Soft Probes and Flow

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The University of Birmingham

On behalf of ALICE, ATLAS, CMS and LHCb

LHCP2017

Content

Selection of mostly Pb-Pb results

For more pp and p-Pb see list of talks at the end of my presentation

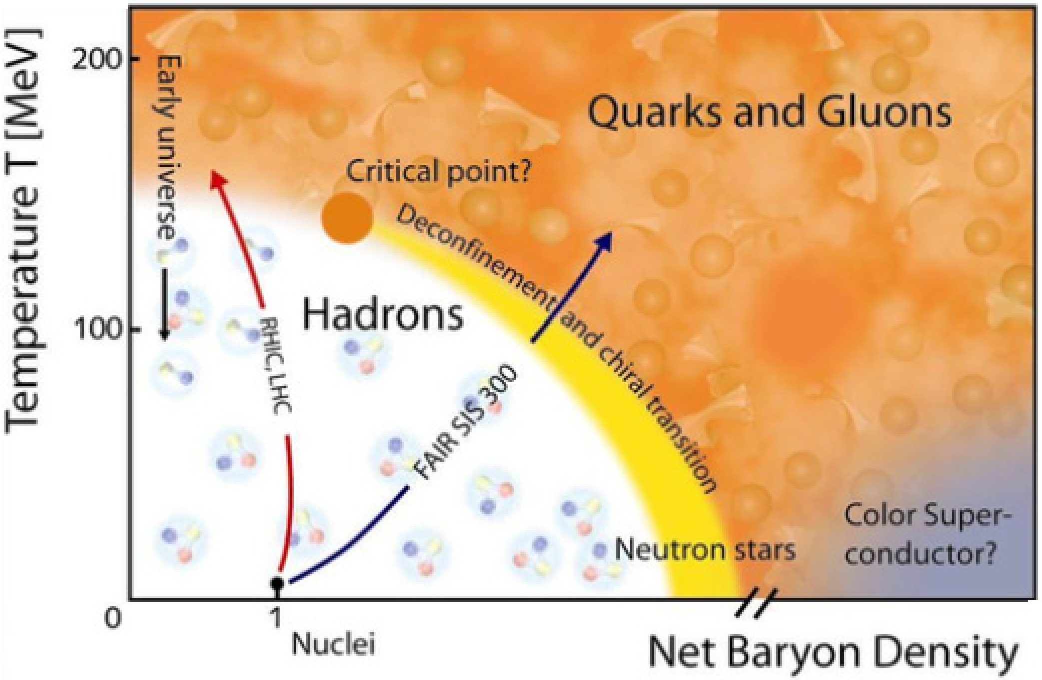
- Introduction to heavy ions
- p_{T} spectra (kinetic freeze-out)
- Yields (chemical freeze-out)
- Anisotropic flow
  - Decomposition of azimuthal spectra:
    - Initial state fluctuations
    - QGP properties – viscosity (η/s)

Goal: study macroscopic properties of strongly interacting matter

The QCD phase transition

The QCD phase transition

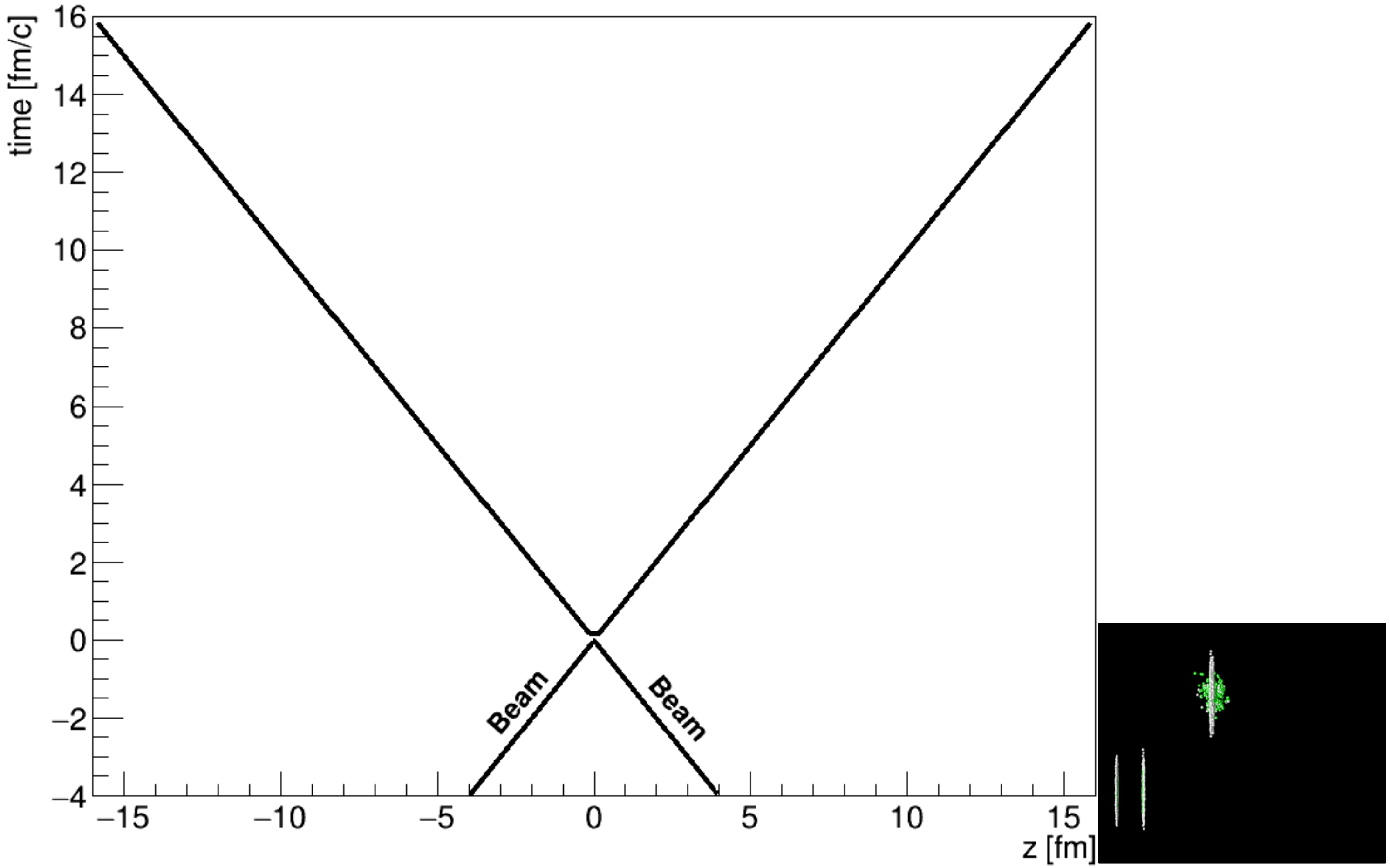
- At LHC net baryon Density ~ 0
- Crossover for physical quark masses
- Confinement and chiral transitions both at $T{\sim}155\ MeV$



