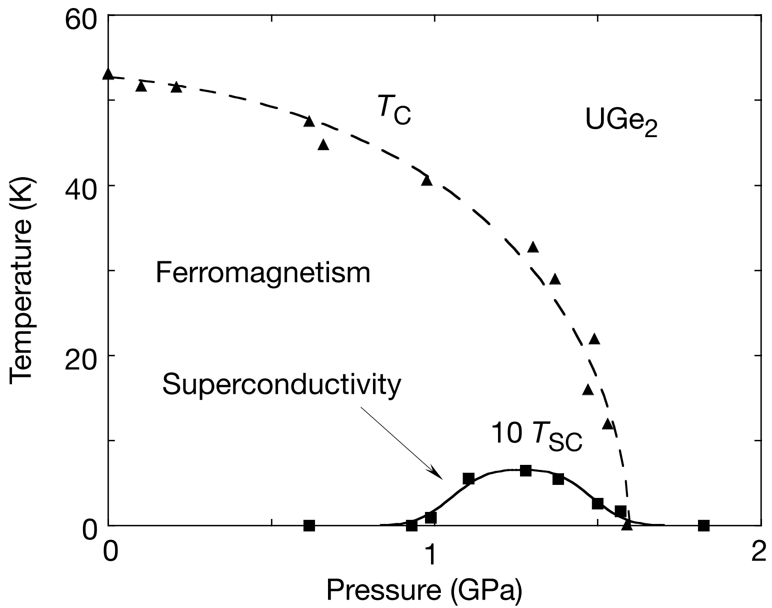


$$\langle N_j^n \rangle = A^{-1} \langle W_j^n \rangle$$

- **Identity Method**
  - Gives folded multiplicity distribution
  - **Maximal efficiency & no PID contamination**
- **Cut based approach**
  - Additional detector || reject a given phase space
  - **Low efficiency & PID contamination**

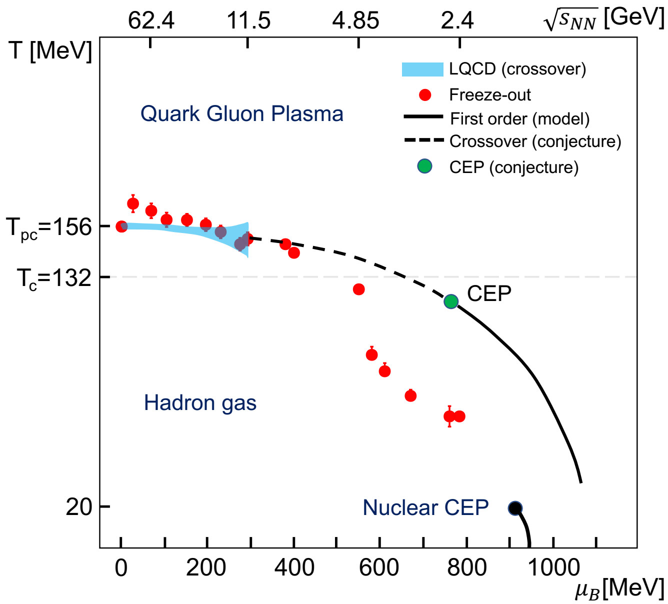


Ferromagnetic phase transition
(Electro-magnetic interaction)



Nature **volume 406**, pages 587–592 (2000)

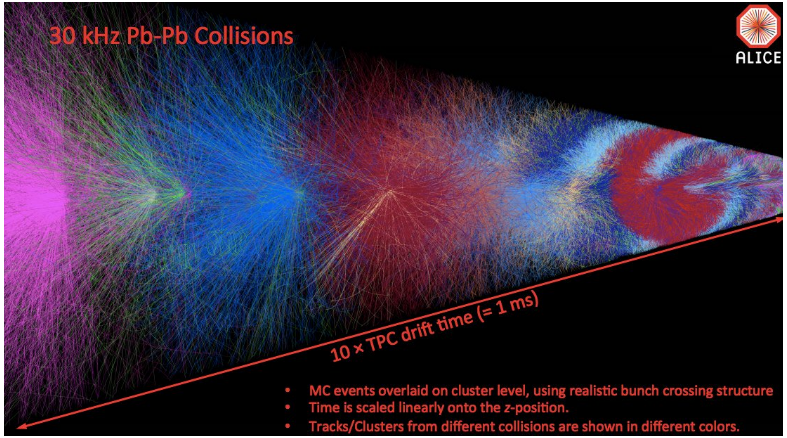
QCD phase diagram
(Strong interaction)



P. Braun-Munzinger, A. Rustamov, J. Stachel, e-Print: 2211.08819

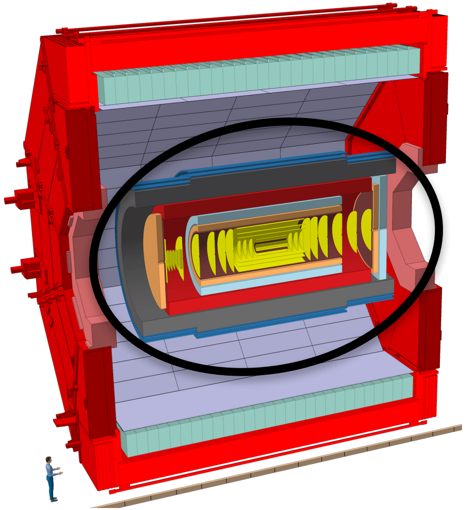
Future of ALICE

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**

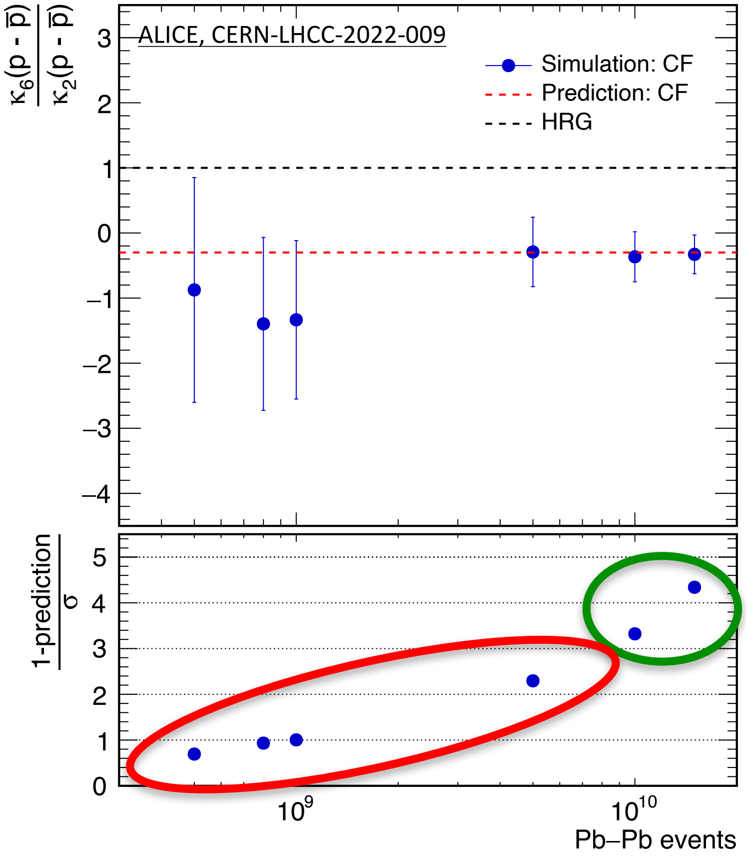
ALICE 3 (beyond early 2030s)



ALICE, CERN-LHCC-2022-009

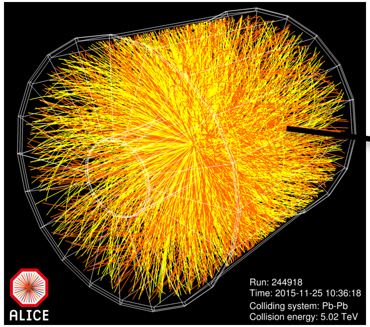
- ✓ **High statistics** → O (10^9) billion events
- ✓ **Large acceptance** → $|\eta| < 4$
- ✓ **High PID purity** → $0.3 < p_T < 10$ GeV/c
- ✓ **High efficiency** → ~95%
- ✓ **Excellent vertexing** → O (3μm) resolution

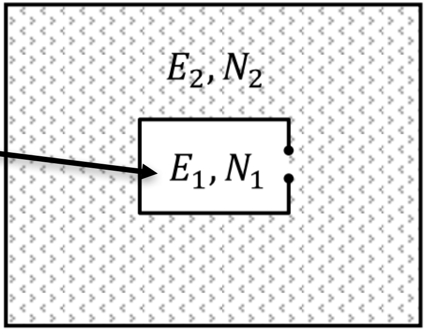
Criticality search in ALICE 2 and 3

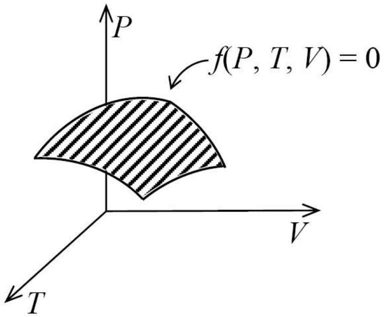


- Simulation of the Critical Fluctuations (CF) is based on PQM model
  G. A. Almasi, B. Friman, and K. Redlich, Phys. Rev.D96 (2017), 014027
- **ALICE 2:**
  → More than 5 billion central Pb-Pb collisions is required
- **ALICE 3:**
  → **x3 larger statistics:** $>4\sigma$ significance with ALICE 2 acceptance

What kind of a system we are talking about?







