Transverse momentum fluctuation in ultra-central Pb+Pb collision

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in collaboration with Jean-Yves Ollitrault, Matthew Luzum, Jiangyong Jia, Somadutta Bhatta, Joao-Paulo Pichhetti

...based on arXiv:2303.15323 and arXiv:2306.09294

BIALASOWKA HEP Seminar

Krakow, December 1, 2023

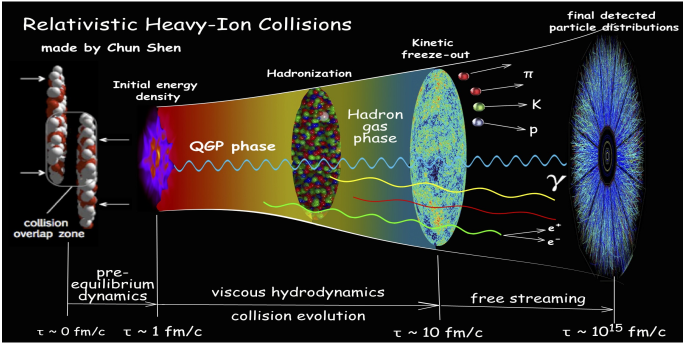
IPhT SACLAY

POLISH NATIONAL AGENCY FOR ACADEMIC EXCHANGE

AGH UNIVERSITY OF SCIENCE AND TECHNOLOGY

NATIONAL SCIENCE CENTRE POLAND

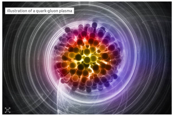
High energy heavy ion(HI) collision: "The Little Bang"



Shen, Heinz, arXiv:1507.01558

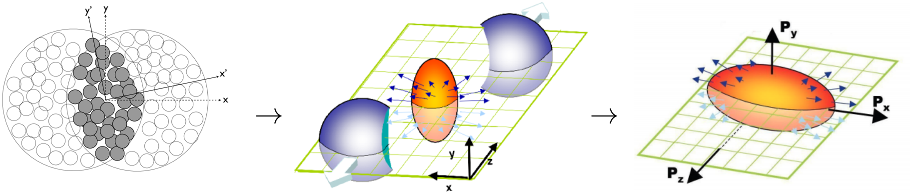
Boiling water : 10^2 K

Core of the Sun : 10^7 K

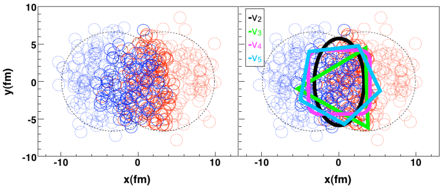


QGP : 10^{12} K !!

Evidence of QGP : Collective flow in HI Collisions



PHOBOS arXiv:0711.3724 → U. Heinz, arXiv:0810.5529 → BNL: RHIC



Alver, Baker, Loizides, Steinberg arXiv:0805.4411

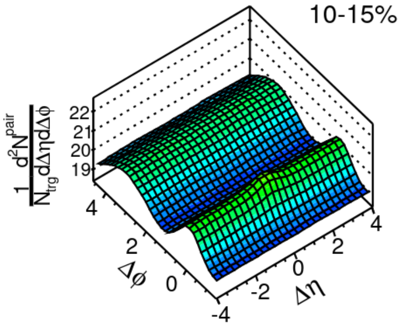
Momentum anisotropy : Harmonic flow

$$\frac{dN}{dp_T\,d\phi} = \frac{dN}{2\pi dp_T}\left(1 + 2\sum_{n=1}^{\infty} v_n(p_T)cos\left[n\left(\phi - \Psi_n\right)\right]\right)$$

$V_2 \rightarrow$ **Elliptic flow** & $V_3 \rightarrow$ **Triangular flow**

Experimental evidence !

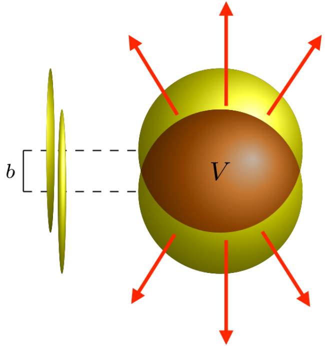
- Experimental evidence for the formation of a little fluid in Pb+Pb collision $\longrightarrow$ azimuthal correlations between particles seen in detectors.



CMS:1201.3158

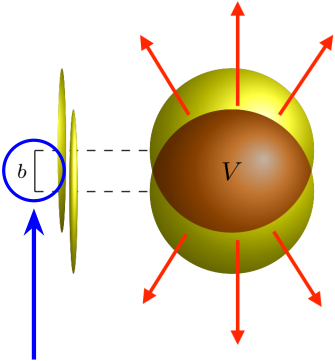
Experimental evidence !

- Experimental evidence for the formation of a little fluid in Pb+Pb collision $\longrightarrow$ azimuthal correlations between particles seen in detectors.
- Evidence is indirect ! $\longrightarrow$ azimuthal distribution of particles is not isotropic $\longrightarrow$ anisotropy driven by pressure gradients within a fluid.



Experimental evidence !

- Experimental evidence for the formation of a little fluid in Pb+Pb collision $\longrightarrow$ azimuthal correlations between particles seen in detectors.
- Evidence is indirect ! $\longrightarrow$ azimuthal distribution of particles is not isotropic $\longrightarrow$ anisotropy driven by pressure gradients within a fluid.
- We report more direct evidence of local thermalization in Pb+Pb collisions $\longrightarrow$ does not involve directions of outgoing particles, but solely their momenta.

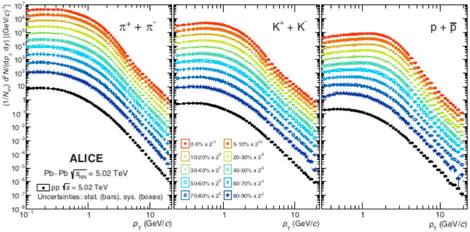


b = impact parameter

(important in this talk !)

