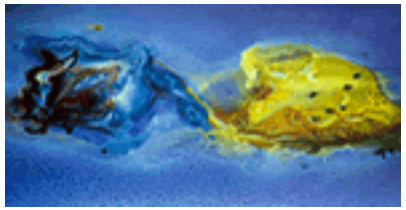


XIIIth Quark Confinement and the Hadron Spectrum

Do we produce quark-gluon plasma in all colliding systems?

Maxime Guilbaud[(1)]

(1) CERN, m.guilbaud@cern.ch

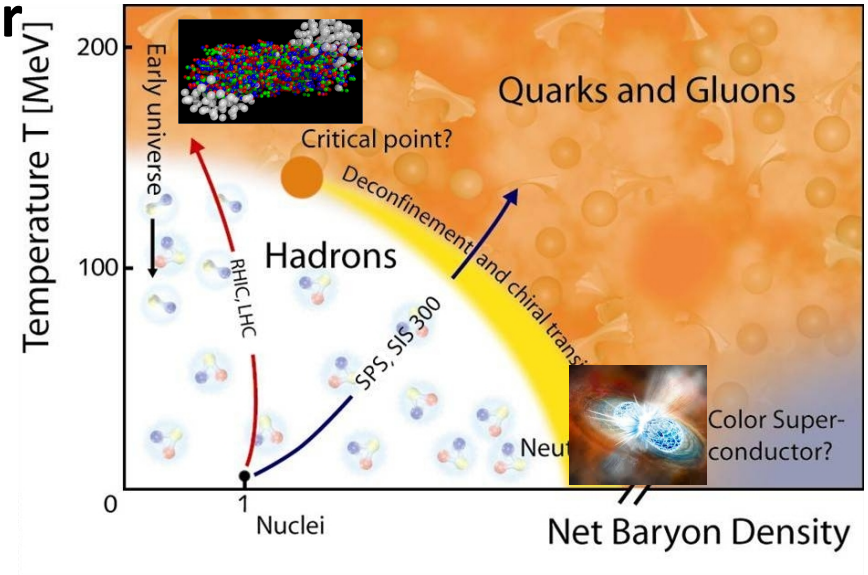
Parallel session: Deconfinement

01/08/18

Brief outline of this talk content…

Studying the phase diagram of nuclear matter

- Phase transition(s)
- Properties of quark-gluon plasma



Brief outline of this talk content…

Studying the phase diagram of nuclear matter

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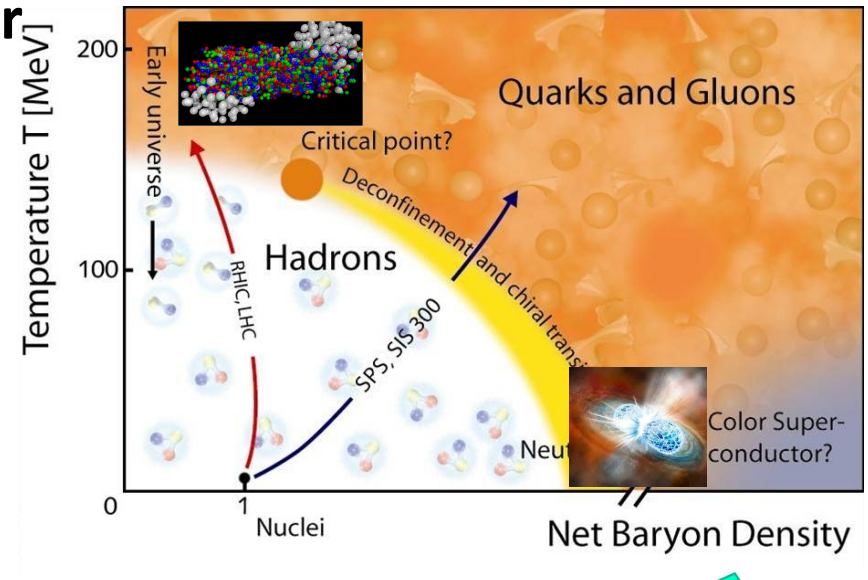
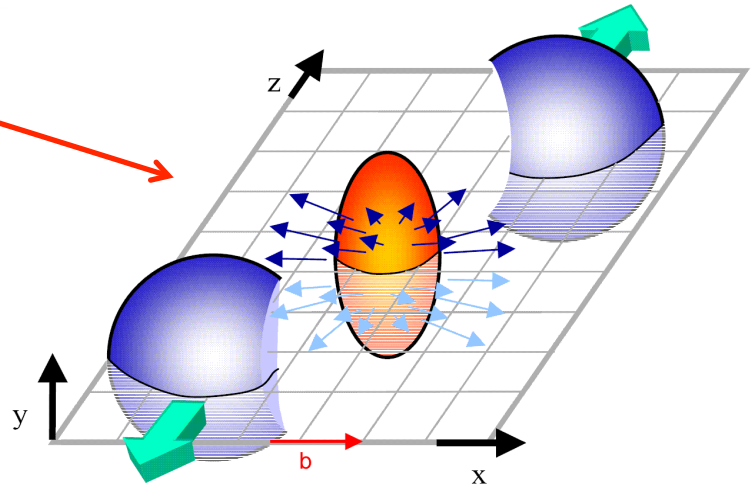
QGP properties:

- Perfect fluid
- In-medium interaction





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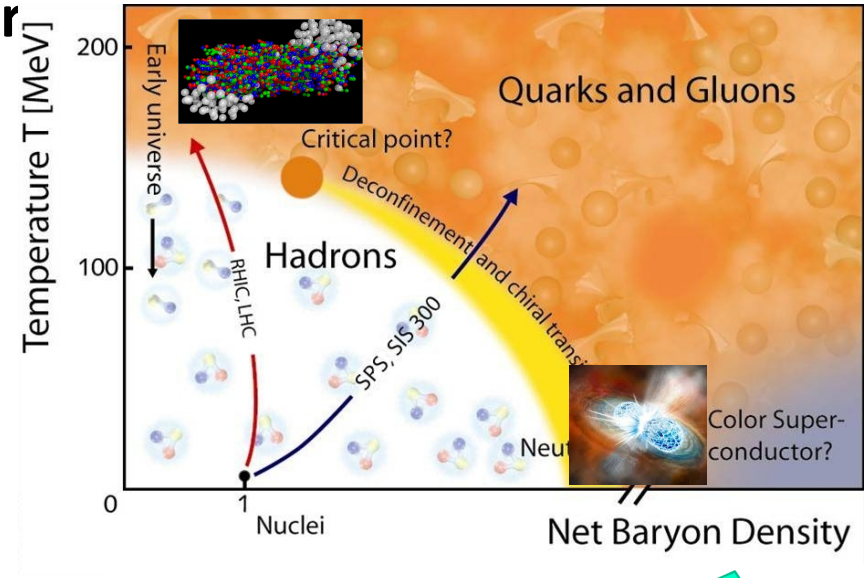
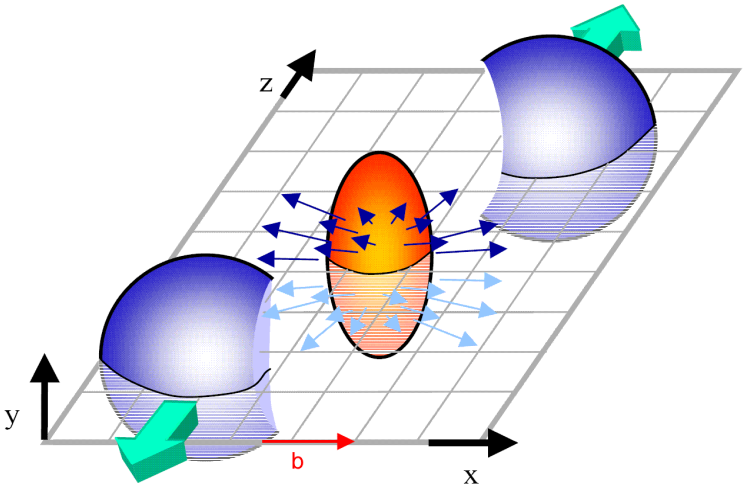


QGP properties:

- Perfect fluid
- In-medium interaction

Onset of deconfinement

- Low density and high T: heavy ion collisions
  - Large system
- Do we produce QGP in smaller systems
  - pp, p-A, …

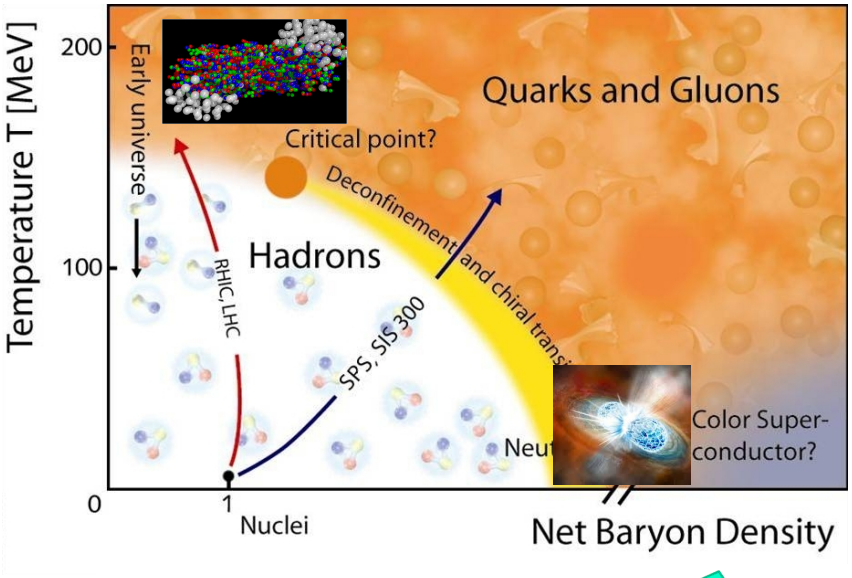


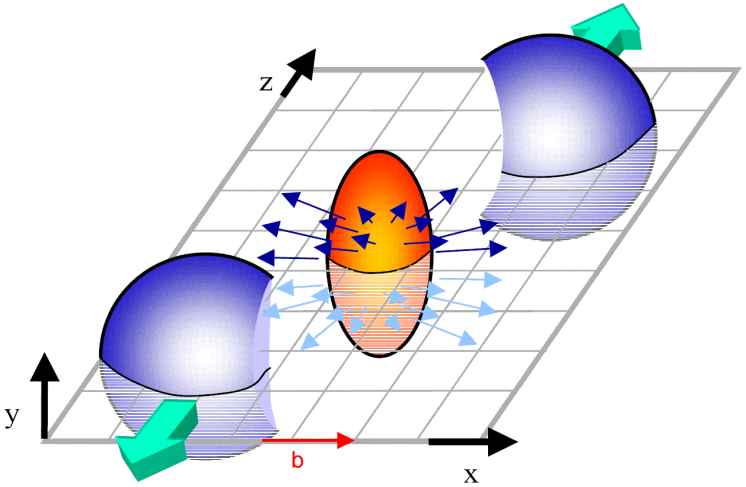
Brief outline of this talk content…

1- What we know from AA

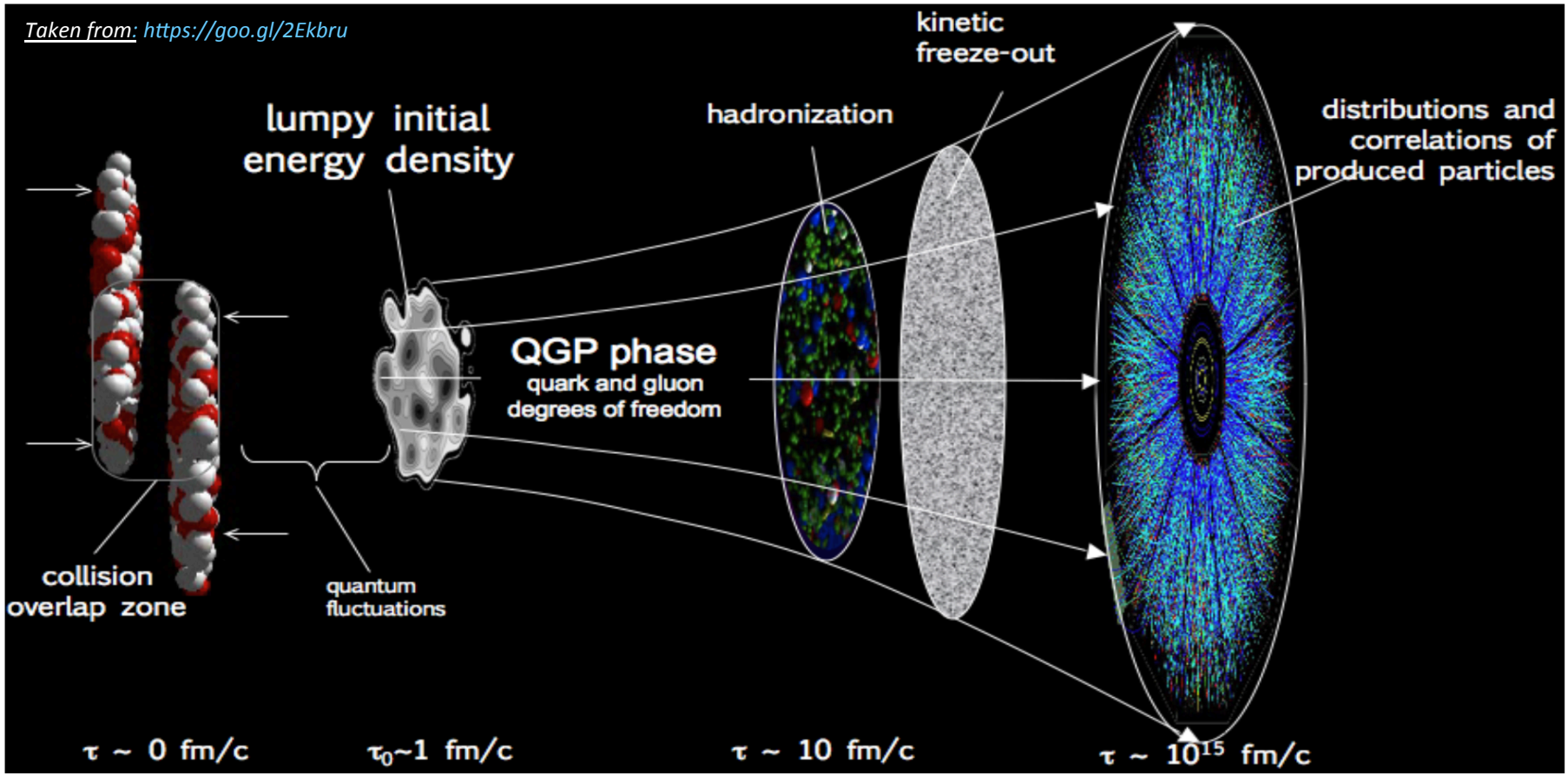
2- What we have learnt from small systems

3- Conclusion and prospective





Heavy Ion collisions



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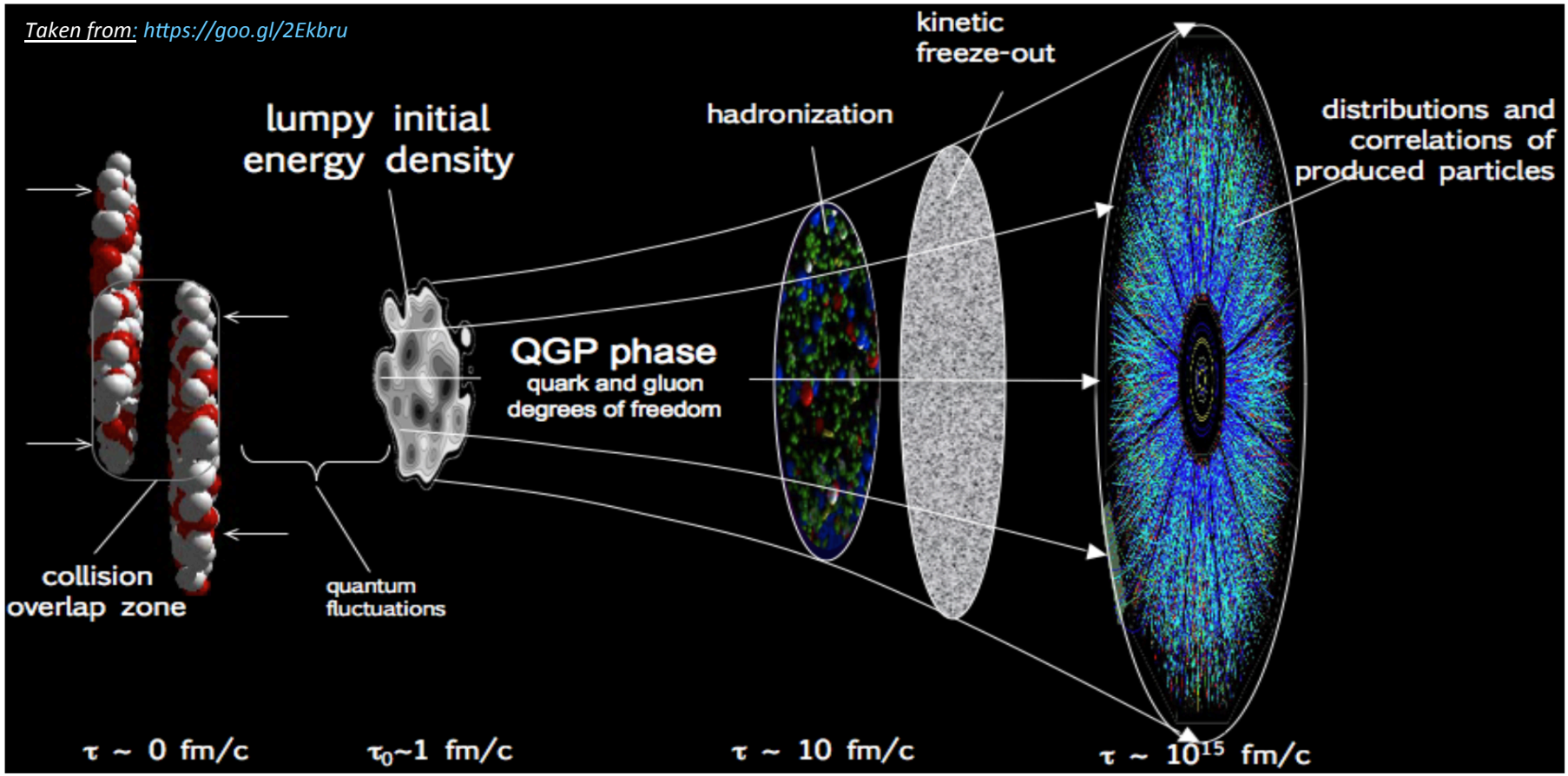
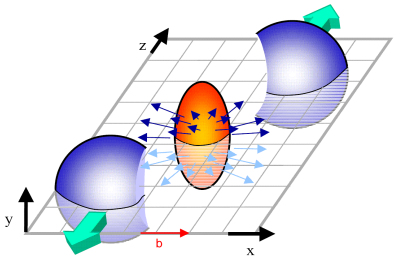


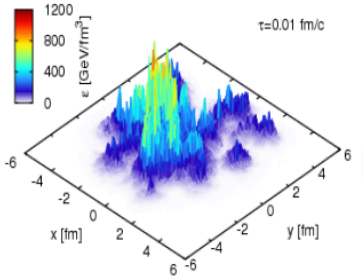
Hydrodynamic evolution

Perfect fluid paradigm

Initial state



$$\varepsilon(x, y, \eta^s)$$



Perfect fluid paradigm

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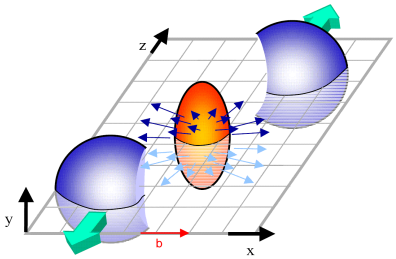

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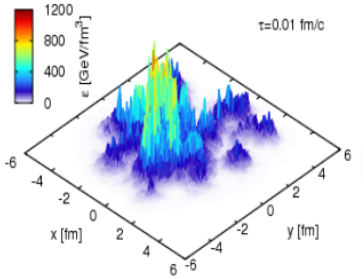


Event by Event

Pre-equilibrium

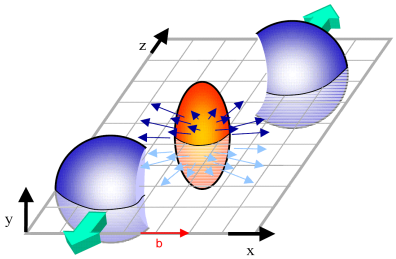
Hydrodynamics
$\delta_\mu T^{\mu\upsilon} = 0 + (\eta, \zeta, \ldots)$

