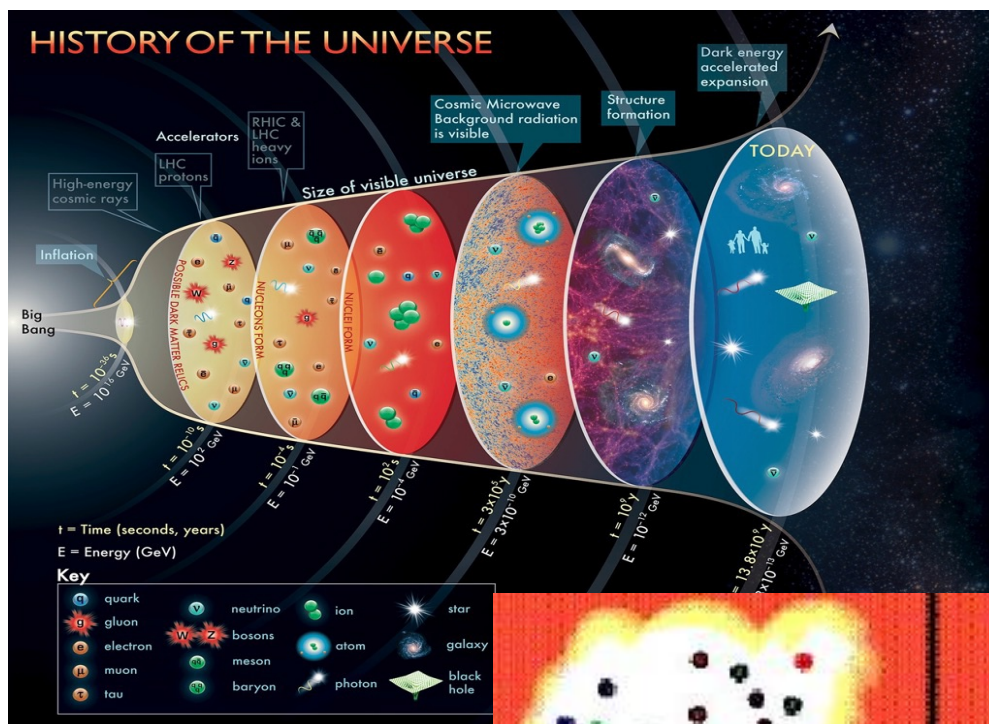
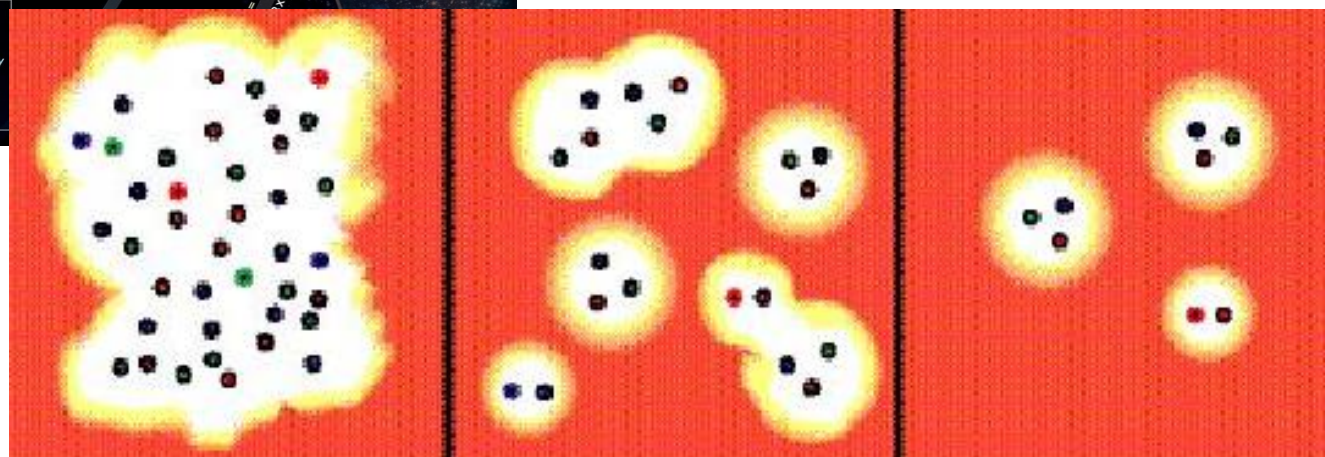
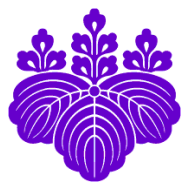


# 研究会「有限温度密度系の物理と格子QCDシミュレーション」 Experimental studies on Quark Gluon Plasma

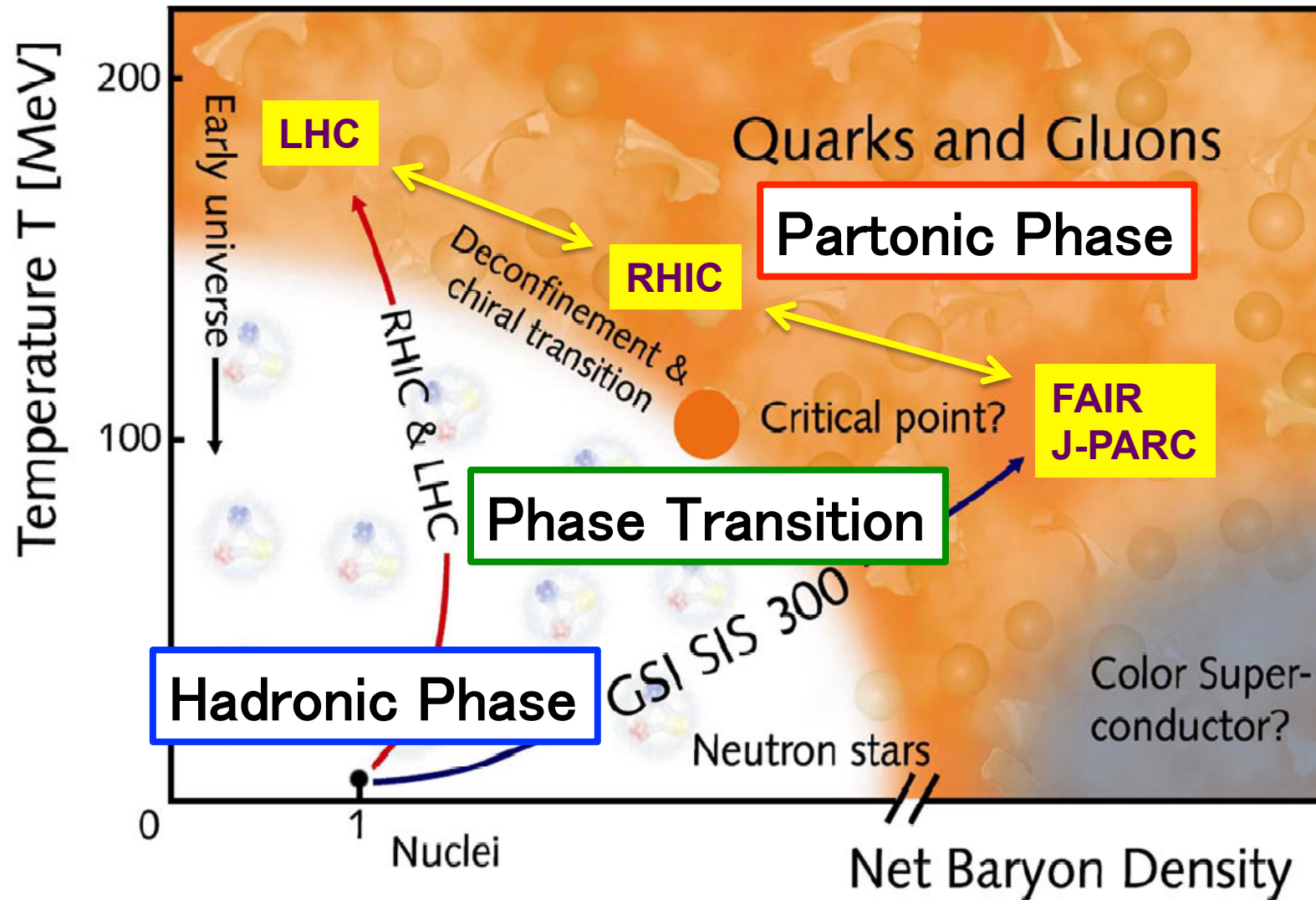


Shinichi Esumi  
Center for Integrated Research  
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江角 晋一  
数理物質融合科学センター  
筑波大学 数理物質系 物理学域

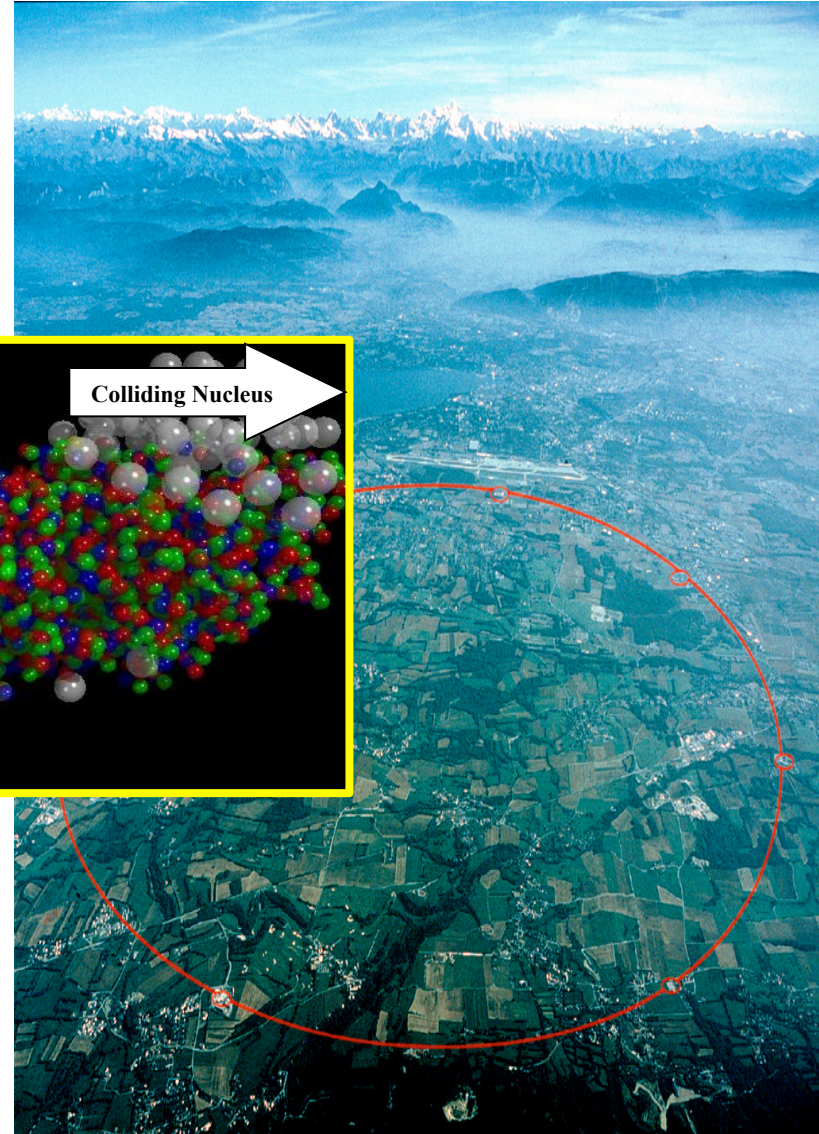
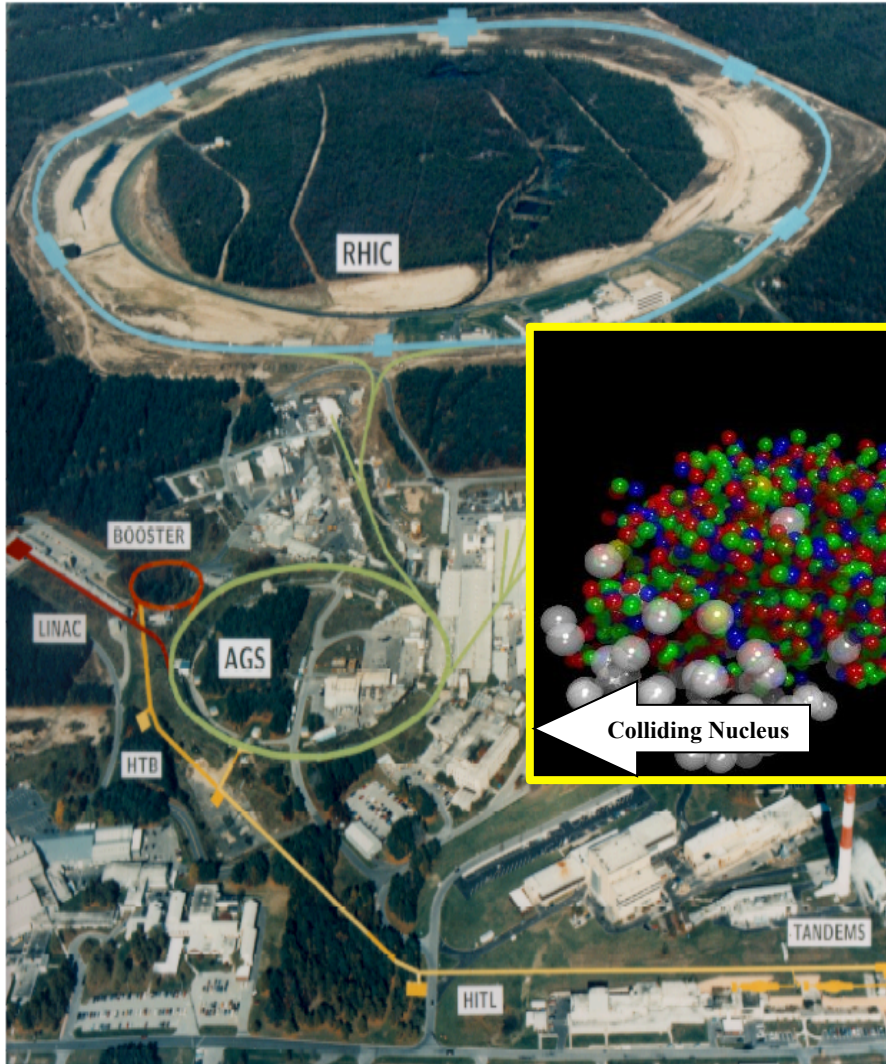


Hadronic Phase  $\rightarrow$  Partonic Phase



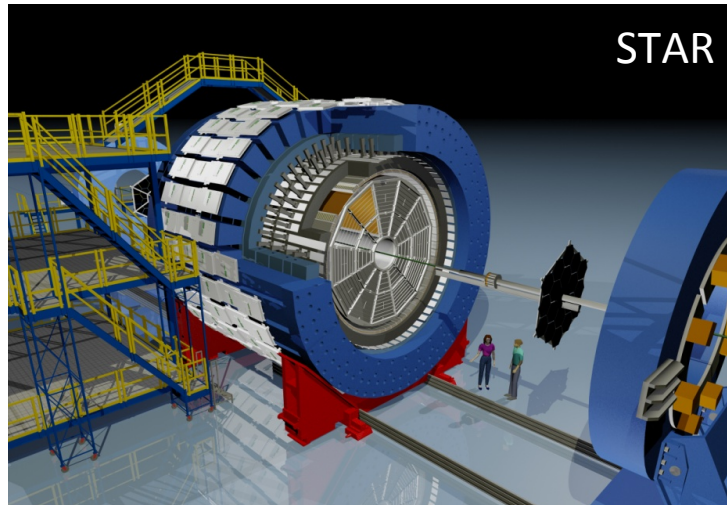
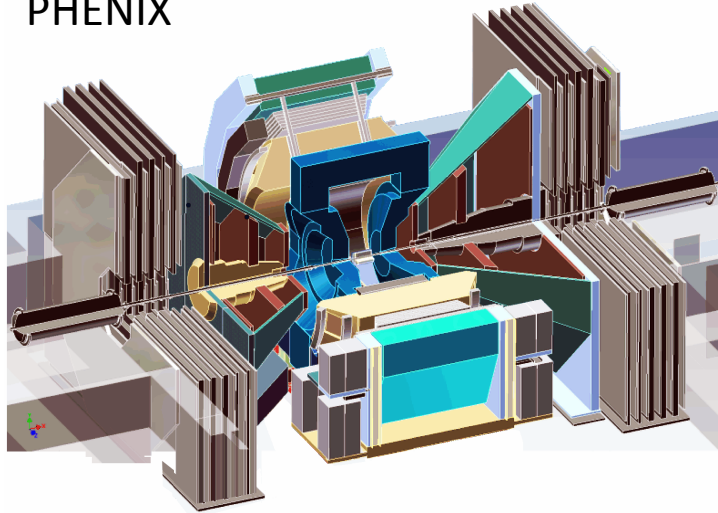
RHIC at BNL,  $\sqrt{s_{NN}} = 10 - 200 \text{ GeV}/c$   
(New York, USA)

LHC at CERN,  $\sqrt{s_{NN}} = 0.5 - 5.5 \text{ TeV}/c$   
(Geneva, Switzerland)

