Caleb Broodo (University of Houston) for the *STAR Collaboration*

Extracting the speed of sound from $\langle p_T \rangle$ measurements in Au+Au collisions at RHIC BES-II program

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U.S. DEPARTMENT OF ENERGY
Office of Science

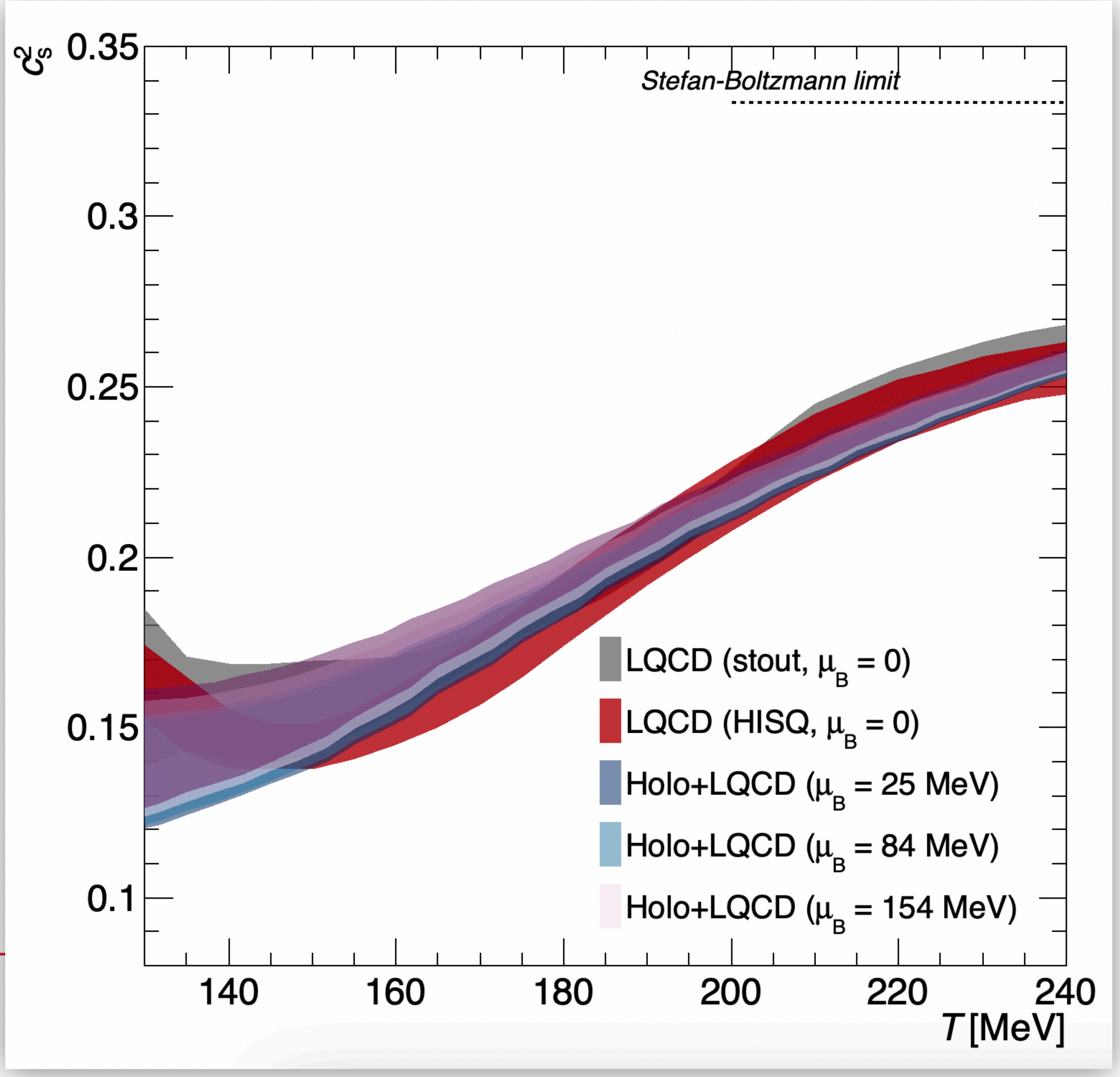
The 22nd International Conference on
Strangeness in Quark Matter
22-27 March, 2026, Los Angeles, CA
SQM 2026

One of the ultimate goals in our field

Verify and constrain the nuclear equation of state...

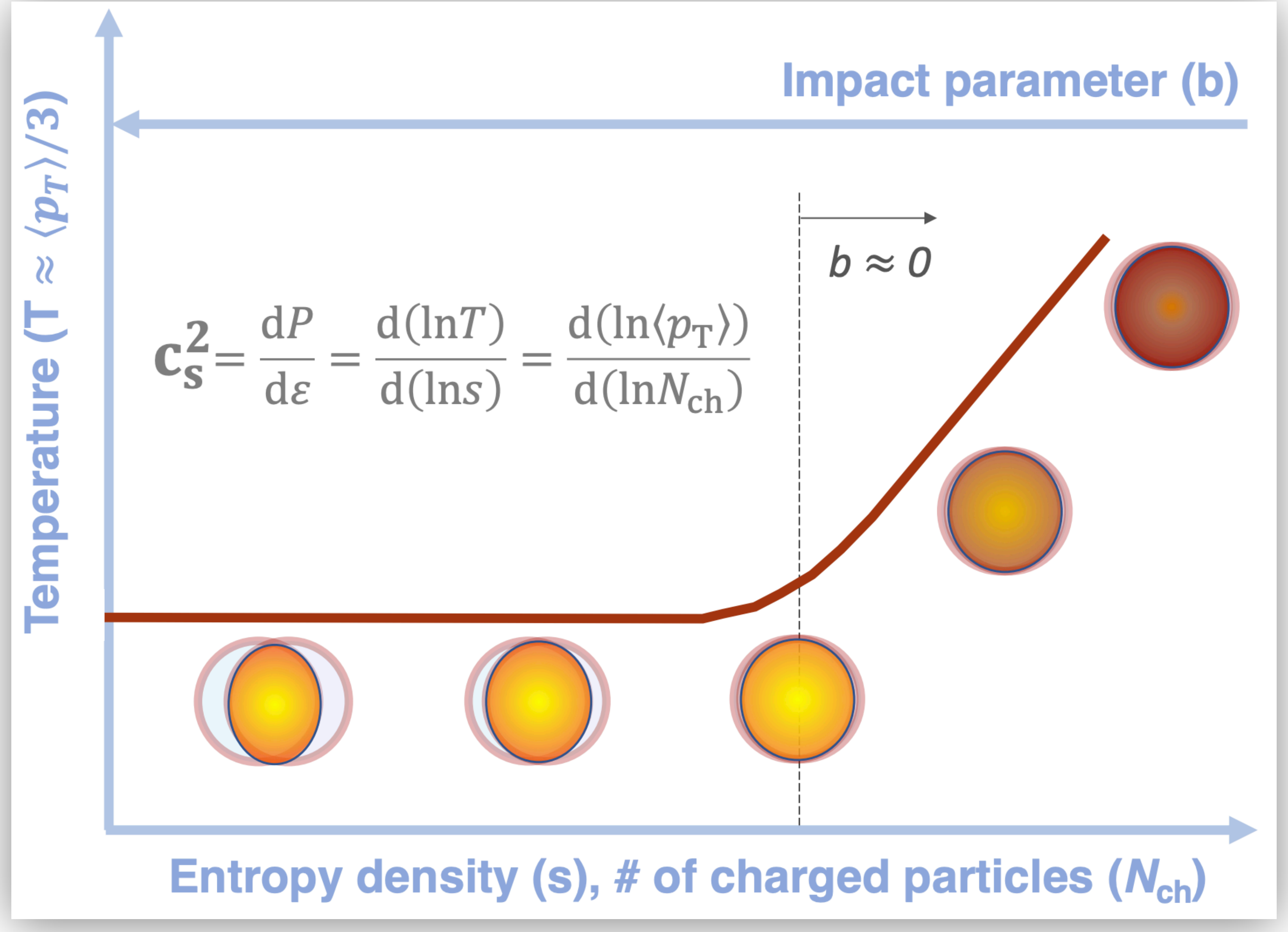
The speed of sound relates changes in temperature **T** to changes entropy density **s**

$$c_s^2 = \frac{dP}{d\epsilon} = \frac{d\ \ln T}{d\ \ln s}$$

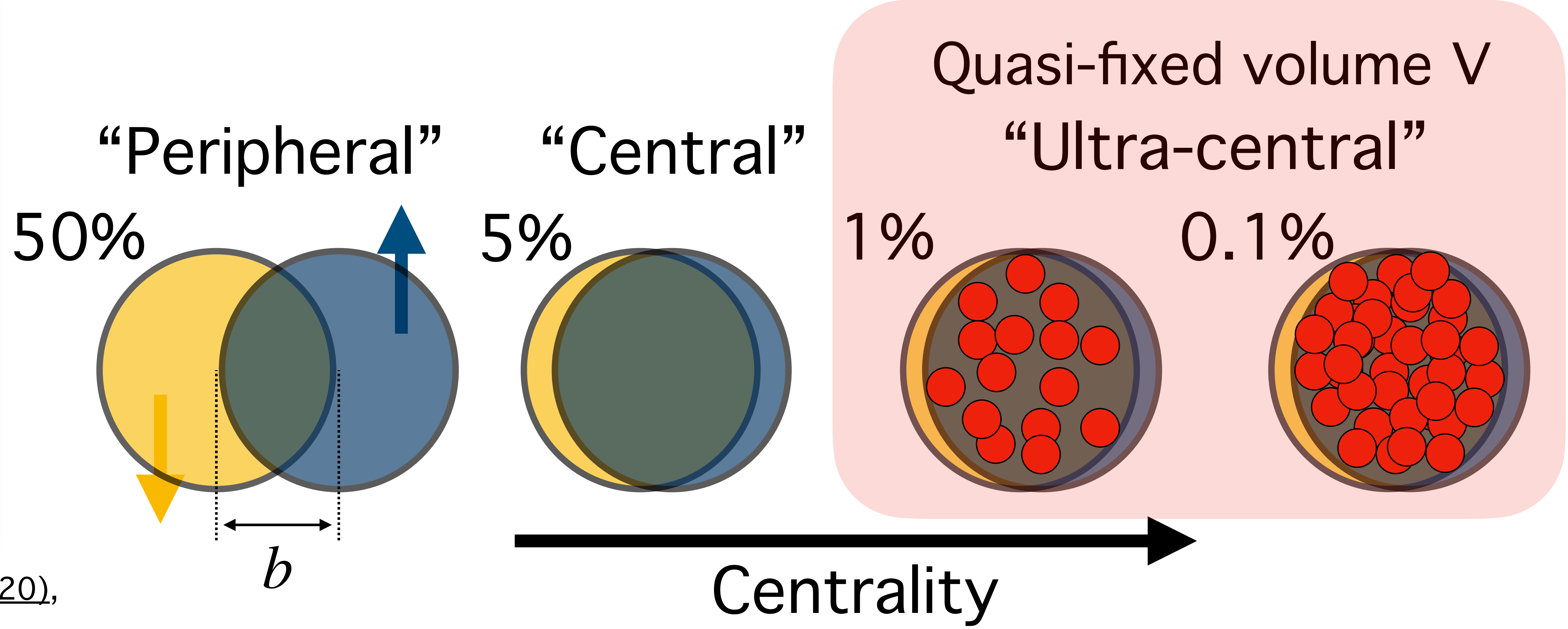


Holo + LQCD - M. Hippert et al., Phys. Rev. D 110, 094006 (2024)
stout - S. Borsanyi et al., Phys. Lett. B 370, 99-104 (2014)
HISQ - A. Bazavov et al., Phys. Rev. D 90, 094503 (2014)

The speed of sound as a "Logarithmic Derivative"



Fit scheme: Gardim et al., Nat. Phys. 16, 615-619 (2020),
Figure: CMS, Rep. Prog. Phys. 87 (2024) 077801



Quasi-fixed V

$\langle p_T \rangle \propto T$

Parameterization scheme

$$s = S/V \rightarrow N_{ch} \propto S \Rightarrow N_{ch} \propto s \rightarrow c_s^2 = \frac{d\ln T}{d\ln s} \Rightarrow c_s^2 \approx \frac{d\ln\langle p_T\rangle}{d\ln N_{ch}} \rightarrow \langle p_T\rangle/\langle p_T\rangle^{\mathrm{ref}} \propto \left(\frac{N^*_{\mathrm{ch}}}{N^*_{\mathrm{ch,knee}}}\right)^{c_s^2}$$

Impact parameter fluctuations minimizes: $\delta b \rightarrow 0 \Rightarrow \langle p_T \rangle$ response to N_{ch} increase driven by pressure response to change in energy density

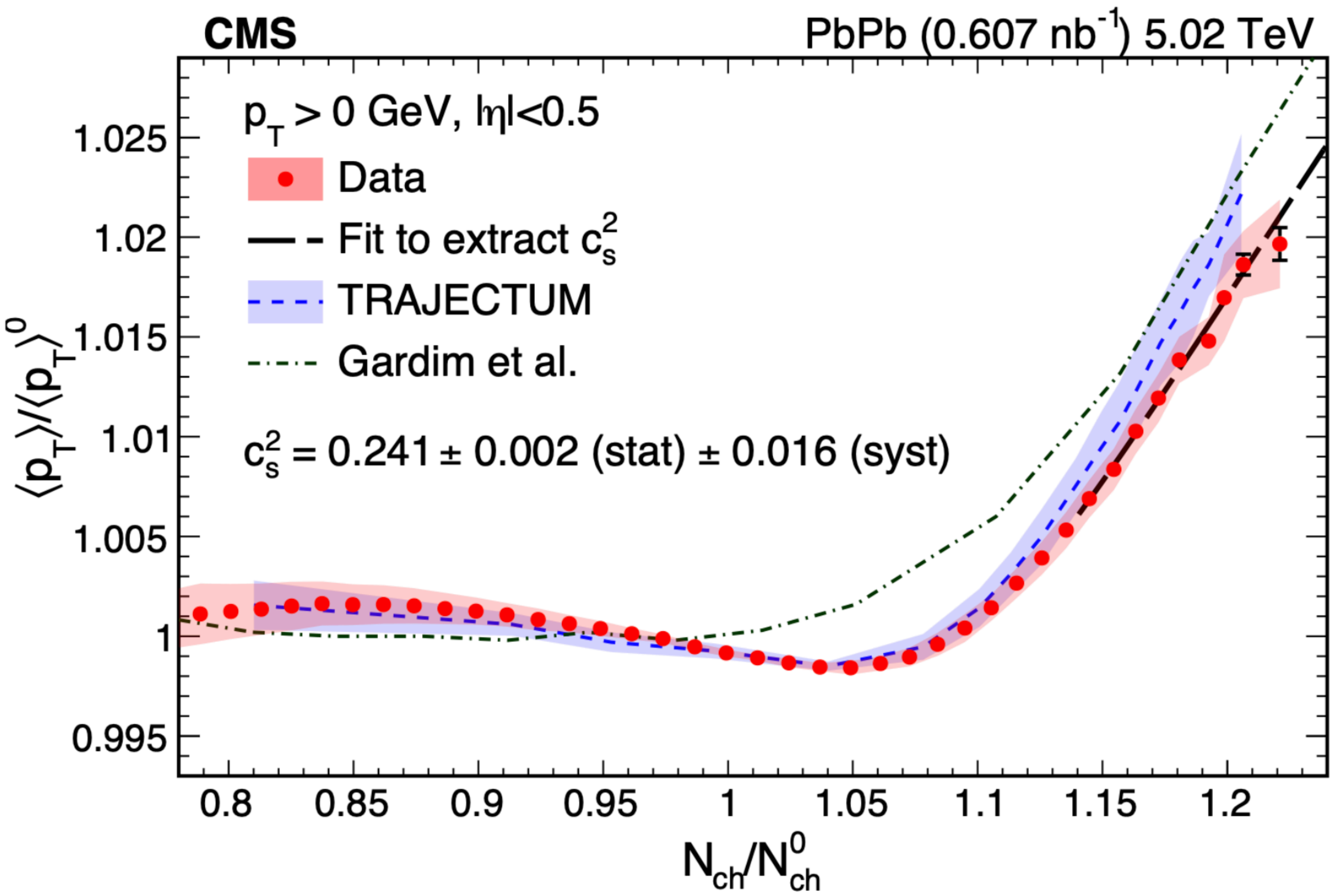
A hat trick from CMS

Innovative approach to measure $\langle p_T \rangle$ vs N_{ch}

- Self normalized quantities

N^0_{ch}: N_{ch} Measured in the 0-5%

$\langle p_T \rangle^0$: $\langle p_T \rangle$ Measured in the 0-5%



CMS, Rep. Prog. Phys. 87 (2024) 077801

A hat trick from CMS

Innovative approach to measure $\langle p_T \rangle$ vs N_{ch}

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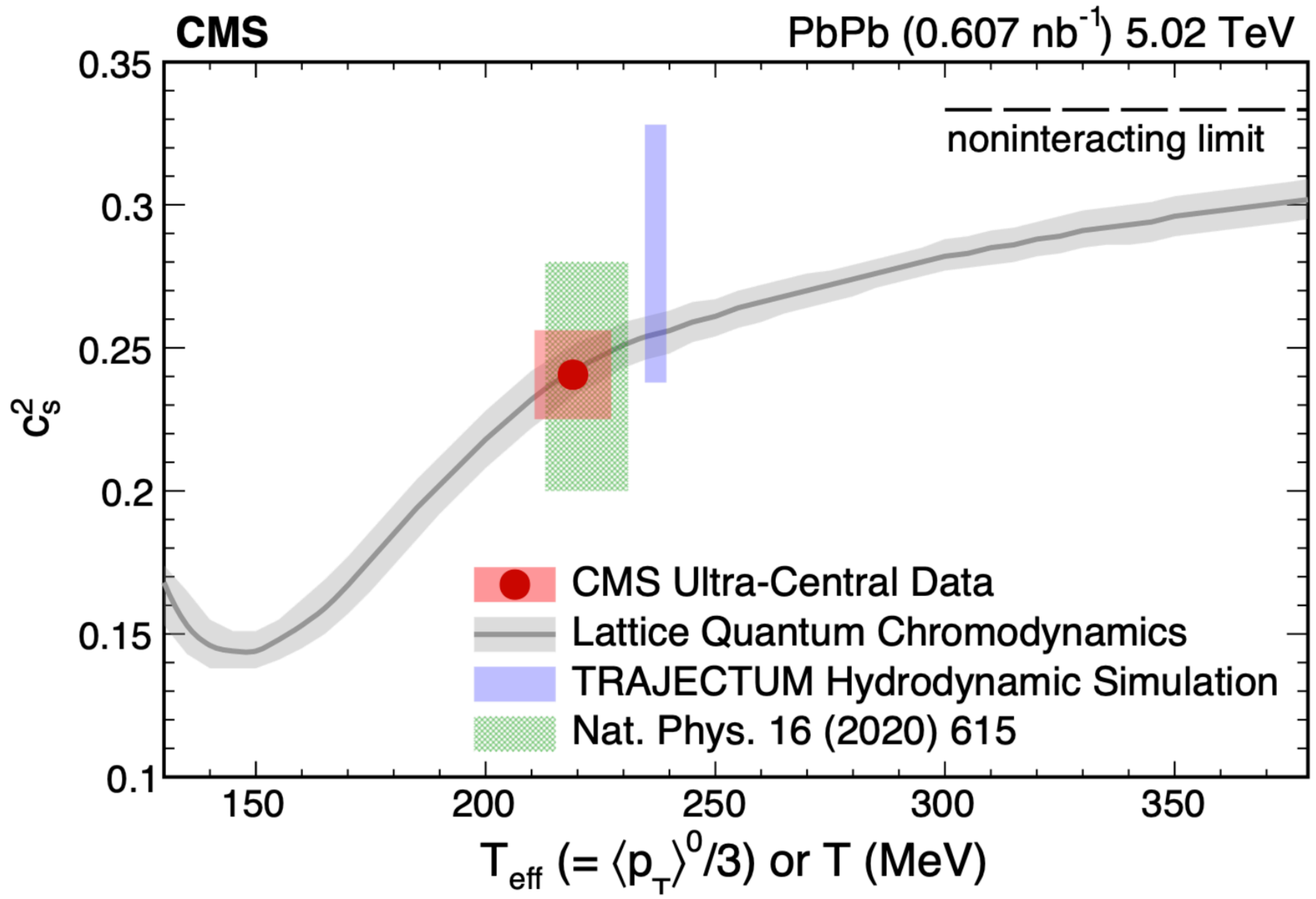


CMS, Rep. Prog. Phys. 87 (2024) 077801

Extraction was consistent with:

1. Later attempts from ATLAS data[1]
2. LQCD[2]
3. Hydro output using Lattice QCD equation of state[3]

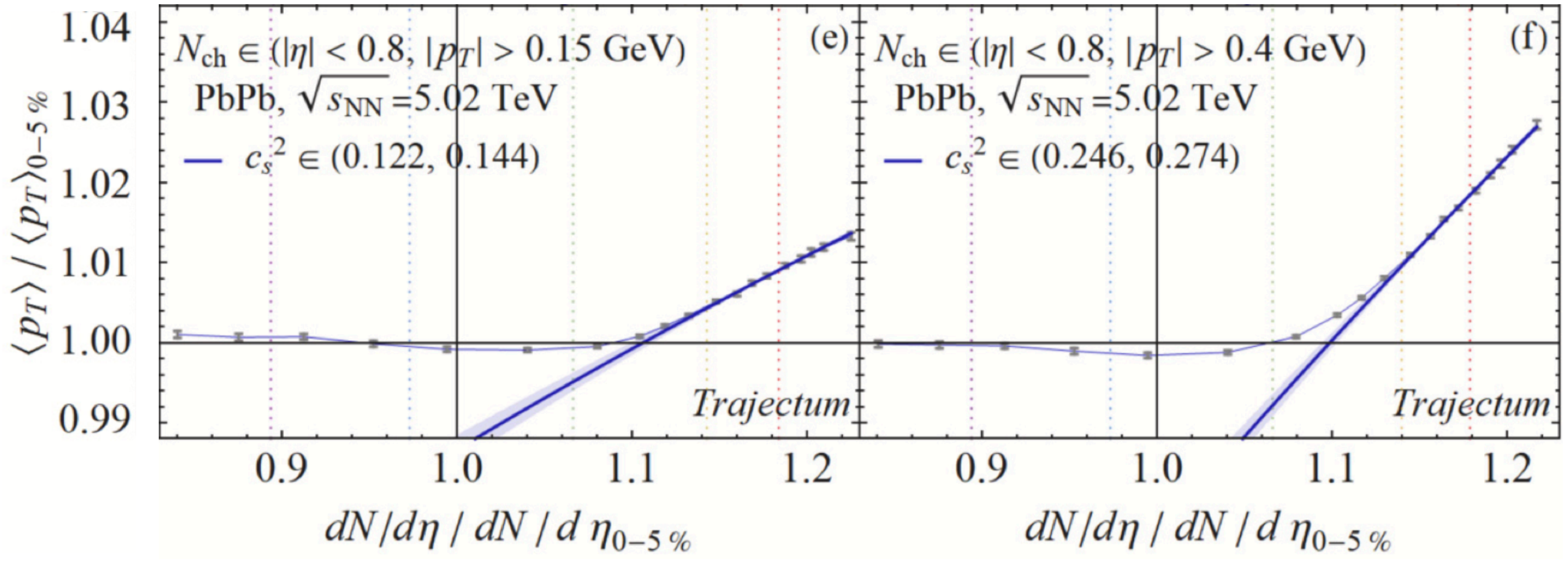
[1] ATLAS, PRL 133, 252301 (2024)

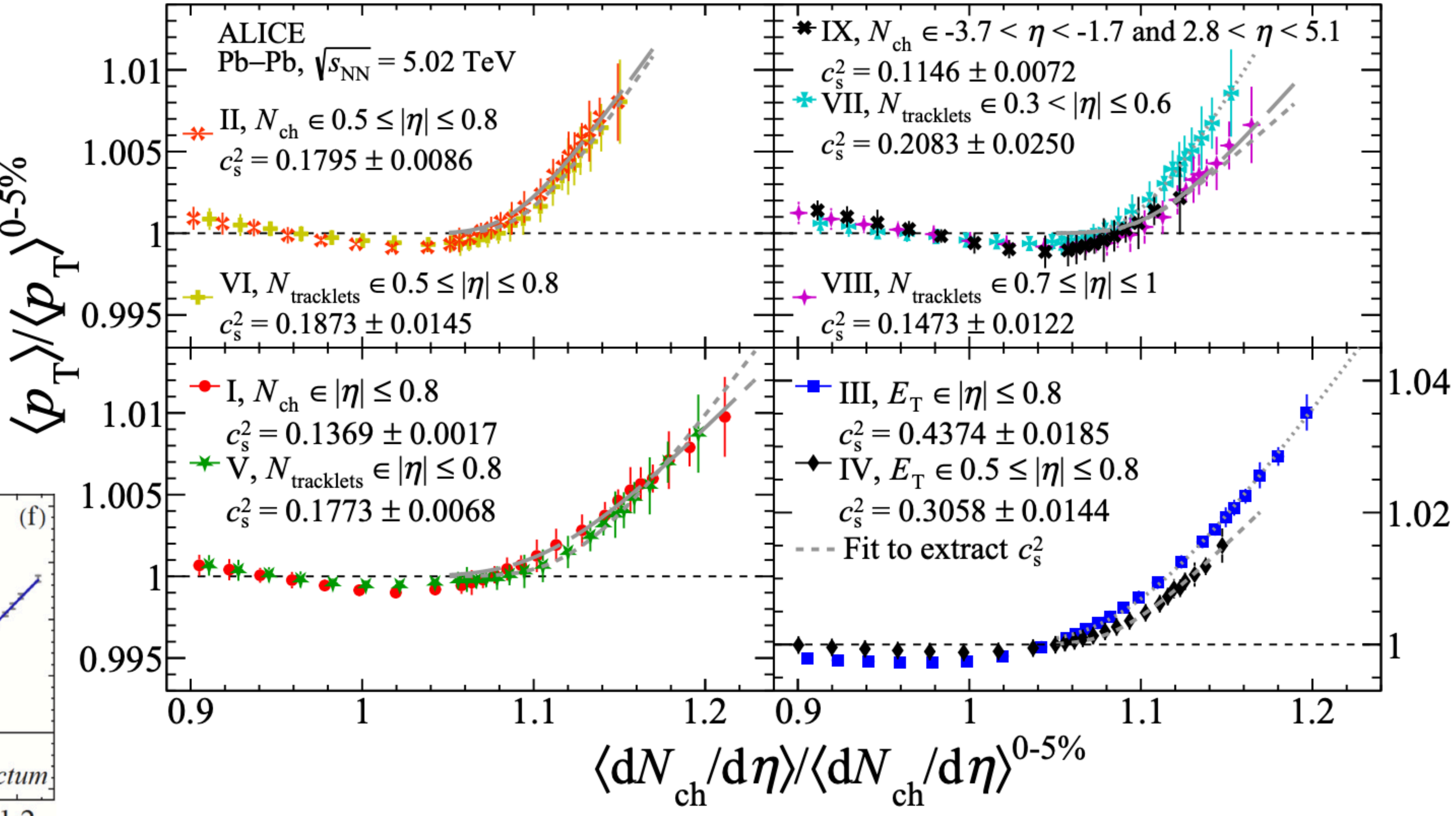
[2] A. Bazavov et al., Phys. Rev. D 90, 094503 (2014)

[3] G. Nijs and W. van der Schee, Phys. Rev. C 106, 044903 (2022)

A closer look from ALICE and Trajectum

But we know from follow up studies from ALICE[1] & Trajectum[2] that the centrality estimator plays a role in the measurement.





Varying centrality qualifiers subject to kinematic constraints

[1] ALICE Collaboration, JHEP 11, 076 (2025)

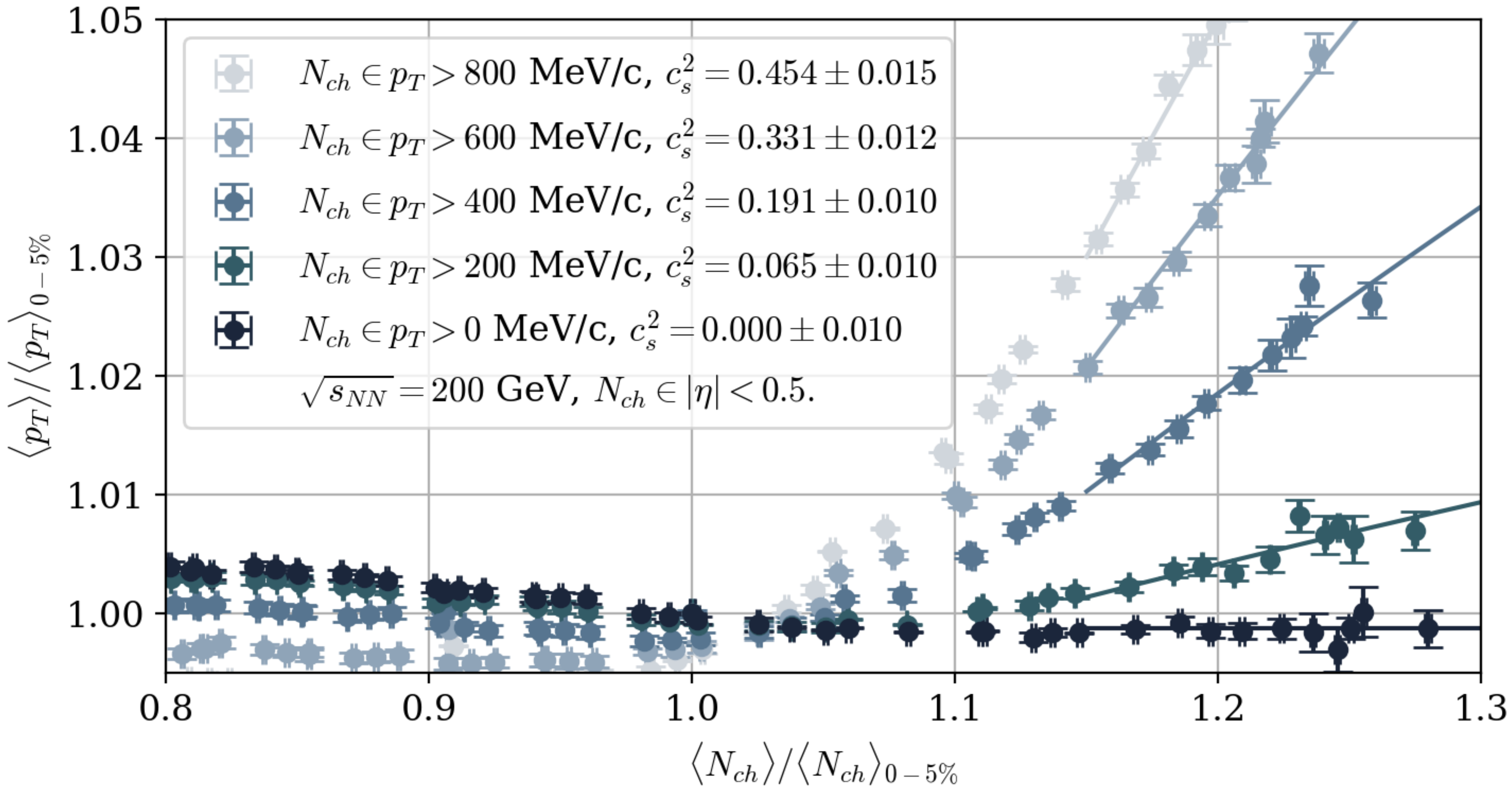
[2] G. Nijs and W. van der Schee, Phys.Lett.B 853, 138636 (2024)

Loss of sensitivity according to *Trajectum*

…more interestingly, Trajectum studies varying p_T threshold of the centrality estimator.

