# Probing the hottest droplet of fluid through collectivity


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10th Asian Triangle Heavy-Ion Conference, Gopalpur, India

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POLISH ACADEMY OF SCIENCES


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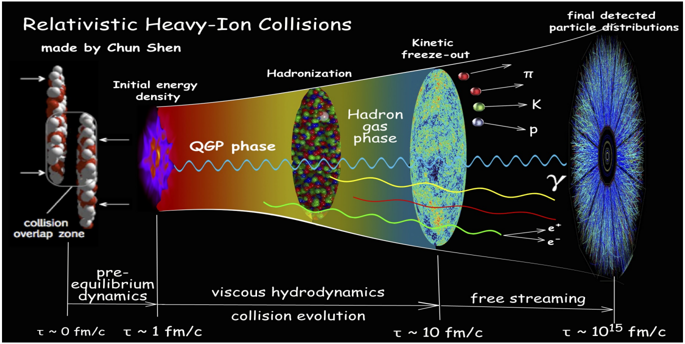
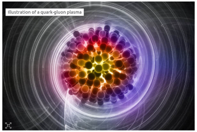
# High energy heavy-ion(HI) collision: “The Little Bang”




Shen, Heinz, arXiv:1507.01558



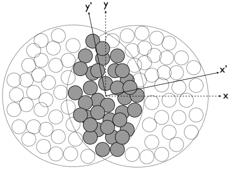

**Boiling water : $10^2$ K**

**Core of the Sun : $10^7$ K**

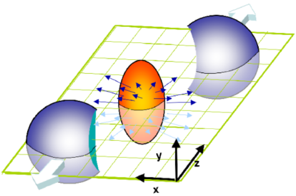
**QGP $\sim$ 212 MeV $\equiv$ $10^{12}$ K !!**

Gardim et al. Nature Physics 16 , 615–619

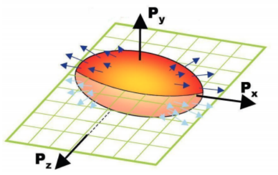
# Classical probe of collectivity : Anisotropic flow




PHOBOS arXiv:0711.3724




U. Heinz, arXiv:0810.5529




BNL: RHIC

**Asymmetry in source distribution** $\Rightarrow$ **Collective expansion of fireball** $\Rightarrow$ **Momentum anisotropy**

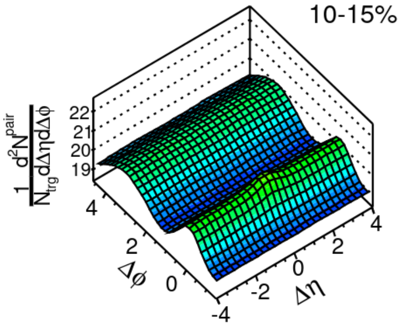
## Modeling momentum anisotropy as fourier expansion

$$\frac{dN}{dp_T d\phi} \propto 1 + 2v_2 \cos\left[2(\phi - \Psi_2)\right] + 3v_3 \cos\left[3(\phi - \Psi_3)\right] + \ldots$$

elliptic flow triangular flow

**Experimental evidence is indirect !**

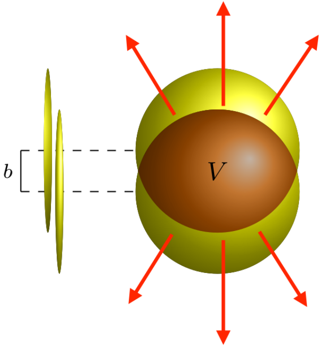
- Experimental evidence for collective dynamics in Pb+Pb collision $\longrightarrow$ azimuthal correlations between particles$\longrightarrow$ understood by near-side peak on ridge-like structures .




CMS:1201.3158

## Experimental evidence is indirect !

- Experimental evidence for collective dynamics in Pb+Pb collision $\longrightarrow$ azimuthal correlations between particles $\longrightarrow$ understood by near-side peak on ridge-like structures .
- Evidence is indirect ! $\longrightarrow$ anisotropic azimuthal distribution of particles is driven by pressure gradients within a fluid $\longrightarrow$ needs to rely on the direction of outgoing particles.



