

When the TPC Meets Fluctuations



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8 September 2026, Georg-C.-Lichtenberg-Haus, Darmstadt, Germany

Yale



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ENERGY

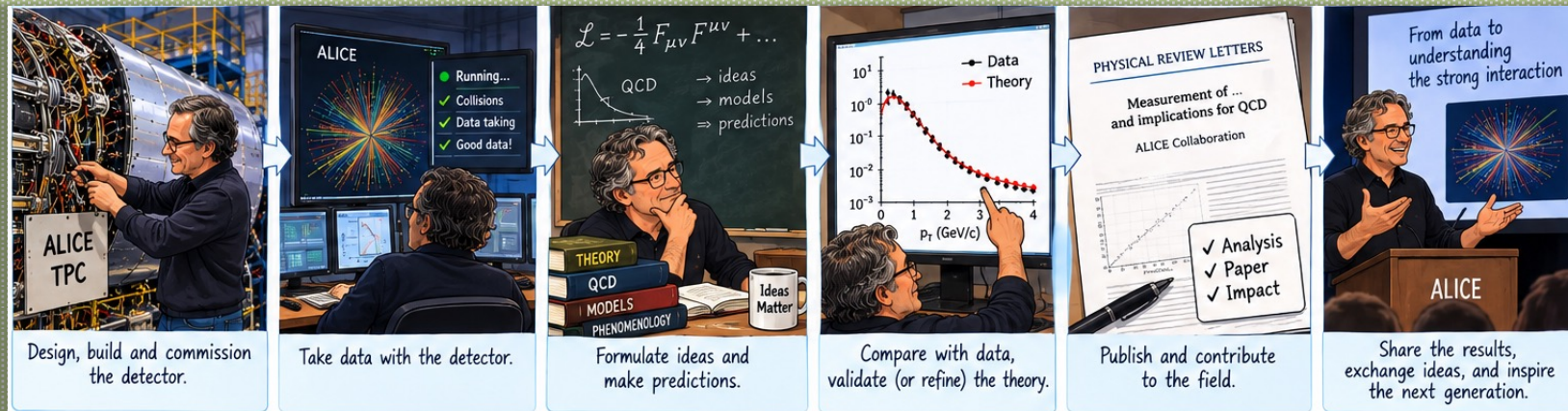
Office of
Science

How I see PBM

How I see PBM



How I see PBM



My story with PBM

❖ **Detector:** The ALICE TPC (2008-present)

My story with PBM

Source: Dariusz



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Source: Dariusz



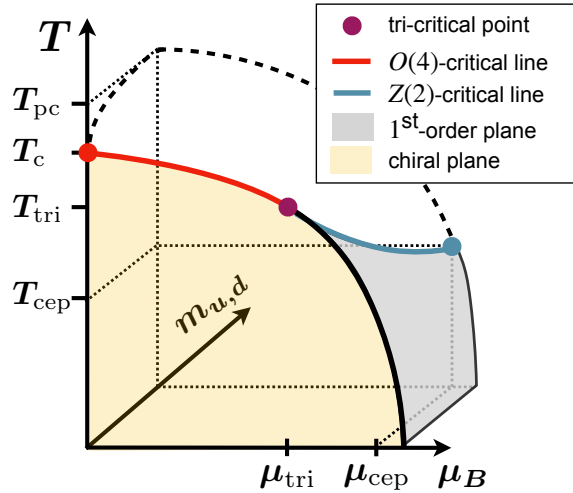
❖ **Detector:** The ALICE TPC (2008-present)

❖ **Physics:** Identity Method (2015-present) && Bridging LQCD to Experiment (2016-present)

Physics motivation

Bridging LCD to experiment

Theory

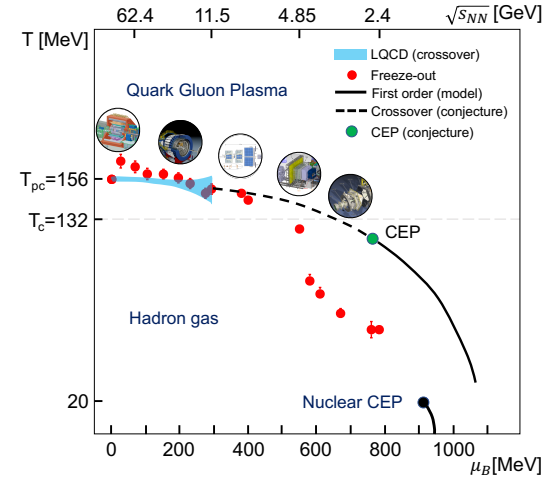


$$\frac{p}{T^4} = \frac{1}{VT^3} \ln Z(V, T, \vec{\mu})$$

Chiral condensate, susceptibilities ...

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

Experiment

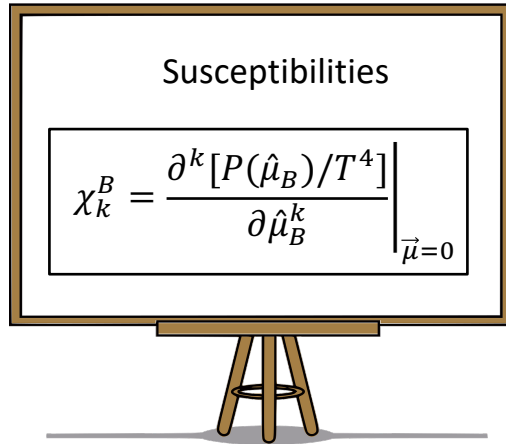


$$\langle N \rangle = \sum_j N_j p_j = T \frac{\partial \ln Z_{GCE}}{\partial \mu} \bigg|_V$$

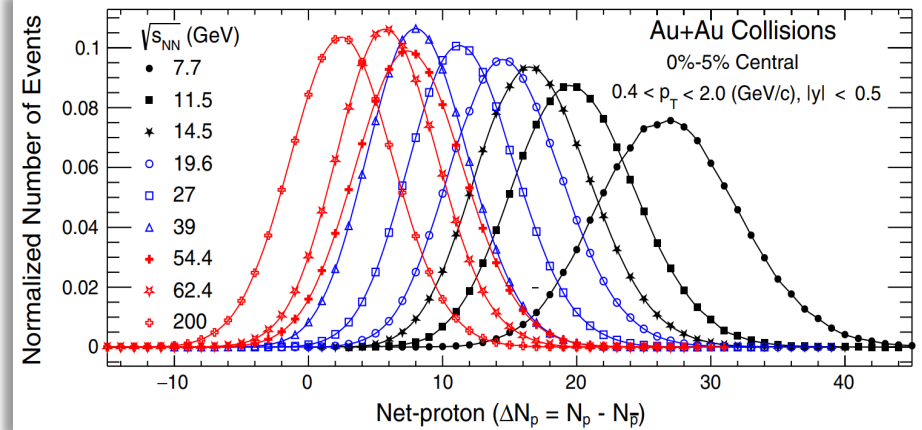
Moments, (factorial) cumulants ...

Bridging LCD to experiment

LQCD



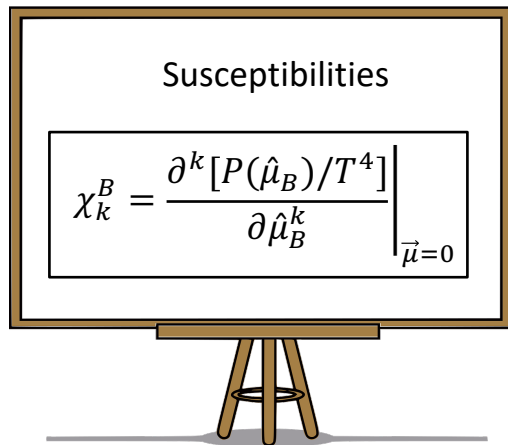
Experiment



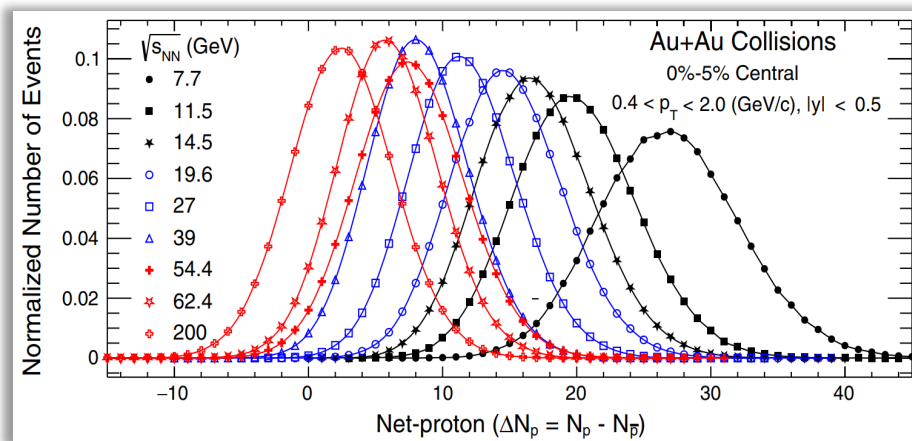
STAR Coll., Phys. Rev. Lett. 126, 092301 (2021)

Bridging LCD to experiment

LQCD



Experiment



STAR Coll., Phys. Rev. Lett. 126, 092301 (2021)

Cumulants

$$\begin{aligned}\kappa_1 &= \langle N \rangle \\ \kappa_2 &= \langle N^2 \rangle - \langle N \rangle^2 \\ \kappa_3 &= \langle N^3 \rangle + 3\langle N^2 \rangle \langle N \rangle + 2\langle N \rangle^3 \\ \kappa_4 &= \langle N^4 \rangle - 4\langle N^3 \rangle \langle N \rangle - 3\langle N^2 \rangle^2 \\ &\quad + 12\langle N^2 \rangle \langle N \rangle^2 - 6\langle N \rangle^4\end{aligned}$$

Link theory to experiment

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

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

$$\kappa_n / \kappa_2 \text{ is } 0 \text{ (n odd) or } 1 \text{ (n even)}$$

Expected signal
beyond 4th order

Analysis tool

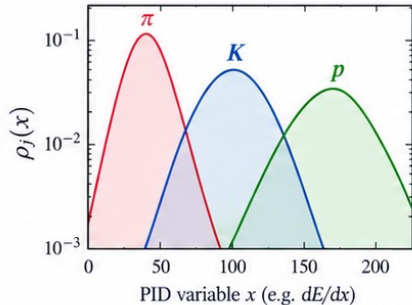
The Identity Method

Anar Rustamov and M. I. Gorenstein

Event-by-event multiplicity moments with incomplete particle identification

1. Inclusive PID signal distributions

Obtain inclusive detector response for each particle species j (e.g. from data or simulation)

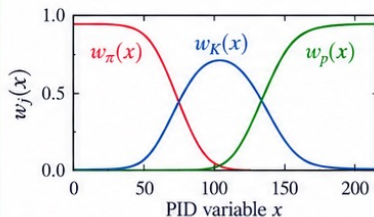


2. Identity weights

For each measured track with PID signal x_i , calculate the identity weights (probability to be of species j)

$$w_j(x_i) = \frac{\rho_j(x_i)}{\sum_k \rho_k(x_i)}$$

$$0 \leq w_j(x_i) \leq 1, \quad \sum_j w_j(x_i) = 1$$



3. Event-by-event sums

For each event, sum the identity weights over all tracks:

$$W_j = \sum_{i=1}^{N_{tr}} w_j(x_i)$$

Example event

track 1 $x_1 \rightarrow (w_\pi, w_K, w_p)$
 track 2 $x_2 \rightarrow (w_\pi, w_K, w_p)$
 track 3 $x_3 \rightarrow (w_\pi, w_K, w_p)$
 $\vdots$
 track N_{tr} $x_{N_{tr}} \rightarrow (w_\pi, w_K, w_p)$

These weights are summed to form the event-level moments W_π, W_K, W_p .

Repeat for all events to obtain distributions and moments of W_j .

4. Reconstruct true multiplicity moments

The measured moments of W are related to the true multiplicity moments of N by a response matrix A , determined from the PID distributions $\rho_j(x)$:

$$\langle W \rangle = A \langle N \rangle \Rightarrow \langle N \rangle = A^{-1} \langle W \rangle$$

Similarly for higher orders (second, mixed moments, ...):

$$\langle W_j W_k \rangle = \sum_{a,b} A_{jk,ab} \langle N_a N_b \rangle$$

$$\langle N_a N_b \rangle = \sum_{j,k} (A^{-1})_{ab,jk} \langle W_j W_k \rangle$$

Example (means):

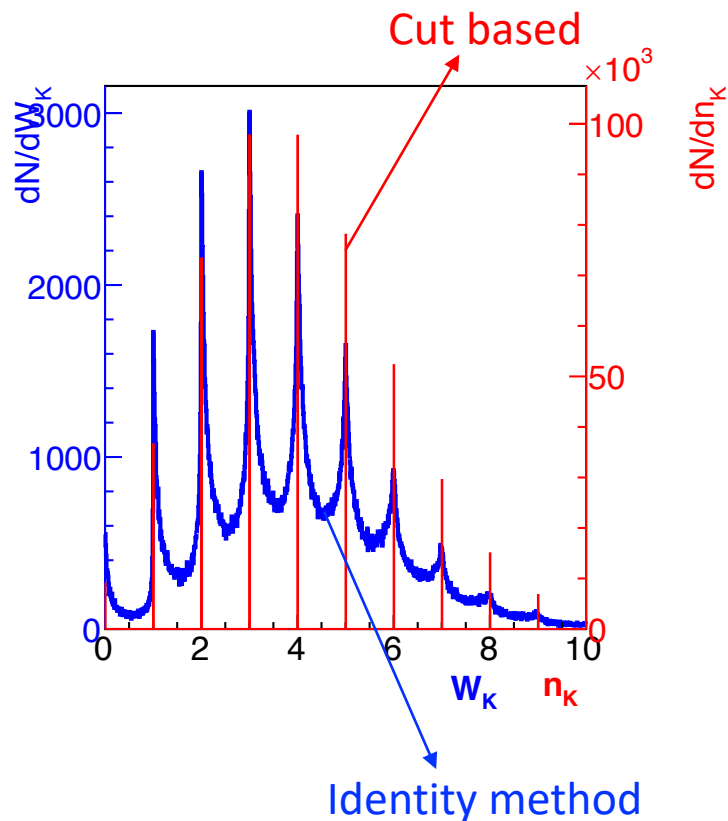
$$\begin{pmatrix} \langle W_\pi \rangle \\ \langle W_K \rangle \\ \langle W_p \rangle \end{pmatrix} = A \begin{pmatrix} \langle N_\pi \rangle \\ \langle N_K \rangle \\ \langle N_p \rangle \end{pmatrix} \Rightarrow \begin{pmatrix} \langle N_\pi \rangle \\ \langle N_K \rangle \\ \langle N_p \rangle \end{pmatrix} = A^{-1} \begin{pmatrix} \langle W_\pi \rangle \\ \langle W_K \rangle \\ \langle W_p \rangle \end{pmatrix}$$

A is calculated from the known $\rho_j(x)$ and detector effects (efficiency, acceptance, etc.).

