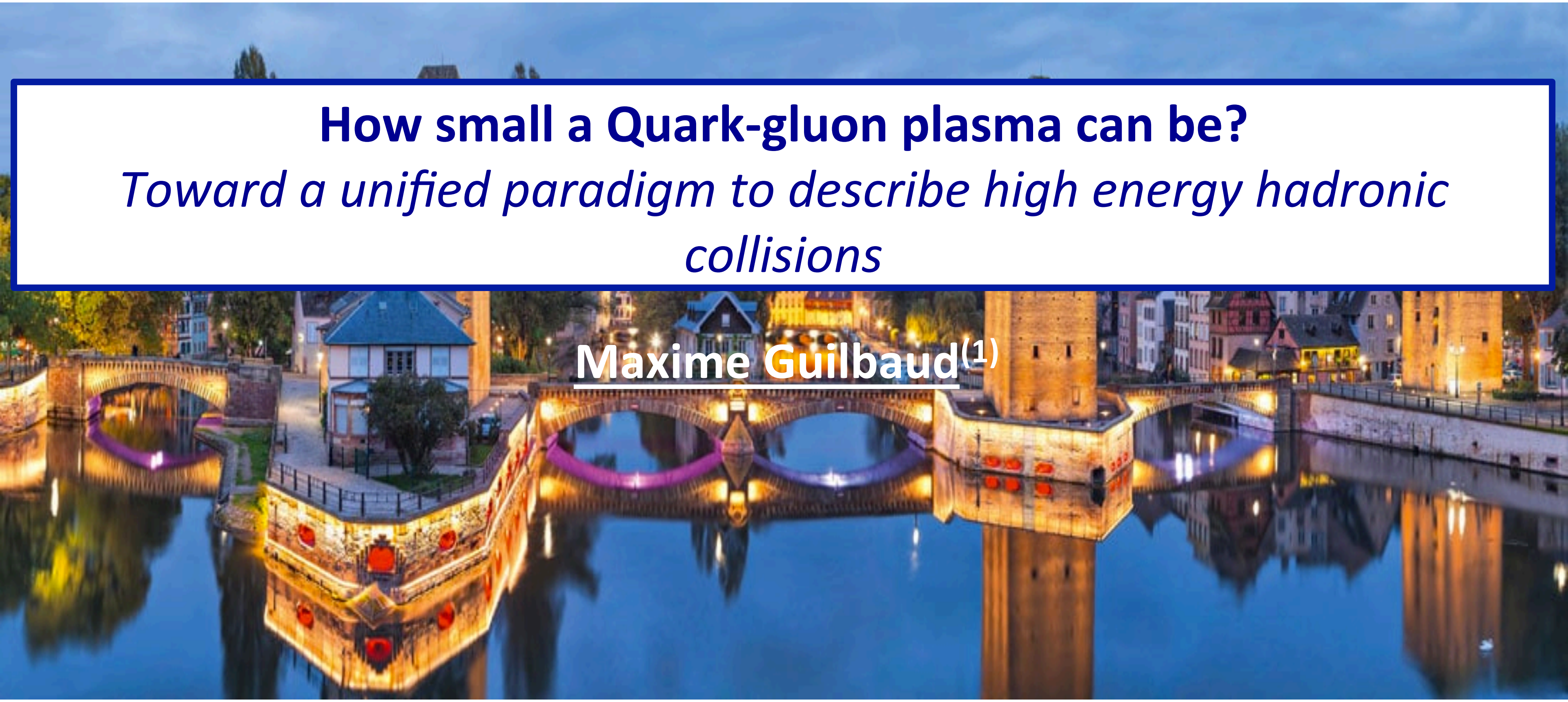
How small a Quark-gluon plasma can be?

Toward a unified paradigm to describe high energy hadronic collisions



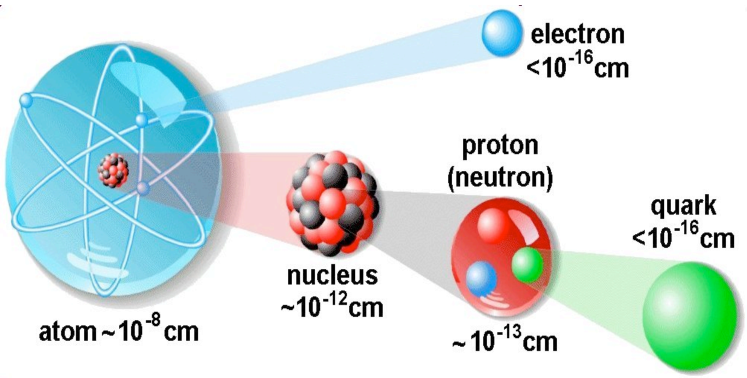
Maxime Guilbaud[1]

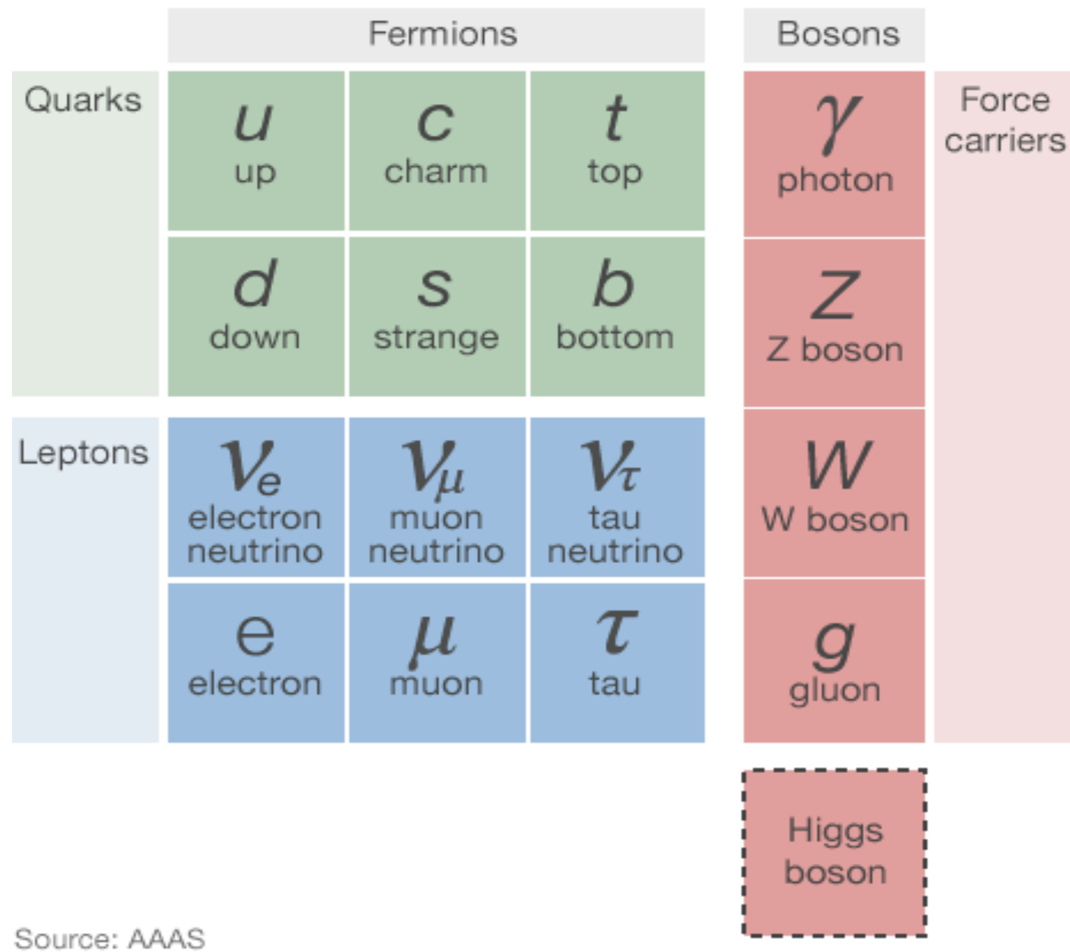
Seminaire - IPHC

28/04/17

(1) RICE University, m.guilbaud@cern.ch

The most fundamental scale



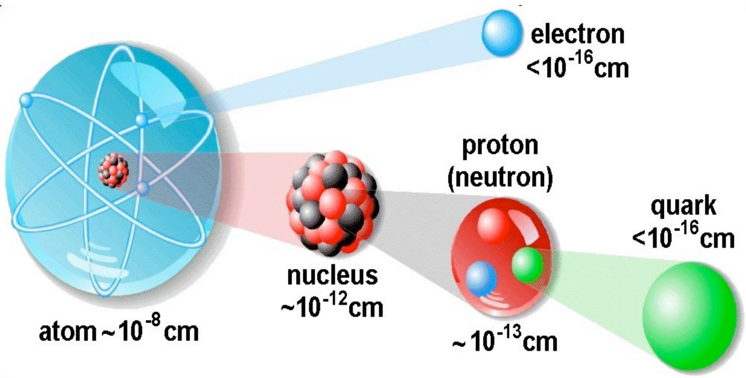


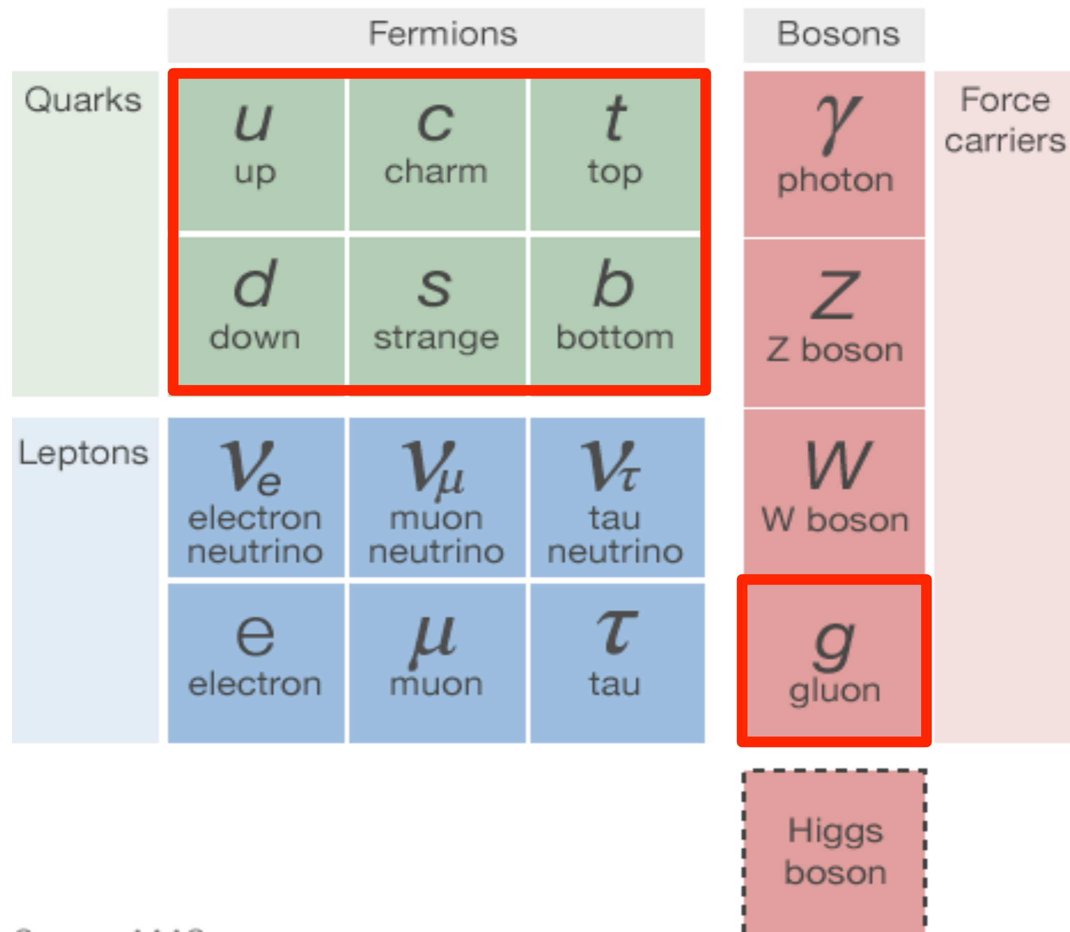
Source: AAAS

<u>Theory of strong interaction:</u>

Quantum ChromoDynamics (QCD)

The most fundamental scale





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Theory of strong interaction:

Quantum
ChromoDynamics
(QCD)

Quark confinement

Quarks carry a color charge
(blue, green, red)

Quark confinement

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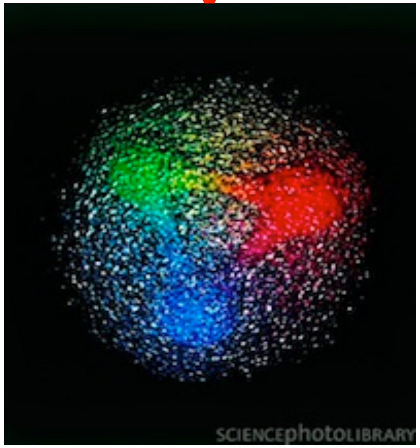


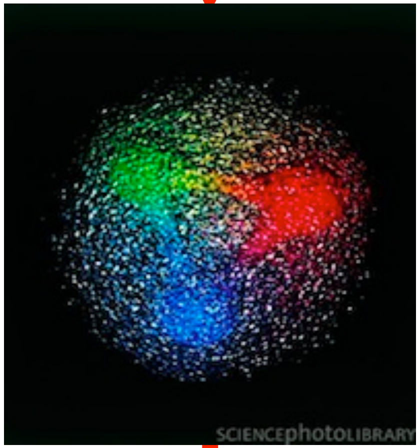
colorless ⟷

How to explain the quark confinement in hadrons?

Is it possible to deconfine quarks?

Quark confinement

Quarks carry a color charge
(blue, green, red)



colorless ↔

How to explain the quark confinement in hadrons?

Is it possible to deconfine quarks?

Only colorless object are observed
=
no free quark

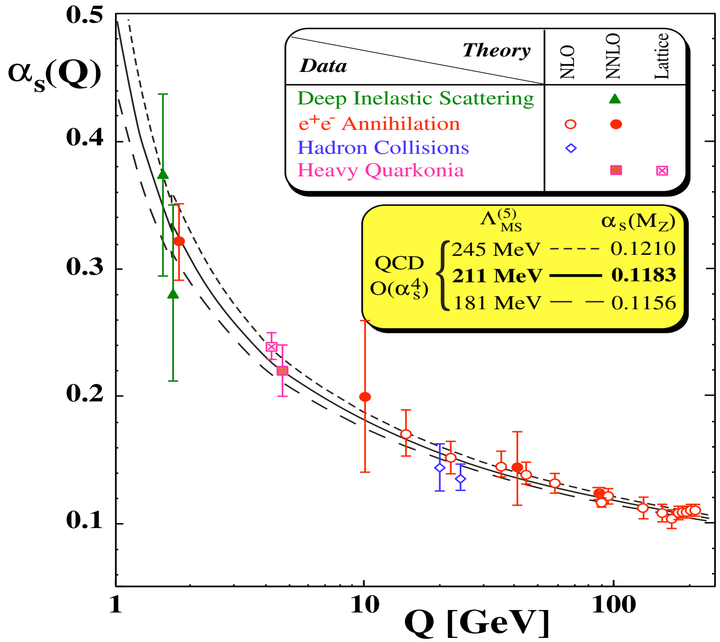
Phase transition

How to explain the confinement in hadrons?

Is it possible to deconfine quark?

Phase transition

How to explain the confinement in hadrons?

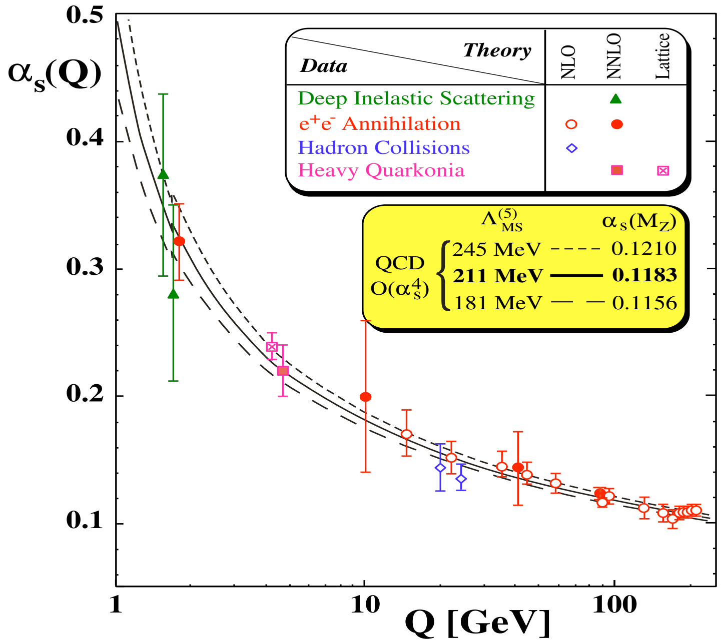


High energy (small distance) ➔ weak coupling

Is it possible to deconfine quark?

Phase transition

How to explain the confinement in hadrons?



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Low energy (large distance) ➔ strong coupling

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Phase transition

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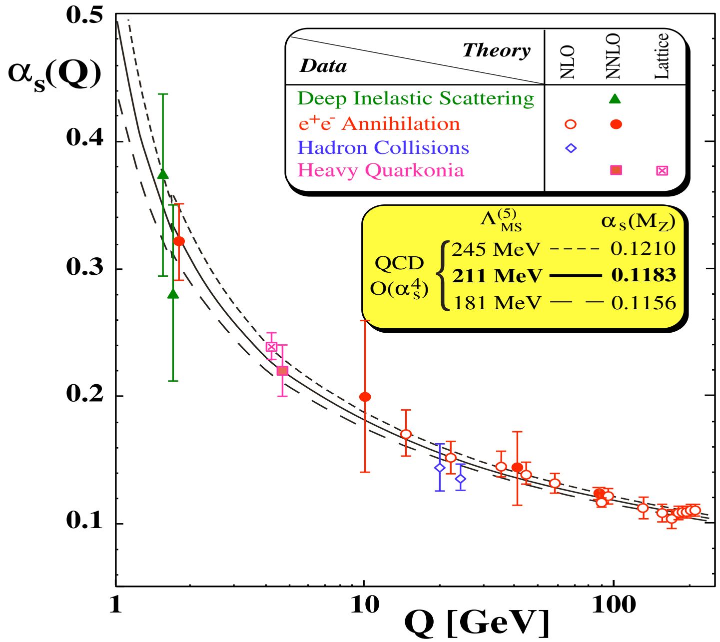

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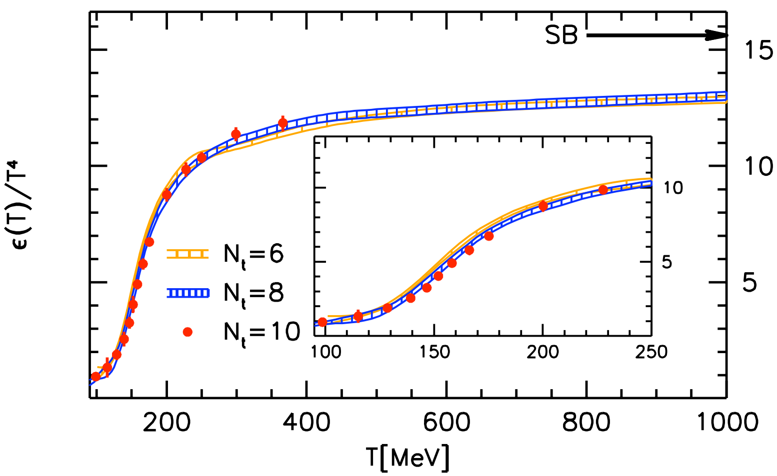
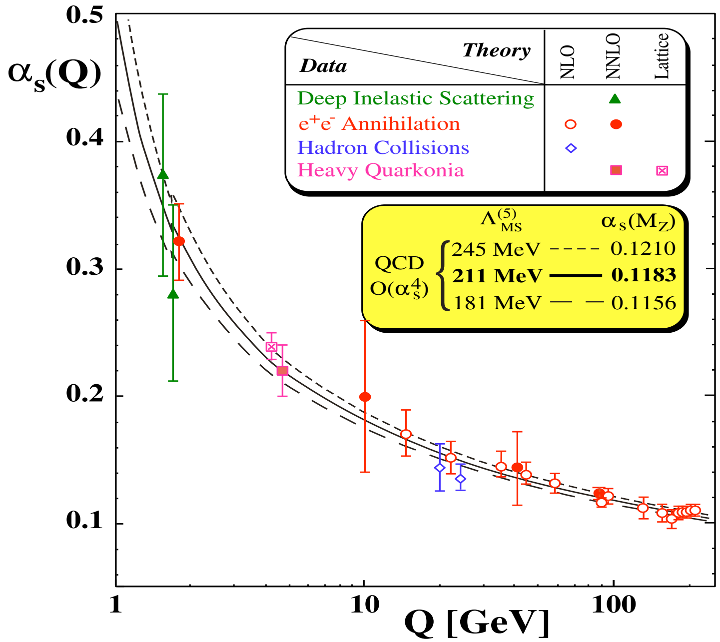


Lattice QCD calculations (lQCD):

- Indicate a phase transition at $T_c \approx 155$ MeV

Phase transition

How to explain the confinement in hadrons?



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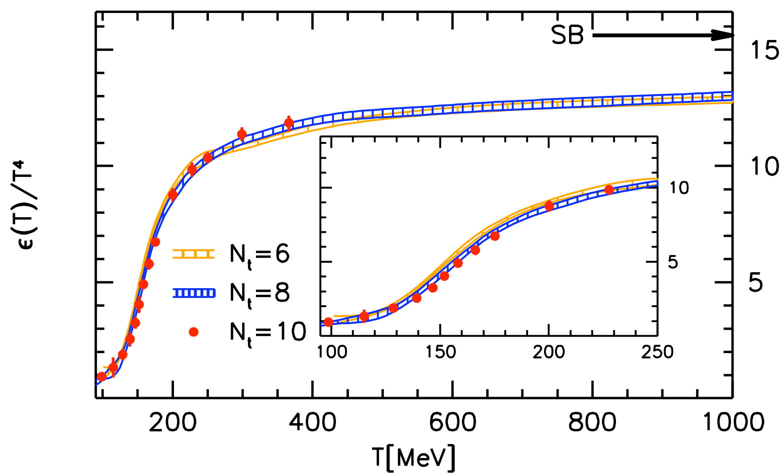
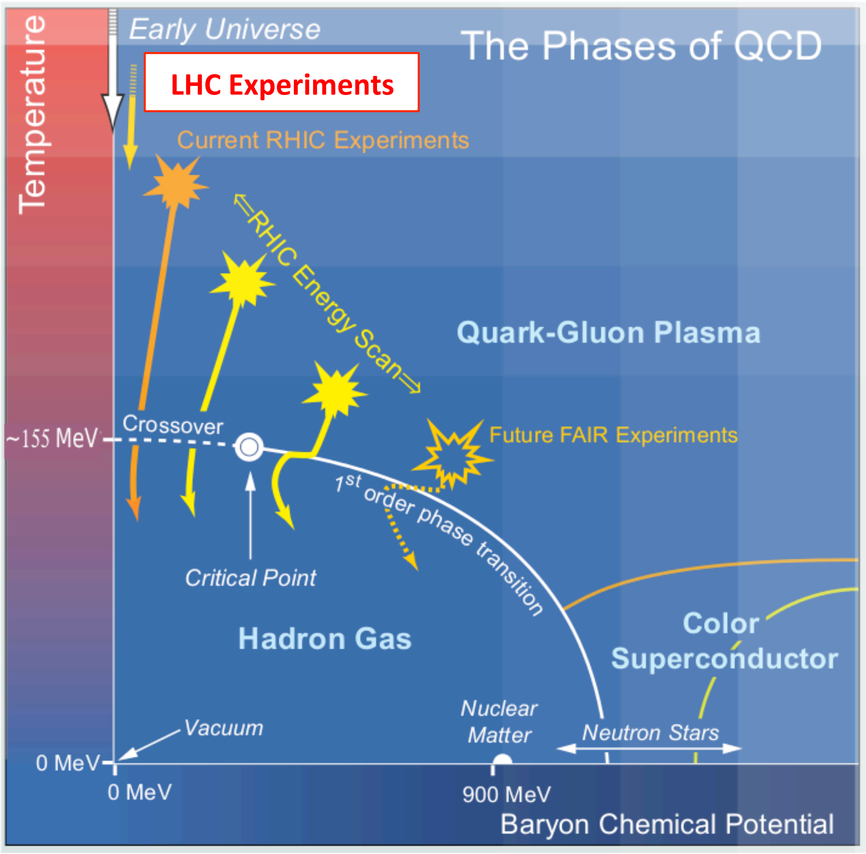


Lattice QCD calculations (lQCD):

- Indicate a phase transition at $T_c \approx 155$ MeV

New phase of the matter called **Quark and Gluon Plasma (QGP)**

Nuclear phase diagram



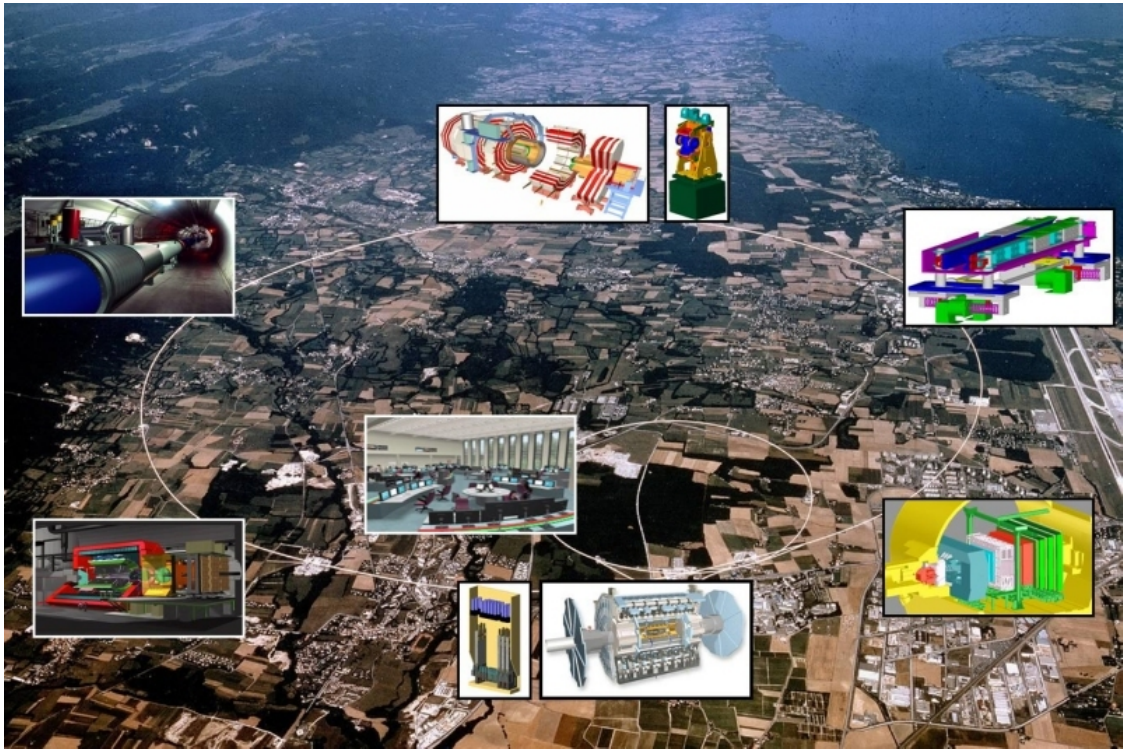
What are the goals?

