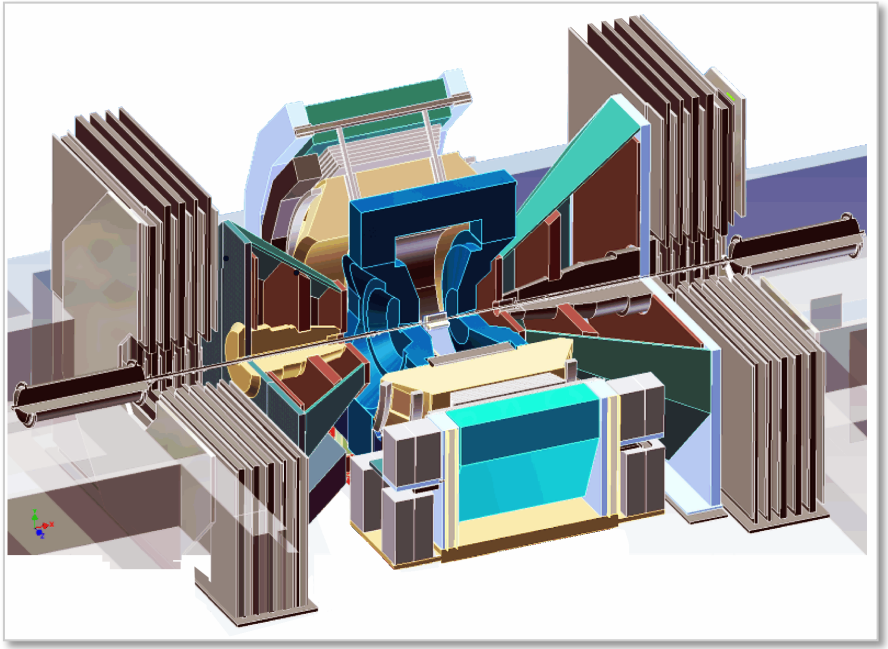
Experimental research on Quark Gluon Plasma with relativistic heavy-ion collisions at RHIC

ShinIchi Esumi
Inst. of Physics, Univ. of Tsukuba
Center for Integrated Research in Fundamental Science and Engineering (CiRfSE)

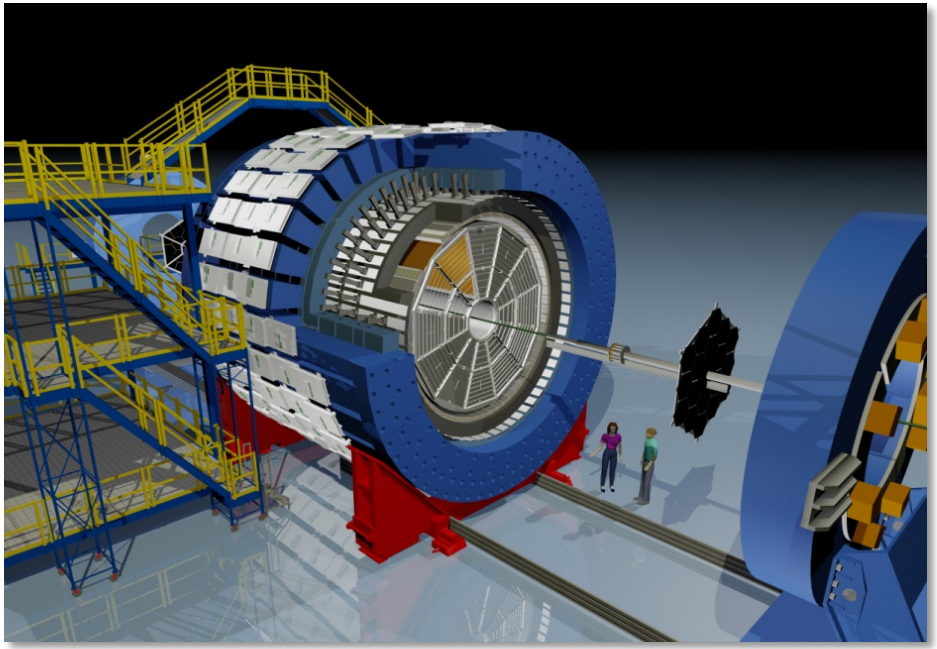
Contents

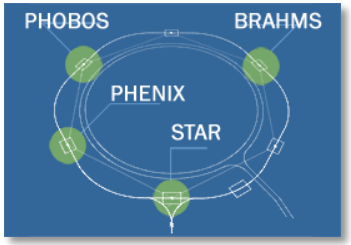
- **Collective flow**
- **Jet quenching**
- **Correlation & fluctuation**
- **Beam energy dependence (Critical point)**

PHENIX experiment



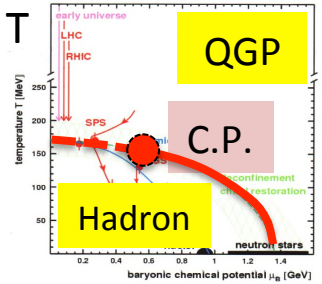
STAR experiment





PHOBOS experiment
BRAHMS experiment

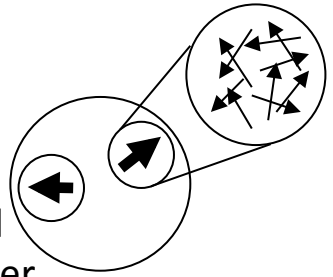
Chemical and Thermal kinetic freeze-out with radial flow

