Rapidity Dependence of Proton Higher-Order Cumulants in $\sqrt{s_{NN}}$ = 3.2 GeV Au+Au Collisions at RHIC

Xin Zhang (Institute of Modern Physics, Chinese Academy of Sciences)

For STAR Collaboration

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Outline

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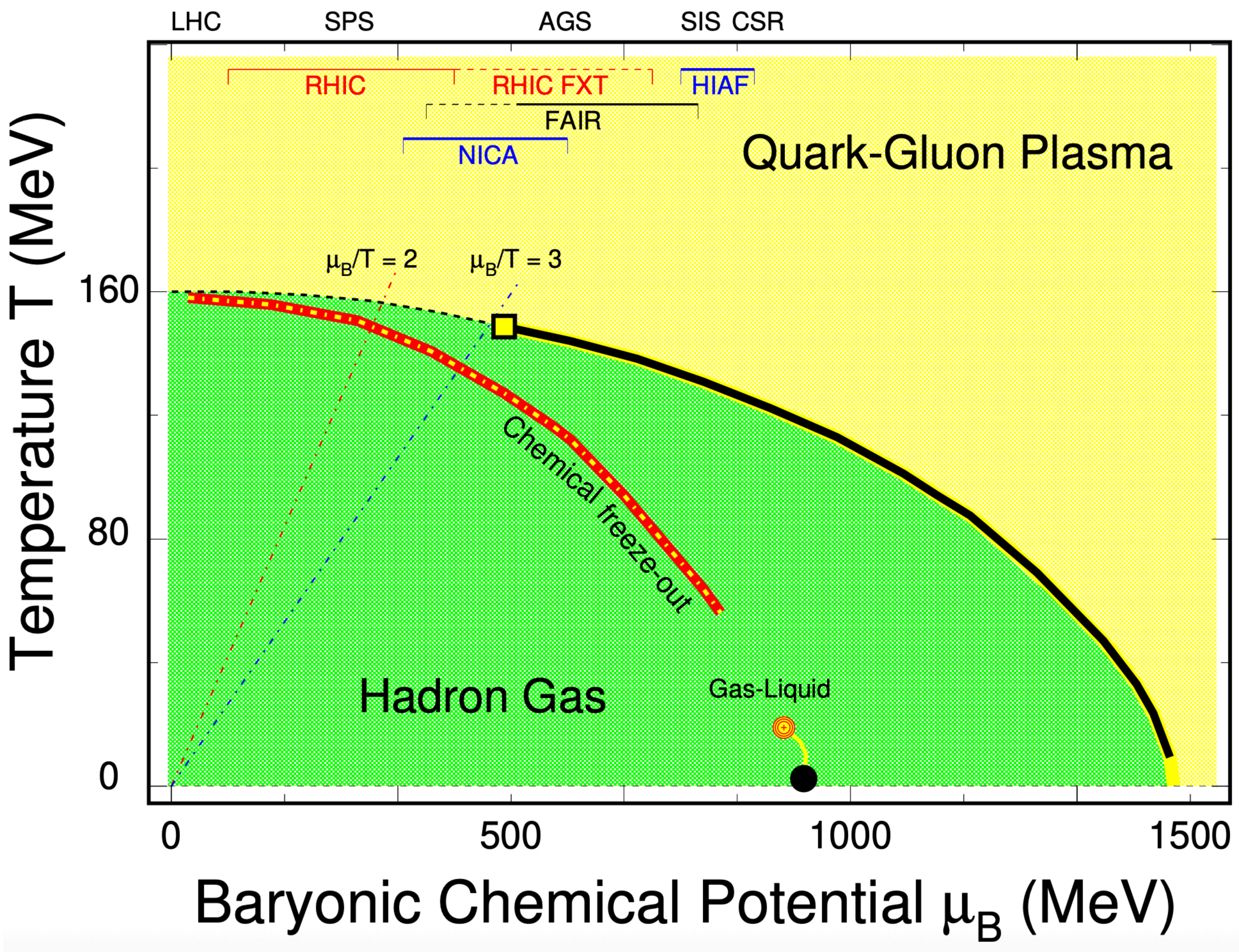
2. STAR Fixed-Target Experiment Setup
3. Analysis Details
4. Results
5. Summary and Outlook

Motivation



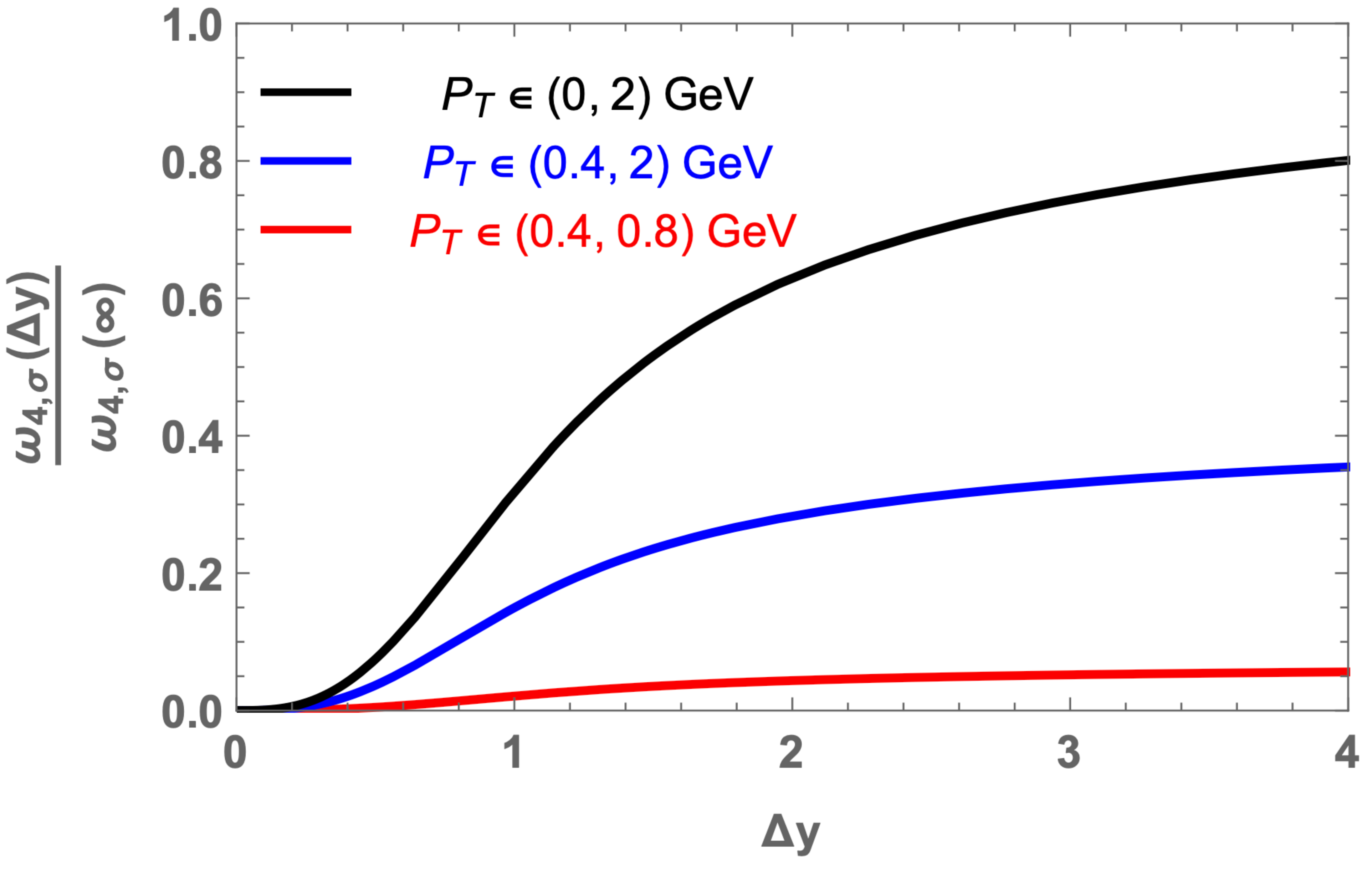
B. Mohanty, N. Xu, arXiv:2101.09210

1. Smooth crossover at $\mu_B = 0$
2. Models predict 1st order phase transition at large μ_B
3. Possible QCD critical point and 1st order phase boundary
4. Scan phase diagram by varying collision energy