Handles incomplete / overlapping particle identification

Allows unbiased determination of multiplicity moments and correlations without requiring explicit PID cuts.

Identity Method

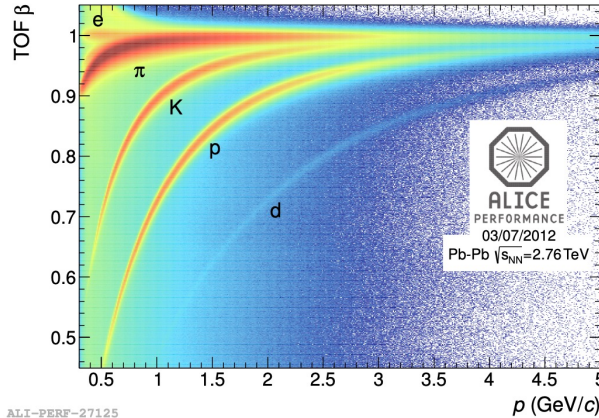
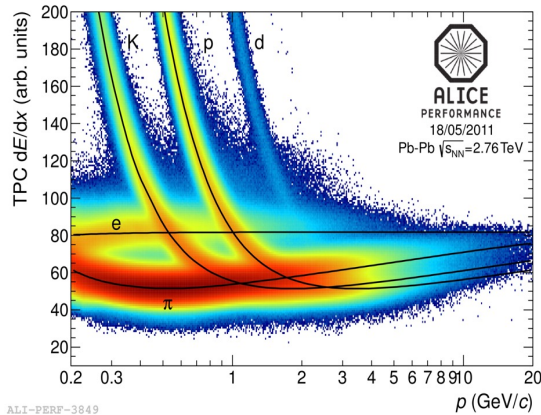


$$\langle N_j^n \rangle = A^{-1} \langle W_j^n \rangle$$

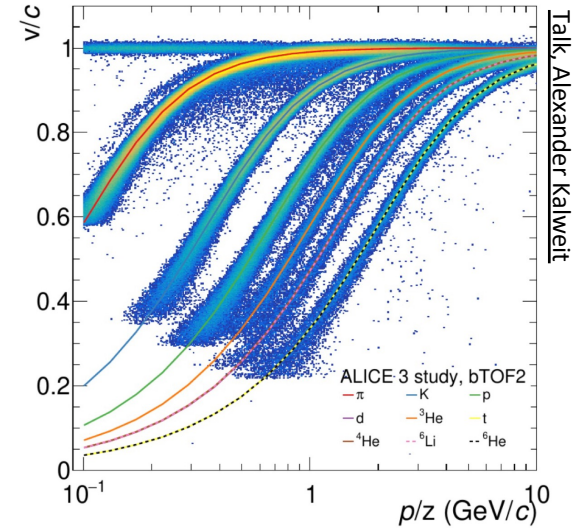
[A. Rustamov, "Fuzzy logic" Phys. Rev. C 110 \(2024\) 6, 064910](#)

Key/Unique tool for the future

ALICE 1,2



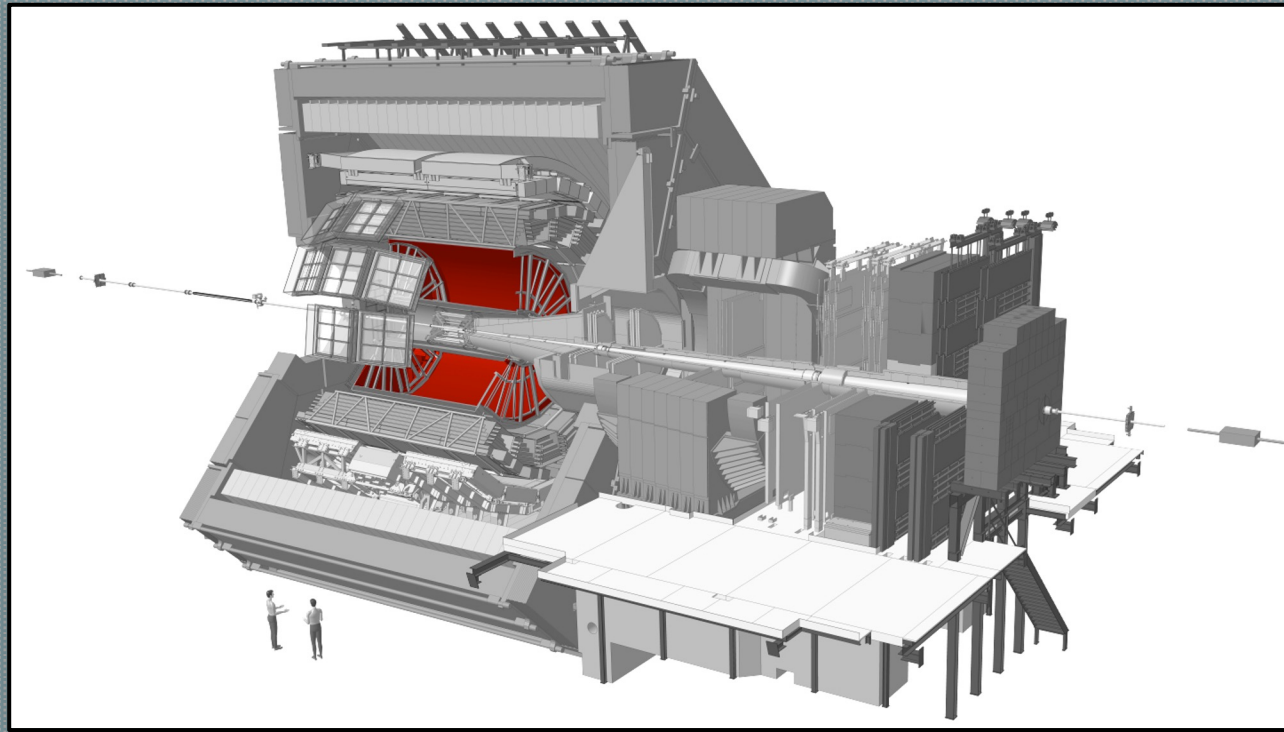
ALICE 3



Talk, Alexander Kalweit

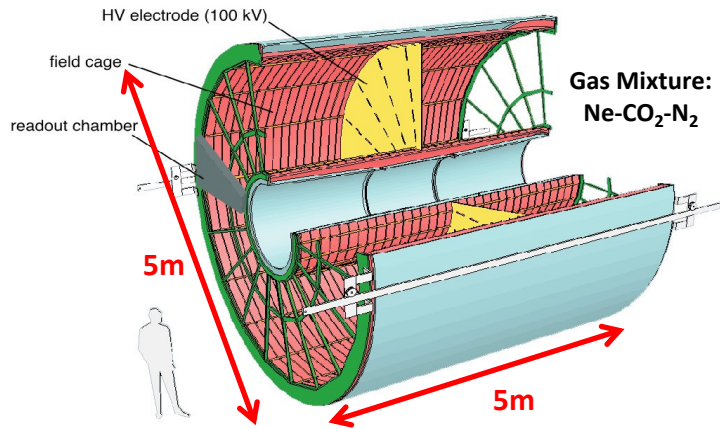
Overlap in the PID variable, and thus identity method, is inevitable

The ALICE Time Projection Chamber (TPC)



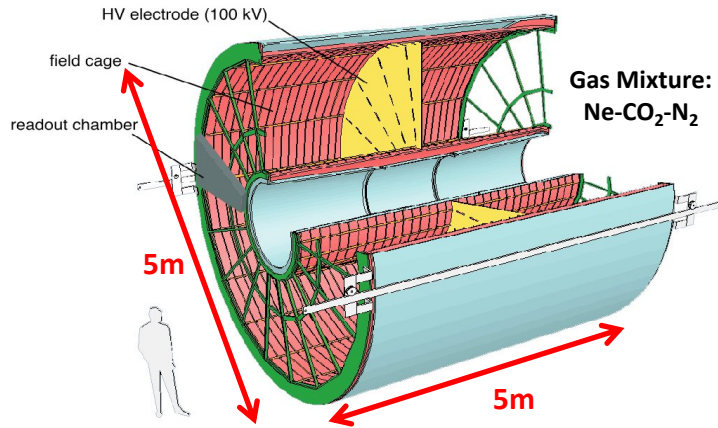
TPC in a nutshell

Schematic view of the TPC

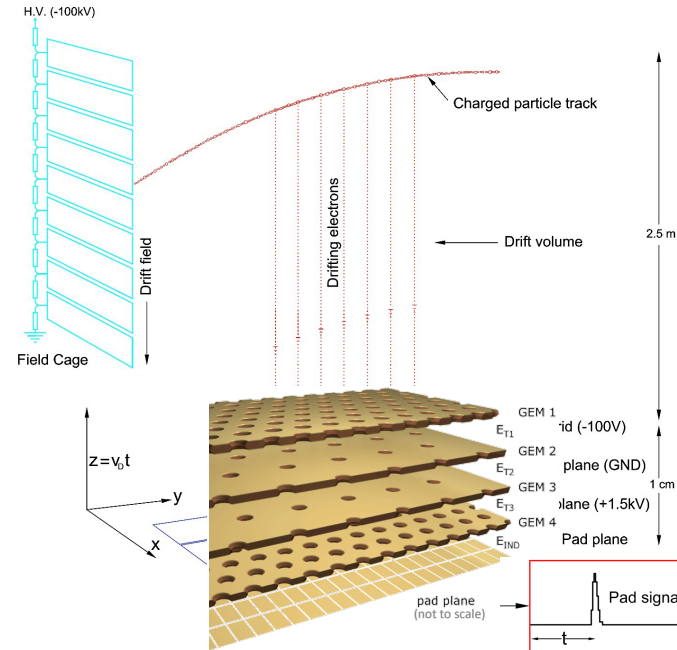


TPC in a nutshell

Schematic view of the TPC



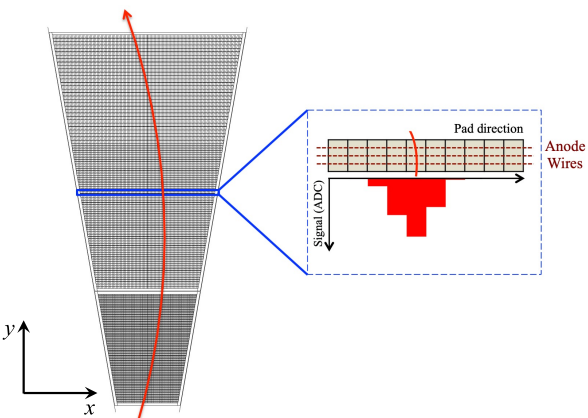
Working principle of the TPC



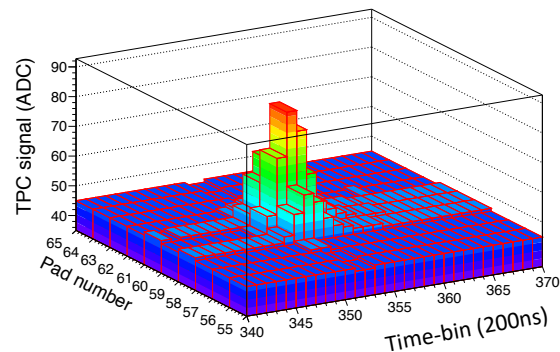
- ➡ Ionization
- ➡ Electron drift
- ➡ Gas amplification
(~2000 e⁻-ion pair)
- ➡ Signal Generation