Freeze-out
Hadronic transport

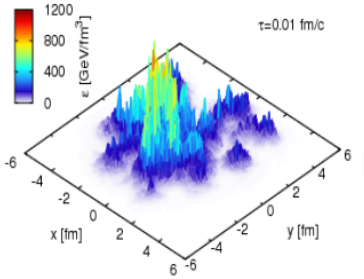
QGP behave like a nearly perfect fluid
(small η/s)

Perfect fluid paradigm

Initial state



$\varepsilon(x, y, \eta^s)$



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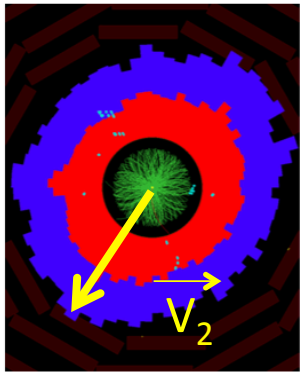
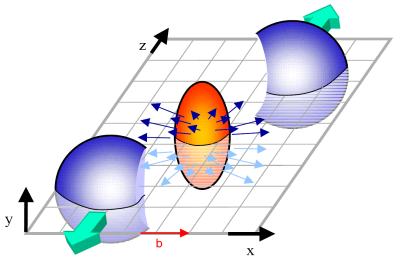
Final state

$f(p_T, \eta, \phi)$

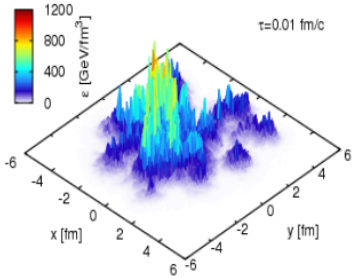


Perfect fluid paradigm

Initial state | **Event by Event** | **Final state**



$\varepsilon(x, y, \eta^s)$



Pre-equilibrium

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Freeze-out
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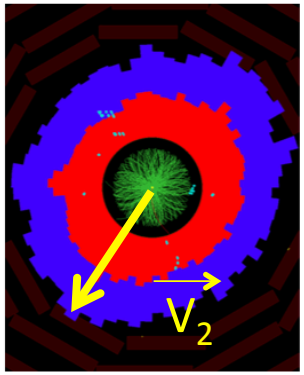
$f(p_T, \eta, \phi)$



QGP behave like a nearly perfect fluid

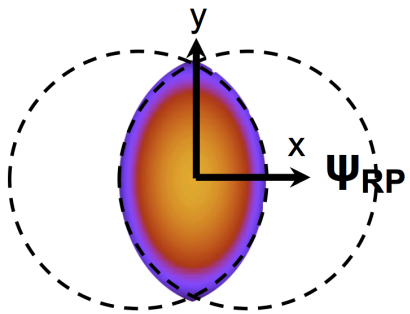
(small η/s)

Fourier bases: $$f(p_T, \eta, \phi) = N(p_T, \eta) \sum_{n=-\infty}^{+\infty} \underbrace{\vec{V}_n(p_T, \eta)} e^{-in\phi}$$

Anisotropic flow

$$\vec{V}_n = v_n e^{in\Psi_n}$$

What does this flow harmonic coefficients means?



Initial-state anisotropy

Flow

≈

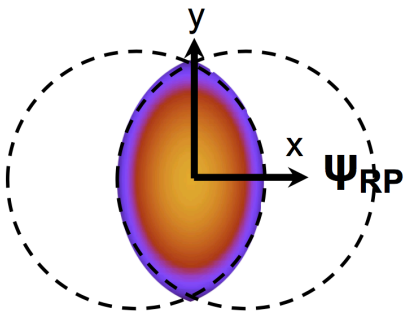
Geometry

Final state:

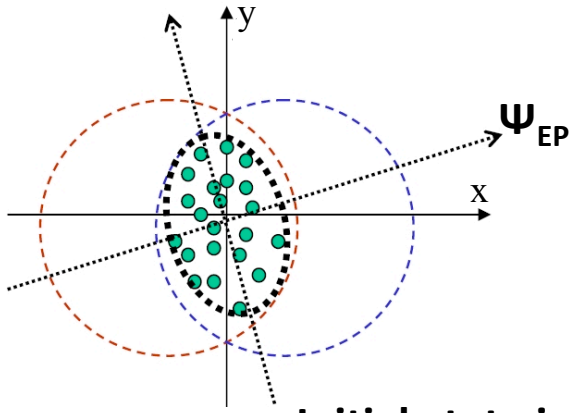
$$f(p_T, \phi, \eta) \sim 1 \quad + 2\boxed{v_2(p_T, \eta)} cos\left[2(\phi - \Psi_2)\right]$$

Elliptic flow

What does this flow harmonic coefficients means?



Initial-state anisotropy



Initial-state inhomogeneity

Flow

≈

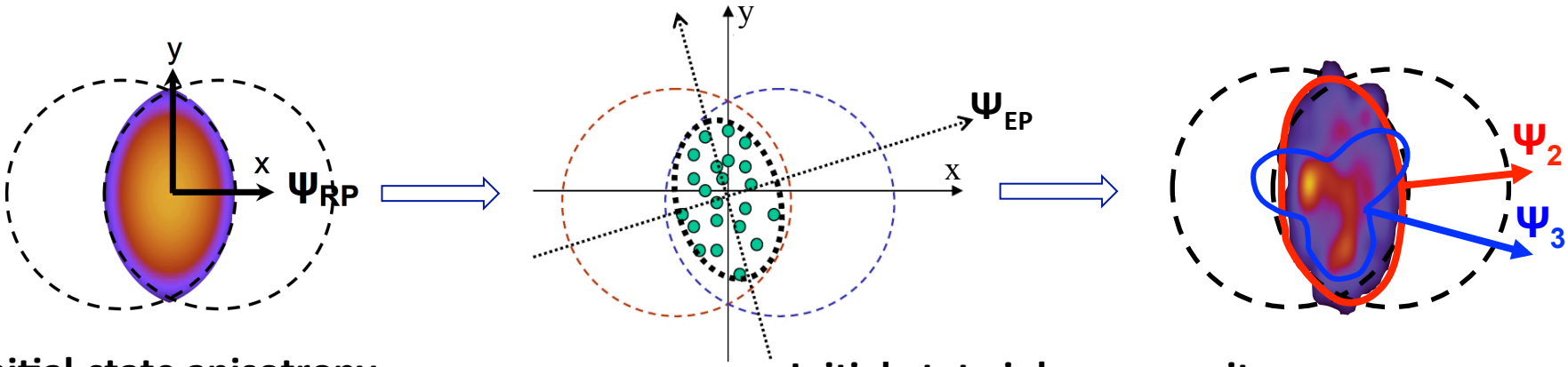
Geometry

Ψ_{EP}: Direction of maximum particle density

Final state:

$$f(p_T, \phi, \eta) \sim 1 \quad +2v_2(p_T, \eta)cos\left[2(\phi - \Psi_2)\right]$$

What does this flow harmonic coefficients means?



Initial-state anisotropy

Initial-state inhomogeneity

Flow

≈

Geometry

+

Fluctuations

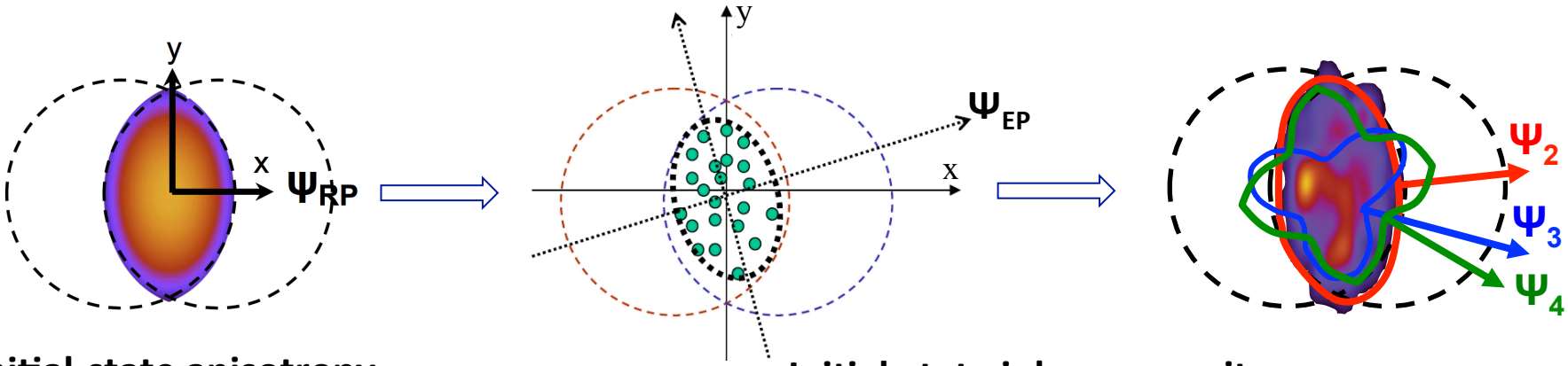
Ψ_{EP}: Direction of maximum particle density

Final state:

$$f(p_T, \phi, \eta) \sim 1 \quad +2v_2(p_T, \eta)cos\left[2(\phi - \Psi_2)\right] \\ +2\boxed{v_3(p_T, \eta)}cos\left[3(\phi - \Psi_3)\right]$$

Triangular flow

What does this flow harmonic coefficients means?



Initial-state anisotropy

Initial-state inhomogeneity

Flow

≈

Geometry

+

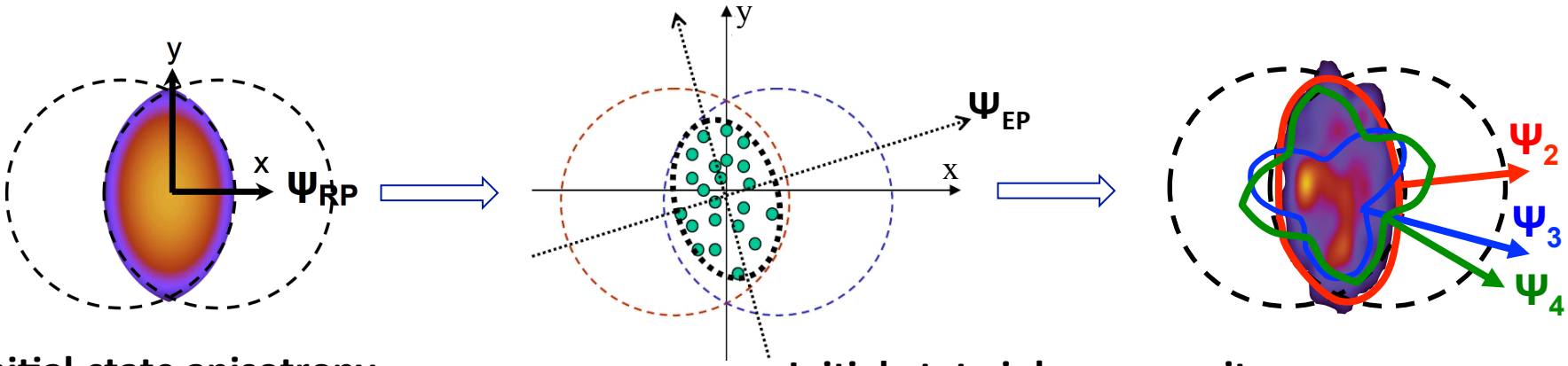
Fluctuations

Ψ_{EP}: Direction of maximum particle density

Final state:

$$f(p_T,\phi,\eta) \sim 1 \quad +2v_2(p_T,\eta)cos\left[2(\phi-\Psi_2)\right] +2v_3(p_T,\eta)cos\left[3(\phi-\Psi_3)\right] +2v_4(p_T,\eta)cos\left[4(\phi-\Psi_4)\right] +2v_5(p_T,\eta)cos\left[5(\phi-\Psi_5)\right] +\ldots$$

What does this flow harmonic coefficients means?

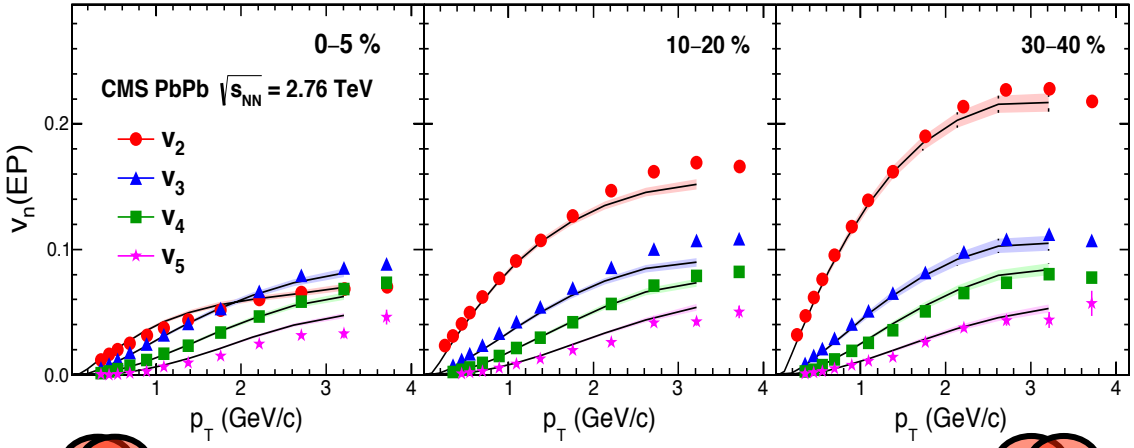


Initial-state anisotropy

Initial-state inhomogeneity

In AA, Rather good understanding of:

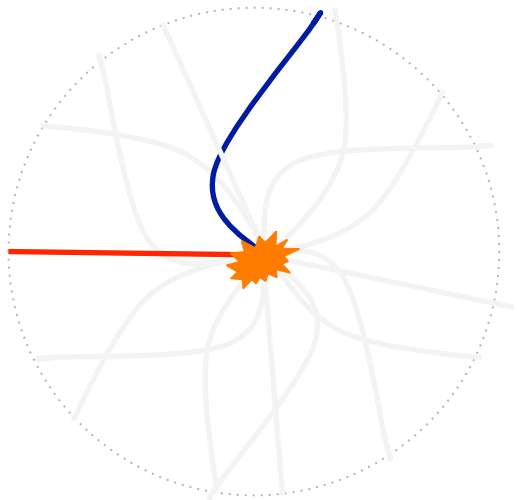
- Initial state geometry
- Initial state fluctuations
- Medium transport coefficients (η/s, …)



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

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

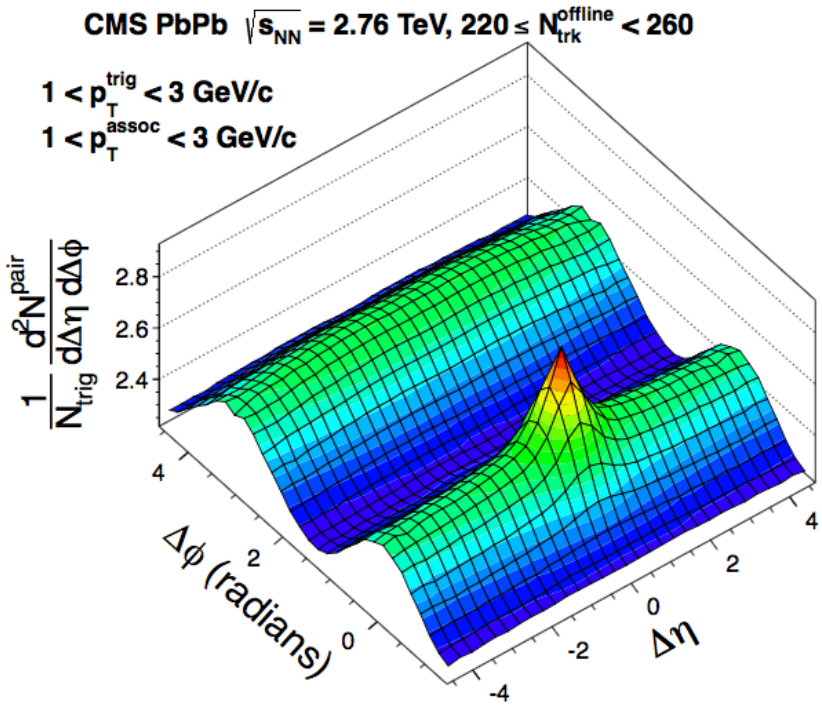
How do we measure this flow coefficients in AA?



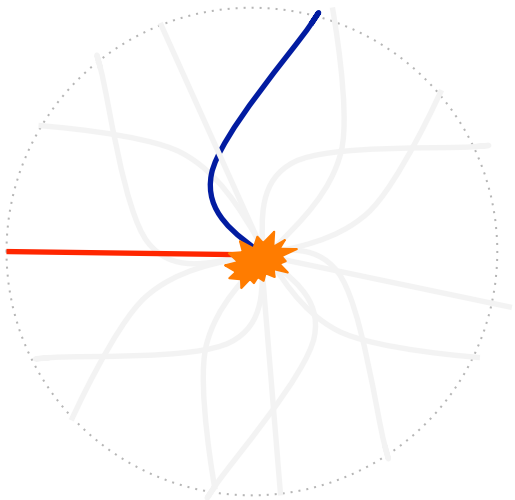
Particle 1
(η_1, φ_1)

Particle 2
(η_2, φ_2)

$$\Delta\eta = \eta_1 - \eta_2$$
$$\Delta\varphi = \varphi_1 - \varphi_2$$



How do we measure this flow coefficients in AA?



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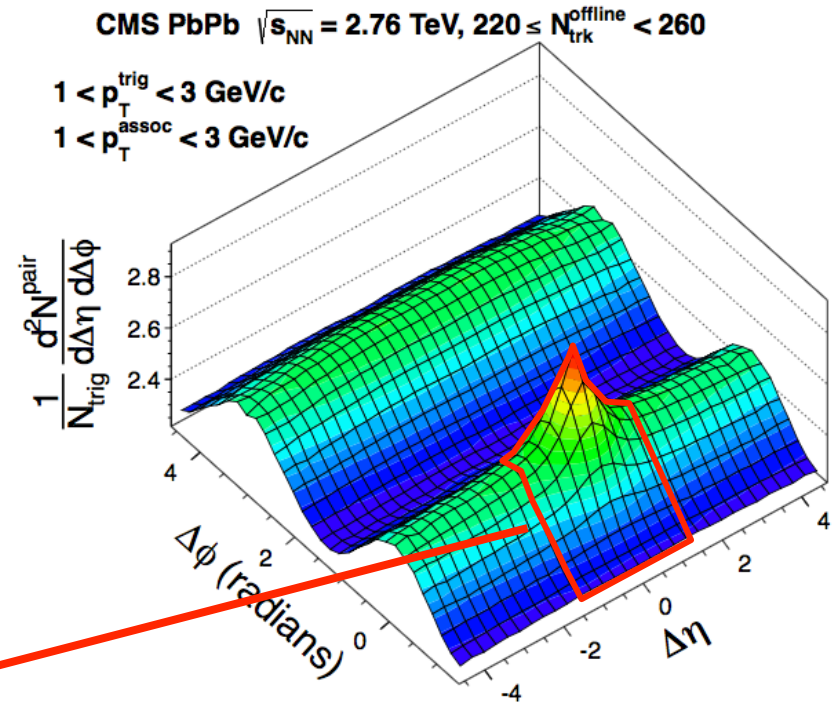
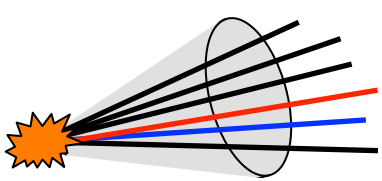
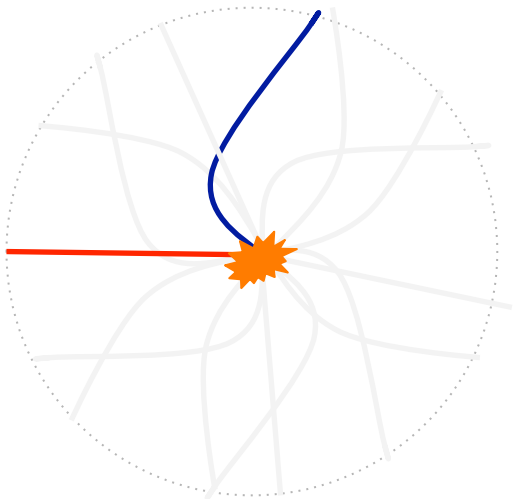




Single jet contribution

How do we measure this flow coefficients in AA?