- **Probe the nuclear phase diagram**
  - Transition order?
  - Critical point?
  - …
- **Characterize the QGP**
  - Equation of state?
  - Dynamics?
  - …

Experimentally: Heavy Ion (HI) collisions are used to study QGP

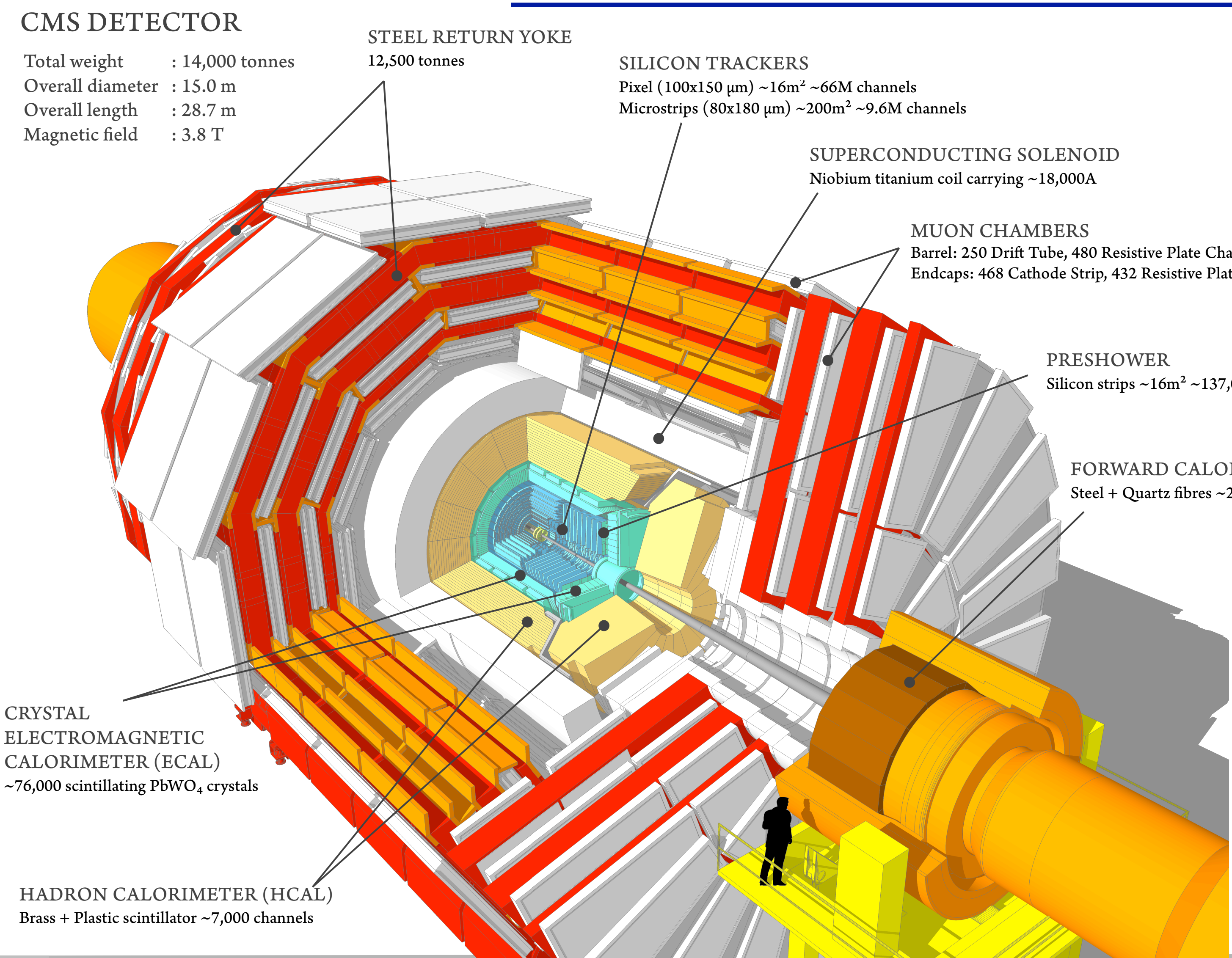
What are the tools to study the QGP: A collider

- **LHC at CERN:**
  - Circumference: 26.7 km
  - Depth ~ 100 m
  - 3 running modes:
    - p-p
    - p-Pb
    - Pb-Pb
- **4 main experiments**
  - LHCb
  - **CMS**
  - ATLAS
  - ALICE



system	Energy (TeV)
p-p	0.9, 2.36, 2.76, 5.02, 7, 8, 13
p-Pb	5.02, 8.16
Pb-Pb	2.76, 5.02

What are the tools to study the QGP: A Compact Muon Solenoid detector



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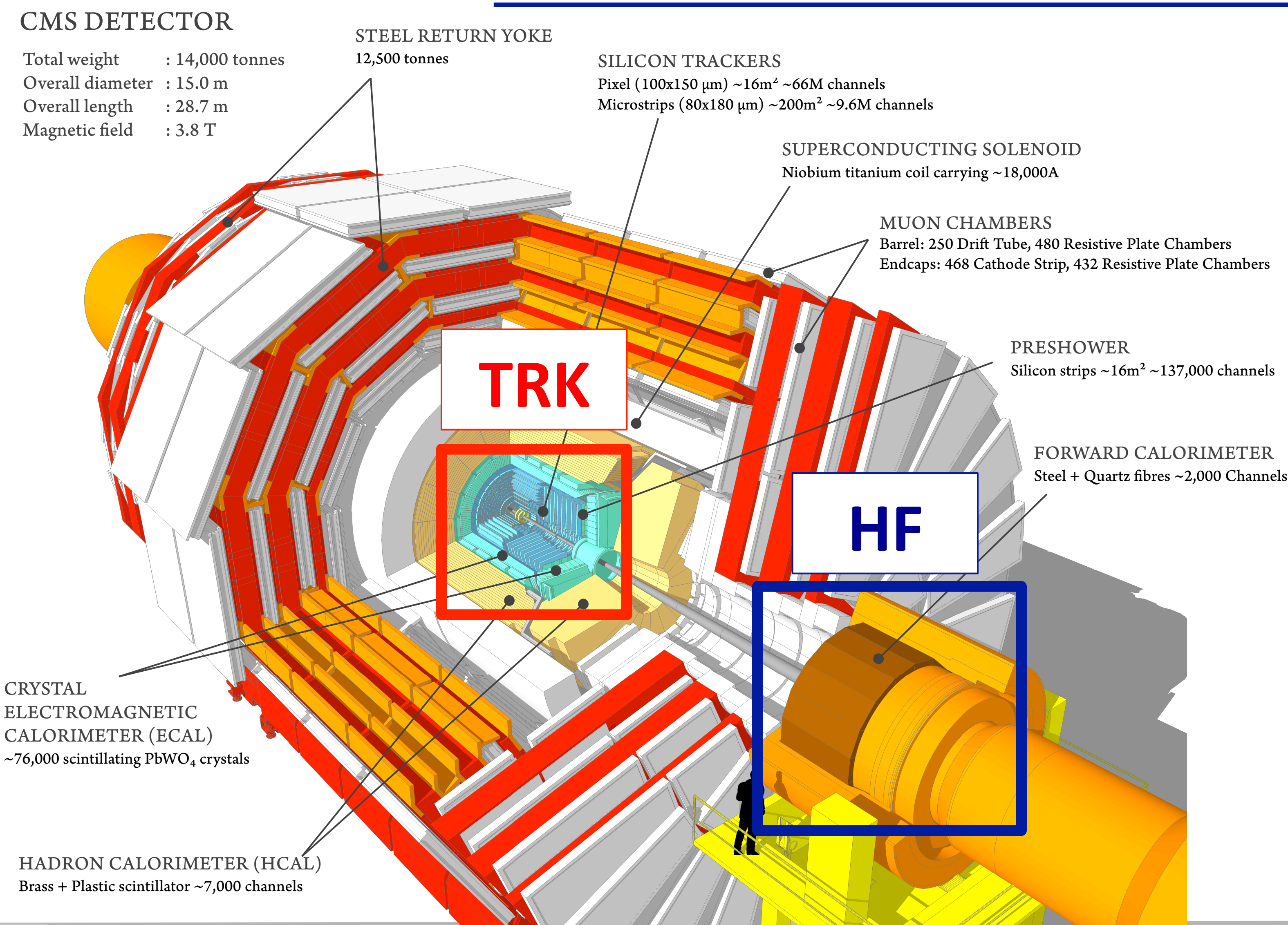

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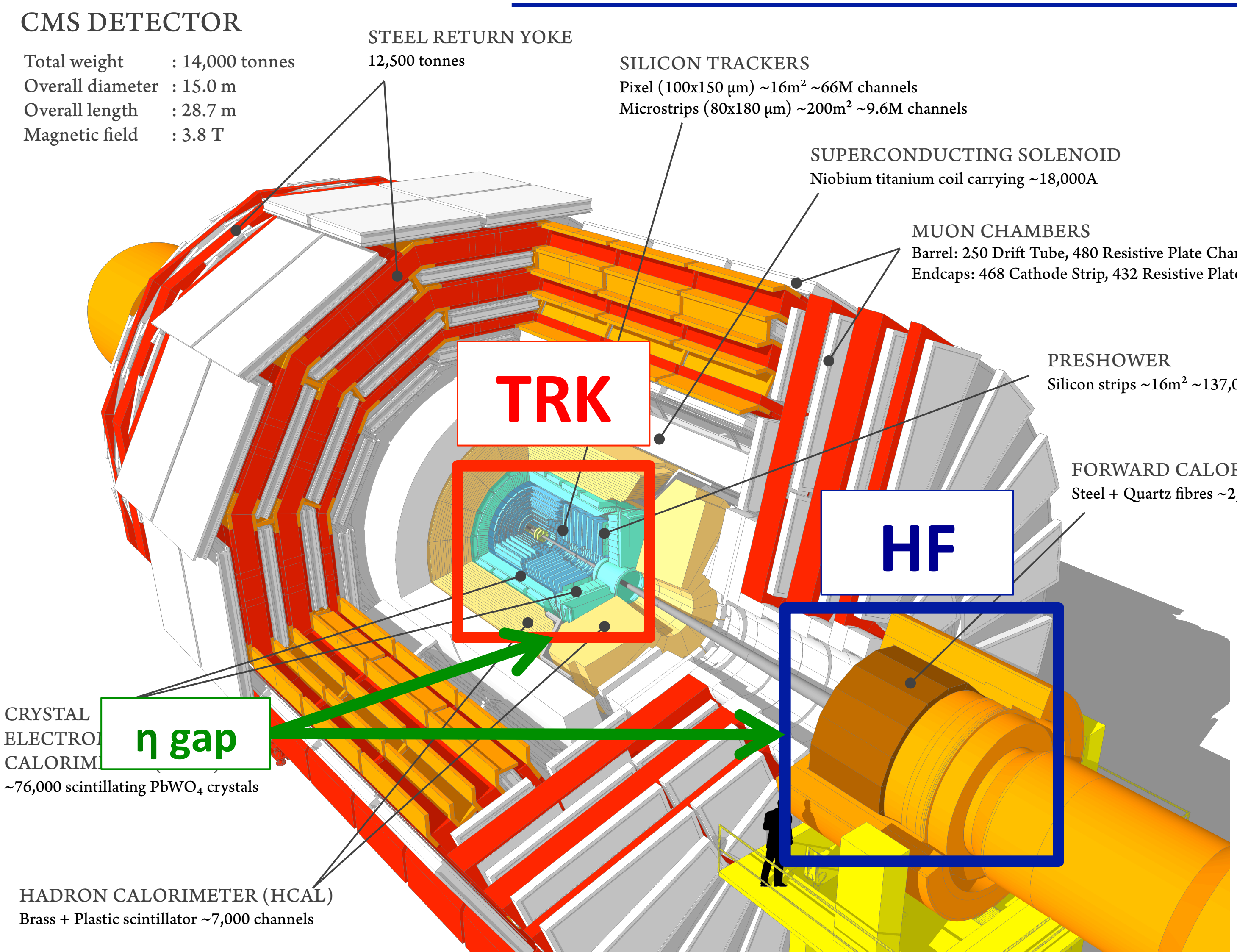
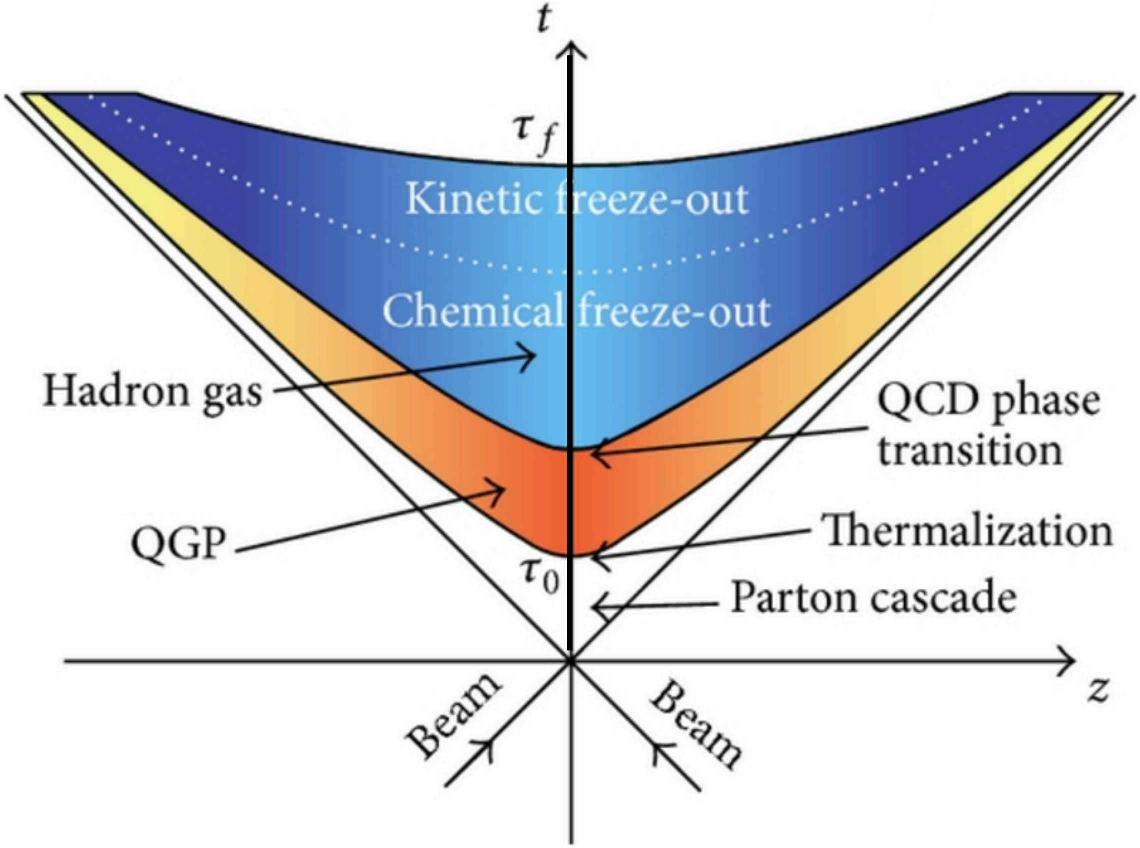
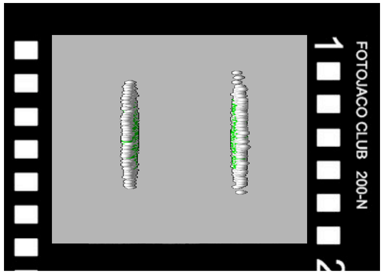


Heavy Ion collisions



Initial state



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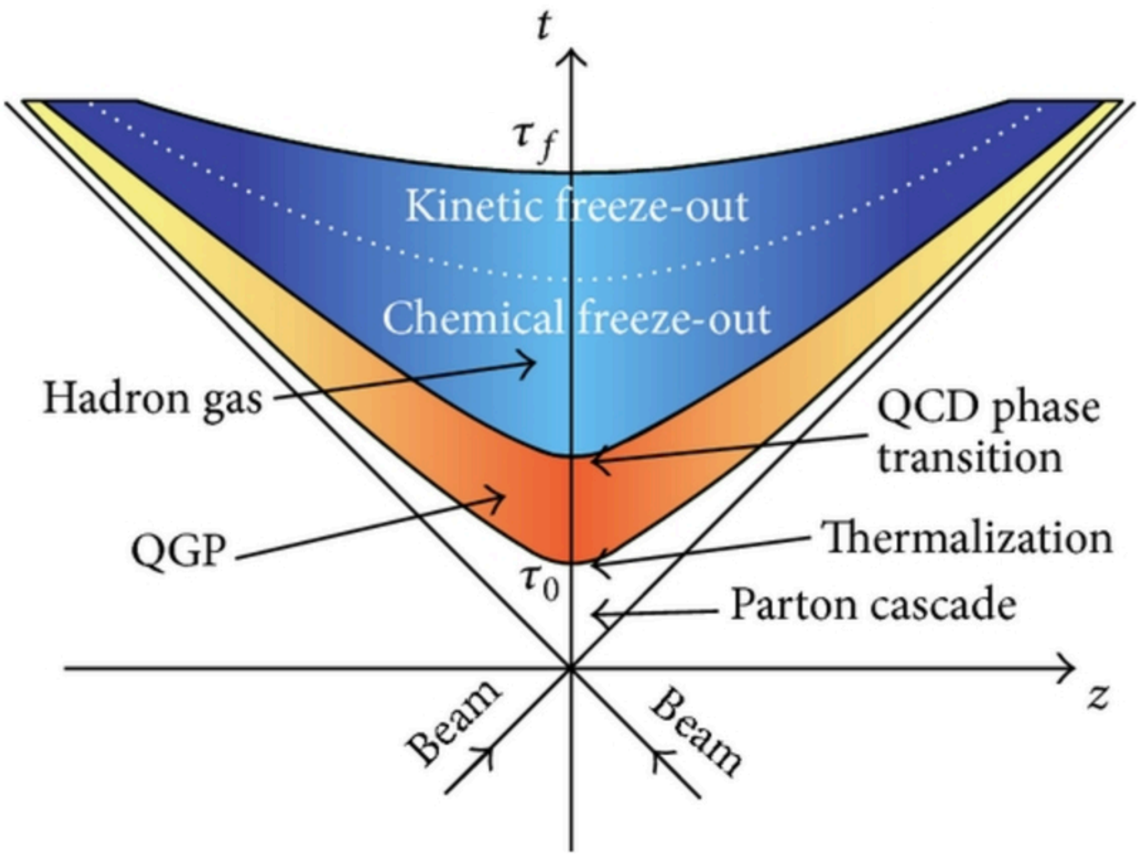
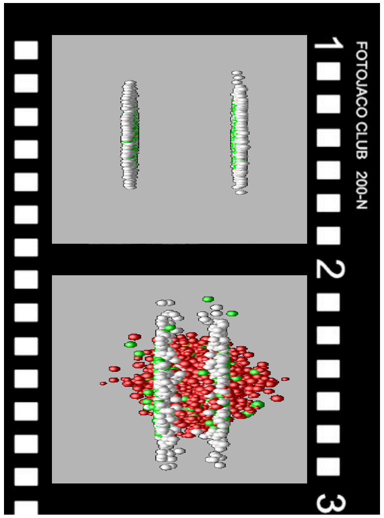


Initial state

0 fm/c



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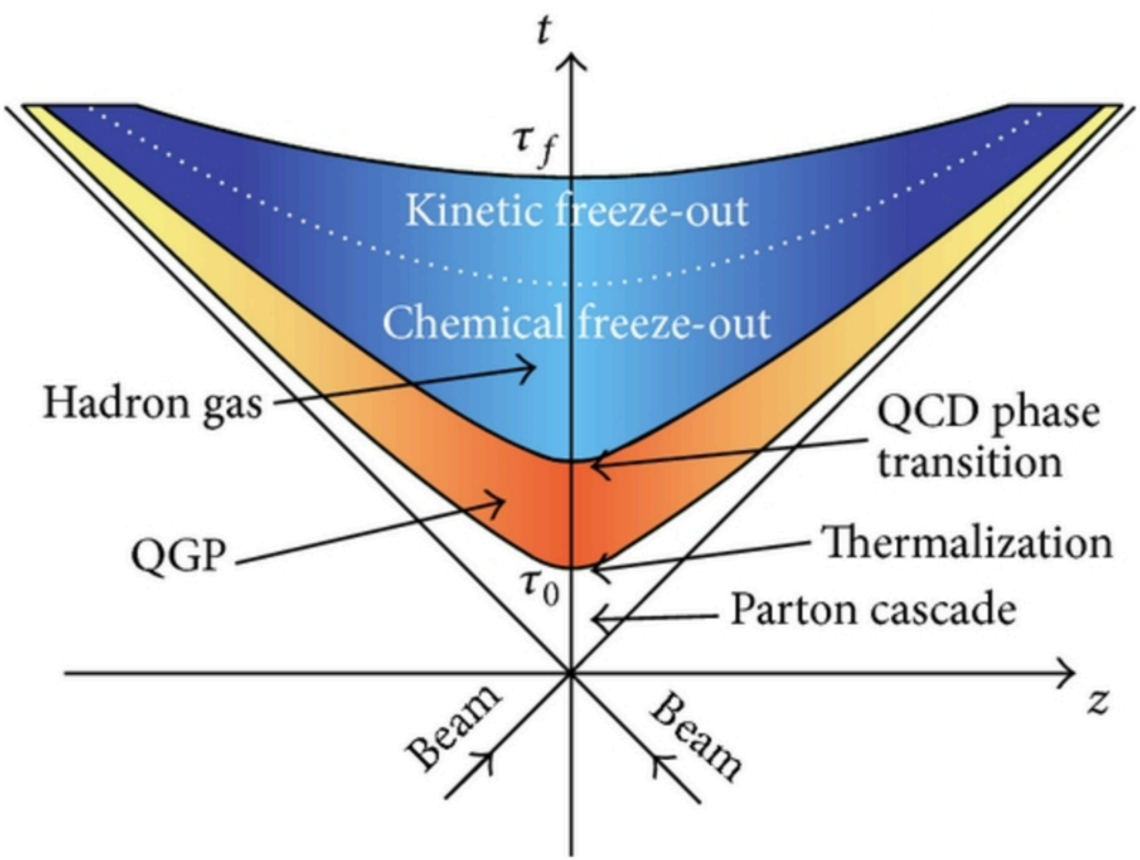

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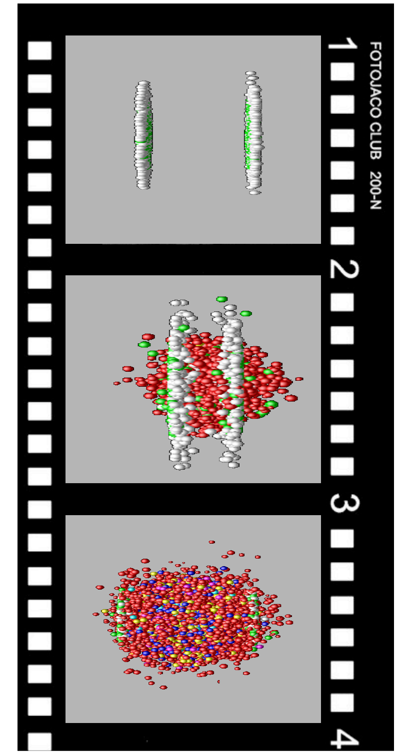
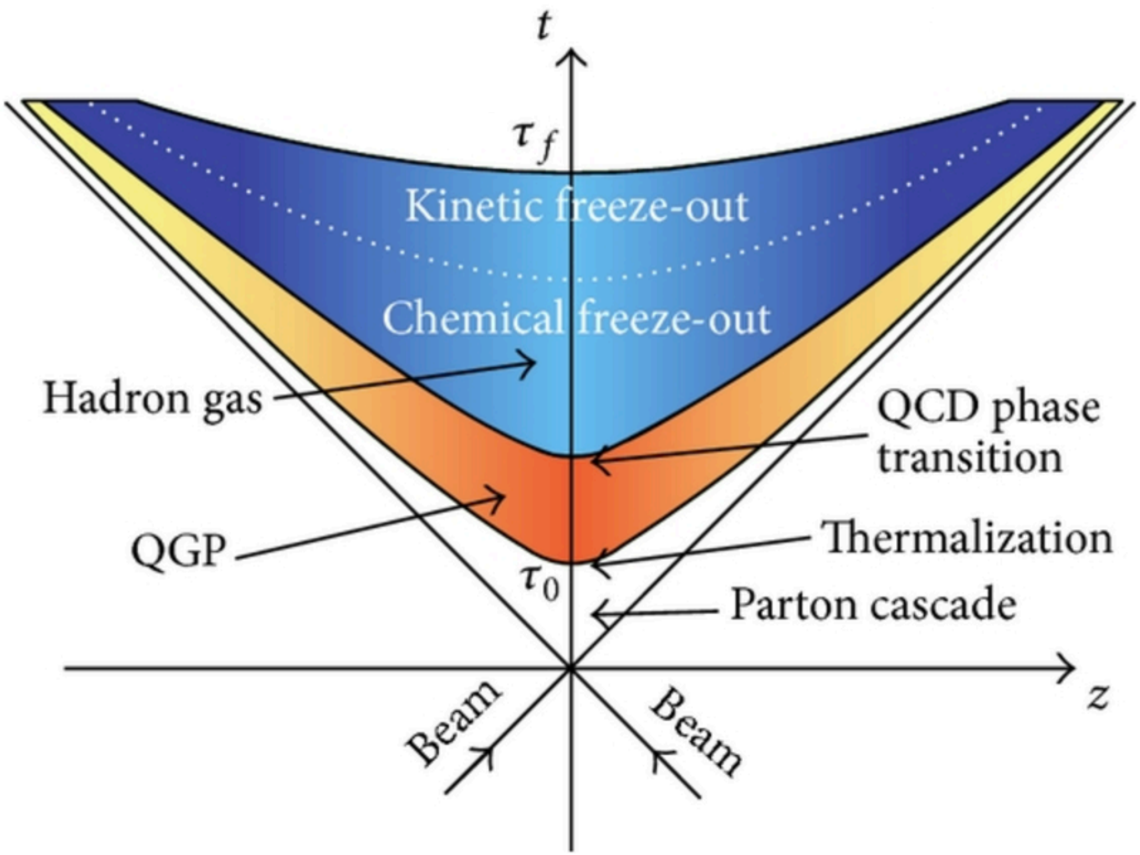


QGP

Thermalized

2 fm/c

Heavy Ion collisions



Initial state

0 fm/c

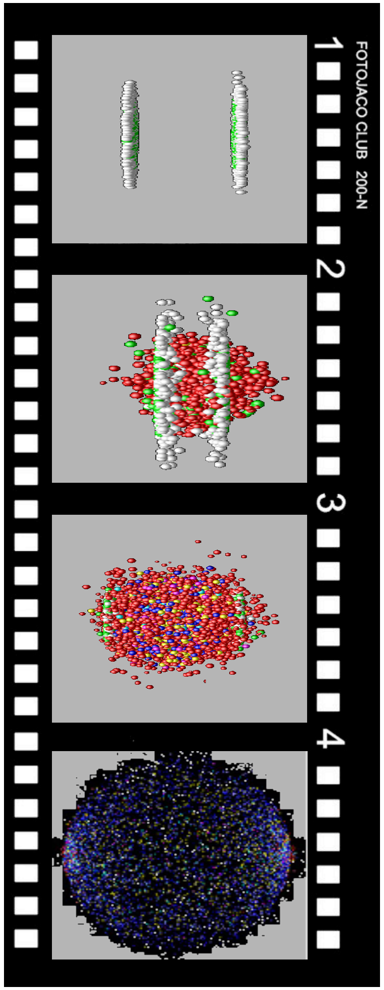
QGP

Thermalized

2 fm/c

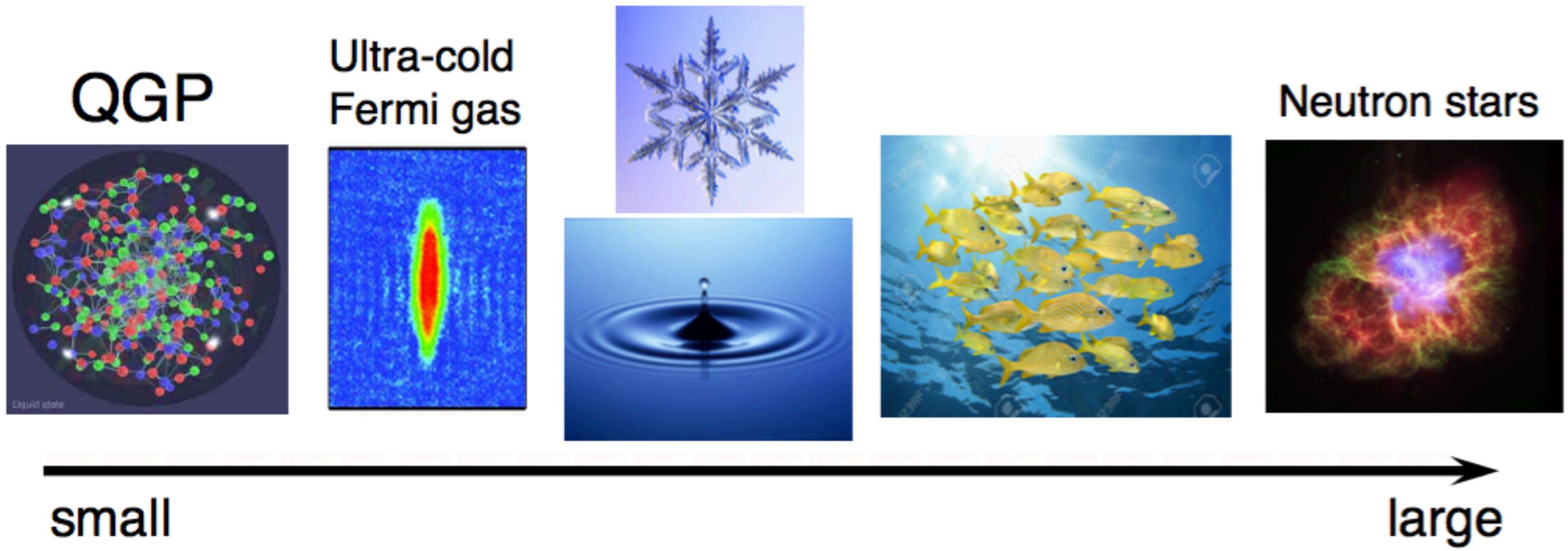
Hadronization

Chemical & thermal freeze-out



How to characterize the QGP?

Collective phenomena a central theme in the study of strongly correlated, **interacting** many-body systems



How to characterize the QGP?

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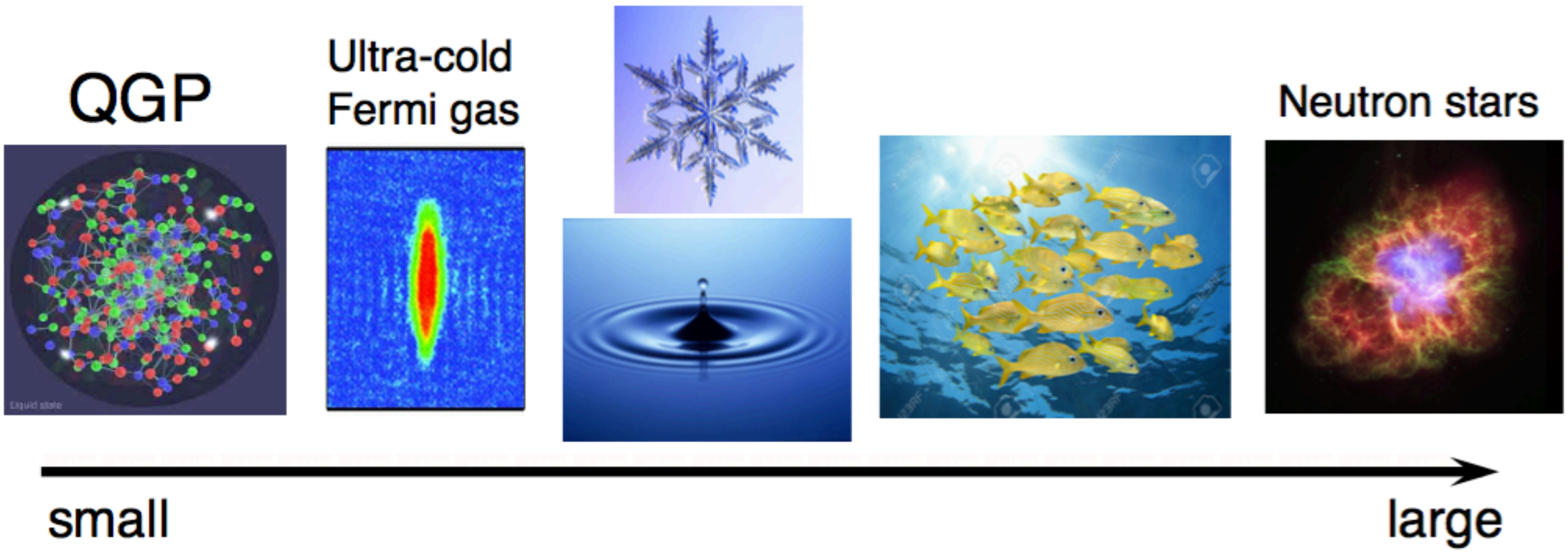


The key questions:

- What is the underlying mechanism to drive?
- Can be understood from fundamental forces?