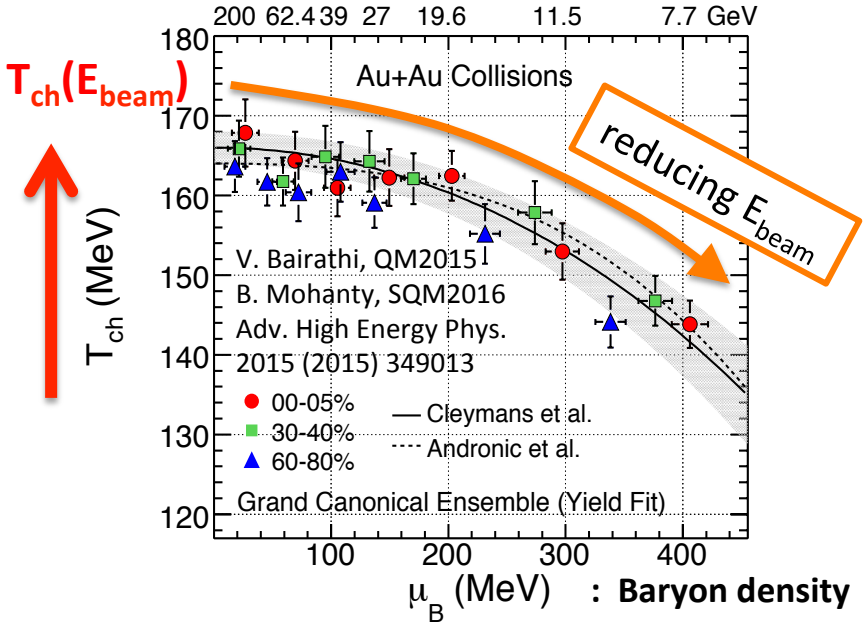


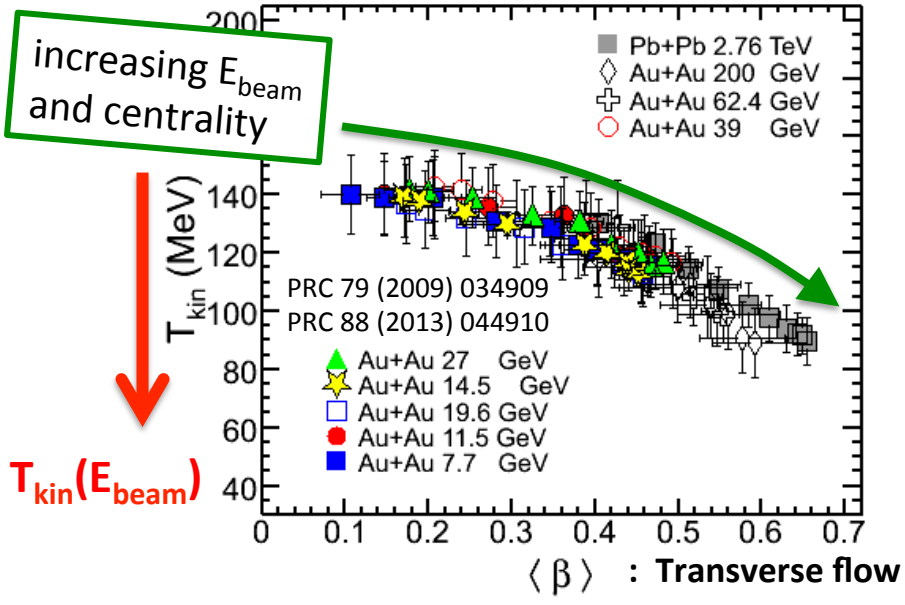
μ_B

Hadron yields are fitted with chemical thermal model in order to extract (T_{ch}, μ_B) parameters.

Hadron pT spectra are fitted with Blast-wave model in order to extract (T_{kin}, β_T) parameters.

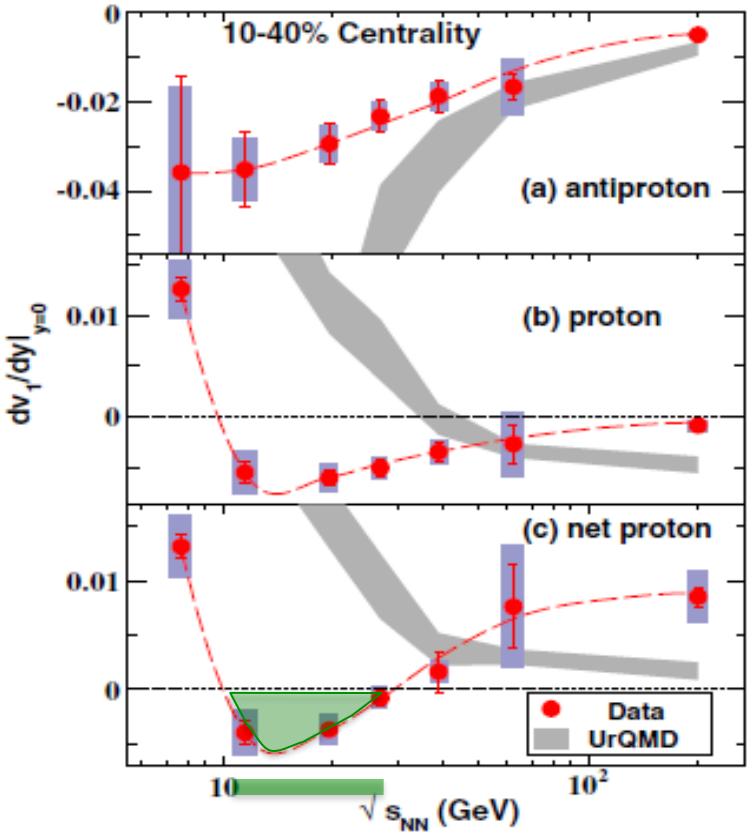




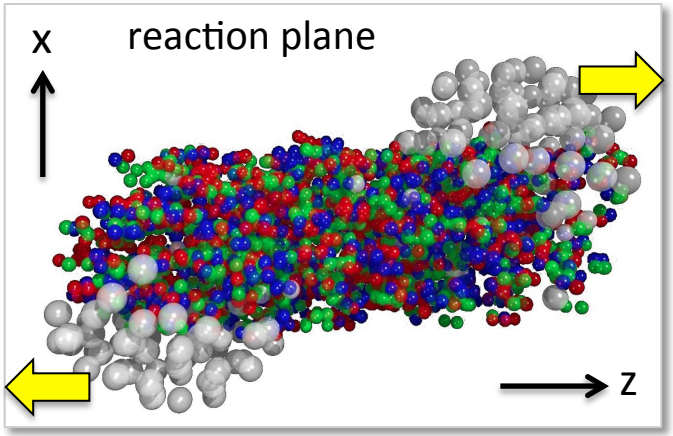


Directed flow (v_1)

