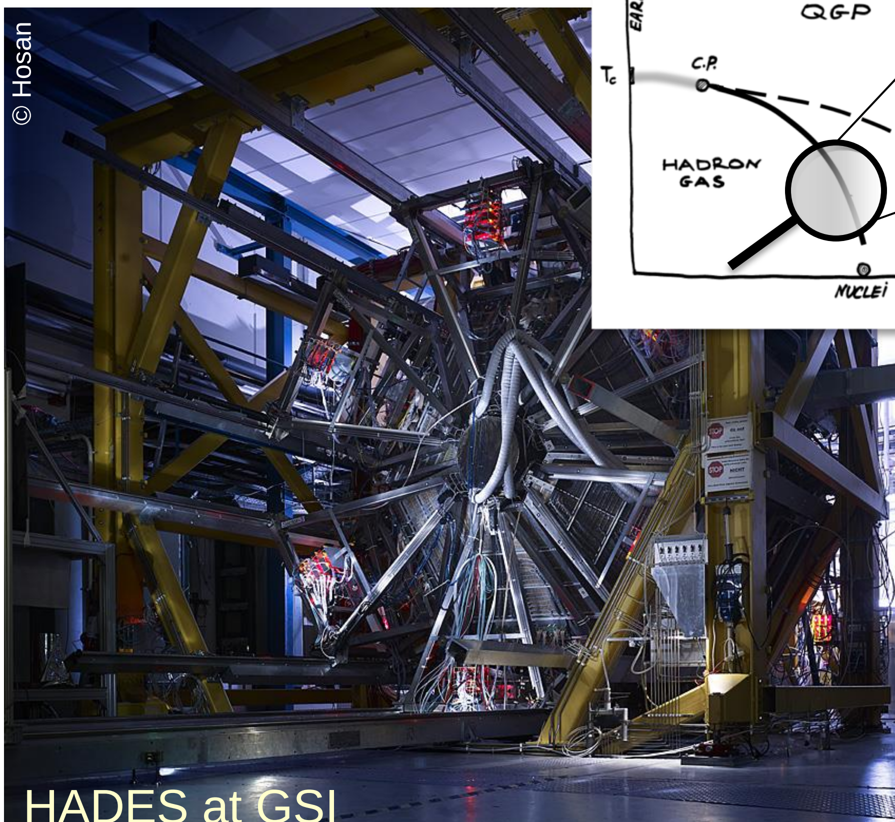
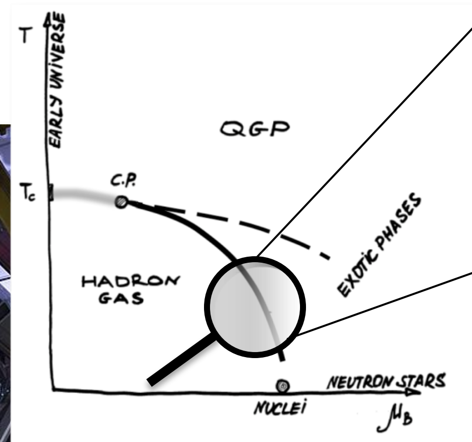
Proton number fluctuations in Au+Au investigated with HADES

Romain Holzmann
GSI Helmholtzzentrum Darmstadt,
for the HADES collaboration





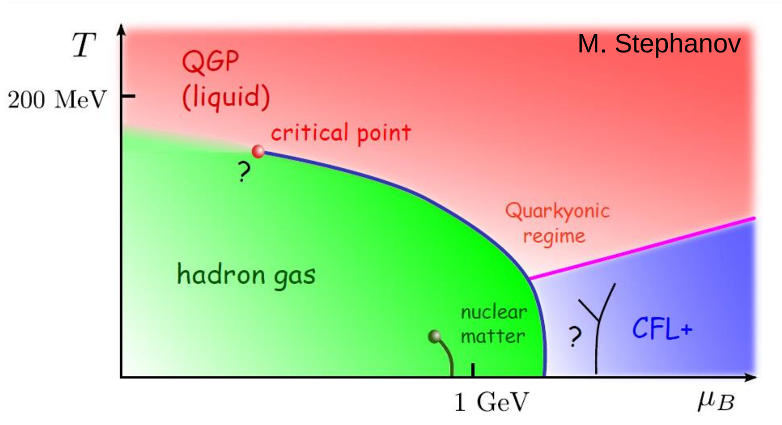
SIS 18 energy regime:

- beam energies 1-2 GeV/u
- moderate T, high μ_B
- baryon dominated

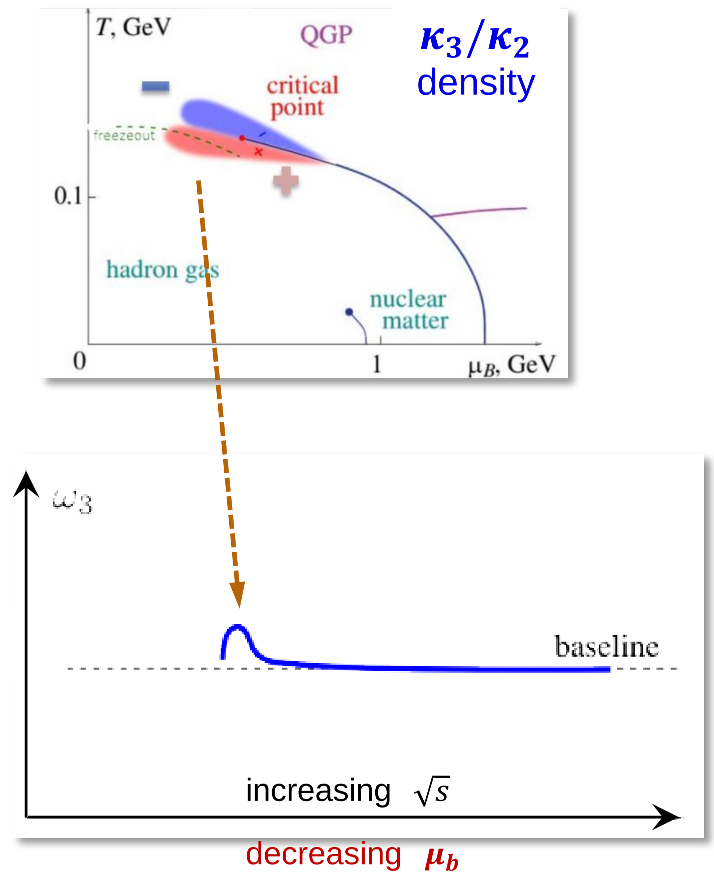
Outline:

- HADES: Au+Au at 1.23 GeV/u
- Net proton nb. fluctuations
  - **corrections (acc., vol. fluc.)**
  - **cumulants → correlations**
  - **protons bound in fragments**
- Summary & Outlook

Fluctuations probe features of QCD phase diagram



M. Stephanov CPOD2014



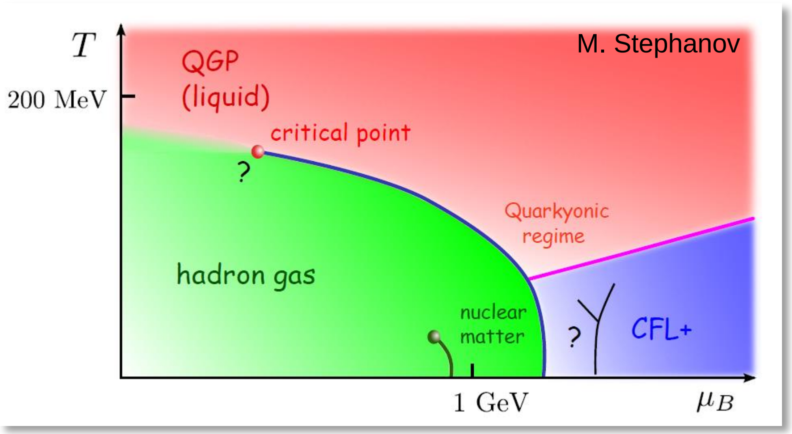
Prominent features of the QCD phase-diagram (phase boundaries, CEP) are expected to result in:

- ➔ diverging susceptibilities & correlation lengths
- ➔ „extra“ fluctuations of conserved quantities (e.g. baryon nb, charge, strangeness)

- ➔ observable discontinuities of the higher moments of particle number distributions, visible in a HIC beam energy scan!

(see e.g. B. Friman et al, EPJC 71 (2011) 1694)

Fluctuations probe features of QCD phase diagram



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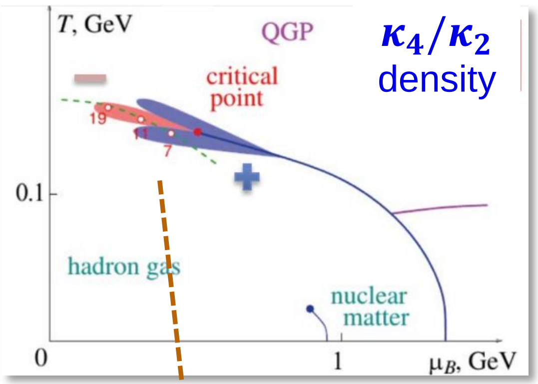

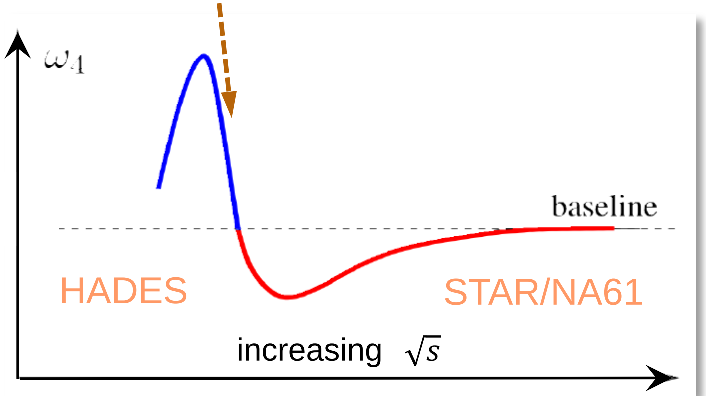

decreasing μ_b

Prominent features of the QCD phase-diagram (phase boundaries, CEP) are expected to result in:

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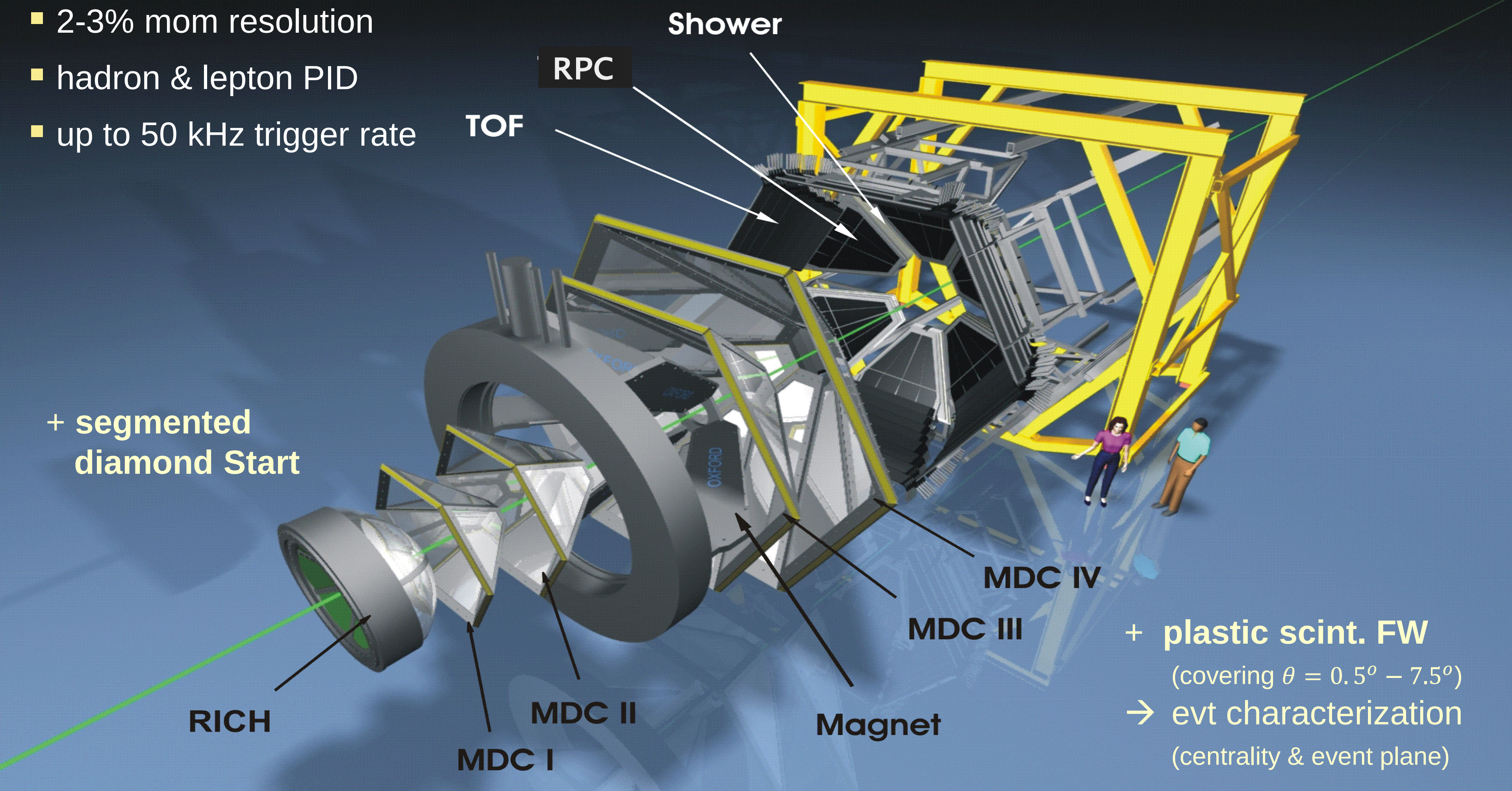
(see e.g. B. Friman et al, EPJC 71 (2011) 1694)

→ Needs high-statistics data sets acquired under well controlled experimental conditions!

