Correlations and Ridge in pp and pPb Collisions at CMS

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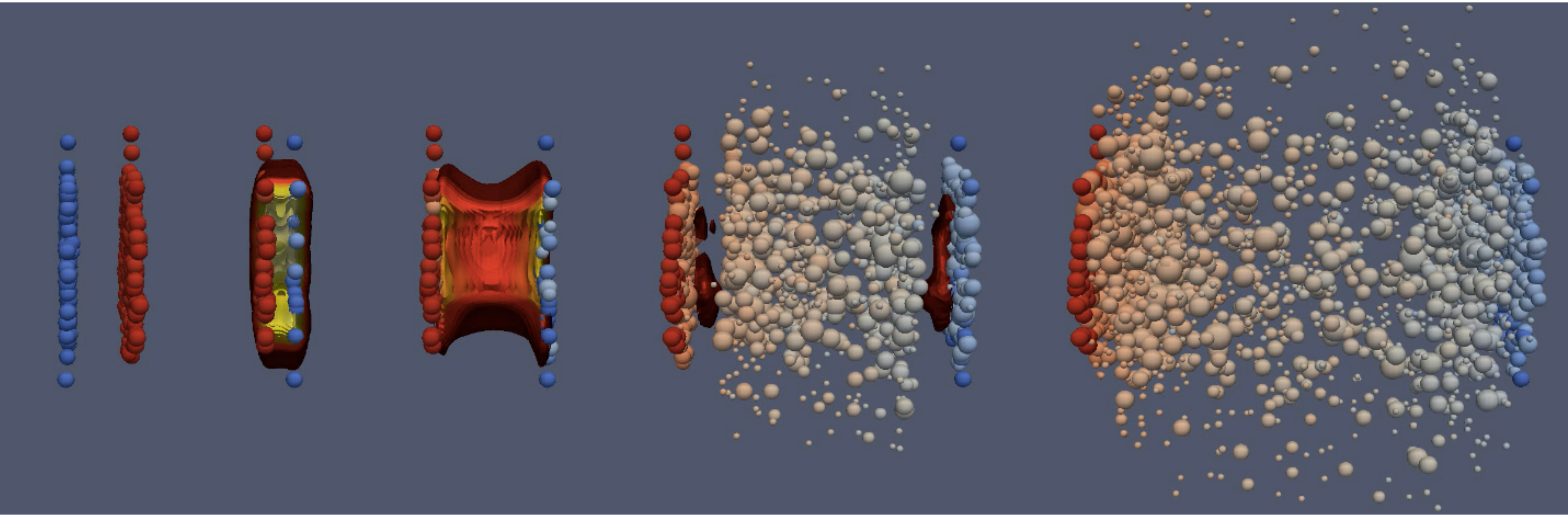
University of Kansas

Introduction

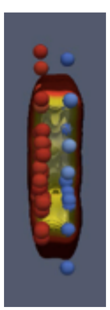
- Hot dense matter (QGP) created in Heavy Ion collisions



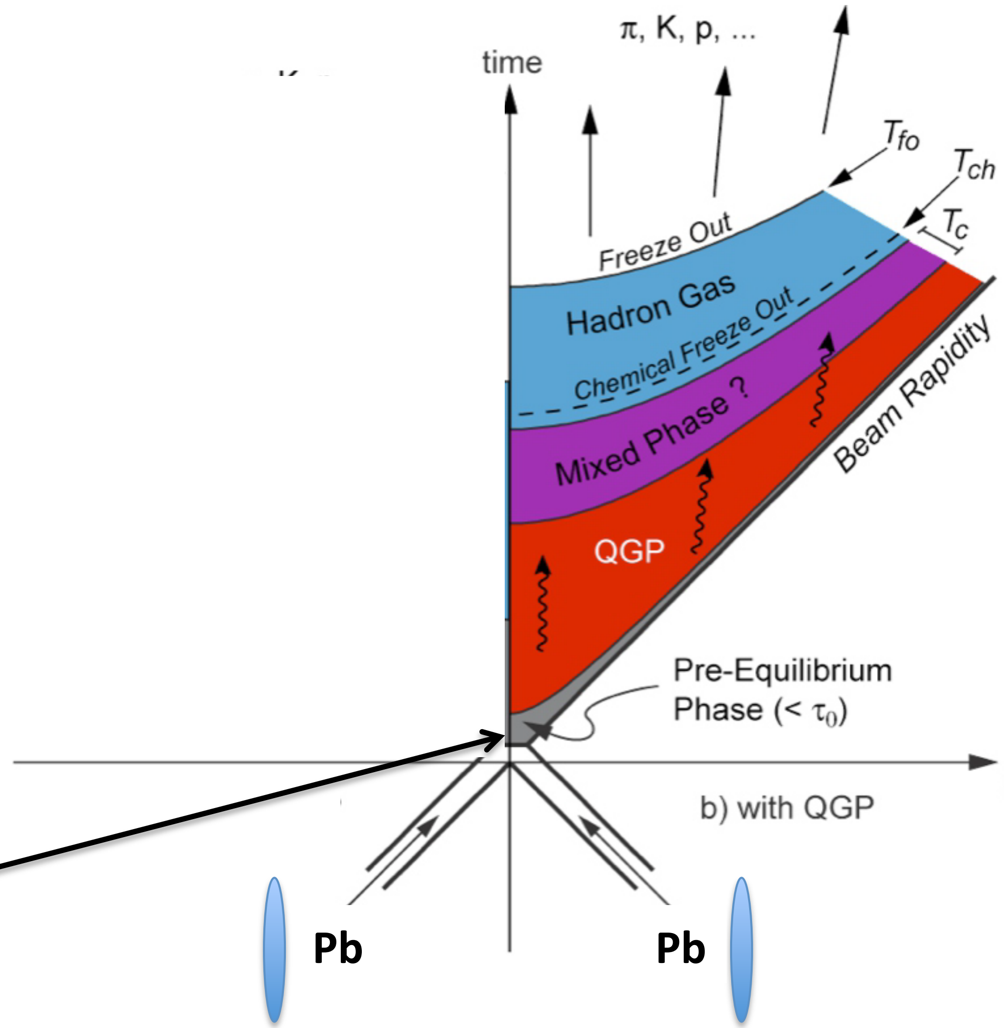
- Nearly ideal hydrodynamic expansion
  - Collectivity

