Small Systems Dynamics
When Few Behave Like Many

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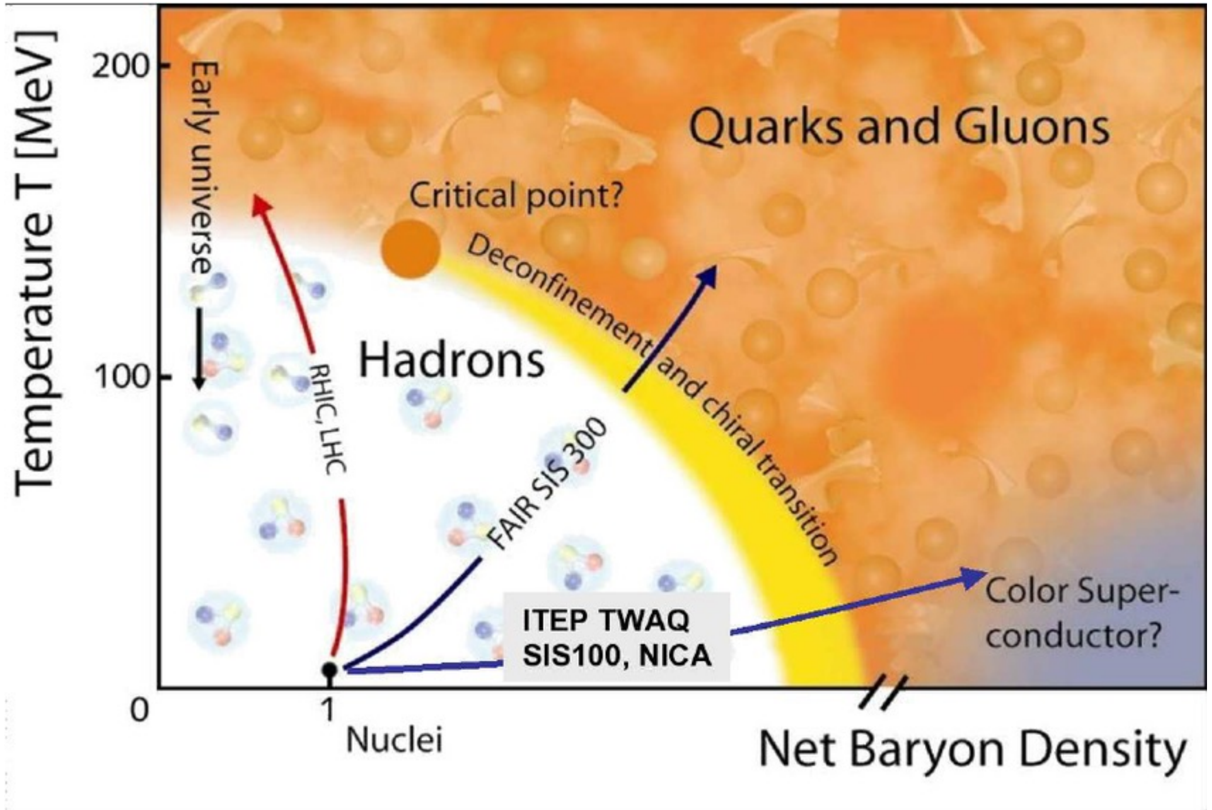
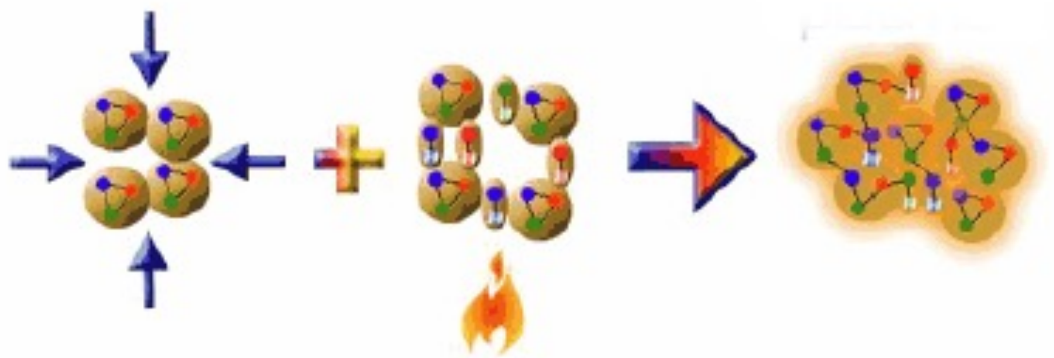
Wayne State University

BNL Seminar August 2025

Nuclear Matter at High Temperature - QGP

Equation of State (EoS) of nuclear matter – **Main goal of nuclear physics!**





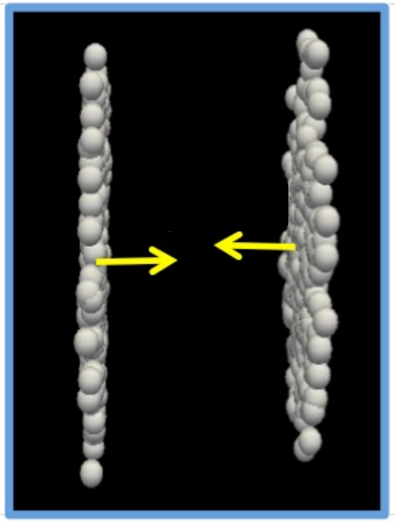
Pressure + Temperature → Phase Transition

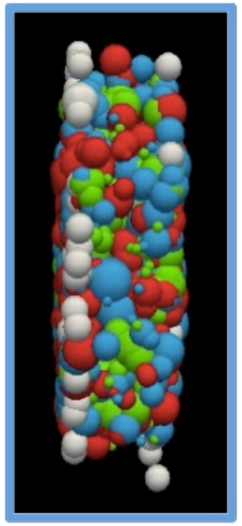
Quark-Gluon Plasma – nearly perfect fluid

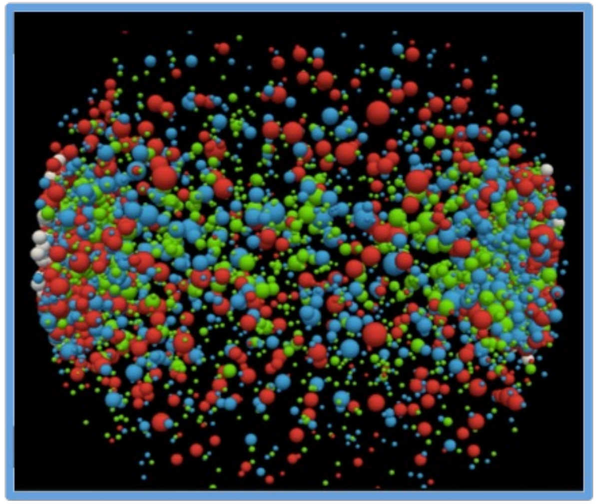
QGP in Laboratory – Heavy Ion Collisions

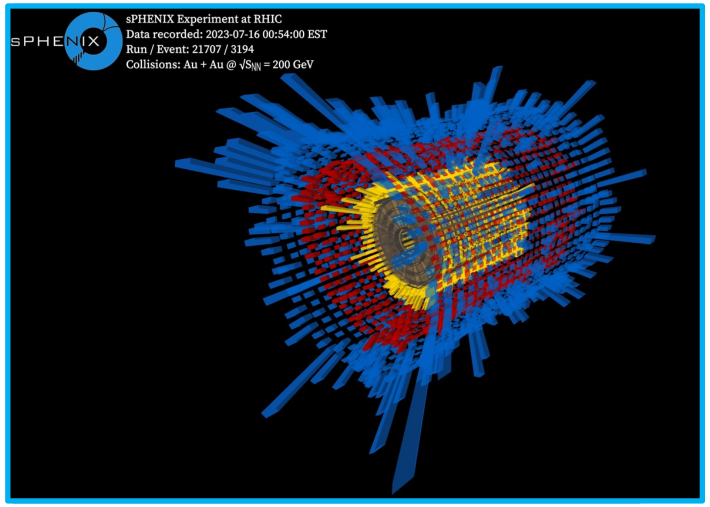
→ time

Initial State | **QGP** | **Hadronization** | **Detection**









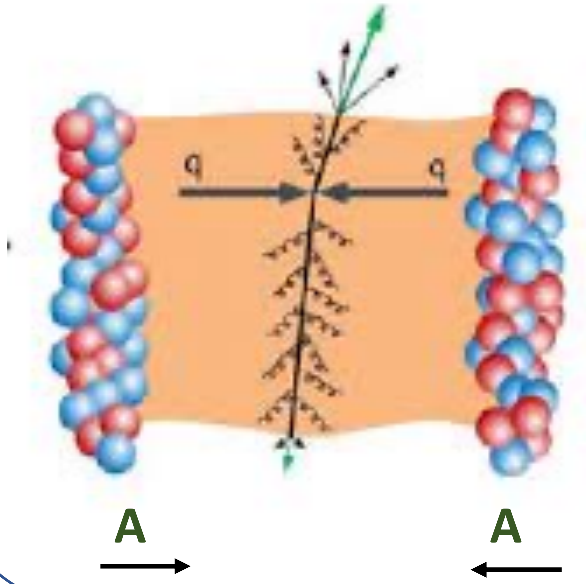
Ultra relativistic Heavy Nuclear Collisions → Transition from Cold Nuclear Matter to QGP

To study QGP we need to understand:

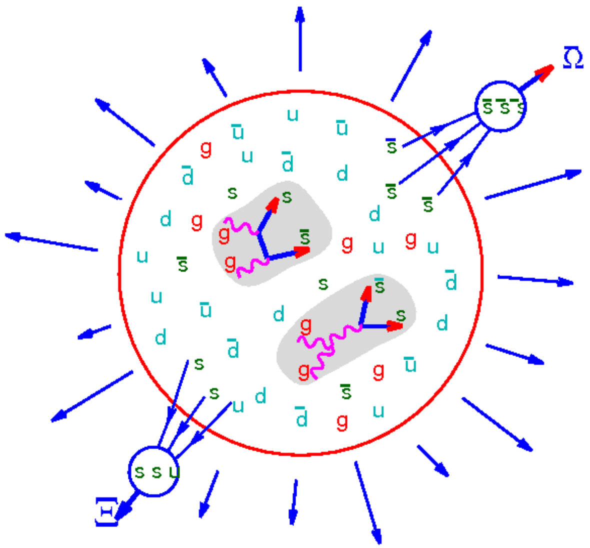
- Initial conditions
- Hadronization
- Detector response

QGP Signatures

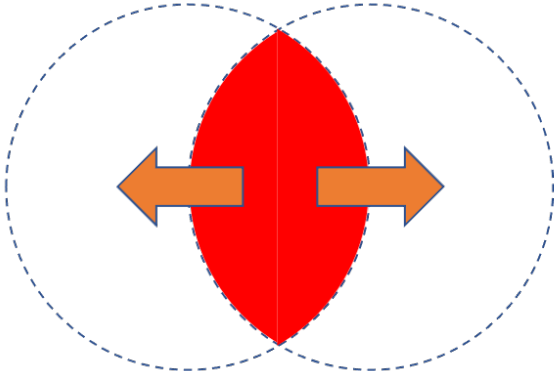
Jet supression



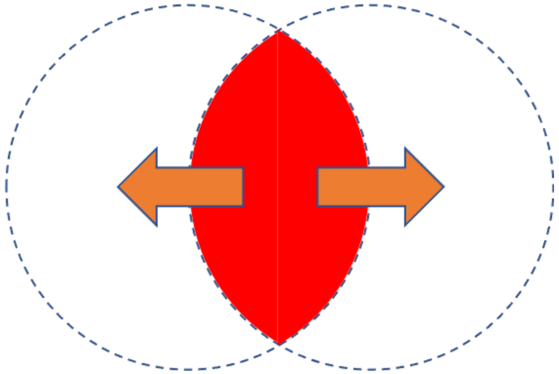
Strangeness enhancement



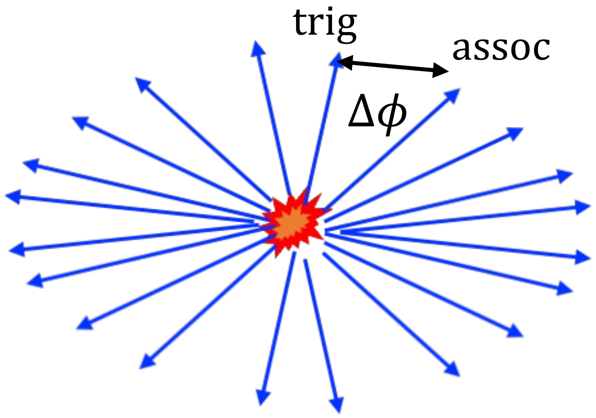
Collective flow

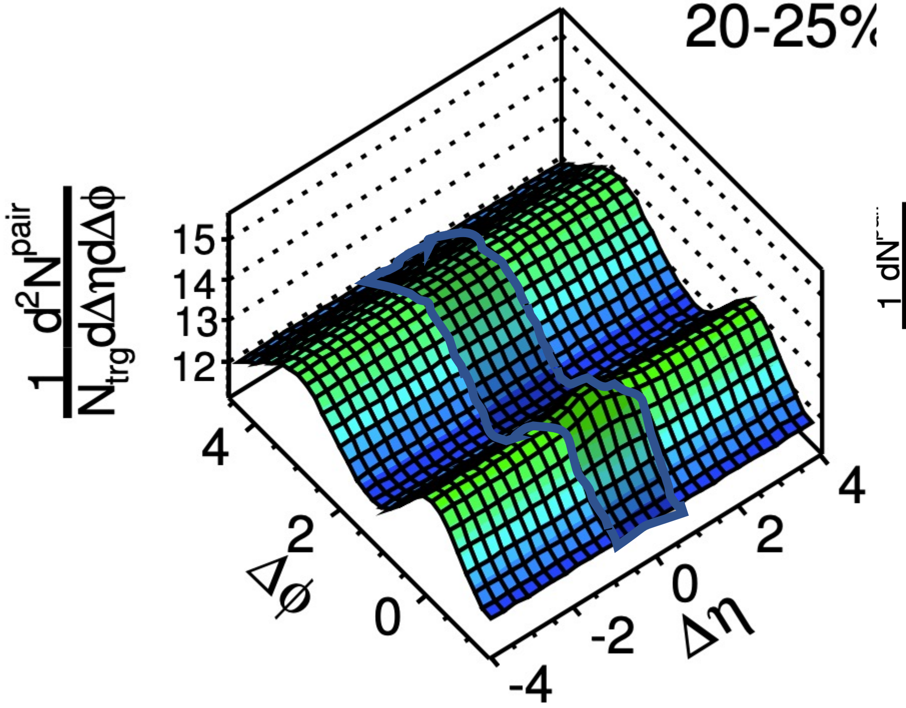


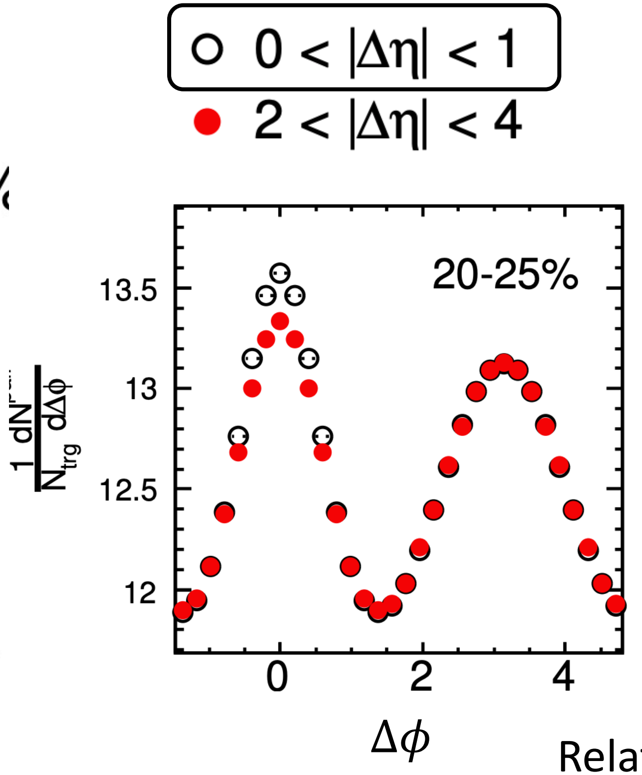
Flow Measurement – 2-particle correlations