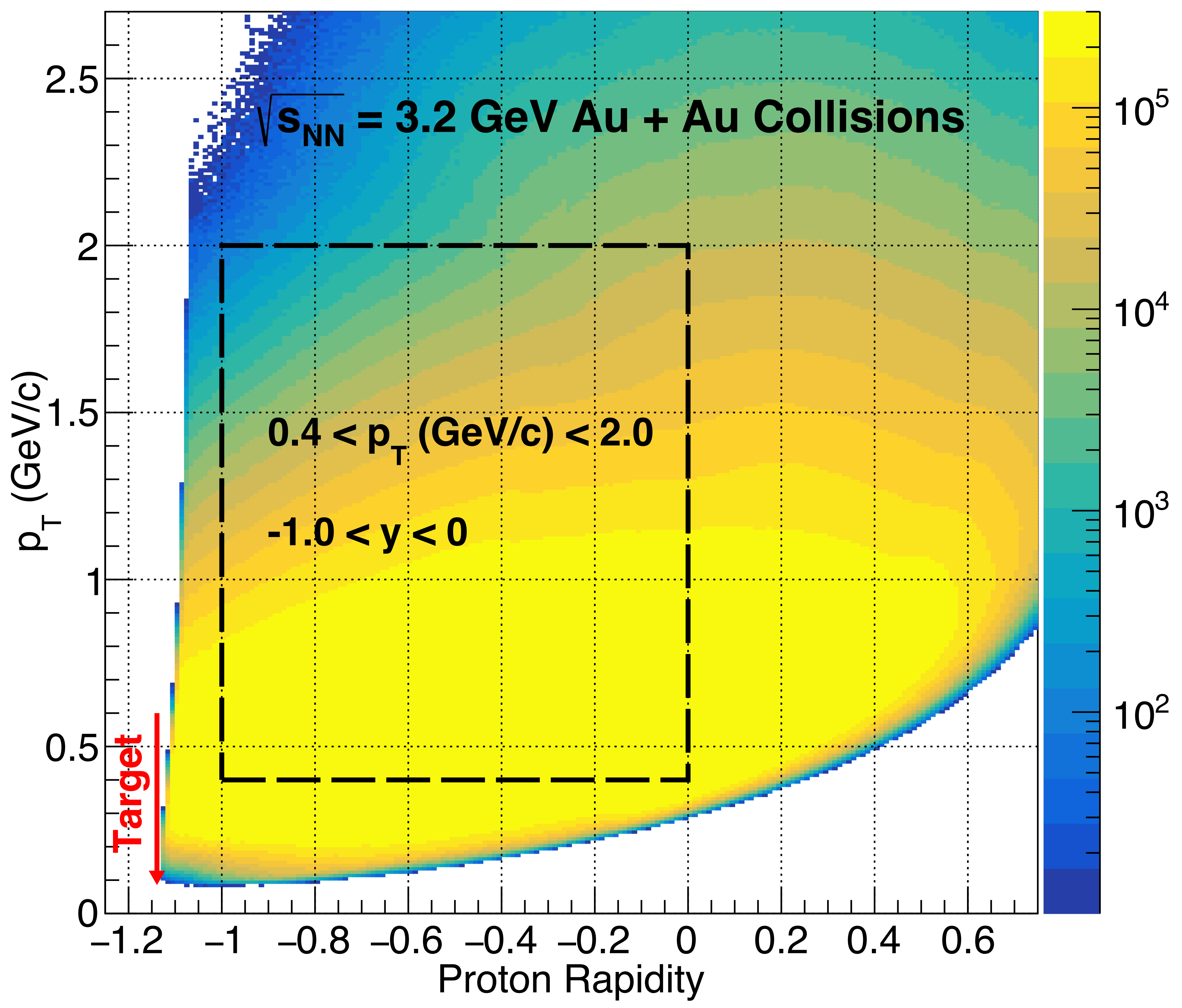
Goals of RHIC Beam Energy Scan Program:
identify phase boundary and QCD critical point

Motivation

1. Should the critical behavior exist, a larger enhancement in fluctuations at wider rapidity and transverse momentum (p_T) bins is expected
   B. Ling and M. A. Stephanov, Phys. Rev. C 93, 034915 (2016)
2. STAR Fixed-Target (FXT) experiment: scan from mid-rapidity (hot medium) to target rapidity (cold nuclear matter)



Acceptance dependence of the critical contribution to the normalized cumulants of proton number



Experimental Observables

Fluctuation: Cumulant

1. Measure non-Gaussian fluctuations
2. Extensive variables for cumulants
   (intensive for cumulant ratios)

Conserved charges:

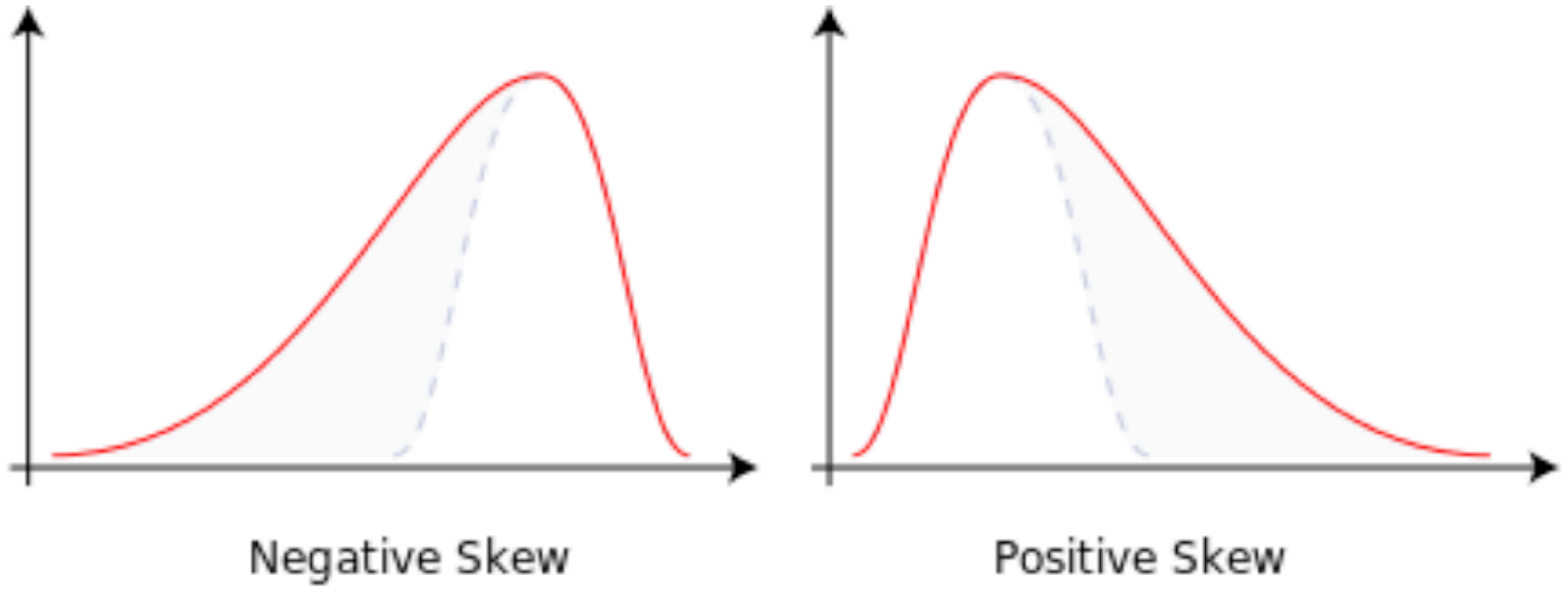
1. Net-baryon number (proton)
2. Net charge number
3. Net strangeness number (net-kaon)

Fluctuations of conserved quantities are sensitive to the critical behavior

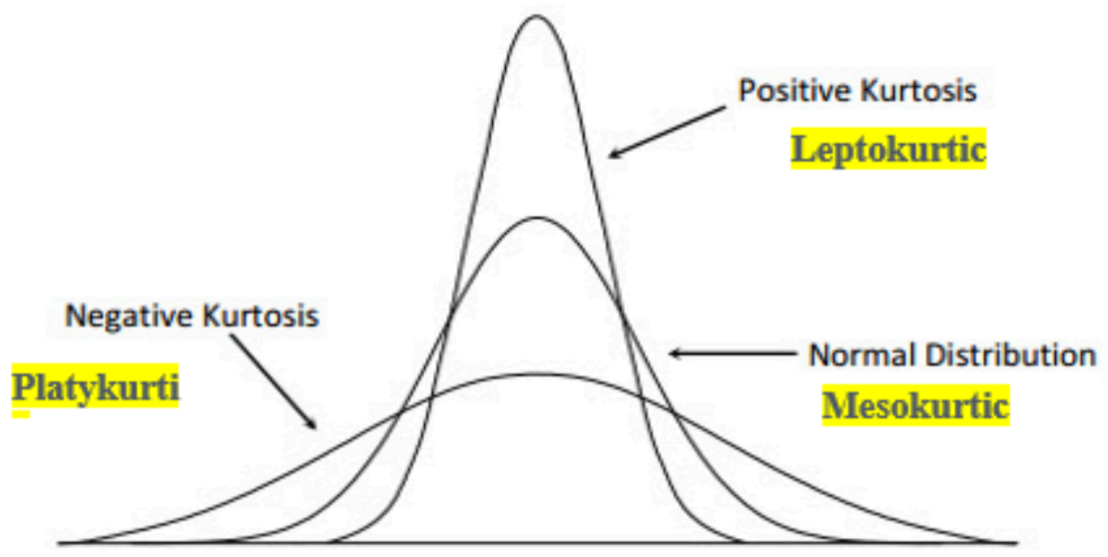
Cumulants:	**Factorial Cumulants:**
$\delta N = N - < N >$, N *is proton multiplicity in an event*	
$C_1 = \langle N \rangle$	$\kappa_1 = C_1$
$C_2 = \langle \delta N^2 \rangle$	$\kappa_2 = -C_1 + C_2$
$C_3 = \langle \delta N^3 \rangle$	$\kappa_3 = 2C_1 - 3C_2 + C_3$
$C_4 = \langle \delta N^4 \rangle - 3\langle \delta N^2 \rangle^2$	$\kappa_4 = -6C_1 + 11C_2 - 6C_3 + C_4$
$C_5 = \langle \delta N^5 \rangle - 10\langle \delta N^3 \rangle \langle \delta N^2 \rangle$	$\kappa_5 = 24C_1 - 50C_2 + 35C_3 - 10C_4 + C_5$
$C_6 = \langle \delta N^6 \rangle - 15\langle \delta N^4 \rangle \langle \delta N^2 \rangle - 10\langle \delta N^3 \rangle^2 + 30\langle \delta N^2 \rangle^3$	$\kappa_6 = -120C_1 + 274C_2 - 225C_3 + 85C_4 - 15C_5 + C_6$

