SPRACE

Multi-Particle Azimuthal Correlations in High-Multiplicity pp & pPb Collisions at CMS

CESAR A. BERNARDES

FOR THE CMS COLLABORATION

Outline

Azimuthal Correlations in AA Collisions

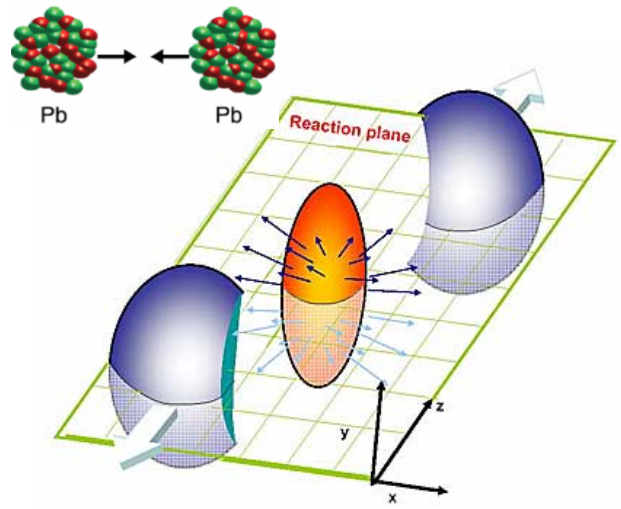
Measurements in PbPb Collisions by CMS

Studies of Small Systems (pp, pPb)

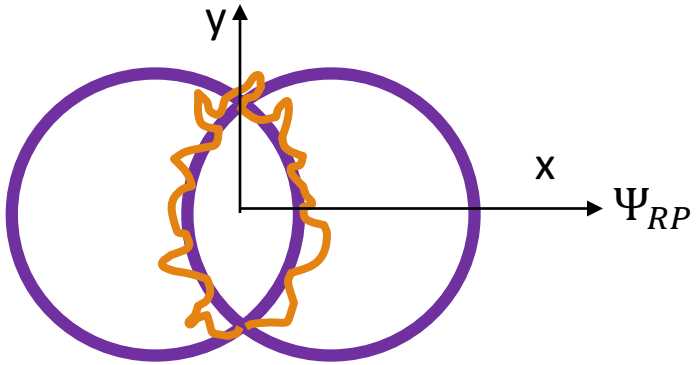
Analysis Methods for Multi-Particle Correlations

Recent Results in Small Systems by CMS

Introduction – Azimuthal Correlations in AA Collisions



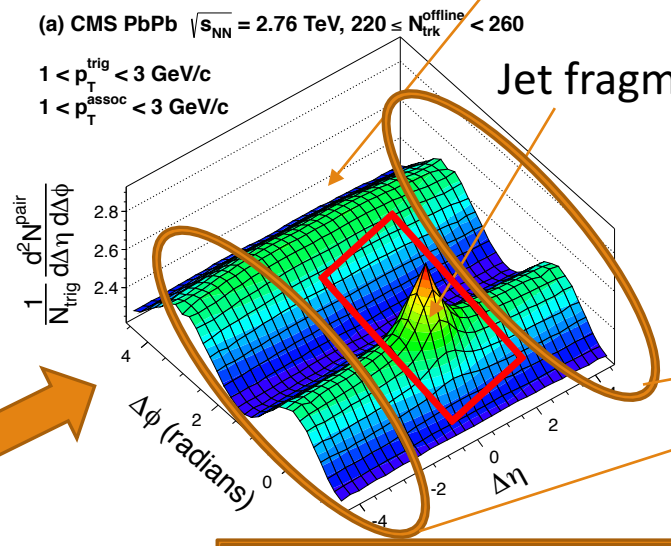
Fluctuating Initial Geometry + Pressure



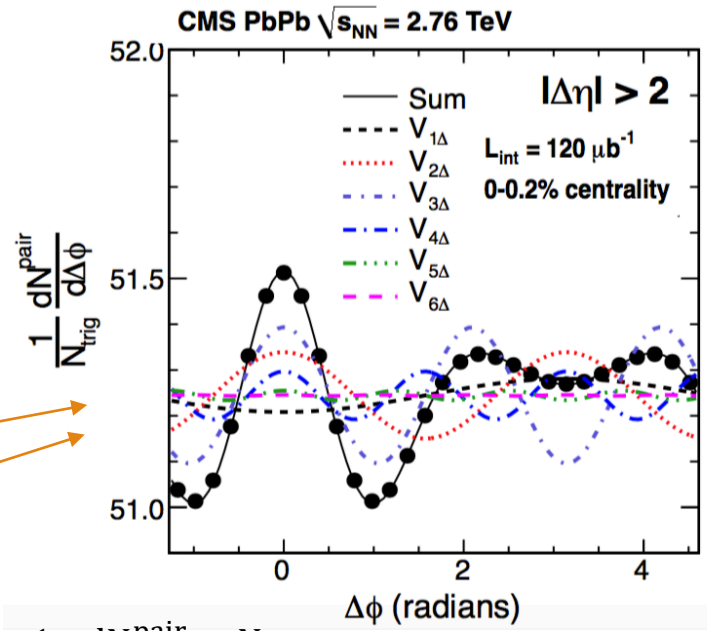
Two-Particle Correlations

Back-to-back jets

Jet fragmentation



Projecting in Δϕ
the long-range correlations



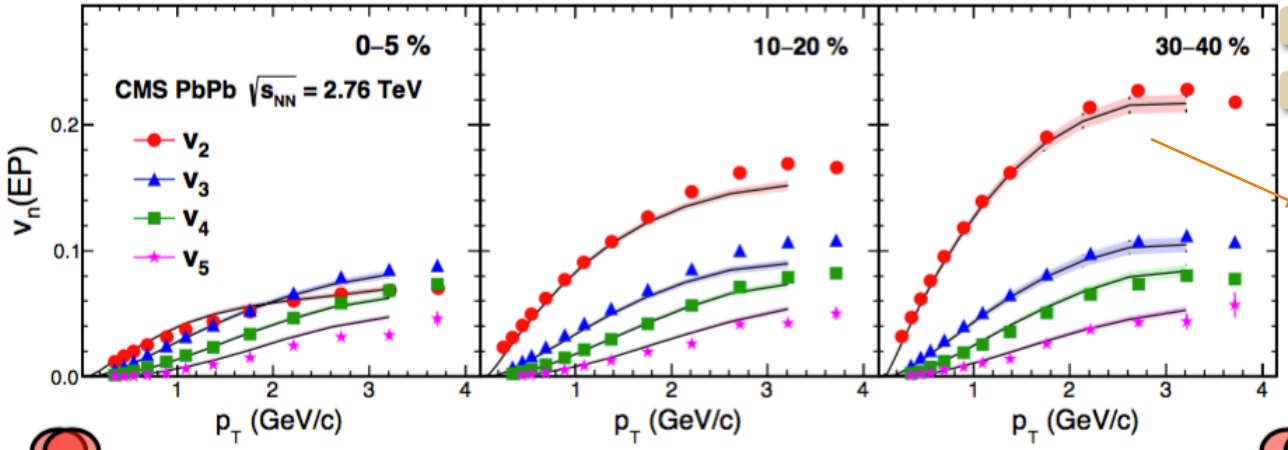
$$\frac{1}{N_{trig}} \frac{dN^{pair}}{d\Delta\phi} = \frac{N_{assoc}}{2\pi}\left[1 + \sum_n 2V_{n\Delta}\cos(n\Delta\phi)\right]$$

$$V_{n\Delta} = v_n^2$$

In Hydrodynamic models : v_2 (elliptic flow) and v_3 (triangular flow)

Related to medium response to initial collision geometry and its fluctuations

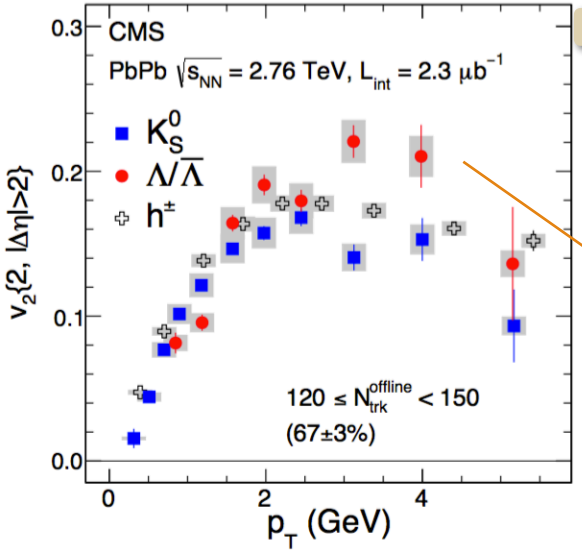
Most of the AA Data well Described by Hydrodynamics