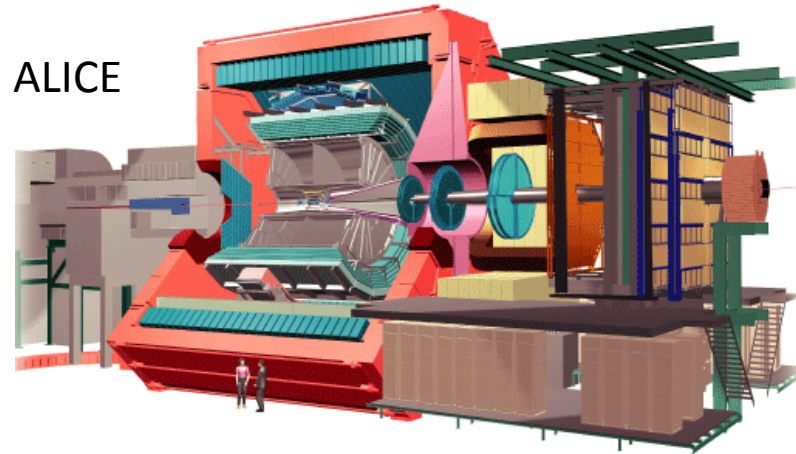


# Experiments at RHIC and LHC

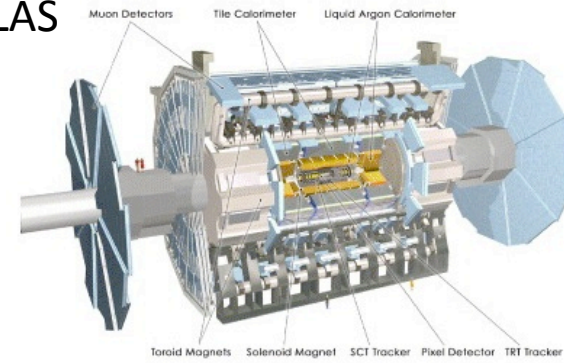
PHENIX



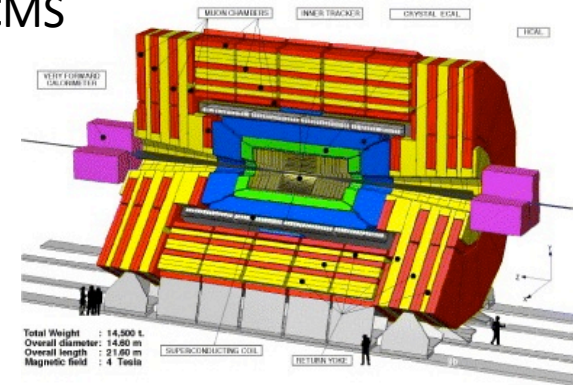
ALICE

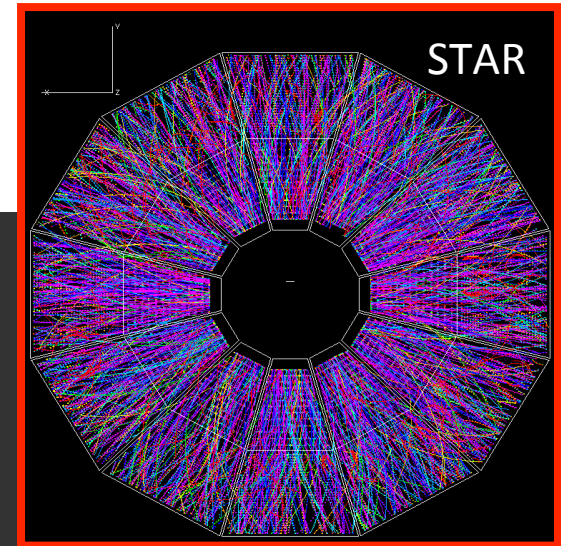
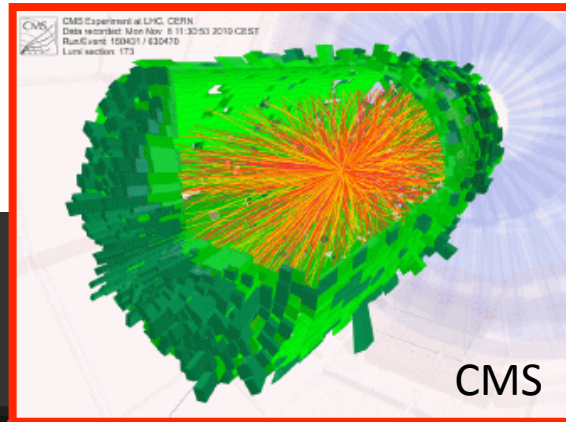
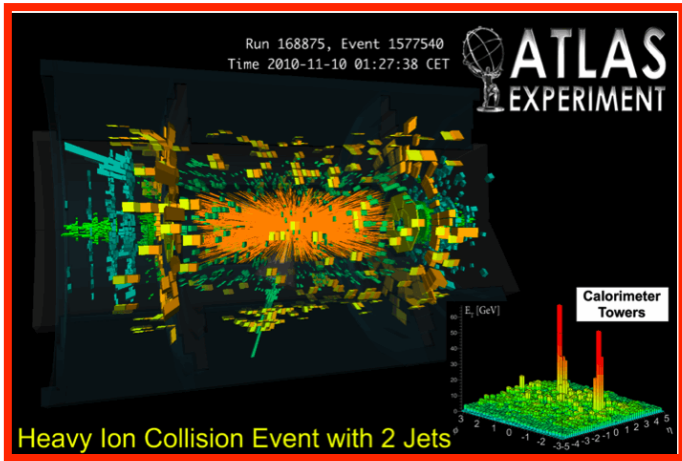


ATLAS

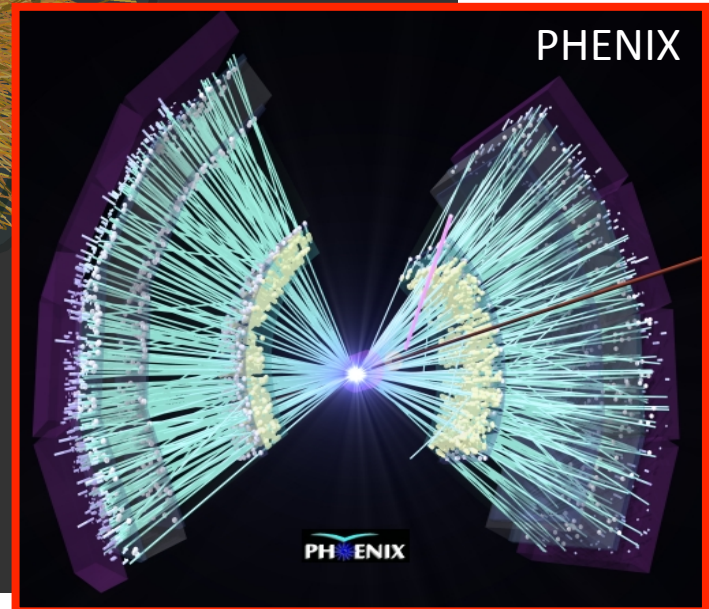
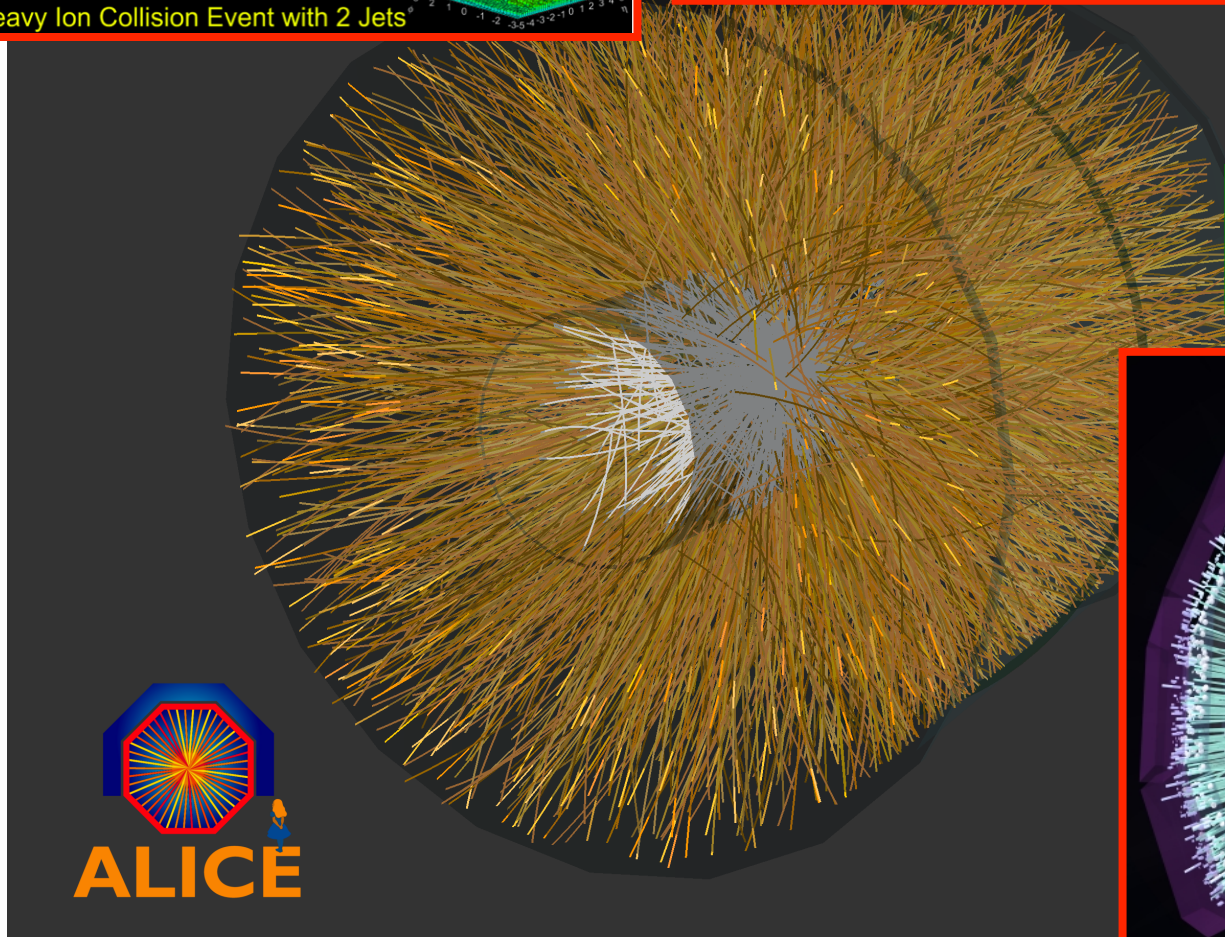


CMS



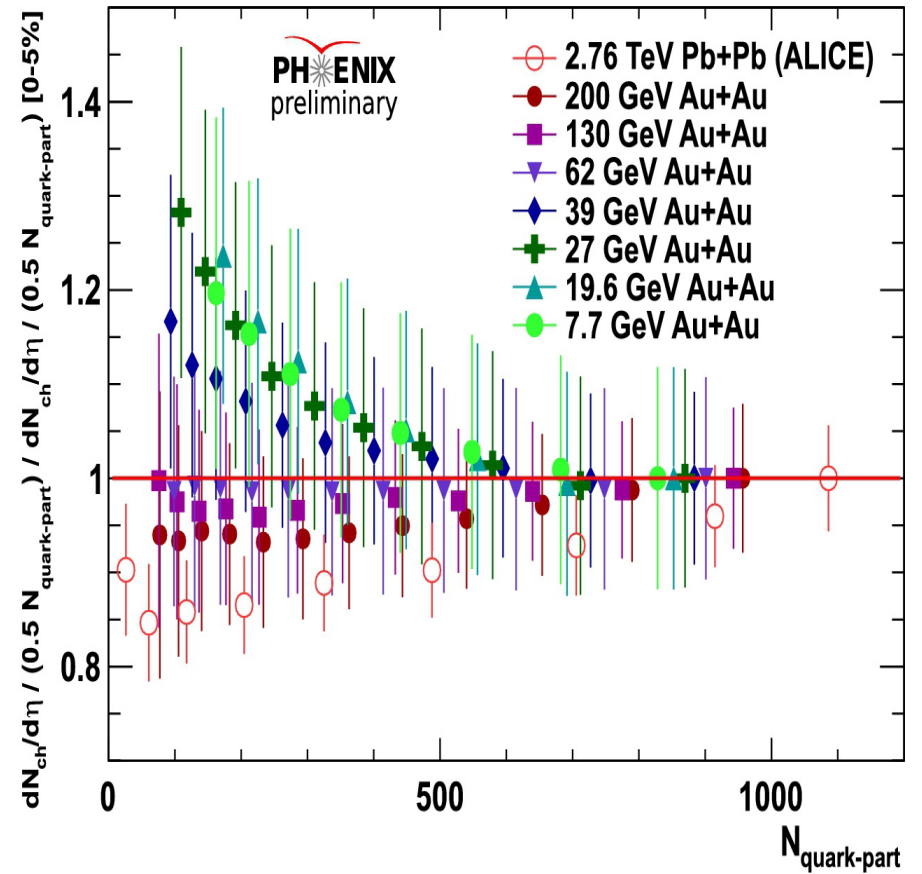
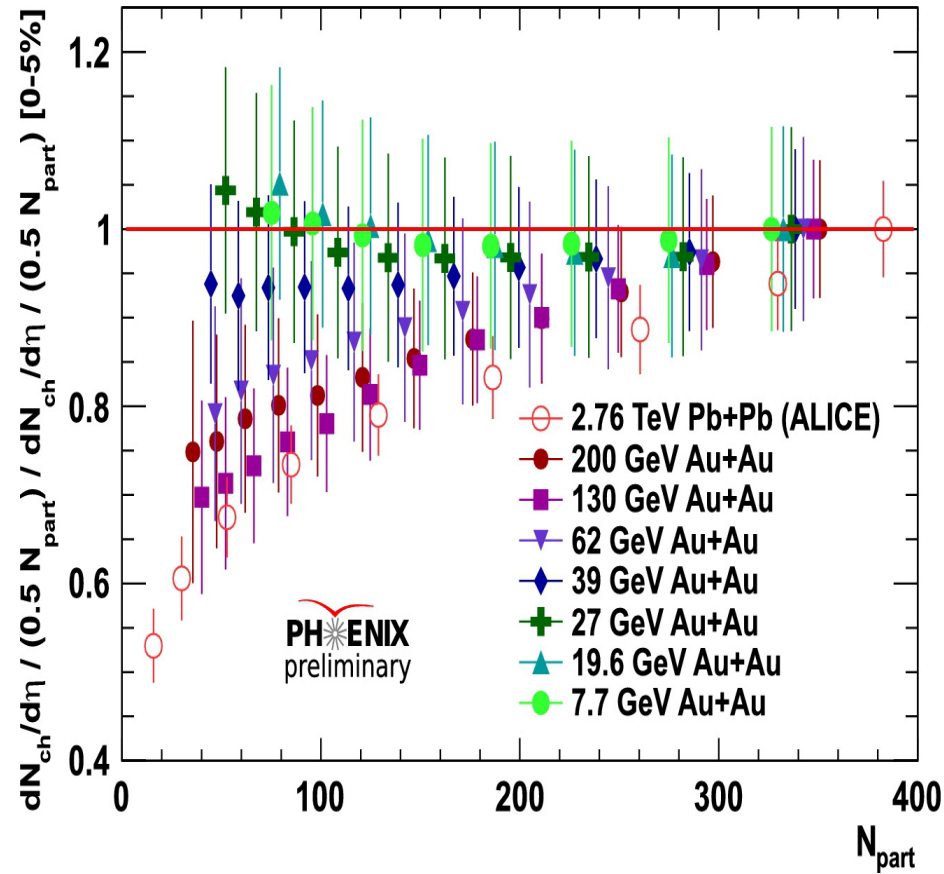


