

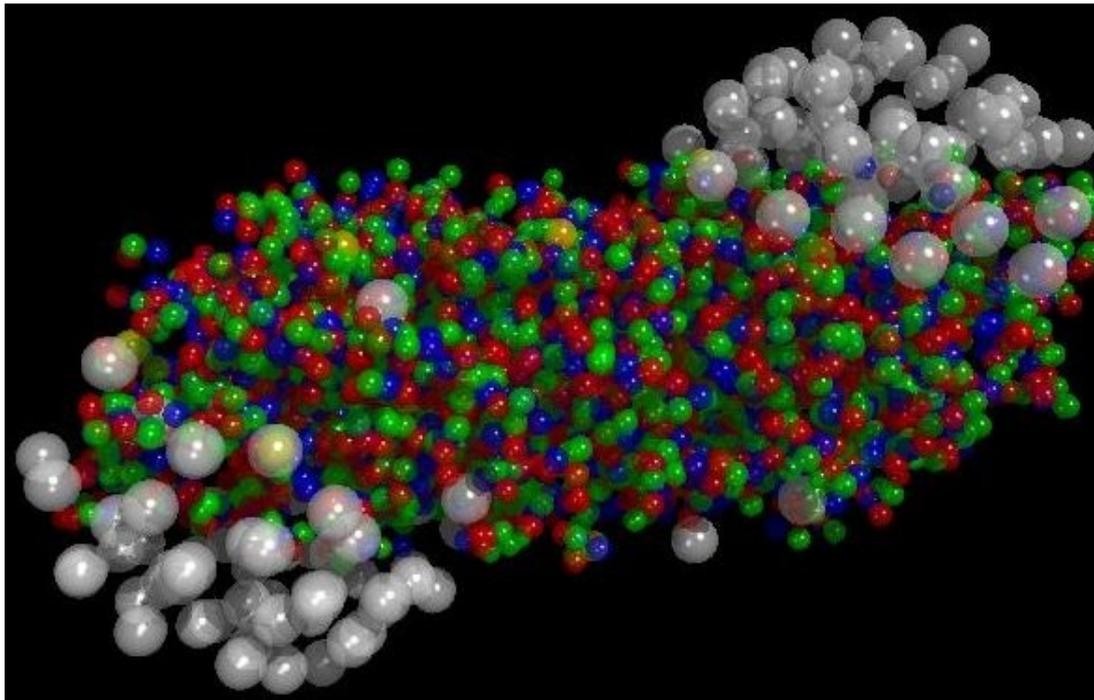
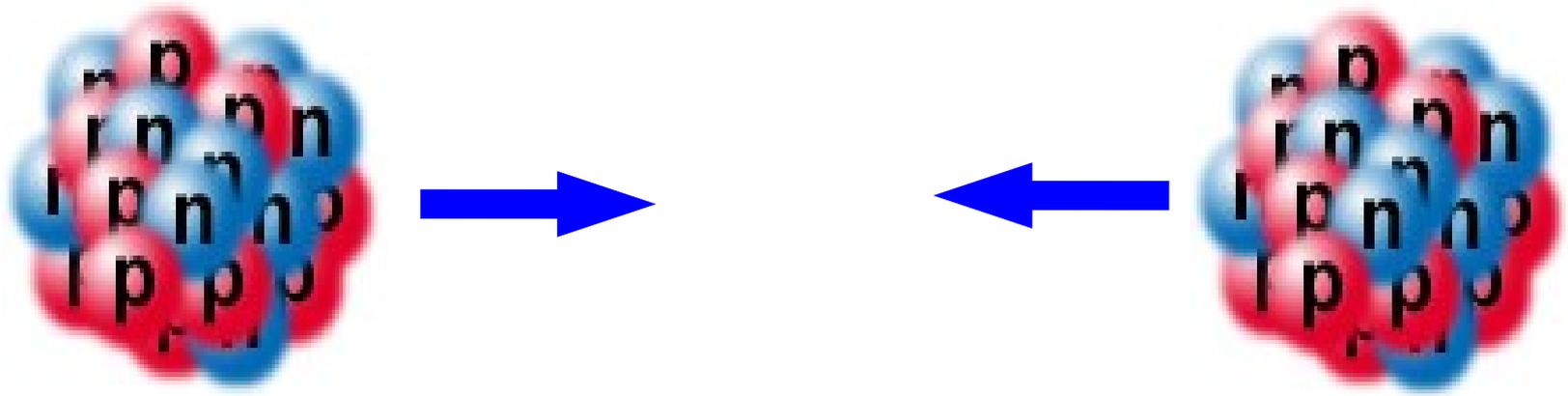
**$pp, pA, AA$  衝突のダイナミクスは  
同時に理解したか？  
**QGP** シミュレーションの理論の現状**

奈良 寧  
国際教養大学

- イントロダクション
- Final state interactions  
(流体 vs パarton・ハドロンカスケード)
- Initial state dynamics (non-QGP)  
(カラーグラス凝縮 vs ストリング相互作用)

# クォーク・グルーオン・プラズマの作り方

Consider a collision of heavy ion such as Gold nucleus Au which has 118 neutrons and 79 protons. Au+Au at RHIC(2000) Pb+Pb at LHC(2011)

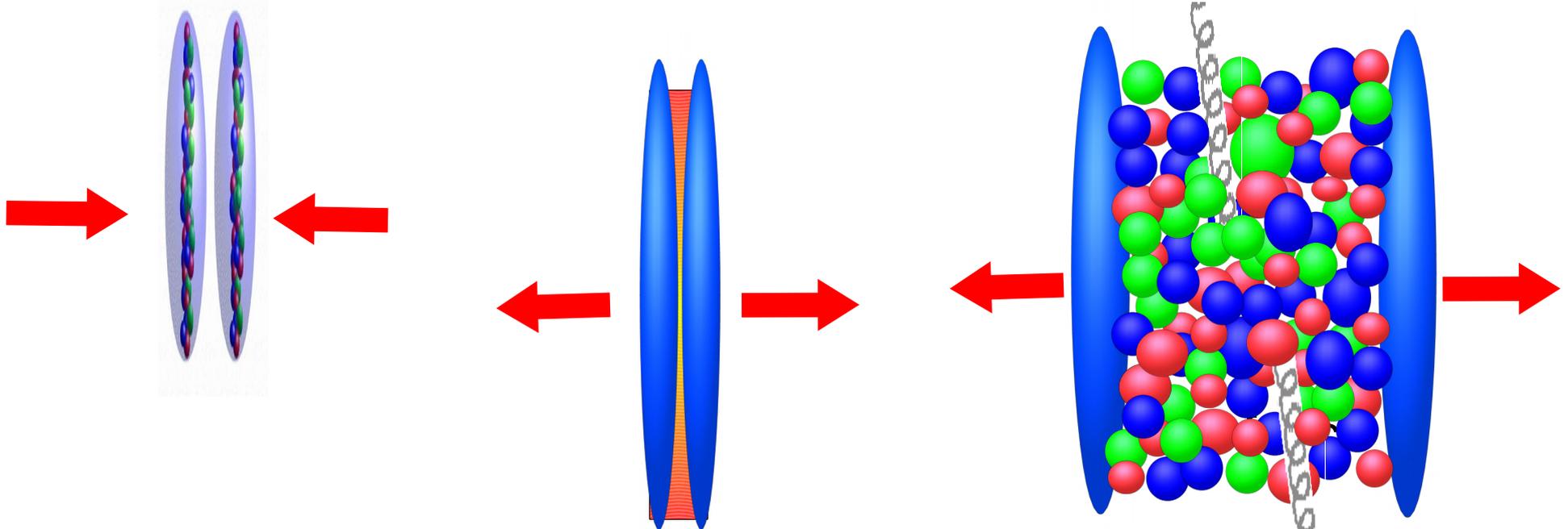


これまでAGS-E802/859実験において28Siまでの軽い原子核ビームを用いて行なってきたが、1992年、BNLのAGS加速器において核子当たり11-12 GeV/cの $^{197}\text{Au}$ 原子核ビームが利用可能となった。AGS-E866実験 志垣氏D論(1995) (世界で初めての重イオン衝突)

CERNでは86年より核子あたり200GeVの硫黄ビーム、94年より核子あたり160GeVの鉛ビームの加速が行われた。

# Separation of Initial and final state interactions at RHIC/LHC

Au + Au collisions



Initial state interaction  
原子核がすり抜ける  
ときにおこる相互作用

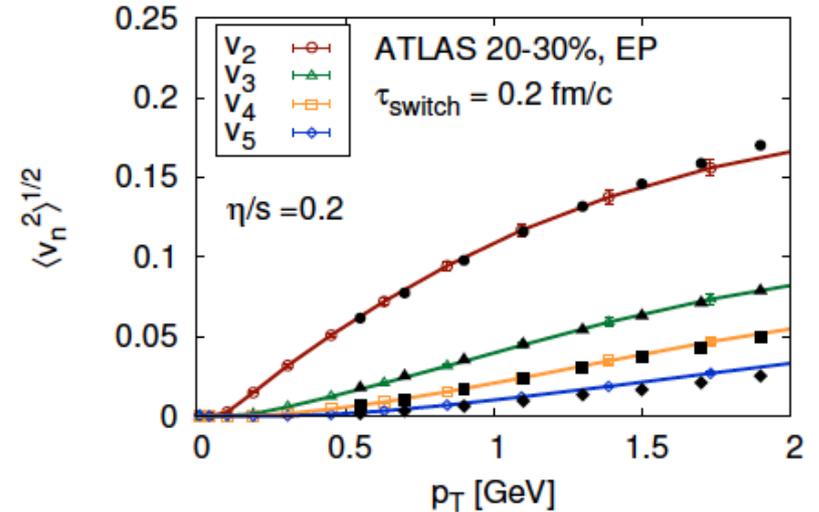
Final state interaction  
among produced particles

# QGP->集団運動の効果

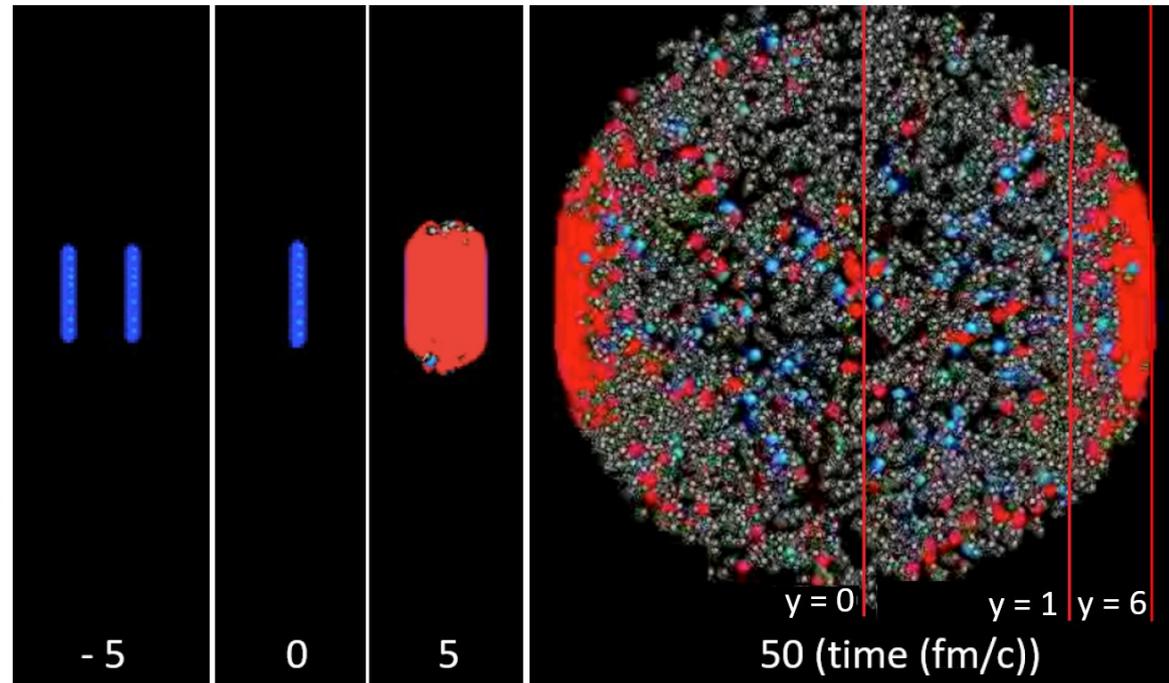
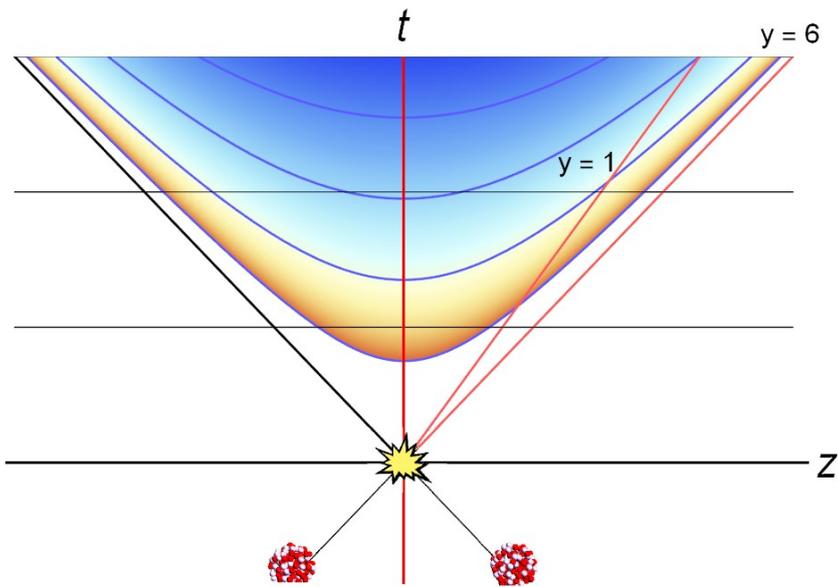
- 集団フロー(collective flow)  
(横運動量分布, 楕円フロー)