Heavy Ion collisions study strongly interacting matter at finite temperature

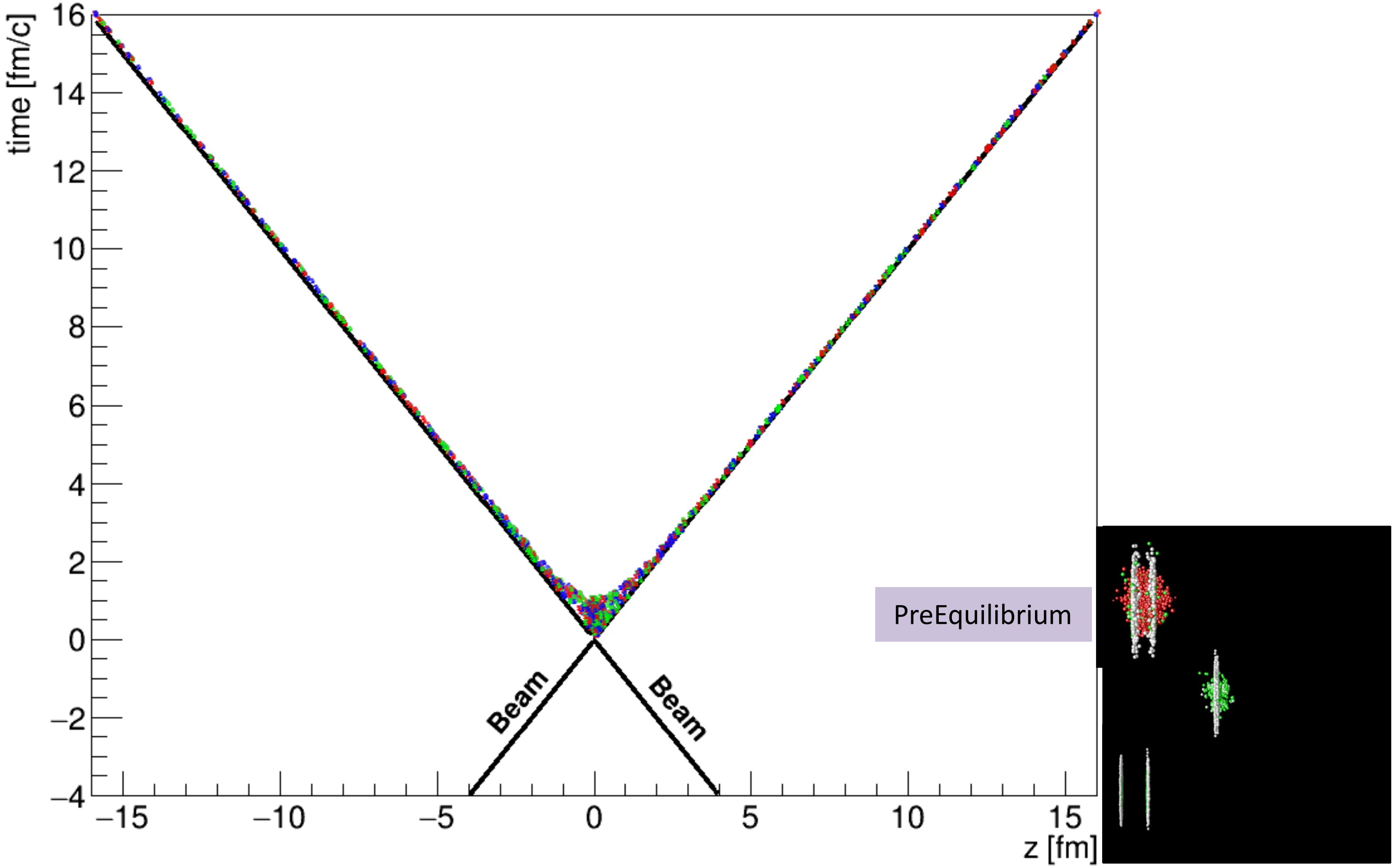
Heavy ion collision

Colliding nuclei



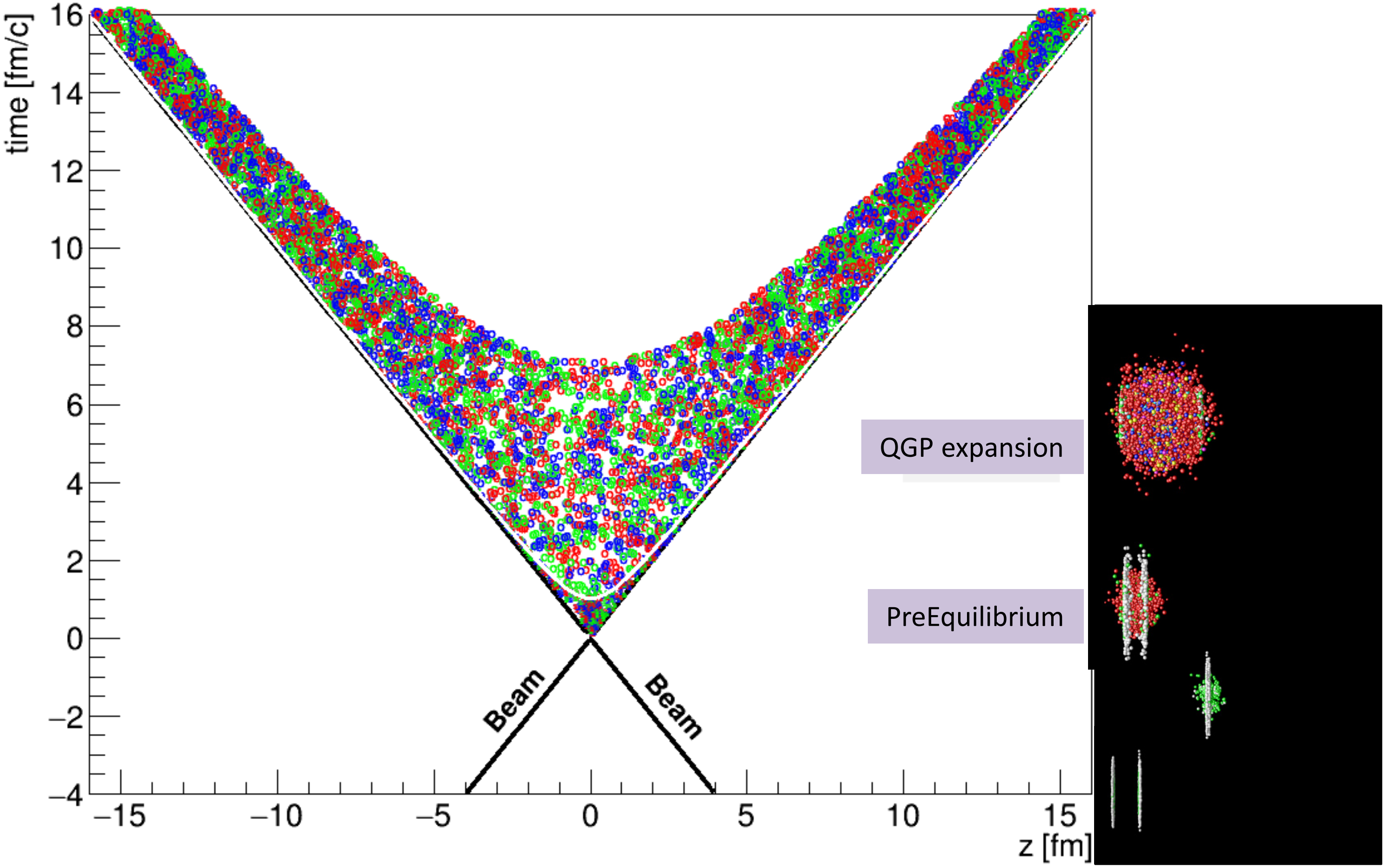
Heavy ion collision

Production of colour medium and equilibration



Heavy ion collision

QGP and expansion

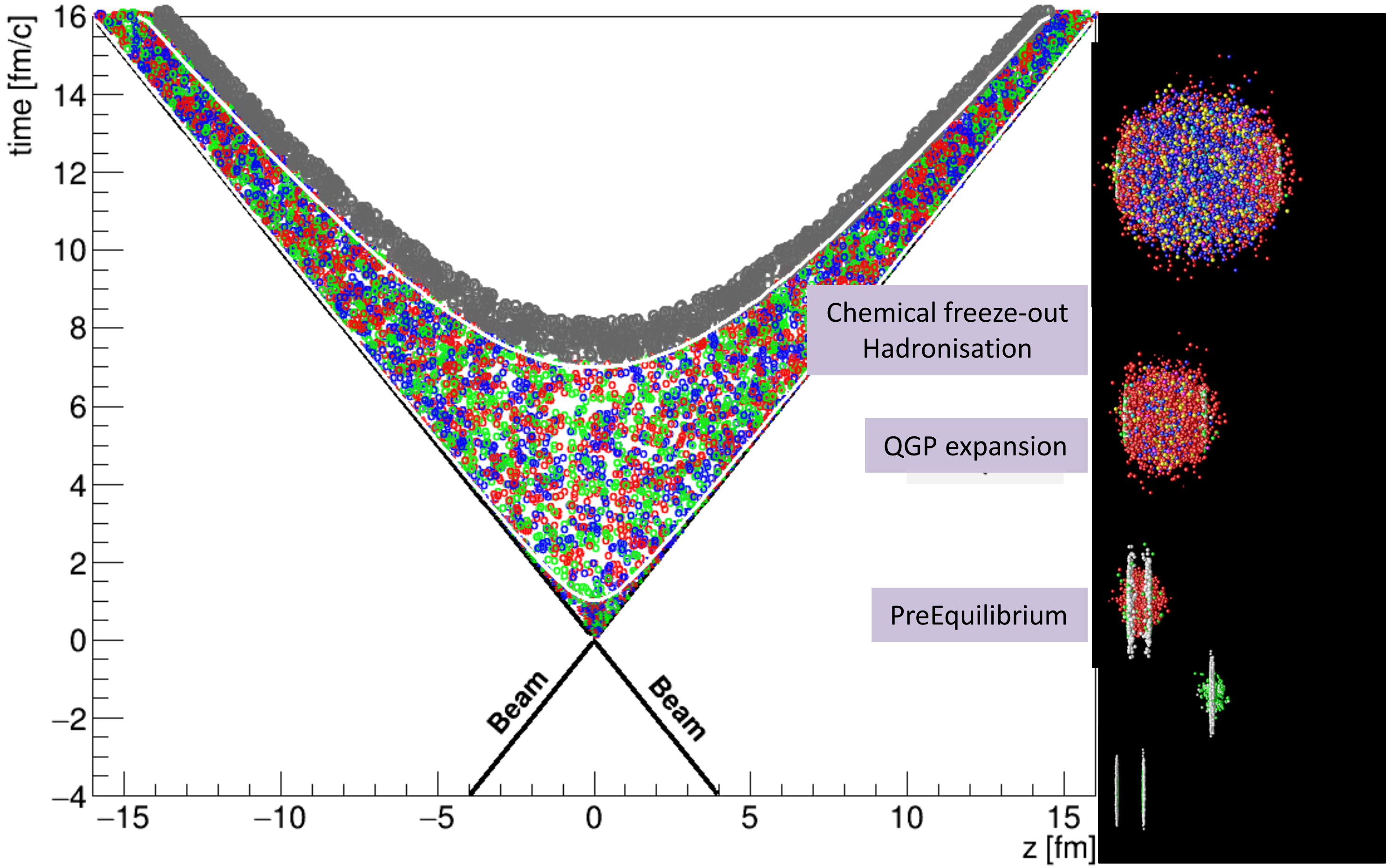


QGP expansion

PreEquilibrium

Heavy ion collision

Hadronisation and Chemical freeze-out



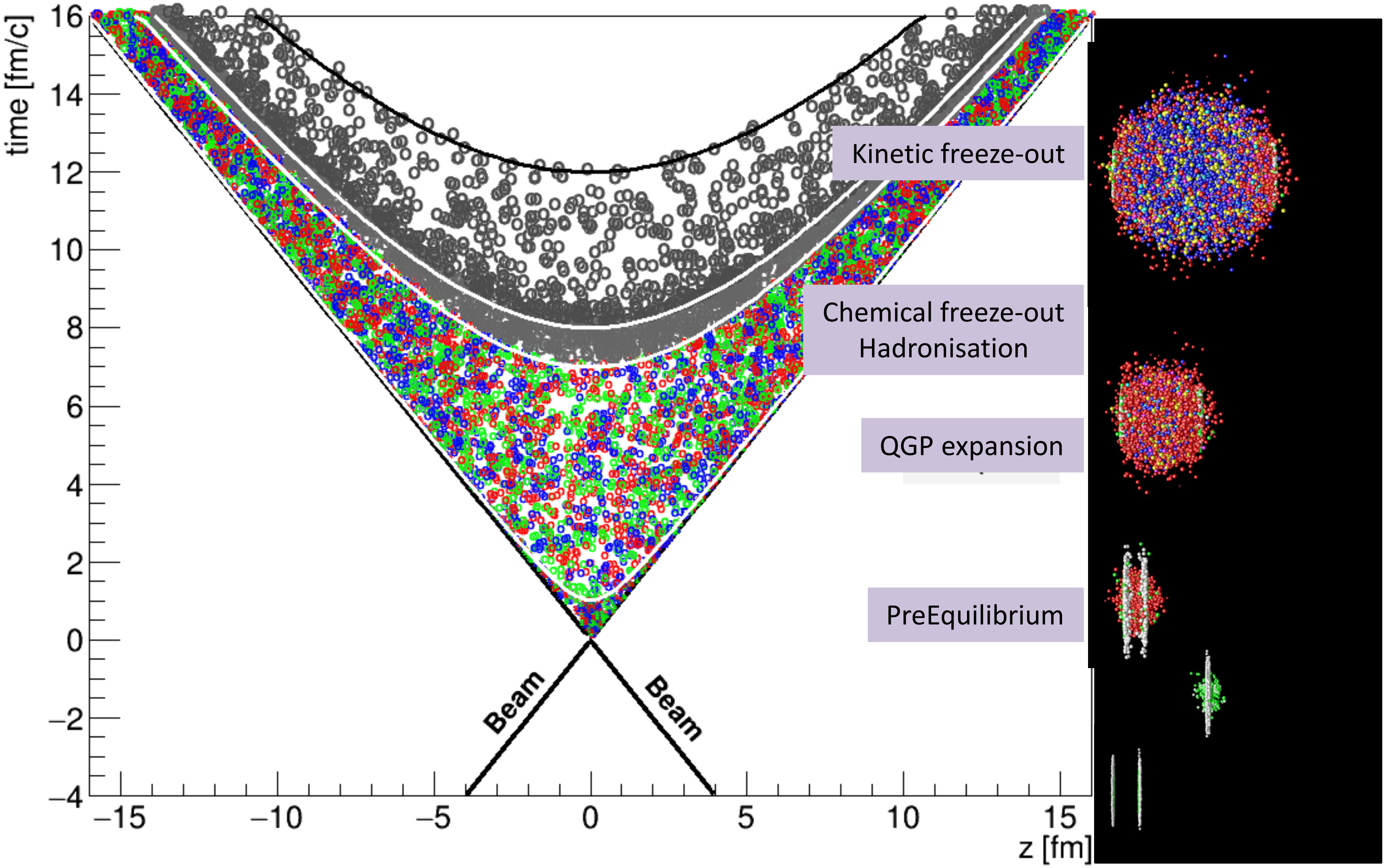
Chemical freeze-out
Hadronisation

QGP expansion

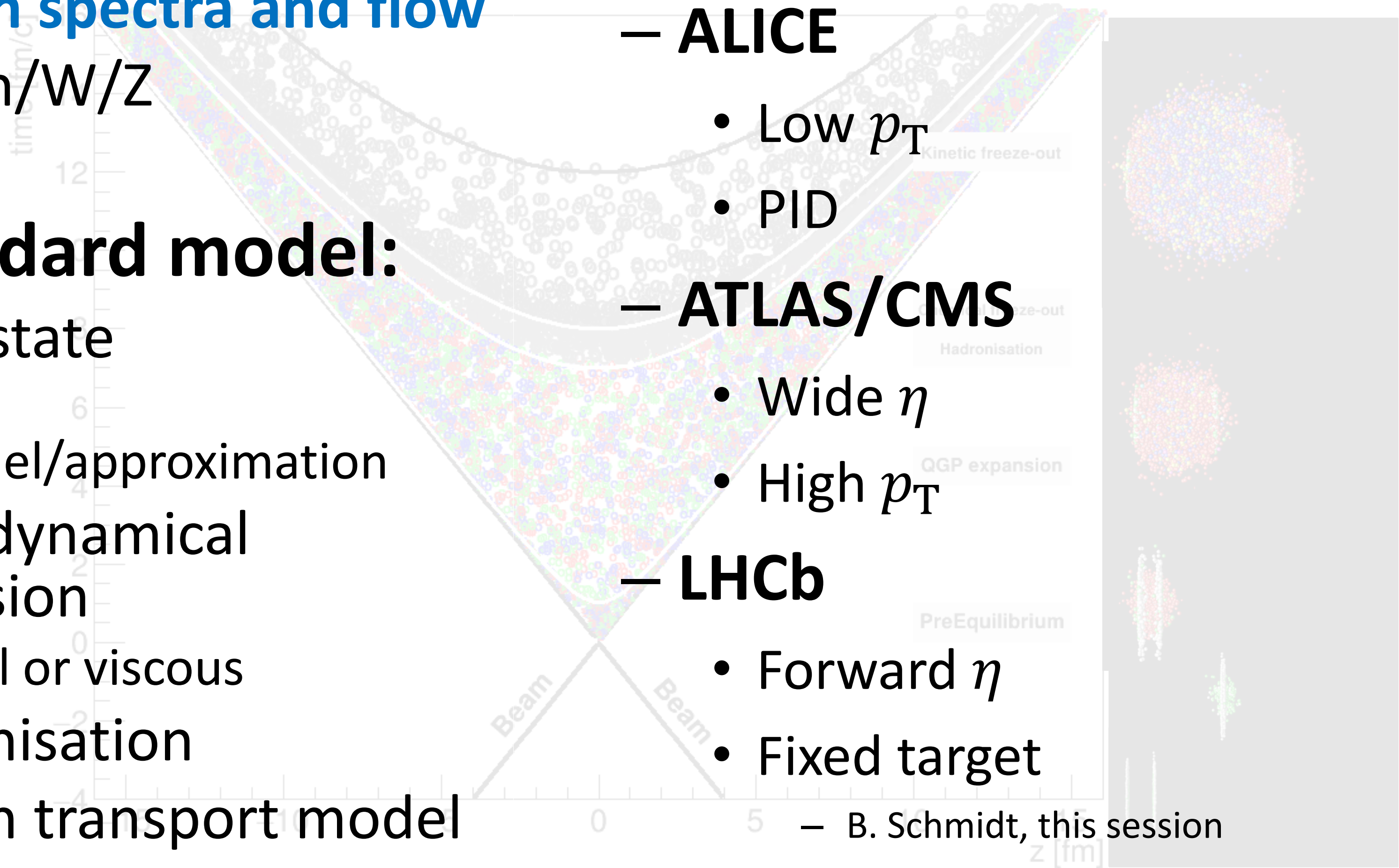
PreEquilibrium

Heavy ion collision

Kinetic freeze-out



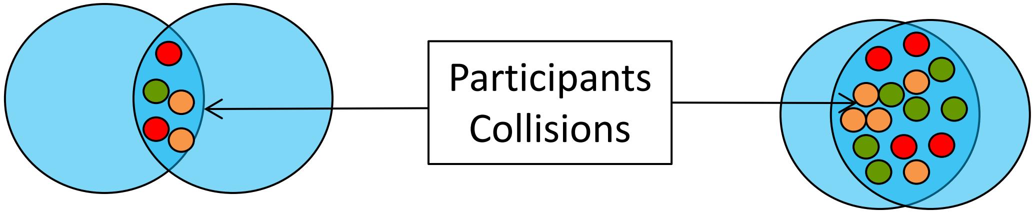
Heavy ion collisions



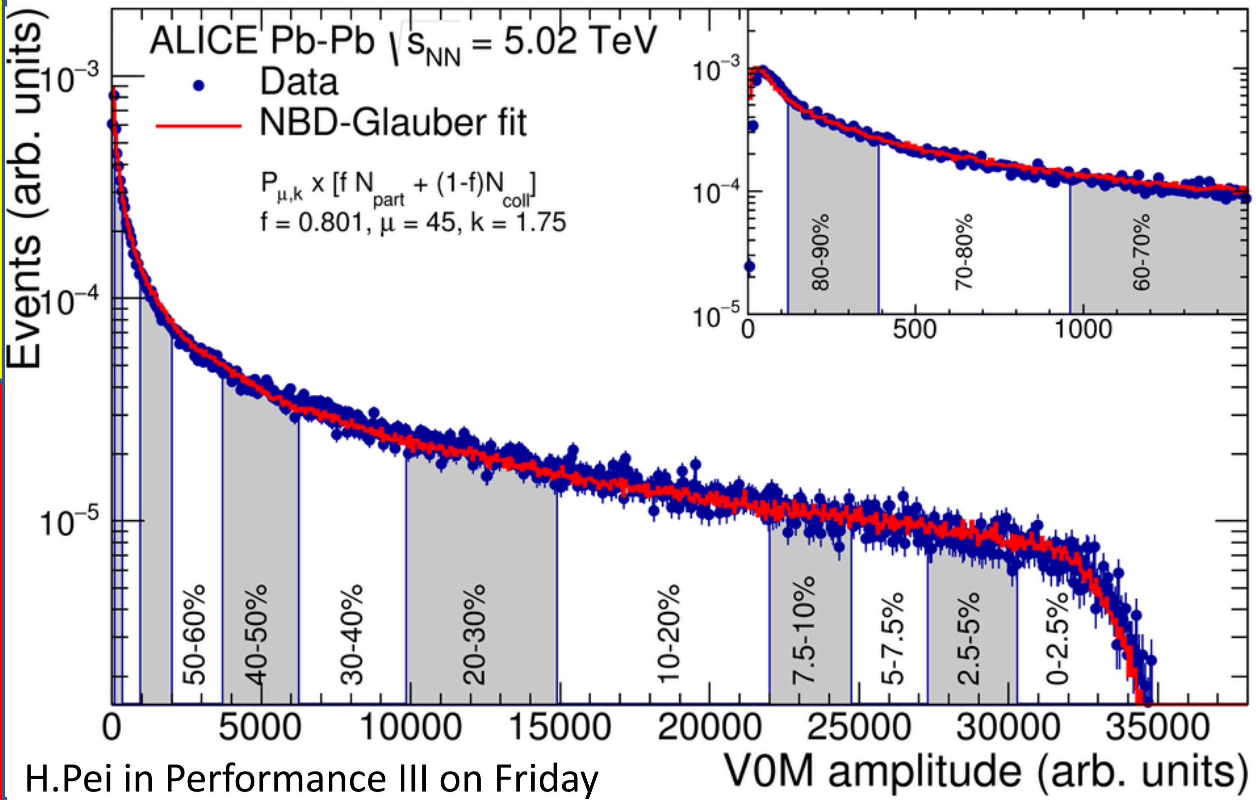
- **Observables:**
  - **Hadron spectra and flow**
  - photon/W/Z
  - Jets
- **HI standard model:**
  - Initial state
    - QCD model/approximation
  - Hydrodynamical expansion
    - Ideal or viscous
  - Hadronisation
  - Hadron transport model
- **Experiments:**
  - **ALICE**
    - Low p_{T}
    - PID
  - **ATLAS/CMS**
    - Wide η
    - High p_{T}
  - **LHCb**
    - Forward η
    - Fixed target
      - B. Schmidt, this session
      - E.Maurice, Thursday, HI II

