Fluctuations-EXP

Anar Rustamov

a.rustamov@gsi.de

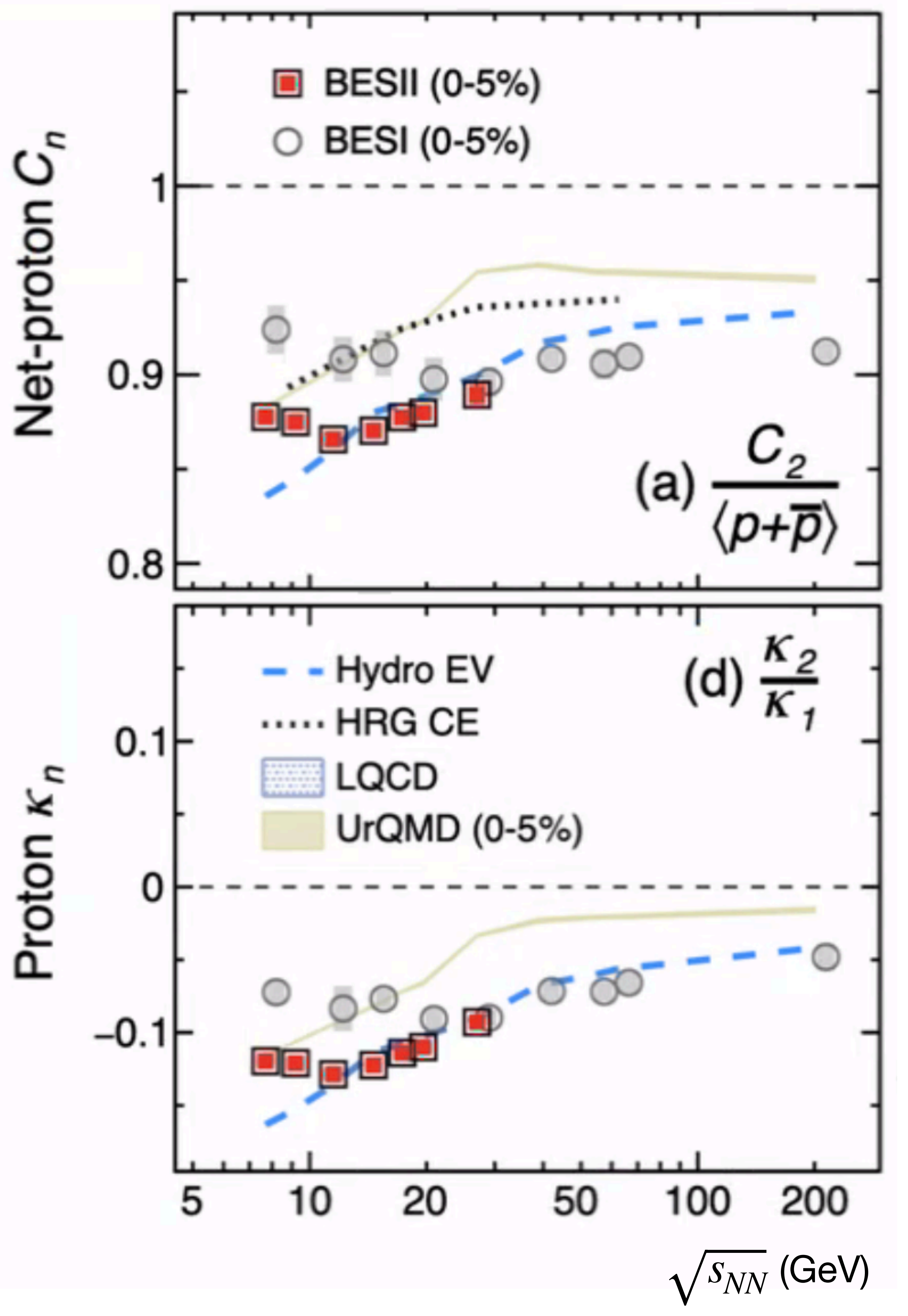
a.rustamov@cern.ch

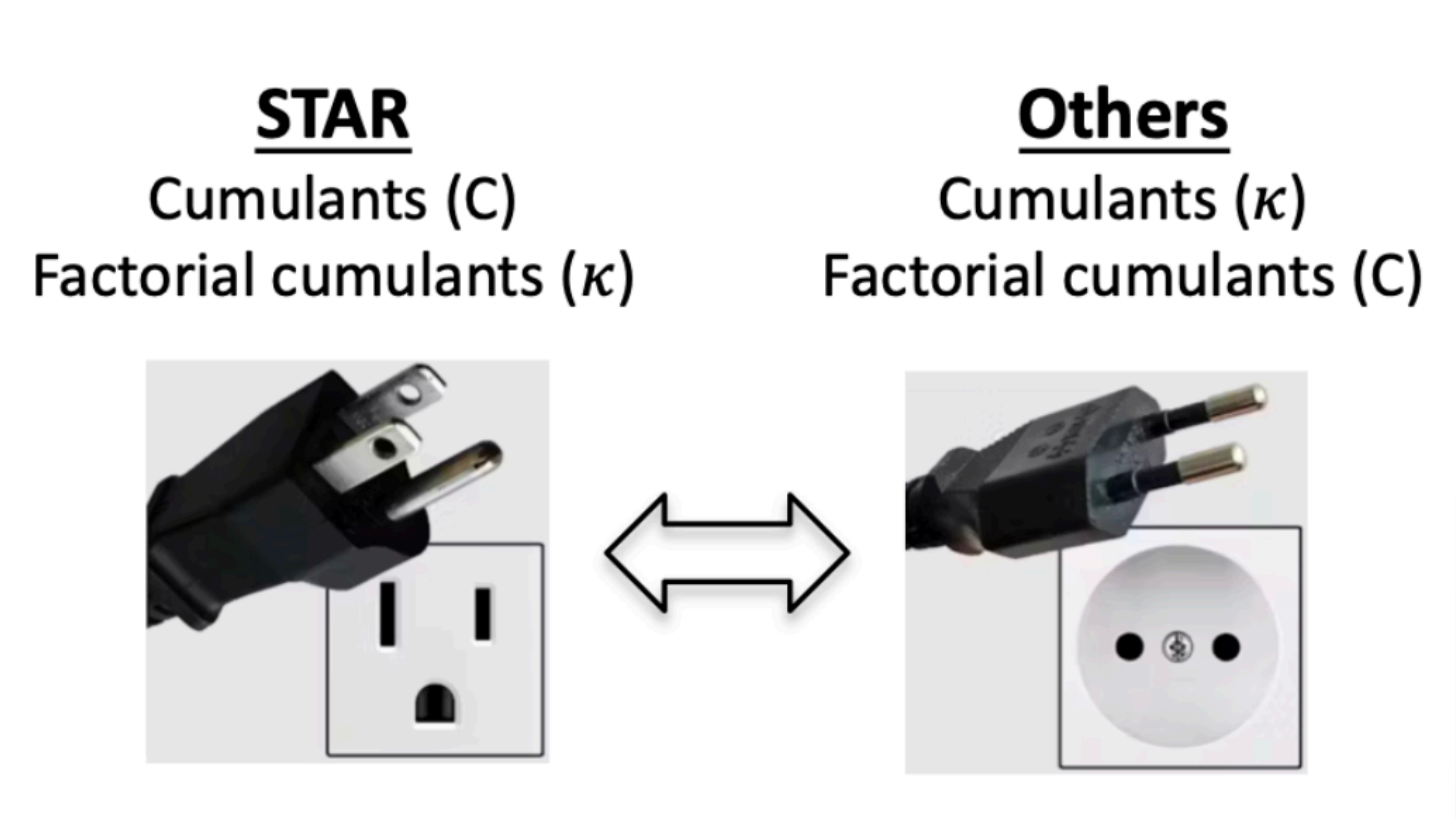
The QCD Critical Point: Are We There Yet?

INT program, Seattle, WA, October 27 - November 7, 2025

STAR Measurements: BES-I vs. BES-II

- Besed on: A. Pandav, CPOD 2024





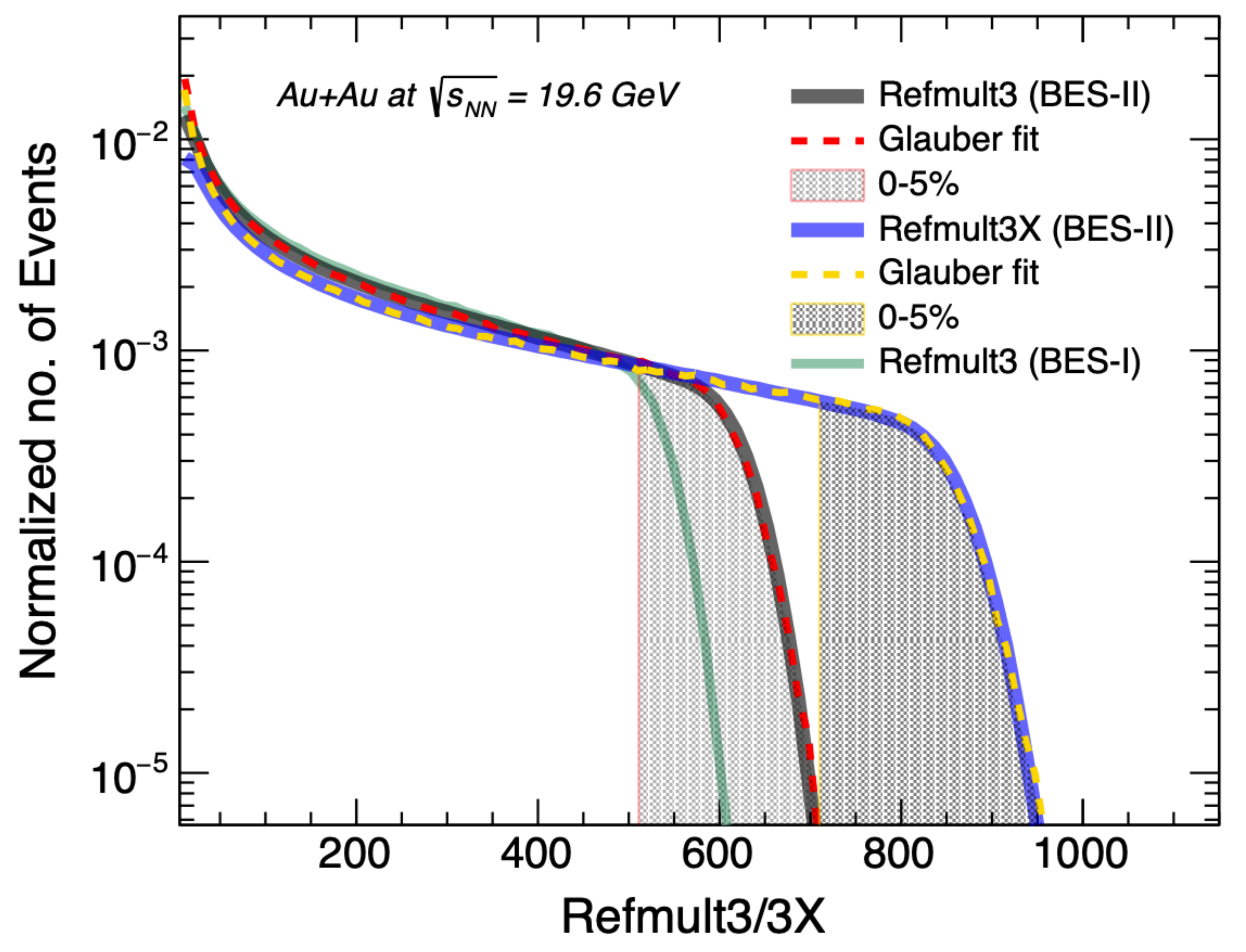
- Mesut Arslandok, Quark Matter

Do we understand the differences between BES-I and BES-II?

Do we have good control of **systematic uncertainties**?

STAR Measurements: Centrality Selection

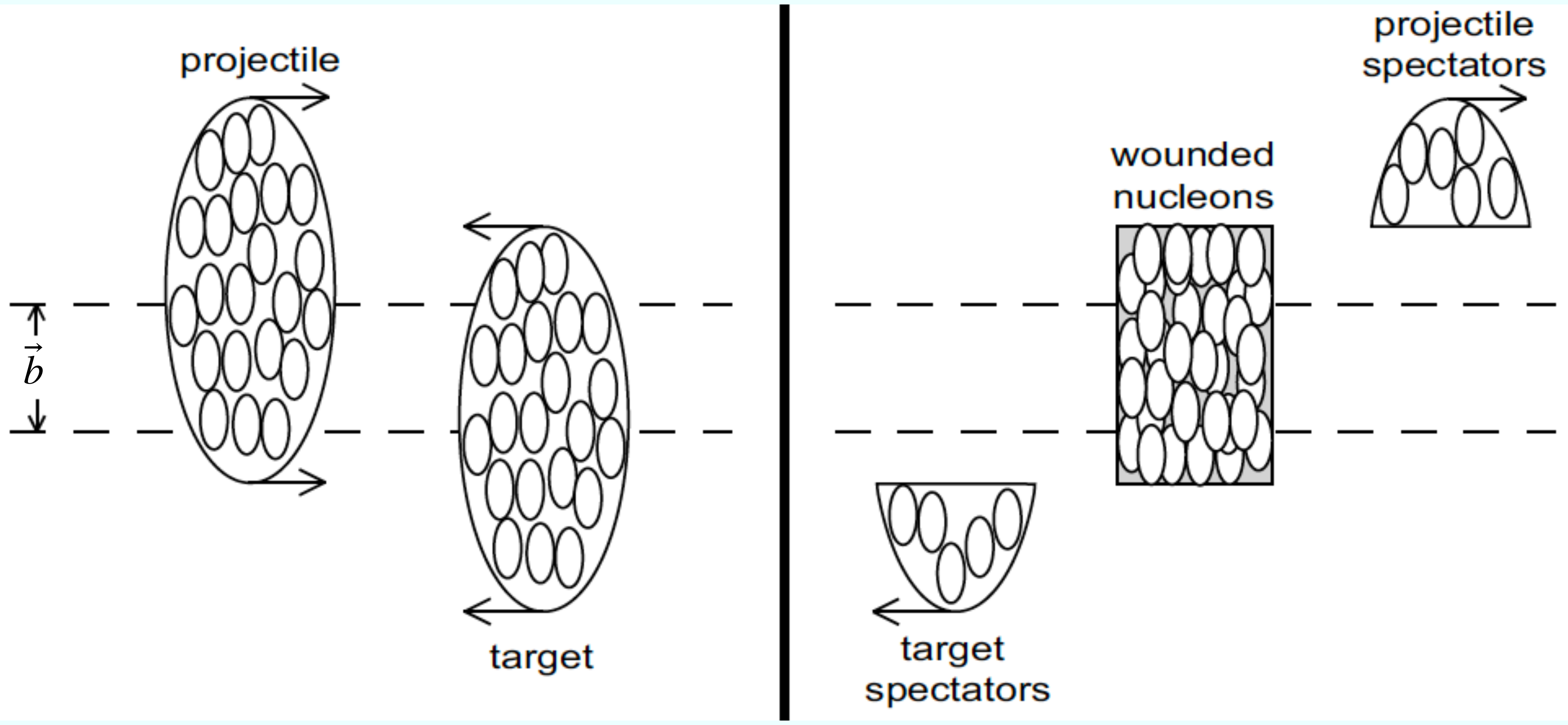
- A. Pandav, CPOD 2024



- **BESI, Refmult3:**
  - Charged-particle multiplicity excluding protons, measured within $|\eta| < 1.0$
- **BESII, Refmult3X:**
  - Charged-particle multiplicity excluding protons, measured within $|\eta| < 1.6$
    - made possible owing to iTPC upgrade
- **Larger multiplicity -> better resolution**
  - Refmult3X (BES-II) > Refmult3 (BES-II) > Refmult3 (BES-I)

