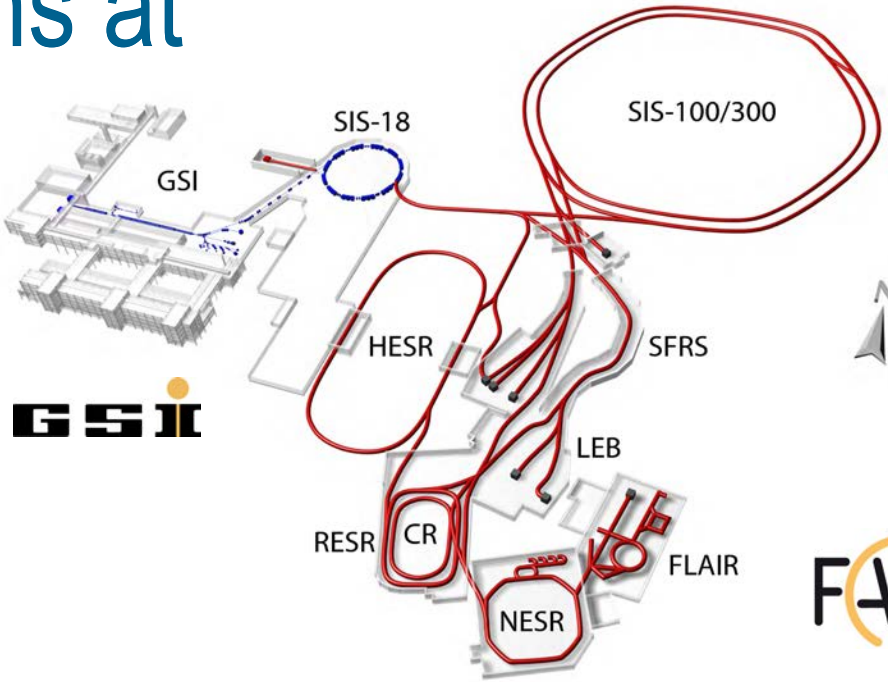
Higher-Order Moments of Proton-Number Fluctuations in Au+Au Collisions at 1.23A GeV with HADES

Melanie Szala



Outline

Motivation

Previous investigations

HADES spectrometer

Higher order moments of proton number fluctuations

- Efficiency corrections
- Volume fluctuations
- Results

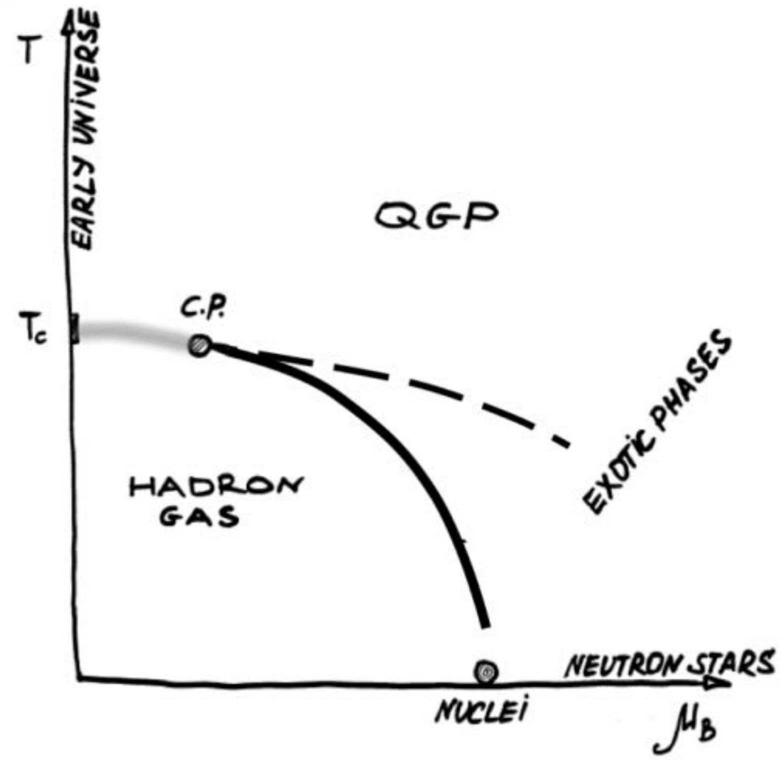
Conclusions

Motivation

- Cross-over at low μ_B and
  1st-order phase transition at high μ_B
  → Critical point

- Event-by-event fluctuations of conserved quantities are expected to be a signature of discontinuity in the QCD phase diagram
  - Charge Q / **baryon number B** / strangeness S

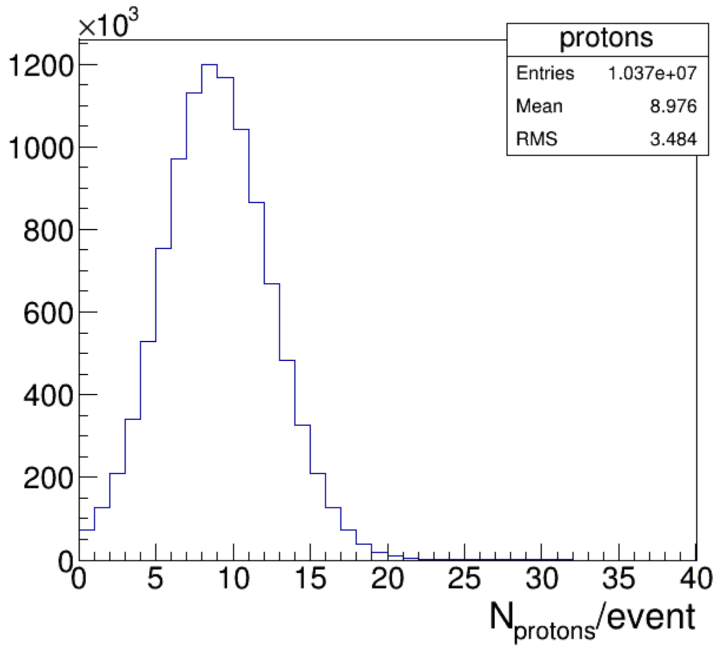
- Experimental observable:
  - Cumulants of event-by-event net-particle multiplicity distributions
  - **(Net-)proton** (proxy for net-baryon)



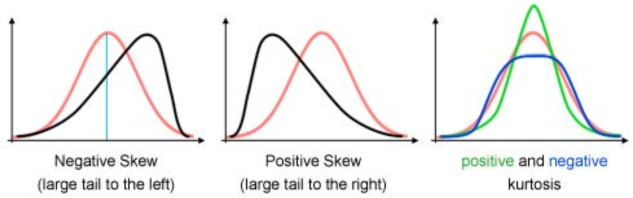
Experimental Observables

Cumulants of event-by-event net-particle multiplicity distributions

- **(Net-)proton** (proxy for net-baryon)



Mean	M	$=$	K_1
Variance	σ^2	$=$	K_2
Skewness	S	$=$	K_3/σ^3
Kurtosis	κ	$=$	K_4/σ^4

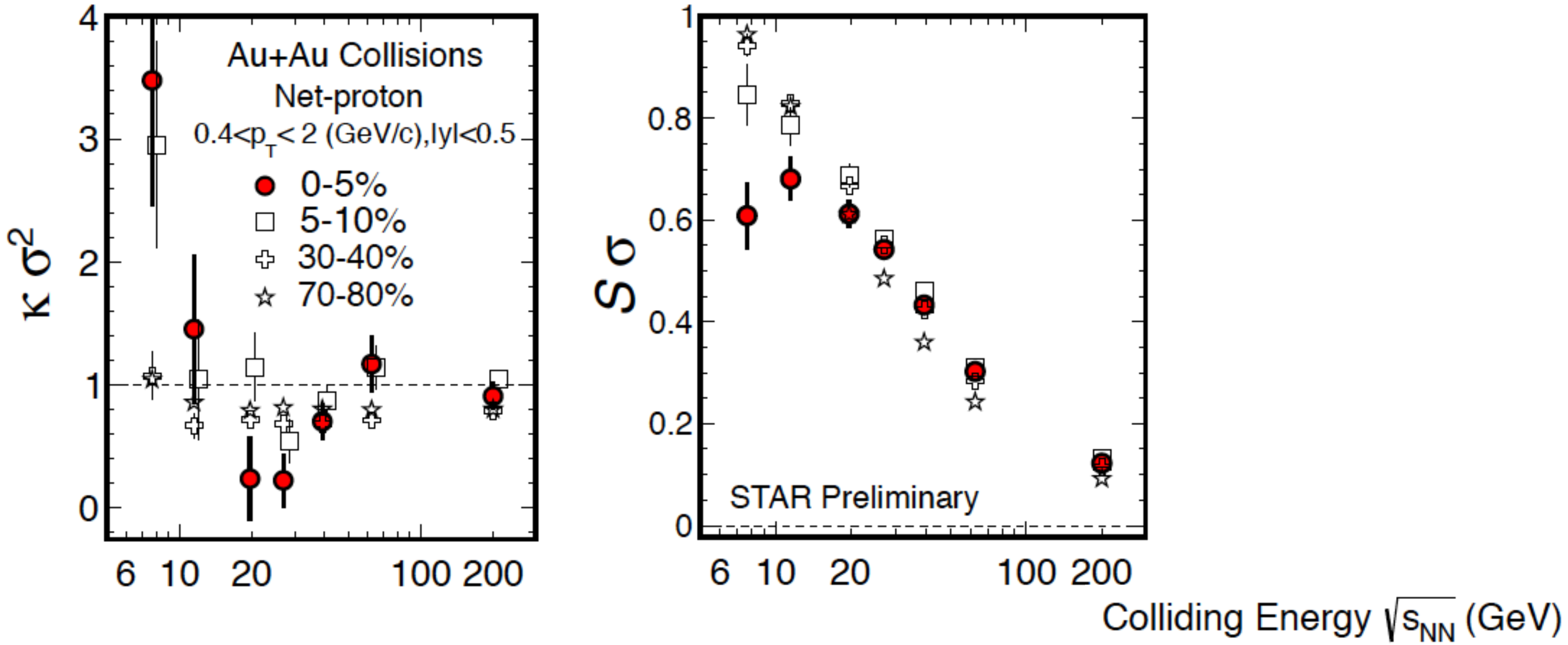


Cumulant ratios to cancel volume effects:

$$S \cdot \sigma = \frac{K_3}{K_2} \qquad \kappa \cdot \sigma^2 = \frac{K_4}{K_2}$$