Initial geometry → momentum anisotropy







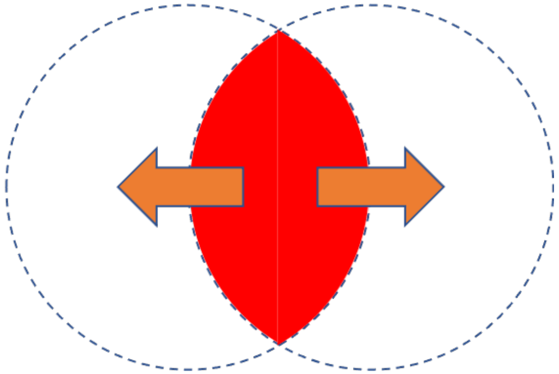
[EPC 72 (2012) 10052]

$$\frac{1}{N_{\mathrm{trig}}}\frac{\mathrm{d}N^{\mathrm{pair}}}{\mathrm{d}\Delta\phi} = \frac{N_{\mathrm{assoc}}}{2\pi}\left\{1 + \sum_{n=1}^{N_{\mathrm{max}}} 2V_{n\Delta}\cos(n\Delta\phi)\right\}$$

$$V_{n\Delta}(p_{\mathrm{T}}^{\mathrm{trig}}, p_{\mathrm{T}}^{\mathrm{assoc}}) = v_n(p_{\mathrm{T}}^{\mathrm{trig}}) \times v_n(p_{\mathrm{T}}^{\mathrm{assoc}}).$$

Relative angle distribution enhanced at 0 and pi

Flow Measurement – 2-particle correlations



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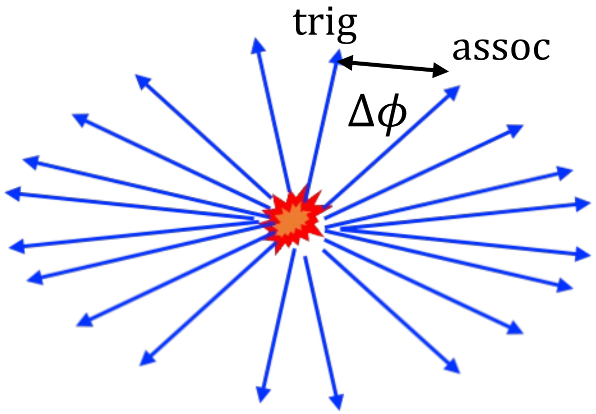

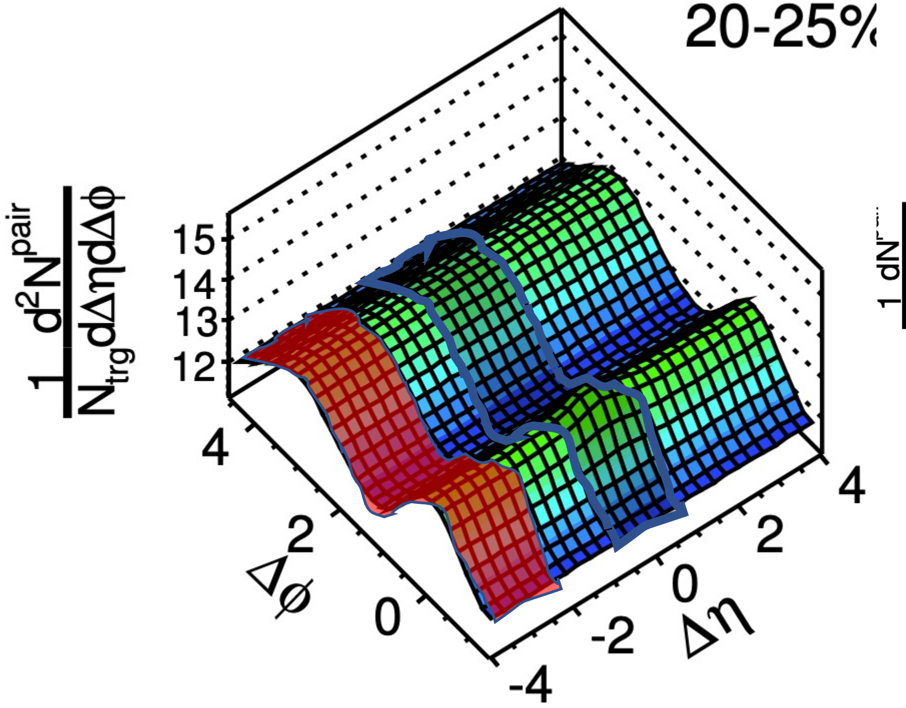

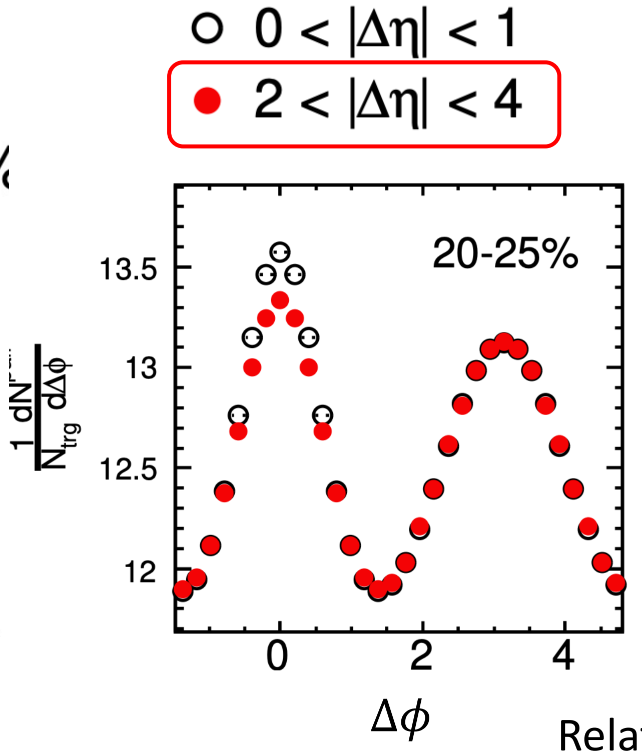

EPC 72 (2012) 10052

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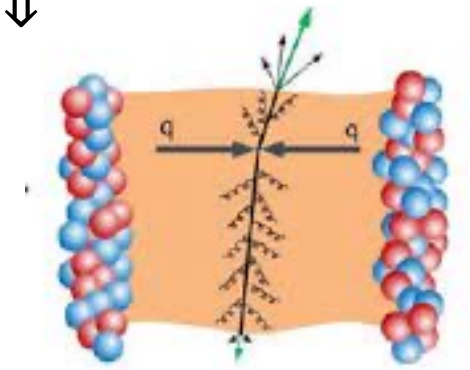
Relative angle distribution enhanced at 0 and pi

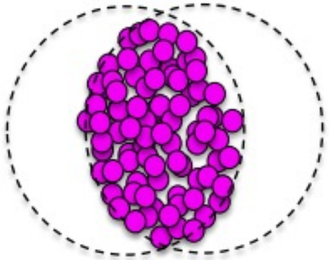
Suppression Measurement – pp as a Reference

$$R_{\mathrm{AA}} = \frac{N_{\mathrm{AA}}}{\langle N_{\mathrm{coll}} \rangle \, N_{\mathrm{pp}}}$$

$\Downarrow$

$R_{\mathrm{AA}} =$





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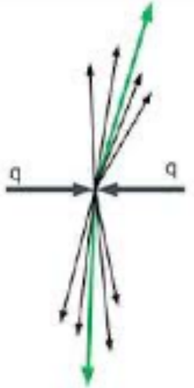
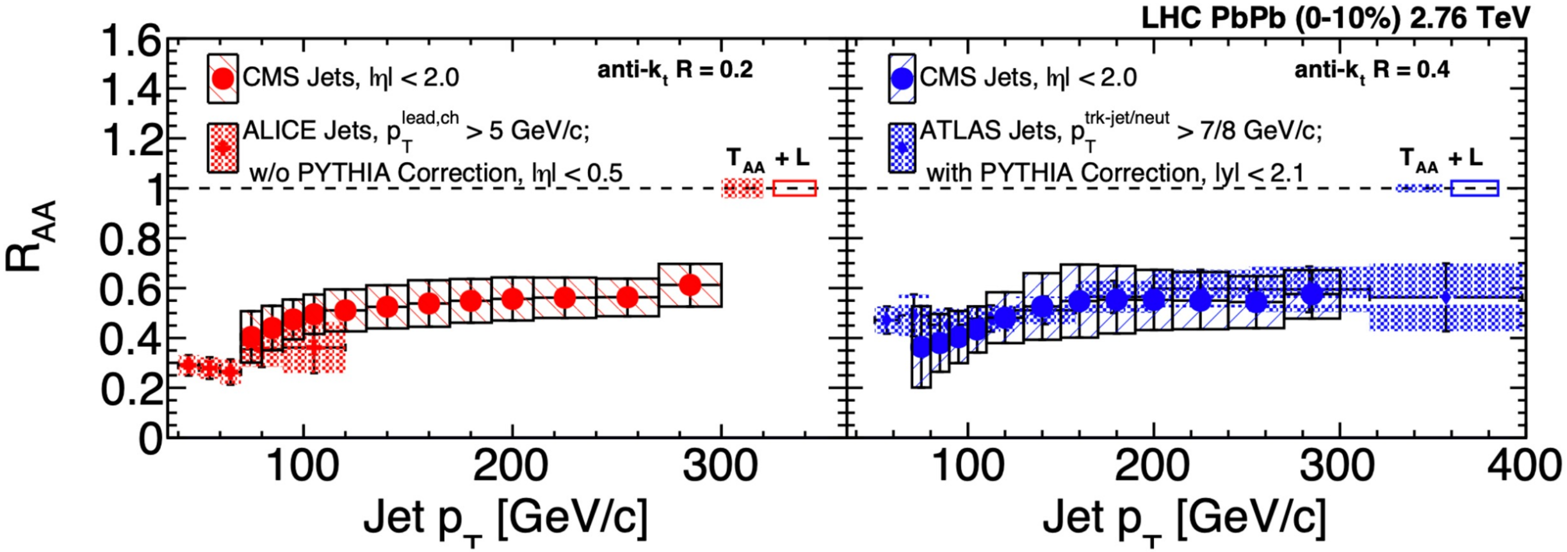


PRC 96 (2017) 015202

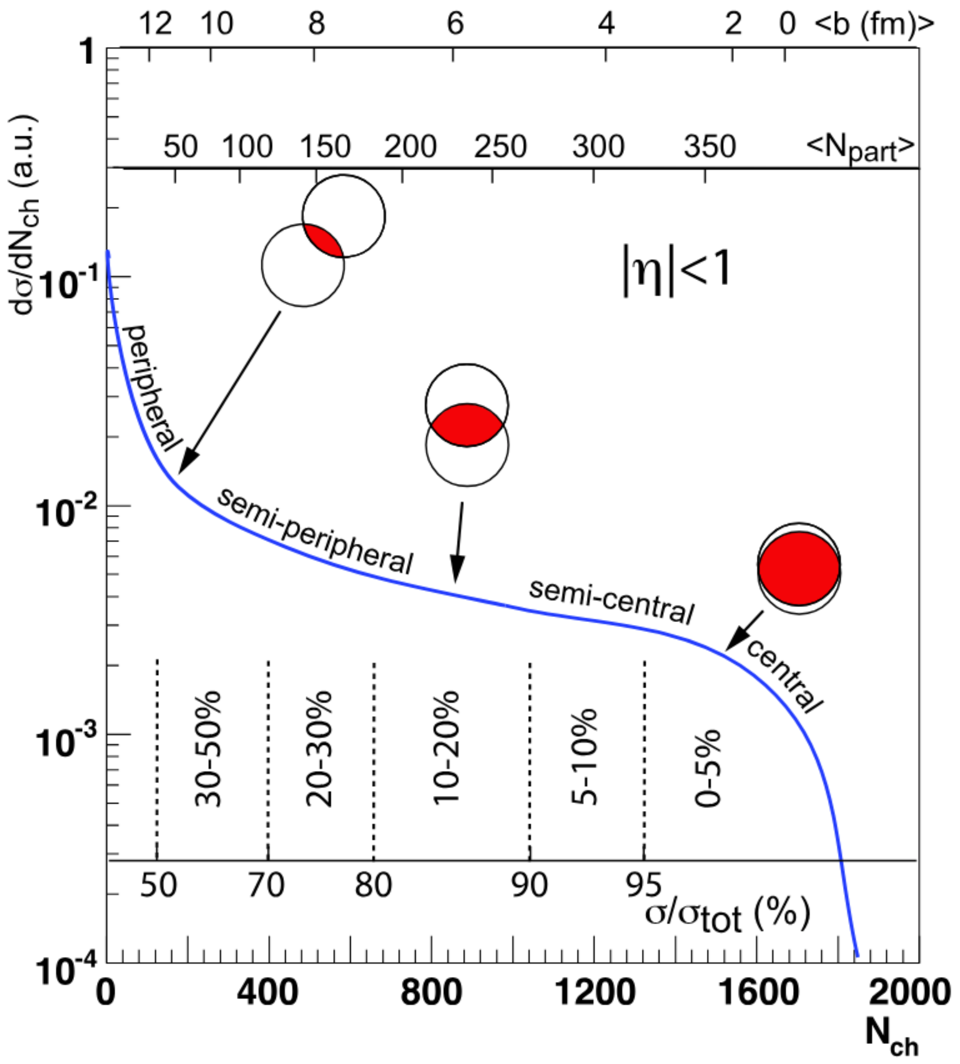


Modification of jets

- ➢ Measured by comparing jet spectra in AA and pp

How well do we understand pp collisions?

What is the Smallest Droplet of QGP



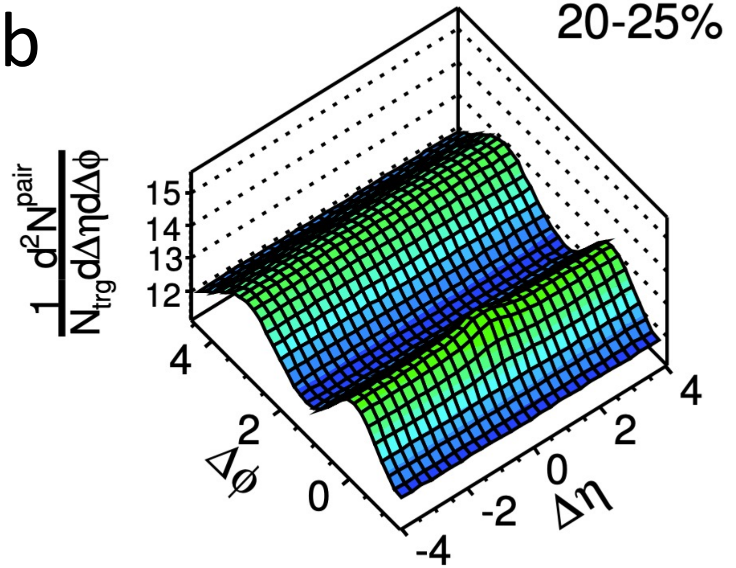
Only a few collisions are “head on”

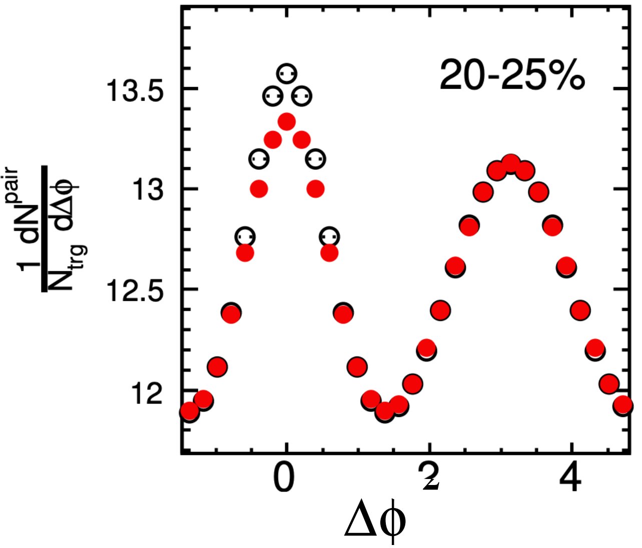
What is the smallest number of nucleon participants to create QGP?