Multiplicity (N_{ch}) and Transverse momentum per particle ($[p_t]$)

- Charged particle spectra; $\frac{dN}{dp_t}$ vs p_t observed in experiments.



p_t spectra , arXiv:1910.07678

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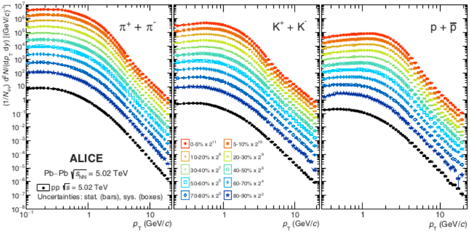
$$N_{ch} = \int_{p_{min}}^{p_{max}} \frac{dN}{dp_t} dp_t$$



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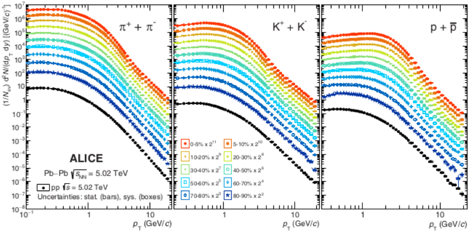
$$N_{ch} = \int_{p_{min}}^{p_{max}} \frac{dN}{dp_t} dp_t$$

- Average transverse momentum per particle,

$$[p_t] = \int_{p_{min}}^{p_{max}} p_t \frac{dN}{dp_t} dp_t$$



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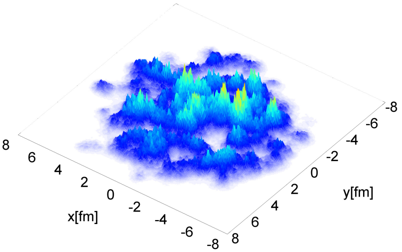
Fluctuation in HI collision

- Event-by-event fluctuation of initial state.



Lumpy structure of the initial density

Schenke, Tribedy, Venugopalan arXiv: 1206.6805

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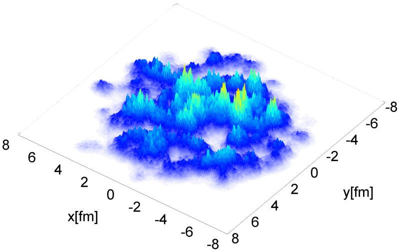
- All final state collective observables ,N_{ch}, $[p_t]$, V_n fluctuates event-by-event.



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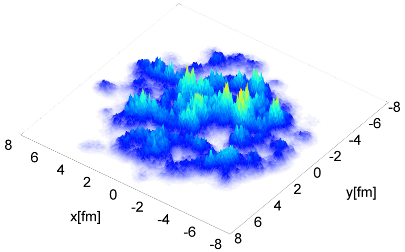

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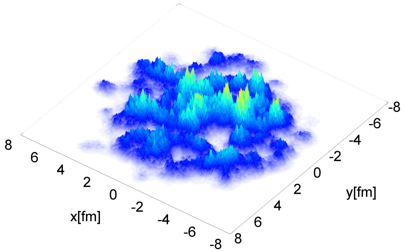
- In this talk : $[p_t]$-fluctuation $\Longrightarrow$ separating geometrical and intrinsic fluctuation !



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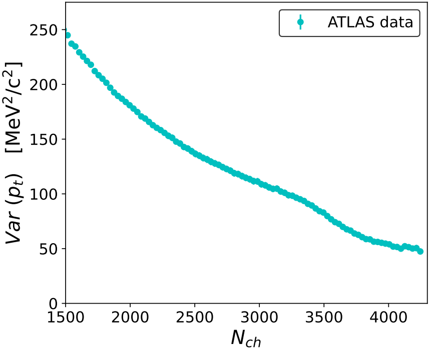
ATLAS data for $[p_t]$ fluctuation

- Recent ATLAS data shows multiplicity (Nch) dependence of the variance of transverse momentum per particle, $[p_t]$.



Variance of $[p_t]$ for Pb+Pb @ 5.02 TeV

PhysRevC.107.054910

Table 374 in https://www.hepdata.net/record/ins2075412

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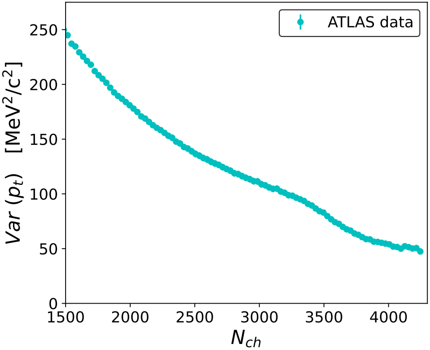

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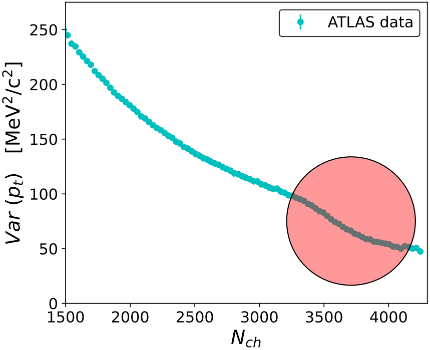
- Puzzling behavior in ATLAS data : steep decrease over a narrow range of N_{ch}



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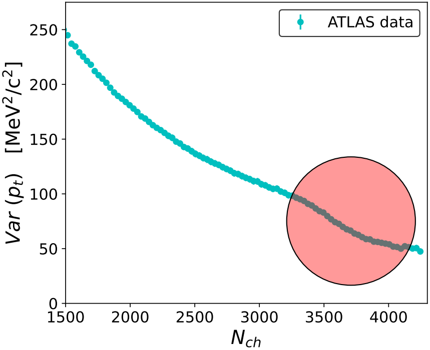
- Puzzling behavior in ATLAS data : steep decrease over a narrow range of N_{ch}
- We will show that this could be a consequence of **thermalization !**



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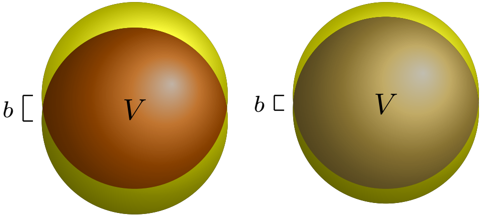
Impact parameter (b) is important !

- In experiment b is not known ! $\Longrightarrow$ $[p_t]$ fluctuation is measured for fixed N_{ch}



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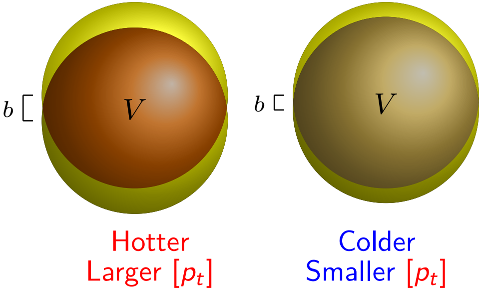
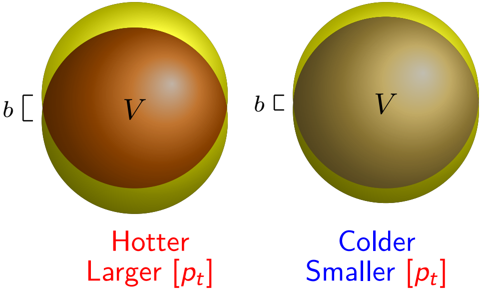


Variation of b at fixed N_{ch}

Impact parameter (b) is important !