The HADES detector at GSI

High Acceptance DiElectron Spectrometer

- large acceptance
- 2-3% mom resolution
- hadron & lepton PID
- up to 50 kHz trigger rate

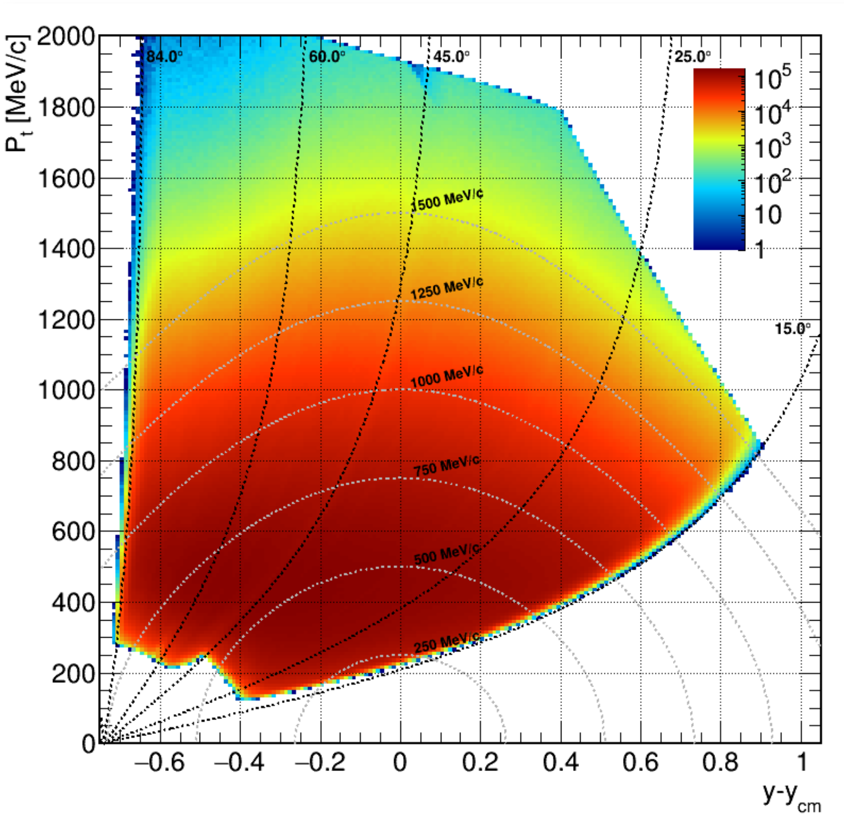


+ **segmented diamond Start**

+ **plastic scint. FW**
(covering $\theta = 0.5^o - 7.5^o$)
→ evt characterization
(centrality & event plane)

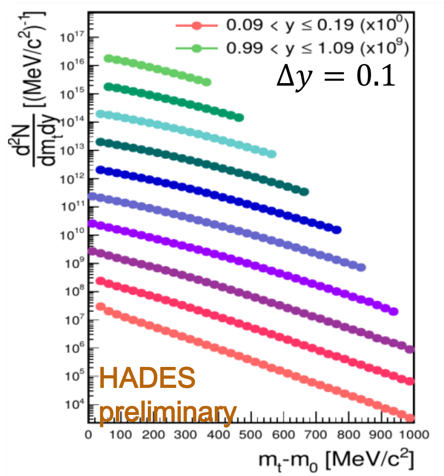
Proton distributions in Au+Au at $\sqrt{s} = 2.41\ GeV$

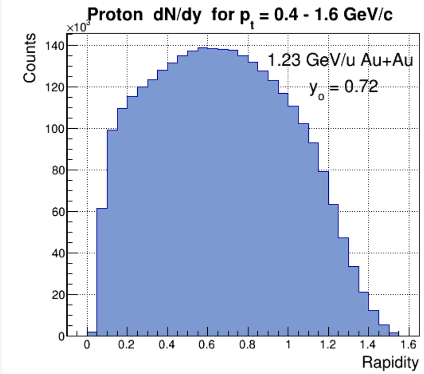
HADES $y - p_t$ coverage for protons



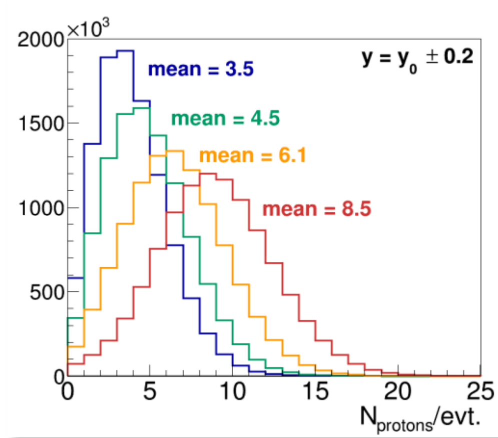
At 1.23 GeV/u y_{cm} = 0.74

Proton mt & y spectra





Proton multiplicity distributions



Fluctuation analysis is based on $50 \cdot 10^6$ Au+Au evts divided into four 10% wide centrality classes:

30-40%, 20-30%, 10-20%, & 0-10%

(I) Efficiency corrections

Note that efficiency = acc x det. eff x rec. eff !

1. Correct the cumulants

   A. Bzdak & V. Koch, PRC 86 (2012); X. Luo, PRC 91 (2015);
   M. Kitasawa, PRC 93 (2016)

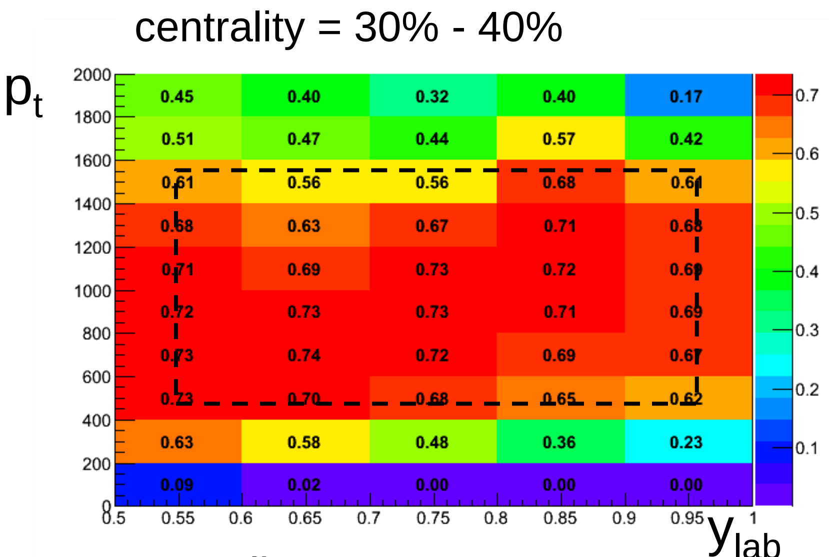
2. Correct measured distributions (bayesian unfolding)

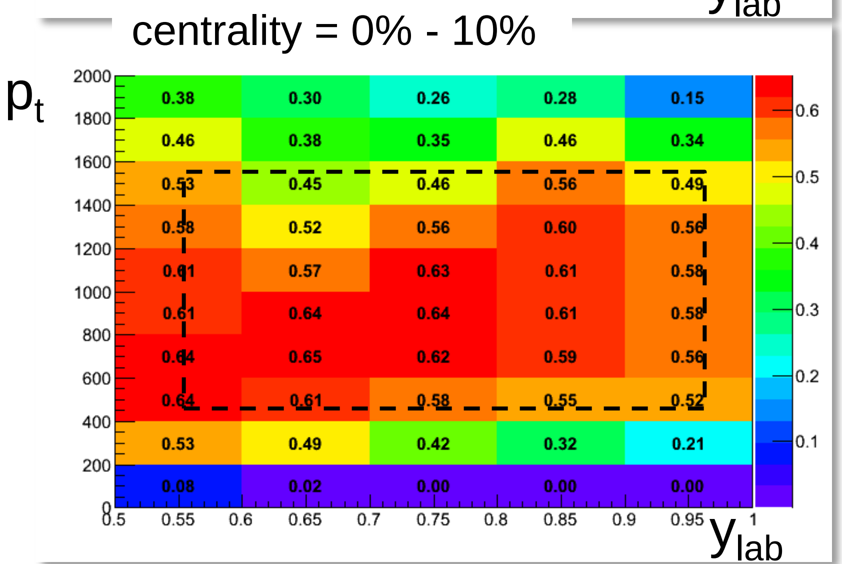
   Garg et al., J. Phys. G: Nucl. Part. Phys. 40 (2013)

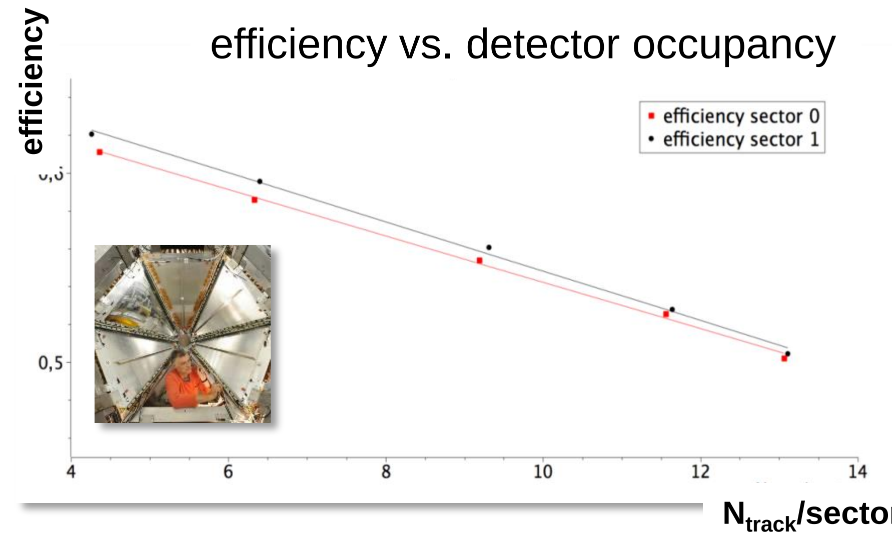
➔ we have investigated both methods

1. in simulations based on UrQMD evts filtered with full HADES response
2. in real Au+Au data

Hades efficiencies vs. p_t, y, centrality & N_{track}/sector







- ➔ Efficiency drops by up to 15% with occupancy, need to do a dynamic efficiency correction!
- ➔ Model $\epsilon = \epsilon(N_{track}, \boldsymbol{sector})$ to correct evt-by-evt!

We verified this correction scheme in full detector simulations using **24, 54** or **96** separate acc. bins ($\Delta y \times \Delta p_t \times sector$).

Method 1: Evt-by-evt efficiency correction of κ_n

Efficiency depends on particle, centrality, pt & y…

➔ correct by phase-space bin and evt-wise !

Bzdak & Koch, PRC 91 (2015)
Tang & Wang, PRC 88 (2013)
Xiaofeng Luo, PRC 91 (2015)
Masakiyo Kitasawa, PRC 93 (2016)

(1)

$$F_{i,k}(N_p, N_{\bar{p}}) = \left\langle \frac{N_p!}{(N_p-i)!} \frac{N_{\bar{p}}!}{(N_{\bar{p}}-k)!} \right\rangle = \sum_{N_p=i}^{\infty} \sum_{N_{\bar{p}}=k}^{\infty} P(N_p, N_{\bar{p}}) \frac{N_p!}{(N_p-i)!} \frac{N_{\bar{p}}!}{(N_{\bar{p}}-k)!}$$

$$f_{i,k}(n_p, n_{\bar{p}}) = \left\langle \frac{n_p!}{(n_p-i)!} \frac{n_{\bar{p}}!}{(n_{\bar{p}}-k)!} \right\rangle = \sum_{n_p=i}^{\infty} \sum_{n_{\bar{p}}=k}^{\infty} p(n_p, n_{\bar{p}}) \frac{n_p!}{(n_p-i)!} \frac{n_{\bar{p}}!}{(n_{\bar{p}}-k)!}$$

$$F_{i,k}(N_p, N_{\bar{p}}) = \frac{f_{i,k}(n_p, n_{\bar{p}})}{(\varepsilon_p)^i (\varepsilon_{\bar{p}})^k}$$

(2)

$$\begin{aligned} A_{i,k}(x_1,\ldots,x_i;\bar{x}_1,\ldots,\bar{x}_k) &= \langle N(x_1)[N(x_2)-\delta_{x_1,x_2}]\ldots[N(x_i)-\delta_{x_1,x_i}-\ldots-\delta_{x_{i-1},x_i}] \\ &\quad \bar{N}(\bar{x}_1)[\bar{N}(\bar{x}_2)-\delta_{\bar{x}_1,\bar{x}_2}]\ldots[\bar{N}(\bar{x}_k)-\delta_{\bar{x}_1,\bar{x}_k}-\ldots-\delta_{\bar{x}_{k-1},\bar{x}_k}]\rangle \\ a_{i,k}(x_1,\ldots,x_i;\bar{x}_1,\ldots,\bar{x}_k) &= \langle n(x_1)[n(x_2)-\delta_{x_1,x_2}]\ldots[n(x_i)-\delta_{x_1,x_i}-\ldots-\delta_{x_{i-1},x_i}] \\ &\quad \bar{n}(\bar{x}_1)[\bar{n}(\bar{x}_2)-\delta_{\bar{x}_1,\bar{x}_2}]\ldots[\bar{n}(\bar{x}_k)-\delta_{\bar{x}_1,\bar{x}_k}-\ldots-\delta_{\bar{x}_{k-1},\bar{x}_k}]\rangle . \end{aligned}$$

