Katarzyna Grebieszkow
Warsaw University of Technology

for the NA61/SHINE Collaboration

Methods of studying event-by-event transverse momentum and multiplicity fluctuations, and two-particle correlations in Δη, Δϕ in NA61/SHINE

"HIC for FAIR Workshop on Fluctuation and Correlation Measures in Nuclear Collisions 2015"
July 29-31, 2015, Frankfurt, Germany

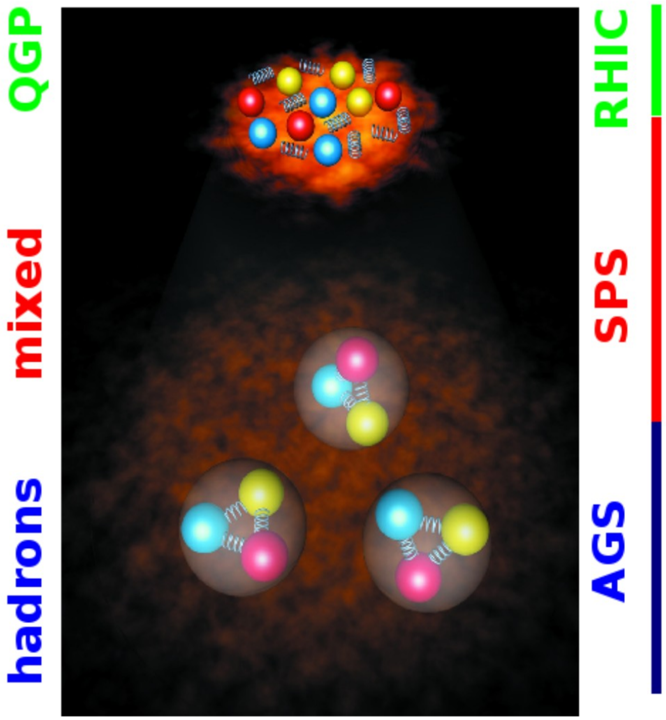
Fluctuations and correlations:

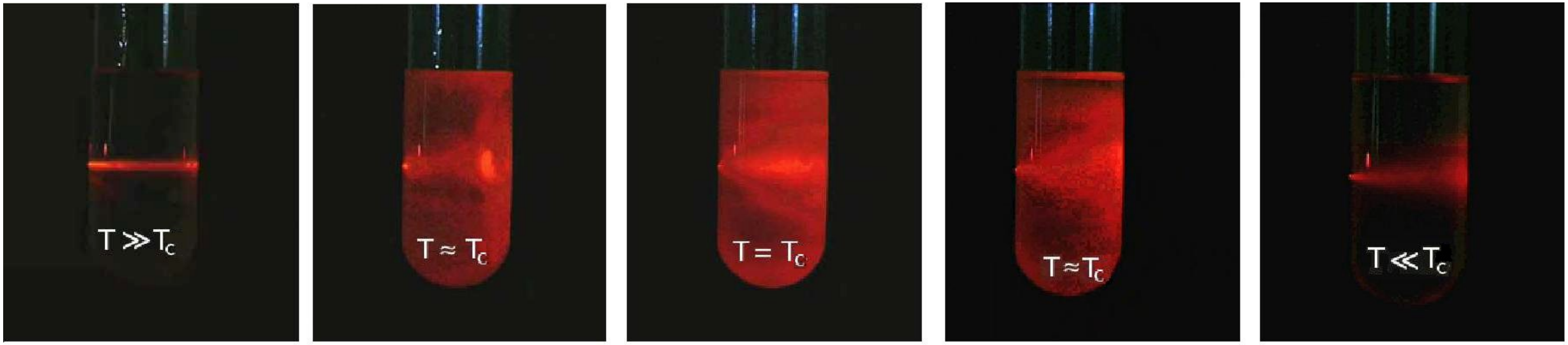
- **May serve as a signature of the onset of deconfinement**

Close to the phase transition Equation of State changes rapidly which can impact energy dependence of fluctuations

- **Can help to locate the critical point of strongly interacting matter**

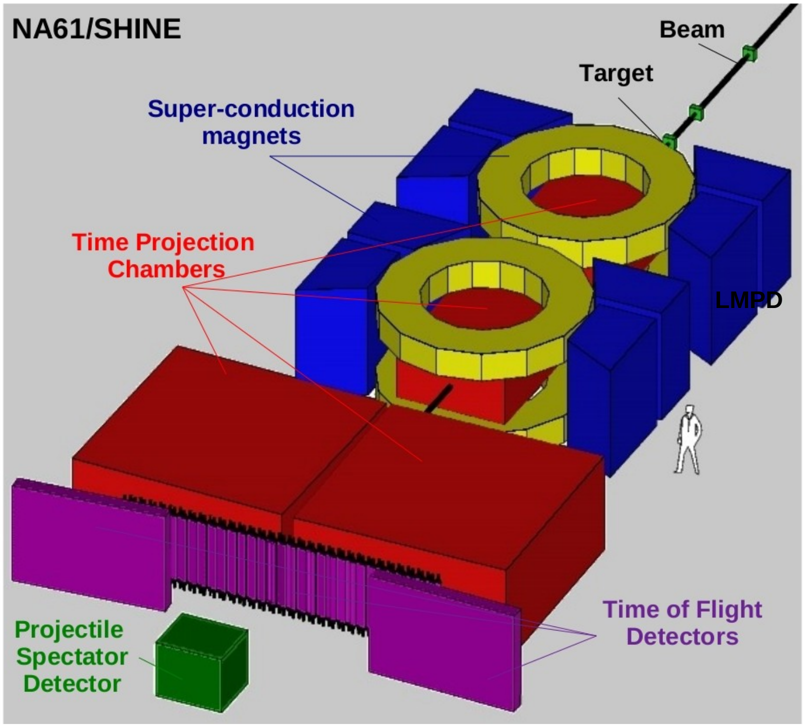
Analogy to critical opalescence – enlarged fluctuations close to the critical point. For strongly interacting matter maximum of CP signal expected when freeze-out happens near CP





http://www.msm.cam.ac.uk/doitpoms/tlplib/solid-solutions/videos/laser1.mov

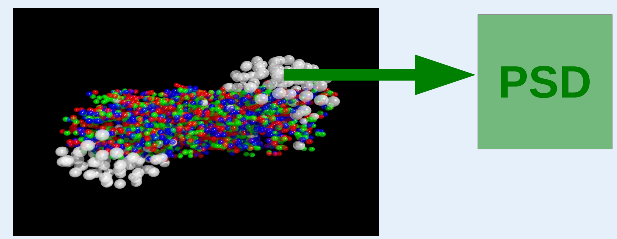
- Fixed target experiment in the north area of the CERN SPS
- Based on the upgraded NA49 detector; started in 2007



- Large acceptance: ≈ 50%
- High momentum resolution: $\sigma(p)/p^2 \approx 10^{-4}(\mathrm{GeV/c})^{-1}$ (at full B=9 T·m)
- ToF walls resolution: ToF-L/R: $\sigma(t) \approx 60$ ps; ToF-F: $\sigma(t) \approx 120$ ps
- Good particle identification: $\sigma(dE/dx)/\langle dE/dx\rangle \approx 0.04$; $\sigma(m_{inv}) \approx 5$ MeV
- High detector efficiency: > 95%
- Event rate: 70 events/sec

- Four large volume **Time Projection Chambers (TPCs)**: VTPC-1, VTPC-2 (inside superconducting magnets), MTPC-L, MTPC-R; measurement of dE/dx and p. **Time of Flight (ToF)** detector walls

- **Projectile Spectator Detector (PSD)** for centrality measurement (energy of projectile spectators) and determination of reaction plane; **resolution of 1 nucleon (!)** in the studied energy range (important for fluctuation analysis)



- **Helium beam pipes** inside VTPC-1 and VTPC-2 (to reduce δ-electrons)

- **Z-detector** (measures ion charge for on-line selection of secondary ions, **A-detector** (measures mass composition of secondary ion beam)

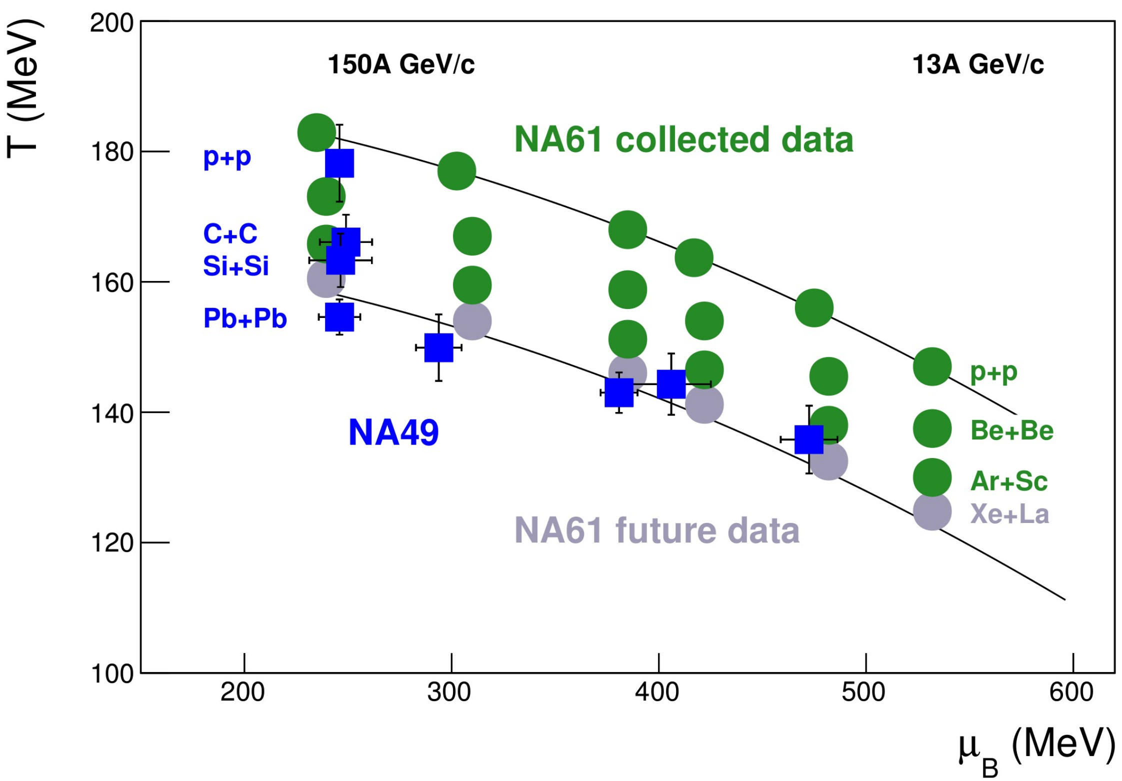
- Low Momentum Particle Detector (**LMPD**) for centrality determination in p+A; measures target nucleus spectators

- Planned: **Vertex Detector** (for open charm measurement)

NA61/SHINE strong interactions program (continuation of NA49 efforts)

The most interesting region of the phase diagram is accessible at the SPS

- Onset of deconfinement at ≅ 30A GeV PR C77, 024903 (2008)
- Critical point? Example: $(T^{CP}, \mu_B^{CP}) = (162(2), 360(40))$ MeV JHEP 0404, 050 (2004)



Estimated (NA49) and expected (NA61) chemical freeze-out points according to PR C73, 044905 (2006)

Comprehensive scan in the whole SPS energy range (13A-150/158A GeV) with **light and intermediate mass nuclei**

- **Search for the critical point**
  Search for a maximum of CP signatures: fluctuations of N, average p_T, etc., intermittency, when system freezes out close to CP

- **Study of the properties of the onset of deconfinement**
  Search for the onset of the horn/kink/step/dale in collisions of light nuclei; additional analysis of fluctuations and correlations (azimuthal, particle ratios, etc.)

History

How we **were** measuring chemical, p_T, and multiplicity fluctuations (in NA49)

Fig. from http://en.wikipedia.org/wiki/Big_History

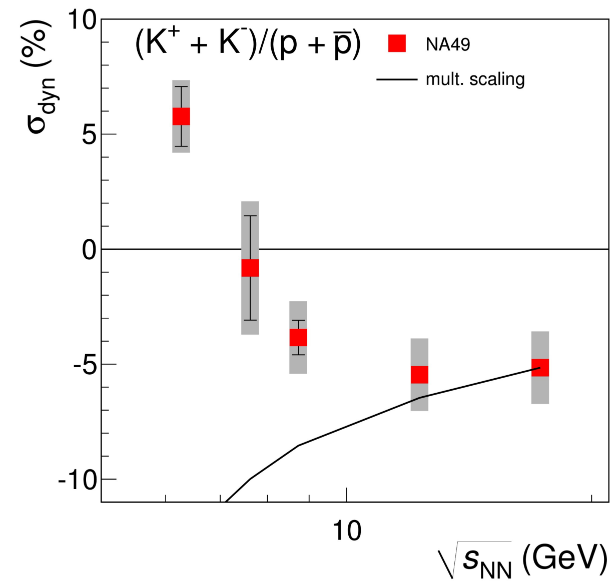
Chemical (particle type) fluctuations

σ_{dyn} measure of particle ratio fluctuations (K/π, p/π, K/p)

☹ **$\sigma^2_{dyn} \sim 1/N_W$** (PR C81, 034910 (2010), PR C84, 014904 (2011))

⇒ σ_{dyn}(K/π) (increase at lower SPS energies) and σ_{dyn}(p/π) fully reproduced in multiplicity scaling model (PR C81, 034910 (2010); J. Phys. G38,124096 (2011))

σ_{dyn}(K/p) – *not* understood as due to multip. scaling (change of sign close to the onset of deconf. energy); see $\Phi_{p,K}$ later



☺ **σ_{dyn}** easy for interpretation

☹ Older NA49 results NOT corrected for the effect of misidentification

Multiplicity fluctuations

scaled variance of multiplicity distribution **ω[N]** (**intensive** – not dependent on N_W)

☺ Proper normalization (ω[N] = 1 for Poisson)

☹ NA49 results NOT corrected for detector inefficiencies and trigger bias

Transverse momentum fluctuations

Φ_{pT} measure (**strongly intensive** – not dependent on N_W and its fluctuations) ☺

☹ Lack of proper normalization

☺☹ NA49 results corrected for detector inefficiencies but NOT corrected for trigger bias

Modern times

How we **are** measuring chemical, [P_T, N], and multiplicity fluctuations

Fig. from http://letsbuildateamfast.blogspot.com/2012/10/importance-of-using-online-render-farm.html

Multiplicity ($\omega[N_i]$) and chemical ($\Phi_{i,j}$, ...) fluctuations of identified particles

Multiplicity and chemical fluctuations of identified particles

- **Instead of σ_{dyn} new strongly intensive measure Φ**

$$\Phi_{ij} = \frac{\sqrt{\langle N_i \rangle \langle N_j \rangle}}{\langle N_i \rangle + \langle N_j \rangle} \cdot \left[\sqrt{\Sigma[N_i, N_j]} - 1 \right]$$

$$\omega[N_i] = \frac{\langle N_i^2 \rangle - \langle N_i \rangle^2}{\langle N_i \rangle}$$

$$\Sigma[N_i, N_j] = C_\Sigma^{-1} \left[\langle N_i \rangle \omega[N_j] + \langle N_j \rangle \omega[N_i] - 2 \left(\langle N_i N_j \rangle - \langle N_i \rangle \langle N_j \rangle \right) \right]$$

$$C_\Sigma = \langle N_i \rangle + \langle N_j \rangle$$

For Poisson multip. distrib. $\omega[N] = 1$
Intensive measure: in WNM
$\omega[N]$ independent of N_W but
dependent on fluctuations of N_W

For independent particle emission $\Phi_{ij} = 0$
Strongly intensive measure: in WNM
Φ_{ij} independent of N_W and fluctuations of N_W

- **New "identity method"**

In experiment chemical fluctuations of multiplicities of identified particles may be distorted by incomplete particle identification

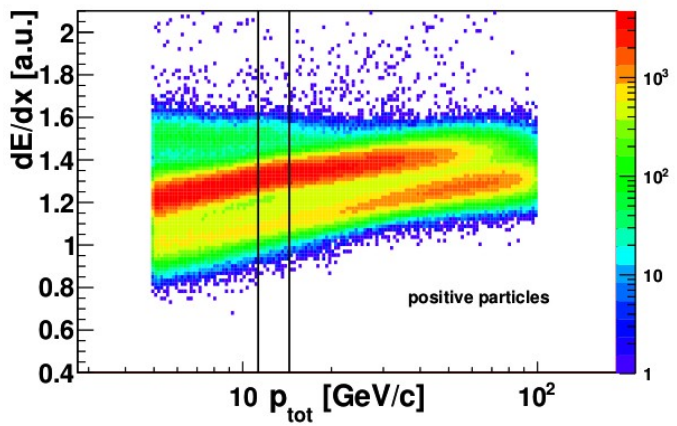
Results on chemical fluctuations in NA49 and NA61 presented below are **corrected for misidentification using the unfolding procedure of the identity method:**

PR C83, 054907 (2011), PR C84, 024902 (2011), PR C86, 044906 (2012)

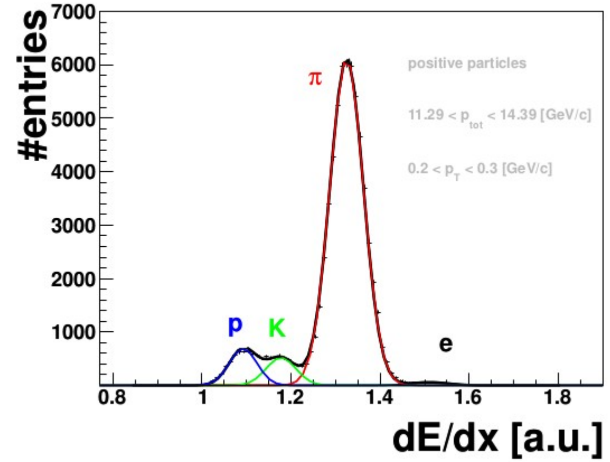
Fluctuations cannot be corrected for the limited acceptance → results are presented in NA61 acceptance (https://edms.cern.ch/document/1237791/1)

Identity method

In experiment chemical fluctuations of multiplicities of identified particles may be distorted by incomplete particle identification



Inclusive dE/dx spectra is sliced in p_{tot}, p_T bins.



sum of Gaussian functions is fitted in each phase-space bin.

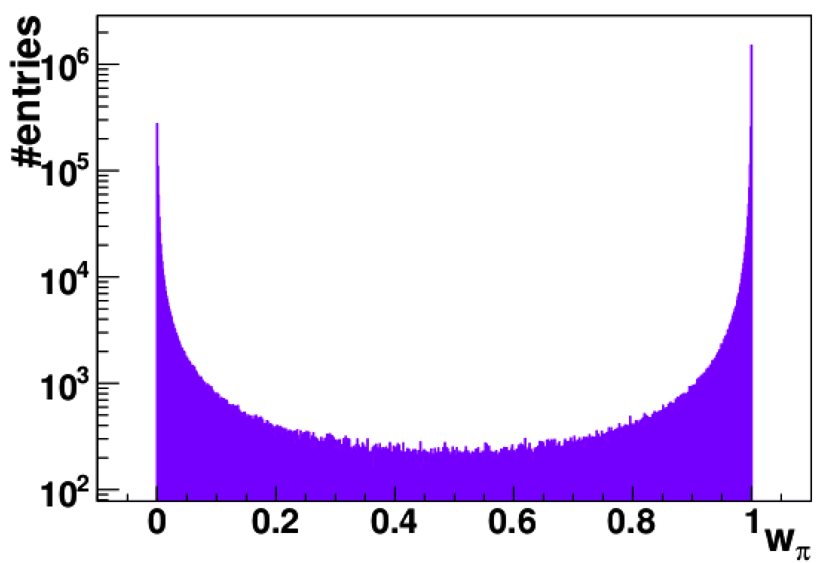
The identity method allows to obtain second and third moments (pure and mixed) of identified particle multiplicity distributions corrected for misidentification effect

Using dE/dx fit a particle identity is calculated as:

$$w_i = \frac{\rho_i(dE/dx)}{\rho(dE/dx)},$$

where ρ_i - function fitted to $i'th$ particle type and ρ - function fitted to total dE/dx distribution in a given phase-space bin (i: π, p, K)

single particle identity

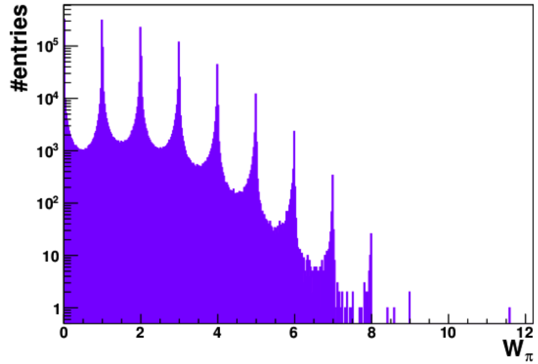


event identity measure

Event quantity W_i defined as:

$$W_i = \Sigma w_i,$$

where summation runs over all particles in an event



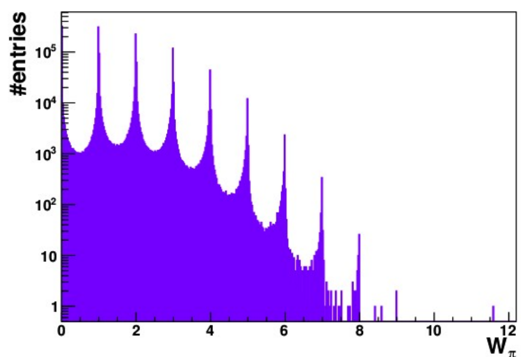
example for p+p at 17.3 GeV

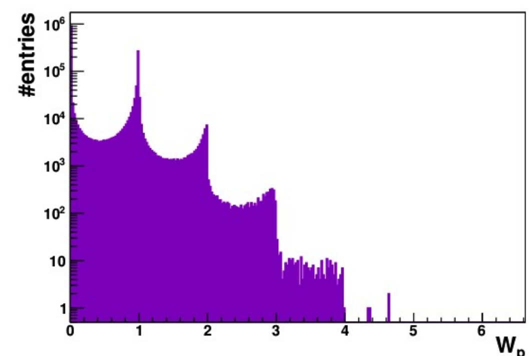
Details of identity method:
PR C83, 054907
PR C84, 024902
PR C86, 044906

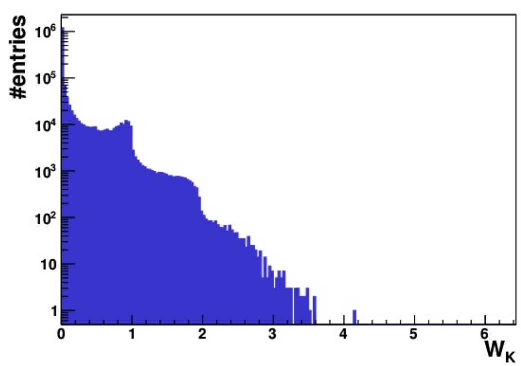
Once, detector response (ρ_i) and W distributions are known the identity method is used to obtain moments of identified particle multiplicity distributions.

$$\rho_i, W_i, \ldots \rightarrow \langle N_i^2 \rangle, \langle N_i N_j \rangle$$

See **PR C84, 024902 (2011)**, PR C86, 044906 (2012) for the details of the matrix used in calculations





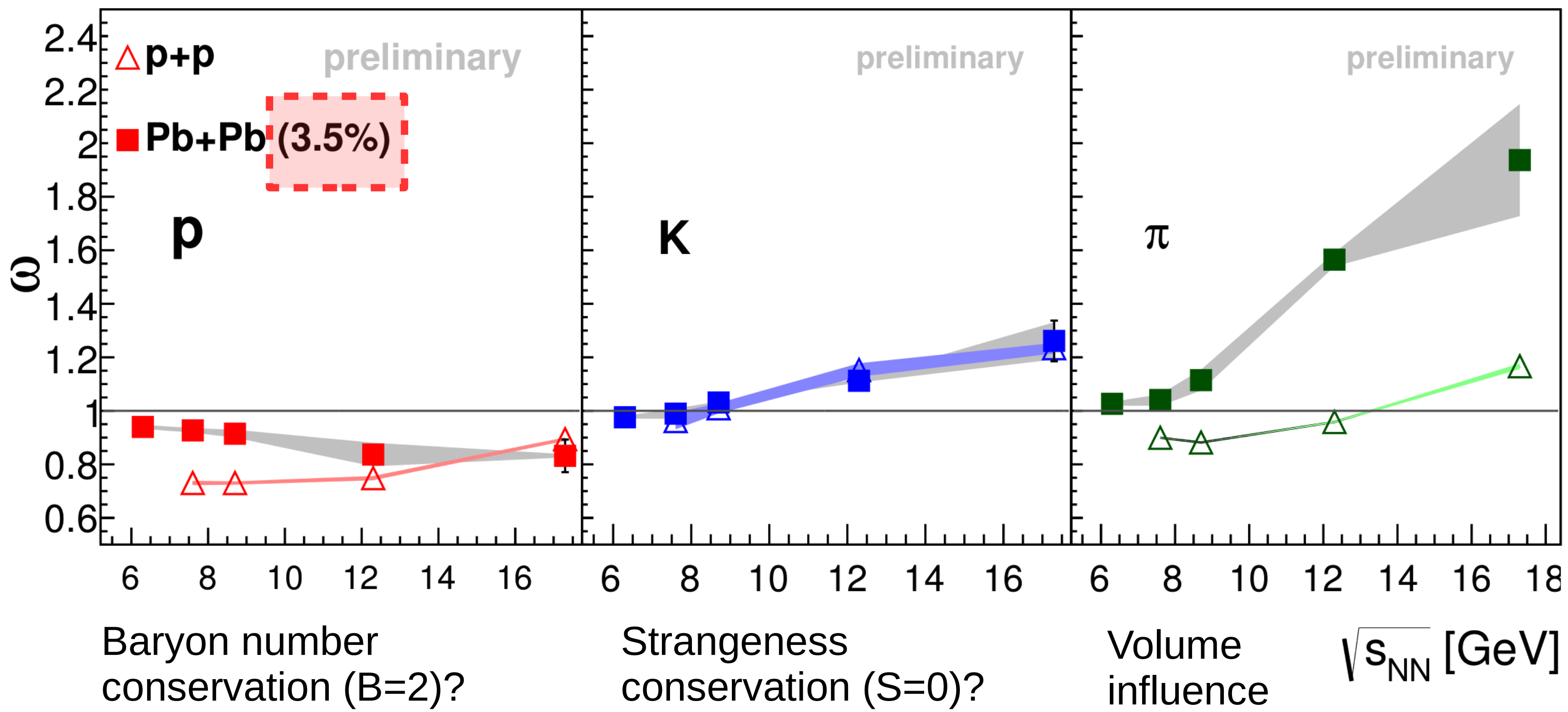


For perfect particle identification W_i distribution equals the multiplicity distribution

For particles with larger PID contamination (like K) W_i distribution gets smoother.

Example for p+p at $\sqrt{s_{NN}} = 17.3$ GeV

Scaled variance of multiplicity distribution:
comparison of p+p (NA61) with central Pb+Pb (NA49) collisions



M. Gaździcki, P. Seyboth, arXiv:1506.08141
More results: PoS (CPOD 2013) 004 and 048

- **$\omega[N_\pi]$ in 3.5% Pb+Pb larger than in p+p, probably due to volume fluctuations**

  → $\omega[N]$ is intensive, but not strongly intensive measure of fluctuations
  (in WNM $\omega[N]$ is independent of N_W but dependent on fluctuations of N_W)

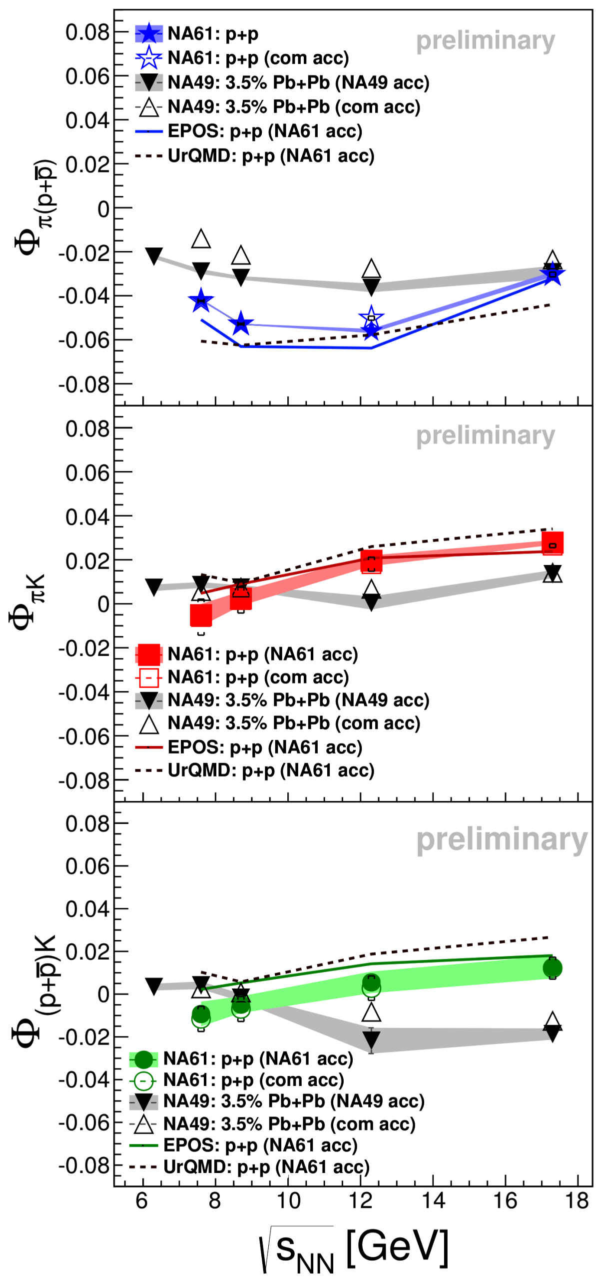
$\omega[N](N_S$ sources$) = \omega[N](1$ source$) + \langle n \rangle \omega_{Ns}$ WNM: $N_S \equiv N_W$

$\langle n \rangle$ - mean multiplicity from a single source

ω_{Ns} - fluctuations in N_S

$\langle n \rangle$ for π > $\langle n \rangle$ for K or p $\Rightarrow$ effect of volume fluctuations better seen for $\omega[N_\pi]$

Φ measure of chemical fluctuations: comparison of p+p (NA61) with central Pb+Pb (NA49)

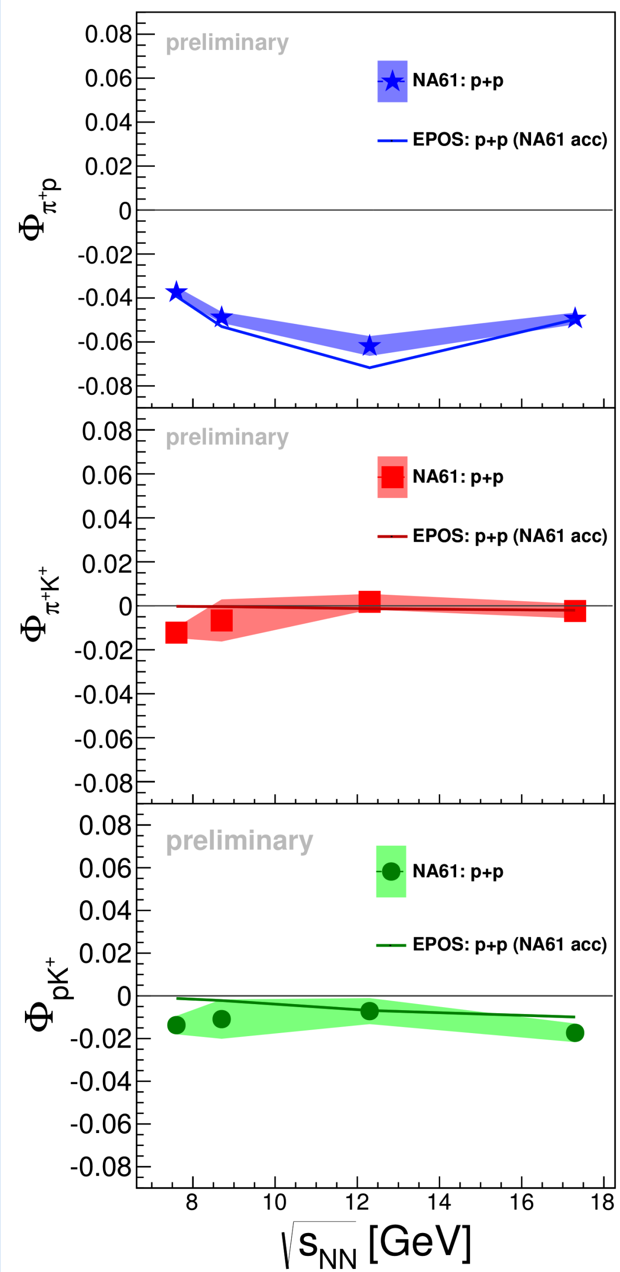


- **$\Phi_{\pi(p+\bar{p})}$ and $\Phi_{\pi+p} < 0$** most probably due to **charge conservation and resonance decays** (PR C70, 064903 (2004)). Similar tendency for NA61 p+p and NA49 Pb+Pb

- In p+p **$\Phi_{\pi K} > 0$** probably due to **strangeness conservation** (**$\Phi_{\pi+K+}$ close to 0** supports this interpretation). For p+p $\Phi_{\pi K}$ slightly increases with energy; such effect not visible for NA49 Pb+Pb