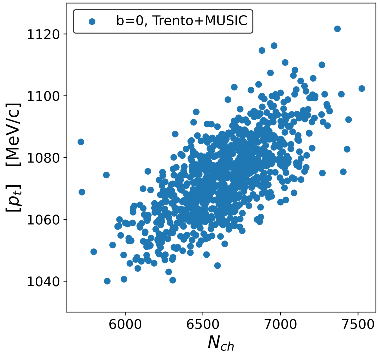
- In experiment b is not known ! $\Longrightarrow$ $[p_t]$ fluctuation is measured for fixed N_{ch}
- Fixed N_{ch} $\Longrightarrow$ finite range of b !
- Variation of b gives a contribution to the variation of $[p_t]$ $\Longrightarrow$ **goes to 0 in ultracentral collisions !**



Variation of b at fixed N_{ch}

Hydrodynamic simulation: b is known !

- Hydro : assumes thermalization !
  $\Longrightarrow$ We simulate Pb+Pb collisions at fixed b $(=0)$ with TRENTO (initial condition)+ MUSIC (hydro)



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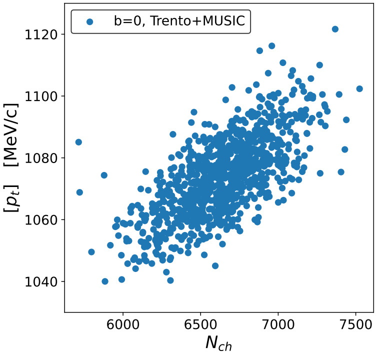
- Significant fluctuation of N_{ch} and modest fluctuation of $[p_t]$. Strong correlation between $[p_t]$ and N_{ch}



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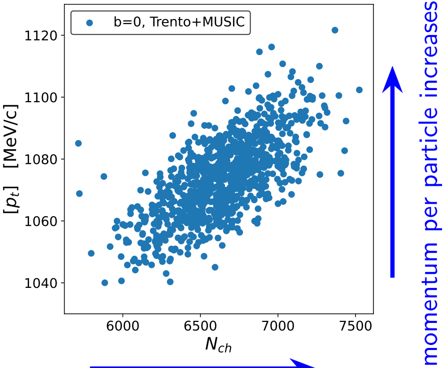
- Significant fluctuation of N_{ch} and modest fluctuation of $[p_t]$. Strong correlation between $[p_t]$ and N_{ch}
- Fixed b $\Longrightarrow$ fixed collision volume
  Larger N_{ch} $\Longrightarrow$ larger density
  $\Longrightarrow$ larger temperature
  $\Longrightarrow$ larger energy per particle
  $\Longrightarrow$ larger $[p_t]$

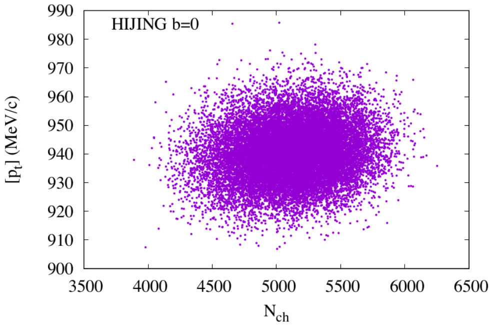


density increases
$\Longrightarrow$ temperature increases

Comparing other models : HIJING simulation

Wang, Gyulassy, arXiv:nucl-th/9502021

- HIJING: microscopic model of HI collision $\Longrightarrow$ the system doesn't thermalize !



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Comparing other models : HIJING simulation

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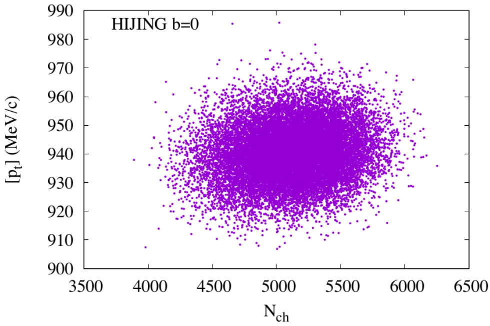
- HIJING: microscopic model of HI collision $\Longrightarrow$ the system doesn't thermalize !
- Very small correlation between N_{ch} and $[p_t] \sim 10 \times$ smaller !!



Pb+Pb @ 5.02 TeV

No thermalization

$\Longrightarrow$ Very little correlation !

Comparing other models : HIJING simulation

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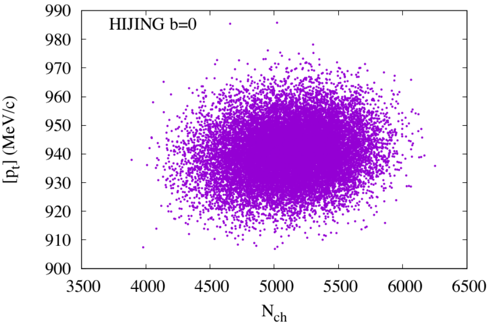
- Very small correlation between N_{ch} and $[p_t] \sim 10 \times$ smaller !!
- Hence the correlation **could be** a signature of thermalization !



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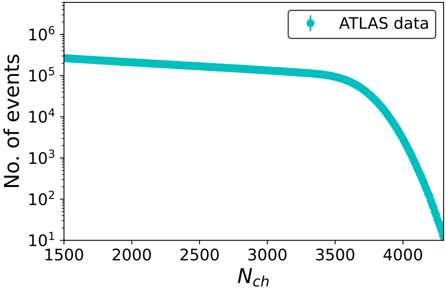
Bayesian reconstruction of P(b $|N_{ch}$)

- First we solve the inverse problem:
  what is the distribution of N_{ch} at fixed b i.e. P(N_{ch}|b) ?



N_{ch} distribution
for centrality classification !

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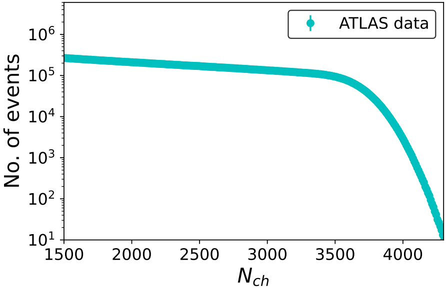
  P(b $|N_{ch}$) P(N_{ch})=P(N_{ch}|b) P(b)



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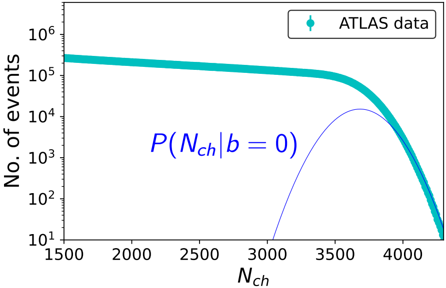
- We assume P(N_{ch}|b) to be **Gaussian !**



N_{ch} distribution at fixed b

Gaussian assupmtion !