Phys. Rev. C 89, 0449076 – CMS Results

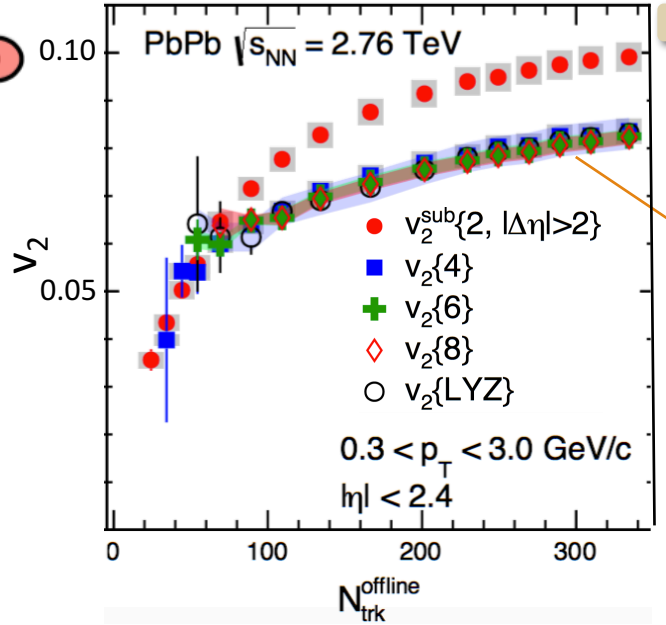
Phys. Rev. Lett. 110, 012302 – IP glasma + MUSIC

Shear viscosity ($0.07 \leq \eta/s \leq 0.2$) → Almost perfect fluid!



Phys. Lett. B 742 (2015), 200

Mass ordering up to ~2 GeV
Connected to Radial Flow



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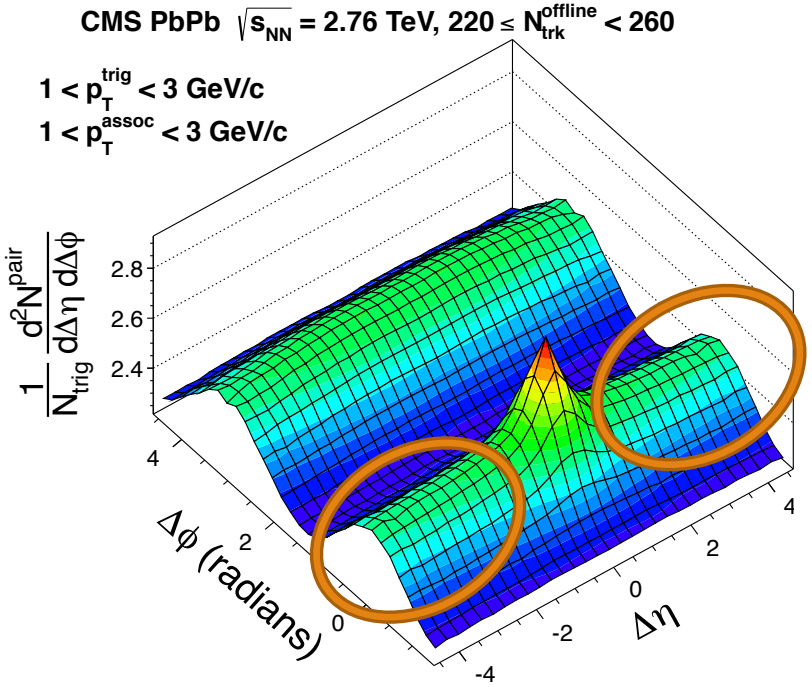
$v_2\{2\} \geq v_2\{4\} \approx v_2\{6\} \approx v_2\{8\} \approx v_2\{\infty\}$
→ Collectivity!!!

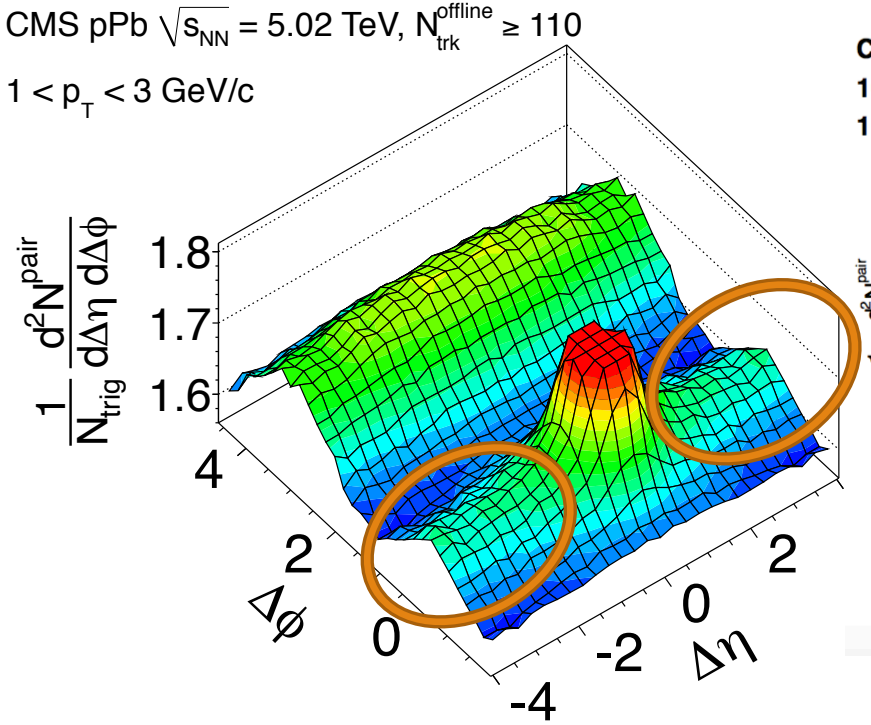
“Ridge” in All Systems

Similar to AA collisions

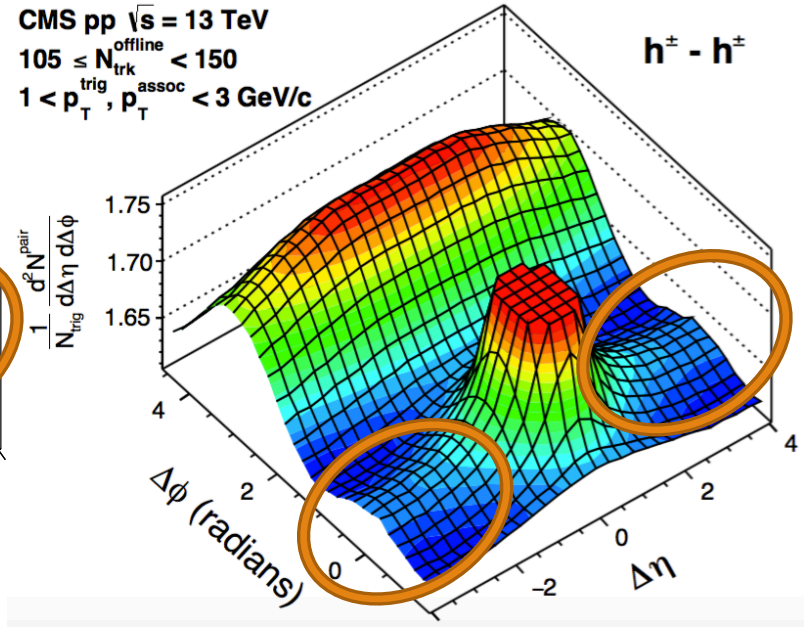
- Long-range near-side correlations in **High-Multiplicity** pp and pPb collisions



PbPb



pPb



pp

Are small systems behavior similar to AA?

Similar ridge structure as in AA

- Higher relative contribution from jets

Questions

- Is collectivity present in small systems?
  - If yes, what is the origin? Is it similar to AA collisions?

