



SPRACE

Research activities of the SPRACE heavy ions group

CÉSAR A. BERNARDES, DENNER S. LEMOS, SANDRA S.
PADULA, SUNIL M. DOGRA

SPRACE

Results discussed in this talk

Analyses of the SPRACE Heavy Ion group as primary authors

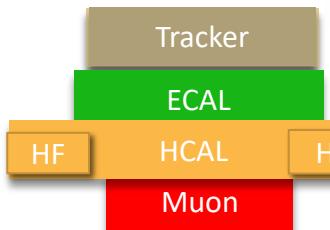
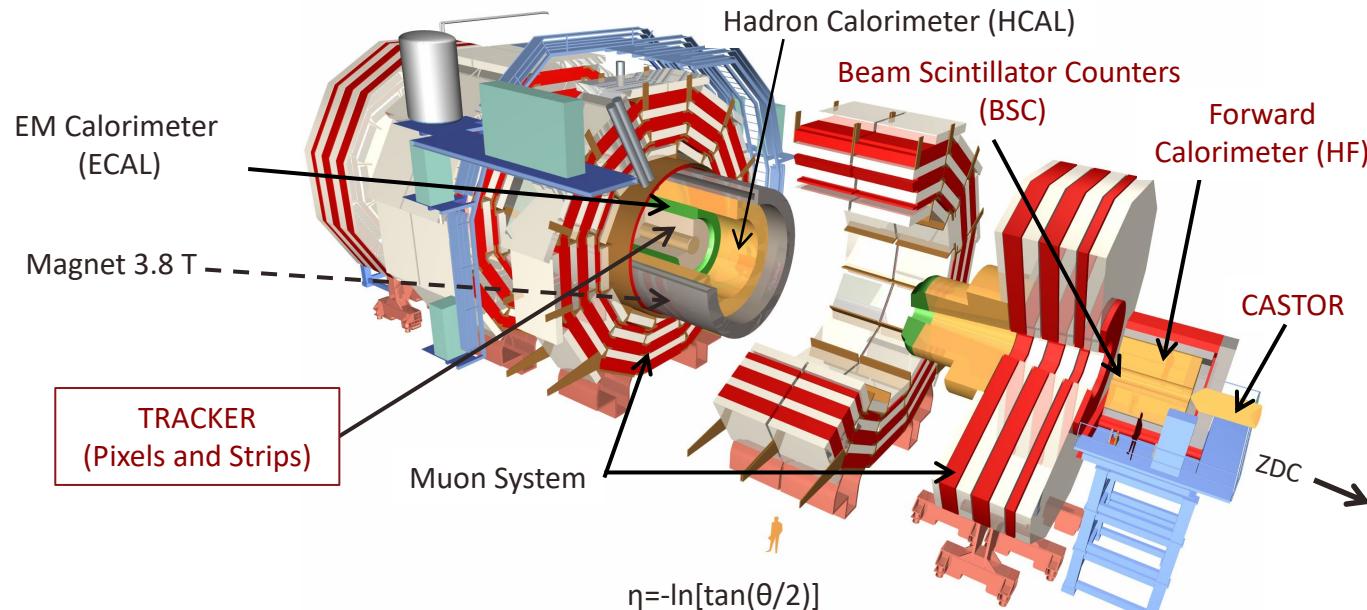
- ❑ Preliminary result – CMS Collaboration:
 - *Femtoscopic Bose-Einstein Correlations of charged hadrons in proton-proton collisions at $\sqrt{s} = 13 \text{ TeV}$*
CMS-PAS-FSQ-15-009 , <https://cds.cern.ch/record/2318575>
- ❑ Published Papers – CMS Collaboration:
 - *Measurement of Bose-Einstein Correlations in proton-proton Collisions at $\sqrt{s}= 7 \text{ TeV}$ at the LHC,*
[Journal of High Energy Physics 05, 029 \(2011\)](#)
 - *Azimuthal anisotropy of charged hadrons at high transverse momentum in PbPb collisions at $\sqrt{s}_{NN} = 2.76 \text{ TeV}$,*
[Phys. Rev. Lett. 109, 022301 \(2012\)](#)
 - *Multiplicity and transverse momentum dependence of two- and four-particle correlations in pPb and PbPb collisions,*
[Phys. Lett. B 724, 213 \(2013\)](#)
 - *Observation of correlated azimuthal anisotropy Fourier harmonics in pp and pPb collisions at the LHC,*
[Phys. Rev. Lett. 120, 092301 \(2018\)](#)
 - *Bose-Einstein correlations in pp, pPb, and PbPb collisions at $\sqrt{s}_{NN} = 0.9\text{-}7 \text{ TeV}$,*
[Phys. Rev. C 97, 064912 \(2018\)](#)

Works presented on behalf of the CMS Collaboration:

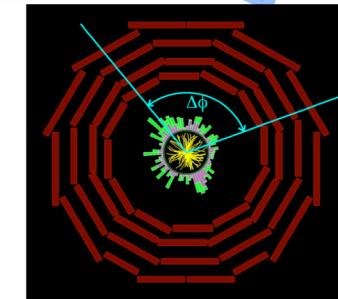
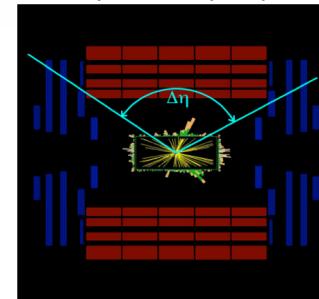
Detailed information in <https://www.sprace.org.br/twiki/bin/view/Main/SpracePublications>; summary:

- ❑ Quark Matter 2011 – Annecy-le-Vieux, France, May/23-28
 - *Bose-Einstein correlations in pp collisions measured at LHC with CMS, plenary talk by Sandra S. Padula*
 - ❑ WPCF 2011 – Tokyo, Japan, Sep/20-24
 - *Long-range dihadron correlations in high multiplicity pp and PbPb with CMS, plenary talk by Sandra S. Padula*
 - ❑ ISMD 2011 – Miyajima, Japan, Sep/26-30
 - *Bose-Einstein correlations in pp collisions measured at the LHC with CMS, plenary talk by Sandra S. Padula*
 - ❑ ICHEP 2012 – Melburn, Australia
 - *Collective flow and charged hadron correlations in 2.76 TeV PbPb collisions at CMS, parallel talk by Sandra S. Padula*
 - ❑ WPCF 2012 – Frankfurt, Germany , Sep/2012
 - *Results on correlations and flow with the CMS detector, plenary talk by Sandra S. Padula*
 - ❑ WPCF 2013–Acireale, Sicily, Italy
 - *Dihadron correlations and azimuthal anisotropy harmonics in pPb and PbPb at CMS, plenary talk by Sandra S. Padula*
 - ❑ WPCF 2013 – Acireale, Sicily, Italy
 - *Inclusive hadron production in pp and p-Pb collisions from CMS, plenary talk Sunil M. Dogra*
 - ❑ Quark Matter 2014, Darmstadt, Germany
 - *Bose-Einstein correlation measurements at CMS, parallel talk by Sunil M Dogra*
 - ❑ WPCF 2014 – Gyöngyös, Hungary
 - *Multidimensional analysis of BEC in pp collisions at 2.76 and 7 TeV in CMS, plenary talk by Sandra S. Padula*
 - ❑ DIS 2015 – Dallas, TX, USA
 - *Bose-Einstein correlations in various collision systems and energies measured with the CMS experiment, parallel talk by Sandra S. Padula*
 - ❑ WPCF 2015
 - *Two-particle correlations in pp collisions at 13 TeV measured with CMS, plenary talk by Sunil M. Dogra*
 - ❑ ICHEP 2016, Chicago, IL, USA
 - *Measurements of flow and correlation phenomena in pp, pPb and PbPb collisions at CMS, parallel talk by Sandra S. Padula*
 - ❑ EPS-HEP 2017
 - *Recent Results on Multi-Particle Azimuthal Correlations in High-Multiplicity pp and pPb Collisions in CMS, parallel talk by César A. Bernardes*
 - ❑ ISMD 2017, Tlaxcala, Mexico
 - *Flow and correlation phenomena measurements in pp, pPb and PbPb collisions at CMS, parallel talk by Sandra S. Padula*
 - ❑ WPCF 2018 – Krakow, Poland, 22-26/May
 - *Femtoscopic Bose-Einstein Correlations of charged hadrons in proton-proton collisions at $\sqrt{s} = 13$ TeV, plenary talk by Sandra S. Padula*
- FSQ-15-009 , <https://cds.cern.ch/record/2318575>