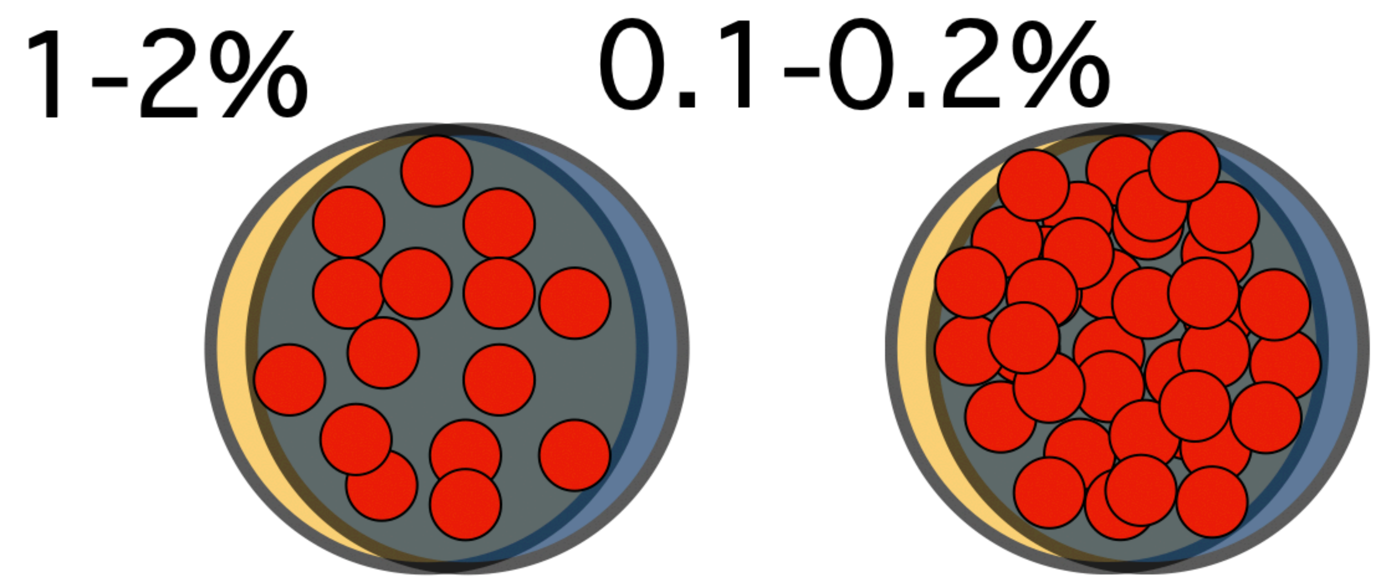
centrality estimator: $N_{ch} \in p_T > p_T^{th}$

Complete loss of sensitivity to the slope as $p_T^{th} \rightarrow 0$



Minimizing event-by-event geometric fluctuations

$\delta b \approx 0$



Centrality estimator

$N_{ch} \in p_T > p_T^{th}$(Ideal)

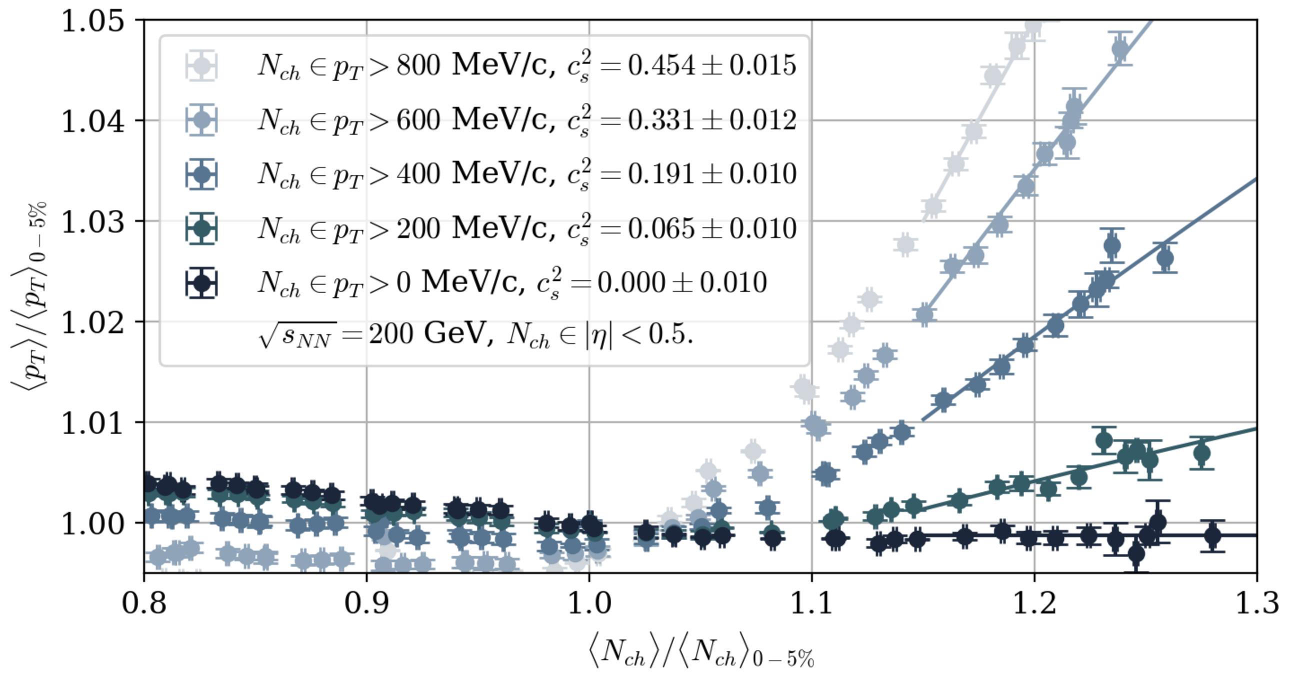
Event classification plays a fundamental role in isolating the $\delta b \approx 0$ regime of collisions from background $\delta b \neq 0$ regime.

Exclusive sensitivity to $\mathbf{s}$

$$c_s^2 = \frac{d \ln \mathrm{T}}{d \ln \mathrm{s}}$$

Minimizing event-by-event geometric fluctuations

Improper choice of the centrality estimator introduces geometric fluctuations that dilute the measurement. How do we account for these fluctuations?



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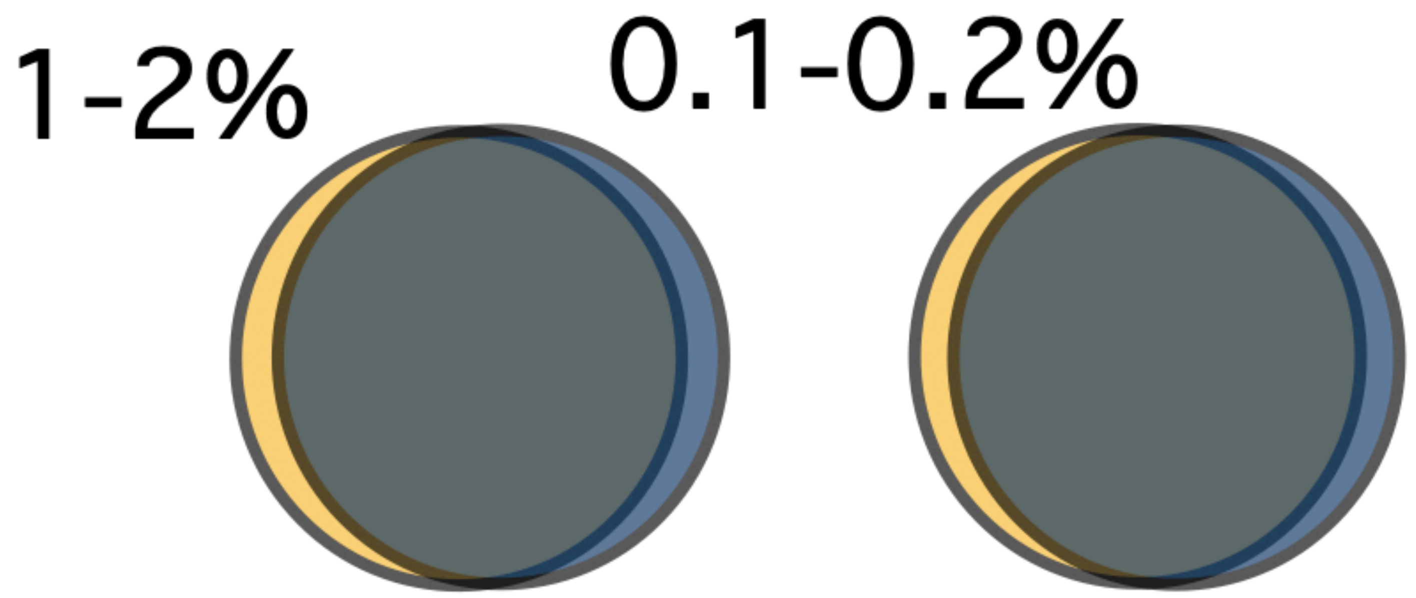
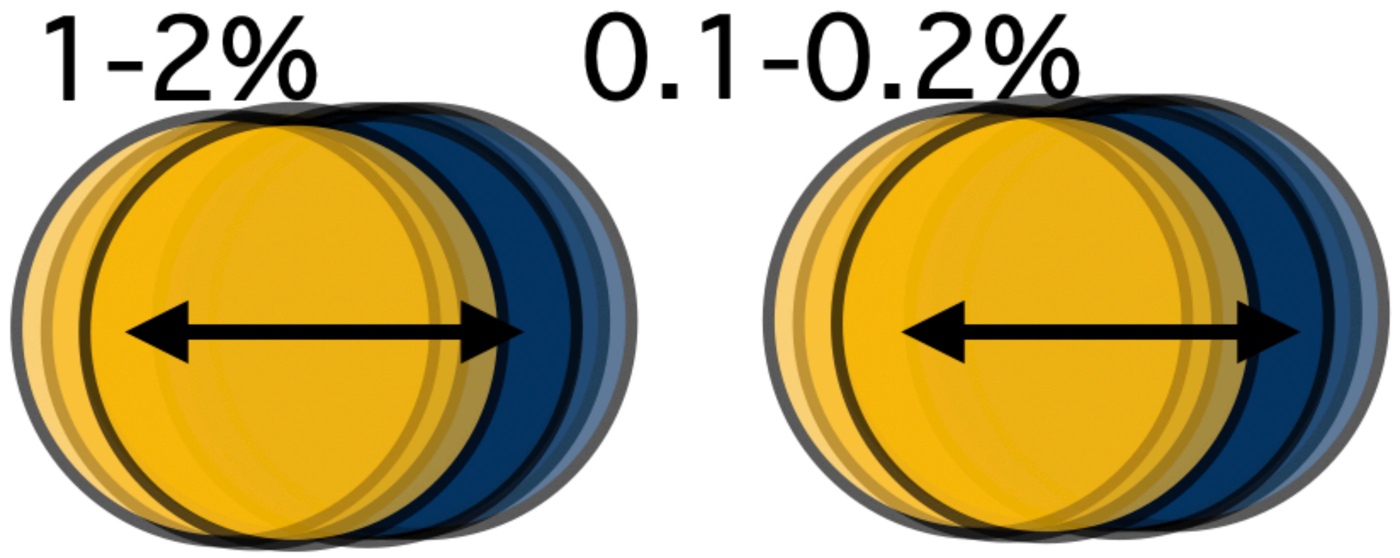


Centrality estimator

$N_{ch} \in p_T > p_T^{th}$(Ideal)

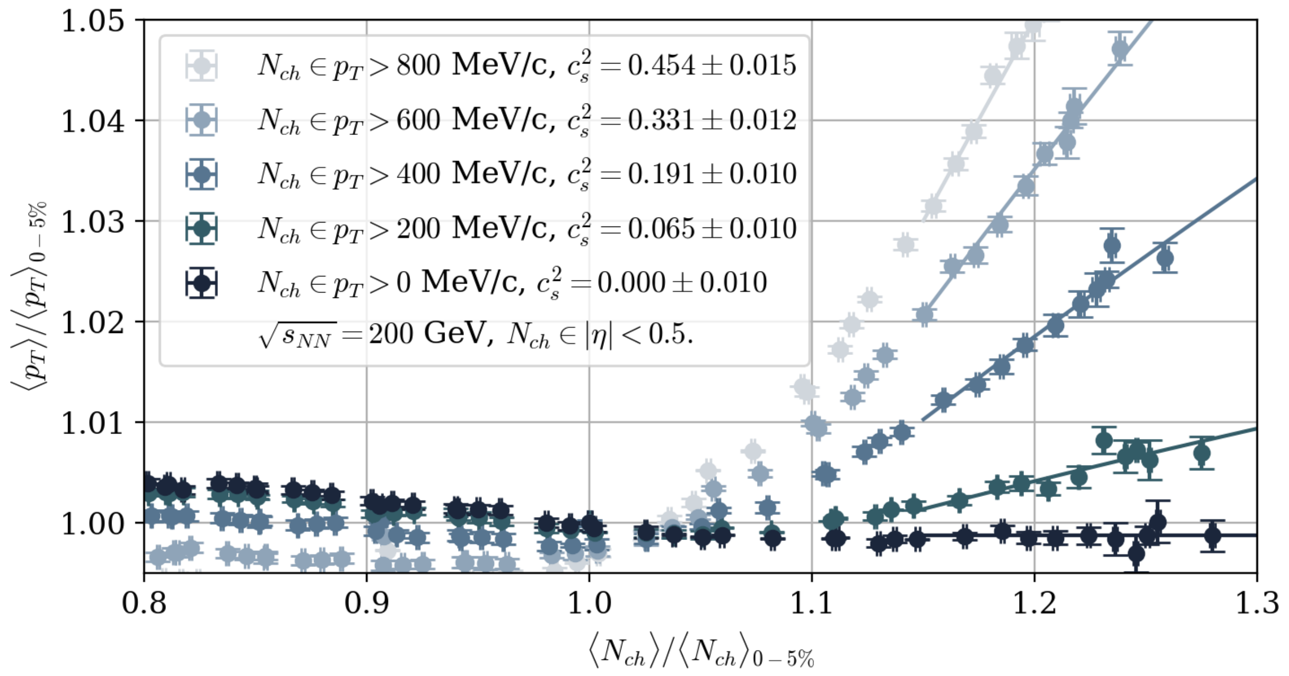
$\delta b > 0$



$N_{ch} \in p_T > p_T^{th}$(Too low)

Minimizing event-by-event geometric fluctuations

Improper choice of the centrality estimator introduces geometric fluctuations that dilute the measurement. How do we account for these fluctuations?

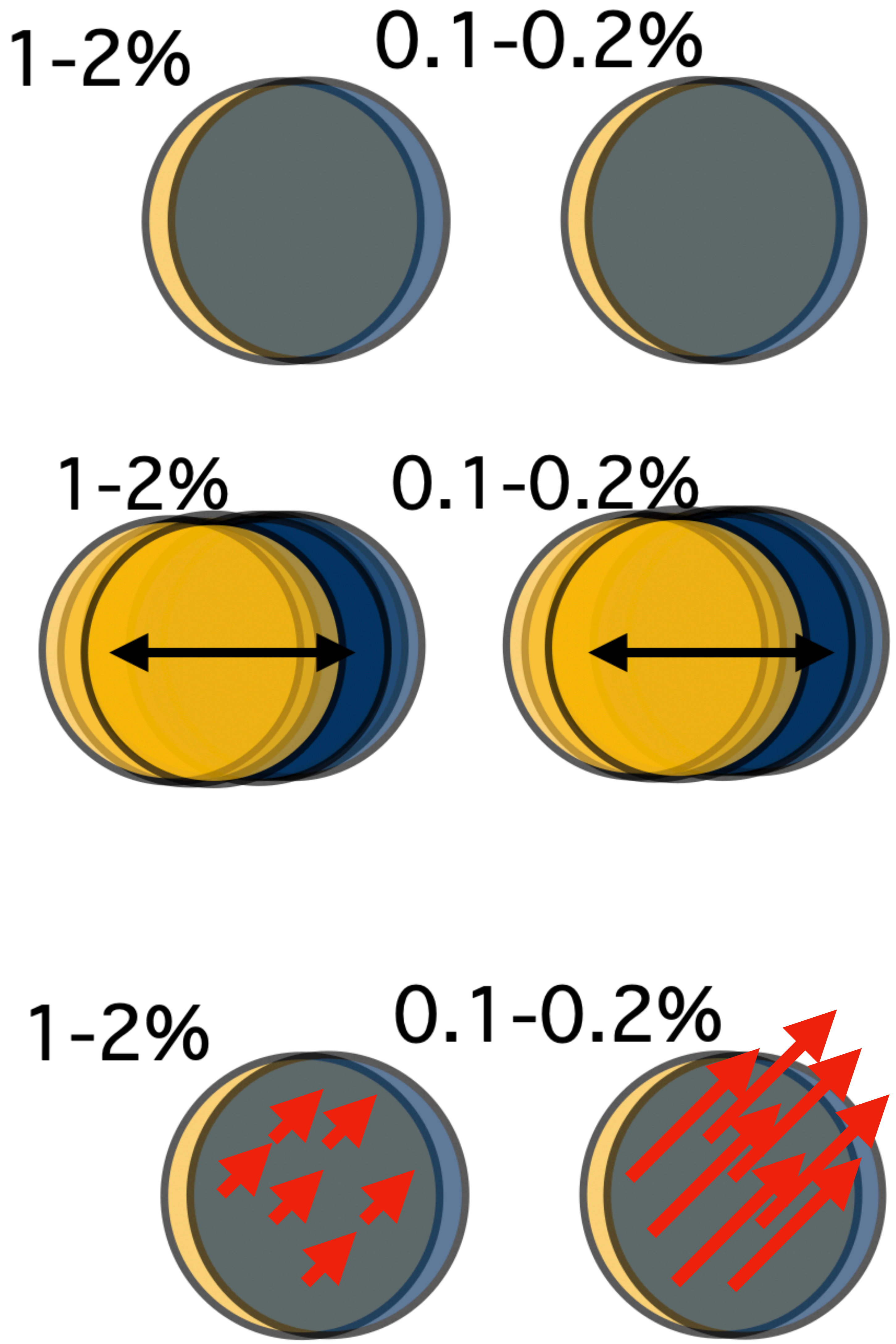


Centrality estimator

$\delta b \approx 0$ — $N_{ch} \in p_T > p_T^{th}$(Ideal)

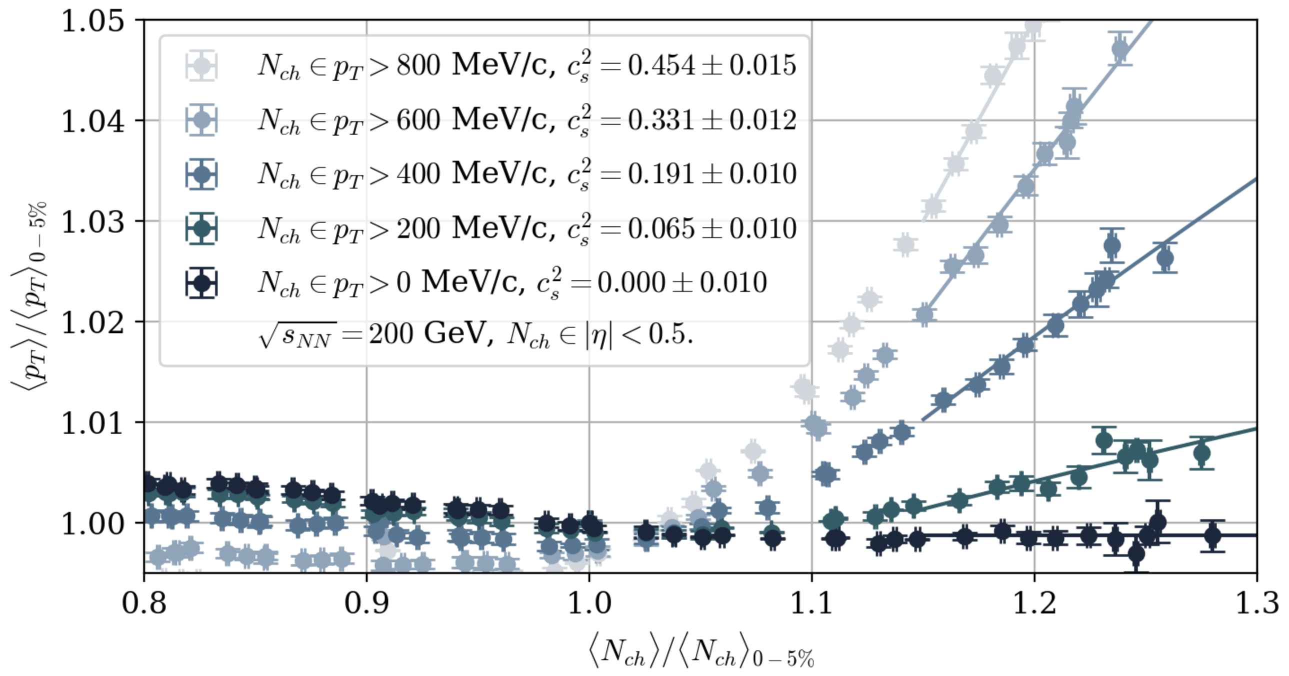
$\delta b > 0$ — $N_{ch} \in p_T > p_T^{th}$(Too low)

$\delta b \approx 0$ — $N_{ch} \in p_T > p_T^{th}$(Too high)



Minimizing event-by-event geometric fluctuations

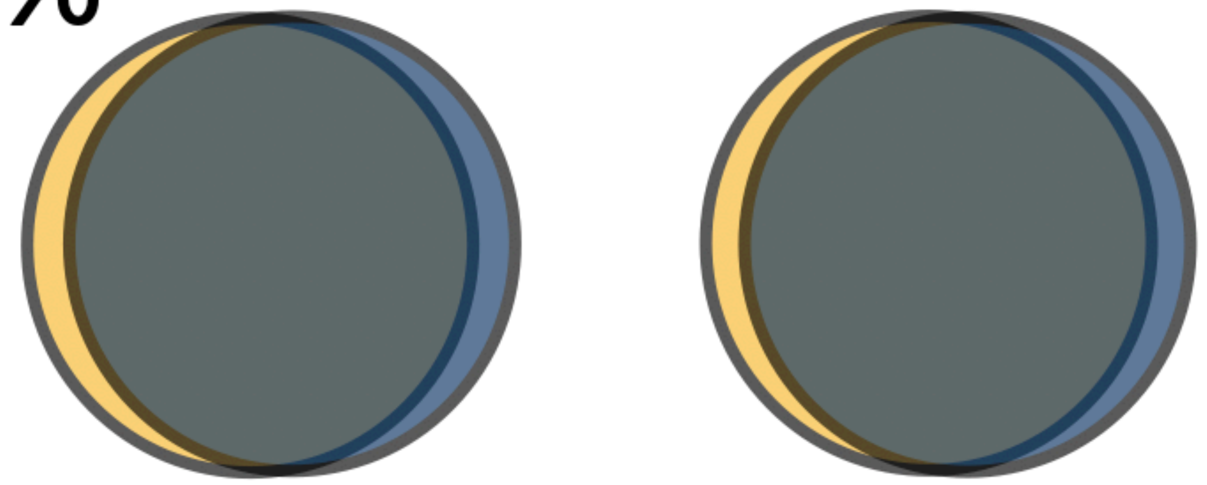
Improper choice of the centrality estimator introduces geometric fluctuations that dilute the measurement. How do we account for these fluctuations?



This becomes relevant in UCCs, where the discriminatory capability in the geometry is reduced. (Think about categorizing events in the 0-5%, 5-10%, ... versus 0-0.1%, 0.1%-0.2%, ...)

Centrality estimator

$\delta b \approx 0$ — 1-2% — 0.1-0.2%



$N_{ch} \in p_T > p_T^{th}$(Ideal)

$\delta b > 0$ — 1-2% — 0.1-0.2%

$N_{ch} \in p_T > p_T^{th}$(Too low)

Geometric contamination

$\delta b \approx 0$ — 1-2% — 0.1-0.2%

$N_{ch} \in p_T > p_T^{th}$(Too high)

Isolated high $[p_T]$ (non-thermal) event selection

The speed of sound as an E by E study

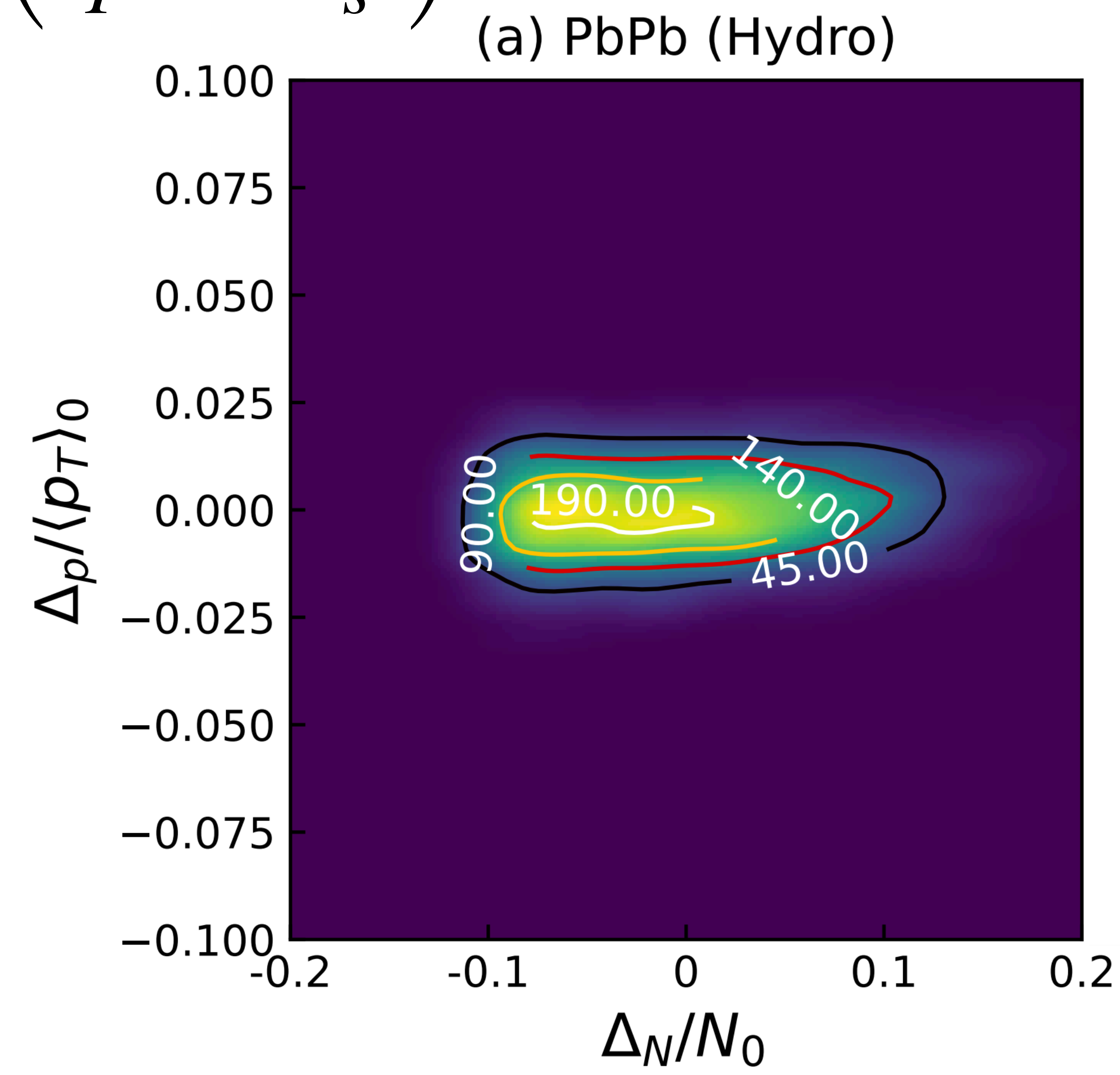
Separating the extracted c_s^2 from fluctuations[1] $\left(\frac{\Delta_T}{T} = c_s^2 \frac{\Delta_s}{s}\right)$

The approximated sound speed $\left(\frac{\Delta_p}{\langle p_T \rangle} = c_s^2 \frac{\Delta_N}{N_0}\right)$ is adjusted for the presence of fluctuations by modeling stochastic contributions accordingly,

$$\frac{\Delta_p}{\langle p_T \rangle} = c_s^2 \frac{\Delta_N + \delta}{N_0}$$

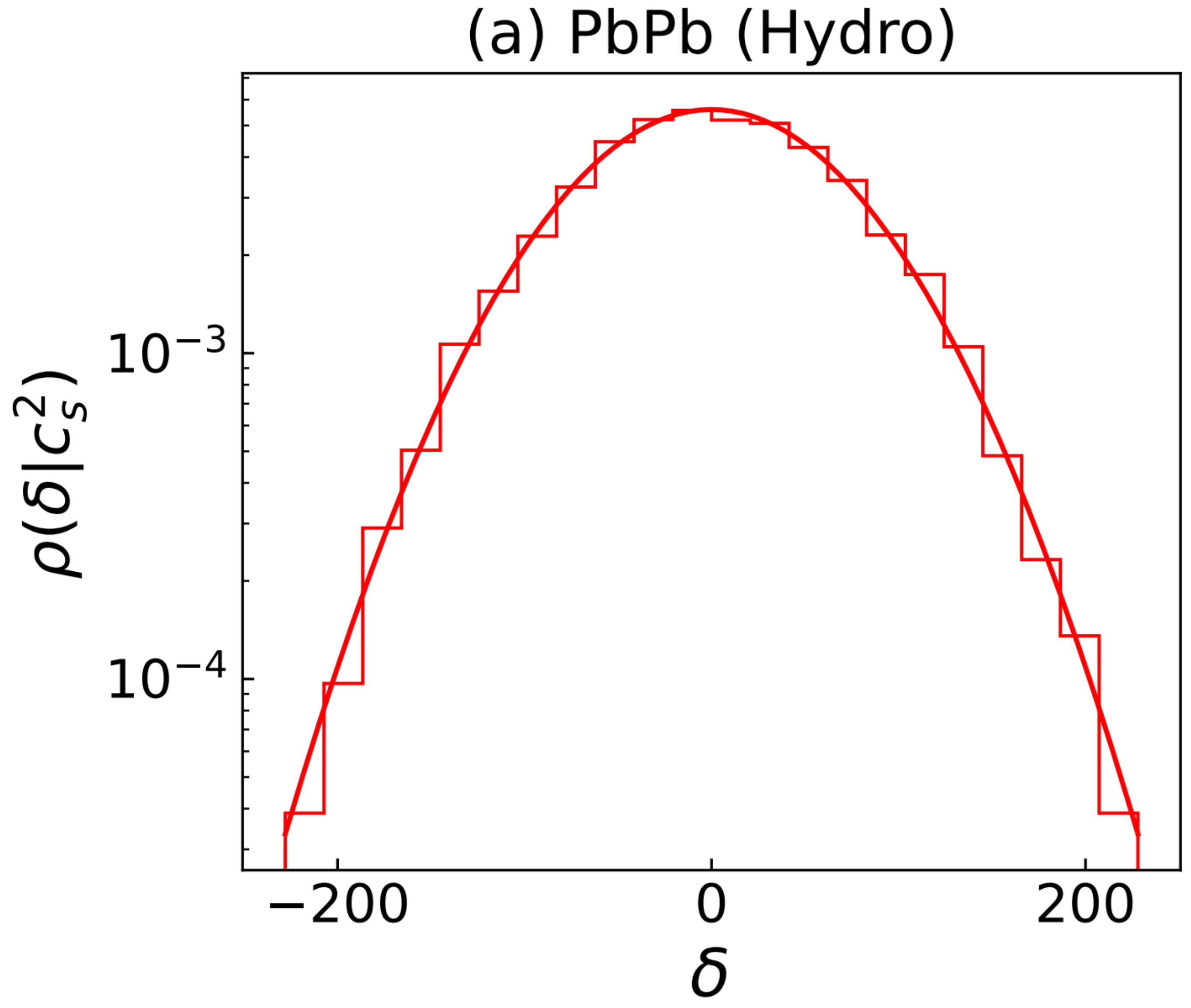
$$\Delta_p = [p_T] - \langle p_T \rangle_0$$

$$\Delta_N = [N_{ch}] - N_0$$



If the system has thermalized ⇒ δ is Gaussian (CLT) and independent of linear macroscopic response

Assume δ is Gaussian → Solve for c_s^2 → Independently verify Gaussianity of δ



[1] Y. S. Mu et al., Phys. Rev. Lett. 135, no.16, 162301 (2025)

Separating the extracted c_s^2 from fluctuations[1]

- Assuming δ distribution is Gaussian, the odd moments vanish.