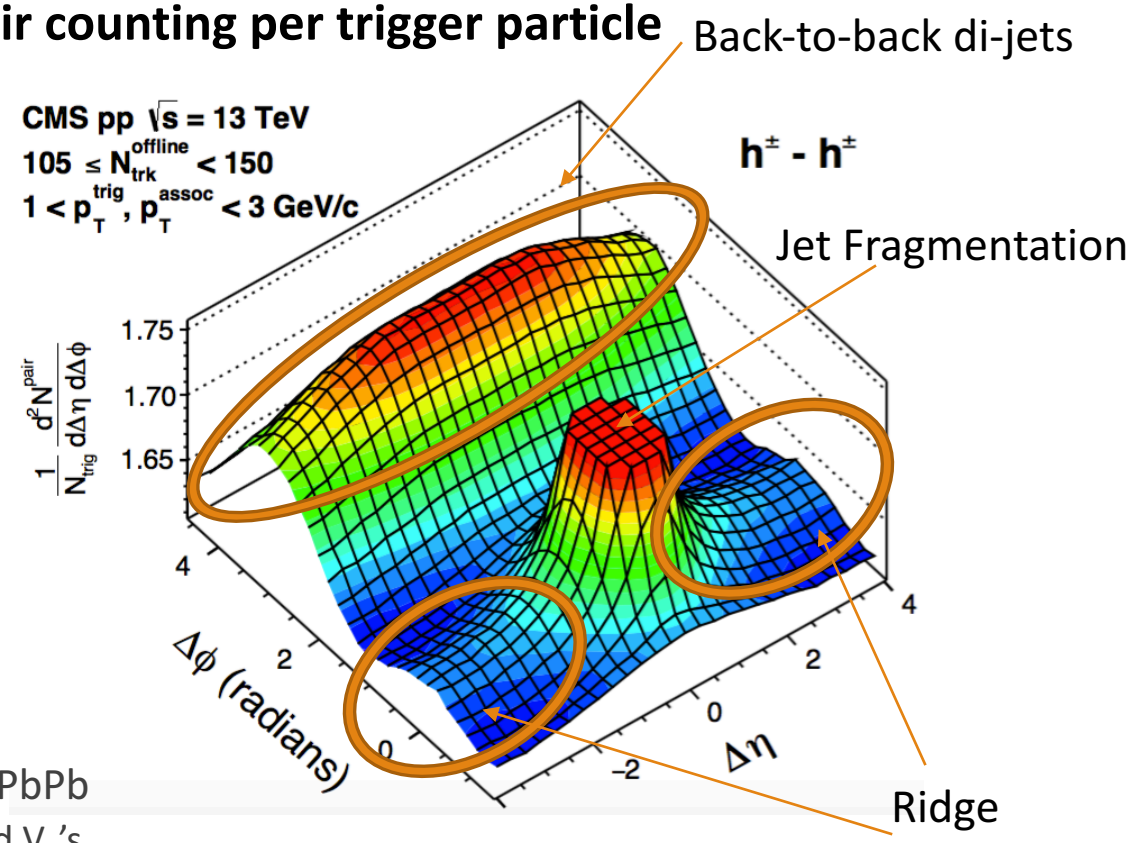
Importance

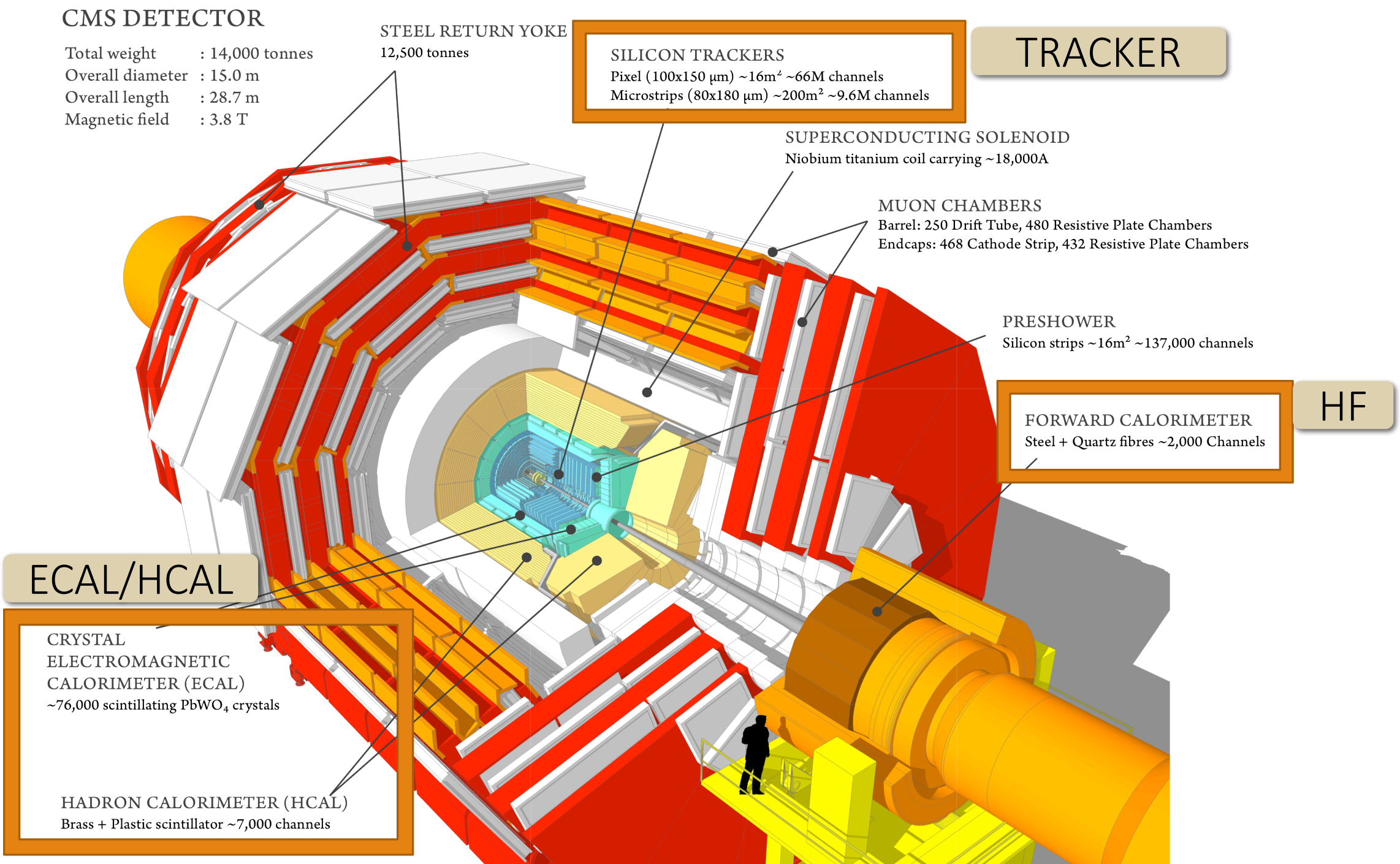
- Opportunity to study non-perturbative QCD in very high density regime

Procedure

- Perform key measurements for pp and pPb to compare with PbPb
  - Two- and Multi-Particle v_n measurements for charged particles and V_0's
  - Comparison with different energies
  - Correlations between v_n coefficients

Pair counting per trigger particle



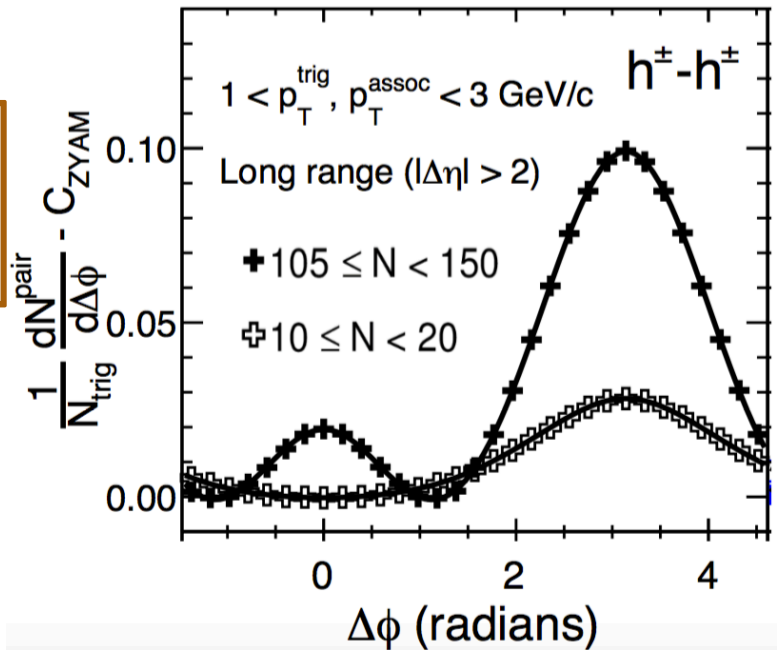

CMS DETECTOR
Total weight : 14,000 tonnes
Overall diameter : 15.0 m
Overall length : 28.7 m
Magnetic field : 3.8 T
STEEL RETURN YOKE
12,500 tonnes
SILICON TRACKERS
Pixel (100x150 μm) ~16m² ~66M channels
Microstrips (80x180 μm) ~200m² ~9.6M channels
TRACKER
SUPERCONDUCTING SOLENOID
Niobium titanium coil carrying ~18,000A
MUON CHAMBERS
Barrel: 250 Drift Tube, 480 Resistive Plate Chambers
Endcaps: 468 Cathode Strip, 432 Resistive Plate Chambers
PRESHOWER
Silicon strips ~16m² ~137,000 channels
FORWARD CALORIMETER
Steel + Quartz fibres ~2,000 Channels
HF
ECAL/HCAL
CRYSTAL ELECTROMAGNETIC CALORIMETER (ECAL)
~76,000 scintillating PbWO4 crystals
HADRON CALORIMETER (HCAL)
Brass + Plastic scintillator ~7,000 channels

