

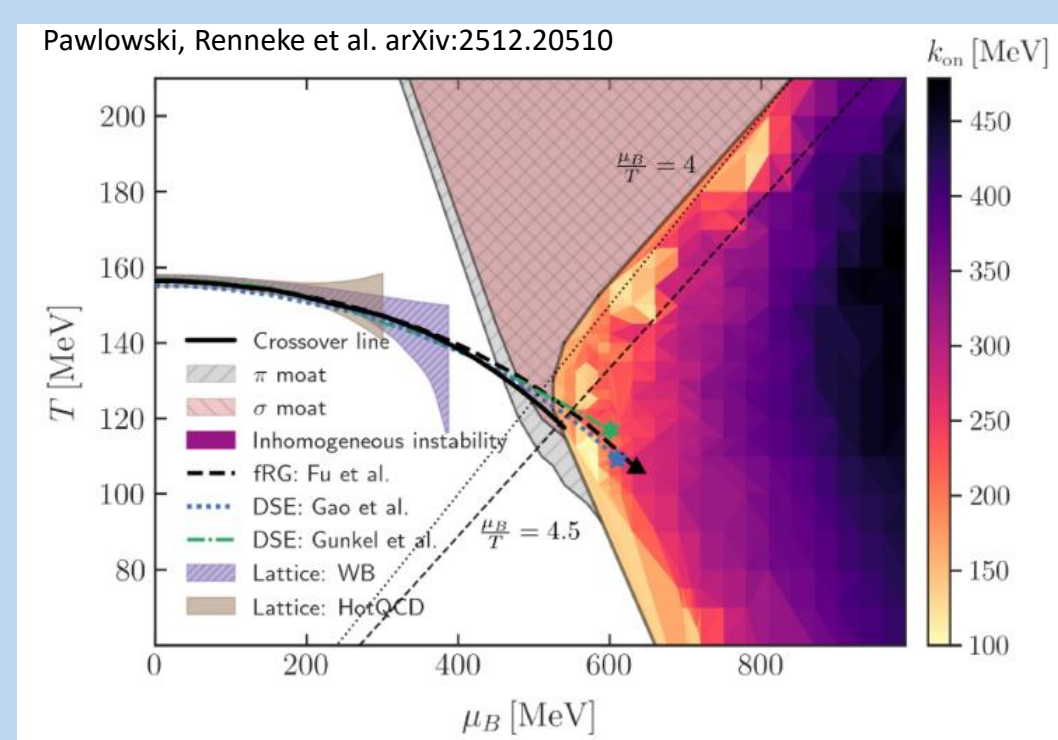
Studying QCD phase structure via event-by-event fluctuations

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Physics Motivation

- The phase diagram of matter in the regime pertinent to cosmic (condensed) matter under extreme conditions is governed by quantum chromodynamics (QCD) in the non-perturbative regime
- Key intrinsic features include color confinement and spontaneous chiral symmetry breaking, together with the associated dynamical generation of hadron masses
- Although lattice QCD predicts a cross over from deconfined to confined matter in the early universe, a possible transition from confined to deconfined matter within neutron stars interiors is conjectured to be of first order
- Exotic forms of QCD matter are predicted by non-perturbative functional methods (fRG, DSE) while lattice QCD allows first-principle calculations near vanishing baryo-chemical potential



Extreme QCD in the laboratory

- Central heavy-ion collisions produce in the collision transient states of matter (fireballs) characterised by elevated density and temperature
- The phase structure of this ephemeral state can be deduced from features in the phase-space distribution of bulk particles emitted from the reaction zone

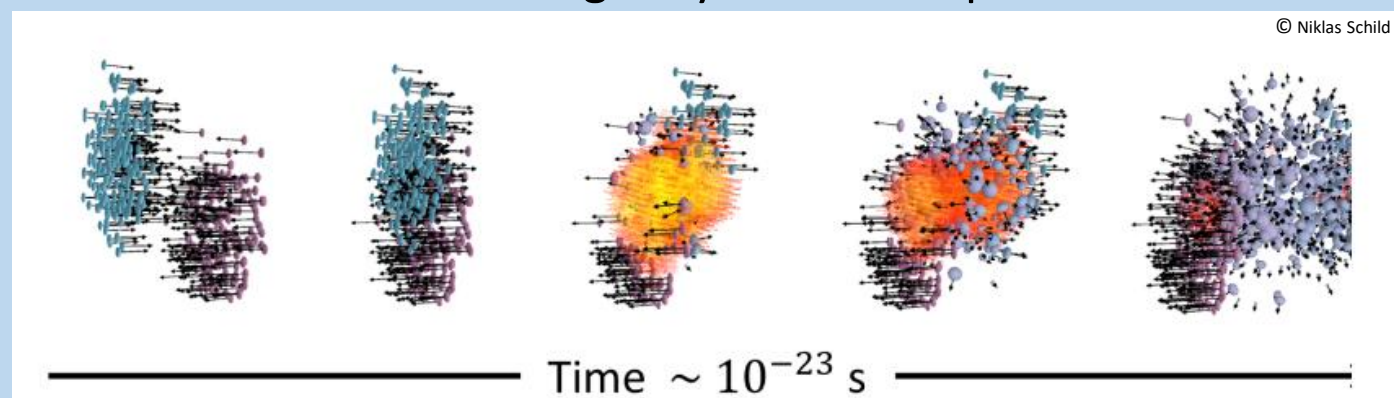
Quantifying fluctuations

- Study event-by-event fluctuations in proton multiplicity and quantify the shape of the resulting multiplicity distribution using cumulants

$$\kappa_n(N_q) = \frac{\partial^n \ln \mathcal{Z}(T, V, \mu_q)}{\partial (\mu_B/T)^n}$$