# Modern and more direct probe of collectivity: $[p_T]$-fluctuation

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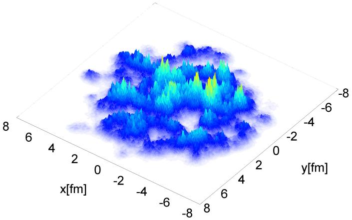


Lumpy structure of the initial density

Schenke, Tribedy, Venugopalan arXiv: 1206.6805

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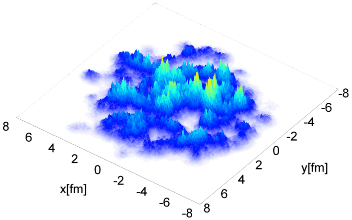


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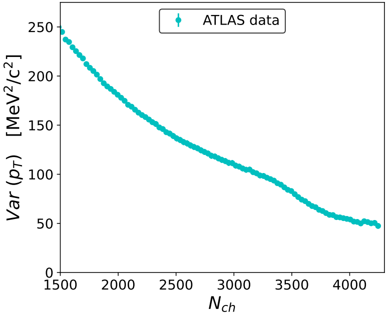


Variance of $[p_T]$ for Pb+Pb @ 5.02 TeV

PhysRevC.107.054910

Table 374 in https://www.hepdata.net/record/ins20754

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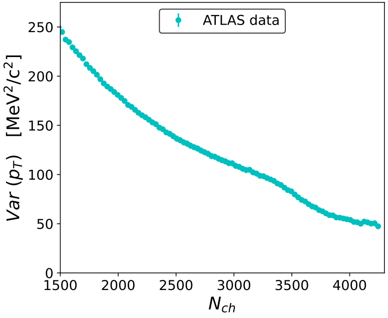
- ATLAS measures true dynamical fluctuation of $[p_T]$ ($\sim 1$ %) as a function of multiplicity ($N_{ch}$).

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RS, Bhatta, Jia, Luzum, Ollitrault Phys.Rev.C 109 (2024) 5, L051902

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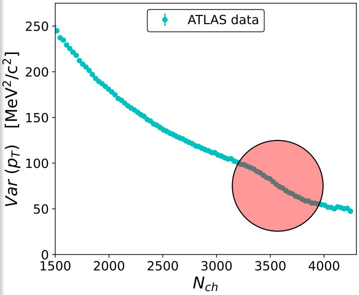
**See S.Bhatta @ Mon, 12:10**

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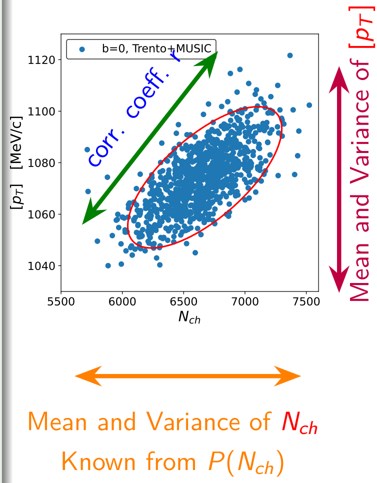

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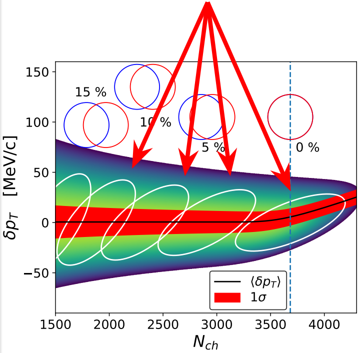
Gaussian distribution at fixed b




2D correlated gaussian distribution of $\delta p_T$ and $N_{ch}$

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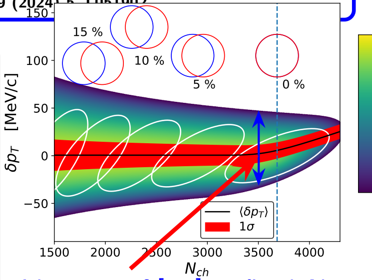
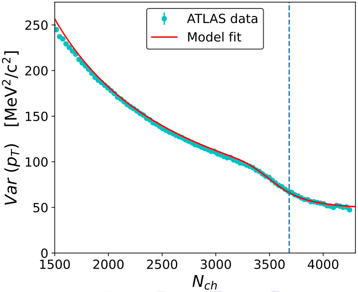



Variance of $[p_T]$ at fixed $N_{ch}$



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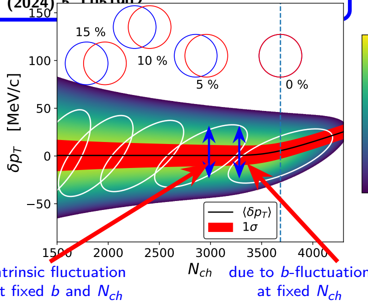