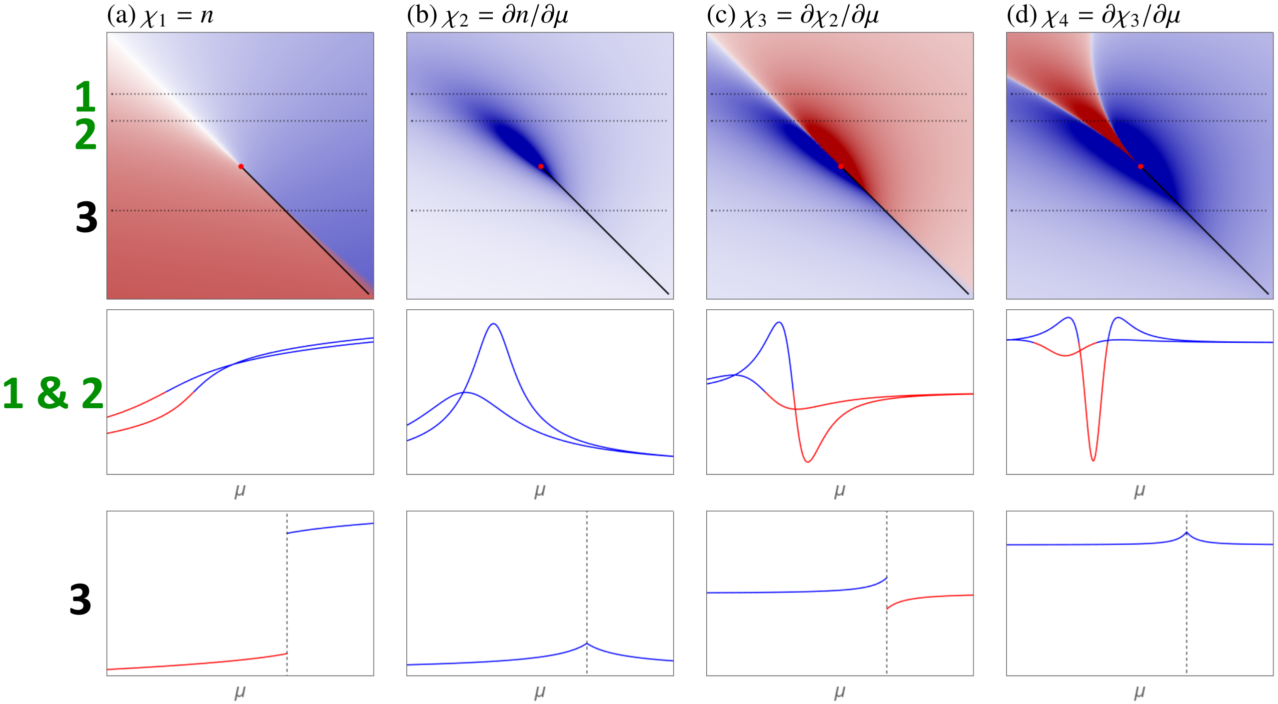
<u>Grand canonical ensemble</u> where particles are in a thermal equilibrium

- Energy (*E*) and number of particles (*N*) are **not conserved** in each microstate
- EOS can be represented **by a surface** in the state space spanned by P, V and T
- Conservation laws are applied **on average**
- Chemical potential **(μ_B)**, Volume **(V)** and Temperature (T) are constant
- For a given state E_j and N_j grand canonical partition function

$$Z_{GCE}(T,V,\mu) = \sum_j \exp\left[-\frac{E_j - \mu N_j}{T}\right] \Rightarrow \langle N \rangle = \sum_j N_j p_j = T \frac{\partial \ln Z_{GCE}}{\partial \mu}\bigg|_V$$

Thermodynamic susceptibilities

$$\langle N \rangle = \sum_j N_j p_j = T \frac{\partial \ln Z_{GCE}}{\partial \mu}\bigg|_V \Rightarrow n \equiv \frac{\langle N \rangle}{V} = \left(\frac{\partial P}{\partial \mu}\right)_T \Rightarrow \chi_k = \left(\frac{\partial^k P}{\partial \mu^k}\right)_T = \left(\frac{\partial^{k-1} n}{\partial \mu^{k-1}}\right)_T$$



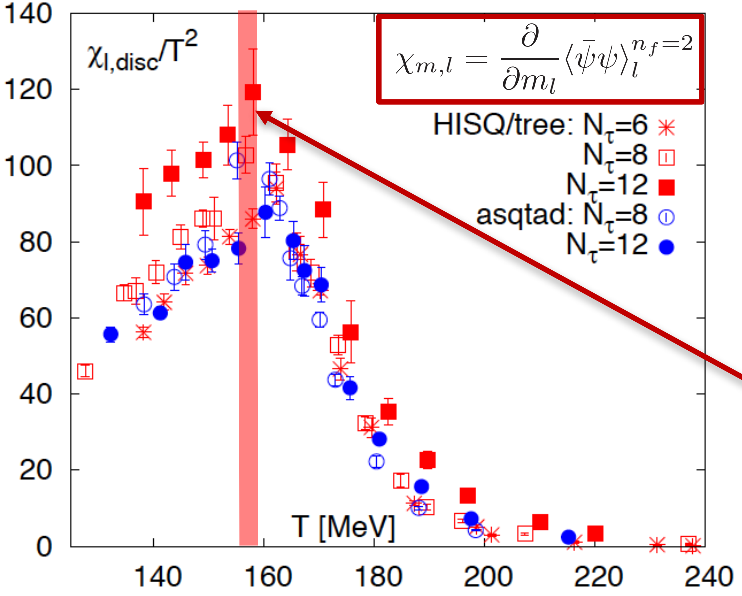
Chiral susceptibility: sum of connected and disconnected Feynman diagrams

Free energy density

$$f = -\frac{T}{V}\ln Z$$

2-flavor light quark chiral condensate

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

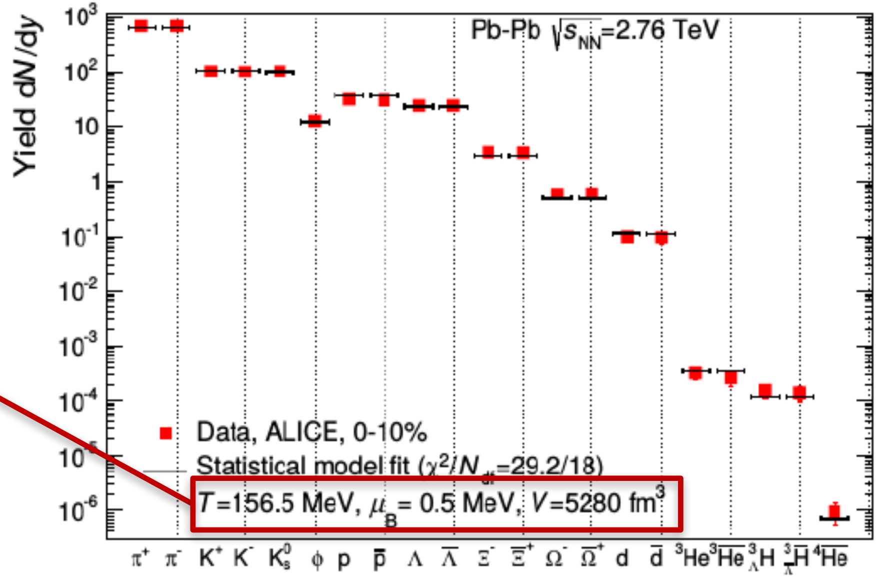


"The disconnected part of the light quark susceptibility describes the fluctuations in the light quark condensate"

