Event-by-event fluctuation analyses in view of the ALICE TPC upgrade

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for the ALICE Collaboration

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ALICE
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ALICE

Outline

① **Analyses of event-by-event fluctuations in ALICE**
- Particle-ratio and net-baryon fluctuations
- Identity Method
- Results

② **ALICE Time Projection Chamber (TPC) in RUN3**
- Introduction to ALICE TPC
- MWPC vs GEM

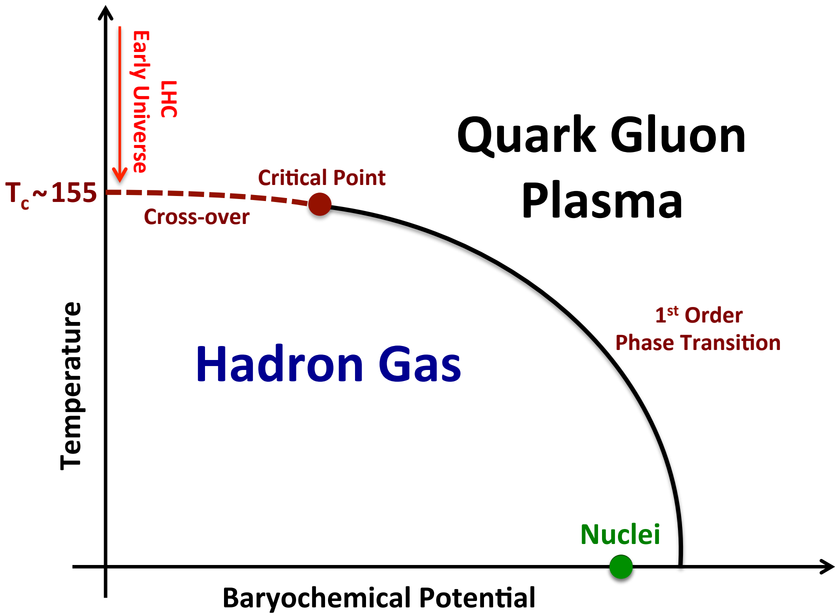
③ **Summary & Outlook**

Analyses of event-by-event fluctuations in ALICE

Motivation: Criticality at crossover

Event-by-Event fluctuations:

- Study dynamics of the phase transitions
- Locate phase boundaries



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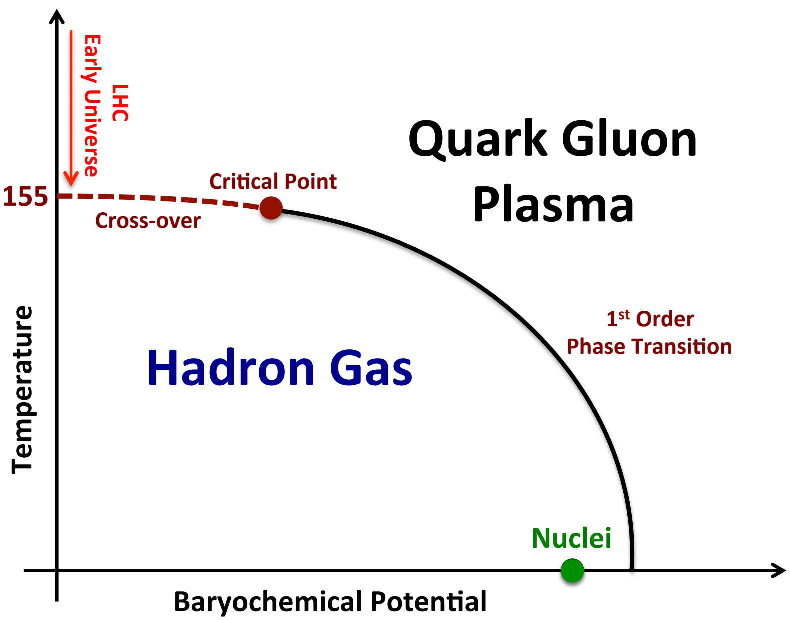

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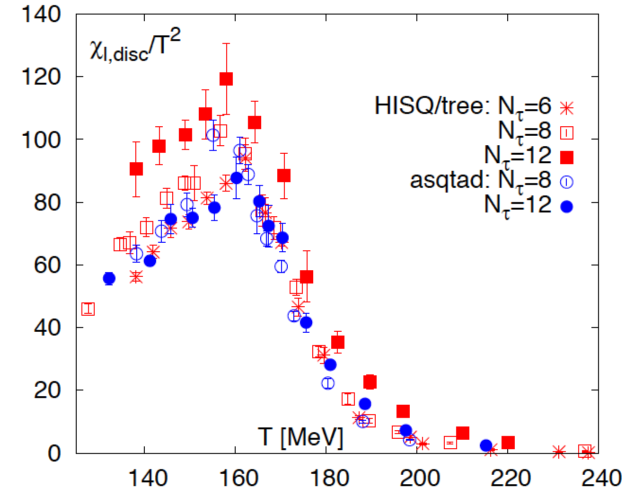
A. Bazavov et al., Phys.Rev. D85 (2012) 054503



freeze-out at the phase boundary!

$$T_c^{lattice} = 154 \pm 9\, MeV, \quad T_{fo}^{ALICE} = 156 \pm 3\, MeV$$

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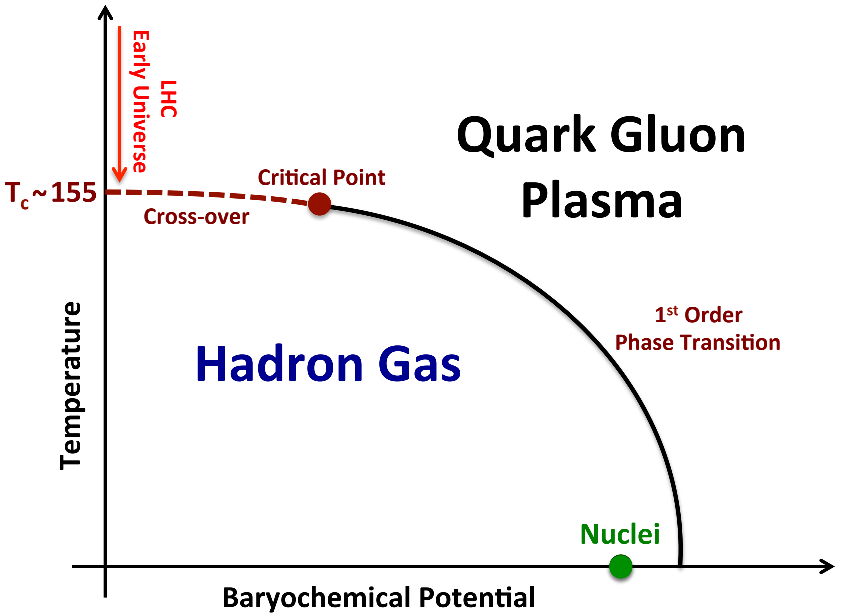

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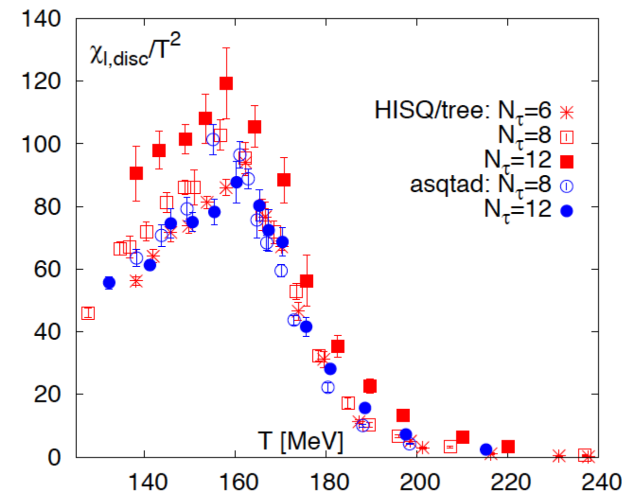

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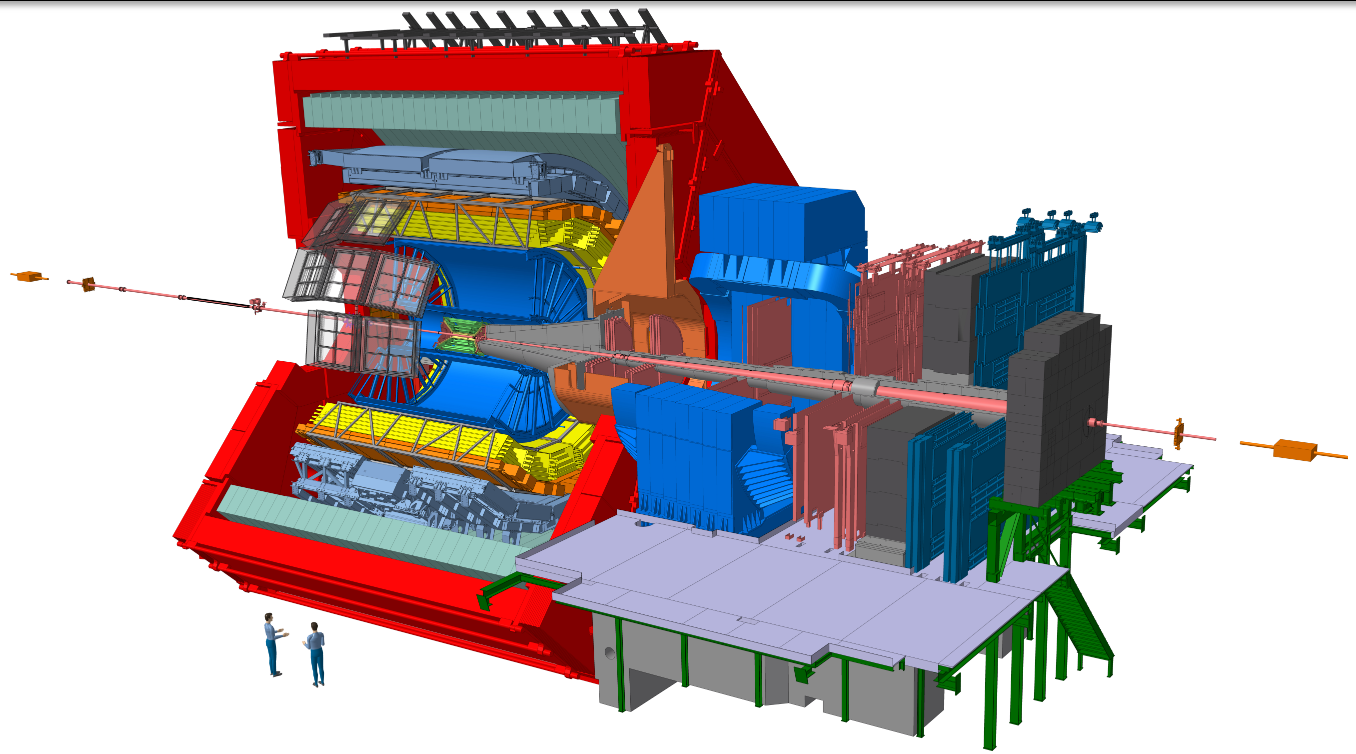
Fluctuation analyses in ALICE

Mean p_T, Multiplicity, Net-charge, **Net proton number, Identified particle ratios** …

A Large Ion Collider Experiment



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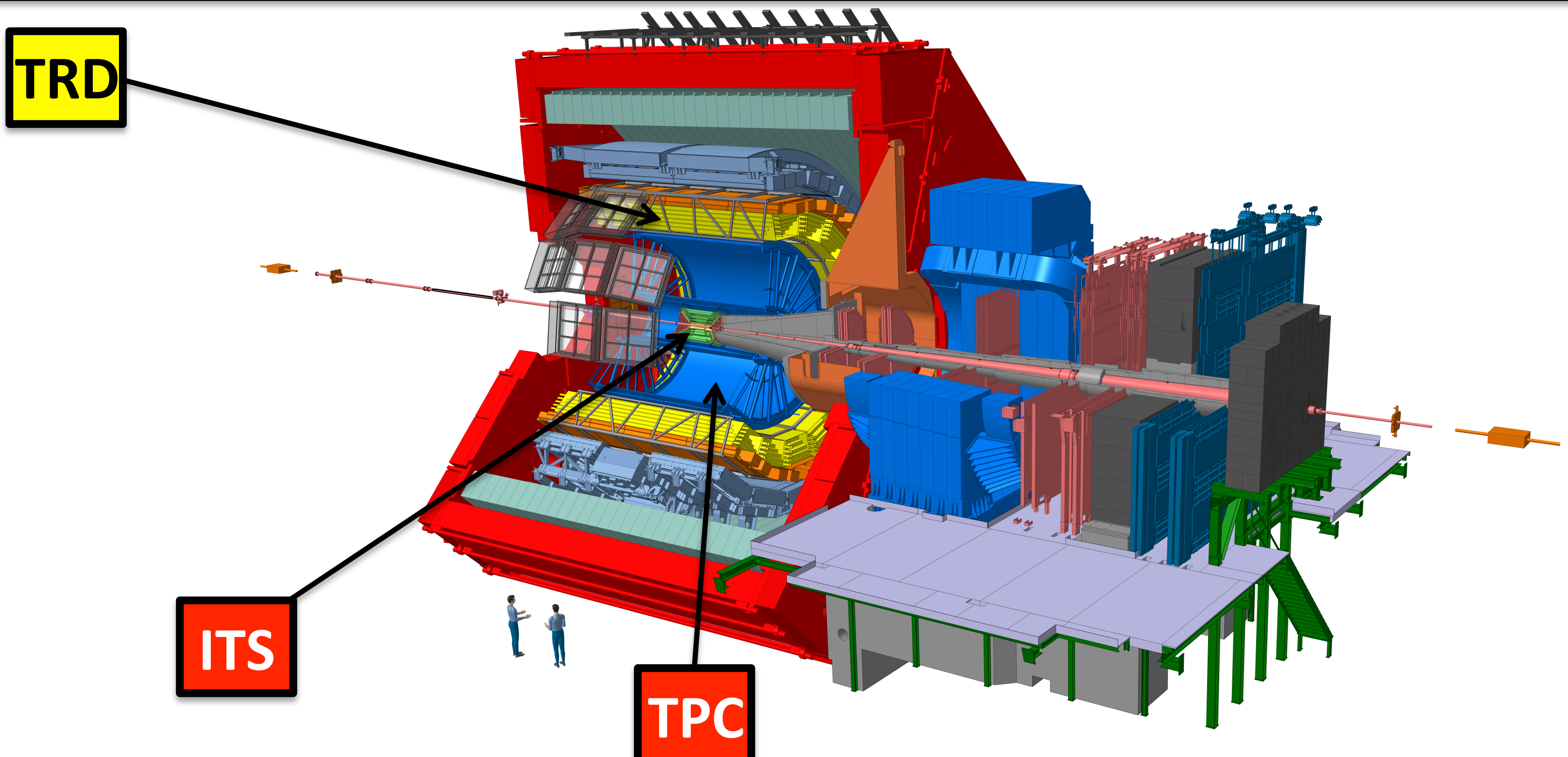

Main detectors used in the analysis:

- **T**ime **P**rojection **C**hamber **(TPC)**
  - Tracking and PID
- **I**nner **T**racking **S**ystem **(ITS)**
  - Vertex

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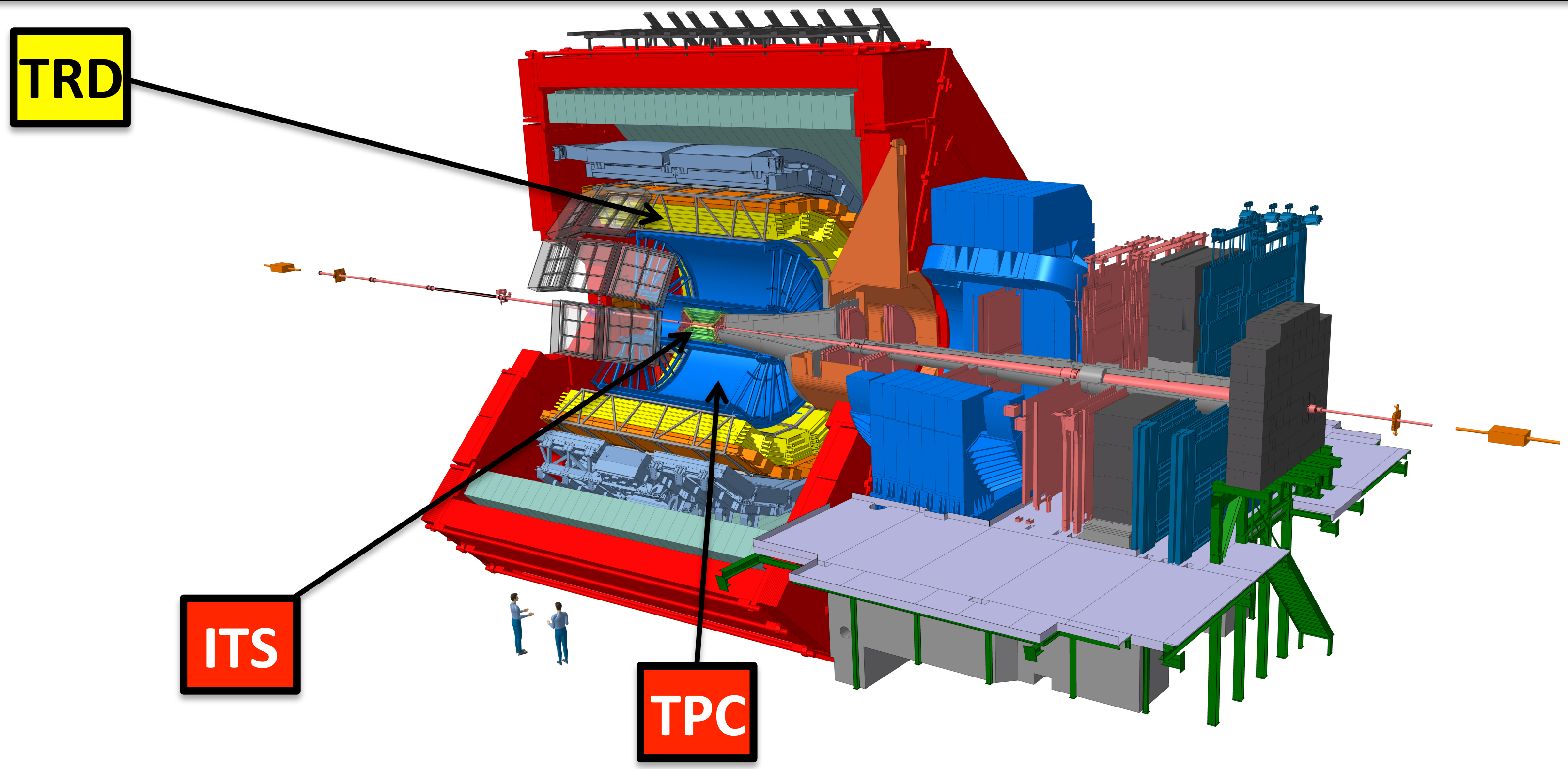