Is there a sign of QGP in a single pp collision?

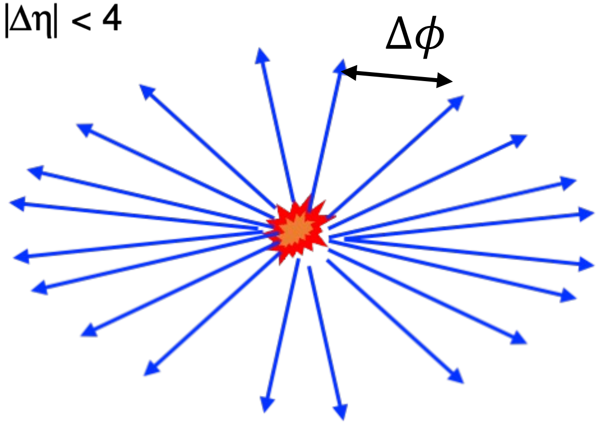
Two-particle Correlations in pp

PbPb

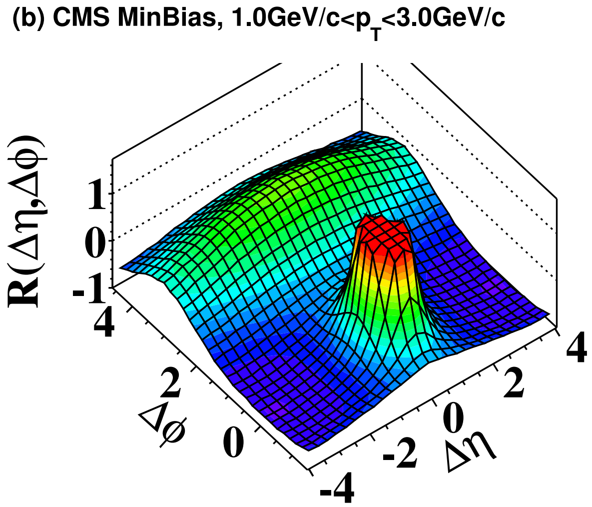


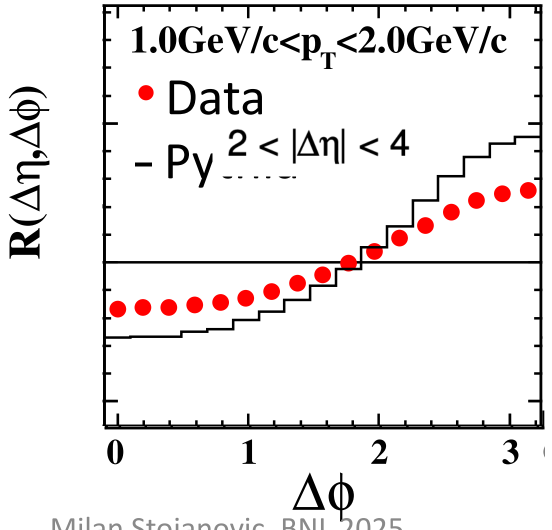


EPC 72 (2012) 10052

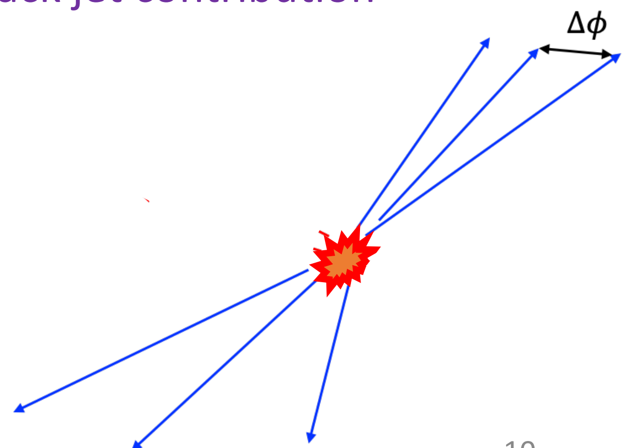


pp





Back-to-back jet contribution



JHEP 091 (2010) 1009

Two-particle Correlations in pp

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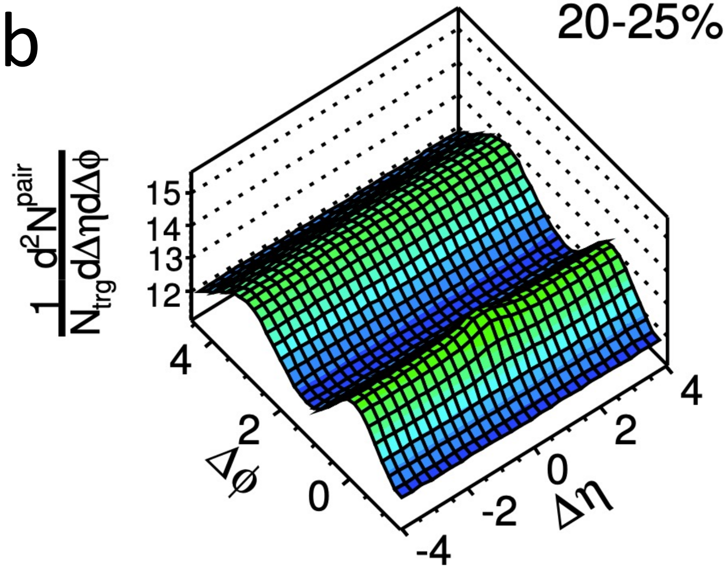
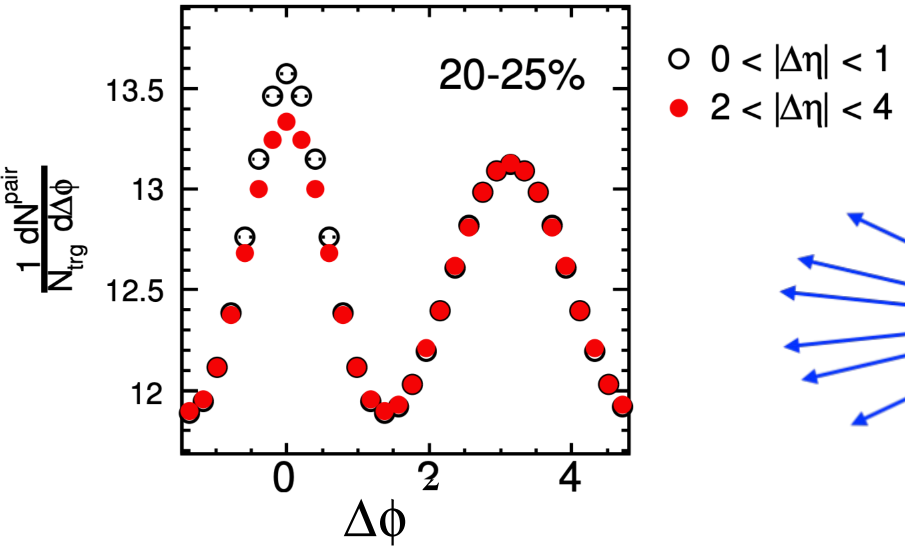
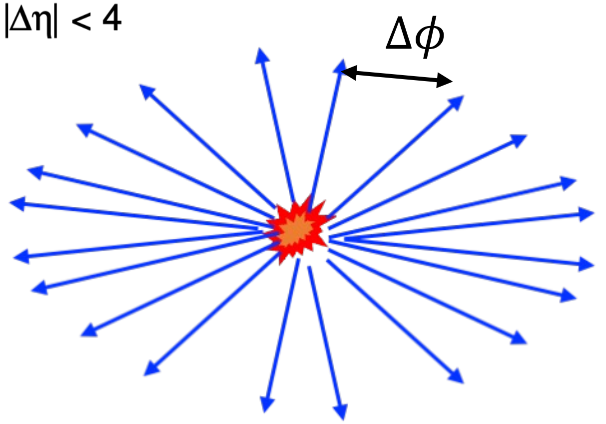




[EPC 72 (2012) 10052]



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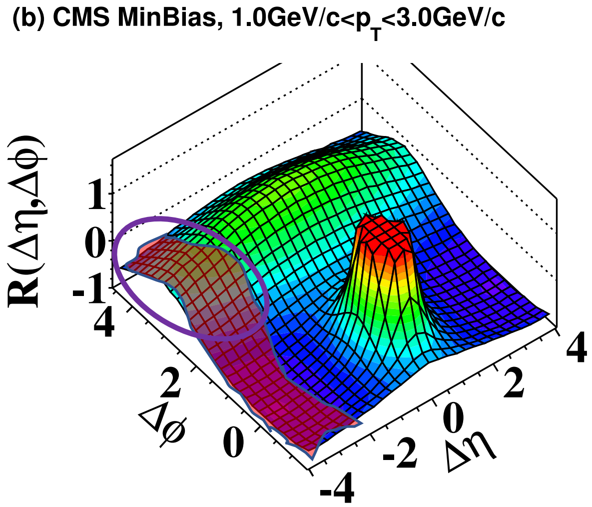

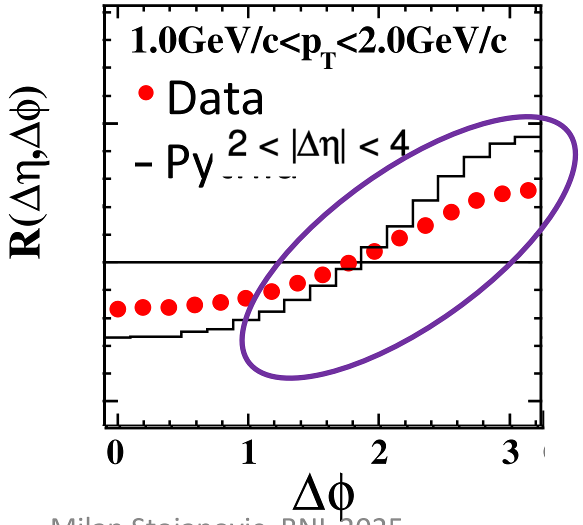

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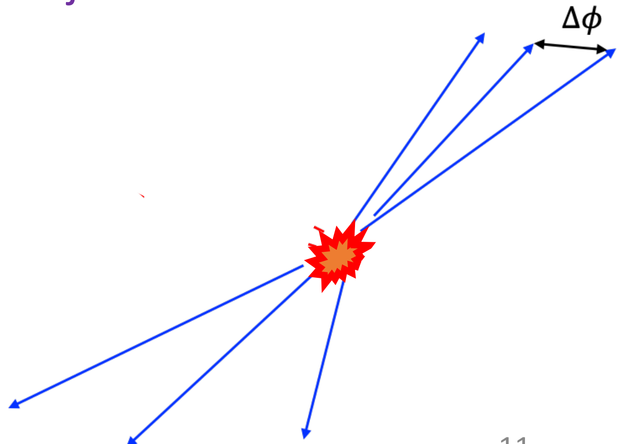

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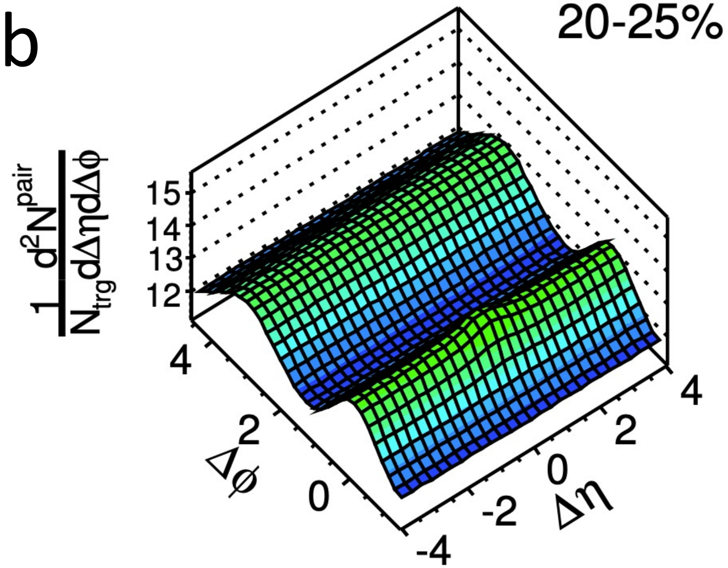

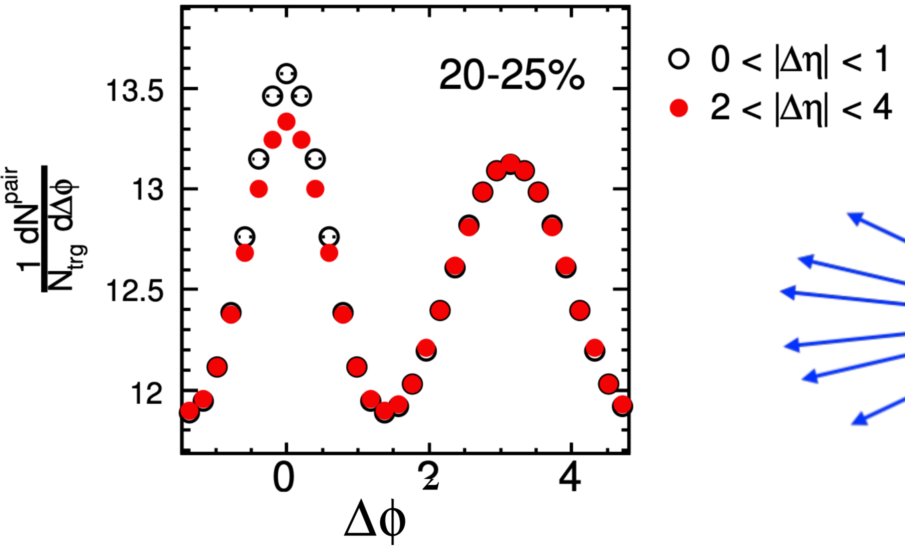

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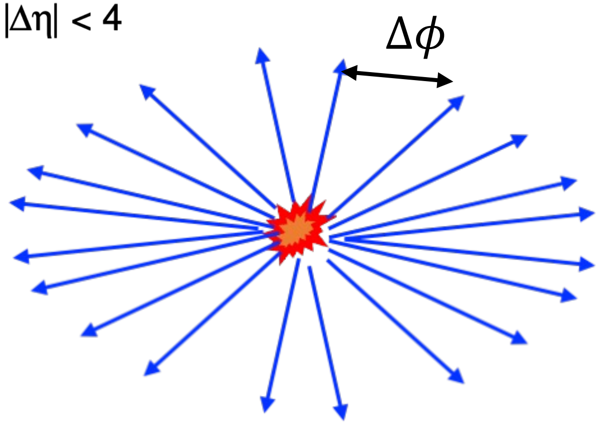

