Flow in Small System

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INTT workshop at Korea University

Outline

① Introduction of QGP physics

② Introduction of high-energy heavy ion collision experiments

③ Flow Measurement in heavy ion collisions

④ Flow Small system

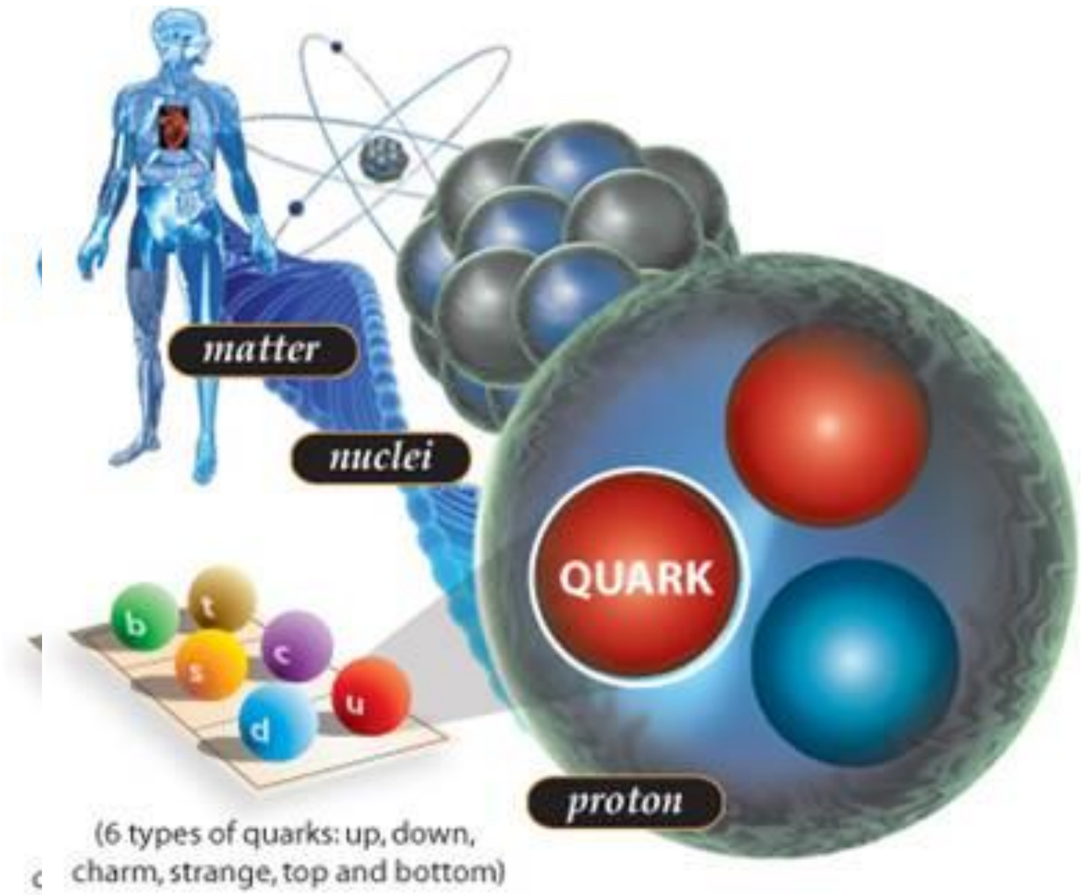
☝ my project for my doctor thesis.

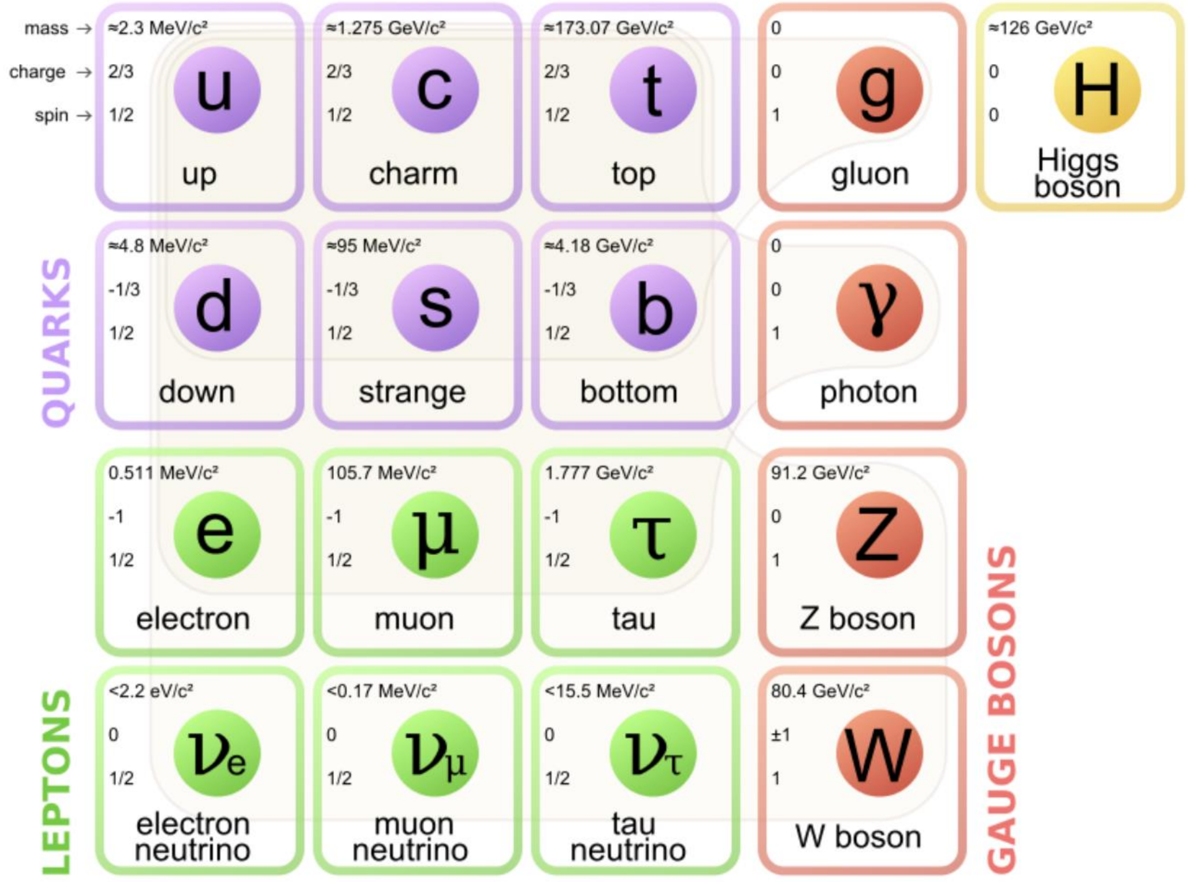
⑤ Summary and outlook at sPHENIX

Introduction of QGP physics

Elementary particles

- Quarks are elementary particles that are the smallest building blocks of matter.





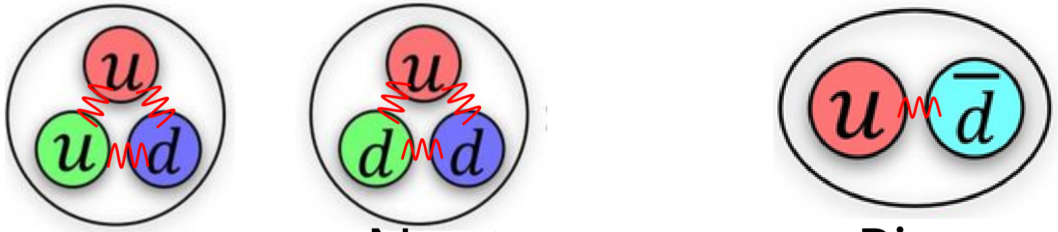
Quark Confinement

- Quarks is confined within hadrons such as mesons and baryons.
- The dynamics of quarks and gluons is described by the Quantum Chromodynamics (QCD).
- The force between quarks does not weaken even as the distance increases

➢Quarks cannot be isolated

3 quark: Baryon

2 quark: meson

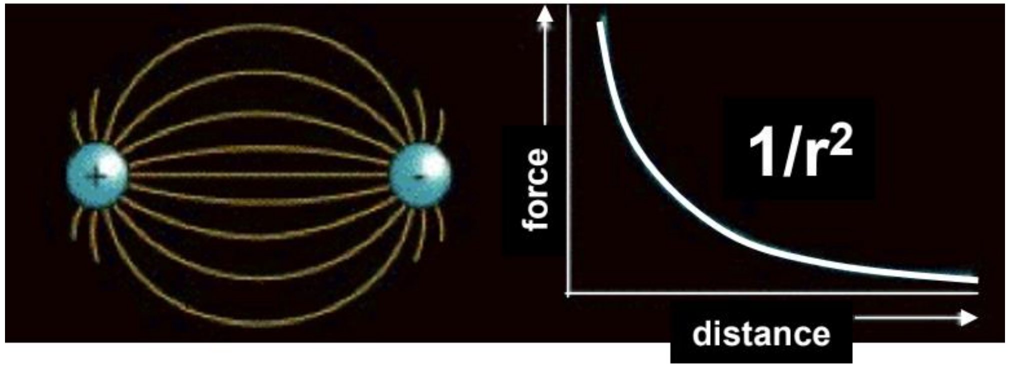


Proton

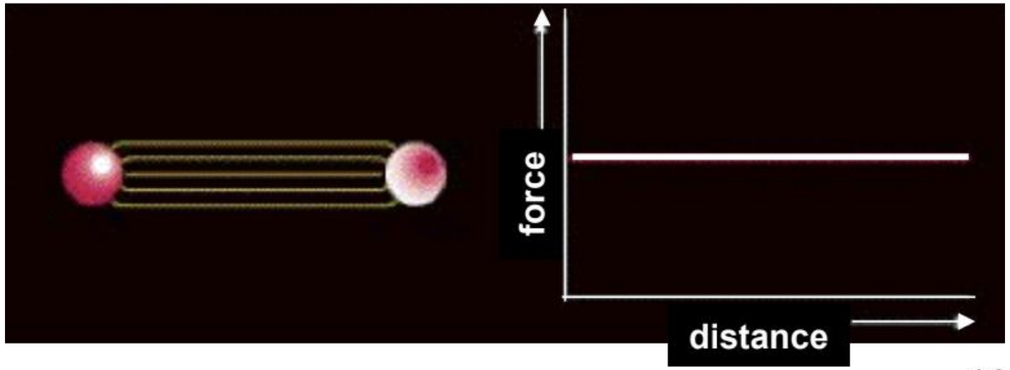
Neutron

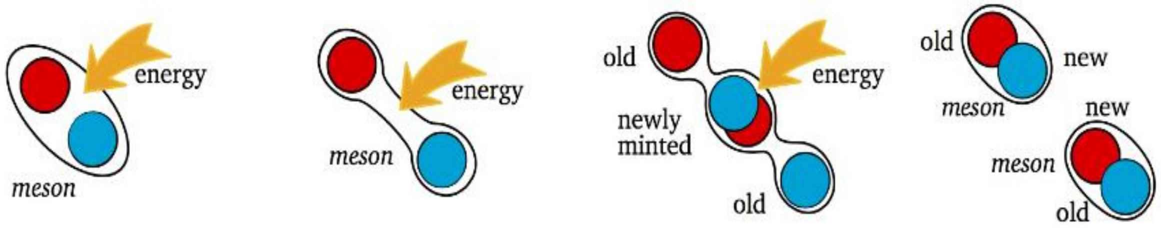
Pion

QED



QCD





Asymptotic freedom

- Interaction strength between quarks and gluons depends on momentum transfer Q

Strong Interaction @ Low Q

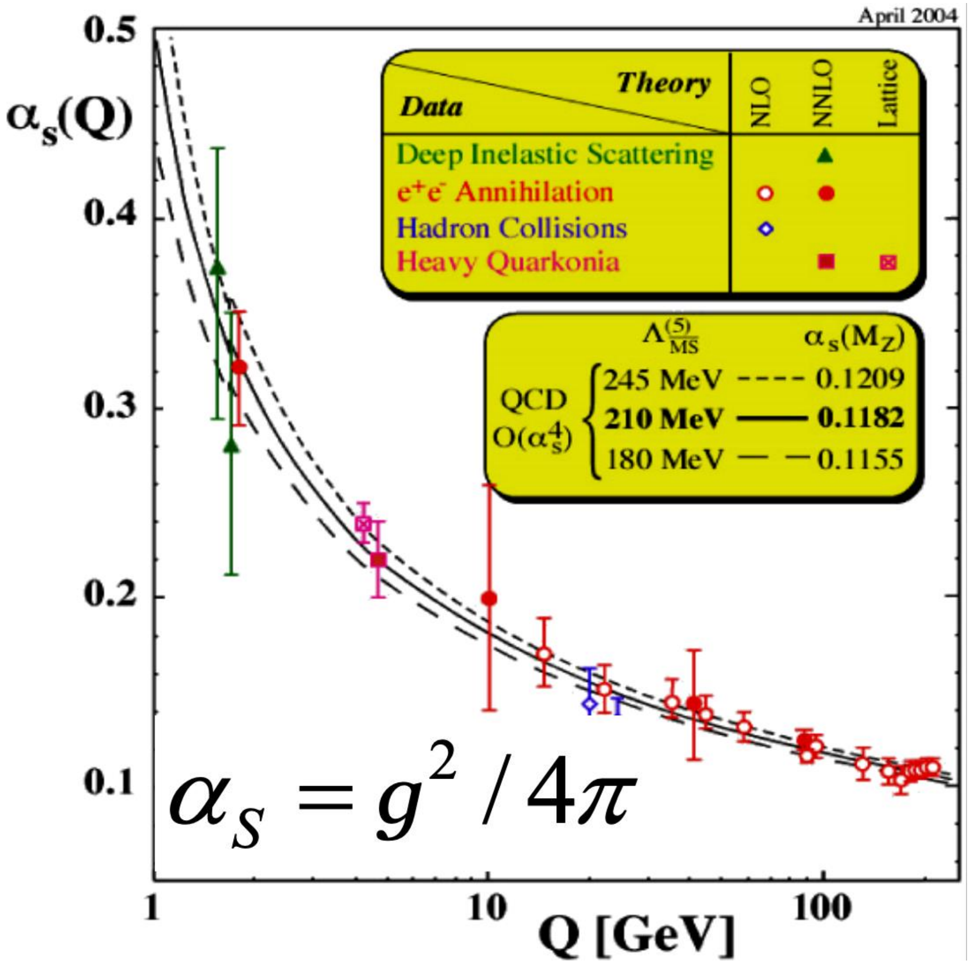
low temperature / low density

Quarks and gluons are confined

Weak Interaction @ High Q

high temperature/ high density

Quarks and gluons behave almost free

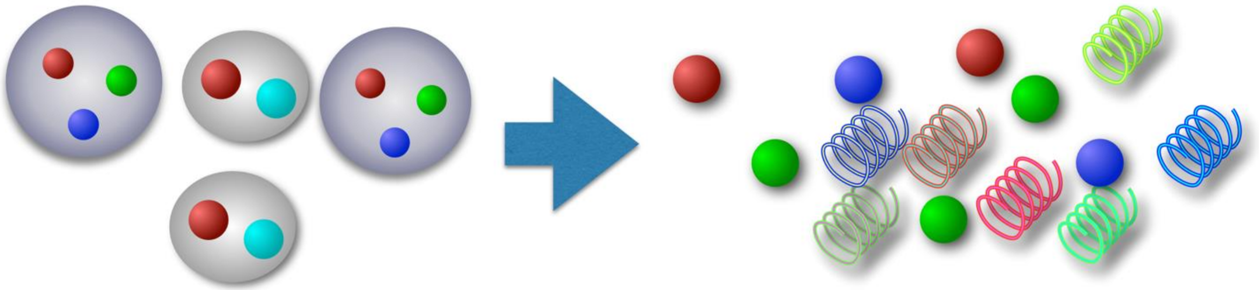


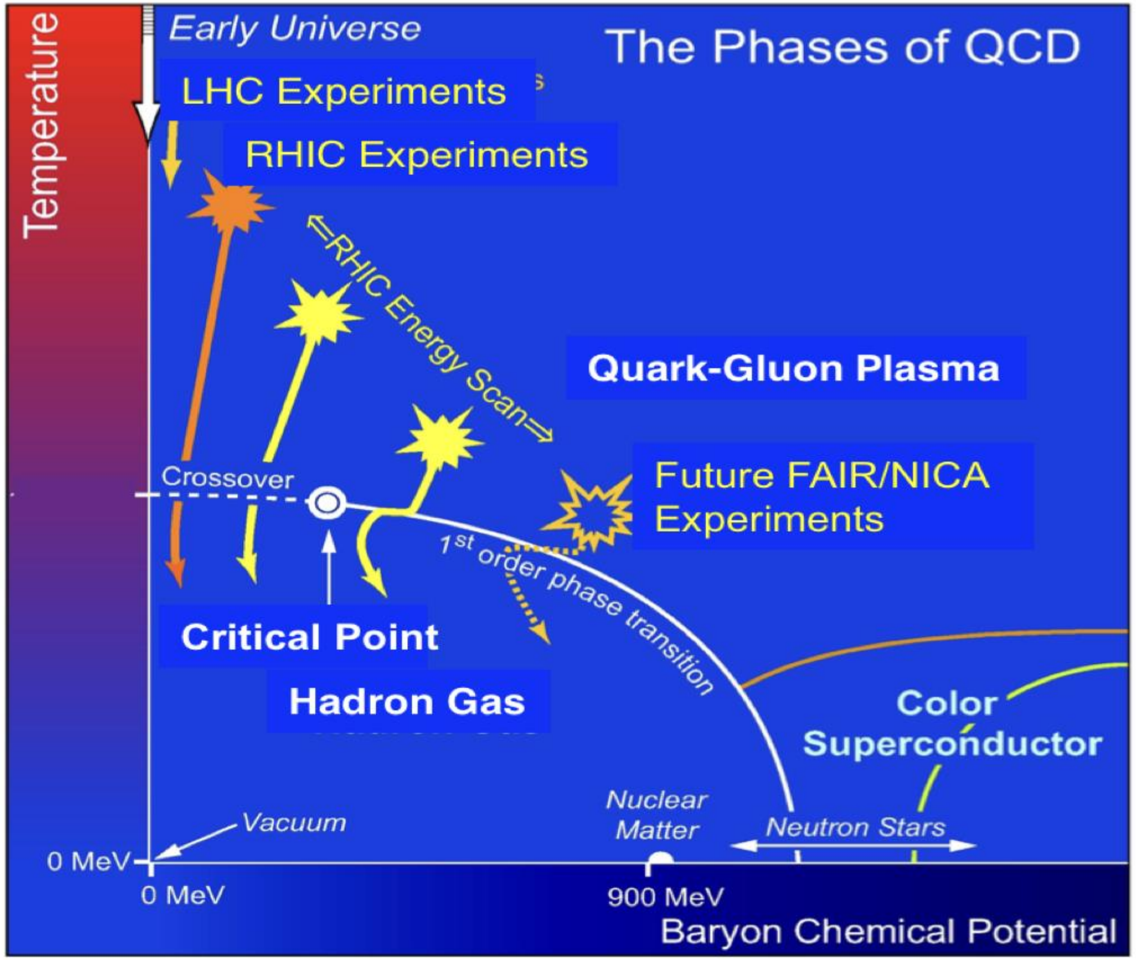
Low ← Temperature → High

Large ← Distance → Small

QCD matter

- In high temperature and high density, Quark-Gluon Plasma (QGP), where quarks and gluons move freely, is realized.
    - Early Universe
- The lattice QCD predicts the critical temperature is 150-200 MeV.