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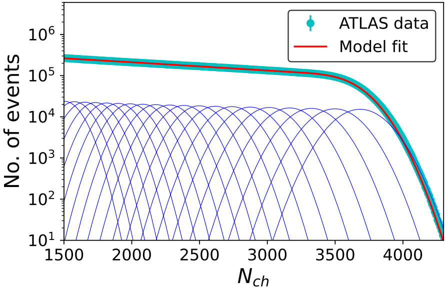
- Fit P(N_{ch}) as sum of Gaussians



Sum of Gaussians at fixed b

Das, Giacalone, Monard, Ollitrault
arXiv:1708.00081

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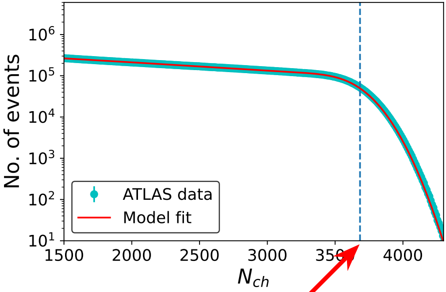
- Fit P(N_{ch}) as sum of Gaussians
- We precisely reconstruct the knee (mean N_{ch} at b=0)



Precise construction of knee
$\langle N_{ch}|b = 0\rangle$

Bayesian reconstruction of P(b $|N_{ch}$)

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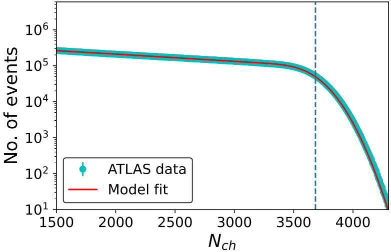
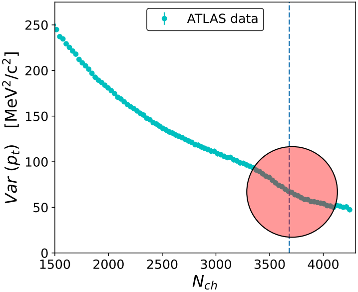
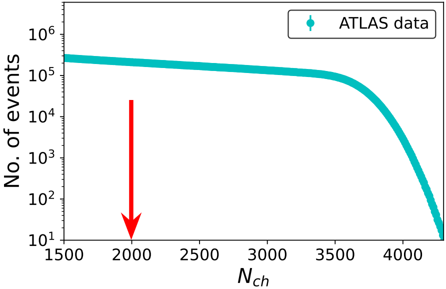
  P(b $|N_{ch}$) P(N_{ch})=P(N_{ch}|b) P(b)
- We assume P(N_{ch}|b) to be **Gaussian !**
- Fit P(N_{ch}) as sum of Gaussians
- We precisely reconstruct the knee (mean N_{ch} at b=0)
- The steep fall of the variance precisely occur at the knee !

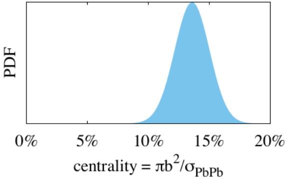




P(b | N_{ch}) from Bayesian reconstruction

- At smaller N_{ch} the distribution P($b|N_{ch}$) is a full Gaussian





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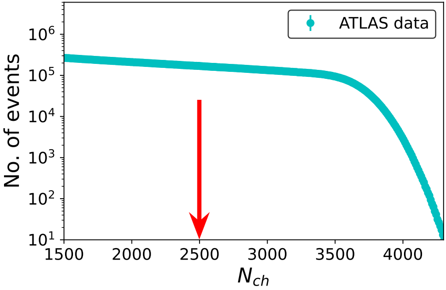
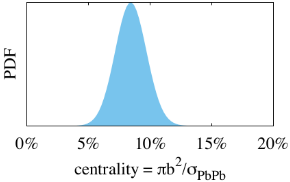
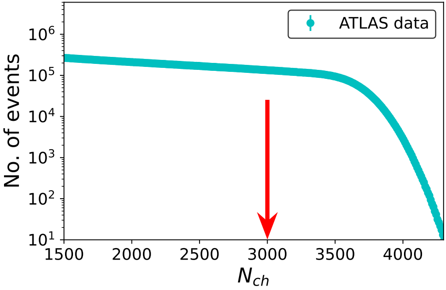
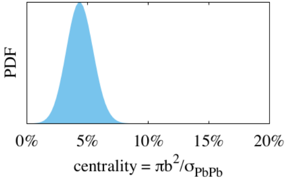




P(b $|N_{ch}$) from Bayesian reconstruction

- At smaller N_{ch} the distribution $P(b|N_{ch})$ is a full Gaussian
- But as we move closer and closer to the knee, $P(b|N_{ch})$ becomes truncated due to the limit $b \geq 0$





P(b $|N_{ch}$) from Bayesian reconstruction

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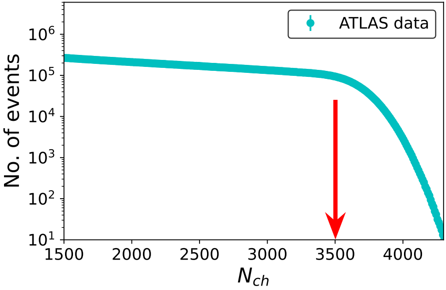
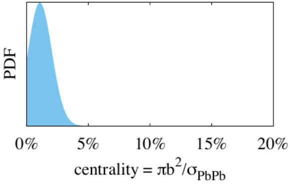
- But as we move closer and closer to the knee, P($b|N_{ch}$) becomes truncated due to the limit b ≥ 0





P(b |N_{ch}) from Bayesian reconstruction

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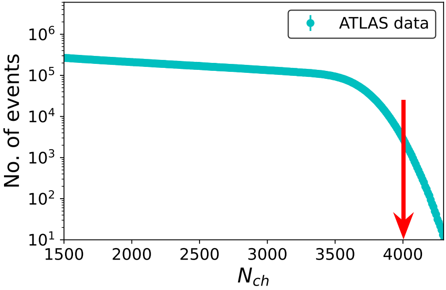
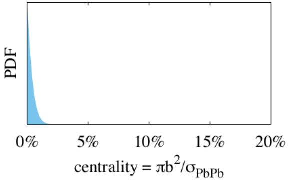
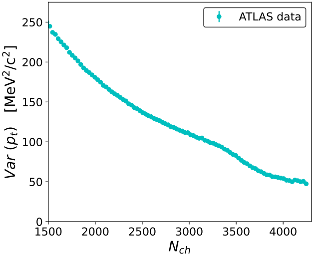
- But as we move closer and closer to the knee, P(b|N_{ch}) becomes truncated due to the limit b $\geq$ 0
- Above the knee it gets extremely truncated $\Longrightarrow$ the impact parameter fluctuation gradually disappears !