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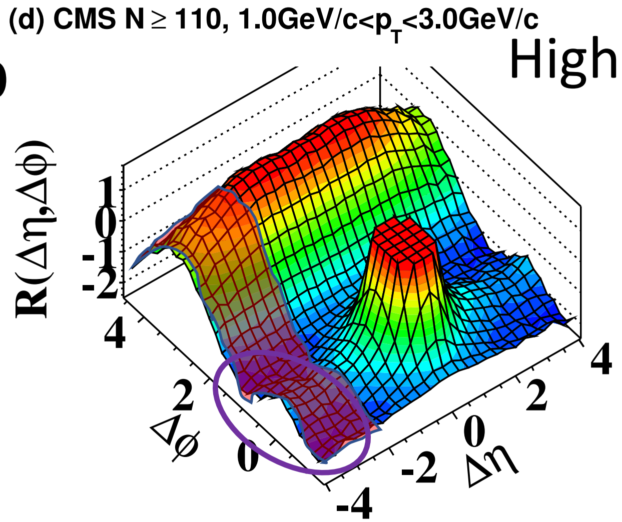
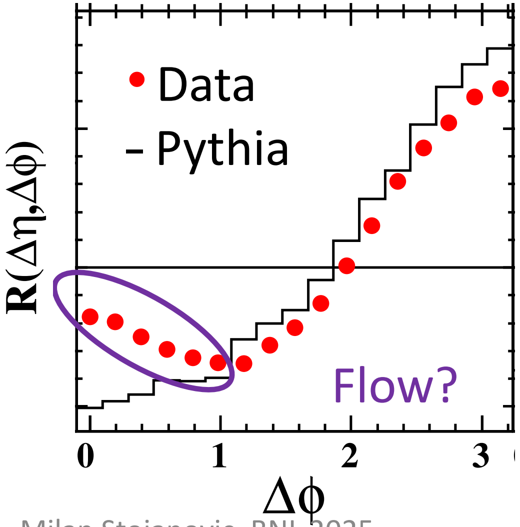
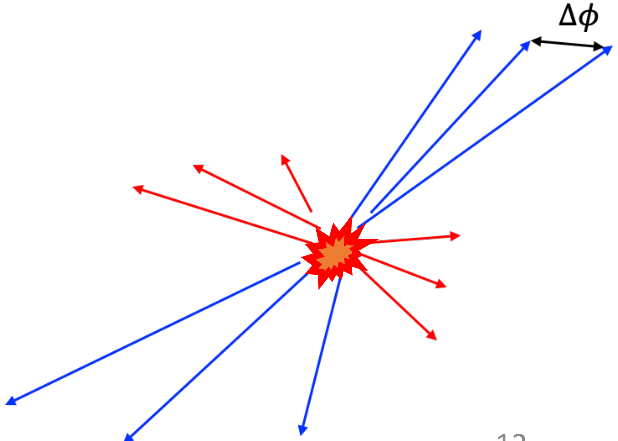


High multiplicity





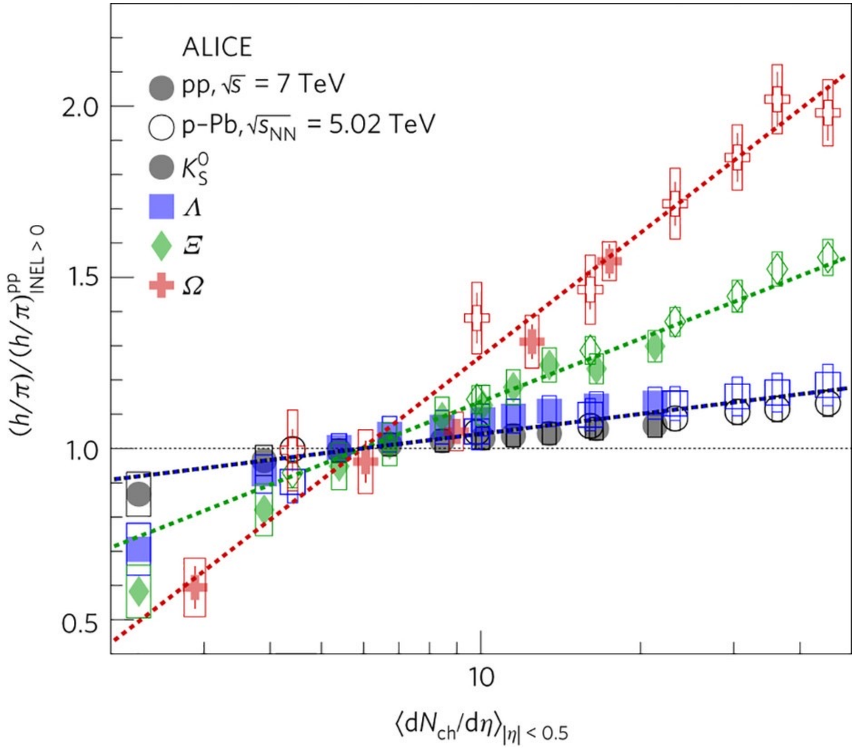
JHEP 091 (2010) 1009

Other QGP Signatures in Small Systems

Ratio of strange hadrons to pions

- ➢ Increases with multiplicity

Strangeness enhancement observed in small systems!



Nat. Phys. 13 (2017) 535

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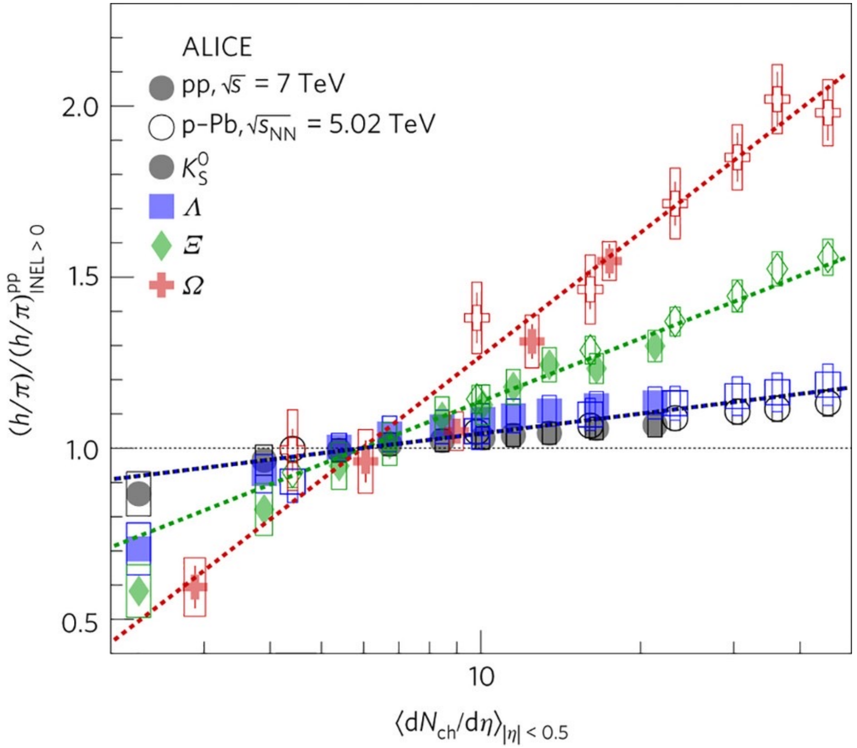
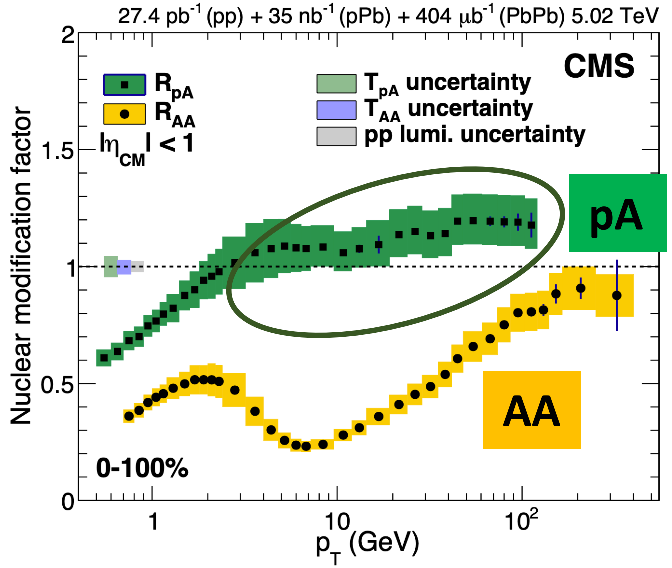


Nat. Phys. 13 (2017) 535



… but NOT suppression!

JHEP, 04 (2017) 039

What causes GQP-like Effects in pp?

Two dominant scenarios

1. Initial state effects

Correlations established prior to collisions

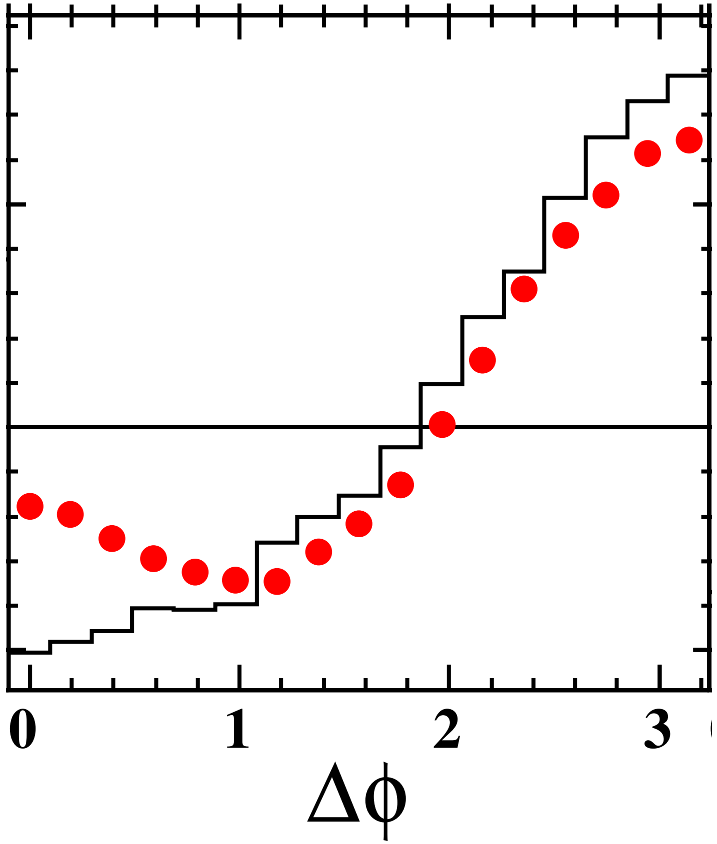
2. Final state effects

Correlations established through interaction of emitted particles

Can we quantify collectivity in pp collisions?

How to Measure Flow in Small Systems?

$$\frac{\mathrm{d}N^{\mathrm{pair}}}{\mathrm{d}\Delta\phi} \approx G\left\{1 + 2\sum_{1}^{\mathrm{n}}\left(V_{\mathrm{n}}^{flow} + V_{\mathrm{n}}^{nonflow}\right)\cos(\mathrm{n}\Delta\phi)\right\}$$



In small systems non-flow is dominant component!

Need to separate flow & non-flow!

JHEP 091 (2010) 1009

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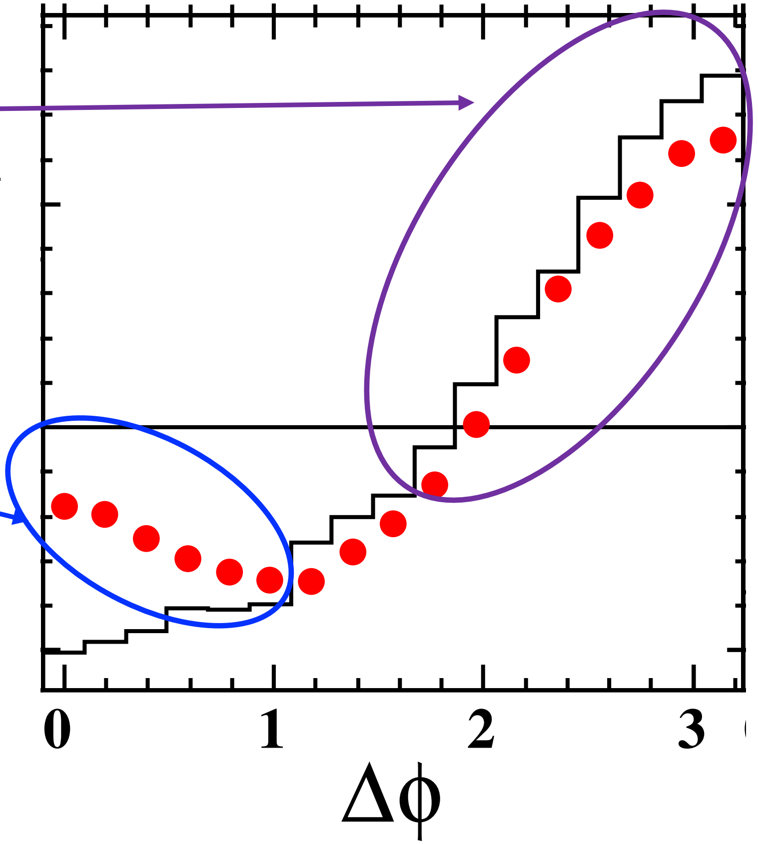
$$V_{\mathrm{n}}^{nonflow} \gg V_{\mathrm{n}}^{flow}$$



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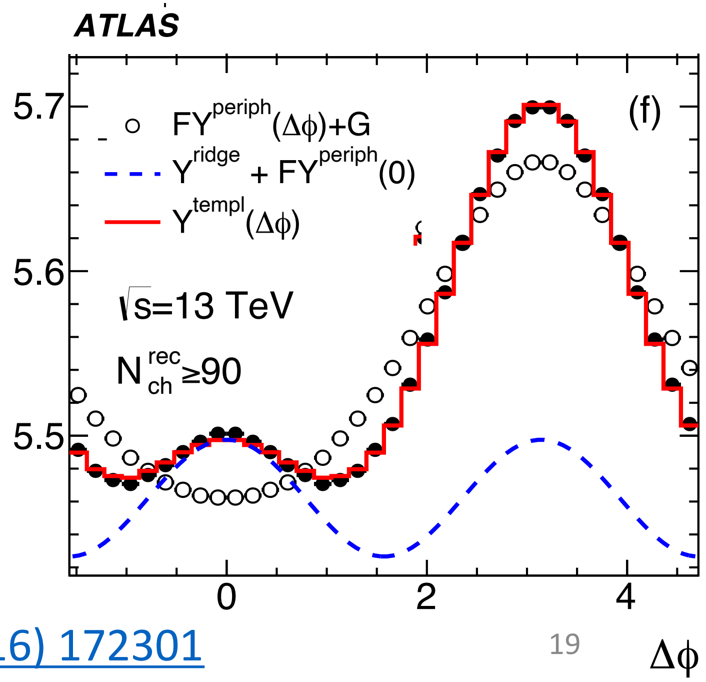
Method 1: Template Fit

Assumptions:

- $V_{n\Delta}^{nonflow,HM} = const * V_{n\Delta}^{nonflow,LM}$
- $V_{1\Delta}^{flow,LM} \equiv 0$



[PRL 116 (2016) 172301](PRL 116 (2016) 172301)

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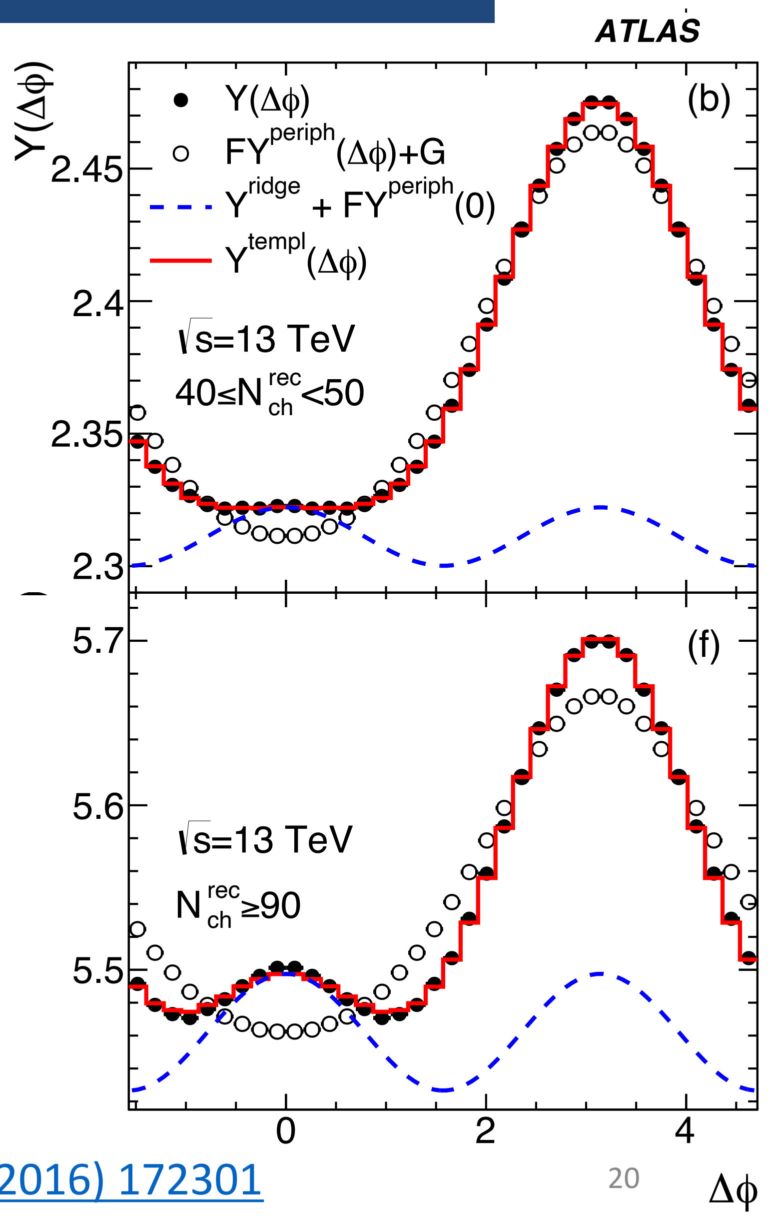
Non-zero v_2 even when there is no "ridge"!