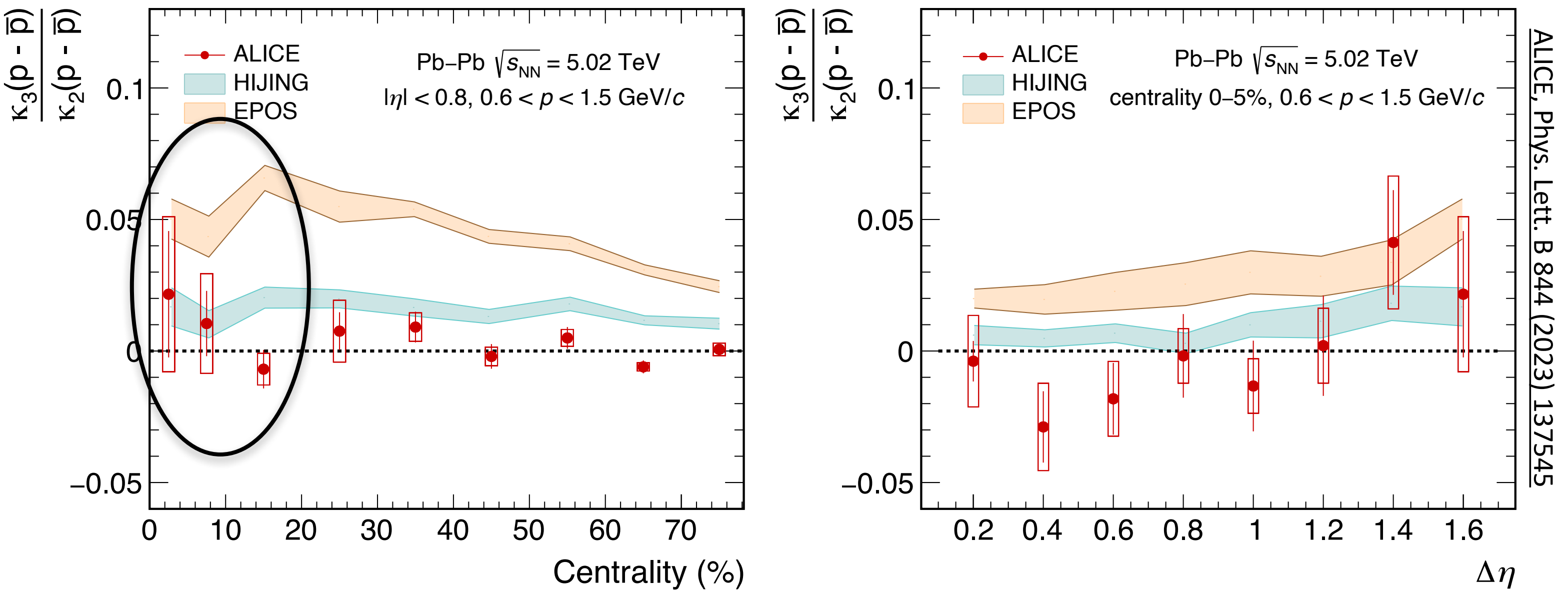
$$\langle N_i\rangle = V\frac{g_i}{2\pi^2}\int_0^\infty \frac{p^2dp}{\exp\left[(E_i-\mu_i)/T\right]\pm 1}$$

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

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



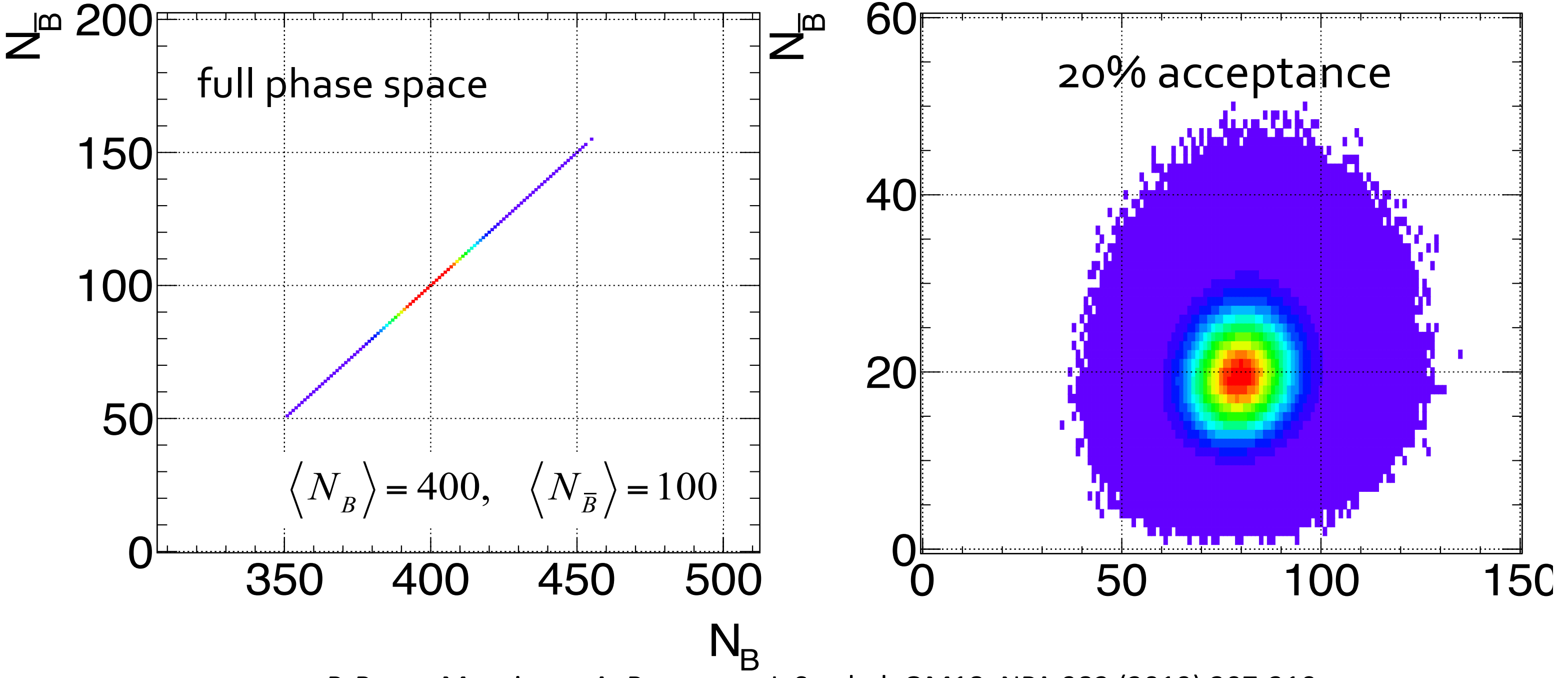
3^{rd} order cumulants of net-p



- **Data agree with Skellam baseline "0"** → **μ_B is very close to 0** (ALICE Collaboration, arXiv:2311.13332v2)
- **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 2^{nd} and 3^{rd} order cumulants are not negligible

