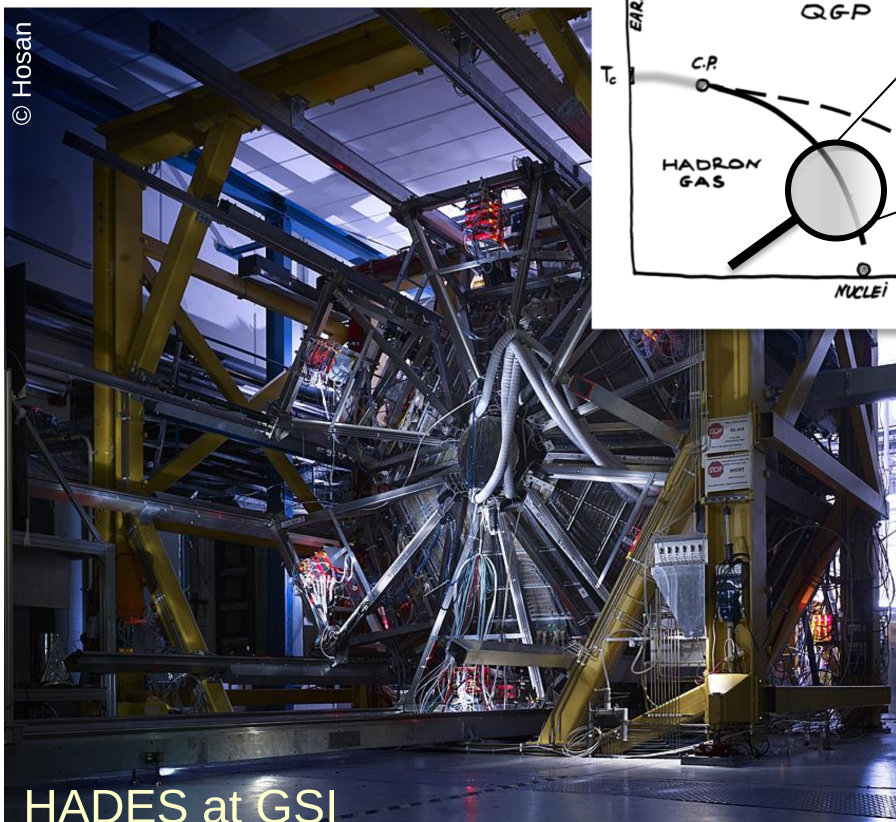
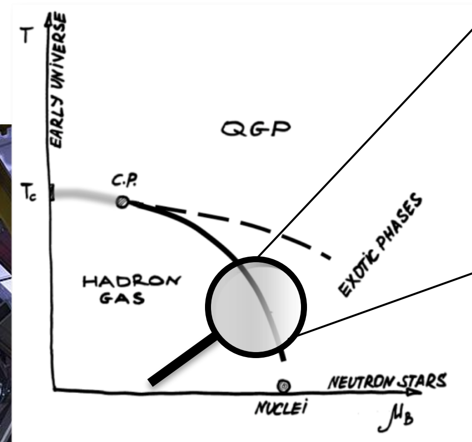
Proton-Number Fluctuations in HADES: Reconstruction of higher moments

Romain Holzmann,
GSI Helmholtzzentrum Darmstadt,
for the HADES collaboration





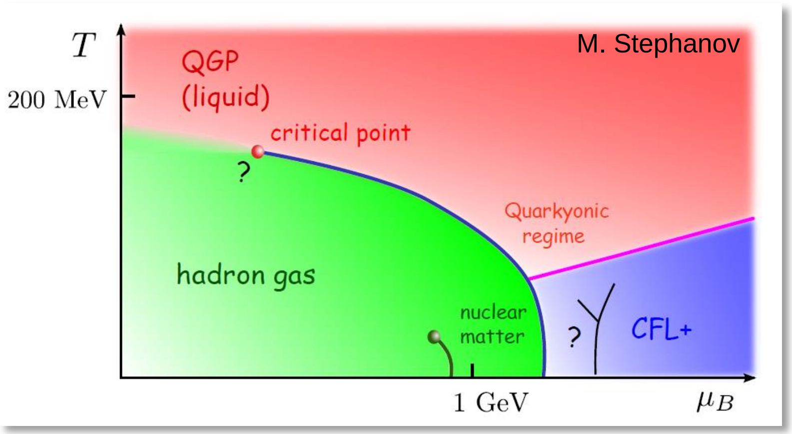
SIS 18 energy regime:

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

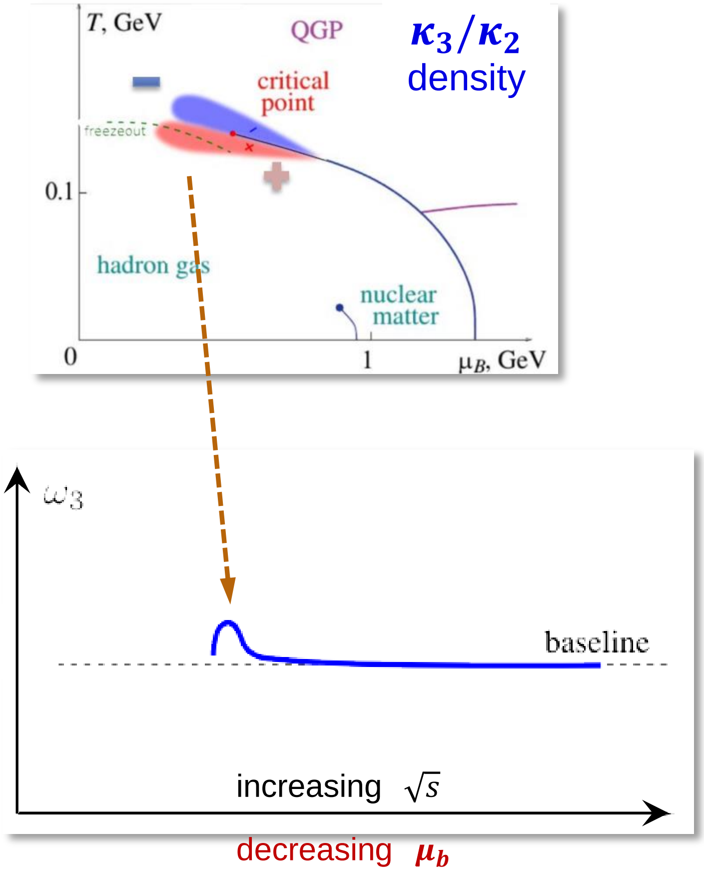
<u>Outline:</u>

- HADES: Au+Au at 1.23 GeV/u
- Net proton nb. fluctuations
  - **efficiency corrections**
  - **volume fluct. effects**
  - **fragments, ie bound protons**
- Summary & Outlook:

Fluctuations probe features of QCD phase diagram



M. Stephanov CPOD2014



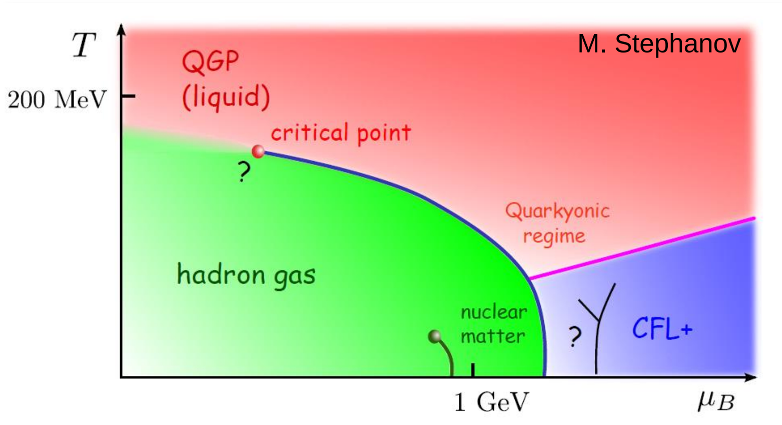
Crossing features of the QCD phase-diagram (phase boundaries, CEP) is expected to result in:

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

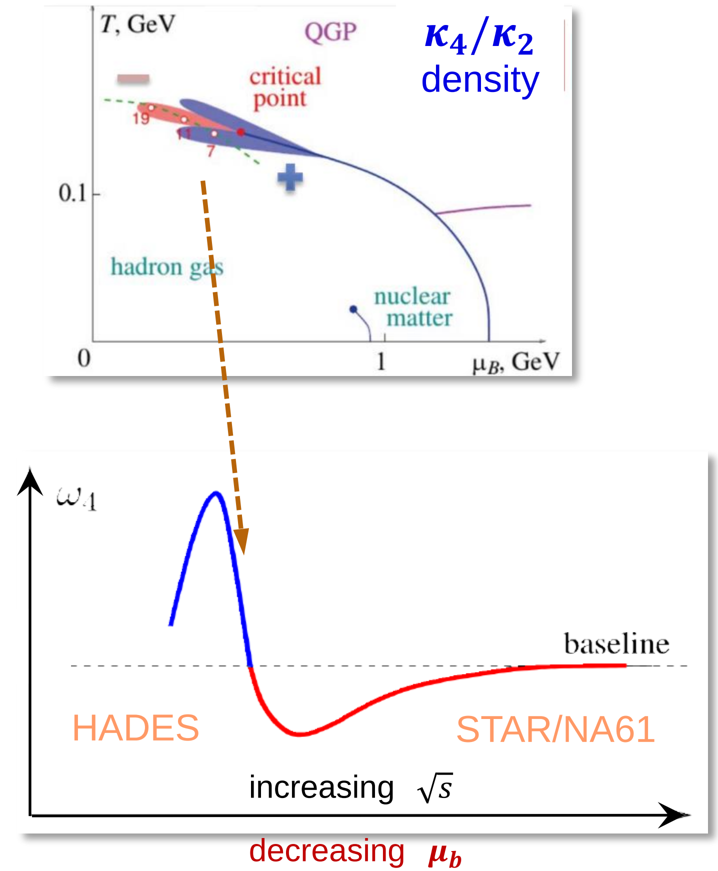
- ➔ observable discontinuities of the higher moments of particle number distributions, visible e.g. in a beam energy scan!

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

Fluctuations probe features of QCD phase diagram



M. Stephanov CPOD2014



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

- ➔ diverging susceptibilities & correlation length
- ➔ „extra“ fluctuations of conserved quantities (e.g. baryon nb, charge, strangeness)
- ➔ observable discontinuities of the higher moments of particle number distributions, visible e.g. in a beam energy scan!

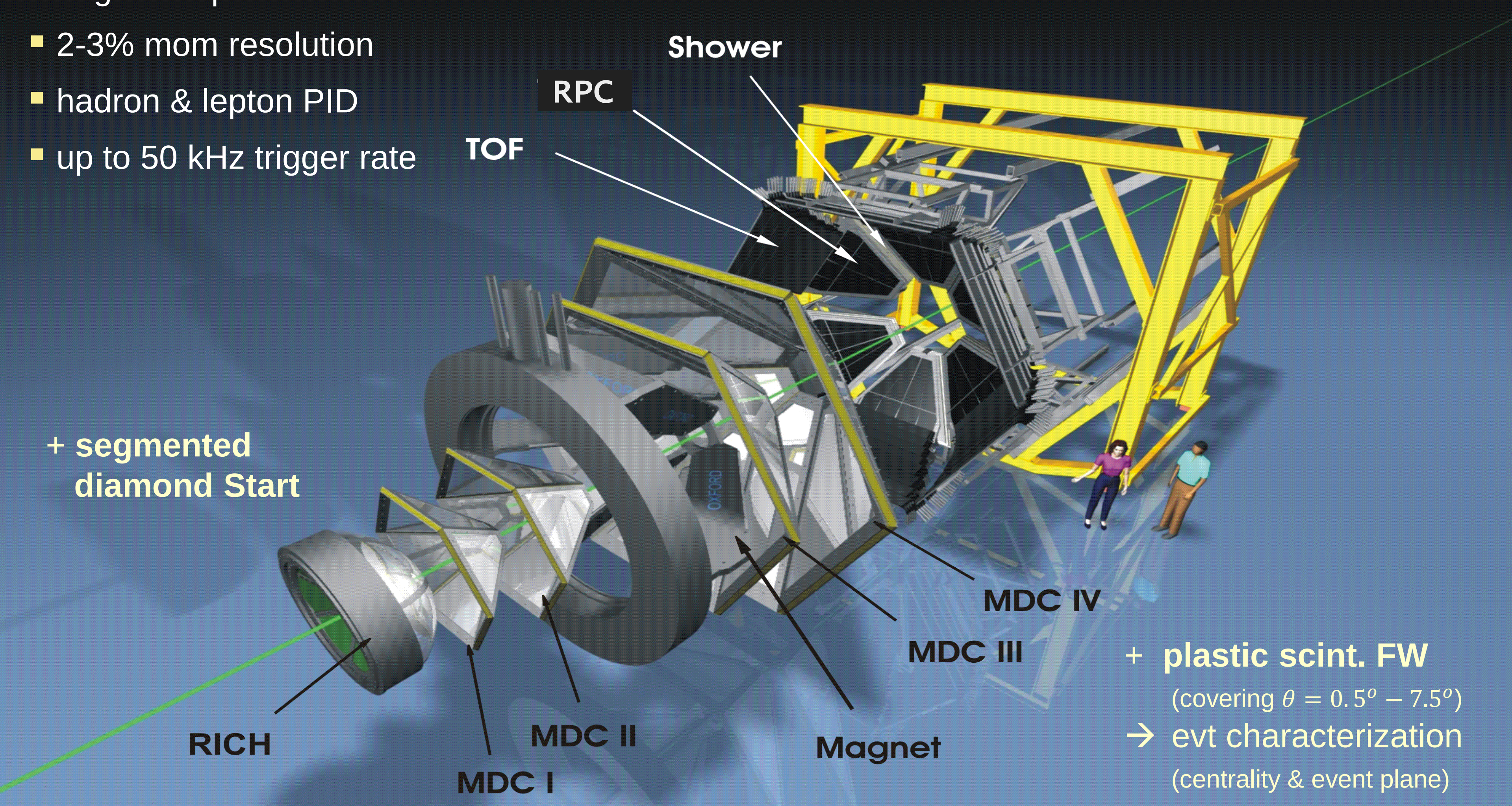
(see e.g. B. Friman et al, EPJC 71 (2011) 1694)

→ Needs high-statistics data!