Can this alone explain the observed differences? 🤔

Volume Fluctuations



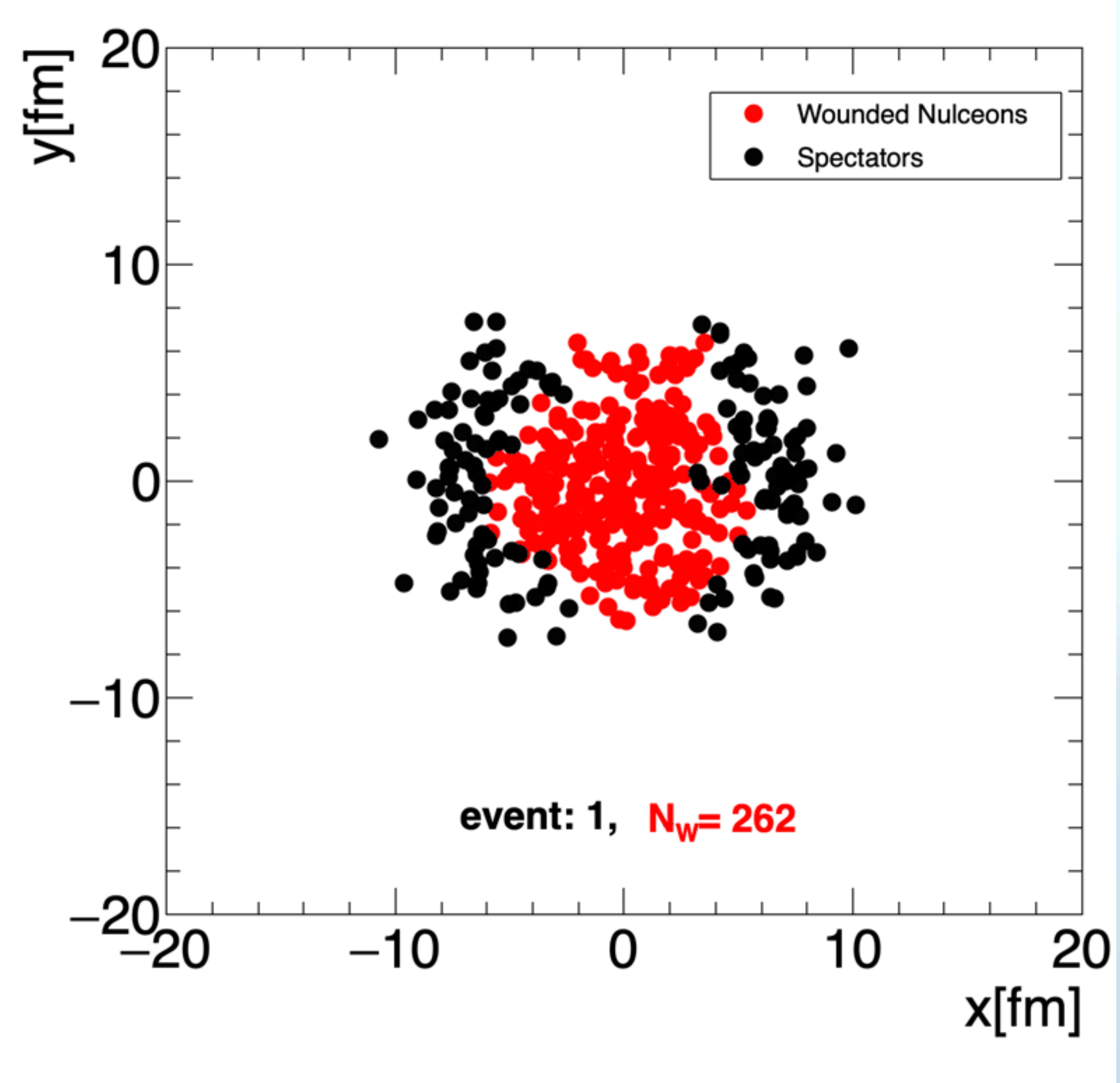
A. Bialas, and M. Bleszynski, W. Czyz, Nucl. Phys. B111 (1976) 461

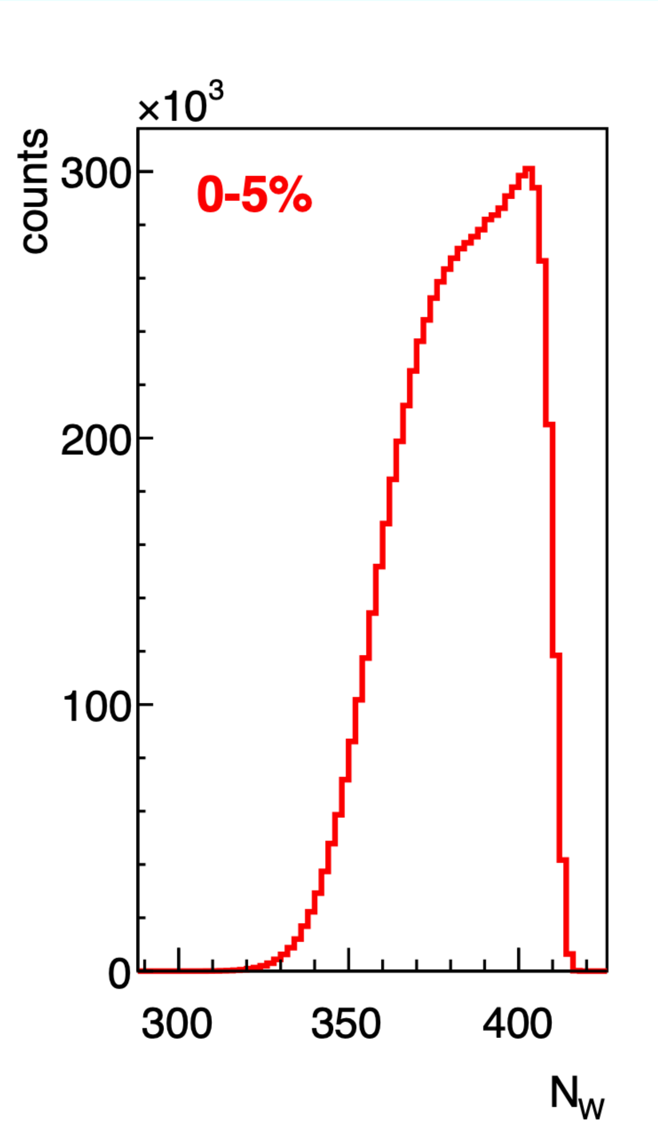
In this paper we propose to describe the nucleus-nucleus collisions in terms of the number of "wounded" nucleons (w) i.e. the number of nucleons which underwent at least one inelastic collisions in this process.

Wounded nucleons, N_W

- Nucleons which collided at least once inelastically

Detailed application: P. Braun-Munzinger, A.R., J. Stachel, NPA 960 (2017) 114





Correction methods for wounded nucleon/volume fluctuations

V. Skokov, B. Friman, and K. Redlich, Phys.Rev. C88 (2013) 034911

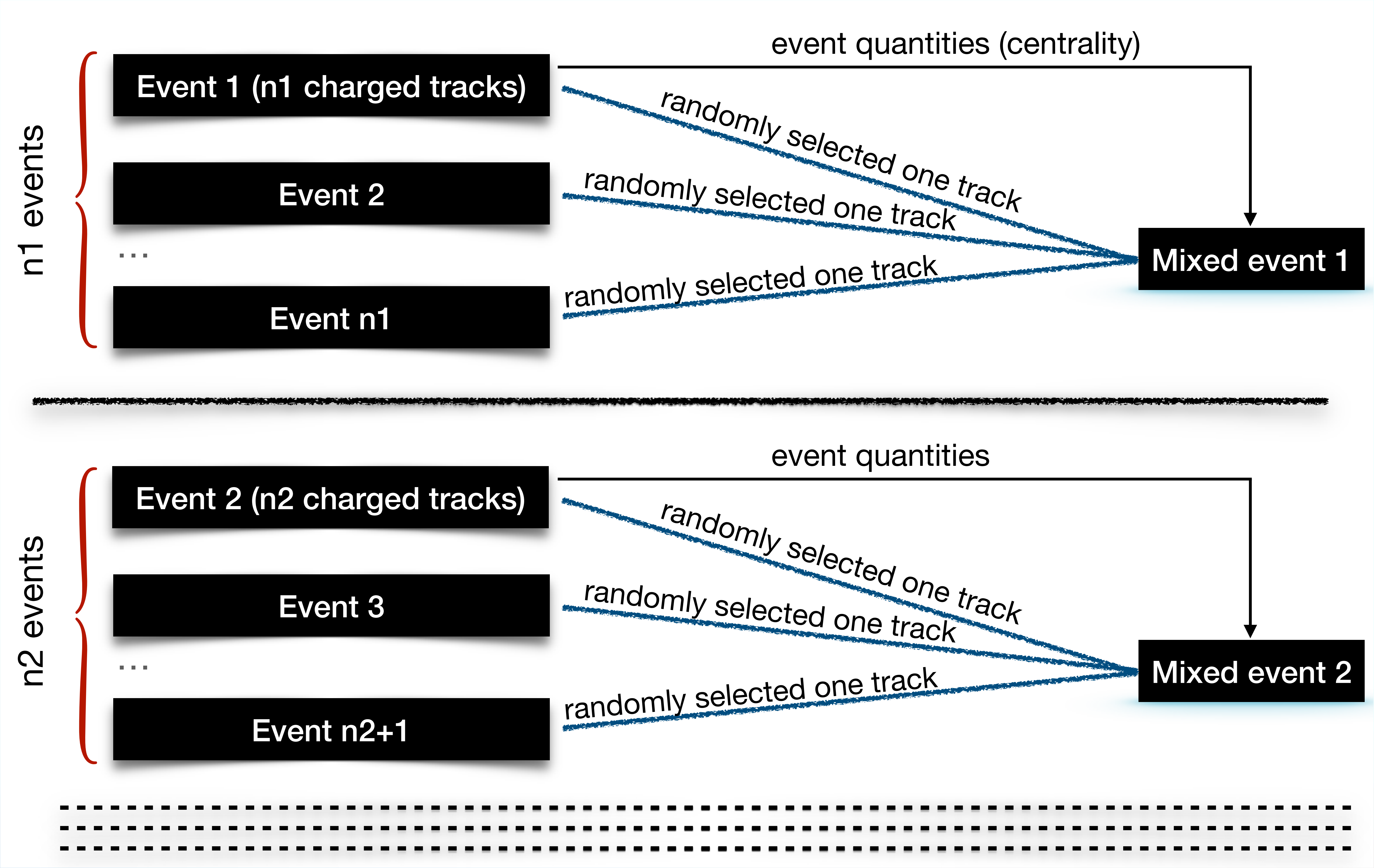
P. Braun-Munzinger, A.R., J. Stachel, NPA 960 (2017) 114

Experiment driven:

A.R., R. Holzmann, J. Stroth, NPA 1034 (2023) 122641

V. Koch, R. Holzmann, A.R., J. Stroth, Nucl.Phys.A 1050 (2024) 122924

Event Mixing Technique



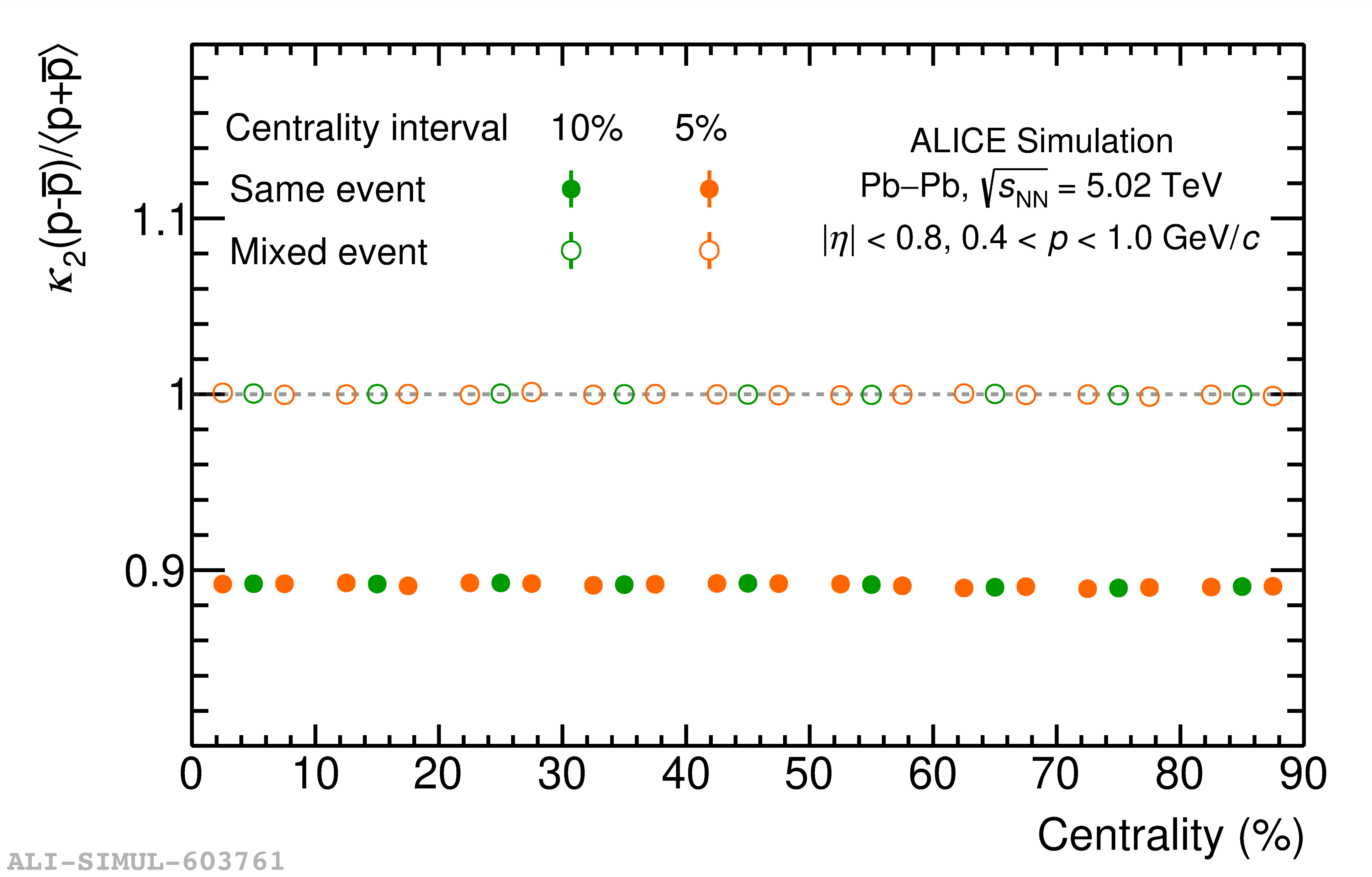
Dedicated Event Mixing Procedure

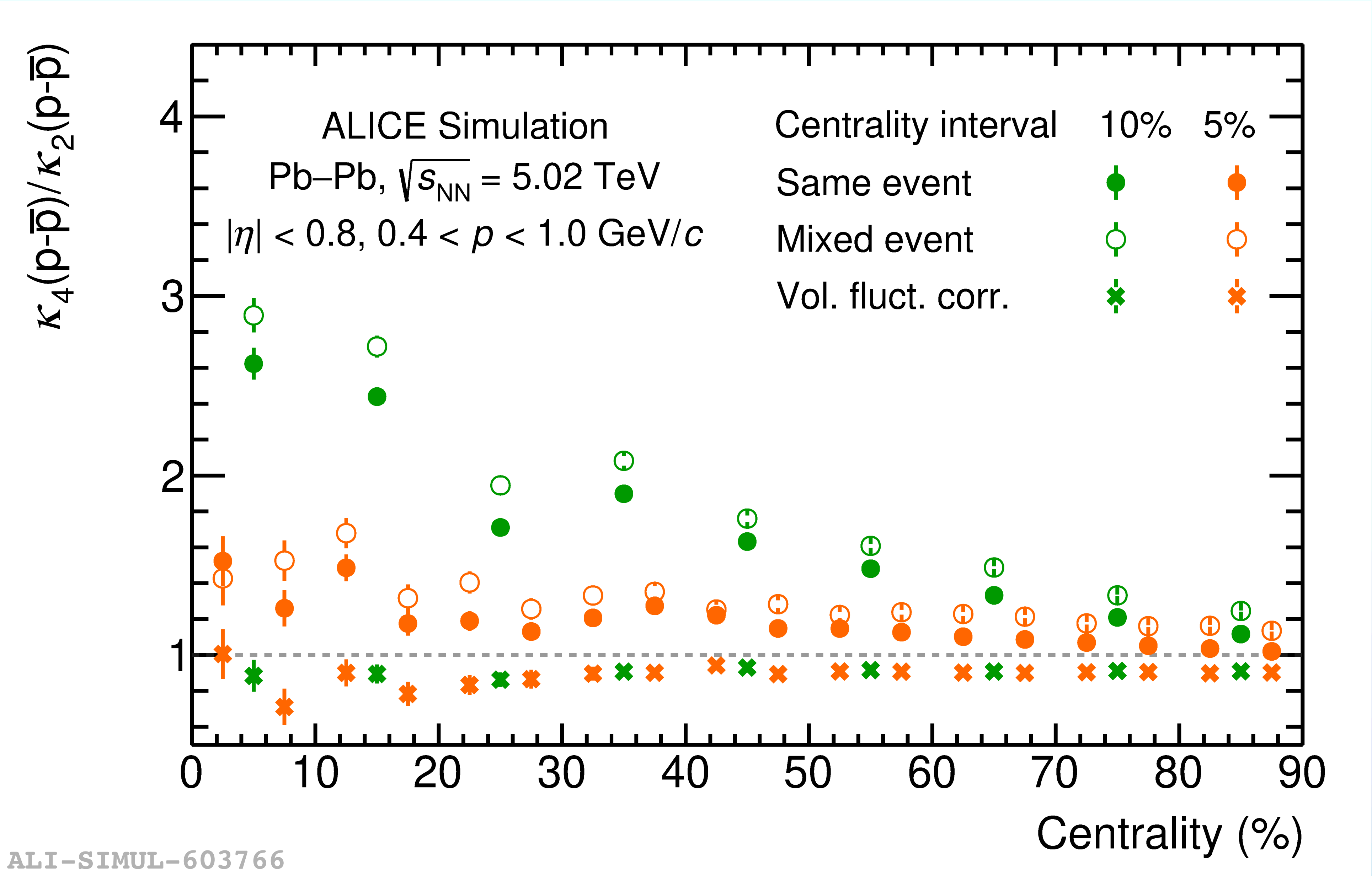
- Preserves volume fluctuations
- Removes genuine physics correlations
  - To a large extent!

A.R., R. Holzmann, J. Stroth, NPA 1034 (2023) 122641

V. Koch, R. Holzmann, A.R., J. Stroth, Nucl.Phys.A 1050 (2024) 122924

Checking the validity of the event mixing approach





$$\kappa_2(\Delta N) = \langle N_W\rangle \kappa_2(\Delta n) + \langle \Delta N\rangle^2 \frac{\kappa_2(N_W)}{\langle N_W\rangle^2}$$

At LHC energies: $\langle \Delta N\rangle = 0$

$$\kappa_4(\Delta N) = \langle N_W\rangle \kappa_4(\Delta n) + 3\kappa_2^2(\Delta n)\,\kappa_2(N_W)$$

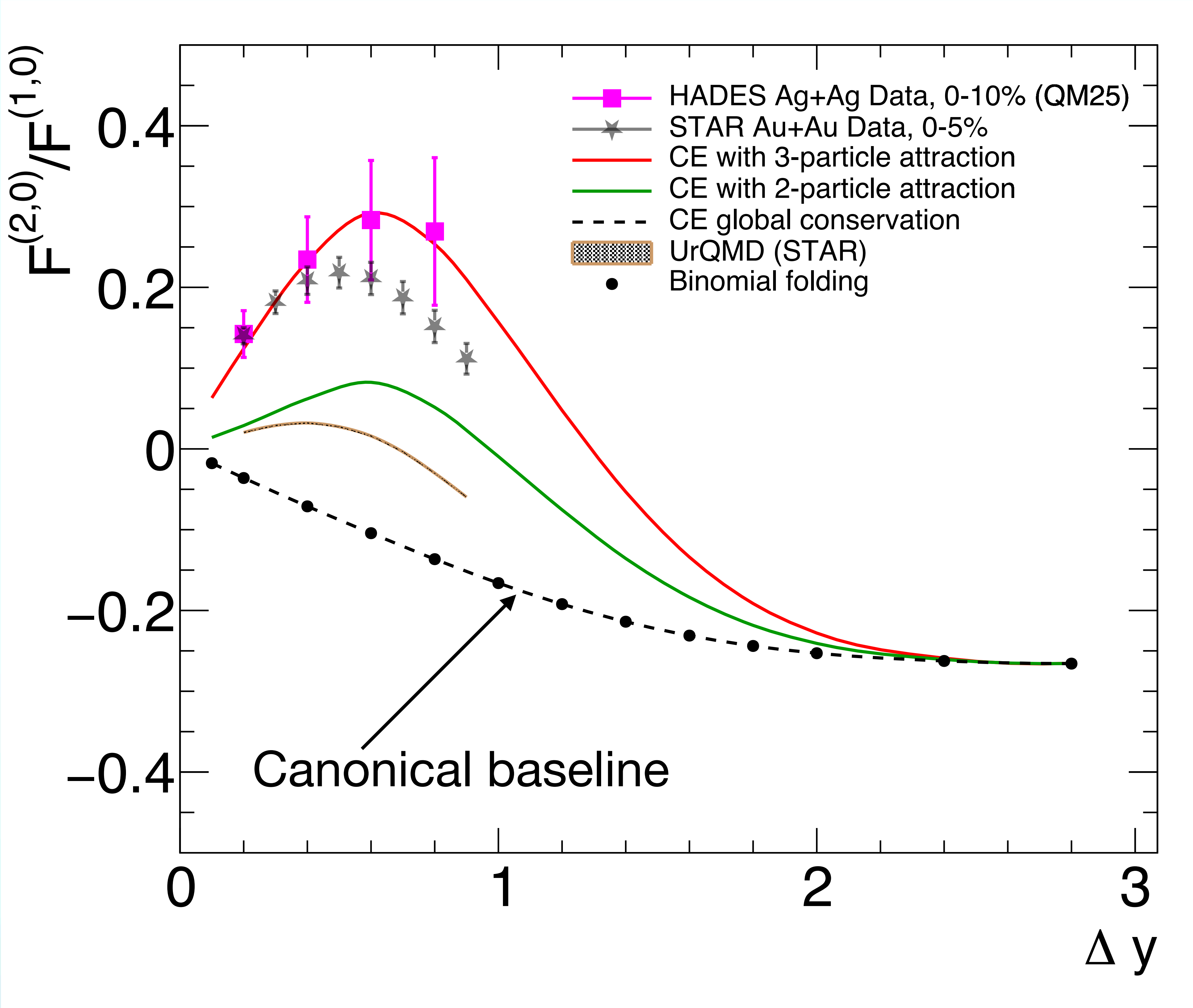
for $\langle \Delta N\rangle = 0$

- Mesut Arslandok, Quark Matter 2025, e-Print: 2510.09115 [hep-ex]

V. Skokov, B. Friman, and K. Redlich, Phys.Rev. C88 (2013) 034911

P. Braun-Munzinger, A.R., J. Stachel, NPA 960 (2017) 114

HADES & STAR-FXT Data



yet another notation for factorial cumulants 😩

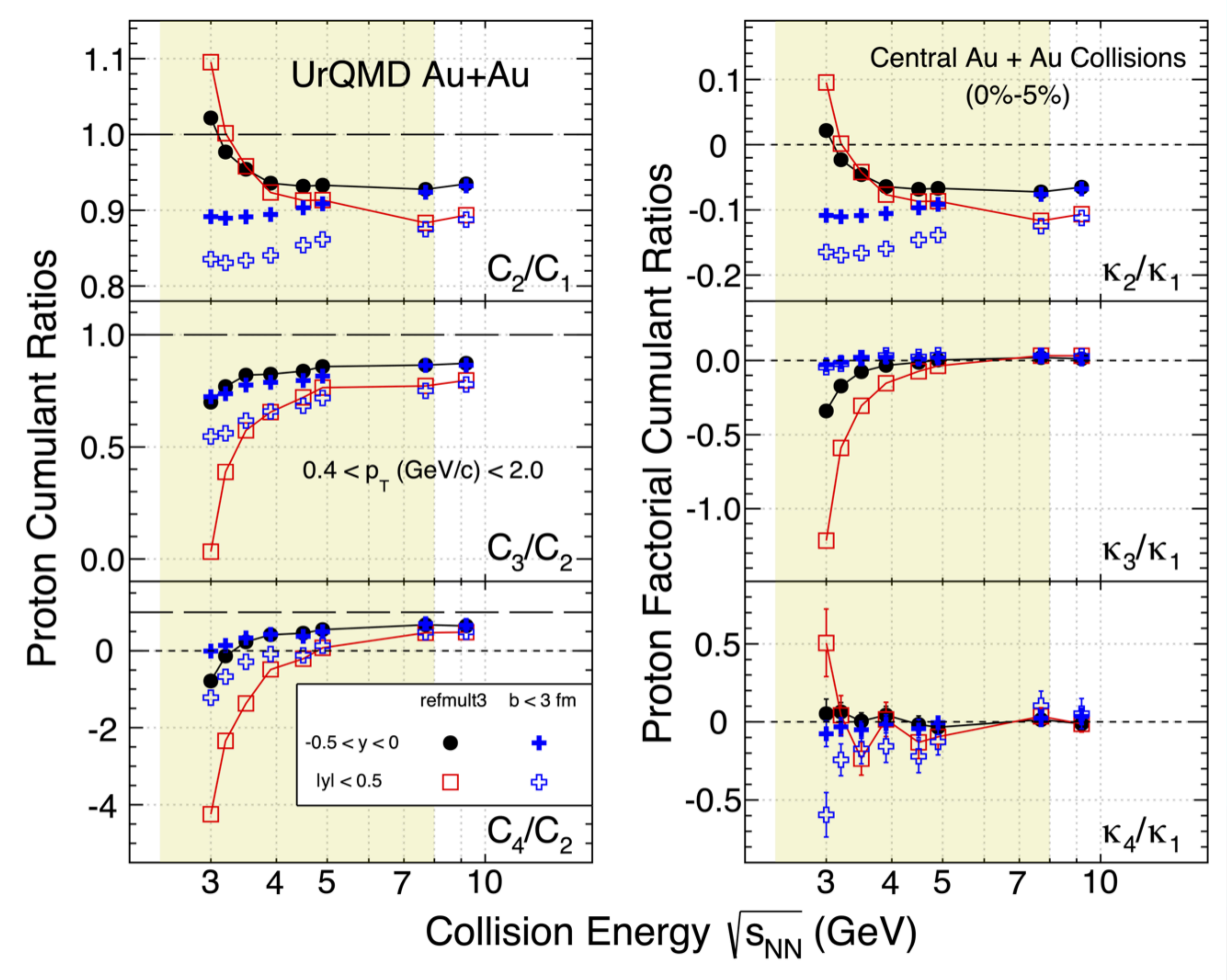
$$F^{(n,0)} \rightarrow C(n)$$

- Calculations: B. Friman, A. R., K. Redlich, e-Print: 2508.18879 [nucl-th]
- HADES: Marvin Nabroth, Quark Matter 2025
- STAR: Phys.Rev.C 107 (2023) 2, 024908

HADES Ag–Ag @ 2.5 GeV and **STAR FXT Au–Au @ 3 GeV** show the same trend

HADES: Ag-Ag, $\langle N_W \rangle \approx 170$	**STAR FXT:** Au-Au, $\langle N_W \rangle \approx 320$
$-0.4 < y < 0.4$	$-0.5 < y < 0$
$0.4 < p_t < 1.6$ GeV/c	$0.4 < p_t < 2$ GeV/c