Geometry of heavy ion collisions

We can control (a posteriori) the geometry of heavy ion collisions



Participants
Collisions



H.Pei in Performance III on Friday

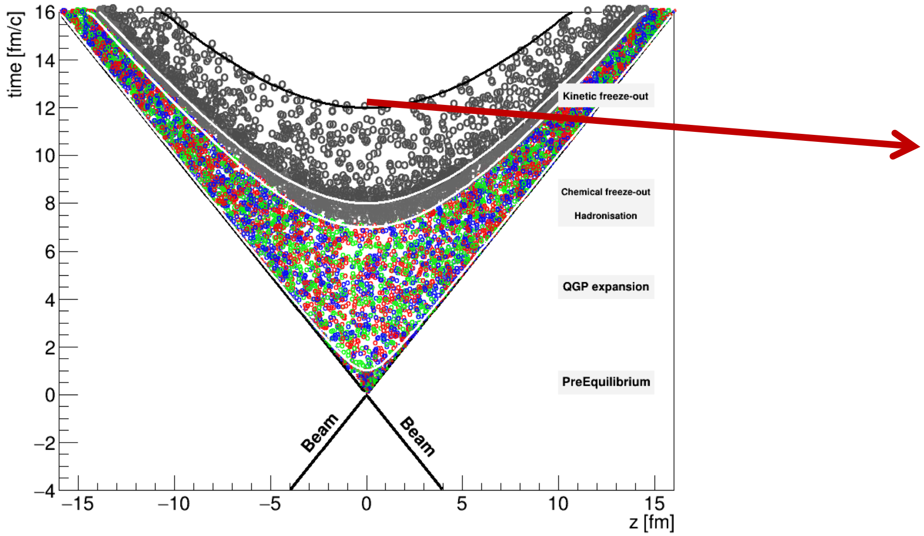
~ # charged particles

Centrality Variables:

- Number of nucleon-nucleon collisions N_{coll}
- Number of nucleon participants N_{part}
- Percentile of hadronic cross section

Transverse momentum spectra

Kinetic freeze-out temperature and expansion velocity



Hadron spectra:

$$\frac{dN}{dy\,dp_{\mathrm{T}}} = \int \frac{d^3N}{dp_{\mathrm{T}}\,dy\,d\varphi}\,d\varphi$$

p_T − *transverse momentum*

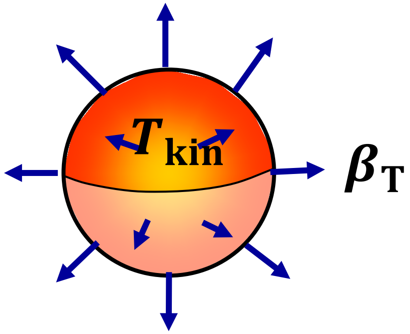
y − *rapidity*

φ − *azimuthal angle*

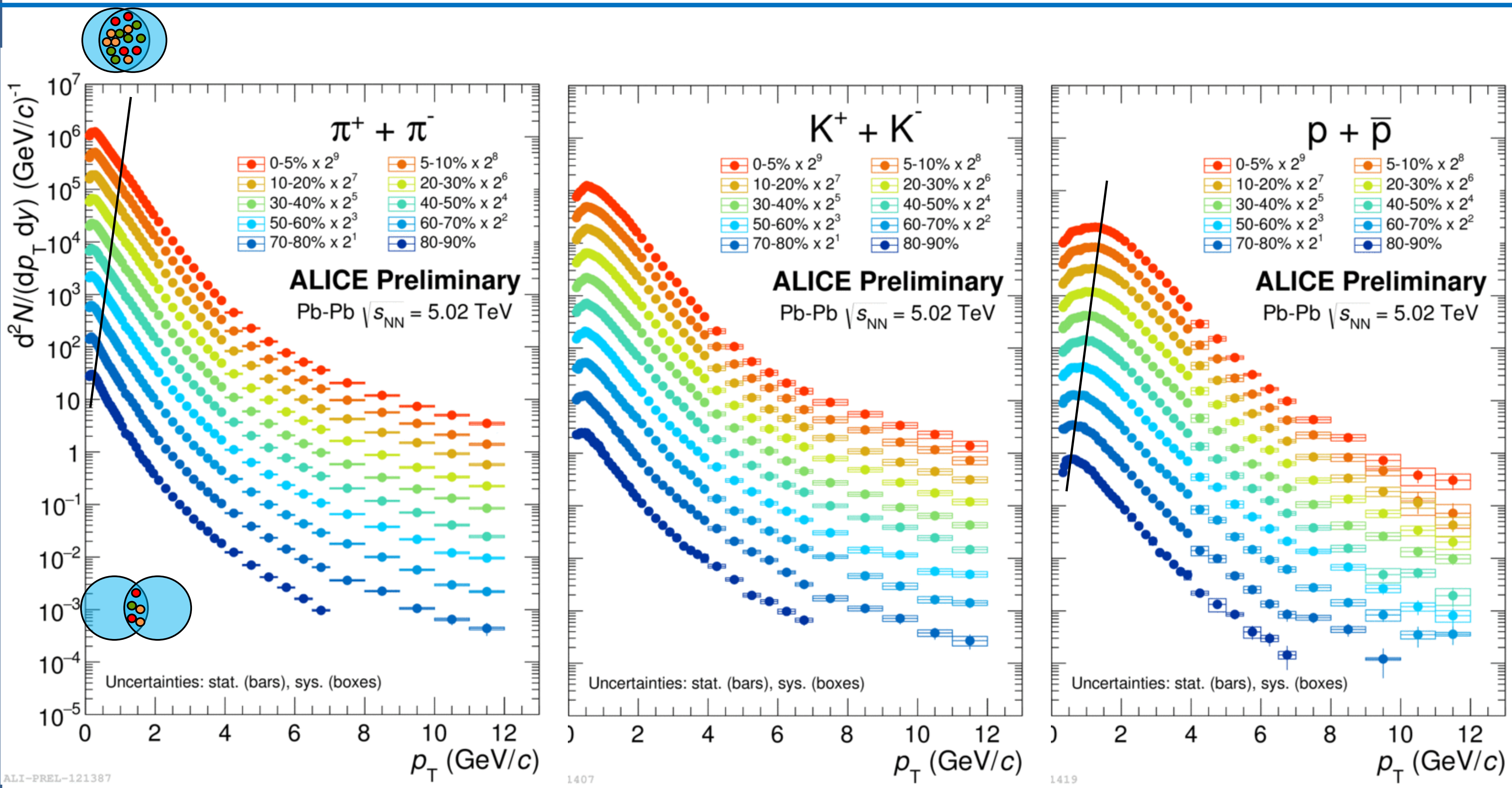
Model:

Blast Wave – hydro inspired parametrisation

- Kinetic freeze-out temperature T_{kin}
- Transverse expansion velocity β_{T}



Hadron spectra Pb-Pb

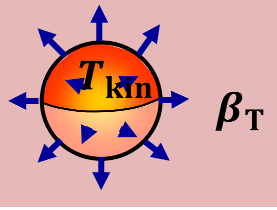


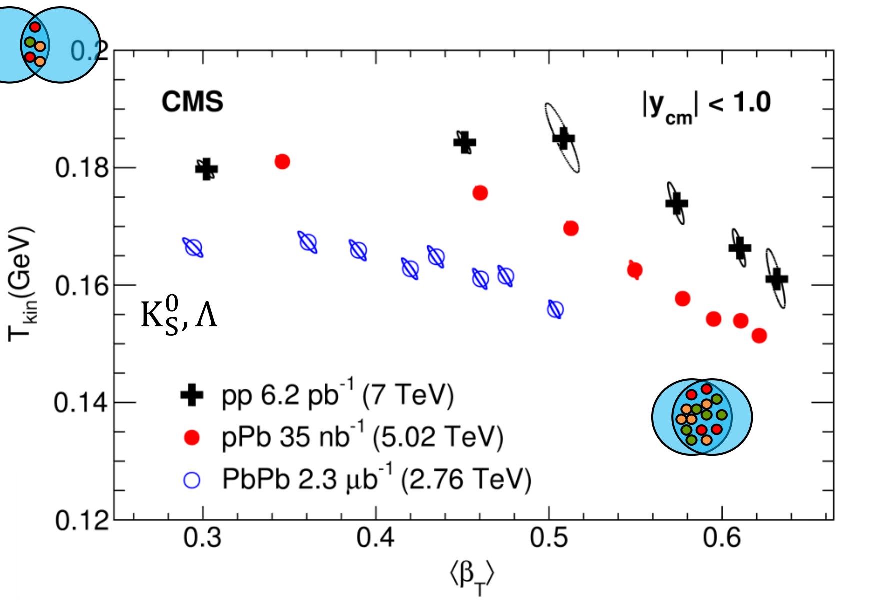
Hardening of spectra as expected in hydro expansion

- With centrality
- With the particle mass $m_\mathrm{T} \rightarrow m_\mathrm{T} + m_0\gamma\beta_\mathrm{T}$

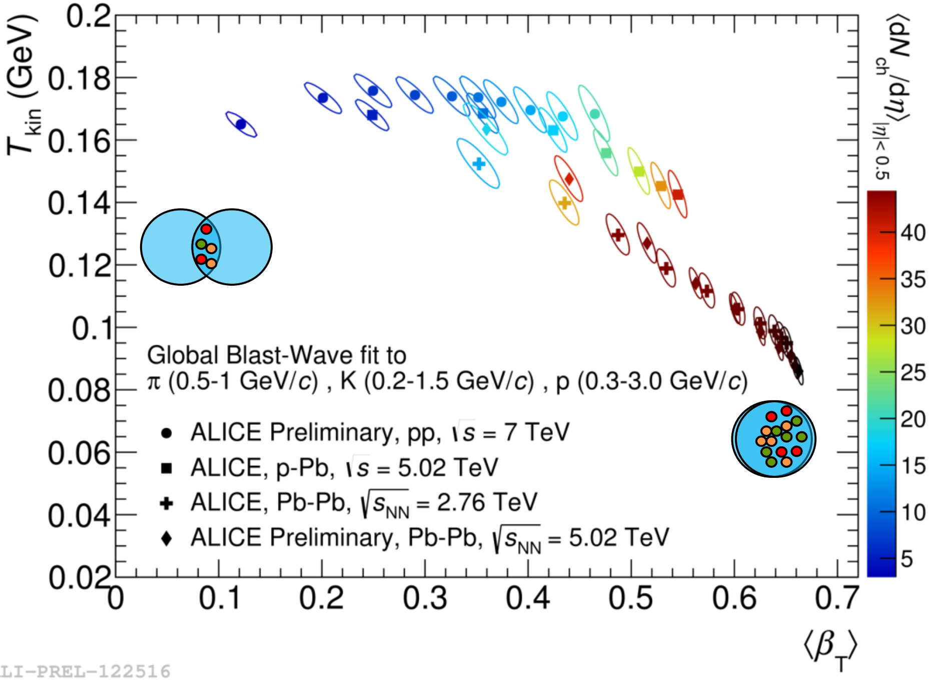
Kinetic freeze-out

- Temperature versus expansion velocity for pp, p-Pb, Pb-Pb





PLB 768 (2017) 103-129



ALI-PREL-122516

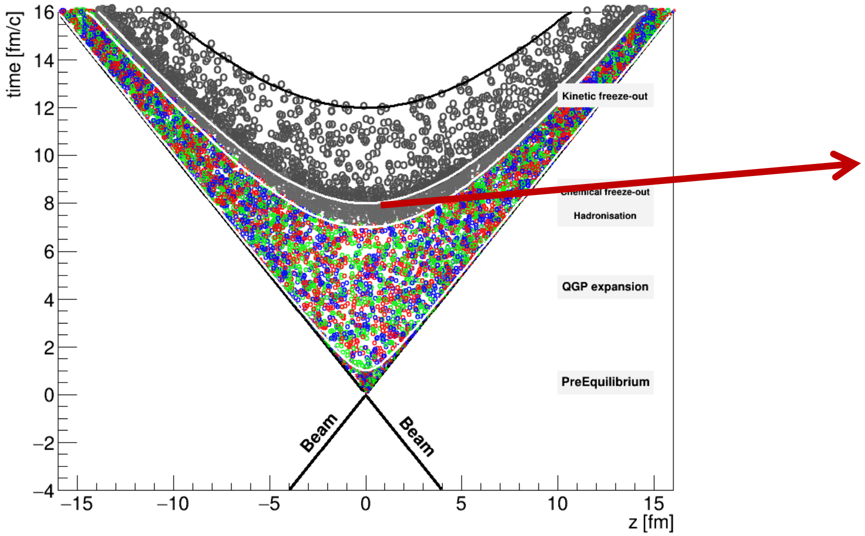
- Similar trend for Pb-Pb, p-Pb and pp

⇒ G.Volpe, QCD II today

⇒ O. Vazquez, HI I today

Particle yields

Chemical freeze-out temperature



Hadron yield:

$$\boldsymbol{Y = \frac{dN}{dy} = \int \frac{d^3N}{dp_T\,dy\,d\varphi}\,d\varphi\,dp_T}$$

$p_T - transverse\ momentum$

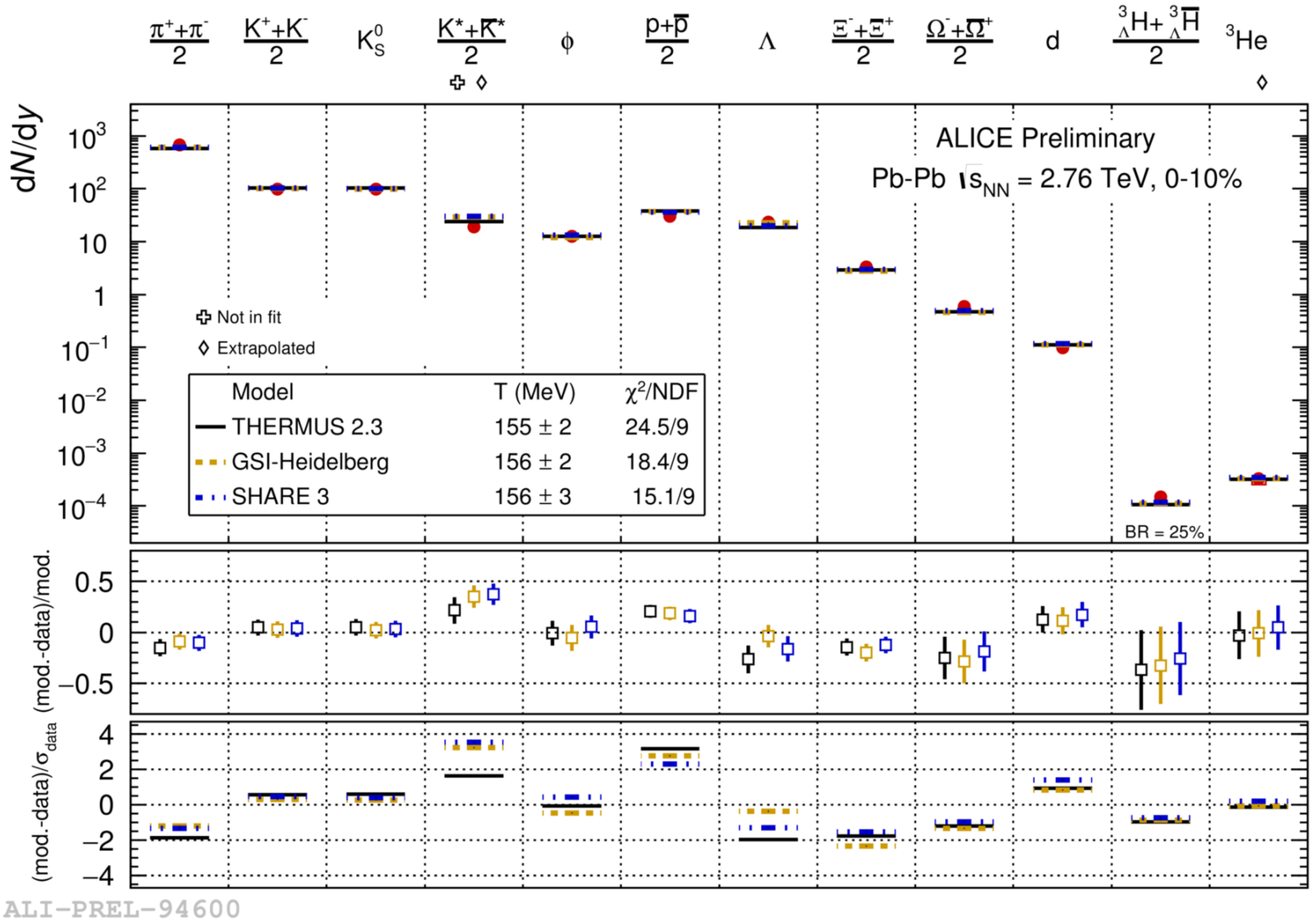
$y\ - rapidity$

$\varphi - azimuthal\ angle$

Models

- Thermal models
- EPOS, (DIPSY,PYTHIA – only pp)