Signal creation to particle identification

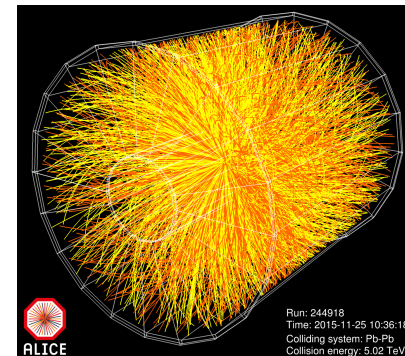
Track projection



Clustering

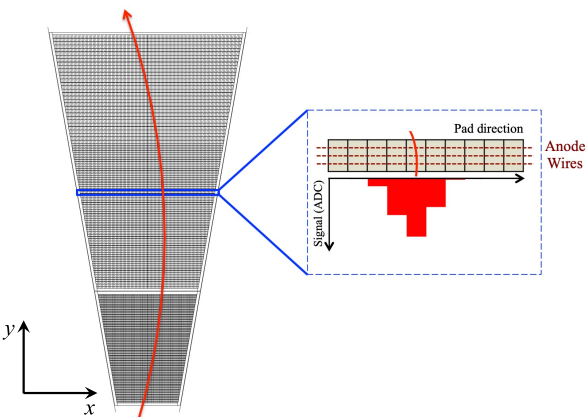


Time projection & Tracking

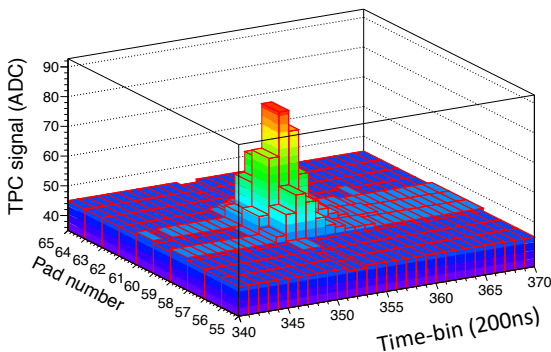


Signal creation to particle identification

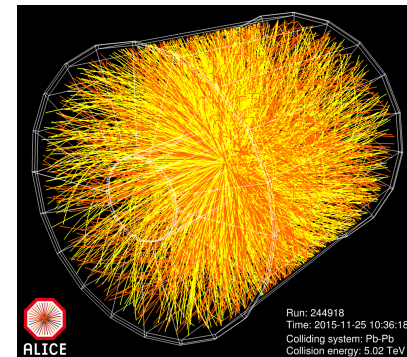
Track projection



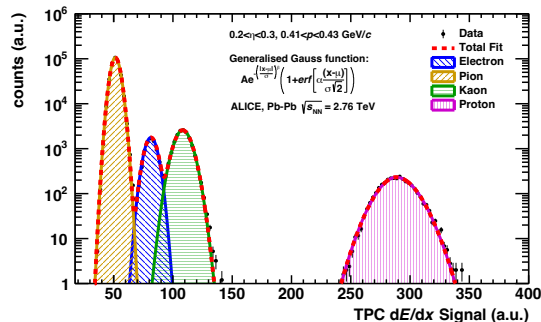
Clustering



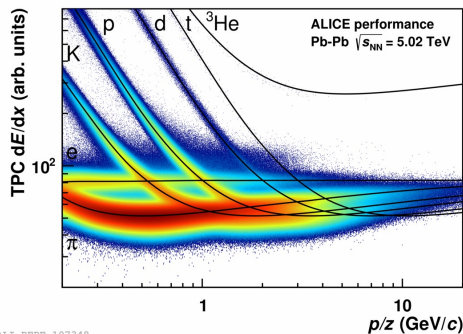
Time projection & Tracking



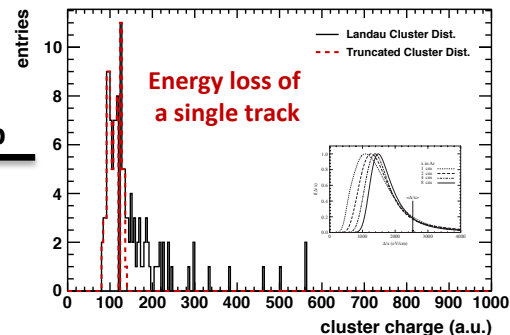
Particle identification (PID)



Bethe-Bloch parametrization



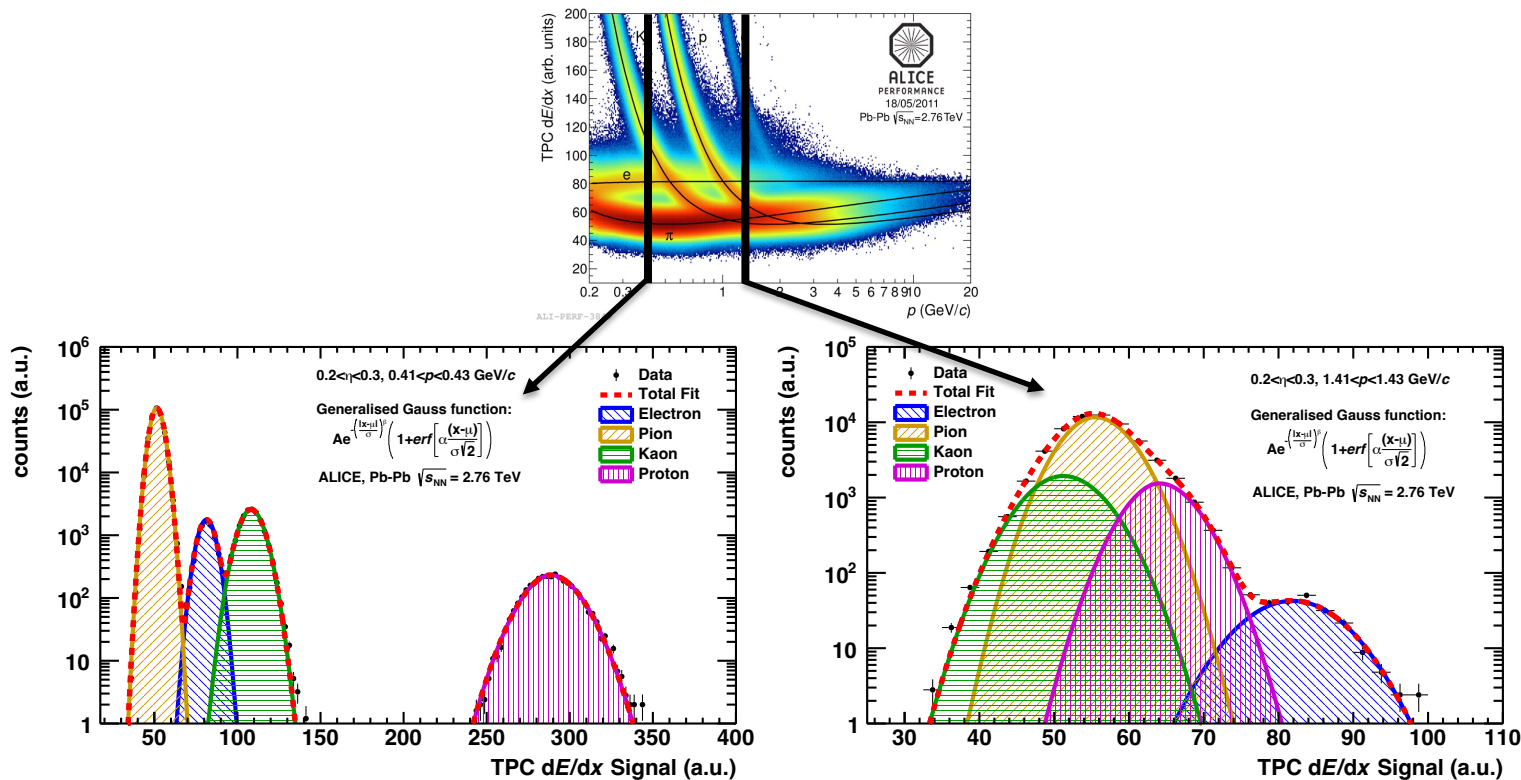
dE/dx calculation: Truncated mean



Performance of the TPC & Identity Method

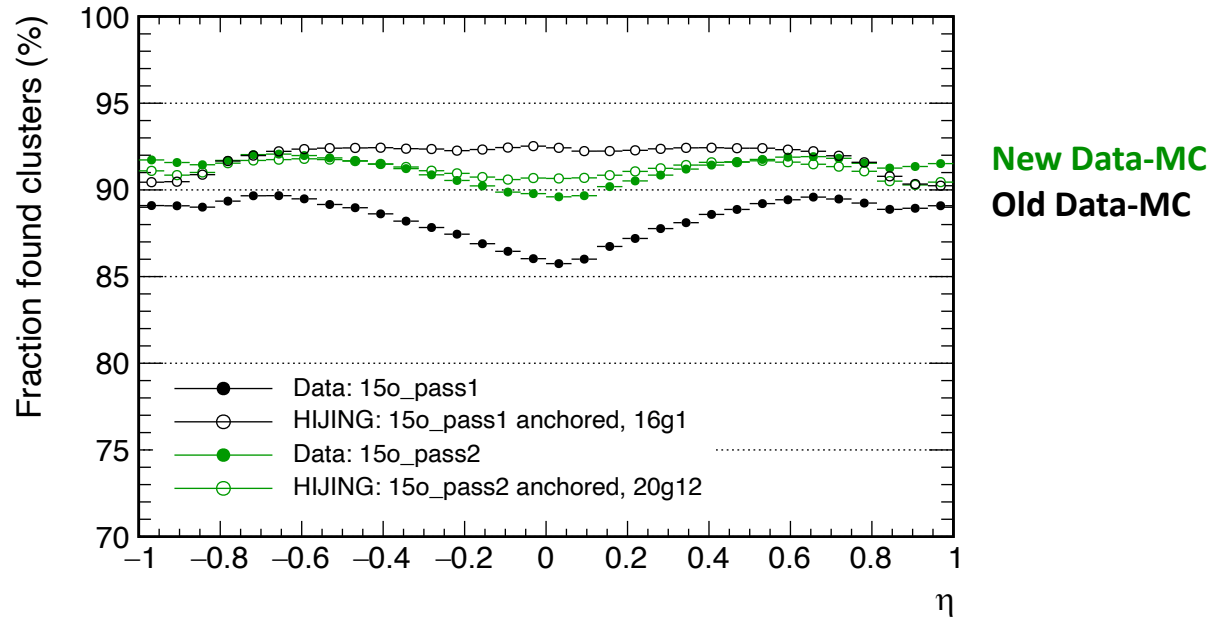
Challenge within Identity Method

“Precise description of **line shapes** → Energy loss calibration” & “Realistic **data-MC matching**”



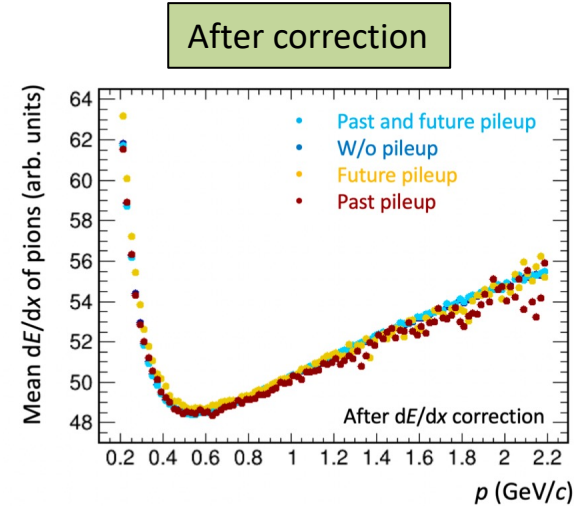
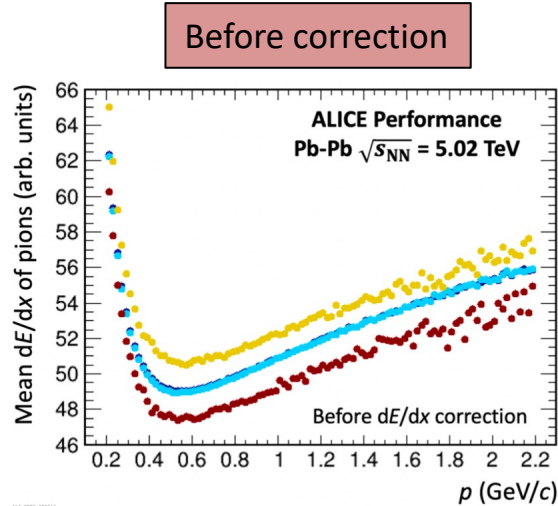
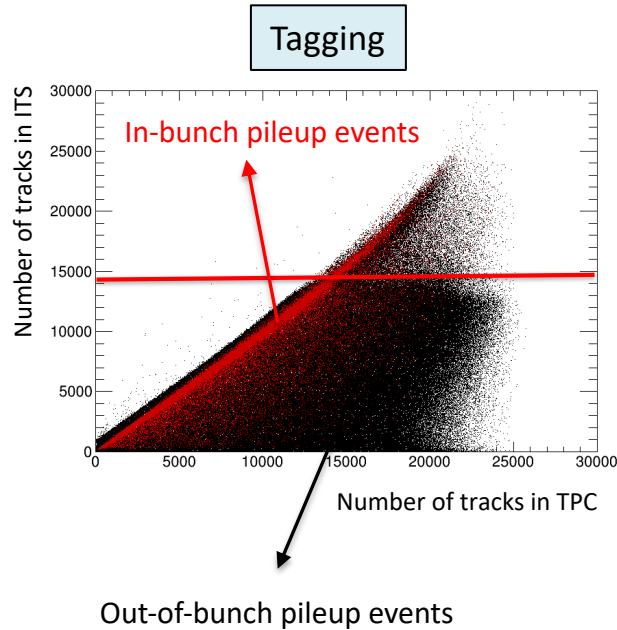
Improved Data-MC matching

