Probing Medium Properties in Ultra-Central Collisions

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On behalf of: ALICE, ATLAS & CMS

Stony Brook University

ALICE

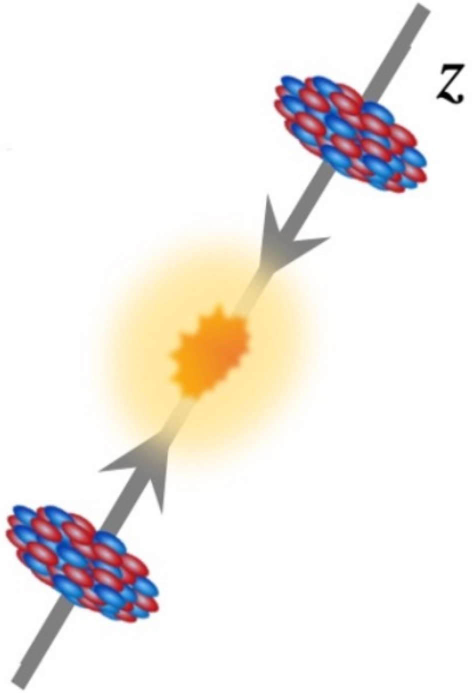
ATLAS EXPERIMENT

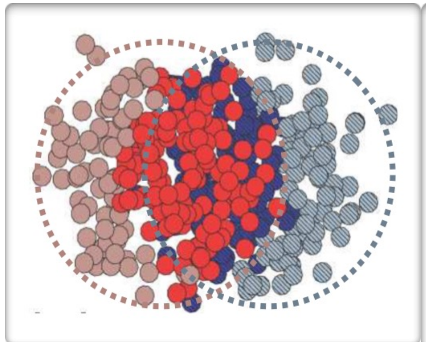
CMS

LHCP Boston 2024

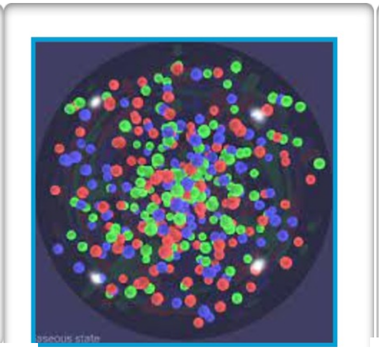
12th Edition of the Large Hadron Collider Physics Conference

Relativistic Heavy-Ion Collisions

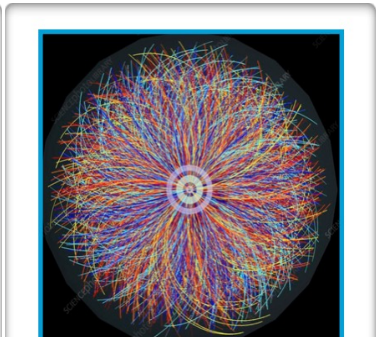




Initial State



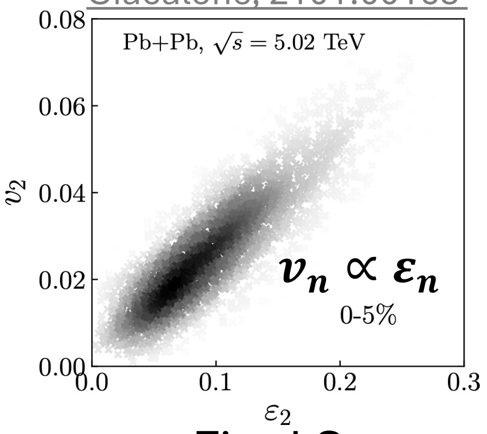
QGP



Hadronization & Free streaming

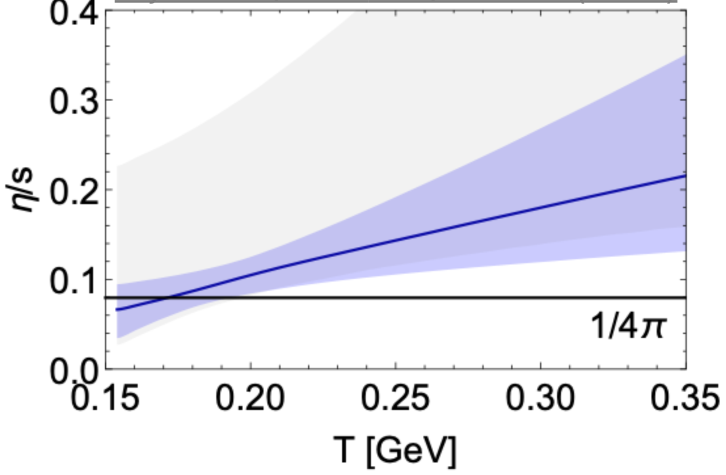
Size, Shape of Overlap

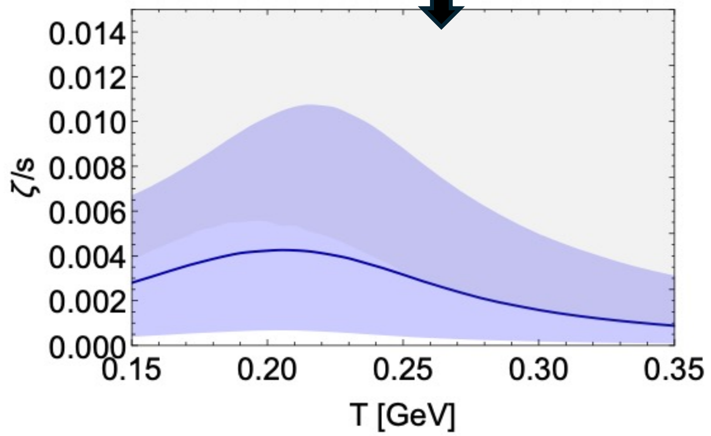
Giacalone, 2101.00168



Final State observables

Nijs et. al, PRL 126, 202301 (2021)

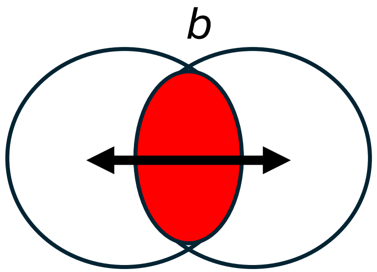




- The EoS and Transport properties of QGP are generally constrained by Bayesian analyses.

➢ Currently, characterization of initial state is the largest source of uncertainties in extracted QGP properties.

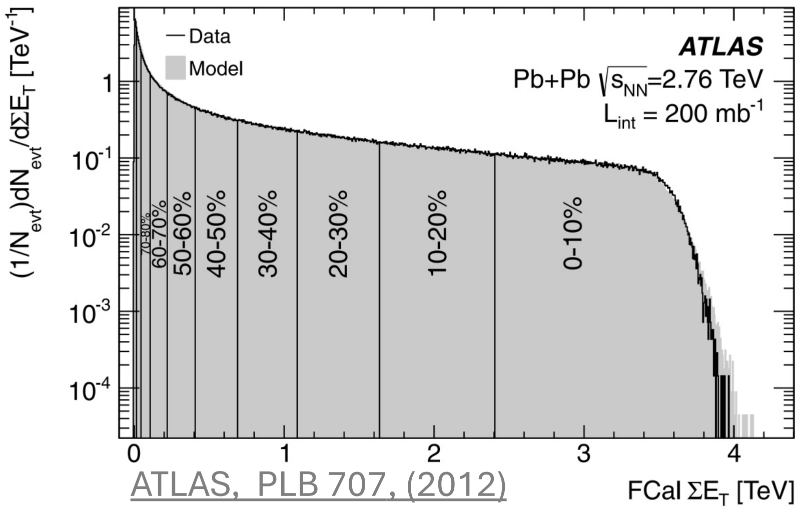
"Geometry" of Initial State Overlap Region



$R_\perp^2 \propto \langle r_\perp^2 \rangle \quad \varepsilon_n \propto \langle r_\perp^n e^{in\phi} \rangle$

"Geometry" of initial state → **Size** **Shape**

Experimentally Characterized by "Centrality" of collisions:



ATLAS, PLB 707, (2012)

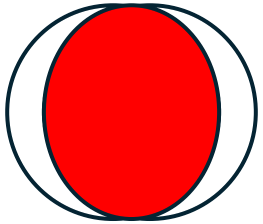
Controlled by: **1. Nuclear Deformation.**
2. Impact Parameter (*b*).
3. Quantum Fluctuations in position of nucleons.

1.

$R_\perp \uparrow, \varepsilon_2 \uparrow$

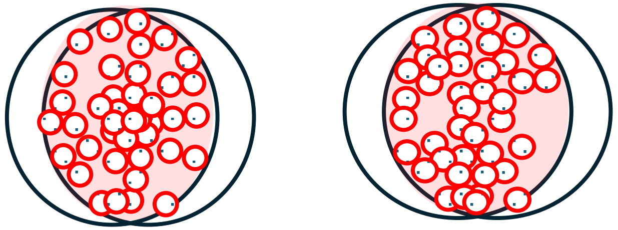
Spherical vs. Deformed Nucleus

2.



$b \downarrow \Rightarrow R_\perp \uparrow, \varepsilon_2 \downarrow$

3.



Same b , but different $R_\perp, \varepsilon_2$

➢ Most-Central collisions have $b \approx 0$, max. overlap Area ⟹ Ideal to probe factors controlling initial state

- Note: Currently no clear definition of UCC, 1% centrality is commonly used.

Effect of Nuclear Deformation on Overlap Geometry

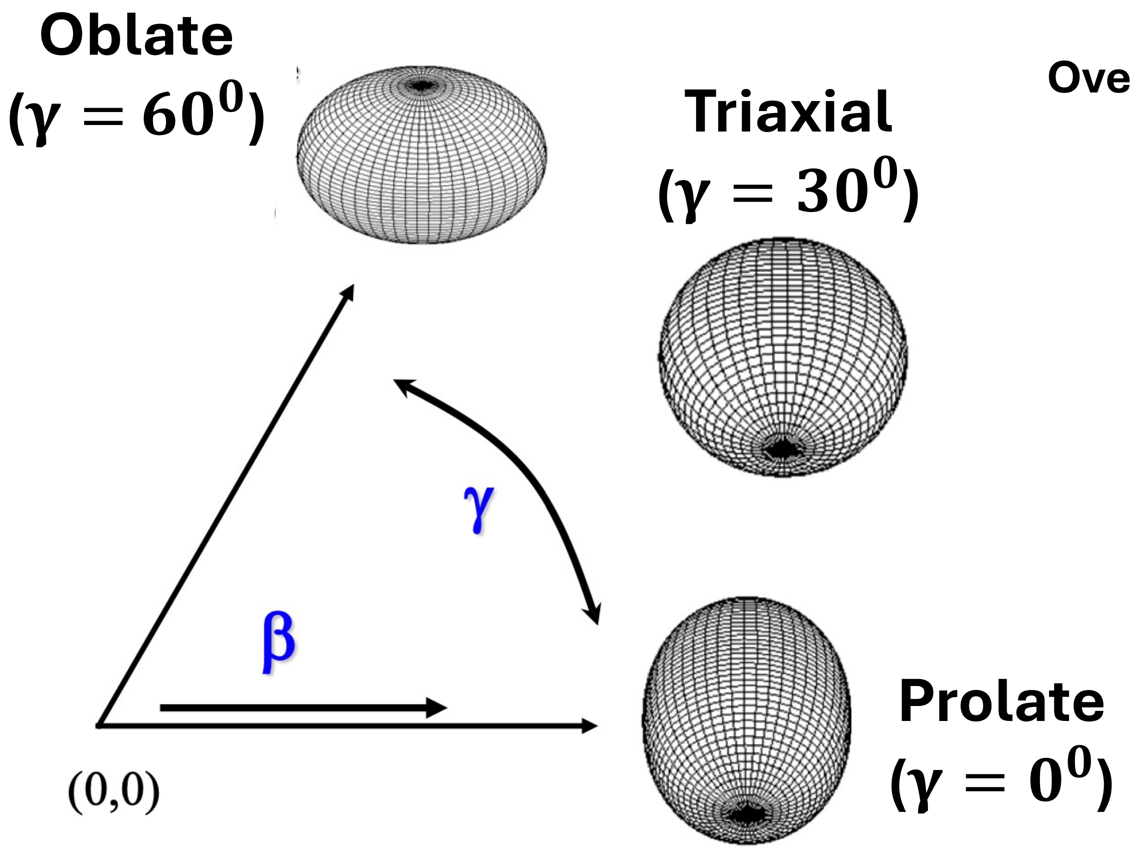
- Usually, the geometry of colliding nuclei approximated using a Woods-Saxon form:

$$\rho(r) = \frac{\rho_0}{[1 + exp(r - R(\theta, \phi))/a]}$$

$$R(\theta, \phi) = R_0(1 + \beta(\cos\gamma Y_{20}(\theta, \phi) + \sin\gamma Y_{22}(\theta, \phi)))$$

Overall Quadrupole Deformation (β)

Triaxiality ($\cos\gamma$, $\sin\gamma$)



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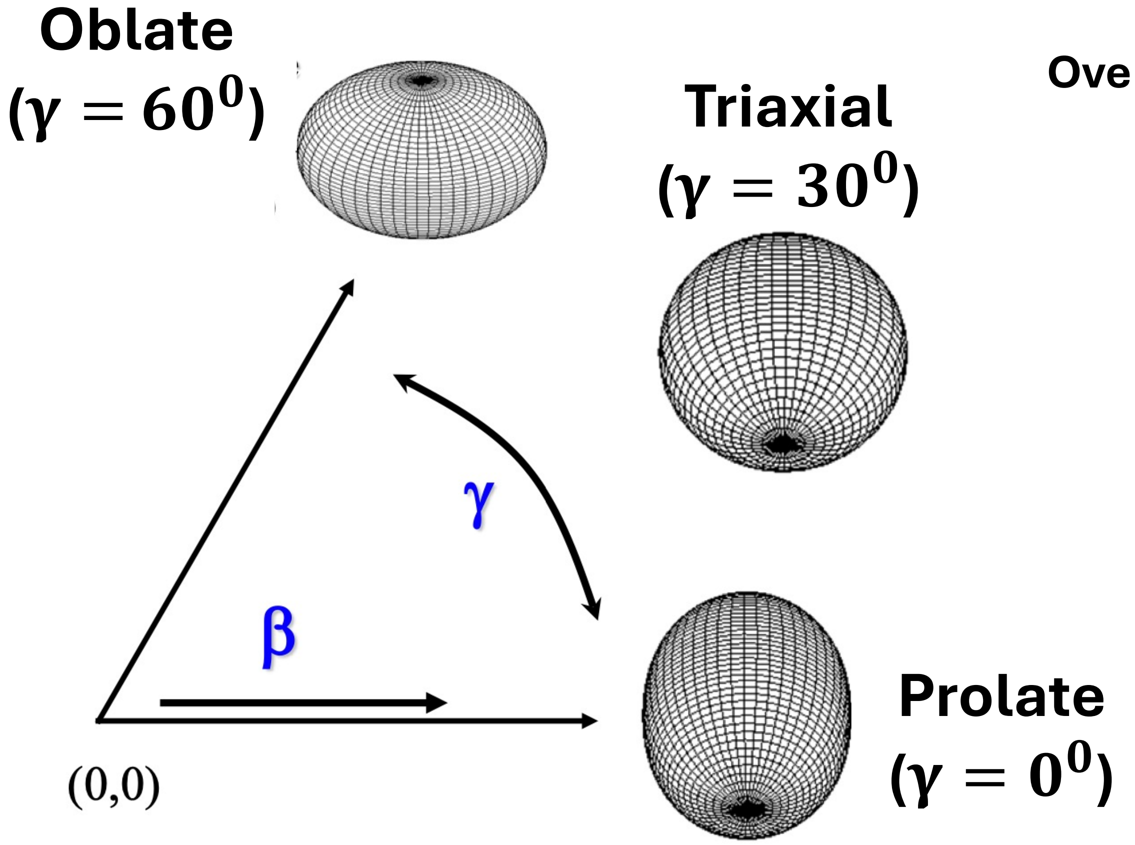
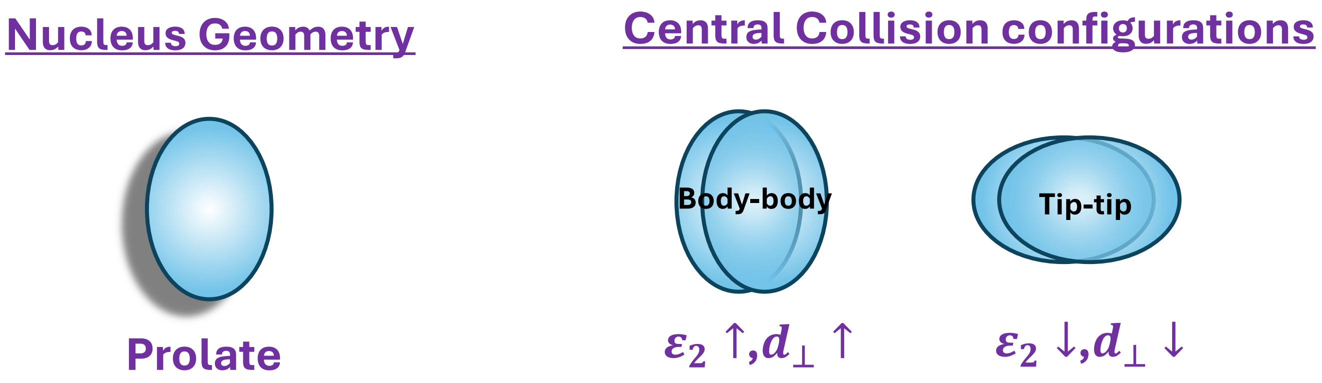
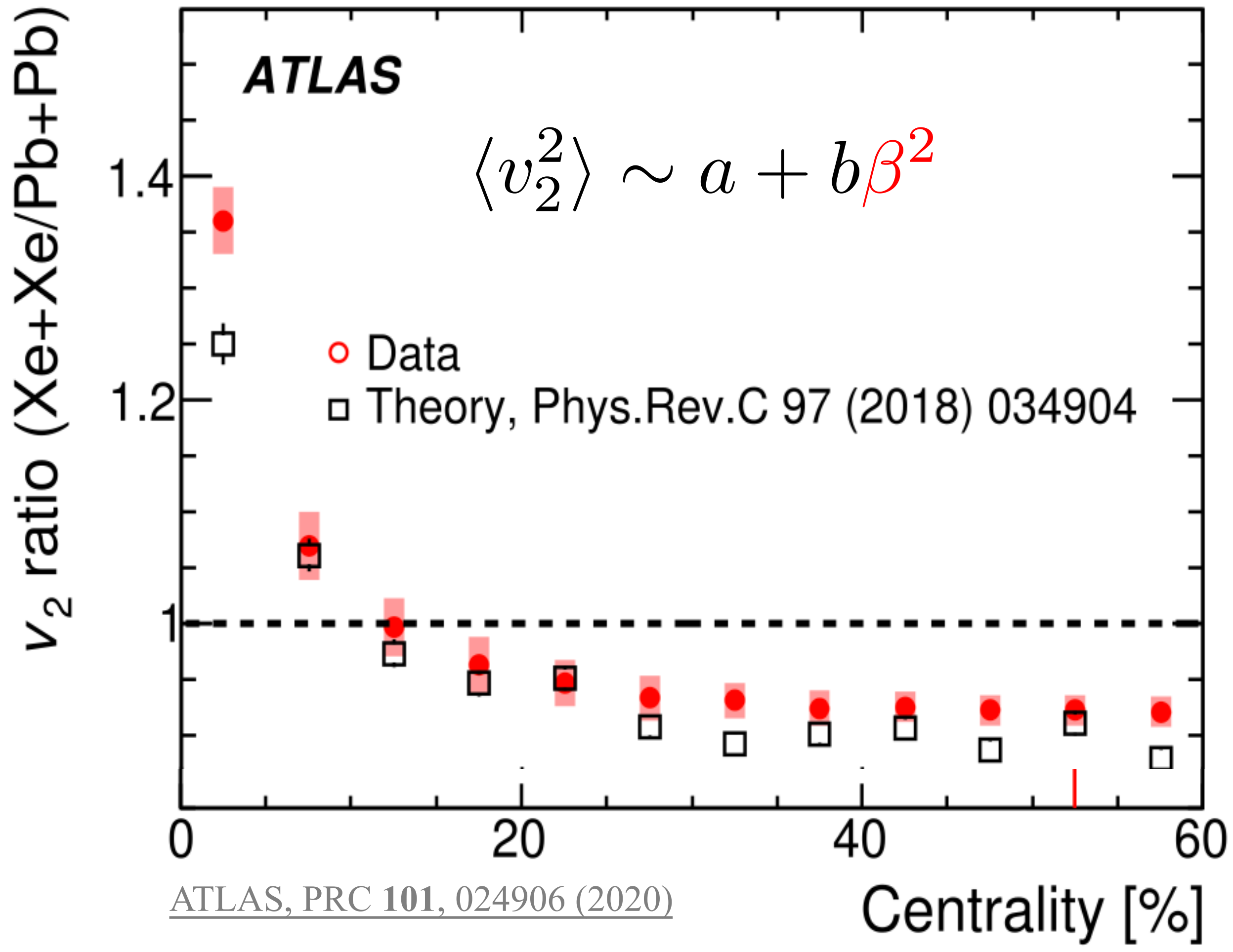
Overall Quadrupole Deformation (β) — **Triaxiality** (γ)



