Fluctuations and correlations at LHC energies

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Yale University

EMMI Symposium: Fluctuations and correlations of conserved charges in nuclear collisions – Challenges and future prospects
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Yale Wright Laboratory
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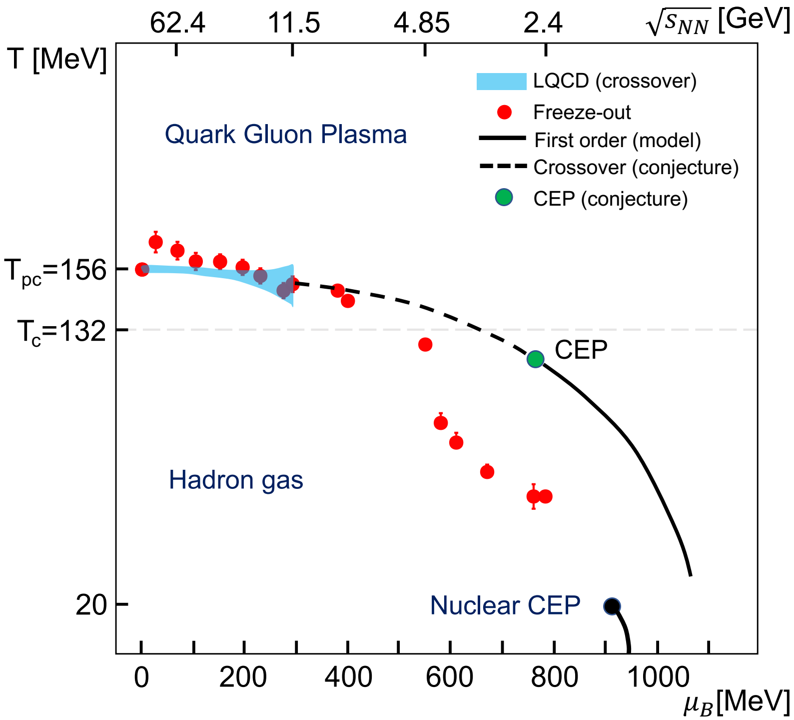
U.S. DEPARTMENT OF ENERGY | Office of Science

Outline



P. Braun-Munzinger, A. Rustamov, J. Stachel,
e-Print: 2211.08819 [hep-ph], 2212.11107 [hep-ph]

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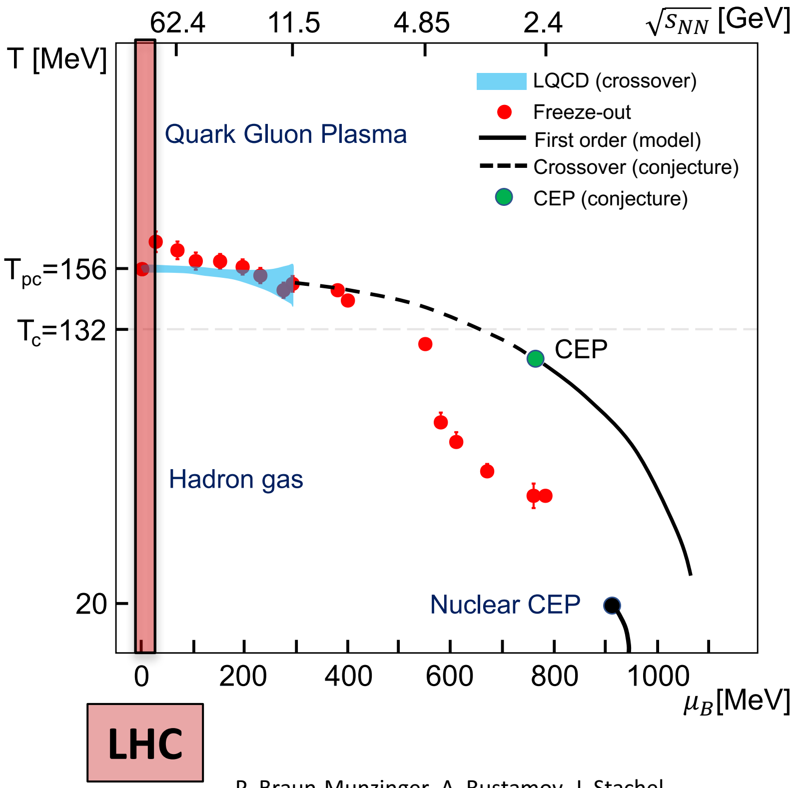

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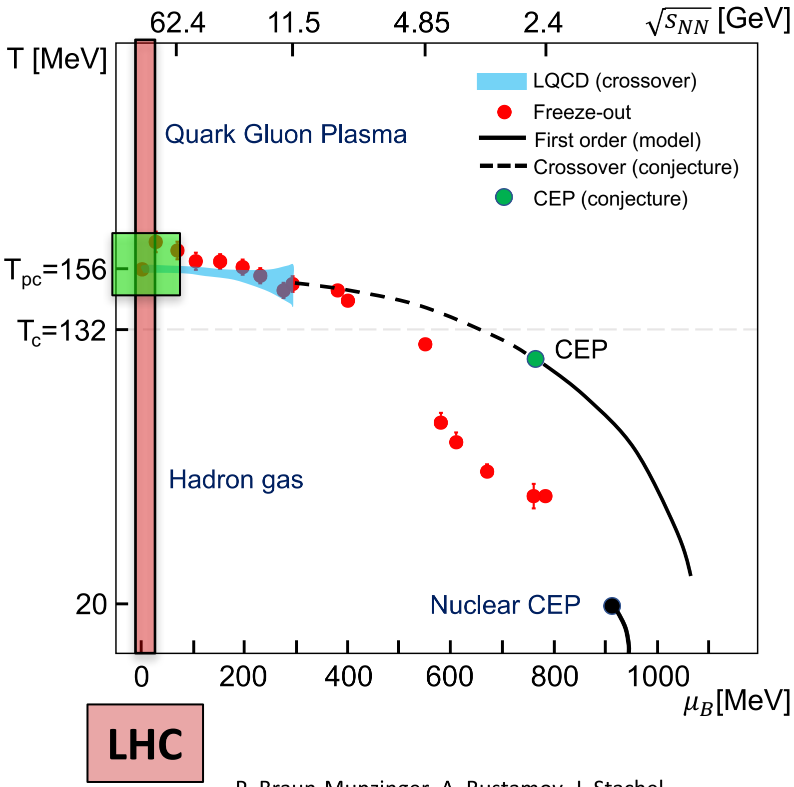

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✓ **How do we measure?**

→ Experimental challenges

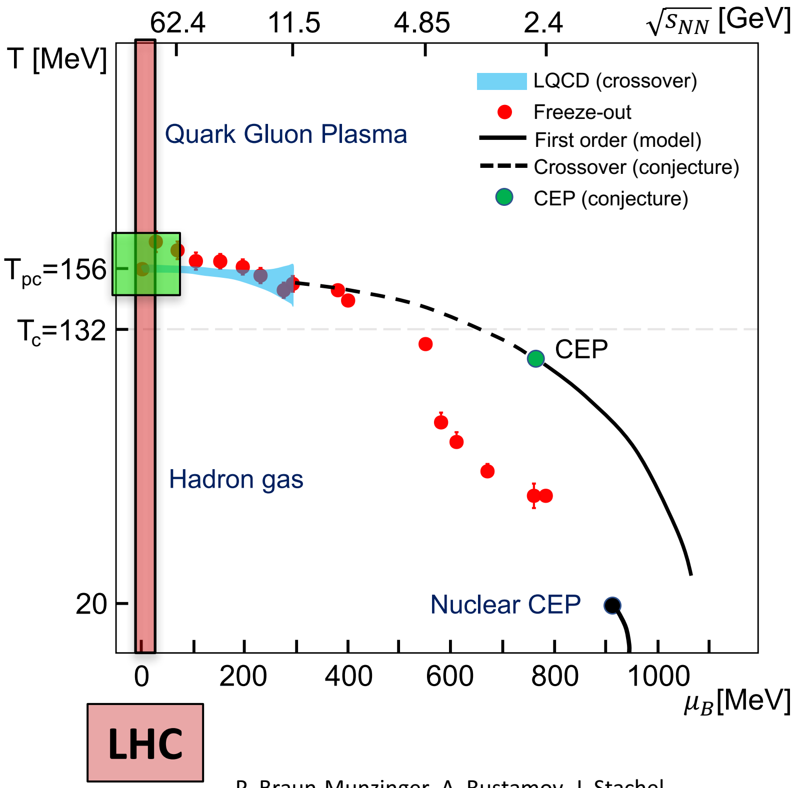
✓ **What did we learn?**

→ Strangeness and baryon number fluctuations

✓ **What can we learn?**

→ A next-generation heavy-ion experiment: ALICE3

→ High precision S and B + charm fluctuations



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LQCD ↔ Experiment

Google Translate

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

English | German | Spanish | **EXPERIMENT**

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

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

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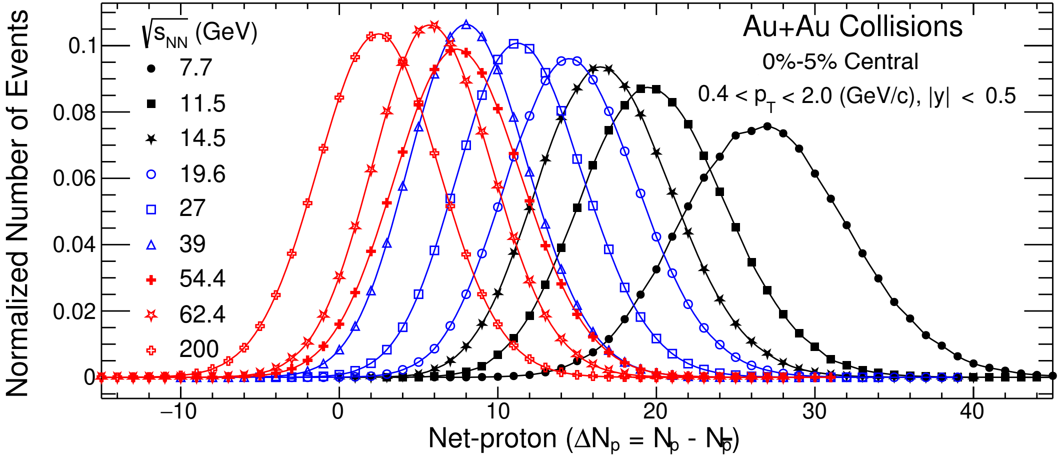
STAR Collaboration, Phys. Rev. Lett. 126, 092301



- Critical signal is in these distributions
- Experimentally very challenging

Brief summary of news from LQCD

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

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

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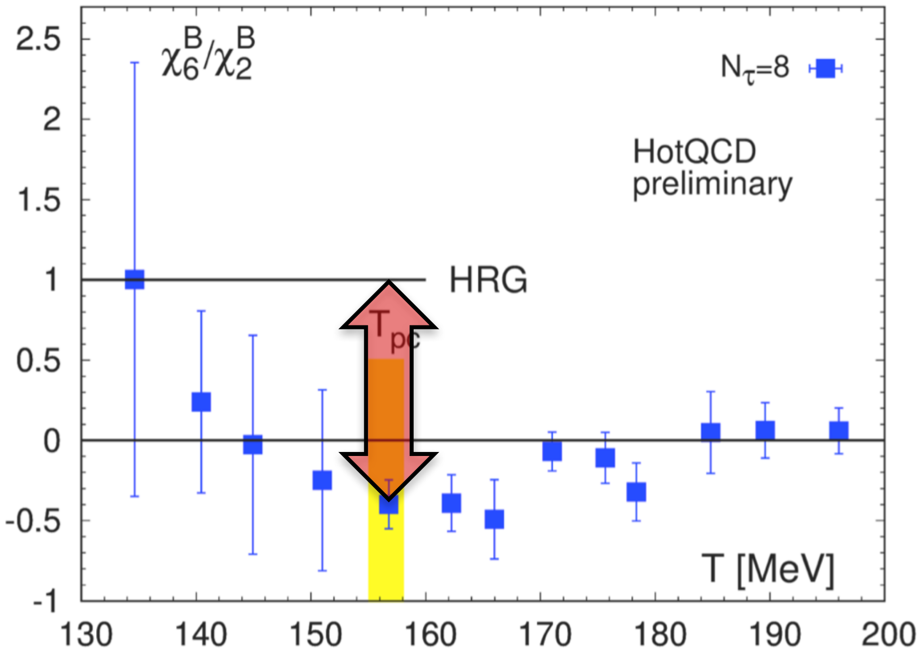
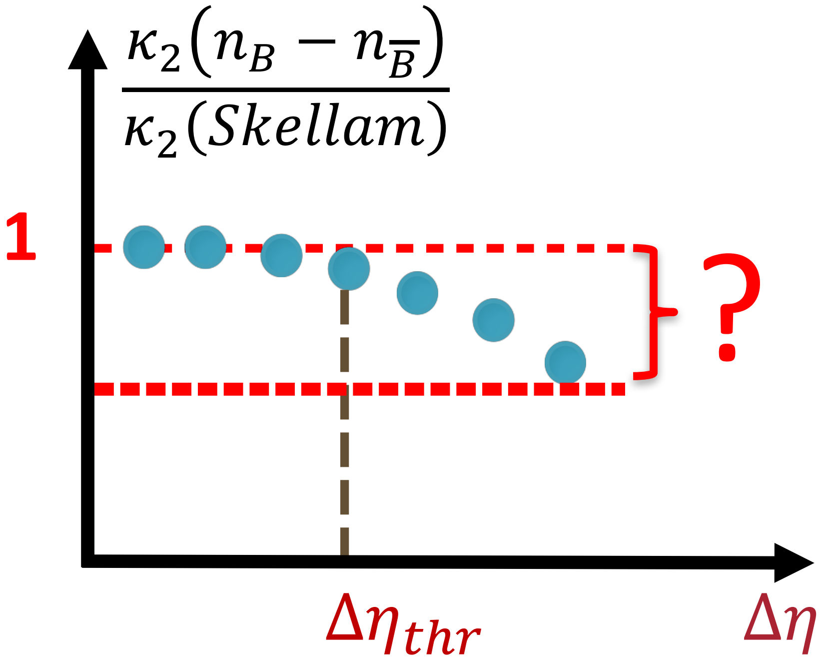
3) **Holy grail:** Critical behavior as from 6th order
   $\Longrightarrow$ 4th order ~30%, **6th order ~150%**



Data is more than LQCD

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



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

How do we measure cumulants?

(Experimental Challenges)

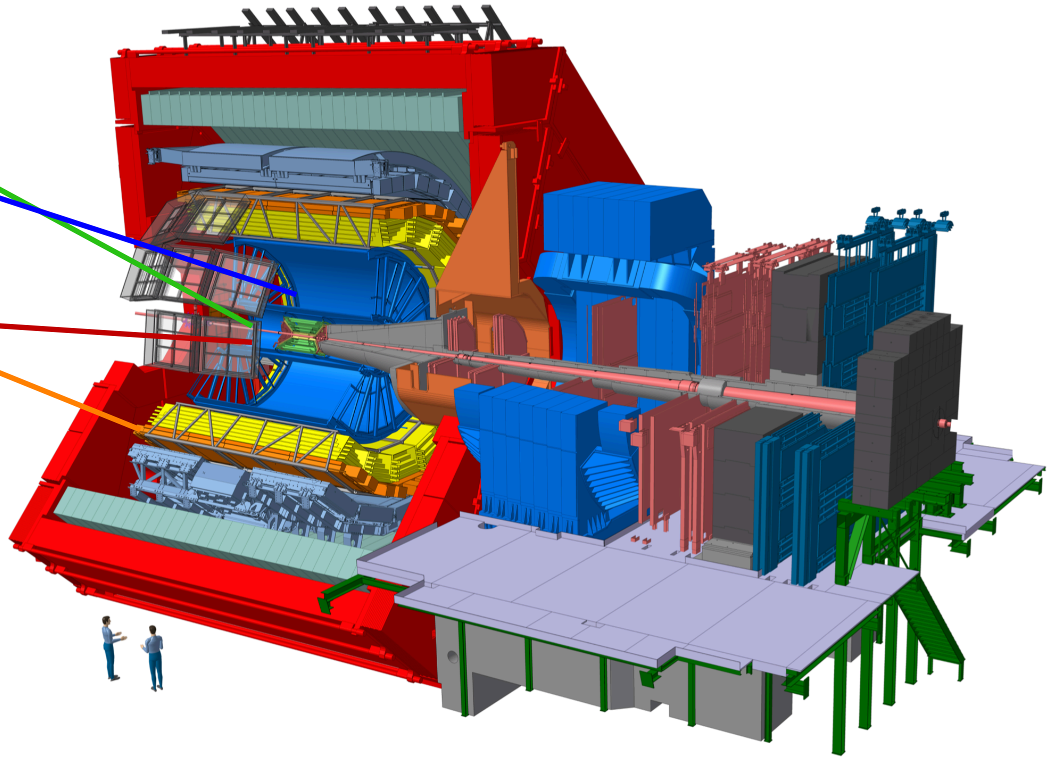
A Large Ion Collider Experiment

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



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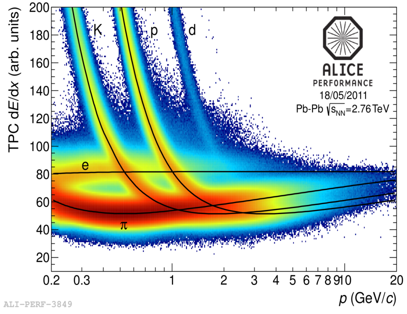
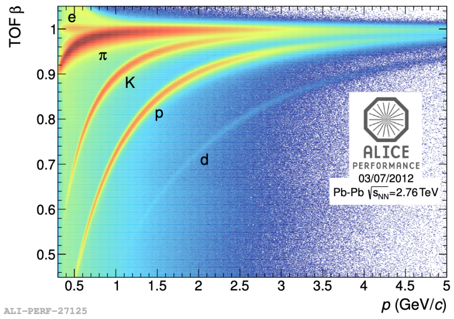
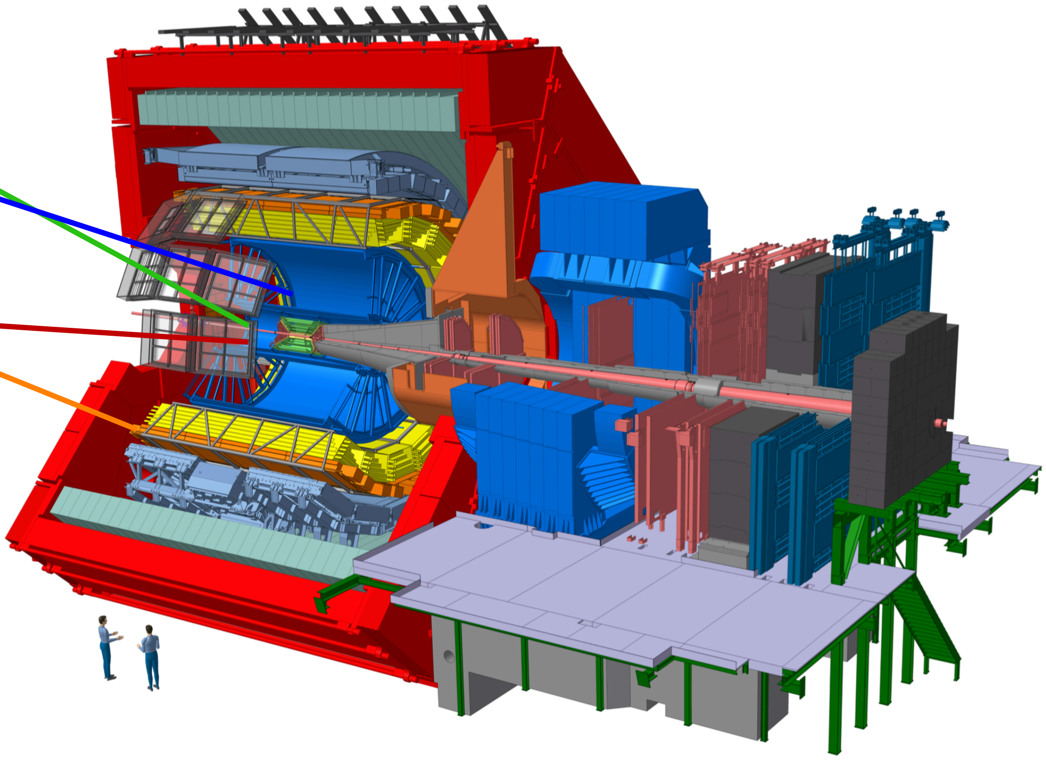


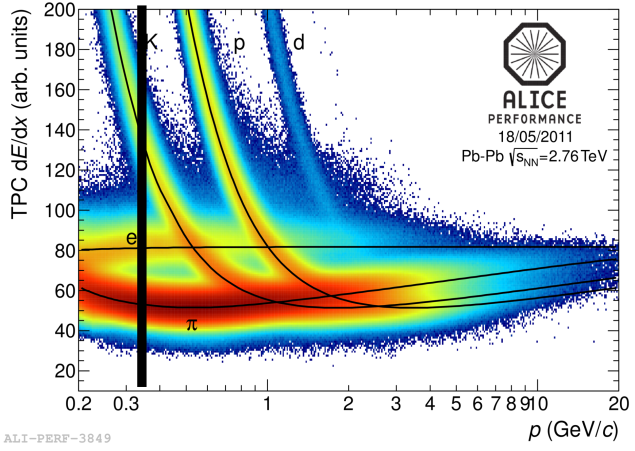


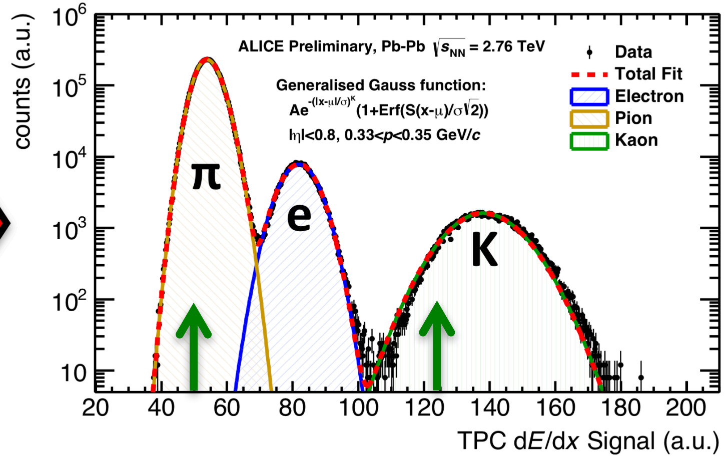


Challenge 1: Particle identification (PID)

We use two methods:

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





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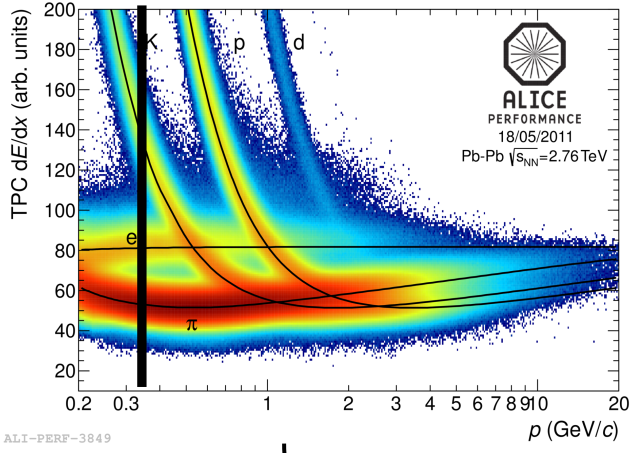
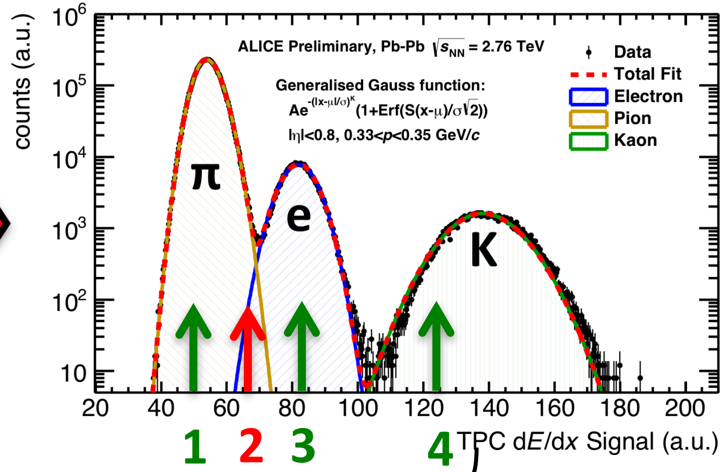


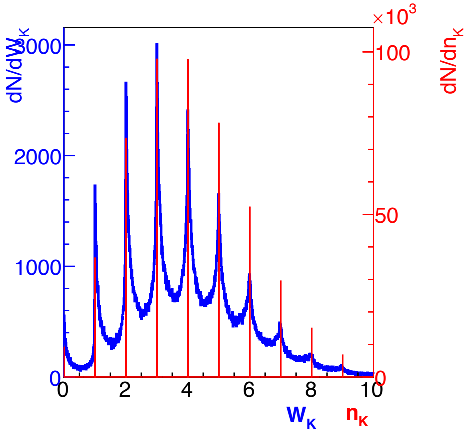


$$\omega_\pi^{(1)} = 1, \quad \omega_\pi^{(2)} \cong 0.6, \quad \omega_\pi^{(3)} = 0, \quad \omega_\pi^{(4)} = 0 \quad \Rightarrow \quad W_\pi = 1.6 \neq N_\pi$$

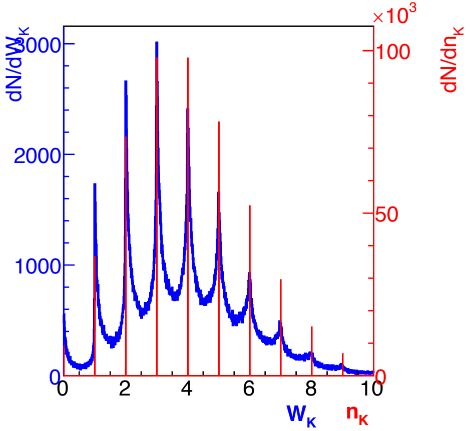
A. Rustamov, M. Gazdzicki, M. I. Gorenstein, PRC 86, 044906 (2012), PRC 84, 024902 (2011)

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

Identity method vs Cut-based approach

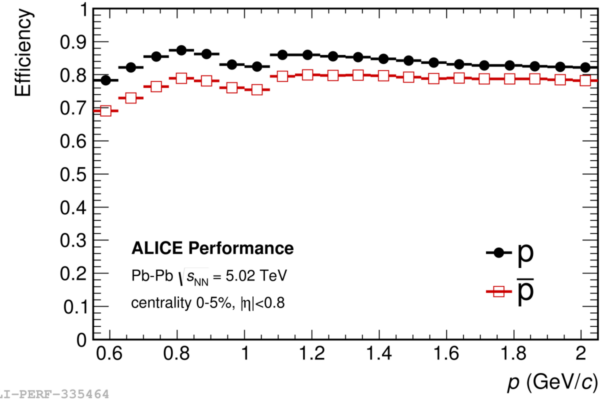


$$\langle N_j^n \rangle = A^{-1} \langle W_j^n \rangle$$

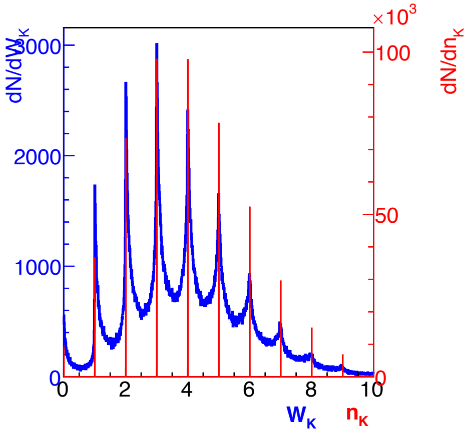


$$\langle N_j^n \rangle = A^{-1} \langle W_j^n \rangle$$

- **Identity Method**
  - Gives folded multiplicity distribution
  - **PID contamination circumvented**
  - **Maximal efficiency**

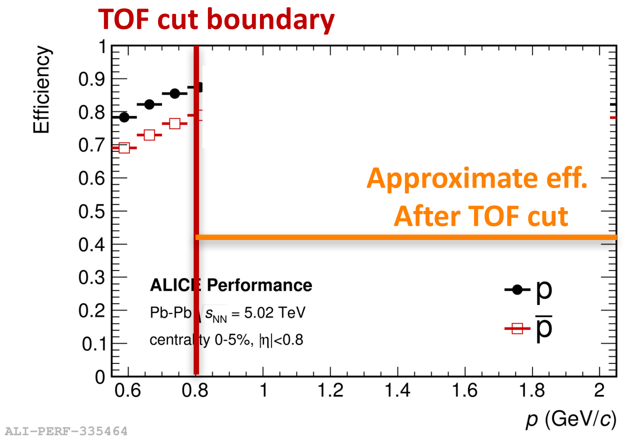


Identity method vs Cut-based approach



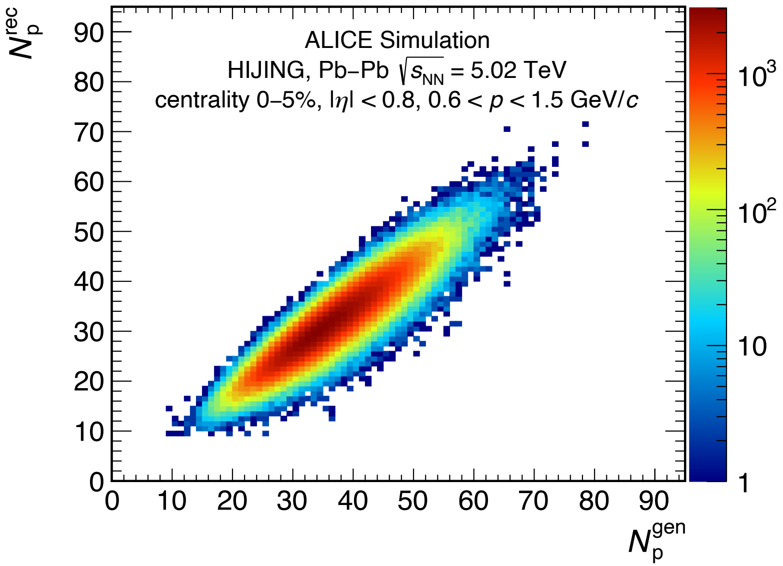
$$\langle N_j^n \rangle = A^{-1} \langle W_j^n \rangle$$

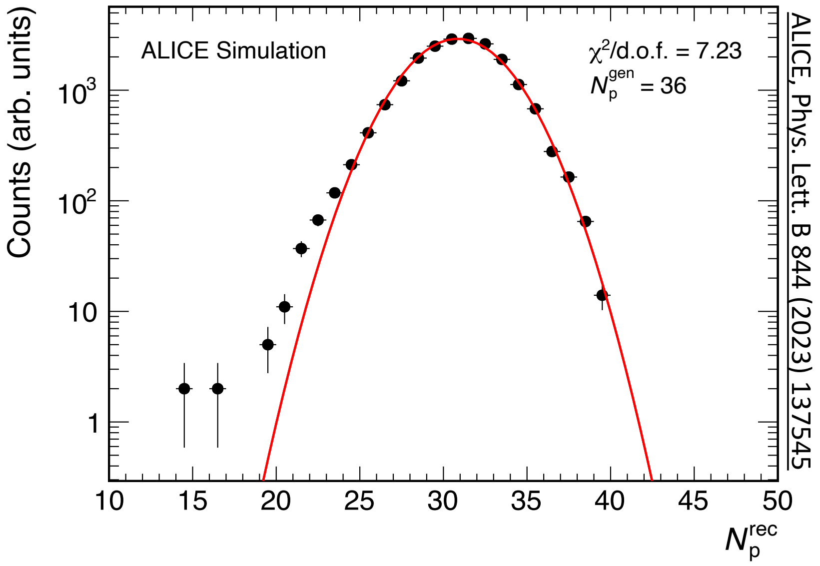
- **Identity Method**
  - Gives folded multiplicity distribution
  - **PID contamination circumvented**
  - **Maximal efficiency**
- **Cut based approach**
  - Use additional detector information or reject a given phase space bin to avoid overlap in TPC dE/dx
  - **Low efficiency & PID contamination**



Challenge 2: Efficiency correction

Binomiality of the detector response is important for the efficiency correction

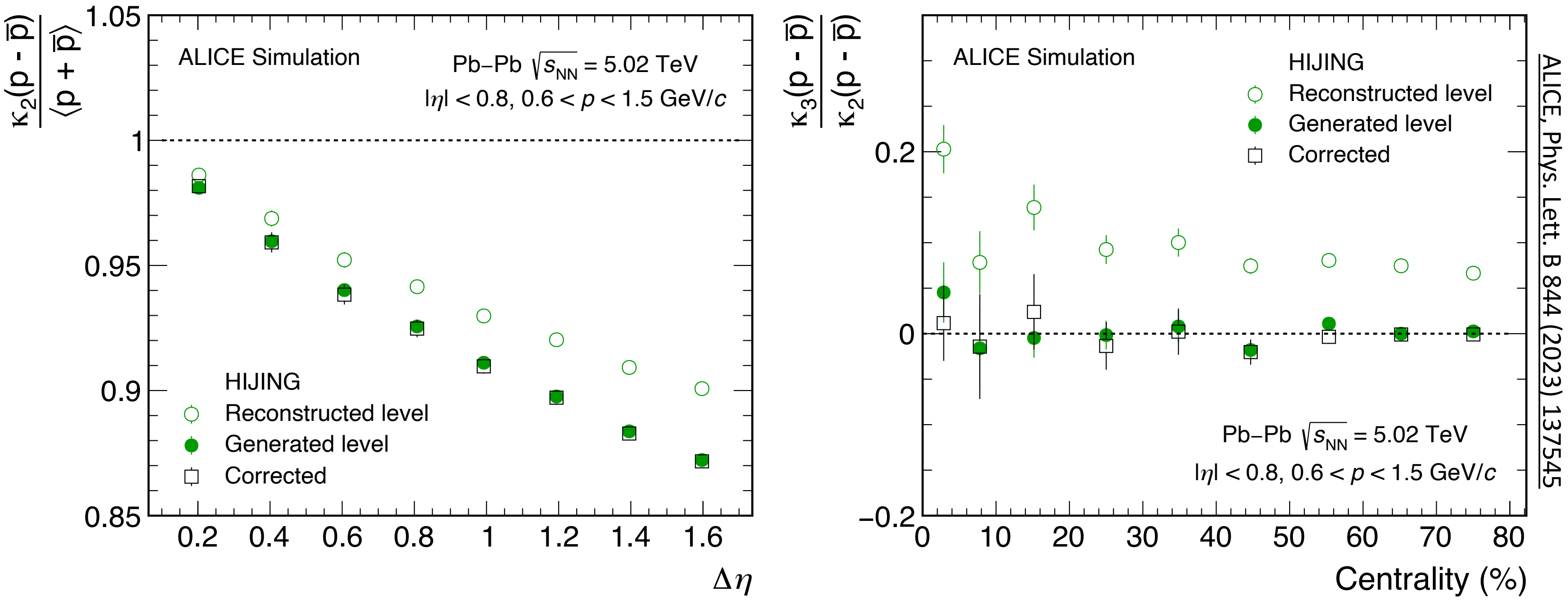




Slight deviation from the binomial efficiency loss

- Event and track selection
- TPC 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

MC closure



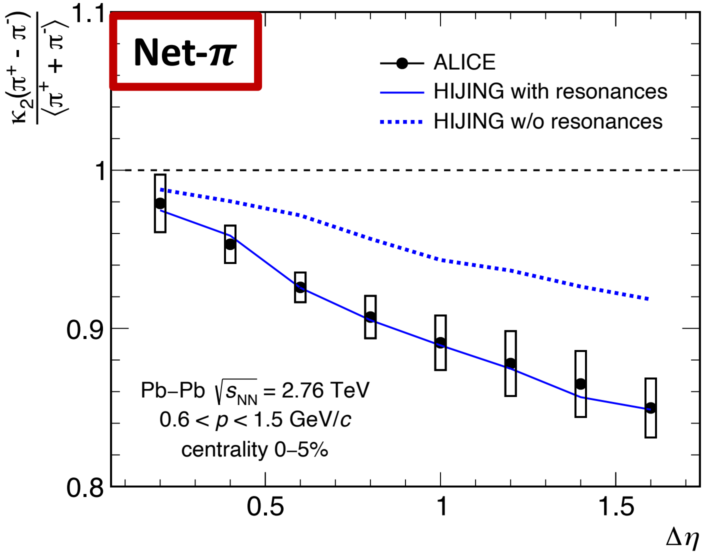
Very good closure despite the slight deviation from binomial loss

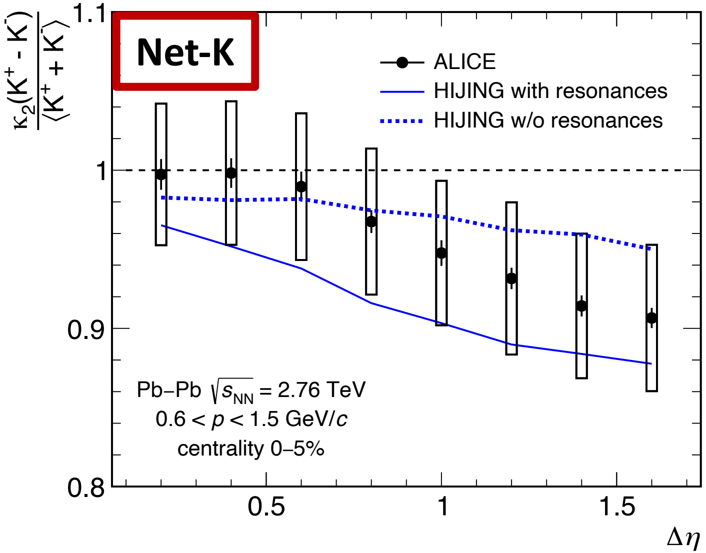
Efficiency correction with binomial assumption:

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

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

Challenge 3: Resonance decays

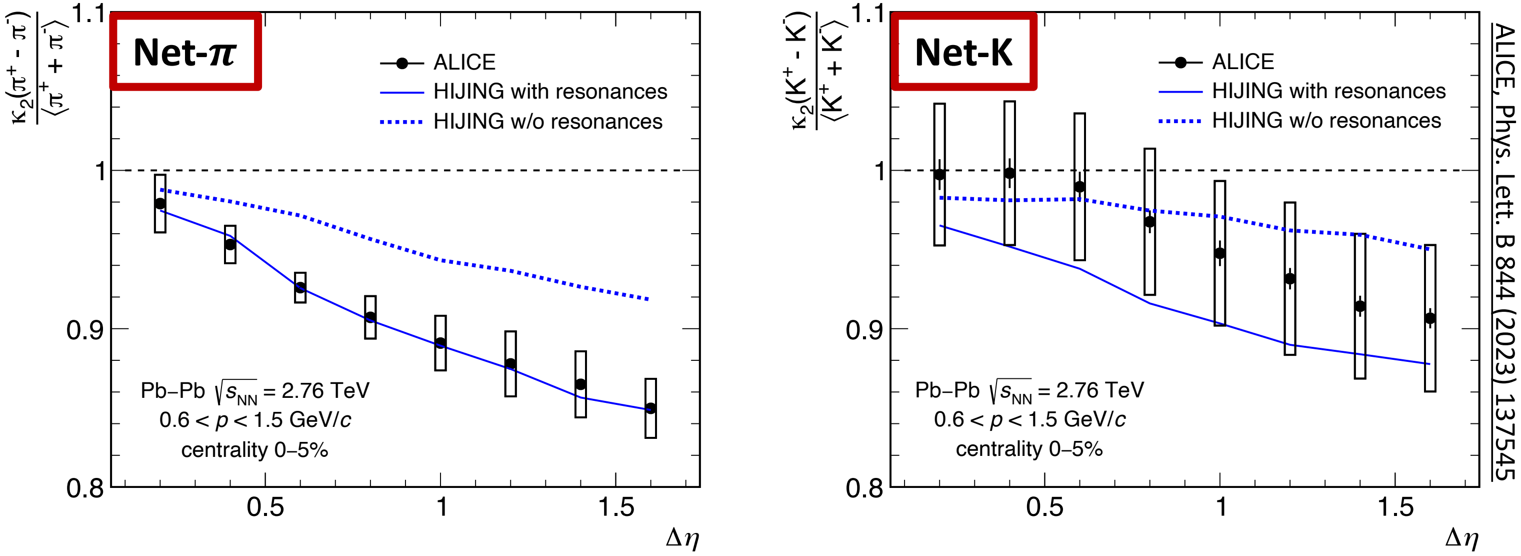




ALICE, Phys. Lett. B 844 (2023) 137545

➢ **Net-π and net-K are** strongly dominated by resonance contributions

Challenge 3: Resonance decays

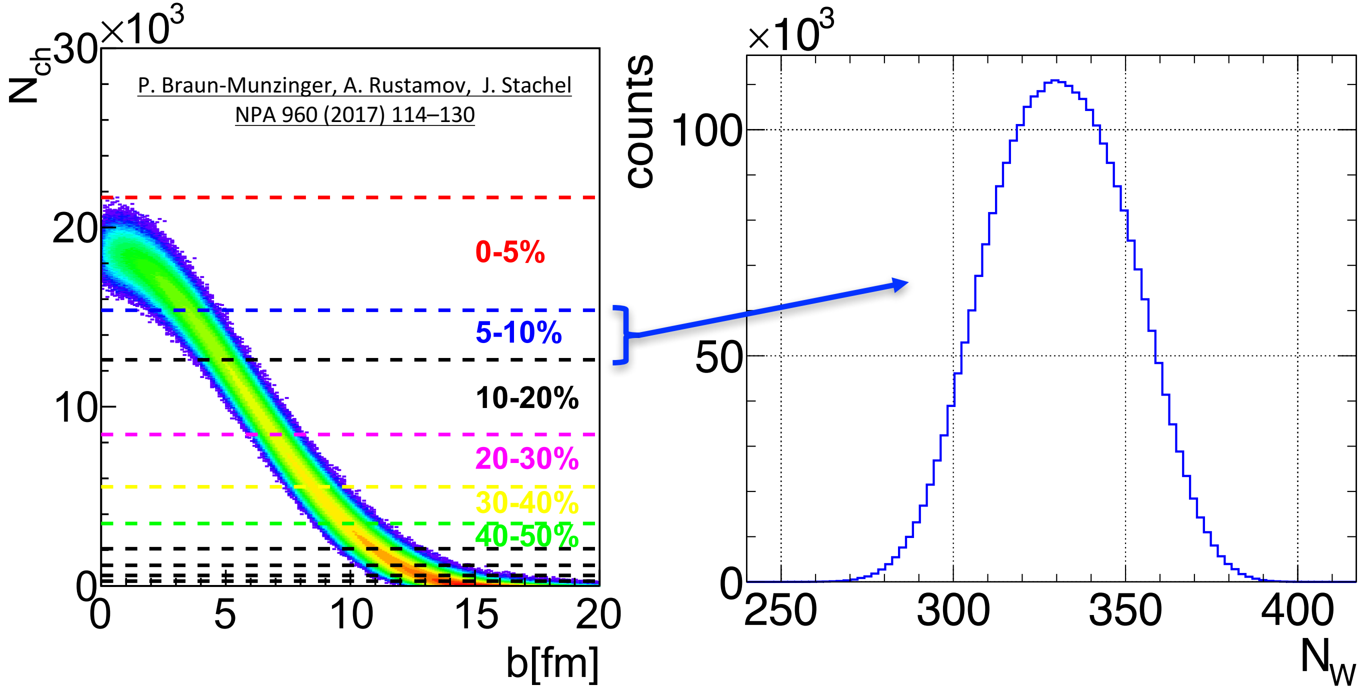


- **Net-π and net-K are** strongly dominated by resonance contributions
- **Net-p and net-Ξ** are free from resonance contributions

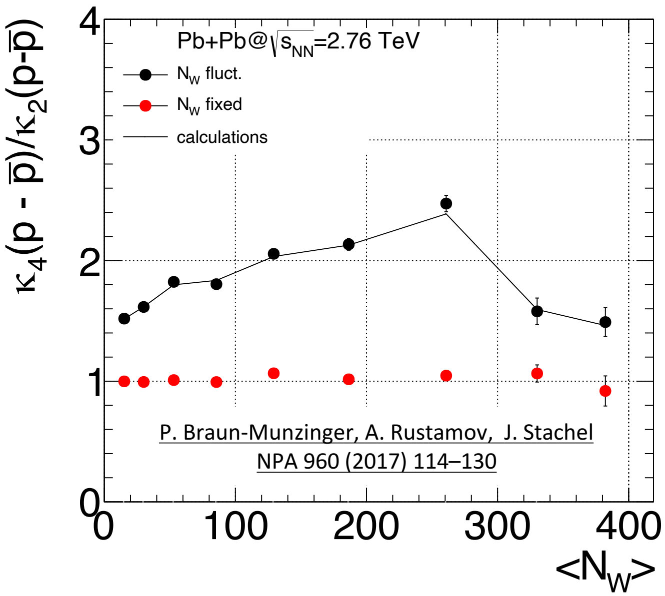
→ **Isospin randomization,** at $\sqrt{s_{NN}}$ > 10 GeV: **net-B ↔ net-p**

(M. Kitazawa, and M. Asakawa, Phys. Rev. C 86, 024904 (2012))