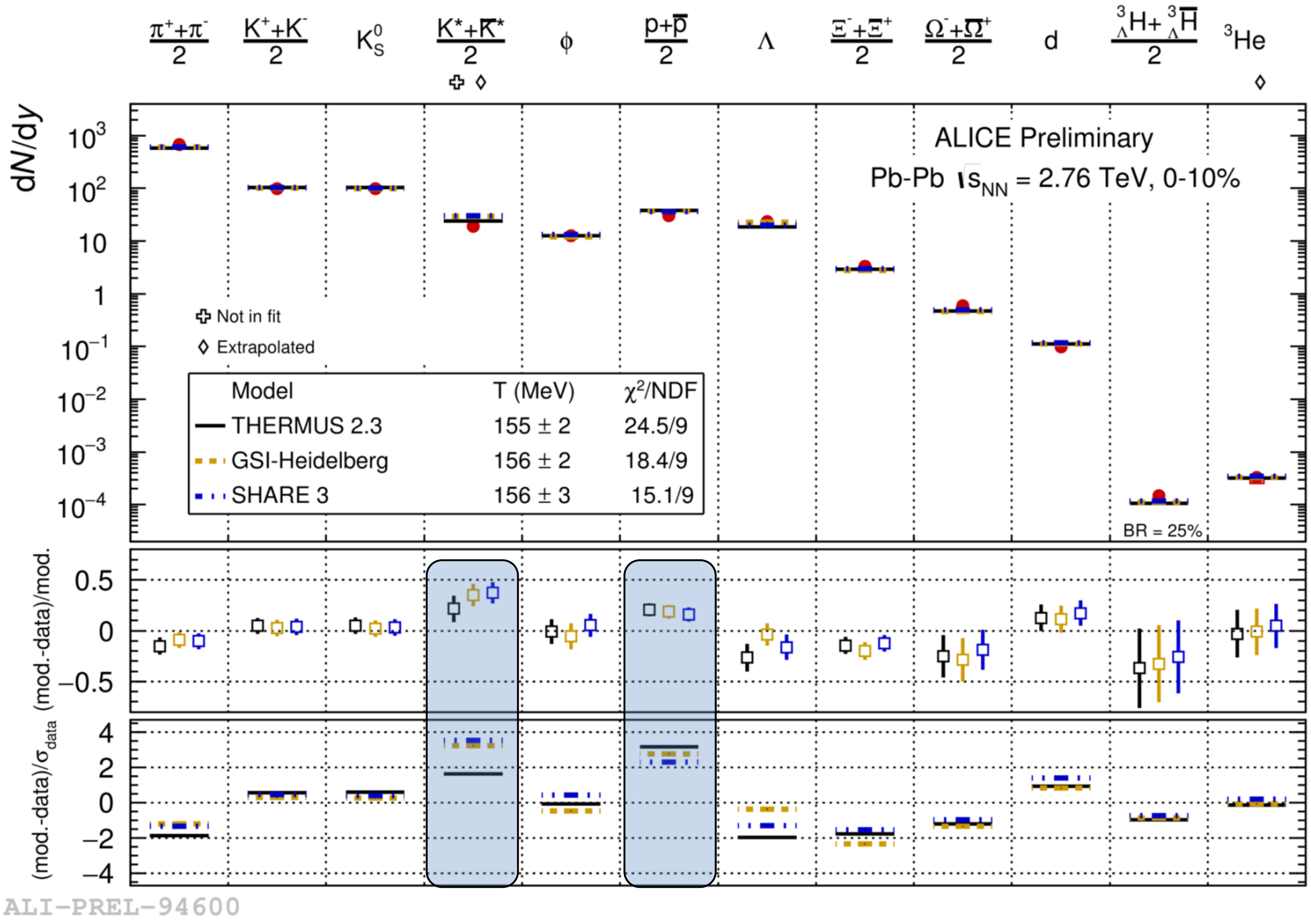
Thermal model



- Describes hadron yields assuming chemical equilibrium
- T ~ 156 MeV ~ lattice QCD phase transition

THERMUS: Wheaton et al,Comput.Phys.Commun, 180 84
GSI-Heidelberg: Andronic et al, PLB 673, 142
SHARE:Petran et al,Comput.Phys.Commun., 185 Issue 7,2056

Thermal model



- Describes hadron yields assuming chemical equilibrium
- T ~ 156 MeV ~ lattice QCD phase transition
- Deviations for: Protons, K^{*0} Sequential freeze-out ?

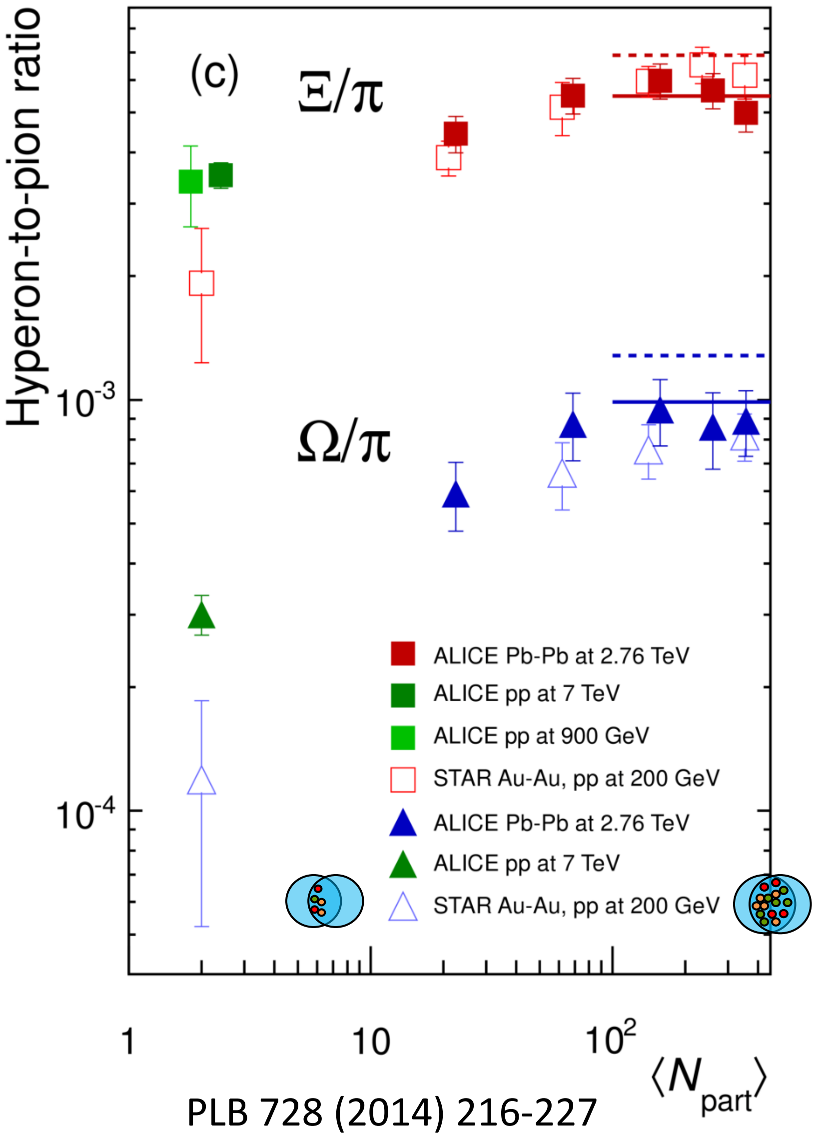
THERMUS: Wheaton et al,Comput.Phys.Commun, 180 84
GSI-Heidelberg: Andronic et al, PLB 673, 142
SHARE:Petran et al,Comput.Phys.Commun., 185 Issue 7,2056

Strangeness enhancement

- Chiral symmetry restored in QGP – strangeness reach chemical equilibrium
- $\text{Enhacement} = \frac{Y(H)}{Y(\pi)}$;

  $H = \Lambda, \Xi, \Omega$
- Thermal models for $N_{part} > 150$ describe saturated ratio at $T \sim 165\ MeV$

Rafelski/Muller PRL48 106 1982

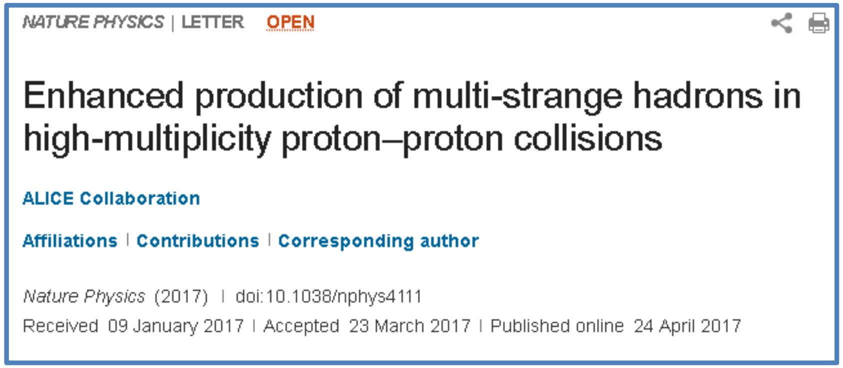


PLB 728 (2014) 216-227

ALI-PUB-78357

Strangeness enhancement

- Enhancement for pp, p-Pb and Pb-Pb in multiplicity classes
- Smooth evolution from pp/p-Pb to peripheral Pb-Pb collisions
- Scaling with $dN/d\eta$
- Models fail to describe
- See also P.Bartalini talk (QCD Tuesday)



NATURE PHYSICS | LETTER OPEN

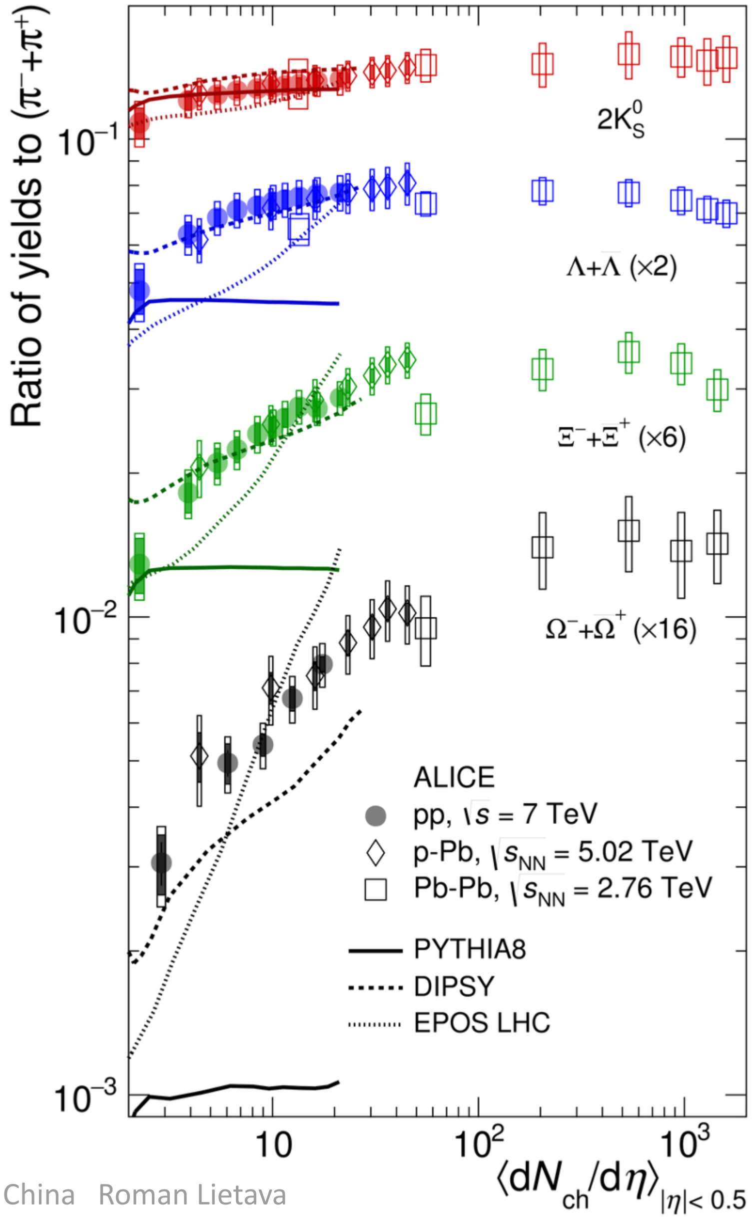
Enhanced production of multi-strange hadrons in high-multiplicity proton–proton collisions

ALICE Collaboration

Affiliations | Contributions | Corresponding author

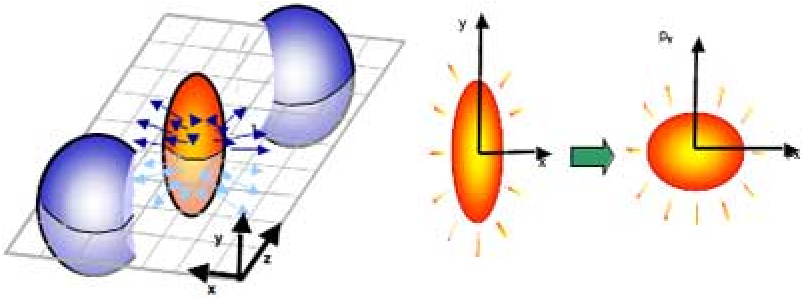
Nature Physics (2017) | doi:10.1038/nphys4111

Received 09 January 2017 | Accepted 23 March 2017 | Published online 24 April 2017



Collective expansion

Observed particle spectrum is the result of the fireball expansion.



If the system is asymmetric in spatial coordinates, scattering converts it to **anisotropy in momentum space**

$$E\frac{d^3N}{d^3p}=\frac{d^2N}{2\pi p_{\mathrm{T}}dp_{\mathrm{T}}dy}\left\{1+2\sum_{n=1}^{\infty}v_n(p_{\mathrm{T}})\cos[n(\varphi-\psi_n)]\right\}$$

Radial flow v_1 – direct flow, **v_2- elliptic flow**

If nuclei overlap is a smooth almond shape odd harmonic are zero.