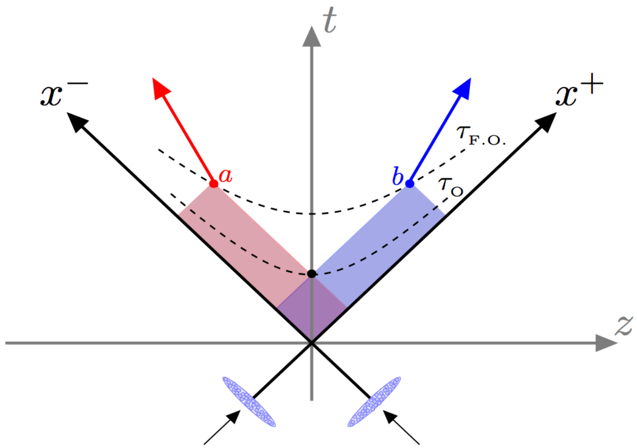
Collectivity and azimuthal anisotropies

Observed long-range correlations in η

⇩

Rooted in **intial/early** stage

$$\tau_O \le \tau_{F.O.} \exp\left(-\frac{1}{2}|y_a - y_b|\right)$$



arXiv:1509.07939

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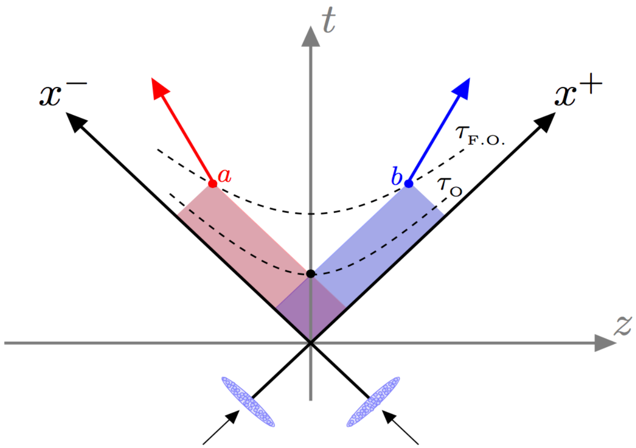
$$\tau_O \leq \tau_{F.O.} \exp\left(-\frac{1}{2}|y_a - y_b|\right)$$ **~ 0.1 fm/c**



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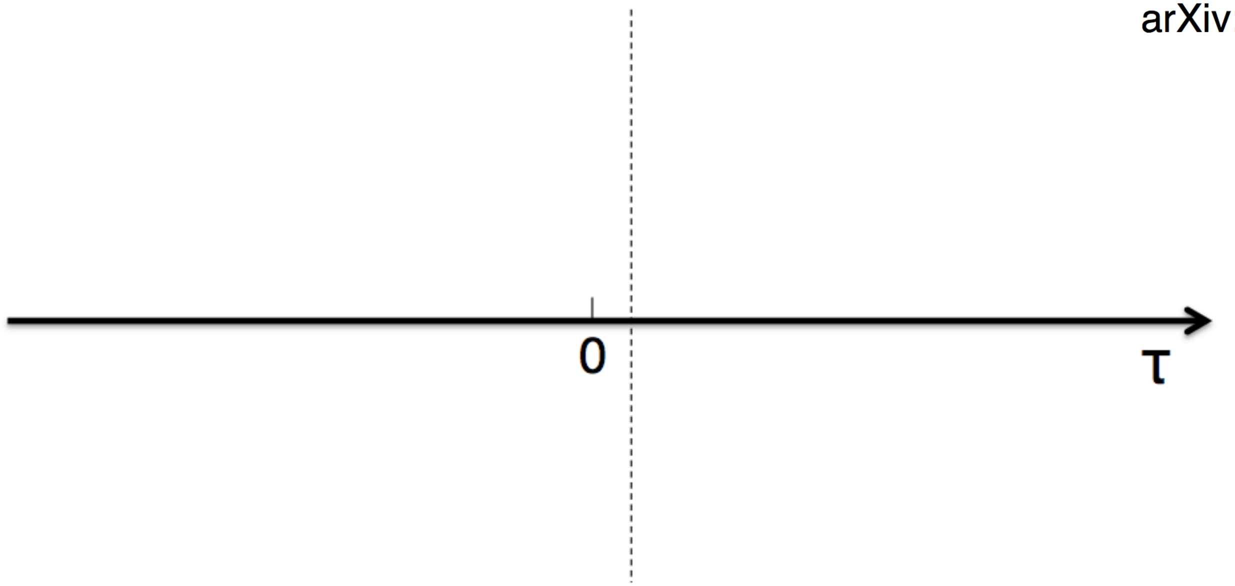

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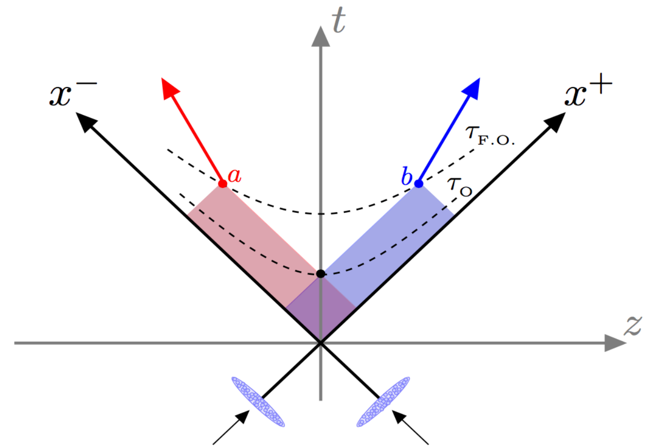

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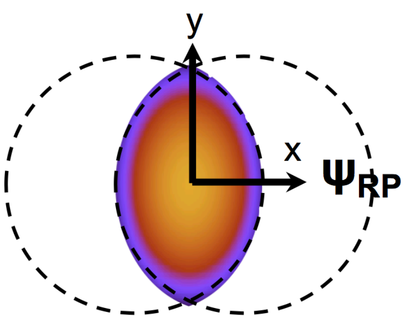
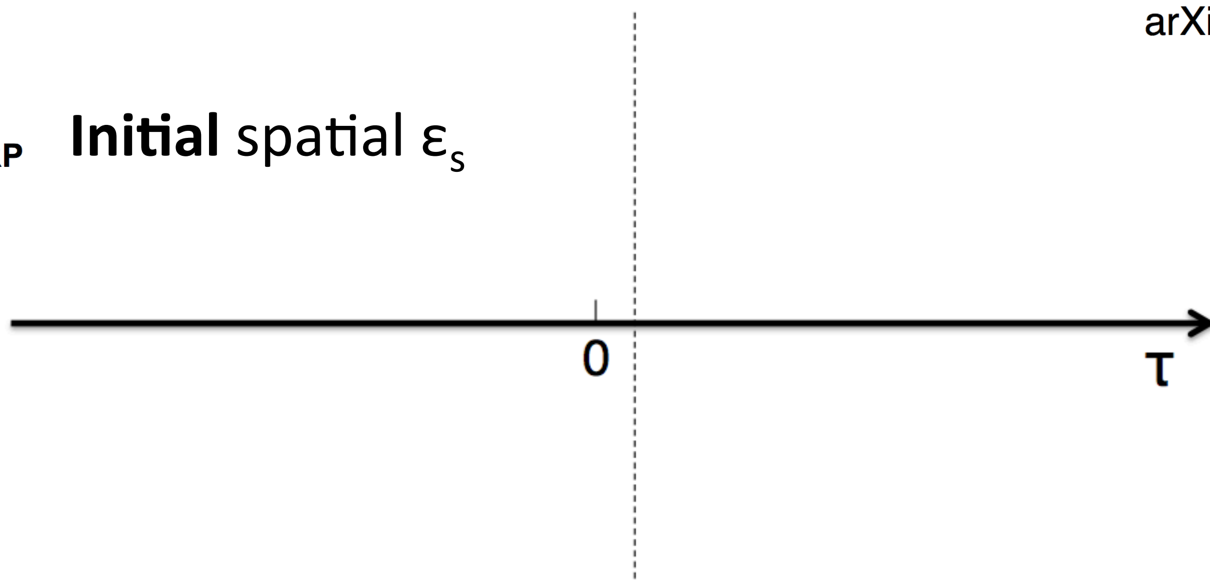


Initial spatial ε_s



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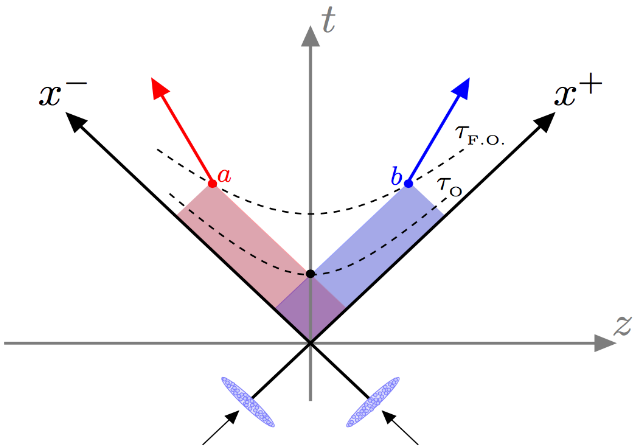

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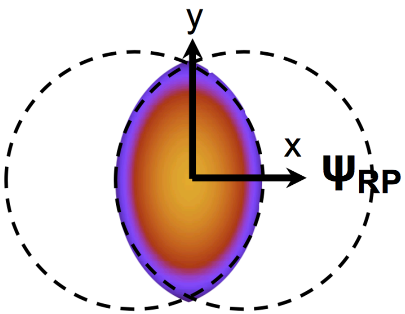
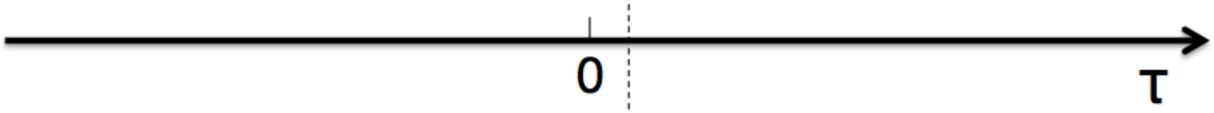
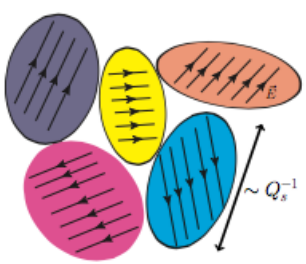


Initial spatial ε_s

+ final interactions





Initial spatial ε_p

Collectivity and azimuthal anisotropies

Observed long-range correlations in η

⇩

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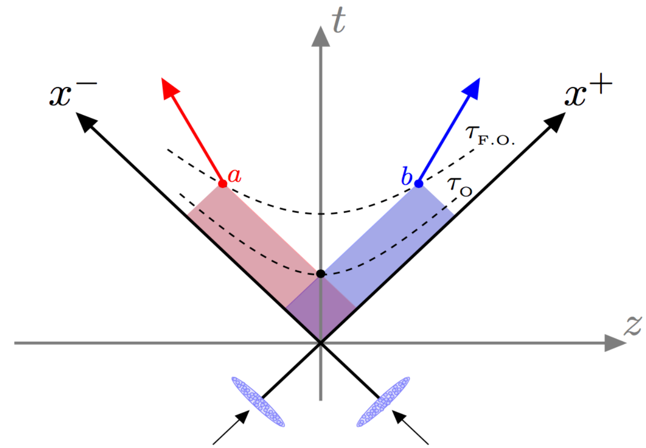

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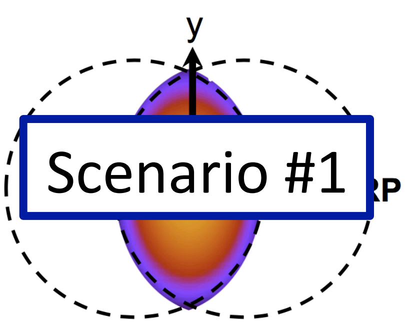
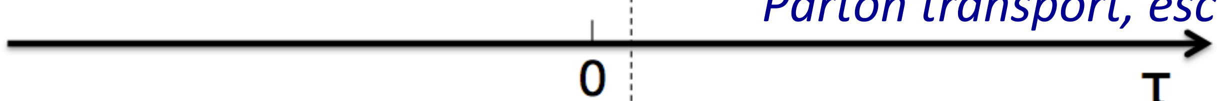


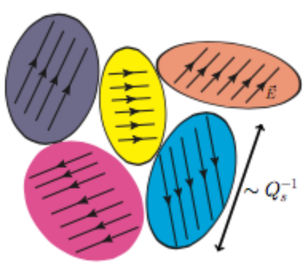
Scenario #1

Initial spatial ε_s **+ final** interactions

Hydrodynamics

Parton transport, escape





Initial spatial ε_p

Collectivity and azimuthal anisotropies

Observed long-range correlations in η

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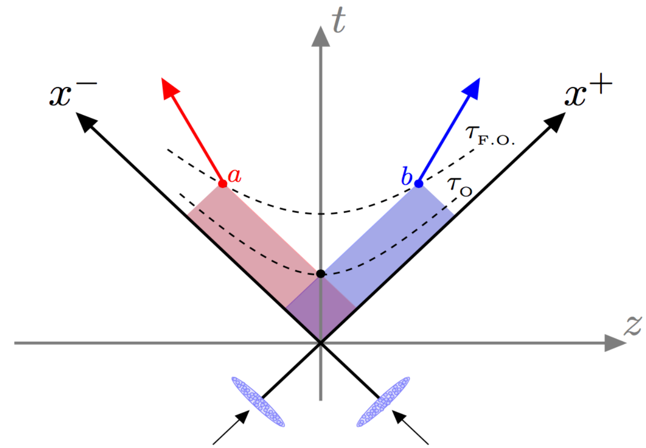

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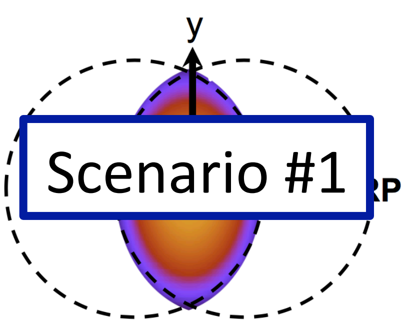


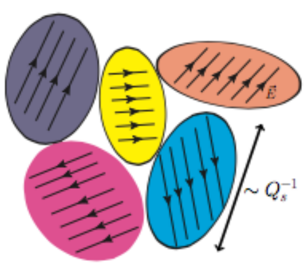
Scenario #1

Initial spatial ε_s **+ final** interactions

Hydrodynamics

Parton transport, escape

0 τ



Initial spatial ε_p
by initial interactions

Collectivity and azimuthal anisotropies

Observed long-range correlations in η

⇩

Rooted in **intial/early** stage

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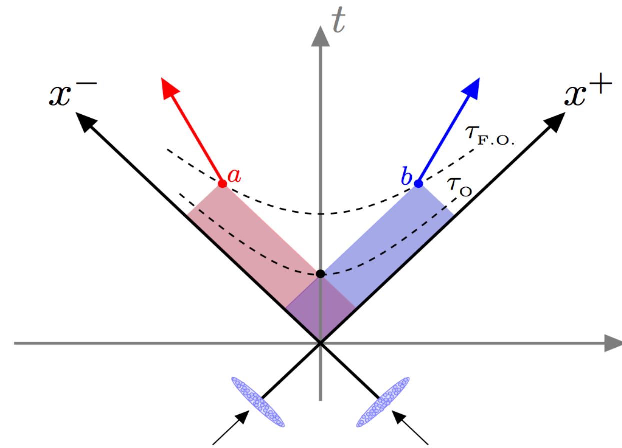

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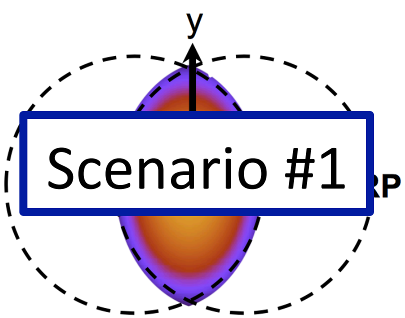
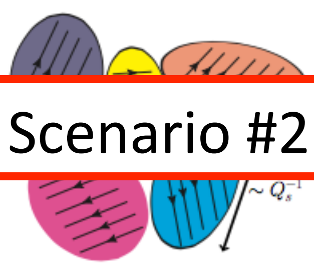


Scenario #1

Initial spatial ε_s **+ final** interactions

Hydrodynamics
Parton transport, escape

0 τ



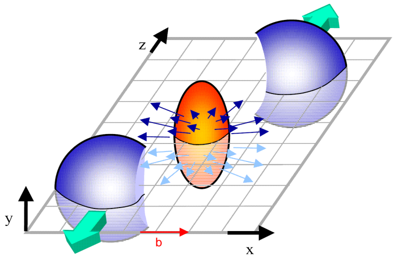
Scenario #2

Initial spatial ε_p
by initial interactions

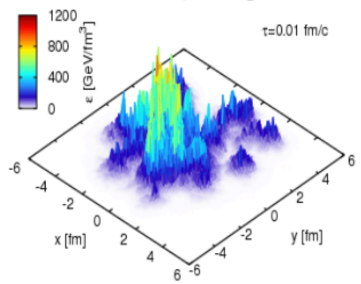
CGC Glasma
Color-field domains, etc.

Perfect fluid paradigm in AA collisions

Initial state



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



Perfect fluid paradigm in AA collisions

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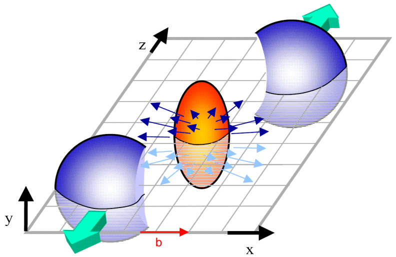
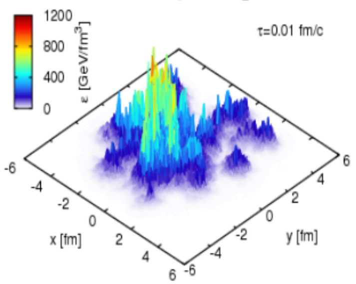


$\varepsilon(x, y, \eta^s)$



Event by Event

Pre-equilibrium

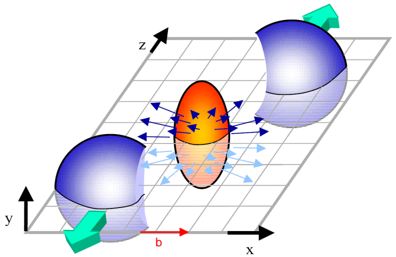
Hydrodynamics
$\delta_\mu T^{\mu\upsilon} = 0 + (\eta, \zeta, \ldots)$

Freeze-out
Hadronic transport

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

Perfect fluid paradigm in AA collisions

Initial state



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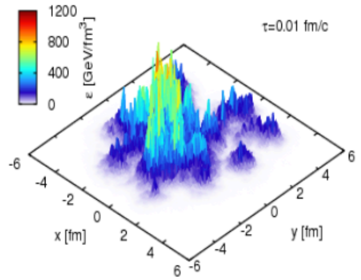

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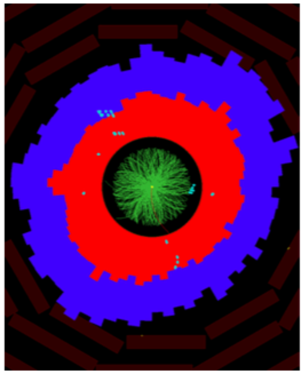
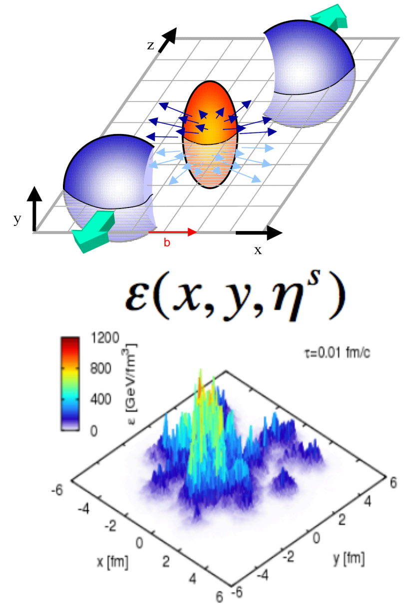
Final state

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



Perfect fluid paradigm in AA collisions

Initial state



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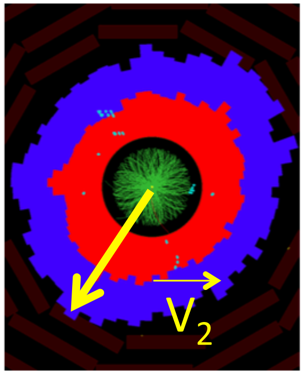
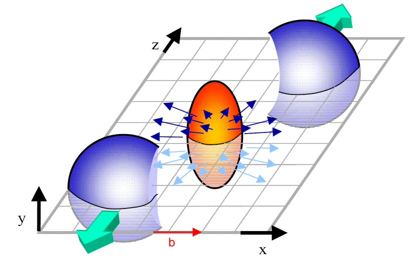


QGP behave like a nearly perfect fluid
(small η/s)

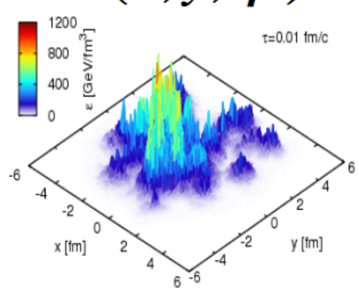
Fourier bases: $$f(p_T,\eta,\phi) = N(p_T,\eta)\sum_{n=-\infty}^{+\infty}\vec{V}_n(p_T,\eta)e^{-in\phi}$$

Perfect fluid paradigm in AA collisions

Initial state



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



Event by Event

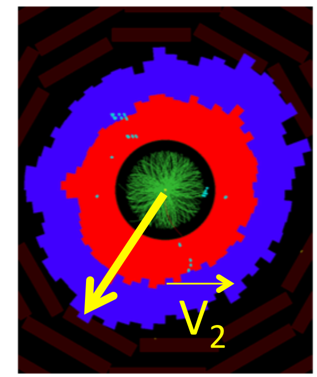
Pre-equilibrium

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

Freeze-out
Hadronic transport

Final state

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



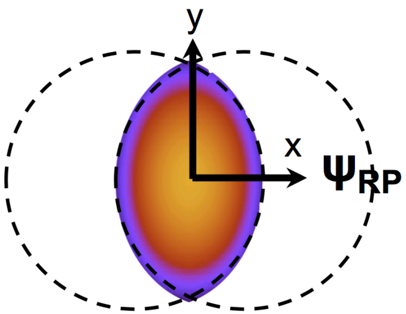
QGP behave like a nearly perfect fluid
(small η/s)

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

Anisotropic flow

$$\vec{V}_n = \mathbf{v_n} e^{in\Psi n}$$

What does the flow harmonic coefficients mean in AA?



Initial-state anisotropy

Flow

≈

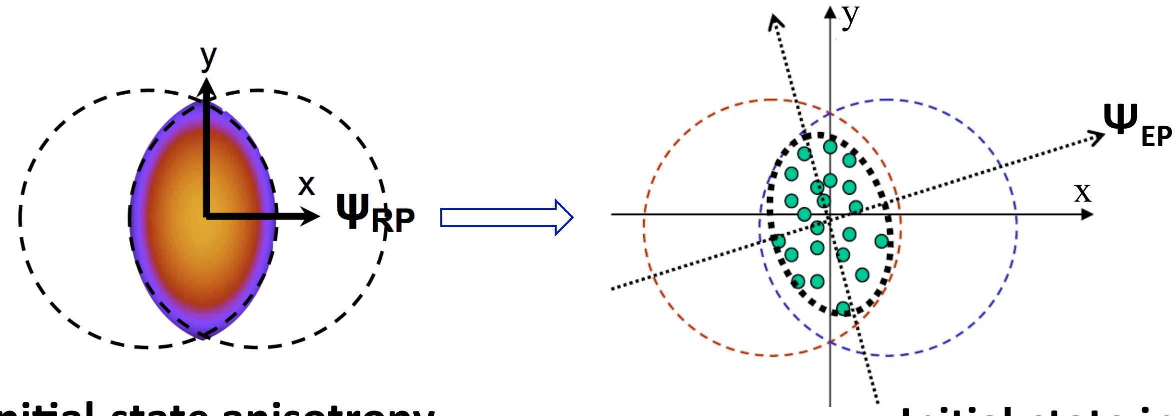
Geometry

Final state:

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

Elliptic flow

What does the flow harmonic coefficients mean in AA?



Initial-state anisotropy

Initial-state inhomogeneity

Flow

≈

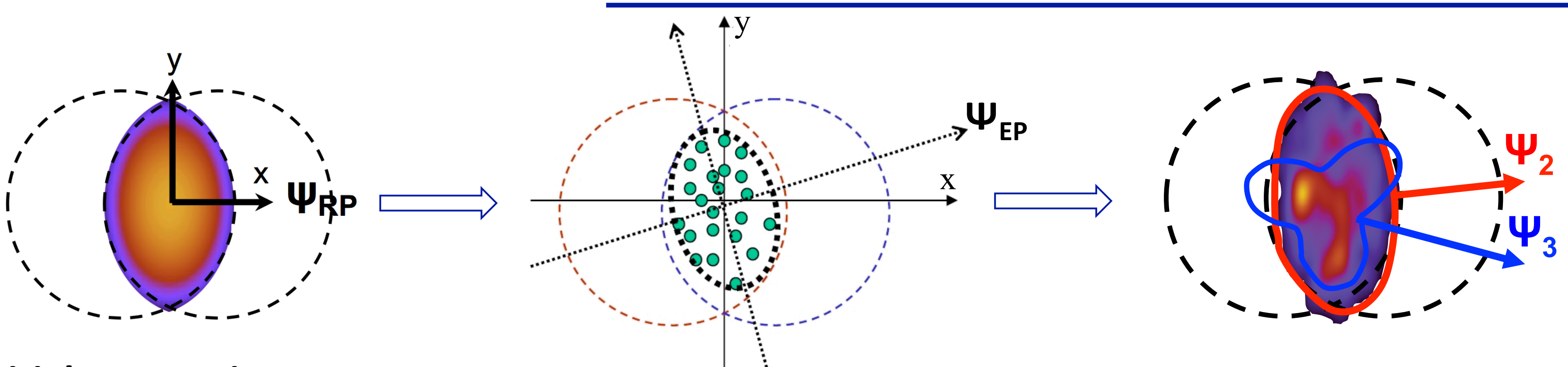
Geometry

Ψ_{EP}: Direction of maximum particle density

<u>Final state:</u>

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

What does the flow harmonic coefficients mean in AA?



Initial-state anisotropy

Initial-state inhomogeneity

Flow

≈

Geometry

+

Fluctuations

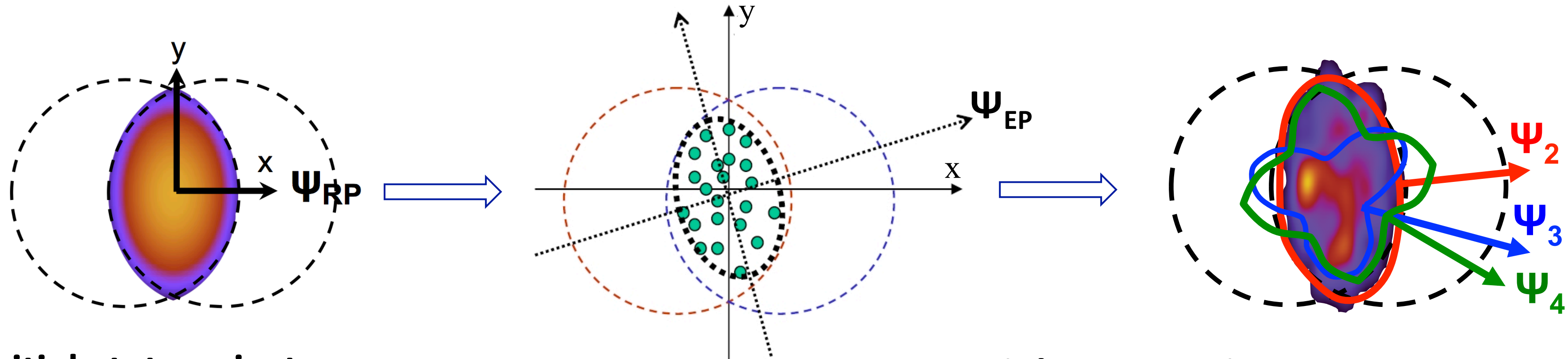
Ψ_{EP}: Direction of maximum particle density

<u>Final state:</u>

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

Triangular flow

What does the flow harmonic coefficients mean in AA?



Initial-state anisotropy

Initial-state inhomogeneity

Flow

≈

Geometry

+

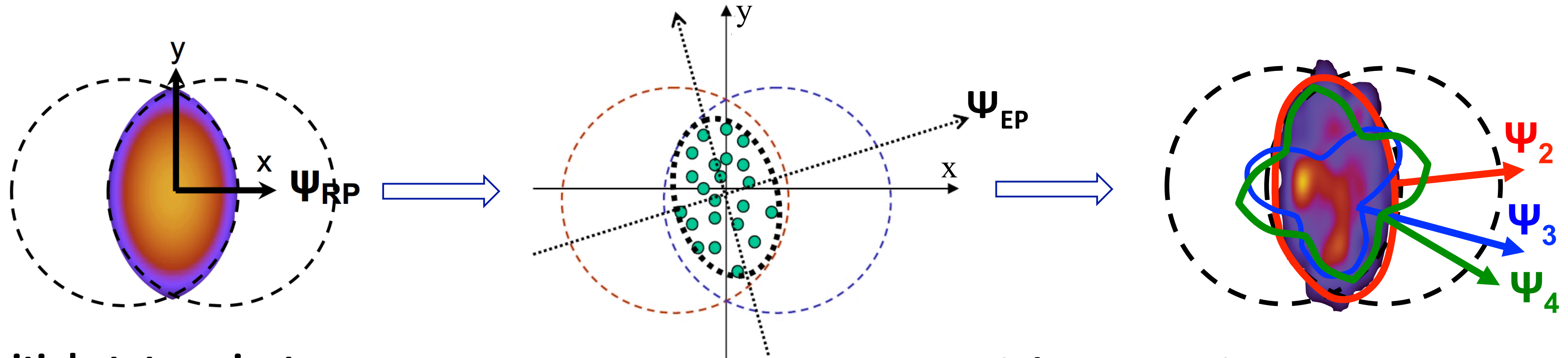
Fluctuations

Ψ_{EP}: Direction of maximum particle density

Final state:

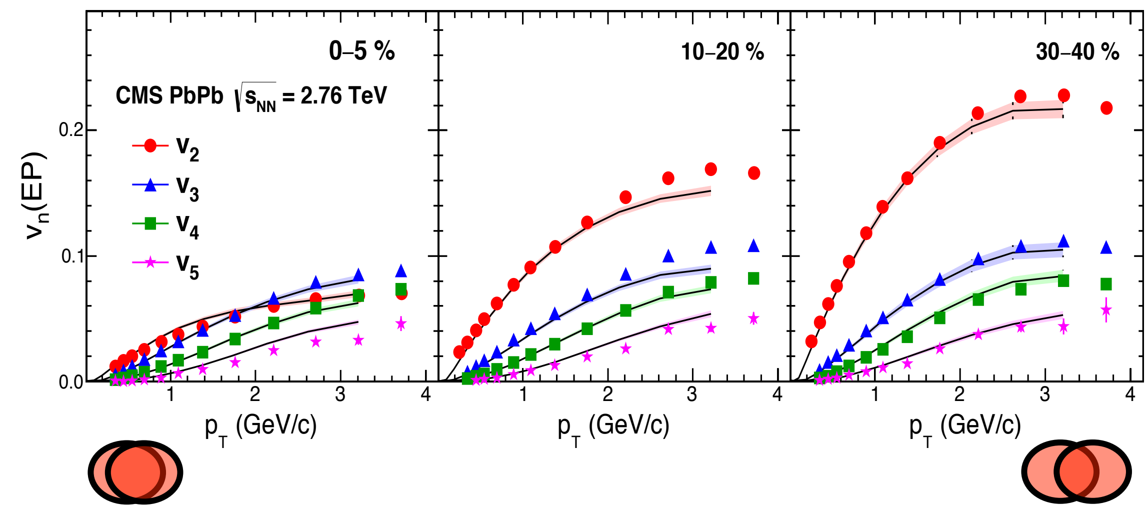
$$f(p_T, \phi, \eta) \sim 1 \quad +2v_2(p_T,\eta)cos\left[2(\phi-\Psi_2)\right]$$
$$+2v_3(p_T,\eta)cos\left[3(\phi-\Psi_3)\right]$$
$$+2v_4(p_T,\eta)cos\left[4(\phi-\Psi_4)\right]$$
$$+2v_5(p_T,\eta)cos\left[5(\phi-\Psi_5)\right]$$
$$+\ldots$$

What does the flow harmonic coefficients mean in AA?