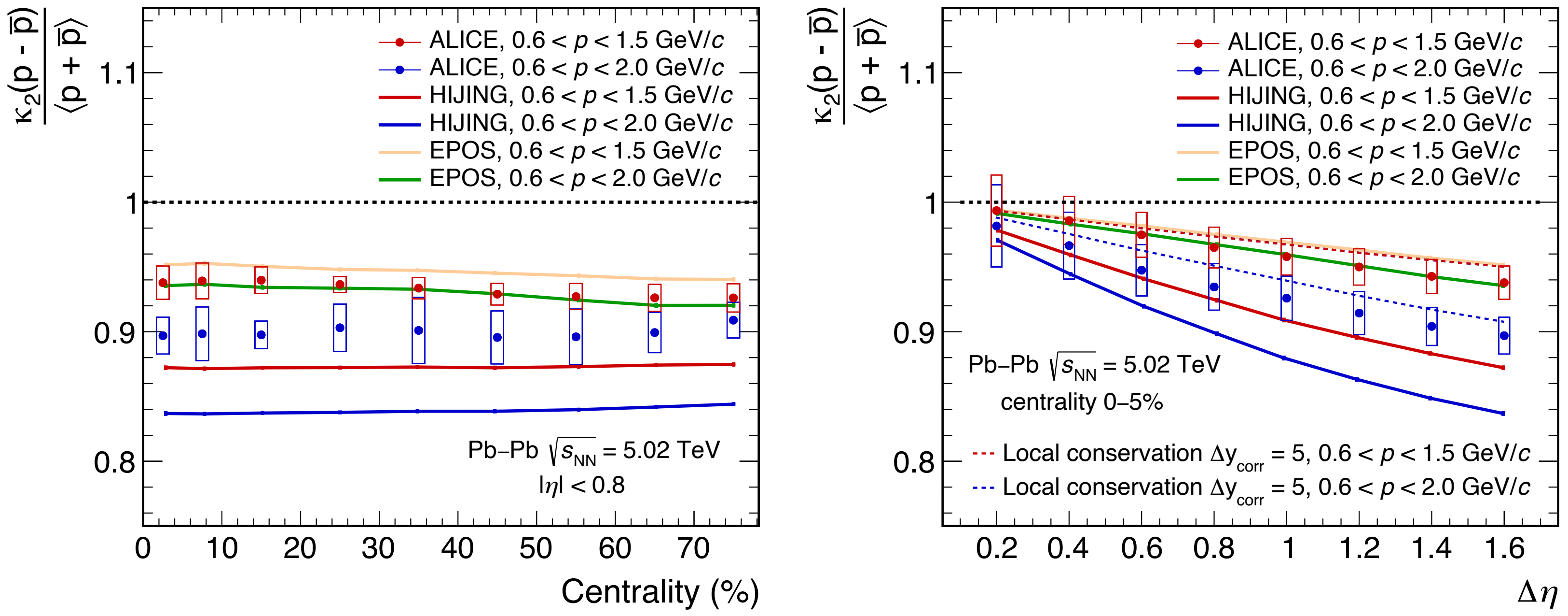
Acceptance effect

Importance of acceptance



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

2nd order cumulants of net-p: Acceptance dependence

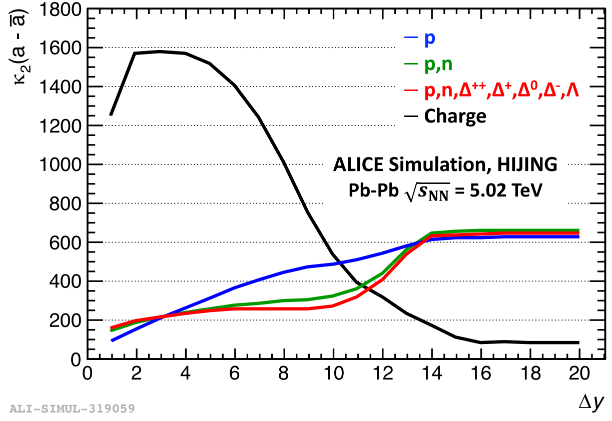


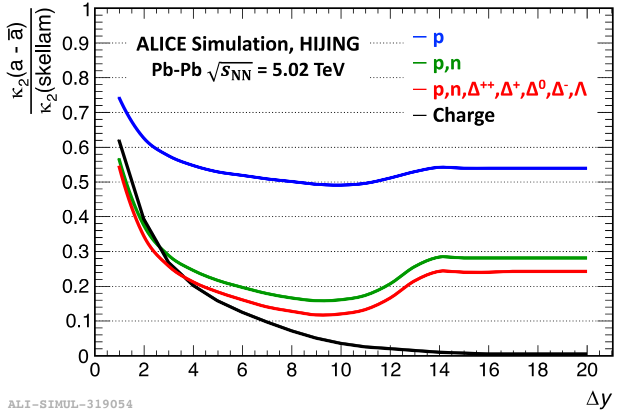
- Consistent with the baryon number conservation picture
  - Increase in fraction of accepted p, $\bar{p}$ -> stronger constraint of fluctuations due to baryon number conservation
- EPOS & HIJING show this drop qualitatively

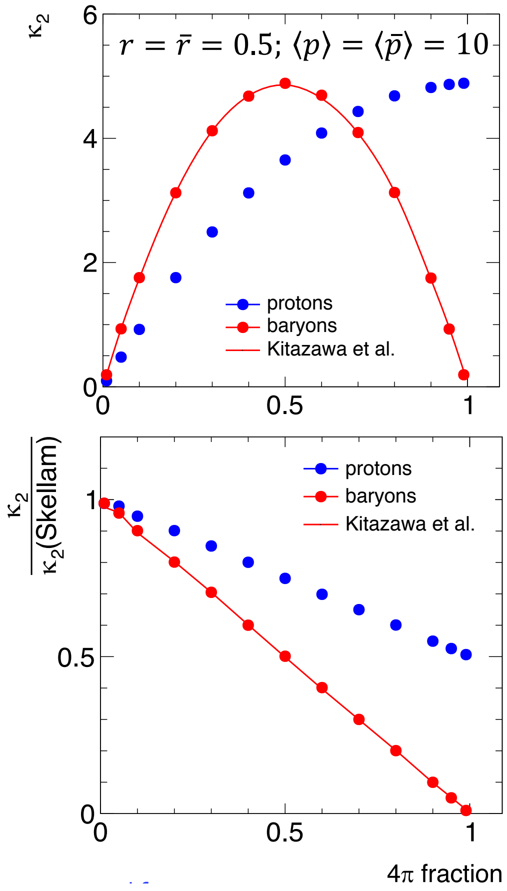
2nd order cumulants in full phase space

- **Net-baryon vs Net-p**
- Due to **isospin randomization** at $\sqrt{s_{NN}}$ > 10 GeV net-baryon fluctuations can be easily obtained from corresponding **net-proton measurements**

M. Kitazawa, and M. Asakawa, Phys. Rev. C86 (2012)



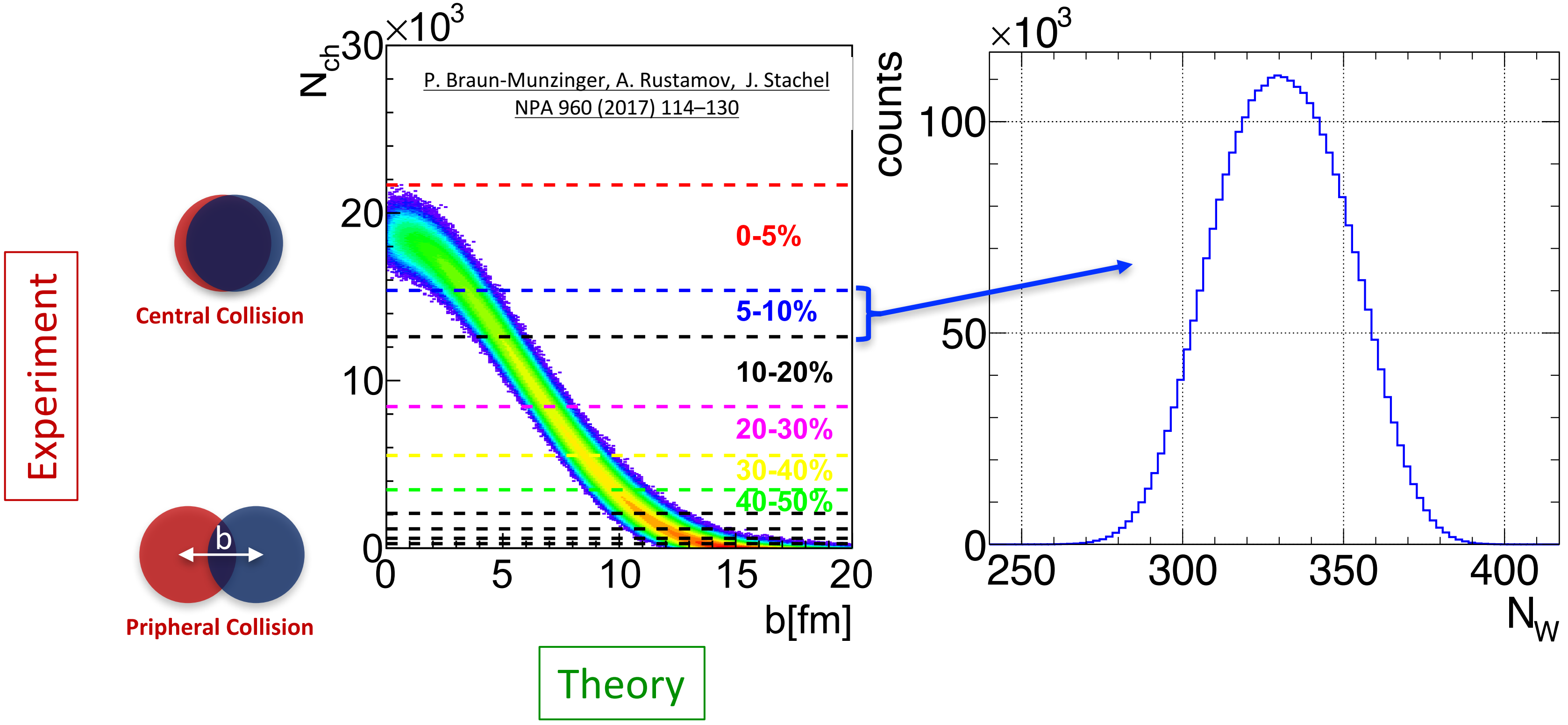




P. Braun-Munzinger, A. Rustamov, J. Stachel, NPA 982 (2019) 307-310

Experimental Effects

Volume fluctuations

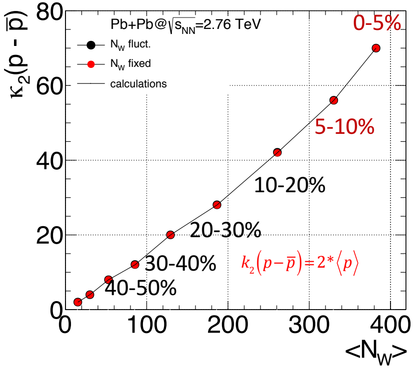


Volume fluctuations: TOY model at LHC

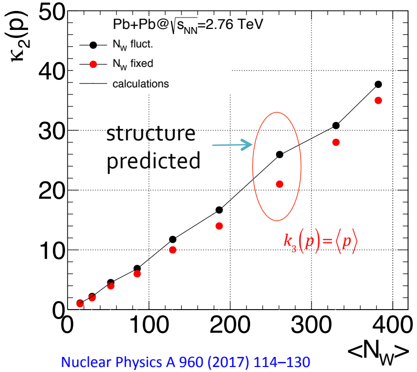
2nd order cumulants

Net-p

150*10^6 Events



p



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

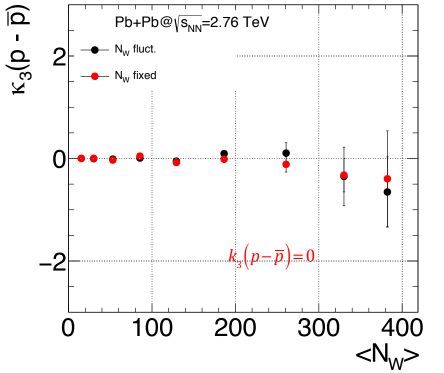
$$k_2(p) = \langle N_w \rangle k_2(n) + \langle n \rangle^2 k_2(N_w)$$