 PRL 116 (2016) 172301

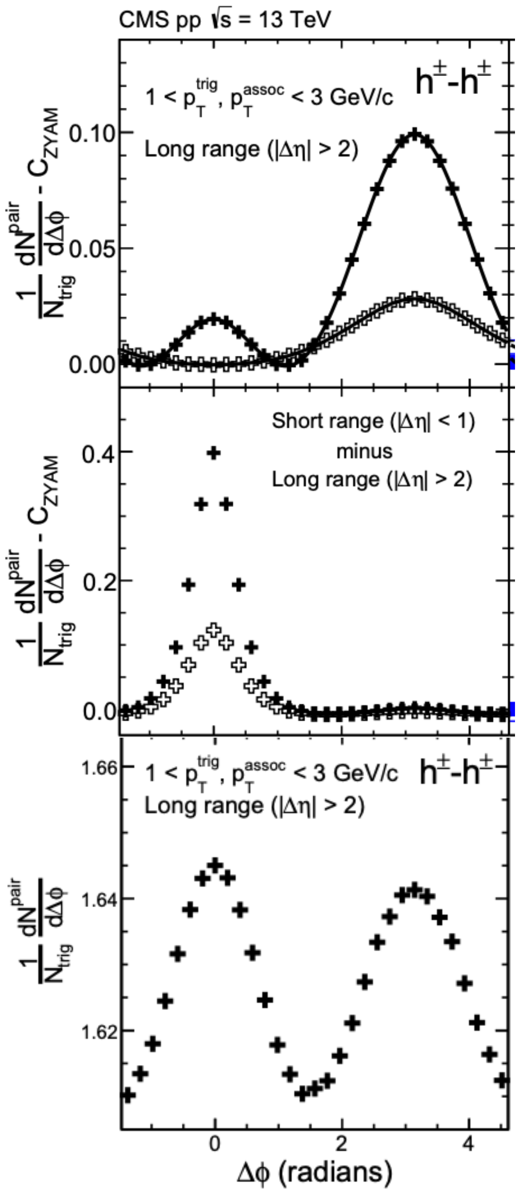
How to Measure Flow in Small Systems?

$$\frac{dN^{\text{pair}}}{d\Delta\phi} \approx G\left\{1 + 2\sum_{1}^{n}\left(V_{n\Delta}^{flow} + V_{n\Delta}^{nonflow}\right)\cos(n\Delta\phi)\right\}$$

Method 2: Low multiplicity subtraction

Assumptions:

- $V_{n\Delta}^{nonflow,HM} = const * V_{n\Delta}^{nonflow,LM}$
- $const = SR_{HM}/SR_{LM}$
  - No jet modification with multiplicity
- $V_{n\Delta}^{flow,LM} \equiv 0$



PLB 765 (2017) 193

Long range

Short range

Non-flow subtracted

- Clear flow modulation

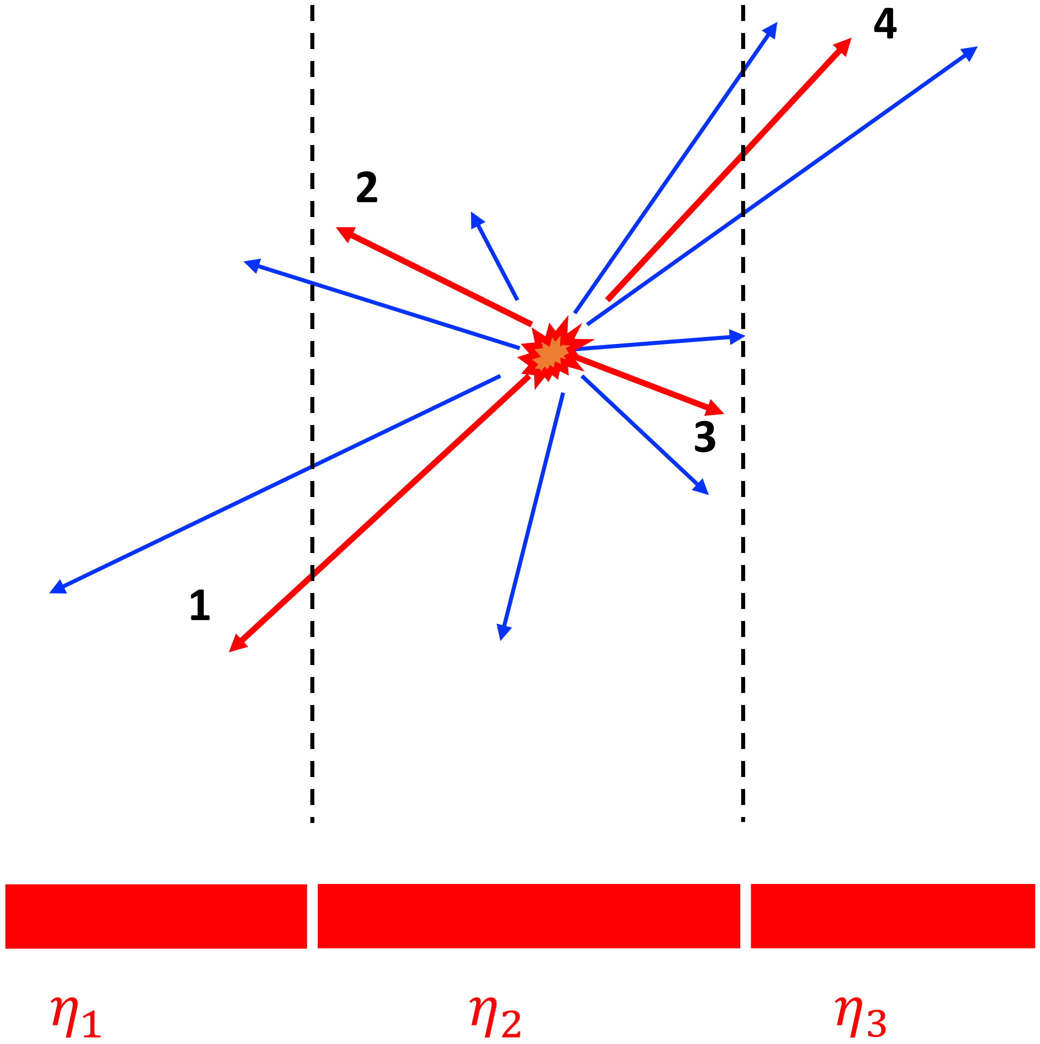
How to Measure Flow in Small Systems?

4-particle correlations

Correlates 4 particles at the same time
- ➢ Reduces few-particle correlations

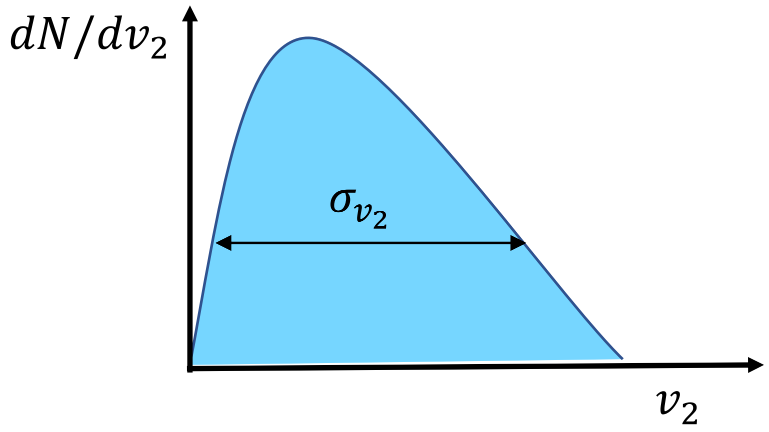
Particle selected from different rapidity-windows (subevents)
- ➢ Reduces back-to-back dijet correlations

Requires:
- ➢ High multiplicities
- ➢ Large acceptance



How to Measure Flow in Small Systems?

4-particle correlations



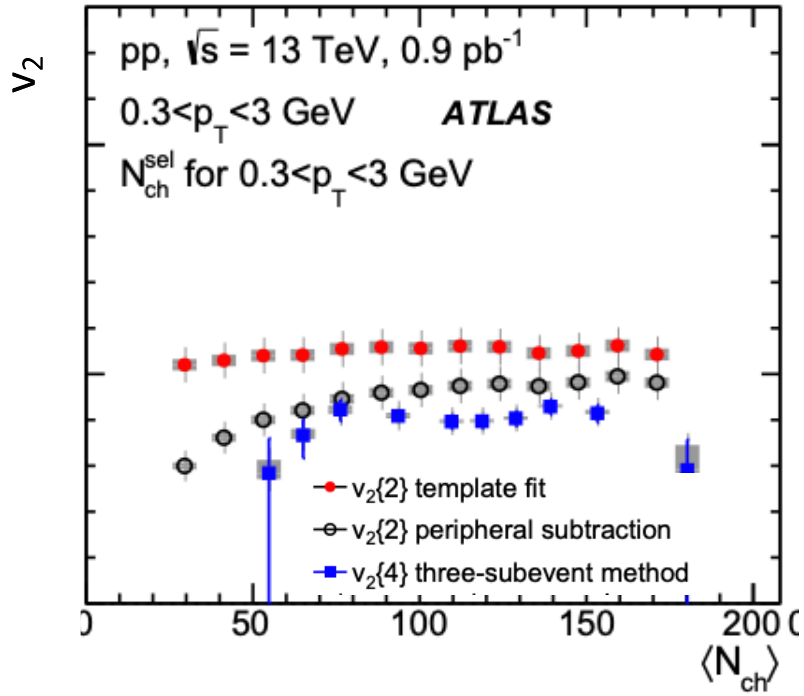
- Two-particle correlations: $v_2\{2\} = \sqrt{\langle v_2 \rangle^2 + \sigma_{v_n}^2}$
- Four-particle correlations: $v_2\{4\} \simeq \sqrt{\langle v_2 \rangle^2 - \sigma_{v_n}^2}$

Does NOT measure the same thing as 2-particle correlations!

v_2 results in pp

Significant differences between two methods!

PRC 97 (2018) 024904



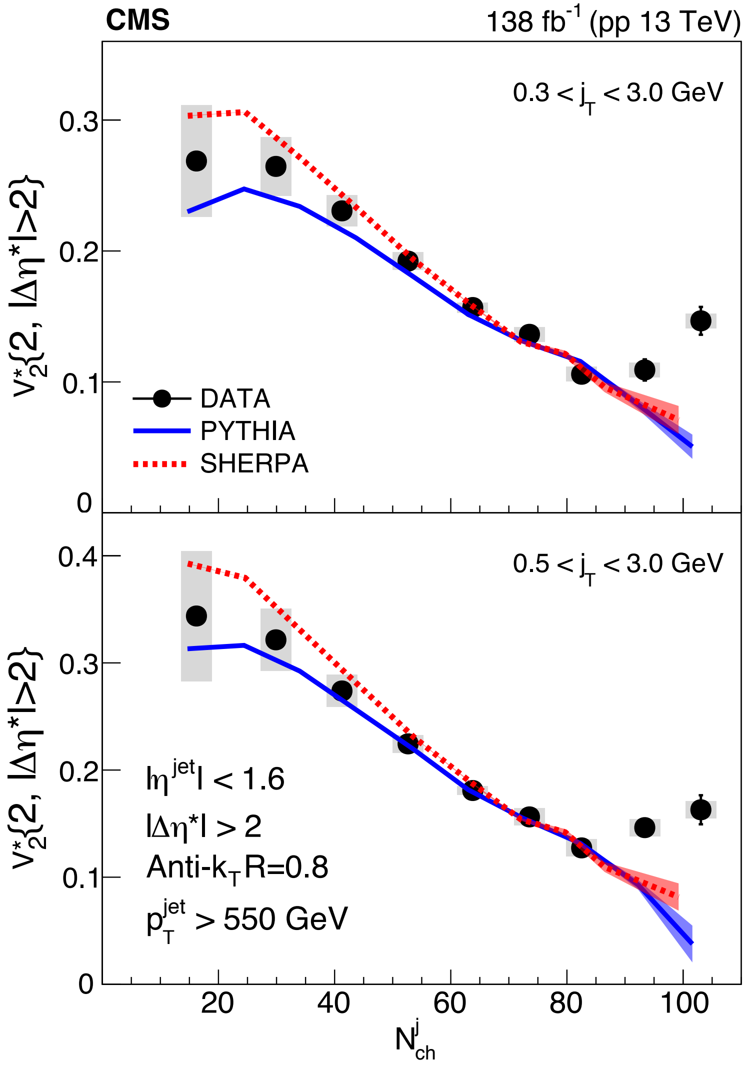
Template fit – weak dependence on multiplicity

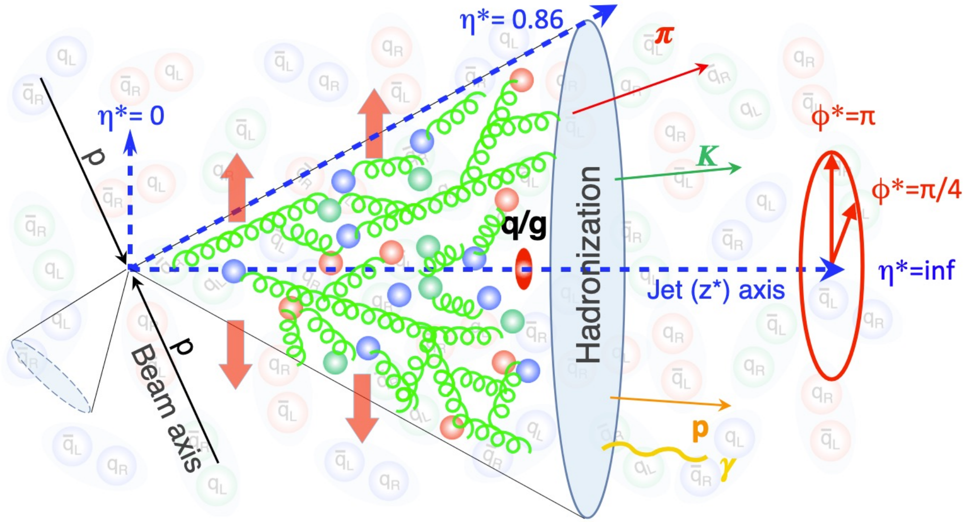
Peripheral subtraction – goes to 0 at low multiplicity by construction

Explore the Onset of Collectivity

Collectivity in a Single Jet?