Dependence on centrality selection; test with UrQMD

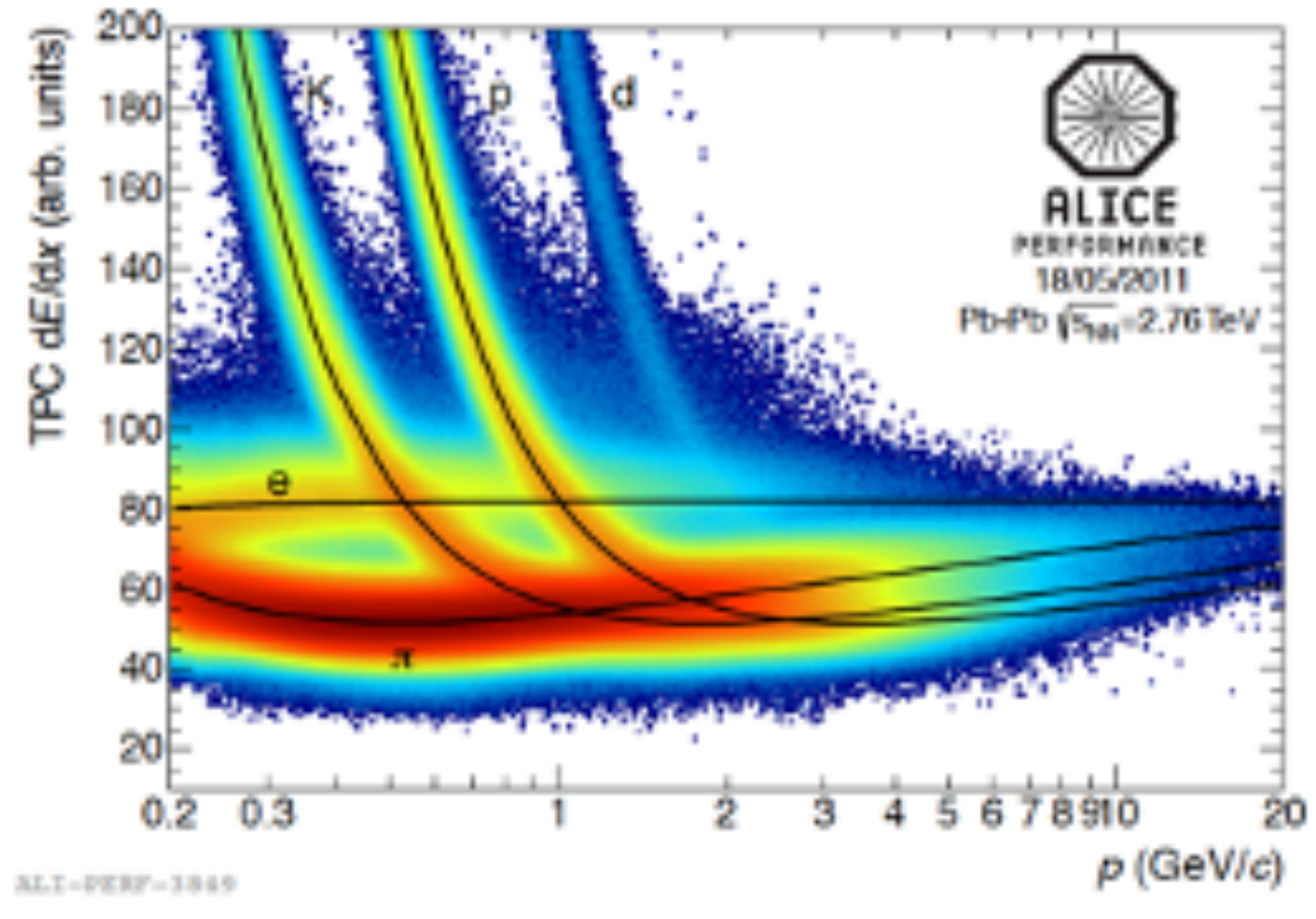


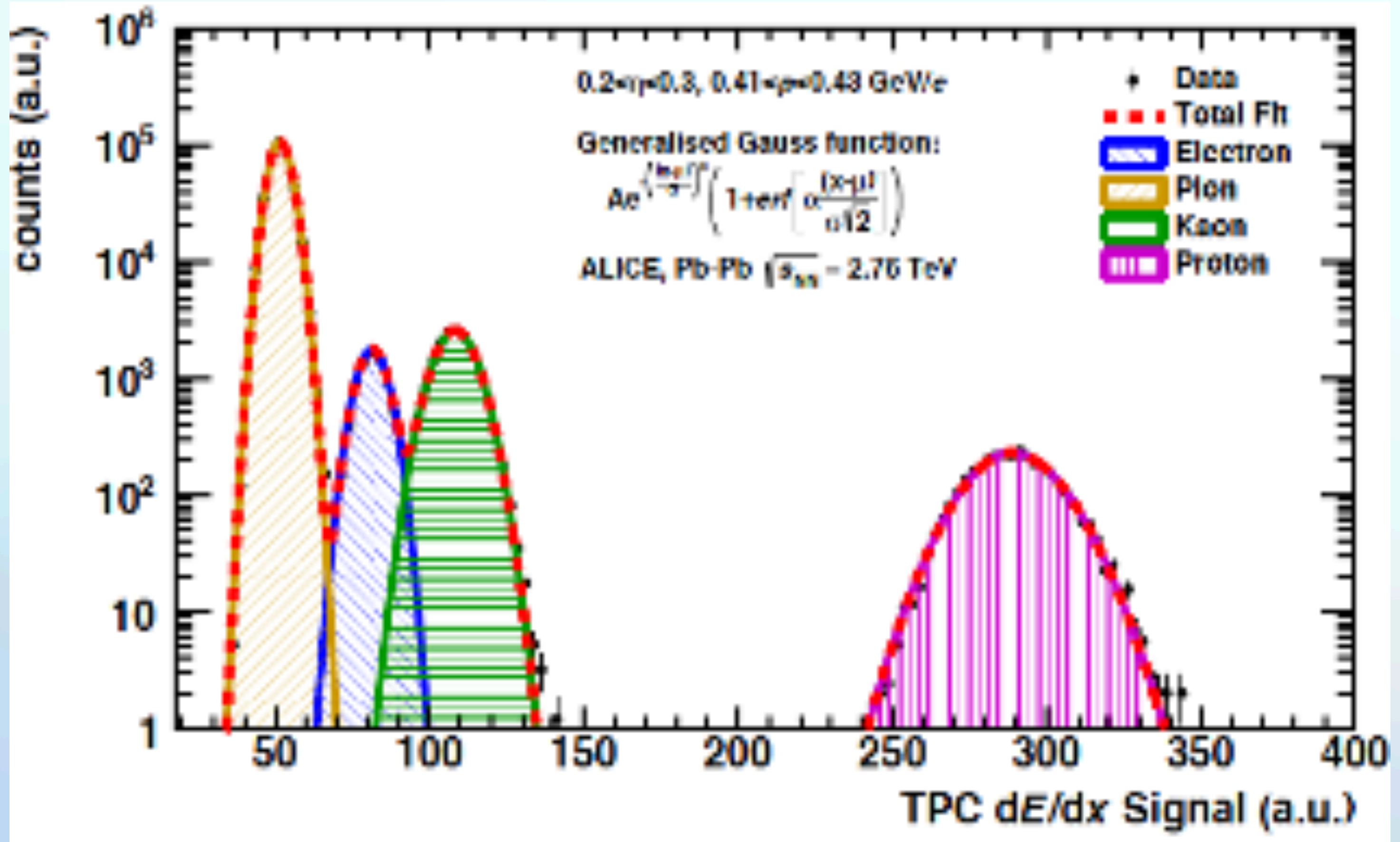
- Centrality determination following STAR procedure 🎯
- Study of residual volume fluctuations using UrQMD ⚙️
- Benchmark for testing CBWC effectiveness 📊

▶ Xin Zhang,1 Yu Zhang, X. Luo,3 and Nu Xu, e-Print: 2506.18832 [nucl-ex]

Artifacts of incomplete Particle Identification (PID)