„local factorial moments“

(3)

$$\begin{aligned} F_{i,k} &= \sum_{x_1,\ldots,x_i} \sum_{\bar{x}_1,\ldots,\bar{x}_k} A_{i,k}(x_1,\ldots,x_i;\bar{x}_1,\ldots,\bar{x}_k) \\ f_{i,k} &= \sum_{x_1,\ldots,x_i} \sum_{\bar{x}_1,\ldots,\bar{x}_k} a_{i,k}(x_1,\ldots,x_i;\bar{x}_1,\ldots,\bar{x}_k) \end{aligned}$$

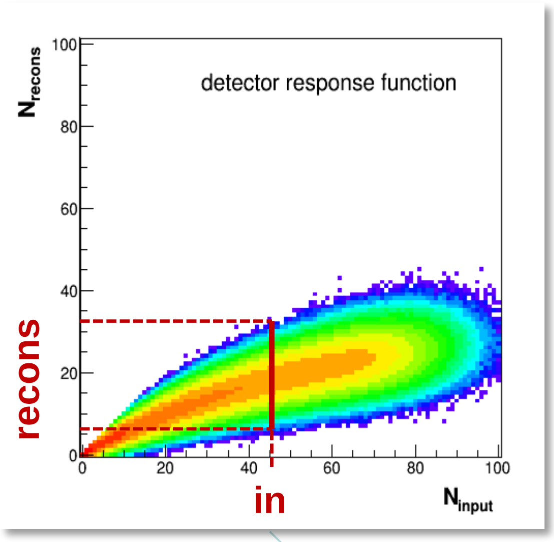
$$F_{i,k} = \sum_{x_1,\ldots,x_i} \sum_{\bar{x}_1,\ldots,\bar{x}_k} \frac{a_{i,k}(x_1,\ldots,x_i;\bar{x}_1,\ldots,\bar{x}_k)}{\epsilon(x_1)\ldots\epsilon(x_i)\bar{\epsilon}(\bar{x}_1)\ldots\bar{\epsilon}(\bar{x}_k)}$$

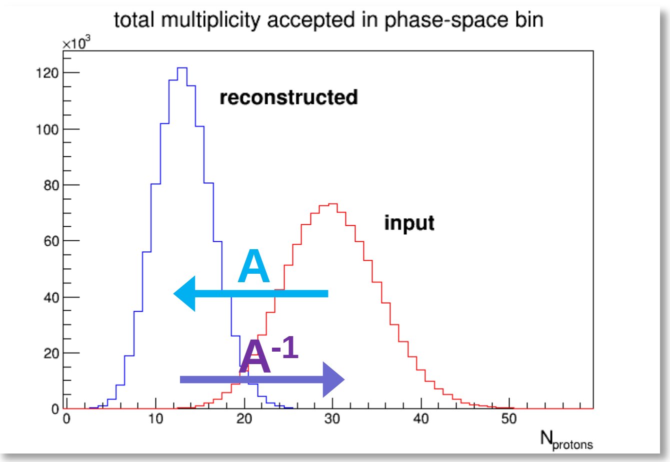
→ correct evt-by-evt with dynamic ε=ε(N)
→ as well EP effects …

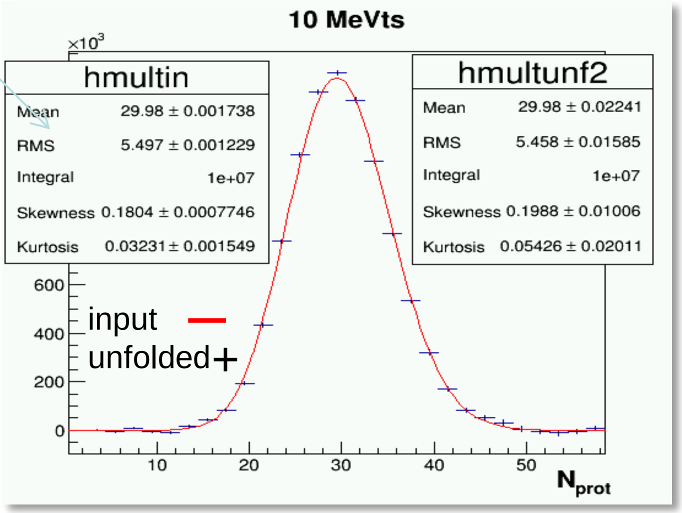
Method 2: Unfold the multiplicity distribution

Response matrix of the system:
(obtained from simul)

$N_{recons} = A \cdot N_{input}$







Tested on simulated proton spectra accepted in HADES.

All moments reproduced within statistical error bars!

Unfolding in a nutshell: regularize A

Literature: ALICE Collaboration, Eur. Phys. J. C 68 (2010) 89; Eur. Phys. J. C 77 (2017) 33.
S. Schmitt, J. Instr. 7 (2012) T10003.
P. Garg et al., J. Phys. G 40 (2013) 055103.

Problem:

y = A · x **x** = true signal, **A** = response matrix, **y** = measured signal

Knowing **y** and **A**, find **x**.

Unfortunately, **A** is often quasi-singular and can not be inverted (ill-conditioned problem!).

Solution:

Minimize via least-squares procedure the „Lagrangian“ ***L(x,λ)***:

$$\mathcal{L}(x,\lambda) = \mathcal{L}_1 + \mathcal{L}_2 + \mathcal{L}_3$$

$$\mathcal{L}_1 = (\boldsymbol{y} - \mathbf{A}\boldsymbol{x})^{\mathsf{T}} \mathbf{V_{yy}}^{-1} (\boldsymbol{y} - \mathbf{A}\boldsymbol{x}),$$

$$\mathcal{L}_2 = \tau^2 (\boldsymbol{x} - f_b \boldsymbol{x_0})^{\mathsf{T}} (\mathbf{L}^{\mathsf{T}}\mathbf{L}) (\boldsymbol{x} - f_b \boldsymbol{x_0}),$$

$$\mathcal{L}_3 = \lambda (Y - \boldsymbol{e}^{\mathsf{T}} \boldsymbol{x})$$

minimization

Tikhonov regularization

area constraint

ROOT implementation:

TUnfold, TUnfoldSys, TUnfoldDensity

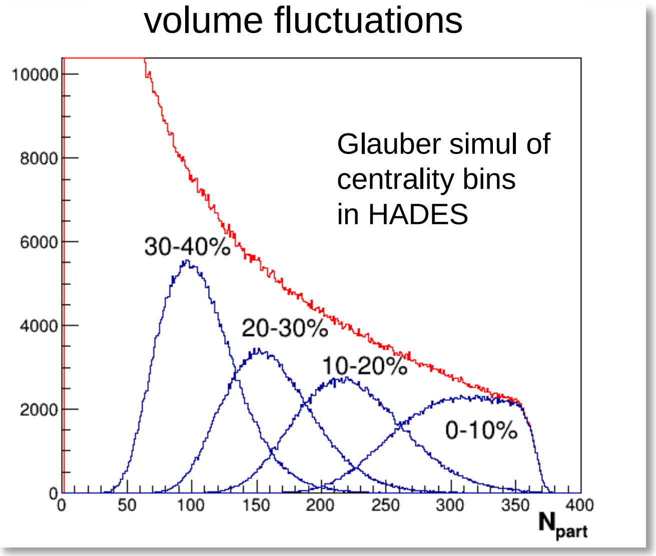
But, choice of τ can be probematic!

(II) Volume fluctuations effects

→ Effect of volume fluctuations due to centrality selection on (reduced) cumulants of the net baryon number discussed by Skokov, Friman & Redlich in PRC 88 (2013):

$$c_1 = \kappa_1,$$
$$c_2 = \kappa_2 + \kappa_1^2 v_2,$$
$$c_3 = \kappa_3 + 3\kappa_2\kappa_1 v_2 + \kappa_1^3 v_3,$$
$$c_4 = \kappa_4 + (4\kappa_3\kappa_1 + 3\kappa_2^2) v_2 + 6\kappa_2\kappa_1^2 v_3 + \kappa_1^4 v_4,$$

- k_n proton number cumulants
- c_n volume affected cumulants
- v_n volume fluctuations cumulants



→ Take volume fluctuations v_n from a model, e.g. **Glauber** or **transport** adjusted to the observable used to define centrality in a given experiment, and correct the data.

→ Effect of centrality selection investigated with UrQMD simul by G. Westfall in PRC 92 (2015)

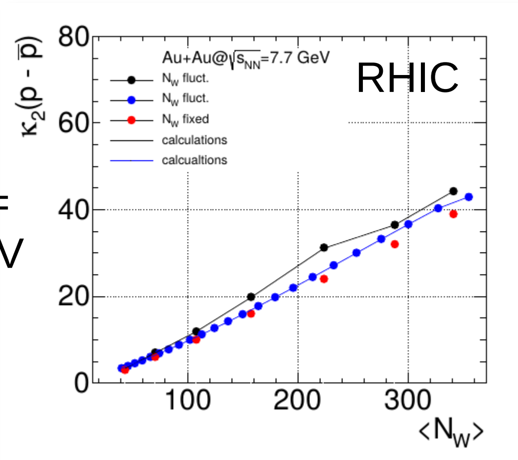
→ Discussed in more detail by PBM, Rustamov & Stachel NPA 960 (2017) 114

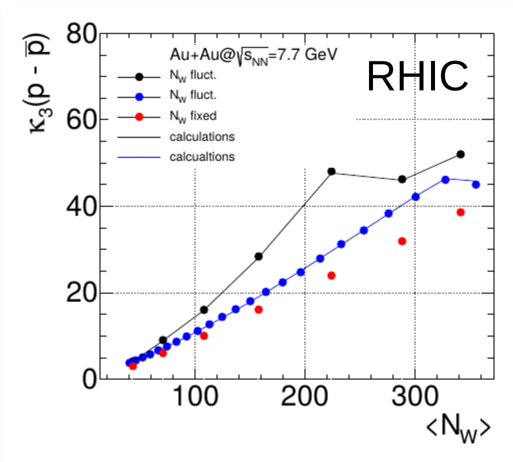
Volume fluctuation effects on cumulants

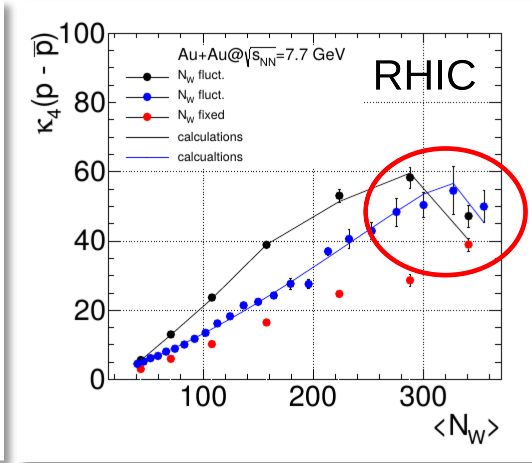
Glauber simul of $N_{wounded}$ + Negative Binomial model of particle production at RHIC & LHC

Braun-Munzinger, Rustamov & Stachel, Nucl. Phys. A 960 (2017) 114

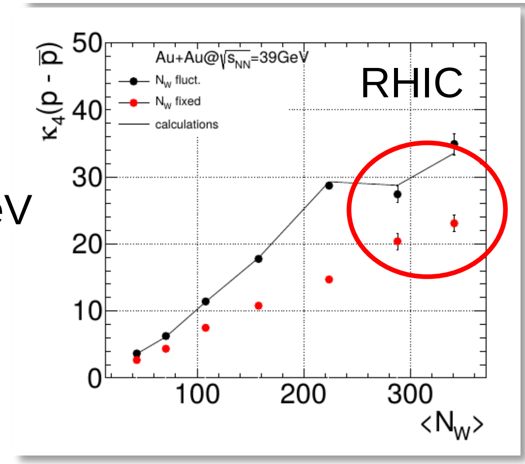
$\sqrt{s_{NN}}$ = 7.7 GeV



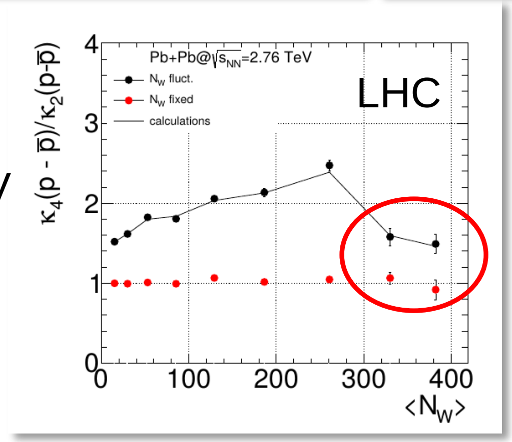




39 GeV



2.76 TeV



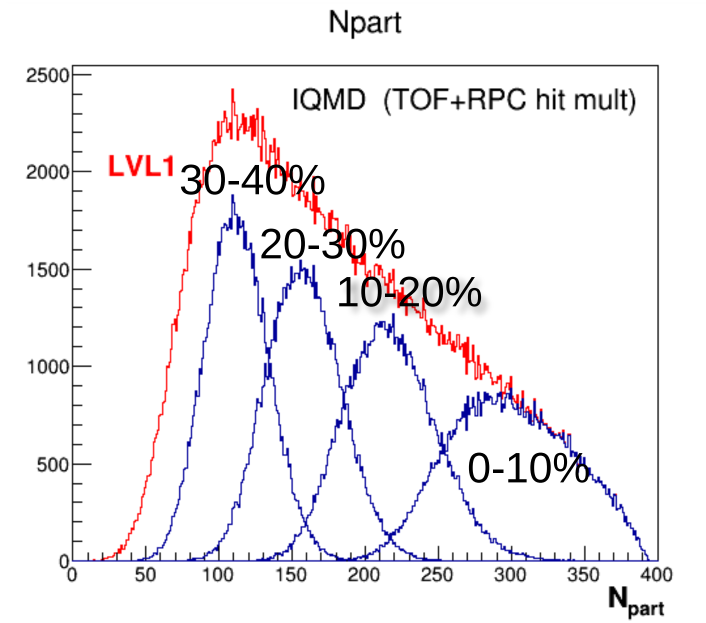
Skokov formulas:

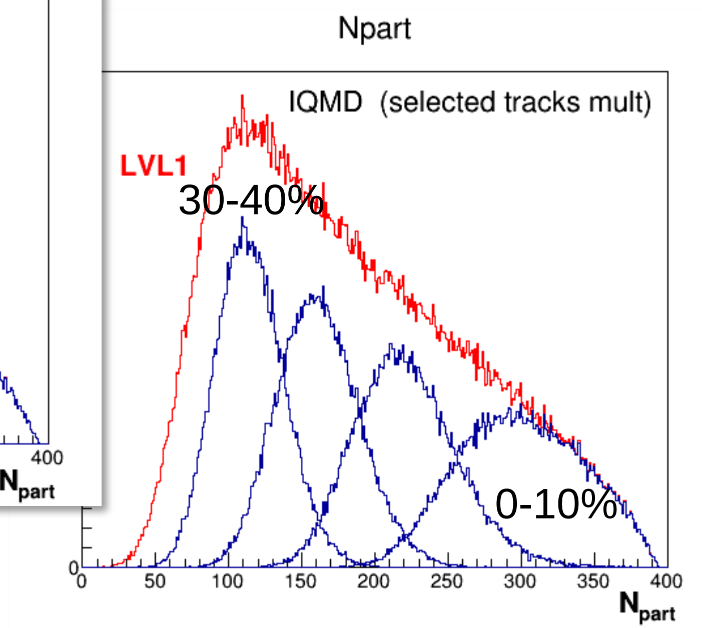
$$\kappa_1 = c_1$$
$$\kappa_2 = c_2 - \kappa_1^2\, v_2$$
$$\kappa_3 = c_3 - 3\,\kappa_2\kappa_1 v_2 - \kappa_1^3 v_3$$
$$\kappa_4 = c_4 - (4\kappa_3\kappa_1 + 3\kappa_2^2) v_2 - 6\kappa_2\kappa_1^2 v_3 - \kappa_1^4\, v_4$$

At large $\sqrt{s}$, odd terms cancel!

→ partial cancellation of volume terms at large N_W?

HADES centrality selection in IQMD simulations

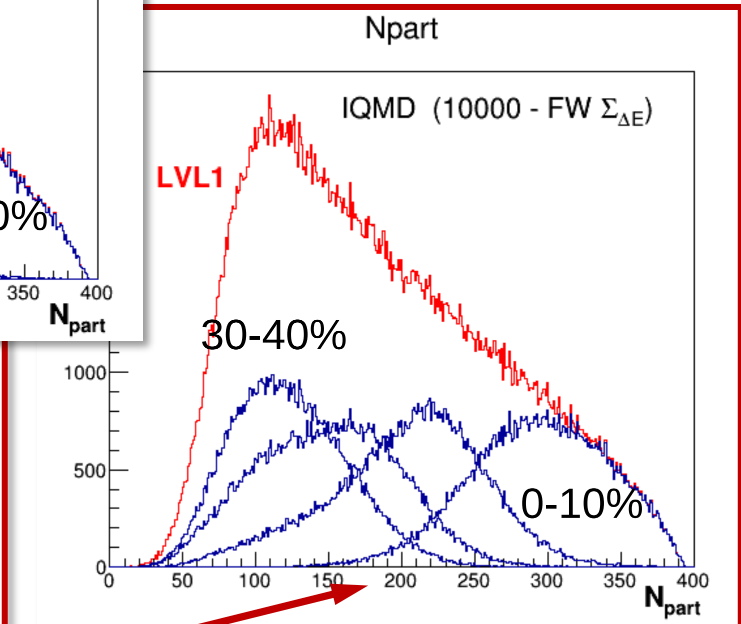




IQMD + clusterizer

→ fragments in final state

(evts provided by Y. Leifels)

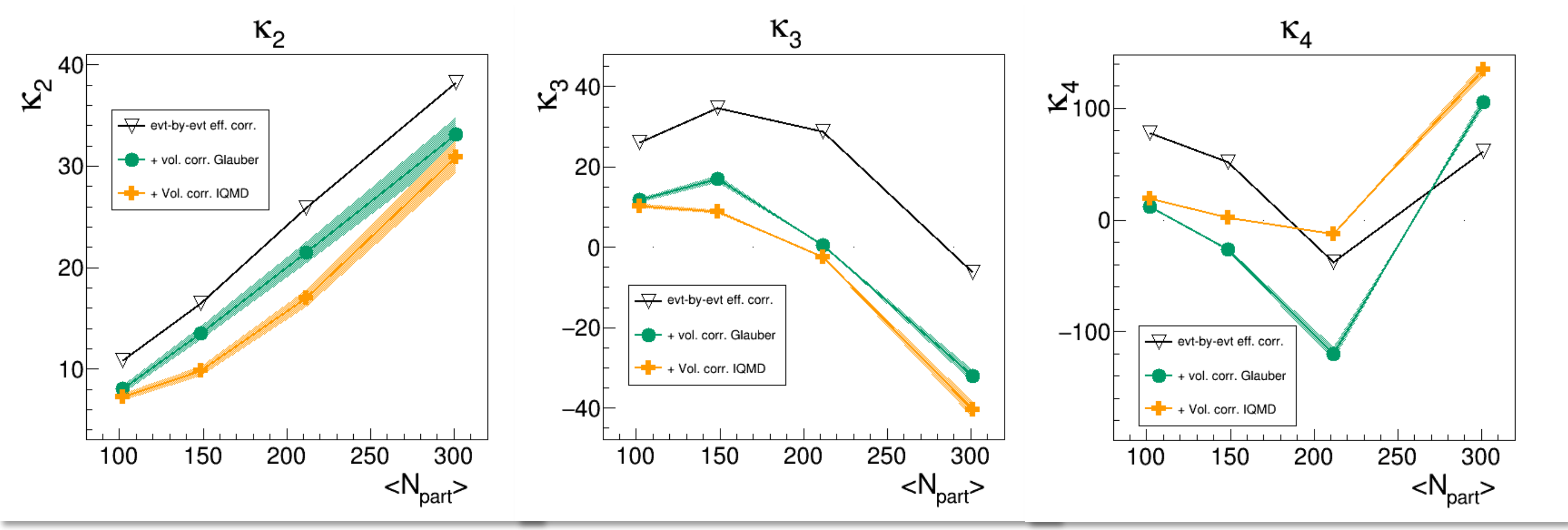


- ➔ TOF+RPC hit mult & track mult are similar to our Glauber fits
- ➔ FW sum of charge has worse resolution

➔ FW used to avoid auto-correlations!

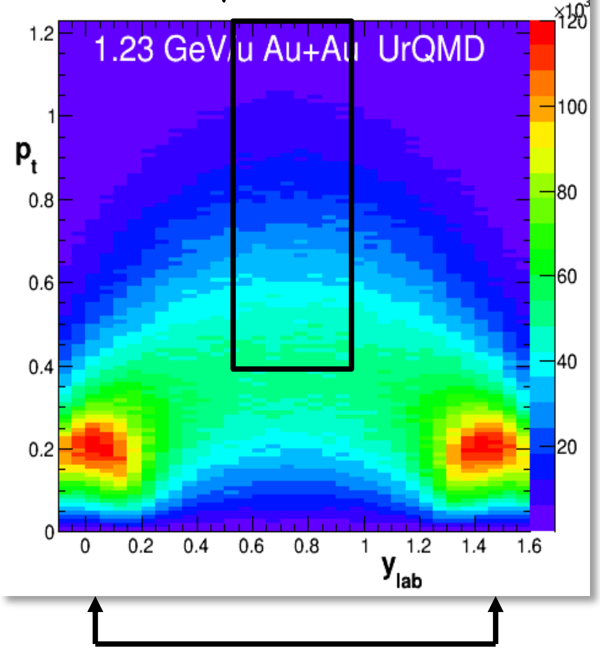
Proton cumulants κ_n vs N_{part} in 1.23 GeV/u Au+Au

Volume-corrected proton cumulants: (model = **Glauber** or **IQMD+clusterizer**)



Choice of phase-space bite for fluctuation analysis

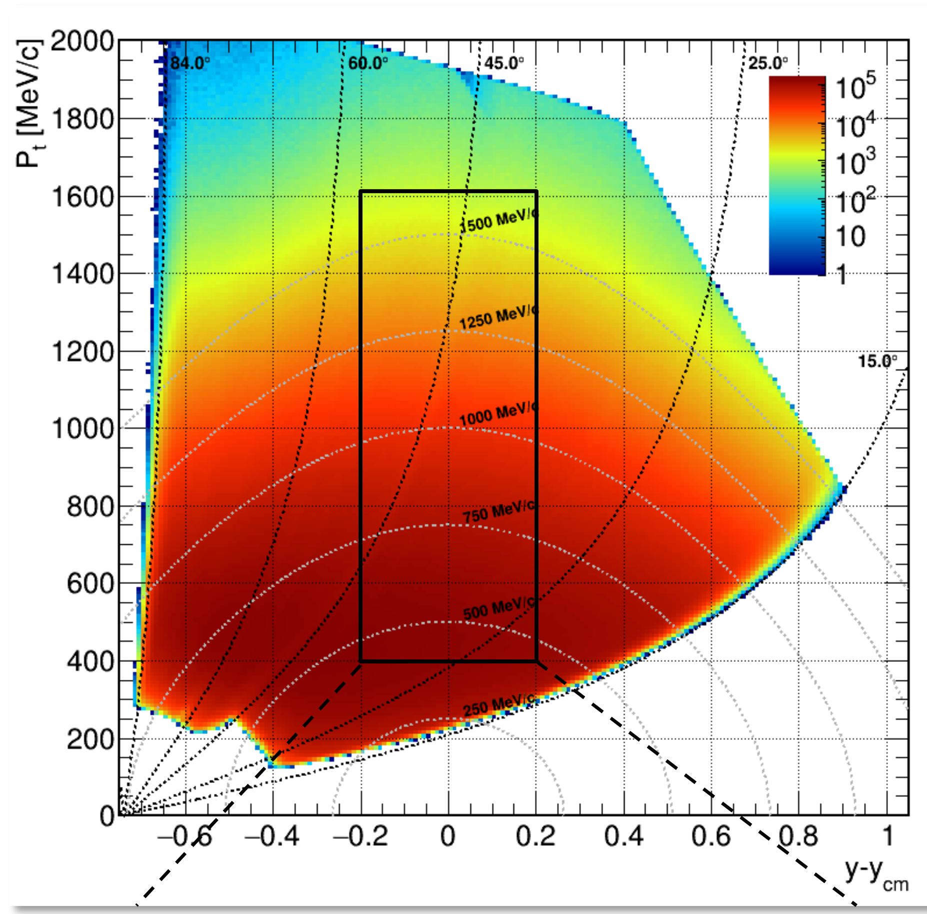
HADES $\sqrt{s_{NN}} = 2.41\ GeV$



rapidity gap = 1.5 units!

➔ Select a phase-space bite
- avoid spectator matter
- avoid baryon nb conservation
- cover relevant correlations
- stay within detector acceptance

HADES $y - p_t$ coverage for protons



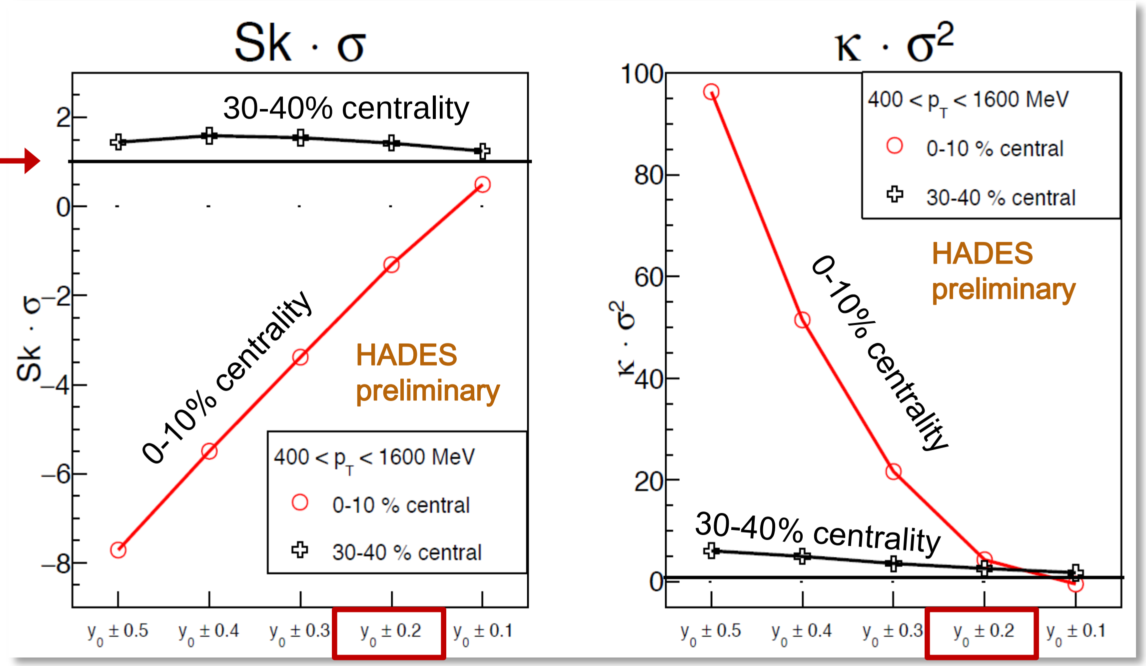
phase-space bite used in fluctuation analysis:

$y = y_0 \pm 0.2$ and p_t= 0.4 – 1.6 GeV/c

Checking the Poisson limit: κ_n vs. Δy

→ Expect to approach **Poisson limit** for narrow enough phase-space bin!

