Probing the hottest droplet of fluid through correlations and fluctuations

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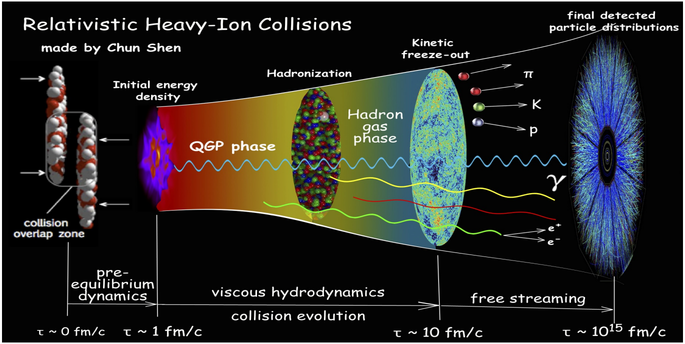
THE HENRYK NIEWODNICZAŃSKI
INSTITUTE OF NUCLEAR PHYSICS
POLISH ACADEMY OF SCIENCES

XVII Polish Workshop on Relativistic Heavy-Ion Collisions: Phase diagram and Equation of State of strongly interacting matter

NATIONAL SCIENCE CENTRE POLAND

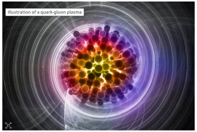
High energy heavy-ion(HI) collision: “The Little Bang”



Shen, Heinz, arXiv:1507.01558

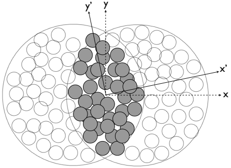
Boiling water : 10^2 K

Core of the Sun : 10^7 K

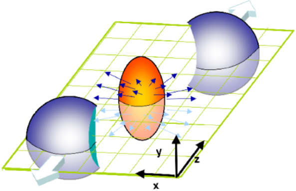


QGP $\sim$ 212 MeV $\equiv$ 10^{12} K !!

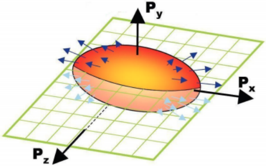
Gardim et al. Nature Physics 16 , 615–619



PHOBOS arXiv:0711.3724



U. Heinz, arXiv:0810.5529



BNL: RHIC

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

Modeling the anisotropy : Harmonic flow

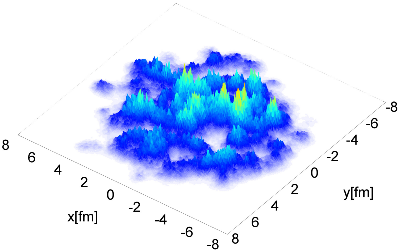
Momentum anisotropy as fourier expansion of flow harmonics

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

elliptic flow triangular flow

Fluctuations 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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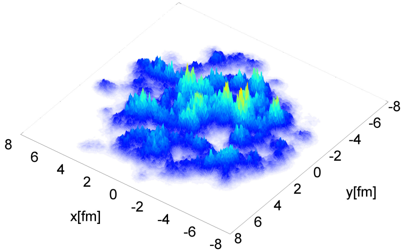
- Event-by-event fluctuation of initial state.
- All final state collective observables ,N_{ch}, $[p_T]$, V_n fluctuates event-by-event.



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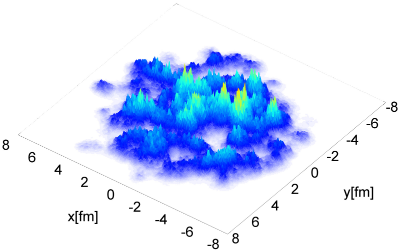
Fluctuations in HI collision

- Event-by-event fluctuation of initial state.
- All final state collective observables ,N_{ch}, $[p_T]$, V_n fluctuates event-by-event.
- Could be a combination of **classical or geometrical** (b fluctuation), **quantum or intrinsic** (at fixed b) and **statistical fluctuation**.