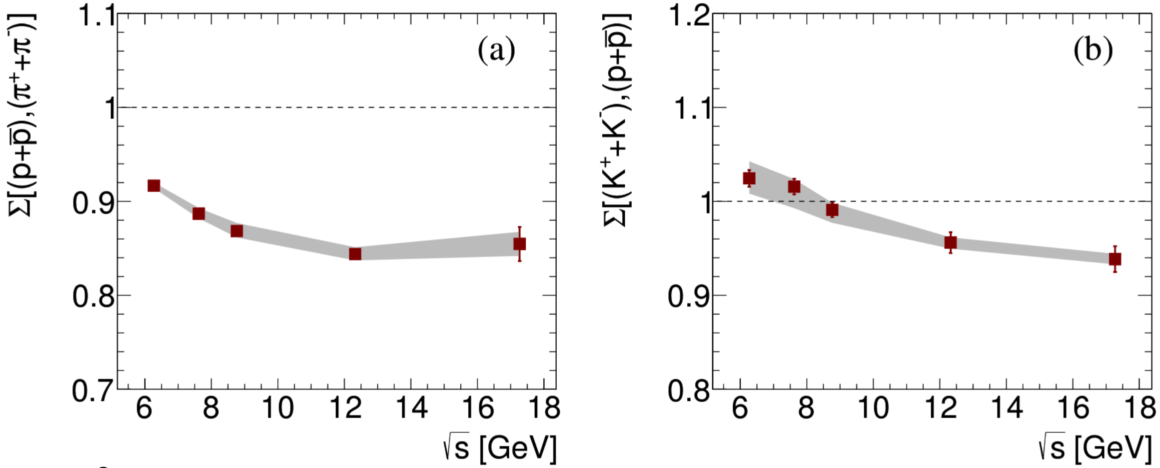
- **Very weak increase of $\Phi_{(p+\bar{p})K}$ with energy in p+p** data, whereas for Pb+Pb $\Phi_{(p+\bar{p})K}$ decreases with energy (high momentum part removed from NA49 Pb+Pb data). **For both systems $\Phi_{(p+\bar{p})K}$ crosses zero at middle SPS energies.** No energy dependence of Φ_{pK+}

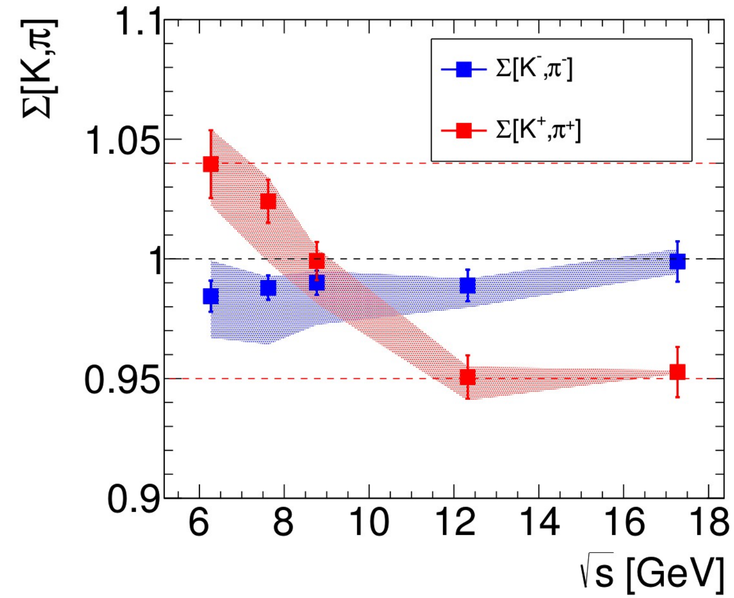
- EPOS and UrQMD model predictions are similar to measurements in p+p



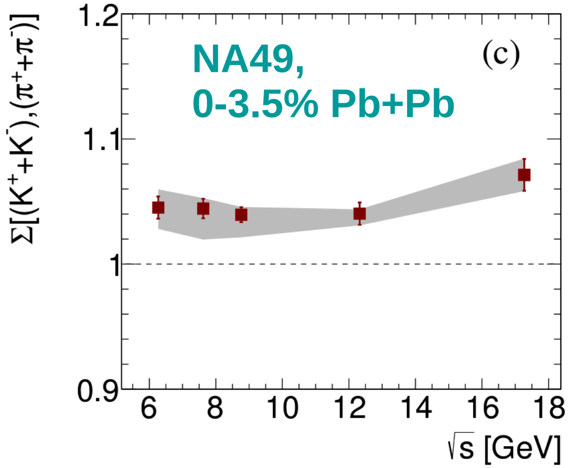
PoS (CPOD 2013) 004 and 048

Other strongly intensive measures of fluctuations ($\Delta[N_i, N_j]$ and $\Sigma[N_i, N_j]$) **for identified particles** are being calculated in NA49 (A. Rustamov) and are planned in NA61 (M. Maćkowiak-Pawłowska)





A. Rustamov, NA49 and NA61
Collaboration Meeting, Paris, 05.2015
Results are NOT official !



In Grand Canonical Ensemble $\Sigma[N_i, N_j]$ does not depend on volume and volume fluctuations

No fluctuations: $\Sigma[N_i, N_j]=0$

Independent Particle Model: $\Sigma[N_i, N_j]=1$

Other plans in NA61: correct $\omega[N_i]$, Φ_{ij} and new planned measures $\Delta[N_i, N_j]$ and $\Sigma[N_i, N_j]$ **for losses of inelastic events (trigger bias) in p+p collisions.** Corrections will be done on the level of moments used to calculate fluctuation measures (M. Maćkowiak-Pawłowska)

Transverse momentum and multiplicity ($\Delta[P_T, N]$, $\Sigma[P_T, N]$) fluctuations of non-identified particles

P_T and multiplicity fluctuations of non-identified particles

- **New strongly intensive measures Δ and Σ** (here applied to P_T and N fluctuations) → PR C88, 024907 (2013)
- **Novel method of correcting (NA61) results (ω, Δ[P_T, N], Σ[P_T, N], Φ_{pT}) for non-target interactions, detector inefficiencies and trigger bias** (see later)

$$\Delta[P_T, N] = \frac{1}{\omega[p_T]\langle N\rangle}\left[\langle N\rangle \omega[P_T] - \langle P_T\rangle \omega[N]\right] \qquad P_T = \sum_{i=1}^{N} p_{Ti}$$

$$\Sigma[P_T, N] = \frac{1}{\omega[p_T]\langle N\rangle}\left[\langle N\rangle \omega[P_T] + \langle P_T\rangle \omega[N] - 2\left(\langle P_T N\rangle - \langle P_T\rangle\langle N\rangle\right)\right]$$

$$\omega[P_T] = \frac{\langle P_T^2\rangle - \langle P_T\rangle^2}{\langle P_T\rangle} \qquad \omega[N] = \frac{\langle N^2\rangle - \langle N\rangle^2}{\langle N\rangle} \qquad \omega[p_T] = \frac{\overline{p_T^2} - \overline{p_T}^2}{\overline{p_T}}$$

important relation:

$$\Phi_{p_T} = \sqrt{\overline{p_T}\,\omega[p_T]}\left[\sqrt{\Sigma[P_T, N]} - 1\right]$$

Δ[P_T, N] uses only first two moments: ⟨N⟩, ⟨P_T⟩, ⟨P_T^2⟩, ⟨N^2⟩

Σ[P_T, N] uses also correlation term: ⟨P_TN⟩-⟨P_T⟩⟨N⟩

thus Δ and Σ can be sensitive to several physics effects in different ways

$z_{p_T} = p_T - \overline{p_T}$ $\qquad$ $\overline{p_T}$ - inclusive average

event variable $Z_{p_T} = \sum_{i=1}^{N} (p_{T,i} - \overline{p_T})$ $\qquad$ $\Phi_{p_T} = \sqrt{\frac{\langle Z_{p_T}^2\rangle}{\langle N\rangle}} - \sqrt{\overline{z_{p_T}^2}}$

Transverse momentum and multiplicity fluctuations

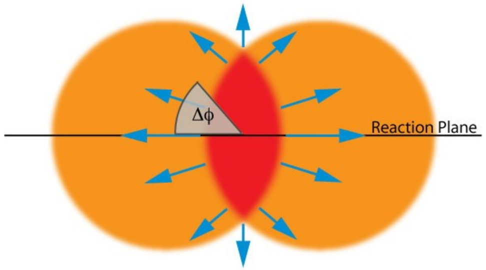
	unit	No fluctuations; N = const. P_T = const.	Independent Particle Model (IPM)	Model of Independent Sources (MIS); for example WNM ($N_S \equiv N_W$)
Φ_{pT}	MeV/c	$\Phi_{p_T} = -\sqrt{\overline{p_T}\,\omega[p_T]}$	$\Phi_{pT} = 0$	**Strongly intensive**: not dependent on N_S and its fluctuations $\Phi_{pT}(N_S \text{ sources}) = \Phi_{pT}(1 \text{ source})$
$\Delta[P_T, N]$	dimensionless	$\Delta[P_T, N] = 0$	$\Delta[P_T, N] = 1$	**Strongly intensive** $\Delta[P_T, N](N_S \text{ sources}) = \Delta[P_T, N](1 \text{ source})$
$\Sigma[P_T, N]$	dimensionless	$\Sigma[P_T, N] = 0$	$\Sigma[P_T, N] = 1$	**Strongly intensive** $\Sigma[P_T, N](N_S \text{ sources}) = \Sigma[P_T, N](1 \text{ source})$

Δ and Σ are dimensionless and have scale which allows for a quantitative comparison of fluctuations of different, in general dimensional, extensive quantities

Multiplicity fluctuations

	unit	No fluct.; N = const.	Poisson N distribution	Model of Independent Sources (MIS); for example WNM ($N_S \equiv N_W$)
$\omega[N]$	dimensionless	$\omega[N] = 0$	$\omega[N] = 1$	**Intensive:** not dependent on N_S but dependent on its fluctuations $\omega[N](N_S \text{ sources}) = \omega[N](1 \text{ source}) + \langle n \rangle\, \omega_{Ns}$ $\langle n \rangle$ - mean multiplicity from a single source ω_{Ns} - fluctuations in N_S

“Know your reference”



- What does the elliptic flow coefficient v_2=0.1 mean?
- It means that 50% more particles are emitted “in plane” than “out of plane”. Huge effect!

- What does the Φ_{pT} = 10 MeV/c mean ?

- Nothing! We do not know whether it is a large or a small effect.
Especially when the magnitudes of Φ_{pT} from several “trivial” effects (BE statistics, resonance decays, etc.) are not estimated

- What does the $\Sigma[P_T, N]$ = 1.1 mean?

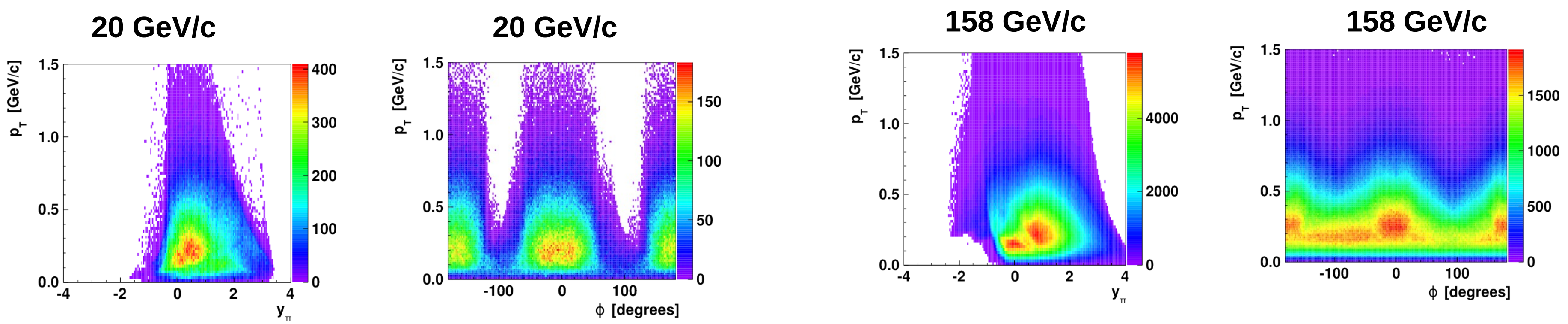
- It means that (for this specific combination of moments → Σ quantity) **we measure 10% deviation from IPM** (fluctuations are 10% larger than in IPM)

Similar advantage for ω[N] → here Poisson N distrib. (instead of IPM) used as the reference:
ω[N] = 0 for N = const. and ω[N] = 1 for Poisson N distribution. Thus for *any* P(N) distribution:
ω[N] > 1 (or ω[N] » 1) corresponds to “large” (or “very large”) fluctuations of N,
ω[N] < 1 (or ω[N] « 1) corresponds to “small” (or “very small”) fluctuations of N

Δ and Σ measures – keep the advantages of both Φ (they are strongly intensive) and ω (they are properly normalized)

Methods of analyzing P_T and N fluctuations in NA61

- **Acceptance** should be **defined** and described (“acceptance map”) → note, it is different (wider!) than that one for chemical fluctuations (where acceptance had to be limited to regions where inclusive dE/dx fit was possible)
  - Prepare y_π-ϕ-p_T histograms for generated (gen) and reconstructed (rec) Monte Carlo data (EPOS)
  - Bin is accepted if (rec/gen) > 90%

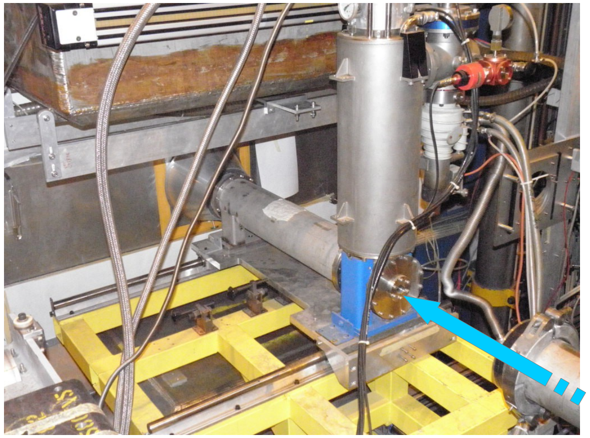


Acceptance and detector efficiency regions – examples for p+p

- Create **text files with N, P_T, $P_{T,2}$** for all charged, neg. charged, and pos. charged particles (for data sets: target inserted, target removed, MC gen, MC rec → see later)

$$P_T = \sum_{i=1}^{N} p_{T\,i} \qquad P_{T,2} = \sum_{i=1}^{N} p_{T\,i}^2$$

- Calculate **target-removed normalization factor (ε)** (using integrals of the fitted vertex.z distributions)



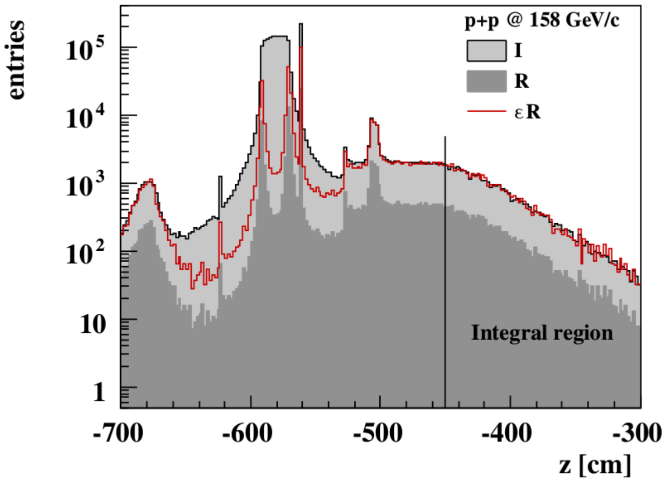


Fig. 3 (Color online) Distributions of the z coordinate of reconstructed interaction vertex for events recorded with the target inserted (I) and removed (R). The target removed distribution was normalized to the target inserted one in the region $z > -450$ cm.

NA61 interaction trigger selects mostly **target** interactions but small fraction of unwanted **non-target** interactions is also included (the problem mostly concerns p+p); for p+p in NA61 target is a 20cm long liquid hydrogen (non-target inter.: collisions with mylar windows, air/gas, etc.)

- In absence of other corrections one may apply data-based correction for non-target interactions to any mean event quantity ($\langle X\rangle = \langle N\rangle$, $\langle P_T\rangle$, $\langle P_T N\rangle$, etc.)

$$\langle X\rangle = \frac{1}{N_{ev}^{I} - \varepsilon \cdot N_{ev}^{R}} \left(\sum_{i=1}^{N_{ev}^{I}} X_i^I - \varepsilon \cdot \sum_{j=1}^{N_{ev}^{R}} X_j^R \right)$$

I – target inserted
R – target removed
N_{ev} - number of events (I or R)
ε – normalization factor

- In absence of non-target interactions one may apply Monte Carlo-based correction for other biases (losses due to event and track selections and reconstruction inefficiency and background of non-primary charged hadrons) to any mean event quantity $\langle X \rangle$
  - Calculate 3D table *) of correction factors $c(N, P_T, P_{T,2})$ as follows:
    $c(N, P_T, P_{T,2}) = gen(N, P_T, P_{T,2}) / rec(N, P_T, P_{T,2})$, where
    gen(...) - number of generated MC events in each bin of $(N, P_T, P_{T,2})$
    rec(...) - number of reconstructed MC events (after event and track cuts) in each bin of $(N, P_T, P_{T,2})$
    c(...) = 1 if it can't be calculated; it is if rec(...) or gen(...) does not exist
    *) 3D table of correction factors is calculated separately for all, neg. and pos. charged particles
  - Then an event "i" of $(N, P_T, P_{T,2})$ is weighted by corresponding factor $c_i = c(N, P_T, P_{T,2})$

$$\langle X \rangle = \frac{1}{M_{ev}} \left(\sum_{i=1}^{N_{ev}} c_i X_i \right), \quad \text{where "corrected" number of events:} \quad M_{ev} = \sum_{i=1}^{N_{ev}} c_i$$

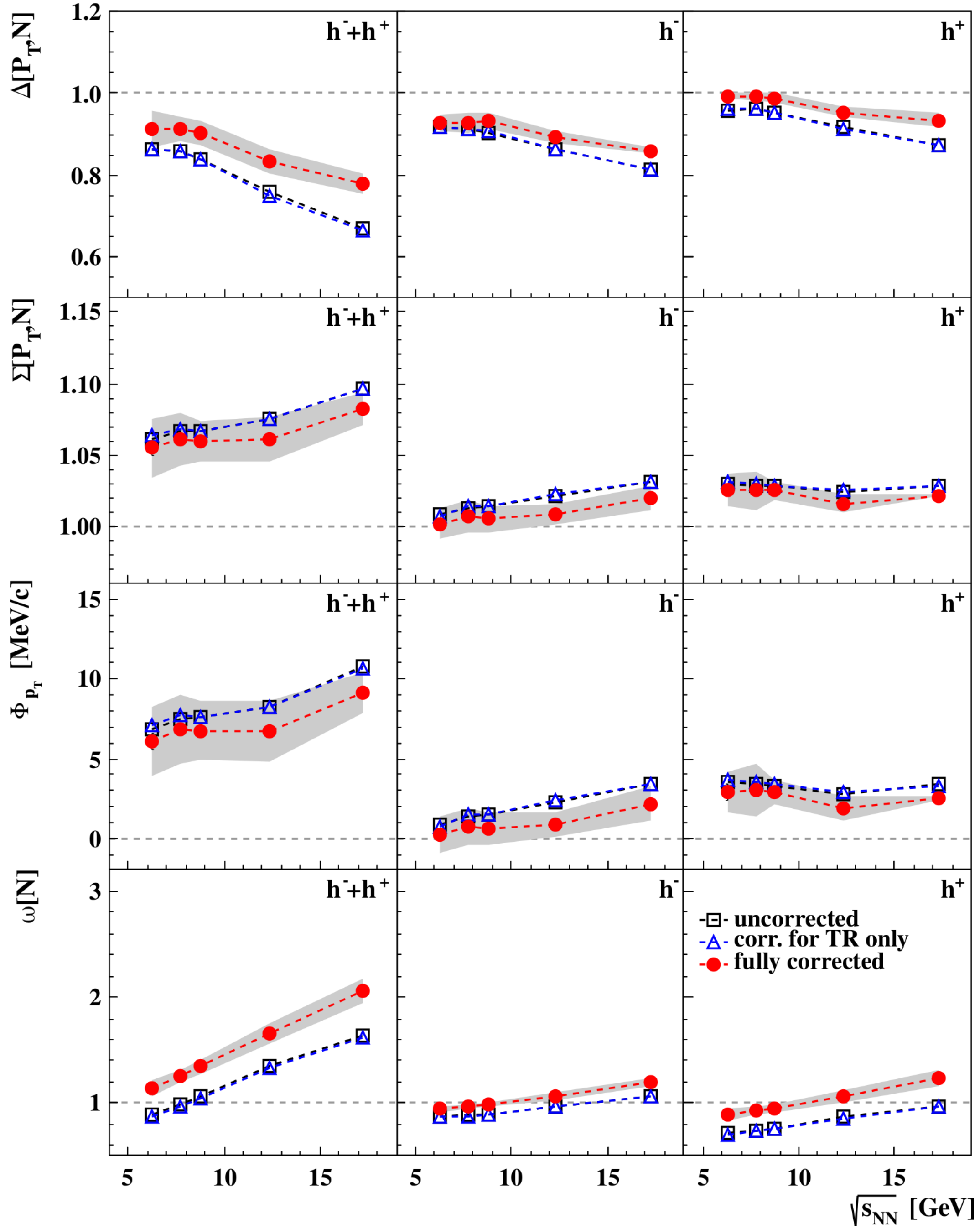
N_{ev} - number of "real" events

- **FINAL CORRECTION**: apply **combined** data-based **correction for non-target interactions** with **Monte Carlo**-based **correction for other biases** to any mean event quantity ($\langle X \rangle = \langle N \rangle$, $\langle P_T \rangle$, $\langle P_T N \rangle$, etc.)

$$\langle X \rangle = \frac{1}{M_{ev}^I - \varepsilon \cdot M_{ev}^R} \left(\sum_{i=1}^{N_{ev}^I} c_i X_i^I - \varepsilon \cdot \sum_{j=1}^{N_{ev}^R} c_j X_j^R \right)$$

- **Calculate any fluctuation measure** using corrected mean event quantities

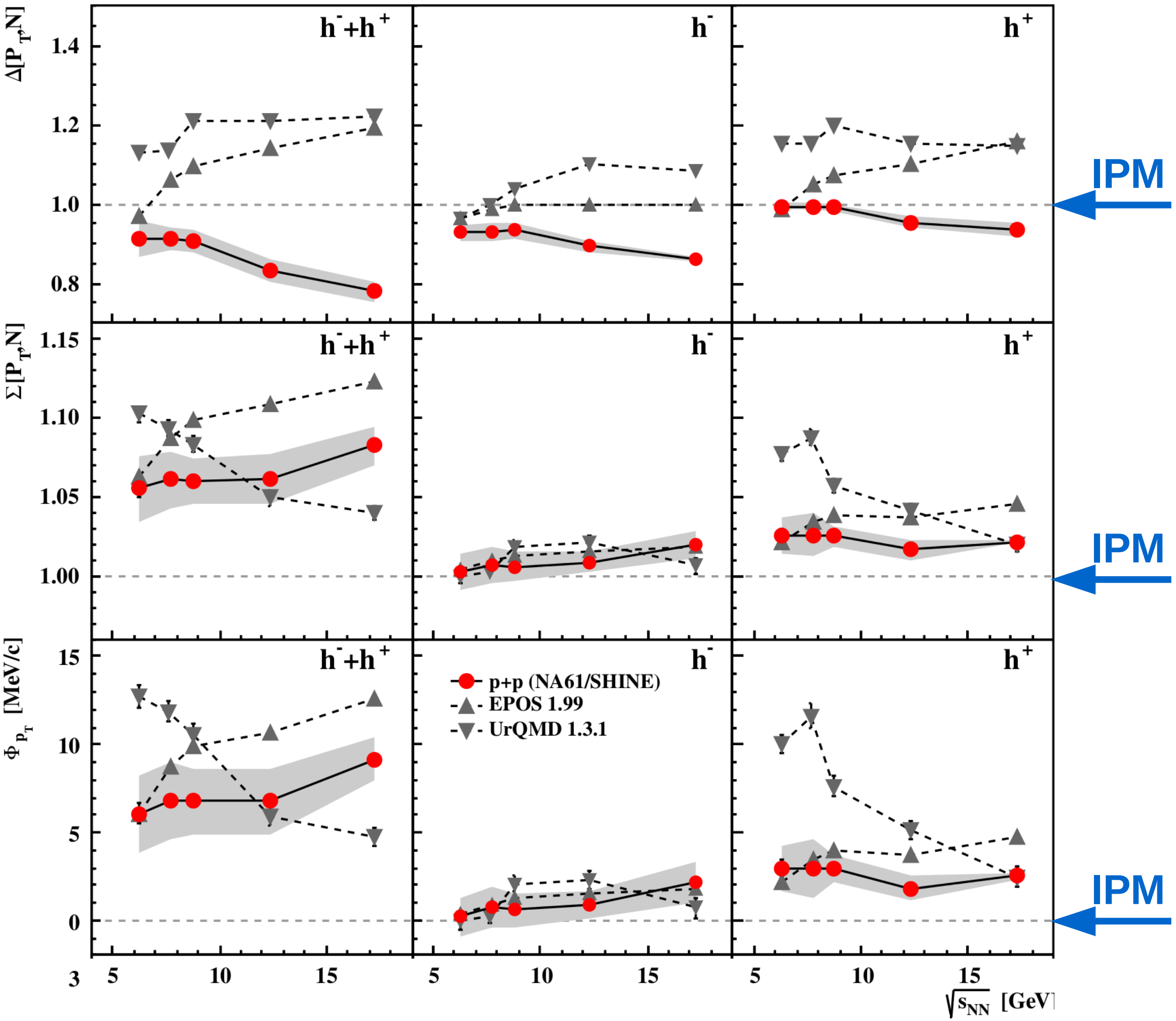
Influence of corrections on NA61 p+p results



- **Correction for contamination of non-target interactions** based on events with removed target **is negligible**
- **Correction for detector inefficiencies and losses of inelastic events** (trigger bias) performed by use of processed through Geant (+fully reconstructed) samples of EPOS events **changes results significantly**
- Statistical uncertainties of fluct. measures: Φ_{pT}, $\Delta[P_T, N]$, $\Sigma[P_T, N]$, $\omega[N]$ → based on (30) subsamples method

NA61, draft of paper

P_T and N fluctuations in inelastic p+p collisions (NA61)



Results within the full NA61 acceptance

Φ_{pT} and $\Sigma[P_T, N]$ - the same "family" of strongly intensive measures (the same moments used)

$\Sigma[P_T, N]$ shows fluctuations above IPM predictions and $\Delta[P_T, N]$ below IPM

Possible explanations of $\Sigma[P_T, N] > 1$, $\Delta[P_T, N] < 1$ and $\Phi_{pT} > 0$

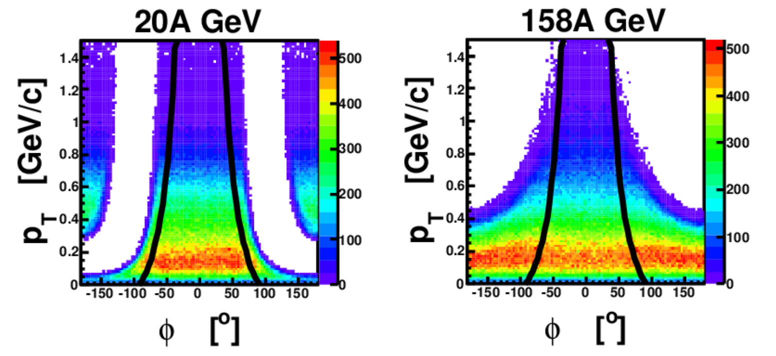
- BE statistics → PL B730, 70 (2014); PR C88, 024907 (2013); PL B439, 6 (1998); PL B465, 8 (1999)
- Average p_T per event P_T/N versus N correlation in pp → PR C89, 034903 (2014)

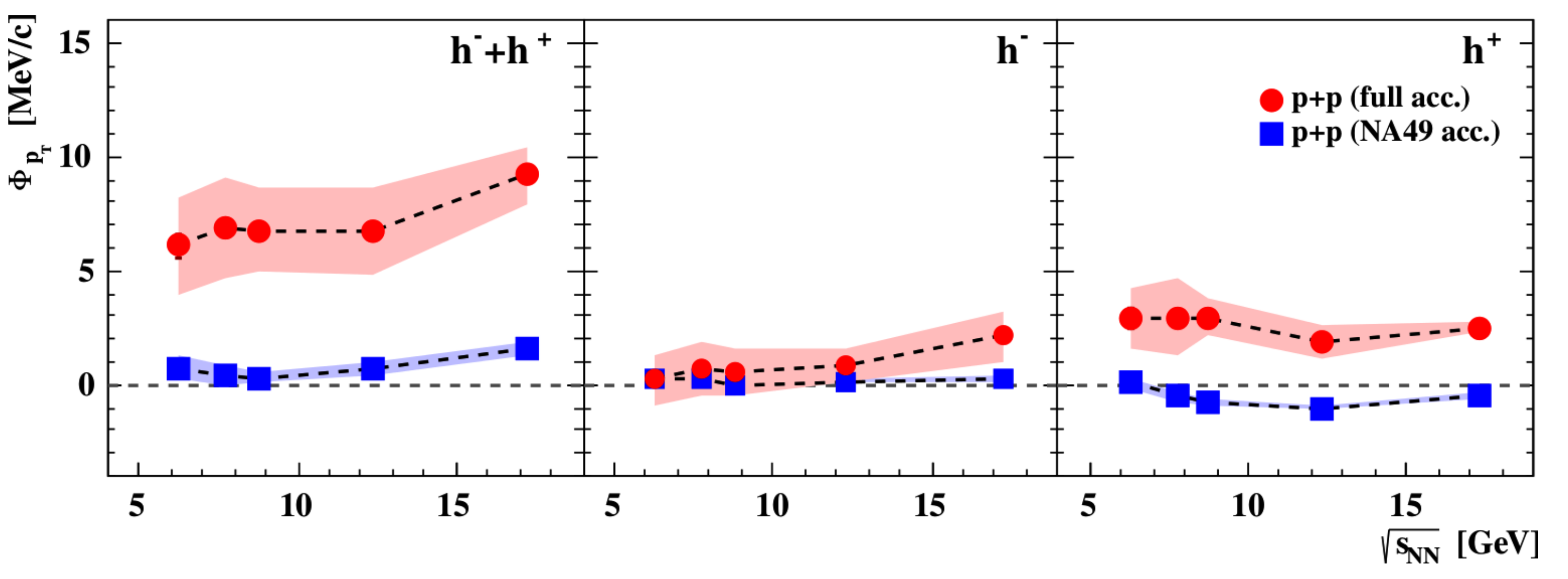
NA61, draft of paper

Energy dependence of p_T fluctuations: NA61 p+p within NA49 Pb+Pb selection cuts

- In NA49 because of high density of tracks, analysis of p_T fluctuations was limited to **forward-rapidity** region ($1.1 < y_\pi < 2.6$)
- common azimuthal acceptance for all energies

NA49 acceptance (common for all energies): $1.1 < y_\pi < 2.6$ and limited azimuthal angle

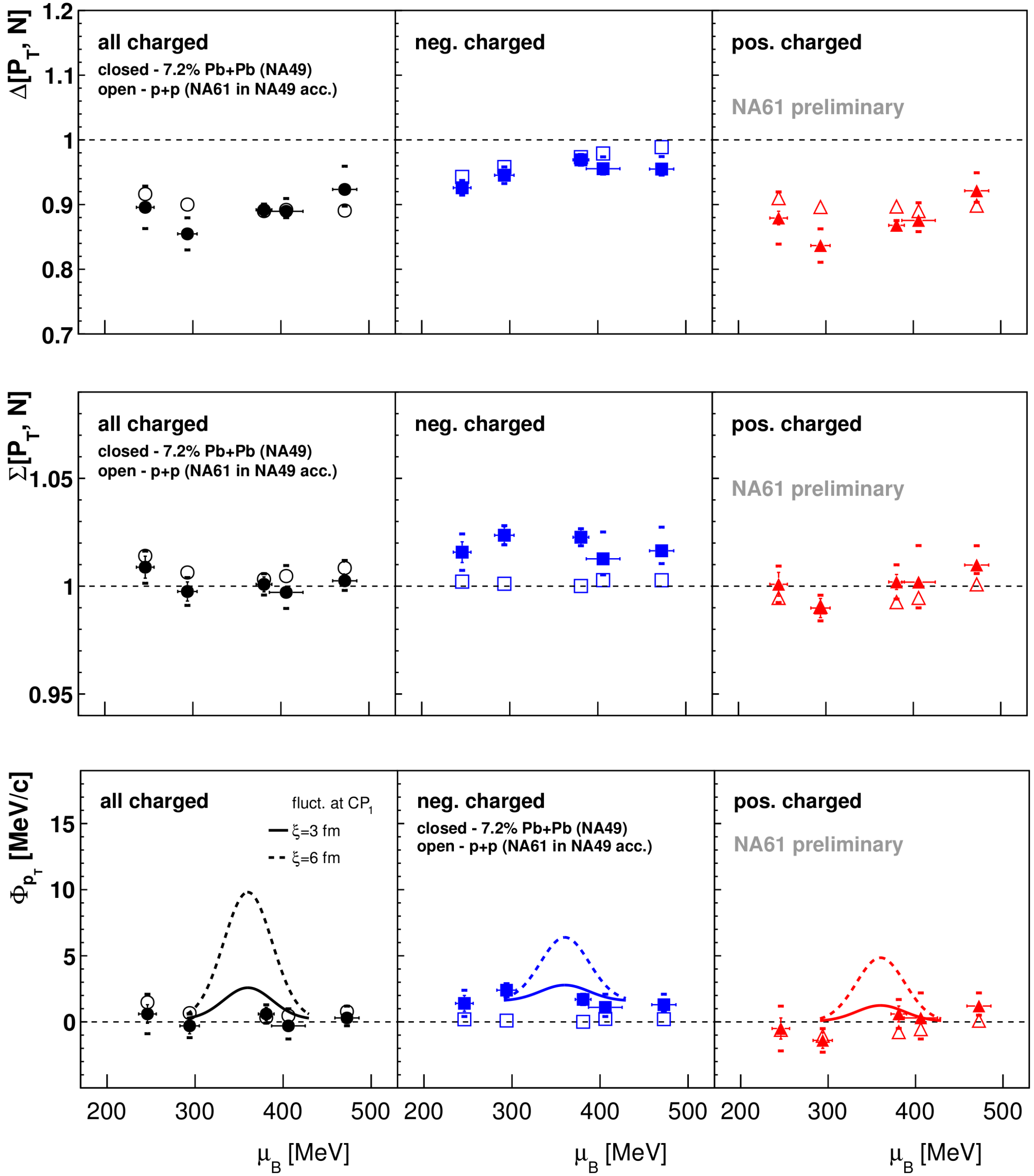




NA61, draft of paper

By applying NA49 cuts Φ_{pT} in p+p decreases (mainly because of narrower rapidity range). NA61 plans to extend the physics program to repeat and complement NA49 Pb+Pb measurements. **The new He beam pipes reduce the number of δ-electrons in VTPCs by a factor of 10 and allow to extend the acceptance towards mid-rapidity**