$$\frac{dN}{d\phi} \propto 1 + \sum_n 2v_n \cos[n(\phi - \Phi_n)]$$

- ジェットエネルギーロス



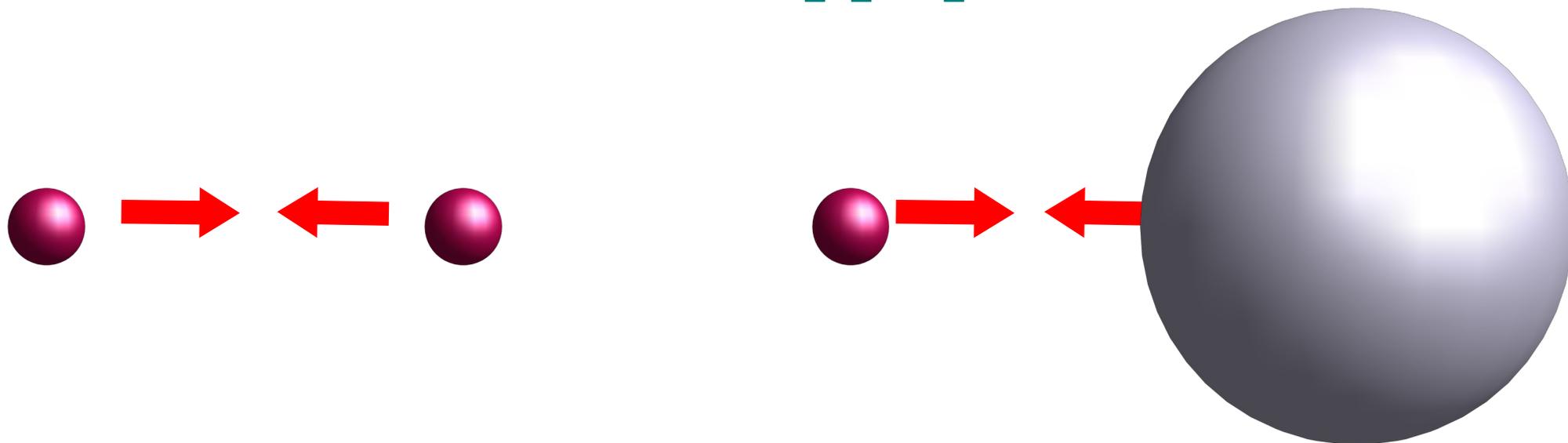
C.Gale, et.al PRL110(2013)012302



Pb+Pb at 2.76 TeV

Ann.Rev.Nucl.Part.Sci. 68 (2018)

## 小さい系 pp, pA



小さい領域で(1fm)、短い時間、粒子の数も少ないので、陽子-陽子,陽子-原子核衝突では、QGPはできないと思われてきた。(pAではジェントクエンチングがない)

ppでも流体が使える可能性の議論はあった。

Landau (1953)

Tevatron E735, MiniMax QGP search in p+p pbar + p collisions

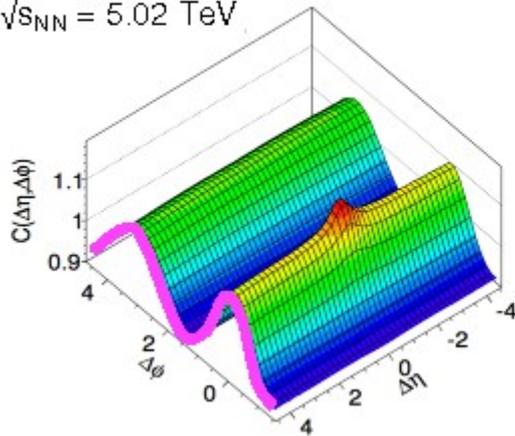
P.Levai and B.Muller, PRL67 (1991)1519

# 小さい系でも集団効果があるような結果がでた

- Long-range rapidity correlations (Ridge)
- Elliptic flow ( $v_2$ ), triangular flow ( $v_3$ )
- Mass ordering:  $\langle p_t \rangle$  and  $v_2$
- Strangeness enhancement

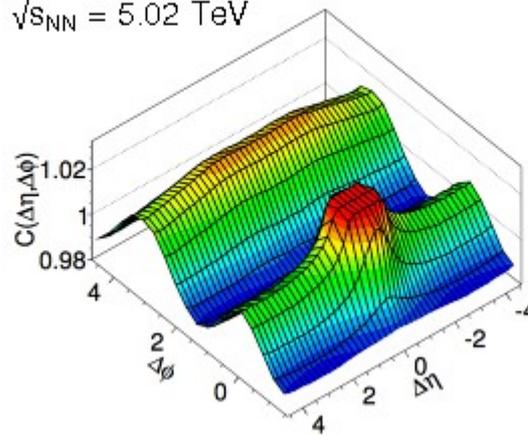
**Pb+Pb**

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



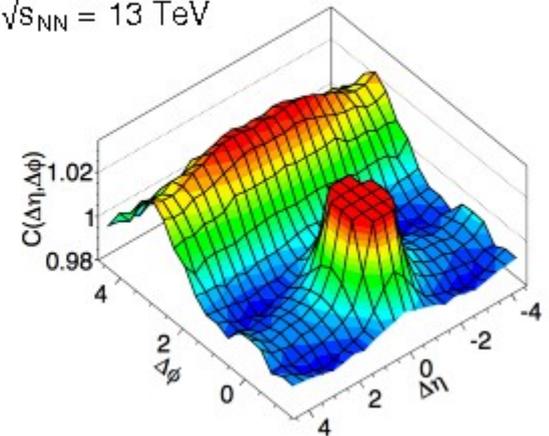
**p+Pb**

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



**p+p**

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



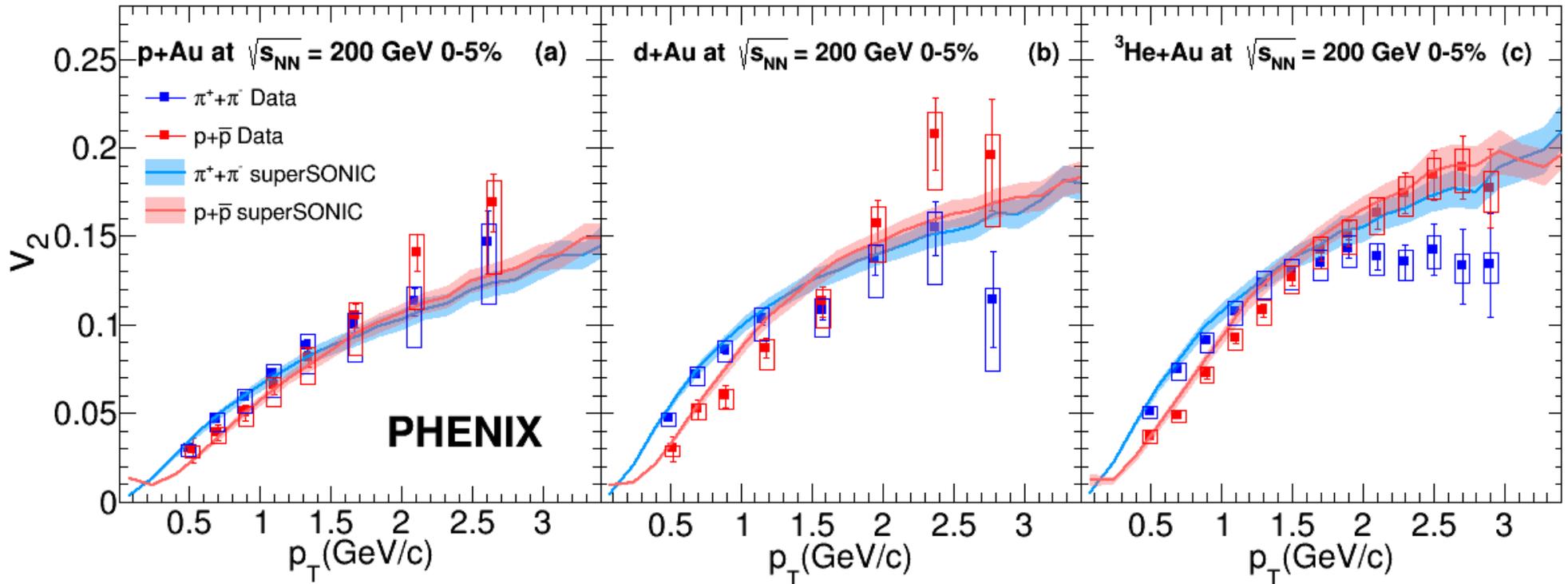
Jet-quenching has not been reported yet in small systems.

# final state effects

- 流体模型
  - superSONIC (Romatschke)
  - iEBE-VISHNU (Ohio)
  - IP-sat. + CYM + MUSIC + UrQMD (Brookhaven)
  - EPOS3 (SUBATECH)
  - MC-Glauber+ hydro (Bozek,Krakow)
  - dynamical initialization (Sophia)
  - TRENTO+Hydro+UrQMD (Nagoya)
- パartonカスケード, ハドロンカスケード
  - AMPT, BAMPS

# V2 at RHIC

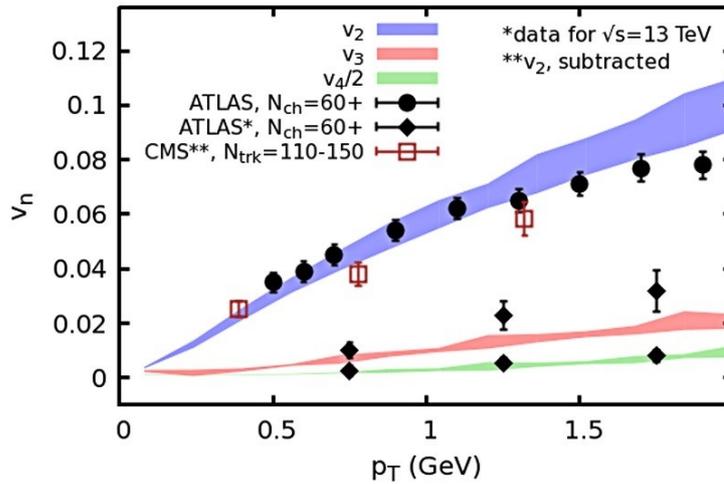
PHENIX Phys.Rev. C97 (2018) 064904



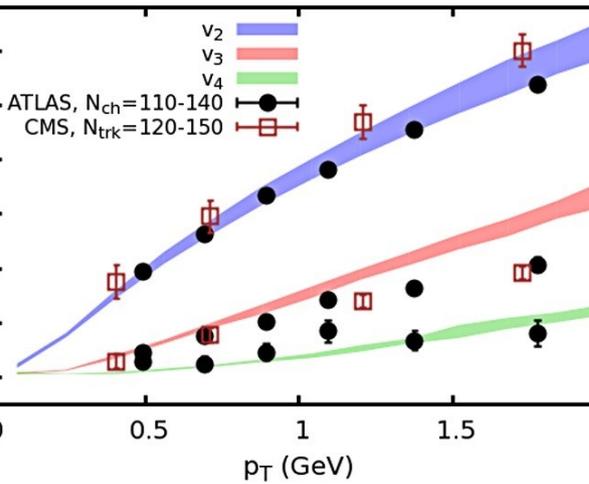
# V2 from superSONIC hydro model at LHC

R.D. Weller and P. Romatschke, Phys.Lett. B774 (2017) 351-356

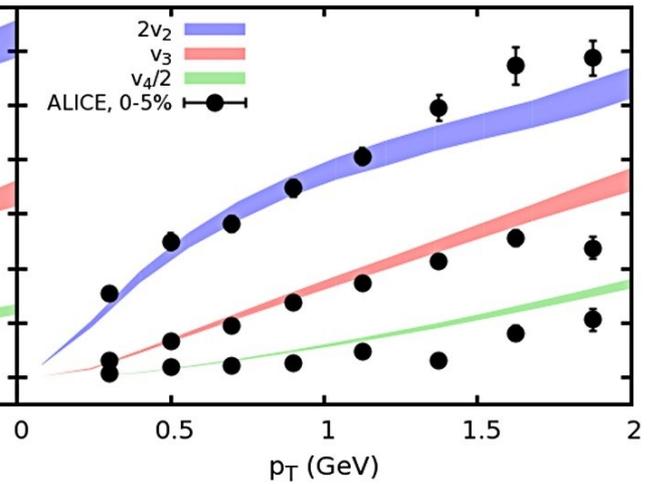
superSONIC for p+p,  $\sqrt{s}=5.02$  TeV, 0-1%



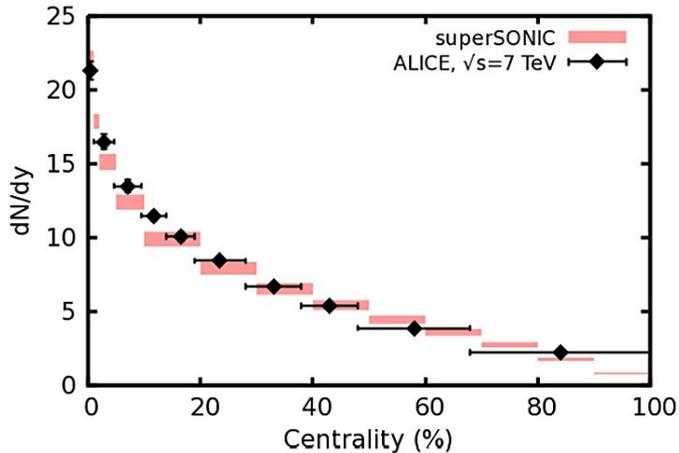
superSONIC for p+Pb,  $\sqrt{s}=5.02$  TeV, 0-5%



