Closing in on critical net-baryon fluctuations: cumulants up to 3rd order in Pb-Pb collisions with ALICE

(arXiv:2206.03343)

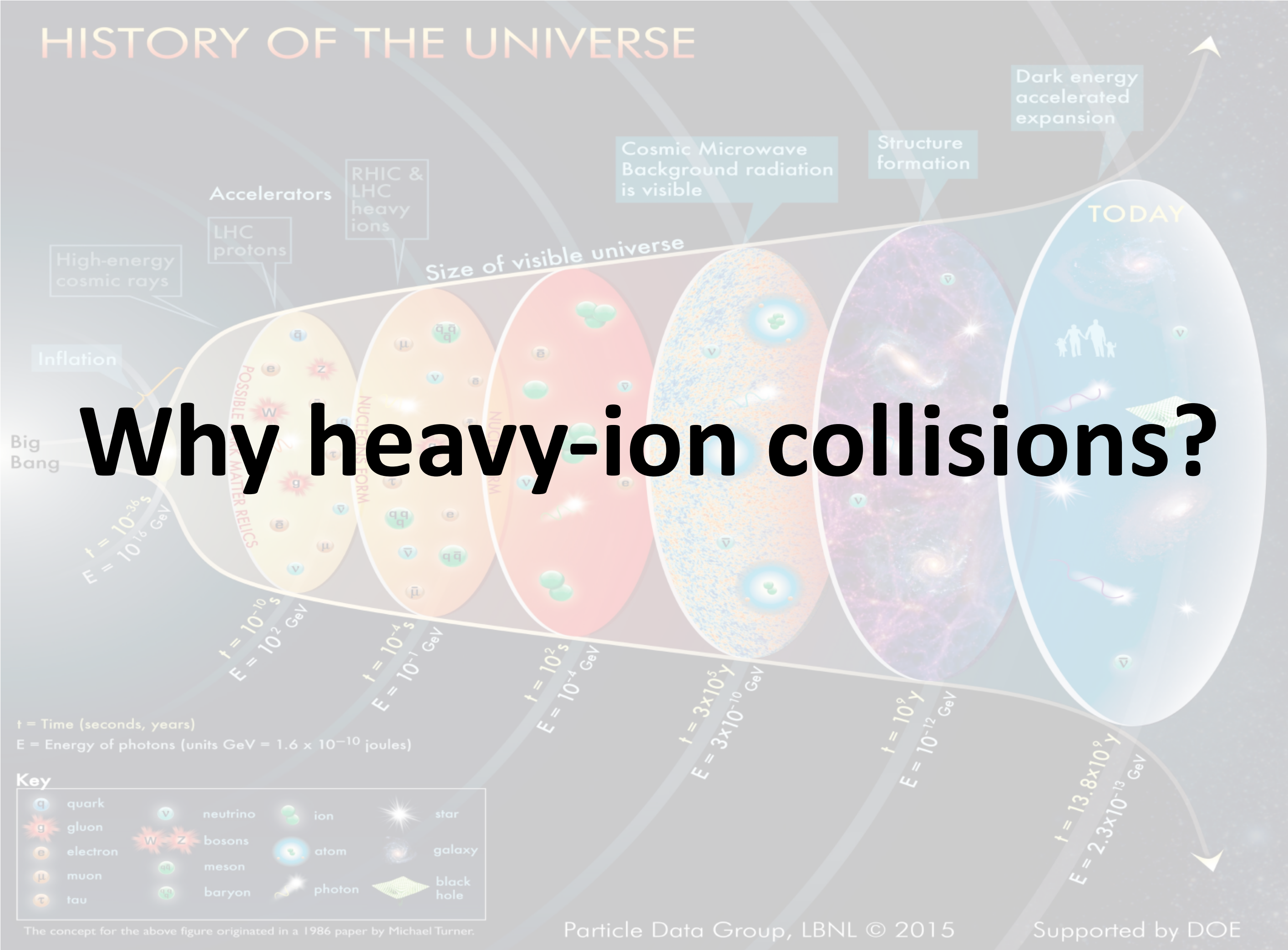
Mesut Arslandok
Yale University / CERN

- Why fluctuations?
- How to link experiment to theory
- Experimental challenges
- What did/will we learn?

CERN LHC Seminar, 21 June 2022, Geneva, Switzerland

In part supported by U.S. DEPARTMENT OF ENERGY Office of Science

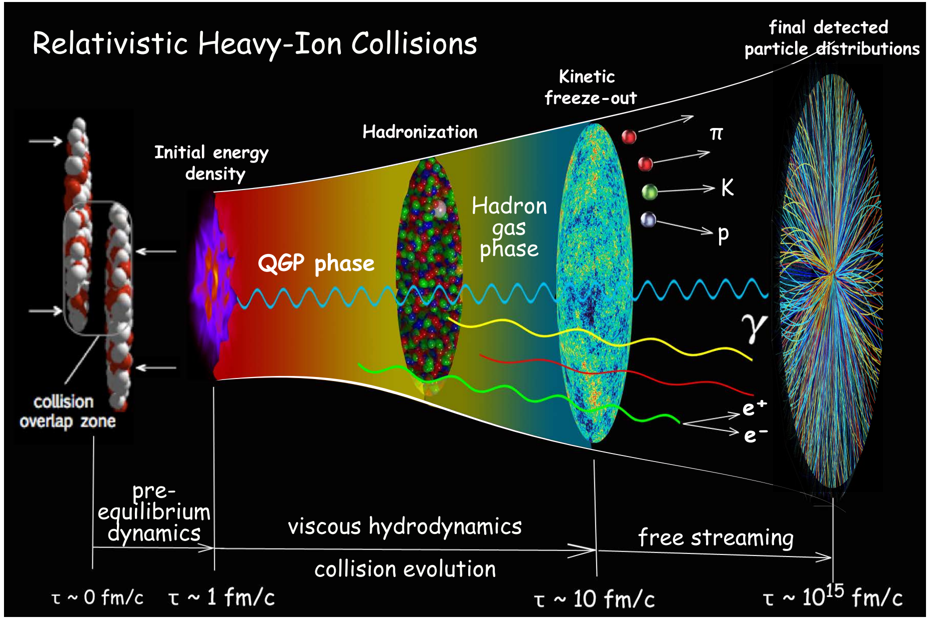
Why heavy-ion collisions?



Quark-gluon plasma (QGP)

A state of matter where the quarks and gluons are the relevant degrees of freedom, exist at few μs after the Big-Bang

- ✓ **Chiral symmetry**: $m_p \approx 937$ MeV $\leftrightarrow$ $2m_u + m_d \approx 10$ MeV
- ✓ **Confinement:** no isolated quarks seen thus far



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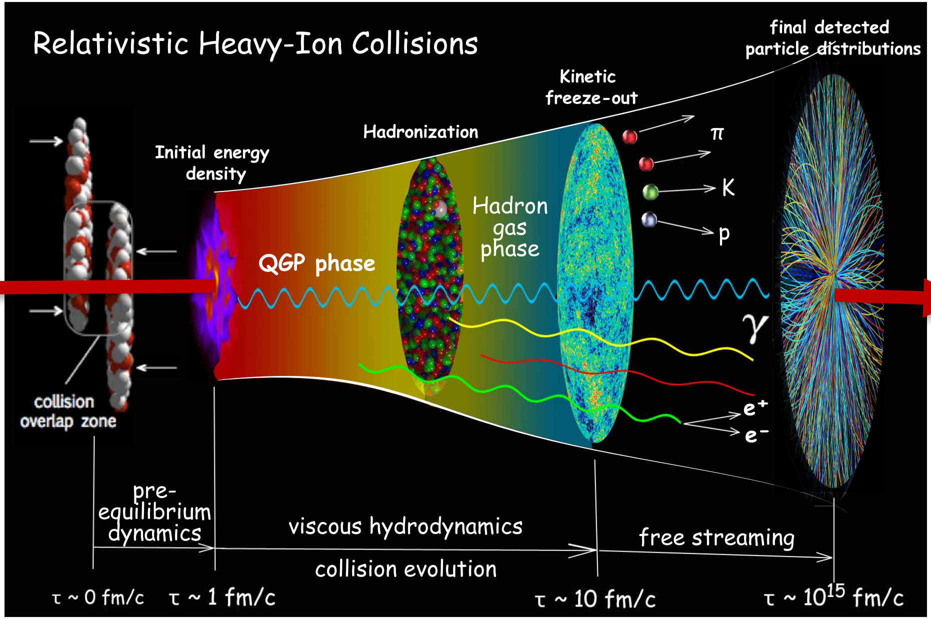

"Psychoanalysis" of Matter

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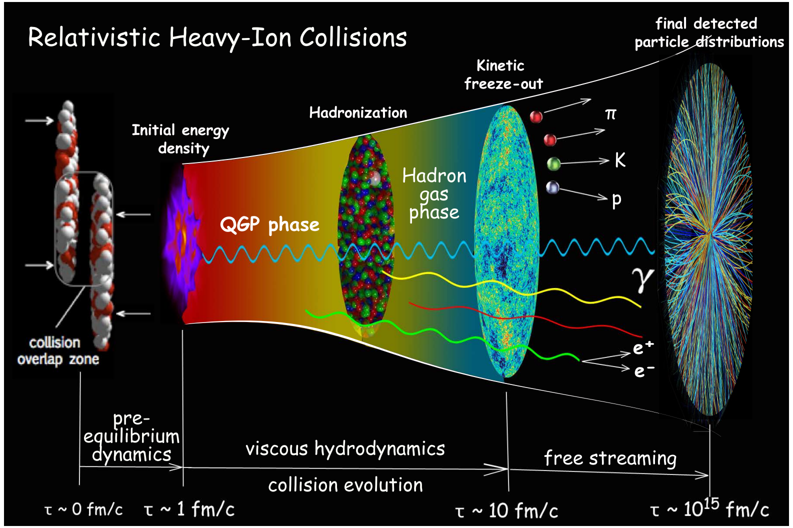
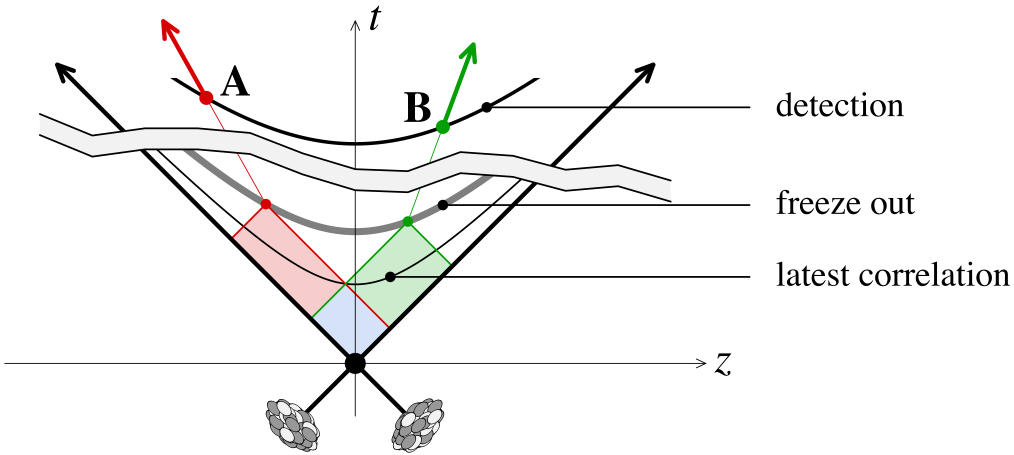


"Psychoanalysis" of Matter

Dumitru, Gelis, McLerran, Venugopalan, Nucl. Phys. A810 (2008) 91

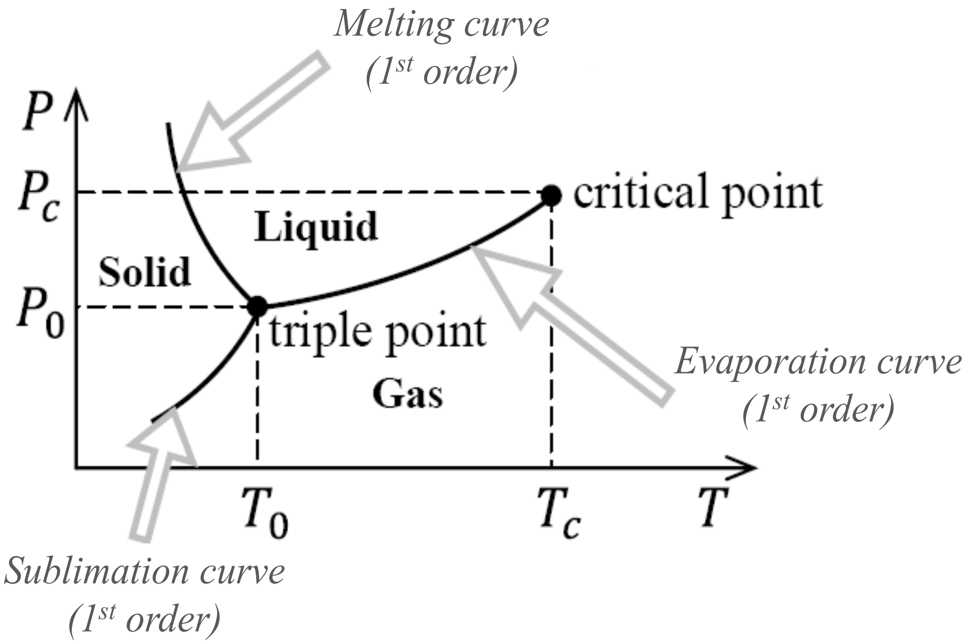


$$\tau \leq \tau_{\text{freeze out}}\, e^{-\frac{1}{2}|y_A - y_B|}$$

Only early correlations can be long range in rapidity

Nature of phase transition

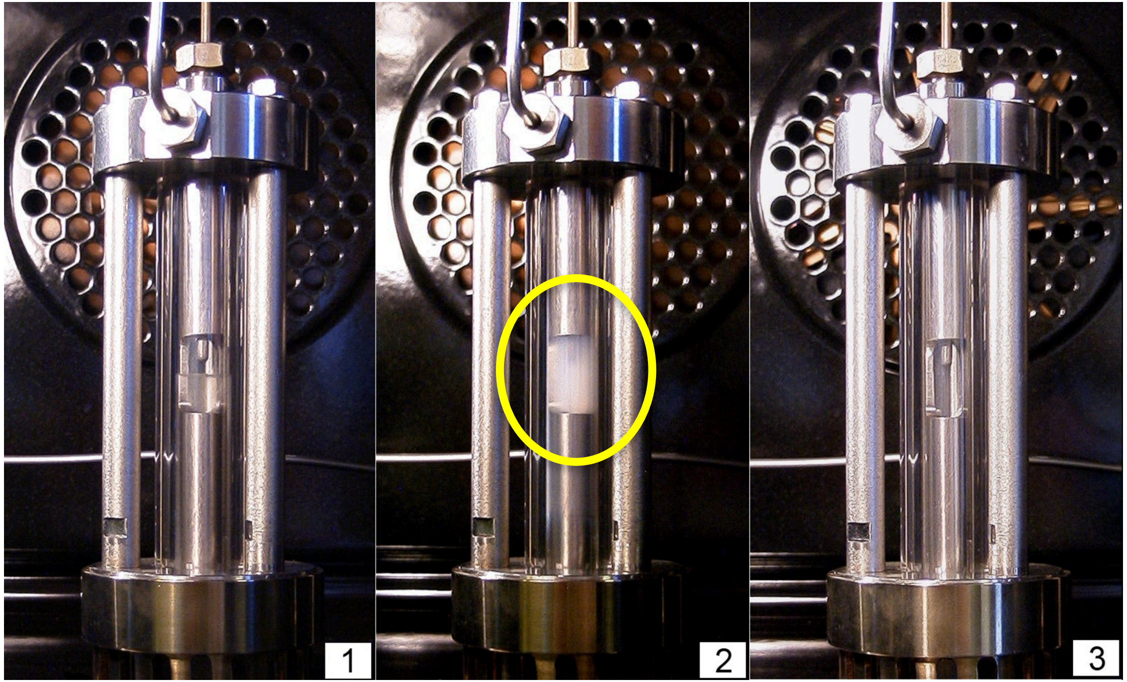
Phase diagram of water
(Electro-magnetic interactions)



- **<u>1st order phase transition:</u>** mixed phase
- **<u>At the critical point (CP):</u>** phase boundaries vanish and **correlation length** diverges → only one phase exists

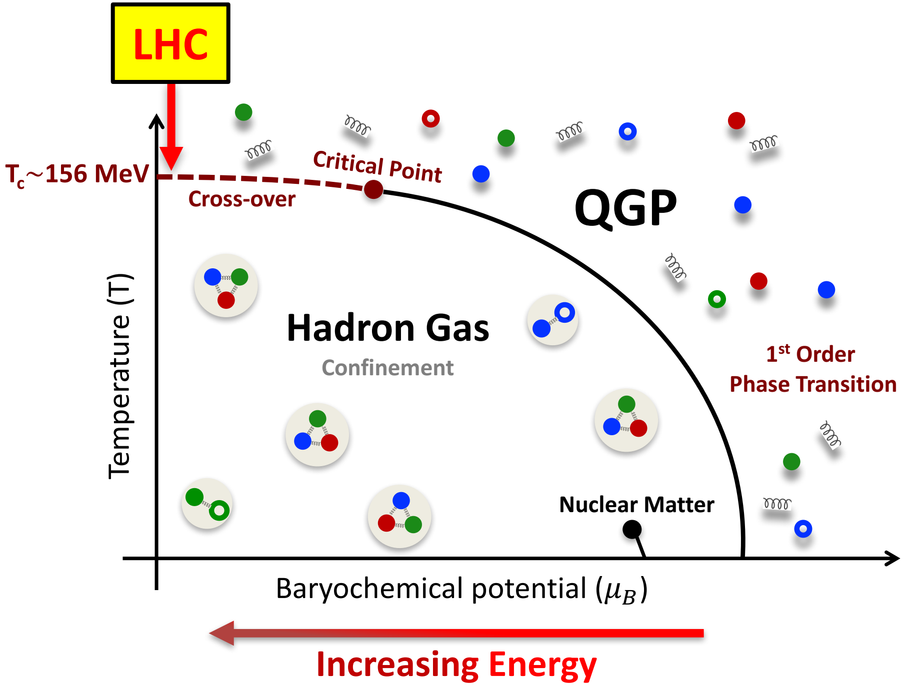
Critical opalescence: 2nd order phase transition

- Density of the gas and the thermal motion of the liquid is so great that **gas and liquid are the same**
- **Density fluctuations** are comparable to the wavelength of light → light is scattered and causes cloudy appearance



Heating a mass of ethane in a constant volume

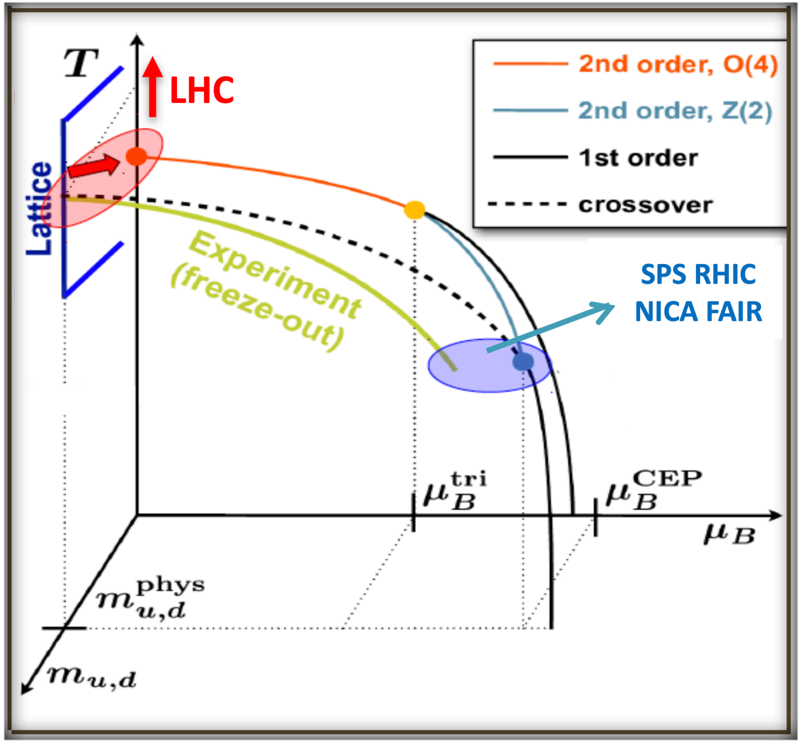
Nature of QCD phase transition



- **How close are we to** $\mu_B = 0$ at LHC energies?
- **Nature of cross over** transition at $\mu_B \sim 0$ MeV?
  $\Longrightarrow$ no experimental confirmation

Nature of QCD phase transition

F. Karsch, Schleching 2016



- **How close are we to** $\mu_B = 0$ at LHC energies?
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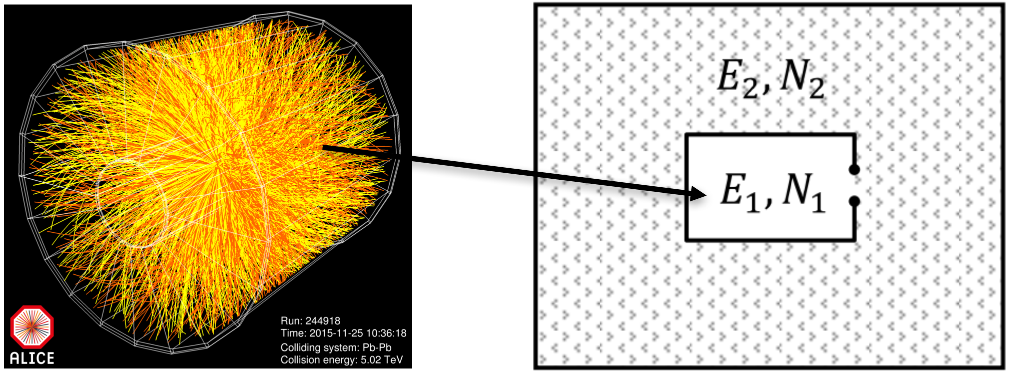
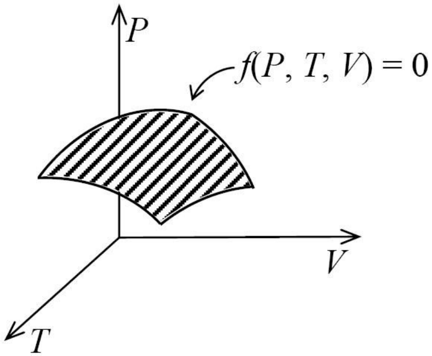
  $\Longrightarrow$ no experimental confirmation
- **Vanishing u, d quark masses?**
  $\Longrightarrow$ vicinity to 2nd order O(4) criticality
  $\Longrightarrow$ pseudocritical features at the crossover due to massless modes
  $\Longrightarrow$ **long range correlations & increased fluctuations**

What kind of a system are we dealing with?

Thermodynamics of heavy-ion collision





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

- Energy (*E*) and number of particles (*N*) are **not conserved** in each microstate
- EOS can be represented **by a surface** in the state space spanned by P, V and T

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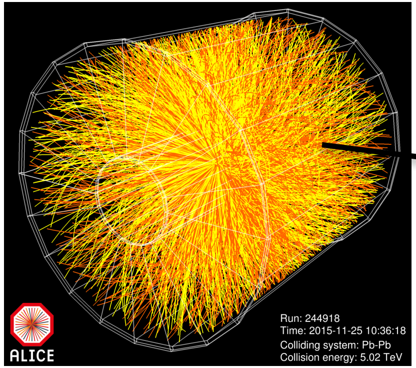

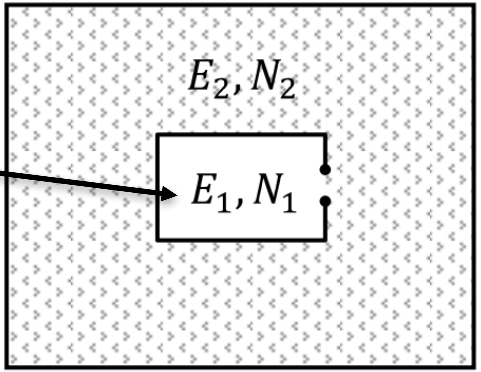

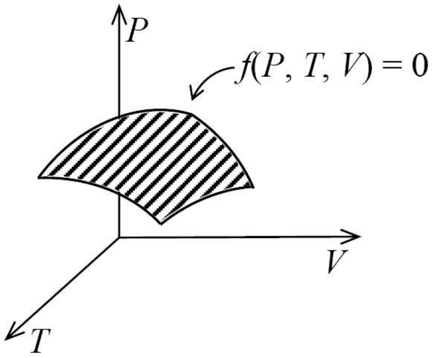

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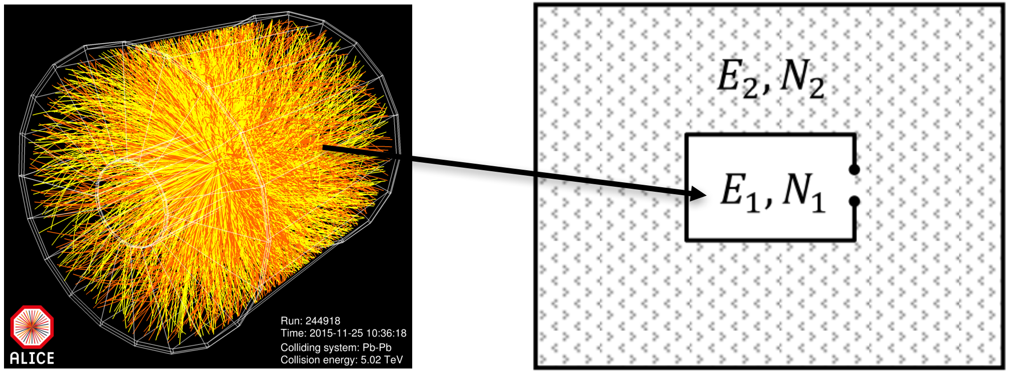

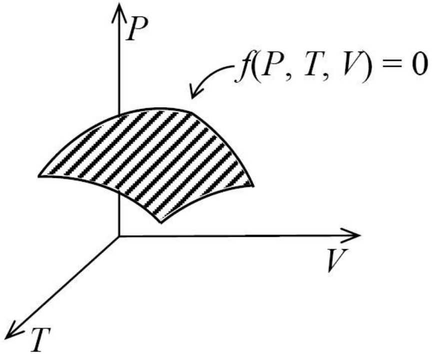

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- EOS can be represented **by a surface** in the state space spanned by P, V and T
- Conservation laws are applied **on average**
- Chemical potential **(μ_B)**, Volume **(V)** and Temperature **(T)** are constant
- For a given state E_j and N_j grand canonical partition function

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

Thermodynamics of heavy-ion collision

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

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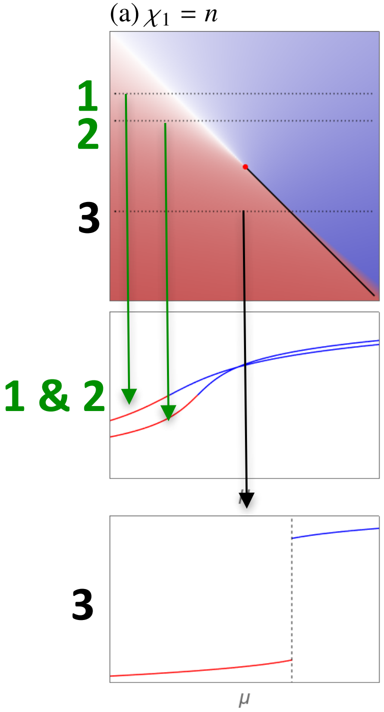