Two-and Multi-Particle Analyses

Description of two-particle correlations via Fourier expansion

$$\frac{dN^{pair}}{d\Delta\phi} \propto 1 + \sum_n 2V_{n\Delta}\cos(n\Delta\phi)\,,\ \ V_{n\Delta} \text{ two-particle coefficient}$$

- $v_n = \sqrt{V_{n\Delta}}$ (single-particle anisotropy coefficient)



Projection in $\Delta\phi$ removing short-range correlations ($|\Delta\eta| > 2$)

Back-to-back di-jets estimated using low-multiplicity events

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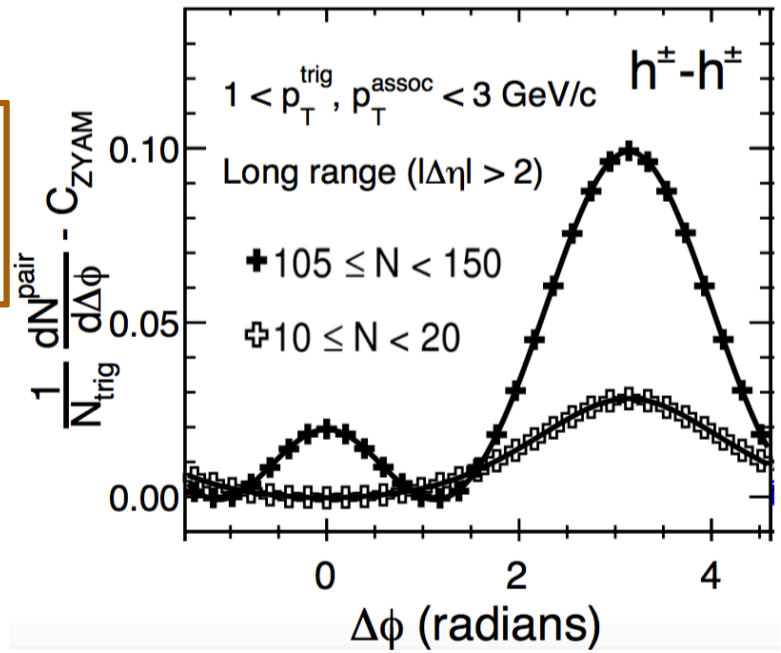
Q-cumulant method for multi-particle correlations

- 2-, 4-, and 6-particle correlators
  - $\langle\langle 2\rangle\rangle_n \equiv \left\langle\left\langle e^{in(\phi_1-\phi_2)}\right\rangle\right\rangle,\ \langle\langle 4\rangle\rangle_n \equiv \left\langle\left\langle e^{in(\phi_1+\phi_2-\phi_3-\phi_4)}\right\rangle\right\rangle$
  - $\langle\langle 6\rangle\rangle_n \equiv \left\langle\left\langle e^{in(\phi_1+\phi_2+\phi_3-\phi_4-\phi_5-\phi_6)}\right\rangle\right\rangle$

  $\langle\langle \dots \rangle\rangle$:= average over all combinations and all events



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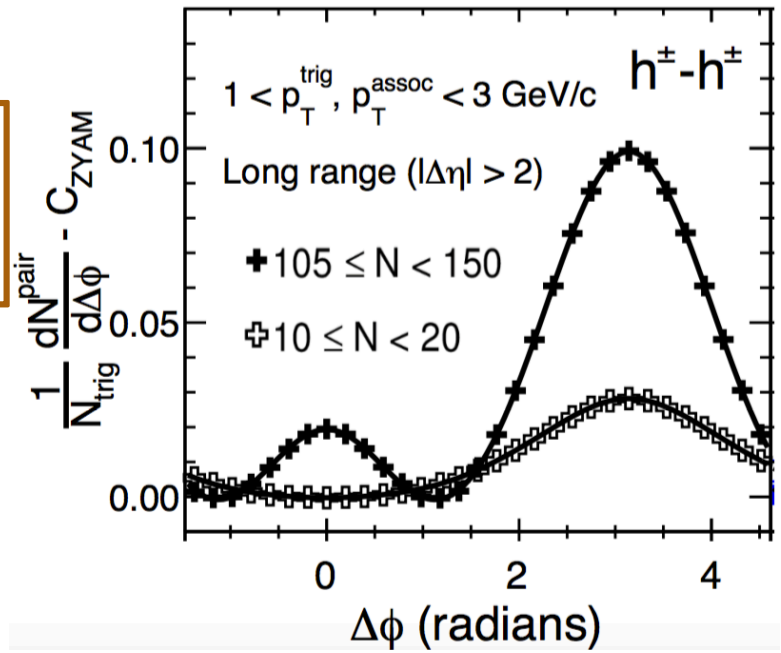
  $\langle\langle \ldots \rangle\rangle$:= average over all combinations and all events
- Cumulants
  - $c_n\{4\} = \langle\langle 4\rangle\rangle - 2\langle\langle 2\rangle\rangle^2\,;\quad v_n\{4\} = \sqrt[4]{-c_n\{4\}}$
  - $c_n\{6\} = \langle\langle 6\rangle\rangle - 9\langle\langle 4\rangle\rangle\langle\langle 2\rangle\rangle + 12\langle\langle 2\rangle\rangle^3\,;\quad v_n\{6\} = \sqrt[6]{c_n\{6\}/4}$

Reduces non-flow effects (jets, resonances, etc…)



Projection in $\Delta\phi$ removing short-range correlations ($|\Delta\eta| > 2$)

Back-to-back di-jets estimated using low-multiplicity events

Results

$(v_2 \,\&\, v_3)$ vs $N_{trk}^{offline}$

v_2

- Similar trends for the three systems
- Smaller magnitudes for small systems
- No or very small dependence as a function of energy

v_3

- Similar trends between pPb and PbPb
  - Different trends for pp collisions at HM
- No or very small dependence as a function of energy

Some descriptions with Hydrodynamics: superSONIC [arxiv:1701.07145]