Experimental Observables

Skewness: Asymmetry



Kurtosis: Peakedness



Skewness and Kurtosis can describe the shape of distribution:

$$S = C_3/(C_2)^{3/2} \qquad \kappa = C_4/(C_2)^2$$

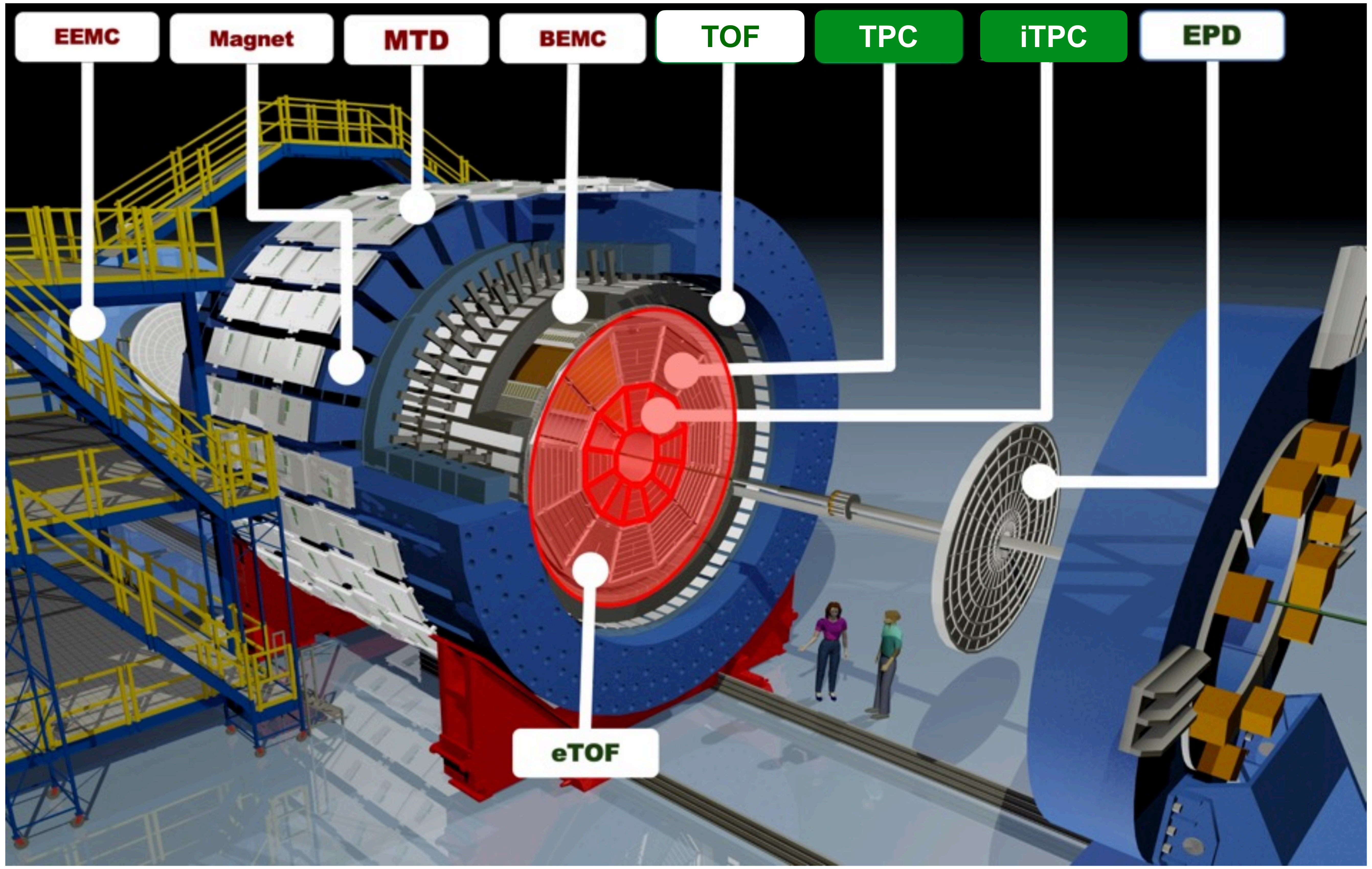
$$\frac{C_2}{C_1} = \frac{\sigma^2}{M}, \quad \frac{C_3}{C_2} = S\sigma, \quad \frac{C_4}{C_2} = \kappa\sigma^2$$

Related to correlation length: *M. A. Stephanov, arXiv:0809.3450*

$$C_3 = <(\delta N)^3> \propto \xi^{\frac{9}{2}}$$
$$C_4 = <(\delta N)^4> - 3<(\delta N)^2>^2 \propto \xi^7$$

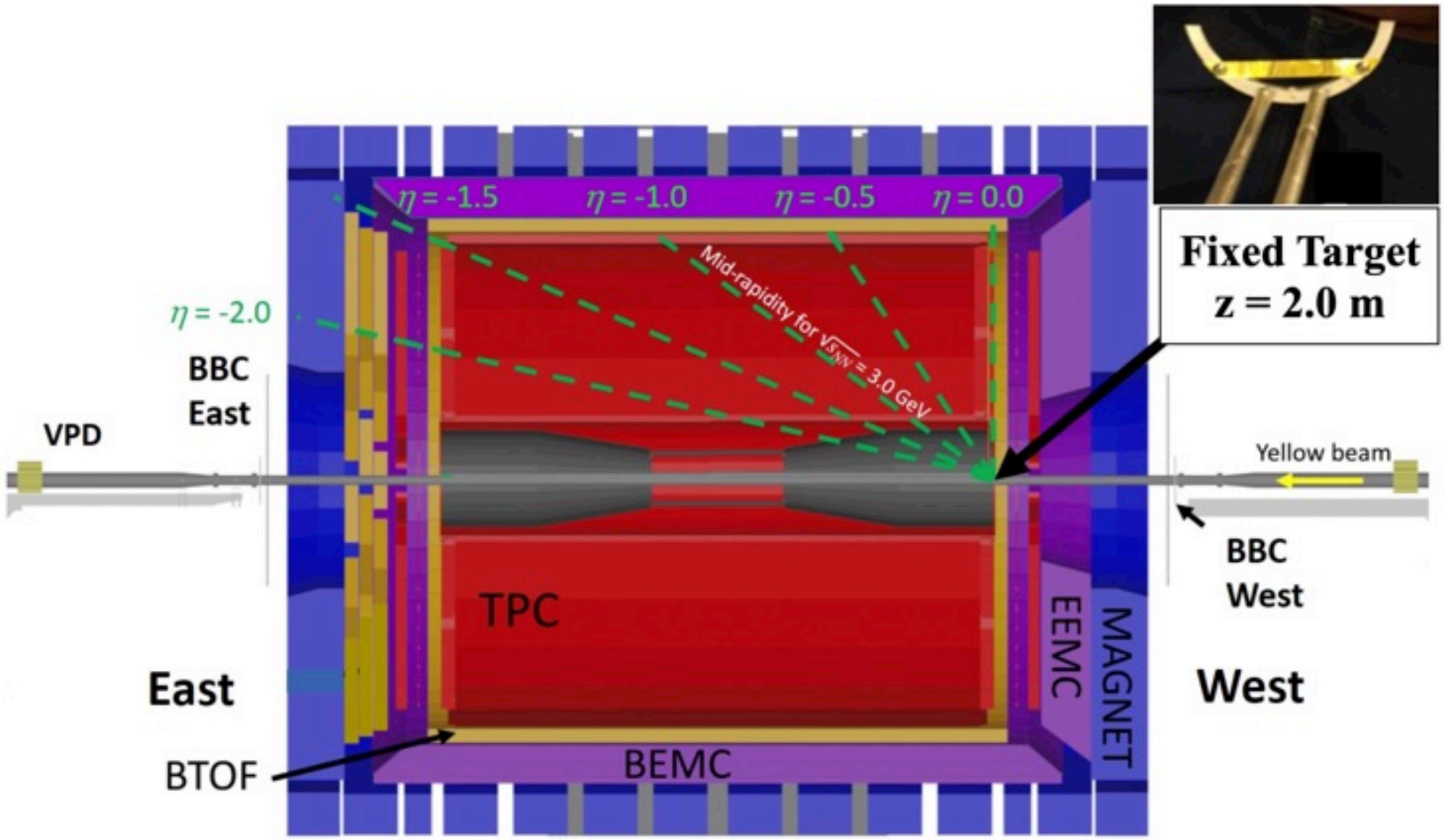
The higher-order cumulants are more sensitive to the critical behavior

