Performance of the MPD detector in the study of strangeness production and event-by-event fluctuations in Au+Au collisions at NICA

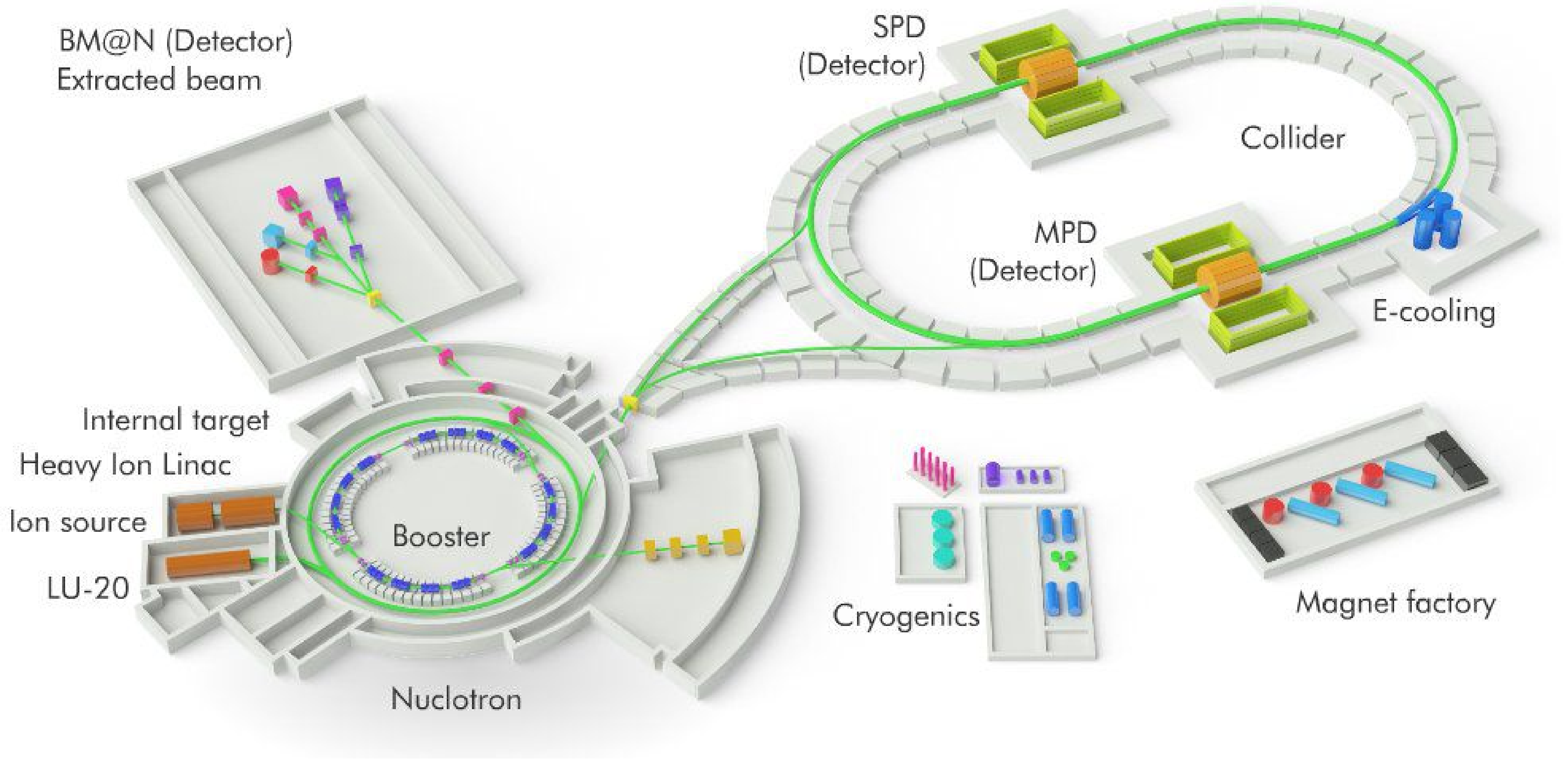
A. Mudrokh* and V. Kolesnikov (VBLHEP)

on behalf of the MPD collaboration

Outline

- **Introduction: NICA complex, QCD phase diagram, critical end point (CEP) and particle production at NICA**
- **MPD setup and particle identification**
- **Strangeness production: spectra and K/π ratio calculation**
- **Fluctuation of conserved quantities. Moments and moment products of the net-proton and net-kaon multiplicity distributions**
- **Conclusions**

Nuclotron-based Ion Collider fAcility

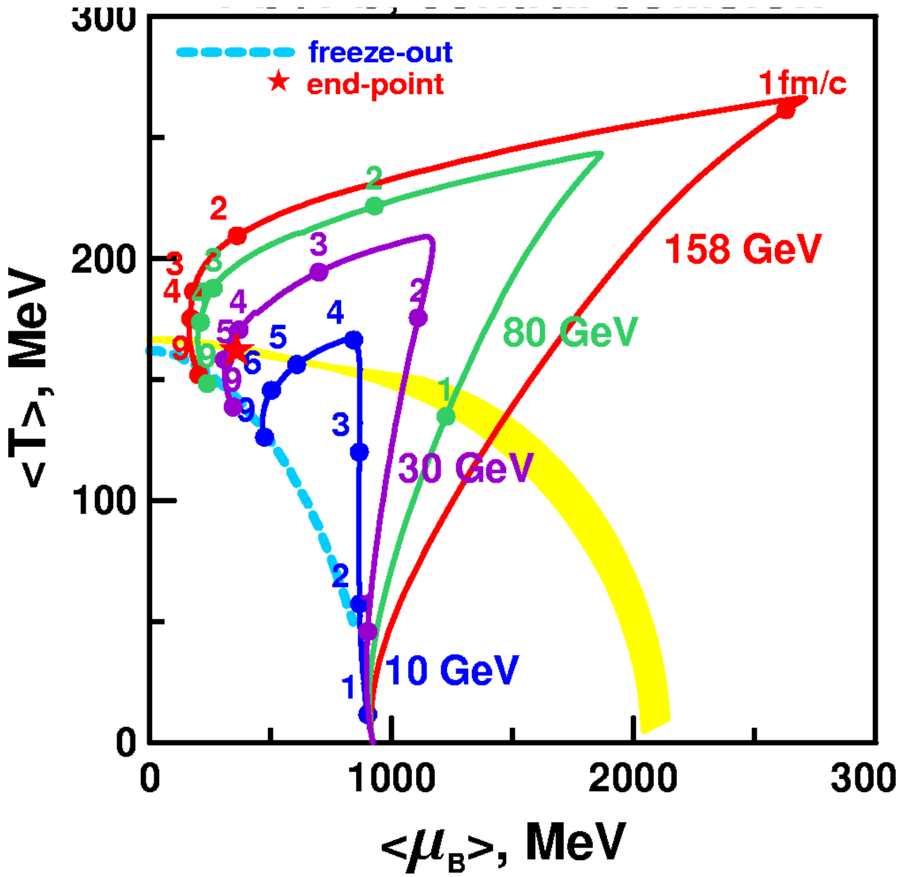


NICA parameters:

Beams: p,d…$^{197}Au^{79+}$ **$\sqrt{s}$ = 4-11 GeV (nuclei)** **L = 10^{27} cm^{-2} s^{-1} (Au), 10^{32} (p)**

QCD phase diagram. Critical end point (CEP)

Trajectories calculated by a 3-fluid hydrodynamics model
Toneev & Ivanov



If the trajectory is in the vicinity of the critical endpoint – abnormal fluctuations can be observed

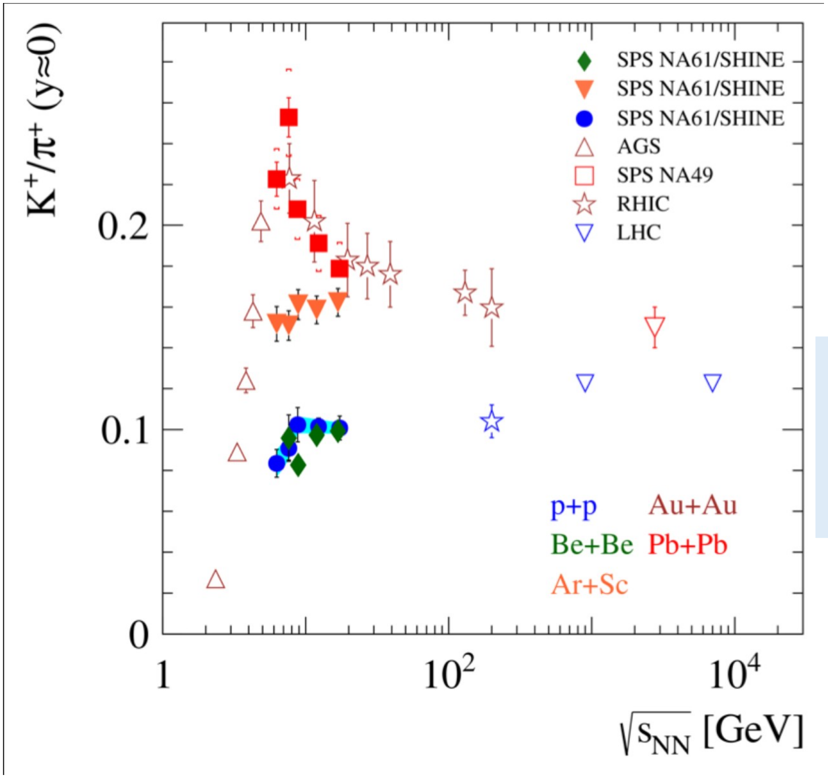
Observables - event-by-event fluctuations:

- multiplicity, charge number
- particle ratios
- mean pT, azimuthal angle
- baryon number

Experimental challenge: fluctuation signal may be suppressed due to final state interactions that washed out the signal. Real CEP signal should show consistency in several observables!