→ Shown here for our Au+Au proton data with volume corrections:



phase-space bin: $y_{acc} = y_0 \pm \Delta y$
$p_t = 0.4 - 1.6\ GeV/c$

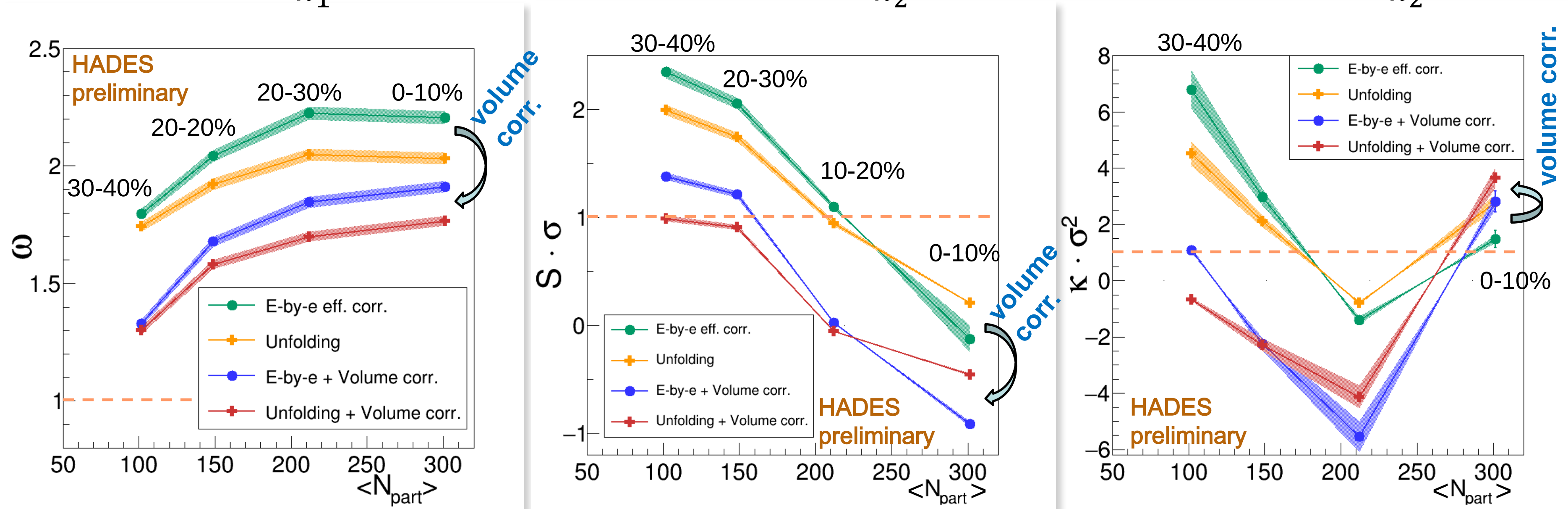
$\boldsymbol{S \cdot \sigma \to 1}$ **and** $\boldsymbol{\kappa \cdot \sigma^2 \to 1}$ **for** $\boldsymbol{\Delta y \to 0}$

→ **ok!**

Fully corrected scaled moments vs. centrality

HADES 1.23 GeV/u Au+Au proton moments:

$\omega = \frac{\kappa_2}{\kappa_1}$ $\qquad$ $Sk \times \sigma = \frac{\kappa_3}{\kappa_2}$ $\qquad$ $\kappa \times \sigma^2 = \frac{\kappa_4}{\kappa_2}$



Error bands correspond to 5% systematic error on proton efficiencies.

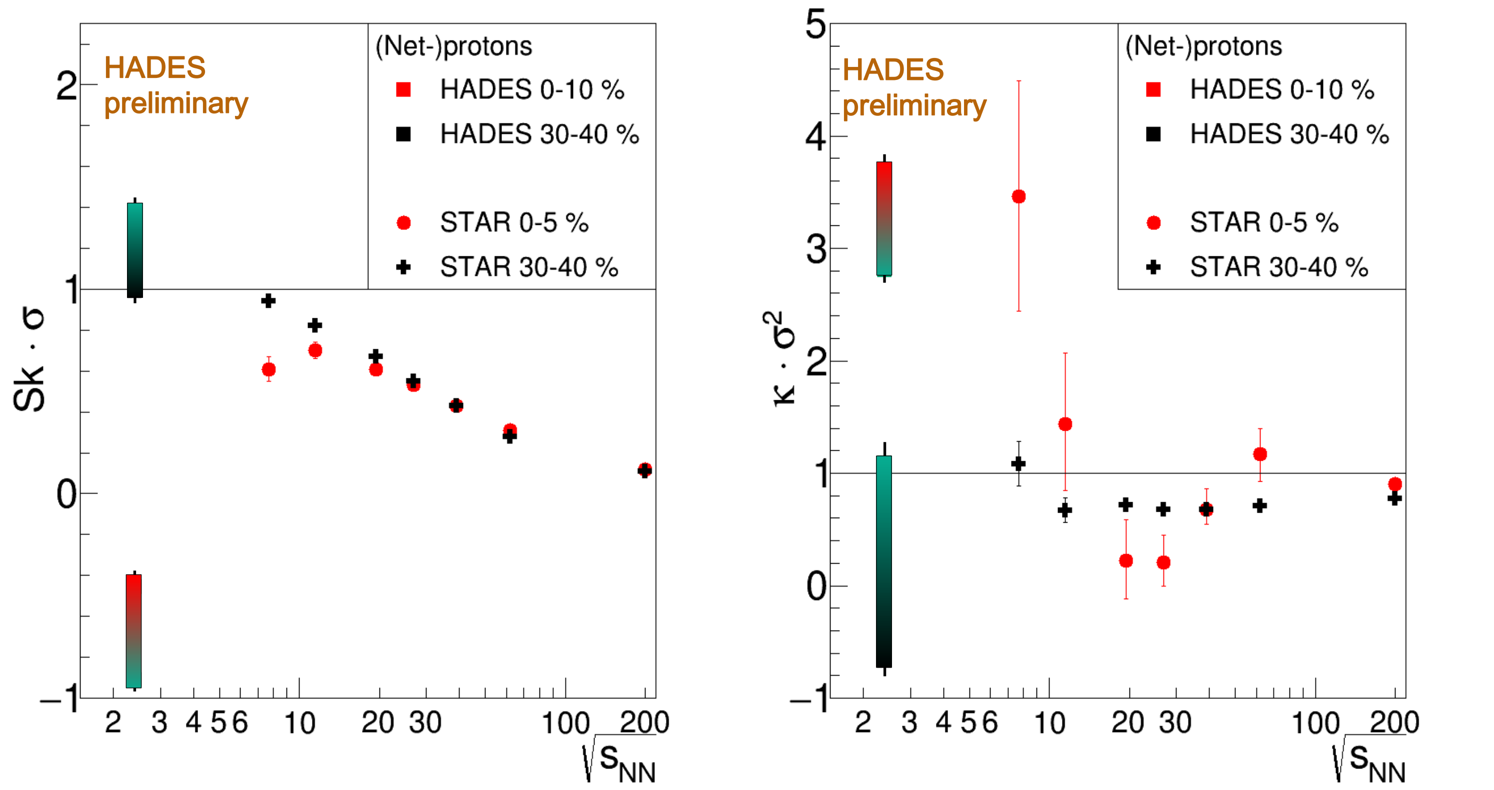
→ Scaled cumulants deviate from Poisson with ↑ N_{part}

→ Volume corrections on κ_4/κ_2 smallest for most central

Comparison with STAR BES-I

STAR analysis: Xiaofeng Luo et al., PoS (CPOD2014) 019

arXiv:1503.02558v2



red/black = unfolding of proton dist. + vol. flucs. corr.

green = evt-by-evt eff correction of factorial moments + vol. flucs. corr.

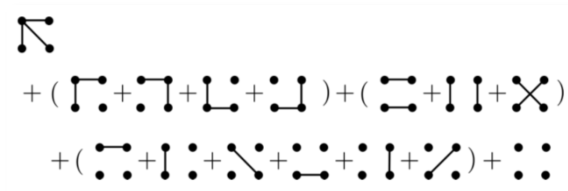
Cumulants & multi-particle correlators

Ling & Stephanov, PRC 93, 034915 (2016)

The cumulants κ_k hold information on multi-particle correlators C_k:

$$\kappa_3 = \langle N \rangle + 3C_2 + C_3$$

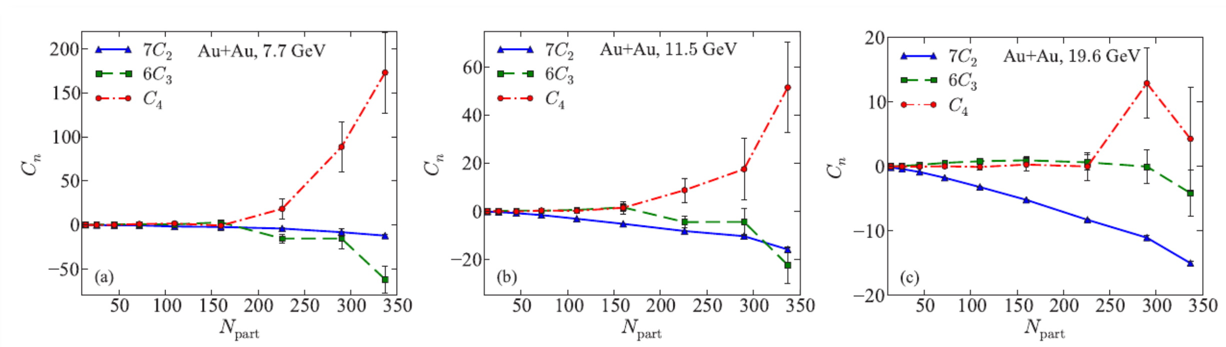
$$\kappa_4 = \langle N \rangle + 7C_2 + 6C_3 + C_4$$



Bzdak, Koch & Strodthoff, PRC 95, 054906 (2017) ← based on STAR data (X. Luo et al., CPOD2014)

Propose C_k vs. N_{part} (& Δy) as a better approach to isolate critical fluctuations:

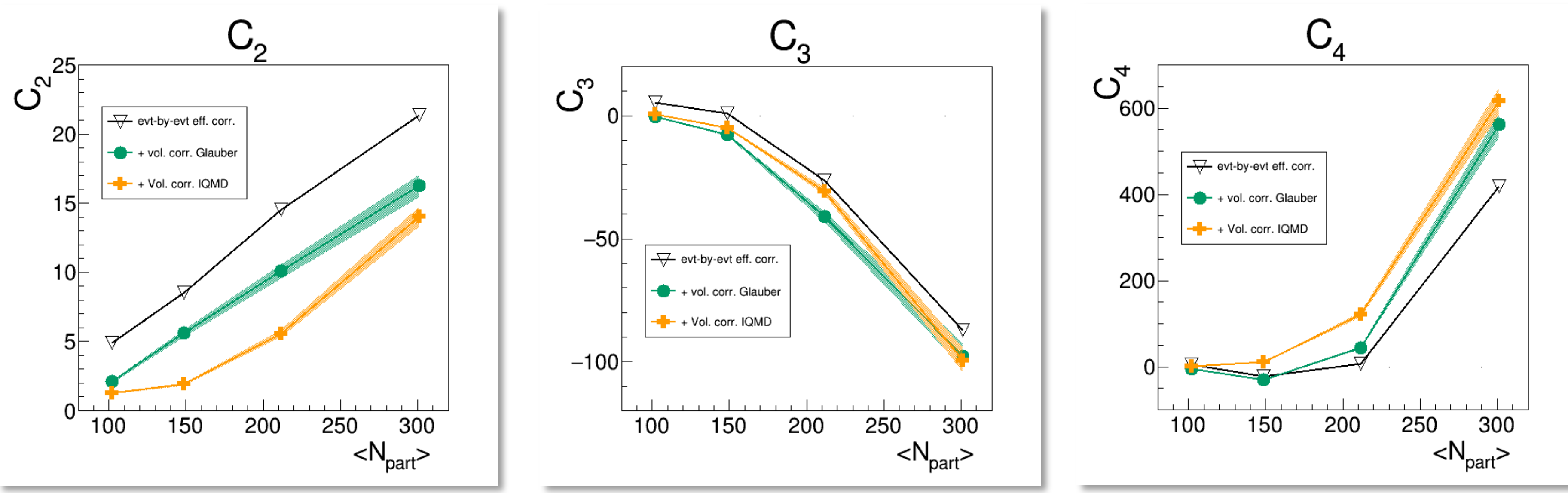
plots based on STAR data →



Proton n-particle correlations: C_n vs N_{part}

HADES → from cumulants κ_n to correlations C_n:

Volume-corrected proton correlations: (model = **Glauber** or **IQMD+clusterizer**)

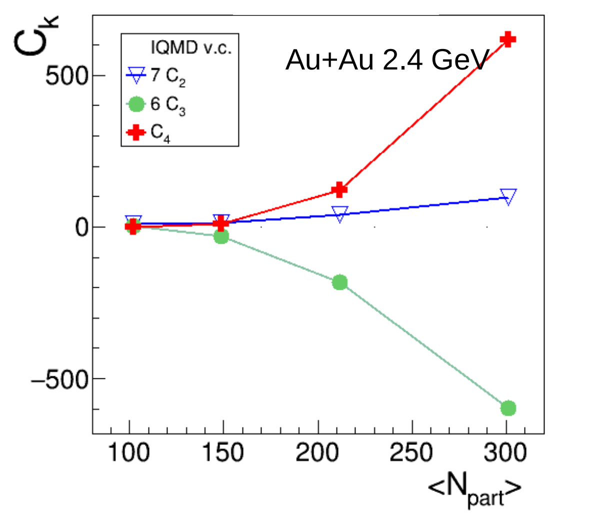


➔ Non-trivial evolution of C_n with proton number $N_p \propto N_{part}$!