CMS Detector



$$|\eta| = -\ln[\tan(\theta/2)]$$

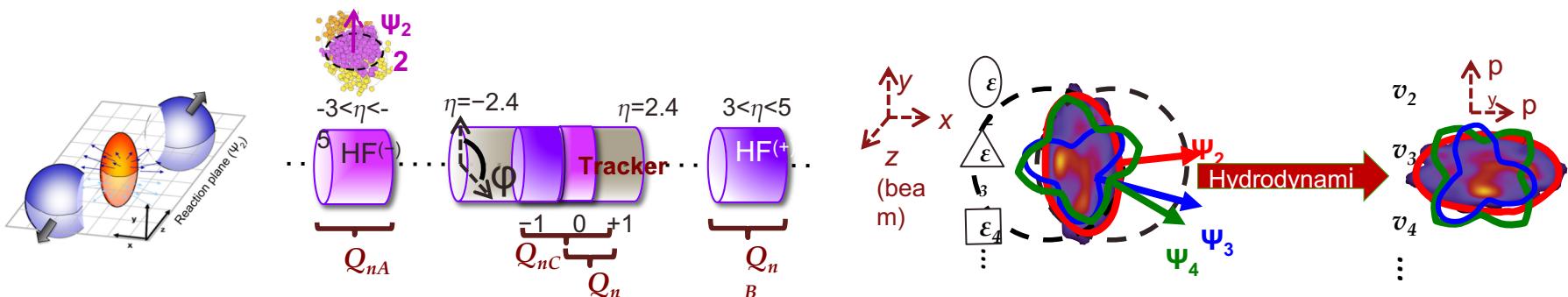


$$|\Delta\phi| \leq 2\pi$$

Brief discussion of analyses as primary authors

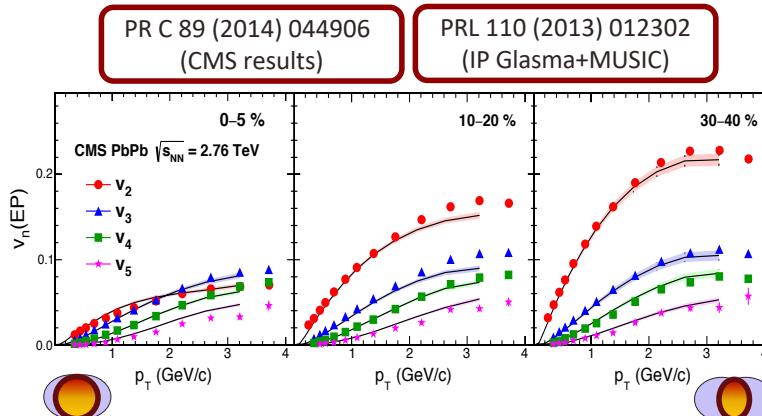
Anisotropic flow
analyses

Hydrodynamic flow in A-A collisions



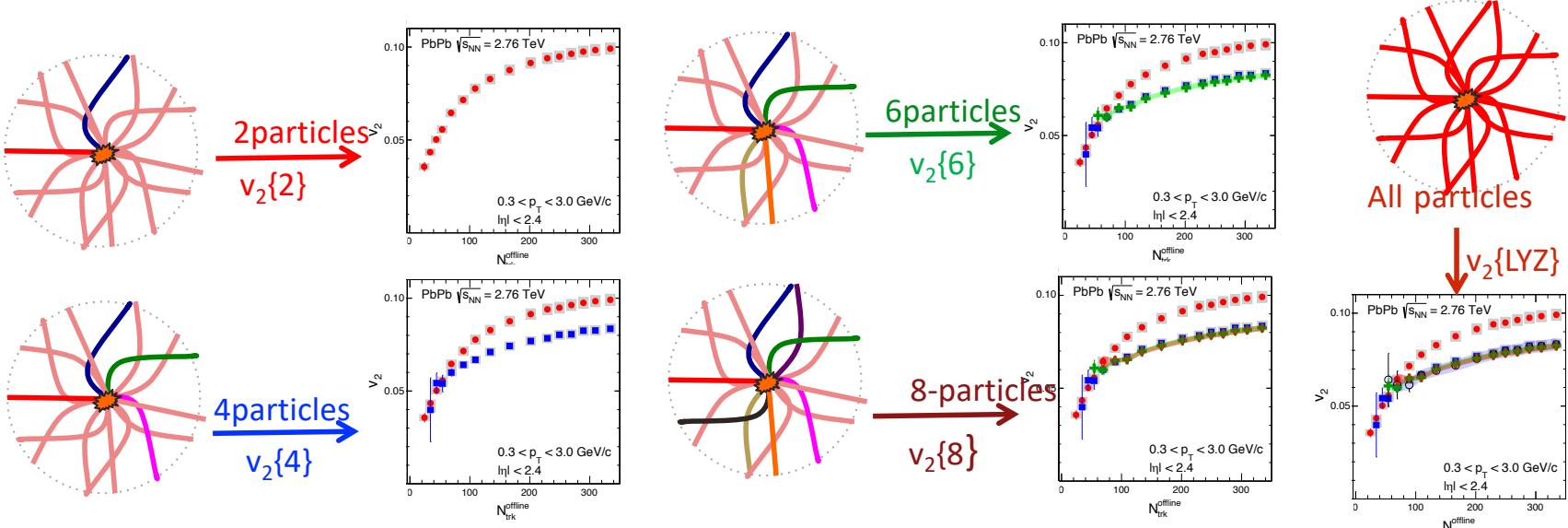
$$E \frac{d^3N}{d^3p} = \frac{1}{2\pi} \frac{d^2N}{p_T dp_T dy} \left(\sum_{n=1}^{\infty} 2v_n \cos[n(\phi - \Psi_{EP})] \right)$$

- v_n depends on:
 - Initial state geometry and its fluctuations
 - Medium transport coefficients (η/s , ...)
- v_n well understood in A-A collisions with hydrodynamics
 - Diagonal terms (v_n^2)



M-particle correlations and collectivity in AA

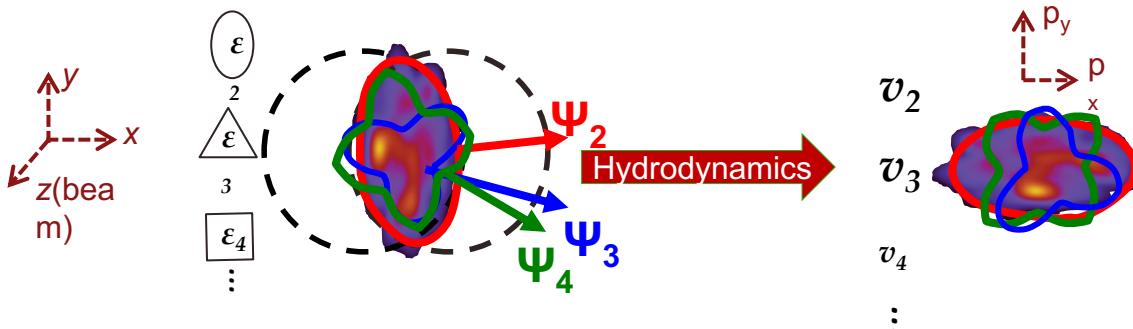
- ❑ Sensitive to non-flow (jets induced correlations)
- ❑ Several techniques: EP/SP + gap; 2-part. cumulant + gap; 2-part. corr. + gap + low $N_{\text{trk}}^{\text{offline}}$ subtraction