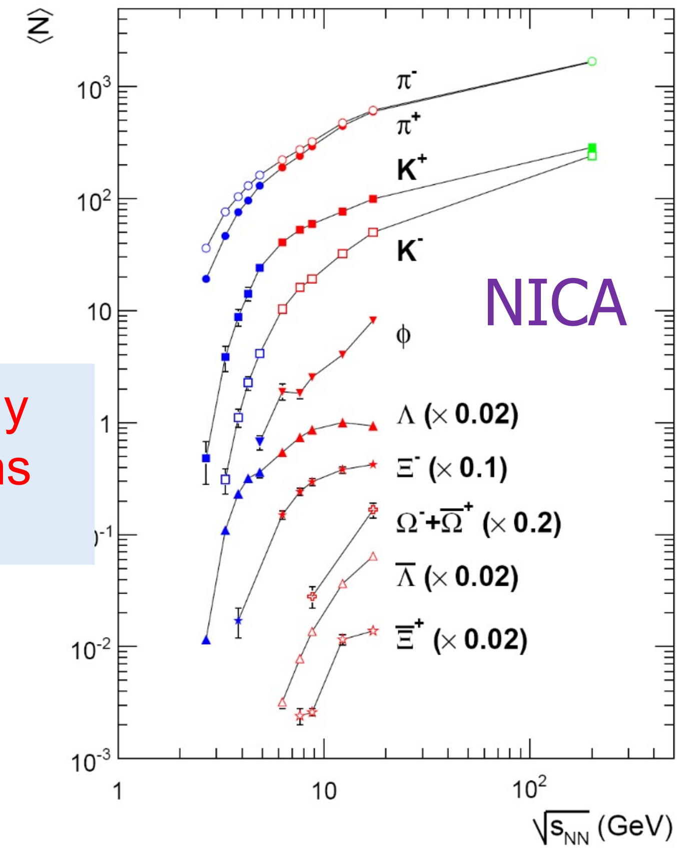
MPD physics cases: strangeness production at NICA

- Excitation function of hadrons, including strangeness (yields, spectra, and ratios)
- Non-monotonic strangeness-to-entropy ratio seen in heaviest systems (phase transformation?)
- Hyperons sensitive to early stage and phase transformations in QCD medium
- Nuclear matter EOS, in-medium effects and chemical equilibration can be probed



System size of the energy dependence is not fully understood

Luck of systematic study of multi-strange hyperons at NICA energies!



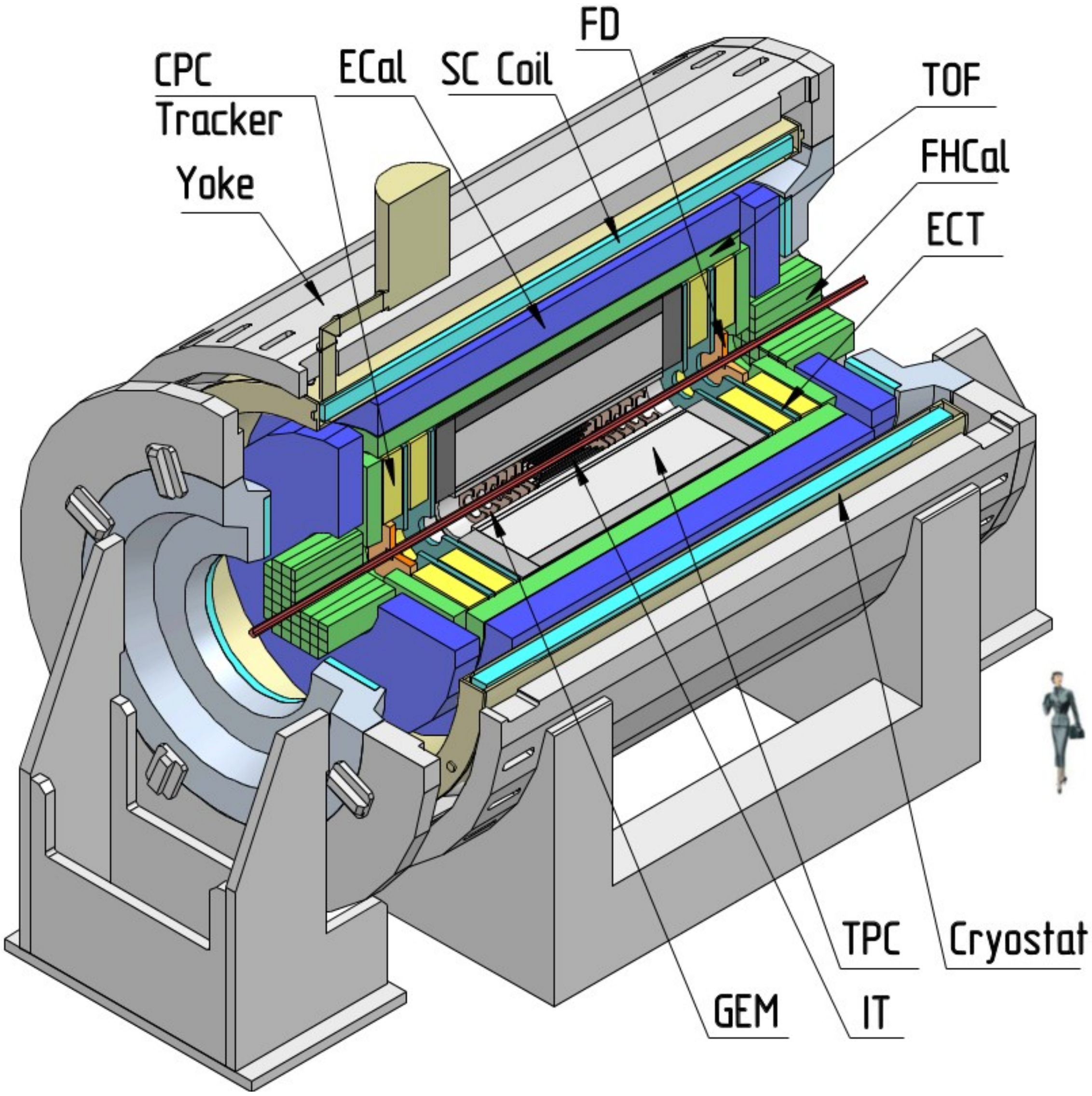
Particle production rates at NICA/MPD

yields for 1 week of running (Stage'1, Au+Au at 11 GeV)

Particle	Multi-plicity	Decay mode	BR	*Effic. %	Yield /1 week
π^+	293	----	---	61	$7.7 \cdot 10^8$
K^+	59	---	----	50	$1.5 \cdot 10^8$
p	140	---	----	60	$4.2 \cdot 10^8$
Λ	35	$p+\pi^-$	64%	4.5	$2 \cdot 10^7$
Anti-Λ	0.5	--	--	8.8	$3.5 \cdot 10^5$
Ξ^-	2	$\Lambda+\pi^-$	~100%	1.8	$1.5 \cdot 10^5$
Anti-Ξ^+	0.1	--	--	3.1	$8.0 \cdot 10^3$
ρ	31	e+e-	$4.7 \cdot 10^{-5}$	35	$2.5 \cdot 10^3$
ω	20	e+e-	$7.1 \cdot 10^{-5}$	35	$2.5 \cdot 10^3$
φ	2.6	e+e-	$3 \cdot 10^{-4}$	5	$2.0 \cdot 10^2$
Ω^-	0.14	Λ+K	0.68	0.6	$7.0 \cdot 10^3$
Anti–Ω^+	0.04	--	--	1	$1.5 \cdot 10^3$

*Efficiency includes the MPD acceptance, realistic tracking and particle ID.
Particle Yields from experimental data (NA49), statistical and HSD models.

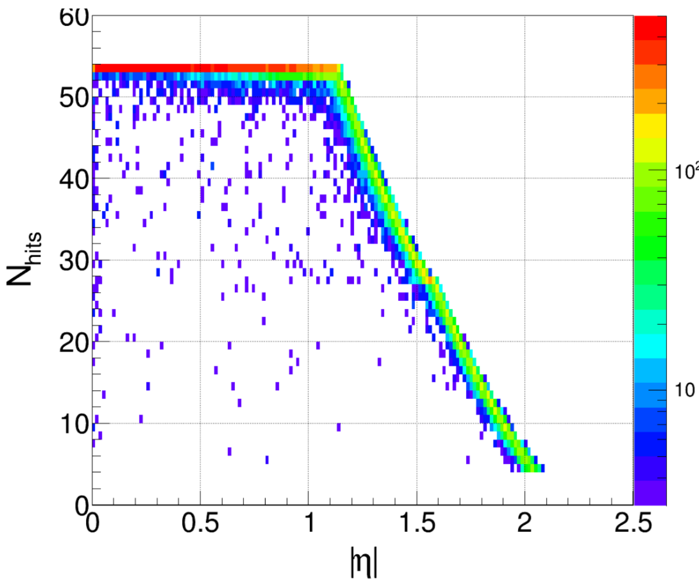
Multi-Purpose Detector (MPD) for A+A collisions @ NICA



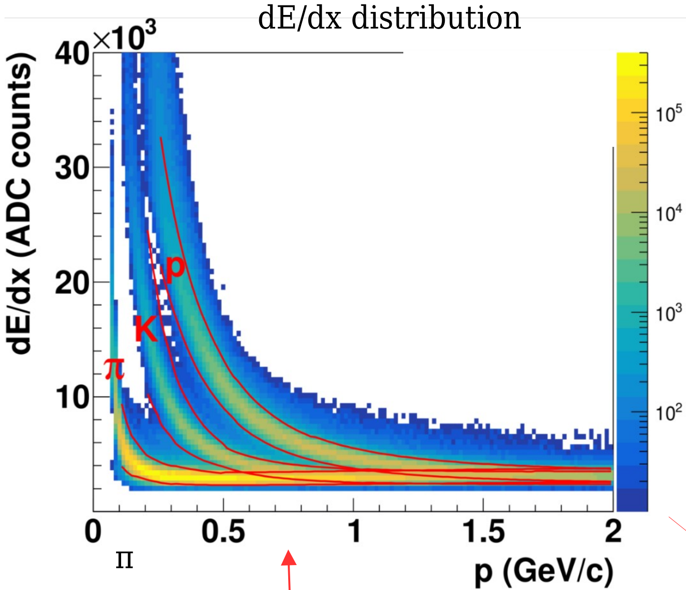
NICA (Nuclotron based Ion Collider fAcility) provides collisions of heavy ions over the atomic mass range A = 1-197 at a centre-of-mass energy from 4 to 11 GeV (for Au^{+})