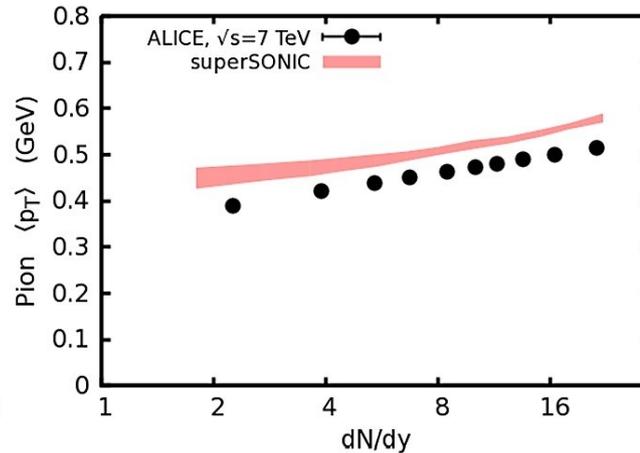
superSONIC for Pb+Pb,  $\sqrt{s}=5.02$  TeV, 0-5%



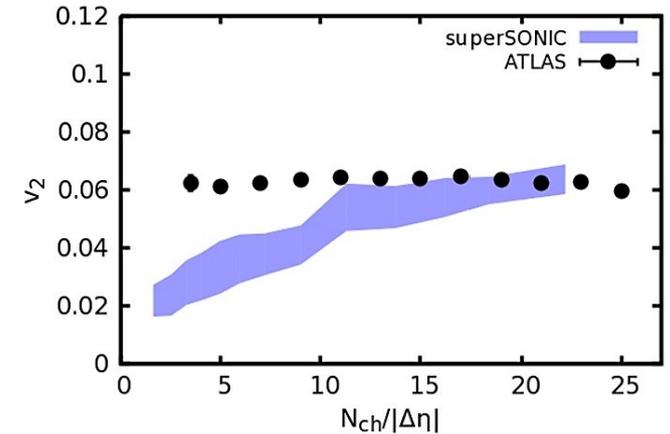
superSONIC for p+p,  $\sqrt{s}=5.02$  TeV



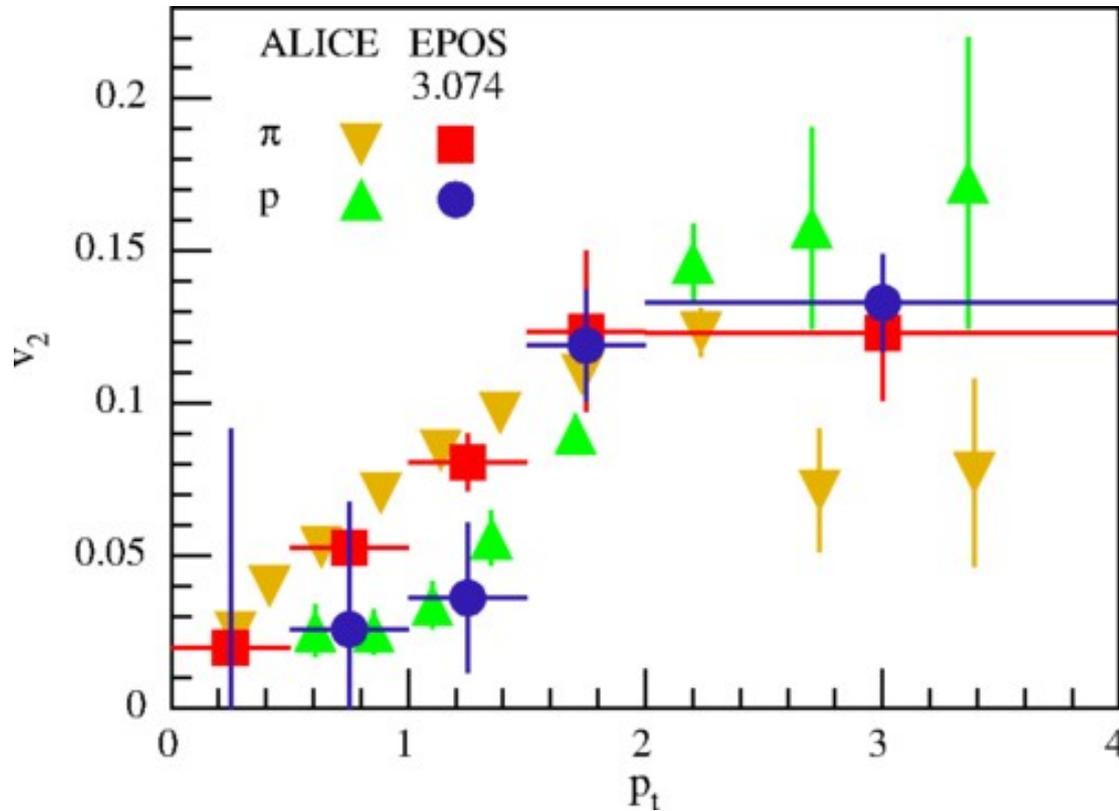
superSONIC for p+p,  $\sqrt{s}=5.02$  TeV



superSONIC for p+p,  $\sqrt{s}=5.02$  TeV

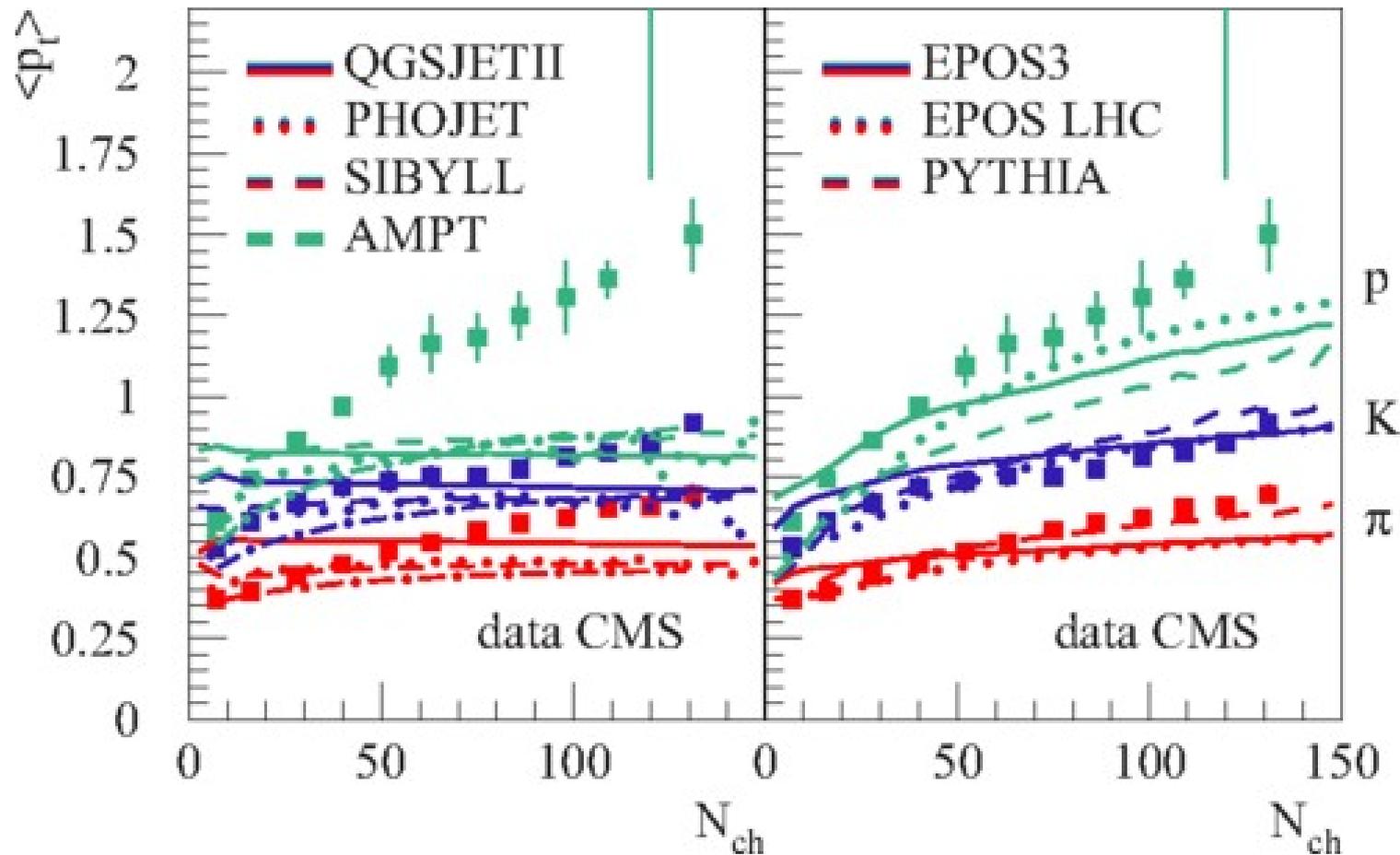


# Elliptic flow from EPOS3 in p-Pb at 5.02TeV

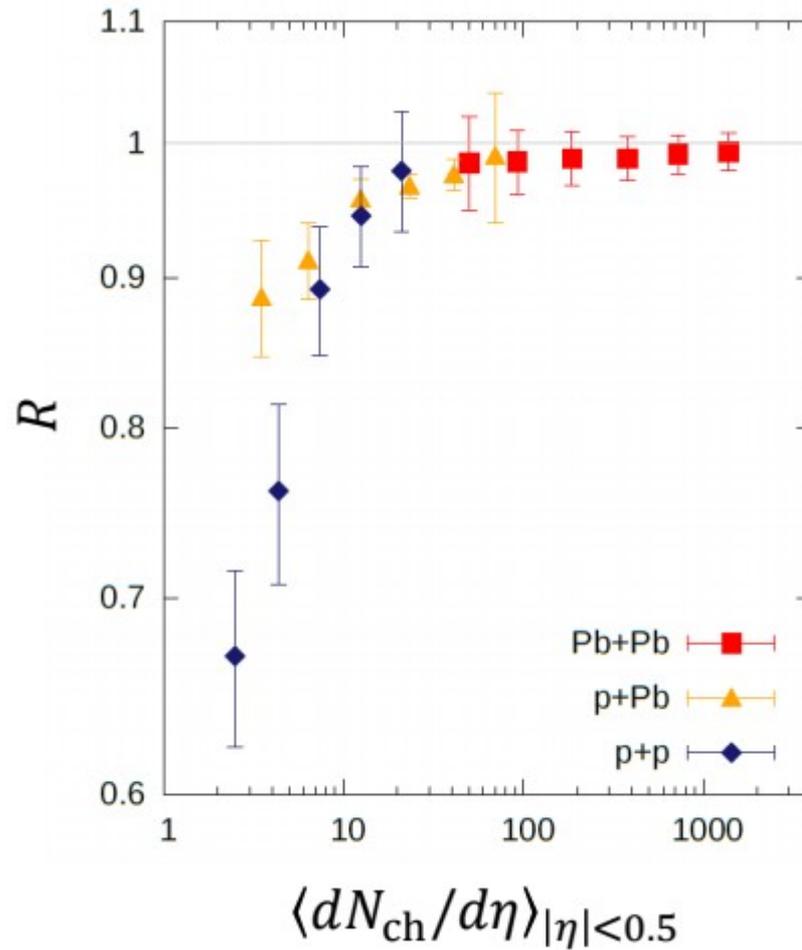
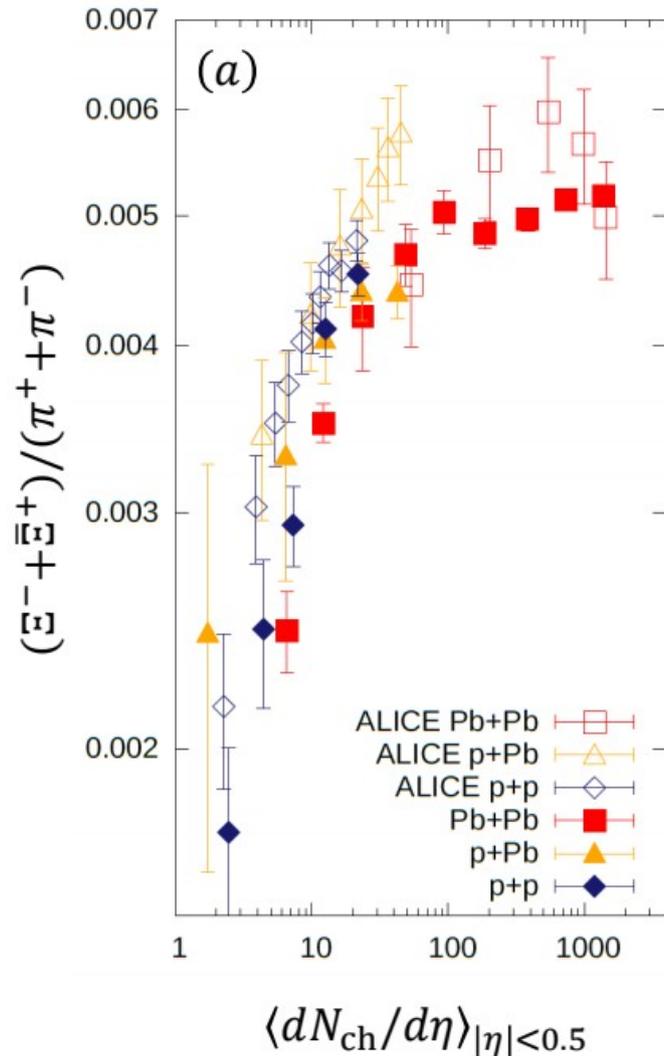