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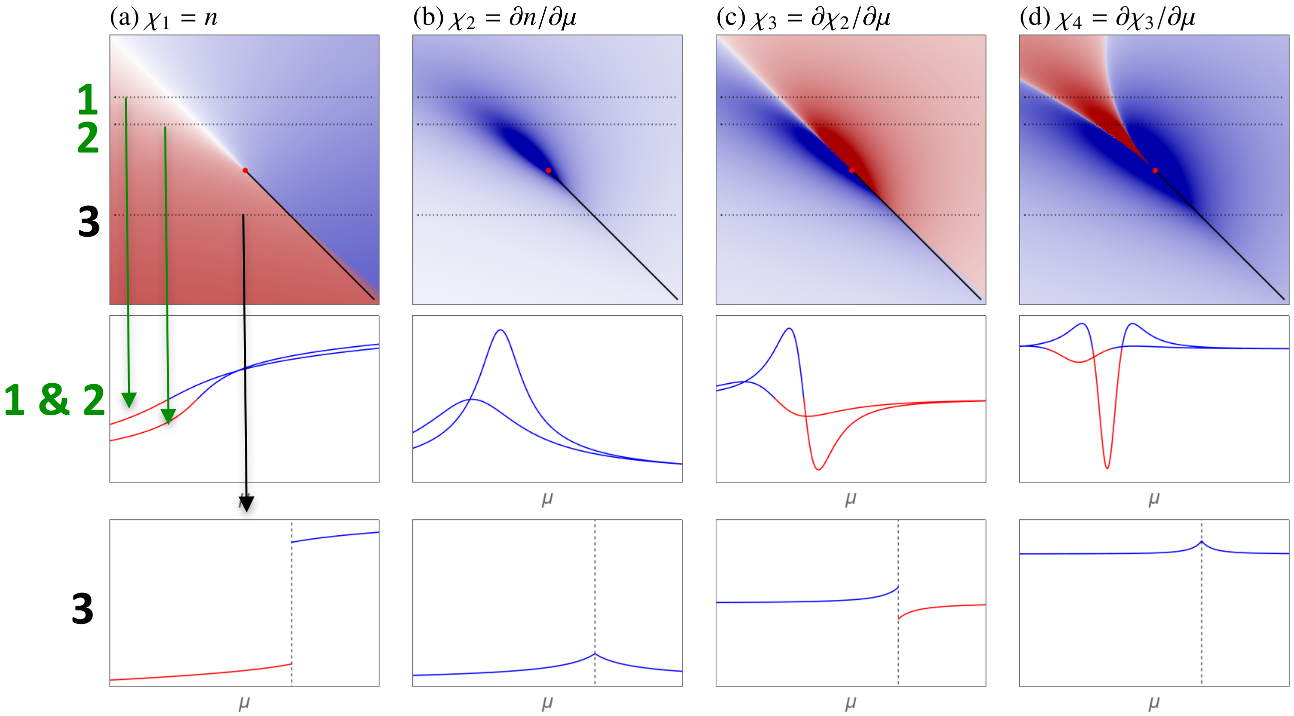
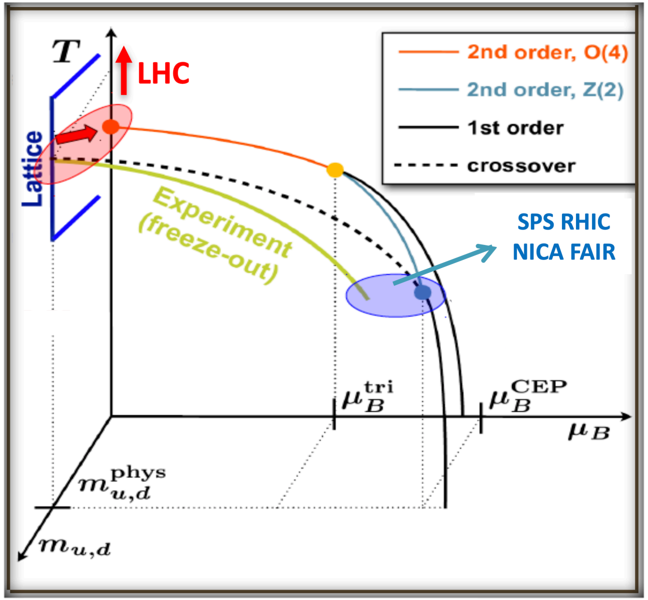


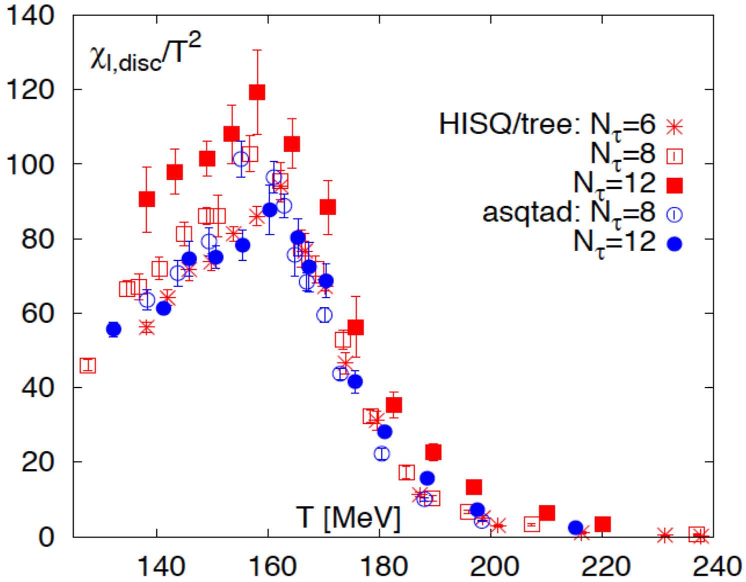
How to link theory to Experiment?

→ Lattice QCD



Light quark susceptibilities

$$\langle\bar{\psi}\psi\rangle_l^{n_f=2} = \frac{T}{V}\frac{\partial \ln Z}{\partial m_l} \Rightarrow \chi_{m,l} = \frac{\partial}{\partial m_l}\langle\bar{\psi}\psi\rangle_l^{n_f=2}$$



HotQCD Collaboration, Phys.Rev. D85 (2012) 054503

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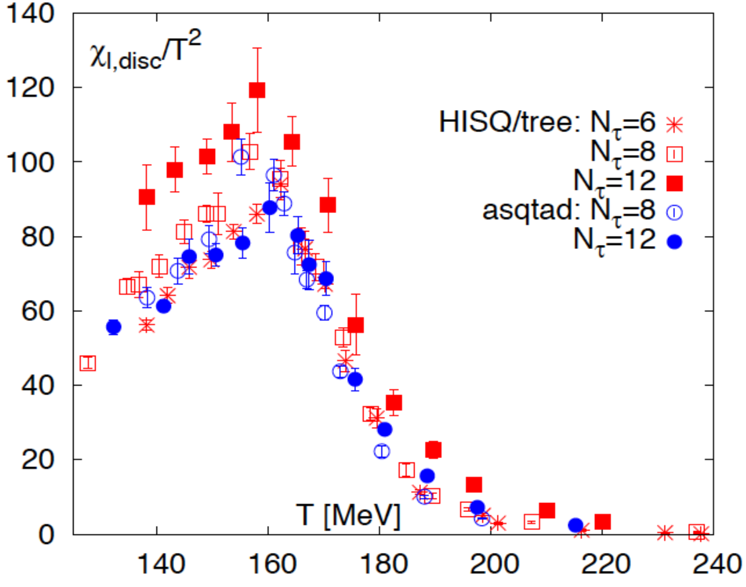
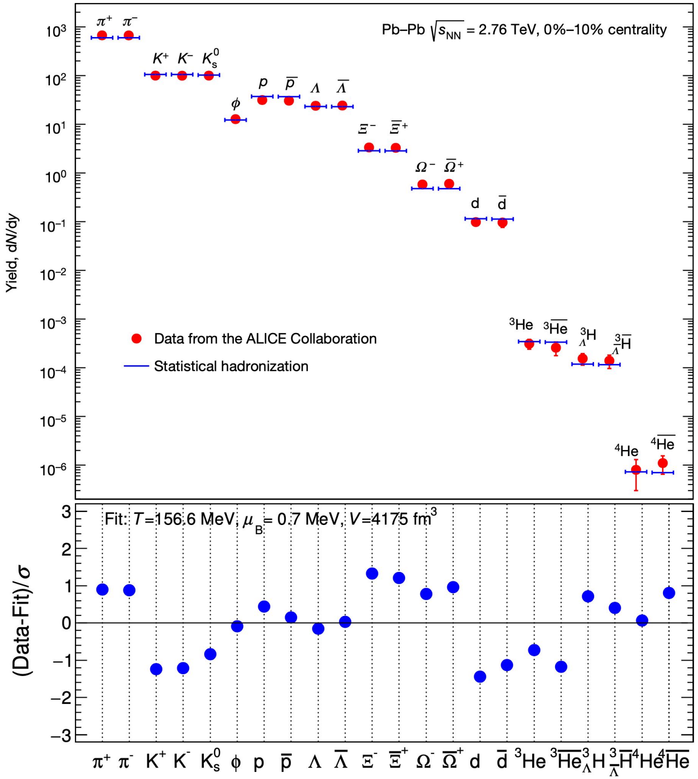


HotQCD Collaboration, Phys.Rev. D85 (2012) 054503

$$T_{\text{pc}} = 156.5 \pm 1.5 MeV \approx T_{\text{fo}}^{\text{ALICE}}$$



A. Andronic, et. al. Nature 561 (2018) 321, Phys. Lett. B 792 (2019) 304

Hunting for criticality: Cumulants of net-charge distributions

LQCD

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

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

EXPERIMENT

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

κ_n → central moments of X

$$\hat{\chi}_2^B = \frac{\kappa_2(\Delta N_B)}{VT^3} \Rightarrow \frac{\kappa_4(\Delta N_B)}{\kappa_2(\Delta N_B)} = \frac{\hat{\chi}_4^B}{\hat{\chi}_2^B}$$

Effect of volume fluctuations:

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

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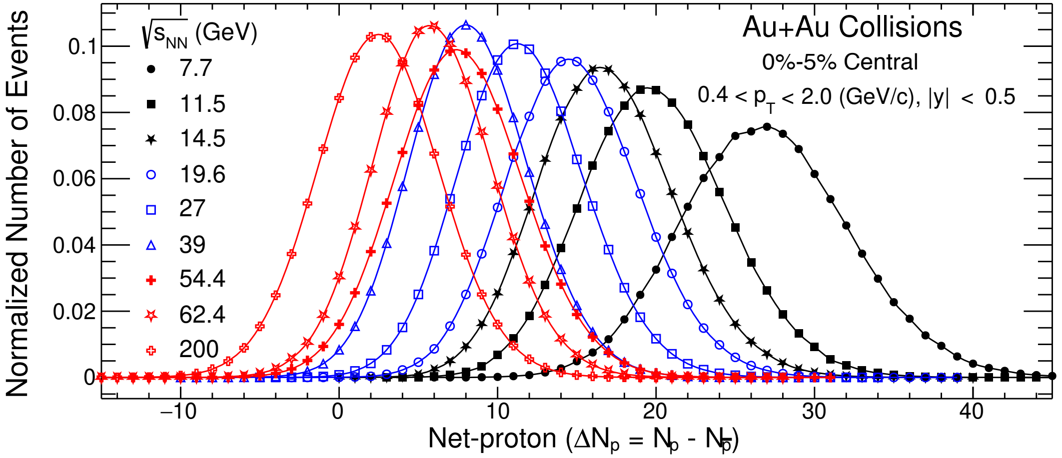
STAR Collaboration, Phys. Rev. Lett. 126, 092301



- Critical signals are hidden in the tails
- Experimentally very challenging

What does theory tell us?

1) **Baseline:** Difference between two independent Poissonian distributions (Skellam distr.)
   $\Longrightarrow$ $\boldsymbol{\kappa_n/\kappa_2}$ **is 0 (odd) or 1 (even)**

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

3) **Higher order** → larger deviation from baseline

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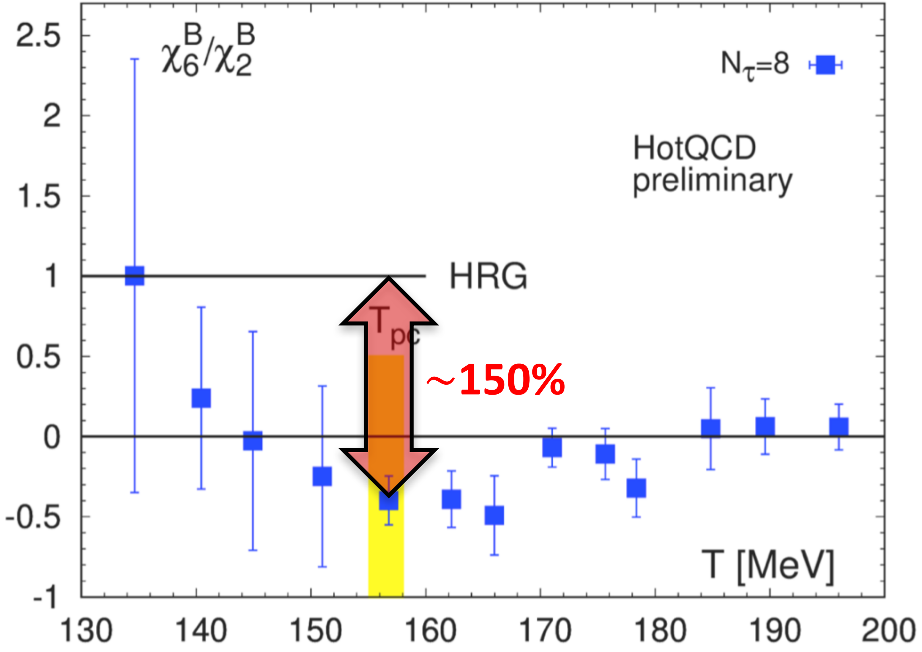
2) **Up to 3rd order** Hadron Resonance Gas (HRG) model agrees with LQCD at $\mu_B = 0$

3) **Higher order** → larger deviation from baseline

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

A. Bazavov et.al. Phys. Rev. D 95 (2017), 054504



LQCD vs Experiment: Caveats

- ✓ Experiments measure final state of the **dynamical evolution**, while LQCD calculates an **equilibrium**
- ✓ Fluctuations are typically calculated in **coordinate space** but measured in **momentum space**
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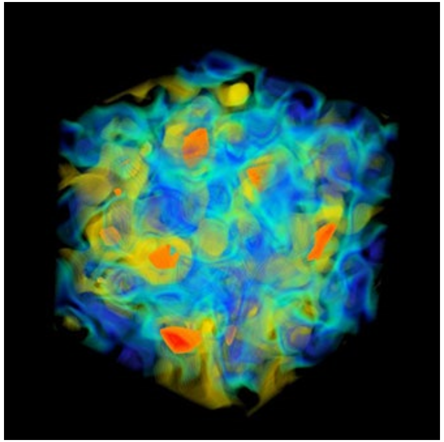
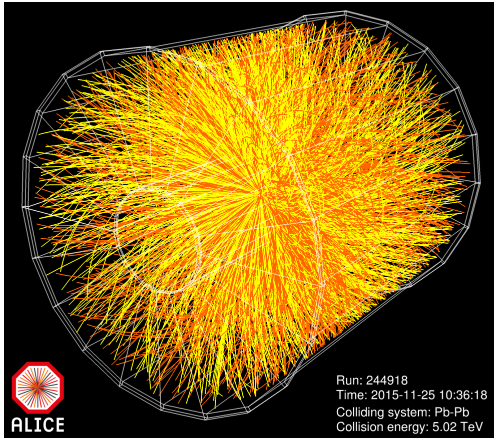


LQCD@BNL



ALICE data

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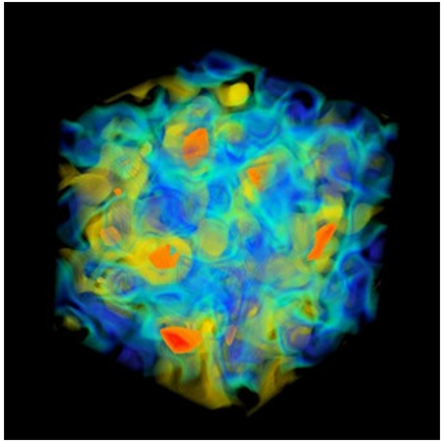

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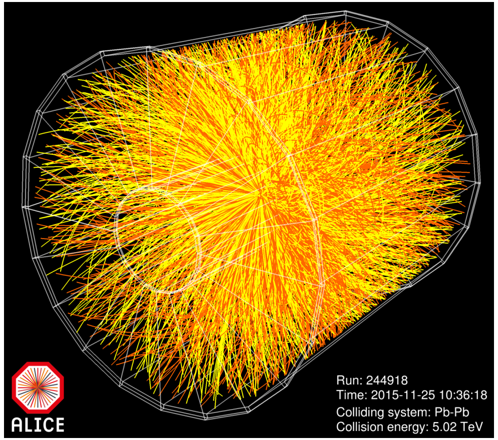
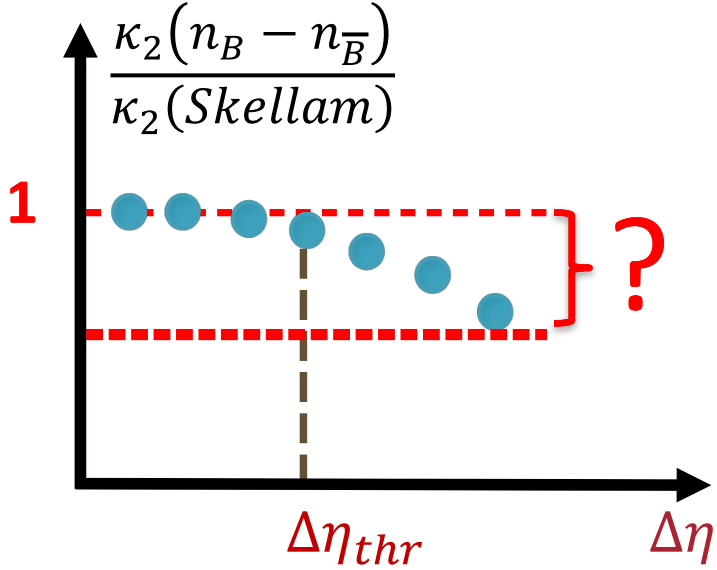
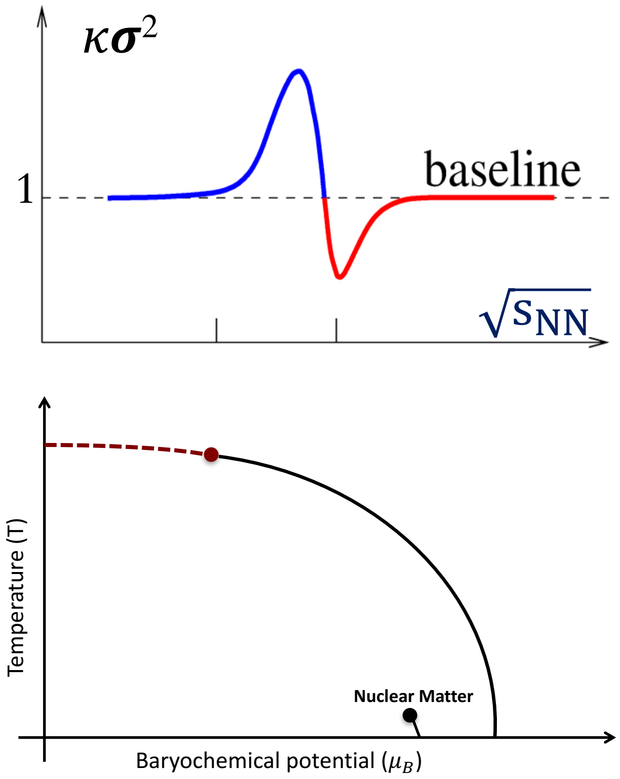


ALICE data

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



Non-monotonic behavior as a function of energy



M. Stephanov, PRL102, 032301 (2009), PRL107, 052301 (2011)

E.g.: Expectation from beam energy scan

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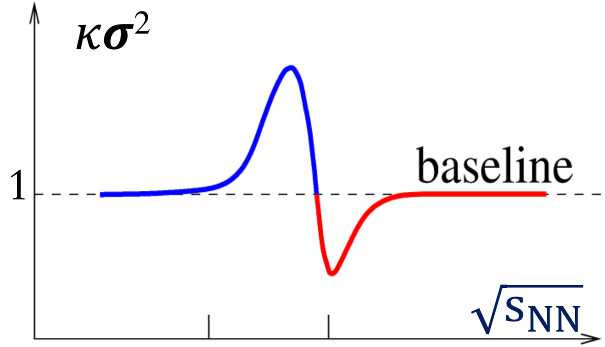

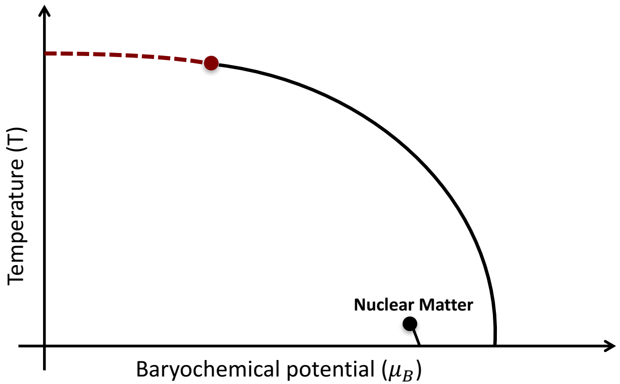

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HADES: Phys.Rev.C 102 (2020) 2, 024914

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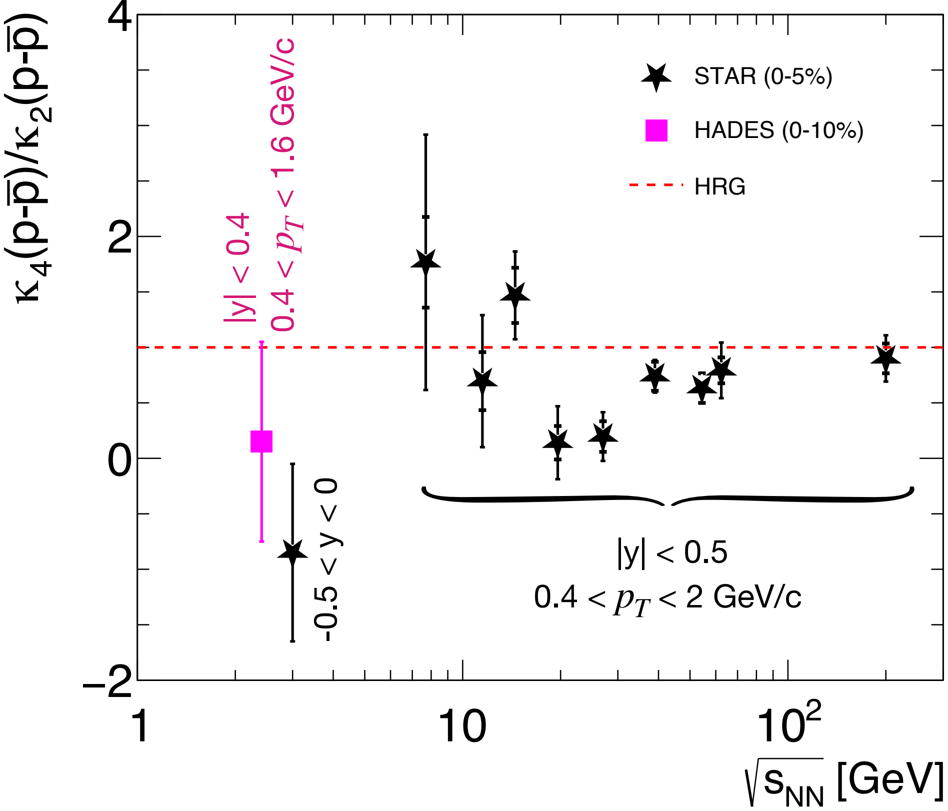

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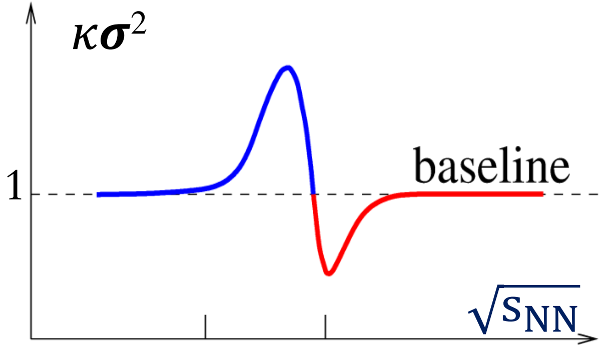

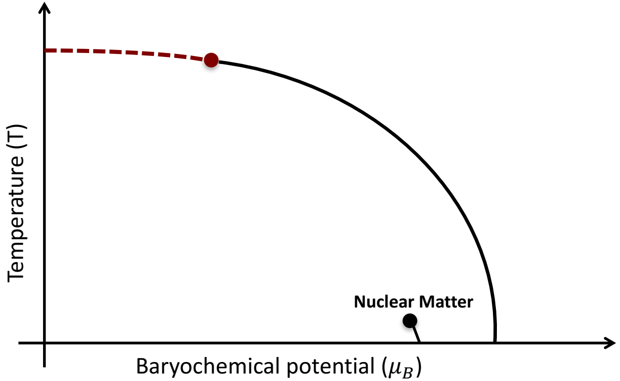

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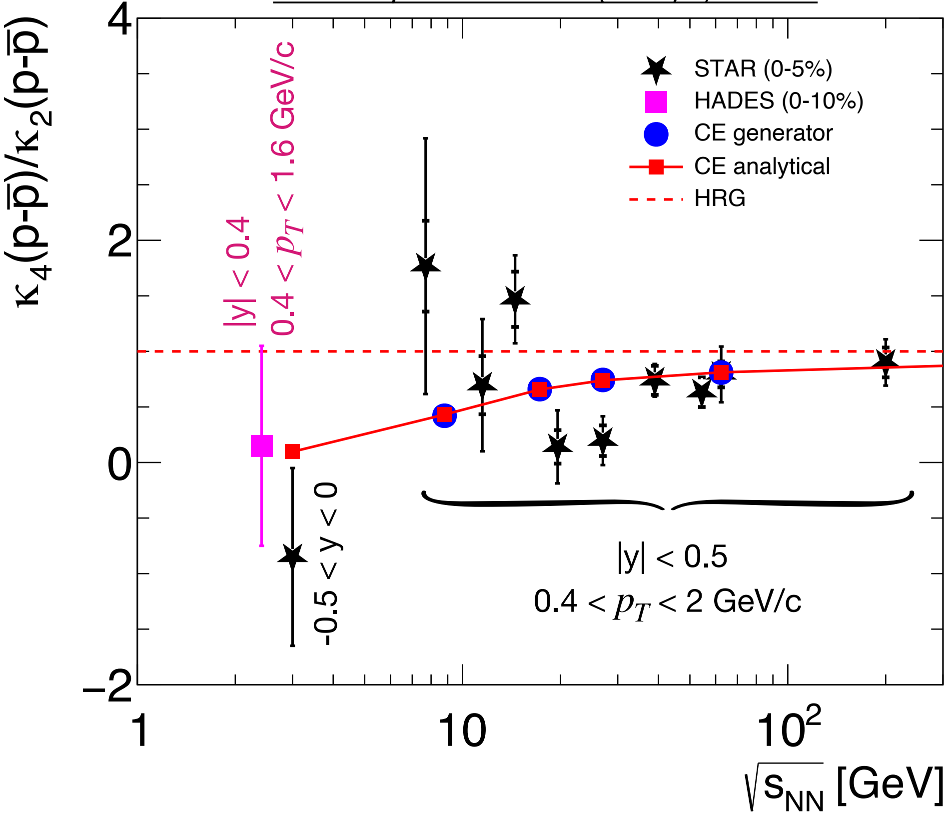
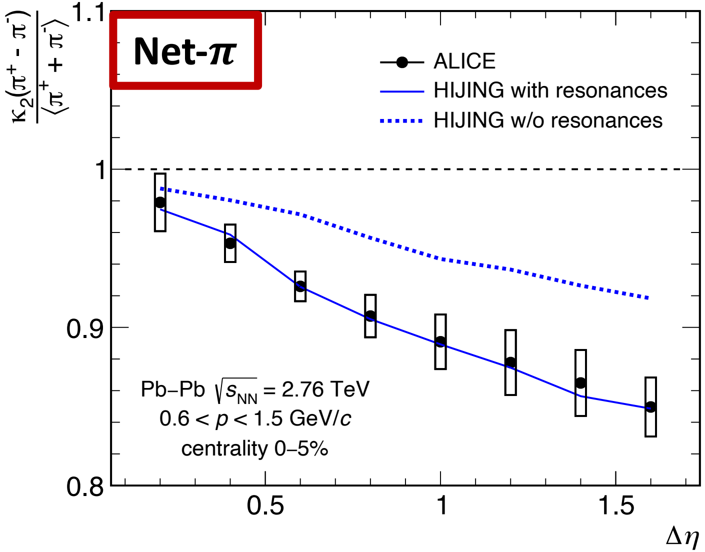
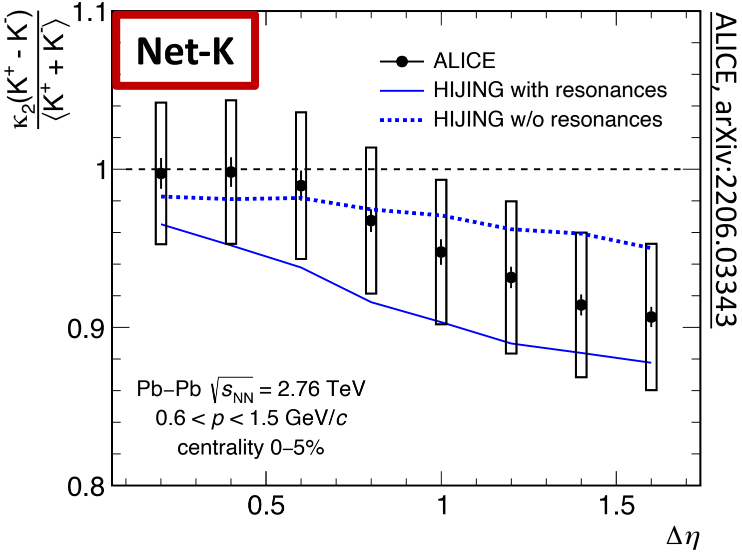