MPD at Stage'1:

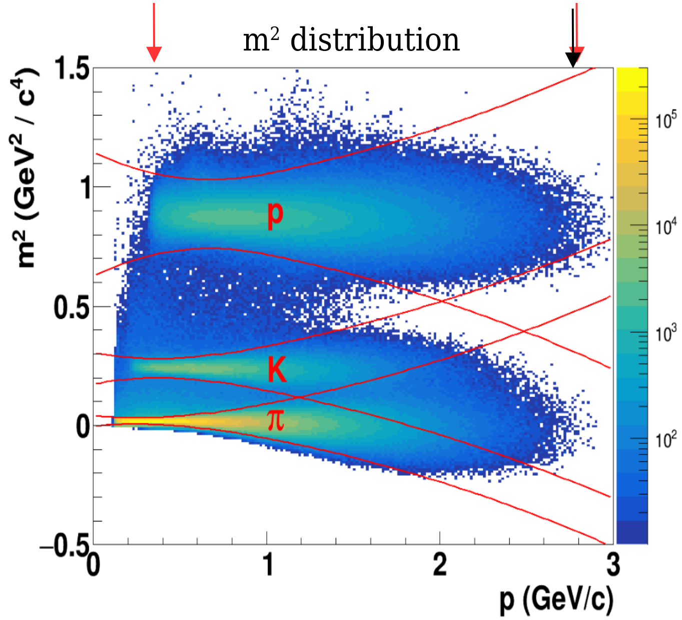
- ➔ **TPC tracking: | η | < 1.6 (N_{HITS} > 15)**
- ➔ **TOF coverage | η | < 1.4**
- ➔ **PID: combined | η | < 1.4, 0.1 < p < 3 GeV/c limited in 1.4 < | η | < 1.6 (dE/dx only)**

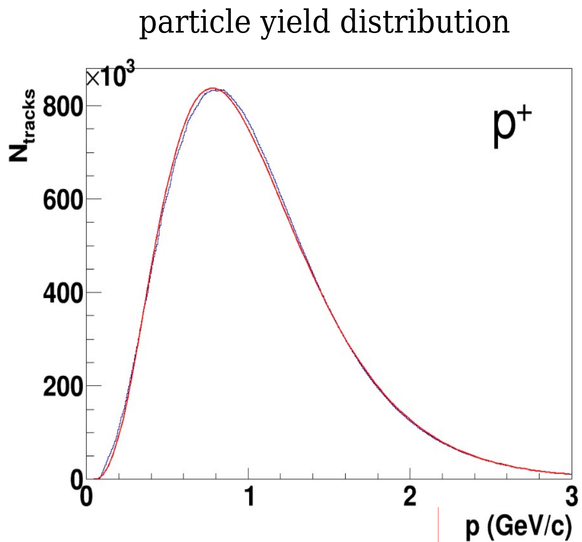


MPD particle ID



Red lines depict 3σ bands

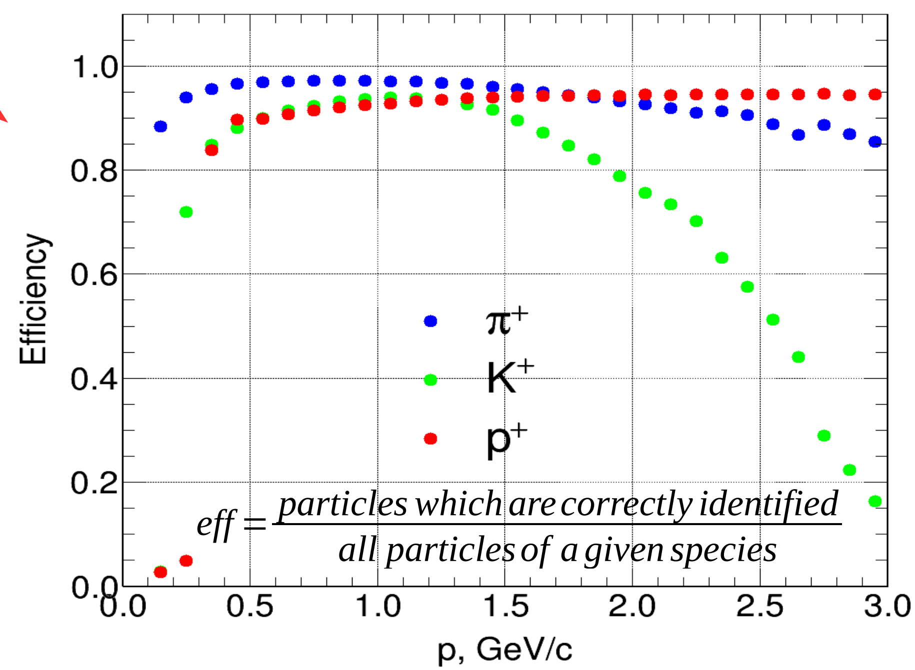




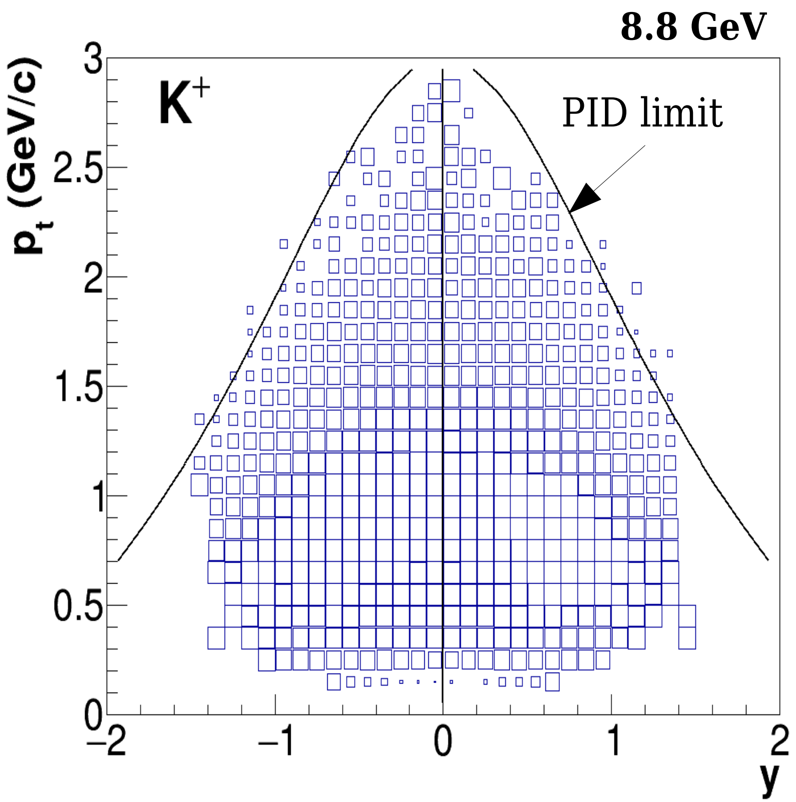
Track selection for PID:

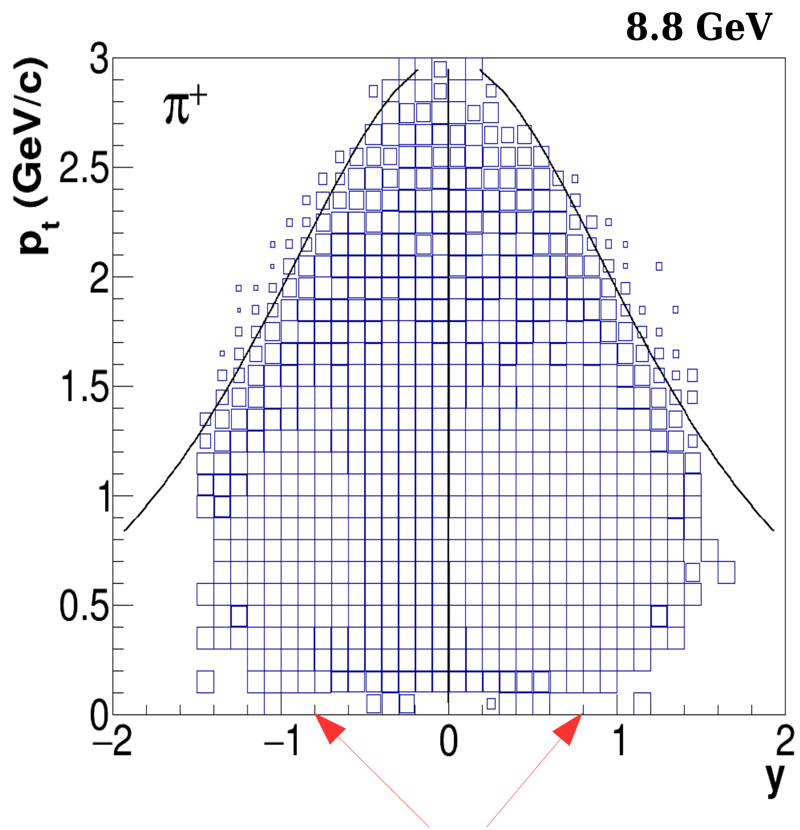
- $|\eta| < 1.6$
- $N_{HITS} \geq 20$
- Primary only (GEANT)

Combined (TPC+TOF) PID efficiency



Strangeness production: K^+ and π^+ phase-space with realistic PID





Data set: ~50K central Au+Au @ 4 – 12.3 GeV

(PHSD – with chiral symmetry restoration ON and OFF)

MPD setup: TPC & TOF, ideal centrality binning (0 – 3 fm)

Selection criteria: $|\eta| < 1.6$, $N_{hits} \geq 20$, primary via DCA

Realistic track reconstruction: clustering in TPC

Realistic PID: combined dE/dx+TOF

In order to reduce statistical errors at high p_T, spectra from the forward and backward part of detector were summed.