Challenge 4: Volume fluctuations

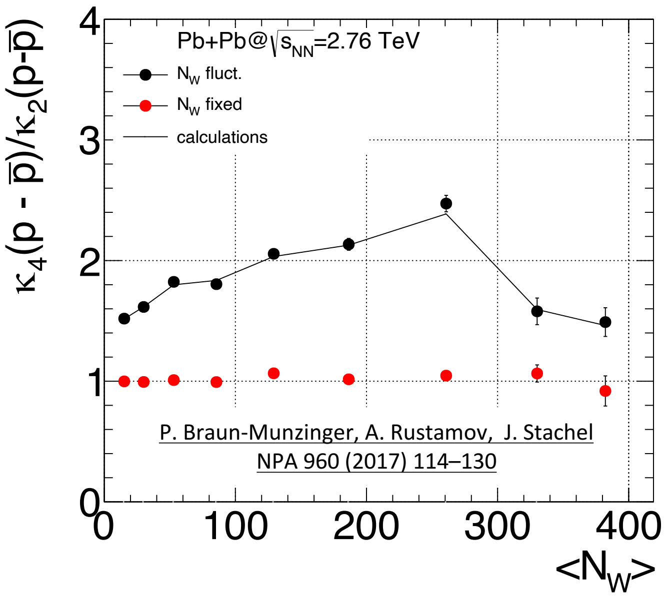


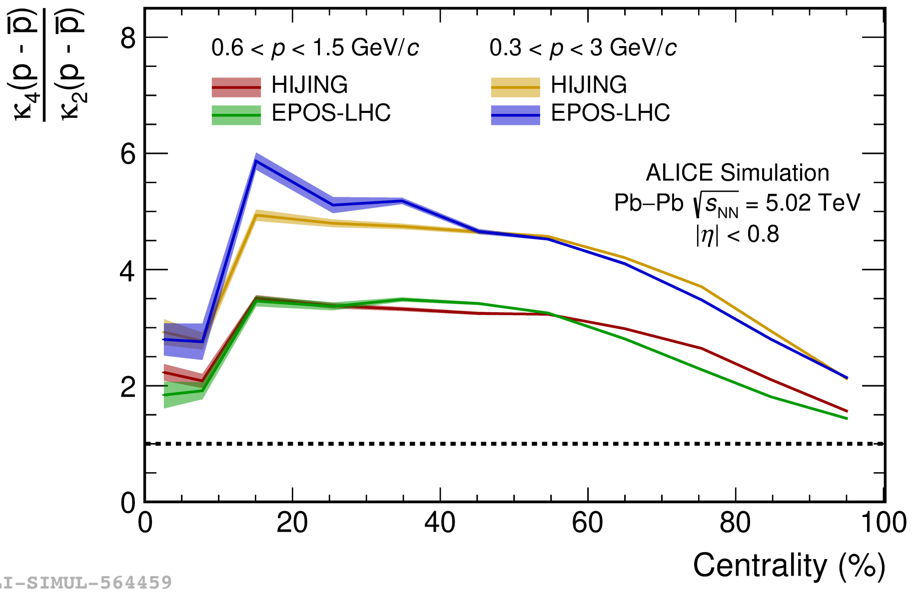
Volume fluctuations at LHC energies



- For the 2nd and 3rd order cumulants it cancels out at LHC

Volume fluctuations at LHC energies





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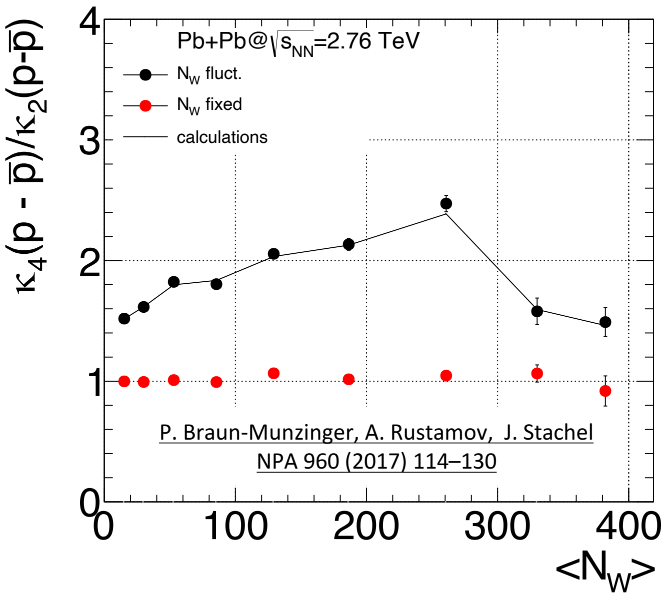
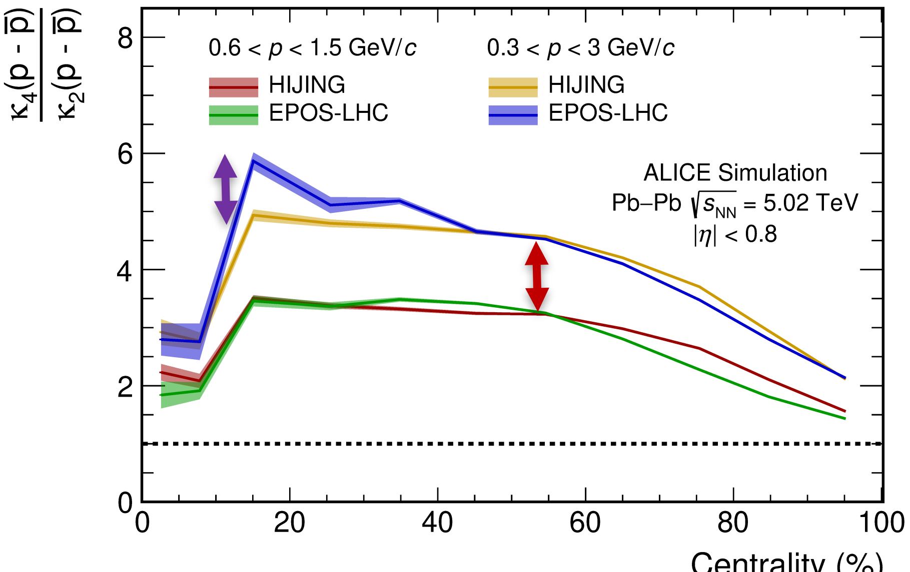
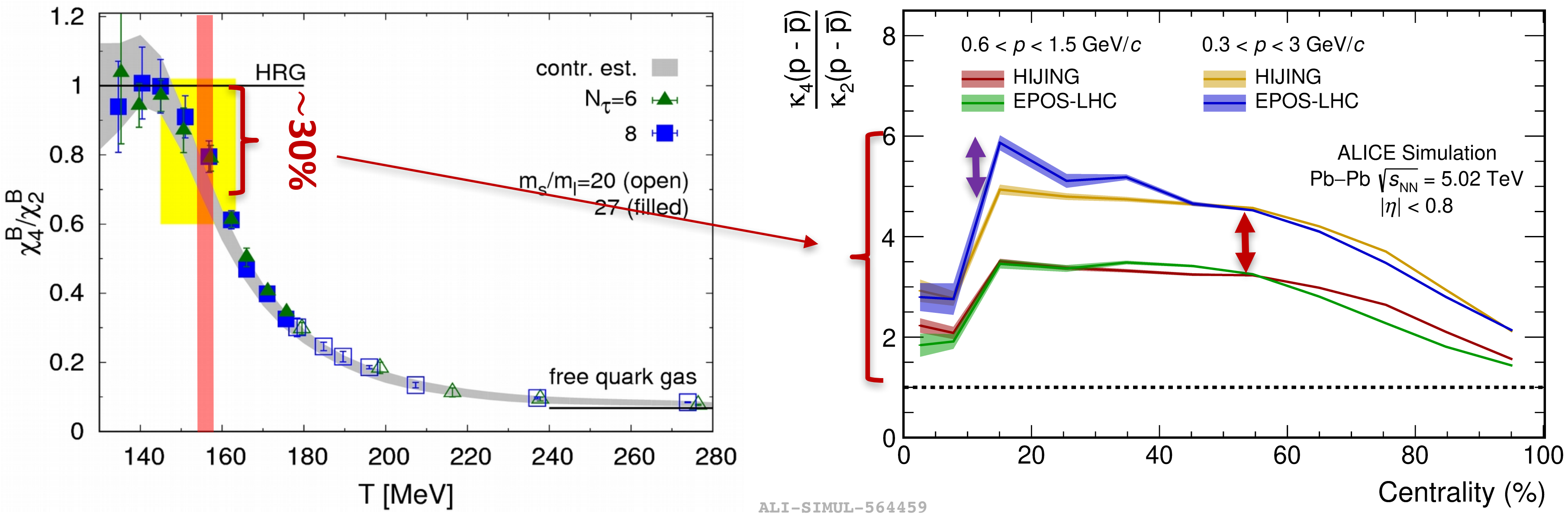




ALI-SIMUL-564459

- 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



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- **LQCD expectation** → for the 4th order the effect can be more than **an order of magnitude larger than the signal**

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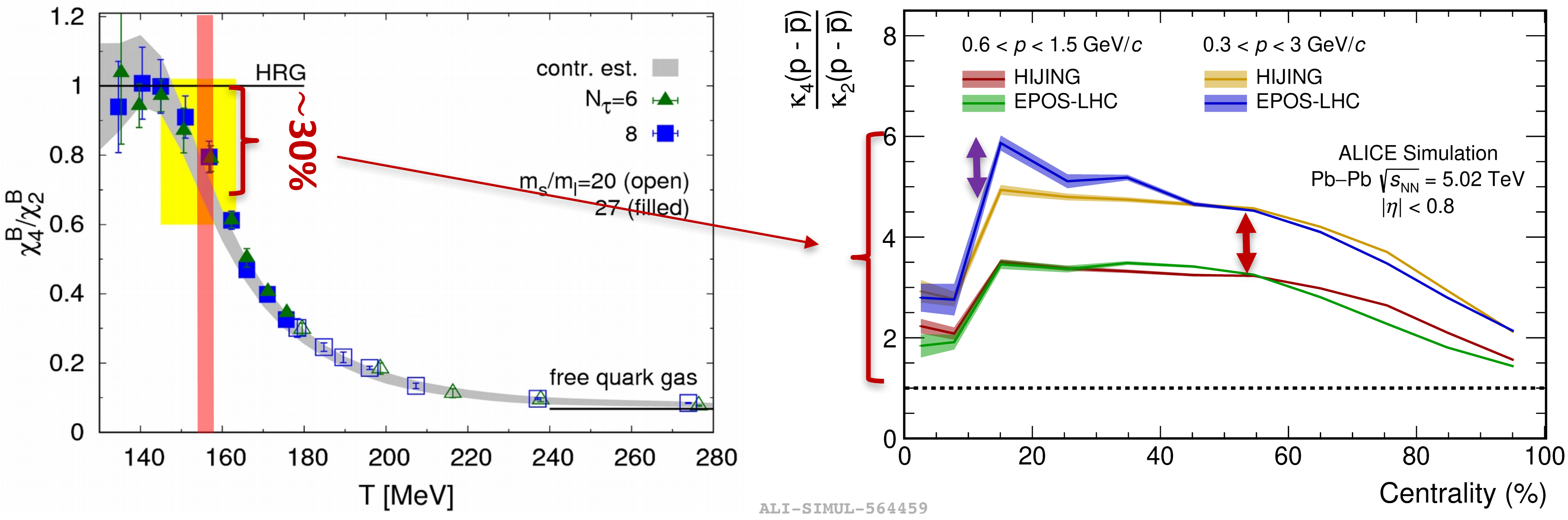

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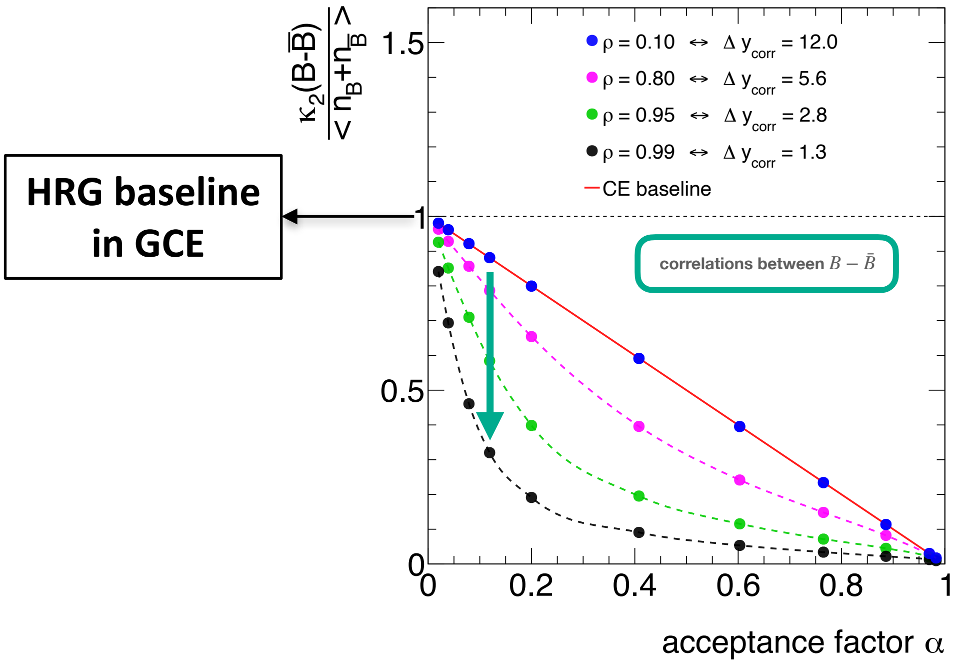
- Strongly depends on the particle multiplicity within the **kinematic acceptance** and the **underlying physics**
- **LQCD expectation** → for the 4th order the effect can be more than **an order of magnitude larger than the signal**
- **Mixed event approach** → work in progress

(A. Rustamov, R. Holzmann, J. Stroth, NPA 1034 (2023) 122641, V.Koch, R. Holzmann, A. Rustamov, J. Stroth, in progress)

What did we learn?

(Net-baryon)

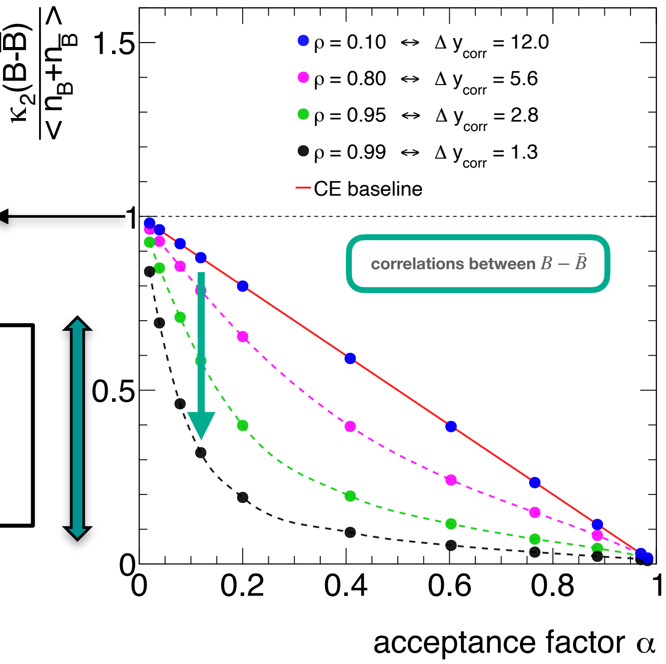
Small introduction



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

HRG baseline in GCE

Larger deviation:
→ Smaller correlation length
→ Late production



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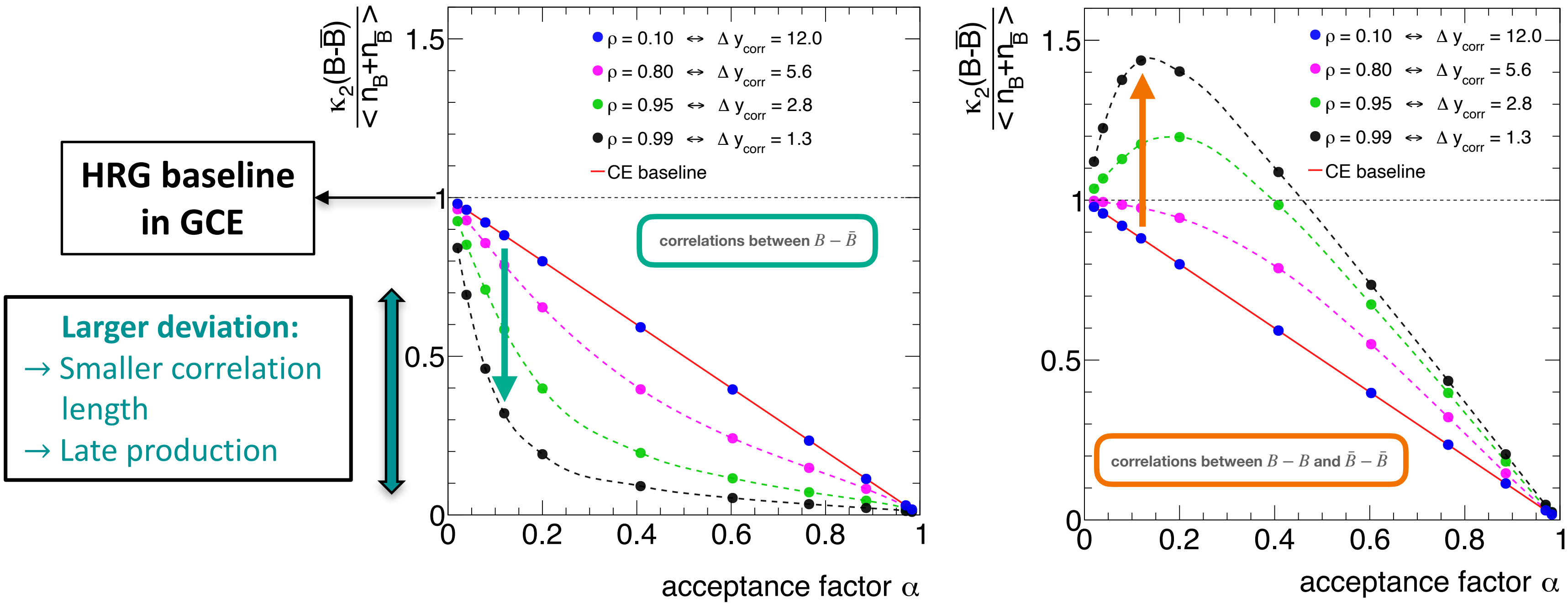
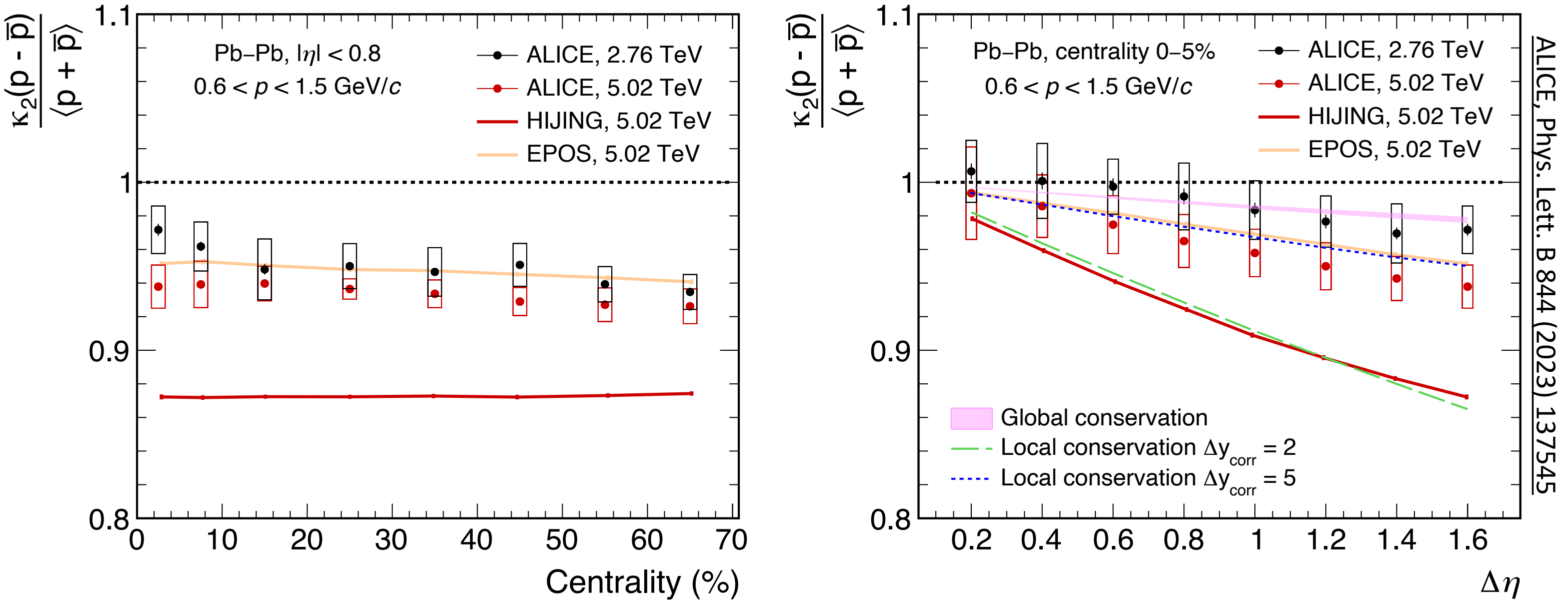


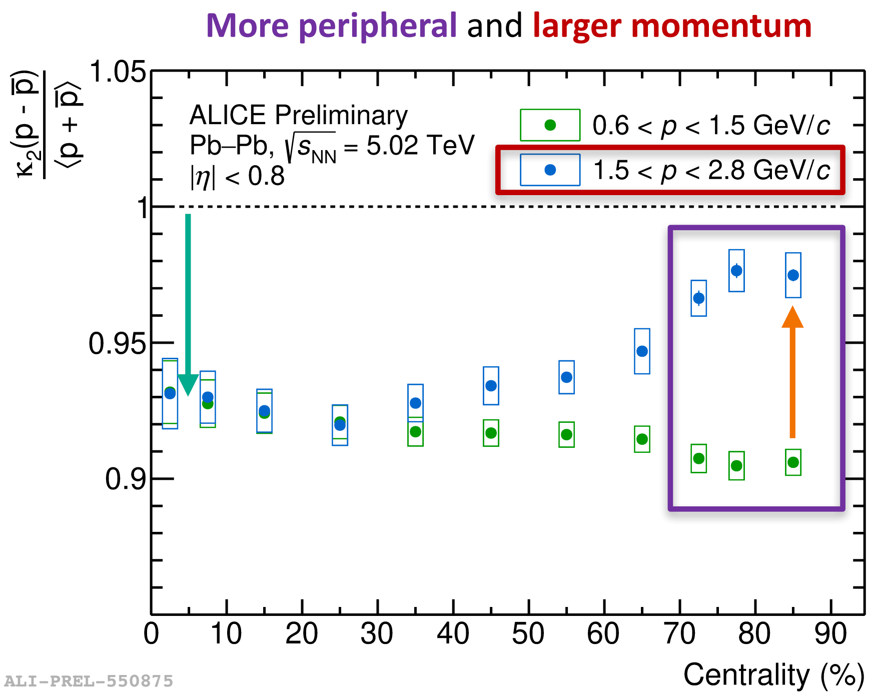
- ➢ Measured values depend on the fraction of (anti-)protons in the acceptance
- ➢ (Global) local baryon number conservation: **unlike-sign correlations**
- ➢ (Anti-)proton clusters: **like-sign correlations**

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**
  A. Dumitru, F. Gelis, L. McLerran, and R. Venugopalan, *Nucl. Phys. A* 810 (2008) 91
- Event generators based on **string fragmentation (HIJING)** conserve baryon number over $\Delta y = \pm 1$ **unit**