The HADES detector at GSI

High Acceptance DiElectron Spectrometer

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

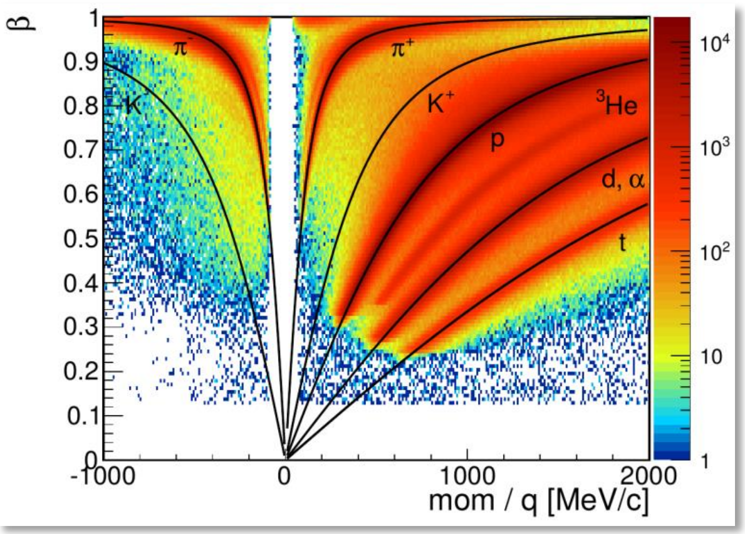


\+ segmented diamond Start

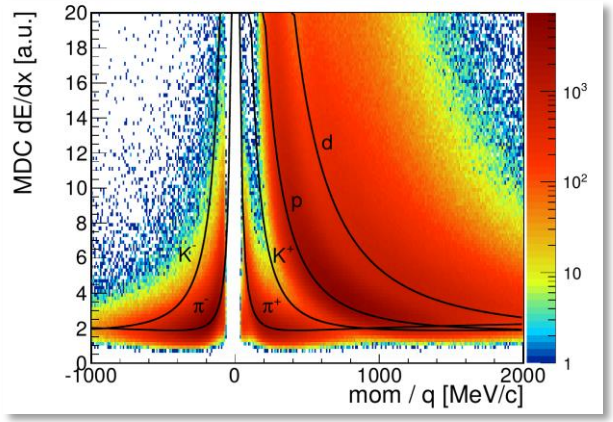
\+ plastic scint. FW
(covering $\theta = 0.5^o - 7.5^o$)
→ evt characterization
(centrality & event plane)

Particle ID in HADES

Velocity vs. p



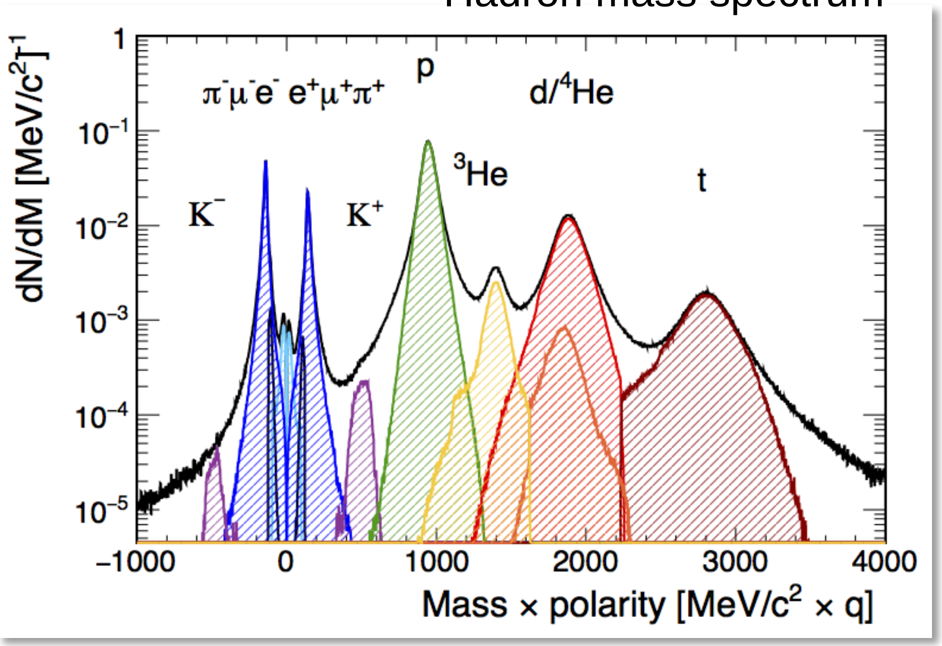
MDC & TOF dE/dx dE/dx vs. p



Hadron ID based on

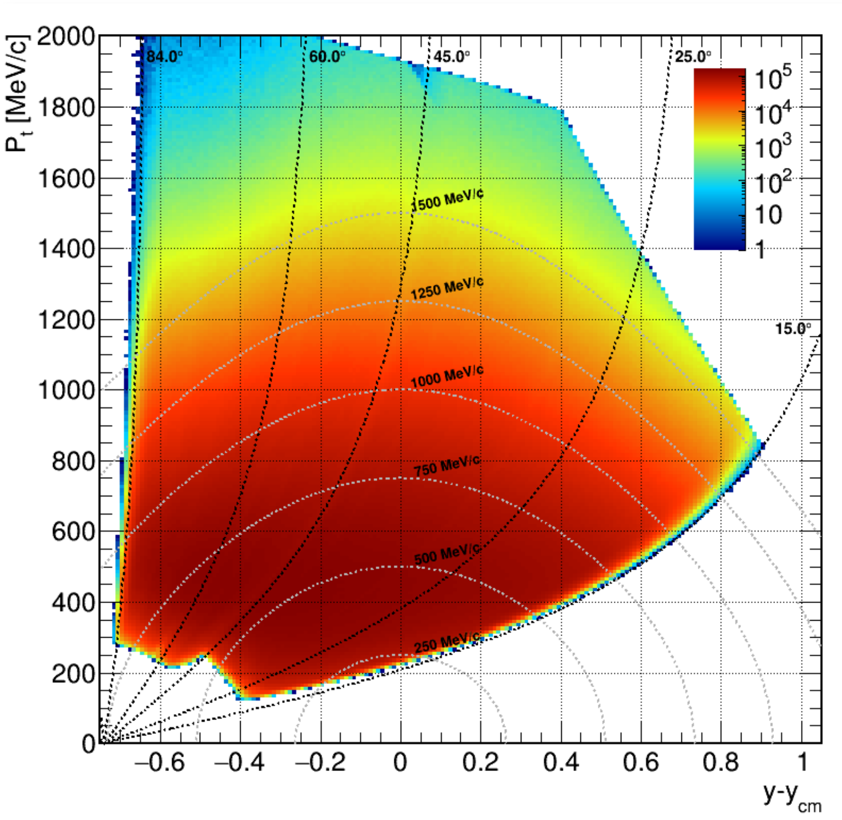
- ToF
- Momentum
- dE/dx

Hadron mass spectrum



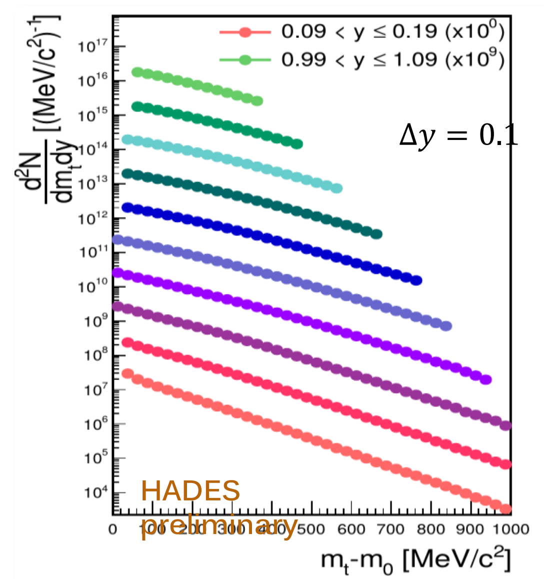
Proton distributions in Au+Au at $\sqrt{s} = 2.41\ GeV$

HADES $y - p_t$ coverage for protons

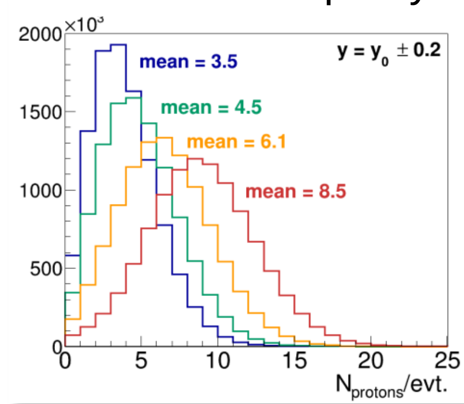


$y_{cm} = 0.74$

Proton mt spectra



Proton multiplicity distributions



Analysis based on $40 \cdot 10^6$ Au+Au evts divided into 4 centrality classes

(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)

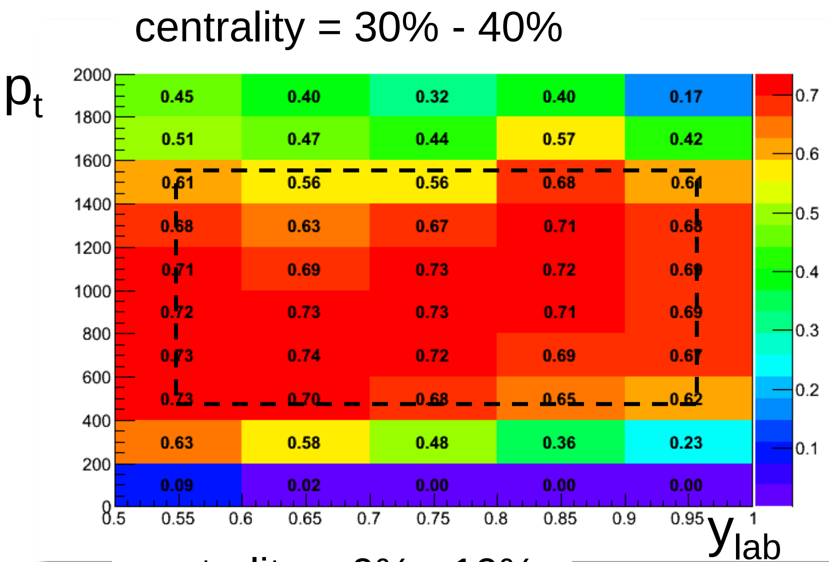
2. Correct measured distributions (bayesian unfolding)

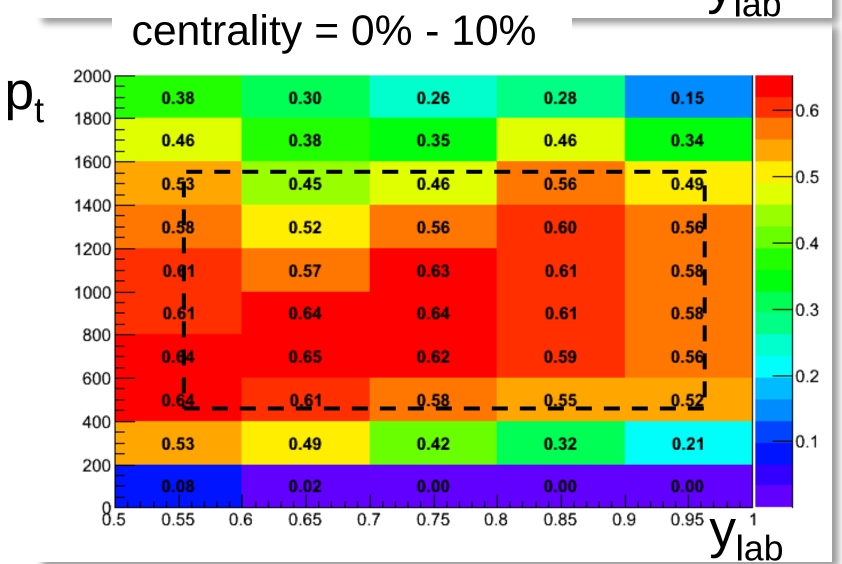
   Garg et al., J. Phys. G: Nucl. Part. Phys. 40 (2013)