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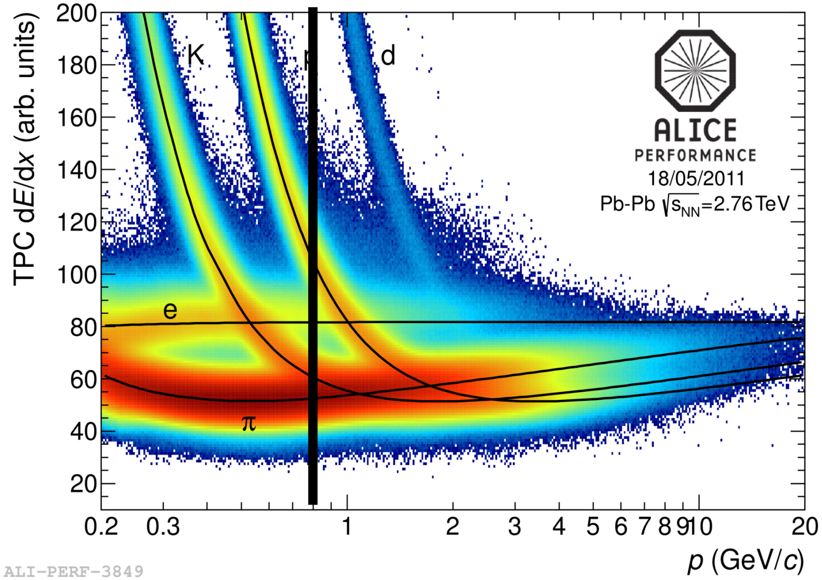
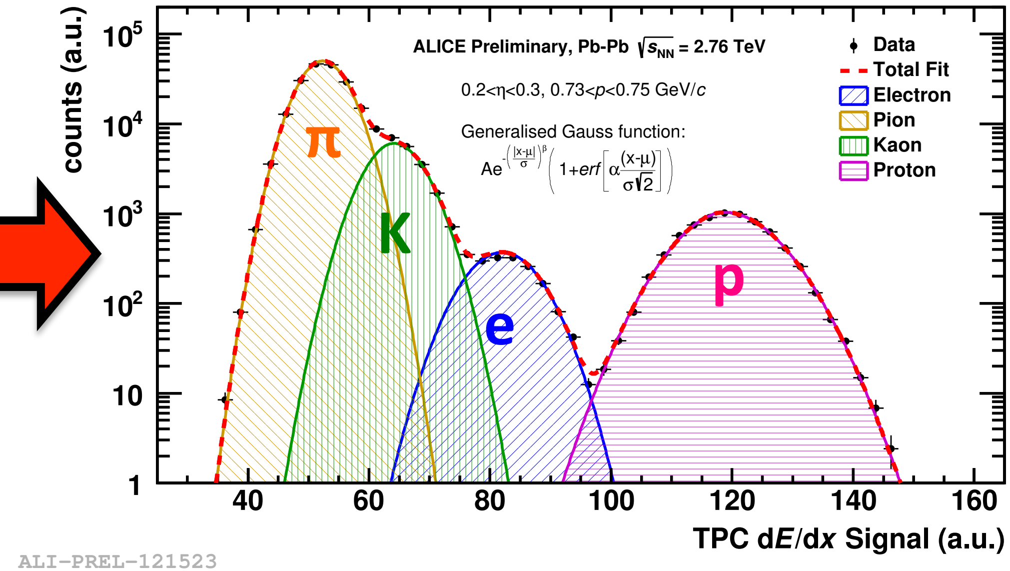
Data Set:

- **Pb-Pb Collisions (RUN1, 2010)**
  - $\sqrt{s_{NN}} = 2.76$ TeV, 13 M events
- **Acceptance:**
  - $|\eta|<0.8$, $0.2\ (0.5) < p < 1.5$ GeV/c

Identity Method





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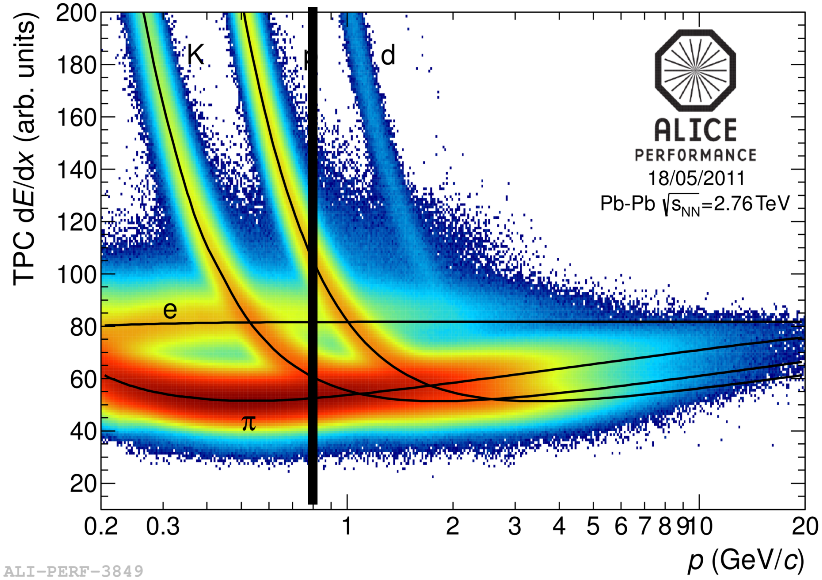

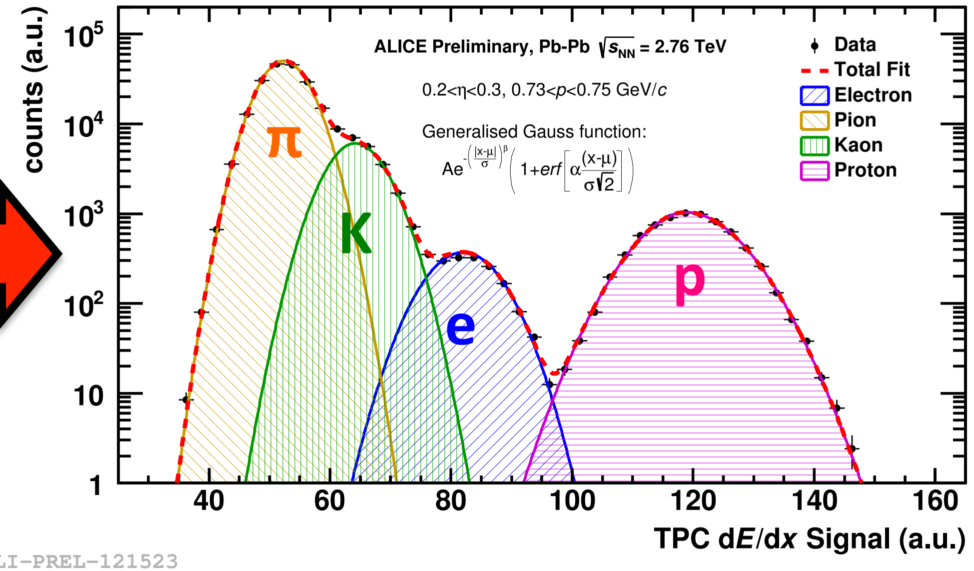

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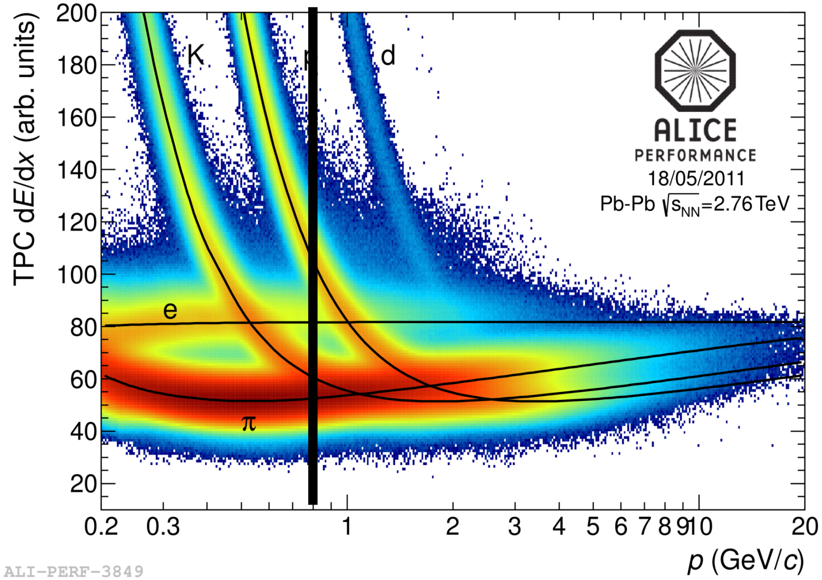

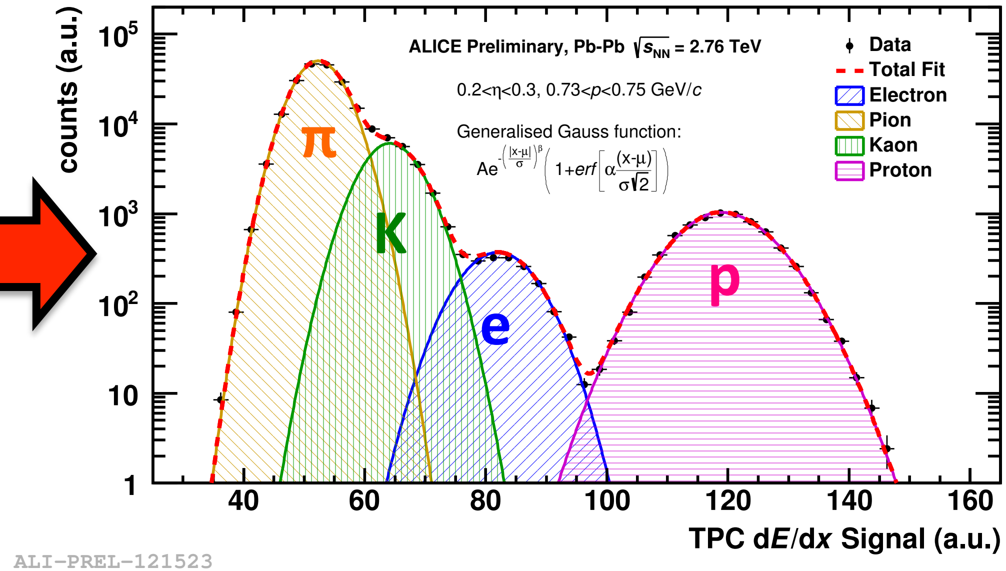

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✧ **Solution to Misidentification**

$$\omega_j(x_i) \in [0,1] \quad \Rightarrow \quad W_j \equiv \sum_{i=1}^{N(n)} \omega_j(x_i) \quad \Rightarrow \quad \boxed{\langle N_j^n \rangle = A^{-1} \langle W_j^n \rangle}$$

Physical Review C 86, 044906 (2012), Physical Review C 89, 054902 (2014)

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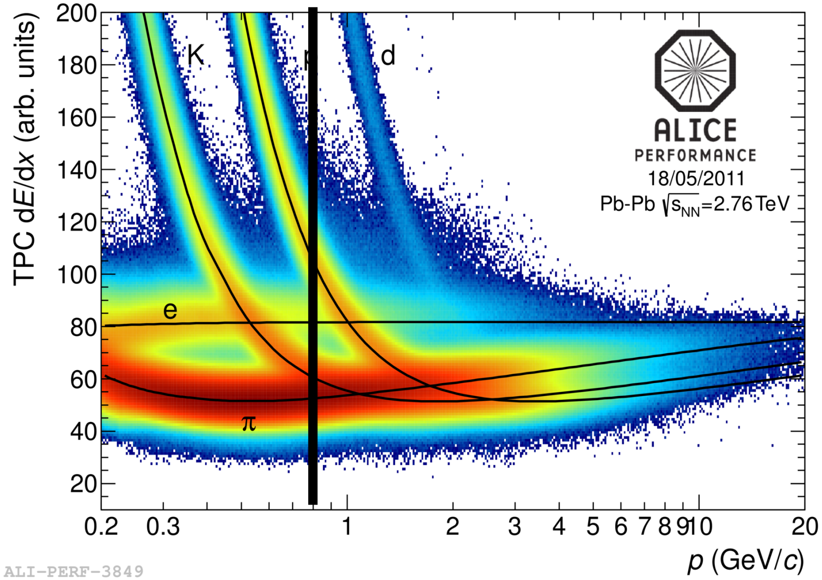

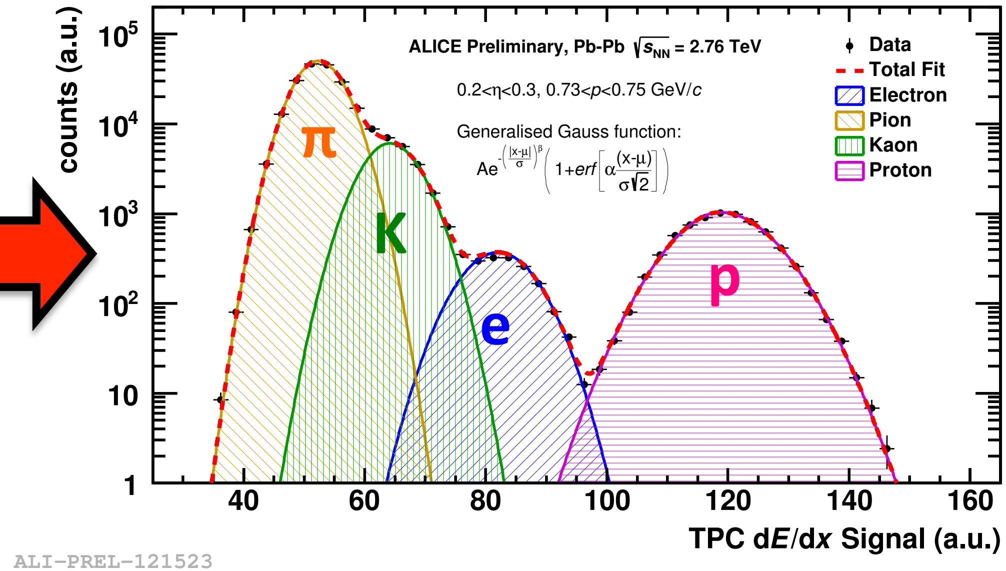

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✧ Keeps the particle **detection efficiencies high and flat**

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Particle-ratio fluct.: Centrality dependence

$$\nu_{dyn} = \frac{\langle N_A(N_A - 1)\rangle}{\langle N_A\rangle^2} + \frac{\langle N_B(N_B - 1)\rangle}{\langle N_B\rangle^2} - 2\frac{\langle N_A N_B\rangle}{\langle N_A\rangle\langle N_B\rangle}$$

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- ✓ Robust against detection **efficiency losses**

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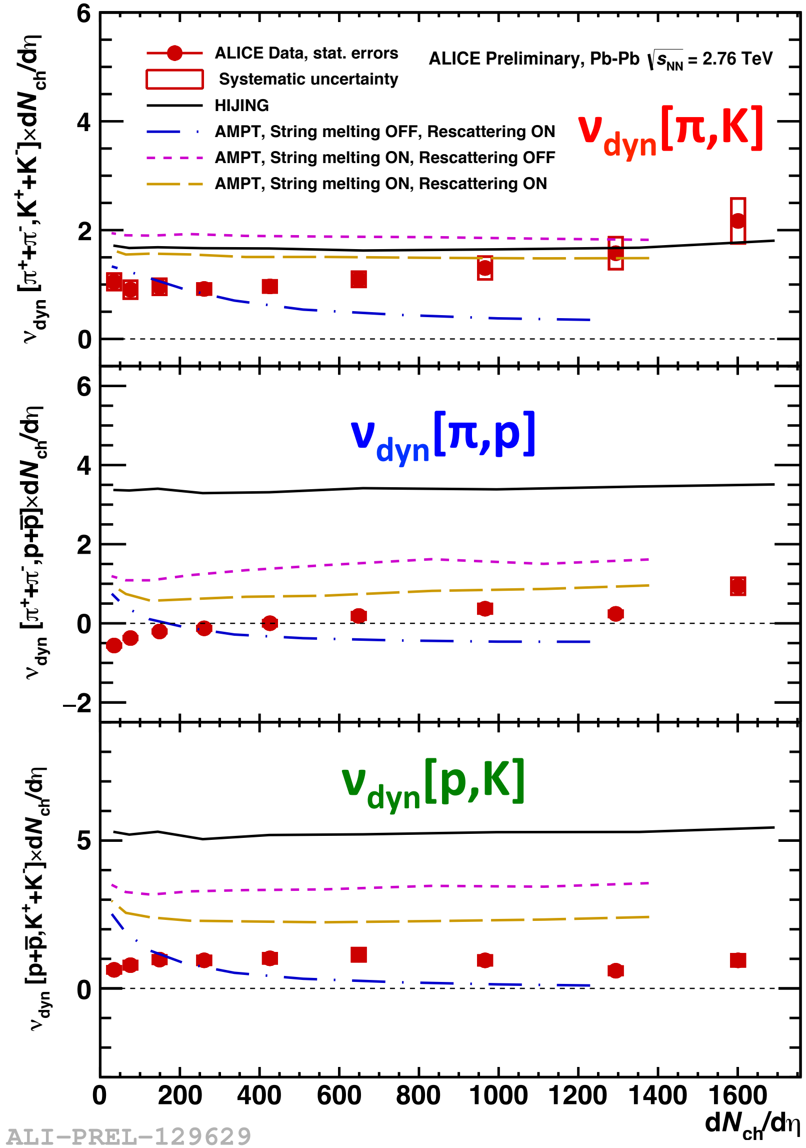