does not vanish

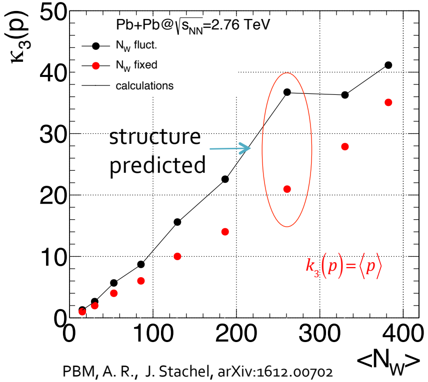
3rd order cumulants

Net-p

150*10^6 Events



p



PBM, A. R., J. Stachel, arXiv:1612.00702

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

vanishes for ALICE

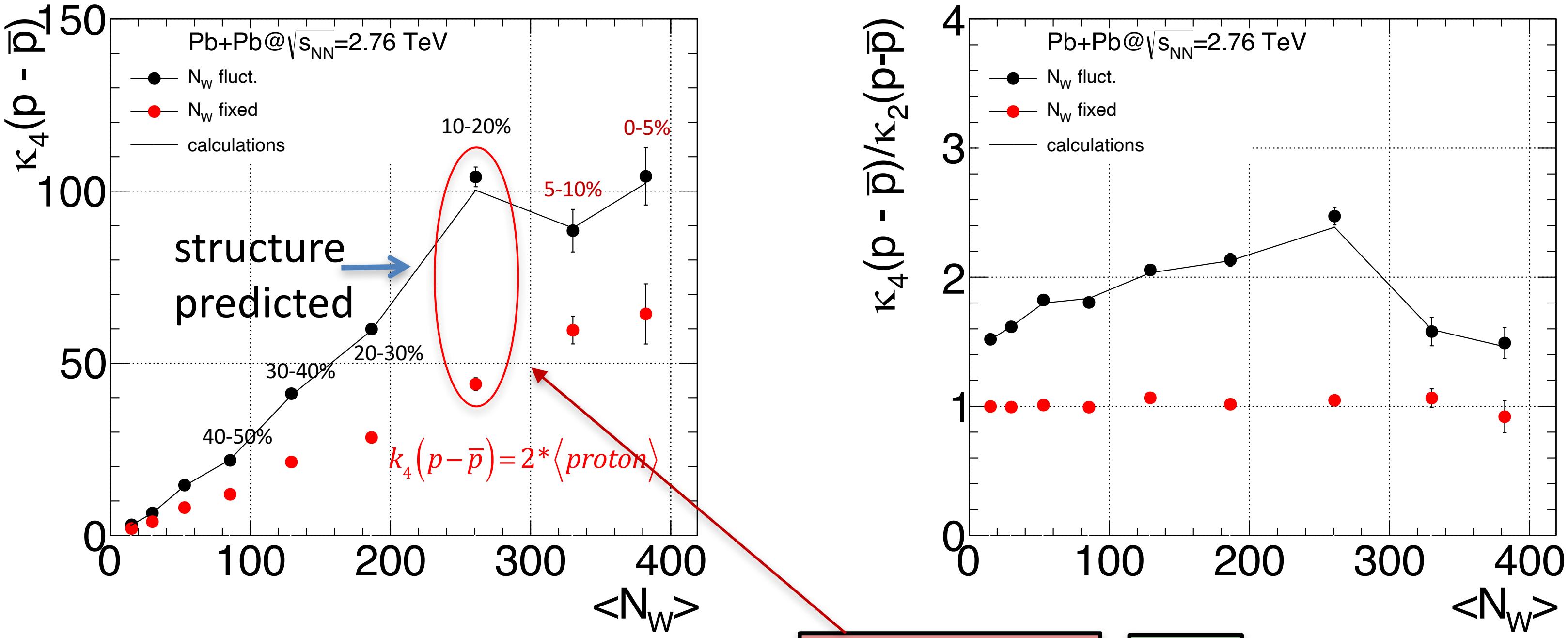
$$k_3(p) = \langle N_w \rangle k_3(n) + \langle n \rangle (\ldots)$$