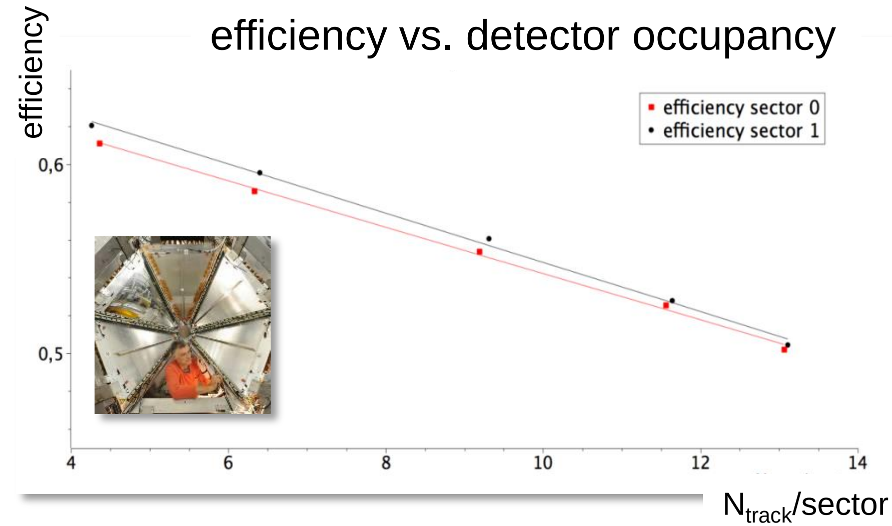
➔ we have investigated both methods

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 $\epsilon = \epsilon(N_{track}, sector)$ to correct evt-by-evt!

We verified this correction scheme in full detector simulations using **54** 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)

$$F_{i,k} = \sum_{x_1,\ldots,x_i}\sum_{\bar x_1,\ldots,\bar x_k} A_{i,k}(x_1,\ldots,x_i;\bar x_1,\ldots,\bar x_k)$$

$$f_{i,k} = \sum_{x_1,\ldots,x_i}\sum_{\bar x_1,\ldots,\bar x_k} a_{i,k}(x_1,\ldots,x_i;\bar x_1,\ldots,\bar x_k)$$

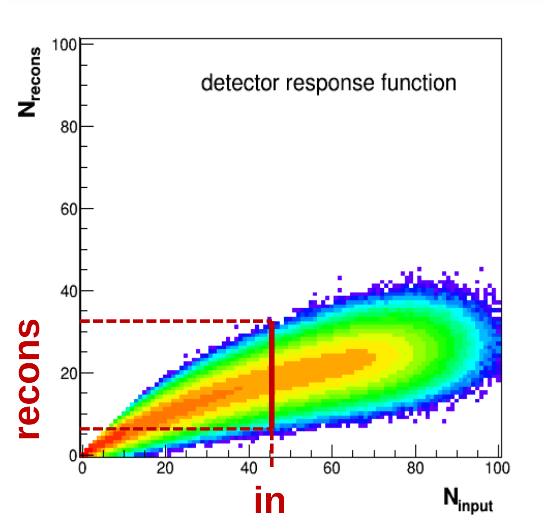
$$F_{i,k} = \sum_{x_1,\ldots,x_i}\sum_{\bar x_1,\ldots,\bar x_k} \frac{a_{i,k}(x_1,\ldots,x_i;\bar x_1,\ldots,\bar x_k)}{\epsilon(x_1)\ldots\epsilon(x_i)\bar\epsilon(\bar x_1)\ldots\bar\epsilon(\bar x_k)}$$

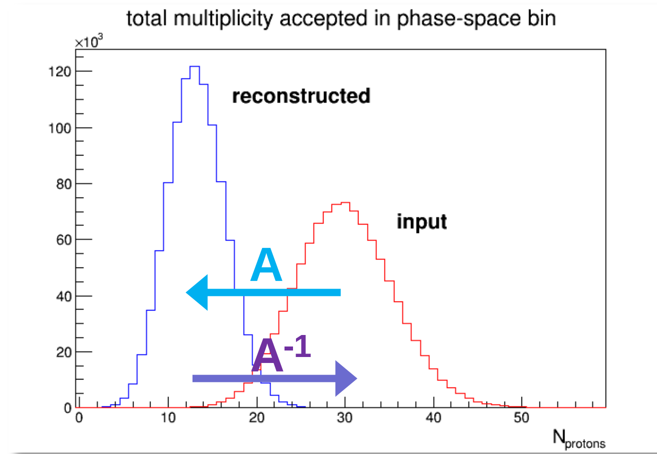
➔ correct evt-by-evt with dynamic ε=ε(N)

Method 2: Unfold the multiplicity distribution

Response matrix
of the system:
(obtained from simul)

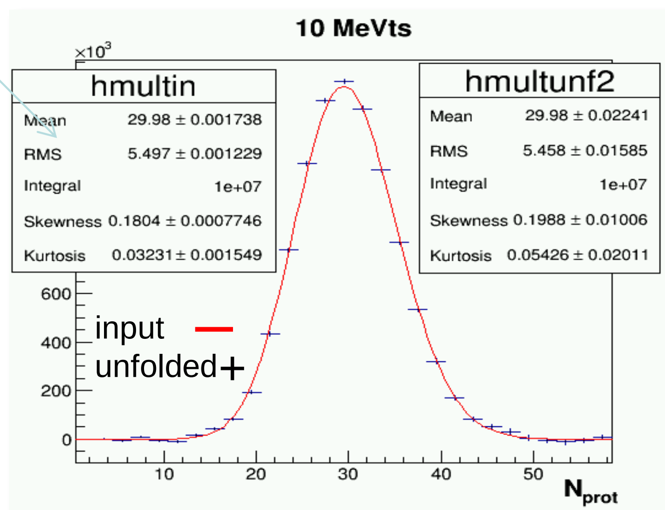
$N_{recons} = A \cdot N_{input}$





Tested on simulated proton spectra
accepted in HADES.

All moments reproduced within
statistical error bars!



Unfolding in a nutshell: regularize A

Literature: G. D'Agostino, Nucl. Instr. Meth. A 362 (1995) 487.
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)***:

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

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

minimization

$$\mathcal{L}_2 = \tau^2 (\boldsymbol{x} - f_b \boldsymbol{x}_{\mathbf{0}})^{\mathsf{T}} (\mathbf{L}^{\mathsf{T}} \mathbf{L}) (\boldsymbol{x} - f_b \boldsymbol{x}_{\mathbf{0}}),$$

Tikhonov regularization

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

area constraint

ROOT implementation:

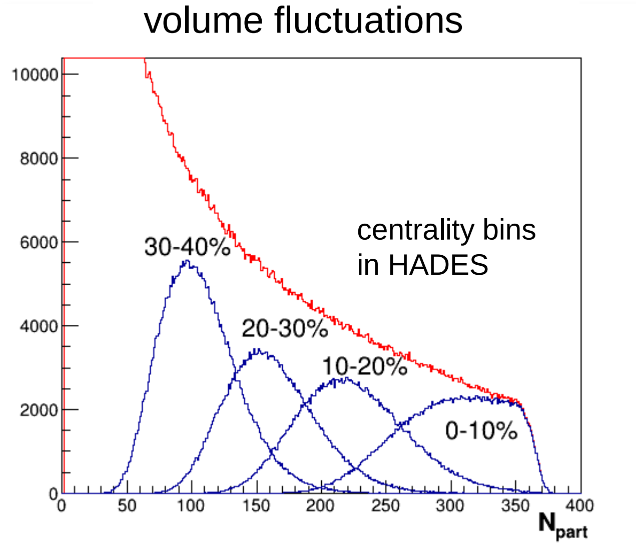
TUnfold, TUnfoldSys, TUnfoldDensity

(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):

$$
\begin{aligned}
c_1 &= \kappa_1, \\
c_2 &= \kappa_2 + \kappa_1^2 v_2, \\
c_3 &= \kappa_3 + 3\kappa_2\kappa_1 v_2 + \kappa_1^3 v_3, \\
c_4 &= \kappa_4 + \left(4\kappa_3\kappa_1 + 3\kappa_2^2\right) v_2 + 6\kappa_2\kappa_1^2 v_3 + \kappa_1^4 v_4,
\end{aligned}
$$

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



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

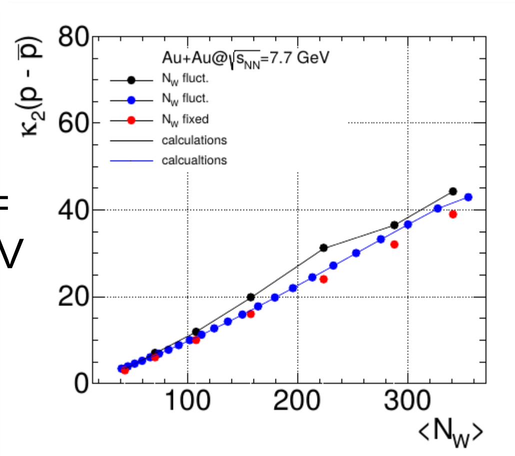
➔ Effect of centrality selection investigated with UrQMD simul by G. Westfall in PRC 92 (2015)	➔ Discussed in more detail by PBM, Rustamov & Stachel NPA 960 (2017) 114

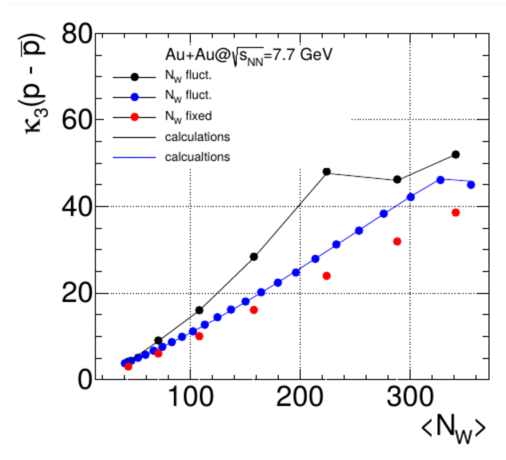
Volume fluctuation effects on cumulants

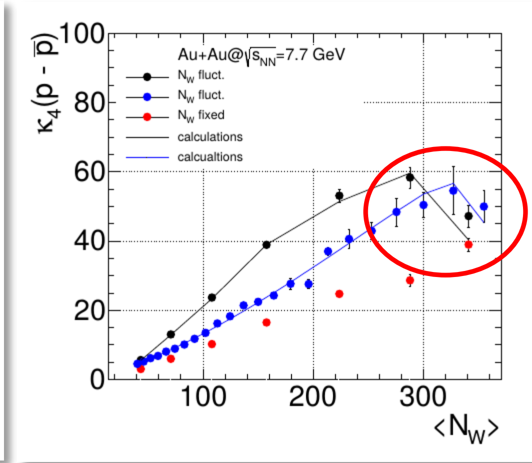
Glauber simulation of $N_{wounded}$ + Negative Binomial model of particle production

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

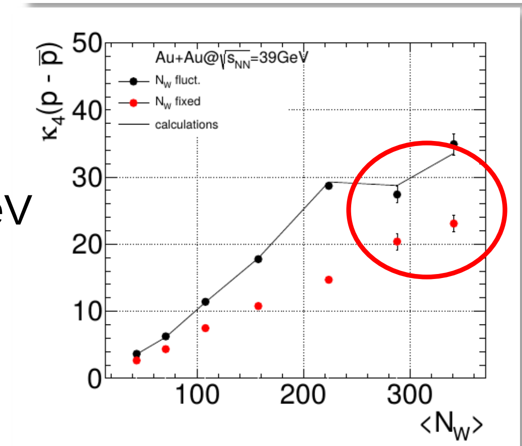
$\sqrt{s_{NN}}$ = 7.7 GeV



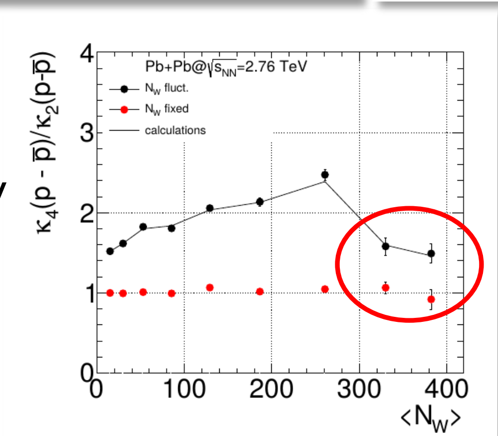




39 GeV



2.76 TeV



Skokov formulas:

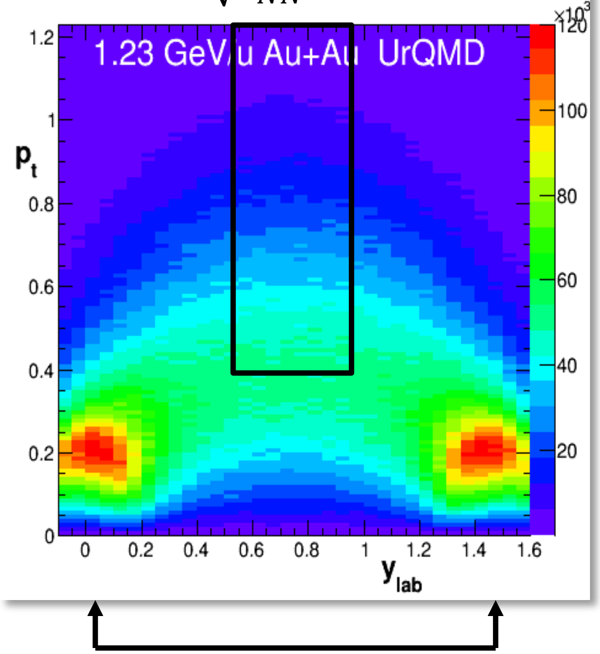
$$\kappa_1 = c_1$$
$$\kappa_2 = c_2 - \kappa_1^2 \, v_2$$
$$\kappa_3 = c_3 - 3\,\kappa_2\kappa_1 v_2 - \kappa_1^3 v_3$$
$$\kappa_4 = c_4 - (4\kappa_3\kappa_1 + 3\kappa_2^2)v_2 - 6\kappa_2\kappa_1^2 v_3 - \kappa_1^4 \, v_4$$

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

→ partial cancellation of volume terms at large N_w?

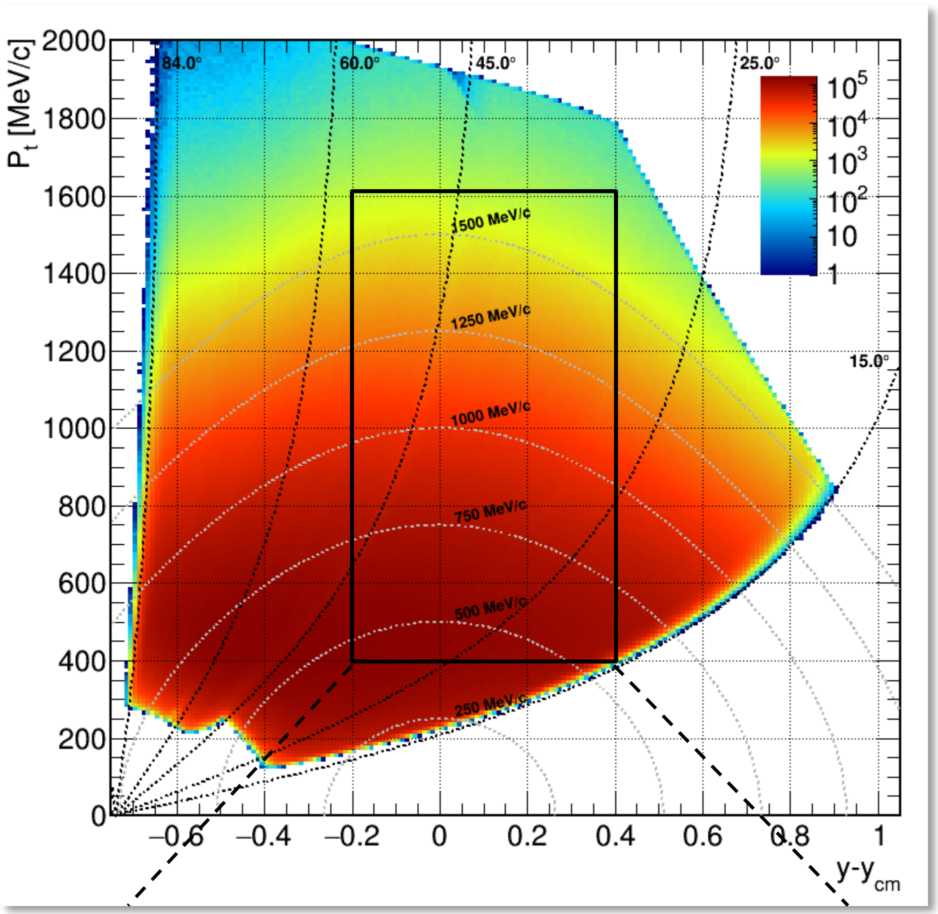
Choice of phase-space bite for fluctuation analysis

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



rapidity gap = 1.5 units!

HADES $y - p_t$ coverage for protons



➔ Need to select a phase-space bite which avoids spectators and stays within the HADES acceptance, but far enough from Poisson limit!

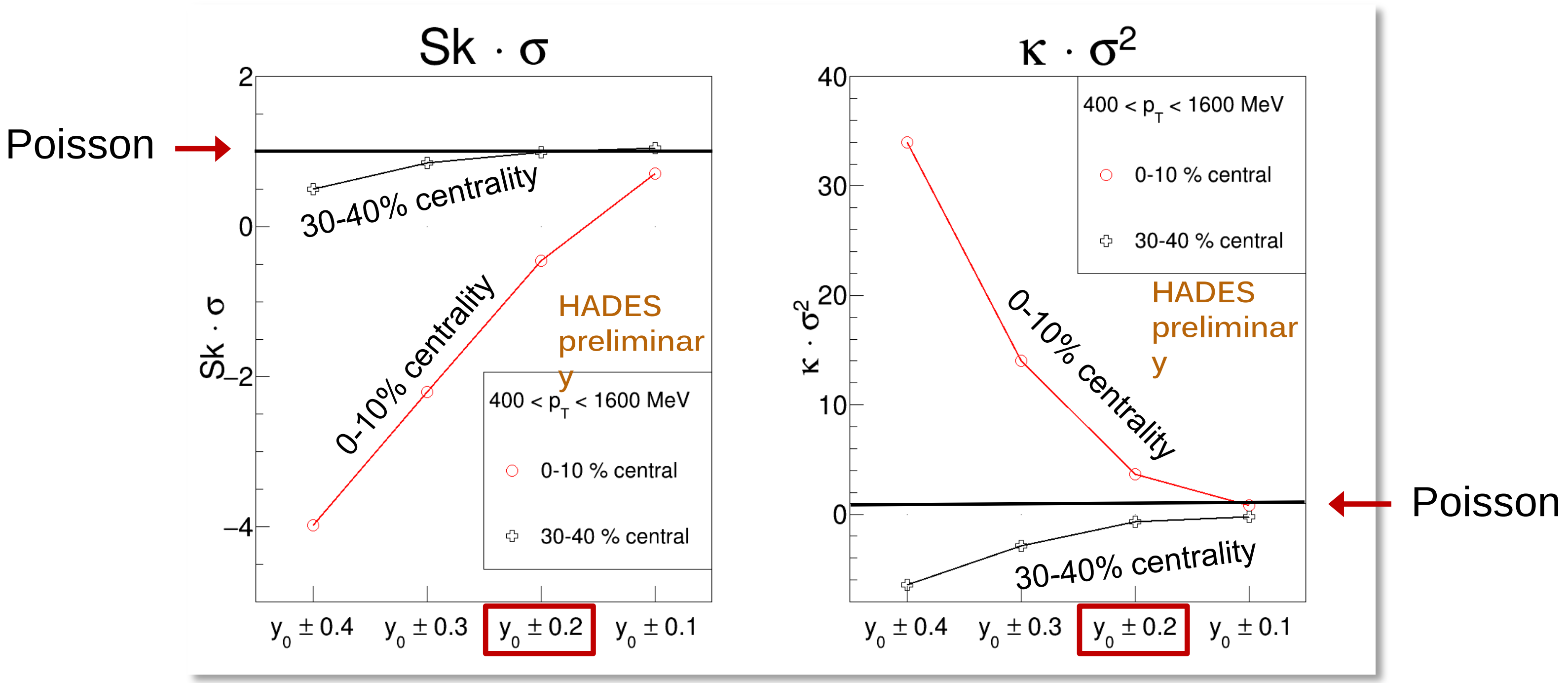
phase-space bite used in fluctuation analysis:

$y = y_0 \pm 0.2$ 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 unfolding & volume correction:



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

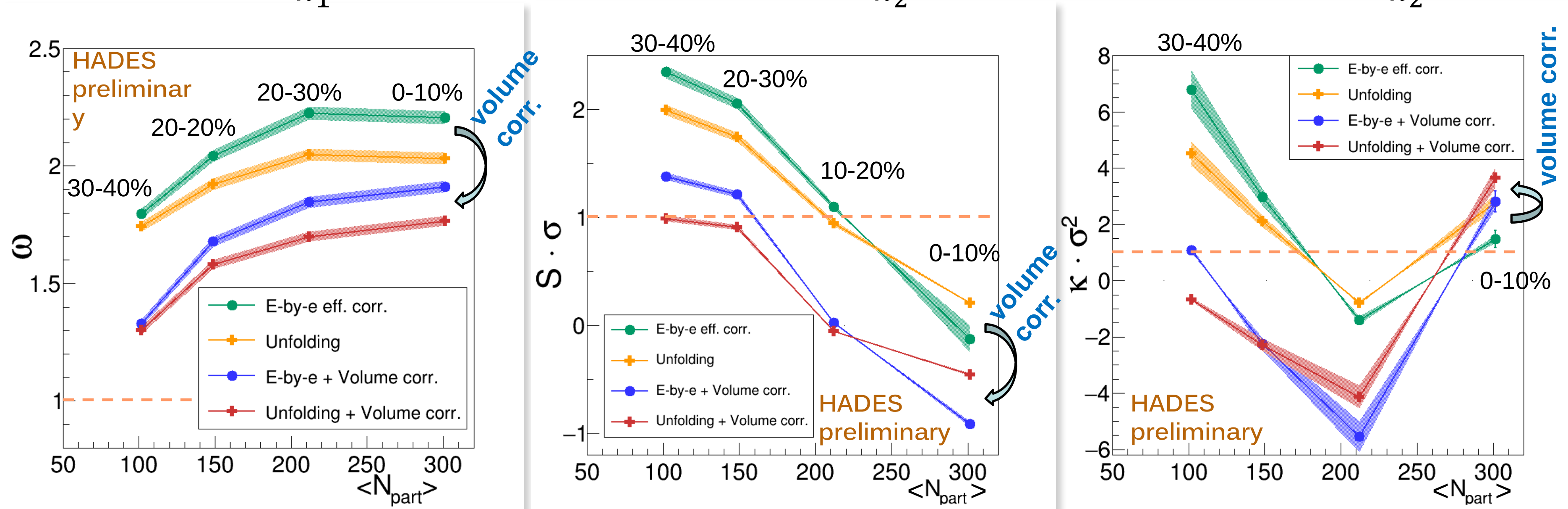
$S \cdot \sigma \rightarrow 1$ **and** $\kappa \cdot \sigma^2 \rightarrow 1$ **for** $\Delta y \rightarrow 0$

➔ ok!