Net-(global) charge fluctuations

NEW





- **Net-Q,S:** → Strongly dominated by **resonance contributions**

(V. Vovchenko and V. Koch Phys. Rev. C 103, 044903 (2021))

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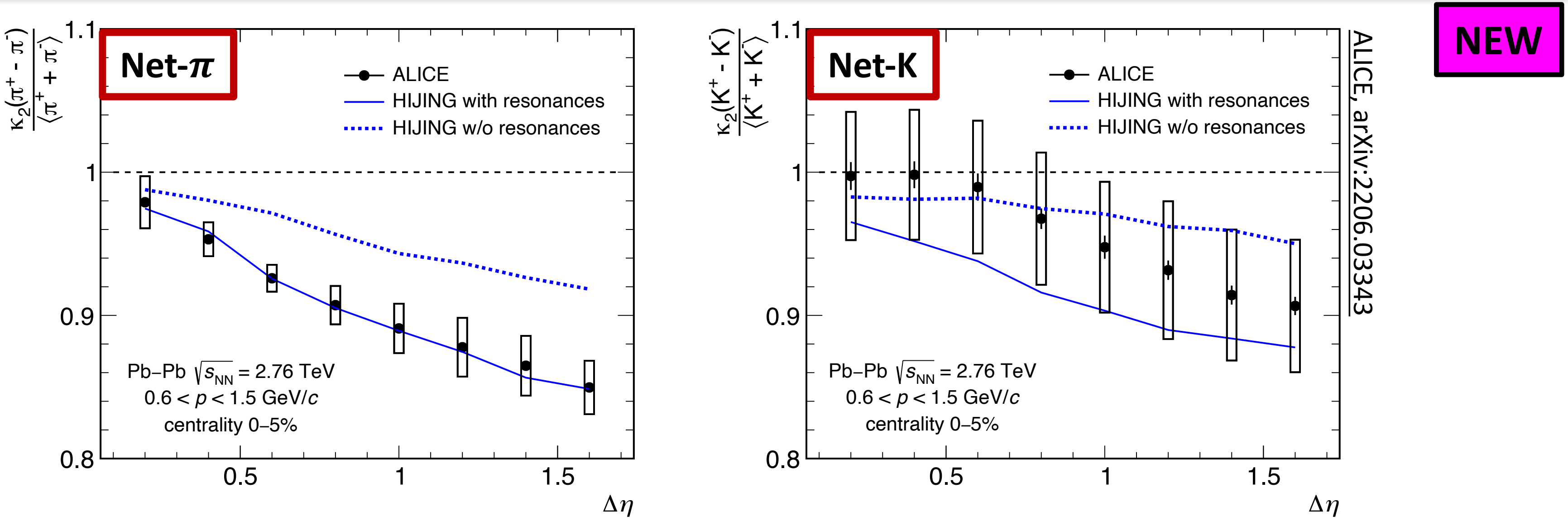

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  (V. Vovchenko and V. Koch Phys. Rev. C 103, 044903 (2021))

- **Net-B:**

  → Due to **isospin randomization,** at $\sqrt{s_{NN}}$ > 10 GeV **net-baryon ↔ net-proton**

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

  → No resonance feeding $\mathrm{p} + \bar{\mathrm{p}}$

  → **Best candidate for measuring charge susceptibilities is net-p**

A Large Ion Collider Experiment

Main detectors used:

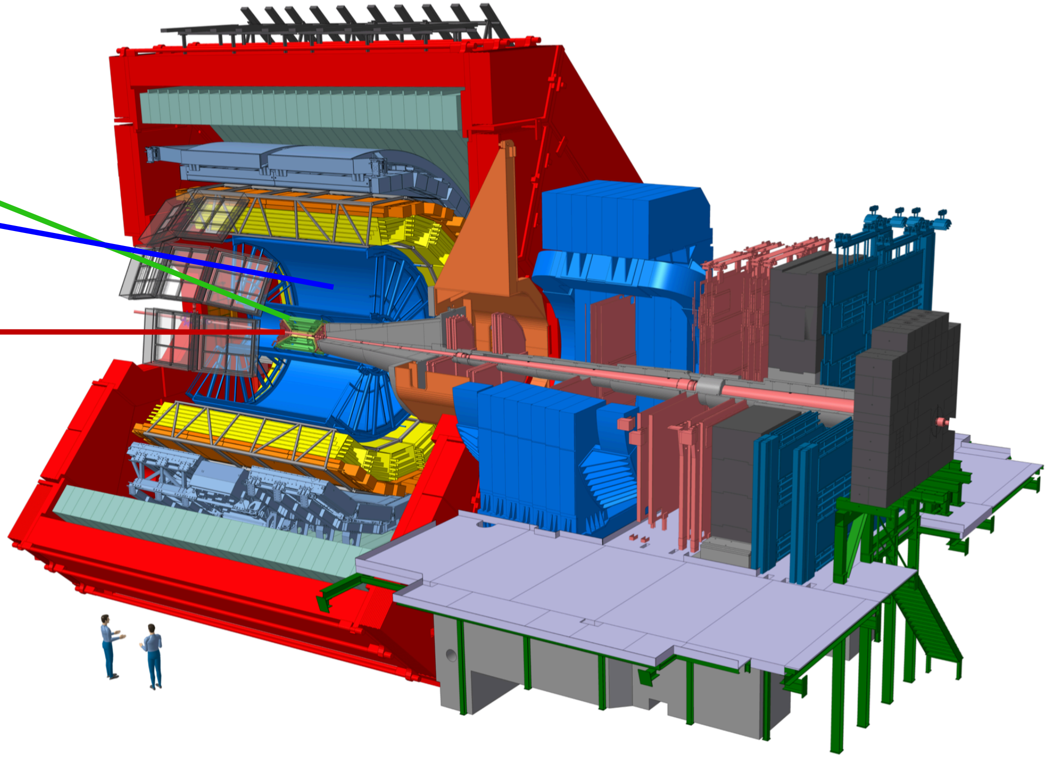
- Inner Tracking System (ITS)
  → Tracking and vertexing
- Time Projection Chamber (TPC)
  → Tracking and
  Particle Identification (PID)
- V0
  → Centrality determination

Data Set:

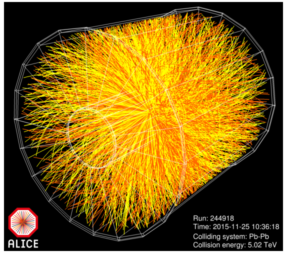
- $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV, ~78 M events
- $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV, ~13 M events

Kinematic acceptance:

- $0.6 < p < [1.5, 2]$ GeV/c
- $|\eta| < 0.2, 0.4, \ldots, 0.8$



Experimental challenges?



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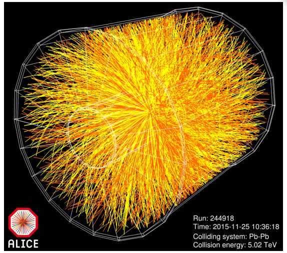
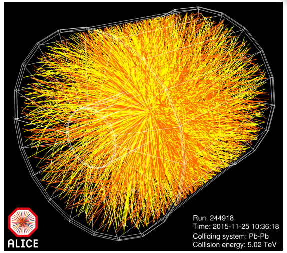


Event/track selection

Experimental challenges?



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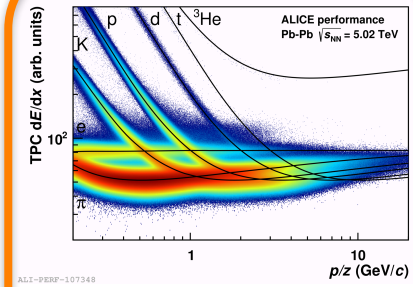
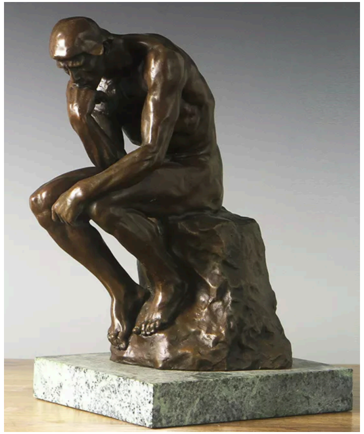
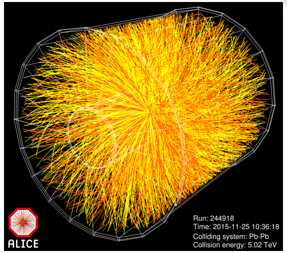
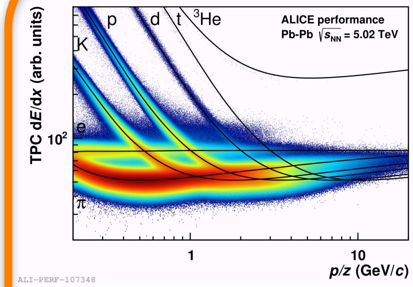


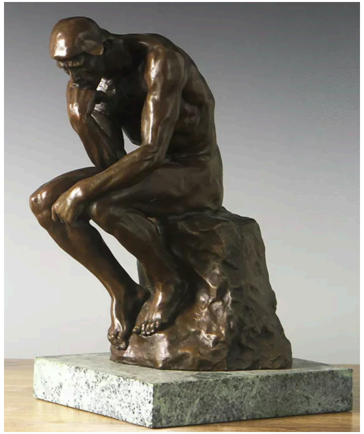


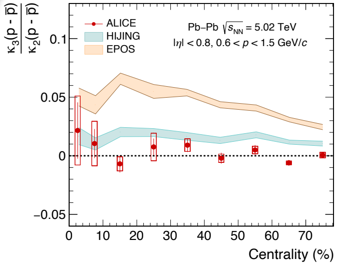
dE/dx calibration and PID

Experimental challenges?







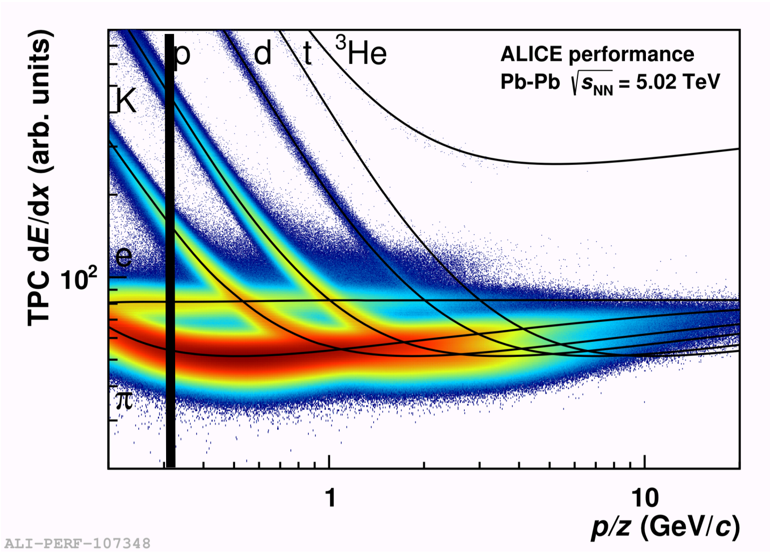


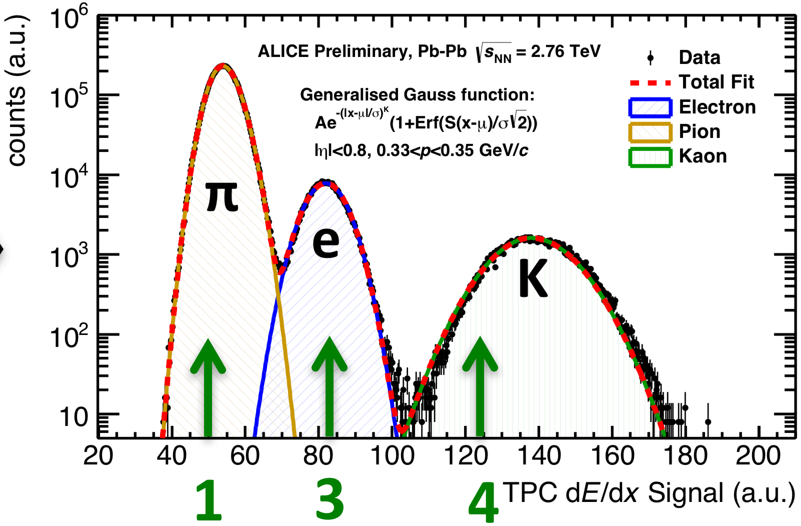
Event/track selection

dE/dx calibration and PID

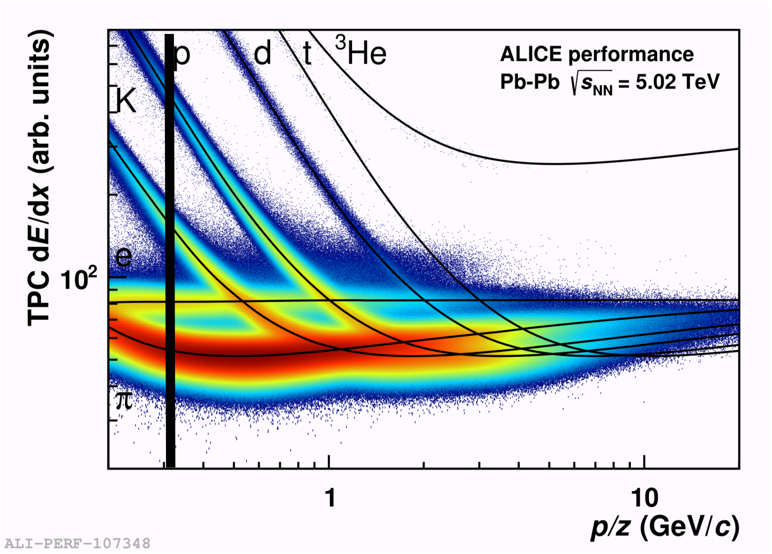
Efficiency correction

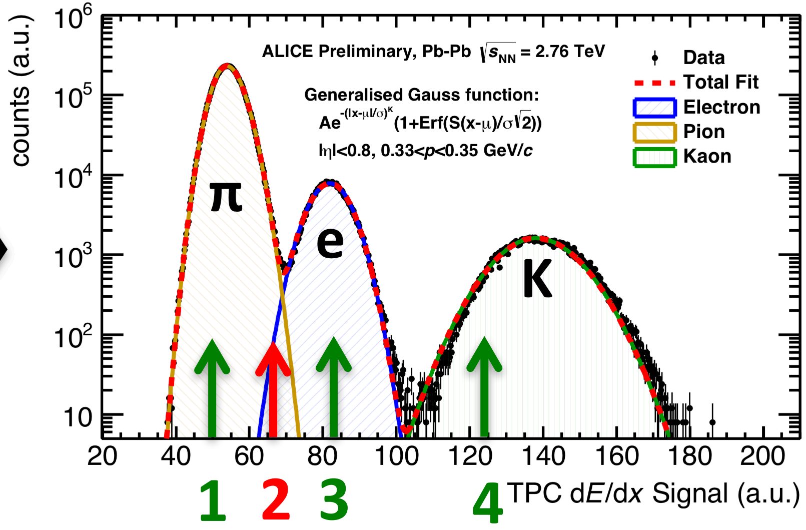
Cut based approach vs Identity Method





Cut based approach vs Identity Method

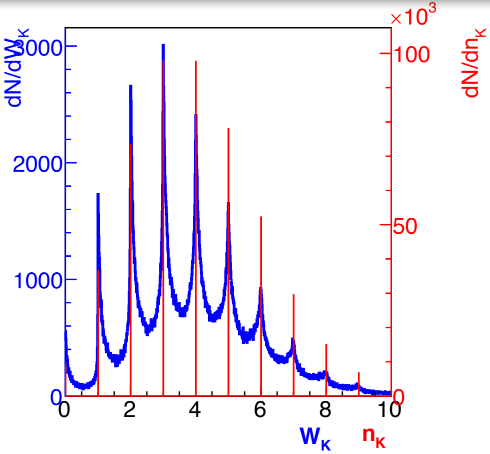




$$\omega_{\pi}^{(1)}=1,\quad \omega_{\pi}^{(2)}\cong 0.6,\quad \omega_{\pi}^{(3)}=0,\quad \omega_{\pi}^{(4)}=0 \quad\Rightarrow\quad W_{\pi}=1.6\neq N_{\pi}$$

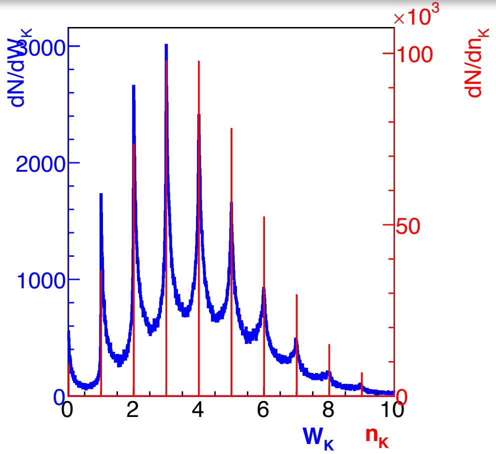
A. Rustamov, M. Gazdzicki, M. I. Gorenstein, PRC 86, 044906 (2012), PRC 84, 024902 (2011)
A. Rustamov, M. Arslandok, Nucl. Instrum. A946 (2019) 162622}

Identity Method



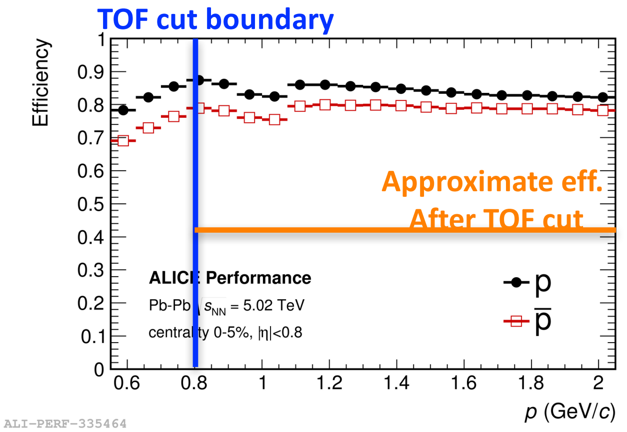
$$\langle N_j^n \rangle = \mathrm{A}^{-1} \langle W_j^n \rangle$$

Identity Method



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

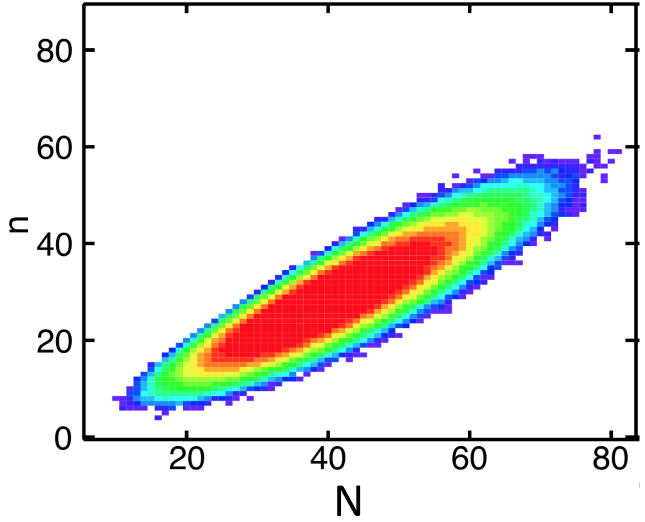
- **Cut based approach**
  - Use additional detector information or reject a given phase space bin
  - Challenge: efficiency correction and contamination
- **Identity Method**
  - Gives folded multiplicity distribution
  - Easier to correct inefficiencies



(2) Efficiency correction

Hypergeometric detector response:

⇒ Draw N balls from the urn without returning balls to the urn
(n: reconstructed, N: generated multiplicity)



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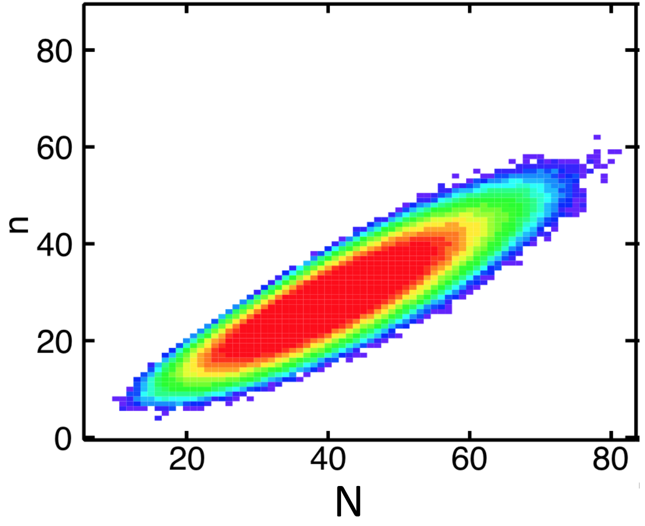
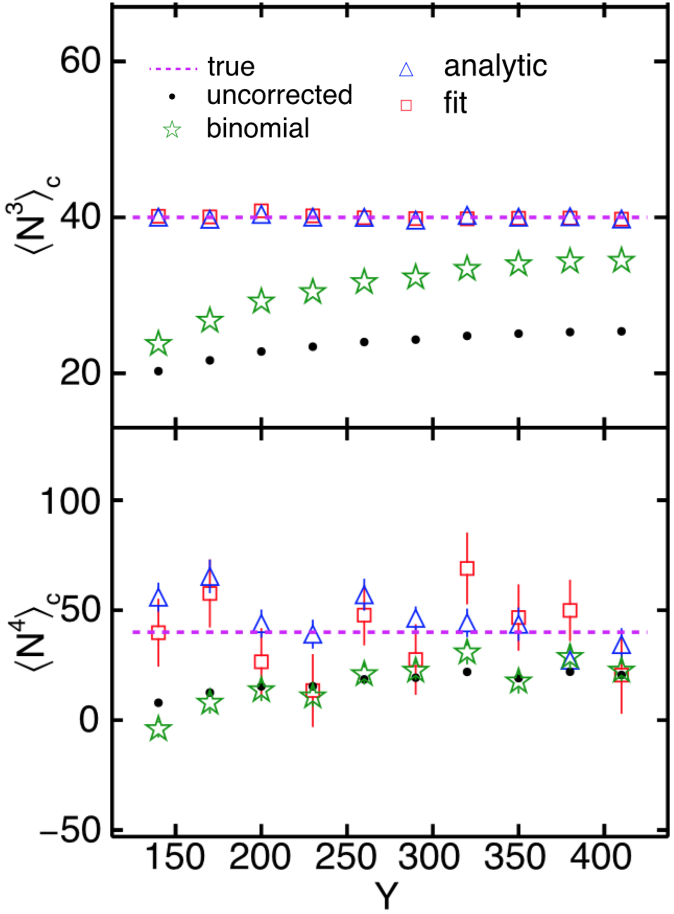


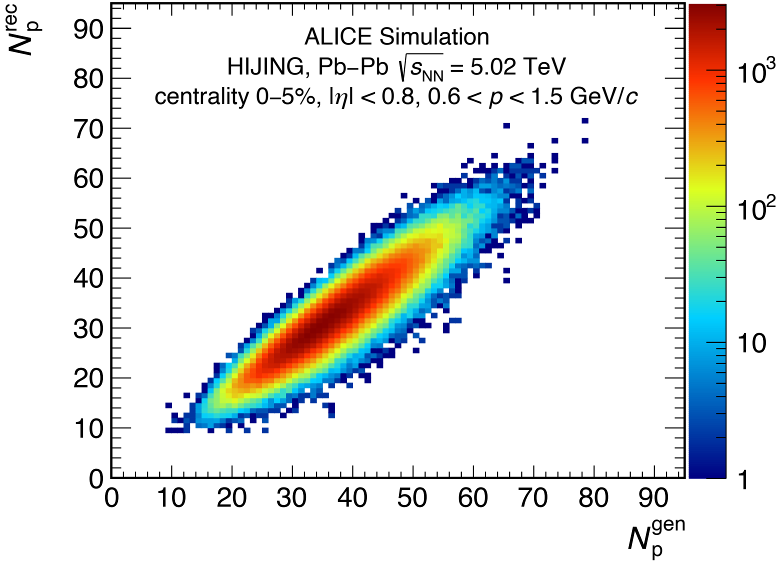


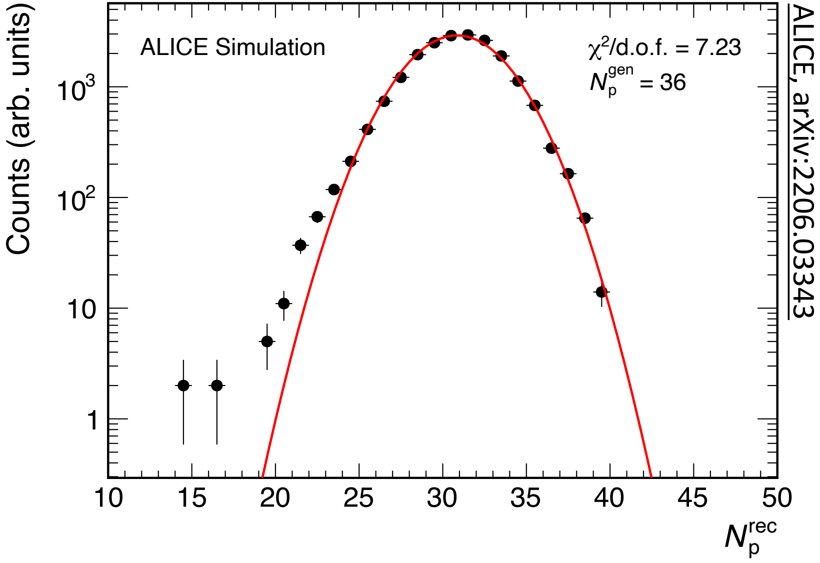
T. Nonaka, M. Kitazawa, S. Esumi, Nucl. Instrum. Meth. A906 (2018) 10-17