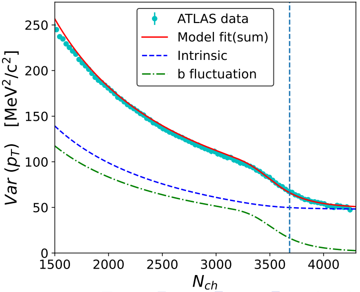

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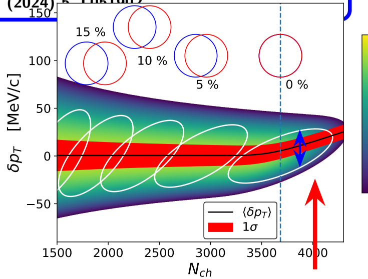
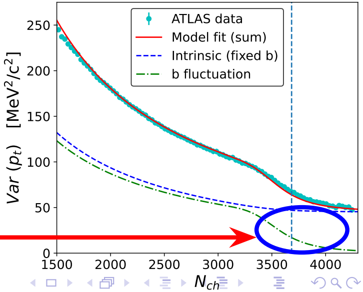
- Below the knee, half of the contribution is from impact parameter fluctuation and other half is due to intrinsic fluctuations
- The contribution of b-fluctuation gradually disappears around the knee !




only intrinsic fluctuation remains in ultracentral collisions



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T. Parida, RS, J-Y. Ollitrault Phys.Lett.B 857 (2024) 138985

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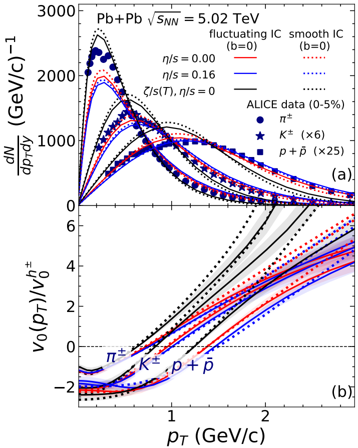


Spectra and $v_0(p_T)/v_0$ for identified particles

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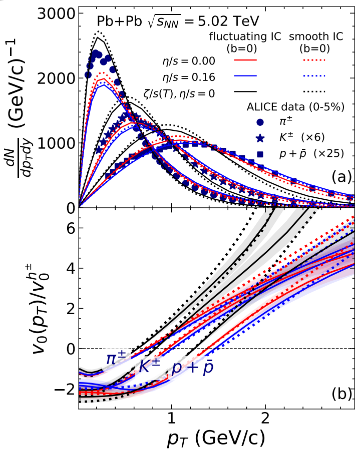


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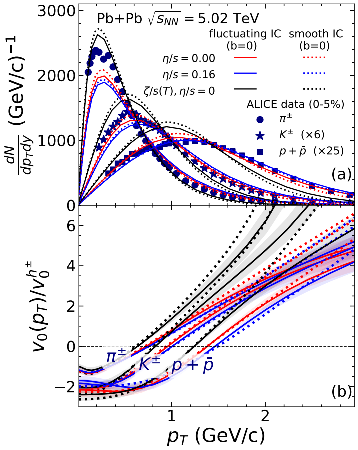


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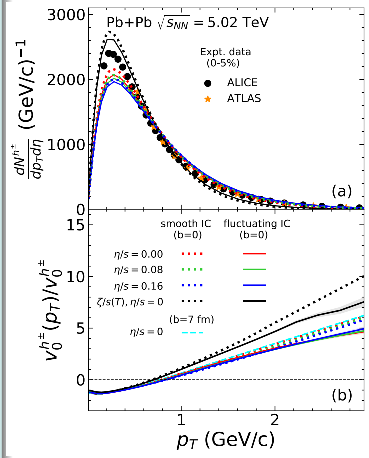


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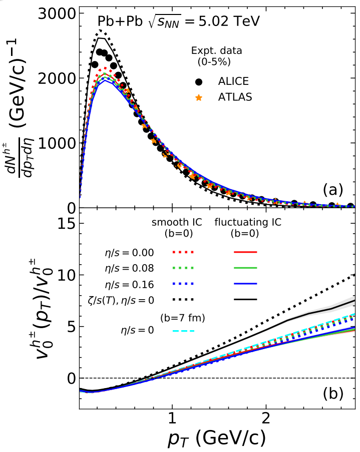
- Difference : insensitive to $\eta/s$, little sensitivity to bulk viscosity.