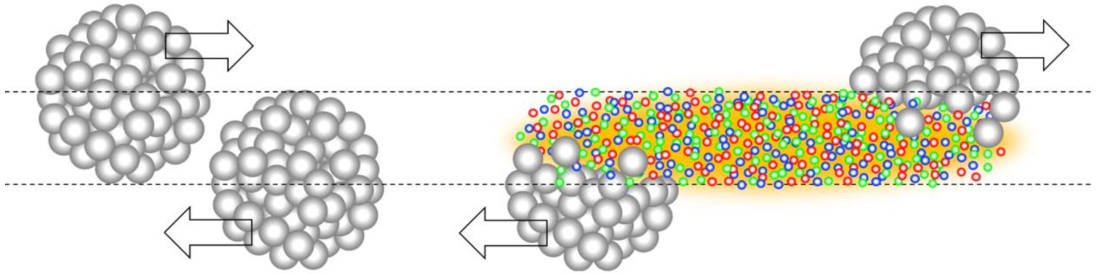


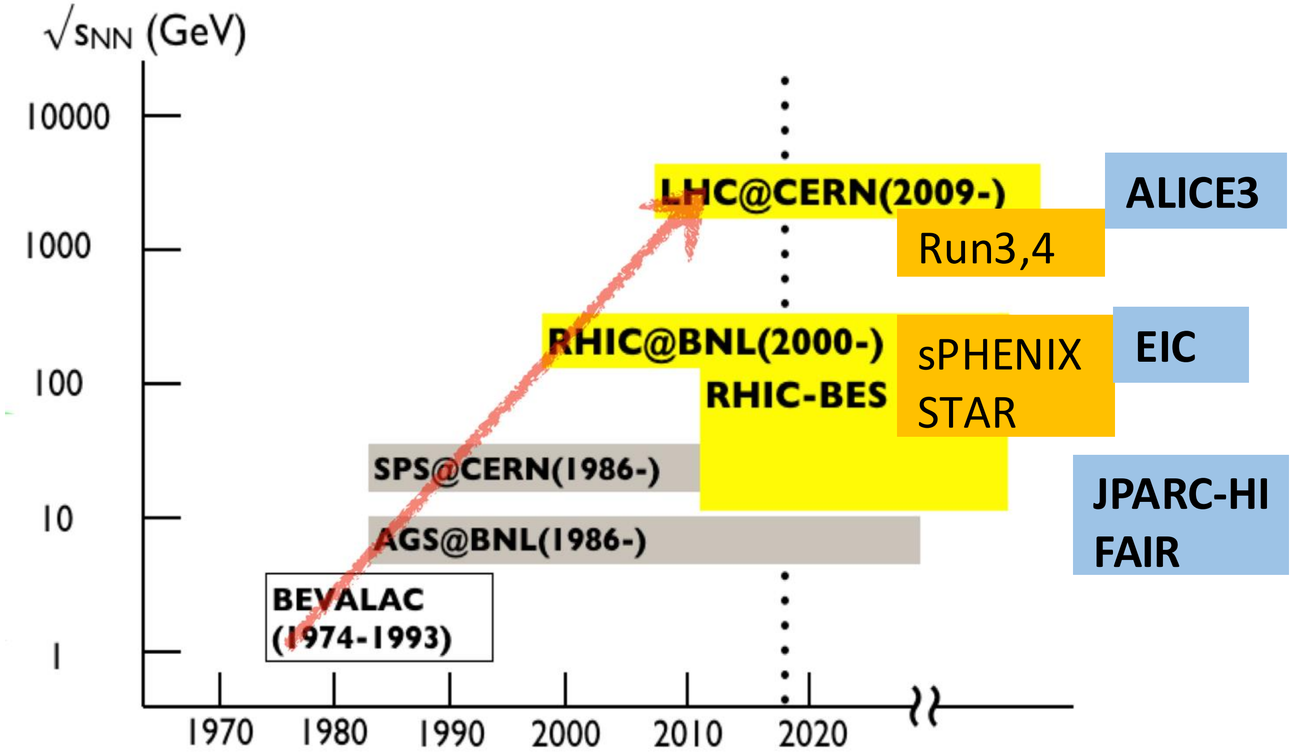
Introduction of high-energy heavy ion collision experiments

Heavy Ion Collision Experiments

- Heavy nuclei, such as gold or lead, are accelerated to near the speed of light and collided with each other to create QGP.

➡Unique opportunity to study QGP experimentally.

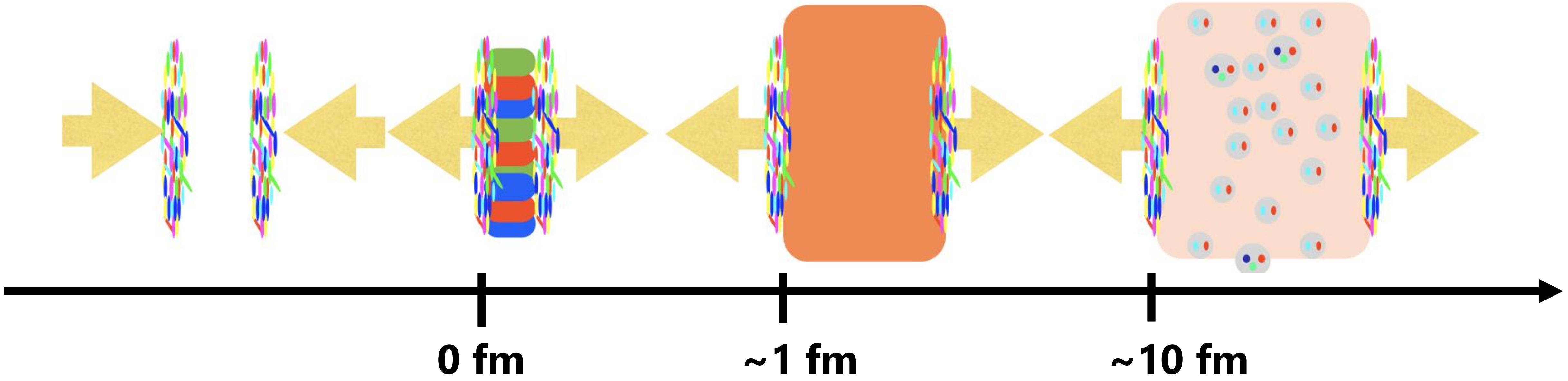




Time evolution of heavy ion collisions

Heavy ion collisions involve various physics processes, not just QGP.

1. Before collision
2. Initial stage of the collision
3. QGP
4. Hadronization



Probes to study properties of QGP

Impurity Probe

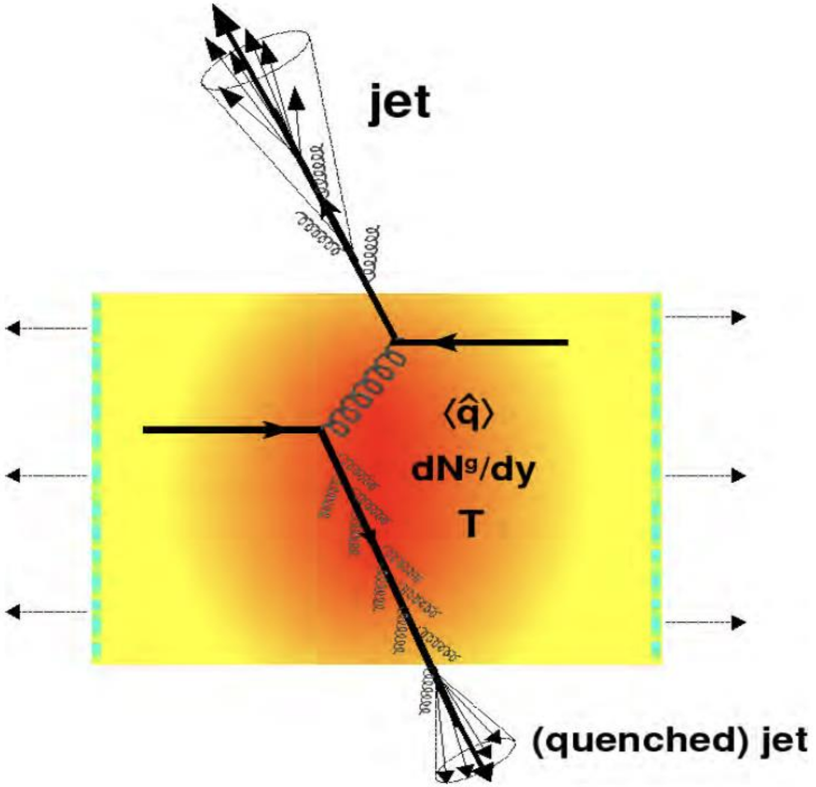
Jet and Heavy Flavor

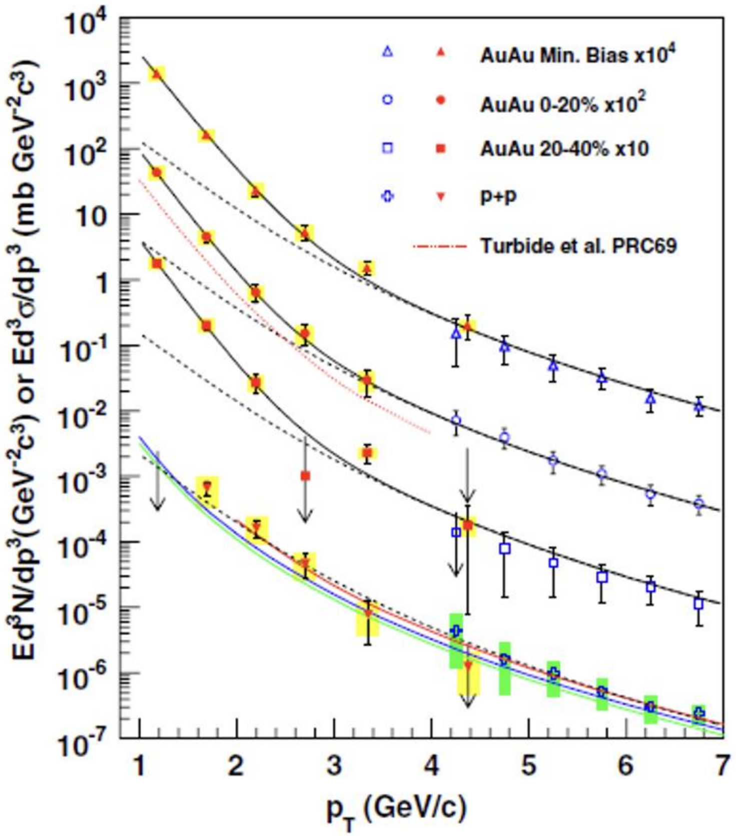
Transparent Probe

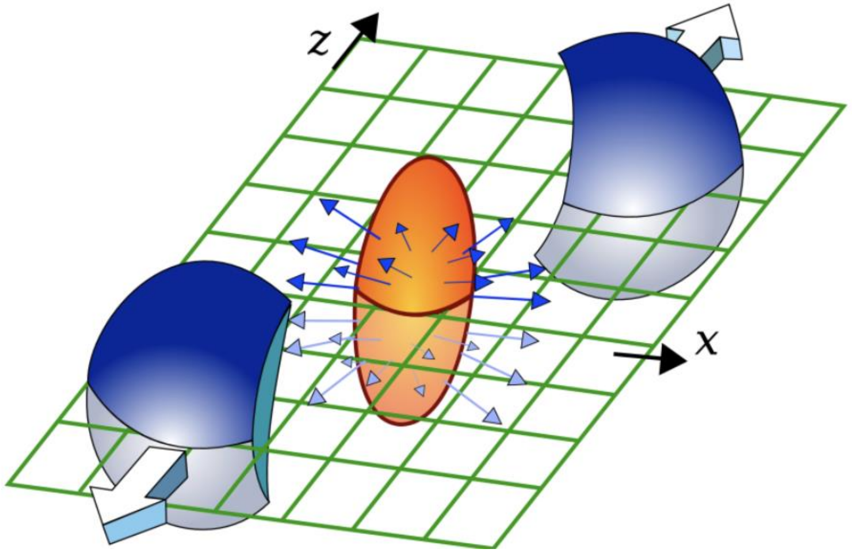
Photon and lepton

Collective behavior

Flow

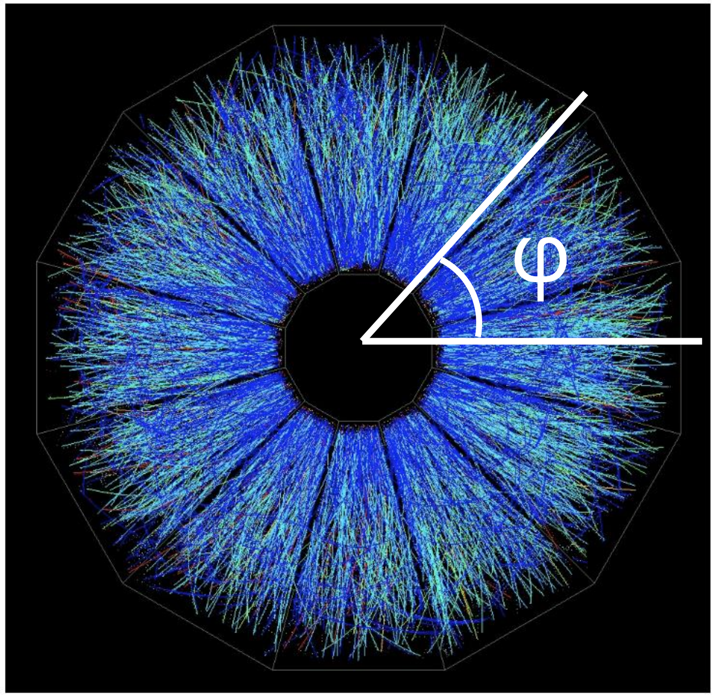


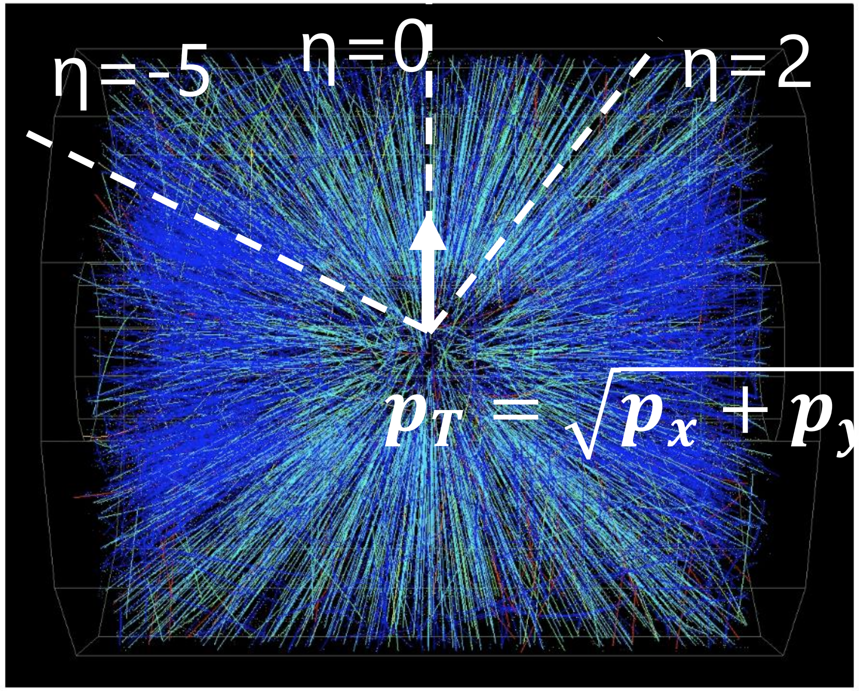




Kinematics variables of experimental observables

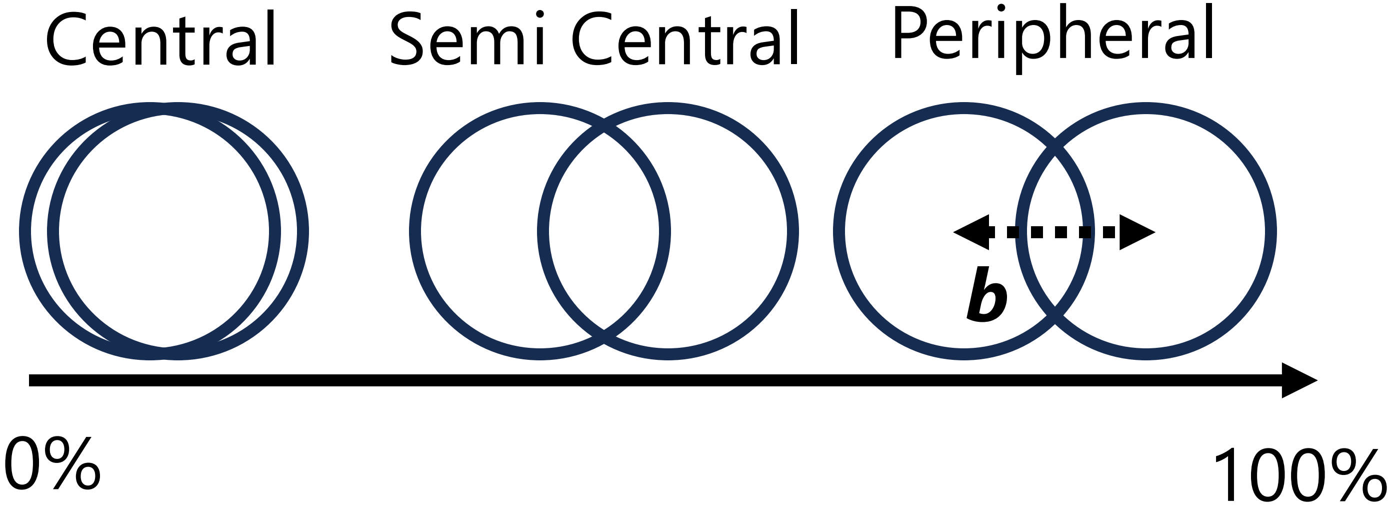
- Experimentally, particles after hadronization are measured.
  - Transverse momentum: $p_T = \sqrt{p_x + p_y}$
  - Azimuthal angle: φ
  - Pseudorapidity: $\eta = \frac{1}{2} \ln \frac{|\boldsymbol{p}|+p_z}{|\boldsymbol{p}|-p_z}$