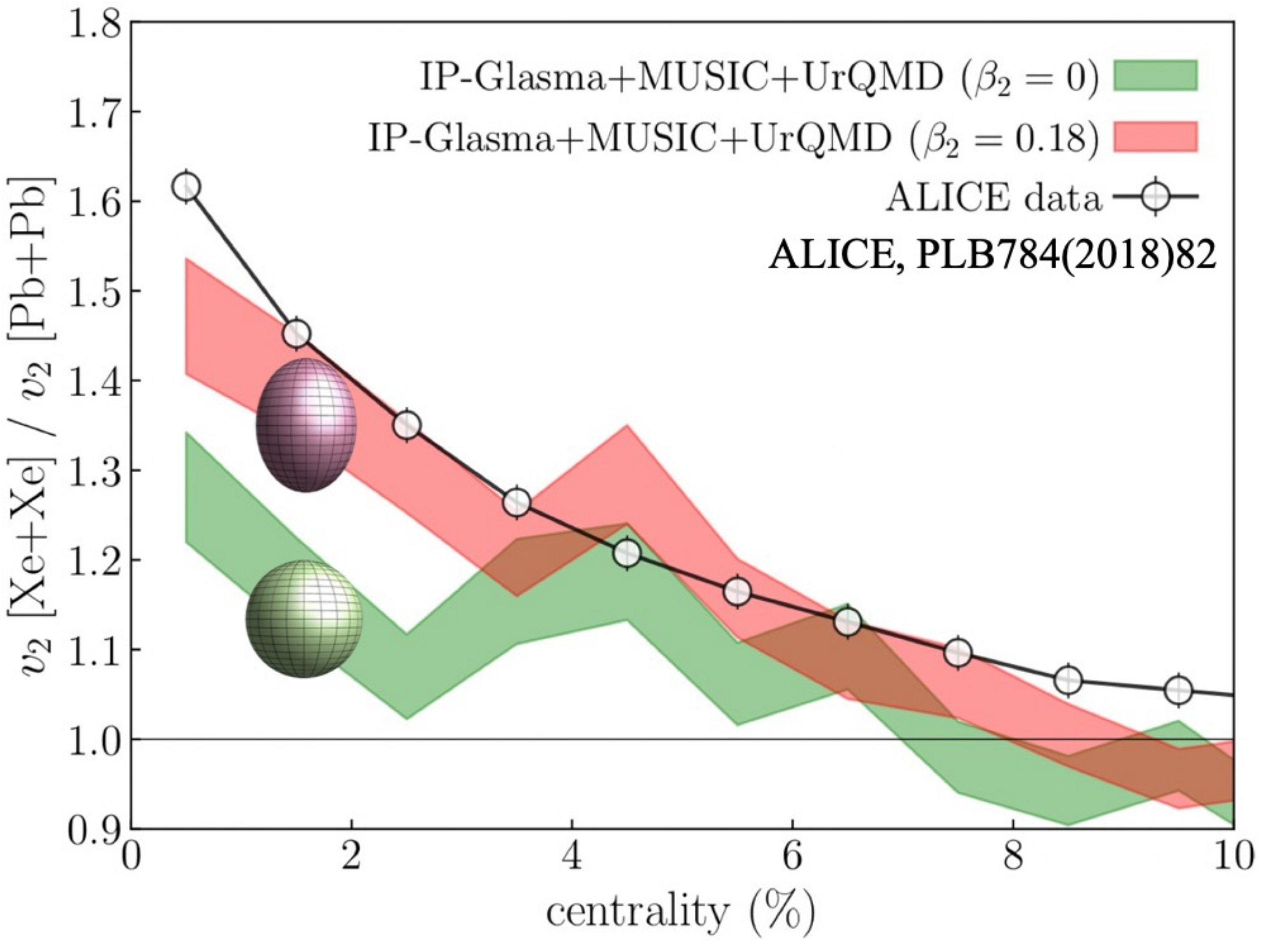


➢ Nuclear deformation expected to enhance eccentricity and size fluctuations of overlap region

Constraining β using 2-particle correlation measurements



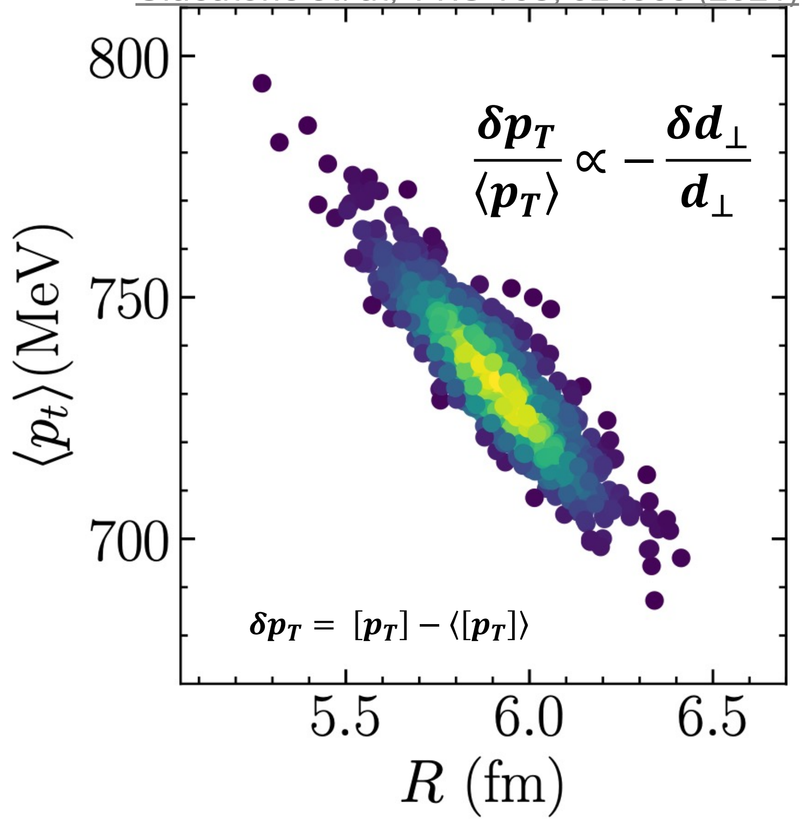
ATLAS, PRC **101**, 024906 (2020)



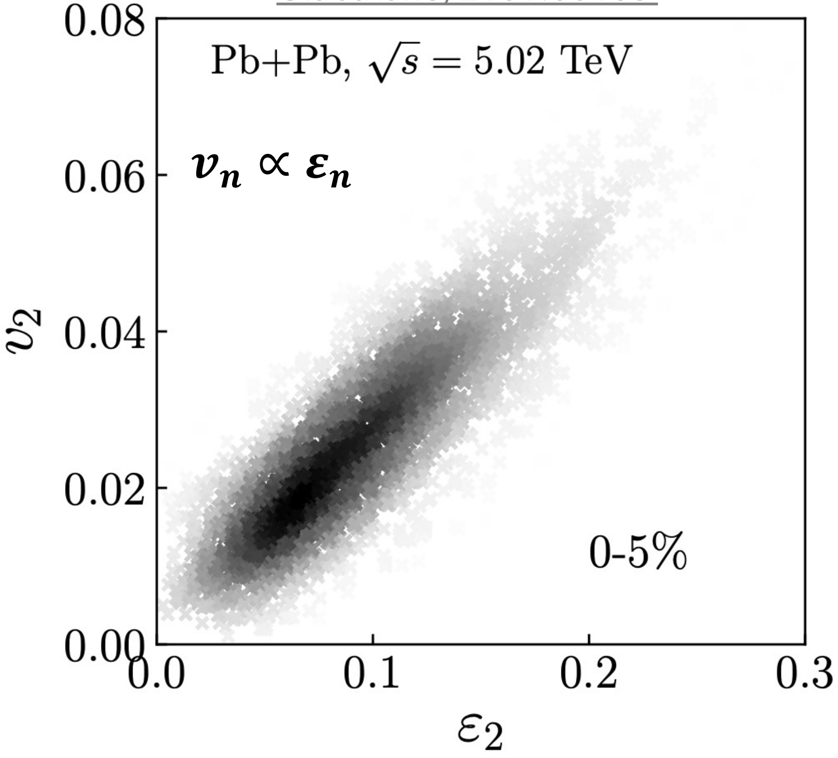
- Nuclear deformation inputs (eg: $\beta_{2,Xe} \geq 0.18$) are essential to describe experimentally measured $v_{2,Xe}$.
- In turn, nuclear deformation should be input in Bayesian analyses to constrain initial state.

Constraining Triaxiality (γ) using Heavy-Ion Collisions

Giacalone et. al, PRC 103, 024909 (2021)



Giacalone, 2101.00168



$\varepsilon_n - d_\perp$ Correlation $\Leftrightarrow$ $v_n - [p_T]$ Correlation (ρ_n):

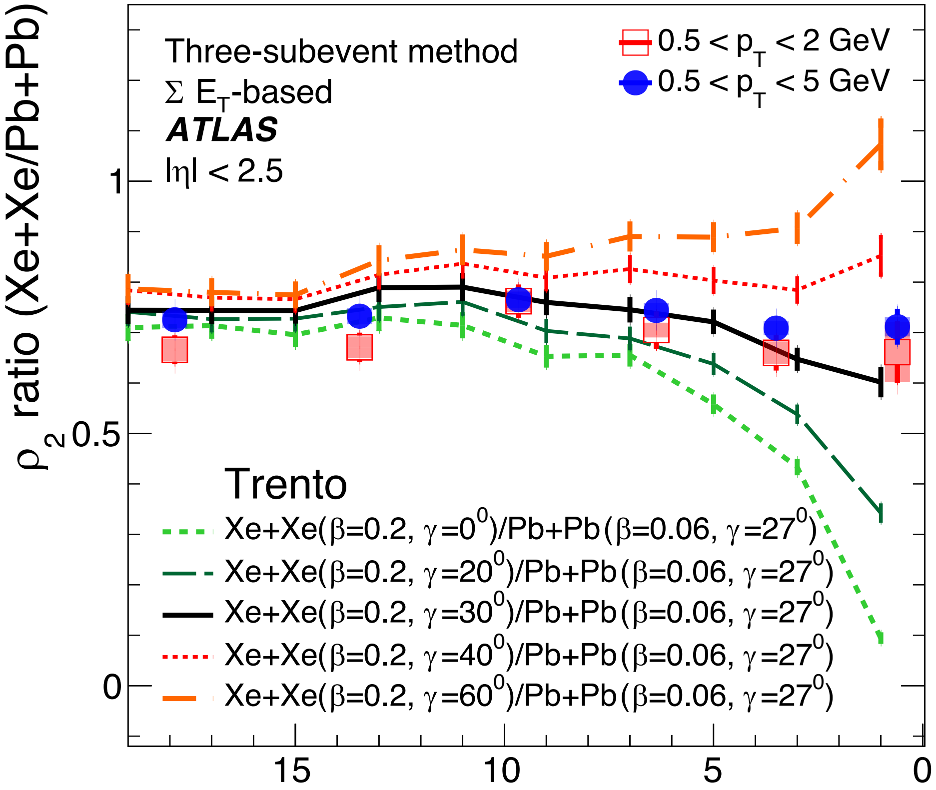
$$\rho(v_n^2, [p_T]) = \frac{cov(v_n^2, [p_T])}{\sqrt{var(v_n^2\{2\})_{dyn} c_k}}$$

3-particle Correlation

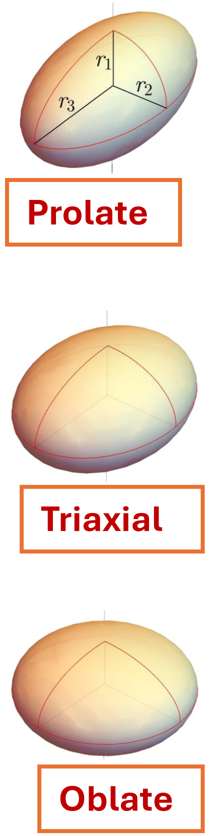
"Shape-Size Correlation"

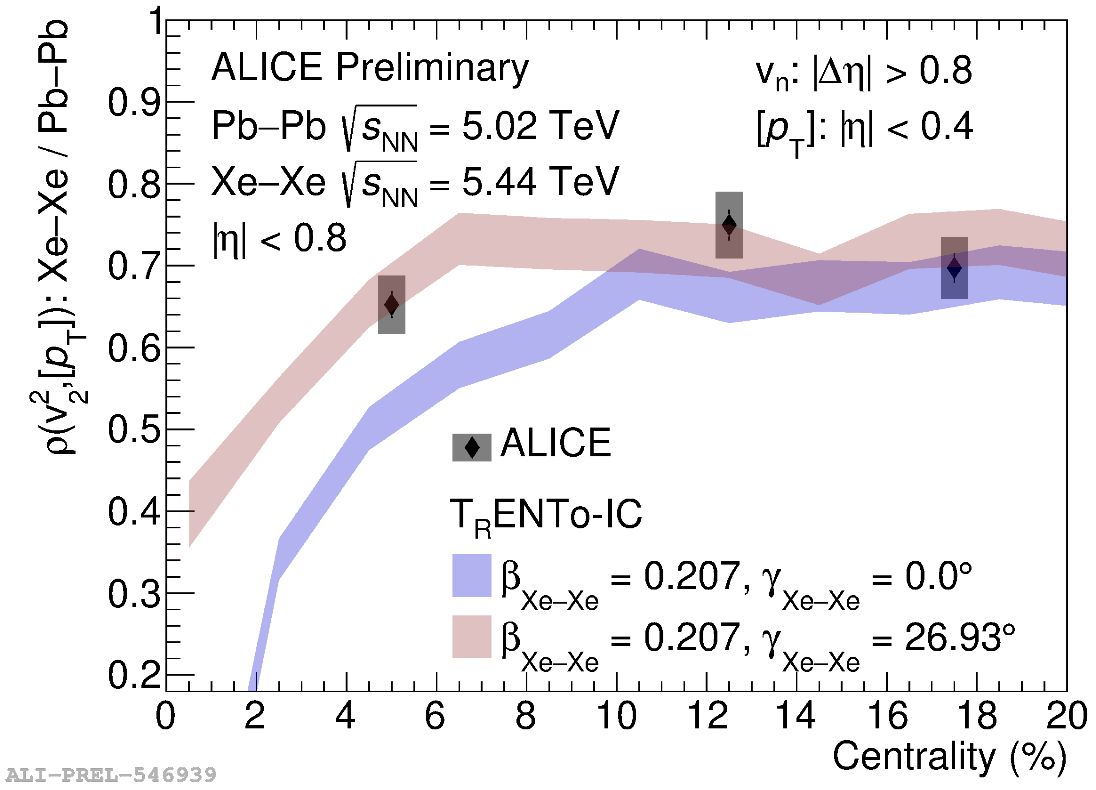
- ρ_n provides important constraint on origin of final state as a response to initial state fluctuations.