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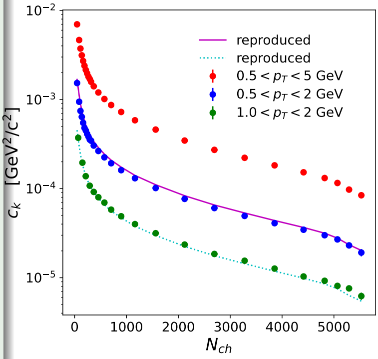
# Mapping the $p_T$-cut dependence using $v_0(p_T)$

T. Parida, RS, J-Y. Ollitrault Phys.Lett.B 857 (2024) 138985

- $v_0(p_T)/v_0$ can be used to capture $p_T$-acceptance effect on observables through correction factor $C_A$ :

$$C_{\mathcal{A}} \equiv \frac{1}{N_{0\mathcal{A}}\langle p_T\rangle_{\mathcal{A}}} \int_{p_T\in\mathcal{A}} (p_T - \langle p_T\rangle_{\mathcal{A}}) \frac{v_0(p_T)}{v_0} N_0(p_T)$$




**Stay tuned for more details @ QM25 by Tribhuban Parida**

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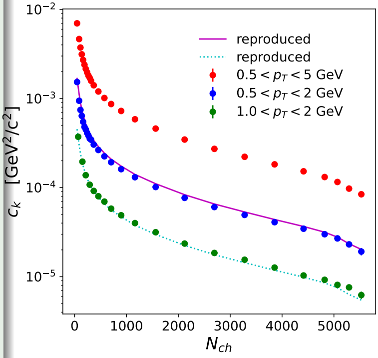
- Then, one can relate :

$$v_{0,\mathcal{A}} = C_{\mathcal{A}} \times v_0$$

$$\Longrightarrow \quad \frac{\sigma_{p_T,\mathcal{A}}}{\langle p_T \rangle_{\mathcal{A}}} = C_{\mathcal{A}} \times \frac{\sigma_{p_T}}{\langle p_T \rangle}.$$

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# Moving towards smaller system : multiplicity fluctuation in p+Pb

RS, J-Y. Ollitrault Phys.Lett.B 855 (2024) 138834

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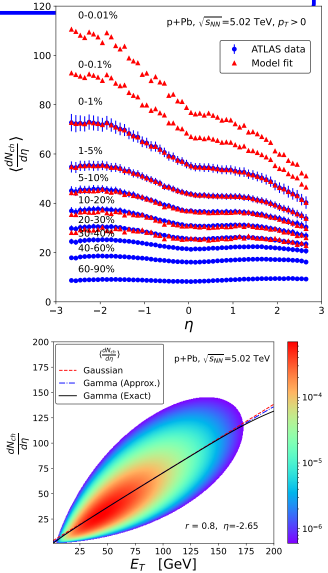

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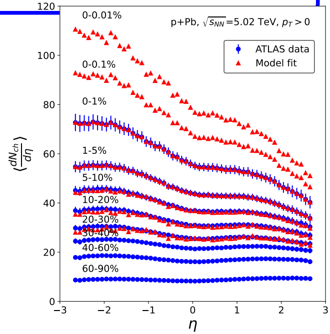


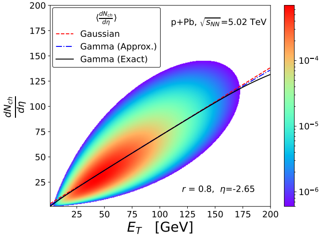

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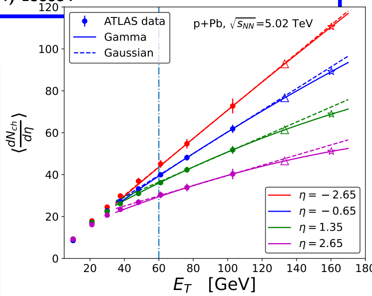


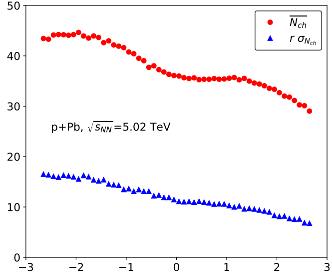

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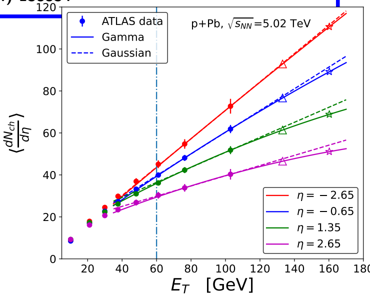
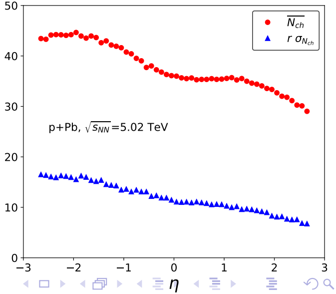
- By fitting the two most centralities, we make robust predictions on multiplicities for more central bins.
- Using different centrality classifier covering a different rapidity window $\longrightarrow$ **direct information on rapidity decorrelation ($r$).**