Previous investigations

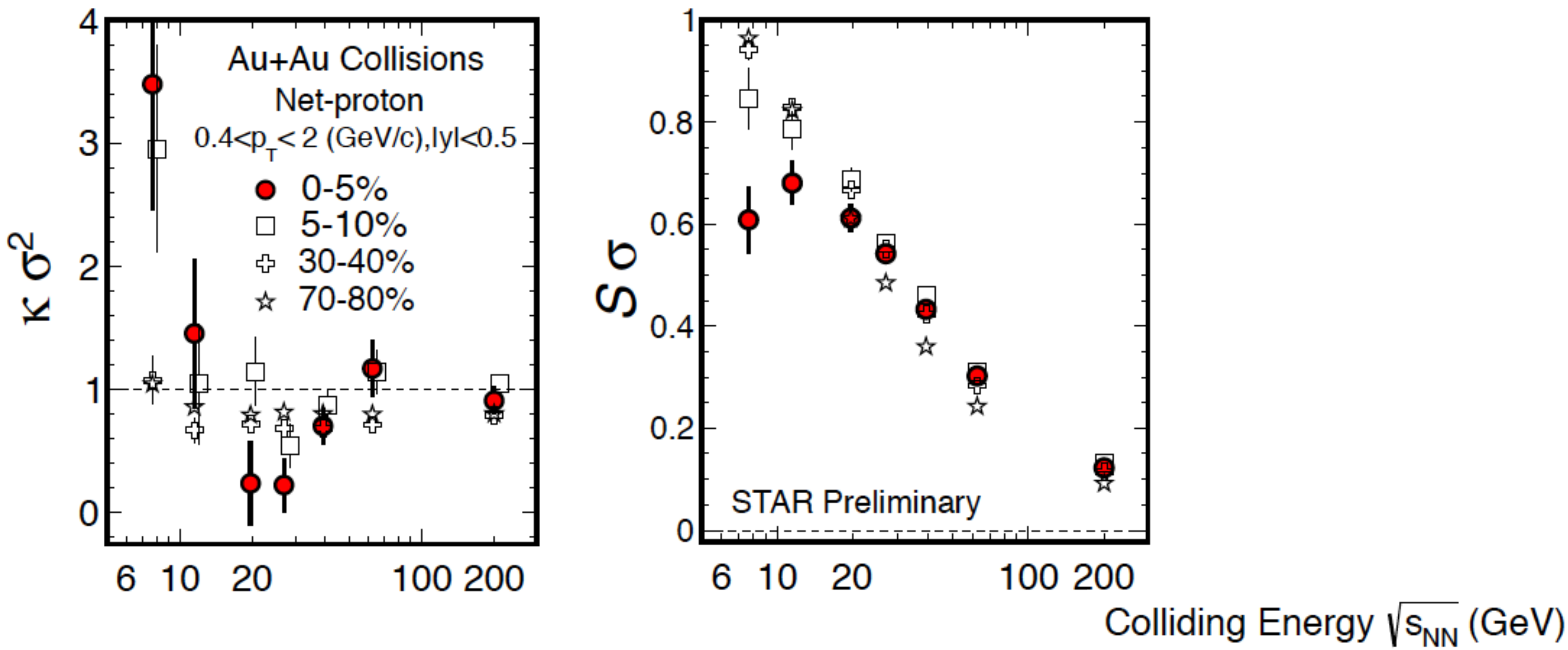
Higher order moments of net-proton distributions from the STAR Collaboration

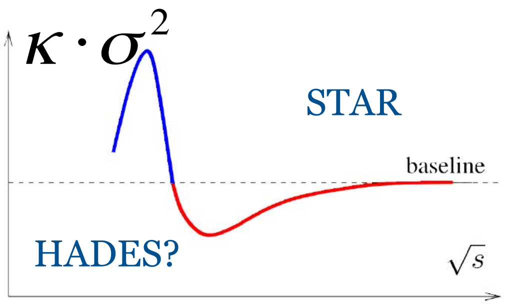


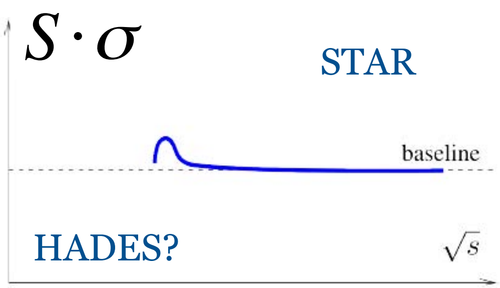
arXiv:1309.5681v1
arXiv:1503.02558

Previous investigations

Higher order moments of net-proton distributions from the STAR Collaboration







arXiv:1309.5681v1
arXiv:1503.02558
Stephanov, CPOD 2014

HADES Spectrometer

High **A**cceptance **D**i**E**lectron **S**pectrometer

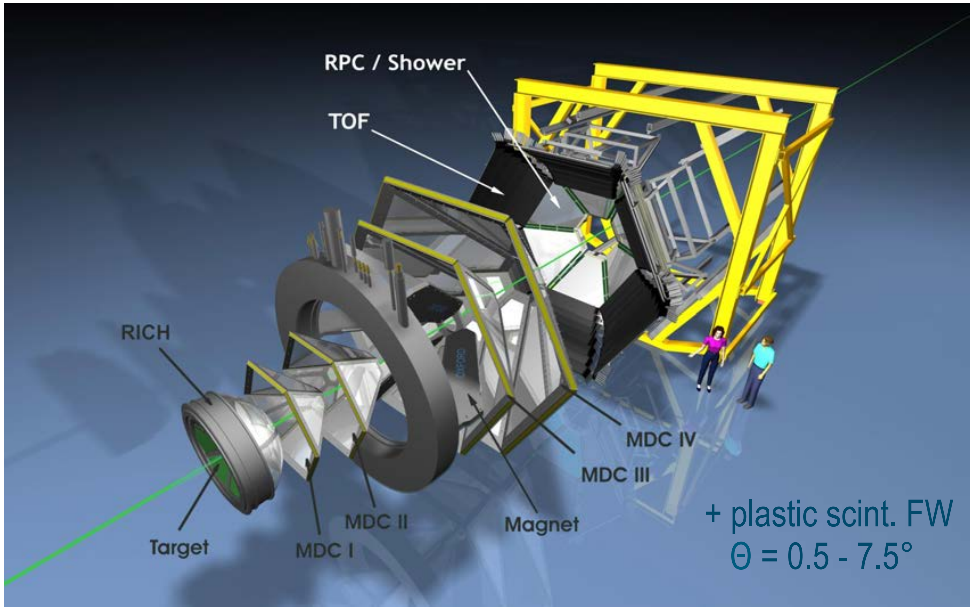
Located at SIS18, GSI

Large acceptance

- Full azimuthal and polar angle coverage of $\Theta = 18 - 85°$

Fast detector

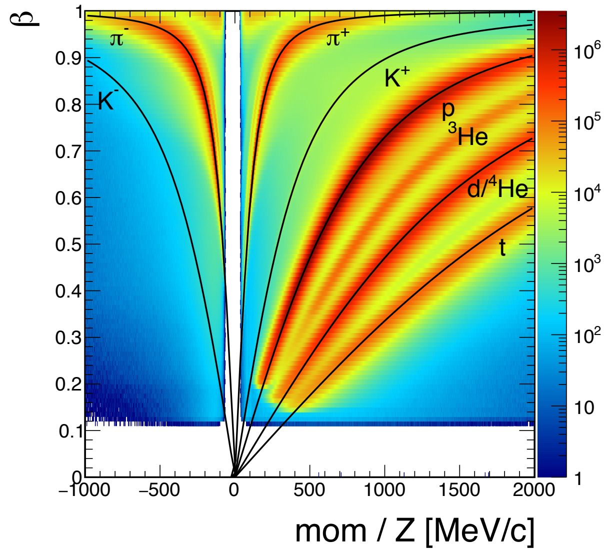
- Trigger rate up to 8kHz (large statistics)

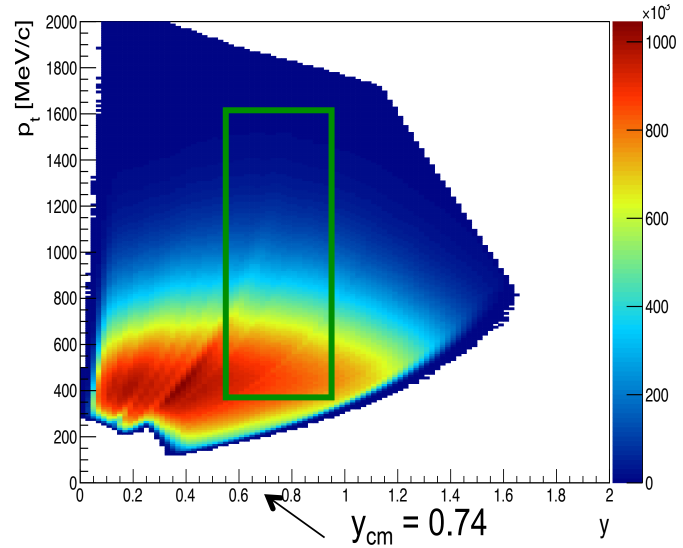


Au + Au @1.23 AGeV, $\sqrt{s_{NN}}$=2.41 GeV

- 15 fold segmented Au target
- 7.4 x 10^9 events recorded
- Trigger on 47% most central collisions

Proton Analysis





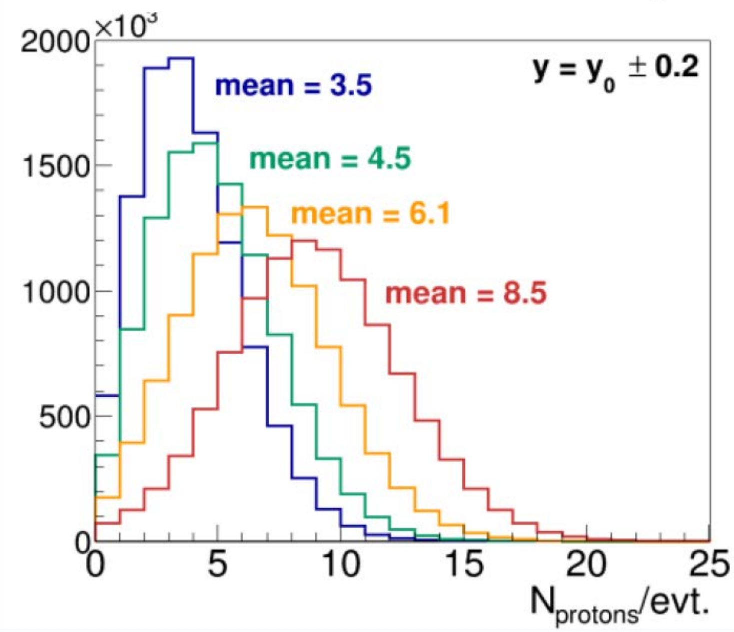
Event selection

- 0-10%, 10-20%, 20-30%, 30-40% central events selected with the Forward Wall

Track selection

- $y = y_{cm} \pm 0.2$
- p_t = 400-1600 MeV/c

If $N_{\bar{p}}$= 0 → Poisson distribution: $\boxed{S \cdot \sigma = \kappa \cdot \sigma^2 = 1}$



Efficiency correction

Efficiency = acc x det. eff x rec. eff

Investigations of efficiency correction in UrQMD simulations:

→ **Correct the moments**

Bzdak & Koch, PRC 86 (2012);

Xiaofeng Luo, arXiv:1410.3914 (2014)

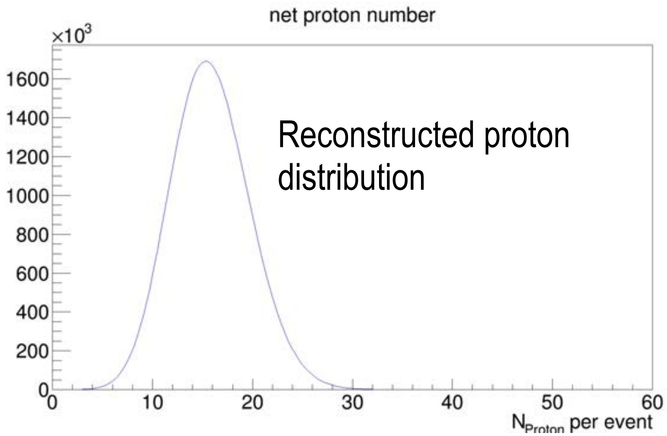
→ **Unfolding**

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

J. Albert et al. (MAGIC), Nucl. Instr. Meth. A 583 (2007) 494.

S. Schmitt, J. Instr. 7 (2012) T10003.

Correct the moments



Calculate moments →

Mean$_{measured}$
Variance$_{measured}$
Skewness$_{measured}$
Kurtosis$_{measured}$