Constraining γ Using ρ_n Measurements



ATLAS, PRC 107, 054910 (2023)
Bally et.al, PRL 128, 082301 (2022)





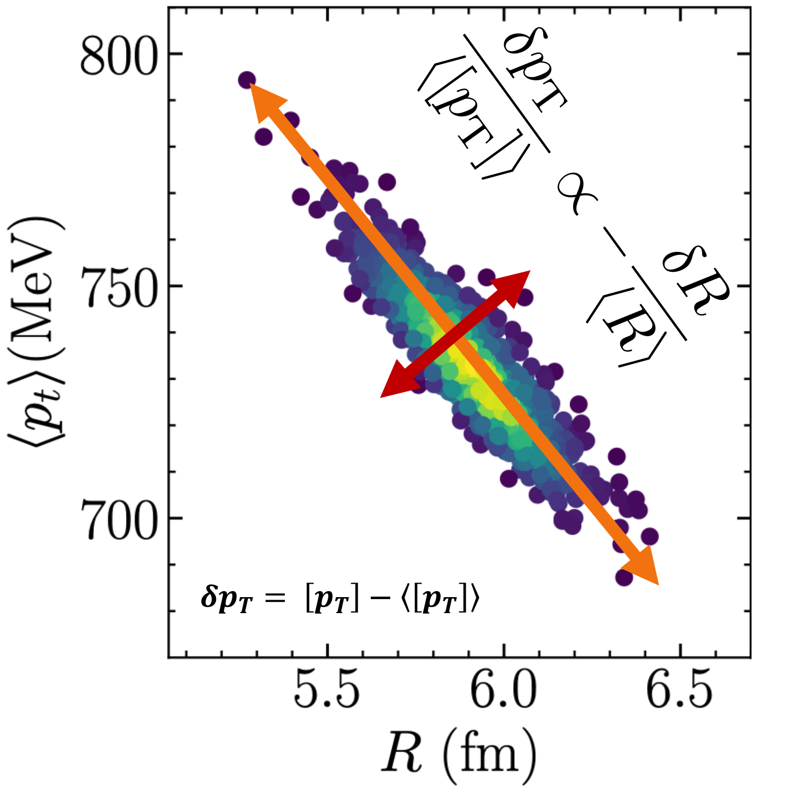
$$\langle v_2^2 \delta p_T \rangle \sim a - b\langle \beta^3 \cos(3\gamma)\rangle$$

- ➢ **Pb corresponds to $\beta \sim 0.06$ and $\gamma \sim 27^0$** ***(near spherical)*** **;**
  Xe corresponds to $\beta \sim 0.21$ and $\gamma \sim 27^0$ ***(highly deformed triaxial nucleus).***
- ➢ Ultra-Central heavy ion collisions provide ideal conditions to constrain Nuclear structure, which controls geometry of initial state

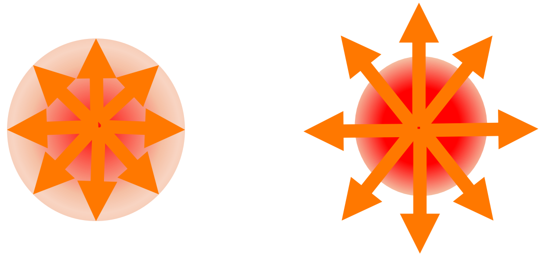
Geometric and Non-Geometric Fluctuations

- On an event-by event basis, there are two sources of fluctuations influencing final state measured $\langle [p_T] \rangle$

Giacalone et. al, PRC 103, 024909 (2021)

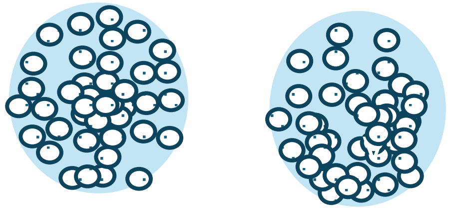


Geometric: hydrodynamic response to the size fluctuations



"Geometric Component"

Intrinsic: Fluctuations arising from Initial state, medium evolution.

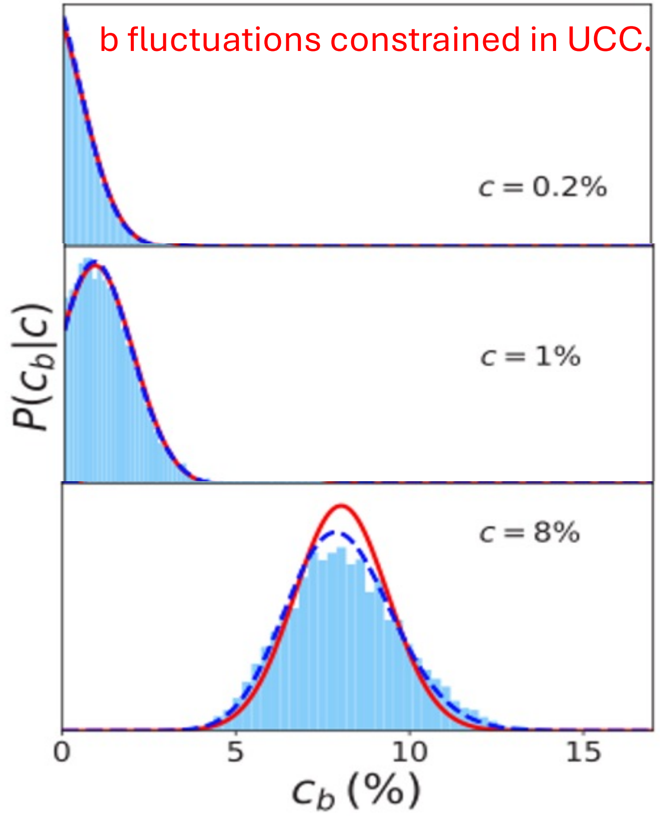


"Intrinsic Component"

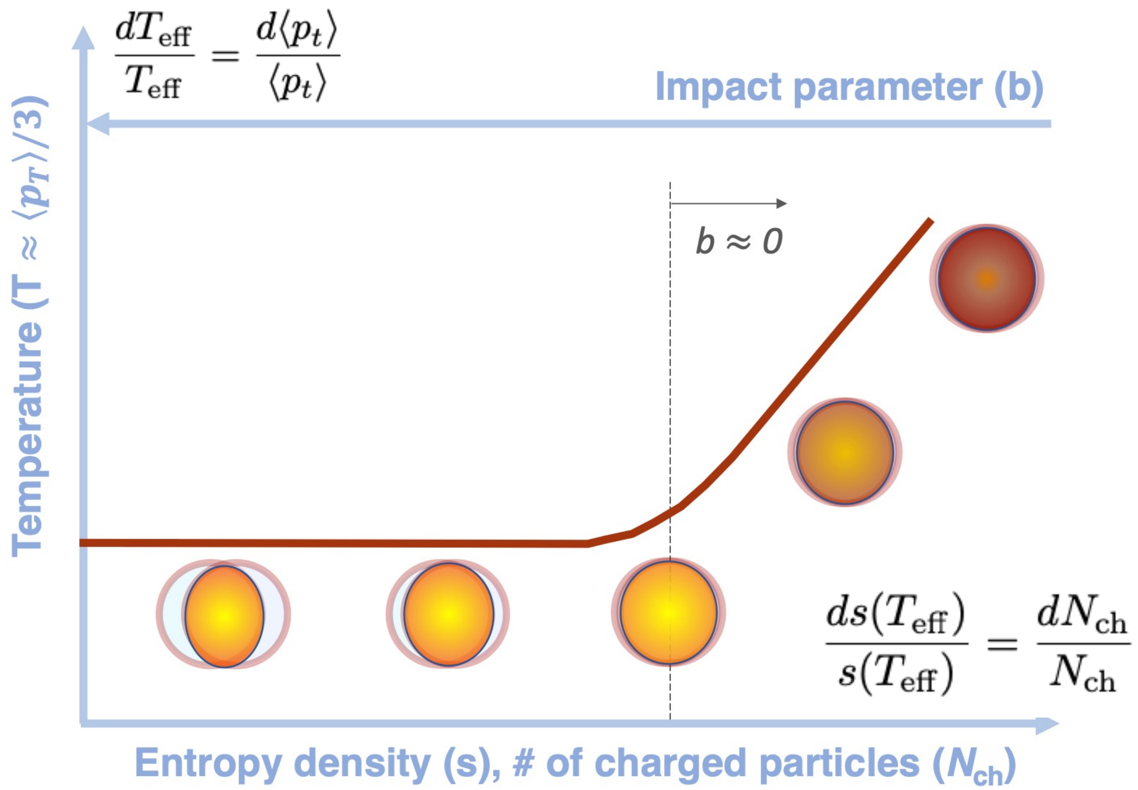
Event-by-Event $[p_T]$ Fluctuations $=$ **Geometric** $+$ **Intrinsic**

➢ Distinguishing Geometric and Intrinsic fluctuations is important to constrain both initial state and medium evolution.

Using Mean of P($[p_T]$) to Constrain c_s



Das et. al, PRC 97, 014905 (2018)

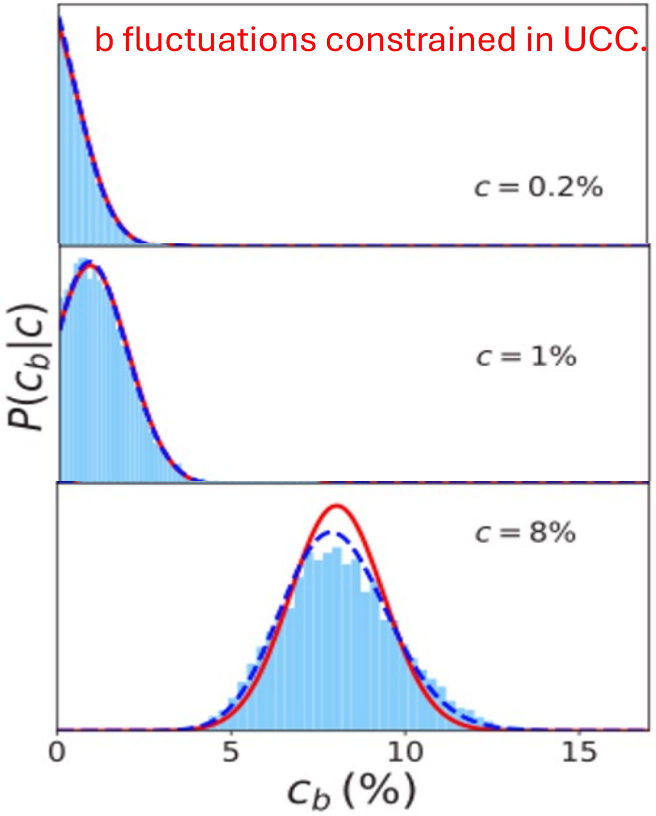


CMS, 2401.06896

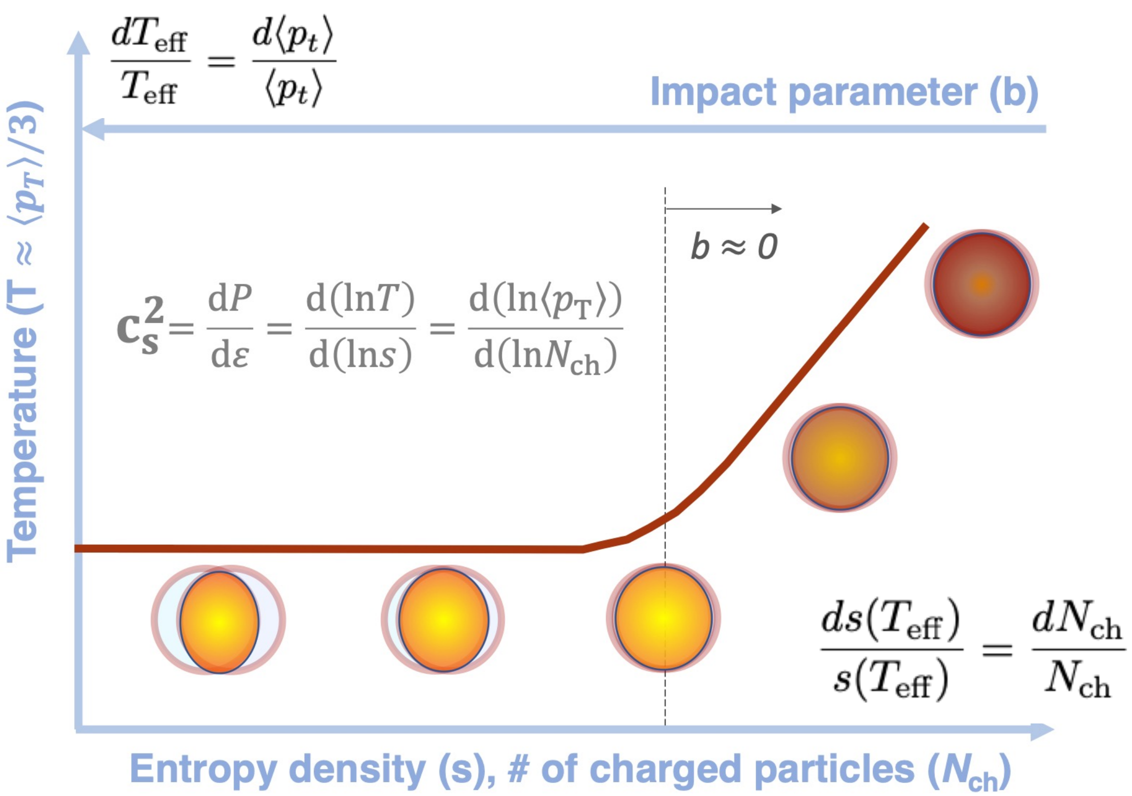
Gardim et. al, PLB 809, 135749 (2020)

- In UCC, within approximately fixed geometry (b), choosing larger N_{ch} chooses events with larger entropy density arising from intrinsic component.
- Larger entropy density within a fixed geometry leads to larger radial push or $\langle [p_T] \rangle$.