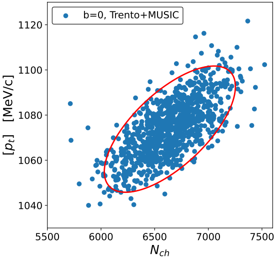




Understanding $[p_t]$ fluctuation data : Parametrizing $P(N_{ch}, [p_t]|b)$

- We assume a simple 2D correlated Gaussian between $[p_t]$ and N_{ch} at fixed impact parameter b : $P([p_t], N_{ch}|b)$.





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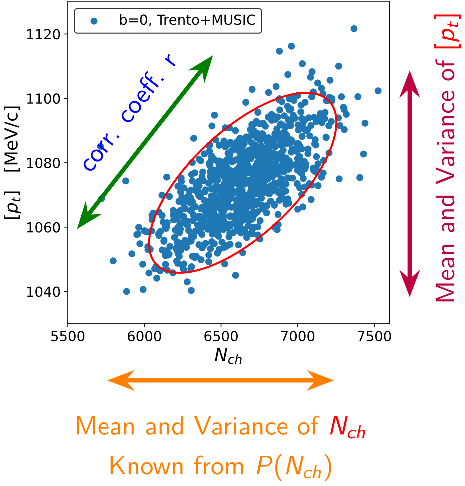

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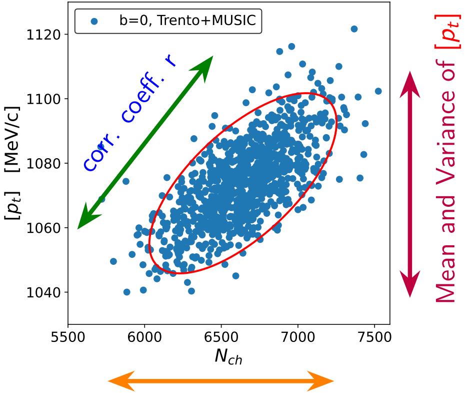
- The distribution has 5 parameters : Mean and variance of N_{ch}, Mean and variance of $[p_t]$ and correlation coefficient r between N_{ch} and $[p_t]$.
- Mean value of $[p_t]$ is constant at fixed b and assuming it is independent of b $\Longrightarrow$ we fit $P(\delta p_t, N_{ch}|b)$
  $\delta p_t = [p_t] - < [p_t] >$



Mean and Variance of N_{ch}

Known from $P(N_{ch})$

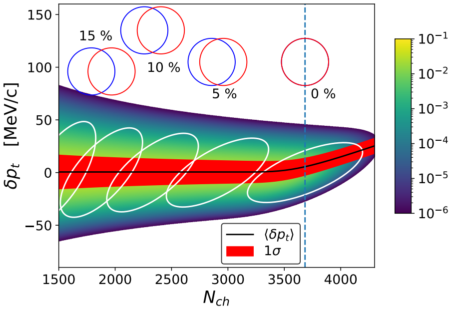
b-dependence of the fit parameters

- We assume mean $[p_t]$ to be independent of b
- We assume Var($[p_t]$) is a smooth function of mean multiplicity :

$$\sigma {p_t}^2 \left(\frac{\langle N_{ch}(0) \rangle}{\langle N_{ch}(b) \rangle} \right)$$

- We also assume r to be independent of b for simplicity

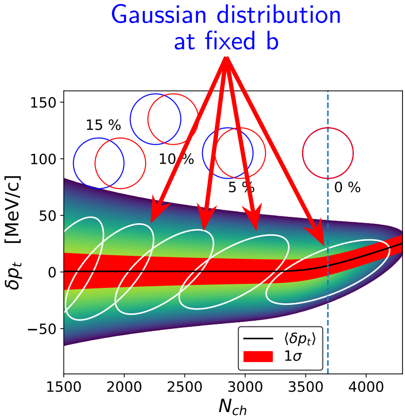
Fit result : $P(N_{ch}, \delta p_t)$



2D correlated gaussian distribution of δp_t and N_{ch}

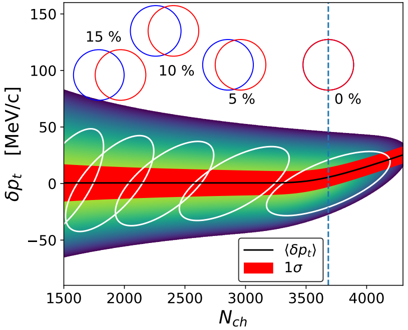
Fit result : $P(N_{ch}, \delta p_t)$

- We get, $P(N_{ch}, \delta p_t) = \int P(N_{ch}, \delta p_t | b) P(b) db$



Fit result : $P(N_{ch}, \delta p_t)$

- We get, $P(N_{ch}, \delta p_t) = \int P(N_{ch}, \delta p_t | b) P(b) db$
- By conditional probability $P(\delta p_t | N_{ch}) = \frac{P(N_{ch}, \delta p_t)}{P(N_{ch})}$ $\implies$ Var($[p_t] | N_{ch}$) is the squared width of $P(\delta p_t | N_{ch})$



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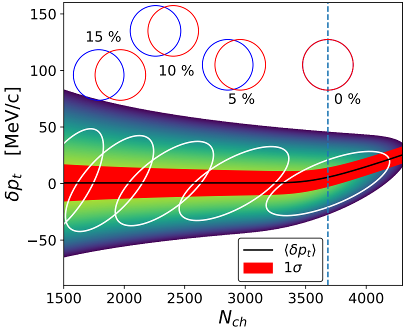
  $\Longrightarrow$ Var($[p_t] | N_{ch}$) is the squared width of $P(\delta p_t | N_{ch})$
- The width of $[p_t]$ fluctuation has two contributions :