does not vanish

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

Volume fluctuations: TOY model at LHC

$150*10^6$ Events

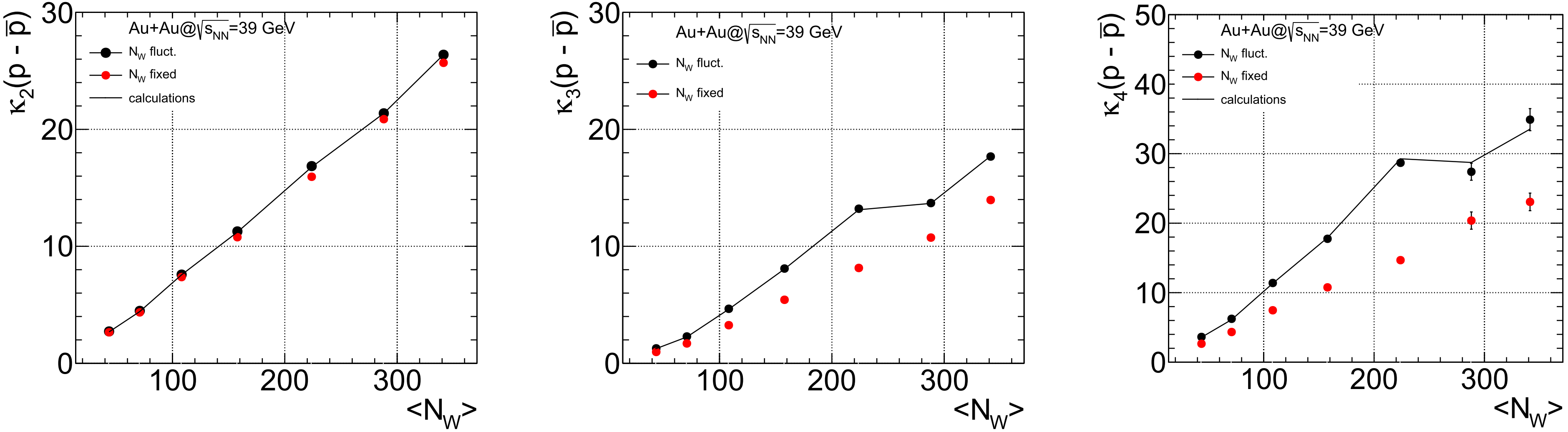


$k_4(p-\bar{p}) = 2 * \langle proton \rangle$

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

Vanishes at LHC

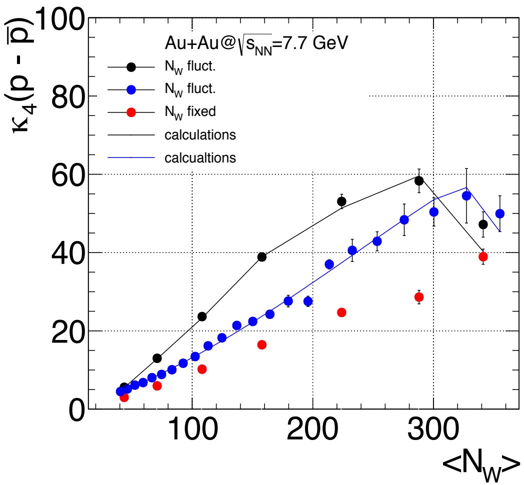
Volume fluctuations: TOY model at RHIC

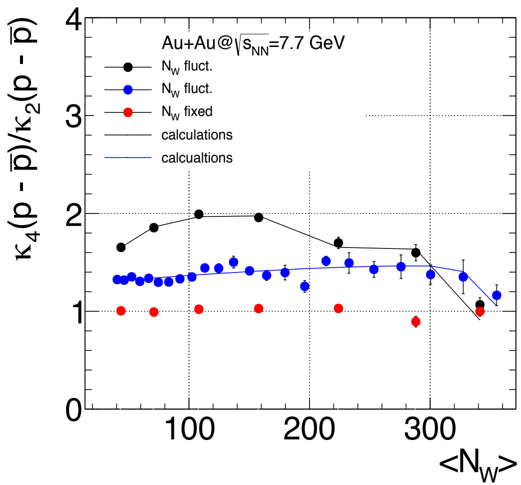


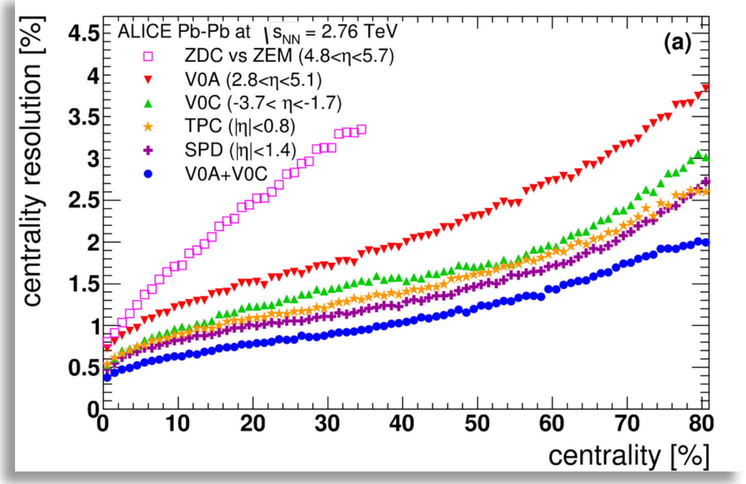
$$k_4(p-\bar{p}) = \langle N_w \rangle k_4(n-\bar{n}) + 3k_2(n-\bar{n})^2 k_2(N_w) + \langle n-\bar{n} \rangle (\ldots)$$

- At lower energies **none of these terms cancel**

Volume fluctuations: CBWC vs centrality resolution

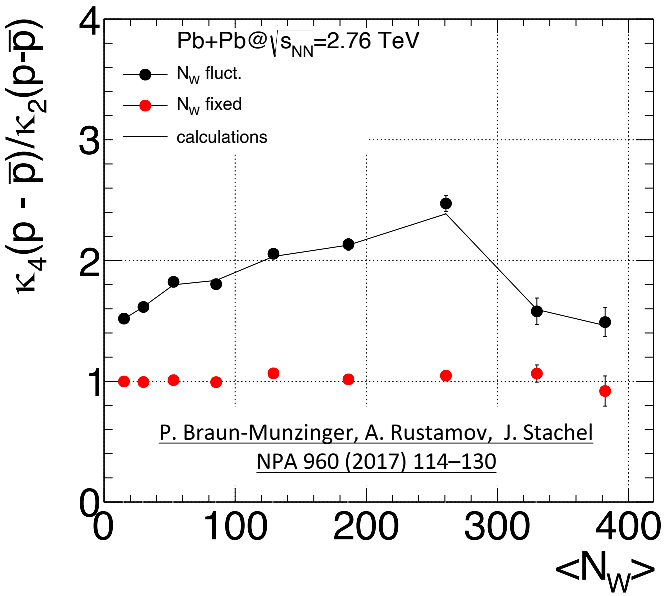


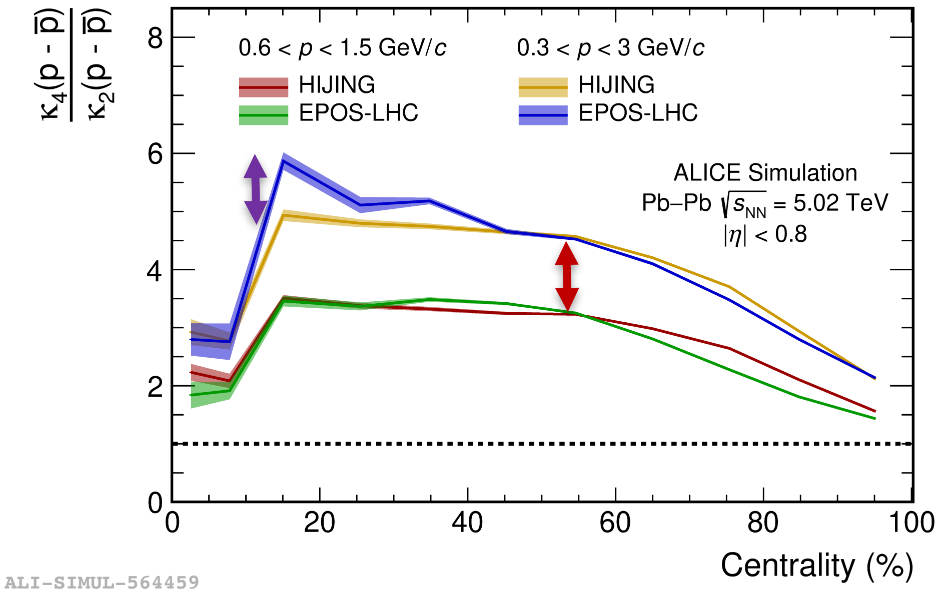




Centrality dependent resolution or centrality bias → Can this have an impact on the performance of CBWC

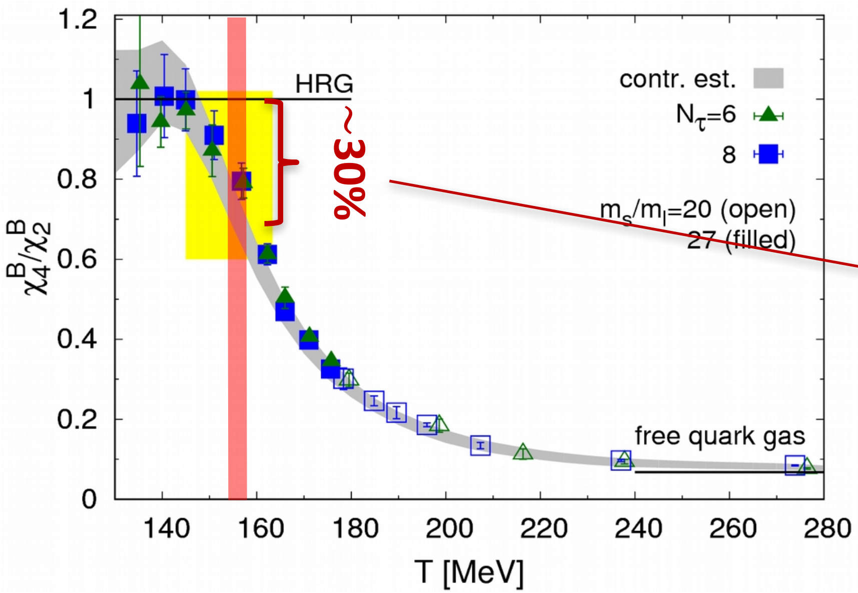
Volume fluctuations at LHC energies

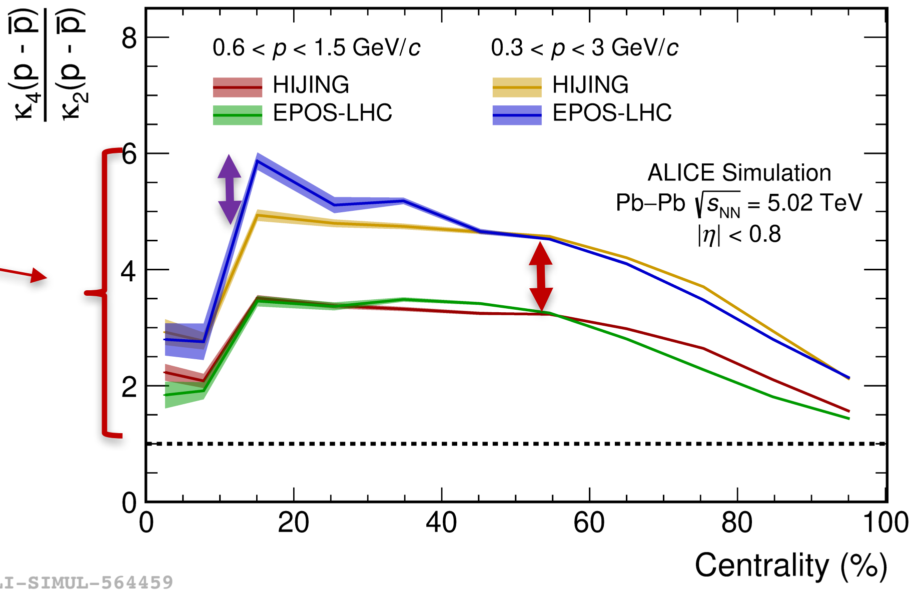




- For the 2nd and 3rd order cumulants it cancels out at LHC
- Strongly depends on the particle multiplicity within the **kinematic acceptance** and the **underlying physics**