Cumulants

$$\begin{aligned} \kappa_1 &= \langle N \rangle, \\ \kappa_2 &= \langle (N - \langle N \rangle)^2 \rangle, \\ \kappa_3 &= \langle (N - \langle N \rangle)^3 \rangle, \\ \kappa_4 &= \langle (N - \langle N \rangle)^4 \rangle - 3 \langle (N - \langle N \rangle)^2 \rangle^2 \end{aligned}$$

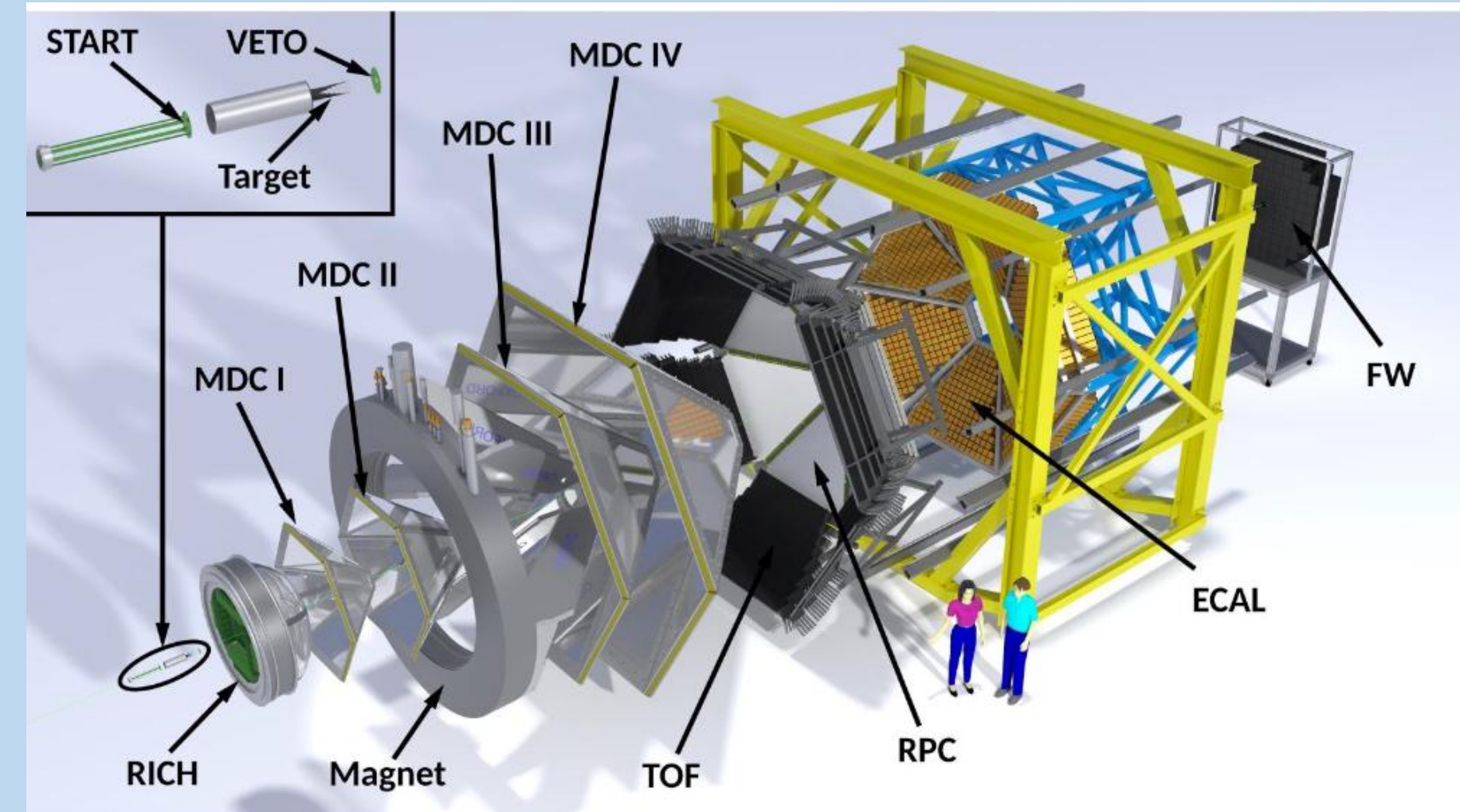


How to detect a phase transition and a CEP?