Pushing 2nd net-p to the limits



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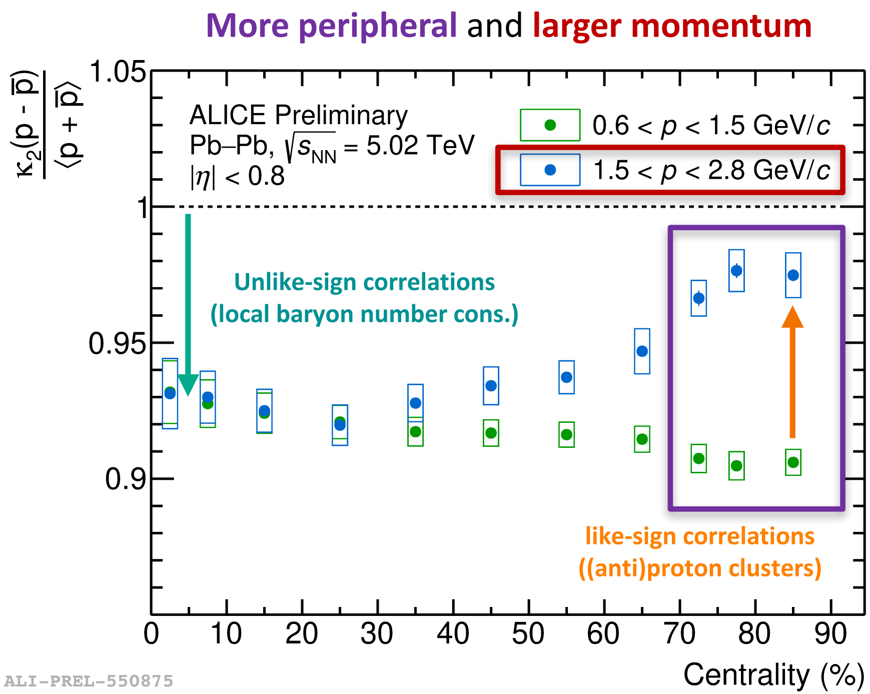
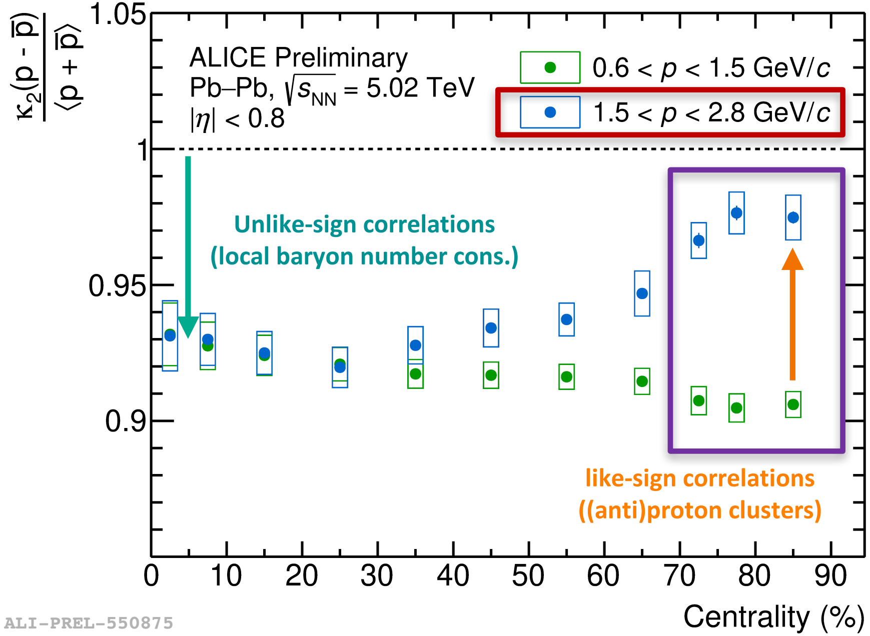
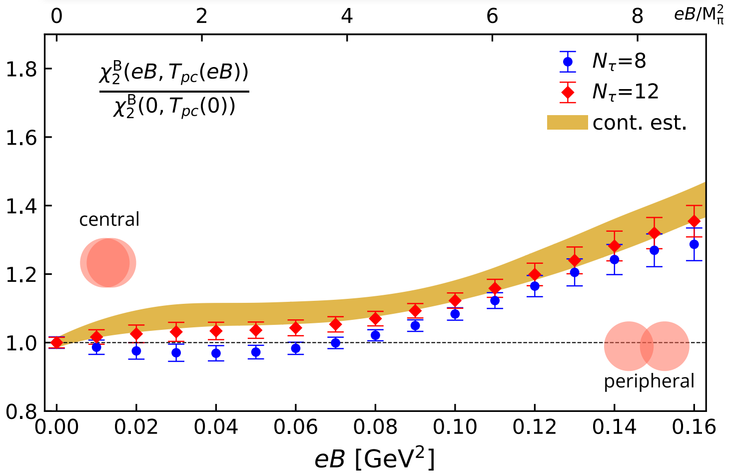


Pushing 2nd net-p to the limits

More peripheral and **larger momentum**



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



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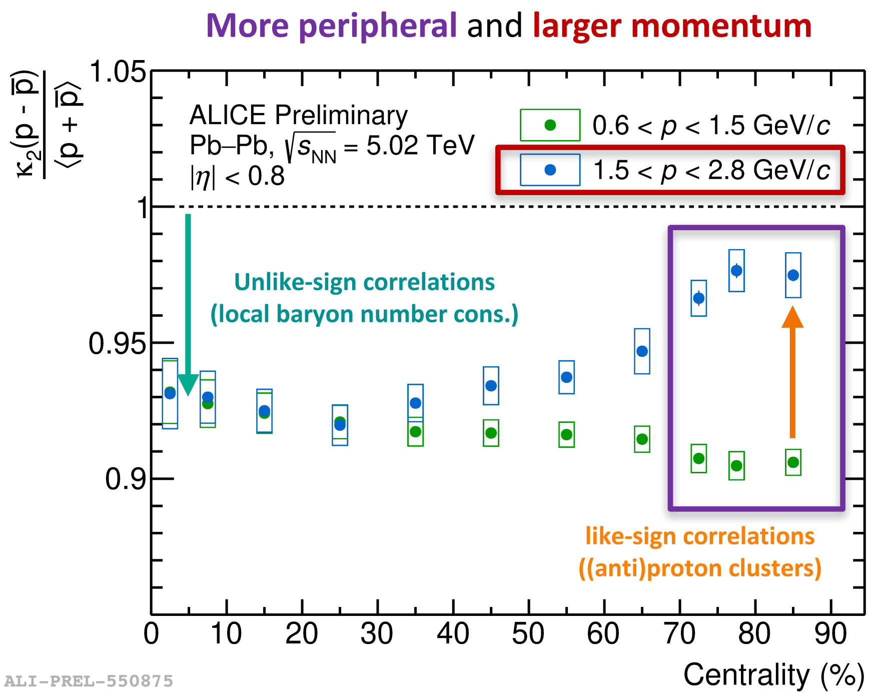
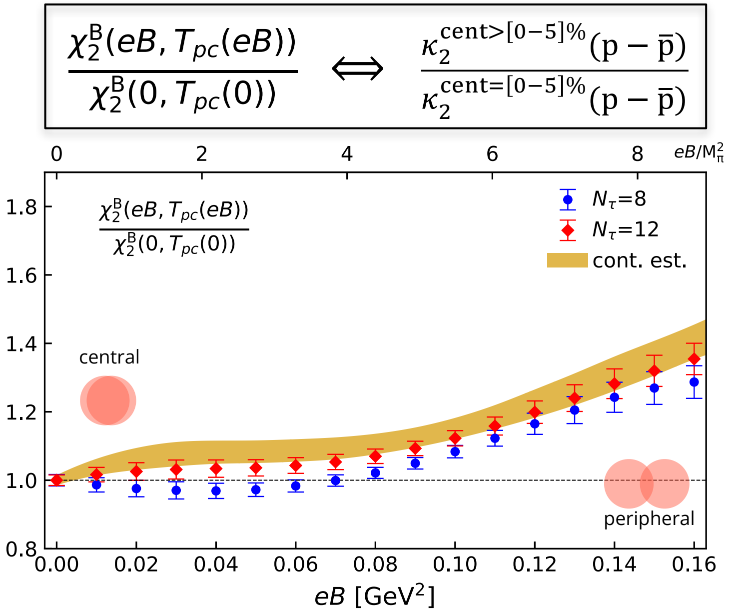
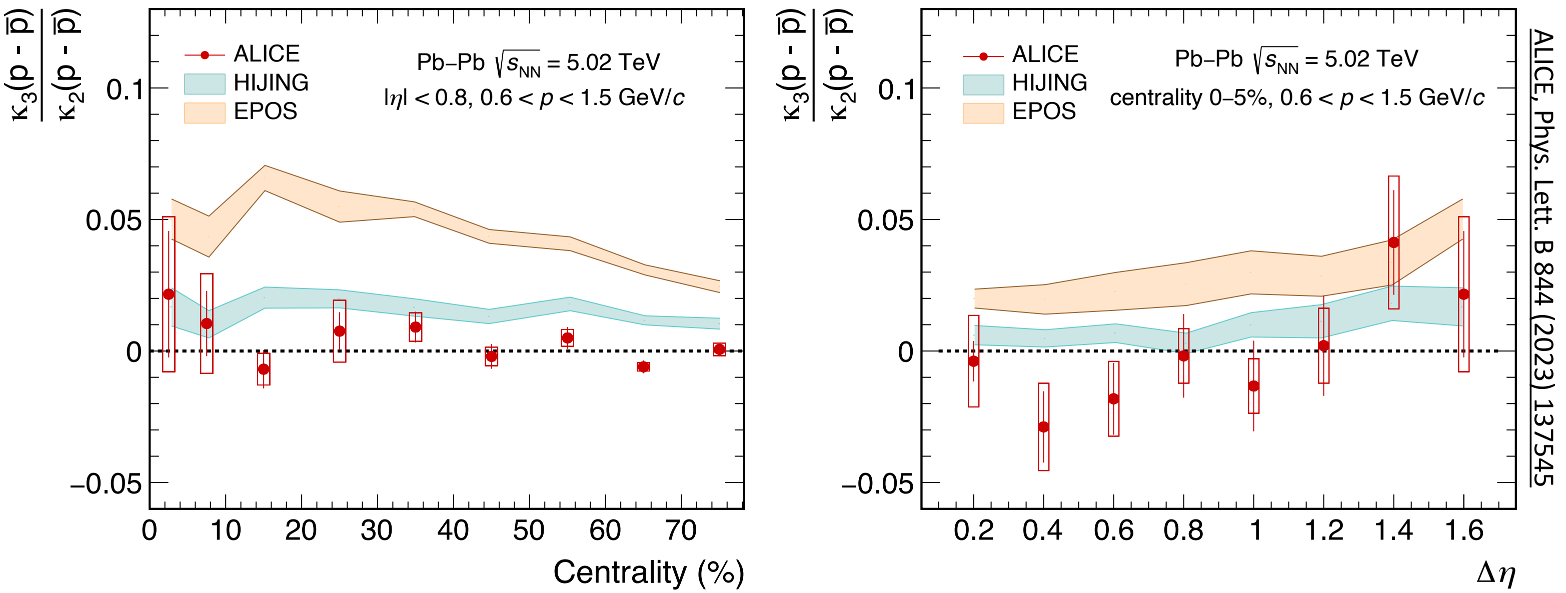




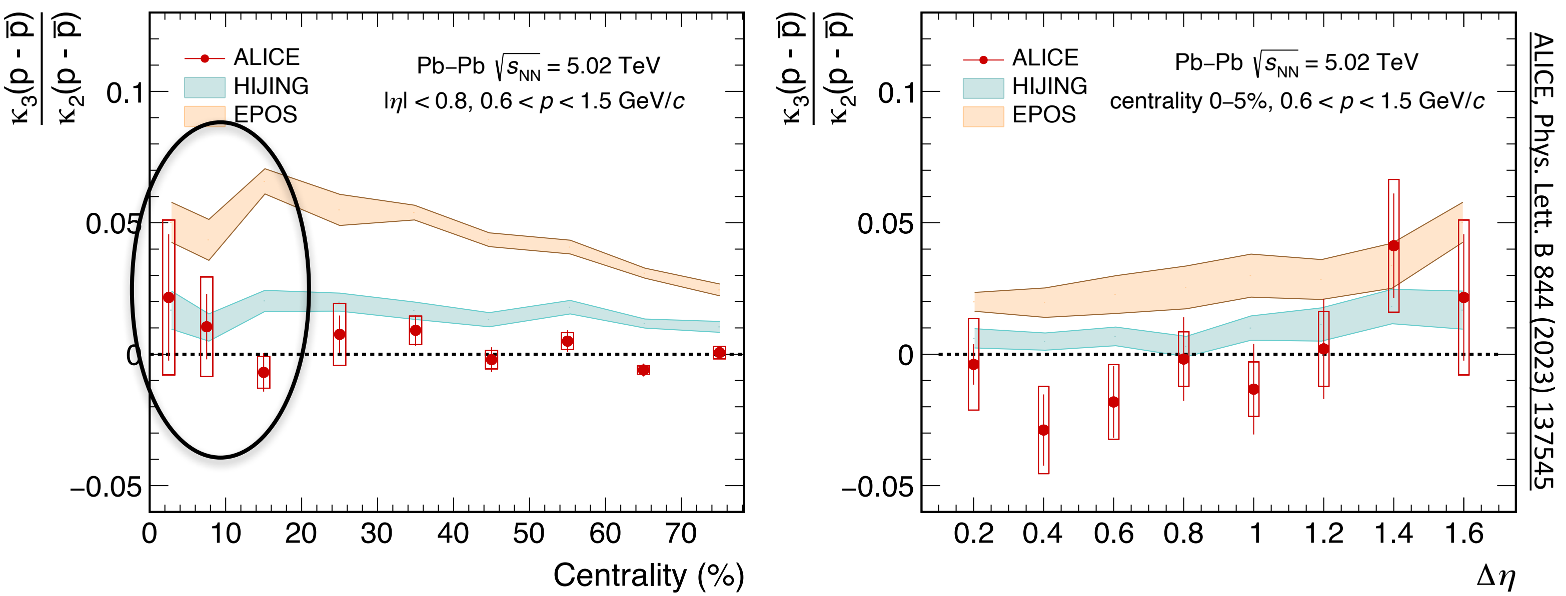
Cluster formation, magnetic field effect or …

3rd order cumulants of net-p



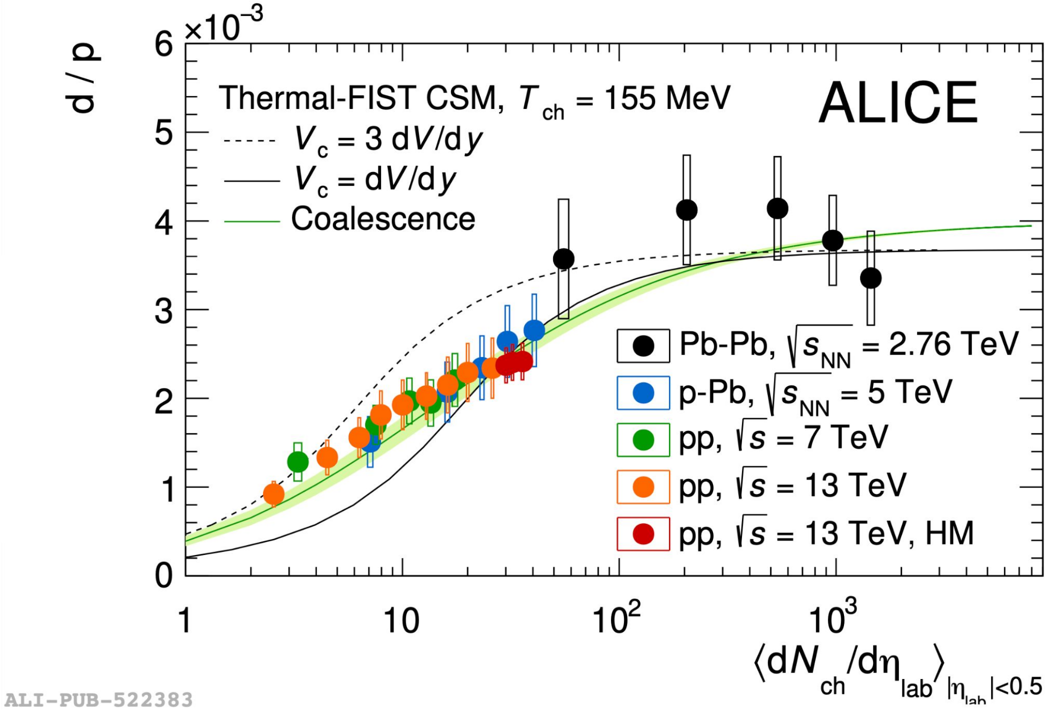
➢ **Data agree with Skellam baseline "0" (precision > 4%)** → **μ_B is very close to 0** at LHC energies

3rd order cumulants of net-p



- **Data agree with Skellam baseline "0" (precision > 4%)** → **μ_B is very close to 0** at LHC energies
- **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

Light nuclei production in view of correlation volume



Reduction in small systems due either to

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

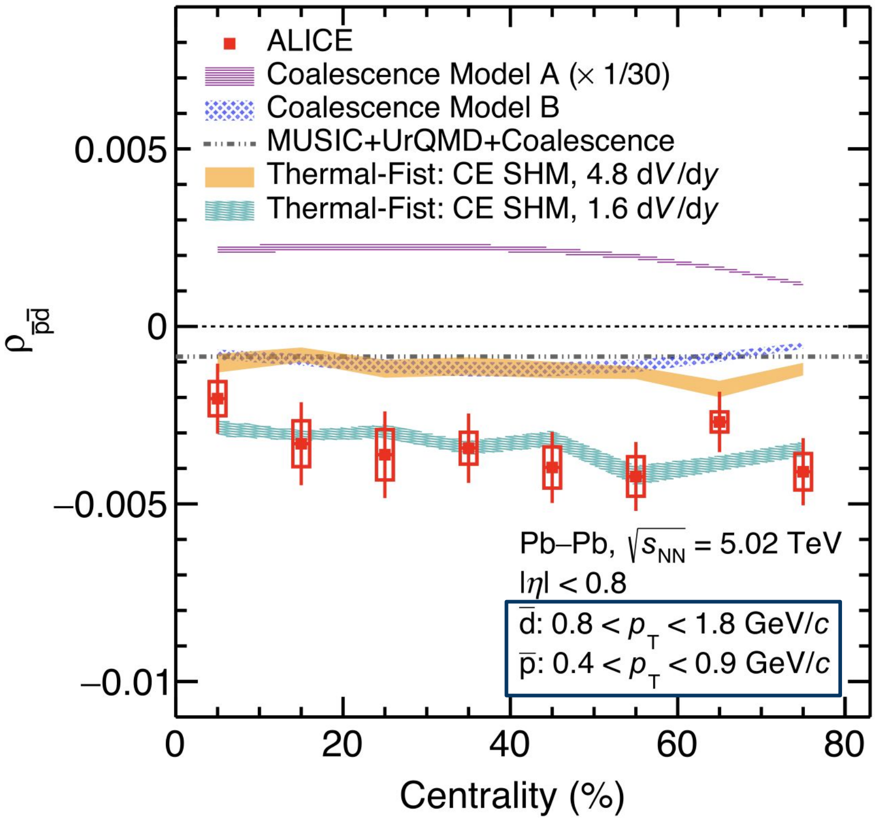
Light nuclei production in view of correlation volume

- **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 for baryon number

- Antideuteron: V_c **= 1.6 d*V*/dy**
- Net-proton: V_c **= 3—5 d*V*/dy**

ALICE, PRL 131 (2023) 041901

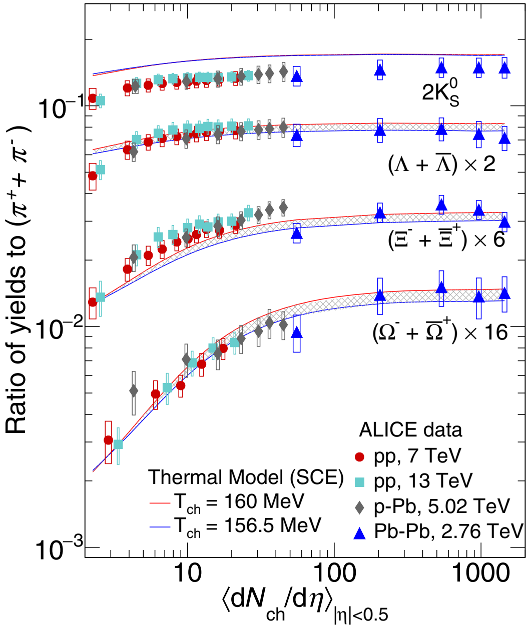


What did we learn?

