Transverse momentum fluctuation in ultra-central Pb+Pb collision

Rupam Samanta

AGH University of Science and Technology, Krakow, Poland

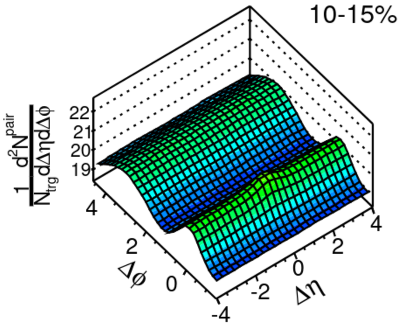
with Somadutta Bhatta, Jiangyong Jia, Matthew Luzum, Jean-Yves Ollitrault

...based on arXiv:2303.15323

NA7-STRONG HFHF 2023, Giardini Naxos, Italy, October 4, 2023

Motivation

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



CMS:1201.3158

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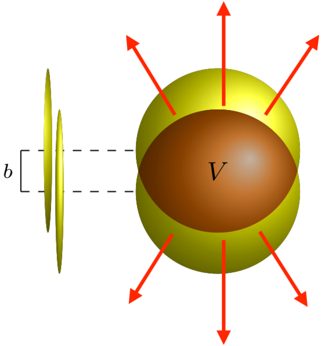
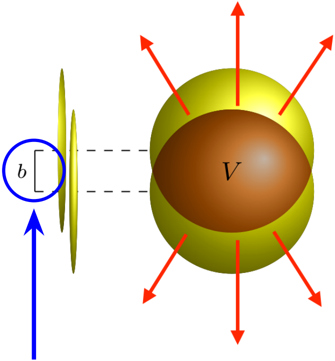
- Evidence is indirect ! $\longrightarrow$ azimuthal distribution of particles is not isotropic $\longrightarrow$ anisotropy driven by pressure gradients within a fluid.



Motivation

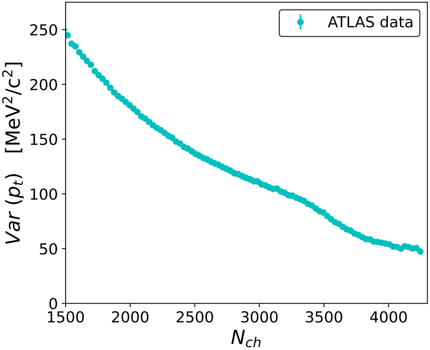
- Experimental evidence for the formation of a little fluid in Pb+Pb collision $\longrightarrow$ azimuthal correlations between particles seen in detectors.
- Evidence is indirect ! $\longrightarrow$ azimuthal distribution of particles is not isotropic $\longrightarrow$ anisotropy driven by pressure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

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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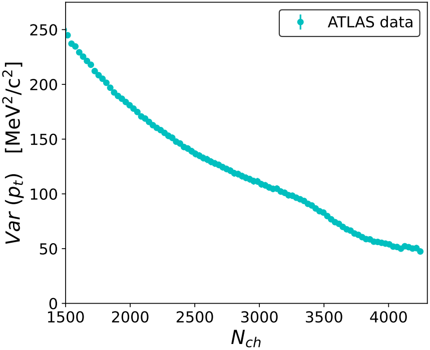

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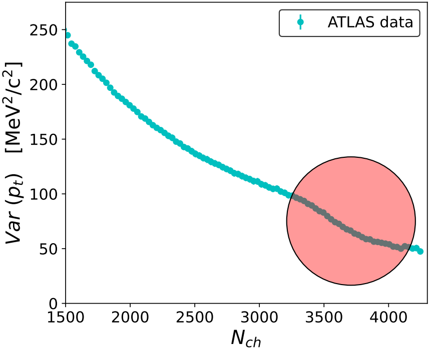

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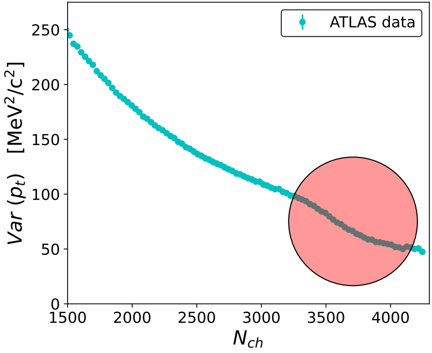
- The relative dynamical fluctuation of $[p_t]$ is very small $\sim 1\ \%$
- Puzzling behavior in ATLAS data : steep decrease over a narrow range of N_{ch}
- We will show that this is a consequence of **thermalization !**



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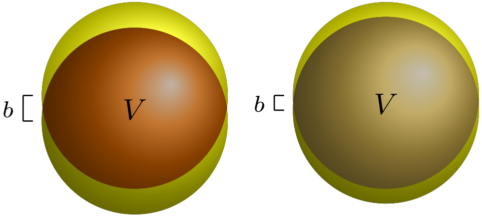
Impact parameter (b) is important !