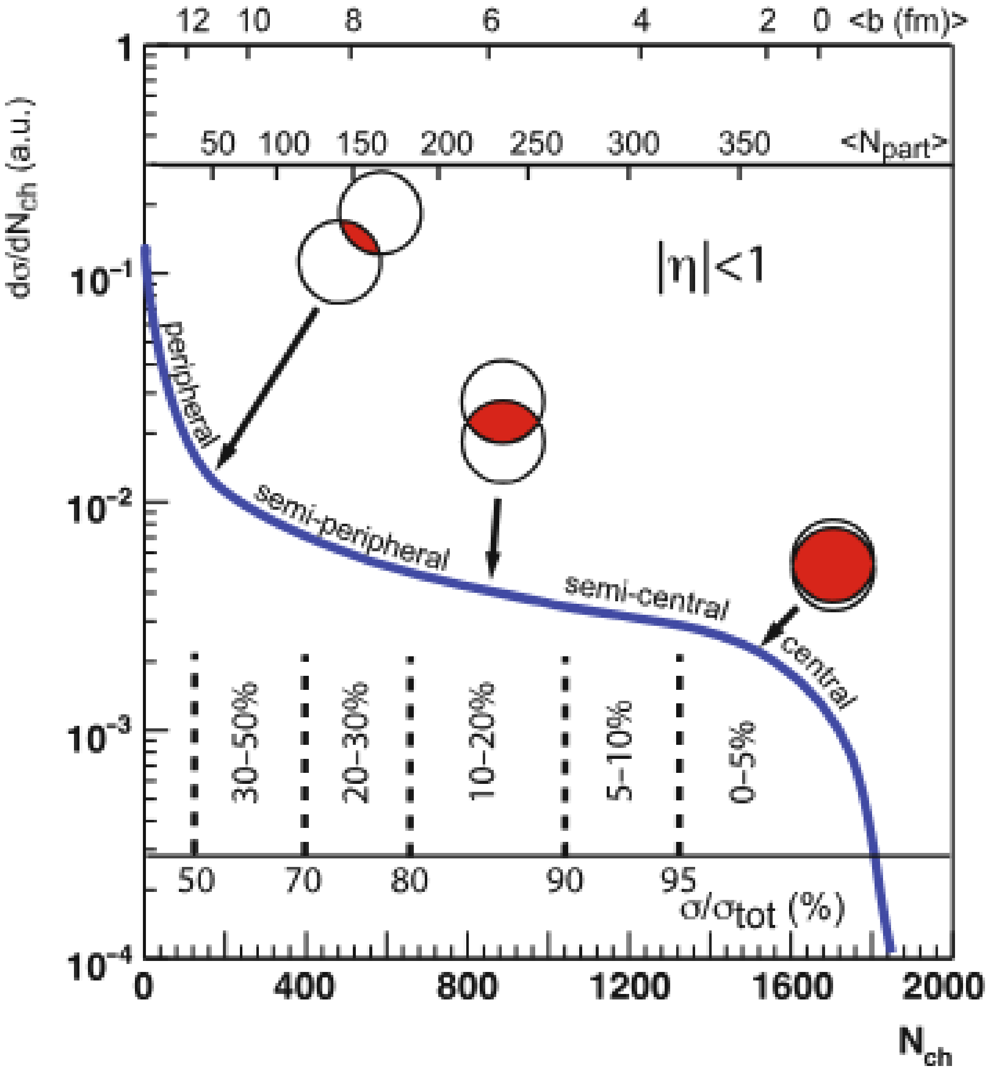




Collision Geometry

- Collision geometry is characterized by impact parameter *b*, which is the distance between nucleus.
  - *b* can not be directly measured.
- Centrality is used instead, which is calculated from particle multiplicity,



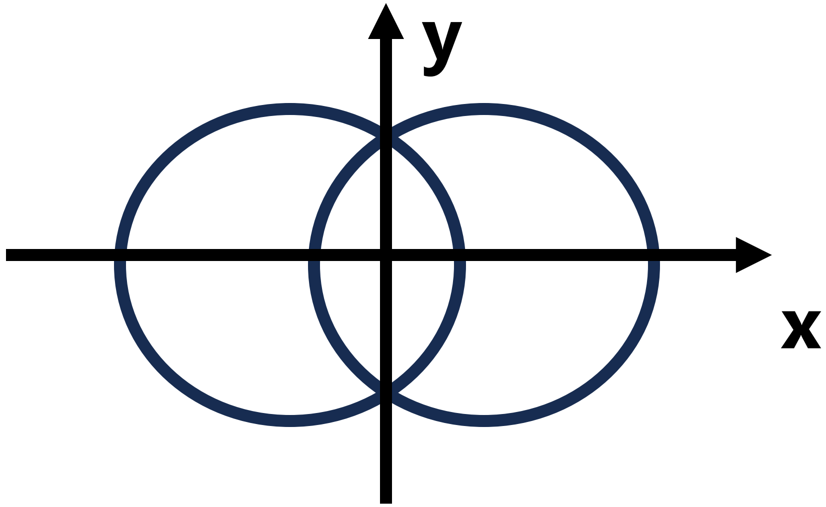


Flow in heavy-ion collisions

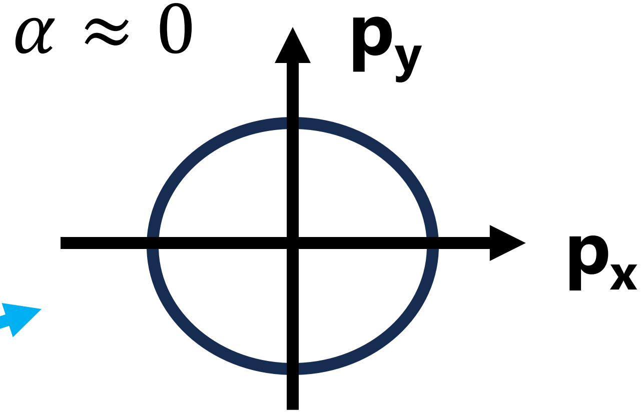
Initial geometrical anisotropy

- The overlapped area In semi central collisions is almond shape.
- Anisotropy in coordinate space is transferred to anisotropy in anisotropy depending on the whether the mean free path λ is longer or shorter than the size of the system R.

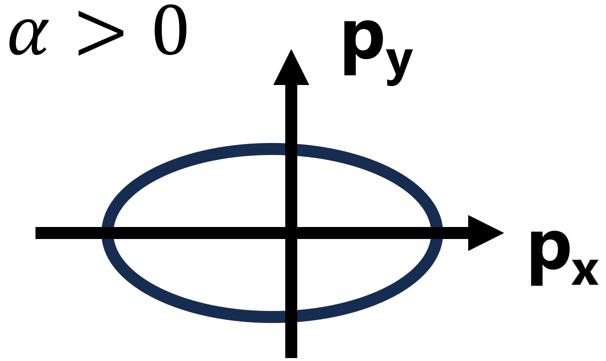
$$\varepsilon = \frac{\langle x + y \rangle}{\langle x - y \rangle} \quad \xrightarrow{v_2 \propto \alpha\varepsilon} \quad v_2 = \frac{\langle p_x + p_y \rangle}{\langle p_x - p_y \rangle}$$



$R \leq \lambda$

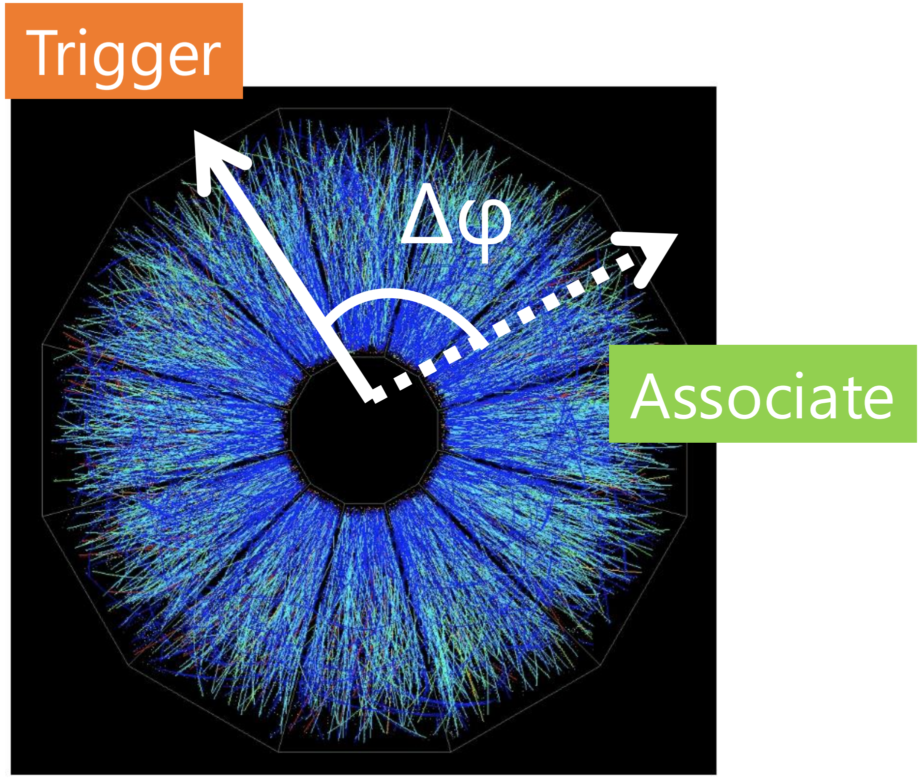


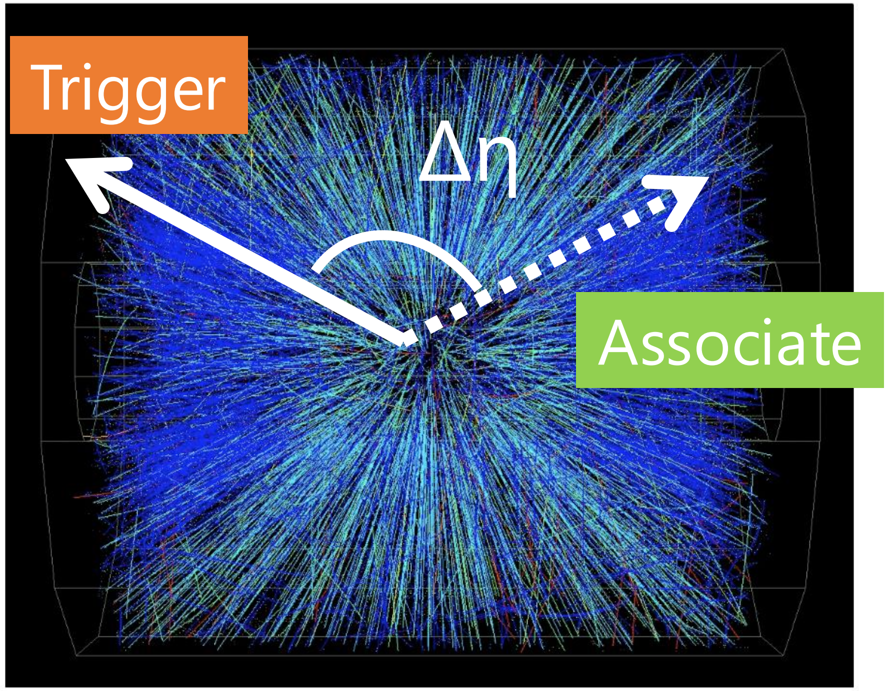
$R \gg \lambda$



Two-particle correlation

- The measurement of two-particle correlation is useful to explore particle production mechanism
  - Flow harmonics
- Two-particle correlation is measured as a function of Δη and Δφ





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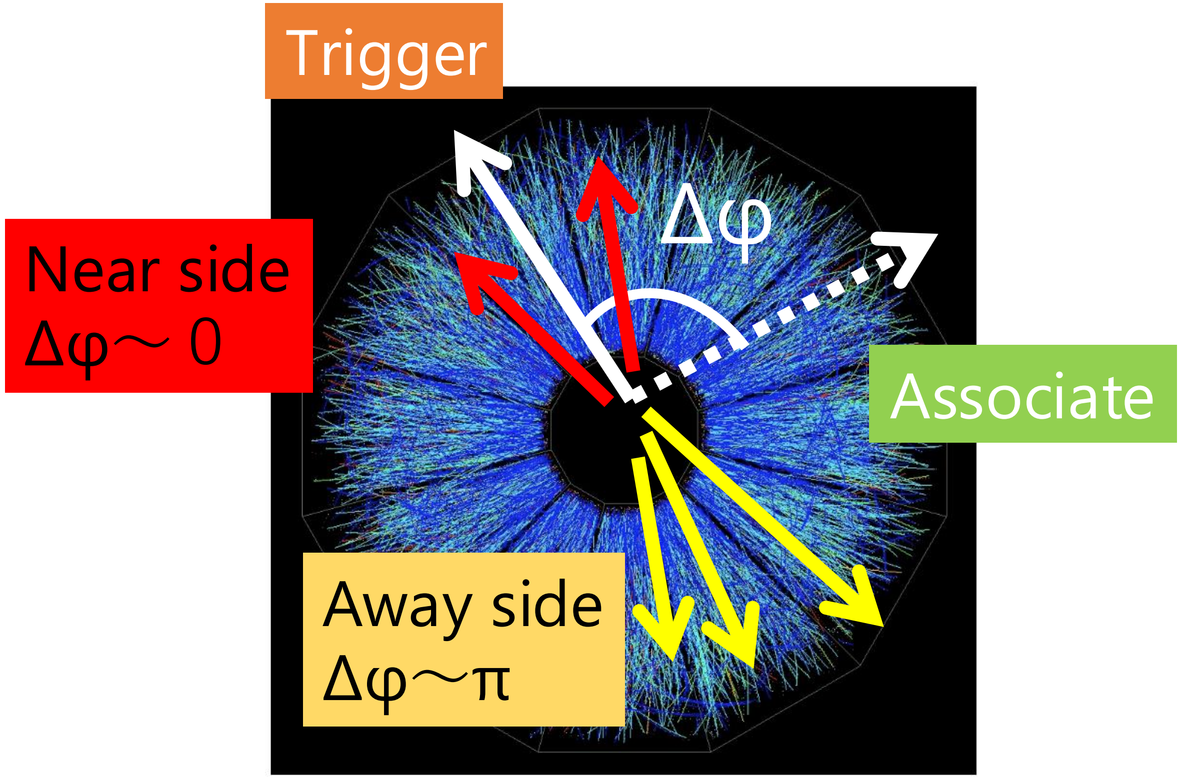
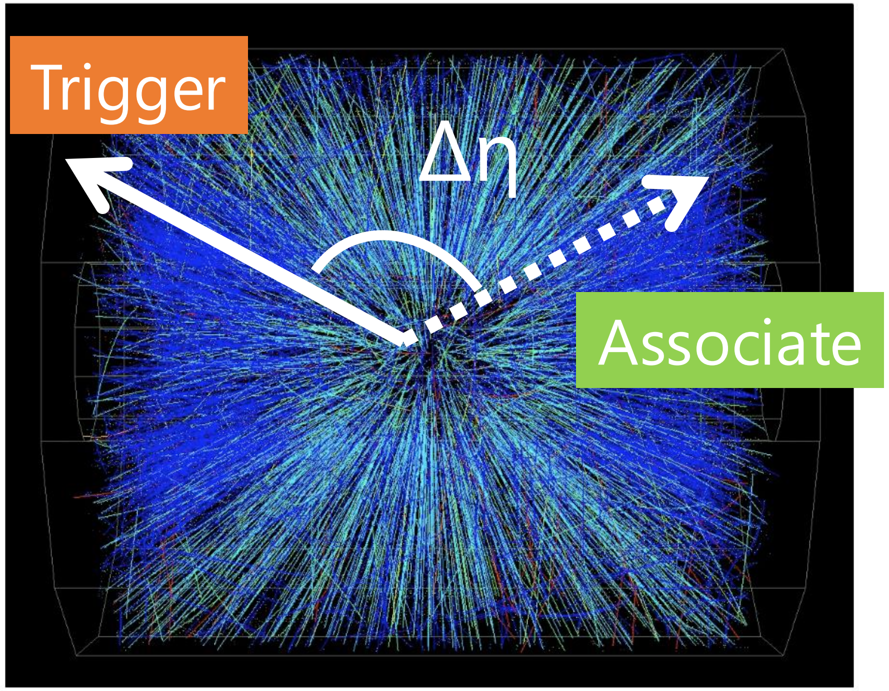
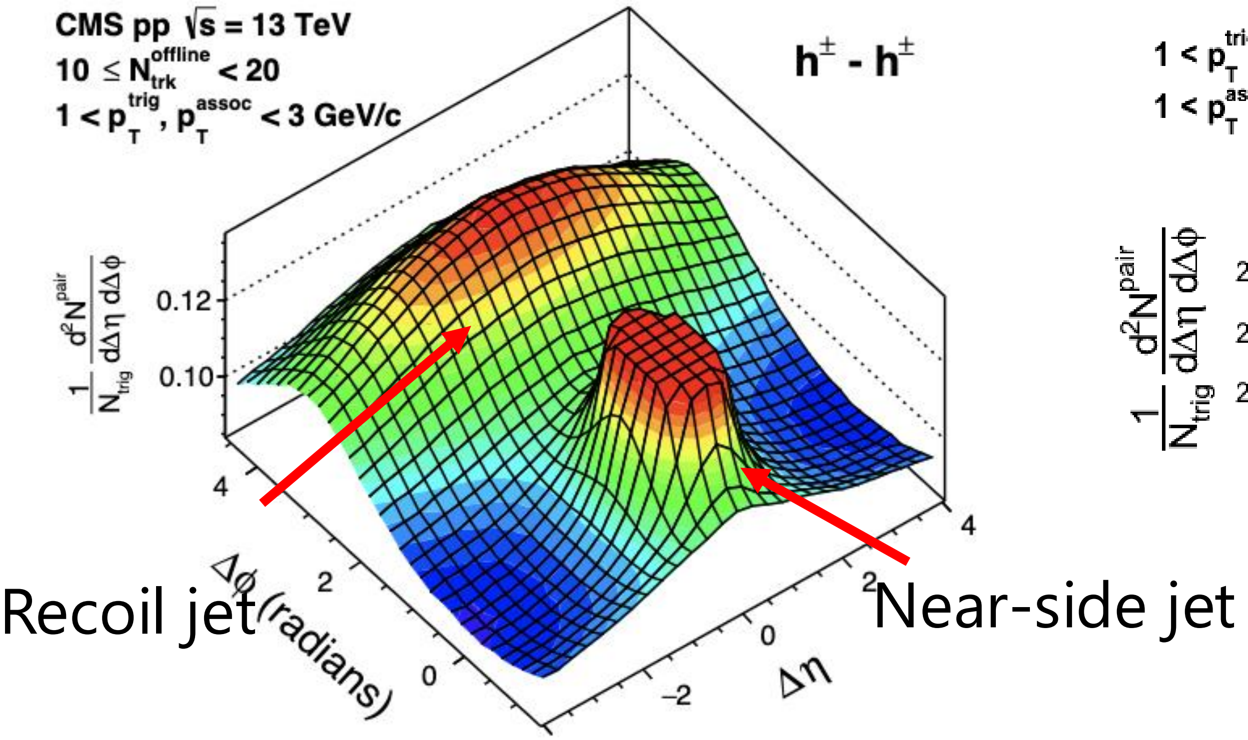