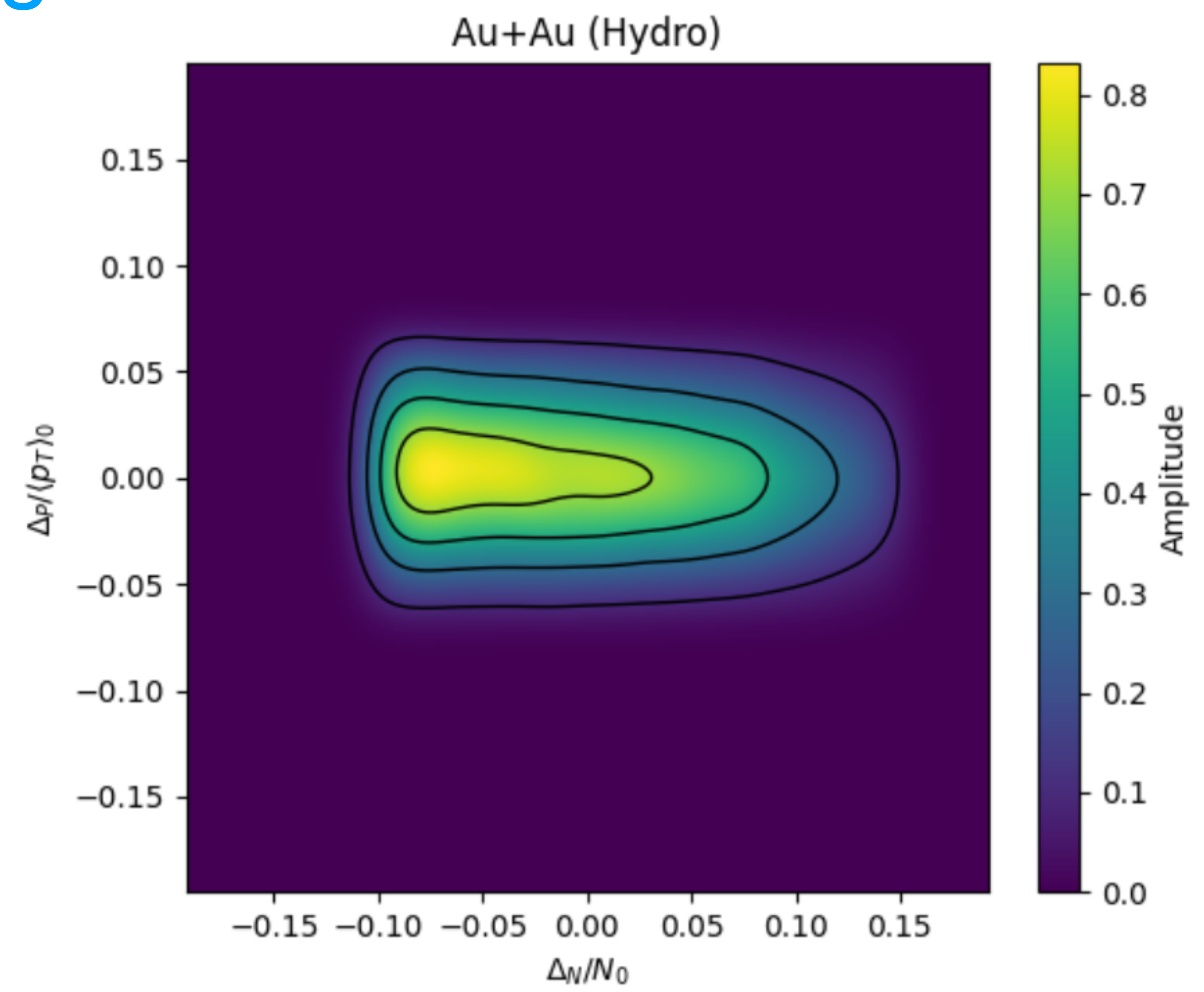
- The vanishing skewness $\langle \delta^3 \rangle = 0$ condition gives the following polynomial (the coefficients are the joint moments):

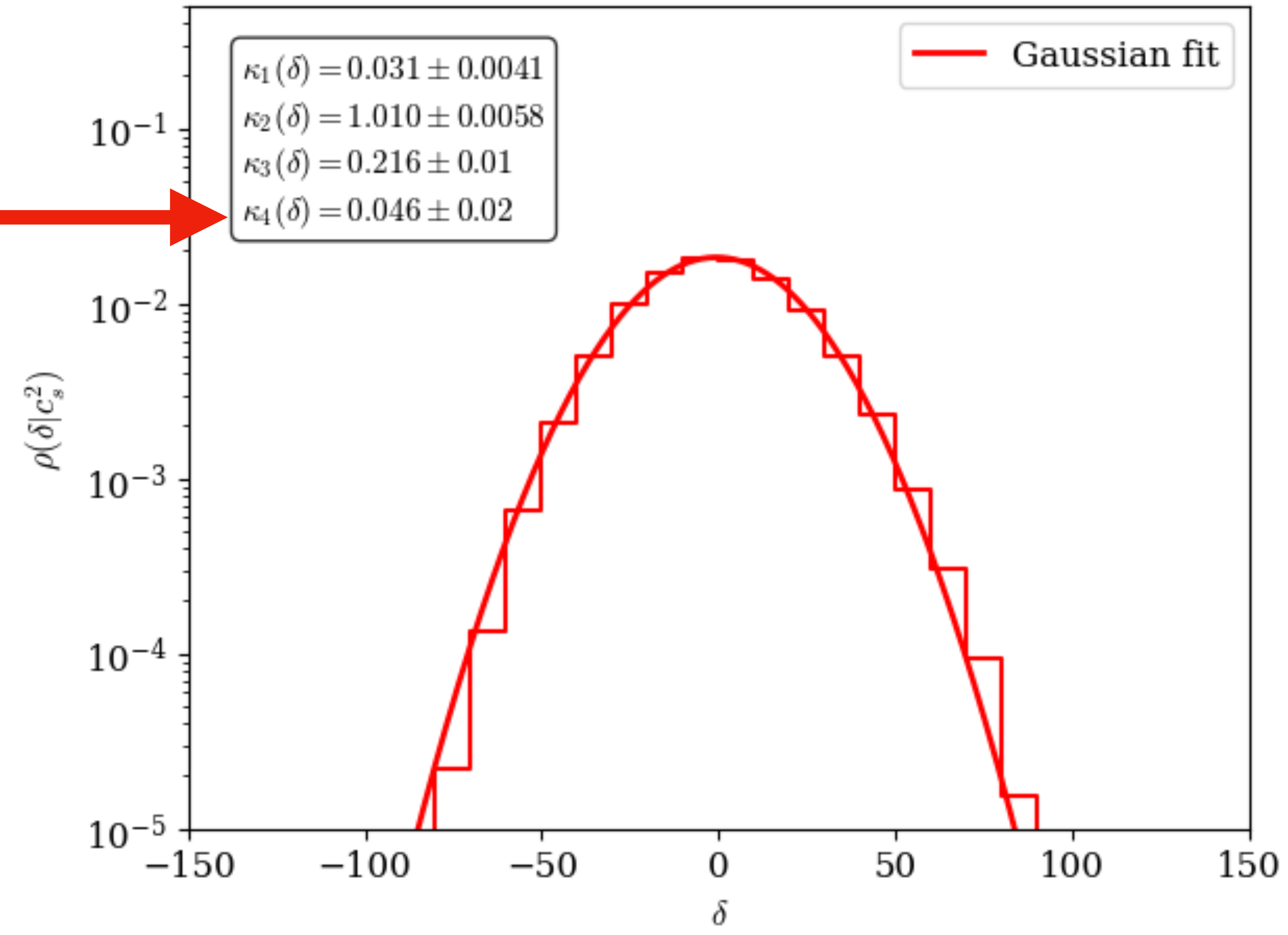
$$(c_s^2)^3 \frac{\langle \Delta_N^3 \rangle}{N_0^3} - 3(c_s^2)^2 \frac{\langle \Delta_N^2 \Delta_p \rangle}{N_0^2 \langle p_T \rangle_0} + 3c_s^2 \frac{\langle \Delta_N \Delta_p^2 \rangle}{N_0 \langle p_T \rangle_0^2} - \frac{\langle \Delta_p^3 \rangle}{\langle p_T \rangle_0^3} = 0$$

- Solving for the real and physical ($c_s^2 \in [0,1/3]$) roots to find the c_s^2

- Reconstruct δ on second pass and verify Gaussianity independently (standardized kurtosis $\kappa_4(\delta) \ll 1$) ✓

$$\frac{\Delta_p}{\langle p_T \rangle} = c_s^2 \frac{\Delta_N + \delta}{N_0} \Rightarrow \delta = \frac{\Delta_p N_0}{c_s^2 \langle p_T \rangle} - \Delta_N$$





[3]Y. S. Mu et al., Phys. Rev. Lett. 135, no.16, 162301 (2025)

Comparing the two methodologies

Conditioning the centrality estimator

Hydro model (Trajectum)[1]

Method A

Logarithmic derivative[2]

$c_s^2 = d\ln\langle p_T\rangle / d\ln\langle N_{ch}\rangle$

Compute $c_s^2(p_T^{\text{th}})$ with centrality estimator: $N_{ch} \in p_T > p_T^{\text{th}}$

Method B

Event-by-event response[3]

$$\frac{\Delta_p}{\langle p_T\rangle} = c_s^2 \frac{\Delta_N + \delta}{N_0}$$

Compute c_s^2 centrality estimator-independent

Find p_T^{th} that yields ratio

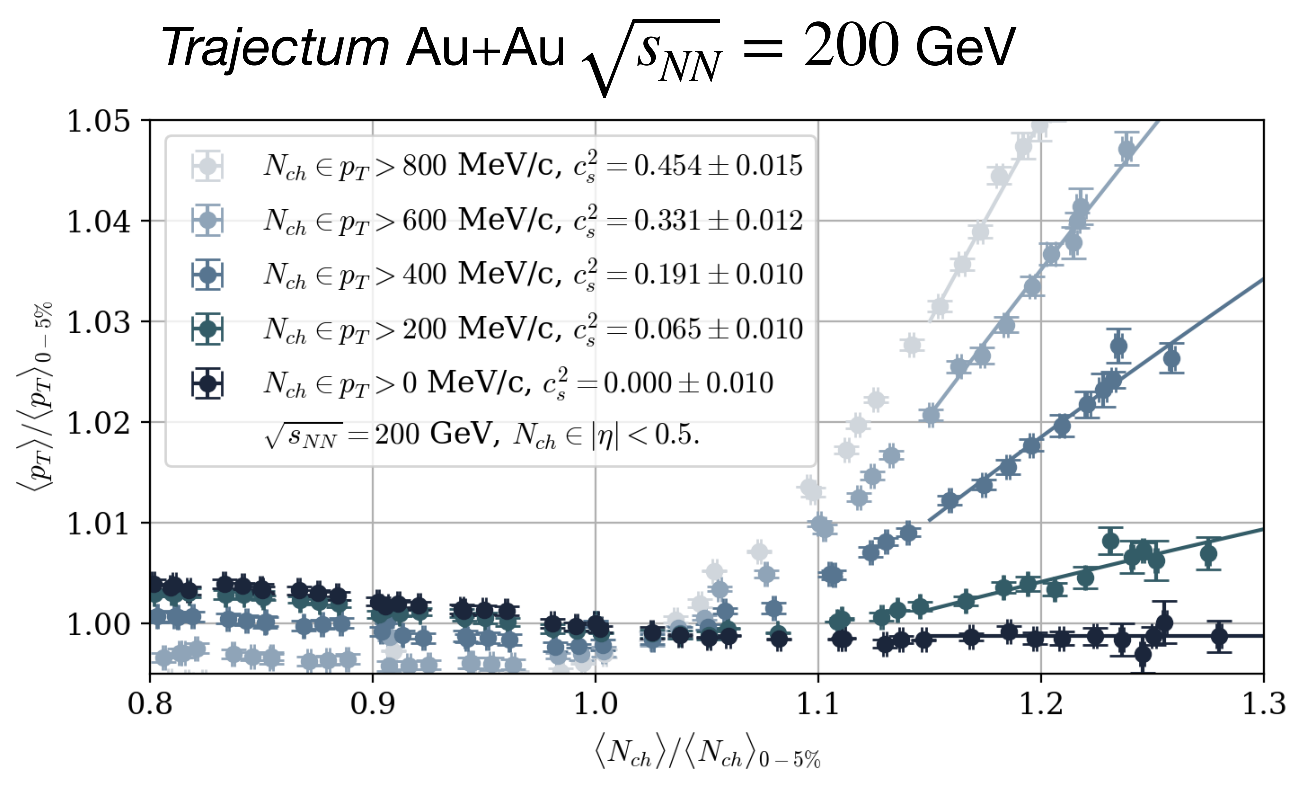
$$\frac{c_s^2(\text{Method A})}{c_s^2(\text{Method B})(p_T^{\text{th}})} \approx 1$$

from comparing methodologies. Use p_T^{th} for STAR analysis.

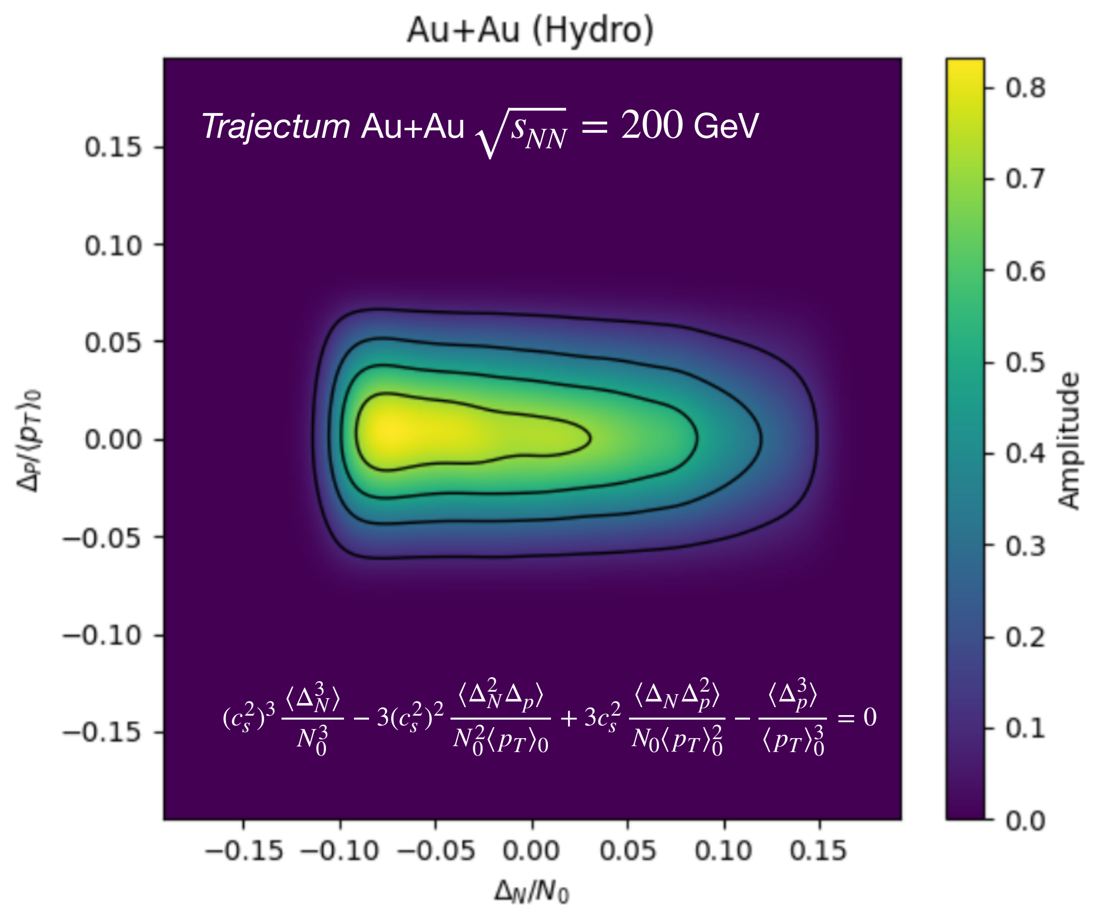
[1] G. Nijs et al., Phys. Rev. C 103, 054909 (2021)
[2] F.G. Gardim et al., Phys. Lett. B 856, 138937 (2024)
[3] Y. S. Mu et al., Phys. Rev. Lett. 135, no.16, 162301 (2025)

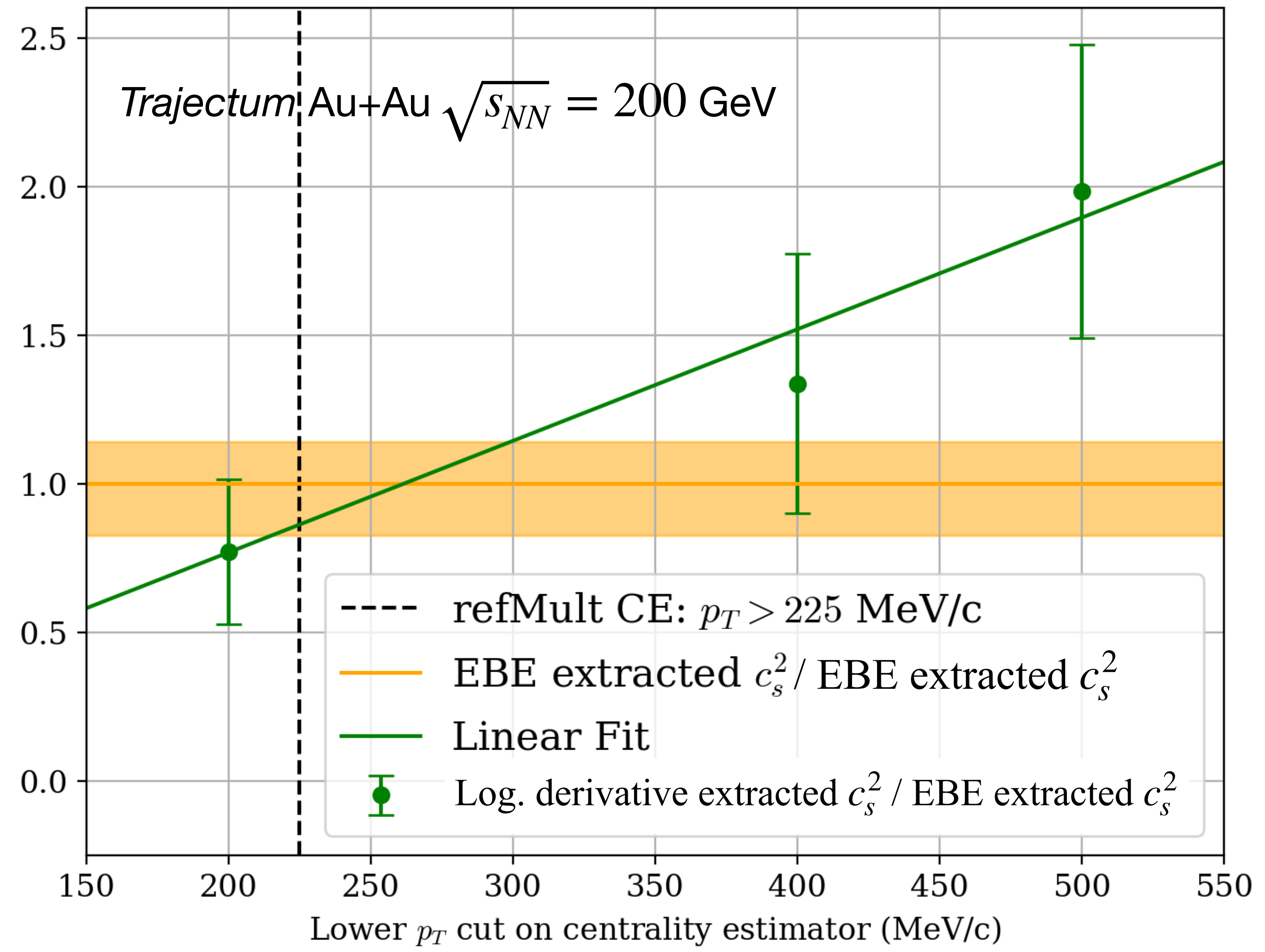
Conditioning the centrality estimator

Logarithmic derivative[1]



Event-by-event response[2]





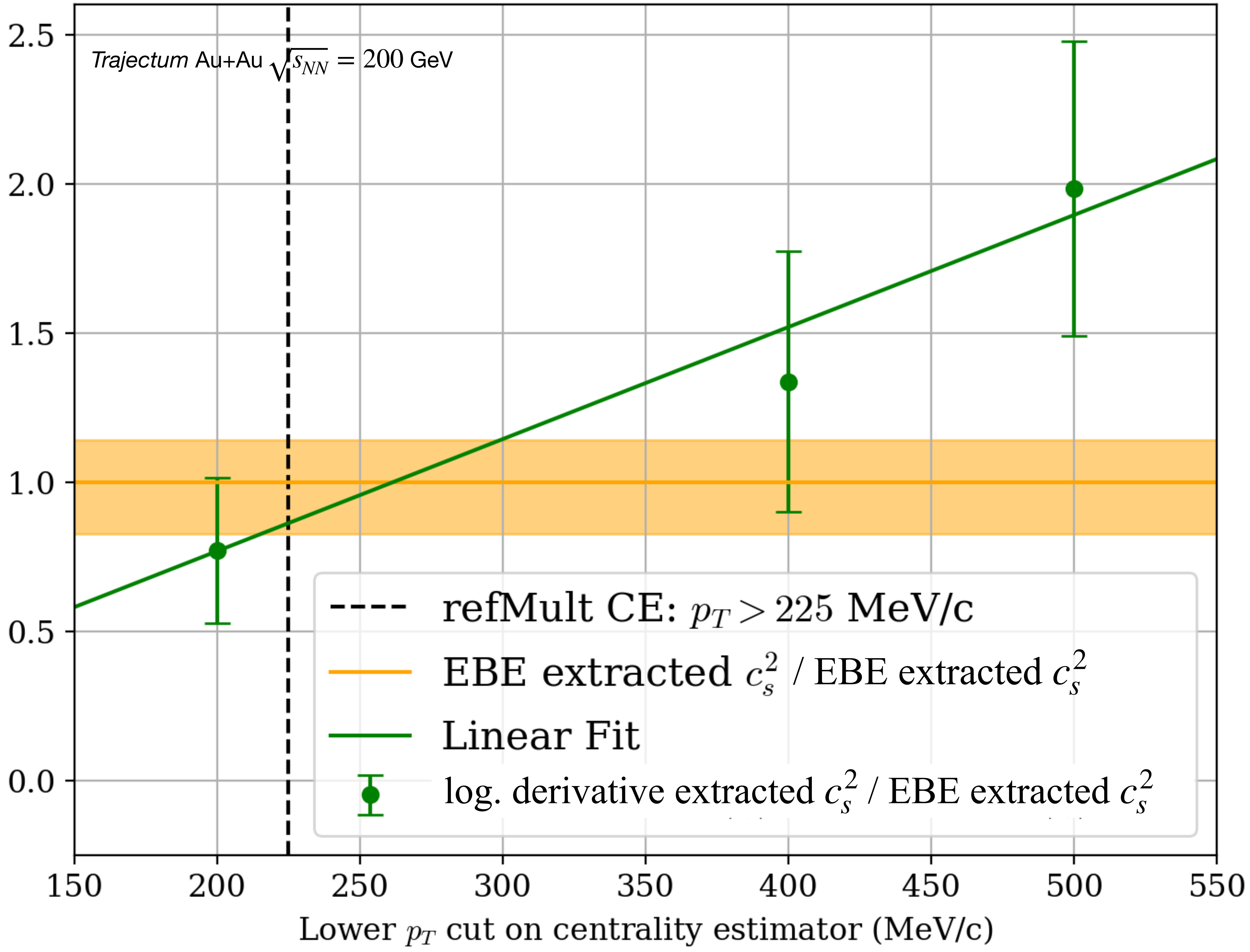
Event-by-event (fluctuation minimized) as a selection test for p_T^{th} used on N_{ch} for event classification: $p_T^{th} = 225$ MeV selected for STAR logarithmic derivative analysis.

[1] F.G. Gardim et al., Phys. Lett. B 856, 138937 (2024)

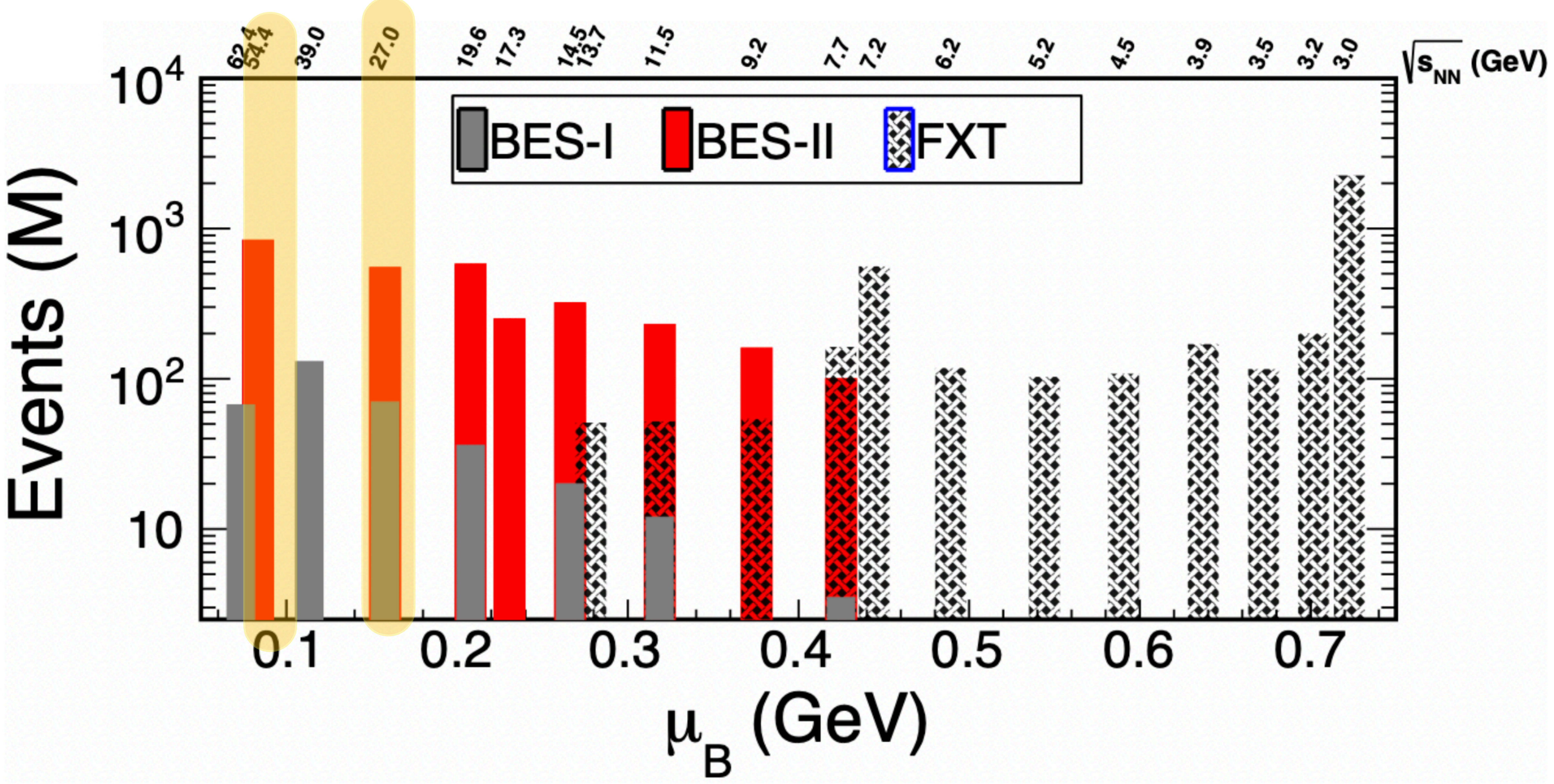
[2] Y. S. Mu et al., Phys. Rev. Lett. 135, no.16, 162301 (2025)

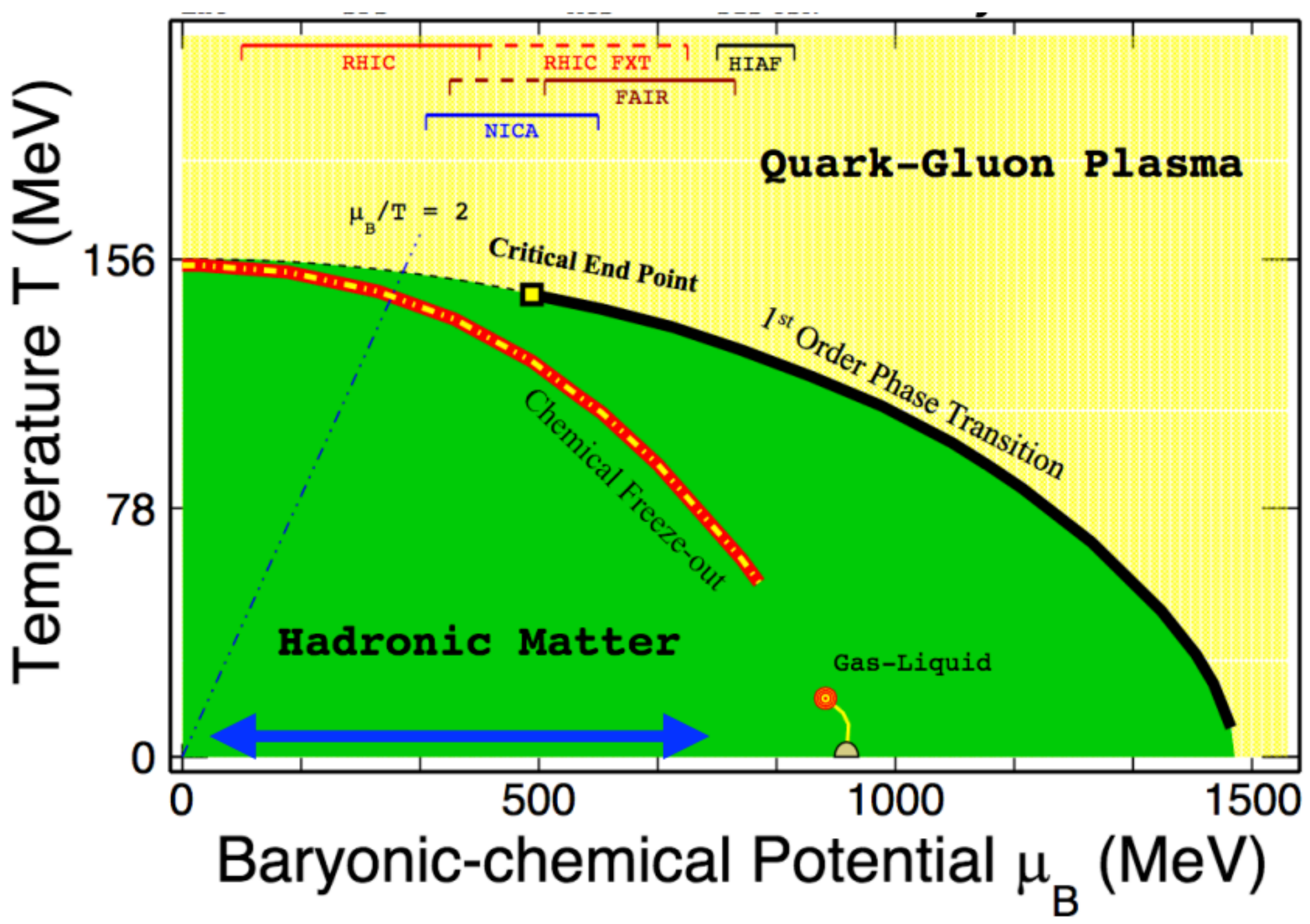
Conditioning the centrality estimator

This study motivates selecting a $p_T^{th} \in [215,300]$ MeV/c selected for STAR logarithmic derivative analysis. We choose $p_T^{th} = 225$ MeV/c.