Fully corrected scaled moments vs. centrality

HADES 1.23 GeV/u Au+Au proton moments:

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



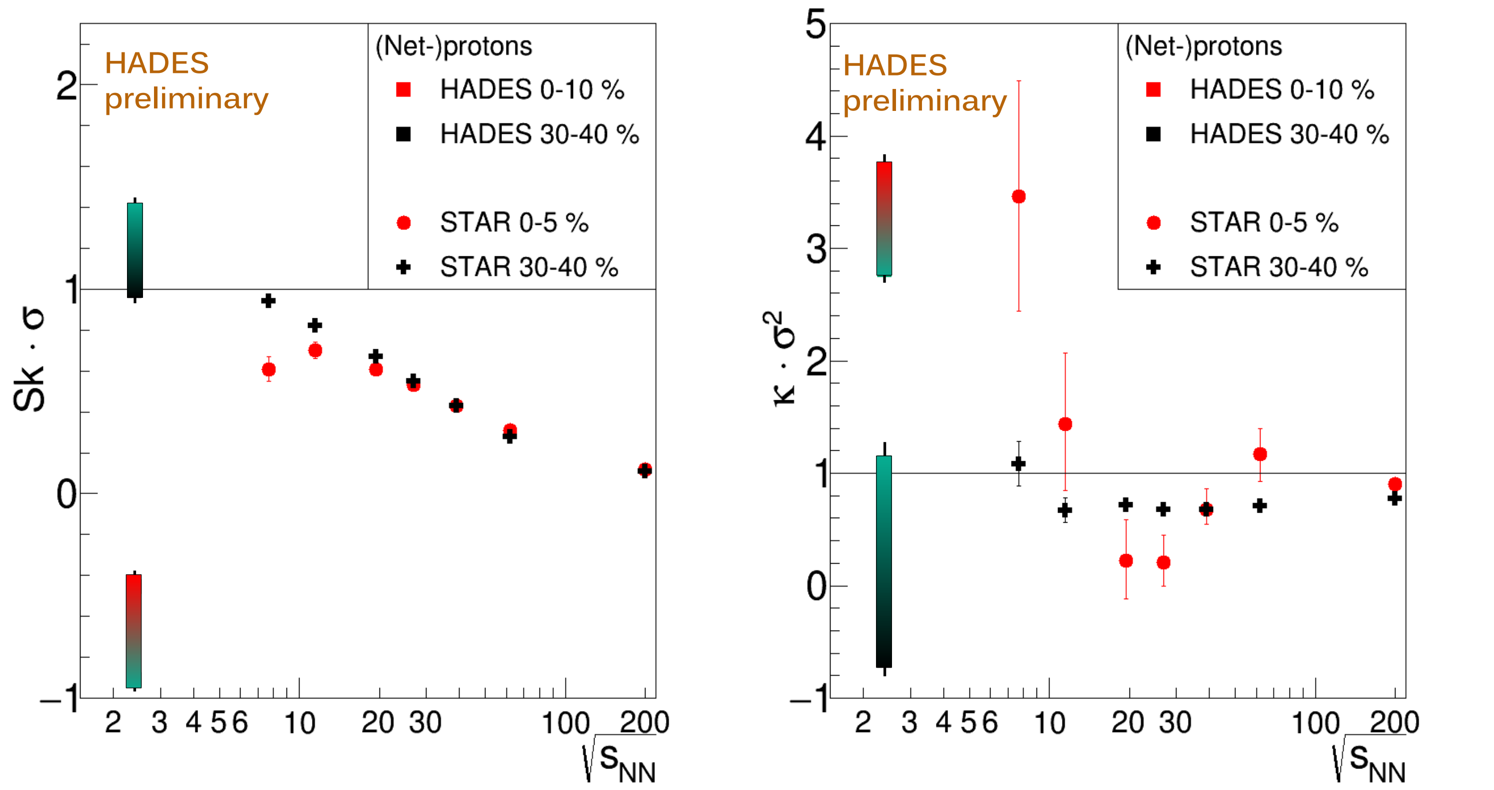
Error bands correspond to 5% systematic error on proton efficiencies.

→ Scaled cumulants deviate from Poisson with ↑ centrality
→ 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

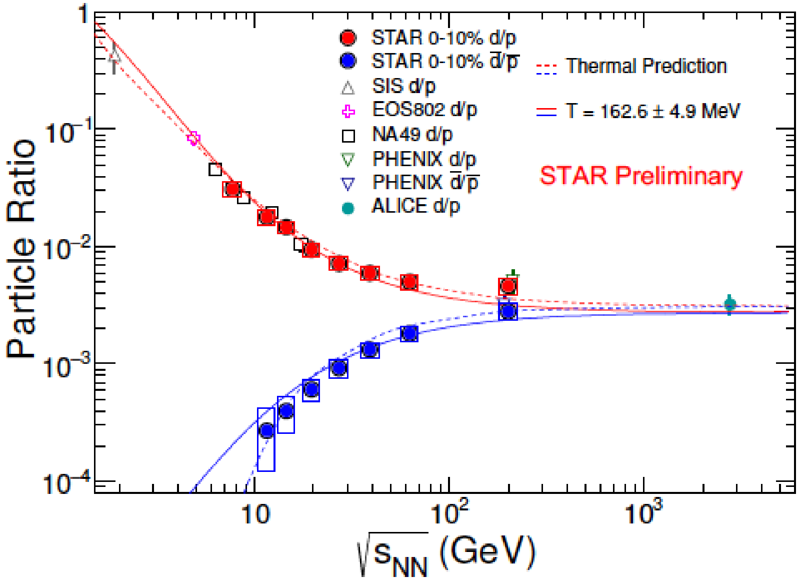
arXiv:1503.02558v2



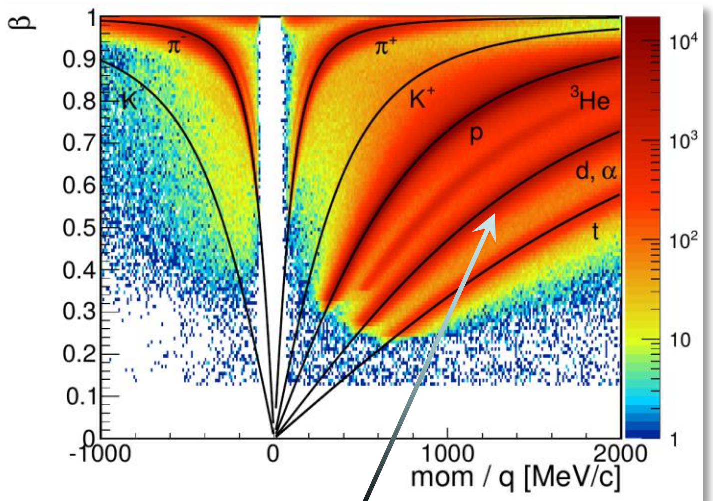
- red/black = unfolding (preferred method) + vol. flucs. corr.
- green = evt-by-evt eff correction of factorial moments + vol. flucs. corr.

(III) What about bound protons?

Systematics of d/p from STAR collaboration (QM2017)



HADES 1.23 GeV/u Au+Au data



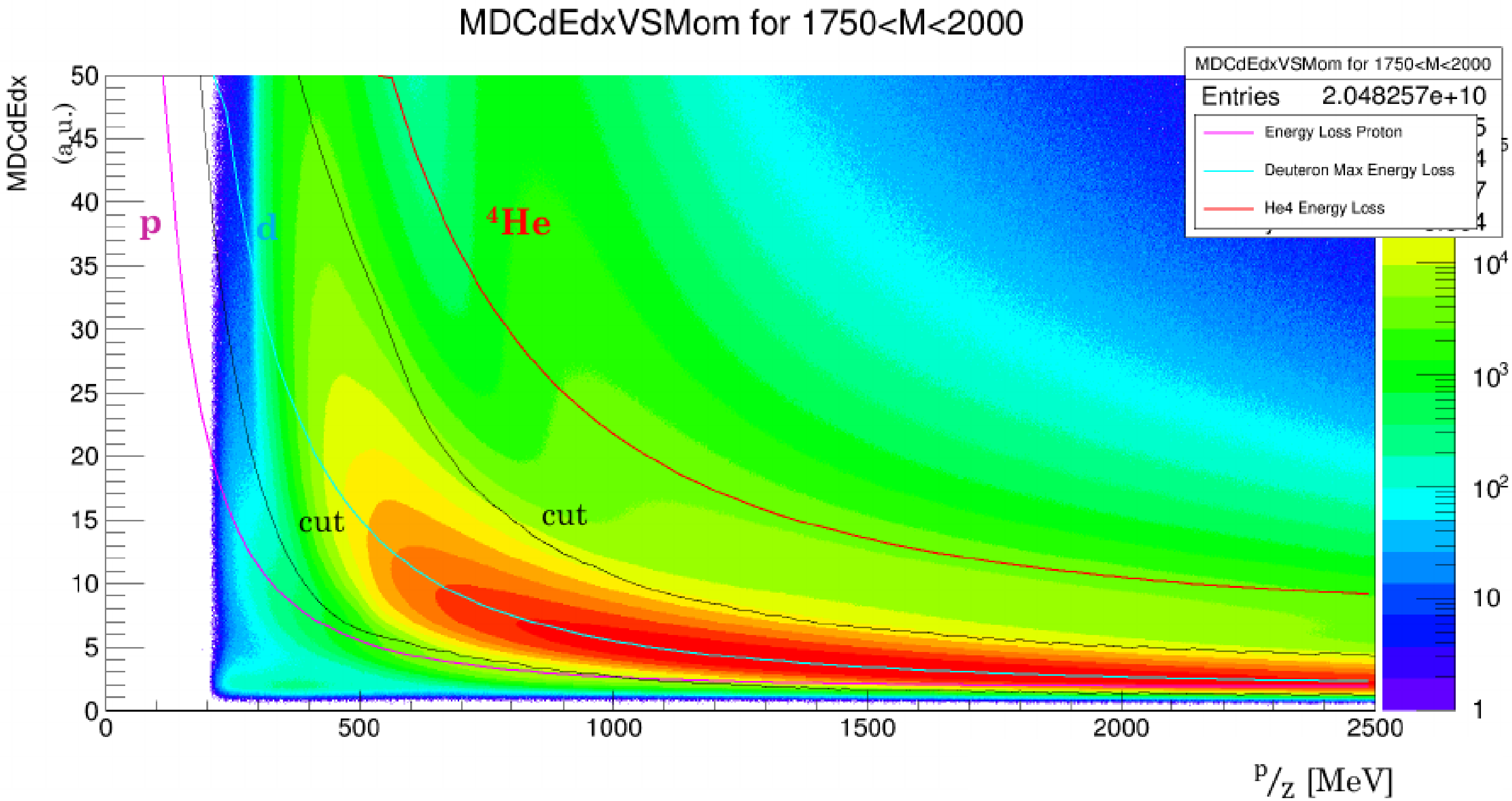
d/p ≈ 0.3 - 0.4 (analysis in progress)

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

- How do they contribute to baryon-number fluctuations?
- Should they be taken into account in a beam-energy scan?

➔ Deuteron nb. fluctuations in Au+Au

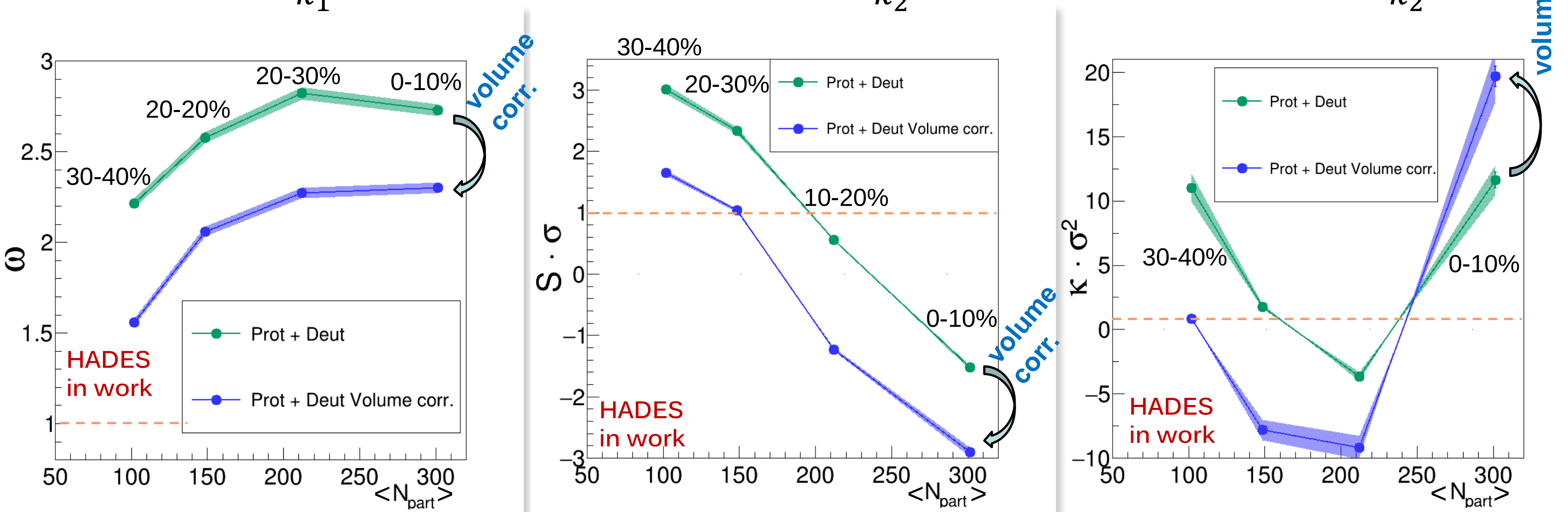
d / ^{4}He separation in HADES MDC via dE/dx



Fully corrected scaled moments of $N_p + N_d$
(ongoing analysis...)

