Chasing Critical Fluctuations with ALICE

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Yale University

The International Workshop "Never at Rest: A Lifetime Inquiry of QGP"
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In part supported by

The Method

"Discourse on the method of rightly conducting the reason and seeking the truth in the sciences", **René Descartes**

" **The 1st** was never to accept anything for true which I did not clearly know to be such; that is to say, carefully to avoid precipitancy and prejudice, and to comprise nothing more in my judgment than what was presented to my mind so clearly and distinctly as to exclude all ground of doubt.

The 2nd, to divide each of the difficulties under examination into as many parts as possible, and as might be necessary for its adequate solution.

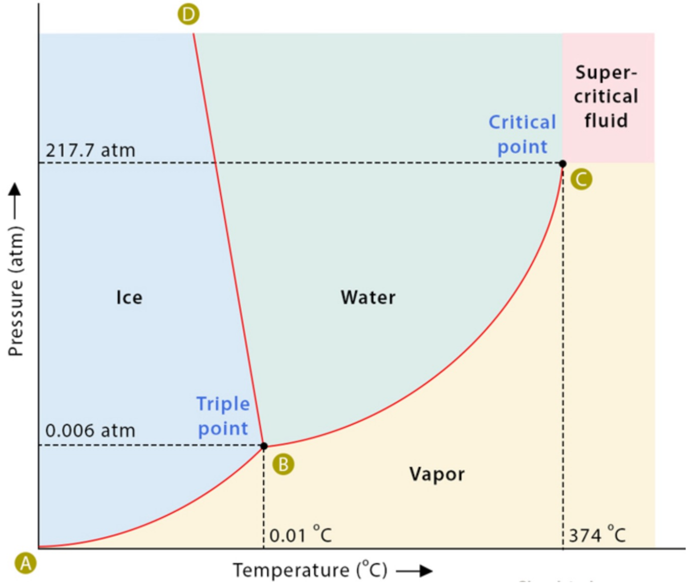
The 3rd, to conduct my thoughts in such order that, by commencing with objects the simplest and easiest to know, I might ascend by little and little, and, as it were, step by step, to the knowledge of the more complex; assigning in thought a certain order even to those objects which in their own nature do not stand in a relation of antecedence and sequence.

The last, in every case to make enumerations so complete, and reviews so general, that I might be assured that nothing was omitted."

Outline

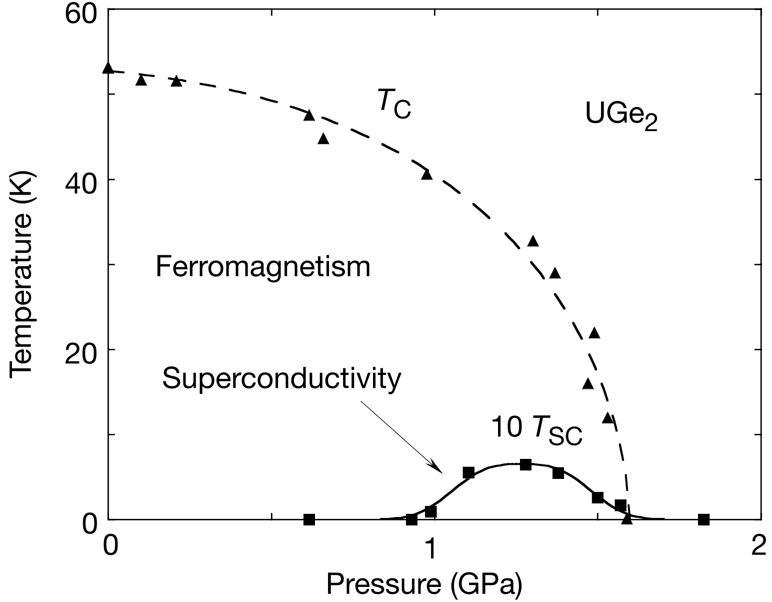
1) **Goal:** Discovery of crossover phase transition → Critical fluctuations
2) **Observable:** net-proton number fluctuations
3) **Experimental challenges:**
    - Proton identification
    - Event pile-up mitigation and energy loss calibration in the TPC
    - Efficiency corrections
    - Establishing a statistical baseline
4) **Results:**
    - Measurement of 2nd and 3rd order cumulants
5) **The quest continues:**
    - Prospects for ALICE 3 era

Phase diagram of water
(Electro-magnetic interaction)



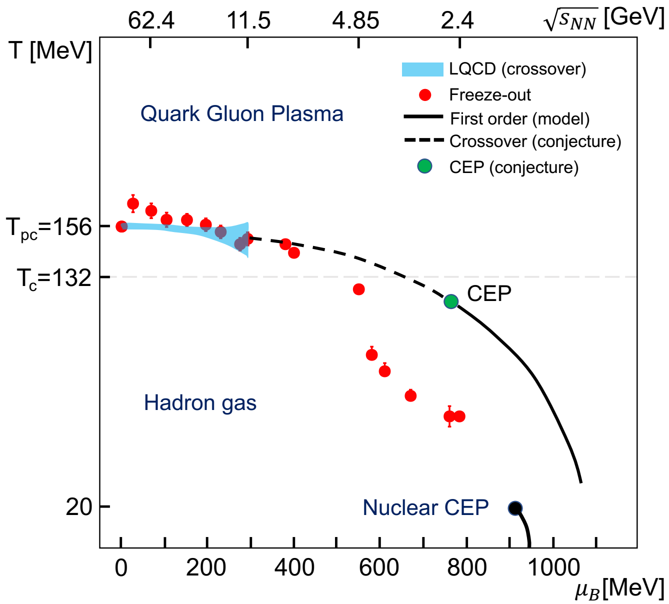
Phase transition: QGP

Ferromagnetic phase transition
(Electro-magnetic interaction)



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

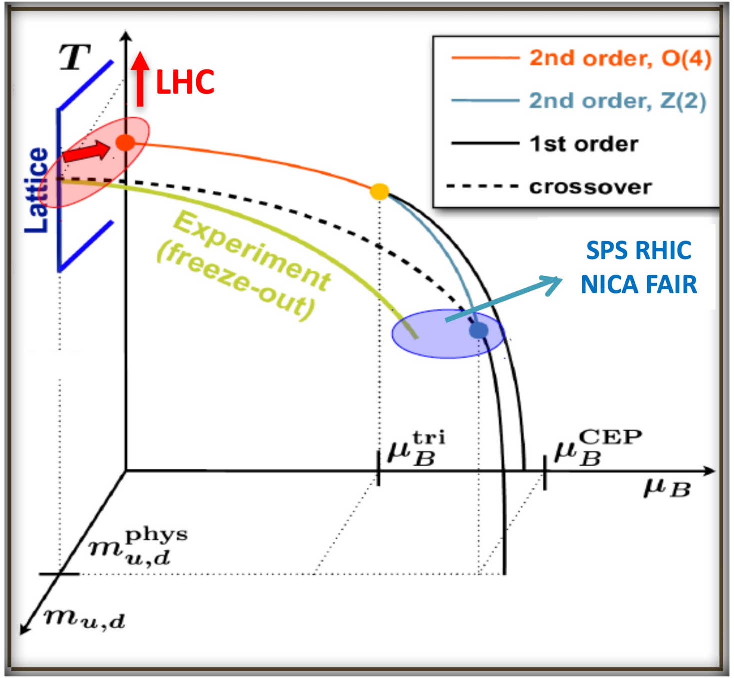
QCD phase diagram
(Strong interaction)



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

Nature of QCD phase diagram

F. Karsch, Schleching 2016



J. Stachel, A. Andronic, P. B. Munzinger and K. Redlich, *Nature 561 (2018) 321*
HotQCD Collaboration, *Phys.Lett. B 795 (2019) 15*
ALICE Collaboration, *Phys. Rev. Lett.* 133 (2024) 9, 092301

- **Vanishing u, d quark masses:**
  $\Longrightarrow$ Vicinity to 2nd order O(4) criticality
  $\Longrightarrow$ Pseudocritical features at the crossover due to massless modes

- **At LHC energies**
  $\Longrightarrow$ $T_{\rm pc}^{\rm LQCD} \approx T_{\rm fo}^{\rm ALICE} = 156.5 \pm 3$ MeV
  $\Longrightarrow$ $\mu_B^{\rm ALICE} = 0.71 \pm 0.45$ MeV

- **Fact:** No experimental confirmation of crossover
- **Signature:** Long range correlations & increased fluctuations

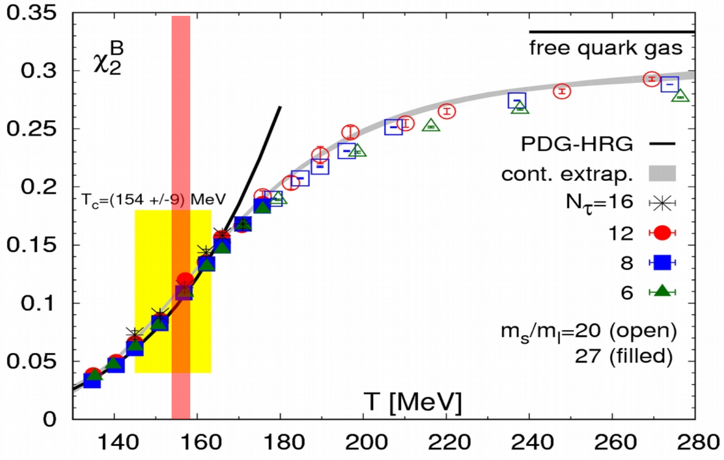
Talk by Frithjof

LQCD ↔ Experiment

LQCD

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

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



LQCD ↔ Experiment

LQCD

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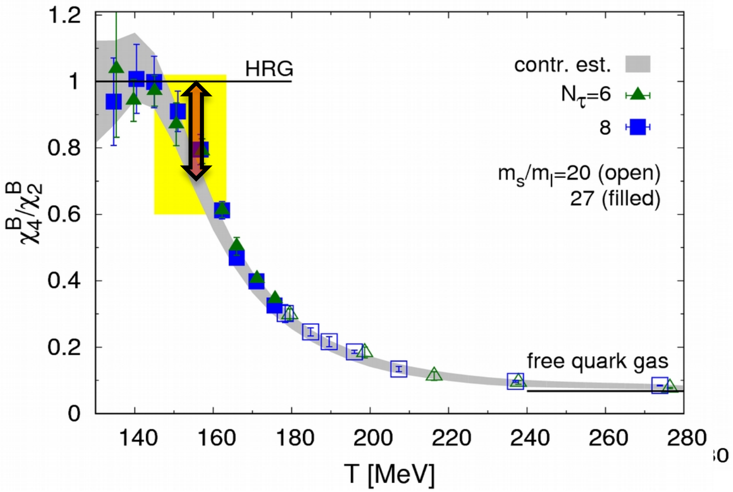