Comparison of P_T and N fluctuations for NA49 A+A and NA61 p+p collisions
in the same (NA49) acceptance



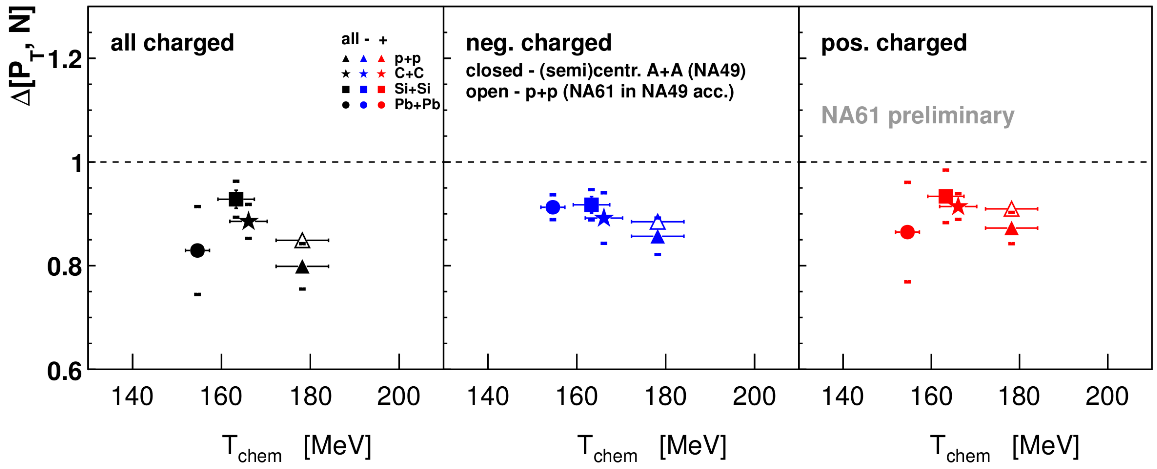
- **Forward-rapidity**
  $1.1 < y_\pi < 2.6$;
  $y_p < y_{beam} - 0.5$
- **Common** (for all energies) **limited azimuthal angle**

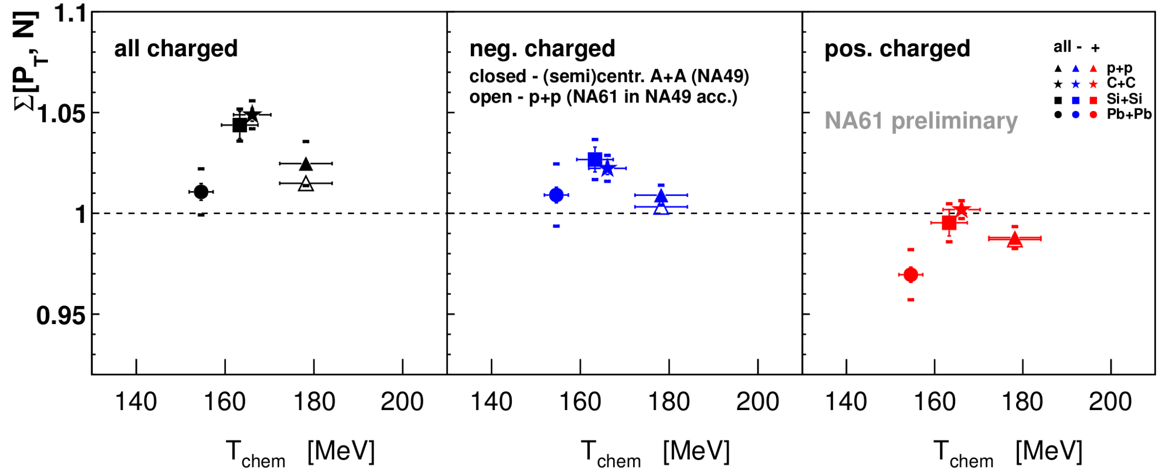
- **Pb+Pb and NA61 p+p results are similar** (difference only for $\Sigma[P_T, N]$ for neg. charged)
- **No effects of CP for Pb+Pb** (NA49) **and p+p** (NA61)

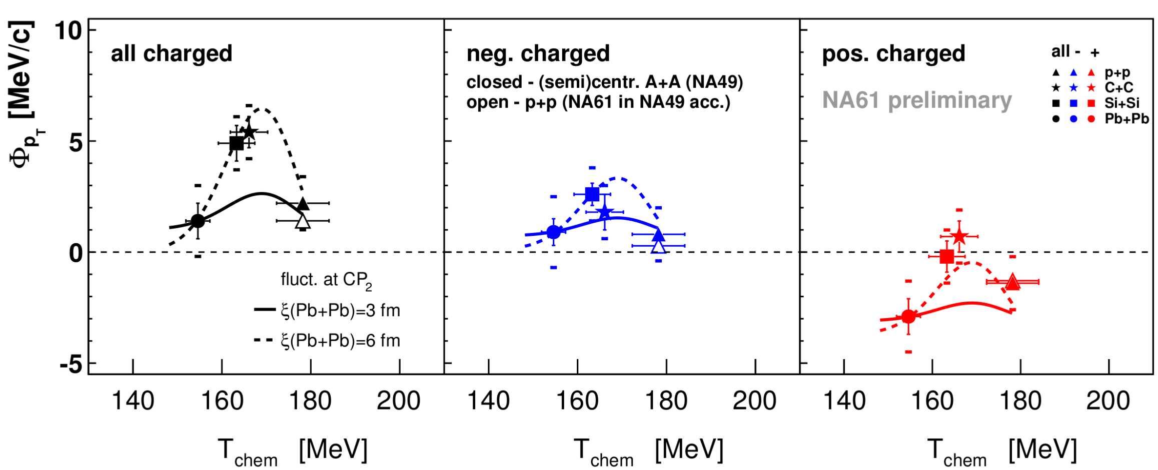
Due to smaller acceptance magnitudes of p+p points are smaller than 2 pages before

For NA61 only
stat. errors shown

P. Seyboth (for NA49 and NA61), arXiv:1402.4619; and NA49, draft of paper
http://www.ujk.edu.pl/homepages/mryb/10thworkshop/files/slides/grebieszkow.pdf







- **Forward-rapidity**
  $1.1 < y_{\pi} < 2.6$

- **Wide azimuthal angle** –
  nearly as available at 158A GeV/c

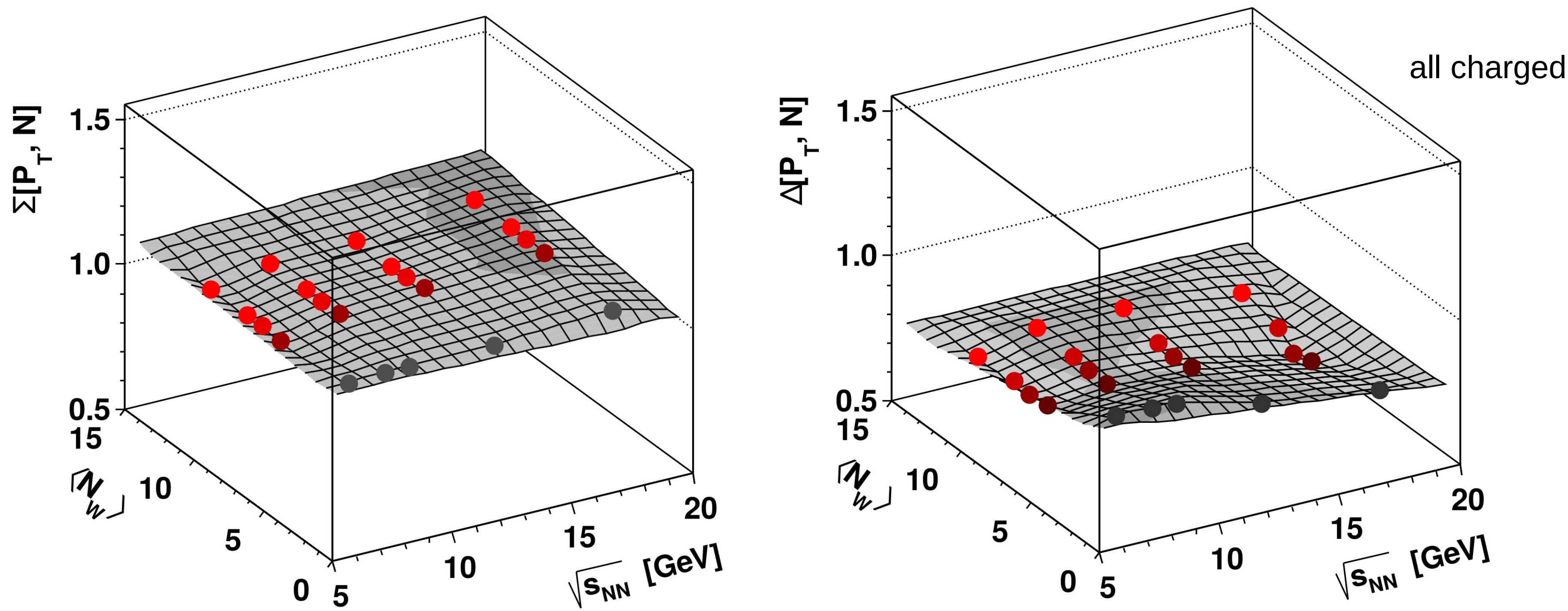
- Only p+p, semi-central C+C, Si+Si, and central Pb+Pb results are shown
- **Maximum for $\Delta[P_T, N]$ and $\Sigma[P_T, N]$ in C+C / Si+Si at 158A GeV/c**
- NA61 and NA49 (p+p) points agree (for more recent NA61 results even better → see Φ_{pT} in T. Czopowicz, arXiv:1503.01619)

Details of CP predictions (curves) for Φ_{pT} → NP A830, 547C (2009)
Predictions for $\Sigma[P_T,N]$ and $\Delta[P_T,N]$ at CP not available

For NA61 only stat. errors shown

http://www.ujk.edu.pl/homepages/mryb/10thworkshop/files/slides/grebieszkow.pdf
P. Seyboth (for NA49 and NA61), arXiv:1402.4619; and NA49, draft of paper

Summary of search for the critical point using P_T and N fluctuations in NA61/SHINE: p+p and Be+Be interactions



Be+Be data are corrected for non-target interactions; corrections for detector effects and trigger bias are estimated to be small but are still under investigation

Results are in NA61 acceptance

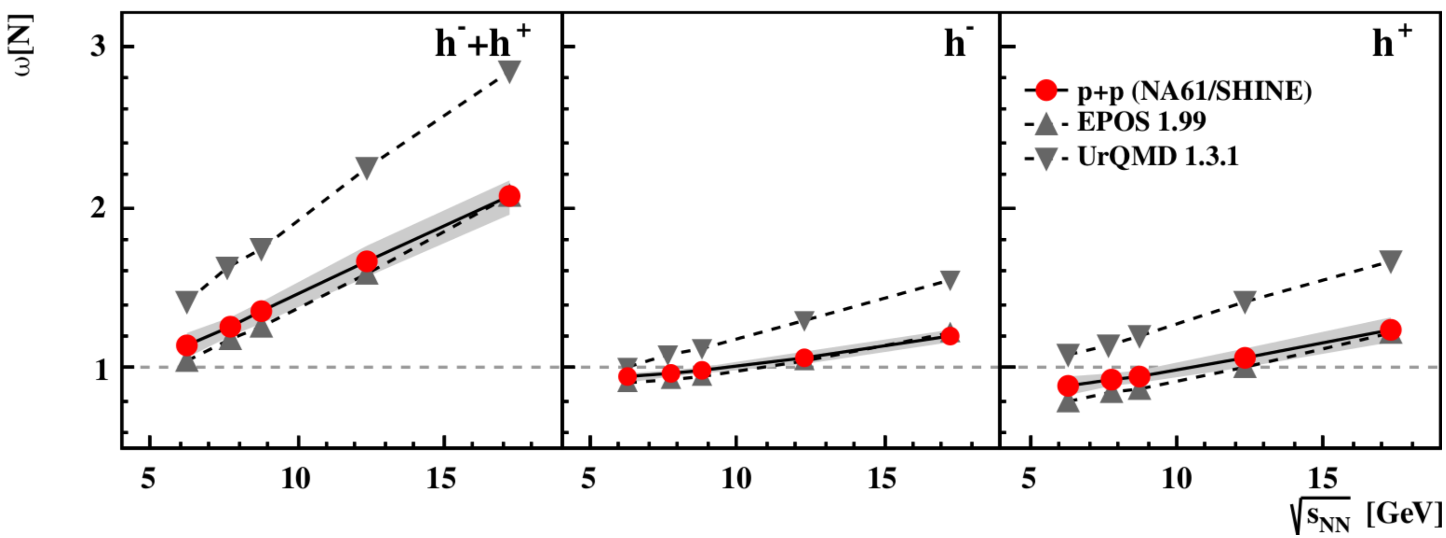
- **No centrality dependence in Be+Be**
- **No sign of any anomaly that can be attributed to CP** (both in p+p and Be+Be)

… waiting for Ar+Sc results …

M. Gaździcki, P. Seyboth, arXiv:1506.08141; based on T. Czopowicz, CPOD 2014 (slides and arXiv:1503.01619)

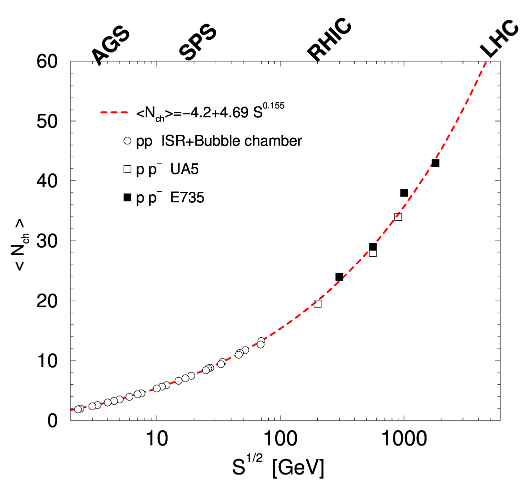
Multiplicity ($\omega[N]$) fluctuations of non-identified particles

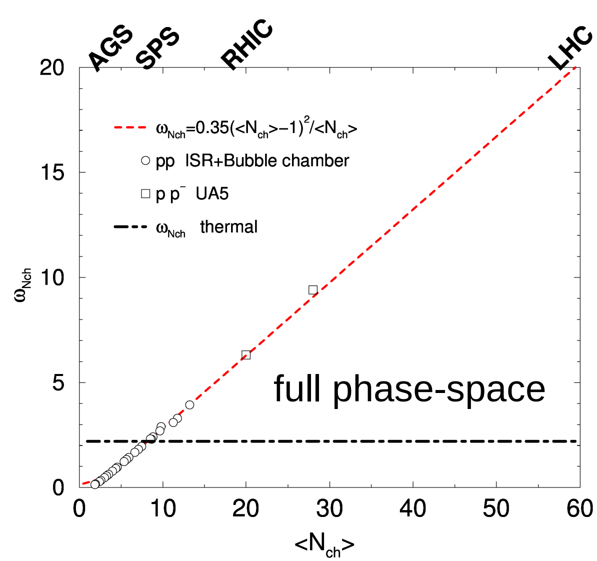
Multiplicity fluctuations of non-identified particles in inelastic p+p collisions (NA61)



NA61, draft of paper

- **Increase of ω[N] with energy** reflecting increase of ω_{Nch} measured in full phase-space (see PR 351, 161 (2001))
- **ω[N_+] and ω[N_-] < ω[N_{ch}] possibly due to charge conservation**



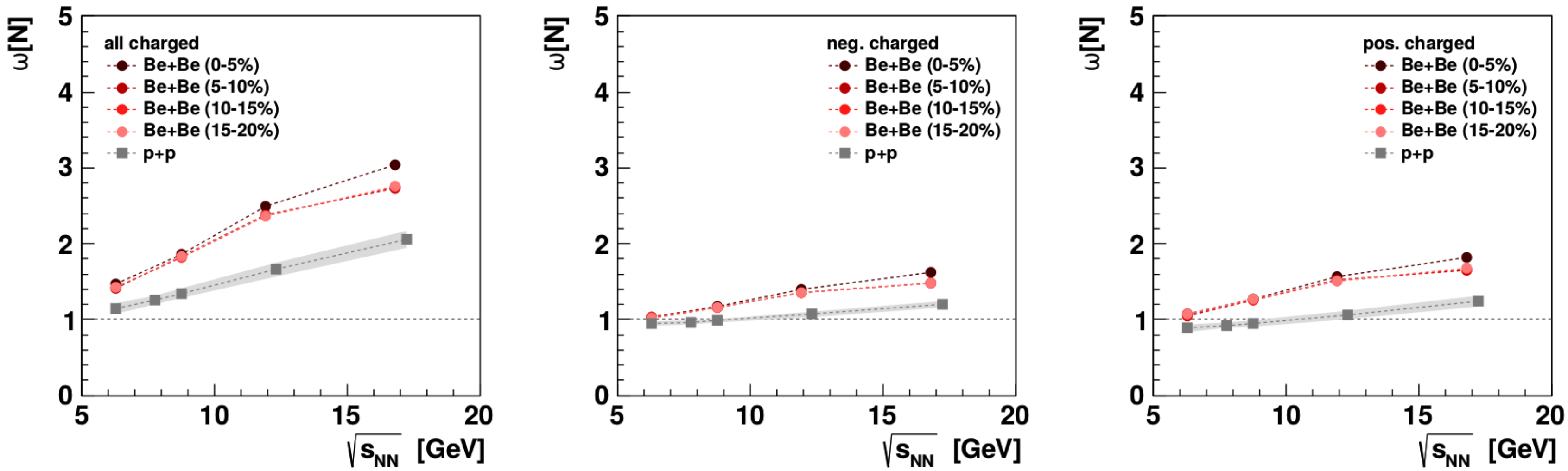


Multiplicity fluctuations in p+p increase linearly with $\langle N_{ch} \rangle$ in full phase-space (reflection of KNO scaling) - Phys. Rept. 351, 161 (2001)

$$\omega^{acc} = (\omega^{4\pi} - 1)\, p + 1$$
$$p = \langle N^{acc} \rangle / \langle N \rangle$$

(valid if no correlations in momentum space)

Multiplicity fluctuations of non-identified particles in Be+Be collisions (NA61)



- Centrality of Be+Be selected based on energy in PSD
- **ω[N] in Be+Be larger than in p+p, probably due to volume fluctuations**

  → ω[N] is intensive, but not strongly intensive measure of fluctuations

$\omega[N](N_S \text{ sources}) = \omega[N](1 \text{ source}) + \langle n\rangle\omega_{N_S}$

WNM: $N_S \equiv N_W$

⟨n⟩ - mean multiplicity from a single source

ω_{N_S} - fluctuations in N_S

T. Czopowicz, arXiv:1503.01619 (CPOD 2014)

Charge ($\Delta[N_+, N_-]$, $\Sigma[N_+, N_-]$) fluctuations of non-identified particles

Charge fluctuations of non-identified particles

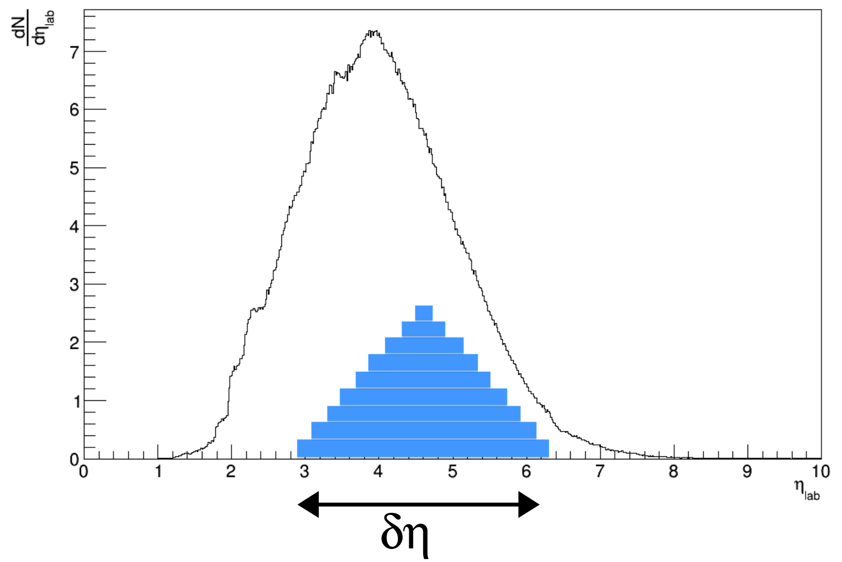
- **New strongly intensive measures Δ and Σ** (here applied to N_+, N_- fluctuations)
  → PR C88, 024907 (2013)
- **Method of correcting results (Δ[N_+, N_-] and Σ[N_+, N_-]) for non-target interactions, detector inefficiencies and trigger bias** → similar to P_T and N fluctuations

$$\Delta[N_+, N_-] = \frac{1}{\langle N_- \rangle - \langle N_+ \rangle}\left[\langle N_- \rangle \omega[N_+] - \langle N_+ \rangle \omega[N_-]\right]$$

$$\Sigma[N_+, N_-] = \frac{1}{\langle N_- \rangle + \langle N_+ \rangle}\left[\langle N_- \rangle \omega[N_+] + \langle N_+ \rangle \omega[N_-] - 2\left(\langle N_+ N_- \rangle - \langle N_+ \rangle \langle N_- \rangle\right)\right]$$

The analysis of $\Delta[N_F, N_B]$ and $\Sigma[N_F, N_B]$ (left-right fluctuations) in NA61 is ongoing

- Acceptance map → the same as for P_T and N fluctuations in Be+Be
- No target-removed subtraction → instead narrow vertex.z cut
- **Corrections for detector effects and trigger bias** → method similar to P_T and N fluctuations (based on generated and reconstructed MC)
- Statistical uncertainties based on subsamples method



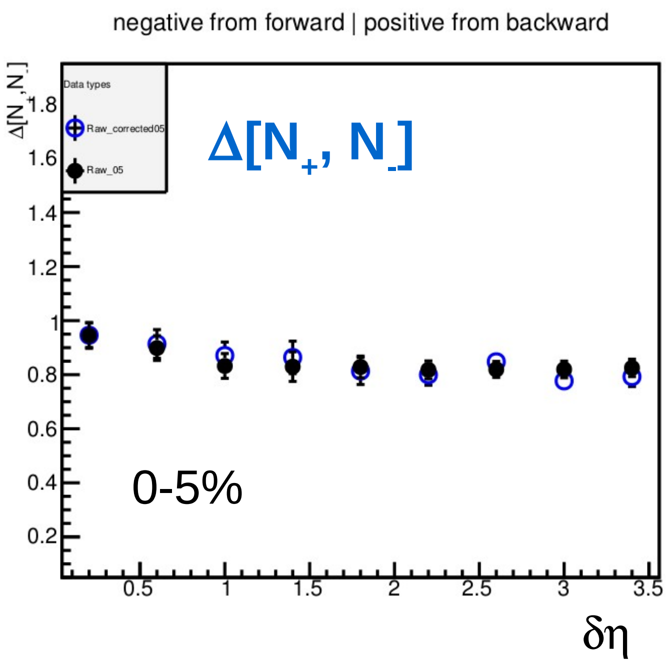
$\Delta[N_+, N_-]$ and $\Sigma[N_+, N_-]$ analysis

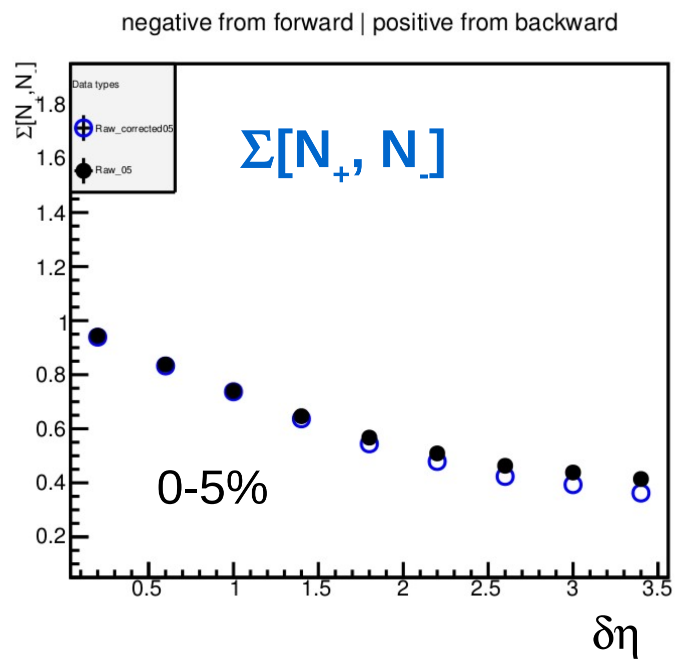
9 pseudorapidity intervals

$\delta\eta = 0.2 + i*0.4 \qquad i \in \{0, \ldots, 8\}$

Can be sensitive to electric charge conservation effect and resonance decays?

Influence of corrections on charge fluctuations in Be+Be at 150A GeV/c

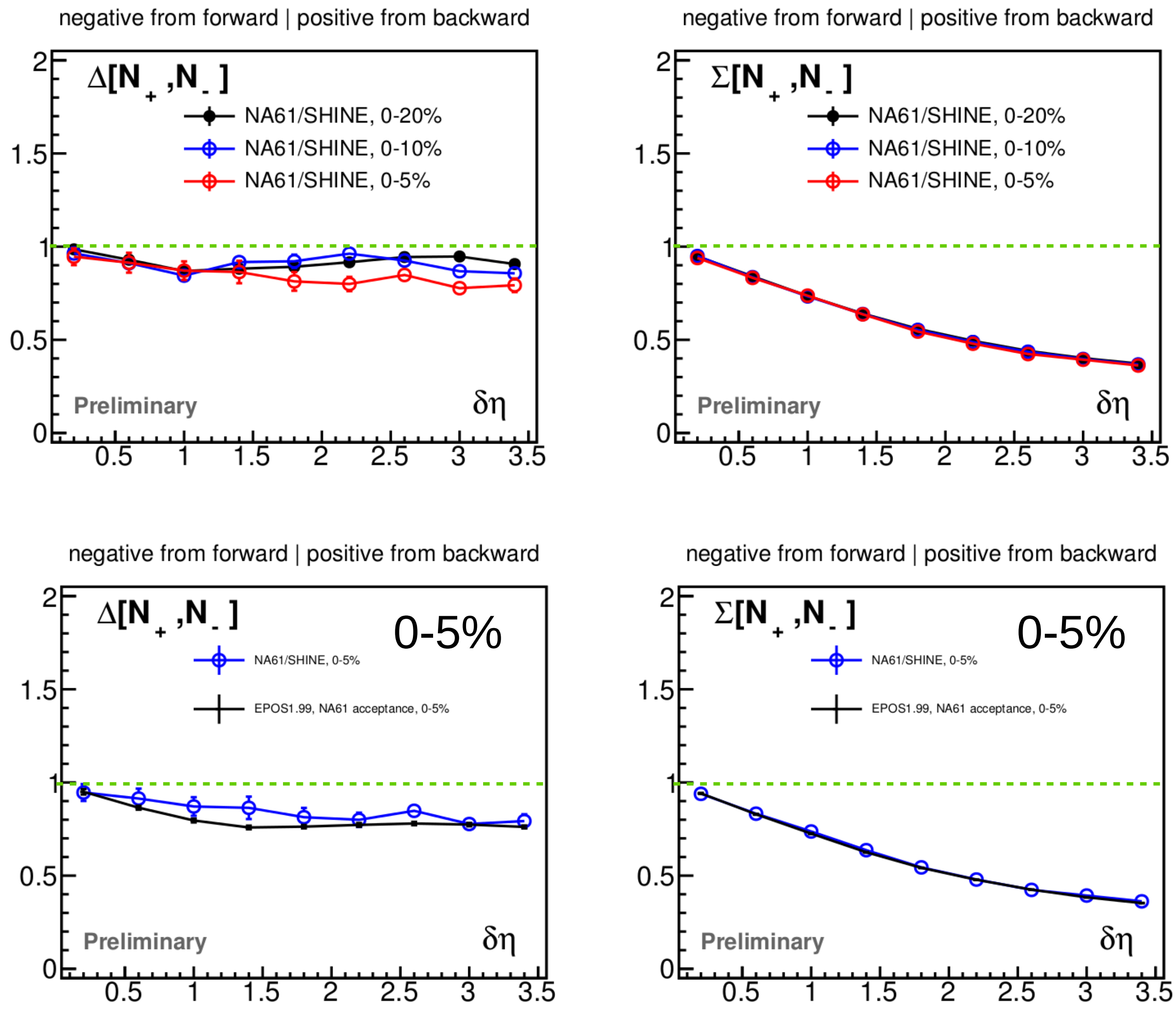




corrected
uncorrected

E. Andronov,
NA61 internal meeting,
30.06.2015

N_+ and N_- fluctuations in Be+Be collisions at 150A GeV/c (NA61)



- **$\Delta[N_+, N_-]$ and $\Sigma[N_+, N_-]$ almost independent of centrality**
- Both $\Delta[N_+, N_-]$ and $\Sigma[N_+, N_-]$ smaller than 1 (possibly due to energy-momentum conservation and charge conservation effects)
- $\Sigma[N_+, N_-]$ decreases significantly with growth of $\delta\eta$
- Tendency **reproduced by EPOS** (perfect agreement for $\Sigma[N_+, N_-]$)

E. Andronov, SQM 2015

Systematic errors were estimated to be less than 5% for all points

Two-particle correlations in $\Delta\eta$, $\Delta\phi$ of non-identified particles

Two-particle correlations in Δη, Δϕ

$$\Delta\eta = |\eta_1 - \eta_2| \qquad \Delta\phi = |\phi_1 - \phi_2|$$

$$C^{raw}(\Delta\eta, \Delta\phi) = \frac{N^{pairs}_{mixed}}{N^{pairs}_{data}} \frac{S(\Delta\eta, \Delta\phi)}{M(\Delta\eta, \Delta\phi)}$$

$$S(\Delta\eta, \Delta\phi) = \frac{d^2 N^{signal}}{d\Delta\eta \; d\Delta\phi}; \qquad M(\Delta\eta, \Delta\phi) = \frac{d^2 N^{mixed}}{d\Delta\eta \; d\Delta\phi}$$

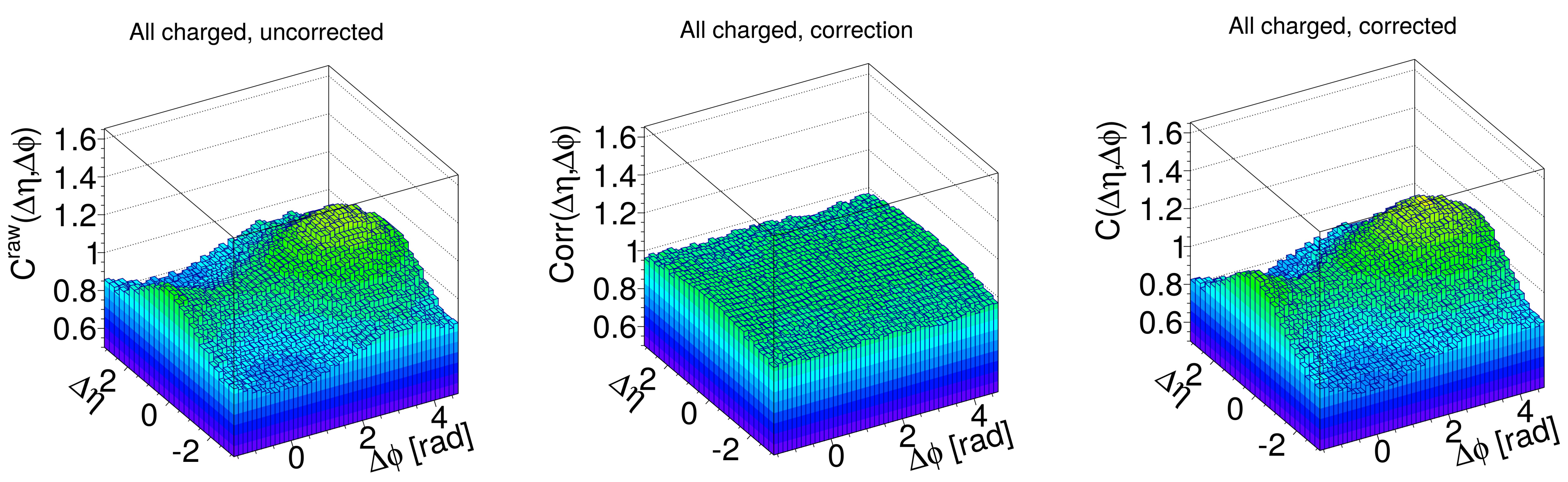
Two-particle correlations in Δη, Δϕ allow to disentangle different sources of correlations: jets, flow, resonance decays, quantum statistics effects, conservation laws

Correlations in NA61 are corrected for the effects of trigger bias and track reconstruction inefficiencies with the use of GEANT3 MC simulation based on EPOS 1.99
(below example for p+p at 80 GeV/c)

Bin-by-bin correction:

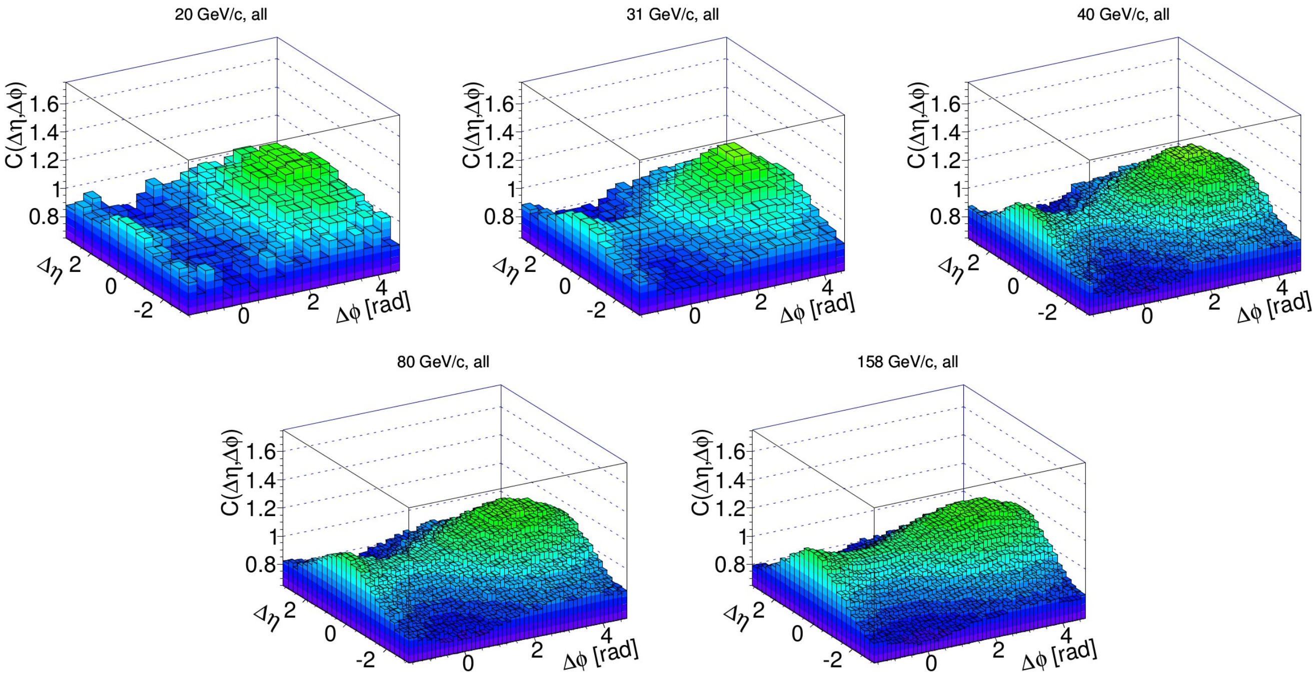
$$Corr(\Delta\eta, \Delta\phi) = \frac{MC_{gen}(\Delta\eta, \Delta\phi)}{MC_{rec}(\Delta\eta, \Delta\phi)}$$

$$C(\Delta\eta, \Delta\phi) = C^{raw}(\Delta\eta, \Delta\phi) \cdot Corr(\Delta\eta, \Delta\phi)$$



Based on B. Maksiak, PoS (CPOD 2014) 055

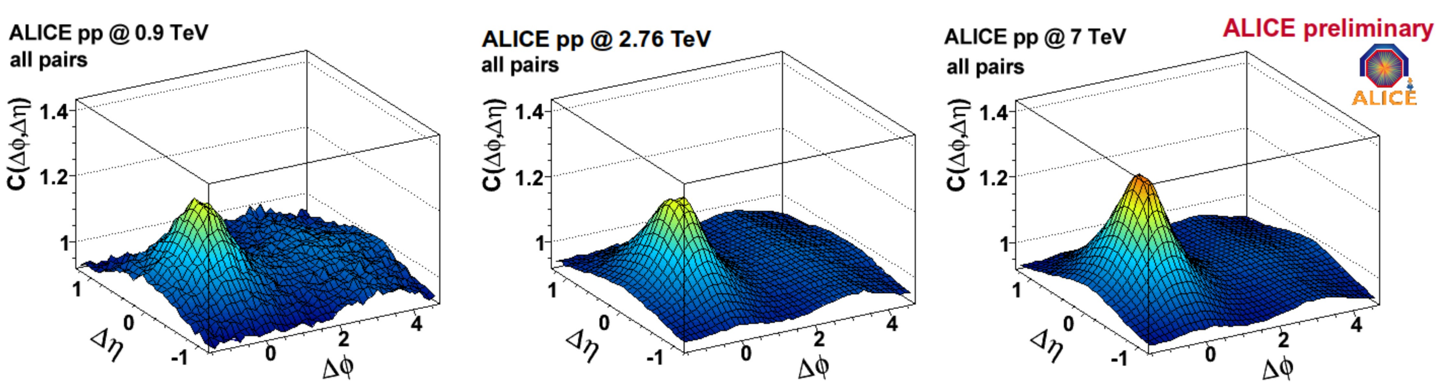
Two-particle correlations in Δη, Δϕ in inelastic p+p collisions (NA61)



B. Maksiak, PoS (CPOD 2014) 055

Pairs of **all charged particles** - comparison with ALICE

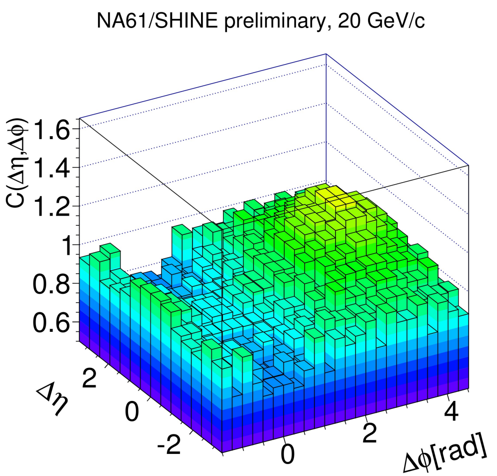
- NA61: maximum at $(\Delta\eta,\Delta\phi) = (0,\pi)$ probably due to resonance decays and momentum conservation
- NA61 results show stronger enhancement in $\Delta\phi \approx \pi$ and no “jet peak” at $\Delta\phi \approx 0$

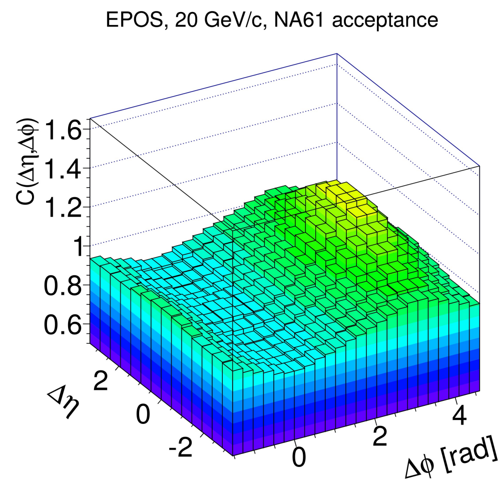


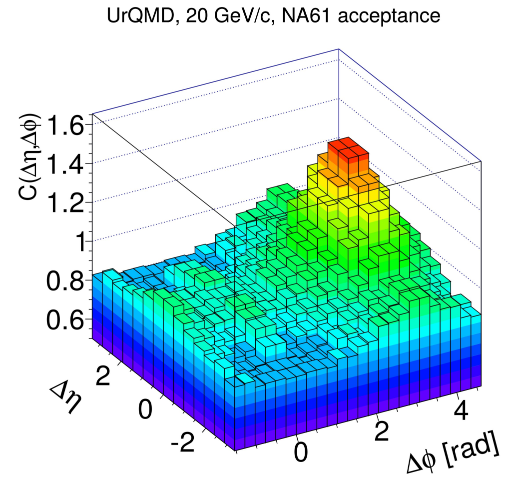
M. Janik,
PoS (WPCF 2011) 026

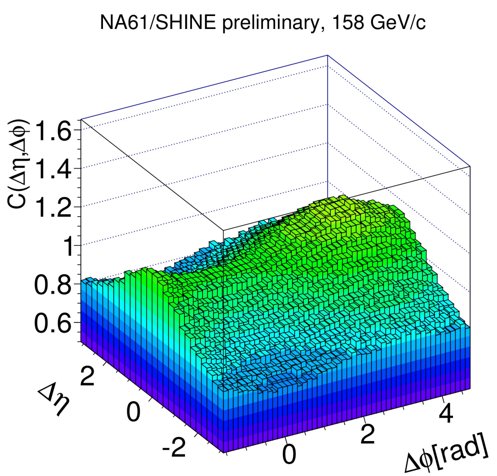
Two-particle correlations in Δη, Δφ – unique tool to test models:

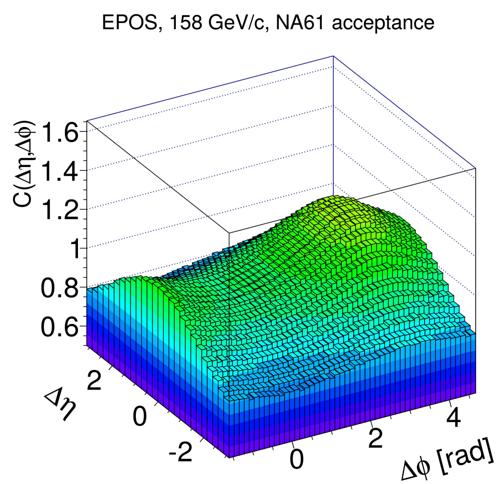
NA61 | **EPOS 1.99** | **UrQMD 3.4**

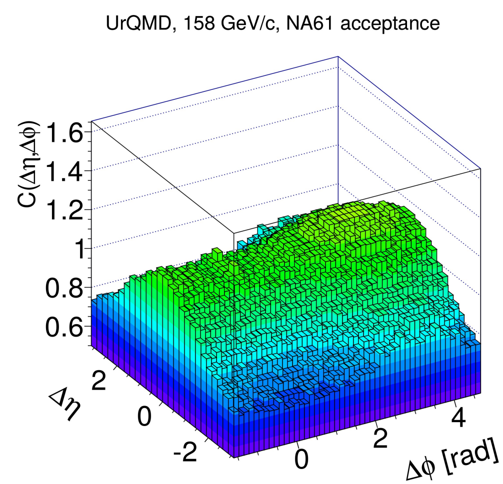












EPOS and UrQMD are with NA61 acceptance; all charged particles

Qualitative agreement of NA61 results with predictions of EPOS

B. Maksiak,
NA61-Theory meeting,
03.12.2014

Summary

New tools and methods:

- **Identity method** to correct chemical fluctuations and multiplicity fluctuations of identified particles on misidentification effect; can be applied to many different fluctuation measures
- Method of **correcting fluctuation measures** (now applied to [P_T, N], [N] and [N_+, N_-] fluctuations of non-identified particles) on non-target interactions (important for p+p), detector inefficiencies, and trigger bias
- Method of **correcting correlations in $\Delta\eta$, $\Delta\phi$** for detector inefficiencies and trigger bias

New measures:

- **Strongly intensive** measure **Φ**, instead of old σ_{dyn}, **used to measure chemical fluctuations** in NA61 p+p and NA49 Pb+Pb collisions. The analysis of "chemical" **Δ** and **Σ is ongoing**
- Strongly intensive and **properly normalized new measures Δ and Σ** used in NA61 to calculate **[P_T, N] and [N_+, N_-] fluctuations** (in NA49 results on [P_T, N] fluctuations are also available)

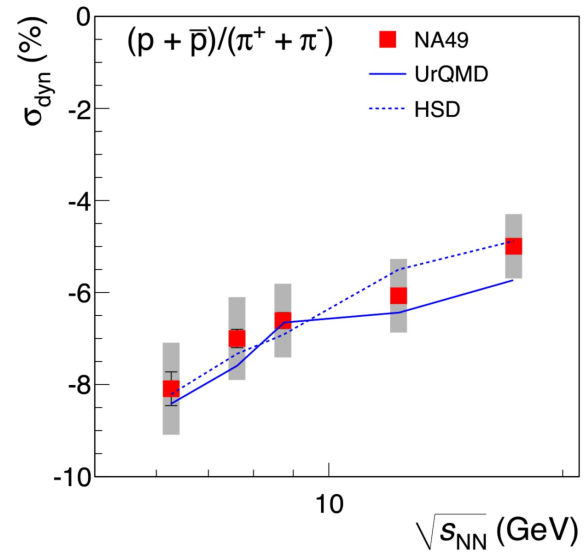
New opportunities:

- Magnitudes of transverse momentum and multiplicity fluctuations in p+p at 20-158 GeV/c are significant in the acceptance of NA61 and much smaller when additional cuts, as used in the energy scan of Pb+Pb in NA49 (forward-rapidity), are applied. But **NA61 acceptance for fluctuation analysis can be enlarged towards mid-rapidity** due to installation of He beam pipes (they reduce the number of δ-electrons in VTPCs). Moreover, in NA61 Pb+Pb collisions are also planned!

Backup

Chemical (particle type) fluctuations

- **σ_{dyn} measure of dynamical particle ratio fluctuations (K/π, p/π, K/p)**



3.5% most central Pb+Pb

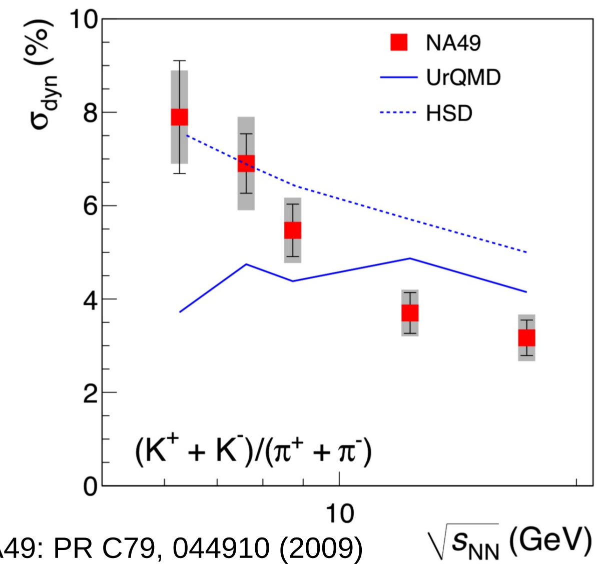
- E-by-e fit of particle multiplicities required in NA49
- Mixed events used as reference
- **σ^2_{dyn} ~ $1/N_W$** (PR C81, 034910 (2010), PR C84, 014904 (2011))

relative width (of K/π, p/π, K/p)

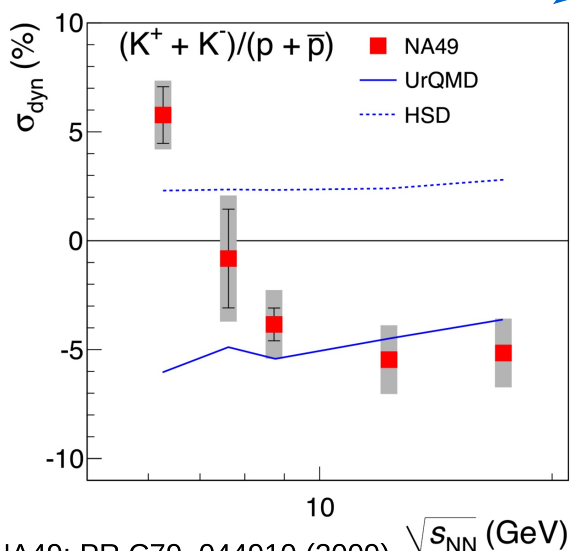
$$\sigma = RMS/Mean \cdot 100[\%]$$

$$\sigma_{dyn} = sign(\sigma^2_{data} - \sigma^2_{mixed})\sqrt{|\sigma^2_{data} - \sigma^2_{mixed}|} \qquad \sigma^2_{dyn} \approx |\nu_{dyn}|$$

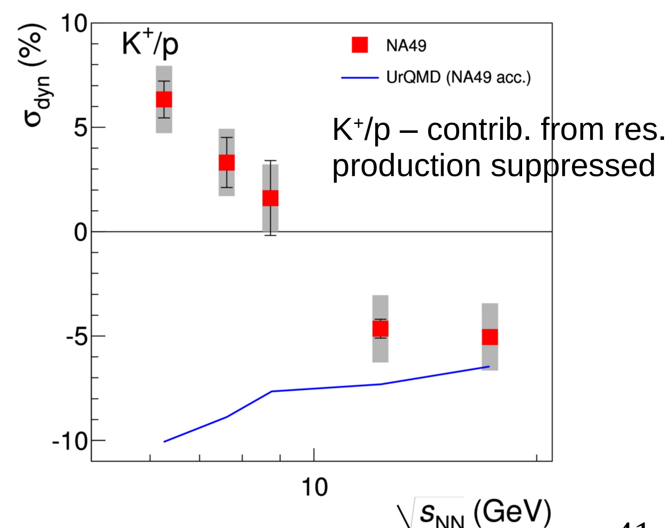
K/p: dynamical fluctuations change sign close to the onset of deconfinement energy



NA49: PR C79, 044910 (2009)
HSD: PR C79, 024907 (2009)



NA49: PR C79, 044910 (2009)
HSD: J. Phys. G36, 125106 (2009)



NA49: PR C83, 061902 (2011)
HSD: J. Phys. G36, 125106 (2009)

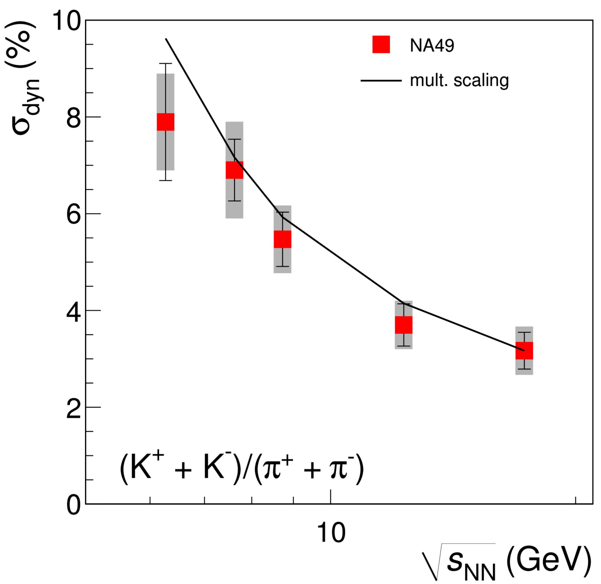
Scaling of particle ratio fluctuations

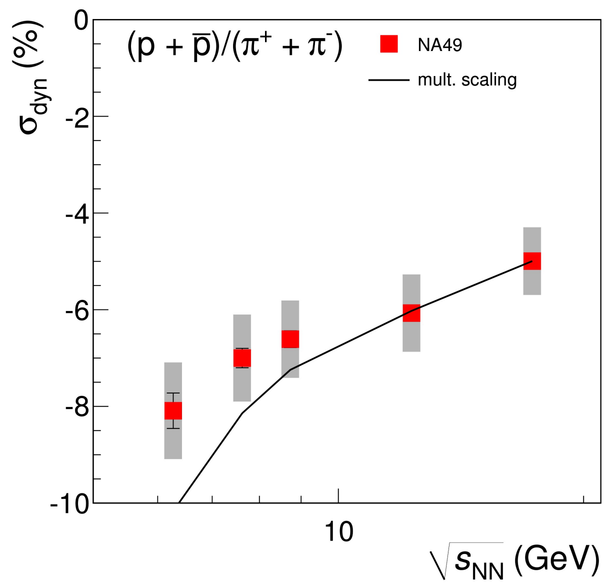
σ_{dyn} can be separated [PR C81, 034910 (2010)] into

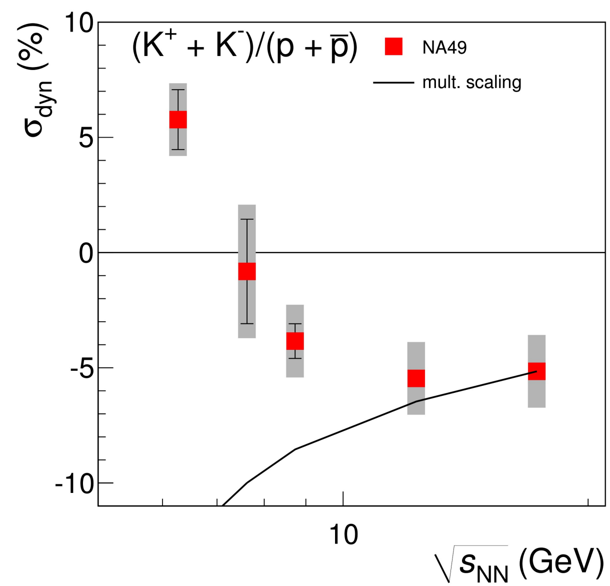
- correlation strength term
- term purely dependent on multiplicities

In case of unchanged correlations (invariant correlation strength) the general expectation is:

$$\sigma_{dyn} \propto \sqrt{\frac{1}{\langle A \rangle} + \frac{1}{\langle B \rangle}} \qquad A, B = N_K, N_\pi, N_p, \ldots$$







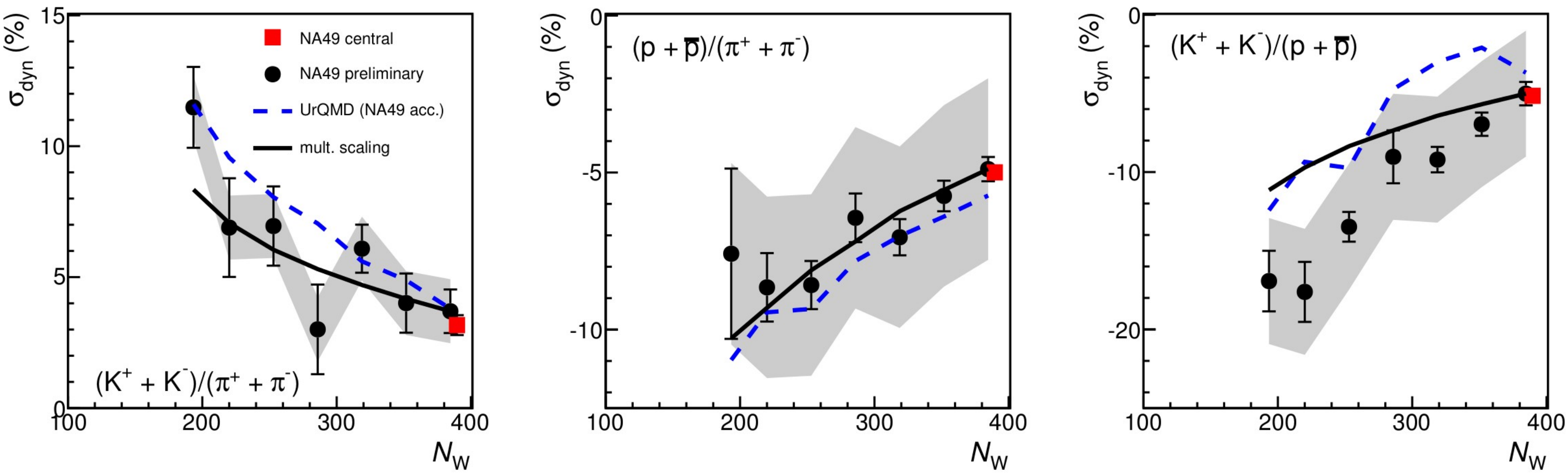
- **Scaling works very well for K/π and p/π fluctuations**
- **The change of sign in K/p fluctuations excludes any simple scaling based on average multiplicities.** The above scaling assumed invariant correlation strength ⇒ underlying correlation between kaons and protons is changing with energy

mult. scaling: V. Koch, T. Schuster PR C81, 034910 (2010); T. Schuster, J. Phys. G38,124096 (2011)

Please note: the difference between STAR and NA49 for K/π and K/p (not shown here) already understood as due to acceptance → NA49, PR C89, 054902 (2014)

Centrality dependence of event-by-event particle ratio fluctuations

$\sqrt{s_{NN}}$ = 17.3 GeV



Fixed physics (energy), varying volume (system size)

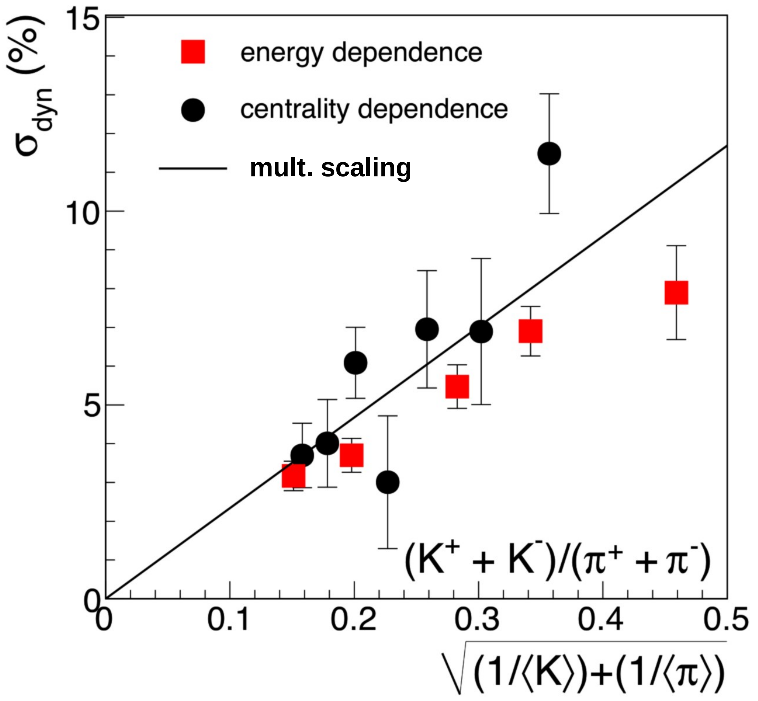
Absolute values rise towards peripheral collisions as in STAR (shown for K/π fluctuations at $\sqrt{s_{NN}}$ = 62 and 200 GeV, PRL 103, 092301 (2009)) and UrQMD

The same multiplicity scaling seems to hold:

(compatible with hypothesis that at constant energy underlying correlations are not significantly changed by variation of the system size

$$\sigma_{dyn} \propto \sqrt{\frac{1}{\langle A \rangle} + \frac{1}{\langle B \rangle}}$$

NA49: D. Kresan, QM 2011 poster
mult. scaling: T. Schuster, J. Phys. G38,124096 (2011); D. Kresan QM 2011 poster

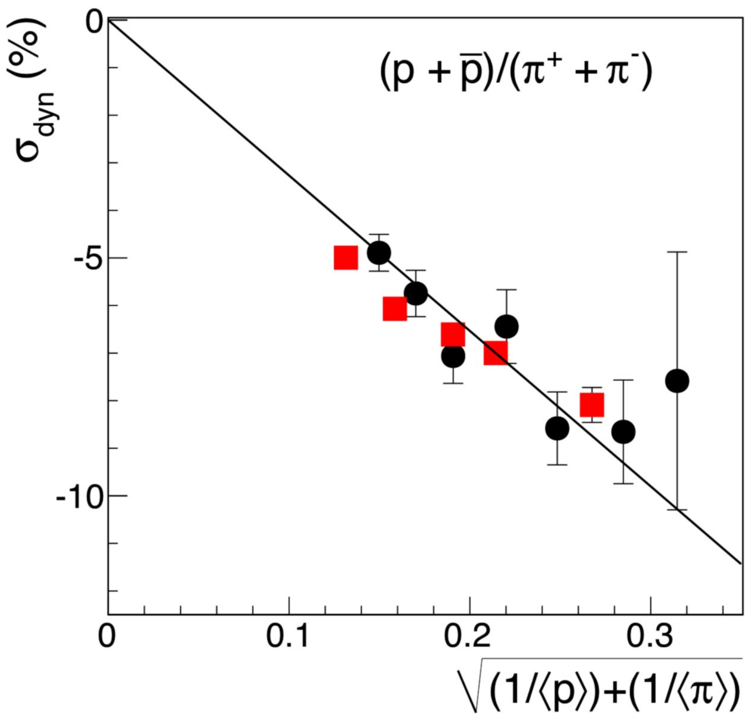


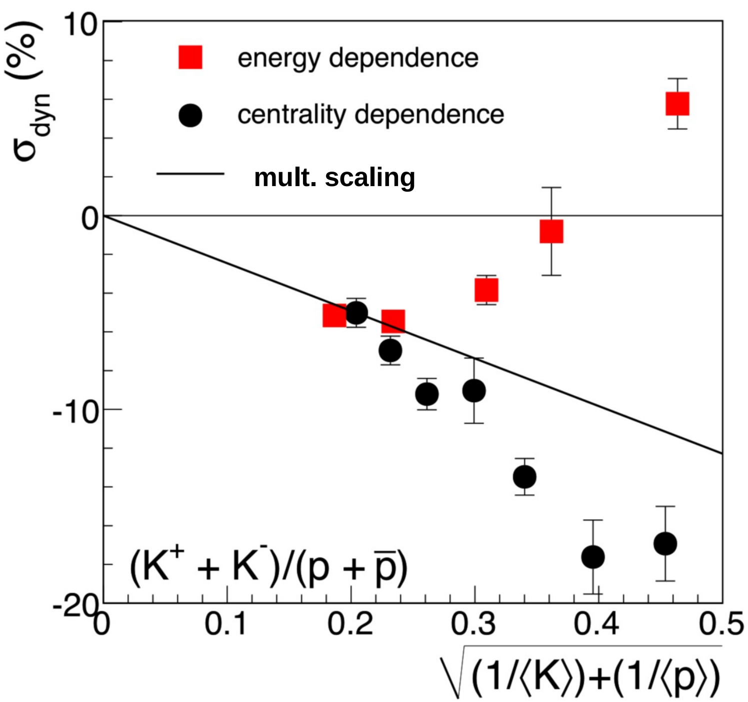
Energy and centrality dependence of particle ratio fluctuations on one scale

The same dependence on multiplicities is observed for K/π and p/π fluctuations

$$\sigma_{dyn} \propto \sqrt{\frac{1}{\langle A \rangle} + \frac{1}{\langle B \rangle}}$$

No common scaling of energy and centrality dependence for K/p fluctuations





Problems with σ_{dyn}? Let's test both σ_{dyn} (or ν_{dyn}) and Φ/ψ) on fast generators

$$\nu_{dyn(Particle\,1,\,Particle\,2)} = \frac{\langle N_1(N_1-1)\rangle}{\langle N_1\rangle^2} + \frac{\langle N_2(N_2-1)\rangle}{\langle N_2\rangle^2} - \frac{2\langle N_1 N_2\rangle}{\langle N_1\rangle\langle N_2\rangle}$$

$$\nu_{dyn} \approx sgn(\sigma_{dyn})\sigma^2_{dyn}$$

$z_x = x - \bar{x}$; $\bar{x}$ - inclusive average

event variable $Z_x = \sum_{i=1}^{N} (x_i - \bar{x})$

$$\Phi_x = \sqrt{\frac{\langle Z_x^2\rangle}{\langle N\rangle}} - \sqrt{\overline{z_x^2}}$$

$$\Psi_x = \frac{\langle Z_x^2\rangle}{\langle N\rangle} - \overline{z_x^2}$$

Old known quantities now used for chemical fluctuations:

Φ and ψ - strongly intensive measures of fluctuations (do not depend on volume and volume fluctuations)

$\Phi_{chemical}$ (p_T, ϕ → x)

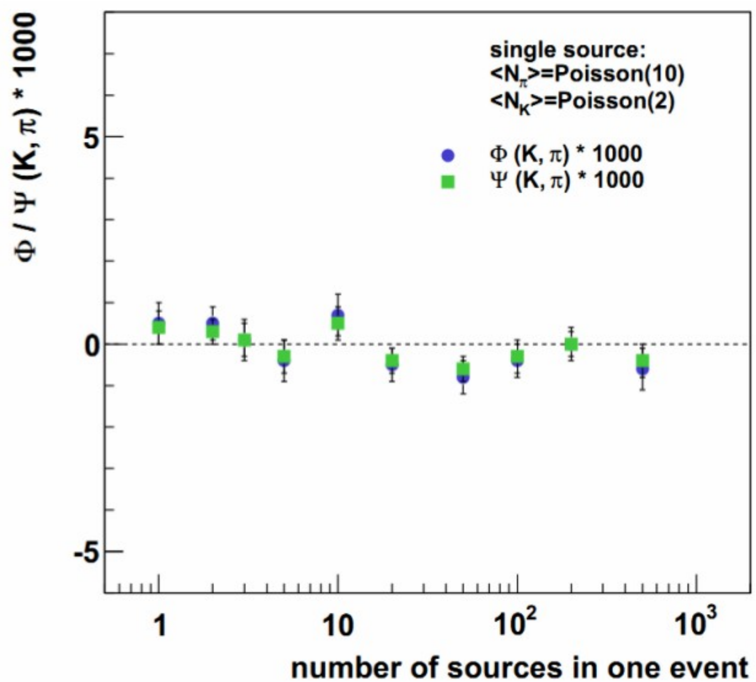
Here for system composed by kaons and pions we use