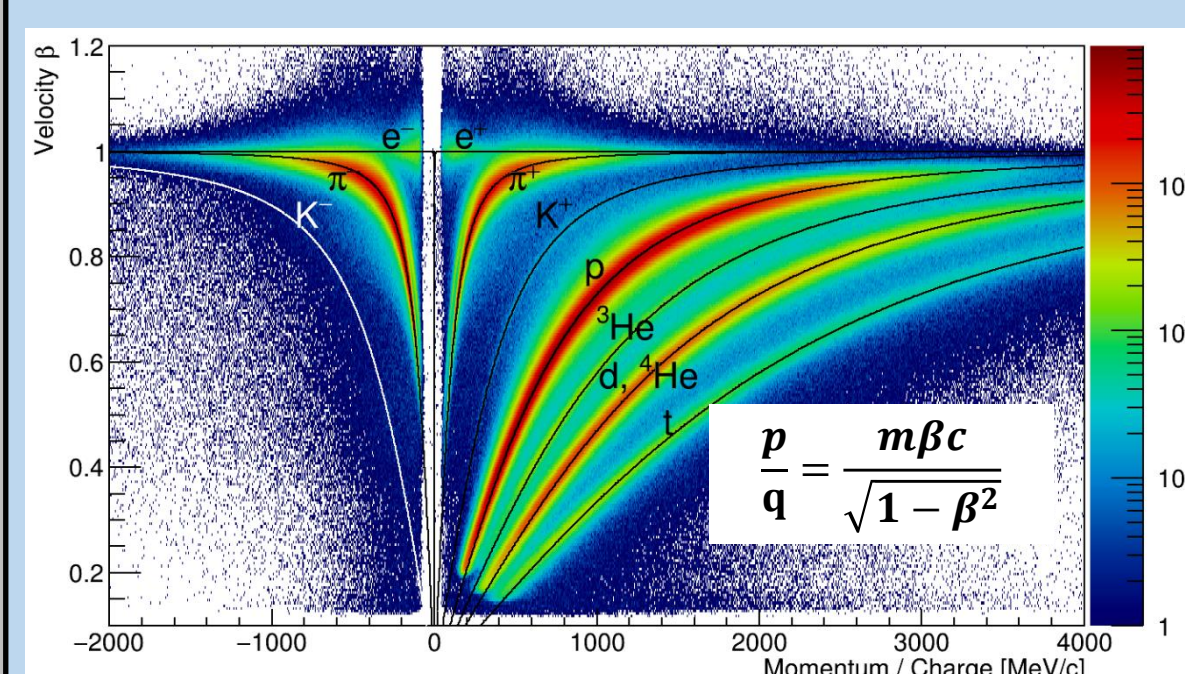
- A first-order phase transition is characterized by latent heat and discontinuities in thermodynamic quantities, such as the net-baryon density
- Near the CEP, a growing correlation length leads to enhanced fluctuations, potentially observable through event-by-event fluctuations of conserved quantities → Experimental signatures in particle number fluctuations
- In the GCE, cumulants of conserved-charge distributions are related to derivatives of the thermodynamic pressure with respect to the corresponding chemical potentials. In heavy-ion collisions, net-proton fluctuations serve as an experimental proxy for net-baryon number fluctuations
- Challenge:** Non-critical contributions to measured fluctuations arising from experimental effects and baryon-number conservation, as well as the possible suppression of critical signals due to finite system lifetime, etc

Experimental Setup

- Fixed target experiment at SIS18 → Probes the high μ_B region
- High-acceptance spectrometer with a six-sector toroidal magnet
- Deflection of charged particles measured in two plane of drift chambers (MDC)
- PID by momentum (MDC) – β (time-of-flight) using TOF/RPC correlation augmented by dE/dx measurement and ring correlation (electrons/positrons) in hadron blind RICH
- Forward Wall for projectile spectator measurement → centrality estimator for fluctuation analysis to avoid auto-correlation effects



Recorded HADES heavy ion data sets:
Au+Au 2.42 GeV (2012), Ag+Ag 2.55 and 2.42 GeV (2019) and Au+Au 1.96 – 2.24 GeV (2025)



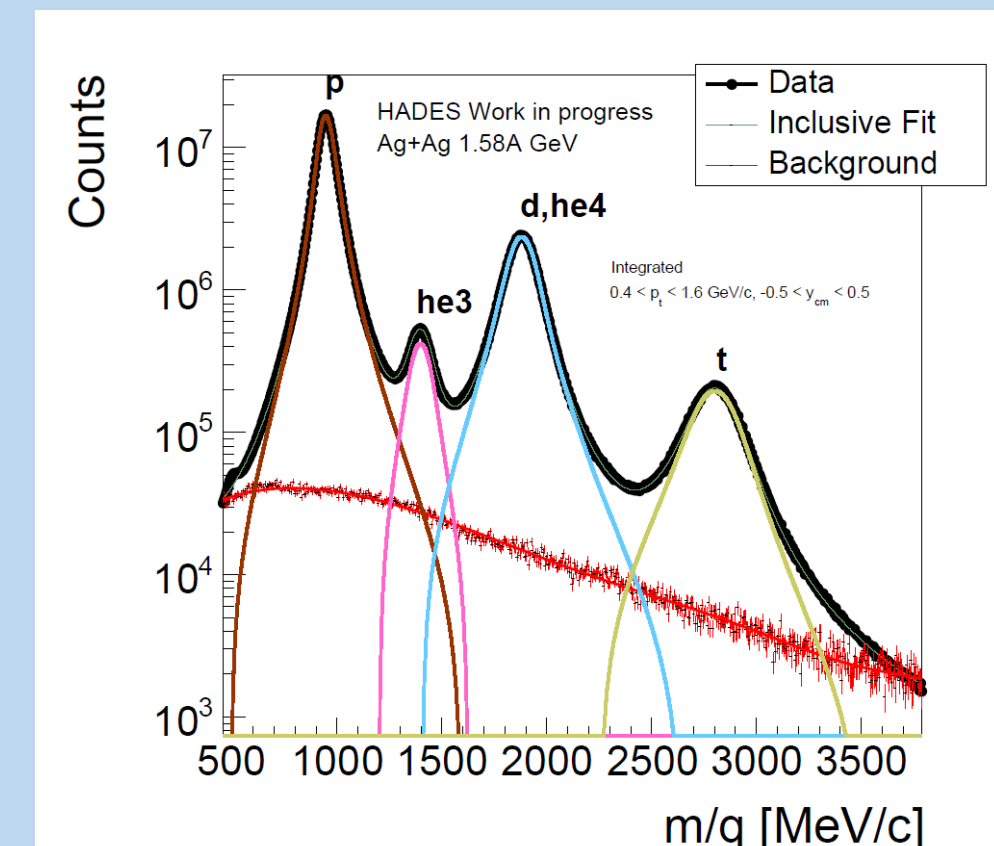
- Measurement of particles differentially in momentum phase space

$$y = \frac{1}{2} \ln \left(\frac{E + p_z}{E - p_z} \right), p_t = \sqrt{p_x^2 + p_y^2}$$

Future detector setup of CBM at GSI



Handling PID purity and detection efficiency fluctuations



- Finite momentum and time-of-flight resolution lead to partial overlap in reconstructed mass distribution of the various particle
- Signal extraction by a combined fit using mass response functions and a phenomenological background shape from de-correlated track (MDC) time-of-flight (META) combinations
- Fitting as a function of pt, y, ϕ , centrality bins