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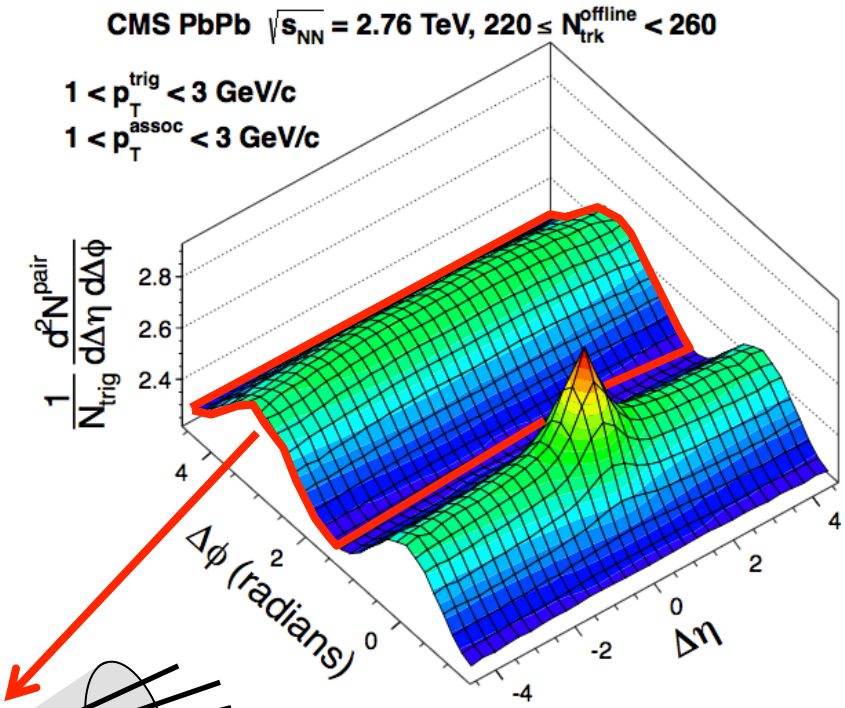
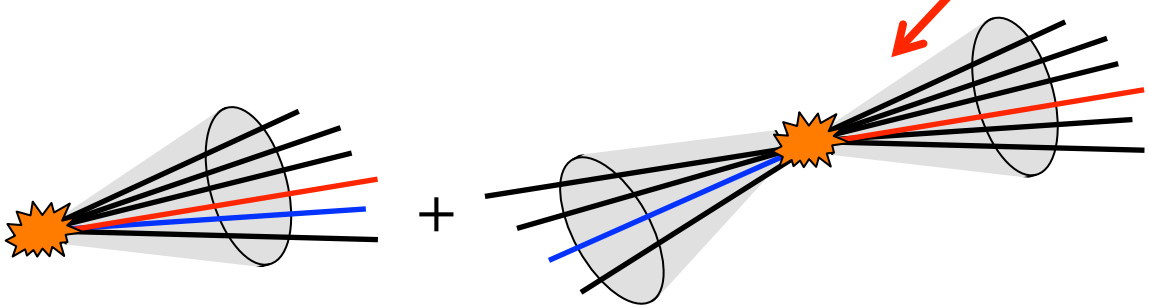
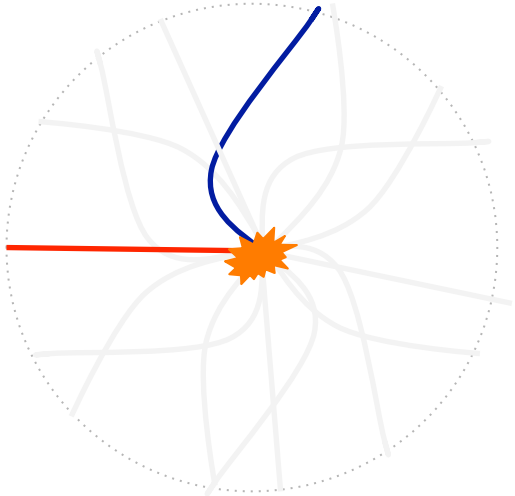




Single jet contribution **Back-to-back jet contribution**

How do we measure this flow coefficients in AA?



Particle 1
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Particle 2
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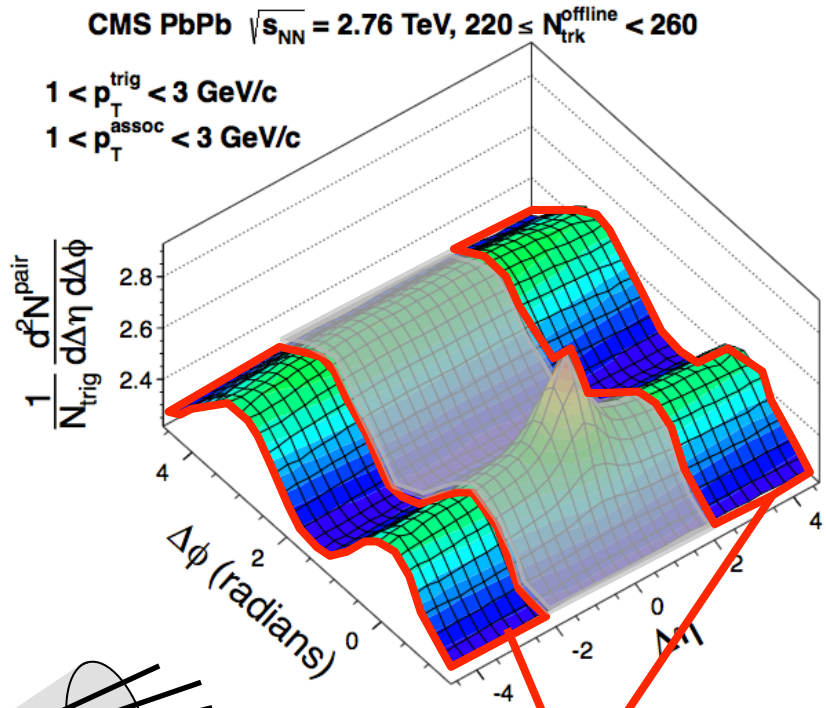
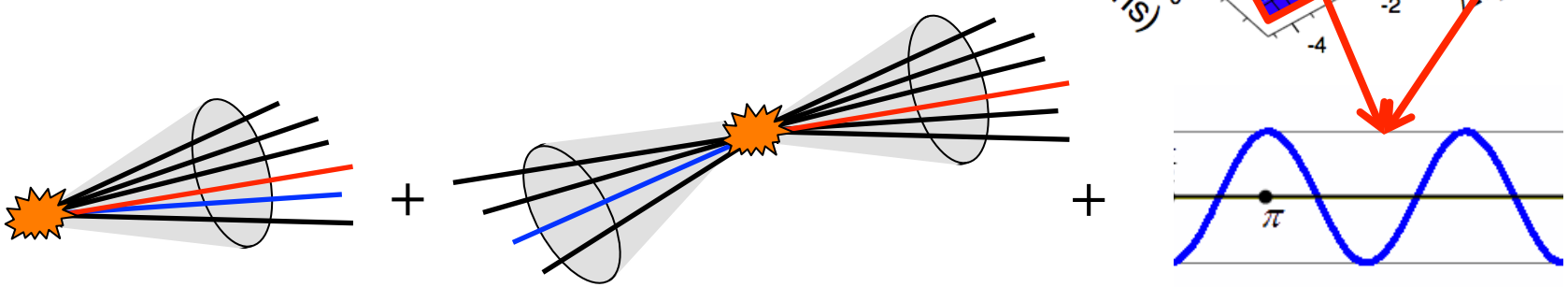
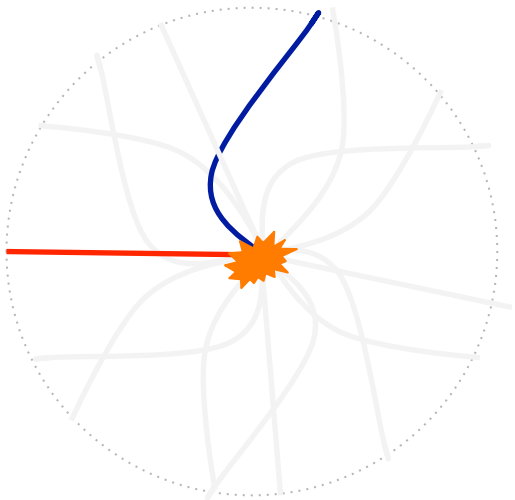




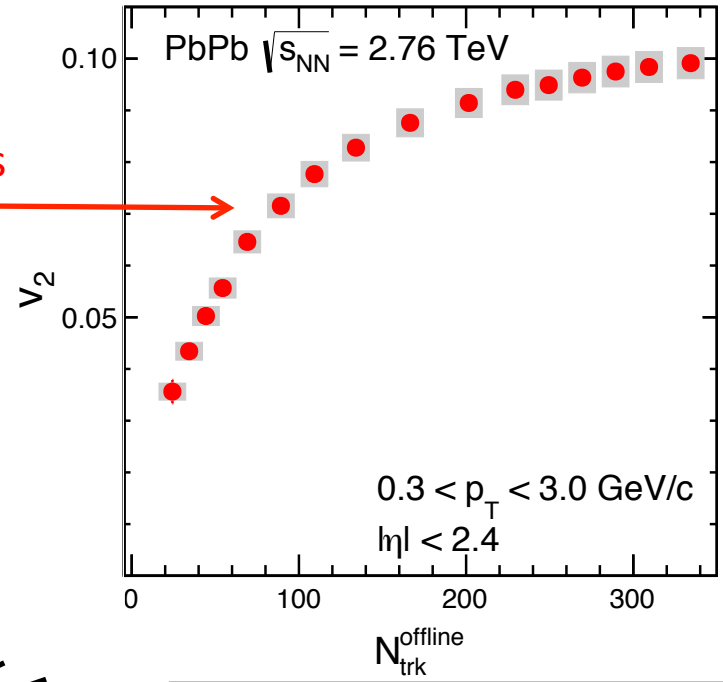
Single jet contribution | Back-to-back jet contribution | Collective effect

How do we measure this flow coefficients in AA?



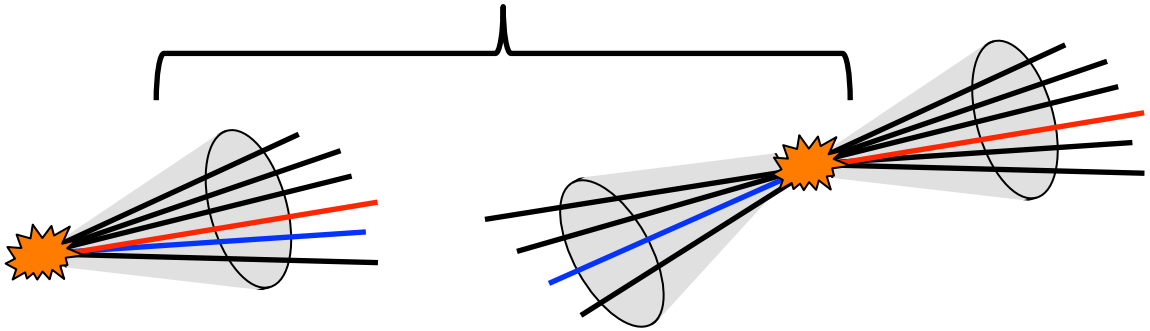
2 particle correlations

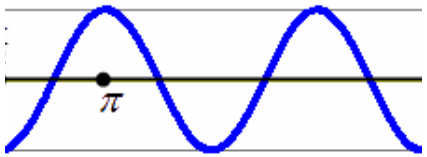
$v_2\{2\}$



PhysLettB.2016.12, 009

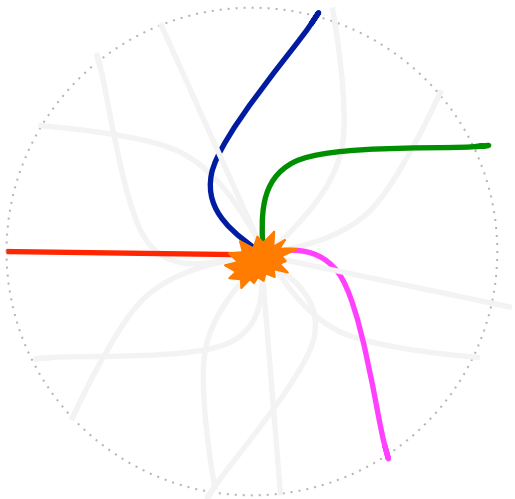
Corrections applied



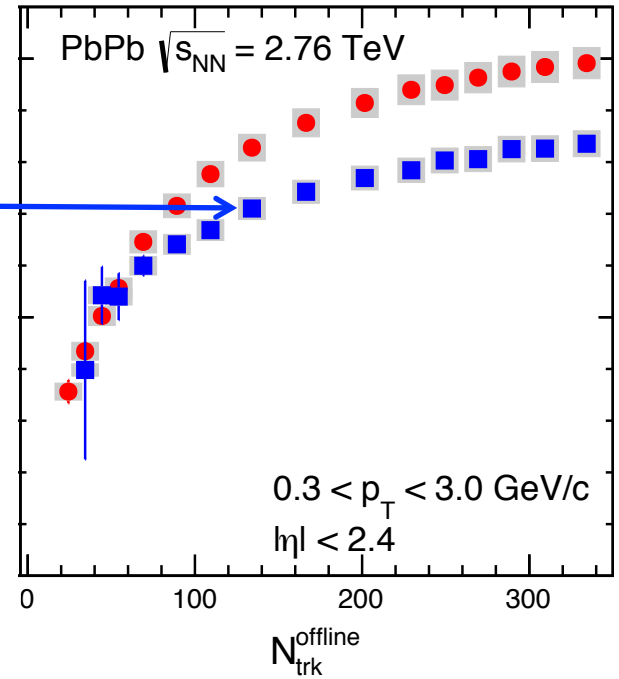


Single jet contribution **Back-to-back jet contribution** **Collective effect**

Study collectivity using multi-particle measurements



4 particle correlations



- Less sensitive to non-flow (i.e. jet induced correlation)
- Needs larger sample of events

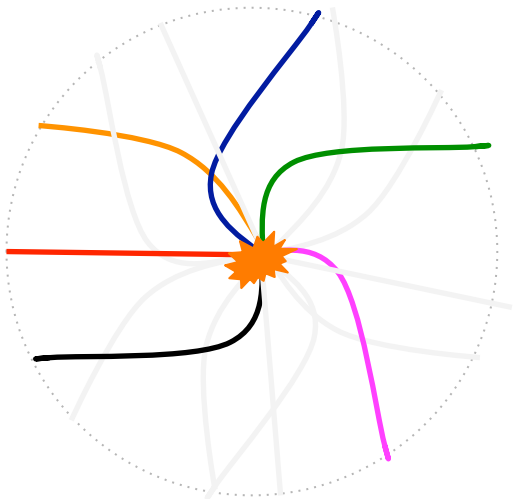
PhysLettB.2016.12, 009

$$\langle 4 \rangle = \frac{1}{P_{M,4}} \sum_{i,j,k,l} e^{in(\phi_i+\phi_j-\phi_k-\phi_l)},$$

$$P_{M,4} = \frac{M!}{4!(M-4)!}$$

$$c_n\{4\} = \langle\langle 4 \rangle\rangle - 2\langle\langle 2 \rangle\rangle^2, \qquad v_n\{4\} = \sqrt[4]{-c_n\{4\}}$$

Study collectivity using multi-particle measurements

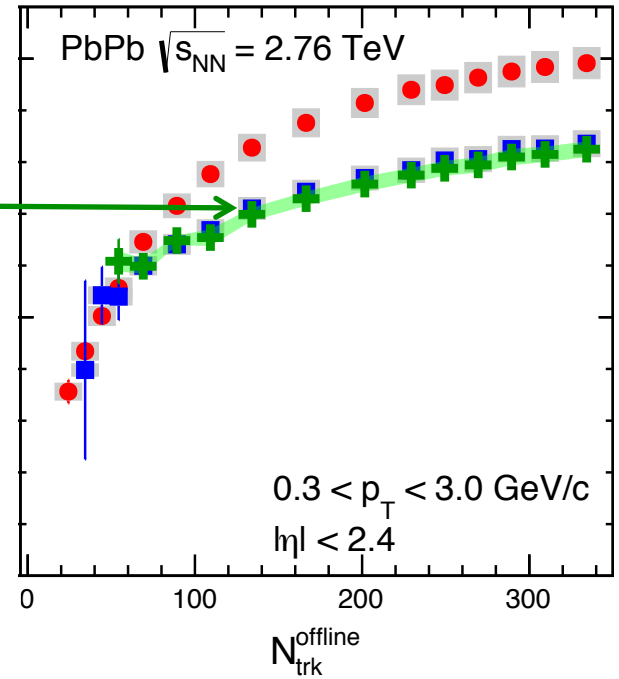


6 particle correlations

$v_2\{6\}$

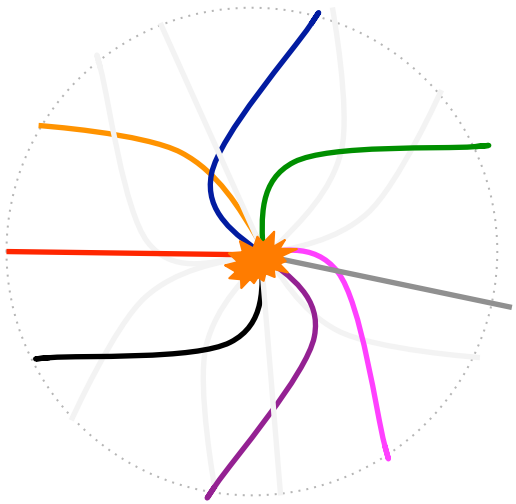
- Less sensitive to non-flow (i.e. jet induced correlation)
- Needs larger sample of events

$$v_n\{6\} = \sqrt[4]{\frac{1}{4} c_n\{6\}}$$



PhysLettB.2016.12, 009

Study collectivity using multi-particle measurements

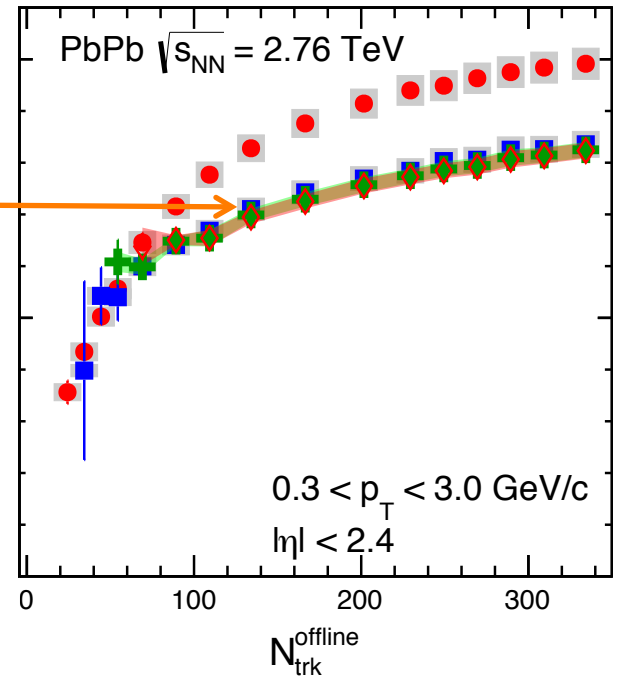


8 particle correlations

$v_2\{8\}$

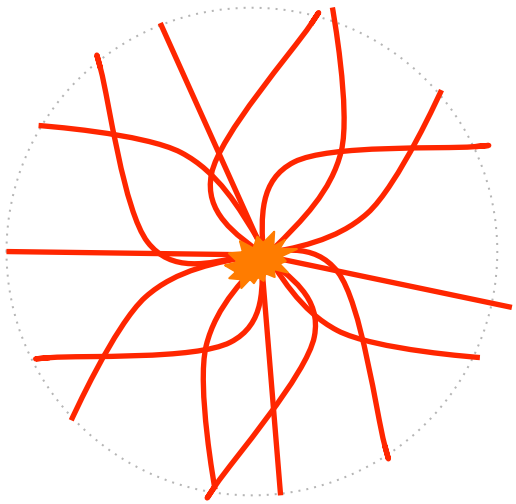
- Less sensitive to non-flow (i.e. jet induced correlation)
- Needs larger sample of events