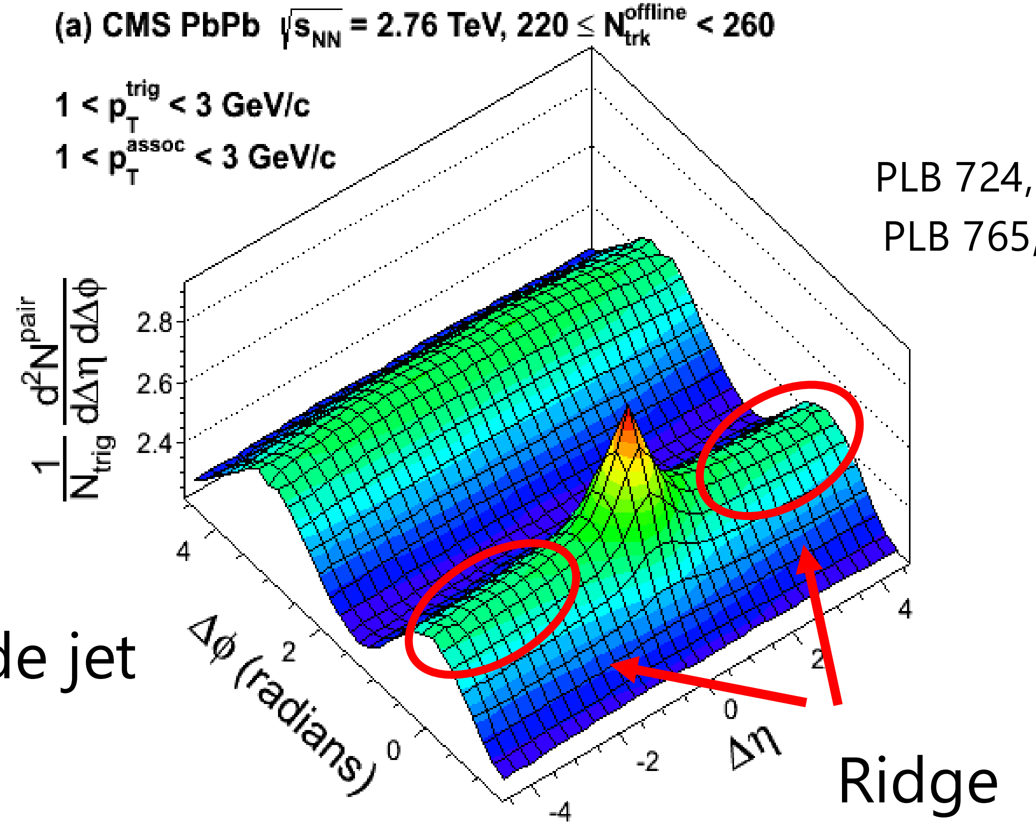


Ridge

- Associated yield per the number of trigger particles:

$$Y(\Delta\eta, \Delta\varphi) = \frac{1}{N_{trig}} \frac{d^2N}{d\Delta\eta d\Delta\varphi}$$





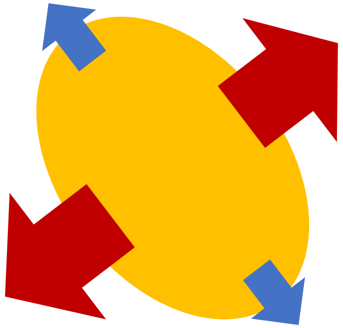
PLB 724, 213 (2013)
PLB 765, 193-220 (2017)

Extract Flow Harmonics

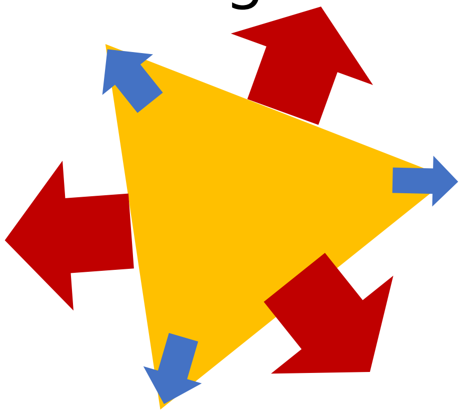
- Fit the distribution with Fourier function

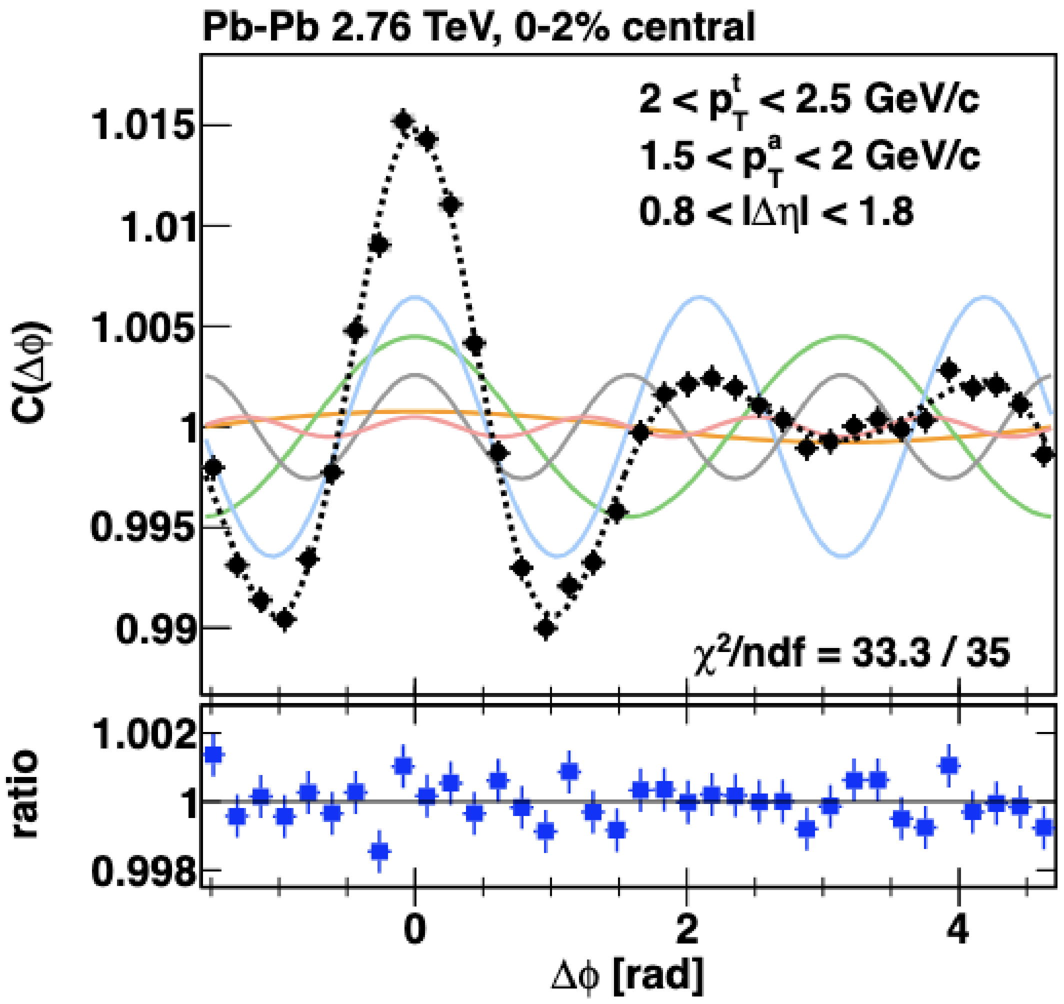
$$Y(\Delta\varphi) = 1 + 2\sum_{n=1} 2v_n \cos n\Delta\varphi$$

n=2 Elliptic flow v_2



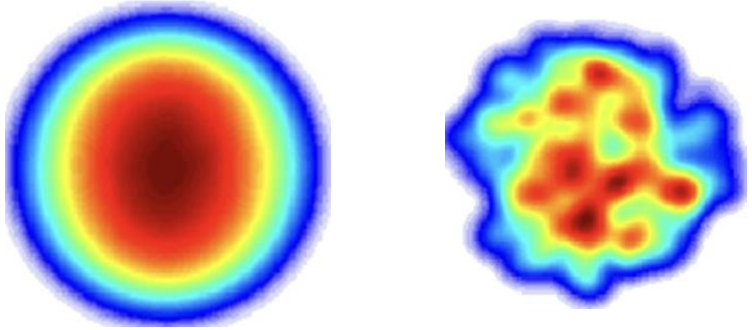
n=3 Triangle flow v_3





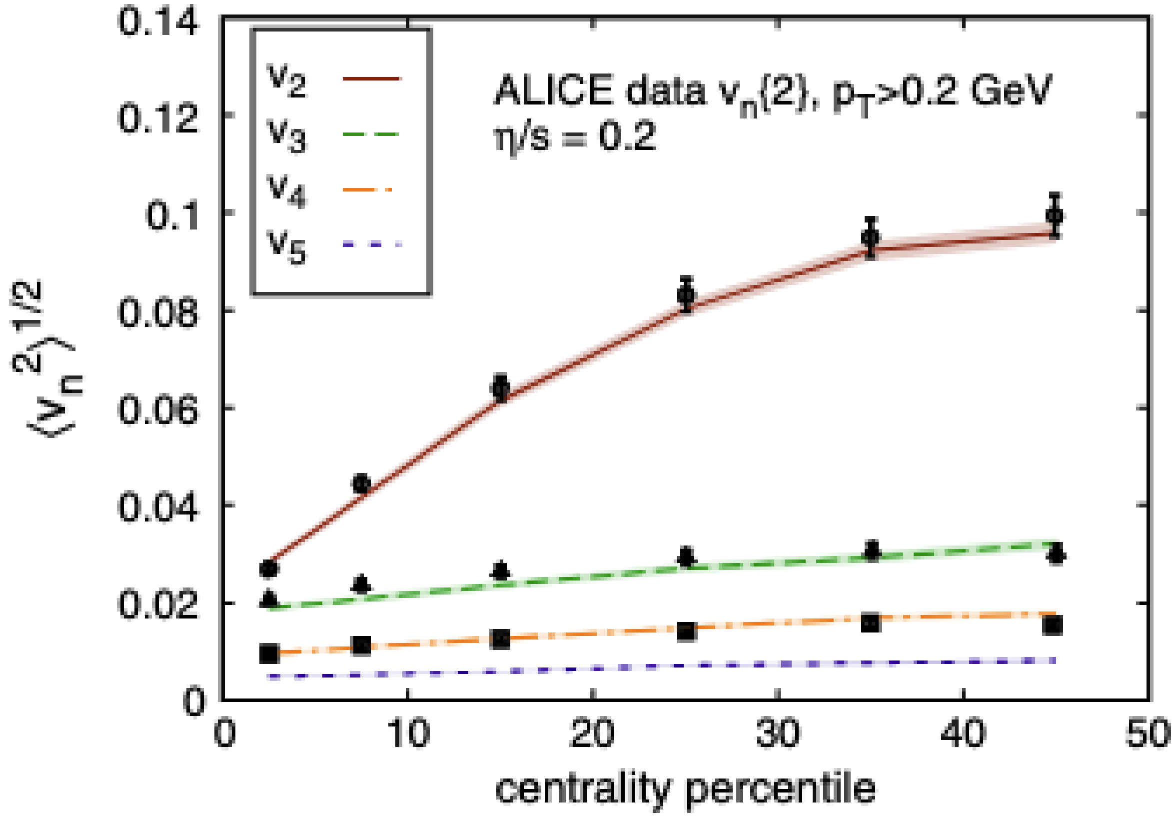
vn vs Centrality in Heavy Ion Collisions

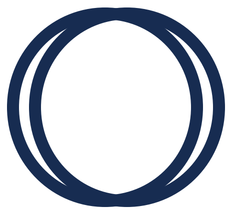
- v_2 strongly depends on centrality
  - v_2 reflects the initial shape of the collision geometry.
- Higher order terms come from fluctuations.

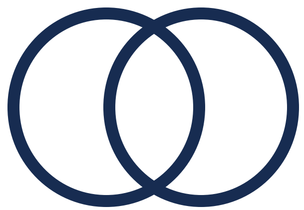


- Hydrodynamic model describes the data with small η/s.

C.Gale, et. al, PRL 110, 012302 (2013)

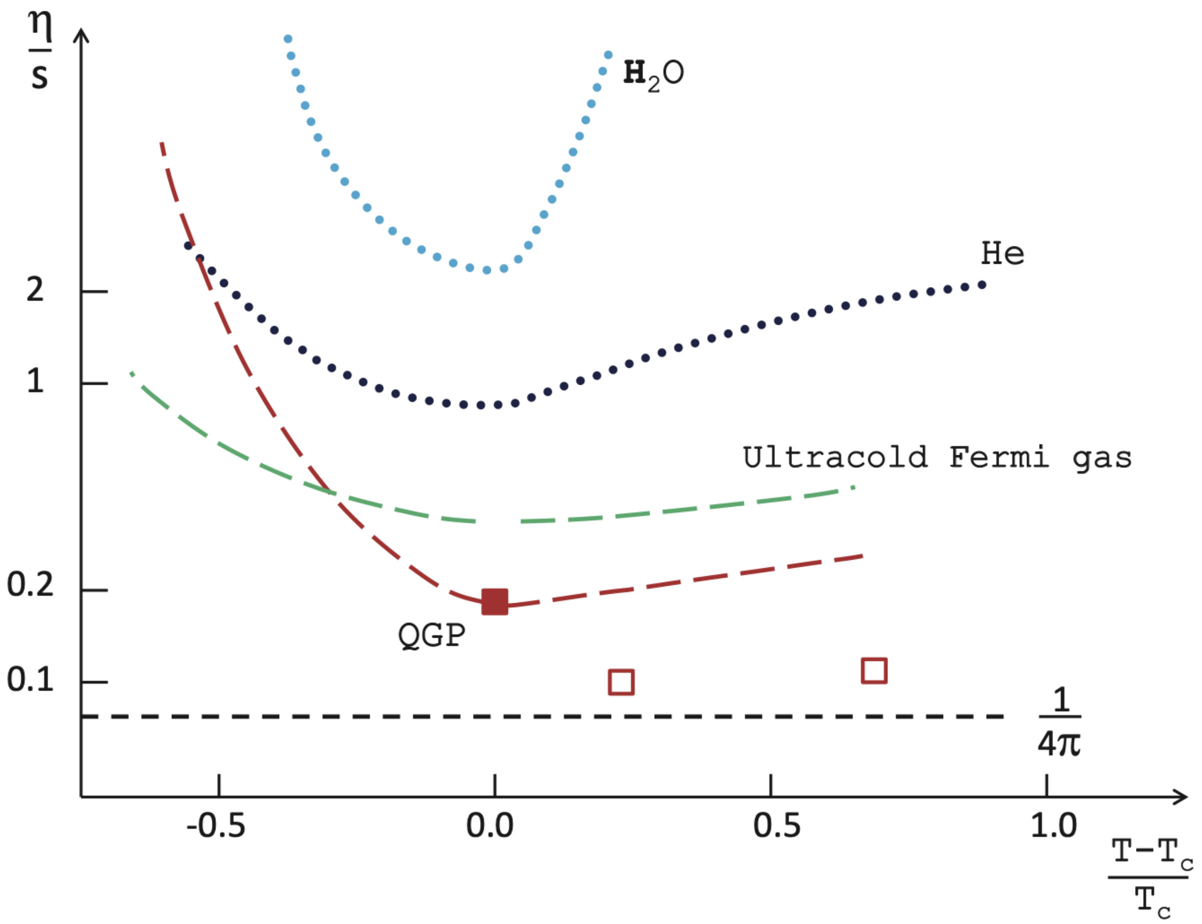


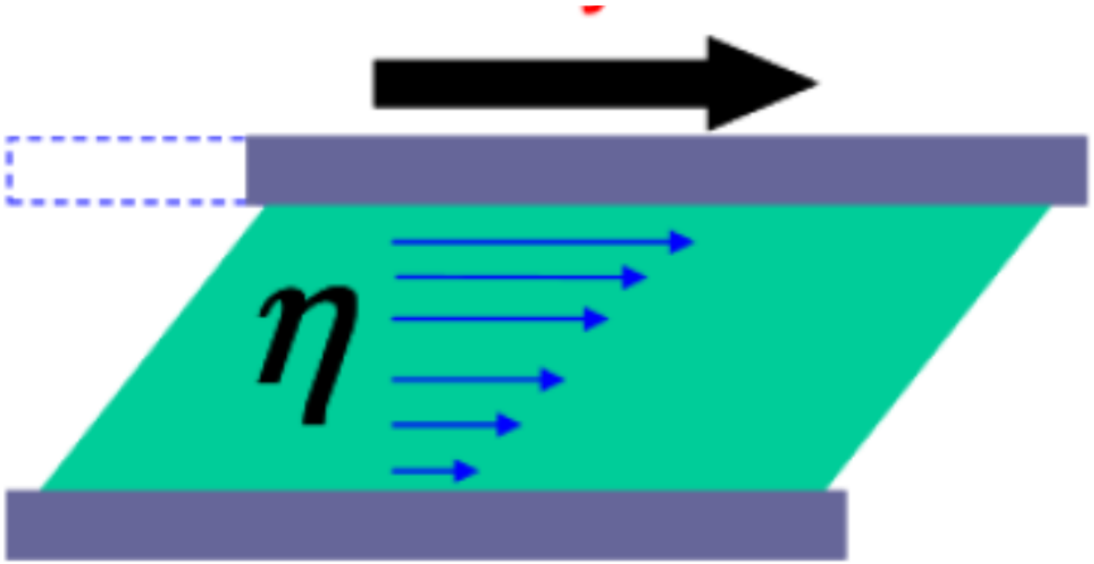




Ideal Fluid

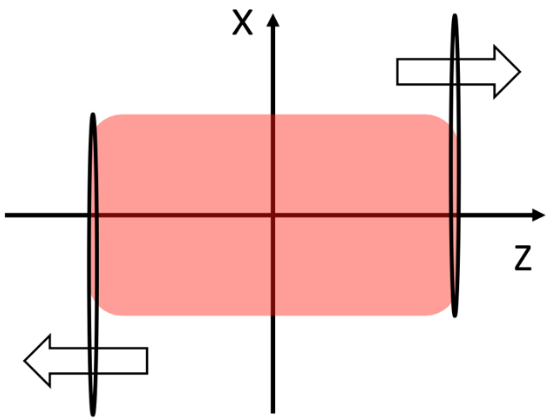
- QGP behaves like a ideal fluid with a very small η/s