- [PRL 133 (2024) 142301](#)





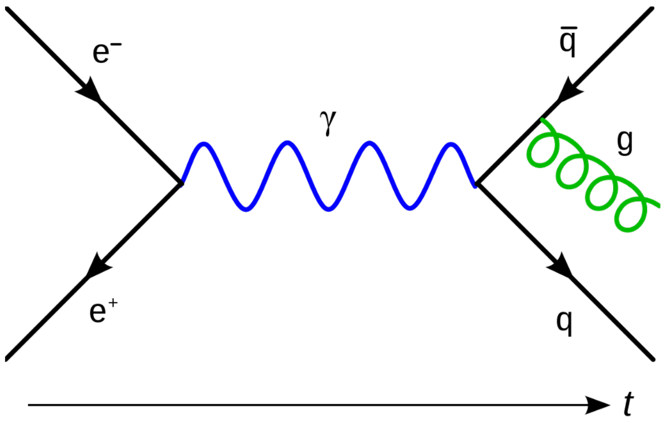
Low multiplicity/MB – described by models w/o collectivity

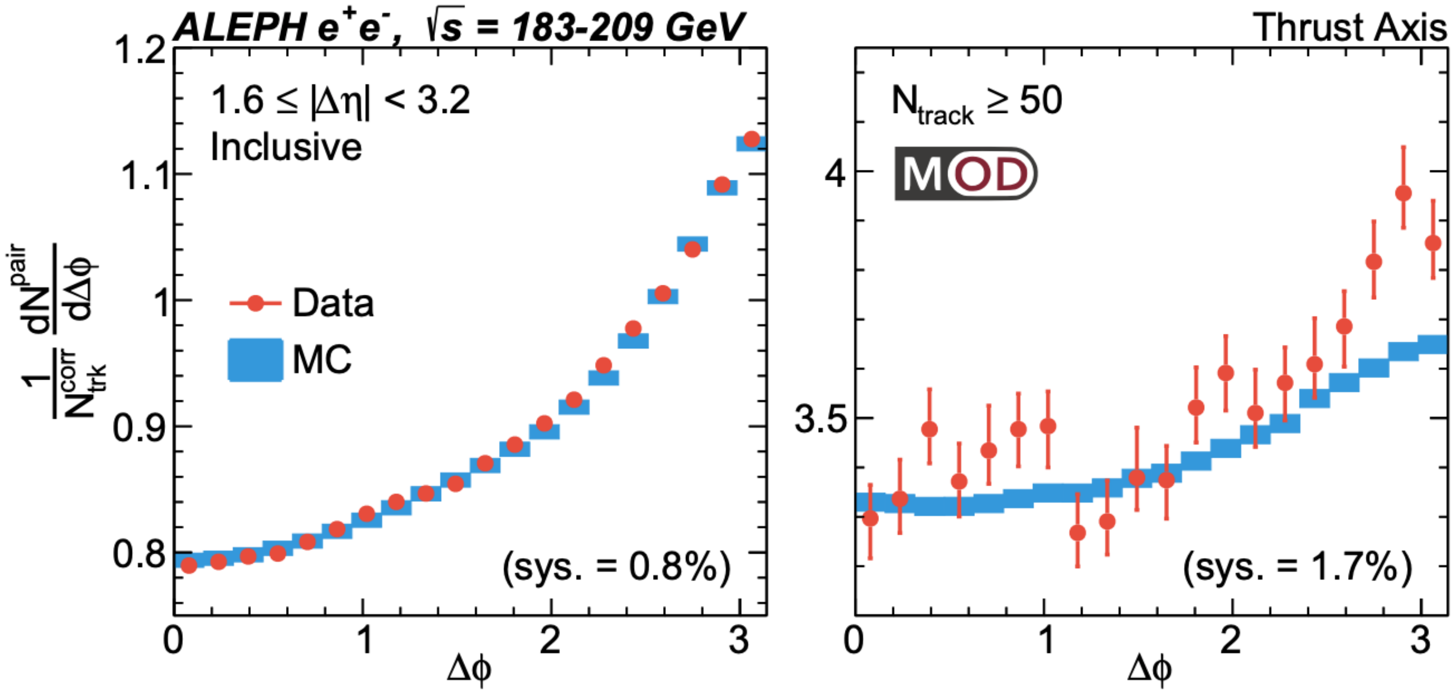
Models unable to describe high multiplicity behavior

e+e- collisions

Can e+e- create environment dense enough for QGP?

PLB 856 (2024) 138957





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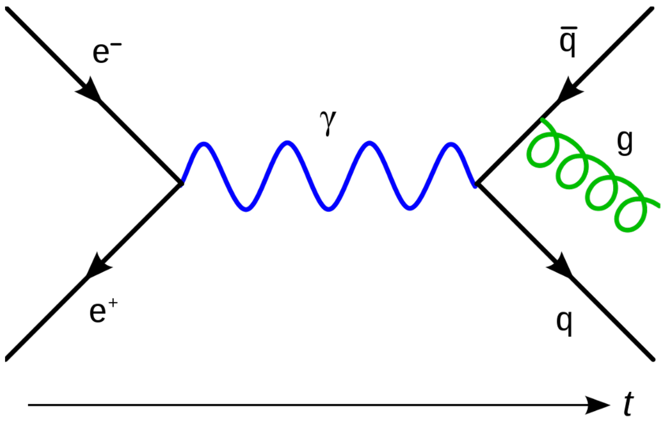

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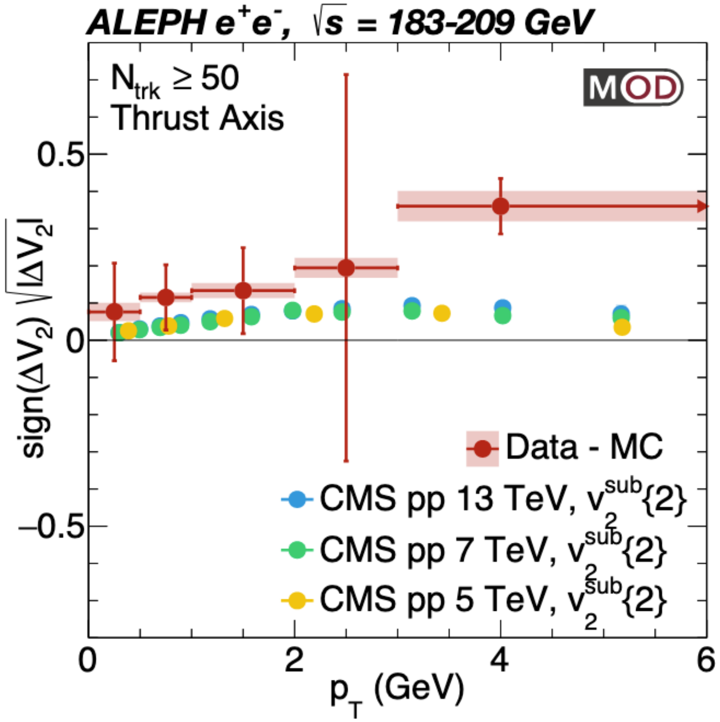

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Models unable to describe high multiplicity behavior

Non-flow subtraction:

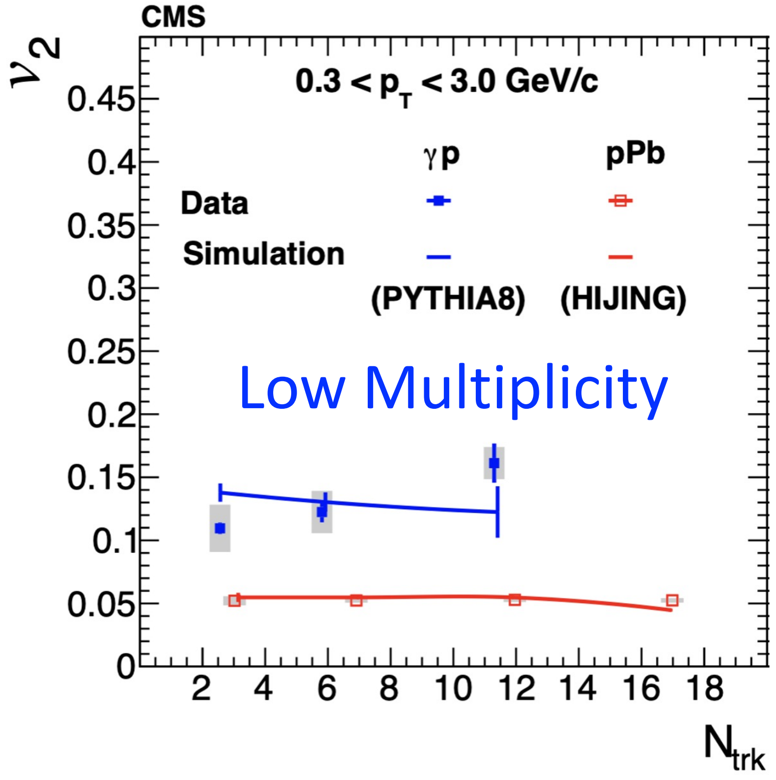
$$\Delta V_2 = \Delta V_{2,\mathrm{data}} - \Delta V_{2,\mathrm{MC}}$$

Entirely relying on MC

Photo-Nuclear Collisions

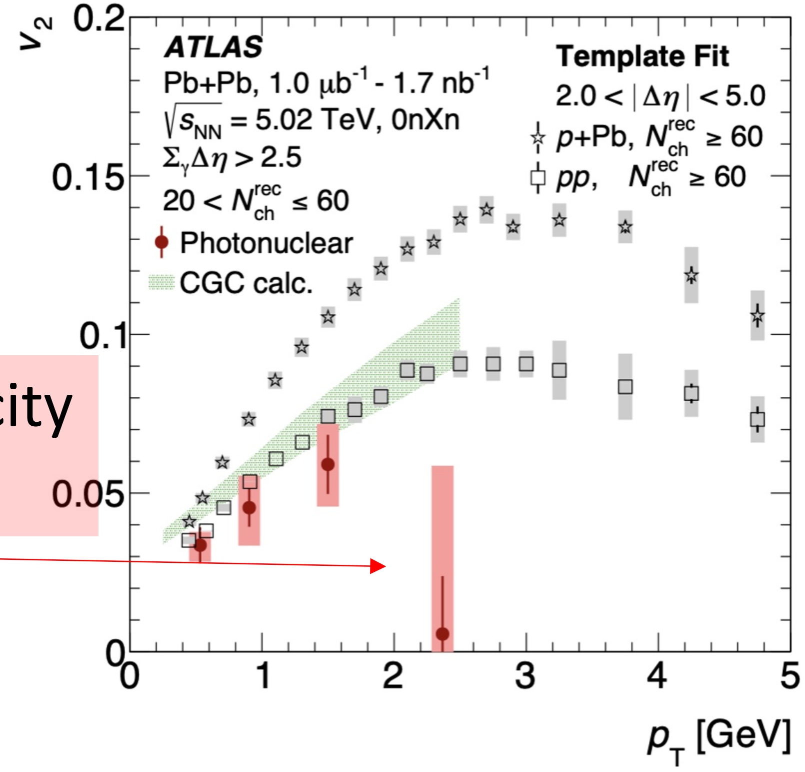
PLB 844 (2023) 137905

No subtraction



Low Multiplicity

Template Fit



High-er Multiplicity
Template Fit

Low multiplicity/MB – described by models w/o collectivity

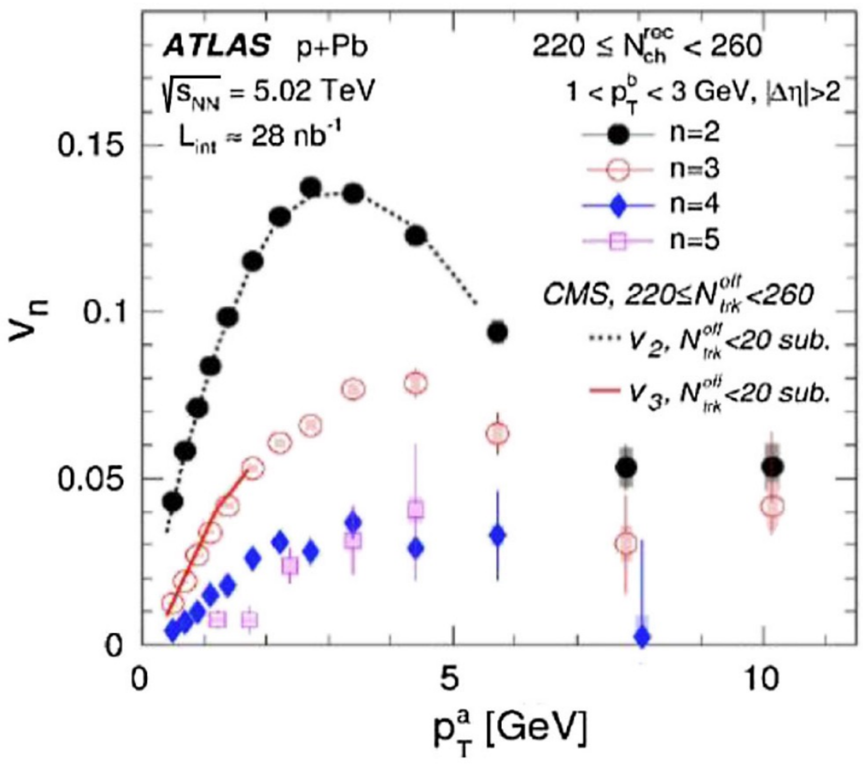
PRC 104, 014903 (2021)

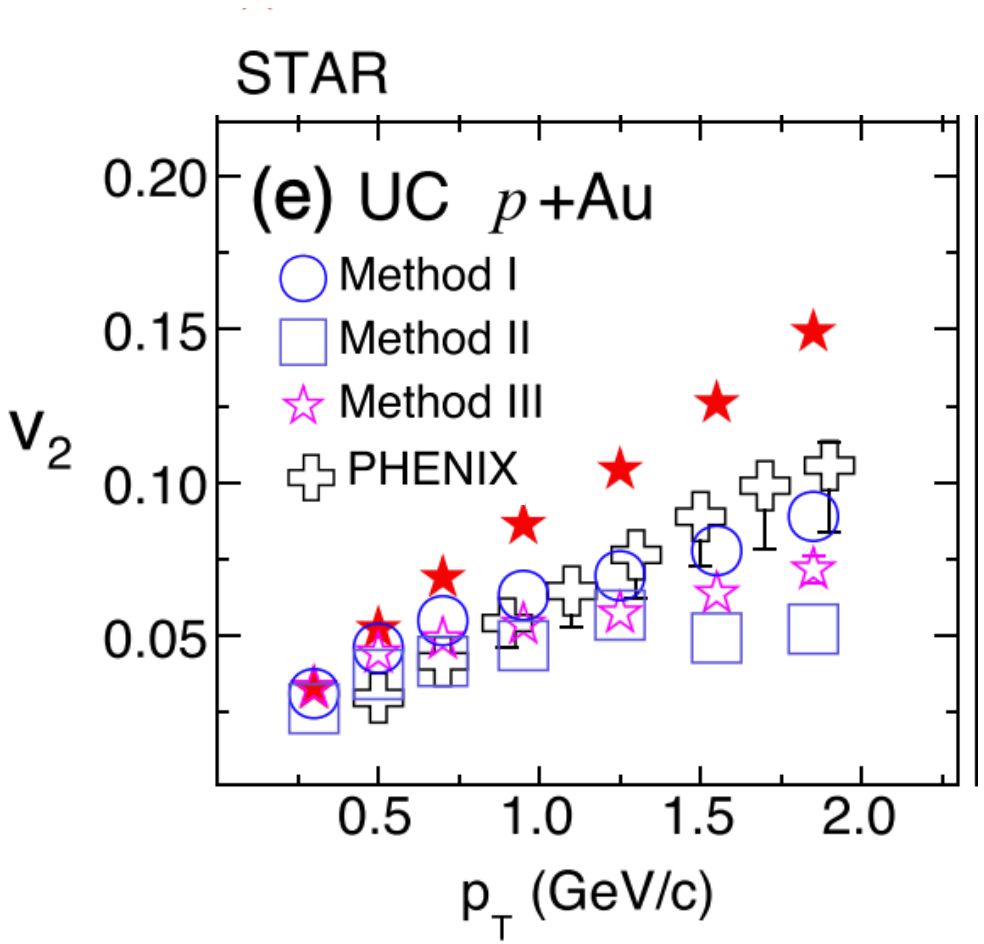
Template fit gives significant v2 at high multiplicity