Detector response

NEW

Binomiality of the detector response is important for the efficiency correction



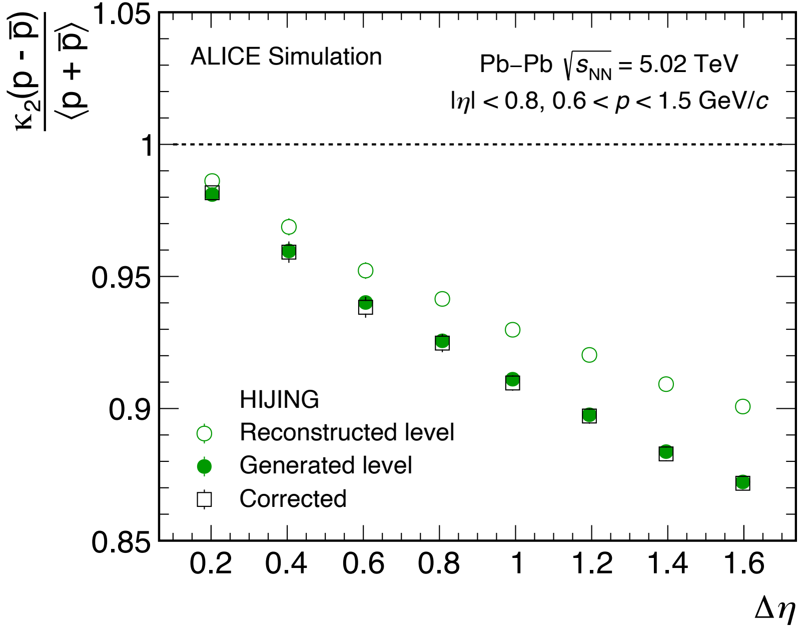


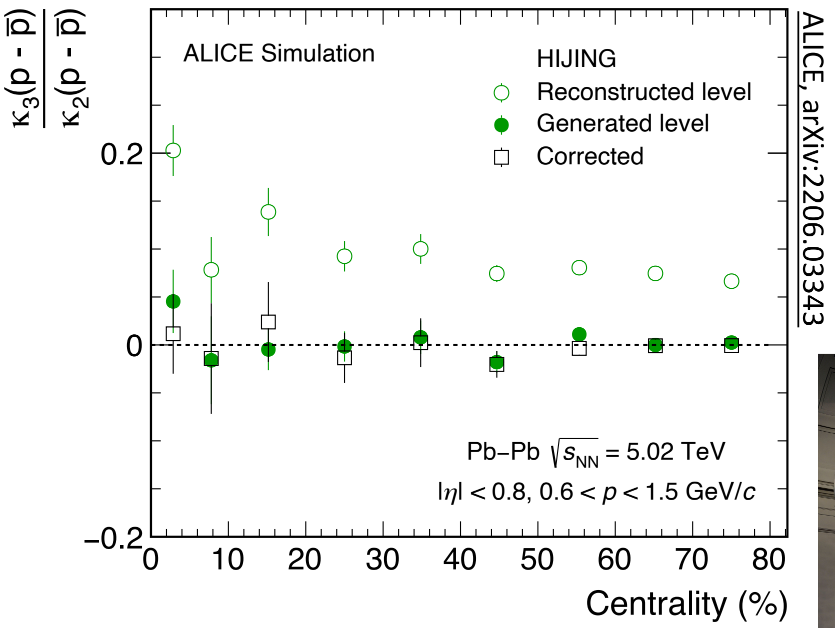
Slight deviation from the binomial efficiency loss

- 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

NEW

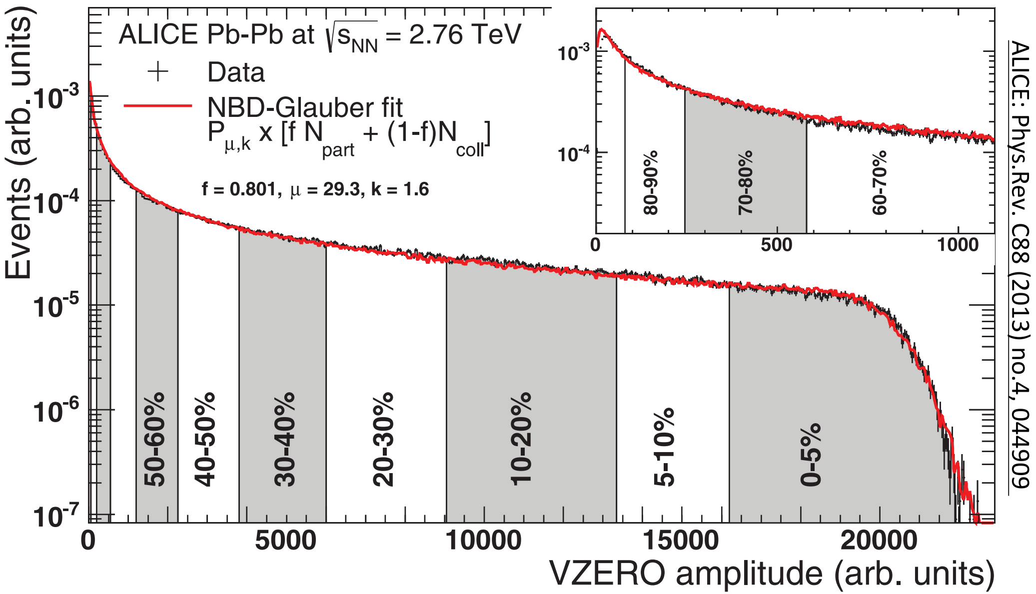


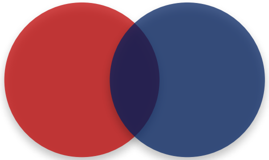


Very good closure despite the slight deviation from binomial loss

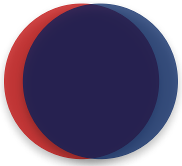
Efficiency correction with binomial assumption: T. Nonaka, M. Kitazawa, S. Esumi, Phys. Rev. C 95, 064912 (2017), Adam Bzdak, Volker Koch, Phys. Rev. C86, 044904 (2012)

(3) Volume fluctuations



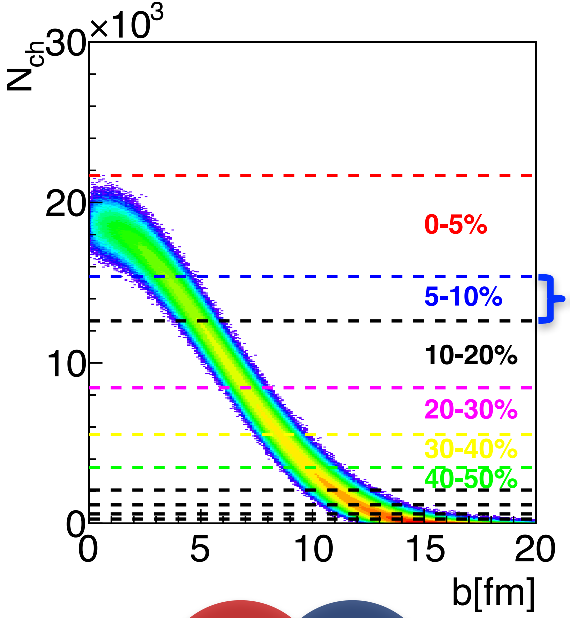


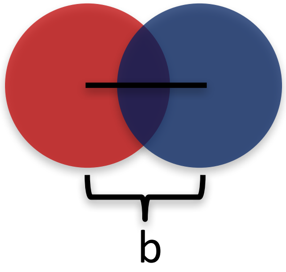
Peripheral collision

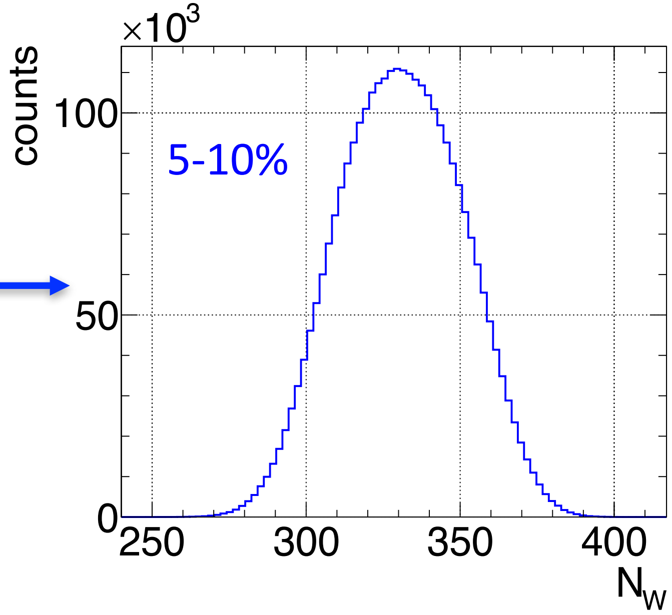


Central Collision

Finite centrality bin width



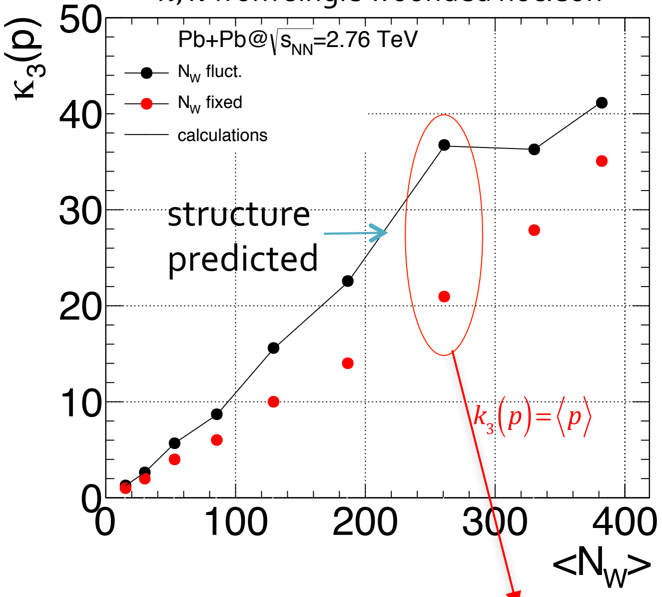




P. Braun-Munzinger, A. Rustamov, J. Stachel, Nucl. Phys. A 960 (2017) 114-130

Volume fluctuations at LHC energies

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



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

Volume fluctuations at LHC energies

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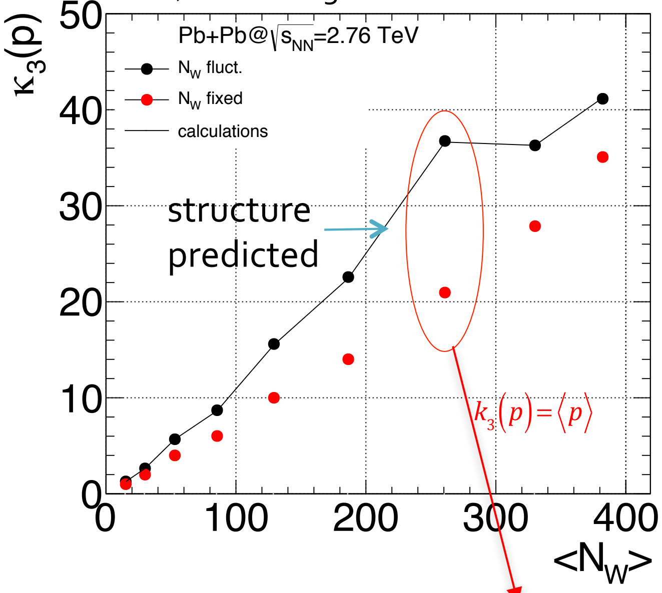
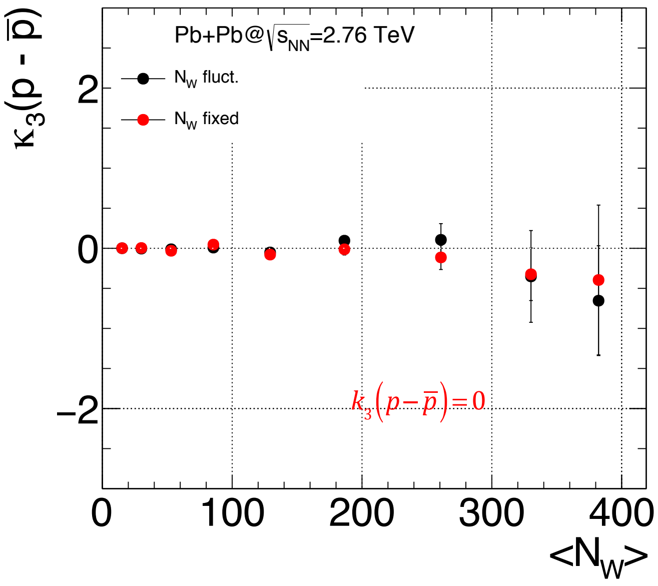


$$k_3(p) = \langle N_w \rangle k_3(n) + \langle n \rangle (\ldots)$$

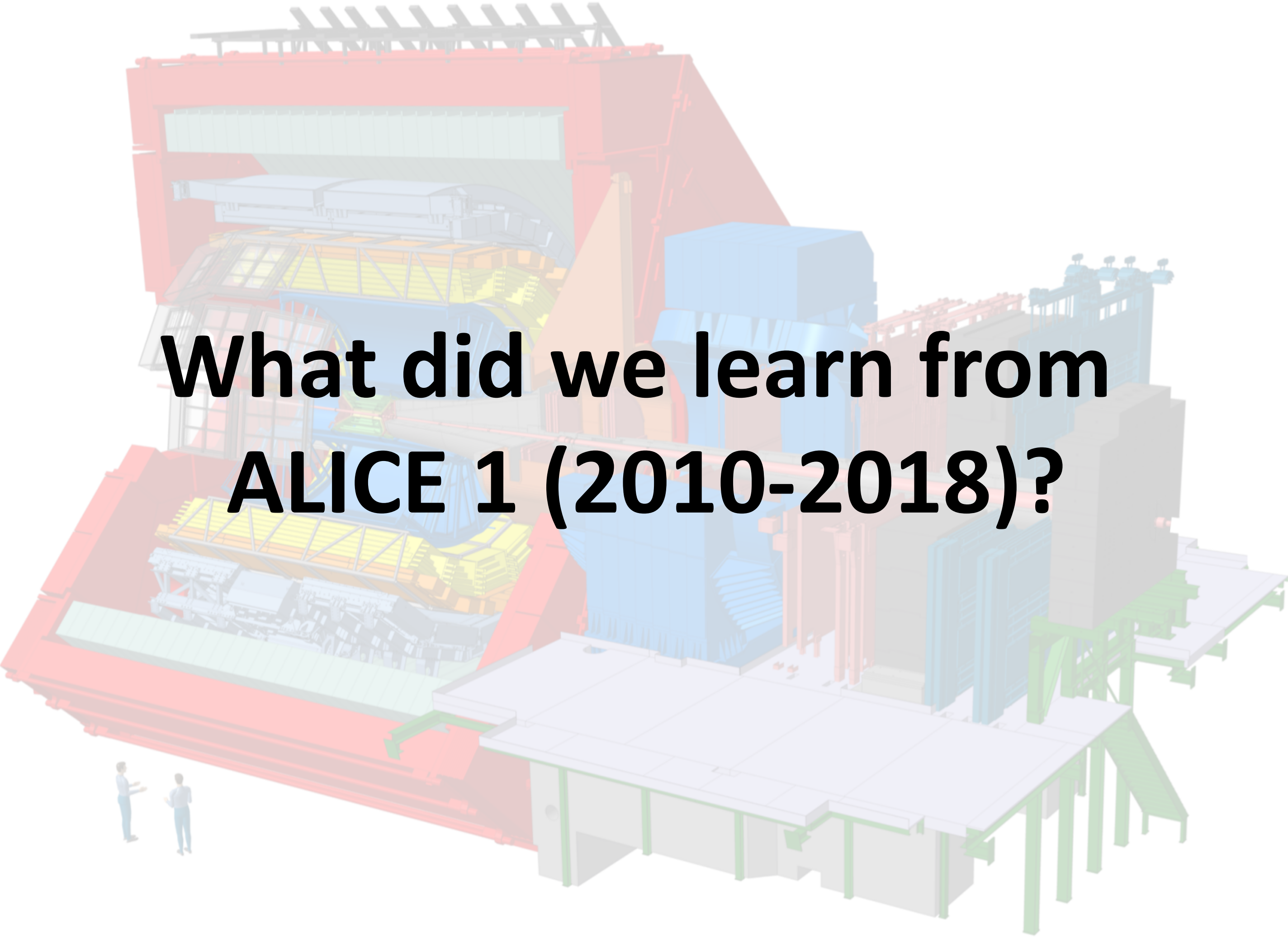


$$k_3(p-\bar{p}) = \langle N_w \rangle k_3(n-\bar{n}) + \langle n-\bar{n} \rangle (\ldots)$$

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

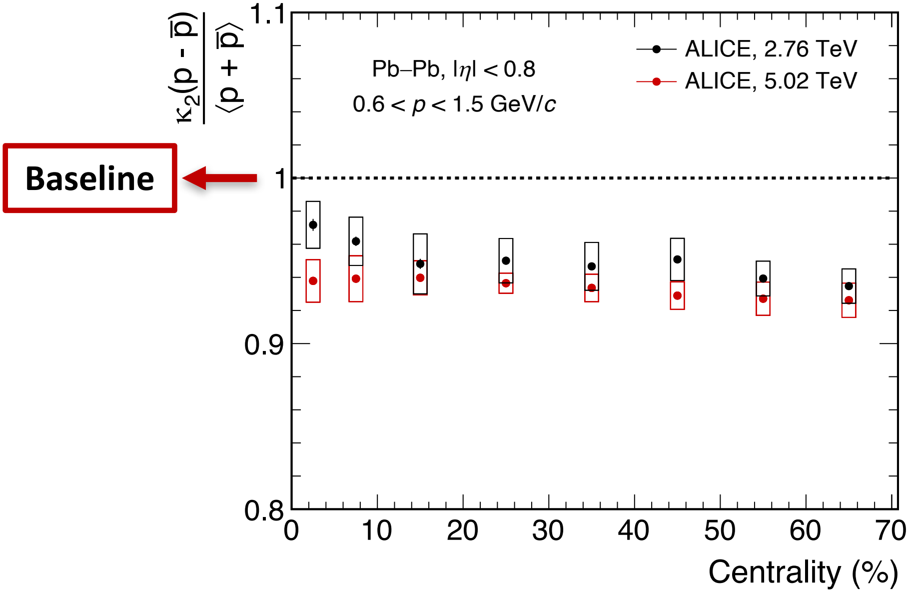
Up to 3rd order net-proton cumulants are free from volume fluctuations

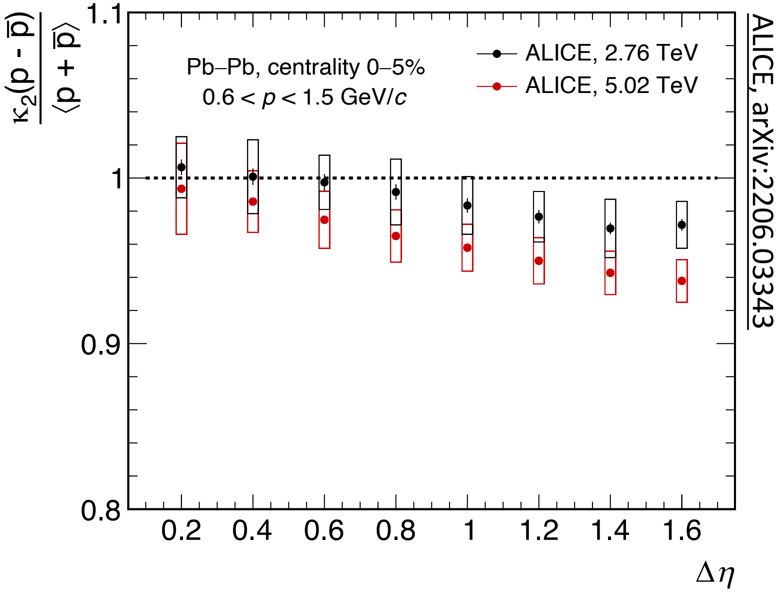
What did we learn from ALICE 1 (2010-2018)?



2^{nd} order cumulants of net-p

NEW



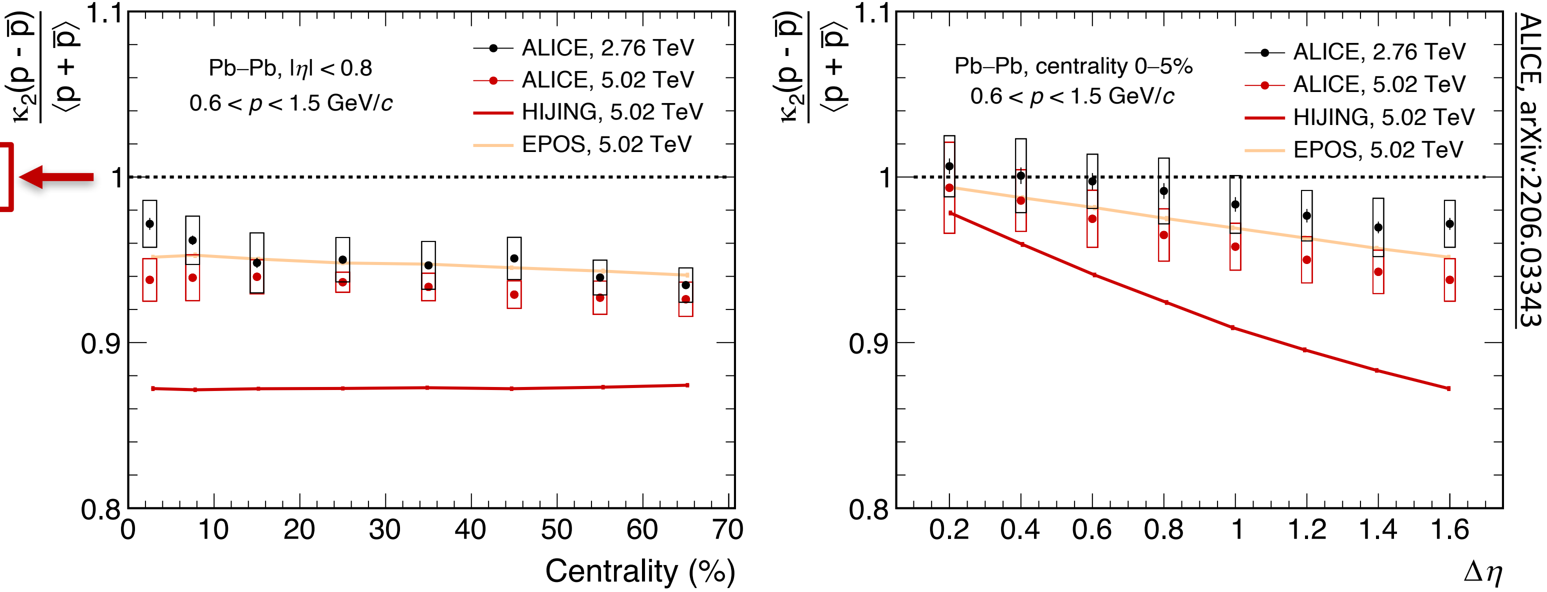


- Deviation from Skellam baseline

2nd order cumulants of net-p

NEW

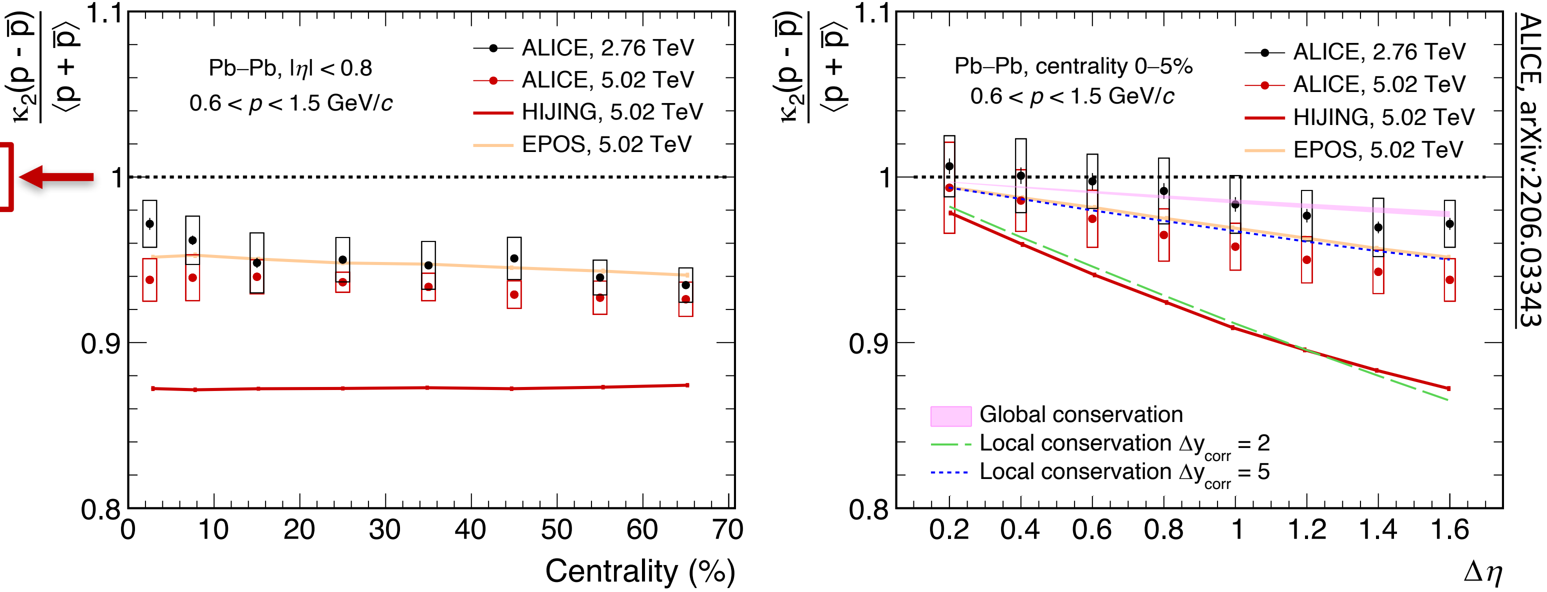
Baseline



- Deviation from Skellam baseline
- EPOS agrees with ALICE data but HIJING deviates significantly