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



PhysLettB.2016.12, 009

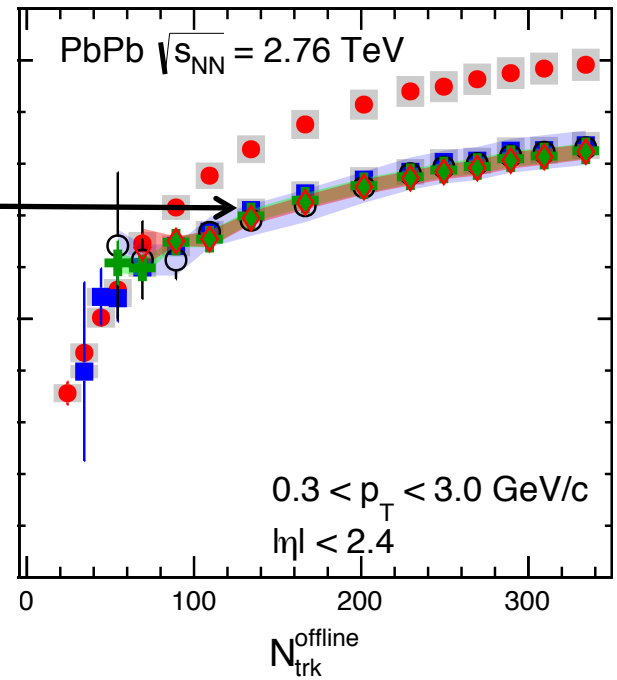
Study collectivity using multi-particle measurements



All particles

$v_2\{LYZ\}$

- Less sensitive to non-flow (i.e. jet induced correlation)
- Needs larger sample of events



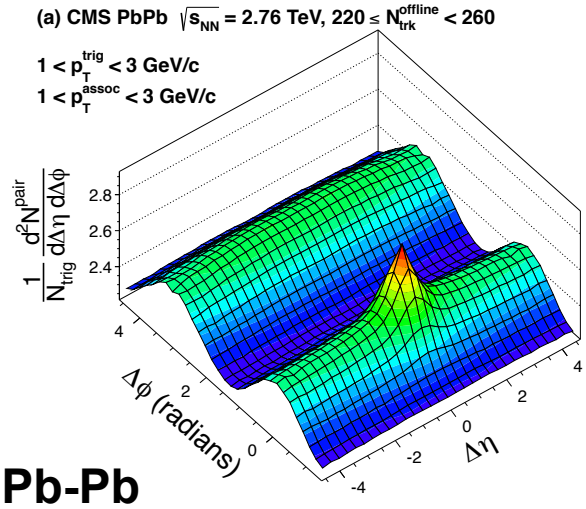
PhysLettB.2016.12, 009

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

Small system puzzle

Hydro behavior in A-A:

- Long-range correlation (Ridge)
- Collective behavior



Pb-Pb

PLB (2013) 06, 028

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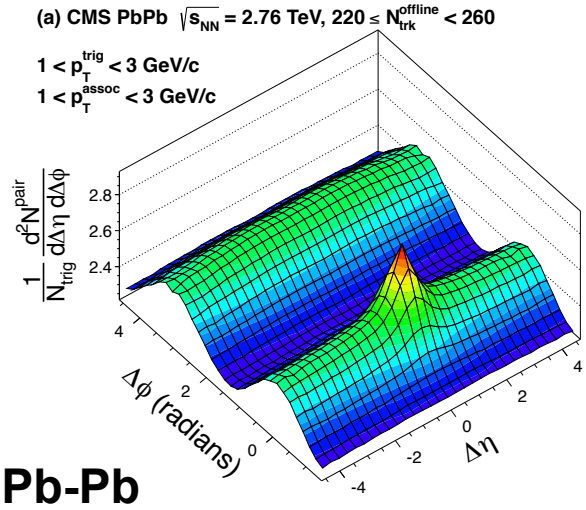
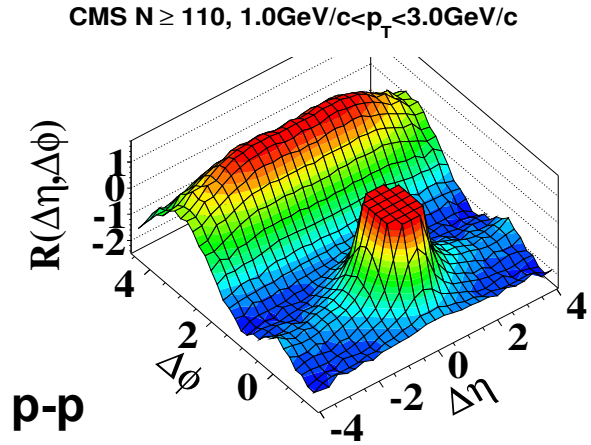


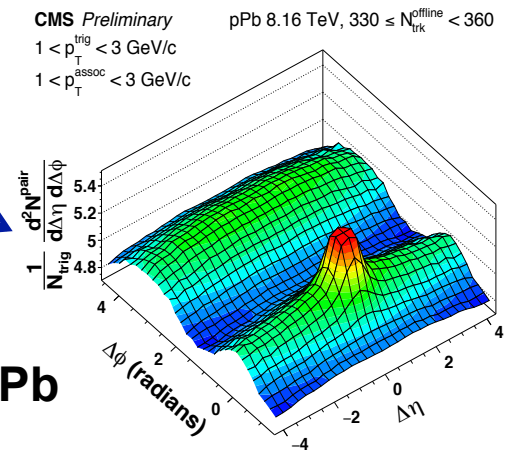
Pb-Pb

PLB (2013) 06, 028

Ridge observed in small systems



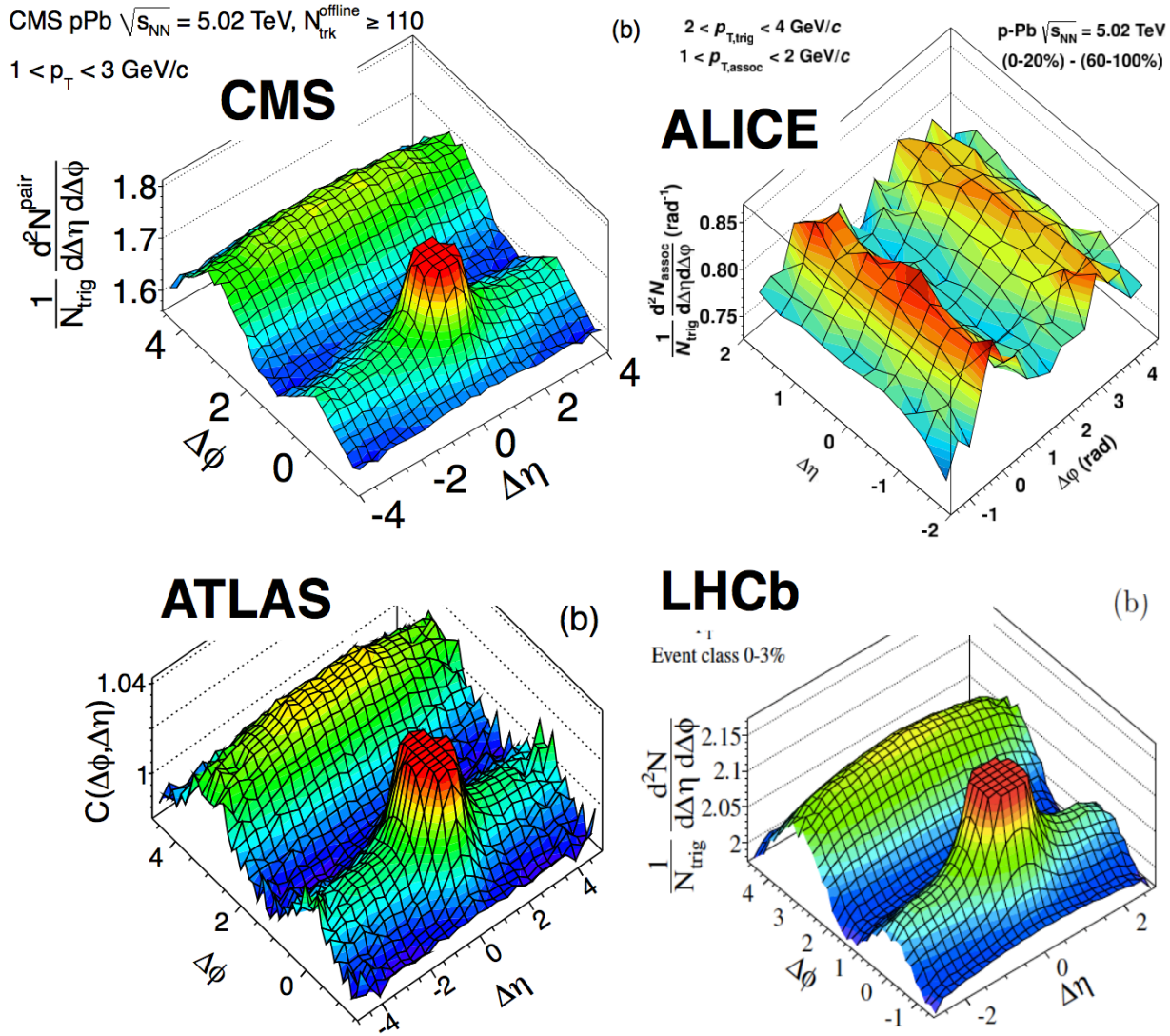
p-p



p-Pb

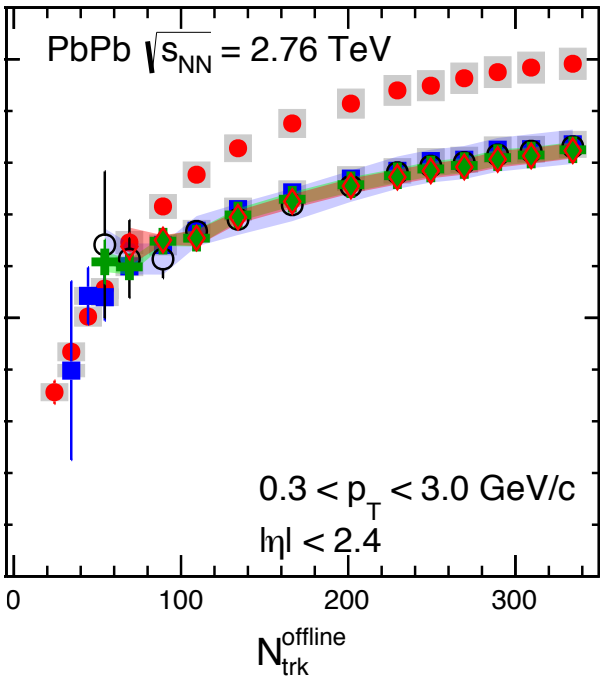
PRL (2018)120, 092301

Ridge tsunami at LHC and RHIC



Ridge observation at various energies and for very different system sizes

Measurement of v_n coefficients



PhysLettB.2016.12, 009

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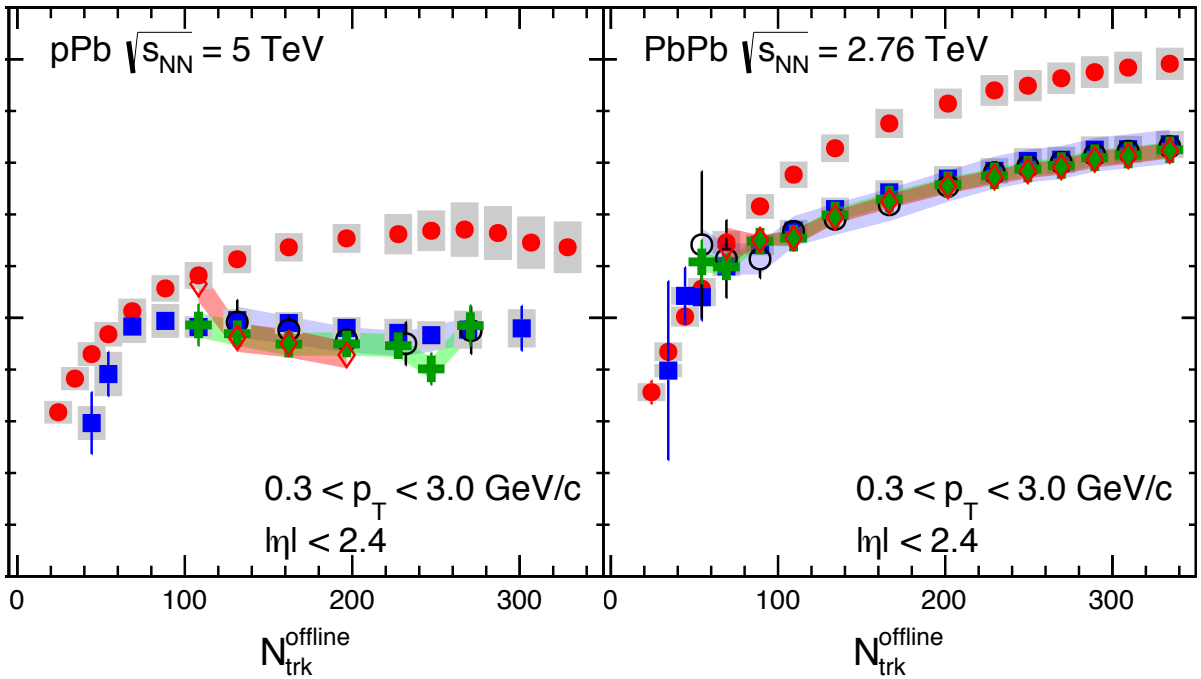

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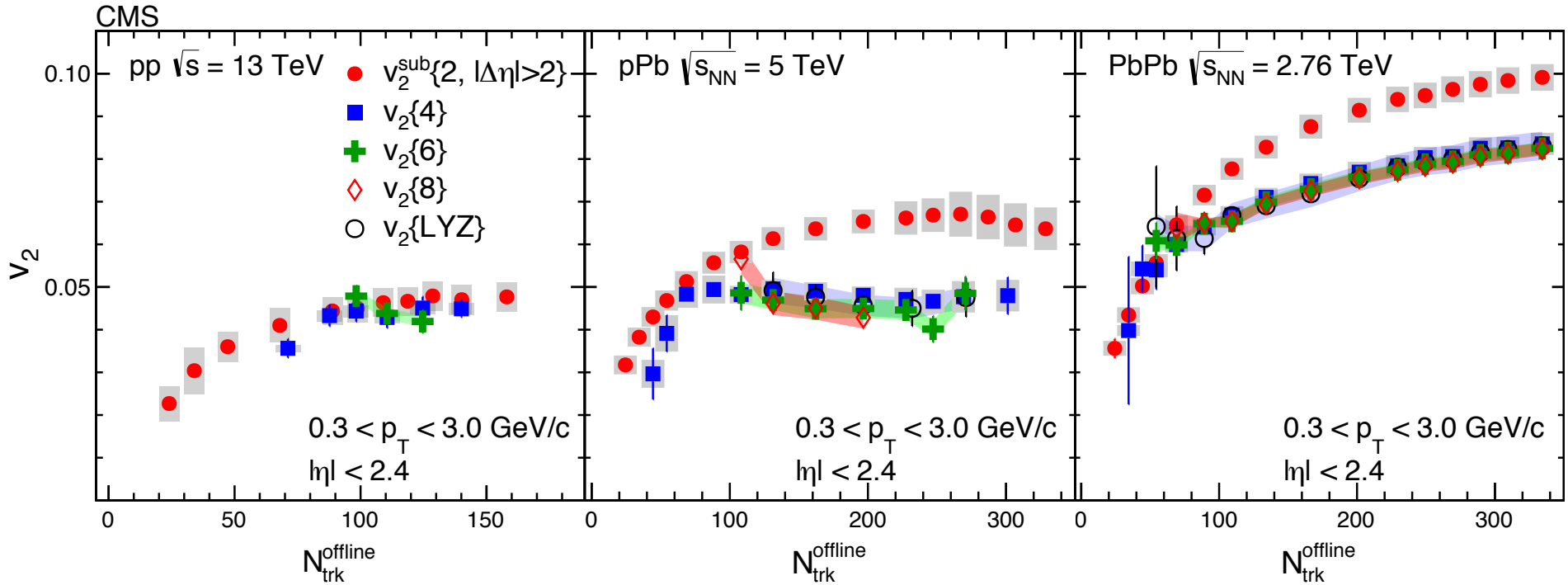


PhysLettB.2016.12, 009

- Collectivity: $v_2\{2\} \approx v_2\{4\} \approx v_2\{6\}$

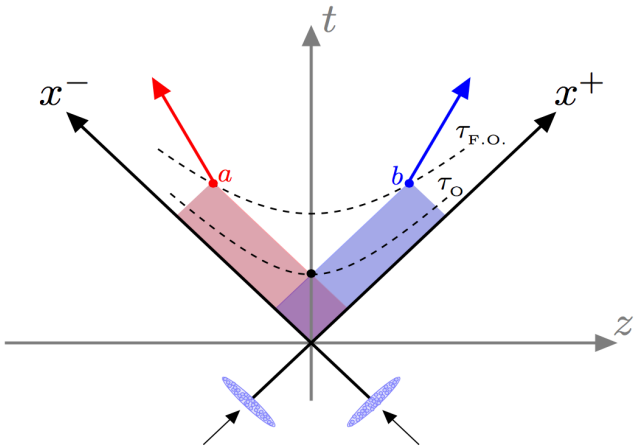
What do we learn here?

Data interpretation: 2 scenarii

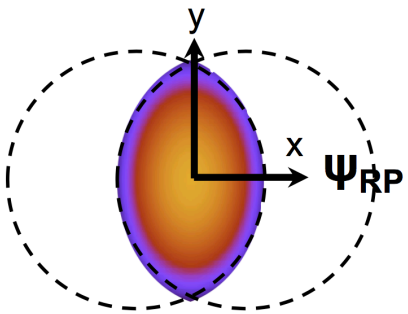
Observed long-range correlations in η

Rooted in **intial/early** stage

$$\tau_O \leq \tau_{F.O.} \exp\left(-\frac{1}{2}|y_a - y_b|\right)$$ **~ 0.1 fm/c**

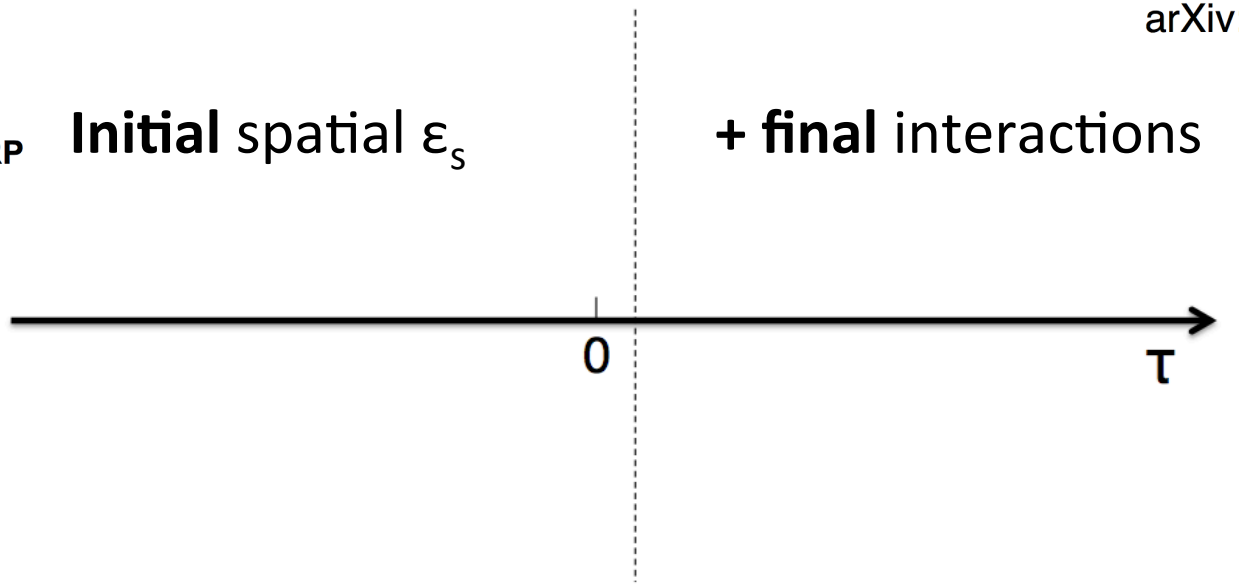


arXiv:1509.07939



Initial spatial ε_s

+ final interactions



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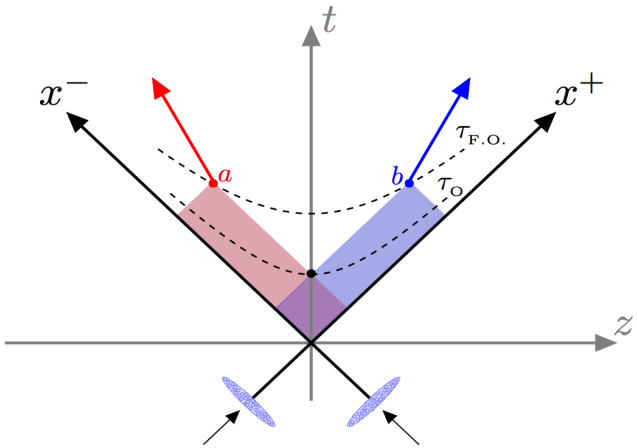