Skew*Sig$_{measured}$
Kurt*Sig$^2_{measured}$

Correct moments →

efficiency correction

Mean$_{true}$
Variance$_{true}$
Skewness$_{true}$
Kurtosis$_{true}$

Skew*Sig$_{true}$
Kurt*Sig$^2_{true}$

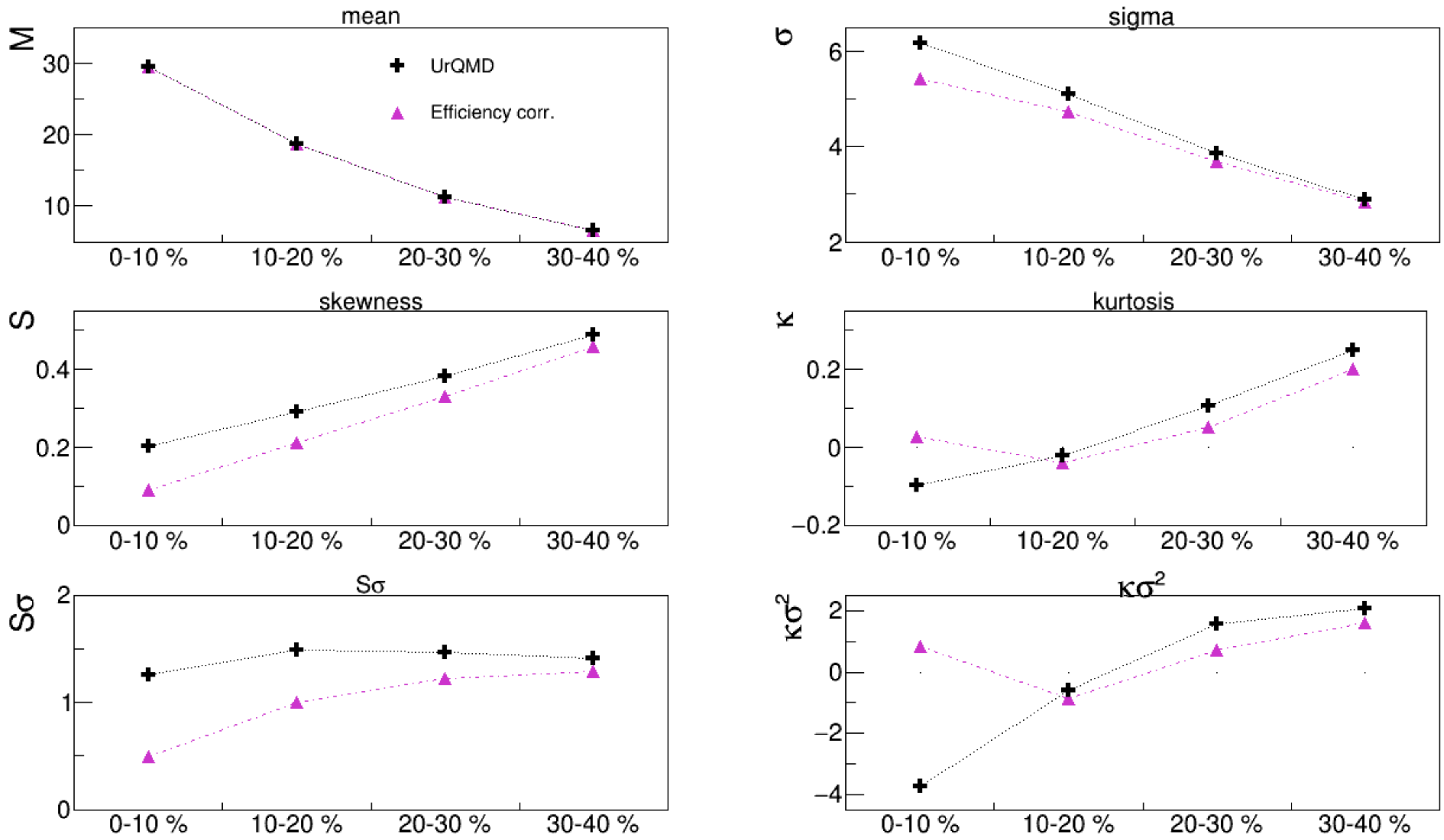
Self-consistency check

- UrQMD protons → reference
- UrQMD + Geant reconstructed protons → efficiency correction

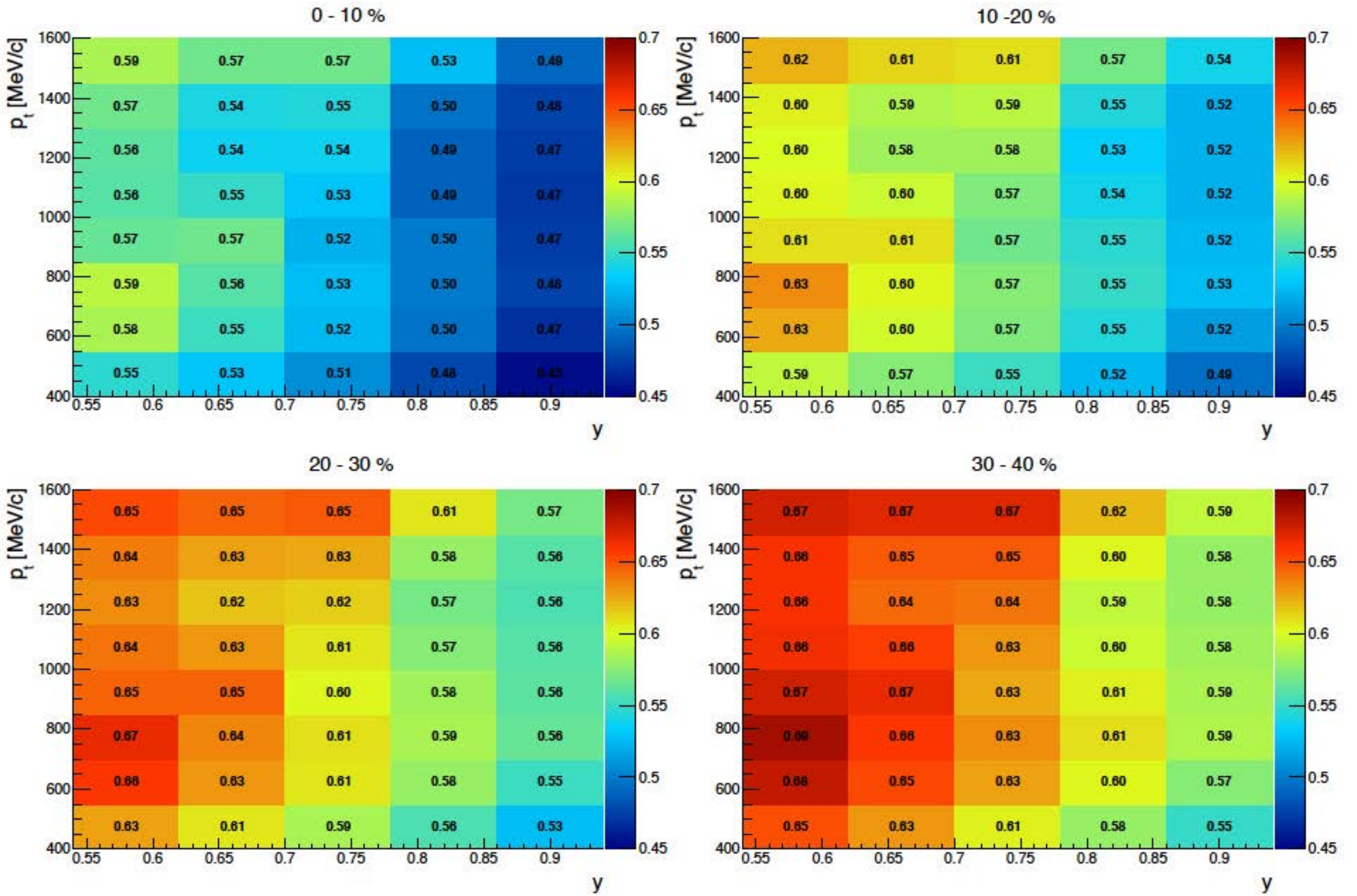
Bzdak & Koch, PRC 86 (2012);
Xiaofeng Luo, arXiv:1410.3914 (2014)

UrQMD

Correct the moments



Efficiency correction



Efficiency correction

Efficiency: strong effect on centrality

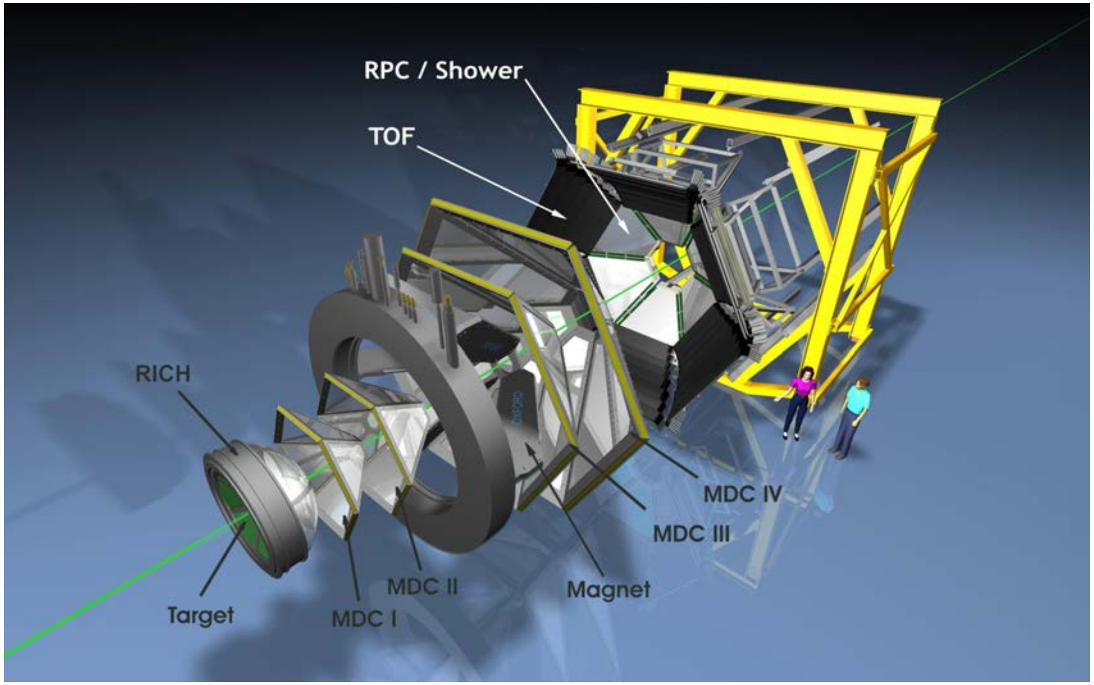
Efficiency depends on number of tracks per event