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Probing flow-fluctuation : Factorization breaking coefficients

P. Bozek, RS PRC 105, 034904 (2022)

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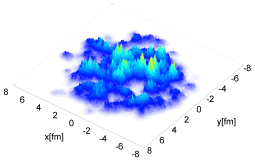
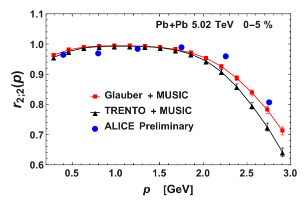


Schenke, Tribedy, Venugopalan arXiv: 1206.6805

- Flow vector, $V_n = |V_n|\ e^{i\ n\Psi_n}$
  $|V_n| \to$ Flow magnitude & $\Psi_n \to$ Flow angle
- **Event by event(ebe) flow vector(V_n) fluctuation $\to$ ebe flow magnitude($|V_n|$) fluctuation + ebe flow angle(Ψ_n) fluctuation**

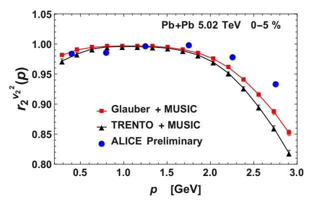
(flow vector)^2-(flow vector)^2 decor.

$$r_{n;2}(p) = \frac{\langle V_n^2 V_n^*(p)^2 \rangle}{\sqrt{\langle |V_n|^4 \rangle \ \langle |V_n(p)|^4 \rangle}}$$



(flow magnitude)^2-(flow magnitude)^2

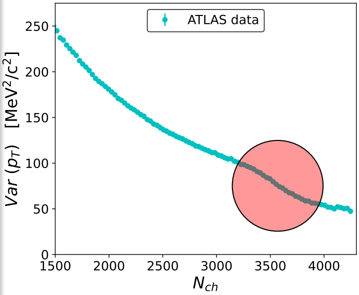
$$r_n^{v_n^2}(p) = \frac{\langle |V_n|^2 |V_n(p)|^2 \rangle}{\sqrt{\langle |V_n|^4 \rangle \ \langle |V_n(p)|^4 \rangle}}$$



Fluctuations of mean transverse momentum per particle ($[p_T]$)

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

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



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

PhysRevC.107.054910

Table 374 in https://www.hepdata.net/record/ins20

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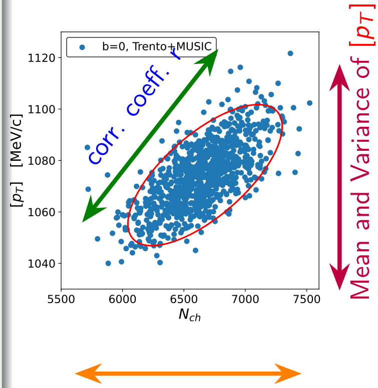

Mean and Variance of N_{ch}

Known from $P(N_{ch})$

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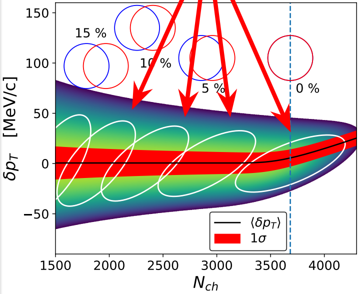
Gaussian distribution at fixed b



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

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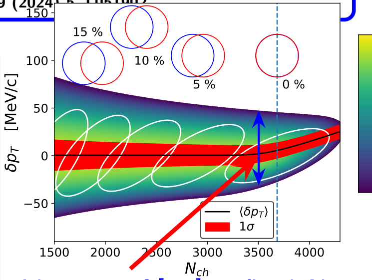
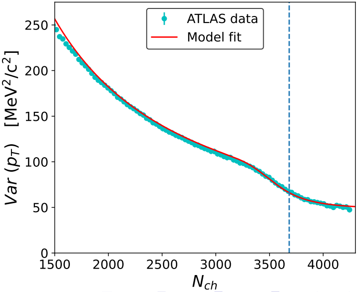