Evolution of QGP

- In HI collisions

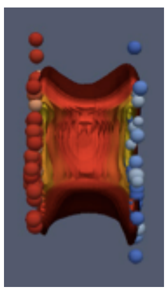


Initial-State



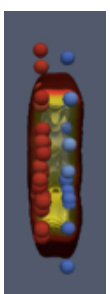
Evolution of QGP

- In HI collisions

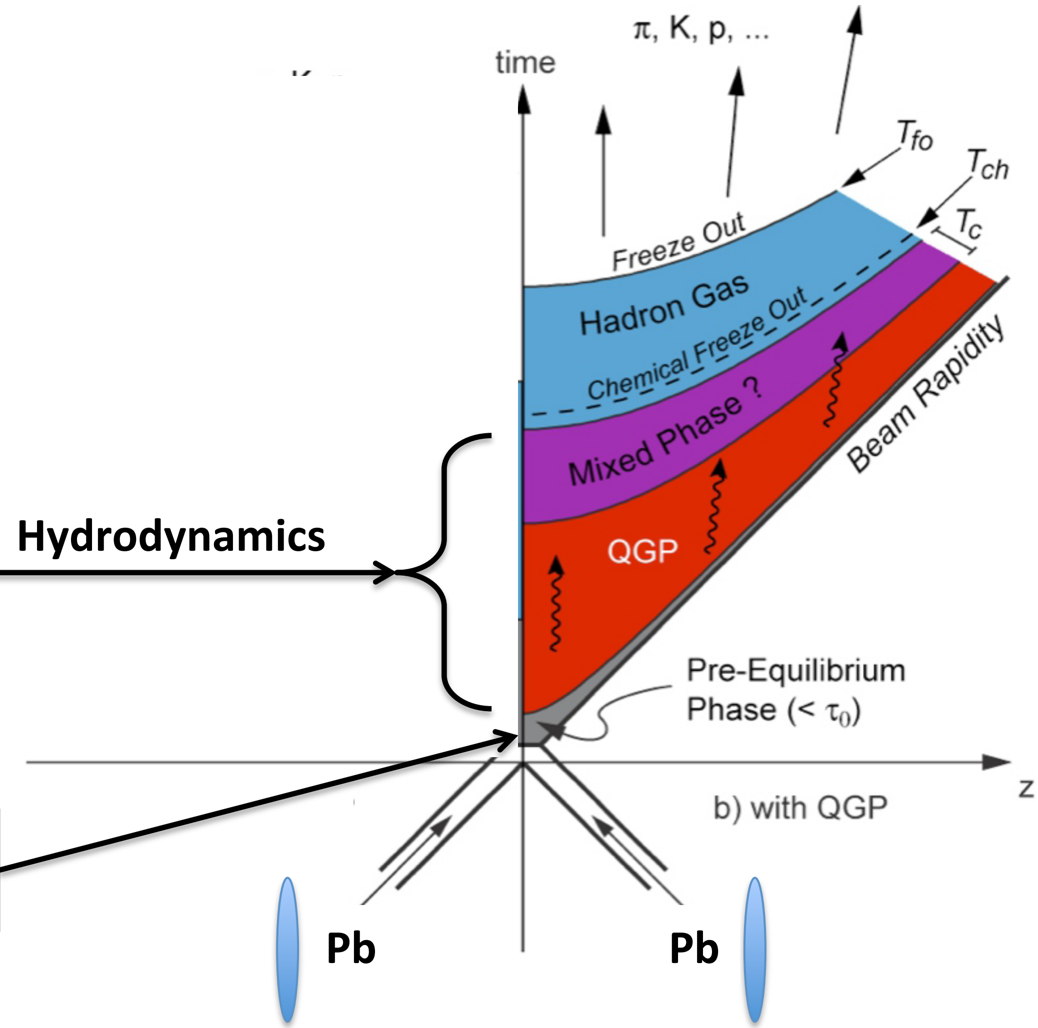


Final-State

Hydrodynamics

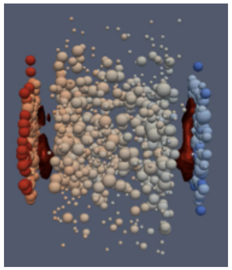


Initial-State

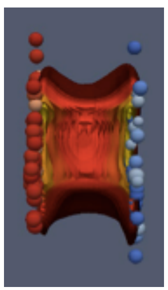


Evolution of QGP

- In HI collisions

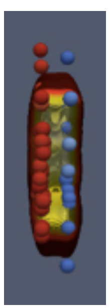


Hadronization

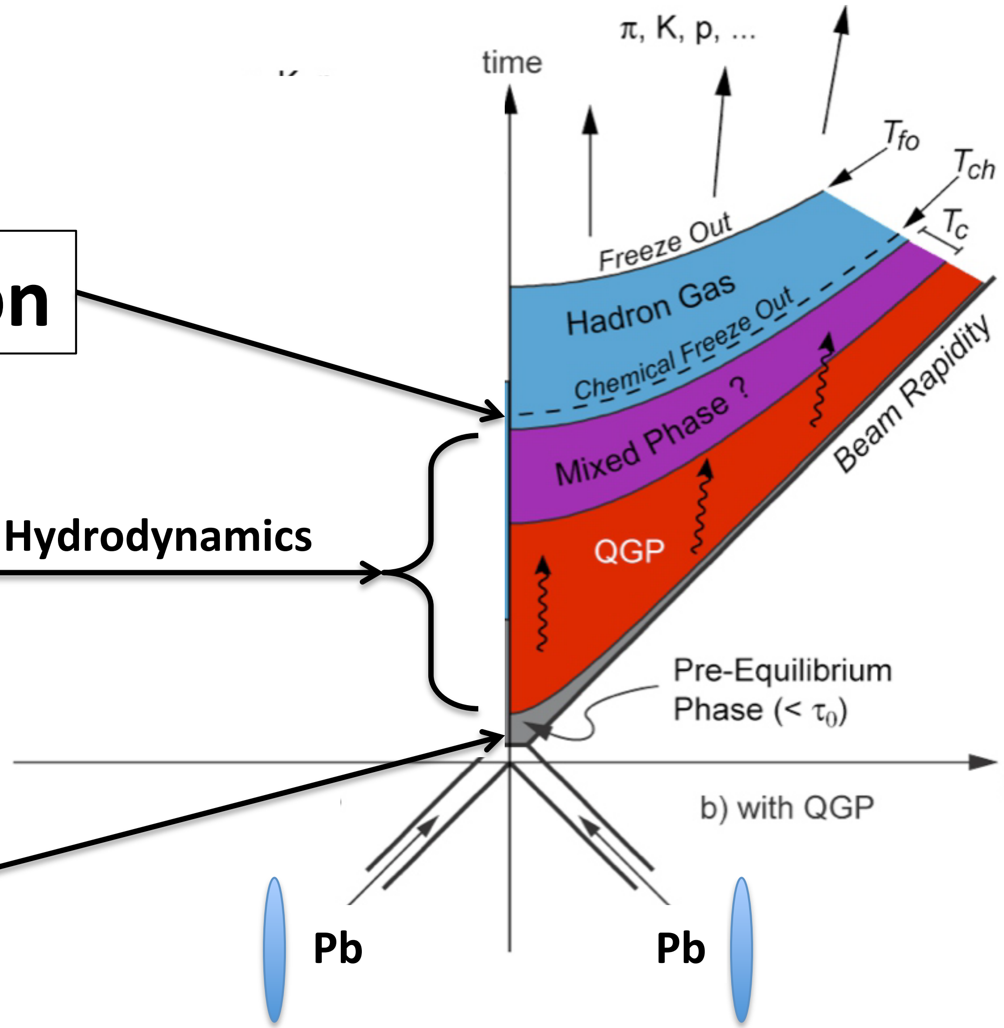


Final-State

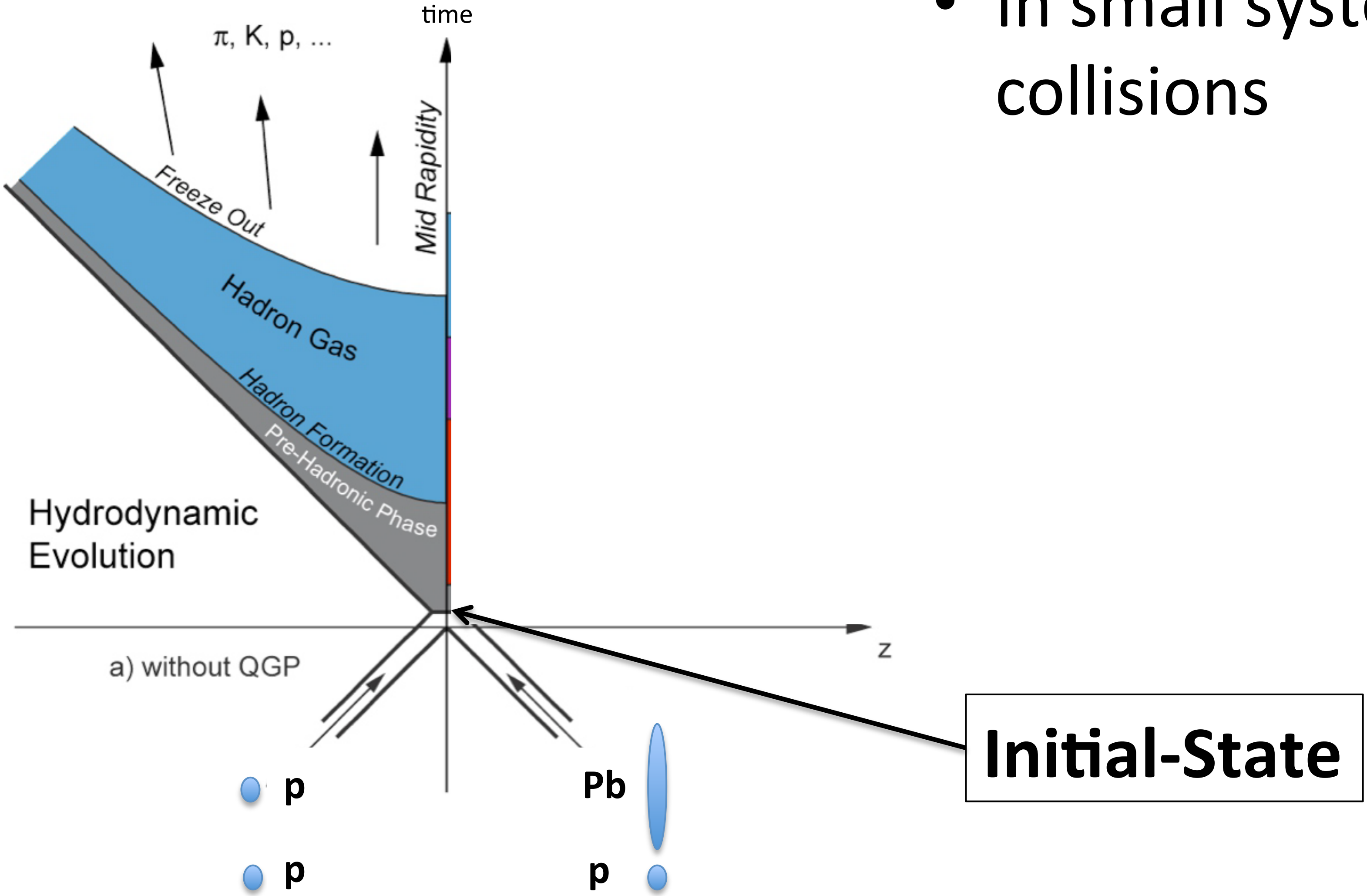
Hydrodynamics



Initial-State



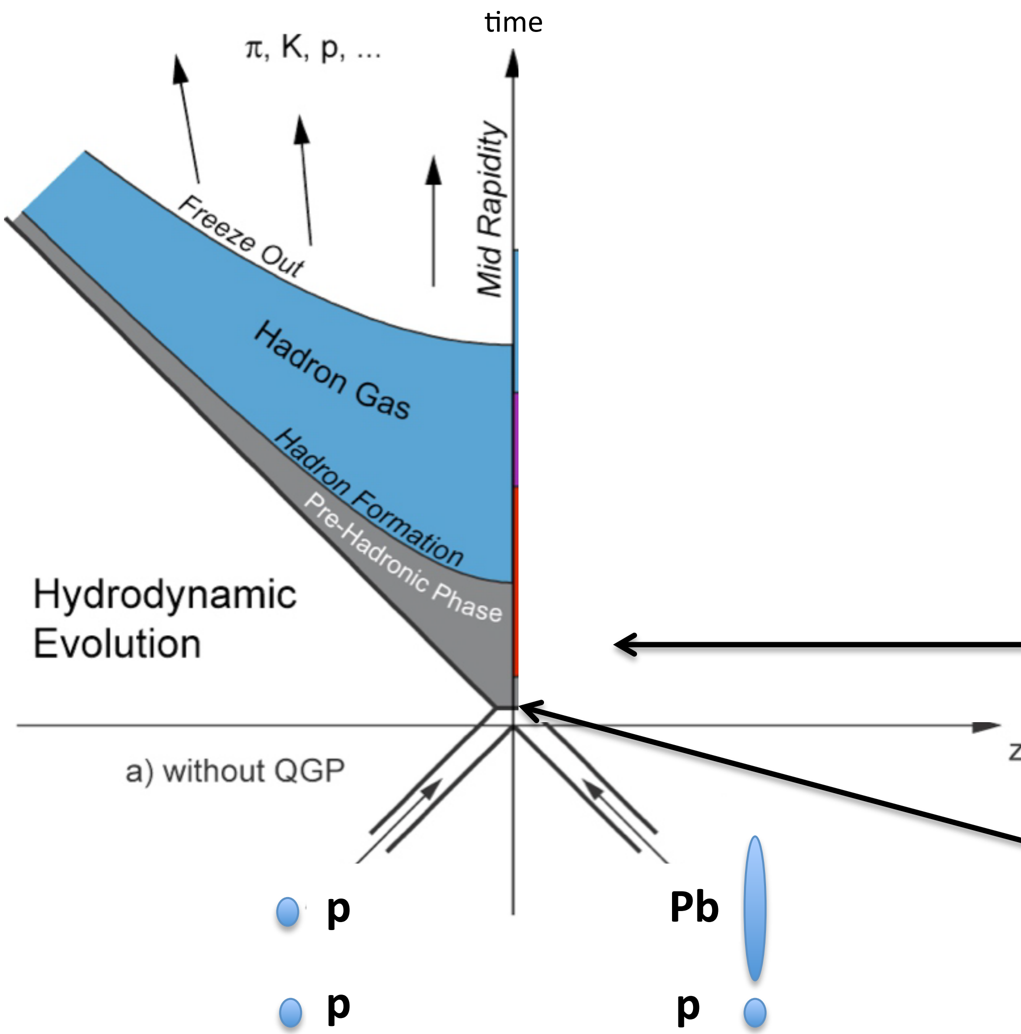
pPb and pp as Reference



- In small system collisions

pPb and pp as Reference

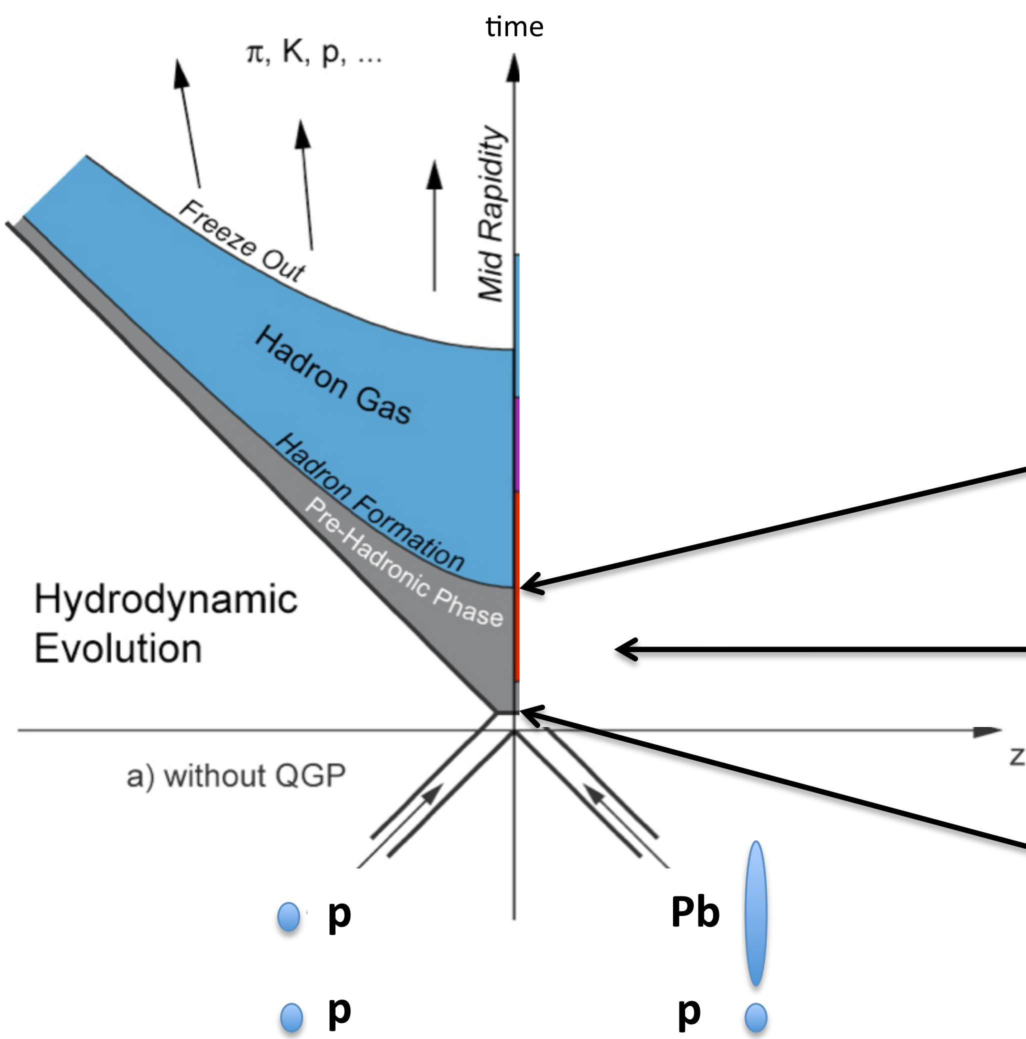
- In small system collisions



Absent Final-State

Initial-State

pPb and pp as Reference



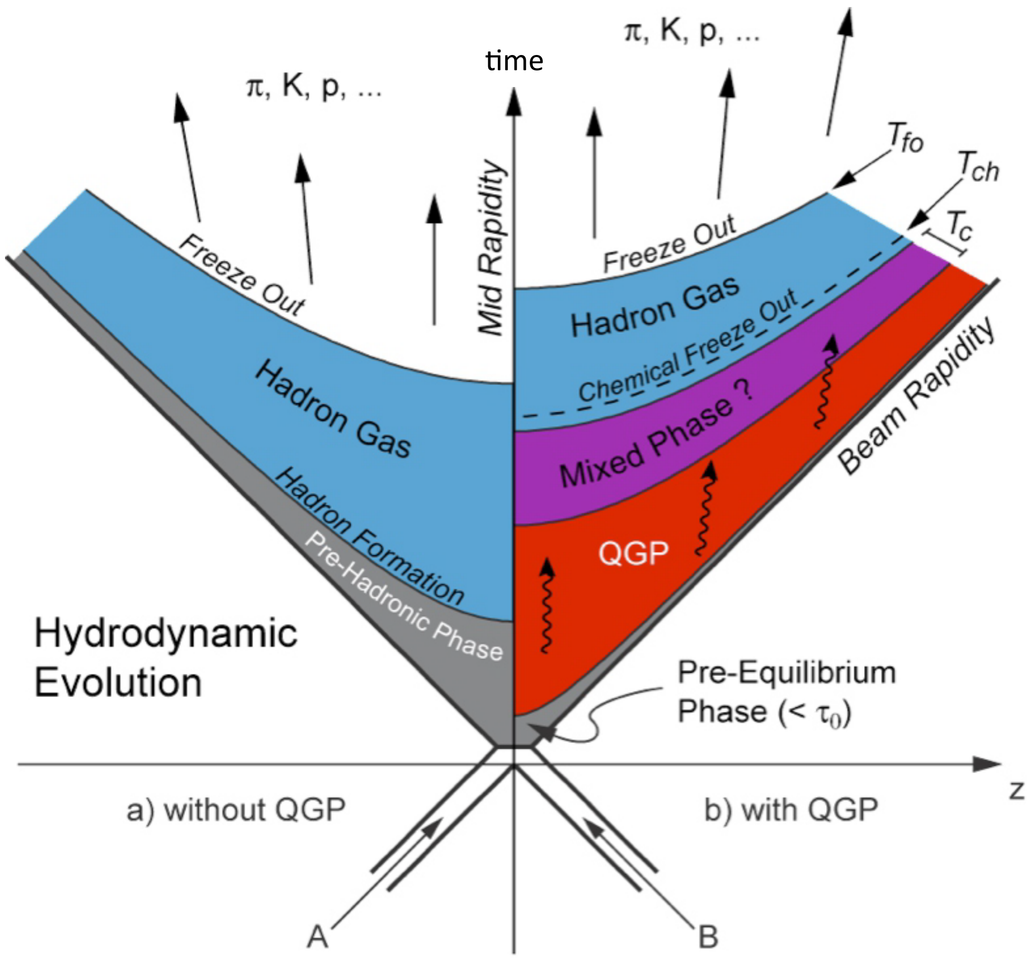
- In small system collisions

Hadronization

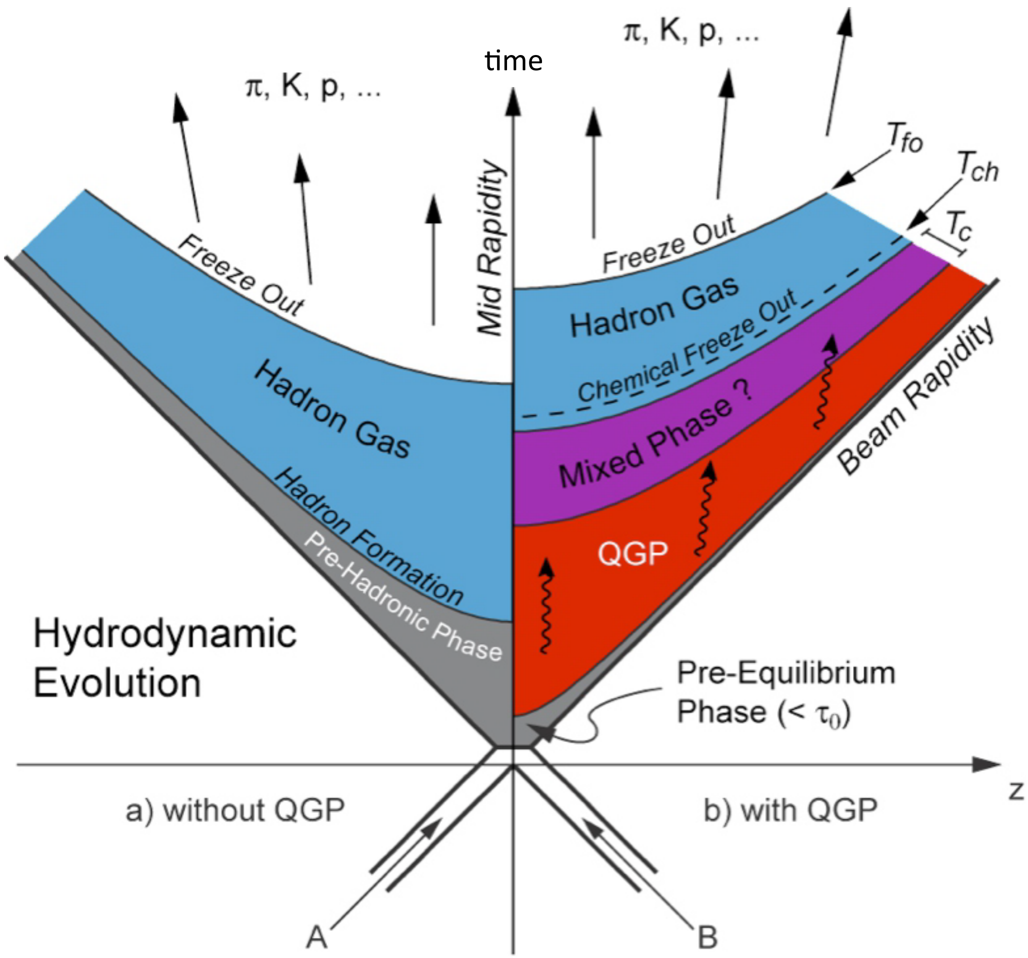
Absent Final-State

Initial-State

Where do we look?

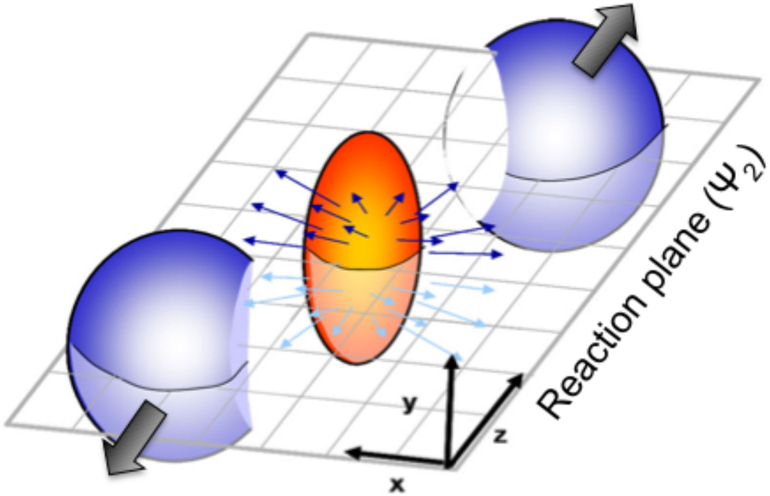


Where do we look?