Initial-state anisotropy | **Initial-state inhomogeneity**

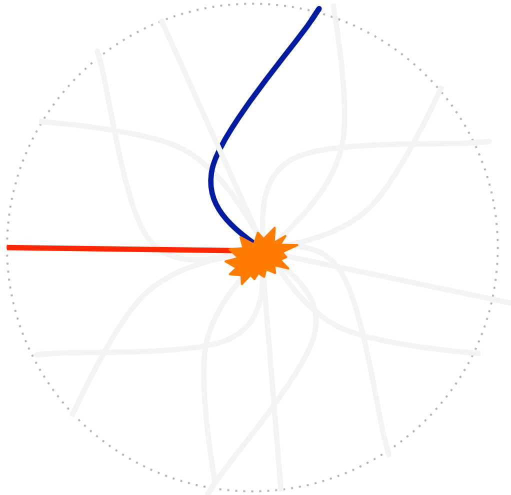
Flow ≈ Geometry + Fluctuations



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

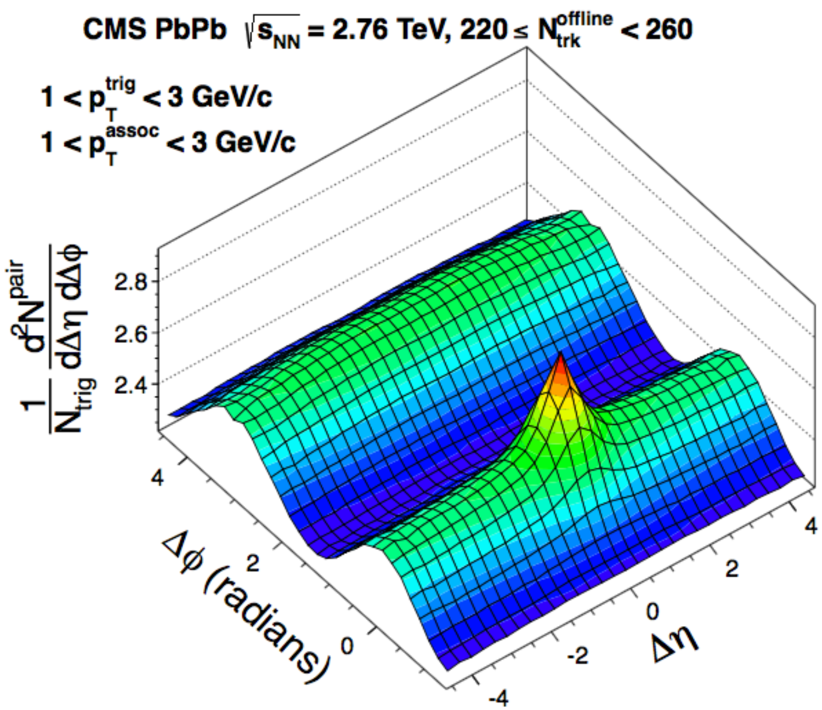
Phys. Rev. Lett. 110, 012302 **IP glasma + MUSIC**

Looking for correlations in data: 2-particle correlations

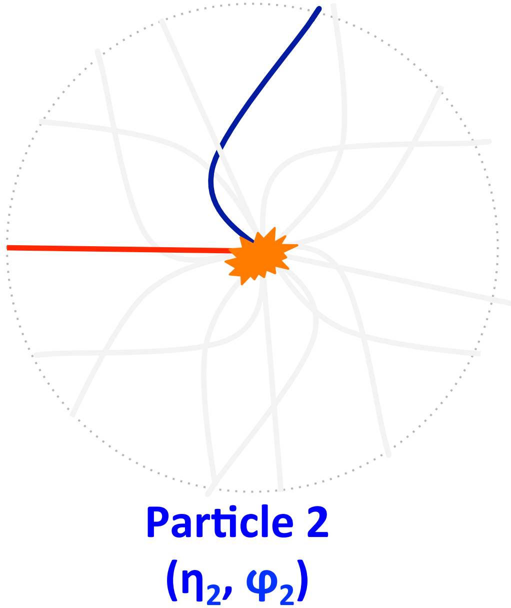


Particle 1
(η_1, φ_1)

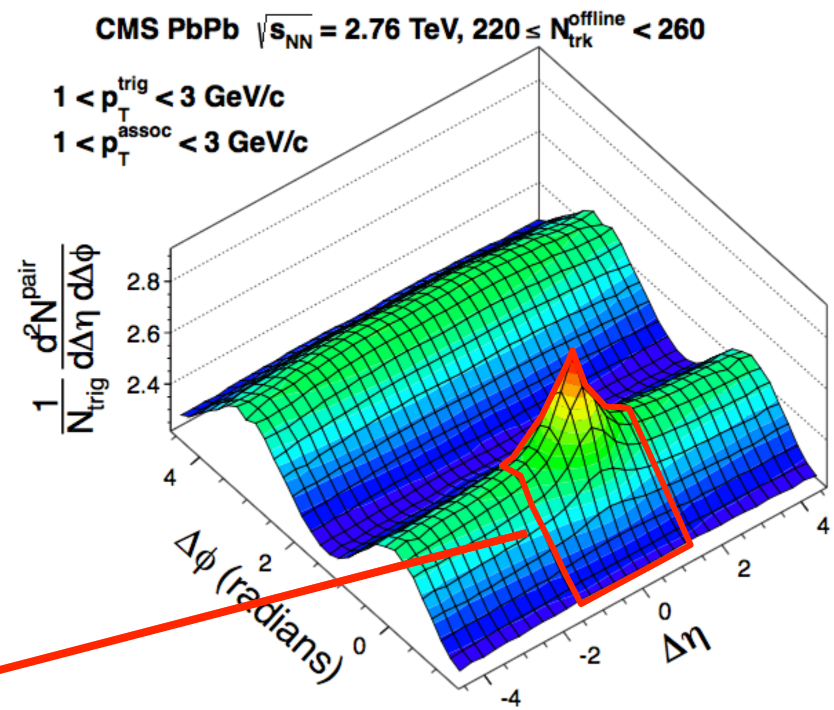
$$\Delta\eta = \eta_1 - \eta_2$$
$$\Delta\varphi = \varphi_1 - \varphi_2$$

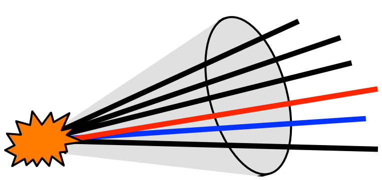


Looking for correlations in data: 2-particle correlations



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

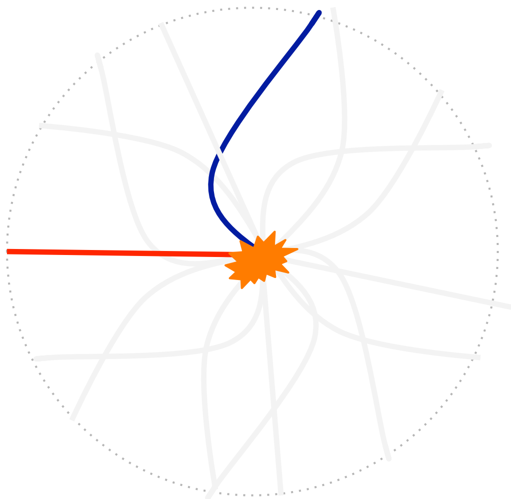




+

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

Looking for correlations in data: 2-particle correlations



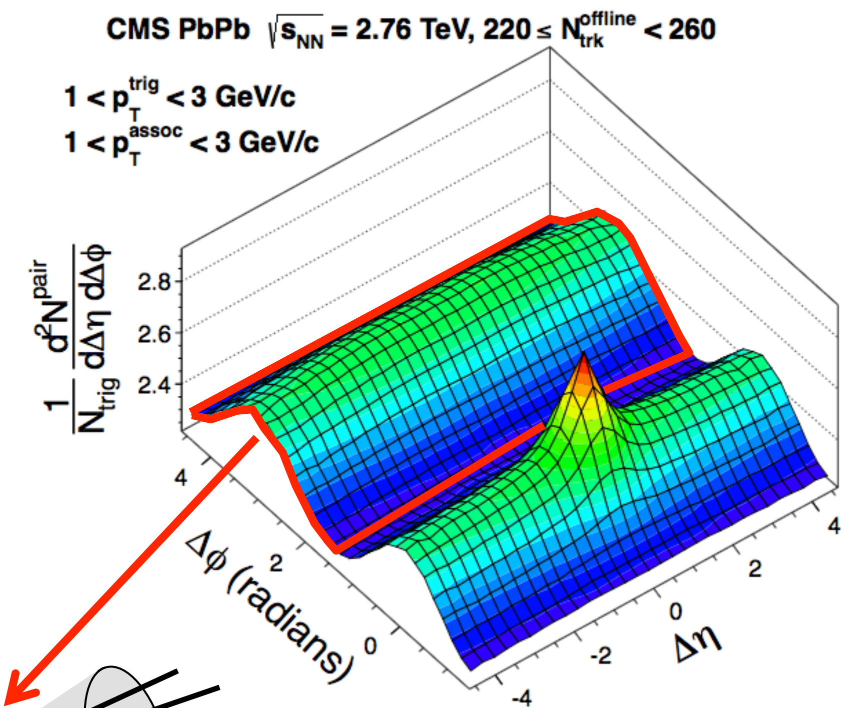
Particle 2

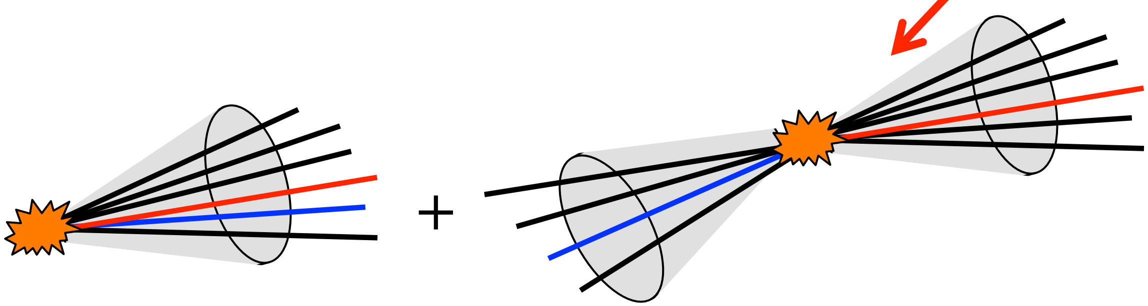
(η_2, φ_2)

Particle 1

(η_1, φ_1)

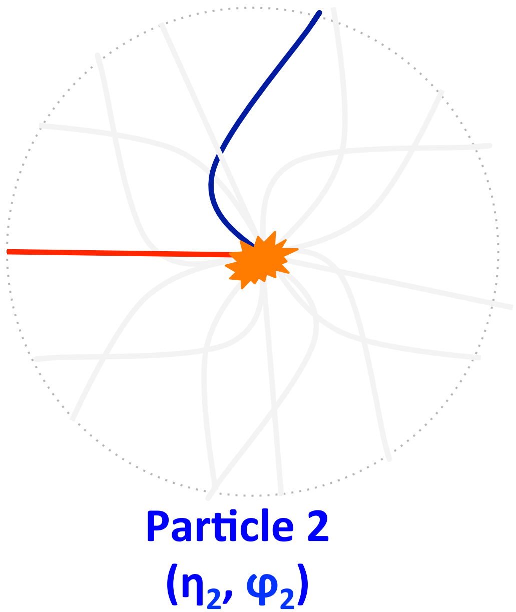
$$\Delta\eta = \eta_1 - \eta_2$$
$$\Delta\varphi = \varphi_1 - \varphi_2$$



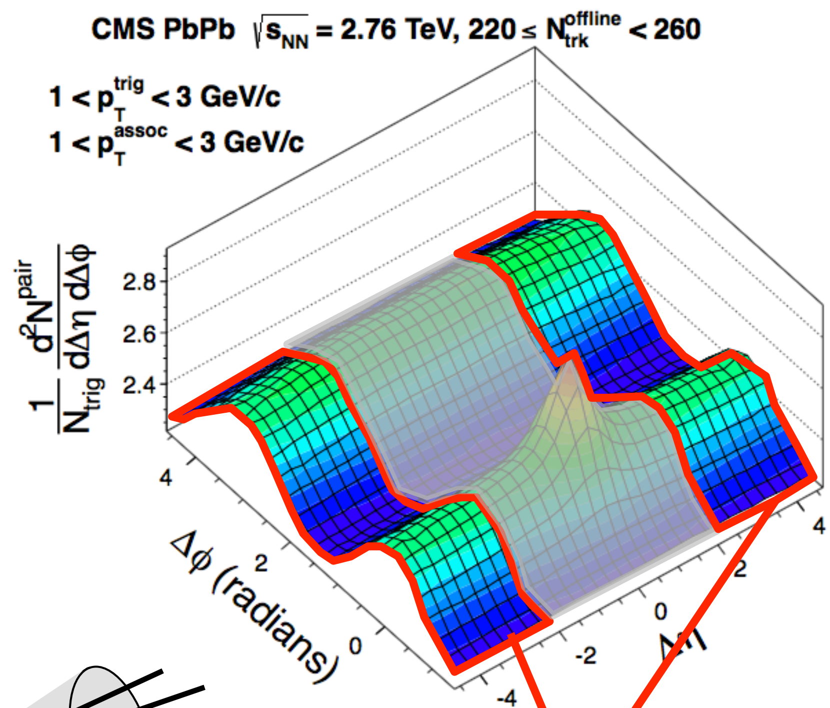


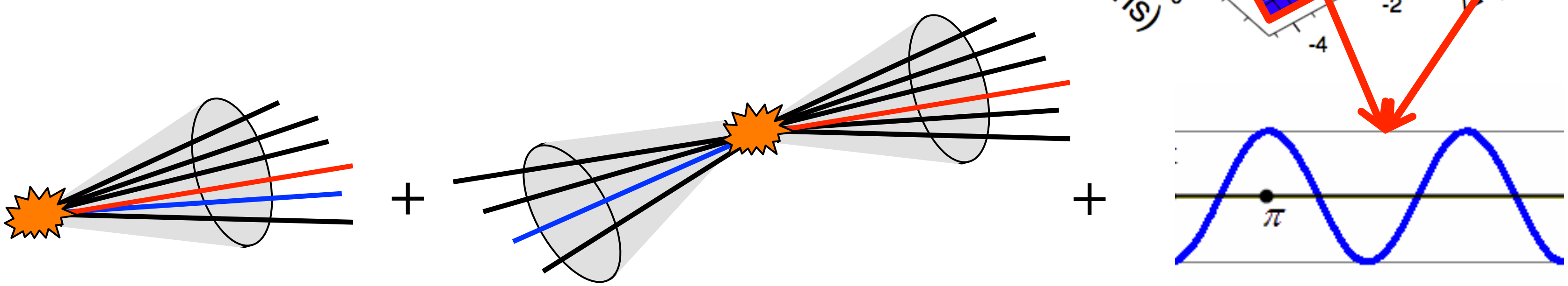
Single jet contribution + Back-to-back jet contribution

Looking for correlations in data: 2-particle correlations



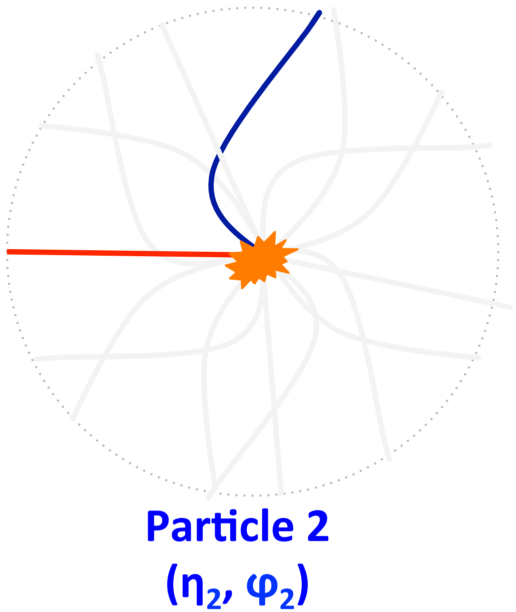
$$\Delta\eta = \eta_1 - \eta_2$$
$$\Delta\varphi = \varphi_1 - \varphi_2$$



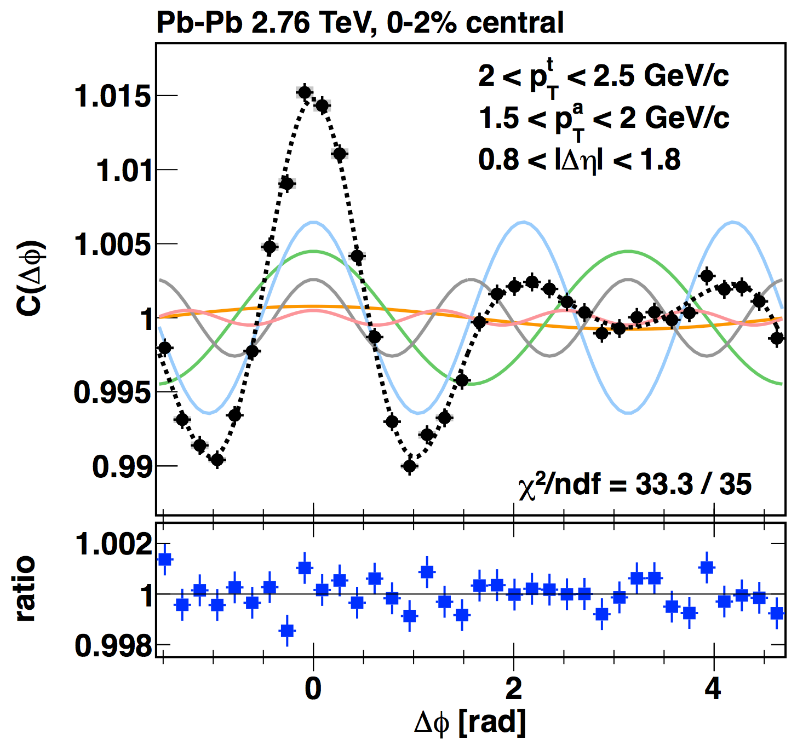


Single jet contribution | Back-to-back jet contribution | Collective effect

Looking for correlations in data: 2-particle correlations



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



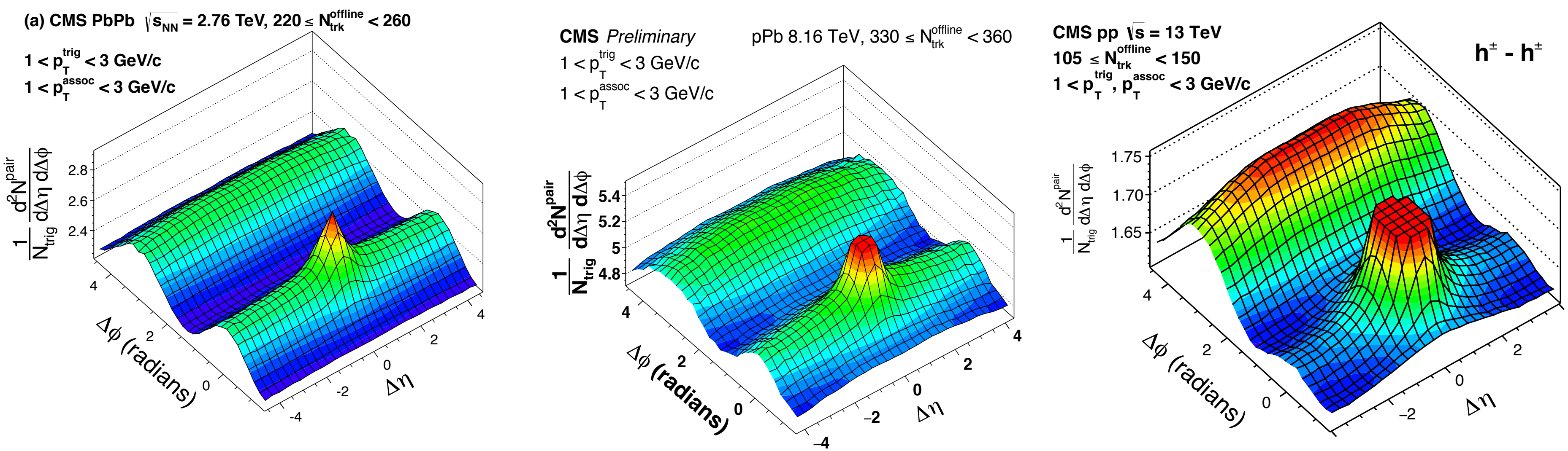
$$\frac{1}{N_{\text{trig}}}\frac{dN^{\text{pair}}}{d\Delta\phi} = \frac{N_{\text{assoc}}}{2\pi}\left\{1 + \sum_n 2V_{n\Delta}\cos(n\Delta\phi)\right\}$$

- Assuming factorization: $V_{n\Delta} = v_n^2$

Still extremely sensitive to "non-flow" correlation like jets, dijets, etc.

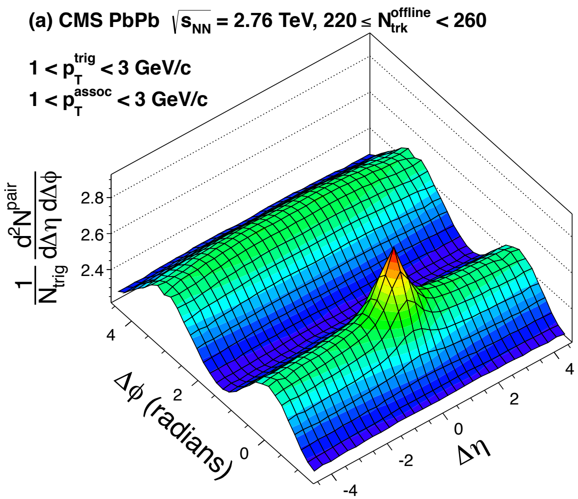
N-particle correlations help to fix the issue

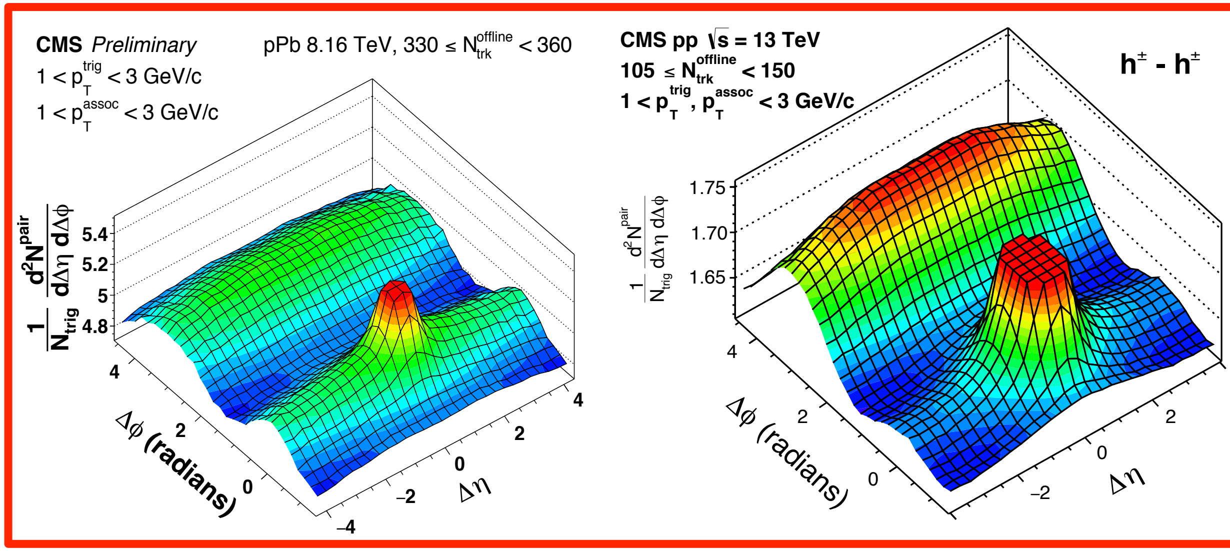
"Surprising" long range correlation in small systems



PhysLettB.2013.06, 028, PhysLettB.2016.12, 009

“Surprising” long range correlation in small systems



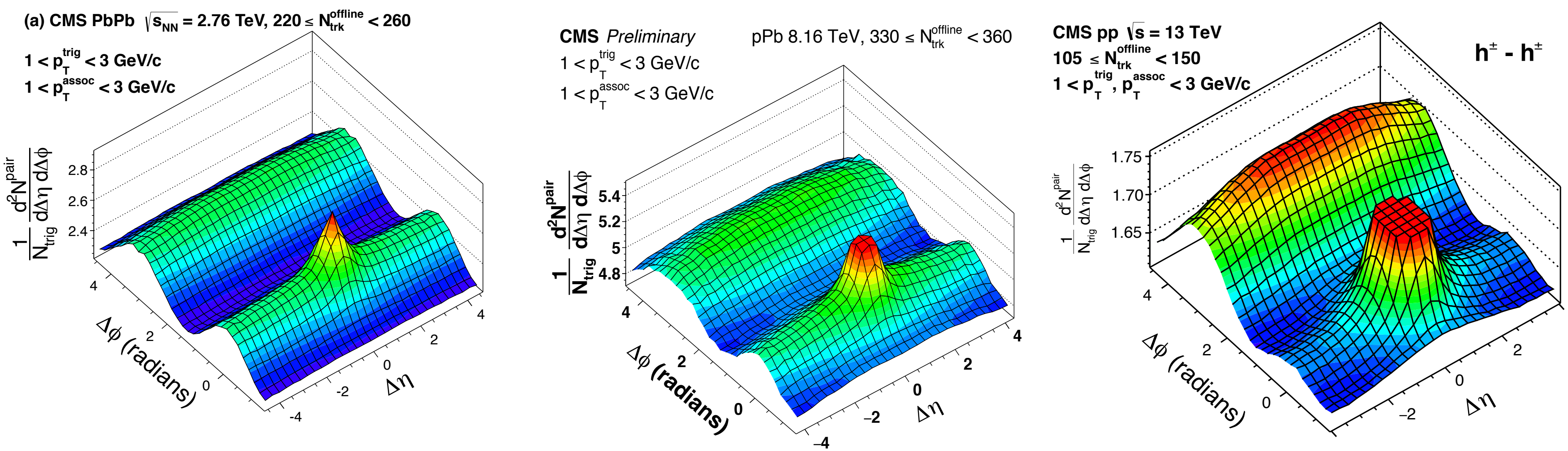


PhysLettB.2013.06, 028, PhysLettB.2016.12, 009

“collective effect” (two particles with very different η are “connected”)

Also observed in small system in **high multiplicity events**

"Surprising" long range correlation in small systems



PhysLettB.2013.06, 028, PhysLettB.2016.12, 009

"collective effect" (two particles with very different η are "connected")

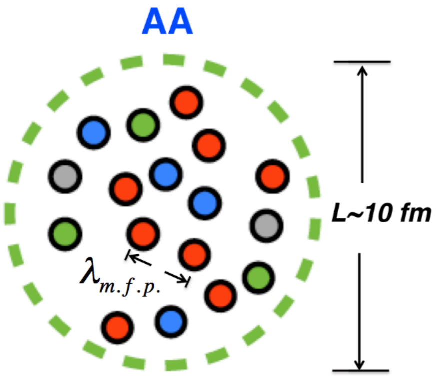
Also observed in small system in **high multiplicity events**

Is it a sign of QGP formation in small system?

How small a QGP can be?

Hydrodynamics apply when:

$\mathbf{L >> \lambda_{mfp}}$ where $\mathbf{\lambda_{mfp} \approx (g^4T)^{-1}}$

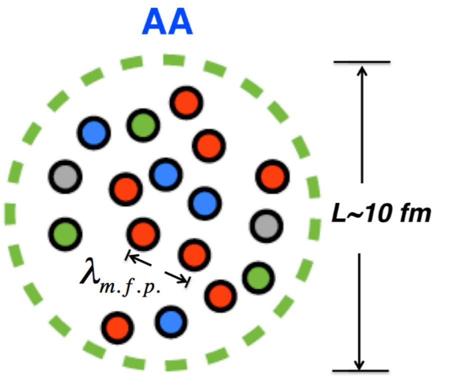


How small a QGP can be?

Hydrodynamics apply when:

$\mathbf{L \gg \lambda_{mfp}}$ where $\mathbf{\lambda_{mfp} \approx (g^4T)^{-1}}$

- For $g \approx 1$, $LT \gg 1$

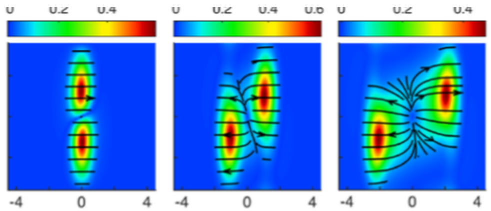


How small a QGP can be?

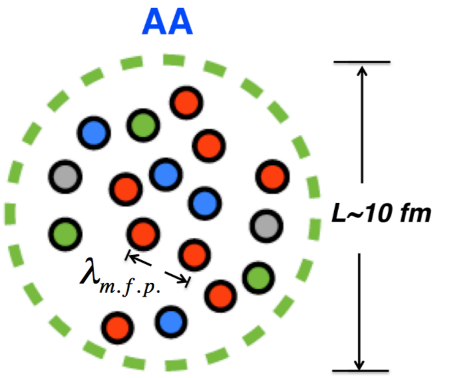
Hydrodynamics apply when:

L >> λ_{mfp} where **$\lambda_{mfp} \approx (g^4T)^{-1}$**

- For $g \approx 1$, $LT >> 1$
- For $g \to \infty$ $LT \approx 1$



QGP fluid in pp



How small a QGP can be?

Hydrodynamics apply when:

$$L \gg \lambda_{mfp} \text{ where } \lambda_{mfp} \approx (g^4 T)^{-1}$$

- For $g \approx 1$, $LT \gg 1$
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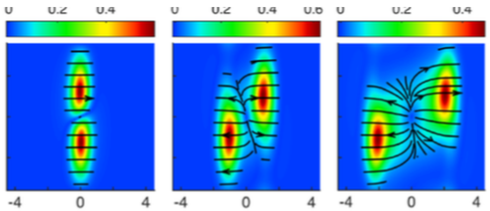
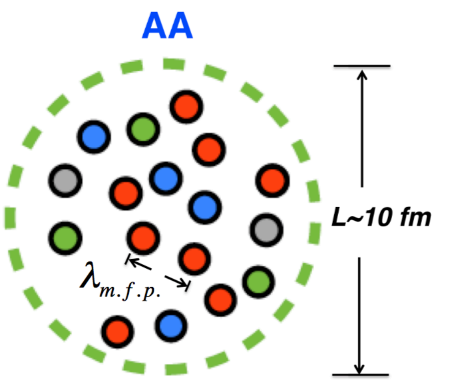


QGP fluid in pp



Experimental conditions:

$$N_{trk} \approx (LT)^3 \rightarrow N_{trk} / L^3 \approx s \approx T^3$$

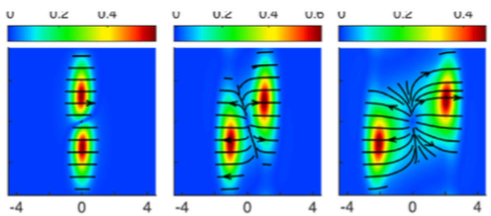
What is the smallest size for a QGP fuild?

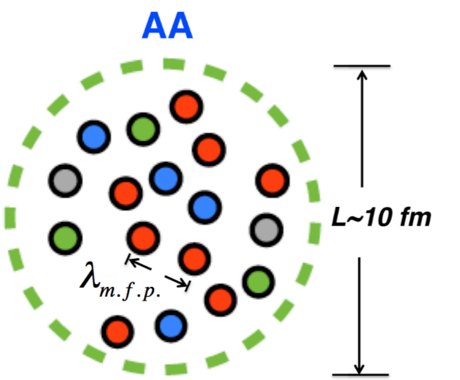
How small a QGP can be?