(Net-strangeness)

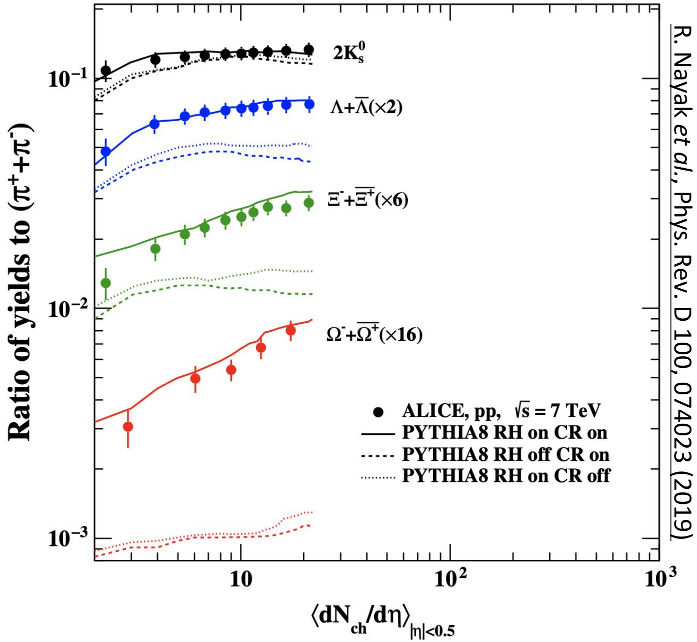
Small introduction

Canonical statistical model



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

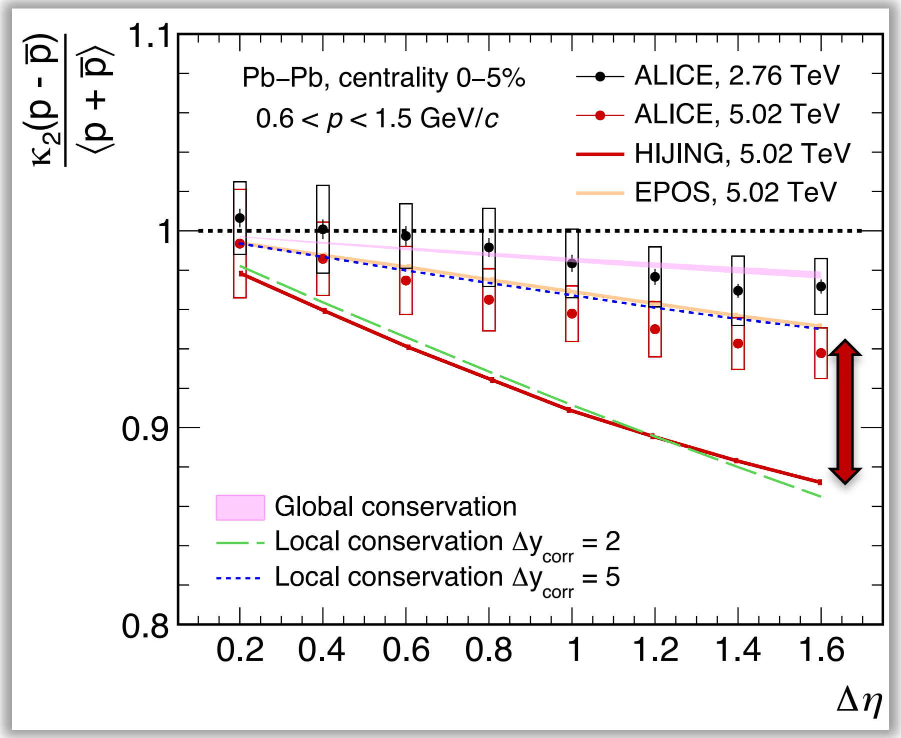
Lund string fragmentation (PYTHIA)



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

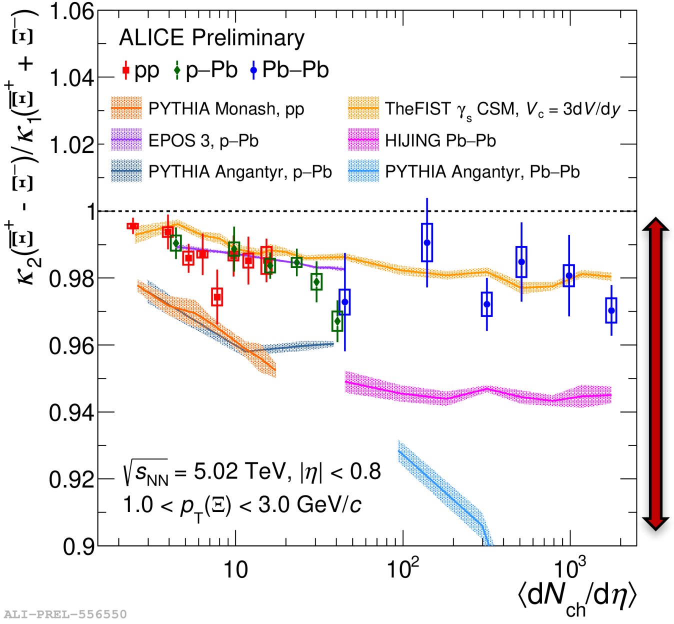
Both models are in a reasonable agreement **for the yields** (first order moments)

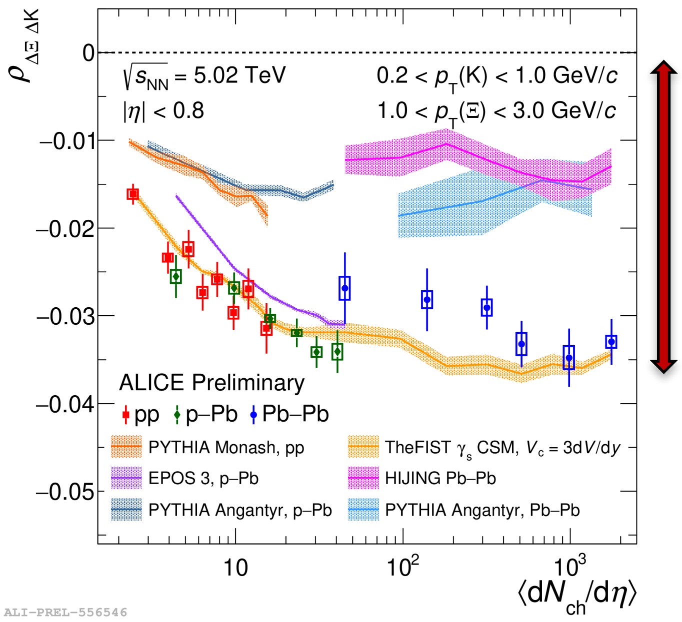
Small introduction



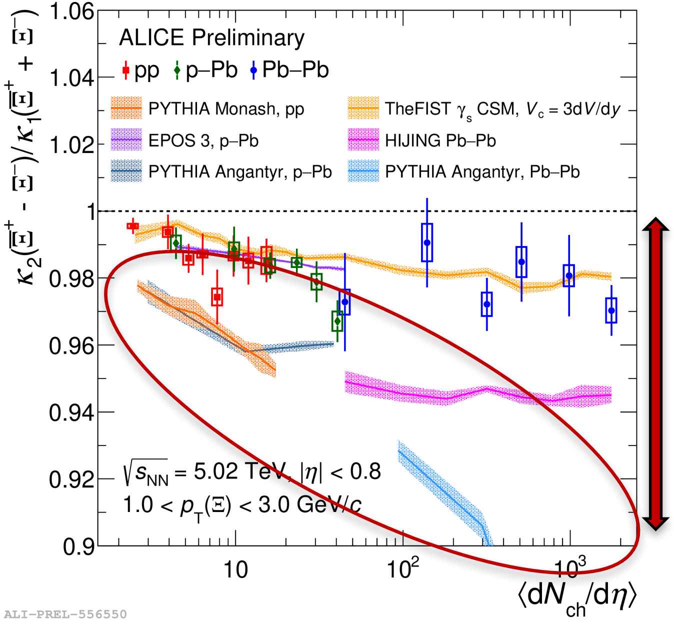
Lund based models fail for net-p which is **described by CE** in 2nd order → How about strangeness?

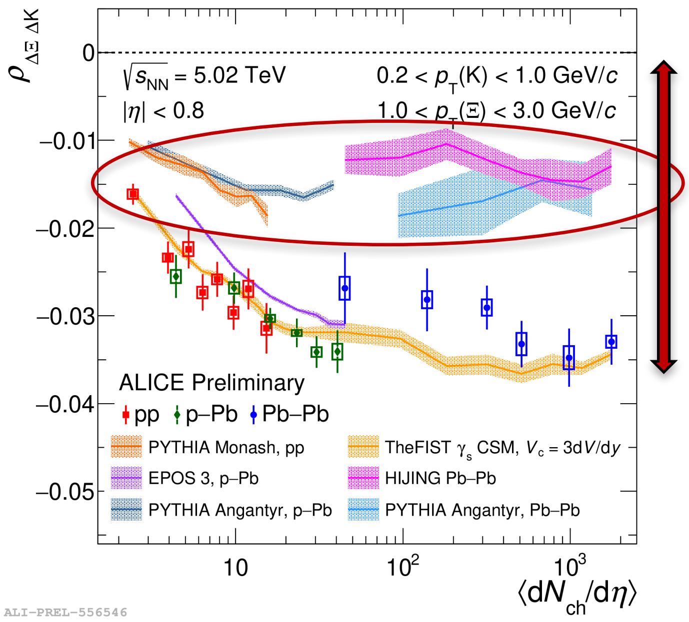
2^{nd} order cumulants of Net-Ξ & Net- Ξ — net-K correlations





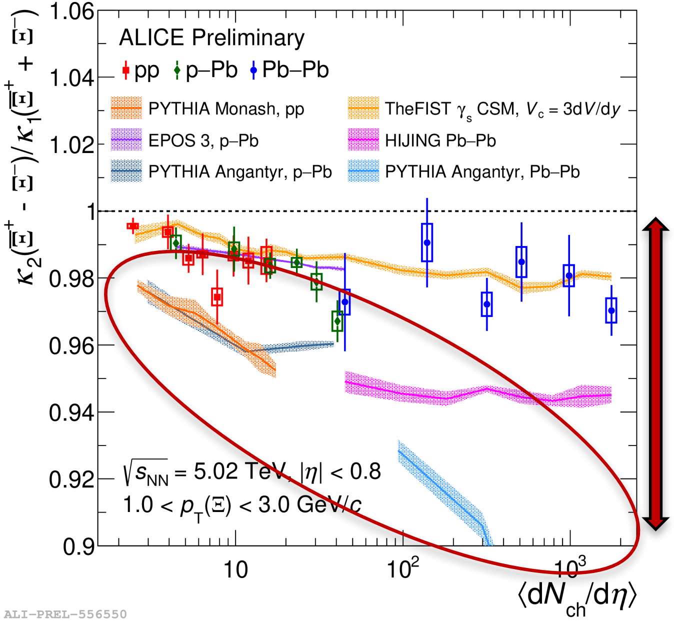
2nd order cumulants of Net-Ξ & Net- Ξ — net-K correlations

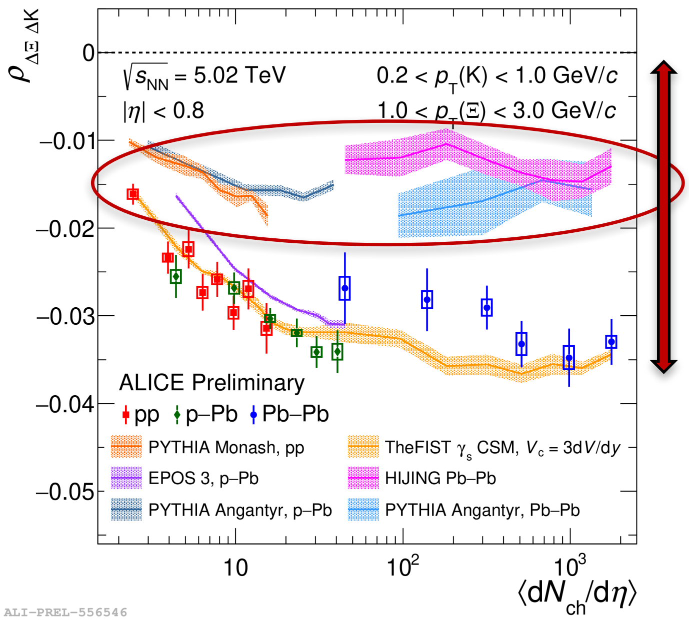




- Event generators based on **string fragmentation fails on the second order**

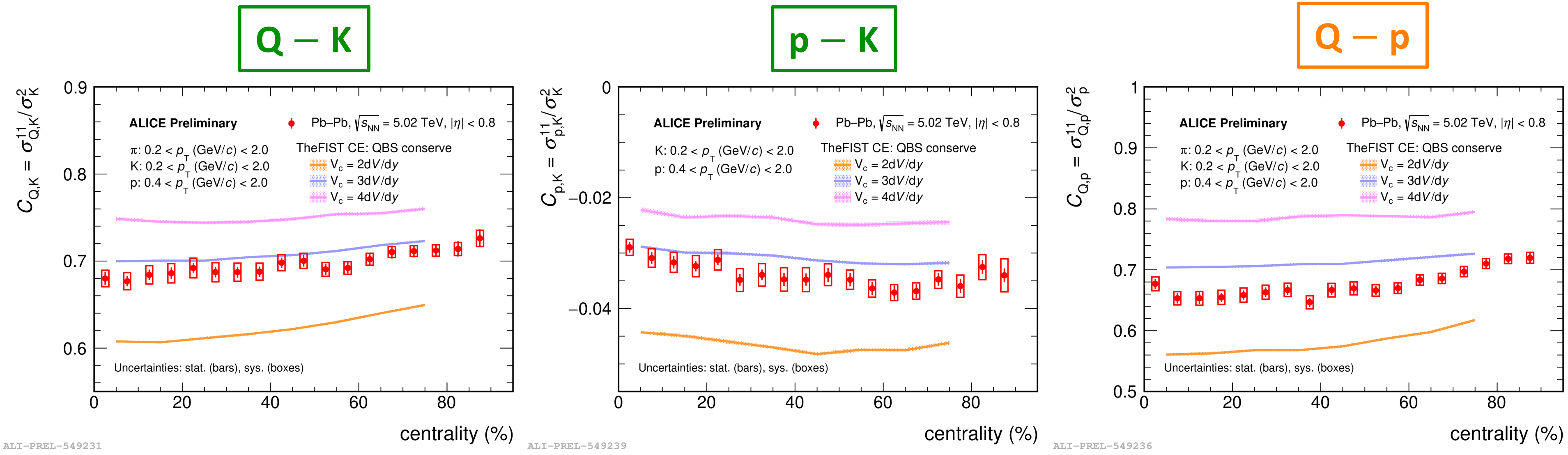
2^{nd} order cumulants of Net-Ξ & Net- Ξ — net-K correlations





- Event generators based on **string fragmentation fails on the second order**
- Canonical picture describes the data with **correlation volume of about 3 d*V*/d*y***
  → Indication of large volume (early production) for strangeness

Cross cumulants in view of correlation volume



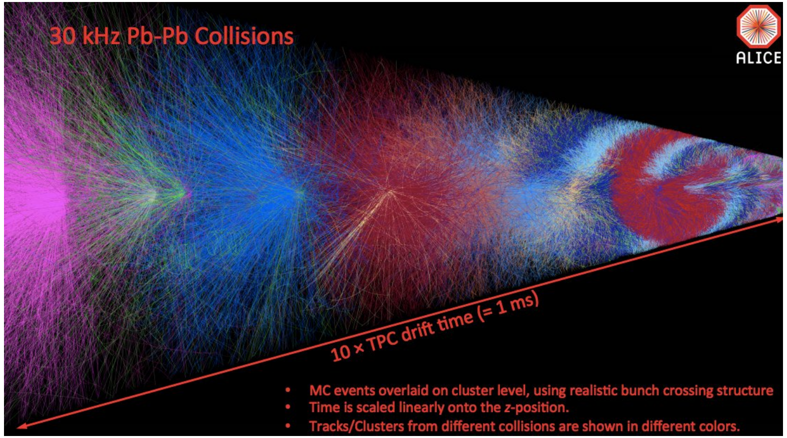
- **Q, B and S conserved** within a correlation volume
  V. Vovchenko *et al.*, Phys. Rev. C 100, 054906 (2019)
- Simultaneous description of cross cumulants with **V_c = ~3 dV/dy fails**

What can we learn?

(ALICE [2,3])

Outline

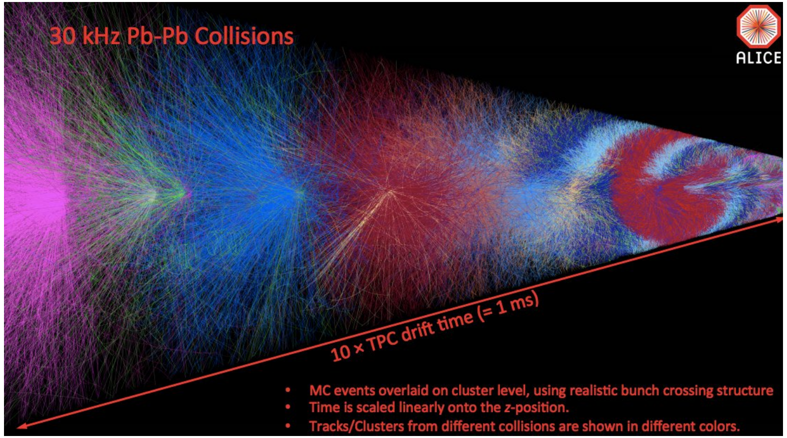
ALICE 2 (2022-2030)



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

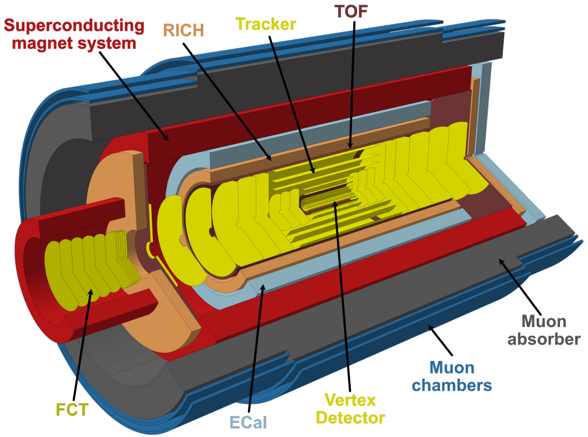
Outline

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**

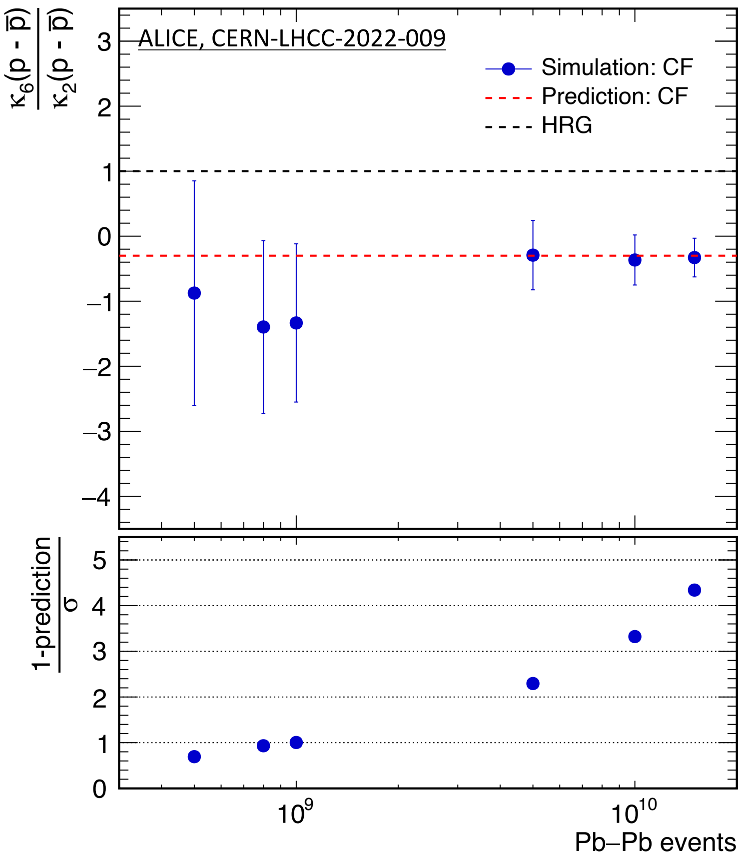
ALICE 3 (beyond early 2030s)



ALICE, CERN-LHCC-2022-009

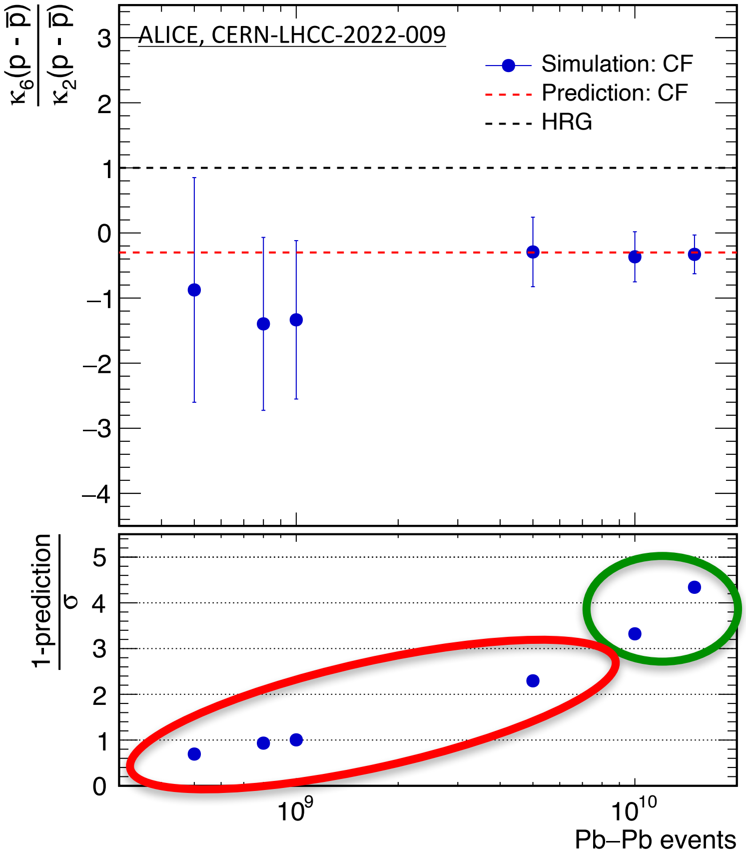
- ✓ **High statistics** → O (10^9) billion events
- ✓ **Large acceptance** → $|\eta| < 4$
- ✓ **High PID purity** → $0.3 < p_T < 10$ GeV/c
- ✓ **High efficiency** → ~95%
- ✓ **Excellent vertexing** → O (3μm) resolution

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

Criticality search in ALICE 2 and 3



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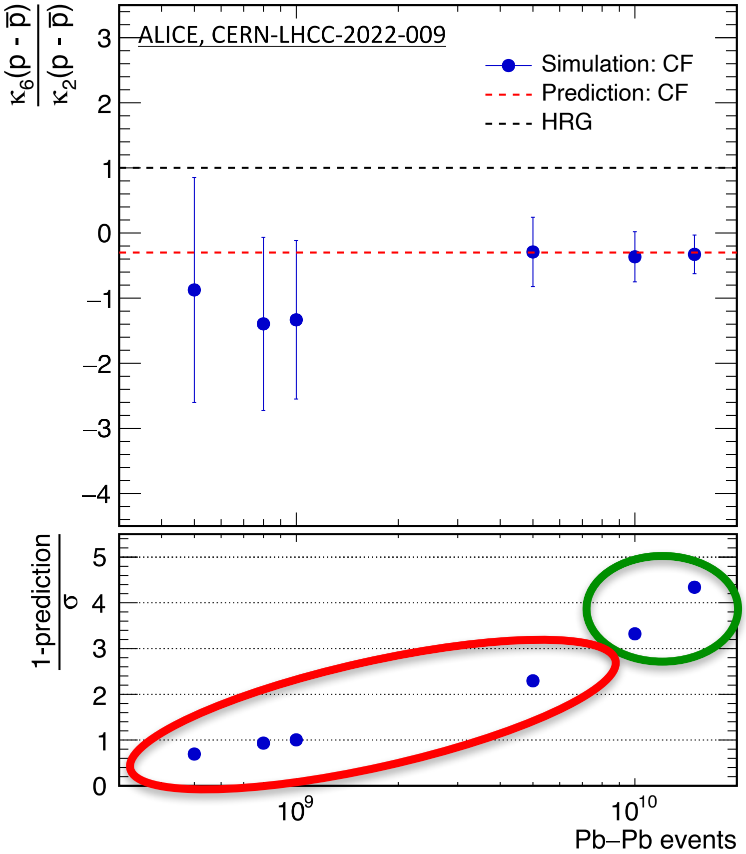
- **ALICE 2:**
  → More than 5 billion central Pb-Pb collisions is required
- **ALICE 3:**
  → **x3 larger statistics:** $>4\sigma$ significance with ALICE 2 acceptance

Criticality search in ALICE 2 and 3



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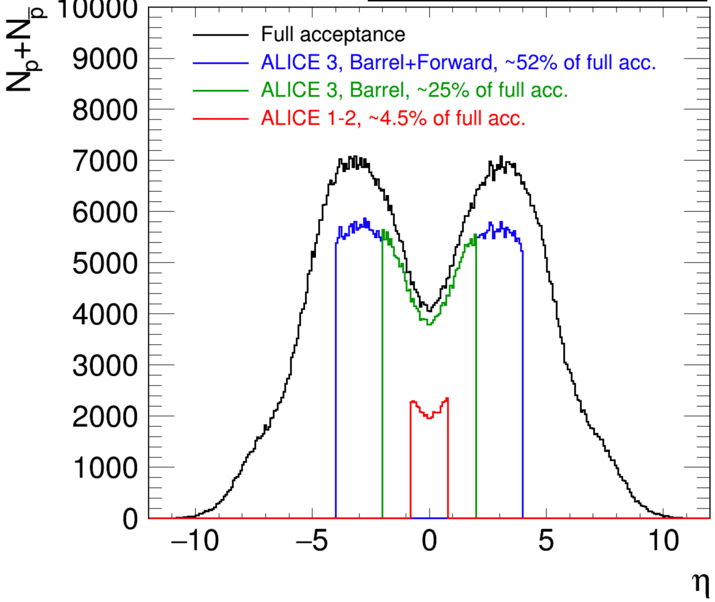
Net baryon and net strangeness fluctuations
for $|\eta| \leq 4$ and for 6^{th} and higher order

