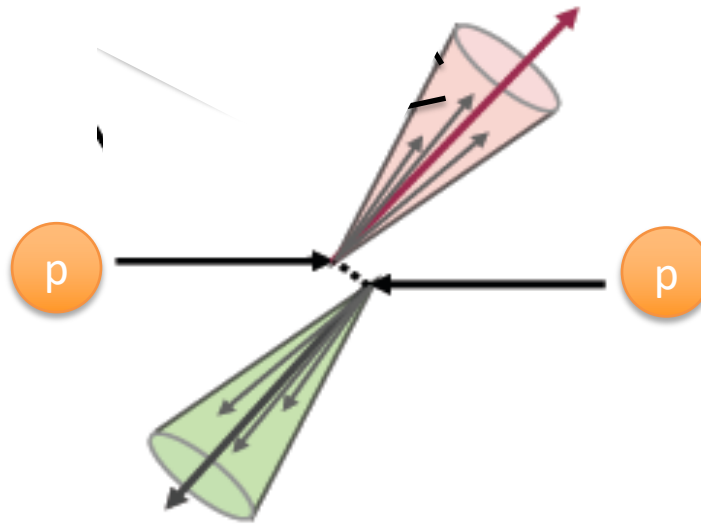


ありえない！？
陽子陽子衝突系でのQGP

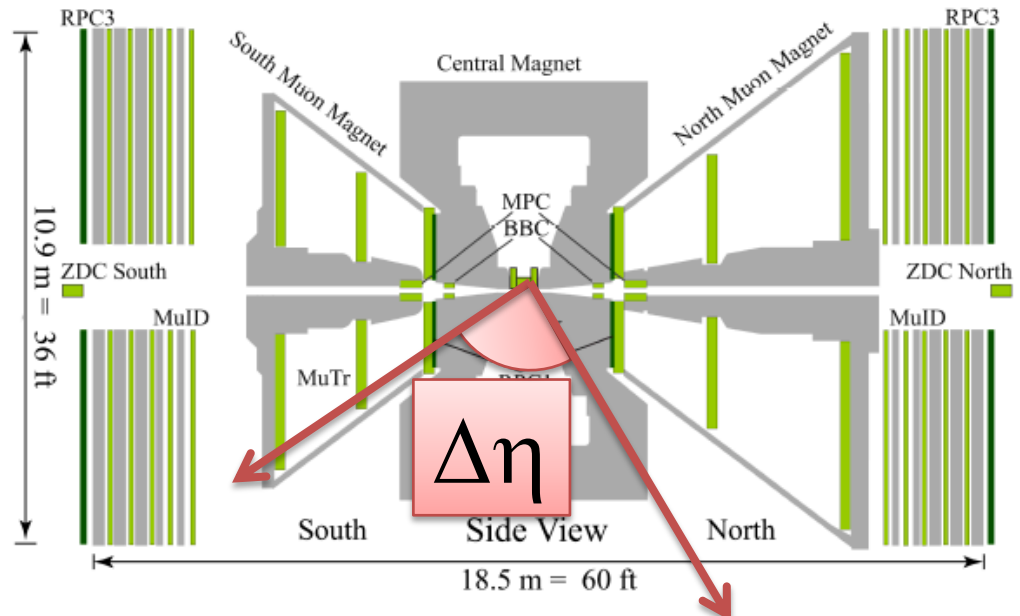
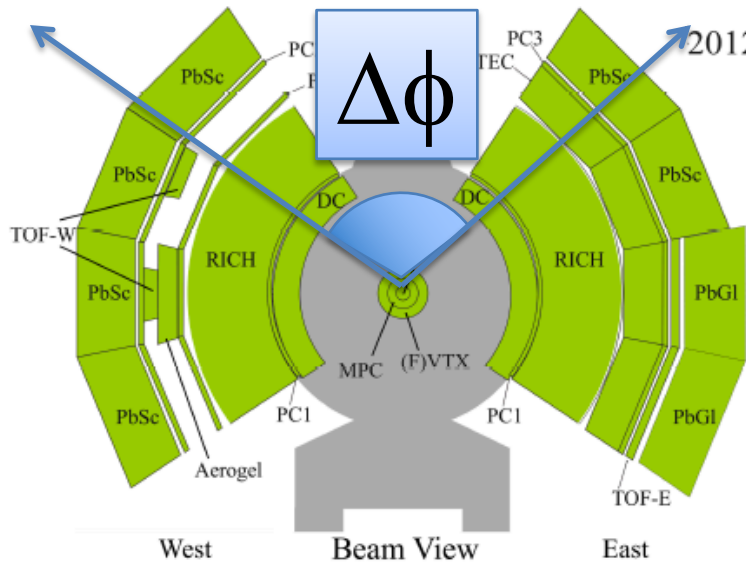
理研
中川 格

2粒子相関

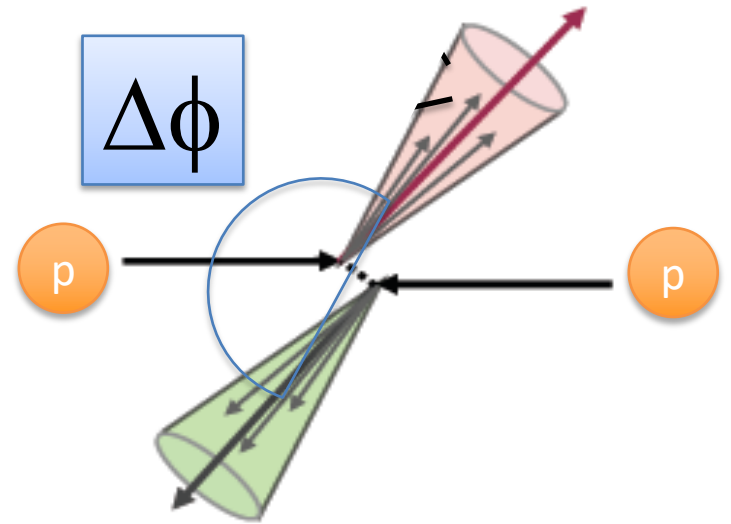
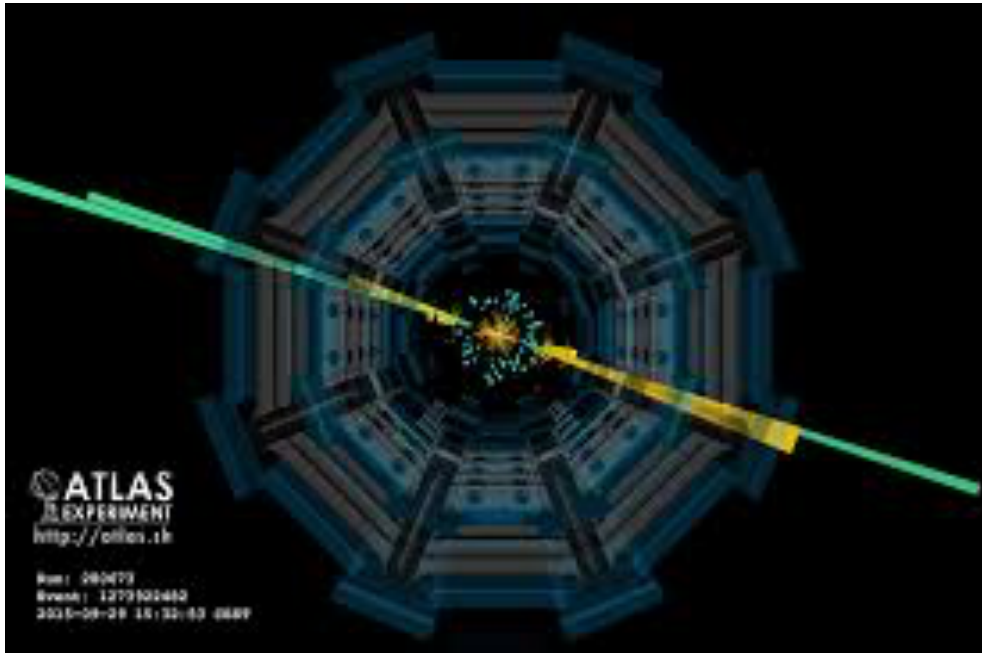
ジェットージェット (2粒子) 相関



PHENIX Detector

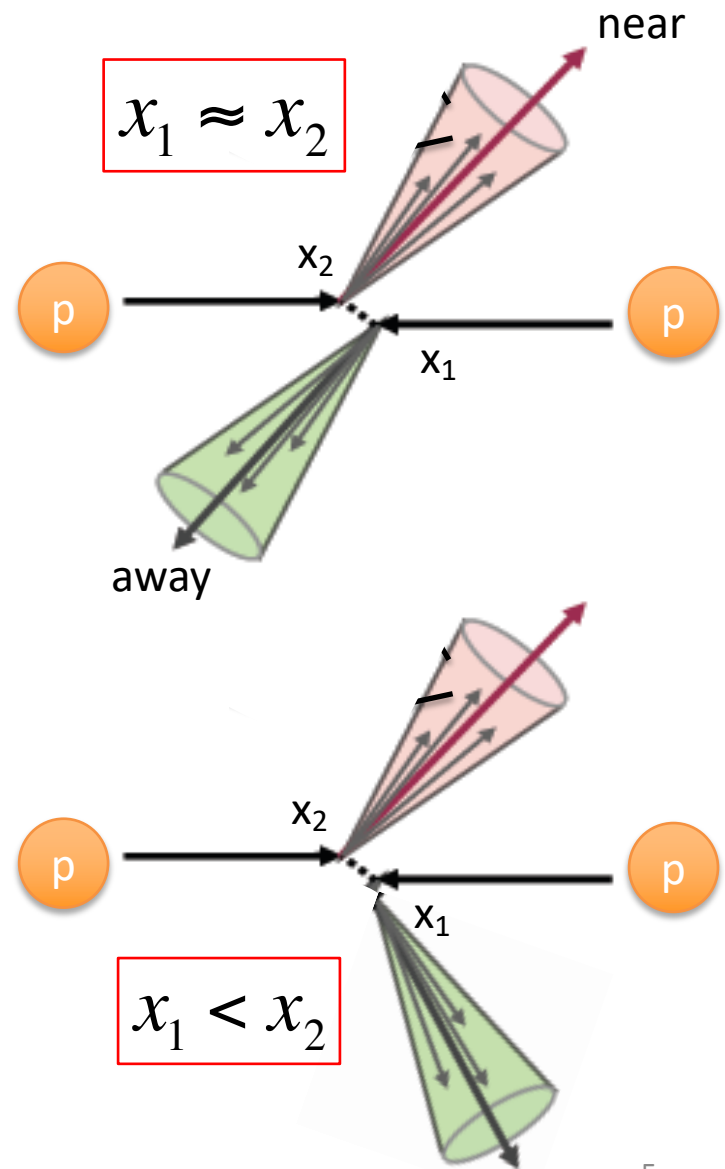
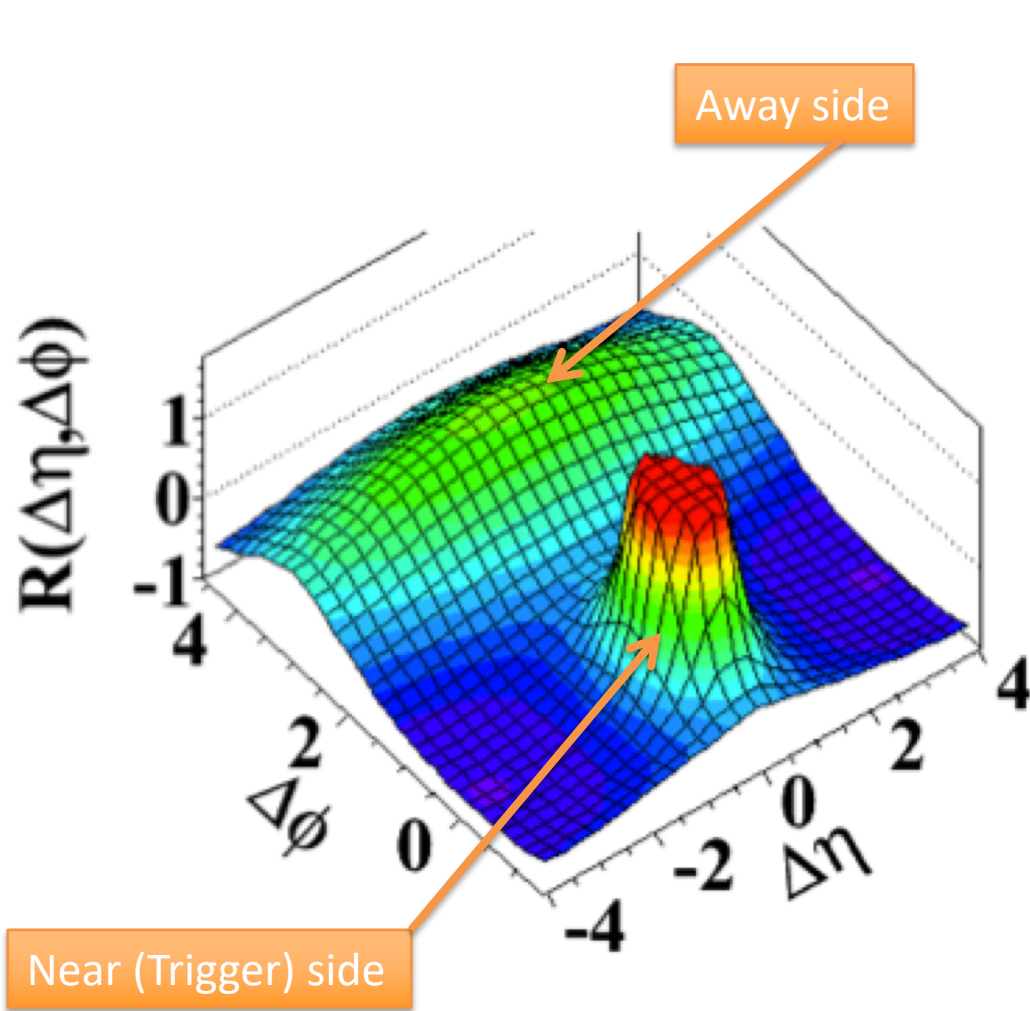