Experimental data  
a few k to 10k particles per collision

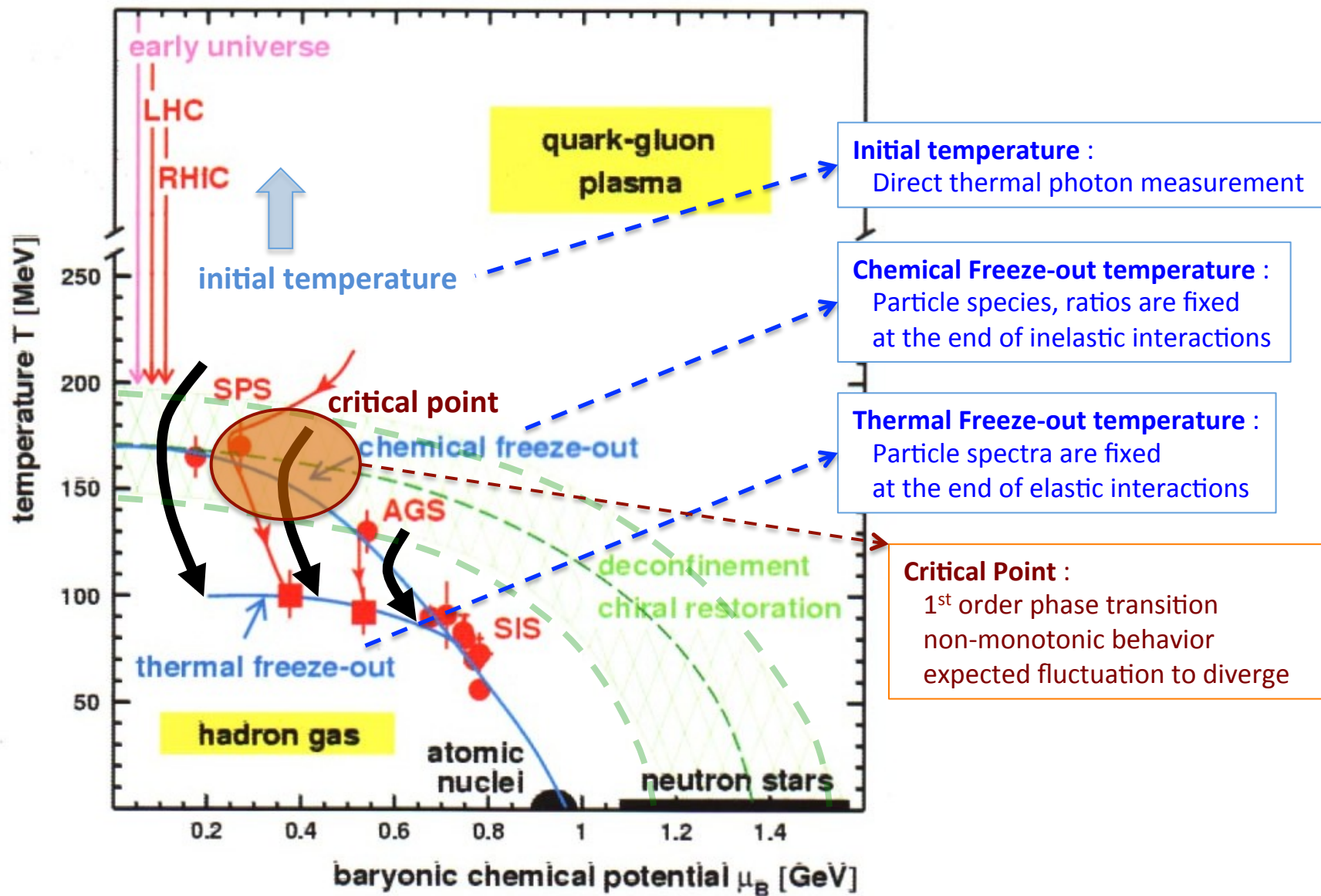


# Nucleon or Quark participant scaling

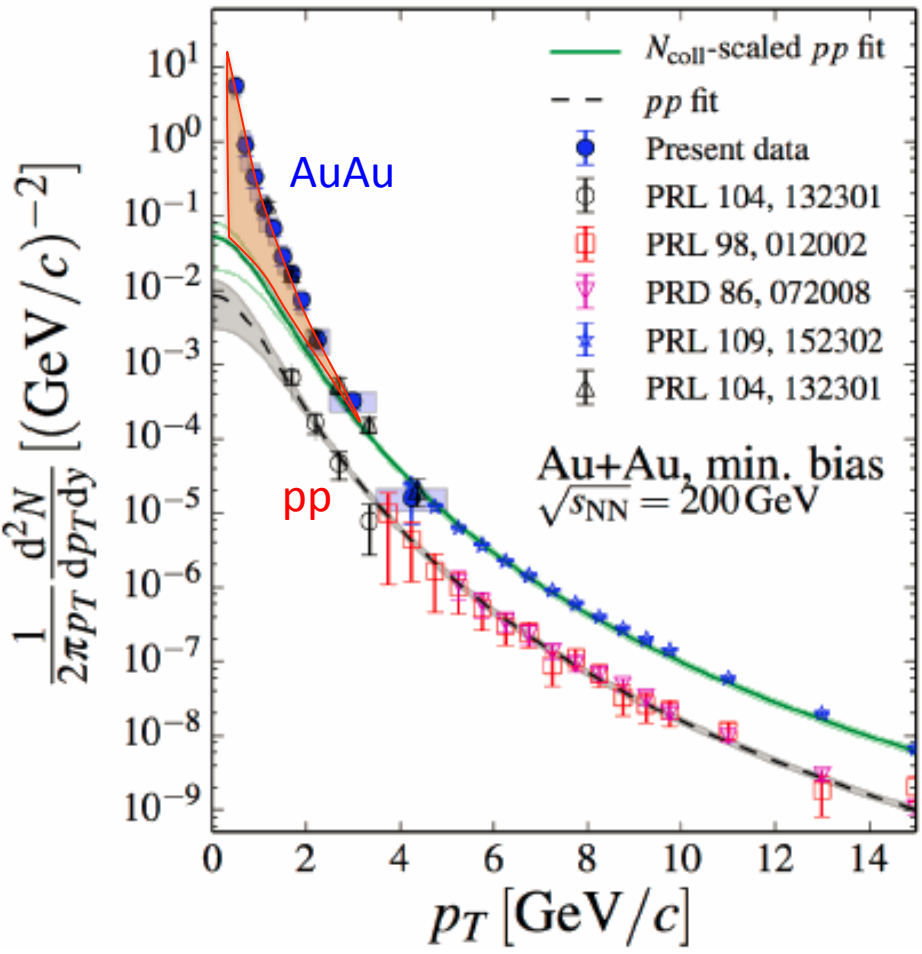
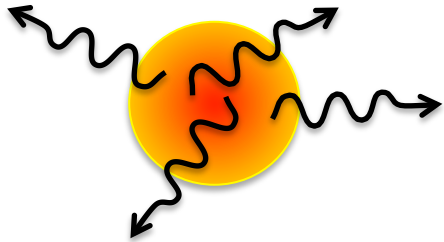
QM14, PHENIX



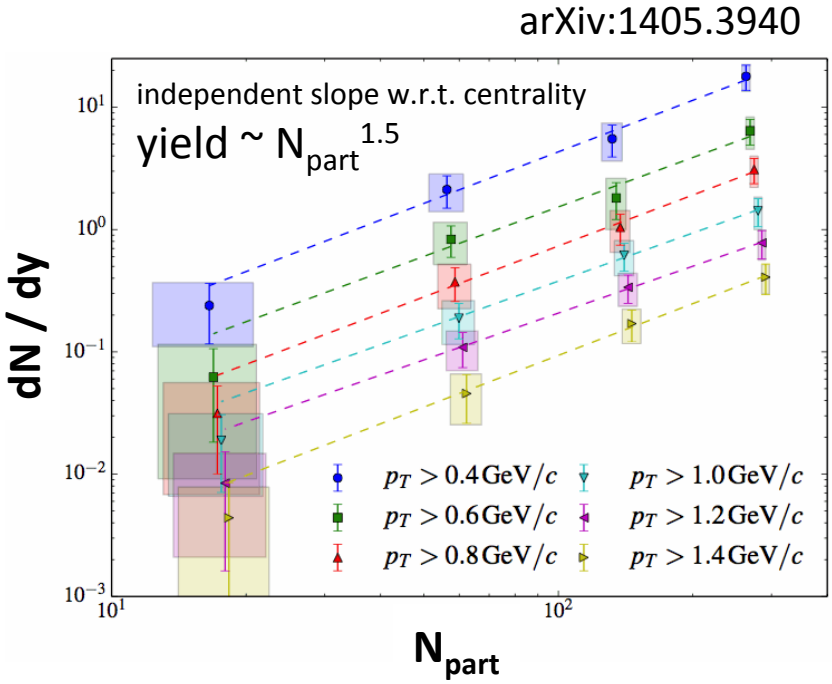
# History of temperature before/after the phase transition



# Enhanced thermal photon production at low $p_T$



- Virtual and real photon measurements via internal and external conversion methods with electron pair measurements
- Real photon measurements with EMcal
- Initial temperature of 300~600MeV

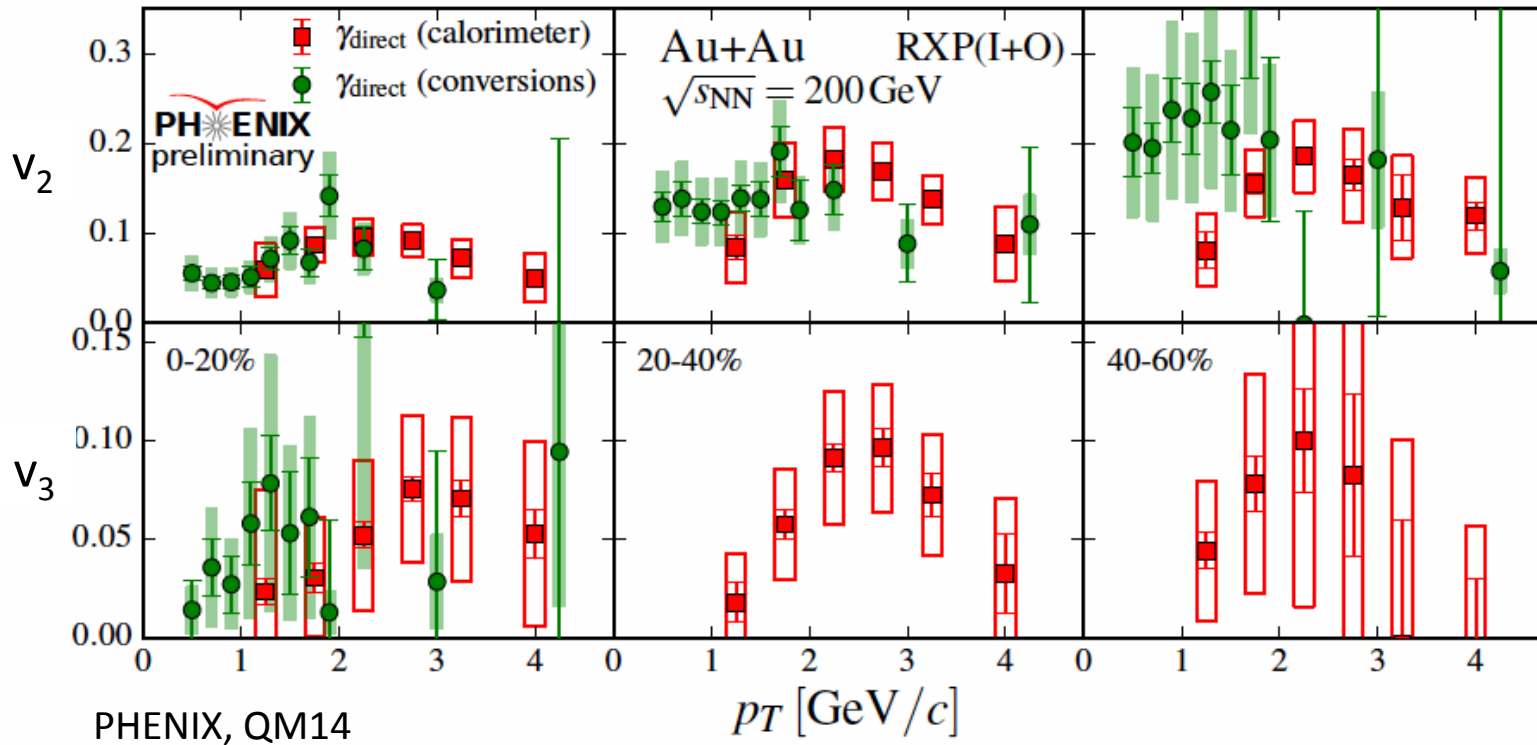
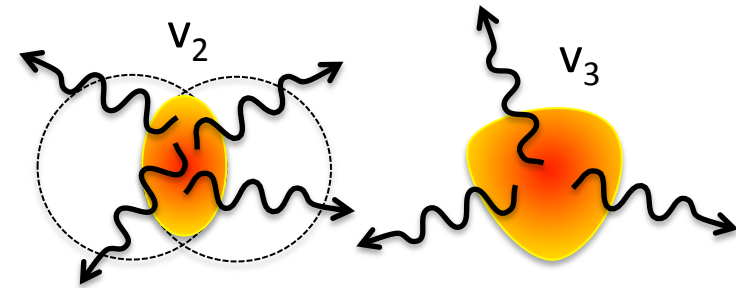




# Direct (thermal) photon $v_2$ and $v_3$

$$v_n = \langle \cos n(\phi^{\text{particle}} - \Phi_n^{\text{plane}}) \rangle$$

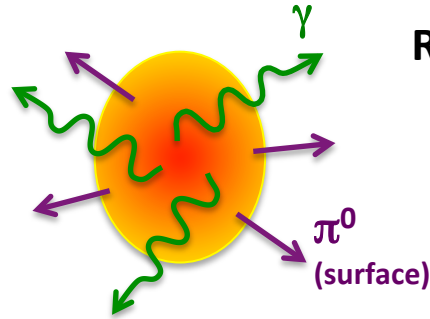
( $n=2$  : elliptic flow), ( $n=3$  : triangular flow)



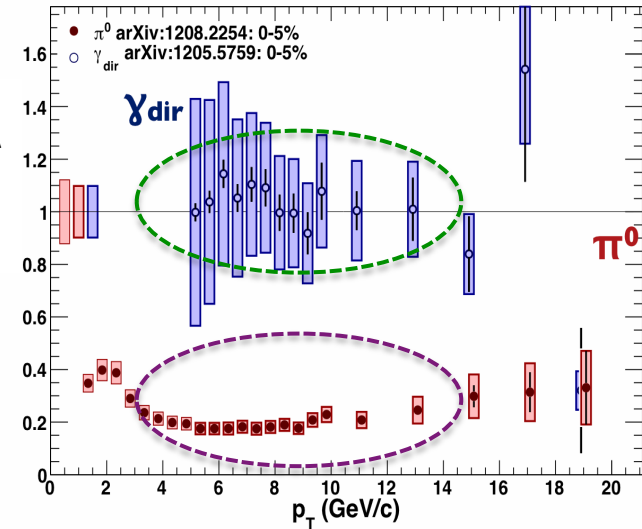
- comparable to hadron for both  $v_2$  and  $v_3$  at 2~3 GeV/c
- significant contribution from photons from later stages (inconsistent with early photons from hotter period)
- flatter  $p_T$  dependence of  $v_2$  at low  $p_T$

# High $p_T$ direct photon as penetrating probe

$p_T > 5 \text{ GeV}/c$	hadron	$\gamma^{\text{dir}}$
$R_{AA}$	$< 1$	$\sim 1$
$v_2$	$> 0$	$\sim 0$

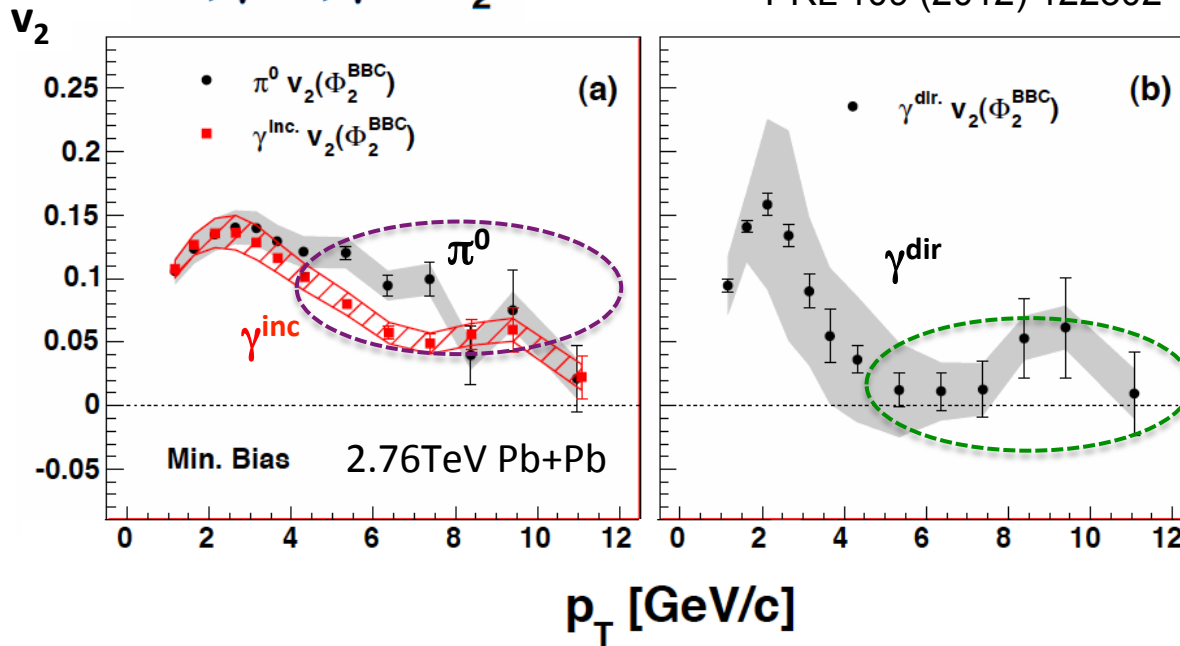


PRL 109 (2012) 152302



PRL 109 (2012) 122302

$\pi^0, \gamma^{\text{inc.}}, \gamma^{\text{dir.}} v_2$



$$R_{AA} = \frac{N(A+A)}{N_{\text{coll}} N(p+p)}$$

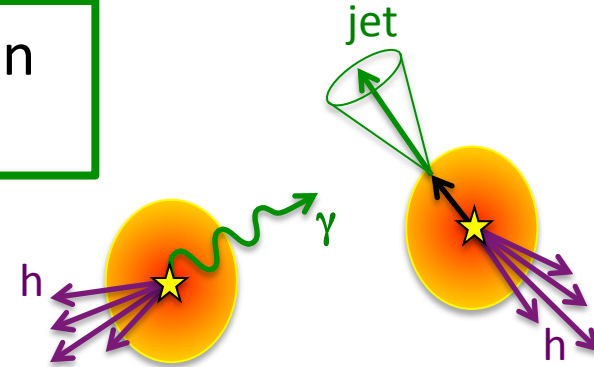
relative yield with respect to a simple independent superposition of pp data

# Energy loss at high $p_T$ and re-distribution of the lost-energy at low $p_T$ at RHIC

## prompt photon - hadron correlation

$N_{PTY}$  = associate hadron yield per trigger  $\gamma$

$$I_{AA} = N_{PTY}(AA) / N_{PTY}(pp)$$



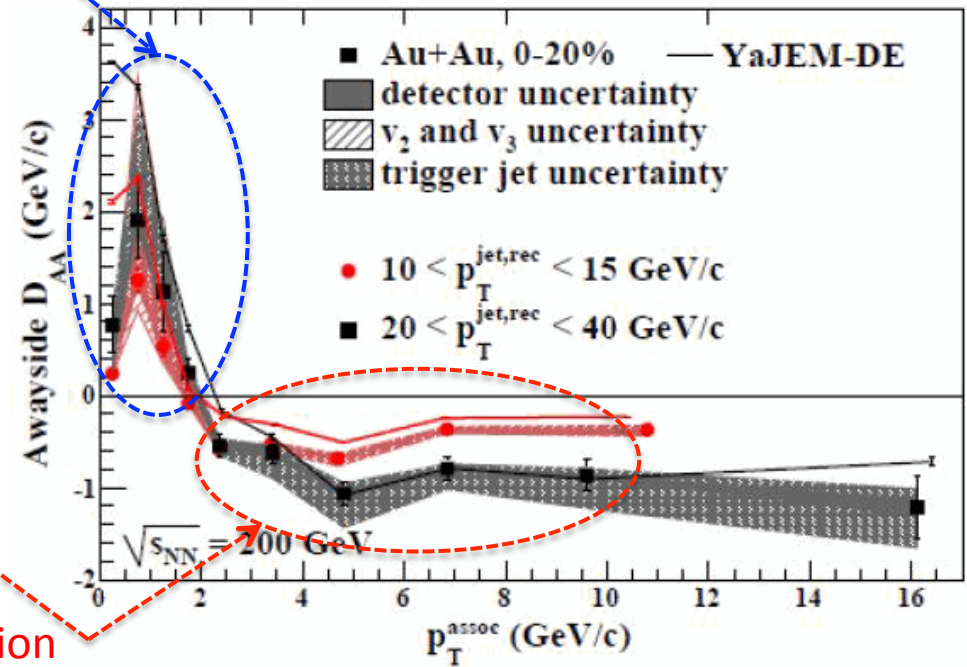
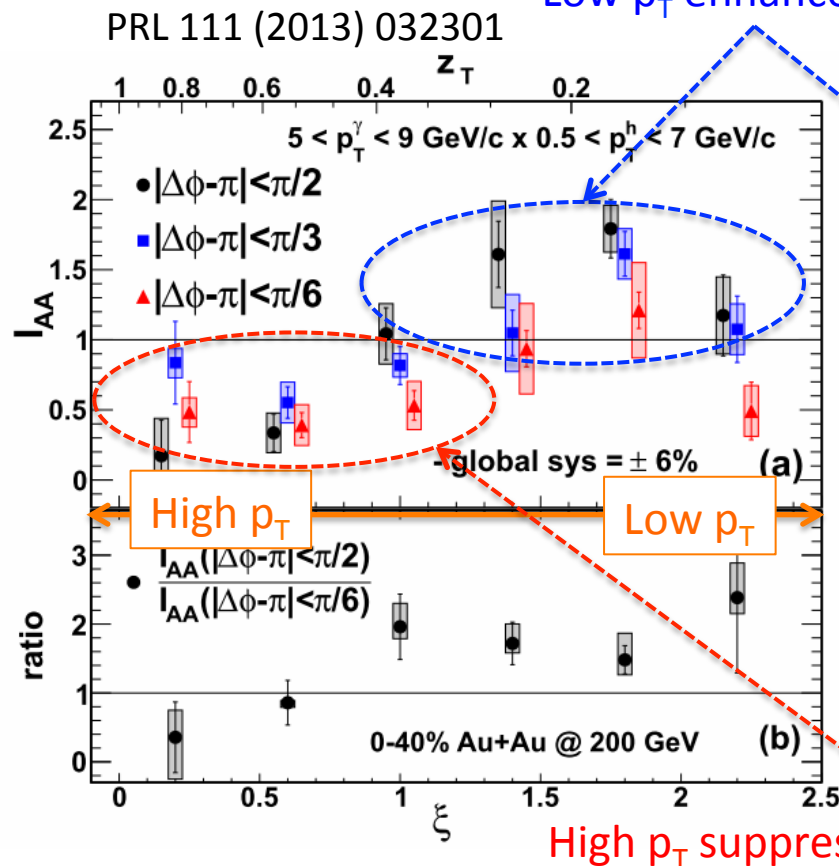
Low  $p_T$  enhancement