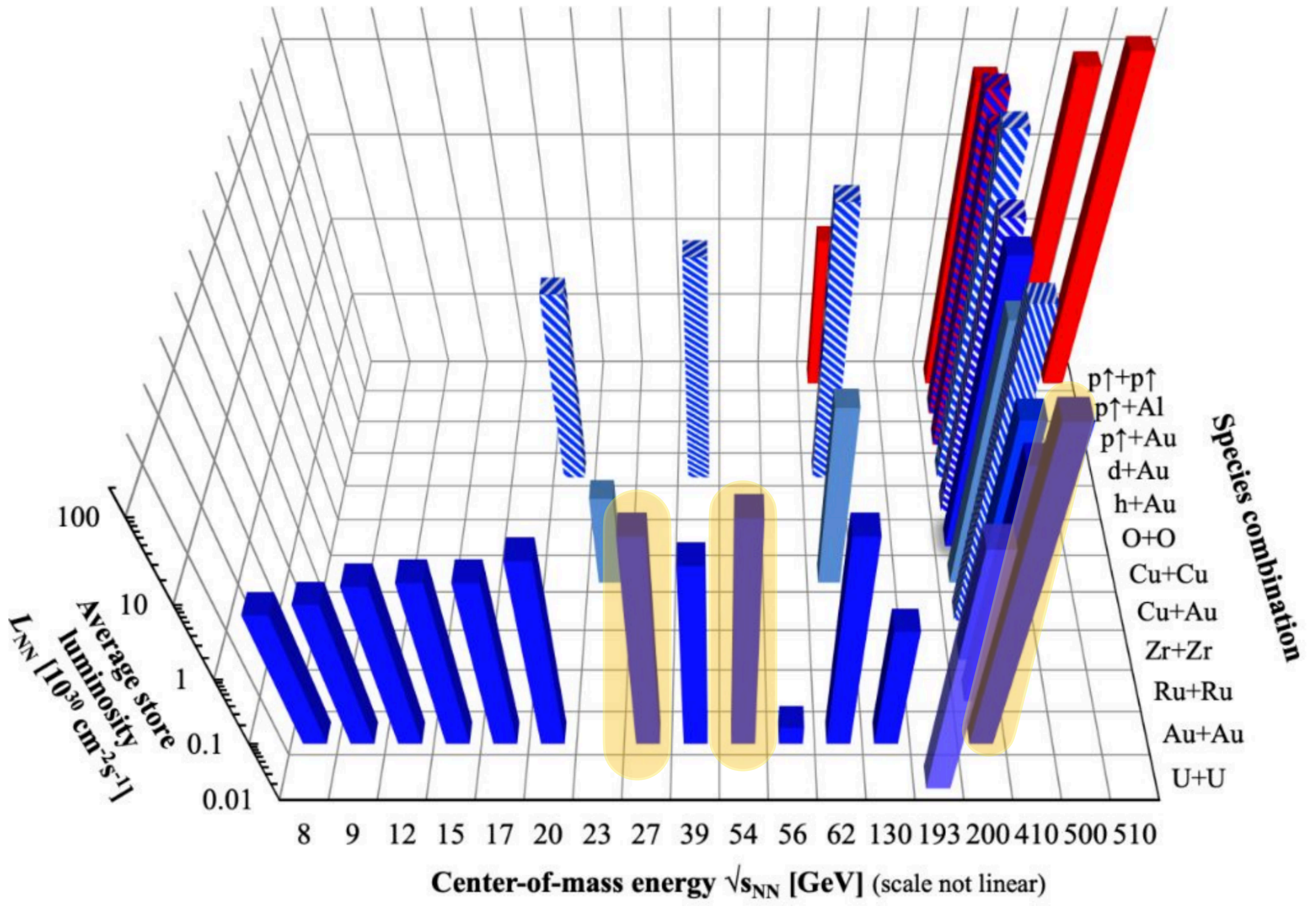


RHIC Beam Energy Scan





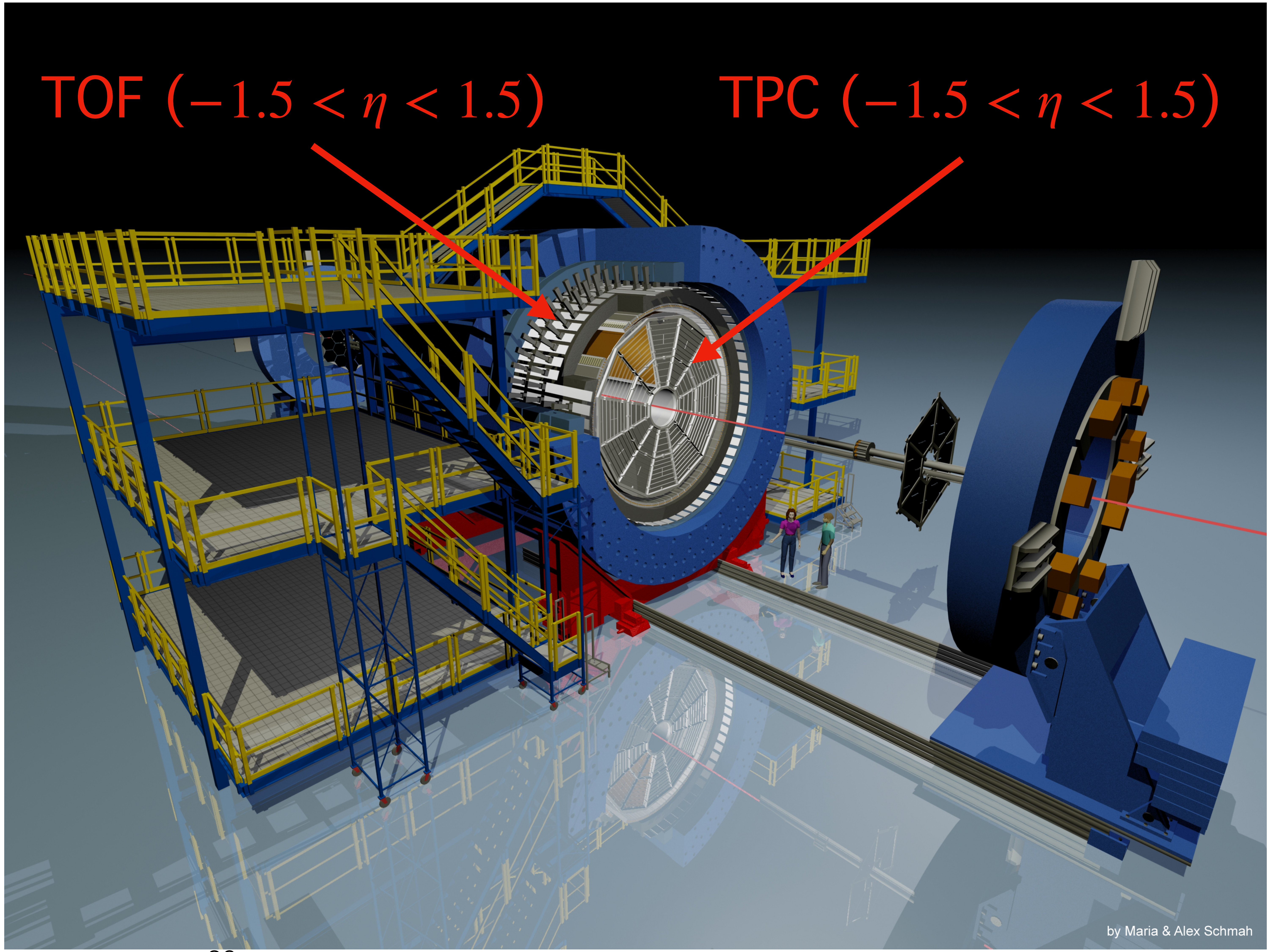
RHIC energies, species combinations and luminosities (Run-1 to 22)



- High statistics datasets corresponding to $100 < \mu_B < 700$ MeV
- Tremendous wealth of data for varied collision systems at top RHIC energies: U+U, Au+Au, Isobars (Ru+Ru, Zr+Zr), Cu+Au, O+O, d+Au, and many more!
- In this work, we analyze Au+Au collisions at the following energies: $\sqrt{s_{NN}} = 200$, 54.4, and 27 GeV

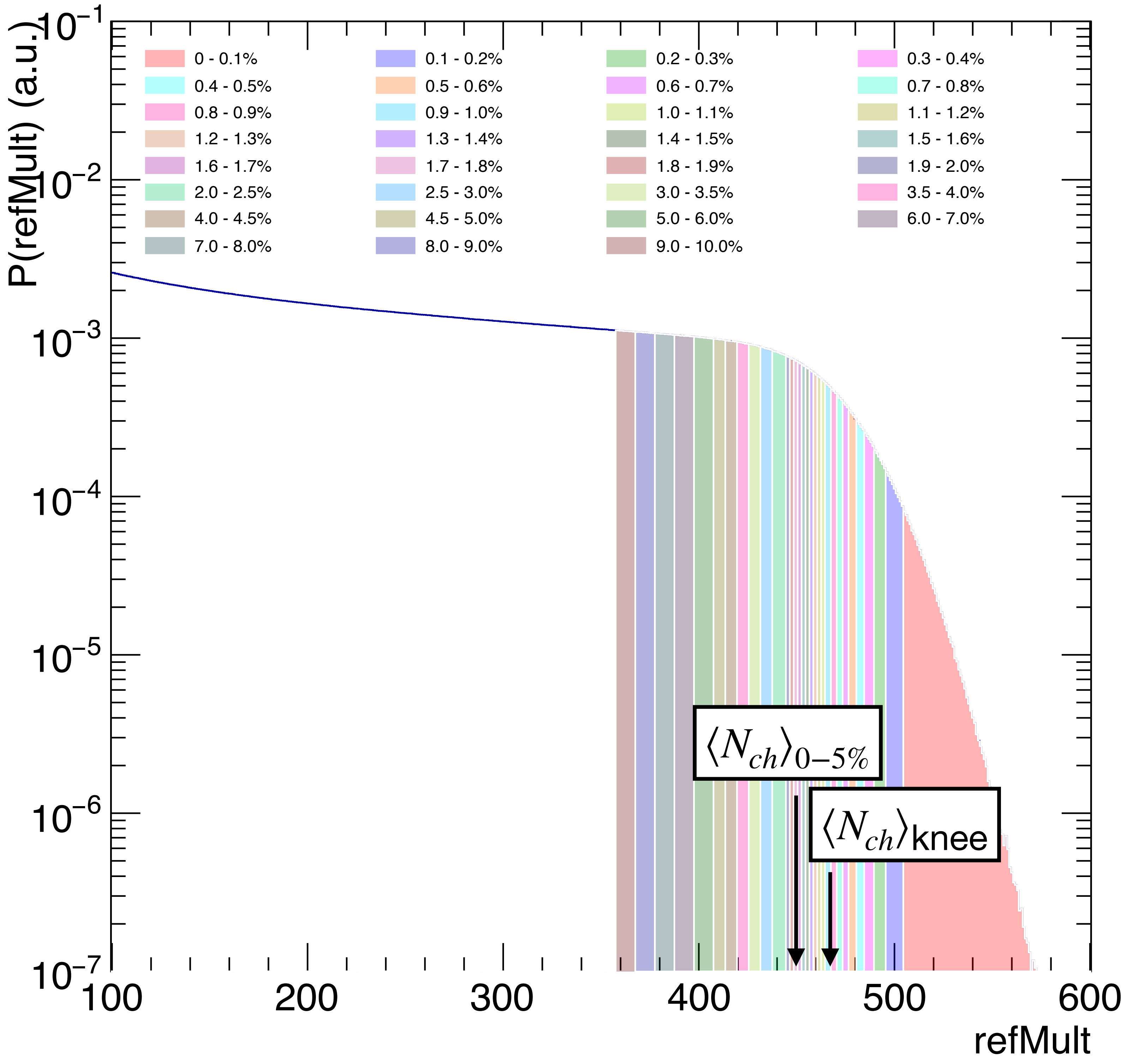
Solenoidal Tracker At RHIC

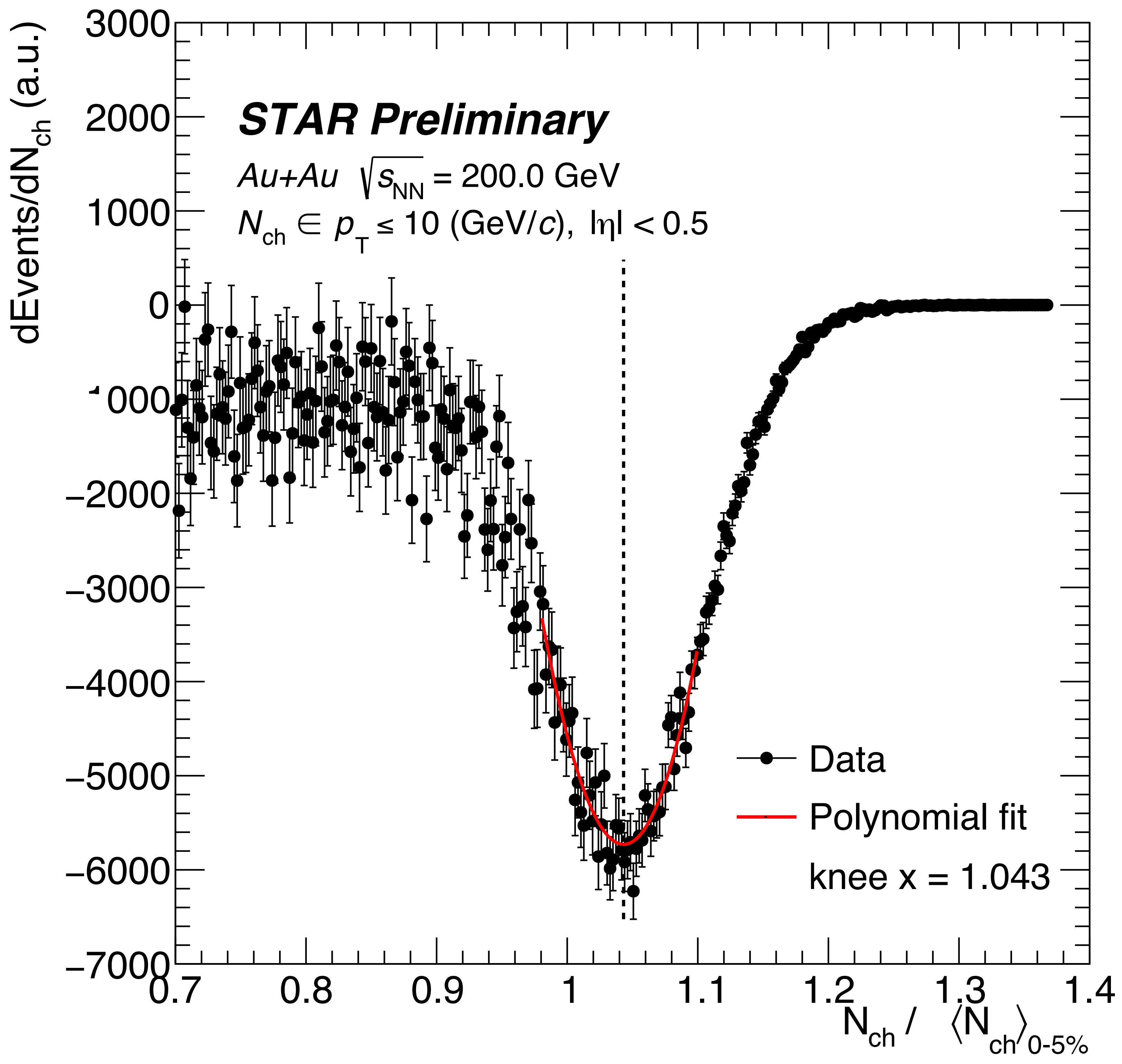
- STAR analysis performed for Run11, Run17, and Run18
- TPC is used to measure $\langle p_T \rangle$ and N_{ch}
- TPC+TOF used for centrality selection and pileup removal



Extracting c_s^2 using the logarithmic derivative

- Centrality estimator: N_{ch} with $p_T > 225$ MeV/c
- $\langle N_{ch} \rangle_{\text{knee}}$ - Mean of the Gaussian fluctuations of N_{ch} at fixed impact parameter $b = 0$ (Generally close to $\langle N_{ch} \rangle_{0-5\%}$)
- Using LevyTsallis[1] or BlastWave[2] to extrapolate $p_T \to 0$





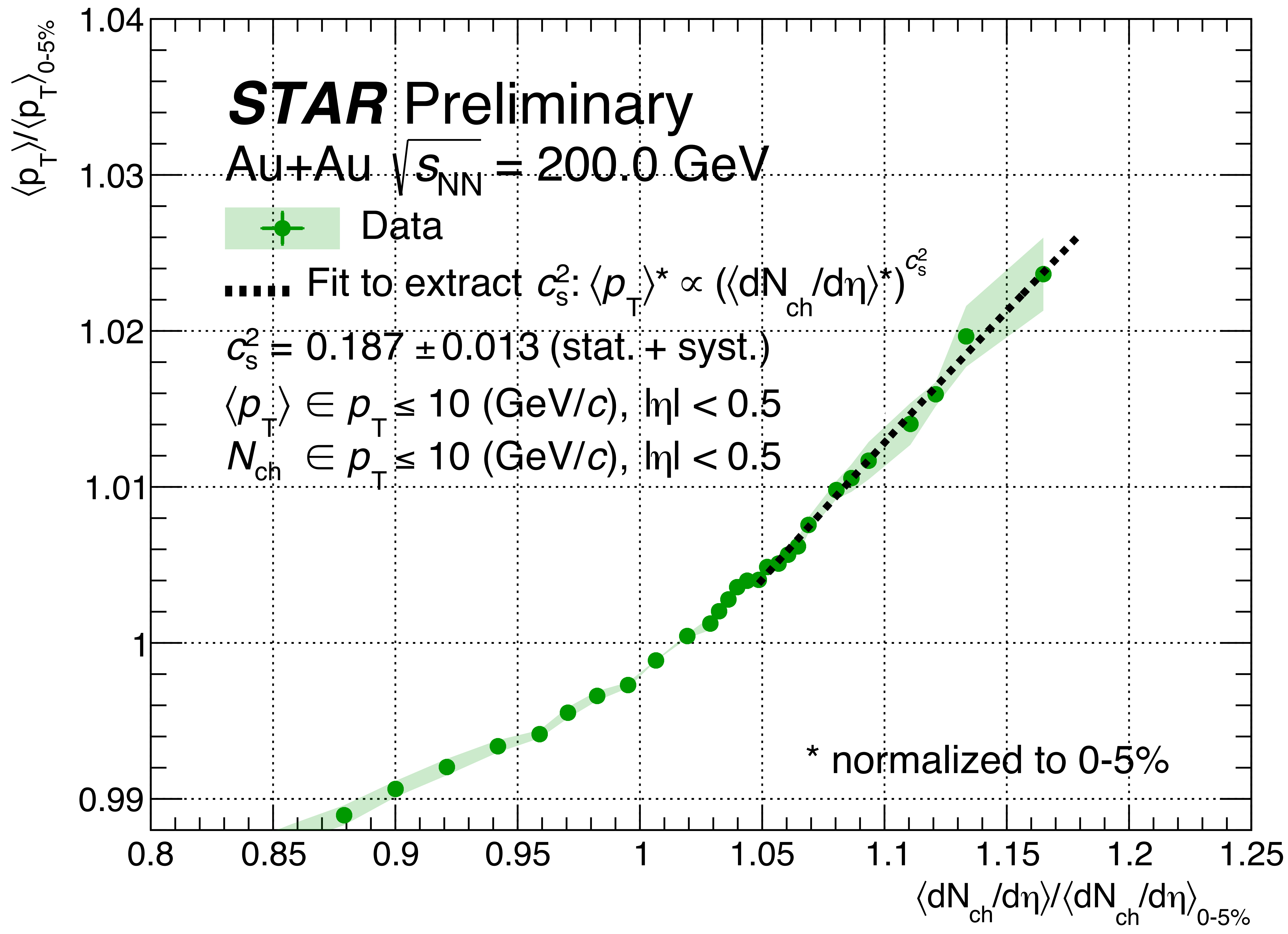
[1]H. Zheng et al., Mod.Phys.Lett.A 35, 1750195 (2020)

[2]E. Schnedermann et al., Phys.Rev.C48:2462-2475 (1993)

Extracting c_s^2 using the logarithmic derivative

Rise of $\langle p_T \rangle$ in the ultra-central region

- Centrality estimator: N_{ch} with $p_T > 225$ MeV/c
- Threshold chosen for consistency with EBE approach to minimize the presence of geometric fluctuations
- Systematic uncertainties are determined by varying the p_T range on the fit used to extrapolate $p_T \to 0$

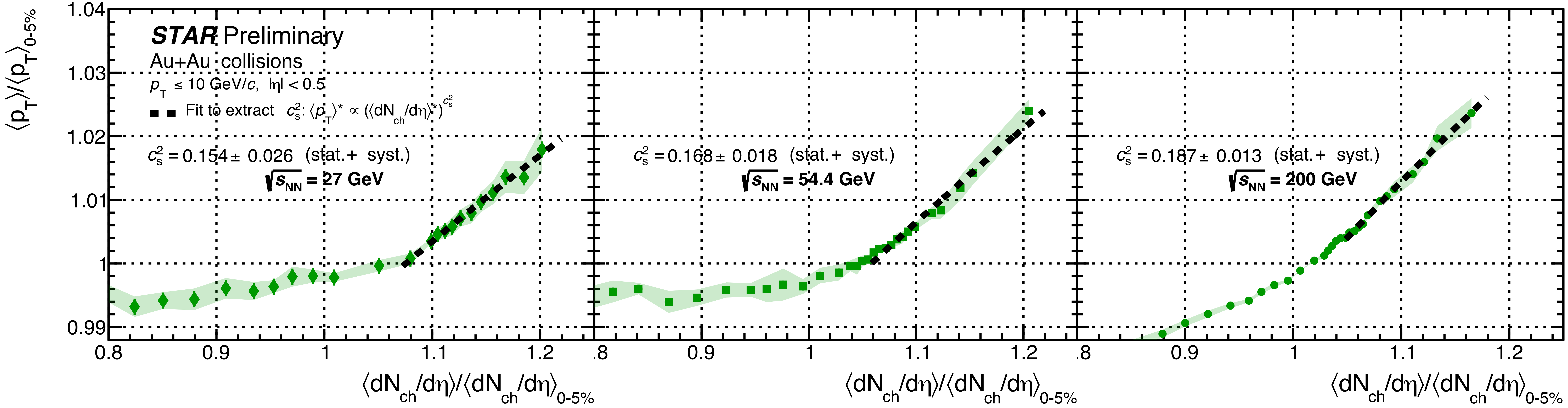


Fit - F.G. Gardim et al., Phys. Lett. B 856, 138937 (2024)

Extracting c_s^2 using the logarithmic derivative

- Centrality estimator: RefMult with $p_T > 225$ MeV/c
- Threshold chosen for consistency with EBE approach to minimize the presence of geometric fluctuations
- Systematic uncertainties are determined by varying the p_T range on the fit used to extrapolate $p_T \to 0$.

c_s^2 increases with $\sqrt{s_{NN}}$ →

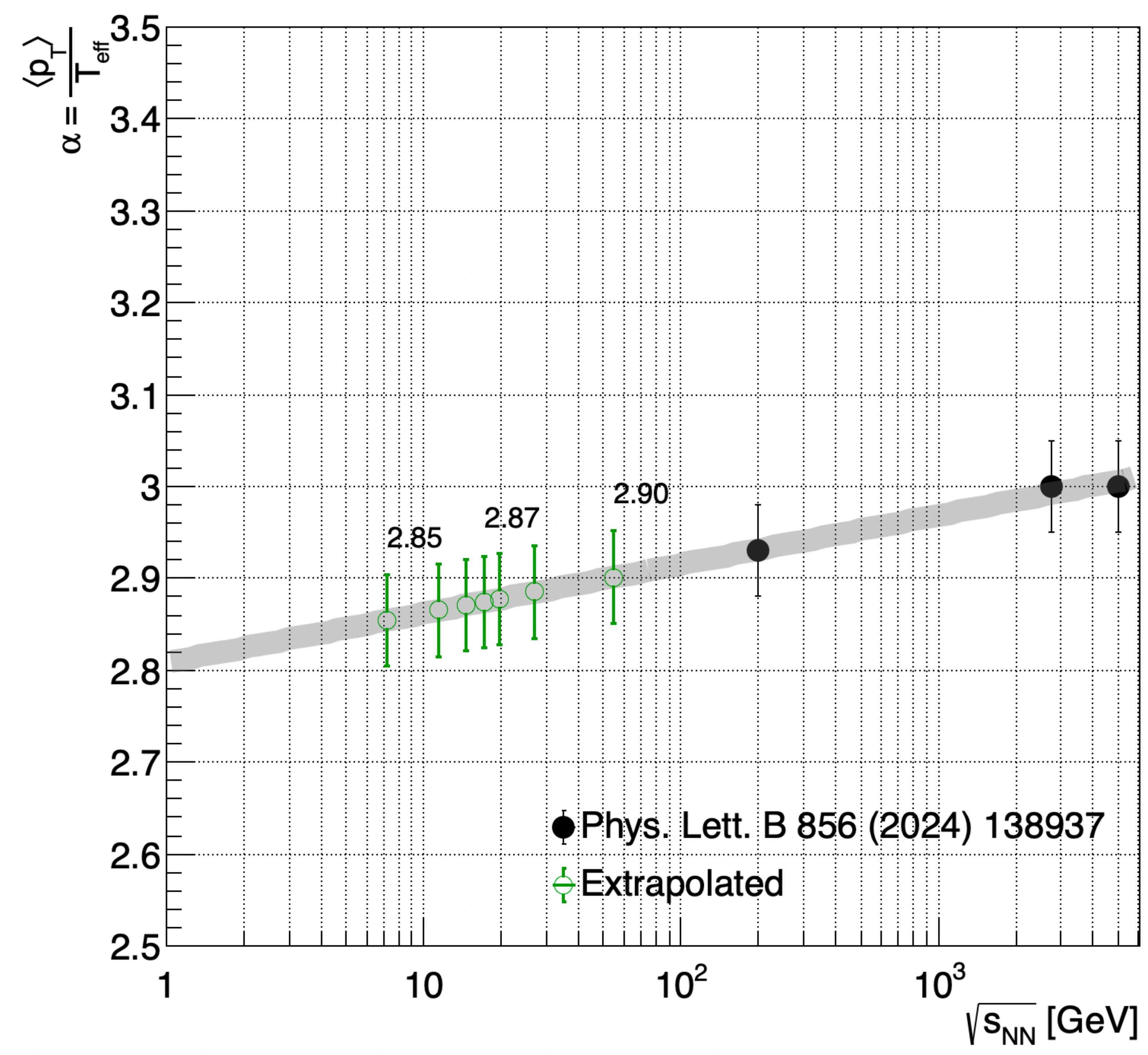


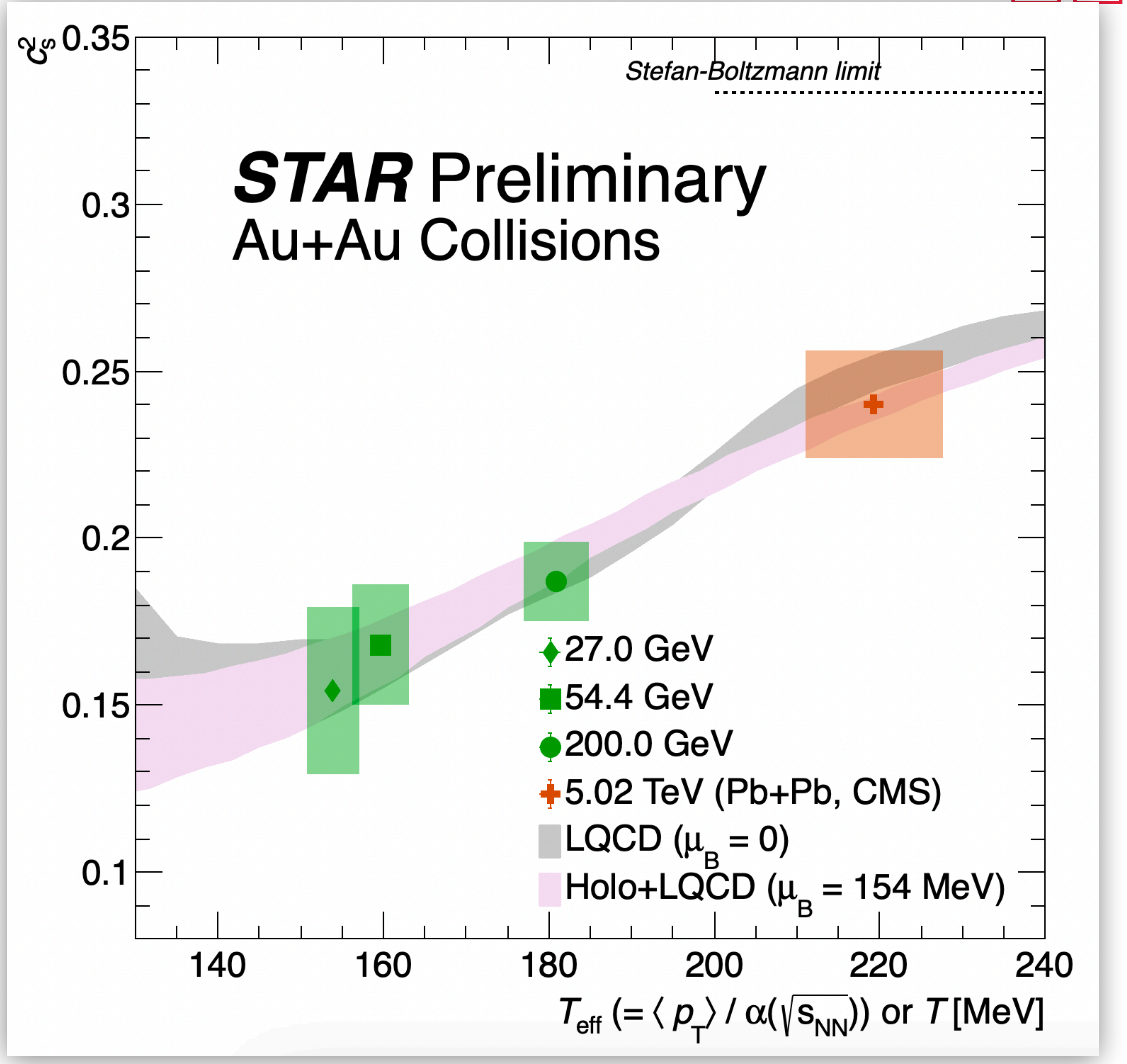
Fit - F.G. Gardim et al., Phys. Lett. B 856, 138937 (2024)

Temperature dependence of c_s^2

T_{eff} - Effective temperature found to be $\sim\langle p_T \rangle/3$ ratio.