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

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



- efficiency corr. via unfolding
- 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

- Started to investigate contribution of bound protons

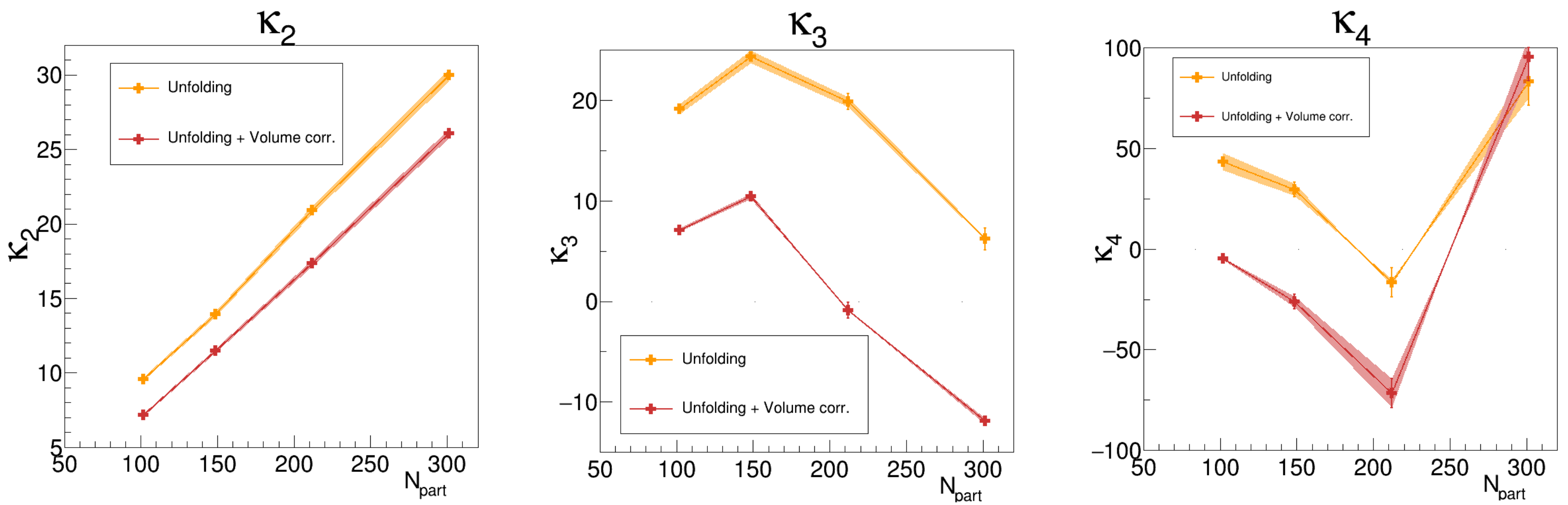
→ interpretation of results needs help from theory (e.g. Bzdak-Koch couplings?)

→→ To be continued in future runs at FAIR (phase 0 and beyond)

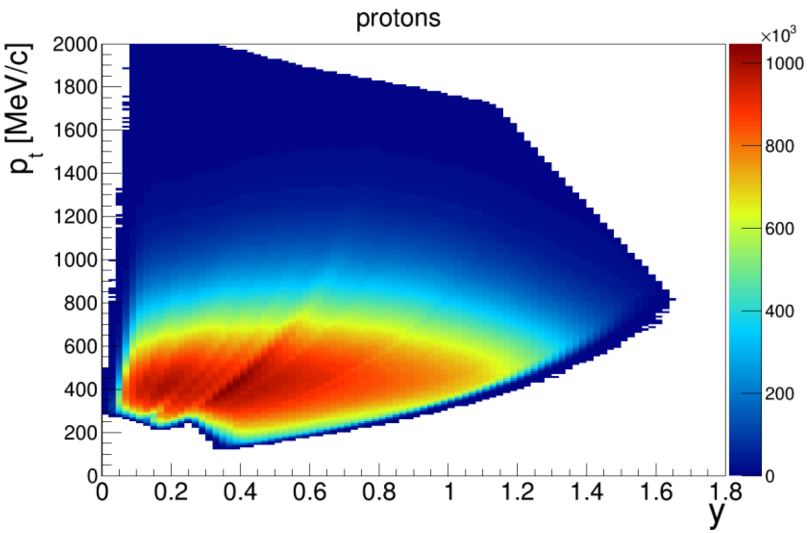
Thrift Shop

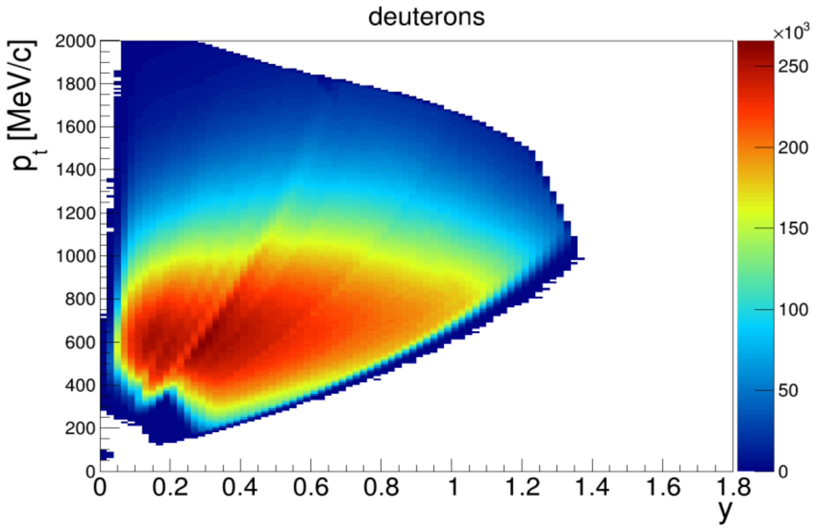
Proton cumulants κ_n vs N_{part} in 1.23 GeV/u Au+Au

Proton cumulants from unfolding + volume corrections



Proton & deuteron coverage

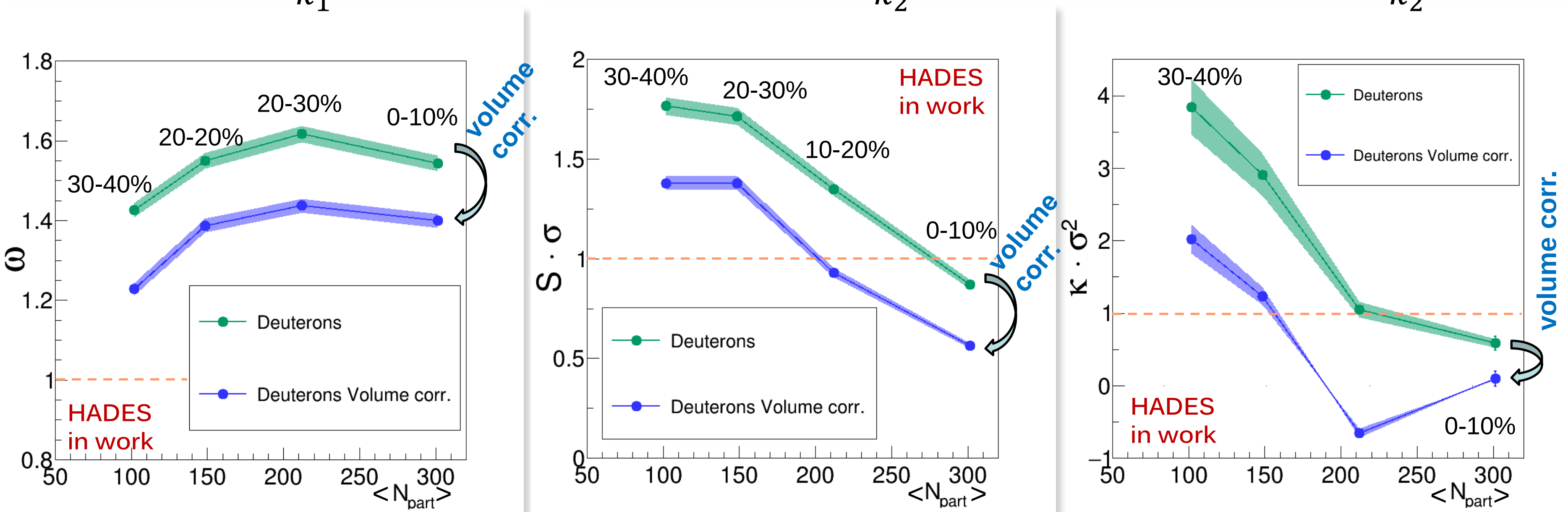




Fully corrected scaled moments of deuterons
(ongoing analysis...)

HADES 1.23 GeV/u Au+Au deuteron moments:

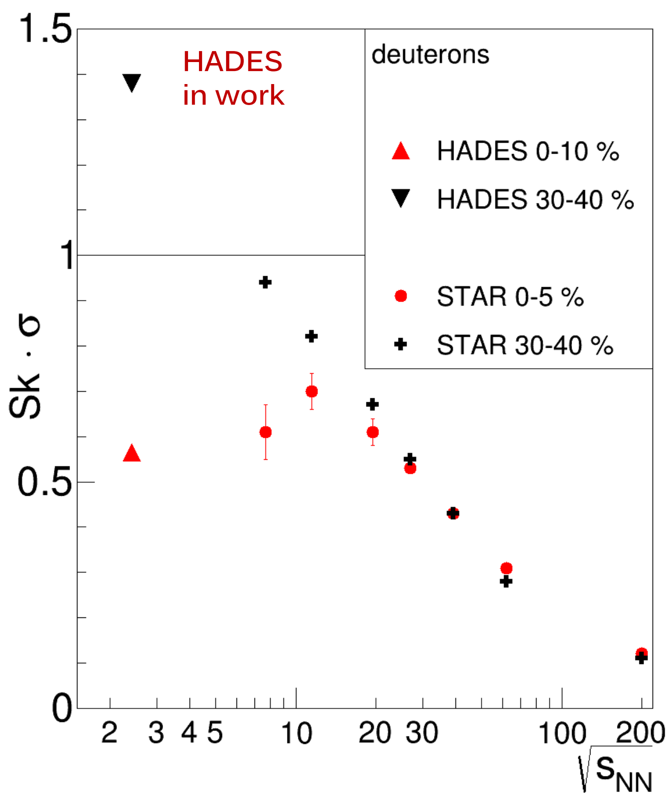
$$\omega = \frac{\kappa_2}{\kappa_1} \qquad Sk \times \sigma = \frac{\kappa_3}{\kappa_2} \qquad \kappa \times \sigma^2 = \frac{\kappa_4}{\kappa_2}$$

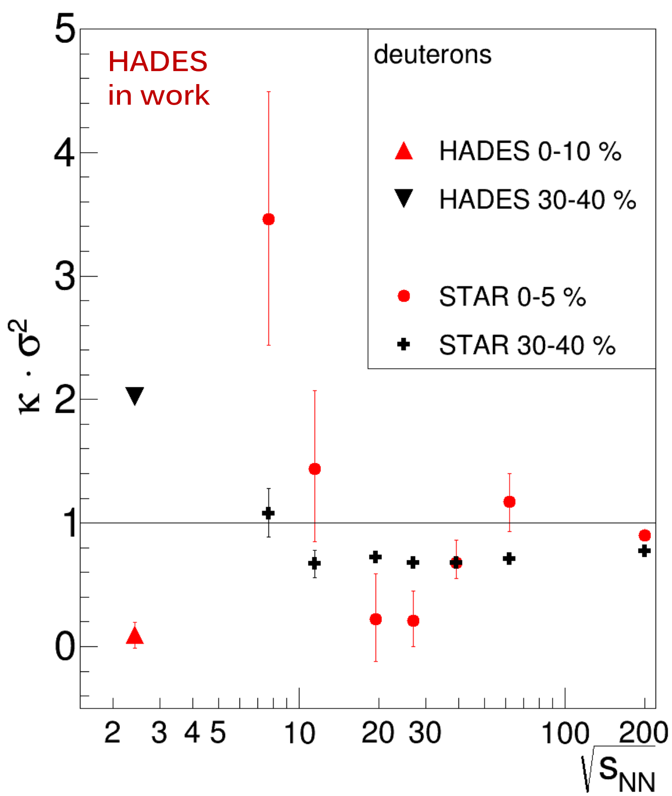


- efficiency corr. via unfolding
- volume flucs. corr.
- error bands = 5% uncertainty on deuteron eff.

HADES deuterons compared with STAR net p
(ongoing analysis...)