Using Mean of P([p_T]) to Constrain c_s



Das et. al, PRC 97, 014905 (2018)



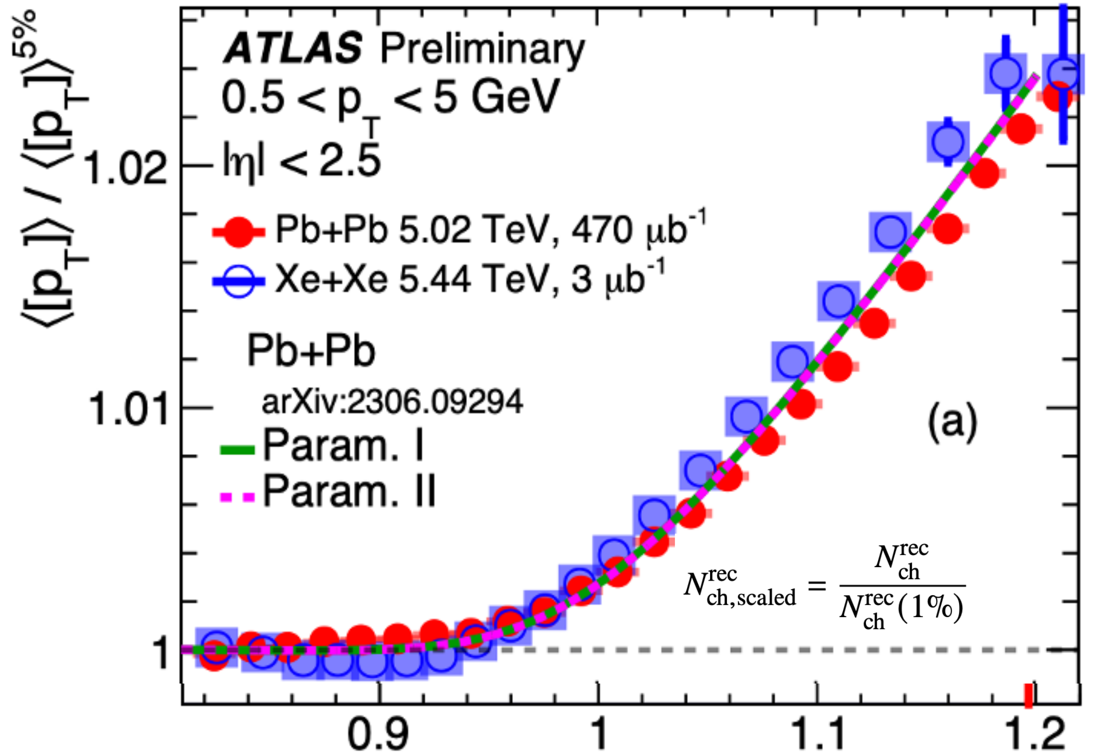
CMS, 2401.06896

Gardim et. al, PLB 809, 135749 (2020)

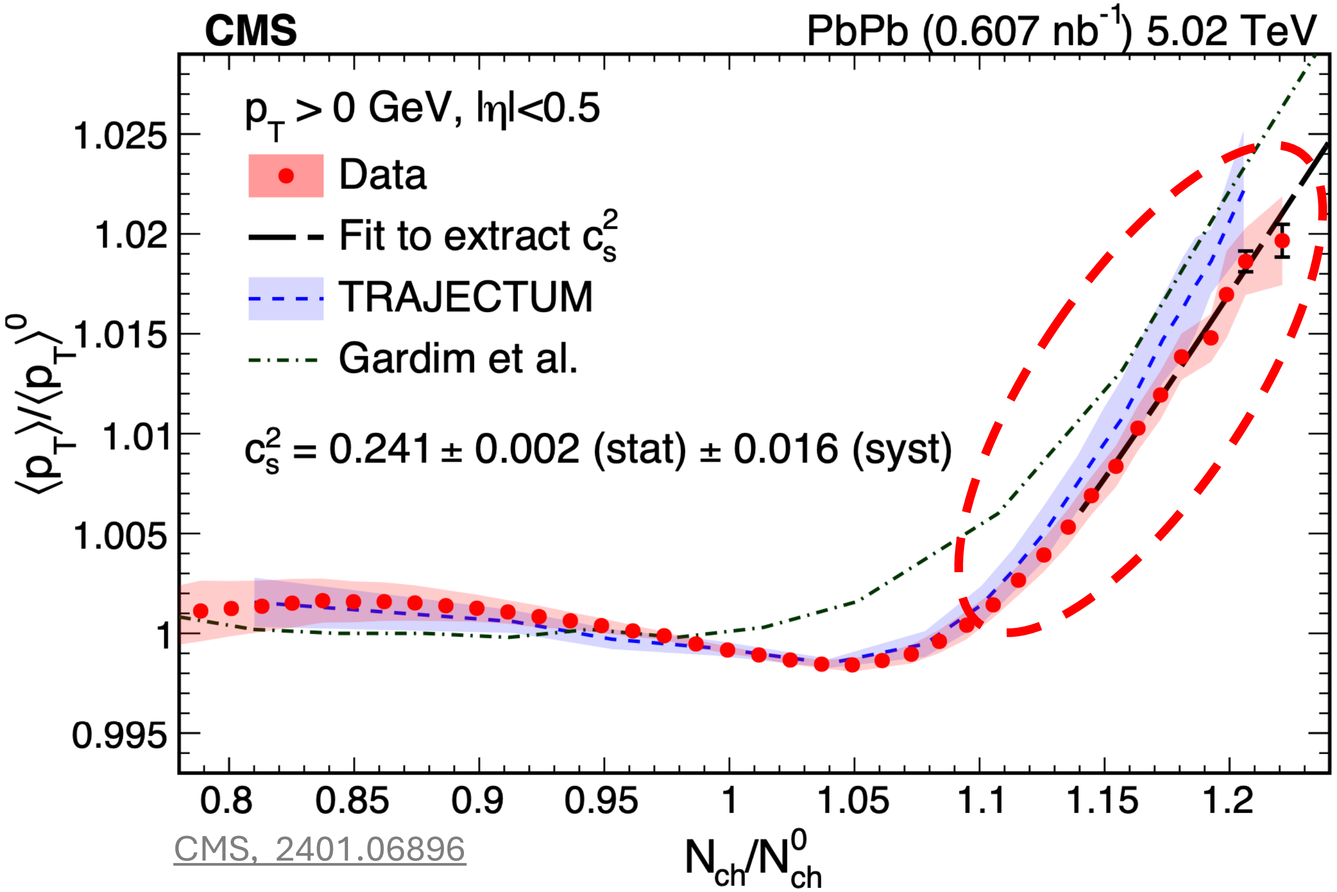
- The slope of this rise of $\langle\langle p_T\rangle\rangle$ in UCC can be related to speed of sound of QGP:

$$c_s^2 = \frac{dP}{d\epsilon} = \frac{d(lnT)}{d(lns)} = \frac{d(ln\langle p_T\rangle)}{d(lnN_{ch})}$$

Using Mean of P($[p_T]$) to Constrain c_S



ATLAS, CONF-2023-061

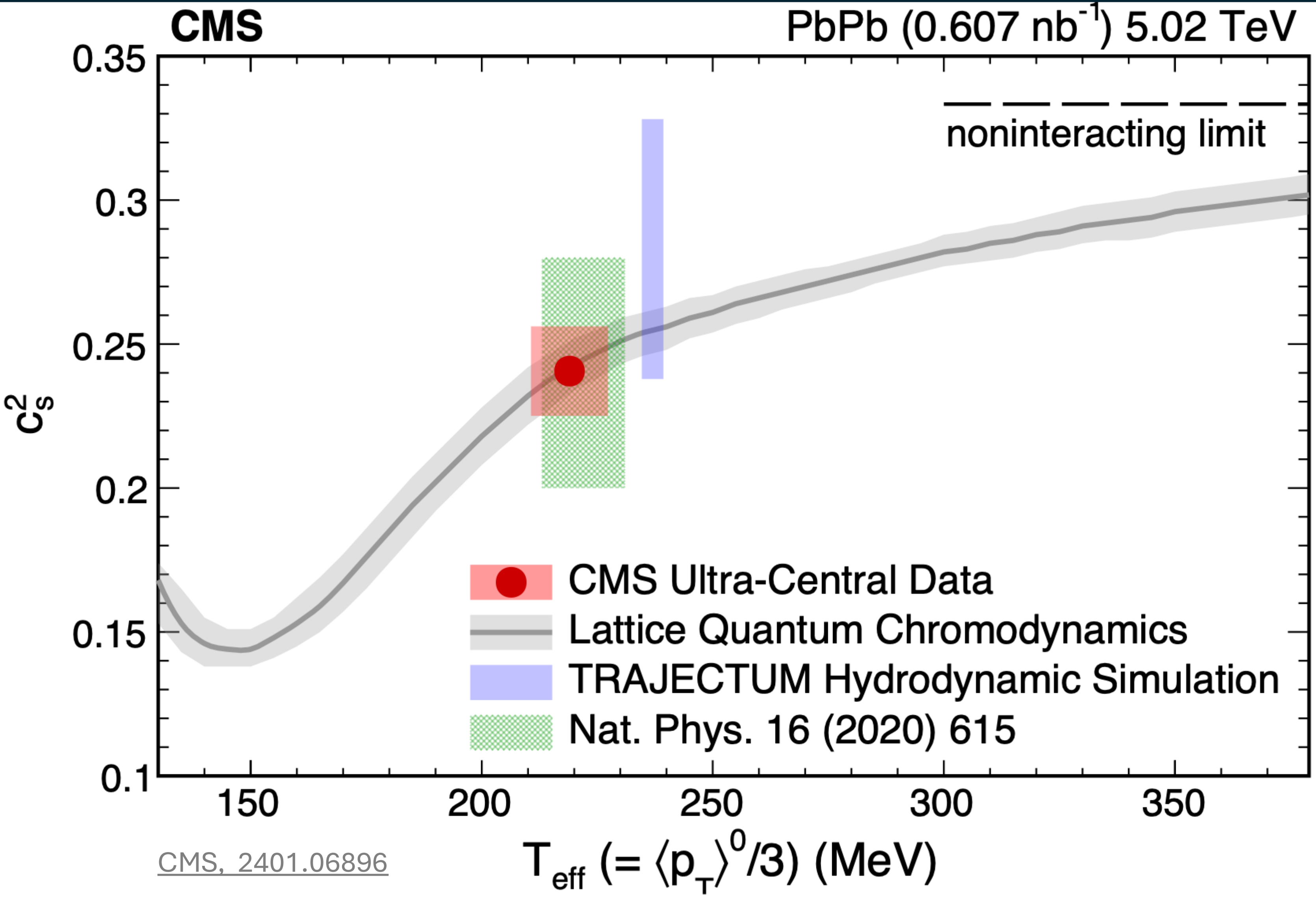


CMS, 2401.06896

- Both ATLAS and CMS have observed the steep increase in slope of $\langle[p_T]\rangle$ in UCC.
  $\Longrightarrow$Evidence of overlap area reaching its maximum and Hydro evolution of system.

- CMS extracted the slope of this rise: claimed the speed of sound of QGP, c_s^2 ≈0.241.

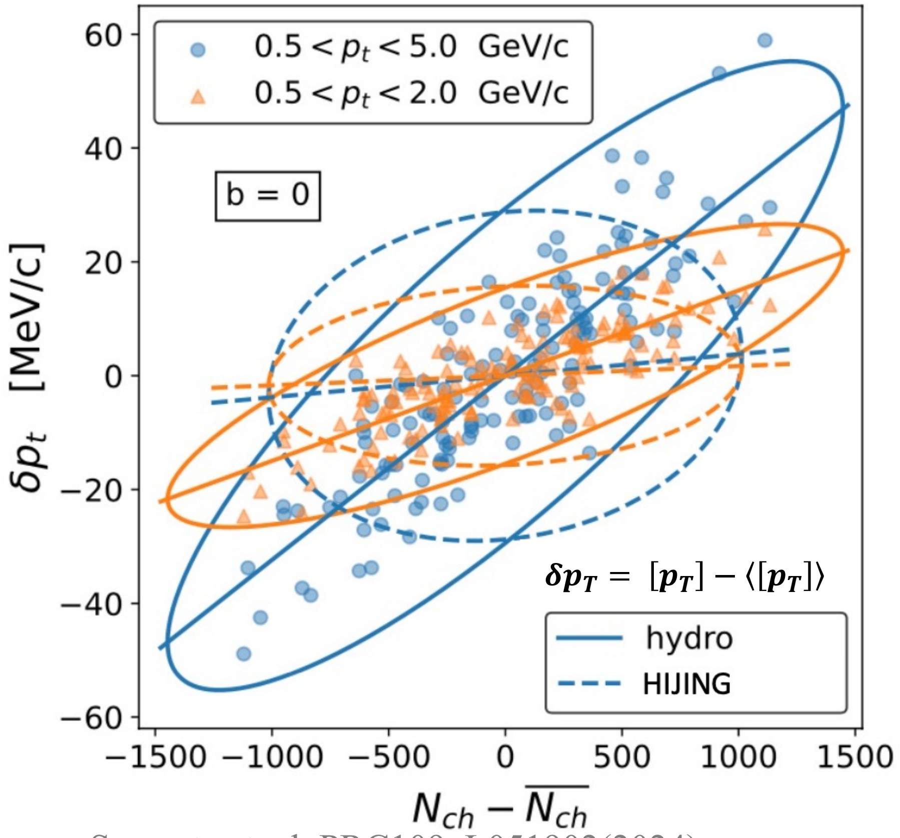
Using Mean of P($[p_T]$) to Constrain c_s



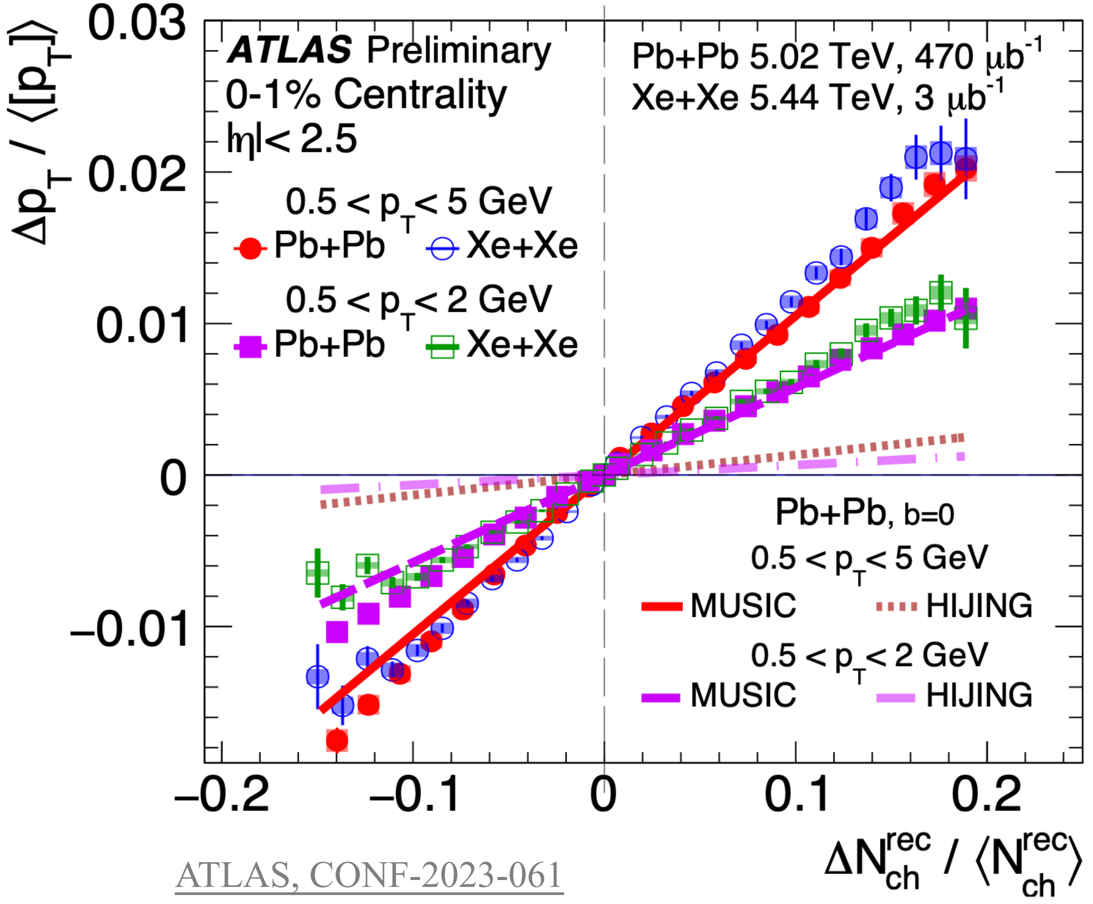
CMS, 2401.06896

- The value of c_s^2 extracted by CMS is consistent with Lattice QCD calculations at an effective temperature of about 220 MeV with small systematic error.
- UCC measurement of $\langle [p_T] \rangle$ provides direct information on c_s^2 of QGP.