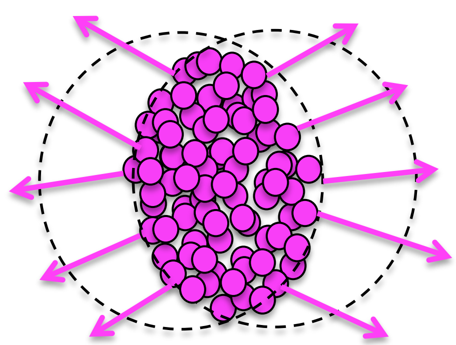
- Jet quenching
- Collectivity
  - Flow harmonics

Flow Harmonics

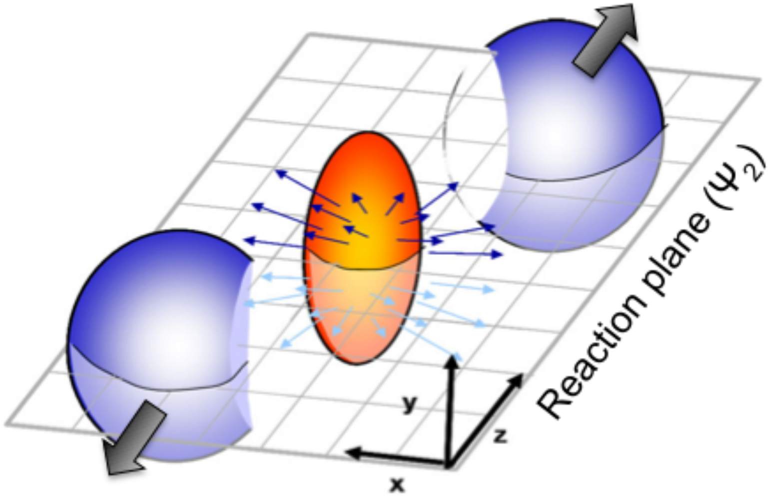


$$\frac{dN}{d\phi} \propto 1 + 2v_2 \cos[2(\phi - \Psi_2)]$$

Flow harmonics v_n ~ initial geometry + pressure gradient

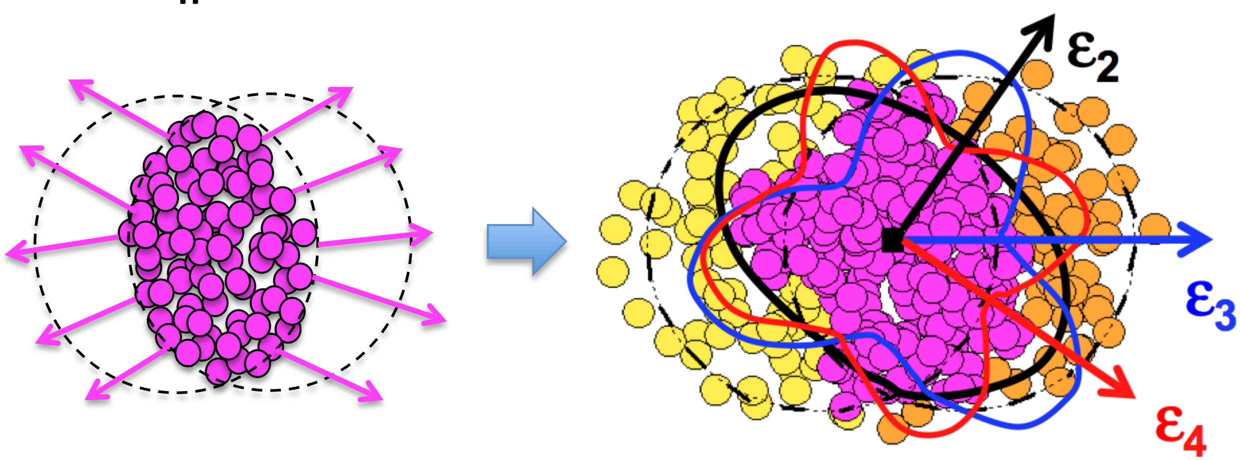


Flow Harmonics

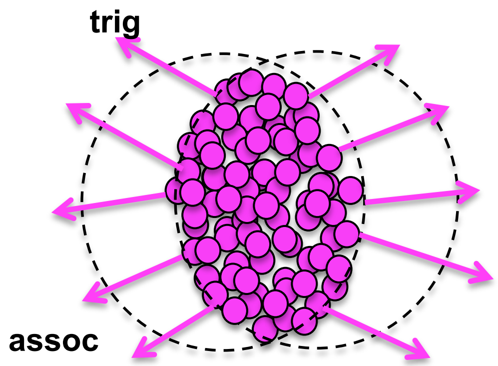


$$\frac{dN}{d\phi} \propto 1 + 2v_2\cos[2(\phi - \Psi_2)]$$
$$+2v_3\cos[3(\phi - \Psi_3)]$$
$$+2v_4\cos[4(\phi - \Psi_4)]$$
$$\ldots$$

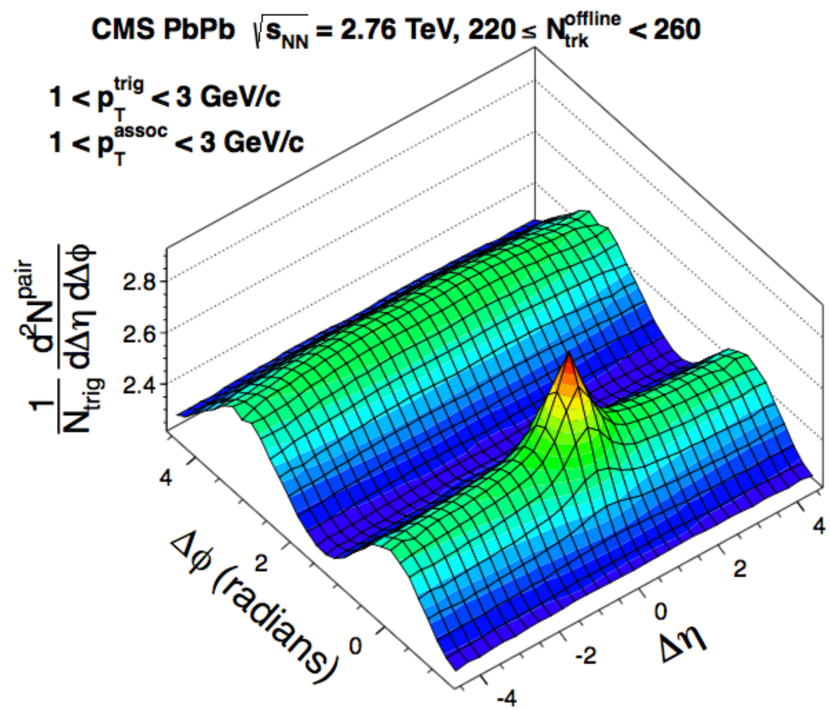
Flow harmonics v_n ~ fluctuating initial geometry + pressure gradient



2-Particle Correlations



$$\Delta\eta = \eta_{assoc} - \eta_{trig}$$
$$\Delta\phi = \phi_{assoc} - \phi_{trig}$$



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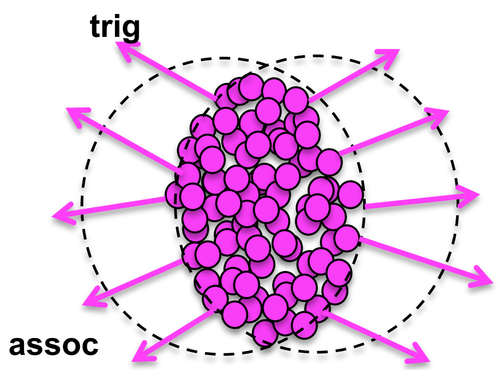
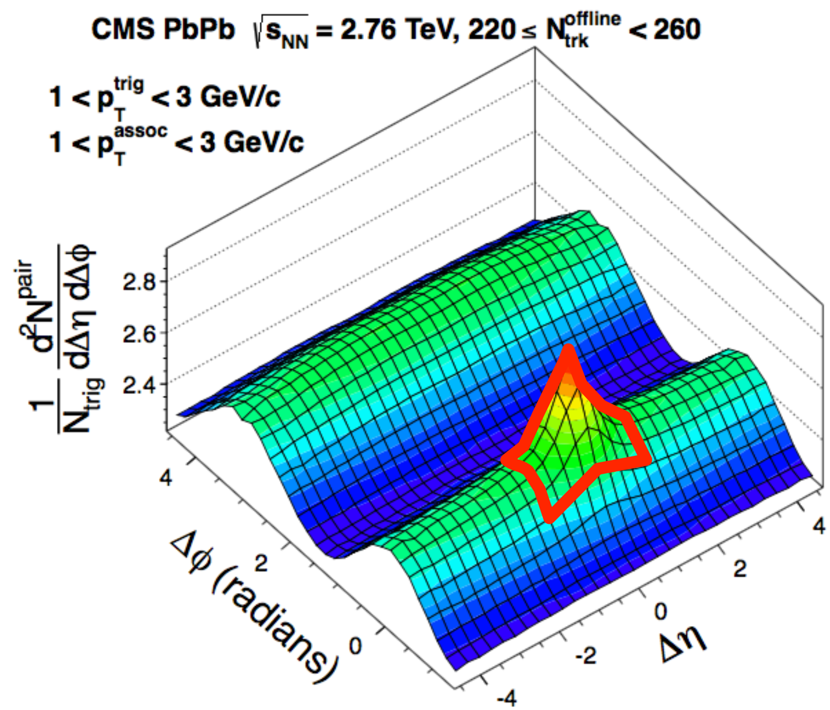
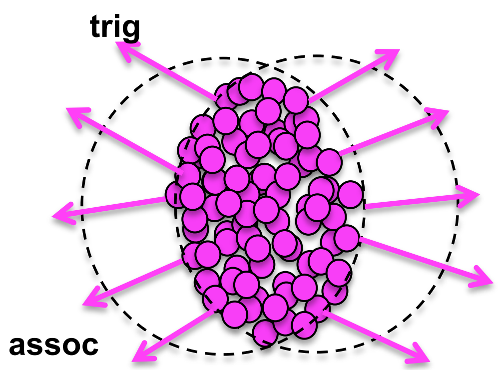


$$\Delta\eta = \eta_{assoc} - \eta_{trig}$$
$$\Delta\phi = \phi_{assoc} - \phi_{trig}$$



- Jet contribution

2-Particle Correlations



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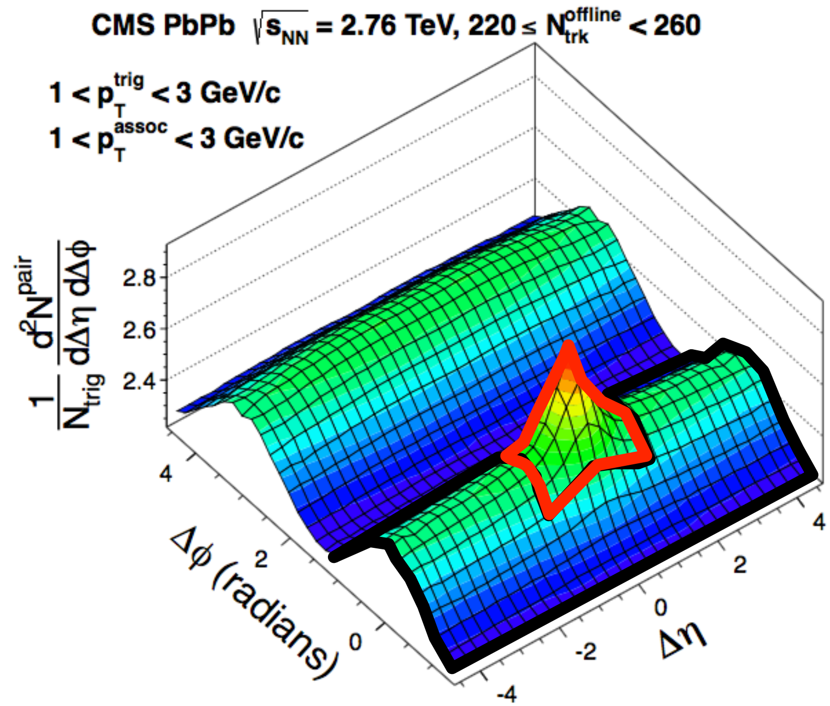
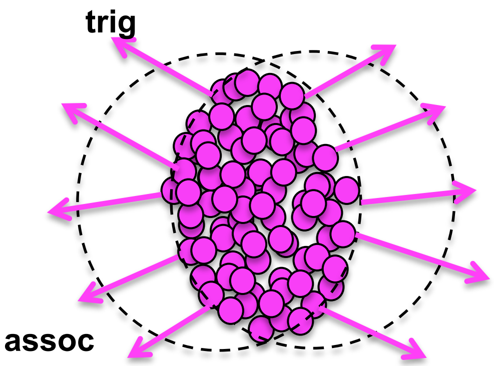


- Jet contribution
- Ridge

2-Particle Correlations



$$\Delta\eta = \eta_{assoc} - \eta_{trig}$$
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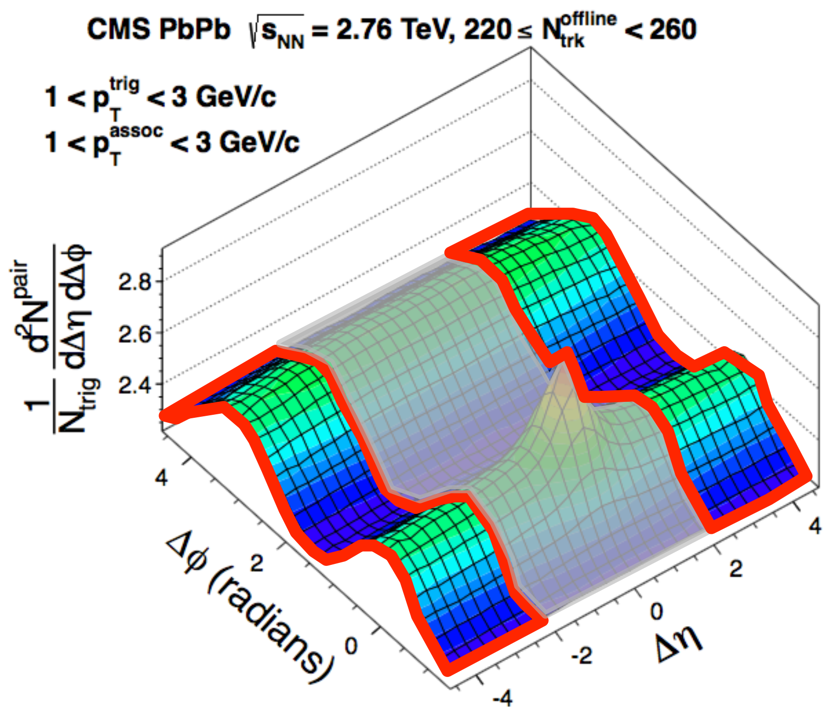
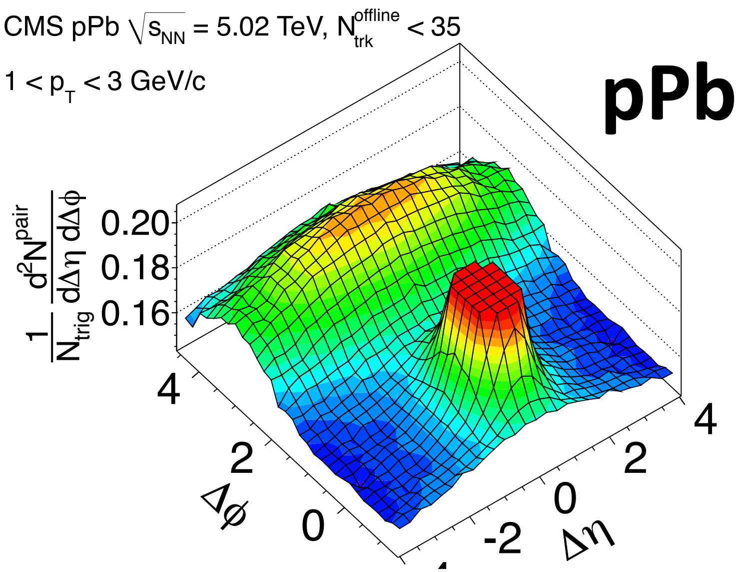
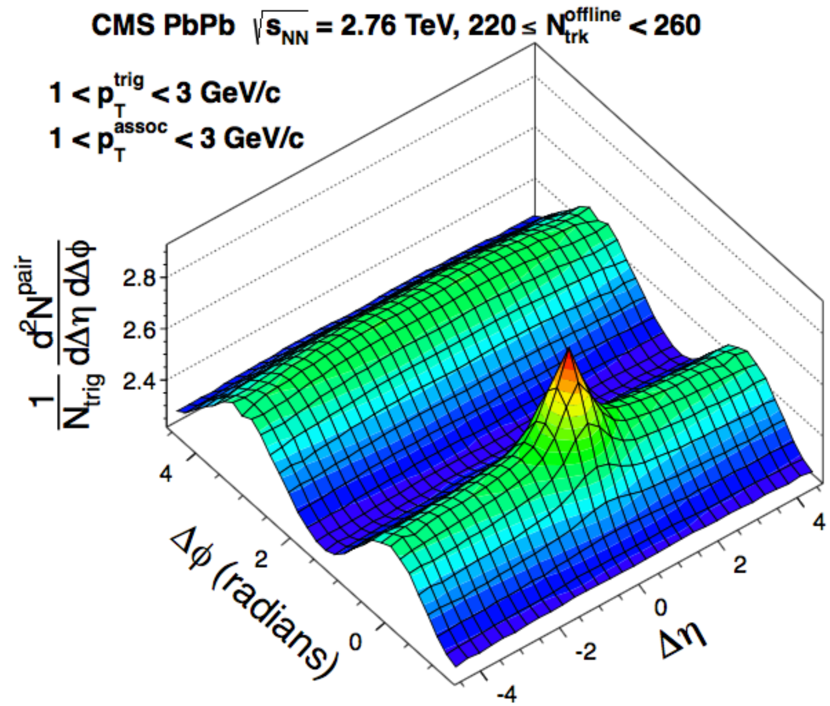