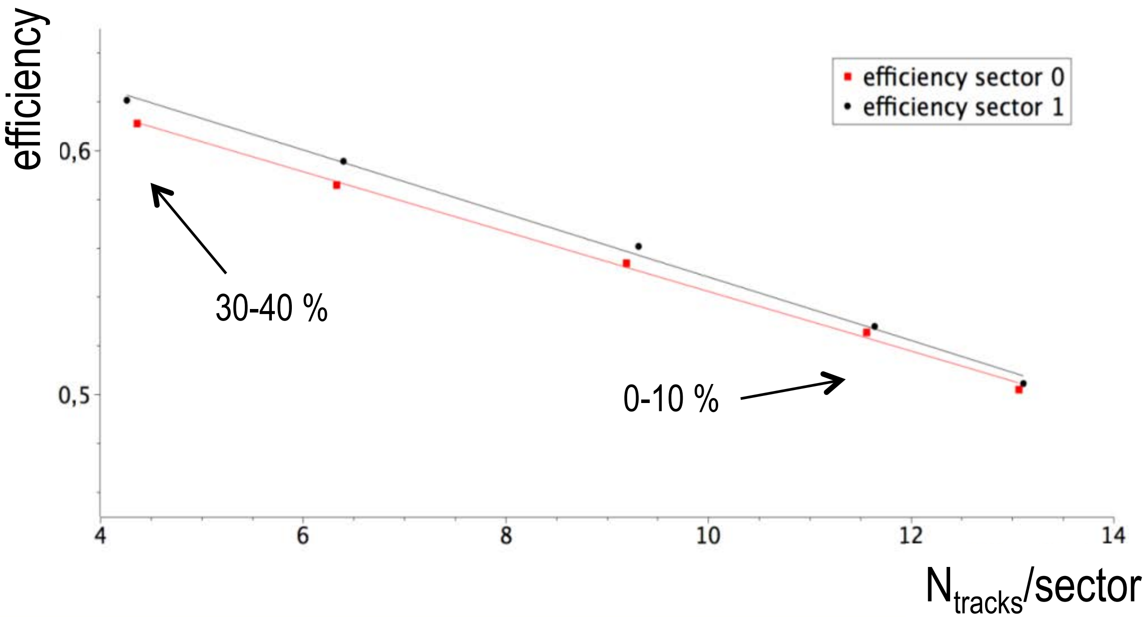
Detector divided into 6 sectors

- Efficiency is sector dependent

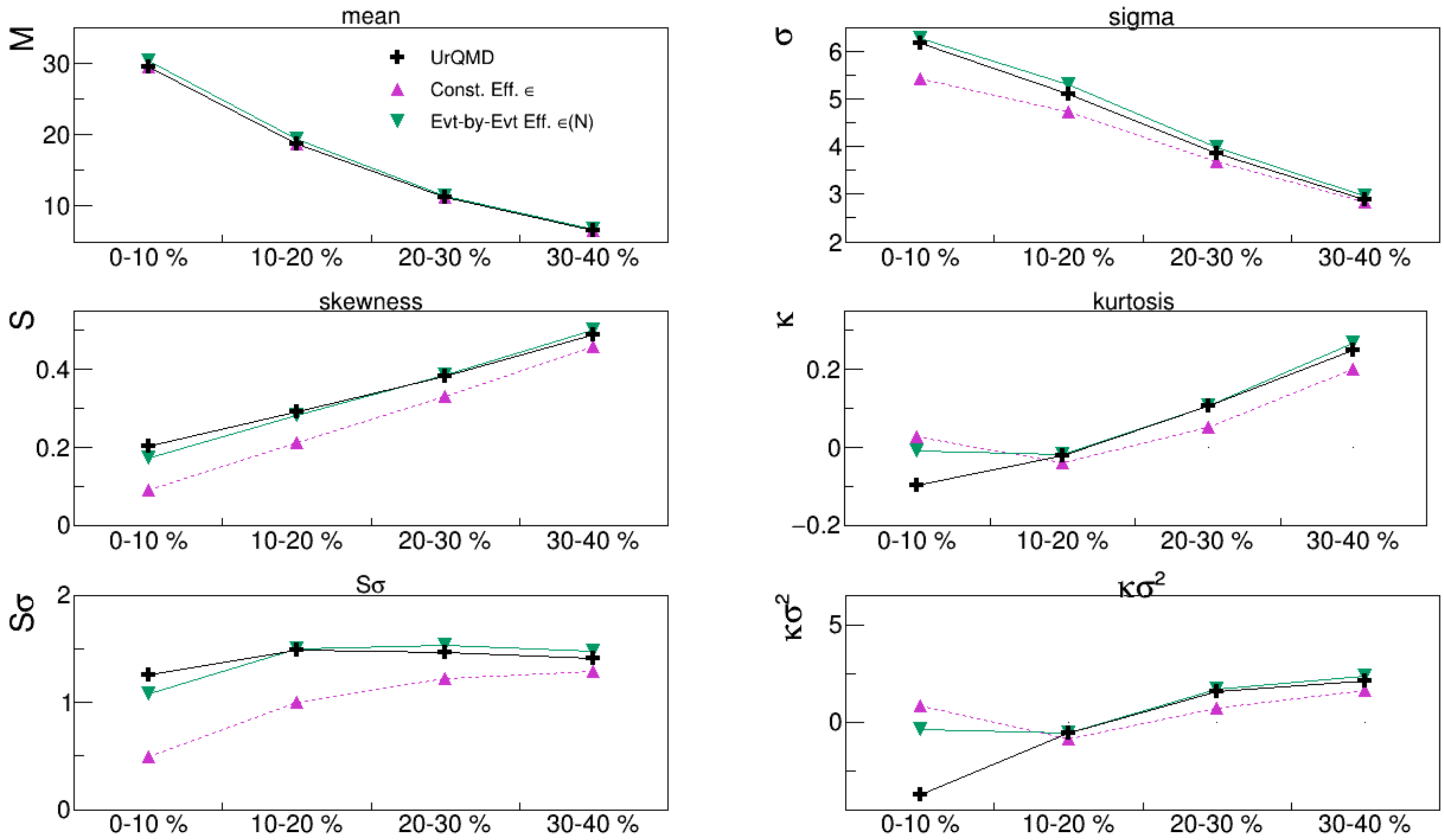
→ Efficiency correction

- Event-by-event
- Particle number in sector
- y and p_t dependent



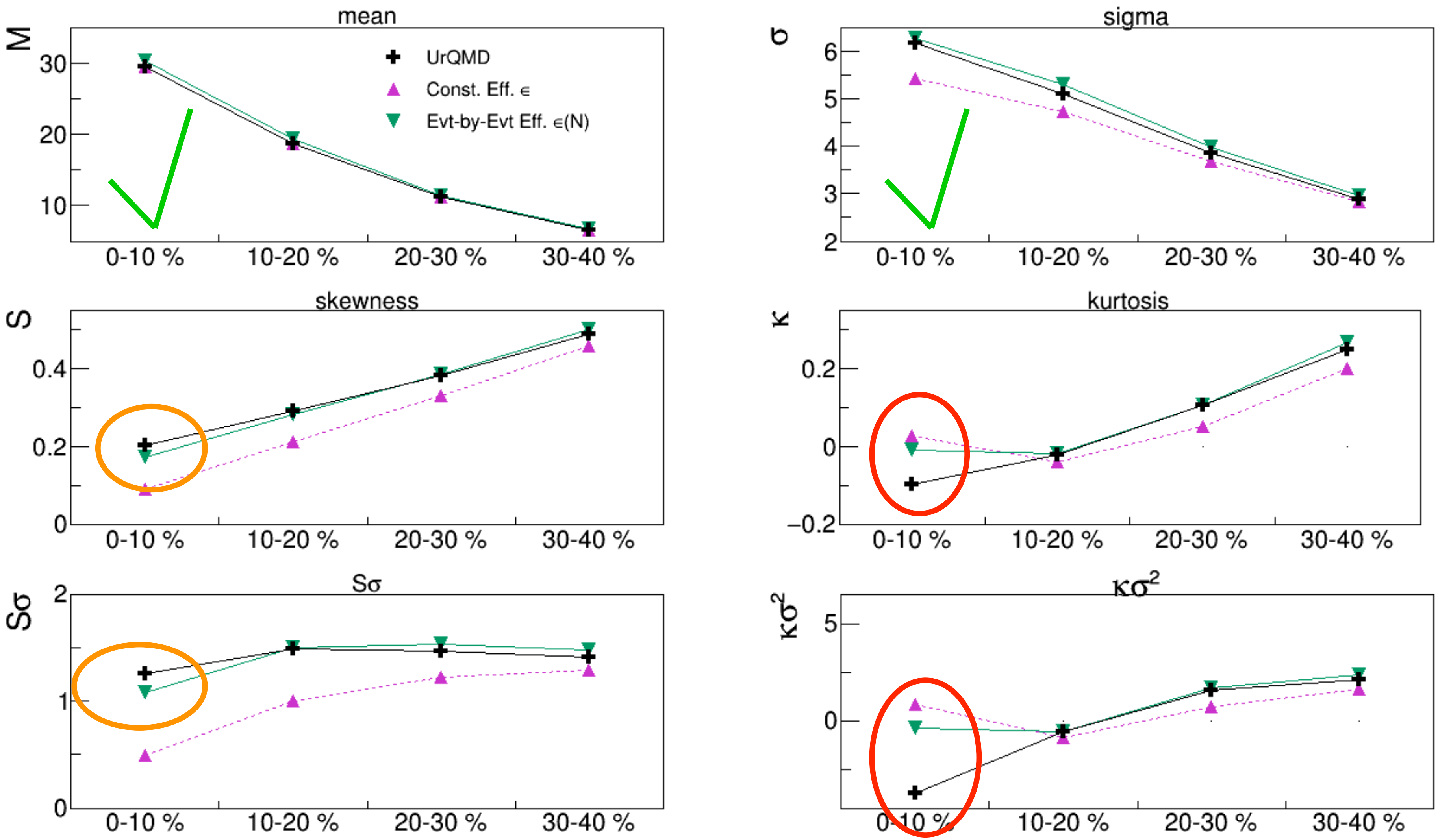


Correct moments – event-by-event -



UrQMD

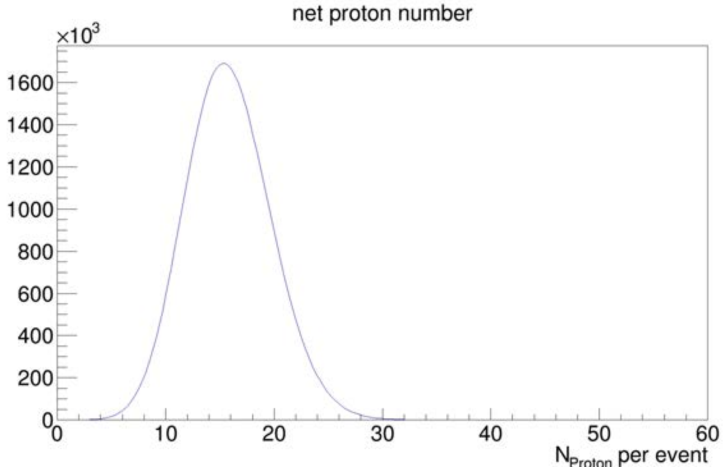
Correct moments – event-by-event -



Unfolding

measured distribution

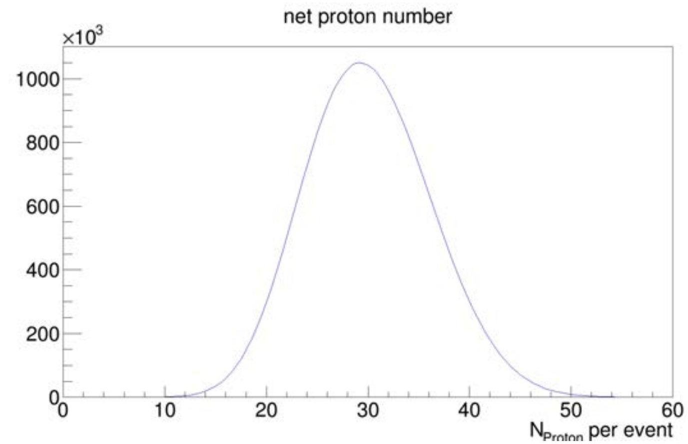
true distribution



Unfolding

Matrix inversion

Folding



UrQMD + GEANT
(recon. protons)