Dependence of UCC Slope of $\langle[p_T]\rangle$ on Evolution Dynamics



Samanta et. al, PRC109, L051902(2024)

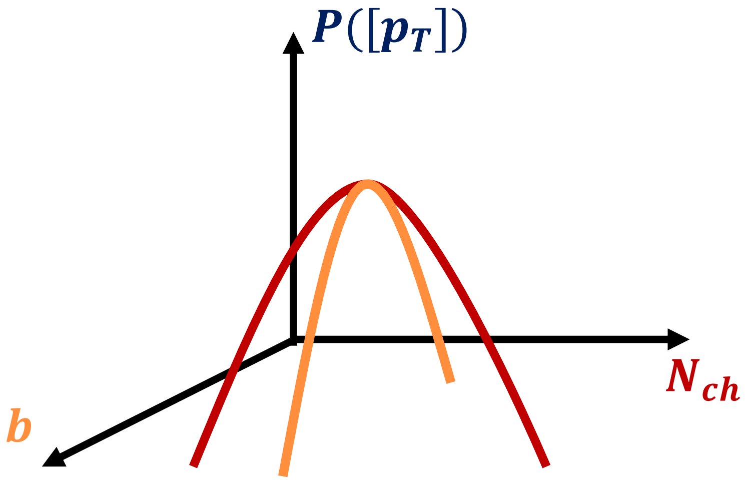


ATLAS, CONF-2023-061

- ATLAS: slope of this rise depends on the p_T-range of the particles, consistent with Hydro models.
- Models without hydro evolution or mechanisms to relate initial entropy densities to number of particles fail to describe slope.

$$c_s^2(T_{\text{eff}}) \propto \frac{d\ln(\langle[p_T]\rangle)}{d\ln(N_{ch}^{rec})} \approx \frac{\Delta p_T/\langle[p_T]\rangle}{\Delta N_{ch}^{rec}/\langle N_{ch}^{rec}\rangle}$$

Using $[p_T]$ Cumulants to Constrain Fluctuations in IS

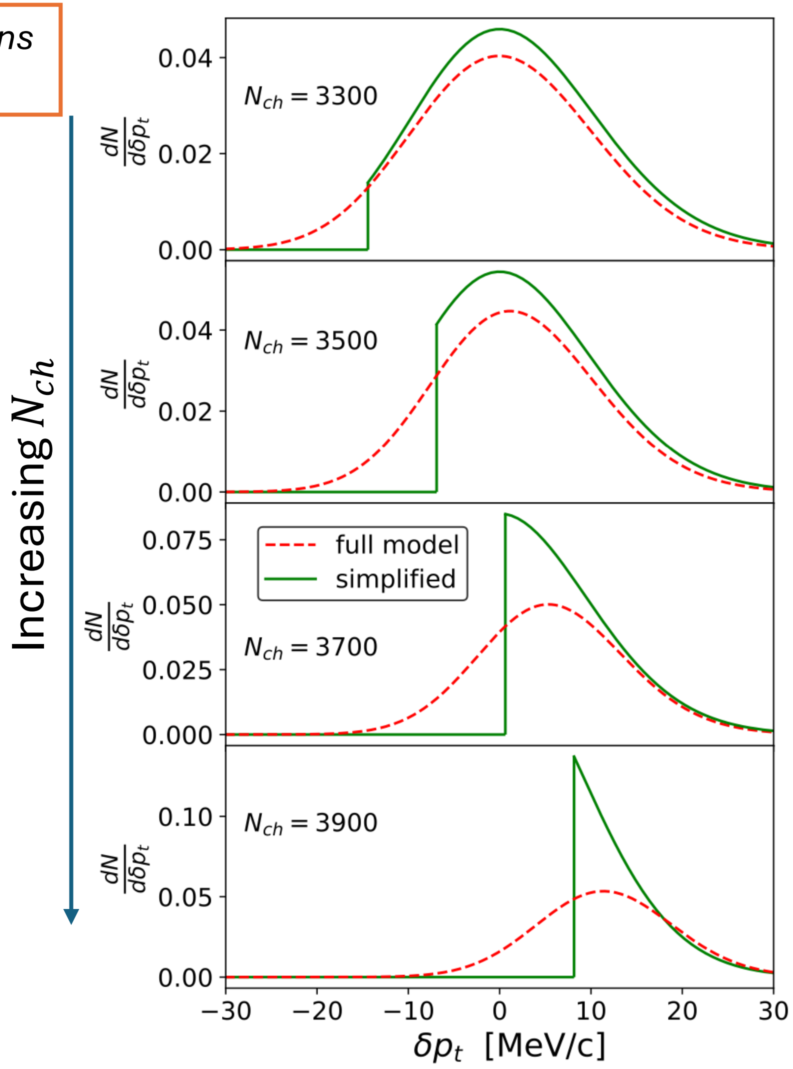


At fixed N_{ch}, b fluctuates : *Geometric*

At fixed b, N_{ch} fluctuates: *Intrinsic*

- In ultra-central collisions, b →0.
  $\Longrightarrow$ upper bound on $R \Longrightarrow$ Imposes lower bound on δp_T. $\frac{\delta p_{\mathrm{T}}}{\langle [p_{\mathrm{T}}] \rangle} \propto -\frac{\delta R}{\langle R \rangle}$

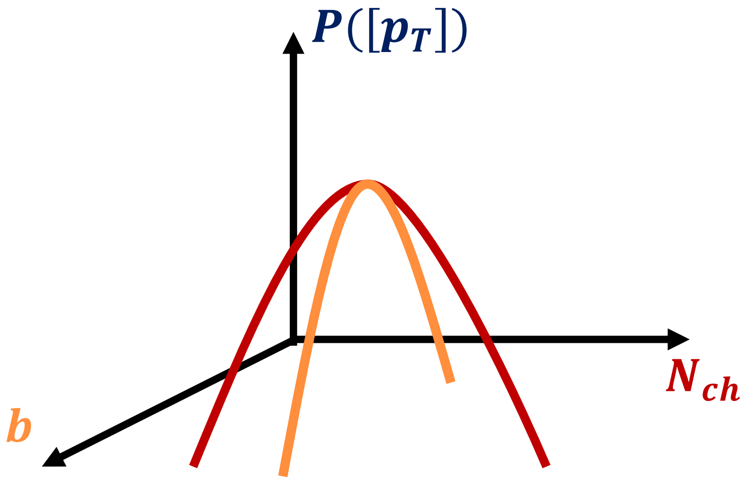
Effect of diminishing b fluctuations with increasing N_{ch}



Samanta et. al, PRC108, 024908 (2023)

Samanta et. al, PRC109, L051902(2024)

Using $[p_T]$ Cumulants to Constrain Fluctuations in IS



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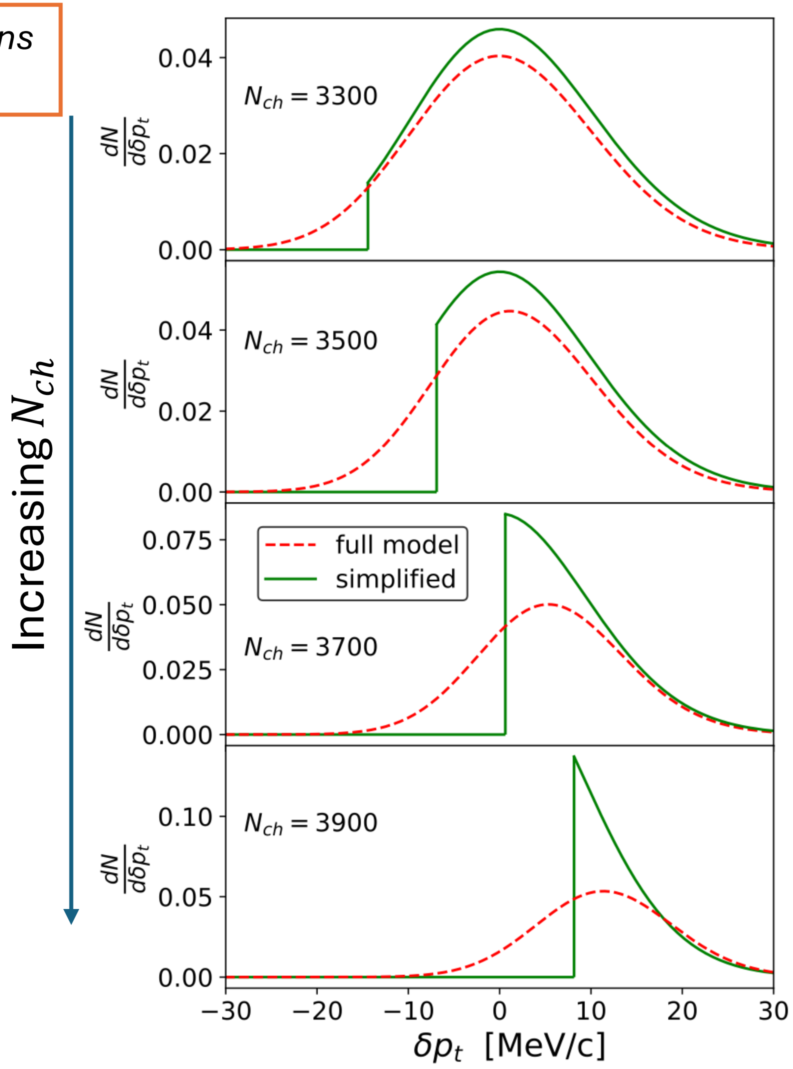

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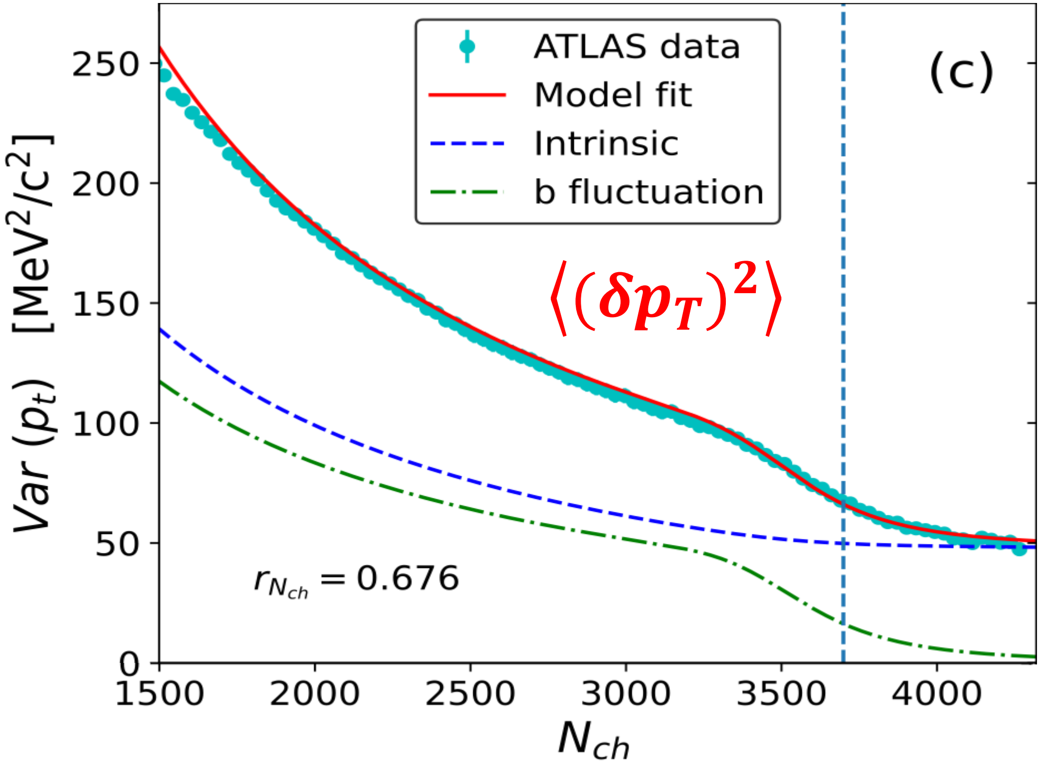
  $\Longrightarrow$ upper bound on $R \Longrightarrow$ Imposes lower bound on δp_T. $\frac{\delta p_{\mathrm{T}}}{\langle [p_{\mathrm{T}}] \rangle} \propto -\frac{\delta R}{\langle R \rangle}$

➢ With increasing N_{ch} in UCC, expect:

1. Decrease variance of $P([p_T])$,
2. Increase skewness of $P([p_T])$,
   due to constraints on geometrical fluctuations

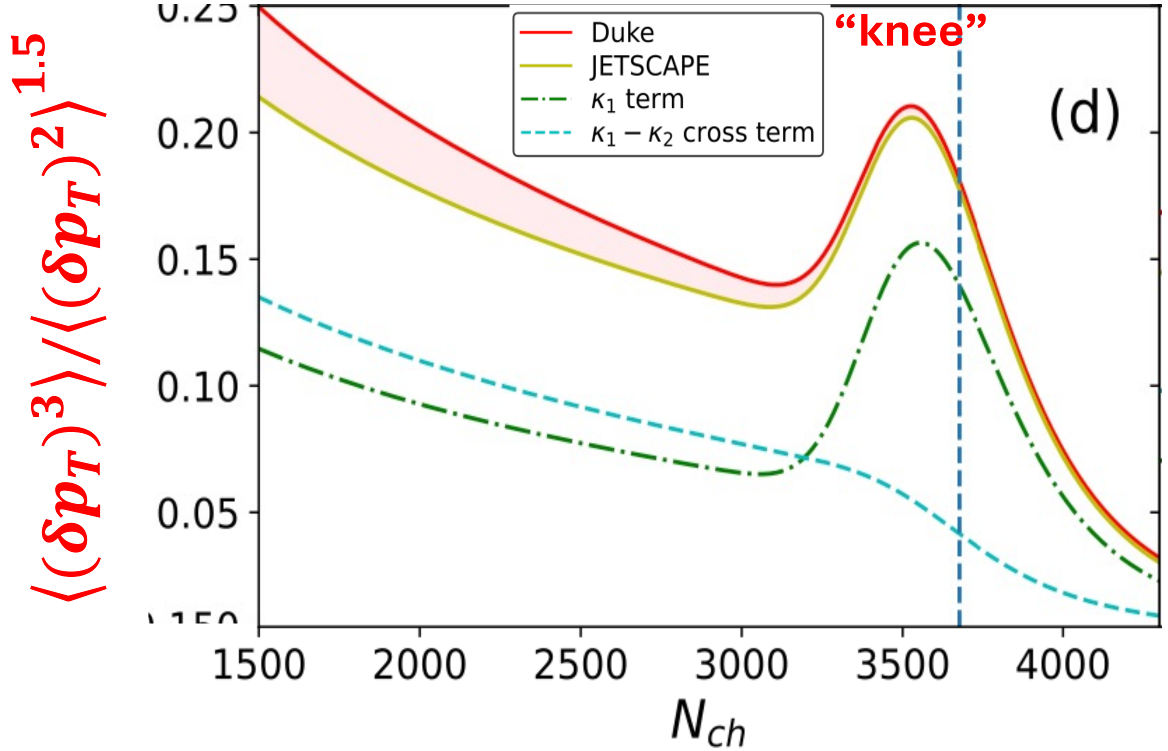
Samanta et. al, PRC108, 024908 (2023)
Samanta et. al, PRC109, L051902(2024)

Constraining Geometric and Non-Geometric fluctuations



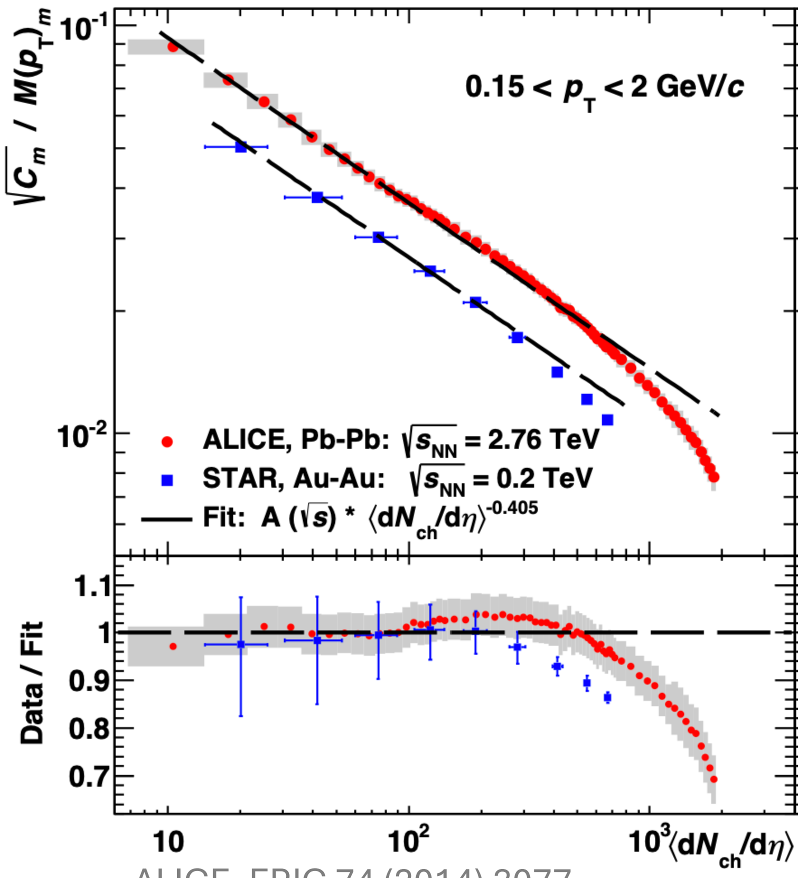
Samanta et. al, PRC108, 024908 (2023)

ATLAS, PRC 107 (2023) 054910

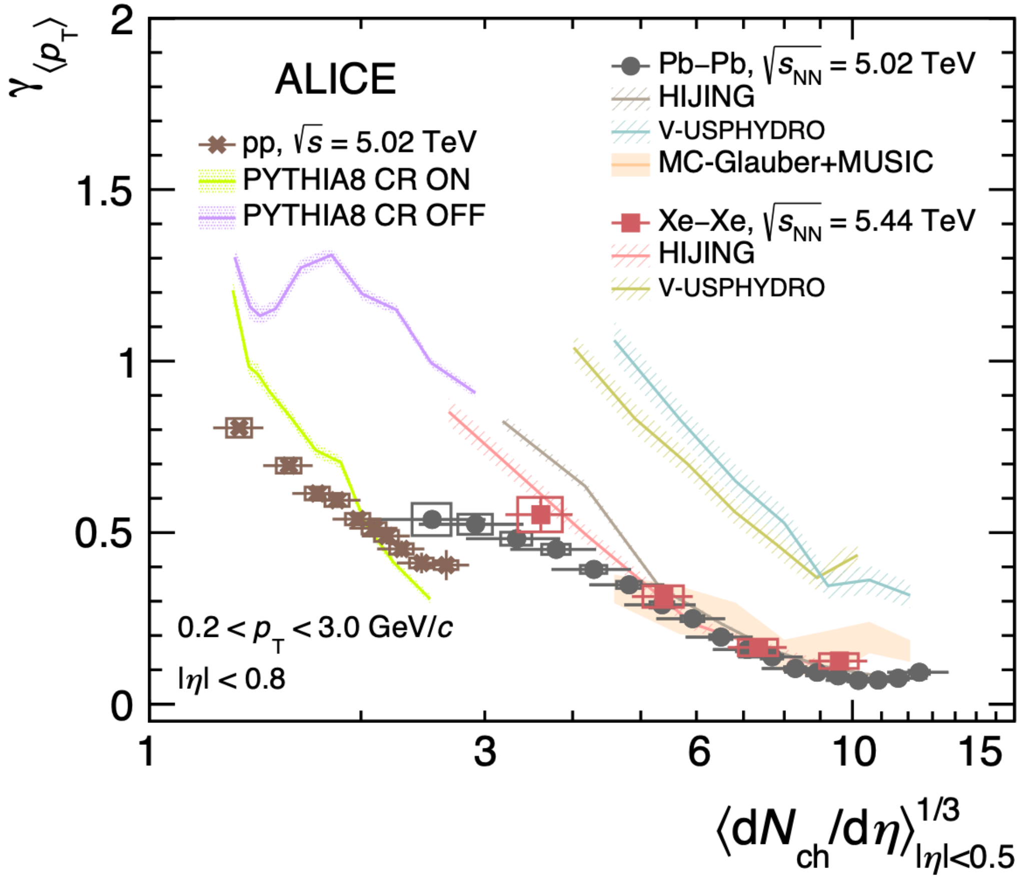


- In Ultra-Central Collisions: 1. The variance of Geometric fluctuations diminishes ⇒ b almost gets fixed.
  2. The skewness goes up due to truncation of distribution of event-wise $\langle p_T\rangle$.
- ➢ Experimental measurement of the cumulants of $P([p_T])$ can help in:
  Isolating magnitude of "*Geometric*-fluctuations" from "*Intrinsic* fluctuations" in HIC.