Hydrodynamics apply when:

$$L >> \lambda_{mfp} \text{ where } \lambda_{mfp} \approx (g^4 T)^{-1}$$

- For g ≈ 1, LT >> 1
- For g → ∞ LT ≈ 1


QGP fluid in pp

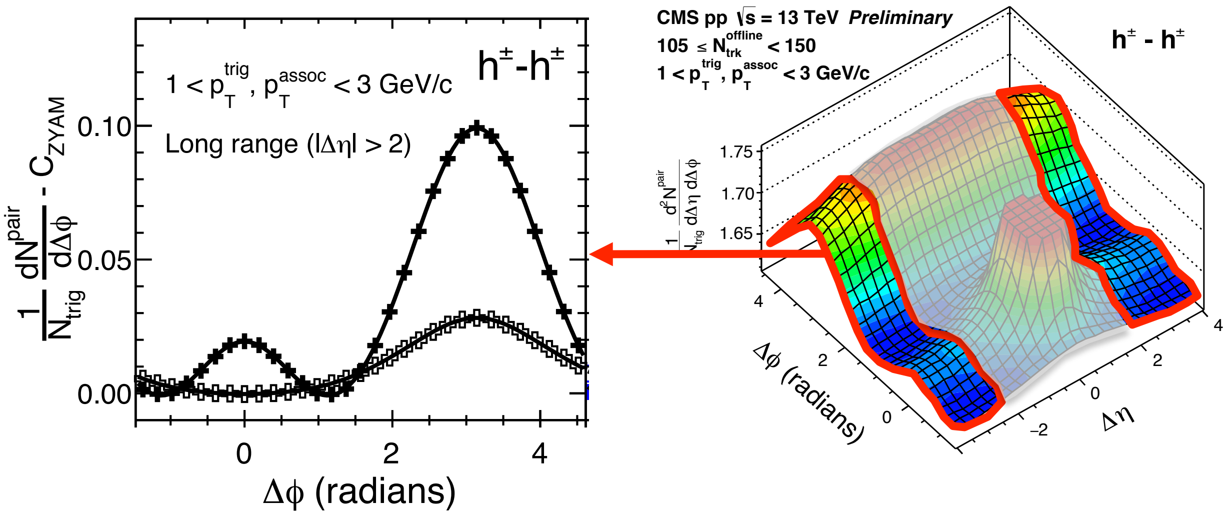


Experimental conditions:

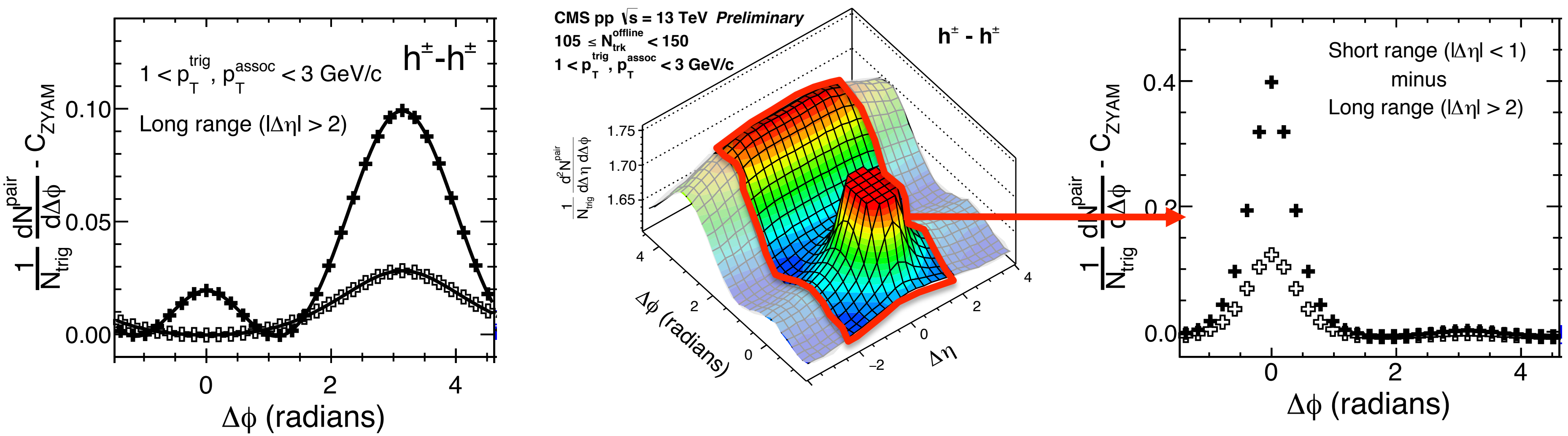
$$N_{trk} \approx (LT)^3 \rightarrow N_{trk} / L^3 \approx s \approx T^3$$

What is the smallest multiplicity/entropy for a QGP fuild?

Fourier harmonics and 2-particle correlation in small systems

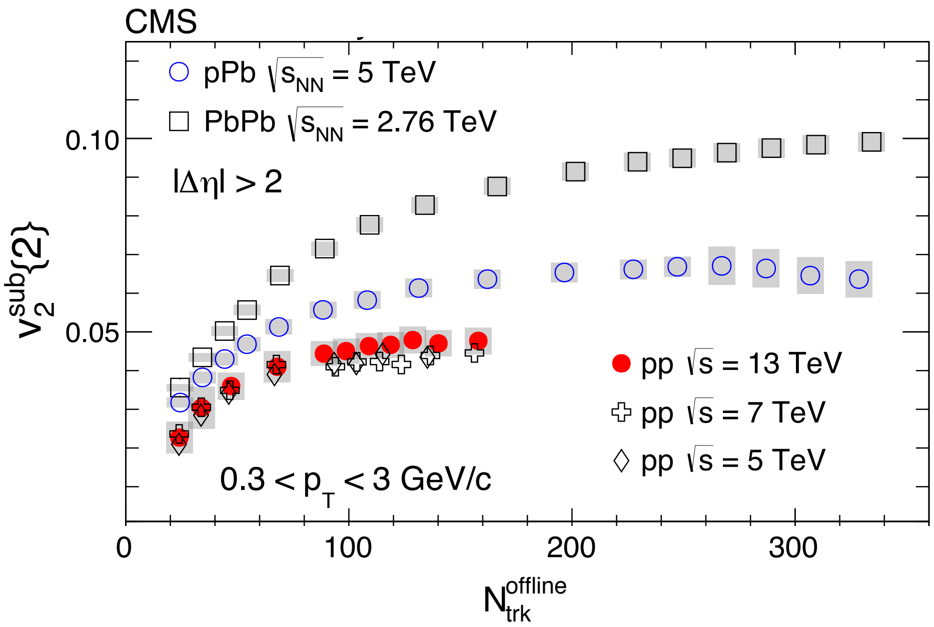


Fourier harmonics and 2-particle correlation in small systems



Fourier harmonics and 2-particle correlation in small systems

- Low multiplicity subtraction applied
- v_2:
  - No energy dependence observed
  - Similar shape as pPb and PbPb
  - Smaller than bigger system



- v_3:
  - No energy dependence observed
  - Different from pPb and PbPb

Fourier harmonics and 2-particle correlation in small systems

- Low multiplicity subtraction applied
- v_2:
  - No energy dependence observed
  - Similar shape as pPb and PbPb
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- v_3:
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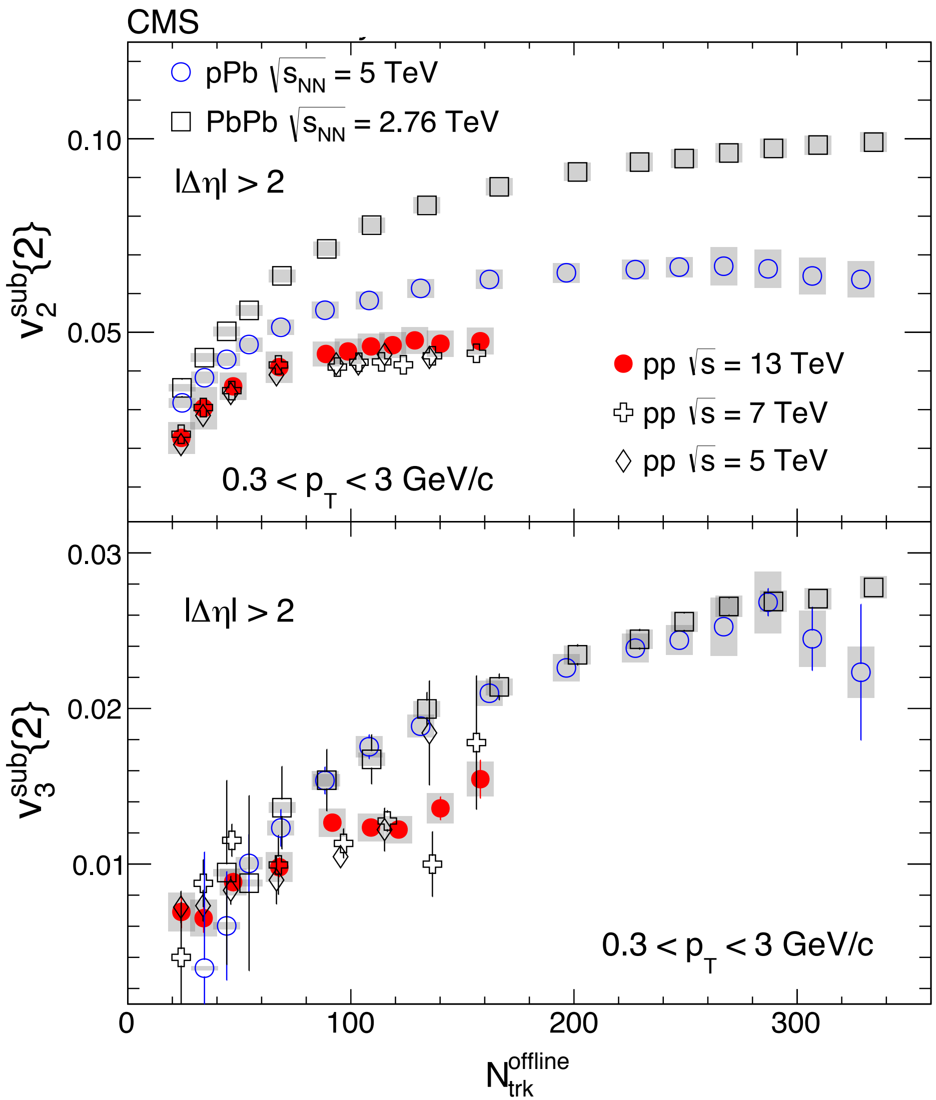
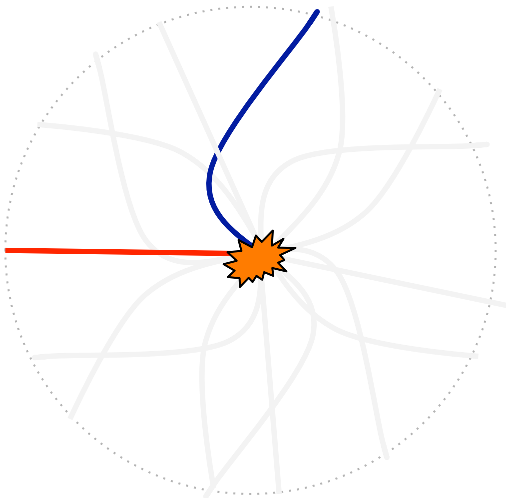
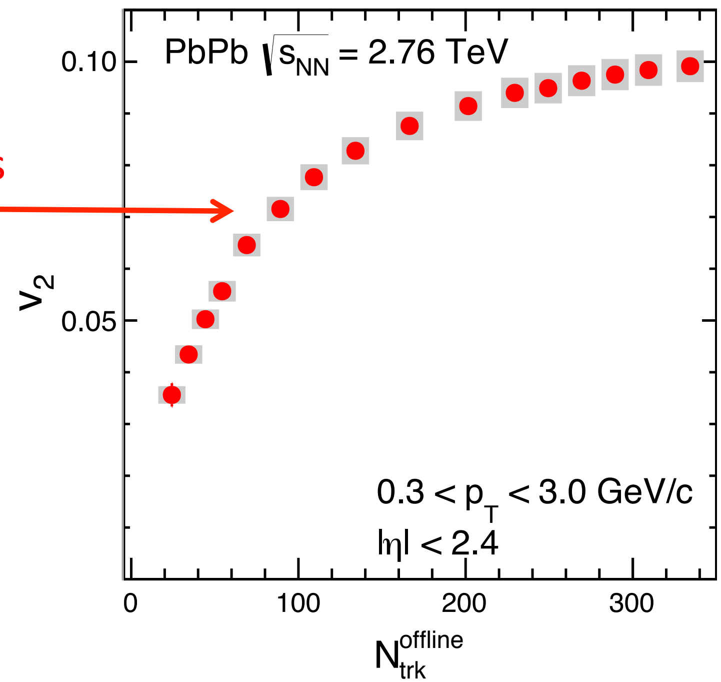


Fourier harmonics and multi-particle cumulants in small systems



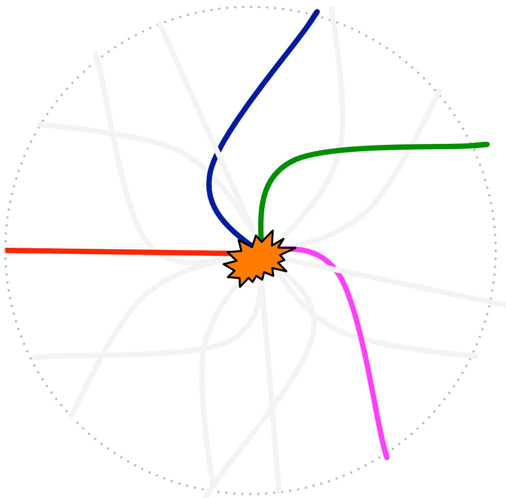
2 particle correlations

$v_2\{2\}$



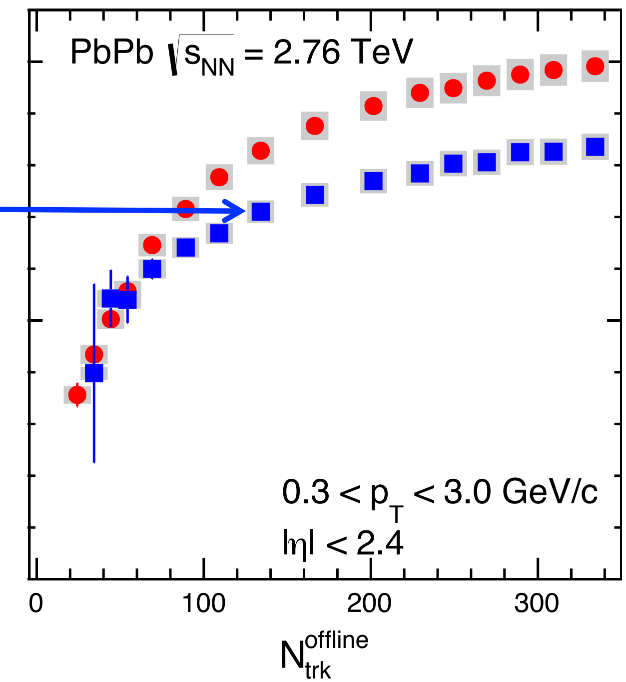
PhysLettB.2016.12, 009

Fourier harmonics and multi-particle cumulants in small systems



4 particle correlations

$v_2\{4\}$



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

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

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

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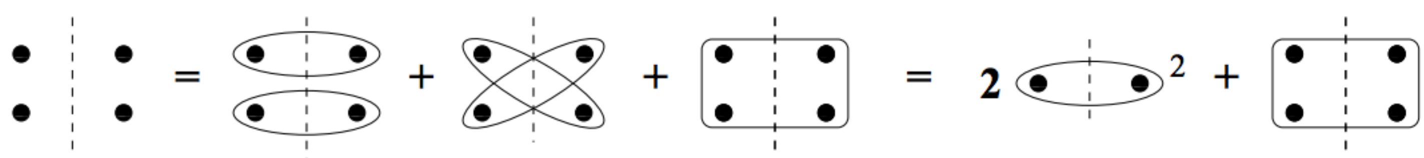
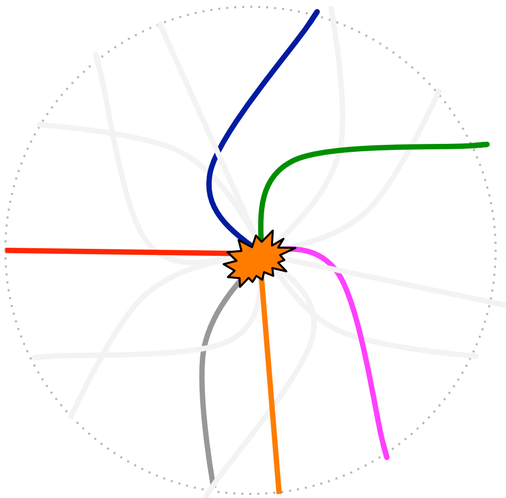


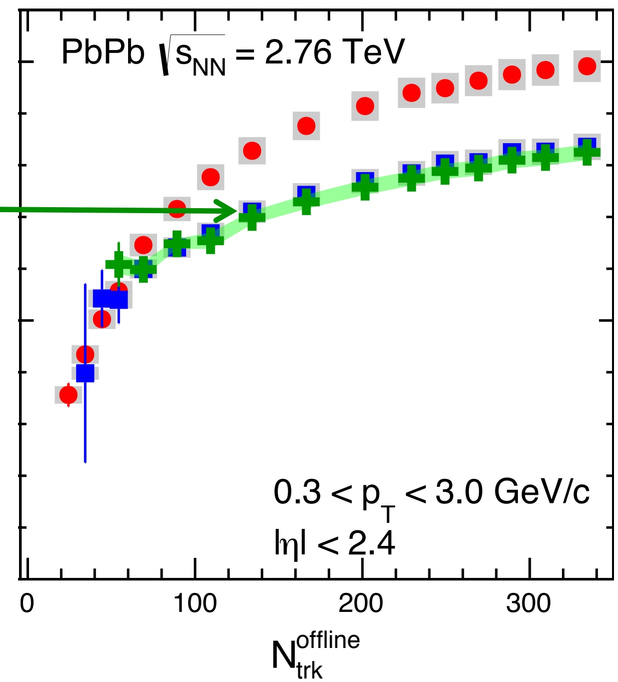
$$c_n\{4\} = \langle\langle 4 \rangle\rangle - 2\langle\langle 2 \rangle\rangle^2, \qquad v_n\{4\} = \sqrt[4]{-c_n\{4\}}$$

Fourier harmonics and multi-particle cumulants in small systems



6 particle correlations

$v_2\{6\}$



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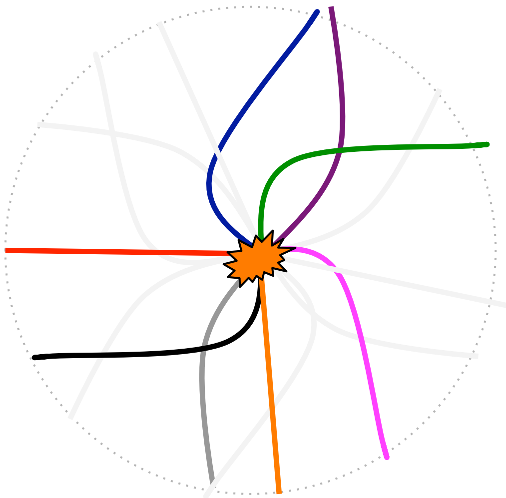
- Less sensitive to non-flow (i.e. jet induced correlation)
- Needs larger sample of events

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

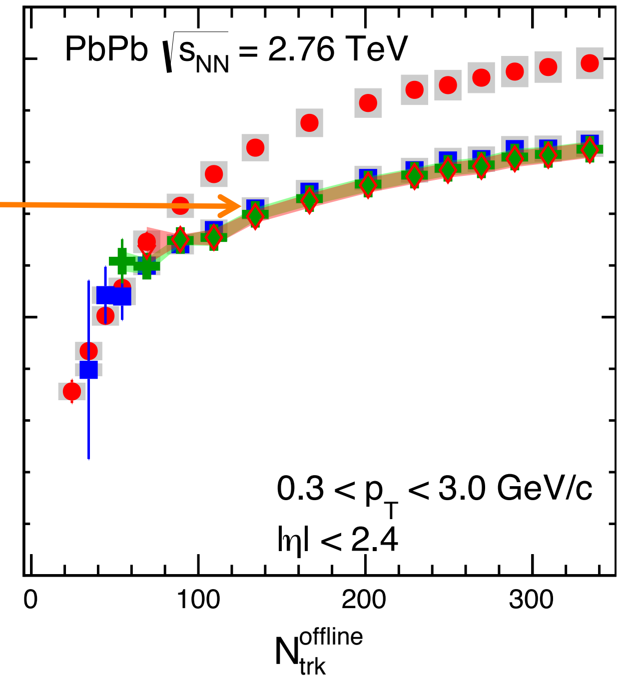
Fourier harmonics and multi-particle cumulants in small systems



8 particle correlations

$v_2\{8\}$

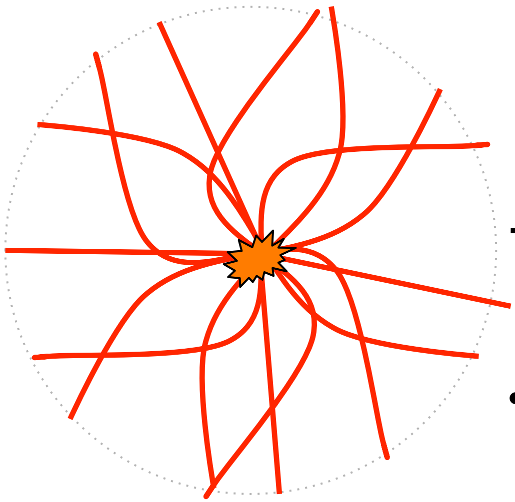
- Less sensitive to non-flow (i.e. jet induced correlation)
- Needs larger sample of events



PhysLettB.2016.12, 009

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

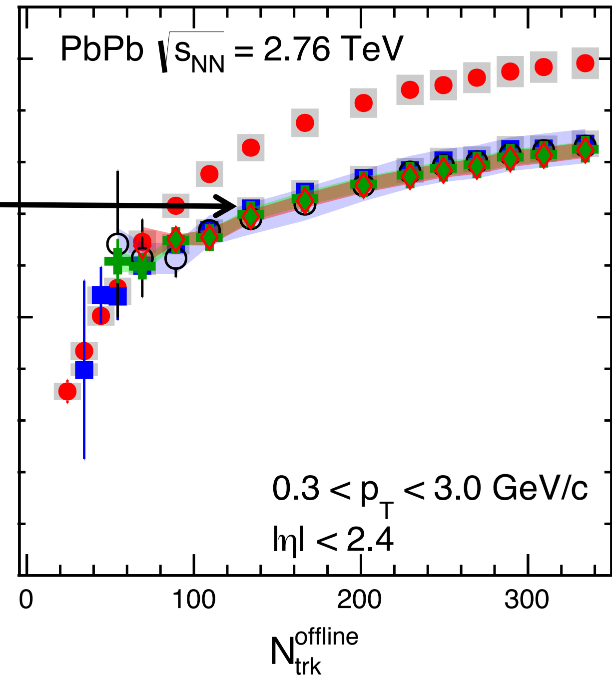
Fourier harmonics and multi-particle cumulants in small systems



All particles

$v_2\{LYZ\}$

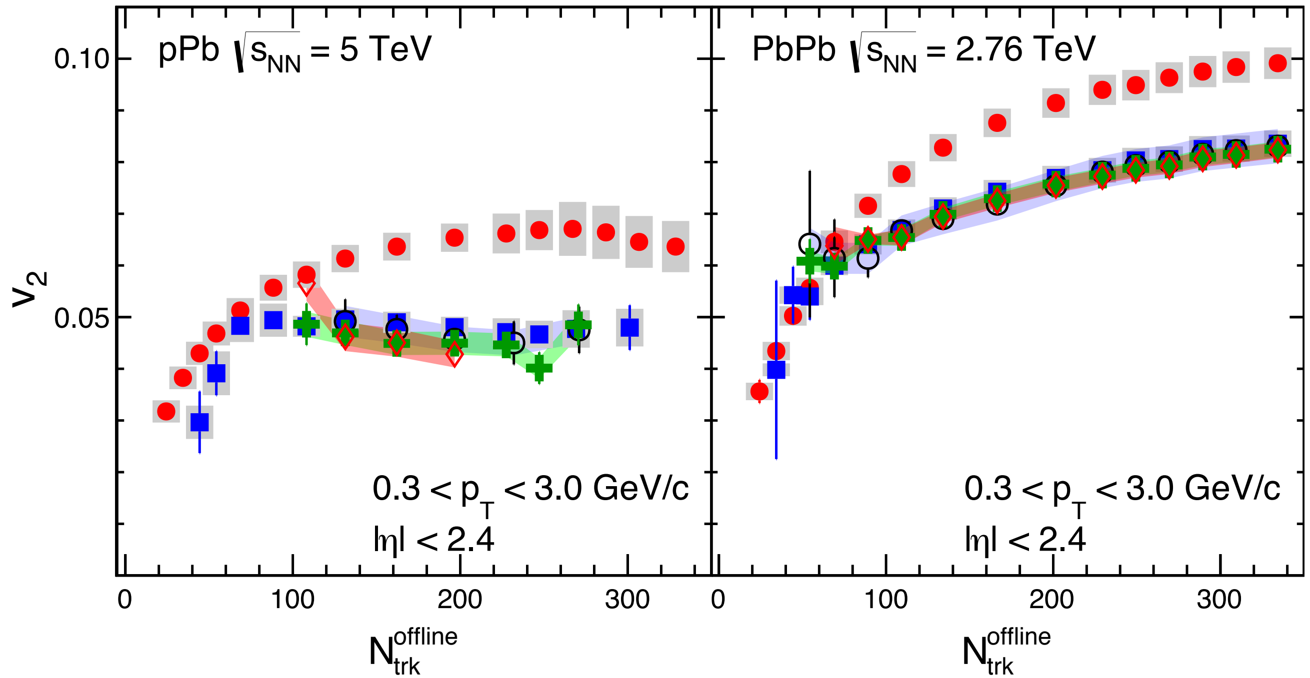
- Less sensitive to non-flow (i.e. jet induced correlation)
- Needs larger sample of events



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)

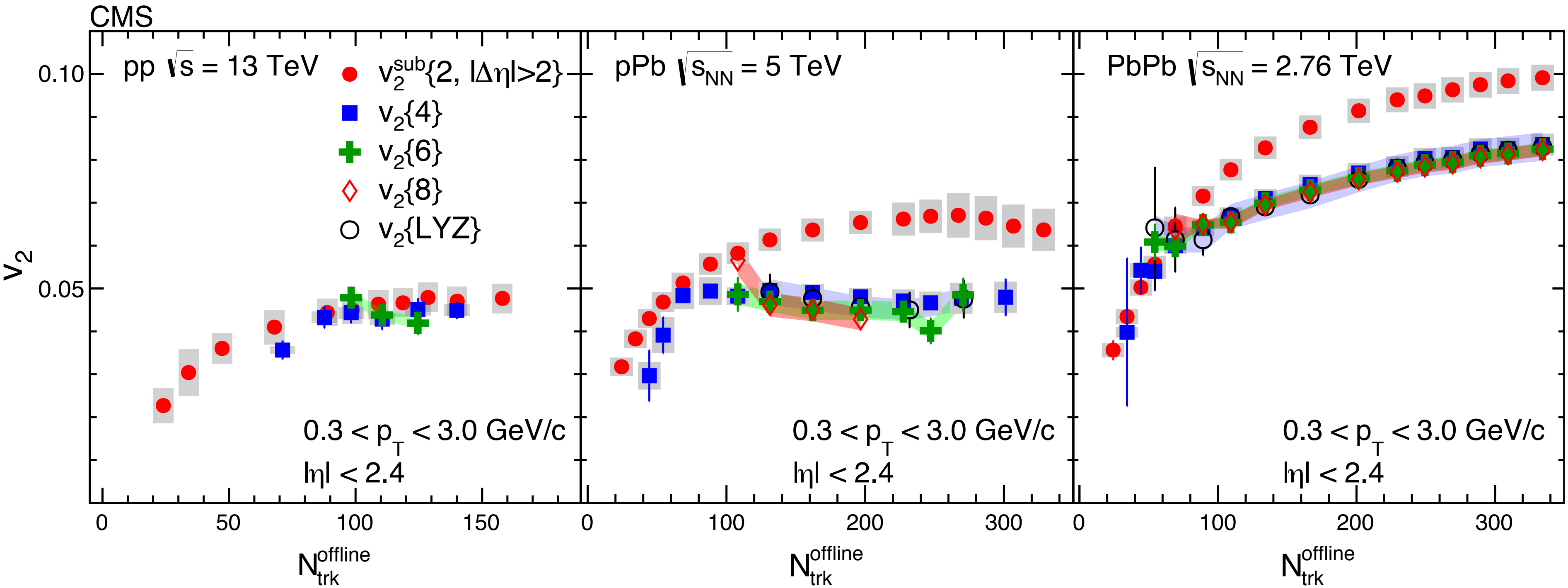
Fourier harmonics and multi-particle cumulants in small systems



PhysLettB.2016.12, 009

- $v_2\{2\} \geq v_2\{4\} \approx v_2\{6\} \approx v_2\{8\}$ ⟶ **Collectivity!**

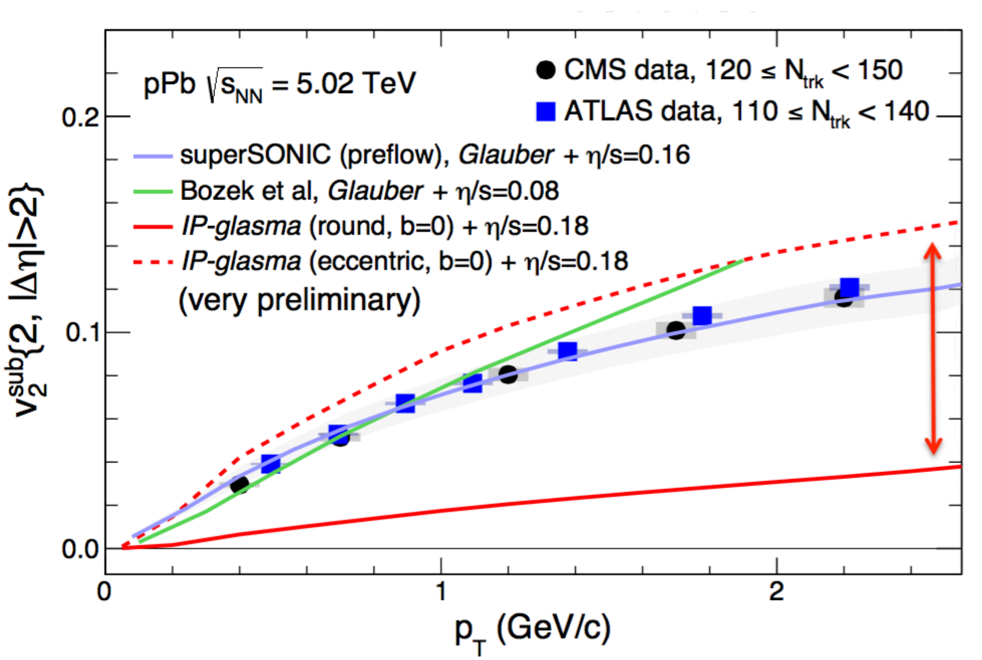
Fourier harmonics and multi-particle cumulants in small systems