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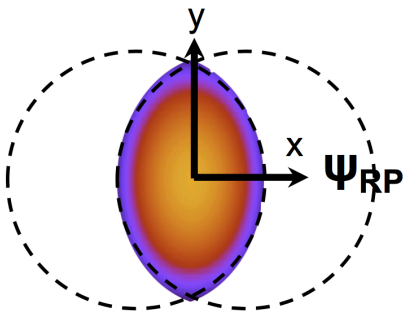

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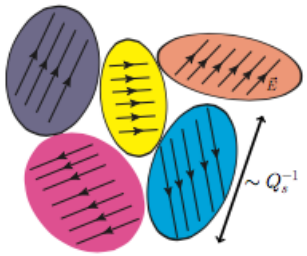

0

τ

Initial spatial ε_p
by initial interactions

Data interpretation: 2 scenarii

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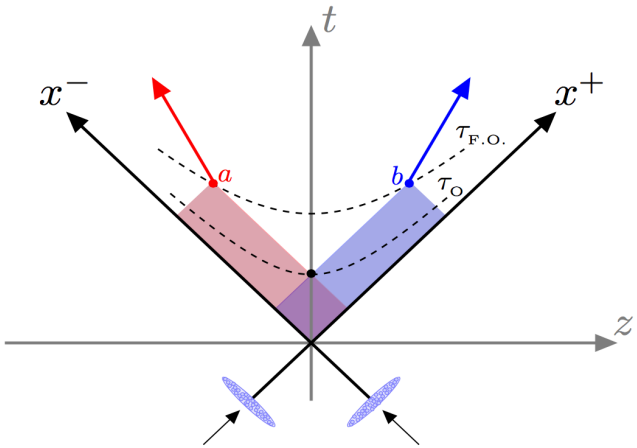

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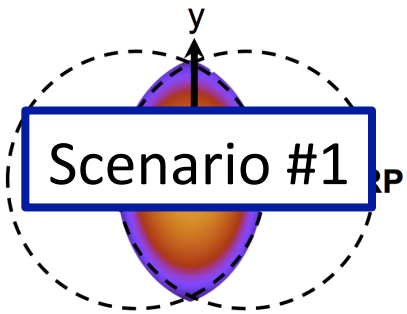


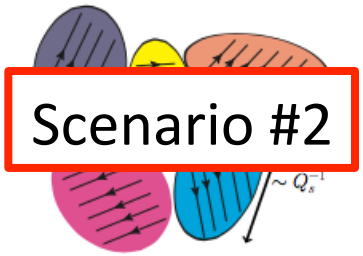
Scenario #1

Initial spatial ε_s **+ final** interactions

Hydrodynamics

Parton transport, escape

0 τ



Scenario #2

Initial spatial ε_p by initial interactions

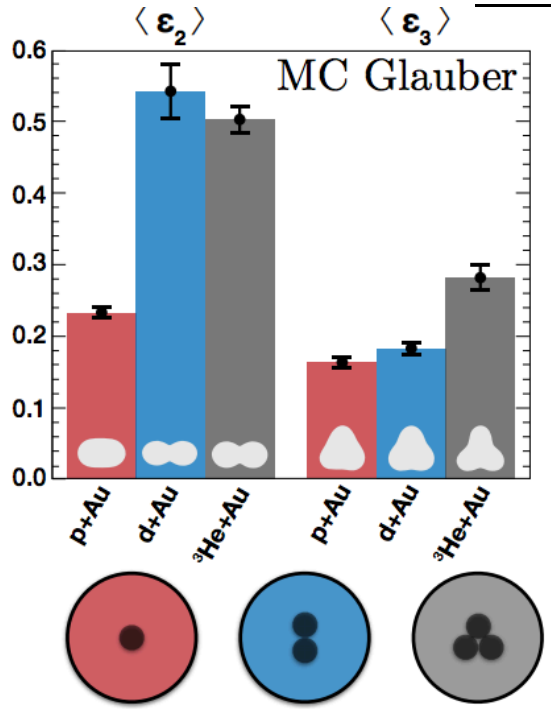
CGC Glasma

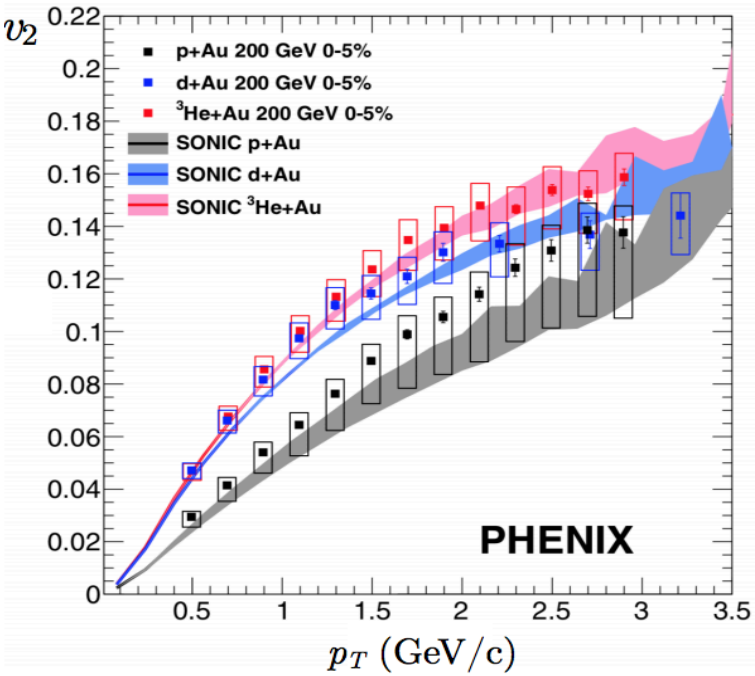
Color-field domains, etc.

Comparison with different scenarii…

- First try from PHENIX to differentiate scenarii
  - Seems to favor hydro-like description
- Nevertheless, quick answer from IS model (color domains) appeared showing similar feature

arXiv:1805.029773





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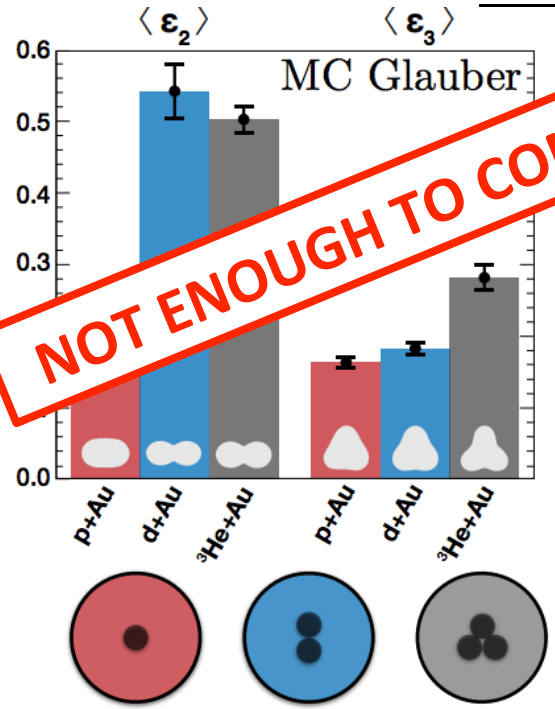
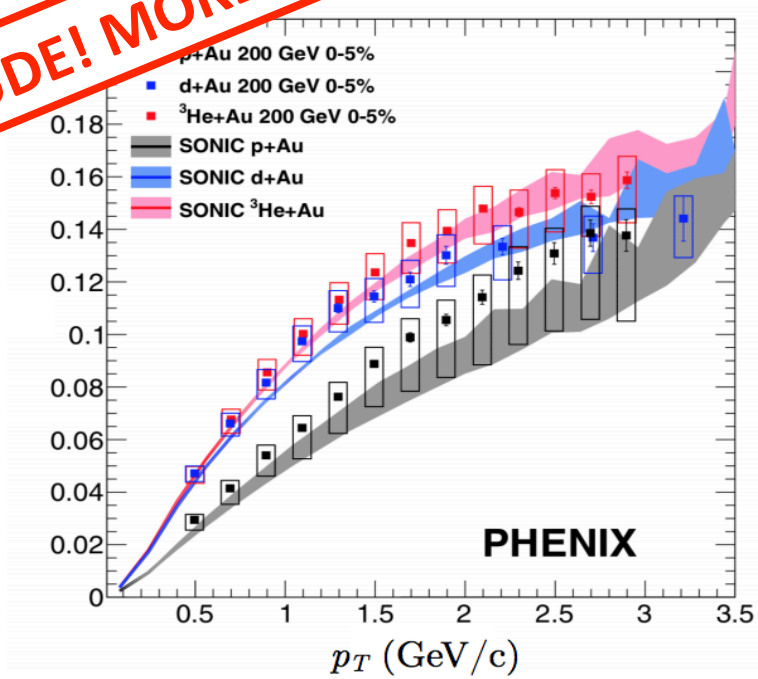
arXiv:1805.029772

NOT ENOUGH TO CONCLUDE! MORE DETAILS NEEDED





Correlation between harmonics

Study correlation between harmonics (n,m)

- Via **S**ymmetric **C**umulants (**SC**) PRL (2016) 117, 182301

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

- Based on 4-particle cumulant calculations

Sensitive to:

- IS fluctuations
- Medium transport coefficient

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- Based on 4-particle cumulant calculations

Sensitive to:

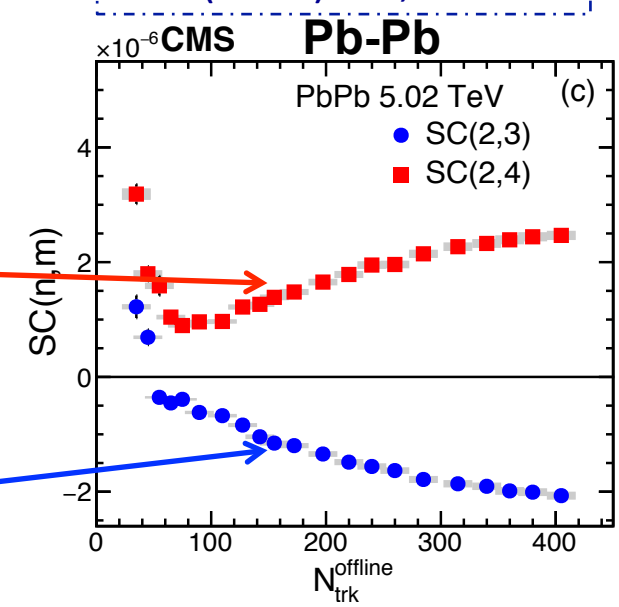
- IS fluctuations
- Medium transport coefficient

Results in Pb-Pb:

SC(2,4): v_2, v_4 correlated

SC(2,3): v_2, v_3 anti-correlated

PRL (2018)120, 092301

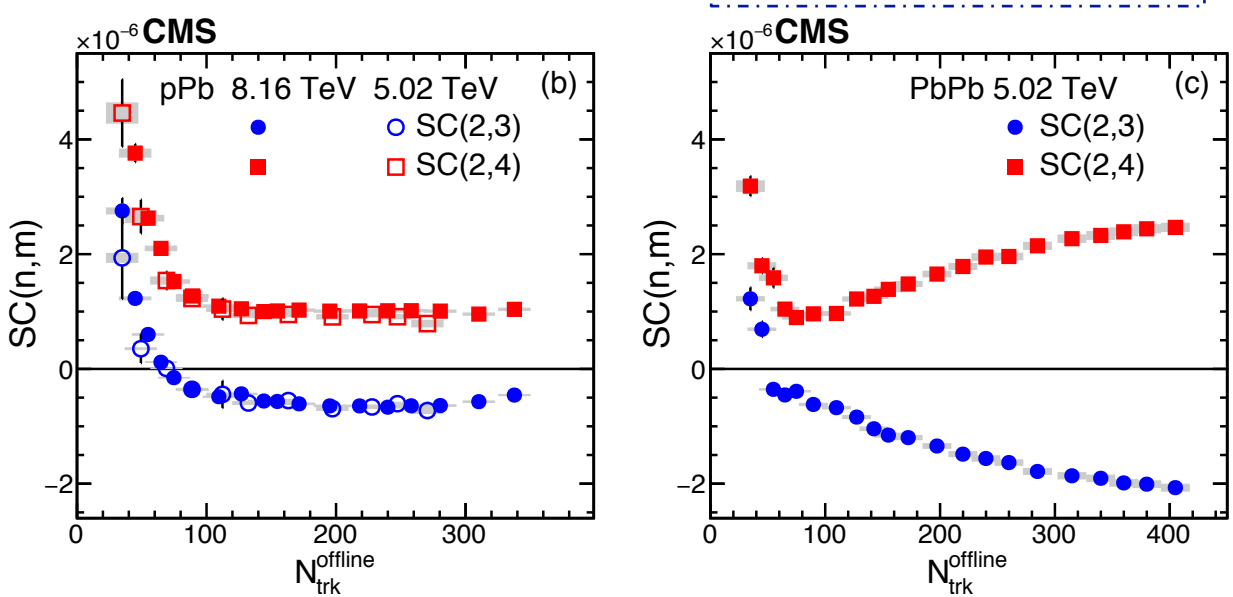


The small system case

Similarities observed for SCs in all systems

- (v_2, v_3) uncorrelated
- (v_2, v_4) correlated
- Small energy dependence (see p-Pb results)

PRL (2018)120, 092301



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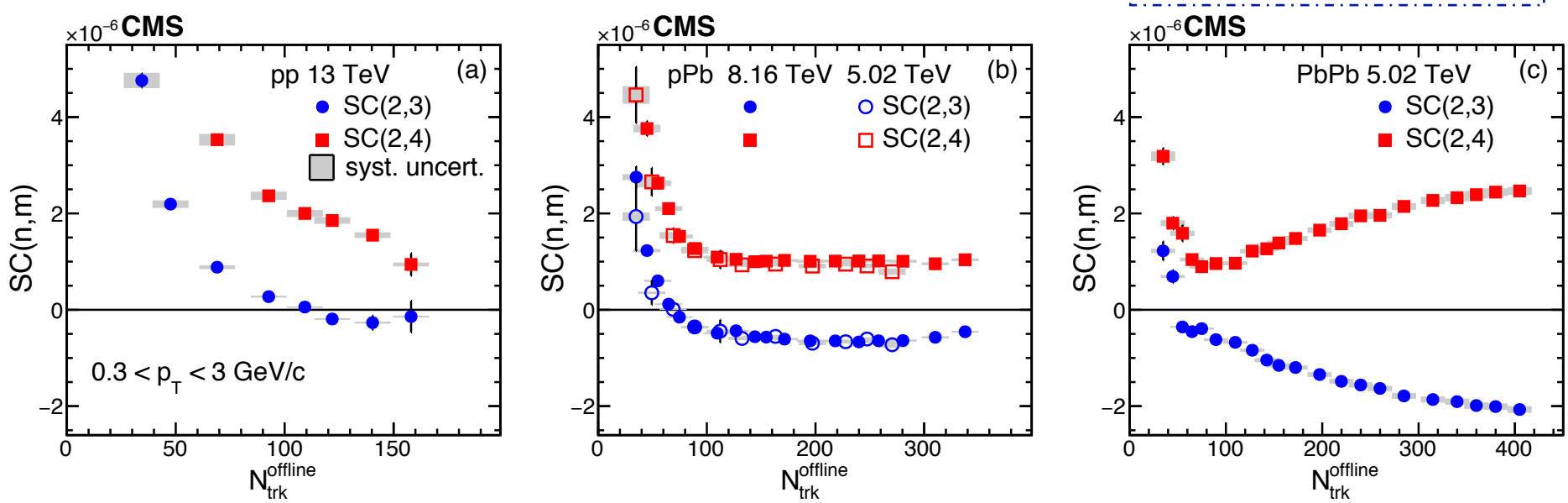

The small system case

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- (v_2, v_4) correlated
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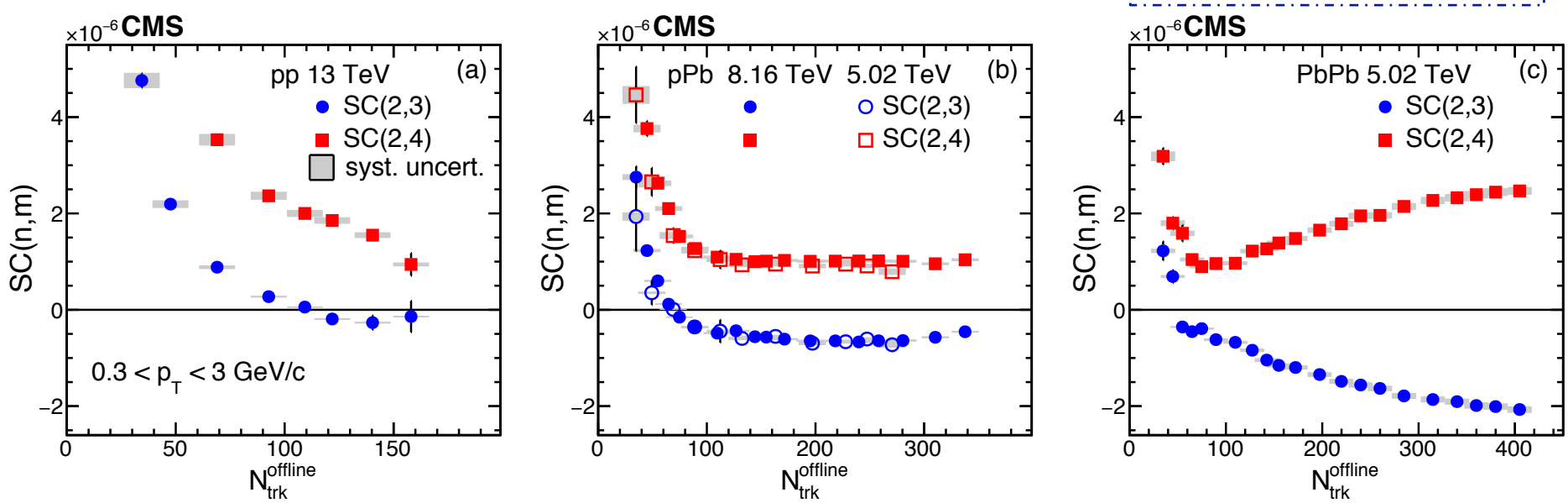
In general, v_n(p-p) ≠ v_n(p-Pb) ≠ v_n(Pb-Pb)

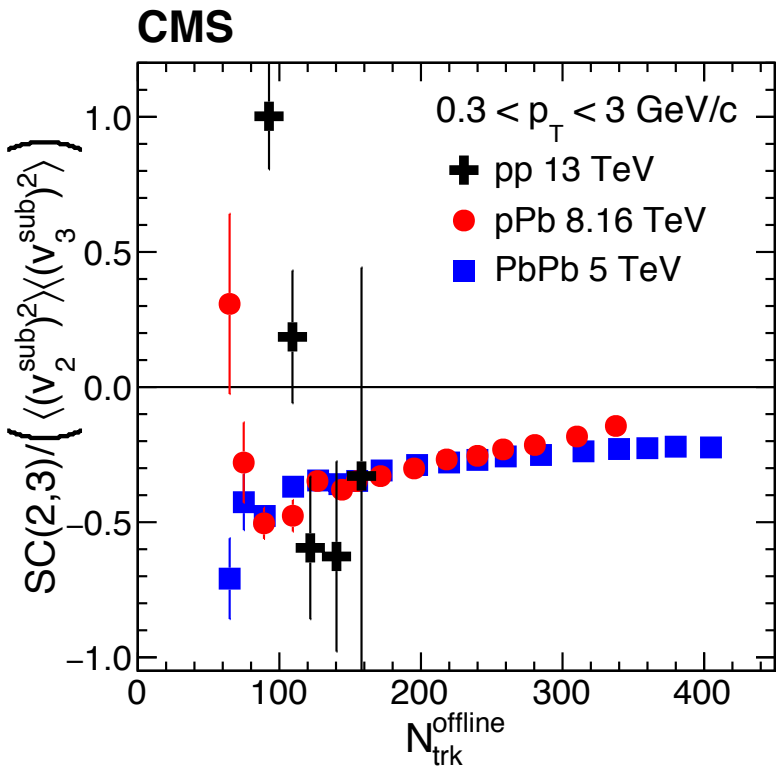
- Normalization needed for comparison

PRL (2018)120, 092301



Normalized SC (NSC)