## jet - hadron correlation

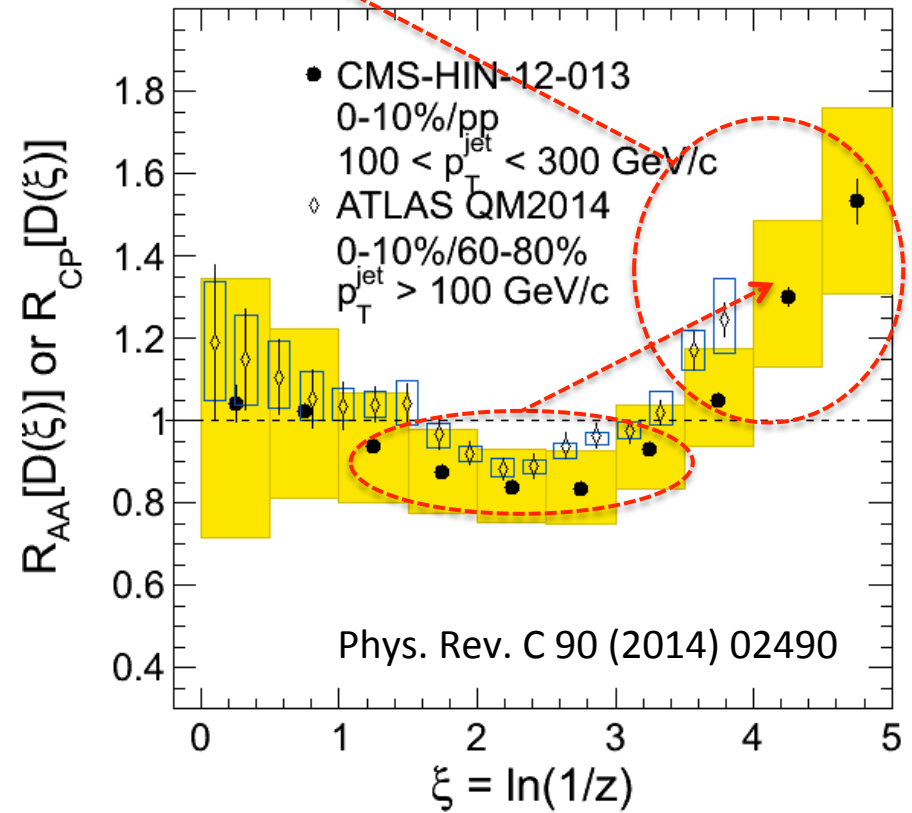
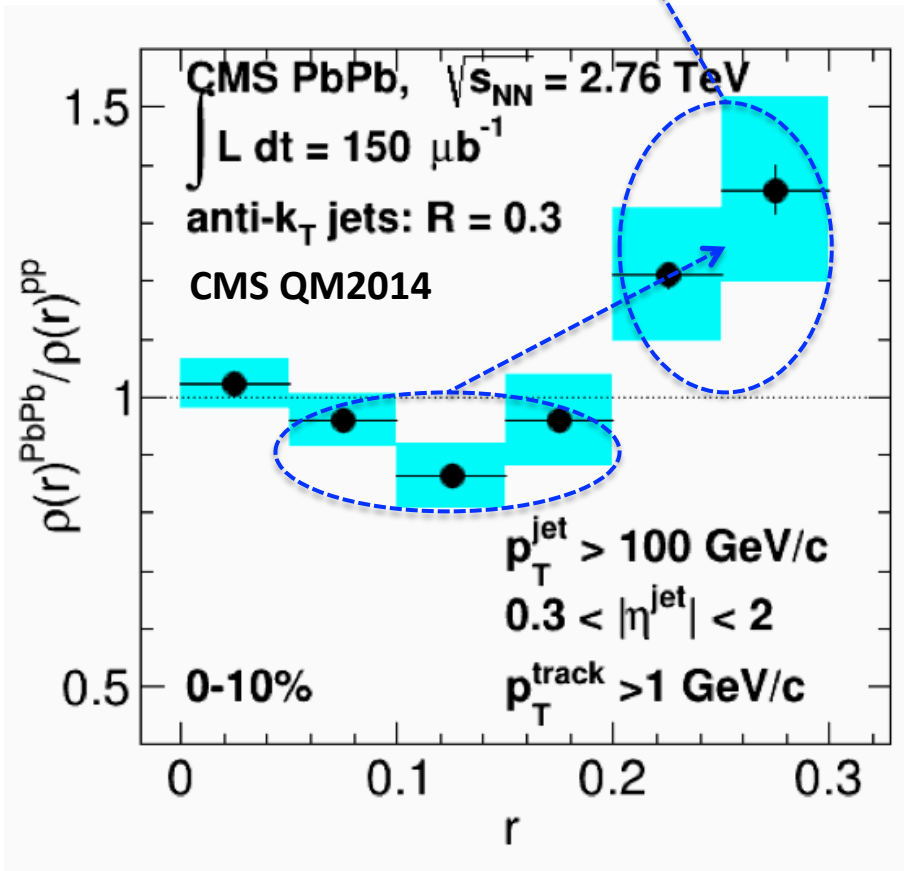
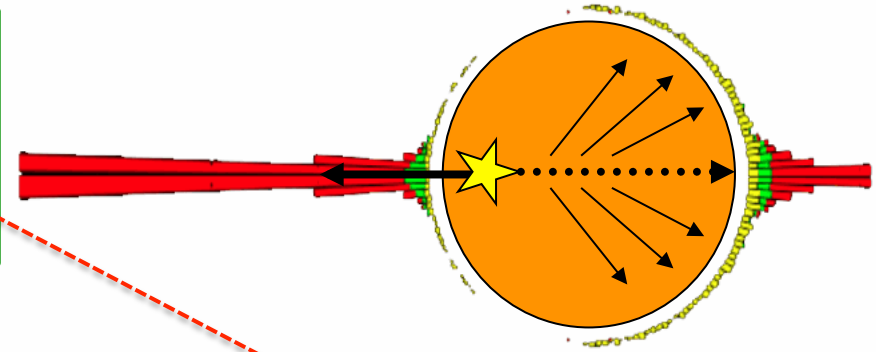
$S_{PT}$  = associate hadron  $p_T$  sum per jet

$$D_{AA} = S_{PT}(AA) - S_{PT}(pp)$$

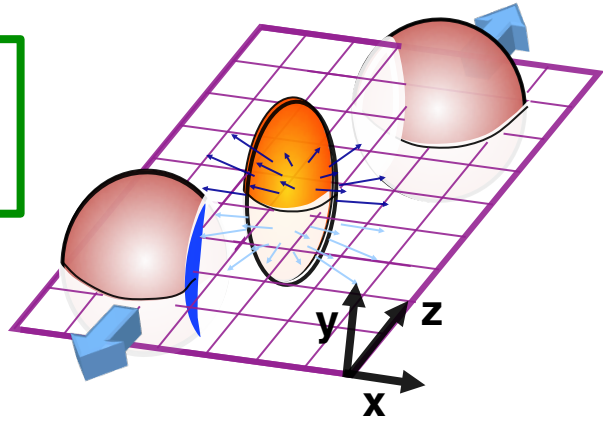
PRL 112 (2014) 122301



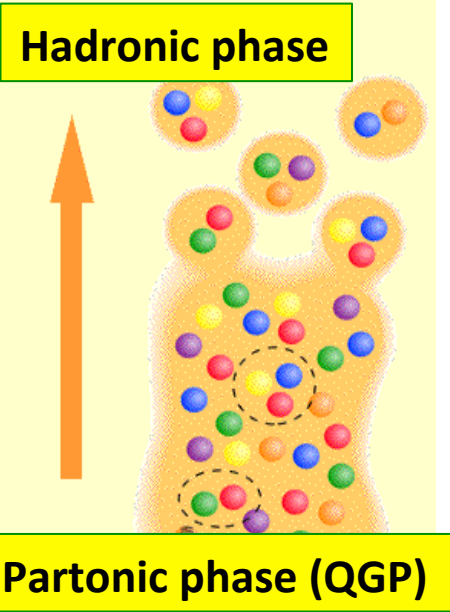
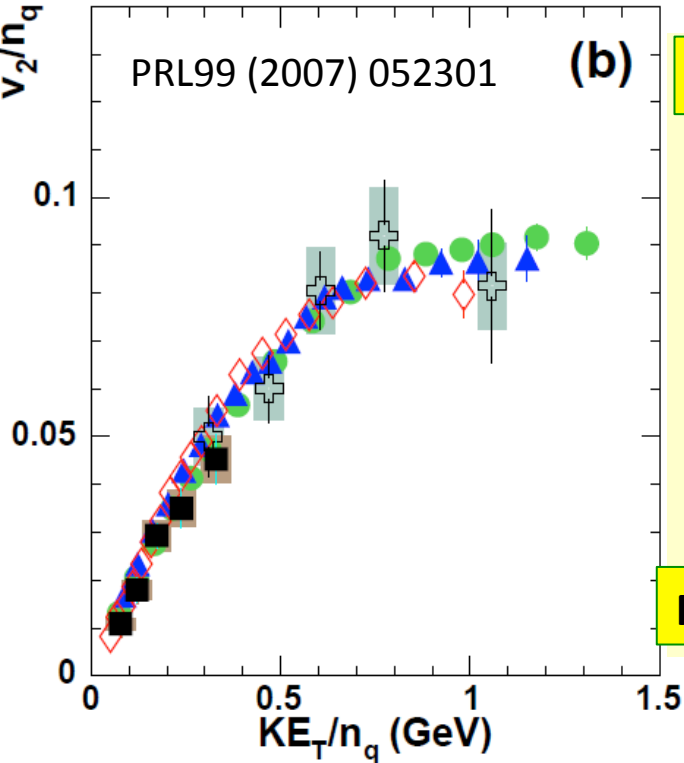
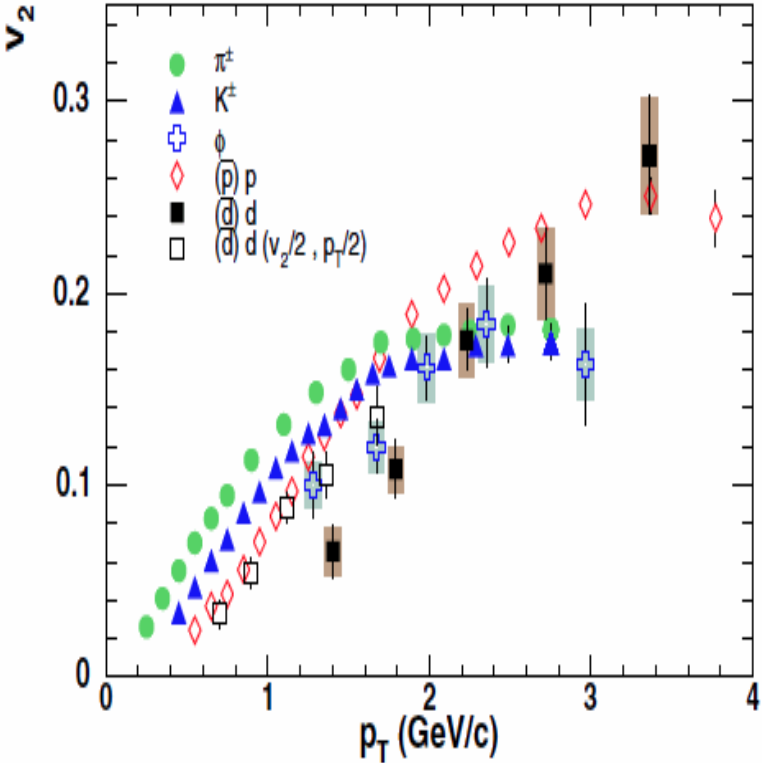
Modification of jet F.F. at LHC  
 re-distribution to lower  $p_T$   
 and to larger angle



Number of quark scaling in elliptic flow  
 --- quark coalescence feature ---

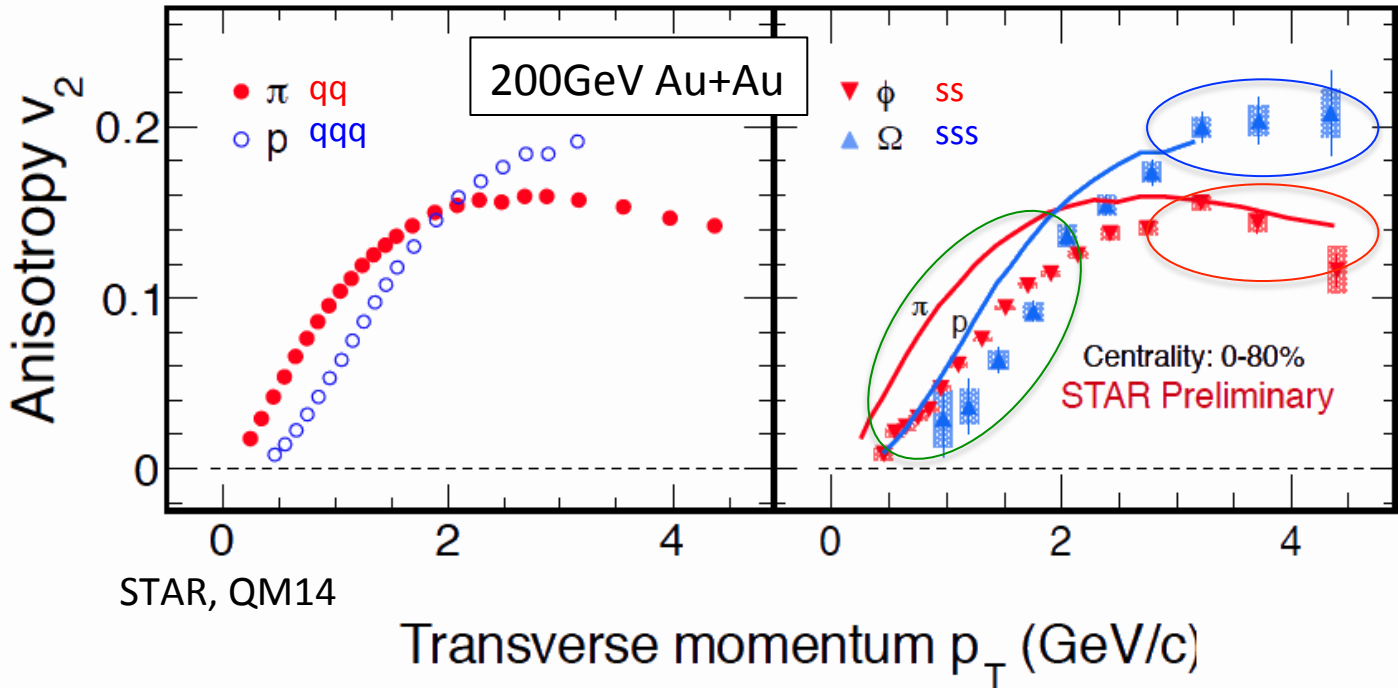
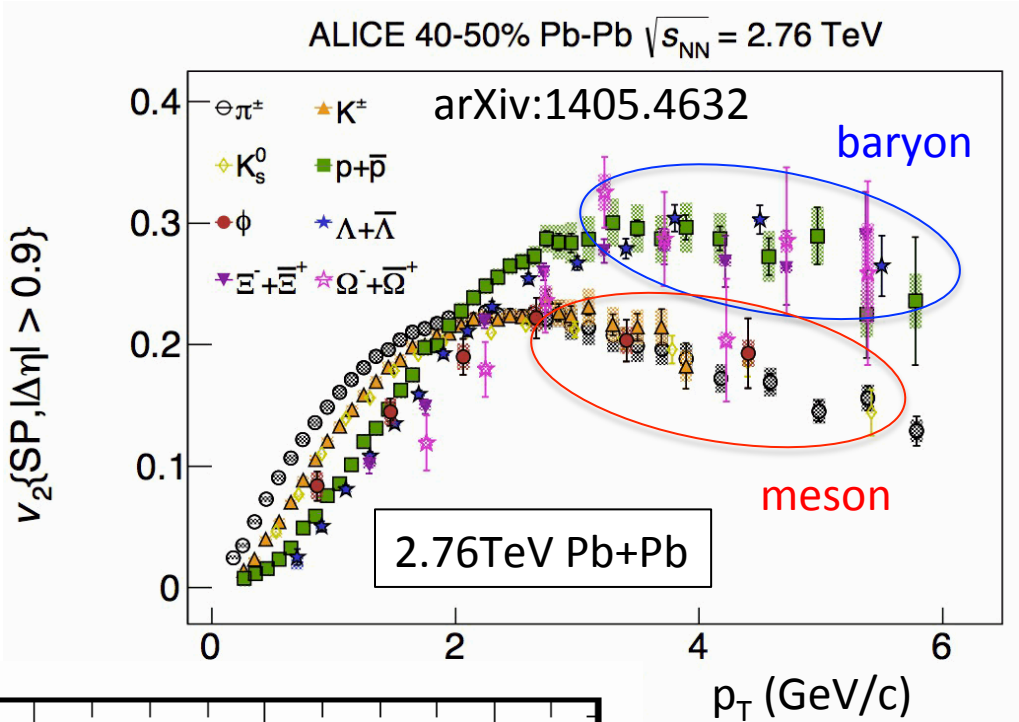