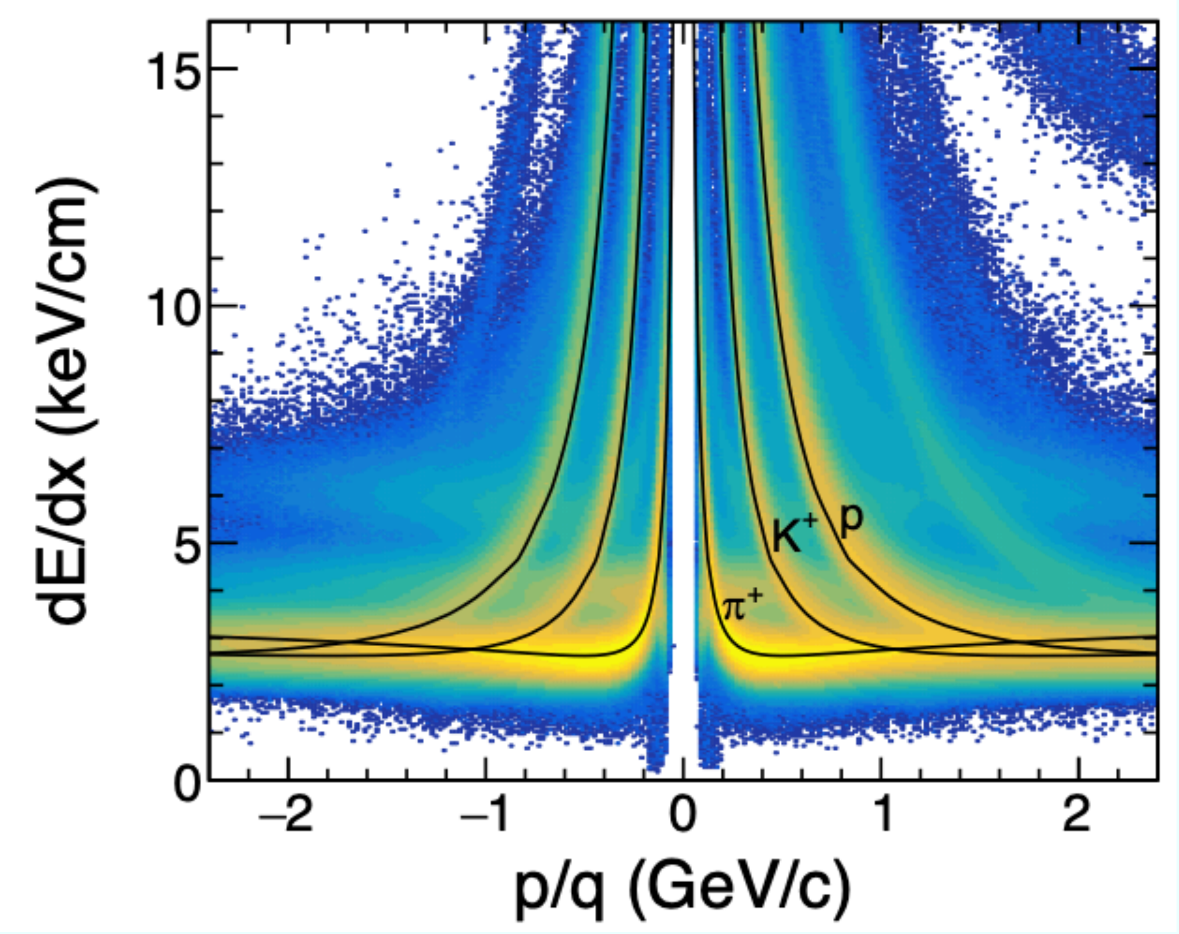
ALICE, Pb-Pb@2.76 TeV

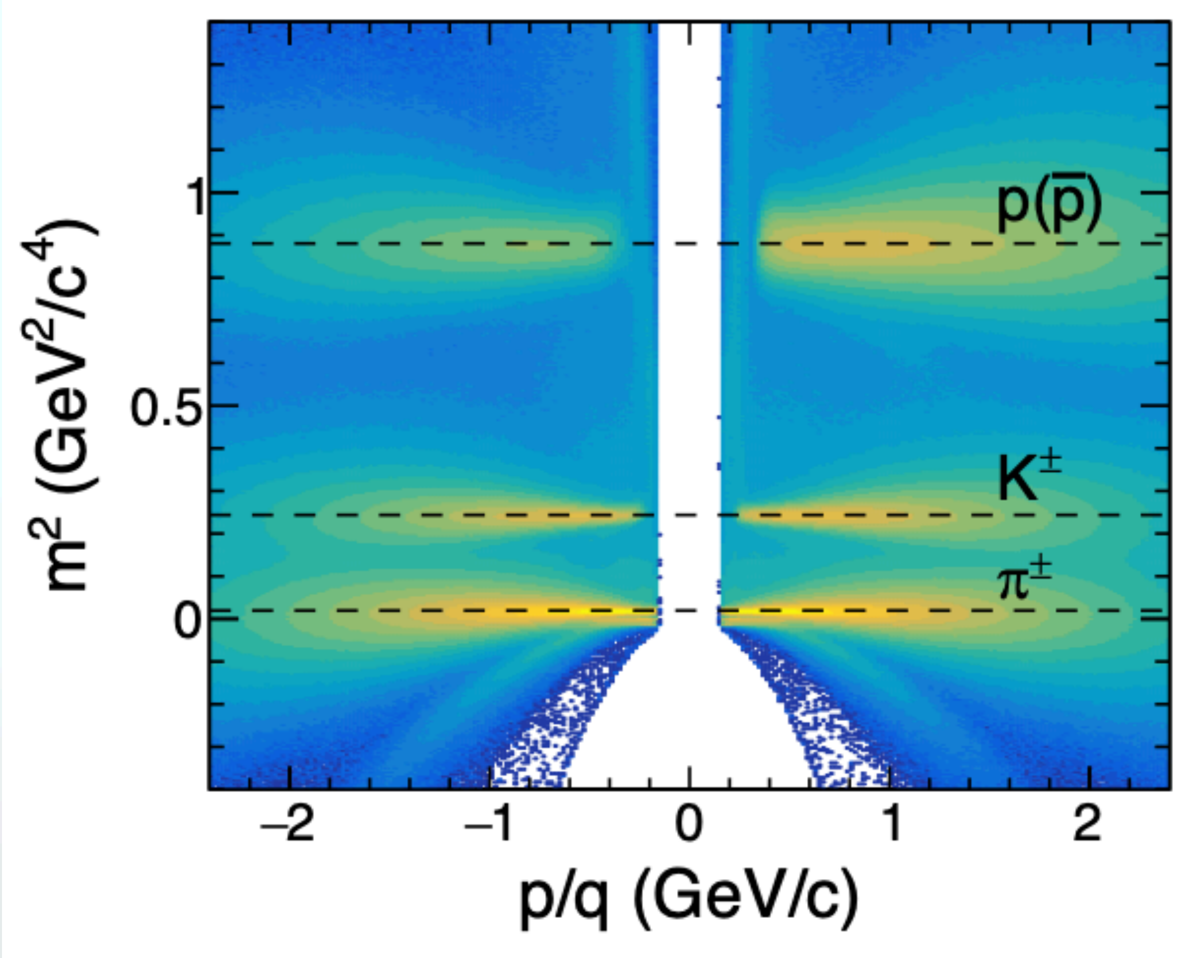




TPC

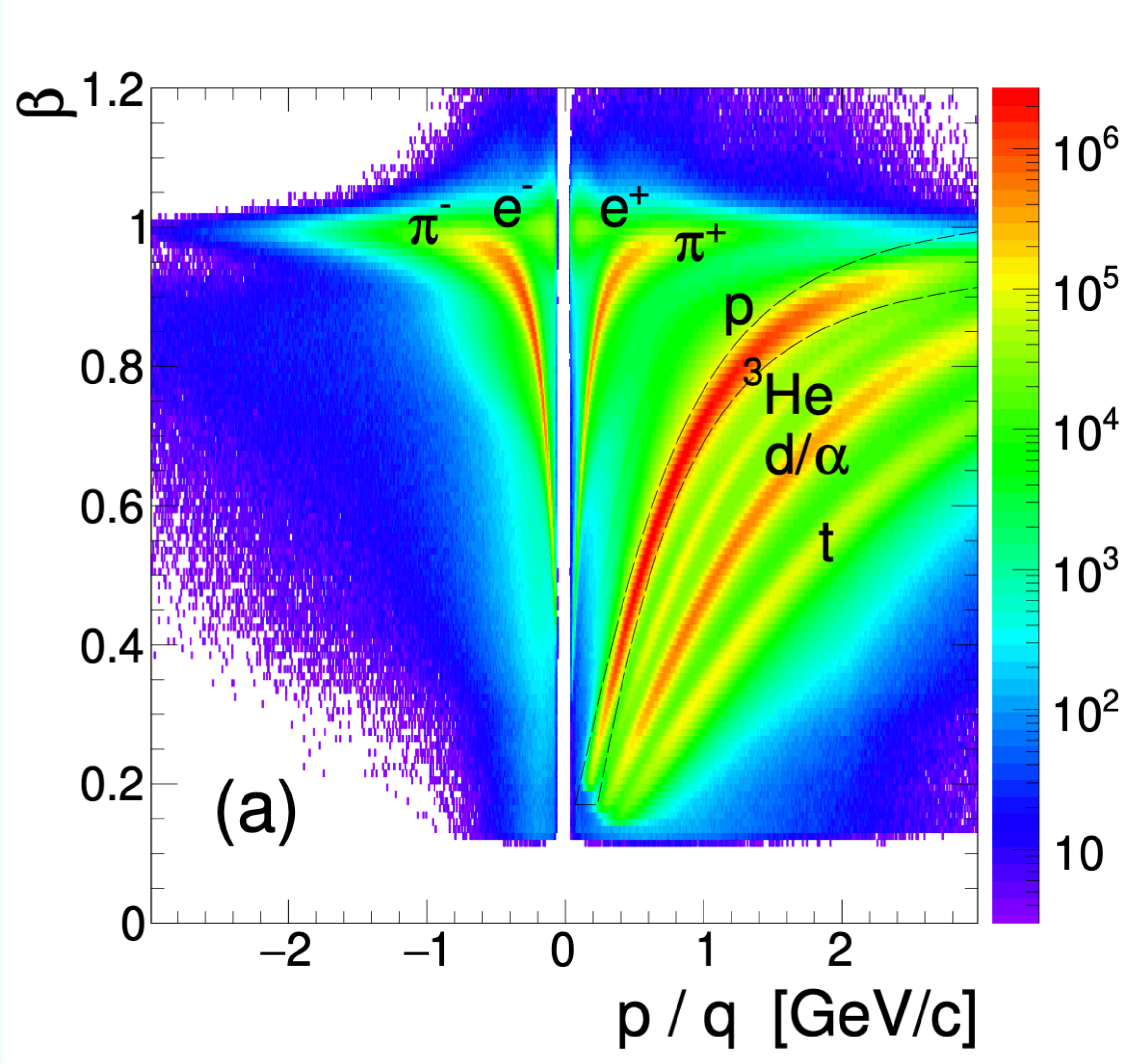
STAR, Au-Au@19.6 GeV

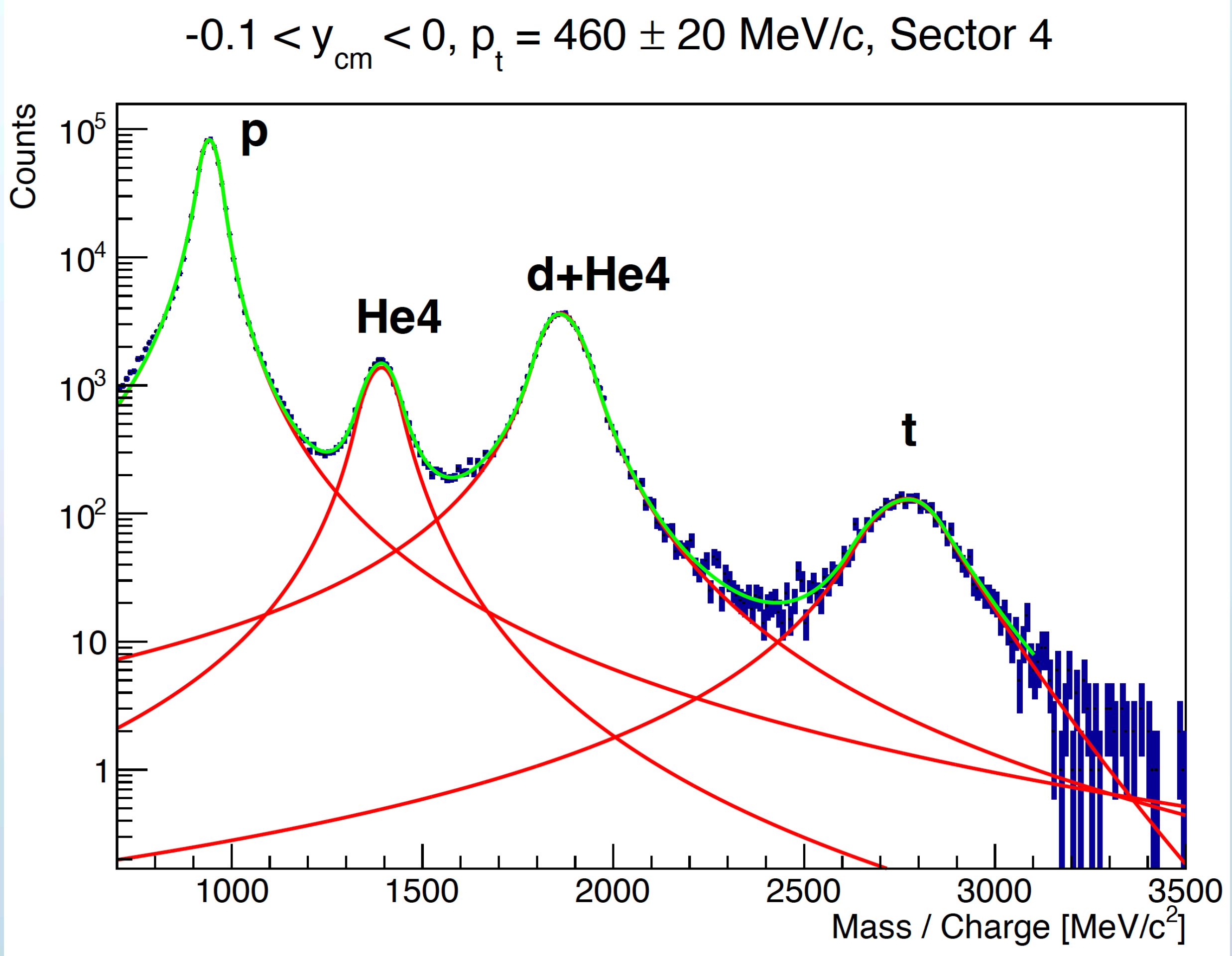




TPC + TOF

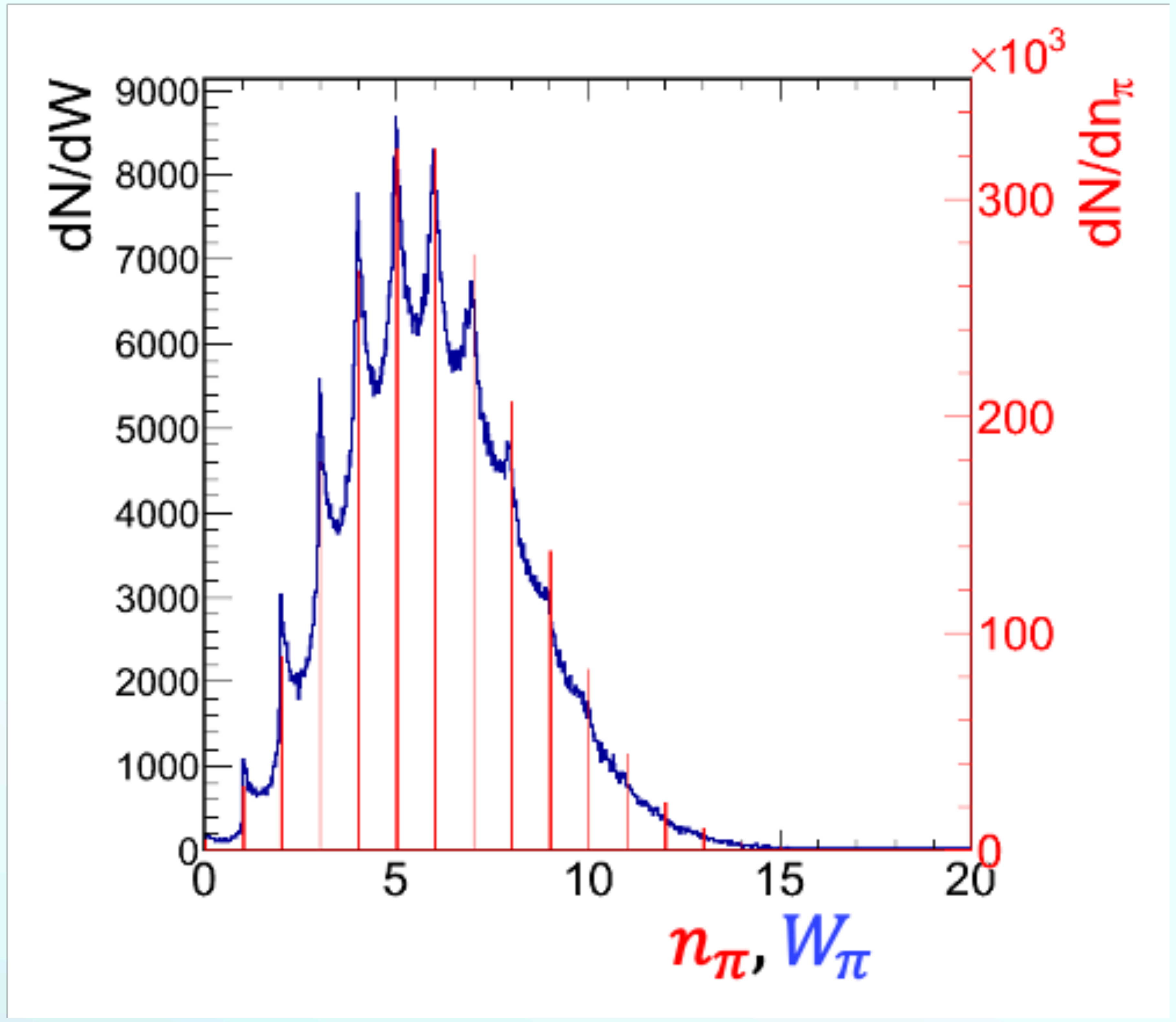
HADES, Au-Au@2.4 GeV





drift chambers+TOF

Fuzzy logic



Fuzzy logic: arbitrary moments

- A. Rustamov, Phys.Rev.C 110 (2024) 6, 064910

Identity Method: 2nd and 3rd moments

- M. I. Gorenstein, PRC 84, 024902 (2011)
- A.R., M. I. Gorenstein, PRC 86, 044906 (2012)
- M. Arslandok, A.R., NIM A946, 162622 (2019)

moment-generating function for an incomplete (*W*) distribution

$$\mathrm{M_W}(\mathrm{t_1}, \ldots, \mathrm{t_n}) = \sum_{\mathrm{N_1,\ldots,N_n=0}}^{\infty} P(n_1, \ldots, n_n) \prod_{i=1}^{n} e^{h_i(t_1,\ldots,t_n)n_i}$$

$$\mathrm{h_i}(\mathrm{t_1}, \ldots, \mathrm{t_n}) = \ln \left[\int_{-\infty}^{+\infty} \mathrm{e}^{\sum_{\mathrm{j=1}}^{\mathrm{n}} \mathrm{t_j}\omega_{\mathrm{j}}(\mathrm{x})} \mathscr{P}_{\mathrm{i}}(\mathrm{x})\mathrm{dx} \right], \quad \mathscr{P}_{\mathrm{i}}(\mathrm{x}) \equiv \frac{\rho_{\mathrm{i}}(\mathrm{x})}{\langle \mathrm{N_i} \rangle}$$

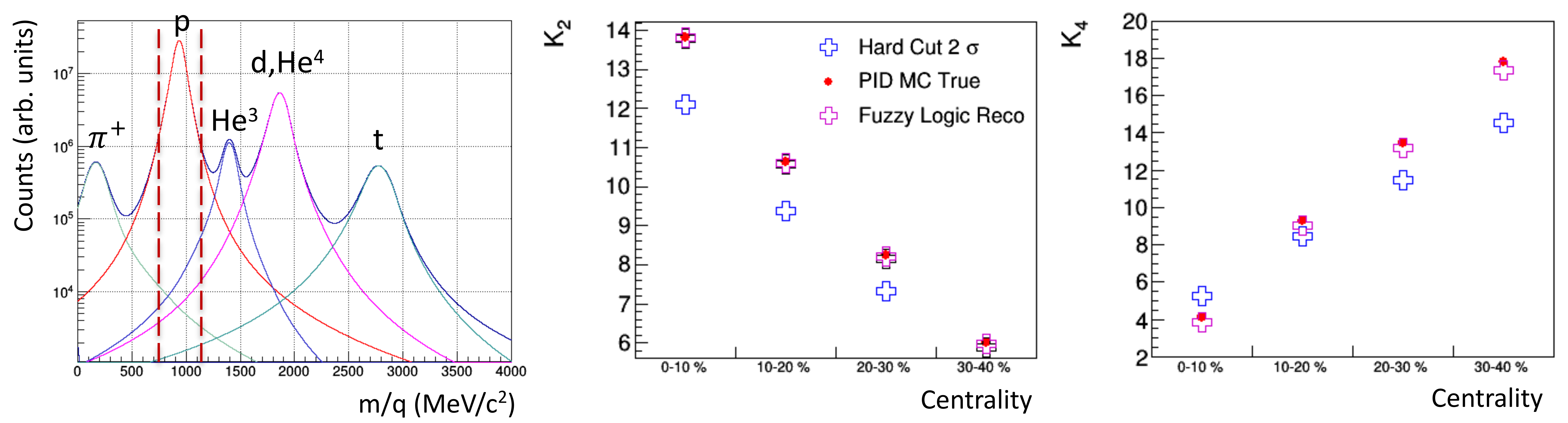
$$\langle W_a^n \rangle = \frac{\partial^n M_W(t_a)}{\partial t_a^n} \qquad \langle W_a^n W_b^m \rangle = \frac{\partial^{n+m} M_W(t_a, t_b)}{\partial t_a^n \partial t_b^m}$$

$$\underbrace{\begin{pmatrix} \langle W_\pi^2 \rangle \\ \langle W_K^2 \rangle \\ \langle W_\pi W_K \rangle \end{pmatrix} = \begin{pmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{pmatrix} \times \begin{pmatrix} \langle n_\pi^2 \rangle \\ \langle n_K^2 \rangle \\ \langle n_\pi n_K \rangle \end{pmatrix}}_{\text{De-Fuzzification}}$$

Applied in: NA49, NA61, ALICE, HADES

Fuzzy logic vs. hard cut

HADES: Marvin Nabroth, Quark Matter 2025



Suggestion / Recommendation 💡

- Perform the analysis with both methods
- Compare the results for consistency

Conclusions

Strong dependence on centrality definition

📊 Most probably driven by volume/participant fluctuations

🔄 Test with **alternative methods** (Event Mixing)