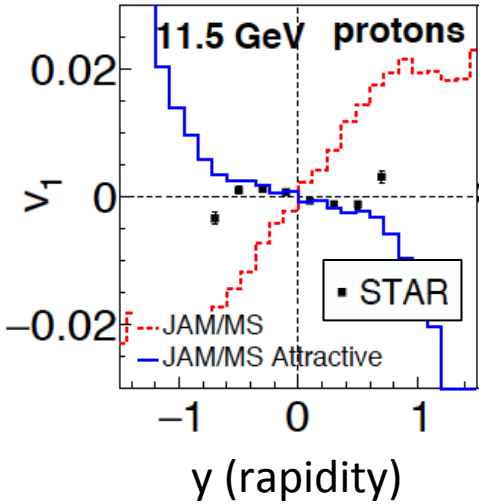
Phys. Rev. Lett. 112 (2014) 162301

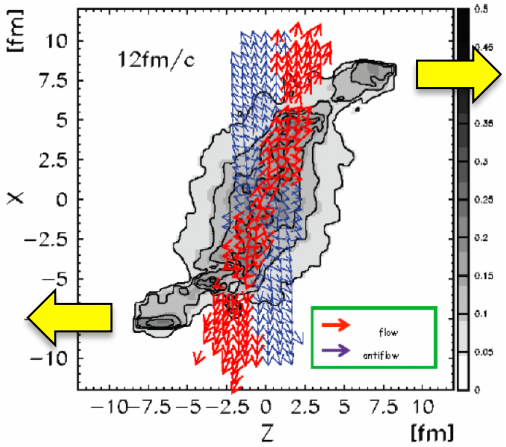


- negative slope of dv_1/dy for net-proton
- softening of Equation of State



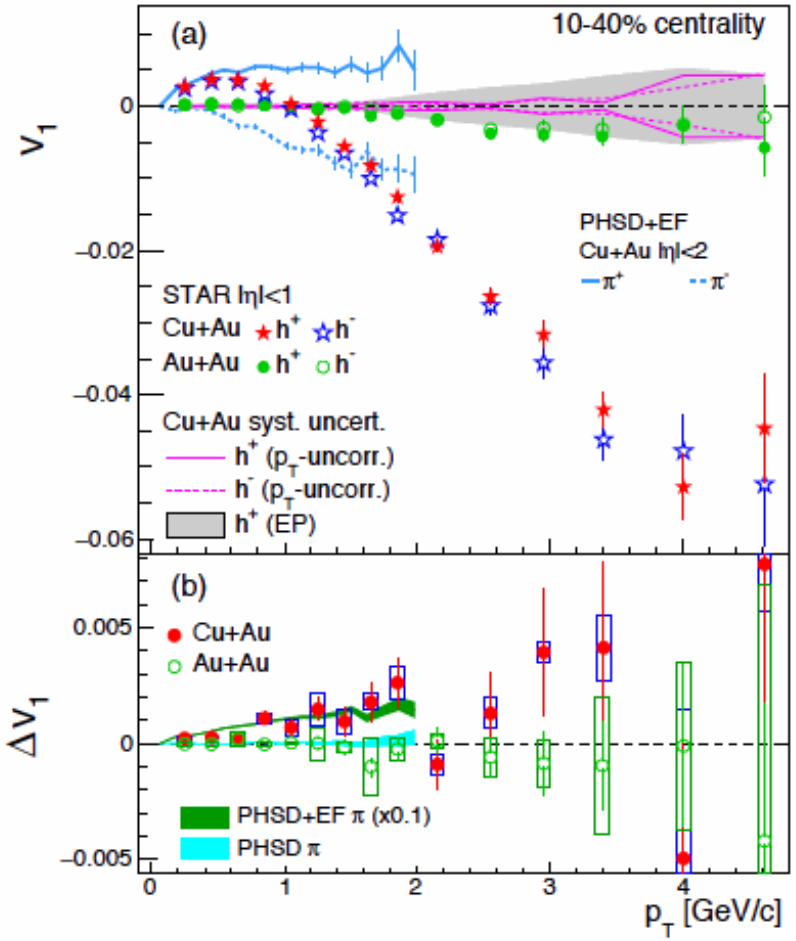
arXiv : 1601.07692





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

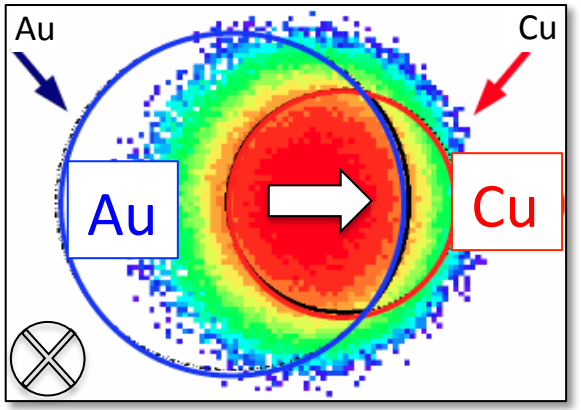
arXiv : 1608.04100, STAR, QM15



Directed flow (v_1) in Cu+Au at RHIC

pressure gradient from asymmetric system :
Non-zero v_1 at $\eta \sim 0$

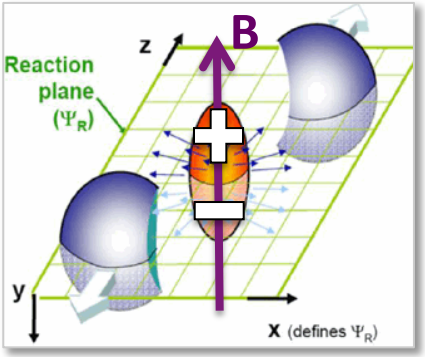
Possible E-field effect :
Charge dependent v_1
$\Delta v_1 = v_1\{h^+\} - v_1\{h^-\}$

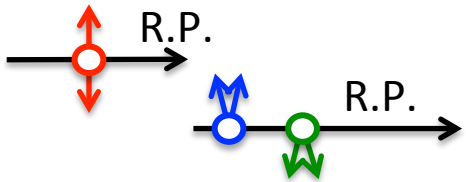


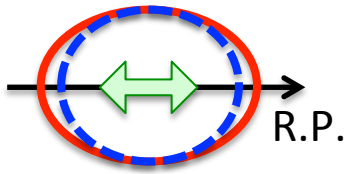
beam view

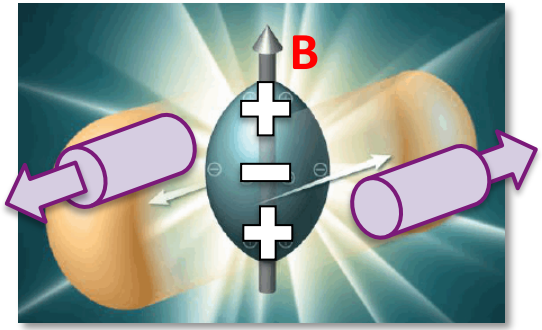
Chiral magnetic effect/wave

--- via strong B-field ---

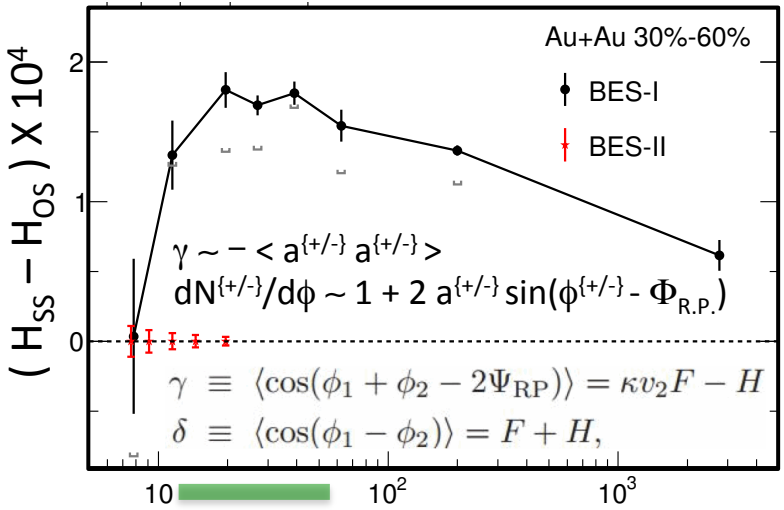






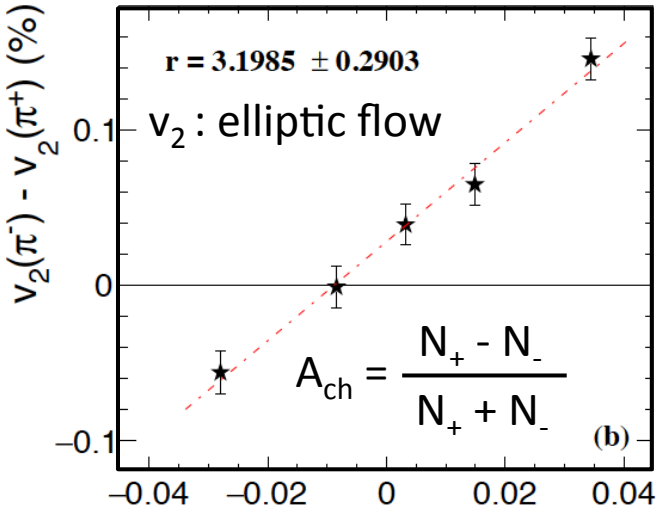


Phys. Rev. Lett. 113 (2014) 052302



charge separation w.r.t. reaction plane
"Same-sign" - "Opposite-sign" charged pair

Phys. Rev. Lett. 114 (2015) 252302



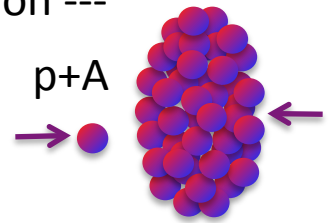
Charge dependent v_2 : $\Delta v_2 = v_2\{\pi^-\} - v_2\{\pi^+\}$
vs charge asymmetry of event : A_{ch}

Small vs Large system

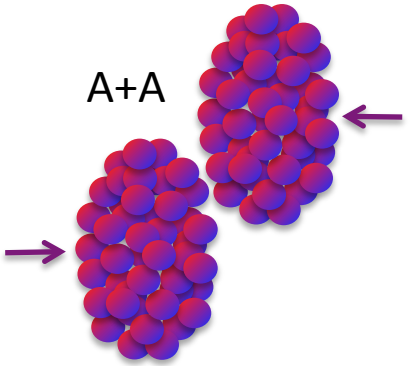
--- indication of elliptic flow (v_2) evolution ---