$v_2$ の粒子の質量依存性も  
粘性流体で説明できる。

# Multiplicity dependence of $\langle p_t \rangle$ in pp collisions at 7 TeV



# Enhancement of multi-strange from Pythia8+hydro

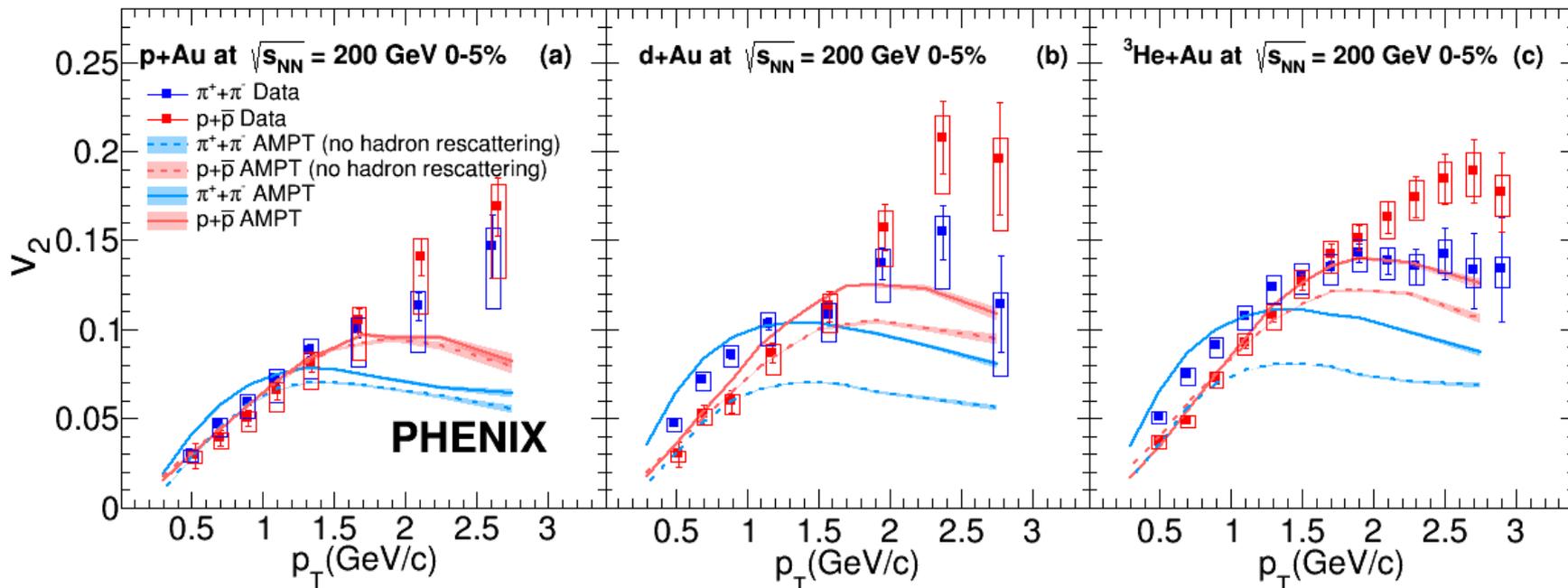
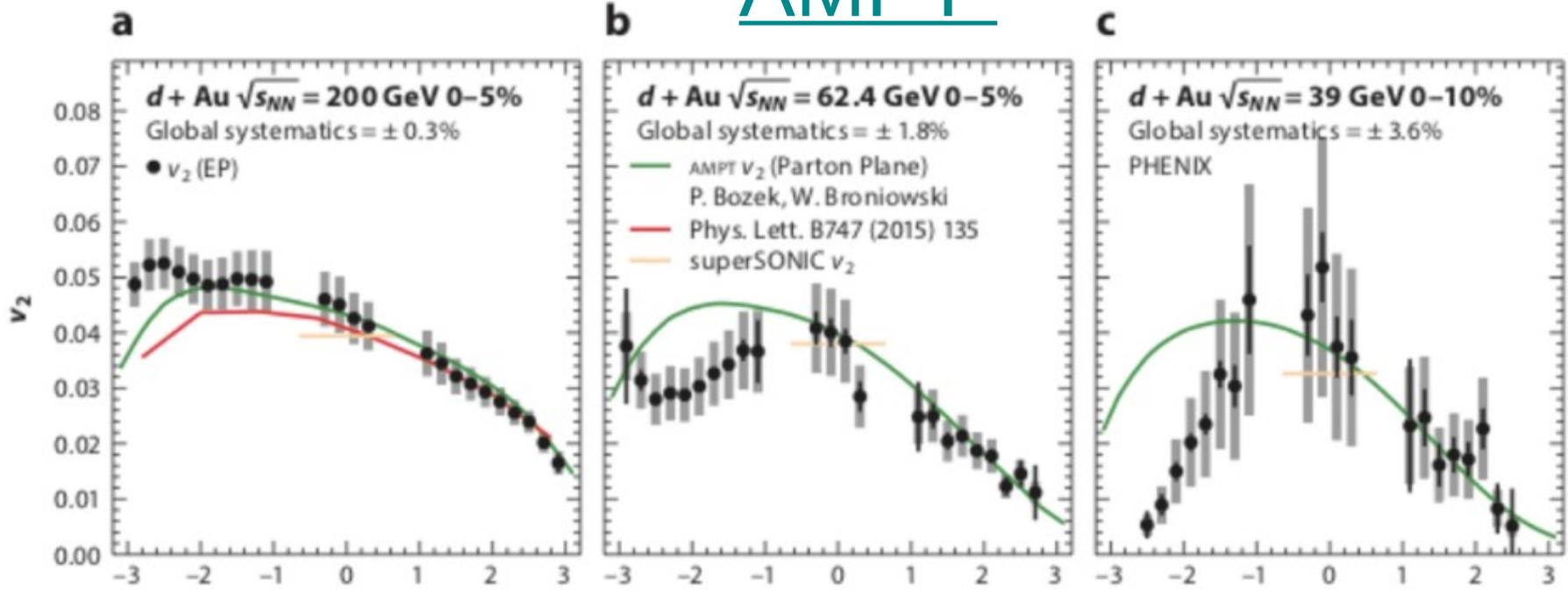


# 流体模型でpp,pA,AAの実験値を 再現できるようだ

AMPT (A multi phase transport) modelでも  
いろいろ再現できるらしい。

- HIJING → string melting
- ZPC (parton cascade)
- coalescence → ART (hadron transport)

# AMPT

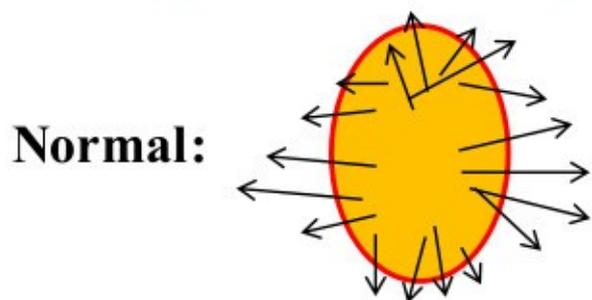


# AMPTのパートン散乱は流体的でない?

AMPTでどのくらいパートンが衝突しているのかを見てみると、1回も衝突しないで、フリーズアウトするパートンが沢山いる。

→ **anisotropic parton escape mechanism**

We design a **Random- $\phi$  Test** (destroy collective flow but keep the anisotropic shape):

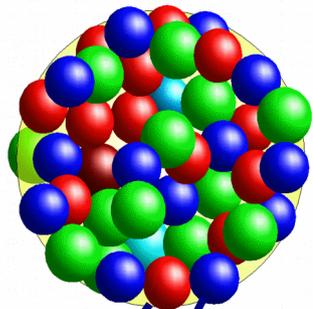
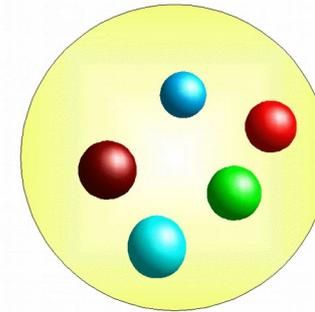
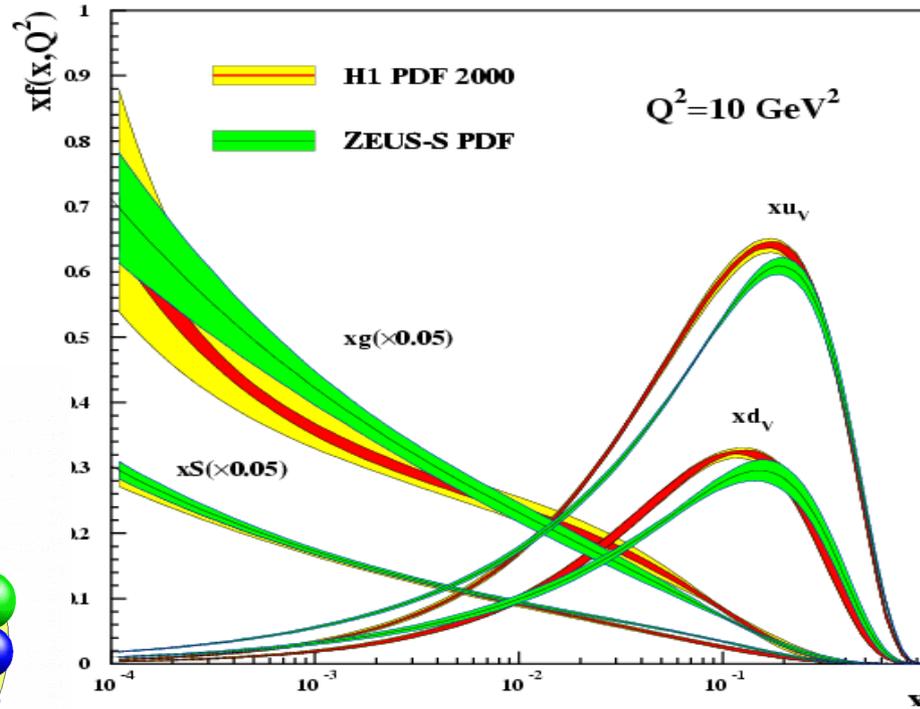


$v_2$  from the Random- $\phi$  Test purely comes from escape

$\langle v_2 \rangle_{\text{random-}\phi} / \langle v_2 \rangle_{\text{normal}}$  ratio  $\sim$  fraction from pure escape:

	dAu@200GeV b=0 fm	pPb@5TeV b=0 fm	AuAu@200GeV b=6.6-8.1 fm	PbPb@2.76TeV b=8 fm
u/d	93%(all quarks)	72.9%	65.6%	42.5%

# Structure of the hadrons at high energies



Nonlinear effect

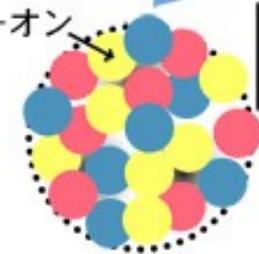
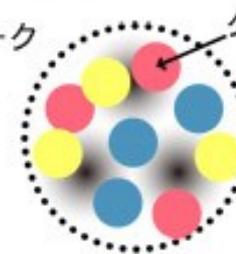
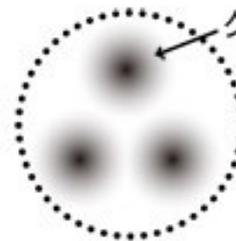
Gluon saturation

$$r \sim \frac{1}{Q_s}$$

Saturation scale

低エネルギー

高エネルギー

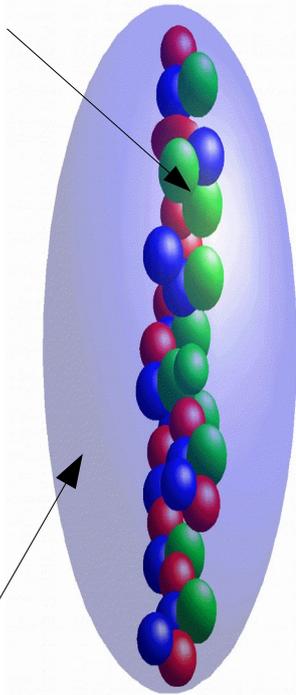


カラーガラス凝縮

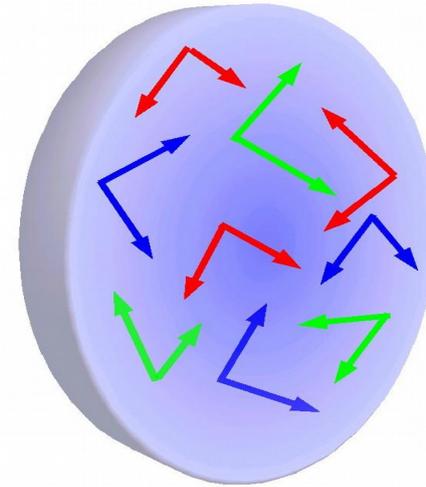
3つのクォーク → グルーオンが増殖 → グルーオンの高密度飽和状態

# カラーグラス凝縮

Hard partons



Cloud of Small x partons

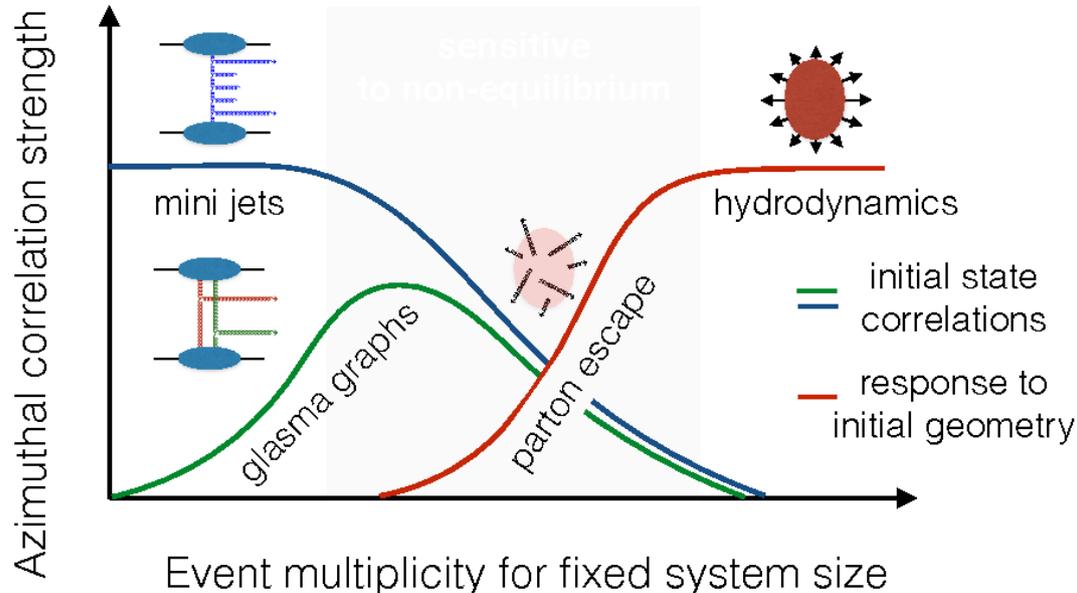


Non-abelian Weizacker-Williams filed

Classical Yang-Mills fields

カラーグラス凝縮：ハドロン,原子核の高エネルギー極限における姿  
板倉 数記 日本物理学会誌 2004 年 59 巻 3 号 p. 148-156  
<https://doi.org/10.11316/butsuri1946.59.148>