# Outlook

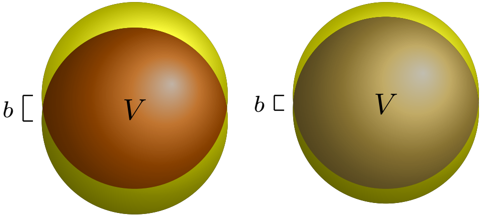
- 30 years of collectivity $\longrightarrow$ first measurement in 2001 !
- **Proposing new probes $\longrightarrow$ better understanding of the QGP medium properties and dynamics**
- Moving towards smaller systems :
  1. $[p_T]$-fluctuation in p+Pb collision
  2. Collectivity in O+O collision : recent surging interests, arXiv: 2103.03345, 2308.06078, 2404.08385, 2404.09780, 2407.15065 $\longrightarrow$ probing its $\alpha$-clustered structure.
- Big questions that need to be answered :
  1. How does flow generate in small systems ? Can we describe collectivity in Pb+Pb, p+Pb and p+p system in a consistent way ? Is QGP formed in all of these systems ? Christiansen and Mechelen, arXiv:2412.02672, ALICE Collaboration, arXiv:2411.09323 (see S. Tripathy @ Tue, 11:10)
  2. **Can we apply hydrodynamics in those systems ? . . .**

Thank you !

**Backup**

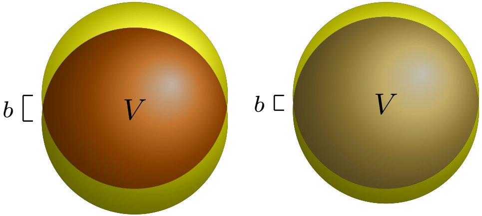
**Impact parameter (b) is important !**

- In experiment b is not known ! $\Longrightarrow$ $[p_T]$ fluctuation is measured for 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 !



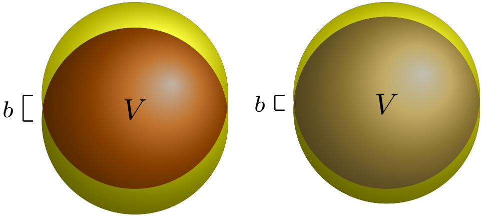

Hotter
Larger $[p_T]$

Colder
Smaller $[p_T]$

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 !**



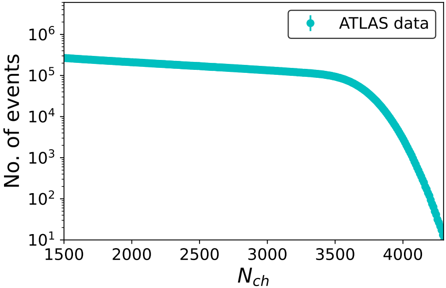

Hotter
Larger $[p_T]$

Colder
Smaller $[p_T]$

Variation of b at fixed $N_{ch}$

# 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 !

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

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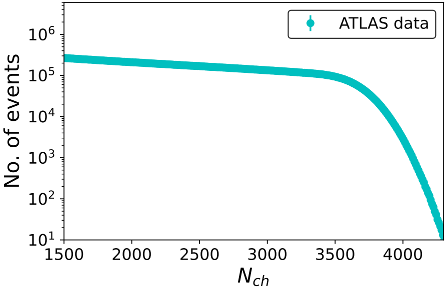
  P(b $|N_{ch}$) P($N_{ch}$)=P($N_{ch}$|b) P(b)

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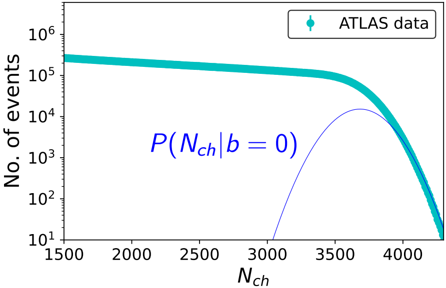
- We assume P($N_{ch}$|b) to be **Gaussian !**




$N_{ch}$ distribution at fixed b

Gaussian assupmtion !