UrQMD protons

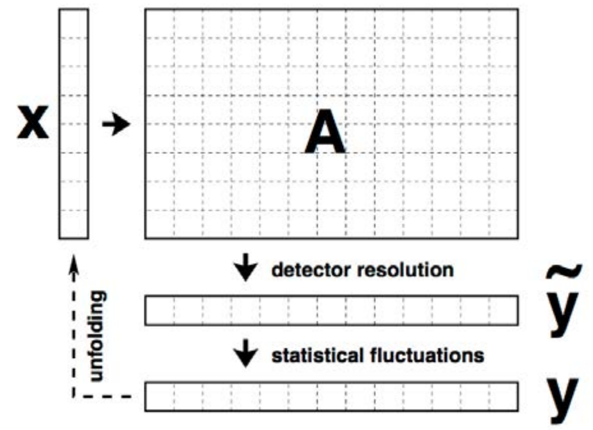
Unfolding procedure

Unfolding via **matrix inversion**

$$\boxed{\mathbf{y = A \bullet x}}$$

→ finding x !

y:	measured histogram
x:	true histogram
A:	response matrix



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

ROOT package by S. Schmitt → **TUnfold, TUnfoldSys, TUnfoldDensity**

Minimize in a least-squares procedure the „Lagrangian“:

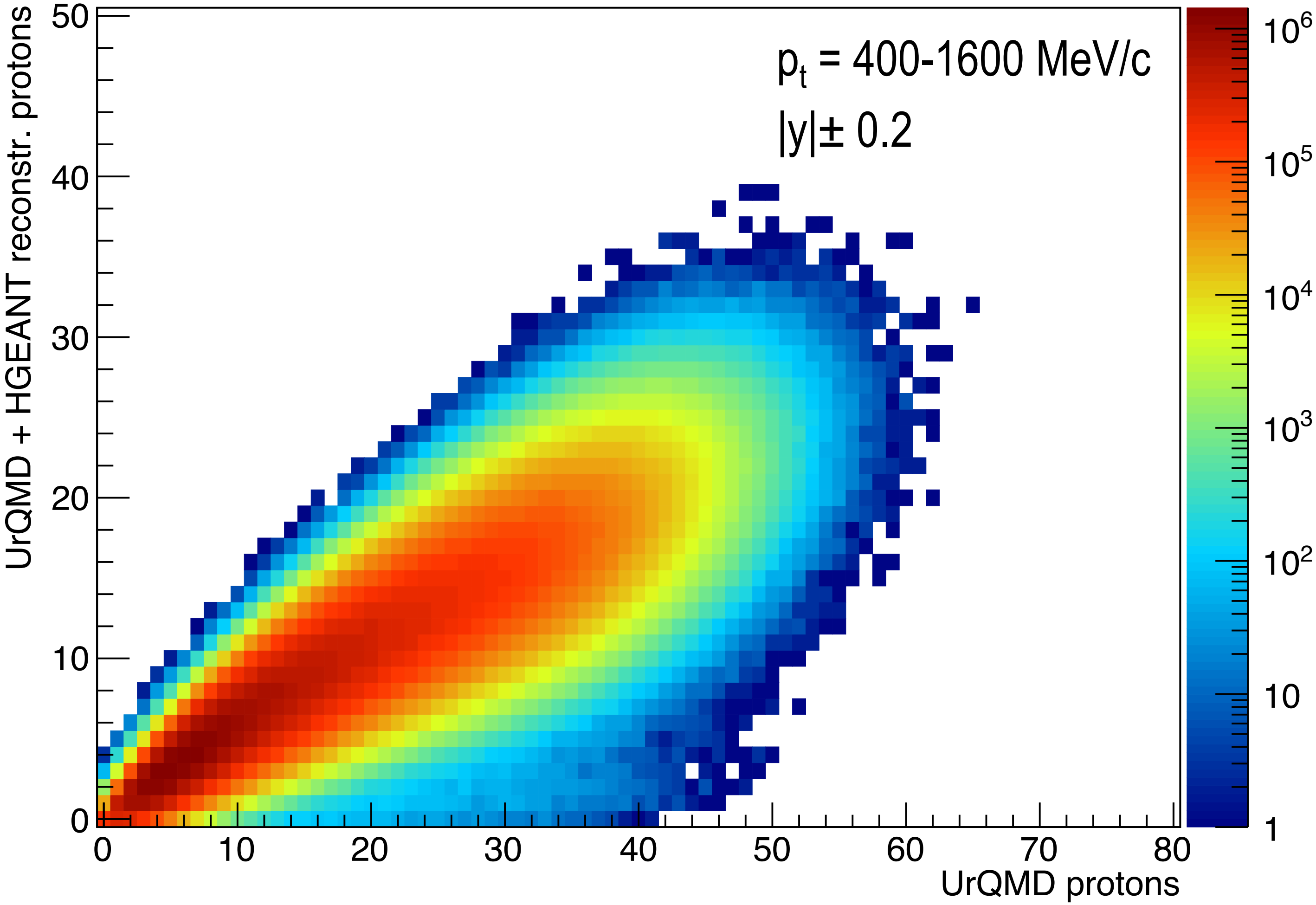
$$\begin{aligned}\mathcal{L}(x,\lambda) =& \mathcal{L}_1 + \mathcal{L}_2 + \mathcal{L}_3\\ \mathcal{L}_1 =& (\boldsymbol{y} - \mathbf{A}\boldsymbol{x})^{\mathsf{T}} \mathbf{V_{yy}}^{-1} (\boldsymbol{y} - \mathbf{A}\boldsymbol{x}),\\ \mathcal{L}_2 =& \tau^2 (\boldsymbol{x} - f_b \boldsymbol{x_0})^{\mathsf{T}} (\mathbf{L}^{\mathsf{T}}\mathbf{L}) (\boldsymbol{x} - f_b \boldsymbol{x_0}),\\ \mathcal{L}_3 =& \lambda (Y - \boldsymbol{e}^{\mathsf{T}} \boldsymbol{x})\end{aligned}$$