Onset of Collectivity

Even in smallest systems models fail to describe high multiplicity events

Energy Dependence of Flow in pA





Magnitude of flow similar between two energies

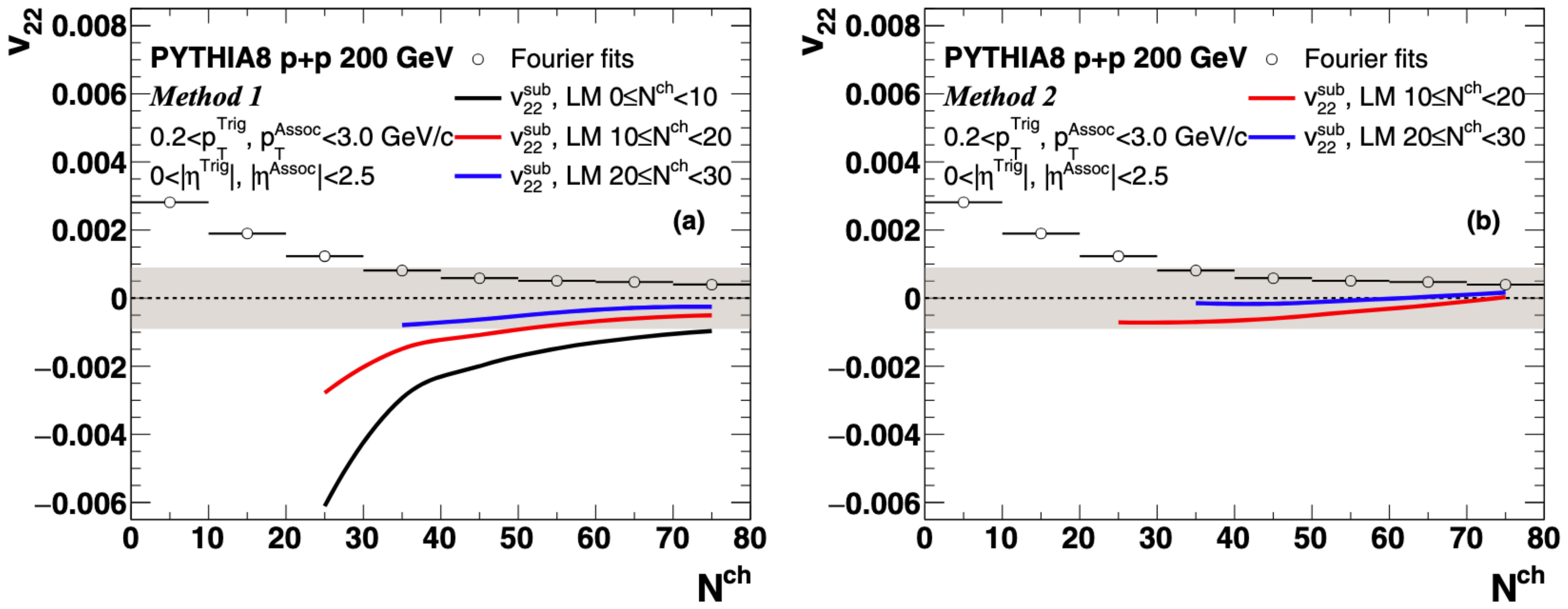
Discrepancies between subtraction methods

Methods I & II – peripheral subtraction
Method III ~ template fit

[PRL 130, 242301 (2023)]

Energy Dependence of (Non)Flow in pp

Energy Dependence of (Non)Flow in pp



PYTHIA

Closure test

No flow input!

Multiplicity

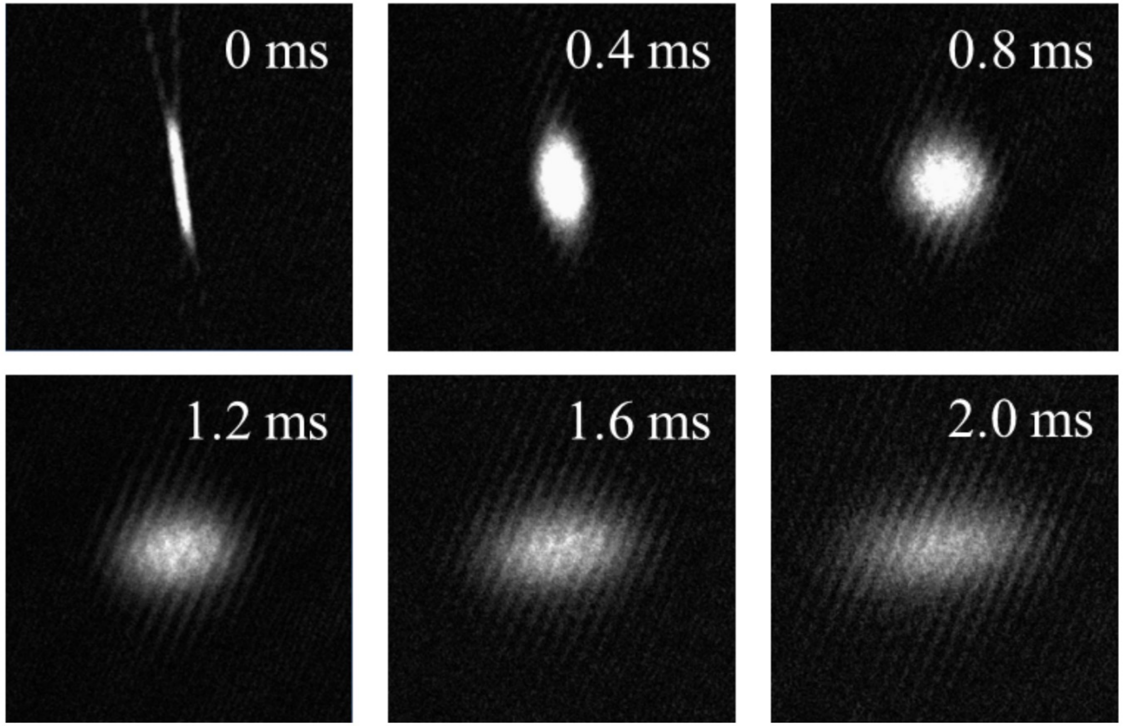
[PRC 100, 024908 (2019)]

Methods developed for LHC not directly applicable at RHIC

- Measured value depends on the choice of low-multiplicity region

Can we study QCD without QCD?

Collective Flow in Ultra Cold Gases

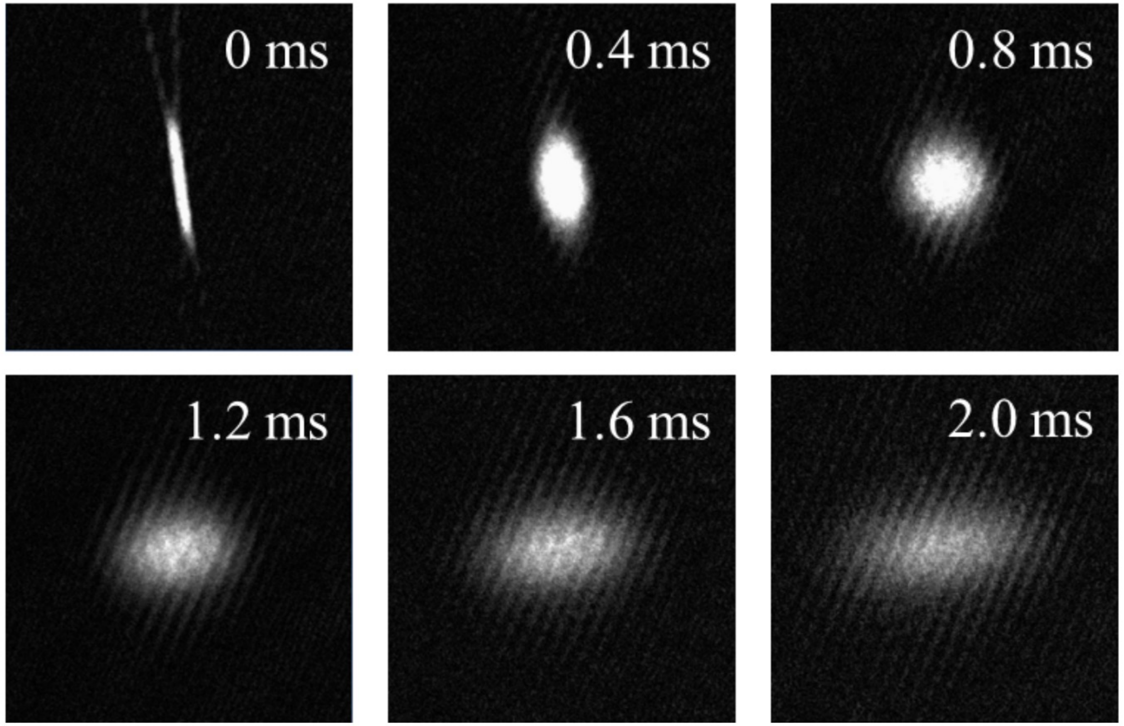


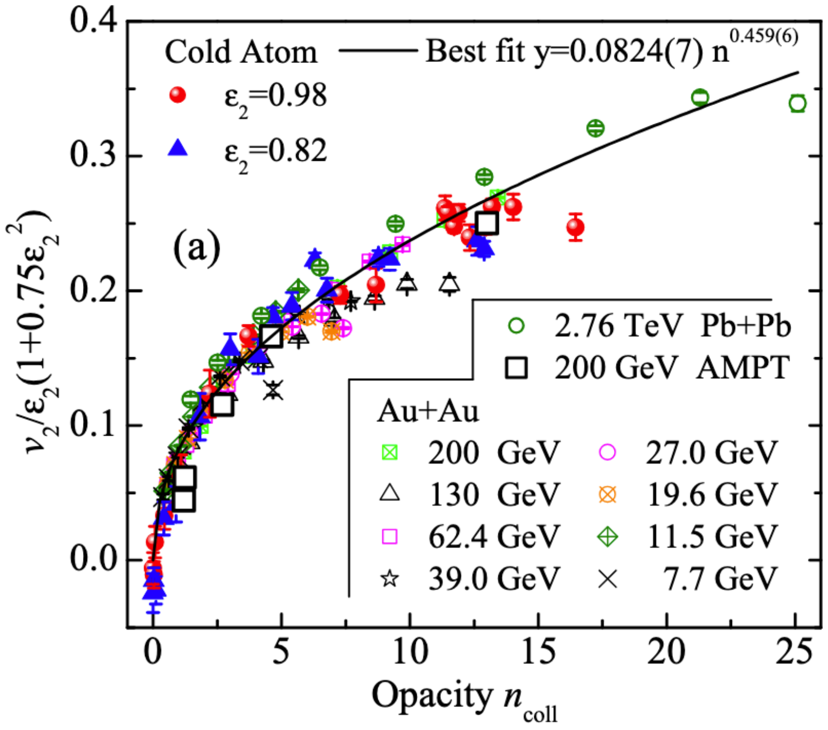
Cold atom gas (T~10^{-6} K) shows a similar expansion as QGP

Interaction tuned with magnetic field

arXiv:2405.02847

Collective Flow in Ultra Cold Gases





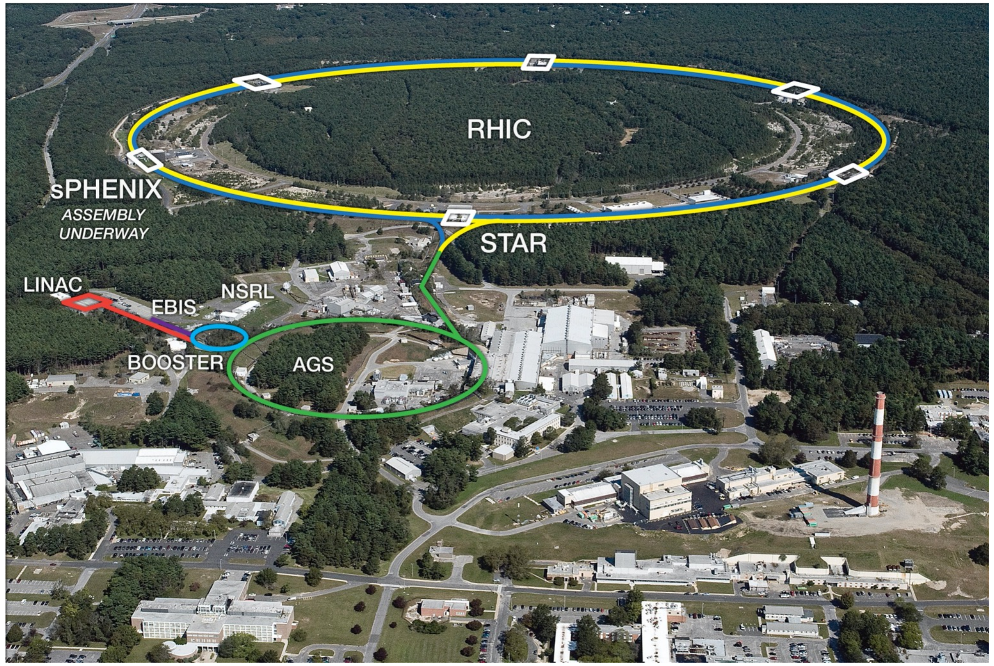
Cold atom gas ($T \sim 10^{-6}$ K) shows a similar expansion as QGP