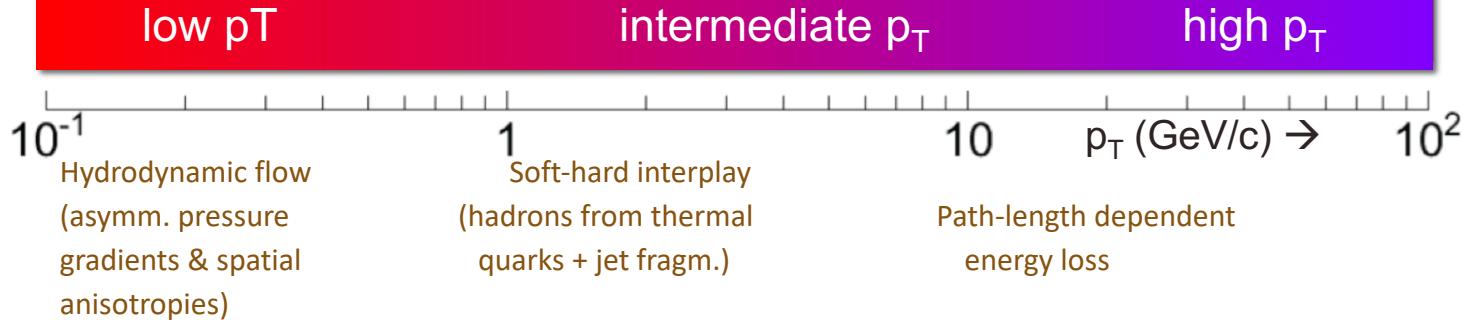
- ❑ v_4 : less sensitive to non-flow
- ❑ Requires larger data sample

- ❑ Collectivity: $v_2\{2\} \geq v_2\{4\} \approx v_2\{6\} \approx v_2\{8\} \approx v_2\{\text{LYZ}\}$
- ❑ Well described by **hydrodynamics** at low p_T ($< 3 \text{ GeV}/c$)

Flow in high energy collisions



- Hydrodynamical picture of eccentricities (fluctuating initial conditions) and the corresponding flow single particle Fourier harmonics

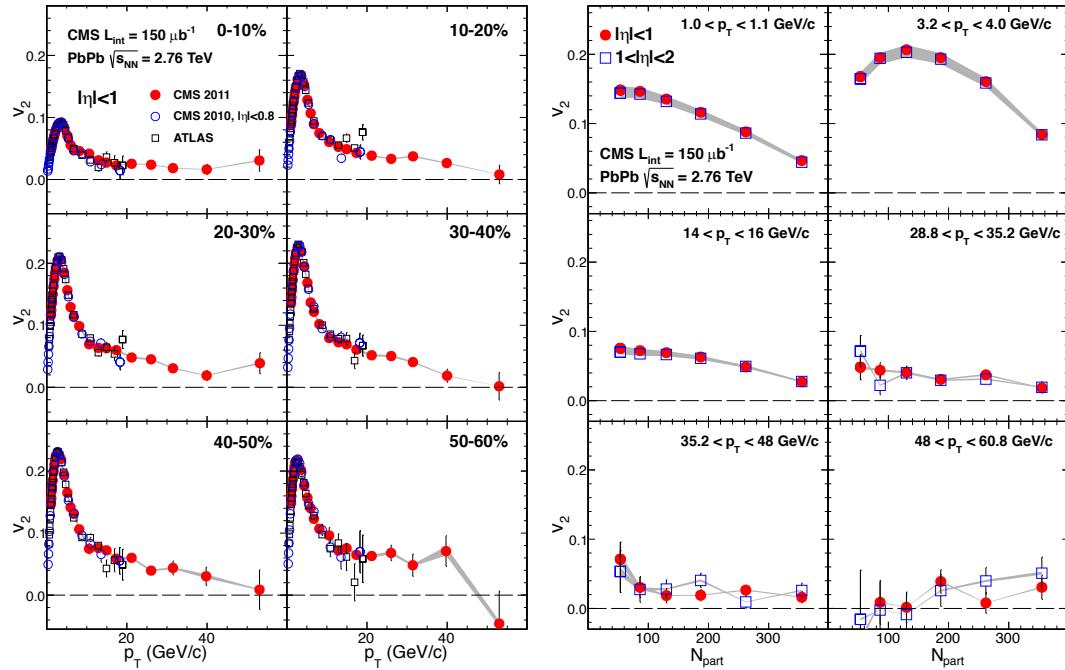


Azimuthal anisotropy at very high p_T

2012 (HIN-11-012):

PRL 109, 022301 (2012)

- ❑ Charged particles azimuthal anisotropy v_2 in PbPb collisions @ $\sqrt{s_{NN}} = 2.76$ TeV → over extended p_T range ($1 < p_T < 60$ GeV/c)
- ❑ $v_2(p_T)$ via **event plane** (six equal centrality bins in 0-60% most central): maximum $\sim p_T = 3$ GeV/c, gradually decrease; non-zero up to at least $p_T = 40$ GeV/c
- ❑ High p_T : reflect shape of the interaction region and path dependence on jets energy loss



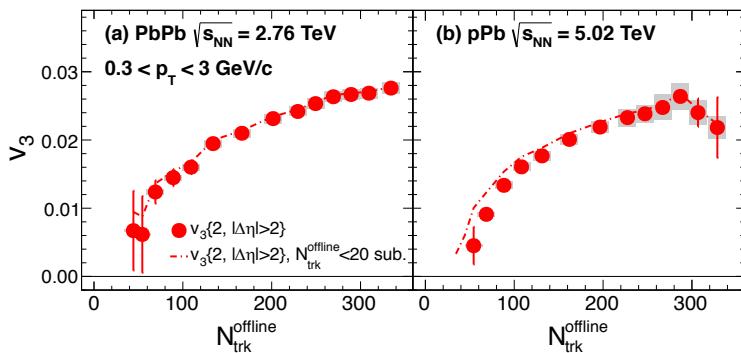
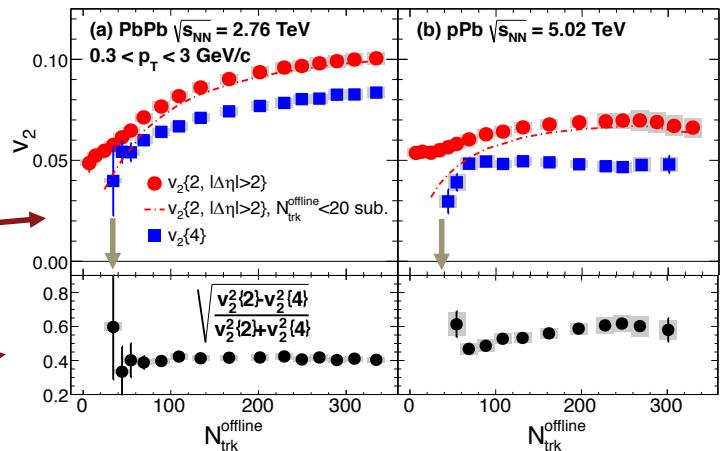
Comparing v_2 and v_3 in pPb and PbPb collisions

2013 (HIN-13-002):

Phys. Lett. B 724, 213 (2013)

PL B 724, 213 (2013)

- ❑ Elliptic (v_2) and triangular (v_3) azimuthal anisotropic harmonics extracted from long-range two-particle $\Delta\phi$ correlations:
 - $v_2\{4\}$ turns on at $N_{\text{trk}}^{\text{offline}} \sim 40$: onset of collective phenomena?
 - v_2 increases with multiplicity for pPb and PbPb collisions
 - Magnitude of event-by-event v_2 fluctuations → upper limit estimated from the difference in the $v_2\{2, |\Delta\eta| > 2\}$ and $v_2\{4\}$ (fluctuations: larger in pPb collisions)
- ❑ Comparison with semi-peripheral (2011) PbPb data covering similar range of particle multiplicities (N_{trk})
- ❑ Associated pair yields, the four-particle v_2 , and the v_3 : apparent at \sim same N_{trk} multiplicity.
- ❑ Remarkable:
 $v_3^{\text{pPb}} (\sqrt{s_{\text{NN}}} = 5.02 \text{ TeV}) \approx v_3^{\text{PbPb}} (\sqrt{s_{\text{NN}}} = 2.76 \text{ TeV})$