Flow measurement

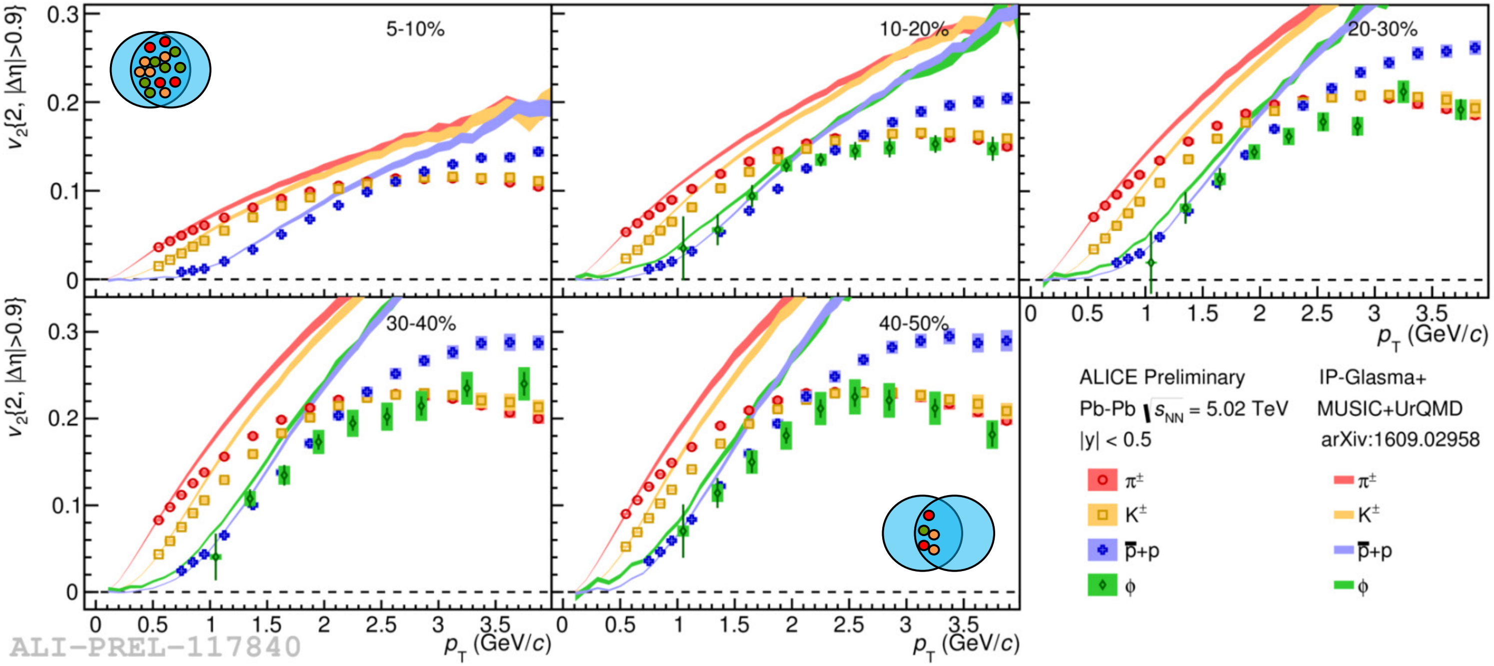
- Flows v_n measured from particle correlations
- Effects other than collective flow can contribute
  - jet/resonance decays/Bose-Einstein correlations
- Suppress non-flow:
  - Correlate in separated phase space, i.e. pseudorapidity gap
  - Correlate more than 2 particles and subtract lower order - technique of multiparticle cumulants

$$v_2\{2\} = \sqrt{c_n\{2\}};\ \boxed{c_n\{2\} = \langle\langle 2\rangle\rangle} = \langle\langle \cos n(\varphi_1 - \varphi_2)\rangle\rangle$$

$$v_n\{4\} = \sqrt[4]{-c_n\{4\}}\ ;\ \boxed{c_n\{4\} = \langle\langle 4\rangle\rangle - 2\langle\langle 2\rangle\rangle;}$$

$$\langle\langle 4\rangle\rangle = \langle\langle cos\, n(\varphi_1 - \varphi_2 + \varphi_3 - \varphi_4)\rangle\rangle$$

Elliptic flow



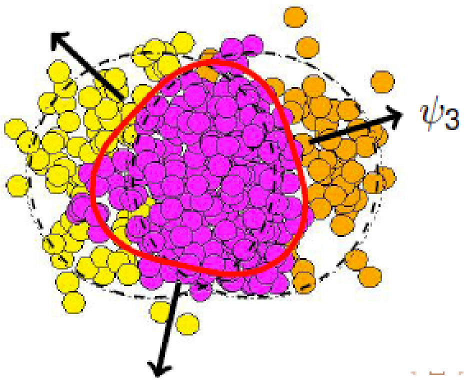
Shear viscosity over entropy density η/s=0.095 (QM bound 0.08)

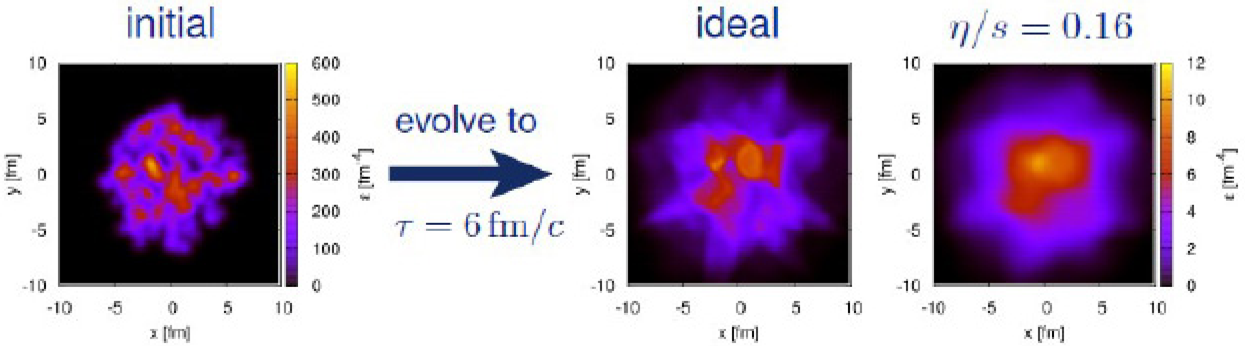
- $v_2(p_T)$ in centrality bins compared with hydro prediction (hydro tuned on 2.76 TeV data)
- Hydro describes mass hierarchy
- QGP behaves as almost ideal fluid

Higher harmonics

- **Initial geometry not described by the ideal almond shape**
  - Fluctuations of initial energy/pressure distributions lead to “irregular” shapes that fluctuate event-by-event
- **Higher harmonics more sensitive to the value of shear viscosity**

arXiv:1209.6330

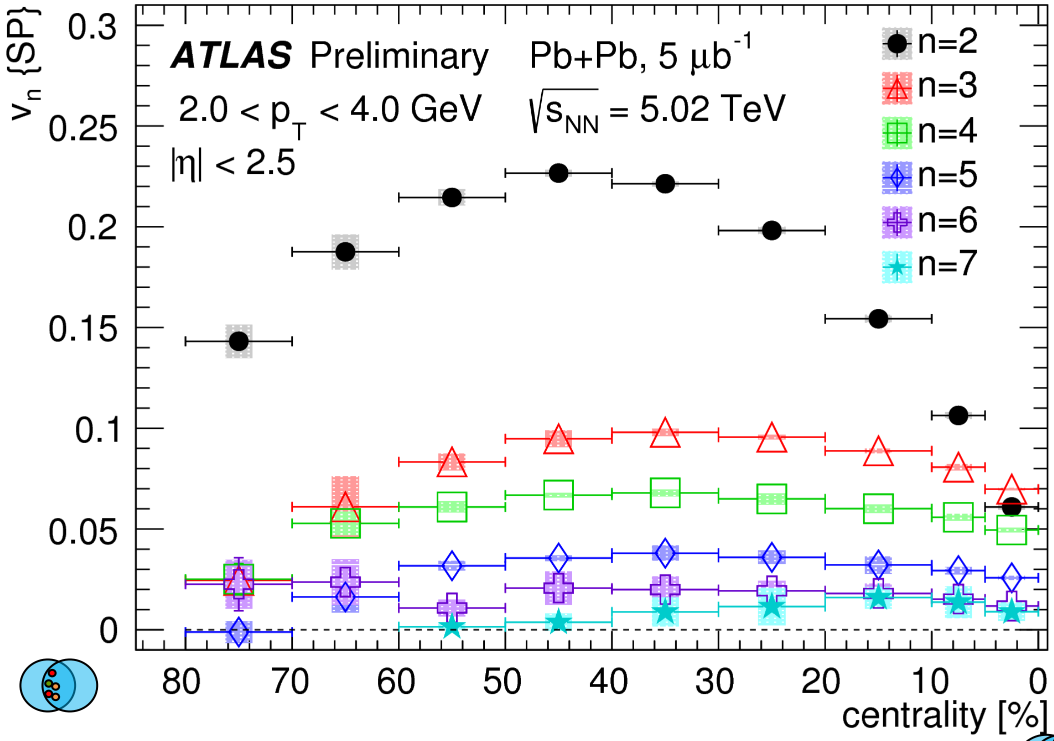




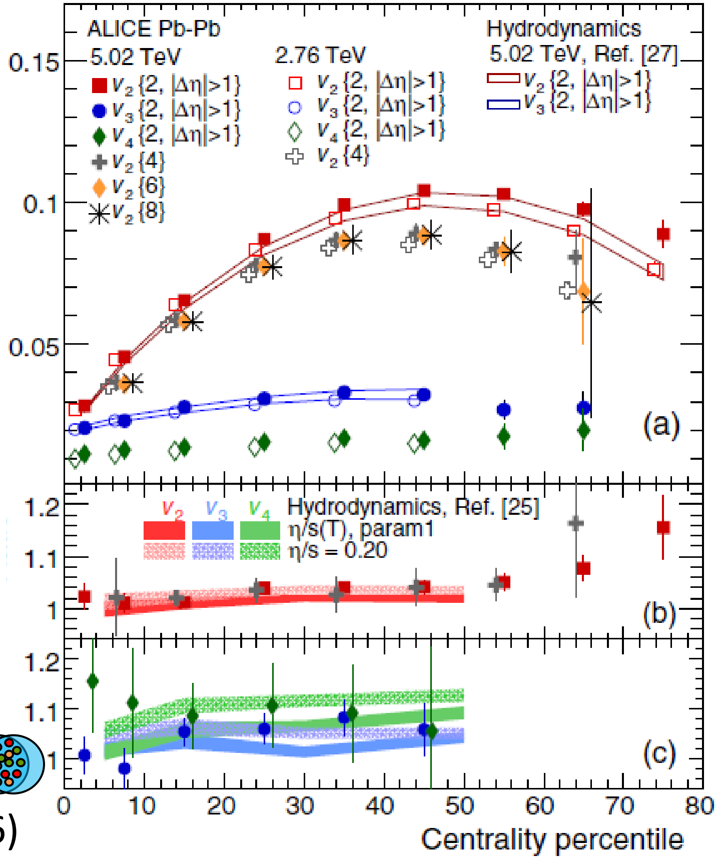
Hydro evolution of initial state (ideal and viscous hydro): fluctuations of initial state are damped by viscosity.

Higher harmonics

- **Initial geometry not described by the ideal almond shape**



ATLAS-CONF-2016-105



ALICE: PRL 116, 132302 (2016)

Hydro evolution of initial state (ideal and viscous hydro): fluctuations of initial state are damped by viscosity.

For viscosity estimate see next slide.

Initial state and viscosity estimate

- **Bayes estimate** using:
  - Multiplicity (yields)
  - p_{T}spectra
  - Flow coefficients $v_{2,3,4}$
- Parametric Initial state model TRENTO
  - Initial state entropy $s(\tau_0) = f(p)$
- Evolution:
  - Viscous hydro
  - Hadron cascade
- 9 parameters

PRC94, 024907 (2016)

Initial state and viscosity estimate

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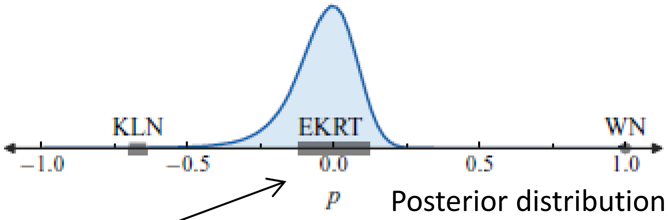
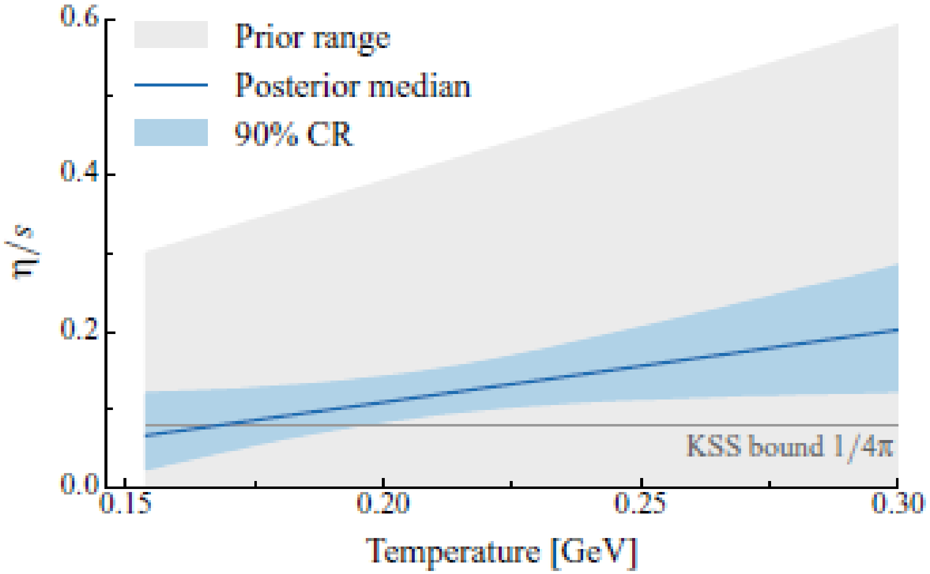
PRC94, 024907 (2016)

Initial state



Posterior distribution

Viscosity



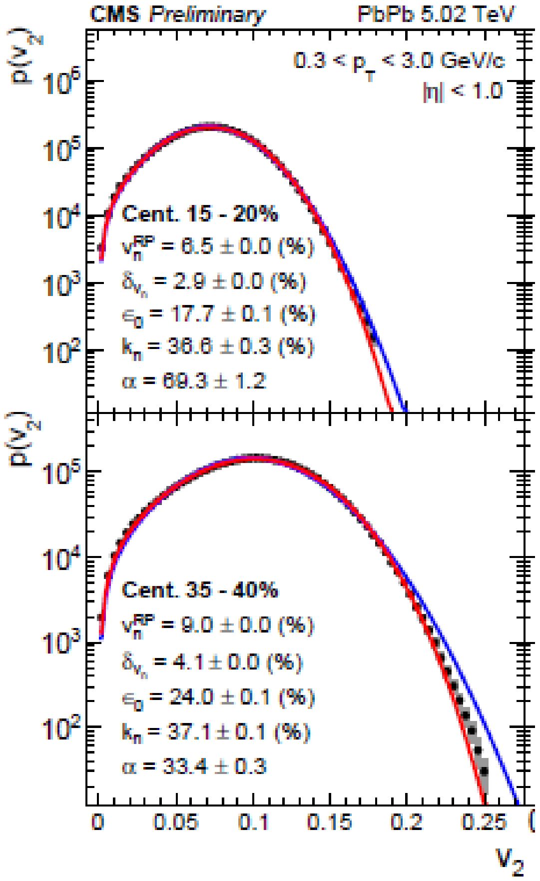
Beyond $\boldsymbol{v_n}$

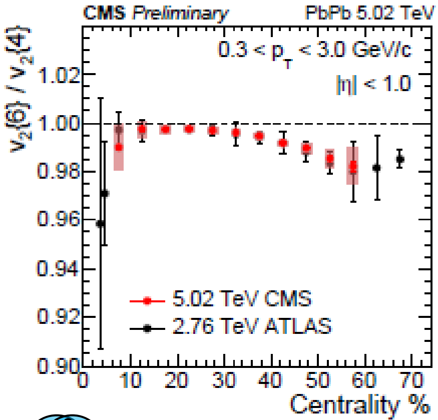
- Optimise sensitivity of flow related variable to disentangle medium properties (η/s) and initial conditions
  - Flow correlations, factorisations, correlations:
    - Direct event by event measurement of $p(v_n)$
      - properties of probability distribution function $p(v_2)$
      - $v_2\{2\}^2 = \langle v_n^2 \rangle$ but if pdf $p(v_2) \neq \delta(v_2)$ then $\langle v_n^2 \rangle \neq \langle v_n \rangle^2$
    - Correlation,factorisation:
      - Fourier coefficients may be correlated due to physics
      - Correlate flows v_n , event planes ψ_n and their combinations in different phase space
      - $c(X(x), n; Y(y), m) = \langle X_n(x) Y_m(y) \rangle - \langle X_n(x) \rangle \langle Y_m(y) \rangle$