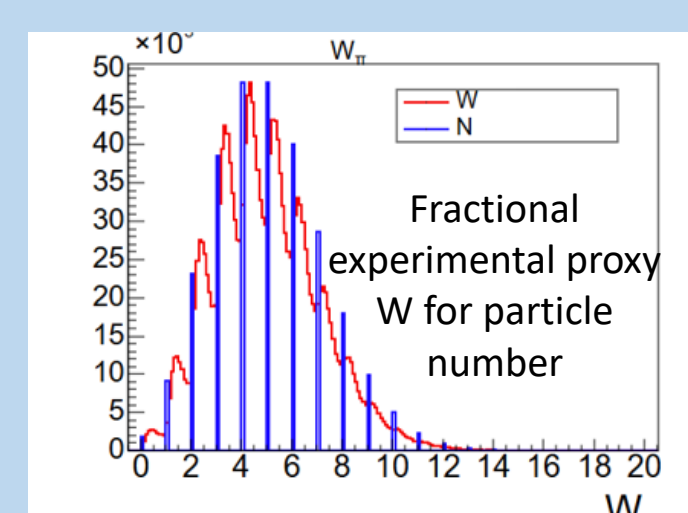
$$\omega_j(x_i) = \frac{\rho_j(x_i)}{\sum_j \rho_j(x_i)}$$

$$W_j = \sum_{i=1}^n \omega_j(x_i)$$

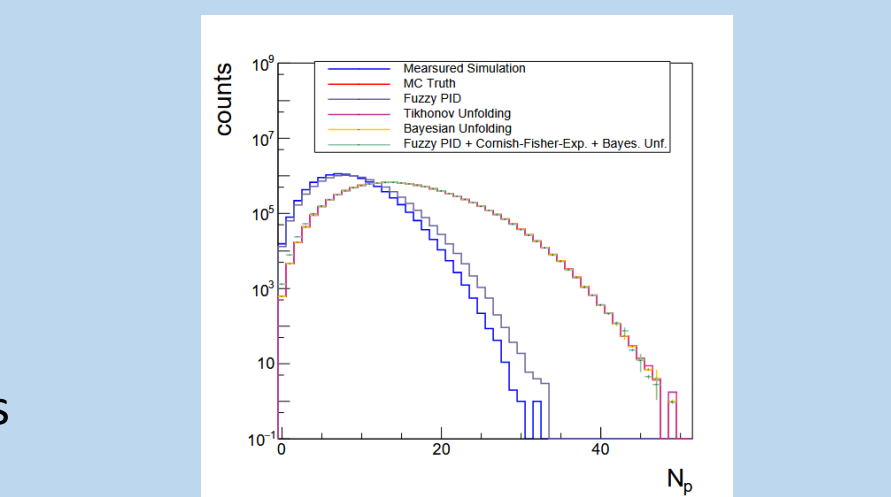
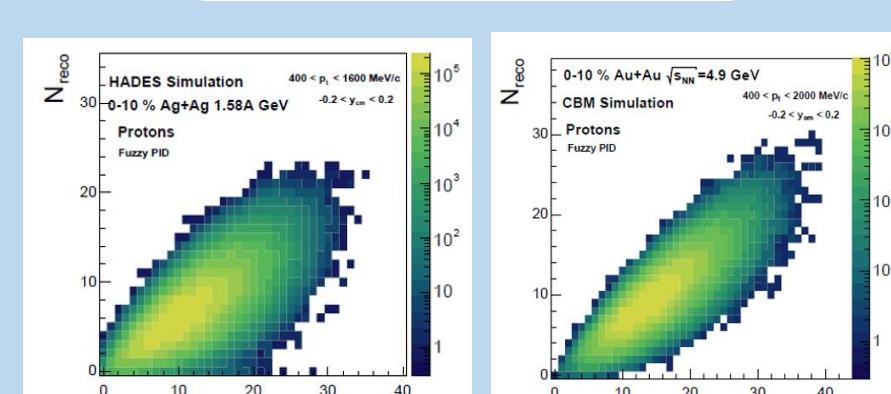
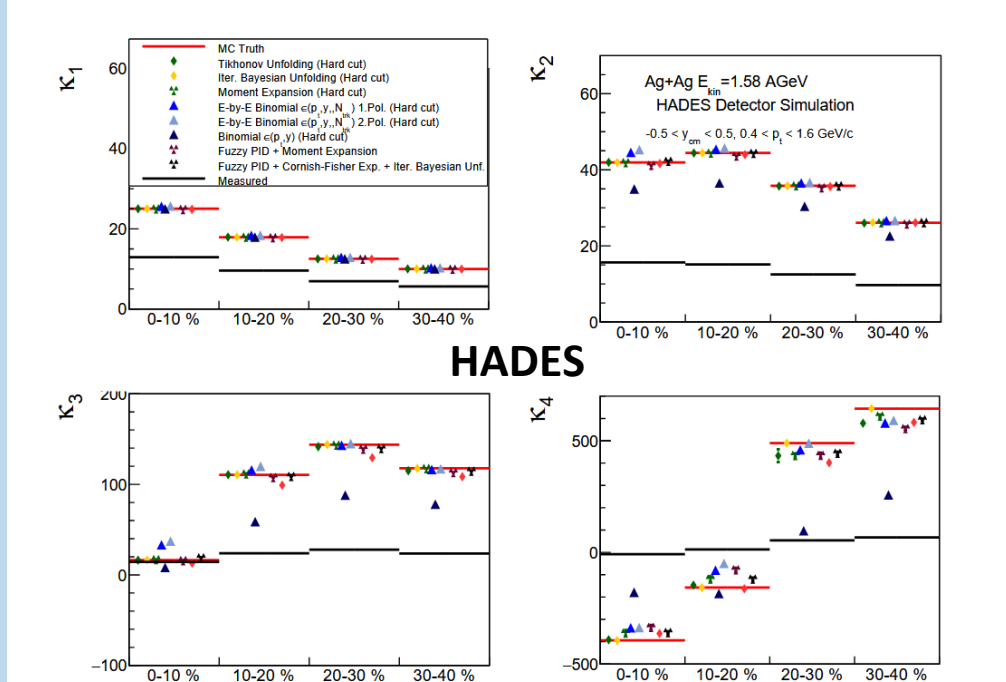
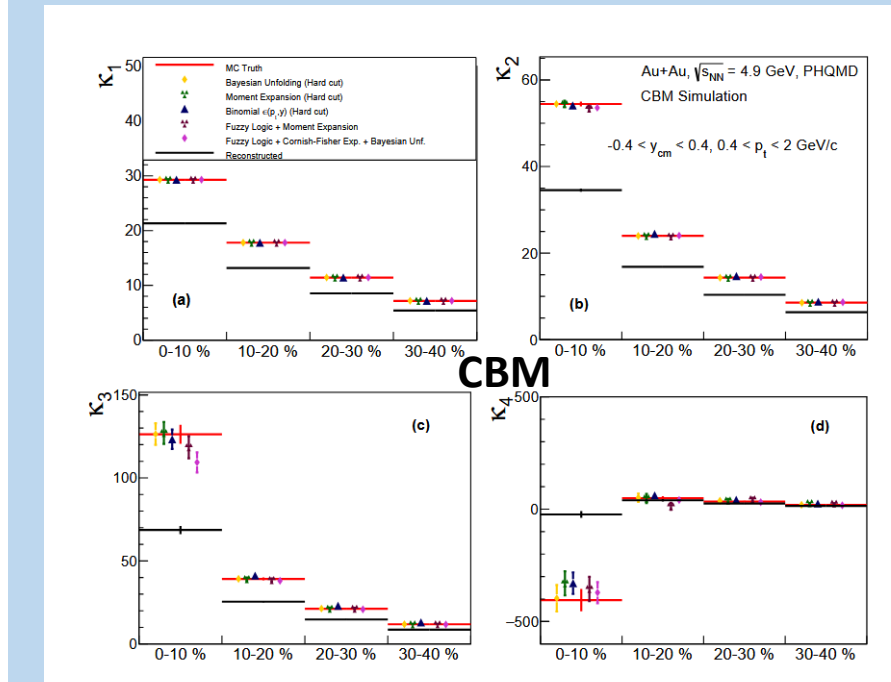
On event level:
“Sum of probabilities”