Using $[p_T]$ Cumulants to Constrain Medium Evolution



ALICE, EPJC 74 (2014) 3077

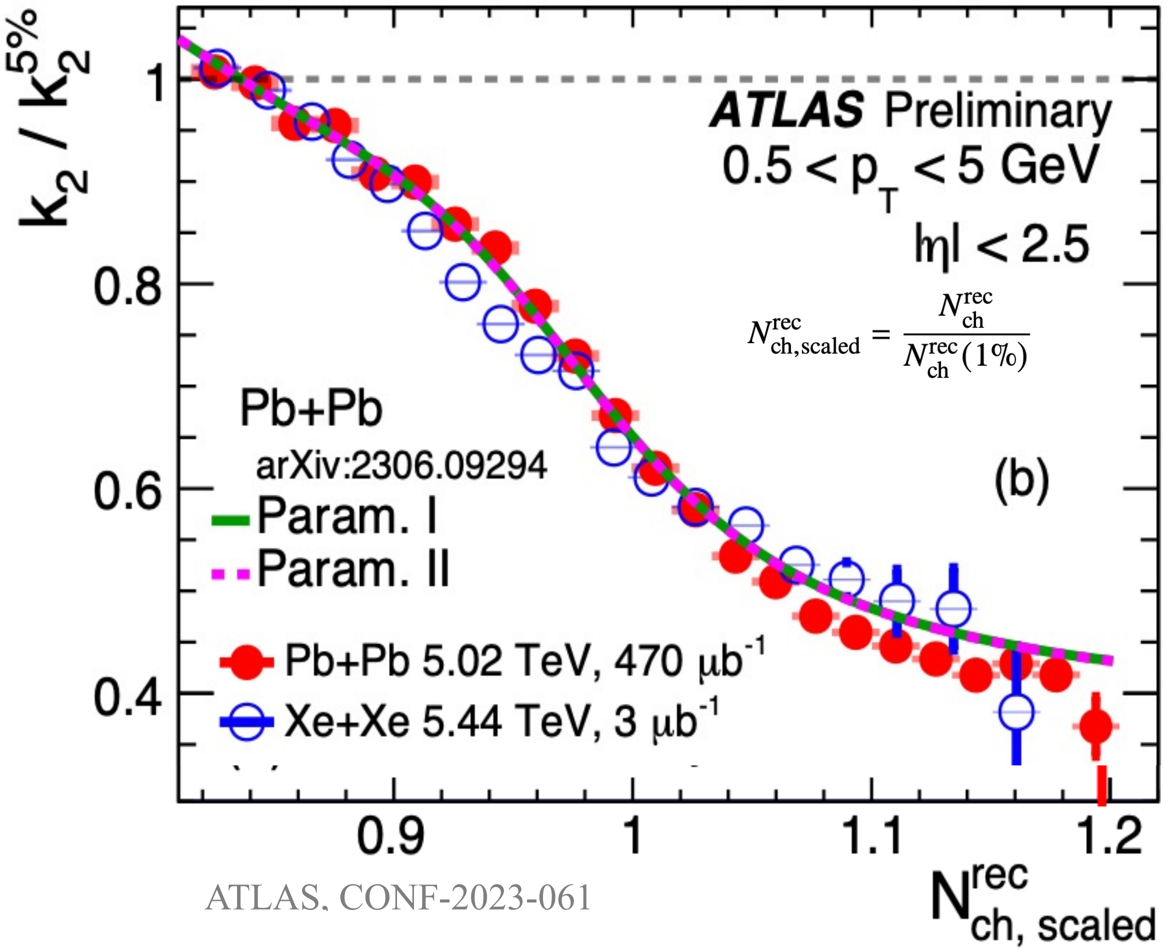


ALICE, PLB 850 (2024) 135841

- ALICE: variance and skewness of $P([p_T])$ show deviations from power-law in UCC.

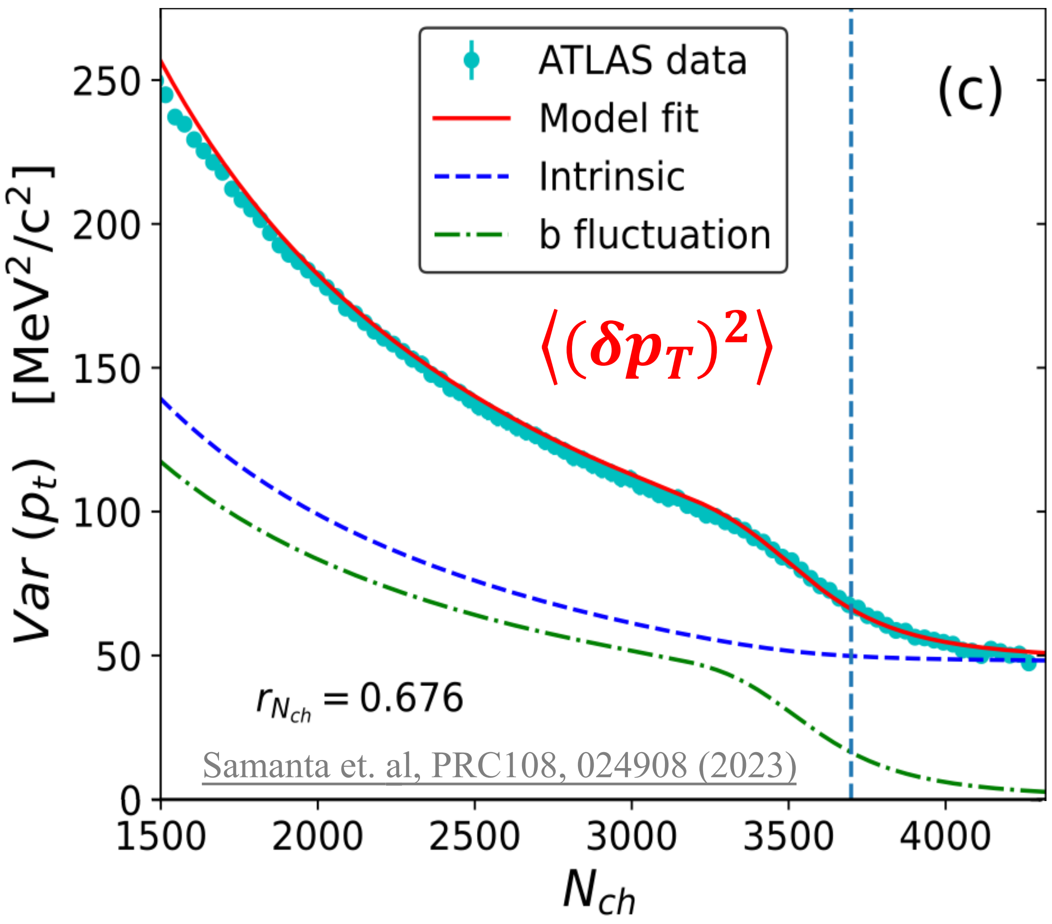
➢ Positive skewness excess from its baseline : indicates hydrodynamic evolution of QGP

Using $[p_T]$ Cumulants to Constrain Fluctuations



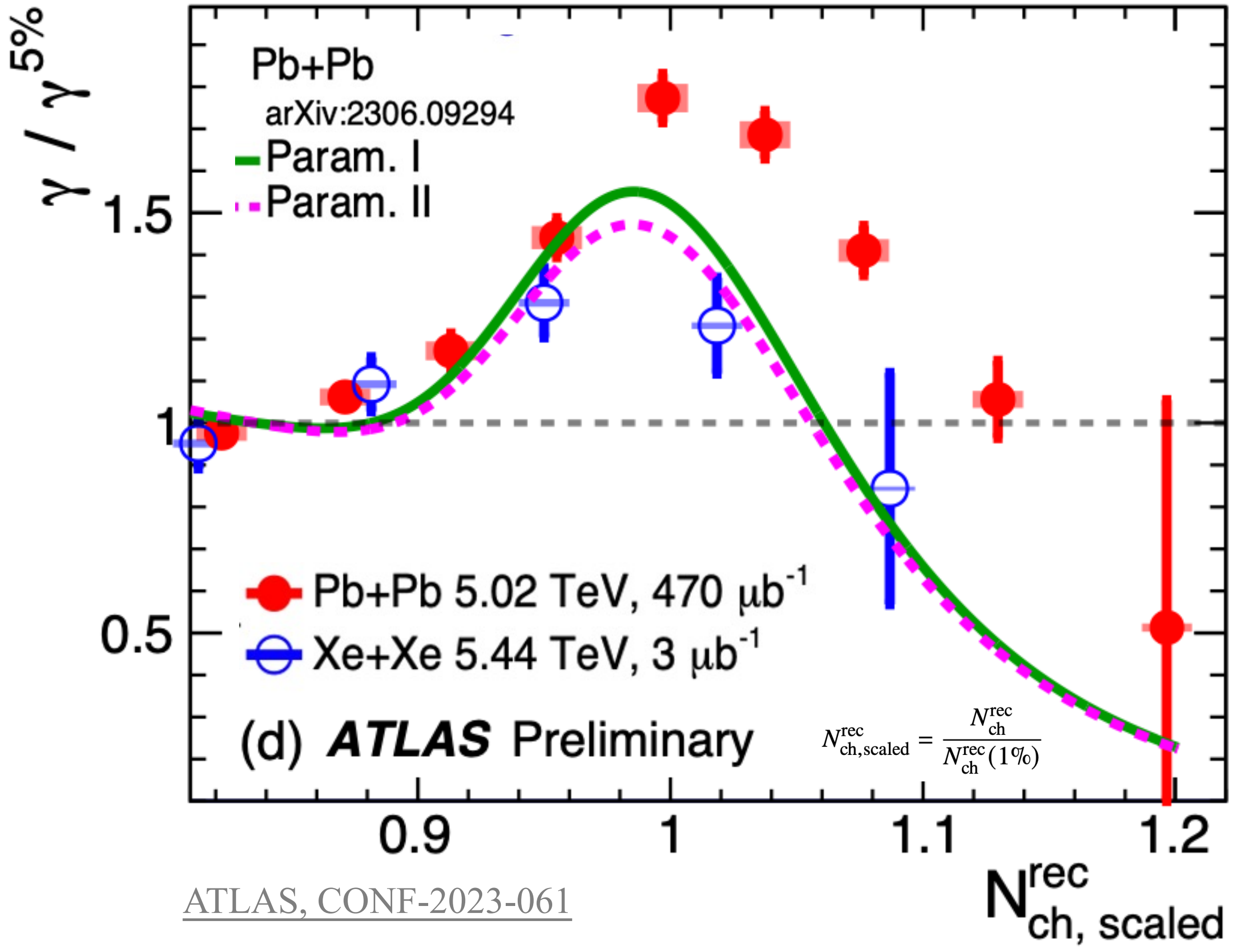
ATLAS, CONF-2023-061

$k_2 = \langle(\delta p_T)^2\rangle / \langle[p_T]\rangle^2$

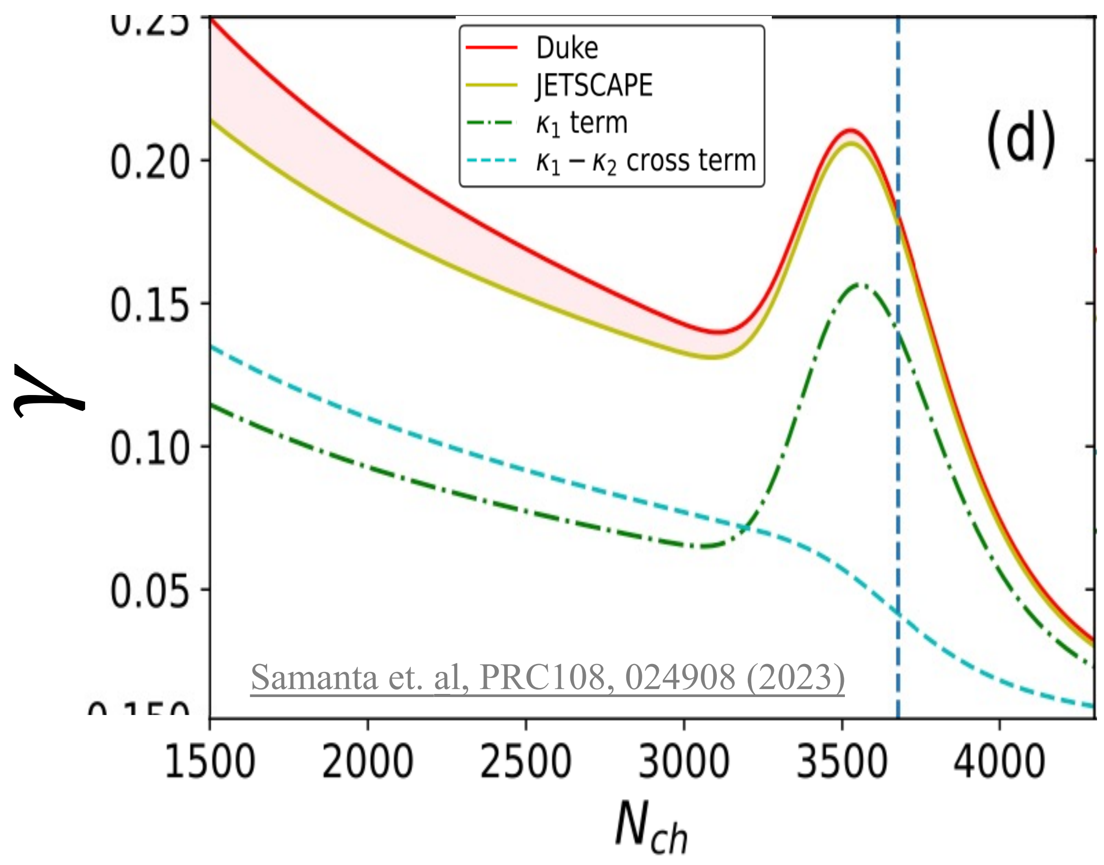


➢ Observed UCC features arise from diminishing component from *b* fluctuations (Geometric component).

Using $[p_T]$ Cumulants to Constrain Fluctuations



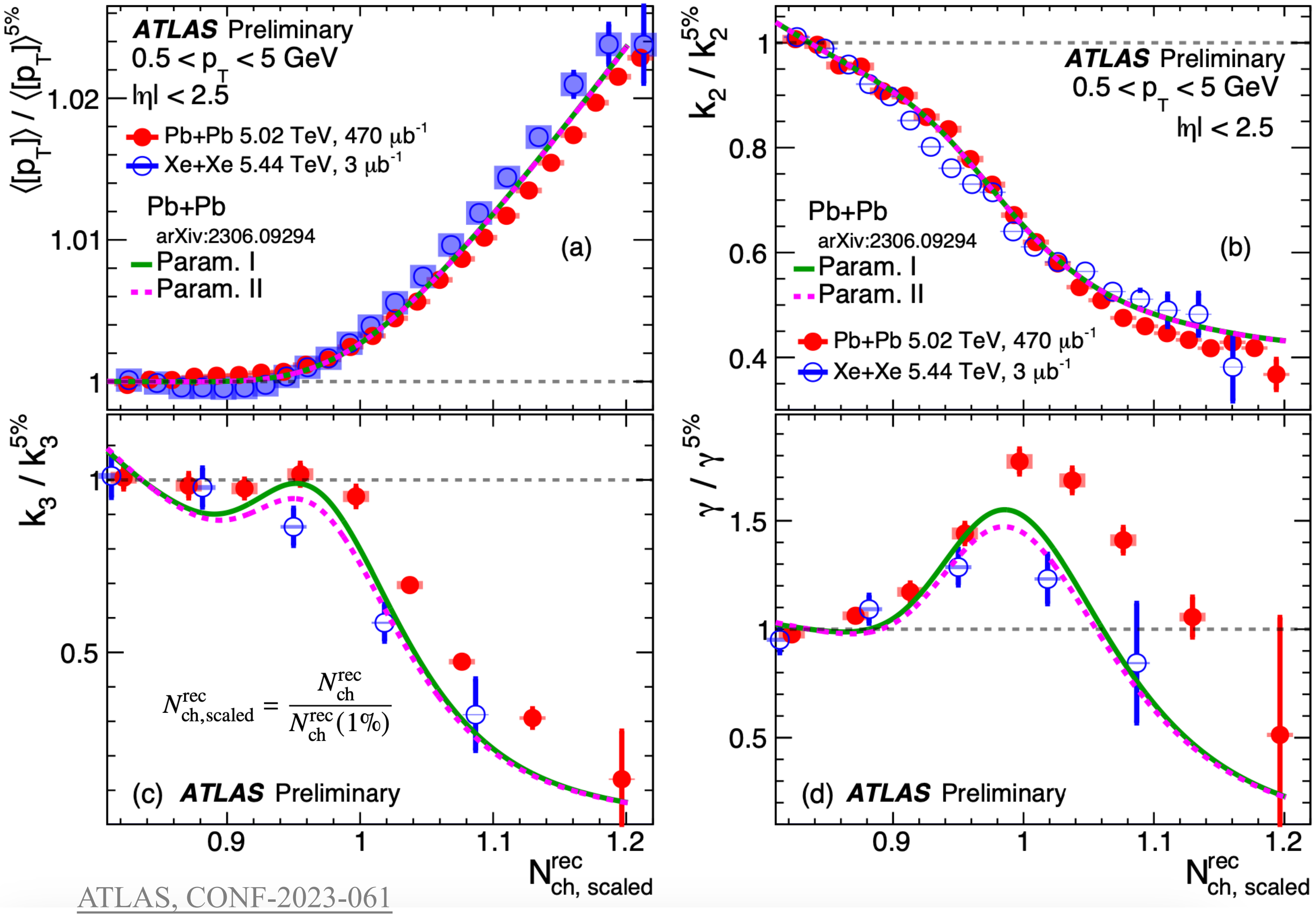
ATLAS, CONF-2023-061



$$\gamma = \langle(\delta p_T)^3\rangle / \langle(\delta p_T)^2\rangle^{1.5}$$

- Observed UCC features arise from diminishing component from *b* fluctuations (Geometric component).