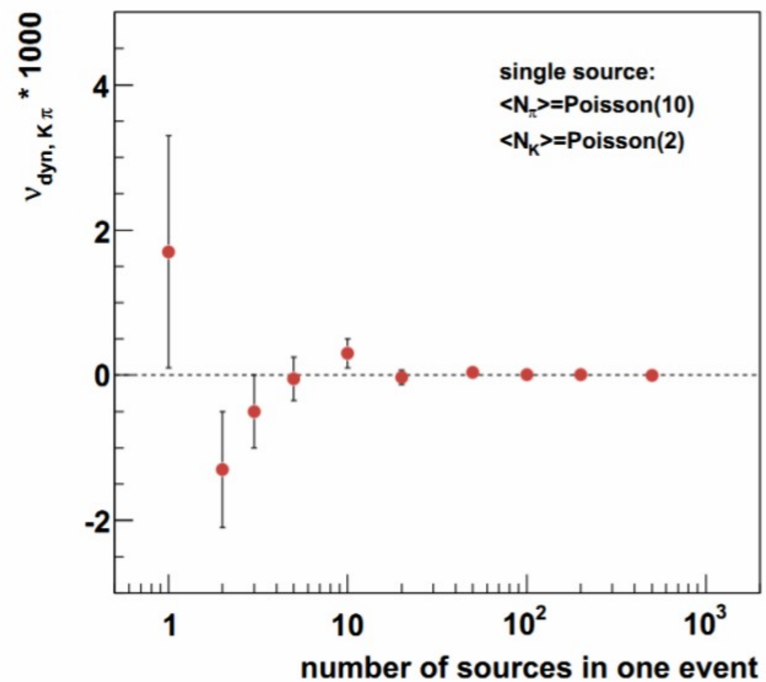
x = 1 for kaons

x = 0 for pions

Simulation of independent particle production

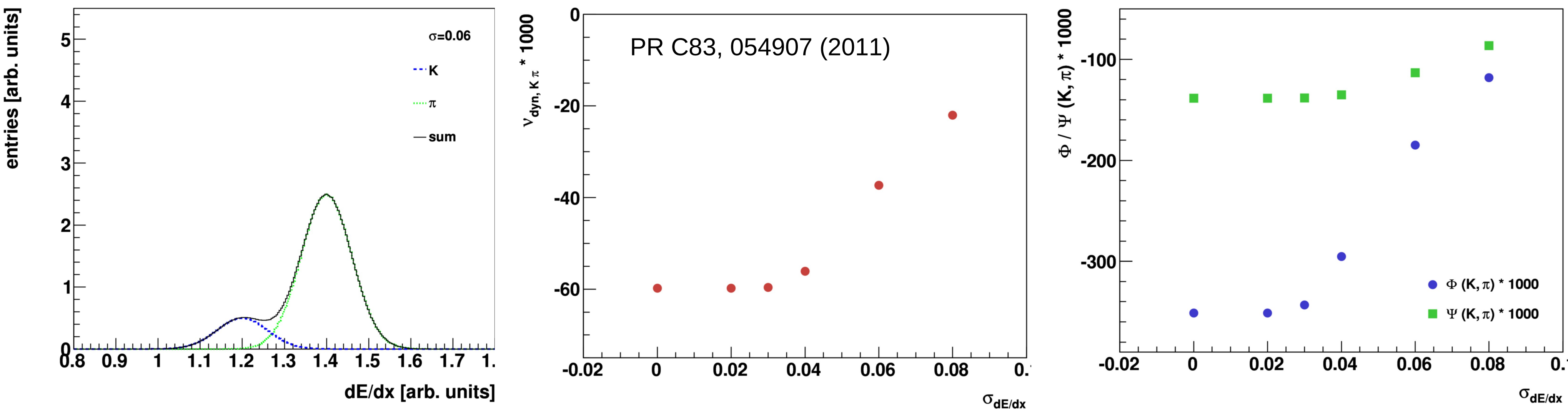
K. Grebieszkow, unpublished





- ν_{dyn} and thus σ_{dyn} are **not** intensive measures
- ratio fluctuations scale roughly as the inverse of the *accepted* multiplicity $\sigma_{dyn}^2 \sim 1/\langle N \rangle_{accepted}$
- $\Rightarrow$ rise toward low $\sqrt{s}$ in K/π fluct. due to low multiplicity rather then due to deconfinement (as originally believed)

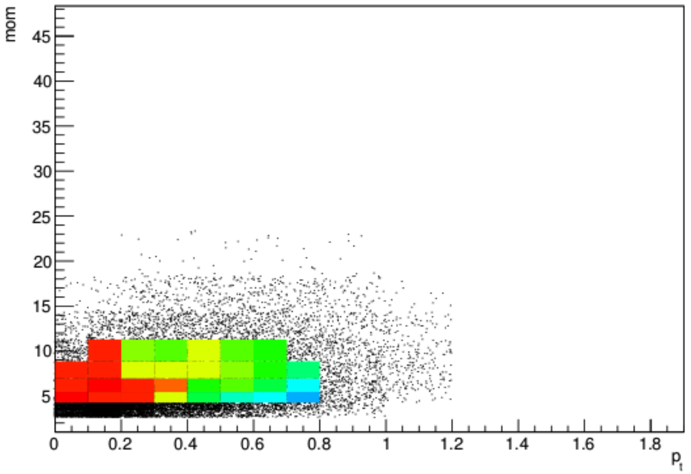
- Moreover: **all existing chemical fluctuation measures are sensitive to non-perfect particle identification :(**



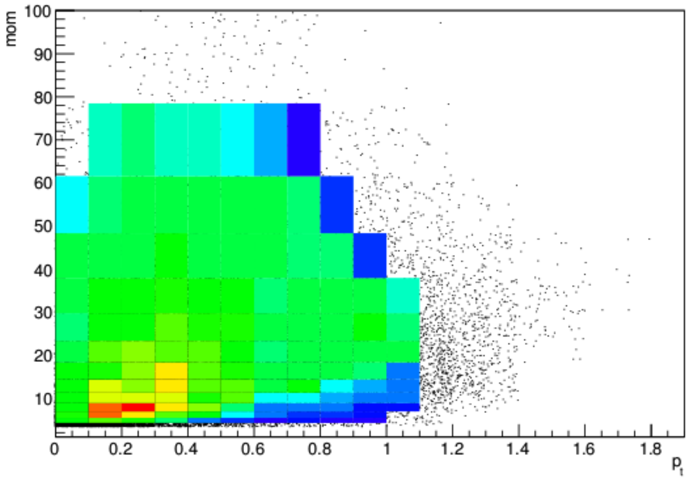
Solution: **identity method** (→ see Gaździcki, Grebieszkow, Maćkowiak, Mrówczyński, PR C83, 054907 (2011)).
Advantages: **e-by-e fits of particle ratios not required** (only global dE/dx fits), mixed events as reference not required, effect of limited dE/dx resolution can be corrected in a model independent way.
x_i (assumed ID) replaced by identity $w_i(dE/dx) = \rho_i(dE/dx)/\rho(dE/dx)$ measuring the probability that the particle is pion or kaon or proton or electron, etc.
Original idea developed and improved in: PR C84, 024902 (2011), PR C86, 044906 (2012) and currently applied to NA49 and NA61 data (M. Maćkowiak-Pawłowska, A. Rustamov).

Common NA61/SHINE and NA49 acceptance for chemical fluctuations

In order to compare p+p (NA61) and Pb+Pb (NA49) results the common acceptance for the chemical fluctuation analysis was defined.
Low particle multiplicity in p+p interactions limits the acceptance to the region in which track statistics is sufficient for the dE/dx fits.



$\sqrt{s_{NN}} = 7.6$ GeV

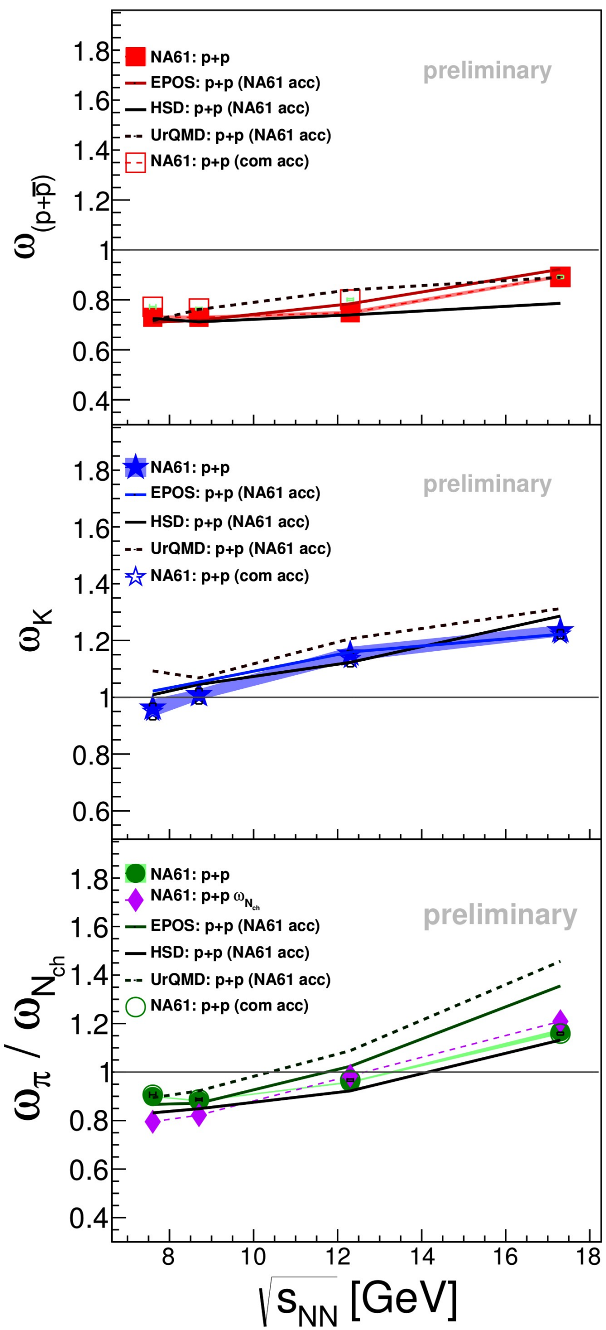


$\sqrt{s_{NN}} = 17.3$ GeV

Colored region marks common acceptance used for comparison of p+p and Pb+Pb results (scattered points indicate acceptance used for Pb+Pb analysis only).
For details see https://edms.cern.ch/document/1237791/1.

Scaled variance of multiplicity distribution in p+p interactions

$\omega[N_i] \equiv \omega_i$



- $\omega_{p+\bar{p}}$ **and** $\omega_p < 1$ probably due to **baryon number conservation**. ω_p and $\omega_{p+\bar{p}}$ similar (small fraction of antiprotons)

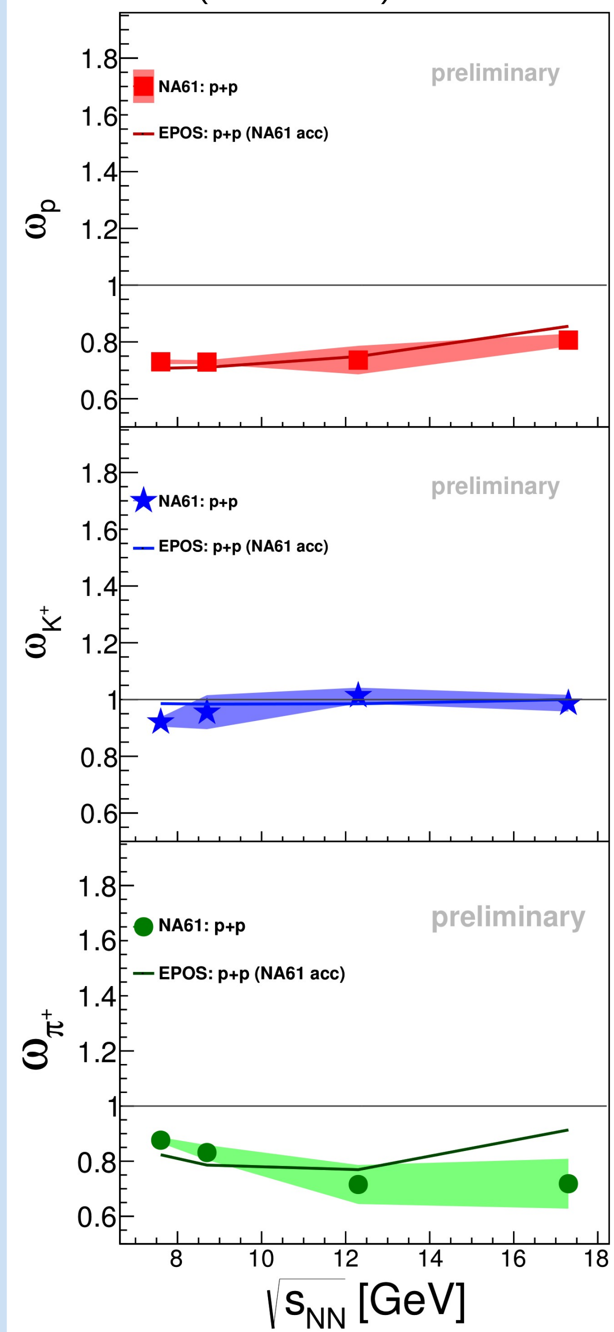
- $\omega_K > 1$ probably due to **strangeness conservation.** ω_{K+} close to 1 and < ω_K, which suggests that strangeness conservation contributes to ω_K

- **Increase of ω_π with energy** reflecting increase of ω_{Nch} measured in full phase-space (see PR 351, 161 (2001)). $\omega_{\pi+} < \omega_\pi$ **possibly due to charge conservation**

- ω_π **and** ω_{Nch} **similar at higher energies** (at lowest energies the fraction of protons is significant)

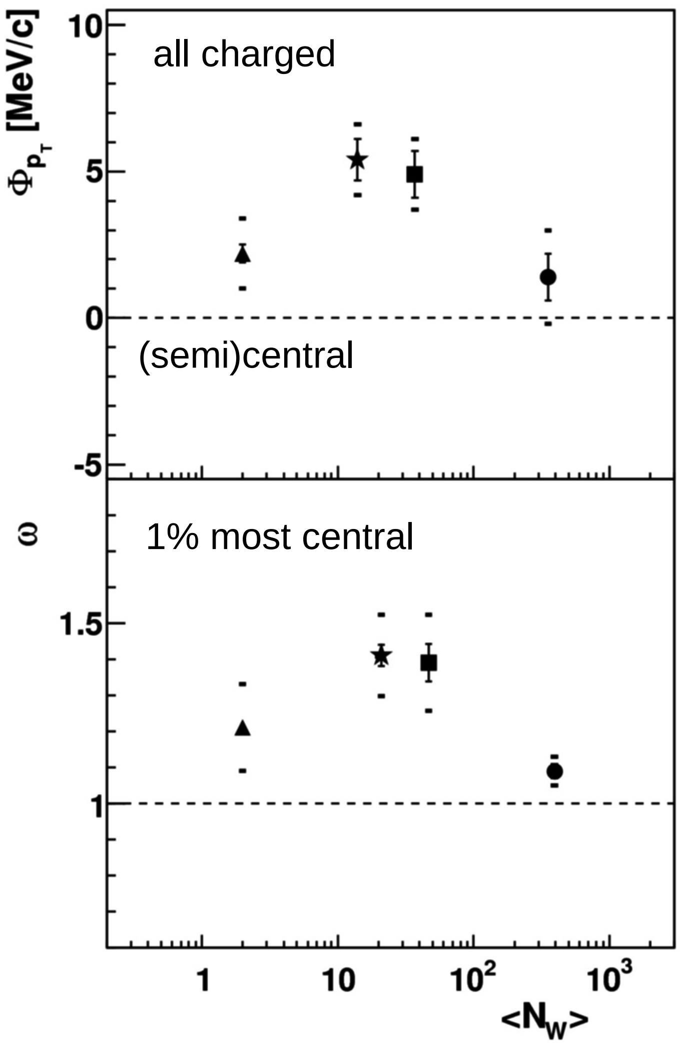
- HSD, EPOS, UrQMD predictions are similar to experimental results

PoS (CPOD 2013) 004 and 048

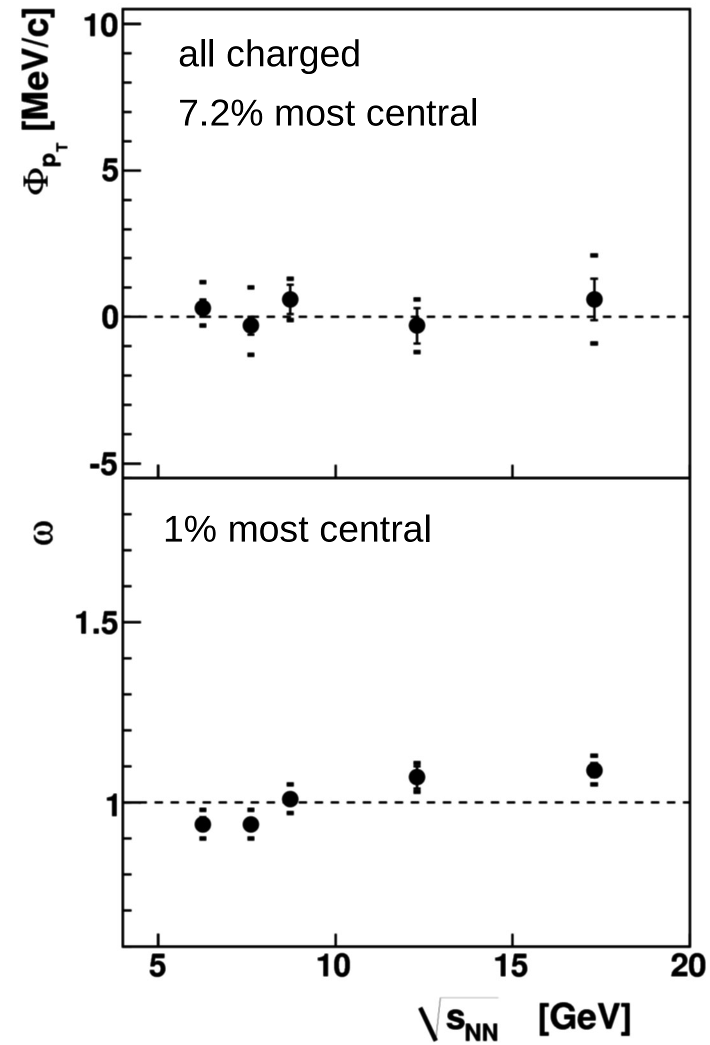


System size dependence
(p+p, C+C, Si+Si, and Pb+Pb)
of average p_T and multiplicity fluctuations at 158A GeV

Energy dependence of average p_T and multiplicity fluctuations for central Pb+Pb



- **Maximum of Φ_{pT} and ω for C+C and Si+Si at 158A GeV**
- **No significant energy dependence**

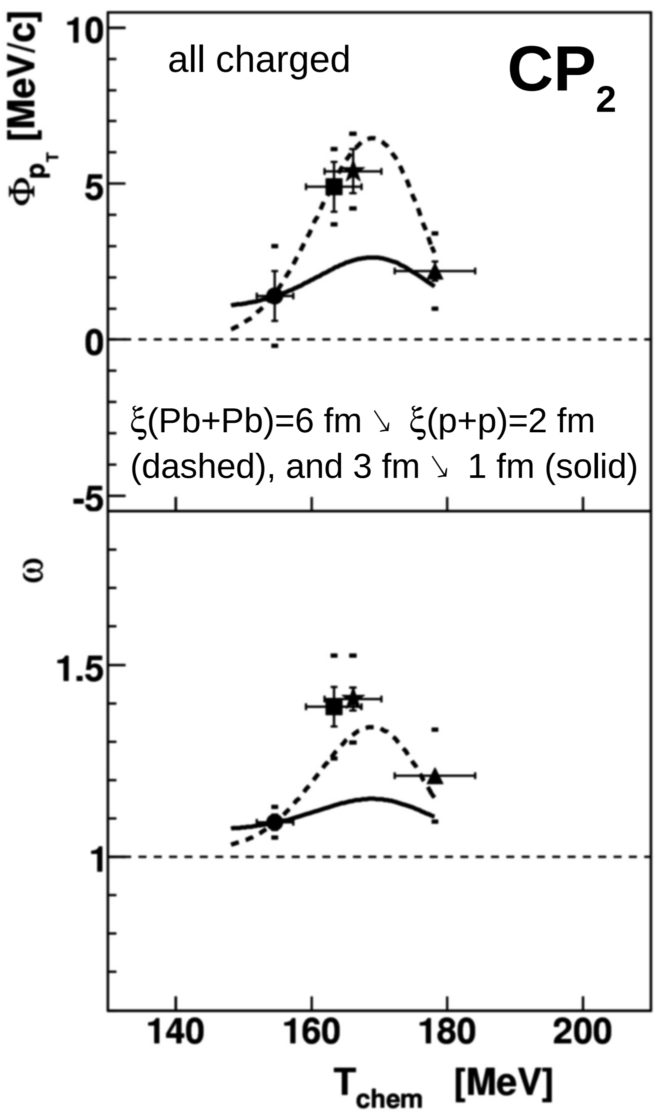


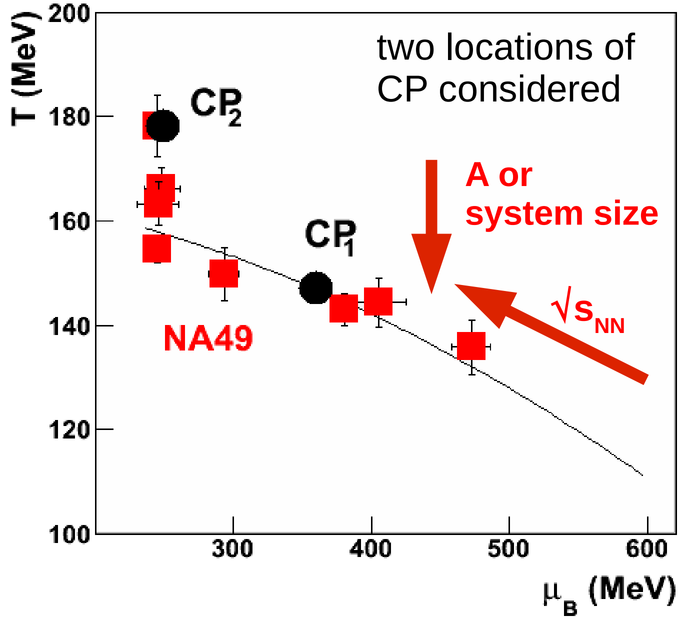
Forward-rapidity, limited azimuthal acceptance

upper left: PR C70, 034902 (2004)
lower left: p+p – PR C75, 064904 (2007); Pb+Pb – PR C78, 034914 (2008); C+C, Si+Si - B. Lungwitz, PhD thesis
upper right: PR C79, 044904 (2009)
lower right: PR C78, 034914 (2008)

For energy dependence of Φ_{pT} important cut on y^*_p to get rid of artificial effect of event-by-event centrality fluctuations while studying only forward-rapidity → for details see separate paper KG, PR C76, 064908 (2007)

Average p_T and N fluctuations: dependence on phase diagram coordinates

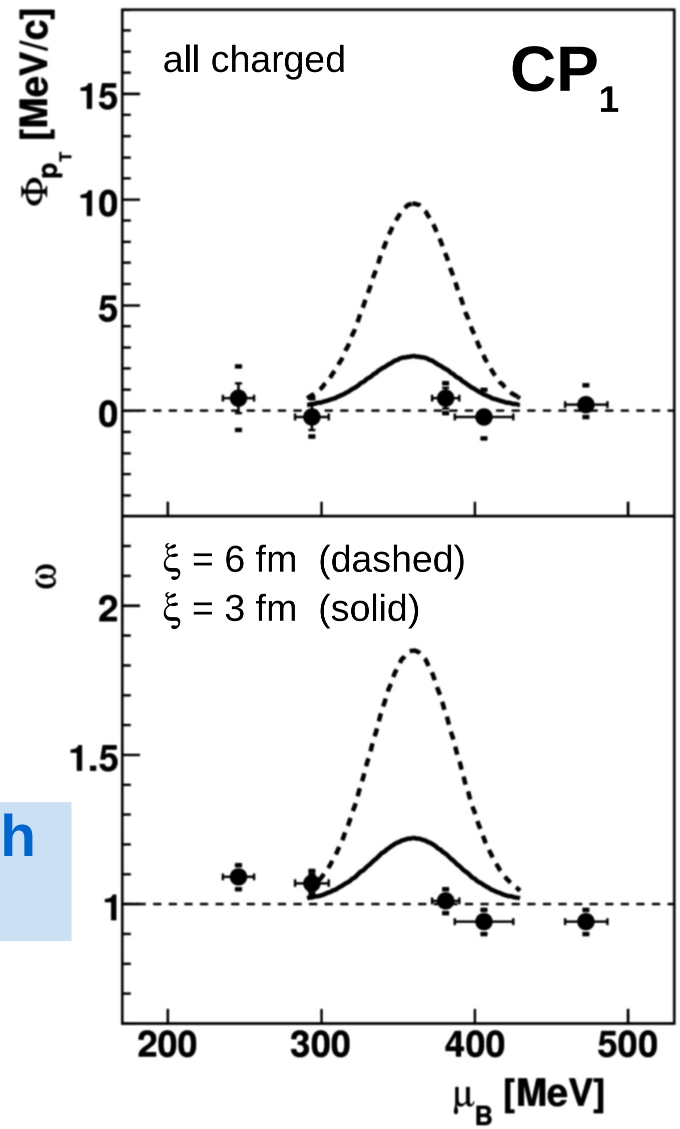




Maximum of Φ_{pT} and ω observed for C+C and Si+Si

Data are consistent with the CP_2 predictions

Grebieszkow, Nucl. Phys. A830, 547C-550C (2009)



Up to now strategy in fluctuation analysis → acceptance described, but results NOT corrected for detector effects (two-track resolution) and trigger bias (only Φ_{pT} was corrected for TTR)

Several effects were studied for new $\Delta[P_T, N]$ and $\Sigma[P_T, N]$ measures:

1. IPM, MIS, source-by-source T fluctuations (example of MIS), event-by-event (global) T fluctuations, P_T/N vs N correlation → PR C89, 034903 (2014)

S-by-s T fluct. (MIS) $\Delta[P_T, N] = \Sigma[P_T, N] > 1$ (≈1.2 for Boltzmann p_T distrib. with $\langle T\rangle$=150 MeV/c)

E-by-e T fluct.: for fixed σ_T $\Delta[P_T, N]$ increases, $\Sigma[P_T, N]$ increases when $\langle N_s\rangle$ increases

for fixed $\langle N_s\rangle$ $\Delta[P_T, N]$ increases, $\Sigma[P_T, N]$ increases when σ_T increases

2. Quantum effects

→ PL B730, 70 (2014); and 3)

Ideal Bose and Fermi gases within GCE:

$\Delta[P_T, N]^{Bose} < \Delta[P_T, N]^{Boltz} = 1 < \Delta[P_T, N]^{Fermi}$

$\Sigma[P_T, N]^{Fermi} < \Sigma[P_T, N]^{Boltz} = 1 < \Sigma[P_T, N]^{Bose}$

Similar analysis done for Φ_{pT} (belongs to Σ-"family"): $\Phi_{pT}^{Boltz} = 0$, $\Phi_{pT}^{Bose} > 0$, $\Phi_{pT}^{Fermi} < 0$

→ PL B439, 6 (1998); PL B465, 8 (1999)

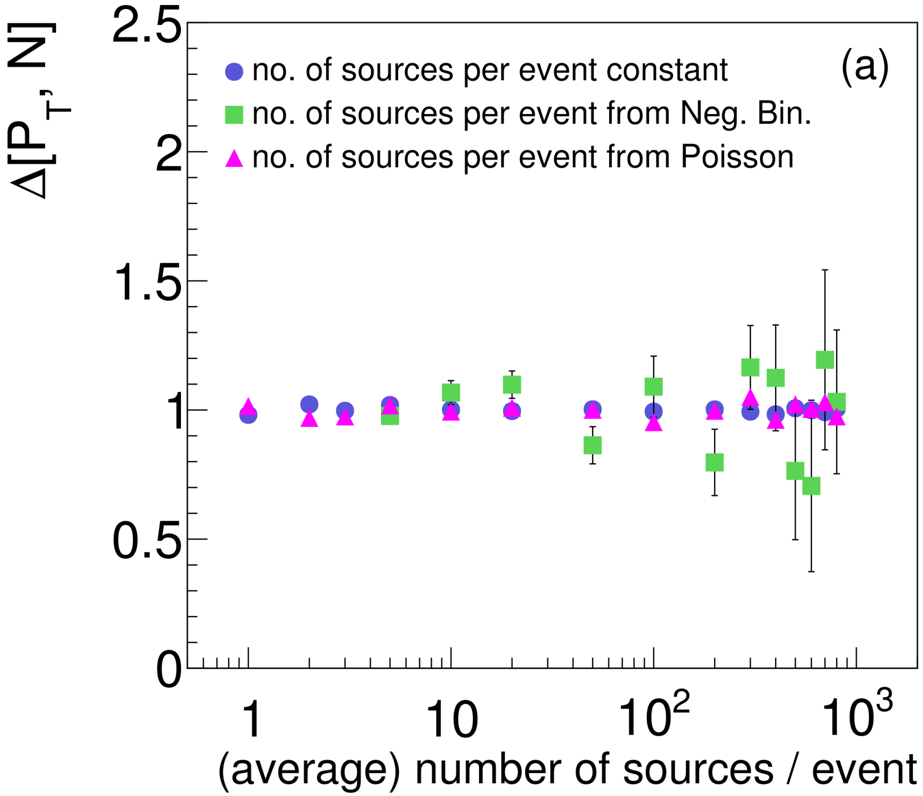
4. system size and energy dependence using UrQMD

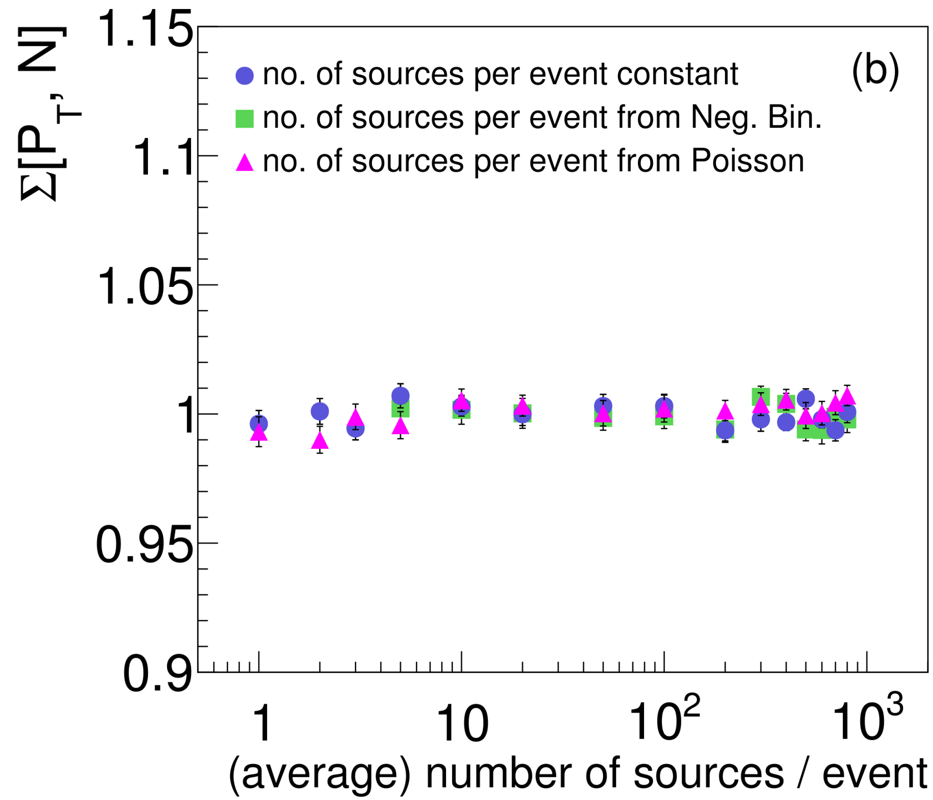
→ PR C88, 024907 (2013)

One of conclusions (supported by UrQMD tests):

Δ and Σ measure deviations from MIS in different ways ⇒ in the analysis of experimental data a simultaneous measurement of both quantities would be highly desirable

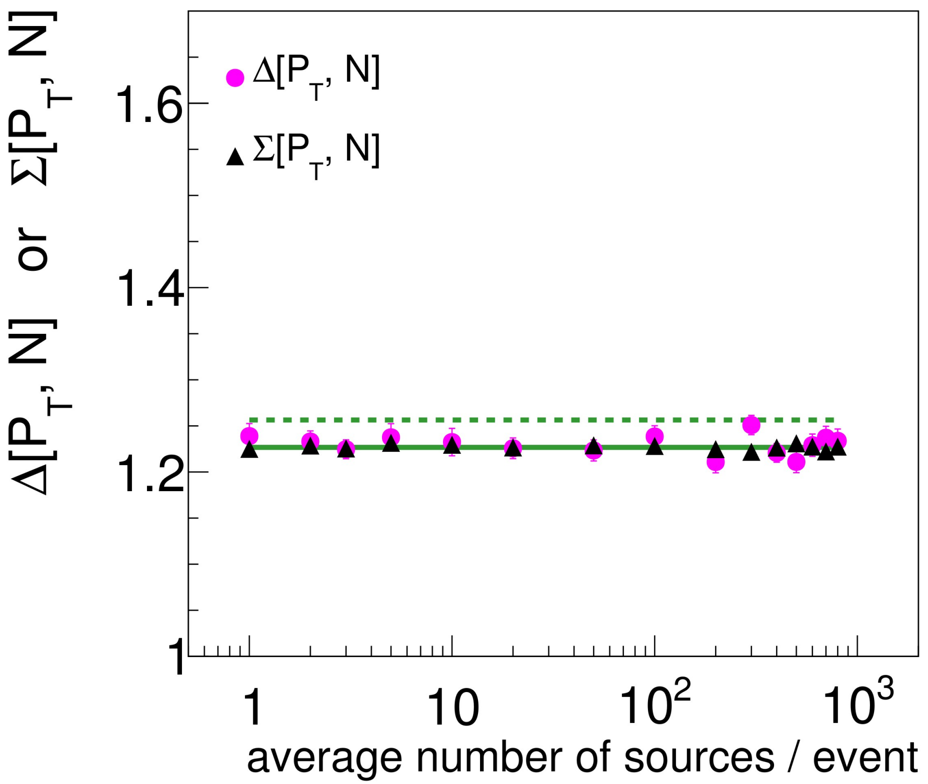
- **Model of Independent Sources (MIS) reduced to Independent Particle Model (IPM)**
- Each event composed by a given number of identical single sources.
- For each source the number of particles generated from the Poisson distribution with a mean value of 5.
- Particle p_T generated from exp. m_T spectrum with inverse slope T=150 MeV.
- Number of sources composing an event was either constant (circles) or selected from Poisson (triangles) or from Negative Binomial distribution (squares). For Negative Binomial distribution its dispersion sqrt(Var(N_S)) was large and taken to be equal $\langle N_S \rangle/2$.