We extrapolate published results[1] to estimate this ratio as a function of collision energy





Holo + LQCD - M. Hippert et al., Phys. Rev. D 110, 094006 (2024)
stout - S. Borsanyi et al., Phys. Lett. B 370, 99-104 (2014)
HISQ - A. Bazavov et al., Phys. Rev. D 90, 094503 (2014)

[1] F.G. Gardim et al., Phys. Lett. B 856, 138937 (2024)

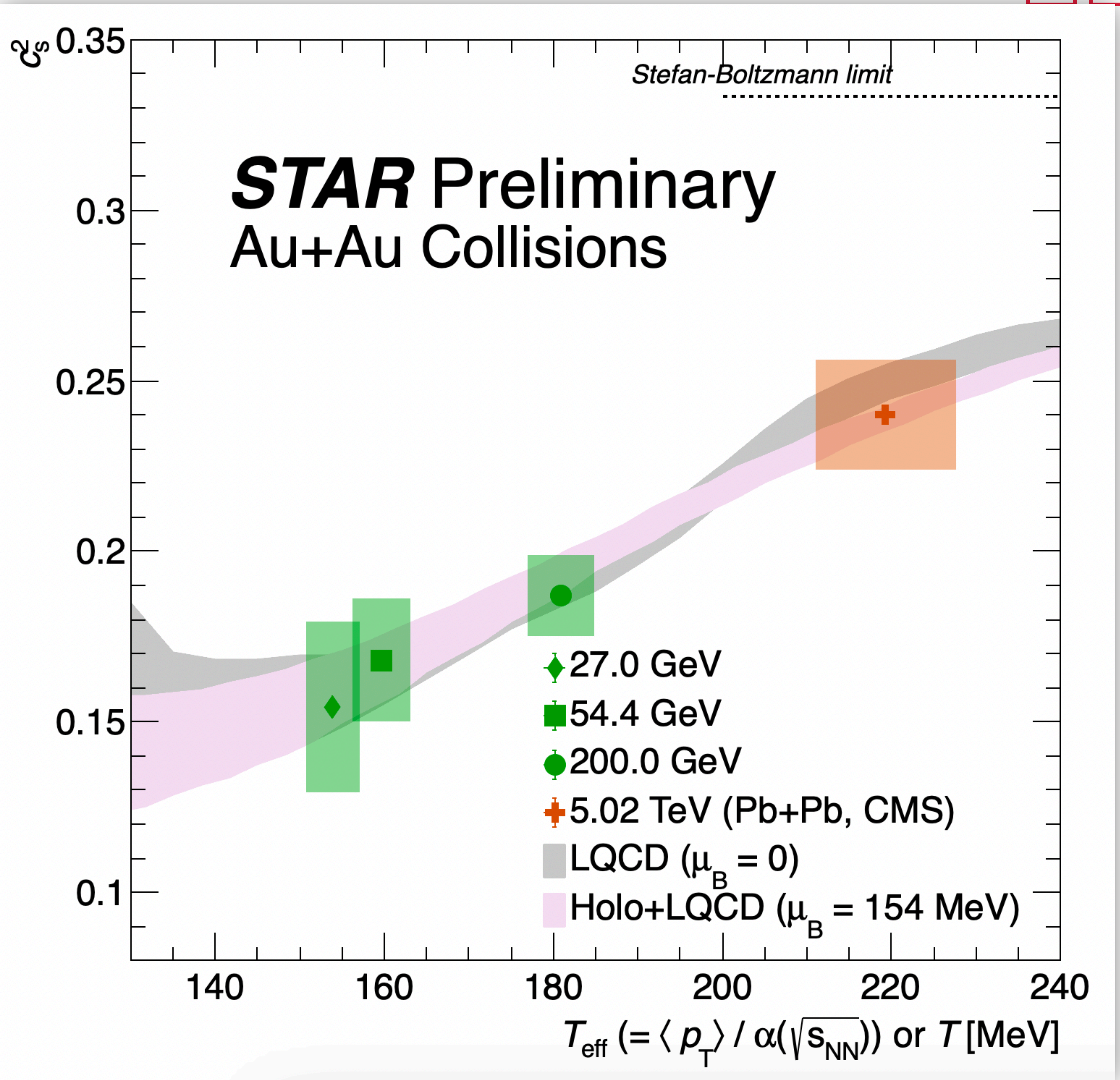
Summary

First controlled extraction of c_s^2 at RHIC energies (with temperature dependence!) using logarithmic derivative approach.

But critically, we are beginning to understand the role of the centrality estimator as a caveat to this extraction.

Extraction of c_s^2 is consistent with LQCD.

Much to be discovered at other RHIC energies. For what collision system should we expect to lose our sensitivity?



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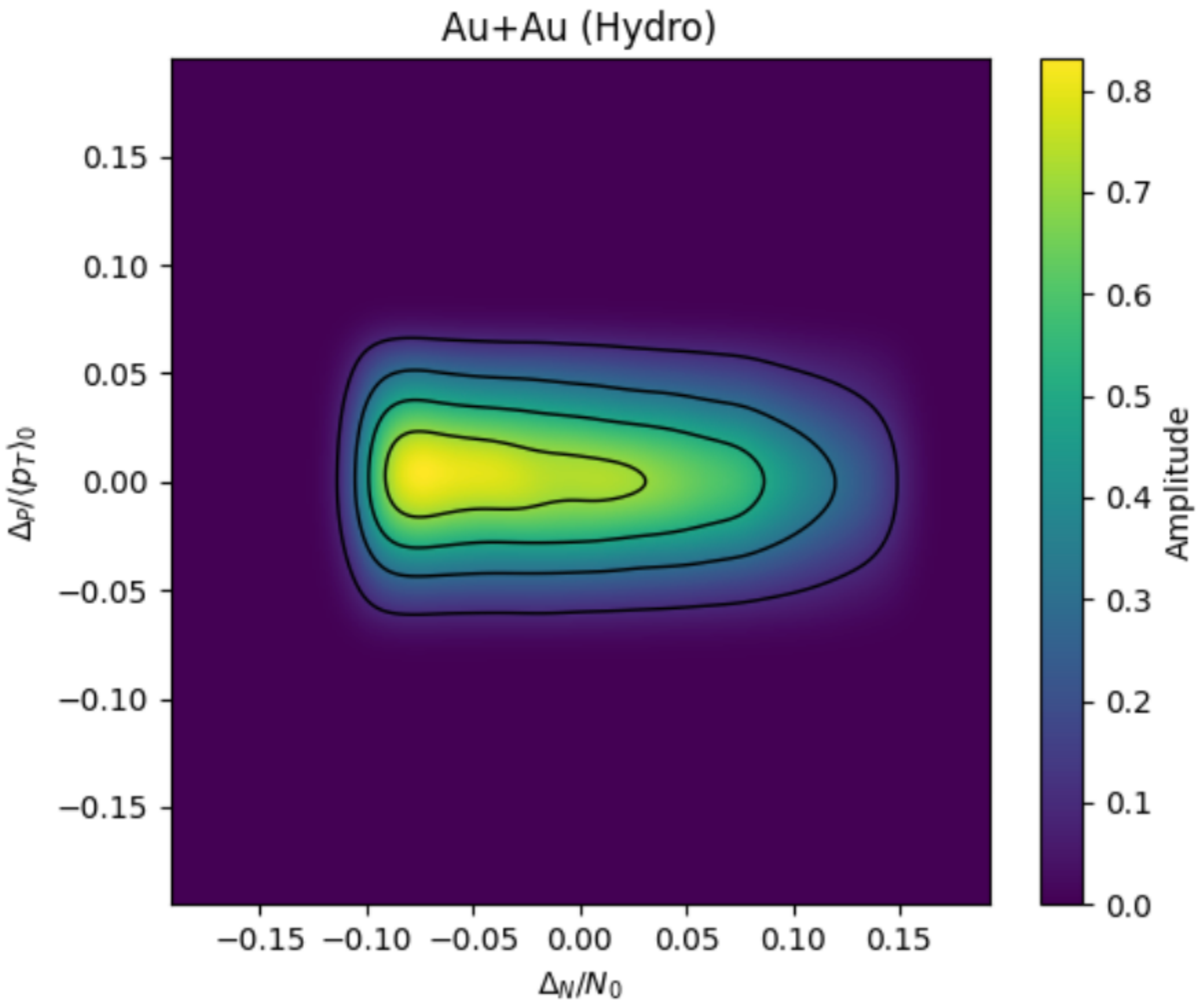
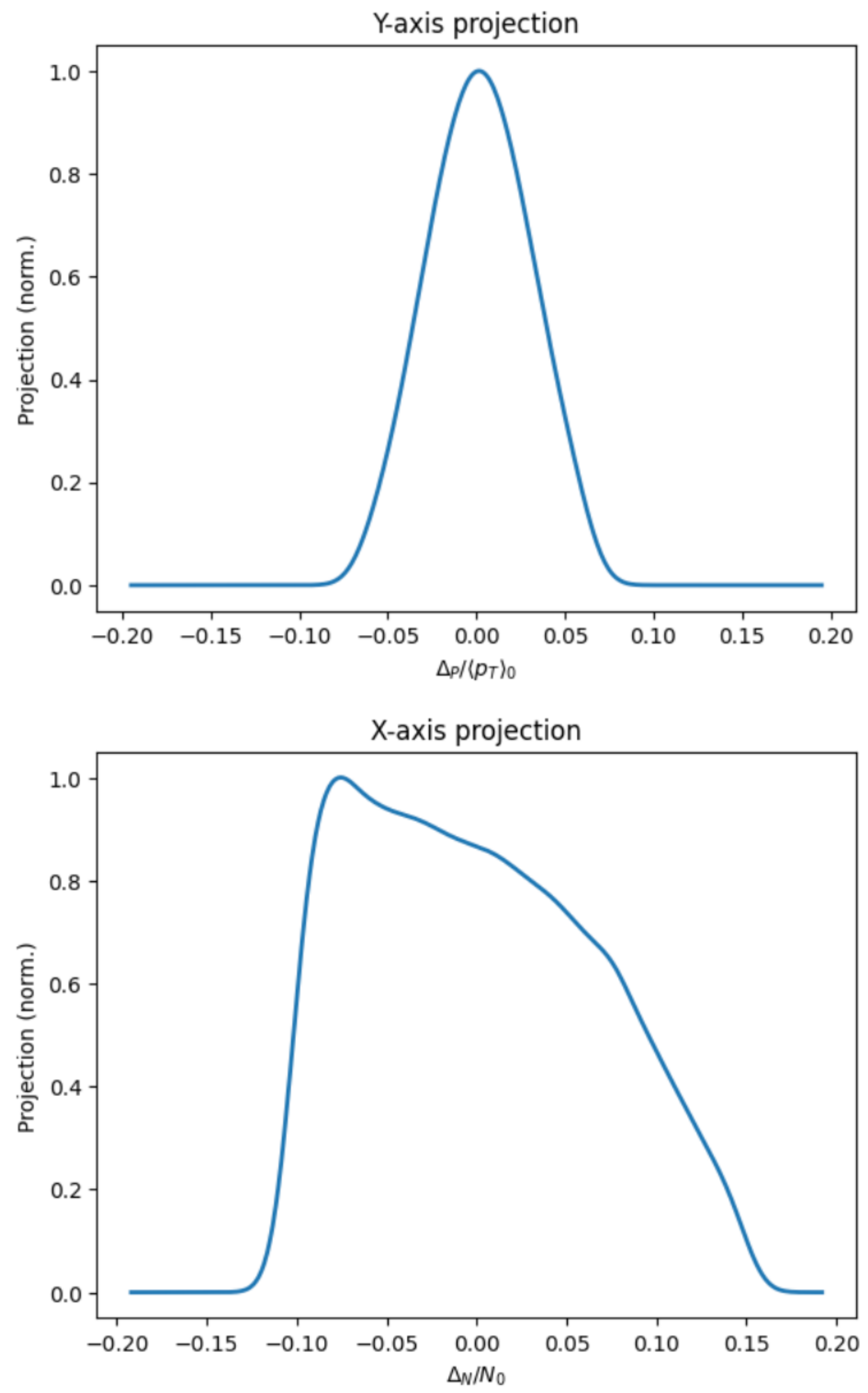
HISQ - A. Bazavov et al., Phys. Rev. D 90, 094503 (2014)

Backup

Event-by-event approach[1] for extracting c_s^2

Joint probability distribution





$$\Delta_p = [p_T] - \langle p_T \rangle_0$$

$$\Delta_N = [N_{ch}] - N_0$$

[1]Yu-Shan Mu et al. arXiv:2501.02777

Note: Hydro study is sensitive to a fully inclusive p_T spectra.

Evidence in Trajectum that event class condition minimizing b fluctuations

Gaussian model of $[p_T]$ and N_{ch} fluctuations predict dramatic changes in the Var($[p_T]$) with vanishing b fluctuations[1,2]

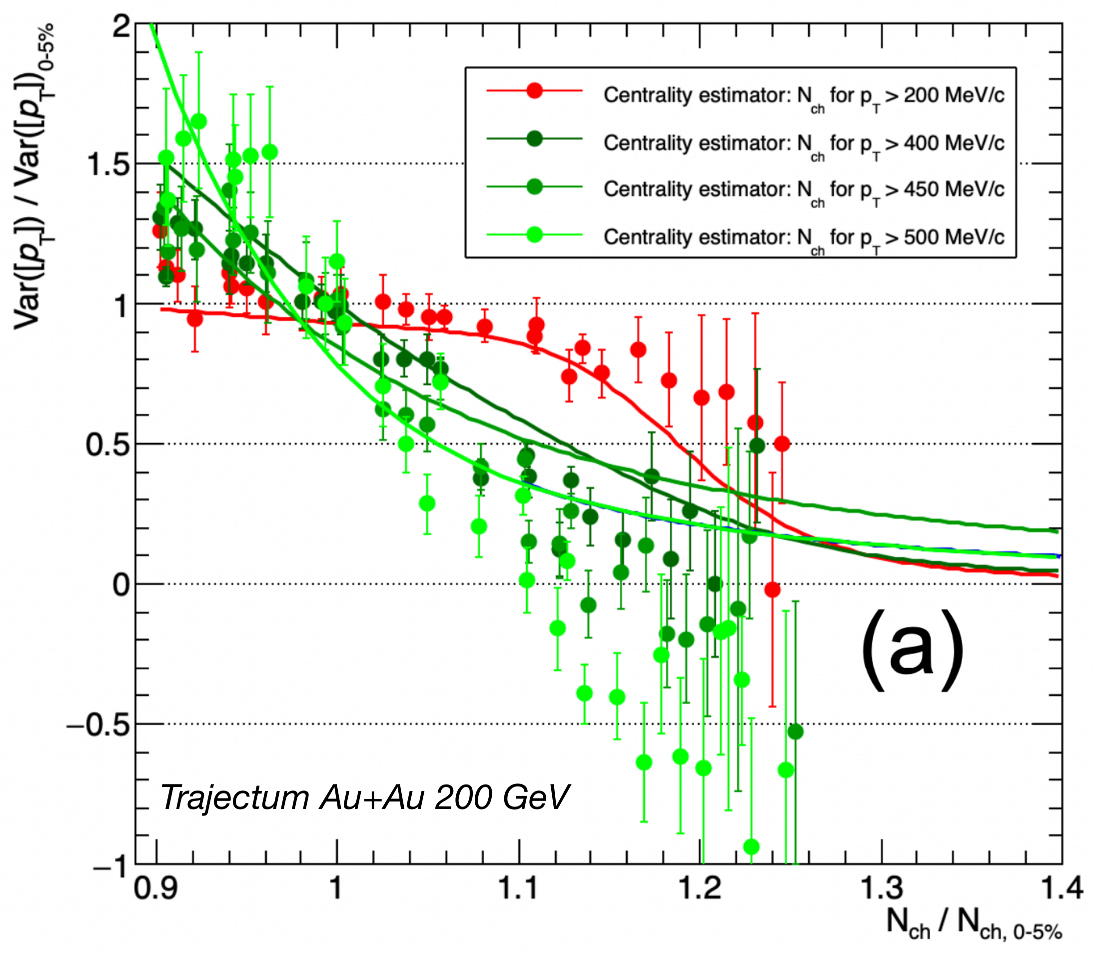
Centrality qualifier: $N_{ch} \in p_T > p_T^{th}$

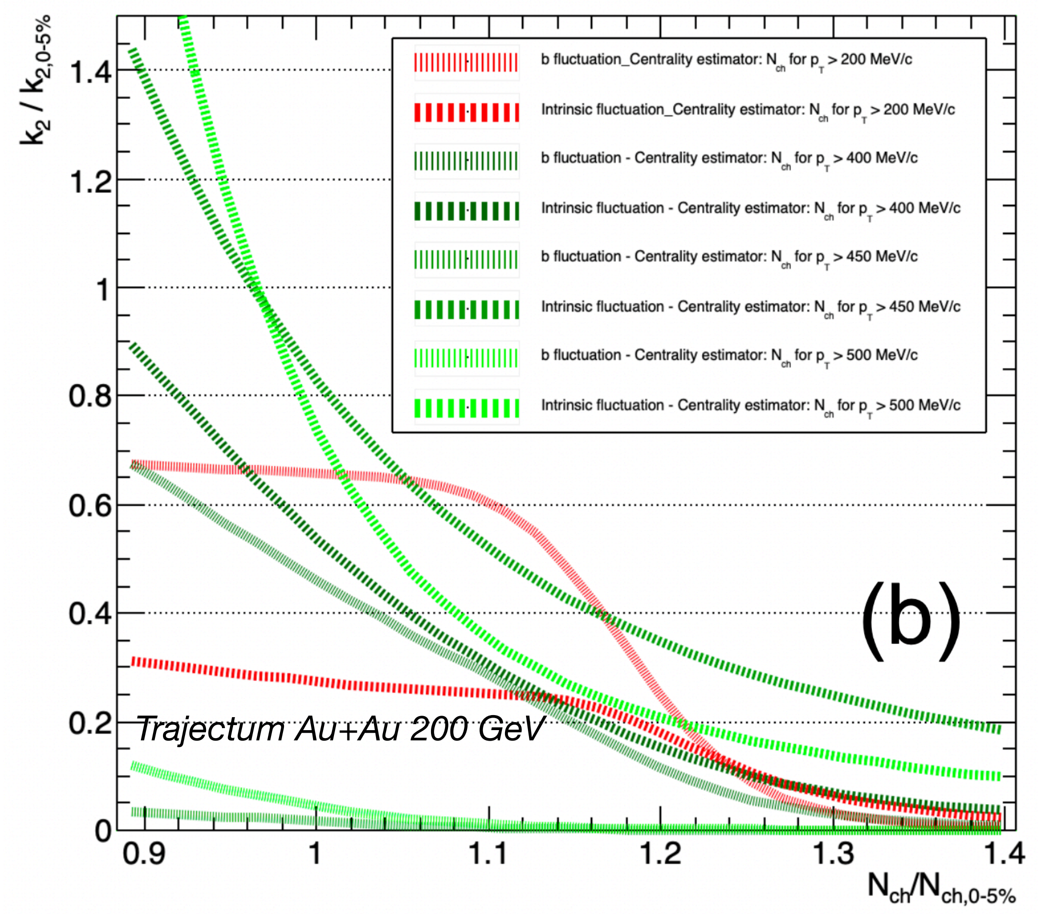
Geometric fluctuations

At fixed multiplicity → $[p_T]$ fluctuations from fluctuations in system size

Intrinsic fluctuations

At fixed b → $[p_T]$ fluctuations from thermal fluctuations in the QGP

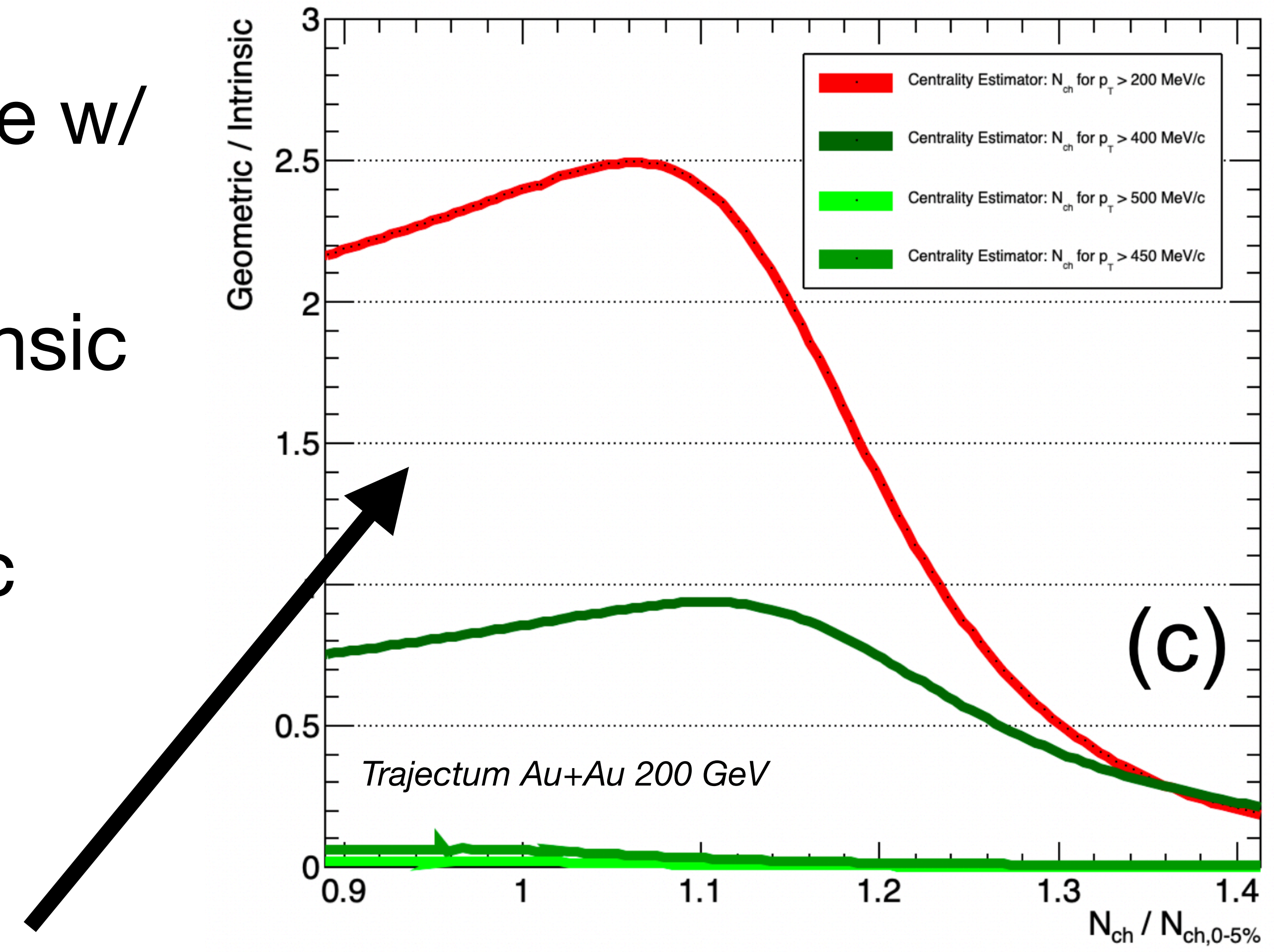




(a) Normalized variance w/ two-component fit

(b) Geometry and Intrinsic components from fit

(c) Geometry / Intrinsic ratio



b fluctuations qualitatively vanish more rapidly relative to thermal fluctuations as p_T^{th} increases

[1]R. Samanta et al., PRC 108, 024908 (2023)
[2]R. Samanta et al., PRC 109, L051902 (2024)

Evidence in Trajectum that event class condition minimizing b fluctuations

Gaussian model of $[p_T]$ and N_{ch} fluctuations predict dramatic changes in the Var($[p_T]$) with vanishing b fluctuations[1,2]