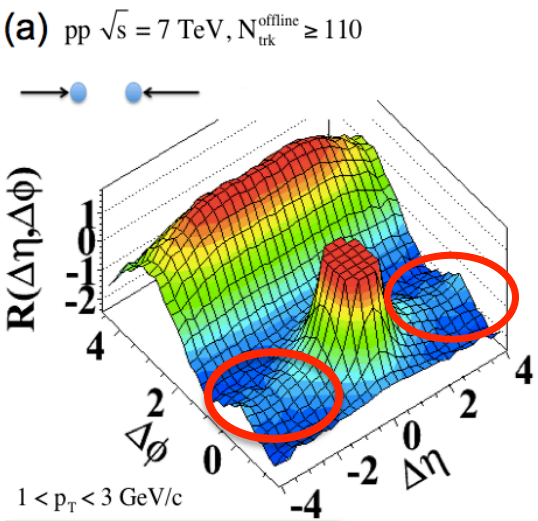
p+p (high mult.)

p+A

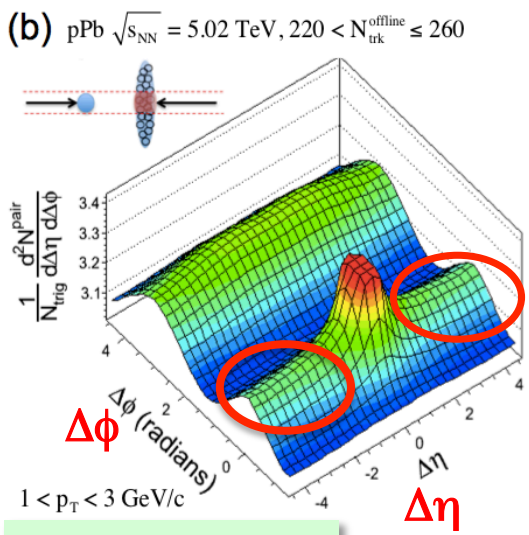


A+A

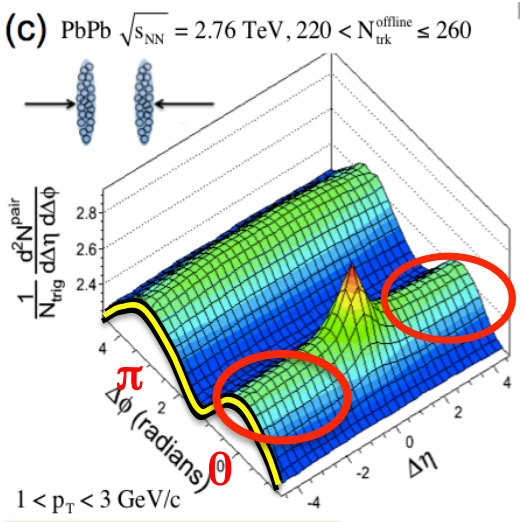




JHEP 09 (2010) 091



PLB 724 (2013) 213



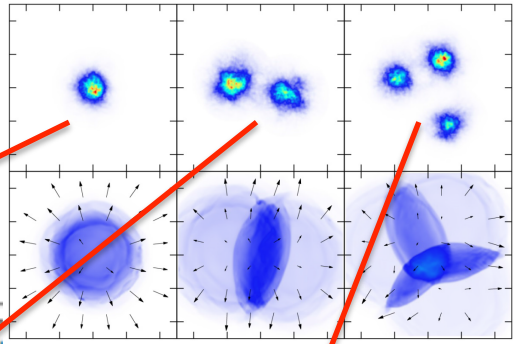
PLB 724 (2013) 213

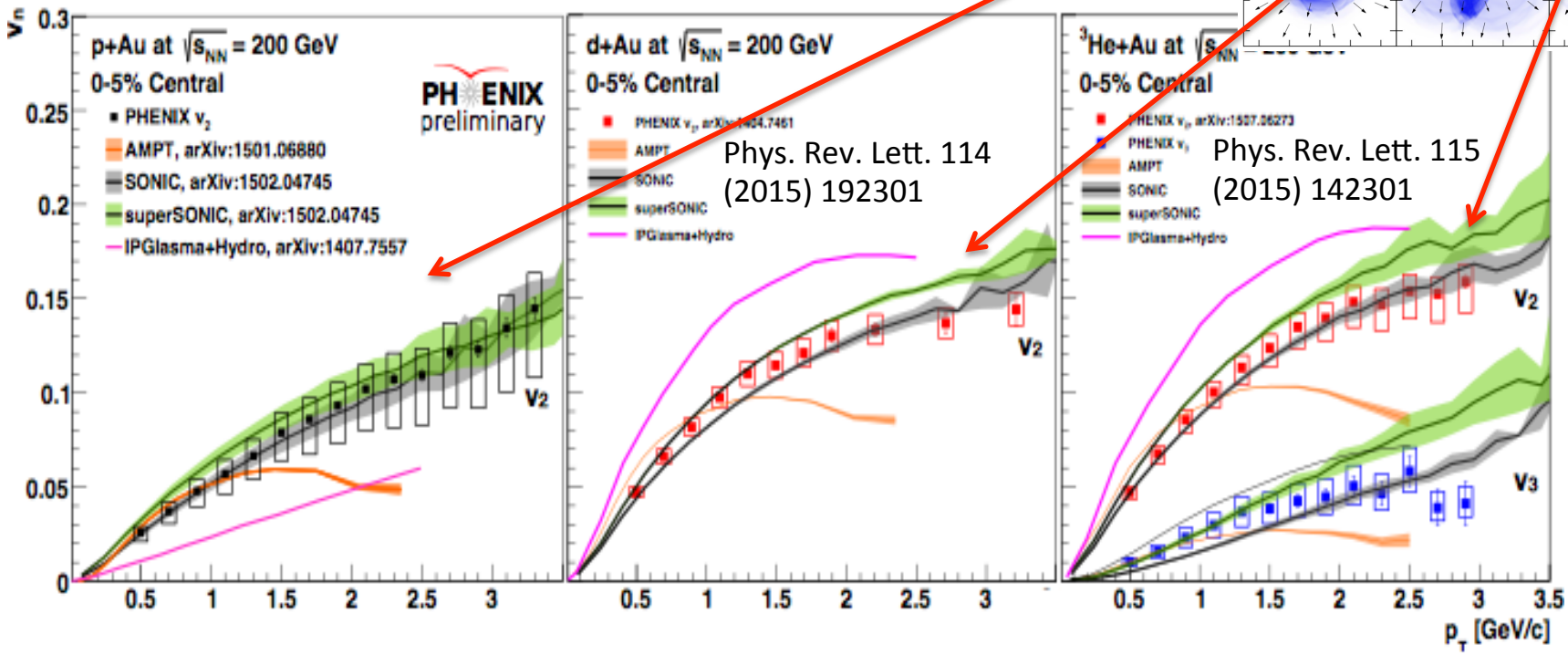
CMS, QM15

pAu, dAu, ^{3}HeAu at RHIC

--- interpretation works with hydro-dynamics, transport model ---

--- new dAu data taken with beam energy scan ---



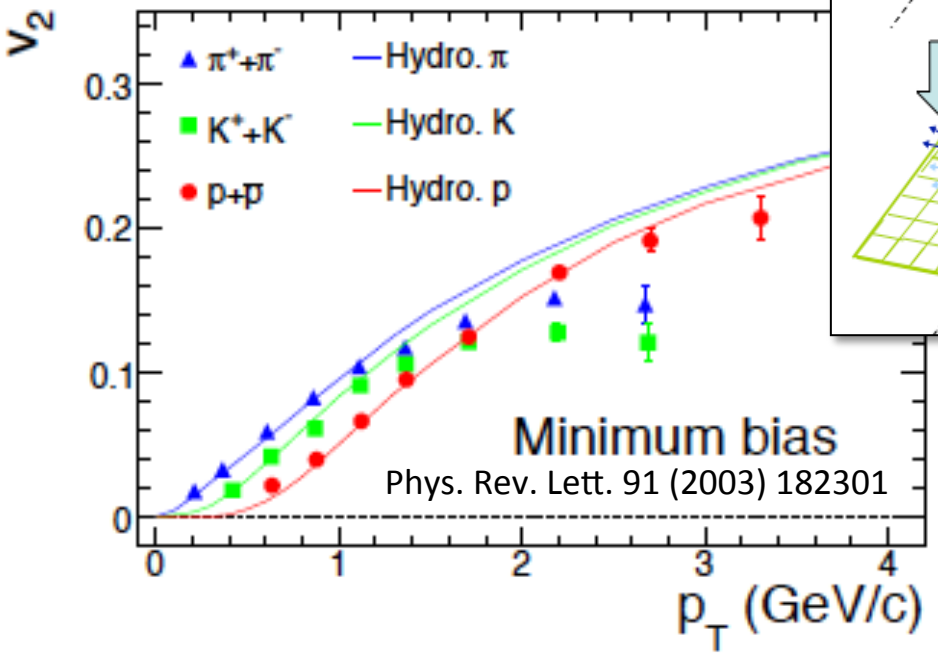


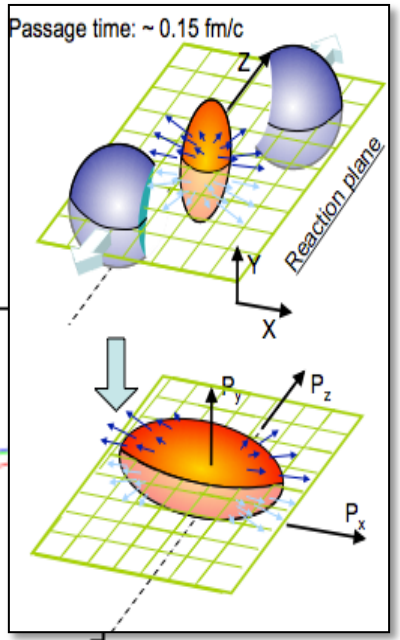