Analysis has been carried out within four rapidity intervals:

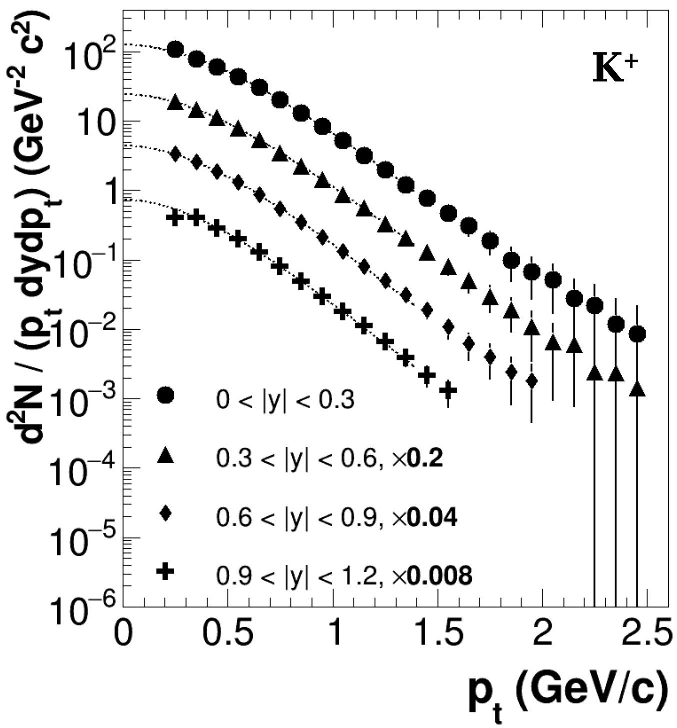
1) $|y| < 0.3$

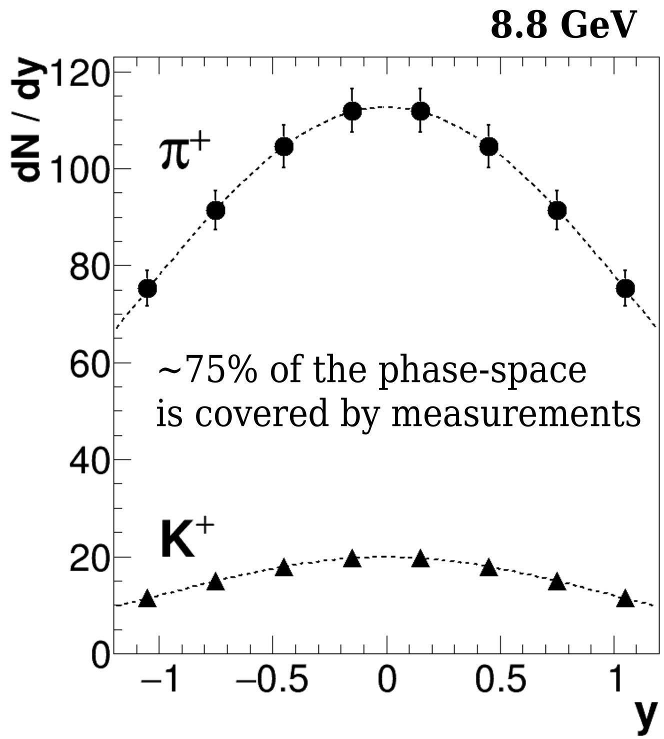
2) $0.3 < |y| < 0.6$

3) $0.6 < |y| < 0.9$

4) $0.9 < |y| < 1.2$

Strangeness production: p_T spectra, corrections and dN/dy calculation





Corrections to RECO-spectrum:

- **PID efficiency and contamination**
- **TPC-TOF (mis)matching**
- **Decay and interactions in TPC volume**
- **And others...**

The p_T-integrated particle yield dN/dy is carried out from the p_T spectra using efficiency corrected data in the measured p_T ranges and extrapolation to the low- and high-p_T regions (up to 5 GeV/c).

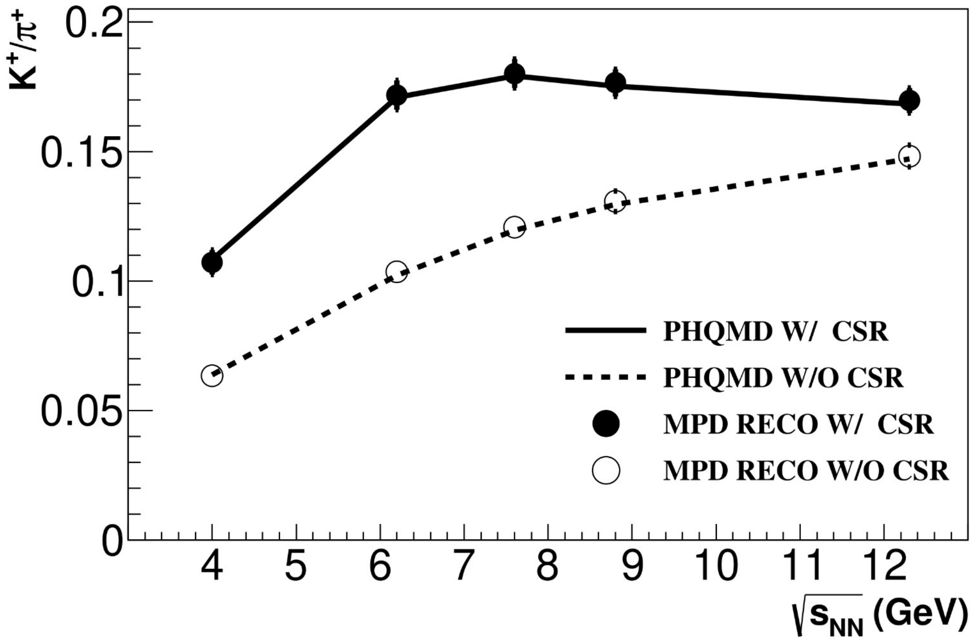
Functions used to obtain dN/dy are m_T-exponential (pions) and blast-wave (kaons):

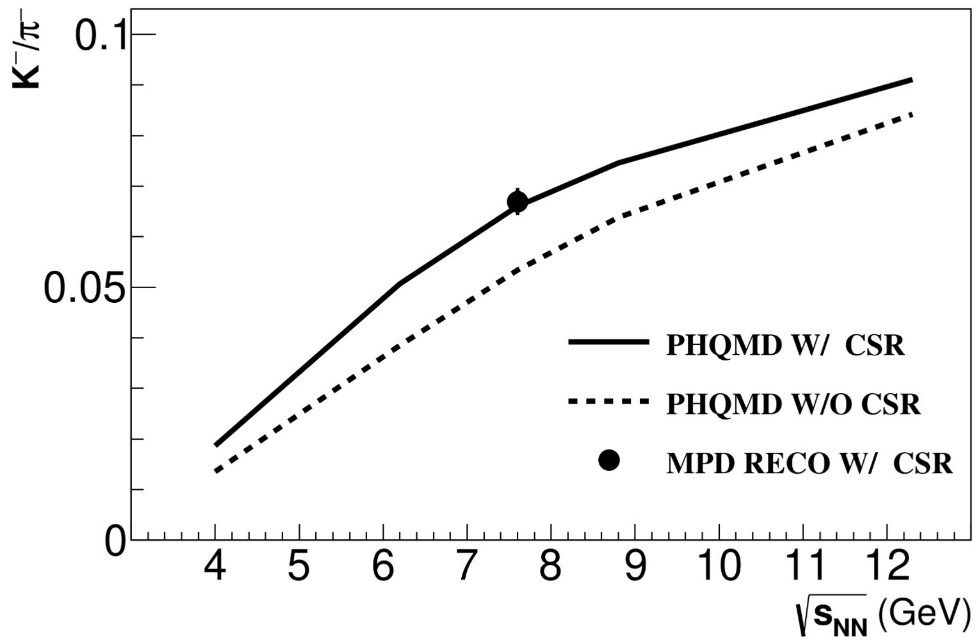
$$\frac{1}{p_T}\times\frac{d^2N}{dy\,dp_T}=\frac{dN/dy}{T(m+T)}\cdot\exp\left(-\frac{m_T-m}{T}\right)$$

$$\frac{d^2N}{p_t\,dp_t\,dy}=C\int_0^1 p_t f(\xi) K_1\left(\frac{m_t\cosh(\rho)}{T}\right) I_0\left(\frac{p_t\sinh(\rho)}{T}\right)\xi\,d\xi$$

The percentage contribution to the yields from extrapolation are typically 25-30% (5-10%) for kaons (pions).

Strangeness production: K/π ratio



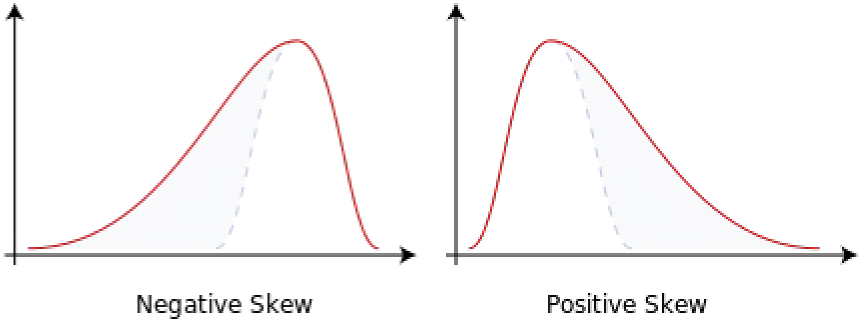


- The numbers for the K^+/π^+ ratio were obtained from Gaussian fits of dN/dy distribution at midrapidity y = 0.
- The errors for the midrapidity yields are taken from the fits.
- The MPD measurements of K^+/π^+ ratio allow to distinguish CSR at experiment definitely.
- The same analysis has been carried out to obtain K^-/π^- ratio.
- The error bar is calculated for the increased statistics of 10^6 central Au+Au events.