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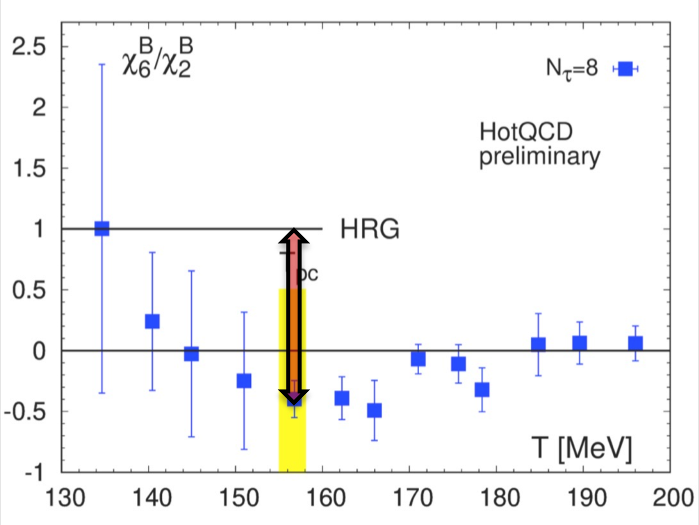


LQCD ↔ Experiment

Google Translate

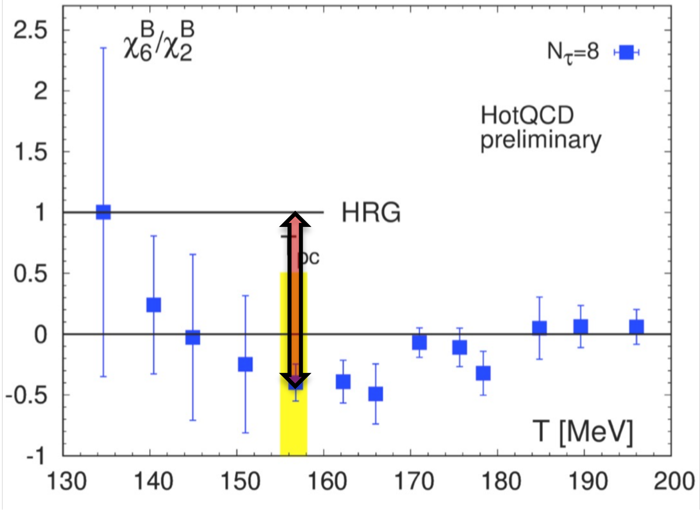
Detect language

LQCD

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

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

0 / 5,000



EXPERIMENT

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 $\Delta N_B = N_B - N_B$

Talk by Anar

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

LQCD ↔ Experiment

Google Translate

Detect language

LQCD

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

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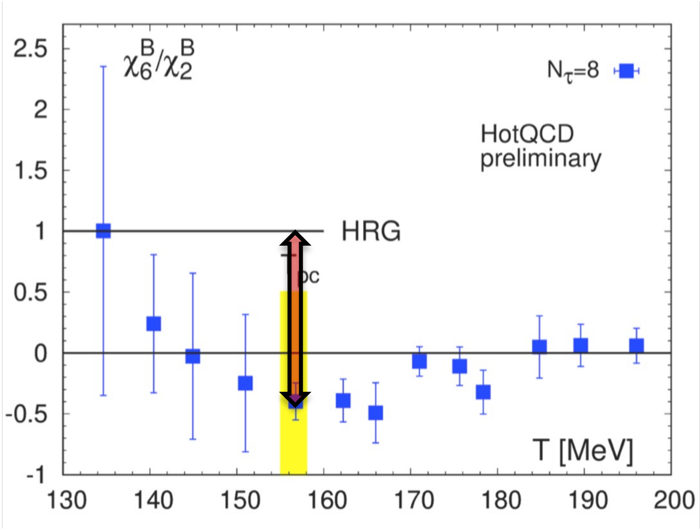

EXPERIMENT

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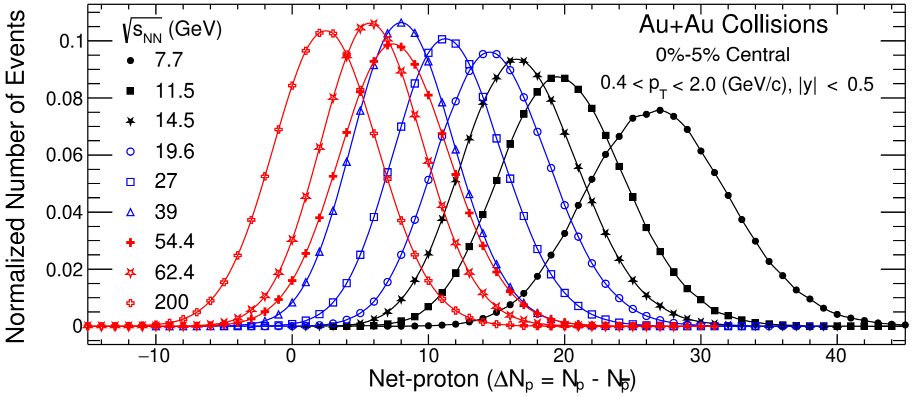
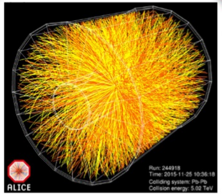
Talk by Anar

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

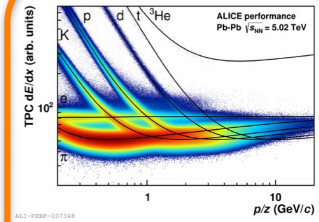


STAR Collaboration, Phys. Rev. Lett. 126, 092301

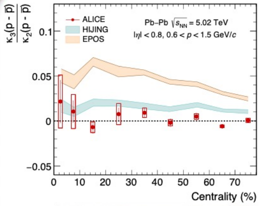
Experimental challenges



Event/track selection



dE/dx calibration and PID

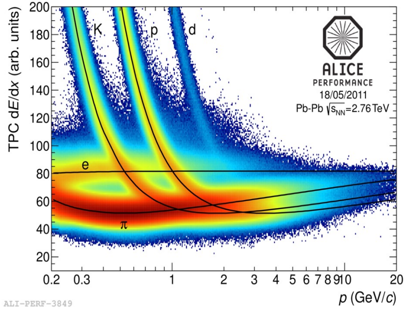


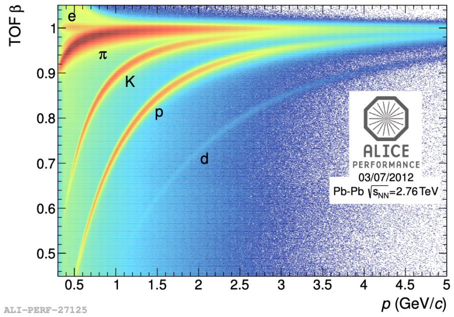
Efficiency correction

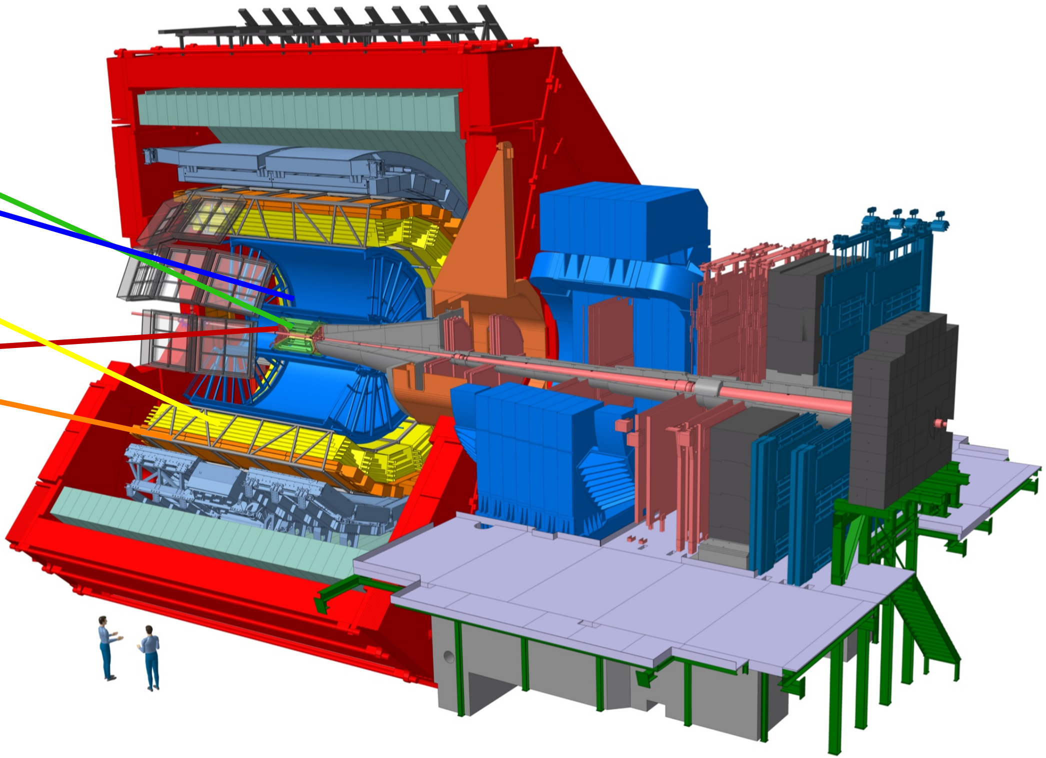
A Large Ion Collider Experiment

Main detectors used:

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

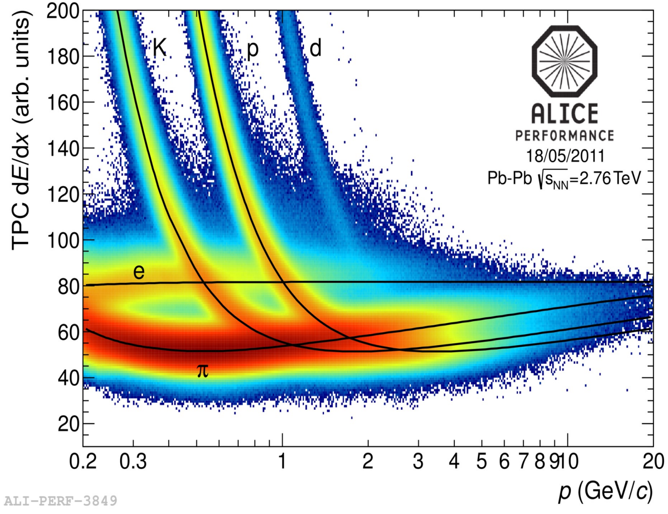




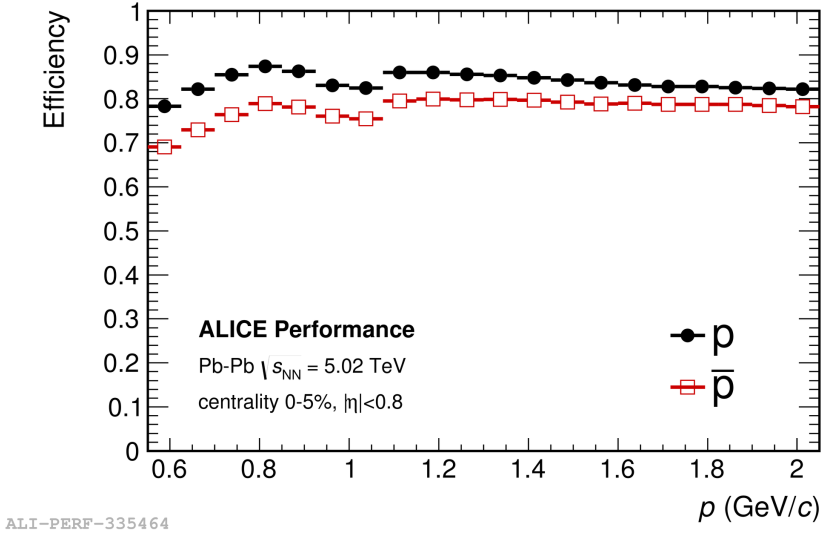


Challenge 1:
Particle identification (PID)

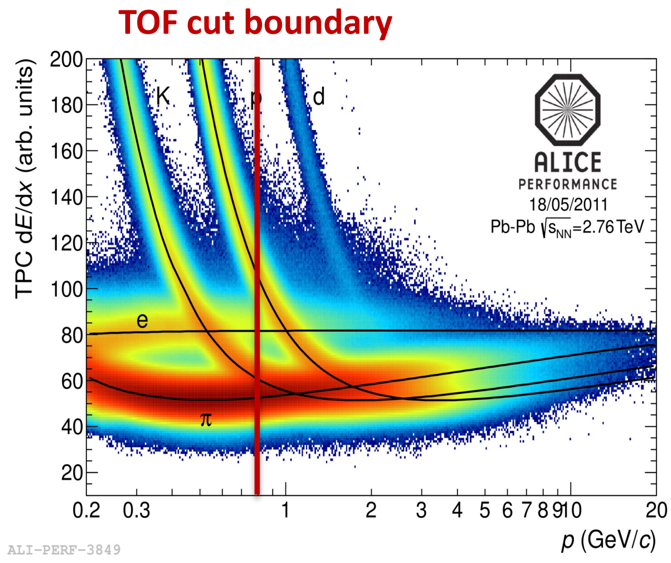
PID vs Efficiency

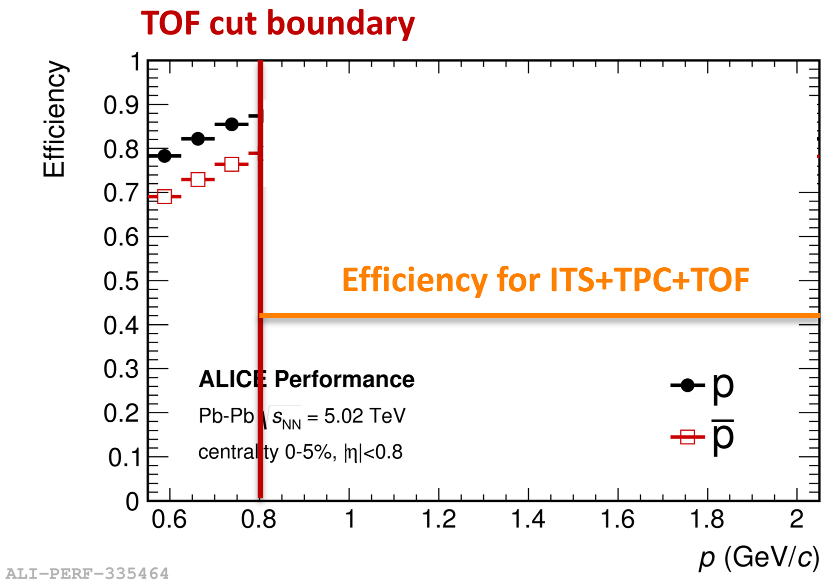


Efficiency for ITS+TPC



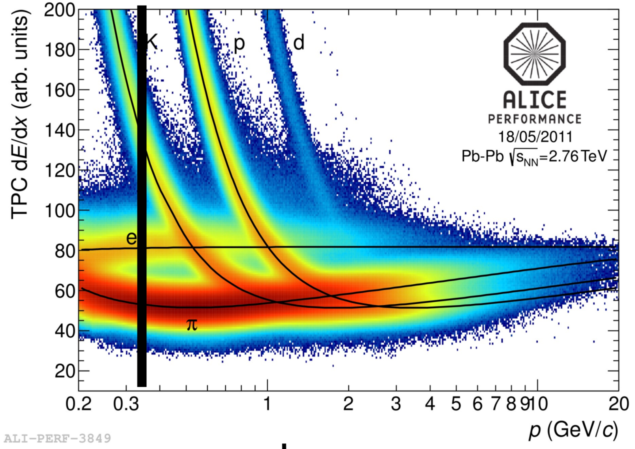
PID vs Efficiency

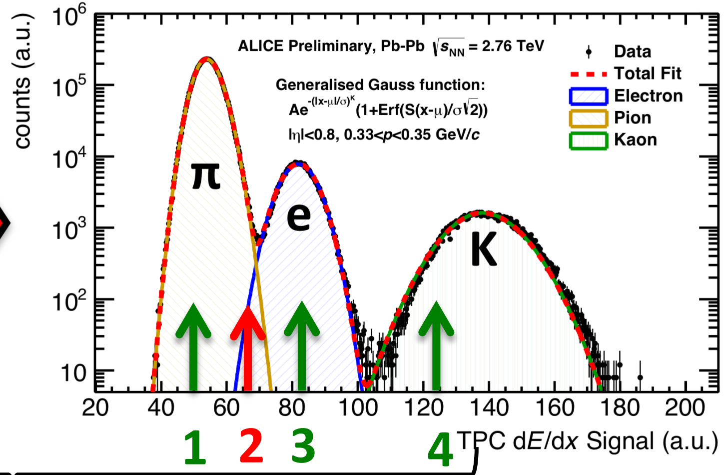




Solution: Identity Method

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



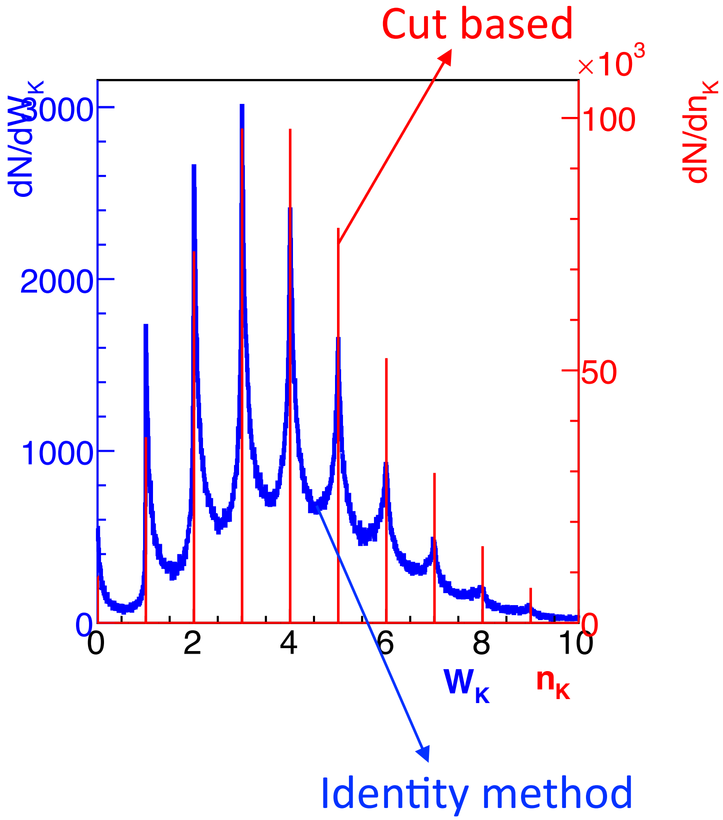


$$\omega_\pi^{(1)} = 1, \quad \omega_\pi^{(2)} \cong 0.6, \quad \omega_\pi^{(3)} = 0, \quad \omega_\pi^{(4)} = 0 \quad \Rightarrow \quad W_\pi = 1.6 \neq N_\pi$$