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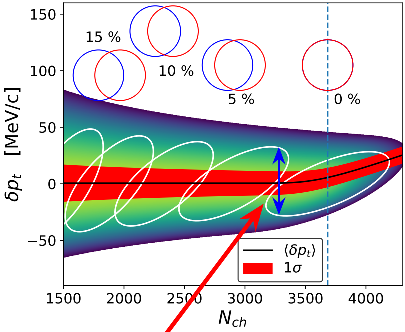
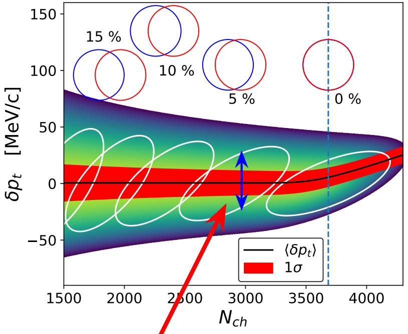


fluctuation from the variation of b (several ellipses contribute)

Fit result : $P(N_{ch}, \delta p_t)$

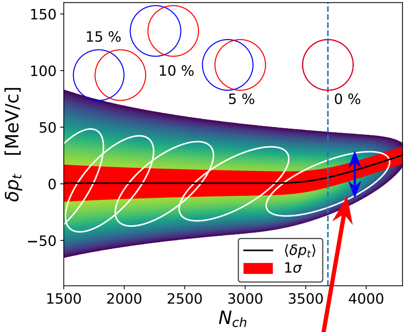
- We get, $P(N_{ch}, \delta p_t)$
  $= \int P(N_{ch}, \delta p_t | b) P(b) db$
- By conditional probability
  $P(\delta p_t | N_{ch}) = \frac{P(N_{ch}, \delta p_t)}{P(N_{ch})}$
  $\Longrightarrow$ Var($[p_t] | N_{ch}$) is the squared width of $P(\delta p_t | N_{ch})$
- The width of $[p_t]$ fluctuation has two contributions :
  1. due to fluctuation of impact parameter b
  2. the true intrinsic fluctuation



fluctuation of $[p_t]$ at fixed b and fixed N_{ch} (height of a single ellipse)

Fit result : $P(N_{ch}, \delta p_t)$

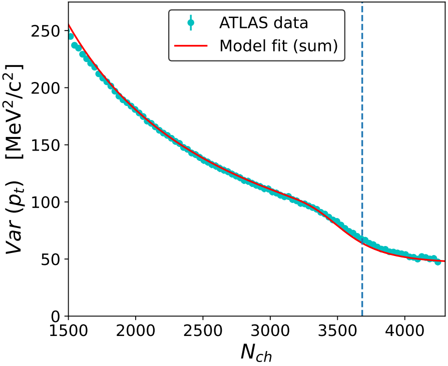
- We get, $P(N_{ch}, \delta p_t) = \int P(N_{ch}, \delta p_t | b) P(b) db$
- By conditional probability $P(\delta p_t | N_{ch}) = \frac{P(N_{ch}, \delta p_t)}{P(N_{ch})}$ $\Longrightarrow \mathrm{Var}([p_t] | N_{ch})$ is the squared width of $P(\delta p_t | N_{ch})$
- The width of $[p_t]$ fluctuation has two contributions :
  1. due to fluctuation of impact parameter b
  2. the true intrinsic fluctuation
- Only the second term contributes above knee in the ultracentral regime.



Only the second term remains in ultracentral collisions

Fit result : $Var([p_t])$ vs N_{ch}

- Our simple model naturally reproduces the steep fall in the ATLAS data very well !



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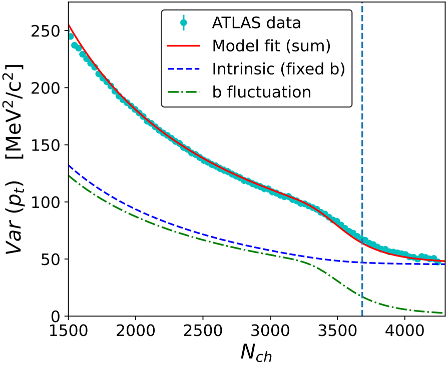
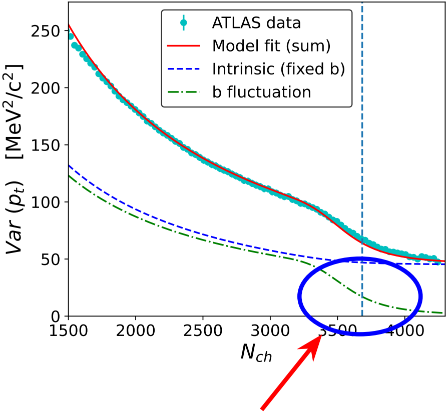


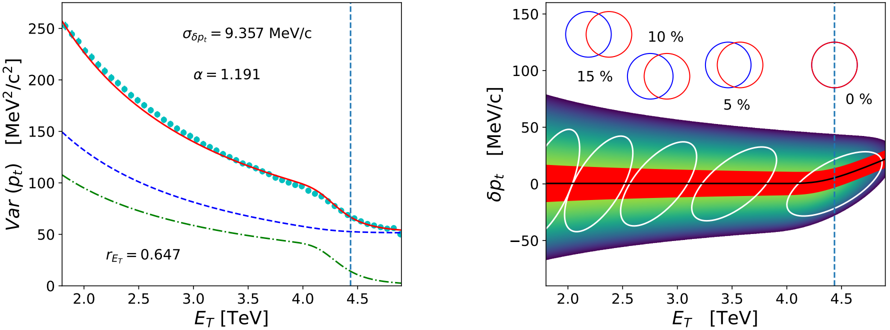
Fit result : $Var([p_t])$ vs N_{ch}

- Our simple model naturally reproduces the steep fall in the ATLAS data very well !
- Below the knee, half of the contribution is from impact parameter fluctuation
- The contribution gradually disappears around the knee !



Contribution of b-fluctuation disappears above knee

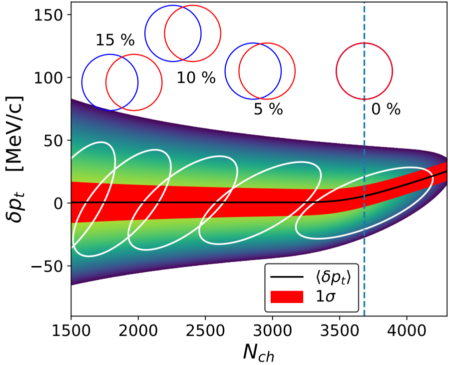
E_T-dependent $[p_t]$-fluctuation (ATLAS)



Impact parameter fluctuation is small !

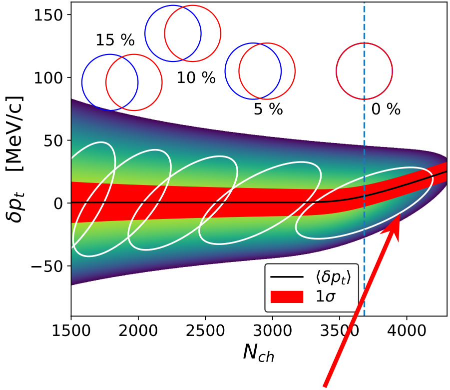
Hint of Thermalization !