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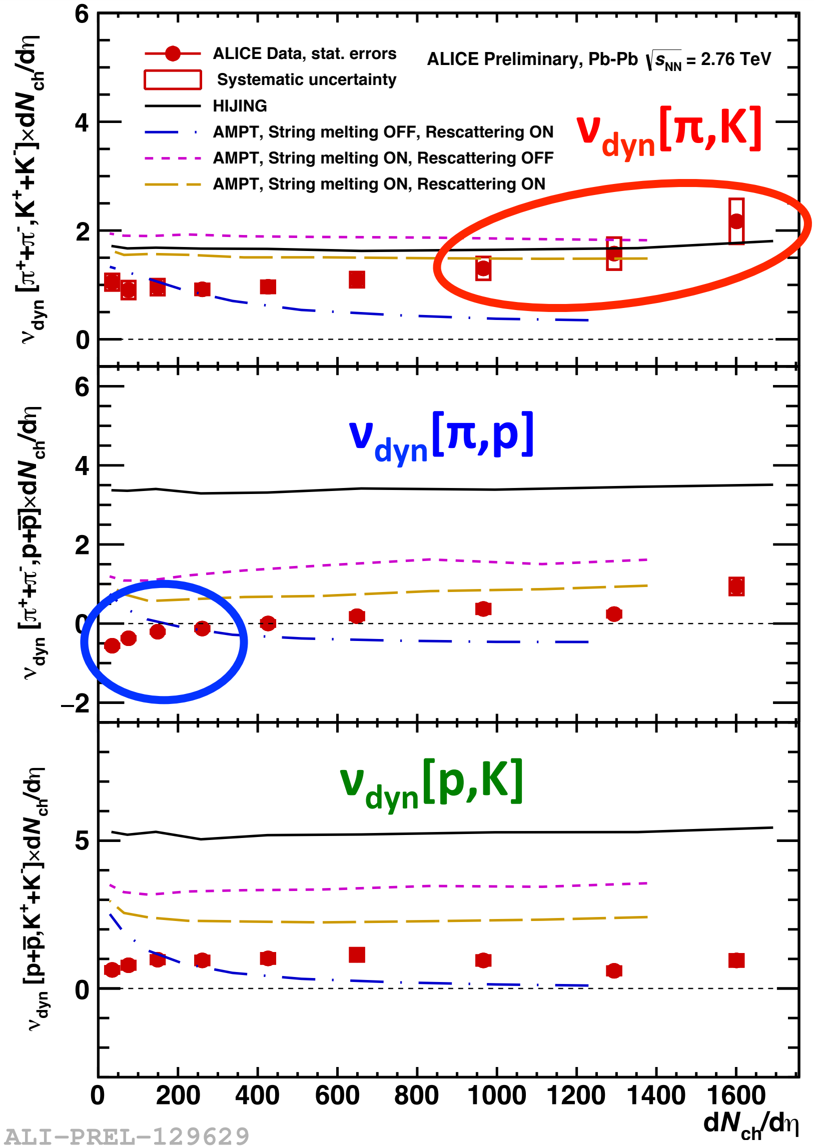
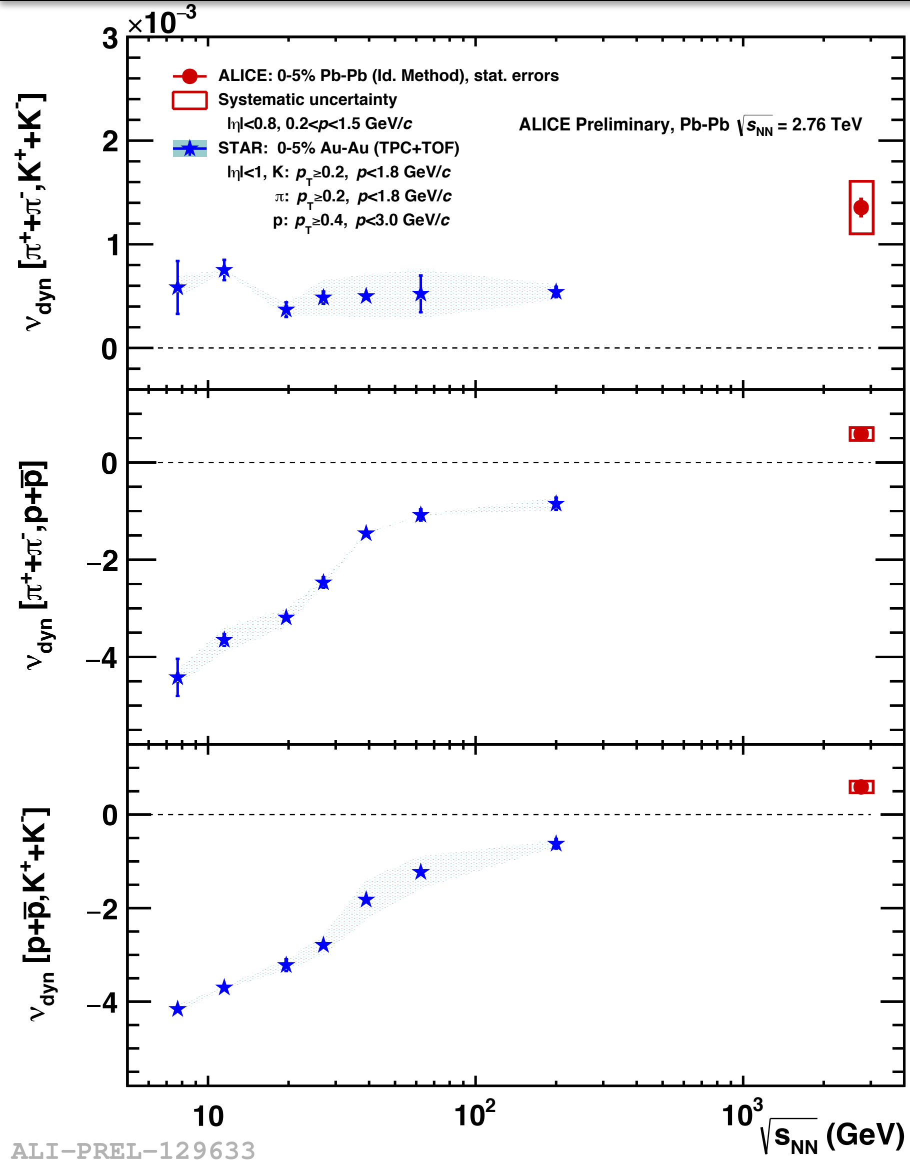


- $\nu_{dyn}[\pi,p]$: **Increasing correlation** with decreasing centrality
- $\nu_{dyn}[\pi,K]$: increasing anti-correlation between **π-K** or increasing dynamical fluctuations

Particle-ratio fluct.: Energy dependence



- ALICE data has larger values for all three cases and exhibits a **sign change** for $\nu_{dyn}[\pi,p]$ and $\nu_{dyn}[p,K]$
  - ✧ **Less correlation** or **larger dynamical fluctuations ?**
- ❑ **Usage of ITS:** Rejection of secondaries
- ❑ Different kinematic ranges
  (Physical Review C 89, 054902 (2014))

Net-proton fluctuations

Tool: Net-particle cumulants

→ **For a thermal system in a fixed volume V within the Grand Canonical Ensemble**

$$\frac{P}{T^4} = \frac{1}{VT^3} \ln Z\left(V, T, \mu_{B,Q,S}\right)$$

$$\hat{\chi}_n^{N=B,S,Q} = \frac{\partial^n P/T^4}{\partial\left(\mu_N/T\right)^n}$$

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Nucl. Phys. A 960 (2017) 114–130

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Correlation term may arise from:

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   $\rho \rightarrow \pi^+\pi^-, \phi \rightarrow K^+K^- ...$

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Poisson limit:

$$\kappa_2\left(N_B\right) = \left\langle N_B \right\rangle$$

$$\kappa_2\left(N_{\bar{B}}\right) = \left\langle N_{\bar{B}} \right\rangle$$

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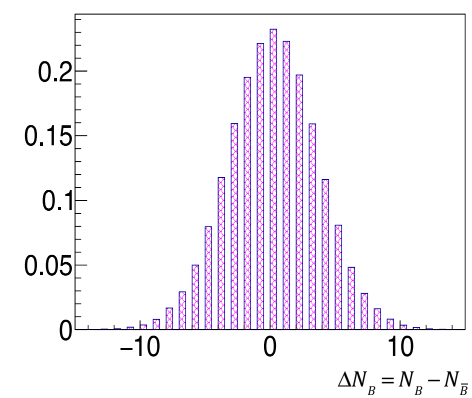
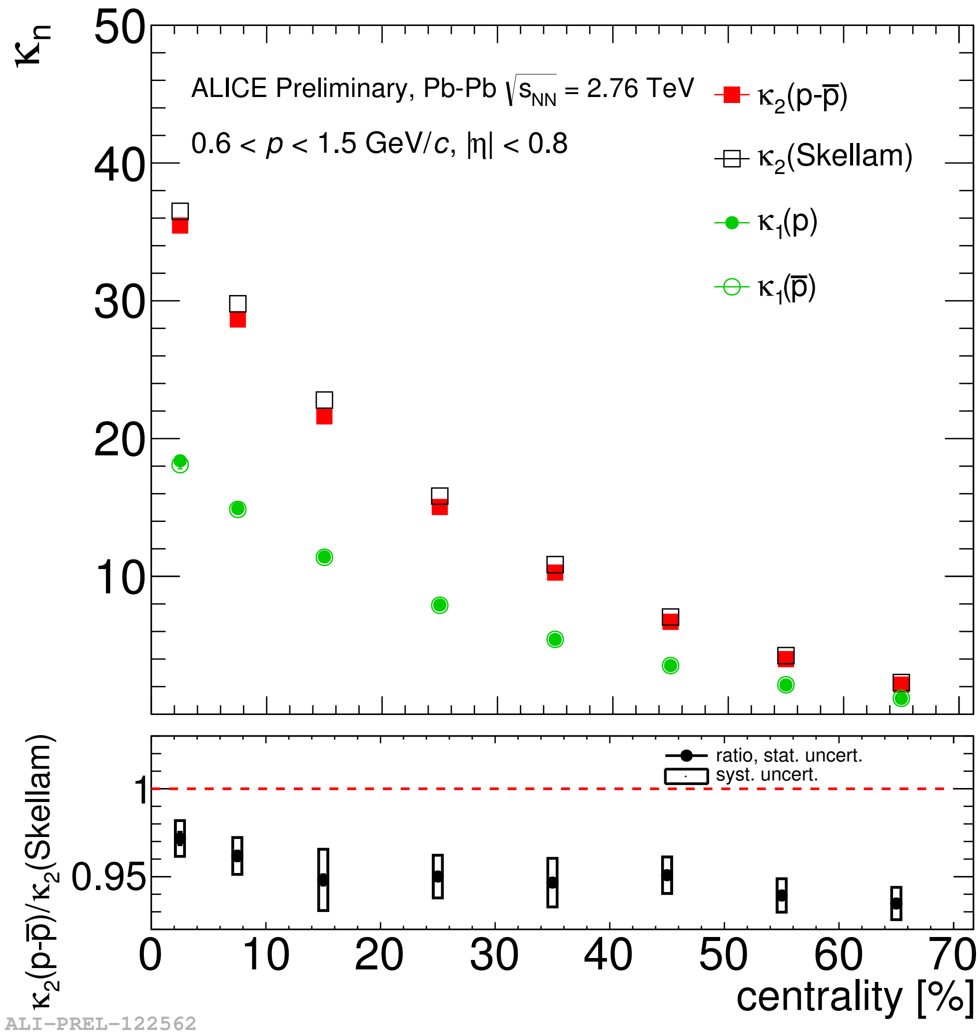


Skellam

Net-proton fluct.: Skellam baseline



arXiv:1704.05329

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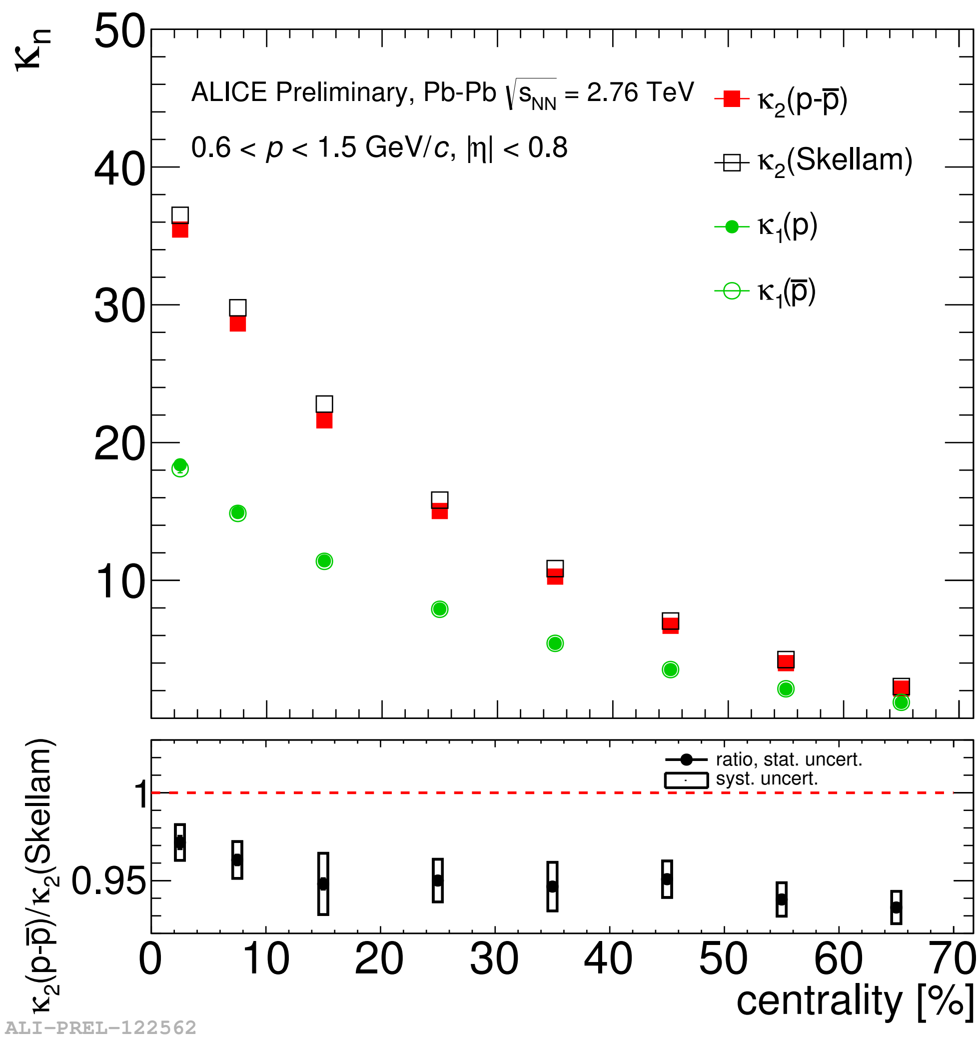

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- **Deviation from skellam**
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  - non Poisson (anti)protons?

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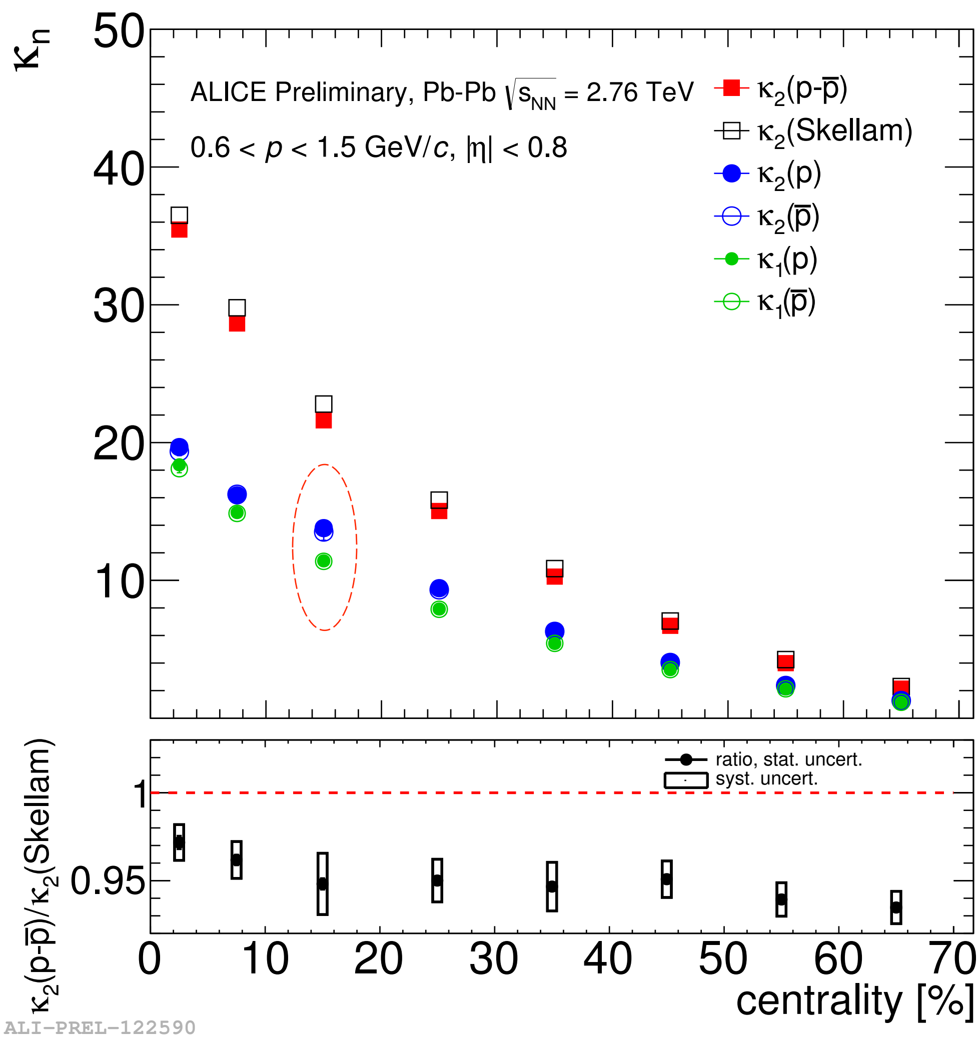

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- **Deviation from skellam**
  - correlation term?
  - non Poisson (anti)protons?
- **Participant fluctuations**
  (Nuclear Physics A 960 (2017) 114–130)

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Net-proton fluct.: **Acceptance Dependence**

- In reality (experiments) conservations depend on the acceptance (p_T, y)
  → Contribution from global baryon number conservation ?