Indication of quark flow (in partonic phase)

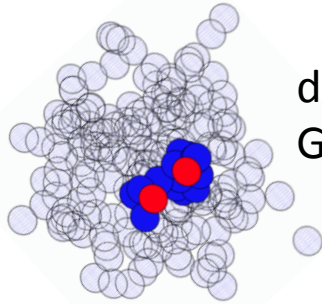


# Elliptic flow with PID at RHIC and LHC

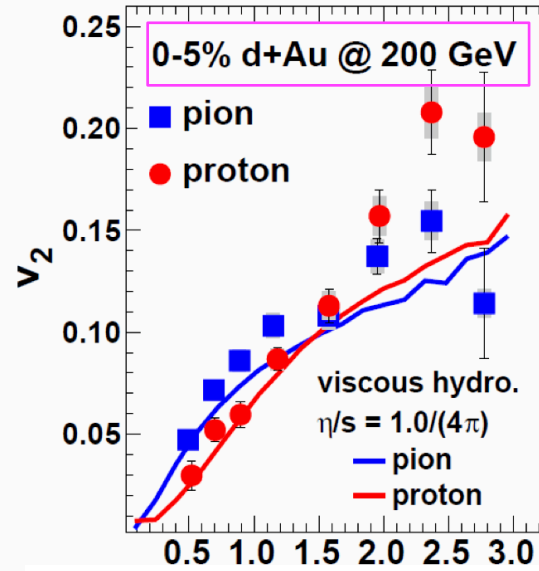
- High statistics measurements allow a precise comparison of  $v_2(p)$  and  $v_2(\phi)$ .
- Some small deviation from hydro-like mass dependence of  $v_2$  at low  $p_T$
- $\phi$  puzzle between peripheral and central at LHC



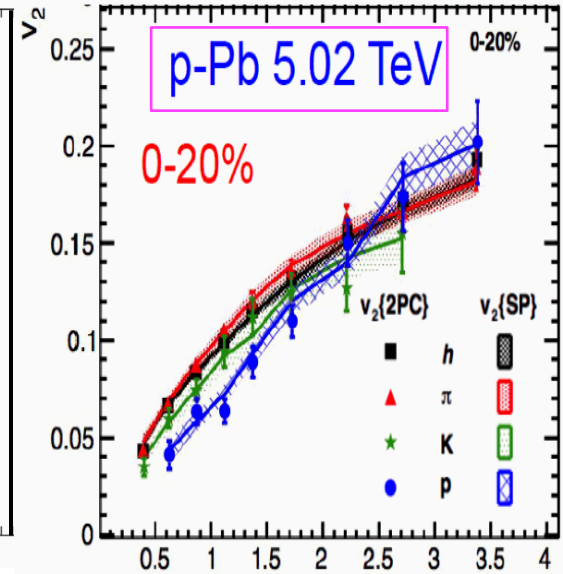
# Elliptic flow in a small system?



d+Au in  
Glauber model

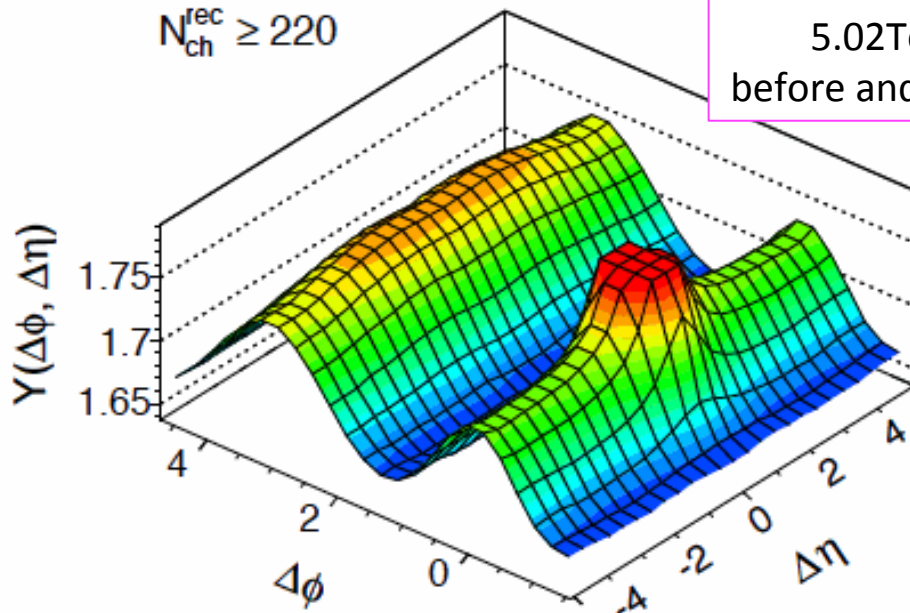


arXiv:1404.7461  $p_T$  (GeV/c)

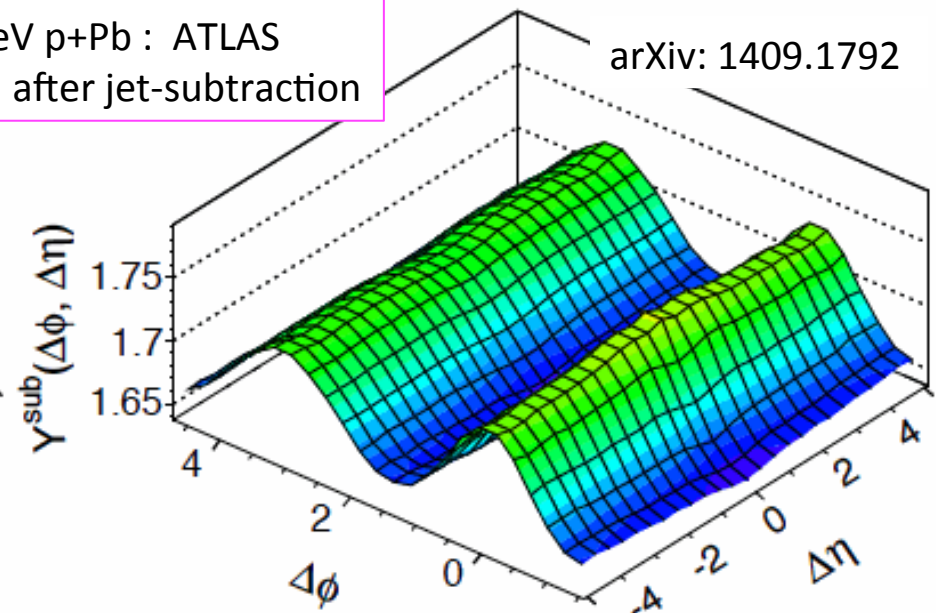


PLB 726 (2013) 164-177  $p_T$  (GeV/c)

$N_{ch}^{rec} \geq 220$

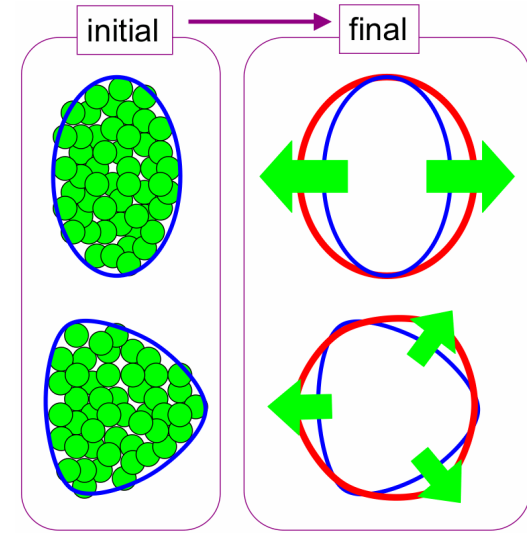
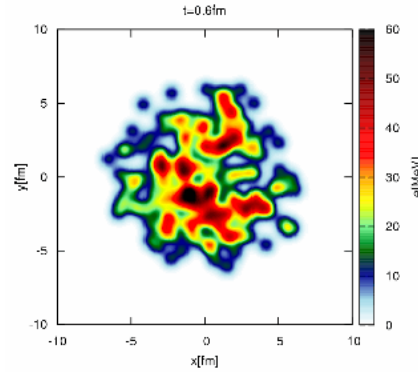
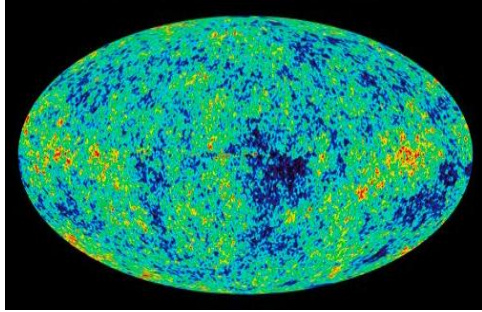


5.02 TeV p+Pb : ATLAS  
before and after jet-subtraction

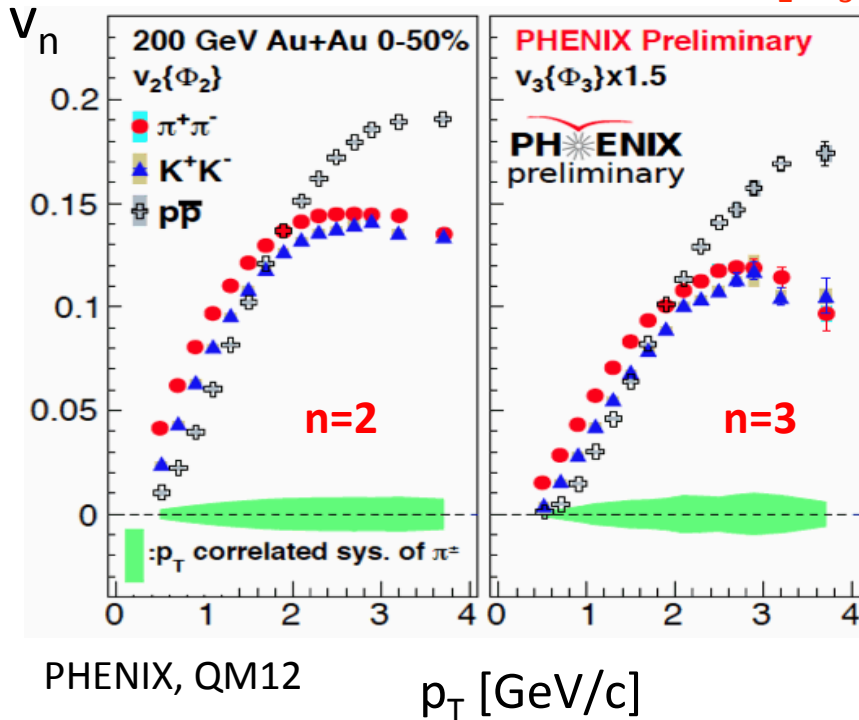


arXiv: 1409.1792

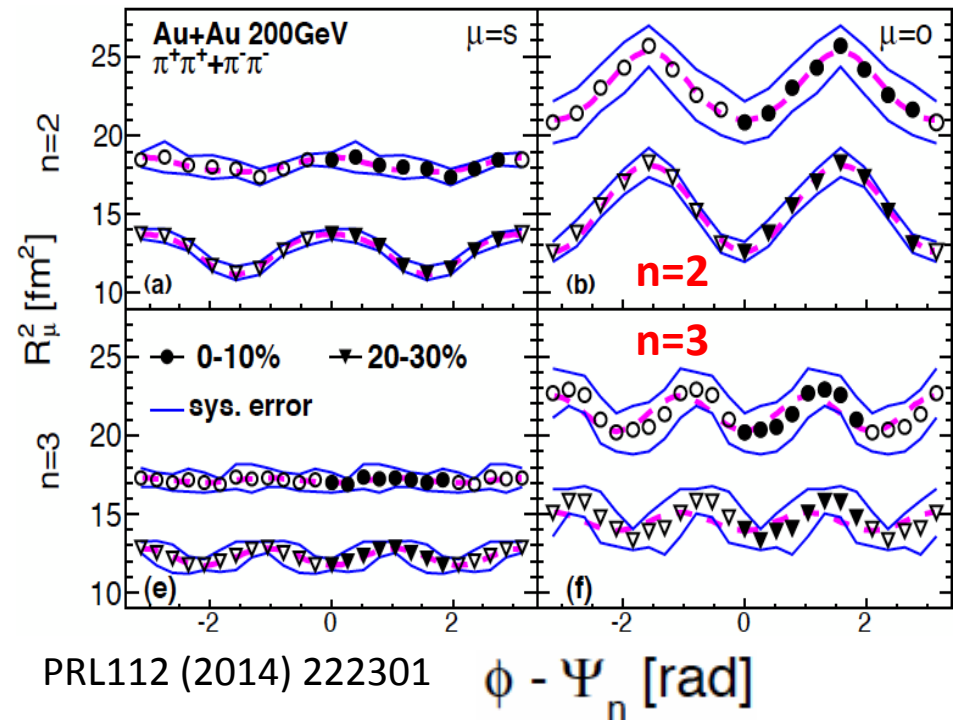
# Triangular expansion and shape



Elliptic and Triangular expansion :  $v_2, v_3$

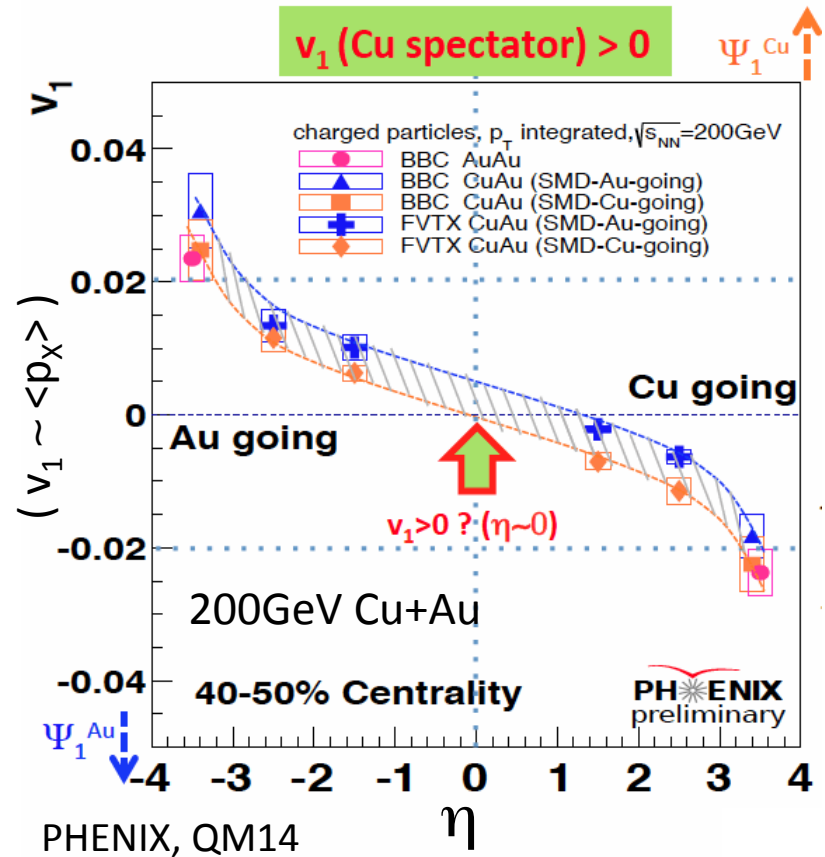
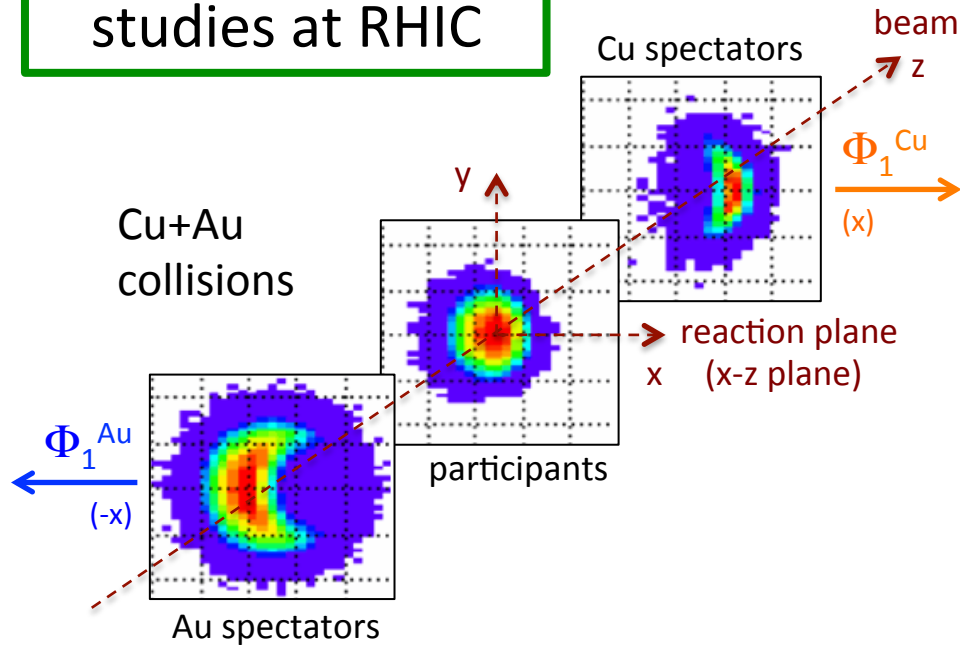


Elliptic and Triangular shape :  $R_{\Phi_2}^{\text{HBT}}, R_{\Phi_3}^{\text{HBT}}$