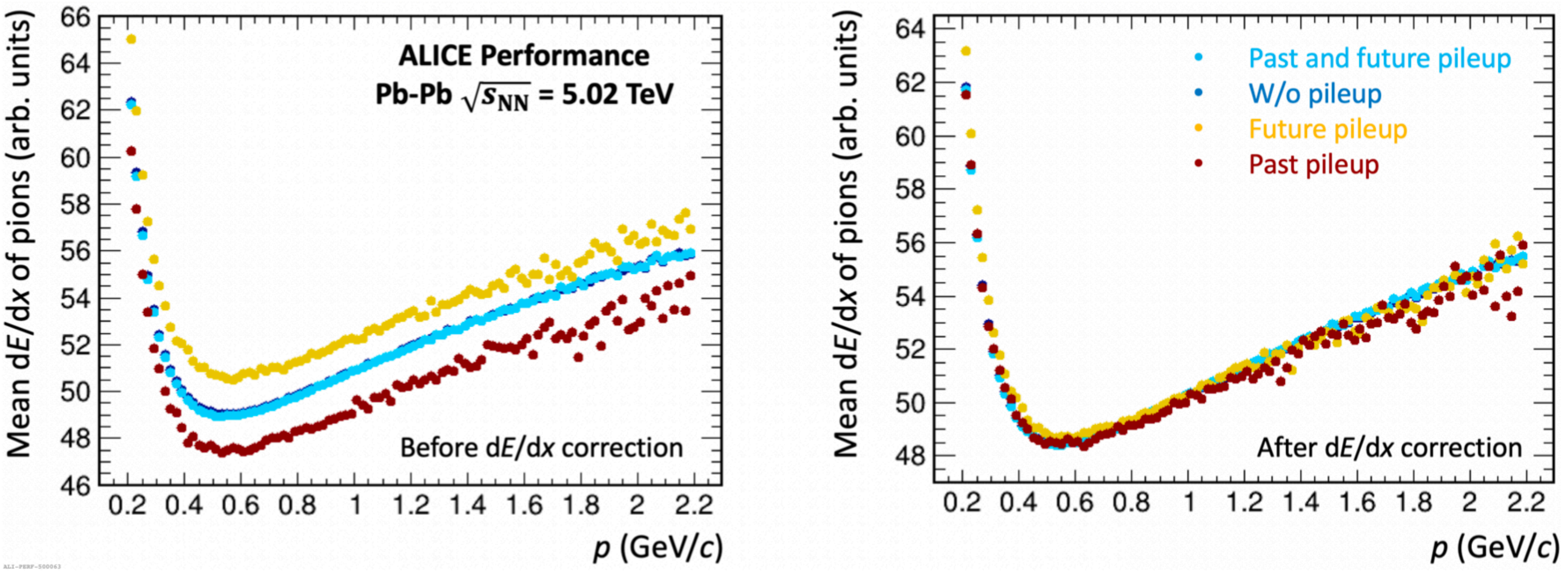
Volume fluctuations at LHC energies





- For the 2nd and 3rd order cumulants it cancels out at LHC
- Strongly depends on the particle multiplicity within the **kinematic acceptance** and the **underlying physics**
- **LQCD expectation** → for the 4th order the effect can be more than **an order of magnitude larger than the signal**
- **Ultimate solution** → R. Holzmann, V. Koch, A. Rustamov, J. Stroth arXiv:2403.03598

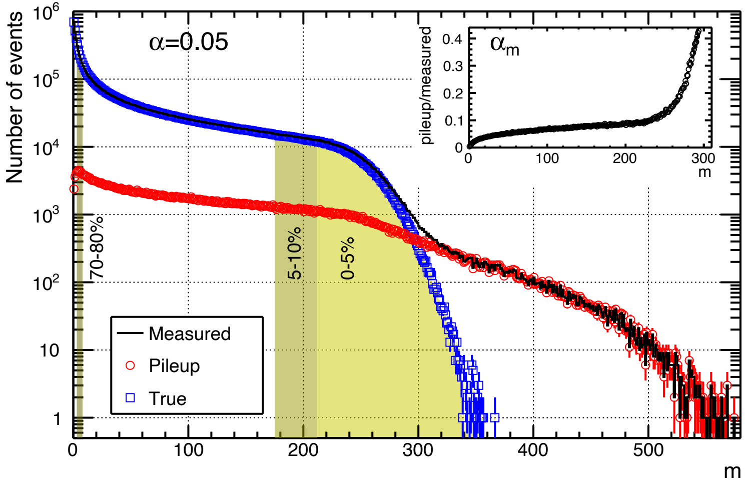
Experimental challenges: E.g. effect of event pileup



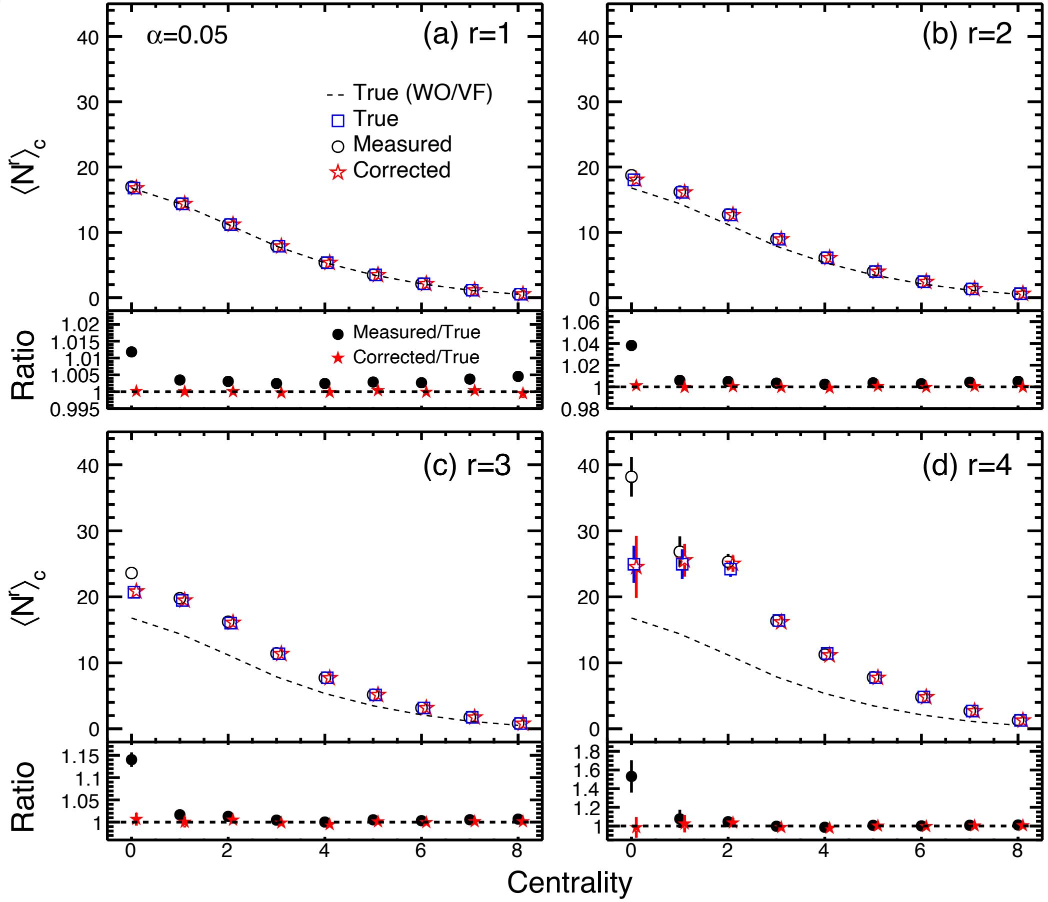
M. Arslandok, E. Hellbär, M. Ivanov, R.H. Münzer and J. Wiechula, Particles 2022, 5(1), 84-95}

Effect of in-bunch pileup

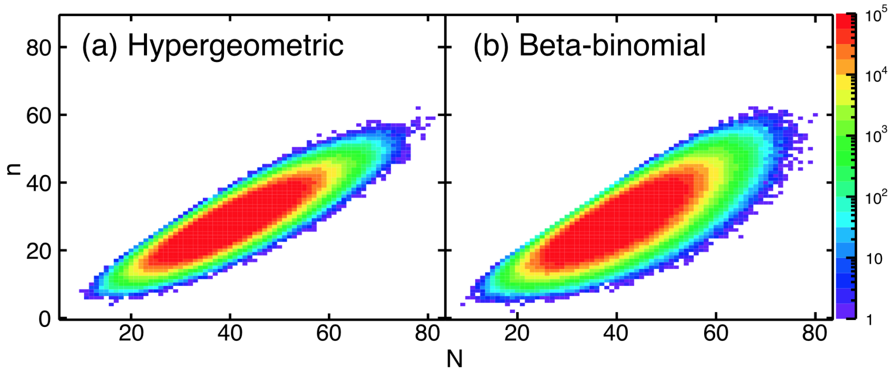
Y. Zhang, Y., T. Nonaka, X. Luo, arXiv:2108.10134
T. Nonaka, M. Kitazawa, S. Esumi, Nucl.Instrum.Meth. A984 (2020)