On track level: Calculate probability of track i belonging to particle j

$$x := \text{PID Observable}$$



- Finite detector tracking capabilities leads to a loss of real particle tracks of interest, on top the efficiency itself fluctuates → modifies shape of the distributions
- Various efficiency-correction methods have been implemented and validated using detector simulations:
 - Binomial, Binomial(pt,y) E-by-E Binomial
 - Distribution unfolding: Tikhonov unfolding, Iterative Bayesian unfolding
 - Direct correction of moments...



➤ Moment expansion and iter. Bayesian unfolding combined with Fuzzy logic

➤ Binomial(pt,y) correction feasible for CBM
➤ Well behaved response shape

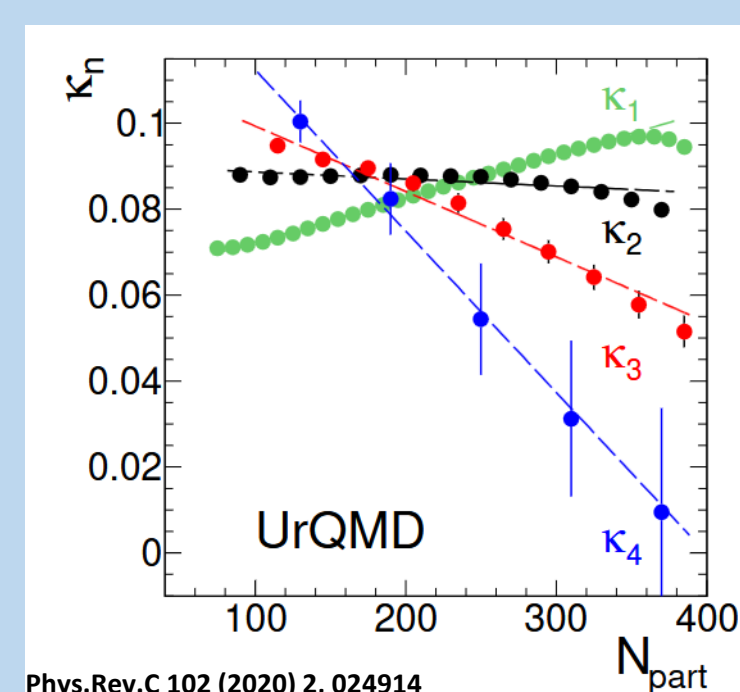
Controlling volume fluctuations

- The impact parameter varies event by event, leading to fluctuations in the number of participating nucleons and the reaction volume
- Separating volume and single-source contributions to measured cumulants requires knowledge of the volume cumulants

$$\begin{aligned} k_m(N) &:= \text{Single particle cumulants per source} \\ k_m(N_{src}) &:= \text{Cumulants of sources/participants} \\ k_m(N) &:= \text{Observed particle cumulants} \end{aligned}$$

Equation follow from factorized moment generation function, in the case the emission can be described as emission from stat. independent sources

- Caveat at lower collision energy:
 - Dominance of transported over newly produced protons
 - Possible interactions of emitted particles with spectator matter
 - Ambiguity in the effective volume definition and relevant particle-emission sources (N_{coll} , N_{part} , $N_{wounded}$ or their combination)?