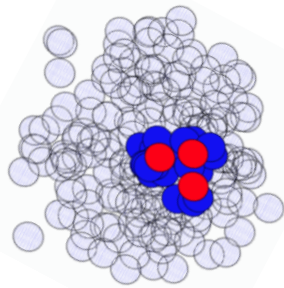


# Various flow studies at RHIC

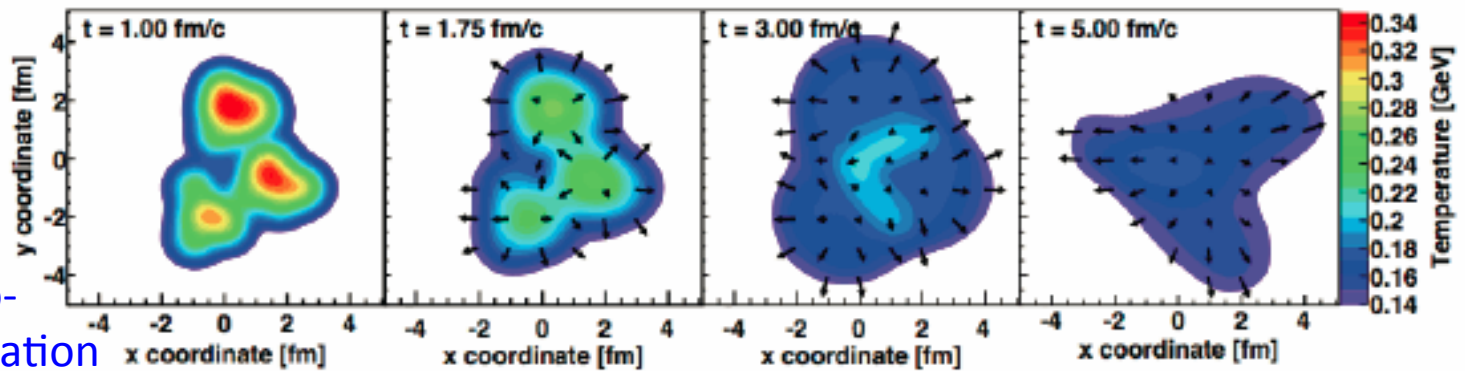


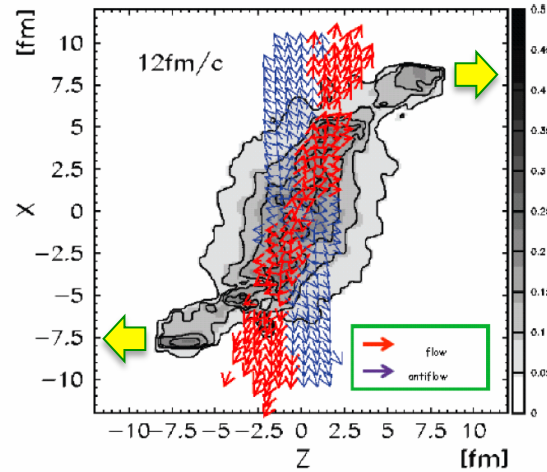
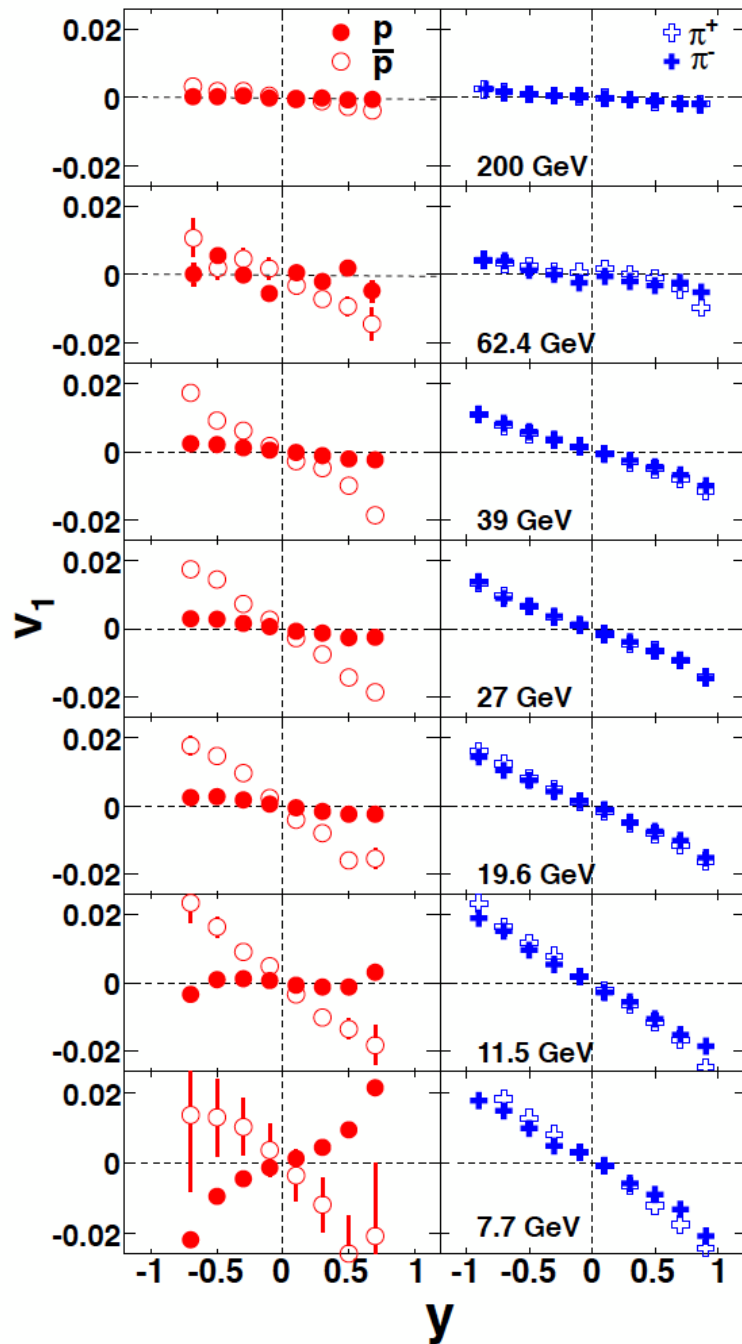
$^3\text{He}+\text{Au}$  collision data on tape in RHIC-RUN14

arXiv: 1312.4565



hydro-calculation





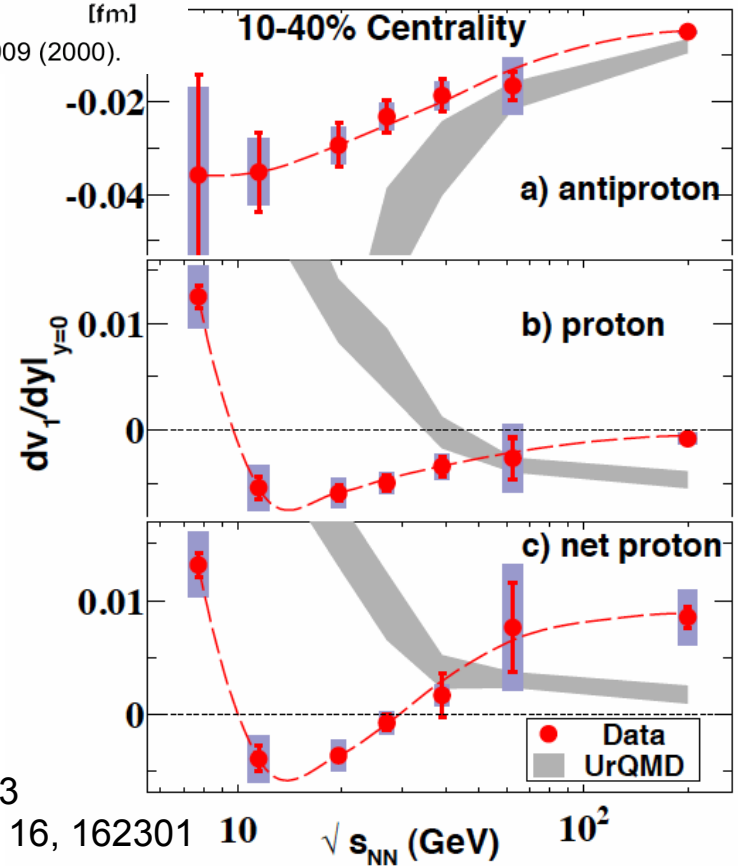
J. Brachmann et al., PRC 61, 24909 (2000).

**Directed Flow  $v_1$**

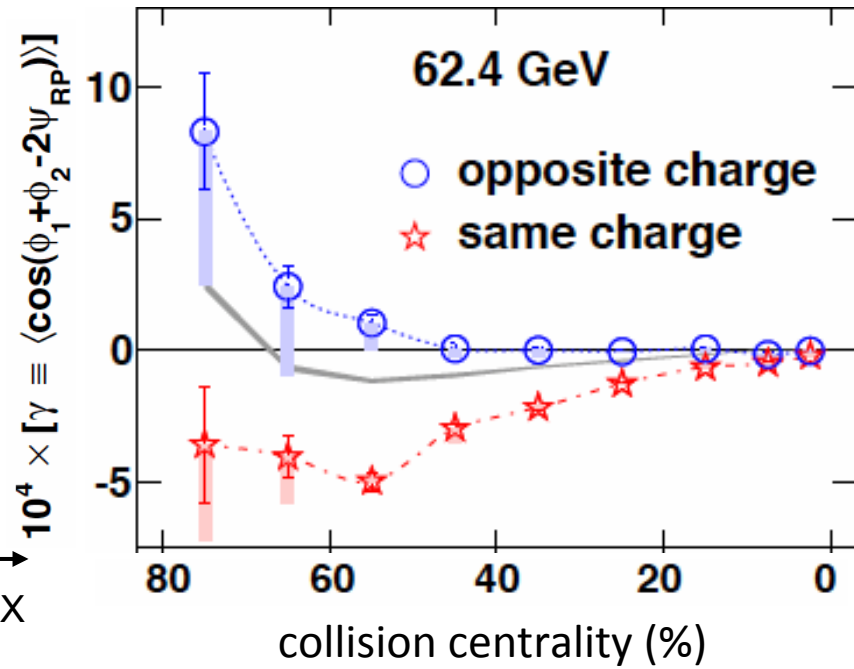
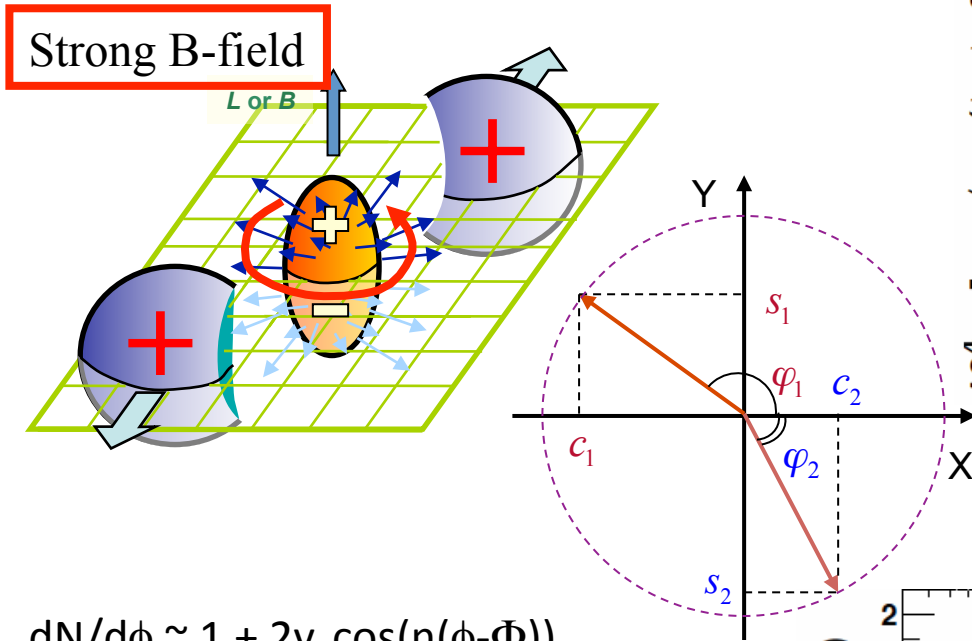
- System pressure via interaction
- Equation of state of quark nuclear matter

arXiv:1401.3043

PRL112 (2014) 16, 162301



charge separation signal w.r.t. reaction plane from local parity violation

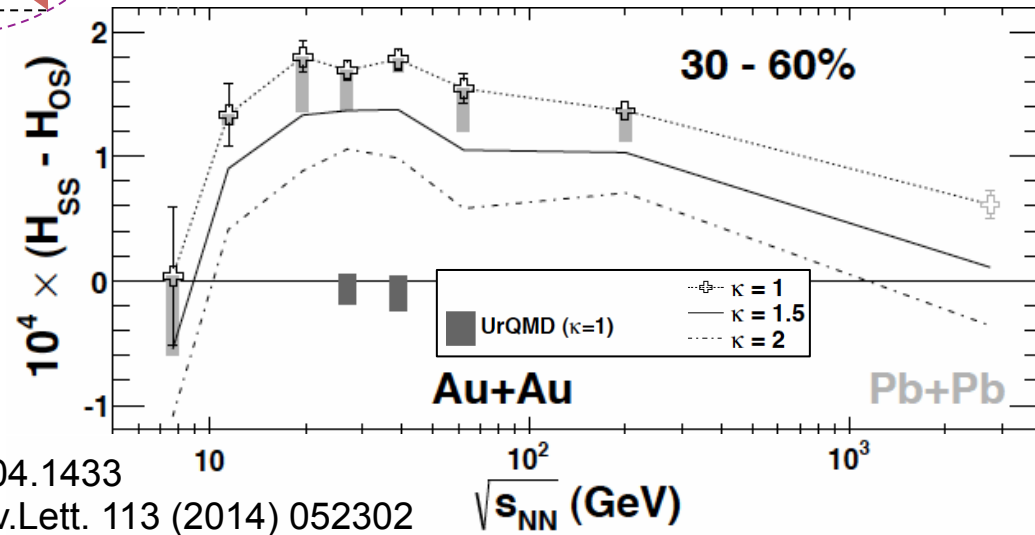


$$dN/d\phi \sim 1 + 2v_n \cos(n(\phi - \Phi)) + 2a_{+/-} \sin(\phi - \Phi)$$

$$\langle \cos(\phi_1 + \phi_2 - 2\Phi) \rangle \sim -\langle a_1 a_2 \rangle$$

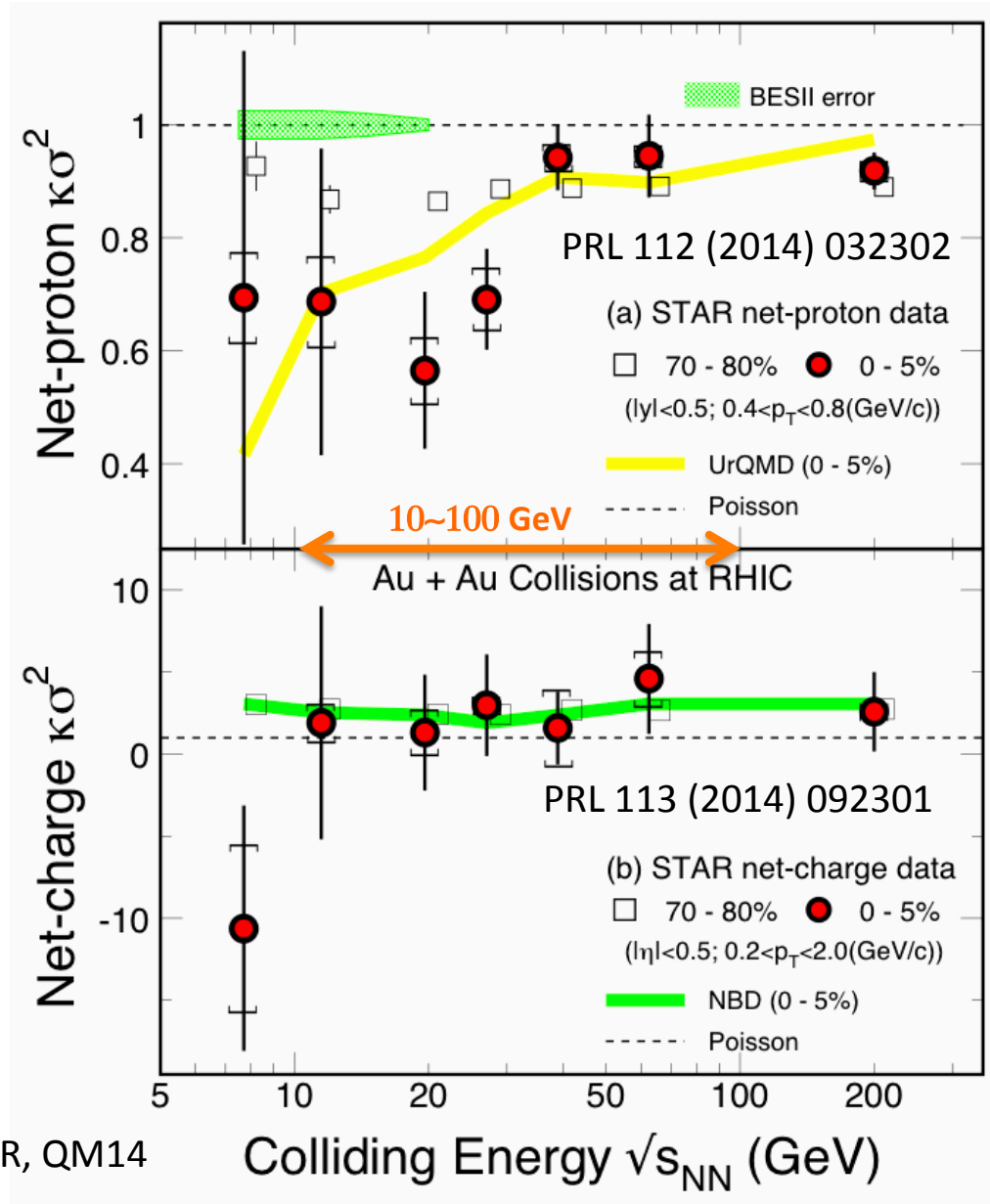
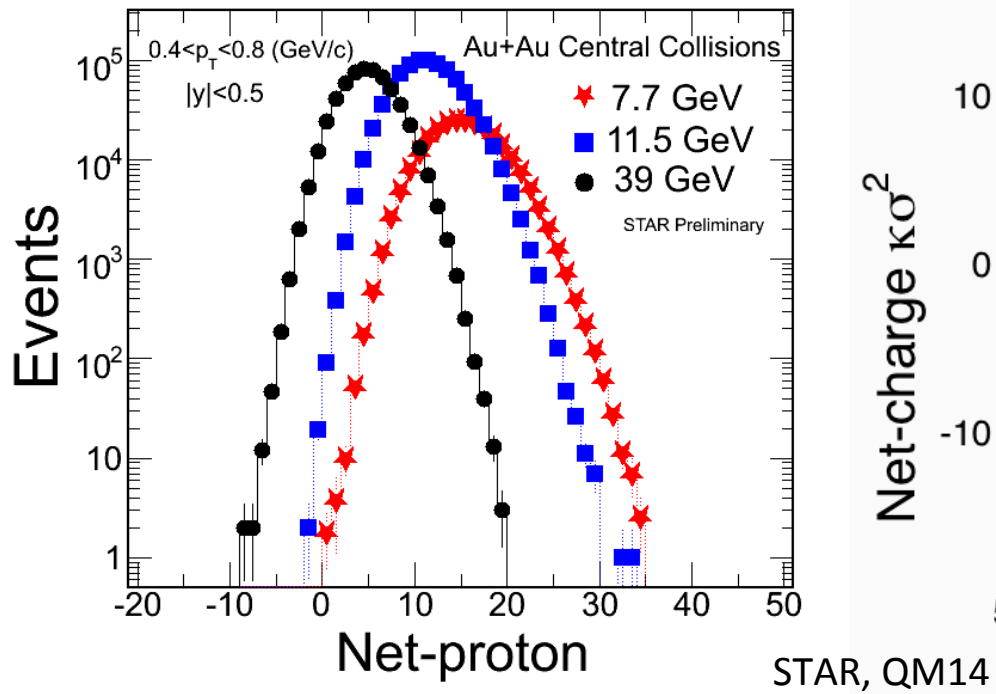
$$\gamma \equiv \langle \cos(\phi_1 + \phi_2 - 2\Psi_{RP}) \rangle = \kappa v_2 F - H$$