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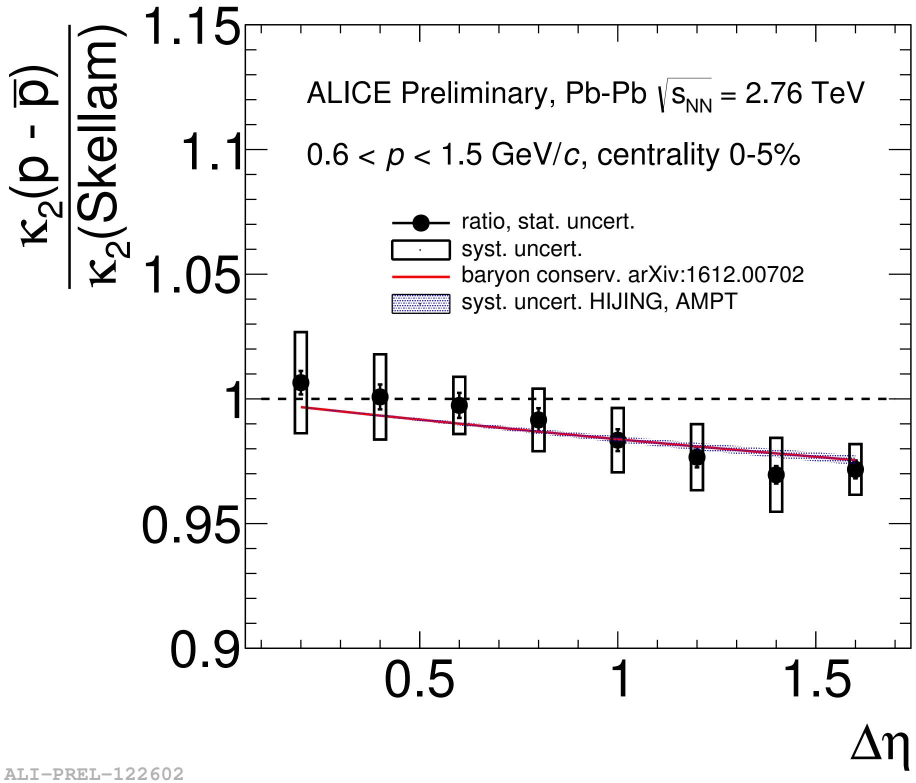

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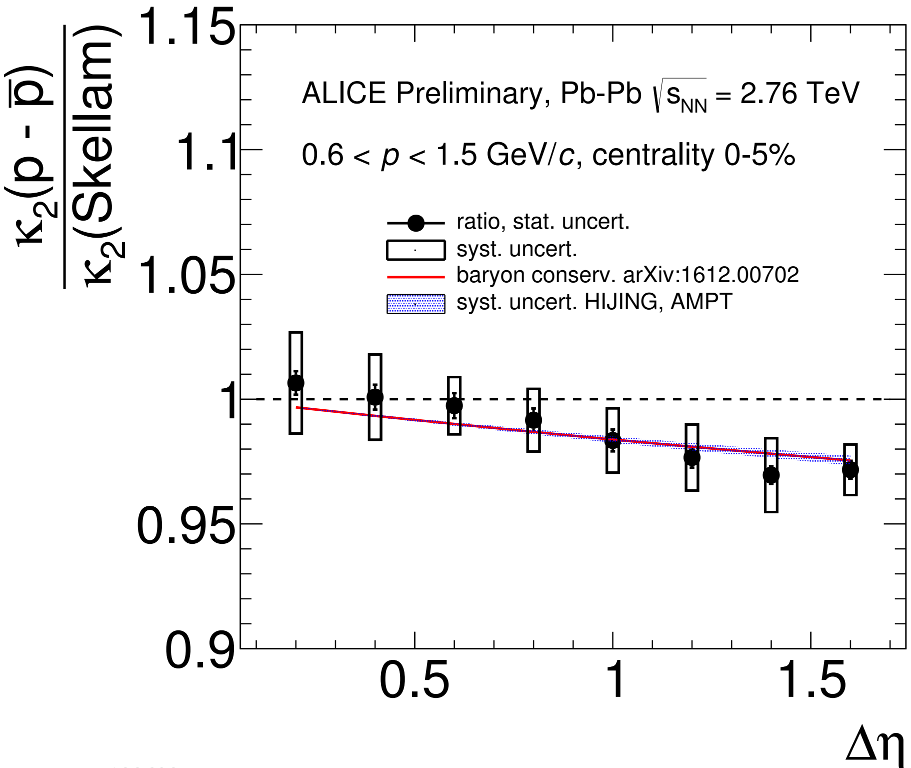

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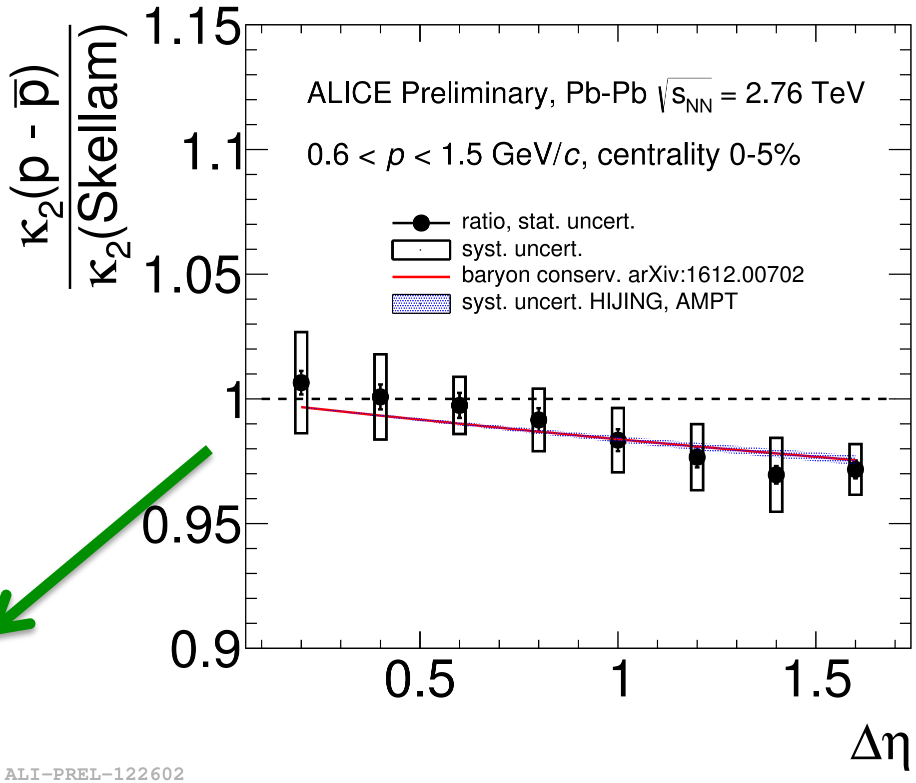

Deviation from Skellam is due to the global **baryon number conservation**

arXiv:1704.05329

Physics Summary

- ✓ Identified-particle-ratio and net-proton fluctuations are measured for the first time at LHC **up to second order** moments (cumulants)
  - **Particle-ratio**: Sign change for $\nu_{dyn}[\pi,p]$ and $\nu_{dyn}[K,p]$ as a function of energy
    Sign change for $\nu_{dyn}[\pi,p]$ as a function of centrality
    HIJING and AMPT do not describe the data
  - **Net-protons**: Deviation from skellam baseline → Baryon number conservation
    Agreement with LQCD predictions

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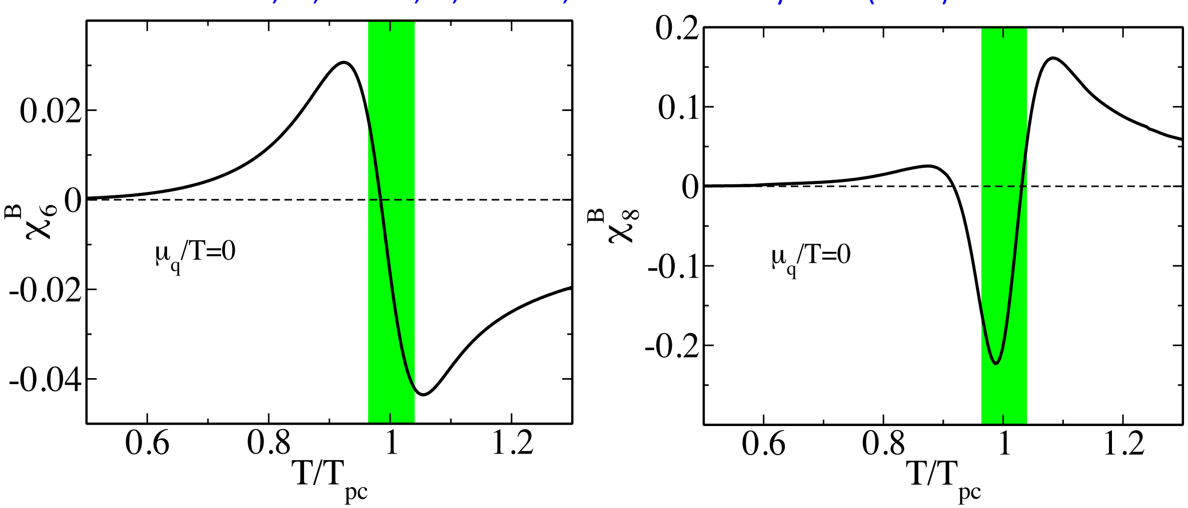
What is next ? → Higher moments → Higher stat. + Good PID

Friman, B., Karsch, F., Redlich, K. et al. Eur. Phys. J. C (2011) 71: 1694



6th and 8th order cumulants of the net baryon number fluctuations at $\mu_q/T = 0$

RUN1: 2nd order (~13M events)

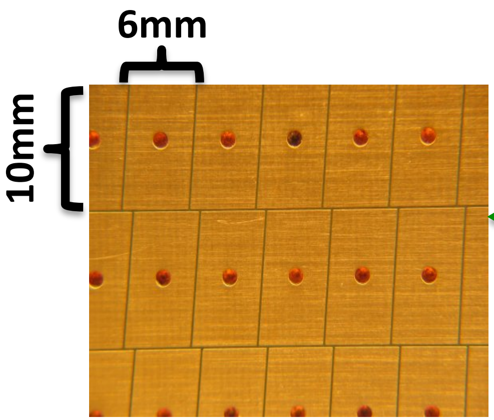
RUN2: 4th order (~150M events)

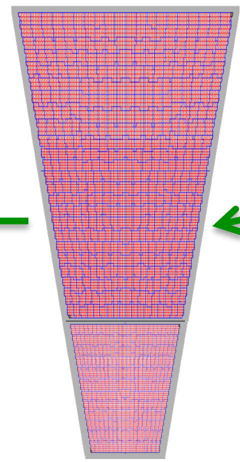
RUN3: ?

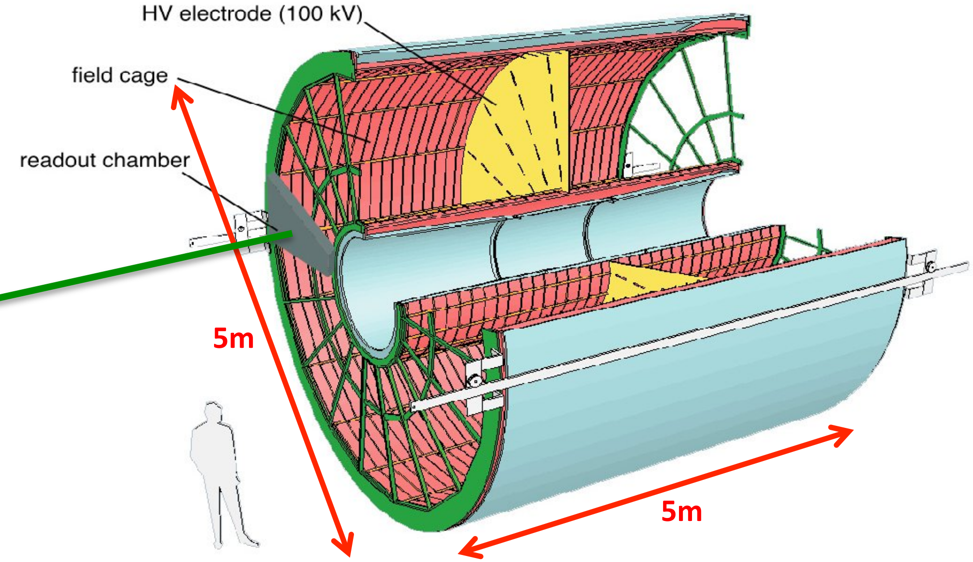
ALICE TPC in RUN3

Current TPC

→ Designed to measure up to **20000 primary and secondary particles** in a single central Pb-Pb collision







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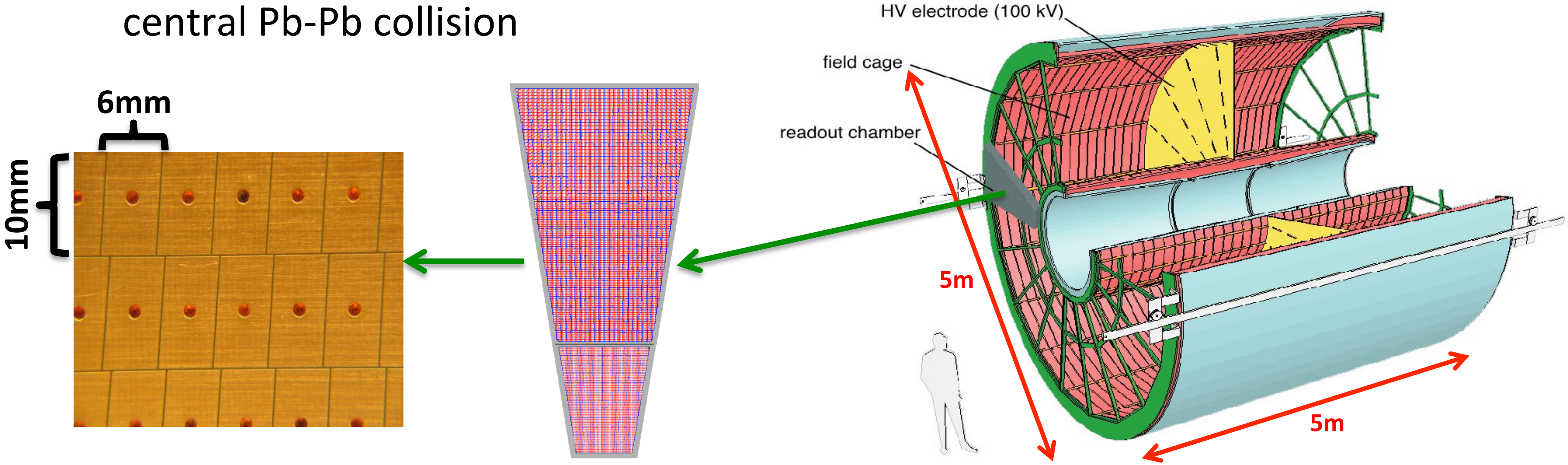
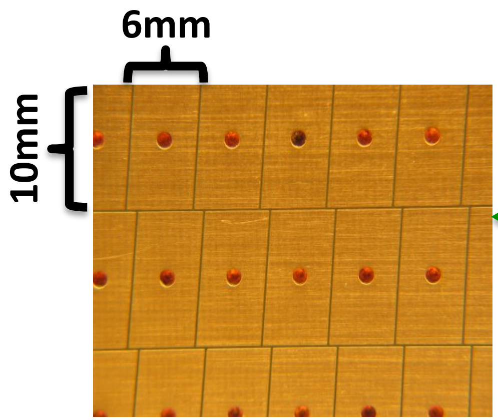
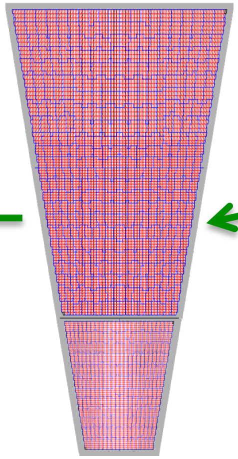


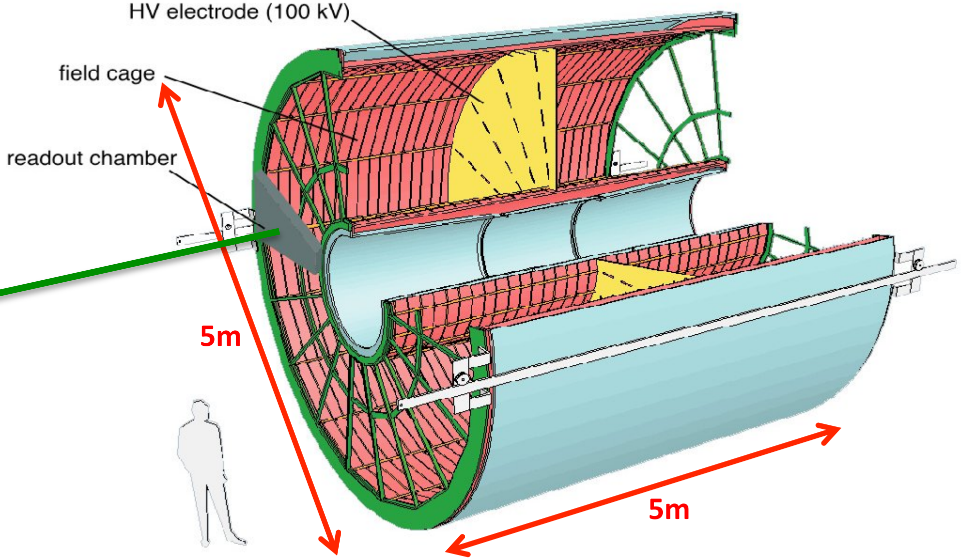
- **Ne-CO_2-N_2:** 90-10-5
- **Read-out chambers:** 72
- **159 rows** (maximum number of clusters per track)
- **Pads** (readout channels): 557568
- **Time bins** (samples in z direction): 1000

Current TPC

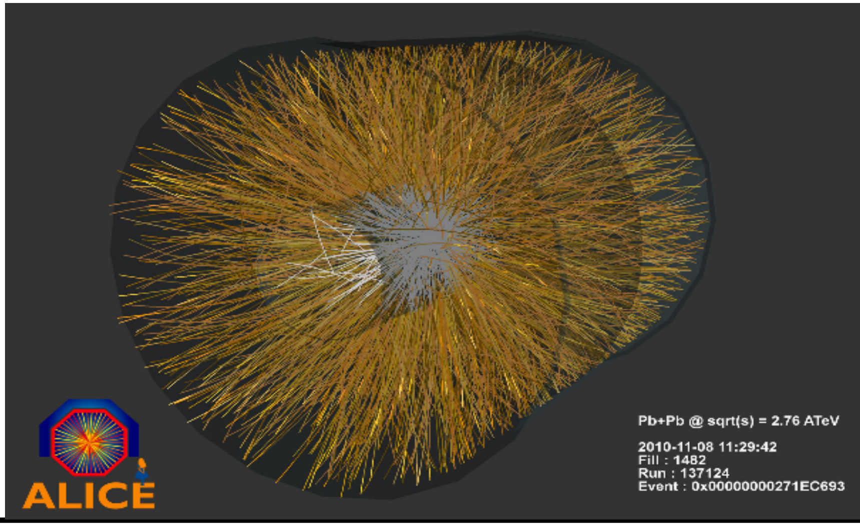
→ Designed to measure up to **20000 primary and secondary particles** in a single central Pb-Pb collision