Confirmation that these measures are intensive (circles) and strongly intensive (triangles, squares). For these simulations Φ_{pT} = 0

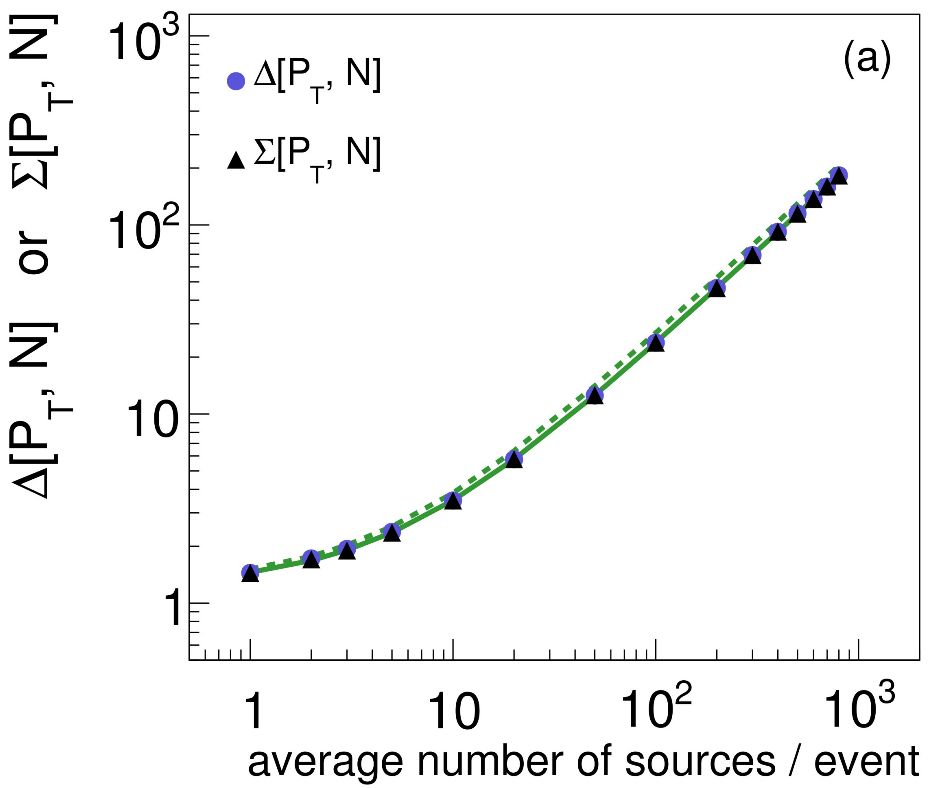
- For each source the number of particles from Poisson with a mean value of 5.
- Particle p_T generated from exp. m_T spectrum with <u>average</u> inv. slope ⟨T⟩=150 MeV. T generated separately for each single source (**source-by-source T fluctuations → MIS**) from Gaussian shape with dispersion σ_T=25 MeV. Number of sources composing an event generated from the Poisson distribution.



Lines → analytical calculations for m_T exponential shape (see the paper); solid line for pion mass and dashed line for massless particles

Positive signal Φ_{pT} > 0 (≈24 MeV/c, not shown) , Δ[P_T, N] and Σ[P_T, N] > 1; the measures are strongly intensive

- The same as previous page, but:
- source-by-source T fluctuations replaced by **event-by-event (global) T fluctuations**. For each event T generated from Gaussian shape with dispersion σ_T=25 MeV.



Lines → analytical calculations for m_T exponential shape (see the paper); solid line for pion mass and dashed line for massless particles

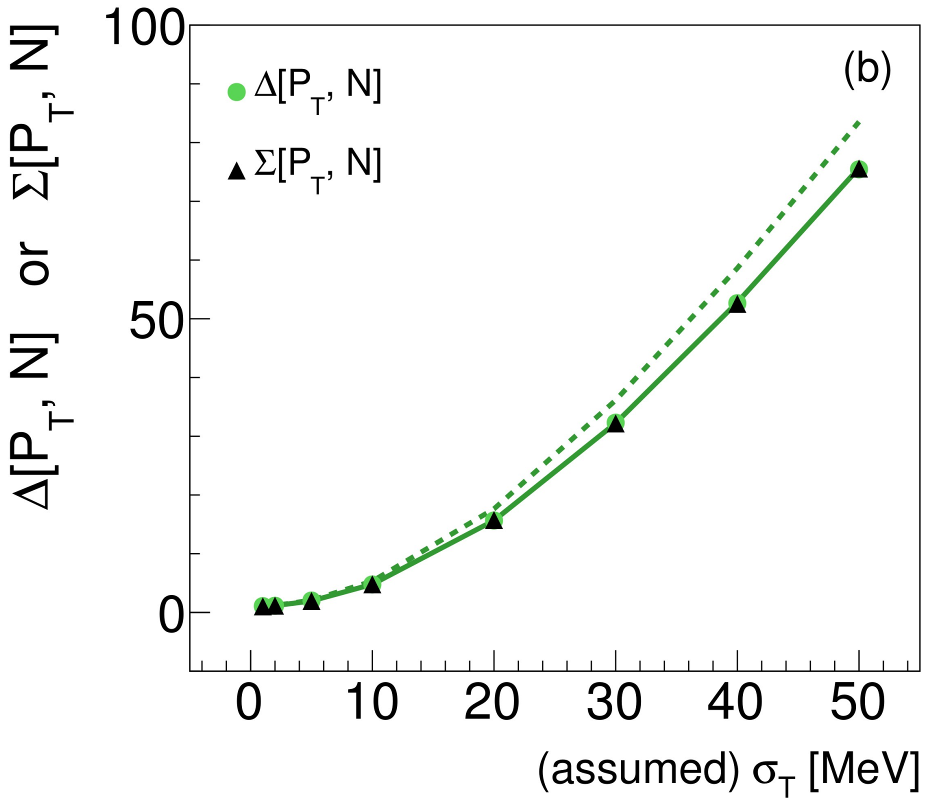
Strong dependence of $\Delta[P_T, N]$ and $\Sigma[P_T, N]$ on the number of sources for event-by-event T fluctuations (the same observation for Φ_{pT} – not shown)

M.I. Gorenstein, K. Grebieszkow, PR C89, 034903 (2014)

- The same as previous page.
- **Event-by-event T fluctuations**.

T varied from event to event following Gaussian distribution with dispersion σ_T. In order to avoid negative T values only events within T=150 $\pm 3\sigma_T$ MeV were accepted.

- The number of sources composing an event was generated from the Poisson distribution with a mean value of 100.



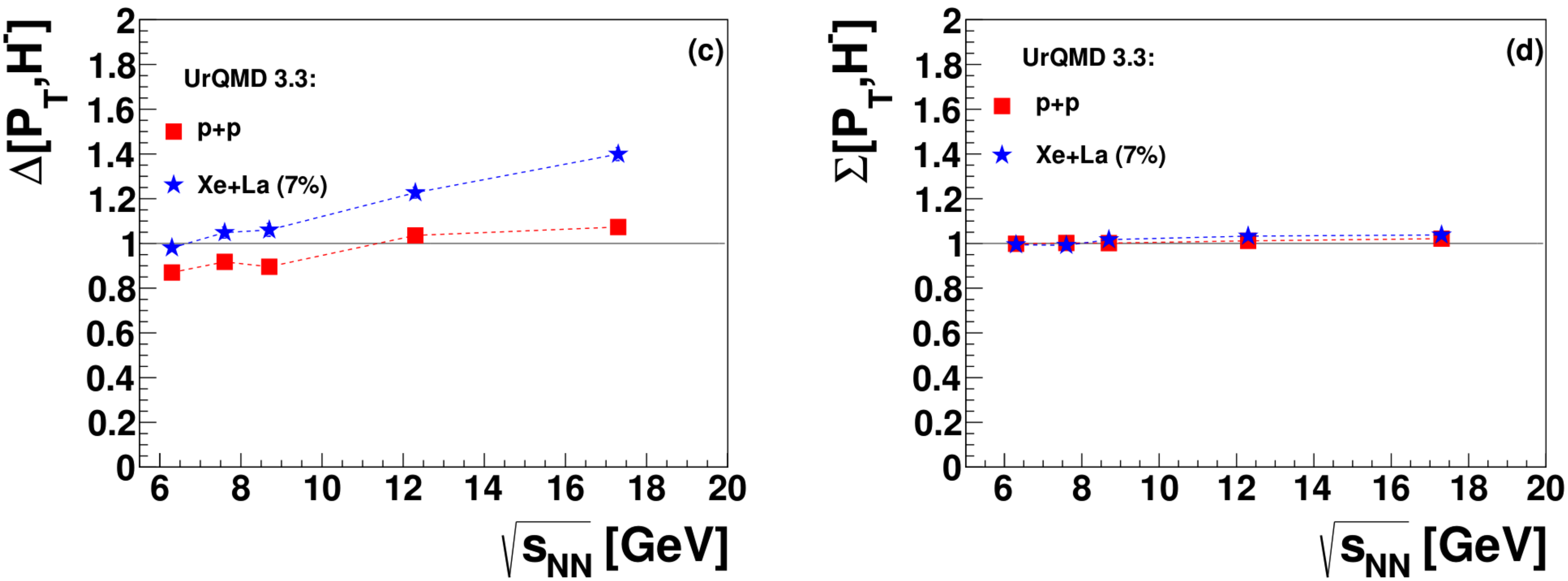
Lines → analytical calculations for m_T exponential shape (see the paper);
solid line for pion mass and dashed line for massless particles

The values of all fluctuation measures (also for Φ_{pT} which is not shown) increase when event-by-event "temperature" fluctuations are stronger (higher σ_T)

Previous slides → the same behaviour and magnitudes of $\Delta[P_T, N]$ and $\Sigma[P_T, N]$

The example that those two measures can be different → see **calculations within UrQMD 3.3 model**

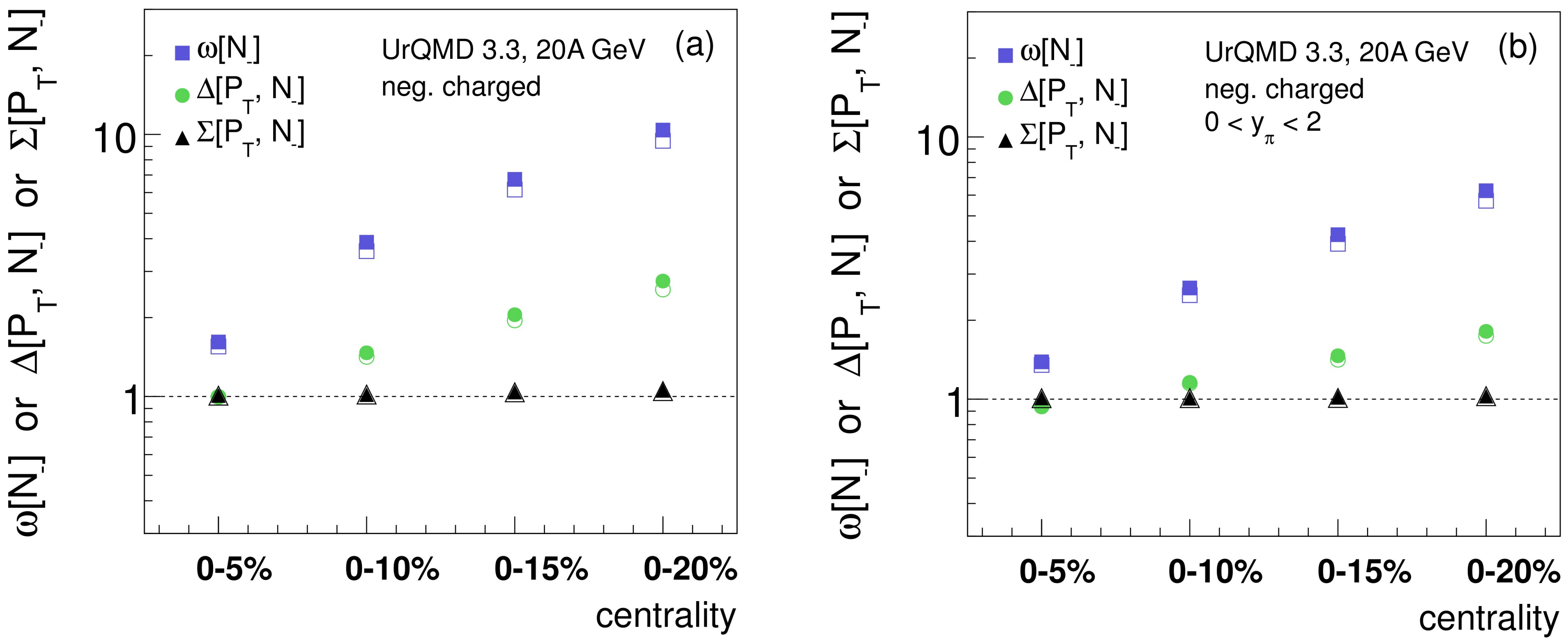
M. Gaździcki, M.I. Gorenstein, M. Maćkowak-Pawłowska, PR C88, 024907 (2013)



More tests within UrQMD 3.3 model (effects of centrality selection and limited detector acceptance and efficiency in Pb+Pb collisions)

M.I. Gorenstein, K. Grebieszkow, PR C89, 034903 (2014)

Forward hemisphere:



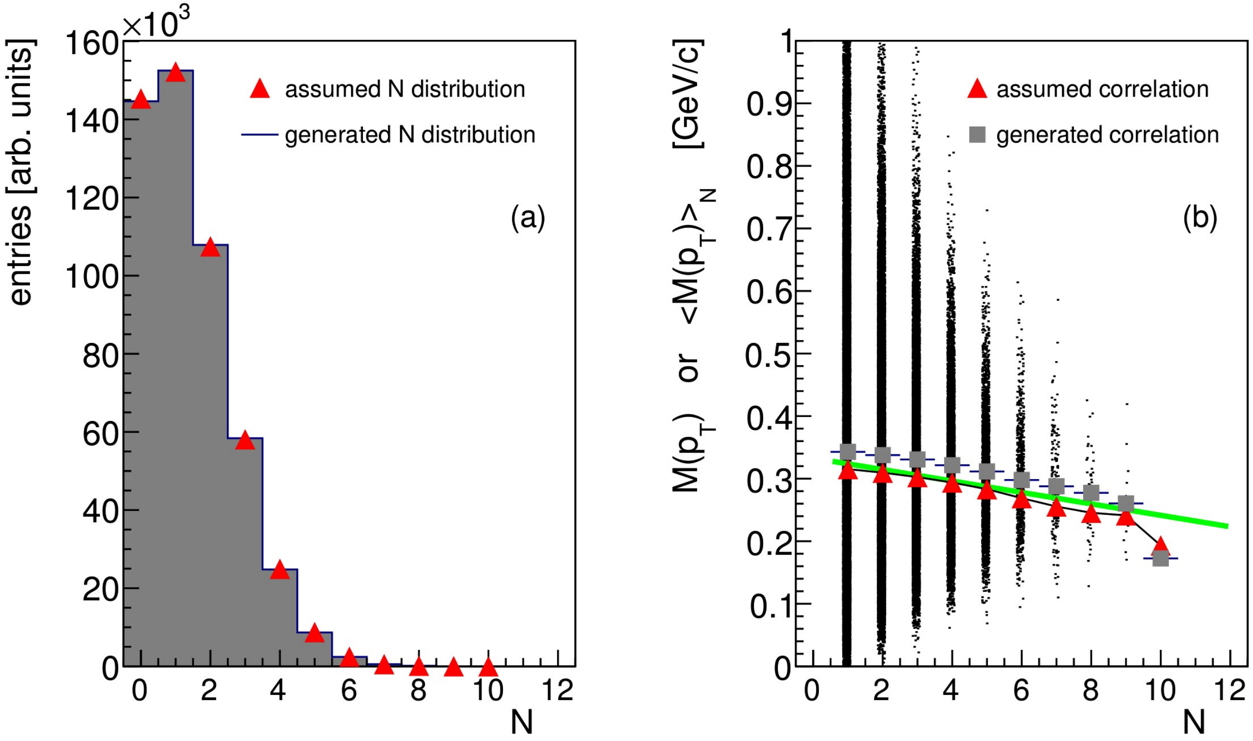
Left ↔ right - effect of acceptance losses
Full ↔ open - effect of (reconstruction) efficiency losses

Open points – 10% of particles randomly rejected

$M(p_T)$ – average transverse momentum per event $(= P_T/N)$

Known from years **correlation between $M(p_T)$ and N in elementary interactions**.

Here such a correlation taken from p+p at 158 GeV/c (forward-rapidty): NA49, PR C70, 034902 (2004). **$\langle M(p_T)\rangle$ versus N values** from NA49 (red triangles in right panel) **used as 2T values in fast generator** where $dn/dm_T = C\, m_T \exp(-m_T/T)$



$$\Delta[P_T, N] = 0.8158\ (0.0051)$$

$$\Sigma[P_T, N] = 1.0075\ (0.0018)$$

$$\Phi_{pT} = 0.82\ (0.19)\ \text{MeV/c}$$

M.I. Gorenstein, M. Rybczyński, PL B730, 70 (2014)

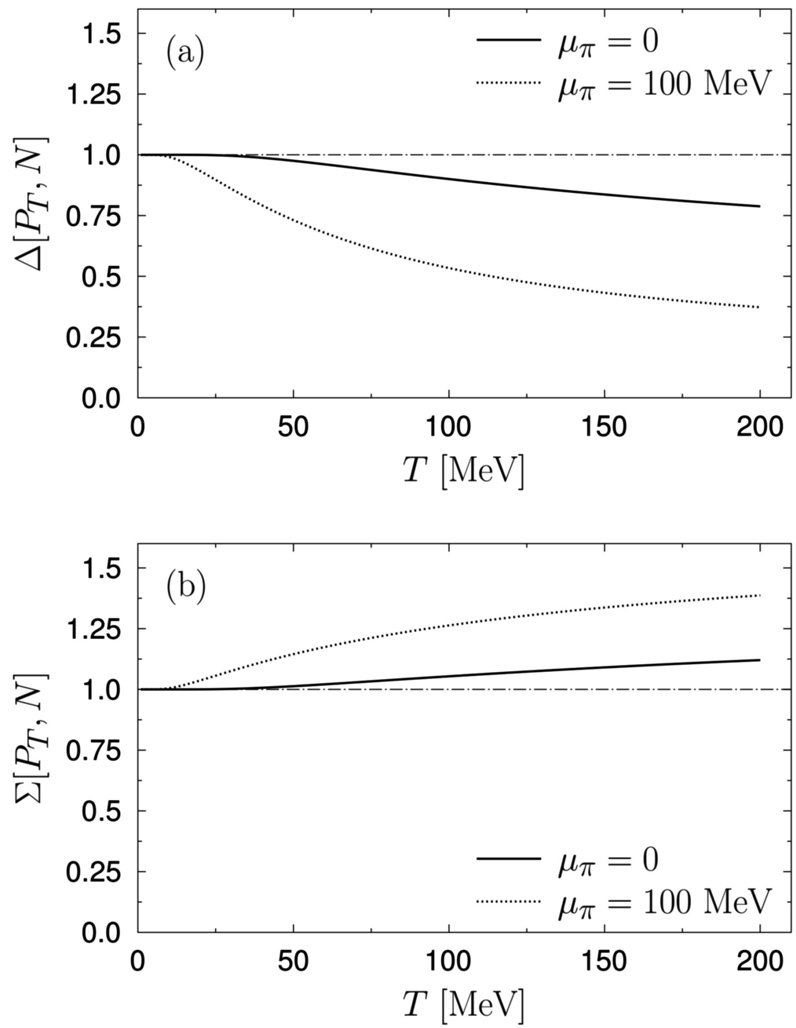


FIG. 3: The (a) $\Delta[P_T, N]$ and (b) $\Sigma[P_T, N]$ for the pion gas as the functions of T. The solid lines correspond to $\mu_\pi = 0$ and dotted lines to $\mu_\pi = 100$ MeV. The horizontal dashed lines show the Boltzmann approximation (19) equal to 1.

S. Mrówczyński / Physics Letters B 465 (1999) 8–14

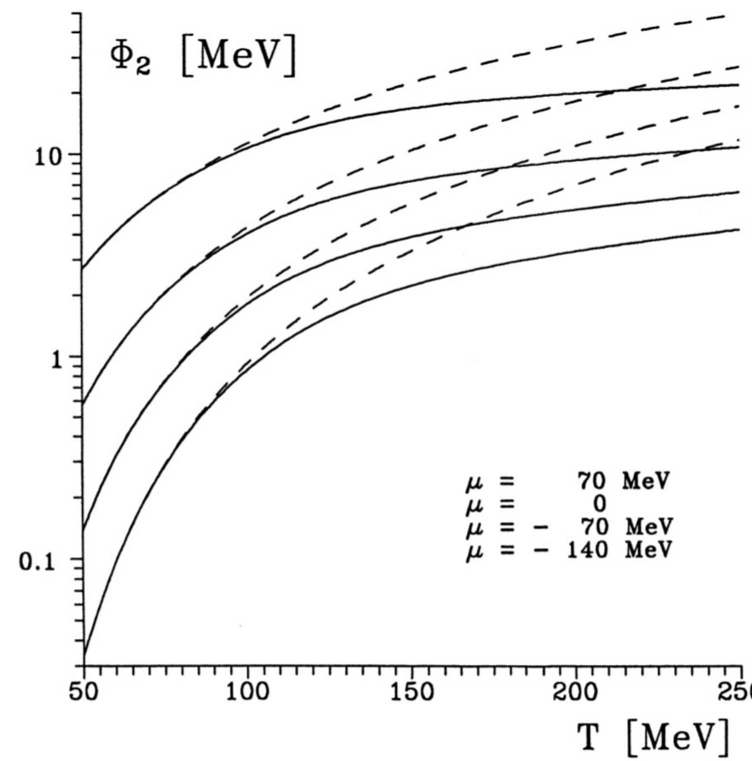
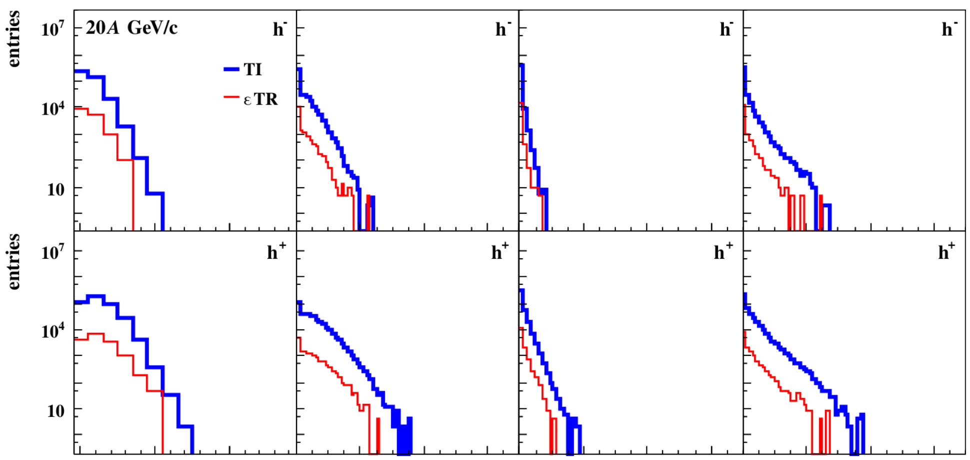
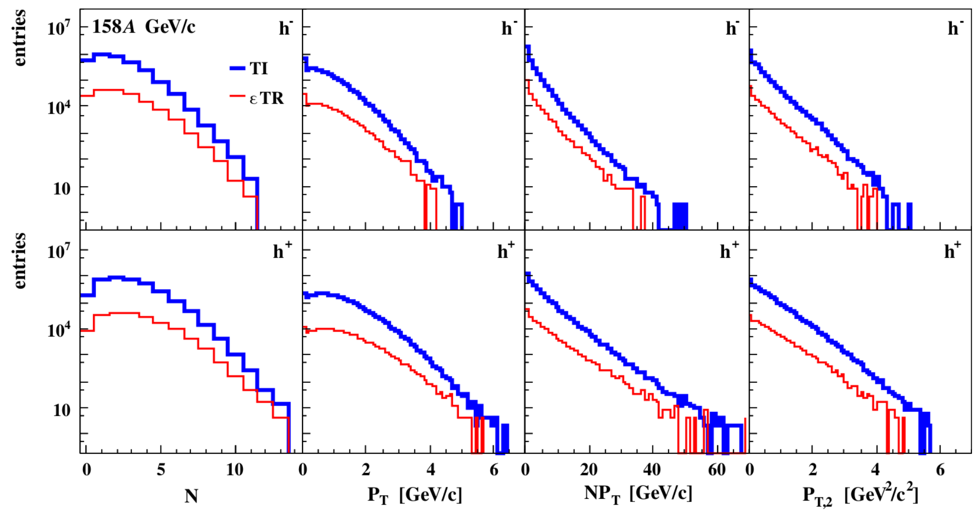


Fig. 1. Φ_2-measure of $p_\perp$-fluctuations in the hadron gas as a function of temperature for four values of the chemical potential. The resonances are either neglected (dashed lines) or taken into account (solid lines). The most upper dashed and solid lines correspond to $\mu = 70$ MeV, the lower ones to $\mu = 0$, etc.

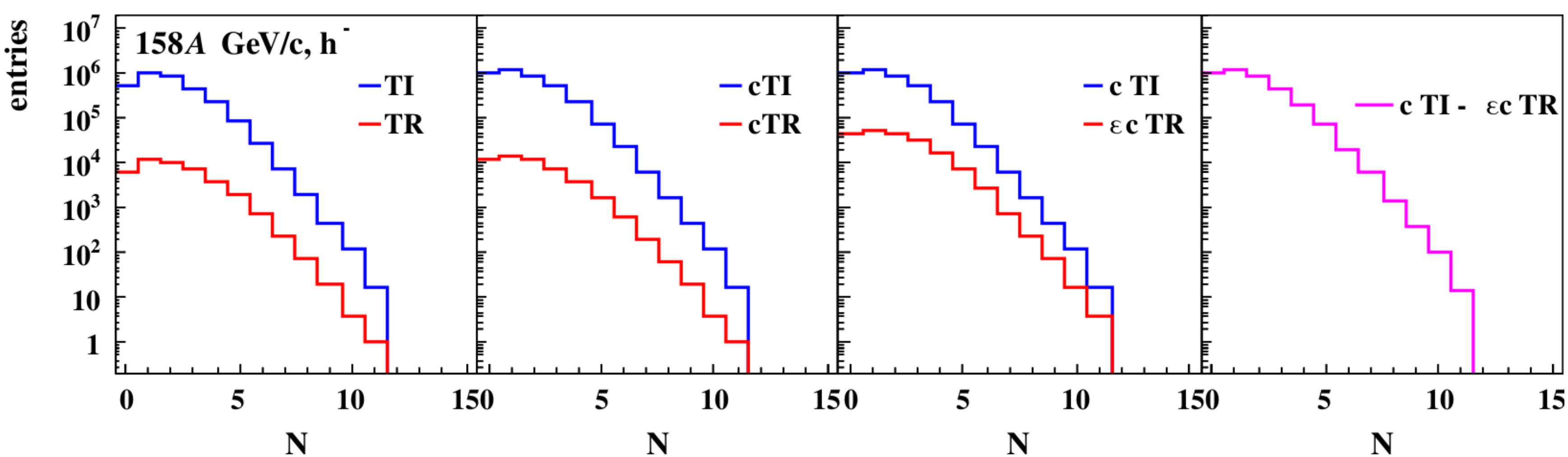
Event quantities: N, P_T, NP_T and $P_{T,2}$ for target inserted and (scaled) target removed p+p events

NA61, draft of paper





Procedure of corrections can be applied not only to event mean quantities ⟨X⟩ but **also to complete spectra**; below example for N distribution of neg. charged particles:

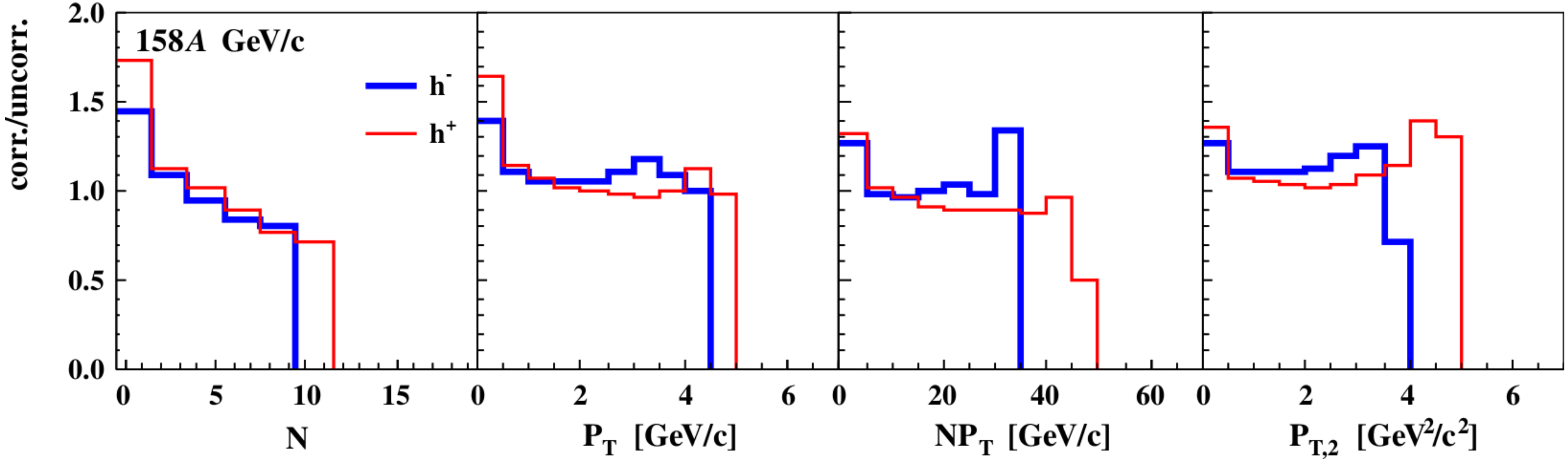


Impact of corrections on spectra of event quantities: N, P_T, NP_T and $P_{T,2}$

Ratios of corrected to uncorrected distributions of event quantities,

example for (NA61) **p+p at 158 GeV/c**

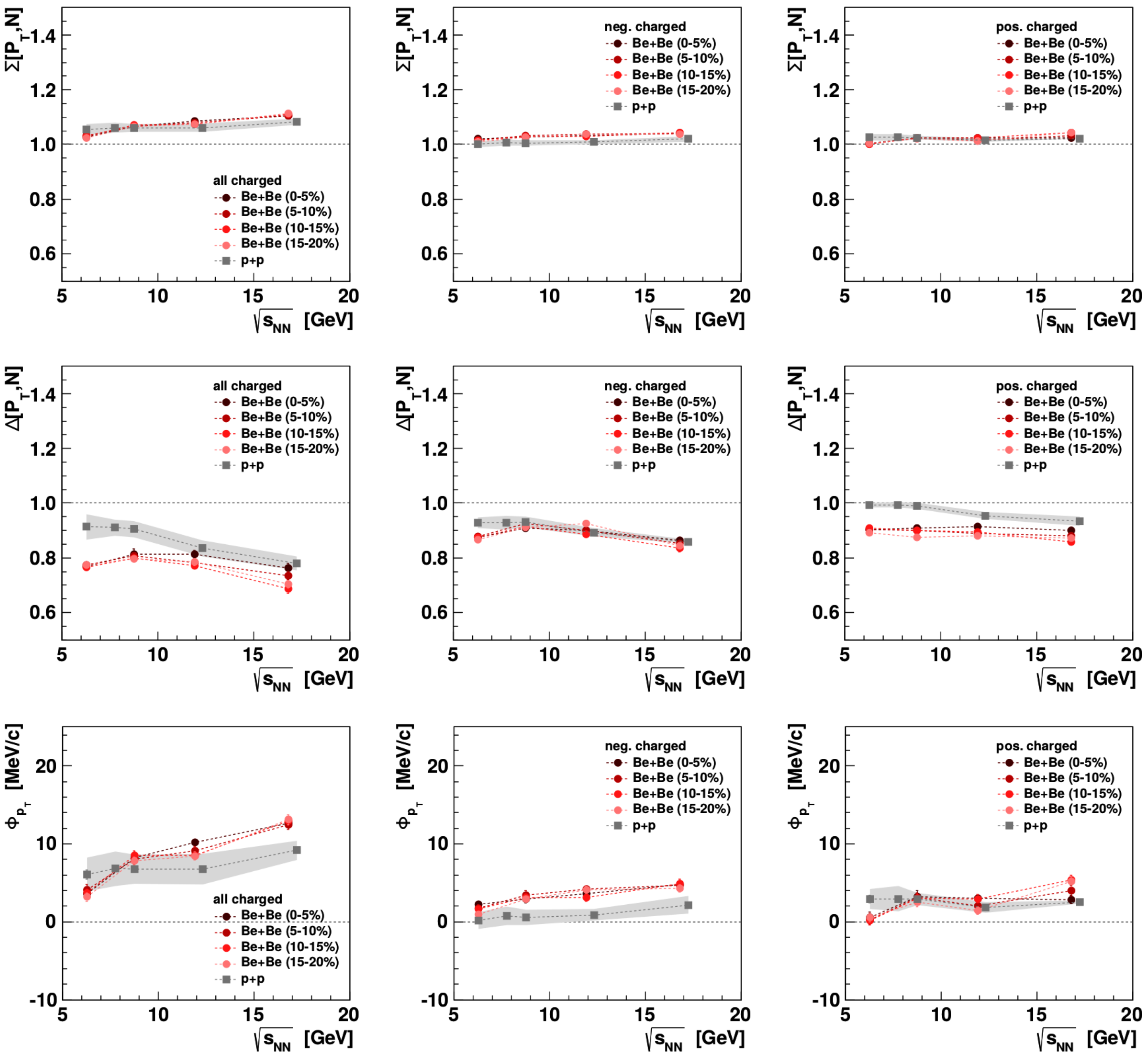
NA61, draft of paper



uncorrected – N, P_T, … values from original text file (target inserted)

corrected – each (target inserted) "real" event (N, P_T, ...)$^{+ \text{ or } -}$ is weighted in the histogram with c_i factor

P_T and N fluctuations in Be+Be collisions (NA61)



- **No centrality dependence in Be+Be**
- **No sign of any anomaly that can be attributed to CP** (both in p+p and Be+Be)

Be+Be results are corrected for non-target interactions; corrections for detector effects and trigger bias are estimated to be small but are still under investigation

T. Czopowicz, arXiv:1503.01619 (CPOD 2014)

Energy scan of P_T and N fluctuations in central Pb+Pb collisions (NA49) – comparison with models

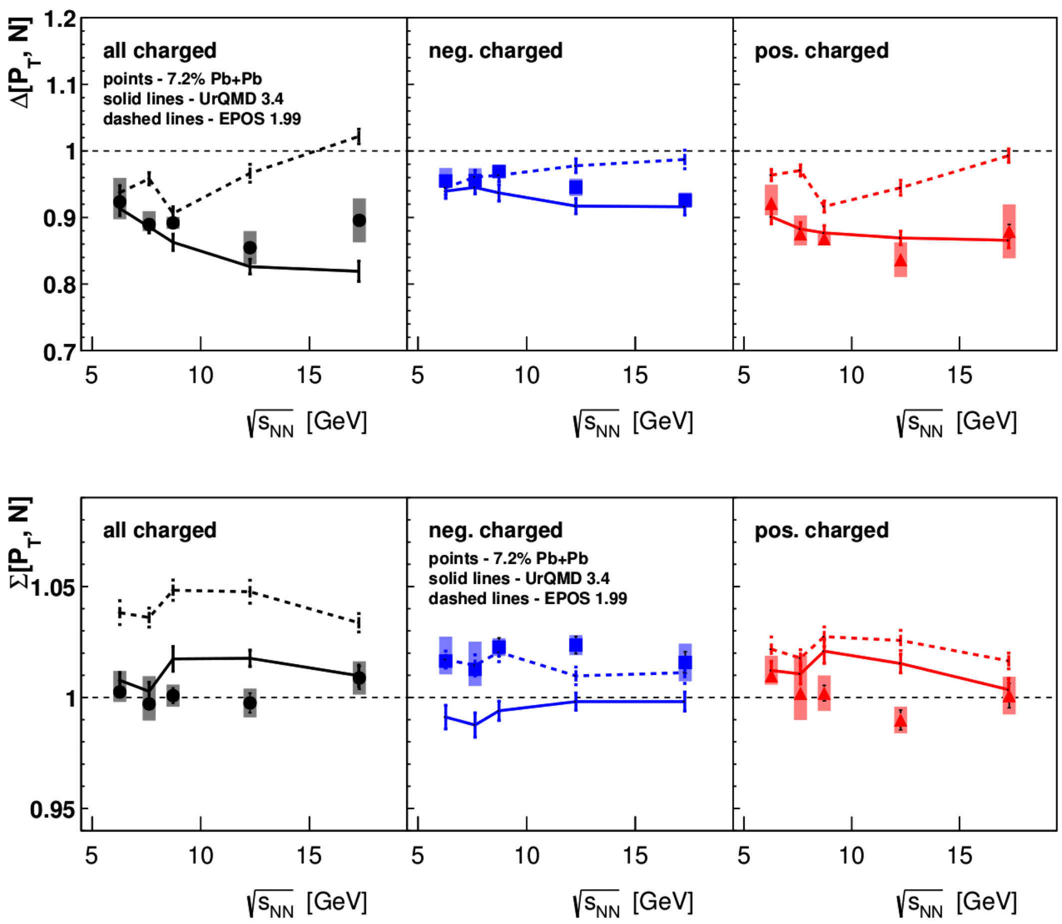


FIG. 4: Energy dependence of $\Delta[P_T, N]$ and $\Sigma[P_T, N]$ for the 7.2% most central $Pb+Pb$ interactions. Statistical uncertainties are denoted by lines, systematic ones by color boxes. Data (points) are compared to predictions of the UrQMD 3.4 (solid lines) and EPOS 1.99 (dashed lines) models with acceptance restrictions as for the data.