- **In-bunch pileup**
  → Significant impact on the higher order cumulants
  → **Less then 0.1% → negligible**
- **Out-of-bunch pileup**
  → Significant impact on the detector response
  → **Effect is corrected to a large extend**



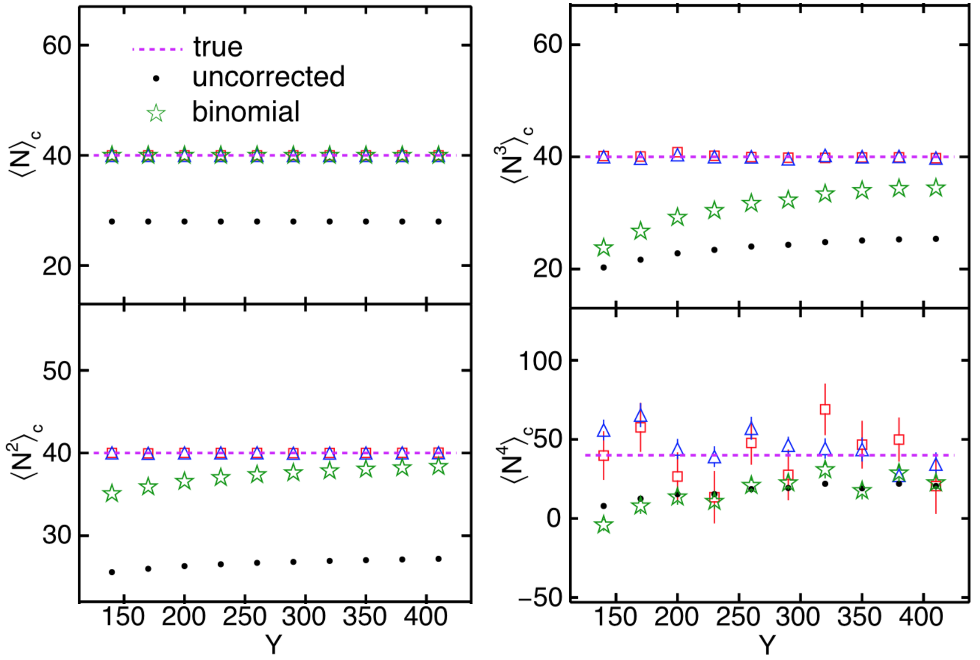
What if efficiency loss is not binomial?



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

Hypergeometric

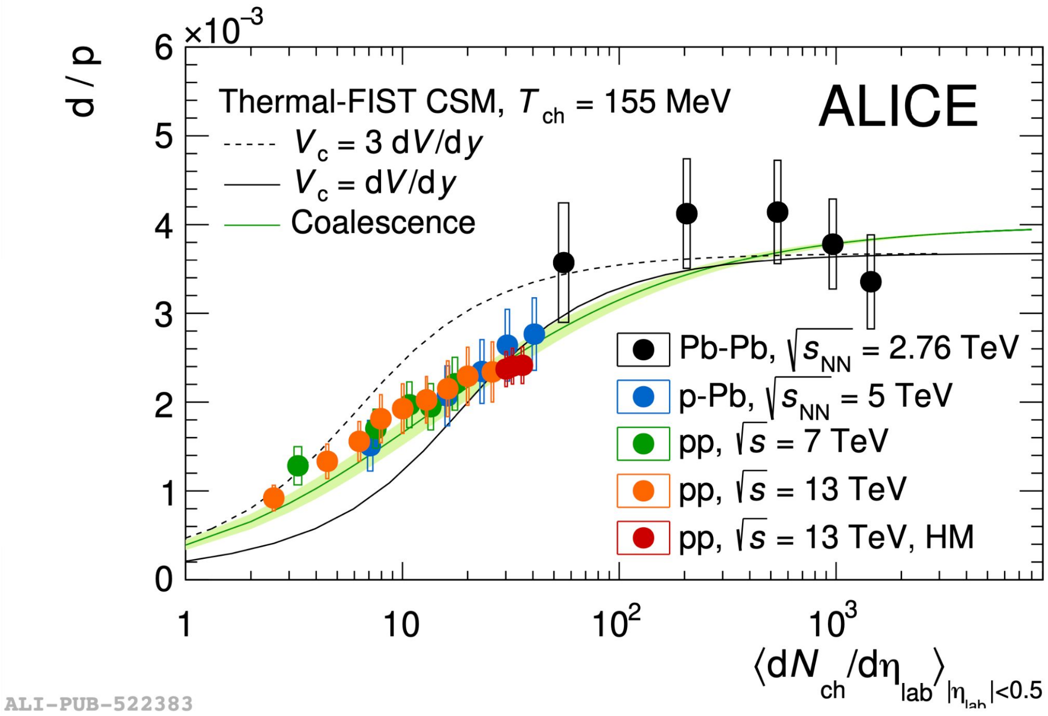


T. Nonaka, M. Kitazawa, S. Esumi, Nucl.Instrum.Meth. A906 (2018) 10-17

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

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

Light nuclei production



Reduction in small systems due either to

baryon conservation (CSM) or **to source vs. deuteron size (coalescence)**

Correlation and cumulant of net-particles

Charged kaons and Ξ baryons

- Same- and opposite-charge correlations → 2 species
- No autocorrelation
  - Negligible resonance feeddown
- Negligible uncorrelated weak feeddown from Ω
- Experimentally → high purity via PID (K) and machine learning selections (Ξ)

Net-kaon net-xi correlation

- Includes both same and opposite strangeness
- Cancellation of initial volume fluctuation

A. Rustamov *et al.*, Nucl. Phys. A 960 (2017) 114-130

$$\varrho(\Delta\Xi, \Delta K) = \kappa_{11}(\Delta\Xi, \Delta K) / \sqrt{(\kappa_2(\Delta\Xi)\kappa_2(\Delta K))}$$

with $\Delta\Xi = \Xi^+ - \Xi^-$ and $\Delta K = K^+ - K^-$

$$\kappa_{11}(\Delta\Xi, \Delta K) = \kappa_{11}(\Xi^+, K^+) + \kappa_{11}(\Xi^-, K^-) - \kappa_{11}(\Xi^-, K^+) - \kappa_{11}(\Xi^+, K^-)$$

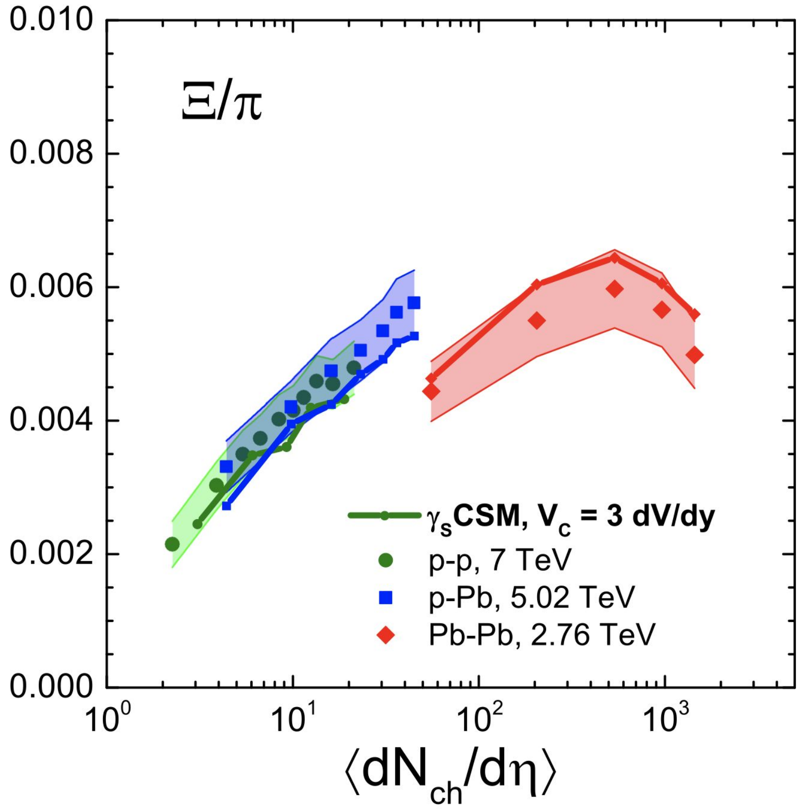
$$\kappa_2(\Delta n) = \kappa_2(n^+) + \kappa_2(n^-) - 2\kappa_{11}(n^+, n^-)$$

Net-xi cumulant ratio

- E-by-e fluctuations of ΔΞ multiplicity distribution

$$\kappa_2 / \kappa_1(\Delta\Xi) = \kappa_2(\Delta\Xi) / \kappa_1(\Xi^+ + \Xi^-)$$

Canonical statistical model



V. Vovchenko *et al.*, PRC 100, 054906 (2019)