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



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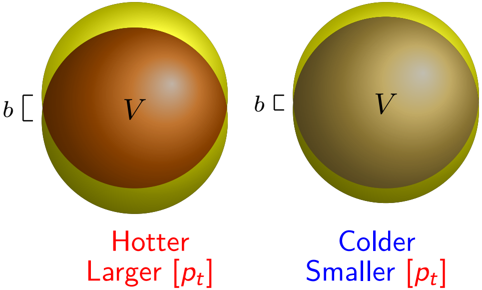
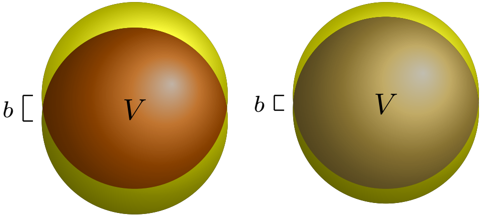


Variation of b at fixed N_{ch}

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 !**



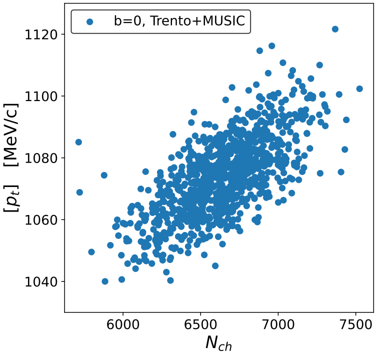
Hotter
Larger $[p_t]$

Colder
Smaller $[p_t]$

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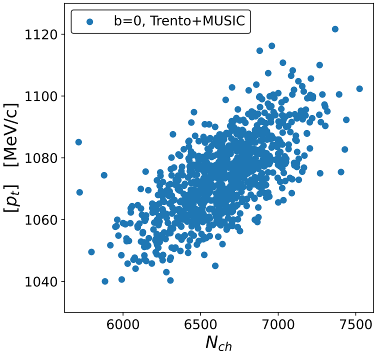
- Significant fluctuation of N_{ch} and modest fluctuation of $[p_t]$. Strong correlation between $[p_t]$ and N_{ch}



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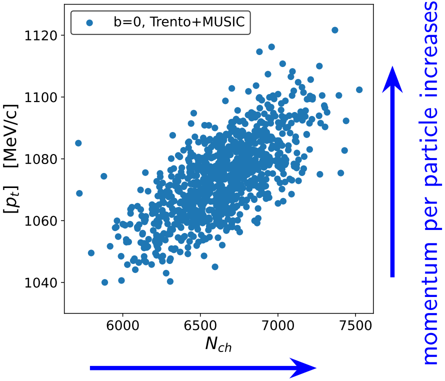
- Significant fluctuation of N_{ch} and modest fluctuation of $[p_t]$. Strong correlation between $[p_t]$ and N_{ch}
- Fixed b $\Longrightarrow$ fixed collision volume
  Larger N_{ch} $\Longrightarrow$ larger density
  $\Longrightarrow$ larger temperature
  $\Longrightarrow$ larger energy per particle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

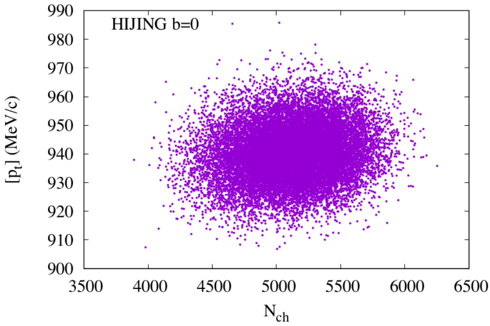


density increases
$\Longrightarrow$ temperature increases

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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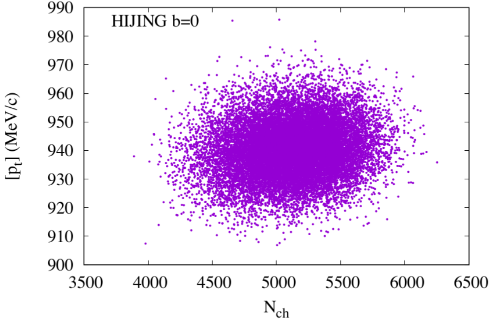
- Very small correlation between N_{ch} and $[p_t] \sim 10 \times$ smaller !!