$$\delta \equiv \langle \cos(\phi_1 - \phi_2) \rangle = F + H,$$



arXiv:1404.1433  
Phys.Rev.Lett. 113 (2014) 052302

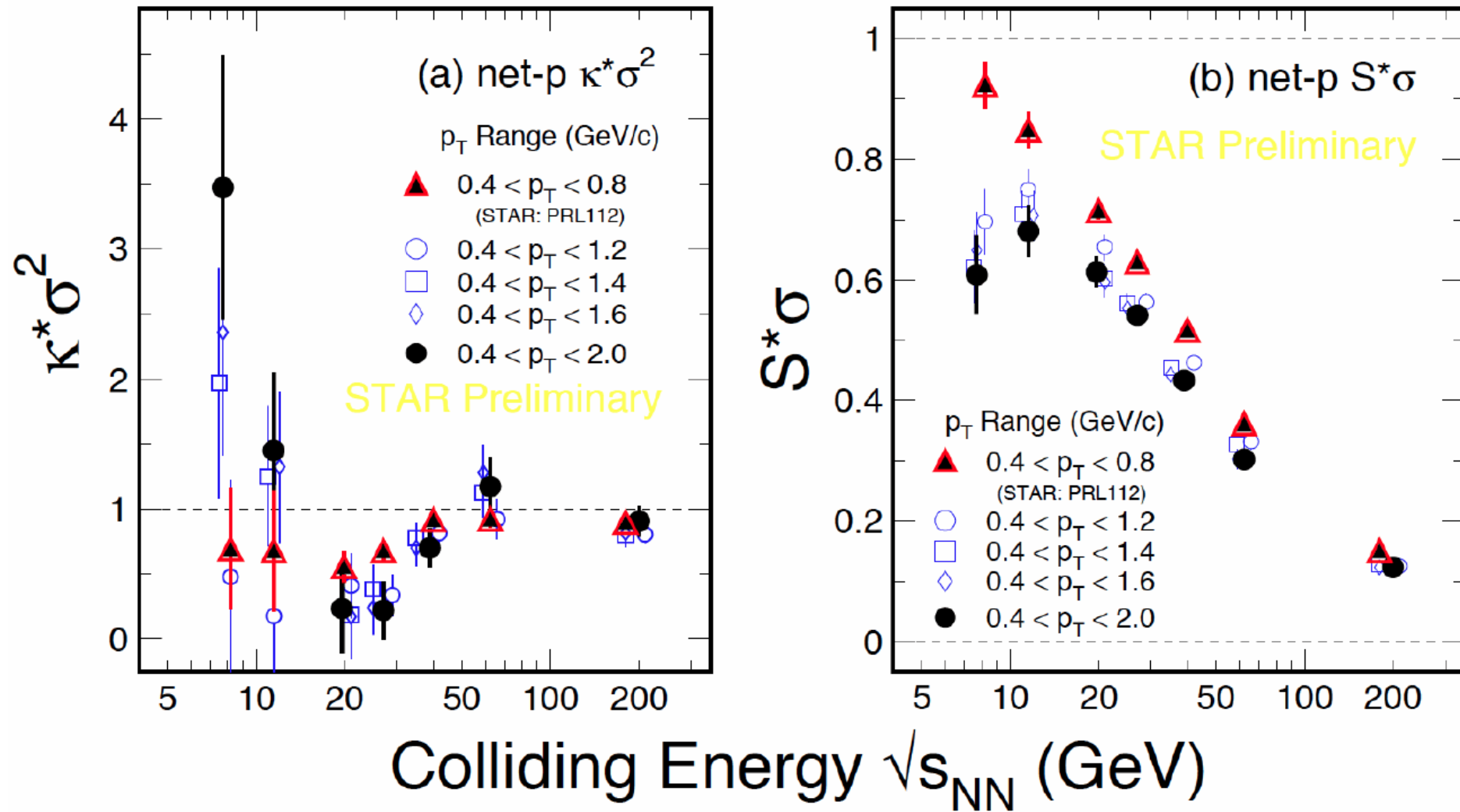
Fluctuation of conserved quantities such as net-baryon, net-charge distribution



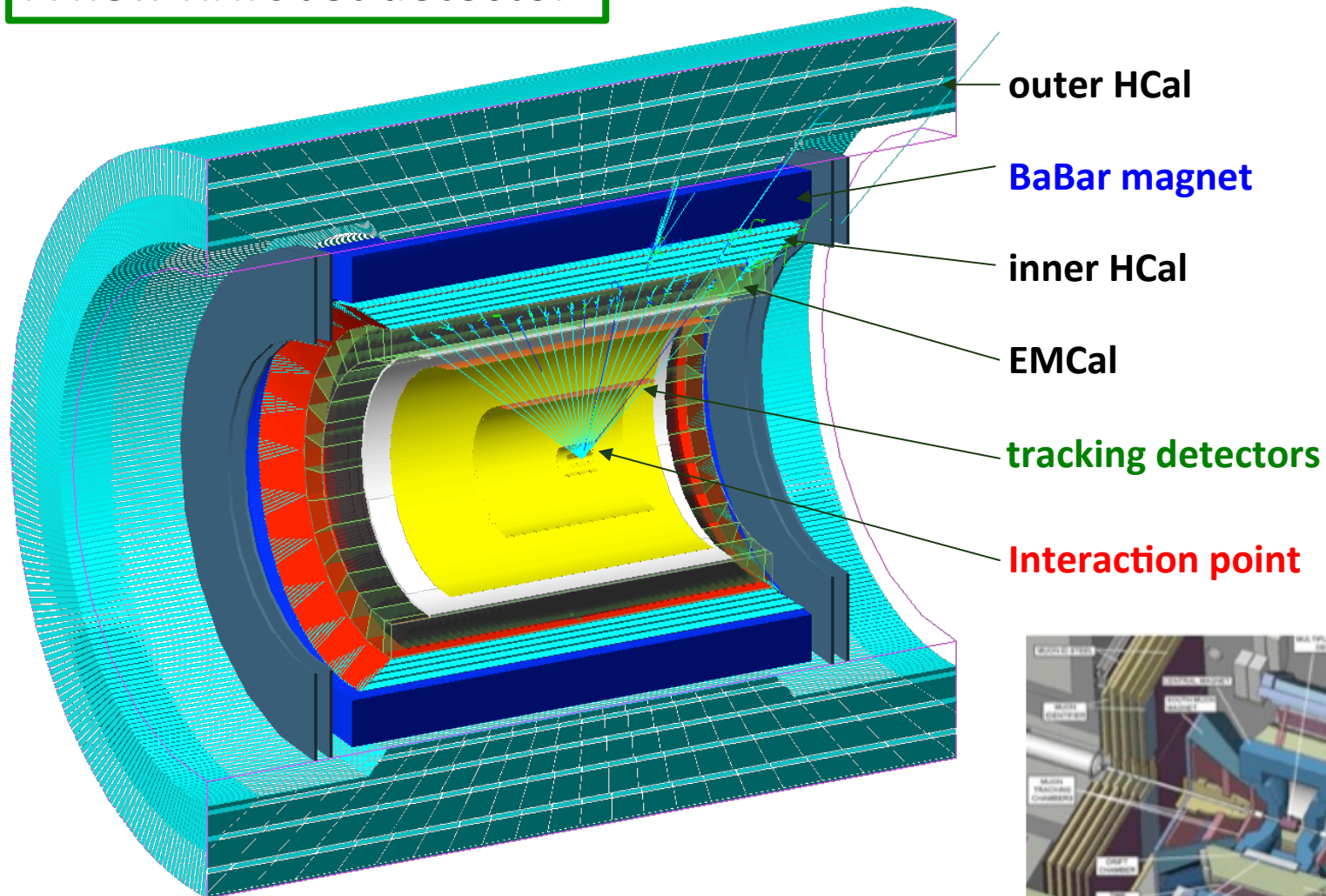
# New data on net-proton distribution

0-5% Au + Au Central Collisions at RHIC

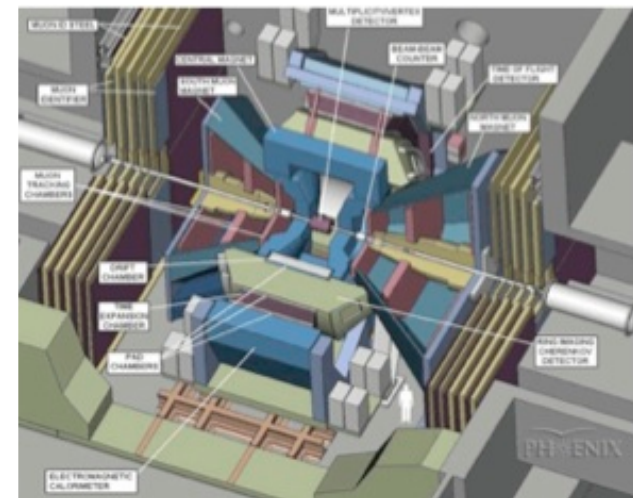
X. Luo, CPOD2014



# A new RHIC Jet detector

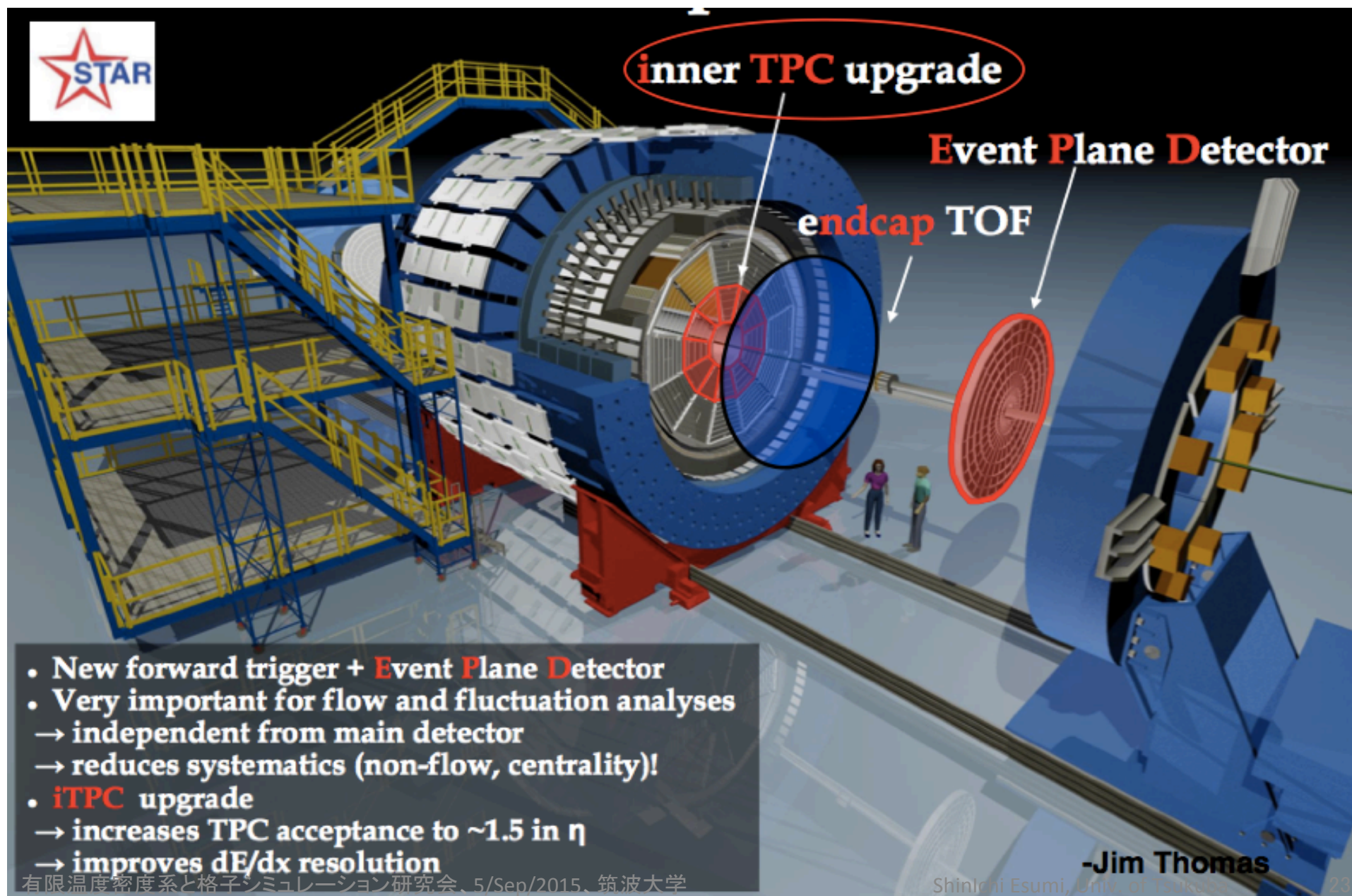


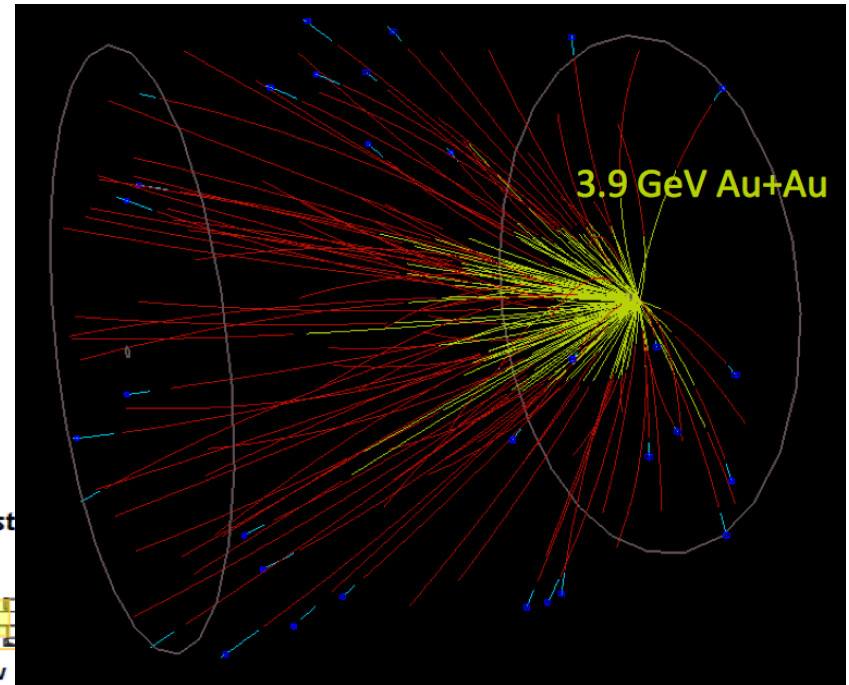
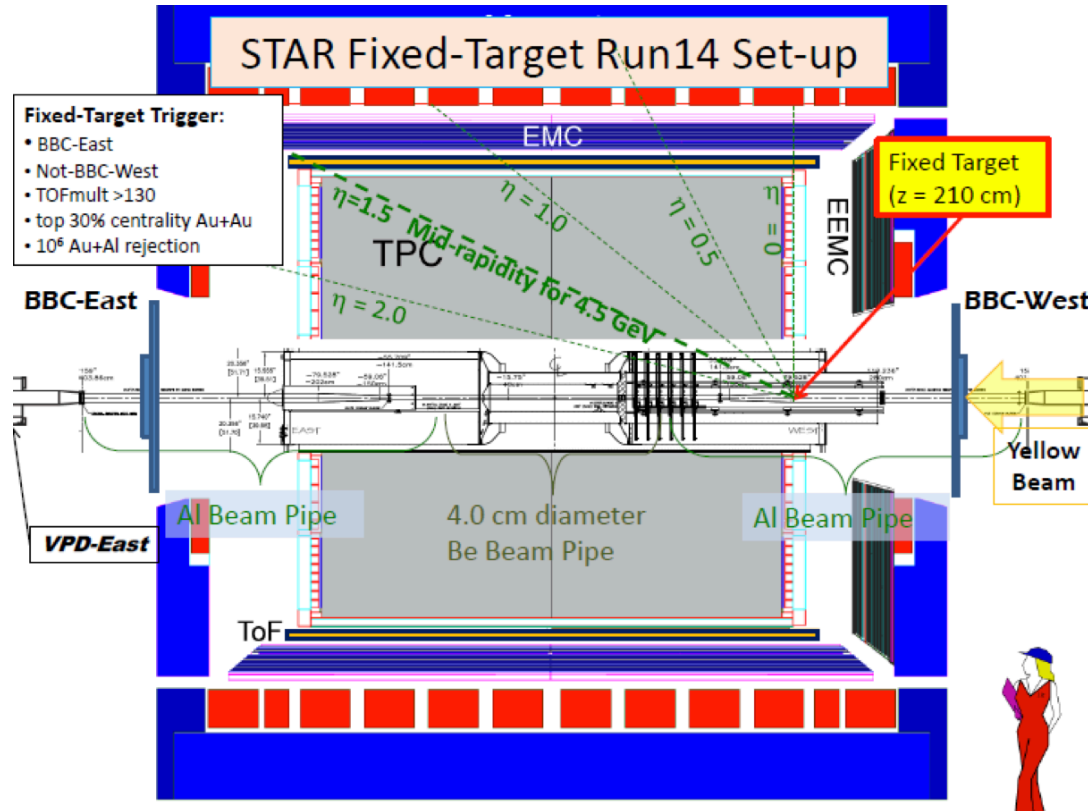
Shutdown PHENIX detector  
after run16 (next year)