L_1: least square minimization

L_2: describes regularisation

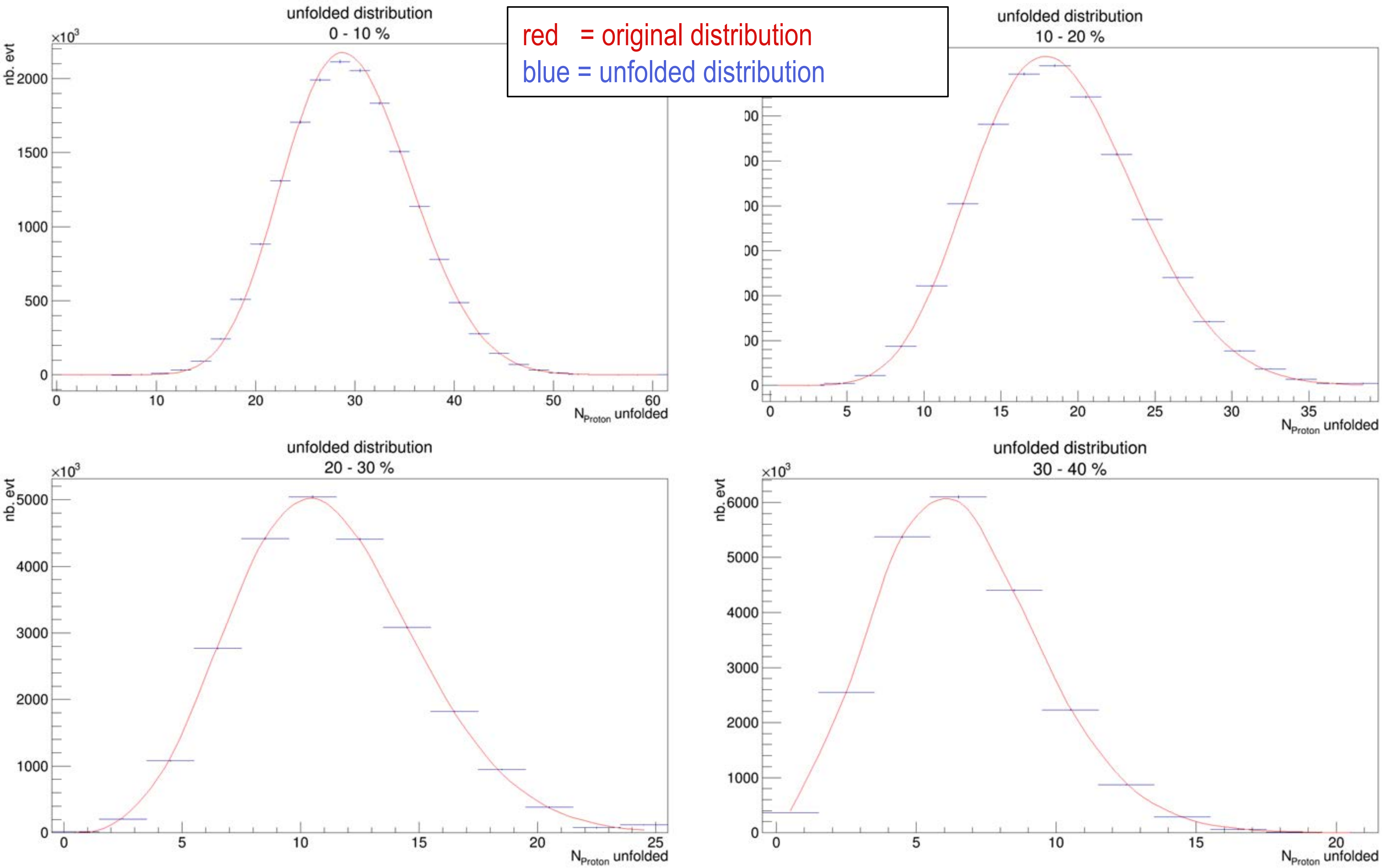
L_3: area constraint

Response function



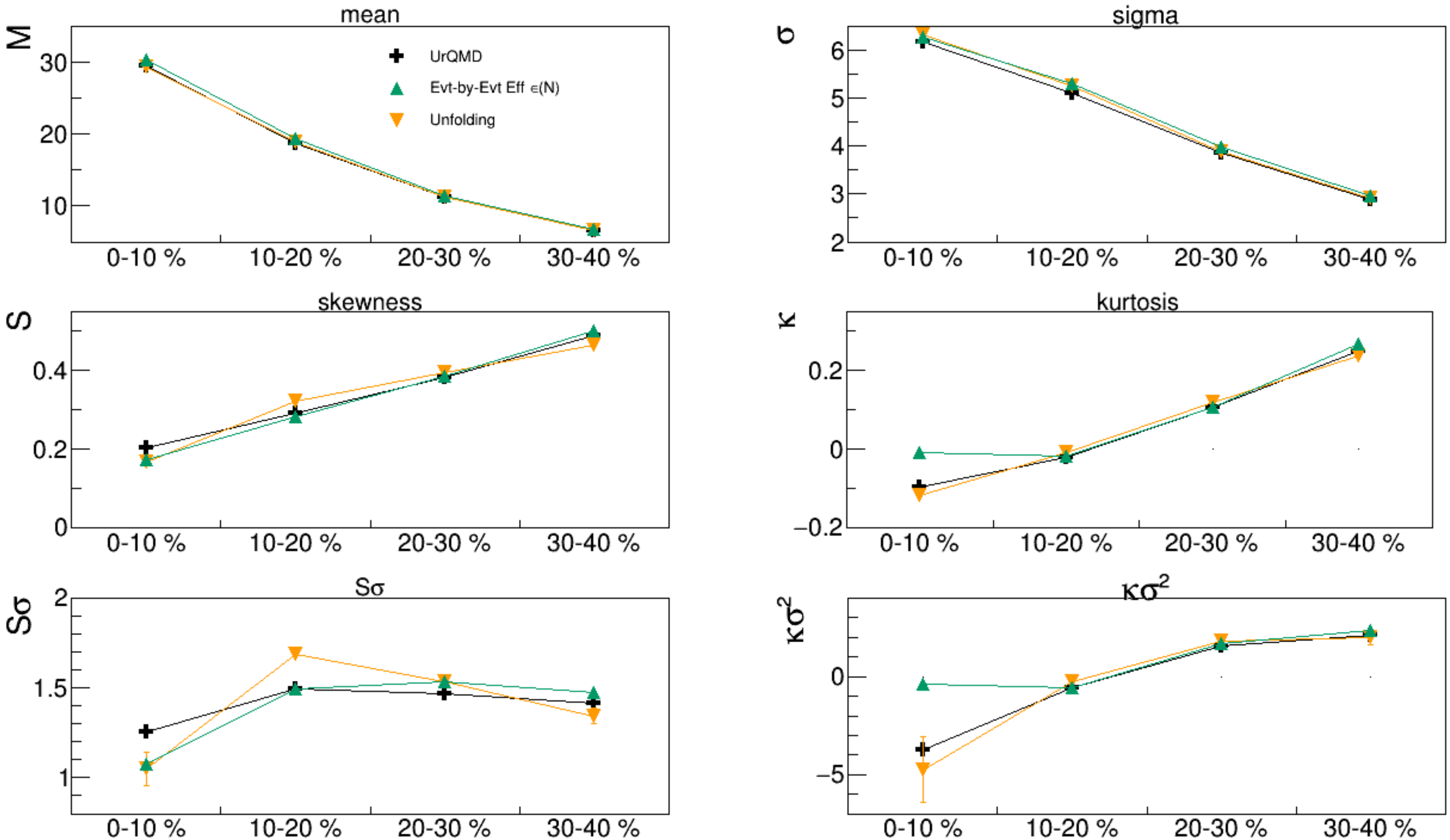
Unfolded distributions

red = original distribution
blue = unfolded distribution



Comparing methods
– Correct moments vs. Unfolding -

UrQMD

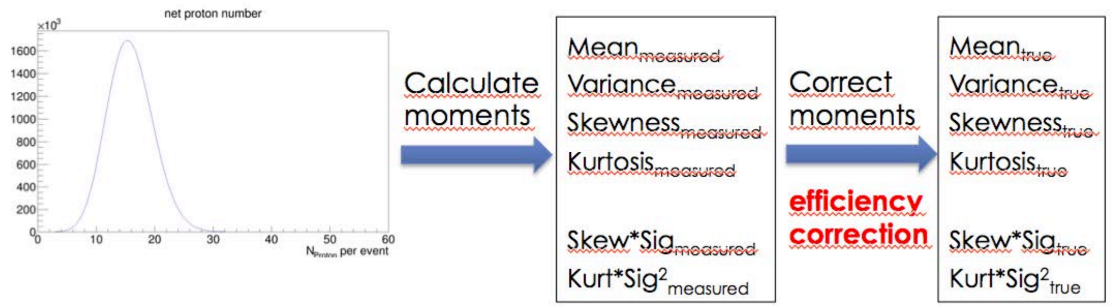


Efficiency correction

→ Correct the moments

Bzdak & Koch, PRC 86 (2012);

Xiaofeng Luo, arXiv:1410.3914 (2014)



→ Correct moment on unfold

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

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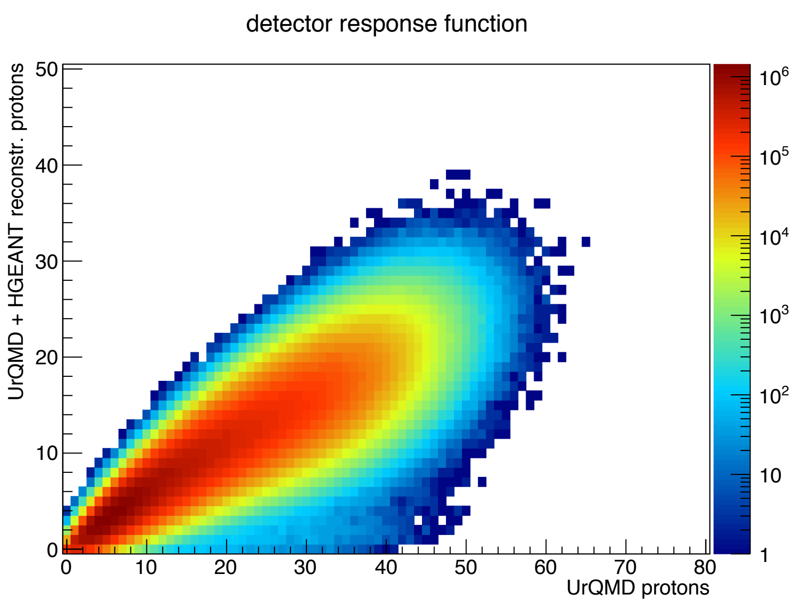
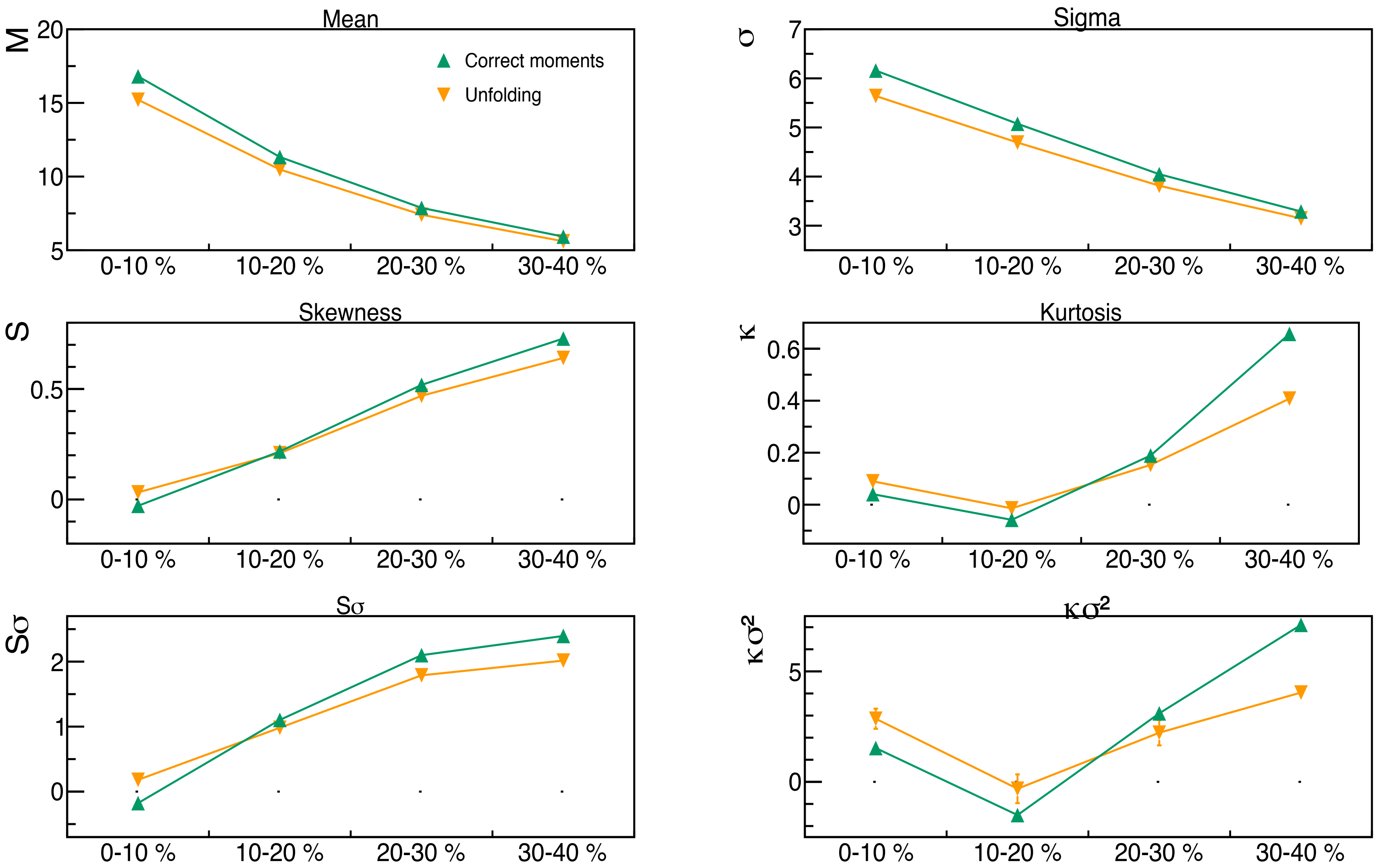
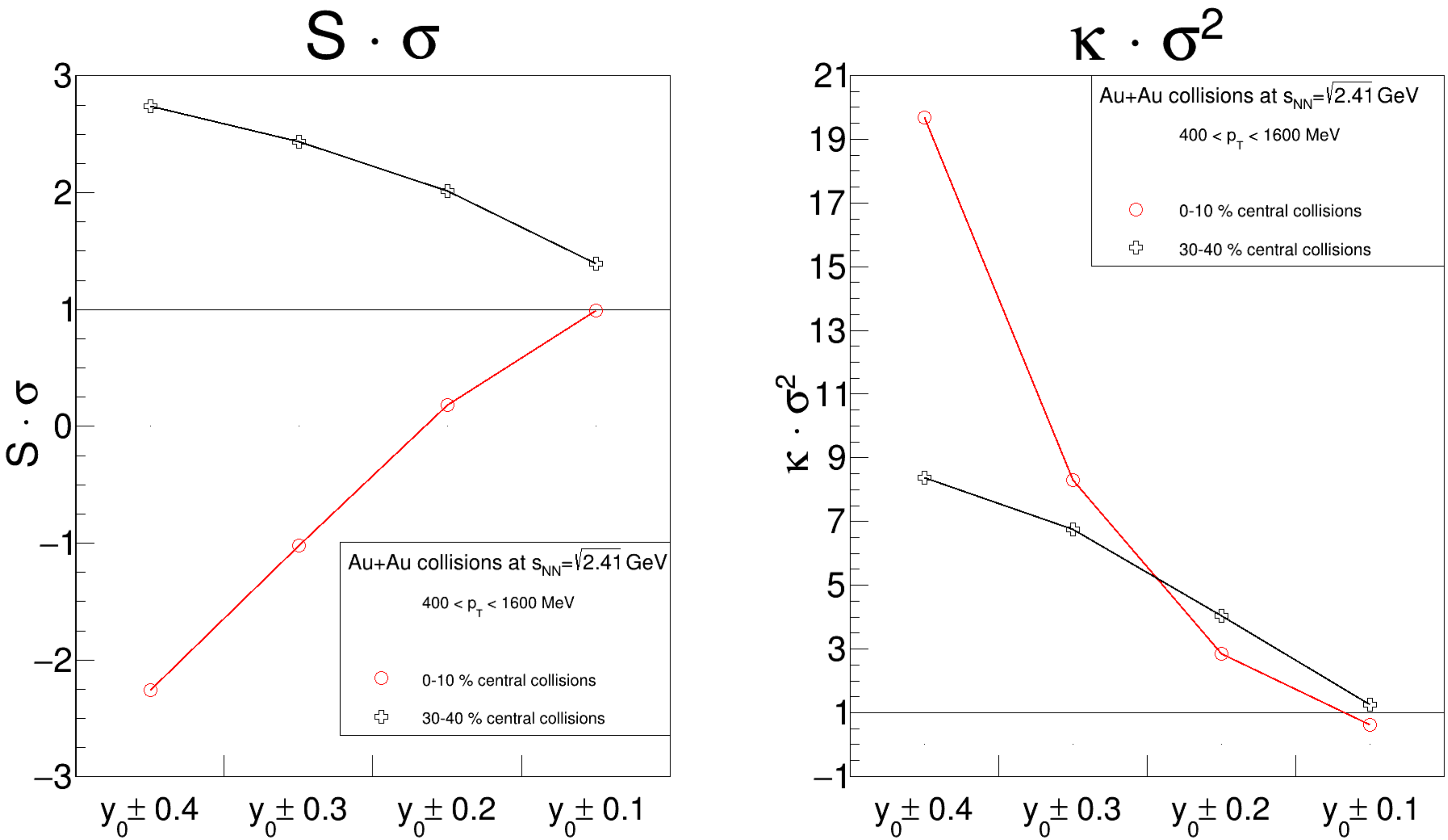


Results (eff. Corr.)