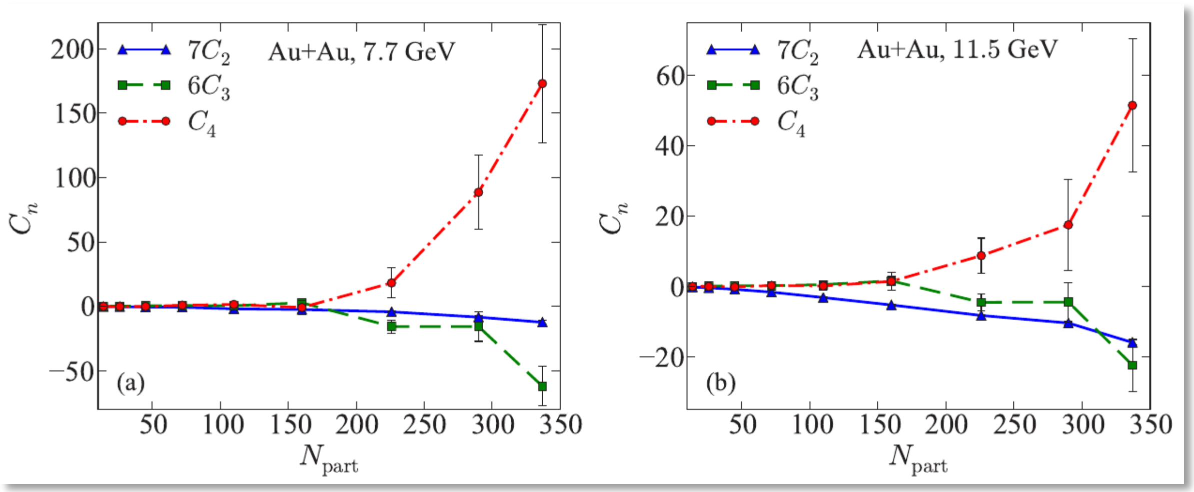
N_{part} dependance of proton correlations

Proton correlation functions vs. centrality in 1.23 GeV/u Au+Au:
Contributions to $\kappa_4 = < N > \ + 7\, C_2 + 6\, C_3 + C_4$

HADES



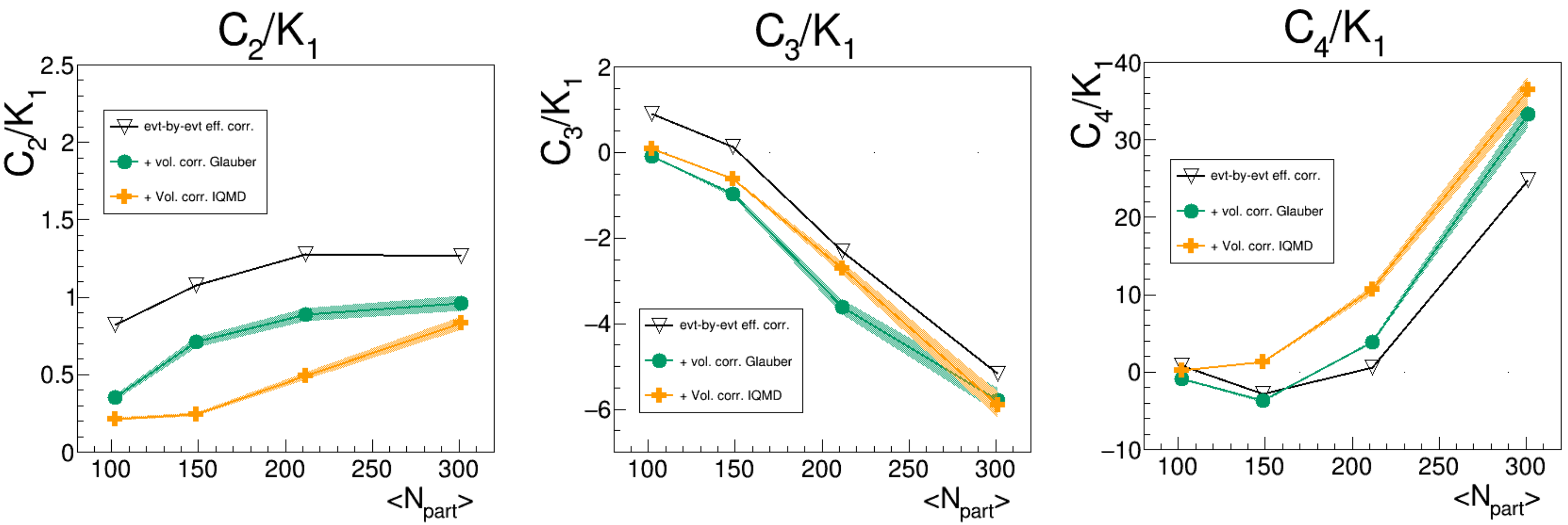
STAR



➔ The increase of C_n with N_{part} is even stronger at low $\sqrt{s}$!

Proton correlations: C_n/N_p vs N_{part}

Scaled proton correlations: (model = **Glauber** or **IQMD+clusterizer**)



All C_n/N_p vary strongly with $N_p \propto N_{part}$! ➔ large correlations

Comparison with STAR: scaled C_n

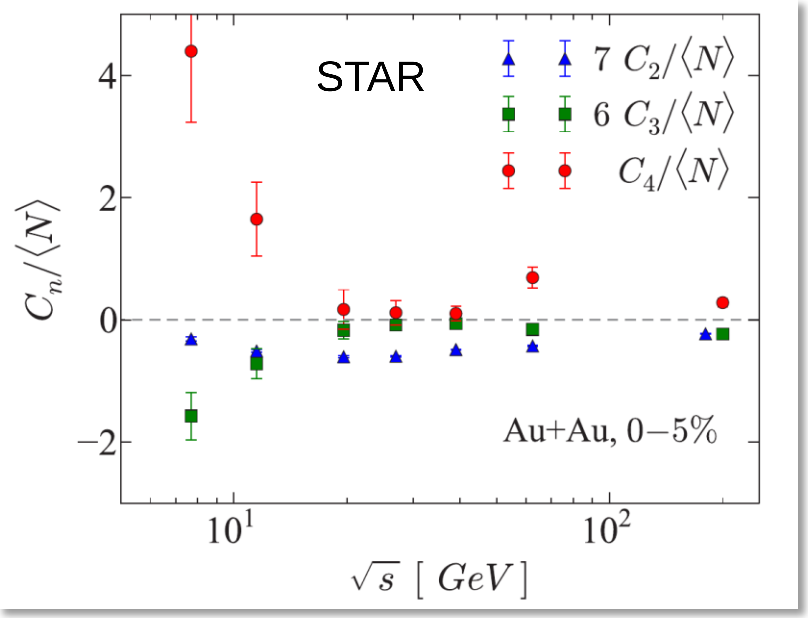
Data: X. Luo et al., PoS CPOD2014, 019 (2015)
Theory: Bzdak, Koch & Strodhhoff, PRC 95, 054906 (2017)

HADES: $\sqrt{s}$ = 2.4 GeV

$C_4/N \simeq 36$

$7\,C_2/N \simeq 6$

$6\,C_3/N \simeq -35$

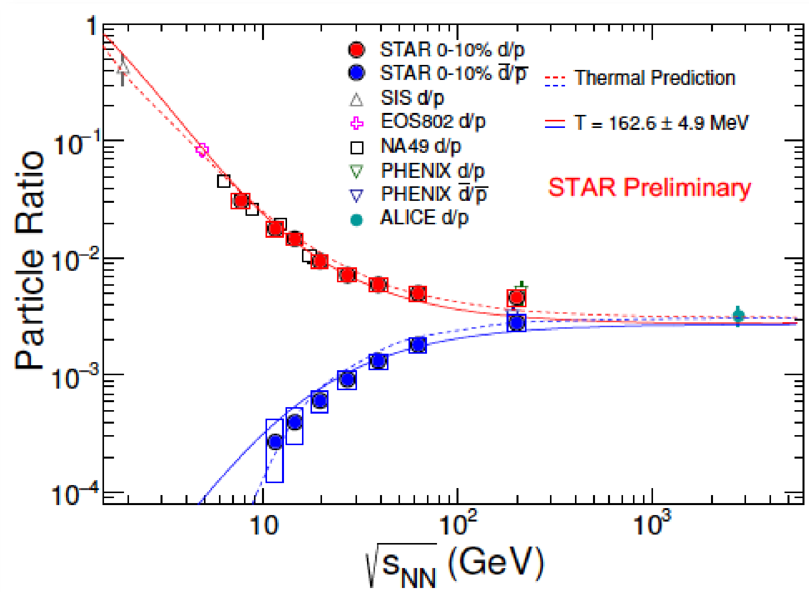


Interpretation of such strong correlations not clear at all.

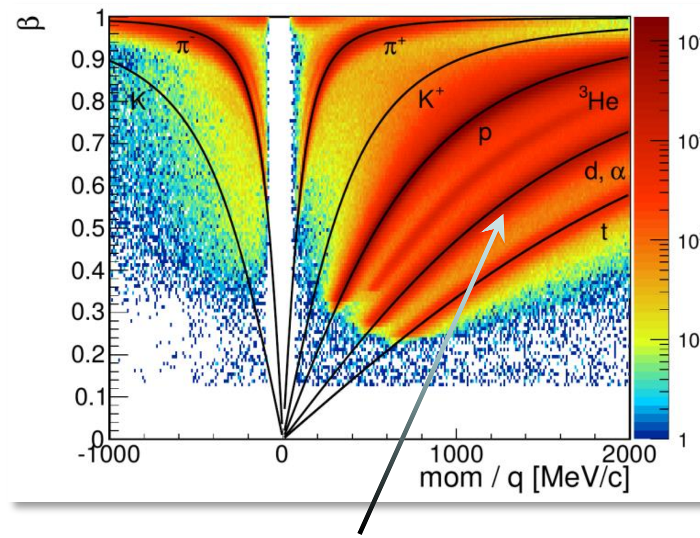
Bzdak, Koch & Skokov e.g. argue in EPJC 77 (2017) 288
that stopping of nucleons may produce mult-particle „clusters“.

What about bound protons ?

Systematics of d/p from STAR collaboration (QM2017)



HADES 1.23 GeV/u Au+Au data



d/p ≈ 0.3 - 0.4 (analysis in progress)

→ Sizeable fraction of protons are bound in fragments: d, t, He, etc.

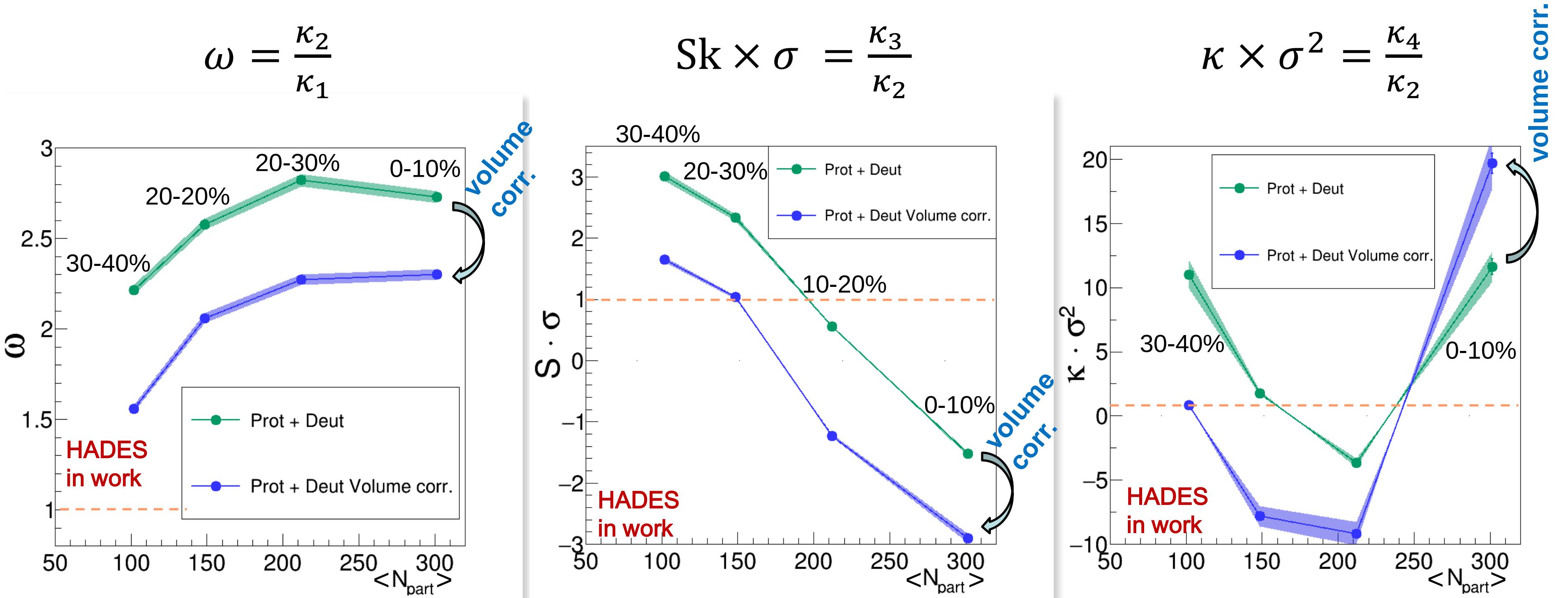
- How do they contribute to baryon-number fluctuations ?
- How should they be taken into account ?