After signal shape and cluster charge correction



Energy loss calibration & event pileup

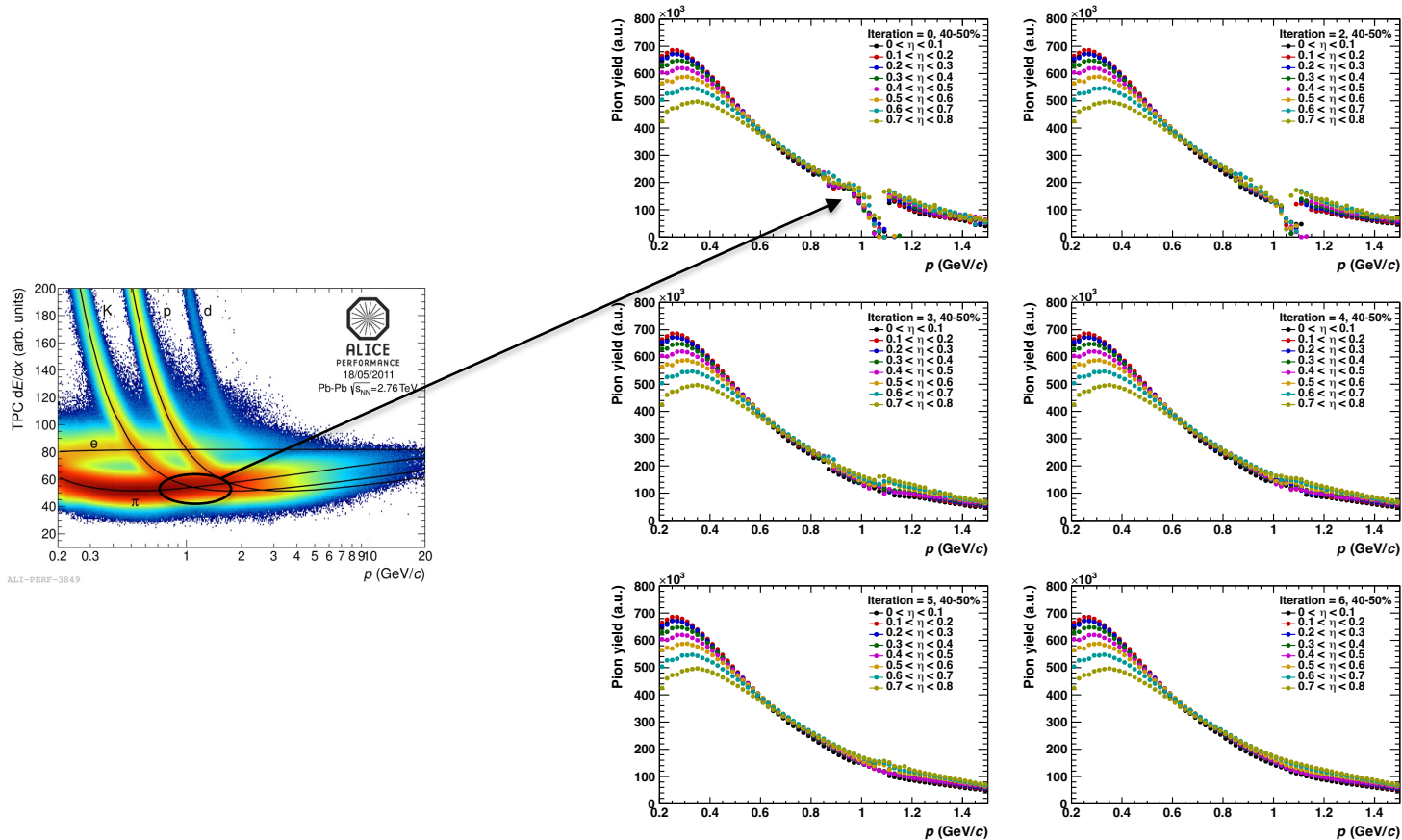
- Tag pileup events and correct energy loss



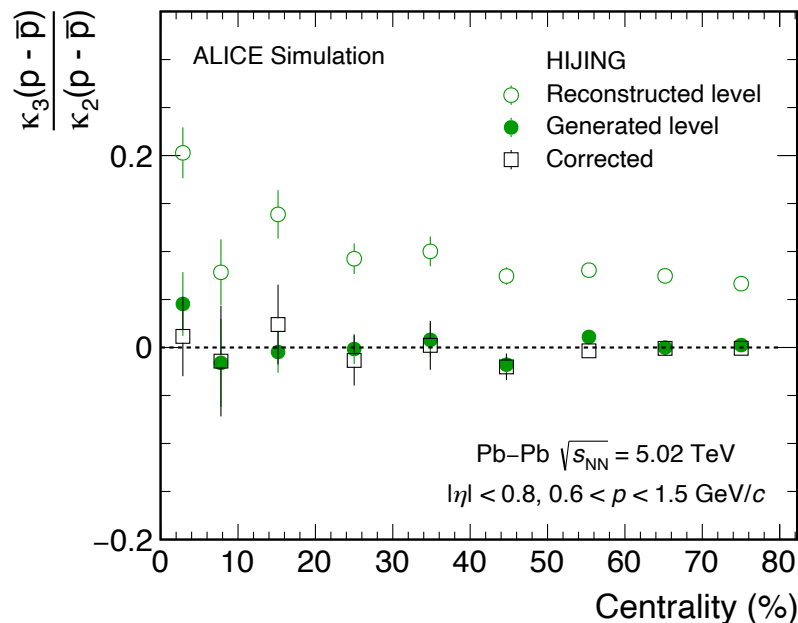
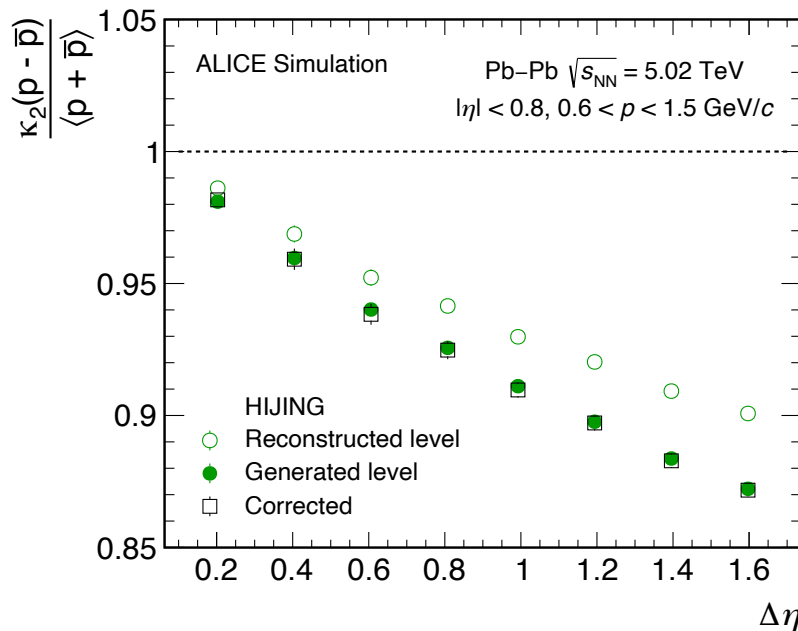
M. Arslanodok, E. Hellbär, M. Ivanov, R.H. Münzer and J. Wiechula, Particles 2022, 5(1), 84-95

ALICE TPC Collaboration JINST 19 (2024) P02038

New TPC dE/dx parametrization using generalized Gauss



Realistic data-MC matching $\Rightarrow$ Efficiency correction



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

Efficiency correction with binomial assumption:

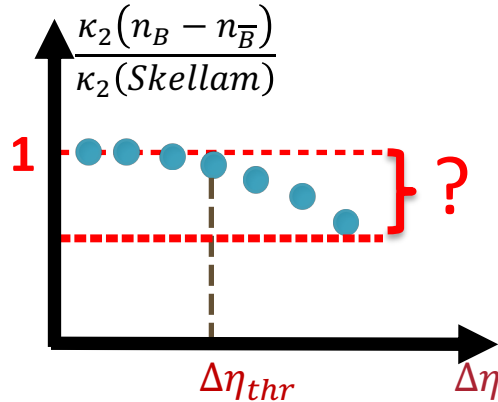
T. Nonaka, M. Kitazawa, S. Esumi, Phys. Rev. C 95, 064912 (2017)

Adam Bzdak, Volker Koch, Phys. Rev. C 86, 044904 (2012)

Net-proton number fluctuations

Acceptance & baseline

What is the source of deviation from baseline?

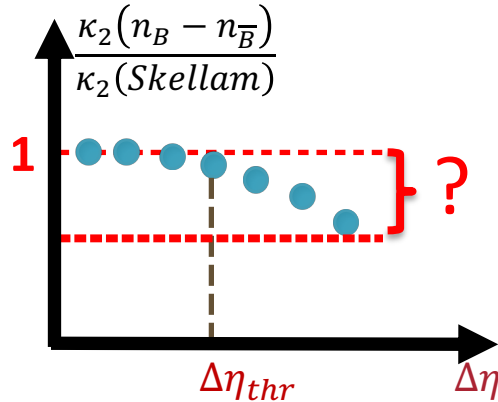


- Baryon number conservation
- Volume fluctuations
- Resonance decays
- Initial-state fluctuations
- Effect of initial magnetic field
- ...

See Anar's talk

Acceptance & baseline

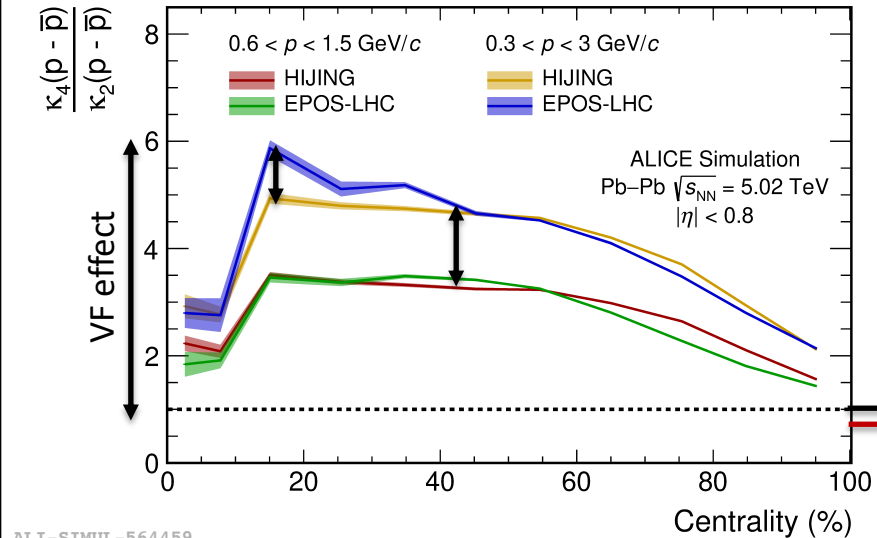
What is the source of deviation from baseline?



- Baryon number conservation
- Volume fluctuations
- Resonance decays
- Initial-state fluctuations
- Effect of initial magnetic field
- ...

See Anar's talk

Volume Fluctuations (VF)



ALI-SIMUL-564459

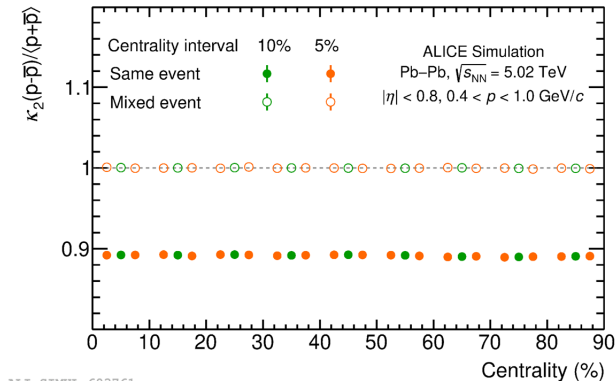
Poissonian
baseline: 1

LQCD:
 ≈ 0.75

How to overcome volume fluctuations?

- Mix events in a given category wrt event shape and centrality

2nd order



It kills all correlations

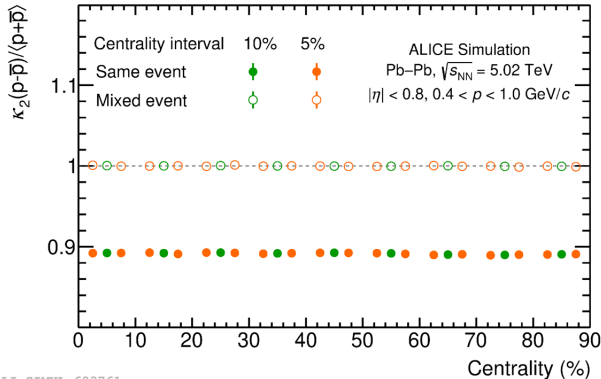
[A. Rustamov, R. Holzmann, J. Stroth, NPA 1034 \(2023\) 122641](#)

[V.Koch, R. Holzmann, A. Rustamov, J. Stroth, NPA 1050 \(2024\) 122924](#)

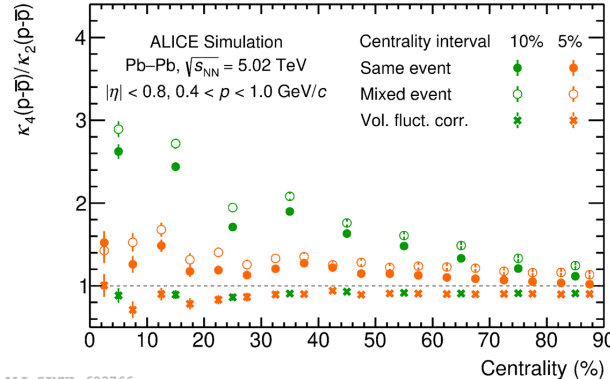
How to overcome volume fluctuations?