Pb+Pb @ 5.02 TeV

No thermalization

$\Longrightarrow$ Very little correlation !

Comparing other models : HIJING simulation

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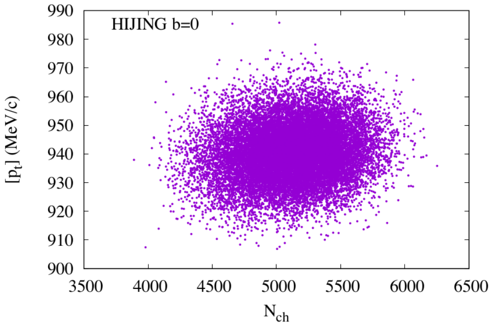
- HIJING: microscopic model of HI collision $\Longrightarrow$ the system doesn't thermalize !
- Very small correlation between N_{ch} and $[p_t]$ $\sim$ 10 $\times$ smaller !!
- Hence the correlation is a signature of thermalization !



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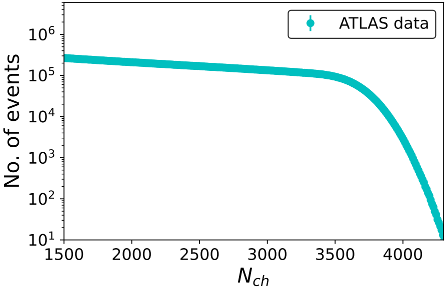
Bayesian reconstruction of P(b $|N_{ch}$)

- 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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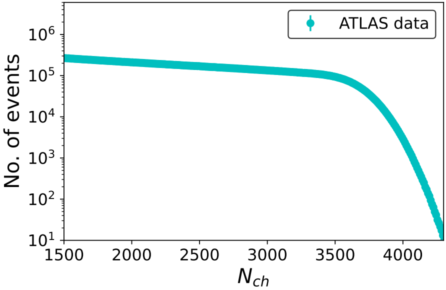

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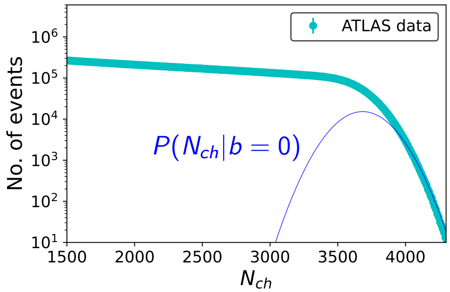
- We assume P(N_{ch}|b) to be **Gaussian !**



N_{ch} distribution at fixed b

Gaussian assupmtion !

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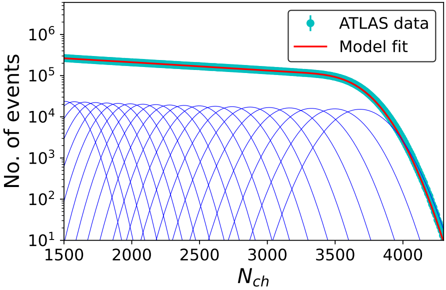
- Fit P(N_{ch}) as sum of Gaussians



Sum of Gaussians at fixed b

Das, Giacalone, Monard, Ollitrault
arXiv:1708.00081

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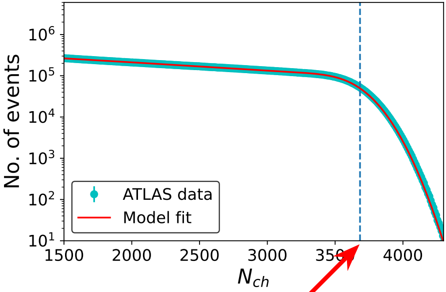
- We precisely reconstruct the knee (mean N_{ch} at b=0)



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

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

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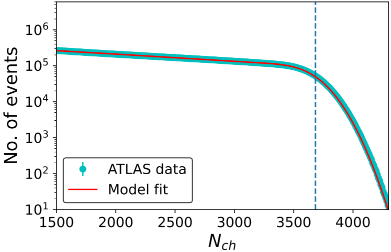
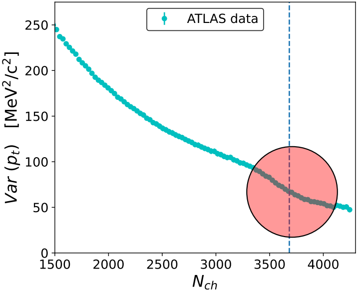
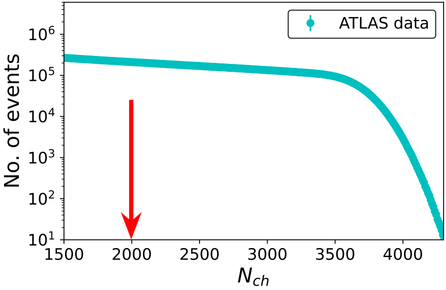
- The steep fall of the variance precisely occur at the knee !