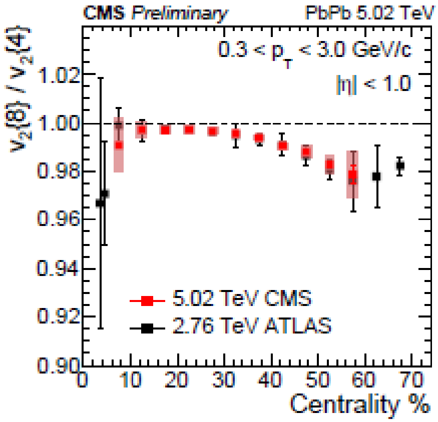
Elliptic Flow fluctuations

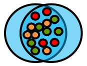
- Technique: Unfolding directly pdf of $p(v_2)$ (see ATLAS JHEP 11(2013) 183)
  - $v_2\{2\}, v_2\{4\}, v_2\{6\}, v_2\{8\}$ calculated using $p(v_2)$
- $p(\vec{v}_2)$ - usually assumed to be Gaussian
- $v_2\{4\} \sim v_2\{6\} \sim v_2\{8\}$
  - splitting characterise departure from

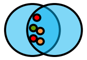
  Gauss of $p(v_2)$









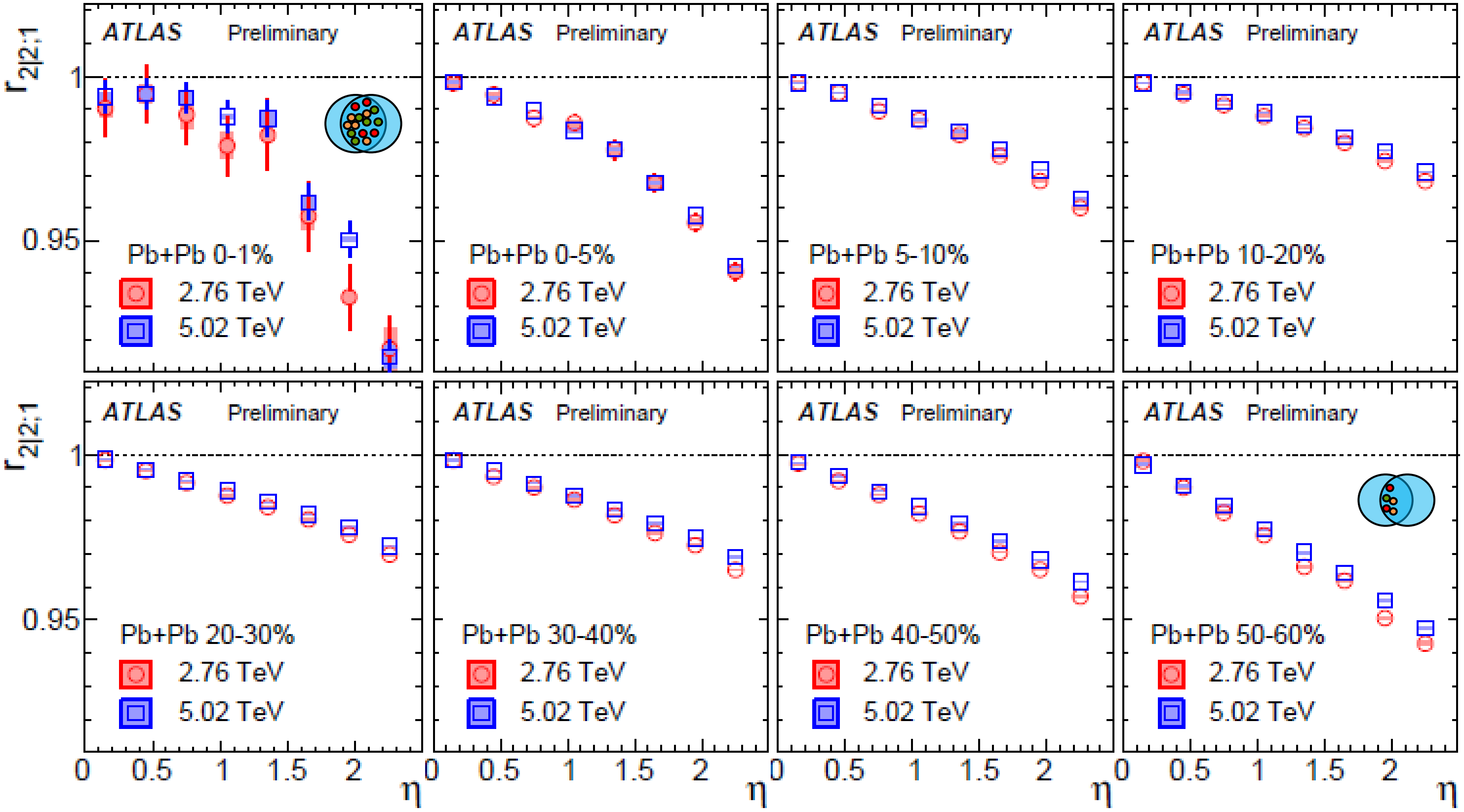


J.Milosevic in Heavy Ions today

CMS: HIN-16-019

Flow factorisation in η

Boost invariance of initial conditions tested



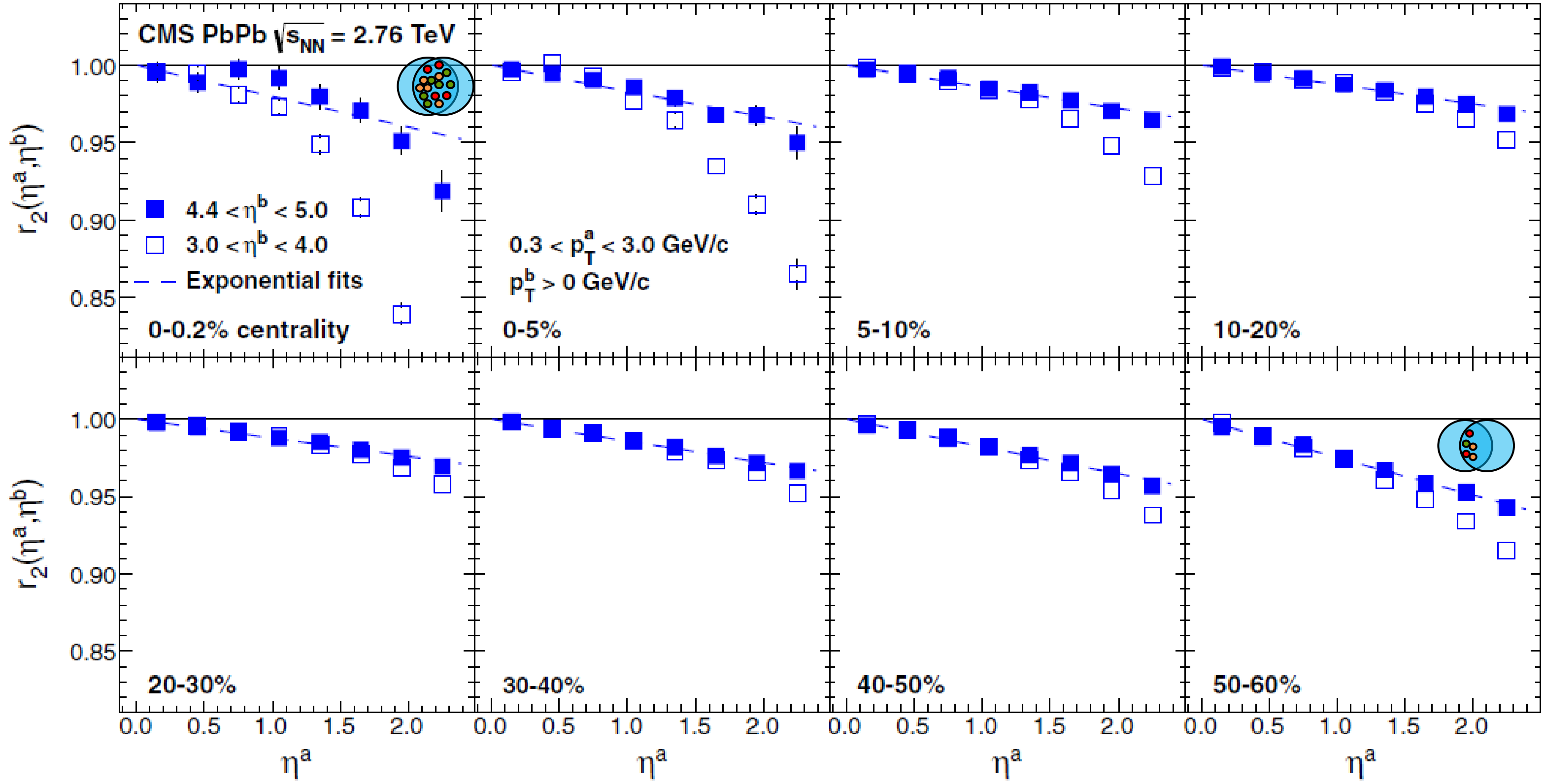
- Broken boost invariance ?
- Fluctuation in η ?

$$r_{n|n;k}(\eta) = \frac{\left\langle [v_n(-\eta)v_n(\eta_{\rm ref})]^k \cos kn(\Phi_n(-\eta)-\Phi_n(\eta_{\rm ref}))\right\rangle}{\left\langle [v_n(\eta)v_n(\eta_{\rm ref})]^k \cos kn(\Phi_n(\eta)-\Phi_n(\eta_{\rm ref}))\right\rangle}$$

ATLAS-CONF-2017-003 K. Wozniak in Heavy Ions today

Flow factorisation in η

Boost invariance of initial conditions tested



- Fluctuation in η ?
- Broken boost invariance ?

$$r_n(\eta^a,\eta^b) = \frac{\langle v_n(-\eta^a)v_n(\eta^b)\cos\{n[\Psi_n(-\eta^a)-\Psi_n(\eta^b)]\}\rangle}{\langle v_n(\eta^a)v_n(\eta^b)\cos\{n[\Psi_n(\eta^a)-\Psi_n(\eta^b)]\}\rangle}.$$

ATLAS-CONF-2017-003 / CMS: PRC92, 034911 (2015)

Summary

- In Pb-Pb collisions at the LHC, a sizeable fireball with initial temperature $T > 300\ MeV$ is created
- Hydrodynamics describes the expansion of the fireball $\Rightarrow$ system behaves like an almost ideal liquid
  - degrees of freedom are quarks and gluons
  - viscosity estimate improves
- **Some QGP signatures observed also in high multiplicity p-Pb and pp systems**
  - What is the smallest size for QGP fluid ?
  - Very exciting and quickly evolving topic
  - Connection to soft pp physics

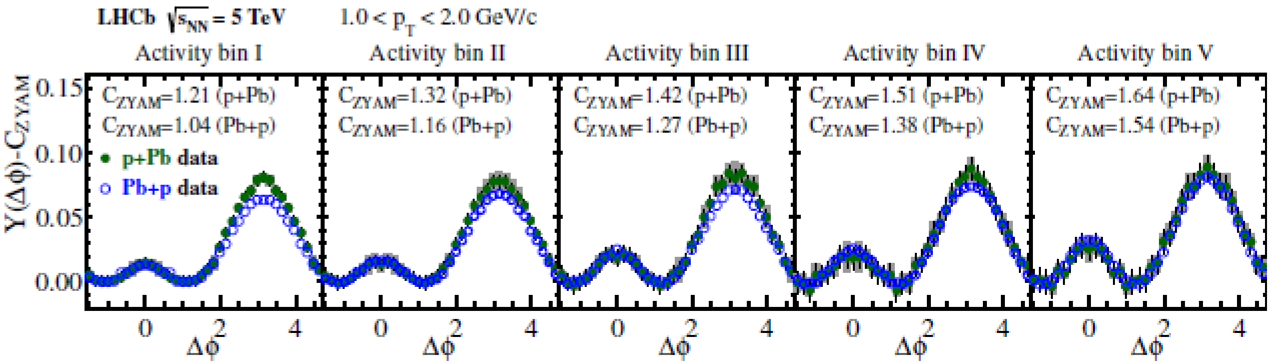
Soft Probes related talks

- V.Zaccolo: Soft-QCD results in pp and p-Pb with ALICE
- G.Volpe: Multiplicity dependence of particle production with ALICE
- P.Bartalini: QCD with ALICE and LHCb
- O. Vazquez Rueda: New results on collectivity with ALICE
- K.Wozniak: New results on collectivity with ATLAS
- J.Milosevic: New results on collectivity with CMS
- R.Kopecna: New results on collectivity with LHCb

- Backup

LHCb p-Pb correlations (5TeV)

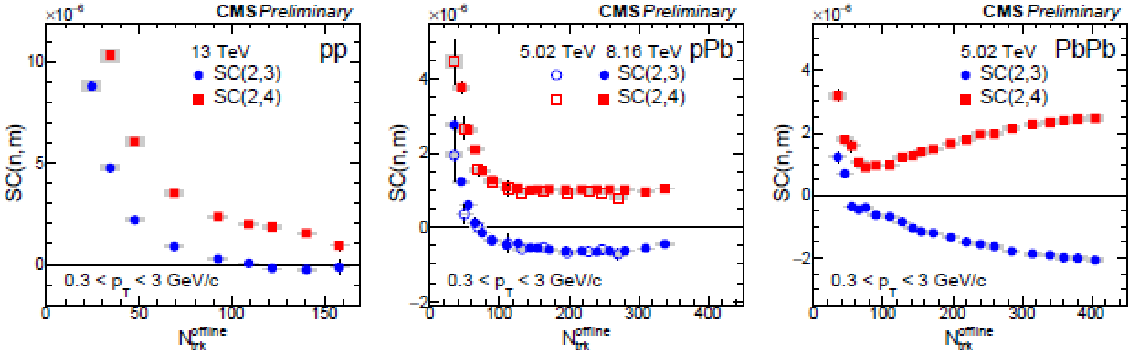
- Asymmetry of detector and p-Pb/Pb-p is used to cover in nucleon-nucleon cms:
  - $1.5 < y < 4.4$
  - $-5.4 < y < -2.5$
- Ridge has similar size in both regions
- The correlation structures grow stronger wit increasing event activity



arXiv:1512.00439v2

Flow amplitude correlations

- Symmetric two particle flow cumulant $SC(m,n)$: $SC(m,n) = \langle v_m^2 v_n^2 \rangle - \langle v_m^2 \rangle \langle v_n^2 \rangle$
  - $SC(m,n) = 0$ if no fluctuations or n and m uncorrelated
- Different behaviour in
  - fluctuation dominated region (central)
  - Geometry dominated region (mid-central)
- Discriminate between models