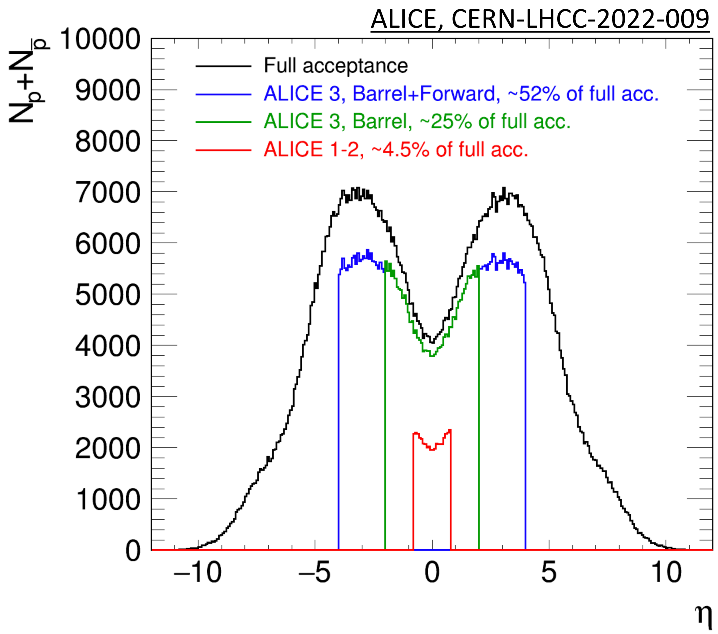
High precision

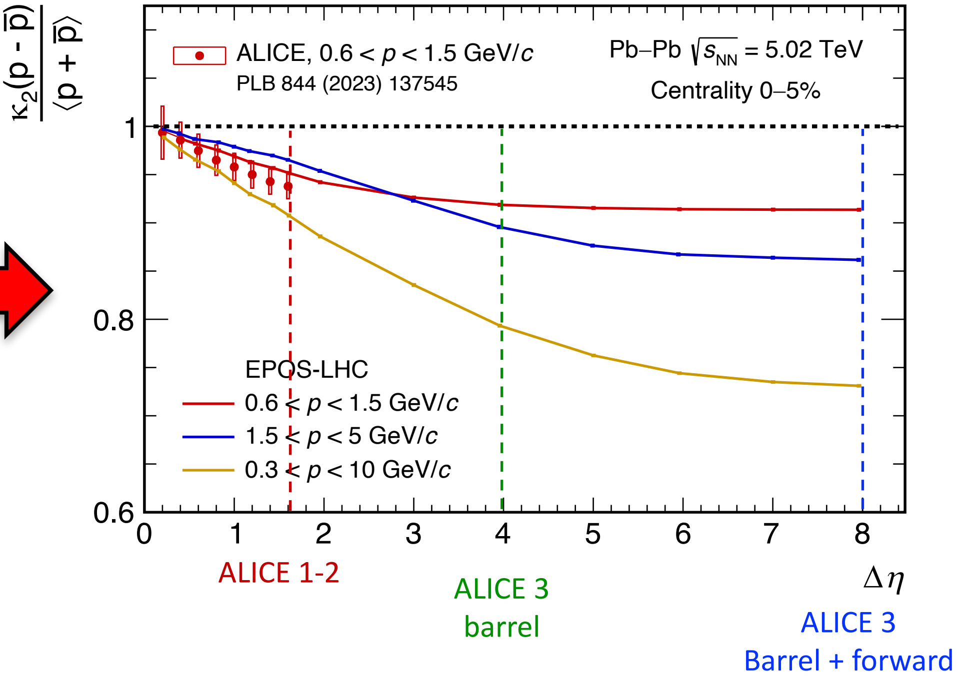
ALICE, CERN-LHCC-2022-009



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

High precision



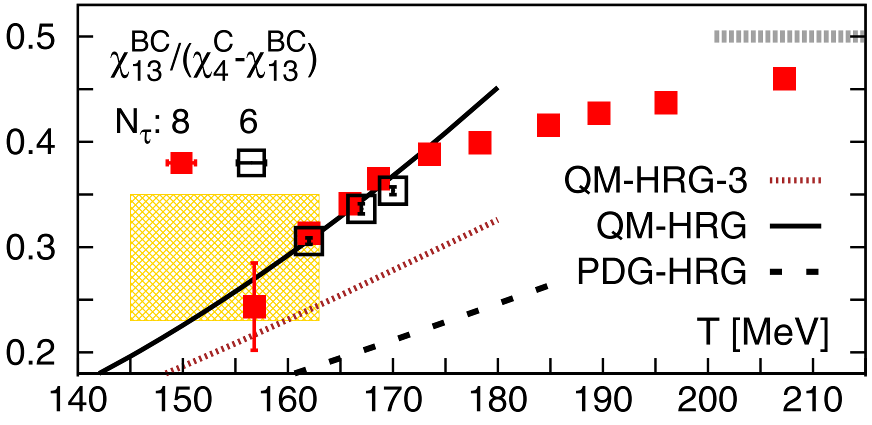


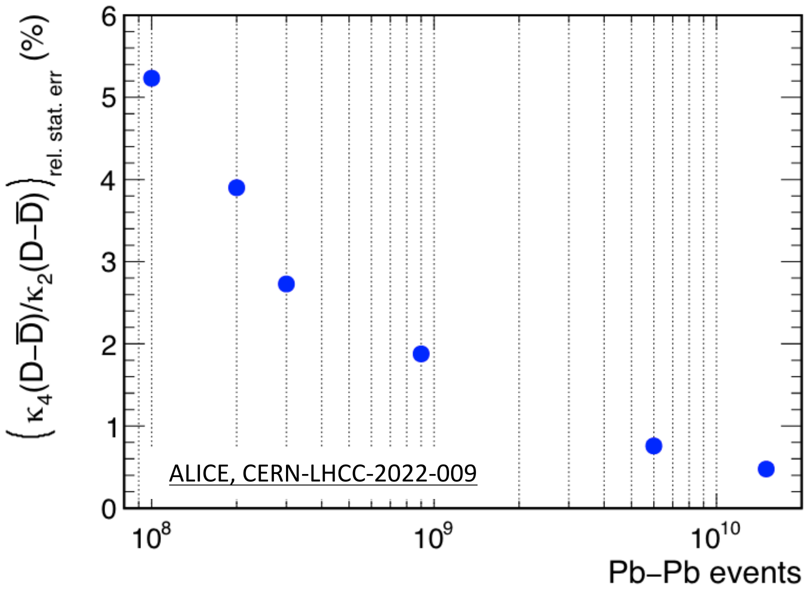
- High PID purity and efficiency within a larger acceptance ($0.3 < p < 10$ GeV/c, $|\eta|<4$)

- **More differential and high precision**

Completely new net-charm fluctuations

A. Bazavov et.al. PLB 737 (2014) 210-215





- **2nd order** → **Correlation length of charm**
- **4th 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

Experimental challenges?

- **PID, Efficiency correction, Resonance decays, Volume fluctuations, Pileup …**

What did we learn from ALICE 1?

- **Net-B and S fluctuations:**
  - ✓ **2^{nd} order:**
    - **Large correlation volume** → early times (V_c = 1.6 dV/dy ($\bar{p}\bar{d}$) and V_c = ~3 dV/dy (net-B and S))
    - **Higher momenta**: Magnetic field, proton clusters …
    - **Lund based models** describe 1^{st} order but fail in 2^{nd} for both B and S
    - **Cross cumulants** can not be described with the same V_c
  - ✓ **3^{rd} order:** Up to 3^{rd} 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?

- **Net B and S:** Criticality search at 6^{th} and higher order cumulants
- **Net-C:** fluctuations up to 4^{th} order
  - Correlation volume for charm
  - Missing states of QCD
- **High precision:** Constraining individual dynamic signals
  - Thermal blurring, Initial-state fluctuations, Baryon annihilation, Excluded volume effects, Baryon number conservation …
- **…**

BACKUP

Observables: 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 $\Delta K = K^+ - K^-$

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

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

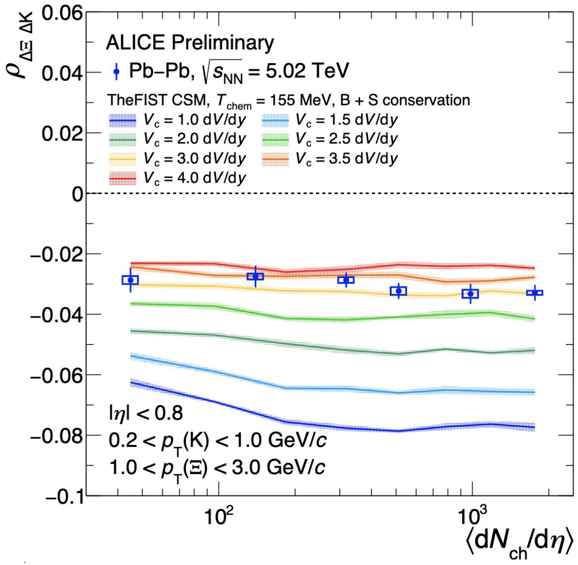
Net-xi cumulant ratio

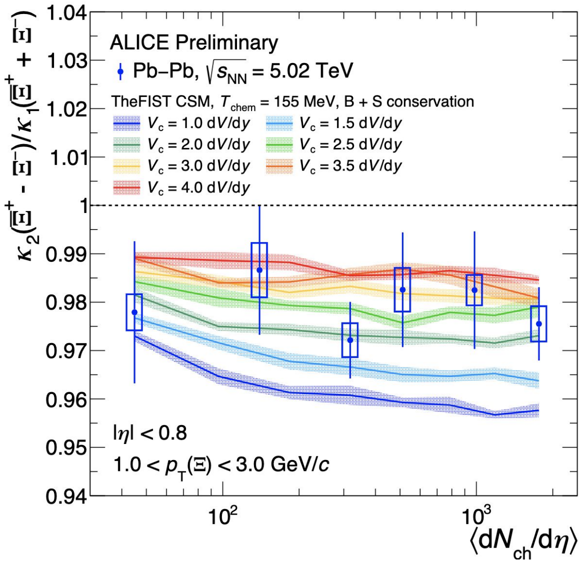
- E-by-e fluctuations of ΔΞ multiplicity distribution

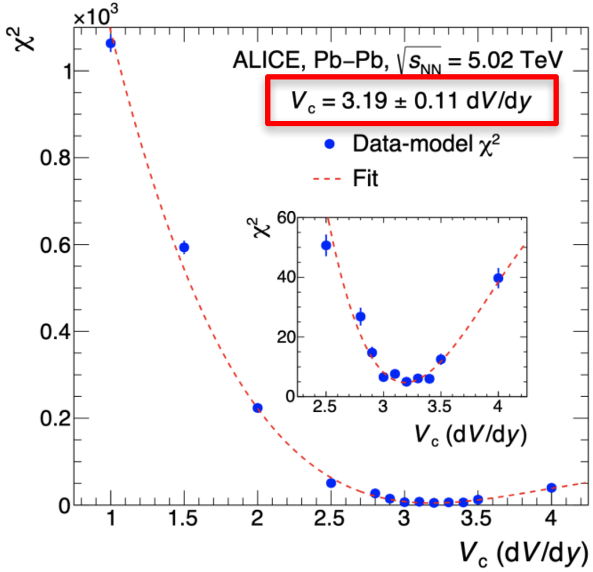
$$\kappa_2 / \kappa_1(\Delta\Xi) = \kappa_2(\Delta\Xi) / \kappa_1(\Xi^+ + \Xi^-)$$

Correlation volume estimation for strangeness

Combined-χ^2 minimization → extract V_c from data



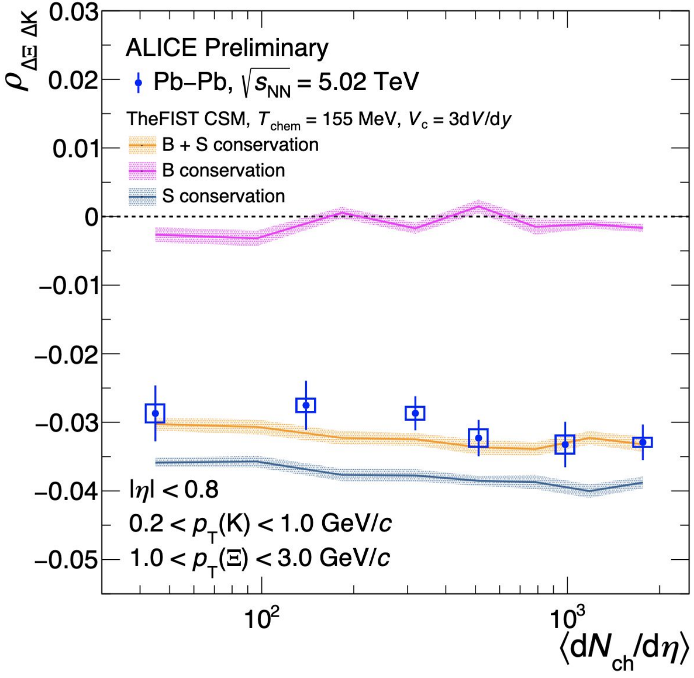


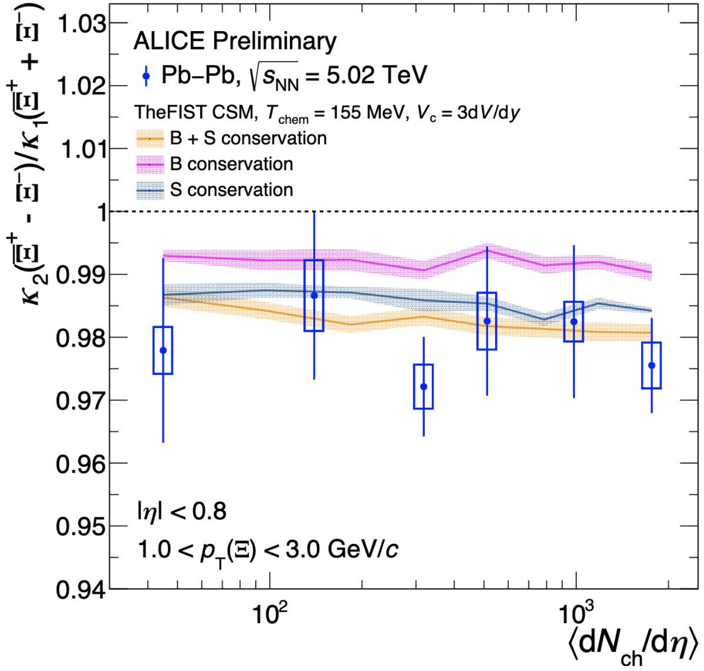


- ➢ Statistical uncertainty in model predictions propagated to observed χ^2
- ➢ Fit of χ^2 profile with pol4
- ➢ ***V_c = 3.19 $\pm$ 0.11 dV/dy***

Charge conservation

- Compare Pb–Pb results with CSM (γ_s = 1, T_{chem} = 155 MeV, V_c = 3 dV/dy)
  - B-only, S-only, B + S conservation
- Strangeness conservation → main contribution to net-particle correlation

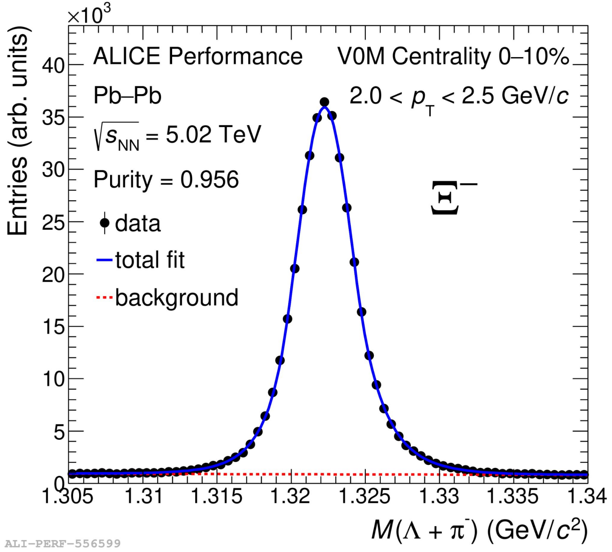




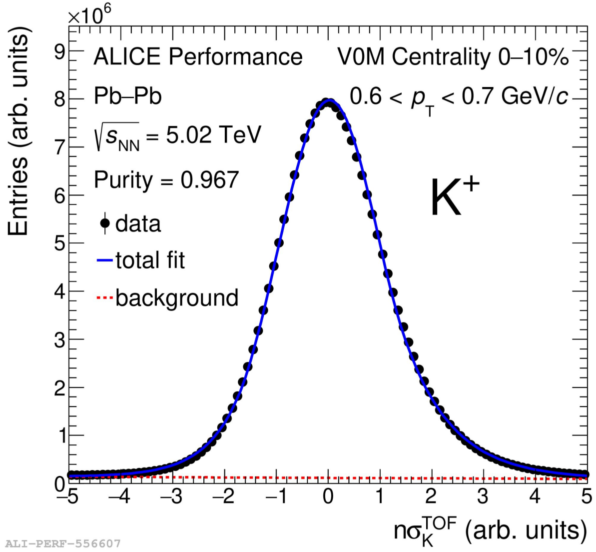
Analysis details

- Efficiency correction → formulae for binomial detector response
- Statistical uncertainty → subensemble method, systematics → multitrial method

- Reconstructed via cascade decay
  - $\Xi^- \rightarrow \Lambda(\rightarrow p + \pi^-) + \pi^- +$ c.c.
- Signal selection w/ machine learning
  - Boosted Decision Trees (BDT)



- Particle identification
  - $0.2 < p_T < 0.4$ GeV/c → TPC
    - +ITS in Pb–Pb
  - $0.4 < p_T < 1.0$ GeV/c → TPC+TOF



Analysis details

Track selection
filter bit 16 (1<<4)
$\|\eta\| < 0.8$
$n_{SPDcls} > 0$, $n_{ITScls} > 1$ and $n_{TPCcls} > 69$
$0.2 \leq p_T < 0.4$ GeV/c → $n_{SDDcls} + n_{SDDcls} > 2$
$X^2_{TPC} \leq 2.5$
$\|DCA\| < 0.1$ cm
PID cuts
$0.2 \leq p_T < 0.4$ GeV/c → $\|n\sigma_{ITS}\| < 3$ and $\|n\sigma_{TPC}\| < 3$
$0.4 \leq p_T < 1.0$ GeV/c → $\|n\sigma_{TPC}\| < 2.5$ and $\|n\sigma_{TOF}\| < 3$

additional ITS cuts for PID only used for Pb–Pb

standard 2011 track selections + loose DCA cuts (see backup)

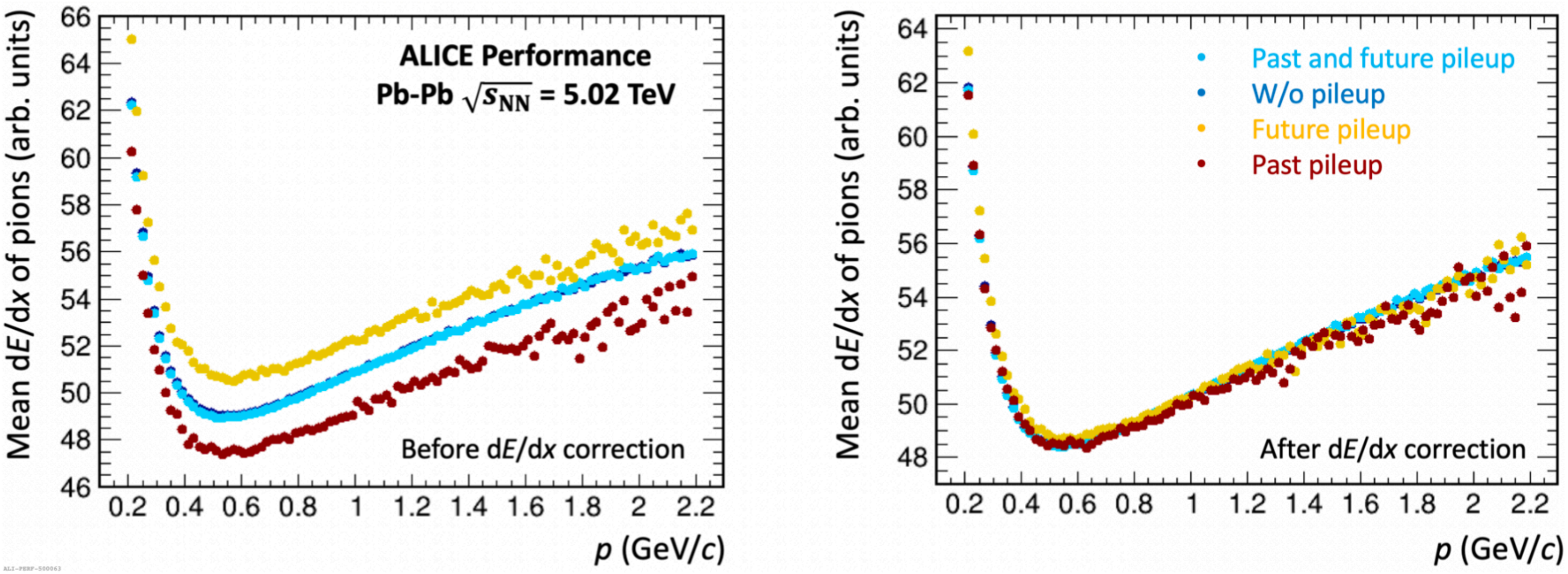
for Ξ daughters $|DCA| > 0.1$ cm

Experimental uncertainties

- Statistical uncertainty
  - subensemble method → 30 subsamples
- Systemaitc uncertainty → Multitrial method
  - Consider all possible combinations of cut variations
  - Repeat the analysis for all combinations → $(\kappa_2/\kappa_1)_i$ and ϱ_i
  - Standard deviation of $(\kappa_2/\kappa_1)_i$ and ϱ_i distribution → systematic uncertainty