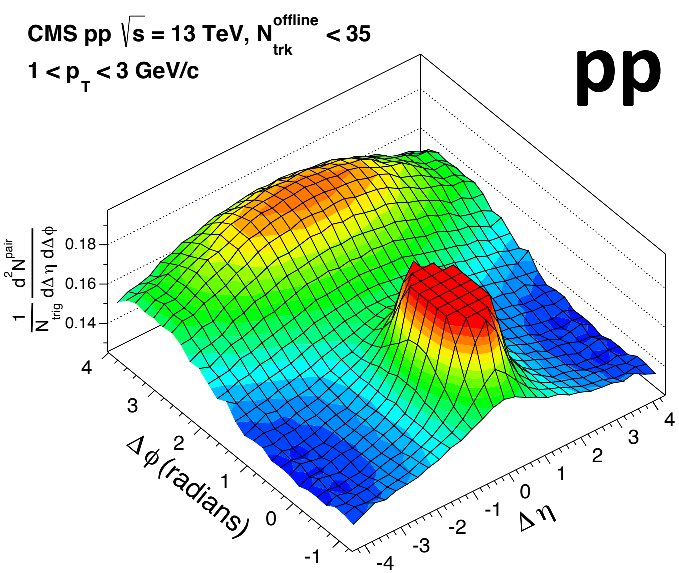
- Jet contribution
- Ridge

- Long range ($\Delta\eta > 2$)
- Extract flow harmonics

2-Particle Correlations

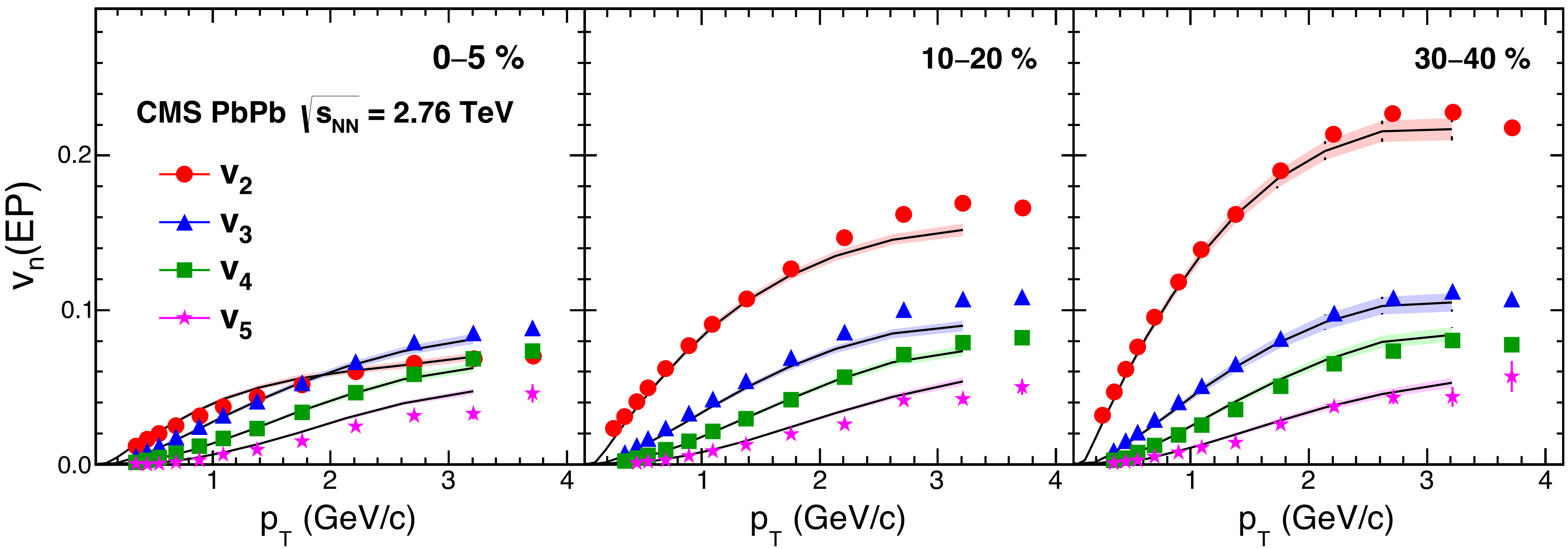






- PbPb: Ridge
- pPb and pp: No Ridge
  - ✓ Perfect reference?

Perfect Liquid

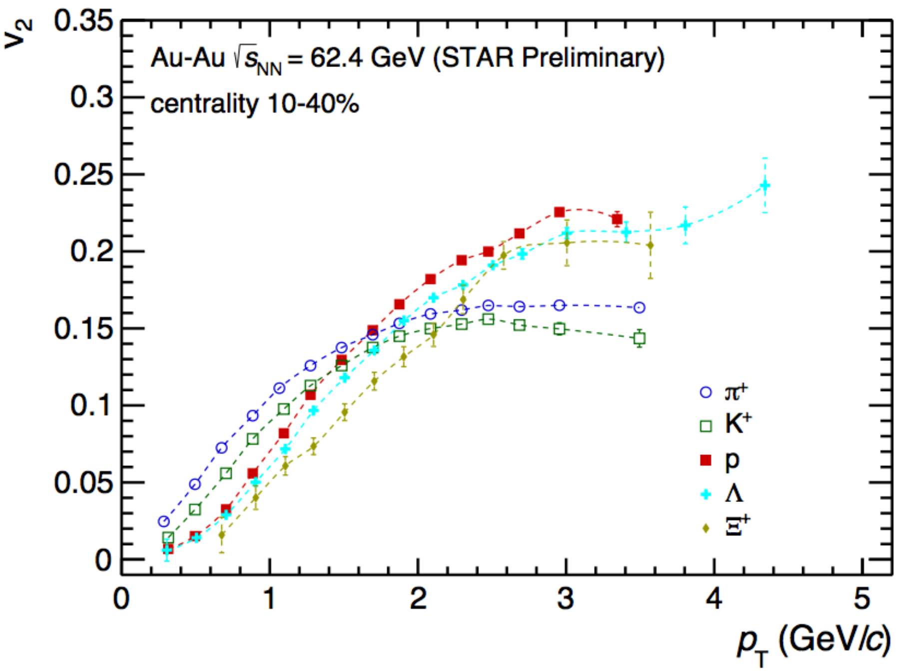


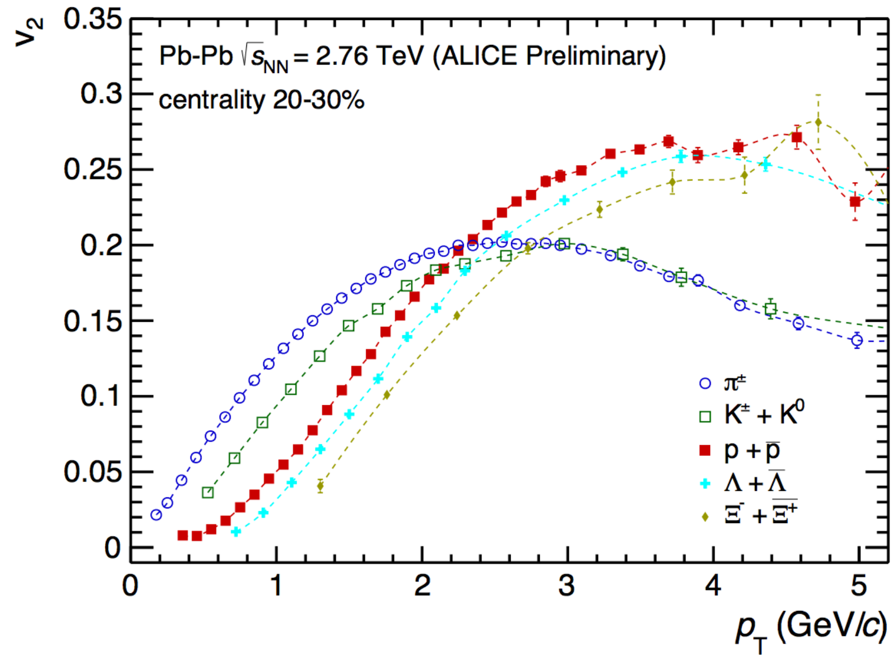
[Phys. Rev. C 89, 0449076] **CMS results**

[Phys. Rev. Lett. 110, 012302] **IP glasma + MUSIC**

- Hydrodynamic describes data well
- η/s close to quantum limit $1/4\pi$ (perfect liquid)