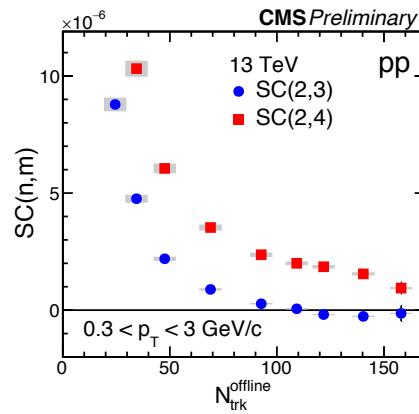
Correlation between flow harmonics (v_n) coefficients – I

HIN-16-022: Phys. Rev. Lett. 120, 092301 (2018)

Correlation between harmonics:

- ❑ Symmetric Cumulant (SC) – developed by ALICE
 - New observable
 - Base on 4-particle cumulant technique
 - Non-flow free at first order
- ❑ $SC(2,4) > 0 \rightarrow v_2$ and v_4 are correlated
 - Medium response + IS fluctuations
- ❑ $SC(2,3) < 0 \rightarrow v_2$ and v_3 are anti-correlated
 - IS fluctuations
- ❑ Well understood with hydro calculations in PbPb

PRL 120, 092301 (2018)



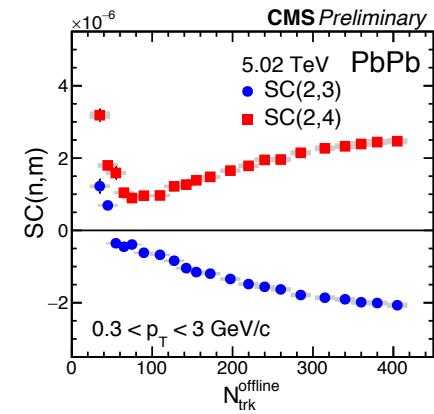
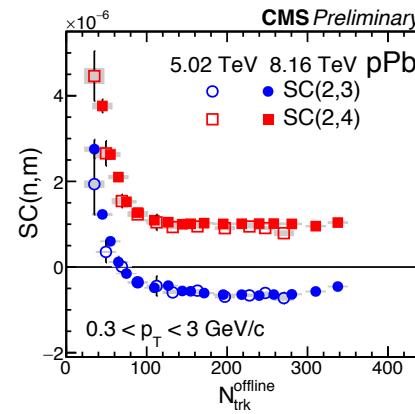
Similar qualitative trend in pPb and PbPb

- ❑ $SC(2,4)$ always positive
- ❑ $SC(2,3)$ positive for $N_{\text{trk}}^{\text{offline}} < 60$, negative beyond that

Very small energy dependence observed in p-Pb results

In pp collisions $SC(2,4) > 0$ always ; behavior of $SC(2,3)$ in high multiplicity not conclusive

$$SC(n, m) = \langle v_n^2 v_m^2 \rangle - \langle v_n^2 \rangle \langle v_m^2 \rangle$$



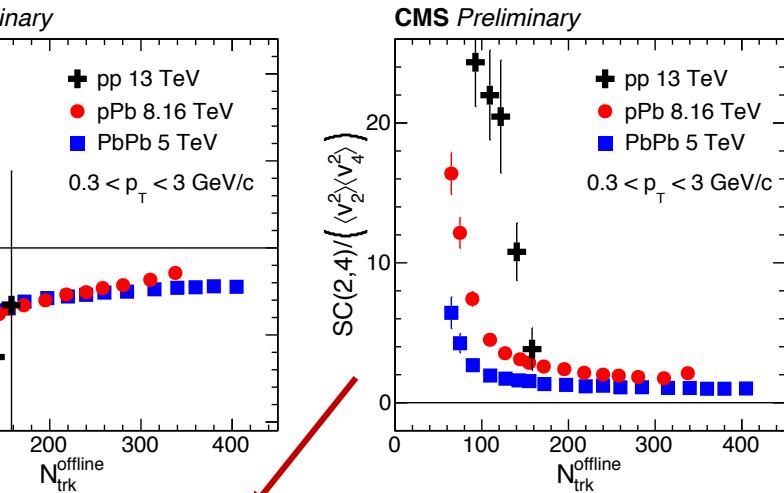
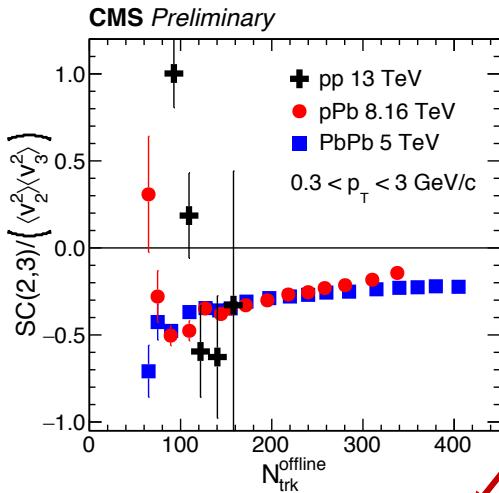
(Normalized) Correlation between flow harmonics (v_n) – II

SC normalized by $\langle v_n^2 \rangle \cdot \langle v_m^2 \rangle$

PRL 120, 092301 (2018)

Similar behavior in p-Pb and PbPb

- Points to similar IS fluctuations
 - Indicates similar origin for collectivity
 - pp is close but with large uncertainties
- First calculations (ε_n correlations only)
 - Right sign
 - Magnitude is off



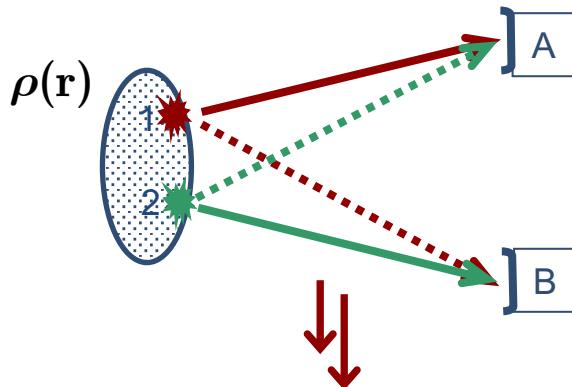
- Ordering observed: p-p > p-Pb > Pb-Pb
- May point to different contributions from initial state fluctuations and/or transport properties of the medium.

Brief discussion of analyses as primary authors

Bose-Einstein
correlations analyses

Bose-Einstein Correlations (BEC) – basic concepts

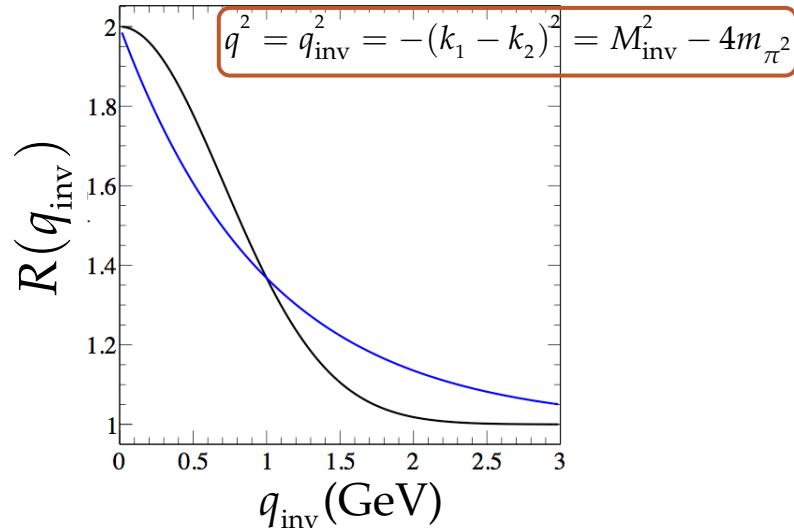
Detecting two identical bosons emitted at A & B from sources 1 & 2