ジェットージェット (2粒子) 相関

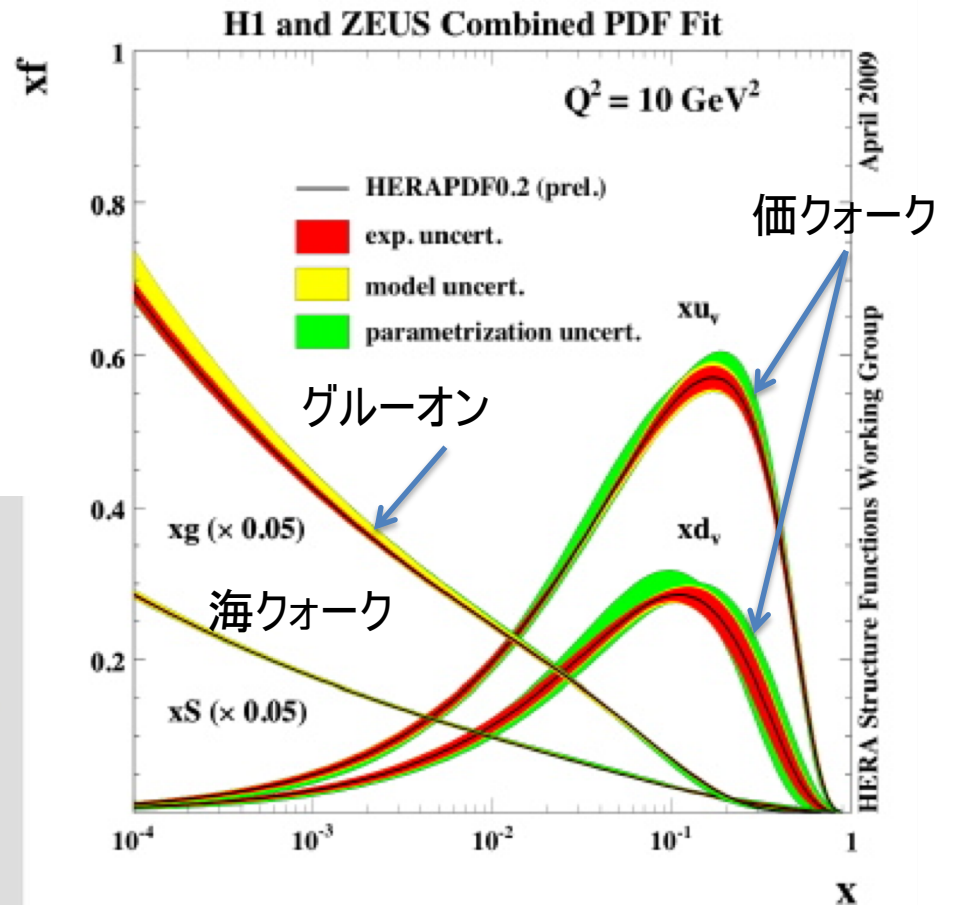
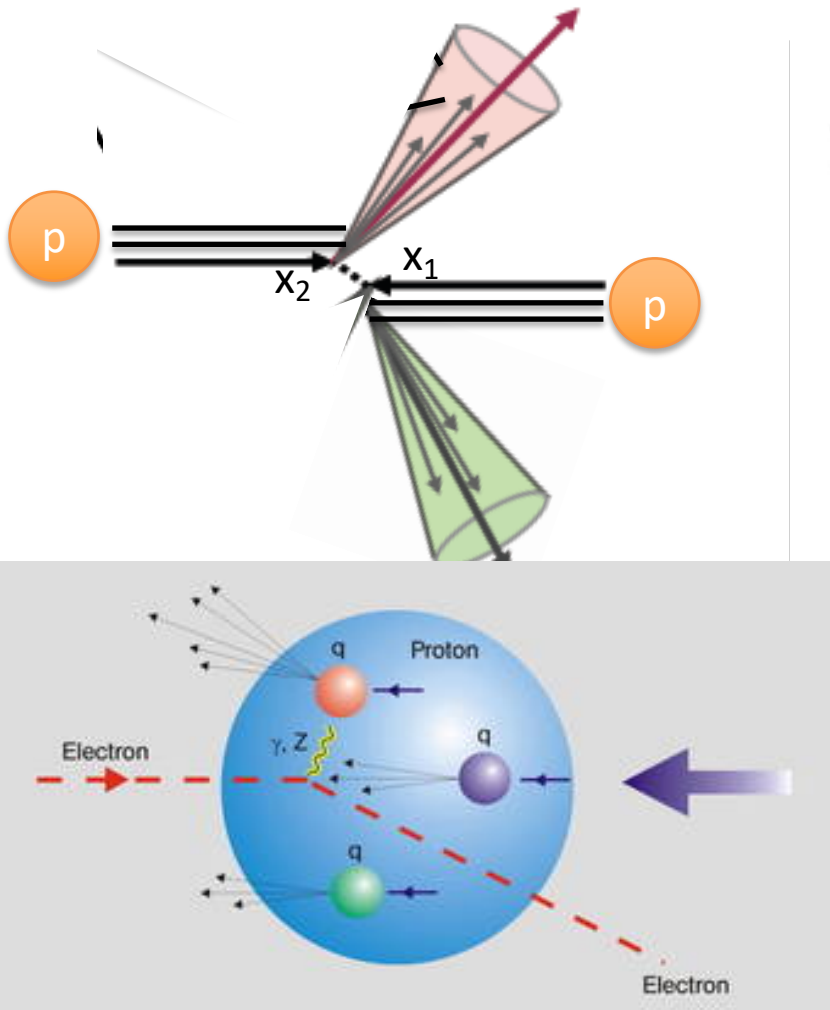


運動量保存則により方角的には真逆の関係になる。

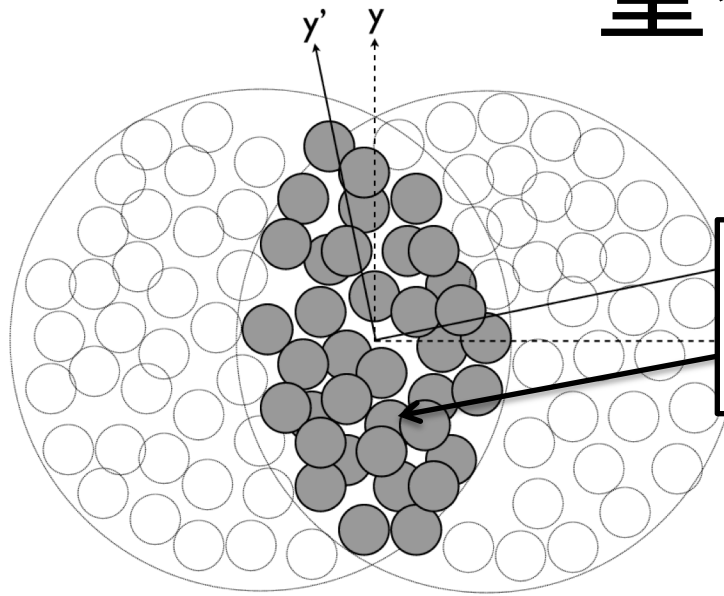
ジェット-ジェット (2粒子) 相関



パートン運動量分布関数

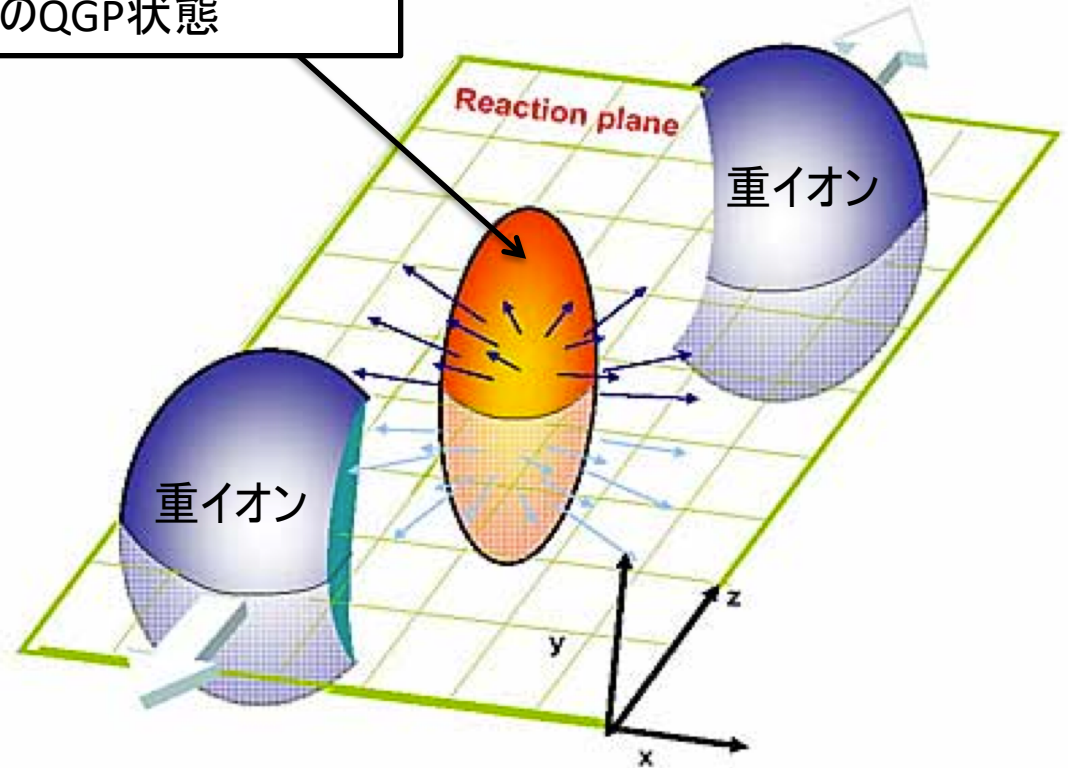


重イオン衝突

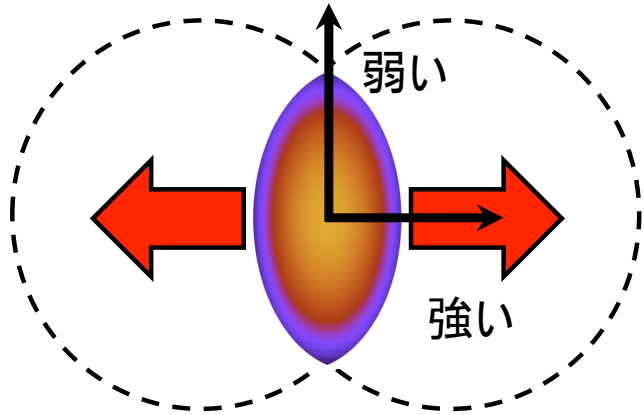


衝突点に生成されたラグビーボール状のQGP状態

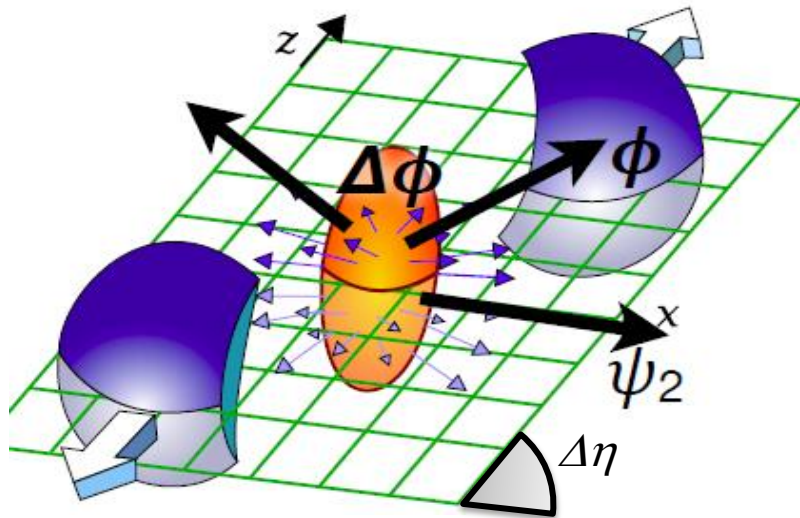
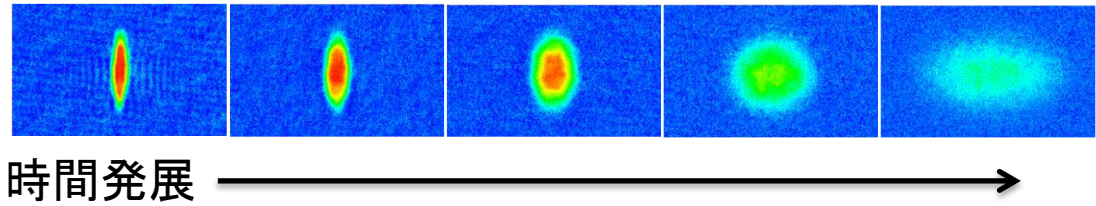
正面から見た衝突の様子