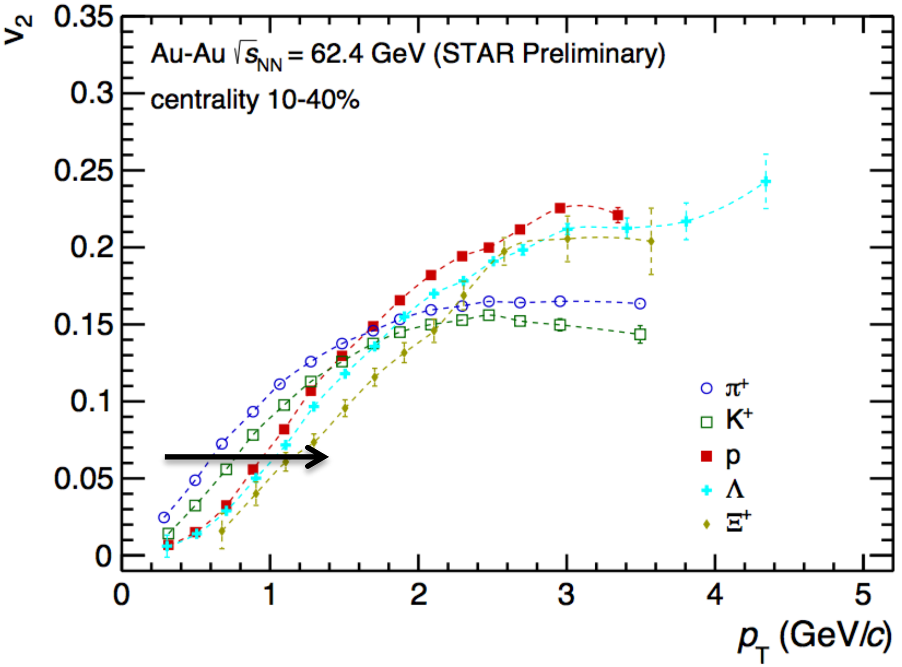
Mass Ordering

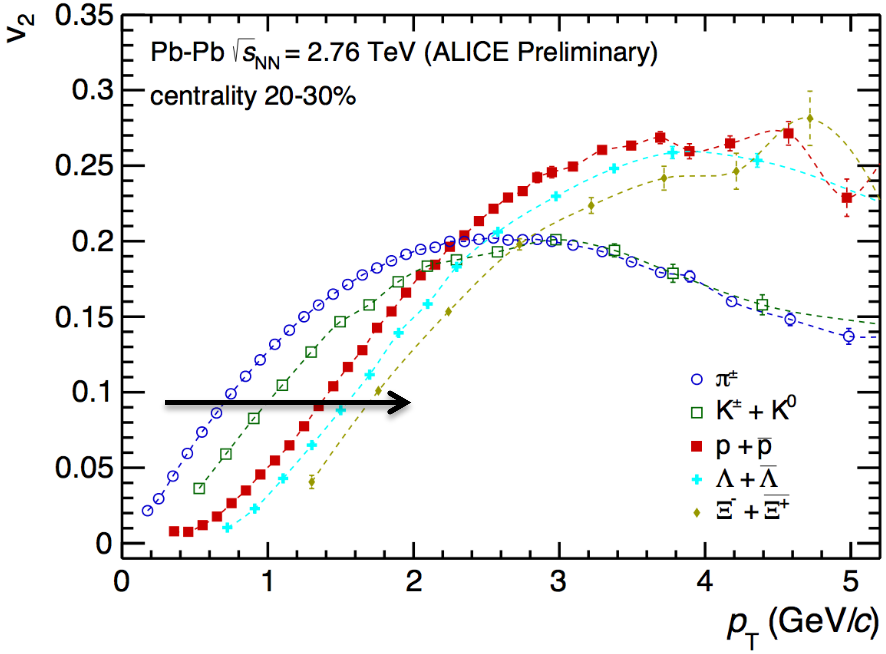




- Common velocity of the medium
- Heavier particles boosted to higher p_T

Mass Ordering

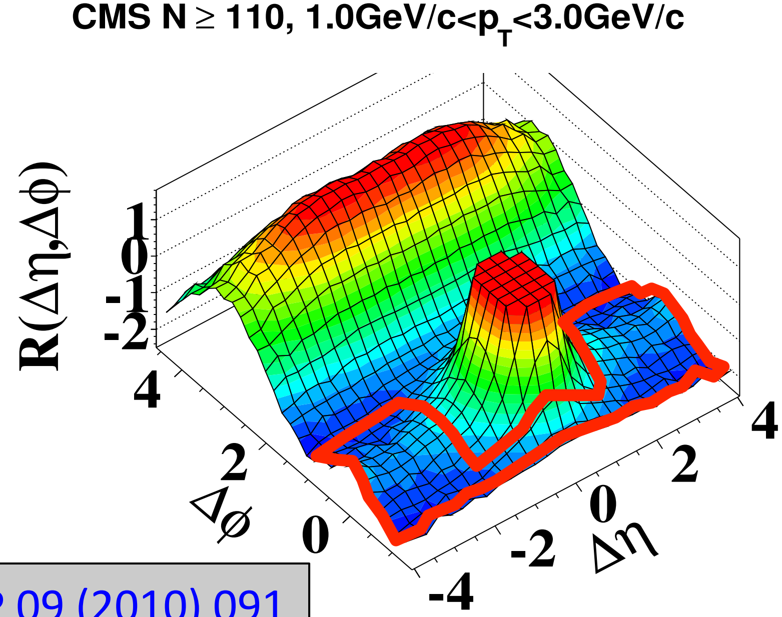




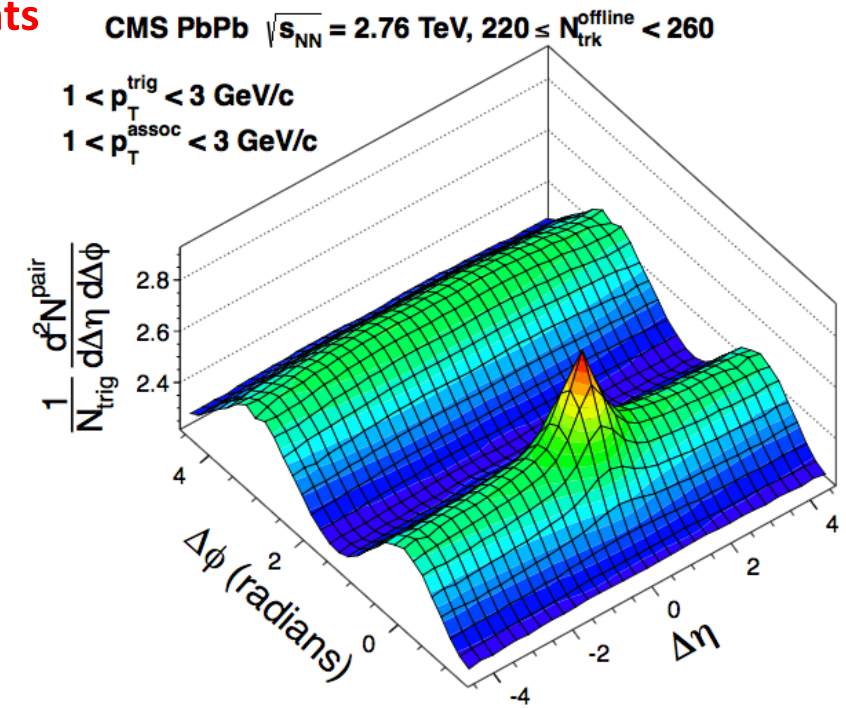
- Common velocity of the medium
- Heavier particles boosted to higher p_T
- Splitting of identified particle v_2

Ridge in pp

2010: **Ridge** observed in **high multiplicity pp events**

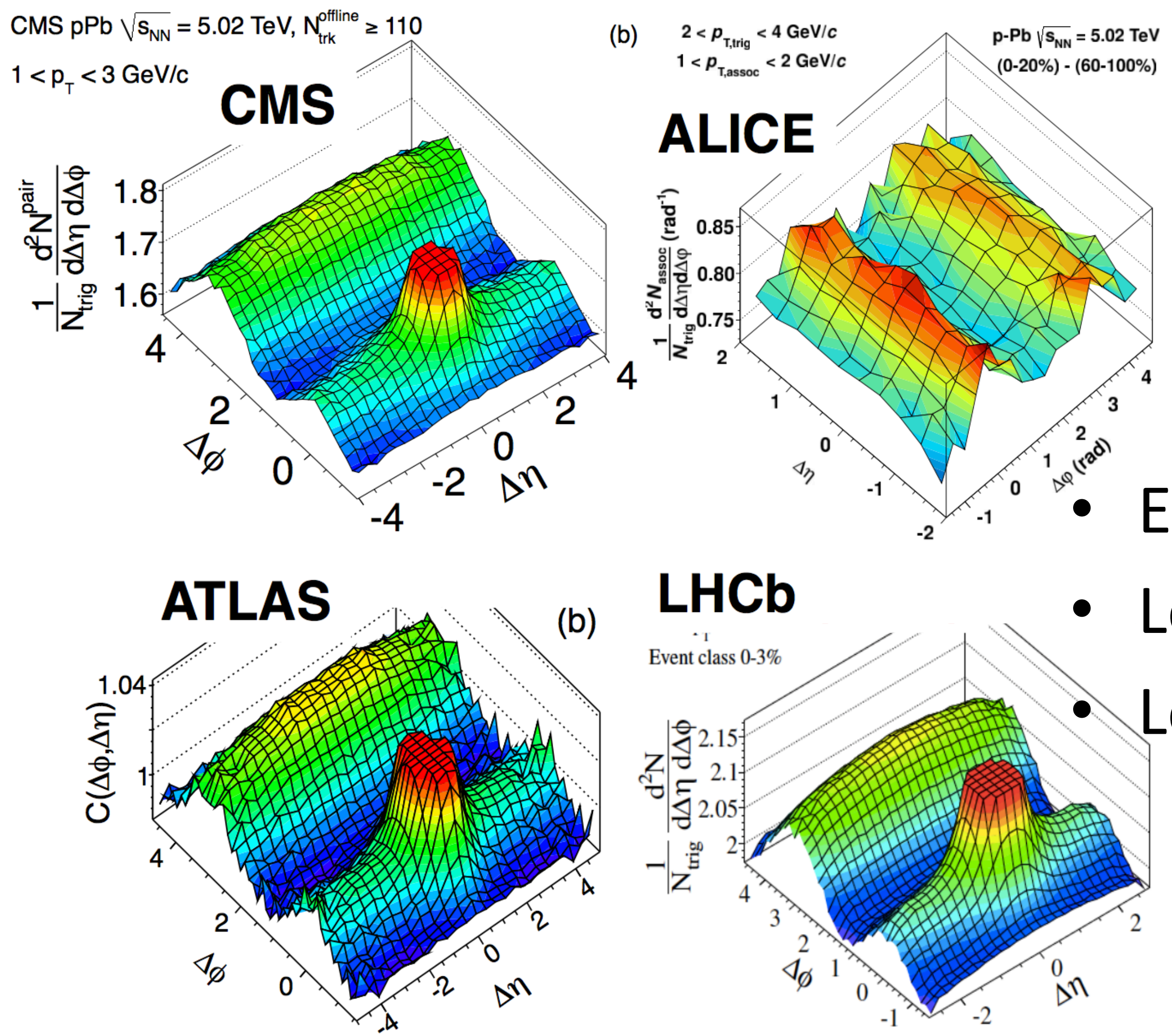


JHEP 09 (2010) 091



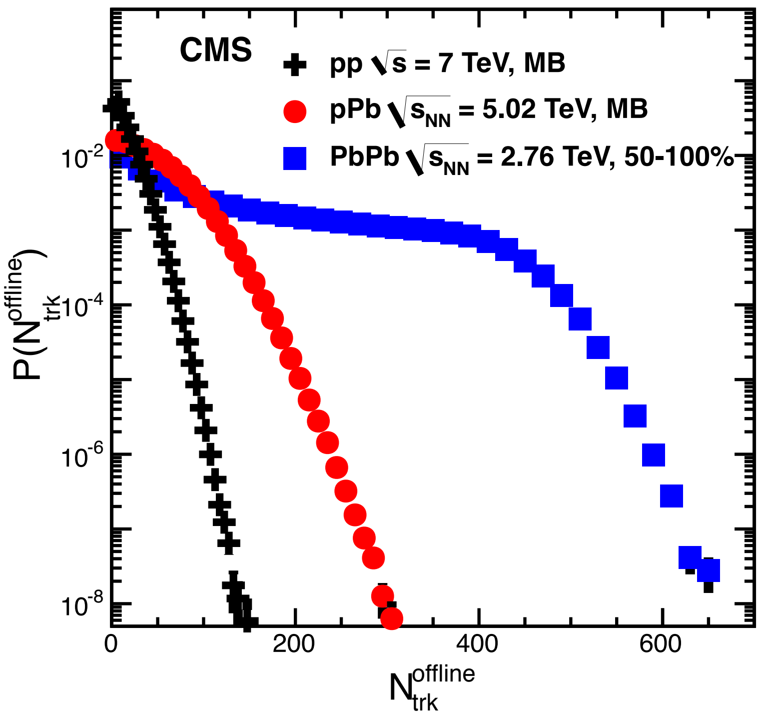
- Unexpected ridge in high multiplicity pp collisions
- Collectivity in pp?

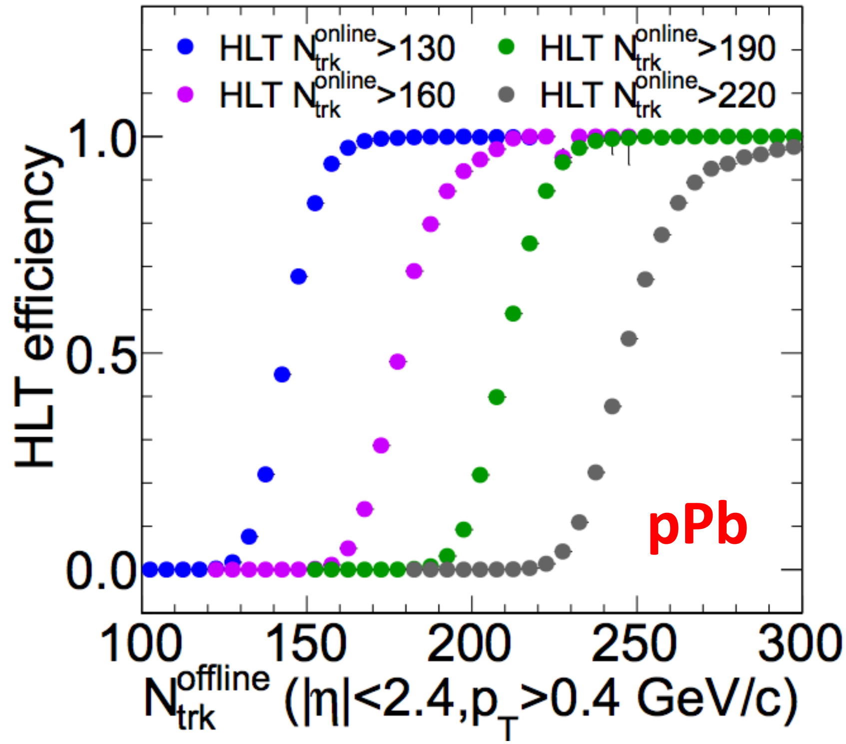
Ridge in pPb



- Enhanced ridge in pPb
- Lots of interests
- Lots of measurements

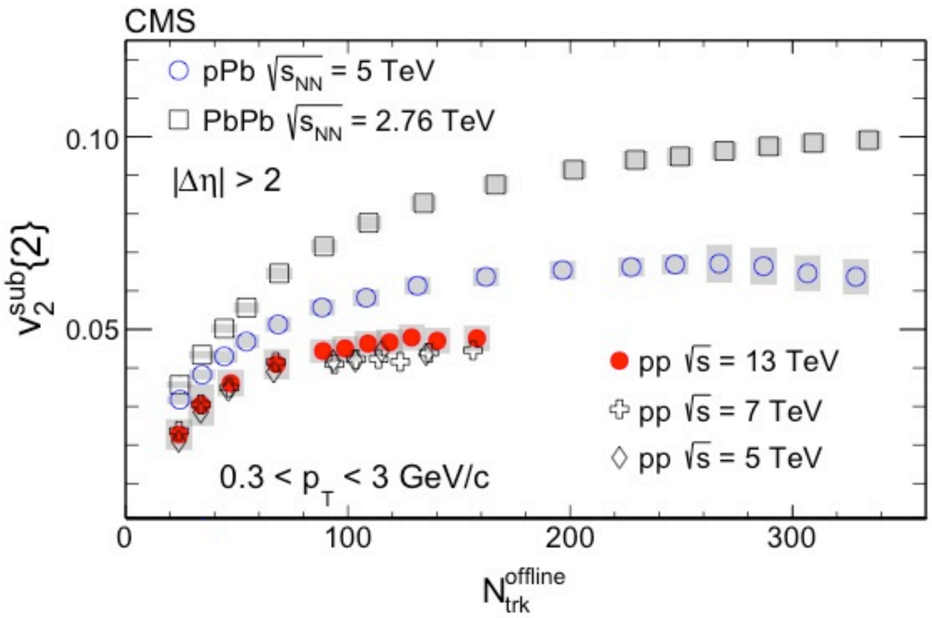
High Multiplicity Triggers





- Final state multiplicity ($N_{trk}^{offline}$)
  - $|\eta| < 2.4$, $p_T > 0.4$ GeV/c
- Comparable to mid-central PbPb collisions

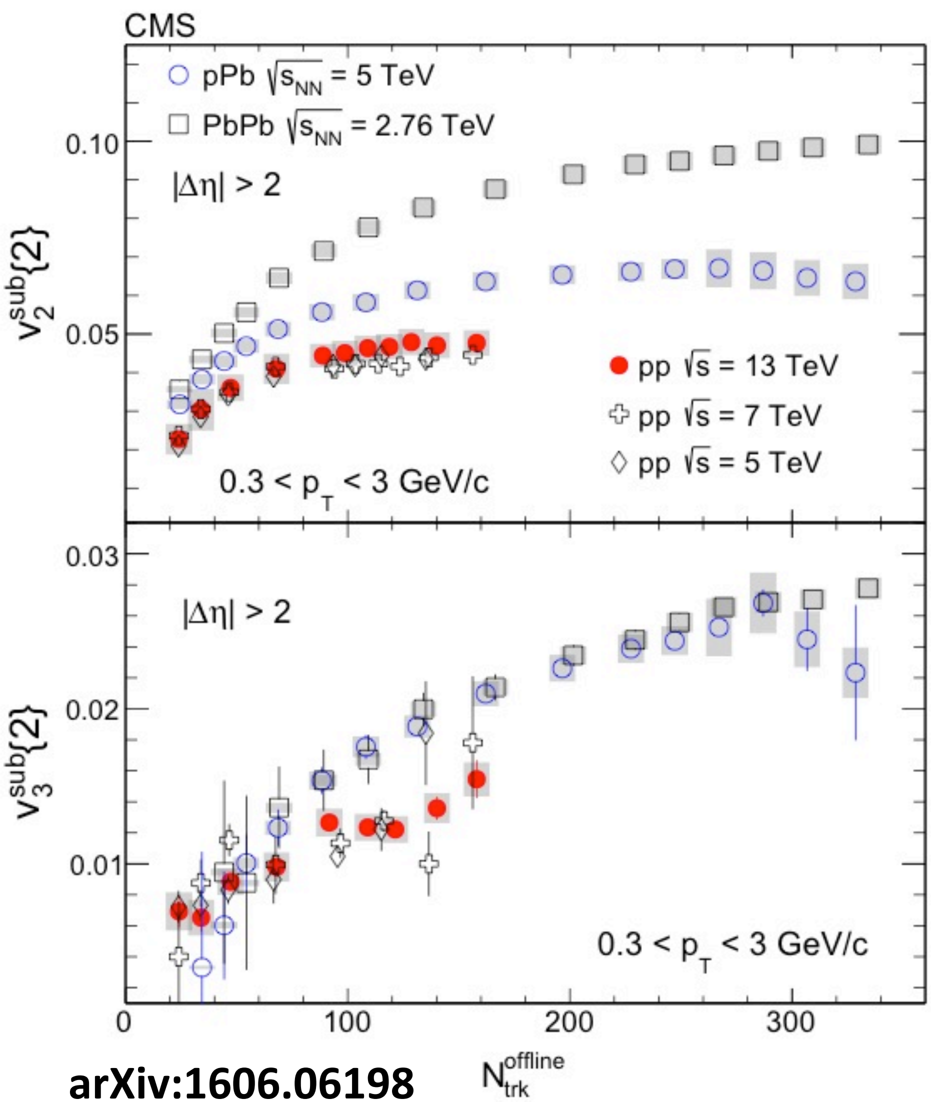
Flow Harmonics in Small Systems



- v_2
  - Little energy dependence in pp
  - Small but similar to pPb and PbPb
  - Similar origin?