➔ Deuteron nb. fluctuations in Au+Au

Fully corrected scaled moments of $N_p + N_d$

HADES 1.23 GeV/u Au+Au proton+deuteron moments:

$$\omega = \frac{\kappa_2}{\kappa_1} \qquad \mathrm{Sk} \times \sigma = \frac{\kappa_3}{\kappa_2} \qquad \kappa \times \sigma^2 = \frac{\kappa_4}{\kappa_2}$$



- efficiency corr. evt-by-evt (assuming $\epsilon_d = \epsilon_p$)
- volume flucs. corr.
- error bands = ±5% uncertainty on particle eff.

Summary and Outlook

- Analyzed proton nb fluctuations in hi-stat Au+Au evt sample at $\sqrt{s_{NN}} = 2.41\ GeV$

➔ 1st time this kind of analysis has been done at low energies

- Systematic study of experimental & instrumental effects:
  - use of fine grained y-pt bins for eff. corr.
  - evt-by-evt changes of efficiency
  - large volume fluctuations due to centrality selection in HADES forward wall
  - contribution of bound protons (to be investigated further)

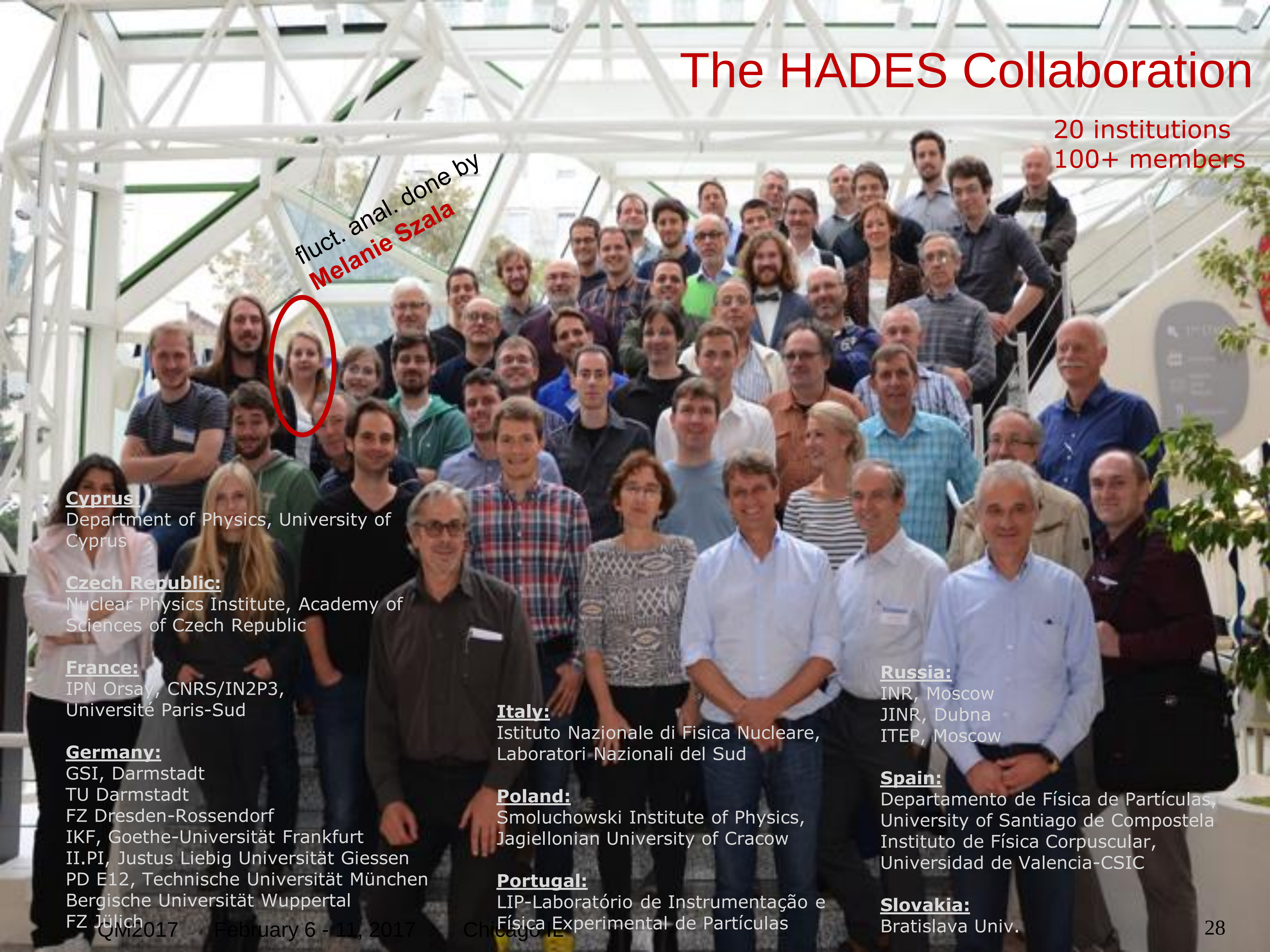
- Very large multi-particle correlation effects observed in HADES Au+Au data

➔ interpretation of these results (also w.r.t. STAR data) needs more input

→→ Program to be continued at FAIR phase 0 (2018+ w. HADES) and beyond (2025+ w. CBM)

The HADES Collaboration

20 institutions
100+ members



Cyprus:
Department of Physics, University of Cyprus

Czech Republic:
Nuclear Physics Institute, Academy of Sciences of Czech Republic

France:
IPN Orsay, CNRS/IN2P3,
Université Paris-Sud

Germany:
GSI, Darmstadt
TU Darmstadt
FZ Dresden-Rossendorf
IKF, Goethe-Universität Frankfurt
II.PI, Justus Liebig Universität Giessen
PD E12, Technische Universität München
Bergische Universität Wuppertal
FZ Jülich

Italy:
Istituto Nazionale di Fisica Nucleare,
Laboratori Nazionali del Sud

Poland:
Smoluchowski Institute of Physics,
Jagiellonian University of Cracow

Portugal:
LIP-Laboratório de Instrumentação e
Física Experimental de Partículas

Russia:
INR, Moscow
JINR, Dubna
ITEP, Moscow

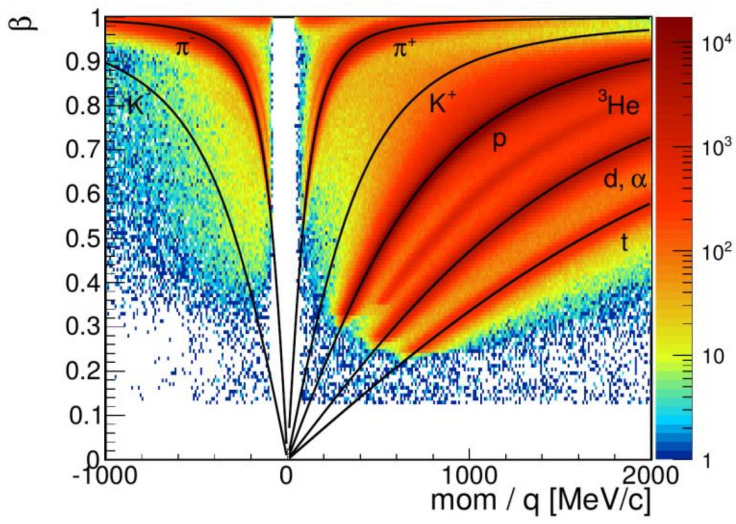
Spain:
Departamento de Física de Partículas,
University of Santiago de Compostela
Instituto de Física Corpuscular,
Universidad de Valencia-CSIC

Slovakia:
Bratislava Univ.

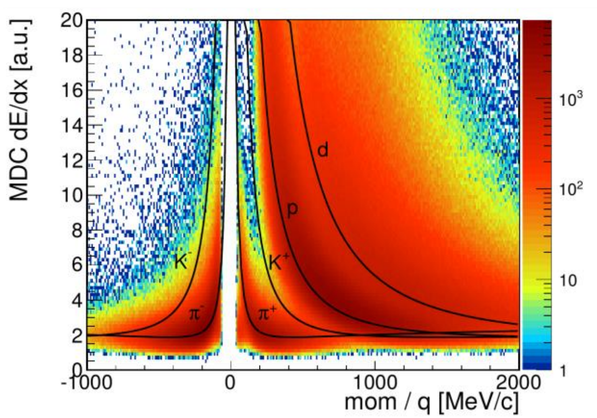
Thrift Shop

Particle ID in HADES

Velocity vs. p



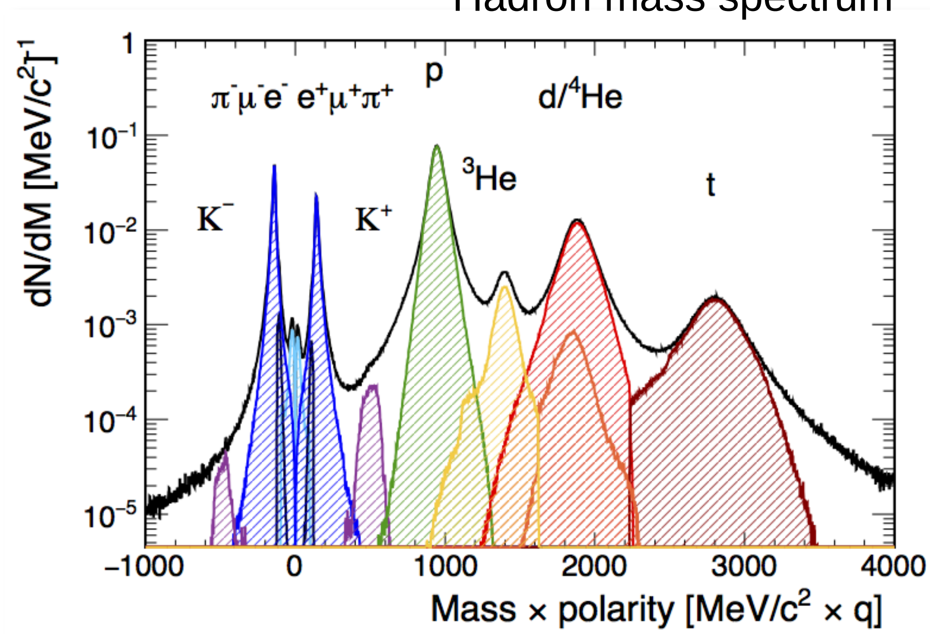
MDC & TOF dE/dx dE/dx vs. p



Hadron ID based on

- ToF
- Momentum
- dE/dx

Hadron mass spectrum

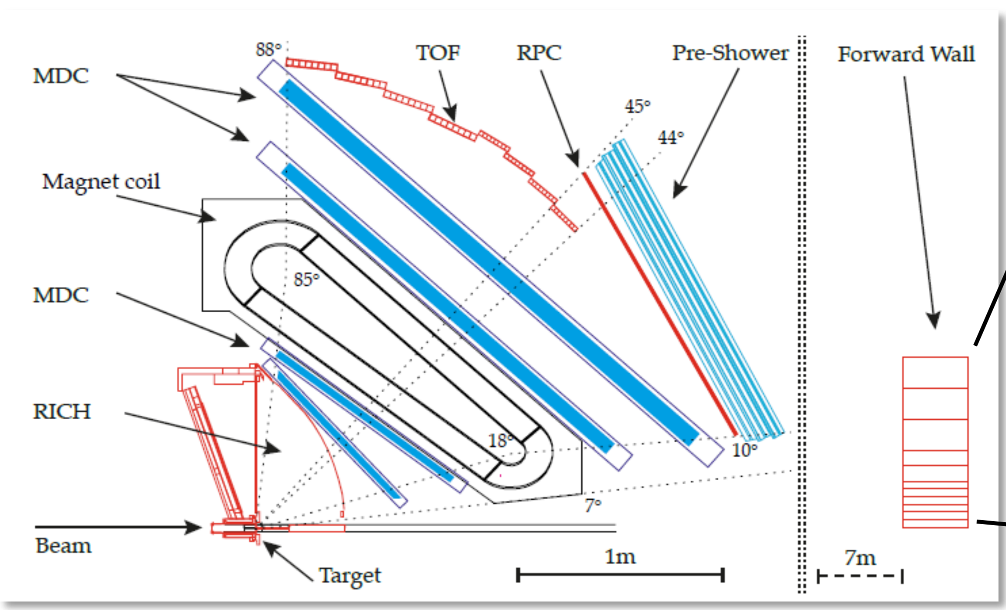


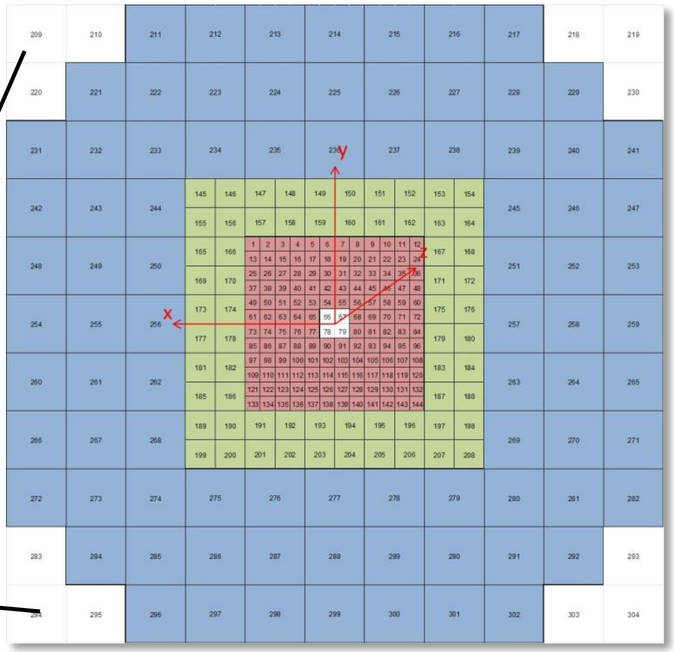
Centrality selection in HADES

In 1.23 GeV/u Au+Au collisions:

- protons & fragments dominate
- centrality selection based on
  - hit mult in TOF & RPC
  - or track mult
  - or **FW mult & charge sum** (avoids auto-corelations!)