🧩 **Best practice:** show results *with & without* VF corrections

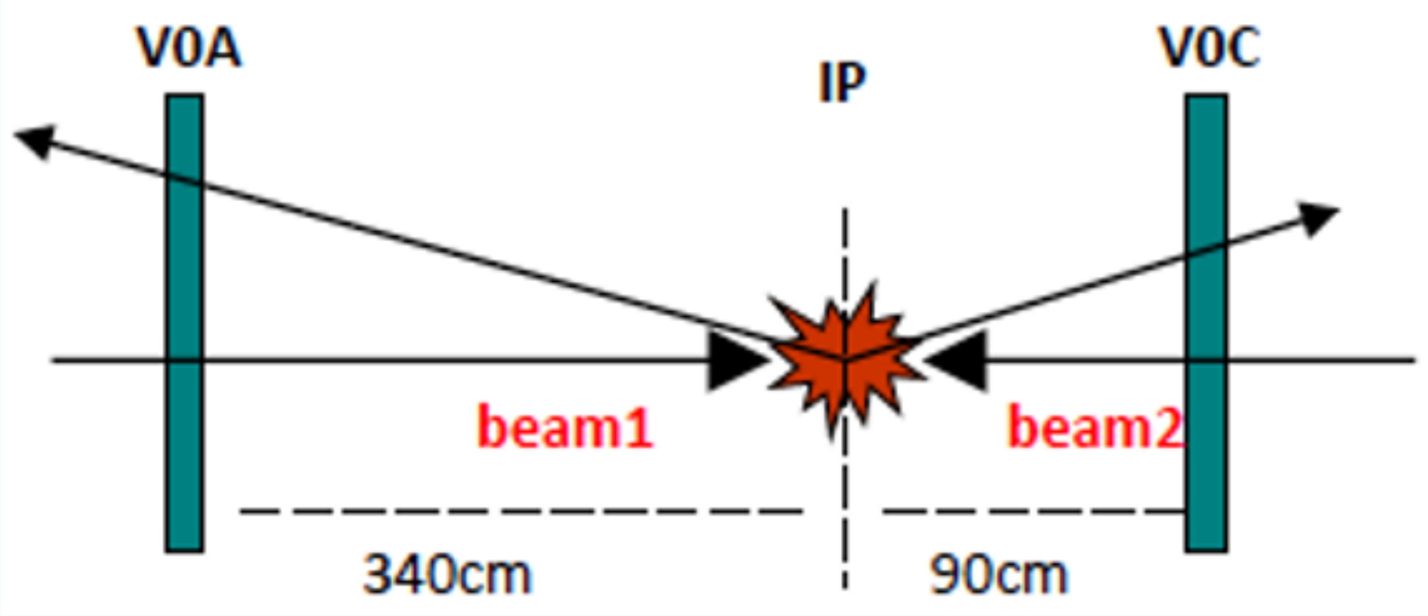
Analysis Technique

⚖️ Compare hard cuts vs Fuzzy Logic approach

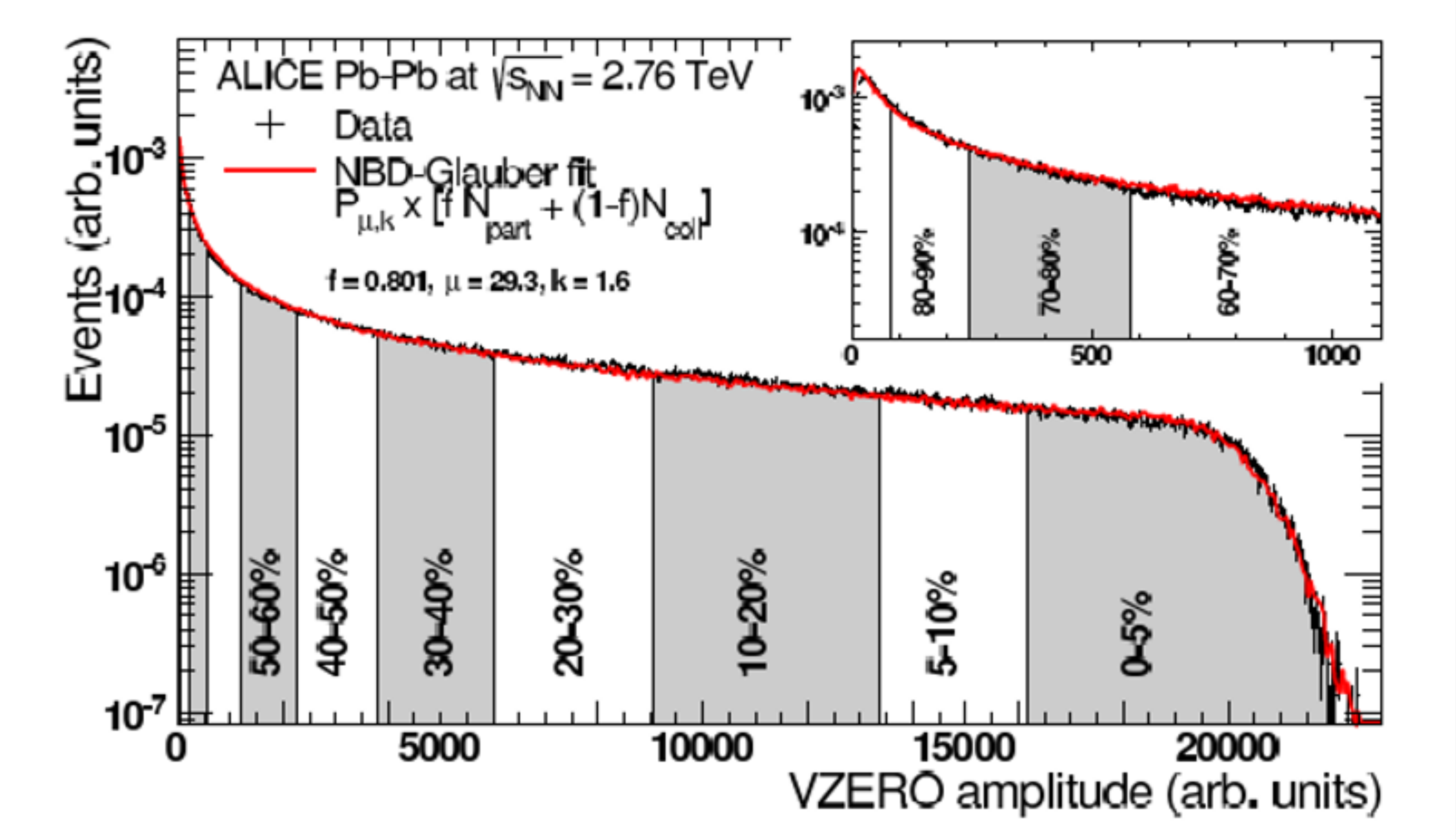
Intricacies at Low Energies

⚠️ Stopping and multiple interactions blur the notion of participants

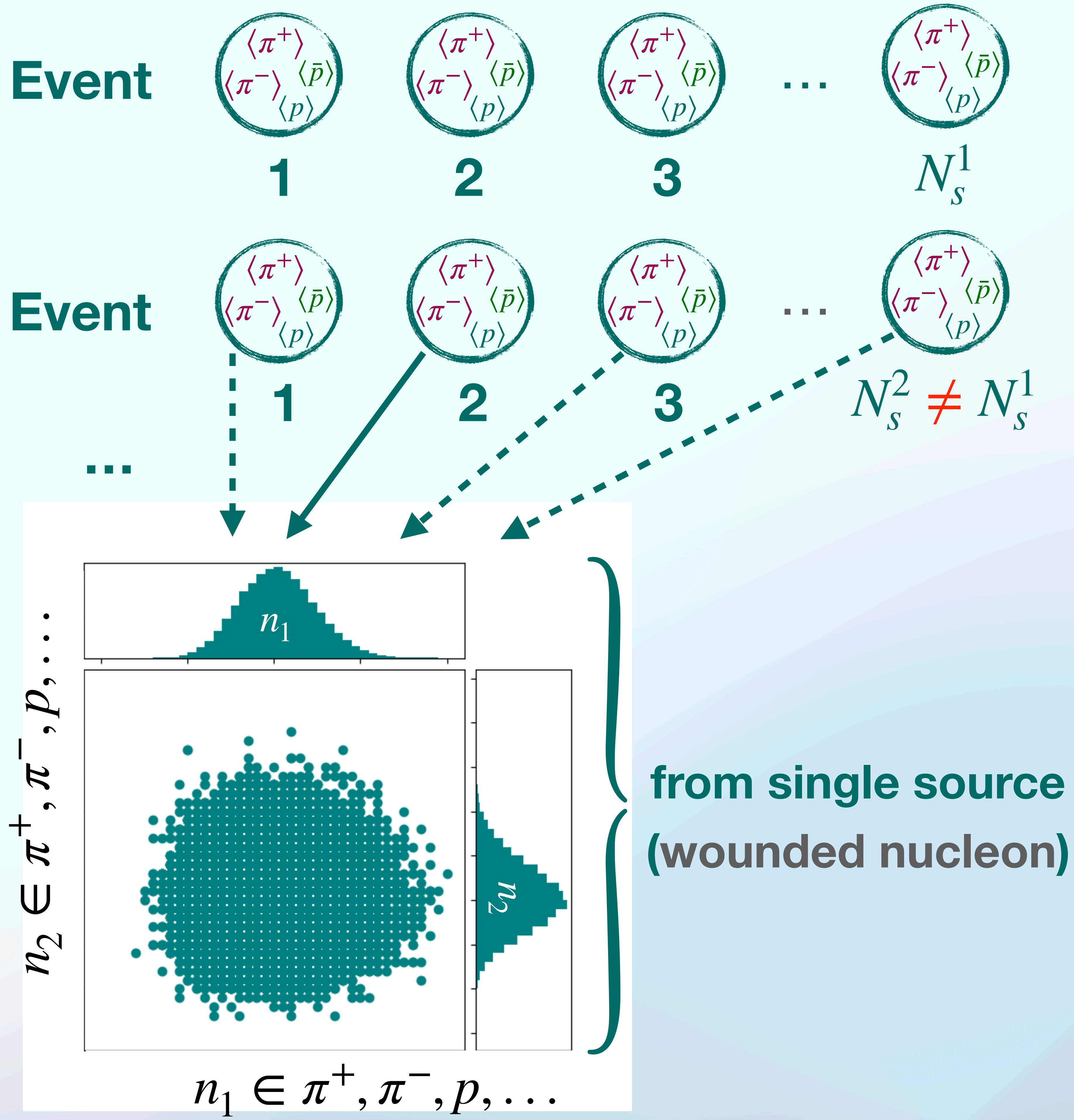
Contributions from wounded fluctuations



$2.8 < \eta < 5.1$ $\qquad$ $-3.7 < \eta < -1.7$



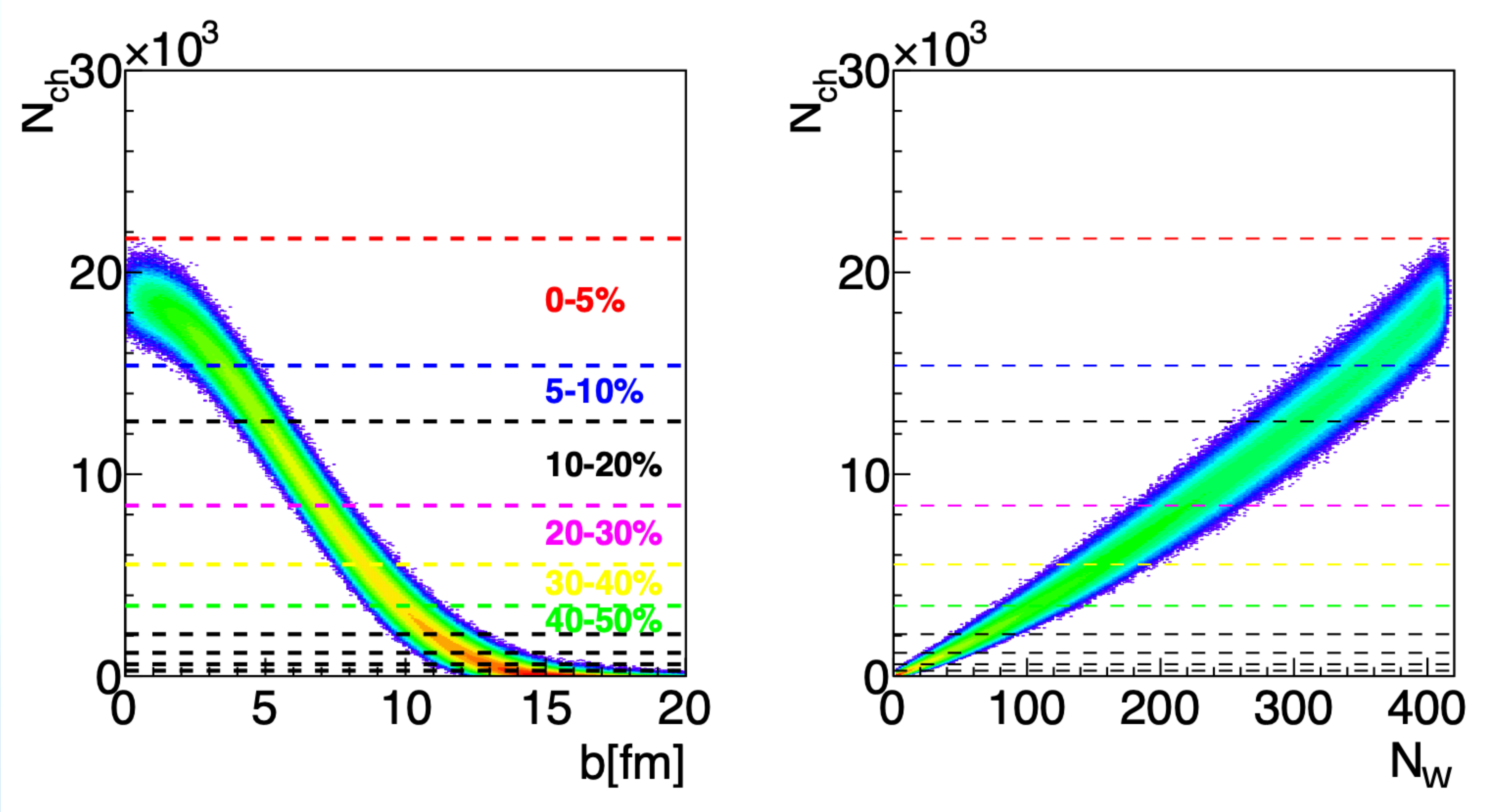
model of independent



from single source (wounded nucleon)

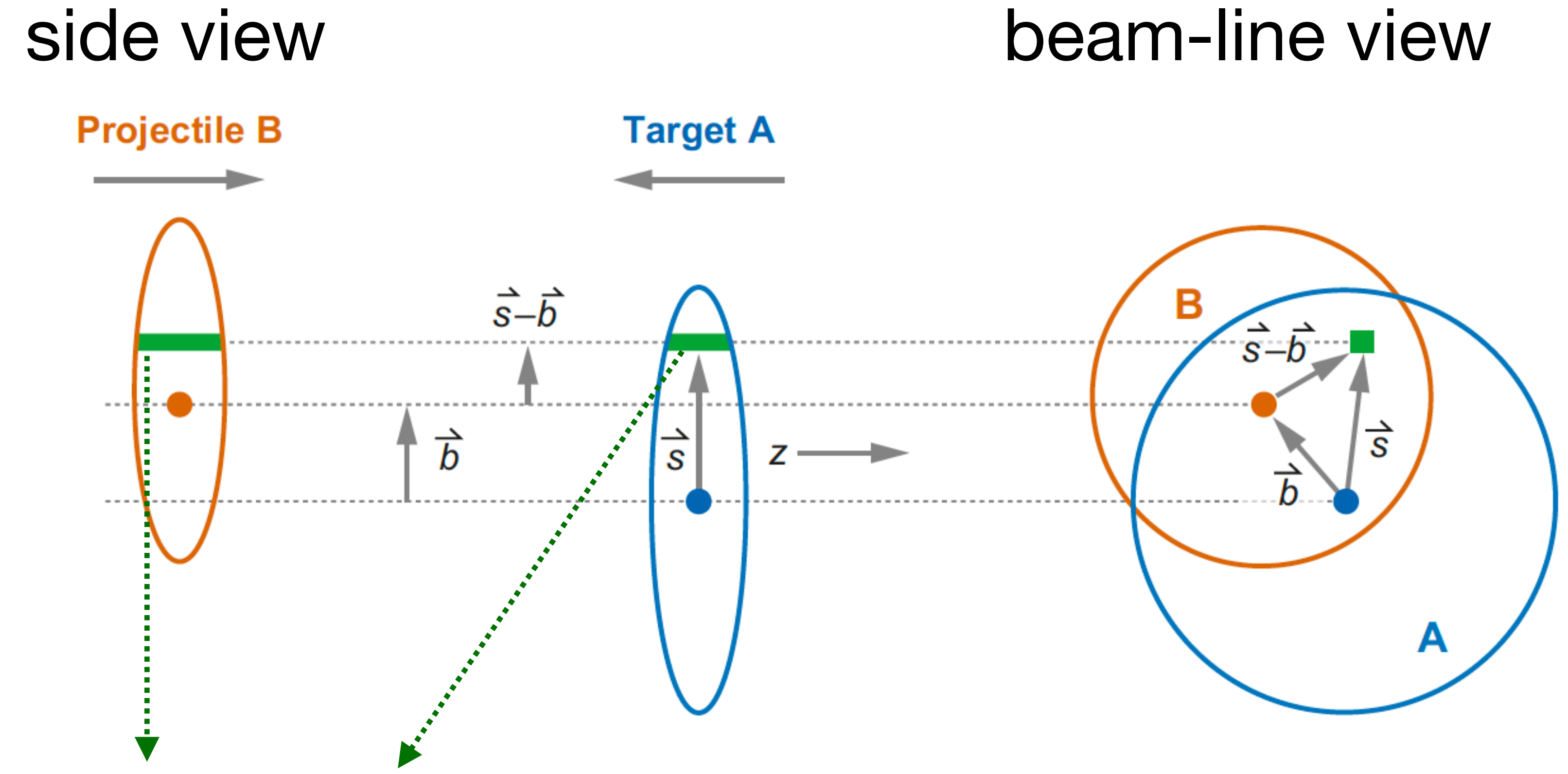
A. R., R. Holzmann, J. Stroth, NPA 1034 (2023) 122641