Two-boson correlation function
→ reflects source dimensions

Correlation Function

$$R(q = k_1 - k_2) = \frac{P_2(k_1, k_2)}{P_1(k_1)P_1(k_2)} = 1 + \lambda |\mathcal{F}[\tilde{\rho}(q)]|^2$$

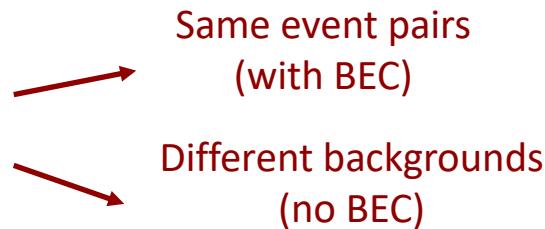


$$\mathcal{R}(q_{\text{inv}}) = C[1 + \lambda e^{-(q_{\text{inv}} R_{\text{inv}})^a}] (1 + \epsilon q_{\text{inv}})$$

BEC in 1D @ CMS single & double ratios

Experimentally

$$R^{\text{exp}}(Q = k_1 - k_2) = \frac{S(k_1, k_2)}{B(k_1, k_2)}$$



❑ Background (reference sample) pair selection

- Same event, \neq charges (resonances)
- Rotation of 1 track of the pair
- Mixed events ()

Coulomb FSI
Gamow factor applied to data

❑ Double ratios → remove non-BEC & reduce bias

$$\mathcal{R}(Q) = \frac{R(Q)}{R_{MC}(Q)} = \frac{\left(\frac{dN_{\text{signal}} / dQ}{dN_{\text{ref}} / dQ} \right)}{\left(\frac{dN_{MC, \text{like}} / dQ}{dN_{MC, \text{ref}} / dQ} \right)}$$

$$r_{ss}(\eta) = \frac{\eta / Q}{e^{\eta/Q} - 1}$$

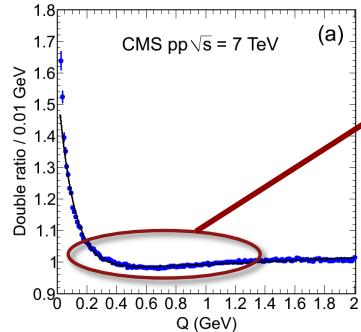
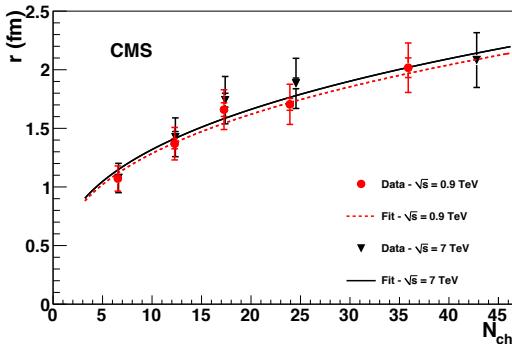
$$\eta = 2\pi\alpha_{em} m_\pi$$

BEC – analysis 1

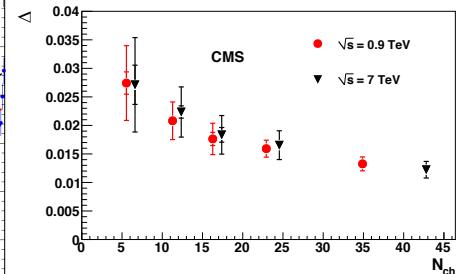
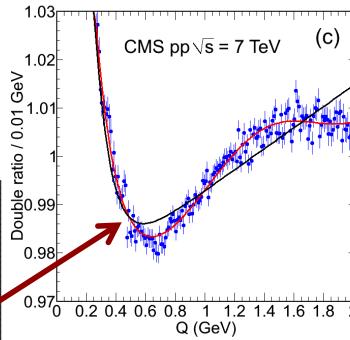
2011 (QCD-10-023): Journal of High Energy Physics 05, 029 (2011)

□ BEC of charged particles in pp collisions @ $\sqrt{s} = 0.9$ and 7 TeV

- Femtoscopic source size R_{inv} grows with multiplicity (as $N_{\text{ch}}^{1/3}$)
- Dependence on k_T also observed
- Practically no \sqrt{s} dependence



- Observation of anticorrelation (dip) [previously only reported in e^+e^- collisions at LEP \rightarrow PLB 663, 114 (2008)]



- exponential fit (black) not good
- Tau model [NPA 517, 588 (1990)] (red) fits better (related to strong x-p correlations)
- Anticorrelation Depth quantified (Δ)

BEC in pp collisions at 2.76 and 7 TeV – 1D, 2D, 3D

2018 (FSQ-14-002): PRC 97, 064912 (2018)

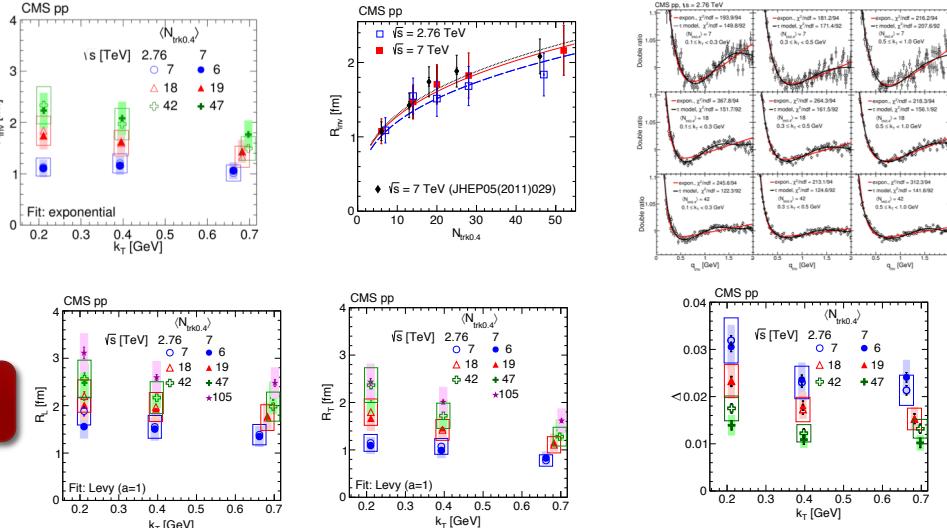
- BEC with charged hadrons
- Double ratios technique
- Studies versus N_{tracks} and k_T
 - R_{inv} ↗ with N_{tracks} and ↘ with k_T
 - Practically scales with \sqrt{s}
 - 1-D dip studied vs (N_{tracks}, k_T)
 - 2-D and 3-D: CM (*) and LCMS frames
 - In LCMS:
 - 2-D: $R_L > R^*_L ; R_L > R^*_T$
 - 3-D: $R_S^* > R_O^* > R_L^*$ (CM frame) and $R_L > R_S > R_O$ (LCMS)
- Fit 2-D & 3-D: stretched exponential
 - 2-D

$$\mathcal{R}(q_T, q_L) = C \left\{ 1 + \lambda \exp \left[- \left| q_T^2 R_T^2 + q_L^2 R_L^2 + 2q_T q_L R_{LT}^2 \right|^{\frac{\alpha}{2}} \right] \right\} \times (1 + \alpha q_T + \beta q_L)$$

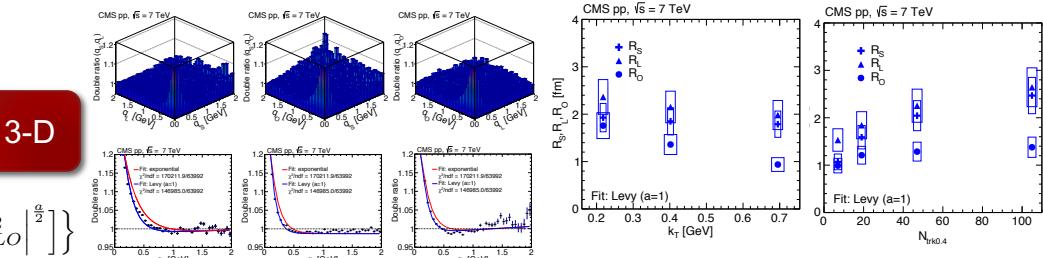
- 3-D

$$\mathcal{R}(q_S, q_L, q_O) = C \left\{ 1 + \lambda \exp \left[- \left| q_S^2 R_S^2 + q_L^2 R_L^2 + q_O^2 R_O^2 + 2q_O q_L R_{LO}^2 \right|^{\frac{\alpha}{2}} \right] \right\} (1 + \alpha q_S + \beta q_L + \gamma q_O)$$