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

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

Solution: Identity Method

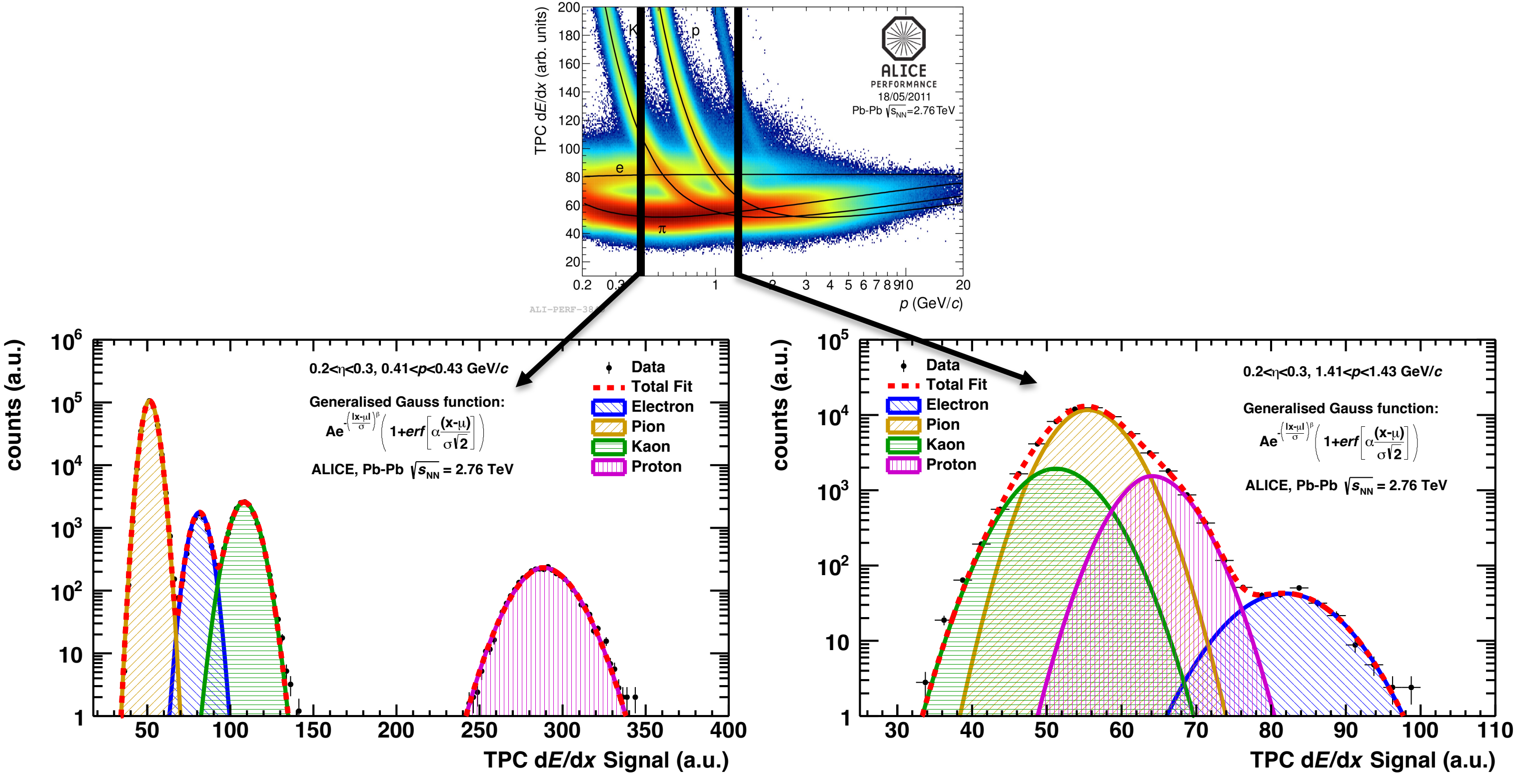


$$\langle N_j^n \rangle = A^{-1} \langle W_j^n \rangle$$

A. Rustamov, "Fuzzy logic" Phys. Rev. C 110 (2024) 6, 064910

Challenge within Identity Method

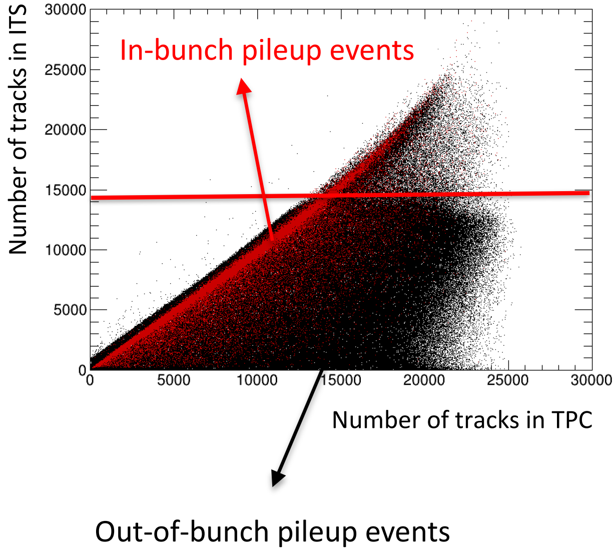
Precise description of **line shapes** → **Energy loss** calibration & event **pileup** mitigation



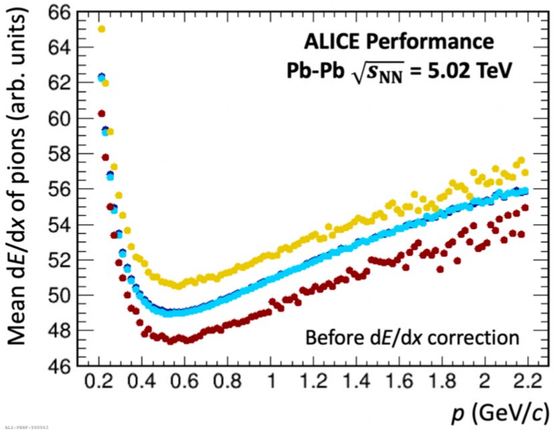
Energy loss calibration & event pileup

Tag pileup events and correct energy loss

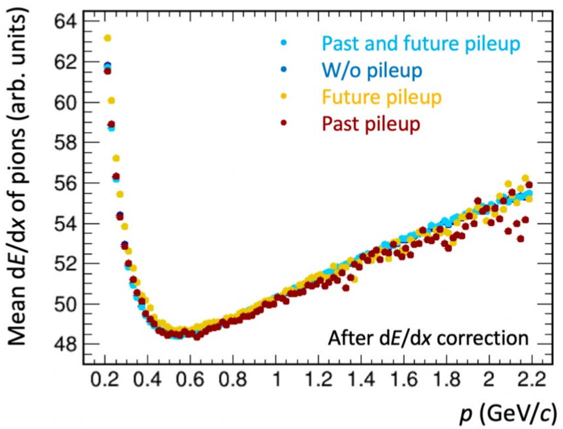
Tagging



Before correction

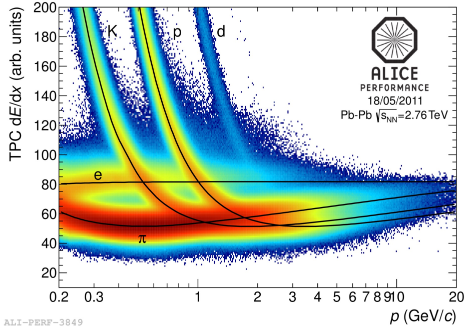


After correction

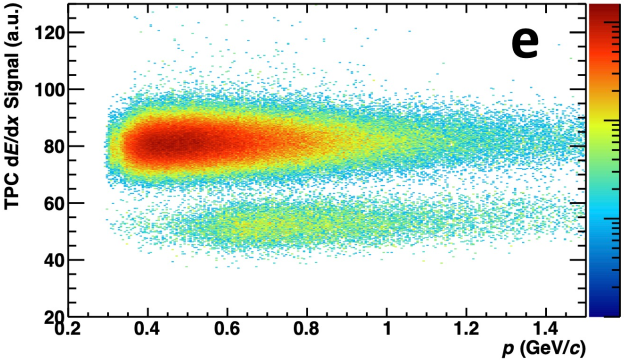


M. Arslandok, E. Hellbär, M. Ivanov, R.H. Münzer and J. Wiechula, Particles 2022, 5(1), 84-95
ALICE TPC Collaboration JINST 19 (2024) P02038