Centrality qualifier: $N_{ch} \in p_T > p_T^{th}$

Geometri

At fixe
fluctu

d variance w/
ent fit

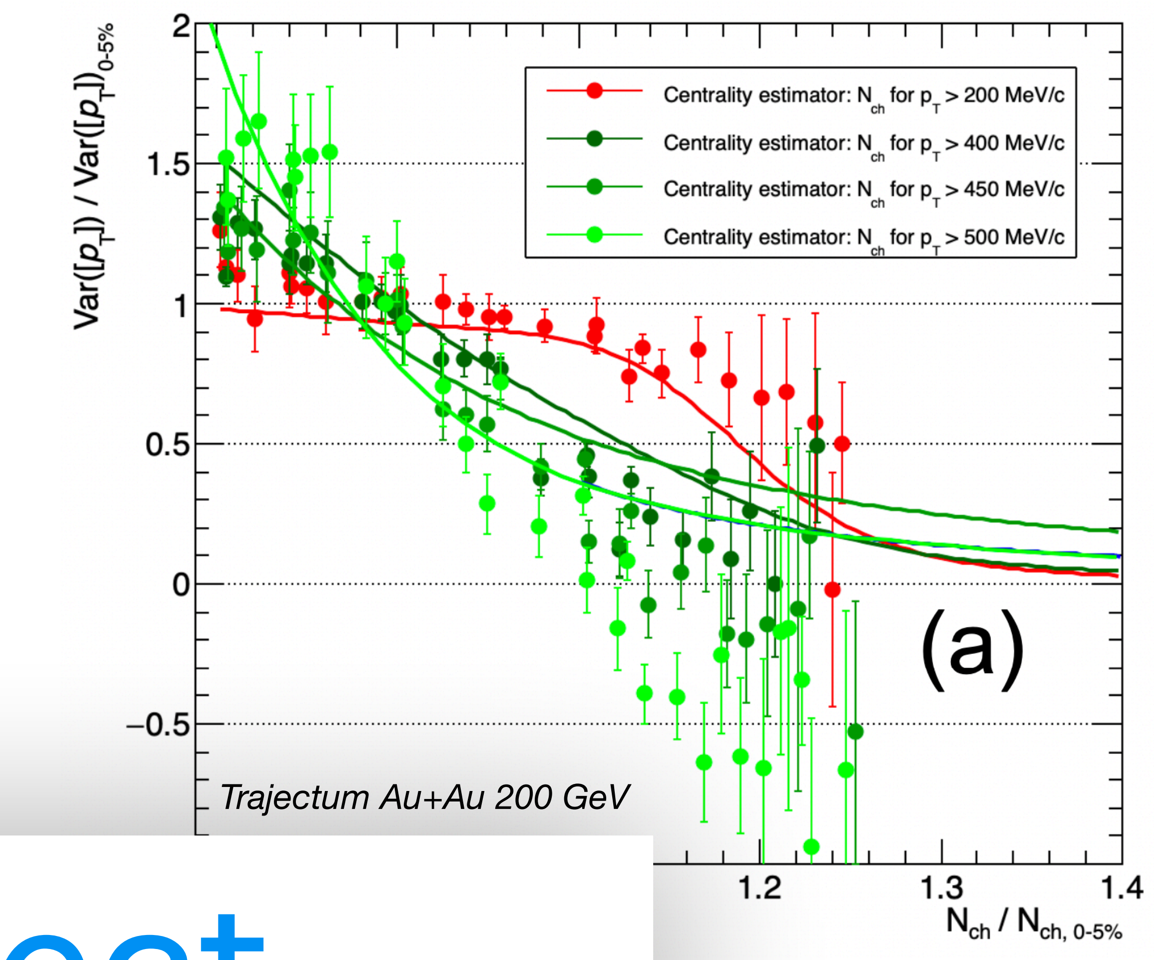
and Intrinsic
from fit

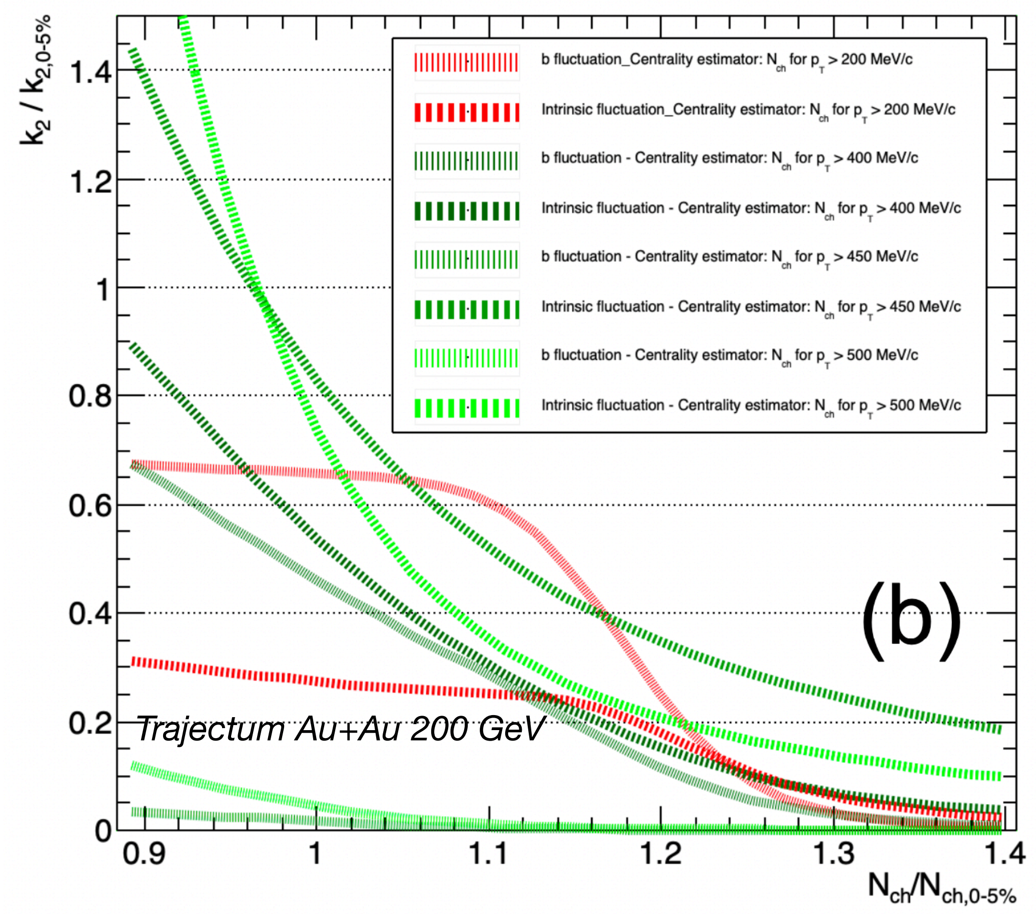
/ Intrinsic

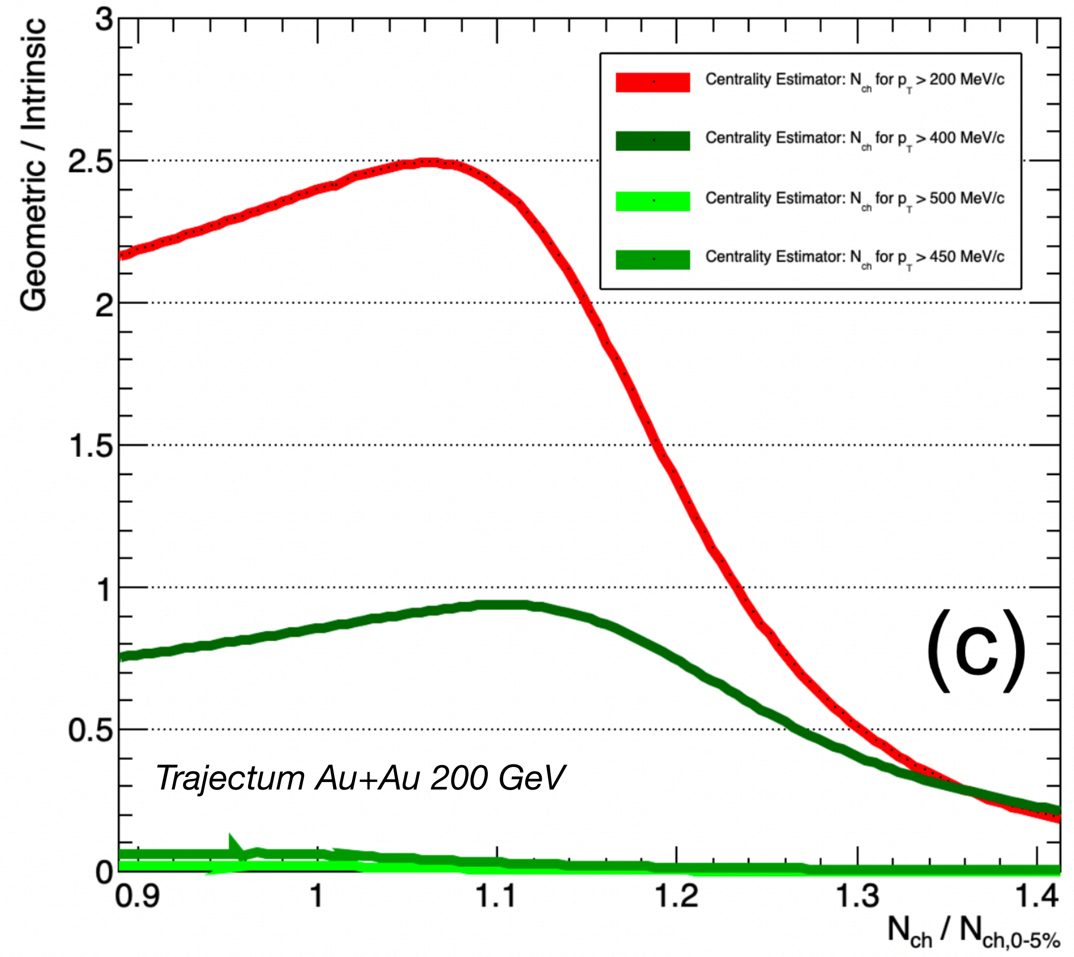
Intrinsic f

At fixe
fluctuations in the QGP

But this is an indirect conclusion. How can we determine more precisely the ideal p_T^{th}?





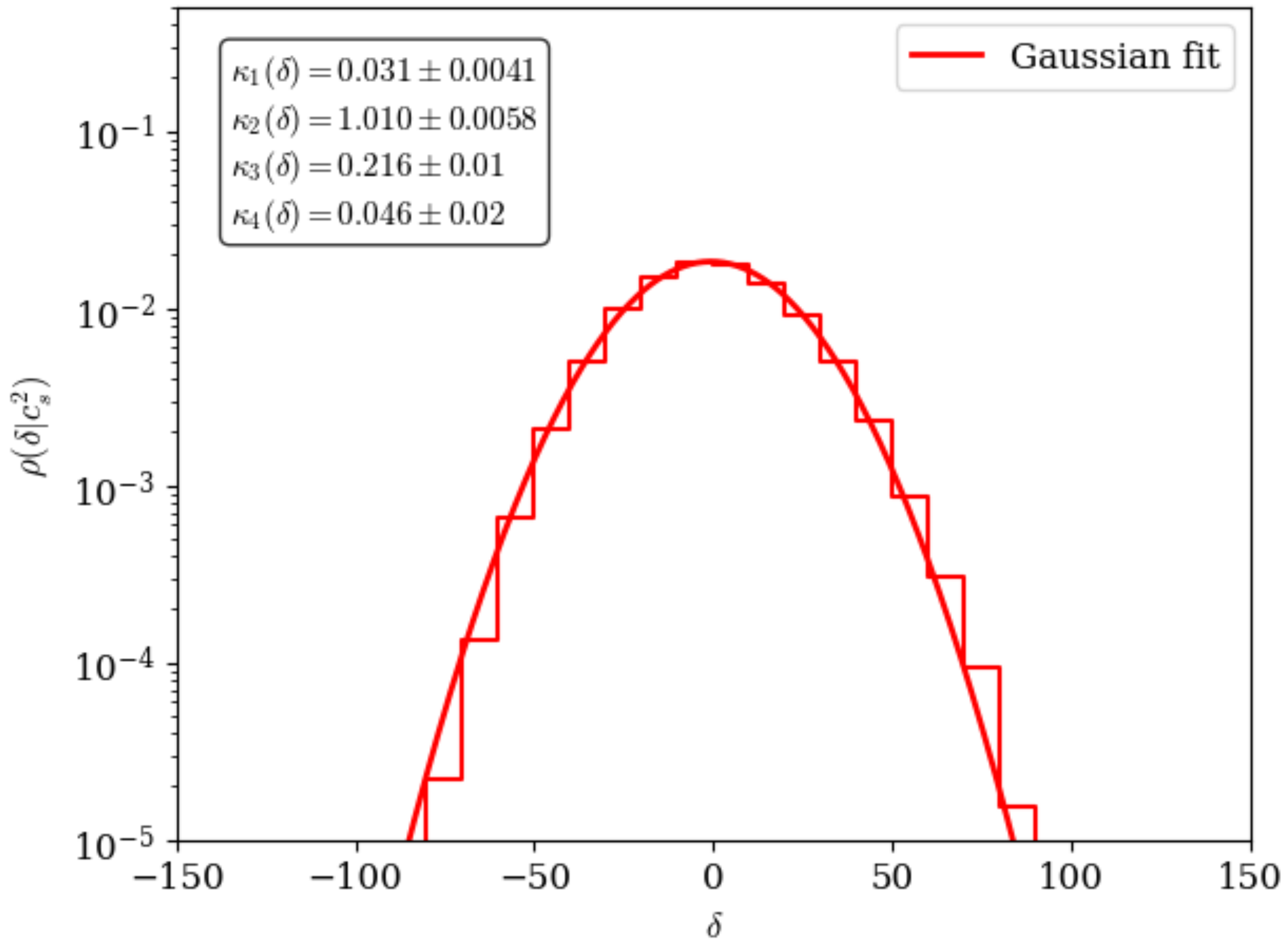


b fluctuations qualitatively vanish more rapidly relative to thermal fluctuations as p_T^{th} increases

[R. Samanta et al., PRC 108 (2023) 024908]
[R. Samanta et al., PRC 109 (2024) L051902]

Final test for validity of event-by-event study

Gaussianity test of δ



Moreover, deviations from thermalization can be quantified using higher-order cumulants of the $\rho(\delta|c_s^2)$ distribution. For example, the standardized kurtosis, defined as $\kappa_4 = \{\delta^4\}/\{\delta^2\}^2 - 3$, should vanish in a system with complete local thermalization but remain finite in the presence of non-thermal contributions. From our numerical simulations, we find $\kappa_4 = 2.15 \pm 0.05$ and 1.91 ± 0.11 in HIJING and PYTHIA models, respectively. In contrast, hybrid hydrodynamic modeling yields $\kappa_4 = 0.16 \pm 0.05$ and 0.18 ± 0.07 for p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV and 8.16 TeV, and $\kappa_4 = -0.064 \pm 0.096$ for Pb-Pb collisions, signaling small but finite non-thermal contributions.

The non-Gaussianity of δ can serve as a robust diagnostic tool for thermalization in QGP systems. When κ_4 of δ exceeds unity, the dominant contribution to the response between Δ_p and Δ_N is no longer thermodynamic, indicating that the system should not be considered thermalized. Noting that a deterministic thermodynamic response involving c_s^2 remains valid in the presence of finite baryon density, the current formulation is expected applicable at lower collision en-

arXiv:2501.02777

Comparing the two methodologies

Event-by-event response[1]

$$\frac{\Delta_p}{\langle p_T \rangle} = c_s^2 \frac{\Delta_N + \delta}{N_0}$$

Logarithmic derivative[2]

$$c_s^2 = d\ln\langle p_T \rangle / d\ln\langle N_{ch} \rangle$$

[1]arXiv:2501.02777

[2]arXiv:2403.06052

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$$\frac{\Delta_p}{\langle p_T \rangle} = c_s^2 \frac{\Delta_N + \delta}{N_0}$$

Advantage

- Single broad bin (0-1% or 0-5%)
- Minimizes geometric (stochastic) fluctuation by construction

Disadvantage

- Cannot extrapolate spectra in EBE study - Loss of general thermodynamic response

Logarithmic derivative[2]

$$c_s^2 = d\ln\langle p_T \rangle / d\ln\langle N_{ch} \rangle$$

$$\Delta_p = [p_T] - \langle p_T \rangle_0 \qquad \Delta_N = [N_{ch}] - N_0$$

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- Ultracentral study
- Fine binning required - Potential loss of categorical collision geometry information

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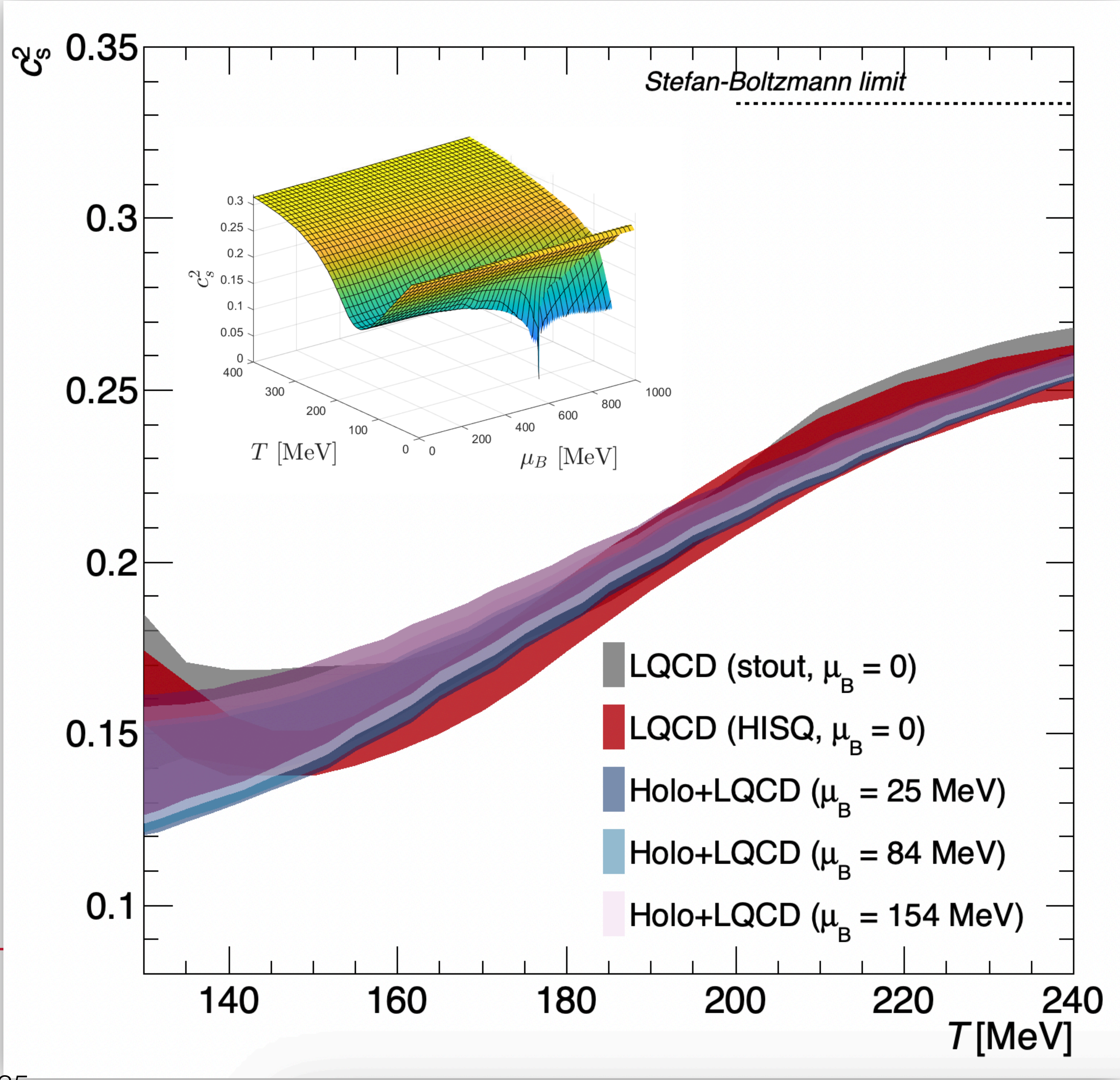
$\Delta_p = [p_T] - \langle p_T \rangle_0 \quad \Delta_N = [N_{ch}] - N_0$

What role does μ_B play in $c_s^2(T)$?

Finite μ_B effects become apparent to $c_s^2(T)$ above $\mu_B = 300$ MeV

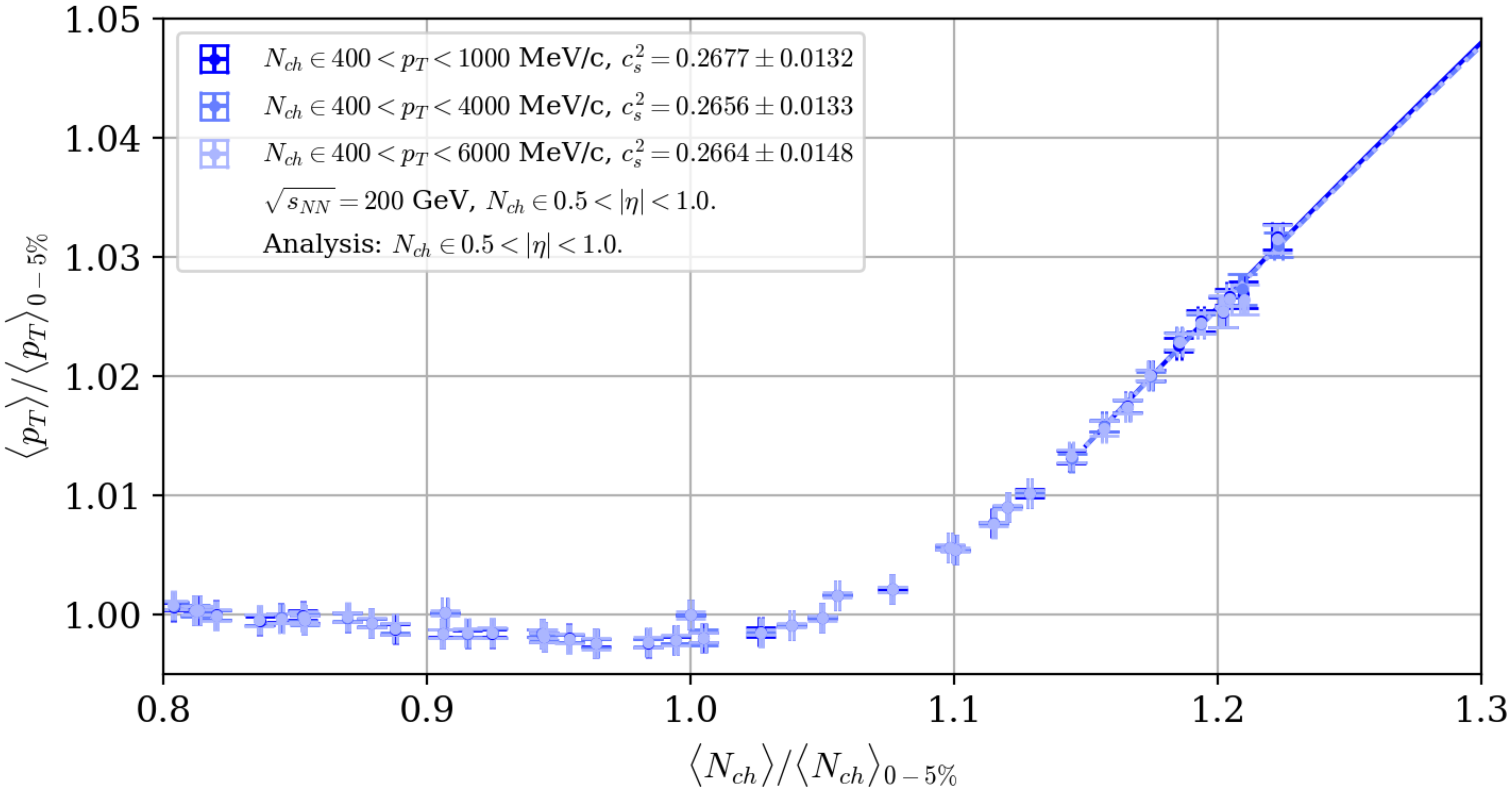


Holo + LQCD - M. Hippert et al., Phys. Rev. D 110, 094006 (2024)

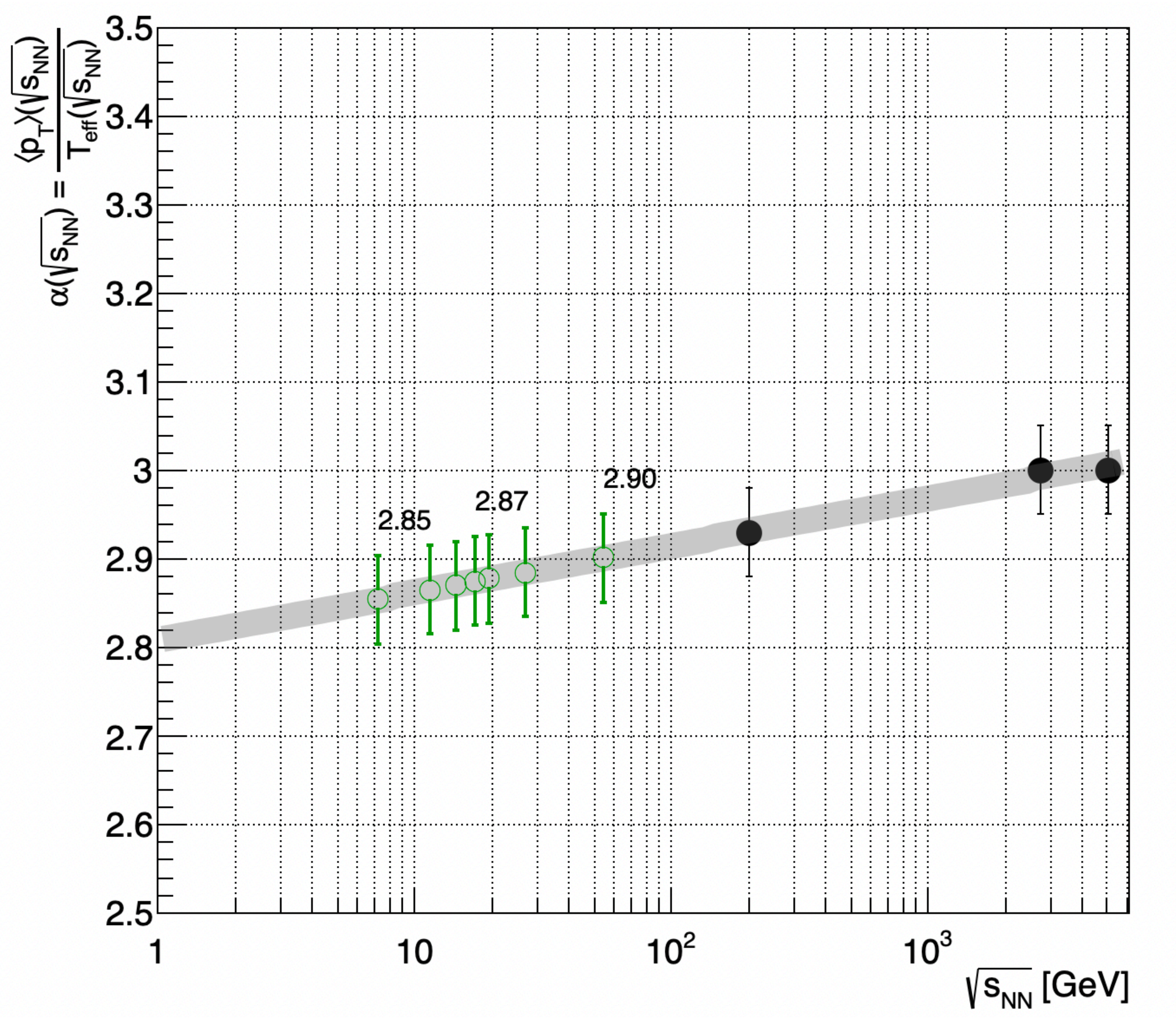
stout - S. Borsanyi et al., Phys. Lett. B 370, 99-104 (2014)

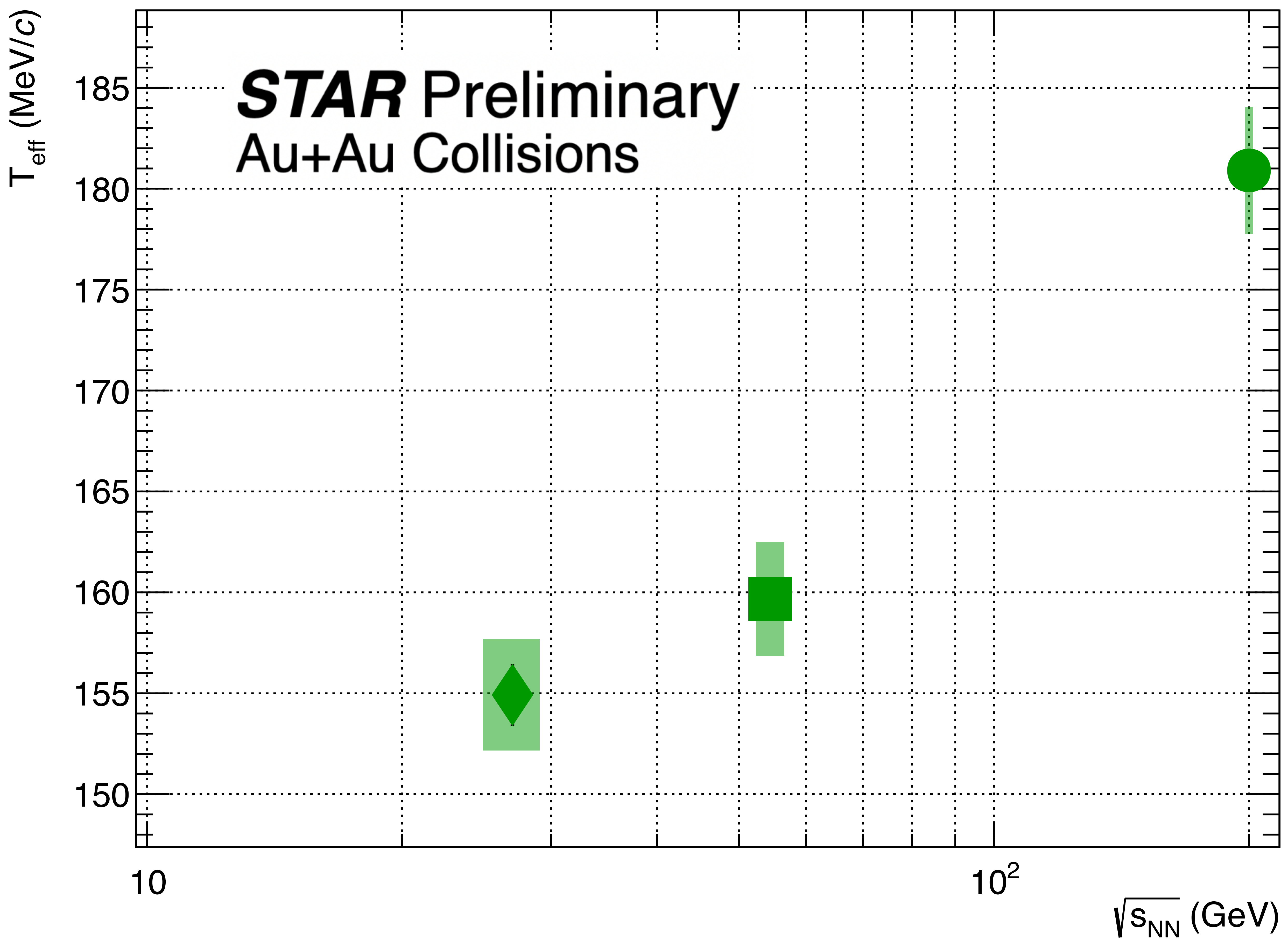
HISQ - A. Bazavov et al., Phys. Rev. D 90, 094503 (2014)