Variance of $[p_T]$ at fixed N_{ch}



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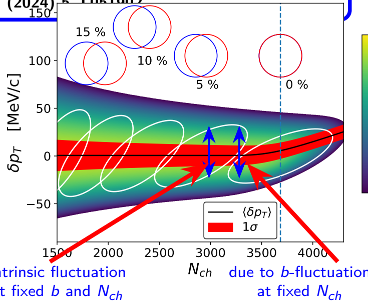

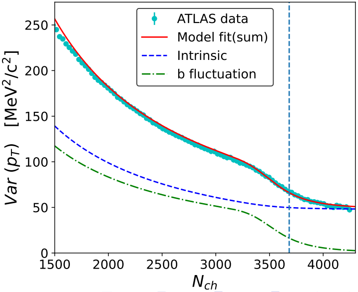

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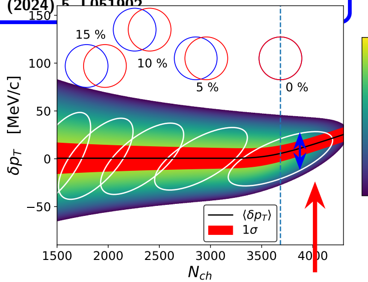
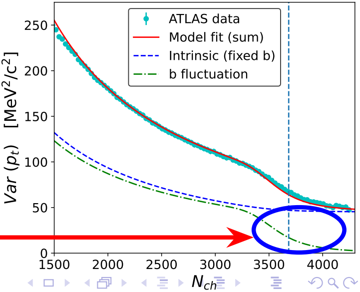
- Below the knee, half of the contribution is from impact parameter fluctuation and other half is due to intrinsic fluctuations
- The contribution of b-fluctuation gradually disappears around the knee !



only intrinsic fluctuation remains in ultracentral collisions



Probing initial state correlation : Correlation between $[p_T]$ and v_n^2

P. Bozek, PRC 93, 044908 (2016), P. Bozek, RS, PRC 104, 014905 (2021)

- **Pearson's correlation coefficient** between $[p_T]$ and v_n^2 (Bozek's correlator) :

$$\rho([p_T], v_n^2) = \frac{\langle [p_T]\ v_n^2 \rangle - \langle [p_T] \rangle \langle v_n^2 \rangle}{\sqrt{(\langle [p_T]^2 \rangle - \langle [p_T] \rangle^2)(\langle (v_n^2)^2 \rangle - \langle v_n^2 \rangle^2)}}$$

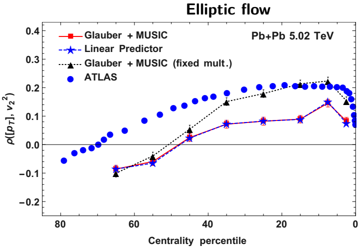
$\langle \ldots \rangle \implies$ average over events

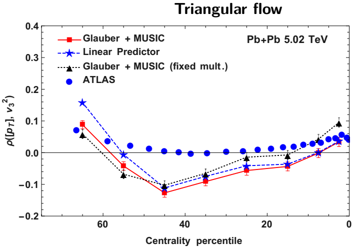
- To map initial state of collision, **linear predictor** for $[p_T]$ and v_n :

$$[p_T] = f(R, S, \epsilon_n^2) \quad \textit{and} \quad v_n^2 = f(\epsilon_n^2, R, S)$$

- R = rms radius of the overlap area
- S = total initial entropy
- ϵ_n = initial eccentricity

- $\rho([p_T], v_2^2)$: model result **qualitatively** describe the data, change of sign occur at more peripheral collision.

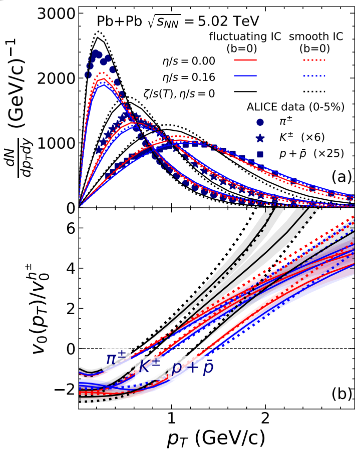




Novel probe of collectivity : $[p_T]$ - 'Spectra' correlation ($v_0(p_T)$)

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

- First introduced by Teaney et al., similar to anisotropic flow (long range correlation, mass ordering at low p_T).