楕円フロー

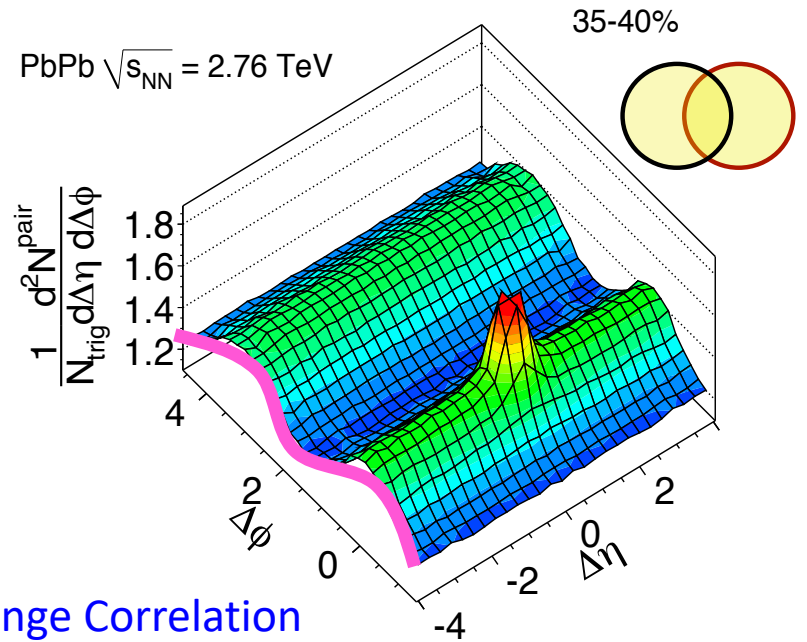


圧力勾配



Long (Rapidity) Range Correlation

2粒子相関

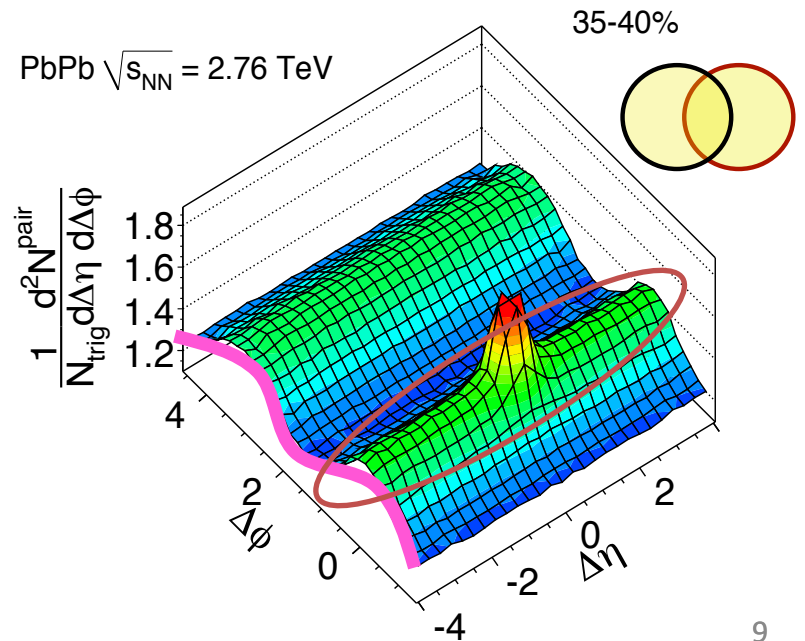
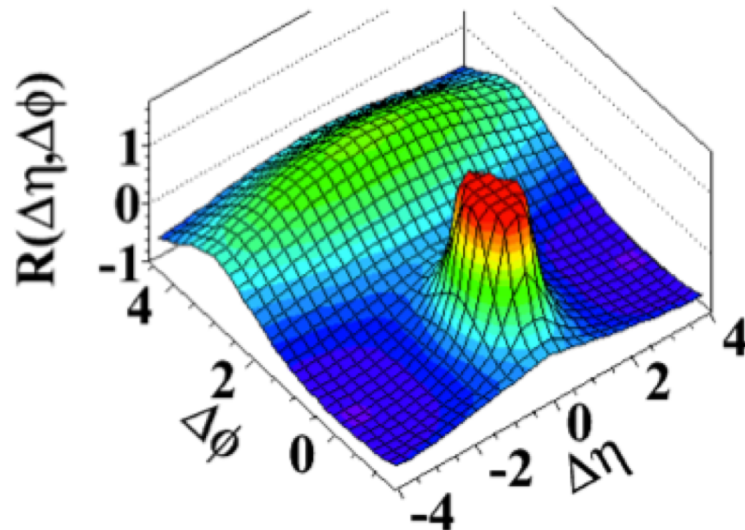


QGPが起きた事を示す有力な手がかり

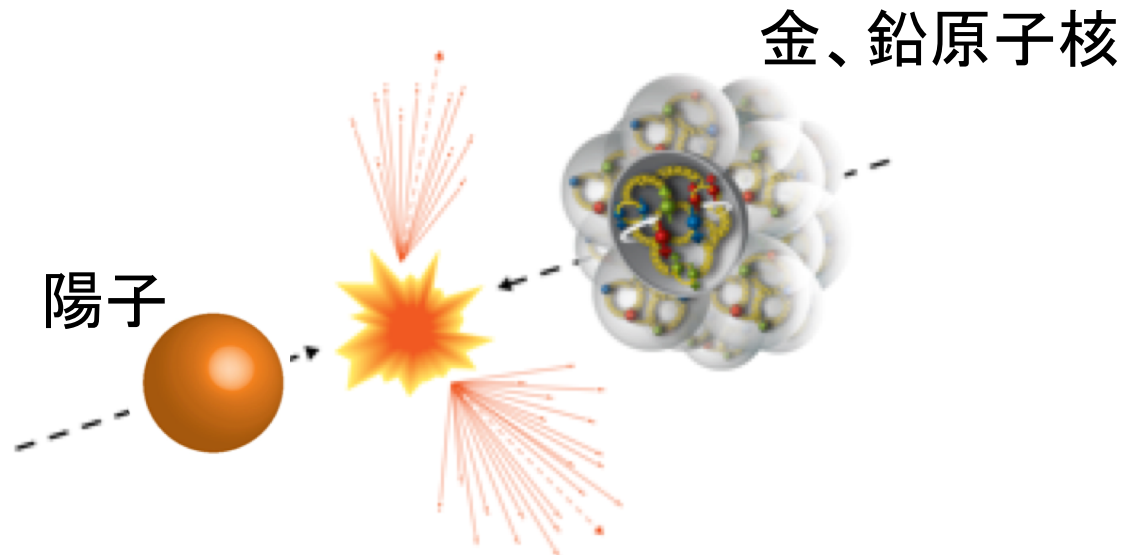
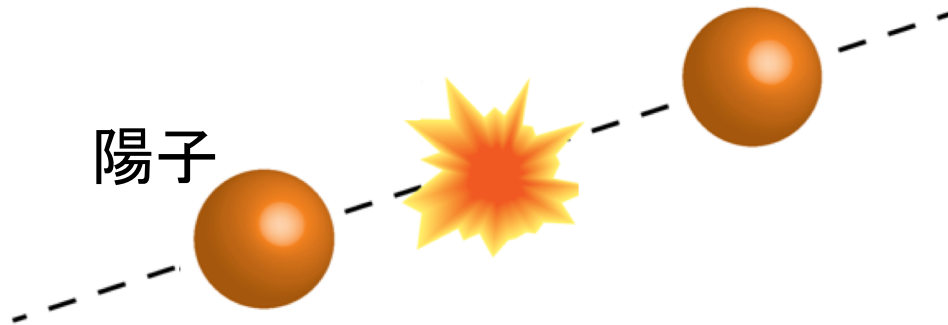
楕円フローとRidge(尾根)現象



$$\frac{1}{N_{\text{trig}}} \frac{dN^{\text{pair}}}{d\Delta\phi} \sim 1 + 2(v_2)^2 \cos(2\Delta\phi)$$

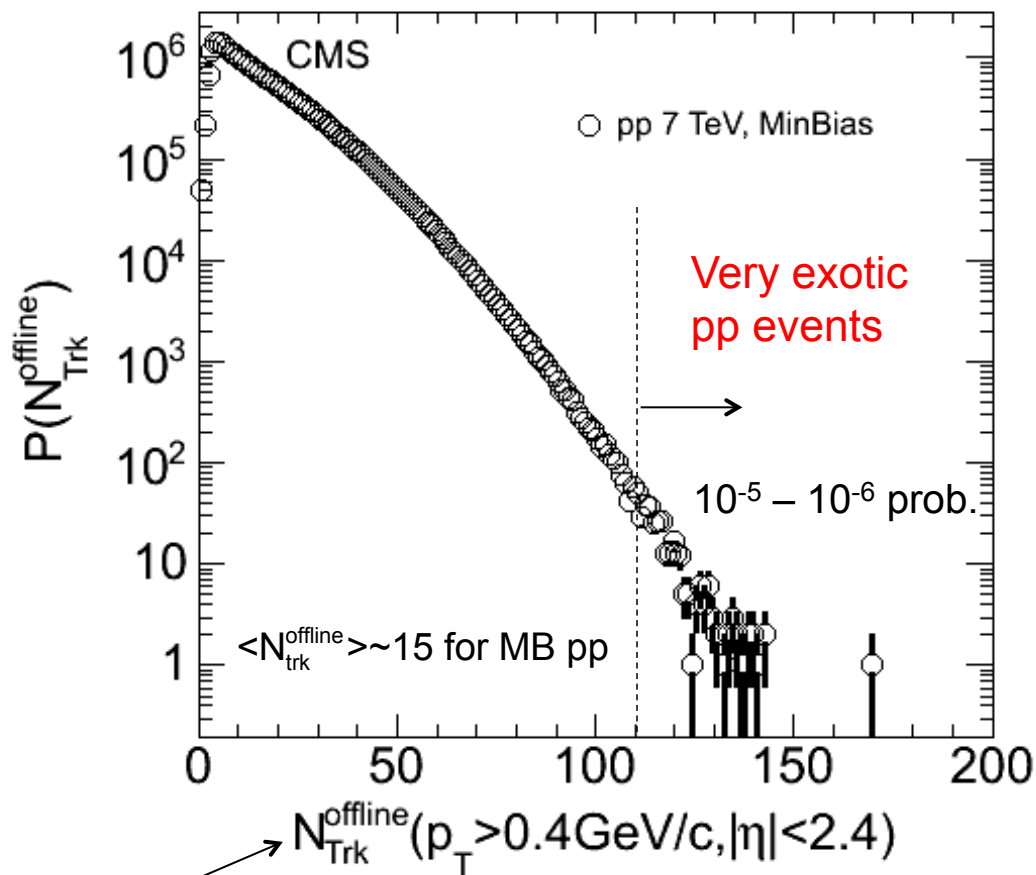


小さい衝突系のQGP?



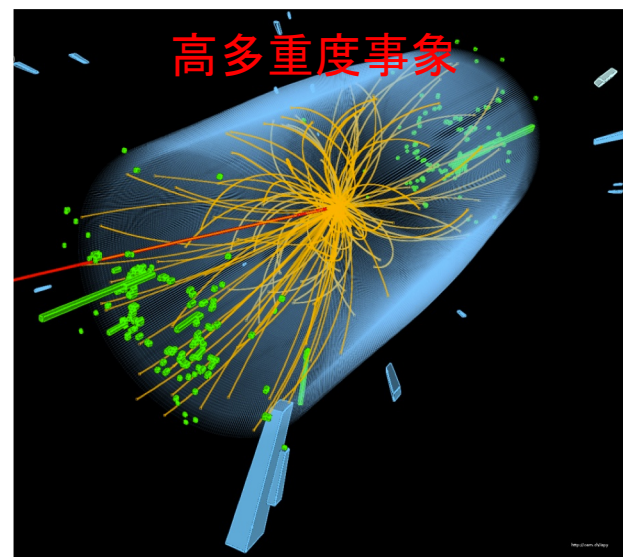
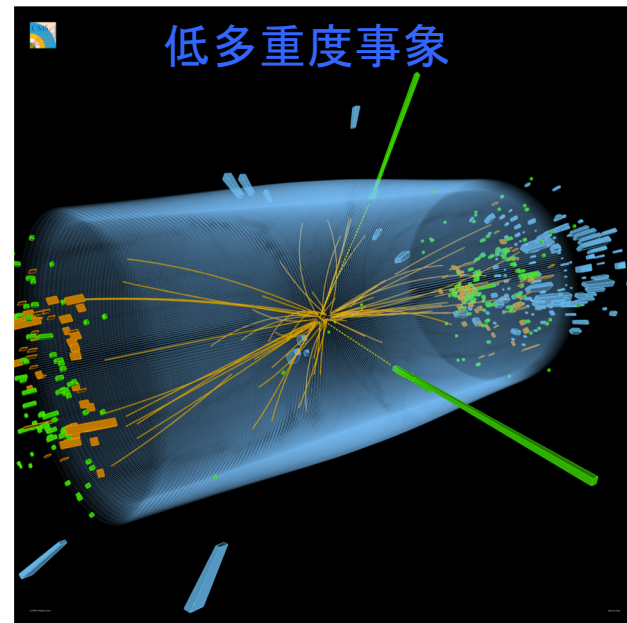
p+p@7TeVの 粒子多重度分布

低多重度事象 ← → 高多重度事象



Raw counts of tracks!