Using $[p_T]$ Cumulants to Constrain Fluctuations



ATLAS, CONF-2023-061

Samanta et. al, PRC108, 024908 (2023)

ATLAS measurement shows:

- Observed UCC features arise from diminishing component from *b* fluctuations (Geometric component).
- First experimental constraint on magnitude of Intrinsic fluctuations in heavy-ion collisions.

Conclusion

- Ultra-Central heavy-ion collisions provide ideal conditions to constrain geometry and sources of fluctuations in the Initial state & from medium evolution.

- Recent measurements from LHC on flow and $[p_T]$ correlations in UCC has shown:

1. Nuclear deformation parameters β, γ can be reliably extracted from Ultra-Central HIC.
   The extracted deformation are valuable inputs for Bayesian analysis to constrain Initial state.

2. Measured slope of rise of $\langle[p_T]\rangle$ provides evidence of hydrodynamic evolution of system. Provided precise and direct constraint on speed of sound of QGP.

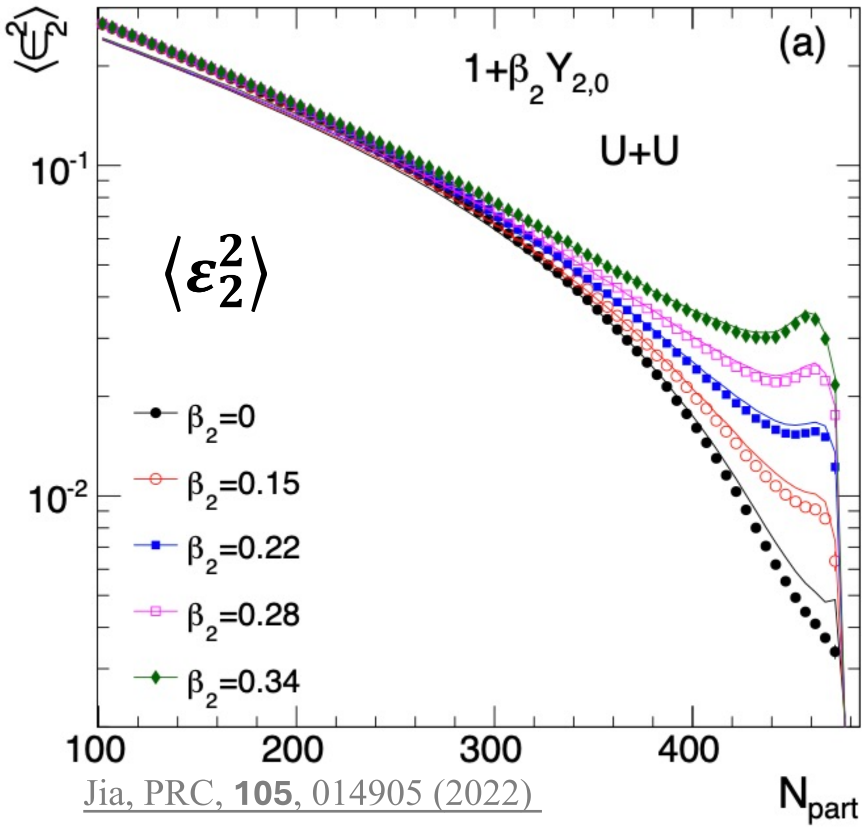
3. In UCC, the $[p_T]$ cumulants show clear signs of diminishing geometric fluctuations. Provide experimental constraint on Geometric and Intrinsic fluctuations from Initial state and medium evolution of HIC.

Backup

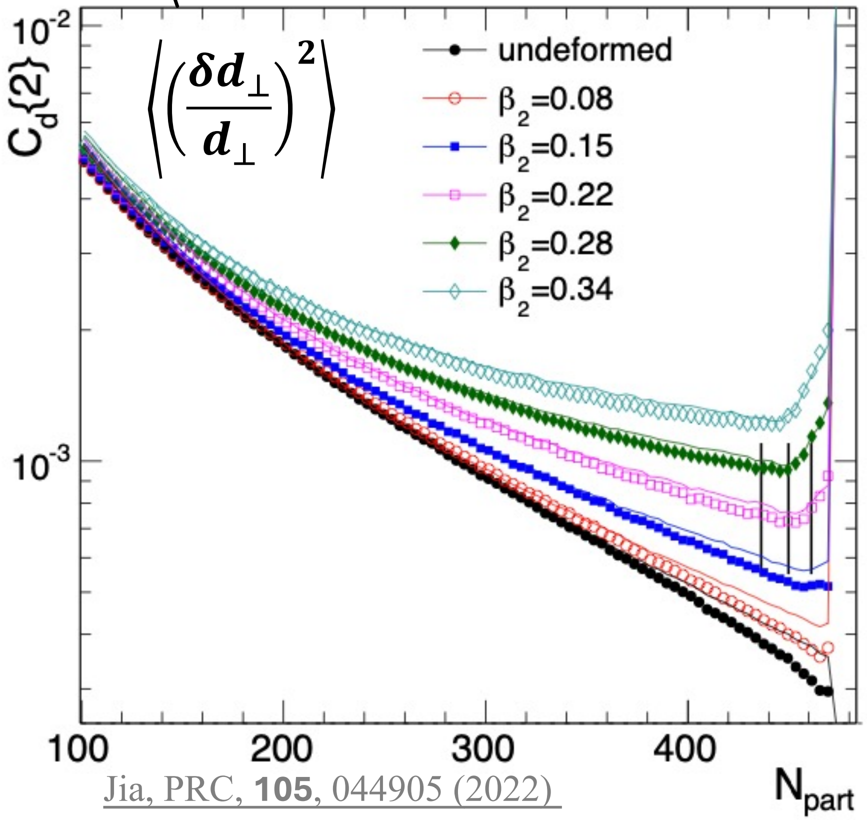
Effect of β on Overlap Geometry

- Nuclear deformation enhances fluctuations in size and eccentricity of overlap region

$$\langle \varepsilon_2^2 \rangle = a + b\beta^2 \qquad \left\langle \left(\frac{\delta d_\perp}{d_\perp} \right)^2 \right\rangle = a' + b'\beta^2 \qquad d_\perp = 1/R_\perp$$

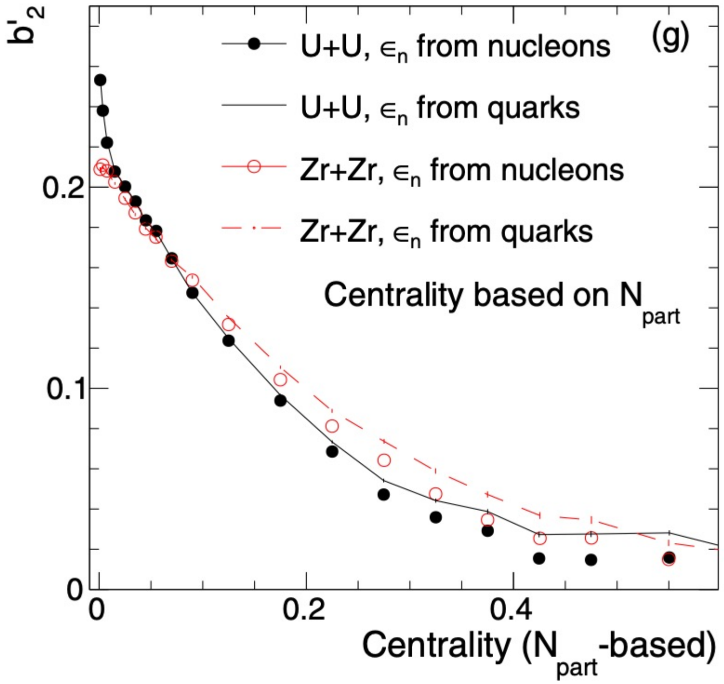


Jia, PRC, **105**, 014905 (2022)



Jia, PRC, **105**, 044905 (2022)

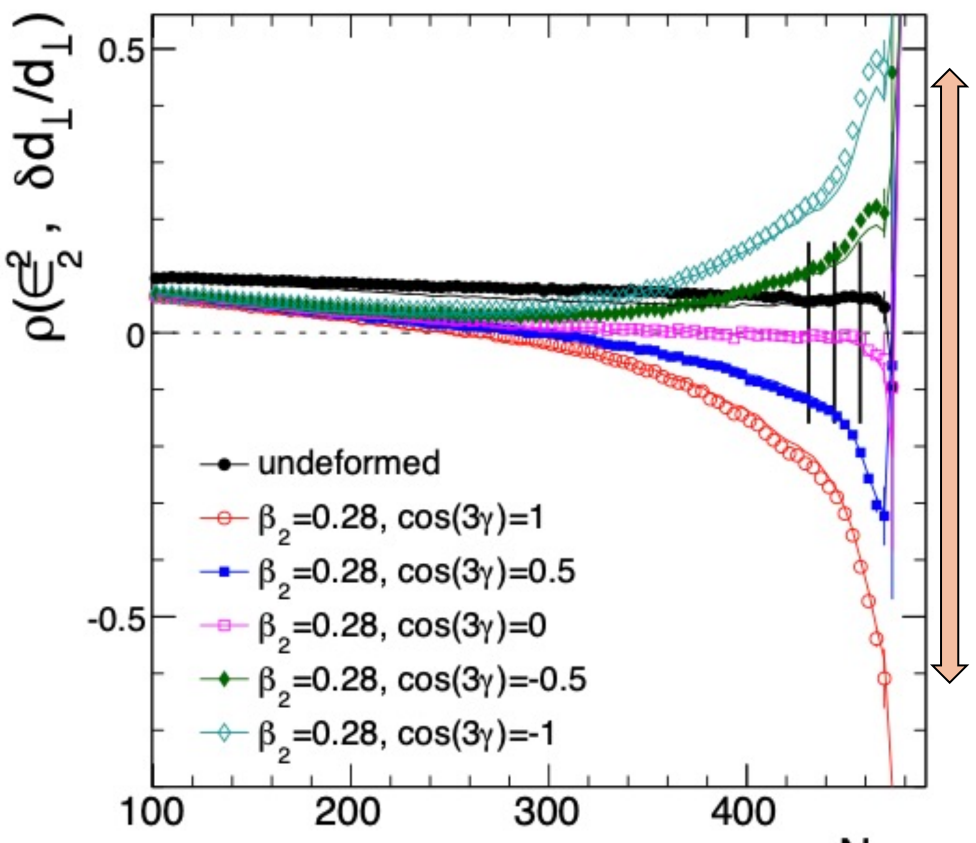
- ➢ Most-Central collisions: max *overlap*
  ⇒ Ideal to probe Nuclear deformation



➢ The effect of deformation on eccentricity and size fluctuations is maximum in ultra central collisions.

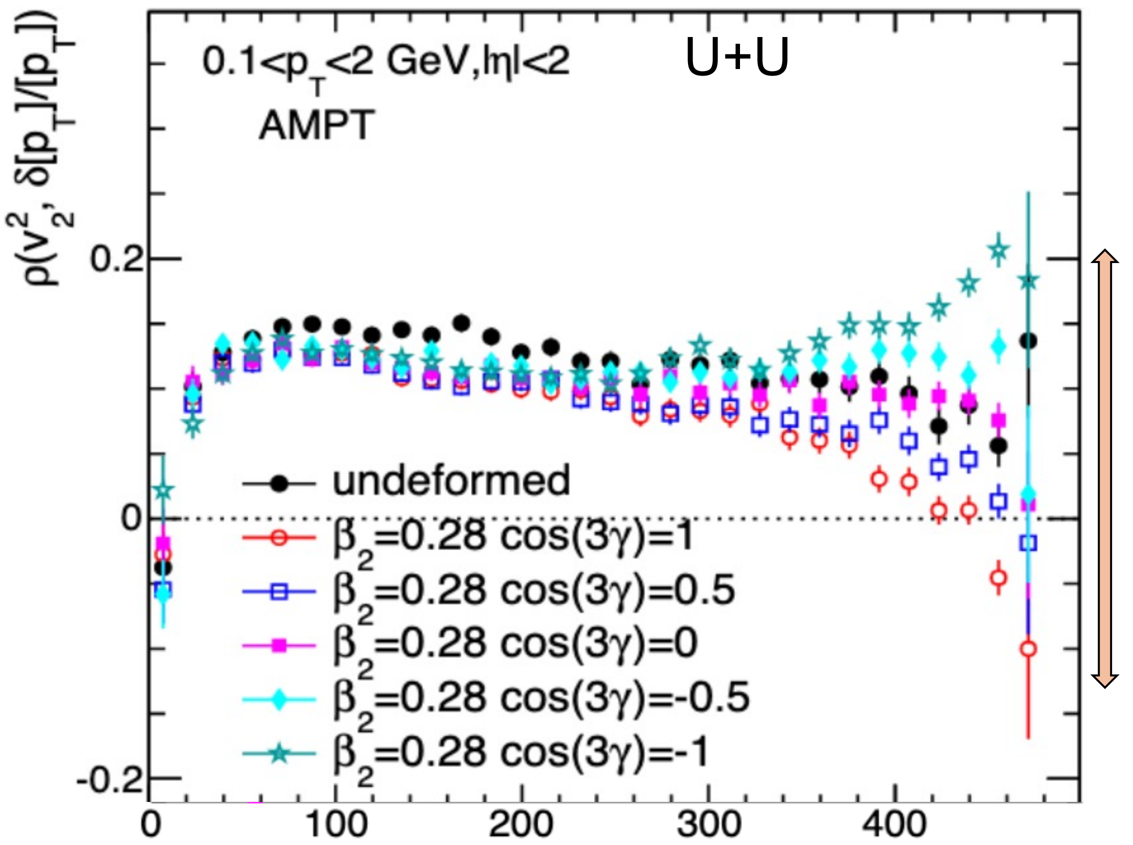
Effect of γ on Shape-Size Correlations of Overlap Geometry

Initial state correlation



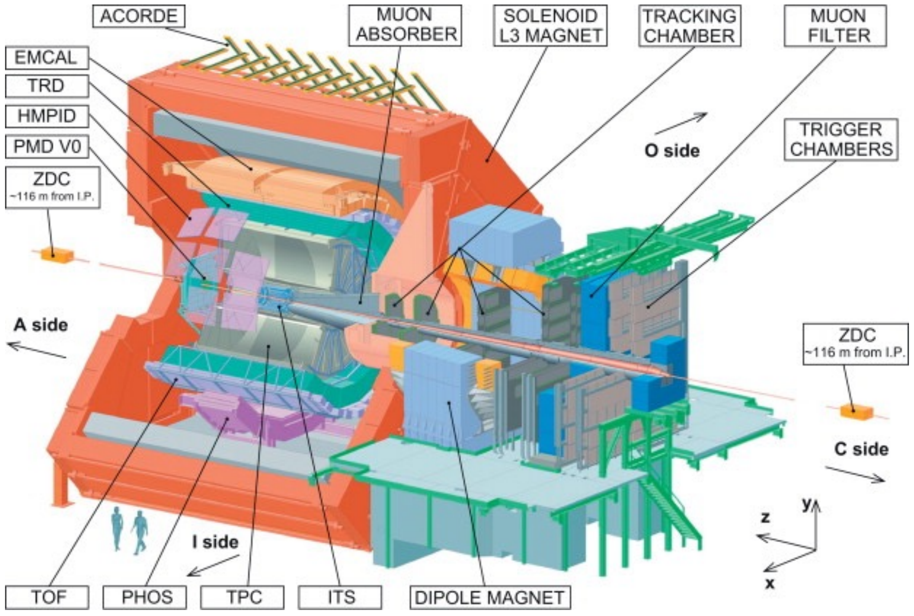
Jia, PRC, **105**, 044905 (2022)