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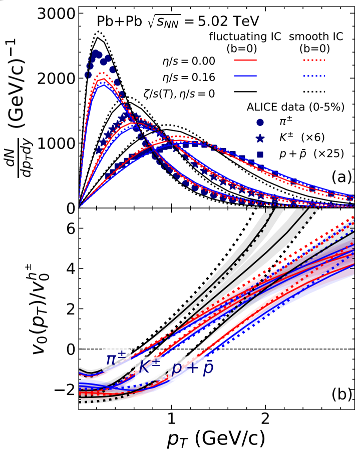

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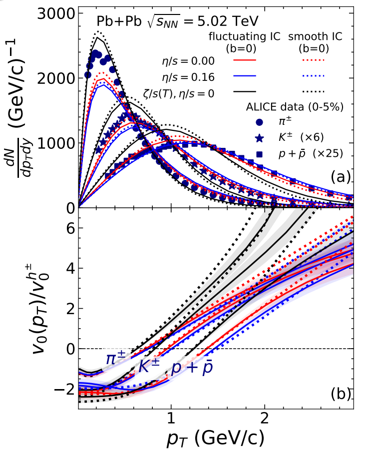

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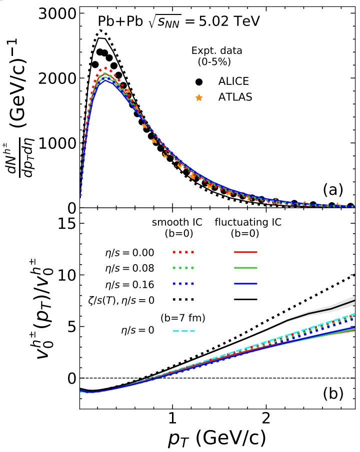

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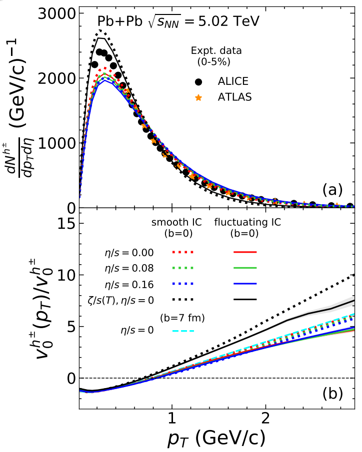
- The scaled quantity $v_0(p_T)/v_0$ is independent of centrality (same observed for $v_n(p_T)/v_n$ by ATLAS !).
- Can constrain medium properties. Difference : sensitive to bulk viscosity only.



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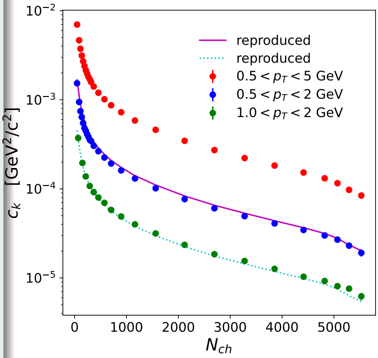
- $v_0(p_T)/v_0$ can be used to capture p_T-acceptance effect on observables through correction factor C_A :

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

- Then, one can relate :

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

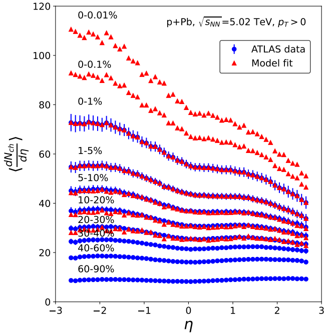
$$\Longrightarrow \quad \frac{\sigma_{p_T,\mathcal{A}}}{\langle p_T\rangle_{\mathcal{A}}} = C_{\mathcal{A}} \times \frac{\sigma_{p_T}}{\langle p_T\rangle}.$$