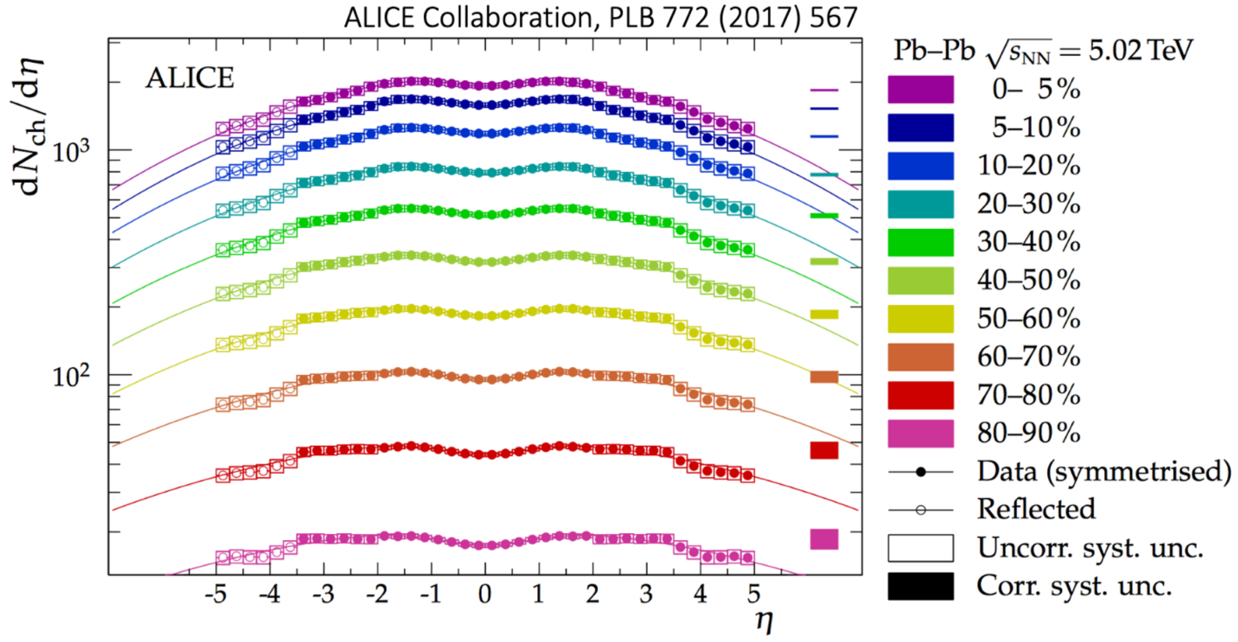


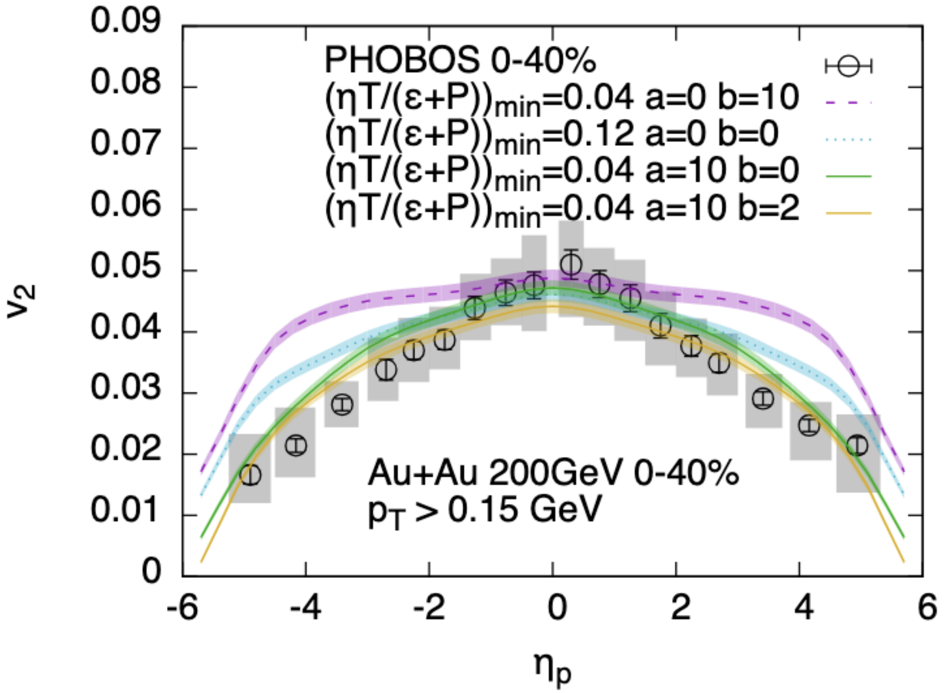


Longitudinal dynamics

- The system also expand into the longitudinal direction.
- The pseudorapidity dependence of flow is sensitive to transport properties such as temperature dependent of η/s and hadronic viscosity

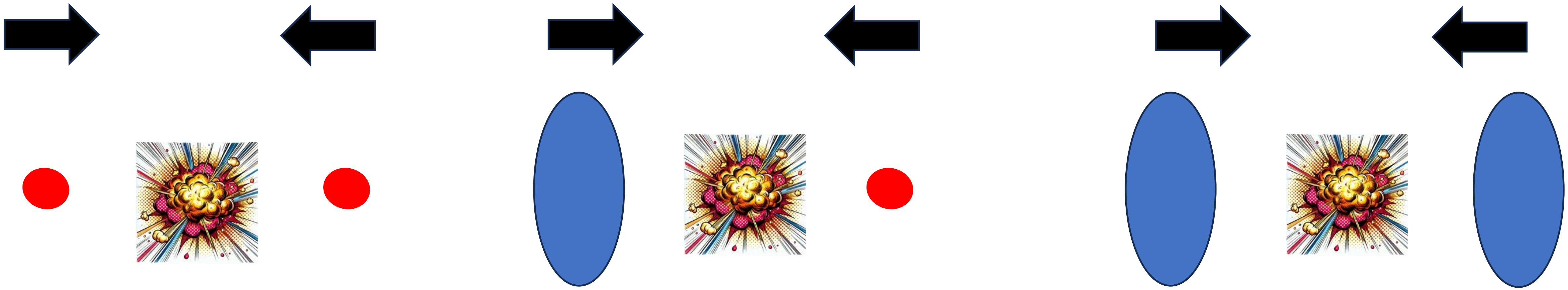






Flow in Small System

Small Collision System

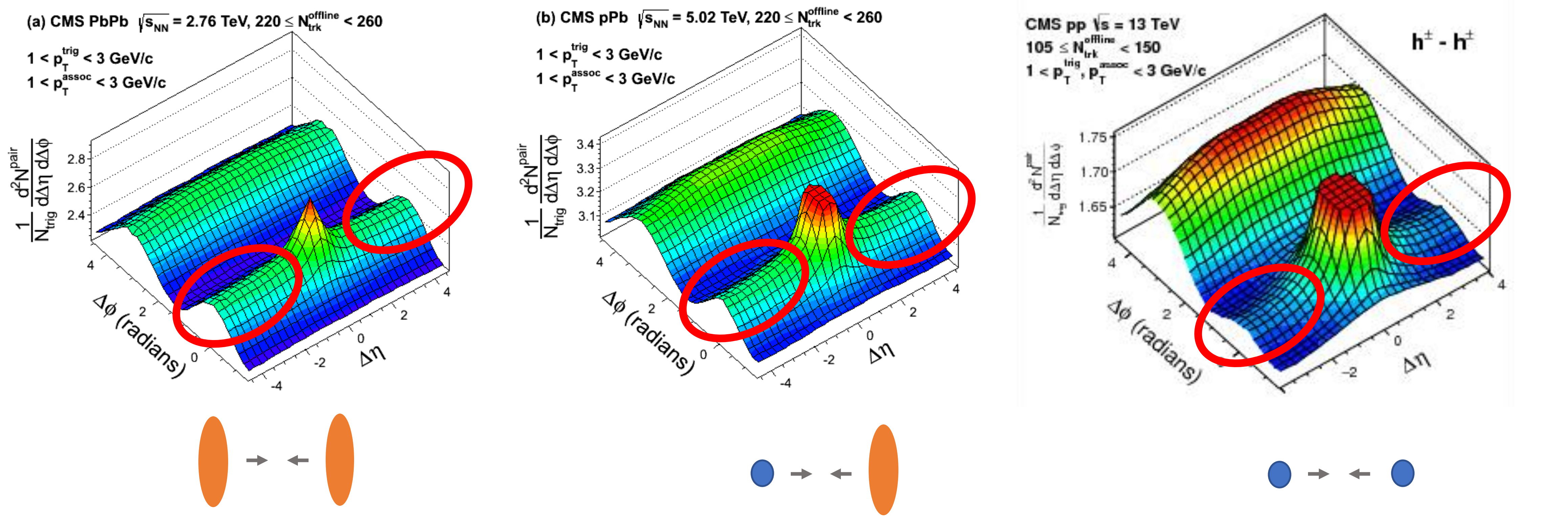


- Small system refers to proton-proton and proton-nucleus collisions.
- QGP was considered not to be produced in small collision systems.
  - Small system is conducted as reference experiments for larger collision systems

Hint of QGP in small system

PLB 724, 213 (2013)

PLB 765, 193-220 (2017)

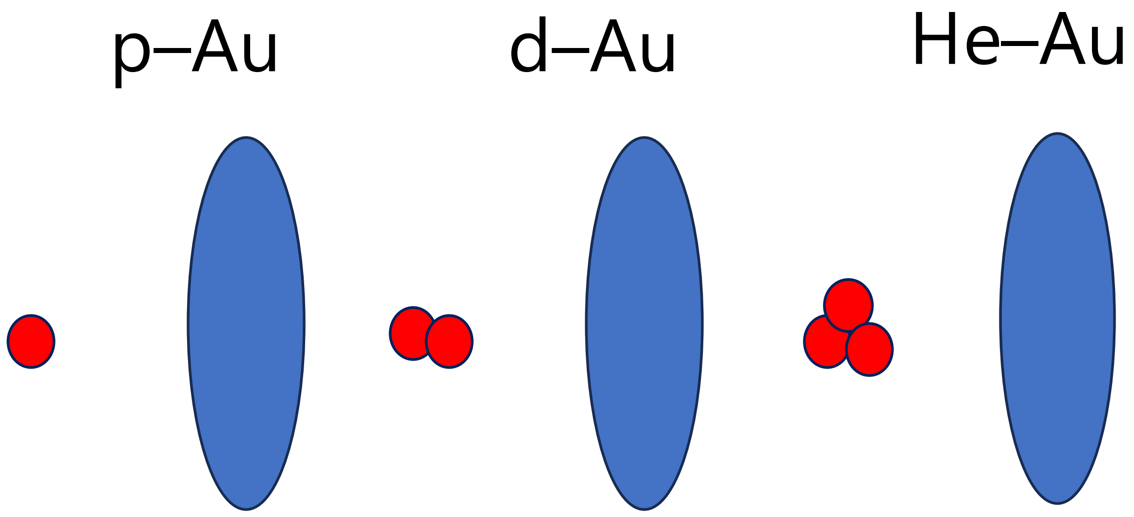


- The ridge is also observed in high-multiplicity pp and p–Pb collisions at the LHC.
  - Hint of collectivity in small collision system. QGP is created in small system?

Geometry Scan

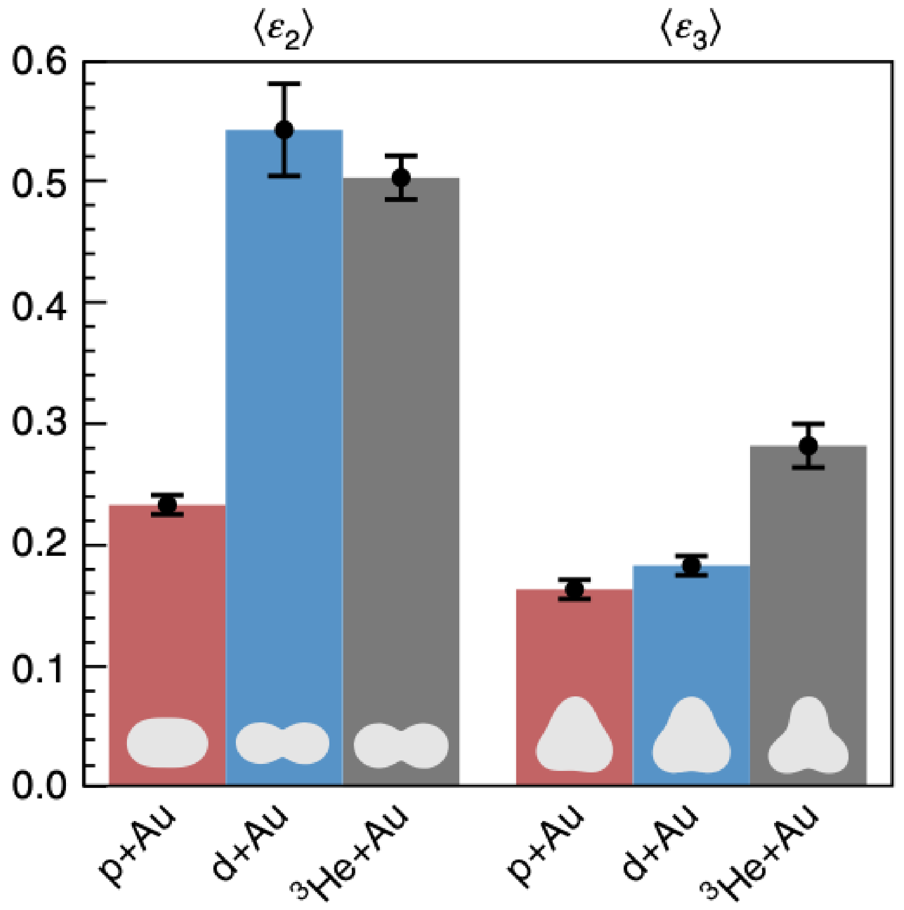
- Several small collision systems were performed at RHIC.

Nature Phys. 15, 214-220 (2019)

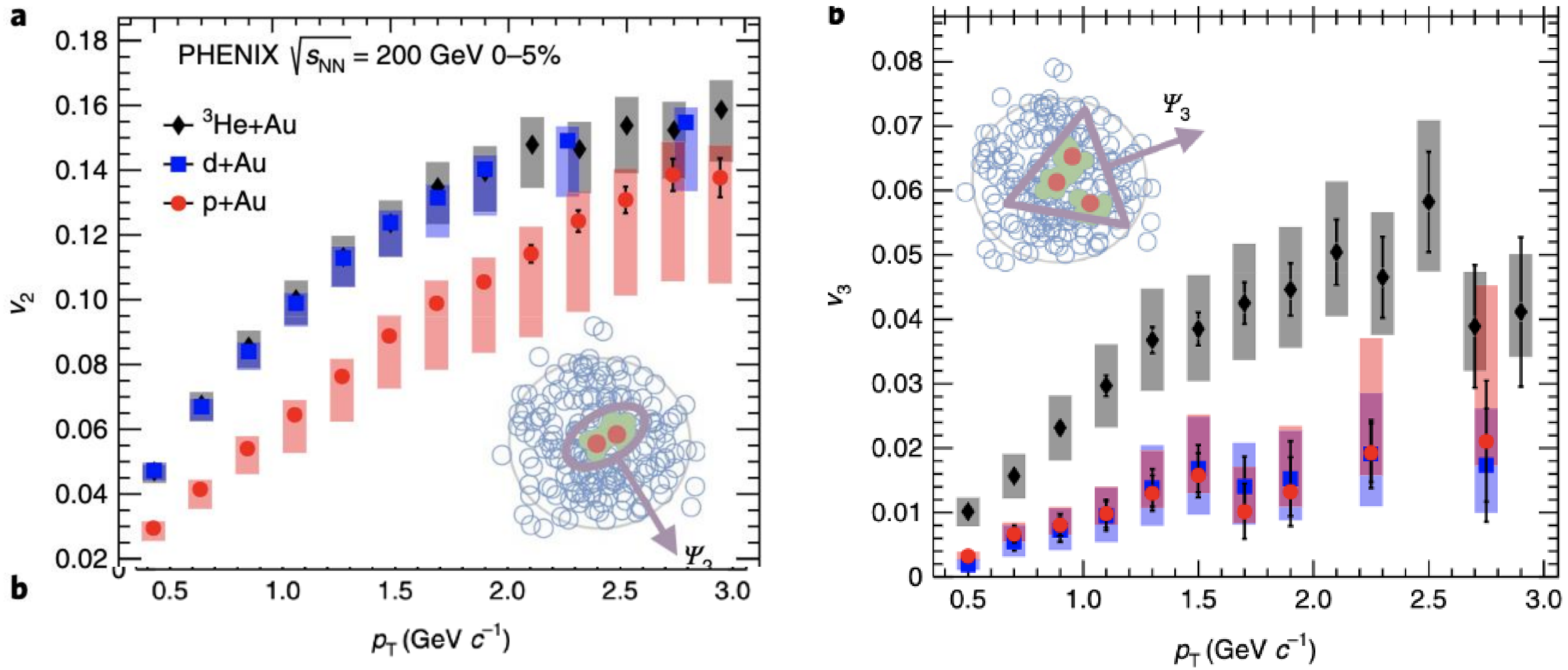


$$\varepsilon_2^{pAu} < \varepsilon_2^{dAu} \approx \varepsilon_2^{HeAu}$$

$$\varepsilon_3^{pAu} \approx \varepsilon_3^{dAu} < \varepsilon_3^{HeAu}$$



v_2 vs collision geometry



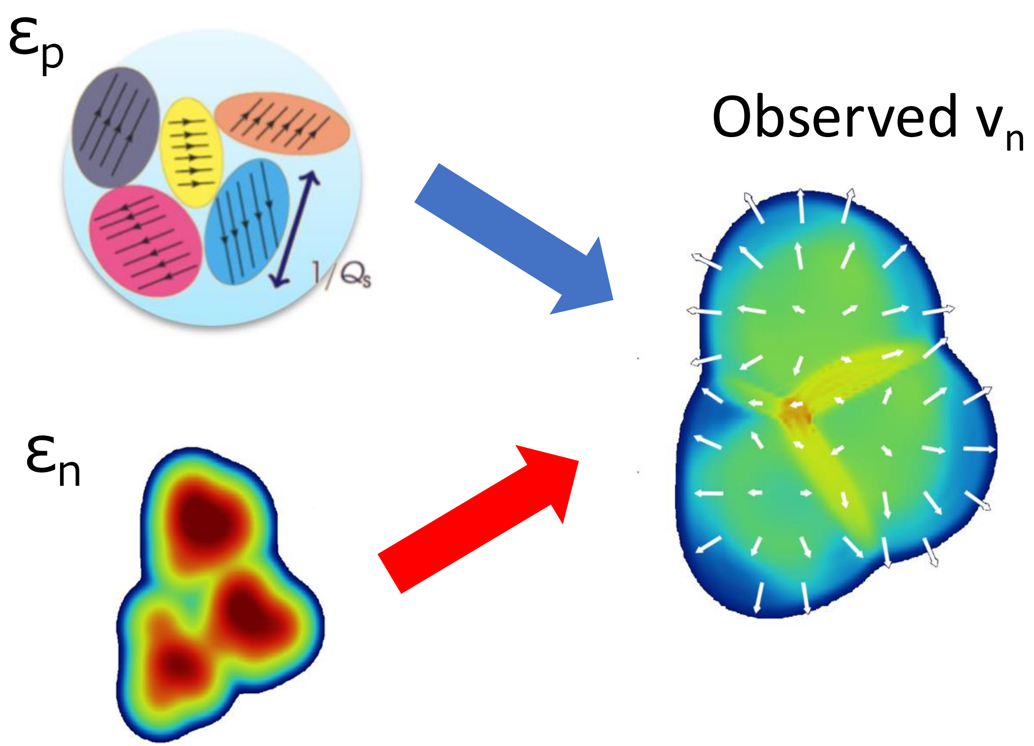
- Same ordering as the initial condition