- $\Delta[P_T, N] < 1$ and $\Sigma[P_T, N] > 1$ (and $\Phi_{pT} > 0$) can be explained as due to effects of BE statistics
- No effects of OD and/or CP

NA49, draft of paper

NA49 published (Φ_{pT})

Points – PR C79, 044904 (2009),
UrQMD 1.3 (35k events per energy)

PHYSICAL REVIEW C **79**, 044904 (2009)

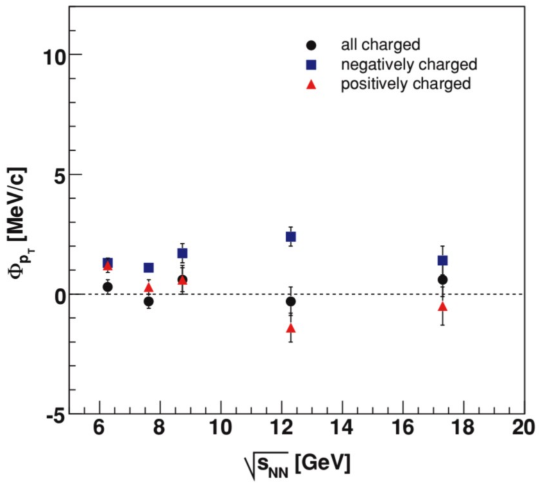


FIG. 12. (Color online) Φ_{p_T} as a function of energy for the 7.2% most central Pb + Pb interactions. Data points are corrected for limited two-track resolution. Errors are statistical only. Systematic errors are given in Table IV.

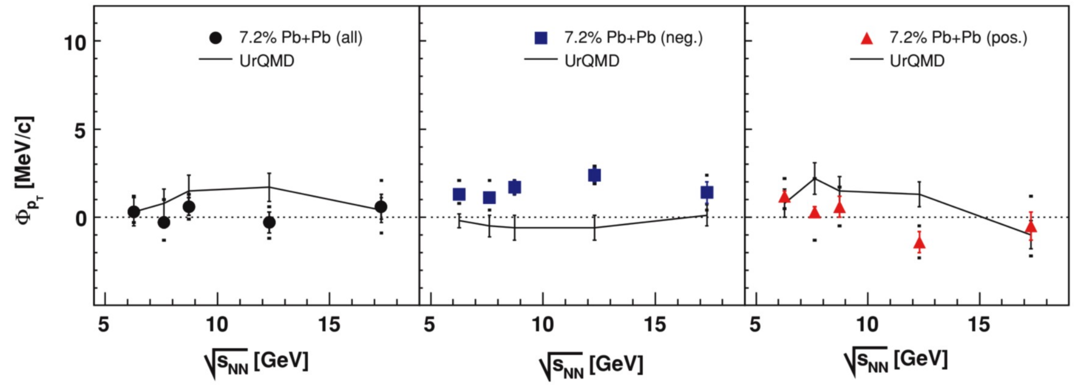
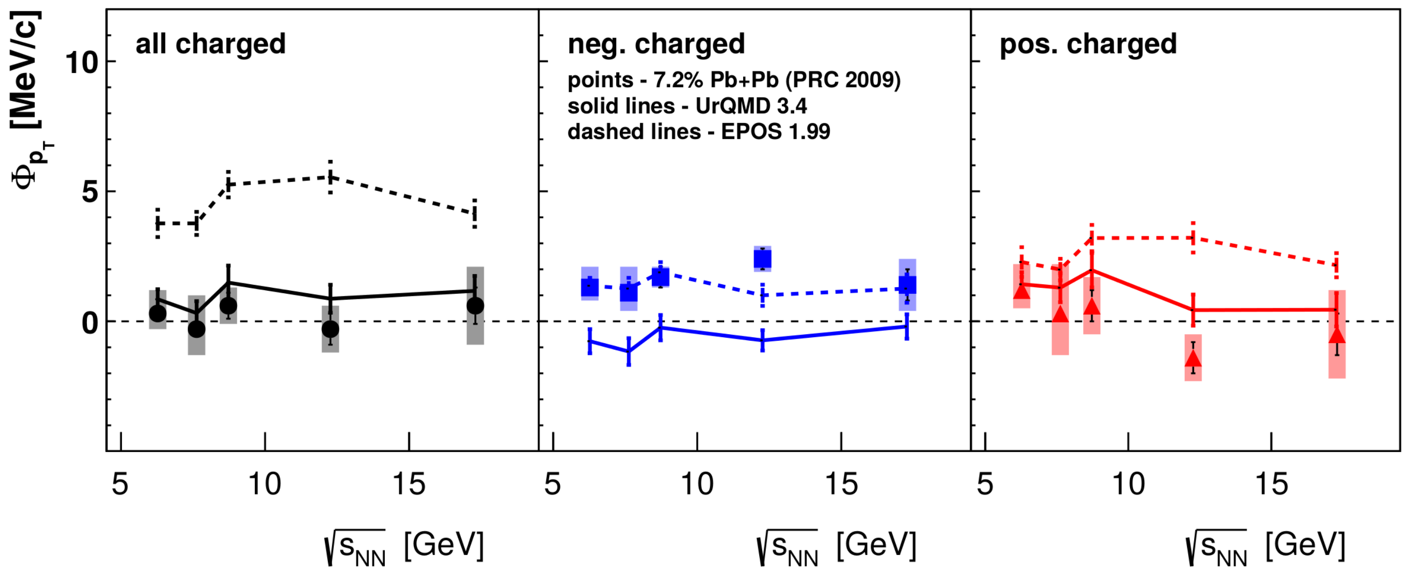


FIG. 16. (Color online) Comparison of Φ_{p_T} as a function of energy from data (data points, corrected for limited two-track resolution) with UrQMD model calculations (black lines) with acceptance restrictions as for the data. The panels represent results for all charged (left), negatively charged (center), and positively charged particles (right).

Current analysis (for models):

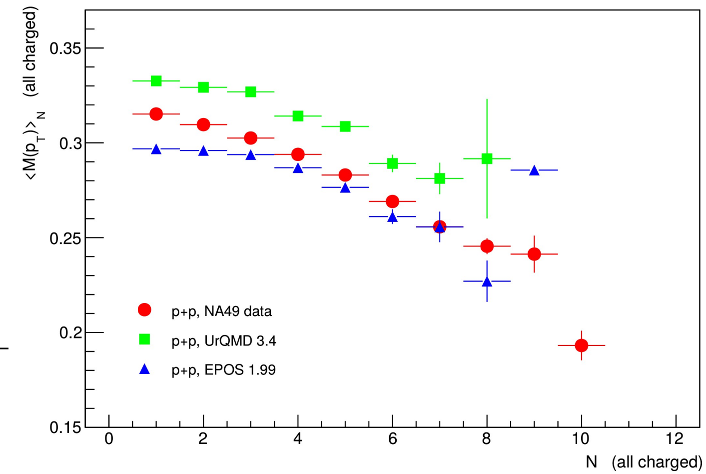
UrQMD 3.4 (100k events per energy),

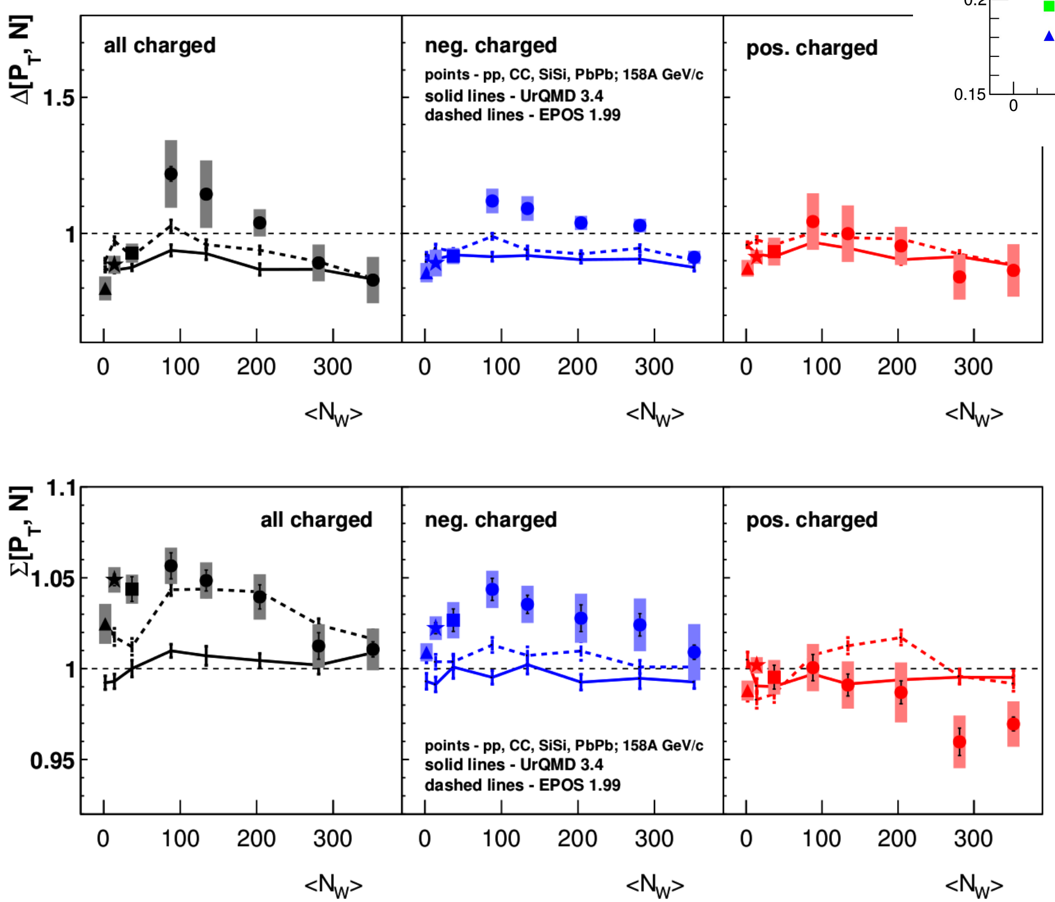
EPOS 1.99 (100k events per energy)



System size dependence of P_T and N fluctuations in A+A collisions at 158A GeV/c (NA49)

– comparison with models





NA49, draft of paper

- Maximum for peripheral Pb+Pb
- Fast generator with P_T/N vs. N anti-correlation (parametrization of p+p) results in $\Delta[P_T, N] = 0.8158\ (0.0051)$ and $\Sigma[P_T, N] = 1.0075\ (0.0018)$

FIG. 5: Dependence of $\Delta[P_T, N]$ and $\Sigma[P_T, N]$ versus the mean number of wounded nucleons $\langle N_W \rangle$ on the size of the colliding nuclei (p, C, Si, Pb) and the centrality of Pb+Pb interactions at 158A GeV/c. Statistical uncertainties are denoted by error bars, systematic uncertainties by colored boxes. Data (points) are compared to predictions of the UrQMD 3.4 (solid lines) and EPOS 1.99 (dashed lines) models with acceptance restrictions as for the data.

NA49 published
(Φ_{pT})

PHYSICAL REVIEW C **70**, 034902 (2004)

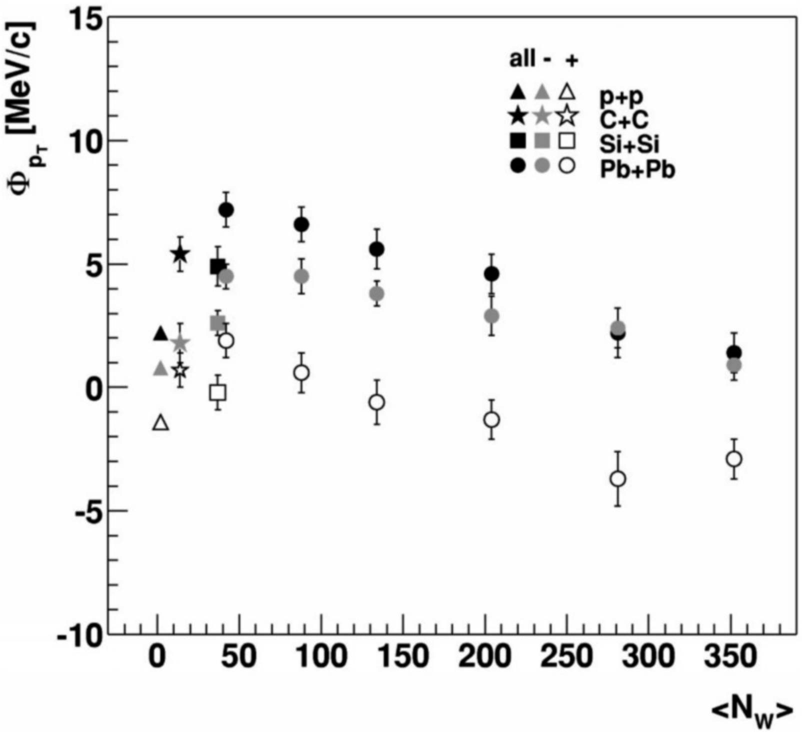


FIG. 8. Φ_{p_T} versus mean number of wounded nucleons $\langle N_W \rangle$. Data points were corrected for limited two-track resolution. Errors are statistical only. Systematic error is smaller than 1.6 MeV/c.

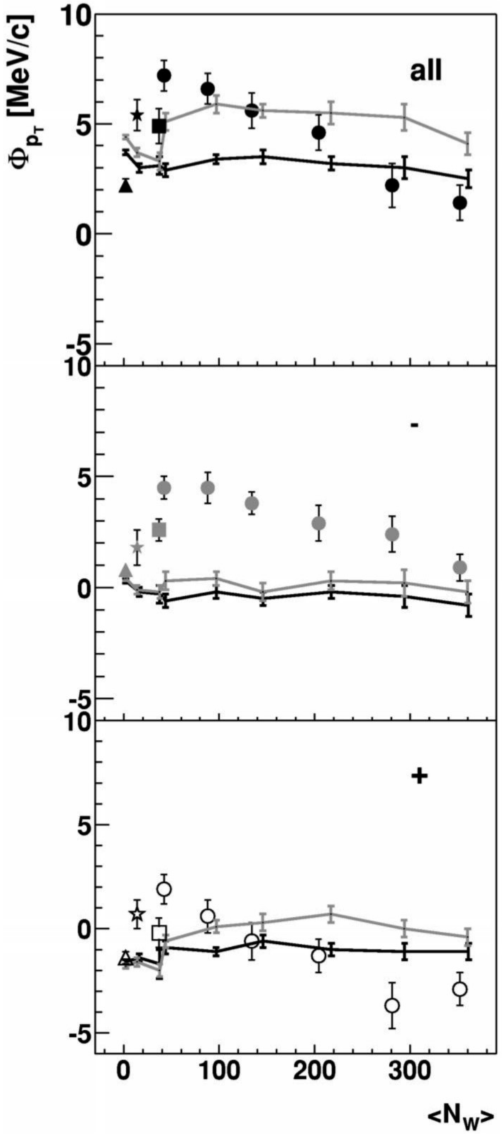


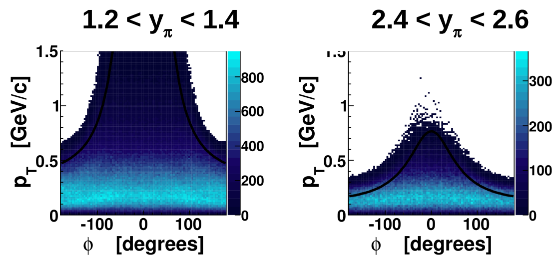
FIG. 10. Φ_{p_T} versus mean number of wounded nucleons calculated using the HIJING model with geometrical acceptance cuts included (black lines) and without geometrical acceptance restrictions (gray lines). Results are compared to data (points) corrected for limited two-track resolution (the markers are the same as in Fig. 8). The panels represent: all charged, negatively charged, and positively charged particles. Data points contain both short and long range correlations. The effects of short range correlations are not incorporated in the HIJING model.

Comparison of NA61 p+p with NA49 A+A

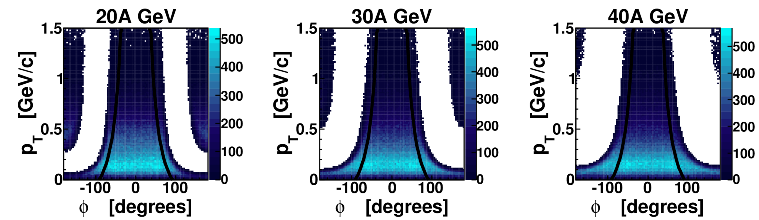
In NA49:

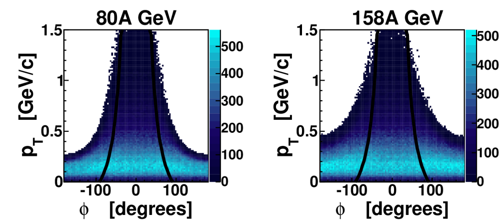
- **p_T fluctuations** (energy dependence for 7.2% central Pb+Pb, and system size dependence for p+p, C+C, Si+Si, and Pb+Pb at $\sqrt{s_{NN}}$ = 17.3 GeV) **were measured in forward-rapidity only** $1.1 < y_\pi < 2.6$ (azimuthal angle was “narrow”- common for all energies or “wide” - for system size dependence at $\sqrt{s_{NN}}$ = 17.3 GeV)

Acceptance for pos. and neg. charged particles is the same, provided the azimuthal angle for one charge is reflected (here neg. charged were reflected)



“wide” acceptance for sys. size dependence at 158A GeV





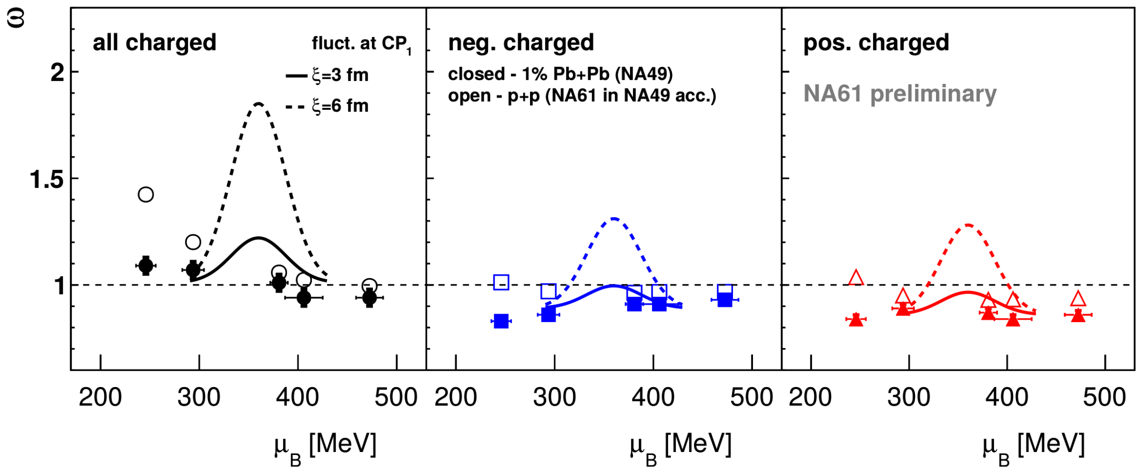
“narrow” acceptance – common at all energies (energy scan of Pb+Pb)

$2.0 < y_\pi < 2.2$

- Complete **system size dependence of multiplicity fluctuations** (p+p, C+C, Si+Si, and Pb+Pb at $\sqrt{s_{NN}}$ = 17.3 GeV) **was shown for forward-rapidity only** 1.1 (1.0) $< y_\pi < 2.6$ (y_{beam}) (“wide” azimuthal angle; almost complete at low p_T)

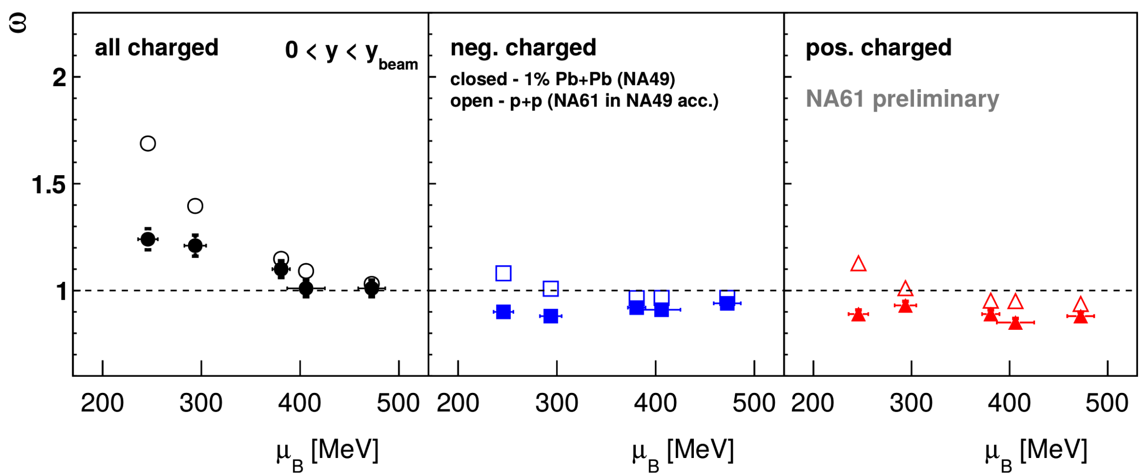
- **Energy dependence of multiplicity fluctuations** (7.2% central Pb+Pb) **was measured for $0 < y_\pi < 1$, $1 < y_\pi < y_{beam}$, and $0 < y_\pi < y_{beam}$** (azimuthal angle was strongly dependent on energy: “narrow” for low SPS energies, “wide” for top SPS)

Comparison of multiplicity fluctuations of non-identified particles in NA61 p+p with NA49 Pb+Pb within the same (NA49) acceptance



- **Forward-rapidity**
  $1 < y_\pi < y_{beam}$
- **Energy dependent azimuthal angle acceptance**
  → as available in NA49 detector

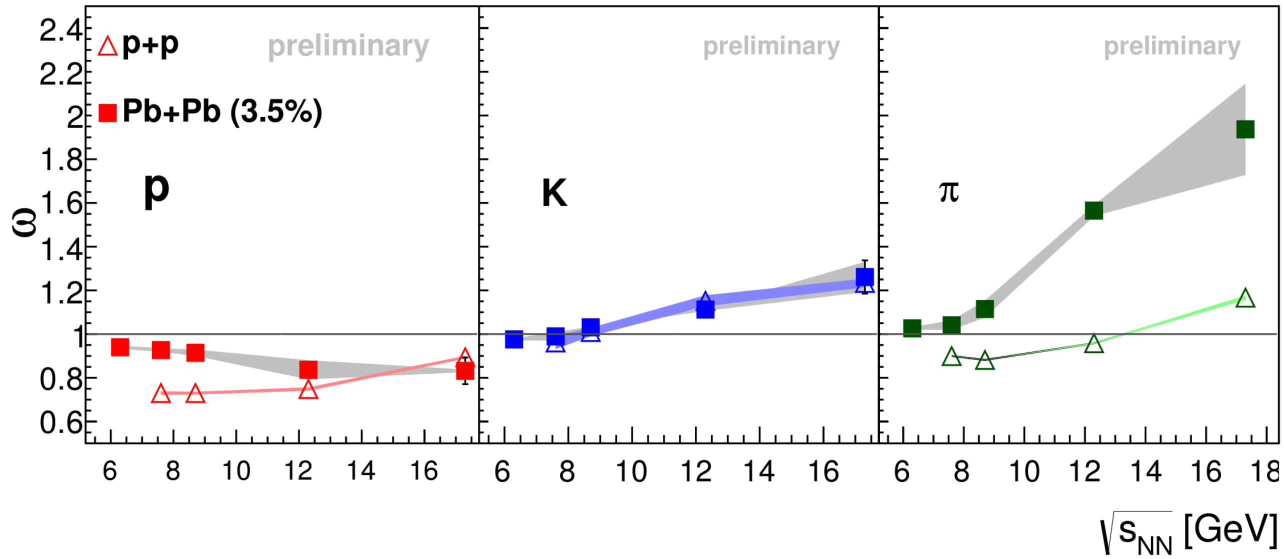
Multiplicity fluctuations in NA49 were measured also in a wider rapidity range: **$0 < y_\pi < y_{beam}$** (energy dependent azimuthal angle acceptance) but **the tendency is similar:**



Difference between Pb+Pb and p+p → violation of the Wounded Nucleon Model

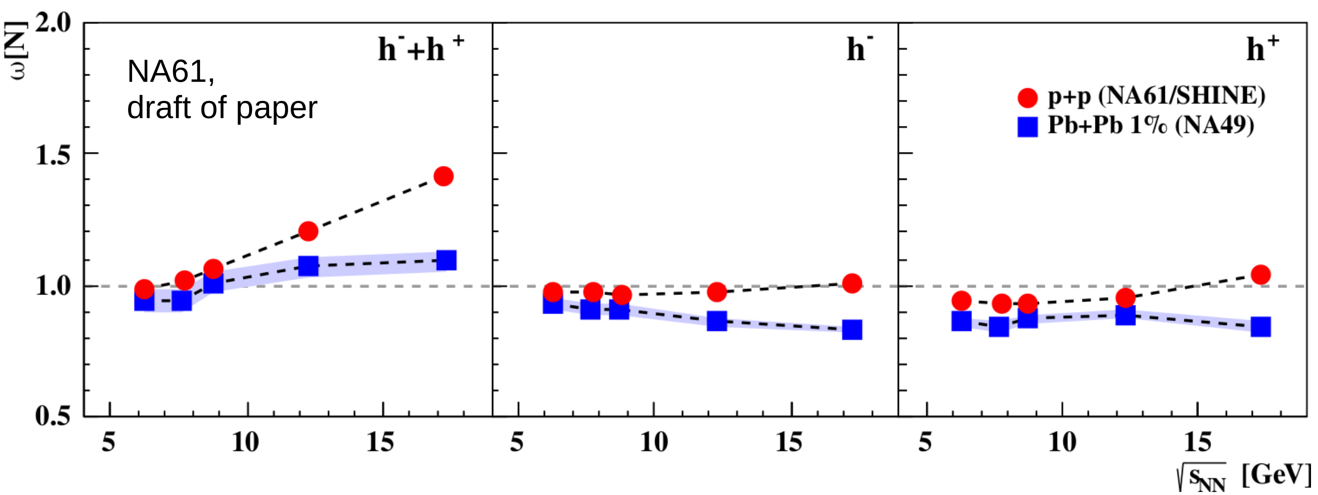
For NA61 only stat. errors shown

http://www.ujk.edu.pl/homepages/mryb/10thworkshop/files/slides/grebieszkow.pdf



M. Gaździcki,
P. Seyboth,
arXiv:1506.08141

For **3.5% most central Pb+Pb** **ω[N_π] (Pb+Pb) > ω[N_π] (p+p)** → volume fluctuations
(ω is not strongly intensive measure of fluctuations)



Lower panel: both p+p and Pb+Pb in NA49 acceptance:

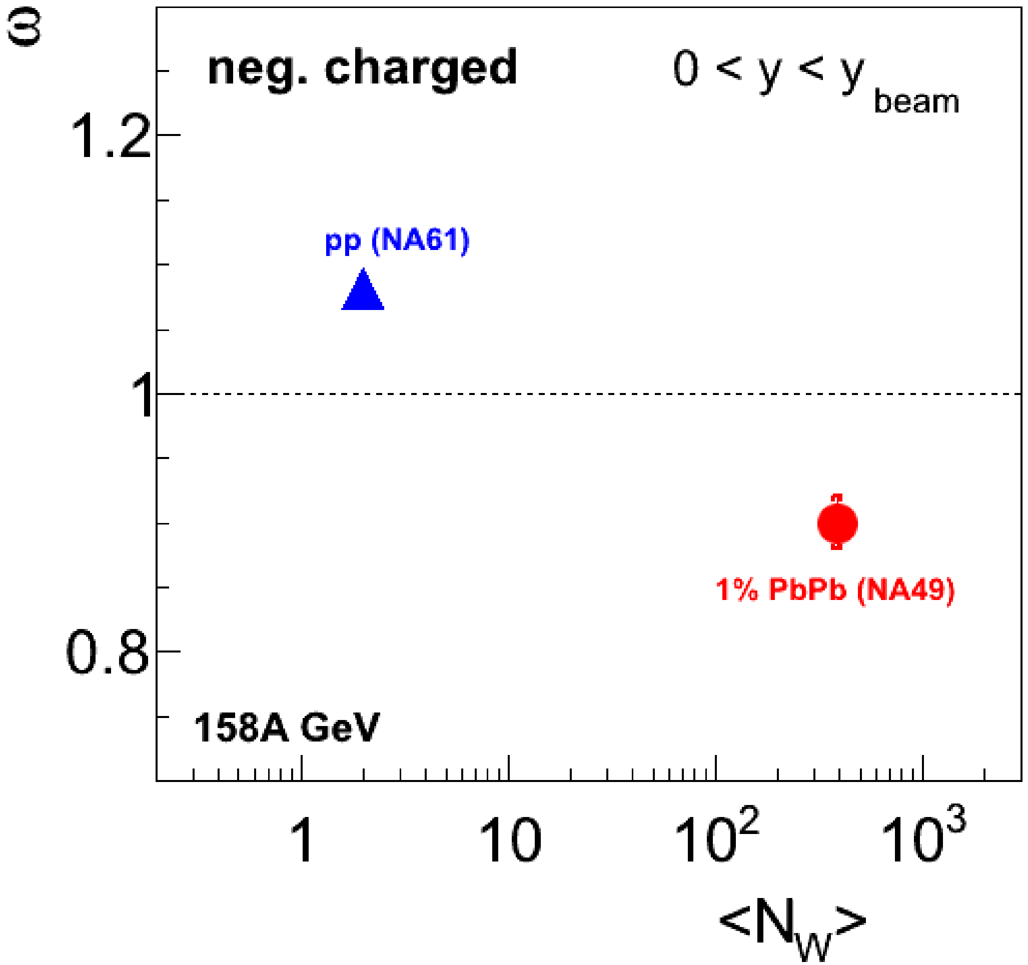
- Forward-rapidity $1 < y_\pi < y_{beam}$
- Energy dependent azimuthal angle acceptance → as available in NA49 detector

For **1% most central Pb+Pb** (volume fluctuations reduced) situation is opposite !!
At higher energies **ω[N] (Pb+Pb) < ω[N] (p+p)** → see next pages for explanations

Comparison with models, it is what about "Unreasonable effectiveness (or not) of statistical approaches to high-energy collisions"

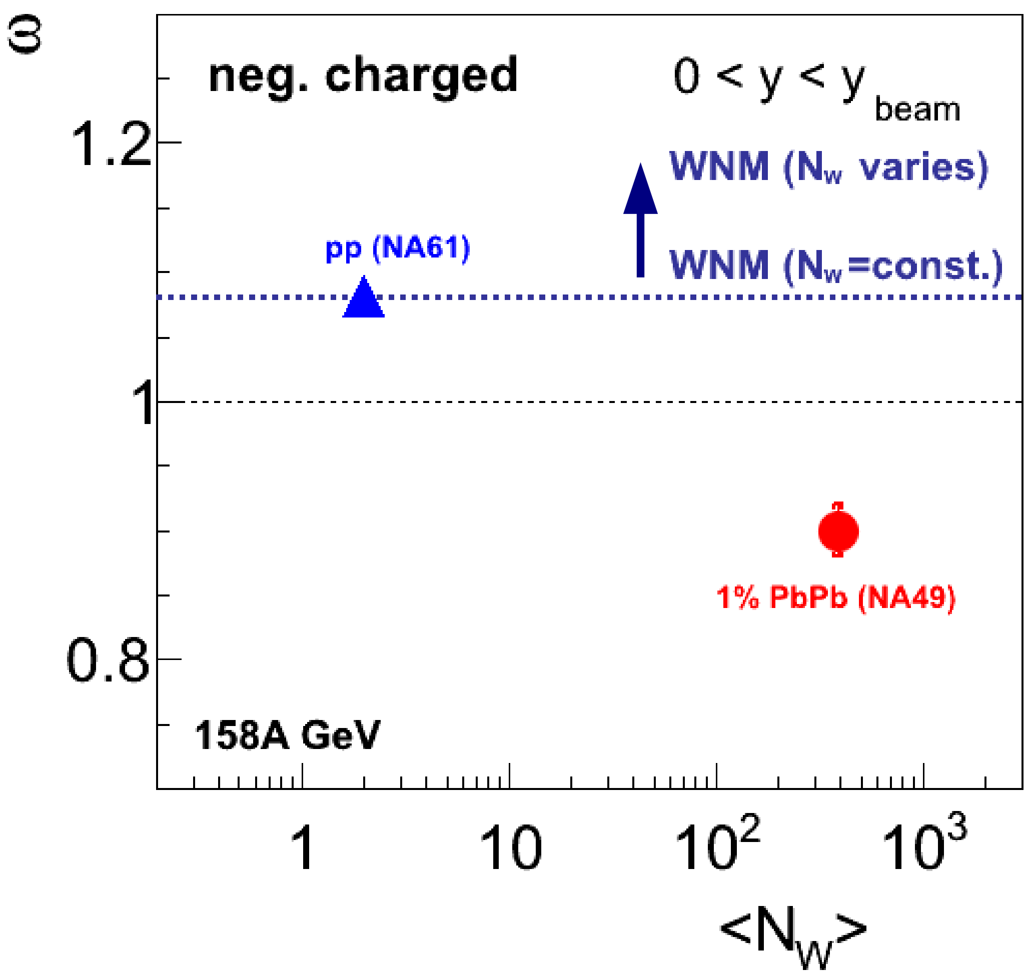
Example for the most intuitive variable - ω

Comparison of NA61 p+p with NA49 1% most central Pb+Pb at the top SPS energy



Negatively charged particles are almost **not** influenced by resonance decays

Predictions of WNM (Wounded Nucleon Model)



$\omega(A+A) = \omega^{Nw=const}(A+A) + \langle N\rangle_{A+A}/\langle N_w\rangle \cdot \omega_W$ →

$\boldsymbol{\omega(A+A) = \omega(N+N) + \langle N\rangle_{A+A}/\langle N_w\rangle \cdot \omega_W}$

ω_W - fluctuations in N_W

- For N_W = const.
  - $\omega_W = 0$
  - $\omega(A+A) = \omega(N+N)$
- For fluctuating N_W
  - $\omega_W > 0$
  - $\omega(A+A) > \omega(N+N)$

$\omega(A+A) < \omega(N+N)$ forbidden in WNM!