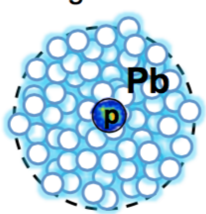


PhysLettB.2016.12, 009

- $v_2\{2\} \approx v_2\{4\} \approx v_2\{6\}$ ⟶ **Collectivity!**
- $v_2\{2\} \approx v_2\{4\}$: Possible interpretation from hydro (Scenario #1)
  - **Less fluctuating sources in the IS**

IS Geometry control





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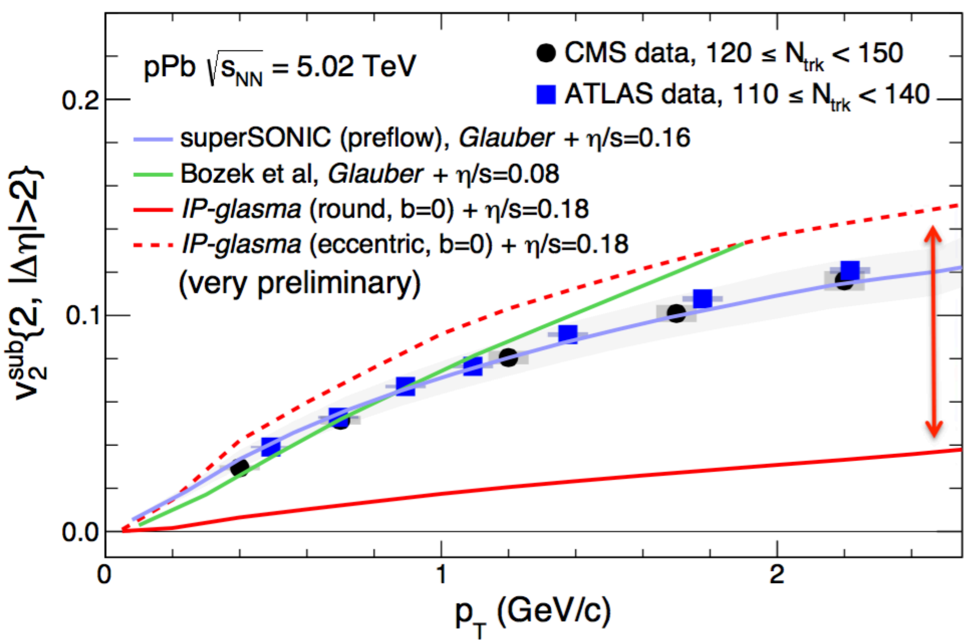

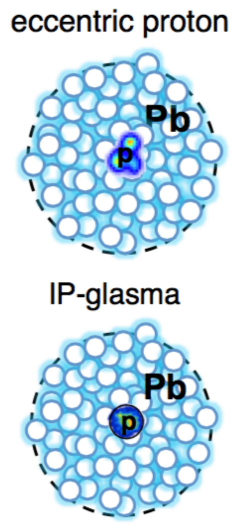

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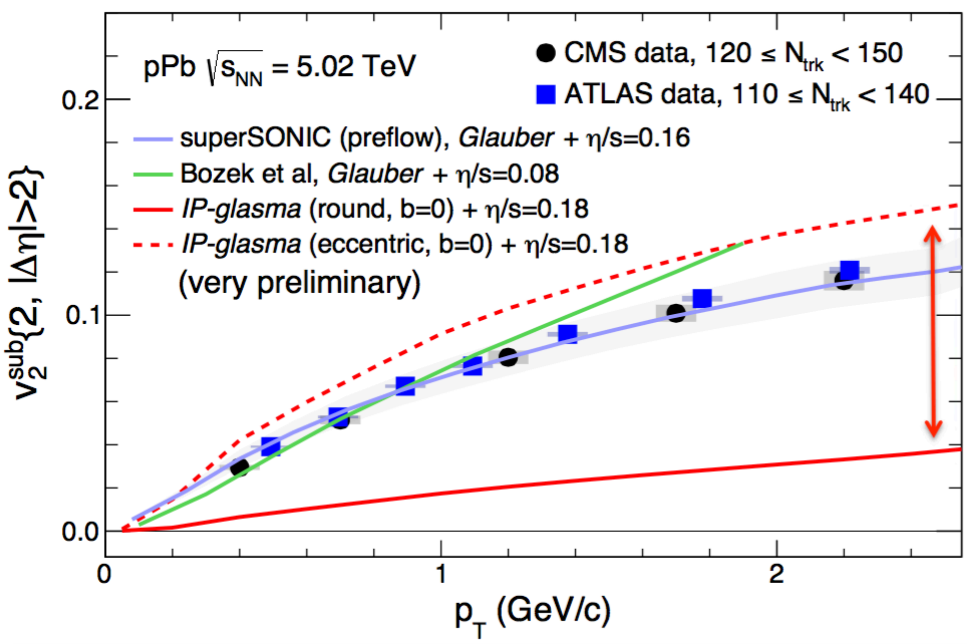

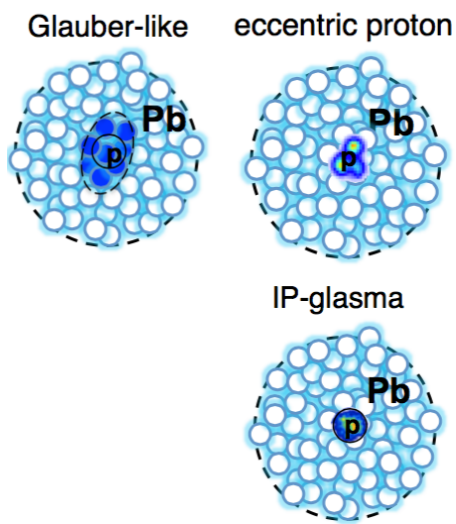

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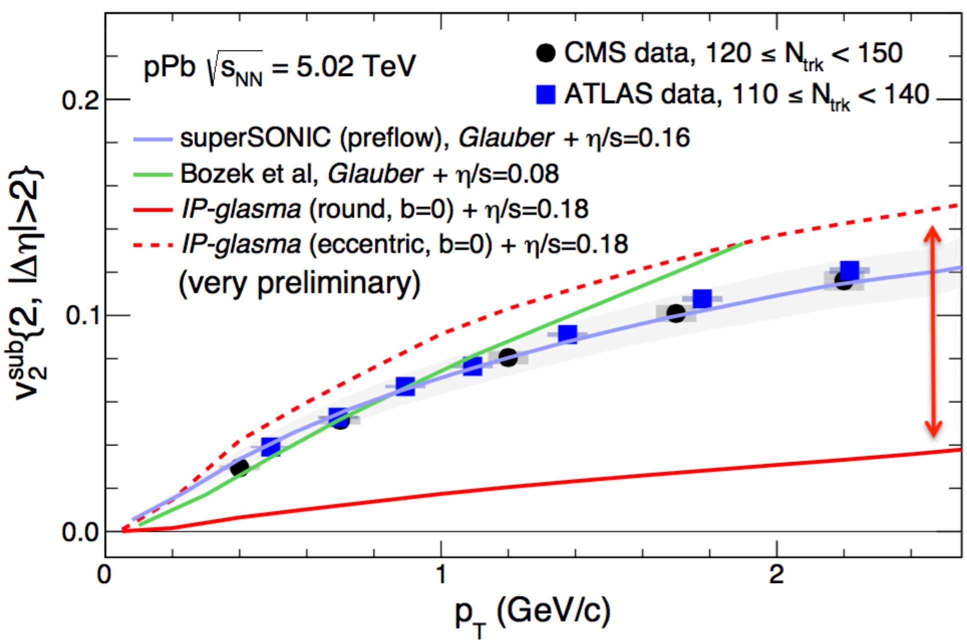
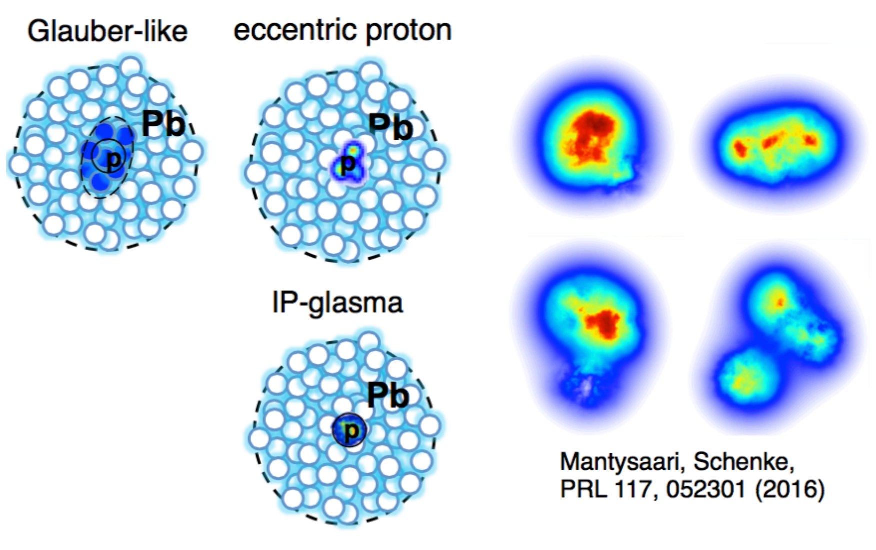
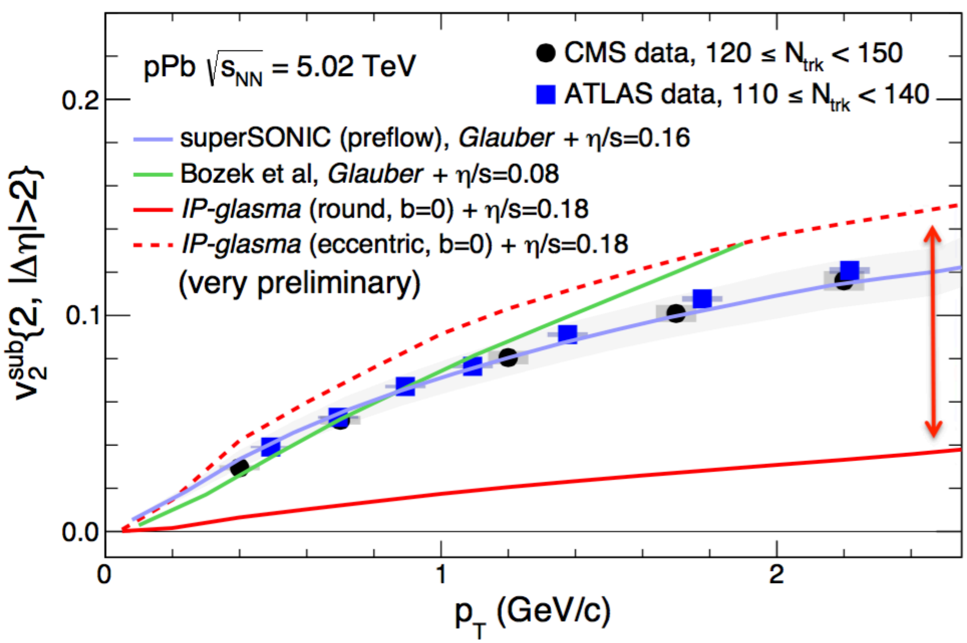
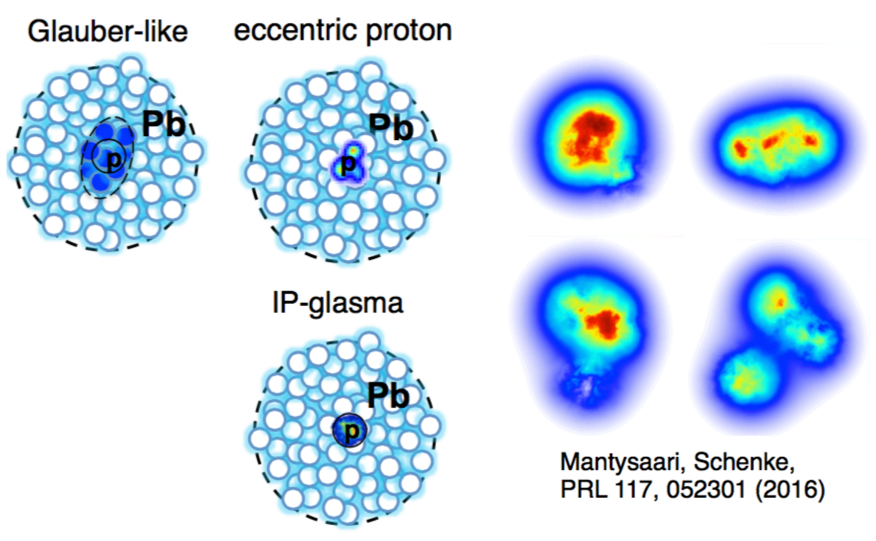




➢ IS modeling has large impact on v_n

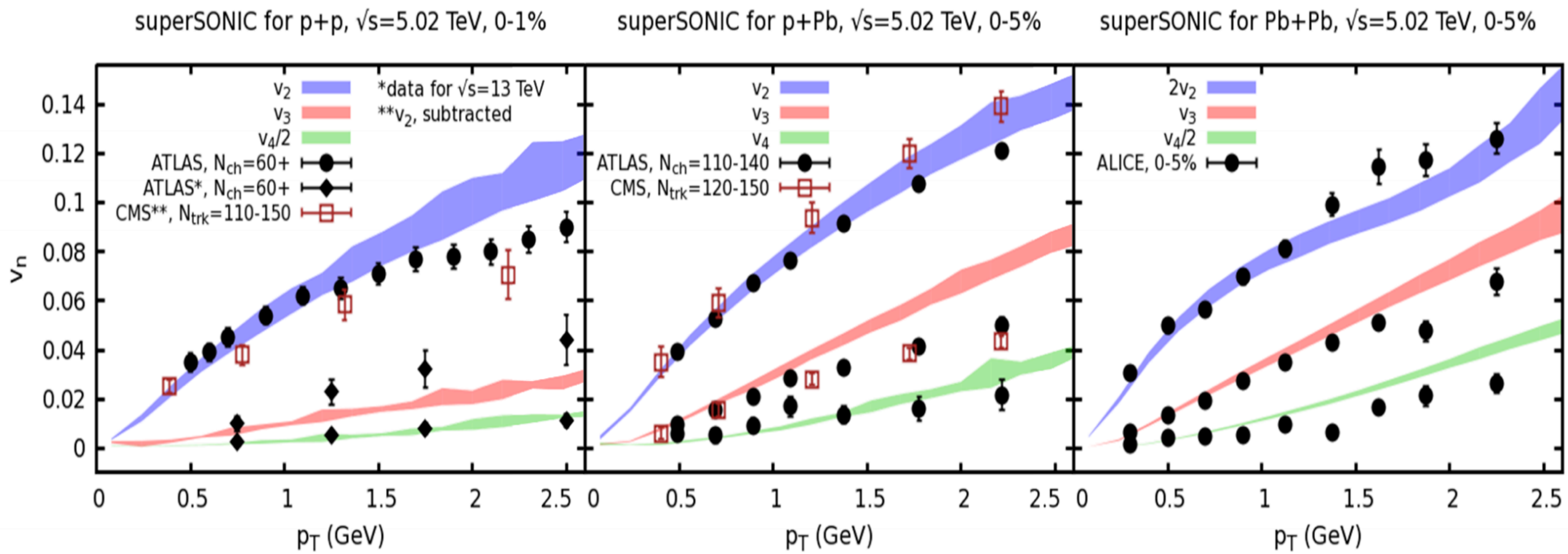
IS Geometry control





- IS modeling has large impact on v_n
- **Unique opportunities** for probing **subnucleonic quantum fluctuations** in yoctoseconds

One fluid to rule them all

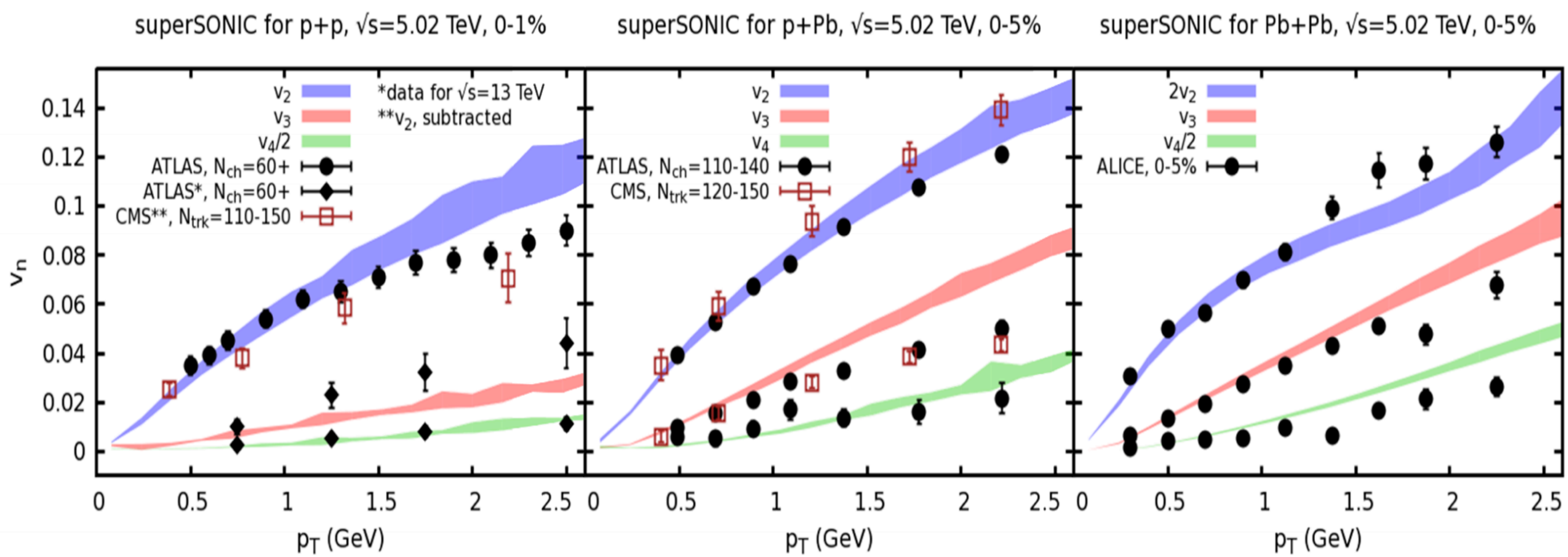


arXiV:1701.071459

Scenario #1

➢ Reproduce the data quite well

One fluid to rule them all

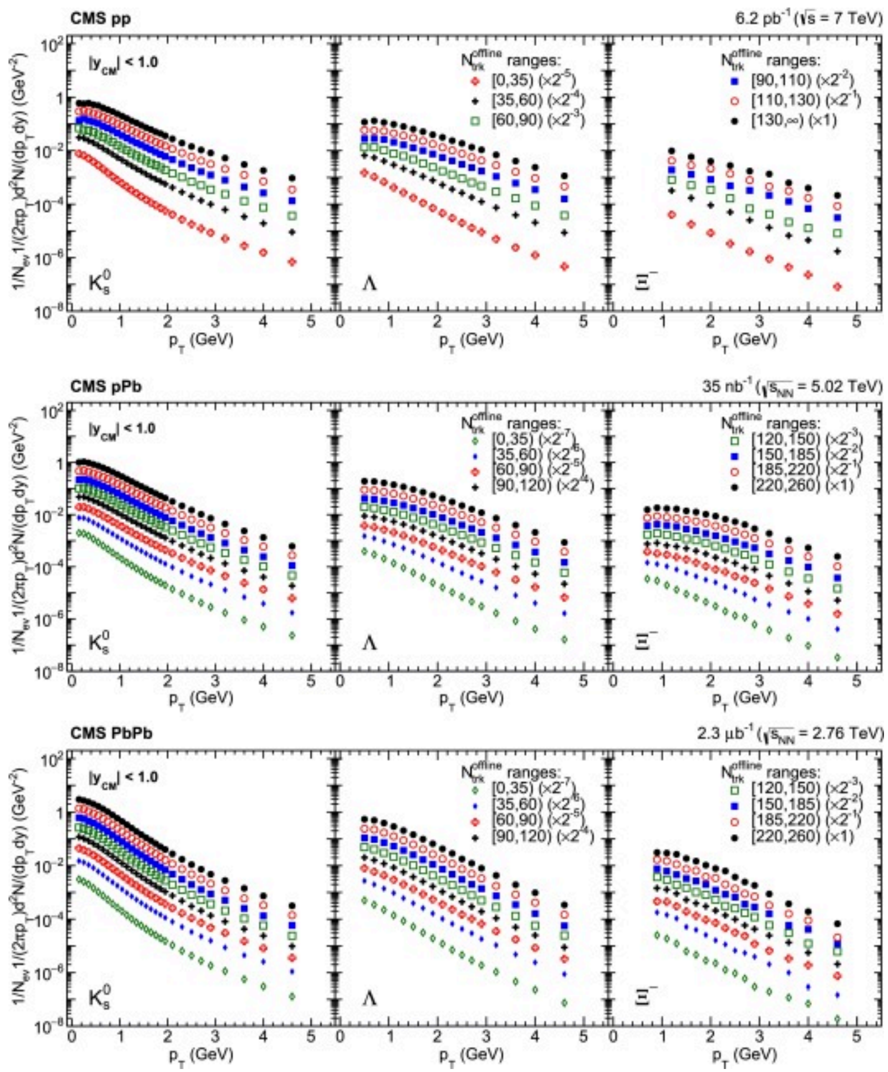


arXiV:1701.071459

Scenario #1

- Reproduce the data quite well
- **Emergence of a unified paradigm?**
  - Not yet… Applicability of hydro is still questionable

Particle ID and mass ordering



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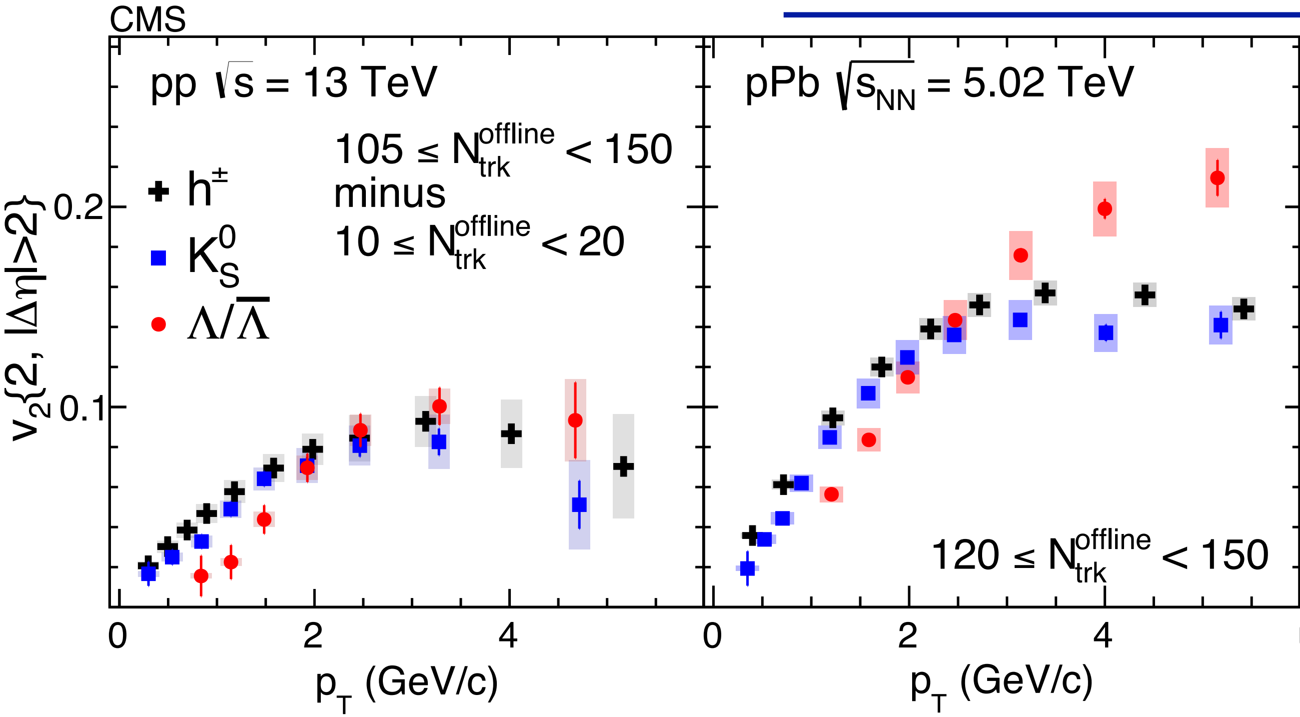
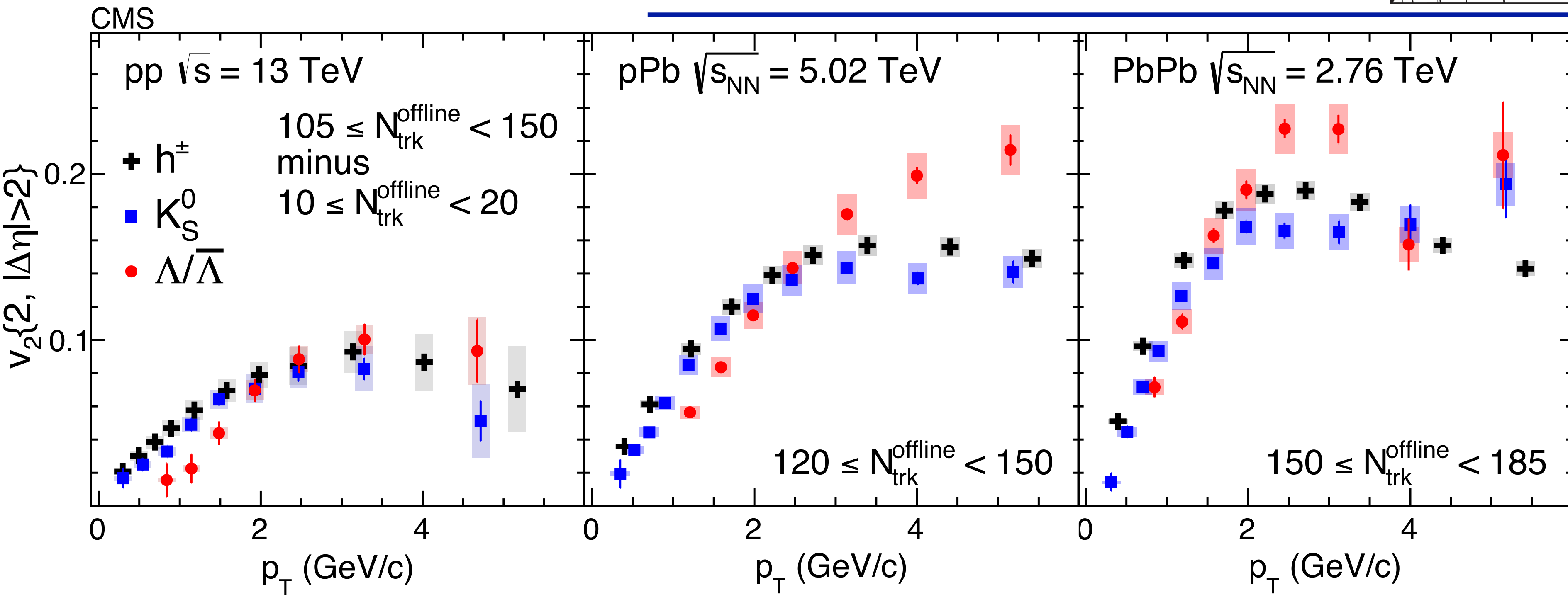


- Large mass splitting at $p_T < 2$ GeV/c in high-multiplicity pp and pPb collisions
  - **Common velocity field**

Particle ID and mass ordering



- Larger mass splitting in pp and pPb than in PbPb

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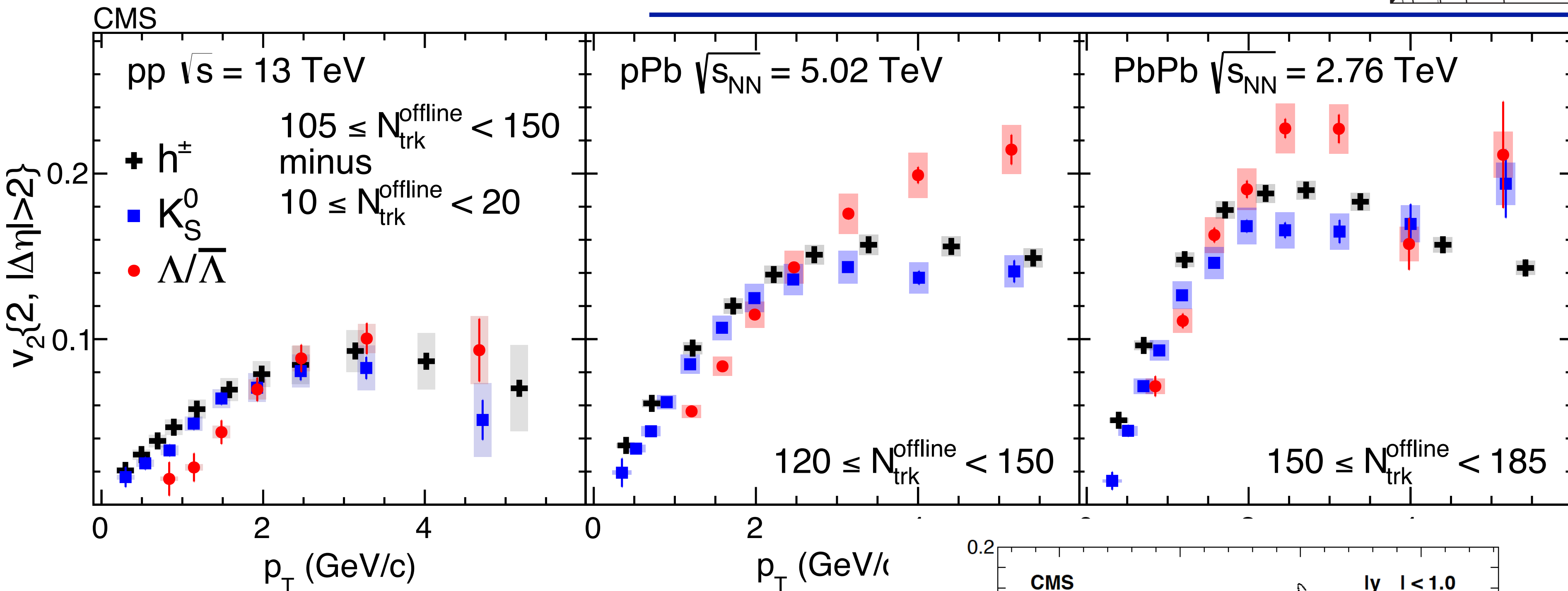
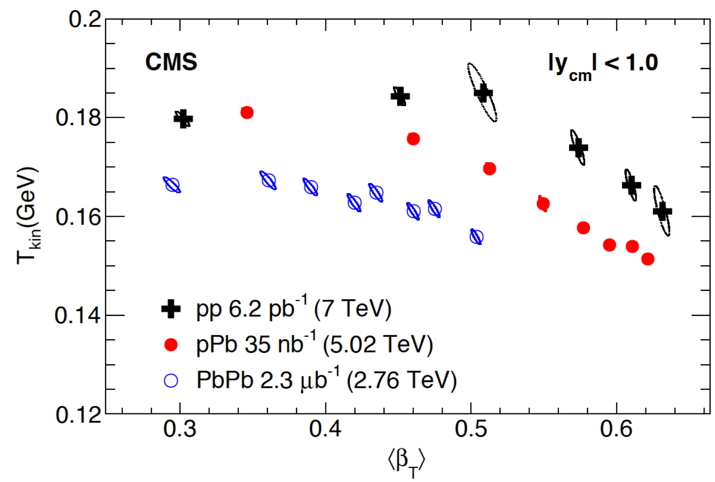




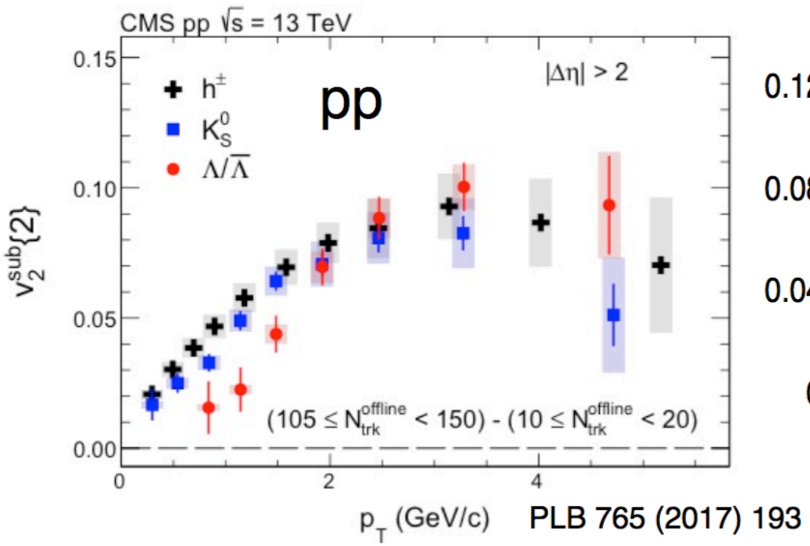
- Larger mass splitting in pp and pPb than in PbPb
  - **Lager radial flow in small systems**
  - More explosive systems

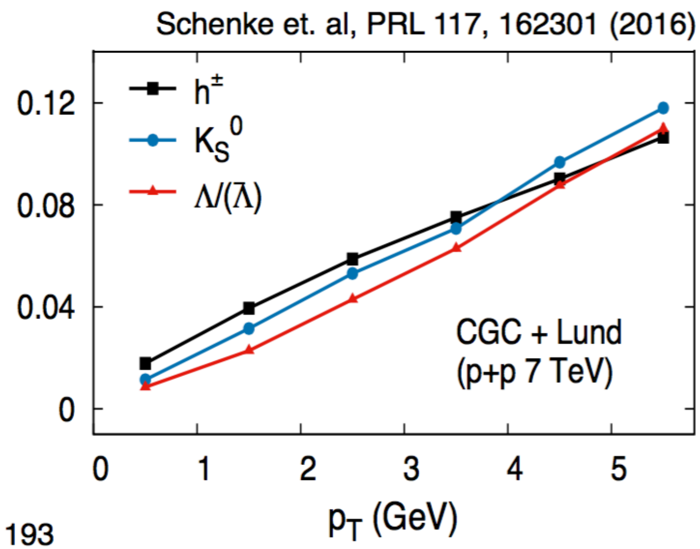
CGC + Lund fragmentation comparison

Scenario #2

- Initial interaction model confronting the data

CGC + Lund (PYTHIA)





- Connection to the initial state is a key to further differentiate the two scenarios

Looking into the details!