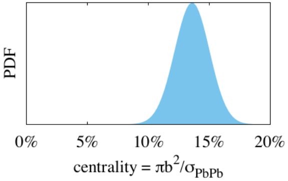




P(b | N_{ch}) from Bayesian reconstruction

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





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

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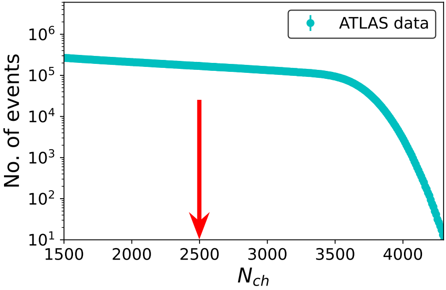
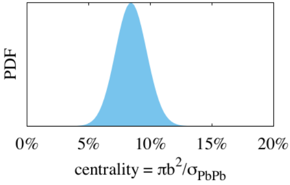
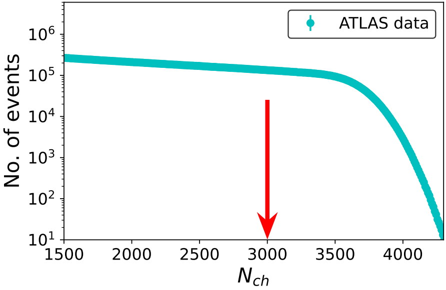
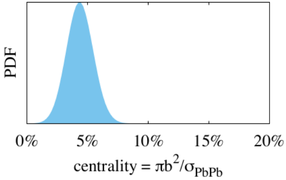




$P(b\,|N_{ch})$ from Bayesian reconstruction

- 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 $b \geq 0$





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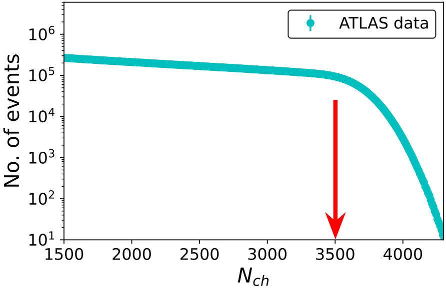

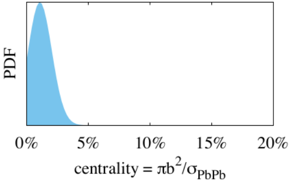

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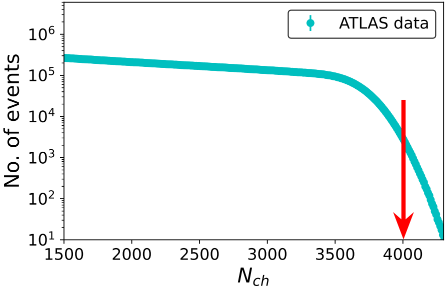
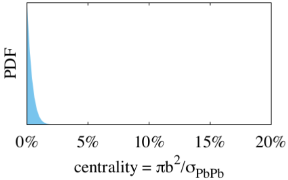
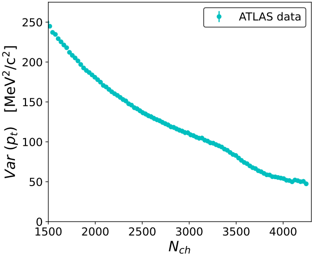
- Above the knee it gets extremely truncated $\Longrightarrow$ the impact parameter fluctuation gradually disappears !