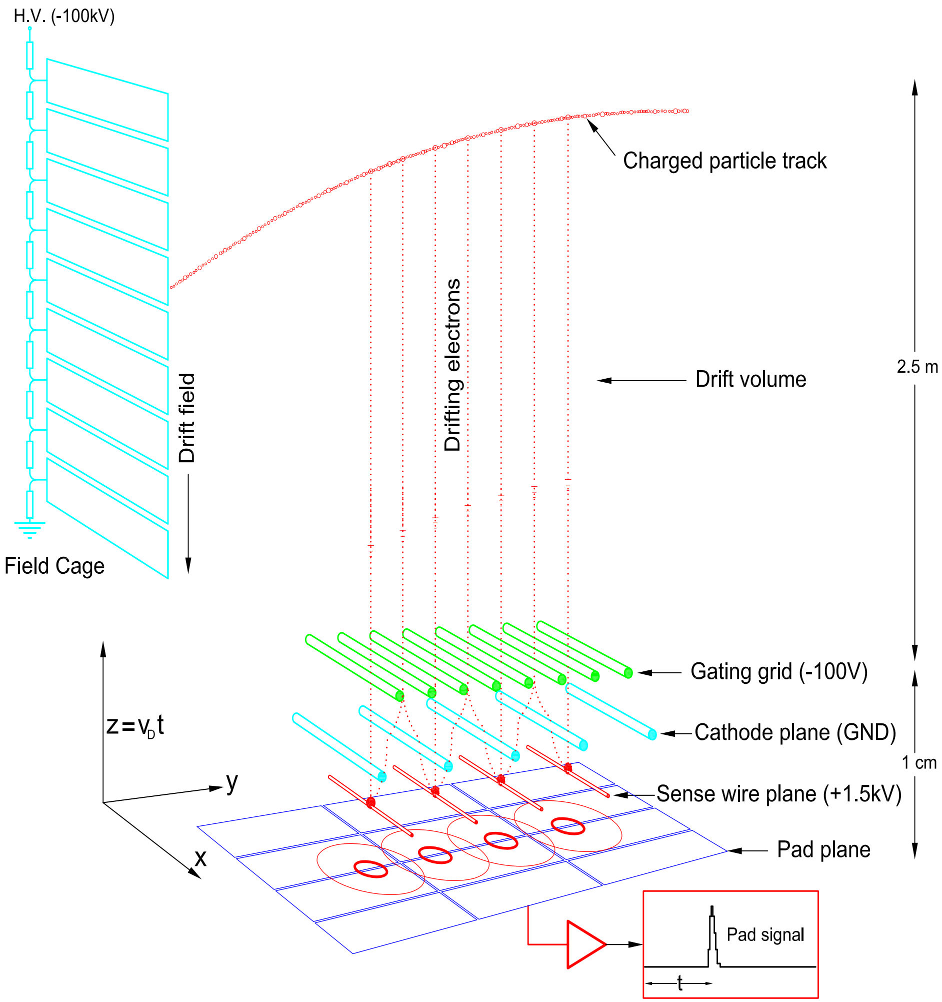




- **Ne-CO_2-N_2**: 90-10-5
- **Read-out chambers:** 72
- **159 rows** (maximum number of clusters per track)
- **Pads** (readout channels): 557568
- **Time bins** (samples in z direction): 1000



Working Principle



Ionization

Electron Drift

Gas Amplification

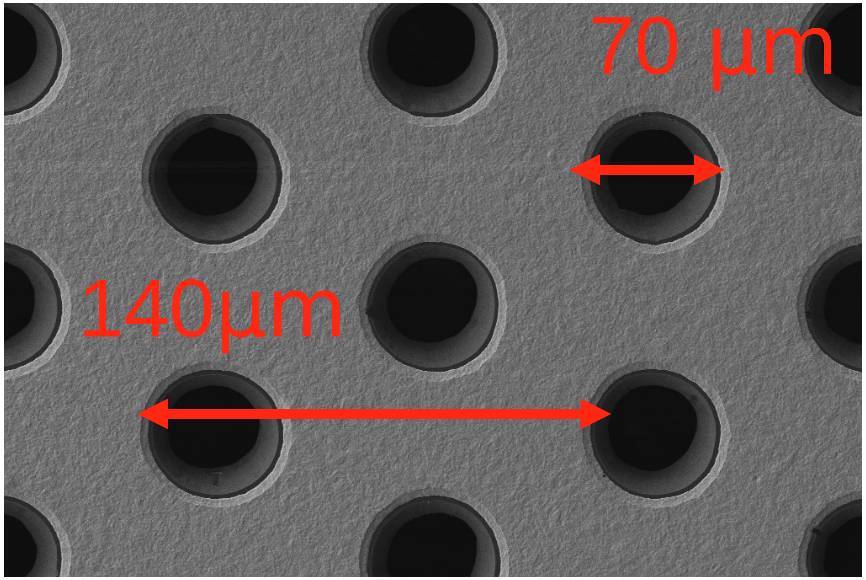
MWPC (Multi-Wire Proportional Chamber) or **GEM**

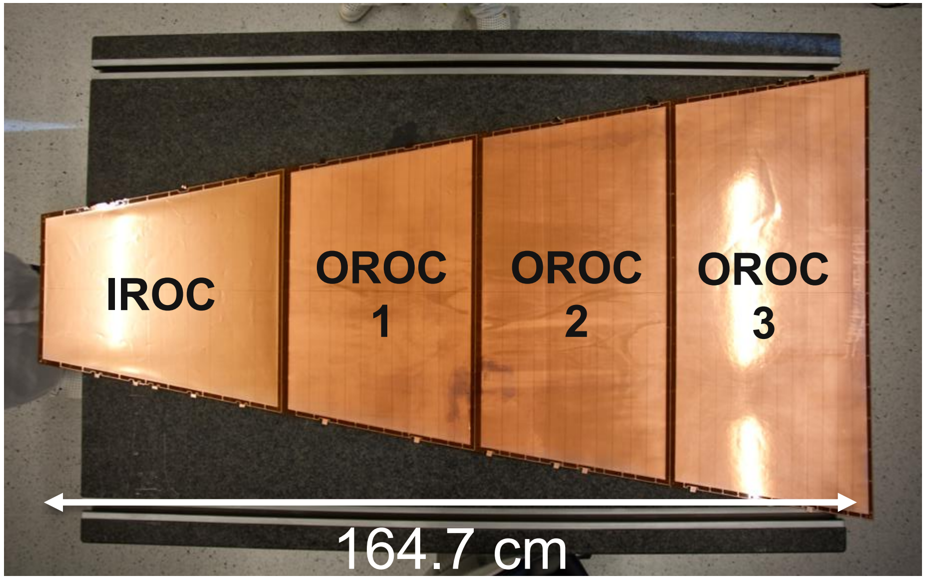
→ Electrons with **~1000 larger drift velocity**

→ Original charge is multiplied by a factor of **several thousands**

Signal Generation

Future TPC: (Gas Electron Multipliers, GEMs)





Why GEM ?: MWPC vs GEM

Collision rates of 50 kHz in Pb-Pb beyond 2019

Why GEM ?: MWPC vs GEM

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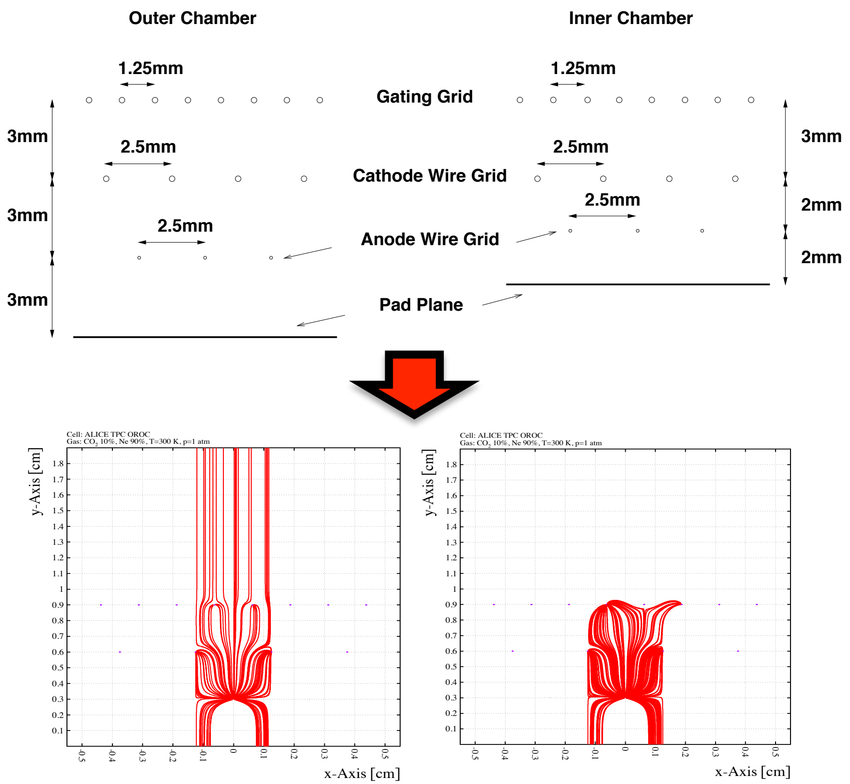
MWPC

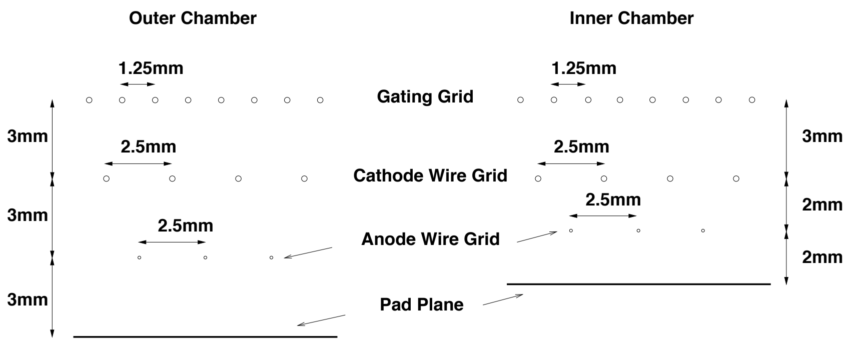


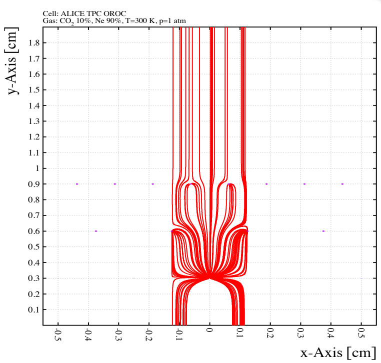
- ✓ Ion backflow → ~10^{-5}%
- ❑ Readout rate → e^- drift 100μs + Ion drift 180μs
  → Max. rate = 1/280 = 3.5kHz

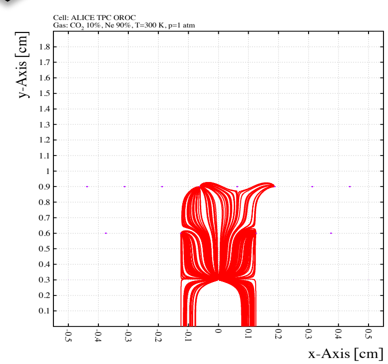
Why GEM ?: MWPC vs GEM

Collision rates of 50 kHz in Pb-Pb beyond 2019

MWPC







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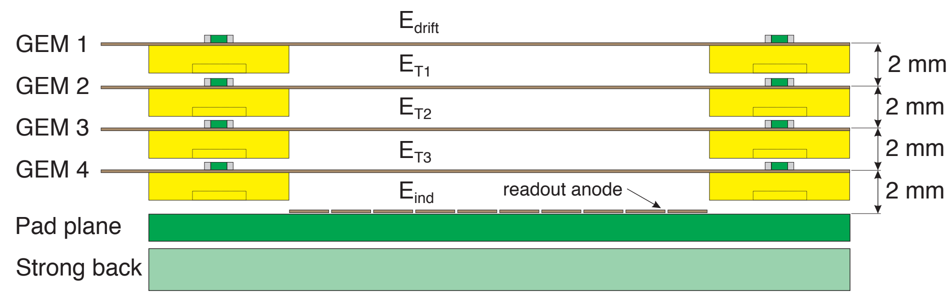
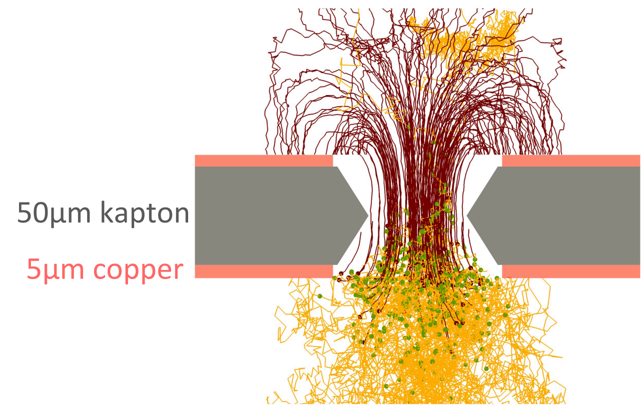
GEM





- ✓ Ion backflow → **~1%**
- ❑ Readout rate → **Continuous readout**

GEM: Challenges

- ✓ Main components of the existing TPC will be **reused**
- ✓ **Nominal gain** = 2000 in **Ne-CO_2-N_2** (90-10-5)

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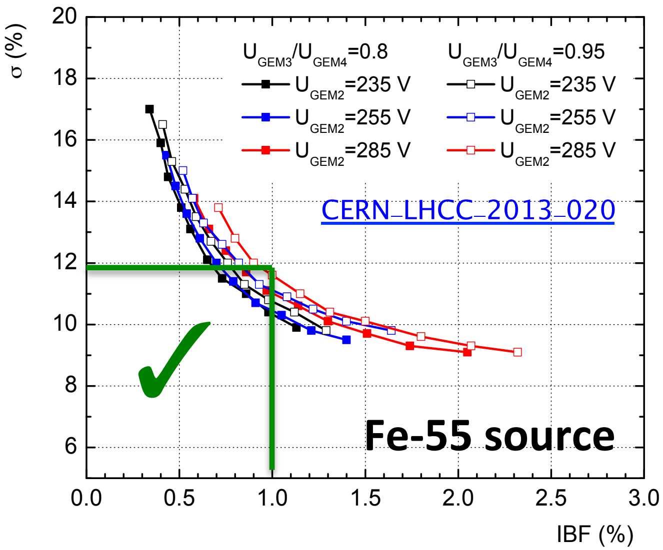

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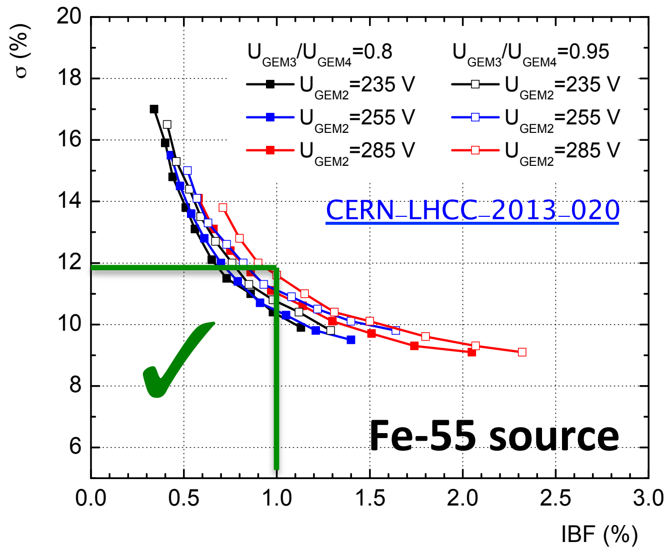
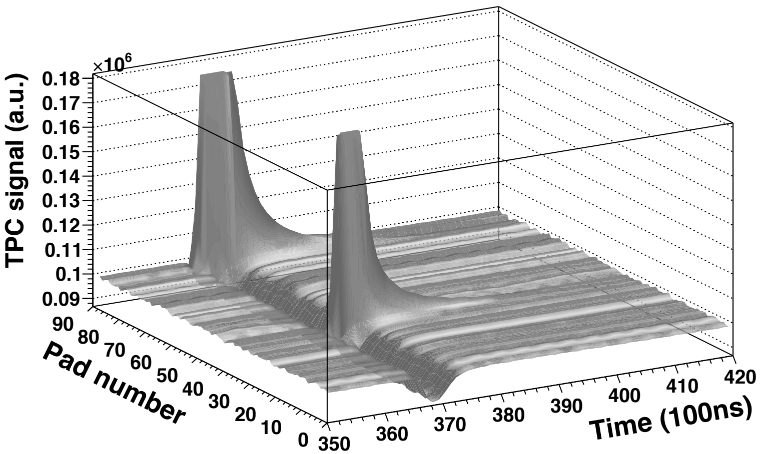


2) Common-mode: Online correction



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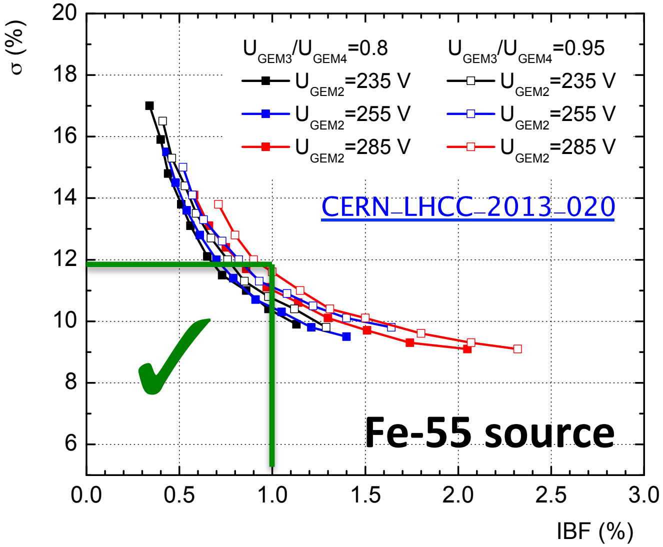