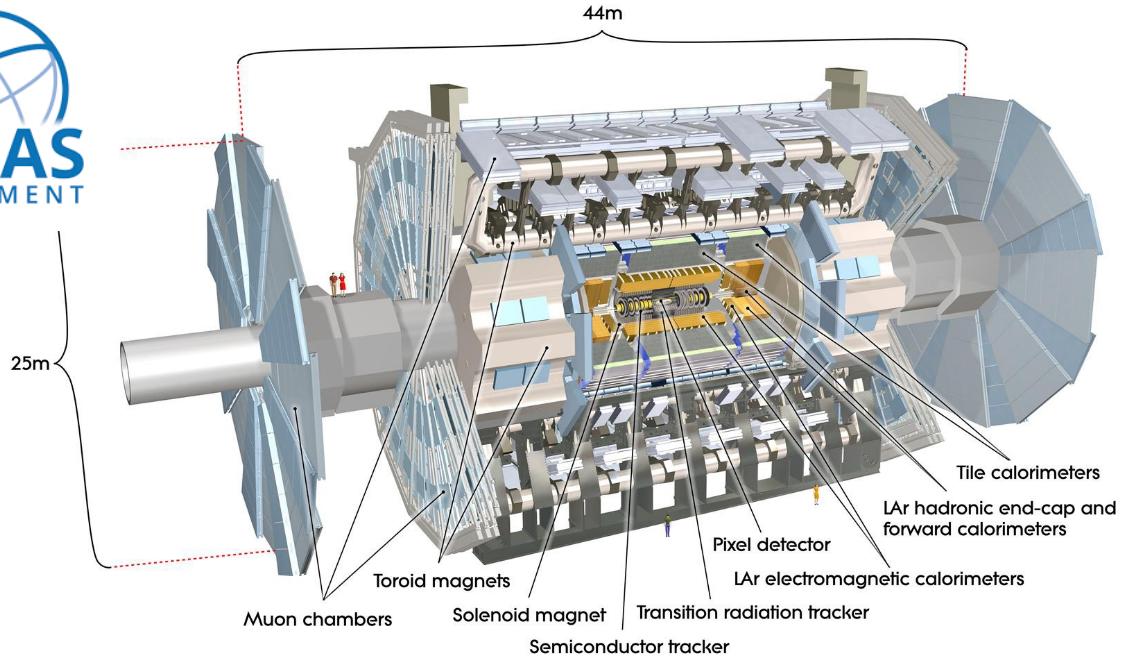
Final state correlation

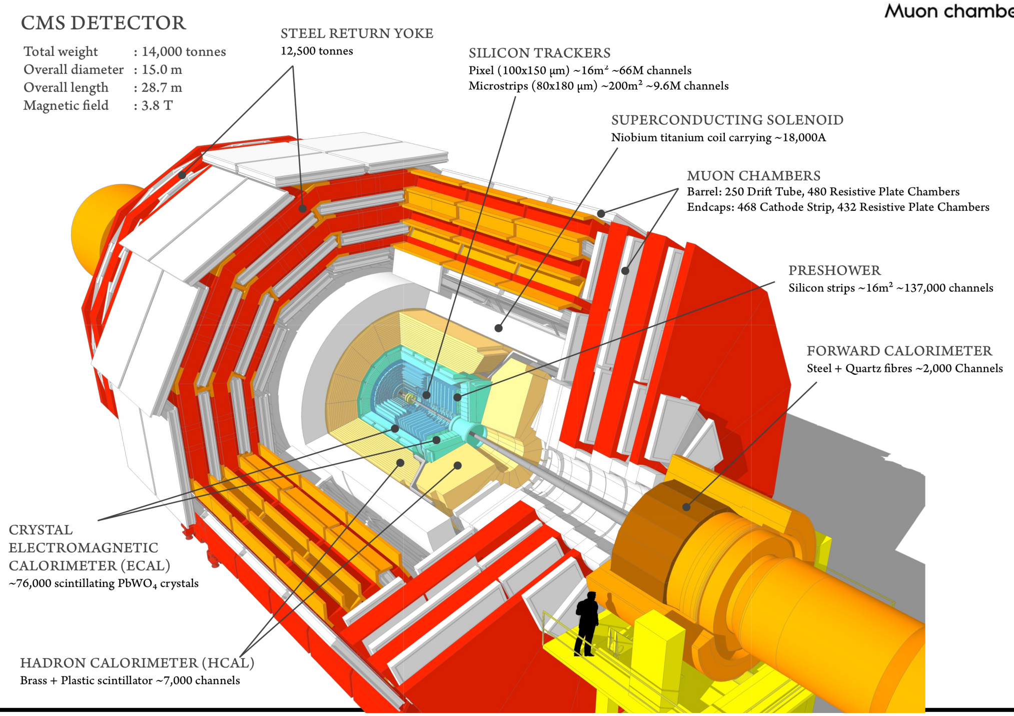


Jia, PRC, **105**, 044905 (2022)

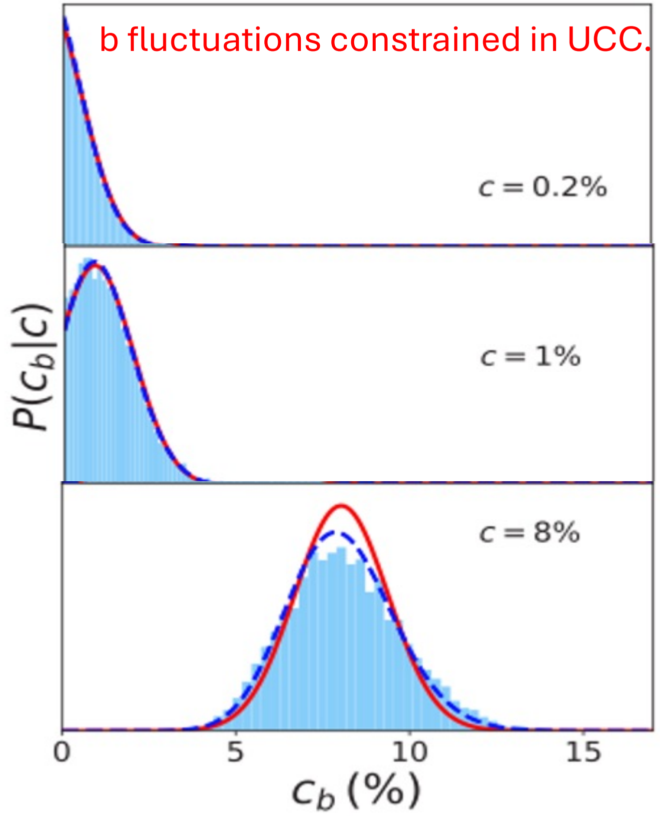
- Clear sensitivity to triaxiality for BOTH Initial state $\rho(\varepsilon_2^2, {}^{\delta d_\perp}/_{d_\perp})$ & final state $\rho(v_2^2, {}^{\delta[p_T]}/_{[p_T]})$ in models.


ACORDE
MUON ABSORBER
SOLENOID L3 MAGNET
TRACKING CHAMBER
MUON FILTER
EMCAL
TRD
HMPID
PMD V0
ZDC ~116 m from I.P.
O side
TRIGGER CHAMBERS
A side
ZDC ~116 m from I.P.
C side
I side
TOF
PHOS
TPC
ITS
DIPOLE MAGNET
z
y
x

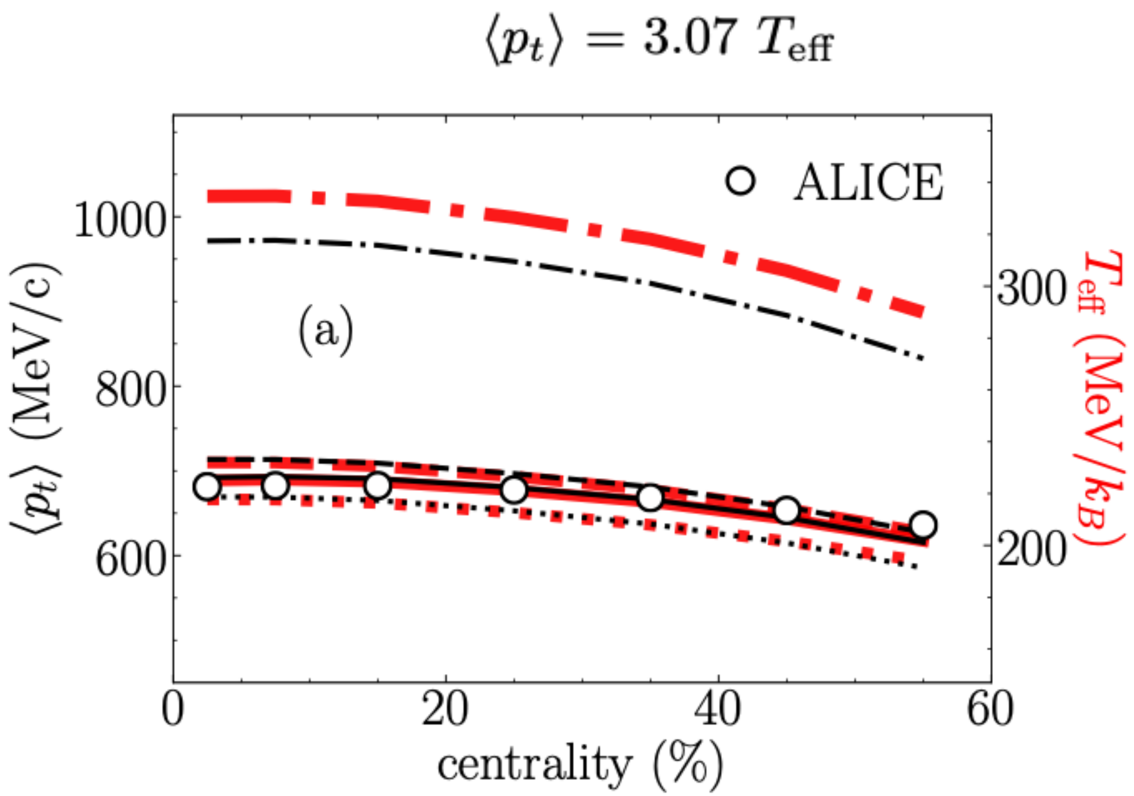

44m
25m
Tile calorimeters
LAr hadronic end-cap and forward calorimeters
Pixel detector
LAr electromagnetic calorimeters
Toroid magnets
Muon chambers
Solenoid magnet
Transition radiation tracker
Semiconductor tracker


CMS DETECTOR
Total weight : 14,000 tonnes
Overall diameter : 15.0 m
Overall length : 28.7 m
Magnetic field : 3.8 T
STEEL RETURN YOKE
12,500 tonnes
SILICON TRACKERS
Pixel (100x150 μm) ~16m² ~66M channels
Microstrips (80x180 μm) ~200m² ~9.6M channels
SUPERCONDUCTING SOLENOID
Niobium titanium coil carrying ~18,000A
MUON CHAMBERS
Barrel: 250 Drift Tube, 480 Resistive Plate Chambers
Endcaps: 468 Cathode Strip, 432 Resistive Plate Chambers
PRESHOWER
Silicon strips ~16m² ~137,000 channels
FORWARD CALORIMETER
Steel + Quartz fibres ~2,000 Channels
CRYSTAL ELECTROMAGNETIC CALORIMETER (ECAL)
~76,000 scintillating PbWO4 crystals
HADRON CALORIMETER (HCAL)
Brass + Plastic scintillator ~7,000 channels

Using Mean of P($[p_T]$) to Constrain c_s



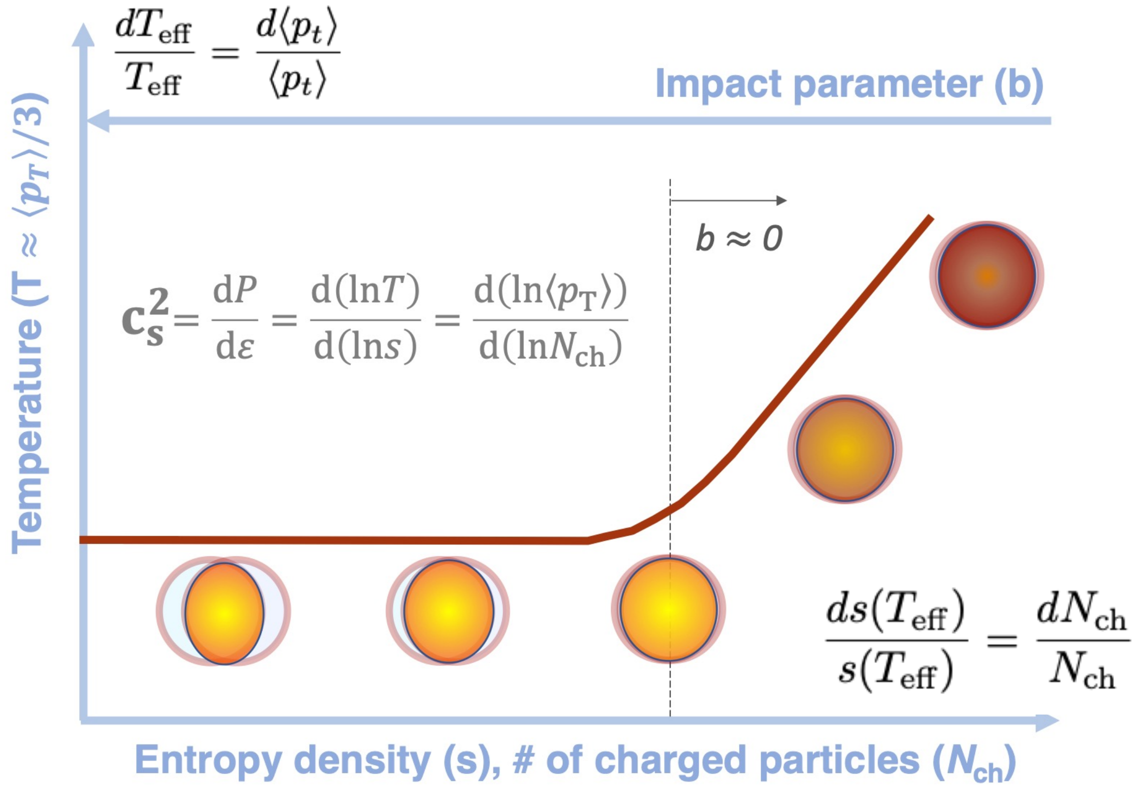
Das et. al, PRC 97, 014905 (2018)



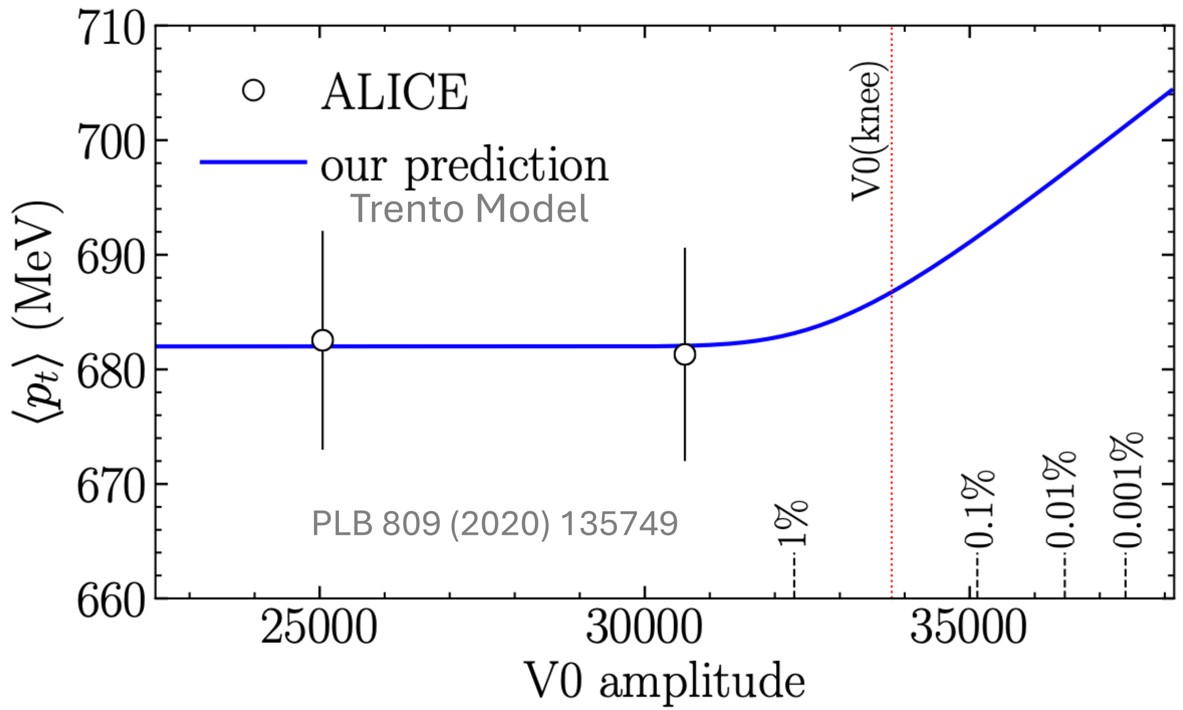
Gardim et. al, Nat. Phys 16, (2020)

- In UCC, within approximately fixed b, choosing larger N_{ch} chooses events with larger entropy density.
- Larger entropy density within a fixed geometry leads to larger radial push or $\langle [p_T] \rangle$.

Using Mean of P($[p_T]$) to Constrain c_s



CMS, 2401.06896



Gardim et. al, PLB 809, 135749 (2020)

- The slope of this rise of $\langle\langle p_T\rangle\rangle$ in UCC can be related to speed of sound following:

$$c_s^2 = \frac{dP}{d\epsilon} = \frac{d(lnT)}{d(lns)} = \frac{d(ln\langle p_T\rangle)}{d(lnN_{ch})}$$