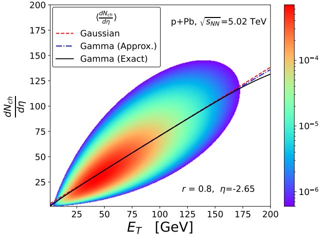


Moving towards smaller system : multiplicity fluctuation in p+Pb

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

- ATLAS presents multiplicity ($dN_{ch}/d\eta$) as a function of η and E_T (centrality estimator) $\longrightarrow$ pseudorapidity dependent correlation between $dN_{ch}/d\eta$ and E_T $\longrightarrow$ long-range correlation $\longrightarrow$ can be modeled by a correlated gamma distribution with two parameters $r * \sigma_{N_{ch}}$ and $\overline{Nch}$





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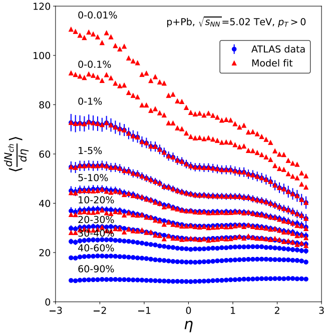

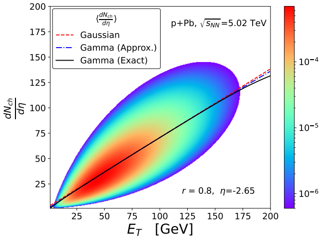

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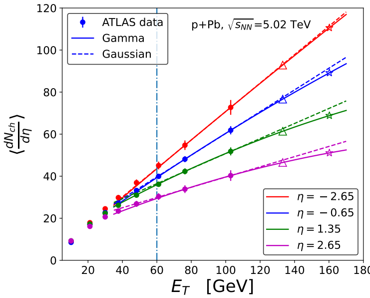

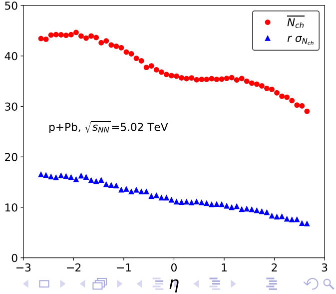

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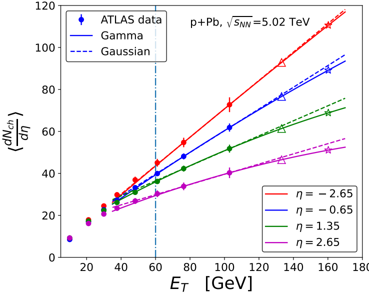
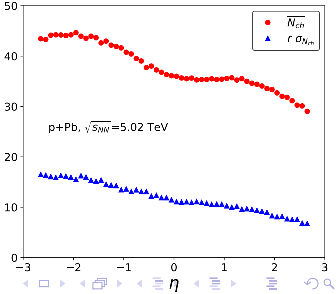
- Impact parameter fluctuation plays negligible role in central collisions (up to 10 %) $\longrightarrow$ **dominated by quantum fluctuations !**
- By fitting the two most centralities, we make robust predictions on multiplicities for more central bins.
- Repeating the same analysis **using different centrality classifier covering a different rapidity window and using the fit parameters, direct information on rapidity decorrelation (r) can be obtained.**





Outlook

- Third decade of collectivity ⟶ first measurement in 2001 !
- **Proposing novel probes ⟶ better understanding of the QGP medium properties and dynamics**
- Moving towards smaller systems :
  1. Collectivity in O+O collision, pioneered by Sivert and Noronha-Hostler arXiv:1901.01319, Rybczynski and Broniowski arXiv: 1910.09489 and recent surging interests, arXiv: 2103.03345, 2308.06078, 2404.08385, 2404.09780, 2407.15065
  2. 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
  3. **Can we apply hydrodynamics in those systems ?**
  4. Machine learning in HI collision...... Mallik et al., arXiv:2203.01246, Hirvonen, Eskola, Niemi, arXiv: 2303.04517, Goswami et al. arXiv: 2404.09839

Thank you !