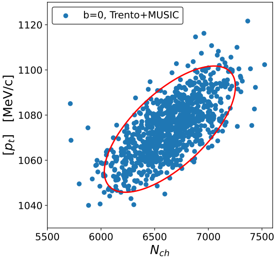




Understanding $[p_t]$ fluctuation data : Parametrizing $P(N_{ch}, [p_t]|b)$

- 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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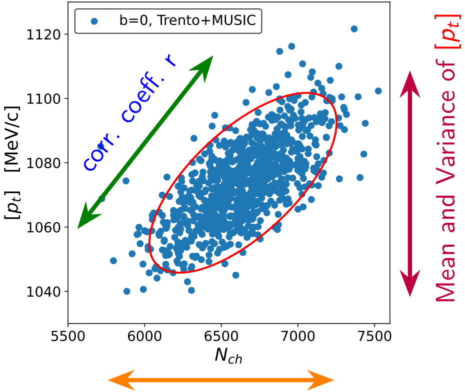

Mean and Variance of N_{ch}

Known from $P(N_{ch})$

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

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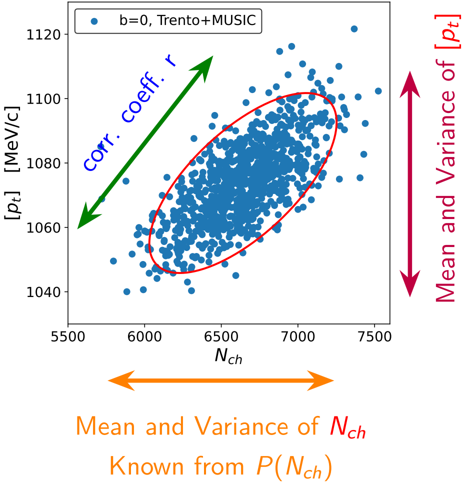
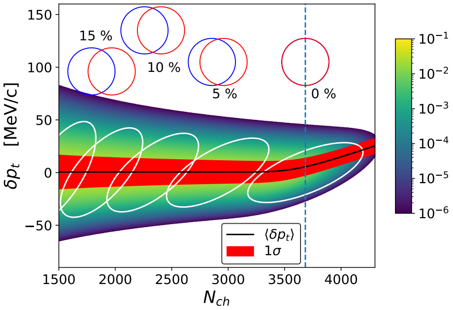
- The distribution has 5 parameters : Mean and variance of N_{ch}, Mean and variance of $[p_t]$ and correlation coefficient r between N_{ch} and $[p_t]$.
- Mean value of $[p_t]$ is constant at fixed b and assuming it is independent of b $\Longrightarrow$ we fit $P(\delta p_t, N_{ch}|b)$ $\delta p_t =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



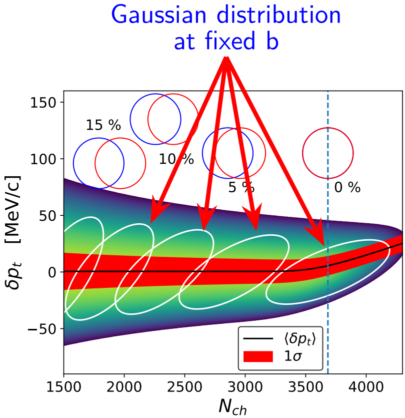
Fit result : $P(N_{ch}, \delta p_t)$



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

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

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



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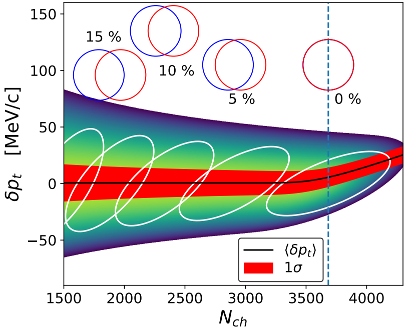

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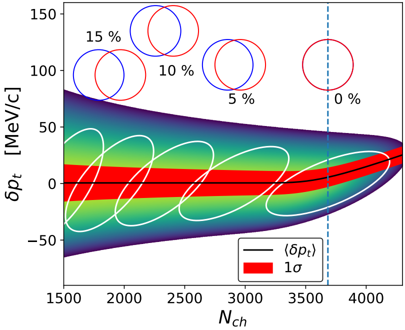

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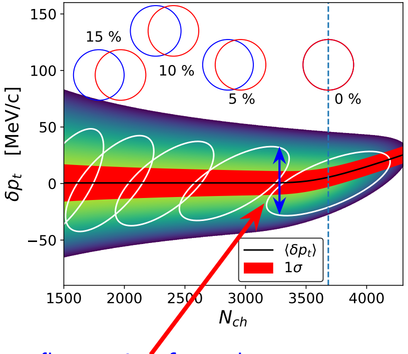
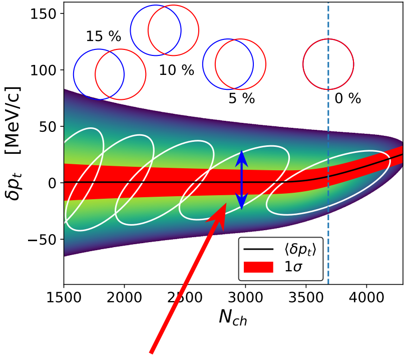
- The width of $[p_t]$ fluctuation has two contributions :
  1. due to fluctuation of impact parameter b