arXiv:1606.06198

Flow Harmonics in Small Systems

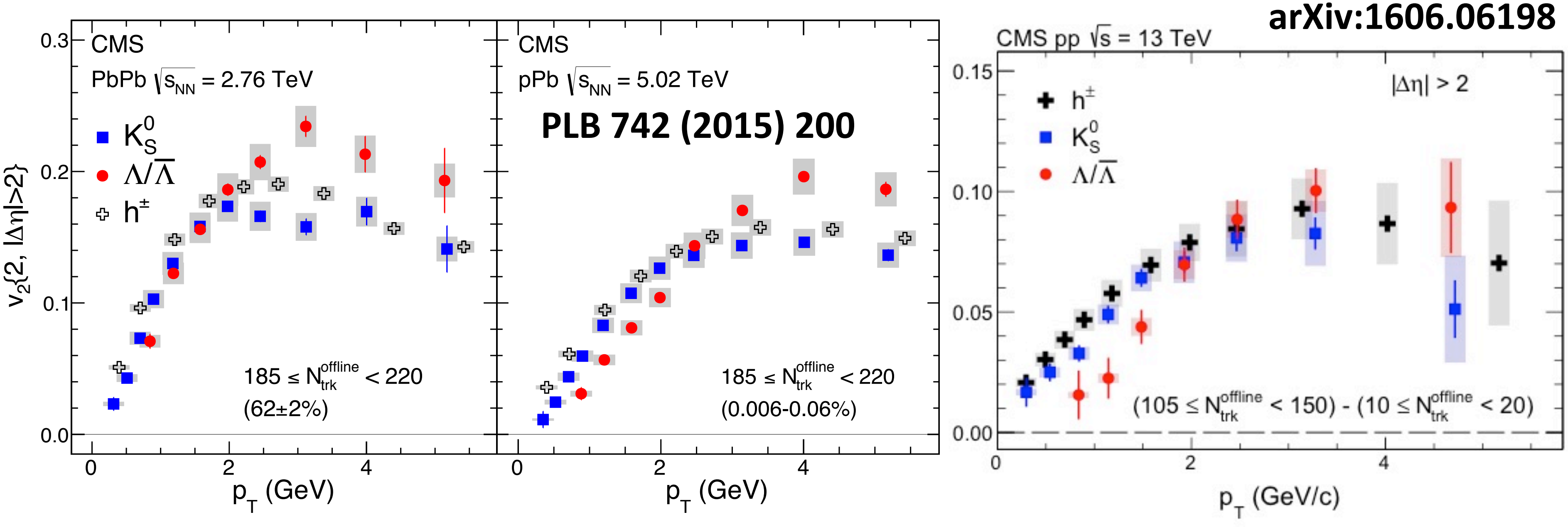


arXiv:1606.06198

- v_2
  - Little energy dependence in pp
  - Small but similar to pPb and PbPb
  - Similar origin?
- v_3
  - Little energy dep.
  - Initial state fluctuation?
- Insights of proton IS fluctuations

Identified Particle Flow

arXiv:1606.06198



- Mass ordering in pp, pPb and PbPb

Identified Particle Flow

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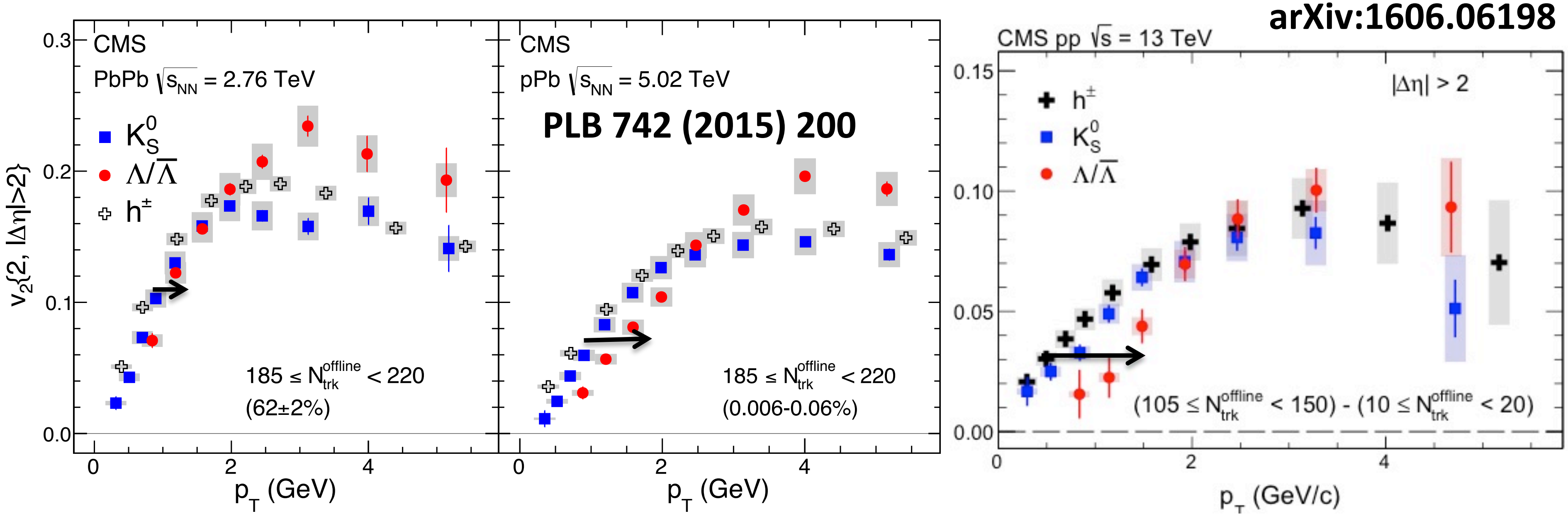

- Mass ordering in pp, pPb and PbPb
- v_2 splitting pp > pPb > PbPb
  - More explosive in smaller system? (Radial flow)

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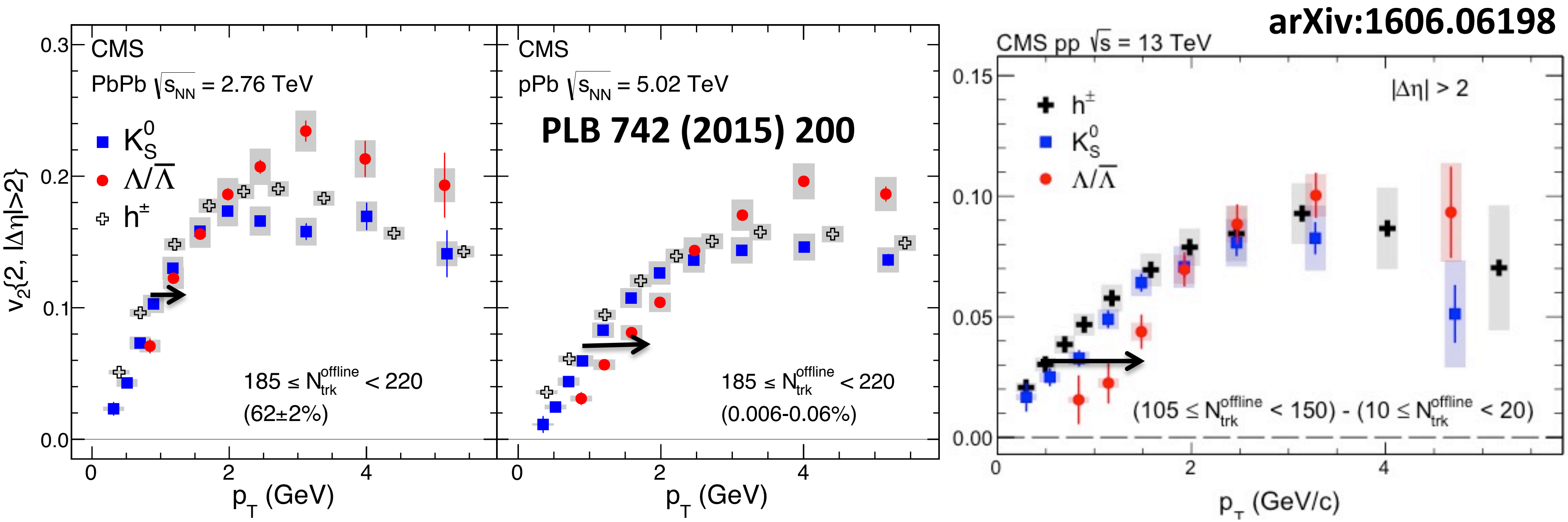

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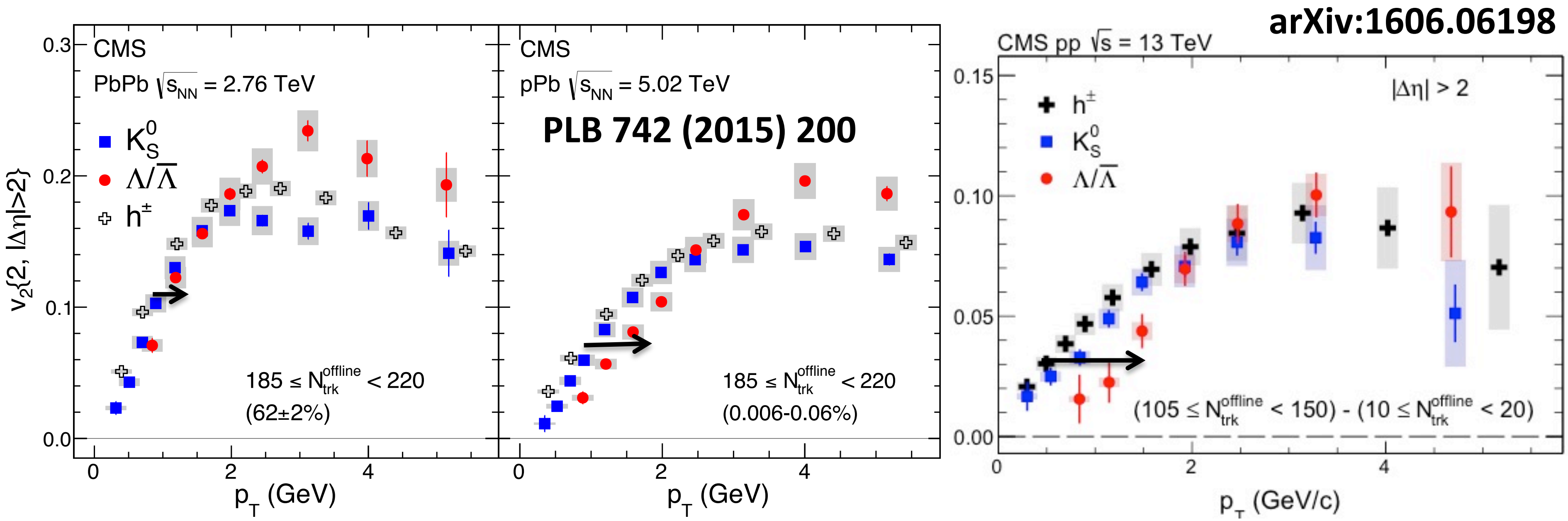


- Mass ordering in pp, pPb and PbPb
- v_2 splitting pp > pPb > PbPb
  - More explosive in smaller system? (Radial flow)
- Measurements favor Hydrodynamics

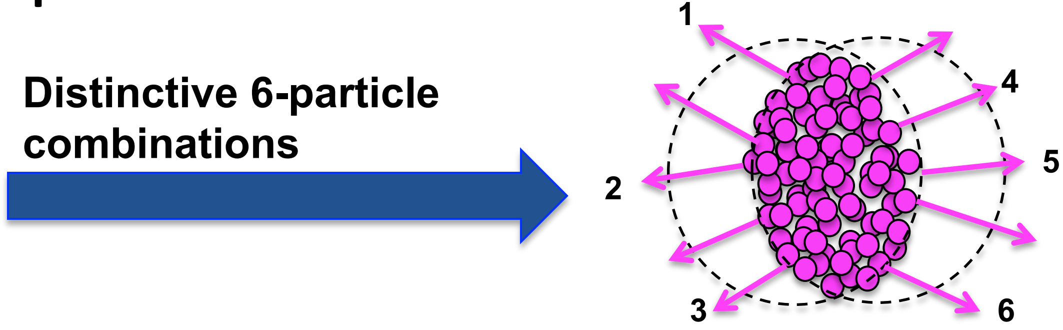
Collective?

Multi-particle Cumulant

- 6-particle correlator, per event

$$\langle 6 \rangle \equiv \left\langle e^{in(\phi_1+\phi_2+\phi_3-\phi_4-\phi_5-\phi_6)} \right\rangle$$

$$\equiv \frac{1}{P_{M,6}} \sum_{\substack{i\neq j\neq k \\ \neq l\neq m\neq n}}^{M} e^{in(\phi_i+\phi_j+\phi_k-\phi_l-\phi_m-\phi_n)}$$



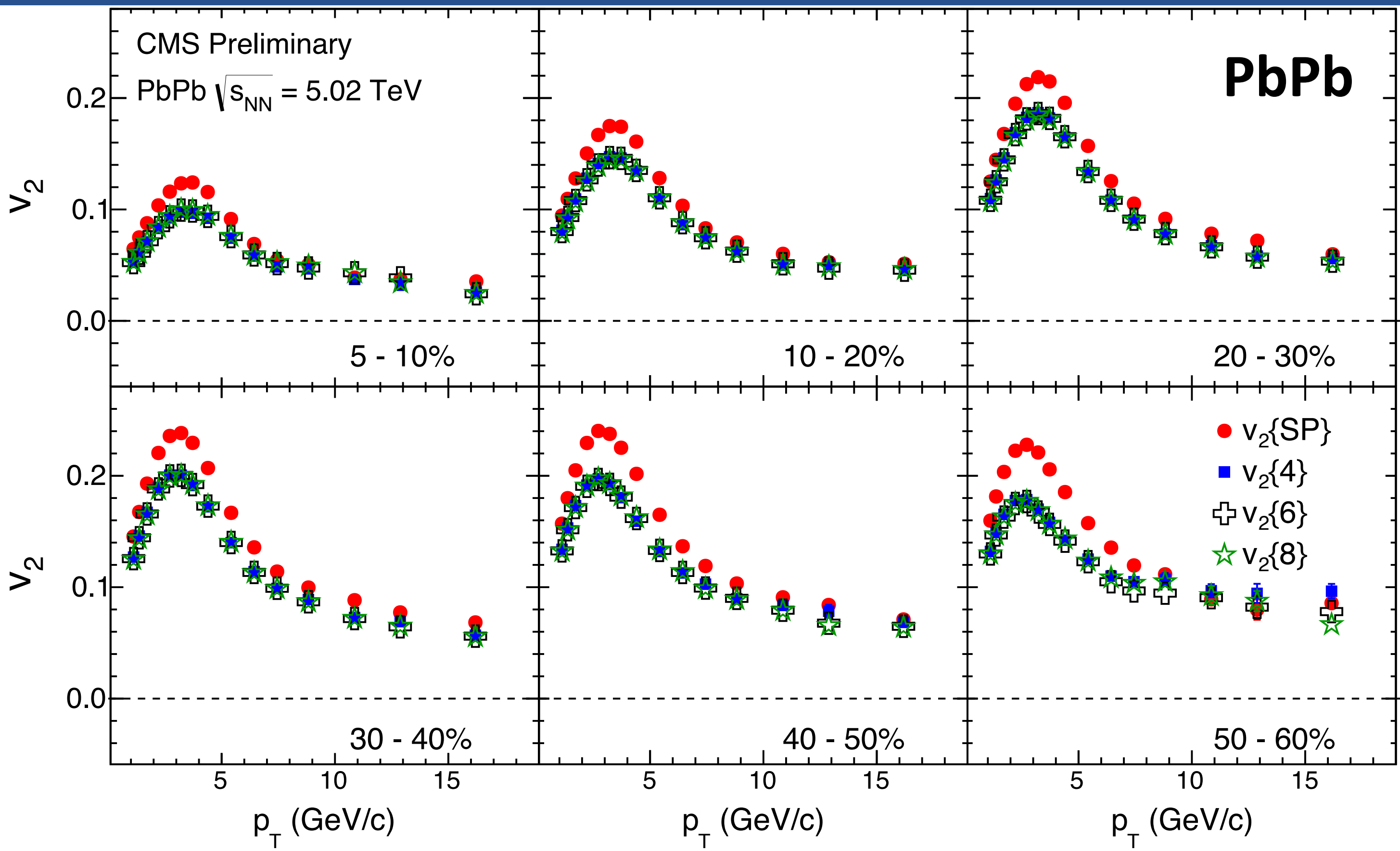
- 6-particle cumulant, all events

$$c_n\{6\} = \langle\langle 6 \rangle\rangle - 9 \bullet \langle\langle 4 \rangle\rangle \langle\langle 2 \rangle\rangle + 12 \bullet \langle\langle 2 \rangle\rangle^3$$