Interpretations using other mechanisms are possible: e.g. CGC

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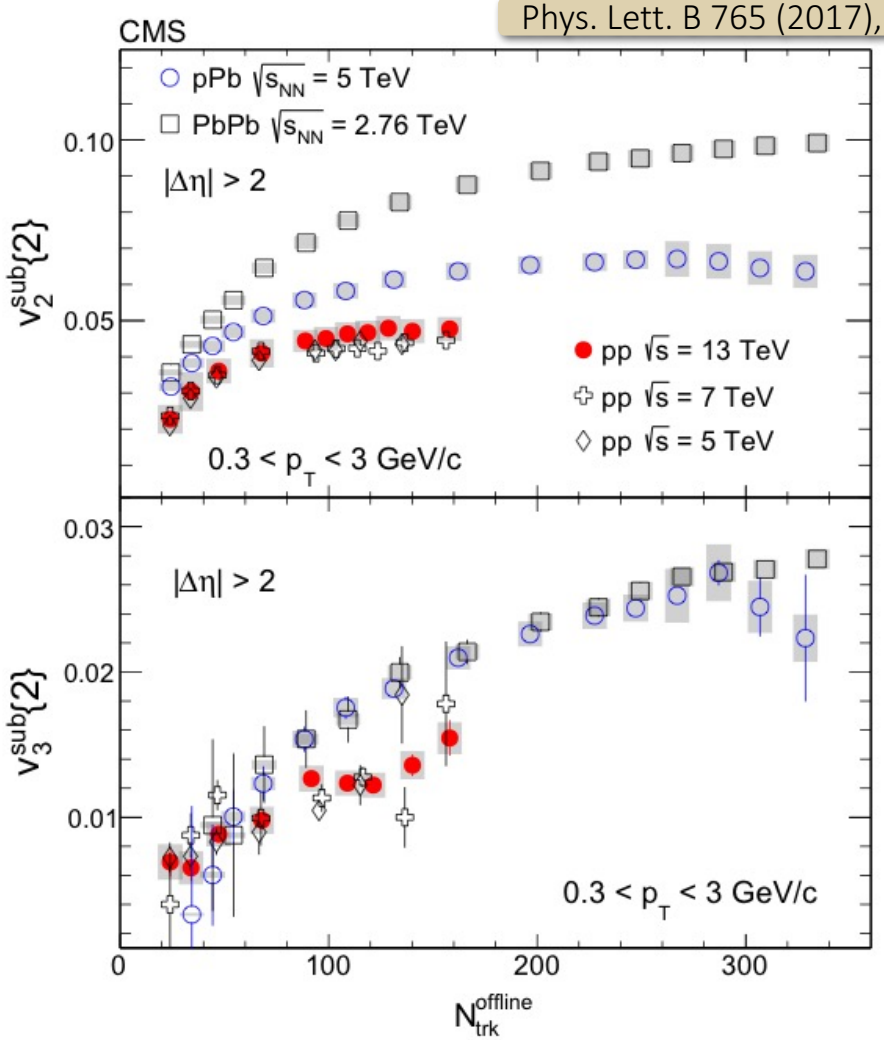

v_2 vs p_T (for $h^{\mp}$, K^0_S, and $\Lambda/\bar{\Lambda}$)

Mass ordering in all systems at HM up to $p_T \sim 2\text{GeV}$

- Connected with radial flow
- Higher separations in pPb and pp collisions
- Interpretations in hydrodynamic models and CGC
  - AMPT – parton scape mechanism [arxiv:1604.07387]
  - UrQMD – hadronic interaction [PRC 91, 064908 (2015)]
  - CGC + string fragmentation [PRL 117, 162301 (2016)]

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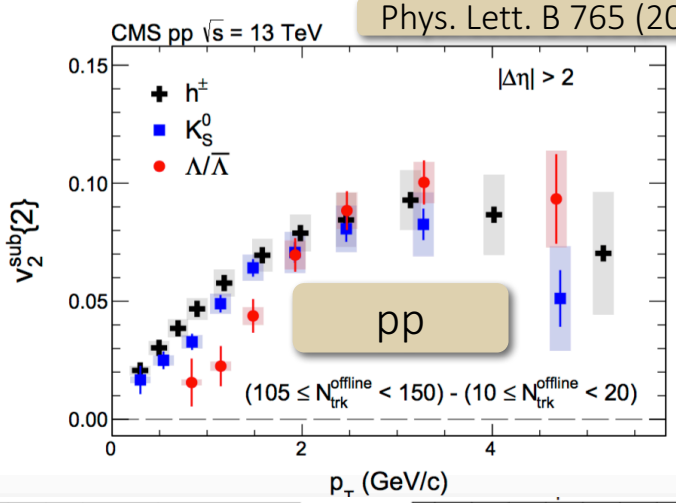

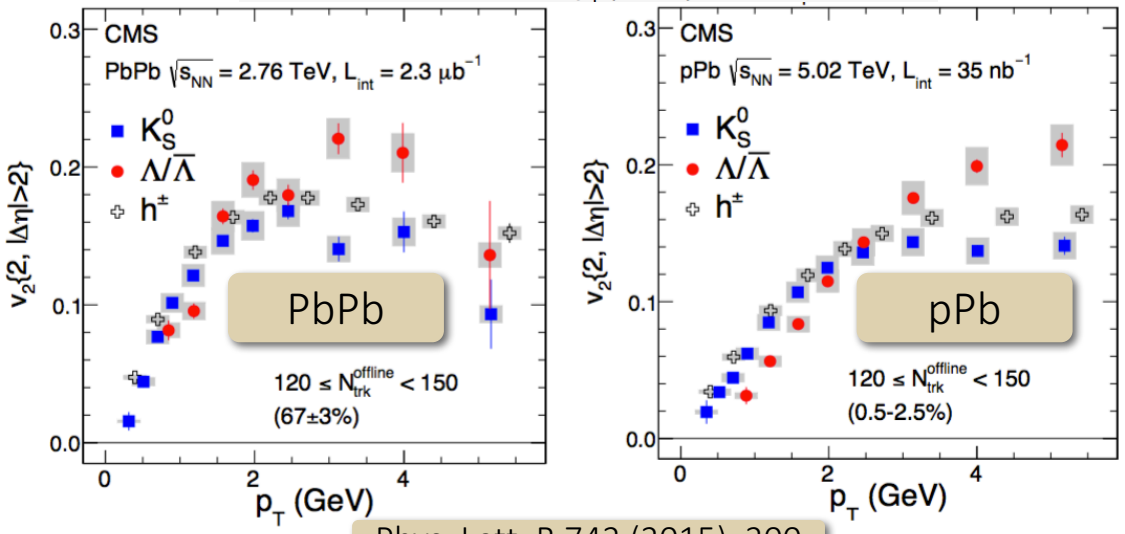

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$(v_2\{2\}, v_2\{4\}, v_2\{6\}, v_2\{8\}, v_2\{\infty\})$ vs $N_{trk}^{offline}$

Similar features among different systems

- $v_2\{4\} \approx v_2\{6\}$ (in pp), $v_2\{4\} \approx v_2\{6\} \approx v_2\{8\}$ (in pPb), and $v_2\{4\} \approx v_2\{6\} \approx v_2\{8\} \approx v_2\{\infty\}$ (in PbPb)
  - **Strong Evidence for Collectivity!**
- Unlike pPb and PbPb: $v_2\{2\} \approx v_2\{4 \,\&\, 6\}$ for pp in higher multiplicities (>100)

In Hydrodynamic models:
Can be connected to Initial-state geometry fluctuations!

Explanations using other mechanisms (i.e. CGC) still possible!

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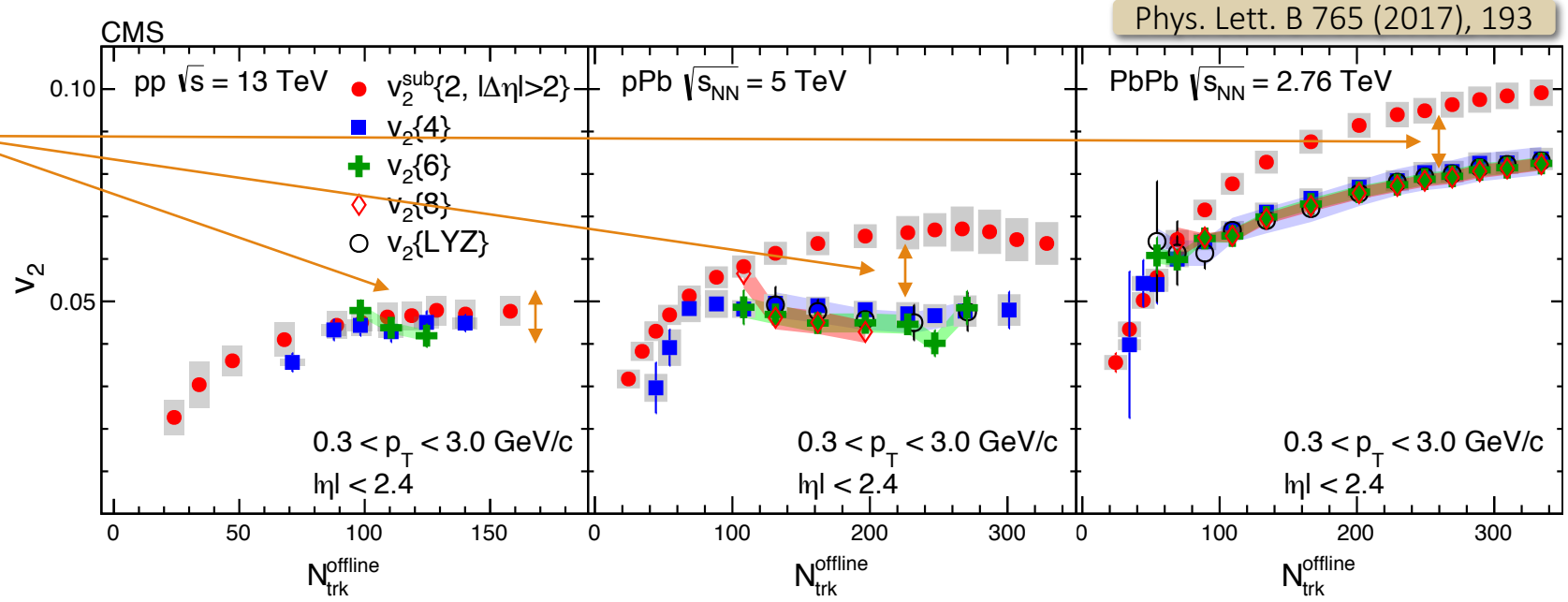