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 $P(\delta p_t | N_{ch}) = \frac{P(N_{ch}, \delta p_t)}{P(N_{ch})}$ $\implies$ 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 : $P(N_{ch}, \delta p_t)$

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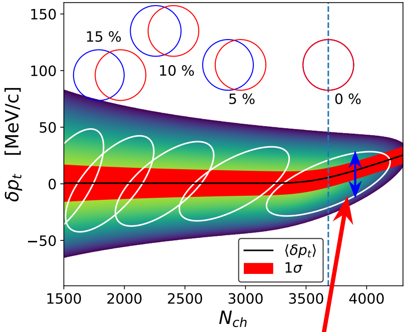
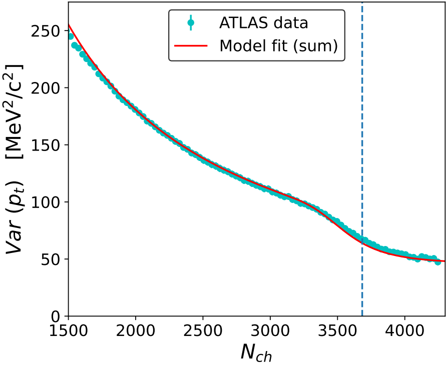
- Only the second term contributes above knee in the ultracentral regime.



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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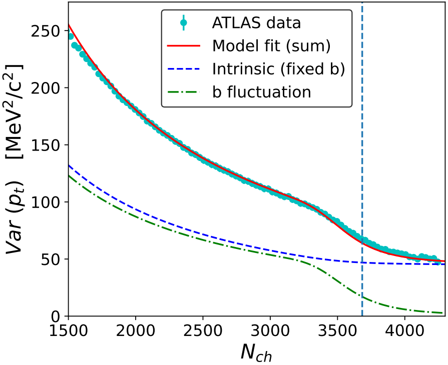
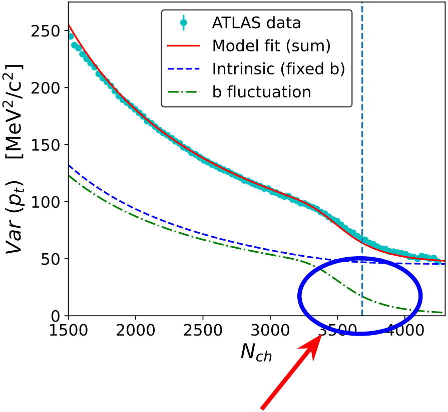


Fit result : $Var([p_t])$ vs N_{ch}

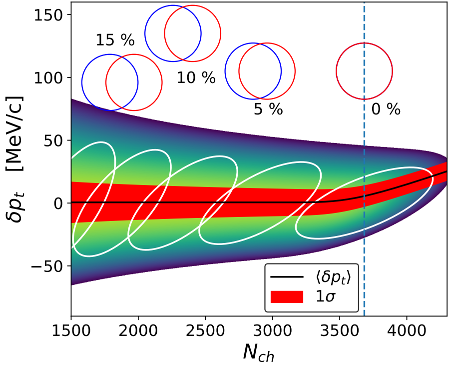
- Our simple model naturally reproduces the steep fall in the ATLAS data very well !
- Below the knee, half of the contribution is from impact parameter fluctuation
- The contribution gradually disappears around the knee !



Contribution of b-fluctuation disappears above knee

Thermalization observed !

- Our model fit returns r = 0.676 !



Thermalization observed !

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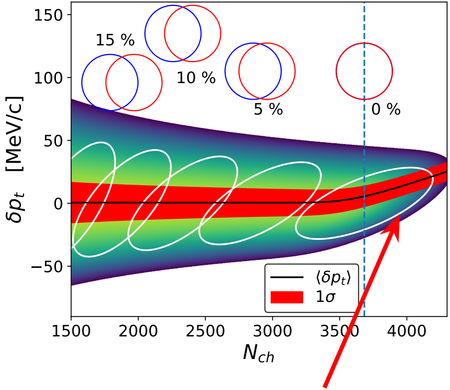
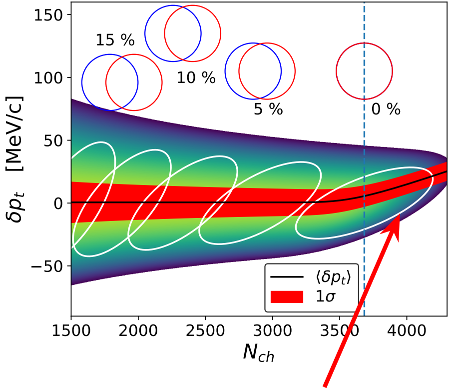


Strong correlation between $[p_t]$ and N_{ch} at fixed b from our model fit

Thermalization observed !