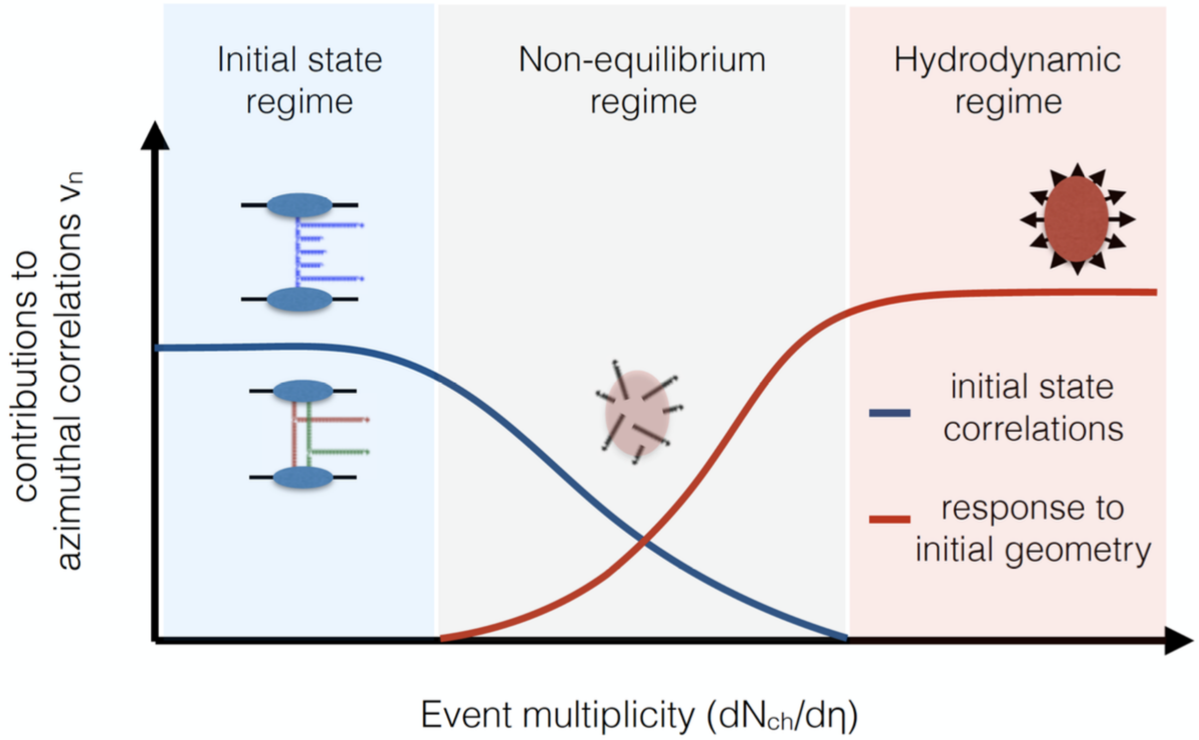
$$v_2^{pAu} < v_2^{dAu} \approx v_2^{HeAu} \quad \longleftrightarrow \quad \varepsilon_2^{pAu} < \varepsilon_2^{dAu} \approx \varepsilon_2^{HeAu}$$

$$v_3^{pAu} \approx v_3^{dAu} < v_3^{HeAu} \qquad \varepsilon_3^{pAu} \approx \varepsilon_3^{dAu} < \varepsilon_3^{HeAu}$$

The origin of collectivity in small system

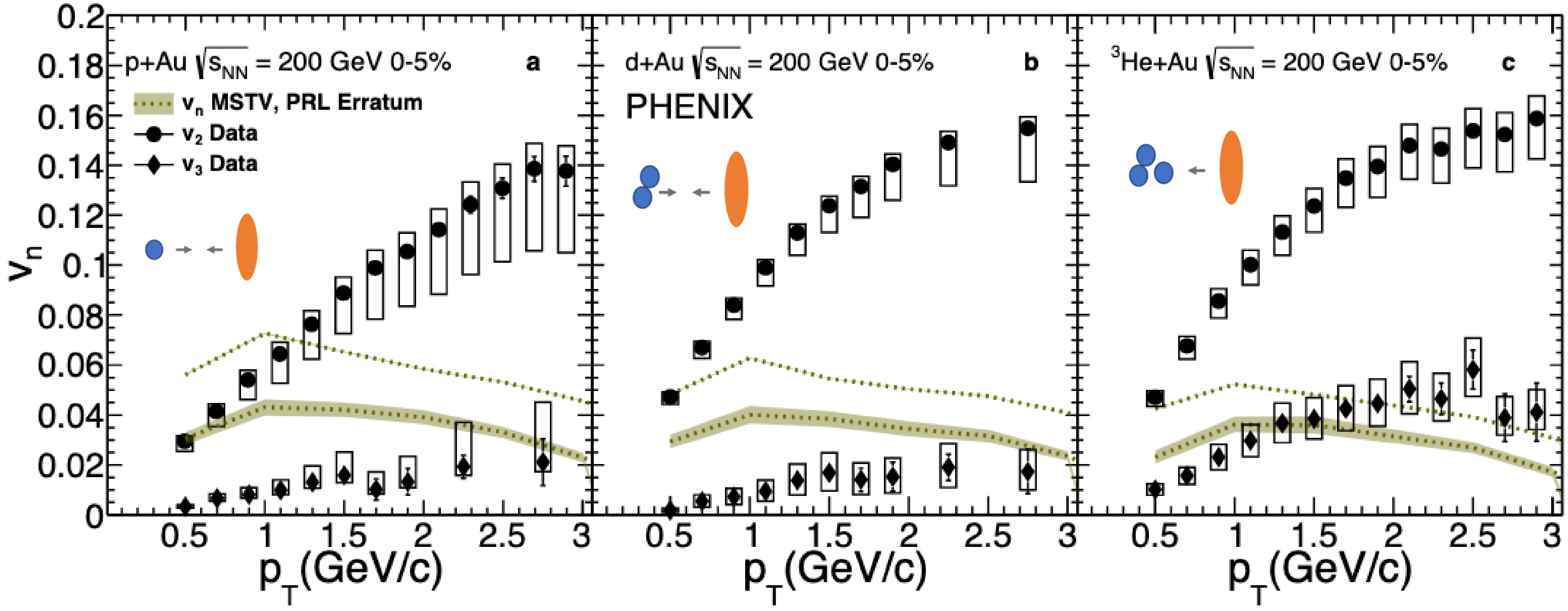
- As the multiplicity decreases, the contribution of initial momentum anisotropy might be greater than that of geometrical anisotropy.





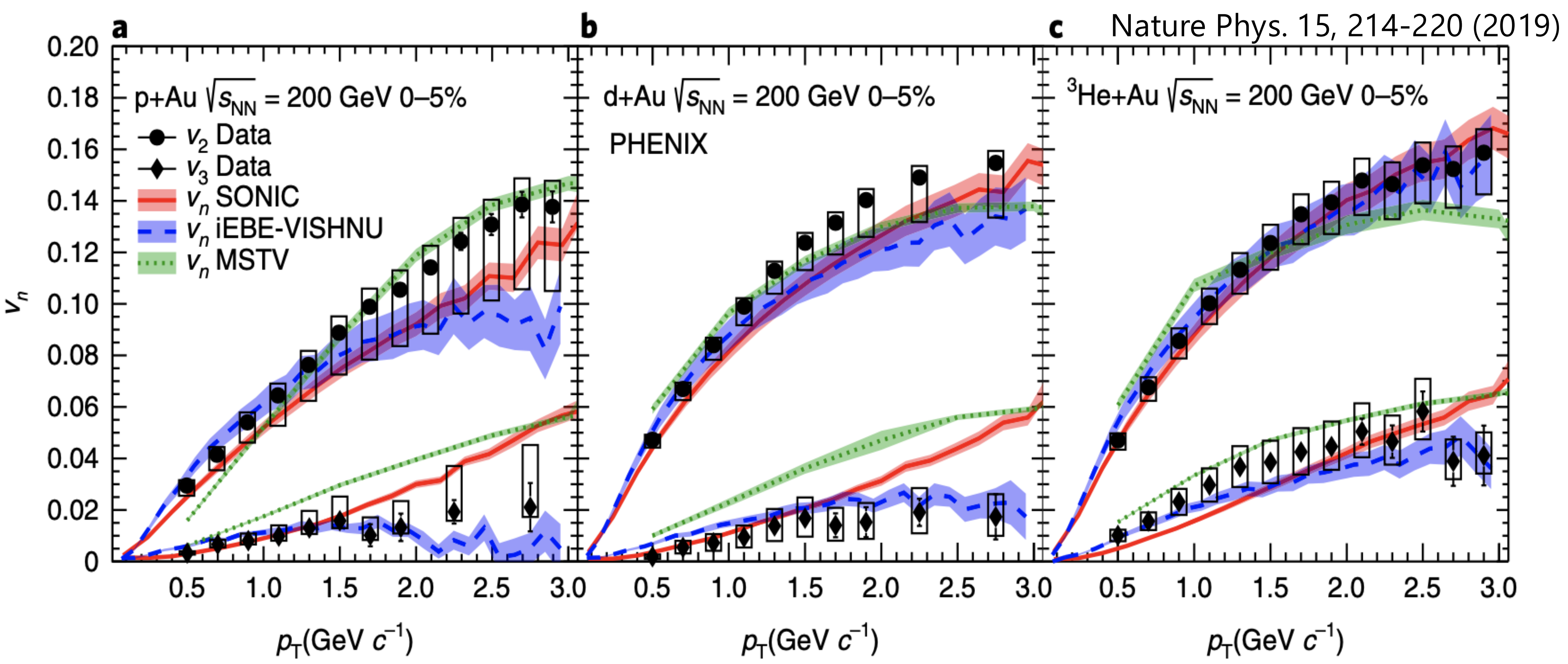
Comparisons with initial model

Nature Phys. 15, 214-220 (2019) , PRL 123, 039901 (2019)



- The initial state model fails to reproduce $v_n(p_T)$: It underestimates v_2 and overestimates v_3.
  - Gluons generated by CGC are fragmented using strings.

Comparisons with hydro model

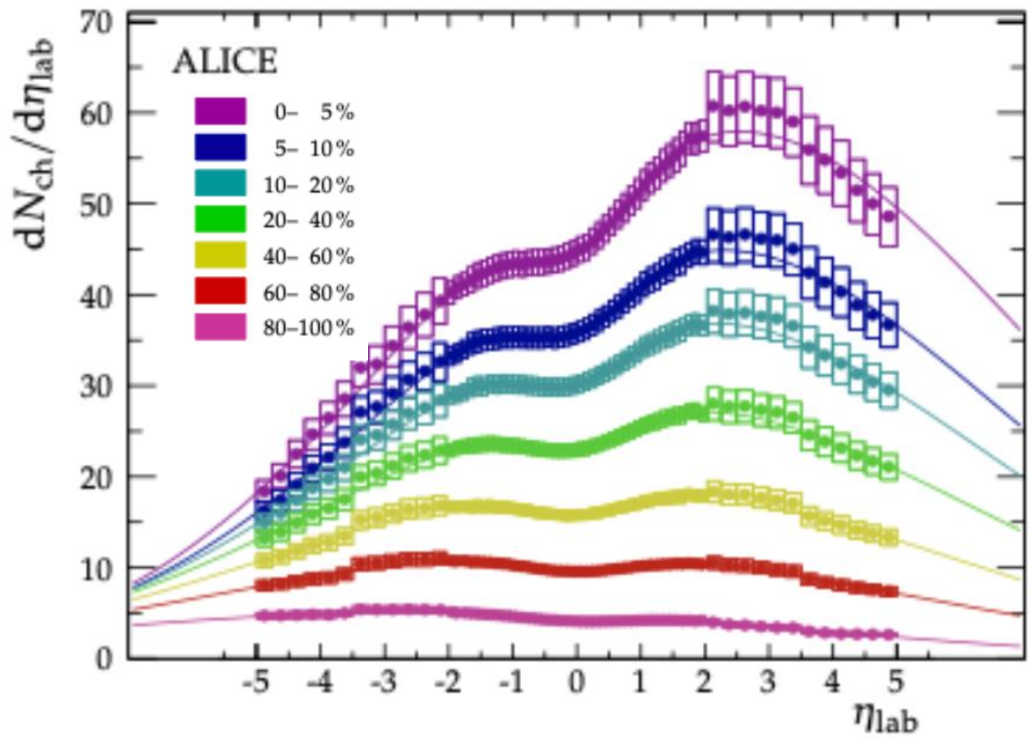


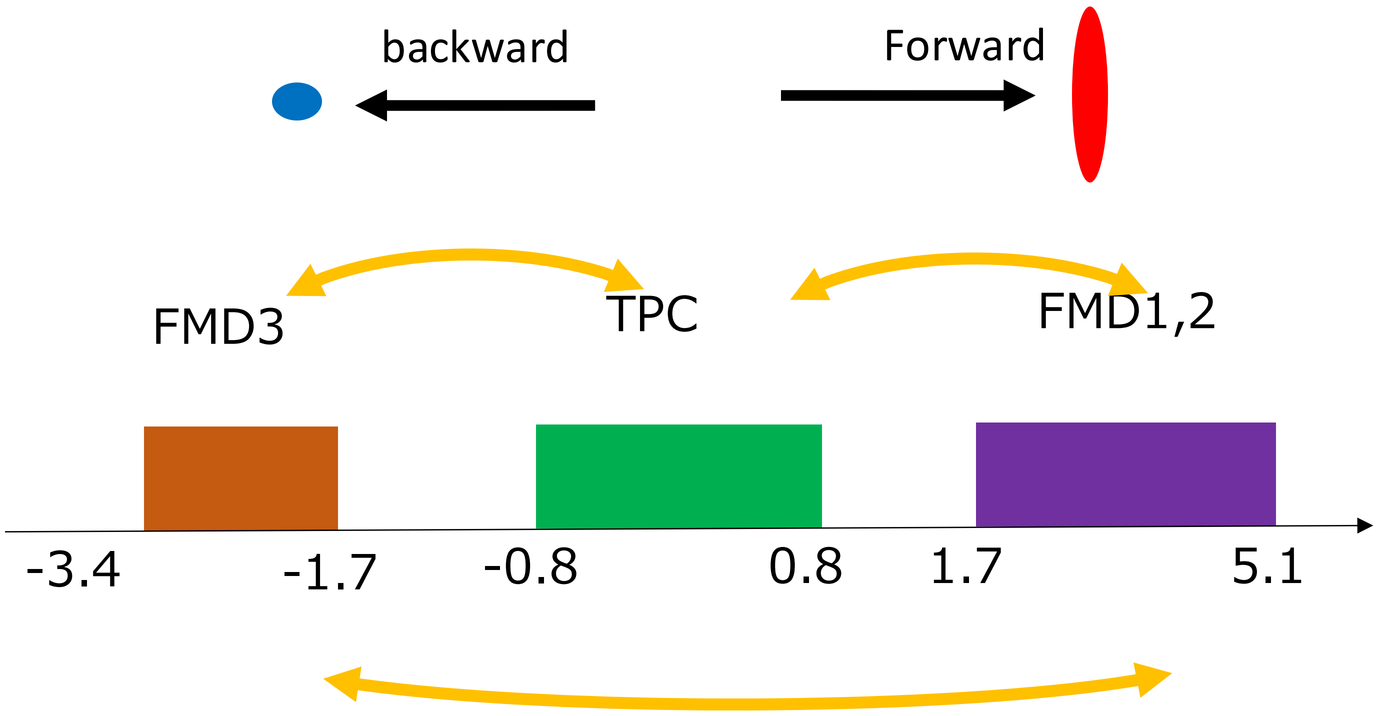
- The hydrodynamic model reproduces the data well

➢Interaction in the final state is essential to reproduce v_n

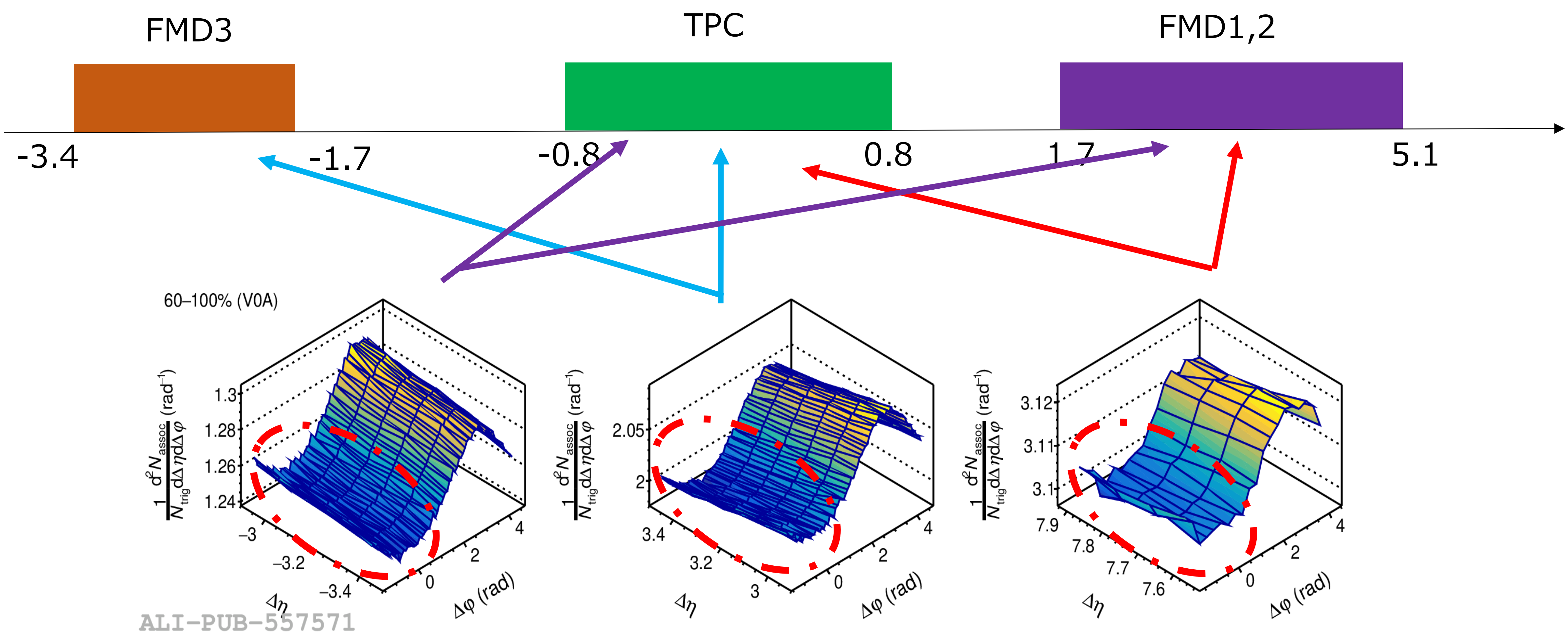
Longitudinal dynamics in pA collisions

- pPb collision is asymmetric
  - Larger multiplicity at forward thank at backward
- Long-range correlation and v2(η) overwide pseudorapidity range are measured using Forward multiplicity Detector (FMD) and TPC



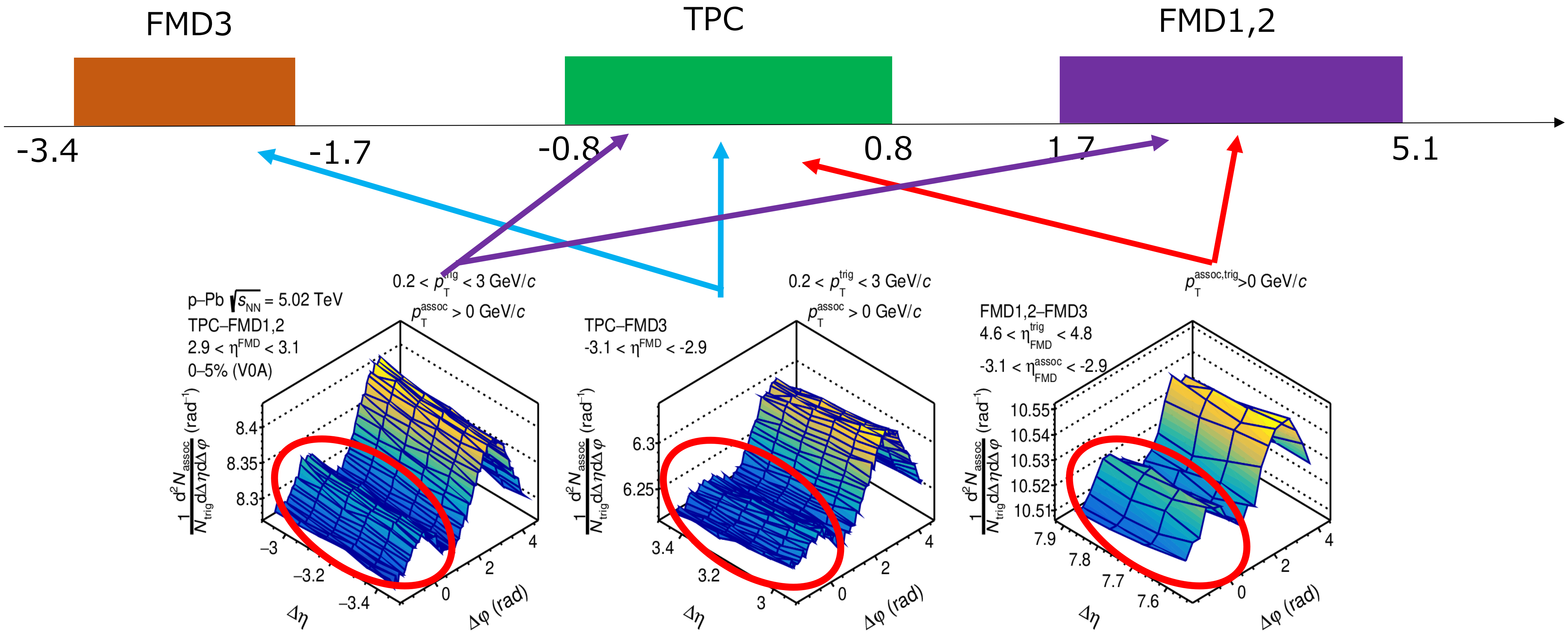


Long-range two-particle correlations



- No significant “ridge” is observed in the 60–100% event class.