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2nd order

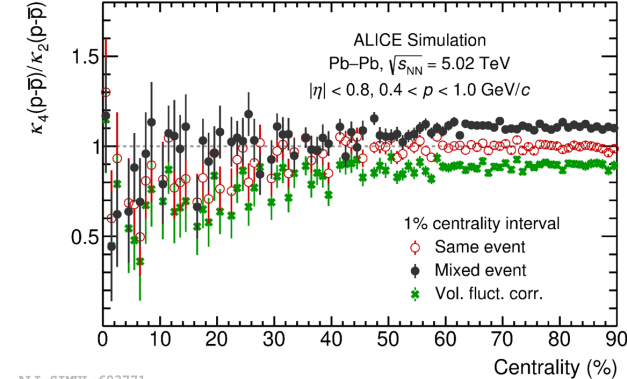


It kills all correlations



Volume fluctuations remain

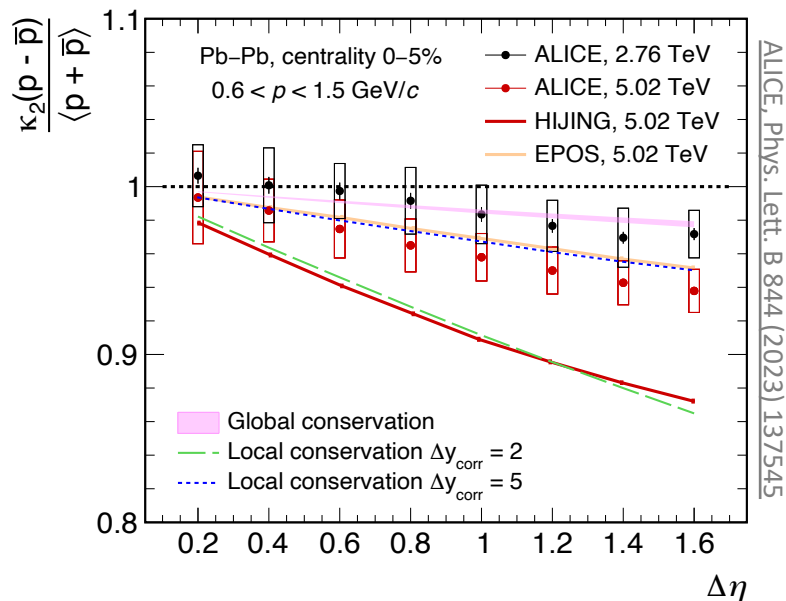
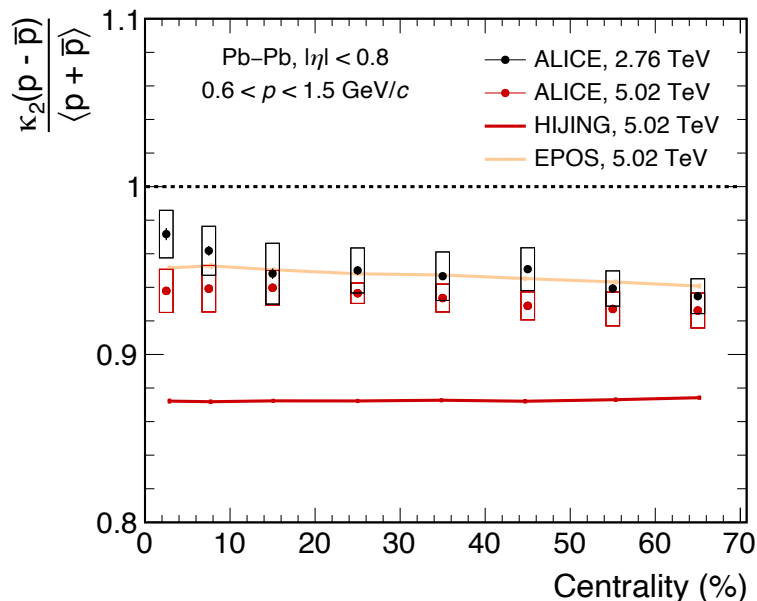
4th order



Very narrow CBW do not help

- CBWC does not completely eliminate VF, but mixed event technique does

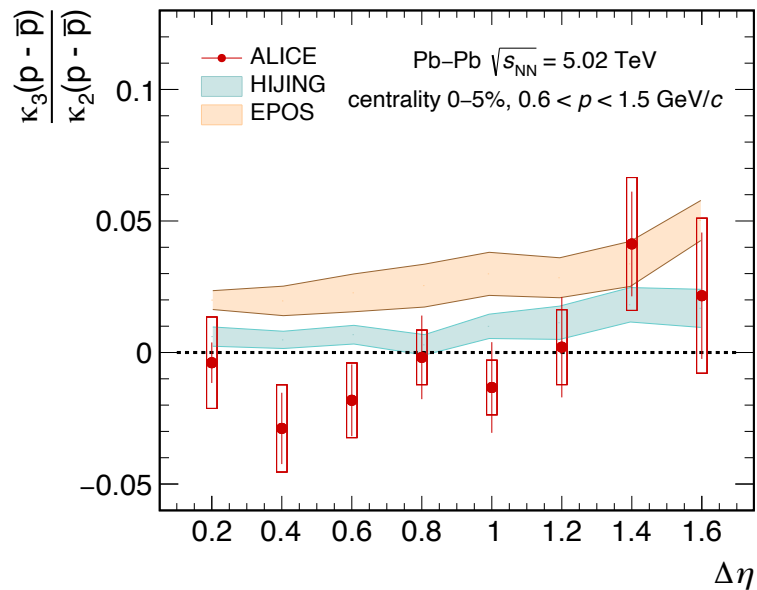
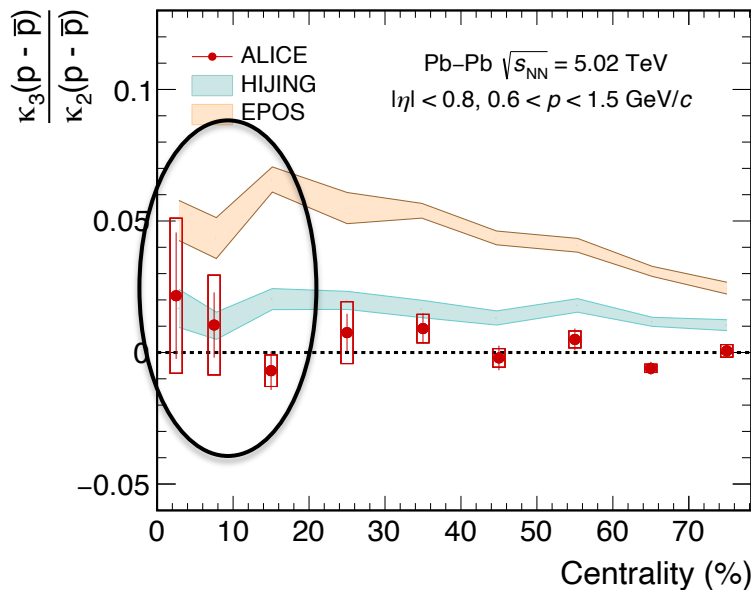
2nd order cumulants of net-p



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

- 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

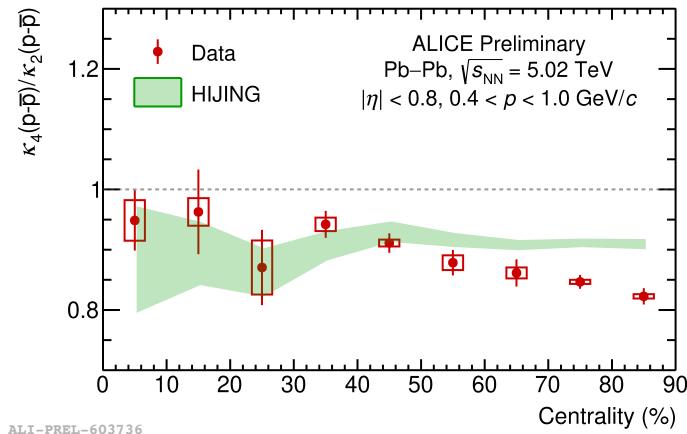
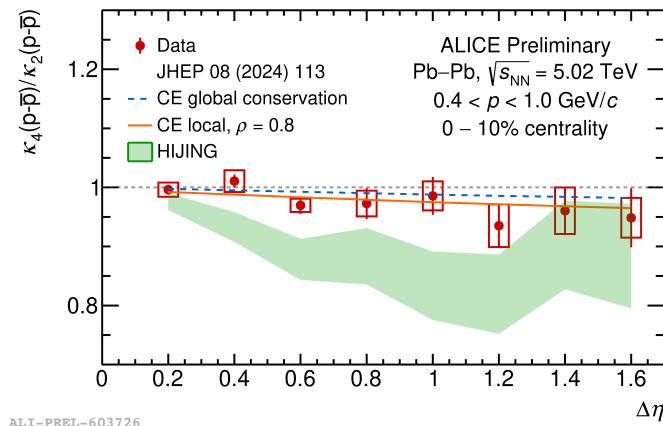
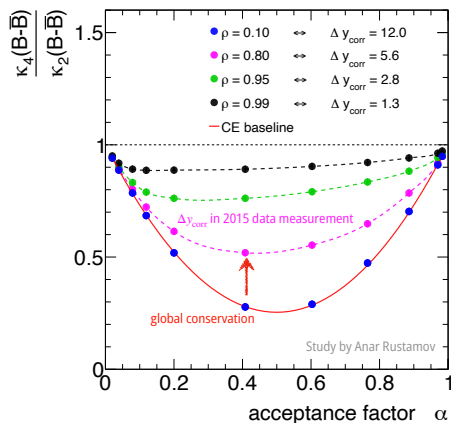
3rd order cumulants of net-p



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

4th order cumulants of net-p in Pb–Pb

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



- Hint of deviation from Poissonian baseline
- CE baseline for the peripheral collisions + Increase acceptance (Fuzzy logic) and statistics (Run [3,4])
(Stay tuned for the results by Ilya Fokin (PhD student of Johanna))

Summary

Detector:

- **Cluster- and signal-level** corrections in the TPC data reconstruction
- Almost perfect description of **Data-MC matching**
- **New dE/dx parametrization**
- Correction of **volume fluctuations** using mixed events
- **Extension of the Identity Method**, the key tool for event-by-event fluctuation measurements, to nth order

Physics:

- **Importance of non-critical baseline** → Baryon number conservation
- **Lund-based models** → describe 1st order but fail in 2nd
- **LQCD expectations** → agreement up to 3rd order and sign of signal at the 4th order
- **Future ALICE [2,3]:**
 - **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, baryon number conservation ...

Happy birthday PBM!

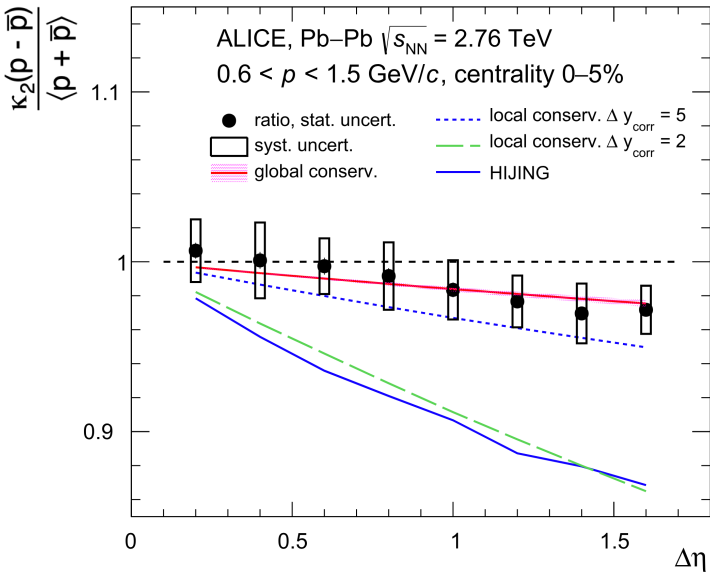
Thank you very much for being such a wonderful example to the new generations of what it means to be a complete physicist.



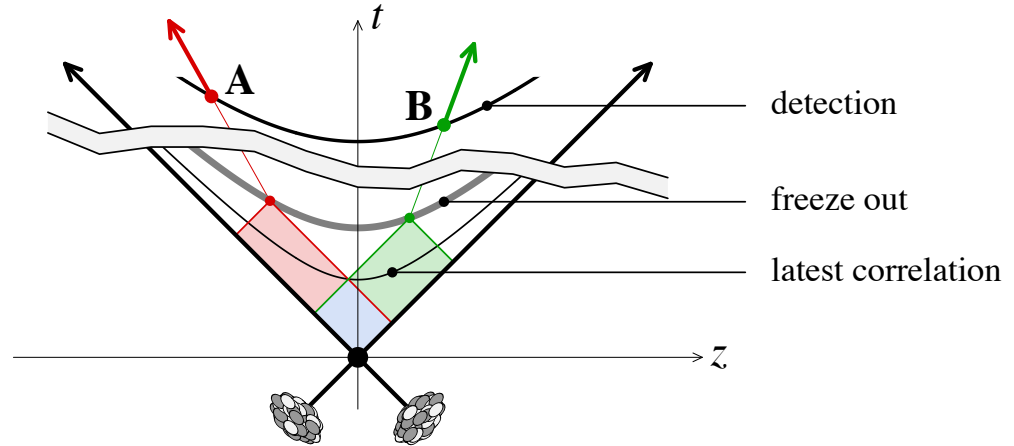
BACKUP

Correlation length

Source of the deviation?