Statistical Independent? → $k_m(N_{part}) = \text{const} \rightarrow$ Not valid for lower energy, equations should contain non-linear N_{part} scaling

□ Ansatz with explicit Npart dependence
Phys.Rev.C 102 (2020) 2, 024914:

$$k_m(N) = k_m(N_{part}) + k_m(N_{wounded}) + k_m(N_{spectator})$$

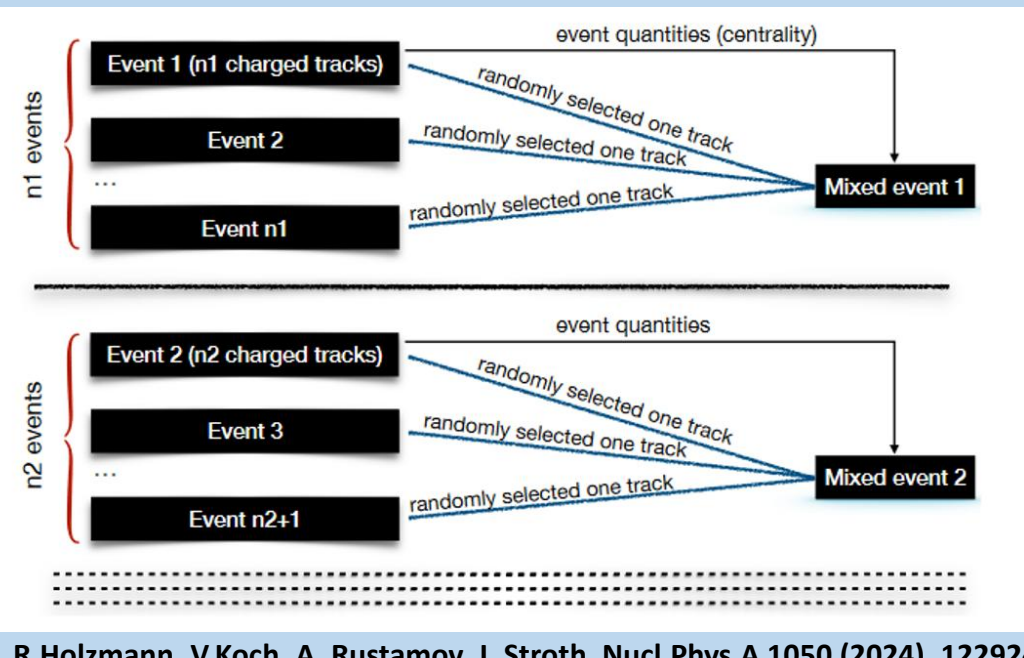
$$k_1(N) = f_1(k_1(N_{part}), k_1(N_{wounded}), k_1(N_{spectator}))$$

$$k_2(N) = f_2(k_2(N_{part}), k_2(N_{wounded}), k_2(N_{spectator}))$$

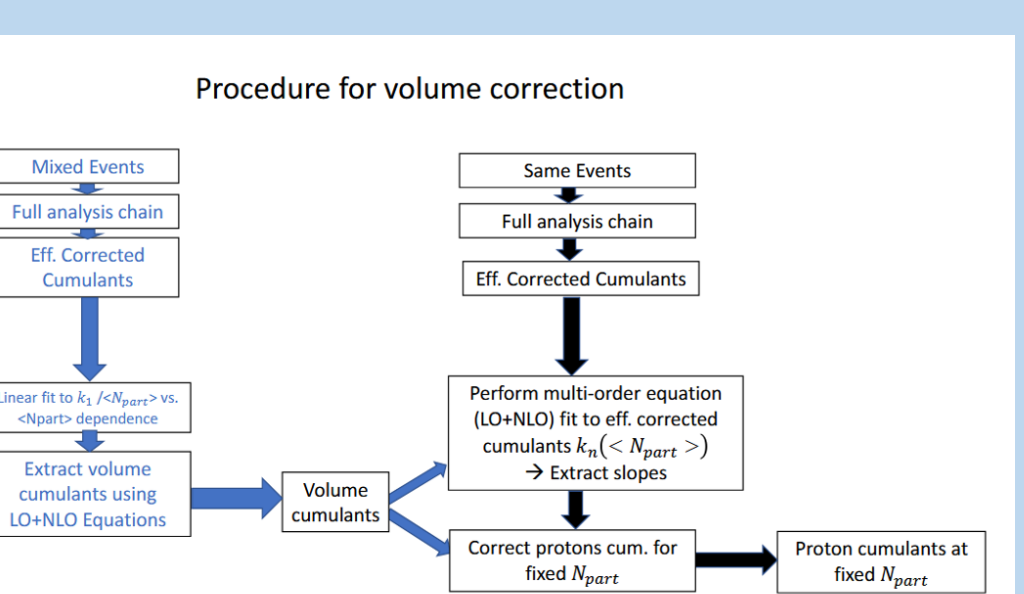
$$k_3(N) = f_3(k_3(N_{part}), k_3(N_{wounded}), k_3(N_{spectator}))$$