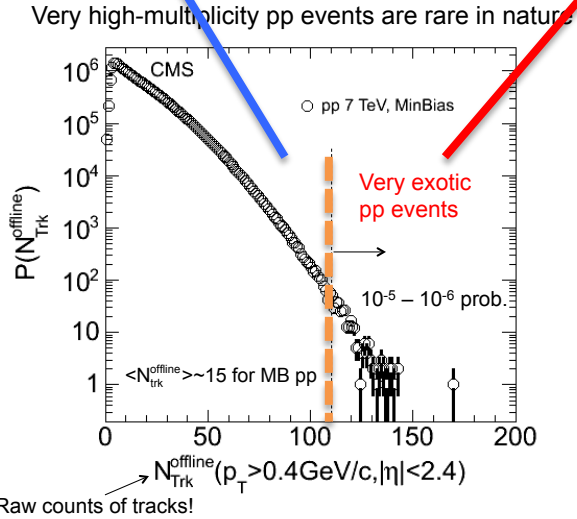
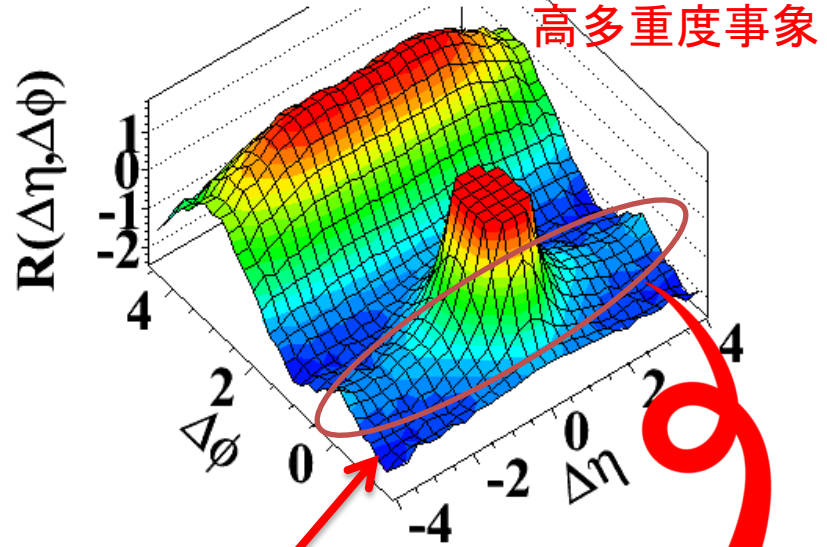
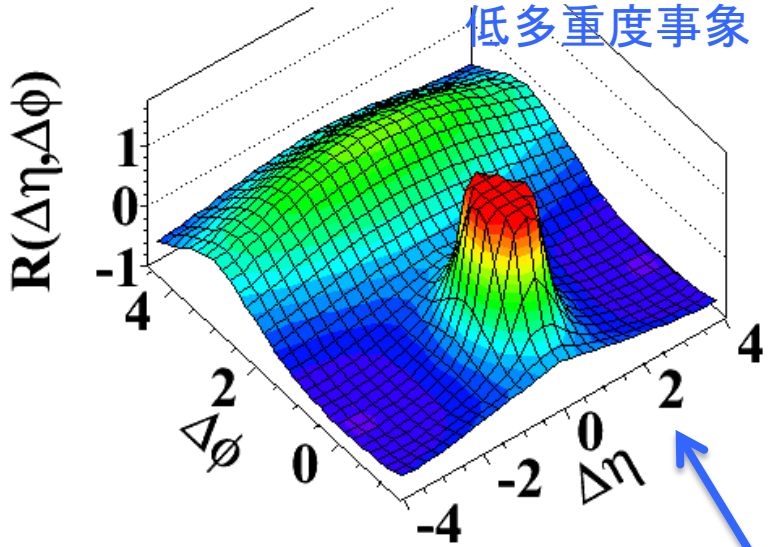
LHCのCMS実験: 7TeV陽子+陽子衝突



粒子多重度による分類

pp $\langle N \rangle \sim 15$, $1 < p_T < 3$ GeV/c

pp $N > 110$, $1 < p_T < 3$ GeV/c

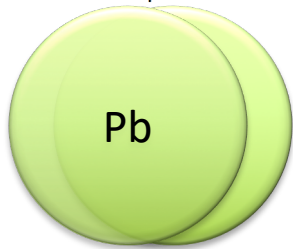
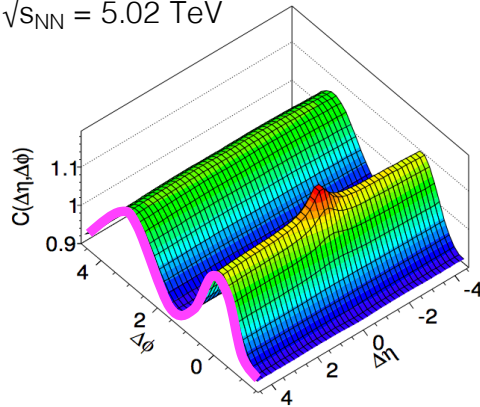


Ridgeらしき現象を観測
QGPか!?

小さい衝突系のRidge現象

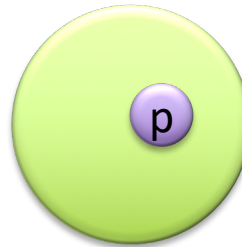
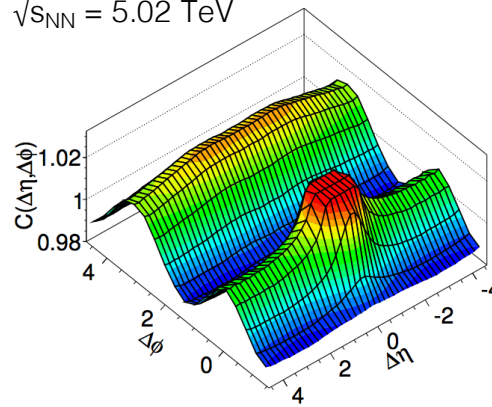
Pb+Pb

$\sqrt{s_{NN}} = 5.02 \text{ TeV}$



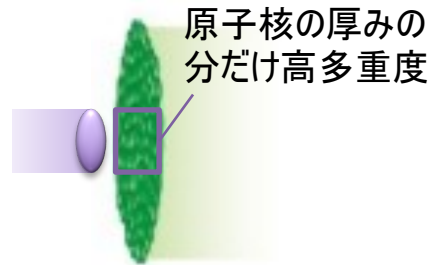
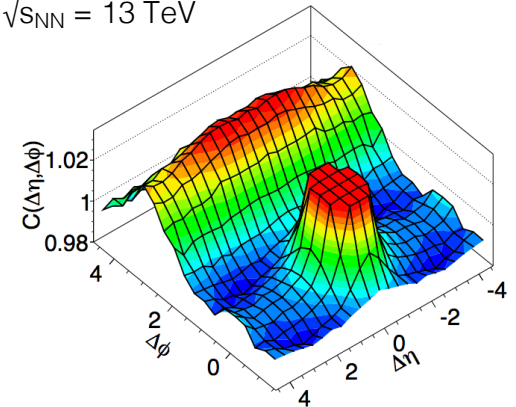
p+Pb

$\sqrt{s_{NN}} = 5.02 \text{ TeV}$

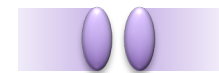


p+p

$\sqrt{s_{NN}} = 13 \text{ TeV}$

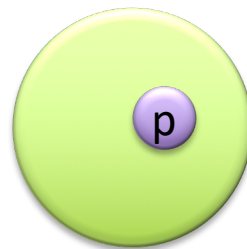
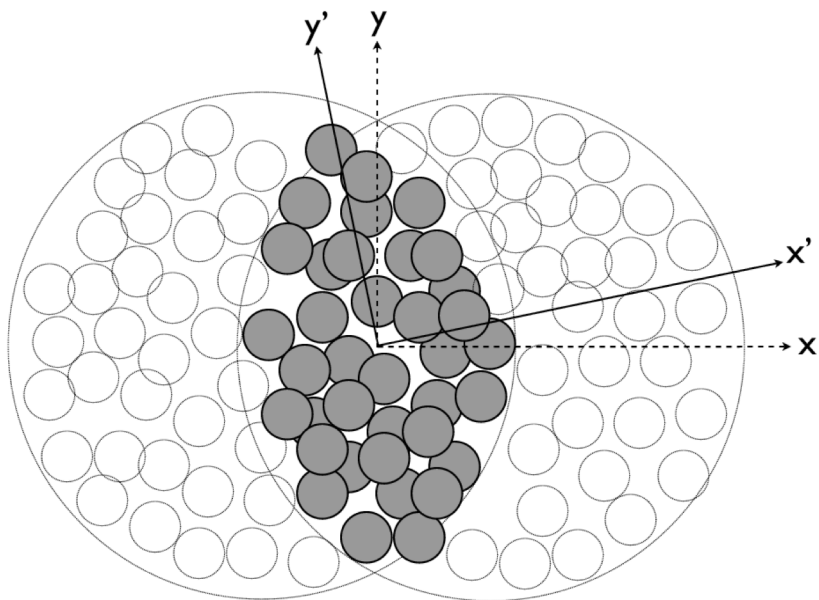


原子核の厚みの分だけ高多重度



p+p, p+PbでPb+Pbと似たリッジを観測

小さい衝突系の楕円フロー

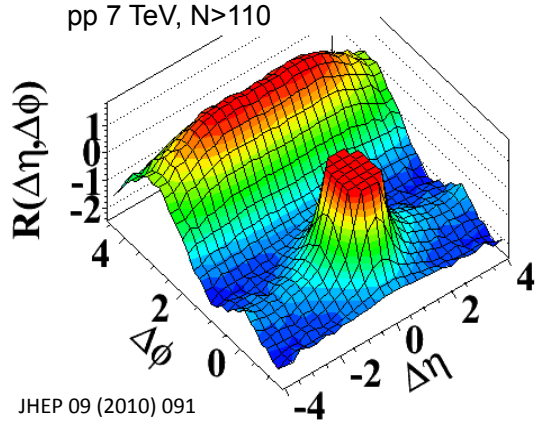


丸い陽子で楕円型？

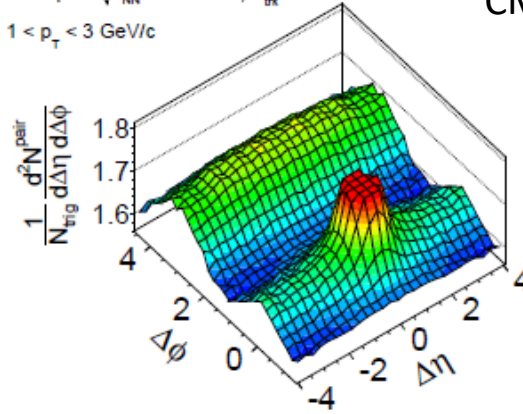


小さい衝突系実験

陽子+陽子



CMS pPb $\sqrt{s_{NN}} = 5.02$ TeV, $N_{tr}^{ch} \geq 110$
 $1 < p_T < 3$ GeV/c



LHC

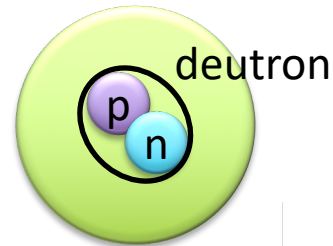
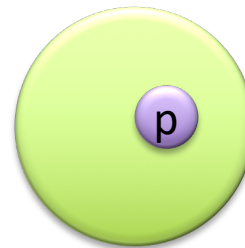
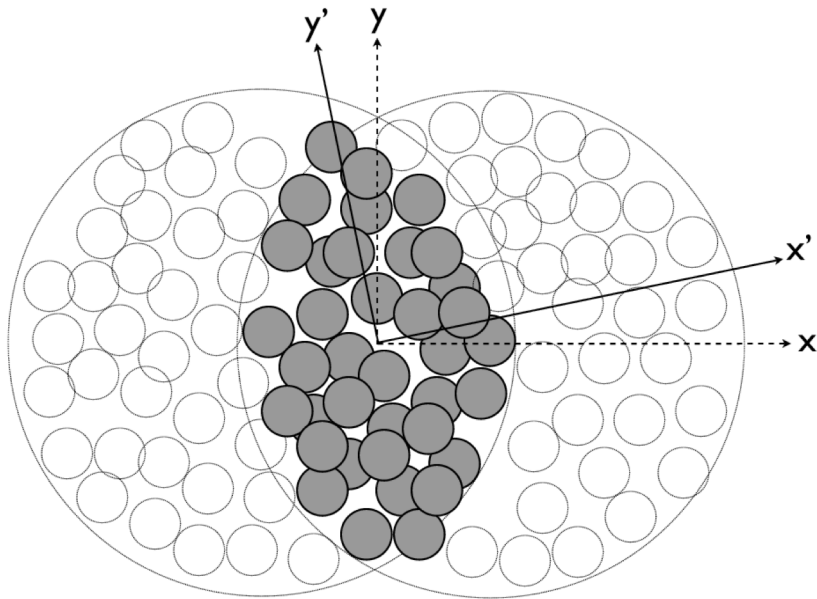
RHIC

$\sqrt{s_{NN}}$ [GeV]	U+U	Au+Au	Cu+Au	Cu+Cu	$^3\text{He}+\text{Au}$	d+Au	p+Au	p+p
510					Nature Physics 15, 214-220 (2019)			✓
200	✓	✓	✓	✓	✓	✓	✓	✓
62.4		✓		✓		✓		✓
39		✓				✓		
19.6		✓		✓		✓		

PRL 120, 062302 (2018)
 PRC 96, 064905 (2017)

p+Au, Al(2015) d+Au(2008) $^3\text{He}+\text{Au}$ (2014)

小さい衝突系の楕円フロー

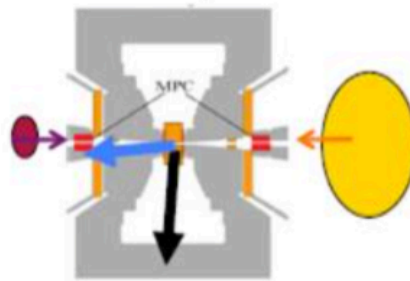
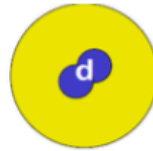
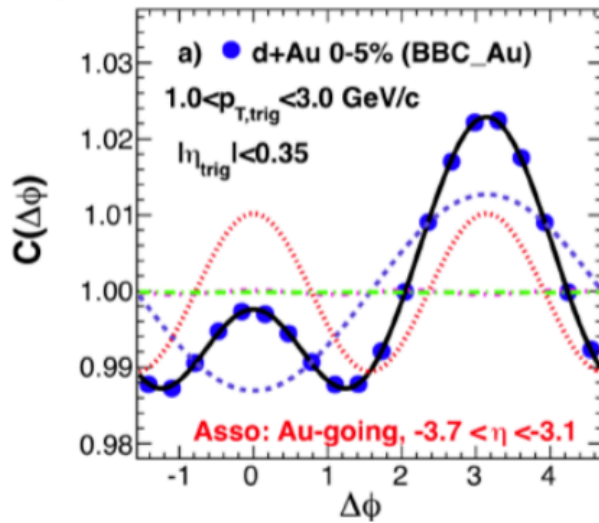


初期状態にv2型を
持っているはず...