STAR Fixed Target Experiment Setup



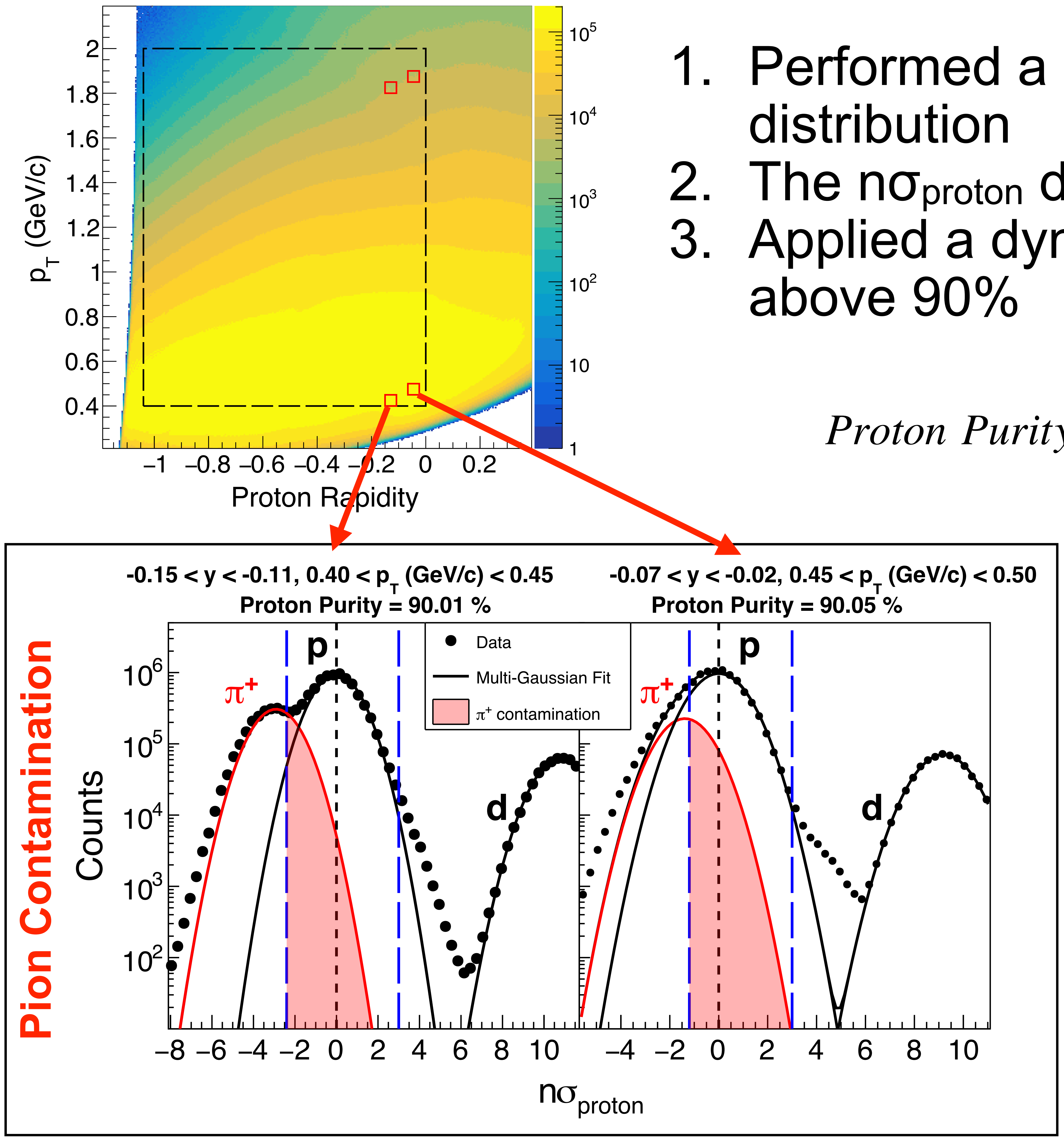
iTPC: inner Time Projection Chamber

eTOF: end-cap Time Of Flight



1. Gold target is 2.0 meters from the center of the TPC
2. Full azimuthal coverage (2π) and extended pseudo-rapidity acceptance (iTPC upgraded)
3. Extend to lower $\sqrt{s_{NN}}$ (higher μ_B, μ_B = 699 MeV for $\sqrt{s_{NN}}$ = 3.2 GeV)

Proton Identification



1. Performed a proton rapidity and p_T dependence of $n\sigma_{proton}$ distribution
2. The $n\sigma_{proton}$ distribution was fitted using multi-Gaussians
3. Applied a dynamical $n\sigma_{proton}$ range to ensure proton purity above 90%

$$Proton\ Purity = \frac{\int_{low\ cut}^{high\ cut} proton}{\int_{low\ cut}^{high\ cut} multi - Gaussians}$$

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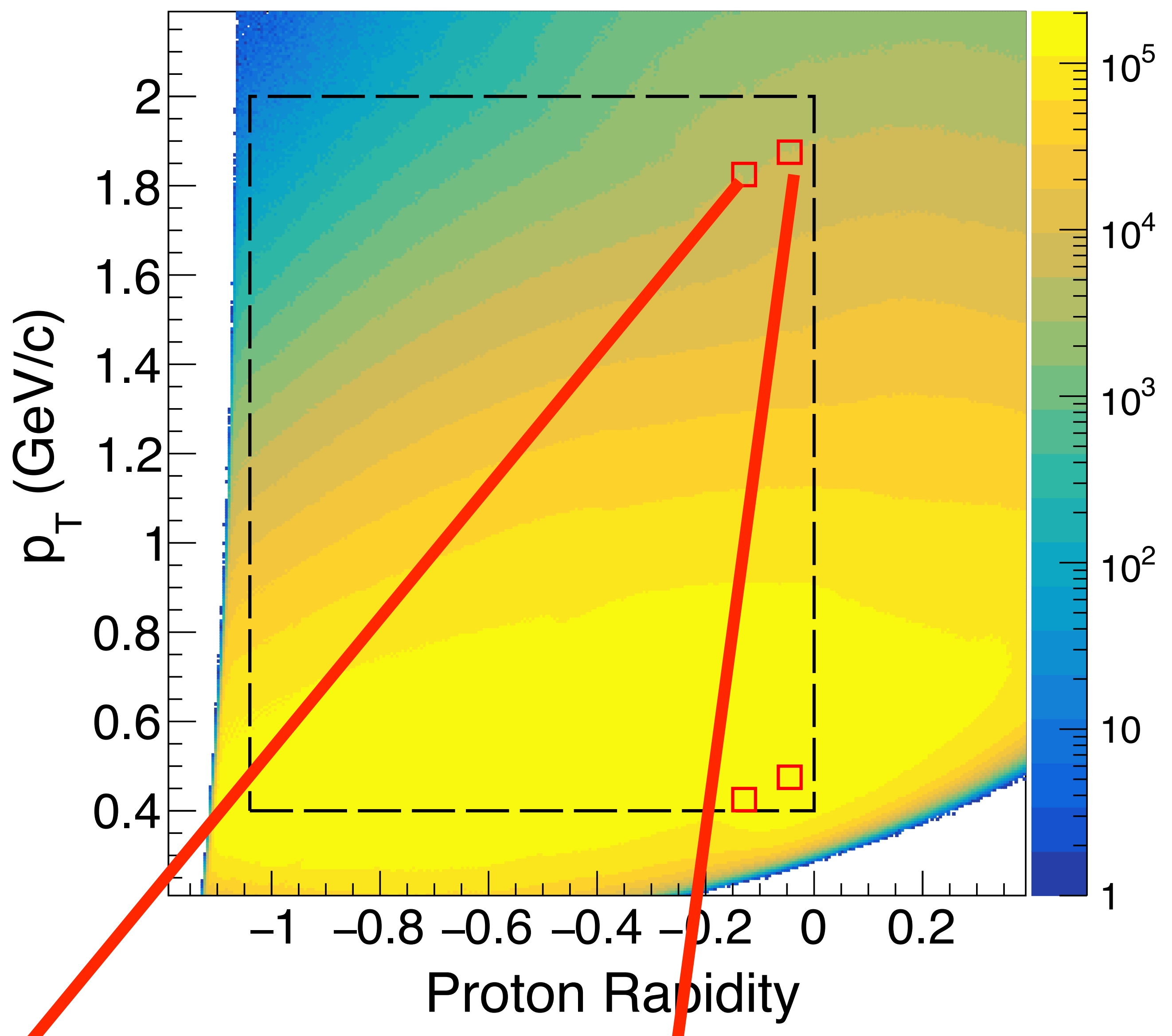