# Initial state effects

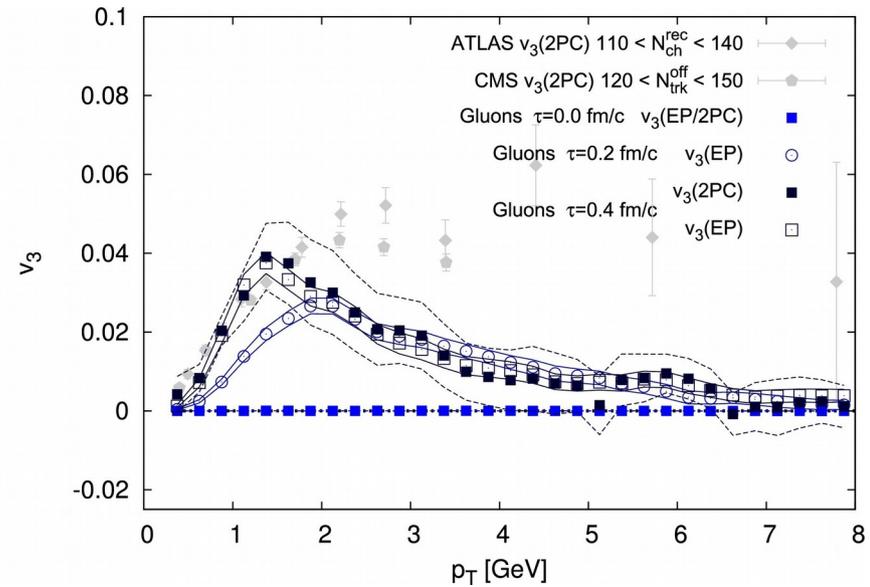
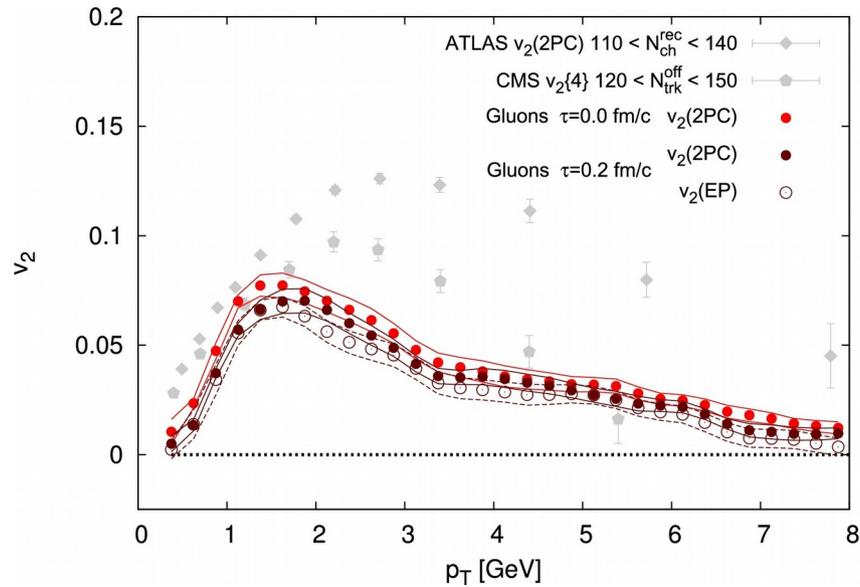


- Glasma graph + jet graph (Dusling and Venugopalan 2013)
- Classical Yang-Mills (BNL group)
- CYM+Pythia  
mass ordering of  $\langle p_t \rangle$  and  $v_2$   
B. Schenke, et. al.  
Phys.Rev.Lett. 117 (2016) no.16, 162301

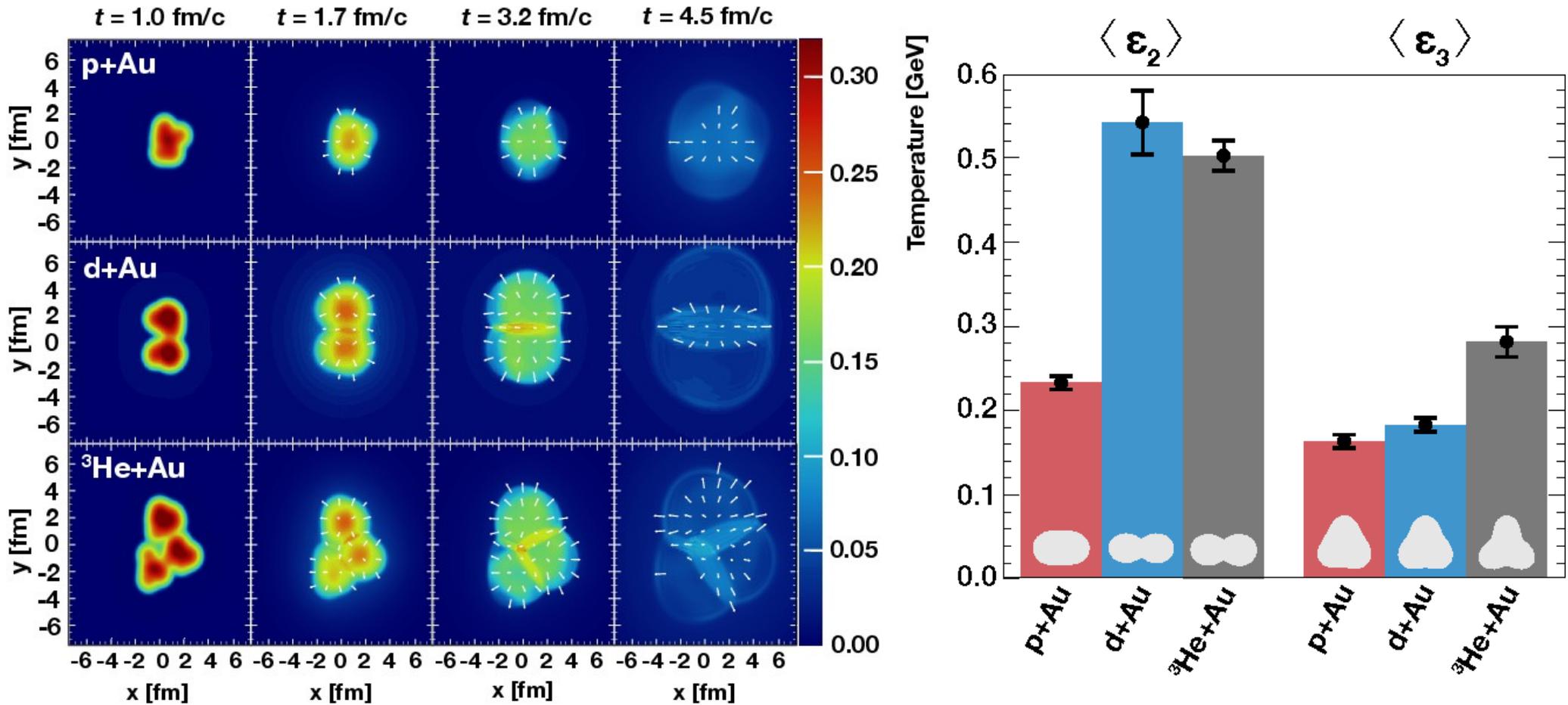
- Color reconnection A.O.Velasquez, et.al.PRL111(2013)04001
- Radiating antennas M. Gyulassy, et.al, PRD90(2014)054025
- Target field anisotropy A.Kovner et.al. PRD83(2011)034017
- Collectivity from interference B.Block, et.al. JHEP 1712(2017)074
- Color dipole orientation bias E.Iancu et.al. PRD95(2017)094003
- Elliptic gluon distributions Y.Hagiwara, et.al. PLB771(2017)374

# IP-Glasma + Classical Yang-Mills

B. Schenke, S. Schlichting, R. Venugopalan, Phys.Lett.B747 (2015)76



# How to discriminate models?

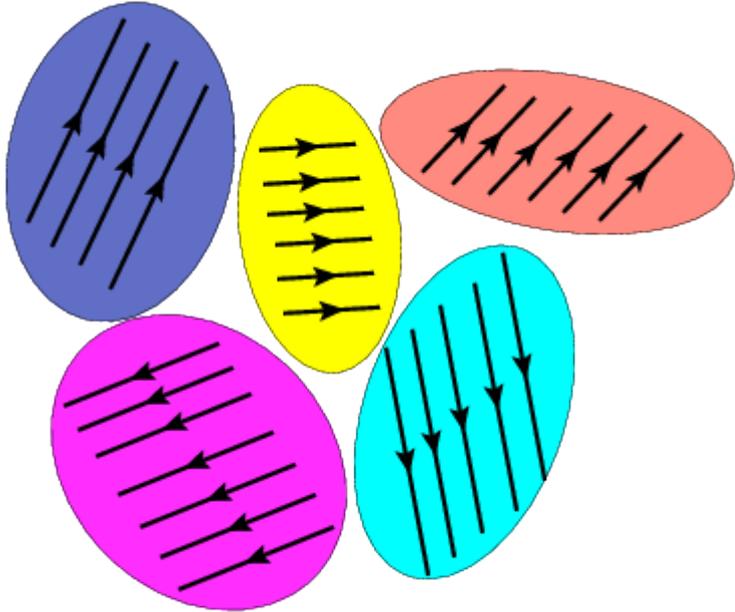


Hydrodynamical models predictions:

$$v_2^{p+Au} < v_2^{d+Au} \approx v_2^{3He+Au} \quad v_3^{p+Au} \approx v_3^{d+Au} < v_3^{3He+Au} \quad 21$$

# Color fields in the domain of $1/Q_s$ in CGC

Color correlation length =  $1/Q_s = 0.1-0.2$  fm

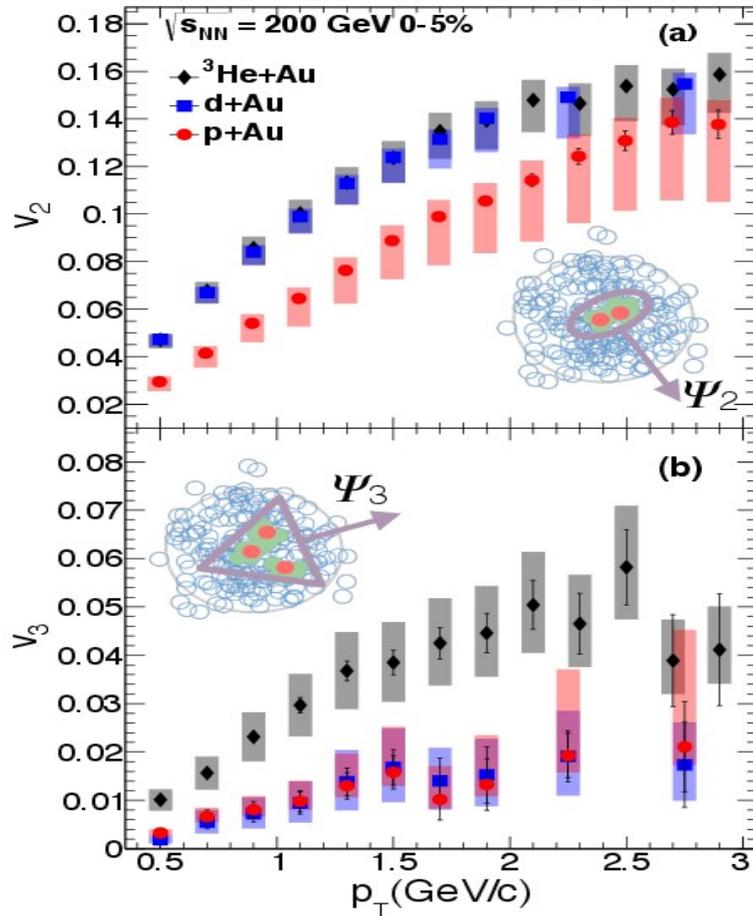


$$v_n^{p+Au} > v_n^{d+Au} > v_n^{^3\text{He}+Au}$$

for large transverse kick  $p_\perp > Q_s$

$v_{2,3}(p_\perp)$  would be identical  
for different small system  
at fixed  $N_{ch}$  at large  $N_{ch}$