Trajectum upper threshold

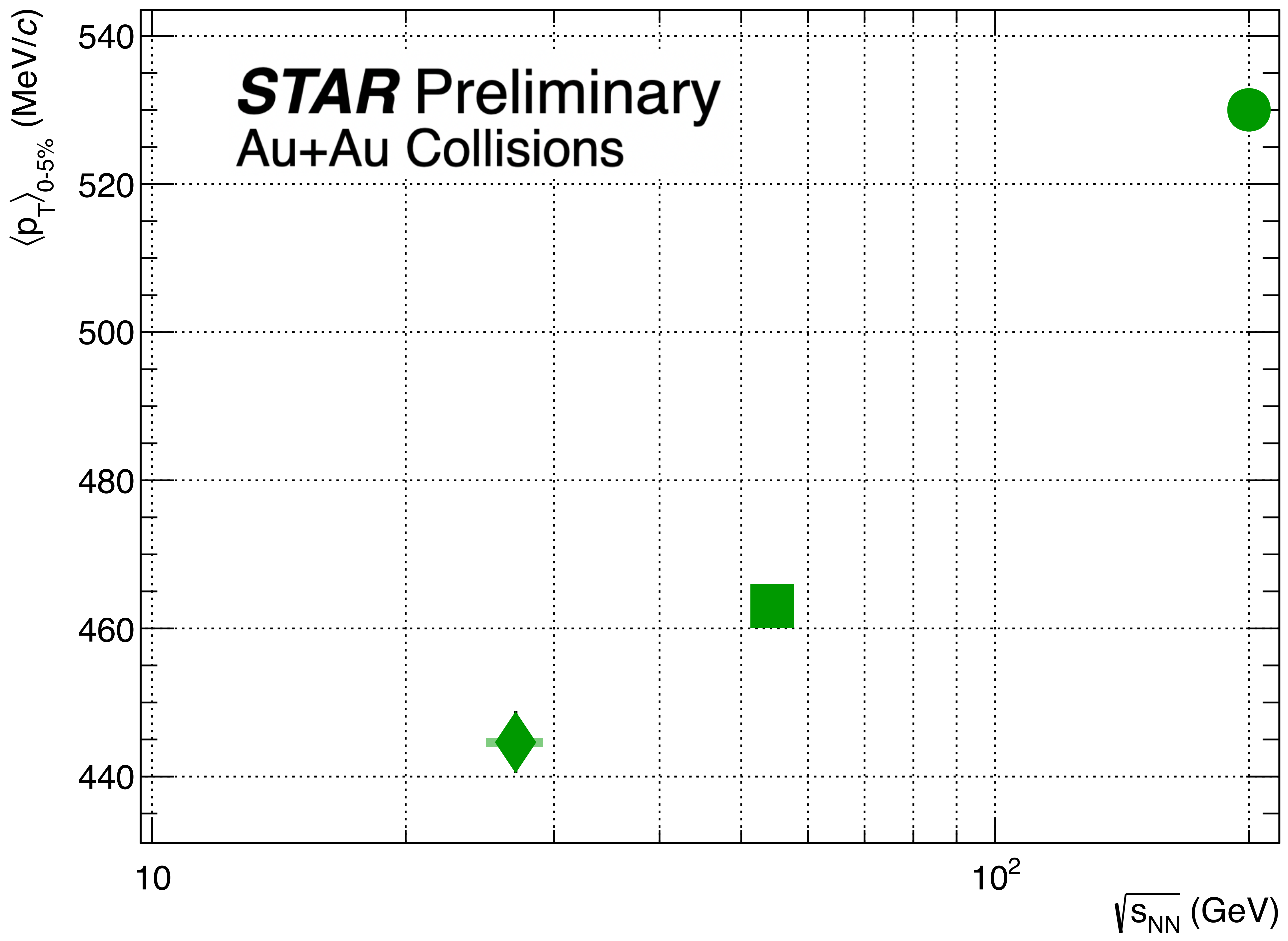


Determining T_{eff}



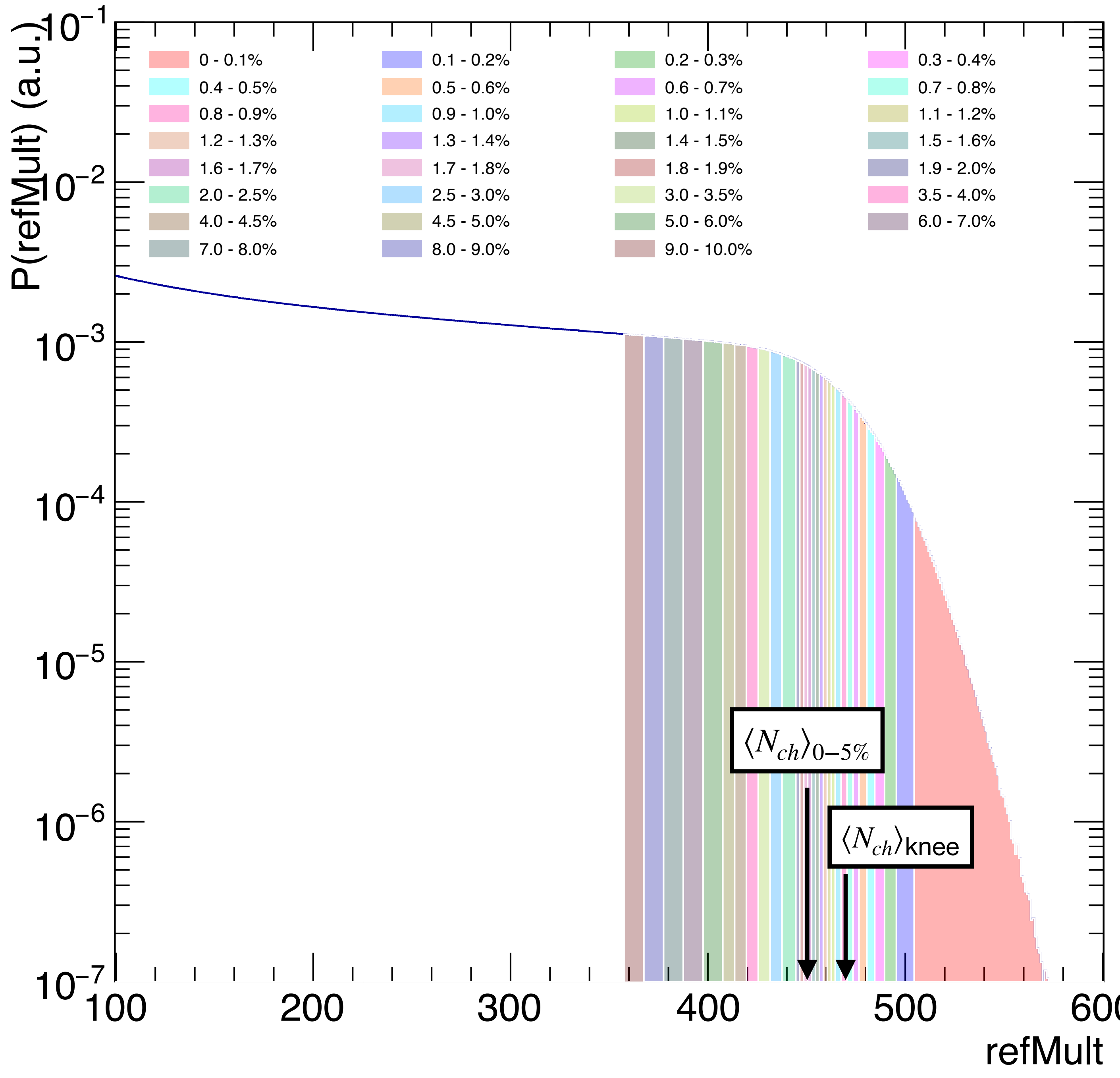


Include Ref. Ollitraut

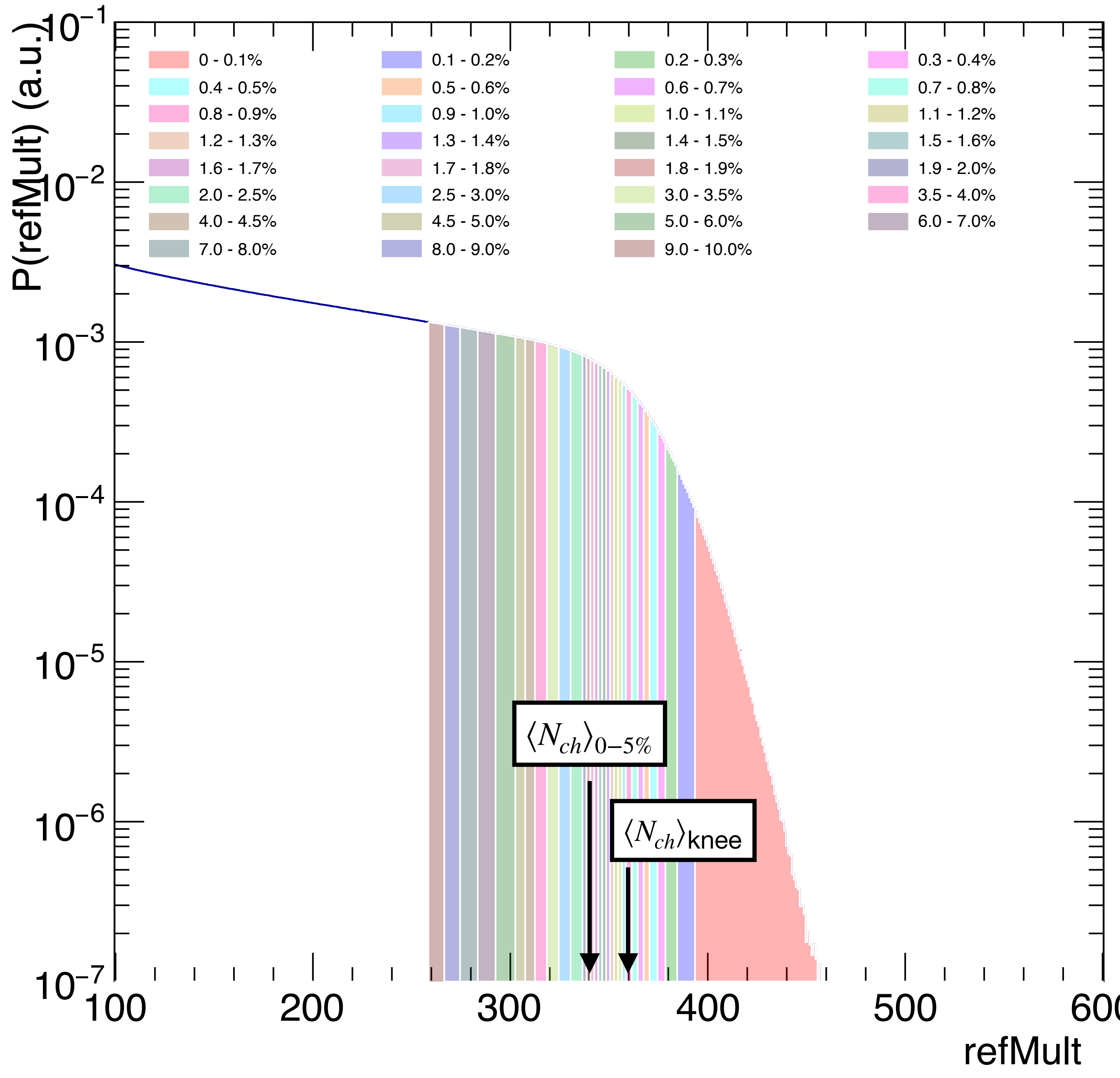

STAR Preliminary
Au+Au Collisions
⟨p_T⟩_0-5% (MeV/c)
540
520
500
480
460
440
10
10^2
√s_NN (GeV)

Centrality estimator: RefMult with $p_T > 225$ MeV/c

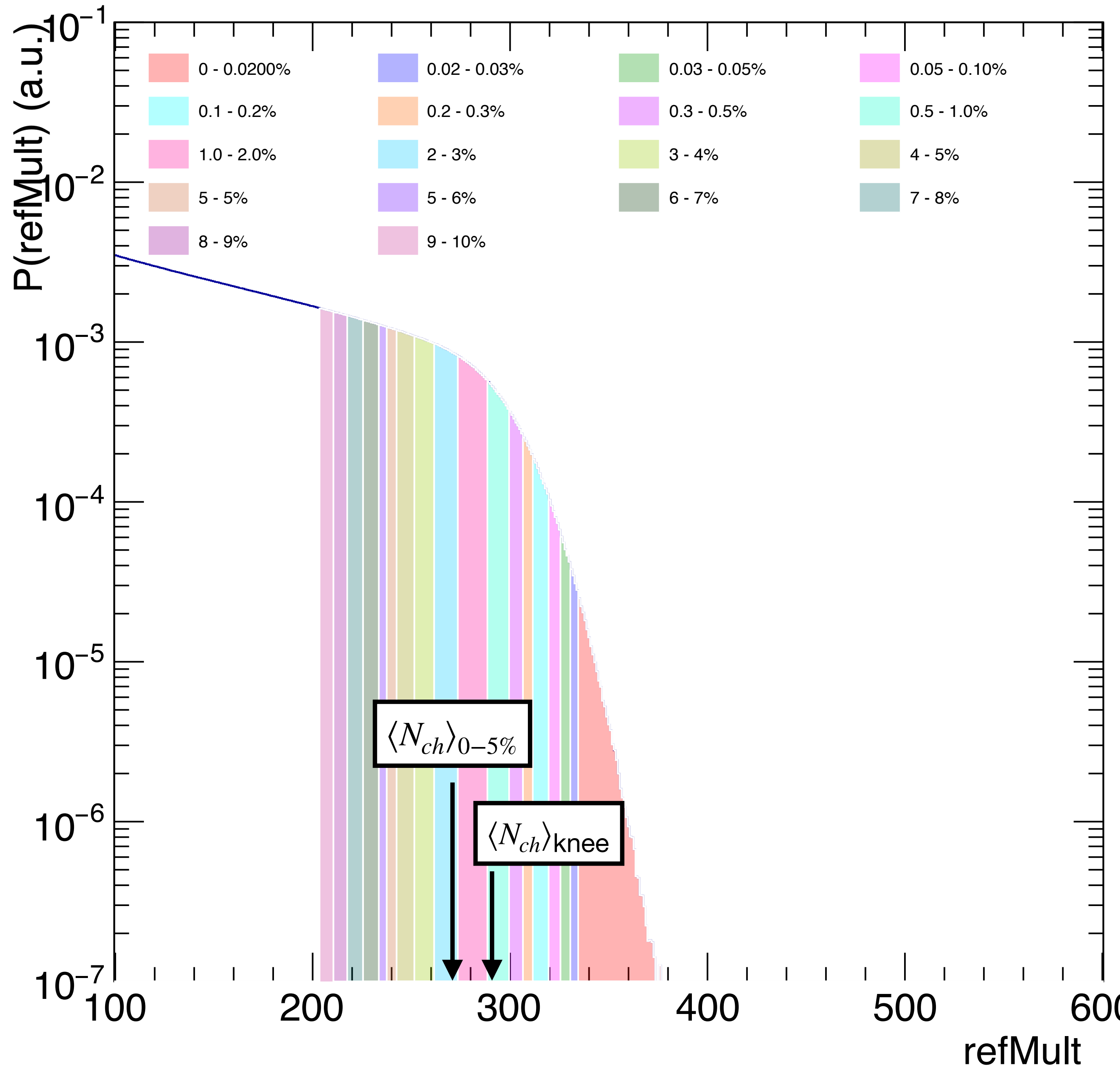
Au+Au $\sqrt{s_{NN}} = 200$ GeV



Au+Au $\sqrt{s_{NN}} = 54.4$ GeV



Au+Au $\sqrt{s_{NN}} = 27$ GeV



Au + Au $\sqrt{s_{NN}}$ = 200 GeV

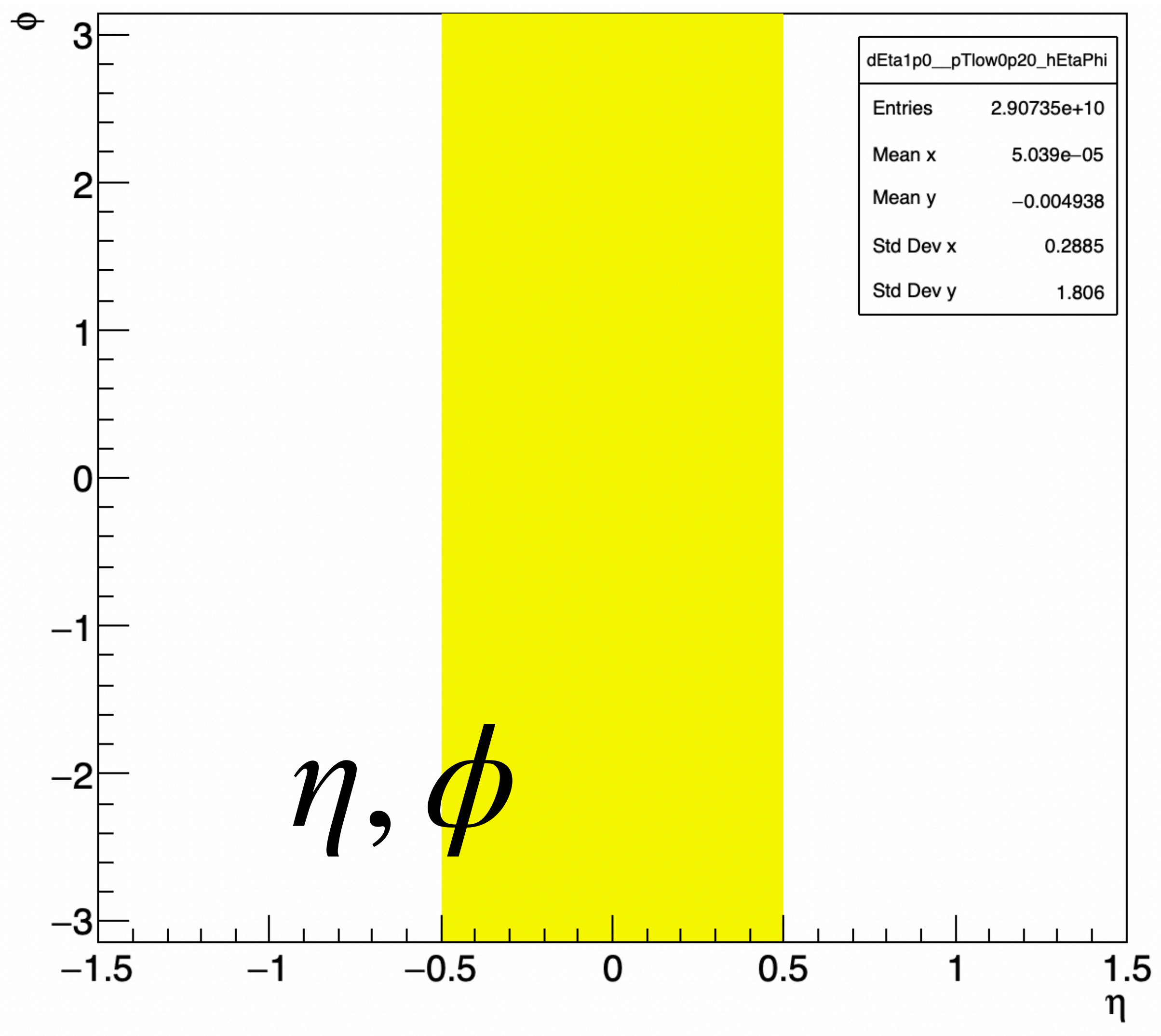
Dataset

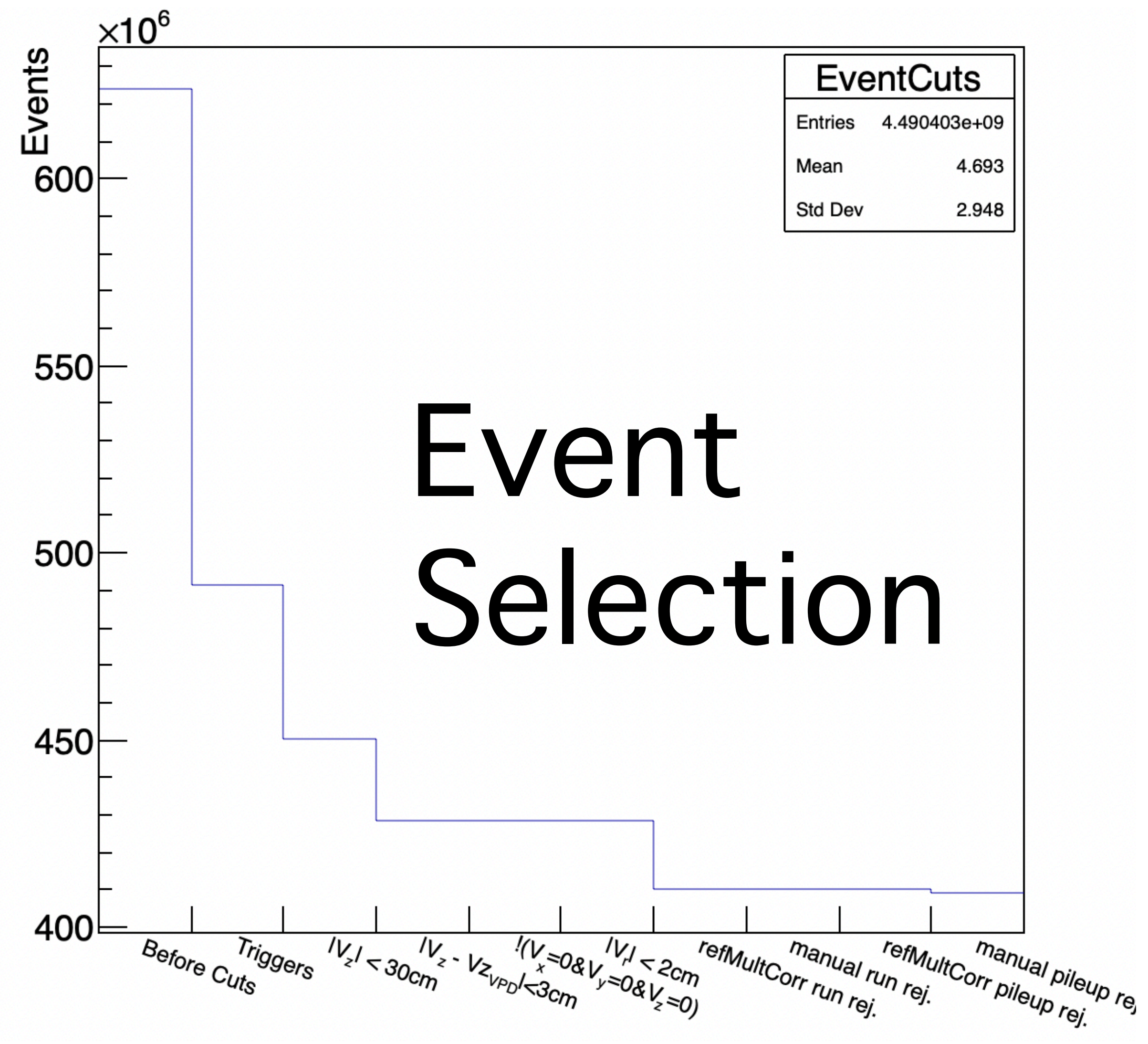
Run 11
- Triggers: 3500X3 (X = 0:4)
- Production tag: P11id
- Filetype: picoDST

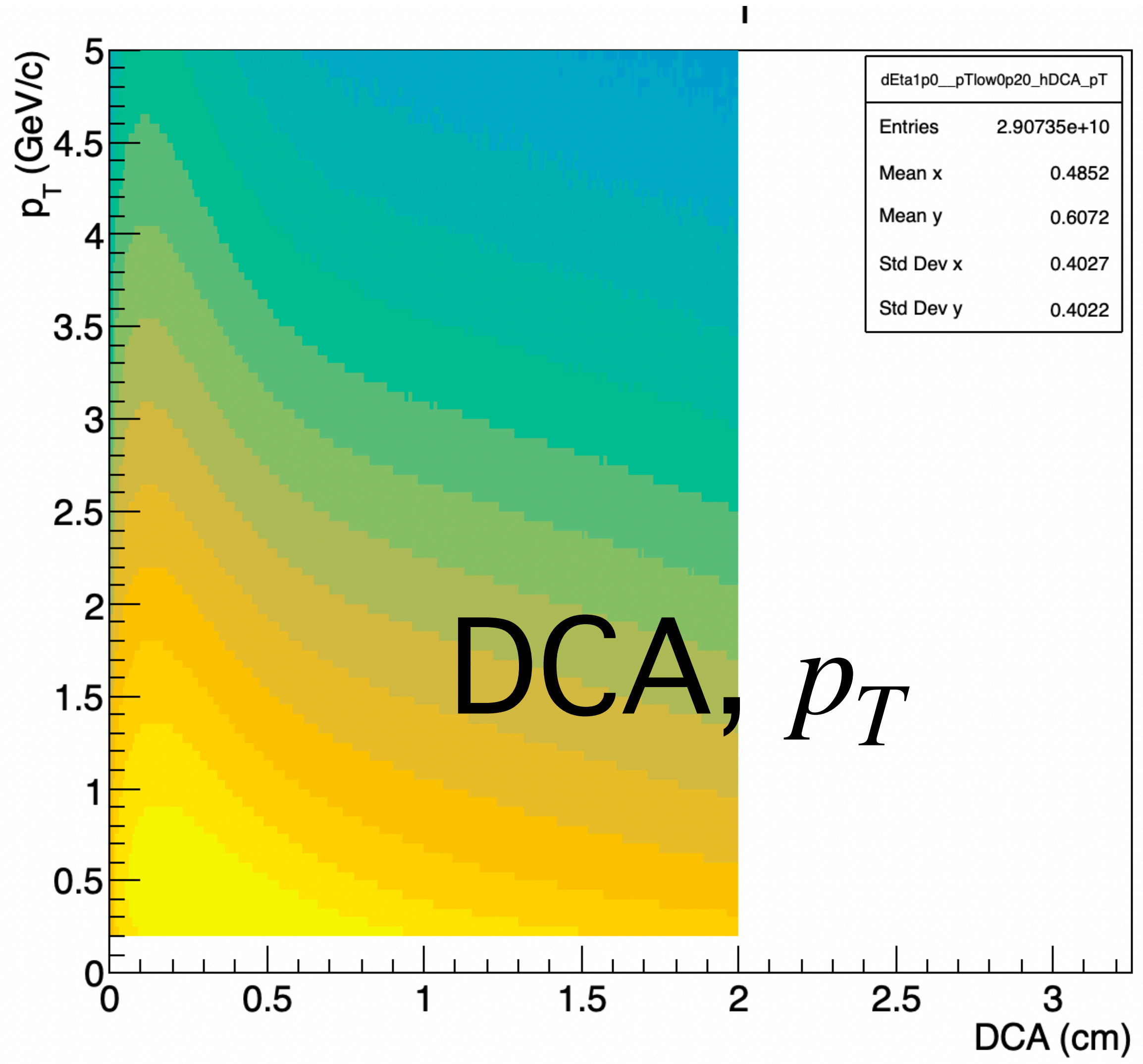
Selection criteria

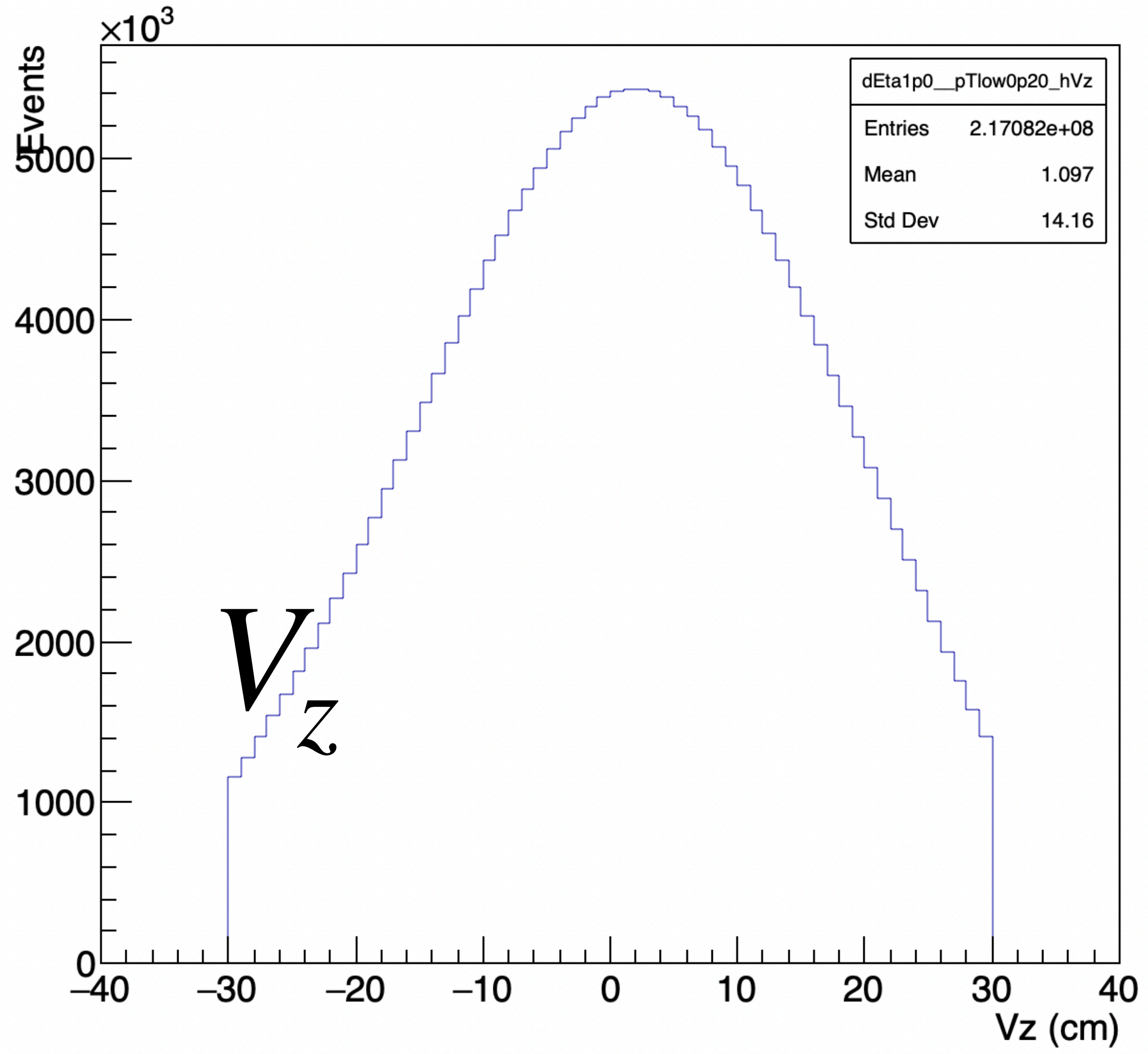
Event
- $!(V_x = 0 \;\; \&\& \;\; V_y = 0 \;\; \&\& \;\; V_z = 0)$
- $|V_z| < 30$ cm
- $|V_r| < 2$ cm
- $|Vz_{TPC} - Vz_{VPD}| < 3$ cm

Track
- Primaries
- Global DCA < 2.0 cm
- $p_T \geq 0.20$ GeV
- Nhitsfit ≥ 20
- Nhitsfit/NhitsMax ≥ 0.52
- NhitsdEdx > 1