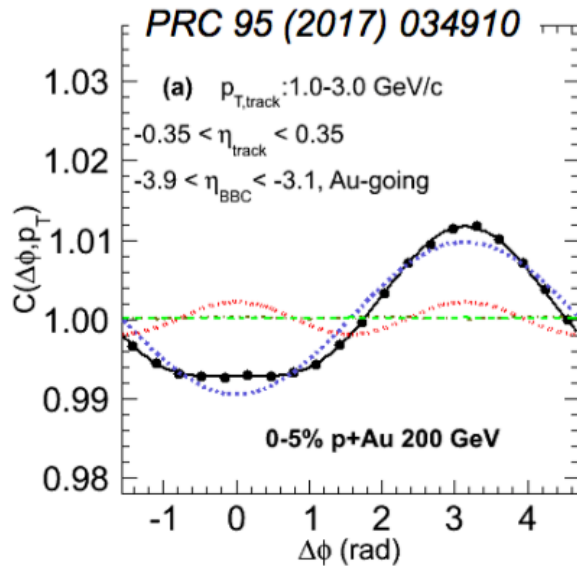
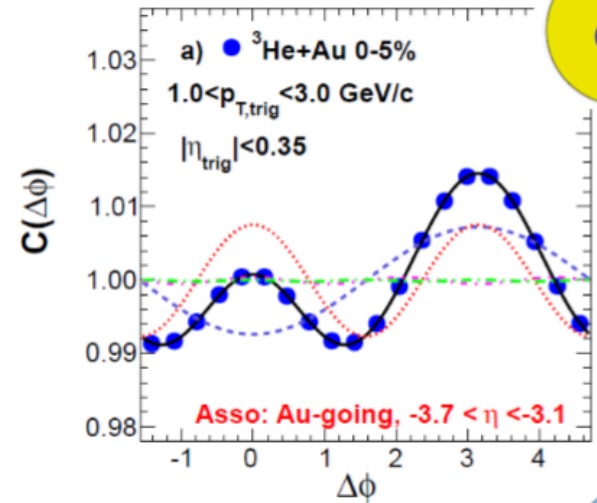


2粒子相関(PHENIX)

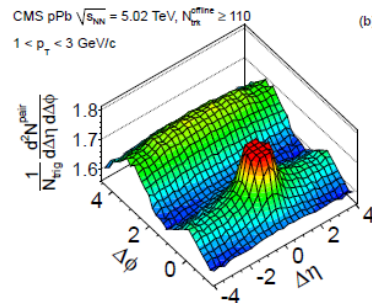
Phys. Rev. Lett. 114, 192301, 2015



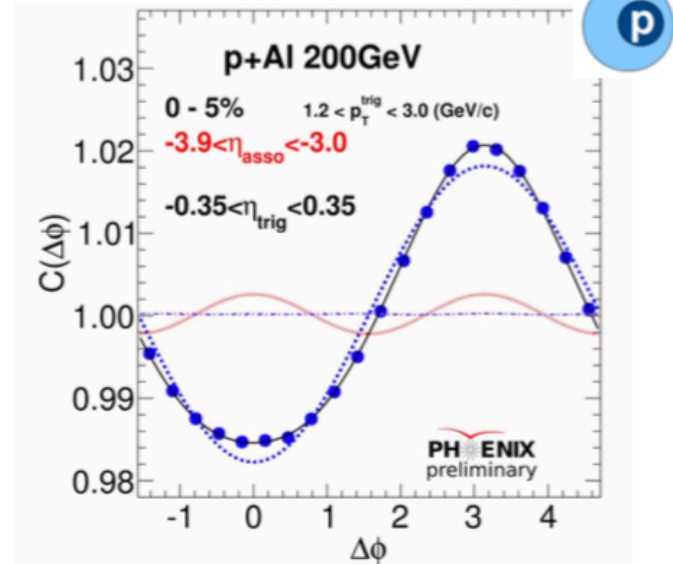
Phys. Rev. Lett. 115, 142301, 2015



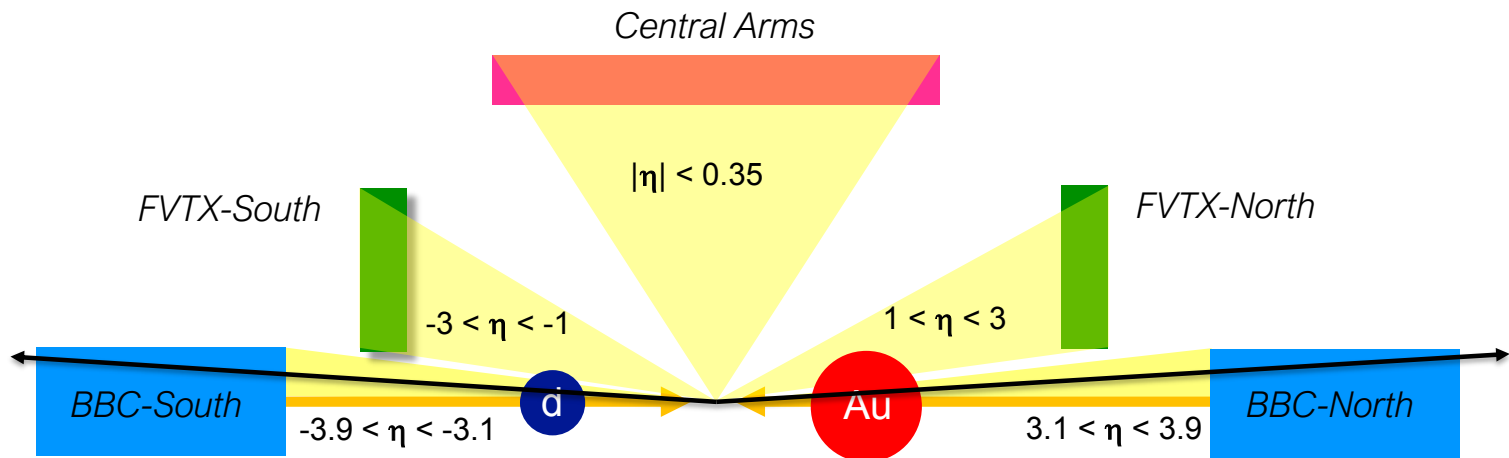
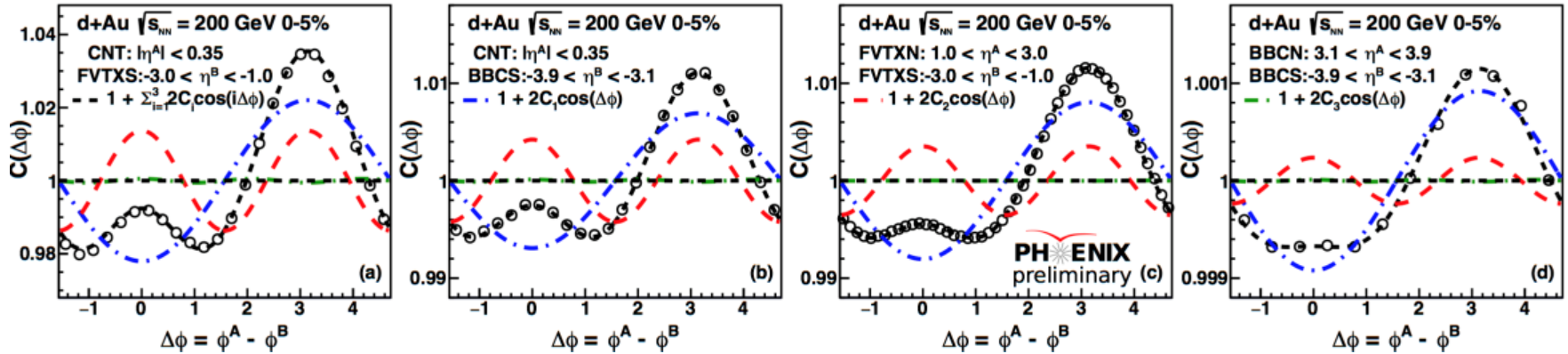
$|\Delta\eta| > 2.75$



(b)



ラピディティギャップ依存性

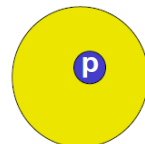
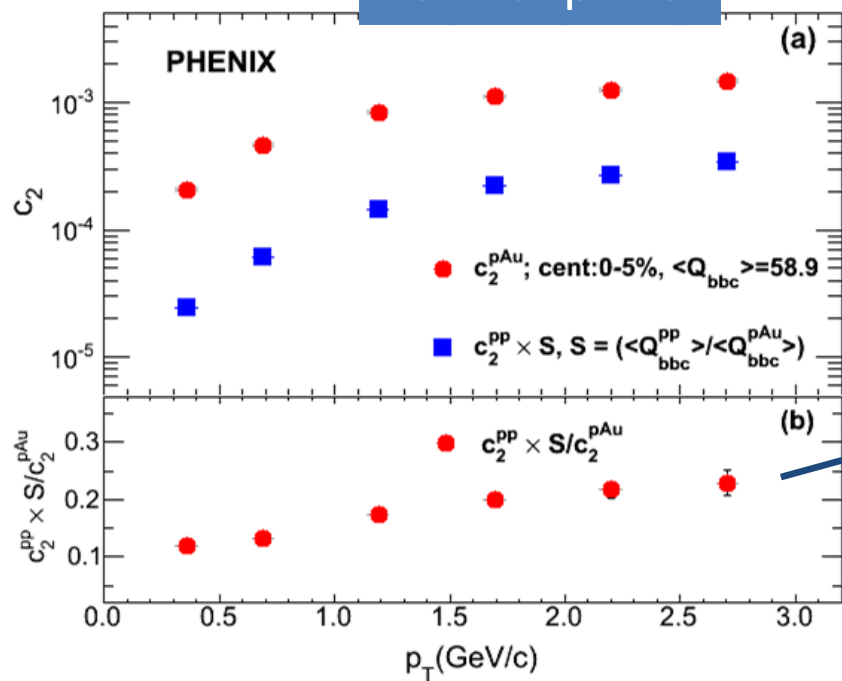


A clear ridge is seen with all detector combinations, even for $\Delta\eta > 6.2$