# How to discriminate models?



## Hydrodynamics

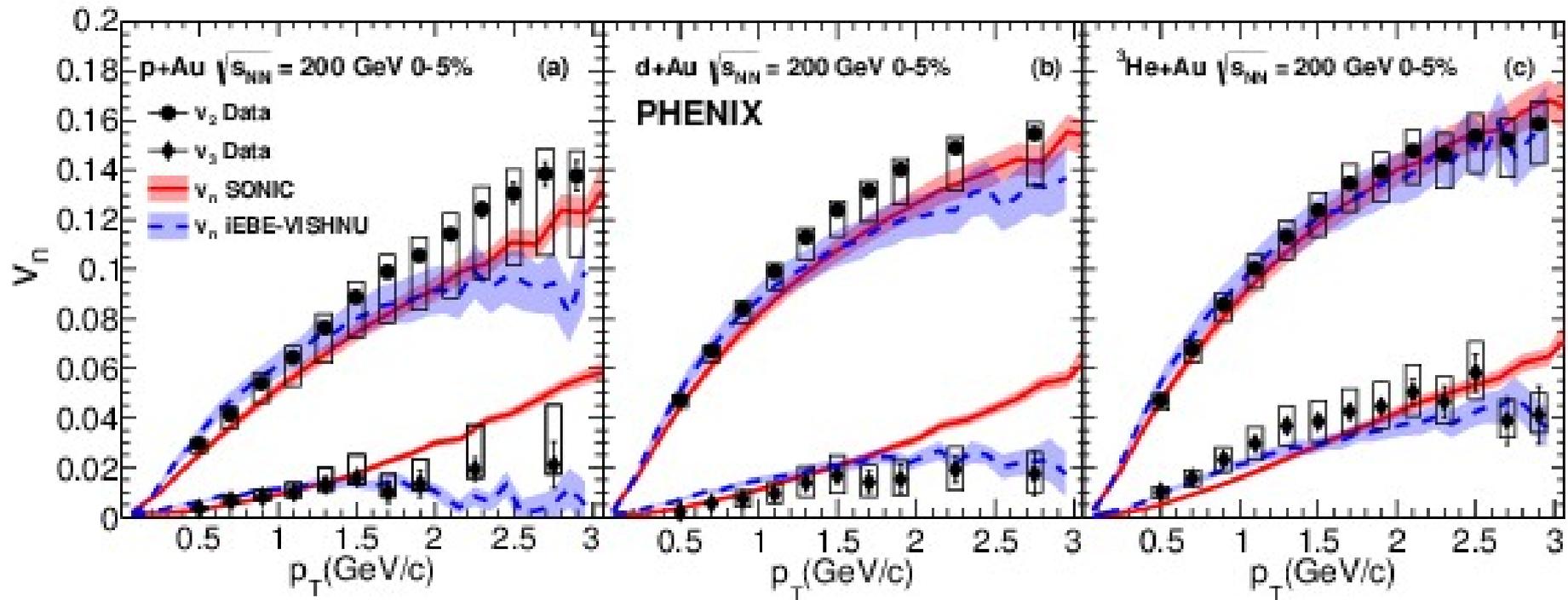
$$v_2^{p+\text{Au}} < v_2^{d+\text{Au}} \approx v_2^{^3\text{He}+\text{Au}}$$

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

## Color Glass Condensate

$$v_n^{p+\text{Au}} > v_n^{d+\text{Au}} > v_n^{^3\text{He}+\text{Au}}$$

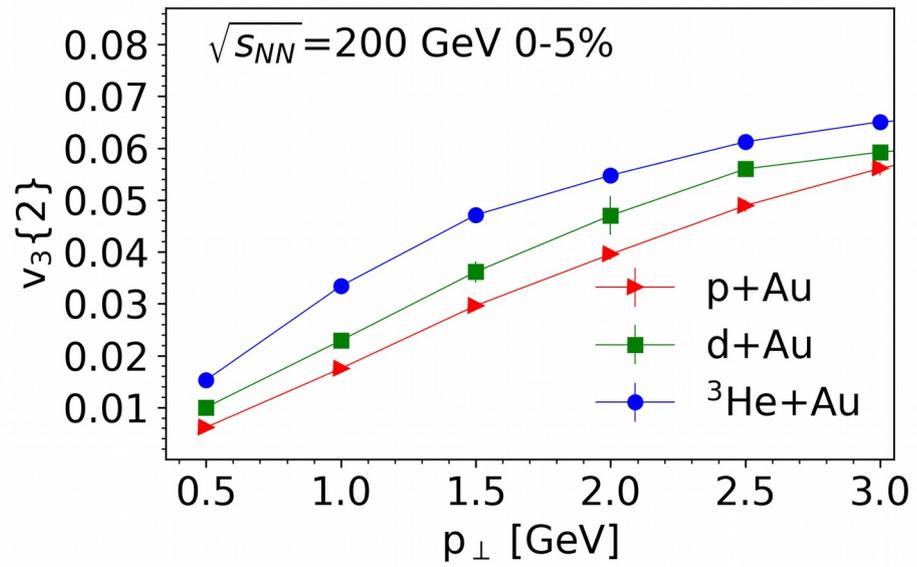
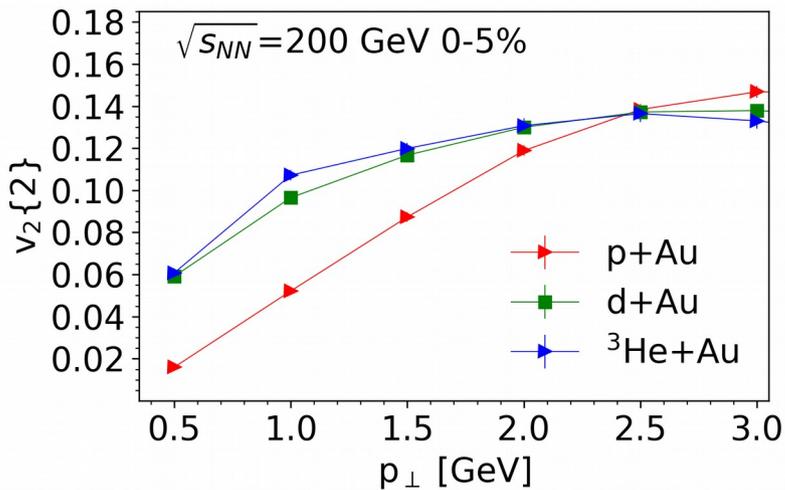
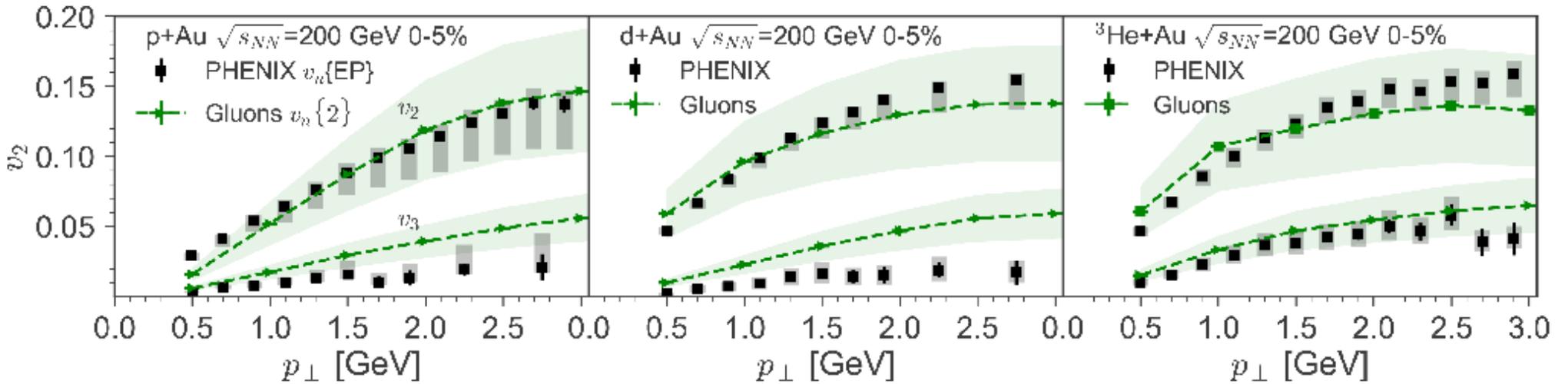
# Comparison of models



流体模型は実験をよく再現している。

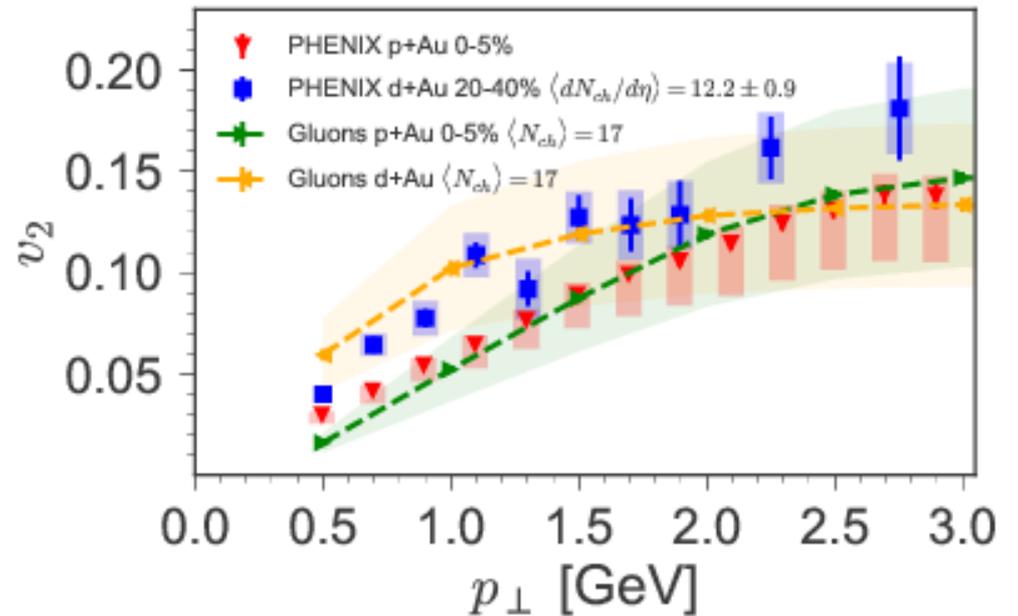
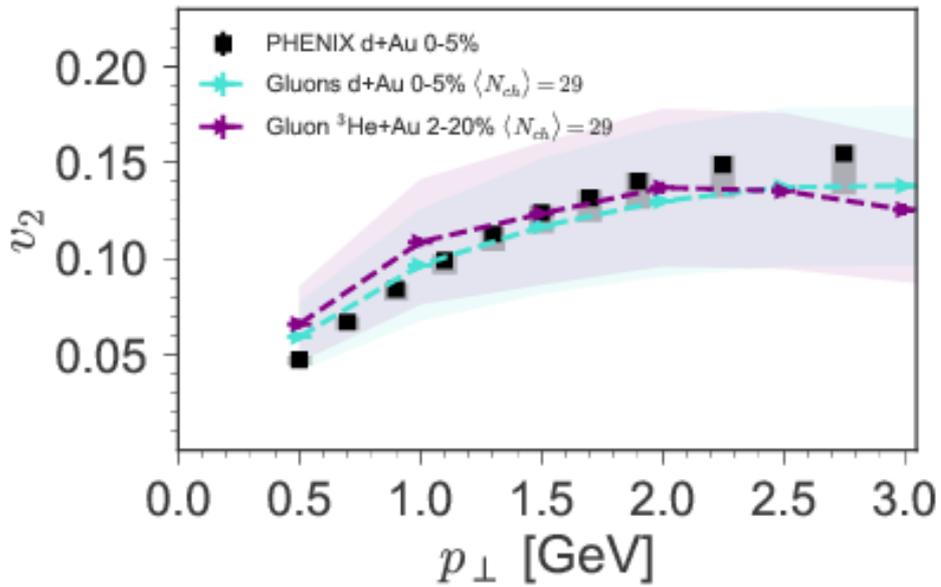
# Color Glass Condensate (MSTV)

Mark Mace, Vladimir V. Skokov, Prithwish Tribedy, and Raju Venugopalan  
 Phys. Rev. Lett. 121, 052301; Hep-ph1901.10506



# MSTV

Mark Mace, Vladimir V. Skokov, Prithwish Tribedy, and Raju Venugopalan  
 Hep-ph1901.10506