New insights to IS fluctuation of pp and pPb

Can we do better?

- Correlations between flow harmonics access details about:
  - Medium response (η/s, …)
  - Initial correlations (geometry + fluctuations)

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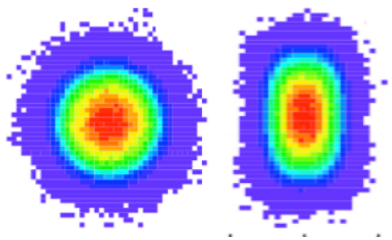
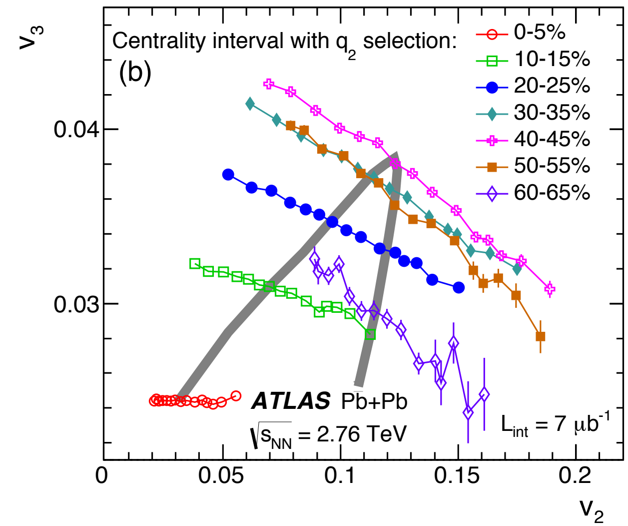
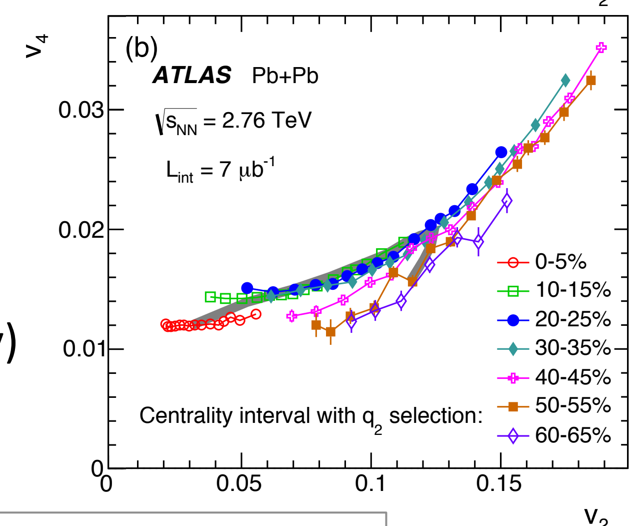


q_2 cut:

- Same centrality (initial geometry)
- Different ellipticity





PhysRevC.92, 034903 **ATLAS results**

Looking into the details!

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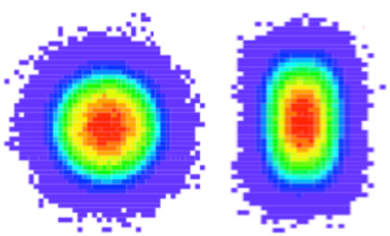

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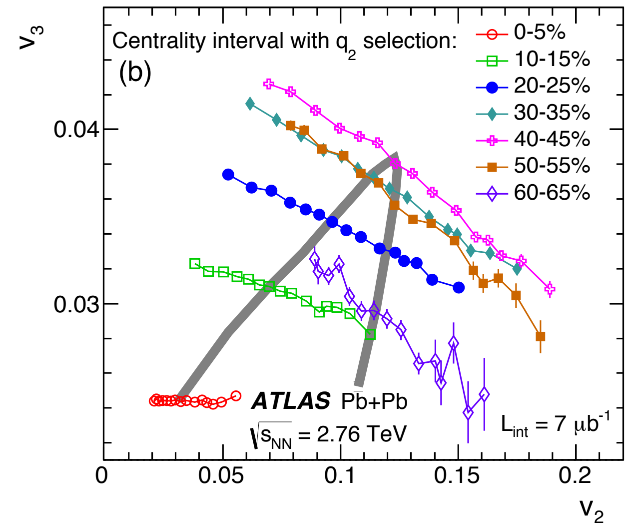
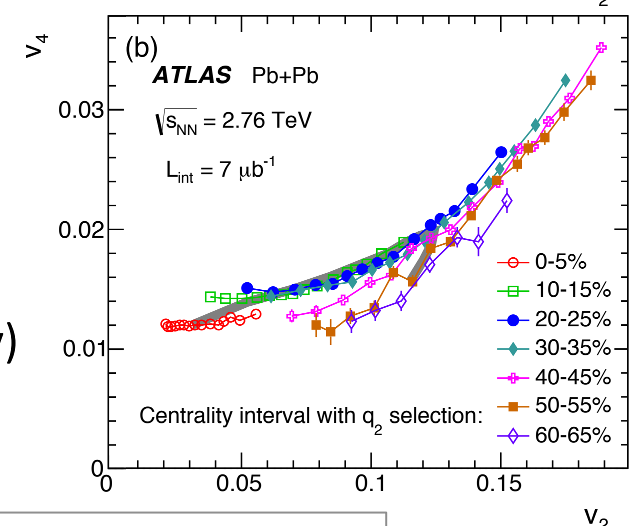
  - **Symmetric cumulant**



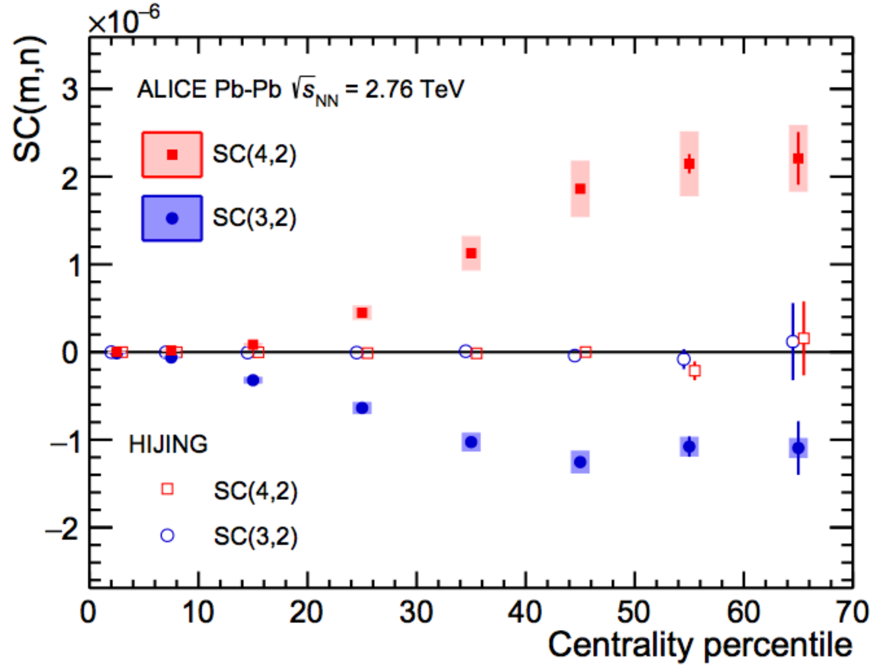


PhysRevC.92, 034903 **ATLAS results**

Symmetric Cumulants (SC) in A-A

- Correlation between harmonics:

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



PhysRevLett.117, 182301 **ALICE results**

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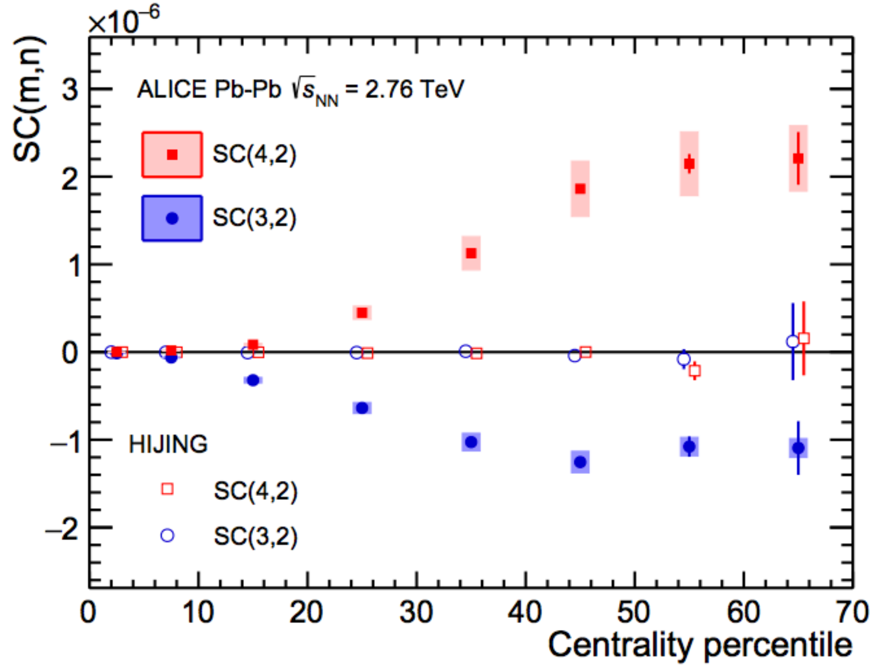
  - New observable
  - **Base on 4-particle cumulant technique**
  - Non-flow free at first order



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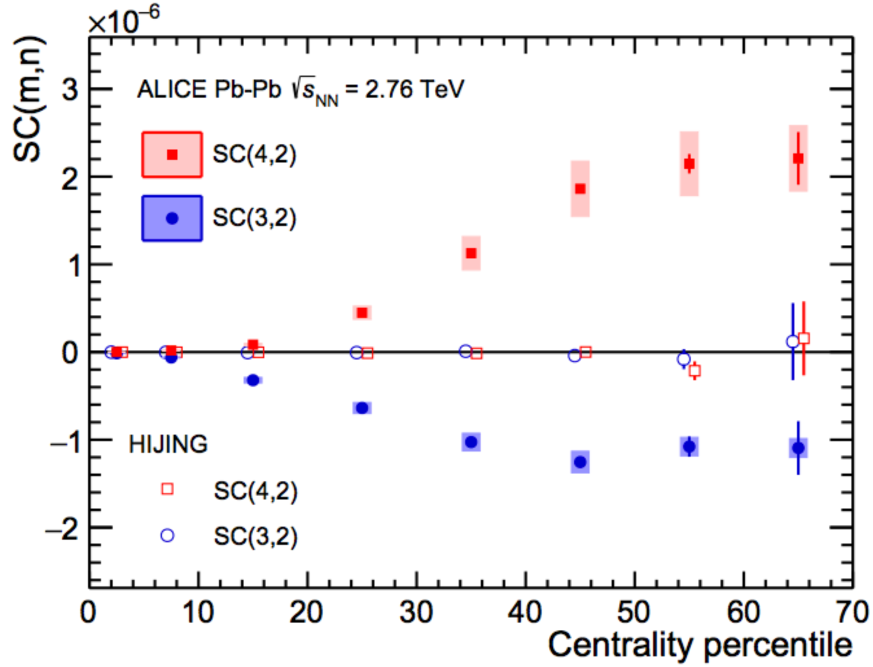
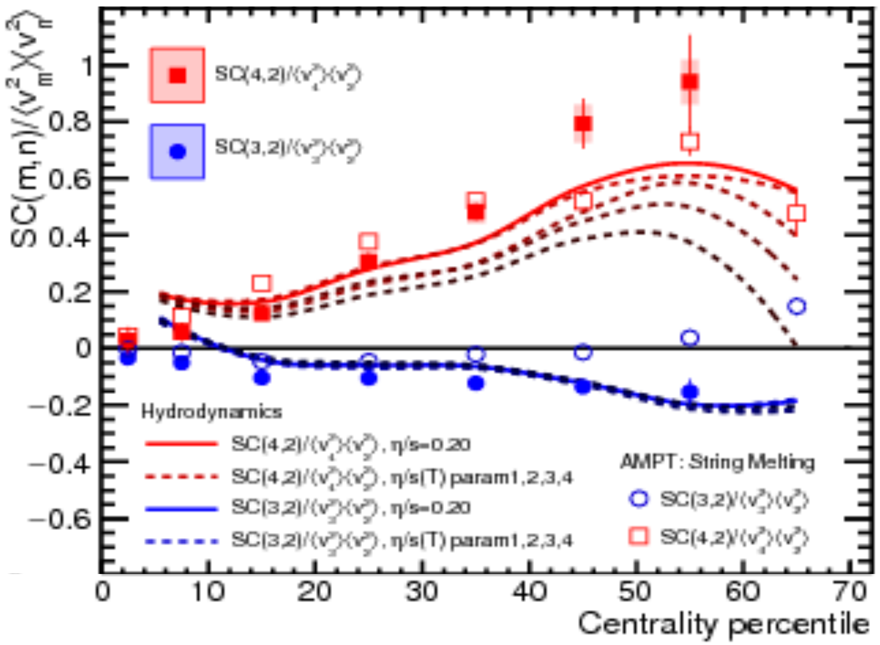


PhysRevLett.117, 182301 **ALICE results**

SC(2,3) < 0 ➔ v_2 and v_3 are **anti-correlated**
SC(2,4) > 0 ➔ v_2 and v_4 are **correlated**

Normalized SC in A-A

- SC normalized by $<\varepsilon_n^2>.<\varepsilon_m^2>$
  - Only $<v_n^2>.<v_m^2>$ accessible experimentally
  - Normalized by v_n magnitude



PhysRevLett.117, 182301

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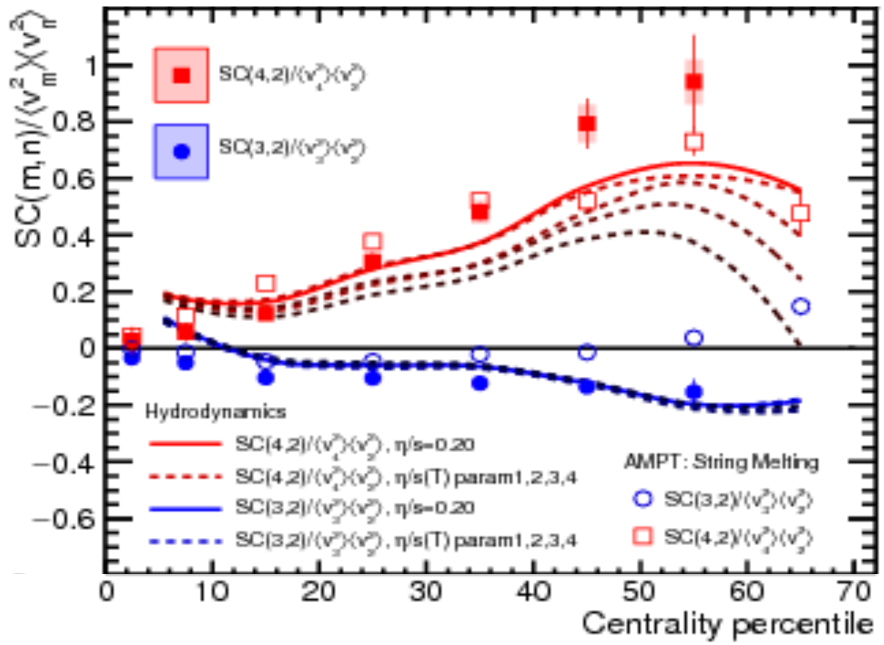

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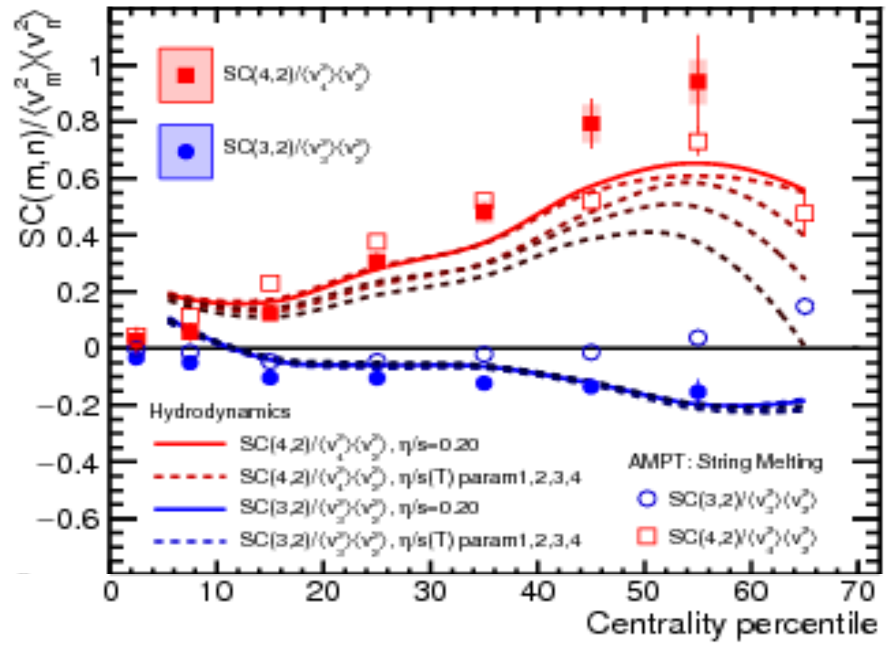

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  - Apples-to-apples comparison across systems (p-p, p-Pb and Pb-Pb)
  - **Stringent constraints on models!**
    - Giacalone et al. **arXiv 1605.08303**
    - Gardim et al. **arXiv 1608.02982**
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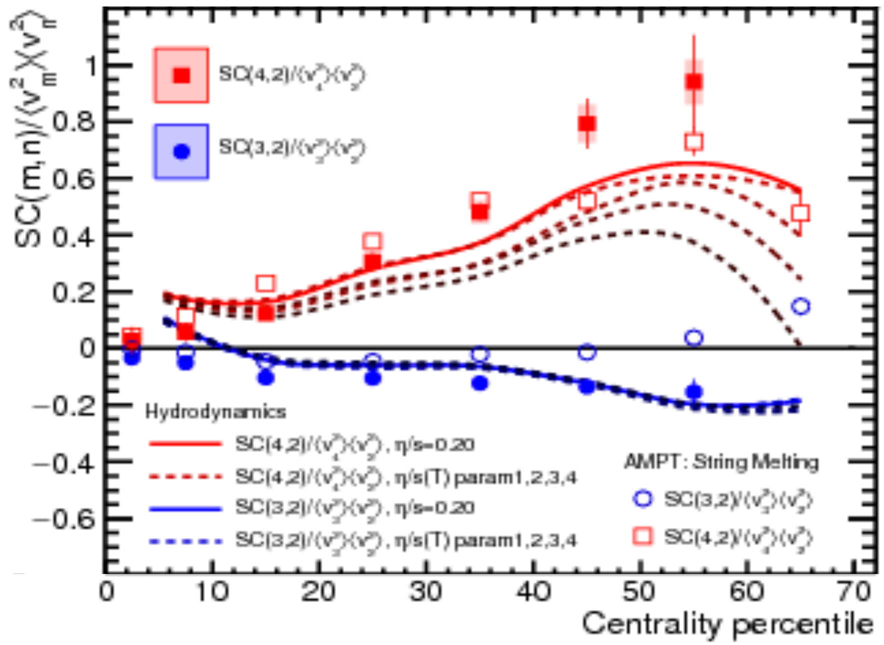

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What about small colliding systems?

SC in small systems

- SC can be measured in small system (p-p and p-Pb)
  - **Never measured**
  - Little knowledge

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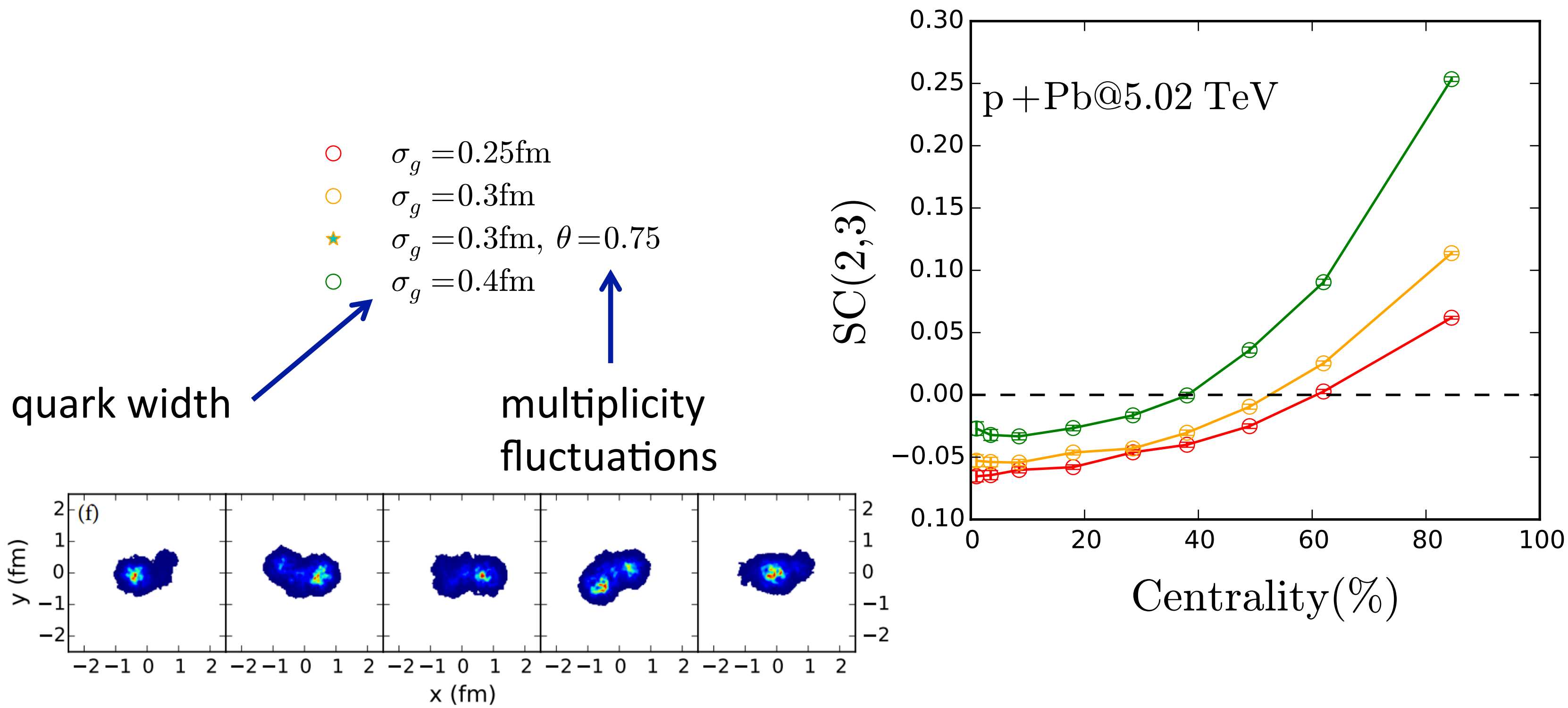

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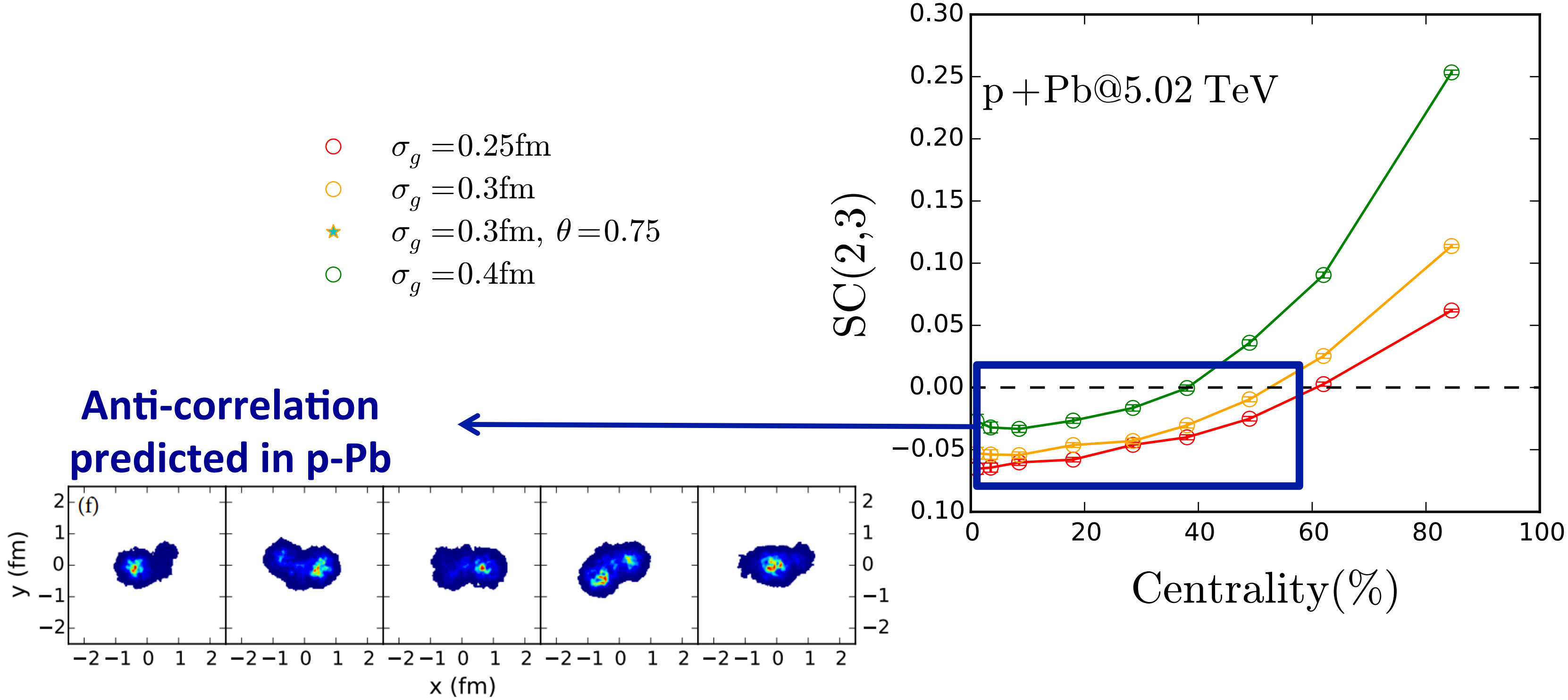

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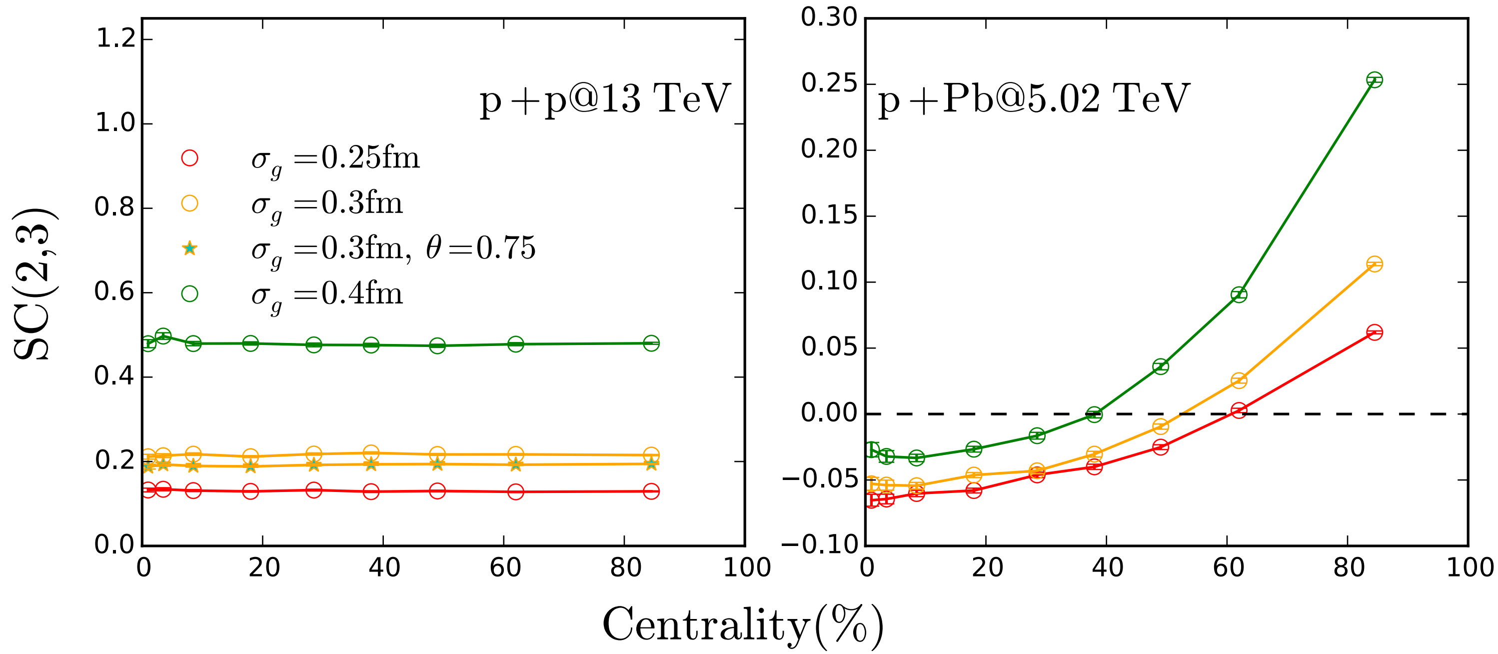