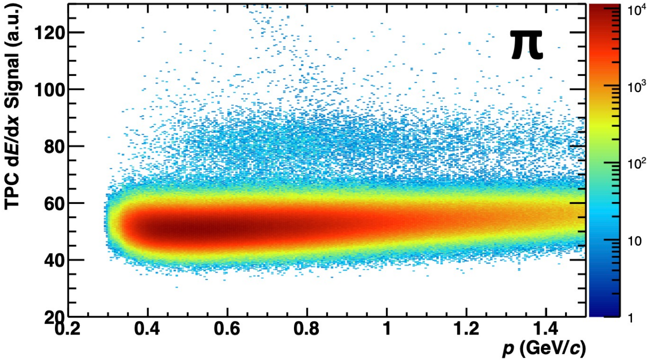
Line shapes



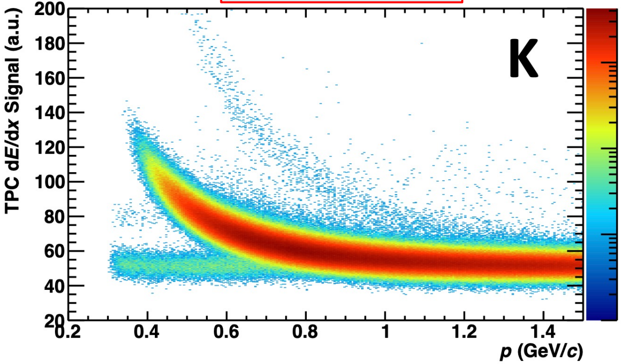
$\gamma \rightarrow e^{+}e^{-}$



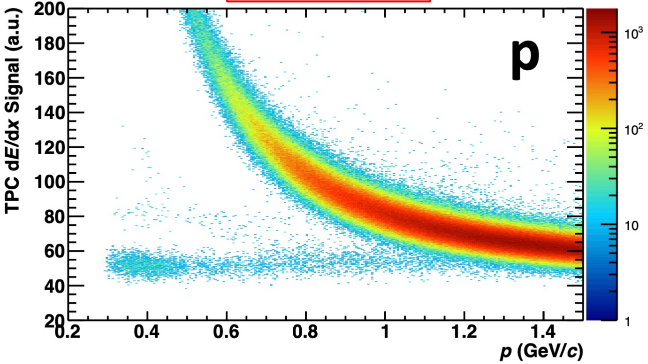
$K_S^0 \rightarrow \pi^{+}\pi^{-}$



TOF + TRD



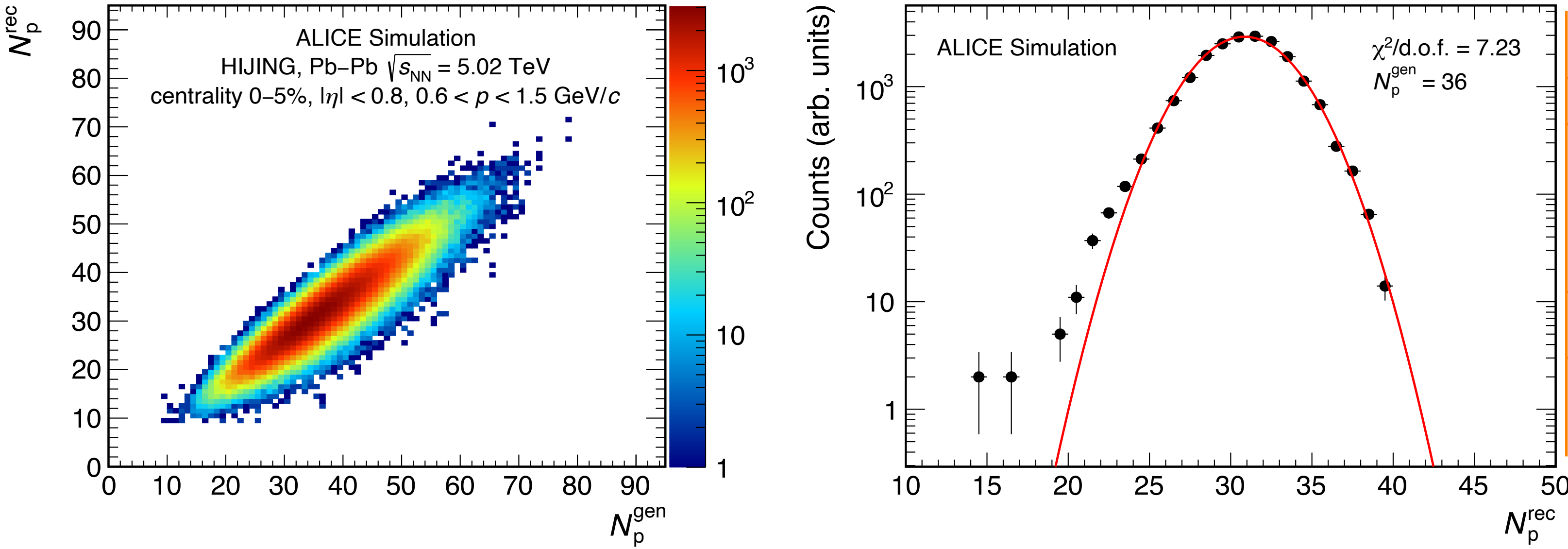
$\Lambda \rightarrow \pi p$



Challenge 2:
Efficiency correction

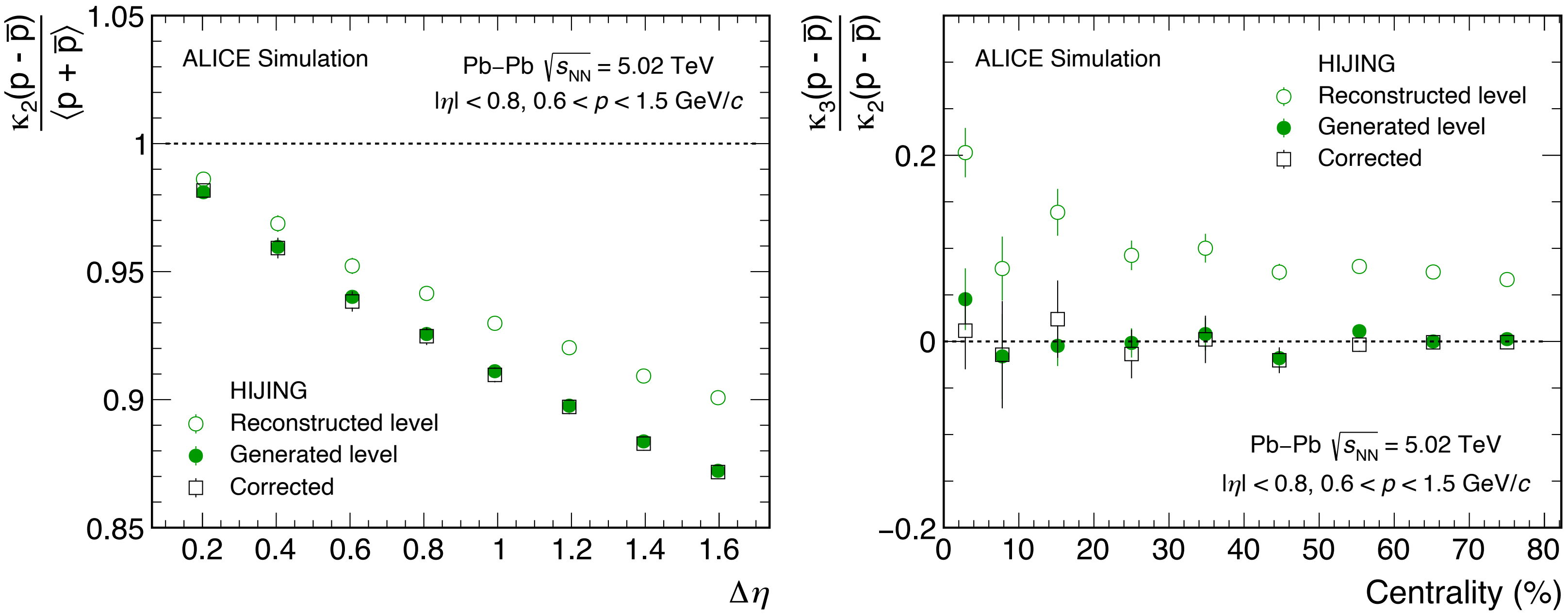
Challenge 2: Efficiency correction

Binomiality of the detector response is important for the efficiency correction



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

Challenge 2: Efficiency correction



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

Very good closure despite the slight deviation from binomial loss

Efficiency correction with binomial assumption:

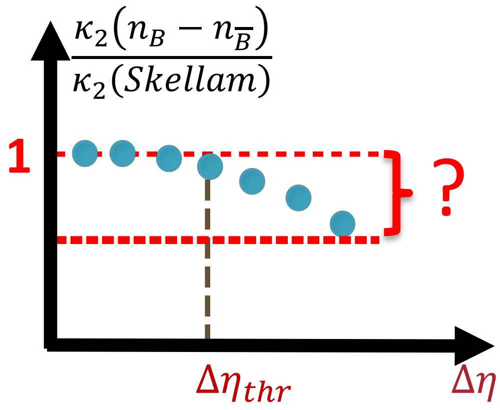
T. Nonaka, M. Kitazawa, S. Esumi, Phys. Rev. C 95, 064912 (2017)

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

Challenge 3:
Establishing a non-critical baseline

How to interpret the data?

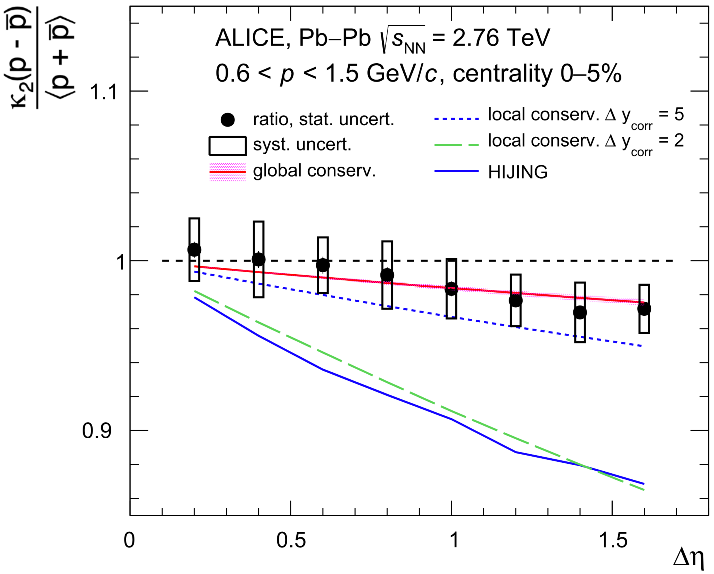
Source of the deviation?



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

How to interpret the data?

Source of the deviation?

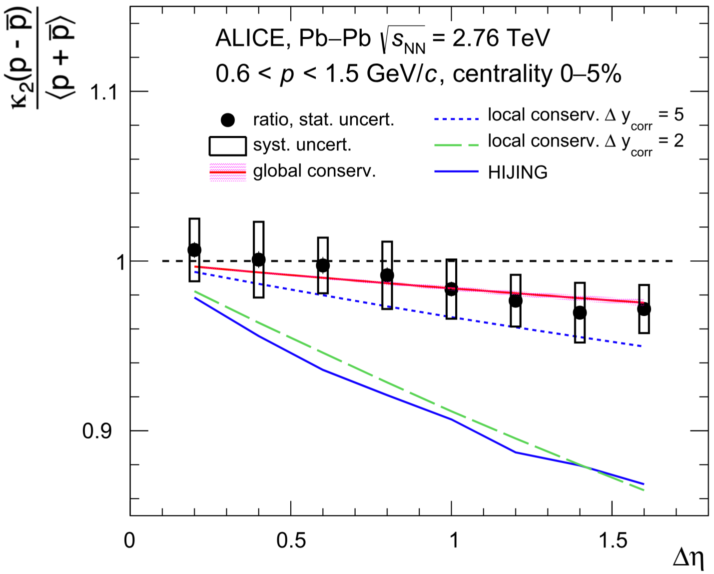


ALICE Coll., Phys. Lett. B 807 (2020) 135564

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

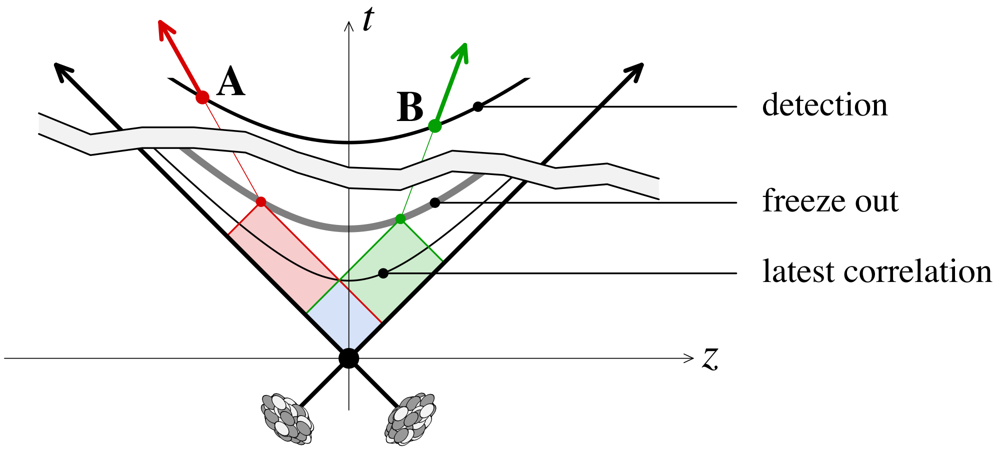
Correlation length

Source of the deviation?