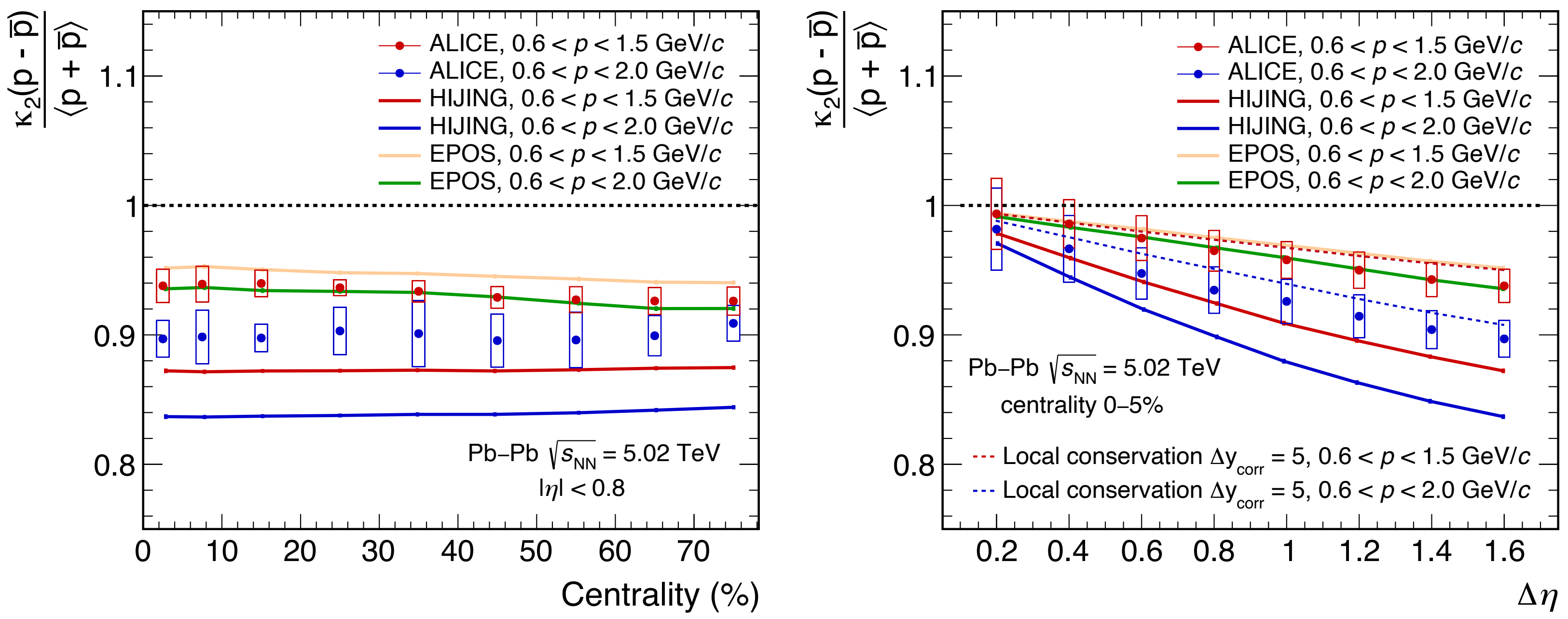
Variable	variations
$n_{\mathrm{TPCClusters}}$	$\geq 60,\ 70,\ 90$
$\chi^2_{\mathrm{TPC}}/n_{\mathrm{TPCClusters}}$	$< 2,\ 2.5$
$\lvert\mathrm{DCA}\rvert$	< 0.05 (for $p_{\mathrm{T}} > 0.5$ GeV$/c$), 0.1 cm
$n\sigma_{\mathrm{TPC,TOF}}$	$< 2,\ 2.5,\ 3,\ 3.5,\ 4$
BDT efficiency	default $\pm 5\%$ ($\Delta\varepsilon_{\mathrm{BDT}} = 1\%$, 10 variations)
$\lvert M(\Lambda + \pi^-$ +c.c.$) - M_{\mathrm{PDG}}\rvert$	$< 2\sigma,\ 3\sigma,\ 4\sigma$

Experimental challenges: E.g. effect of event pileup



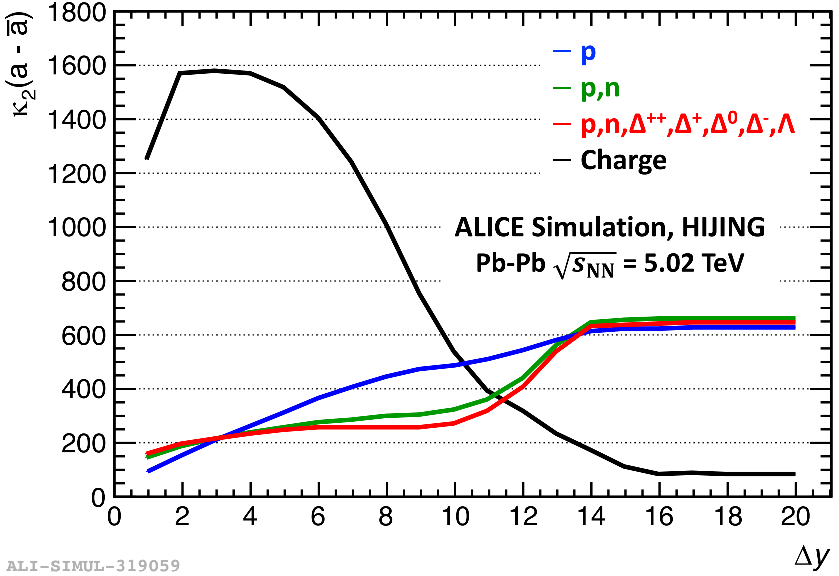
M. Arslandok, E. Hellbär, M. Ivanov, R.H. Münzer and J. Wiechula, Particles 2022, 5(1), 84-95}

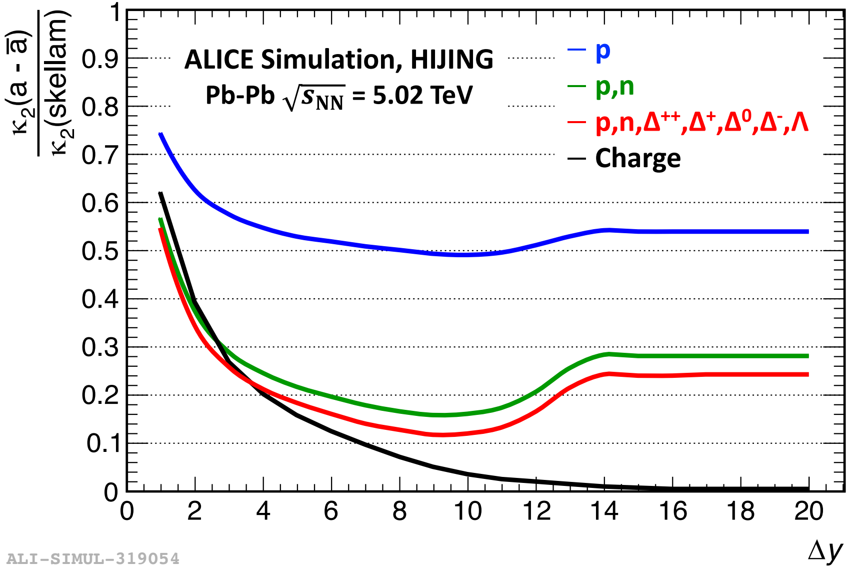
2^{nd} order cumulants of net-p: Acceptance dependence



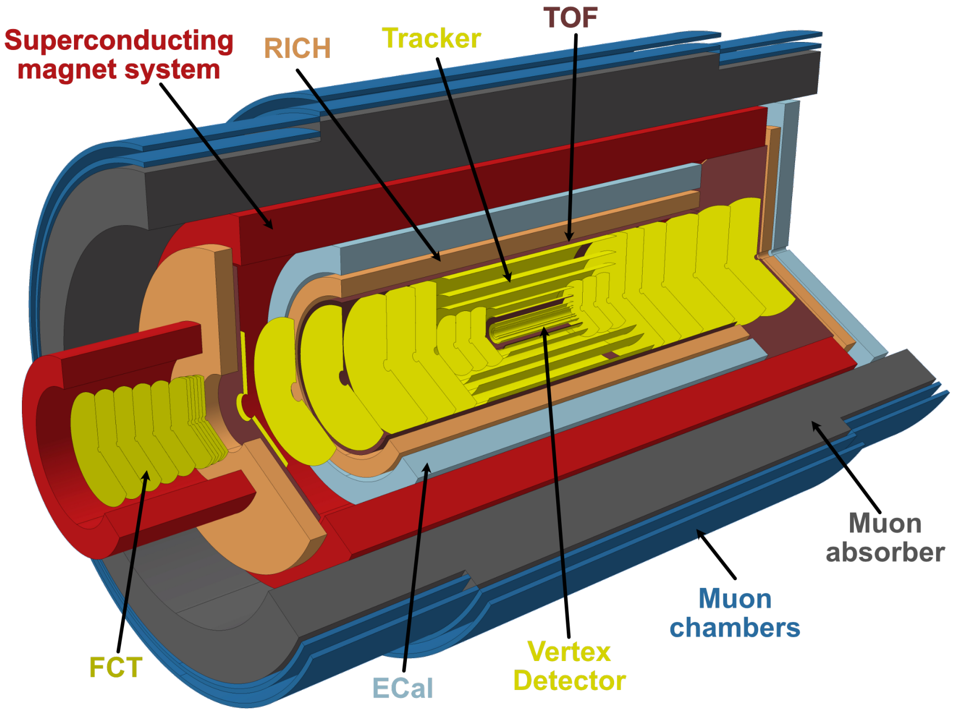
- Consistent with the baryon number conservation picture
  - Increase in fraction of accepted $p, \bar{p}$ -> stronger constraint of fluctuations due to baryon number conservation
- EPOS & HIJING show this drop qualitatively

2^{nd} order cumulants in full phase space





ALICE 3



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

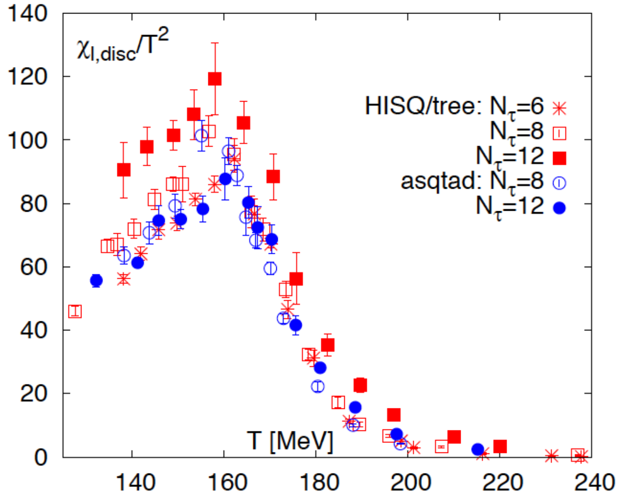
⟹ **Fast** to sample large luminosity
  → 50-100 x Run 3/4 → MHz level

⟹ **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

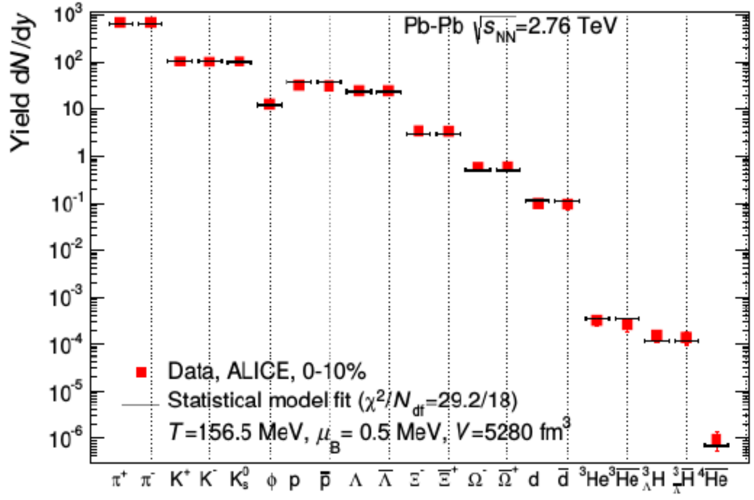
⟹ **Precise time measurements** for PID
  → σ ~ 20 ps

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



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

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

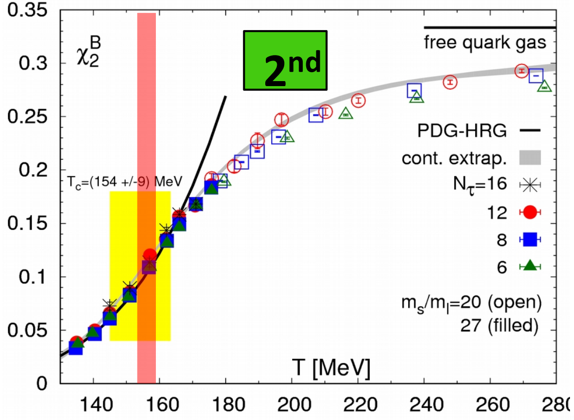


$T_{fo}^{ALICE} = 156.5 \pm 3$ MeV

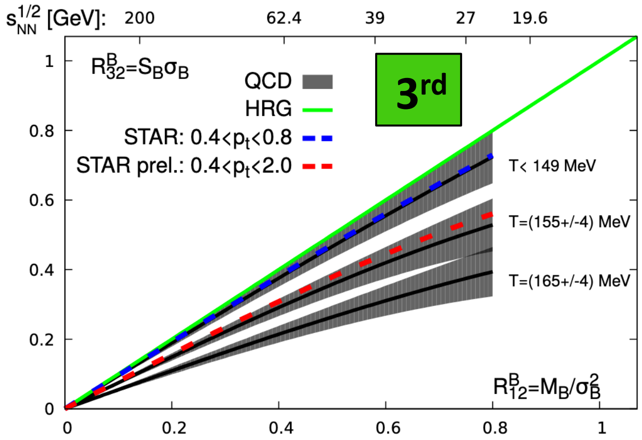
Chemical freeze-out at the phase boundary!

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

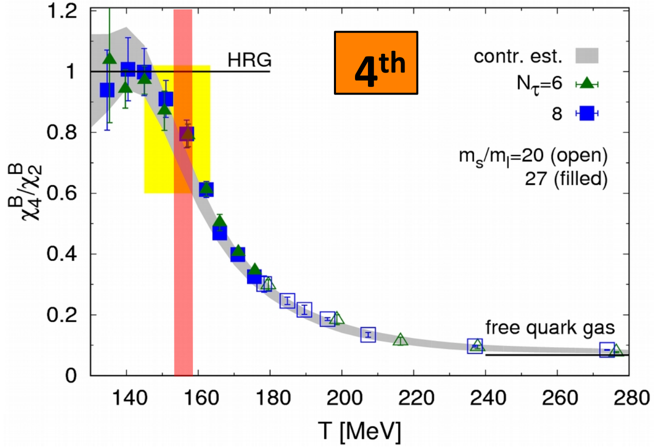
Link to LQCD



χ_2^B
2nd
free quark gas
PDG-HRG
cont. extrap.
N_τ=16
12
8
6
T_c=(154 +/-9) MeV
m_s/m_l=20 (open)
27 (filled)
T [MeV]

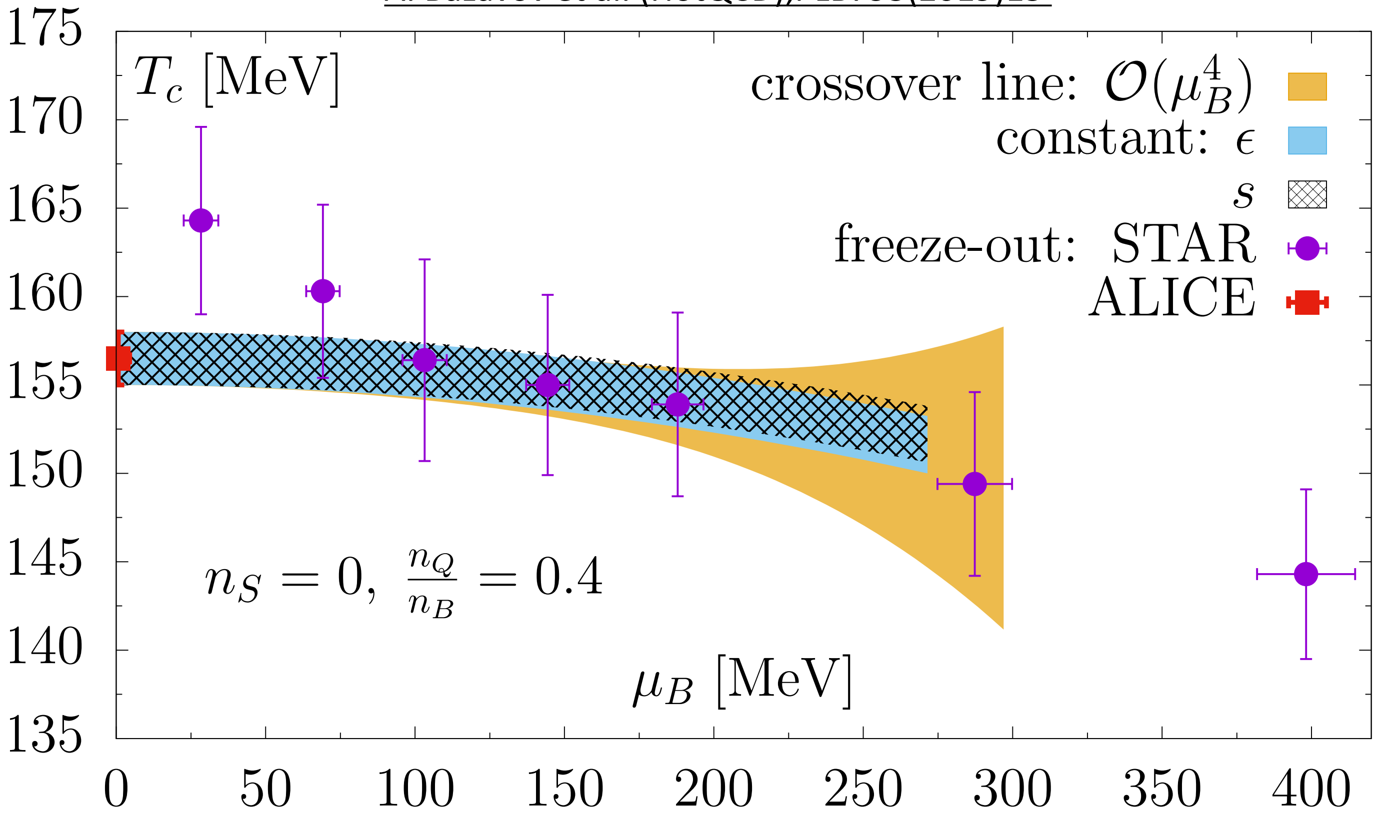


$s_{NN}^{1/2}$ [GeV]: 200 62.4 39 27 19.6
$R_{32}^B=S_B\sigma_B$
QCD
HRG
STAR: 0.4<p_t<0.8
STAR prel.: 0.4<p_t<2.0
3rd
T< 149 MeV
T=(155+/-4) MeV
T=(165+/-4) MeV
$R_{12}^B=M_B/\sigma_B^2$



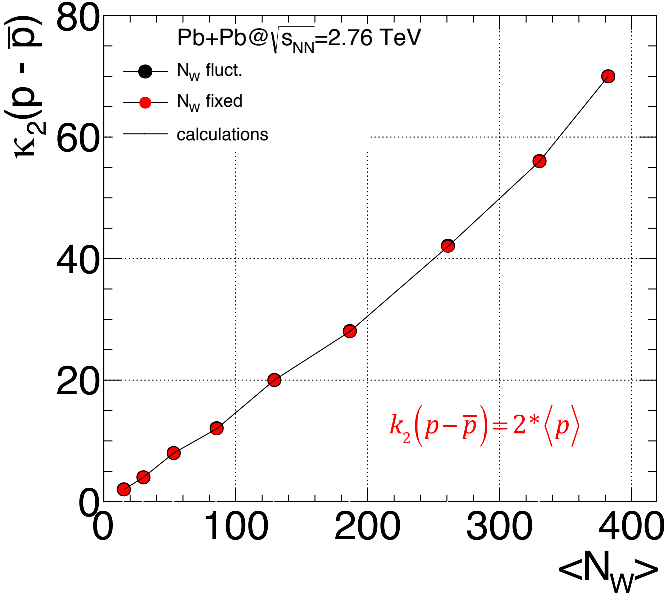
χ_4^B/χ_2^B
HRG
4th
contr. est.
N_τ=6
8
m_s/m_l=20 (open)
27 (filled)
free quark gas
T [MeV]

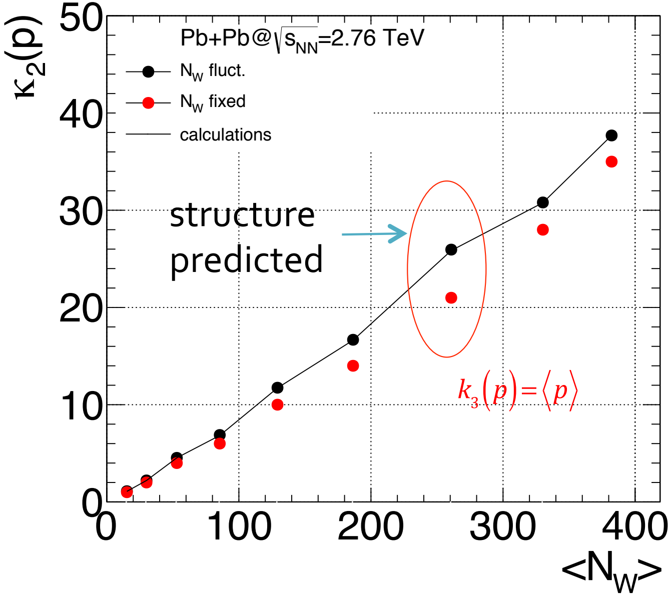
A. Bazavov et al. (HotQCD),PLB795(2019)15