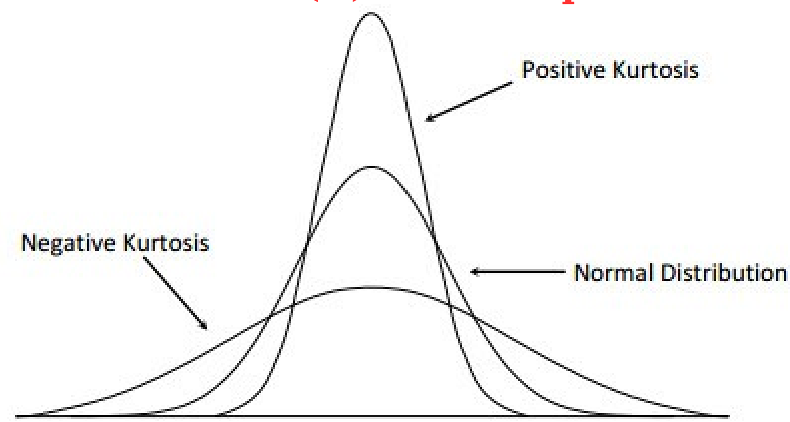
Fluctuations of conserved quantities

- Net-proton (proxy of net-baryon), conserved charge is ***B***, or net-kaon, conserved charge is ***S***
- Calculate protons instead of net-protons
- High moments describe the shape of distributions:

Skewness (S) → assymetry



Kurtosis (K) → sharpness



$$< \delta N >= N - < N >$$
$$C_1 = M =< N >$$
$$C_2 = \sigma^2 =< (\delta N)^2 >$$
$$C_3 = S\sigma^3 =< (\delta N)^3 >$$
$$C_4 = \kappa\sigma^4 =< (\delta N)^4 > -3 < (\delta N)^2 >^2$$

Cumulants are sensitive to correlation length

$$C_2 =< (\delta N)^2 >_c \approx \xi^2$$
$$C_3 =< (\delta N)^3 >_c \approx \xi^{4.5}$$
$$C_4 =< (\delta N)^4 >_c \approx \xi^7$$

Cumulant ratios are directly related to susceptibilities:

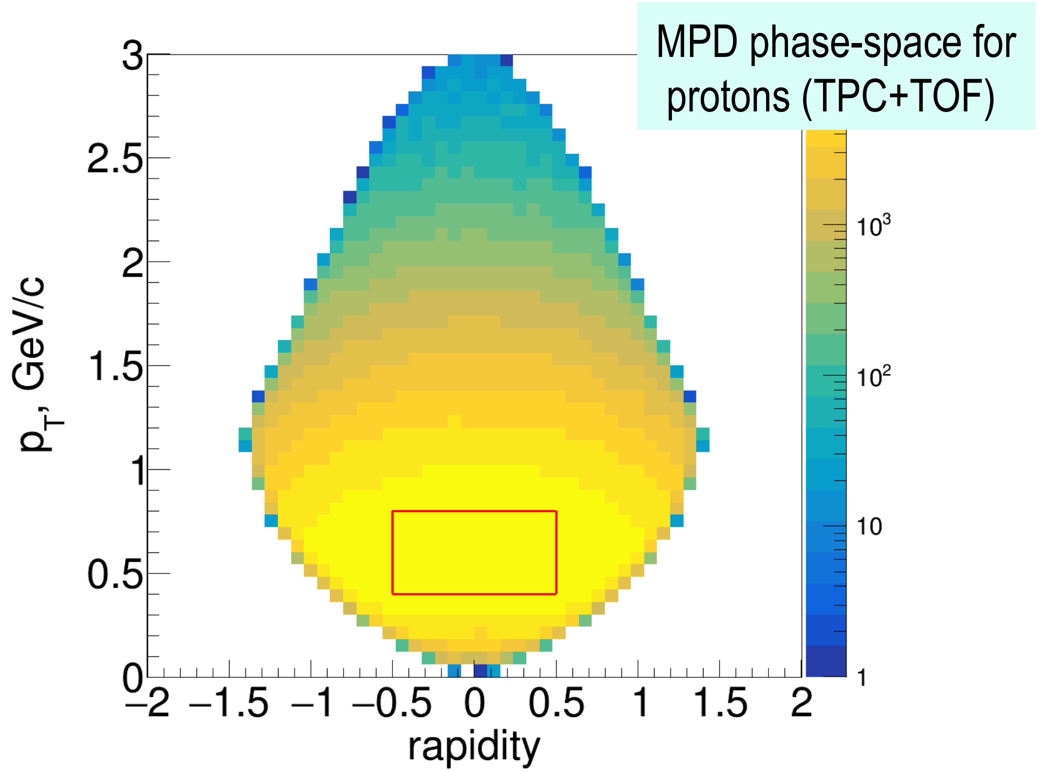
$$S\sigma = \frac{C_3}{C_2} = \frac{\chi_3}{\chi_2}$$
$$\kappa\sigma^2 = \frac{C_4}{C_2} = \frac{\chi_4}{\chi_2}$$

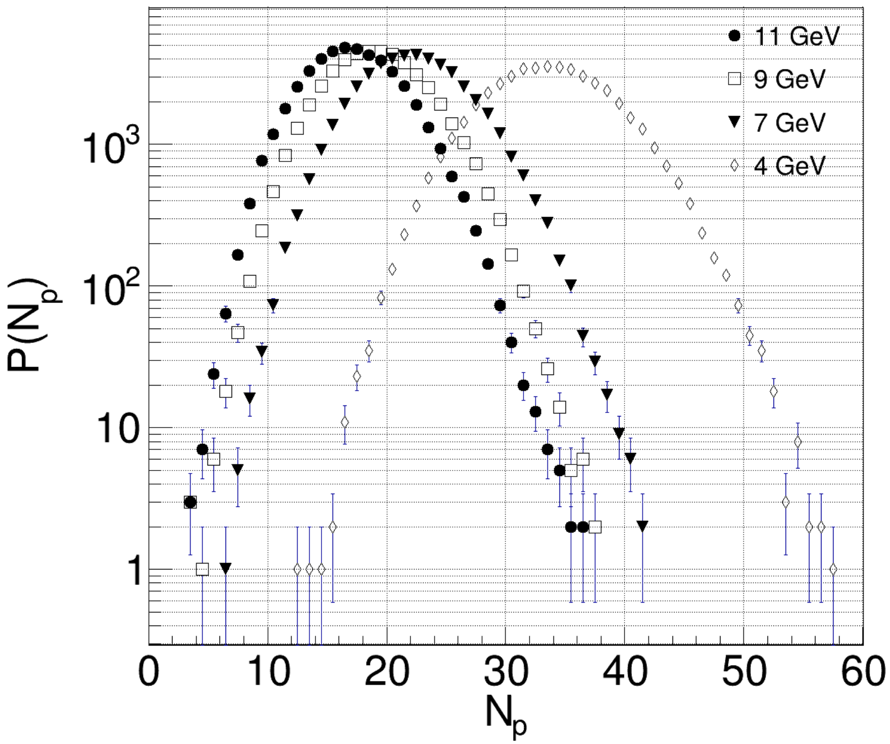
$$\chi_n^q = \frac{1}{VT^3} \times C_n^q = \frac{\partial^n p/T^4}{\partial \mu_q^n}, \quad q = B, Q, S$$

Volume dependence can be canceled by forming the ratio

Fluctuations of conserved quantities: phase space for *p*

- Au+Au collisions were simulated with UrQMD v3.4 event generator (**5 • 10⁴** events at 4, 7 and 9 GeV and **5 • 10⁵** at 11 GeV)
- Cumulant measurements are carried out within $|y| < 0.5$ and $0.4 < p_t < 0.8$ GeV/c
- Measurements of proton multiplicity are carried out with dE/dx + TOF bayesian PID
- This p_T interval accounts for approximately 50% of the total uncorrected p + anti-p multiplicity at midrapidity
- Typical value of detection efficiency ε in the given phase-space is 92% (protons are wasted due to tracking uncertainties, TPC-TOF mismatching, PID, cuts etc.)





Net-protons: measured cumulants and moments

Cumulants:

$k_1 = \langle N \rangle$

$k_2 = \langle (\delta N)^2 \rangle$

$k_3 = \langle (\delta N)^3 \rangle$

$k_4 = \langle (\delta N)^4 \rangle - 3 \langle (\delta N)^2 \rangle^2$

Moments:

$\mu = k_1 \qquad \sigma^2 = k_2$

$S = \dfrac{k_3}{k_2^{3/2}}$

$K = \dfrac{k_4}{k_2^{2}}$

if $\boldsymbol{K_i}$ is a cumulant associated with MC-distribution and $\boldsymbol{c_i}$ with the measured one with detecting efficiency ε, their relation is following:

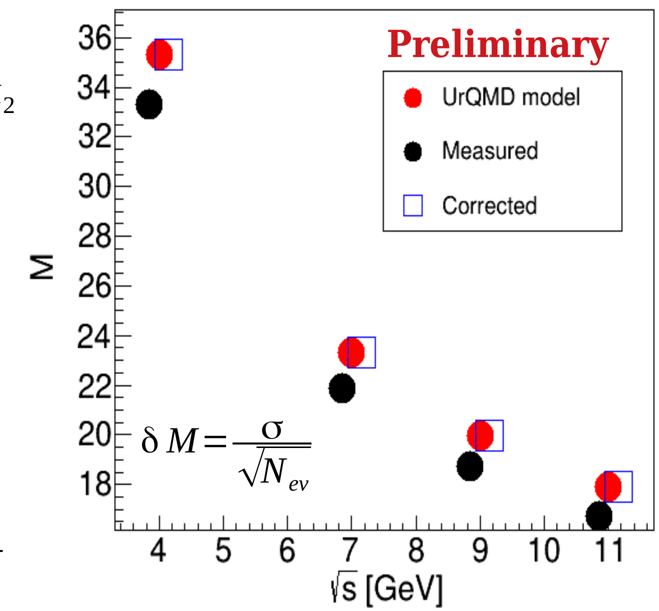
$\epsilon K_1 = c_1$

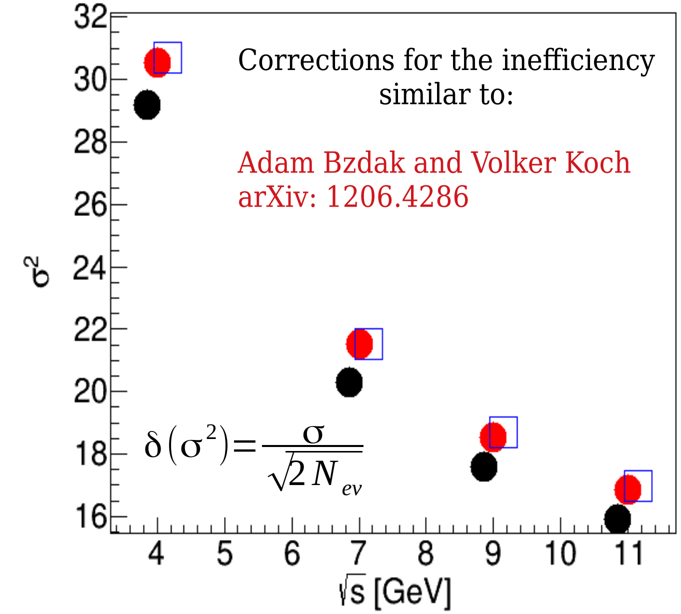
$\epsilon^2 K_2 = c_2 - c_1(1-p)$

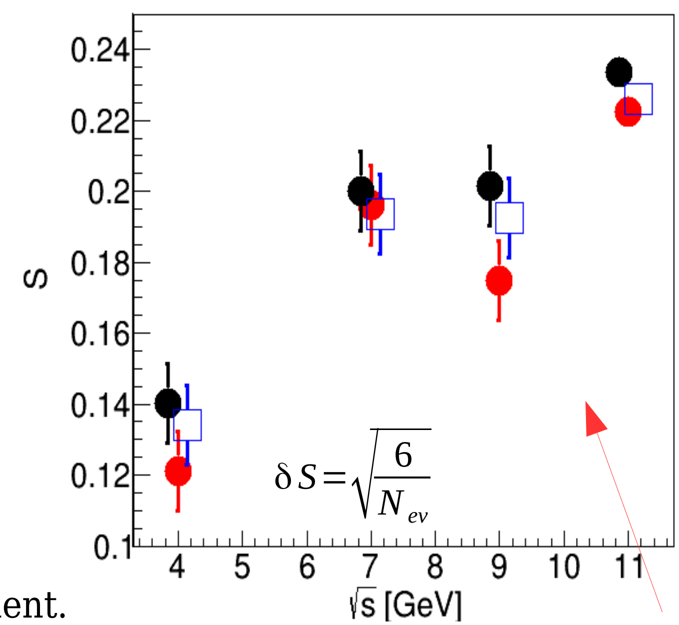
$\epsilon^3 K_3 = c_3 - c_1(1-\epsilon^2) - 3(1-\epsilon)(f_2 - c_1^2)$

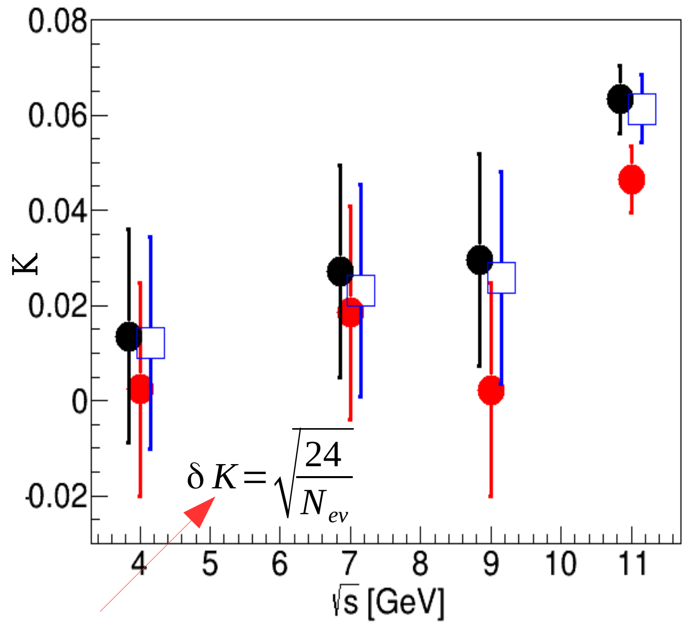
$$\epsilon^4 K_4 = c_4 - c_1 \epsilon^2 (1-\epsilon) - 3 c_1^2 (1-\epsilon)^2 - 6\epsilon(1-\epsilon) f_2 + 12 c_1 (1-\epsilon) f_2 - (1-\epsilon^2)(c_2 - 3c_1^2) - 6 c_1 (1-\epsilon)(c_1^2 - c_2) - 6(1-\epsilon)(f_2 + f_3)$$

where $f_i = \left\langle \dfrac{N_p!}{(N_p - i)!} \right\rangle$ – factorial moment.







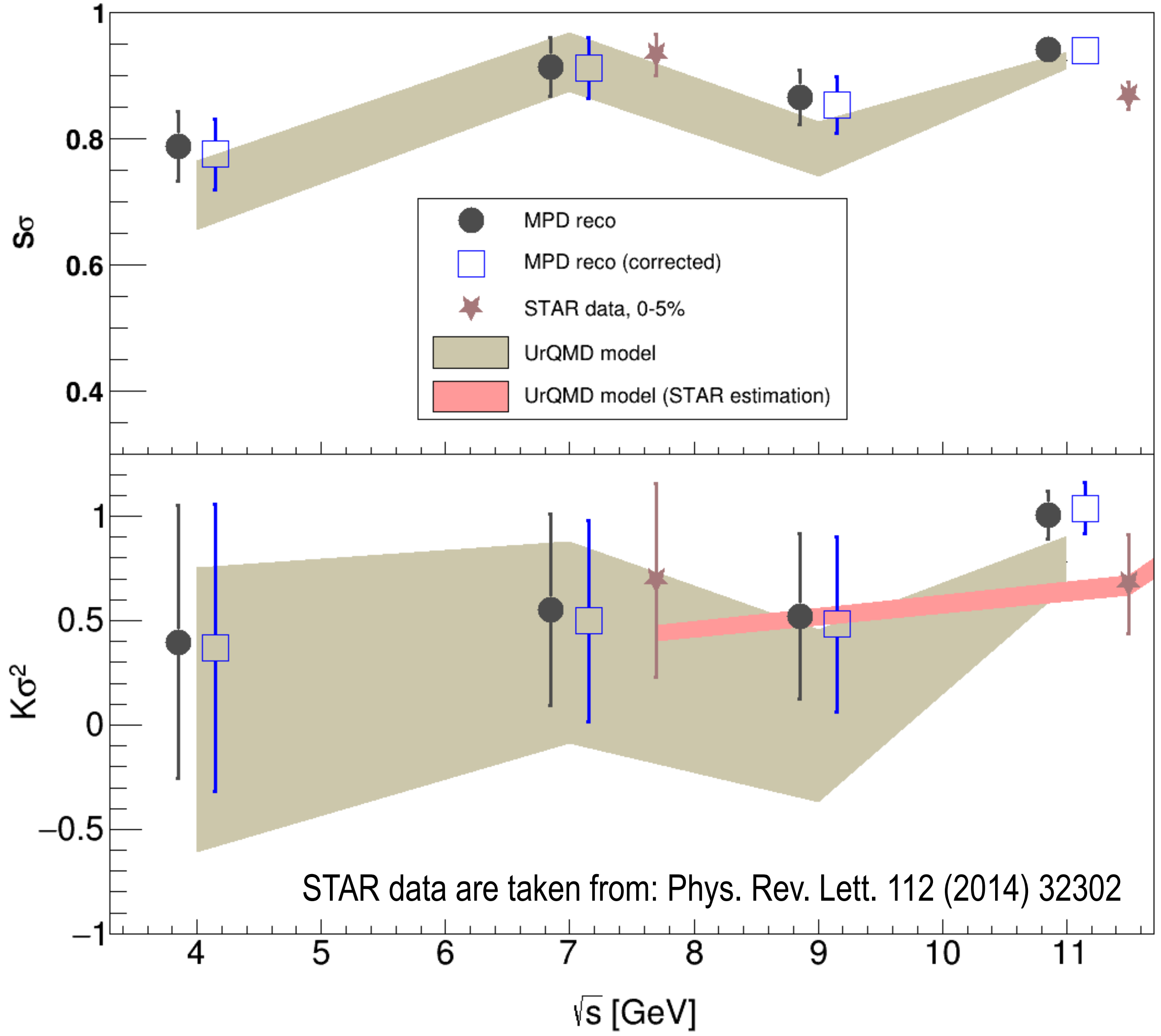


Statistical error bars only

Net-protons: measured cumulants and moments

Cumulant ratios are directly compared to susceptibilities and allow fireball volume cancellation

$$\frac{k_3}{k_2} = S\sigma \qquad \frac{k_4}{k_2} = K\sigma^2$$



$$\epsilon_K = \frac{\delta K}{|K|} \qquad \epsilon_{\sigma^2} = \frac{\delta \sigma^2}{|\sigma^2|}$$

$$\epsilon_{K\sigma^2} = \epsilon_K + \epsilon_\sigma$$

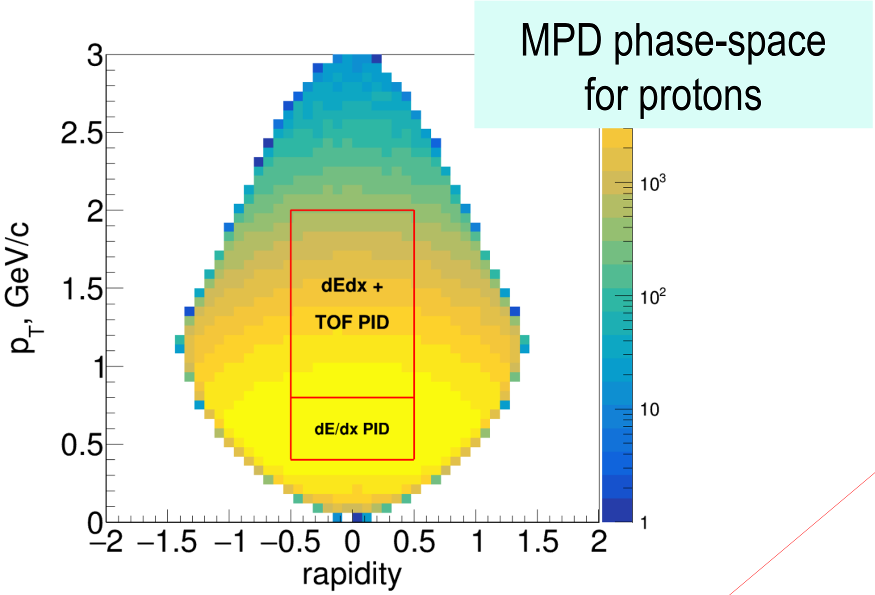
Statistics is not sufficient – large error bars