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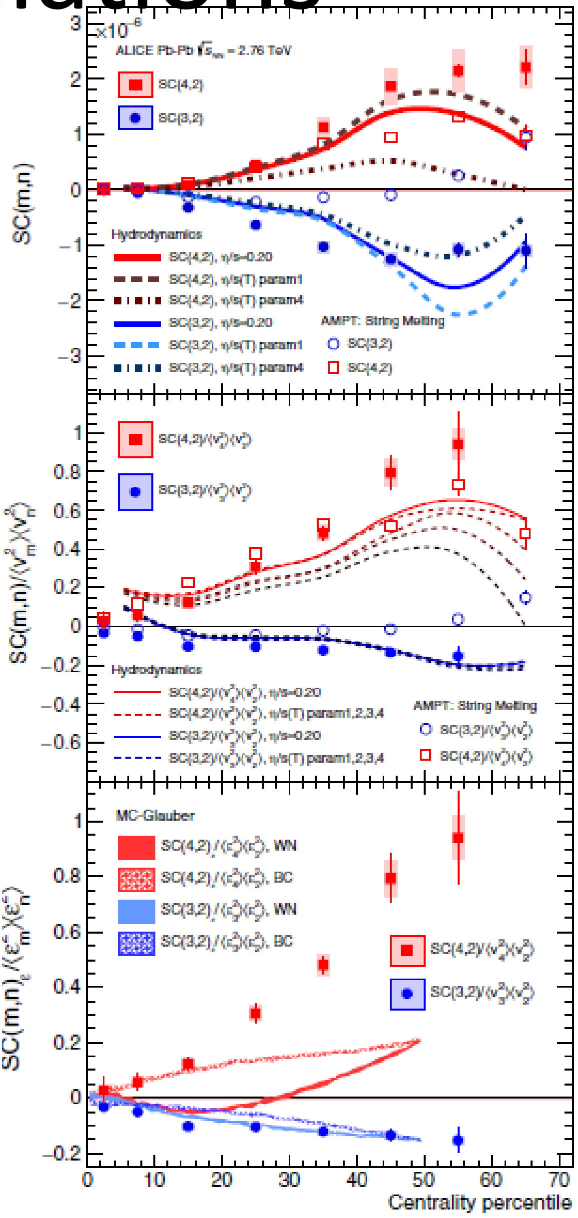
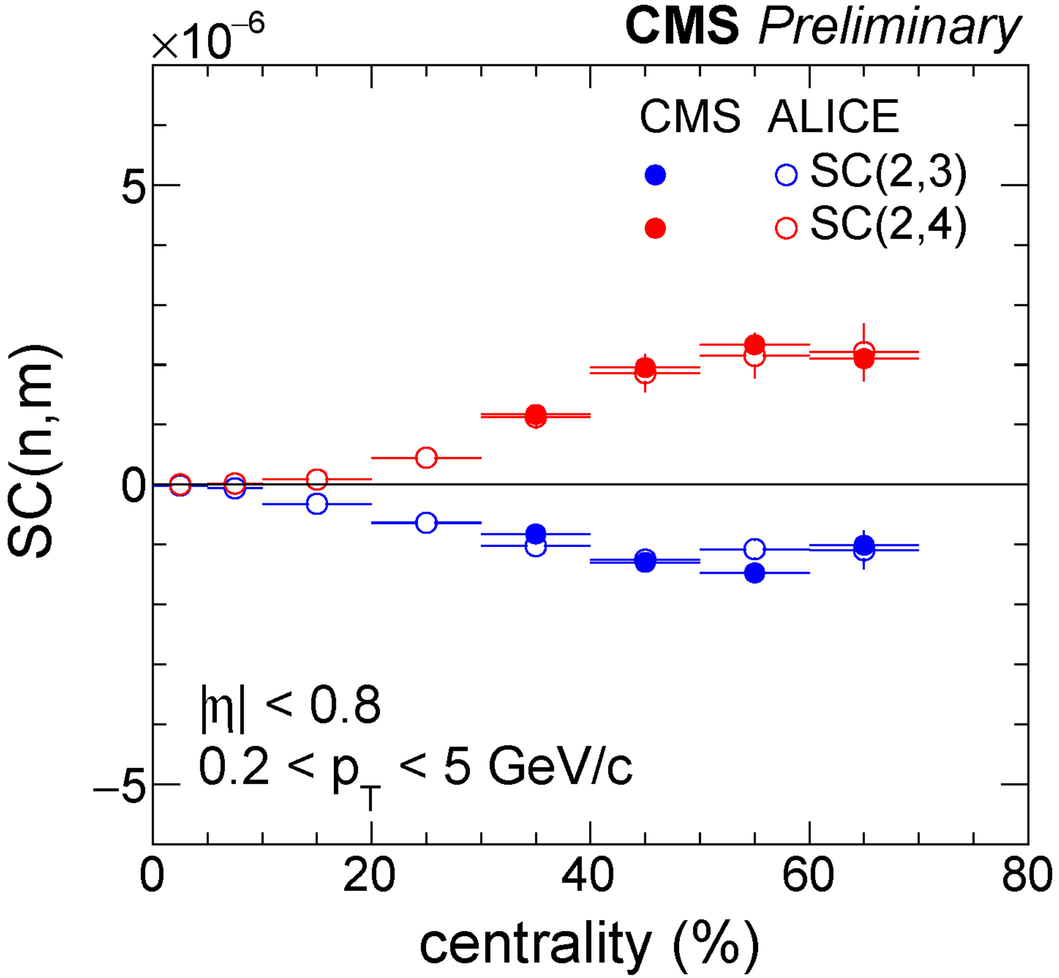


PRL 117 182301 (2016)

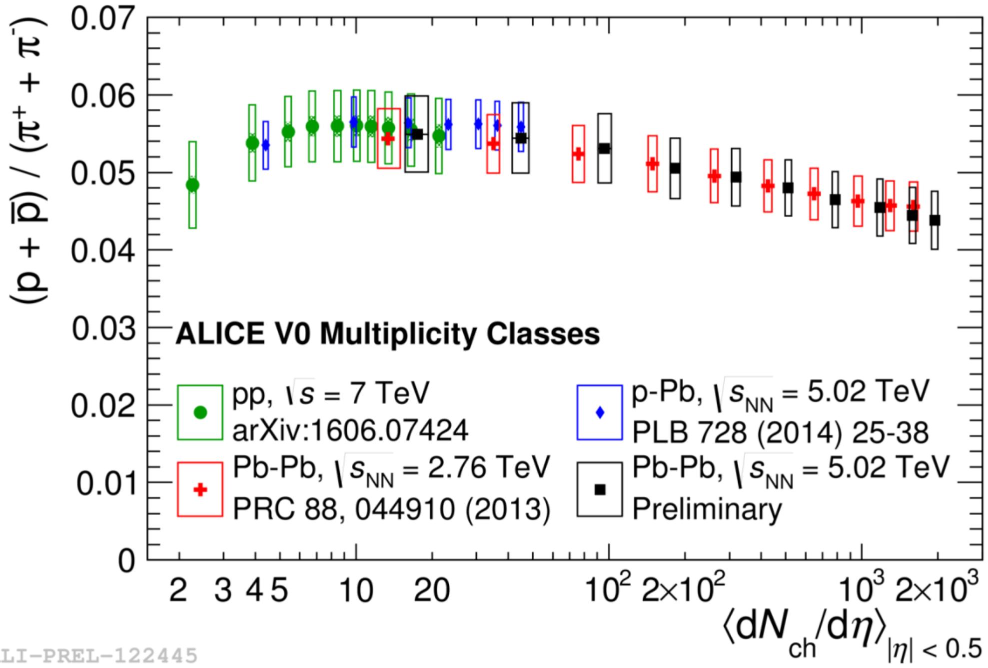
ALICE/CMS comparison

- Different bins in centrality



Proton in thermal model

- p/π same at 2 and 5 tev
- anihilation $p\bar{p} \rightarrow 4\pi$, reverse reaction less likely with expansion
- sequential freeze out



Blast wave

Hydro picture:

m_T spectra sensitive to the transverse flow

Blast wave description of the spectra:

$$\frac{\mathrm{d}^2 N_j}{m_T \mathrm{d}y \mathrm{d}m_T} = \int_0^{R_G} A_j m_T \cdot K_1\left(\frac{m_t \cosh\rho}{T}\right) \cdot I_0\left(\frac{p_t \sinh\rho}{T}\right) r dr$$

$$\rho(r) = \tanh^{-1}\beta_\perp(r)$$

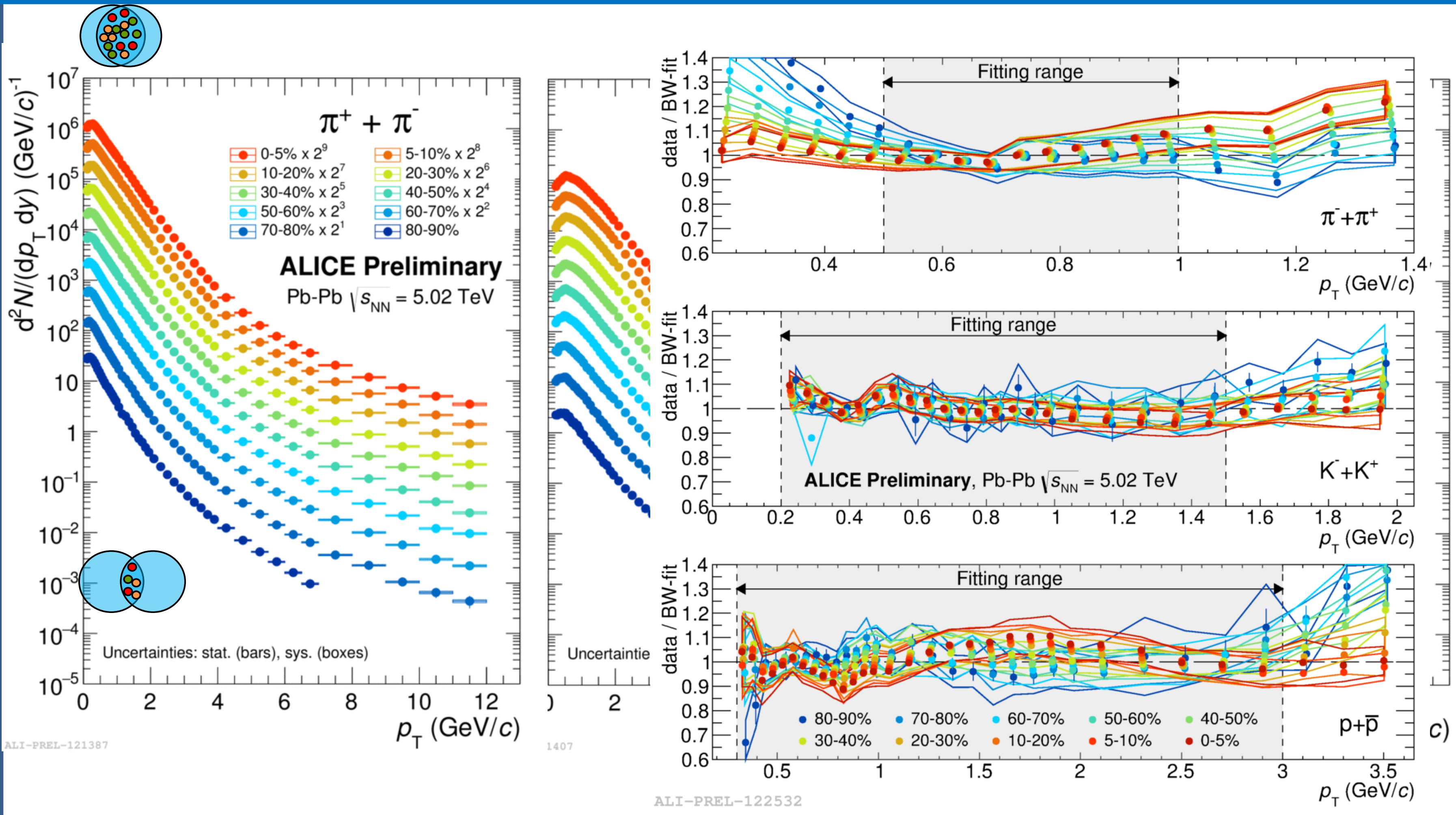
$$\beta_\perp(r) = \beta_S\left[\frac{r}{R_G}\right]^n \quad r \le R_G$$

Uniform particle density

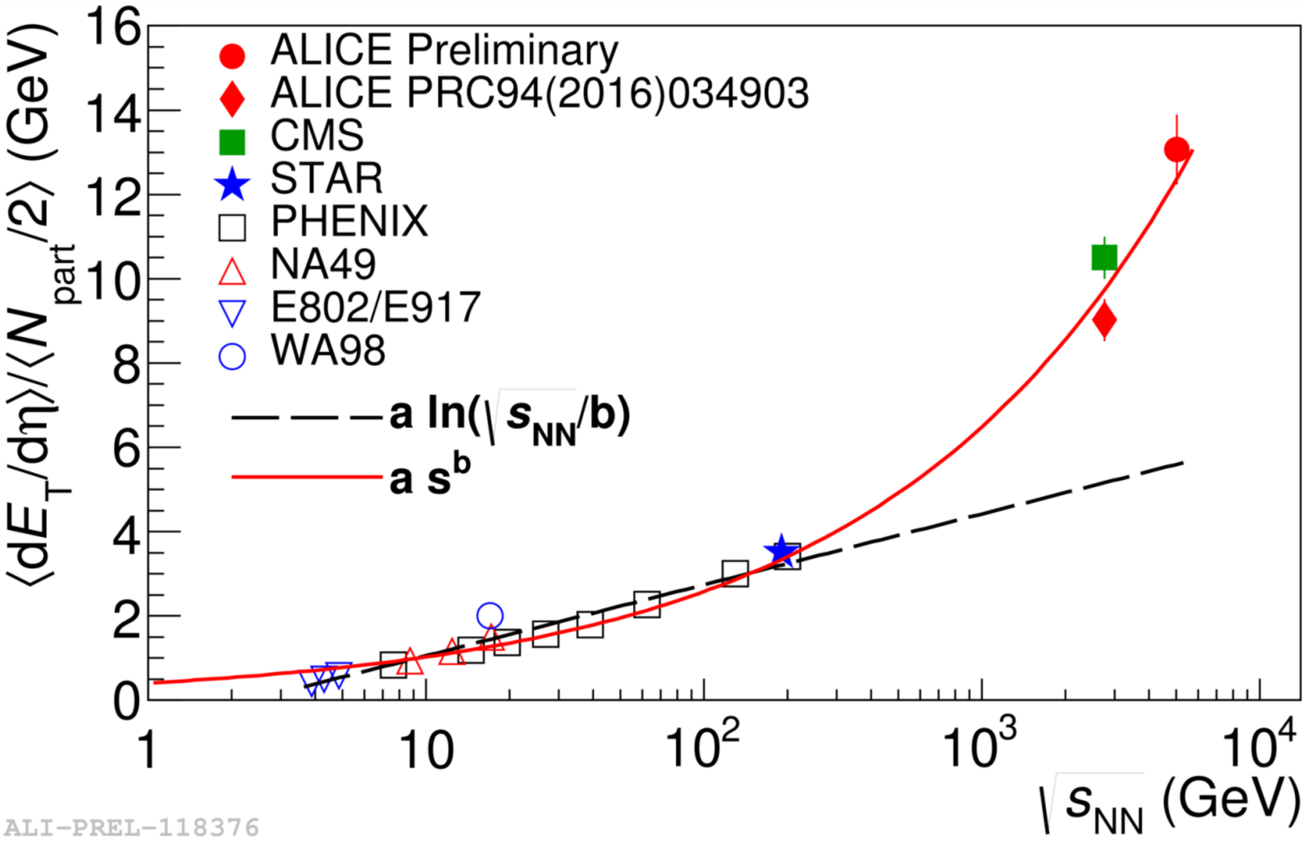
$$\boxed{<\beta_\perp>= \frac{2}{2+n}\beta_S}$$