NEW

Baseline

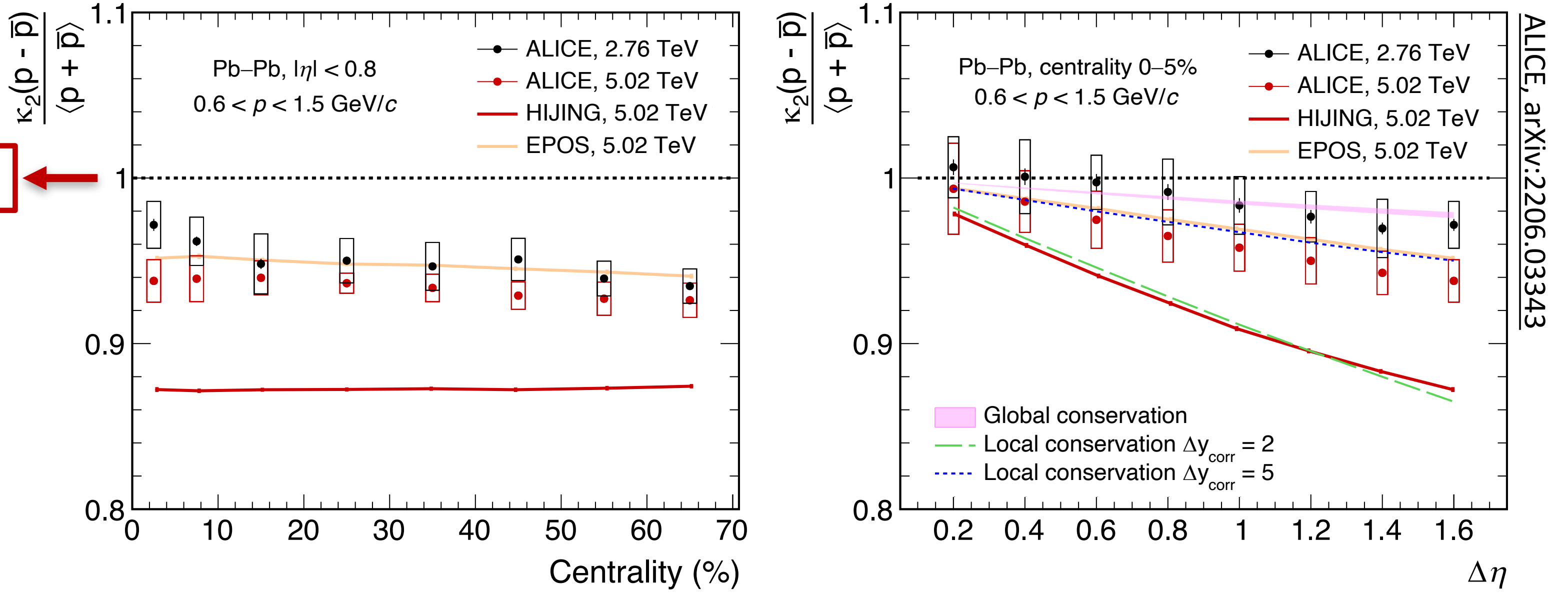


- Deviation from Skellam baseline
- EPOS agrees with ALICE data but HIJING deviates significantly
- **Baryon number conservation?**
  - **ALICE data:** Long range correlations, **$\Delta y = \pm 2.5$ unit or longer** → **Earlier in time**

2^{nd} order cumulants of net-p

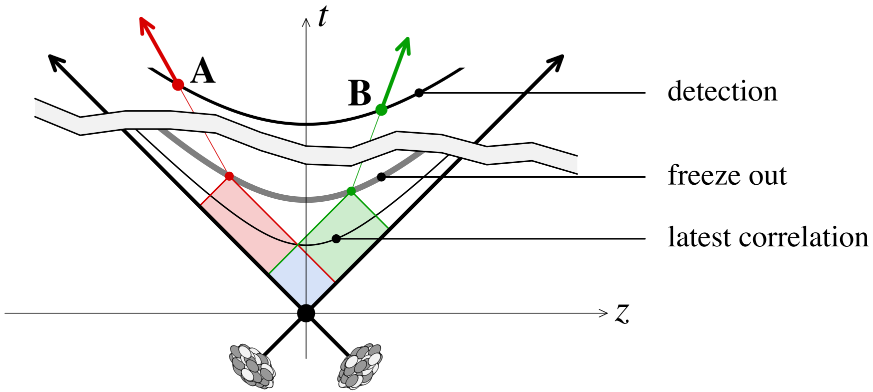
NEW

Baseline



- ➢ Deviation from Skellam baseline
- ➢ EPOS agrees with ALICE data but HIJING deviates significantly
- ➢ **Baryon number conservation?**
  - **ALICE data:** Long range correlations, $\Delta y = \pm$**2.5 unit or longer** → **Earlier in time**
  - **HIJING:** Short range correlations, $\Delta y = \pm$**1 unit** → **Lund string fragmentation?**

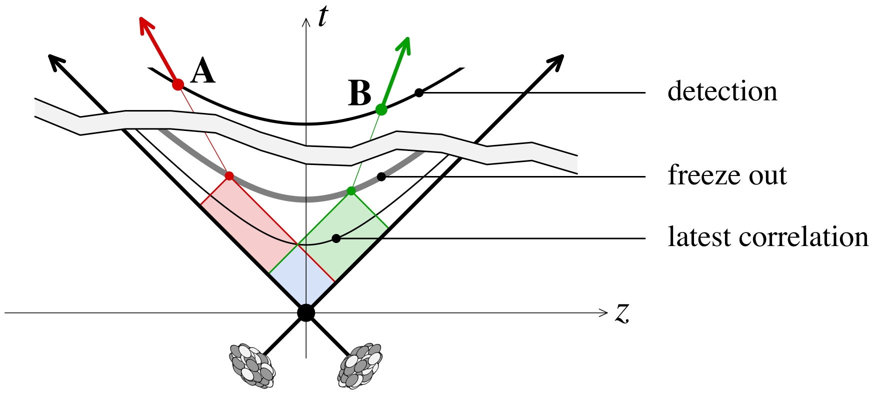
Lund String Fragmentation



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

- Only early correlations can be long range in rapidity

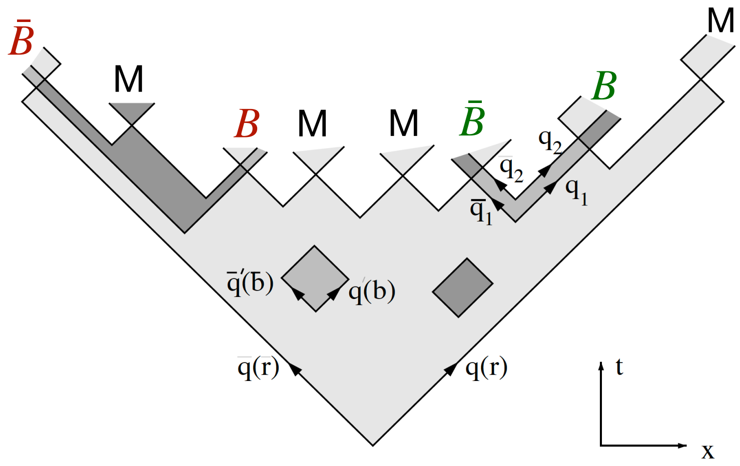
Lund String Fragmentation



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

- Only early correlations can be long range in rapidity

Popcorn mechanism



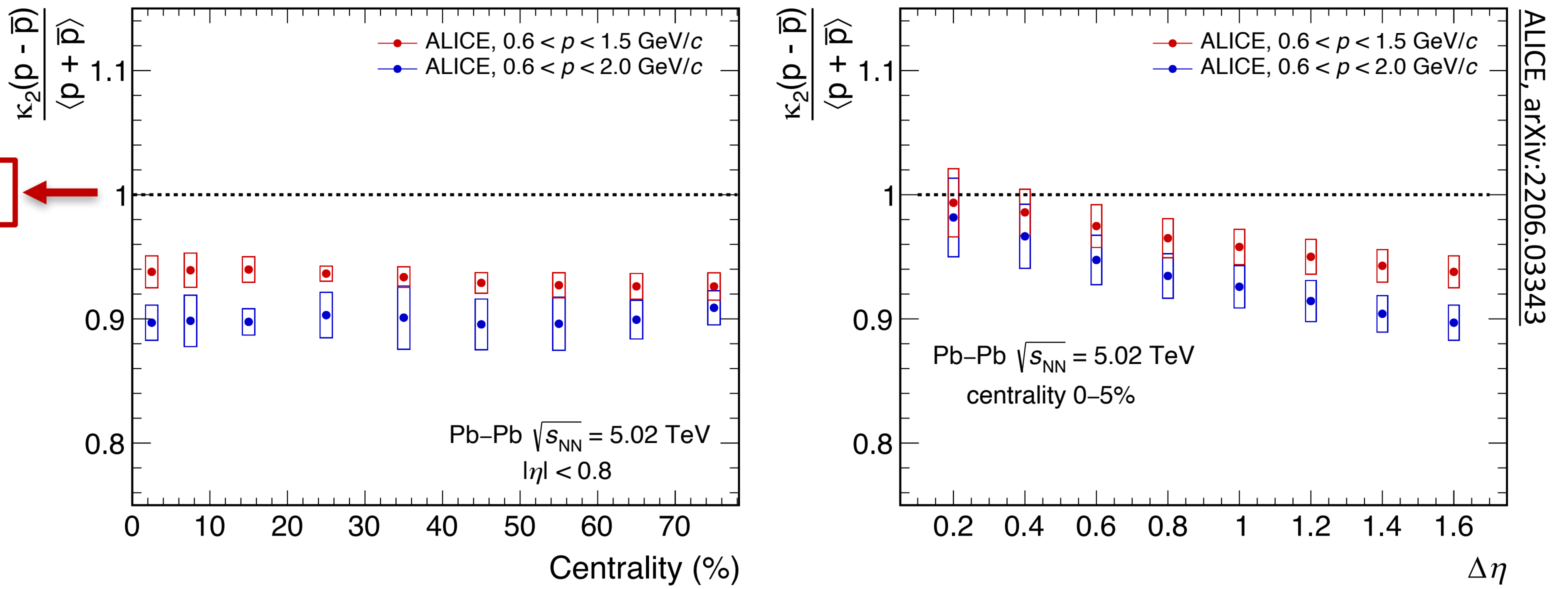
- Baryon production:
  → $q\bar{q}$ is replaced by qq-$\bar{q}\bar{q}$ pair

B. Andersson, G. Gustafson, G. Ingelman, T. Sjostrand
Phys.Rept. 97 (1983) 31-145

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

NEW

Baseline

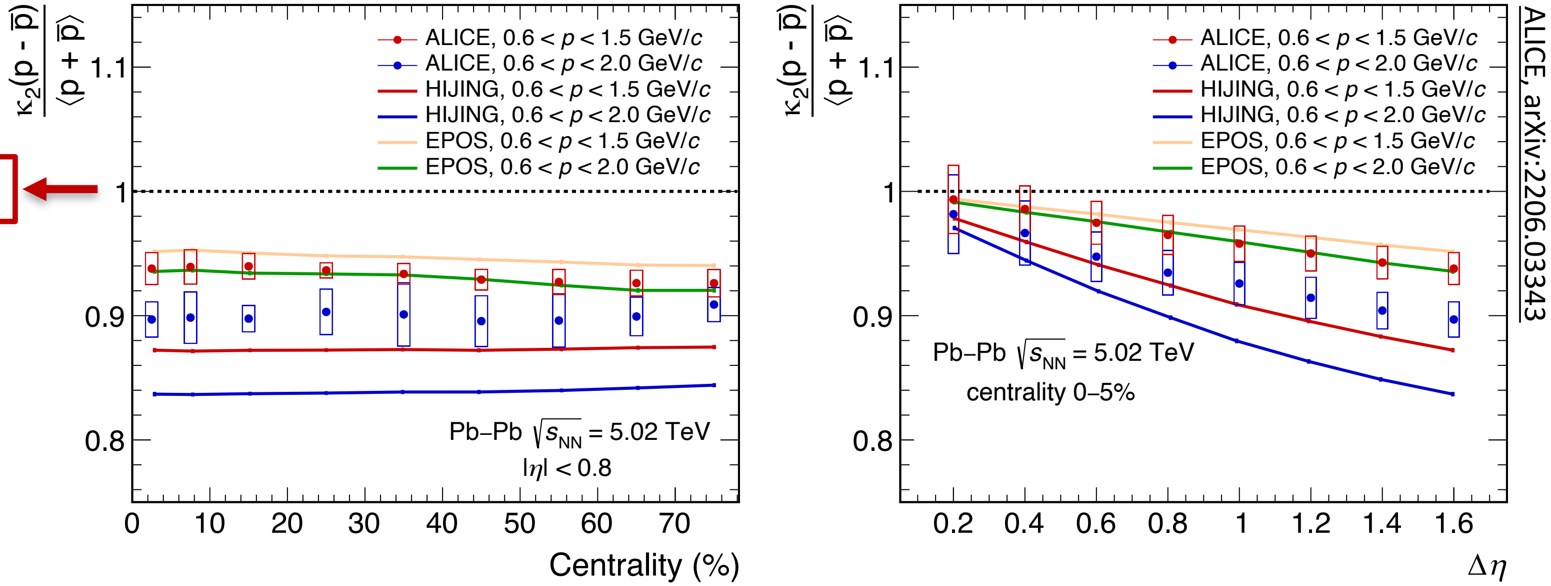


- **Consistent with the baryon number conservation picture**
  - Increase in fraction of accepted $p, \bar{p}$ → stronger constraint of fluctuations due to baryon number conservation

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

NEW

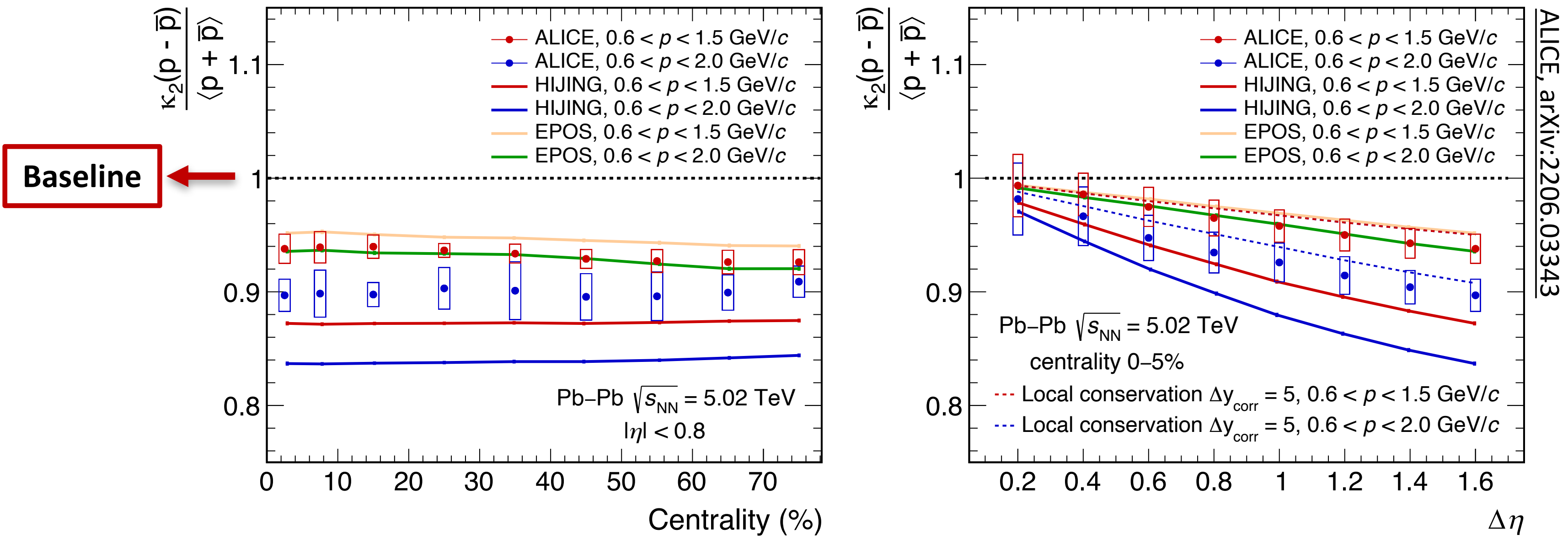
Baseline



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

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

NEW

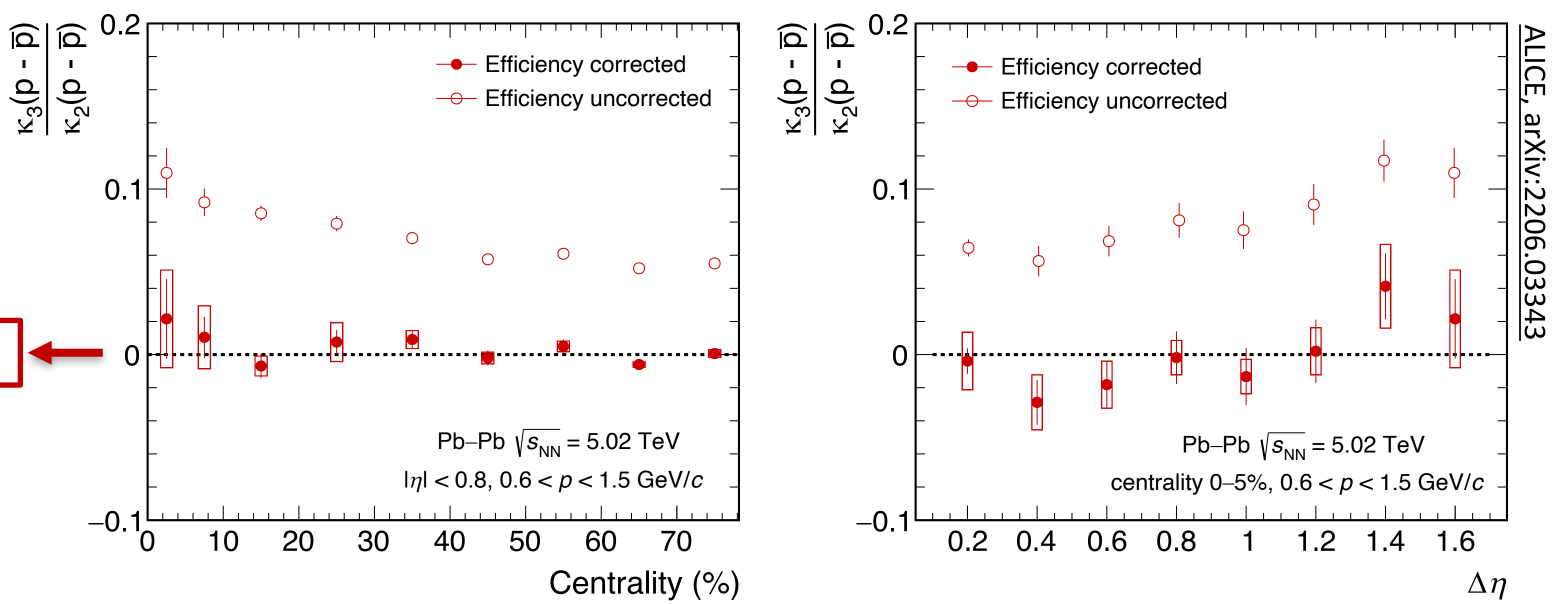


- **Consistent with the baryon number conservation picture**
  - Increase in fraction of accepted $p, \bar{p}$ → stronger constraint of fluctuations due to baryon number conservation
- **EPOS** & HIJING show this drop qualitatively

3rd order cumulants of net-p

NEW

Baseline

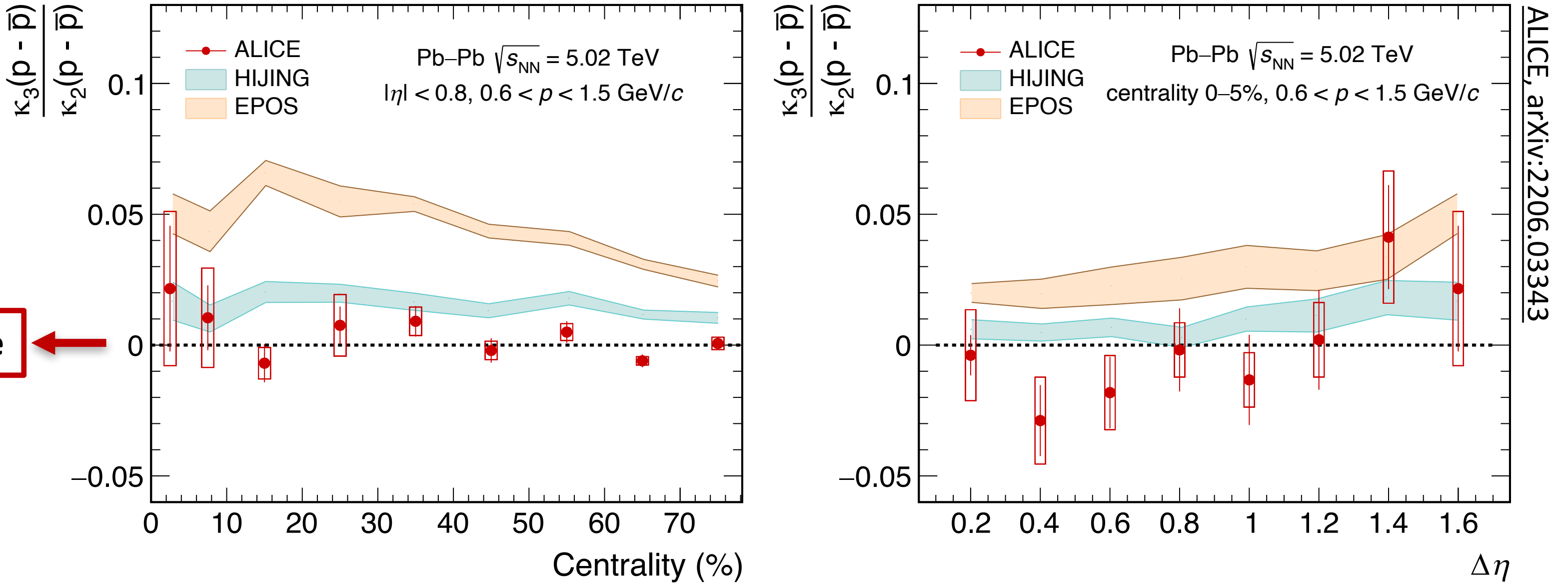


- Data agree with Skellam baseline “0” → **μ_B is very close to 0** at LHC energies
- Achieved precision of **better than 4%**

3^{rd} order cumulants of net-p

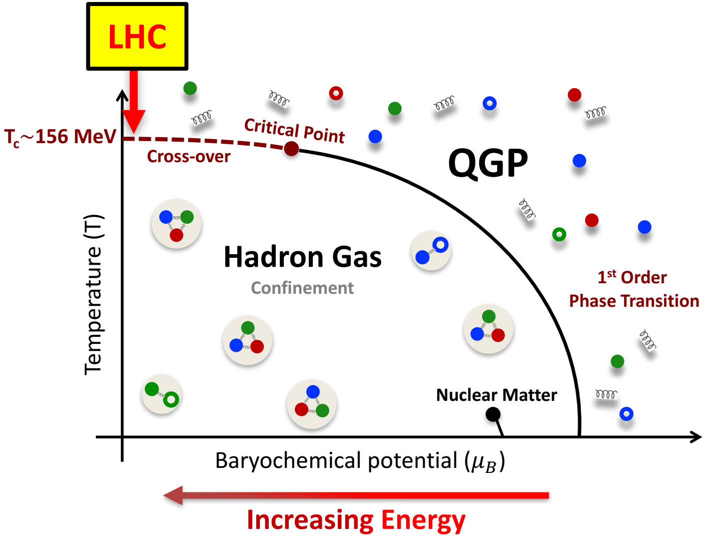
NEW

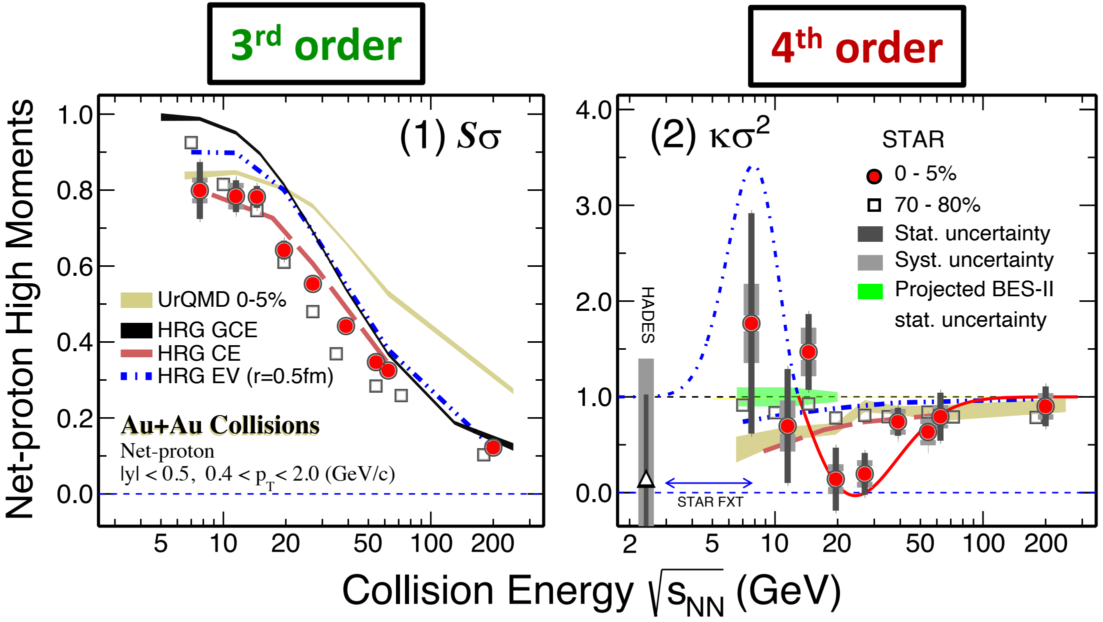
Baseline

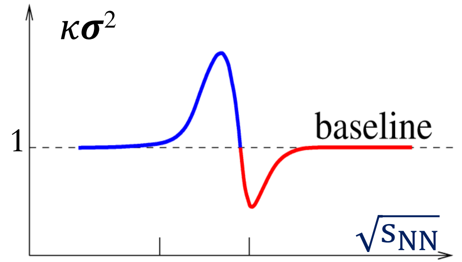


- Data agree with Skellam baseline "0" → **μ_B is very close to 0** at LHC energies
- Achieved precision of **better than 4%**
- **EPOS and HIJING deviate from "0"**
  - They conserve global charge but **$p/\bar{p}$ deviates from unity**: 1.025±0.004 (EPOS), 1.008±0.002 (HIJING)
  - **Volume fluctuations** for 2^{nd} and 3^{rd} order cumulants are not negligible

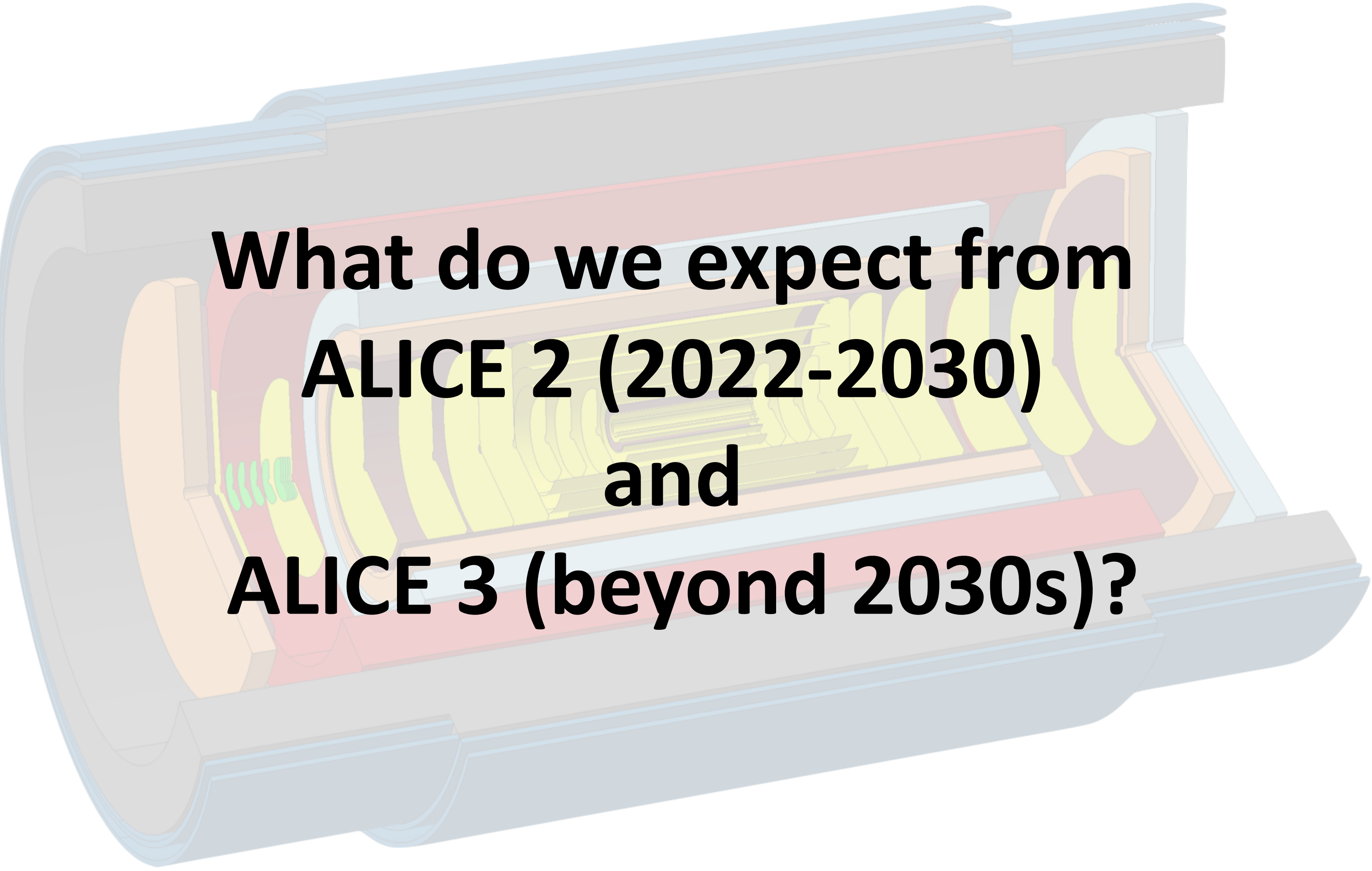
From STAR to LHC current status





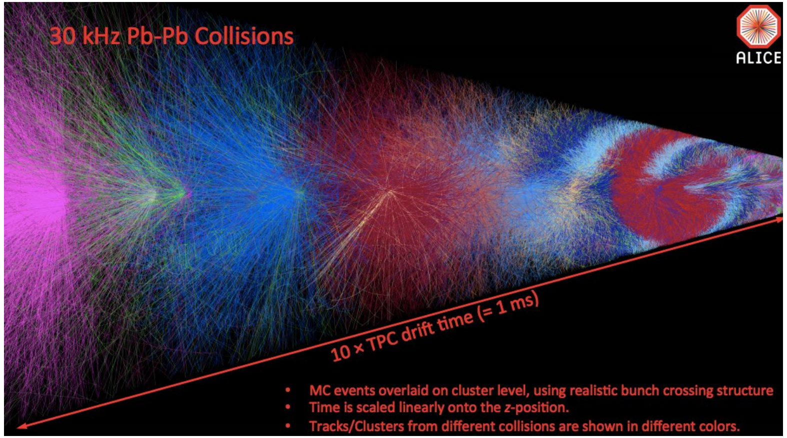


What do we expect from ALICE 2 (2022-2030) and ALICE 3 (beyond 2030s)?