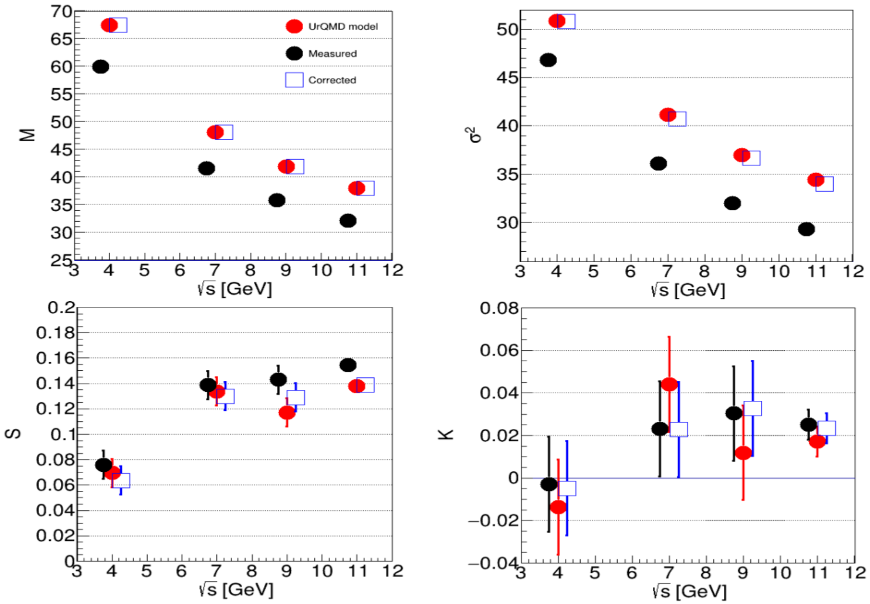
It is observed that this correction procedure does not work well. It can stem from our assumption that detection efficiency *p* is a single number. However, this does not imply that in each event *i* the number of observed particles is

$$n_i = pN$$

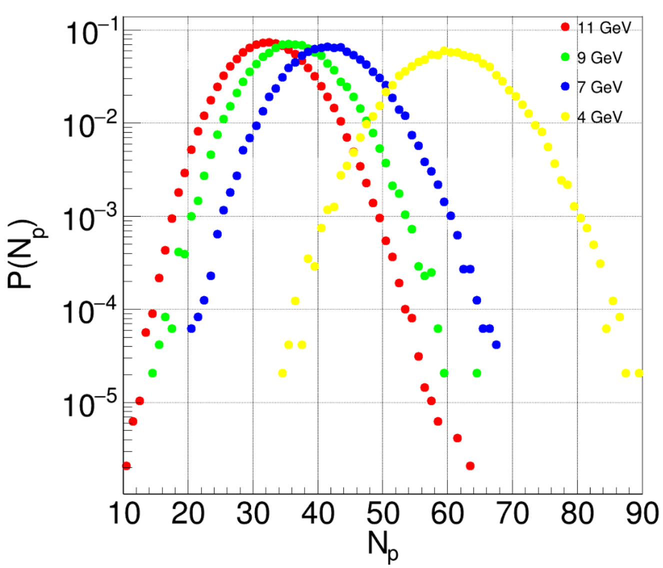
So, in order to improve correction results, local detection efficiency $p(y, p_T)$ has to be used instead of the global one.

Net-protons: measured cumulants and moments



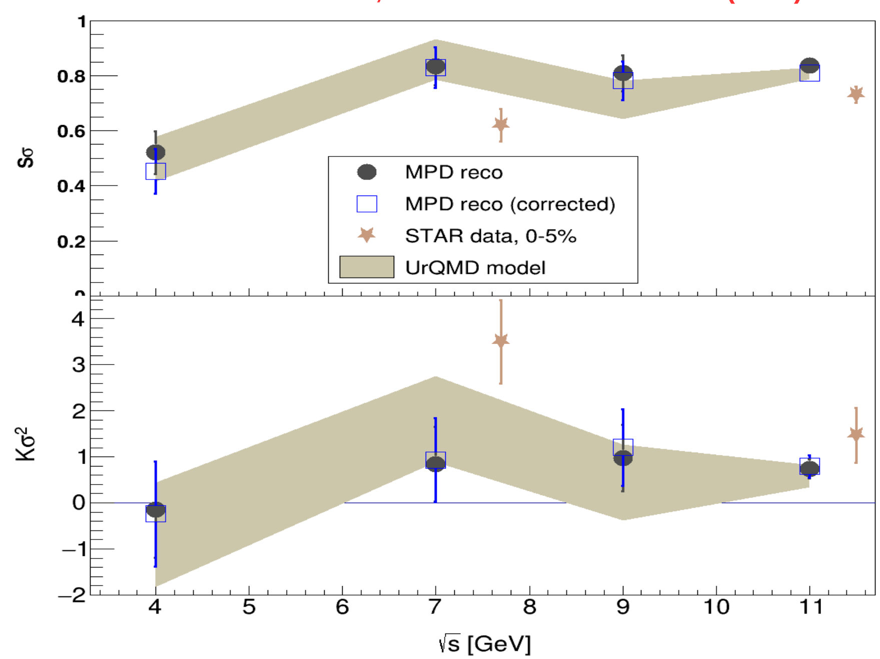


Moments and cumulants
within |y| < 0.5 and
$0.4 < p_T < 2.0$ GeV/c

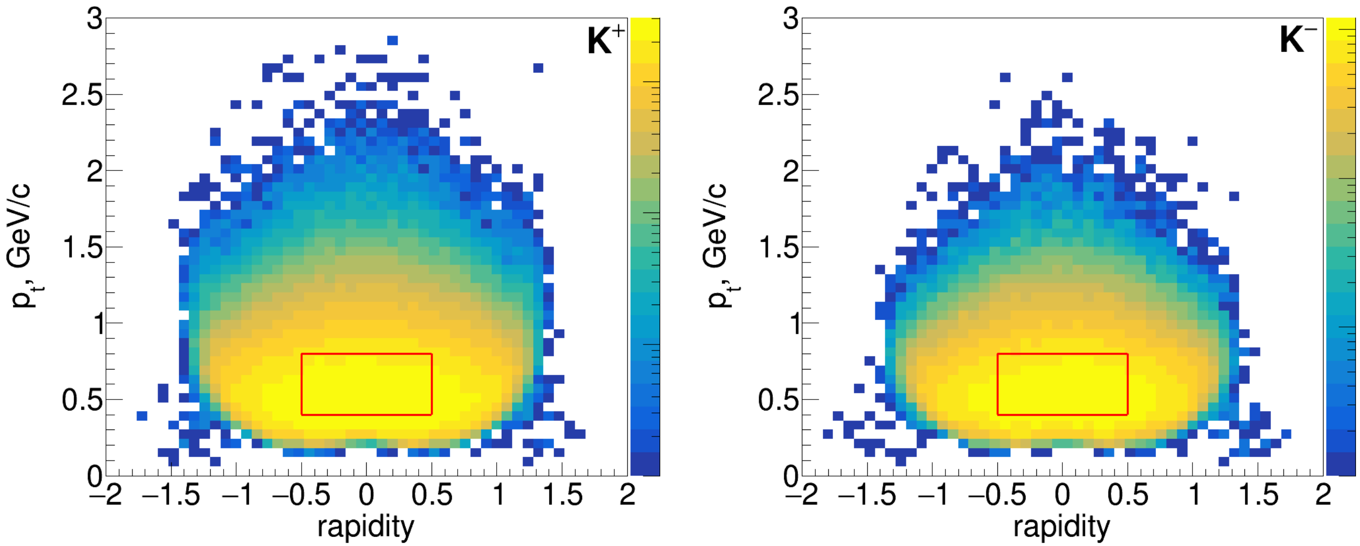


STAR data are taken from

X. Luo and N. Xu, 10.1007/s41365-017-0257-0(2017)



Fluctuations of conserved quantities: phase space for *K*⁺ and *K*⁻



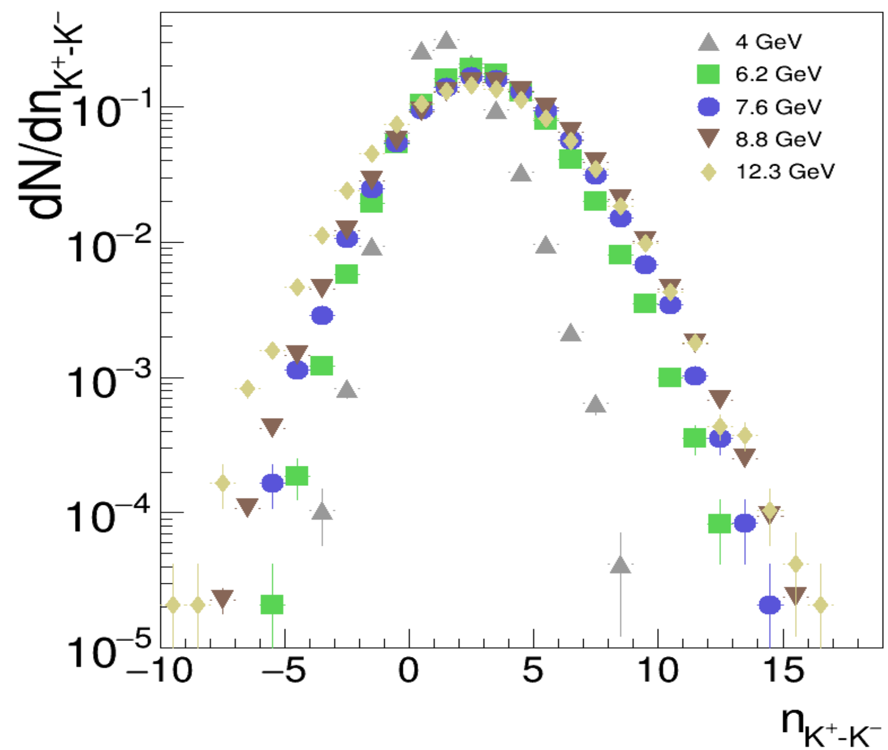
Event samples:

~**5•10⁴** central Au+Au events at √s = **4**, **6.2**, **7.6** and **12.3** GeV and ~**10⁶** central Au+Au events at √s =**8.8** GeV (PHSD model)

Ideal centrality definition 0 < b < 3 fm

Track selection criteria in analysis:

1) | Z_{vertex} | < 50 cm (event selection)
2) 0.4 < p_t < 0.8 GeV/c, | y | < 0.5
3) DCA cut: R_{DCA} < 3 cm
4) $N_{hits} \geq 27$



PID configuration:

1) dE/dx + TOF (combined) PID only
2) PID probability to be ***K***⁺ and ***K***⁻ is 95% or bigger

Net-kaons: measured cumulants and moments

Cumulants:

$k_1 = \langle N \rangle$

$k_2 = \langle (\delta N)^2 \rangle$

$k_3 = \langle (\delta N)^3 \rangle$

$k_4 = \langle (\delta N)^4 \rangle - 3\langle (\delta N)^2 \rangle^2$

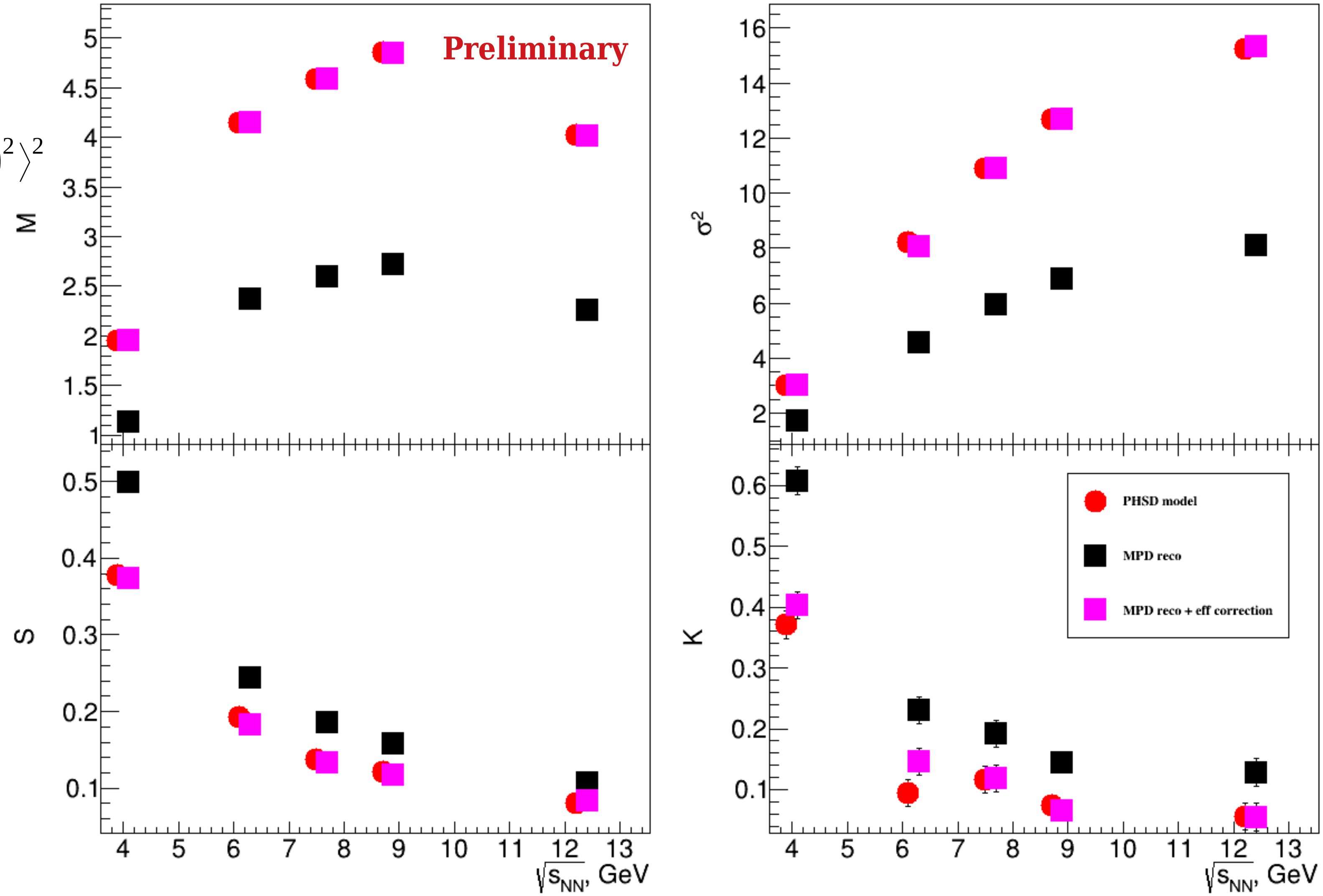
Moments:

$\mu = k_1 \qquad \sigma^2 = k_2$

$$S = \frac{k_3}{k_2^{3/2}}$$

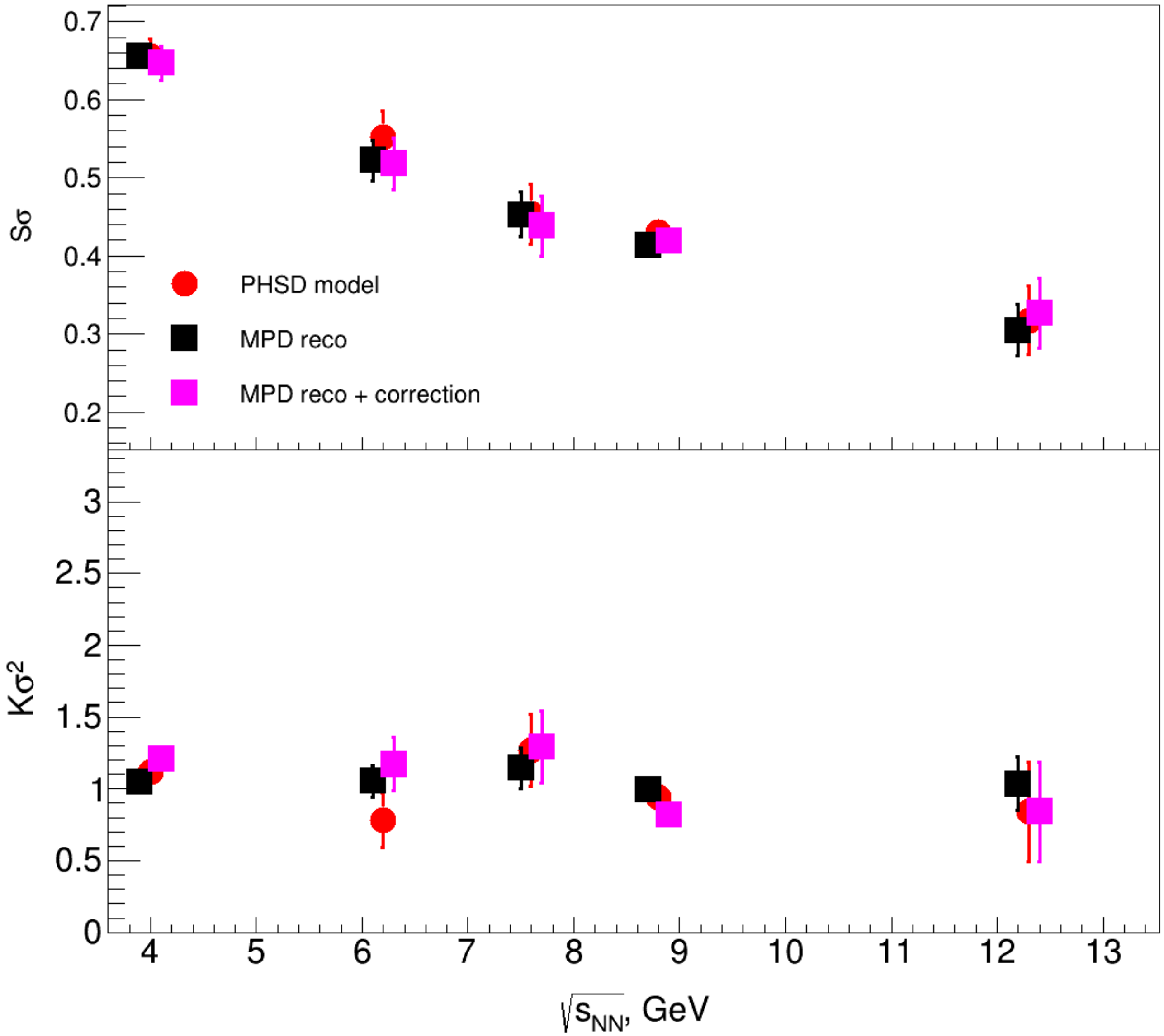
$$K = \frac{k_4}{k_2^{2}}$$

Correction procedure included p_t-depended efficiency determination *is* similar to Phys. Rev. C 91, 027901 (2015)



Net-kaons: measured cumulants and moments

Cumulant ratios are directly compared to susceptibilities and allow fireball volume cancellation



$$\frac{k_3}{k_2} = S\sigma \qquad \frac{k_4}{k_2} = K\sigma^2$$

$$\epsilon_K = \frac{\delta K}{|K|} \qquad \epsilon_{\sigma^2} = \frac{\delta \sigma^2}{|\sigma^2|}$$

$$\epsilon_{K\sigma^2} = \epsilon_K + \epsilon_\sigma$$

Conclusions

- Particle identification (PID) based on realistic tracking has been developed and implemented within the MpdRoot software package. Effective π/K separation is working up to 1.5 GeV, π/p separation is working up to 3 GeV.

- The estimated MPD potential in reconstruction of the efficiency-corrected $\boldsymbol{p_t}$ spectra of K^+, π^+ and K/π ratio is reasonably well.

- MPD performance in the study of event-by-event fluctuations is estimated with the emphasis of (net)-particle cumulants reconstruction. Cumulants of (net)-proton multiplicity distributions are reconstructed at midrapidity within two transverse momentum ranges: $0.4 < p_t < 0.8$ GeV/c and $0.4 < p_t < 2.0$ GeV/c. Cumulants of net-kaon multiplicity distributions are reconstructed within p_t range of $0.4 < p_t < 0.8$ GeV/c.

Acknowledgments

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Thank you for attention!