ALICE Coll., Phys. Lett. B 807 (2020) 135564
J. Stachel , P. Braun-Munzinger, A. Rustamov, NPA 960 (2017) 114–130

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



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

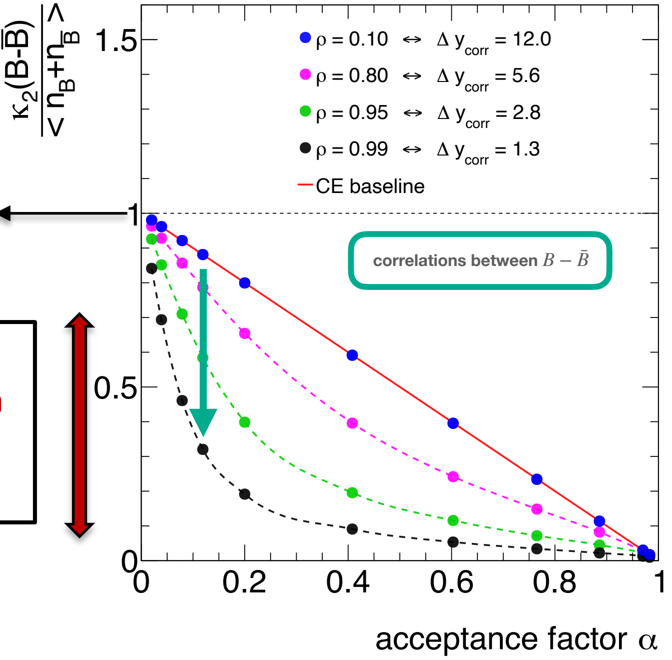
A. Dumitru, F. Gelis, L. McLerran, and R. Venugopalan, *Nucl. Phys. A* 810 (2008) 91

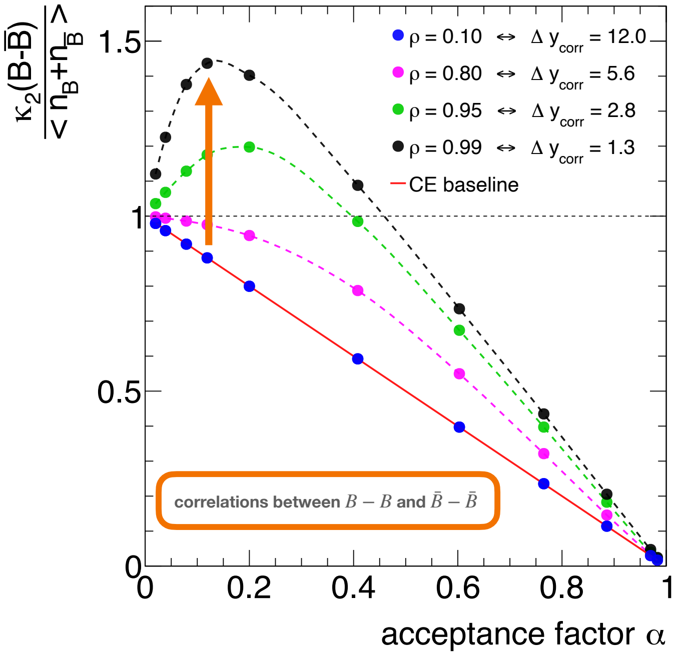
Baryon number conservation & cluster formation

J. Stachel, P. Braun-Munzinger, K. Redlich, A. Rustamov, *JHEP* 08 (2024) 113

HRG baseline in GCE

Larger deviation:
→ Smaller correlation length
→ Late production

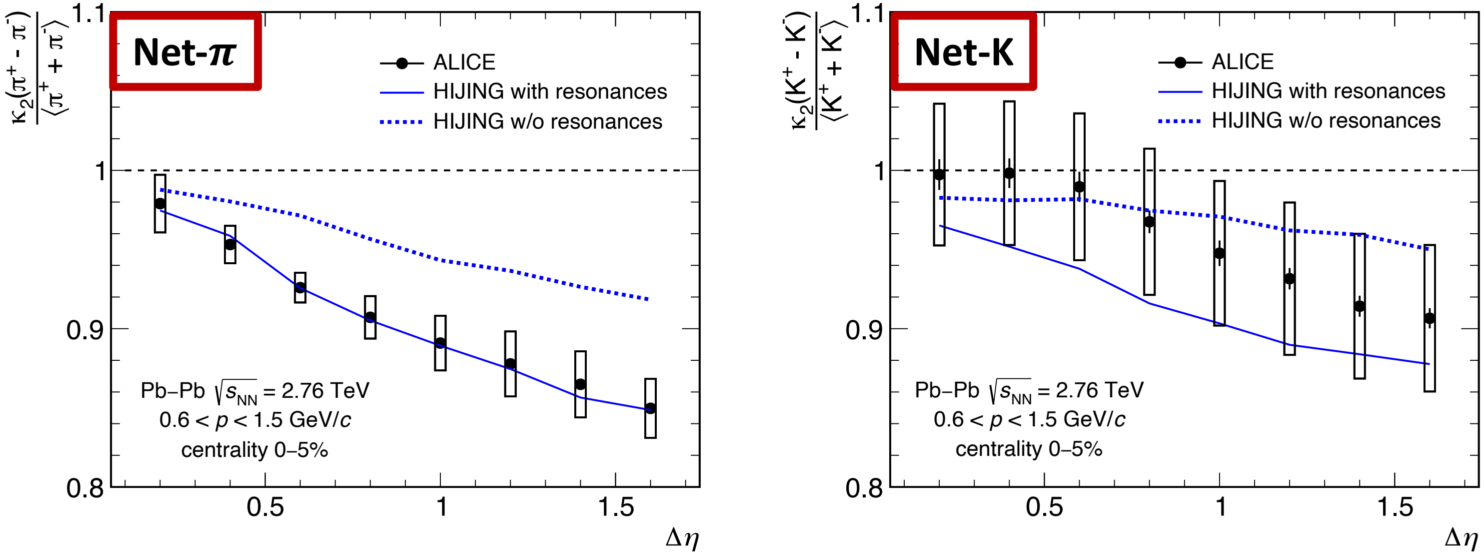




- Measured values depend on the fraction of (anti-)protons in the acceptance
- (Global) local baryon number conservation: **unlike-sign correlations**
- (Anti-)proton clusters: **like-sign correlations**

Talk by Anar

Resonance decays



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

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

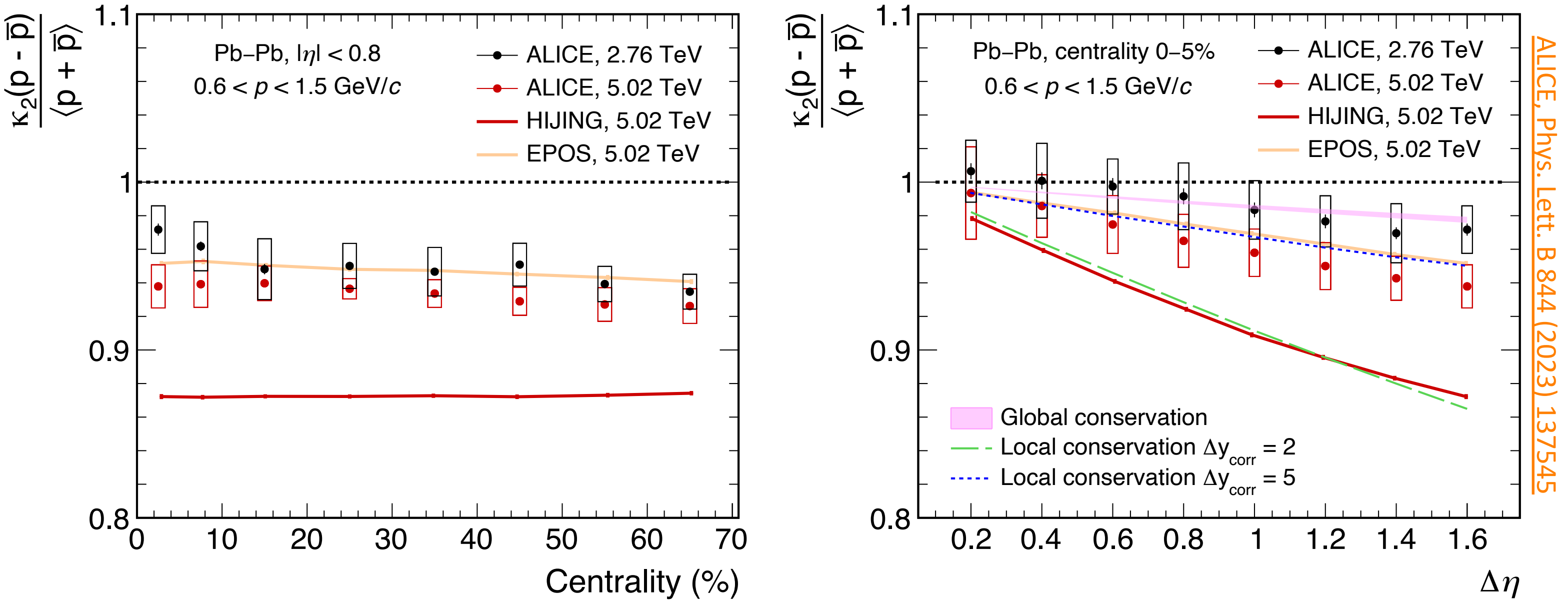
  → **Isospin randomization,** at $\sqrt{s_{\rm NN}}$ > 10 GeV: **net-B ↔ net-p**

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

Results:

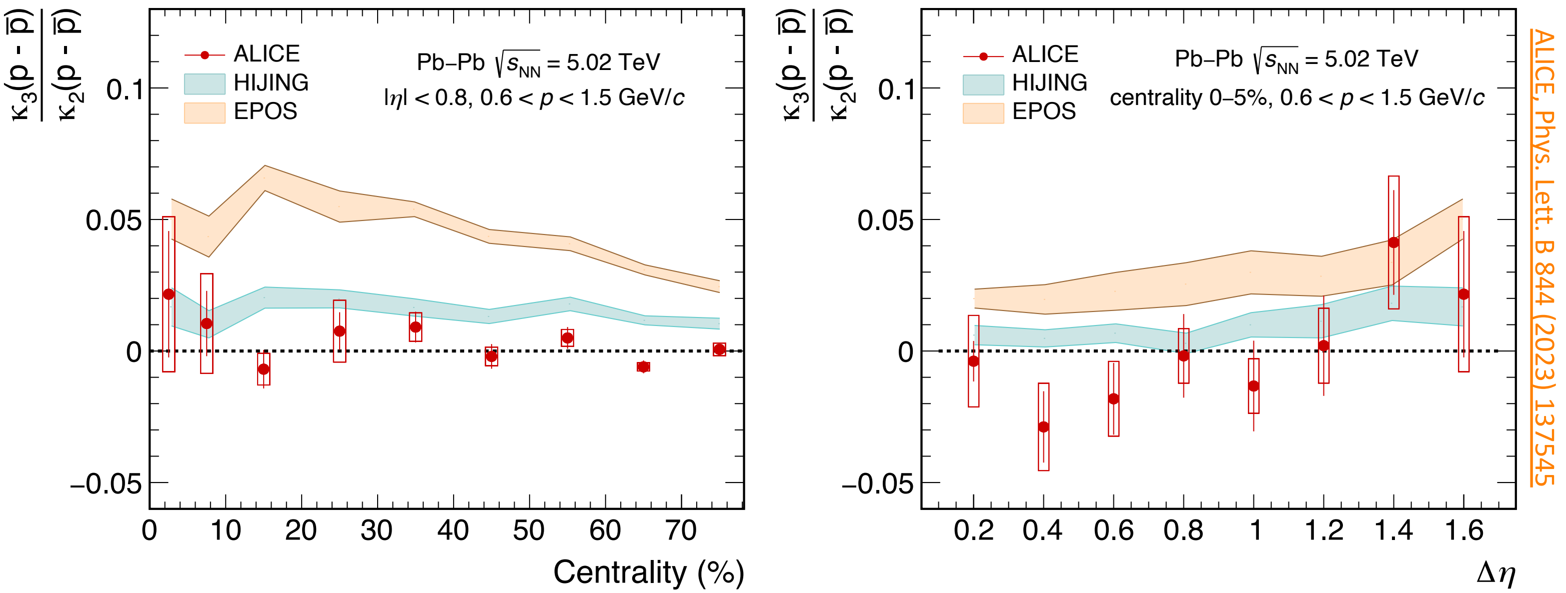
2nd and 3rd order cumulants of net-p

2^{nd} order cumulants of net-p



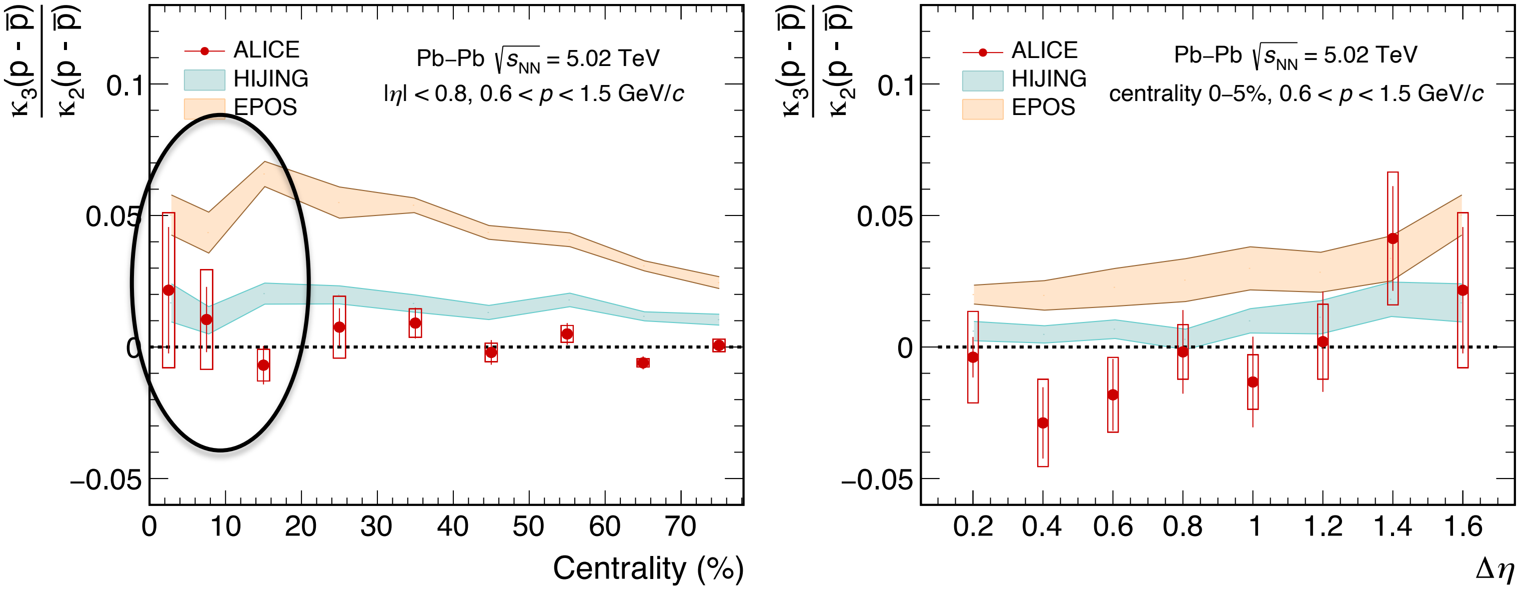
- Deviation from Skellam baseline is due to **baryon number conservation**
- ALICE data suggest **long range correlations**, $\Delta y = \pm 2.5$ **unit or longer → earlier in time**
  A. Dumitru, F. Gelis, L. McLerran, and R. Venugopalan, *Nucl. Phys. A* 810 (2008) 91
- Event generators based on **string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

3^{rd} order cumulants of net-p



- **Data agree with Skellam baseline "0"** → **μ_B is very close to 0** (ALICE Collaboration, *PRL.* 133 (2024) 9, 092301)

3^{rd} order cumulants of net-p



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

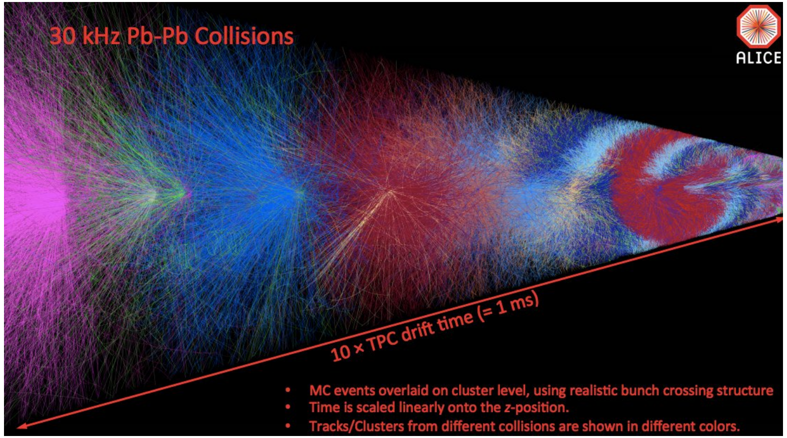
- **Data agree with Skellam baseline "0"** → **μ_B is very close to 0** (ALICE Collaboration, *PRL.* 133 (2024) 9, 092301)
- **EPOS and HIJING deviate from "0"**
  - They conserve global charge but **$p/\bar{p}$ deviates from unity**: 1.025±0.004 (EPOS), 1.008±0.002 (HIJING)
  - **Volume fluctuations** for 2^{nd} and 3^{rd} order cumulants are not negligible

The quest continues

(ALICE [2,3])

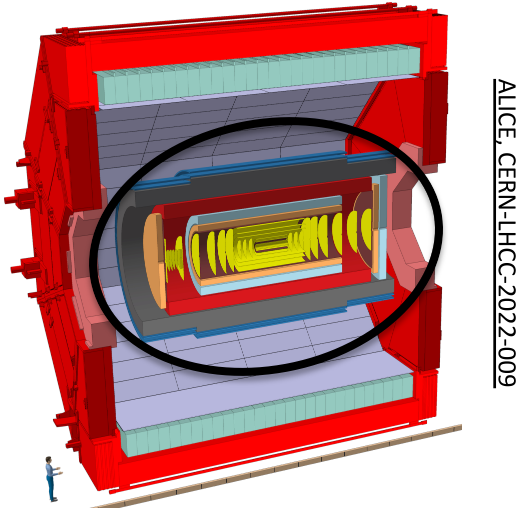
Future of ALICE

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**

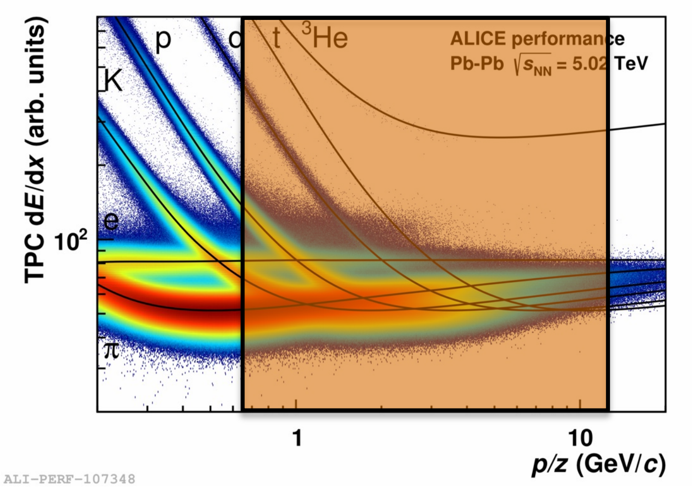
ALICE 3 (beyond early 2030s)

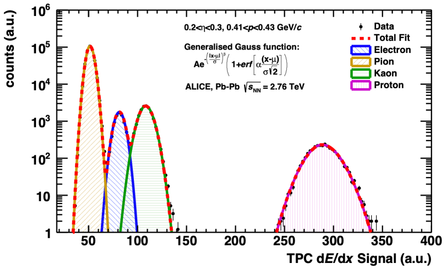


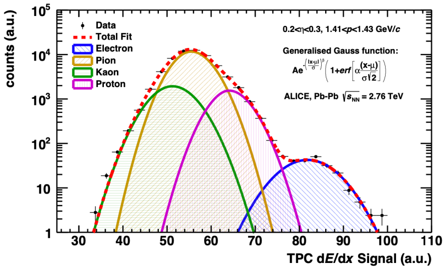
- ✓ **High statistics** → O (10^9) billion events
- ✓ **Large acceptance** → $|\eta| < 4$
- ✓ **High PID purity** → $0.3 < p_T < 10$ GeV/c
- ✓ **High efficiency** → ~95%
- ✓ **Excellent vertexing** → O (5μm) resolution