Future of conserved charge fluctuations in ALICE

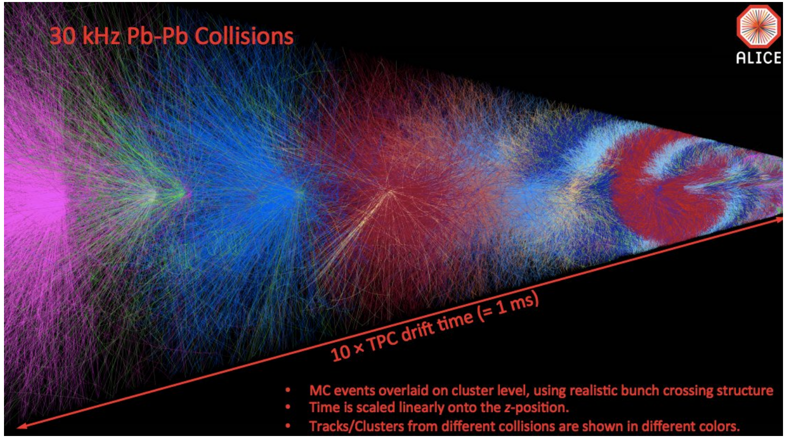
ALICE 2 (2022-2030)



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

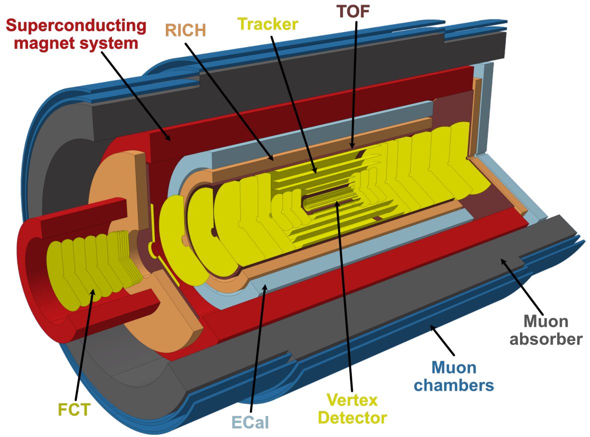
Future of conserved charge fluctuations in ALICE

ALICE 2 (2022-2030)



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

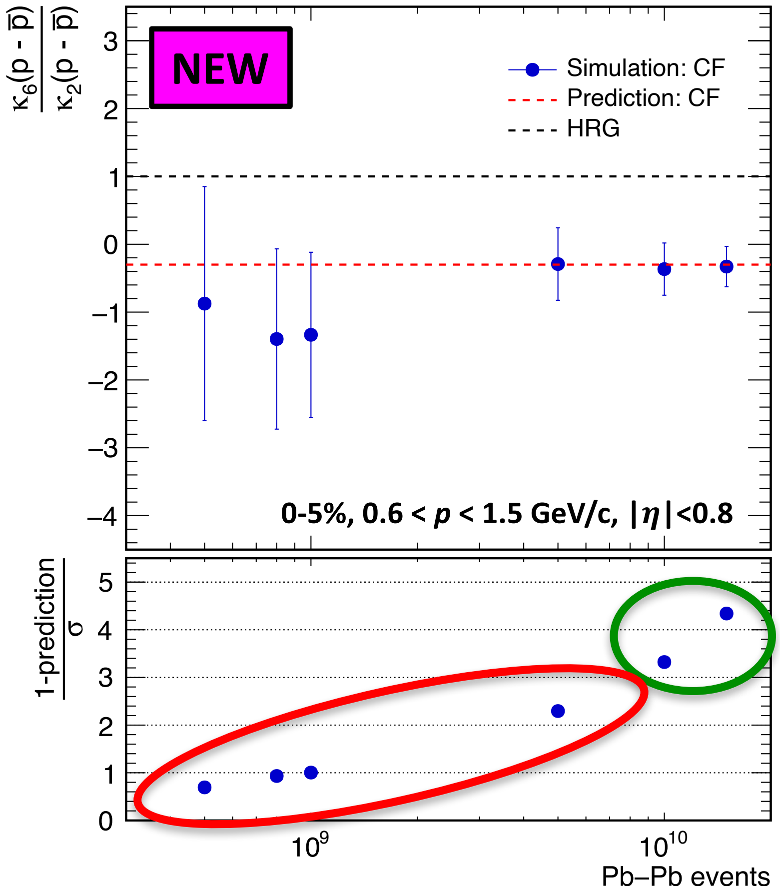
ALICE 3 (beyond early 2030s)



ALICE, CERN-LHCC-2022-009

- ✓ **High statistics** → O (10^9) billion events
- ✓ **Large acceptance** → |η|< 4
- ✓ **High PID purity** → 0.3 < p_T < 7 GeV/c
- ✓ **High efficiency** → ~95%
- ✓ **Excellent vertexing** → O (3μm) resolution

Criticality in ALICE 2 and 3: 6th and higher order cumulants



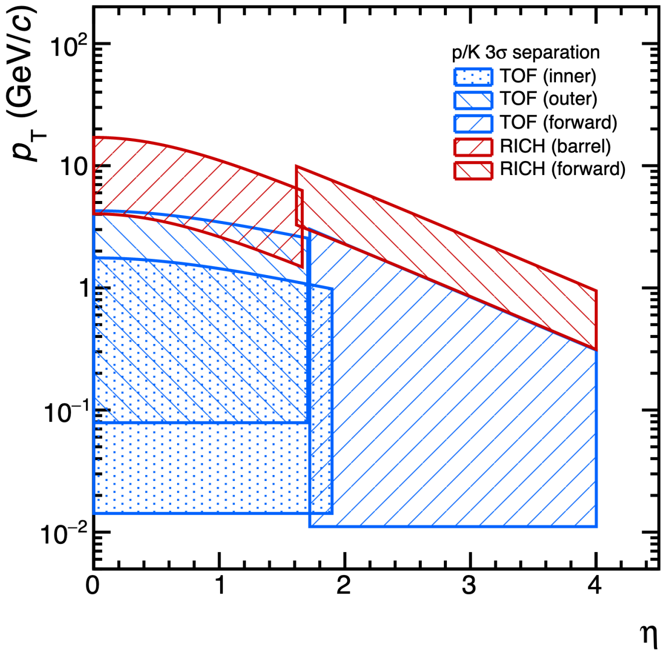
- Simulation of the Critical Fluctuations (CF) is based on PQM model
  G. A. Almasi, B. Friman, and K. Redlich, Phys. Rev.D96 (2017), 014027
- **ALICE 2:**
  → More than 5 billion central Pb-Pb collisions is required
- **ALICE 3:**
  → **x3 larger statistics:** $>4\sigma$ significance with ALICE 2 acceptance

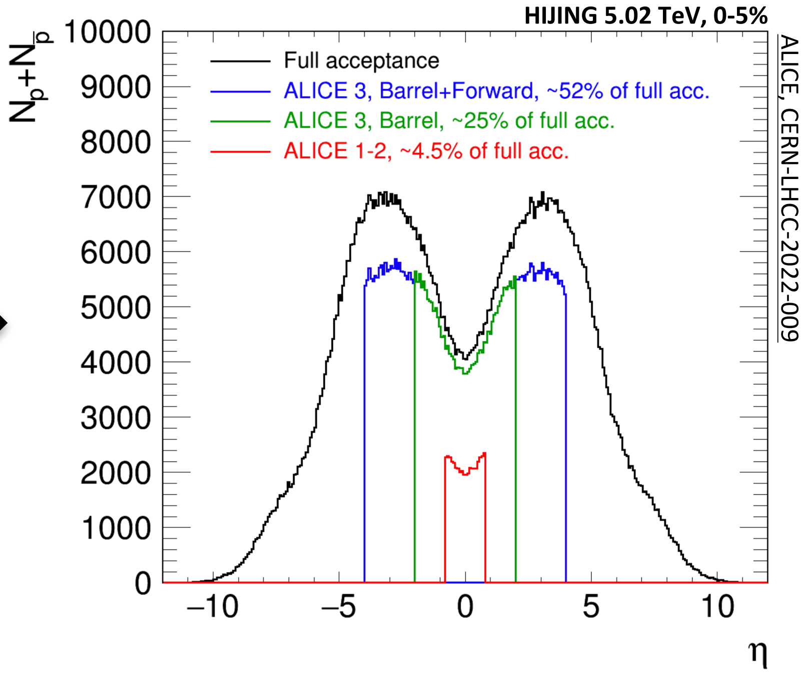
Net baryon and net strangeness fluctuations
for $|\eta| \leq 4$ and for 6th and higher order

ALICE 3: High PID purity in large kinematic acceptance

NEW

- ✓ **Significant increase in the number of measured protons**
- ✓ **Larger acceptance:** in p_T and η: (0.3 < p < 7 GeV/c, $|\eta|$<4)
- ✓ **Smaller systematics:** high PID purity and efficiency

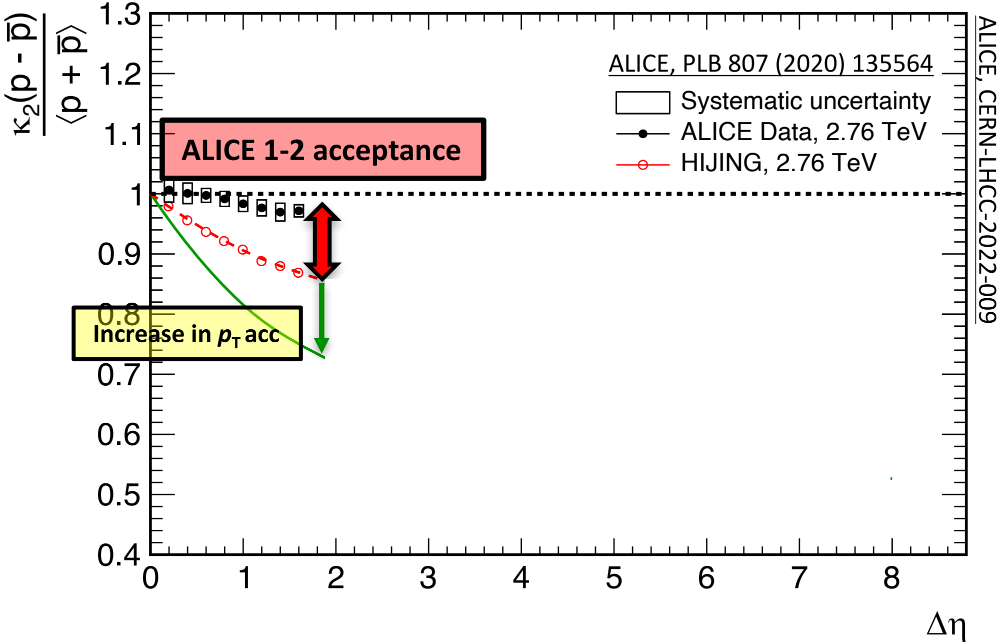




High precision & more differential measurements

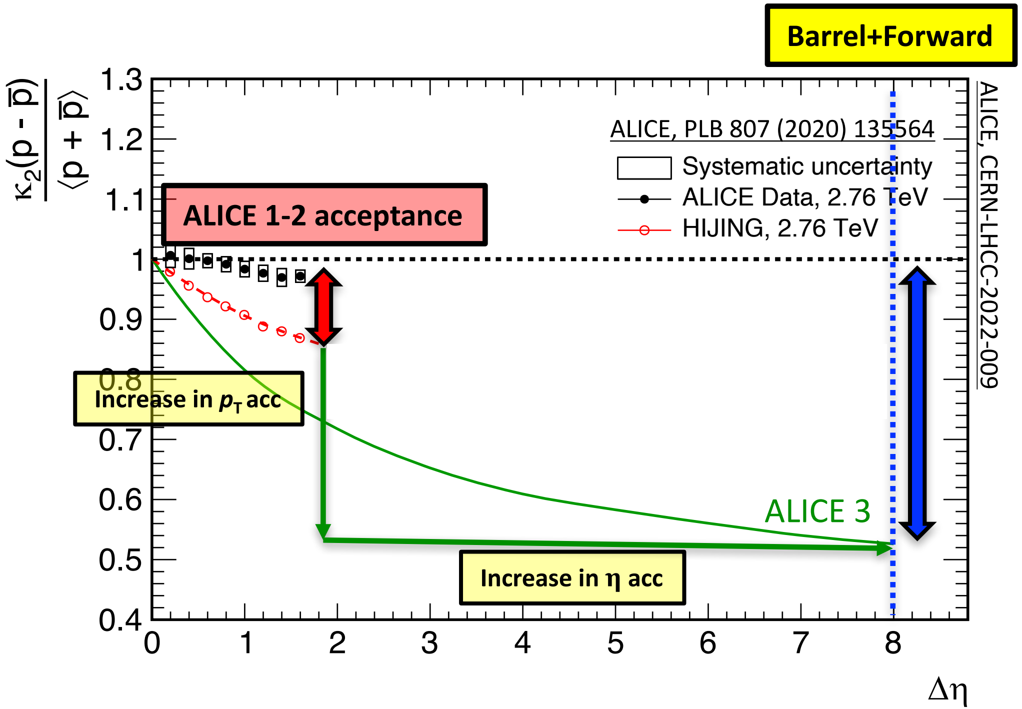
ALICE 3: Correlation length → Baryon number conservation

NEW



ALICE 3: Correlation length → Baryon number conservation

NEW



- Precise mapping of **correlation length of conserved charges, B, S, C**
- **Constraining individual dynamic signals** such as volume fluctuations, baryon number conservation, thermal blurring, annihilation, effect of hydrodynamic evolution etc.

Summary

What did we learn from ALICE 1?

- **Net-Q,S fluctuations:** → resonance contributions
- **Net-p fluctuations:**
  - ✓ **1st order:** $T_{fo}^{ALICE} \sim T_{pc}^{LQCD}$
  - ✓ **2nd order:** Deviation from Skellam baseline is due to baryon number conservation
    - Long range correlations originating from **early phase of the collision**
  - ✓ **3rd order:** Up to 3rd order ALICE data agree with the LQCD expectations
    - μ_B **is very close to 0** at LHC energies

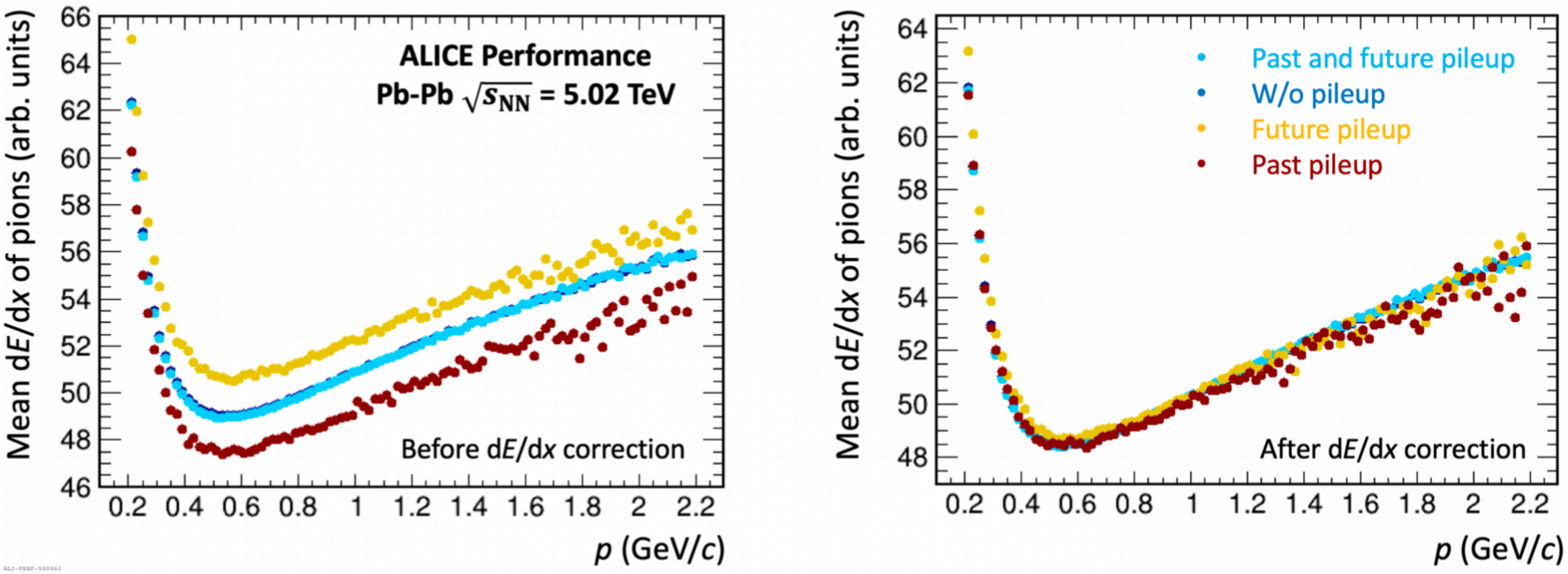
What do we expect from ALICE 2-3?

- **Criticality signals at 6th and higher order cumulants for B and S**
- Constraining **individual dynamic signals**
- **Correlation length** of conserved charges: B, S, C
- …

BACKUP

Effect of event pileup

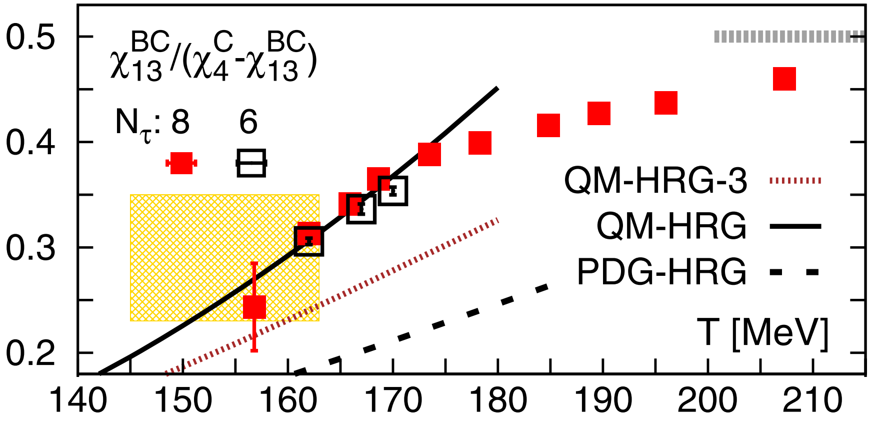
NEW

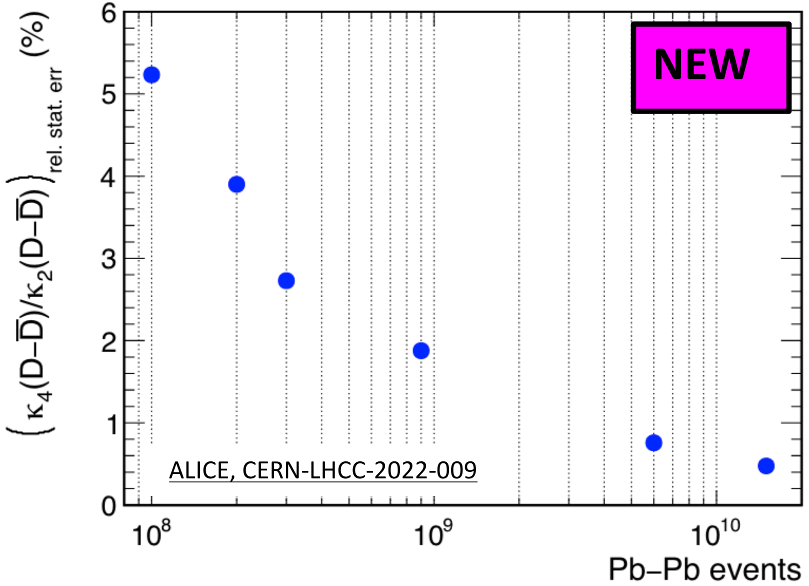


M. Arslandok, E. Hellbär, M. Ivanov, R.H. Münzer and J. Wiechula, Particles 2022, 5(1), 84-95}

ALICE 3: Net-charm fluctuations

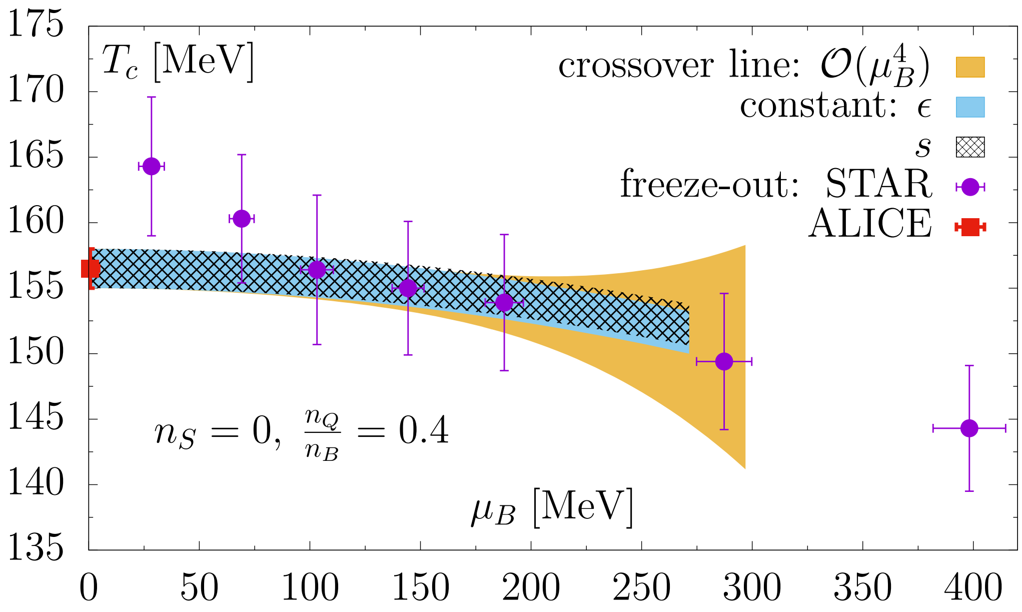
A. Bazavov et.al. Phys.Lett.B 737 (2014) 210-215





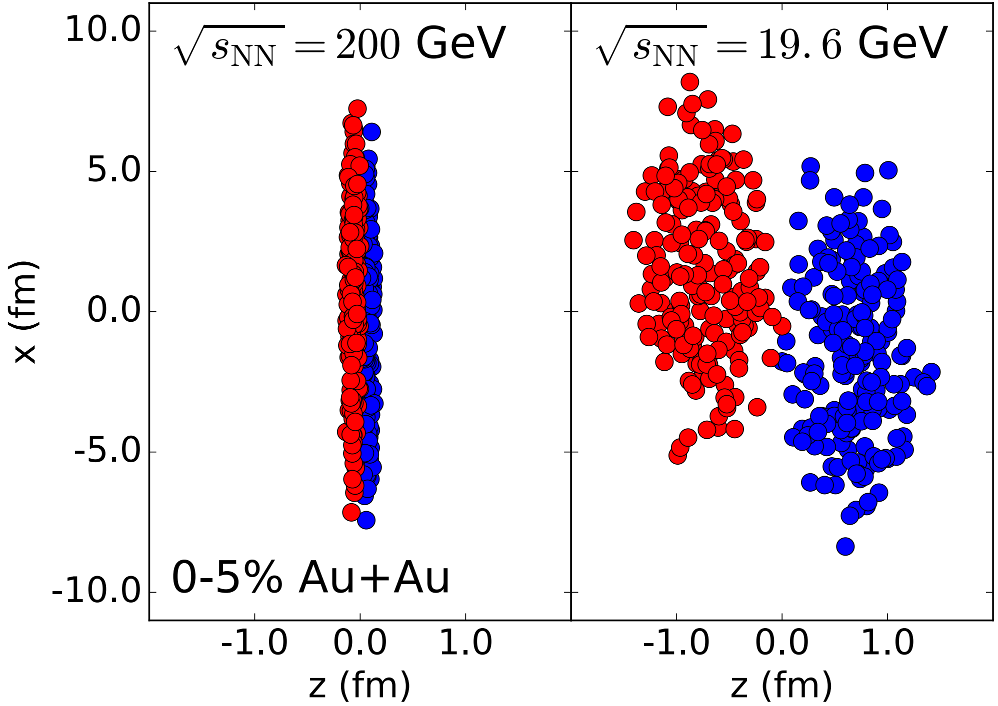
- **2^{nd} order** → **Correlation length of charm**
- **4^{th} order** → Close to T_{pc} charmed baryon fluctuations are about 50% larger than expected in a HRG based on known charmed baryon resonances (PDG-HRG) → **missing states of QCD**

$$T_{\mathrm{pc}} = 156.5 \pm 1.5 MeV \approx T_{\mathrm{fo}}^{\mathrm{ALICE}}$$



A. Andronic et.al. Nature 561 (2018) 321
HotQCD Collaboration, Phys.Lett. B795 (2019) 15,
S. Borsanyi et.al. Phys. Rev. Lett. 125, 052001 (2020)