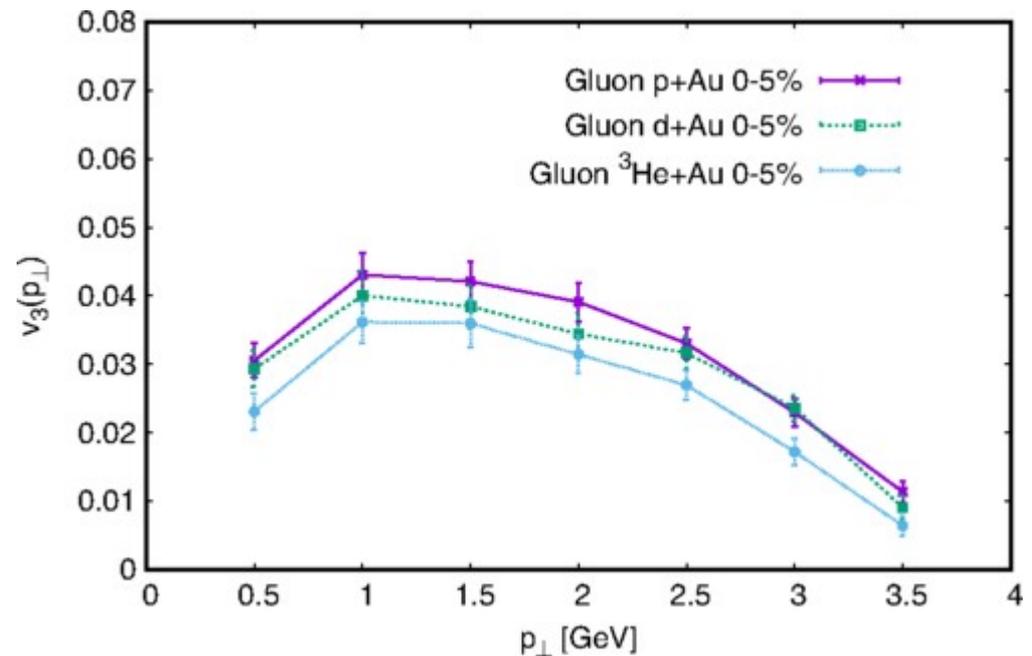
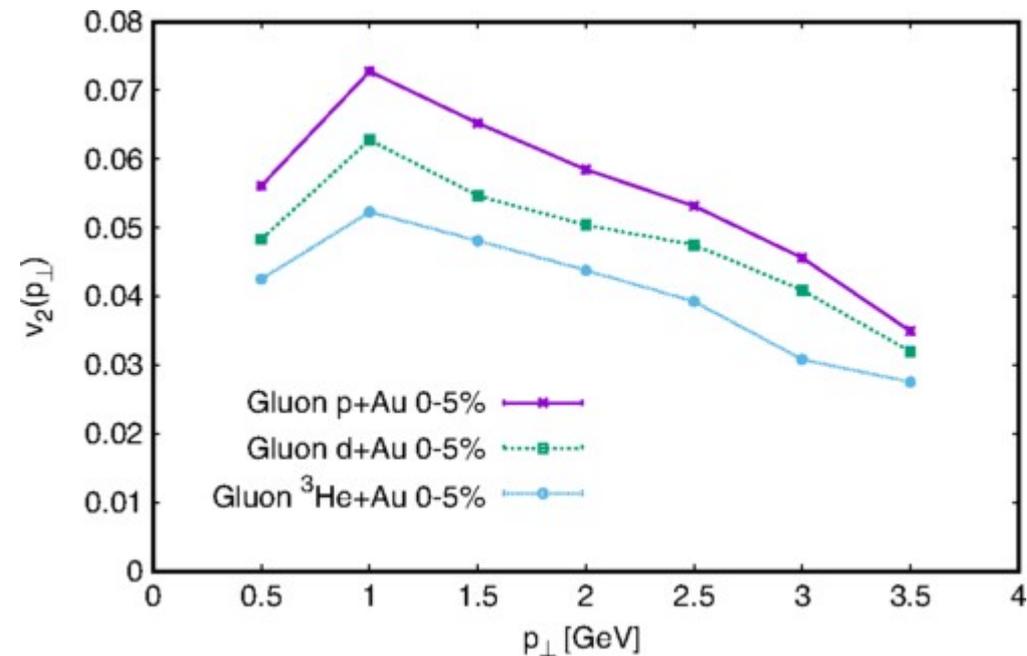


$$v_2^{d+\text{Au}} = v_2^{^3\text{He}+\text{Au}} \text{ at } \langle N_{ch} \rangle = 29$$

$$v_2^{p+\text{Au}} < v_2^{d+\text{Au}} \text{ at } \langle N_{ch} \rangle = 17$$

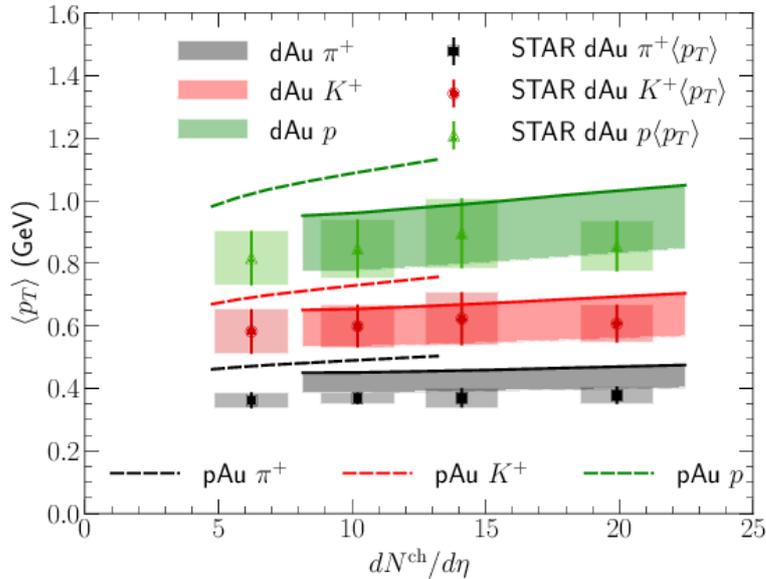
# CGC (MSTV)

Mark Mace, Vladimir V. Skokov, Prithwish Tribedy, and Raju Venugopalan  
Erratum: Phys.Rev.Lett.121,052301(2018) received 13 June 2019

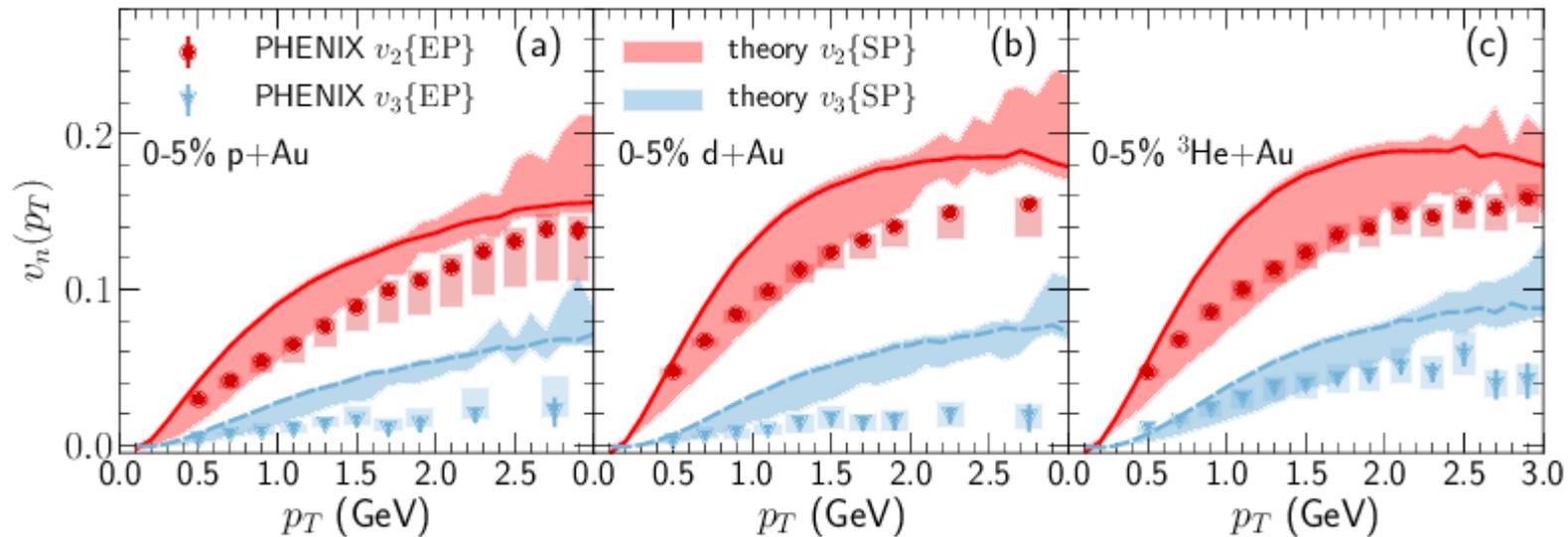


# CGC+Hydro+UrQMD

B. Schenke, C. Shen, P. Tribedy, nucl-th1908.06212



初期条件(anisotropy in CGC)と終相互作用(hydro)の両方が重要である。



# Pythia8 and collectivity

$\tau \approx 0 \sim 0.6 \text{ fm}/c$

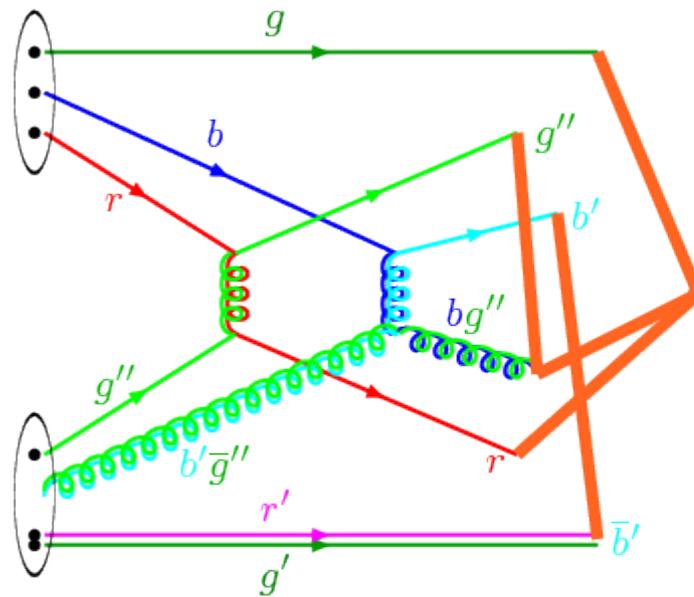
Multi parton interaction (MPI)

$\tau \approx 0.6 \sim 1 \text{ fm}/c$

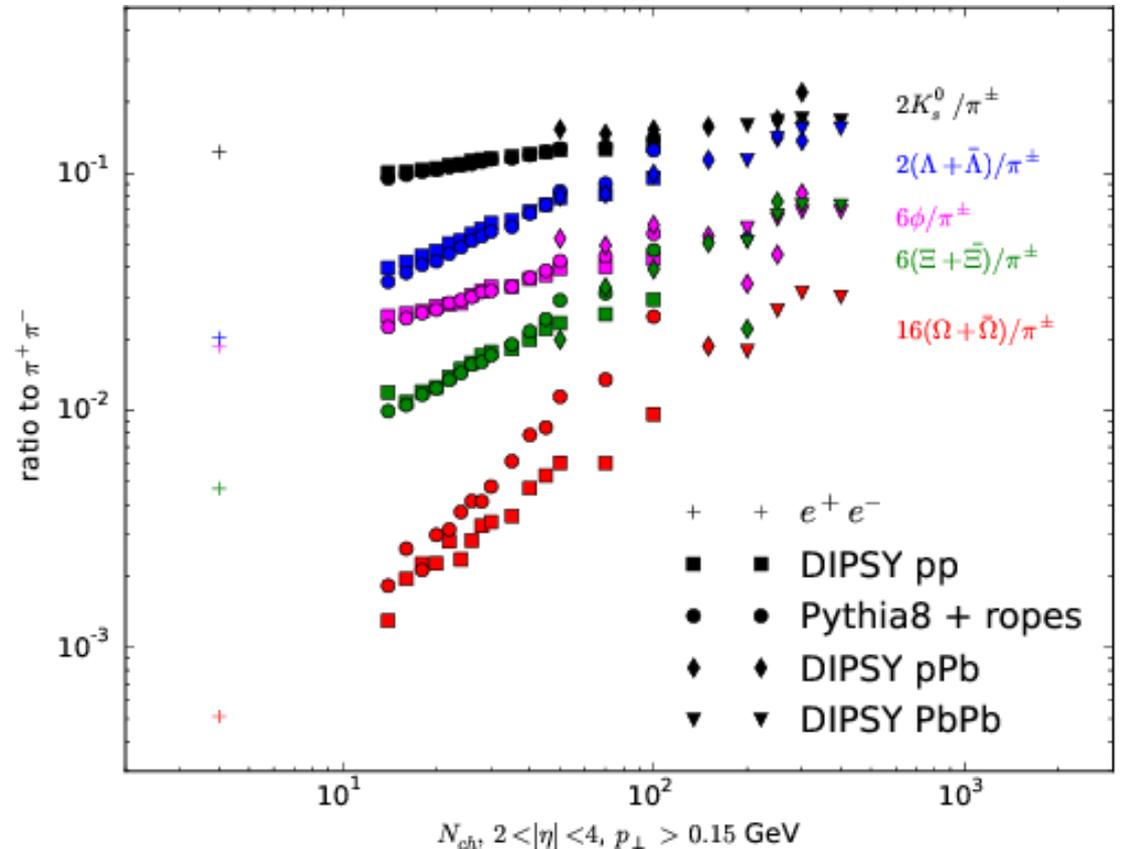
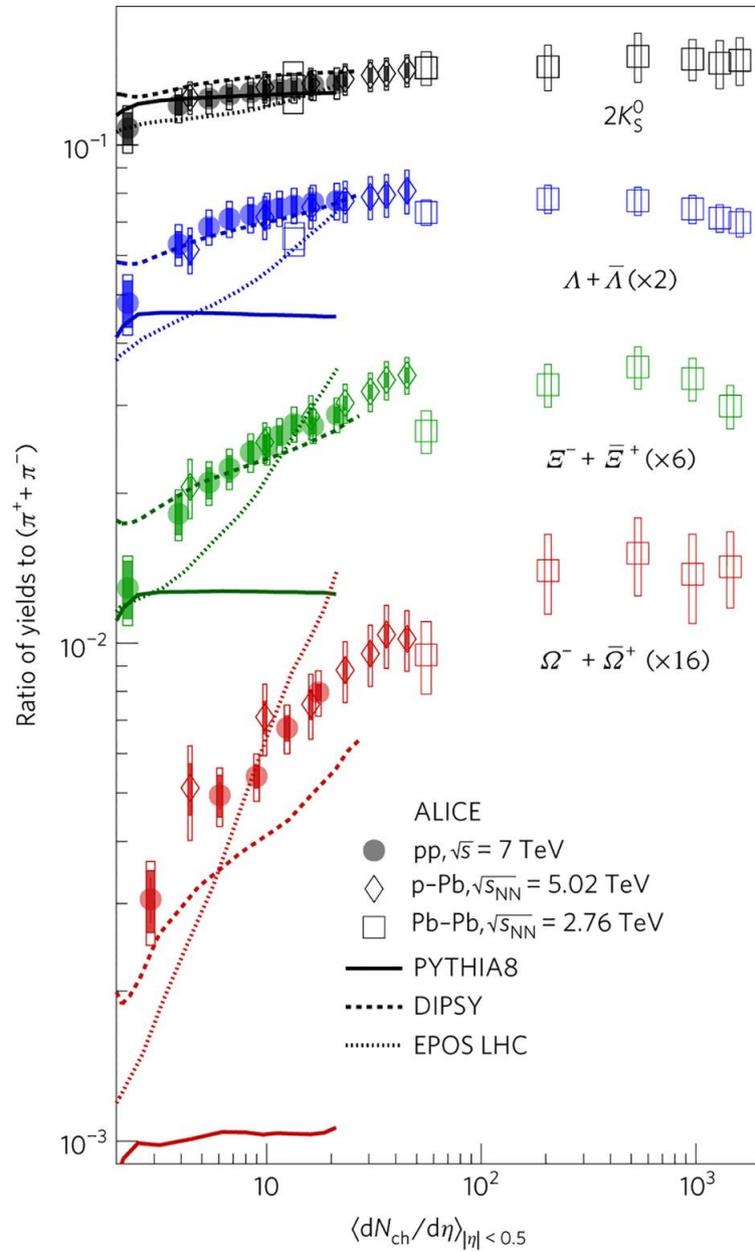
String shoving, transverse push, recombination