Only early correlations can be long range in rapidity



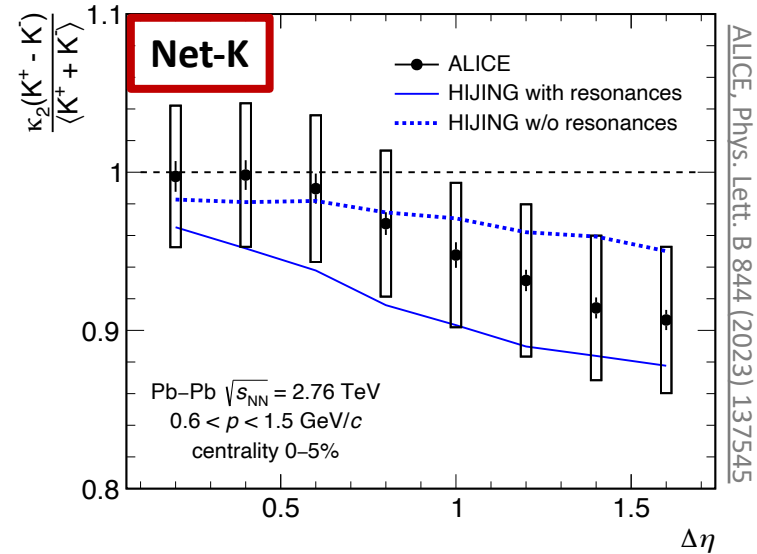
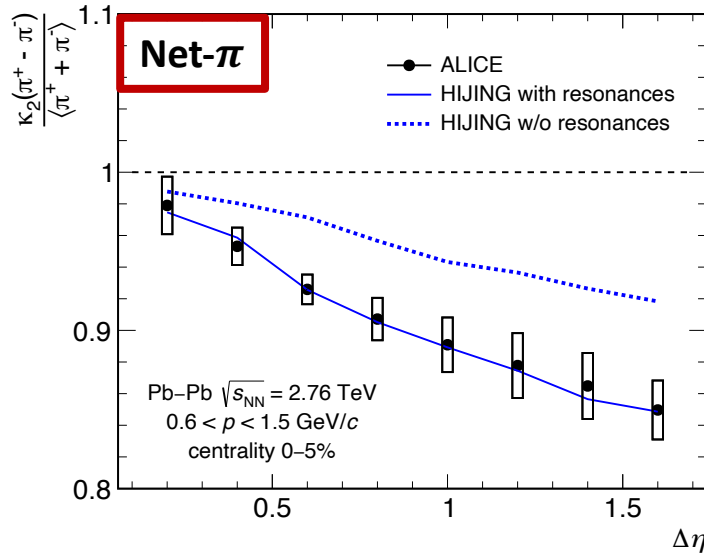
$$\tau \leq \tau_{\text{freeze out}} e^{-\frac{1}{2}|y_A - y_B|}$$

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

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

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

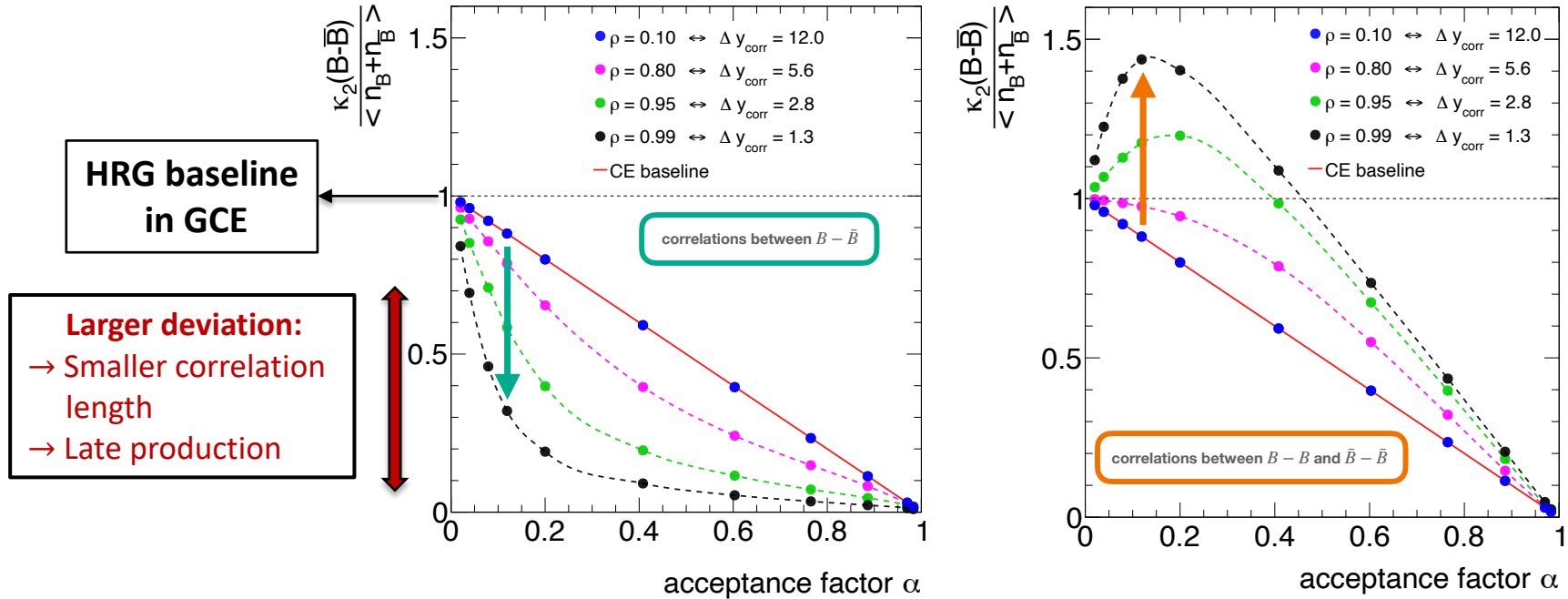
Why not pions and kaons? $\Rightarrow$ Resonance decays



- **Net- π and net-K** are strongly dominated by resonance contributions
- **Net-p** is free from resonance contributions
 - $\rightarrow$ **Isospin randomization**, at $\sqrt{s_{NN}} > 10$ GeV: **net-B $\leftrightarrow$ net-p**
 - (M. Kitazawa, and M. Asakawa, Phys. Rev. C 86, 024904 (2012))

Baryon number conservation & cluster formation

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

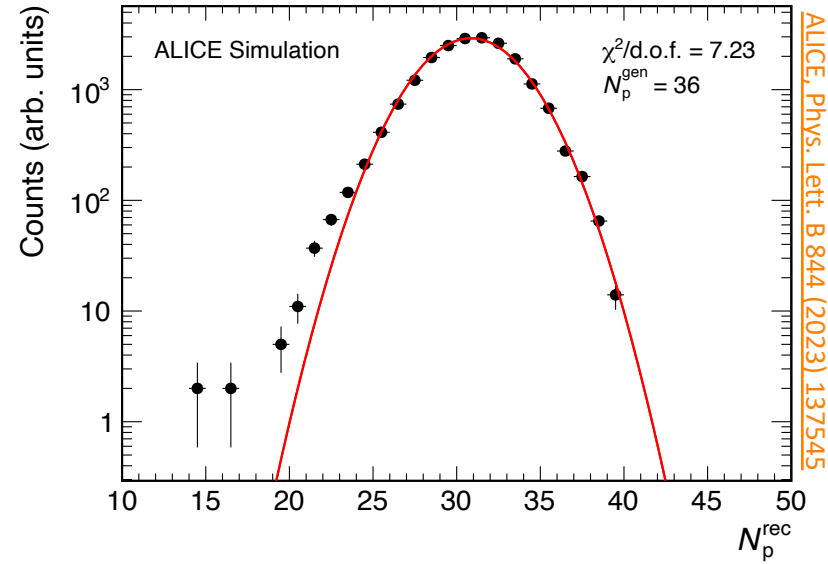
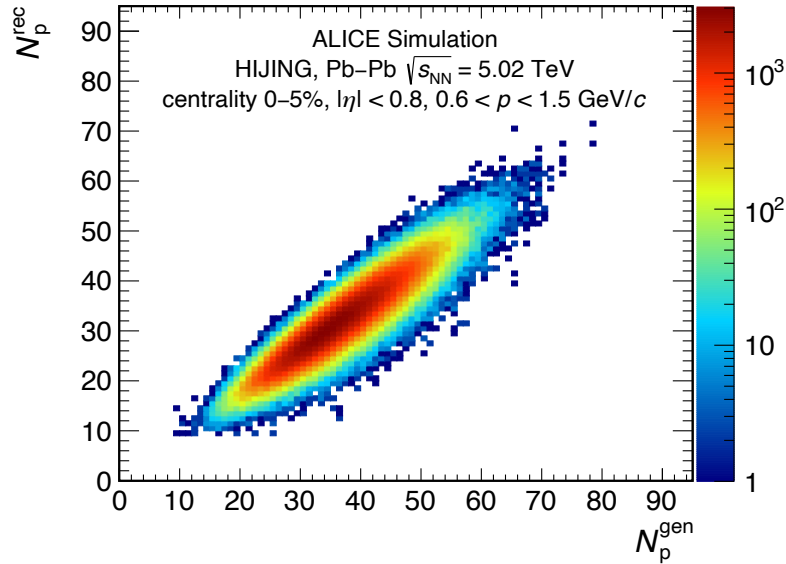


- Measured values depend on the fraction of (anti-)protons in the acceptance
- (Global) local baryon number conservation: **unlike-sign correlations**
- (Anti-)proton clusters: **like-sign correlations**

Talk by Anar

Challenge 2: Efficiency correction

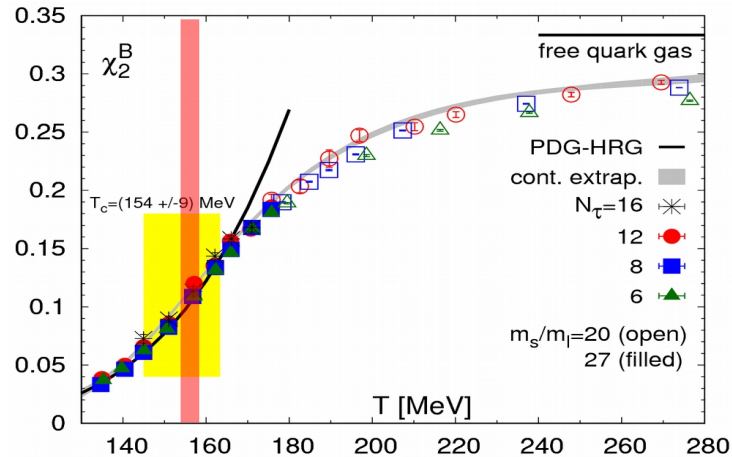
Binomiality of the detector response is important for the efficiency correction



LQCD

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

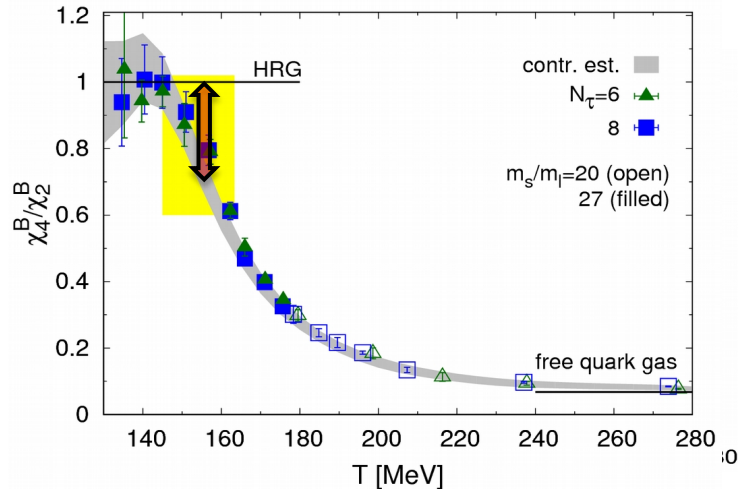
Baryon number (**B**), Strangeness (**S**), Electric charge (**Q**), Cham (**C**)



LQCD

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

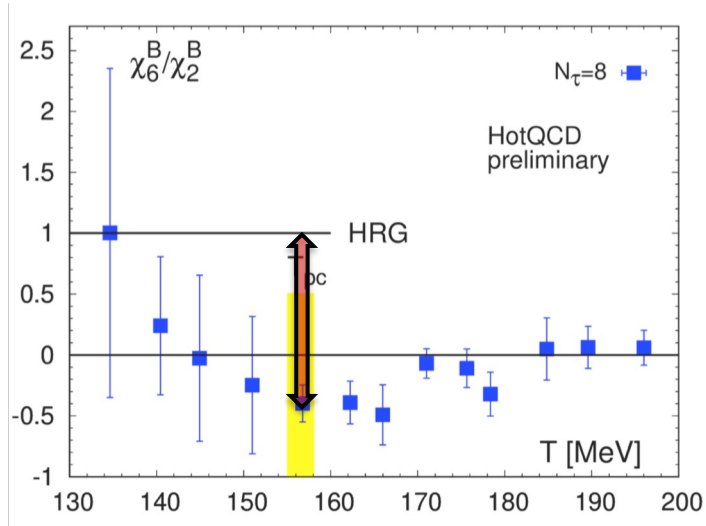
Baryon number (**B**), Strangeness (**S**), Electric charge (**Q**), Charm (**C**)



LQCD

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

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



LQCD ↔ Experiment

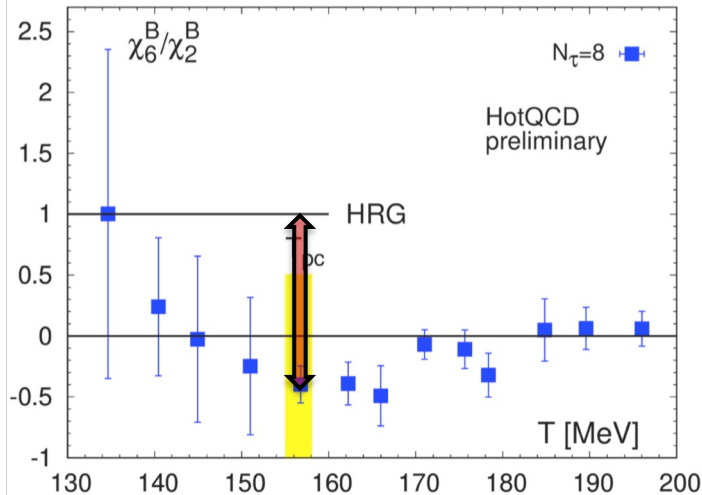
Google Translate

Detect language

LQCD

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

Baryon number (**B**), Strangeness (**S**), Electric charge (**Q**), Charm (**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 $\Delta N_B = N_B - N_{\bar{B}}$