- Our model fit returns r = 0.676 !



Hint of Thermalization !

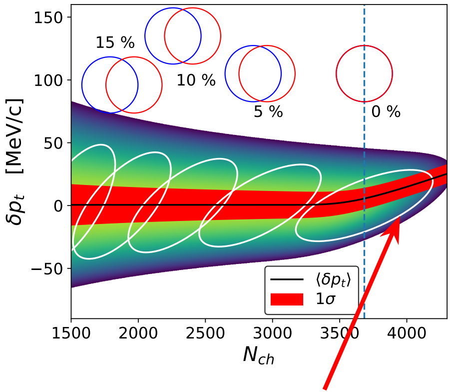
- Our model fit returns r = 0.676 !
- It suggests strong correlation between $[p_t]$ and N_{ch} at fixed b



Strong correlation between $[p_t]$ and N_{ch} at fixed b from our model fit

Hint of Thermalization !

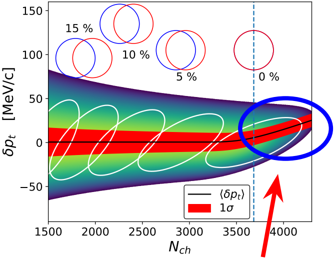
- Our model fit returns $r = 0.676$!
- It suggests strong correlation between $[p_t]$ and N_{ch} at fixed b
- **thermalization is at work ?**

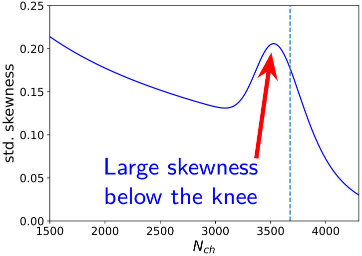


Strong correlation between $[p_t]$ and N_{ch} at fixed b from our model fit

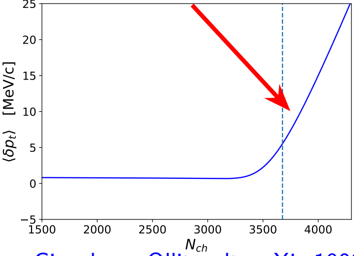
Further predictions : Mean, Skewness and kurtosis

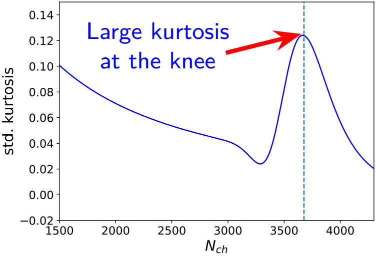
RS, Picchetti, Luzum, Ollitrault, arXiv:2306.09294





Slight increase of mean $[p_t]$
in ultracentral collision





Gardim, Giacalone, Ollitrault, arXiv:1909.11609

$P(\delta p_t | N_{ch}, c_b)$ in terms of k1 and k2

$$P(\delta p_t | N_{ch}, c_b) = \frac{1}{\sqrt{2\pi \kappa_2(c_b)}} \exp\left(-\frac{(\delta p_t - \kappa_1(c_b))^2}{2\kappa_2(c_b)} \right)$$

$$\kappa_1(c_b) = r \frac{\sigma_{p_t}(c_b)}{\sigma_{N_{ch}}(c_b)} (N_{ch} - \overline{N_{ch}}(c_b)),$$

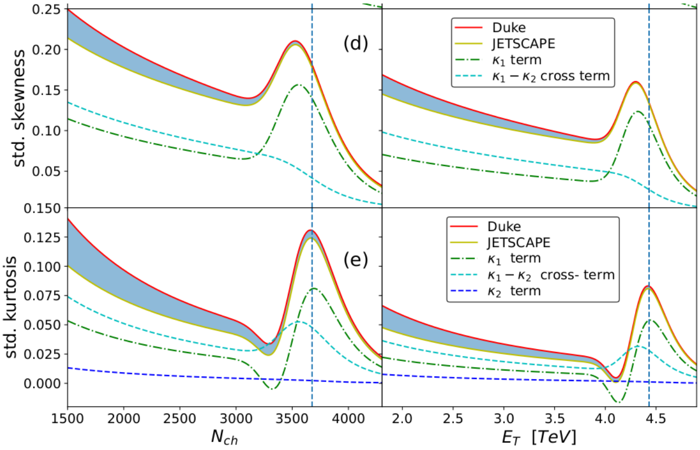
$$\kappa_2(c_b) = (1 - r^2)\sigma_{p_t}^2(c_b).$$

Moments and cumulants of $[p_t]$-fluctuation

$$
\begin{aligned}
\langle \delta p_t | c_b \rangle &= \kappa_1, \\
\left\langle \delta p_t^2 \middle| c_b \right\rangle &= \kappa_1^2 + \kappa_2, \\
\left\langle \delta p_t^3 \middle| c_b \right\rangle &= \kappa_1^3 + 3\kappa_2\kappa_1, \\
\left\langle \delta p_t^4 \middle| c_b \right\rangle &= \kappa_1^4 + 6\kappa_2\kappa_1^2 + 3\kappa_2^2,
\end{aligned}
$$

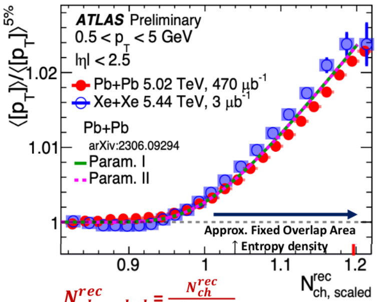
$$
\begin{aligned}
\langle \delta p_t \rangle &= \langle \kappa_1 \rangle, \\
\mathrm{Var}(p_t) &= \left(\langle \kappa_1^2 \rangle - \langle \kappa_1 \rangle^2 \right) + \langle \kappa_2 \rangle, \\
\mathrm{Skew}(p_t) &= \langle \kappa_1^3 \rangle - 3\langle \kappa_1^2 \rangle \langle \kappa_1 \rangle + 2\langle \kappa_1 \rangle^3 \\
&\quad + 3(\langle \kappa_2\kappa_1 \rangle - \langle \kappa_2 \rangle \langle \kappa_1 \rangle), \\
\mathrm{Kurt}(p_t) &= \langle \kappa_1^4 \rangle - 4\langle \kappa_1^3 \rangle \langle \kappa_1 \rangle + 6\langle \kappa_1^2 \rangle \langle \kappa_1 \rangle^2 - 3\langle \kappa_1 \rangle^4 \\
&\quad + 6\left(\langle \kappa_2\kappa_1^2 \rangle - \langle \kappa_2 \rangle \langle \kappa_1^2 \rangle - 2\langle \kappa_2\kappa_1 \rangle \langle \kappa_1 \rangle \right. \\
&\quad \left. + 2\langle \kappa_2 \rangle \langle \kappa_1 \rangle^2 \right) + 3\left(\langle \kappa_2^2 \rangle - \langle \kappa_2 \rangle^2 \right),
\end{aligned}
$$

Anatomy of skewness and kutosis prediction !