1-D

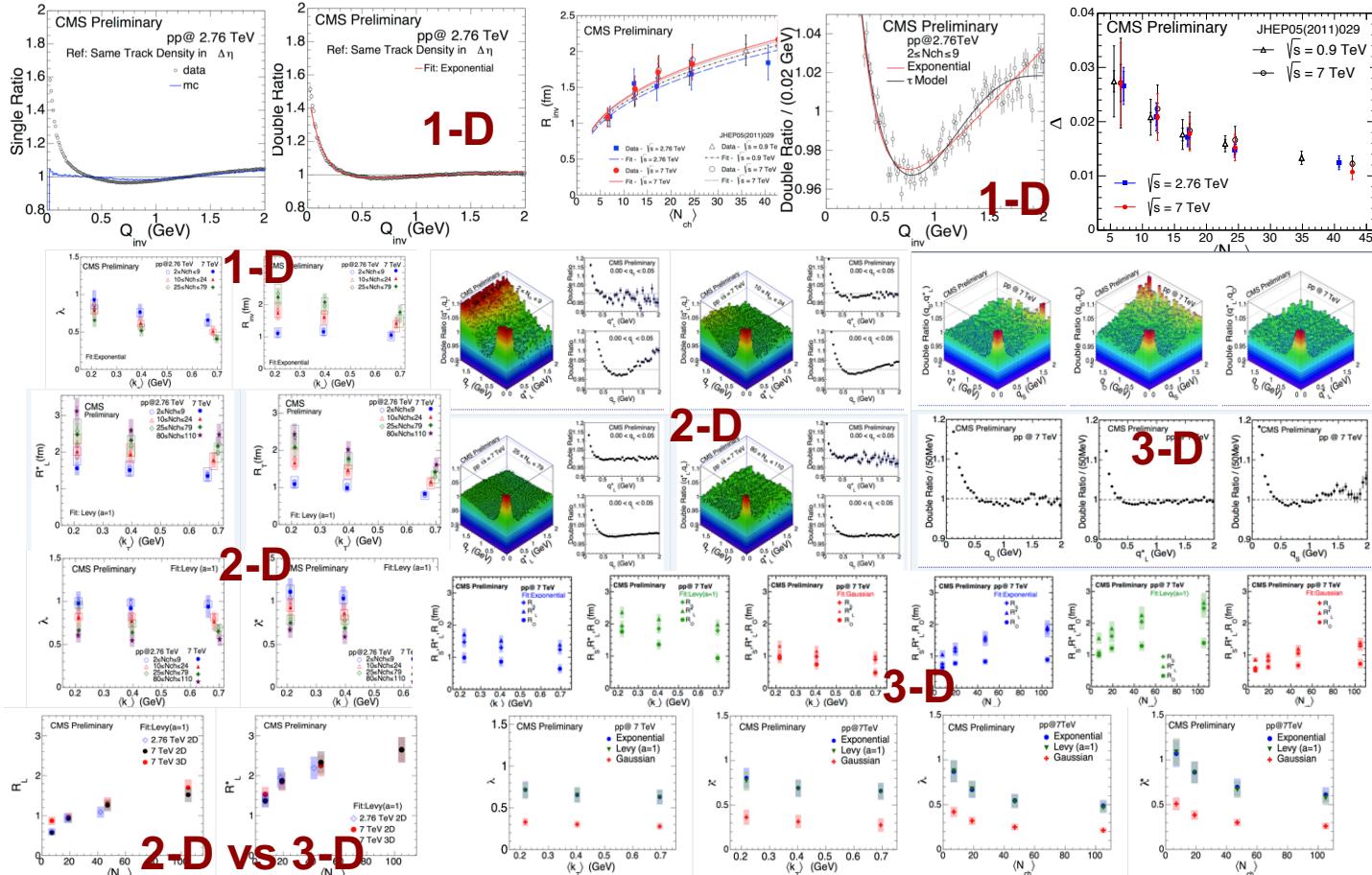


2-D



3-D

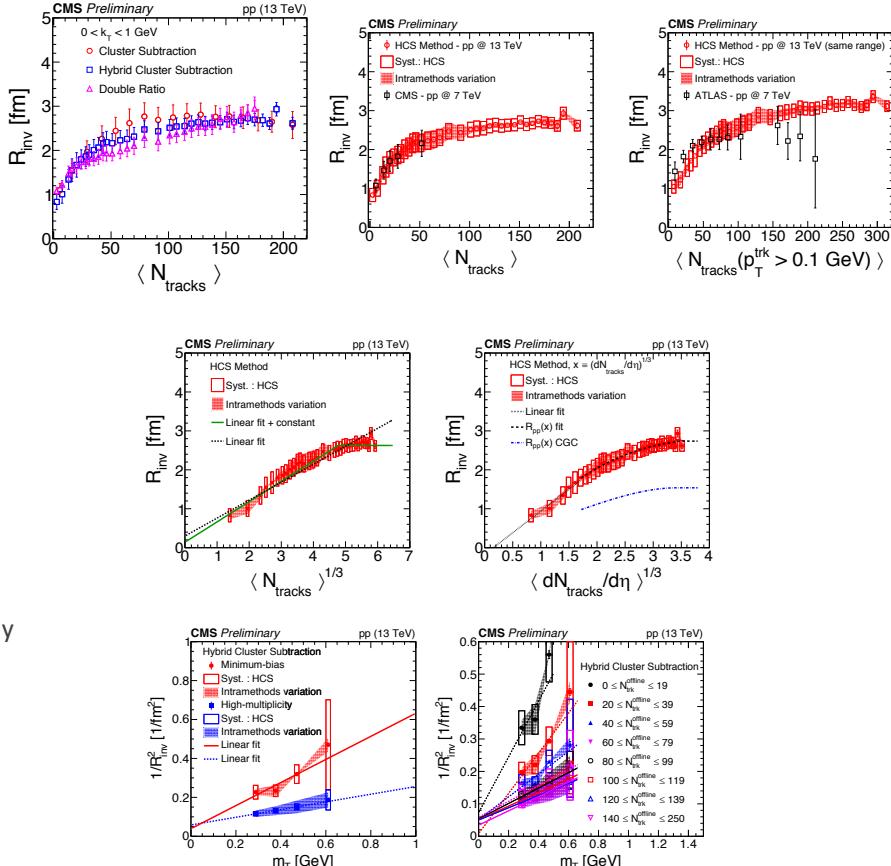
Full collection of BEC results in pp at 2.76 and 7 TeV



BEC in pp @ 13 TeV: up to very high N_{tracks}

2018: CMS-PAS-FSQ-15-009

- ❑ Charged hadrons
 - First measurement with good statistics up to N_{tracks} > 250
 - Three experimental techniques
 - Similar results in all three → one selected for comparisons with theory and experiment
- ❑ 1-D BEC (exponential fit): R_{inv} (and λ)
 - Scrutinized in detail as a function of multiplicity N_{tracks}:
 - Search for changes of slope in R_{inv} vs N_{tracks} [PLB 703 (2011) 237]
 - Continuous increase with (N_{tracks})^{1/3}: compatible with data
 - Possible saturation of R_{inv} in the high multiplicity range also compatible with data
- ❑ Detailed investigation as a function of k_T, searching for:
 - Possible change in behavior of R_{inv} results while moving from event in the MB to the HM regions, etc.
- ❑ Hydro expectation (NPA 946 (2016) 227): $1/R_{\text{inv}}^2$ vs m_T = $\sqrt{m_{\pi}^2 + k_T^2}$
 - m_T – scaling with different slopes in MB and HM:
 - Hubble-type of flow larger in MB than in HM
 - Similar to RHIC results in peripheral and central AuAu, respectively
- ❑ Comparison with CGC prediction [NPA 916 (2013) 210; PRC 87 (2013) 064906]
- ❑ <https://cds.cern.ch/record/2318575>