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

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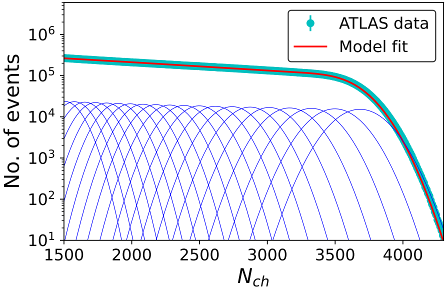
- We assume P($N_{ch}$|b) to be **Gaussian !**
- Fit P($N_{ch}$) as sum of Gaussians




Sum of Gaussians at fixed b

Das, Giacalone, Monard, Ollitrault
arXiv:1708.00081

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

- First we solve the inverse problem:
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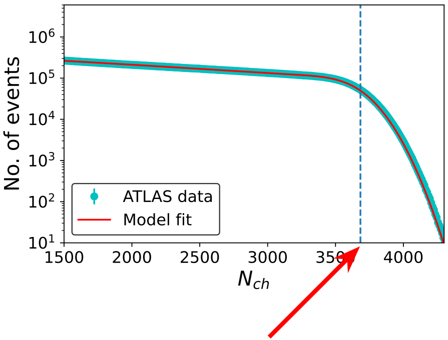
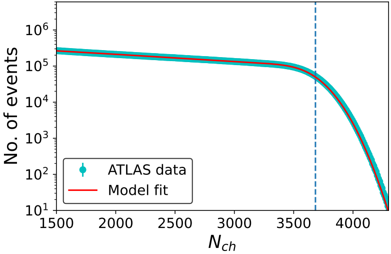
  P(b $|N_{ch}$) P($N_{ch}$)=P($N_{ch}$|b) P(b)
- We assume P($N_{ch}$|b) to be **Gaussian !**
- Fit P($N_{ch}$) as sum of Gaussians
- We precisely reconstruct the knee (mean $N_{ch}$ at b=0)

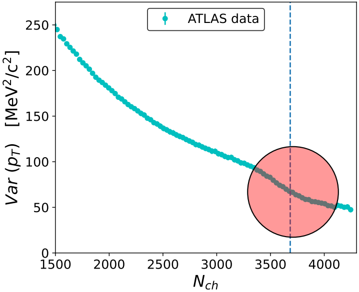



Precise construction of knee
$\langle N_{ch}|b = 0\rangle$

# 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) ?
- Then we apply Bayes' theorem to find P(b $|N_{ch}$):
  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 !



## b-dependence of the fit parameters

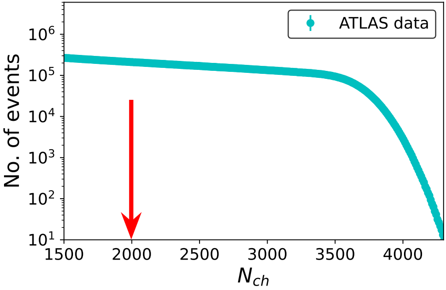
- We assume mean $[p_T]$ to be independent of b
- We assume Var($[p_T]$) is a smooth function of mean multiplicity :

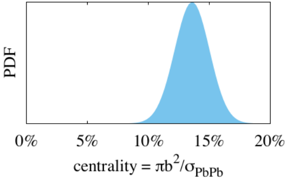
$$\sigma {p_T}^2 \left( \frac{\langle N_{ch}(0) \rangle}{\langle N_{ch}(b) \rangle} \right)$$

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

# 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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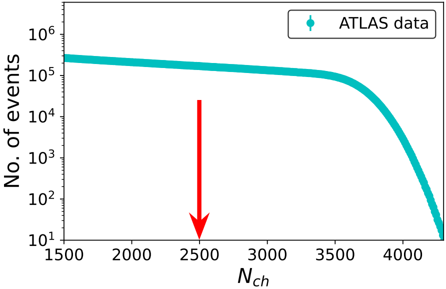
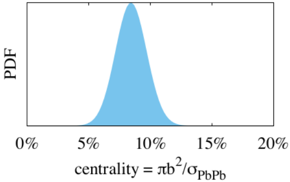
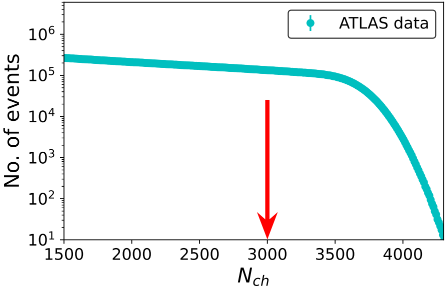
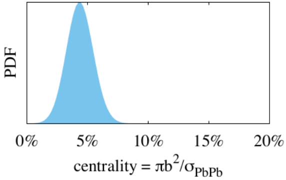