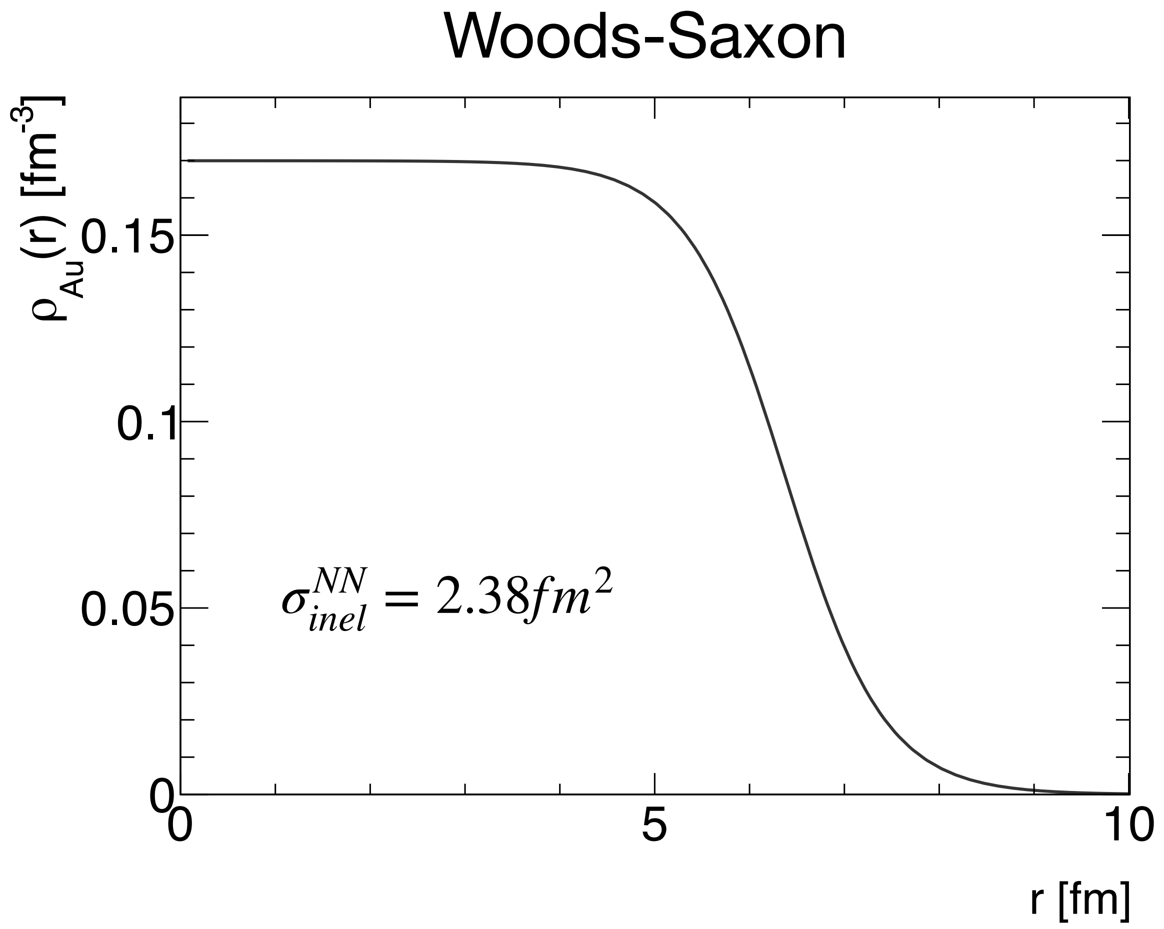
V. Koch, R. Holzmann, A. R., J. Stroth, Nucl.Phys.A 1050 (2024) 122924



P. Braun-Munzinger, A.R., J. Stachel, NPA 960 (2017) 114

Glauber model, Optical





row-on-**row** collisions

Nuclear thickness function $\hat{T}_A(\vec{s}) = \int \hat{\rho}_A(\vec{s}, z)dz$ $\quad \hat{T}_B(\vec{s}-\vec{b}) = \int \hat{\rho}_B(\vec{s}-\vec{b}, z)dz$ $\quad \hat{\rho}(\vec{r}) = \rho(\vec{r})/A$

prob. nucleon from A interacts with none of the B nucleons from B

$$N_{part}^A(b) = A\int \hat{T}_A(\vec{s})\left[1 - \left(1 - \hat{T}_B(\vec{s}-\vec{b})\sigma_{inel}^{NN}\right)^B\right] d^2s$$

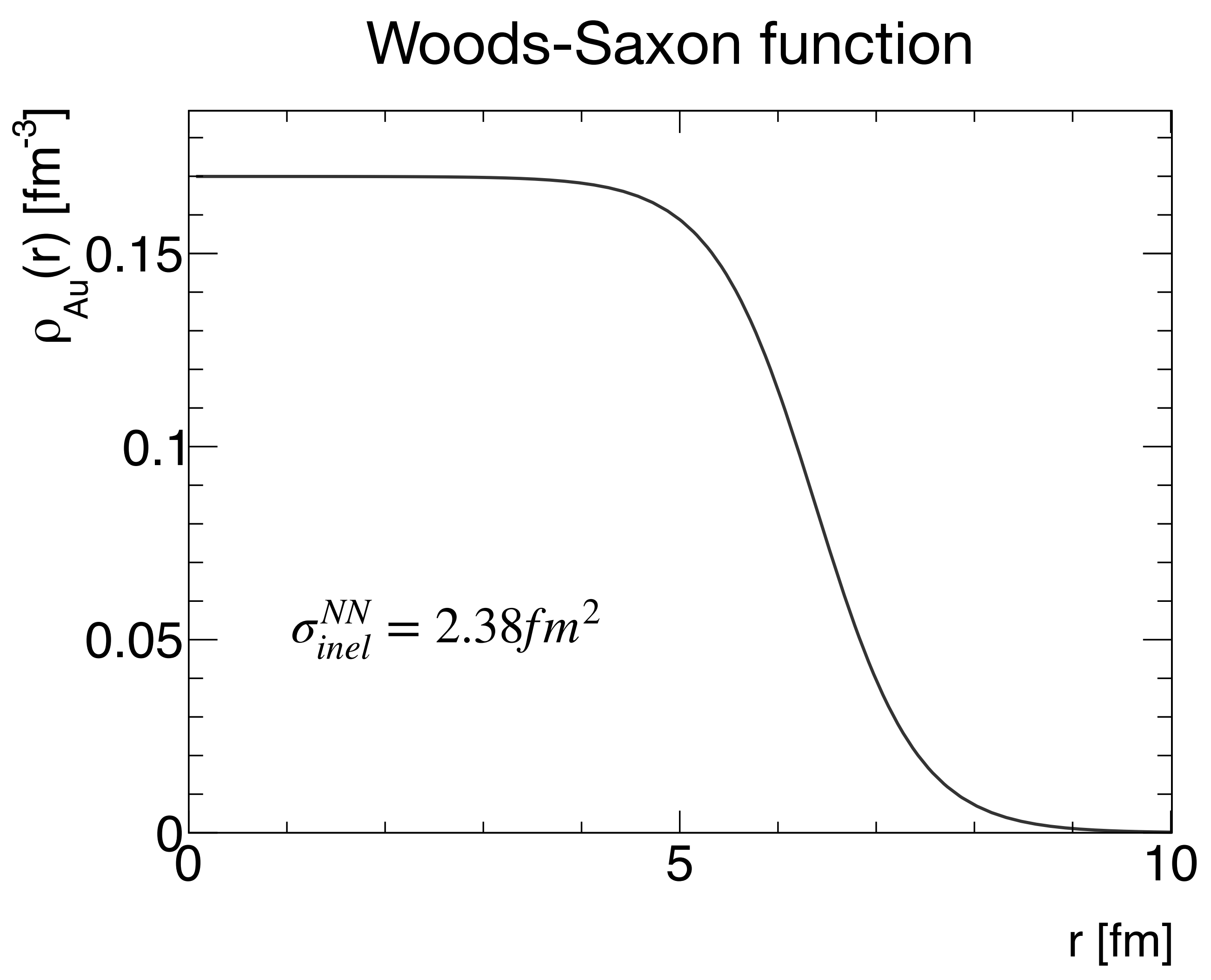
ptob. nucleon from A interacts with the one from B

nucleon from A undergoes at least one inelastic nucleon-nucleon collision

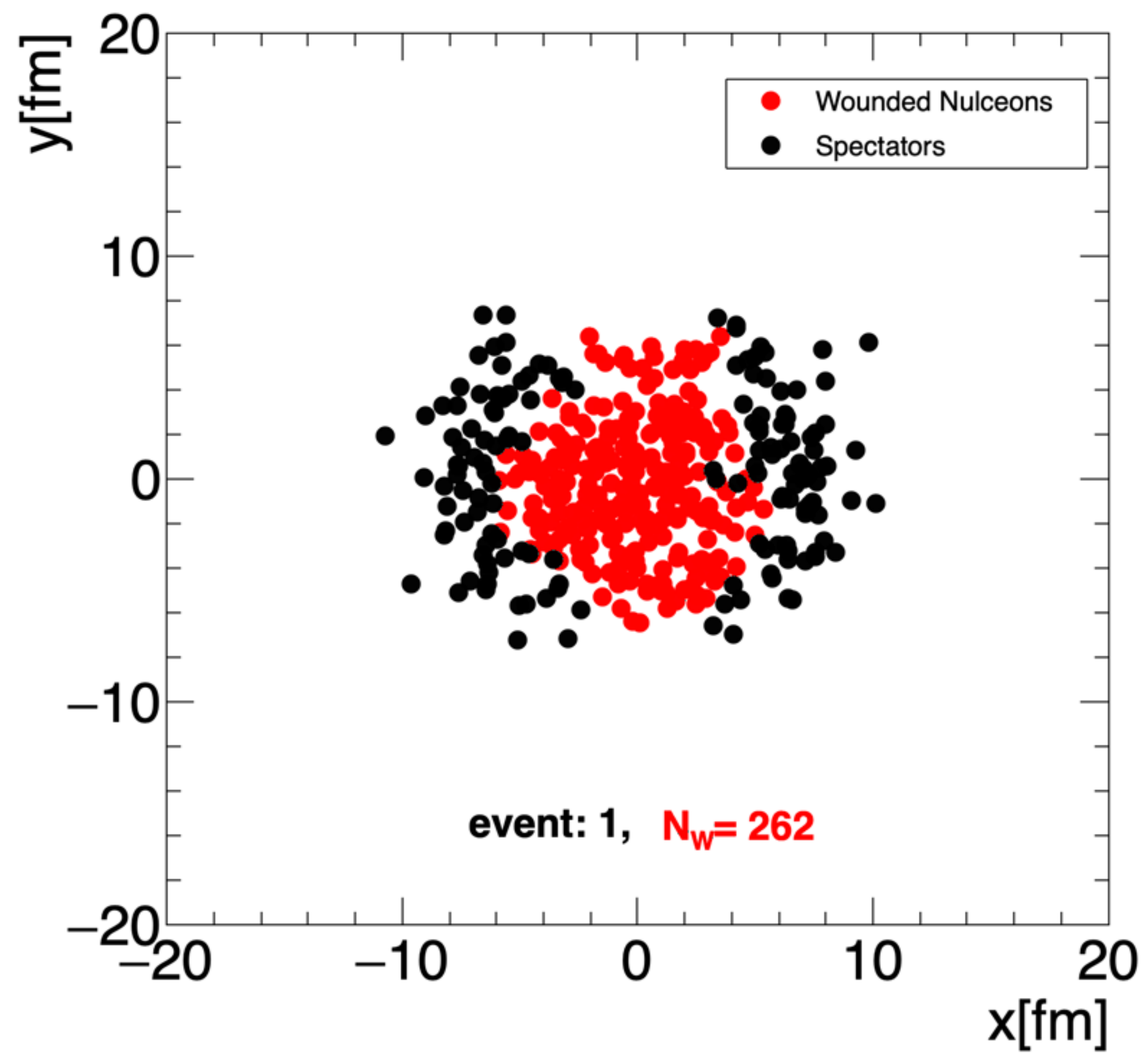
$$N_{part}(b) = N_{part}^A(b) + N_{part}^B(b)$$

nucleons travel along straight trajectories (high energy limit)
nucleus is seen as a homogeneous object