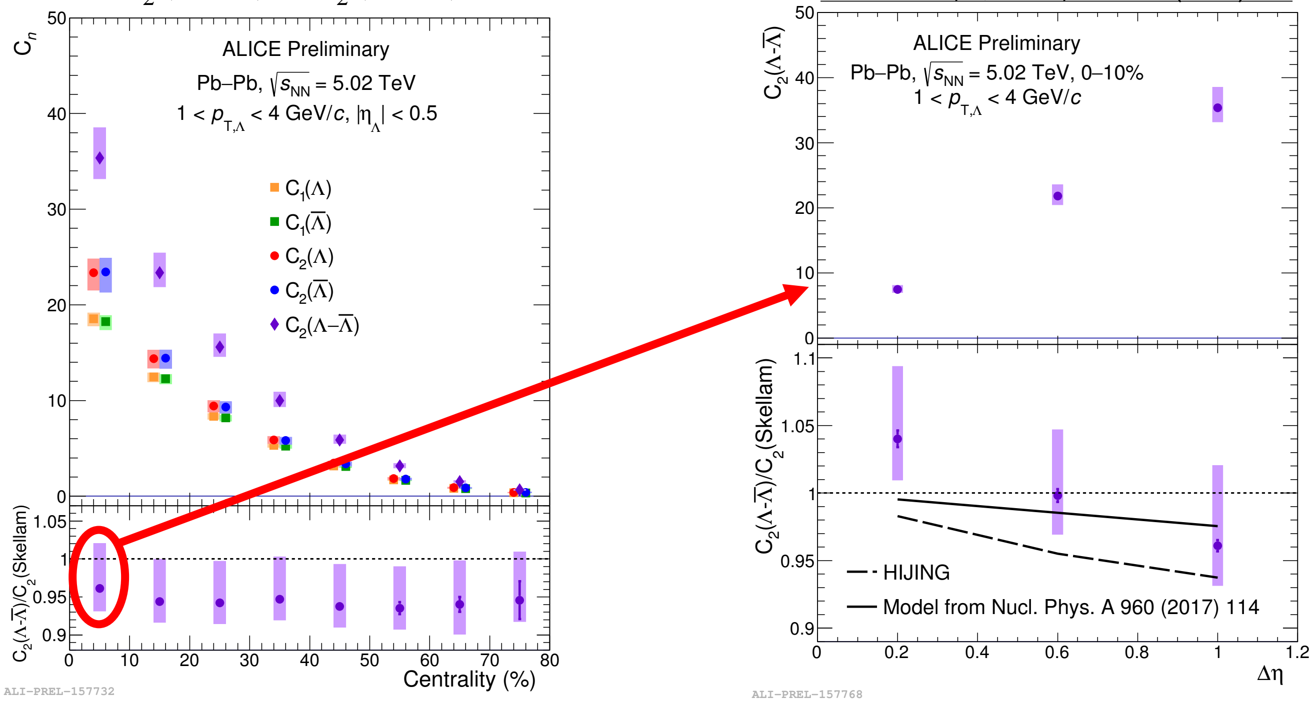
Phys. Rev. C 97, 024907 (2018)



2^{nd} order Net-Λ cumulants

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

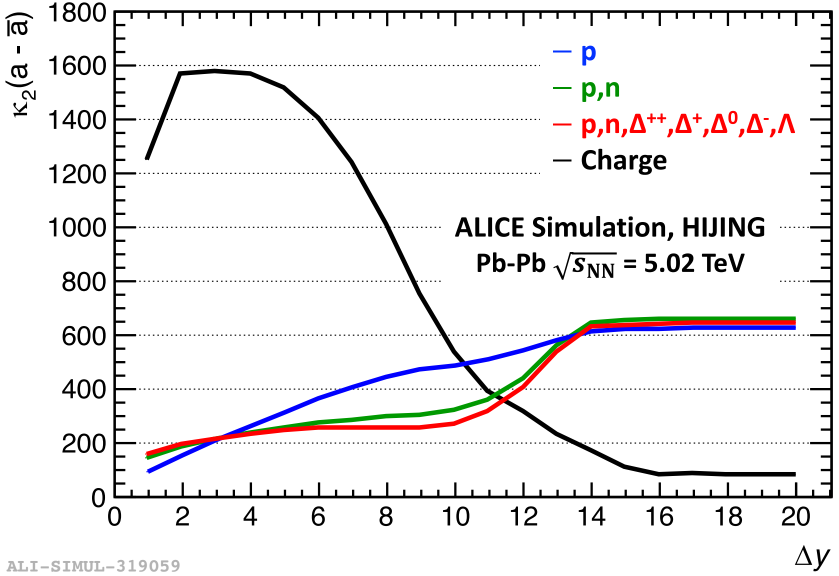
Alice Ohlson, QM2018, NPA 982 (2019) 299

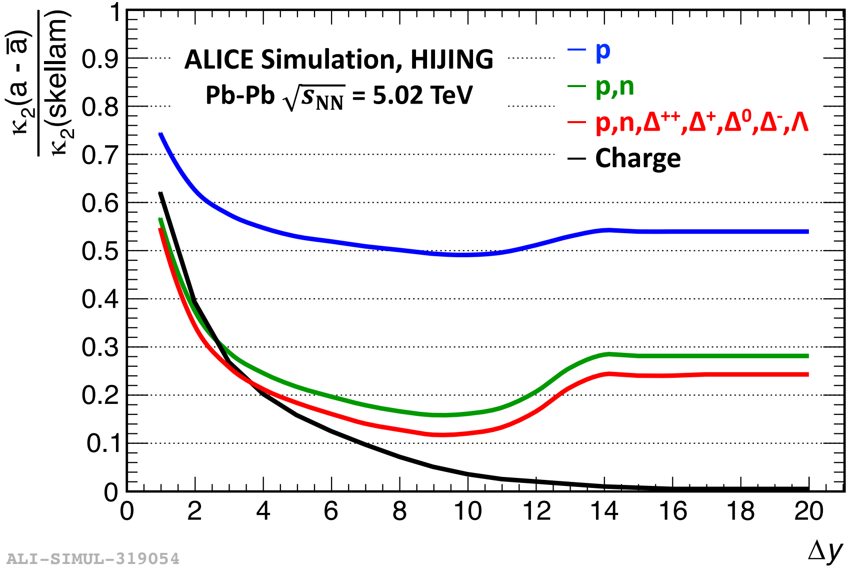


- Similar trend as for **net-p**
- Better precision is needed to disentangle global vs local conservation laws

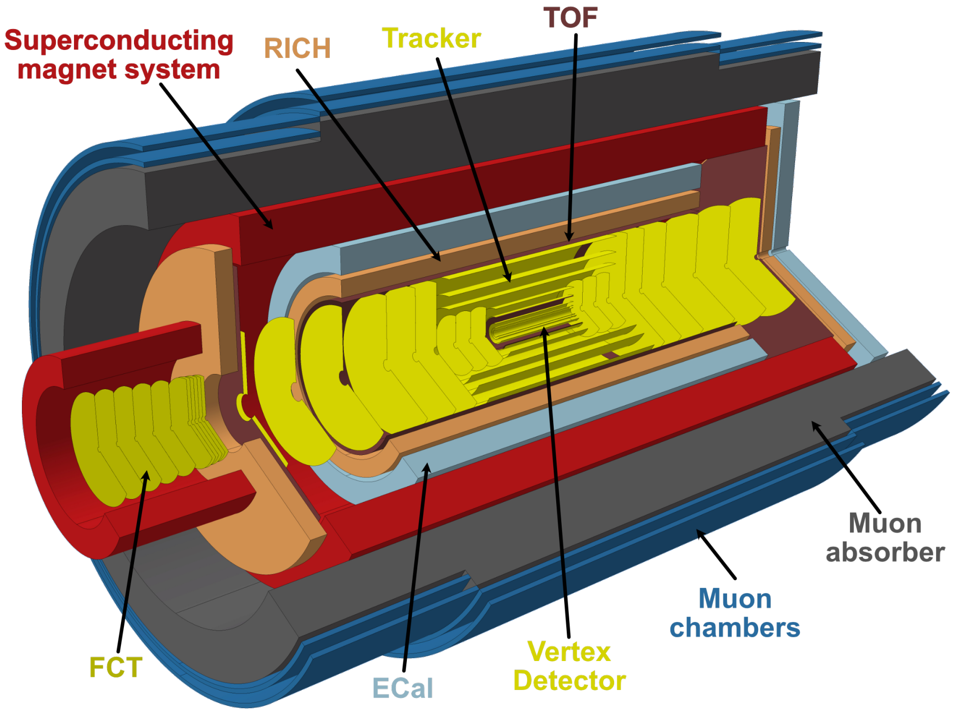
2nd order cumulants in full phase space

NEW





ALICE 3



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

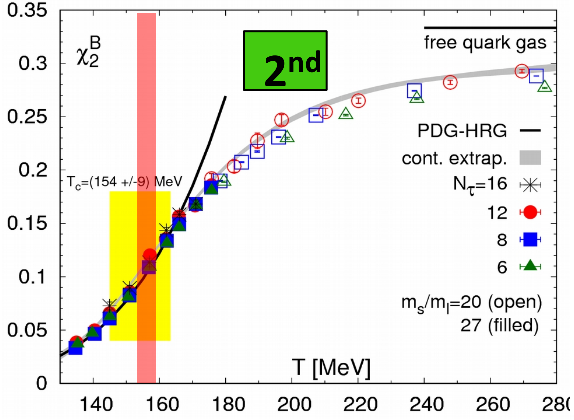
⟹ **Fast** to sample large luminosity
→ 50-100 x Run 3/4 → MHz level

⟹ **Large acceptance**
→ $|\eta|<1.4$ (central barrel), $|\eta|<4$ (total)

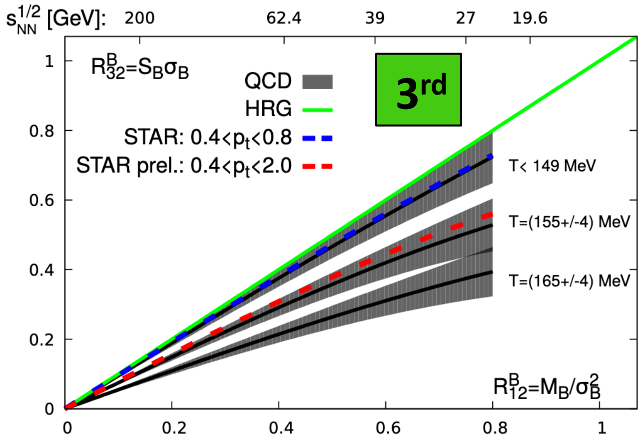
⟹ **Excellent spatial resolution** for tracking and vertexing
→ Innermost layers: σ < 3 µm
→ Outer layers: σ ~5 µm

⟹ **Precise time measurements** for PID
→ $\sigma \sim$ 20 ps

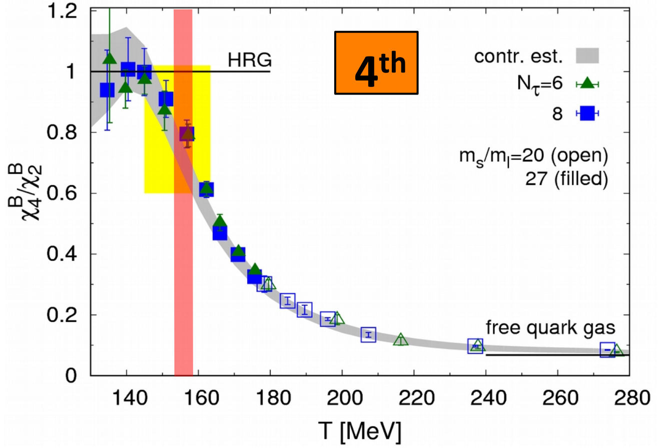
Link to LQCD



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]

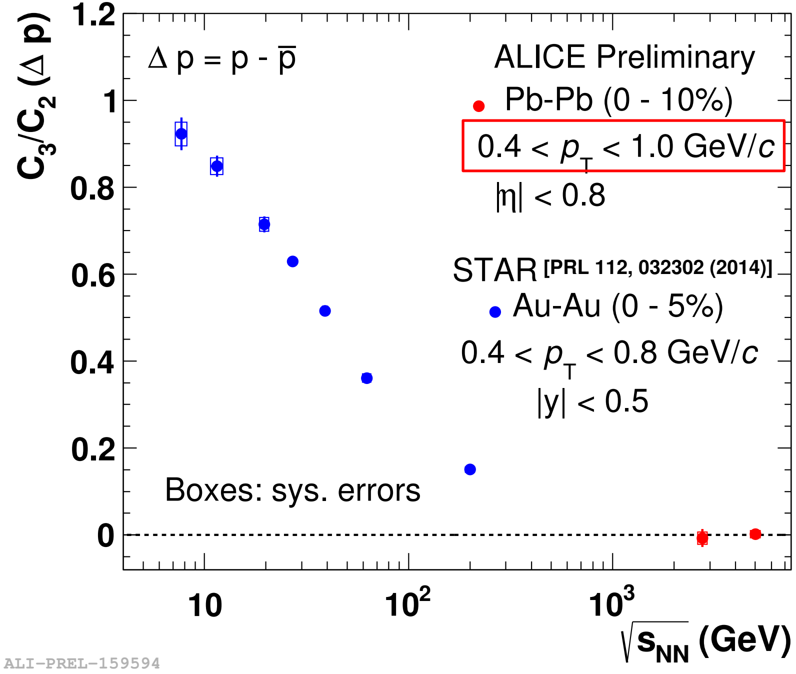


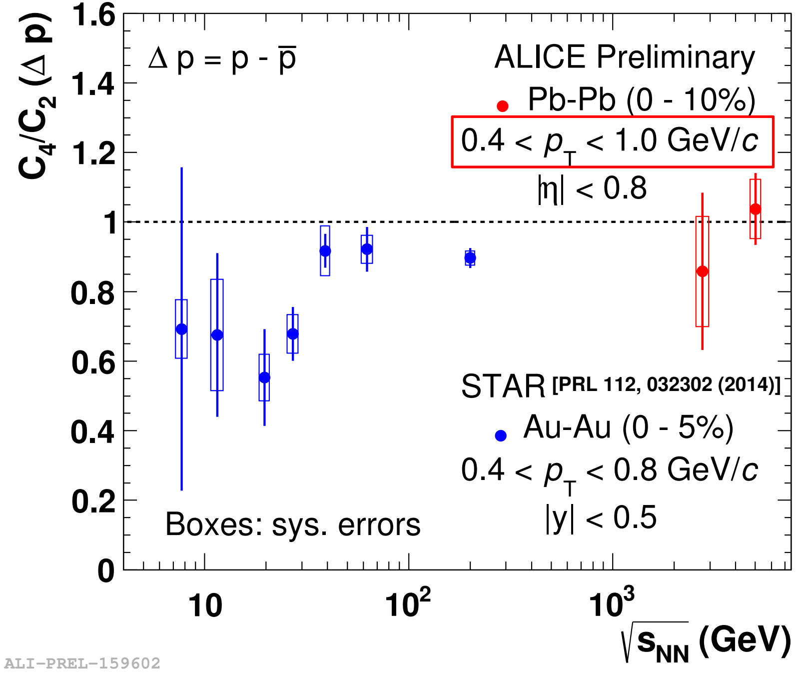
$s_{NN}^{1/2}$ [GeV]: 200 62.4 39 27 19.6
$R_{32}^B=S_B\sigma_B$
3rd
QCD
HRG
STAR: 0.4<p_t<0.8
STAR prel.: 0.4<p_t<2.0
T< 149 MeV
T=(155+/-4) MeV
T=(165+/-4) MeV
$R_{12}^B=M_B/\sigma_B^2$



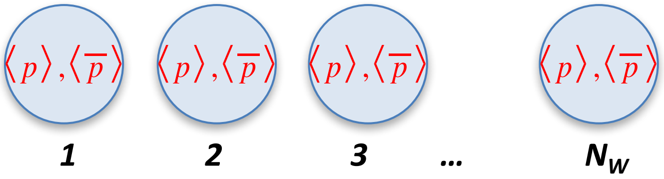
χ_4^B/χ_2^B
4th
HRG
contr. est.
N_τ=6
8
m_s/m_l=20 (open)
27 (filled)
free quark gas
T [MeV]

Nirbhay Kubera, QM18, NPA 982 (2019) 851



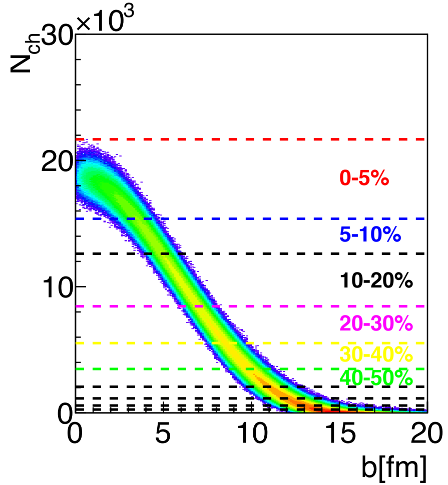


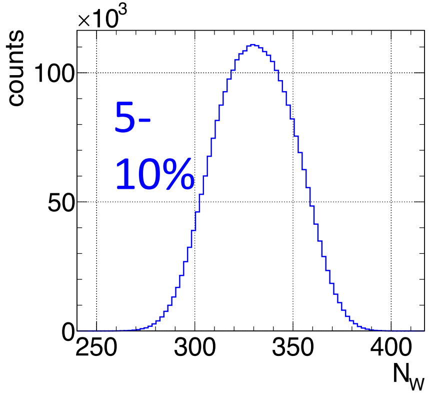
Volume Fluctuations



- N_W fluctuates with **MC Glauber initial conditions**
- Each source is treated **Grand Canonically**
- Mean proton multiplicities taken **from real data**
- **Centrality selection like in experimental data**

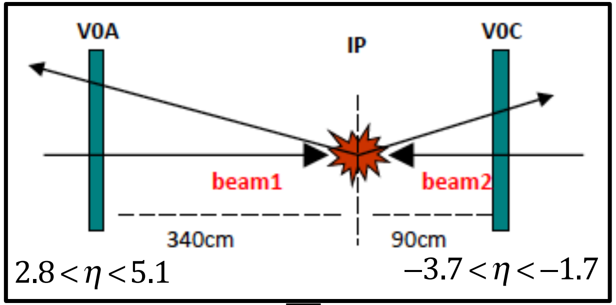
- **Expectxed results without volume fluctuations**
  - Particles: $k_n = N_w \langle n \rangle = \langle p \rangle = \langle \bar{p} \rangle$
  - Net-particles: $k_n = \langle p \rangle + (-1)^n \langle \bar{p} \rangle$

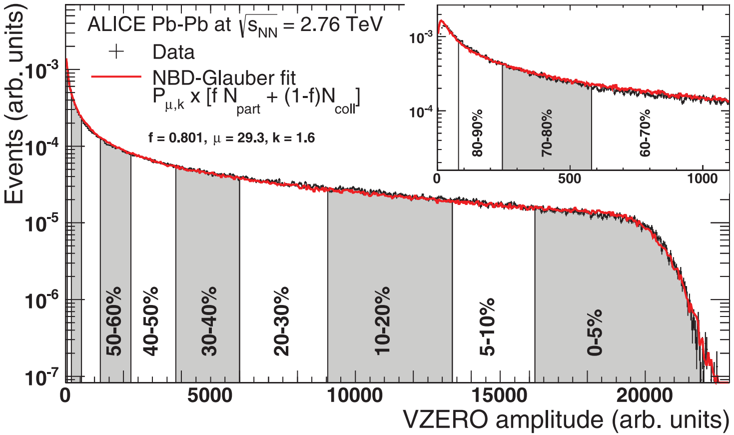


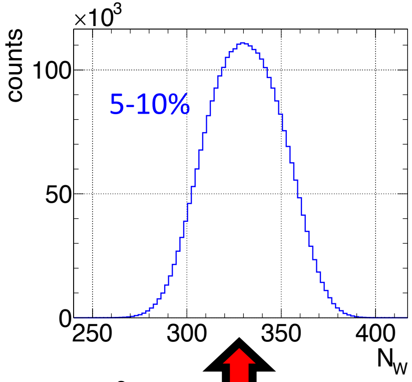


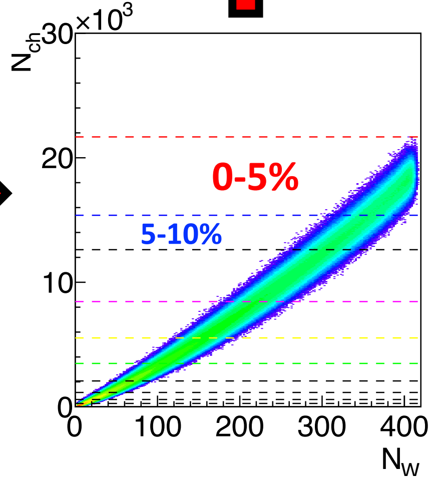
Volume Fluctuations

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



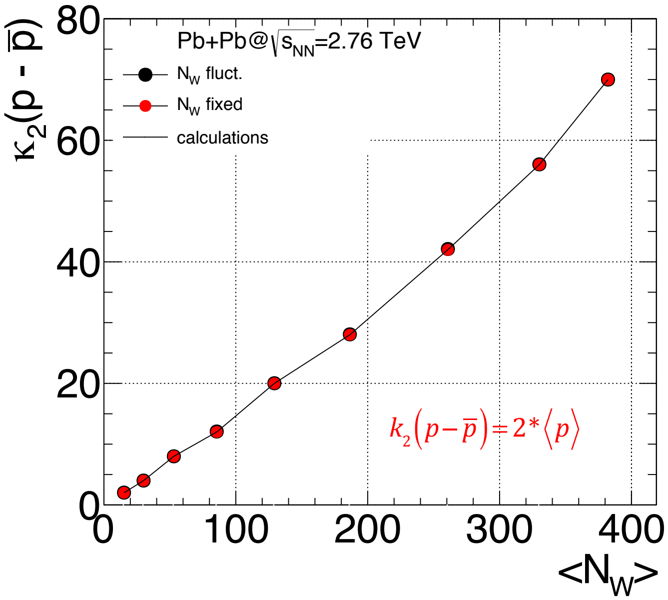


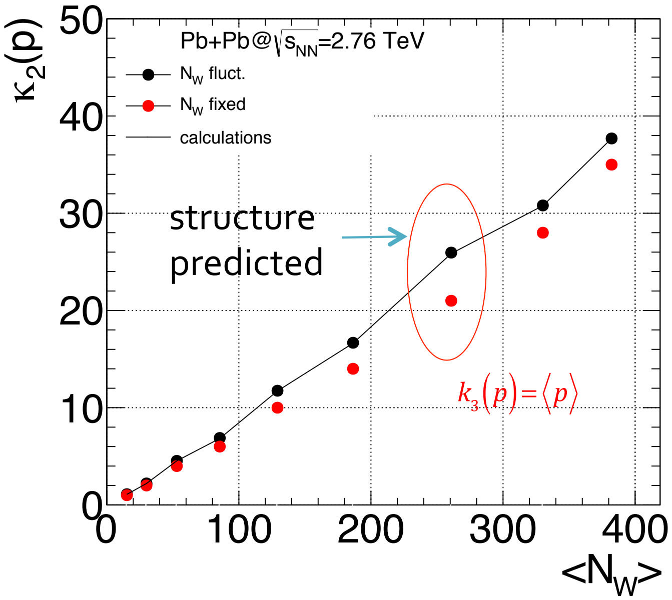




Volume Fluctuations

150*10⁶ Events





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

vanishes for ALICE

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

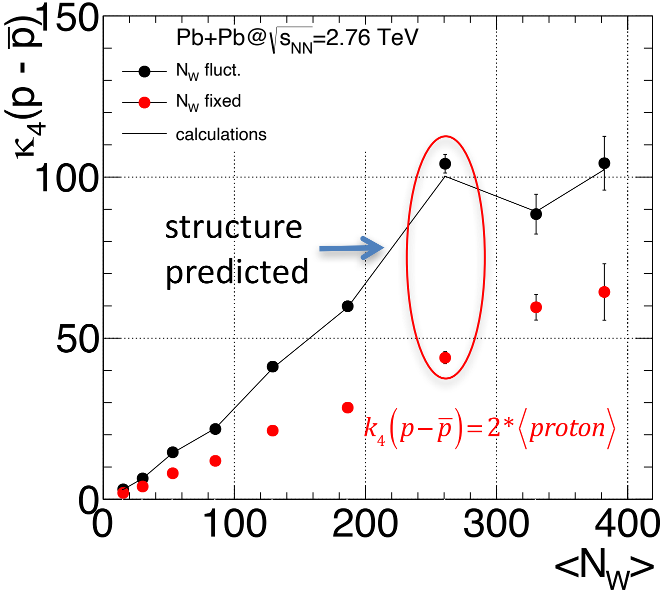
does not vanish

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

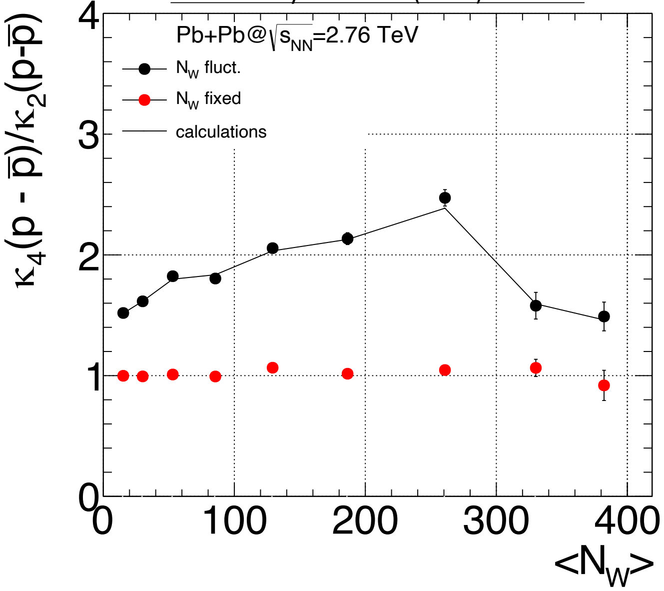
P. Braun-Munzinger, A. Rustamov, J. Stachel, Nuclear Physics A 960 (2017) 114–130

Volume Fluctuations

$150*10^6$ Events



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



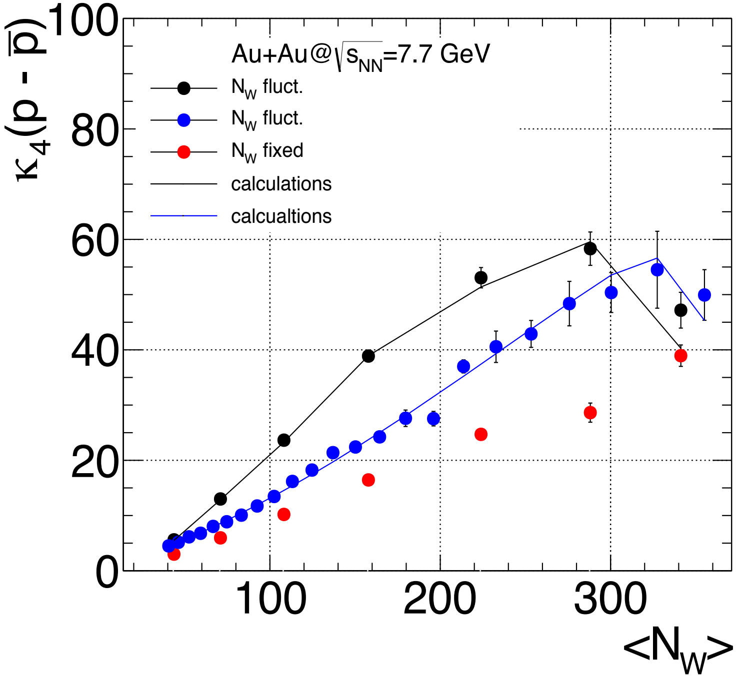
$$k_4(p-\bar{p}) = \langle N_w \rangle k_4(n-\bar{n}) + 3k_2(n-\bar{n})^2 k_2(N_w) + \langle n-\bar{n} \rangle (\ldots)$$