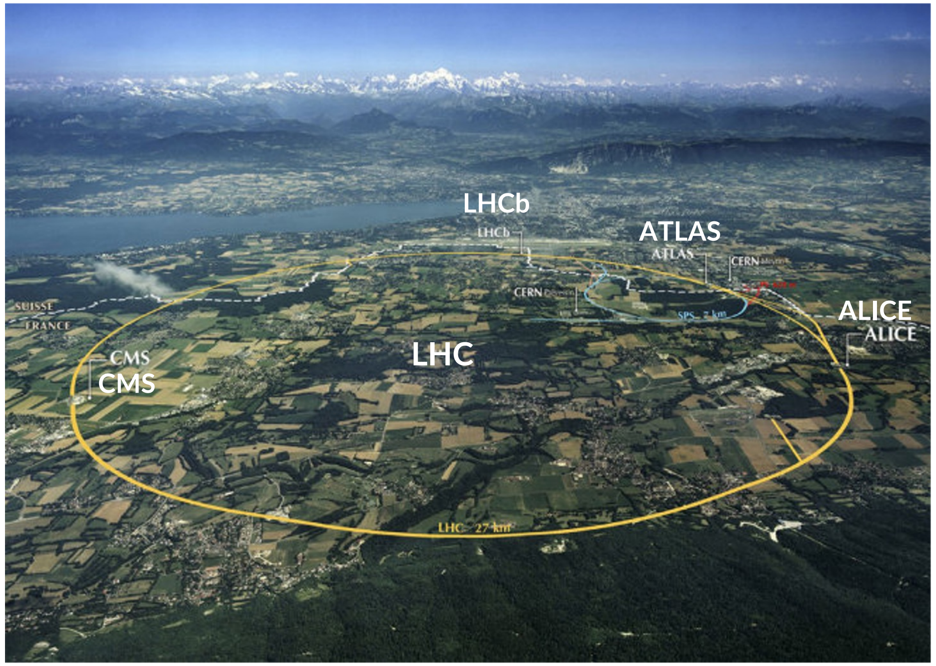
Interaction tuned with magnetic field

Cold atoms v_2 consistent with heavy ions

arXiv:2405.02847

Near Future - Experiments





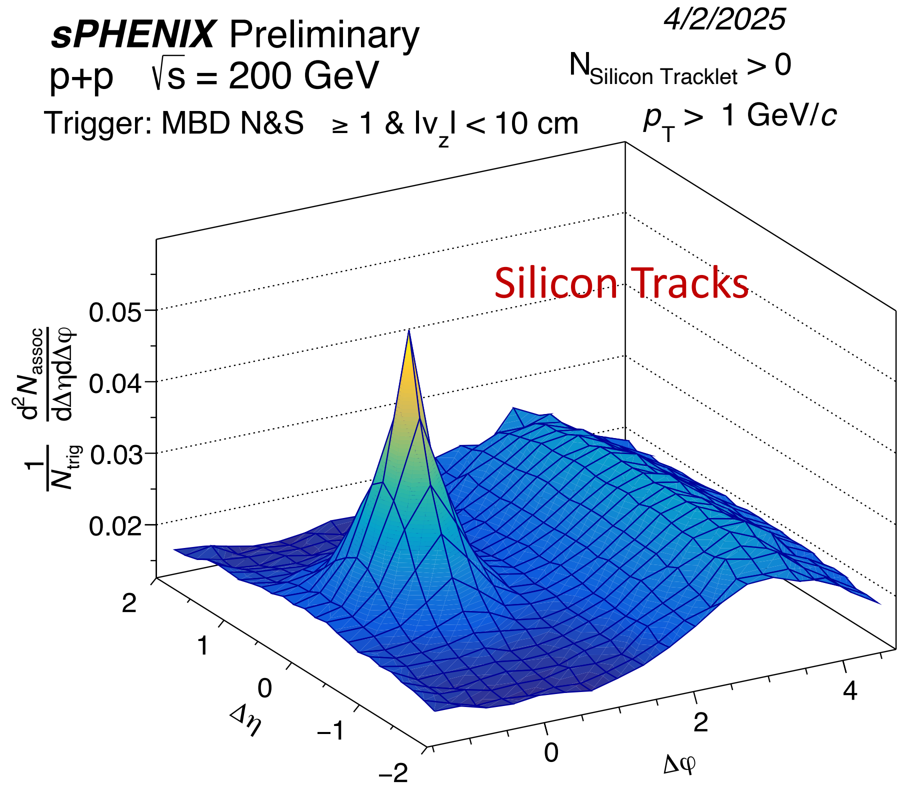
Huge dataset collected in 2024

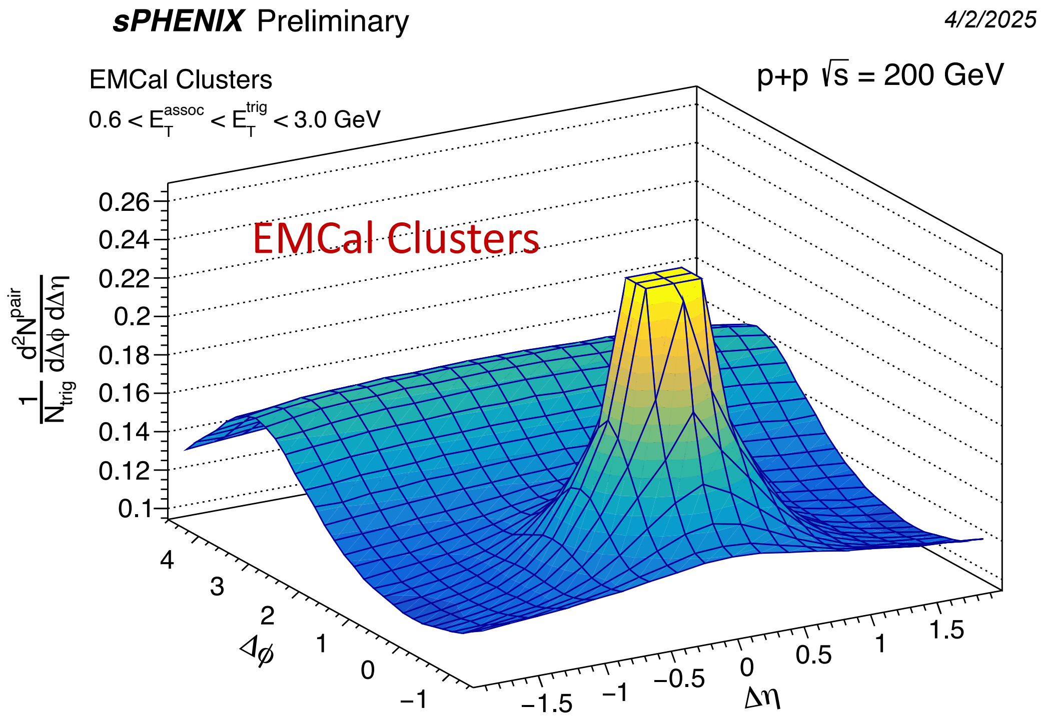
- HM dataset with STAR
- Jet dataset with sPHENIX
- pAu run?

Run3 & Run4

- High multiplicity pp
- High multiplicity UPC

sPhenix – two-particle correlations in pp





First look at sPHENIX data!

Near Future - Modeling

We've entered an era of AI gold rush!

Can we use it for nuclear physics modeling?

What Future Brings - Modeling

We've entered an era of AI gold rush!

Can we use it for nuclear physics modeling?

MUSIC:

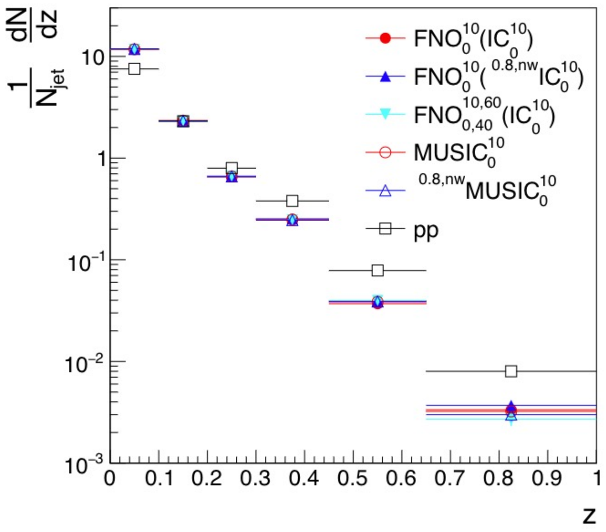
- an PDE solver for QGP hydrodynamic flow

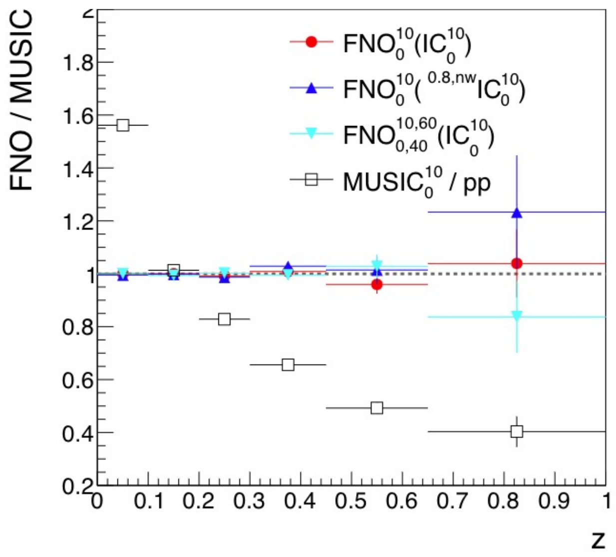
FNO

- AI trained on solutions of Hydro differential equations

Jet quenching from FNO consistent with MUSIC

Significant improvement in computation time!





Summary

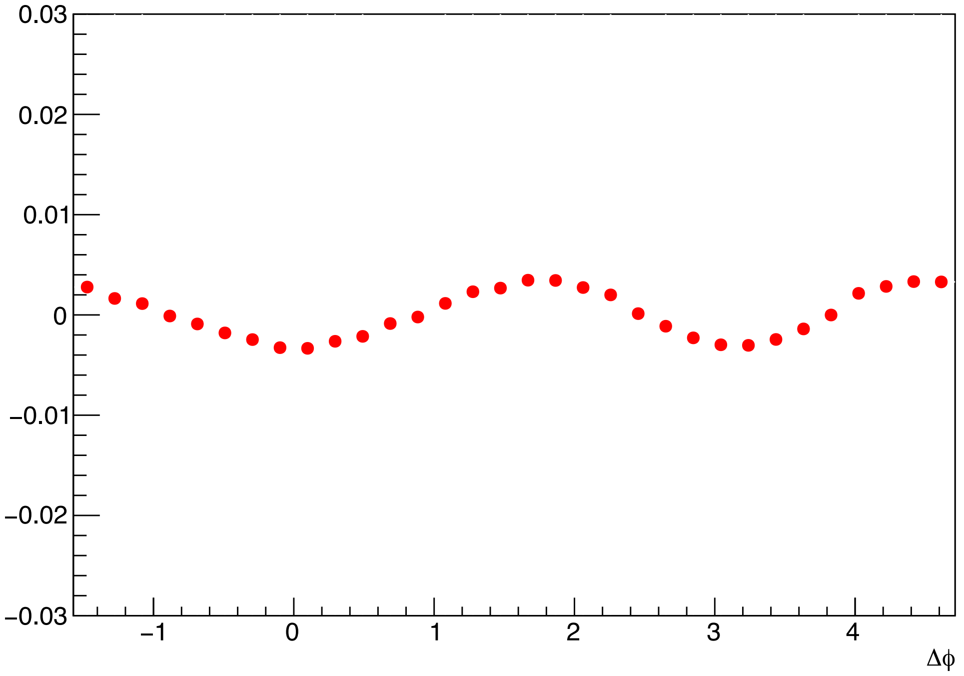
- Discrepancies between flow measurements in pp at LHC
- Non-closure at RHIC energies
- Is there a significant v2 in other small systems?

In order to understand flow we need to understand non-flow!

Looking forward to the RHIC pp measurement!

Backup Slides

Energy Dependence of (Non)Flow in pp



PYTHIA

Closure test

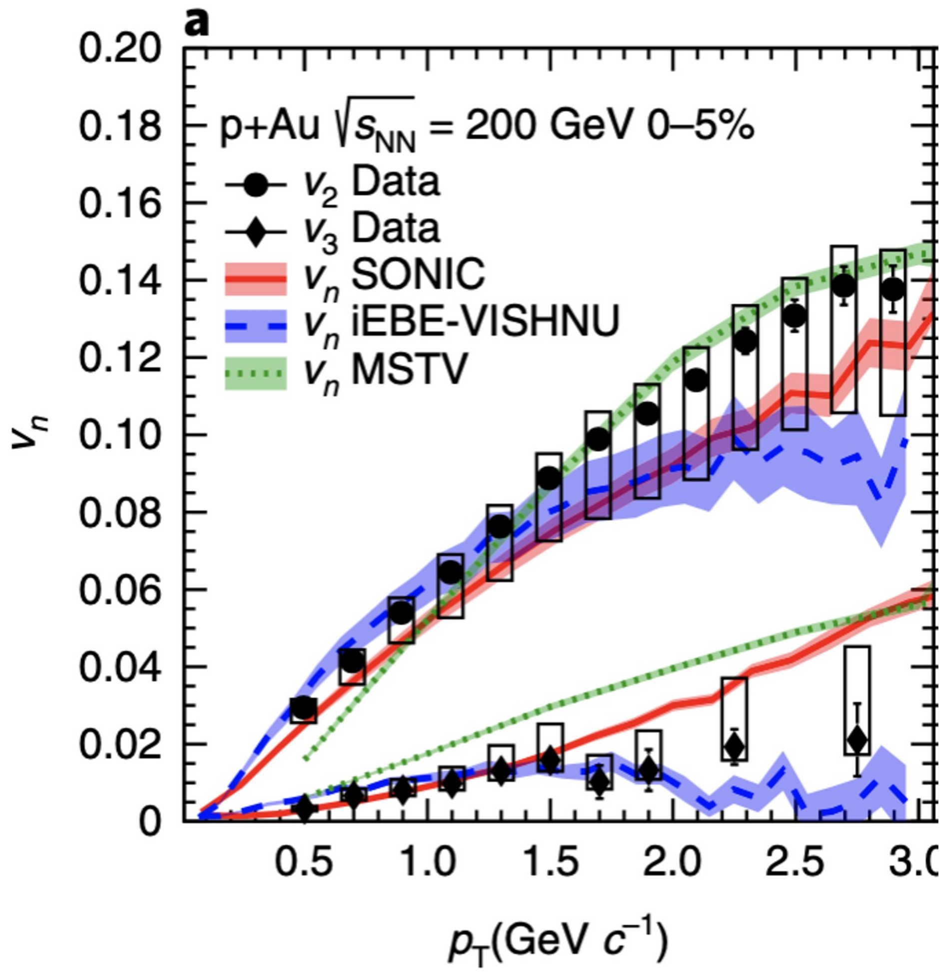
No flow input!

There is still a modulation after non-flow subtraction!

Methods developed for LHC not directly applicable at RHIC

- Measured value depends on the choice of low-multiplicity region
- Non-closure!

Flow in pA at RHIC

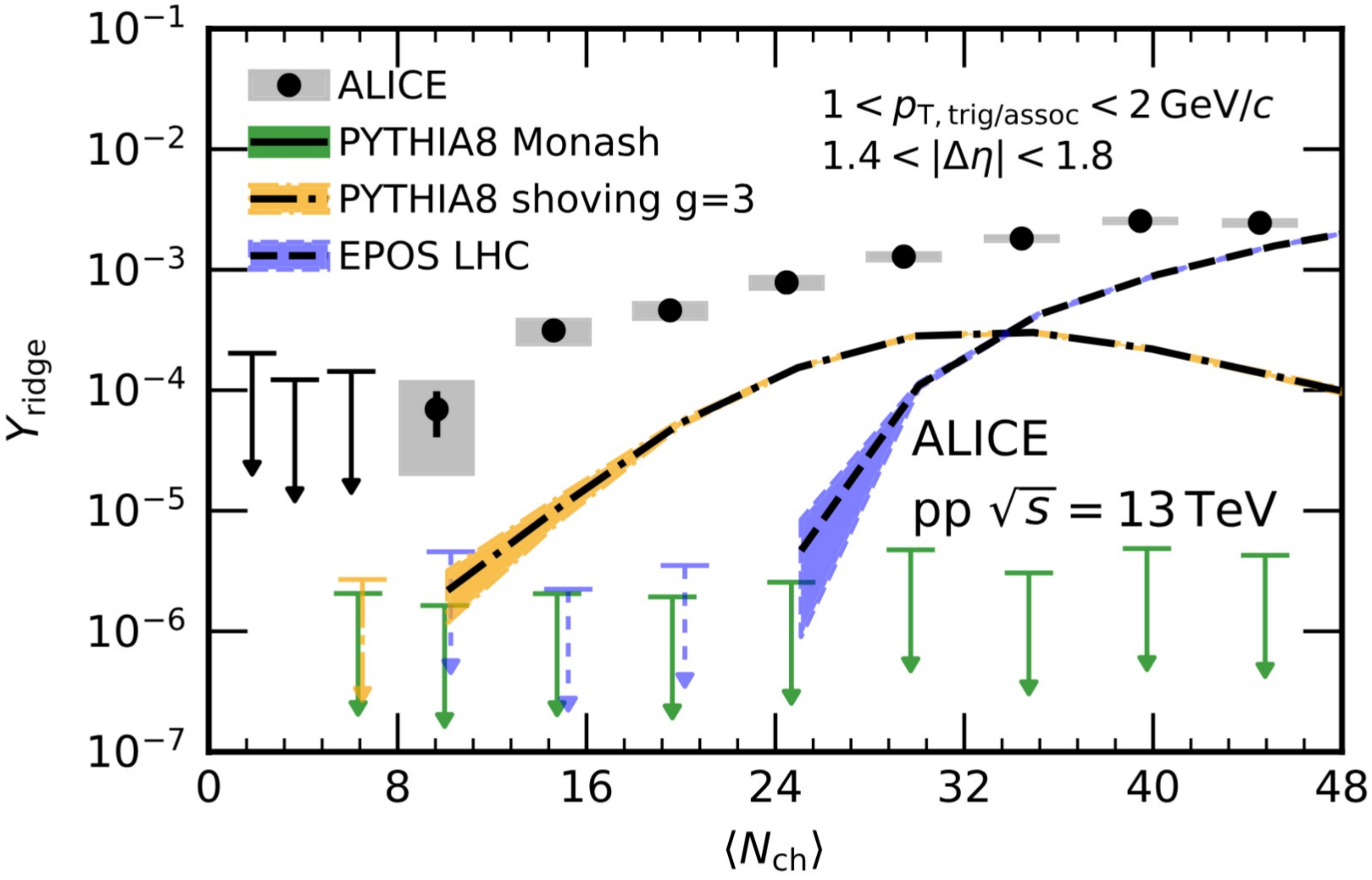


Flow in pAu collisions

- Described well with hydrodynamics

[Nat. Phys. 15, 214 (2019)]

Ridge in Low Multiplicity Events



PRL 132 (2024) 172302