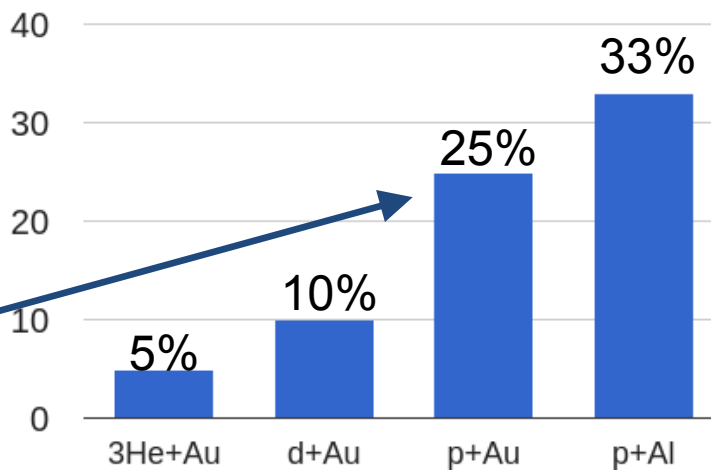
非フロー成分の見積もり

PRC 95 (2017) 034910

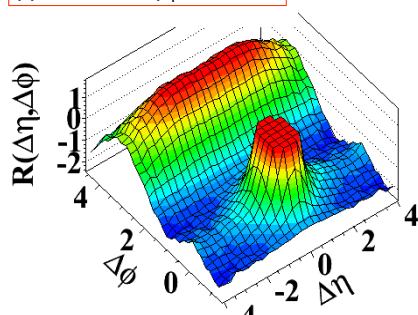
Central p+Au



Non flow at high pT

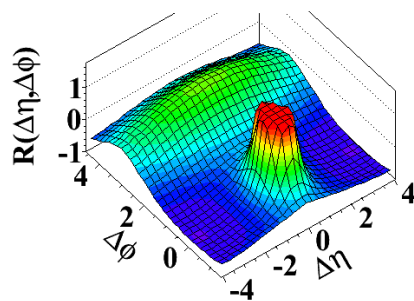


pp $\langle N \rangle > 110$, $1 < p_T < 3$ GeV/c

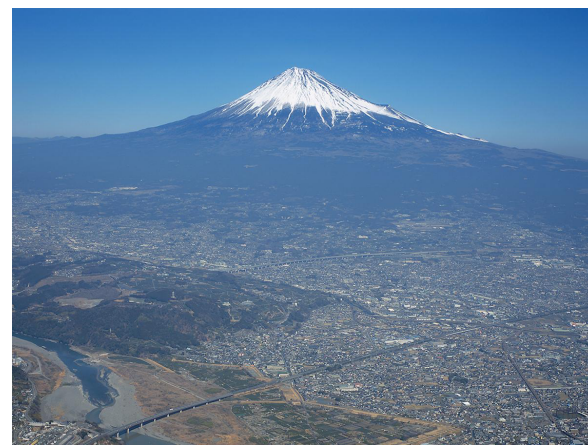


ジェット+フロー

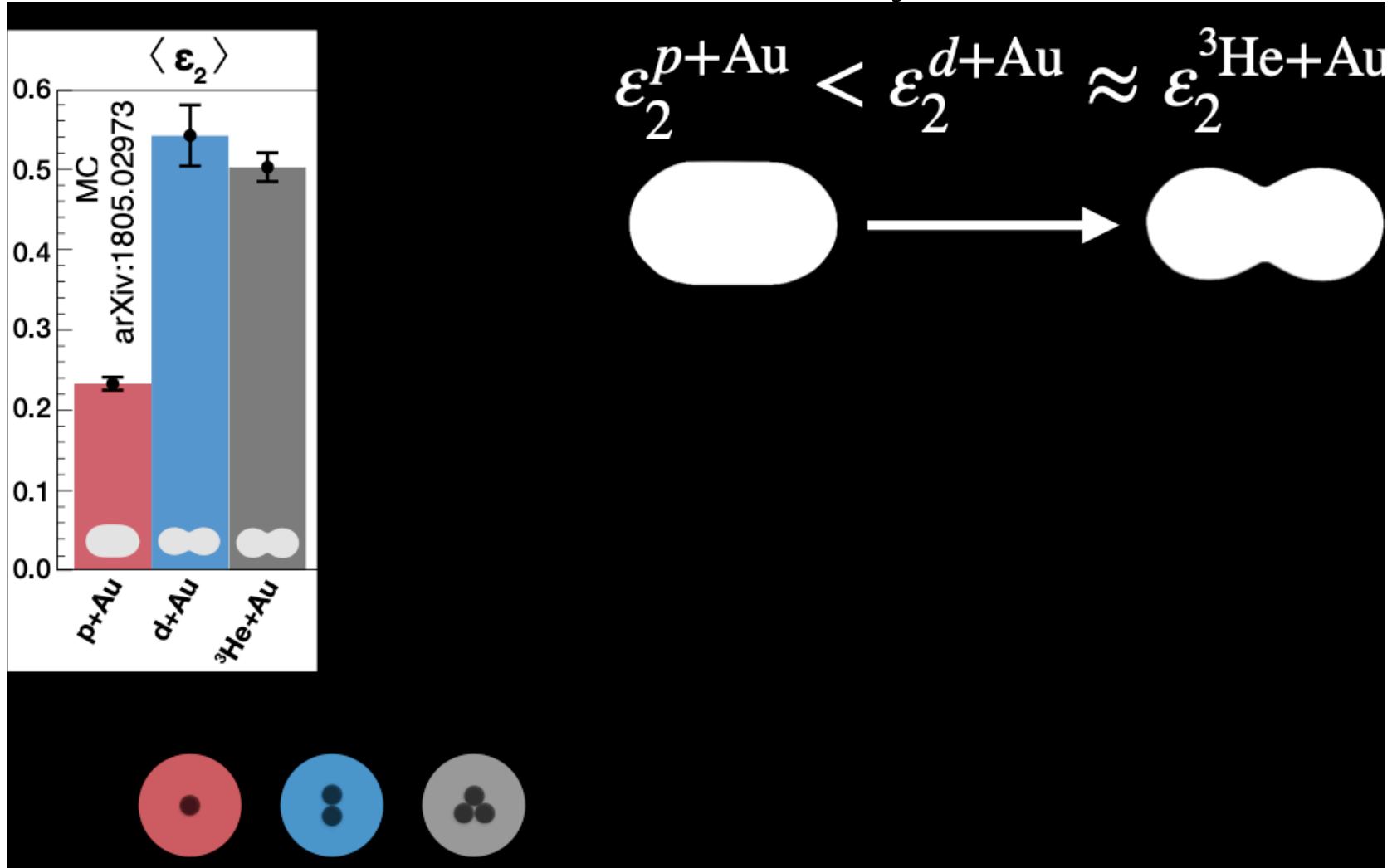
pp $\langle N \rangle \sim 15$, $1 < p_T < 3$ GeV/c



ジェット

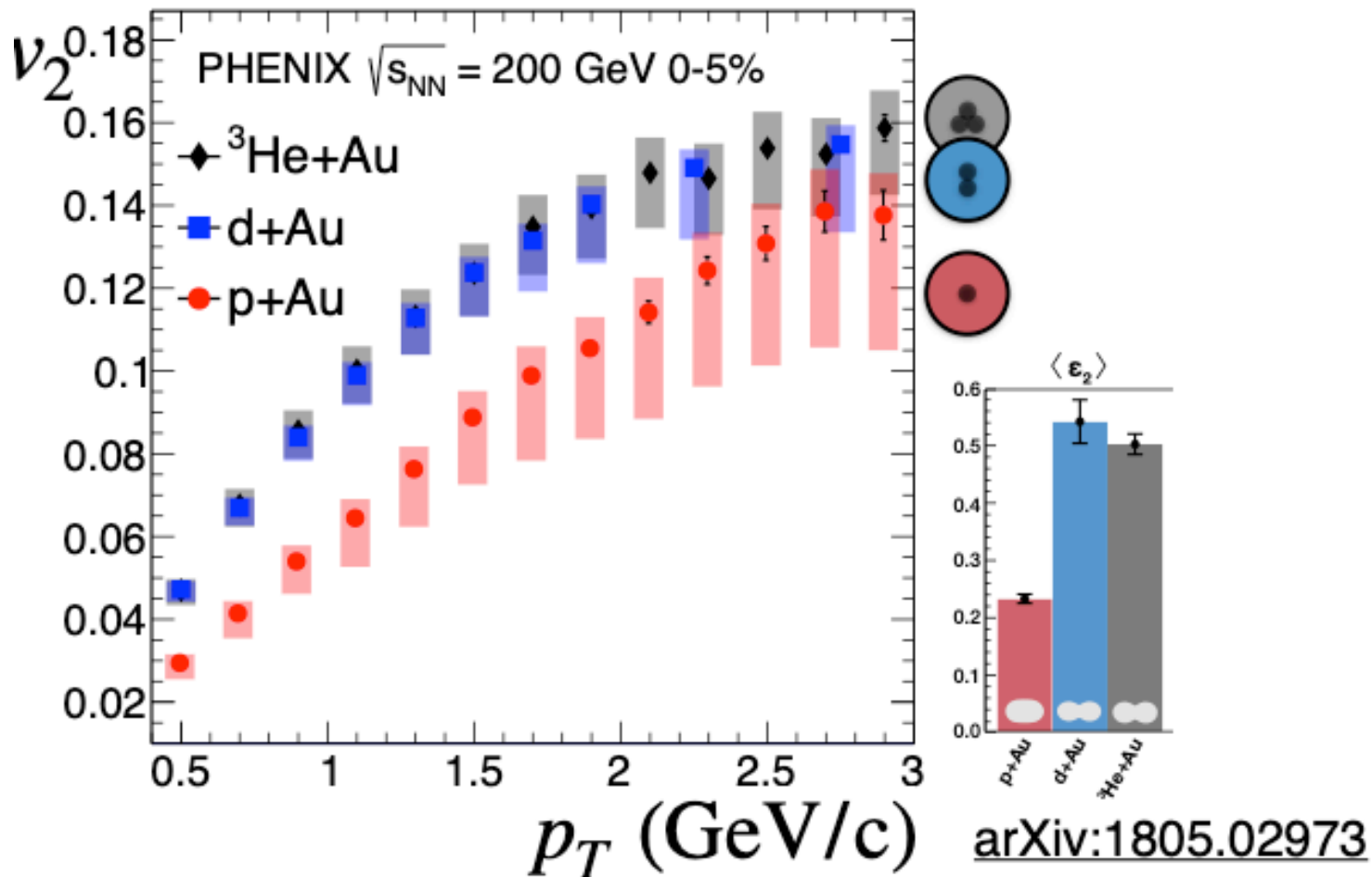


Eccentricity

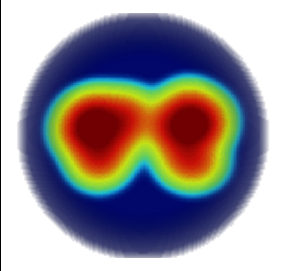
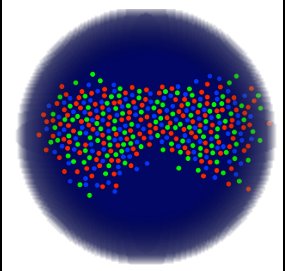


小さい衝突系の v_2 結果

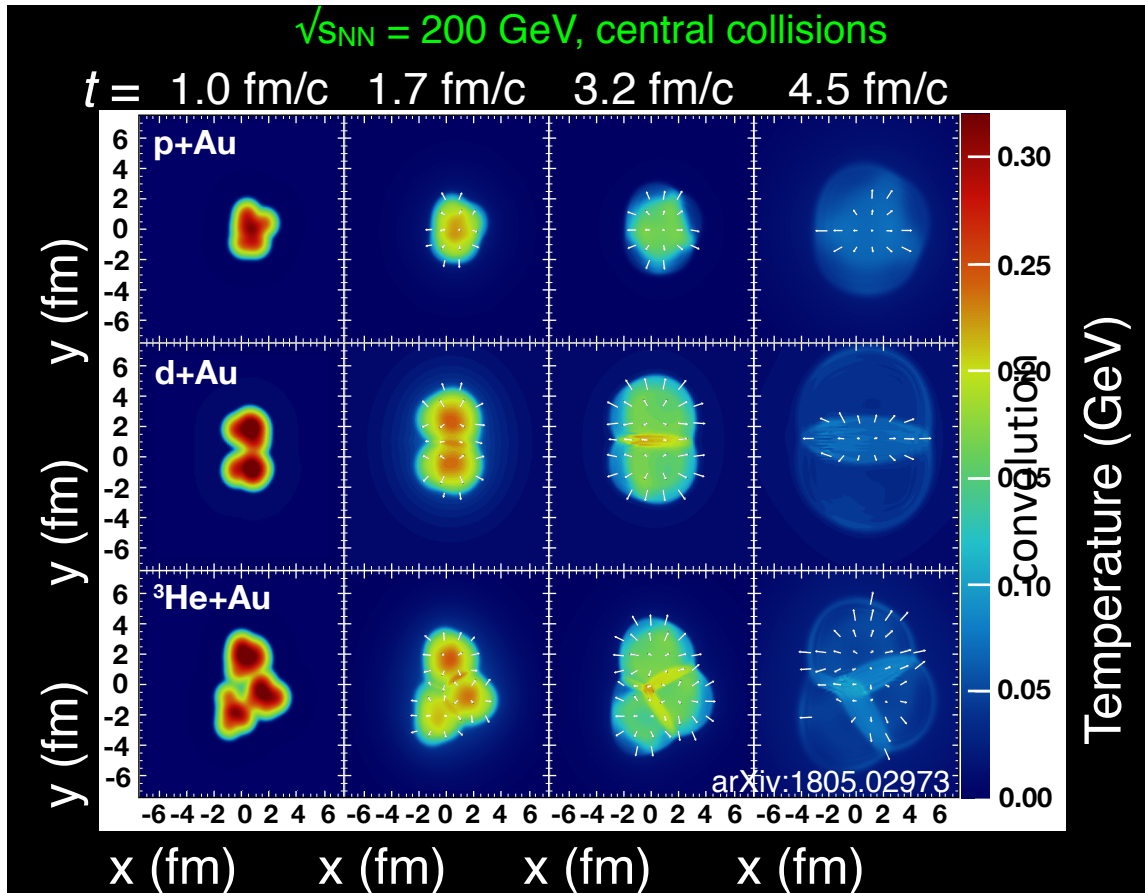
$$v_2^{p+Au} < v_2^{d+Au} \approx v_2^{^3\text{He}+Au}$$



モデル計算

	<u>Hydrodynamic</u>	<u>Parton transport</u>	
	SONIC	AMPT	
Initial conditions	MC Glauber	MC Glauber HIJING	
Particle production	N/A	String melting	
Expansion	Viscous hydrodynamics	Parton scattering	
Hadronization	Cooper-Frye	Spatial coalescence/quark recombination	
Final stage	Hadron cascade	Hadron cascade	
Macroscopic			Microscopic

流体の時間発展モデル



初期状態効果

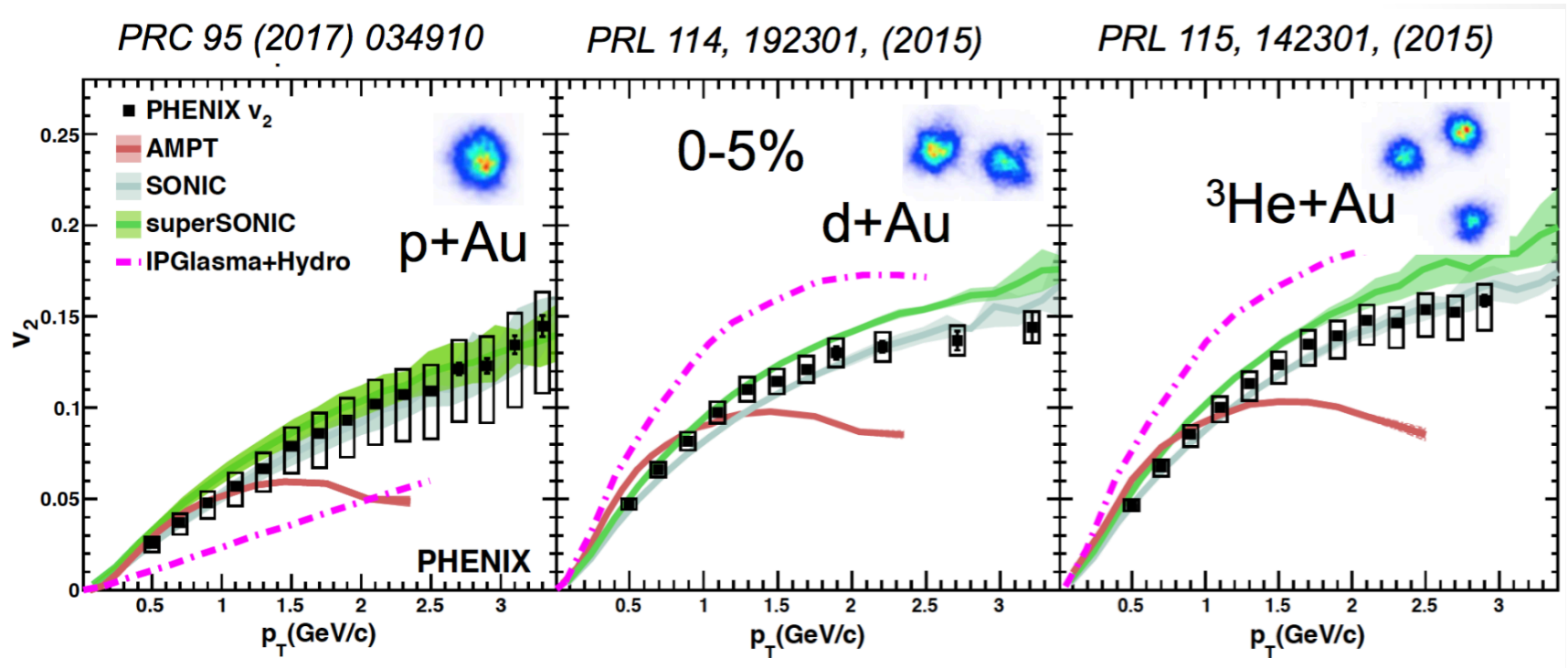
- 初期状態のゆらぎ
- 基底状態の波動関数
- カラーグラス凝縮(CGC)