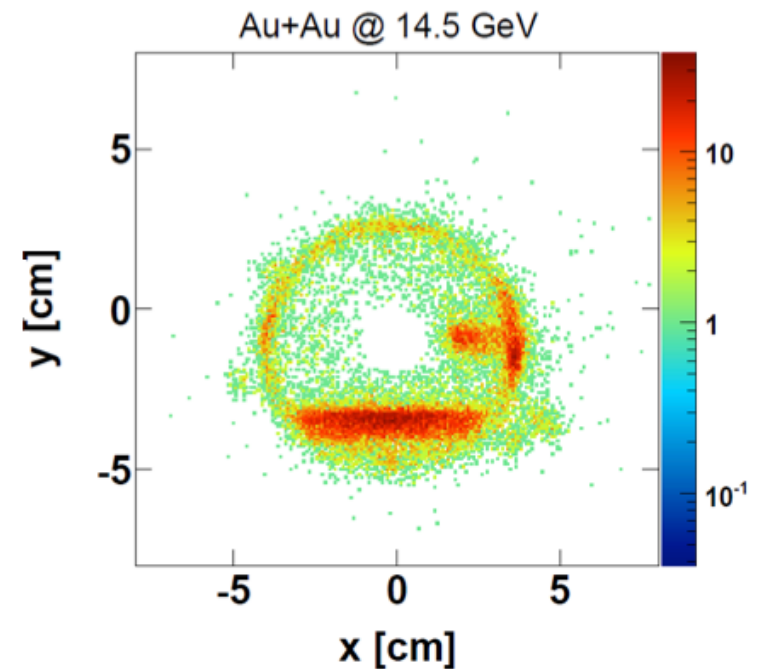
## Beam Energy Scan Program II at RHIC-STAR

R. Vértési, Dec/2014,  
14. Zimányi Winter School



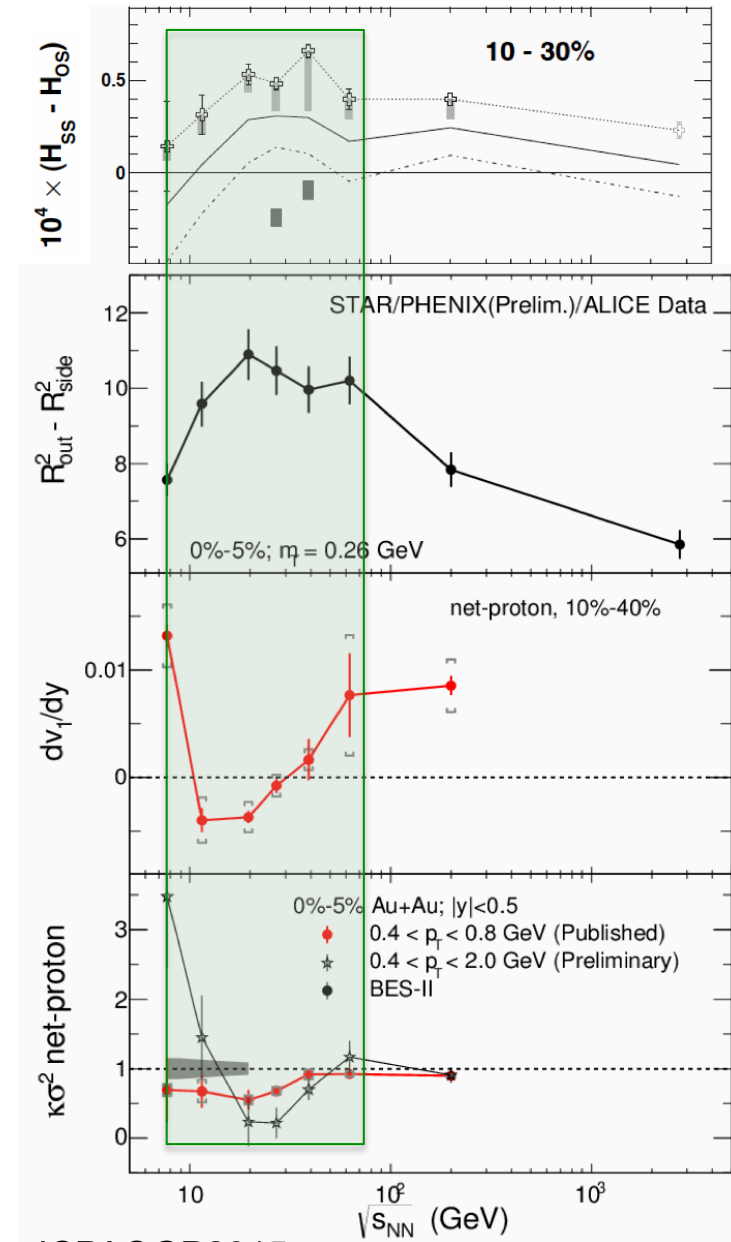
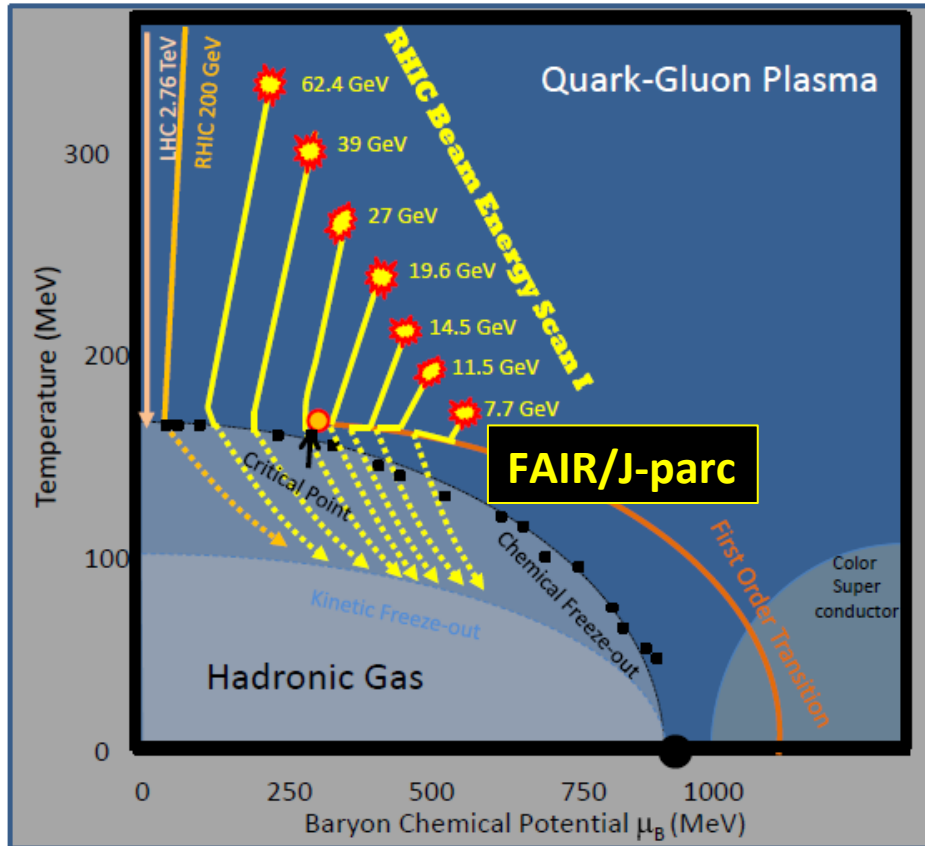


- Target inserted into beam pipe
- Only a small percentage
- Does not interfere with collider mode data taking

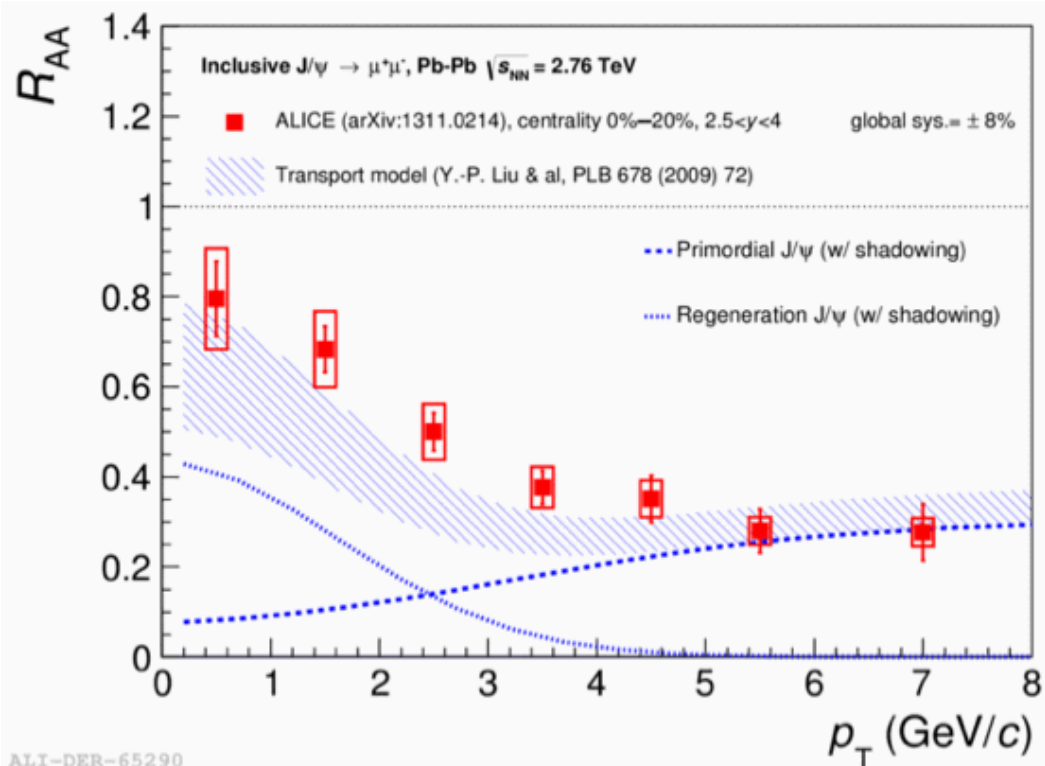




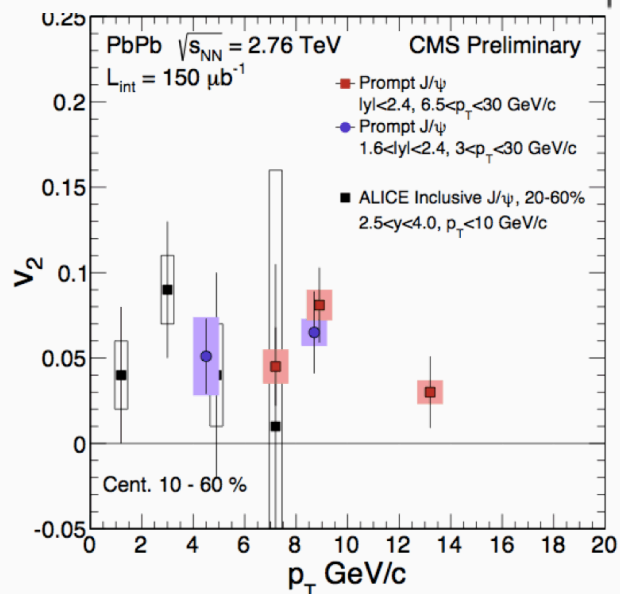
# Summary of Beam Energy Scan Program I



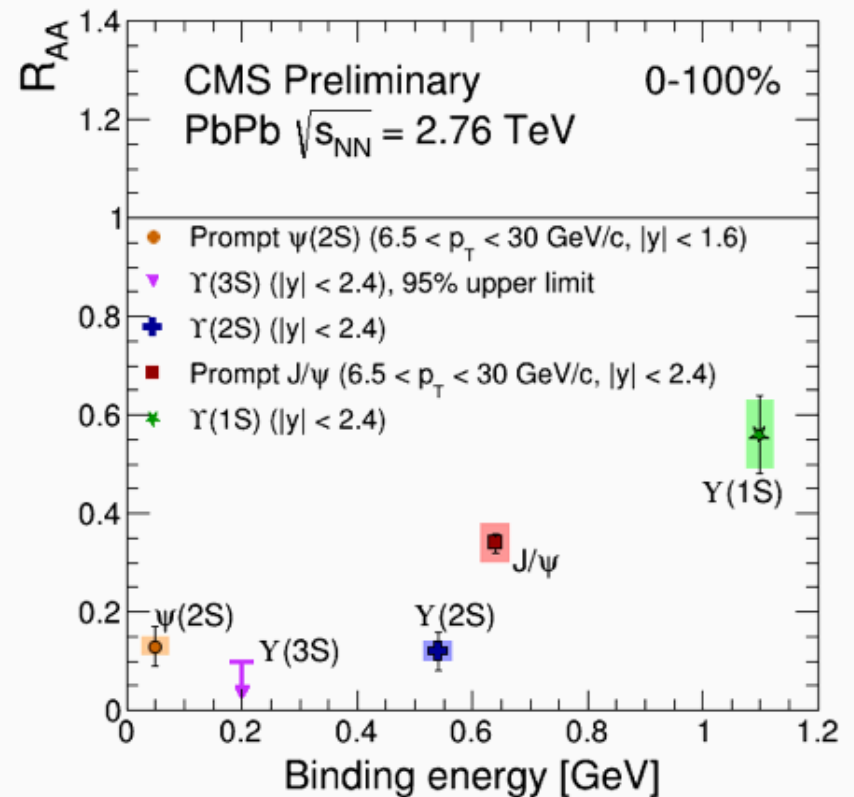
Z. Xu, ICPAQGP2015



ALI-DER-65290



## J/psi suppression and regeneration

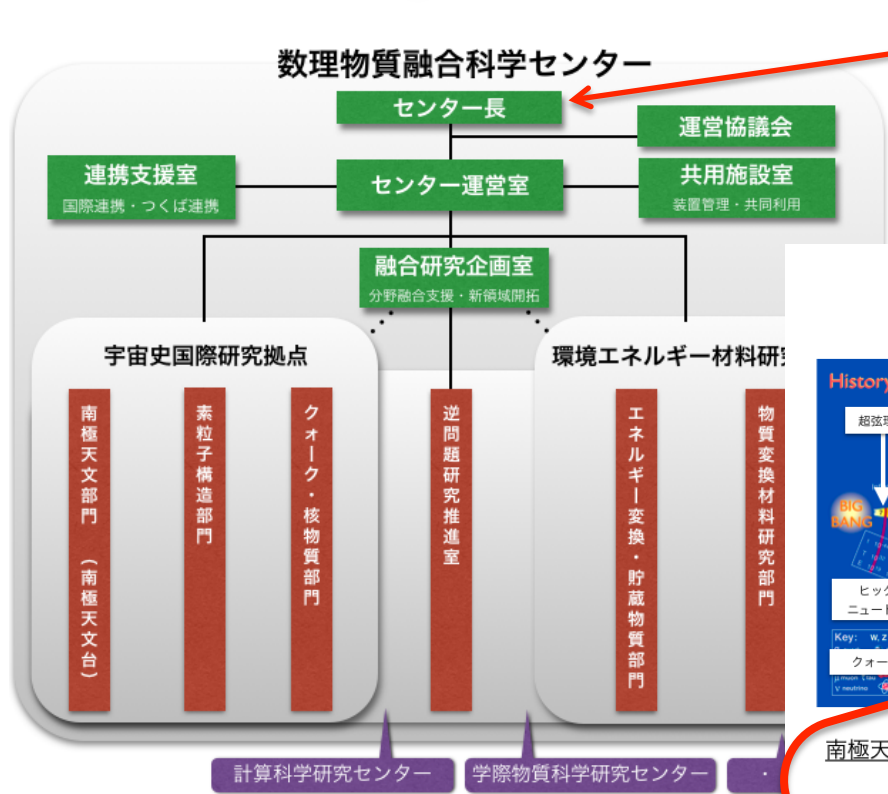


# 数理物質融合科学センター

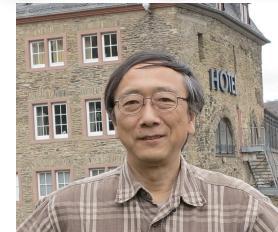
CiRfSE (サーフス)

筑波大学 数理物質系

Center for Integrated Research in Fundamental Science and Engineering, University of Tsukuba



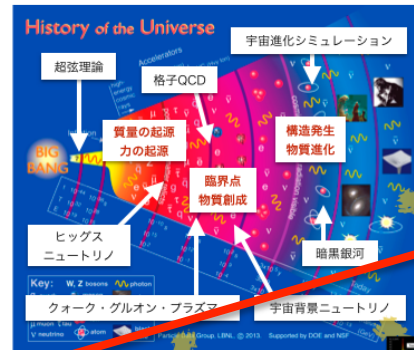
金谷センター長



<http://www2.ccs.tsukuba.ac.jp/people/kanaya/>



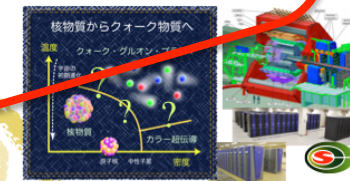
## 宇宙史国際研究拠点



ミッション：素粒子・原子核・宇宙物理学の融合と、実験的・理論的アプローチの協調により、宇宙史を統一的に理解

拠点長(コーディネータ)：金信弘教授

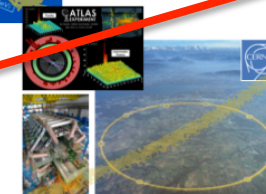
クォーク・核物質部門



部門長(PI)：江角晋一准教授

ビッグバン数 $\mu$ 秒後の初期宇宙における高温クォーク・グルオン・プラズマ(QGP)状態と中性子星・クォーク星内部における高密度QGP状態の解明、及び、高温と高密度の中間領域に予測される臨界点の探索

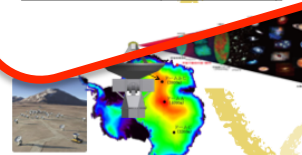
素粒子構造部門



部門長(PI)：受川史彦教授

ヒッグス粒子とニュートリノの実験的研究および超弦理論の研究により、素粒子の基本的性質を理解し、宇宙史の統一的描像を構築

南極天文部門(南極天文台)



部門長(PI)：中井直正教授

南極望遠鏡および関連装置による遠方宇宙等の観測により、銀河の形成と進化および宇宙の構造を解明

「南極天文コンソーシアム」

「宇宙史コンソーシアム」

逆問題研究推進室との協力によるデータ解析手法開発

人類の知識が及んでいない「暗黒」の解明

=> 暗黒物質、暗黒エネルギー、暗黒銀河、…  
=> 物質創成・構造発生とそれらの進化

<http://www.pas.tsukuba.ac.jp/~CiRfSE/index.html>

Back-up slides