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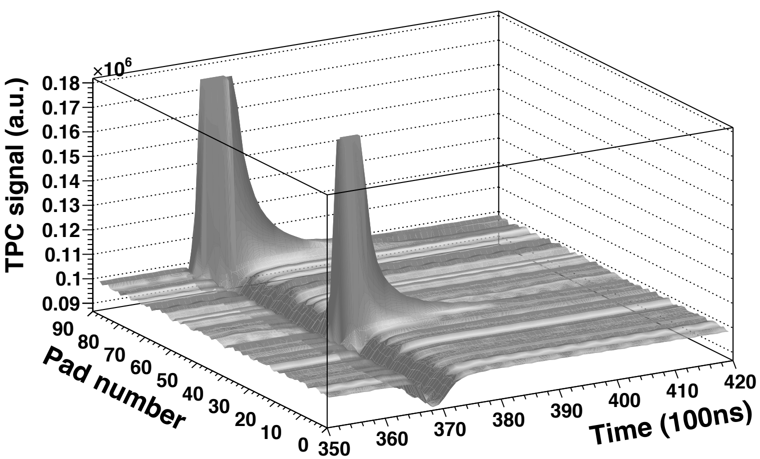


3) Discharge probability < 10^{-10} (measured with alpha particles)
< $(6.4\pm3.7)\times10^{-12}$ (measured with a close-to-MIP beam)

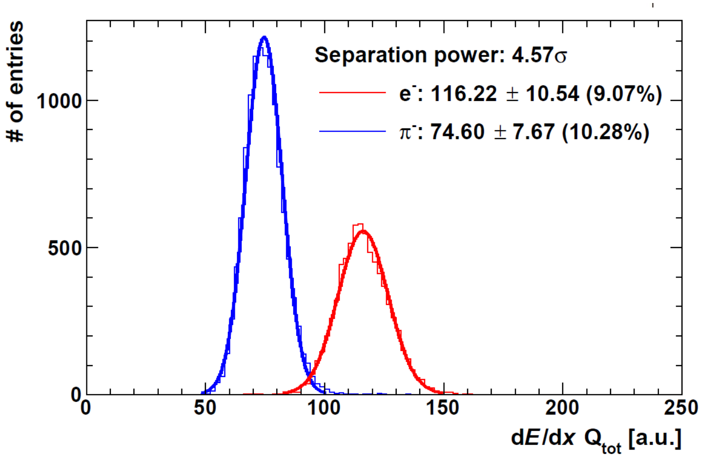
4) Average pileup of 5 events at 50kHz

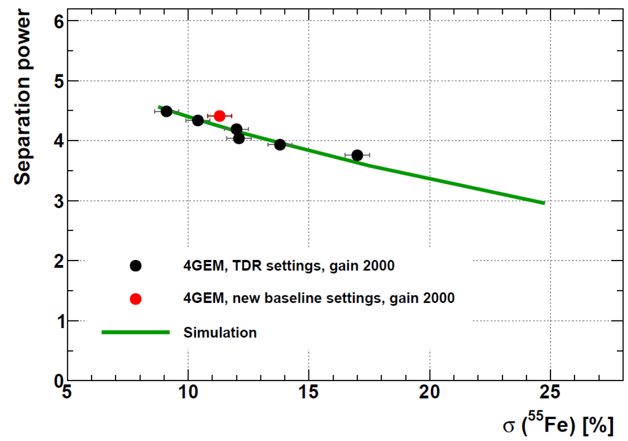
5) Space charge distortions up to 20cm: Reduction down to 200μm using ITS and TRD matching

6) Data processing: New electronics (SAMPA)
Online reconstruction and data compression by a factor of 20

GEM: Performance

Excellent d*E*/d*x* performance maintained demonstrated also with **test beams**





$$S = \frac{\mu_e - \mu_\pi}{\left(\frac{\sigma_e + \sigma_\pi}{2}\right)}$$

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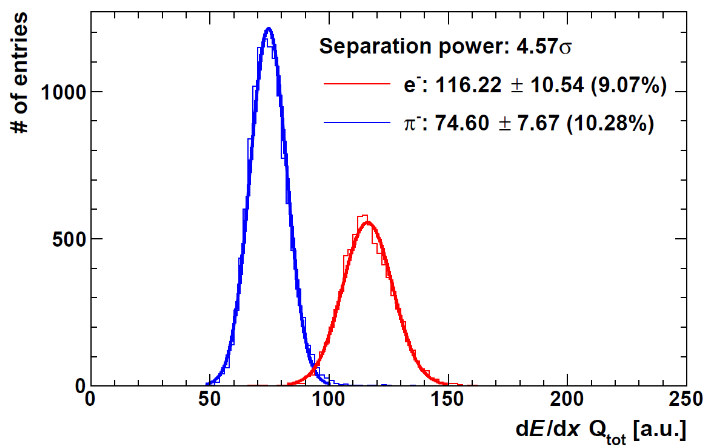
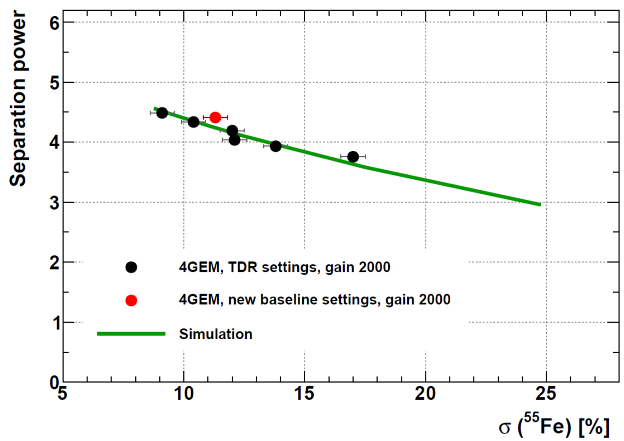
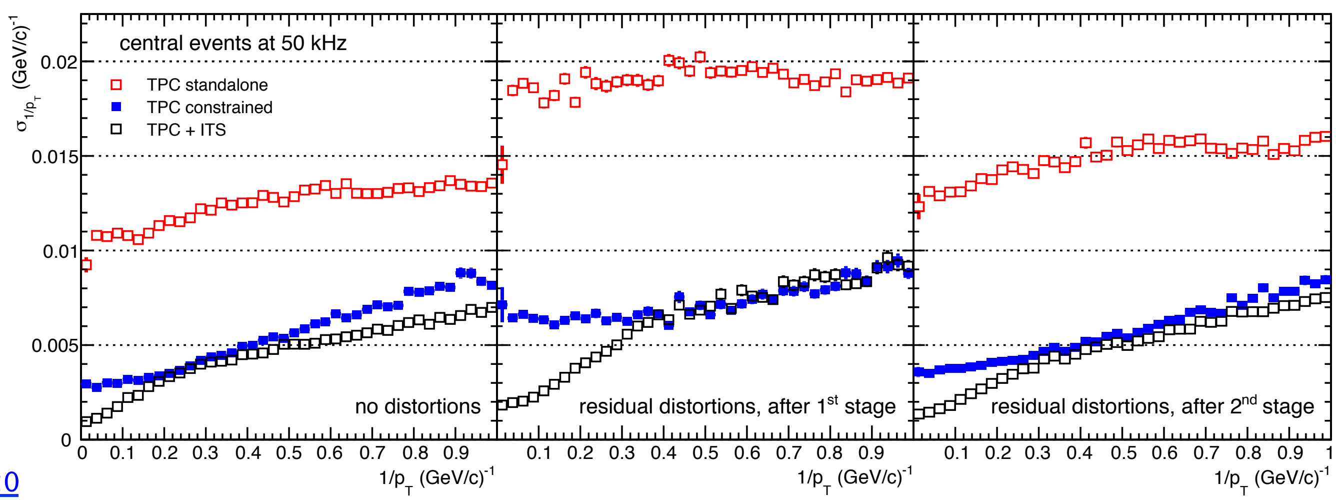




$$S = \frac{\mu_e - \mu_\pi}{\left(\frac{\sigma_e + \sigma_\pi}{2}\right)}$$

Simulation studies show that calibrations will **restore momentum resolution**

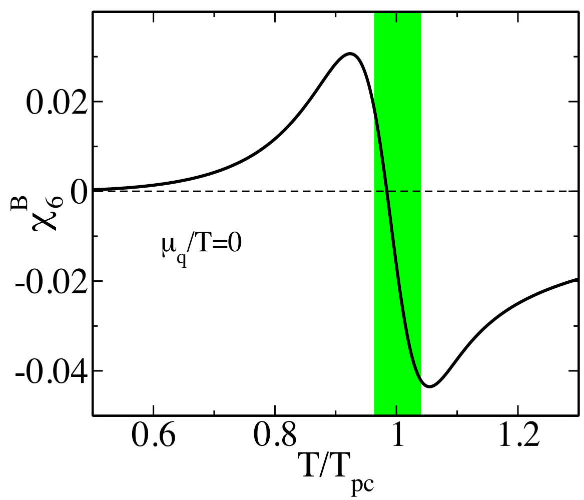


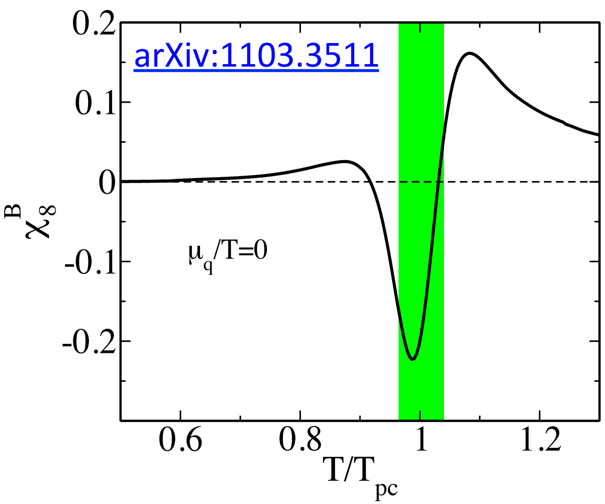
CERN_LHCC_2013_020

Summary & Outlook

What will TPC upgrade bring us ?

- ✓ **Excellent d*E*/dx performance** as in MWPC-based readout.
- ✓ **Operational stability** against electrical discharges
- ✓ **A factor 100 more statistics**
  - → **Moments of particle multiplicities up to 6th and 8th order.**





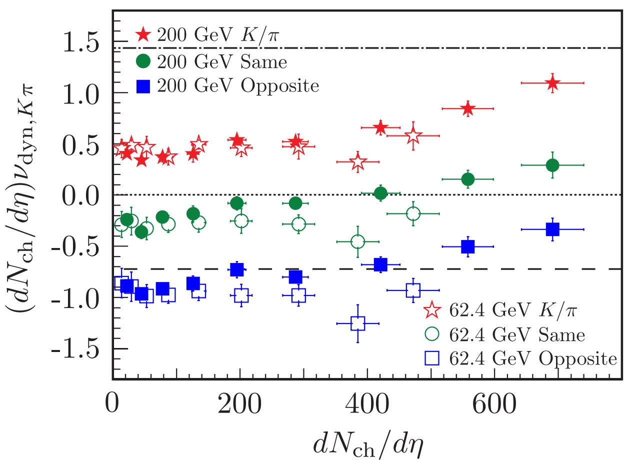
And more :

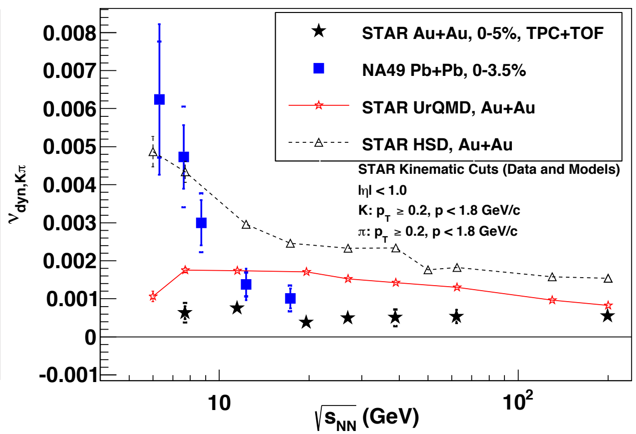
- ➢ Low mass dielectrons and heavy flavor hadrons
- ➢ Production of quarkonia
- ➢ Production of (anti) nuclei and hyper-nuclei as well as exotic hadronic states
- ➢ …

BACKUP

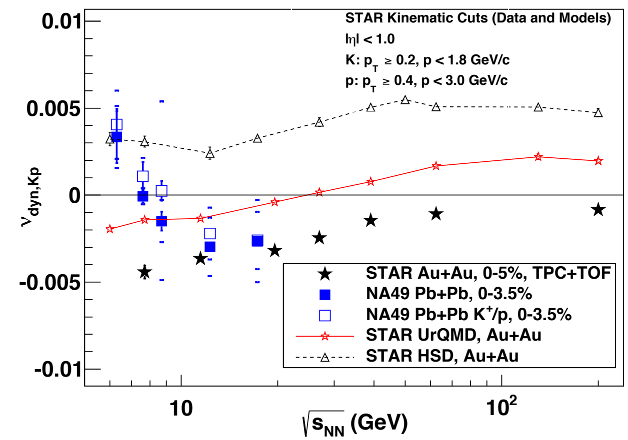
ν_{dyn}: STAR vs NA49

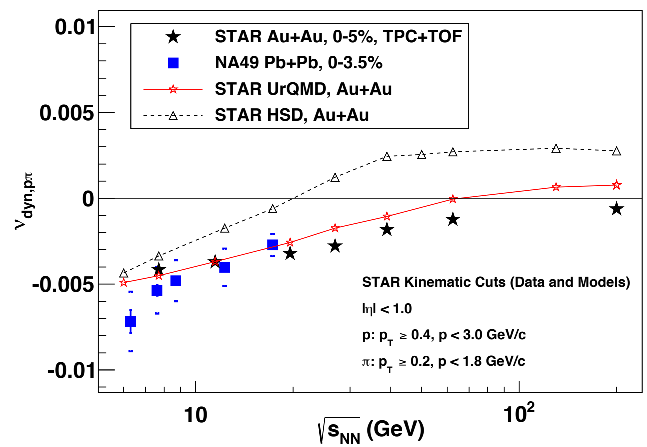
PRL 103, 092301 (2009)





Phys. Rev. C 92, 021901 (2015)





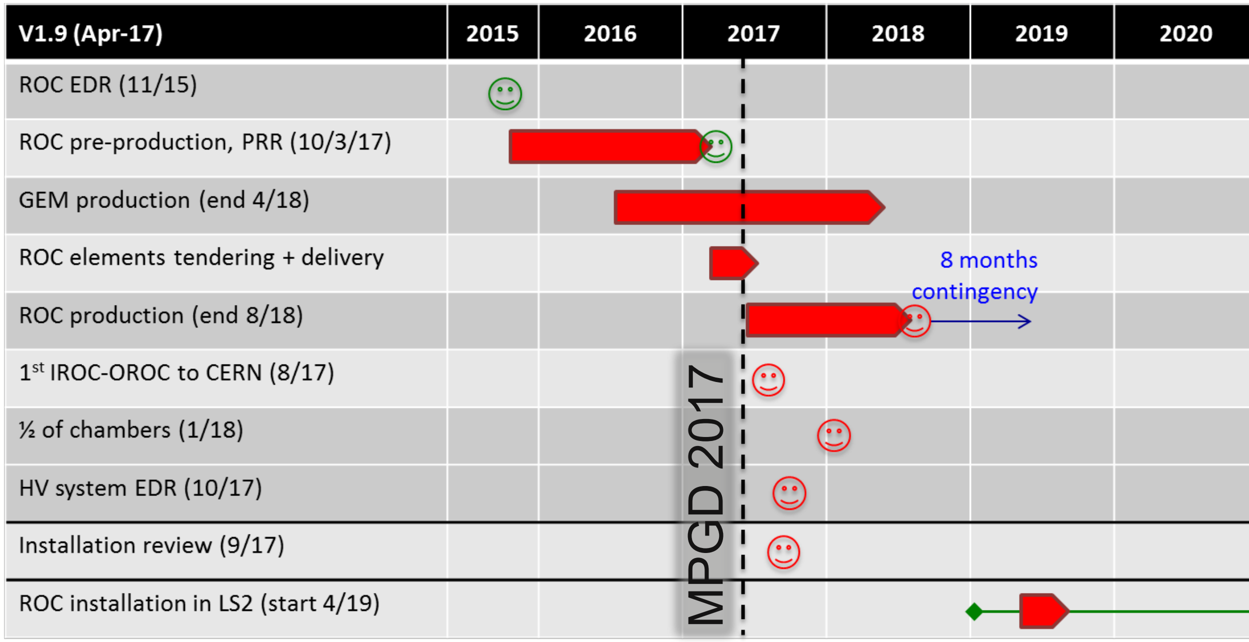
HIJING: independent superposition of p-p interactions

AMPT: HIJING + collectivity

- ✧ **String melting:** Quark coalescence
- ✧ **Hadronic rescattering:** Additional resonances

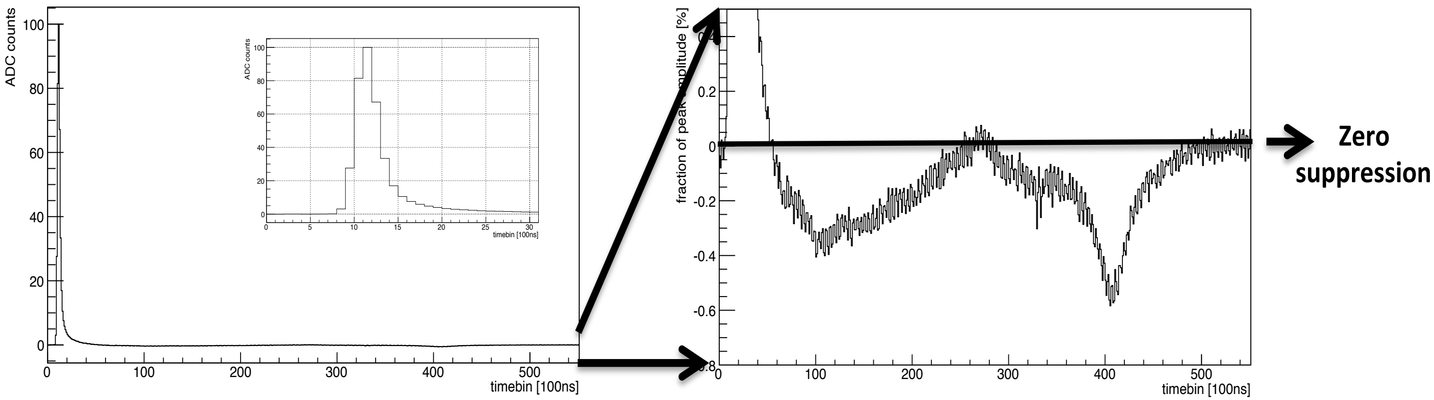
UrQMD: strings → heavy baryonic and mesonic resonances → light hadrons such as K, π

HSD: strings → decay directly to 'light' hadrons (from the pseudoscalar meson octet) or the vector mesons ρ, ω and K* (or the baryon octet and decouplet in case of baryon number ±1)