# P(b $|N_{ch}$) from Bayesian reconstruction

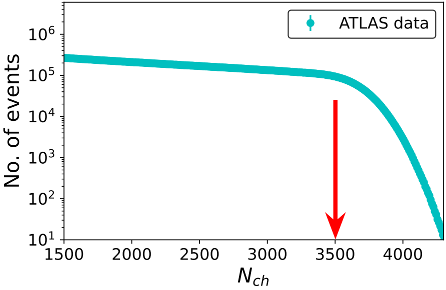
- At smaller $N_{ch}$ the distribution P($b|N_{ch}$) is a full Gaussian
- But as we move closer and closer to the knee, P($b|N_{ch}$) becomes truncated due to the limit b $\geq$ 0

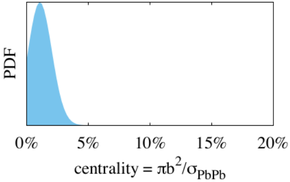


# P($\mathbf{b}$ $|N_{ch}$) from Bayesian reconstruction

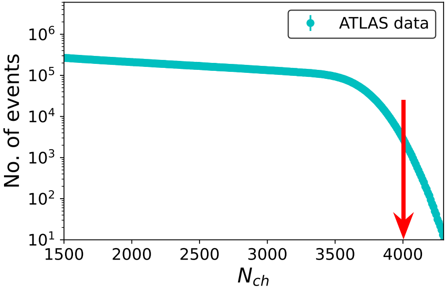
- At smaller $N_{ch}$ the distribution P($b|N_{ch}$) is a full Gaussian
- But as we move closer and closer to the knee, P($b|N_{ch}$) becomes truncated due to the limit b $\geq$ 0

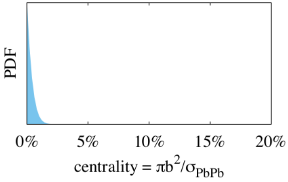


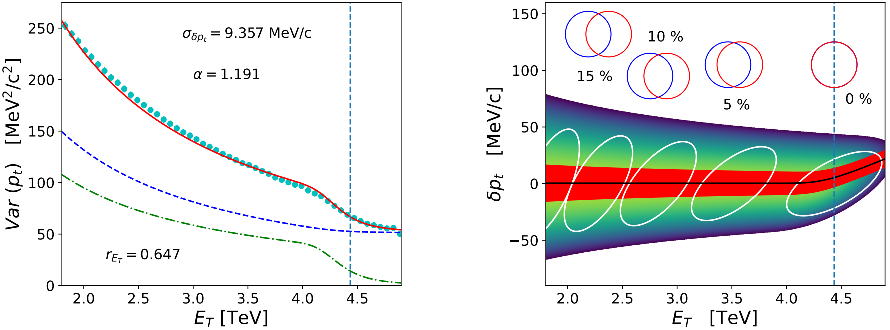
# P($b$ | $N_{ch}$) from Bayesian reconstruction

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



# $E_T$-dependent $[p_T]$-fluctuation




Impact parameter fluctuation is small !

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

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

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

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

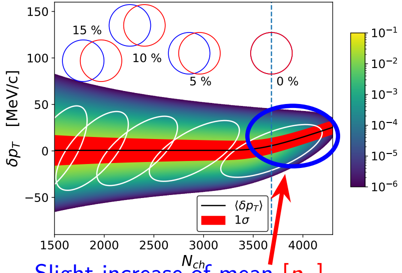
# Moments and cumulants of $[p_t]$-fluctuation

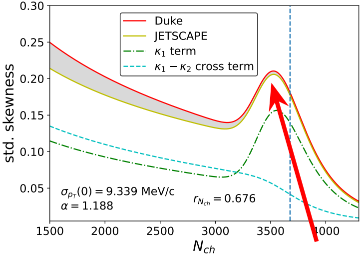
$$\langle \delta p_t | c_b \rangle = \kappa_1,$$
$$\left\langle \delta p_t^2 \middle| c_b \right\rangle = \kappa_1^2 + \kappa_2,$$
$$\left\langle \delta p_t^3 \middle| c_b \right\rangle = \kappa_1^3 + 3\kappa_2\kappa_1,$$
$$\left\langle \delta p_t^4 \middle| c_b \right\rangle = \kappa_1^4 + 6\kappa_2\kappa_1^2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