終状態効果

- 流体力学
- 粘性

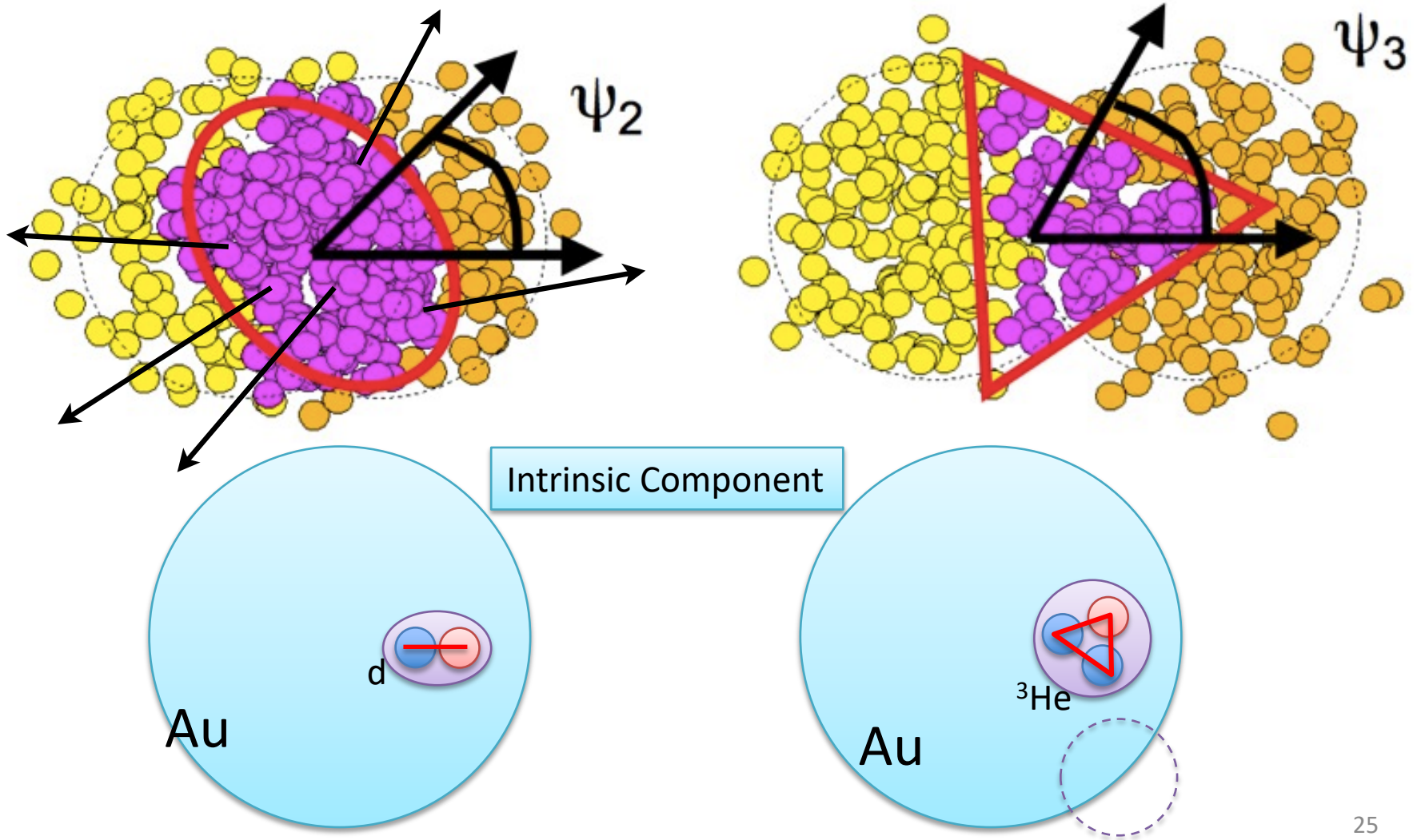
流体モデルとの比較



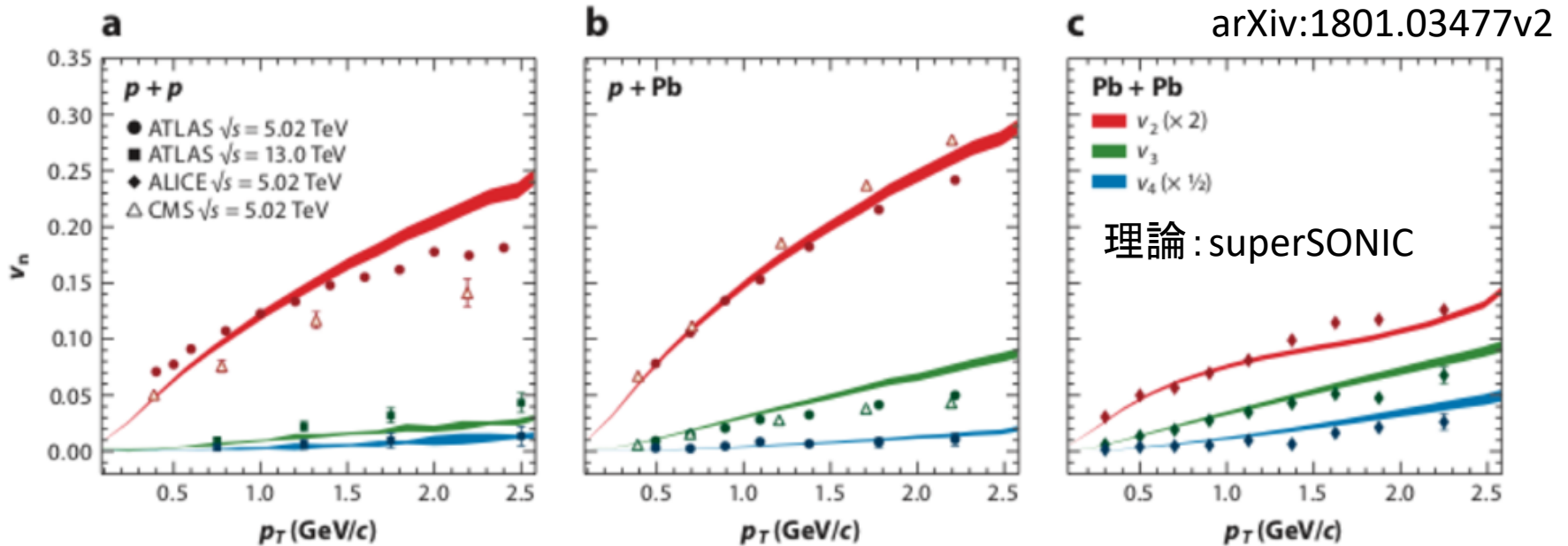
- 3つの衝突系とも流体モデルでよく記述される。
- AMPTは1GeV以下まで記述。

高次の異方性

原子核中核子の初期揺らぎ

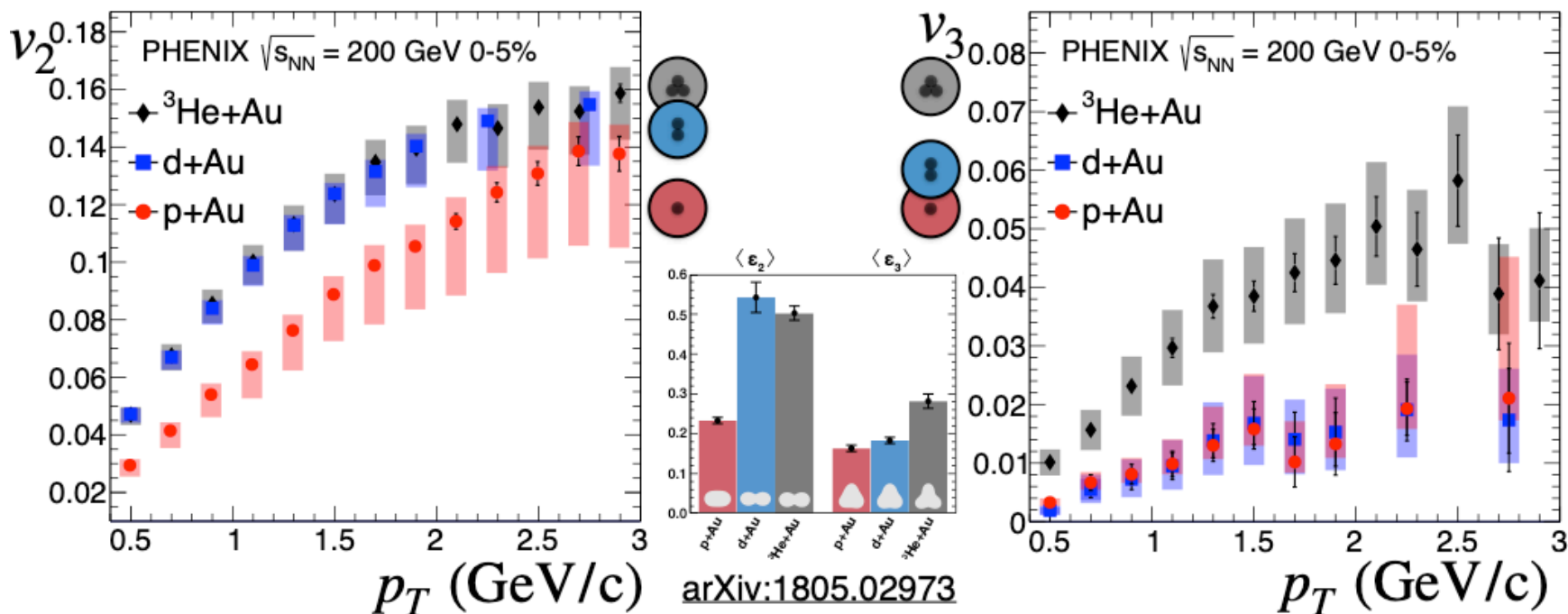


LHCの高次異方性



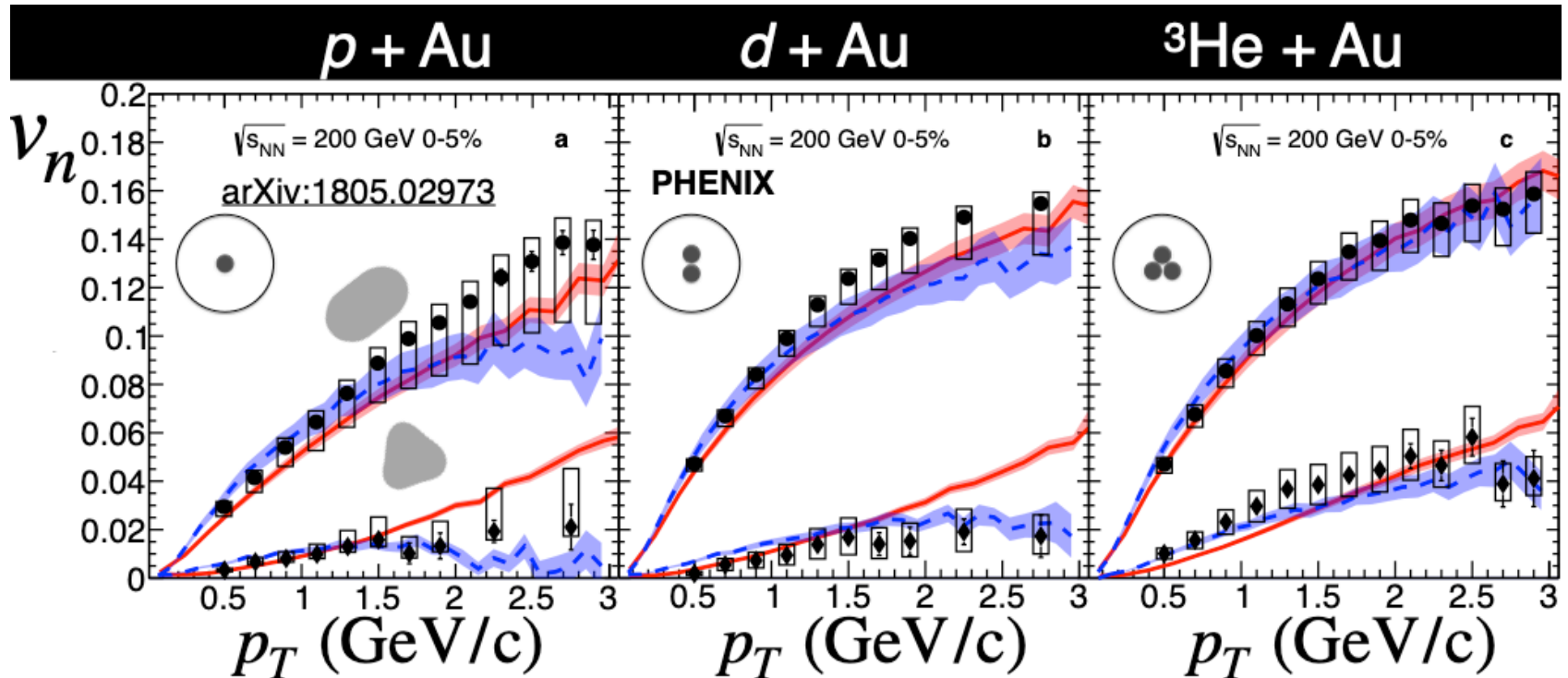
- 小さい衝突系でも高次の異方性が観測される
- 高次の異方性も初期状態のゆらぎを考慮した流体計算でよく再現される。