Heavy Ions: Phenomenology

Equation of State

Azimuthal correlations

BEC

Effects of equation of state on hydrodynamic expansion, spectra, flow harmonics and two-pion interferometry

To be published in

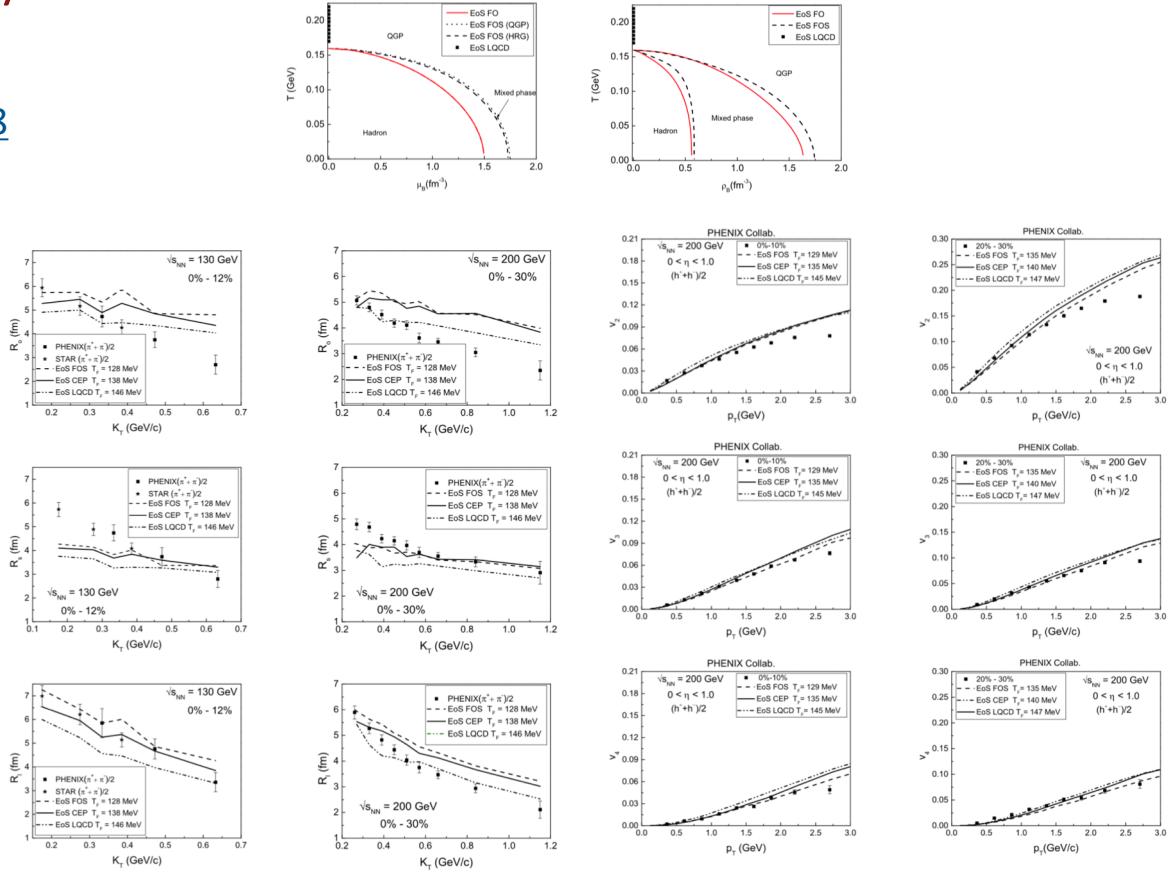
Int. J. Mod. Phys. E

<https://arxiv.org/abs/1409.0278>

Effects of equation of state on
hydrodynamic expansion,
spectra, flow harmonics and
two-pion interferometry]

Wei-Liang Qian, Danuce M. Dudek,
Yogiro Hama, Takeshi Kodama,
Otavio Socolowski Jr., Sandra
S.Padula

- ❑ Ideal Hydrodynamics with SPHERIC code
 - at RHIC energies
 - fluctuating Initial Conditions
- ❑ Study of some observables to the Equation of State
 - v_2, v_3, v_4
 - R_L, R_o, R_s



CHESS code

Complete Hydrodynamical Evolution SyStem (CHESS), Dener S. Lemos & Otavio Socolowski Jr.

Presented at Quark Matter 2018

- ❑ Structure: three public codes:
 - T_RENTo (Reduced Thickness Event-by-event Nuclear Topology)
 - vHLLE (viscous-Harten-Lax-van Leer-Einfeldt)
 - THERMINATOR2 (THERMal heavy IoN generATOR 2)
 - Choice of EoS (ideal or viscous hydro)
 - Femtoscopy radii R_L, R_o, R_s: results with/without viscosity
 - versus k_T (e ranges of N_{ch})
 - versus (dN/deta)^{1/3}

https://indico.cern.ch/event/656452/contributions/2859548/attachments/1648463/2635452/D_Lemos.pdf



Results on femtoscopy from hydrodynamics

in pp collisions at $\sqrt{s} = 7 \text{ TeV}$

*D. S. LEMOS¹ AND O. SOCOLOWSKI JR.²

¹São Paulo State University (UNESP) and ²Rio Grande Federal University (FURG)

*dener.lemos@sprace.org.br



OVERVIEW

The hydrodynamical model is an important tool for describing the collective behavior of the matter produced in relativistic heavy-ion collisions. Recently, experimental results show evidence of the same collective behavior in small systems (pp and pPb) in high multiplicity [1]. In this work, we calculated the pion femtoscopy in pp collisions at $\sqrt{s} = 7 \text{ TeV}$ with event-by-event hydrodynamics for both viscous and ideal cases.

HYDRODYNAMICAL MODEL

In the hydrodynamical description, we assume that a matter in local thermal equilibrium is formed and its evolution is governed by the conservation of energy-momentum and other conserved numbers.

- Equations of Motion
- Israel-Stewart
- $\Delta^{AB} \Delta^{\beta\delta} u^\gamma \partial_\gamma \pi_{A\beta} = -\frac{1}{\tau_T} [\pi^{\mu\nu} - \pi_{\text{NS}}^{\mu\nu}] - \frac{4}{3} \Pi^{\mu\nu} \partial_\gamma u^\gamma$
- $u^\gamma \partial_\gamma \Pi = -\frac{1}{\tau_I} [\Pi - \Pi_{\text{NS}}] - \frac{4}{3} \Pi \partial_\gamma u^\gamma$
- Solved by vHLLE code [2] in 2D+1;

FEMTOSCOPY

Bose-Einstein correlations or femtoscopy are a powerful probe of the space-time geometry of the particle emitting source.

$$\begin{aligned} \text{Source} & \xrightarrow{\text{A}} \text{Detectors} \\ \text{Source} & \xrightarrow{\text{B}} \text{Detectors} \end{aligned}$$

$$\mathcal{C}(p_1^\mu, p_2^\mu) = \frac{\mathcal{P}_2(p_1^\mu, p_2^\mu)}{\mathcal{P}_1(p_1^\mu) \mathcal{P}_1(p_2^\mu)}$$

- Bertsch-Pratt (3D Fit)
- $\mathcal{C} = 1 + \lambda \exp[-R_{\text{qg}}^2 - R_s^2 q_s^2 - R_\ell^2 q_\ell^2]$

RESULTS

INGREDIENTS

1. Initial Conditions (IC)

Give us information about the state of the matter formed in the collisions at the instant it enters in a local thermal equilibrium.