(v_2, v_3, v_4) vs $N_{trk}^{offline}$

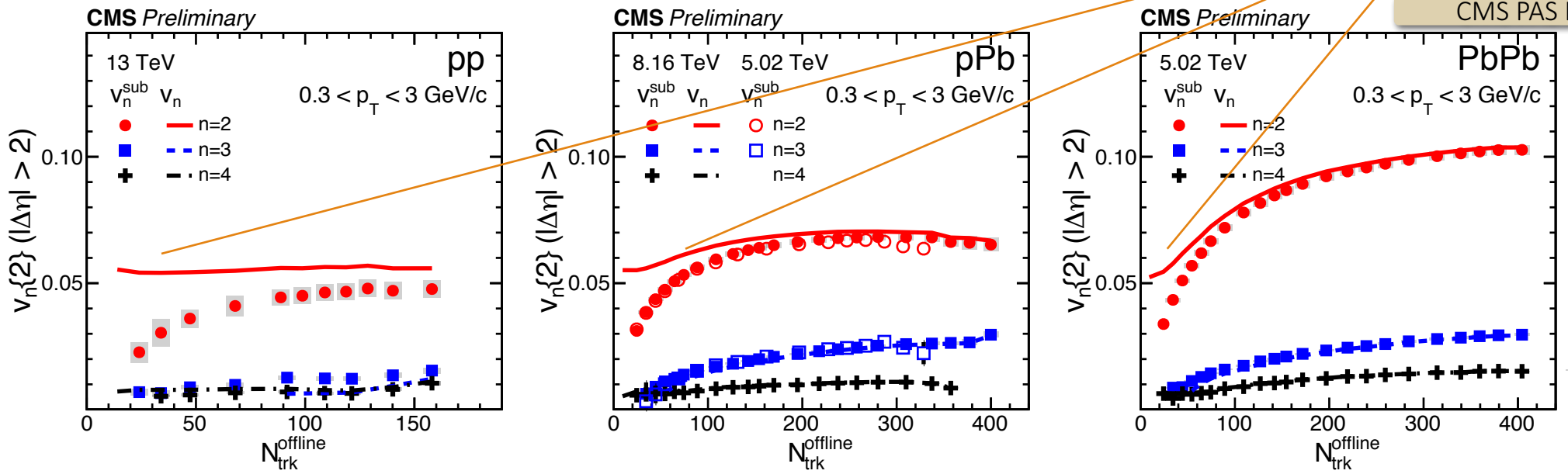
Similar trends among the three systems!

New : 8 TeV pPb Collisions!

- For pPb: compatible results between 5 and 8 TeV for both v_2 and v_3
- Di-jets corrections have higher effects in pp and lower multiplicities

Before subtraction of di-jets correlations

CMS PAS HIN-16-022



Correlations between (v_2 & v_3), (v_2 & v_4) vs $N_{trk}^{offline}$ [I]

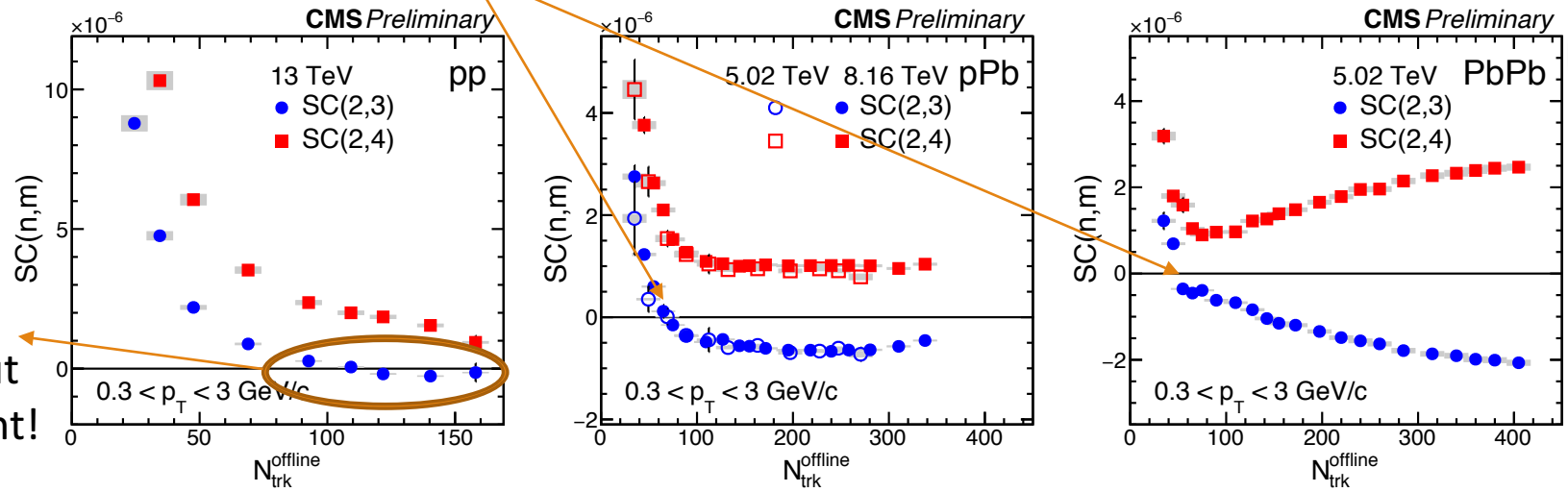
Symmetric Cumulants (SC) from 4-particle correlations

- $SC(n,m) = \langle\langle 4\rangle\rangle_{n,m} - \langle\langle 2\rangle\rangle_n \cdot \langle\langle 2\rangle\rangle_m = \langle v_n^2 v_m^2\rangle - \langle v_n^2\rangle\langle v_m^2\rangle$
  - $\langle\langle 4\rangle\rangle_{n,m} \equiv \left\langle\left\langle e^{i(n\phi_1+m\phi_2-n\phi_3-m\phi_4)}\right\rangle\right\rangle, \langle\langle 2\rangle\rangle_n \equiv \left\langle\left\langle e^{in(\phi_1-\phi_2)}\right\rangle\right\rangle$

New : 8 TeV pPb Collisions!

Overall similar behavior for pPb and PbPb (same origin of correlations???)

- SC(2,3) becomes negative (anti-correlation) for $N_{trk}^{offline} > 60$



CMS PAS HIN-16-022

SC(2,3) becomes negative in pp, but not very significant!

Correlations between (v_2 & v_3), (v_2 & v_4) vs $N_{trk}^{offline}$ [II]

Normalize SC(2,3) by $\langle v_2^2 \rangle \langle v_3^2 \rangle$ & SC(2,4) by $\langle v_2^2 \rangle \langle v_4^2 \rangle$

- $\langle v_n^2 \rangle \langle v_m^2 \rangle$ from 2-particle correlations

New : 8 TeV pPb Collisions!