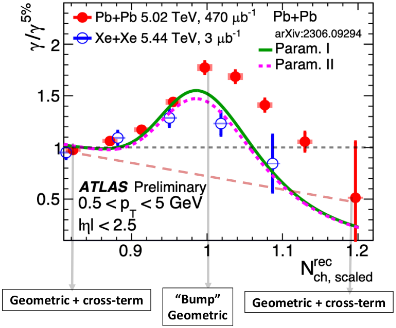
ATLAS Preliminary, presented in QM2023

T.Bold's Bialasowka talk on Oct 27



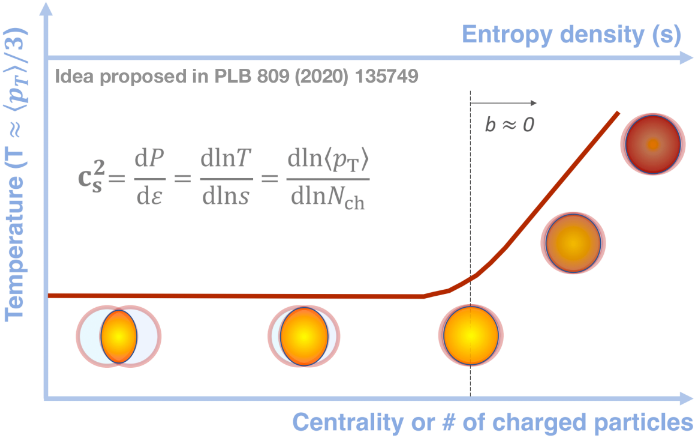
$$N^{rec}_{ch,scaled} = \frac{N^{rec}_{ch}}{N^{rec}_{ch}(1\%)}$$

mean $[p_t]$



$[p_t]$- skewness

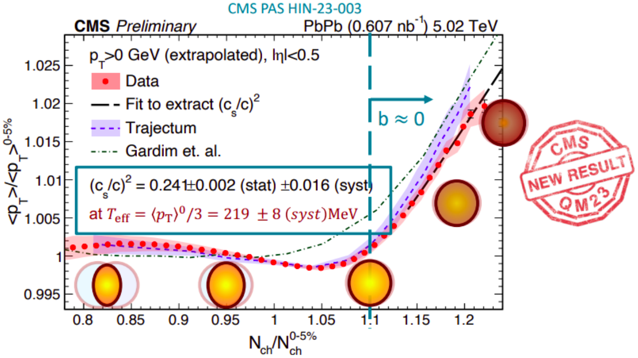
Application : Extraction of speed of sound in QGP from mean $[p_t]$



CMS Result on mean $[p_t]$!

See CMS preliminary in QM 2023

Significant increase of $\langle p_T \rangle$ toward UCC events as predicted by the simulations

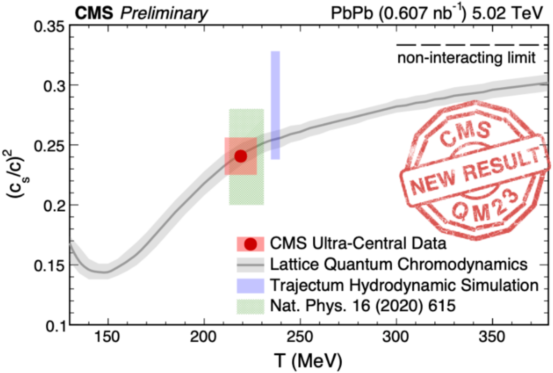


Speed of sound extracted from the fit and T_{eff} from $\langle p_T \rangle^0$

How precise is the measurement ?

See CMS preliminary in QM 2023

CMS PAS HIN-23-003



Speed of sound in QGP is predicted and measured with great precision !!

Summary and Outlook

- Two separate contributions to $[p_t]$ fluctuation :
  1. intrinsic fluctuation $\longrightarrow$ originates from quantum fluctuation in the initial state
  2. impact parameter fluctuation at fixed N_{ch} $\longrightarrow$ disappears in ultracentral region $\longrightarrow$ **causes the steep fall at the knee**

  Our methodology paves a way to separate the geometrical and quantum fluctuations

- We present predictions for mean $[p_t]$, skewness and kurtosis of $[p_t]$-fluctuation $\longrightarrow$ the **unique patterns of the cumulants** of $[p_t]$ fluctuation at the ultracentral regime originates mostly due to b-fluctuation !
- Prediction of increase of mean $[p_t]$ with N_{ch} leads to the precise extraction of speed of sound (c_s^2) in QGP
- **Transverse momentum fluctuation in ultra central collision could be a probe of the thermalization !**

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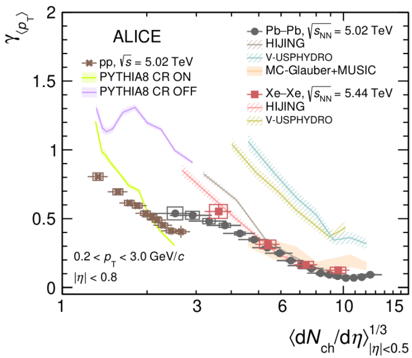
- **Transverse momentum fluctuation in ultra central collision could be a probe of the thermalization !**

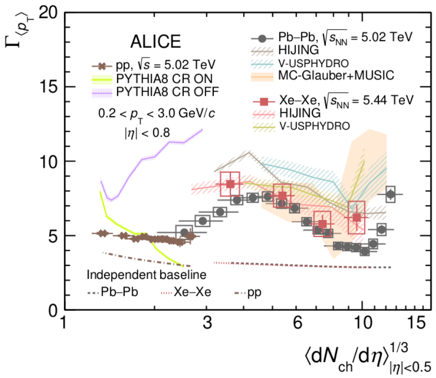
. . . Thank you for your attention !

ALICE Measurements of $[p_t]$-skewness !

arXiv: 2308.16217



standardized $[p_t]$-skewness



intensive $[p_t]$-skewness