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

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

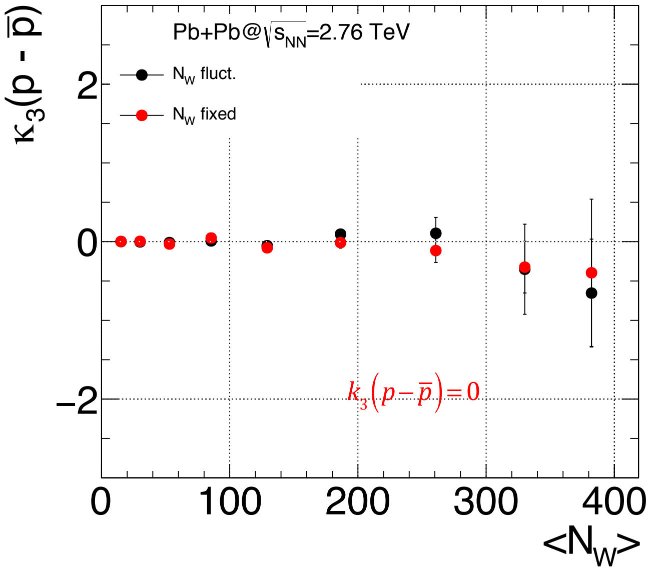
does not vanish

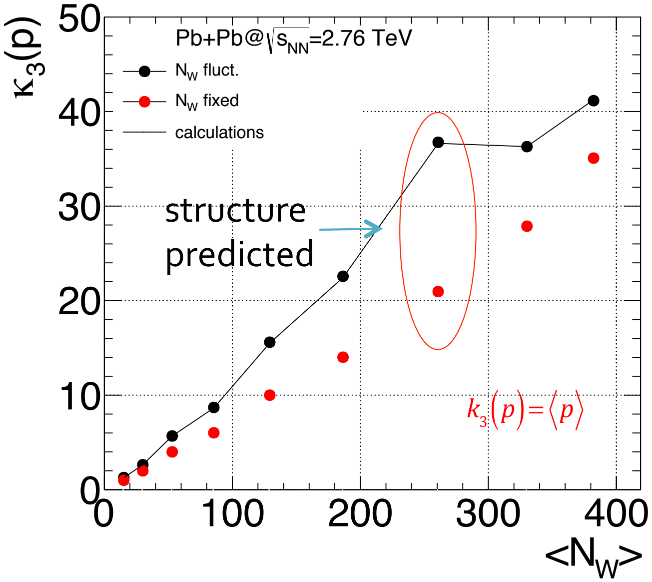
$n,\bar{n}$ from single wounded nucleon

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

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

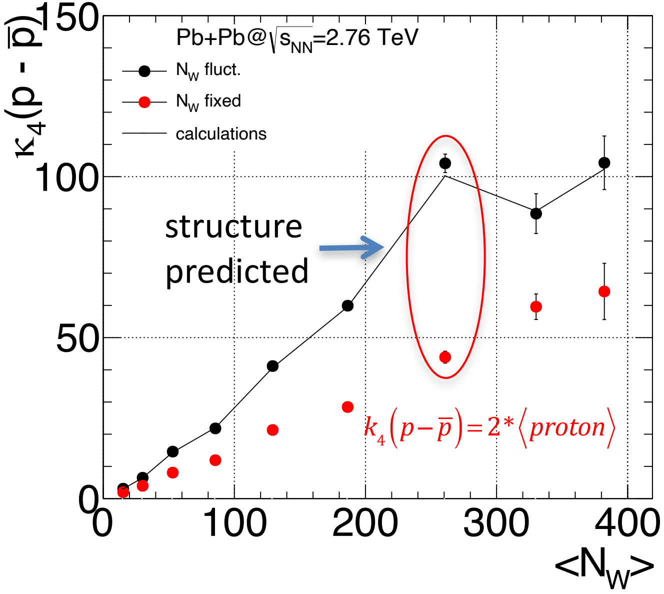
does not vanish

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

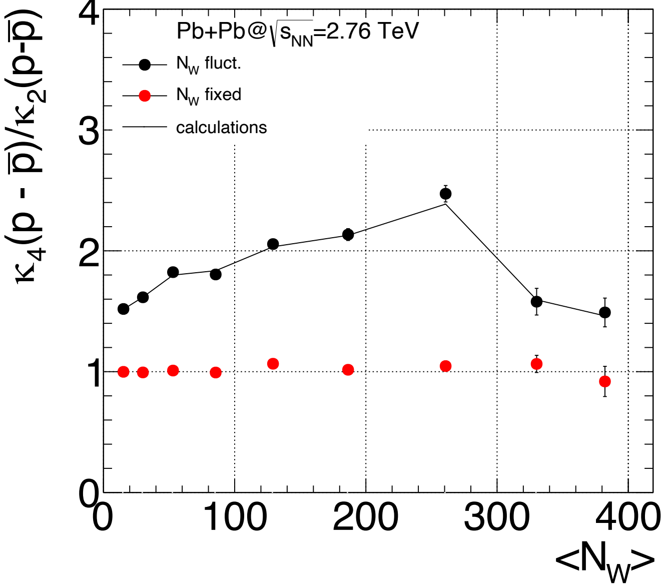
P. Braun-Munzinger, A. Rustamov, J. Stachel, Nuclear Physics A 960 (2017) 114–130

Volume Fluctuations

150*10^6 Events



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



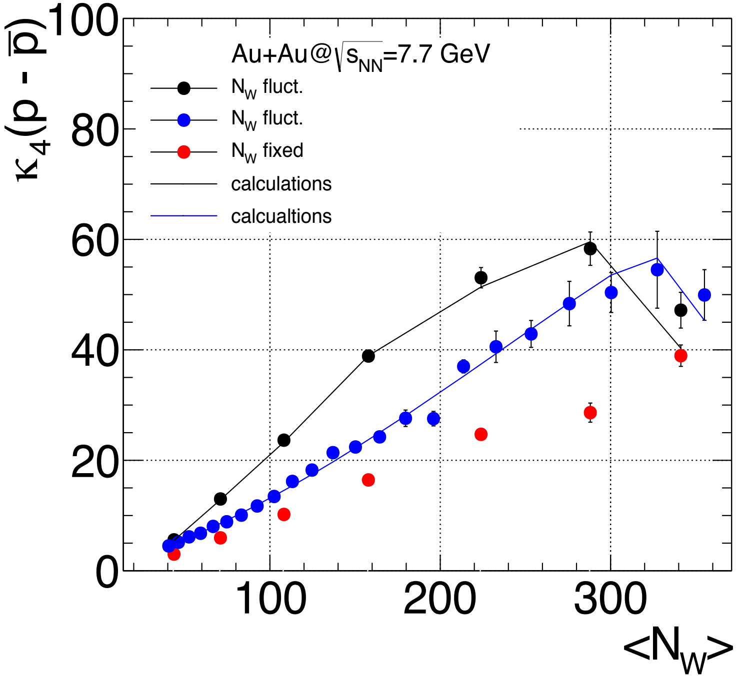
$$k_4(p-\bar{p}) = \langle N_w \rangle k_4(n-\bar{n}) + 3k_2(n-\bar{n})^2 k_2(N_w) + \langle n-\bar{n} \rangle (\ldots)$$

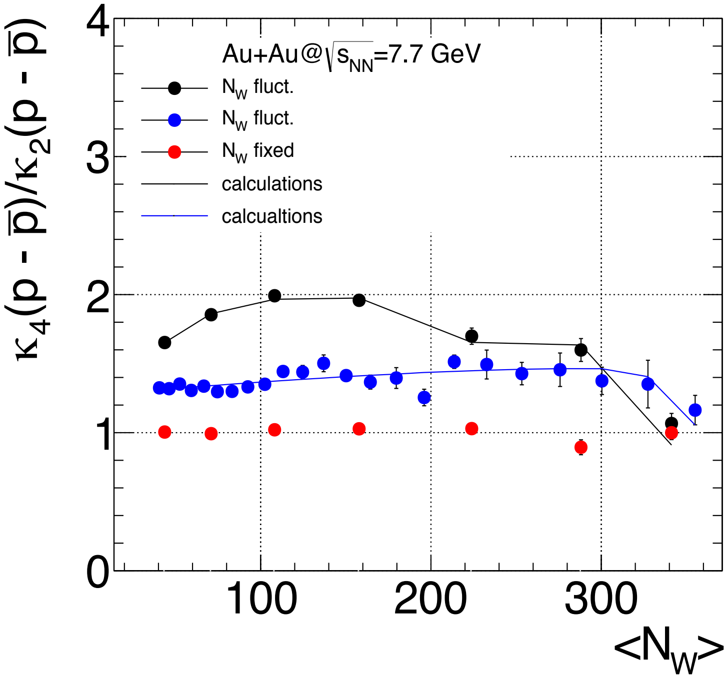
$n, \bar{n}$ → from single wounded nucleon

vanishes for ALICE

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

Volume Fluctuations

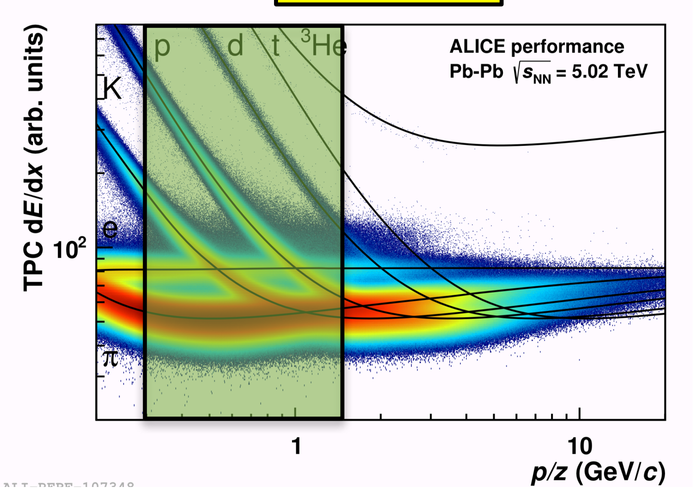


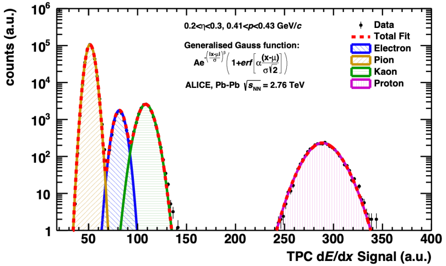


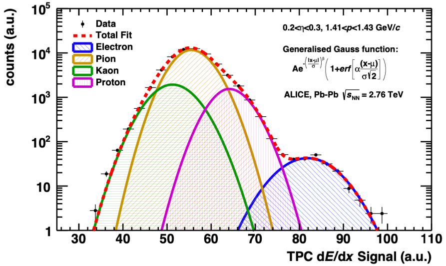
P. Braun-Munzinger, A. Rustamov, J. Stachel, Nuclear Physics A 960 (2017) 114–130

Identity Method in ALICE 3: Purity in PID

ALICE 1-2



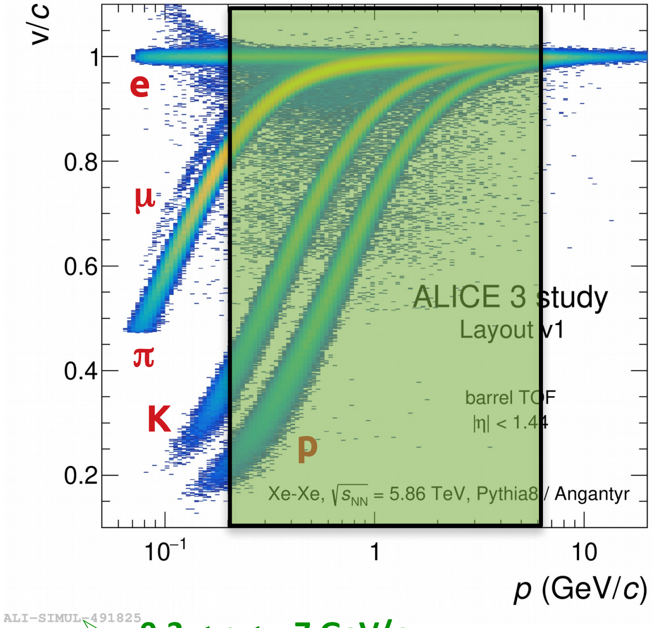




- $0.6 < p < 1.5$ GeV/c
- $p > 0.8$ GeV/c → less than one sigma separation

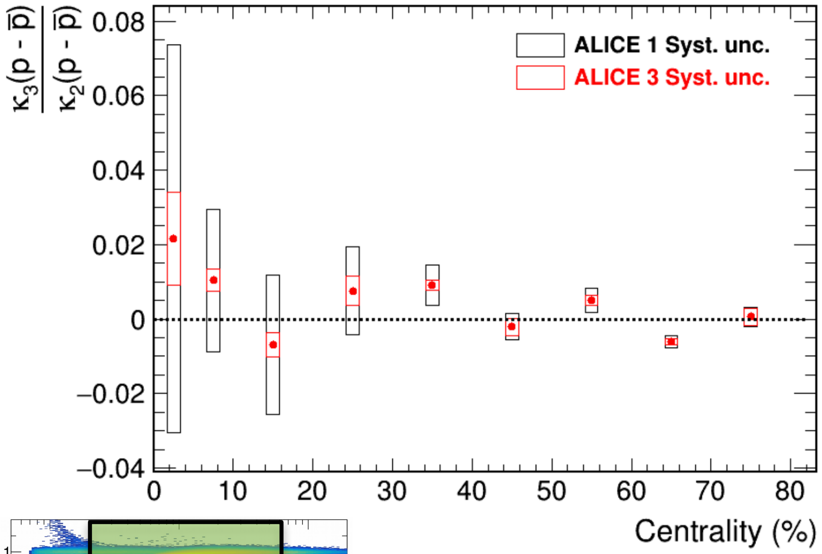
ALICE 3

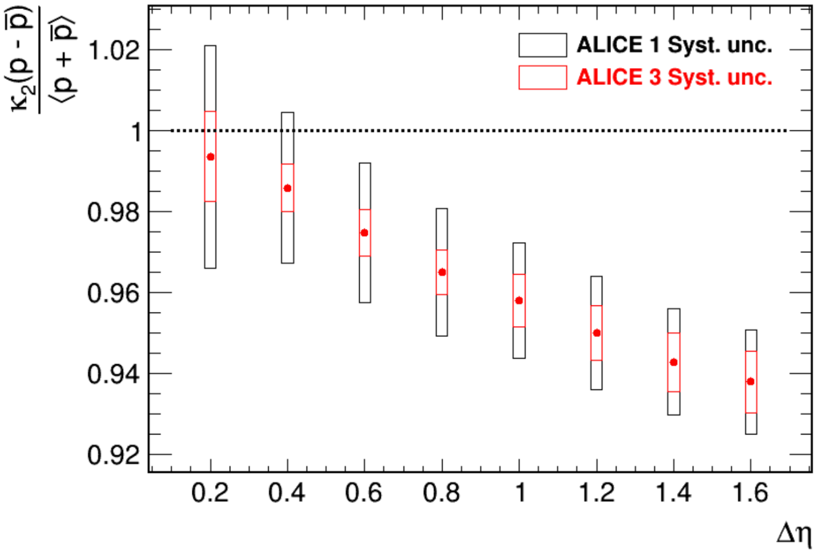
Significant improvement in the purity + IM

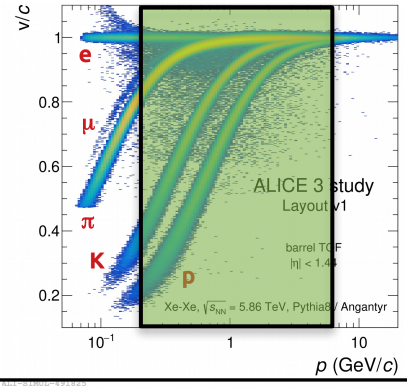


- $0.3 < p < \sim 7$ GeV/c
- No full overlap of the TOF signal

ALICE 3: Systematic uncertainties



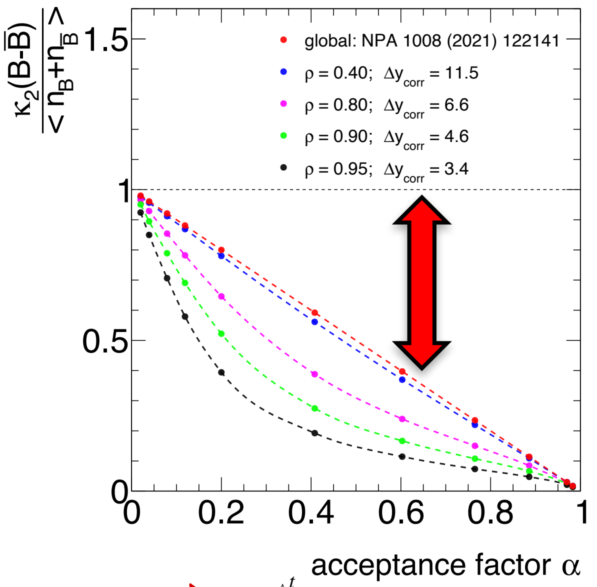


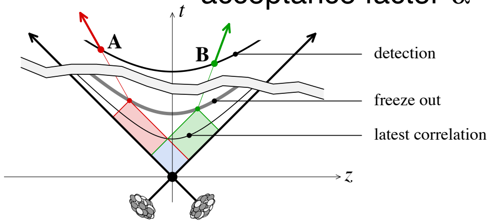


❖ **Main uncertainty is from the dE/dx fits, which will vanish in ALICE 3**
(thanks to Identity Method (IM) and improved PID)

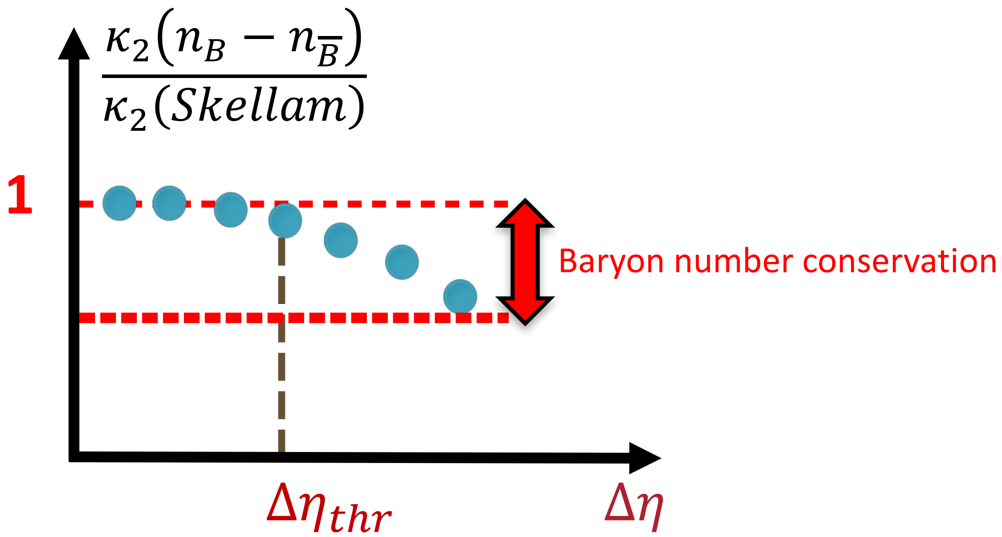
2^{nd} order cumulants of net-p: Correlation length

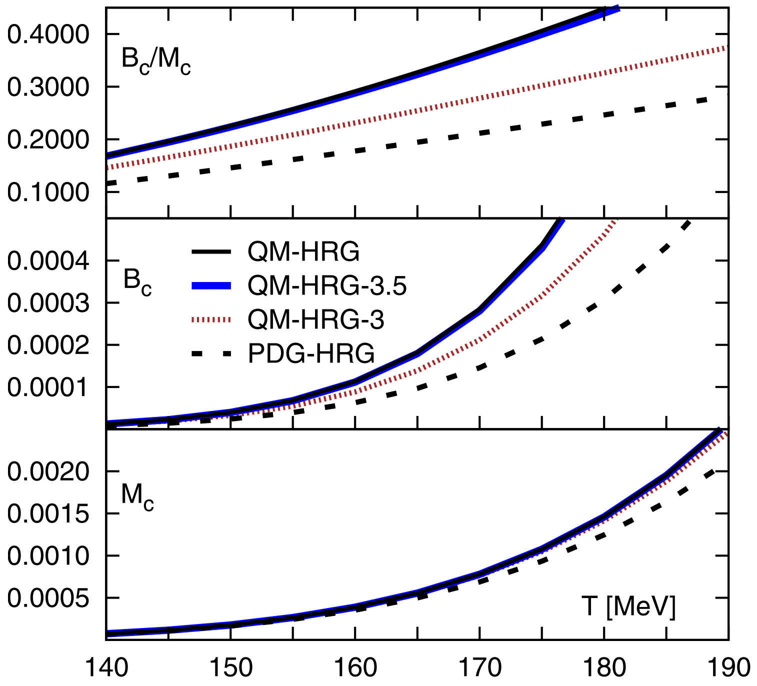
P. Braun-Munzinger, A. Rustamov, J. Stachel, to be published





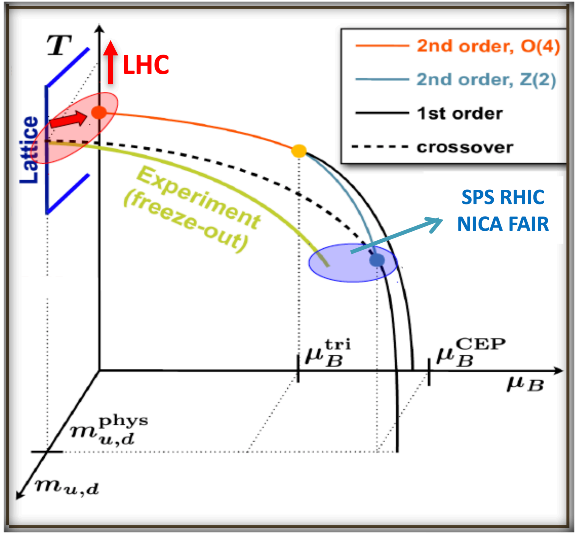
Early correlations → long range in rapidity





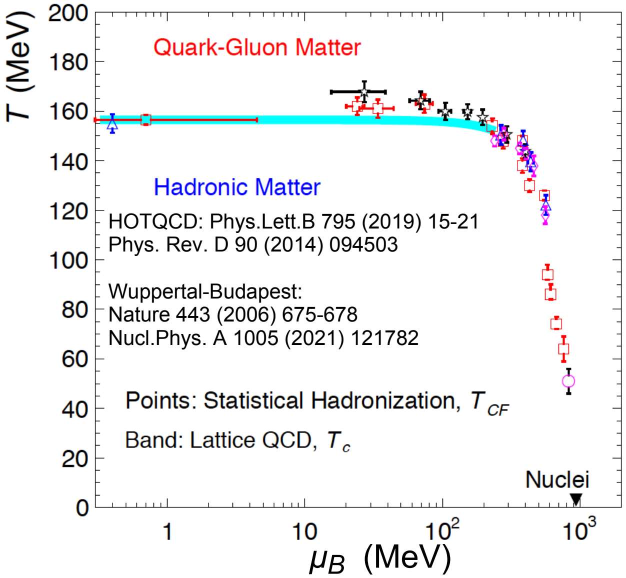
- Partial pressure of open charm mesons (M_c) and baryons (B_c) in a gas of uncorrelated hadrons,
  - **PDG-HRG**: All open charm resonances in PDG
  - **QM-HRG:** Relativistic quark model.
  - **QM-HRG-X:** open charm resonance spectrum is cut off at mass X GeV
- Below 160 MeV the latter coincides with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

Motivation: Nature of the chiral phase transition



F. Karsch, Schlechinq 2016

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



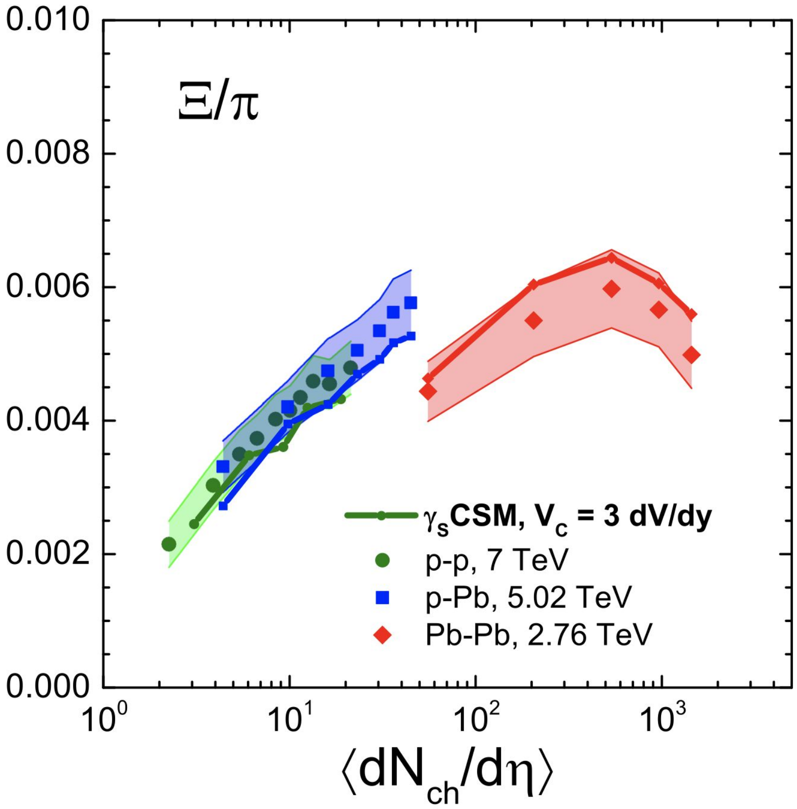
A. Andronic et.al. Nature 561 (2018) 321

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

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

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

Canonical statistical model



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