Gas	Drift velocity v_d (cm/μs)	Diffusion coeff. D_L ($\sqrt{\text{cm}}$)	D_T ($\sqrt{\text{cm}}$)	$\omega\tau$	Eff. ionization energy W_i (eV)	Number of electrons per MIP N_p (primary) (e/cm)	N_t (total) (e/cm)
$Ne-CO_2-N_2$ (90-10-5)	2.58	0.0221	0.0209	0.32	37.3	14.0	36.1
$Ne-CO_2$ (90-10)	2.73	0.0231	0.0208	0.34	38.1	13.3	36.8
$Ar-CO_2$ (90-10)	3.31	0.0262	0.0221	0.43	28.8	26.4	74.8
$Ne-CF_4$ (80-20)	8.41	0.0131	0.0111	1.84	37.3	20.5	54.1

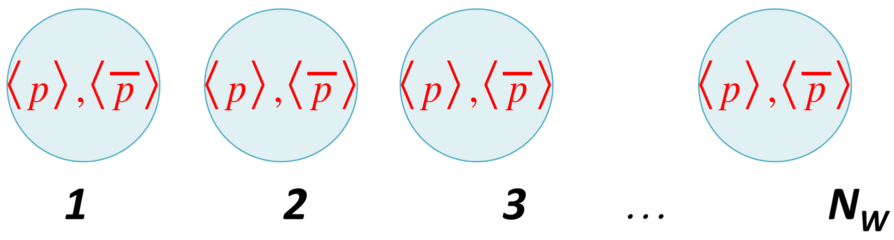
Ion-tail Effect

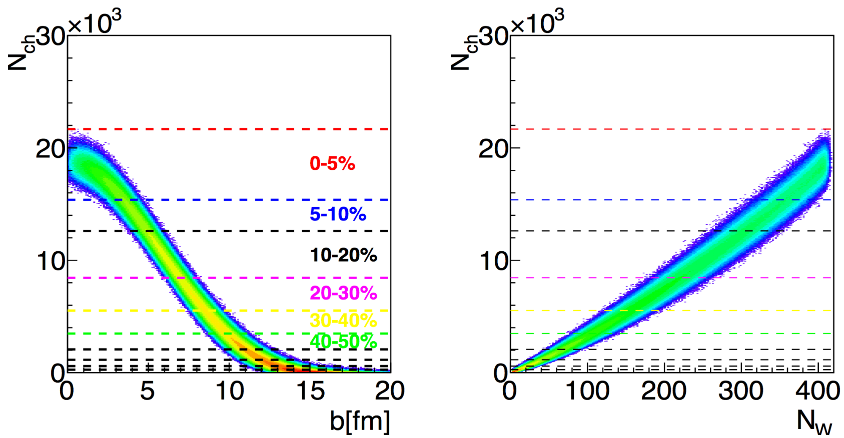


Ion-tail
Along time direction

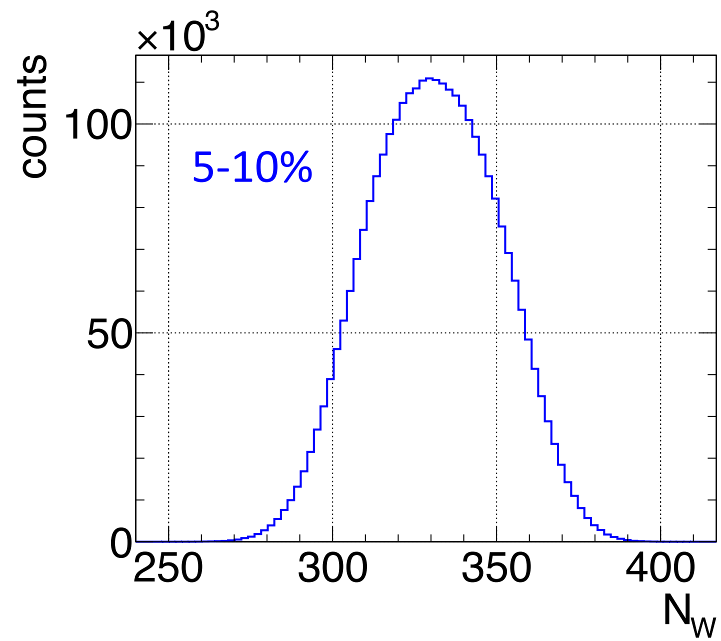
Worsening of dE/dx resolution and cluster loss

Modeling Participant Fluctuations



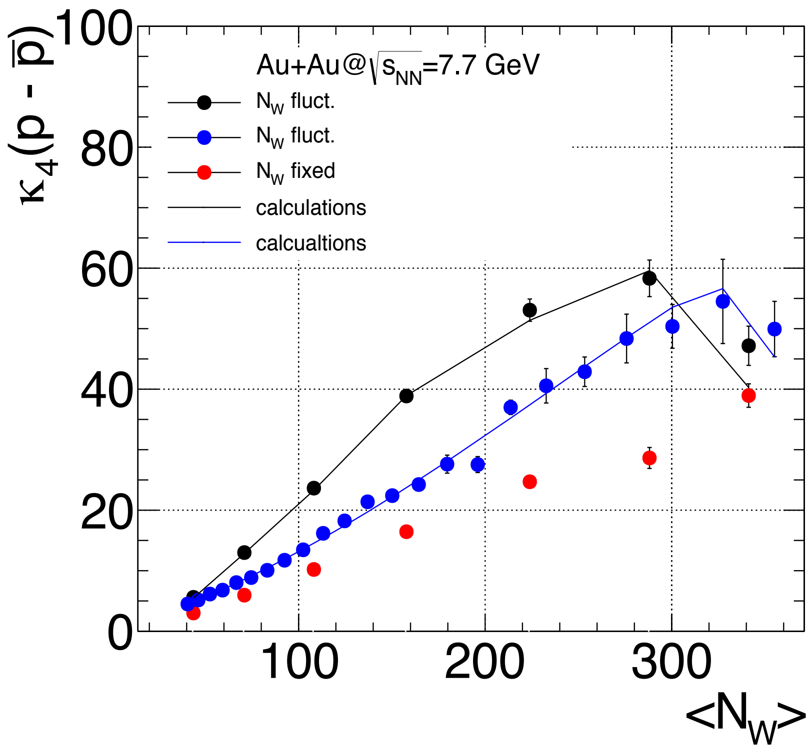


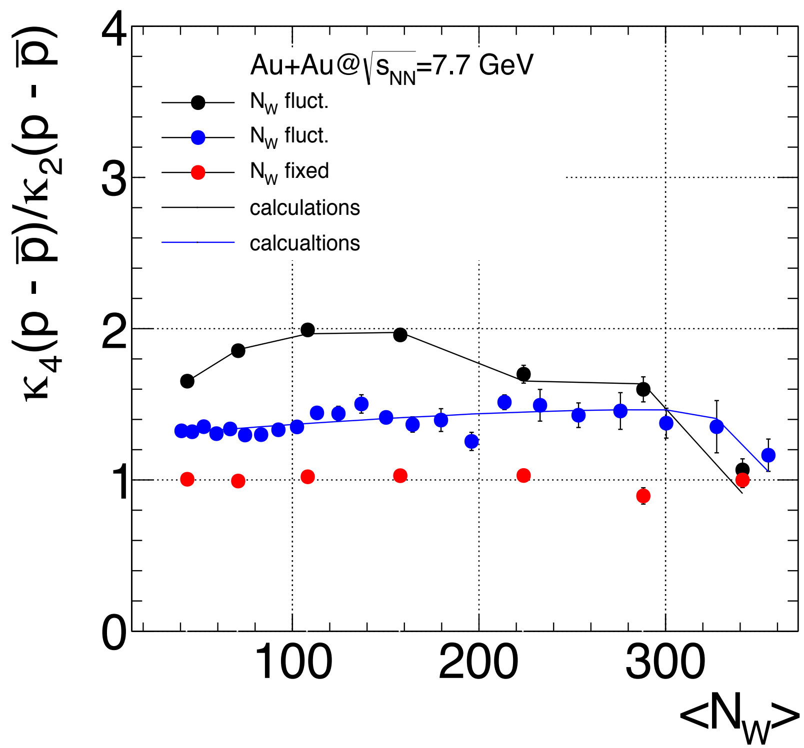
- ***N_W fluctuates with MC Glauber initial conditions***
- ***Each source is treated Grand Canonically***
- ***Mean proton multiplicities*** $\langle p \rangle$, $\langle \overline{p} \rangle$ ***from real data***
- ***Centrality selection like in experimental data***
- ***Expected results without volume fluctuations:***
  - Particles: $k_n = N_w \langle n \rangle = \langle p \rangle = \langle \overline{p} \rangle$
  - net-particles: $k_n = \langle p \rangle + (-1)^n \langle \overline{p} \rangle$



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

RHIC Energies

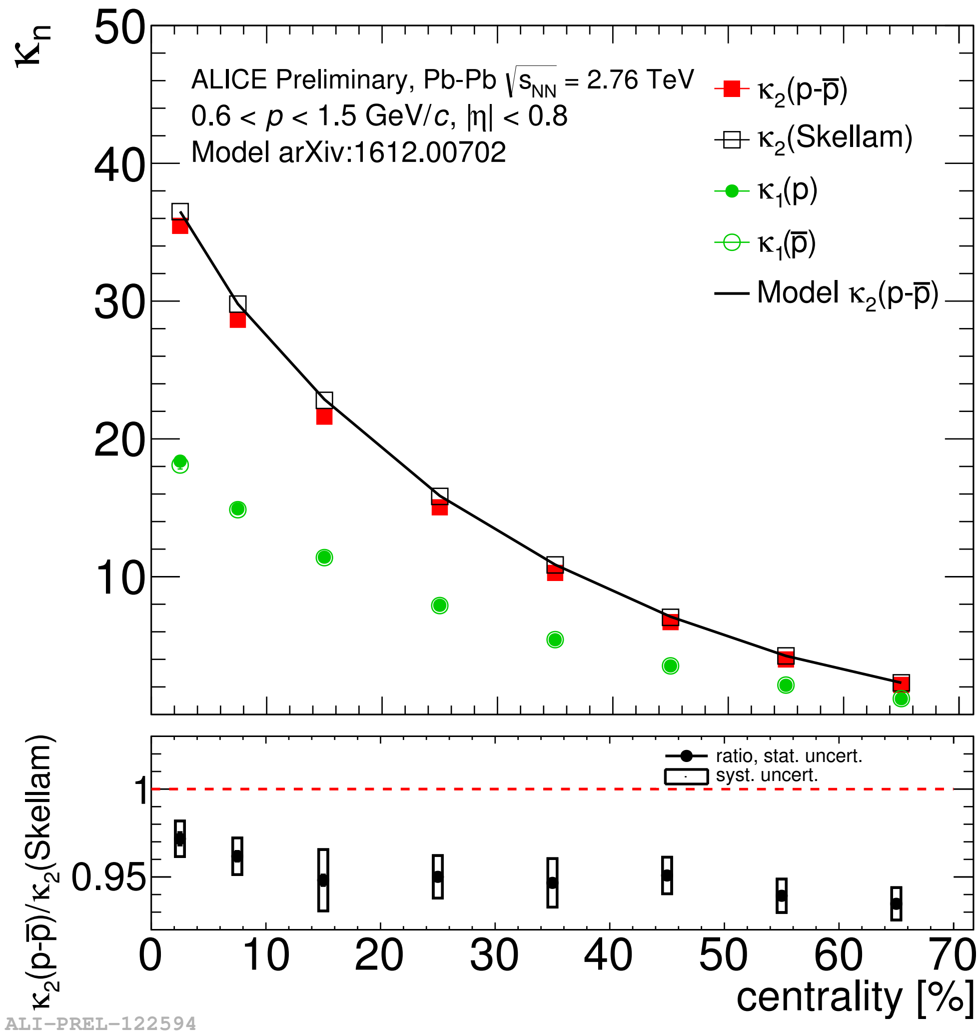




✧ **Solution for volume fluct. : Centrality bin width correction ???**

- Subdividing a given centrality bin into smaller ones and then merging them together incoherently.
- Incoherent addition of data from intervals with very small centrality bin width will eliminate true dynamical fluctuations.

`Model` vs ALICE data



Input to the Model

$\kappa_1(p)$, $\kappa_1(\bar{p})$

centrality selection procedure

Predictions

———— $\kappa_2(p-\bar{p})$

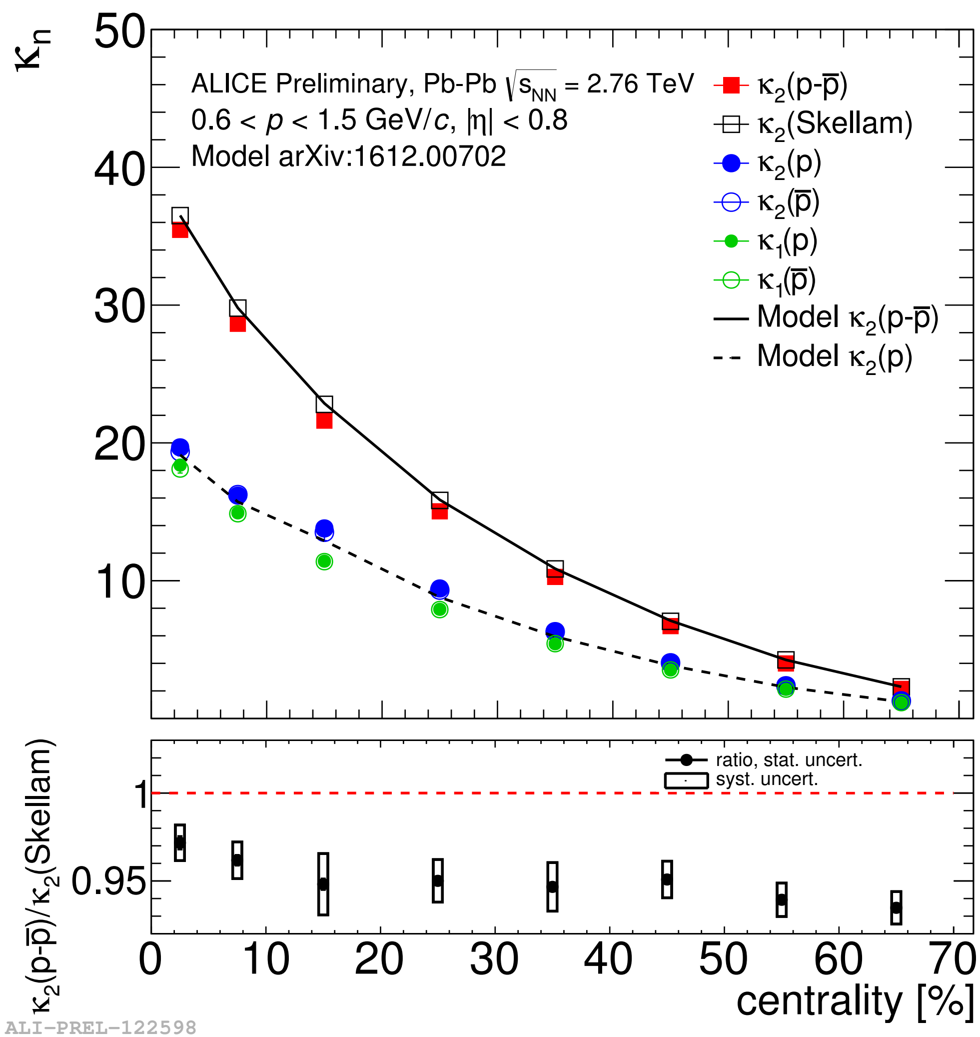
participants　　　vanishes at LHC

$$\kappa_2(N_B - N_{\bar{B}}) = \langle N_W \rangle \kappa_2(n_B - n_{\bar{B}}) + \langle n_B - n_{\bar{B}} \rangle^2 \kappa_2(N_W)$$

from single participant

Second cumulants of net-particles at LHC are not affected by participant fluctuations

`Model` vs ALICE data



Input to the Model

$\kappa_1(p),\ \kappa_1(\bar{p})$

centrality selection procedure

Predictions

———— $\kappa_2(p-\bar{p})$

- - - - - $\kappa_2(p)$

participants

$$\kappa_2(N_B) = \langle N_W \rangle \kappa_2(n_B) + \langle n_B \rangle^2 \kappa_2(N_W)$$

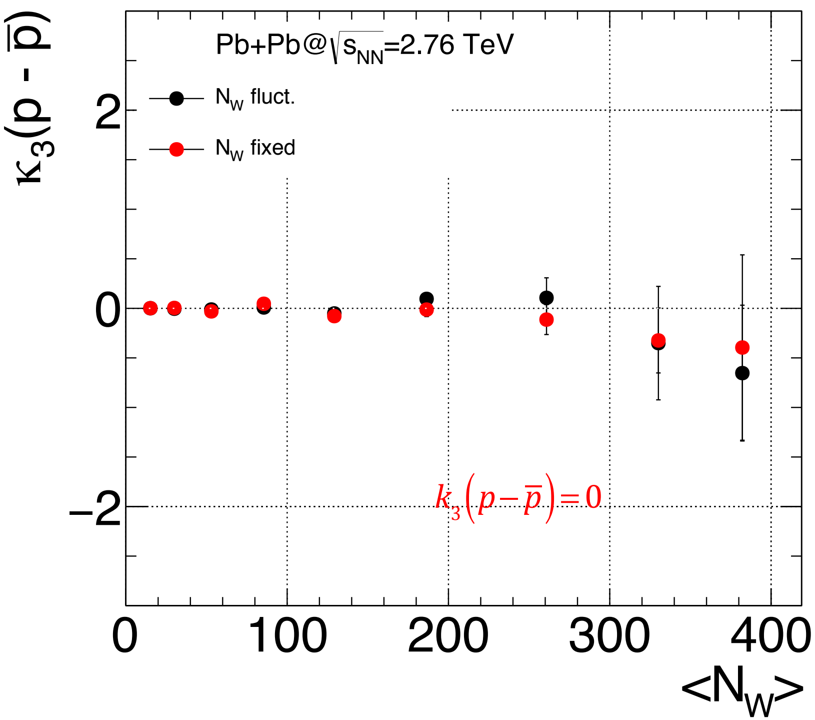
from single participant

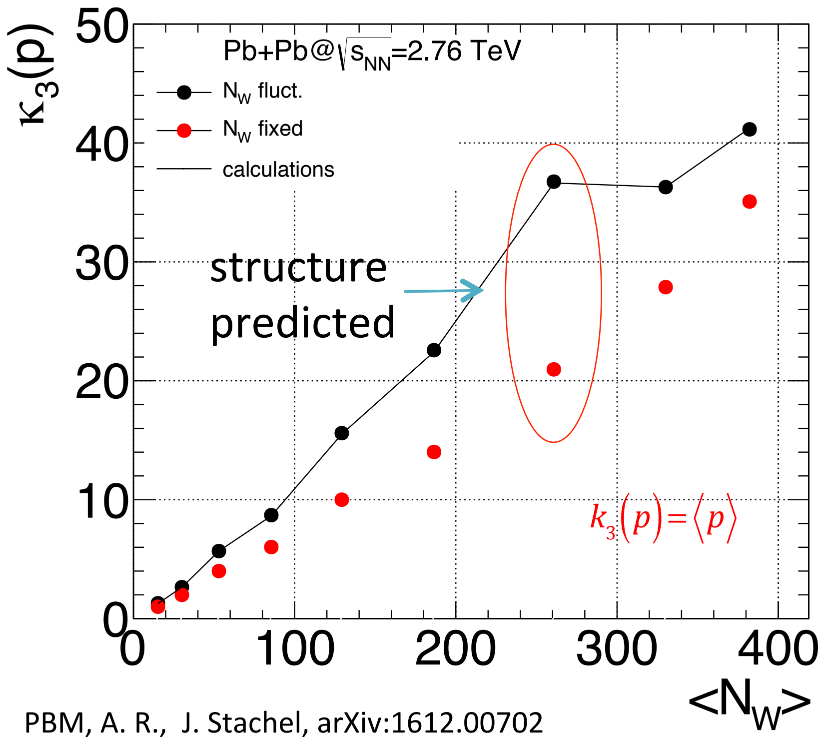
Consistent predictions for net-protons, protons and antiprotons