Phys. Rev. Lett. 114 (2015) 192301

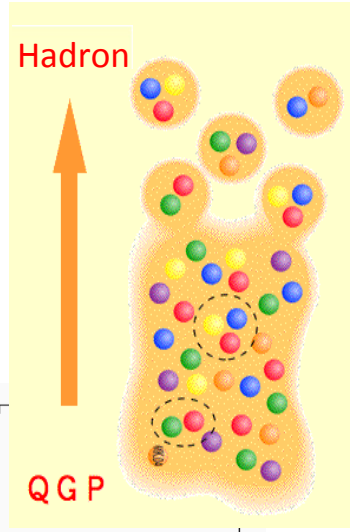
Phys. Rev. Lett. 115 (2015) 142301

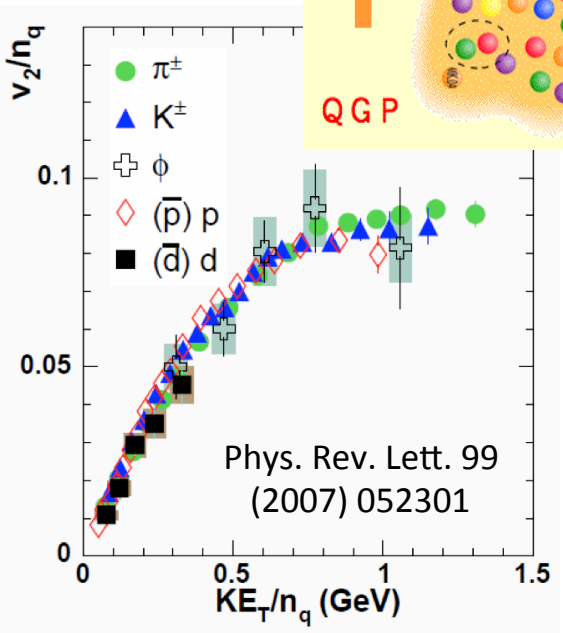
Elliptic flow (v_2)

- hadron mass dependence from hydro
- quark number scaling from coalescence



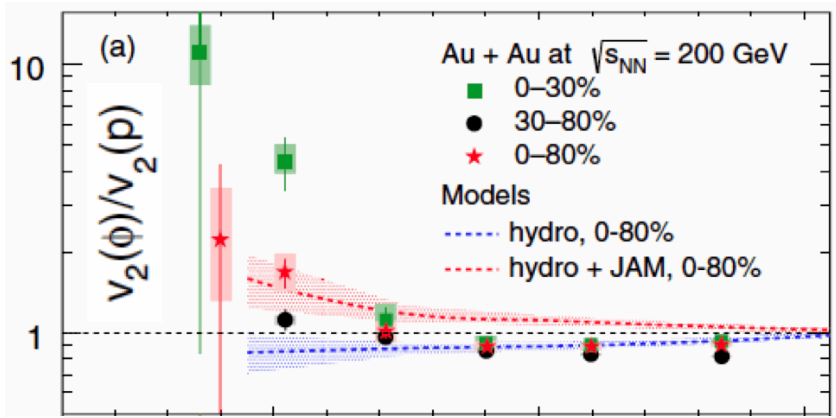


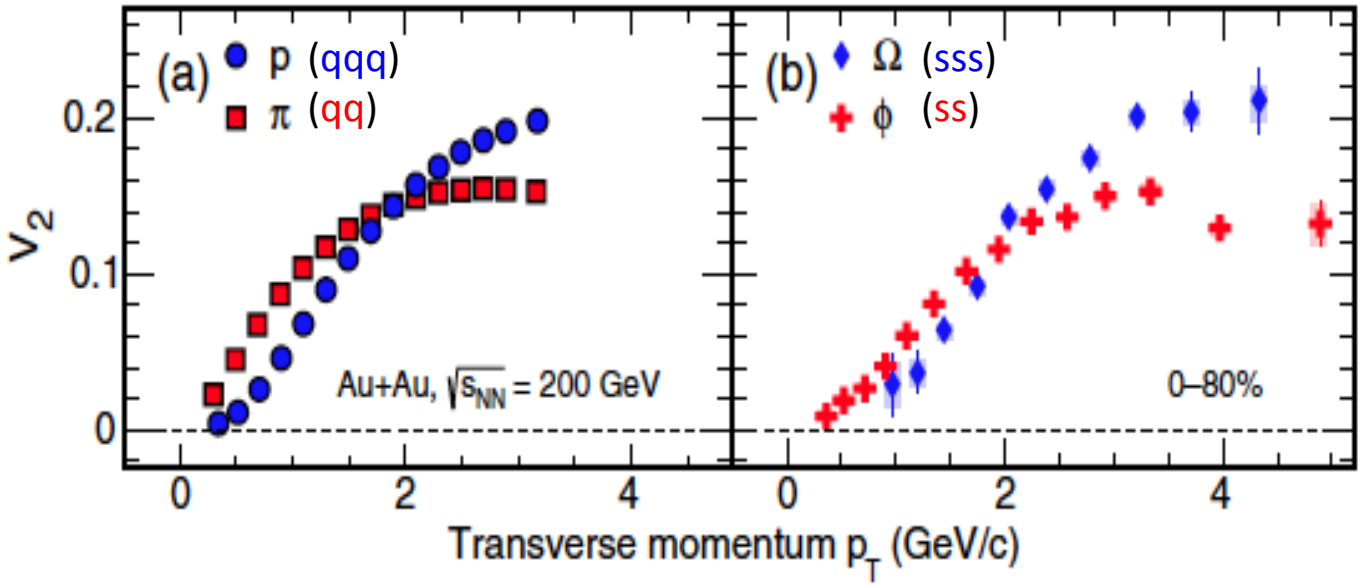




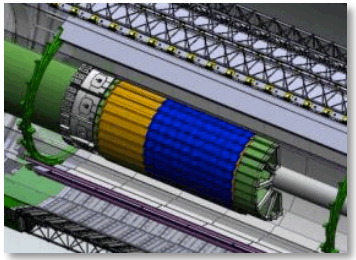
v_2 scaling with n_{quark} and m_{hadron}

separation of collective flow in partonic and hadronic stages with multi-strangeness hadrons