Normalized SC(2,3)

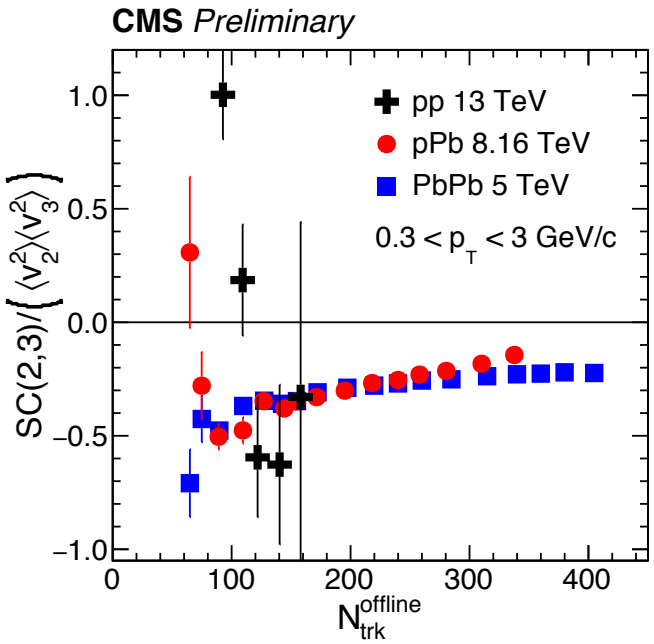
- Similar values for pPb and PbPb for $N_{trk}^{offline} > 120$
  - Indicates similar origin for collectivity
  - pp is close but with large uncertainties

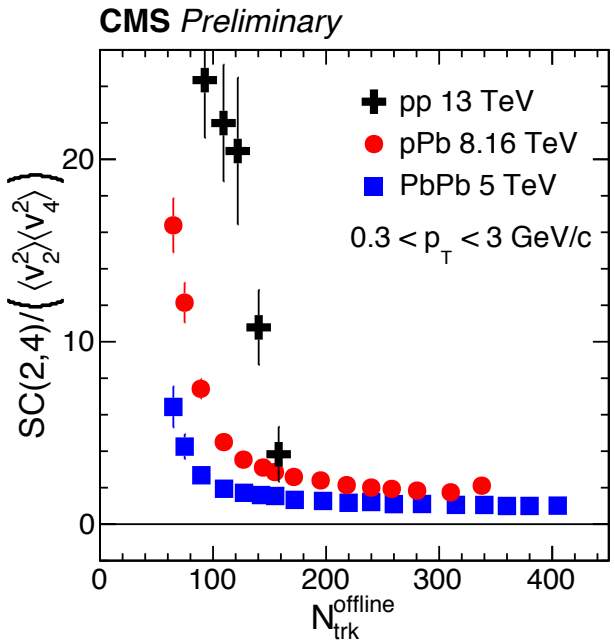
Normalized SC(2,4)

- Different magnitudes in pPb and PbPb

May point to different contributions from initial state fluctuations and/or transport properties of the medium.

CMS PAS HIN-16-022





Summary

Latests results on azimuthal correlations in small systems from CMS

- Evidence for collectivity in pp and pPb collisions
- Similar trends compared to PbPb in:
  - v_n's as a function of multiplicity
  - v_2 for inclusive charged hadrons (mostly pions) and V_0's as a function of p_T
  - Correlations between v_2 and v_3 as a function of multiplicity
- Different trends in the correlations between v_2 and v_4
  - Indicating different contributions from initial state fluctuations and/or transport properties of the medium

This is a VERY active area…

- Many results comming from different experiments
- Many theoretical studies being developed

Is QGP formed in small systems? Not enough information to answer this yet...

- Additional studies and more precise measurements will come soon.

Thank You

BACKUP

Event Reconstruction & Track Selections

Similar event reconstruction and track selections in pp, pPb, and PbPb

- Minimum Bias events
  - Trigger: HF energy deposits (coincidence)
  - Multiplicity < 85
- High-multiplicity events
  - Trigger:

    ECAL/HCAL energy deposits (Level1)

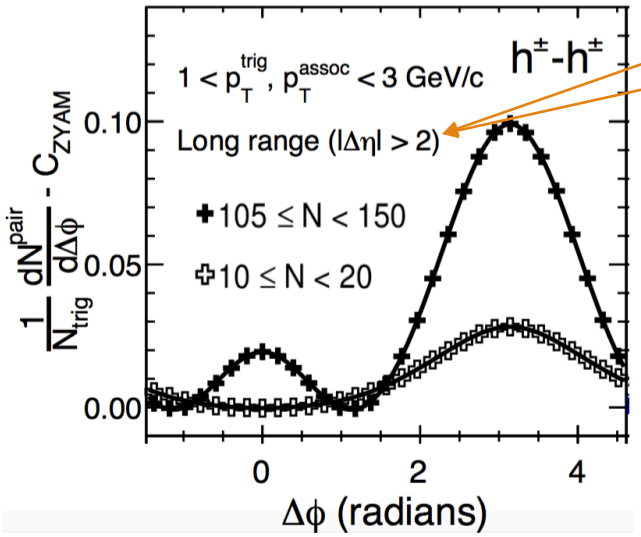
    Tracking (High Level Trigger)
  - Multiplicity > 85
- Tracks selected for analyses
  - $0.3 < \mathrm{p_T} < 3\ \mathrm{GeV}$ and $|\eta| < 2.4$
- For multiplicity classification ($\mathrm{N_{trk}^{offline}}$)
  - Selected tracks: $\mathrm{p_T} > 0.4\ \mathrm{GeV}$ and $|\eta| < 2.4$ (to match trigger selection)

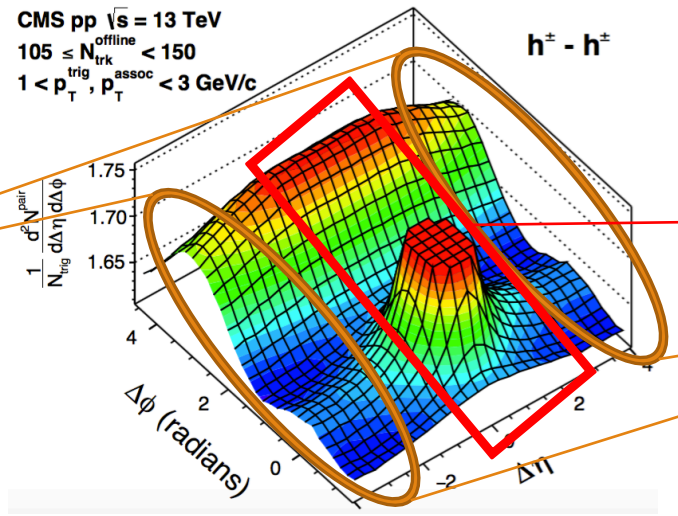
Di-jet Correlation Subtraction Method (I)

Subtraction is done in two-particle coefficient ($V_{n\Delta}$)

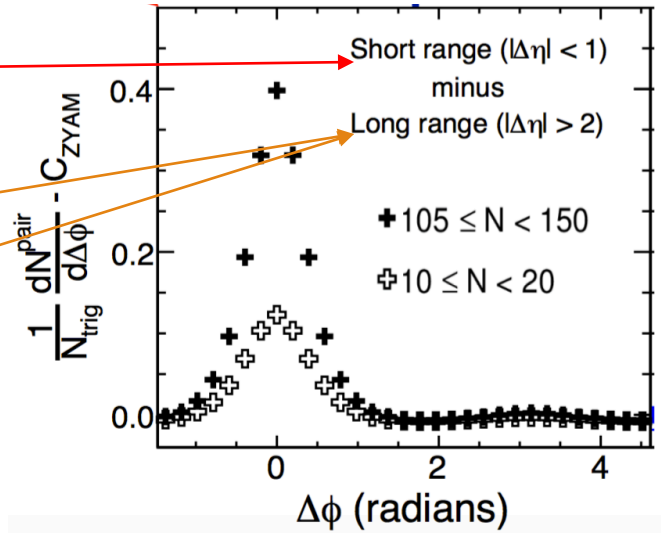
- Assumes similar shapes for jet correlations in low ($10 < N_{trk}^{offline} < 20$) and high-multiplicities
- Assumes there is no signal (ridge) contribution to v_2 in low multiplicity