$\tau \approx 1 \sim 2 \text{ fm}/c$

Hadronize. Color rope



# Enhancement of multi-strange hadrons in high-multiplicity pp



C.Bierlich Nucl.Phys. A982 (2019) 499-502

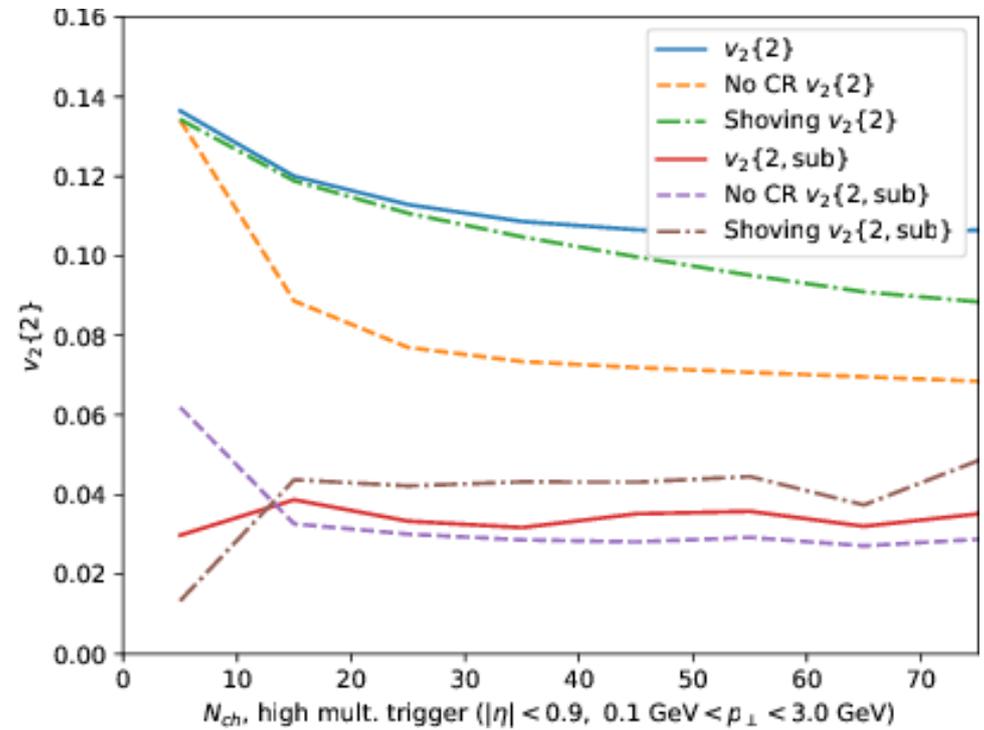
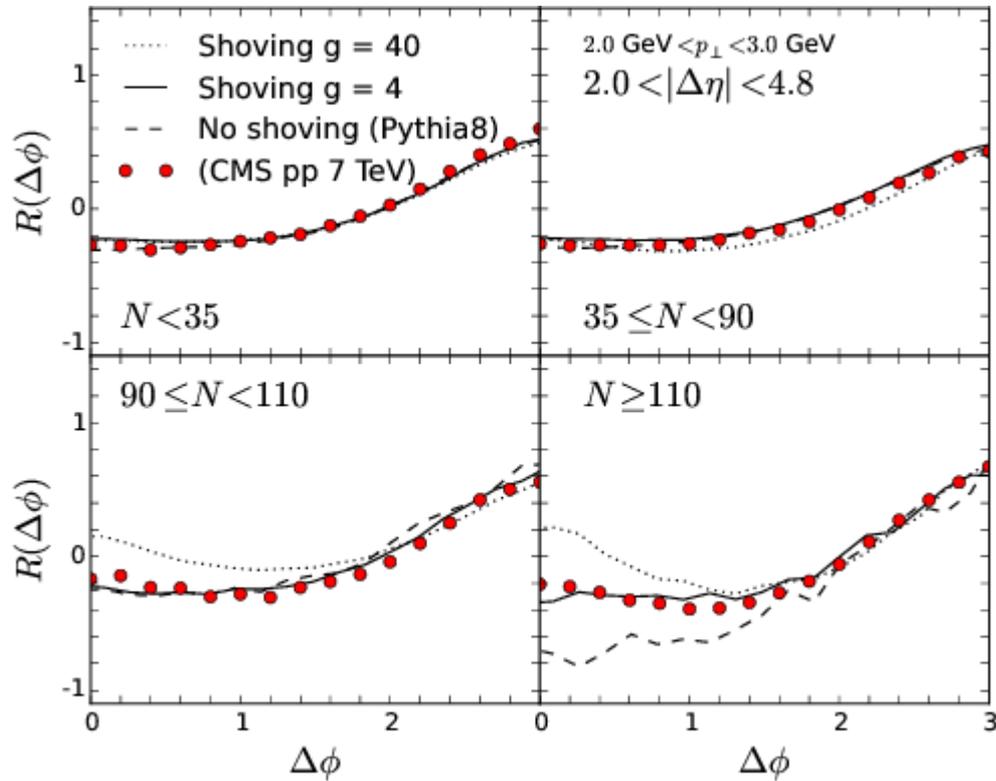
ロープからのハドロン生成でストレンジネスが増大する。

ALICE Nature Phys. 13 (2017)535

# String shoving in pythia8

Christian Bierlich Phys.Lett.B779(2018)58

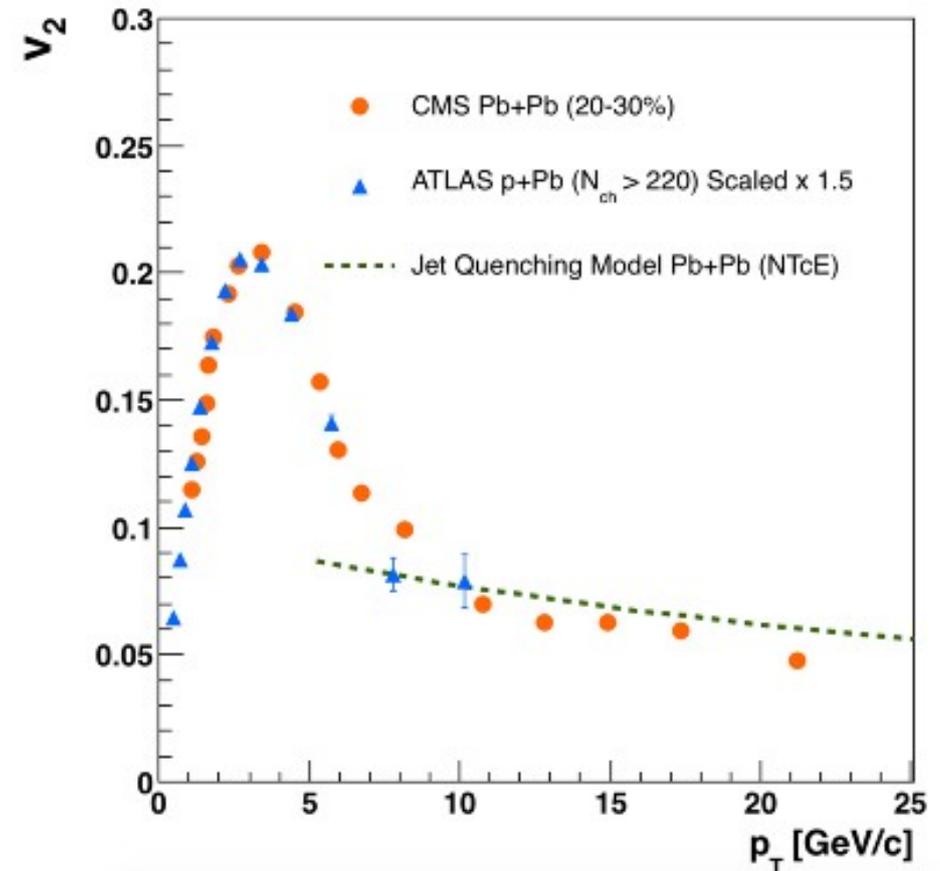
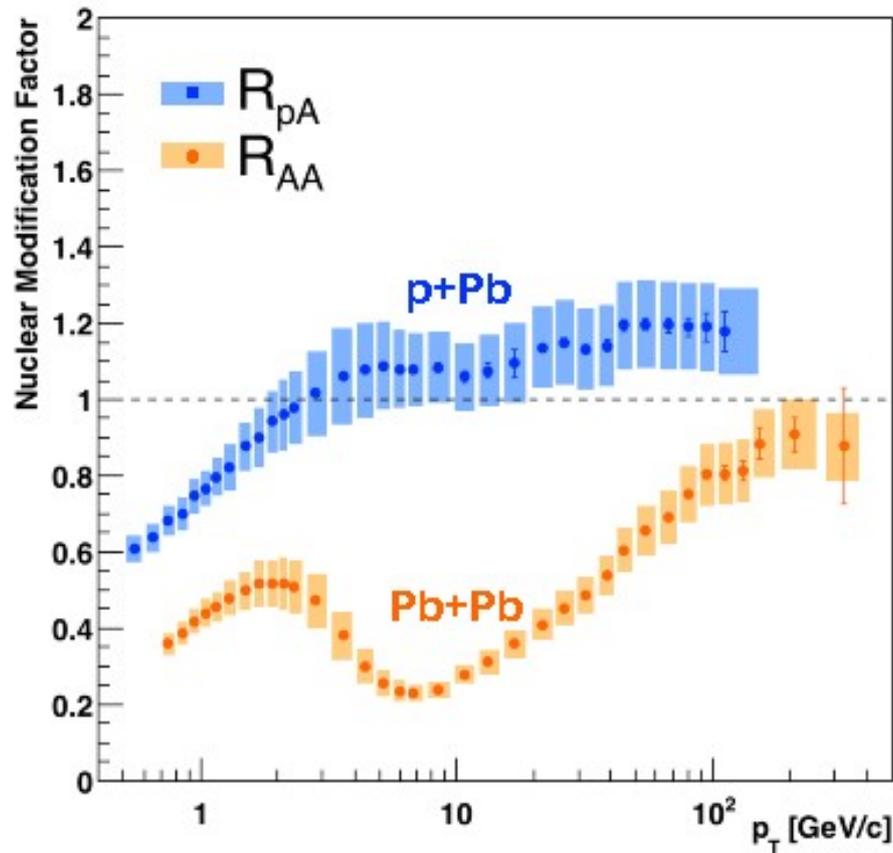
QM2018



ストリングの斥力反発の効果

# Jet-quenching and $v_2$ at high $p_T$

Nagle, Ann.Rev.Nucl.Part.Sci68 (2018)211



pAではジェットクエンチングがないのに、高横運動量の $v_2$ があるのはなぜか？

# Summary 2019年10月現在

- 流体模型でpp, pA, AAの集団効果は説明できる。
- Parton cascade model (AMPT)で集団効果はptの大きい領域は説明できない。
- カラーグラス凝縮モデル(MSTV)でcorrelationは説明できない。
- String recombination, shaving and fusion to rope in Pythia8でも集団効果はでてくるが、 $p/\pi$ を過大に評価するなど、解決すべき点もいろいろある。
- HERWIG event generator: cluster hadronization → new model:  $p/\pi$  ratio があうようになったが、ストレンジ粒子が多すぎ。

# 課題

- 流体模型 vs パartonカスケード(anisotropic parton escape mechanism)  
両方の描像で実験値が説明できるのは不思議である。
- ジェットクエンチングなしで、high-ptの $v_2$ をどう説明する? Parton escape mechanism をサポートしているのか? あるいは、initial dynamicsだけで説明するCGCをサポートしているのか? Pythia8?
- カラーグラス凝縮モデルにもとづく計算の拡張 i.e. CYM + jet  
ハドロニ化
- $e+e^-$ ,  $e-p$ , and  $e-A$  ?