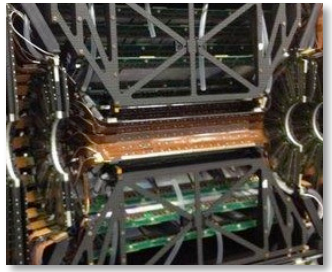
Phys. Rev. Lett. 116 (2016) 062301

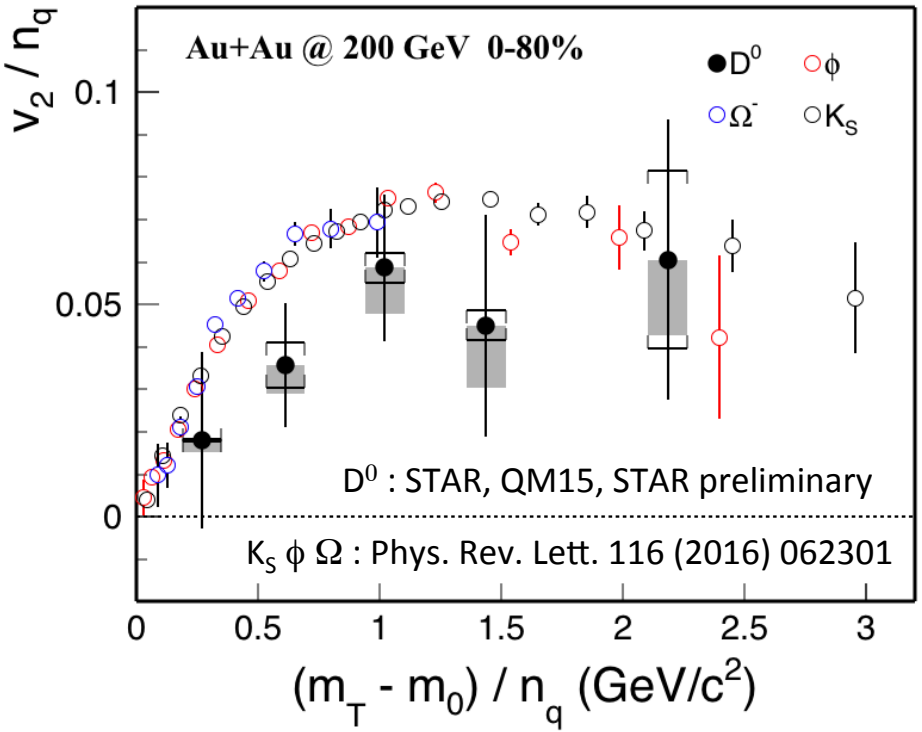


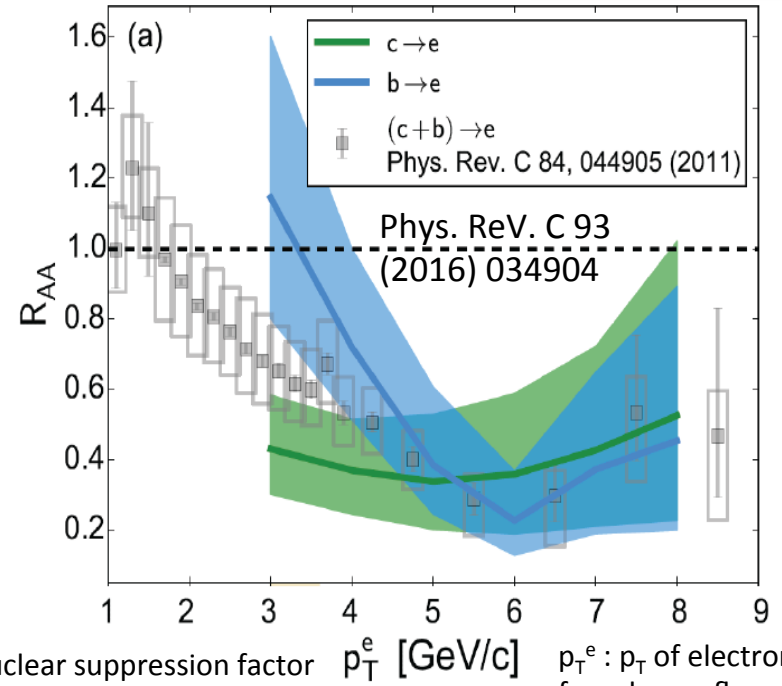
Flow and quenching of heavy quarks

Heavy-Flavor Tracker
(HFT) upgrade at STAR

Silicon Vertex Detector
(VTX) upgrade at PHENIX



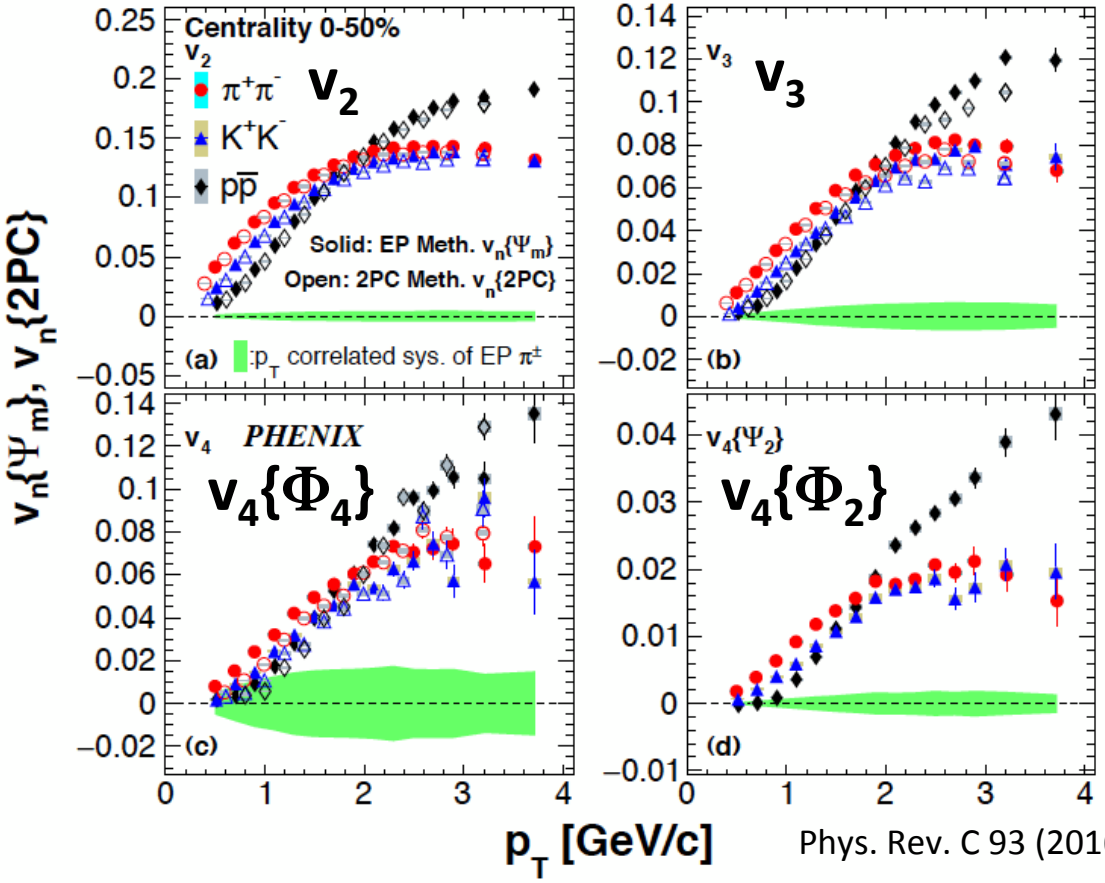


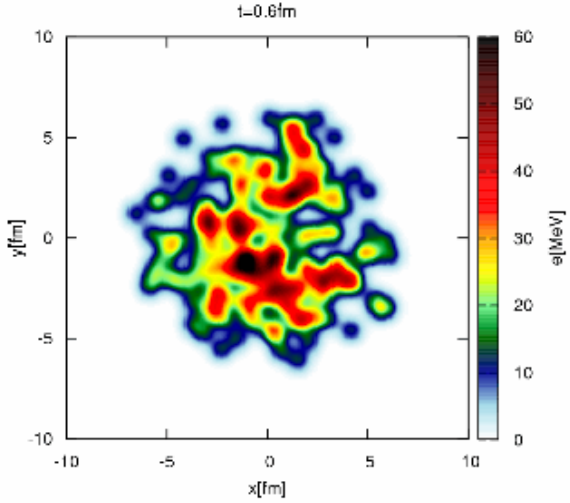


R_{AA} : nuclear suppression factor