Au + Au $\sqrt{s_{NN}}$ = **54.4 GeV**

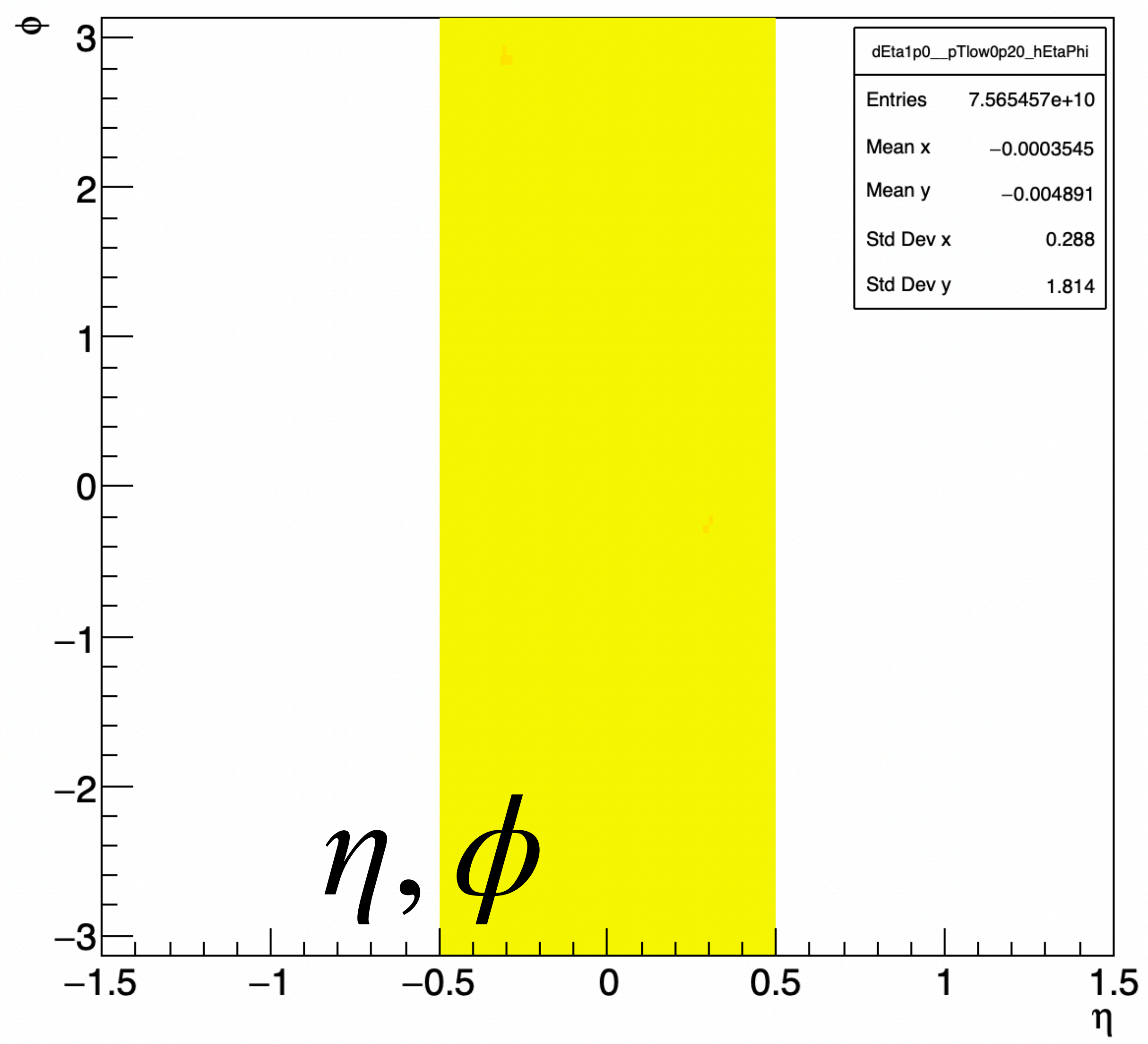
Dataset

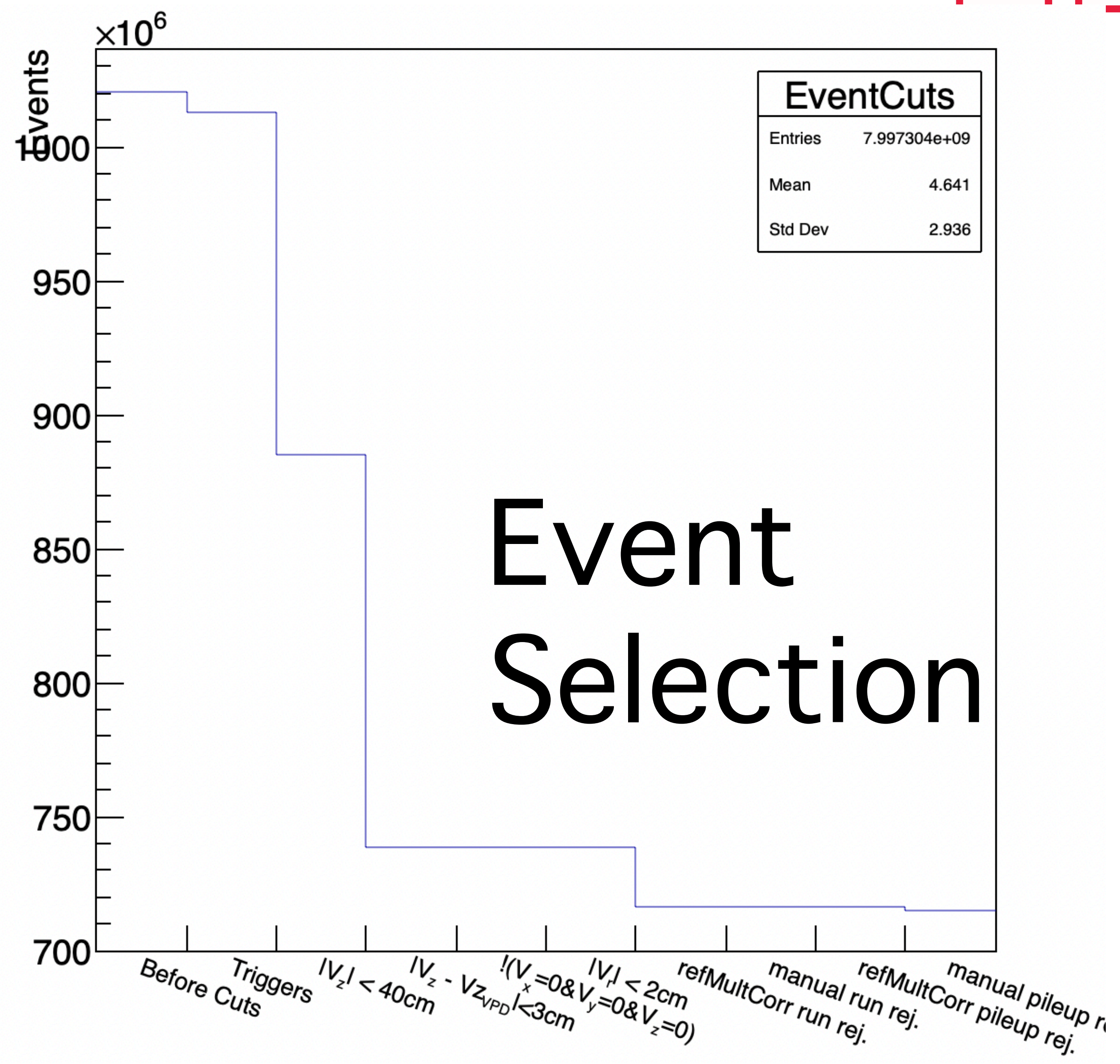
Run 17
- Triggers: 5800X1 (X = 0:2)
- Production tag: P18ic
- Filetype: picoDST

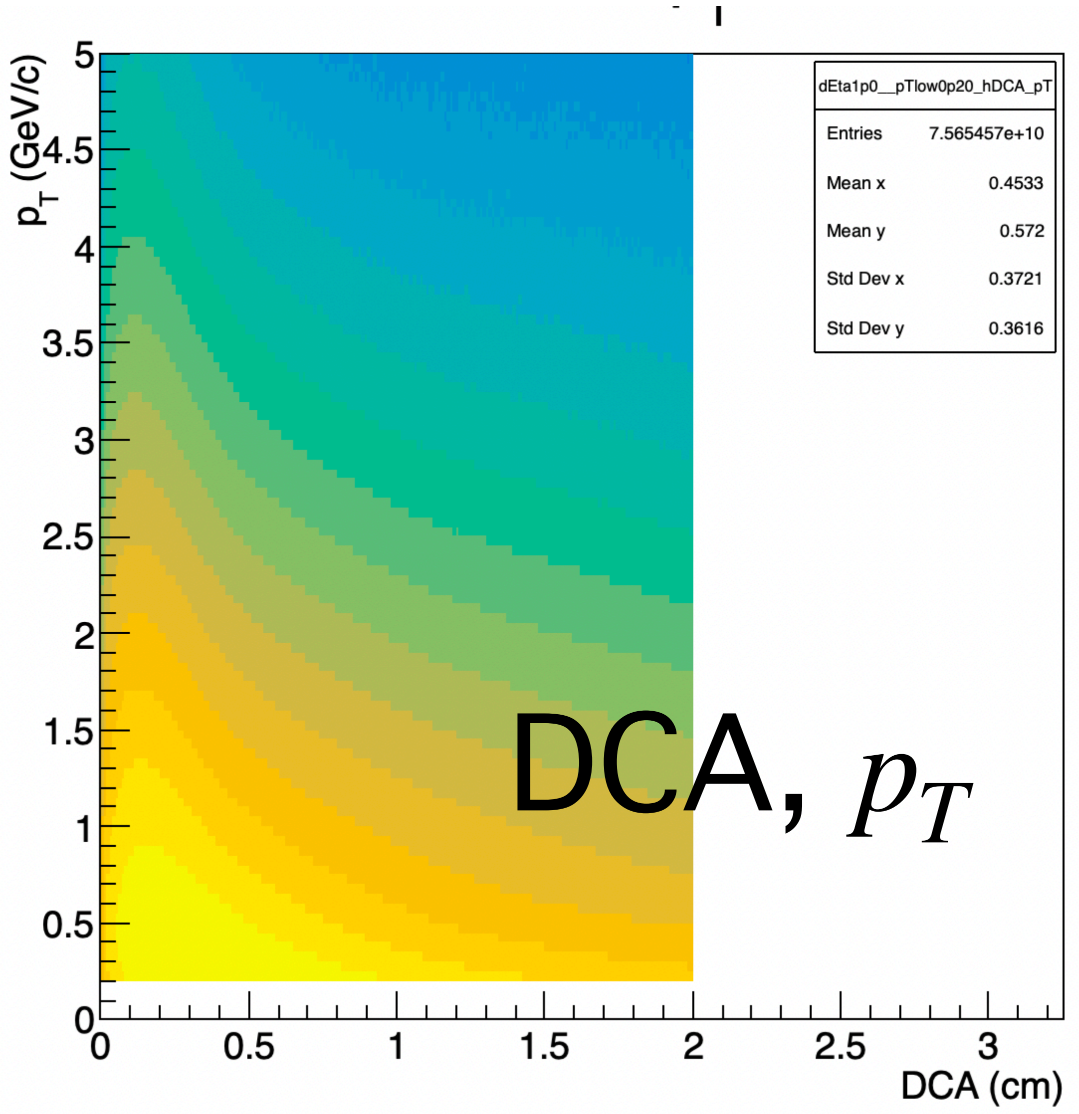
Selection criteria

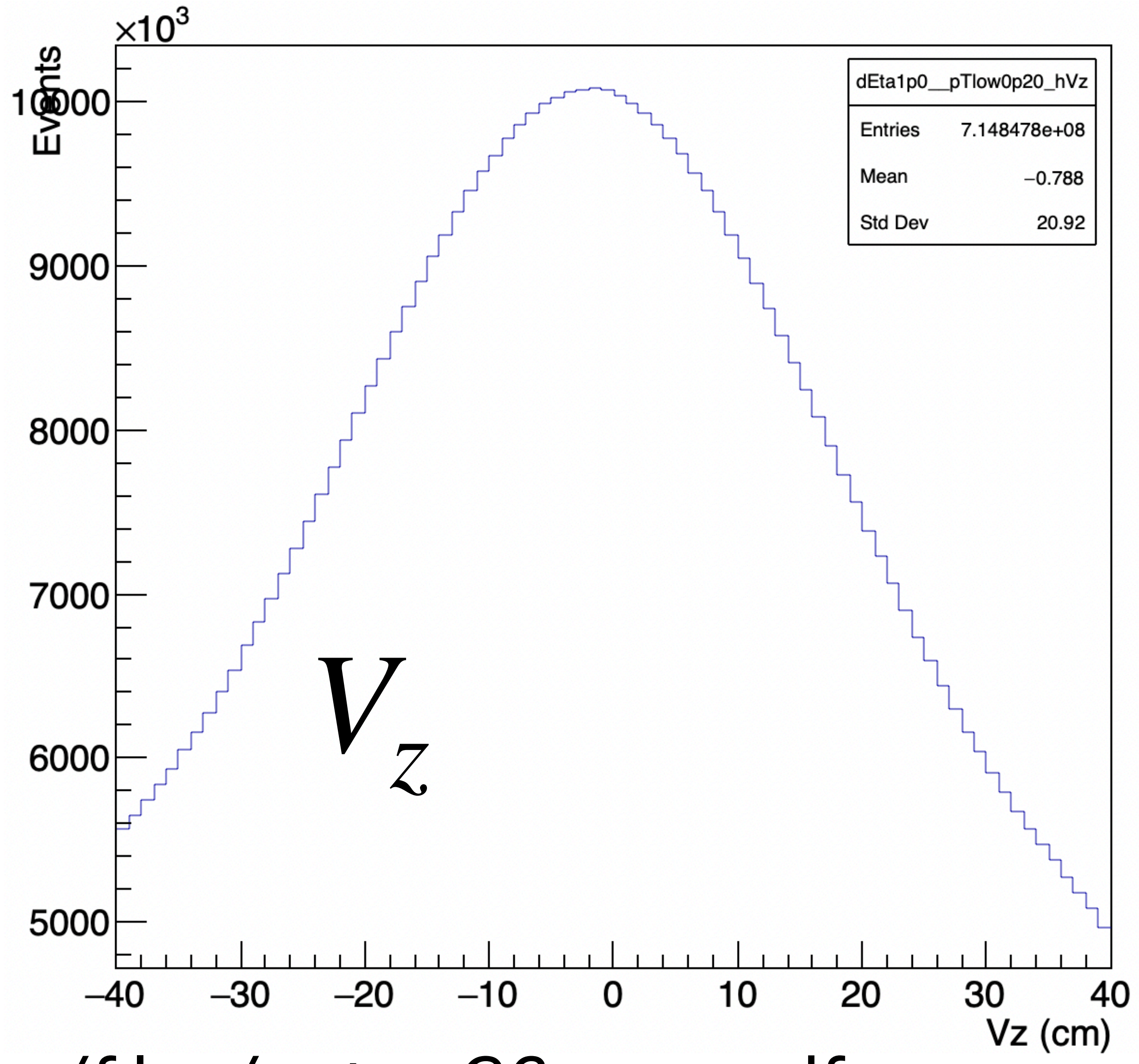
Event
- $!(V_x = 0 \ \ \&\& \ \ V_y = 0 \ \ \&\& \ \ V_z = 0)$
- $|V_z| < 50$ cm
- $|V_r| < 2$ cm

Track
- Primaries
- Global DCA < 2.0 cm
- $p_T \geq 0.20$ GeV
- Nhitsfit ≥ 20
- Nhitsfit/NhitsMax ≥ 0.52









- https://drupal.star.bnl.gov/STAR/system/files/netp_C6_ana.pdf
- https://drupal.star.bnl.gov/STAR/system/files/NPE_v2_5427_note_Jan13.pdf

Au + Au $\sqrt{s_{NN}}$ = **27 GeV**

Dataset

Run 18

- Triggers: 6100X1 (X = 0:5)
- Production tag: P19ie
- Filetype: picoDST

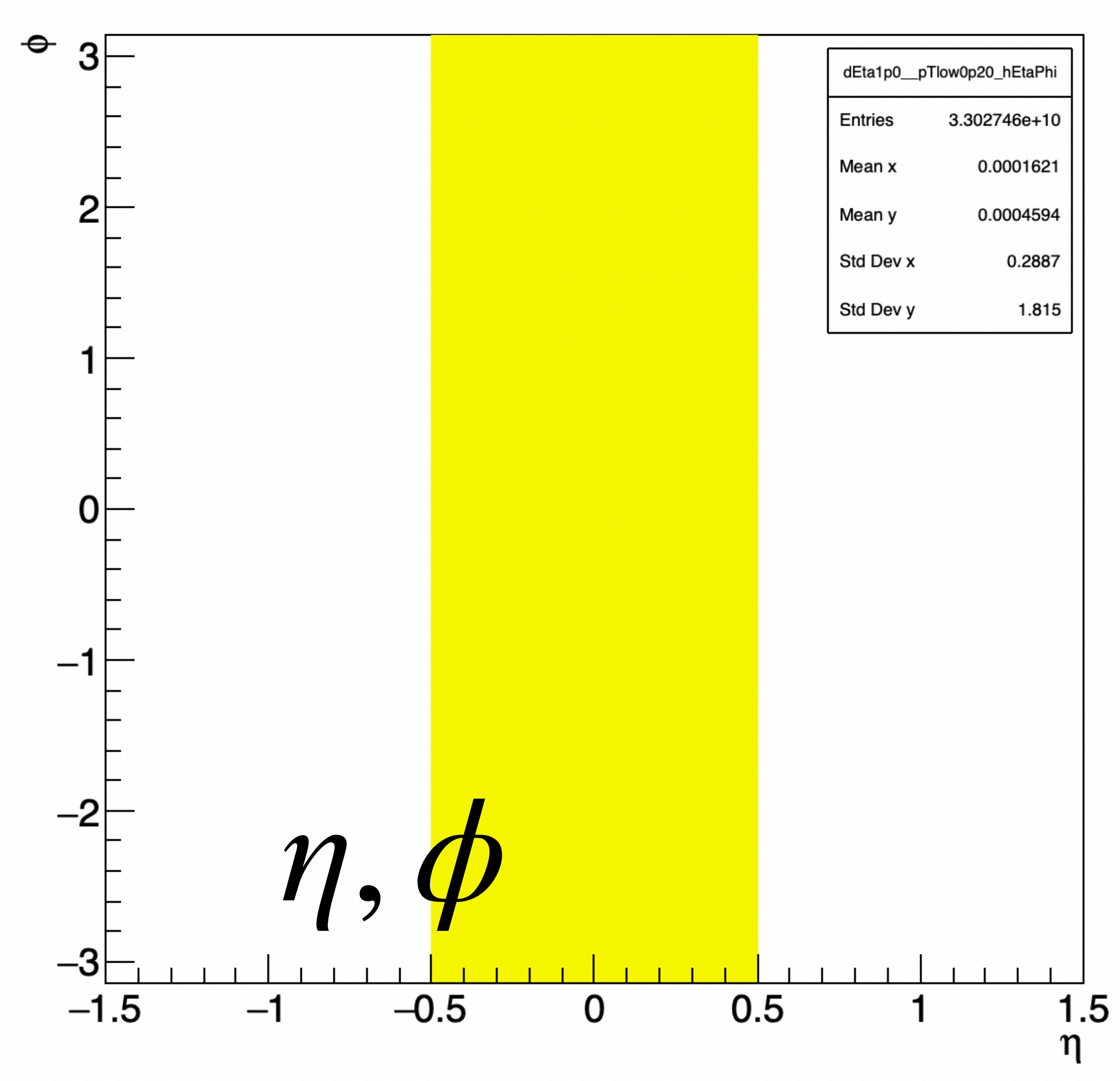
Selection criteria

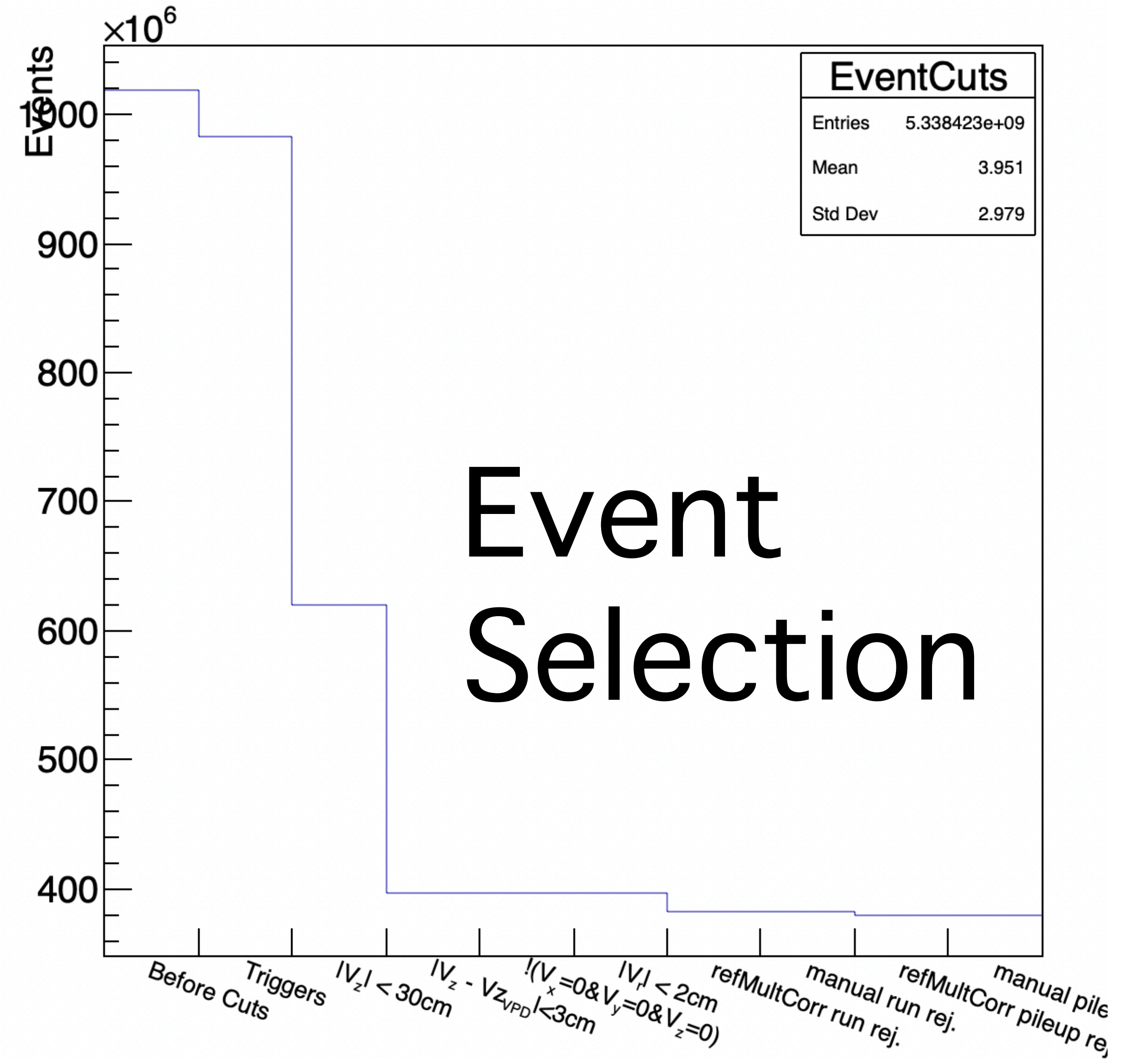
Event

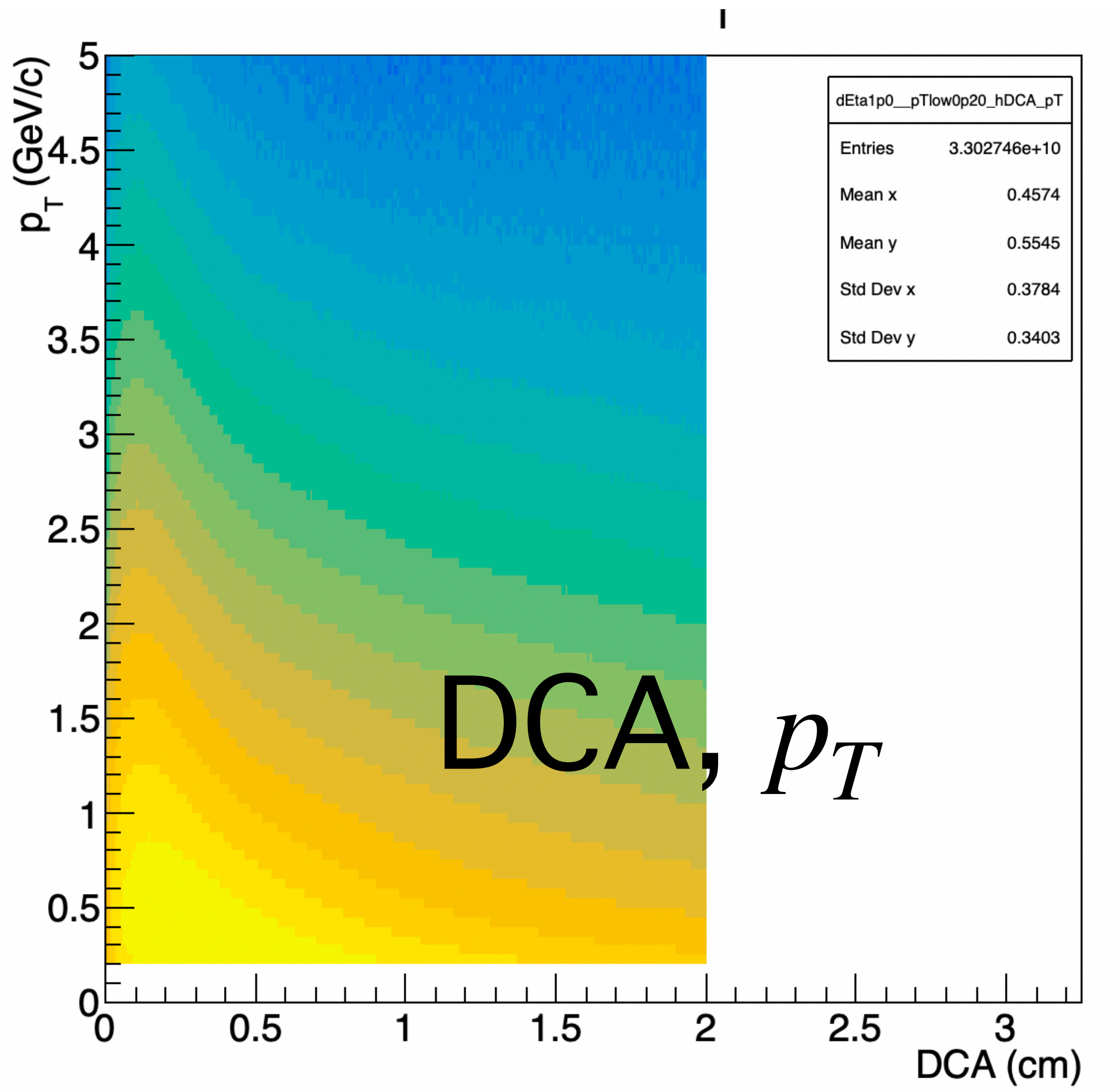
- $!(V_x = 0 \;\; \&\& \;\; V_y = 0 \;\; \&\& \;\; V_z = 0)$
- $|V_z| < 70$ cm
- $|V_r| < 2$ cm

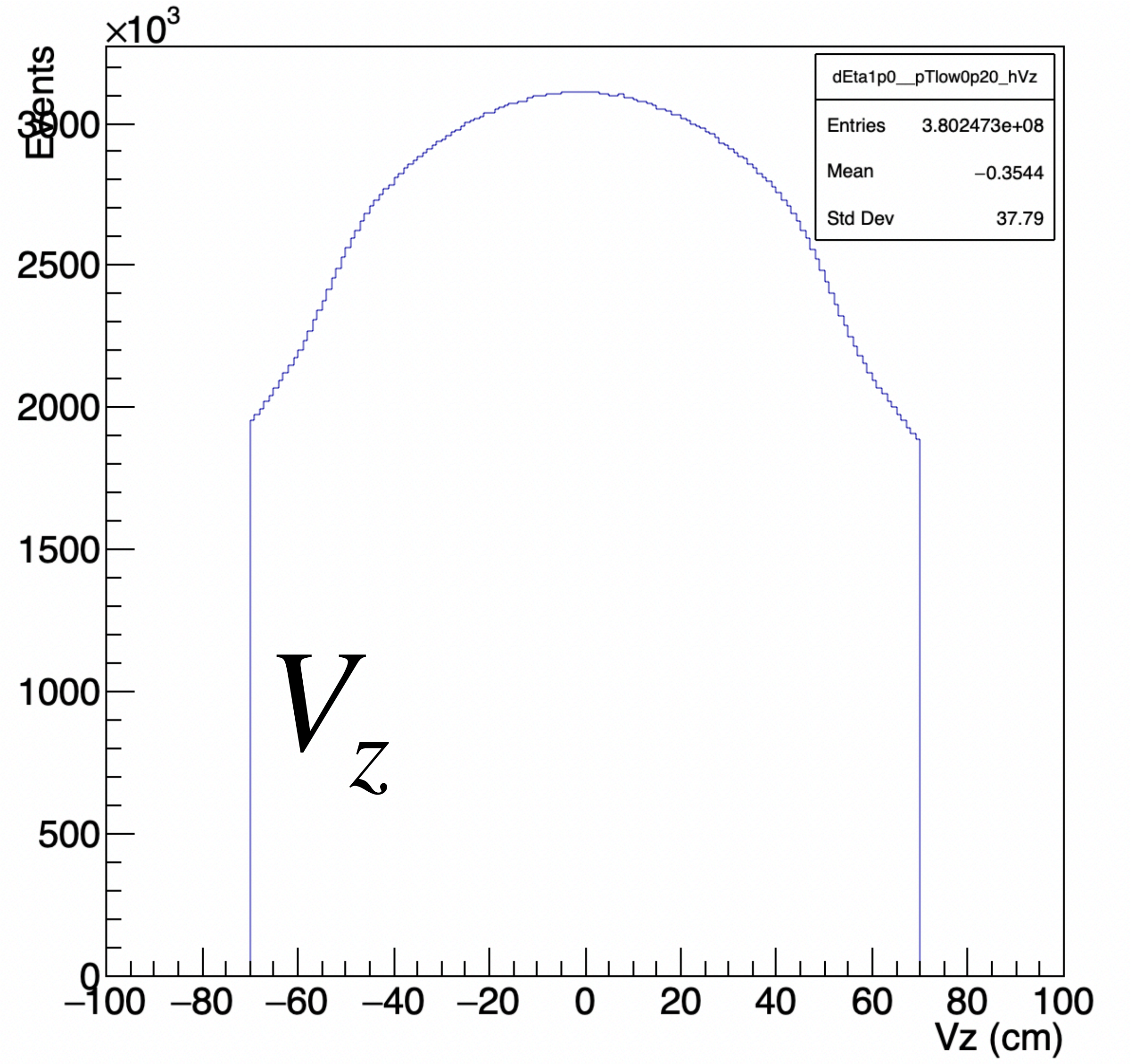
Track

- Primaries
- Global DCA < 2.0 cm
- $p_T \geq 0.20$ GeV
- Nhitsfit ≥ 20
- Nhitsfit/NhitsMax ≥ 0.52









- https://drupal.star.bnl.gov/STAR/system/files/GlobalPolariationSplitting_19_27GeV_AnalysisNote.pdf
- https://drupal.star.bnl.gov/STAR/system/files/NPE_v2_5427_note_Jan13.pdf

Previous updates

https://drupal.star.bnl.gov/STAR/system/files/cbroodo_200GeV_SOS_07_24_25.pdf (Centrality determination, extrapolating p_T spectra, selecting knee)

https://drupal.star.bnl.gov/STAR/system/files/cbroodo_200GeV_SOS_08_12_25.pdf (STAR summer collaboration meeting)

https://drupal.star.bnl.gov/STAR/system/files/cbroodo_200GeV_SOS_09_11_25.pdf (Tracking efficiency corrections, multiplicity corrections and closure test)

https://drupal.star.bnl.gov/STAR/system/files/cbroodo_200GeV_SOS_10_09_25.pdf (systematics)

https://drupal.star.bnl.gov/STAR/system/files/cbroodo_SOS_2_04_26.pdf (200GeV & BES-II)