Long-range two-particle correlations

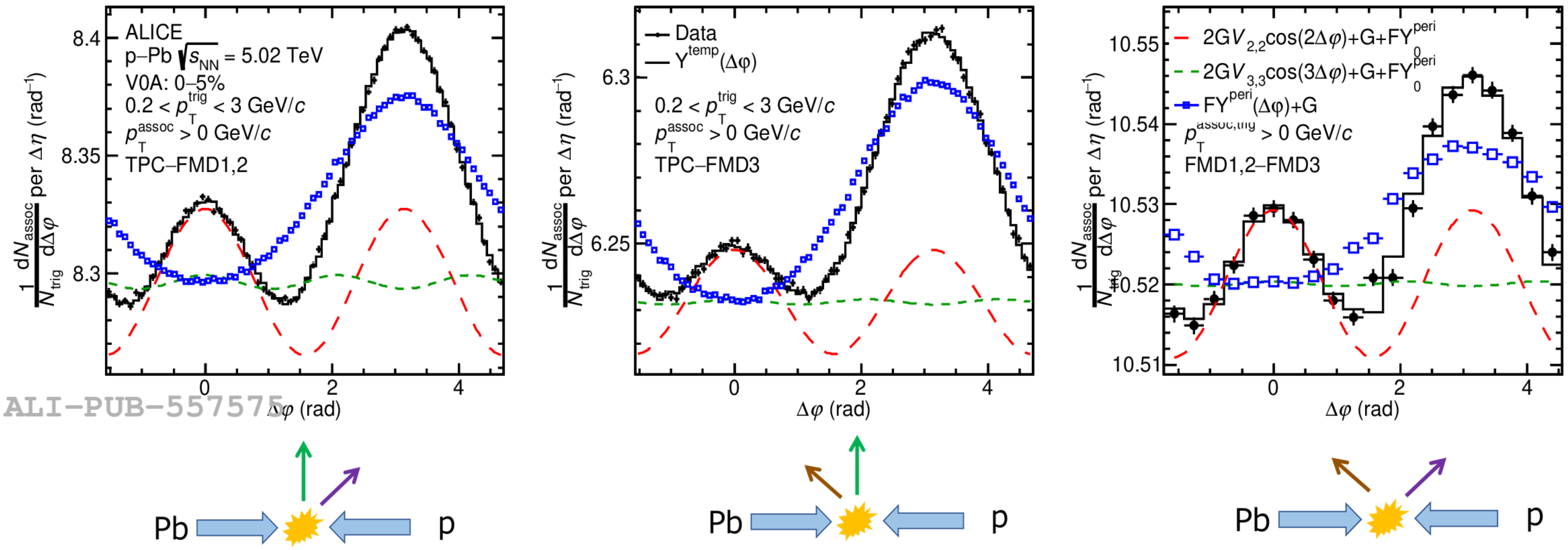


- The significant near-side ridge structure is observed in 0–5% p–Pb collisions

Non-flow subtraction

- To estimate and subtract the non-flow effects due to dijet, the template fit procedure is employed. (ATLAS, PRL 116 (2016) 172301)

$$Y^{\text{temp}}(\Delta\varphi) = FY^{\text{peri}}(\Delta\varphi) + G\left\{1 + 2\sum_{n=2}^{3} V_{n,n}\cos(n\Delta\varphi)\right\}$$

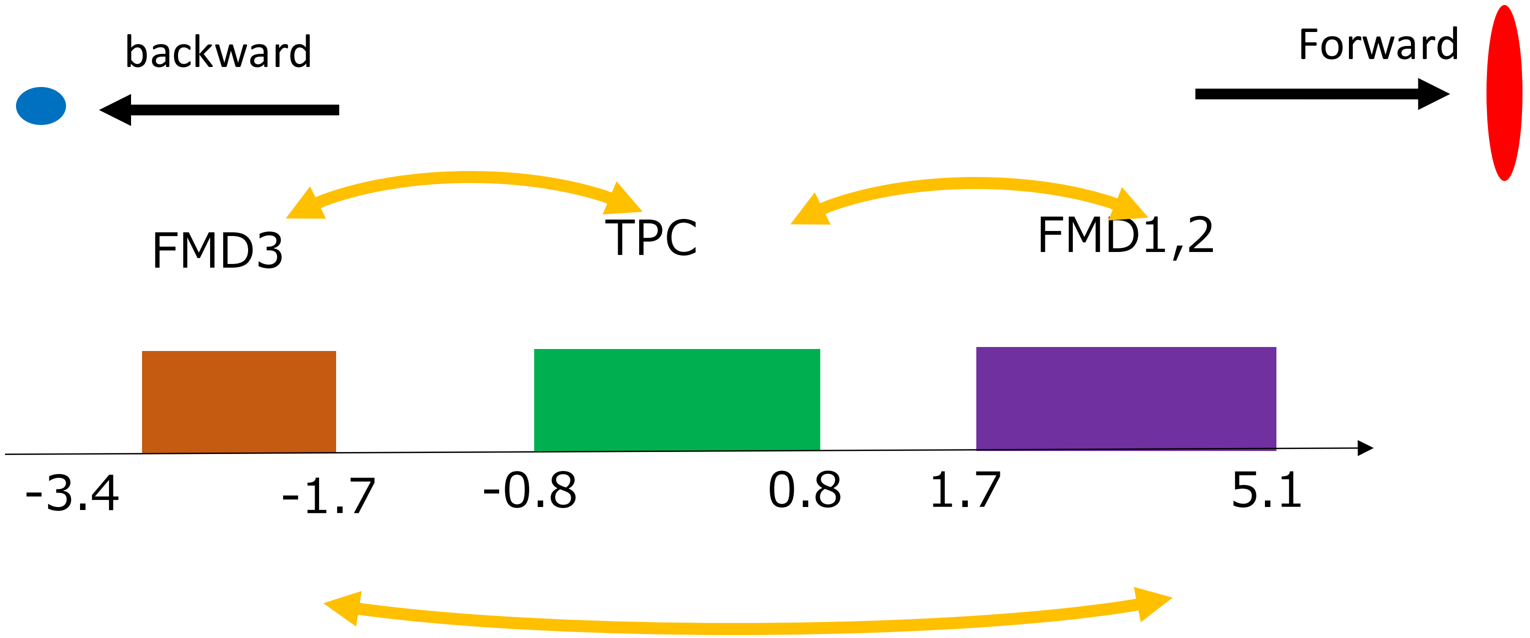


Extraction $v_2(\eta)$: 3x2PC

- v_2 at a certain η is extracted by assuming factorization, $V_{2,2}(\eta_a,\eta_b) = v_2(\eta_a)v_2(\eta_b)$, using TPC–FMD1,2, TPC–FMD3, and FMD1,2–FMD3

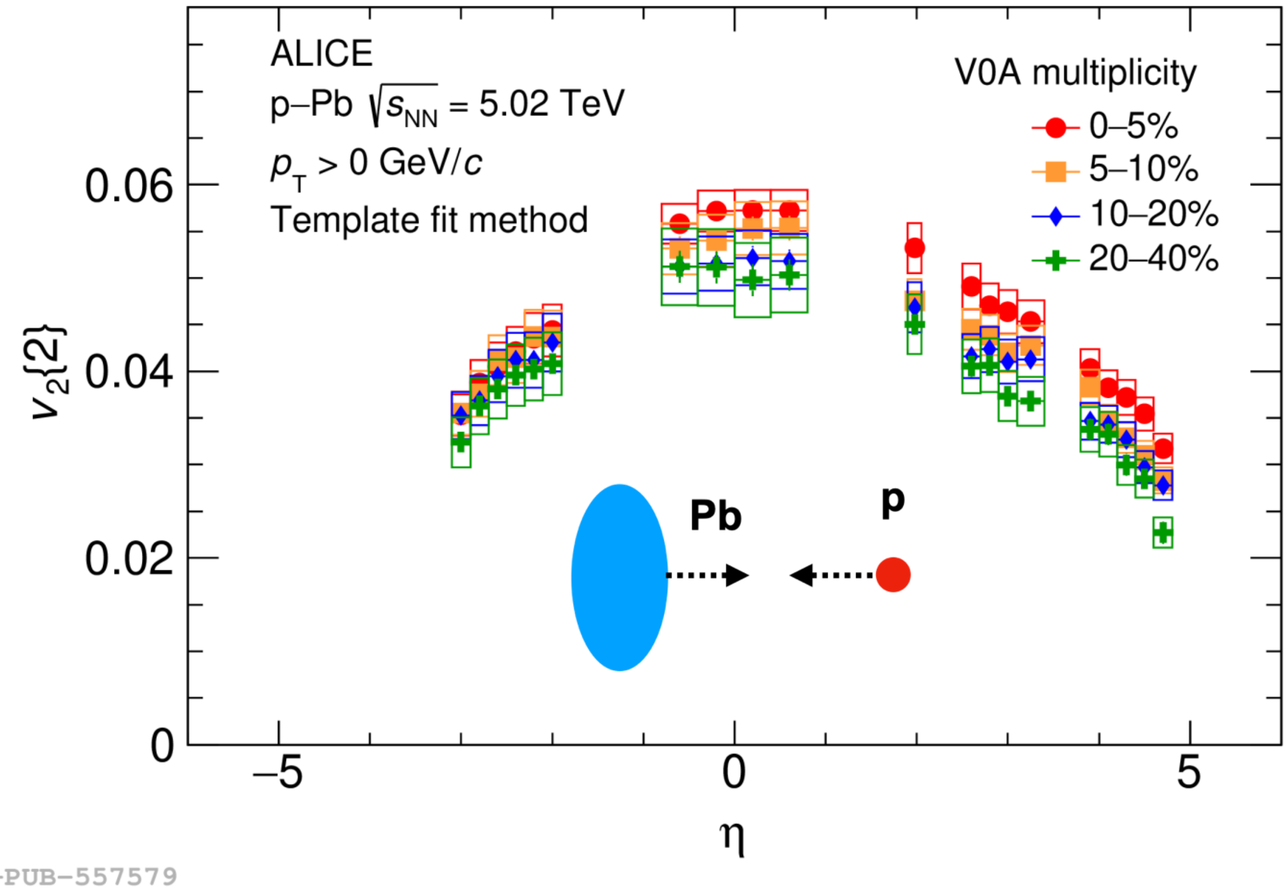
$$v_2(\eta_a) = \sqrt{\frac{V_{2,2}(\eta_a,\eta_b)V_{2,2}(\eta_a,\eta_c)}{V_{2,2}(\eta_b,\eta_c)}}$$

$v_2(\eta)$ at $-3.4<\eta<5.1$



$v_2(\eta)$ in p–Pb

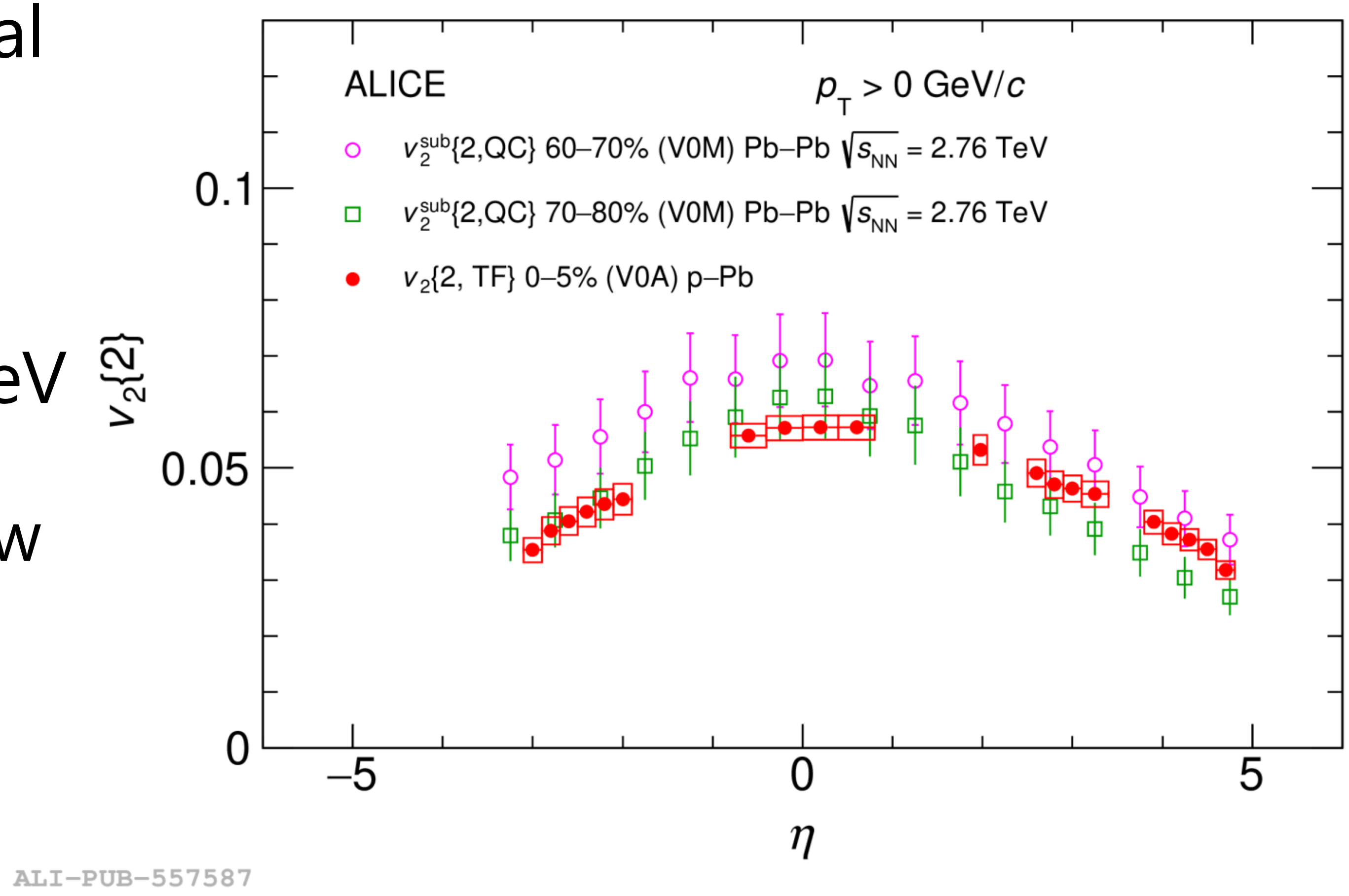
- Non-zero v_2 is observed over a wide pseudorapidity range in p–Pb collisions up to 40%
- Significant pseudorapidity dependence
- The centrality dependence is smaller in the p direction than in the Pb direction.
- v_2 in the Pb-going direction (positive η) is larger than in the p-going direction (negative η).



Comparison with peripheral Pb–Pb

- v_2 in 0-5% p–Pb central events is comparable with v_2 in peripheral Pb–Pb collisions, where the multiplicities at forward η are comparable. (dN/dη~60)
- $v_2\{2\}$ in Pb–Pb at $\sqrt{s_{NN}}$ = 2.76 TeV is extracted by the standard Q-cumulant method with non-flow subtraction using pp collisions.

(PLB 762 (2016) 376)



Comparisons with hydrodynamic model

- v_2 results are compared to the hydrodynamical calculations.

  (W. Zhao et al., PRL 129 (2022) 252302)
  - 3D Glauber as initial condition + viscous hydrodynamics based on MUSIC + UrQMD
- The hydrodynamic model describes the data qualitatively up to 40 %.
- In the model, v_2 mainly originates from the 3D initial geometry and develops over the course of the hydrodynamical evolution.