PRL (2018)120, 092301

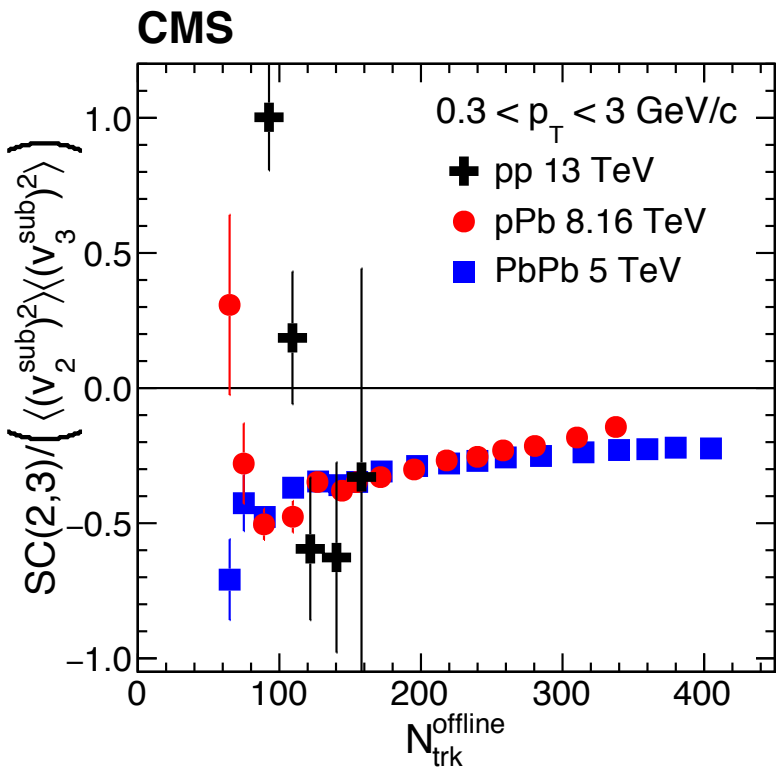


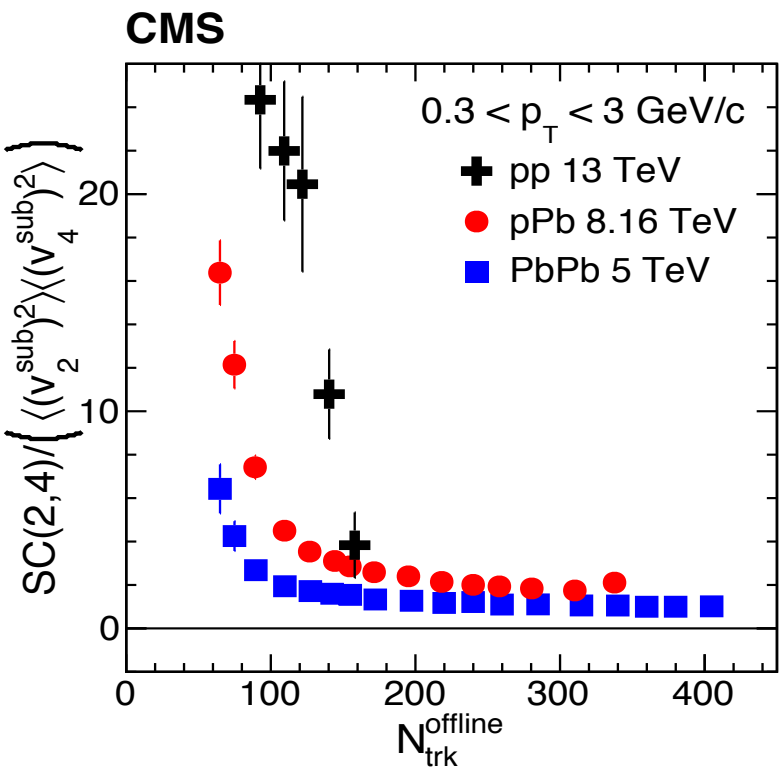
- Similar behavior in p-Pb and Pb-Pb
- Points to similar IS fluctuations

Common paradigm?

Normalized SC (NSC)

PRL (2018)120, 092301





- Similar behavior in p-Pb and Pb-Pb
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Common paradigm?

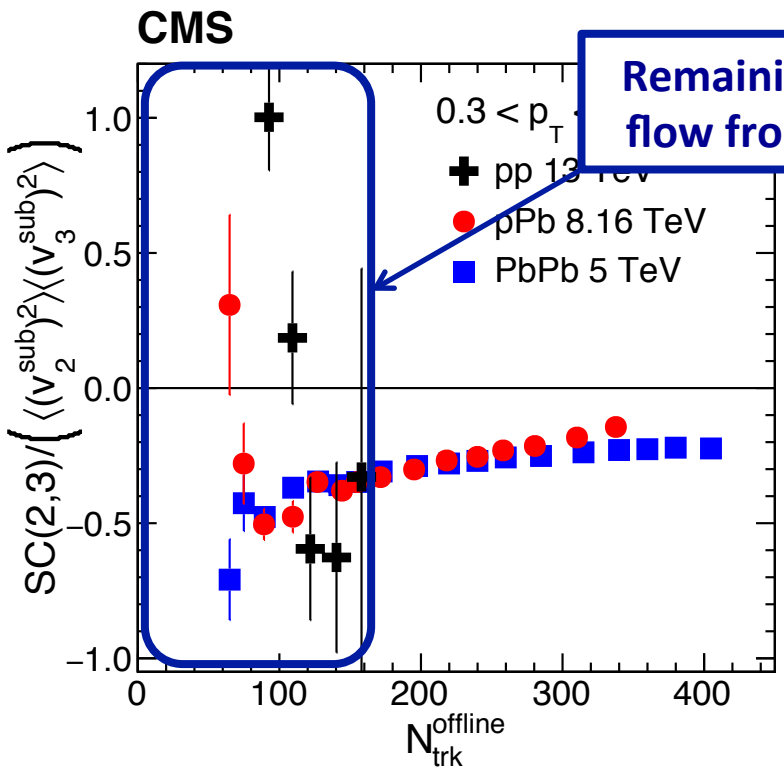
- Ordering observed:

  p-p > p-Pb > Pb-Pb

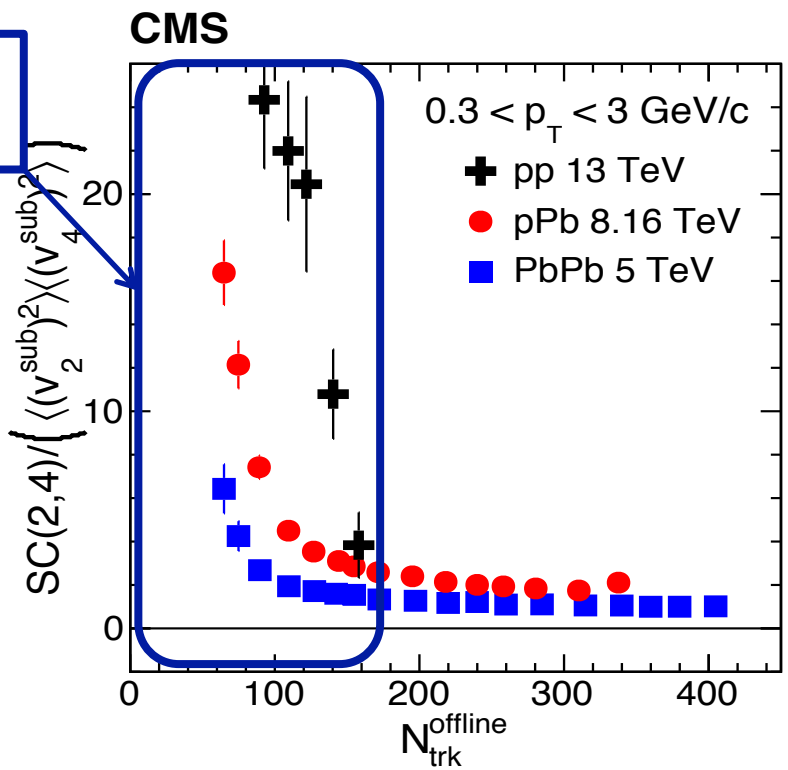
What is the origin?

Normalized SC (NSC)

PRL (2018)120, 092301



Remaining non-flow from jets!



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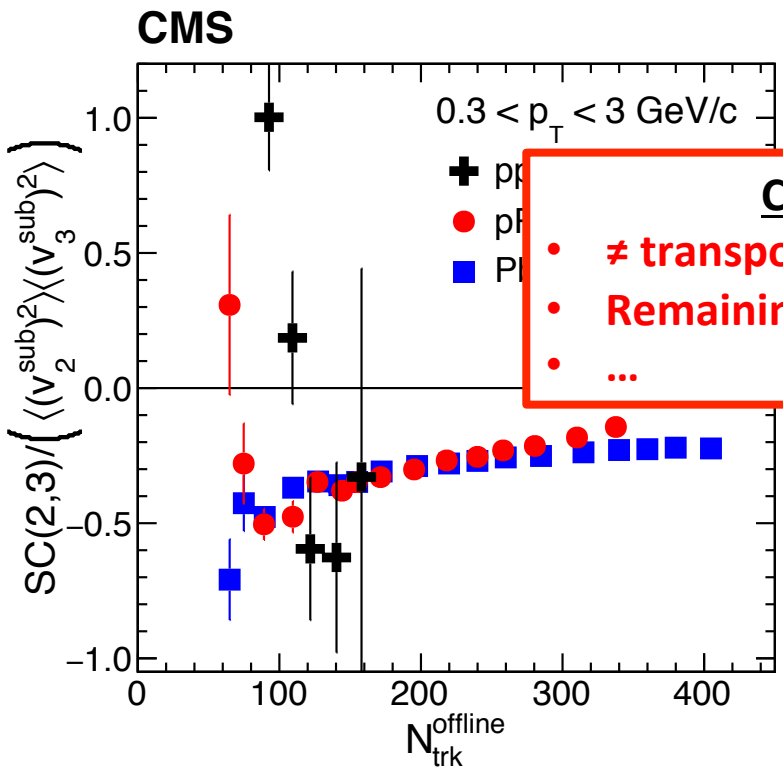
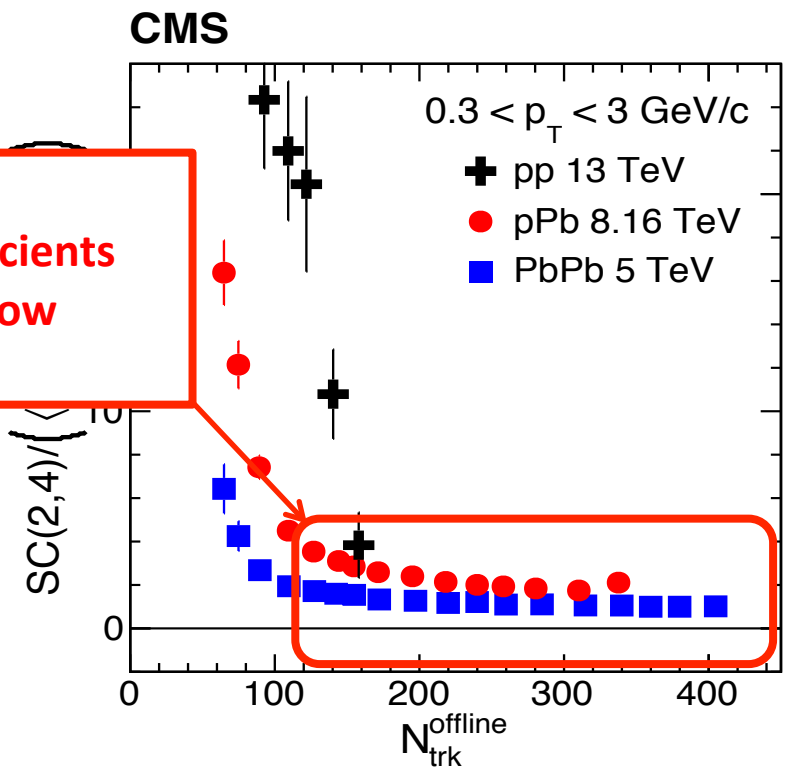
PRL (2018)120, 092301





Can be:

- **≠ transport coefficients**
- **Remaining non-flow**
- **…**

- Similar behavior in p-Pb and Pb-Pb
- Points to similar IS fluctuations

Common paradigm?

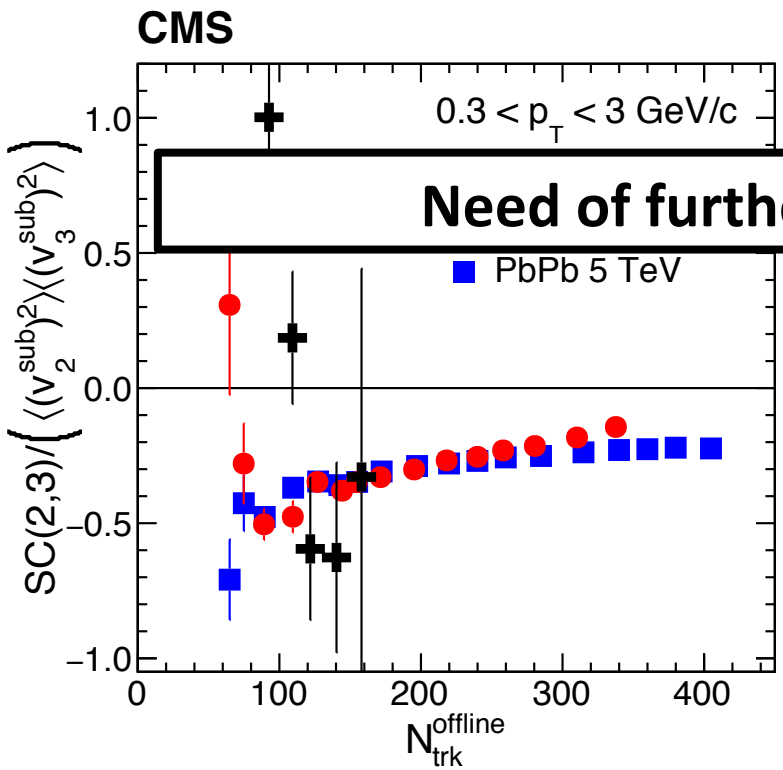
- Ordering observed:

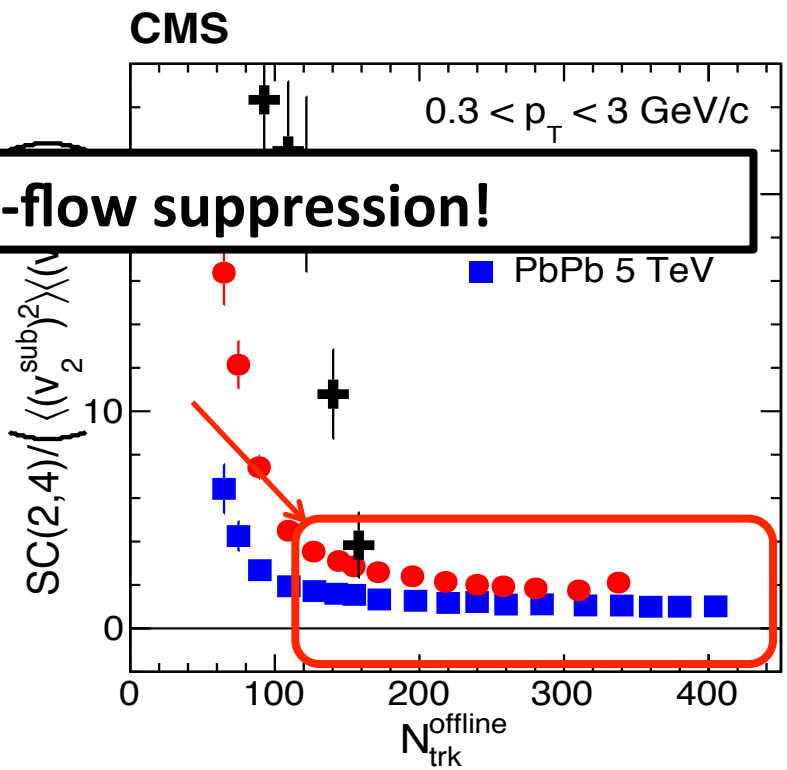
  p-p > p-Pb > Pb-Pb

What is the origin?

Normalized SC (NSC)

PRL (2018)120, 092301





Need of further non-flow suppression!

- Similar behavior in p-Pb and Pb-Pb
- Points to similar IS fluctuations

Common paradigm?

- Ordering observed:

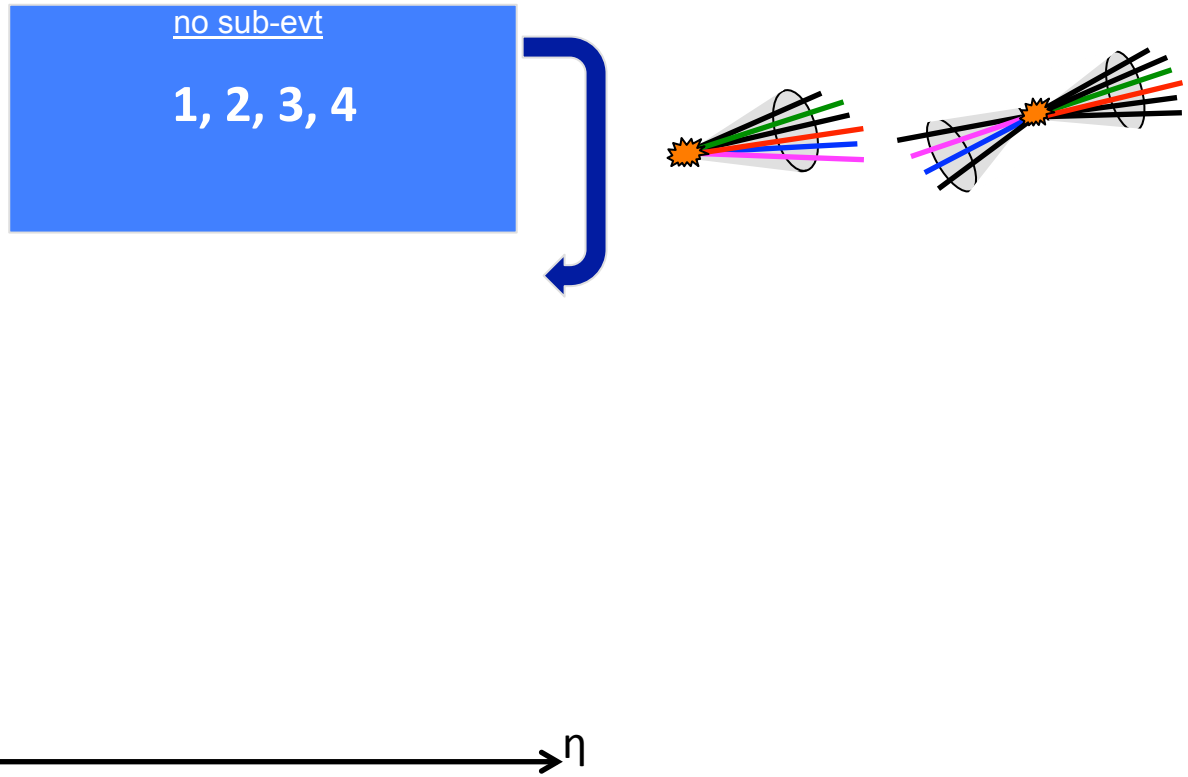
  p-p > p-Pb > Pb-Pb

What is the origin?

How to suppress non-flow?