- Q-Cumulant: decompose ➔ flow vector $Q_n \equiv \sum_{i=1}^{M} w_i e^{in\varphi_i}$

- Cumulant v_n ➔ $v_n\{4\} = \sqrt[4]{-c_n\{4\}}, v_n\{6\} = \sqrt[6]{\frac{1}{4}c_n\{6\}}, v_n\{8\} = \sqrt[8]{-\frac{1}{33}c_n\{8\}}$

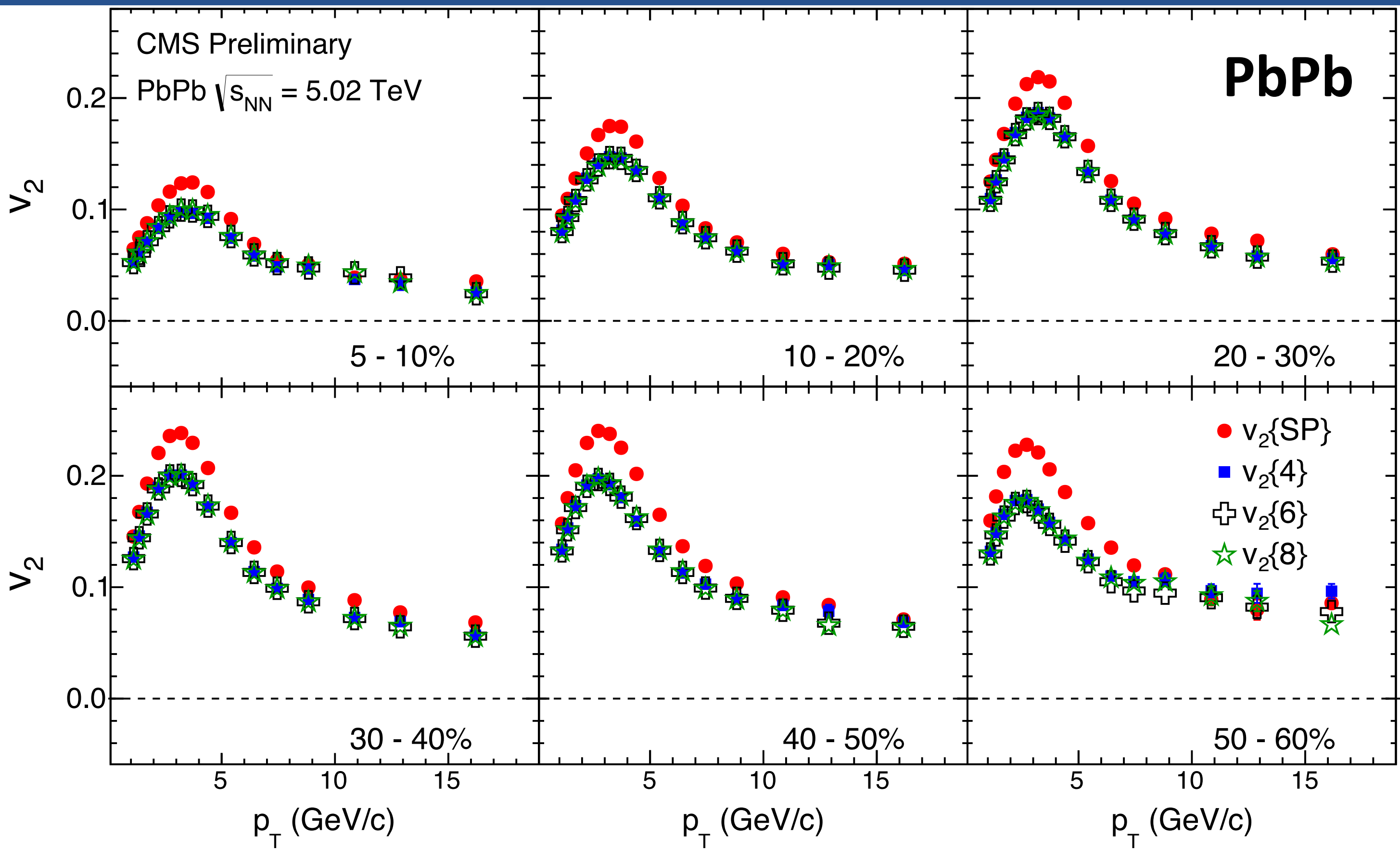
Multi-particle Cumulant



CMS-HIN-15-014

- Collectivity in PbPb

Multi-particle Cumulant



$$v\{2\} = \langle v\rangle + \frac{1}{2}\frac{\sigma_v^2}{\langle v\rangle},$$

$$v\{4\} = \langle v\rangle - \frac{1}{2}\frac{\sigma_v^2}{\langle v\rangle},$$

$$v\{6\} = \langle v\rangle - \frac{1}{2}\frac{\sigma_v^2}{\langle v\rangle},$$

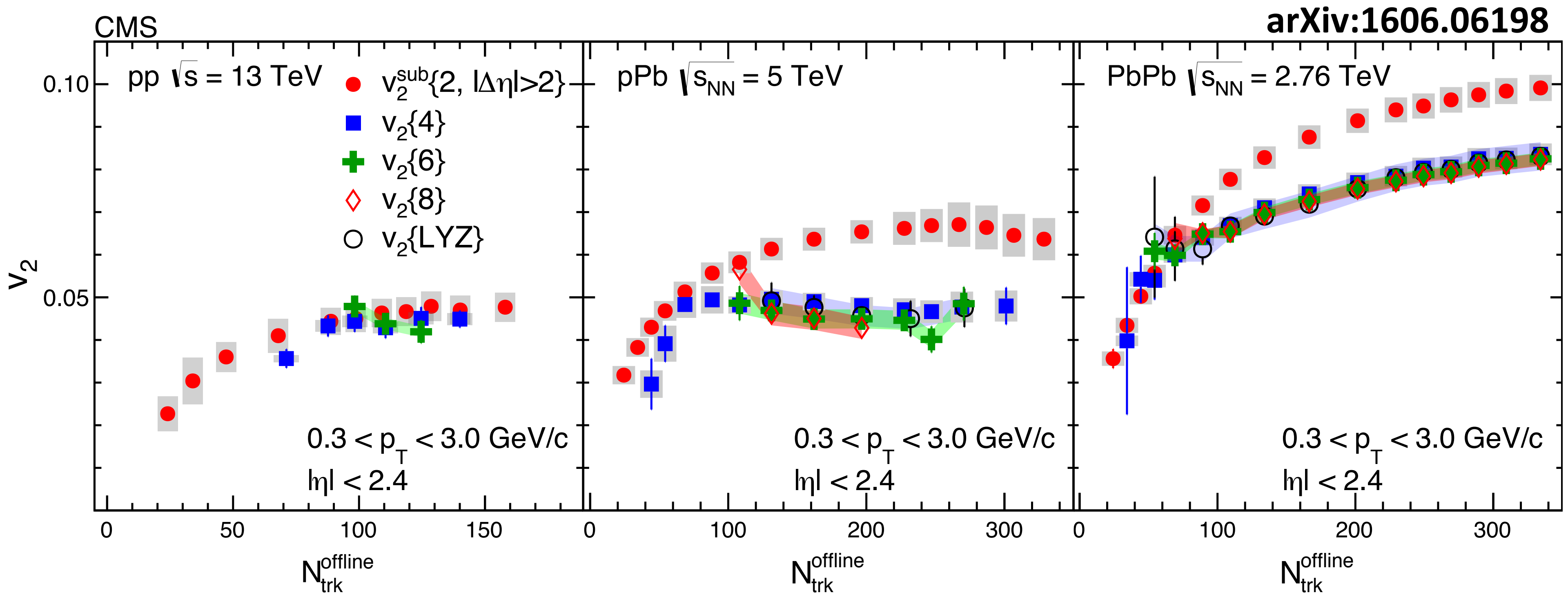
$$v\{8\} = \langle v\rangle - \frac{1}{2}\frac{\sigma_v^2}{\langle v\rangle}$$

CMS-HIN-15-014

- Collectivity in PbPb
- Hydrodynamics: $v_2\{2\} > v_2\{4\} \approx v_2\{6\} \approx v_2\{8\}$

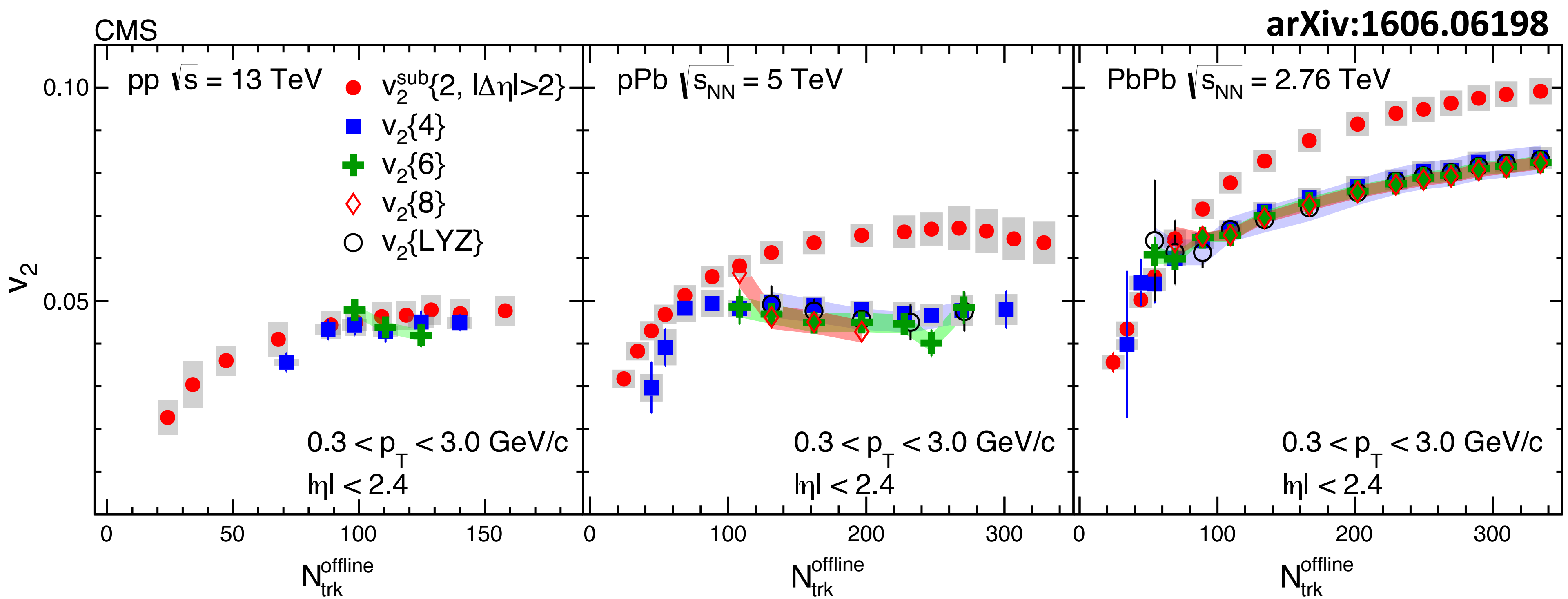
Multi-particle Cumulant

arXiv:1606.06198



- Collectivity in pp, pPb and PbPb

Multi-particle Cumulant

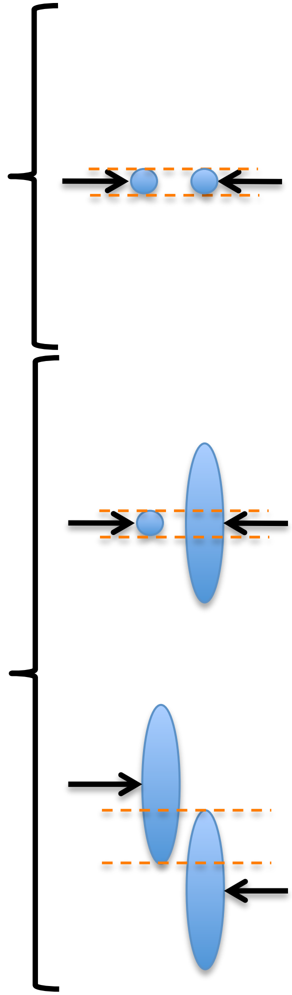


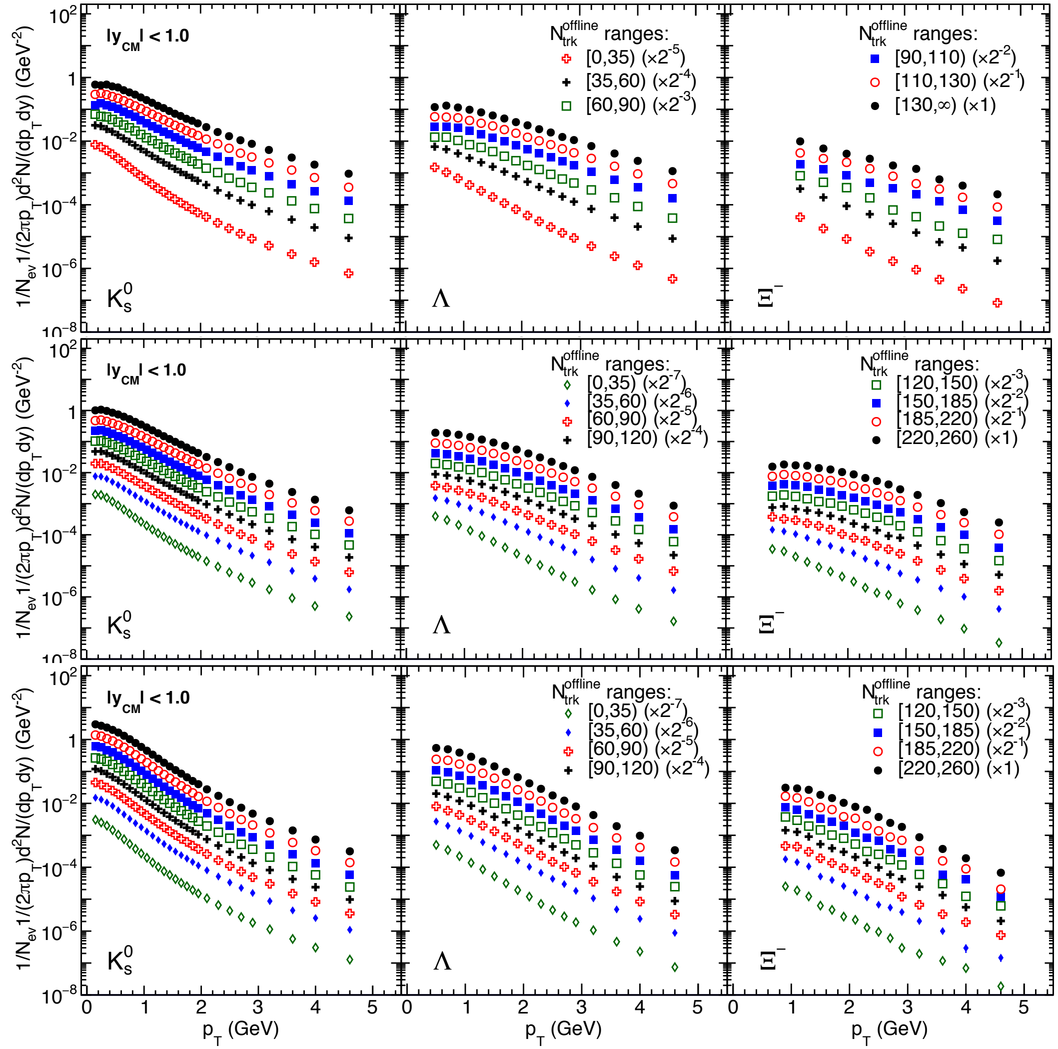
- Collectivity in pp, pPb and PbPb
- pPb and PbPb: $v_2\{2\} > v_2\{4\} \approx v_2\{6\} \approx v_2\{8\}$
- pp: $v_2\{2\} \approx v_2\{4\} \approx v_2\{6\} \approx v_2\{8\}$ why?