Talk by Anar

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

LQCD ↔ Experiment

Google Translate

Detect language

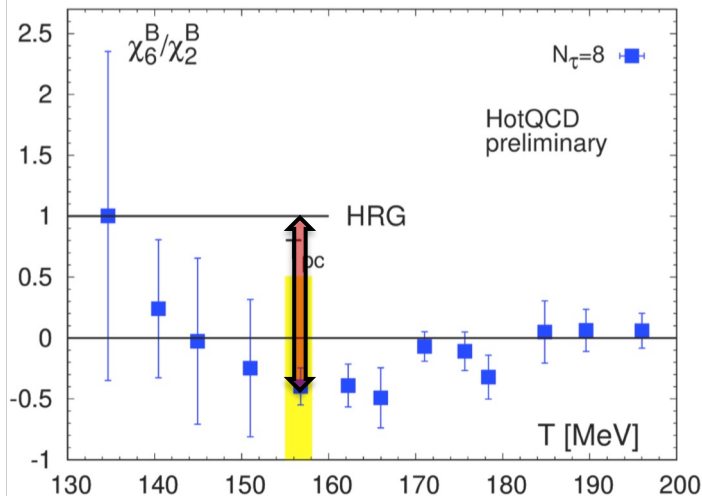
LQCD

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



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

0 / 5,000



EXPERIMENT

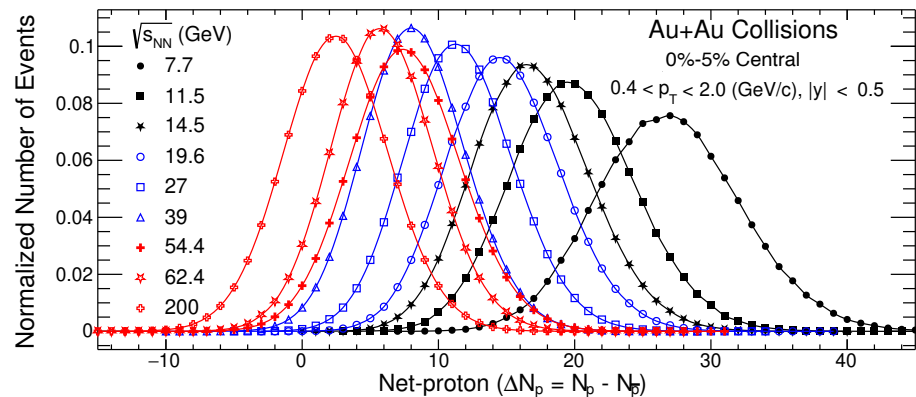
Translation

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

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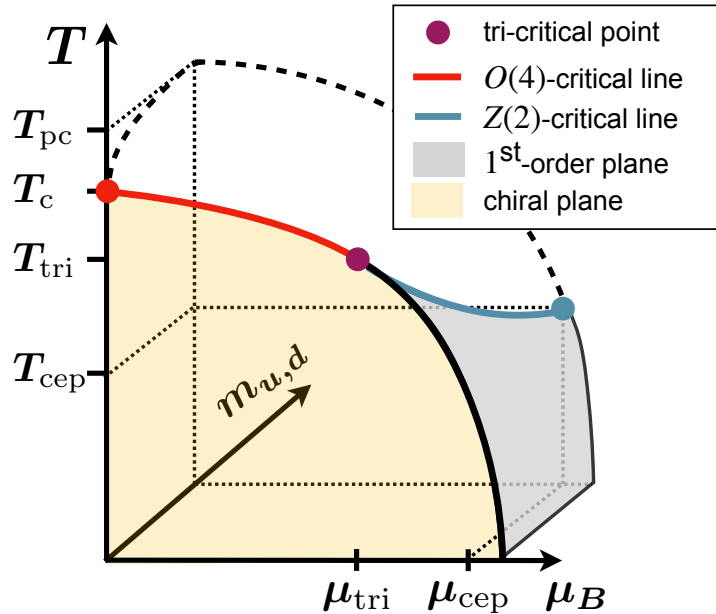
Talk by Anar

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



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

Nature of QCD phase diagram



- **Vanishing u, d quark masses:**
 - ⇒ Vicinity to 2nd order $O(4)$ criticality
 - ⇒ **Pseudocritical features** at the crossover due to massless modes
- **At LHC energies**
 - ⇒ $T_{pc}^{LQCD} \approx T_{fo}^{ALICE} = 156.5 \pm 3 \text{ MeV}$
 - ⇒ $\mu_B^{ALICE} = 0.71 \pm 0.45 \text{ MeV}$

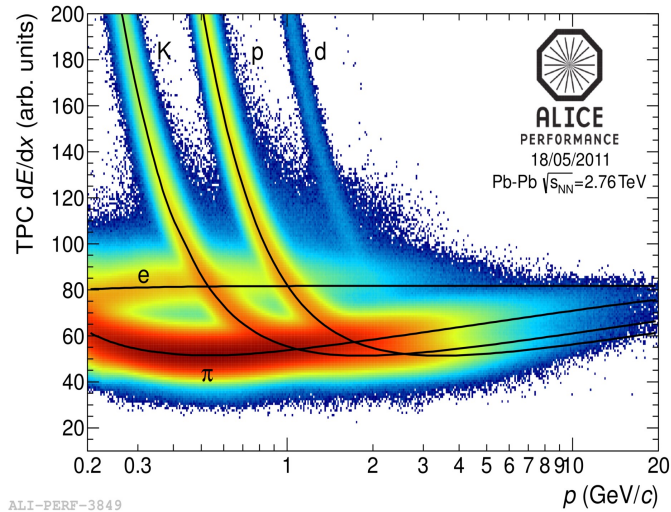
- **Fact:** No experimental confirmation of crossover
- **Signature:** Long range correlations & increased fluctuations

J. Stachel, A. Andronic, P. B. Munzinger and K. Redlich, *Nature* 561 (2018) 321

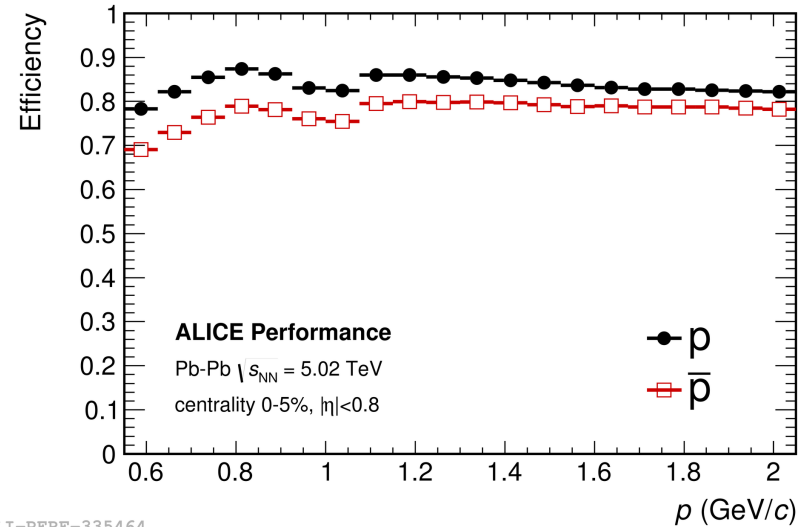
HotQCD Collaboration, *Phys.Lett. B* 795 (2019) 15

ALICE Collaboration, *Phys. Rev. Lett.* 133 (2024) 9, 092301

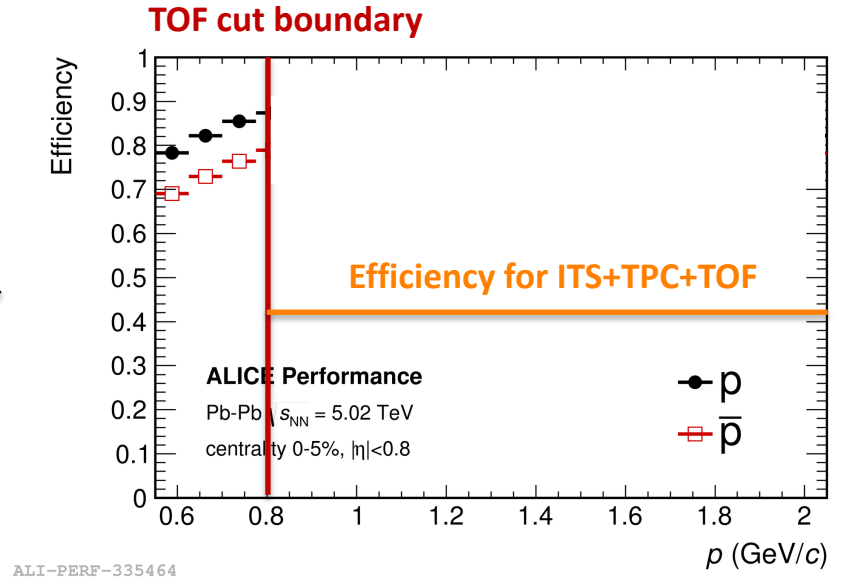
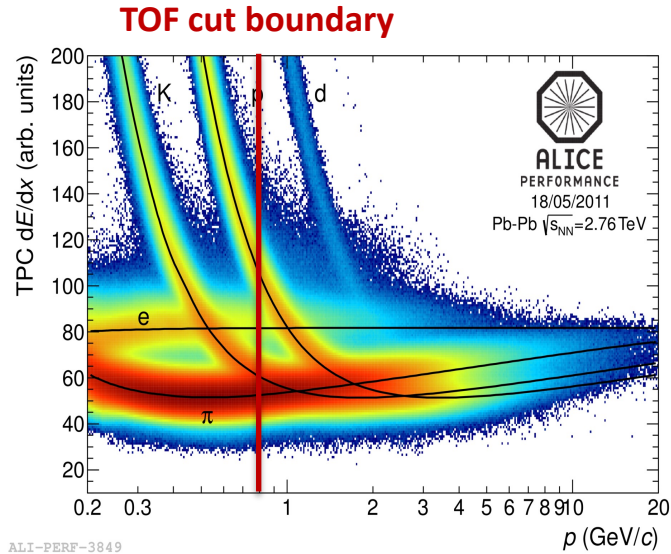
PID vs Efficiency



Efficiency for ITS+TPC

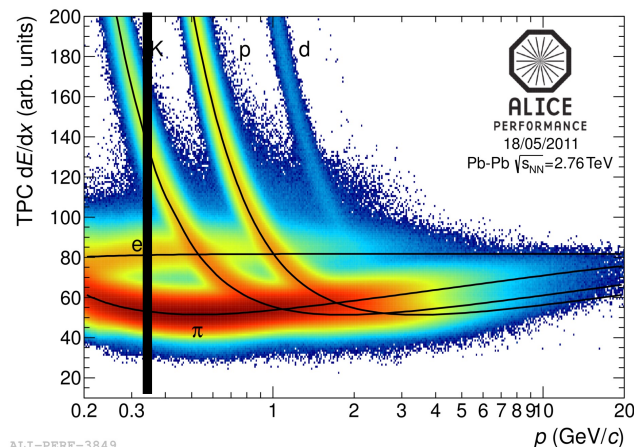


PID vs Efficiency

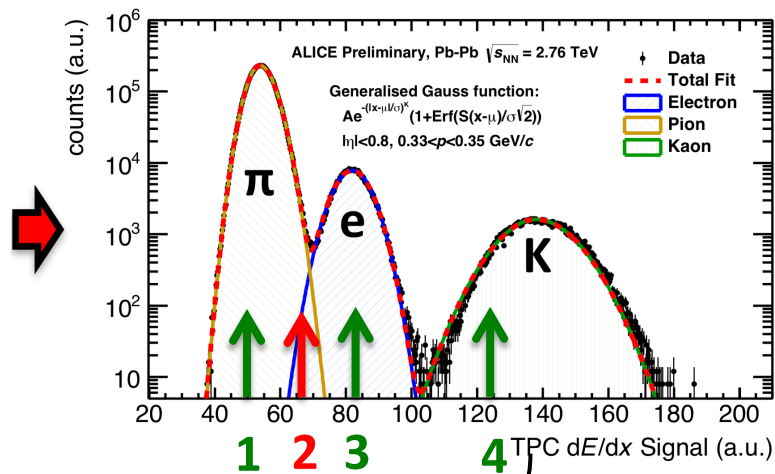


Solution: Identity Method

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



ALI-PERF-3849

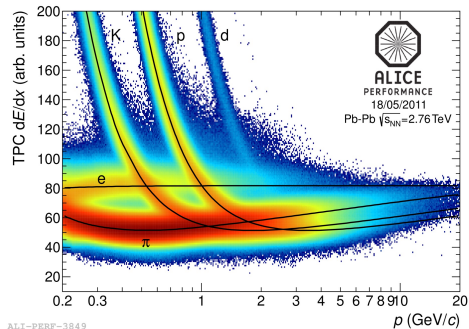


$$\omega_{\pi}^{(1)} = 1, \quad \omega_{\pi}^{(2)} \cong 0.6, \quad \omega_{\pi}^{(3)} = 0, \quad \omega_{\pi}^{(4)} = 0 \Rightarrow W_{\pi} = 1.6 \neq N_{\pi}$$

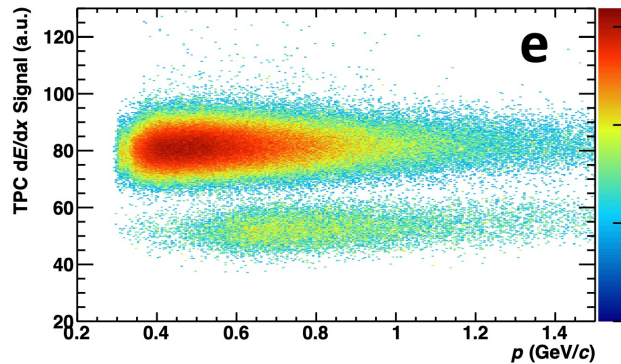
A. Rustamov, M. Gazdzicki, M. I. Gorenstein, PRC 86, 044906 (2012), PRC 84, 024902 (2011)