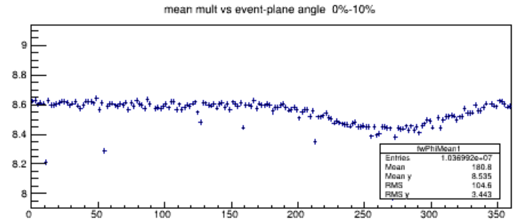
FW made of plastic scintillator tiles covering polar angles $\theta = 0.5^o - 7.5^o$



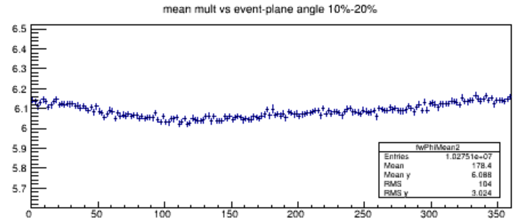


4x4, 8x8, 16x16 cm^2 tiles

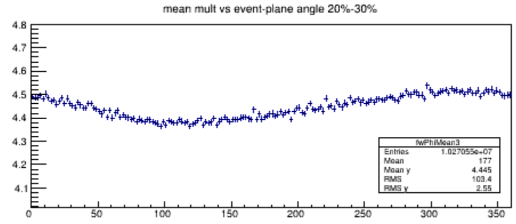
Average proton mult vs event-plane angle



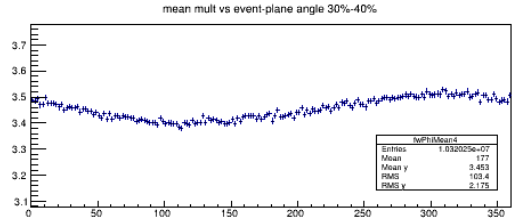
0 - 10%



10 - 20%



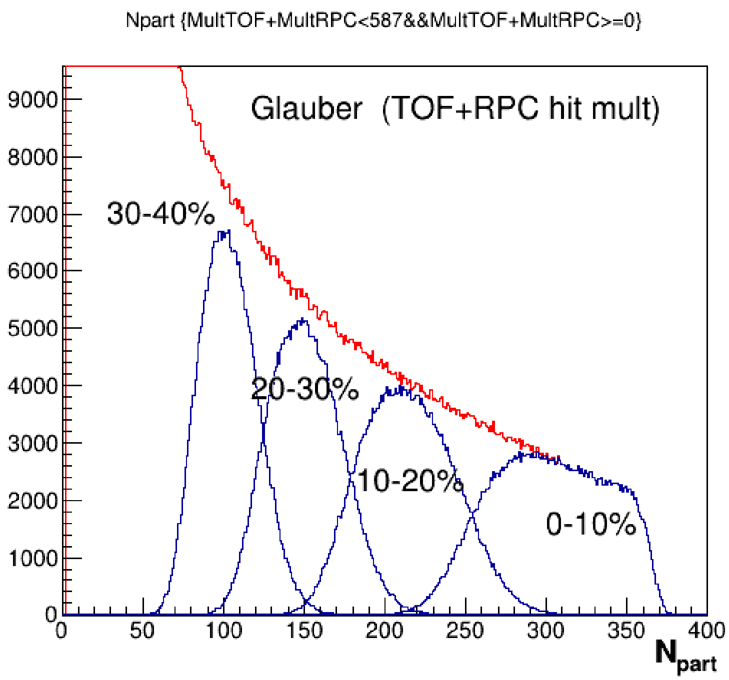
20 - 30%



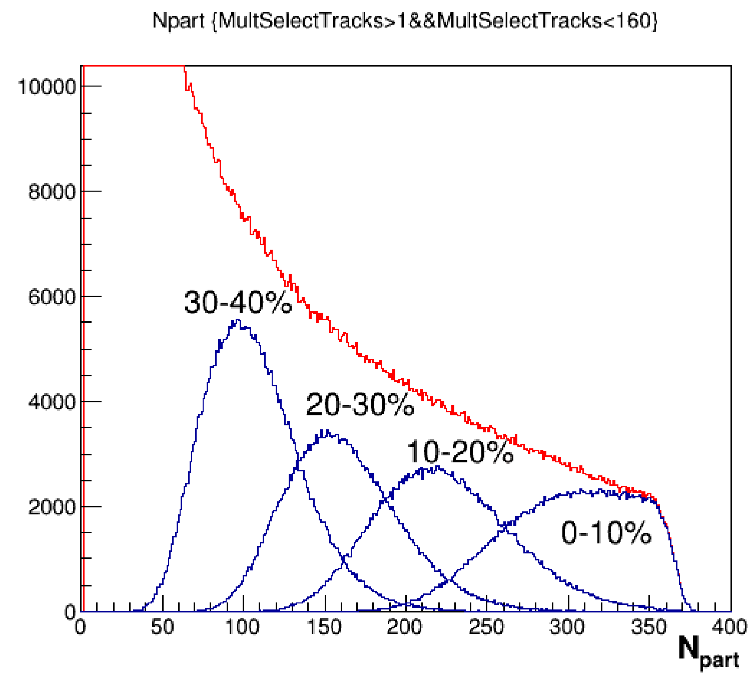
30 - 40%

N_{part} from Glauber fits to hit/track observables

adjusted to hit distribution in TOF & RPC:



adjusted to track distribution in MDC:

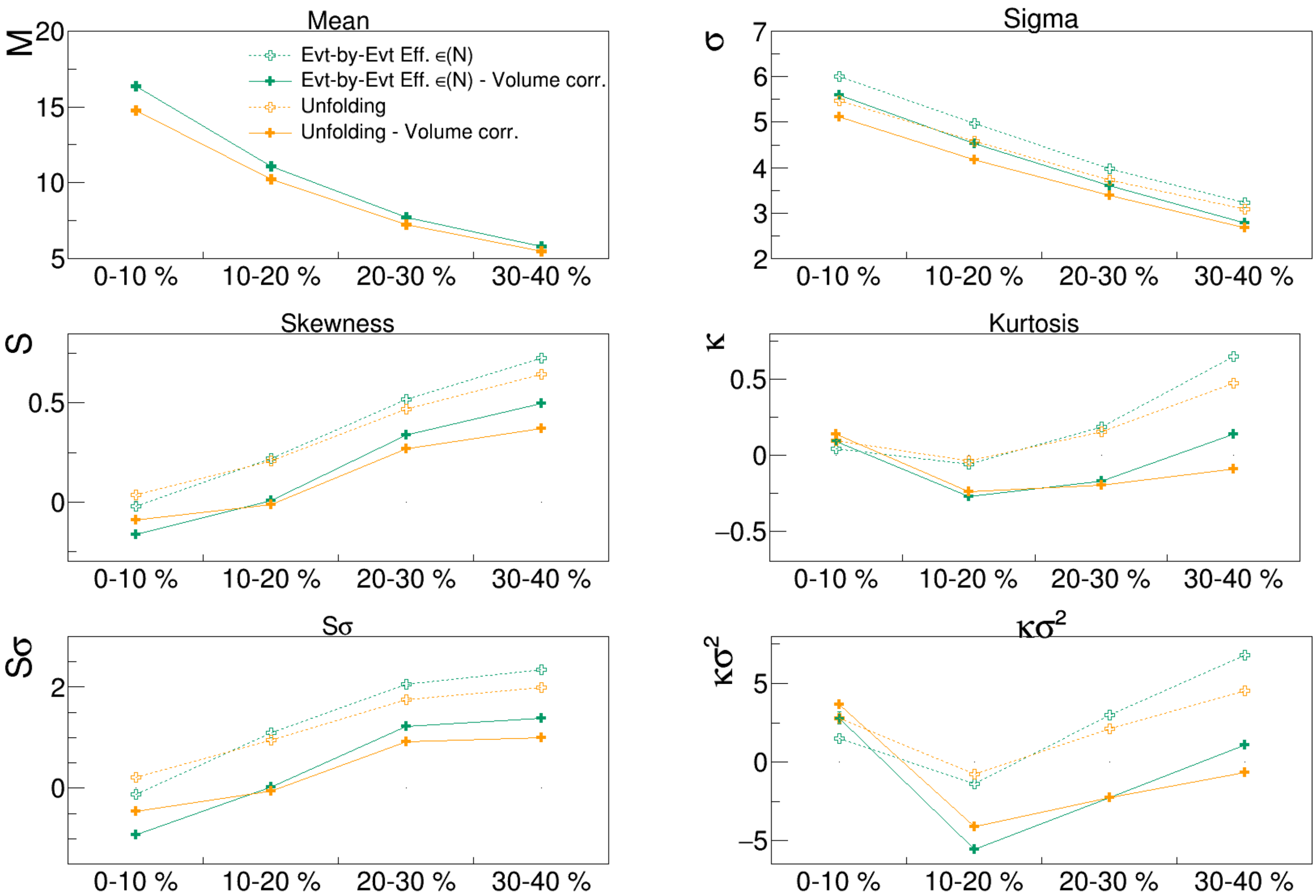


4 centrality bins used within HADES LVL1 trigger

➔ used as estimate for FW selection

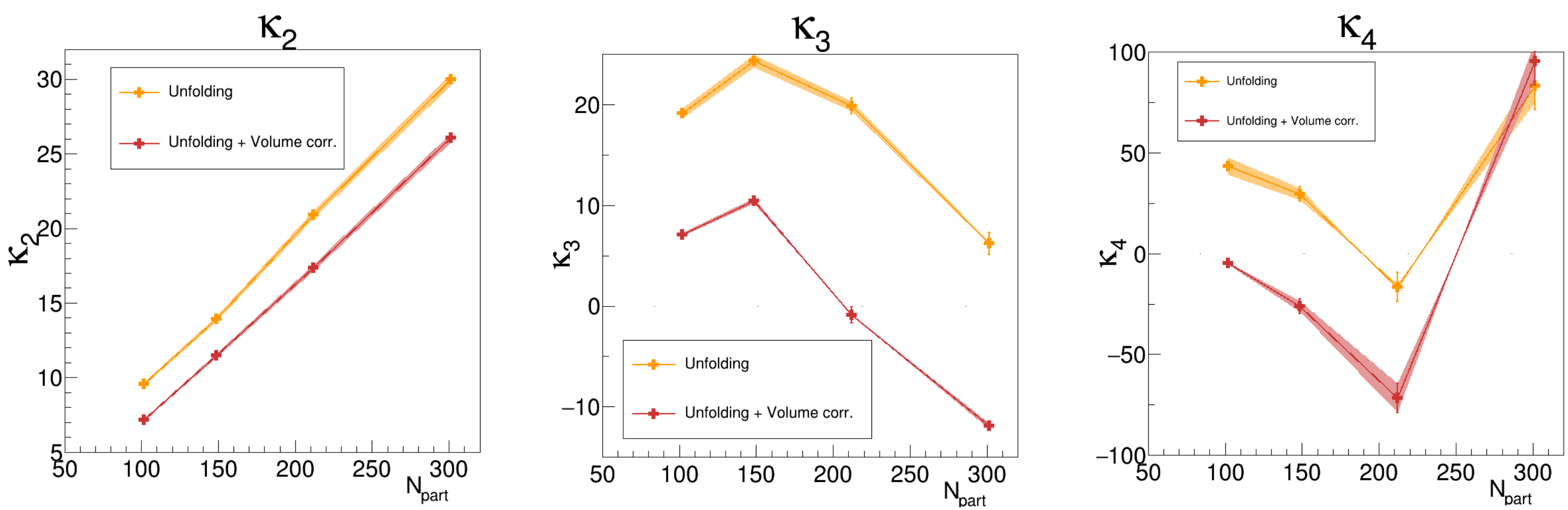
N_{part} fluctuations, also called volume fluctuations, must be corrected for in the data!

Volume corrections (evt-by-evt vs. unfolding)



Proton cumulants κ_n vs N_{part} in 1.23 GeV/u Au+Au

Proton cumulants from unfolding + volume corrections



Centrality dependance of proton correlations

Proton correlation functions vs. centrality in 1.23 GeV/u Au+Au:
contributions to $\kappa_4 = < N > + 7\,C_2 + 6\,C_3 + C_4$