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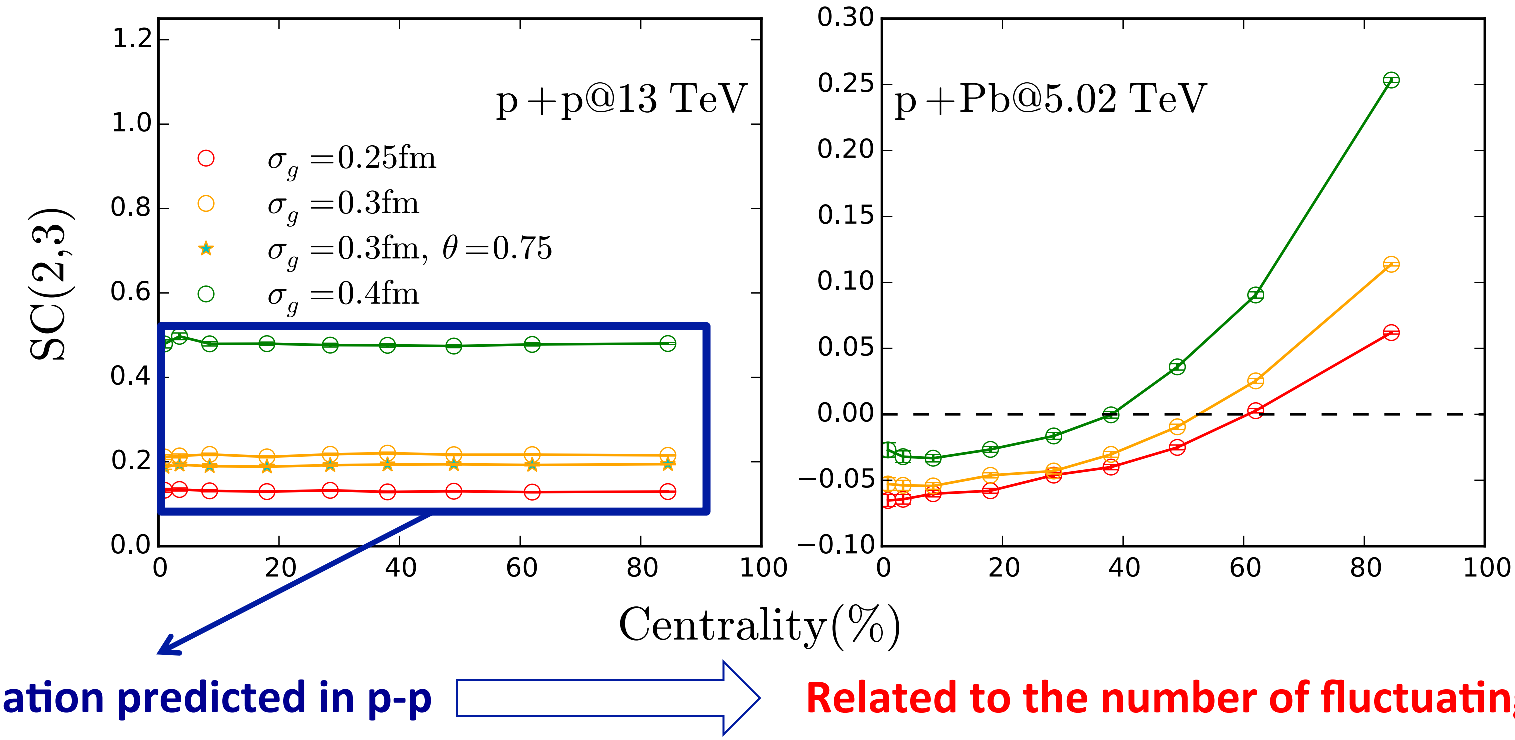
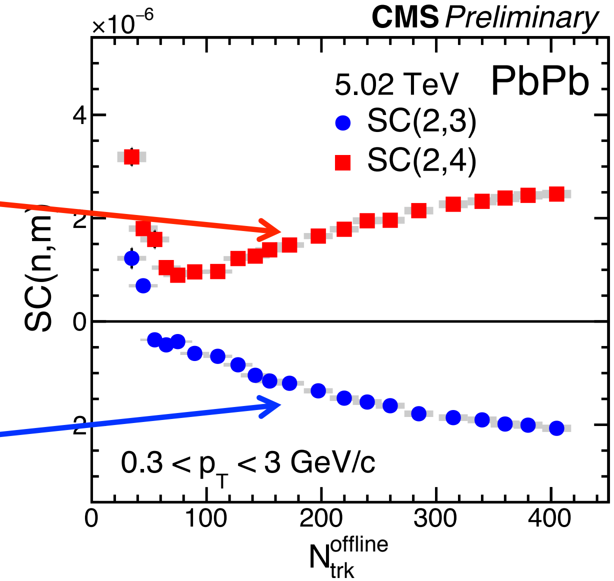


SC as a function of multiplicity

Correlation between v_2 and v_4

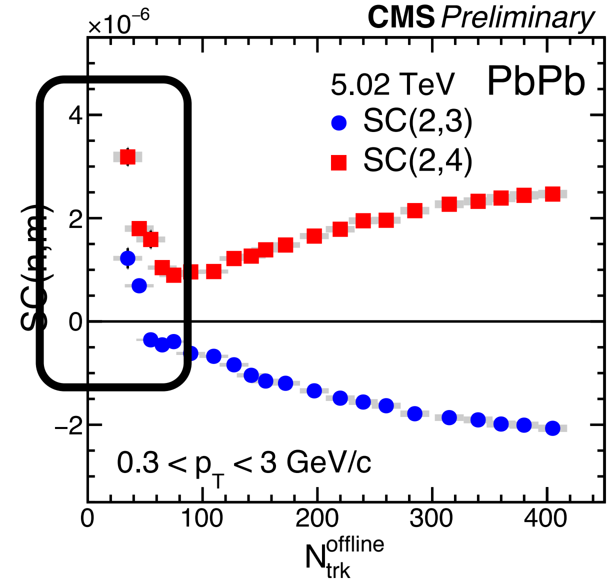
Anti-correlation between v_2 and v_3



CMS-PAS-HIN-16-022

SC as a function of multiplicity

Large contribution from non-flow (e.g. dijets, …)



CMS-PAS-HIN-16-022

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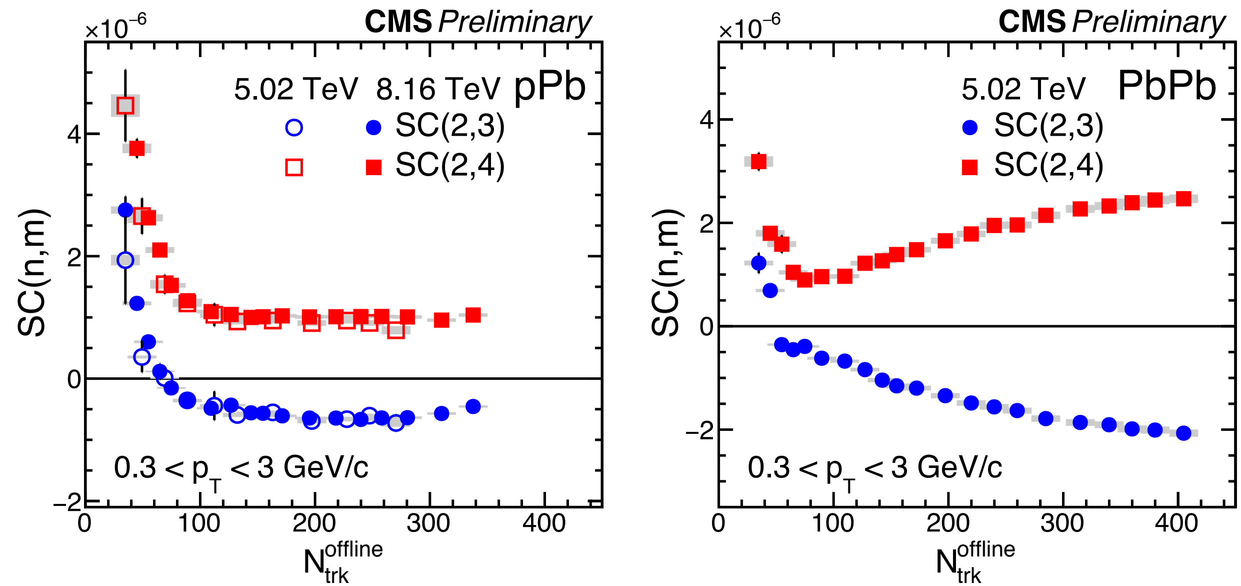

CMS-PAS-HIN-16-022

- Very small energy dependence observed for p-Pb results
- pPb similar to PbPb:
  - Naturally explained by initial geometry! **Scenario #1**
  - A new challenge to initial interaction models?! **Scenario #2**

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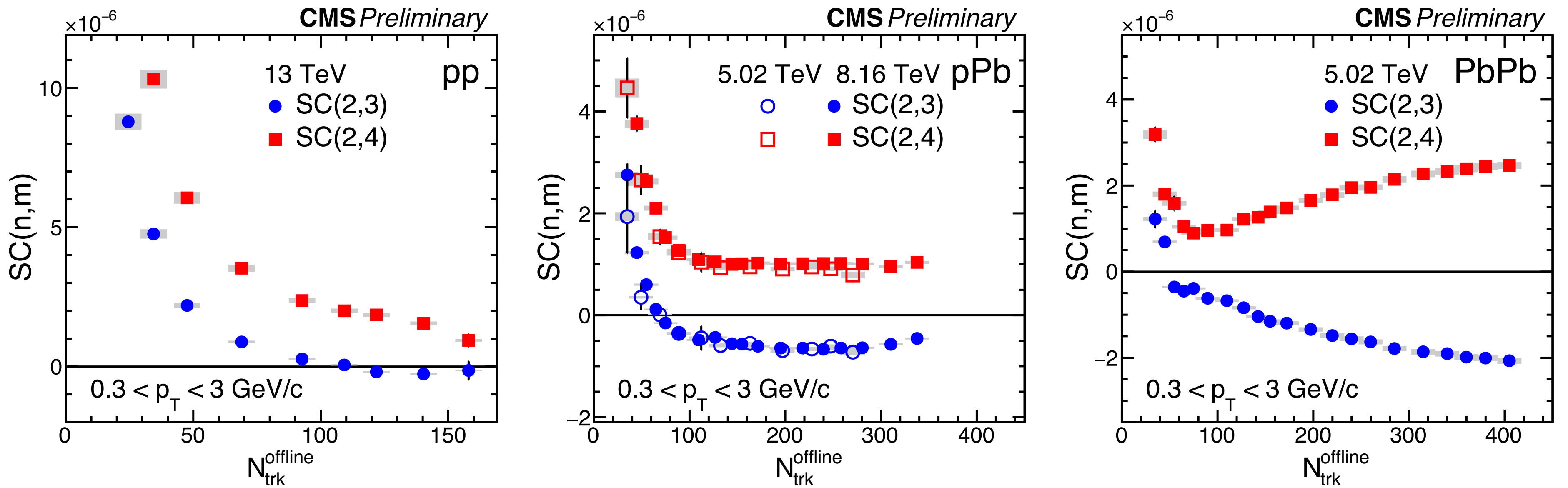
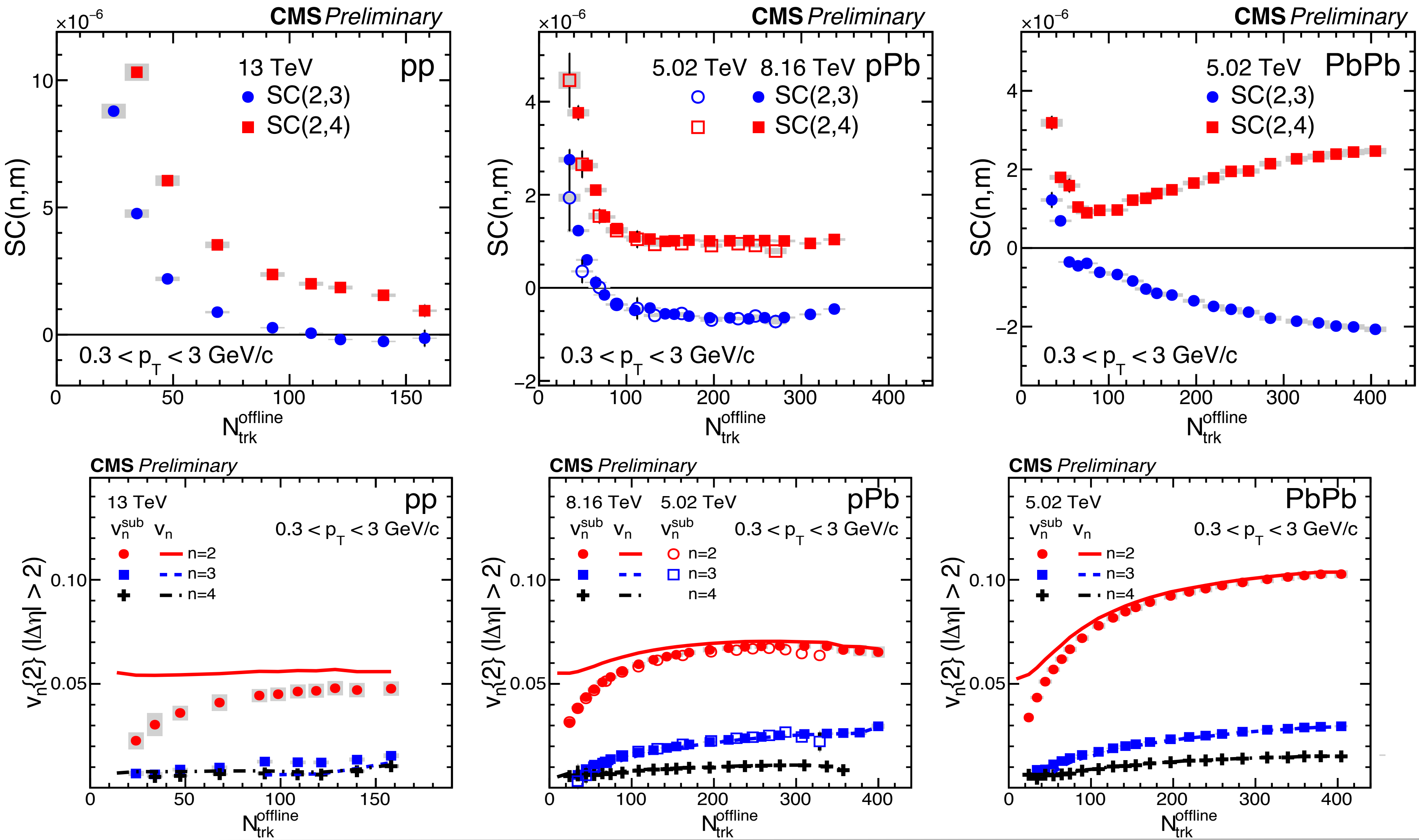


CMS-PAS-HIN-16-022

- Very small energy dependence observed for p-Pb results
- pPb and pp? similar to PbPb:
  - Naturally explained by initial geometry! **Scenario #1**
  - A new challenge to initial interaction models?! **Scenario #2**
    - **Some workaround currently worked on:** correlated hot spot

SC as a function of multiplicity



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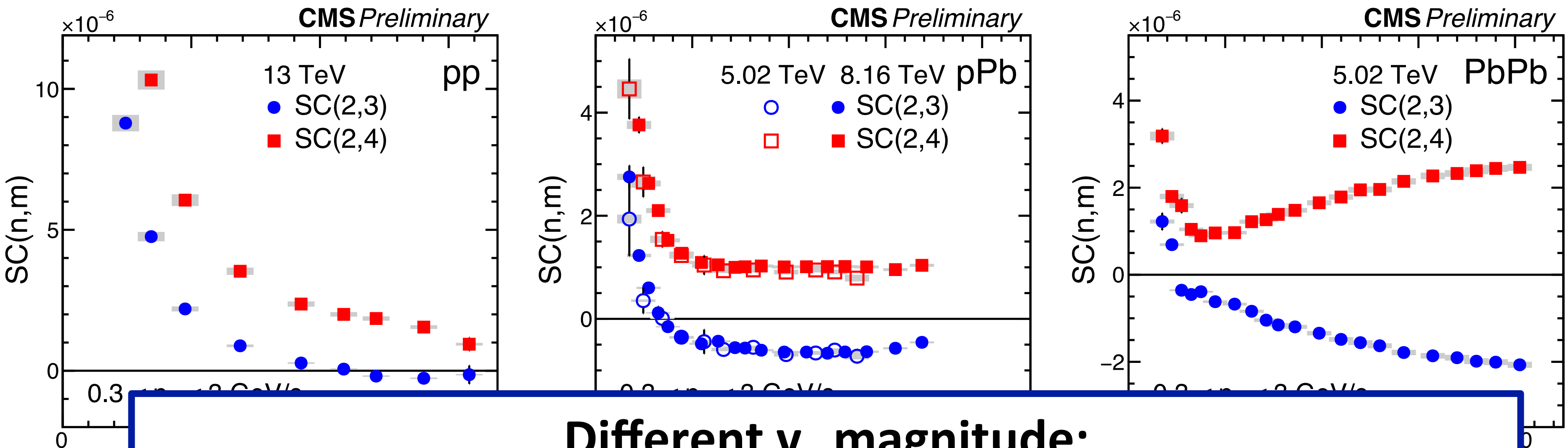
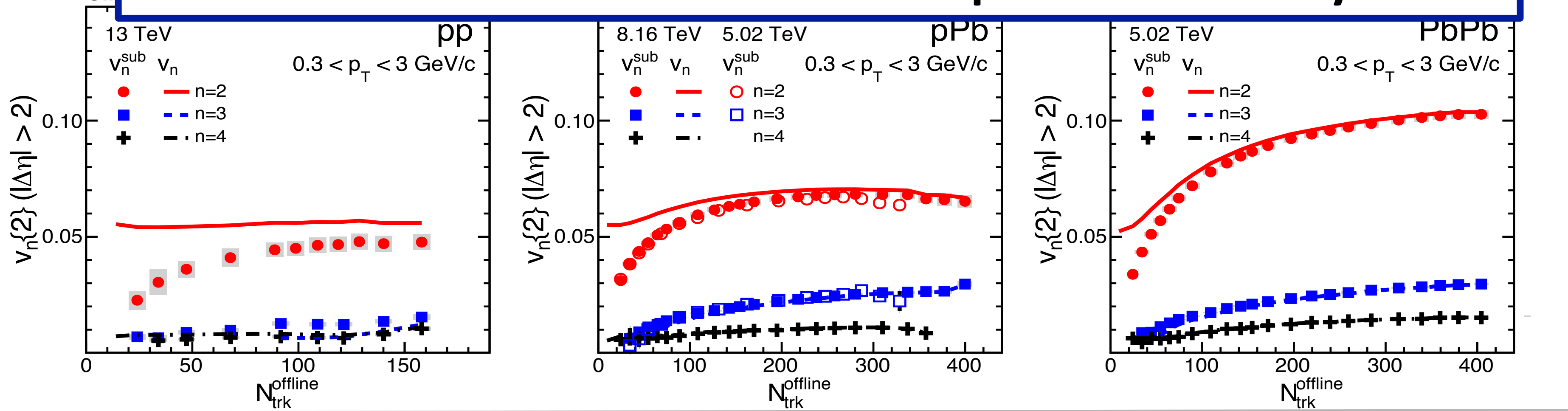


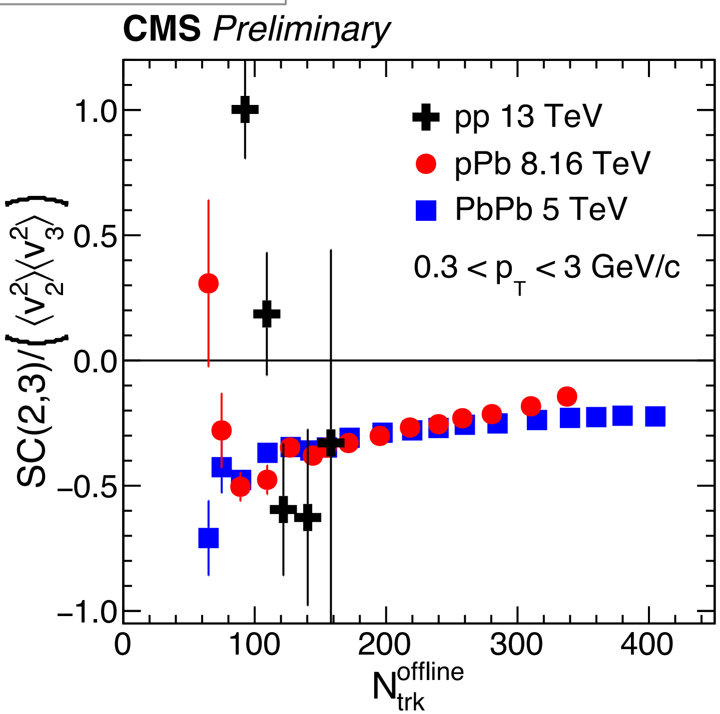
Different v_n magnitude:
Normalization needed for a fair comparison across systems

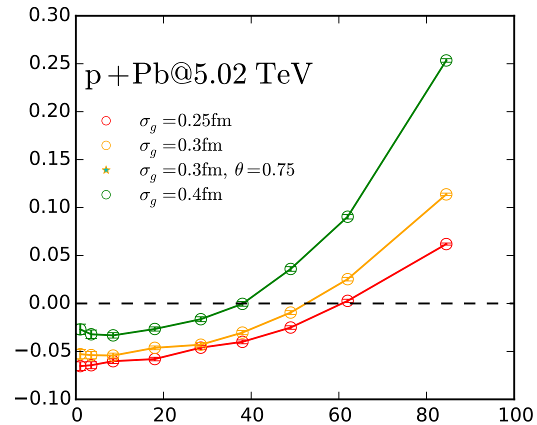


SC normalized

CMS-PAS-HIN-16-022

SC normalized by $<v_n^2>.<v_m^2>$





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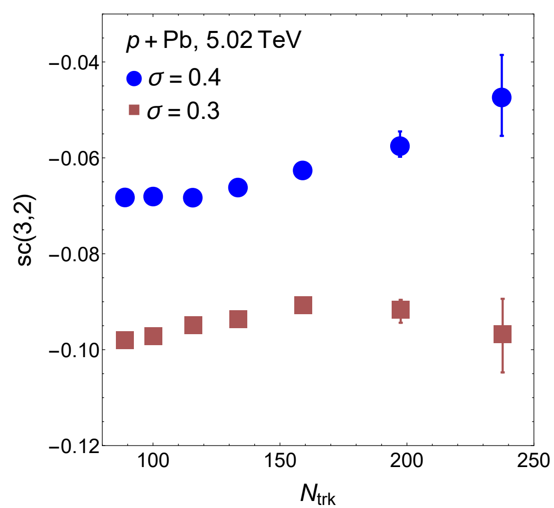

Wounded nucleon model

arXiv 1609.05171

- Similar behavior in p-Pb and PbPb
- Points to similar IS fluctuations
- First calculations (ε_n correlations only)
  - Right sign
  - Magnitude is off

SC normalized

CMS-PAS-HIN-16-022

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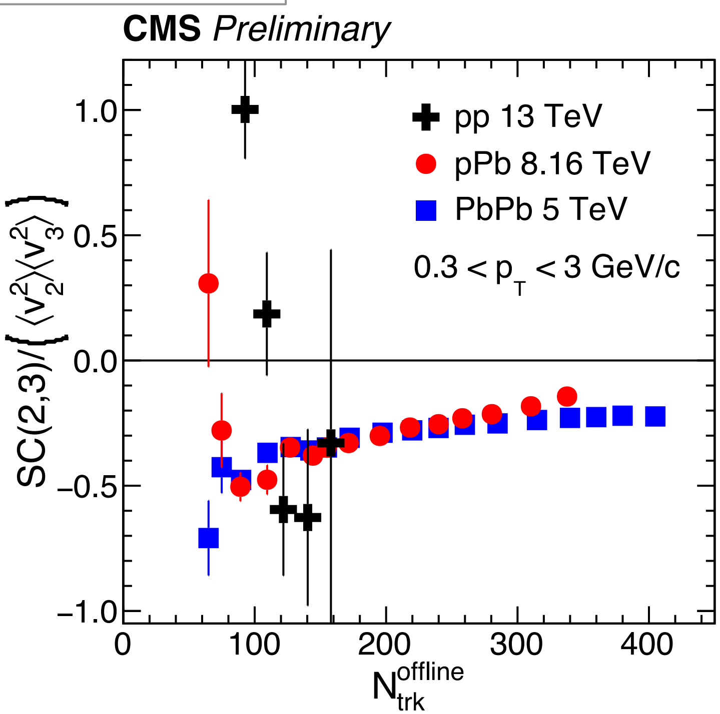

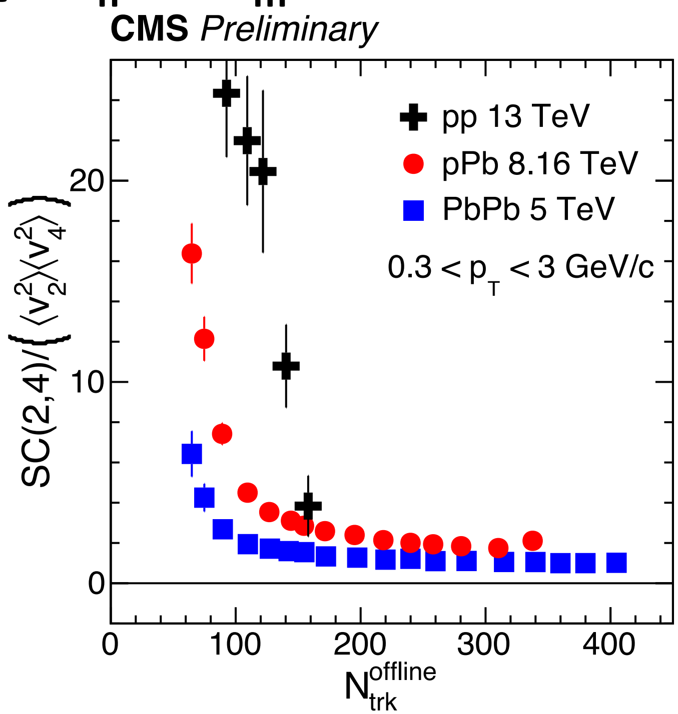

- Similar behavior in p-Pb and PbPb
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- First calculations (ε_n correlations only)
  - Right sign
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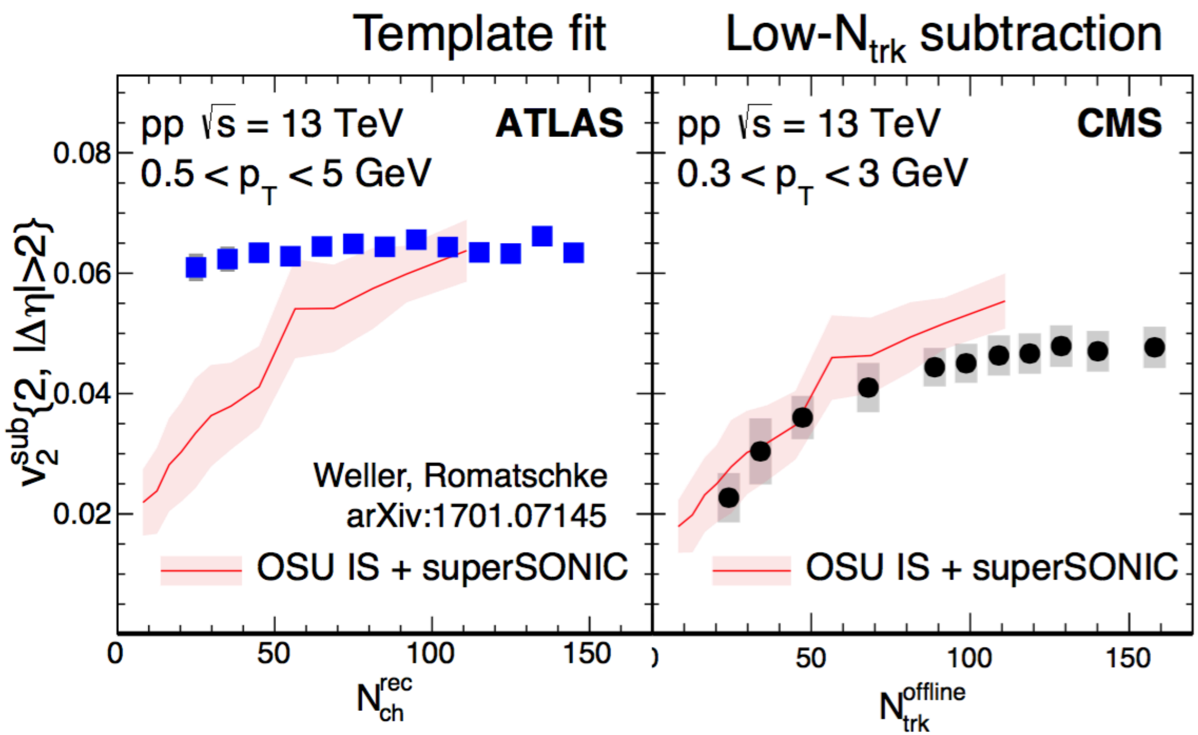
- Ordering observed:
  p-p > p-Pb > Pb-Pb
- May point to different transport properties

What still need to be understood?

Does the collectivity turn off at low N_{trk}?



- If hydro is the explanation, v_2 should go down!
- New methods using N-particle correlations with gap arXiv:1612.05634, arXiv:1701.03830

Summary

Clear evidence of *long-range*, *collective* phenomena! **universal** in all **high-multiplicity** hadronic collisions

Scenario #1

Initial spatial ε_s **+ final** interactions

Scenario #2

Initial spatial ε_p by initial interactions

AA is consistent with **Scenario #1**: nearly perfect fluid

In pp/pA?

- The understanding of the initial and its fluctuation is the key to disentangle **#1** and **#2**
- Small system are unique probes of subnucleonic fluctuations
- $v_n\{m\}$, PID v_n and SC results suggest that a **unified paradigm to describe all hadronic system is plausible**

Outlook

Do we form a QGP in small systems?

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  - Collectivity have been shown
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NO

- No in medium parton interaction observed so far
  - No jet quenching
  - No HF suppression

What next?

Seems important to bridge the gap between peripheral PbPb and high multiplicity pp or pA collisions

At low multiplicities, non-flow contribution becomes dominant and new tools has to be developed to get ride of it more efficiently

The search for in medium parton energy loss could be pursue with correlation studies looking at charged hadrons or HF v_n at high-p_T in particular