Method: PRC (2017) 84, 044911 | PRC (2017) 96, 034906 | PLB (2018) 777, 201

Concept: *Suppressing non-flow contribution with subevents*



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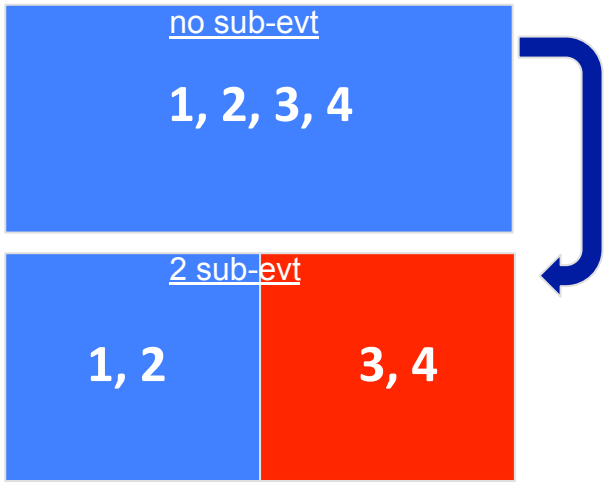

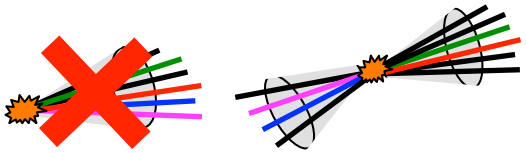

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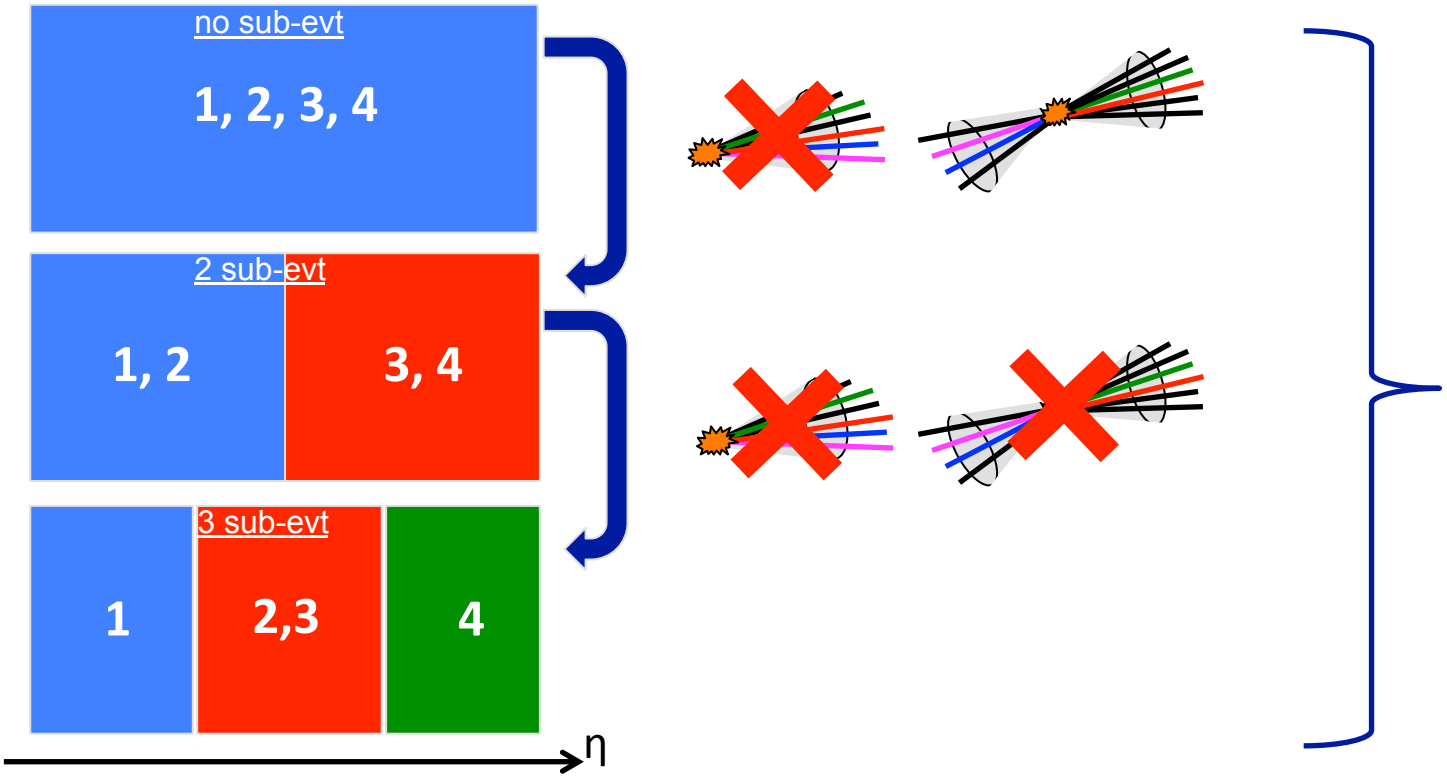
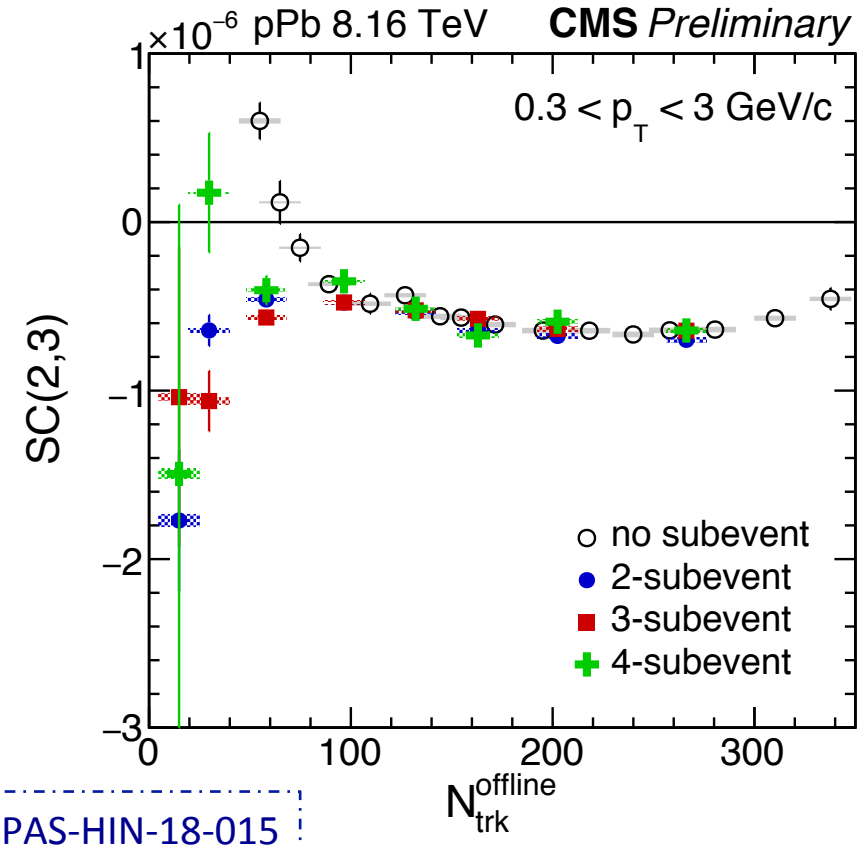


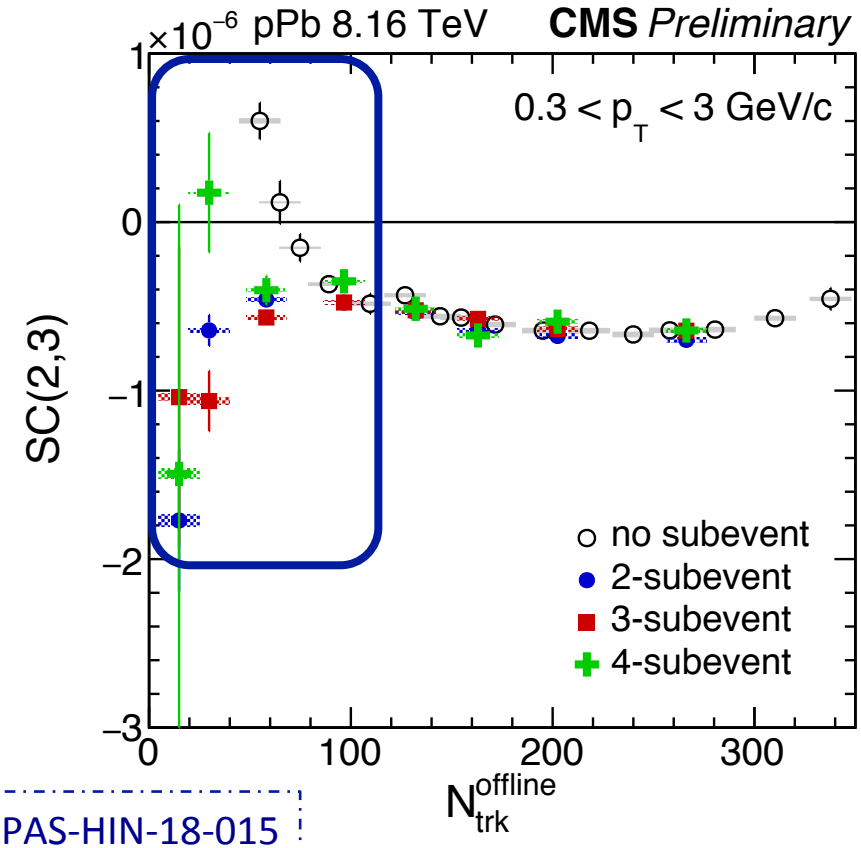
Larger suppression of non-flow contribution using more subevents

SCs with subevents



CMS-PAS-HIN-18-015

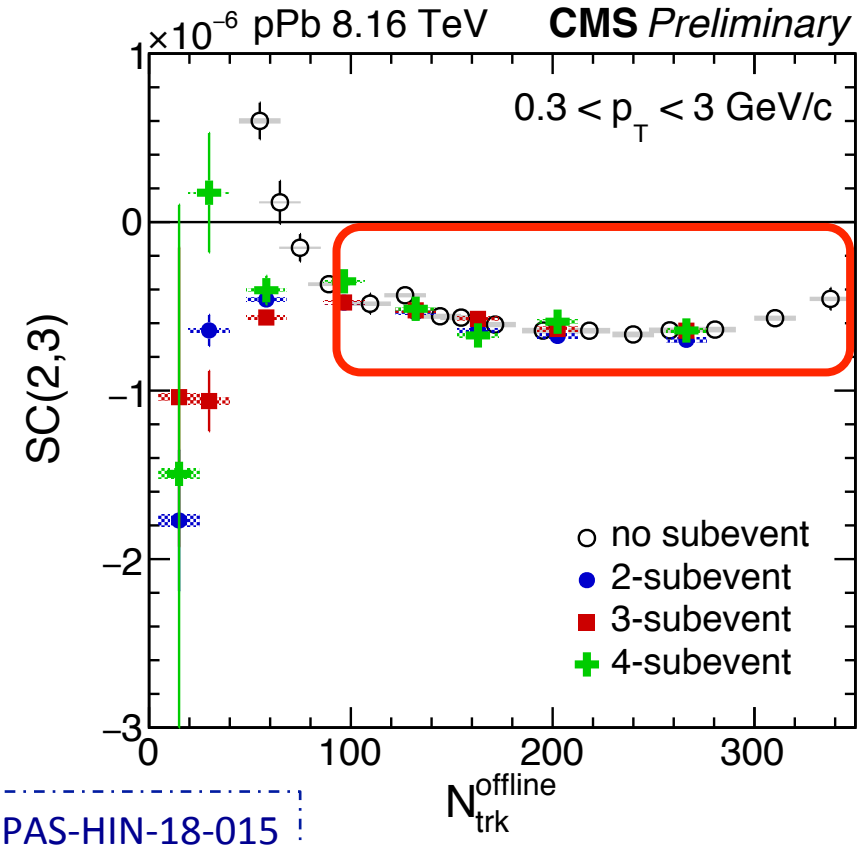
SCs with subevents



CMS-PAS-HIN-18-015

- Non-flow suppressed at low-multiplicities

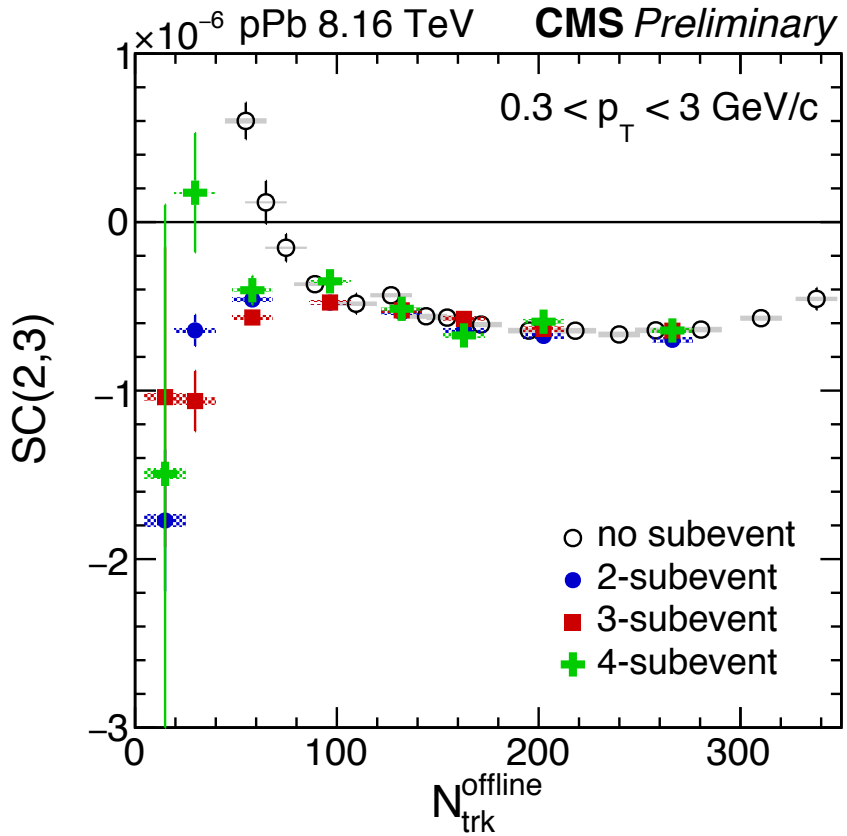
SCs with subevents

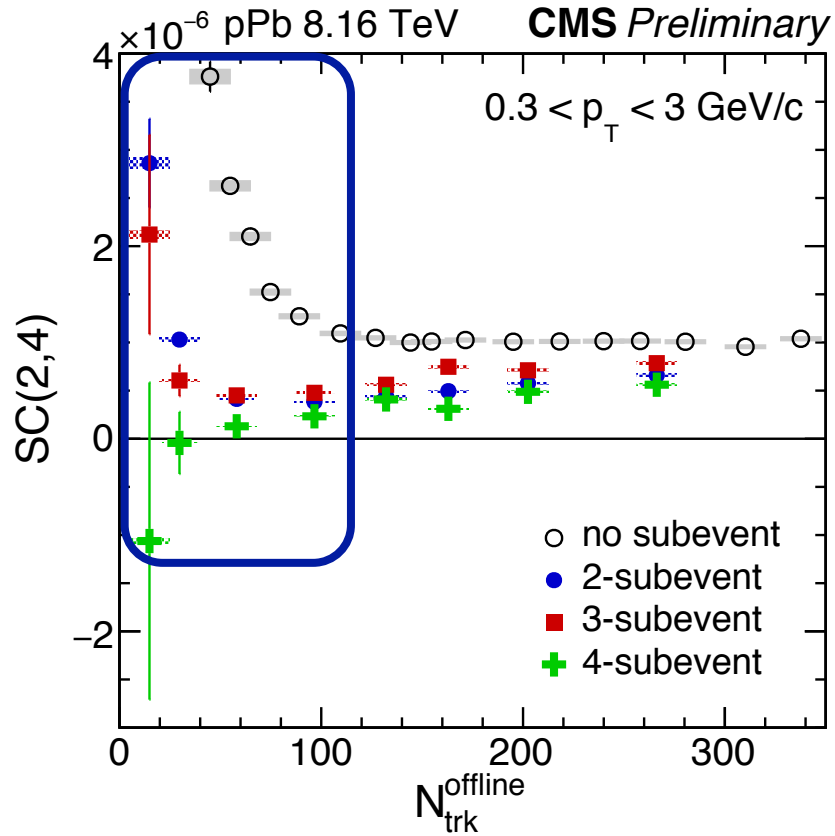


CMS-PAS-HIN-18-015

- Non-flow suppressed at low-multiplicities
- Similar results at high multiplicities for SC(2,3)