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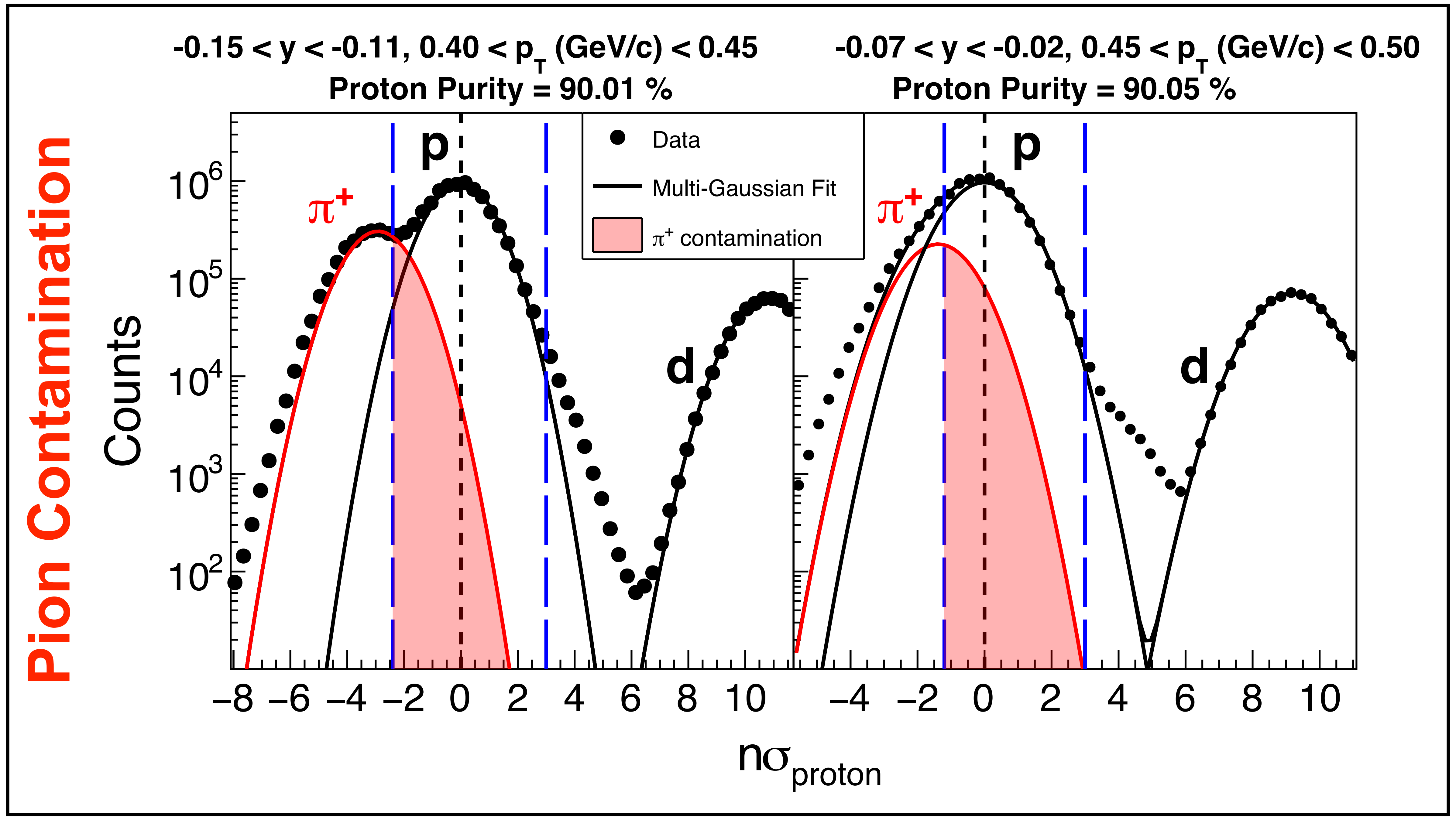
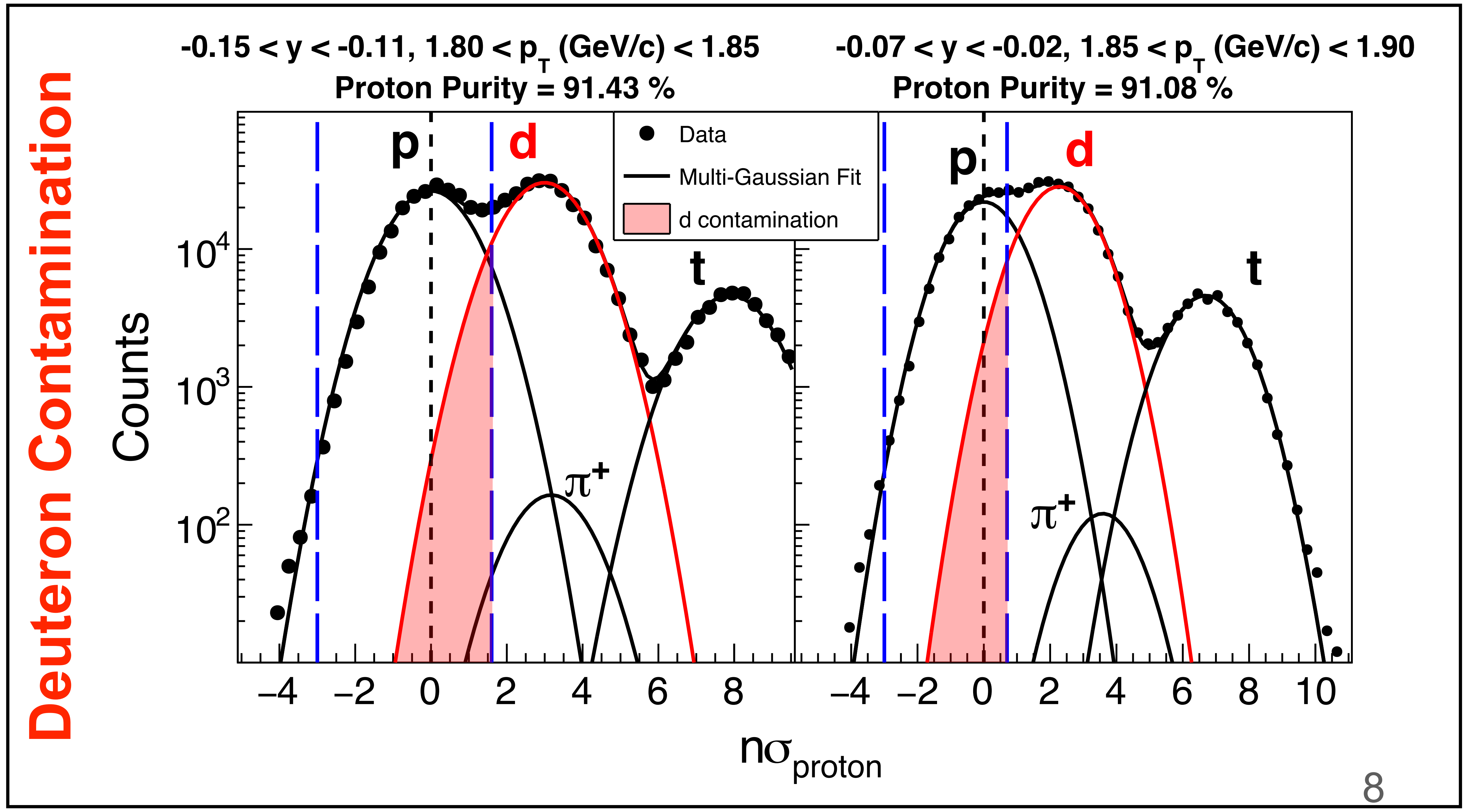
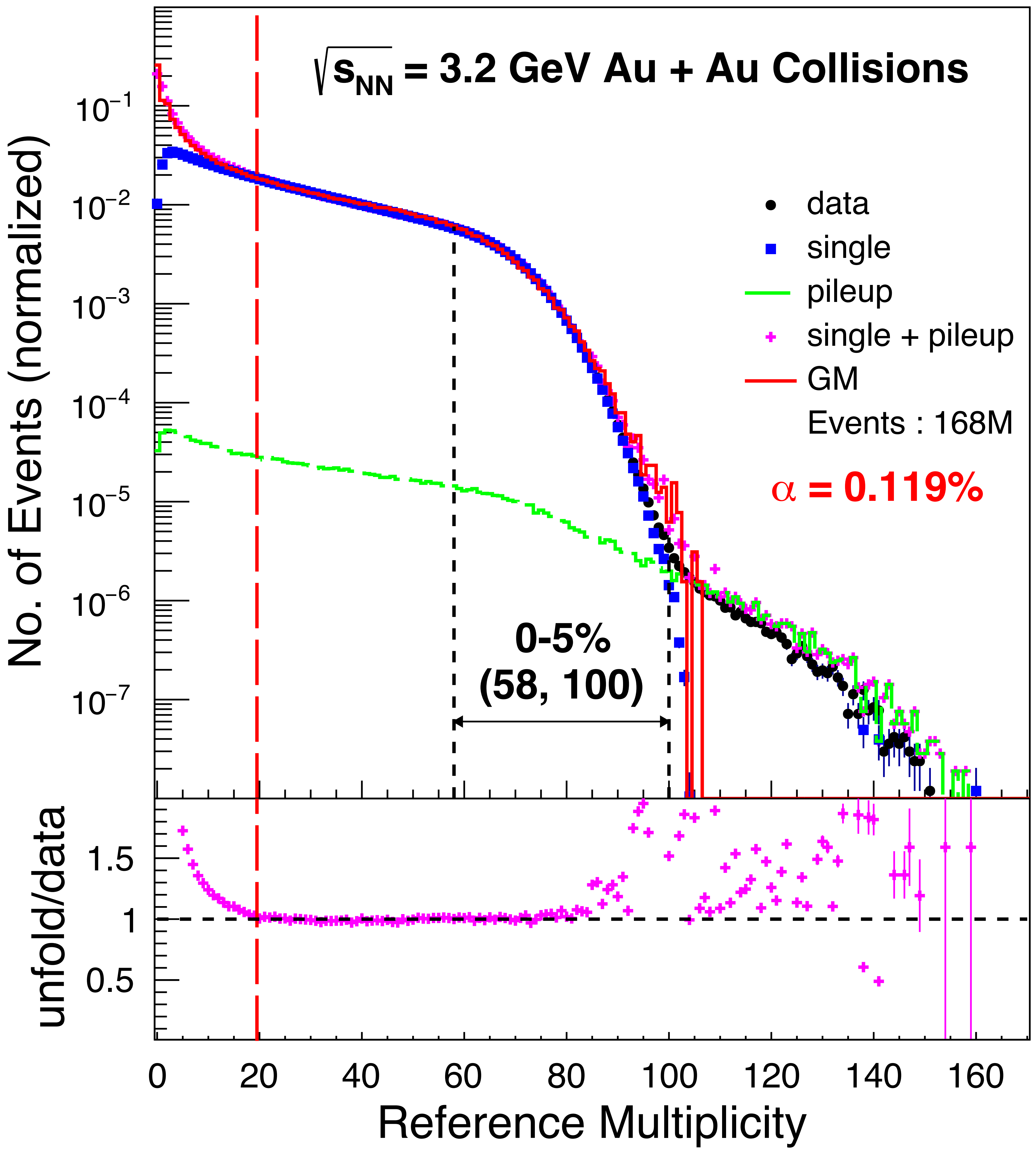