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

# Further predictions : Mean, Skewness and kurtosis

RS, Picchetti, Luzum, Ollitrault Phys.Rev.C 108 (2023) 2, 024908

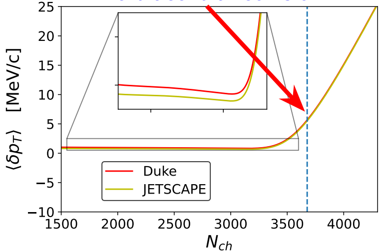


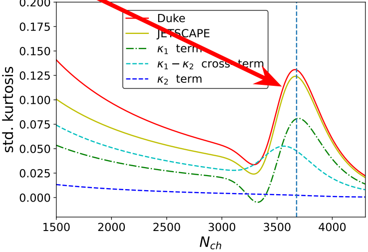




Slight increase of mean $[p_T]$ in ultracentral collision

Large kurtosis at the knee

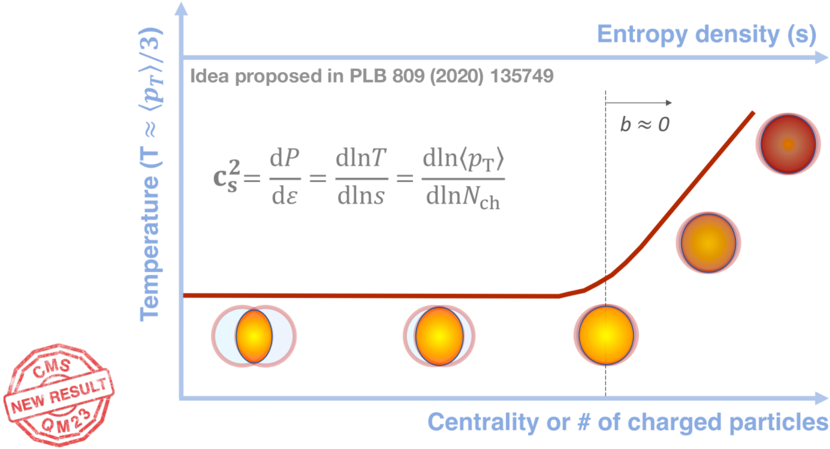
Large skewness below the knee




Gardim, Giacalone, Ollitrault, arXiv:1909.11609

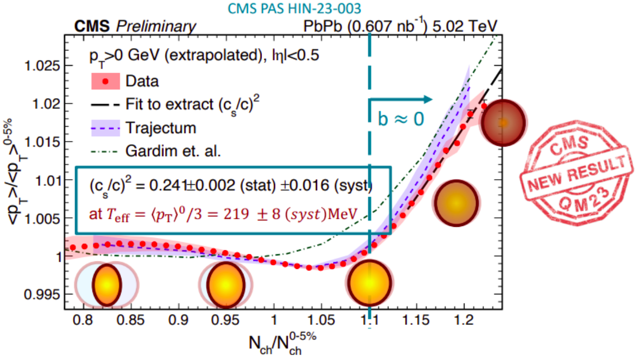
# Application : Extraction of speed of sound in QGP from mean $[p_T]$



## CMS Result on mean $[p_T]$ !

**Rept.Prog.Phys. 87 (2024) 7, 077801**

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

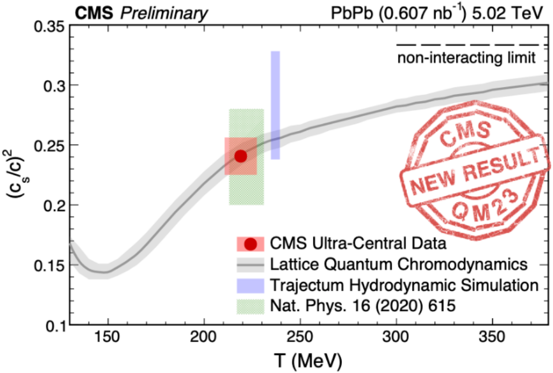



Speed of sound extracted from the fit and $T_{\rm eff}$ from $\langle p_T \rangle^0$

**How precise is the measurement ?**

**Rept.Prog.Phys. 87 (2024) 7, 077801**

CMS PAS HIN-23-003




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