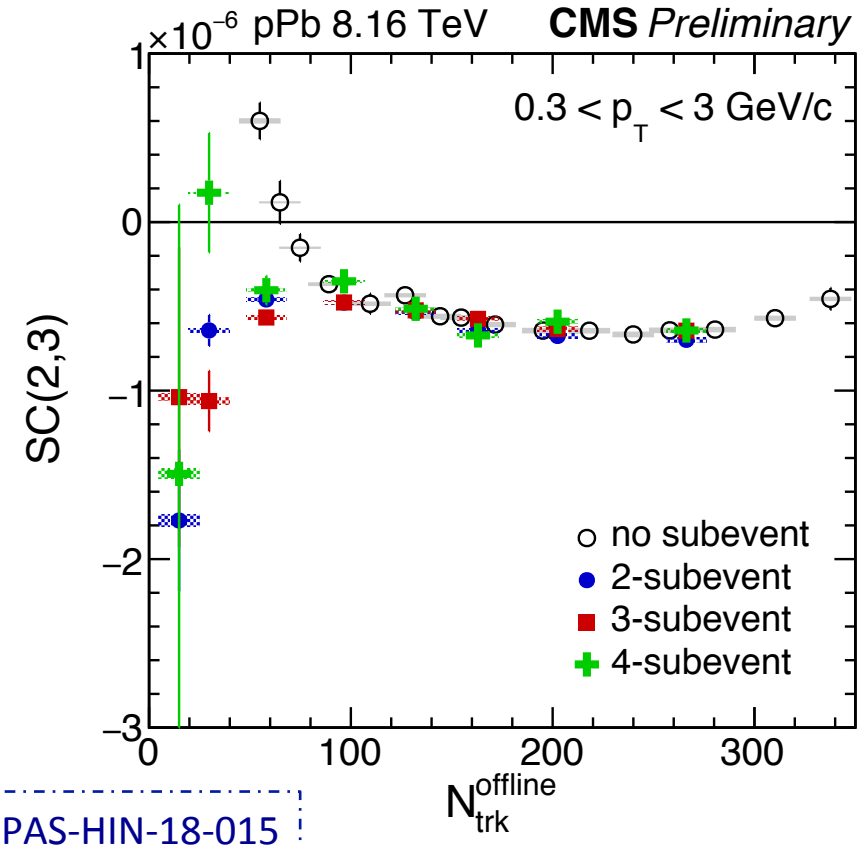
SCs with subevents

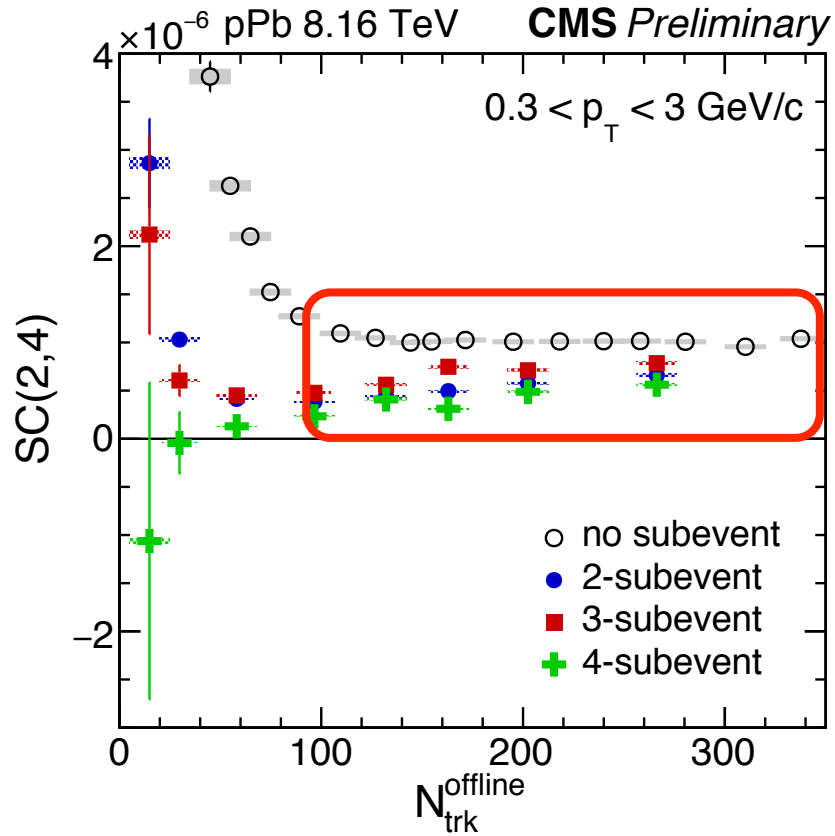




CMS

SCs with subevents

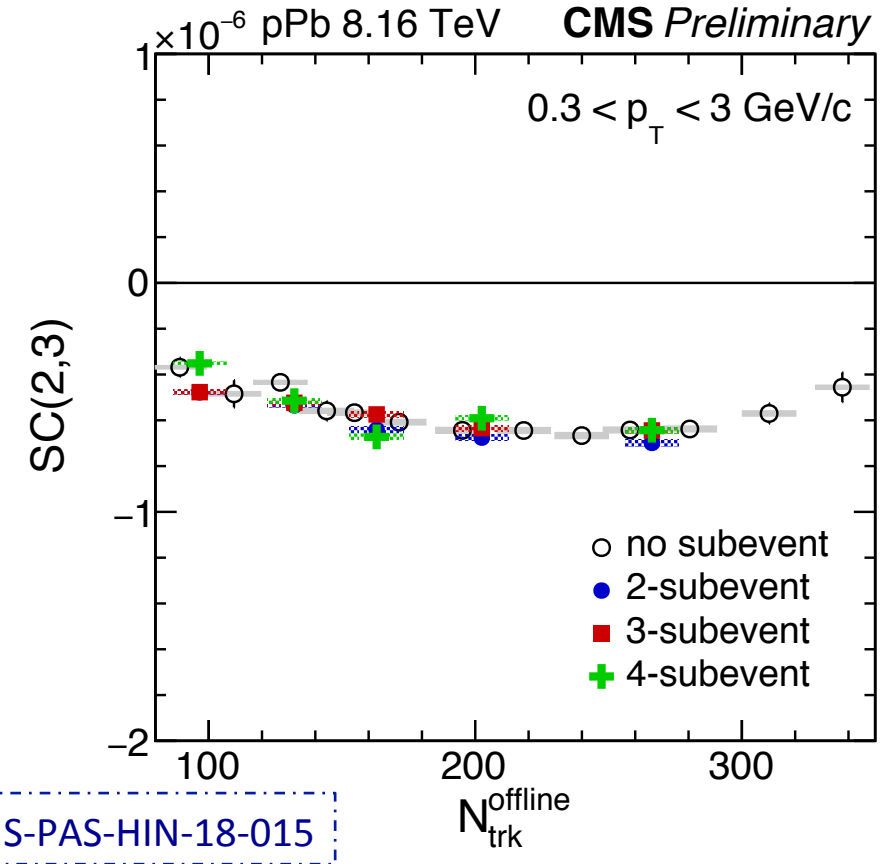


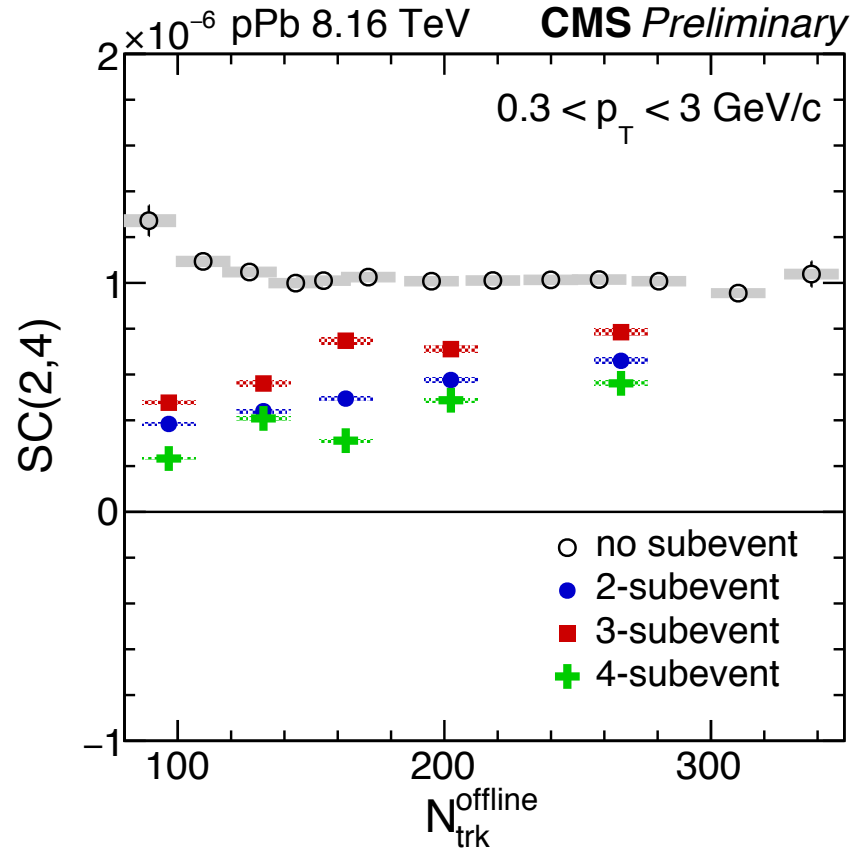


CMS-PAS-HIN-18-015

- Non-flow suppressed at low-multiplicities
- Similar results at high multiplicities for SC(2,3)
- Different results between no- and ***n***-subevents at high-multiplicities for SC(2,4)

Zooming to the high multiplicity region

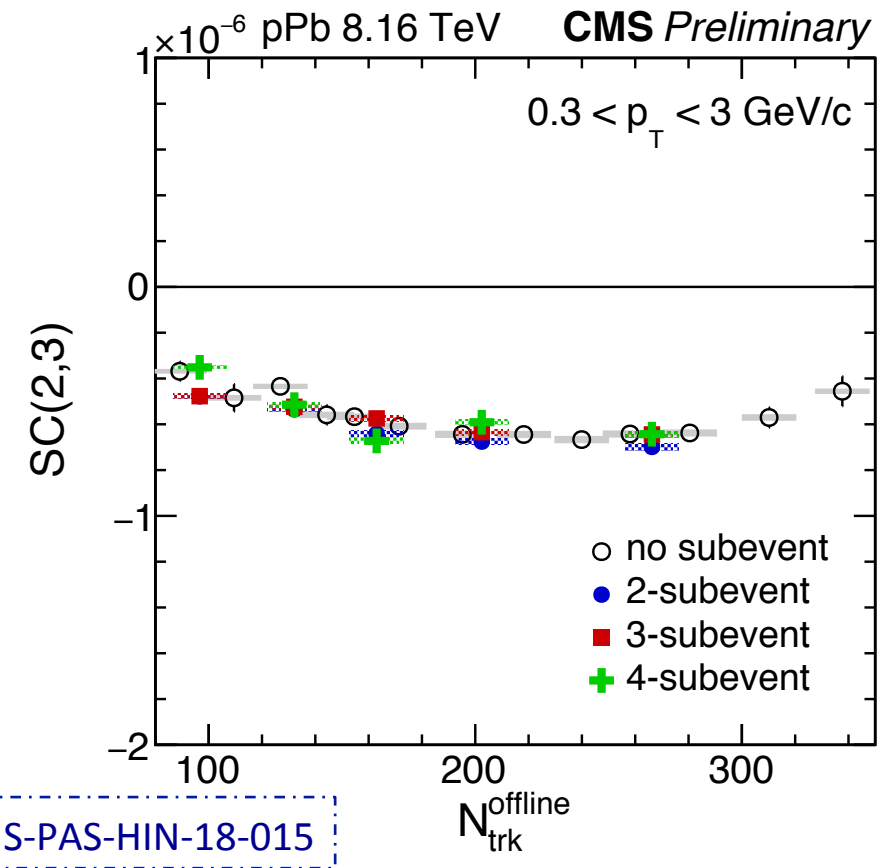


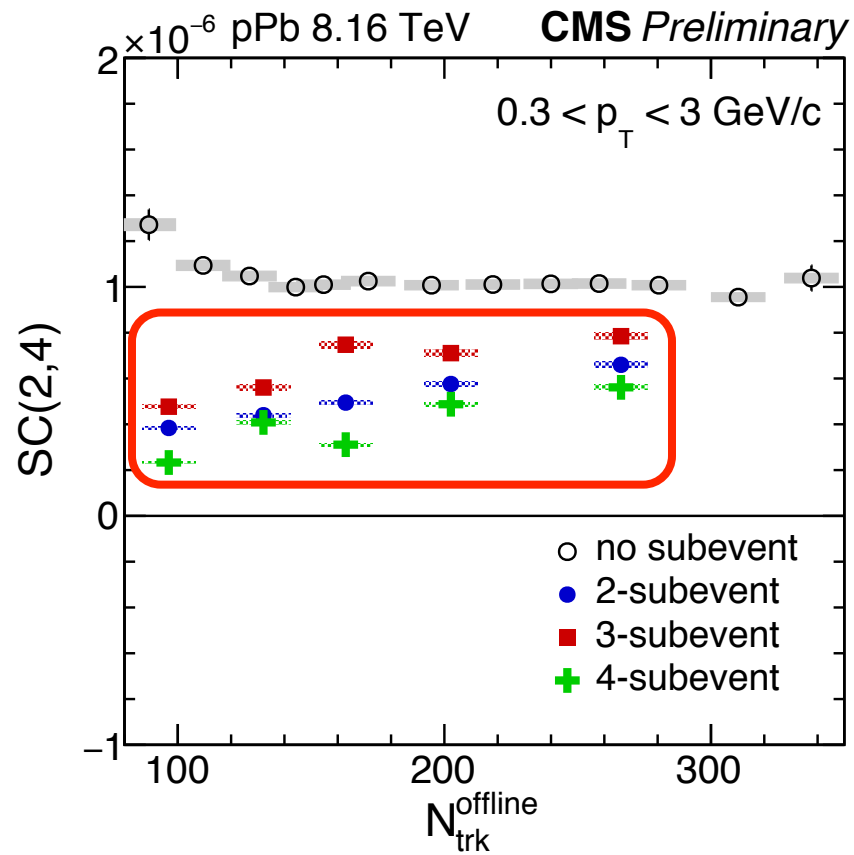


CMS-PAS-HIN-18-015

- **SC(2,3):** Negligible contribution from non-flow
- **SC(2,4):** Remaining contribution of non-flow in the no-subevent case?

Zooming to the high multiplicity region





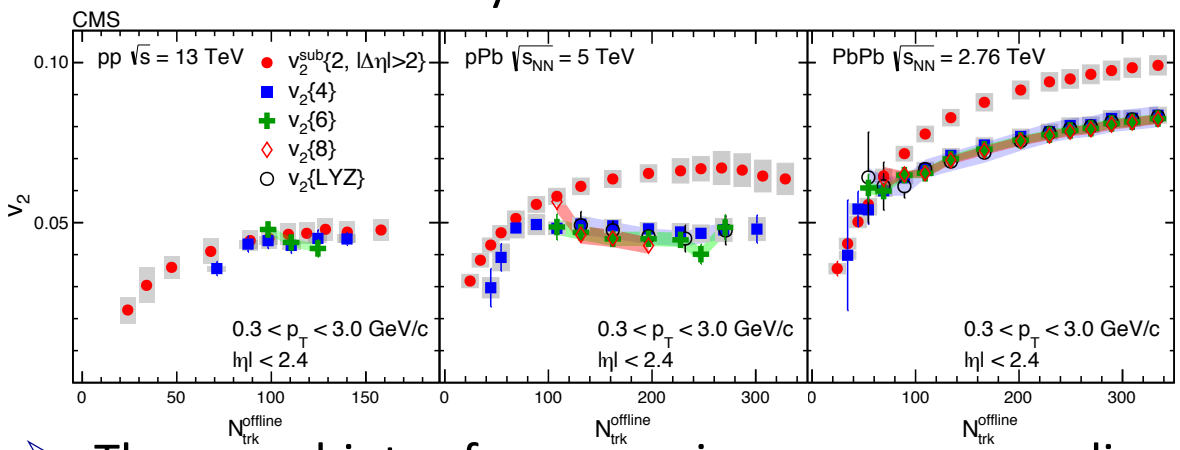
CMS-PAS-HIN-18-015

- **SC(2,3):** Negligible contribution from non-flow
- **SC(2,4):** Remaining contribution of non-flow in the no-subevent case?
  - Difference among subevent results observed: unexpected ordering!

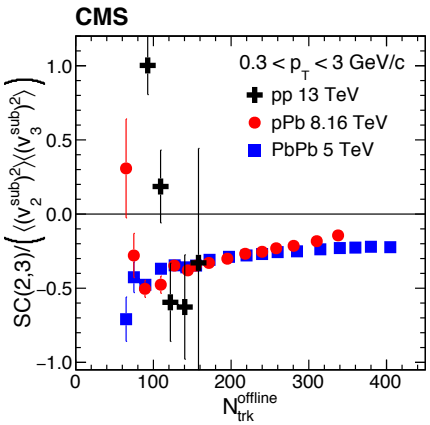
What did we learn? An emerging common paradigm

Similar effects are observed in all hadronic colliding systems

- The effect is clearly collective: 2 scenarii available



- There are hints of an emerging common paradigm



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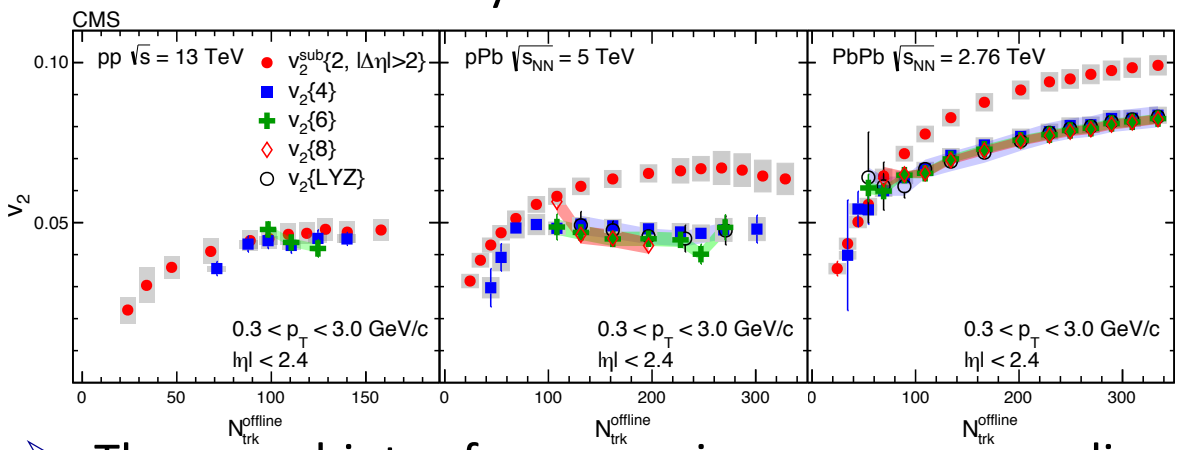

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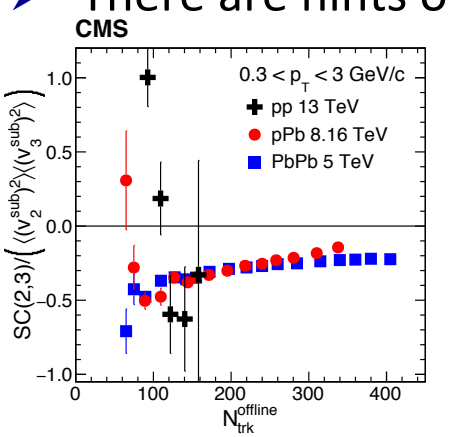
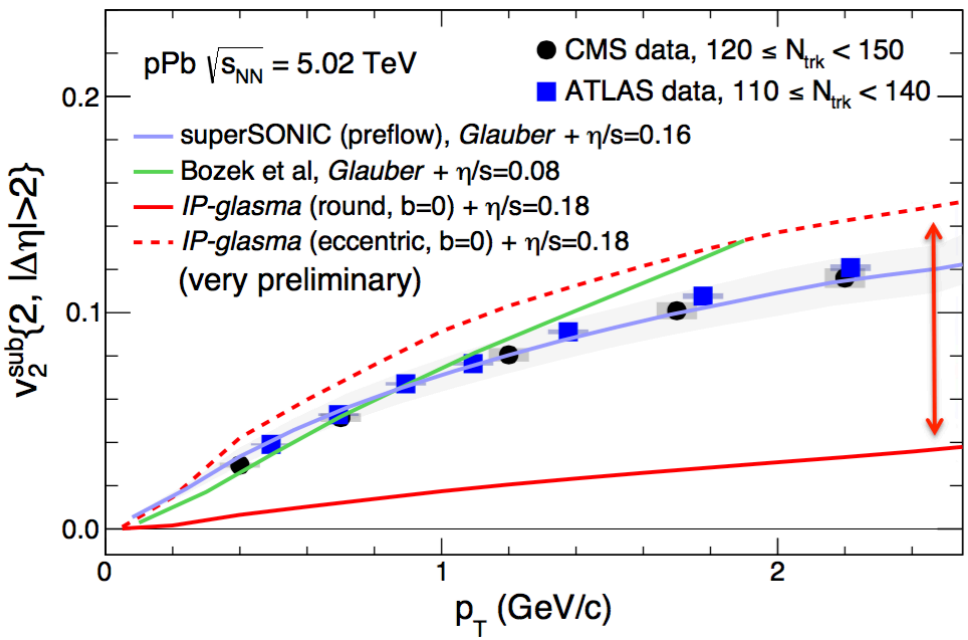


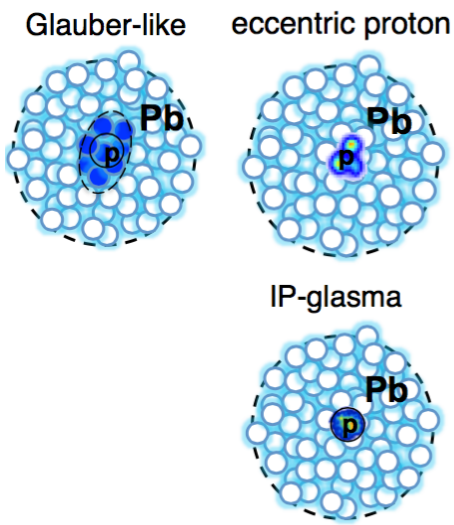
Too early to conclude, **more data** and **quantitative theoretical prediction** are needed

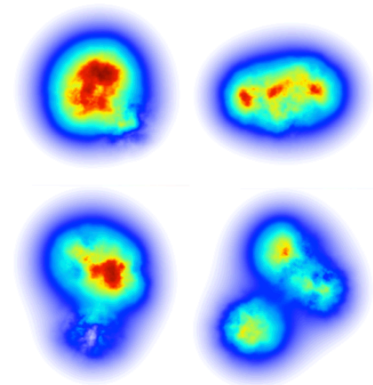
What did we learn? Geometry and fluctuation of IS at the collisions

In small systems, fluctuations matters

- For example, small systems results can probe proton sub-nucleonic fluctuations
- Better understanding of IS in small systems **will help to understand large ones**







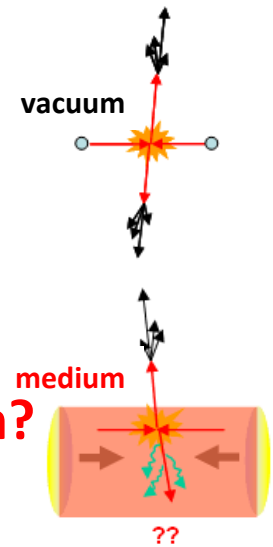
Mantysaari, Schenke, PRL 117, 052301 (2016)

What's next or more?

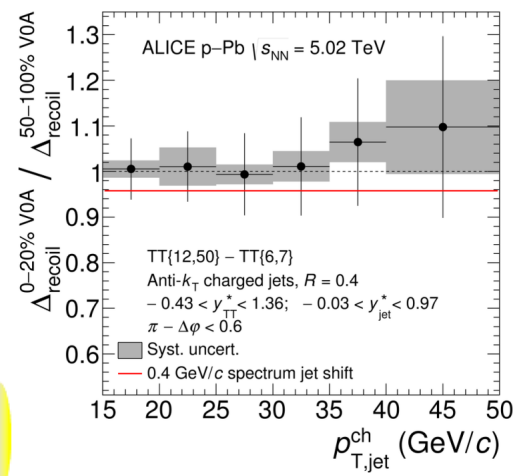
Emergence of hot QCD phenomena in small colliding systems

- Standard descriptions of pp and AA physics may lack ingredients
- We are missing one big part to claim for a QGP!

Where are the interactions with the medium?



arXiV:1712.05603



Where is the onset of deconfinement?

- What are the least ingredients needed to reach deconfinement?
- No observation in electron-positron collisions so far