RHICの高次の異方性



$$v_2^{p+Au} < v_2^{d+Au} \approx v_2^{^3\text{He+Au}} \quad v_3^{p+Au} \approx v_3^{d+Au} < v_3^{^3\text{He+Au}}$$

流体計算との比較



- Both use $\eta/s=0.08$, MC Glauber initial conditions, 2+1D viscous hydrodynamic evolution
- Different hadronic rescattering packages

● v_2 Data
 ◆ v_3 Data

— v_n SONIC Eur. Phys. J. C 75, 15 (2015)
 - - v_n iEBE-VISHNU PRC 95, 014906 (2017)

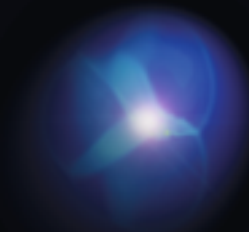
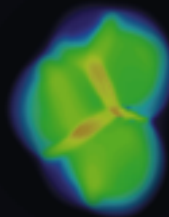
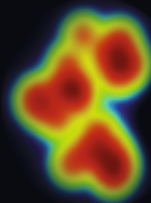
まとめ

- 従来重イオン同士の衝突で観測されたQGPのような現象が陽子＋陽子、陽子＋原子核のような小さい衝突系でも観測された。
- 初期状態効果とフローの効果の流体モデル計算で異方性が説明できるか検証。
- RHICではp+Au, Al, d+Au, 3He+Auと幾何学を変えて、初期状態の記述を検証。
- これまでのところ、流体モデルでよく合っているようだ。
- 核内グルーオン分布やCGCなどの効果も検証されている。

nature physics

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The geometry of a
quark-gluon plasma



BLACK HOLES
Analogue horizons

TOPOLOGICAL INSULATORS
A local marker

AMORPHOUS SUPERCONDUCTIVITY
Energy of preformed pairs

BACKUP

Long Range Two Particle Correlation

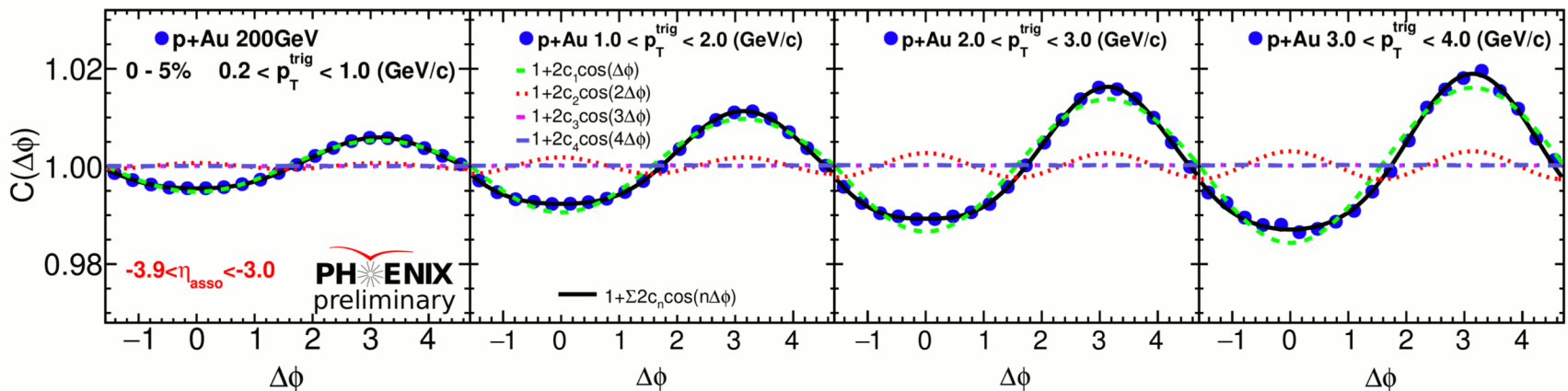
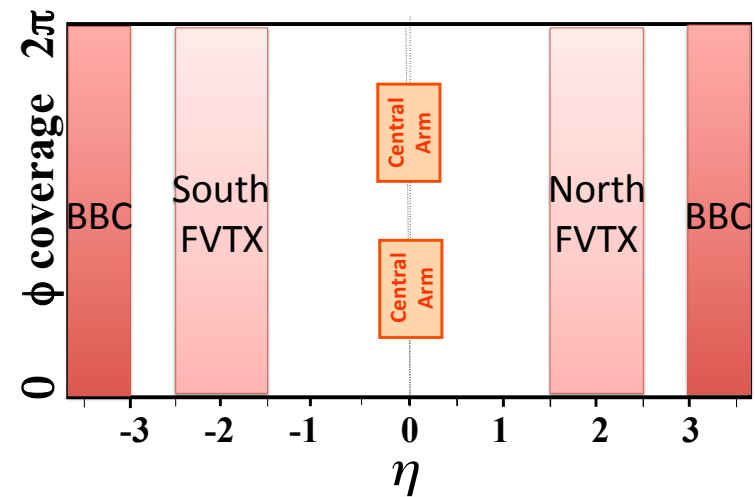
- Two Particle Correlation

$$\Delta\varphi = \varphi_{track} - \varphi_{BBC}$$

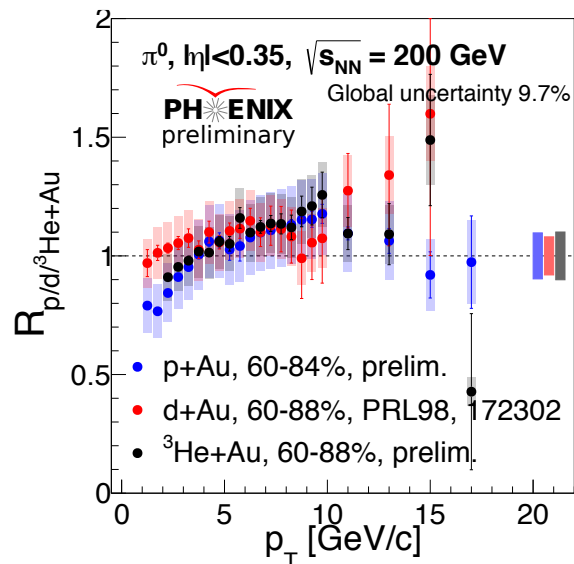
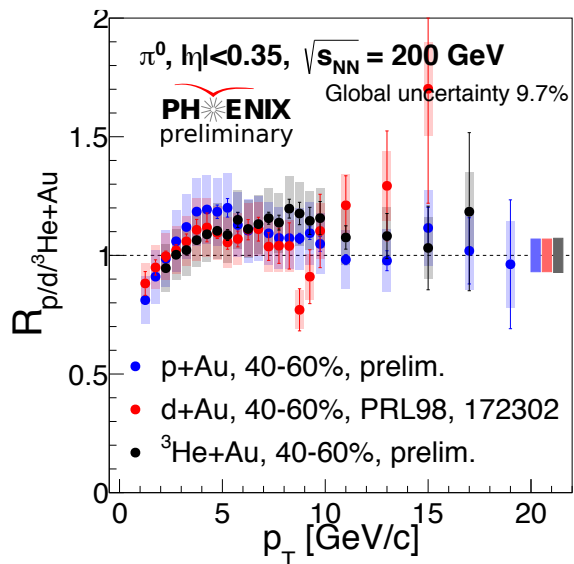
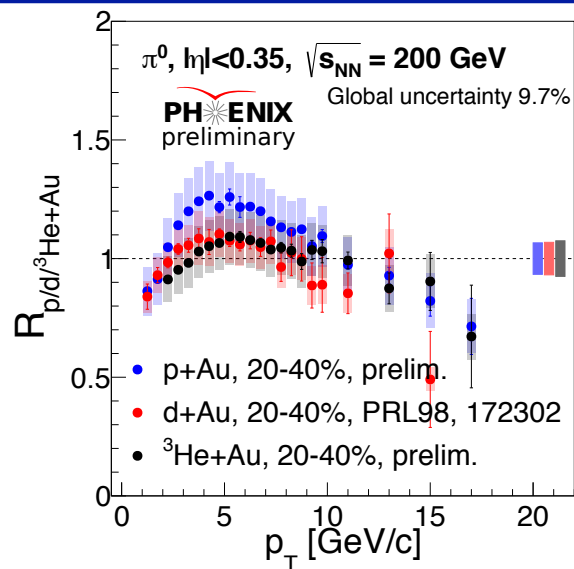
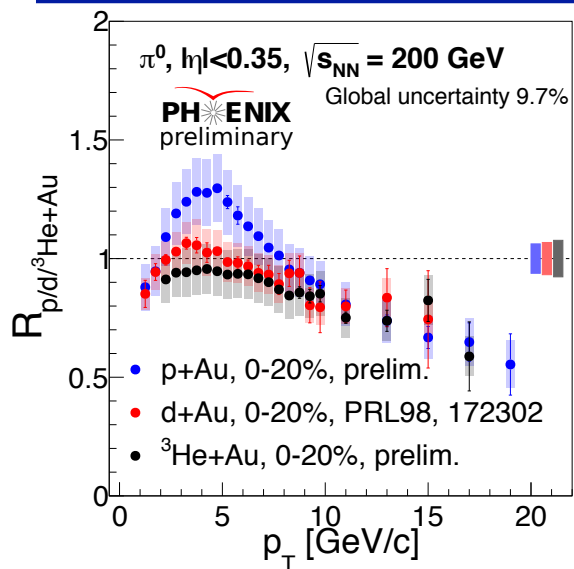
$$S(\Delta\varphi, p_T) = \frac{d(w_{PMT} N_{same\ event}^{track(p_T)-PMT})}{d\Delta\varphi}$$

- Event Mixing

$$C(\Delta\varphi, p_T) = \frac{S(\Delta\varphi, p_T)}{M(\Delta\varphi, p_T)} \frac{\int M(\Delta\varphi', p_T) d\Delta\varphi'}{\int S(\Delta\varphi', p_T) d\Delta\varphi'}$$



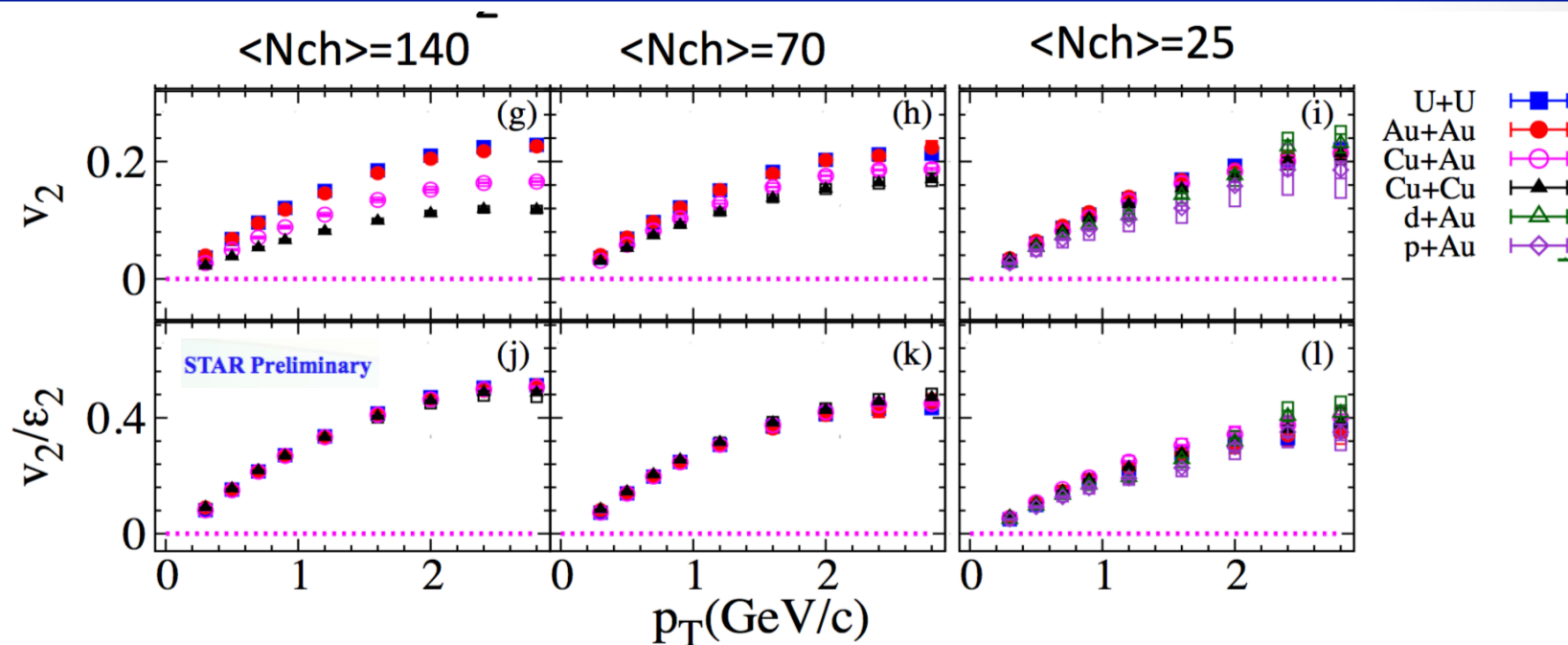
$R_{p/d/^3\text{He+Au}}$ – centralities



Nuclear modification in centralities:

- Centrality determined similarly as for large systems (PRC90,034902)
- **p+Au results show large centrality dependence**
- **d+Au results agree with p+Au at high- p_T**
- $^3\text{He+Au}$ results agree with p+Au and d+Au at high- p_T
- **At moderate p_T an ordering is seen in most central collisions**

v_2 at fixed charged multiplicity



STAR study the correlation for fixed multiplicity rather than centrality:

- v_2 show similar trends for all systems.
- v_2 is system dependent (shape).
- $v_2/\epsilon_2(p_T)$ in all systems scales into single curve – initial geometry matters