Centrality Determination

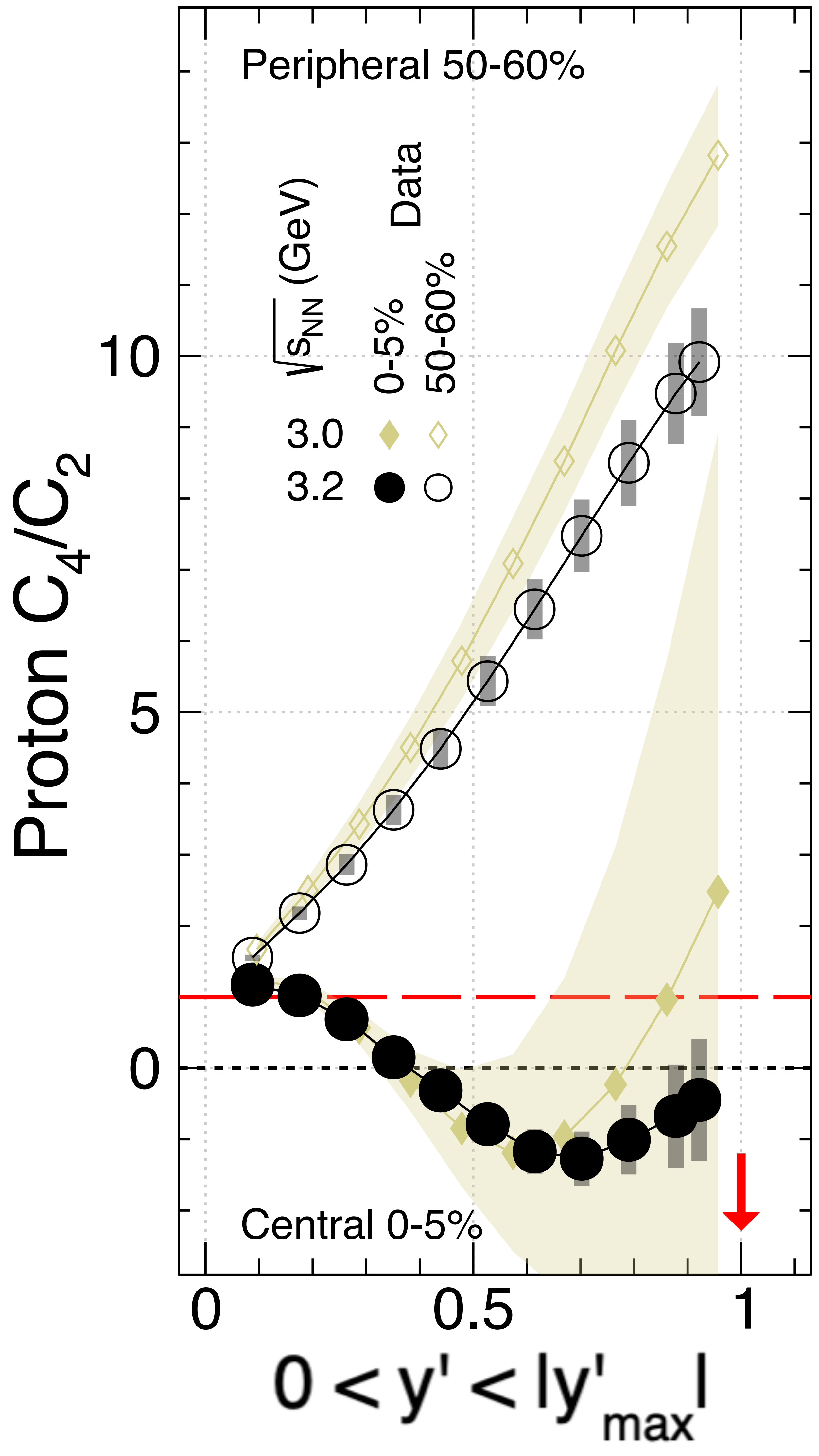


1. Pileup correction was performed using unfolding methods
   T. Nonaka et al., NIM A 984, 164632 (2020)
2. The Glauber model used to determine the collision centrality

Centrality	Reference Multiplicity	Pileup Fraction
0-5%	(58,100)	$0.40^{+0.05}_{-0.04}$ %
5-10%	(47,57)	$0.22^{+0.03}_{-0.02}$ %
10-20%	(32,46)	$0.19^{+0.02}_{-0.02}$ %
20-30%	(22,31)	$0.17^{+0.01}_{-0.02}$ %
30-40%	(14,21)	$0.14^{+0.01}_{-0.01}$ %
40-50%	(9,13)	$0.12^{+0.01}_{-0.01}$ %
50-60%	(5,8)	$0.09^{+0.01}_{-0.01}$ %