STAR analysis: Xiaofeng Luo et al., PoS (CPOD2014) 019
arXiv:1503.02558v2

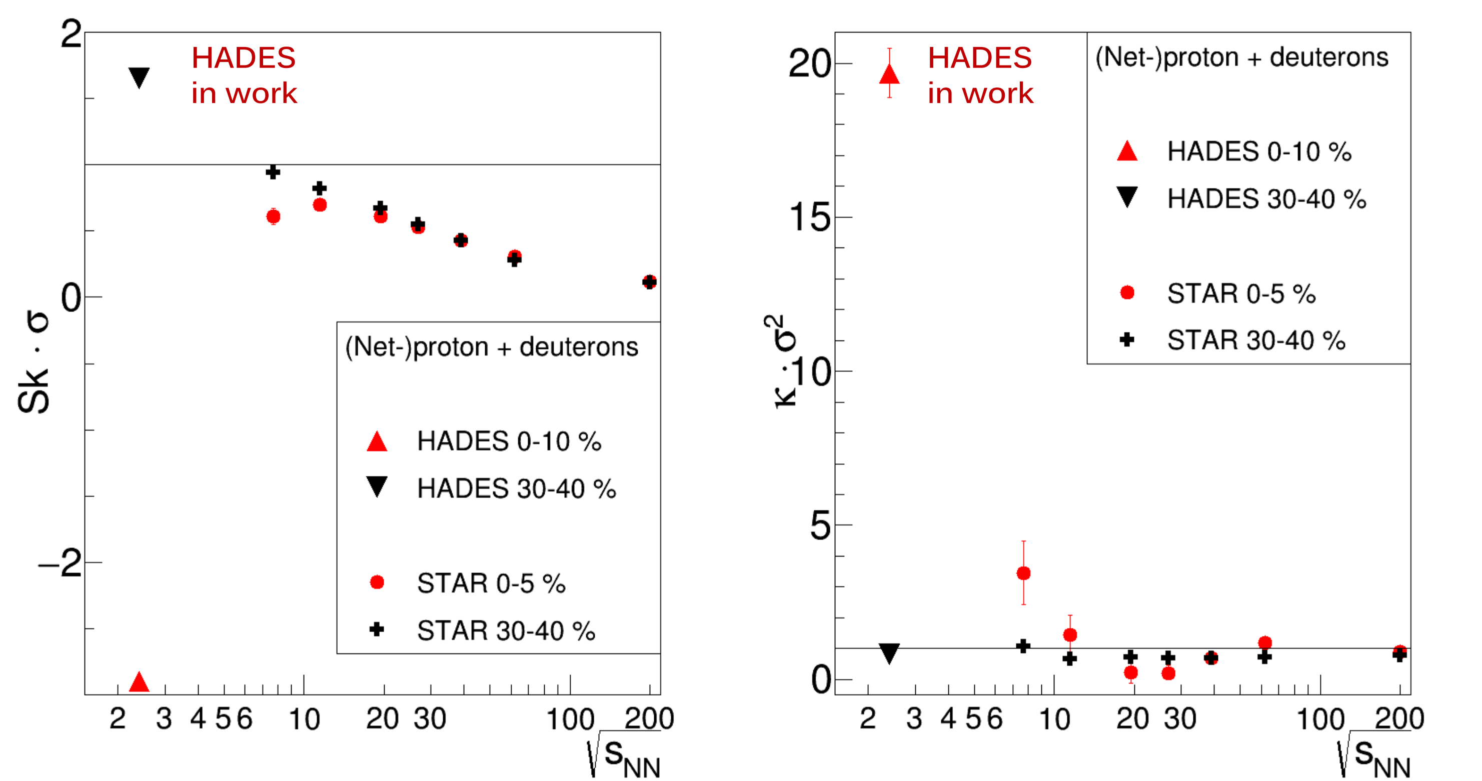




HADES: - efficiency corr. via unfolding
- volume flucs. corr.
- no realistic errors yet!

HADES p+d compared with STAR net p
(ongoing analysis...)

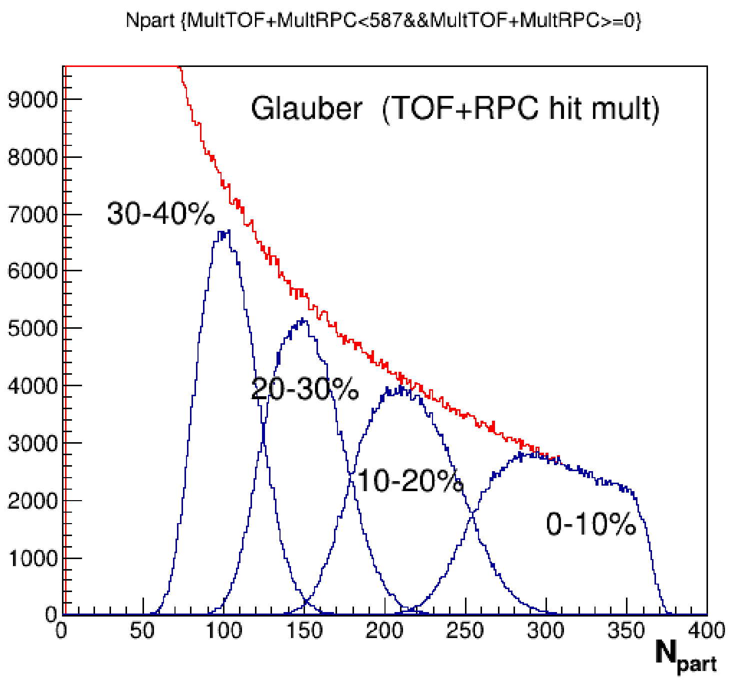
STAR analysis: Xiaofeng Luo et al., PoS (CPOD2014) 019
arXiv:1503.02558v2



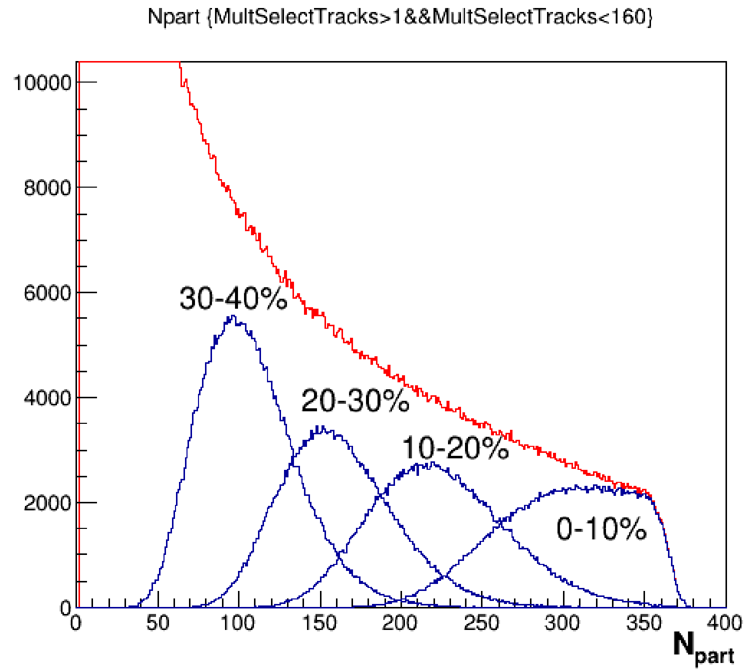
HADES: - efficiency corr. via unfolding
- volume flucs. corr.
- no realistic errors yet!

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

adjusted to hit distribution in TOF & RPC:



adjusted to track distribution in MDC:



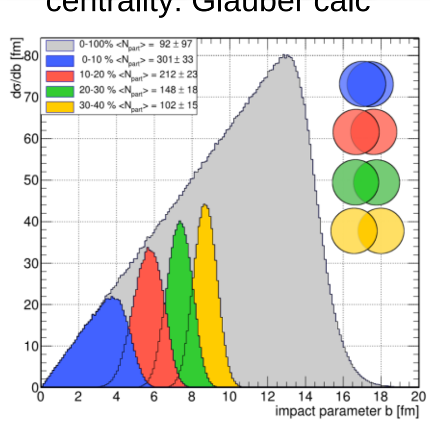
4 centrality bins used within HADES LVL1 trigger

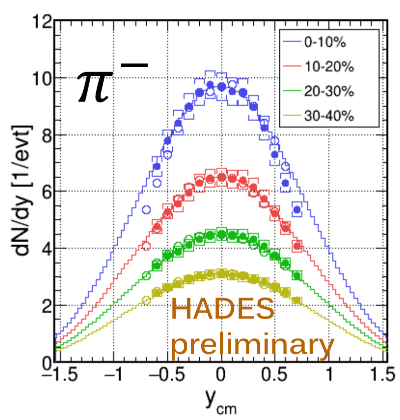
➔ used as estimate for FW selection

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

Pion production in 1.23 GeV/u Au+Au

centrality: Glauber calc



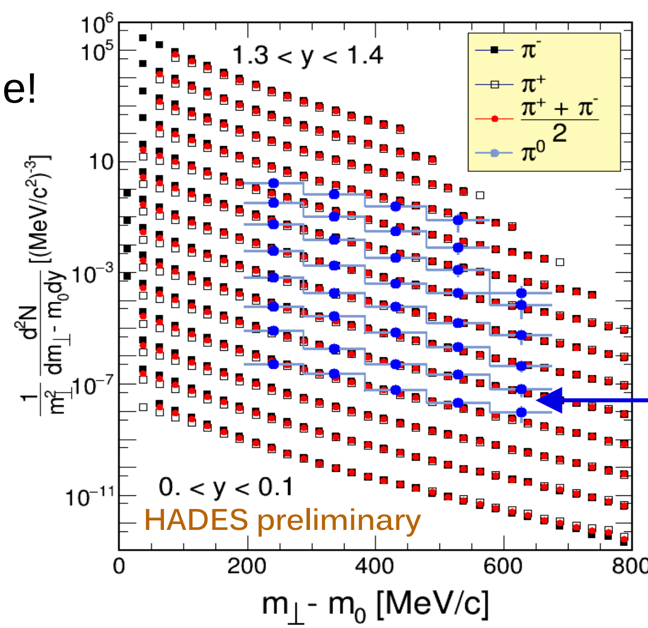


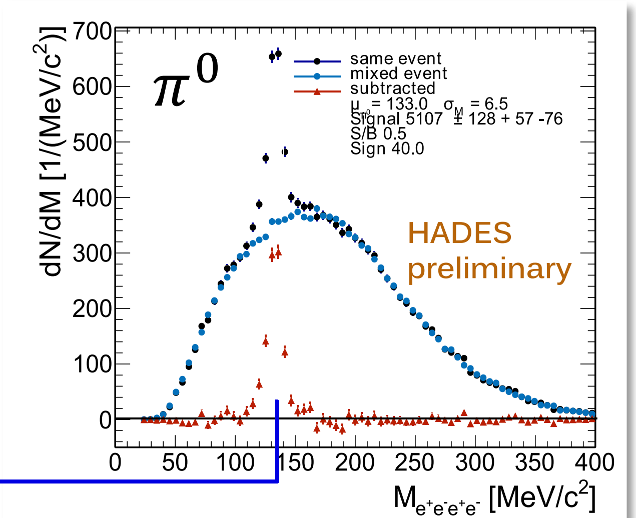
Pseudo-scalar mesons measured in HADES via photon conversion:

$\pi^0, \eta \rightarrow 2\gamma \rightarrow e^+e^- \, e^+e^-$

➔ very hi-stat **π** sample!

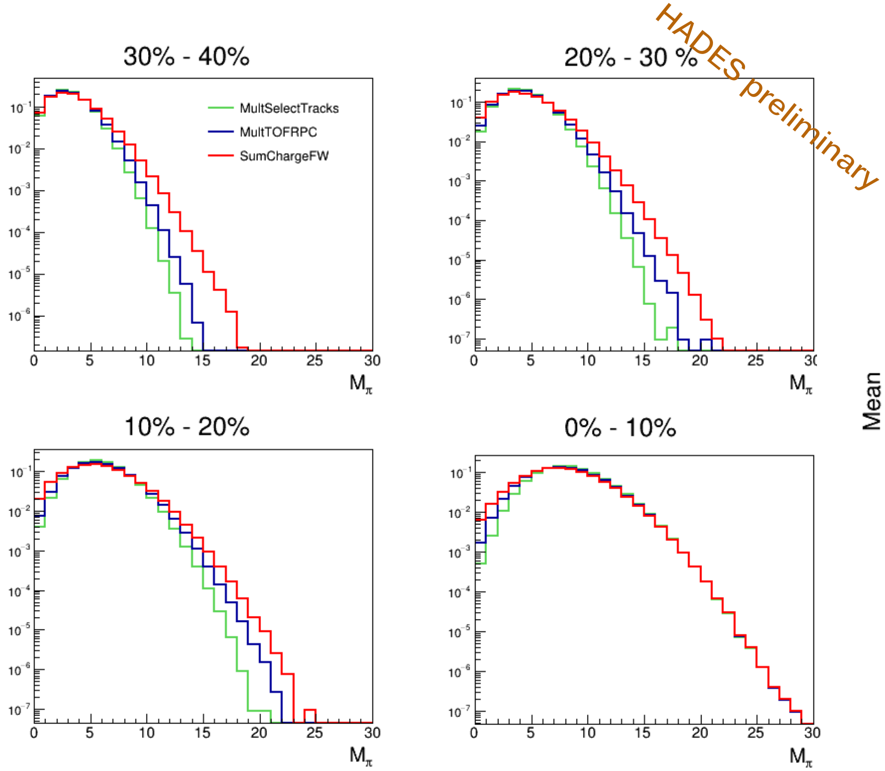
➔ $\boldsymbol{\pi^0}$ consistent with ½ $(\pi^+ + \pi^-)$