Identified Particle Spectra

$N_{trk}^{offline}$ ranges:
- [0,35) ($\times 2^{-5}$)
- [35,60) ($\times 2^{-4}$)
- [60,90) ($\times 2^{-3}$)
- [90,110) ($\times 2^{-2}$)
- [110,130) ($\times 2^{-1}$)
- [130,∞) (×1)

$N_{trk}^{offline}$ ranges:
- [0,35) ($\times 2^{-7}$)
- [35,60) ($\times 2^{-6}$)
- [60,90) ($\times 2^{-5}$)
- [90,120) ($\times 2^{-4}$)
- [120,150) ($\times 2^{-3}$)
- [150,185) ($\times 2^{-2}$)
- [185,220) ($\times 2^{-1}$)
- [220,260) (×1)

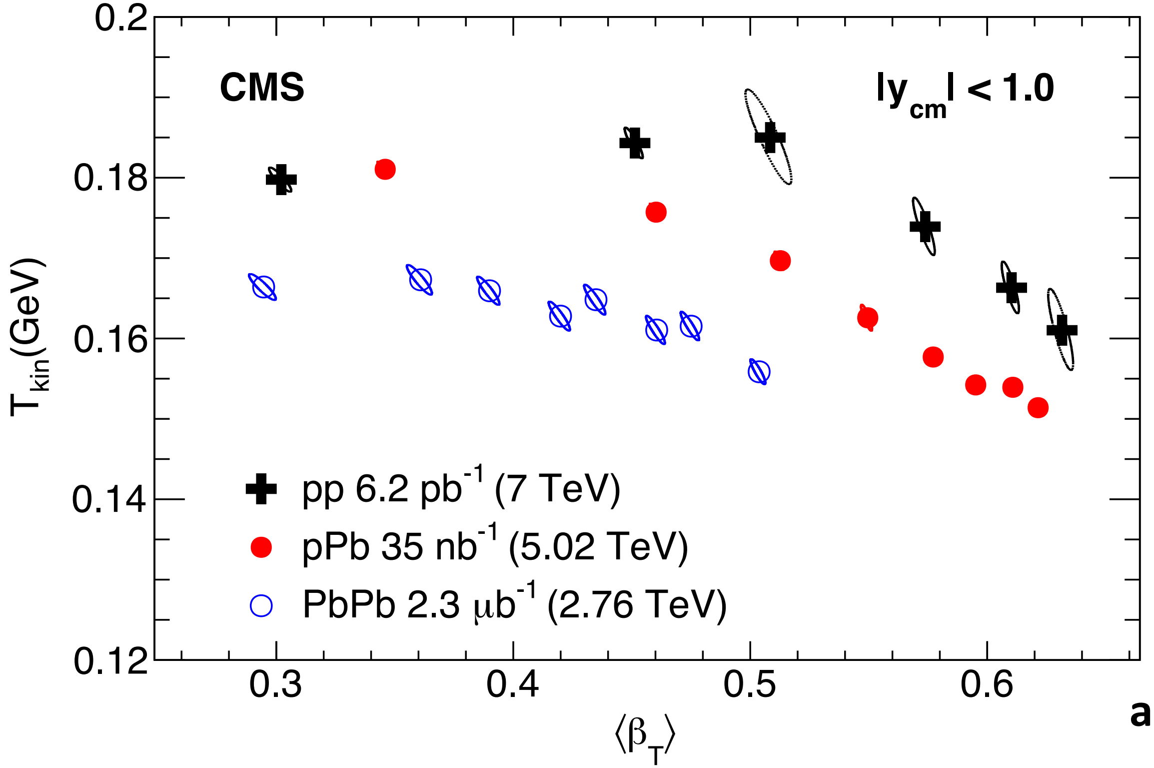




- More boosted of heavier particles

arXiv:1605.06699

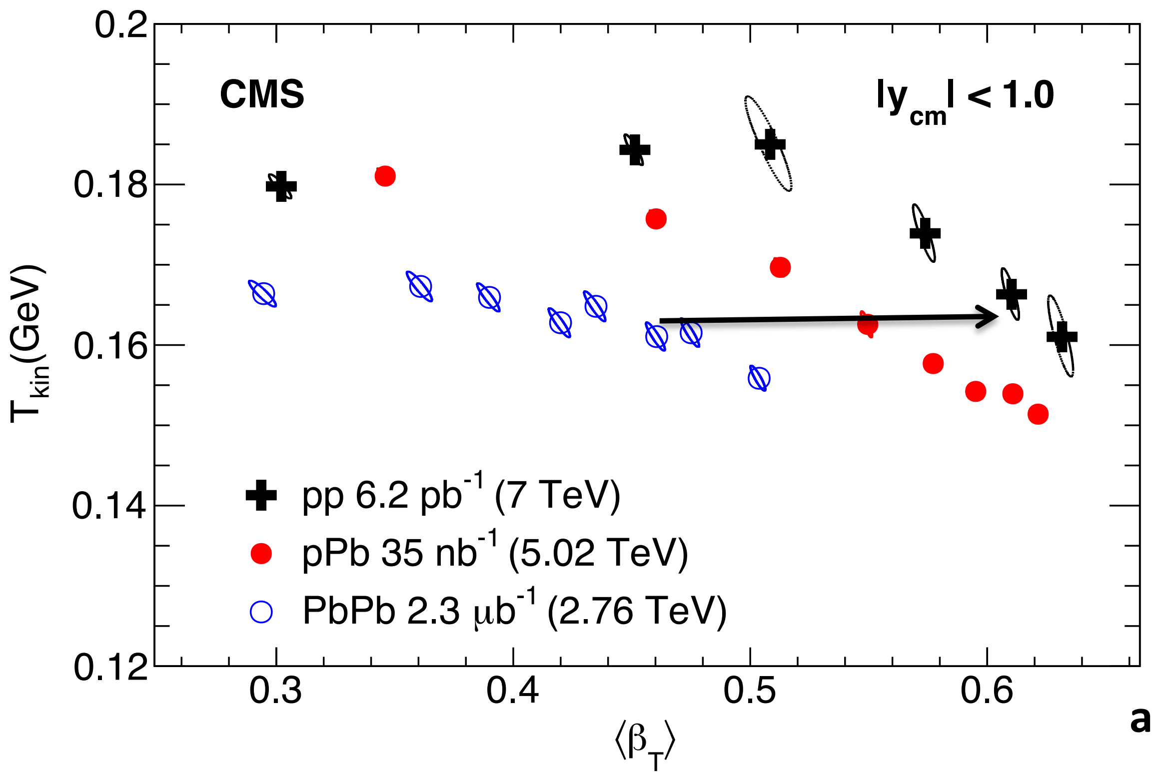
Blast Wave Fit



arXiv:1605.06699

- Assuming hydro, Blast Wave fit can be applied

Blast Wave Fit



arXiv:1605.06699

- Assuming hydro, Blast Wave fit can be applied
- Similar $N_{trk}^{offline}$, similar T_{kin}
  but $<\beta_T>$: pp > pPb > PbPb (explosive)

Underlying Physics

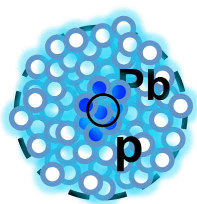
- Hydro is successful in AA
- Still valid in small systems?

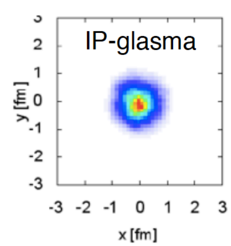
Underlying Physics

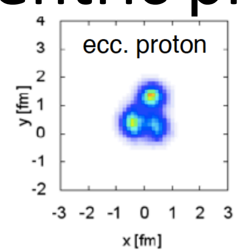
- Hydro is successful in AA
- Still valid in small systems?
- Alternatives
  - CGC, EPOS, Pomerons, parton escape …

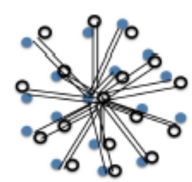
Underlying Physics

- Hydro is successful in AA
- Still valid in small systems?
- Alternatives
  - CGC, EPOS, Pomerons, parton escape …
- Initial states
  - Glauber, IP-Glasma, eccentric proton, pomerons



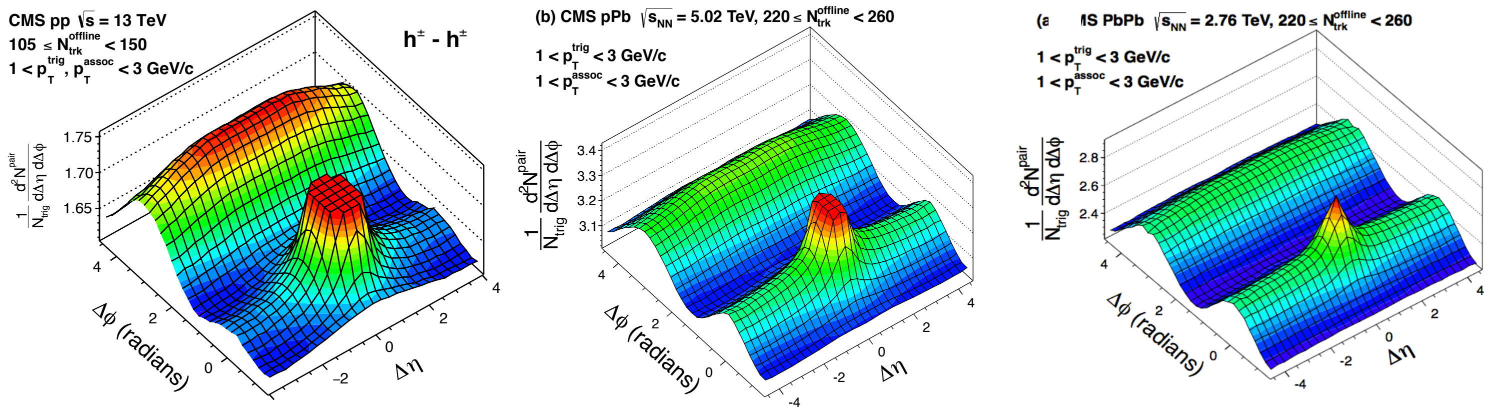






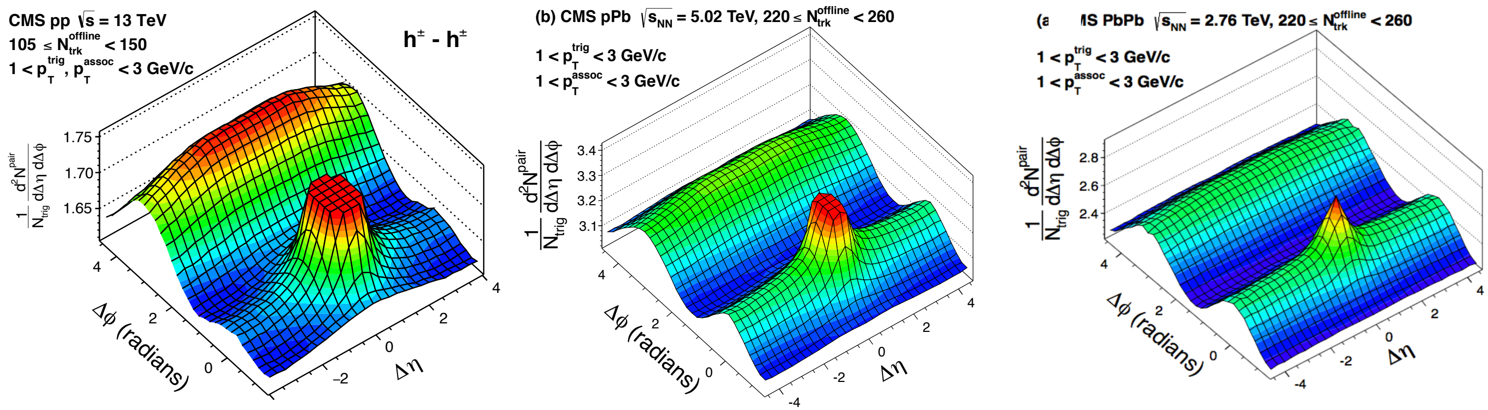
Summary

- Ridge everywhere

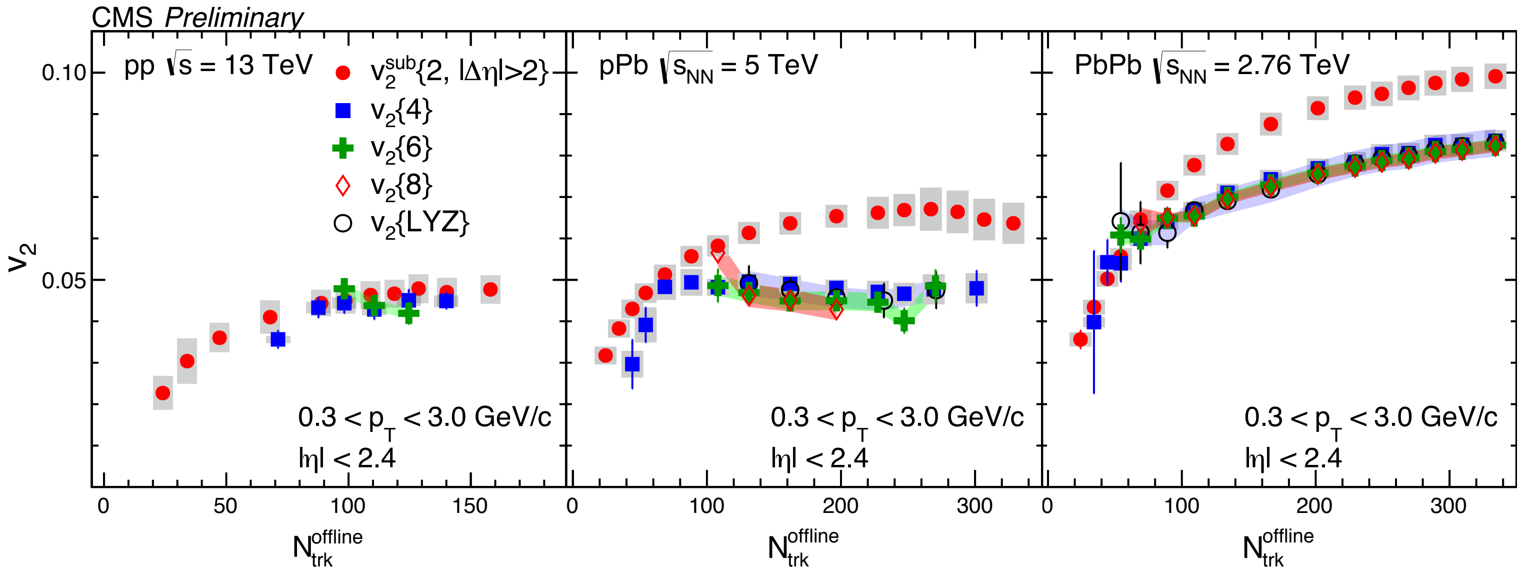


Summary

- Ridge everywhere



- Collectivity everywhere



Summary

- New data is coming
  - 8 TeV pPb end of the year
- Detailed measurements
- Missing component in small systems
  - Jet quenching
- Stay tuned