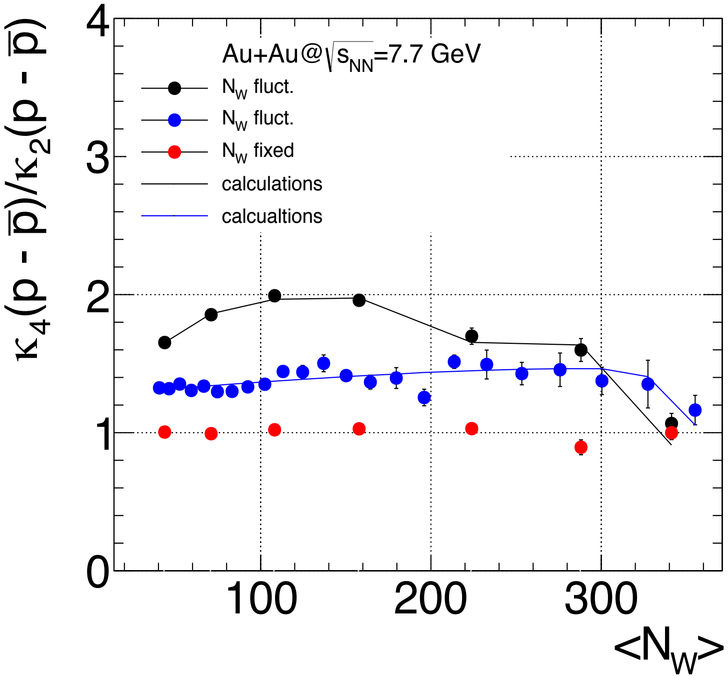
$n, \bar{n}$ → from single wounded nucleon

vanishes for ALICE

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

Volume Fluctuations

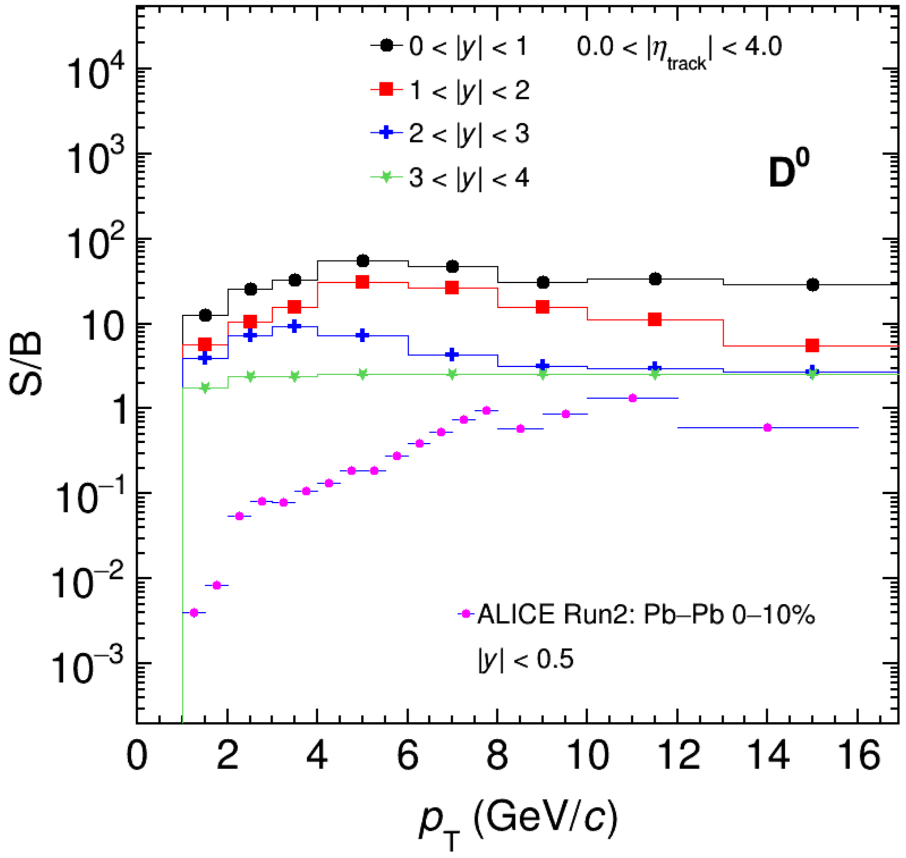




P. Braun-Munzinger, A. Rustamov, J. Stachel, Nuclear Physics A 960 (2017) 114–130

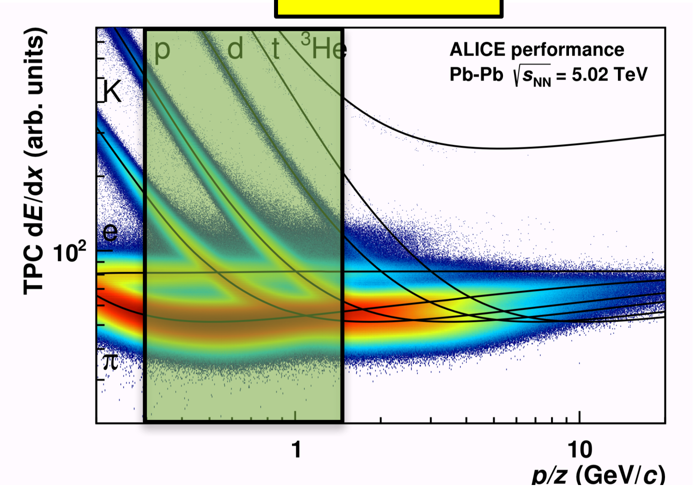
Excellent vertexing: Charm fluctuations

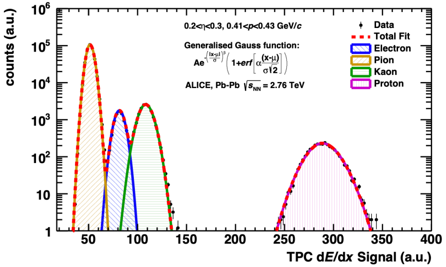
- **Barrel PID improves S/B by a factor ∼10**
  → Close to 'ideal PID'
  → Much smaller systematic uncertainty
- **Net charm fluctuations for |η| ≤ 4 and up to 4th moments**

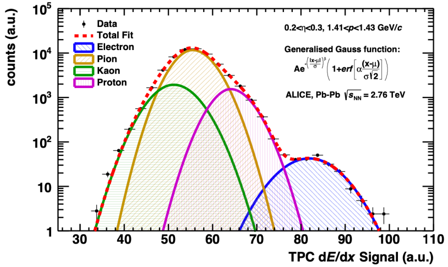


Identity Method in ALICE 3: Purity in PID

ALICE 1-2



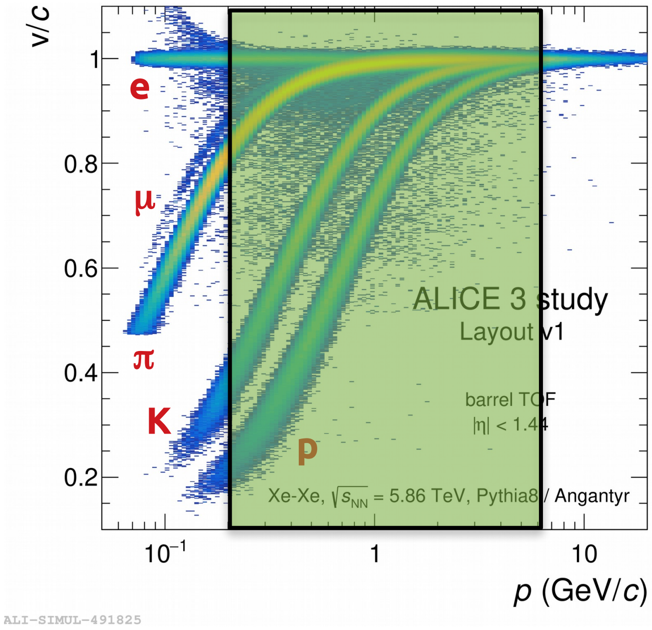




- $0.6 < p < 1.5$ GeV/c
- $p > 0.8$ GeV/c → less than one sigma separation

ALICE 3

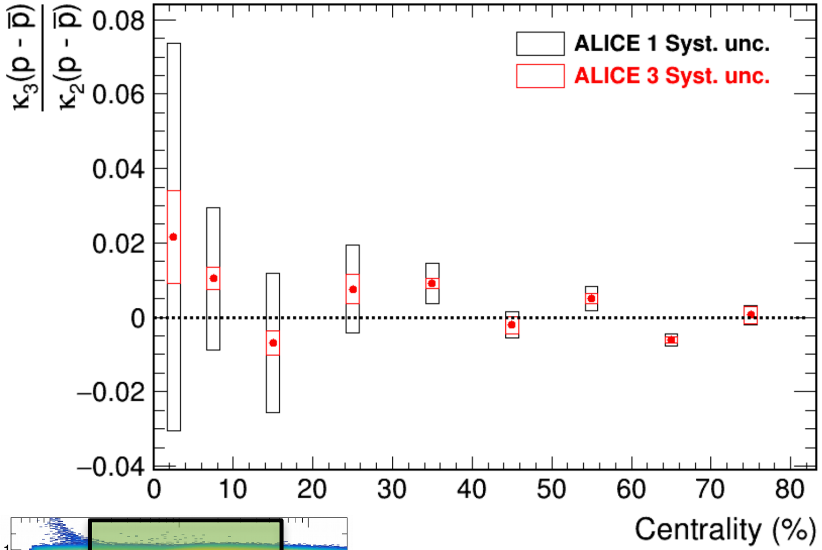
Significant improvement in the purity + IM

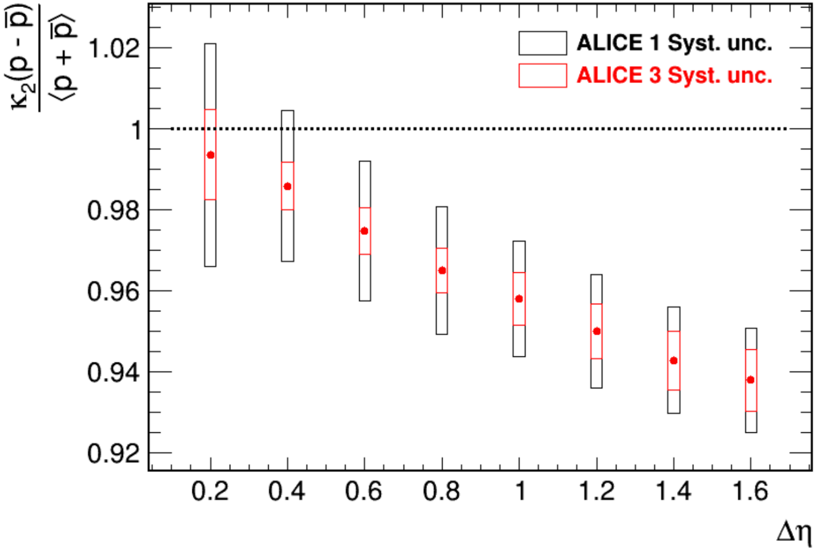


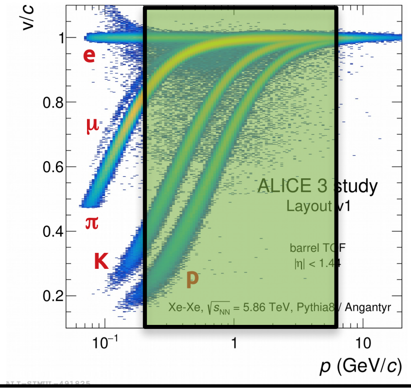
- $0.3 < p < \sim 7$ GeV/c
- No full overlap of the TOF signal

ALICE 3: Systematic uncertainties

NEW



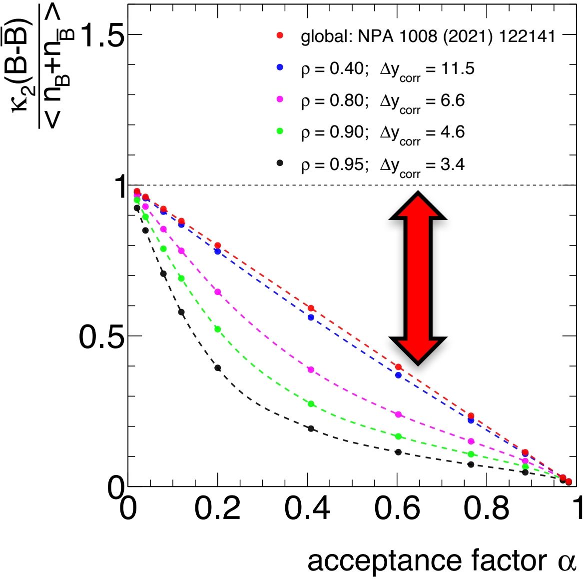


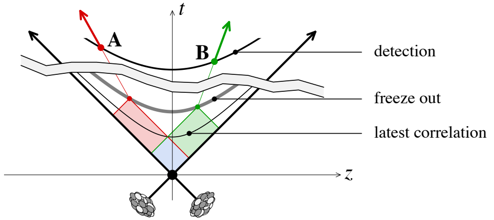


❖ **Main uncertainty is from the dE/dx fits, which will vanish in ALICE 3**
(thanks to Identity Method (IM) and improved PID)

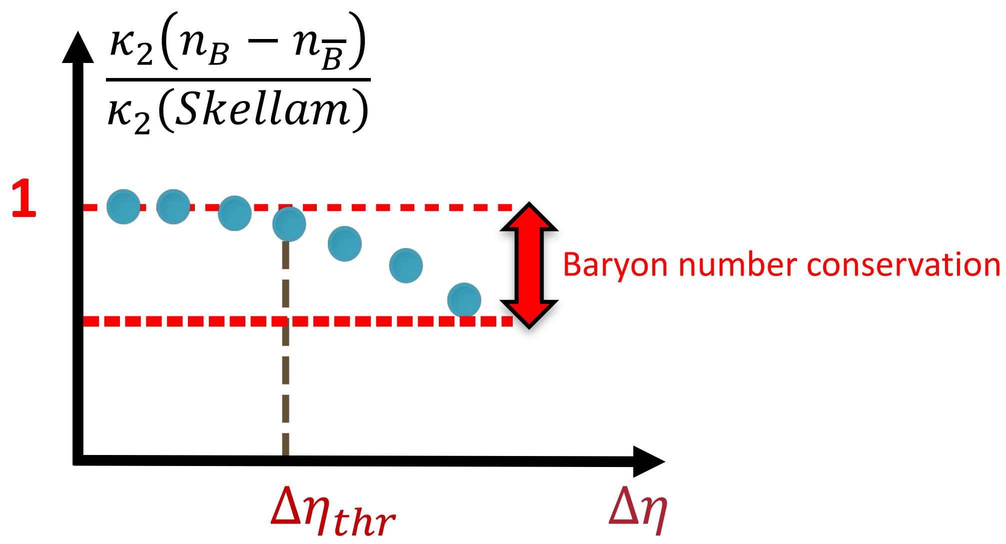
2^{nd} order cumulants of net-p: Correlation length

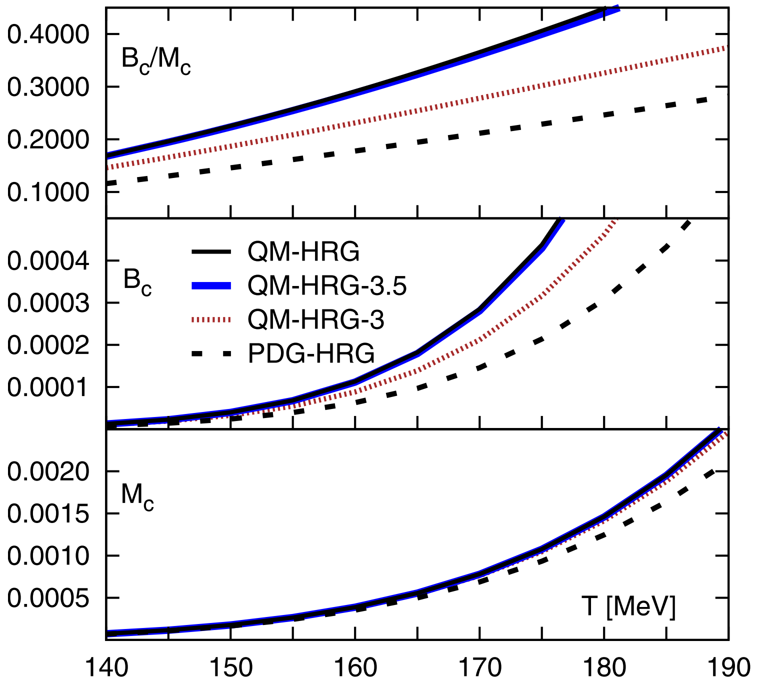
P. Braun-Munzinger, A. Rustamov, J. Stachel, to be published





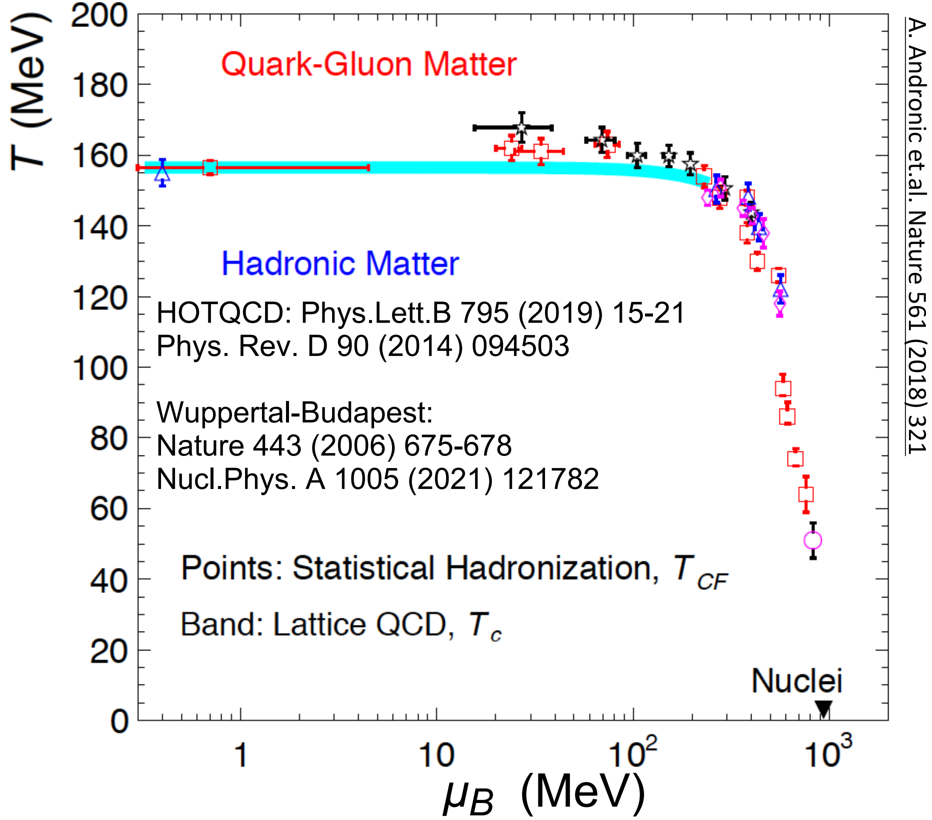
Early correlations → long range in rapidity





- 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

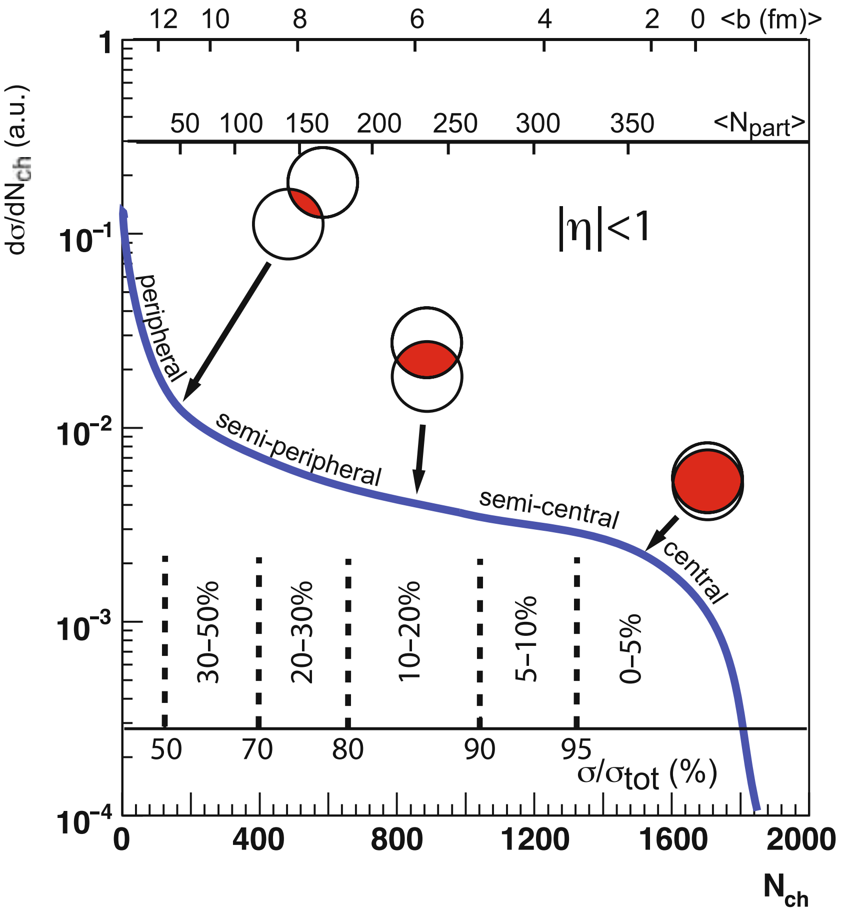


- Quantitative **agreement** of chemical freeze-out parameters **with most recent LQCD predictions** for $\mu_B < 300$ MeV

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

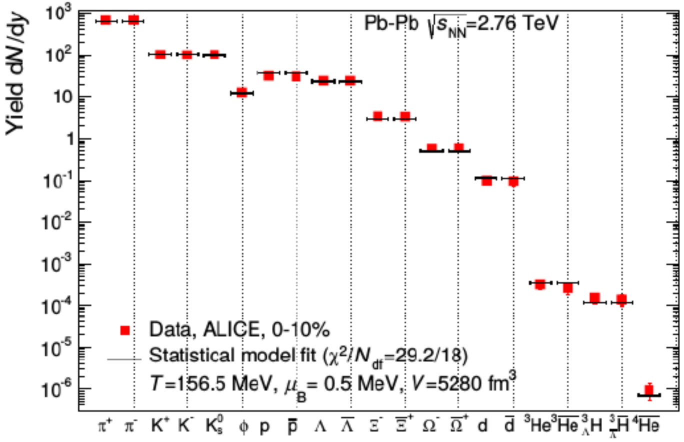
HotQCD Collaboration, Phys.Lett. B795 (2019) 15
S. Borsanyi et.al. Phys. Rev. Lett. 125, 052001 (2020)

Centrality



12
10
8
6
4
2
0
<b (fm)>
50
100
150
200
250
300
350
<Npart>
1
10⁻¹
10⁻²
10⁻³
10⁻⁴
dσ/dNch (a.u.)
|η|<1
peripheral
semi-peripheral
semi-central
central
30–50%
20–30%
10–20%
5–10%
0–5%
50
70
80
90
95
σ/σtot (%)
0
400
800
1200
1600
2000
Nch

A. Andronic, P. Braun-Munzinger, J. Stachel and K. Redlich
Nature 561, 321–330 (2018), ALICE, PLB 726 (2013) 610



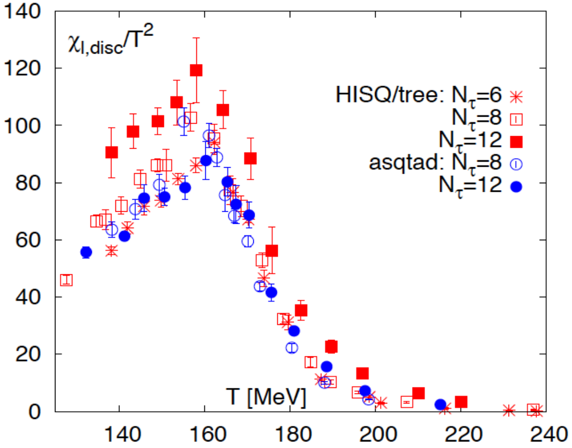
$$T_{fo}^{ALICE} = 156.5 \pm 3MeV$$

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

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

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

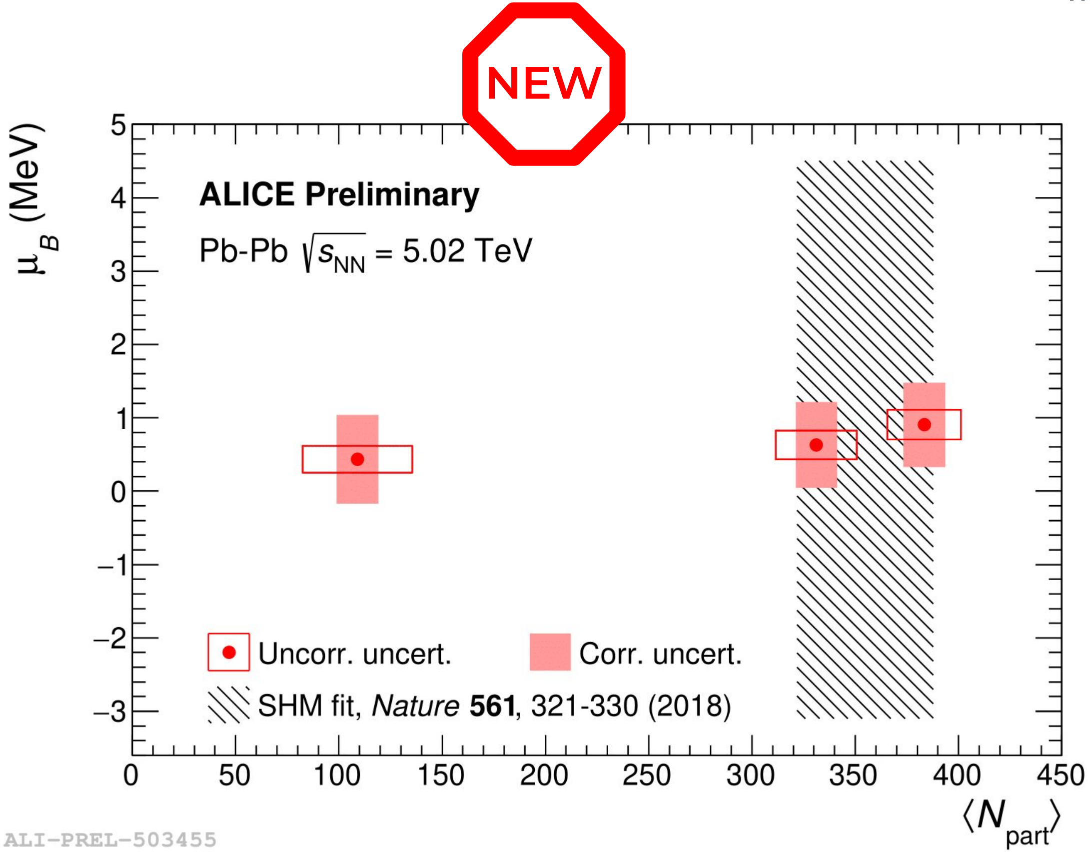
HotQCD Collaboration
Phys.Rev. D85 (2012) 054503, arXiv:1904.09951



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

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

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


NEW
ALICE Preliminary
Pb-Pb $\sqrt{s_{NN}}$ = 5.02 TeV
μ_B (MeV)
$\langle N_{part} \rangle$
Uncorr. uncert.
Corr. uncert.
SHM fit, *Nature* **561**, 321-330 (2018)
ALI-PREL-503455