Reference multiplicity is all negative particles and π+

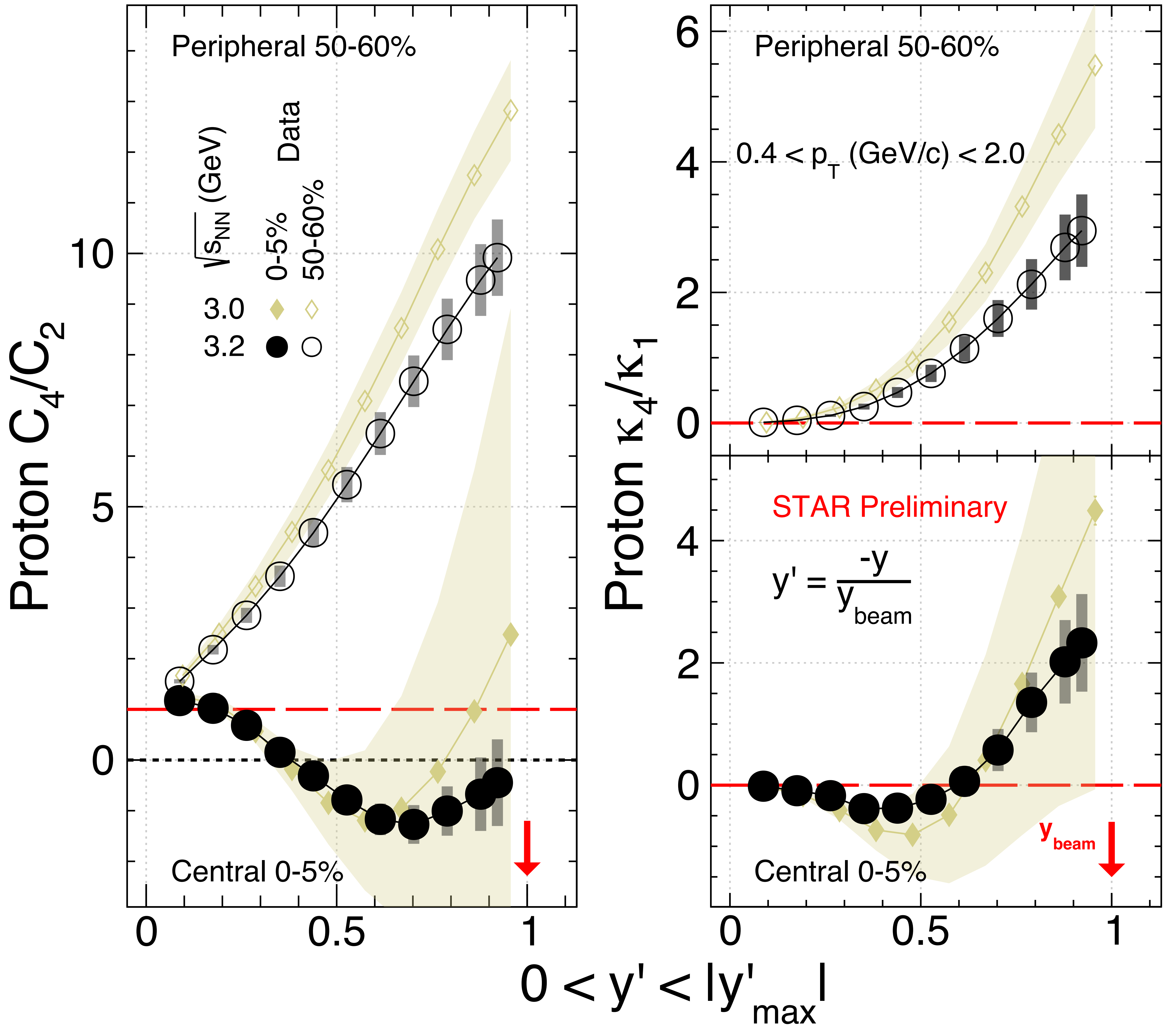
Rapidity Dependence of Proton C_4/C_2



1. From mid- to projectile-rapidity, clear rapidity and centrality dependence in C_4/C_2. Also in the published 3.0 GeV
   M. Abdallah, Phys. Rev. C 107, 024908 (2023)

y' is the normalized rapidity, $y' = \frac{-y}{y_{beam}}$

Rapidity Dependence of Proton C_4/C_2 and κ_4/κ_1



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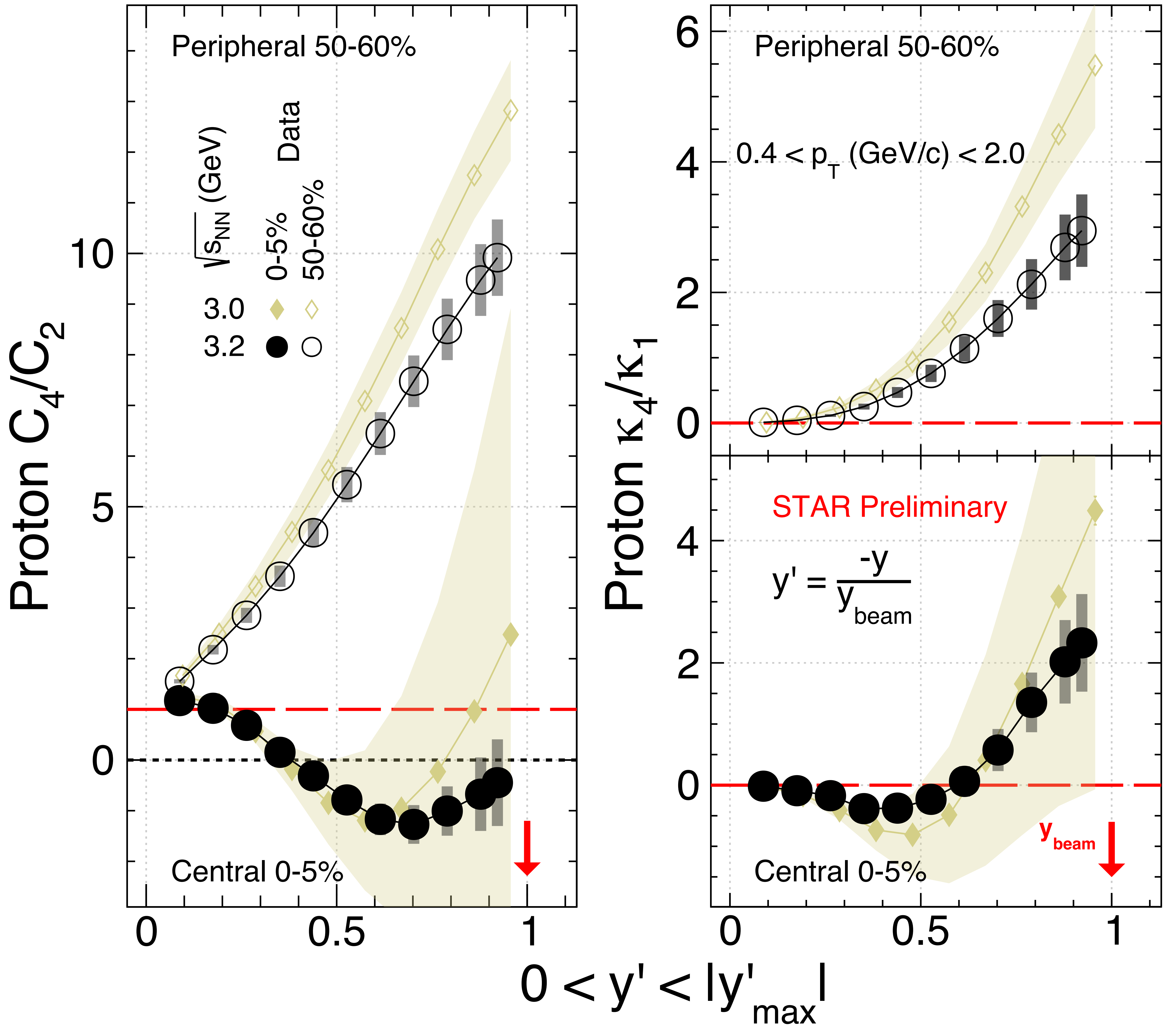

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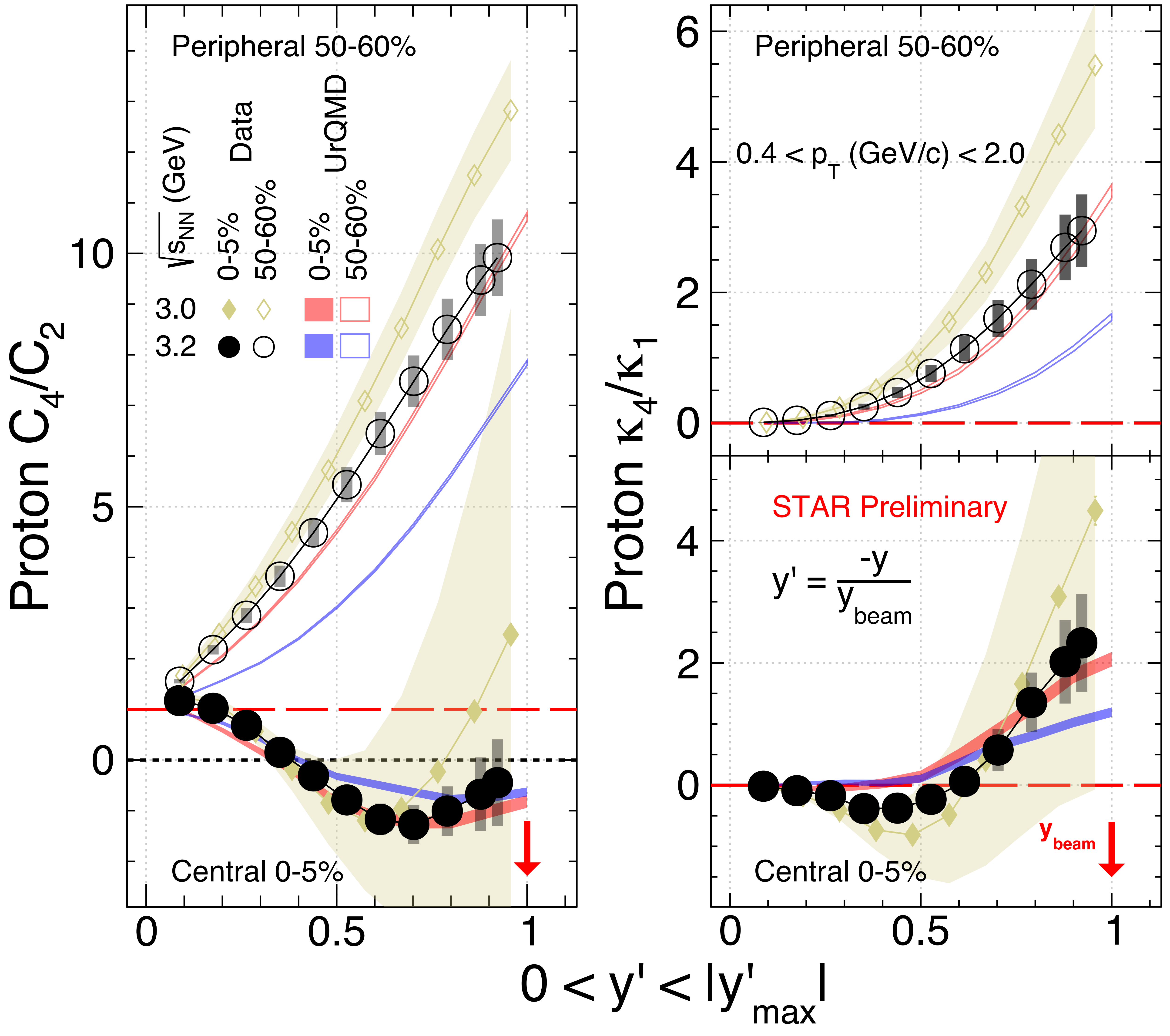