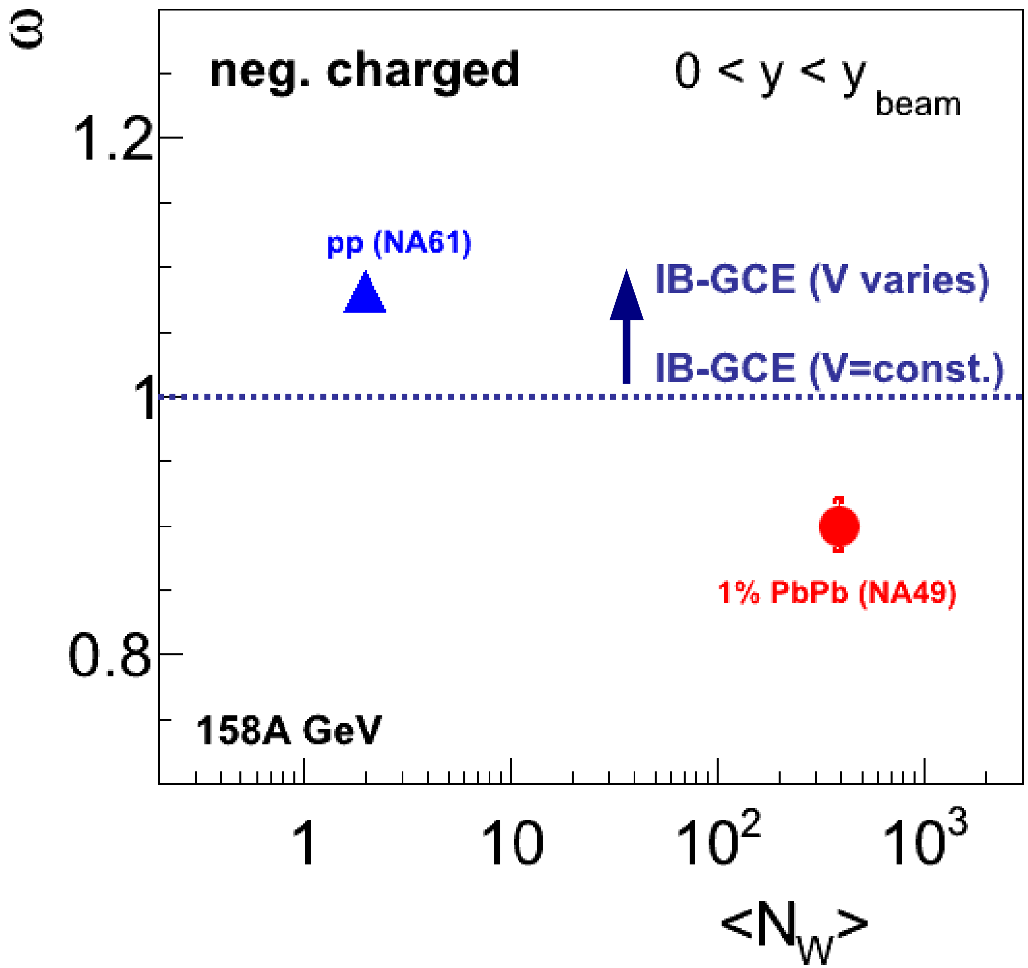
WNM already falsified by spectra and yields, but here:

Falsification of Wounded Nucleon Model via results on fluctuations

Why predictions of WNM are so important? String models are essentially based on WNM

WNM + isospin effect → under investigations; $V(N^-)$ and $\langle N^-\rangle$ results from p+p and n+p will be used to predict ω^- for Pb+Pb (limited NA49 acceptance should be also taken into account)

Predictions of IB-GCE (Grand Canonical Ensemble, Ideal Boltzmann)



$\omega(A+A) = \omega^{V=const}(A+A) + \langle N \rangle_{A+A}/\langle V \rangle \cdot \omega_V$

ω_V - volume fluctuations

For neg. charged $\omega^{V=const}(A+A) \approx 1$

- For V = const.
  $\omega_V = 0$
  $\omega(A+A) \approx 1$

- For fluctuating V
  $\omega_V > 0$
  $\omega(A+A) > 1$

$\omega(A+A) < 1$
forbidden in IB-GCE!

IB-GCE is falsified by Pb+Pb point; see also NA49 older results (low → top SPS energies) compared to models – Fig. 4 in PR C76, 024902 (2007)

p+p result alone can be interpreted as an evidence of volume fluctuations in p+p !

GCE and CE (and MCE) are close to each other in the limit of large volumes ...

(called: thermodynamical equivalence of all statistical ensembles)

z – single particle partition function (~ V)

For large systems (z»1)
$\langle N_{+/-}\rangle_{IB-CE} \approx \langle N_{+/-}\rangle_{IB-GCE} = z$

For small systems (z«1)
$\langle N_{+/-}\rangle_{IB-CE} \approx z^2 \ll \langle N_{+/-}\rangle_{IB-GCE} = z$

… but this is true for average multiplicities, <u>not</u> for fluctuations !!

Average multiplicities – difference between IB-GCE and IB-CE only for <u>small</u> systems

Scaled variance of multiplicity distribution – difference between IB-GCE and IB-CE remains even for <u>large</u> systems

PHYSICAL REVIEW C **70**, 034901 (2004)

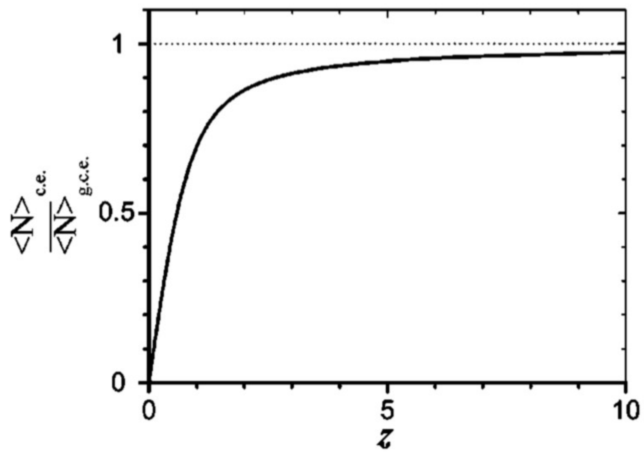


FIG. 1. The ratio of $\langle N_\pm\rangle_{c.e.}$ (6) to $\langle N_\pm\rangle_{g.c.e.}$ (5)

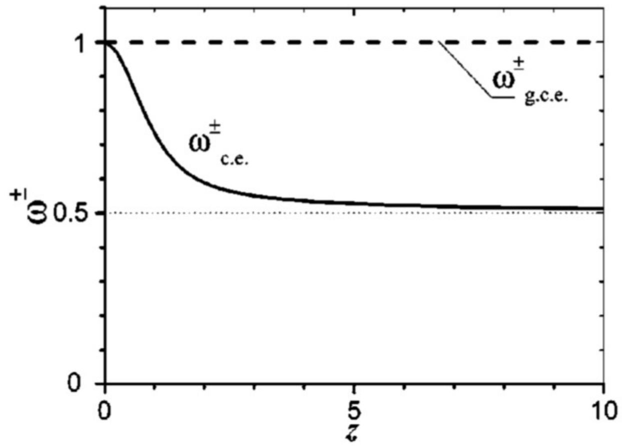
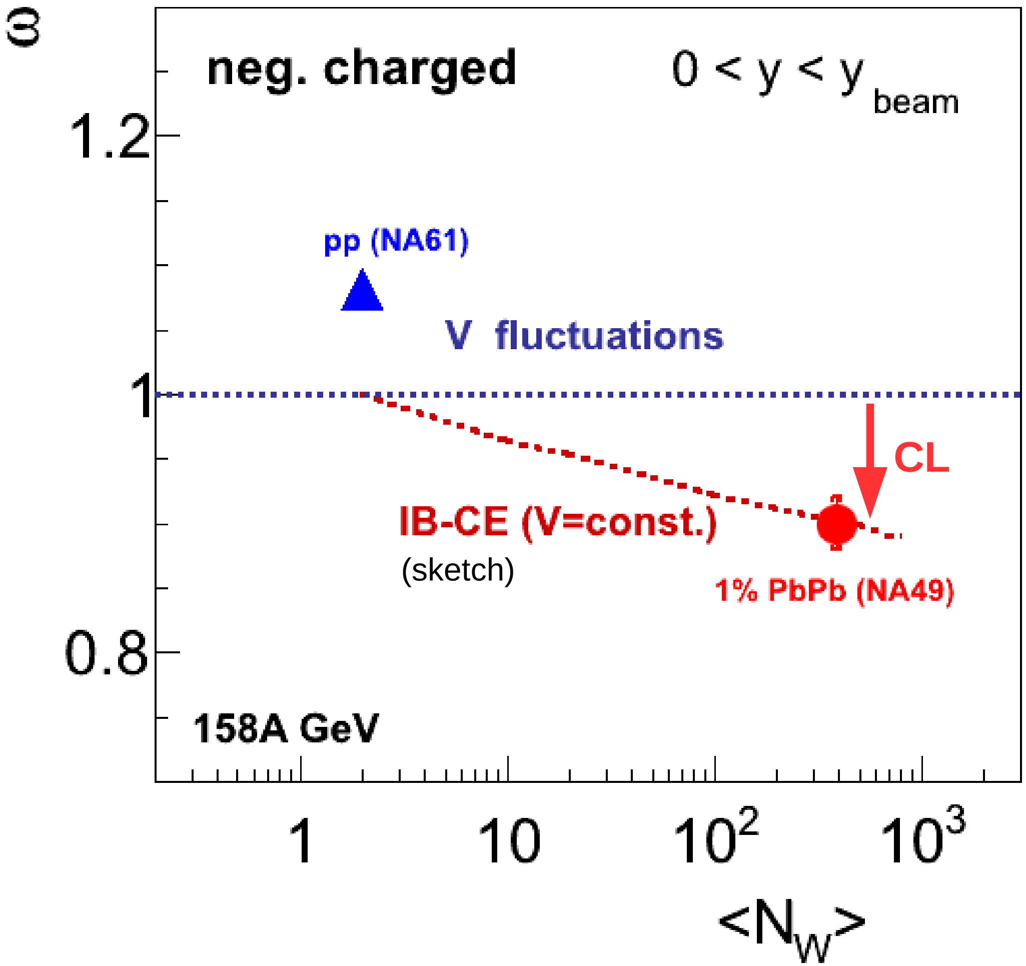


FIG. 2. The scaled variances of $N_\pm$ calculated within the g.c.e., $\omega^\pm_{g.c.e.}=1$ (14), and c.e., $\omega^\pm_{c.e.}$ (15).

Example for IB-CE with charge conservation (Q=0); results for single charge only

Predictions of IB-CE (Canonical Ensemble, Ideal Boltzmann)



- For V = const.
  $\omega(A+A) \leq 1$ (see also Fig. below)
- For V → 0
  $\omega(A+A) \nearrow 1$ (single charge)

PHYSICAL REVIEW C **70**, 034901 (2004)

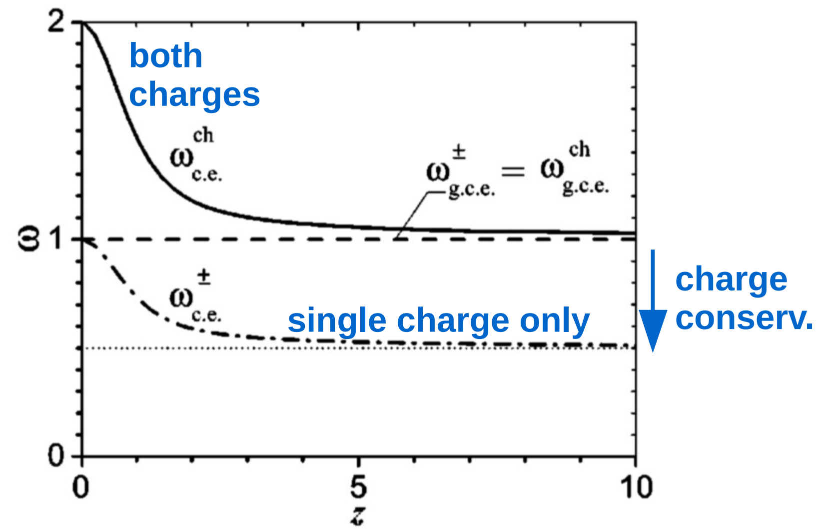
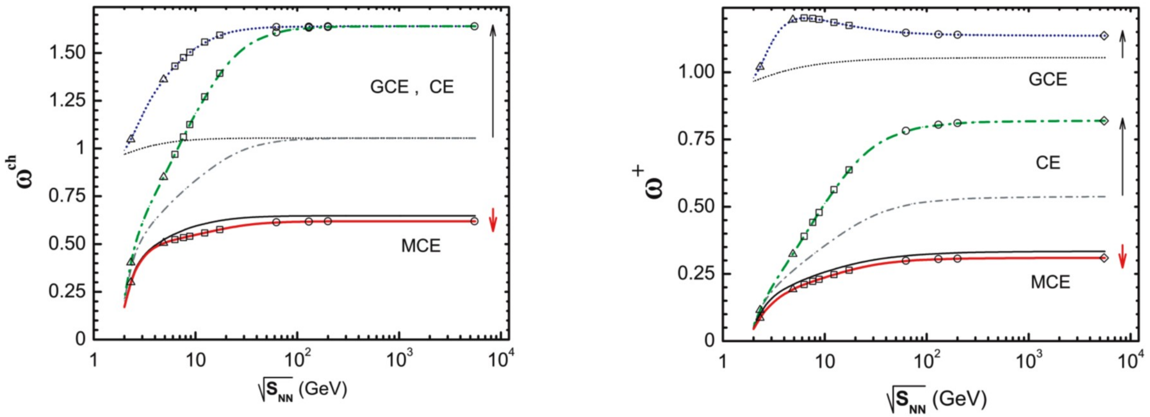


FIG. 5. The scaled variances $\omega^{ch}_{\text{c.e.}}$ (28), $\omega^{\pm}_{\text{c.e.}}$ (15) and $\omega^{\pm}_{\text{g.c.e.}} = \omega^{ch}_{\text{g.c.e.}} = 1$ (14) and (25) as functions of z.

For more detailed calculations within GCE, CE and MCE, including quantum effects (FD, BE), resonance decays and the influence of limited acceptance → see PR C76, 024902 (2007)



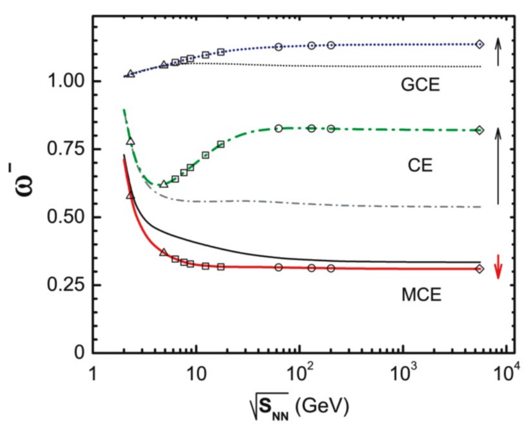


FIG. 1. (Color online) The scaled variances for negatively charged particles, ω^{-}, both primordial and final, along the chemical freeze-out line for central Pb + Pb (Au + Au) collisions. Different lines present the GCE, CE, and MCE results. Symbols at the lines for final particles correspond to the specific collision energies pointed out in Table I. The arrows show the effect of resonance decays.

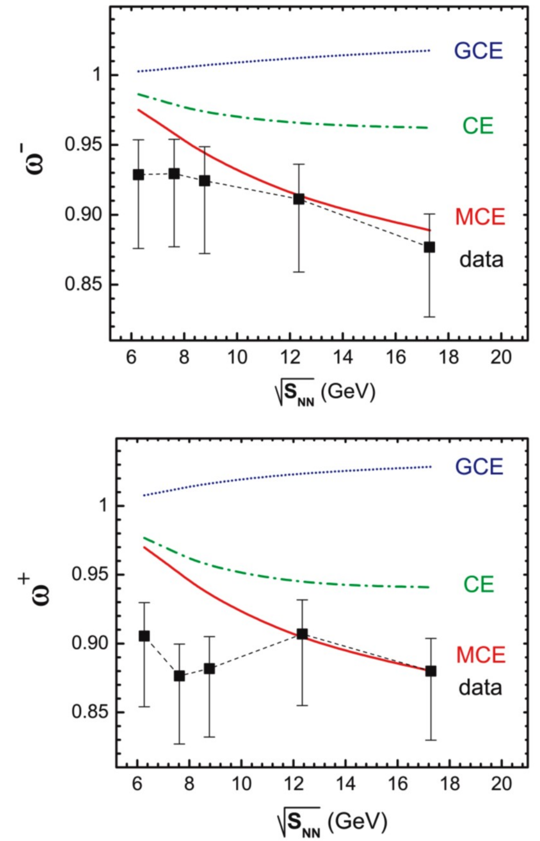


FIG. 4. (Color online) The scaled variances for negative (top) and positive (bottom) hadrons along the chemical freeze-out line for central Pb + Pb collisions at the SPS energies. The points show the preliminary data of NA49 [14]. Total (statistical + systematic) errors are indicated. The statistical model parameters T, μ_B, and γ_S at different SPS collision energies are presented in Table I. Lines show the GCE, CE, and MCE results calculated with the NA49 experimental acceptance according to Eq. (22).

older NA49 data;
$1 < y_{\pi} < y_{beam}$ + az. angle restrictions

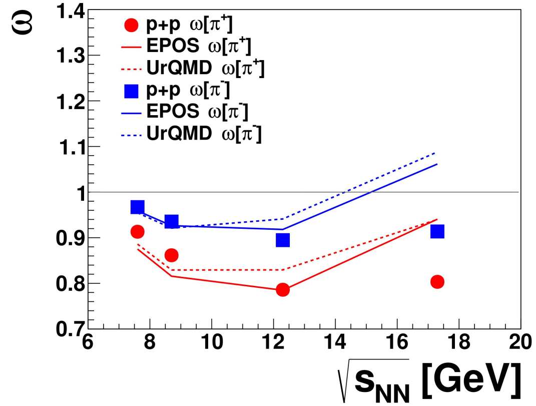
Fluctuations of charged pions in p+p (NA61)

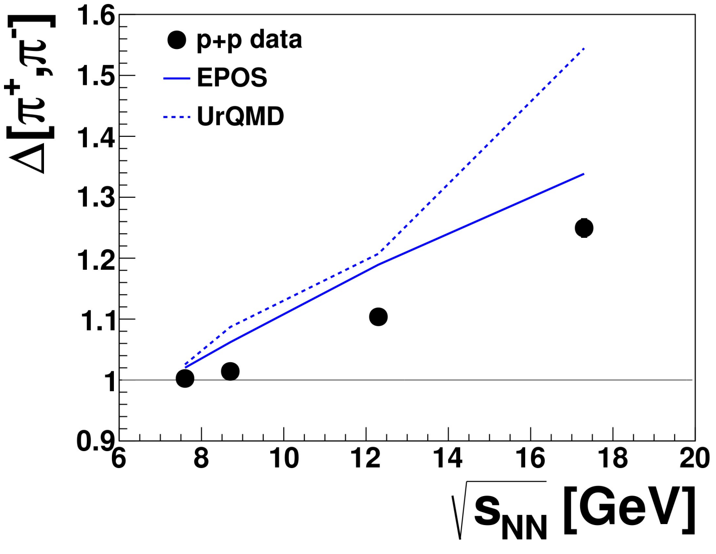
- Fluctuations of charged pions can be sensitive to critical point (long-wavelength fluctuations of the magnitude of the σ-field (PRD 60, 114028; PRL 81, 4816)
- Resonance abundances at chemical freeze-out can be found by measuring fluctuations of π^+ and π^- (J. Phys. G42 (2015) 7, 075101)

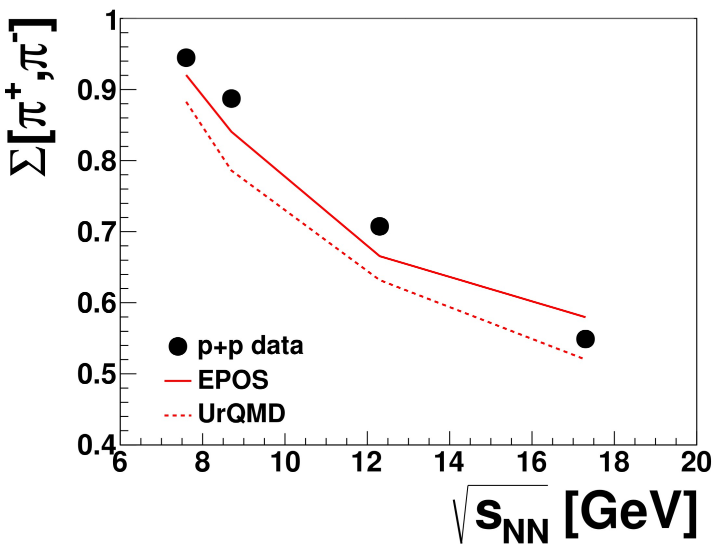
$$\Delta[\pi^+,\pi^-]=\frac{1}{\langle\pi^-\rangle-\langle\pi^+\rangle}\left[\langle\pi^-\rangle\,\omega[\pi^+]-\langle\pi^+\rangle\,\omega[\pi^-]\right]$$

$$\Sigma[\pi^+,\pi^-]=\frac{1}{\langle\pi^+\rangle+\langle\pi^-\rangle}\left[\langle\pi^+\rangle\,\omega[\pi^-]+\langle\pi^-\rangle\,\omega[\pi^+]-2\left(\langle\pi^+\pi^-\rangle-\langle\pi^+\rangle\langle\pi^-\rangle\right)\right]$$

$$\omega[\pi^+]=\frac{\langle\pi^{+2}\rangle-\langle\pi^+\rangle^2}{\langle\pi^+\rangle}\qquad\omega[\pi^-]=\frac{\langle\pi^{-2}\rangle-\langle\pi^-\rangle^2}{\langle\pi^-\rangle}$$







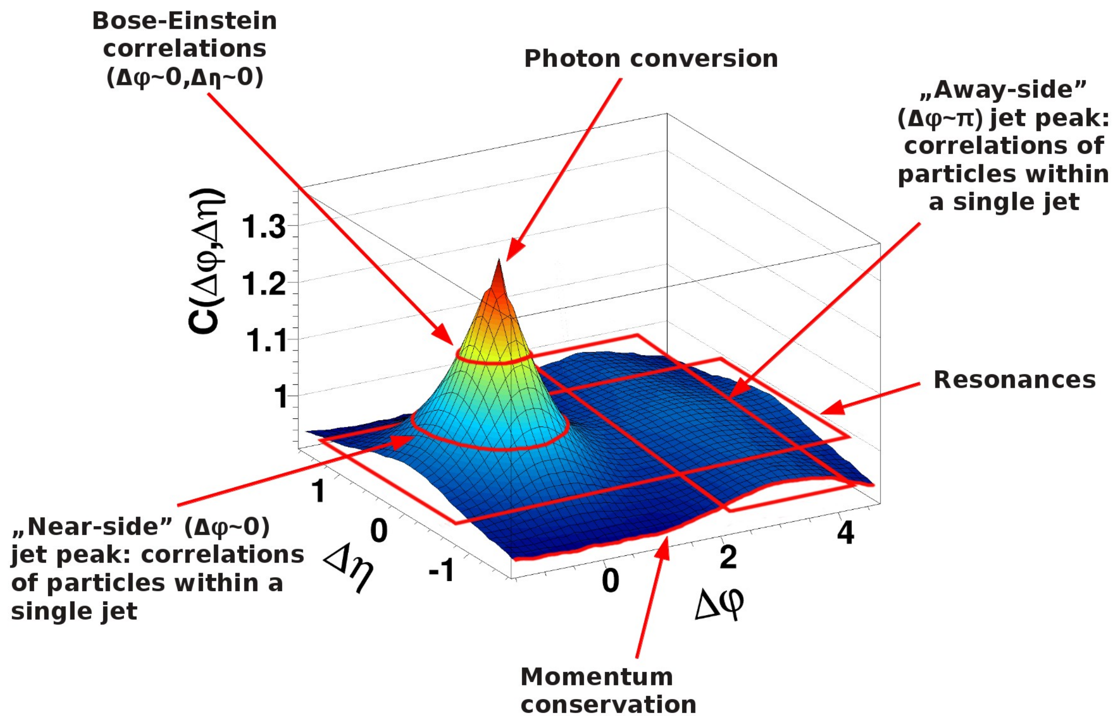
- NA61 results are in rather good agreement with models
- p+p collisions show no effects of critical point

For both π^+ and π^- the same (smaller) acceptance of π^- was used, see: https://edms.cern.ch/document/1237791/1

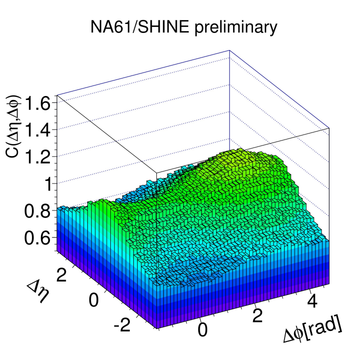
Correlations in Δη, Δϕ in p+p (NA61)

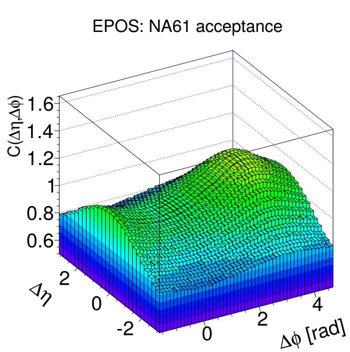
Two-particle correlations in Δη, Δϕ studied at RHIC and LHC

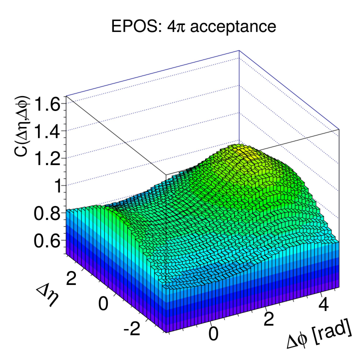
They allow to disentangle different sources of correlations:
jets, flow, resonance decays, quantum statistics effects, conservation laws



p+p at 158 GeV/c, all charged:

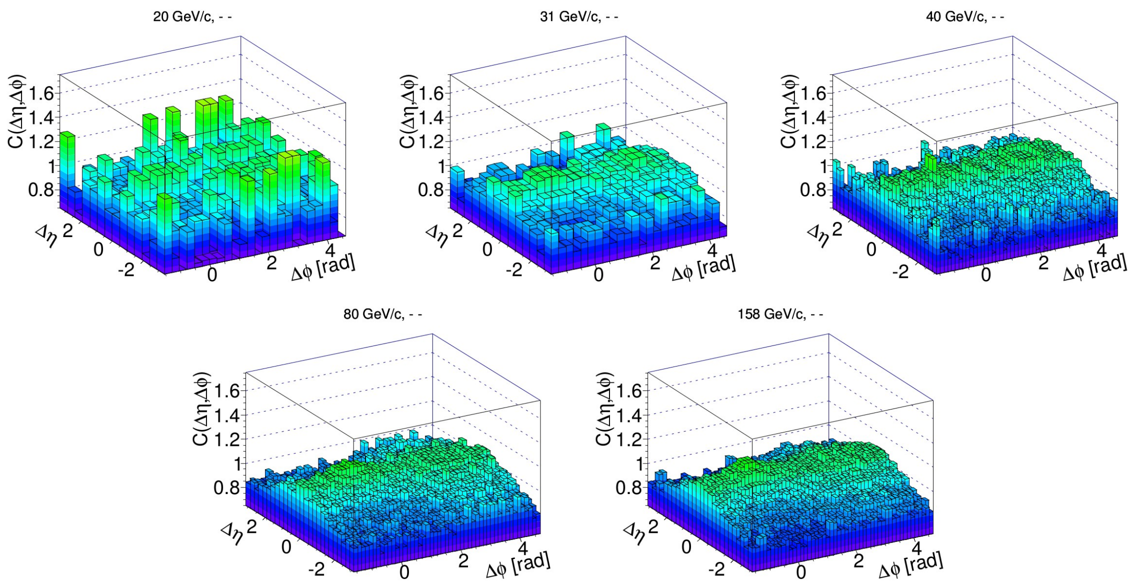






- Qualitative agreement of NA61 results with predictions of EPOS
- Weak effect of NA61 acceptance

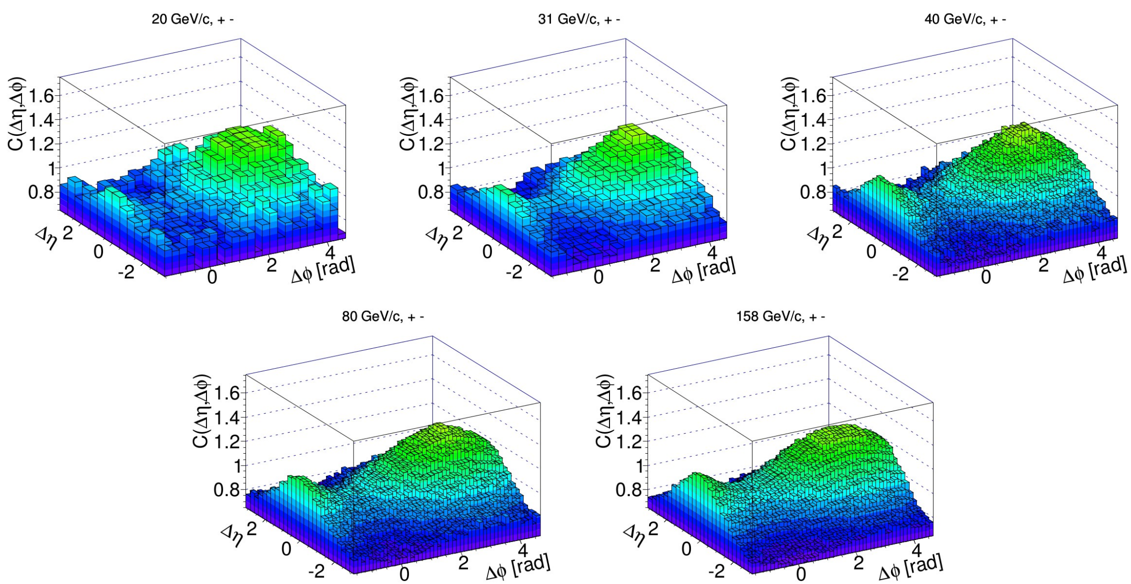
A. Seryakov, SQM 2015;
based on results of B. Maksiak



Pairs of **negatively charged particles**

- Quantum effects (B-E) contribute to enhancement at (0,0). Effect stronger for higher energies
- Maximum at $(\Delta\eta,\Delta\phi) = (0,\pi)$ may be due to momentum conservation

Similar structures in EPOS but without Bose-Einstein



Pairs of **unlike-sign charged particles**

- Maximum at $(\Delta\eta,\Delta\phi) = (0,\pi)$ probably due to resonance decays and momentum conservation
- Coulomb effects contribute to a weak enhancement at (0,0)

Similar structures in EPOS but without SRC (Bose-Einstein + Coulomb)

B. Maksiak, PoS (CPOD 2014) 055