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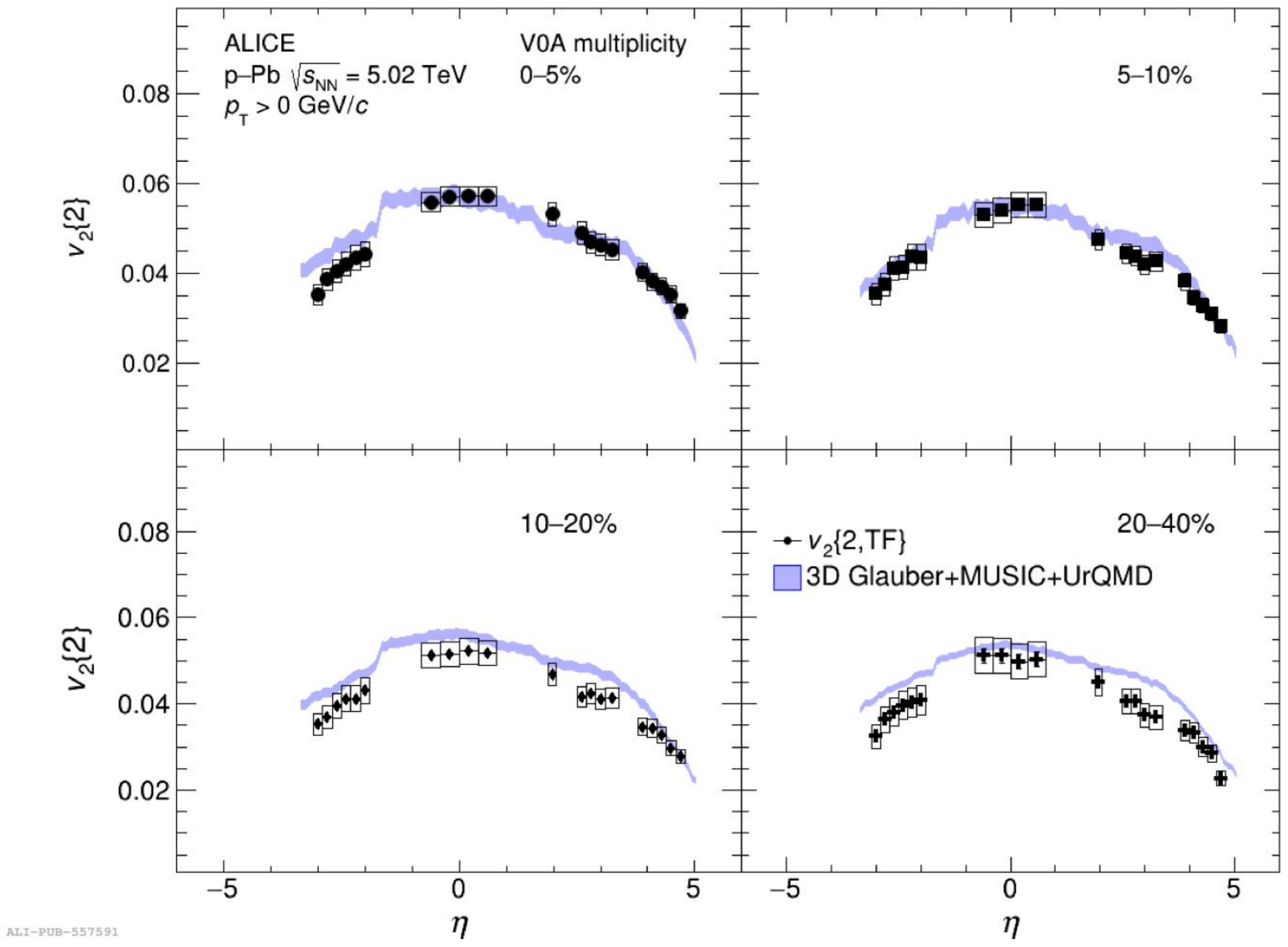


Summary

- QGP is a state in which quarks and gluons are released from confinement.
- Heavy Ion collision experiment is a unique opportunity to study properties of QGP
- Flow is one of key measurements to study property of QGP
- In heavy ion collisions, large v2 is observed and the hydrodynamic model calculation describes the data very well
  - QGP created in HIC is like ideal fluid
- Collectivity is observed in high-multiplicity small collision system
  - Reflects the initial shape
  - Ridge exists up to $\Delta\eta \sim 8$
  - Non-zero v2 over wide rapidity range
  - Hydrodynamic model describes the data very well.

My plan at sPHENIX

- My first interest is measuring charmed hadrons in p–Au collisions, however it was canceled.
- For now, I will measure two particle correlation in pp collisions and p_T differential flow at midrapidity.
  - Subdetectors for the analysis: silicon(+EMCAL) tracking and sEPD
  - Middle-term goals:
    - System size dependence: Au–Au (and p–Au??)

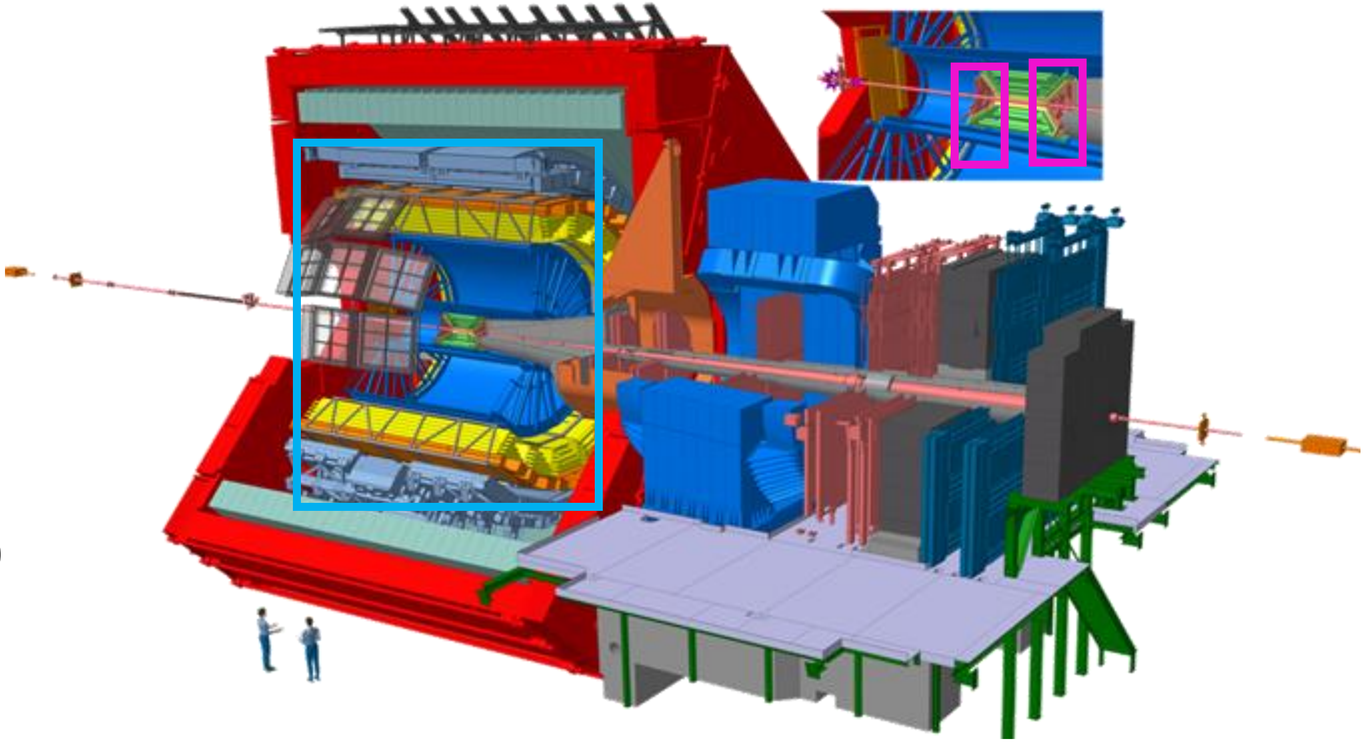
I look forward to working with you!

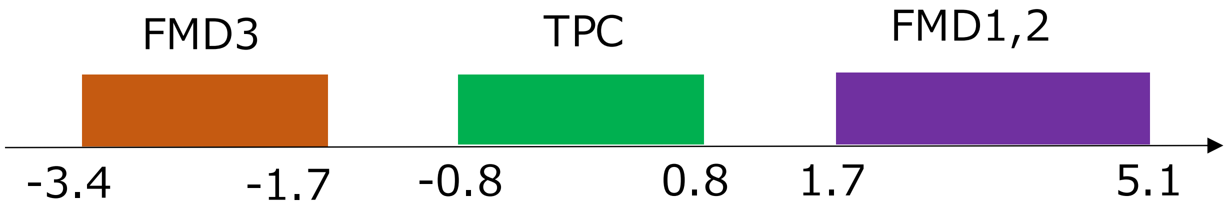
Back up

ALICE Experiment

- **Inner Tracking System (ITS) and Time Projection Chamber (TPC)**
  - Charged-particle tracking
  - $|\eta|<0.8$
- **Forward Multiplicity Detector(FMD)**
  - FMD3：$-3.4<\eta<-1.7$
  - FMD1,2: $1.7<\eta<5.1$
  - Segmentation in $(\Delta\eta,\Delta\varphi)=(0.05,\pi/20)$
  - Charged-particle counter
- **V0 Detector**
  - Trigger and centrality determination
  - V0C: $-3.7<\eta<-1.7$, V0A: $2.8<\eta<5.1$

~500 M events with MB trigger in p–Pb at 5.02 TeV





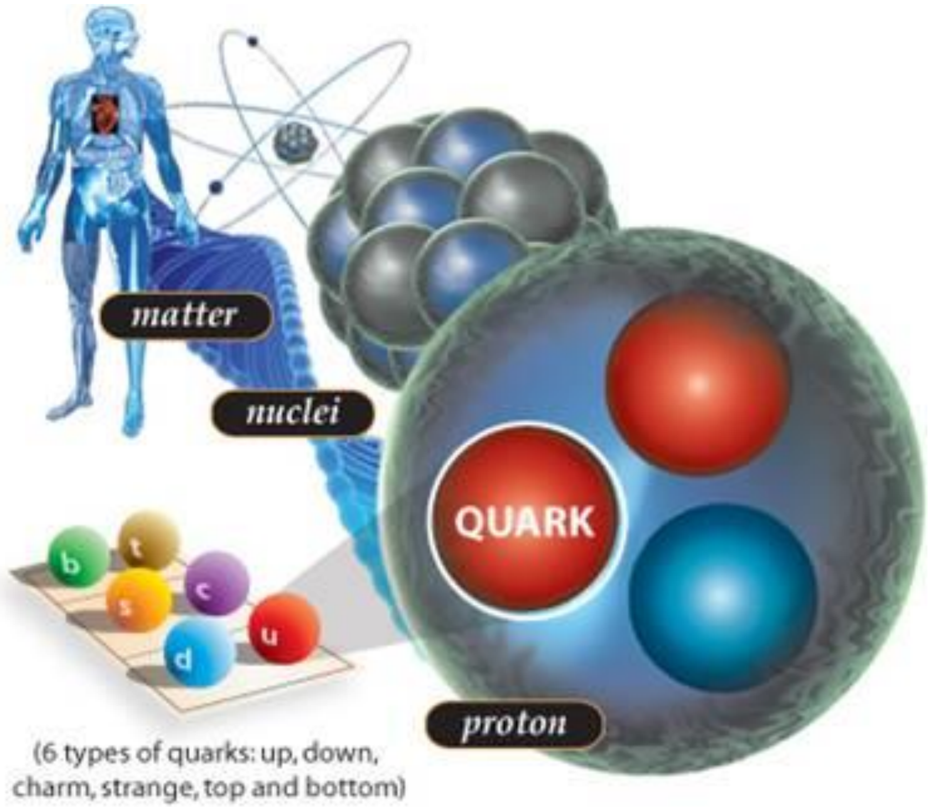
Long-range correlations up to $\Delta\eta$~8 and $v_2(\eta)$ at $-3.4<\eta<5.1$

Study onset of Collectivity

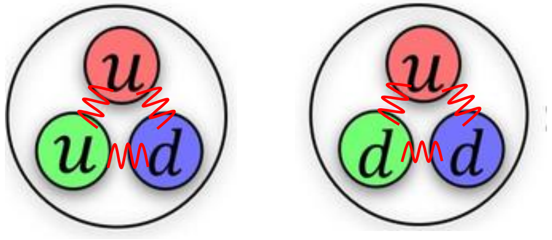
- The onset of collective motion is performed in increasingly smaller collision systems such as γ+A and e+e.
- A finite v2 has also been observed in γ+A and the non-zero ridge yield is observed in

Elementary particles

- Quarks are elementary particles that are the smallest building blocks of matter.
- Quarks is confined within hadrons such as mesons and baryons and gluons intermediate the strong interaction.



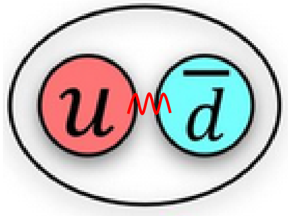
3 quark: Baryon



Proton Neutron

~170 types

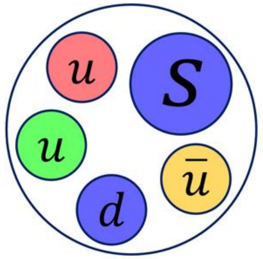
2 quark: meson



Pion

~210 types

>3 quark: Exotic hadron



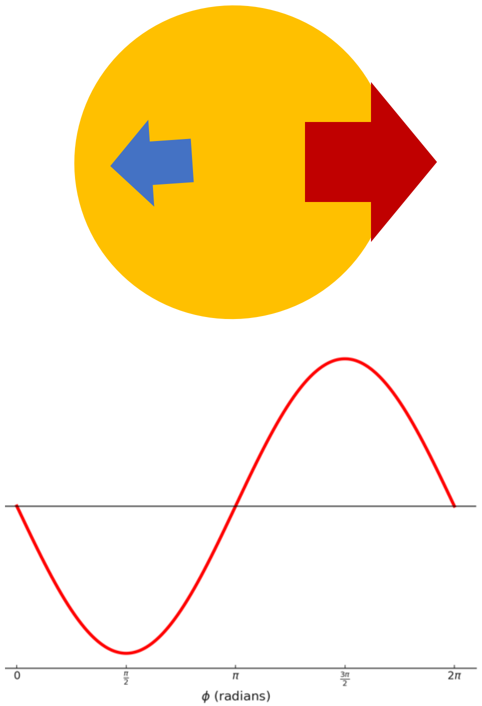
Azimuthal Anisotropy of emitted particles

- Fourier expansion of azimuthal distributions for emitted particles

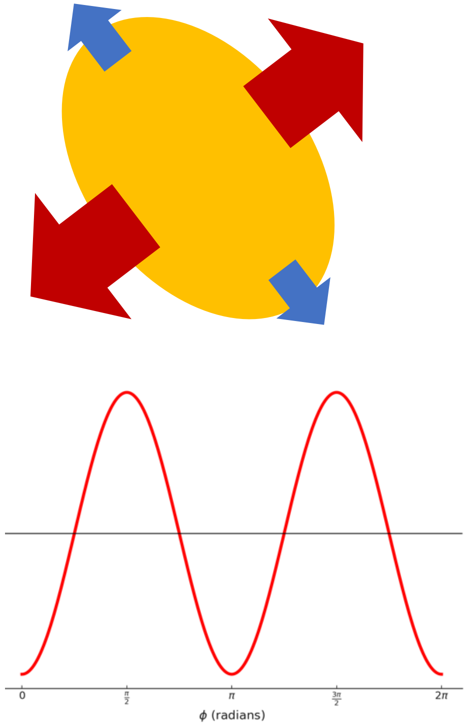
$$E\frac{d^3N}{d^3\vec{p}} = \frac{1}{2\pi}\frac{dN}{p_T dy dp_t}\sum_{n=0} 2v_n \cos n\varphi$$

v_n : Flow harmonics

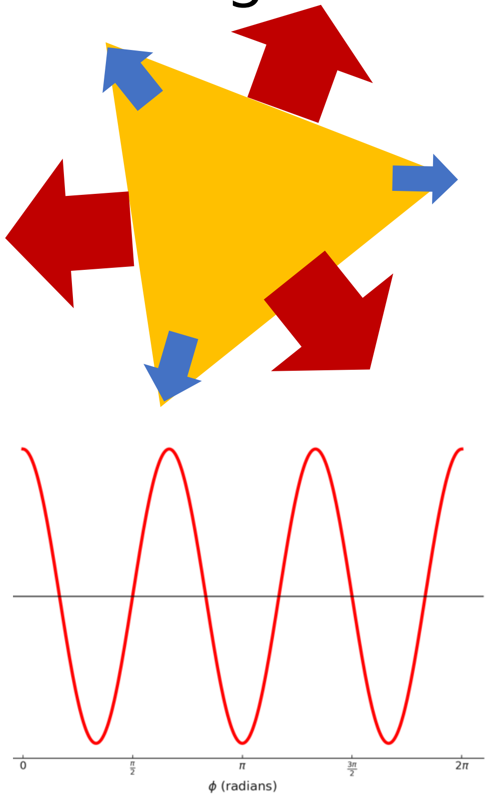
n=1 Directed flow v_1



n=2 Elliptic flow v_2

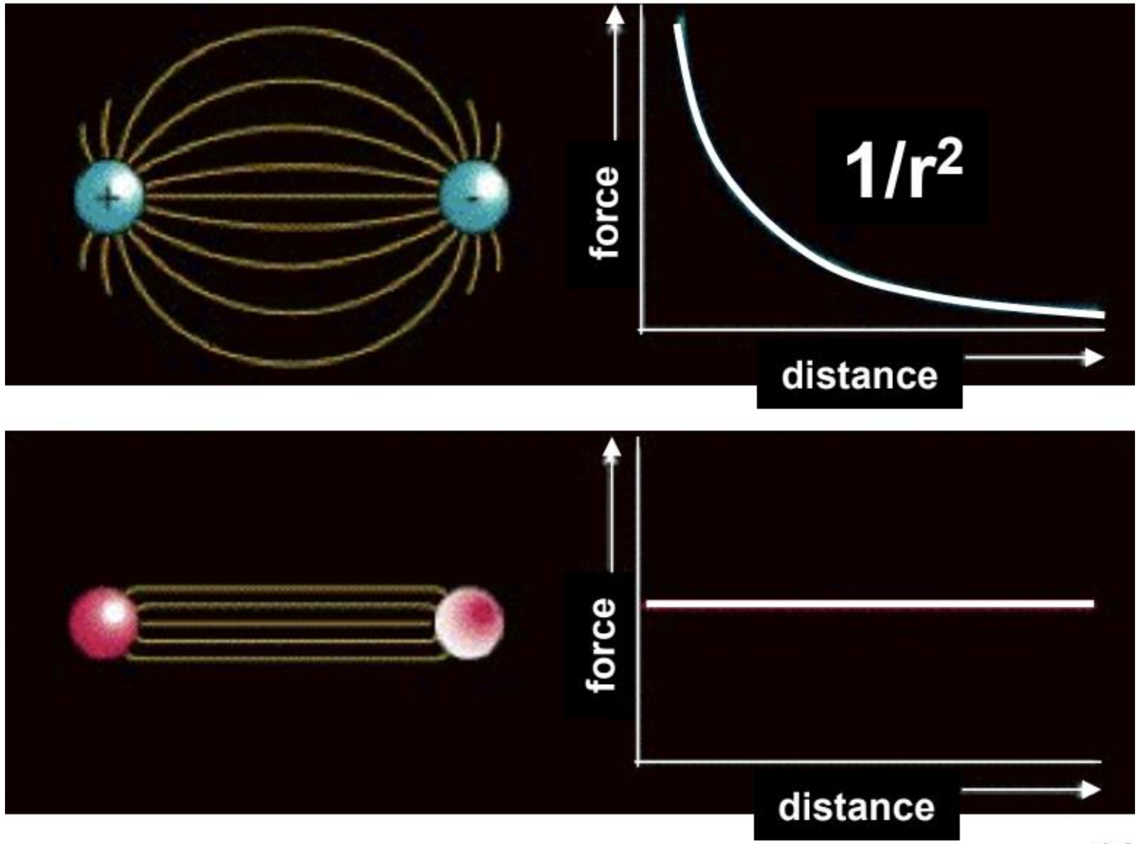


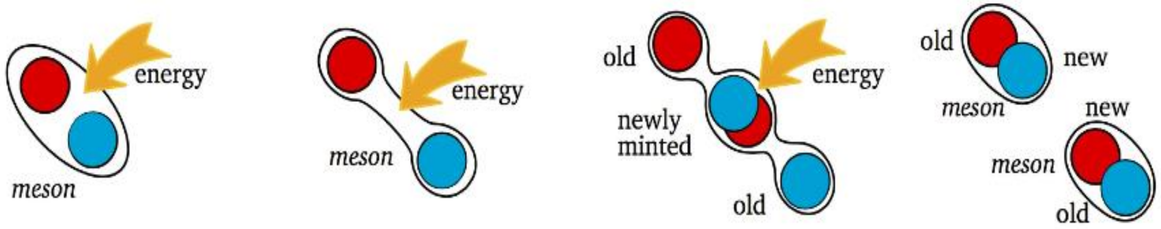
n=3 Triangle flow v_3



Quark Confinement

- The dynamics of quarks and gluons is described by the Quantum Chromodynamics (QCD).
- The force between quarks does not weaken even as the distance increases.





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