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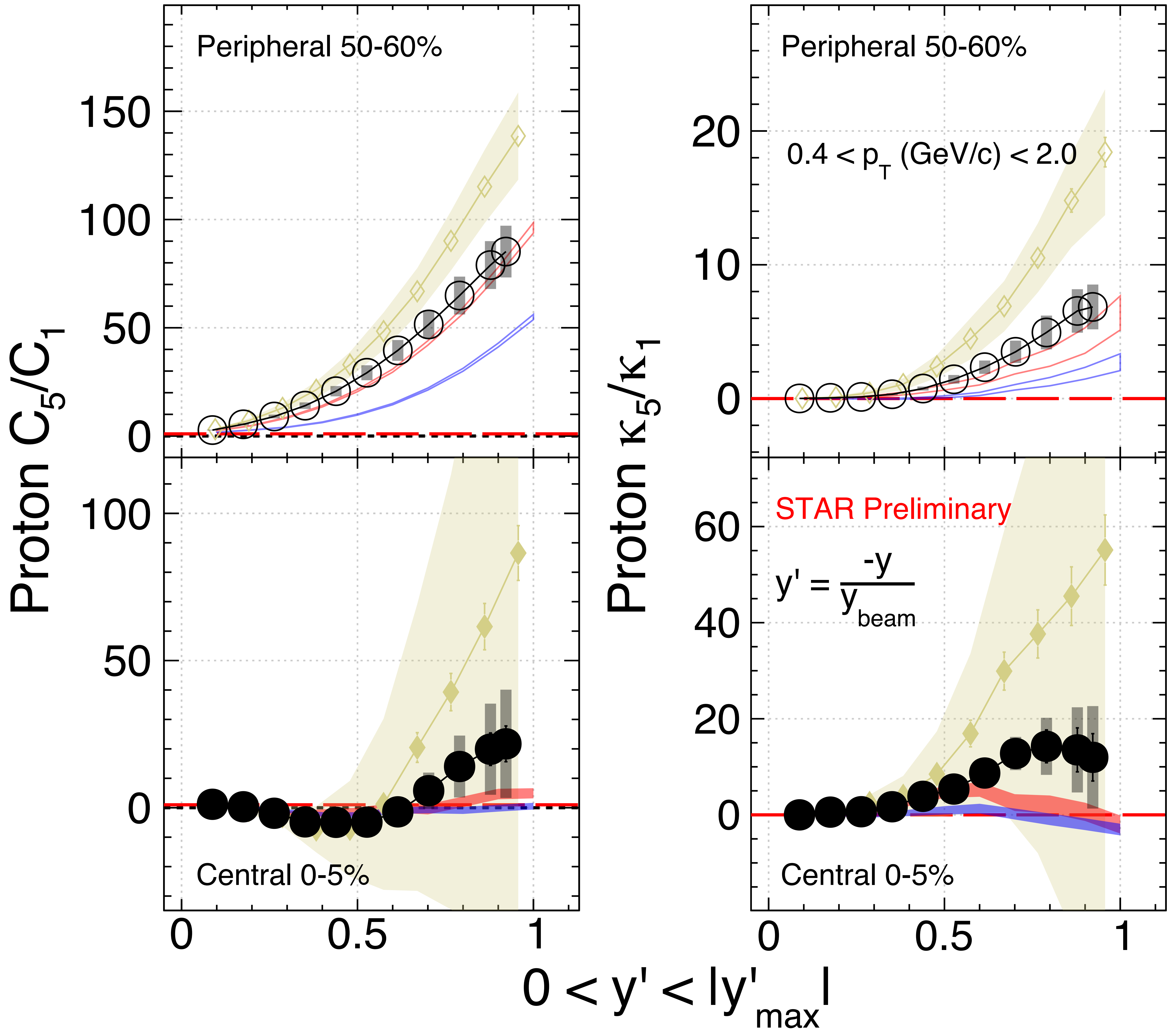
Rapidity Dependence of Proton C_5/C_1 and κ_5/κ_1



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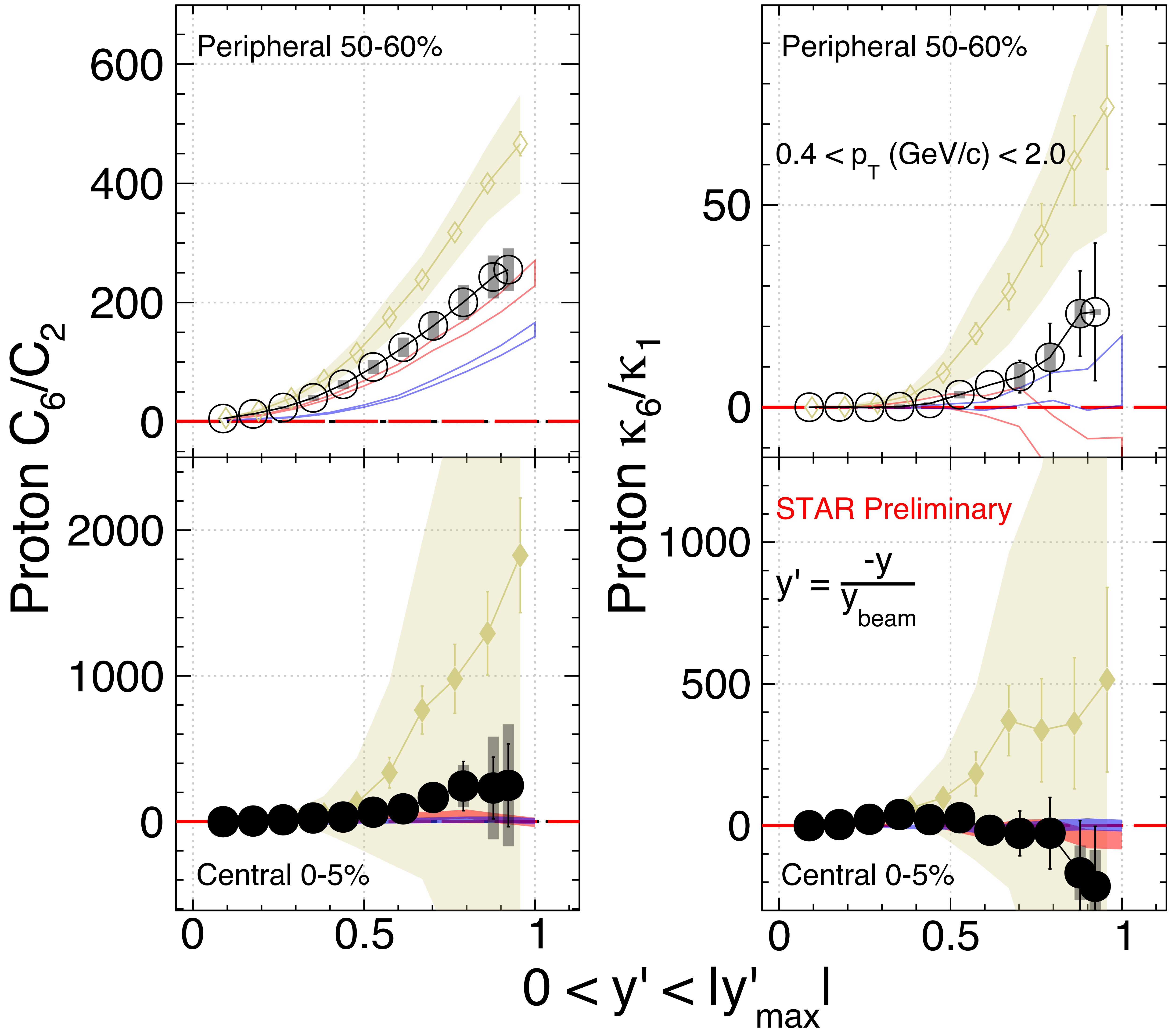

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Summary

1. Strong centrality and rapidity dependence is observed in the proton (factorial) cumulant ratios in Au+Au collisions at $\sqrt{s_{NN}}$ = 3.2 GeV
2. Hadronic transport model UrQMD qualitatively reproduces the centrality and rapidity dependence of proton (factorial) cumulant ratios. Larger deviations are seen in peripheral collisions and at high rapidity regions in central collisions

Outlook

1. 3.0 GeV was recollected in 2021 with iTPC and eTOF upgrade, we can aim to have full mid-rapidity ($|y|<0.5$, used in collider energy measurements) coverage, and statistical and systematic uncertainties may be reduced
2. The analysis of the rapidity dependence of proton high-order cumulants at 3.5, 3.9 GeV is in progress
3. Interesting rapidity dependence behavior may be further explored by the CBM experiment at 2.4 - 4.9 GeV

Thank you for your attention!