$$k_4(N) = f_4(k_4(N_{part}), k_4(N_{wounded}), k_4(N_{spectator}))$$

Volume cumulants from mixed events



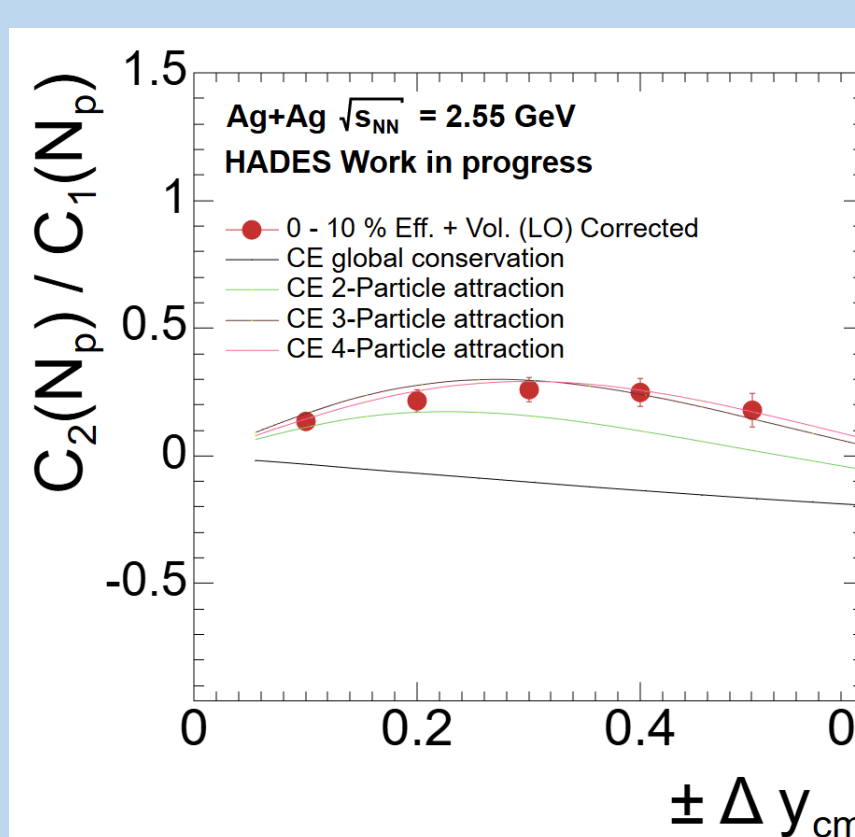
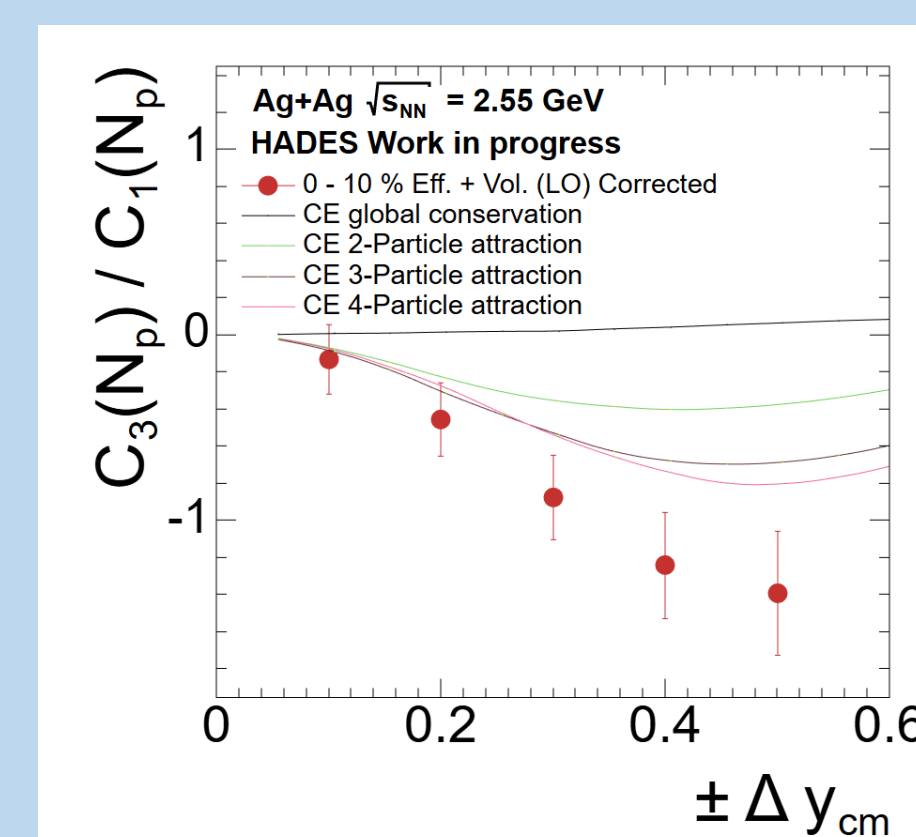
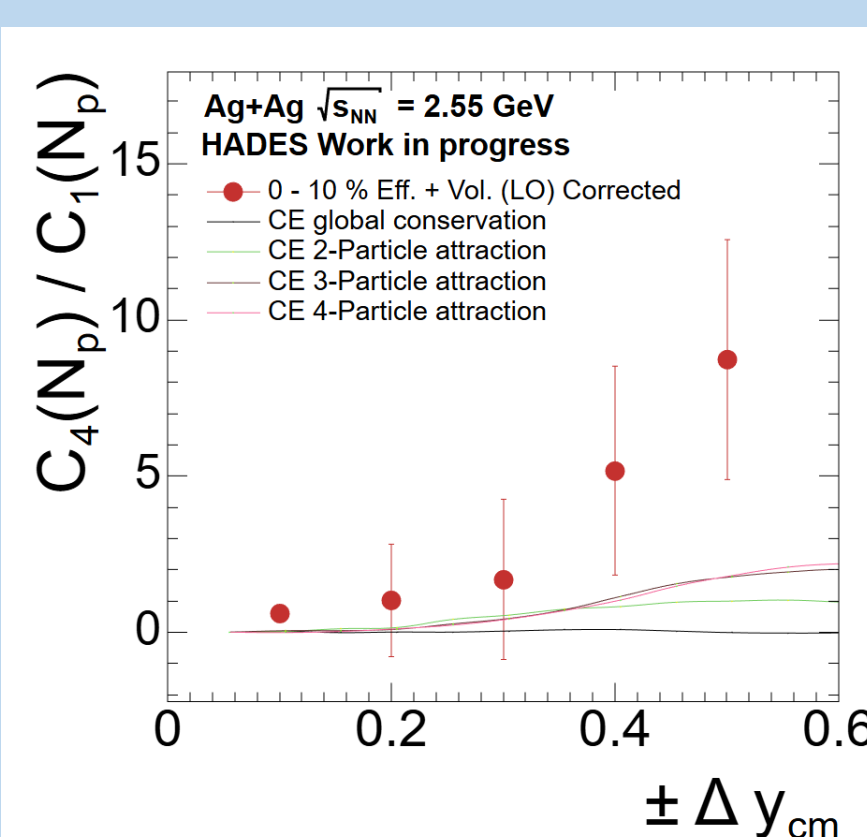
- Event mixing removes correlations between particles → In this case one expects Poisson like behaviour for the emission per source: $k_m(N) = \langle n \rangle$, $cov(n_1, n_2) = 0$
- $k_2(N_{part}) = k_2(N_{wounded}) + k_2(N_{spectator})$