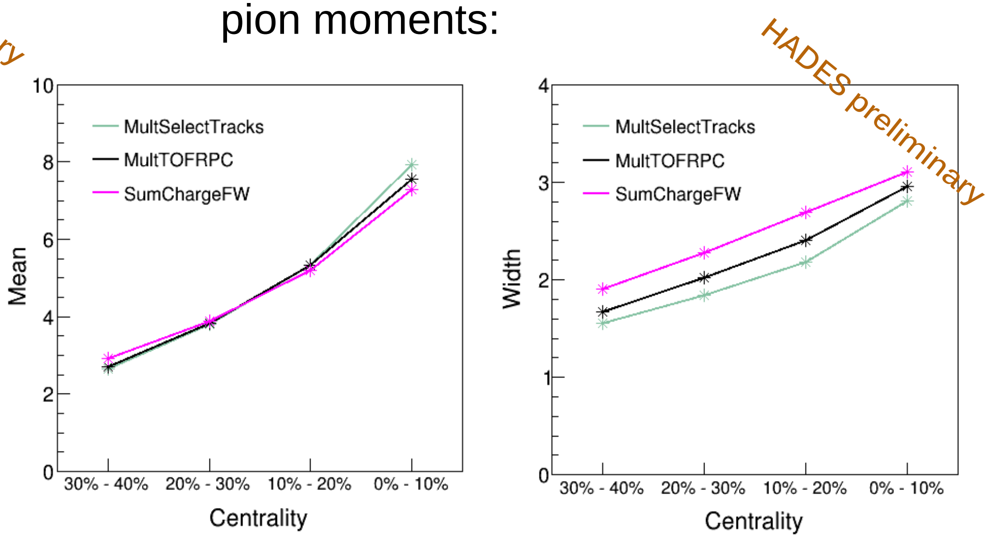


Pion production vs. centrality selection method

charged pion distributions:



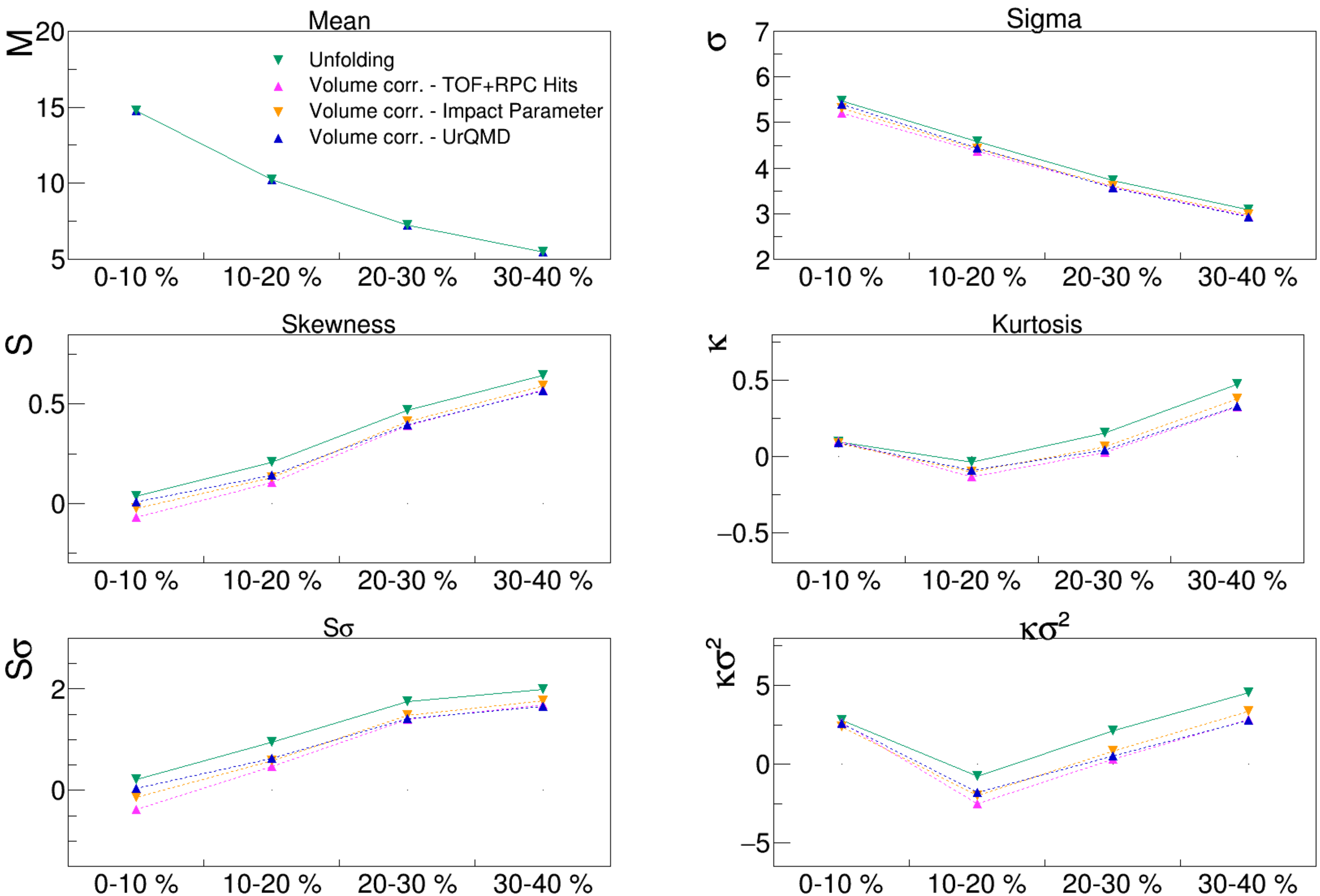
pion moments:



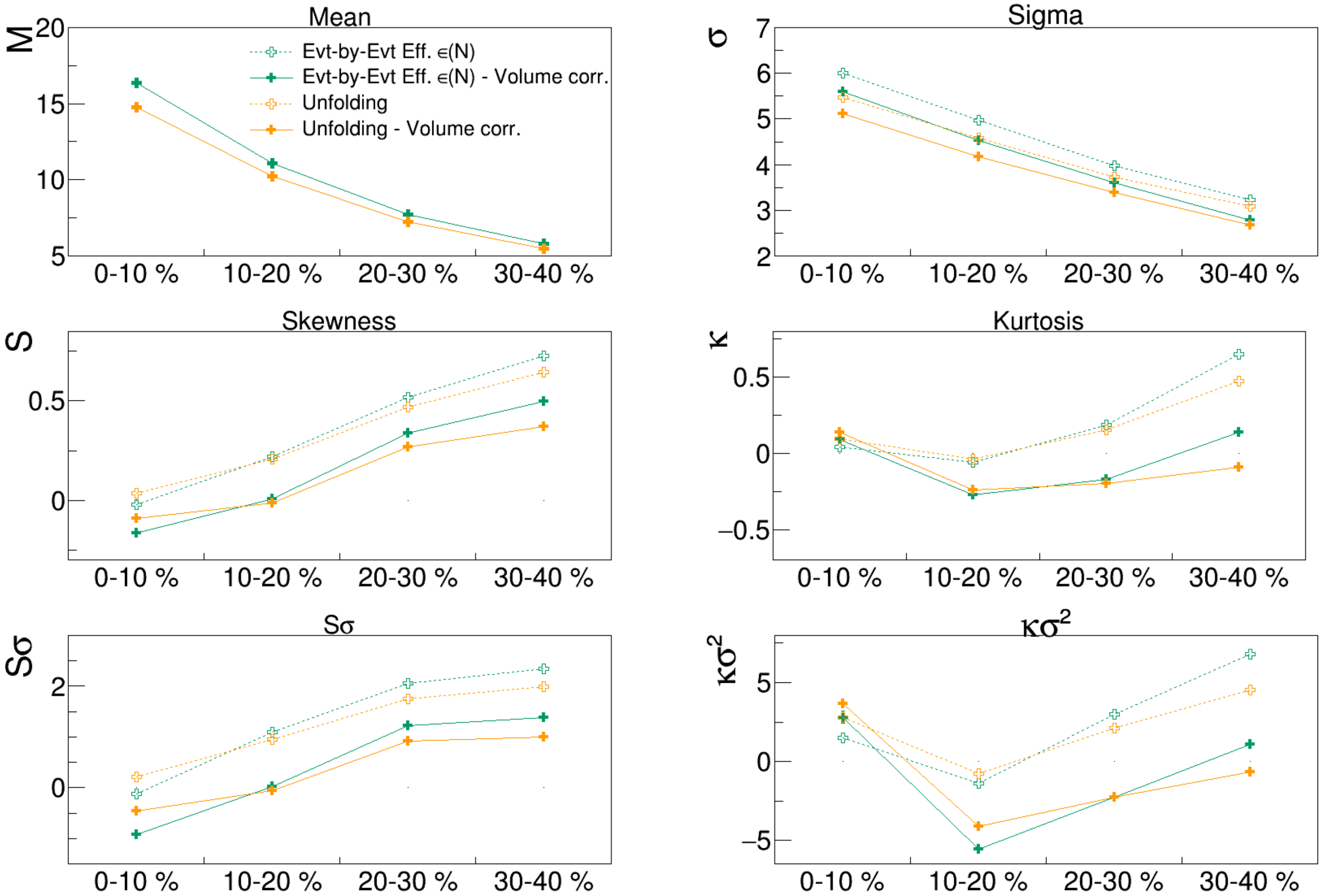
skewness (within 15%), kurtosis (within 30%)

→ expect very similar N_{part} distributions for 3 selection methods

Volume corrections (choice of centrality selection)



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

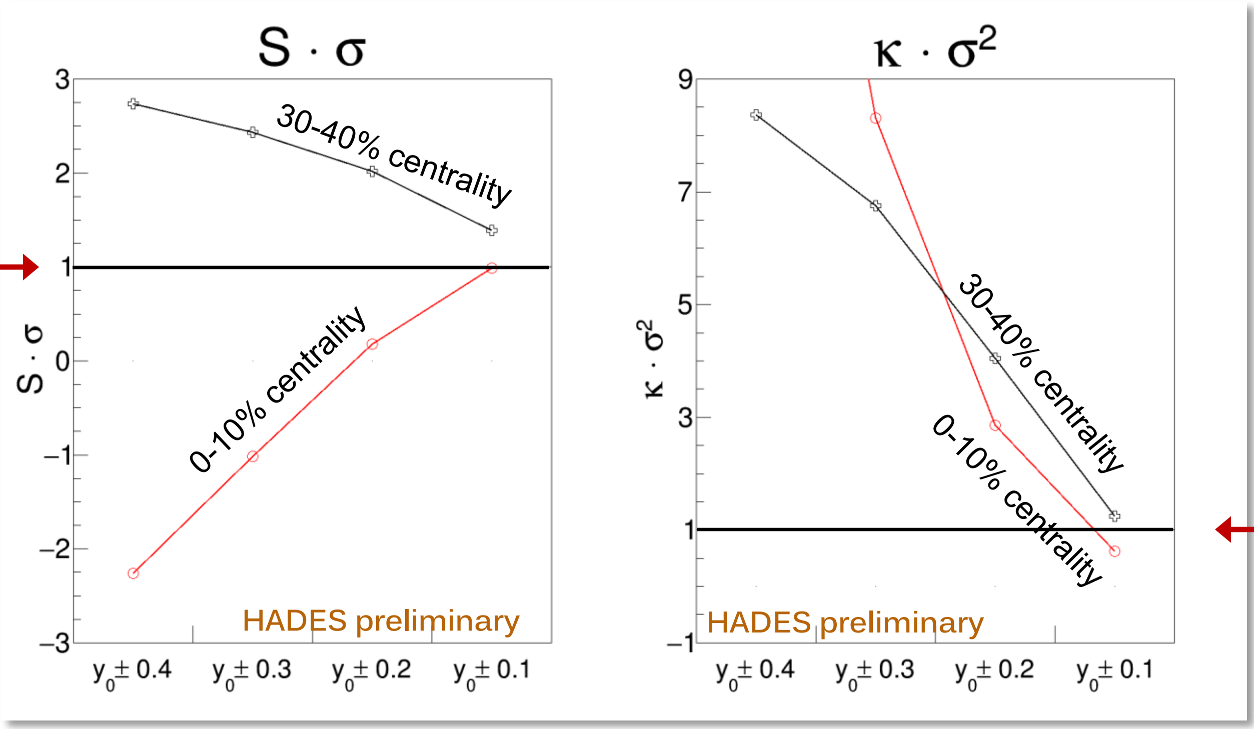


Poisson limit (w/o corr. volume flucs.)

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

→ Checked on Au+Au proton data with the unfolding method:

Poisson →



← Poisson

phase-space bin: $y_{acc} = y_0 \pm \Delta y$

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