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

LHC Energies

150*10^6 Events





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

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

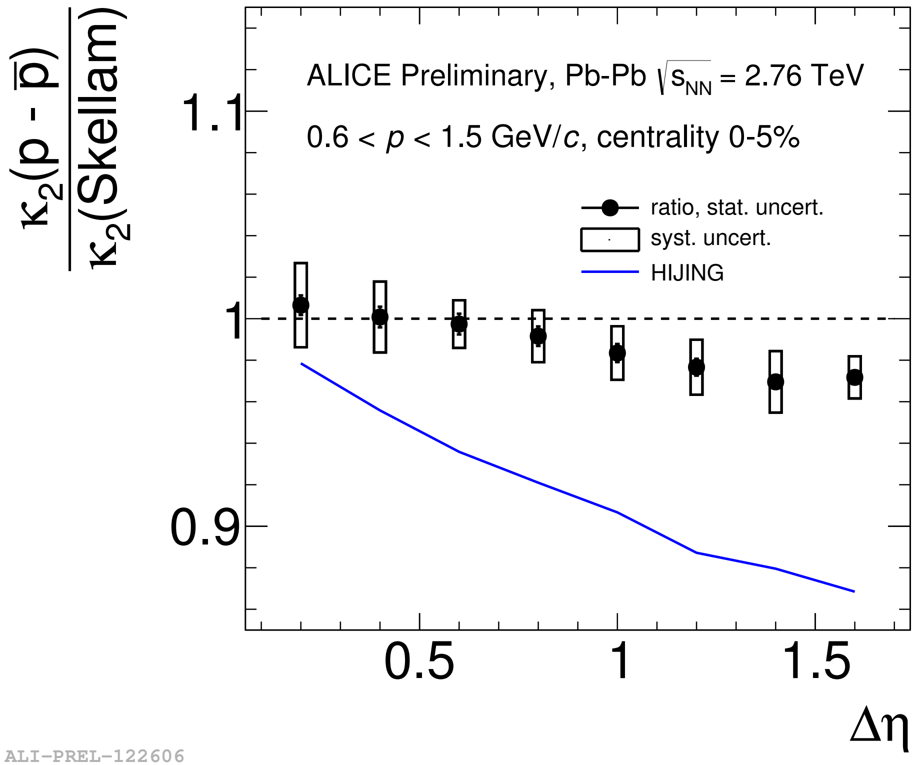
vanishes for ALICE

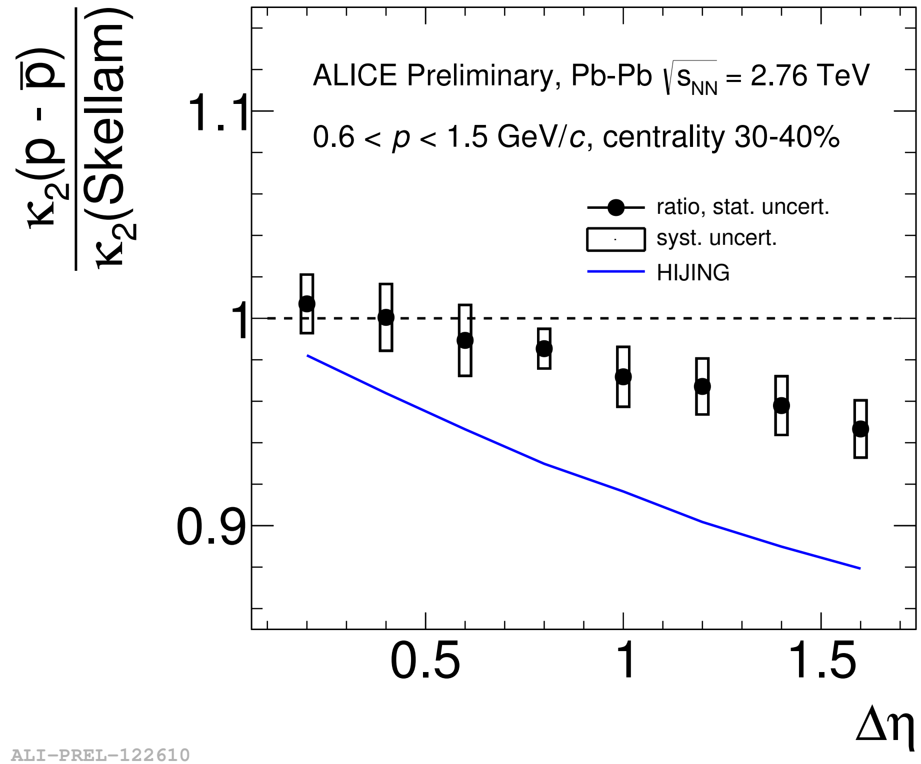
$$k_3(p)=\langle N_w\rangle k_3(n)+\langle n\rangle(...)$$

does not vanish

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

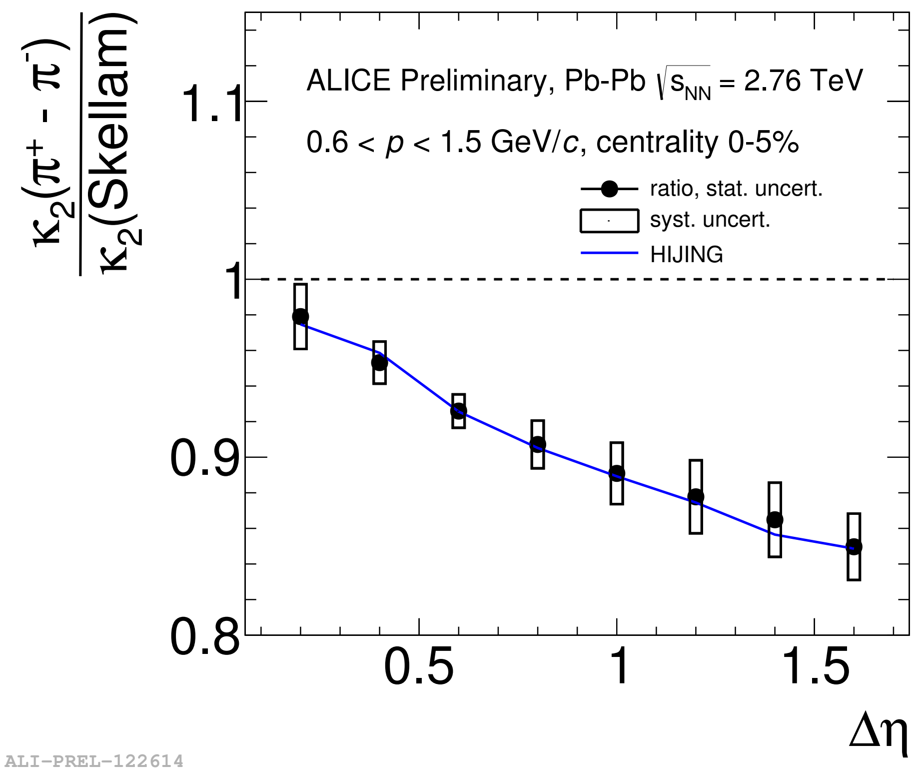
Acceptance and centrality dependence

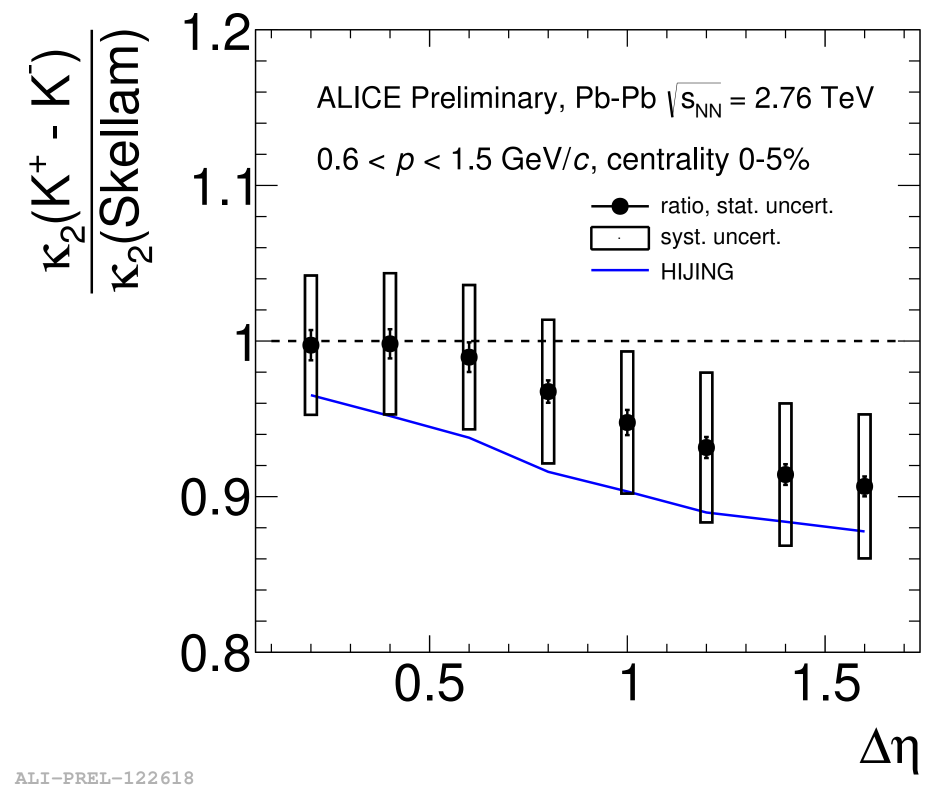




Effect of global baryon number conservation is more significant in peripheral collisions

Net-pions and Net-kaons





perfect agreement with HIJING

reasonable agreement with HIJING

resonance pion and kaon production is likely to explain the measured trend

<u>Warning:</u> **Skellam is not a proper baseline for net-pions and net-kaons**

Efficiency Correction

$$\kappa_2(n-\overline{n})\_\nu_{dyn} = \nu_{dyn}\left[N_+, N_-\right] * \left\langle N \right\rangle^2 + 2\left\langle N \right\rangle$$

$$\left\langle N_+ \right\rangle \approx \left\langle N_- \right\rangle = \left\langle N \right\rangle = \frac{\left\langle N_+ \right\rangle + \left\langle N_- \right\rangle}{2}$$

ν_{dyn} is robust against efficiency losses
only mean multiplicities will be corrected

ITS Upgrade: Low mass dielectrons

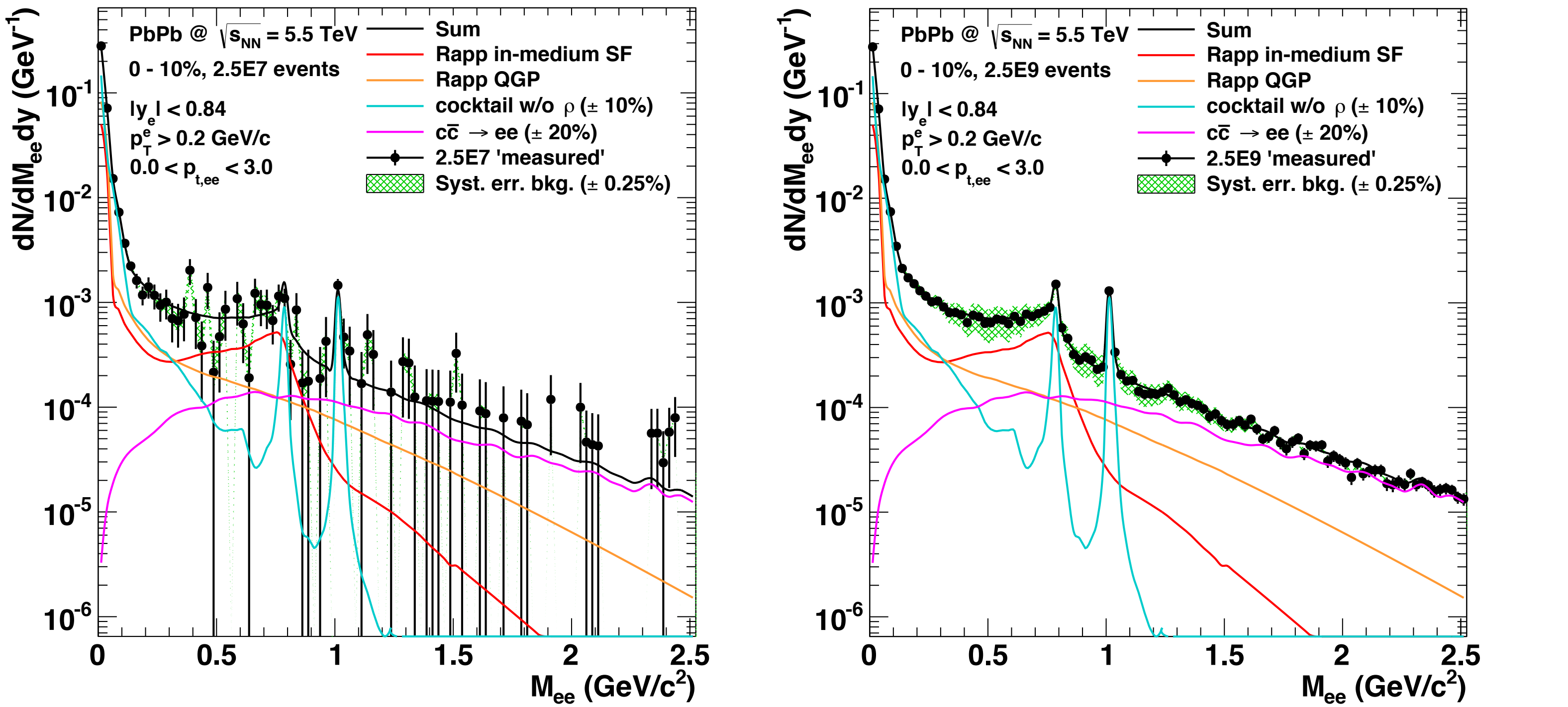
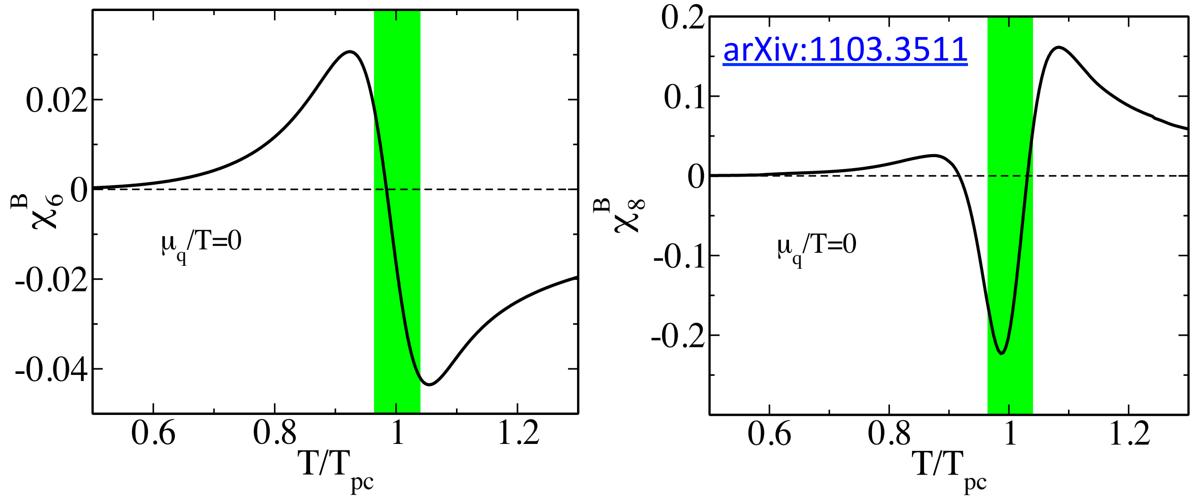


Figure 1.1: Inclusive e^+e^- invariant mass spectrum for $0-10\,\%$ most central Pb–Pb collisions at $\sqrt{s_{NN}} = 5.5\,\text{TeV}$, assuming $2.5 \cdot 10^7$ events (left panel) and $2.5 \cdot 10^9$ events (right panel). The spectra include a set of tight primary track cuts based on the new ITS system to suppress leptons from charm decays. Also shown are curves that represent the contributions from light hadrons (blue), charm (magenta) and thermal radiation from a hadronic gas (red) and a QGP (orange). The figures are from [2].



freeze-out conditions	χ_4^B/χ_2^B	χ_6^B/χ_2^B	χ_4^Q/χ_2^Q	χ_6^Q/χ_2^Q
HRG	1	1	~ 2	~ 10
QCD: $T^{freeze}/T_{pc} \lesssim 0.9$	$\gtrsim 1$	$\gtrsim 1$	~ 2	~ 10
QCD: $T^{freeze}/T_{pc} \simeq 1$	~ 0.5	< 0	~ 1	< 0

Table 1: Values for ratios of cumulants of net baryon number (B) and electric charge (Q) fluctuations for the case that freeze-out appears well in the hadronic phase (third row) or in the vicinity of the chiral crossover temperature (fourth row). We give results based on current lattice calculations [20, 33] and on the calculations presented here. In the second row we give results of a HRG model calculation [33]. We also note that unlike the cumulants of net baryon number fluctuations the ratios of cumulants of electric charge fluctuations vary somewhat as a function of the baryon chemical potential along the freeze-out line.