Poissonizer

$\Delta y_{total} \gg \Delta y_{accept} \gg \Delta y_{corr}$



Experimental Observables

Cumulants of event-by-event net-particle multiplicity distributions

- **(Net-)proton** (proxy for net-baryon)

Mean	M	$=$	K_1
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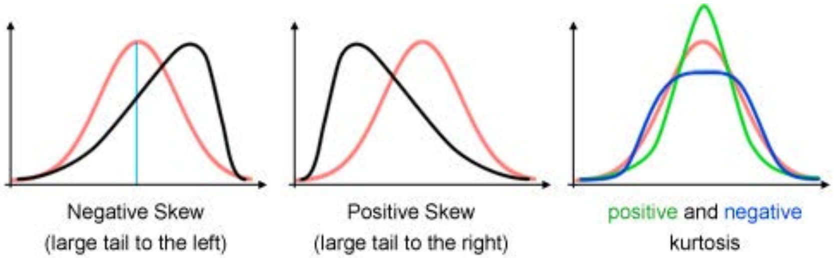


Cumulant ratios to cancel volume effects

$$S \cdot \sigma = \frac{K_3}{K_2} \qquad \kappa \cdot \sigma^2 = \frac{K_4}{K_2}$$

→ Cumulant ratios cancel only mean volume effects!

Volume Fluctuations

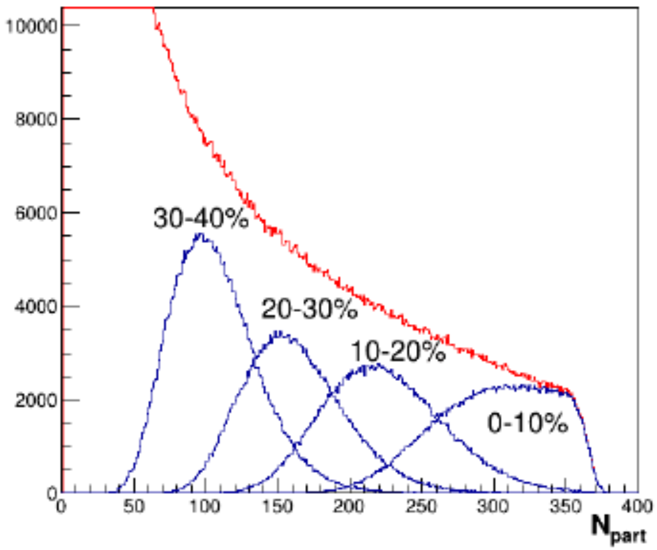
V. Skokov, B. Friman, and K. Redlich, Physical Review C 88, 034911 (2013)

→ The effect of volume fluctuations on cumulants of the net baryon number

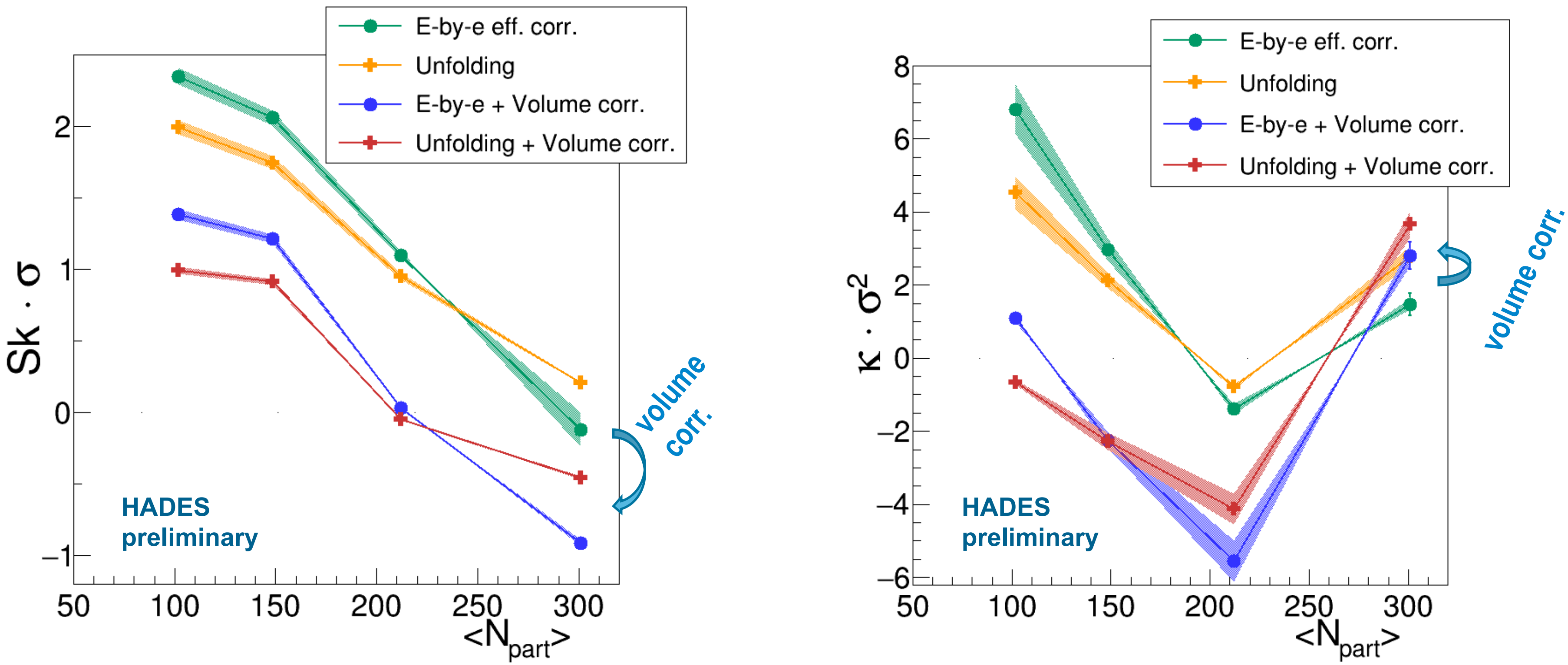
$$\boxed{\begin{aligned} c_1 &= \kappa_1, \\ c_2 &= \kappa_2 + \kappa_1^2 v_2, \\ c_3 &= \kappa_3 + 3\kappa_2\kappa_1 v_2 + \kappa_1^3 v_3, \\ c_4 &= \kappa_4 + \left(4\kappa_3\kappa_1 + 3\kappa_2^2\right) v_2 + 6\kappa_2\kappa_1^2 v_3 + \kappa_1^4 v_4, \end{aligned}}$$

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

→ Npart ~ volume
→ Modeled (Glauber and iQMD) N_{part} distribution to calculate the volume fluctuation cumulants