Glauber Model, MC vs optical



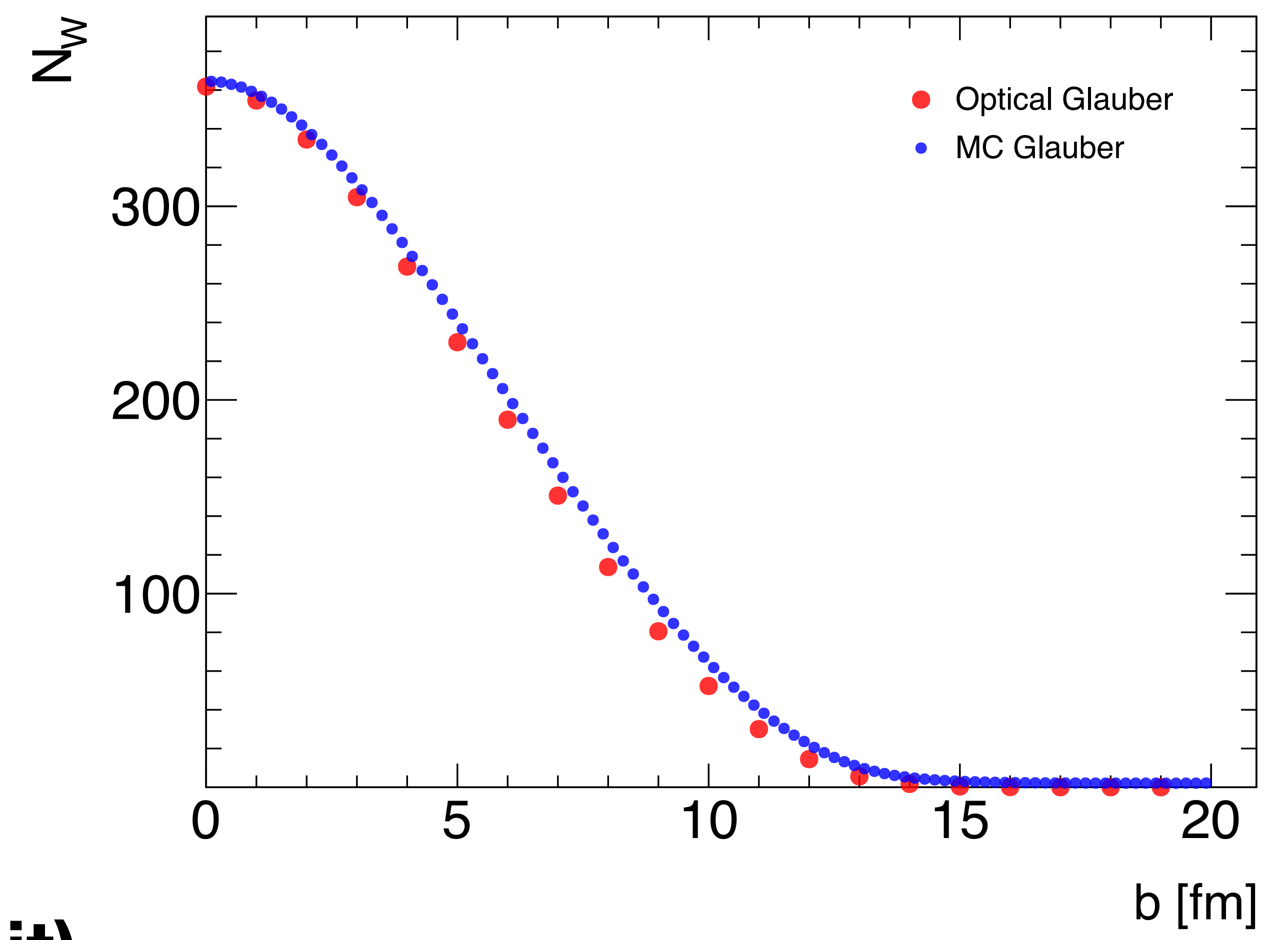
HADES centrality paper: Eur.Phys.J.A 54 (2018) 5, 85



- generation of impact parameter $dN/db \sim b$
- generation of nucleon positions
- a collision between two nucleons takes place if their distance in transverse plane satisfies:

$$d^2 \leq \sigma_{inel}^{NN}/\pi$$

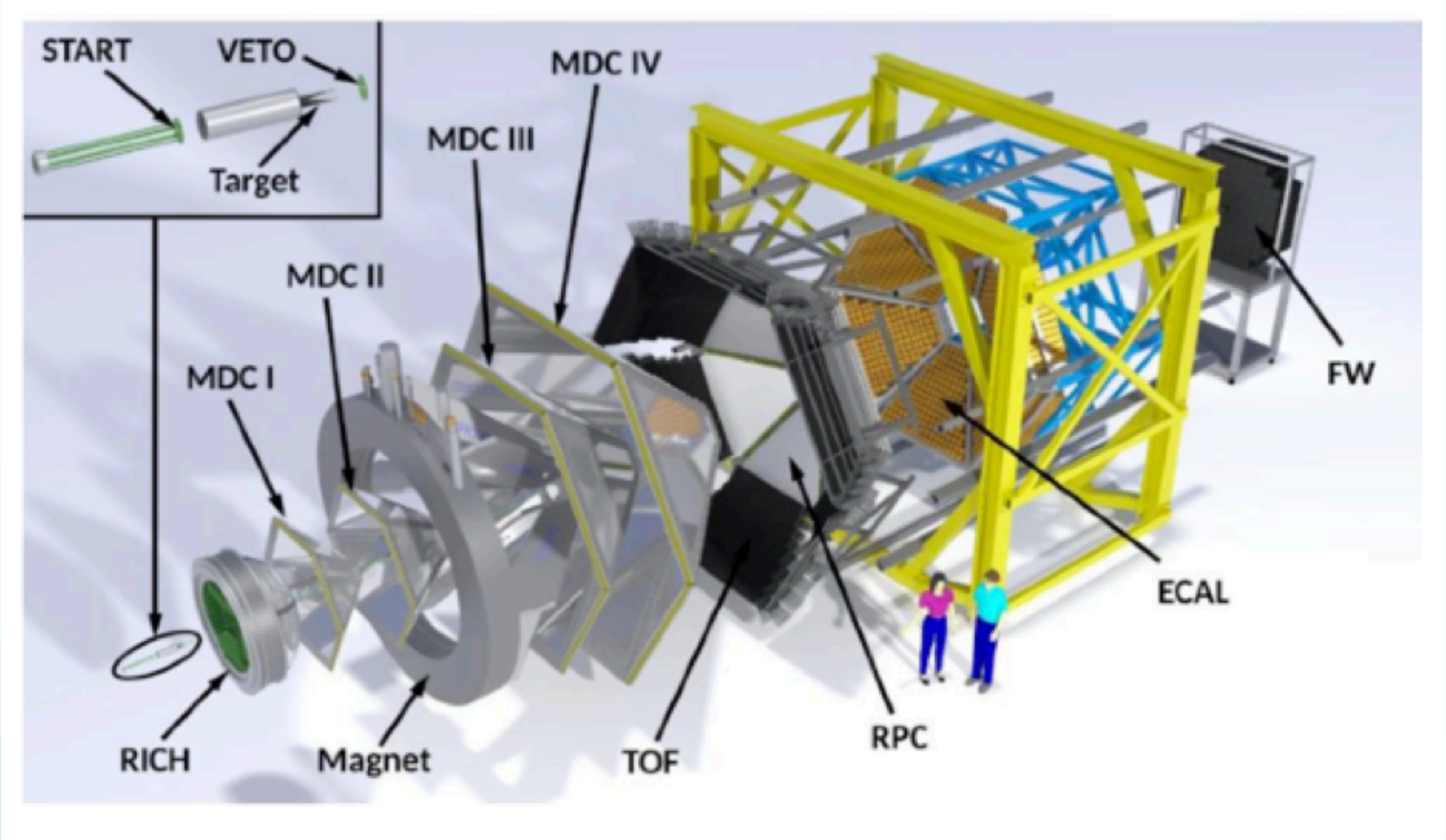
C. Loizides, J. Nagle, P. Steinberg, SoftwareX 1-2 (2015) 13-18 • e-Print: 1408.2549 [nucl-ex]

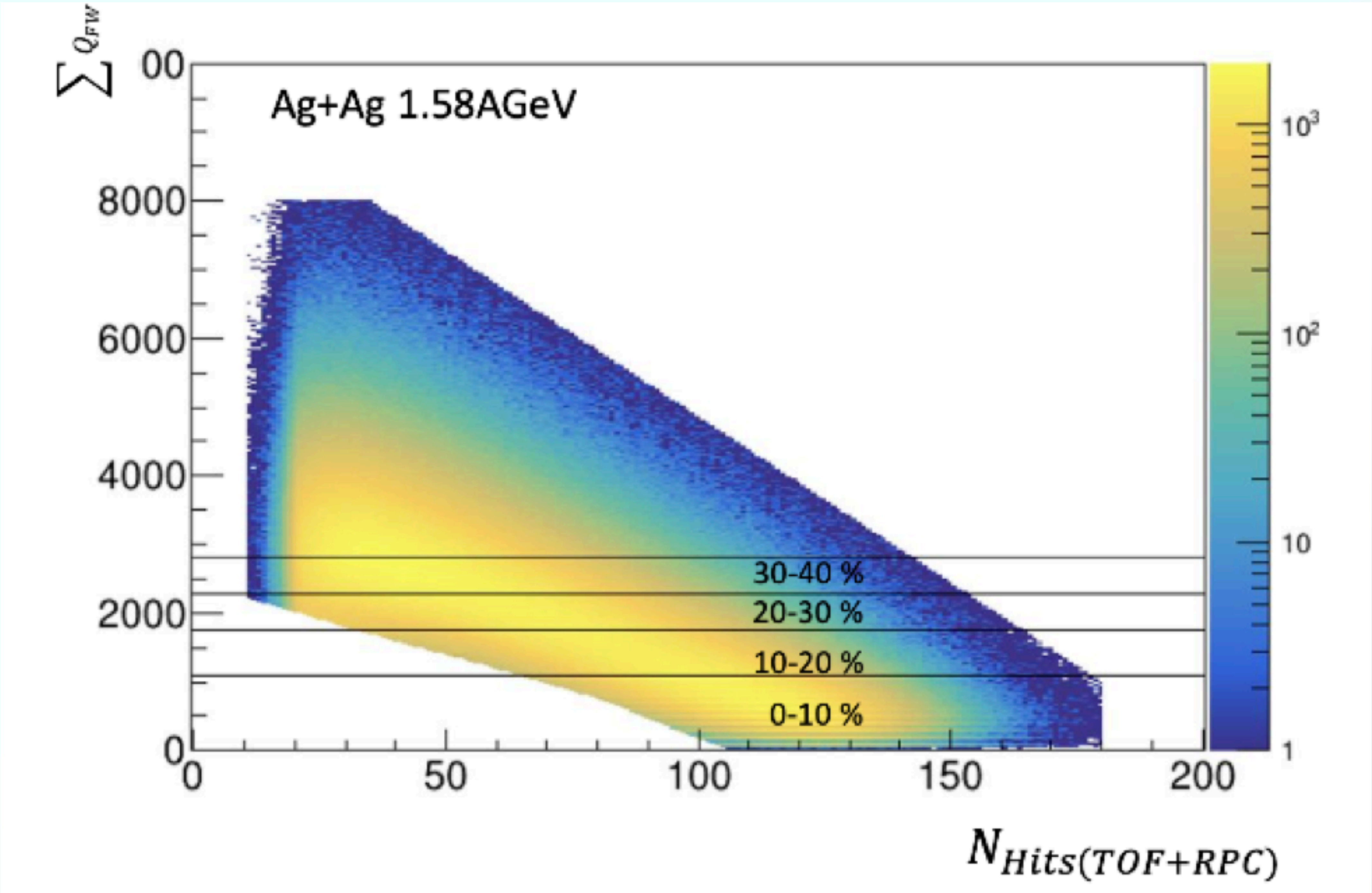


nucleons travel along straight trajectories (high energy limit)

σ_{inel}^{NN} **does not change after a collision**

HADES, Centrality selection





Quantifying distributions

Regular Cumulants

$$K(t) = \ln\left[\sum_X P(X)e^{tX}\right], \ \kappa_n = \frac{d^n}{dz^n}K(t)\Big|_{t=0}$$

Factorial Cumulants

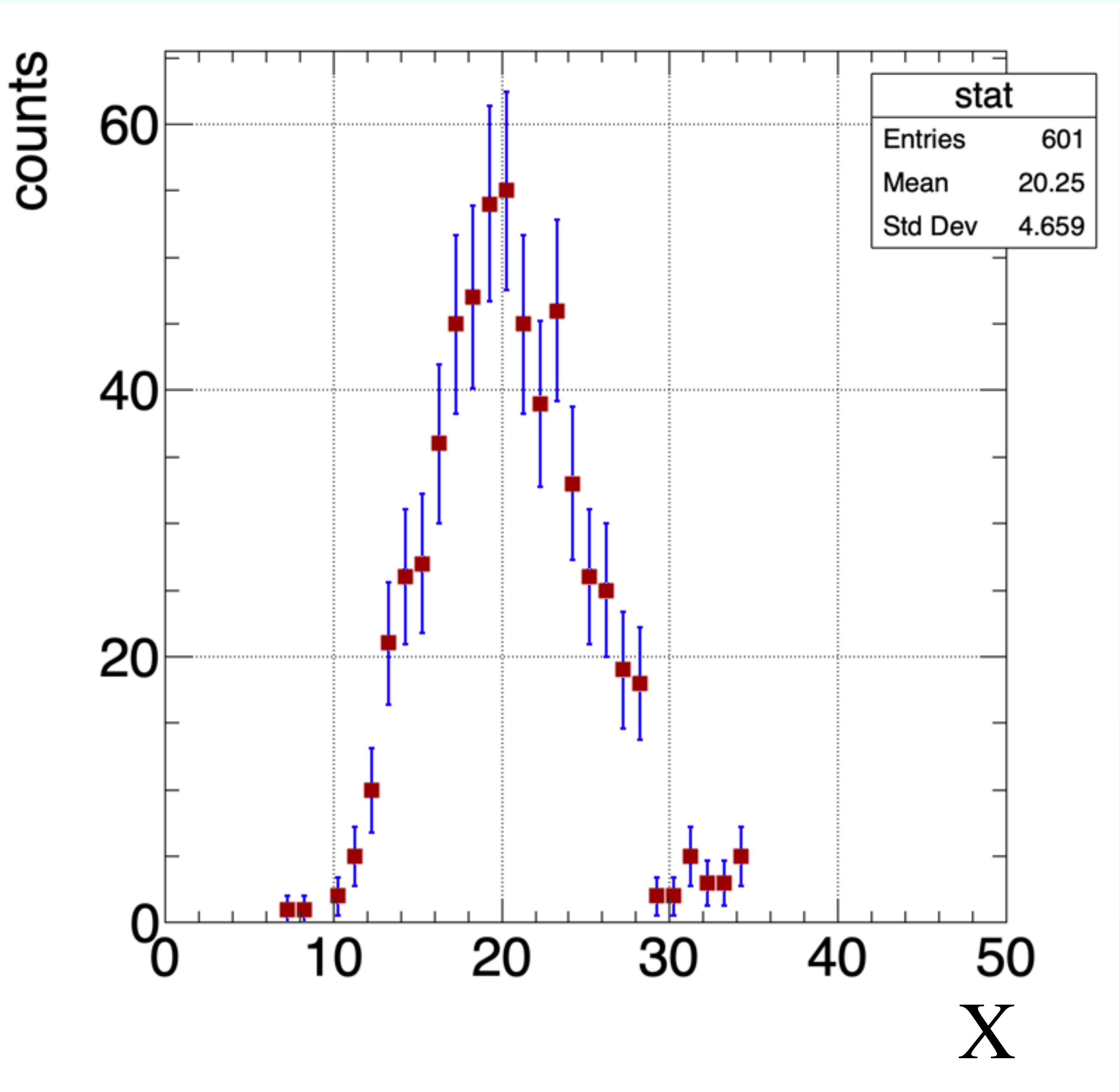
$$G(z) = \ln\left[\sum_X P(X)z^X\right], \ C_n(X) = \frac{d^n}{dz^n}G(z)\Big|_{z=1}$$

$$C_1(X) = \kappa_1(X) = \langle X \rangle$$

$$C_2(X) = -\kappa_1(X) + \kappa_2(X)$$

$$C_3(X) = 2\kappa_1(X) - \kappa_2(X) + \kappa_3(X)$$

$$C_4(X) = -6\kappa_1(X) + 11\kappa_2(X) - 6\kappa_3(X) + \kappa_4(X)$$



Poisson Limit: $P(X) = e^{-\lambda}\frac{\lambda^X}{X!}$

$K(t) = \lambda(e^1 - 1)$, $\kappa_n = \lambda$ $(n \geq 1)$

$G(z) = \lambda(z - 1)$, $C_1 = \lambda$, $C_n = 0$ $(n \geq 2)$

R. Holzmann, V. Koch, A. R., J. Stroth, Nucl. Phys.A 1050 (2024) 122924

Factorial cumulants isolate genuine correlations