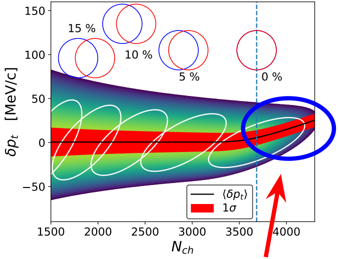
- Our model fit returns r = 0.676 !
- It suggests strong correlation between $[p_t]$ and N_{ch} at fixed b
- Hence **thermalization is observed !**

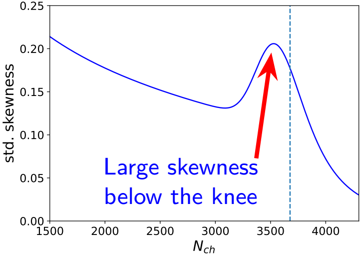


Strong correlation between $[p_t]$ and N_{ch} at fixed b from our model fit

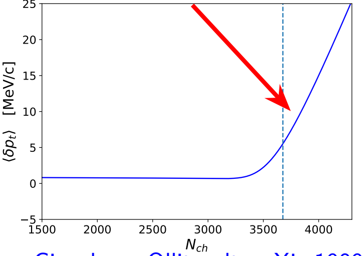
Further predictions !

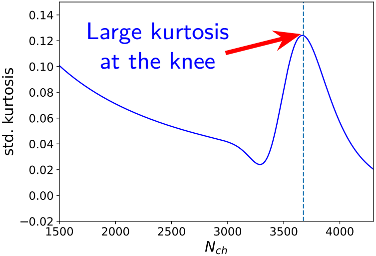
RS, Picchetti, Luzum, Ollitrault, arXiv:2306.09294





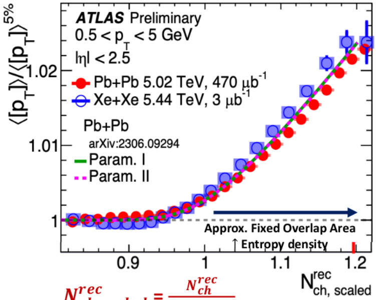
Slight increase of mean $[p_t]$
in ultracentral collision





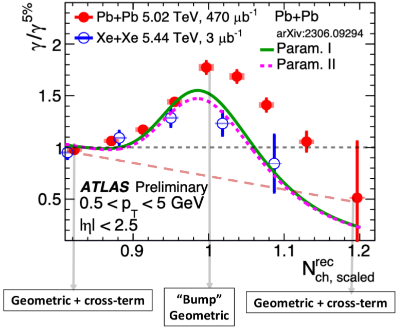
Gardim, Giacalone, Ollitrault, arXiv:1909.11609

ATLAS Preliminary, presented in QM2023



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

mean $[p_t]$



$[p_t]$- skewness

Summary and Outlook

- Impact parameter fluctuation at fixed N_{ch} plays an important role in ultracentral collision !
- 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 $\longrightarrow$ the **unique patterns of the cumulants** of $[p_t]$ fluctuation at the ultracentral regime originates mostly due to b-fluctuation !
- **Transverse momentum fluctuation in ultra central collision provides a new , direct probe of the thermalization !**

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- **Transverse momentum fluctuation in ultra central collision provides a new , direct probe of the thermalization !**

. . . Thank you for your attention !