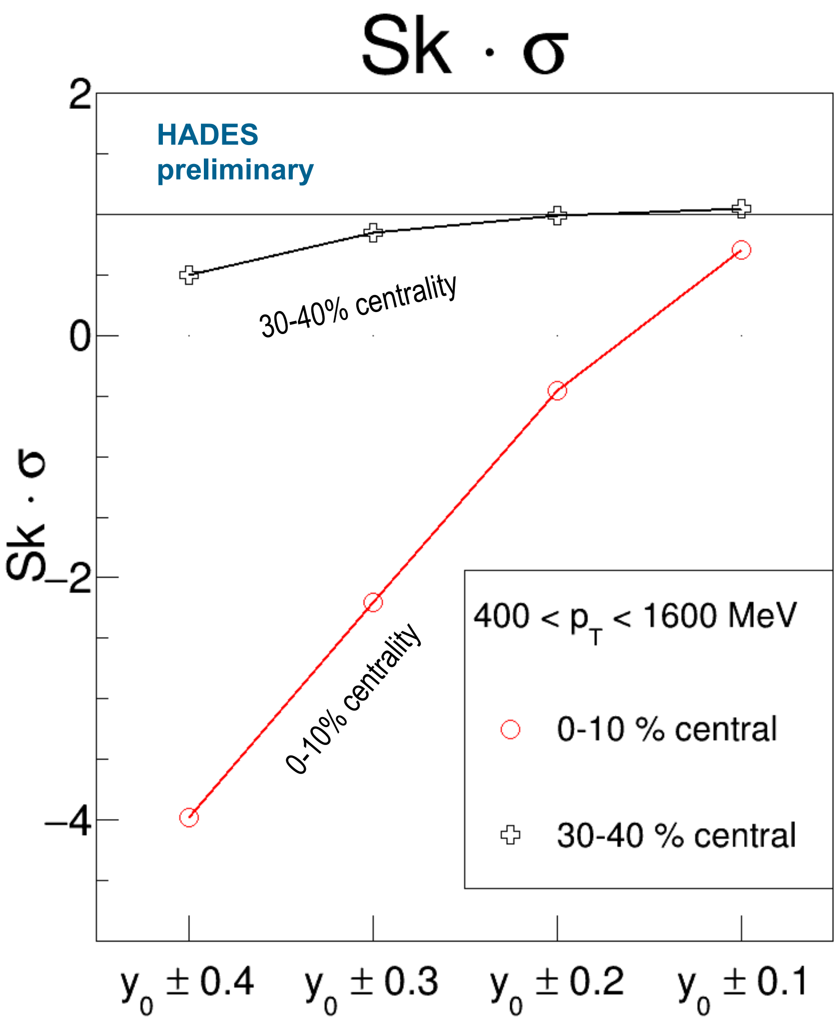


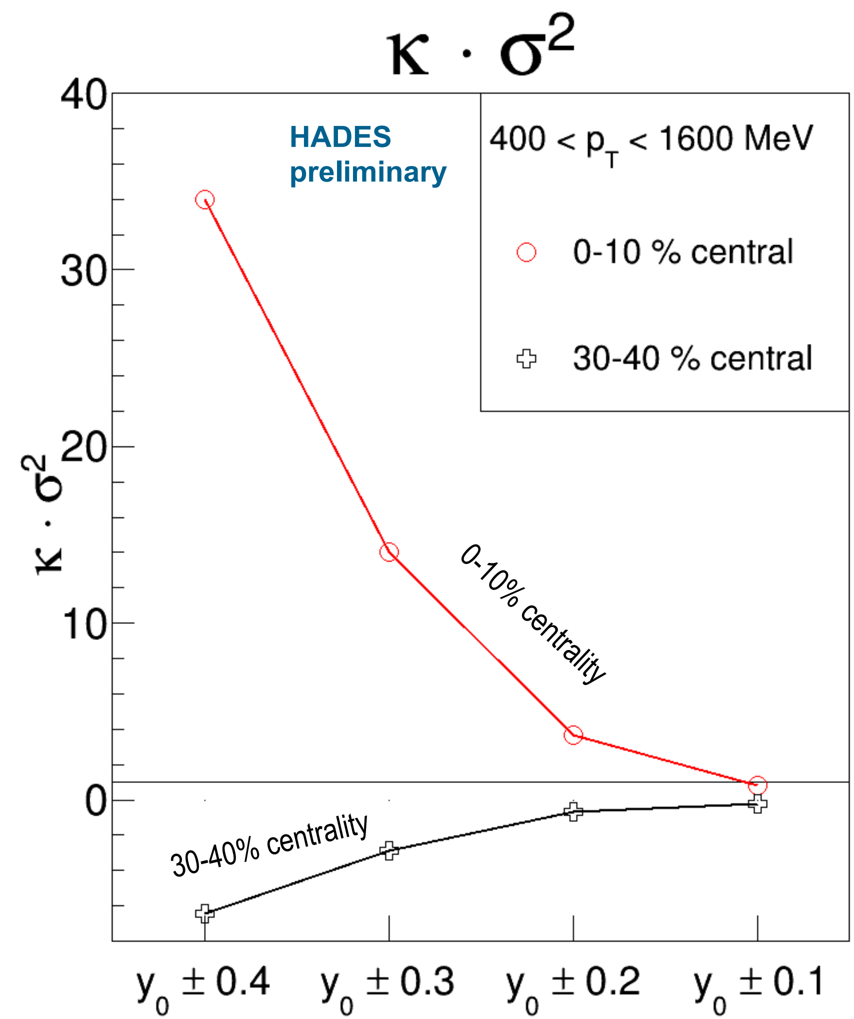
Fully corrected scaled moments



- Error bands corresponds to 5% systematic error on proton efficiencies
- Scaled cumulants deviate from Poisson
- Volume corrections on $\kappa 4/\kappa 2$ smallest for most central

Poisson Limit: Δy→0



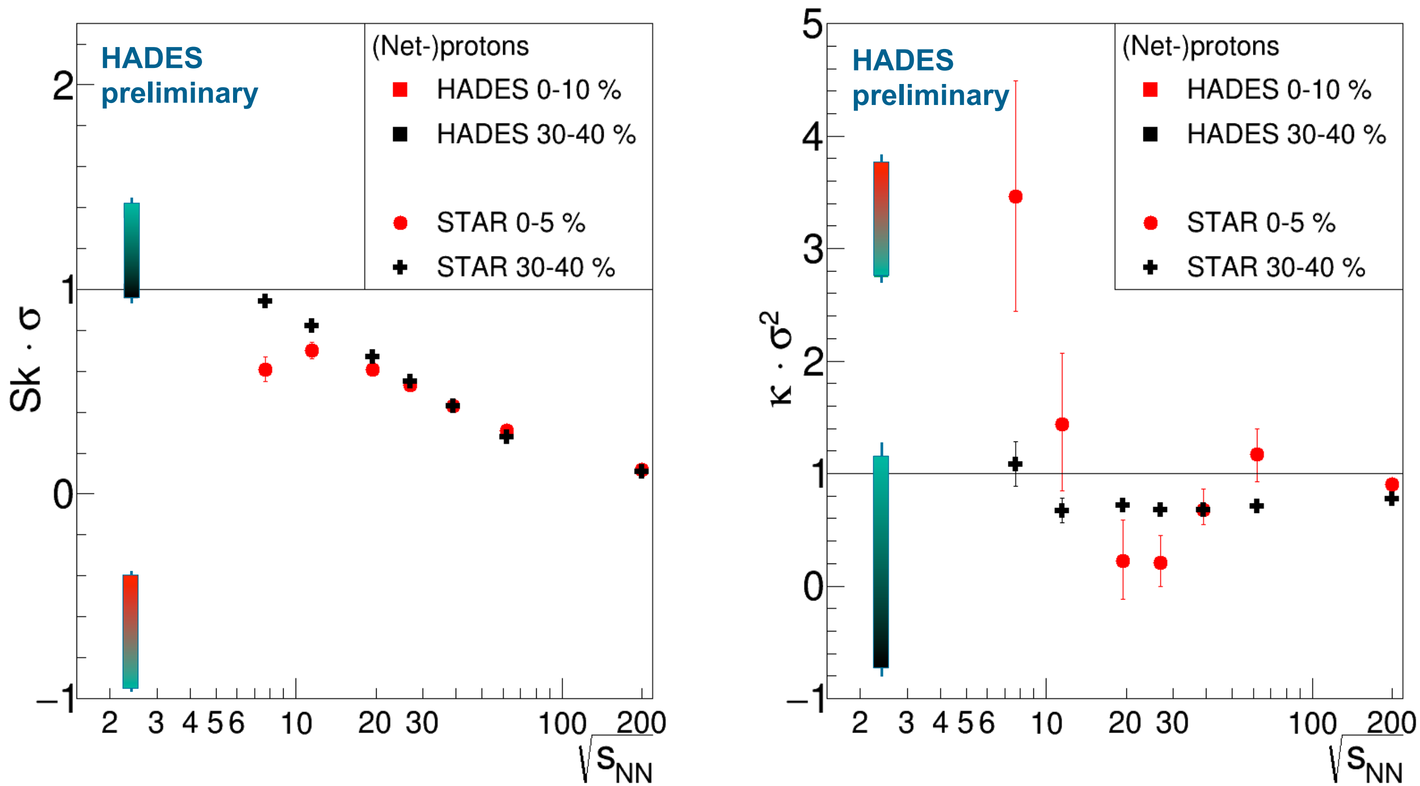


Comparison with STAR - (Net-) Proton

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

HADES:
p_t = 400 – 1600 MeV/c
$y = y_0$ +- 0.2
Forward Wall
Volume Corrected

STAR:
p_t = 400 – 2000 MeV/c
$y = y_0$ +- 0.5
NOT Volume Corrected



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

Conclusions

Study of centrality selection and efficiency correction in simulation

Introduction of two different eff. correction methods

- Within error bars, both methods deliver compatible results

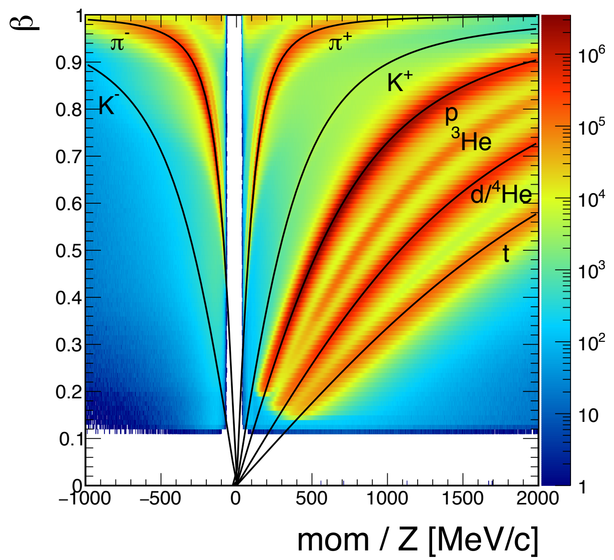
First look to volume fluctuation correction

- Volume correction influences higher order moments

Choice of phase-space bin ? (p_t, y)

Fluctuations on baryon number

- Bound protons?!

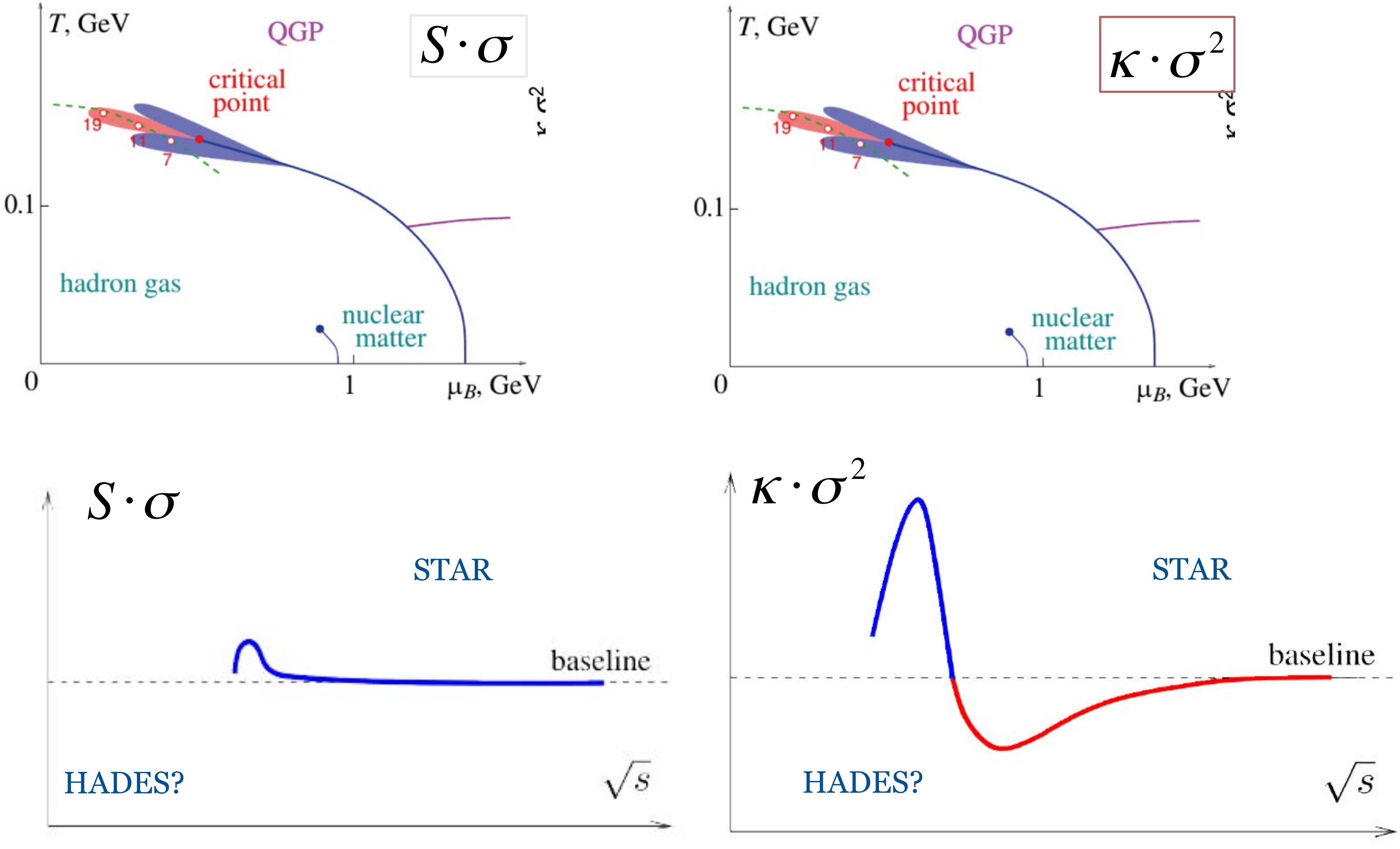


The HADES Collaboration

Backup

Theoretical Expectation

Misha Stephanov, CPOD 2014



Correct the moments

(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)

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

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

Bzdak & Koch, PRC 86 (2012);
Xiaofeng Luo, arXiv:1410.3914 (2014)

Volume Corrections