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

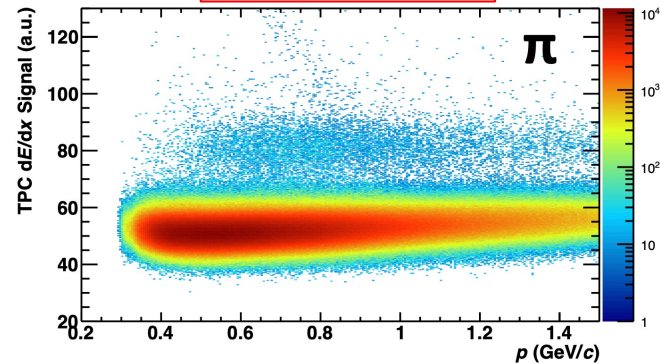
Line shapes



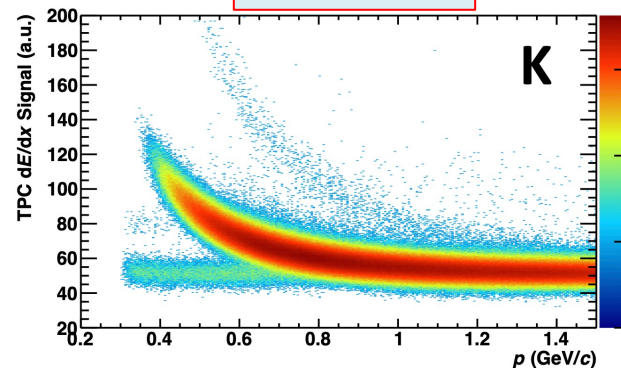
$$\gamma \rightarrow e^+e^-$$



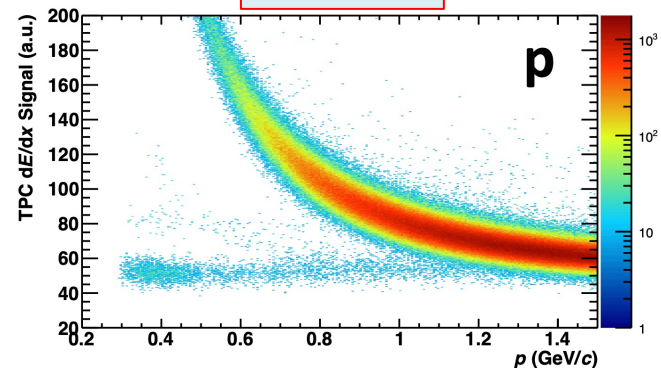
$$K_S^0 \rightarrow \pi^+\pi^-$$



$$\text{TOF + TRD}$$

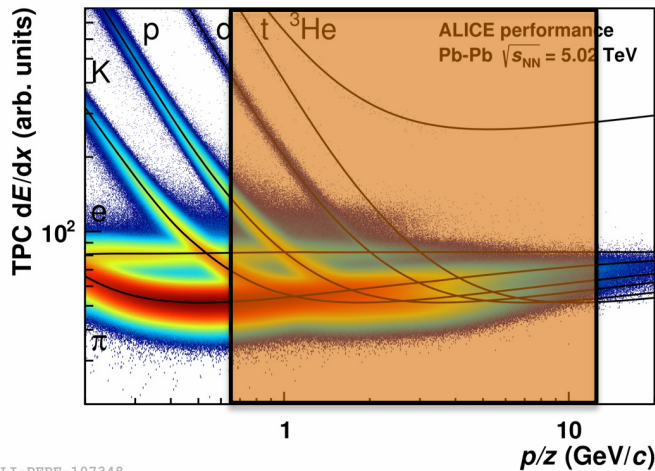


$$\Lambda \rightarrow \pi p$$

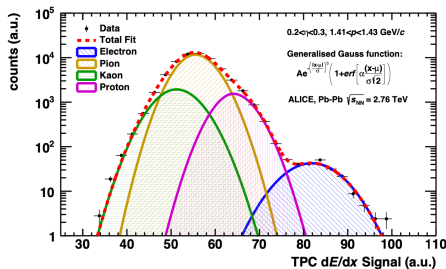
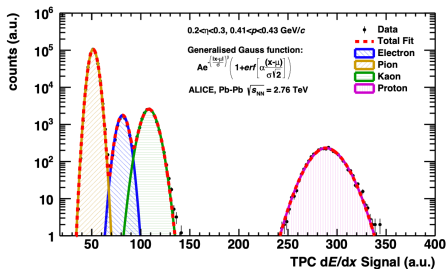


Identity Method in ALICE 3: Purity in PID

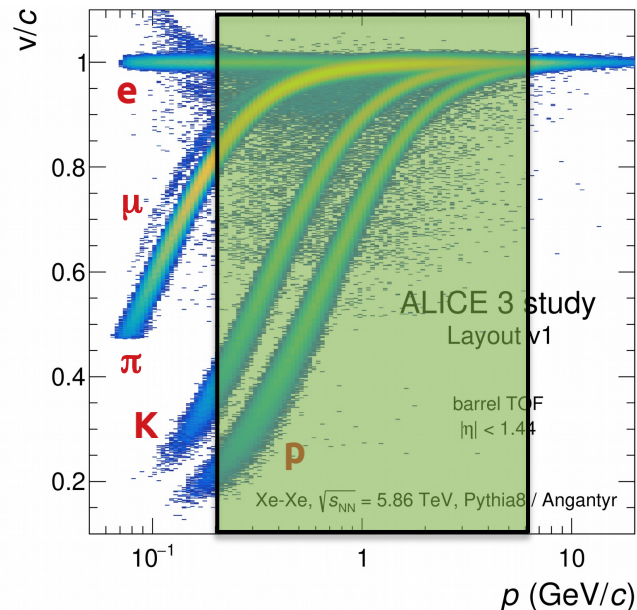
ALICE 1-2



ALI-PERF-107348



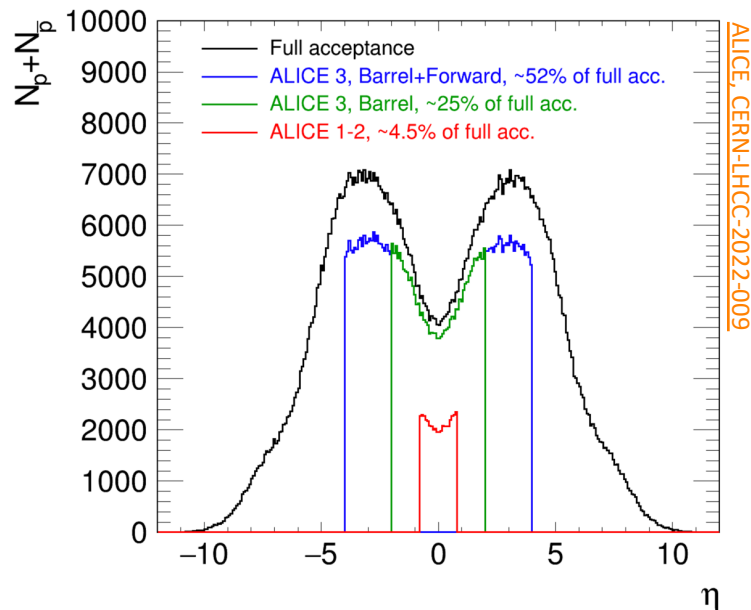
ALICE 3



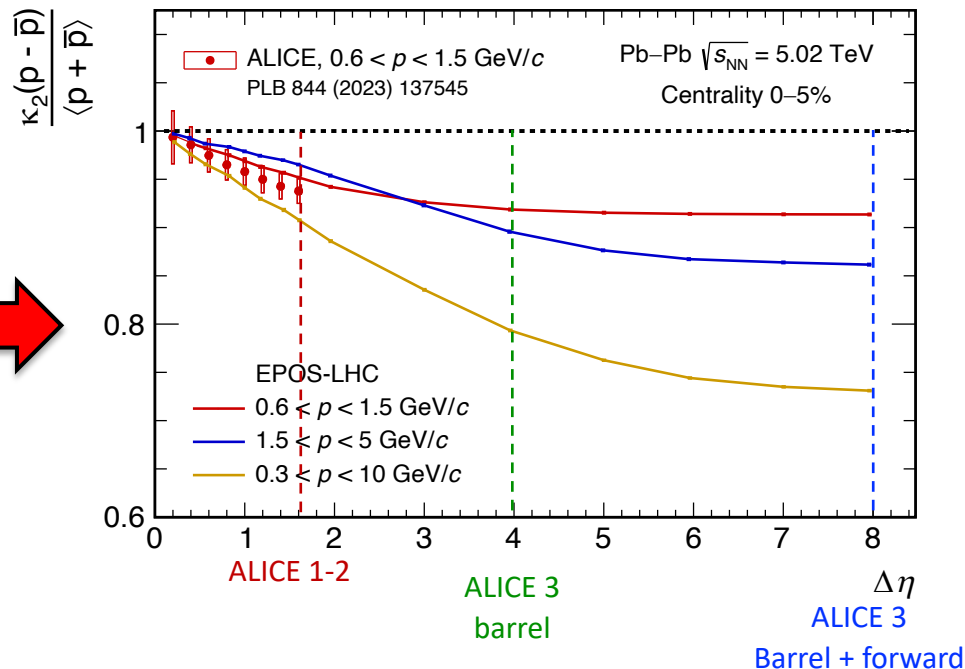
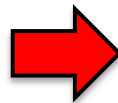
ALI-SIMUL-491825

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

2nd order cumulants of net-p in ALICE 3

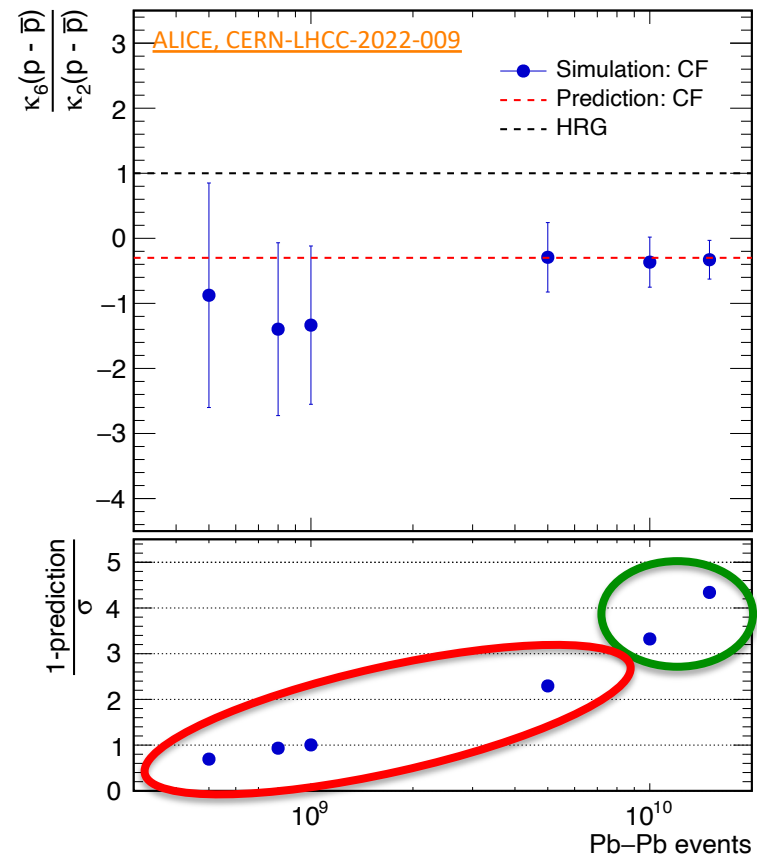


- **High PID purity and efficiency within a larger acceptance**
($0.3 < p < 10$ GeV/c, $|\eta| < 4$)



- **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

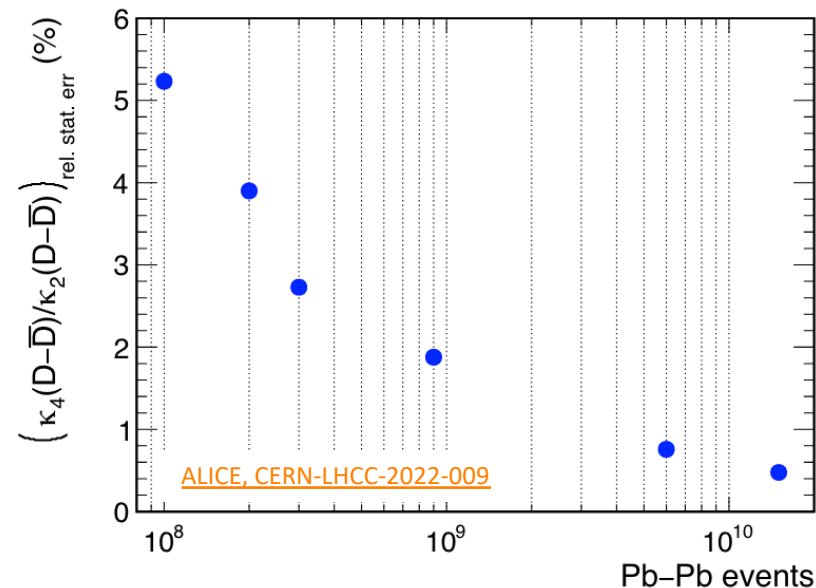
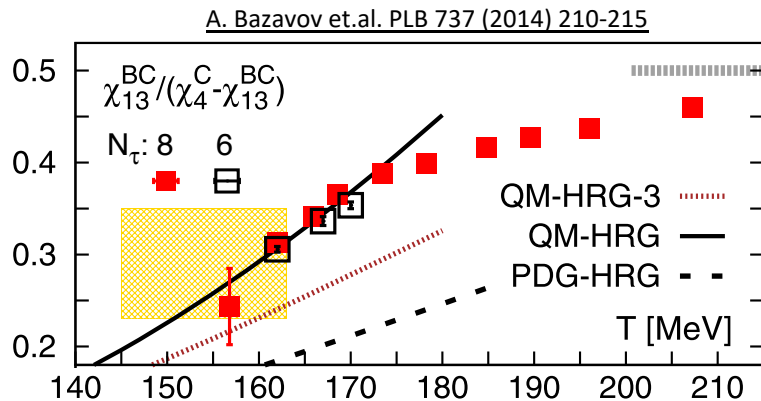
➤ **ALICE 2:**

→ 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



- **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**