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

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

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

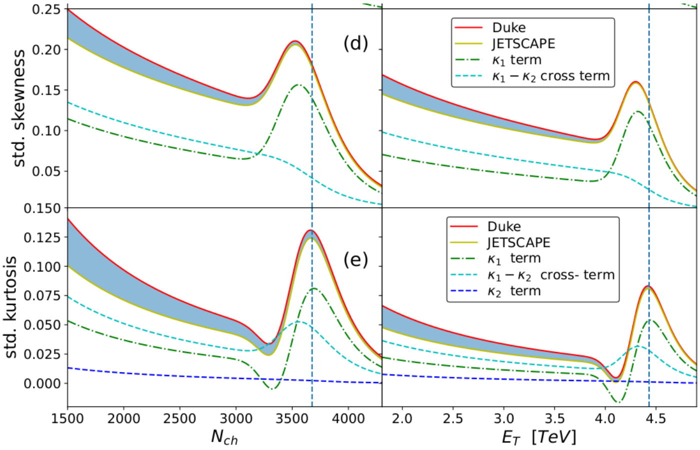
$$\kappa_2(c_b) = (1 - r^2)\sigma_{p_t}^2(c_b).$$

Moments and cumulants of $[p_t]$-fluctuation

$$\langle \delta p_t | c_b \rangle = \kappa_1,$$
$$\left\langle \delta p_t^2 \middle| c_b \right\rangle = \kappa_1^2 + \kappa_2,$$
$$\left\langle \delta p_t^3 \middle| c_b \right\rangle = \kappa_1^3 + 3\kappa_2\kappa_1,$$
$$\left\langle \delta p_t^4 \middle| c_b \right\rangle = \kappa_1^4 + 6\kappa_2\kappa_1^2 + 3\kappa_2^2,$$

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

Detailed structure of skewness and kutosis



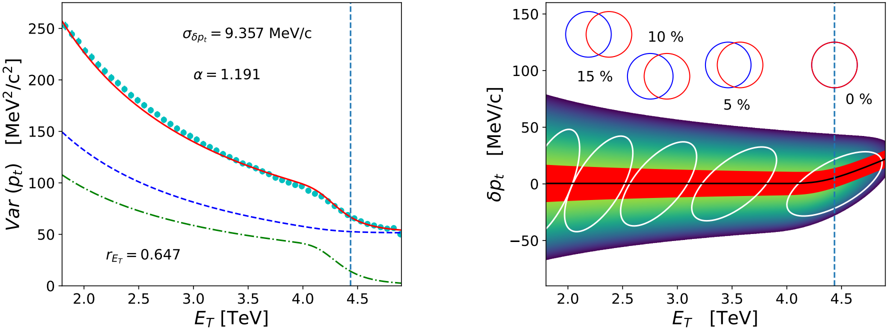
b-dependence of the fit parameters

- 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

E_T-dependent $[p_t]$-fluctuation

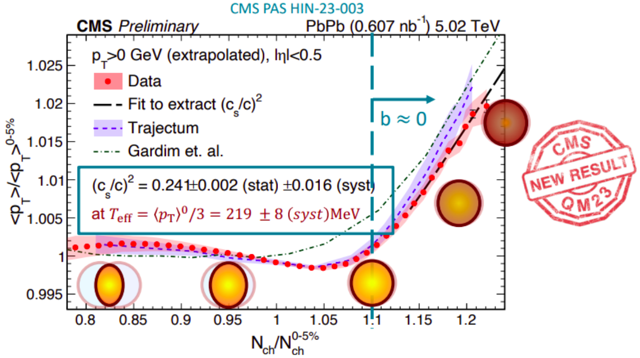


Impact parameter fluctuation is small !

CMS Result on mean $[p_t]$!

See CMS preliminary in QM 2023

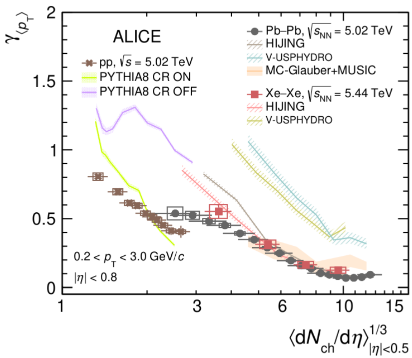
Significant increase of $\langle p_T \rangle$ toward UCC events as predicted by the simulations



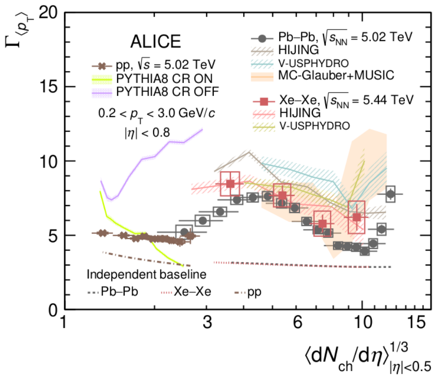
Speed of sound extracted from the fit and $T_{\rm eff}$ from $\langle p_T \rangle^0$

ALICE Measurements of $[p_t]$-skewness !

arXiv: 2308.16217



standardized $[p_t]$-skewness



intensive $[p_t]$-skewness