- Need to input additional slope parameters
- For mixed events, in Poisson case: $k_{m,0} = k_{m,1}$ $k_{m,2} = k_{m,1}^2$

Contribution of higher order vol. cumulants in lower order multiplicity cumulant is small. If this contribution is set to zero the volume cumulants can be derived

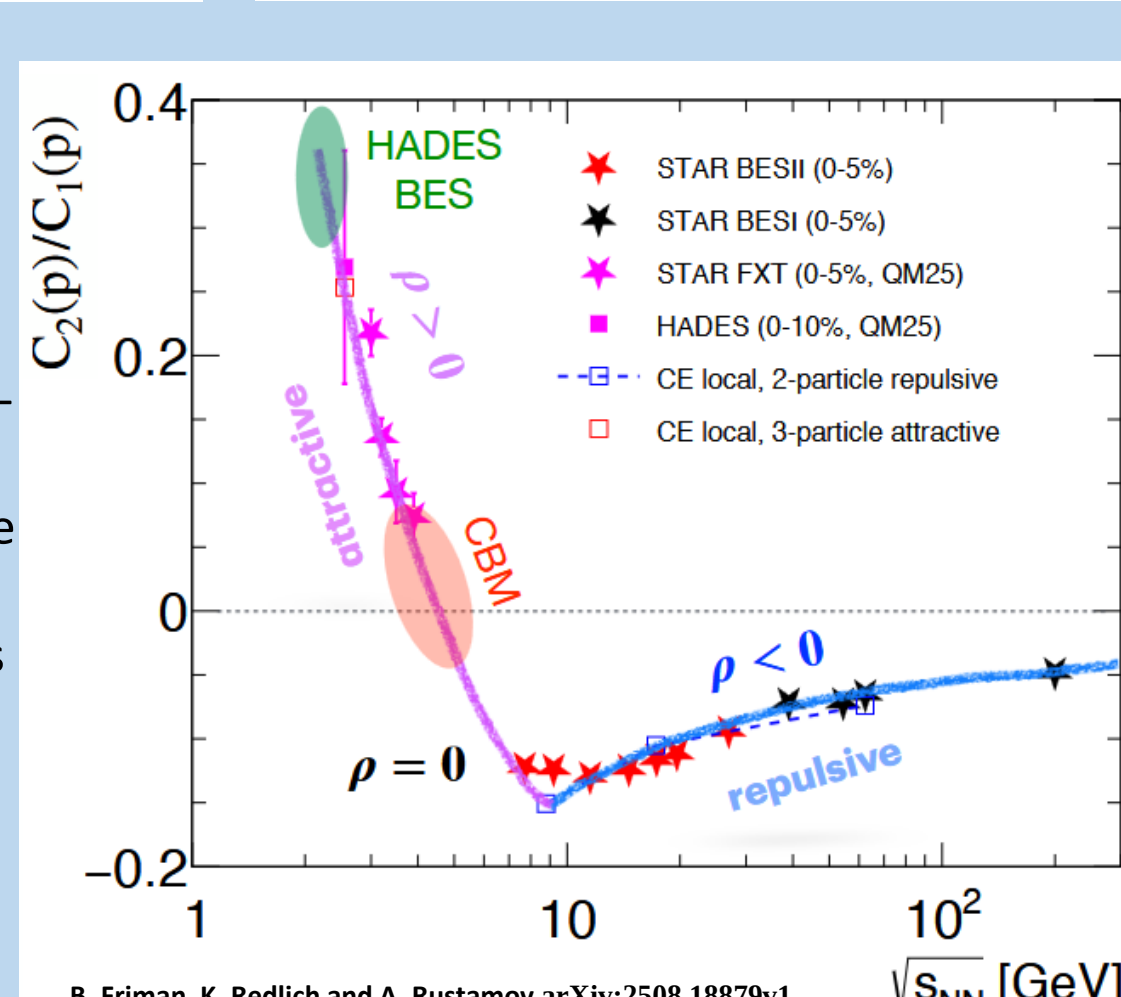
Results and future prospects



- In experiment: study as a function of increasing rapidity window to see deviation from Poisson expectations

Factorial Cumulants := Measure for genuine m-particle correlations
 $C_2 = \kappa_2 - \kappa_1^2$
 $C_3 = \kappa_3 - 3\kappa_2\kappa_1 + 2\kappa_1^3$
 $C_4 = \kappa_4 - 6\kappa_3\kappa_1 + 11\kappa_2\kappa_1^2 - 6\kappa_1^4$

- The ideal-gas CE baseline, including only baryon-number conservation, cannot reproduce the data, particularly the observed trend of the second-order cumulant
- Canonical ensemble baselines including attractive interactions reproduce the observed trend of the rapidity-window dependence
- Within the model, attractive interactions involving multi-particle clusters are required to reproduce the observed maximum in C_2/C_1
- World data indicate a sign change in the energy dependence of C_2/C_1 , which, within a thermal framework, could be interpreted as a transition from predominantly attractive to repulsive interactions with increasing collision energy
- Higher moment e-b-e fluctuations are a promising (new) tool to search for the critical behaviour → CBM will enable high-precision measurements in the region of the conjectured CEP



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