To extract the shape of the jet contribution

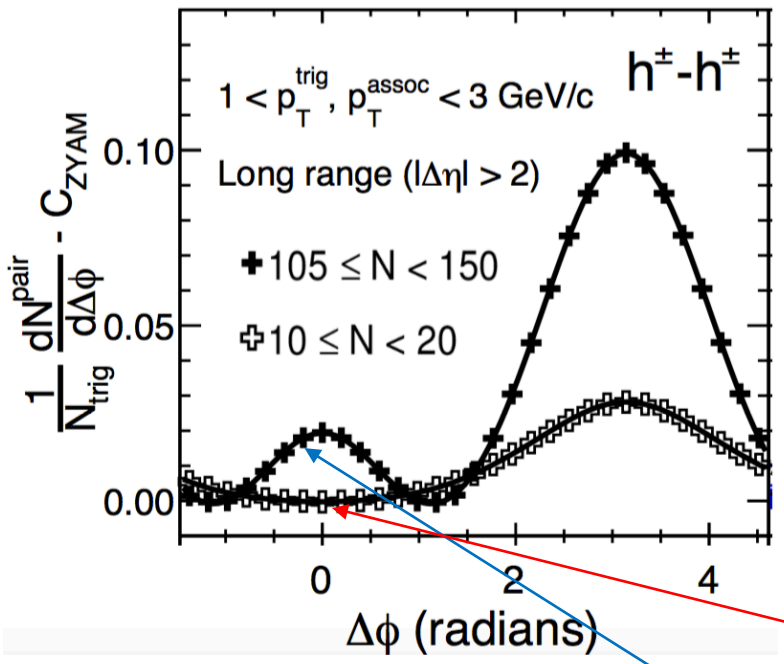


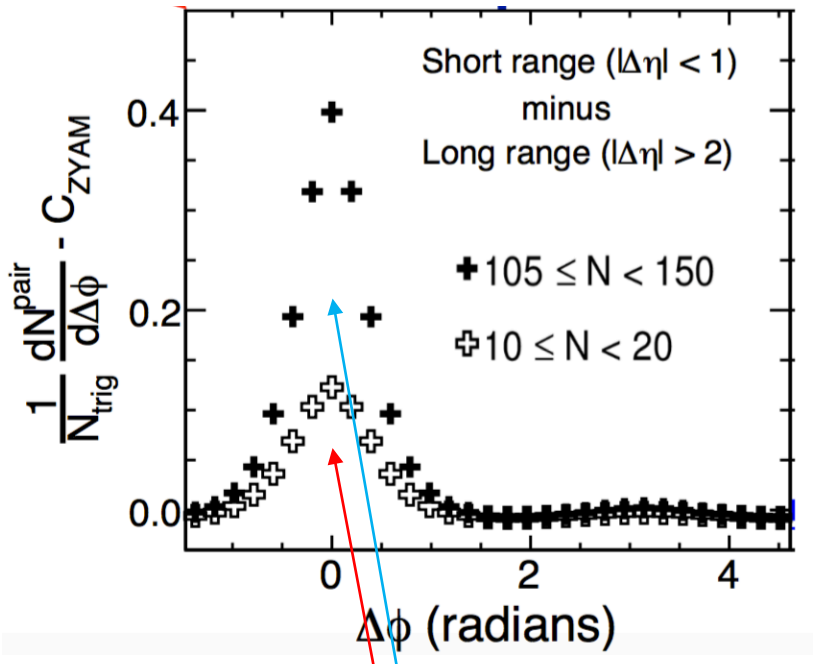


Used for modulation of the jet contribution in High-Multiplicity



Di-jet Correlation Subtraction Method (II)





$$V_{n\Delta}^{high,sub} N_{assoc}^{high} = V_{n\Delta}^{high} N_{assoc}^{high} - V_{n\Delta}^{low} N_{assoc}^{low} \left[\frac{\gamma_{jet}^{high}}{\gamma_{jet}^{low}} \right]$$

N_{assoc} := average number of pairs per trigger particle

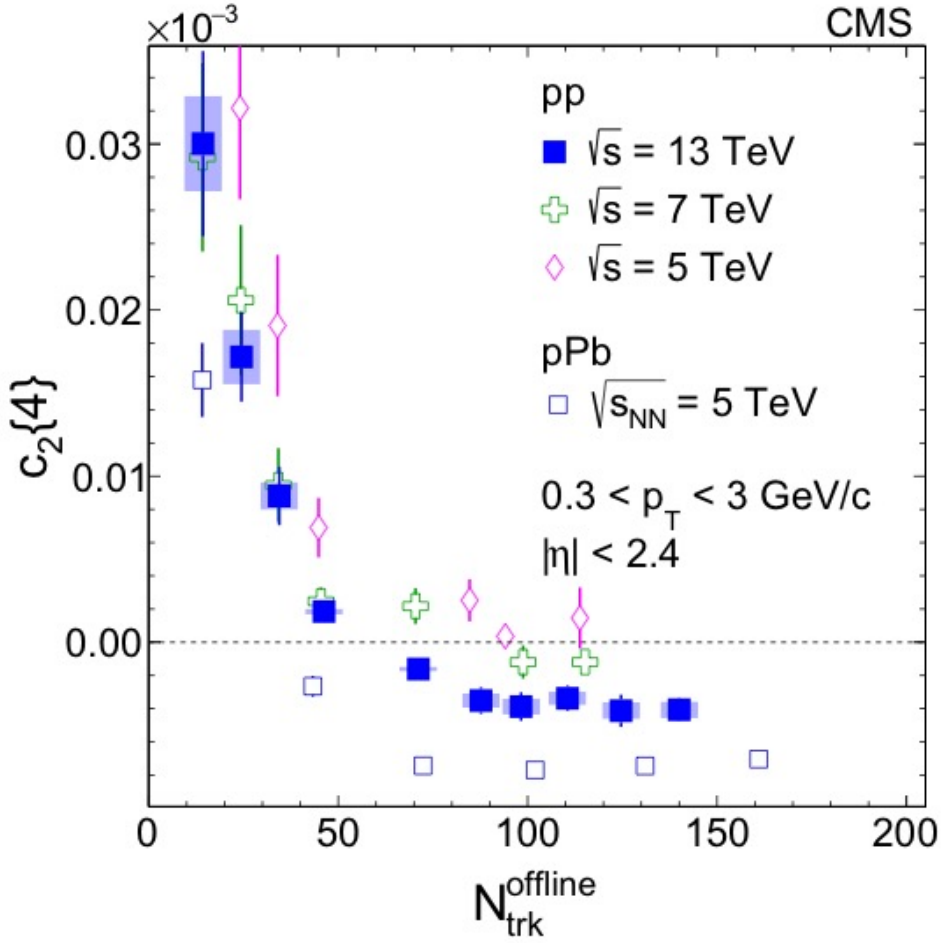
Ratio of jet yields in short- minus long-range.

$c_2\{4\}$ as a function of $N_{trk}^{offline}$ for charged particles

Similar trends between pPb and pp!

Indication of energy dependence for pp

- Larger $c_2\{4\}$ for lower energies
  - Can be connected to the fact that average p_T values are slightly smaller at lower energies → smaller negative contribution to $c_2\{4\}$.

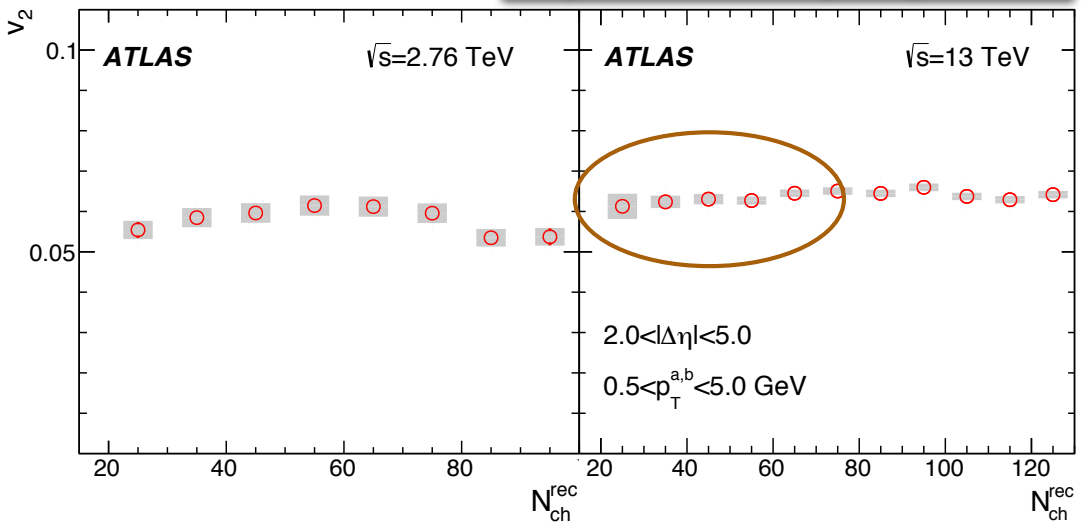


ATLAS vs CMS Results from pp Collisions

Different magnitudes in all multiplicity ranges and trends in lower multiplicities

- This was checked to be mainly due to distinct procedures applied
  - Mainly in the jet correlation removal
  - Discussions and cross-checks ongoing among the experiments
- When using the same procedure get consistent results between CMS and ATLAS data

Phys. Rev. Lett. 116 (2016), 172301



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