(relative yield over p+p superposition)

p_T^e : p_T of electron from heavy flavor

Higher order event anisotropy (v_n)



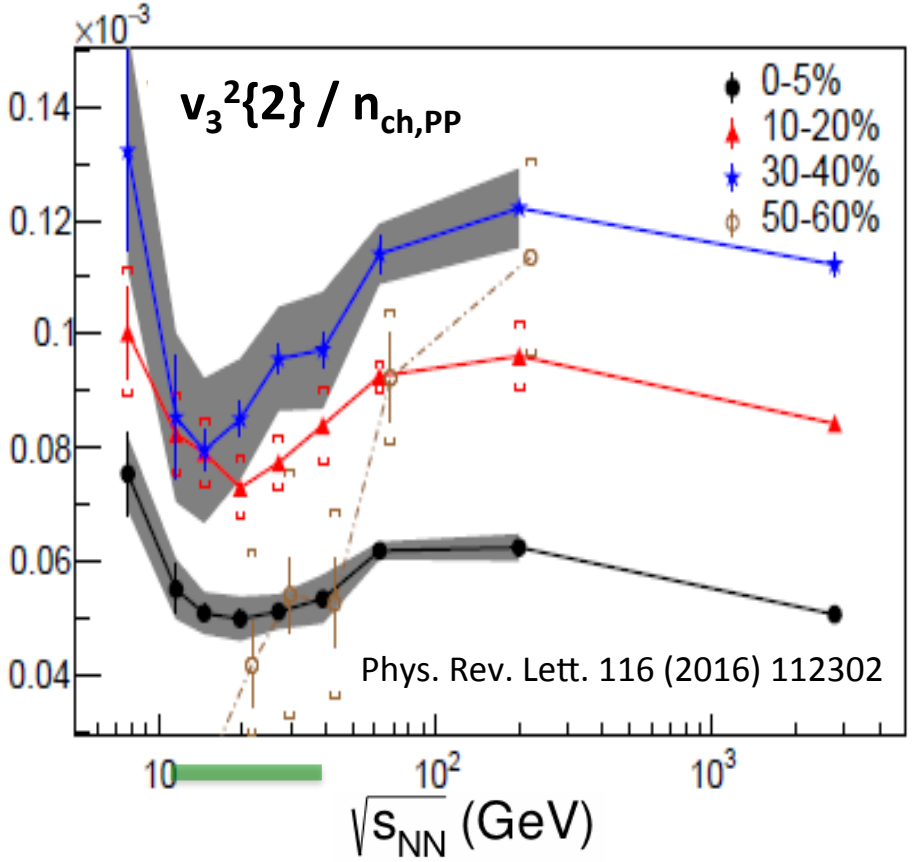


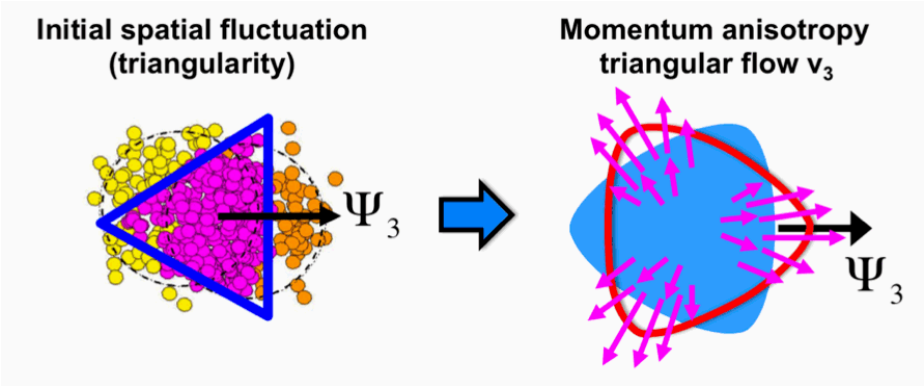
Collective expansion originated from fluctuating initial density distribution

Mass dependence and meson/baryon separation

Phys. Rev. C 93 (2016) 051902R

3rd order (triangular) event anisotropy (v_3)