Identity Method in ALICE 3: Purity in PID

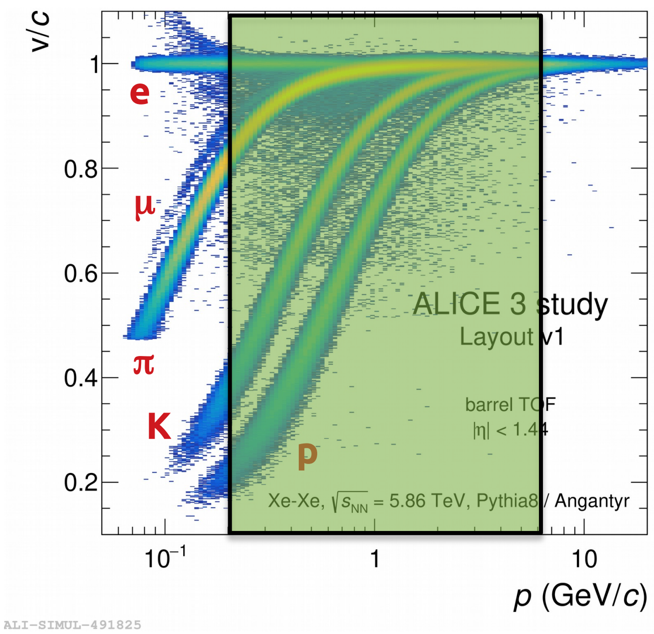
ALICE 1-2





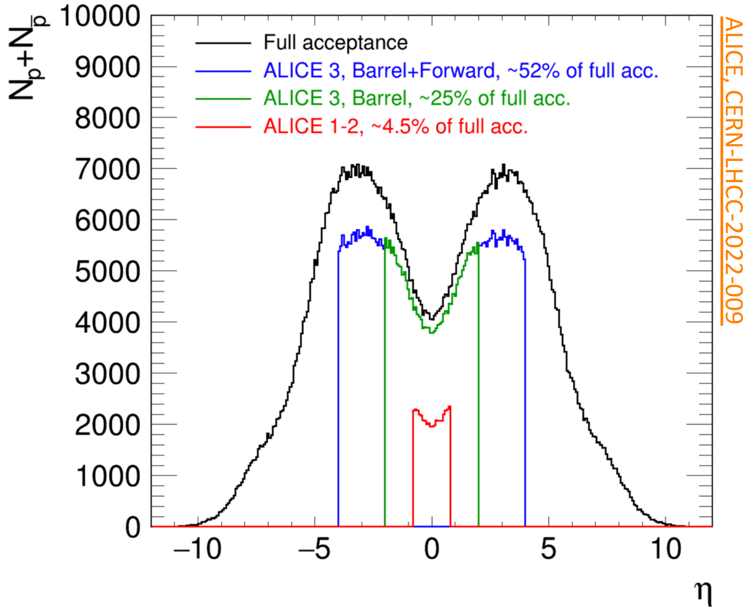


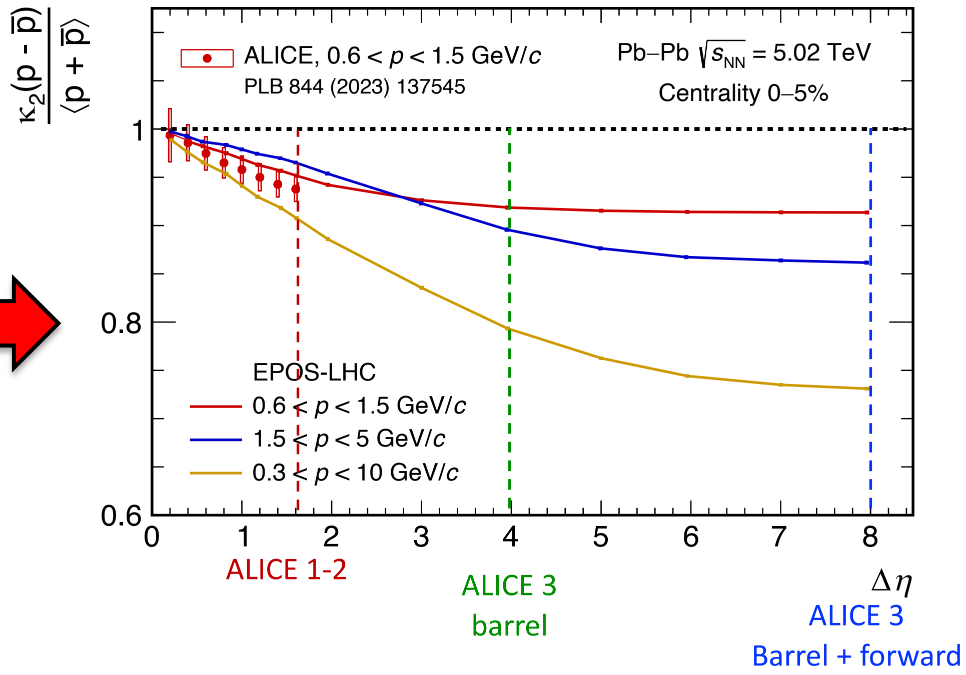
ALICE 3



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

2^{nd} order cumulants of net-p in ALICE 3

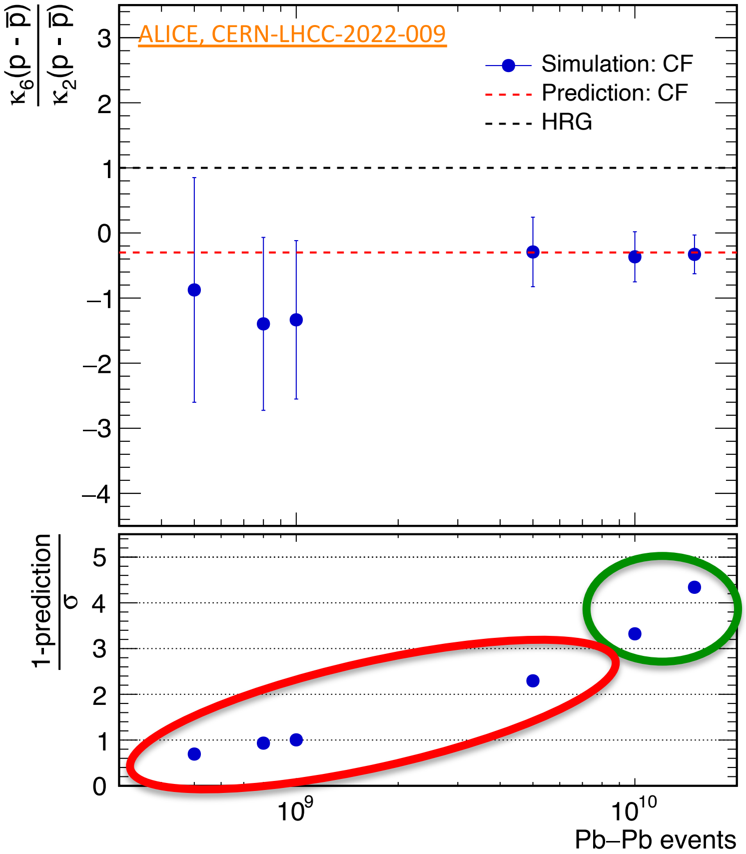




- **High PID purity and efficiency within a larger acceptance** (0.3 < p < 10 GeV/c, $|\eta|$<4)

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

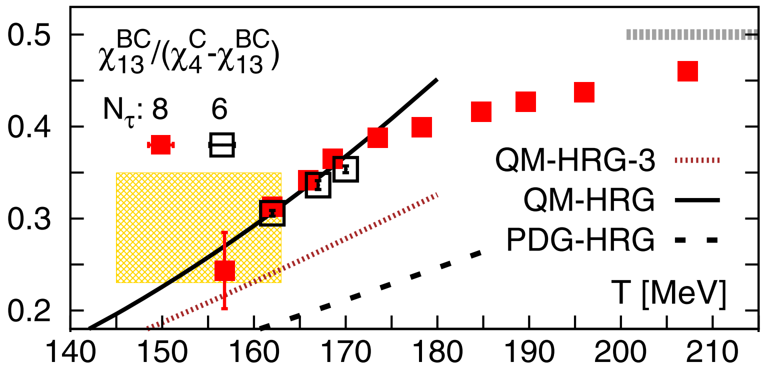
Criticality search in ALICE 2 and 3

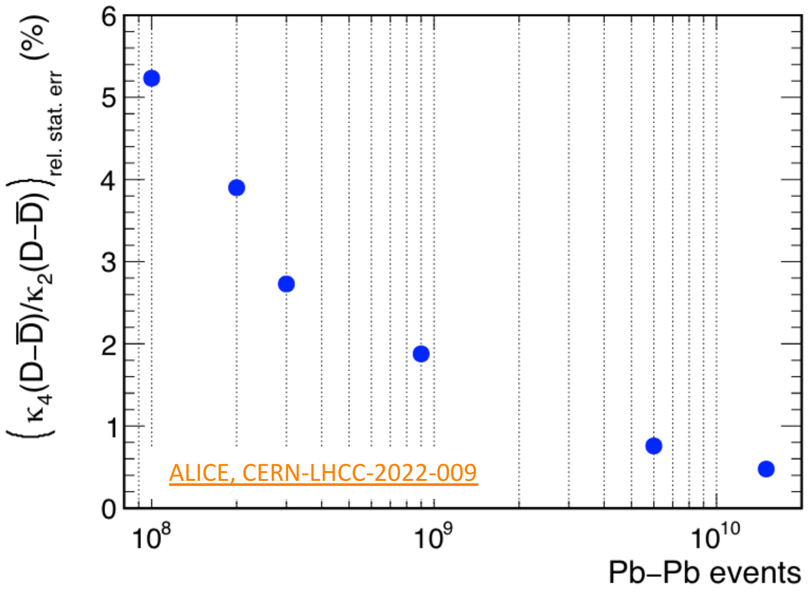


- Simulation of the Critical Fluctuations (CF) is based on PQM model
  G. A. Almasi, B. Friman, and K. Redlich, Phys. Rev.D96 (2017), 014027
- **ALICE 2:**
  → More than 5 billion central Pb-Pb collisions is required
- **ALICE 3:**
  → **x3 larger statistics:** $>4\sigma$ significance with ALICE 2 acceptance

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

ALICE 1 (2010-2018)

- **LQCD expectations** → agreement up to 3rd order
- **Large correlation volume** → B and S correlation come from early times
- **Lund-based models** → describe 1st order but fail in 2nd for both B and S

ALICE 2-3 (2023-203?)

- **4th order** cumulants of net-B are in progress
- **Net B and S:** Criticality search at **6th and higher order cumulants**
- **Net C:** correlation length in charm sector
- **High precision and more differential:** Constraining individual dynamic signals
    - Thermal blurring, Initial-state fluctuations, Baryon annihilation, Excluded volume effects, Baryon number conservation …
- **…**