Ref: E Schnedermann, J Sollfrank and U Heinz, **Phys. Rev. C48** (1993) 2462

Hadron spectra Pb-Pb



Transverse energy – *Energy density*



- Produced particles:

$dE_T/d\eta$ = (2016.5±5.7±144.3) GeV

- Energy density (Bjorken):

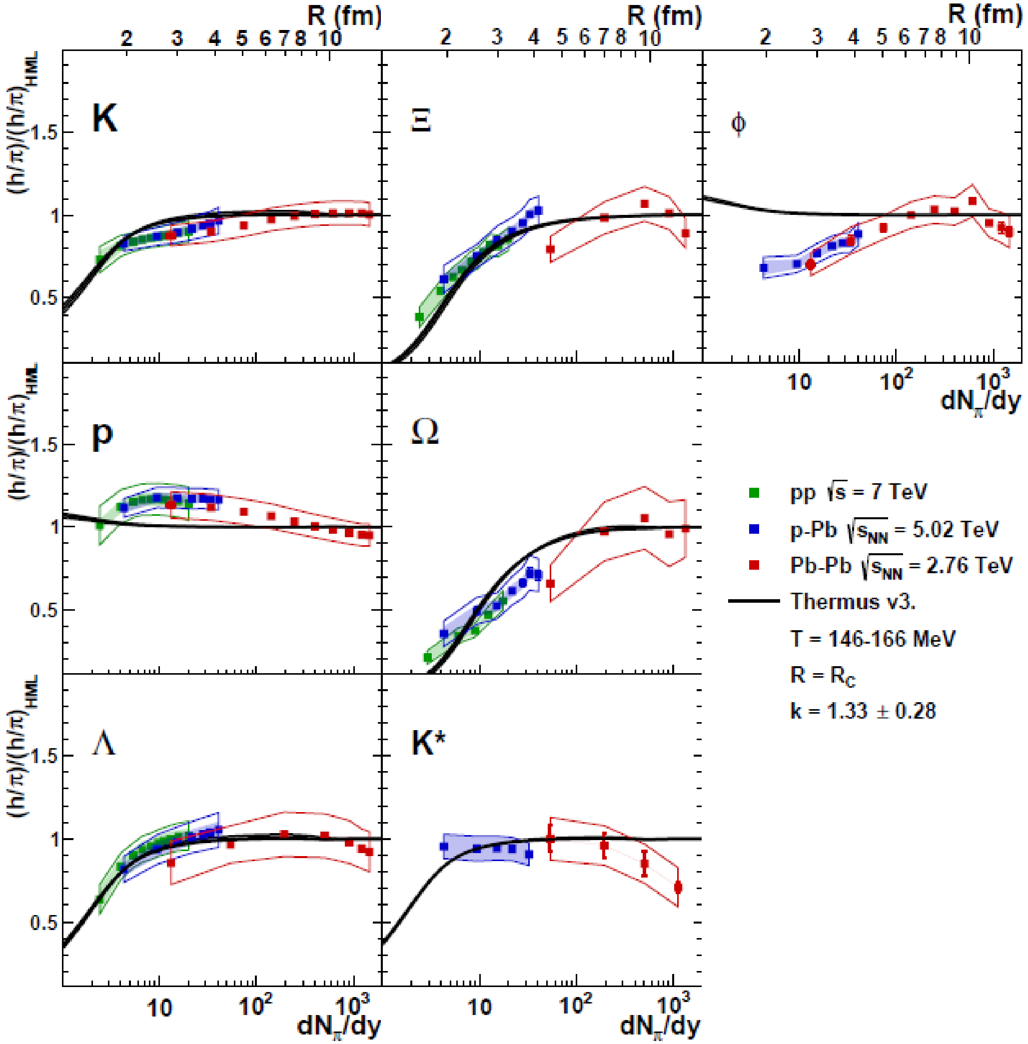
ε ~ 10 GeV/fm³ ,T~ 300 MeV at τ_0=1fm/c

$$\varepsilon(\tau) = \frac{E}{V} = \frac{1}{\tau_0 A}\frac{dE_T}{dy}$$

Thermal model

- ALICE data
- Canonical suppression
- THERMUS – thermal model with correlation radius
- Reasonable description
- see Collectivity in small systems talks

arXiv:1610.03001



v_n {2k} for Gauss Bessel

$$
\begin{aligned}
v_n\{2\}^2 &\equiv \langle v_n^2\rangle, \\
v_n\{4\}^4 &\equiv -\langle v_n^4\rangle + 2\langle v_n^2\rangle^2, \\
v_n\{6\}^6 &\equiv \left(\langle v_n^6\rangle - 9\langle v_n^4\rangle\langle v_n^2\rangle + 12\langle v_n^2\rangle^3\right)/4, \\
v_n\{8\}^8 &\equiv -\left(\langle v_n^8\rangle - 16\langle v_n^6\rangle\langle v_n^2\rangle - 18\langle v_n^4\rangle^2 + 144\langle v_n^4\rangle\langle v_n^2\rangle^2 - 144\langle v_n^2\rangle^4\right)/33 \\
&\vdots
\end{aligned}
$$

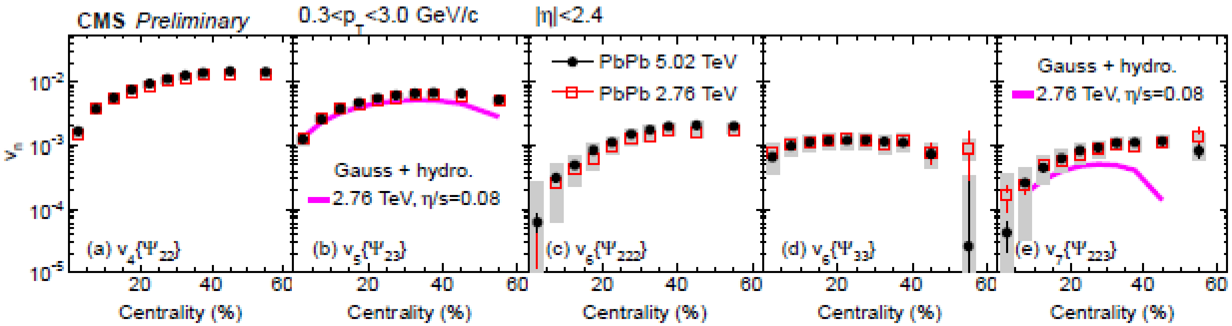
$$
p(v_n) = \frac{v_n}{\delta_{v_n}^2} \exp\left[-\frac{(v_n)^2 + (v_n^{RP})^2}{2\delta_{v_n}^2}\right] I_0\left(\frac{v_n v_n^{RP}}{\delta_{v_n}^2}\right),
$$

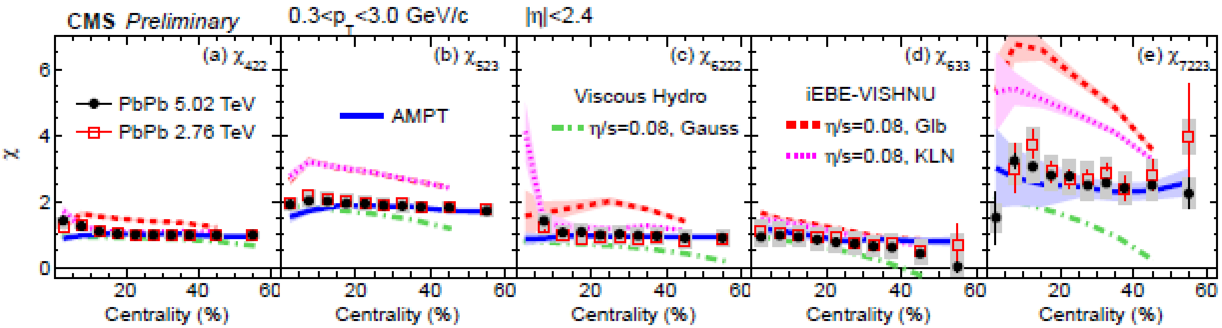
$$
v_n\{2k\} = \begin{cases} \sqrt{(v_n^{RP})^2 + 2\delta_{v_n}^2} & k = 1 \\ v_n^{RP} & k > 1 \end{cases}
$$

- Constant 2k harmonic -> consistent with Gauss-Bessel
- One can extract sigma

CMS Plane correlations

- HIN-16-018

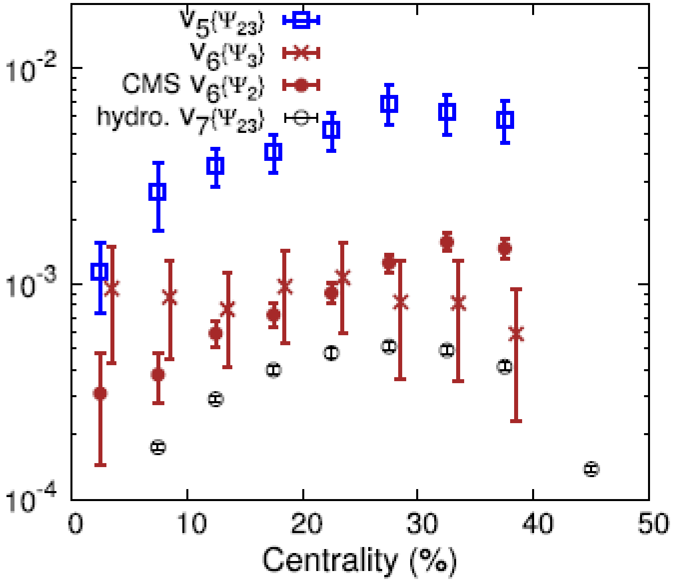




The data are compared with AMPT and hydrodynamic predictions with different shear viscosity to entropy density ratios and initial condition models. The predictions from AMPT are favored by the measurement. These results will provide constraints on the theoretical description of the medium close to the freeze-out temperature, which is poorly understood so far.

Harmonics: linear/nonlinear

- Motivation:
  - Linear part depends on initial conditions
  - Nonlinear part sensitive to freeze-out



$$P(\varphi) = \frac{1}{2\pi} \sum_{n=-\infty}^{+\infty} V_n e^{-in\varphi},$$

$$V_4 = V_{4L} + \chi_4 (V_2)^2$$
$$V_5 = V_{5L} + \chi_5 V_2 V_3$$
$$V_6 = V_{6L} + \chi_{62} (V_2)^3 + \chi_{63} (V_3)^2$$
$$V_7 = V_{7L} + \chi_7 (V_2)^2 V_3,$$

$$\langle |V_n|^2 \rangle = v_2\{2\}^2$$
$$\langle |V_n|^4 \rangle = 2v_2\{2\}^4 - v_2\{4\}^4$$
$$\langle |V_n|^6 \rangle = 4v_n\{6\}^6 - 9v_n\{4\}^4 v_n\{2\}^2 + 6v_n\{2\}^6.$$

$$\chi_4 = \frac{\langle V_4 (V_2^*)^2 \rangle}{\langle |V_2|^4 \rangle} = \frac{v_4\{\Psi_2\}}{\sqrt{\langle |V_2|^4 \rangle}}$$

$$\chi_5 = \frac{\langle V_5 V_2^* V_3^* \rangle}{\langle |V_2|^2 |V_3^2| \rangle} = \frac{v_5\{\Psi_{23}\}}{\sqrt{\langle |V_2|^2 |V_3^2| \rangle}}$$

$$\chi_{62} = \frac{\langle V_6 (V_2^*)^3 \rangle}{\langle |V_2|^6 \rangle} = \frac{v_6\{\Psi_2\}}{\sqrt{\langle |V_2|^6 \rangle}}$$

$$\chi_{63} = \frac{\langle V_6 (V_3^*)^2 \rangle}{\langle |V_3|^4 \rangle} = \frac{v_6\{\Psi_3\}}{\sqrt{\langle |V_3|^4 \rangle}}$$

$$\chi_7 = \frac{\langle V_7 (V_2^*)^2 V_3^* \rangle}{\langle |V_2|^4 |V_3^2| \rangle} = \frac{v_7\{\Psi_{23}\}}{\sqrt{\langle |V_2|^4 |V_3^2| \rangle}}.$$

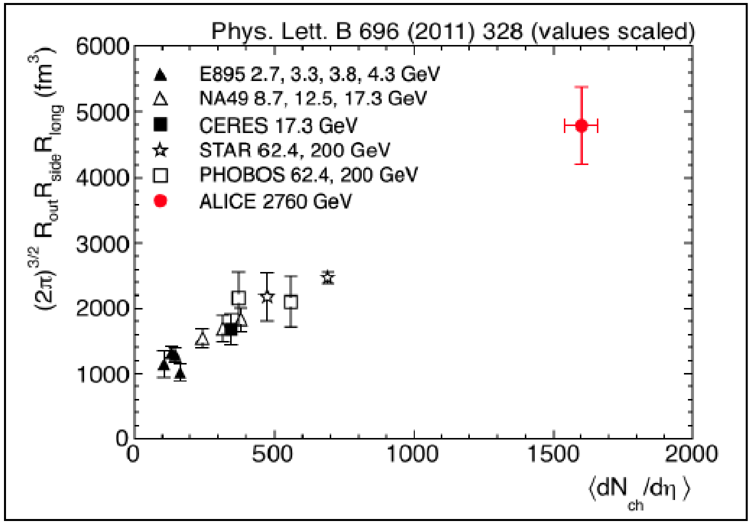
Geometry and flow

$$v_2 \sim \epsilon_2$$

$$\varepsilon_2 = \langle e(x,y)\cos\big(2(\varphi - \psi_2)\big)\rangle$$

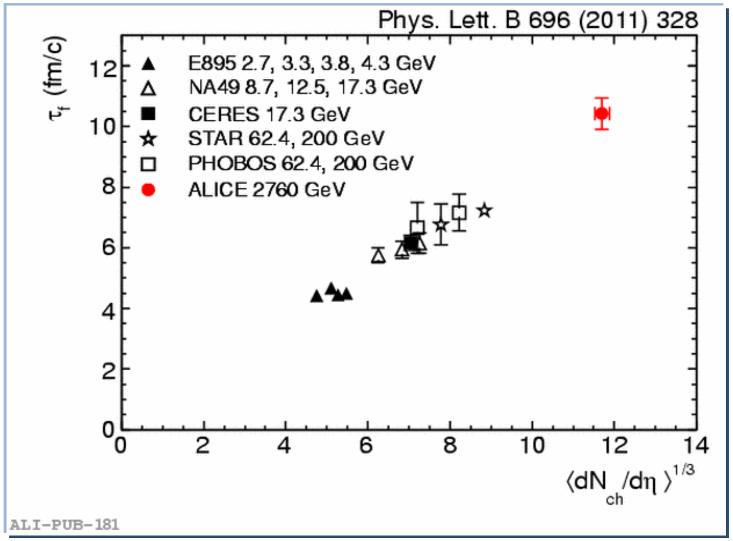
$e(x,y)$ – distribution of energy density of initial state

HBT radii – *System Size*



QM Interference of identical particles (Hanbury-Brown & Twiss interferometry) allows to measure source size and duration of emission.

Fireball volume at freeze-out:
$V \approx 5000 \text{fm}^3 \approx 4$ x Pb volume



Lifetime ~ 10 x QCD scale ($1/\Lambda_{QCD}$)