- Generated by TRENTO [3].
- $p = 0.0$;
- $k = 2.0$;
- $w = 0.4 \text{ fm}$;
- $\tau_0 = 0.1 \text{ fm}$;

2. Equations of State (EoS)

Relate the thermodynamic quantities and bring information about the phase transition of the matter created in the collisions;

- HotQCD EoS with 2 + 1 flavors [4];
- $T_c = 154 \pm 9 \text{ MeV}$;

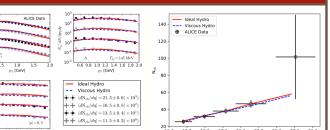
3. Freeze-out

The stage when the mean free-path becomes of the order of the size of the system. In that case, the hydrodynamical model is no longer valid and the particles decouple by traveling straight to the detector.

$$E \frac{d^3 N}{d^3 p} = \int_{\Sigma} d\Sigma_p p^\mu f(x, p)$$

- Solved by THERMINATOR 2 [5];

SPECTRA AND PSEUDORAPIDITY



Although our results show a similar behavior compared to the experimental data [6], in general, the obtained radii overestimate the data for \mathcal{R}_{L} , \mathcal{R}_{o} , and \mathcal{R}_{s} . We also see the small influence of viscous effects on the radii in pp collisions. We expect our results will be improved by including Coulomb interaction between the produced pions (work in progress).

REFERENCES

- [1] CMS Collaboration, *Phys. Lett. B*, 765:193, (2017).
- [2] Iu. Karpenko *et al.*, *Comput. Phys. Commun.*, 185:3016, (2014).
- [3] J. S. Moreland *et al.*, *Phys. Rev. C*, 92:01901, (2015).
- [4] A. Bazavov *et al.* (HotQCD Collaboration), *Comput. Phys. Rev. D*, 90:094503, (2014).
- [5] M. Chojnacki *et al.*, *Comput. Phys. Commun.*, 183:746, (2012).
- [6] ALICE Collaboration, *Eur. Phys. J. C*, 68:345, (2010). *Nature Phys.*, 13:535, (2017). *Phys. Rev. D*, 84:112004, (2011).

ACKNOWLEDGEMENTS

This material is based upon work supported by the São Paulo Research Foundation (FAPESP) under Grant No. 2017/02675-6. DSL acknowledges the financial support by IFT/UNESP and Quark Matter Organizing Committee for participating in the QM2018.

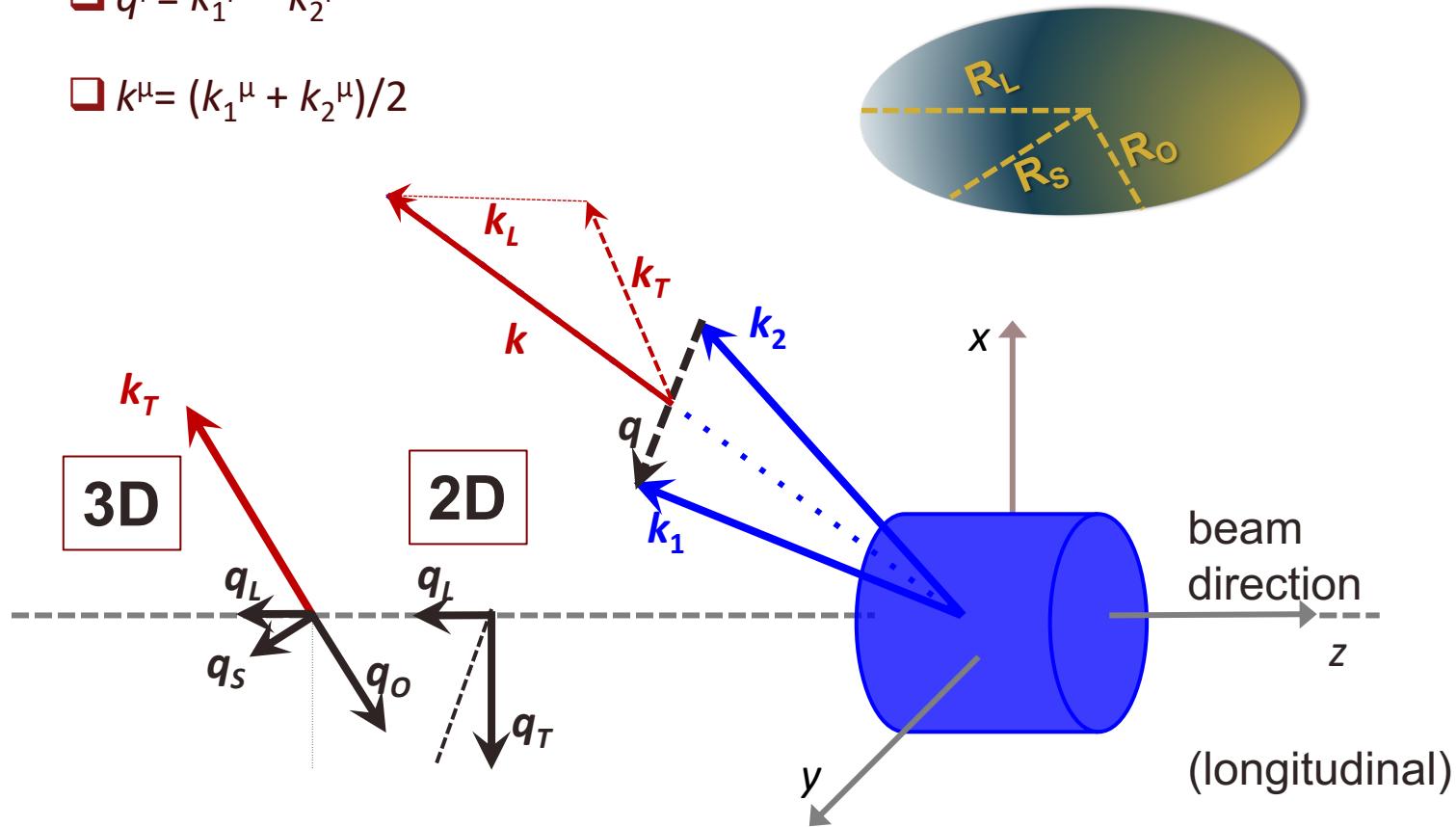
Obrigada!

Extras

Decomposition: (q_L, q_T) in 2-D and (q_L, q_O, q_S) in 3-D

$q^\mu = k_1^\mu - k_2^\mu$

$k^\mu = (k_1^\mu + k_2^\mu)/2$



Outline of analysis methods

Double Ratio (DR)

- ❑ Ratio of Single Ratios (SR)
 - Single ratio in data divided by Single ratio in MC
 - Non-BEC contributions: removed by directly performing the ratio of data to MC

Fit double ratio with a function representing the BEC signal alone

References:

- PRL **105** (2010) 03200 & JHEP **05** (2011) 029
- CMS-FSQ-13-002-PAS & PRC 97, 064912 (2018) & CMS-FSQ-15-009-PAS

Hybrid Cluster Subtract (HCS)

– data-driven

- ❑ Employs Single Ratios only
- ❑ Non-BEC effects: estimated from data (+ –) SR
 - Uses MC to translate this contribution into the bkg in the ($\pm \frac{1}{2}$) single ratio

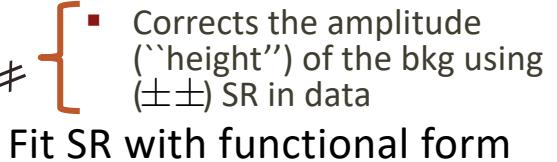
Fit single ratio data with combined function for signal + bkg

References:

- ATLAS-CONF-2016-027
- CMS-FSQ-15-009-PAS

Cluster Subtraction (CS) – fully data-driven

- ❑ Employs Single Ratios only
- ❑ Bkg is estimated directly from data (+ –) SR
 - Corrects the amplitude (“height”) of the bkg using ($\pm \frac{1}{2}$) SR in data

 ≠ 
Fit SR with functional form combining sig+bkg components

References:

- CMS-HIN-14-013-PAS & PRC 97, 064912 (2018) & CMS-FSQ-15-009-PAS