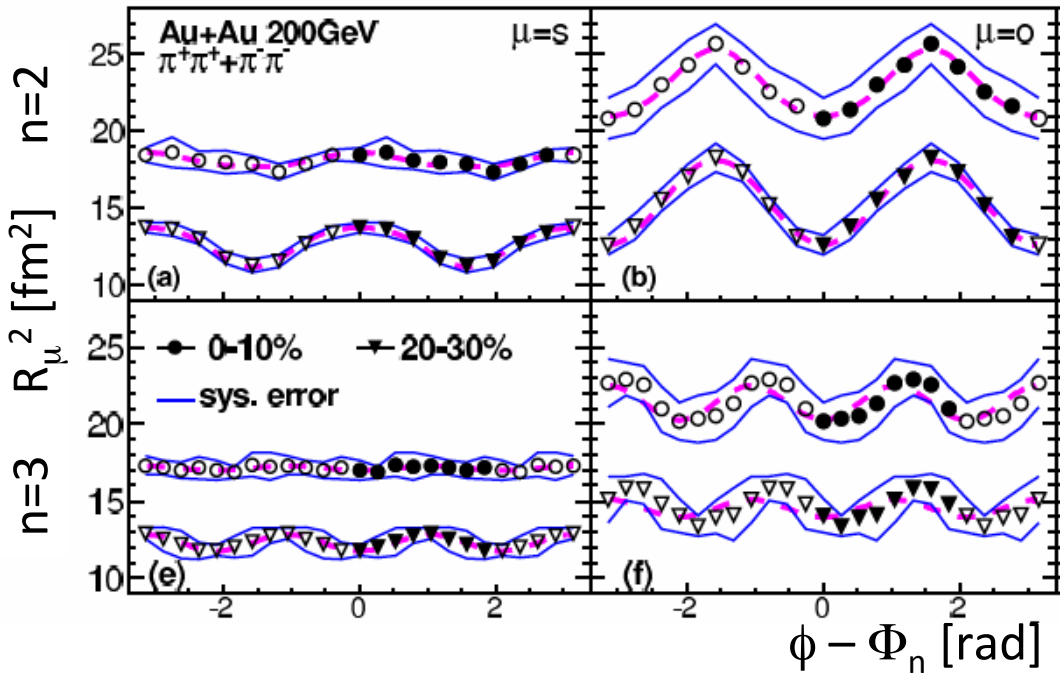


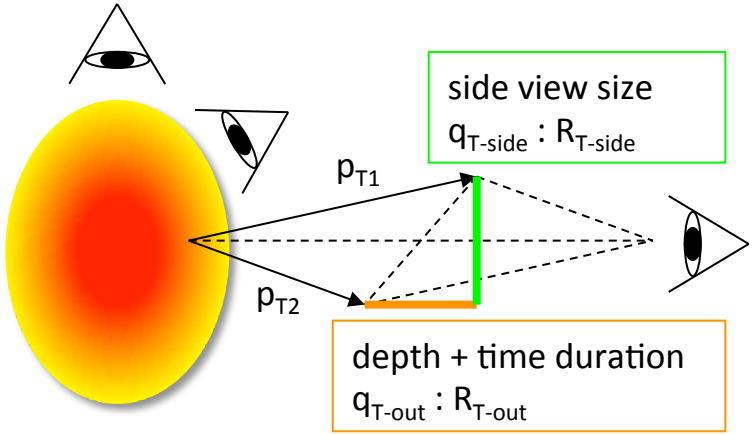
--- Triangular expansion ---
normalized by system energy density :
$n_{ch,PP} = (dN_{ch}/d\eta) / (N_{part}/2)$

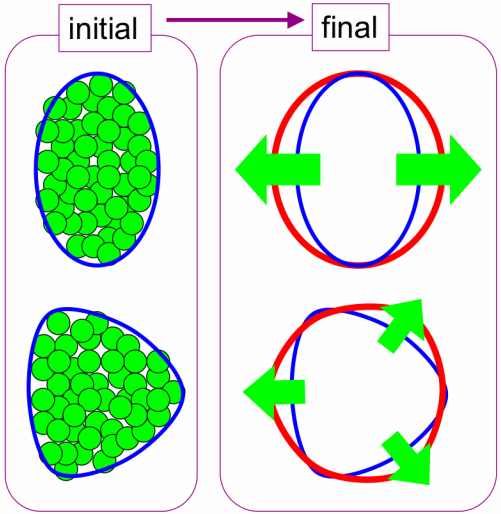
Anisotropic shape after expansion

Elliptic and Triangular shape at freeze-out remained (2nd) and/or reversed (3rd)

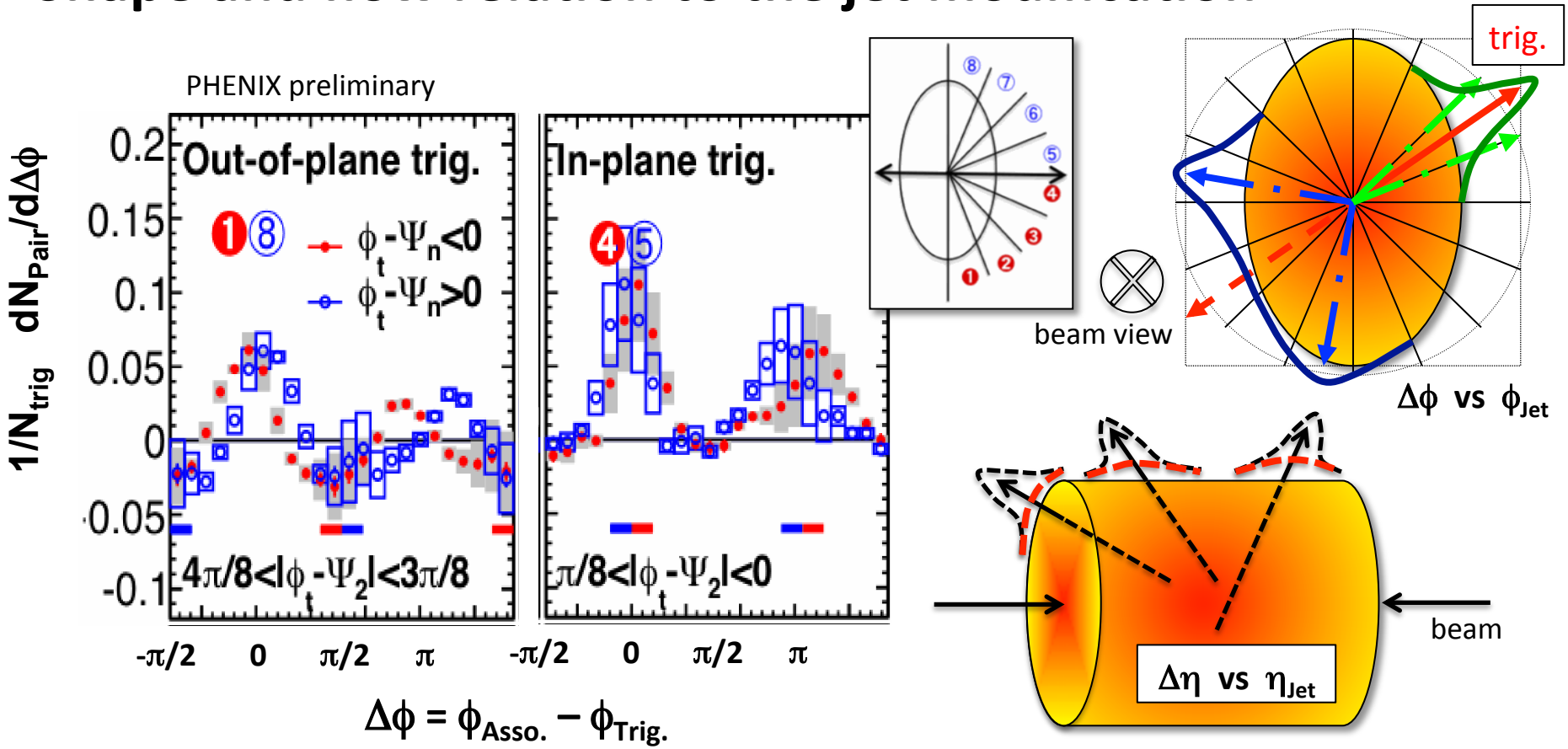
Phys. Rev. Lett. 112 (2014) 222301



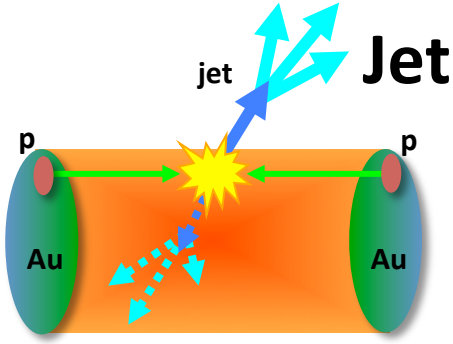




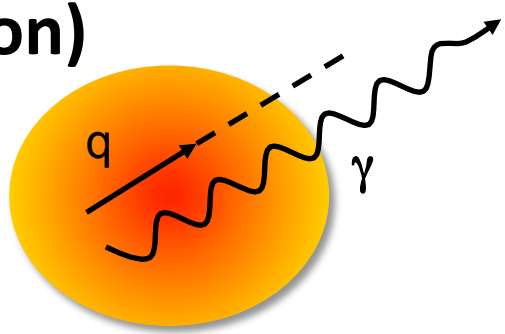
Shape and flow relation to the jet modification



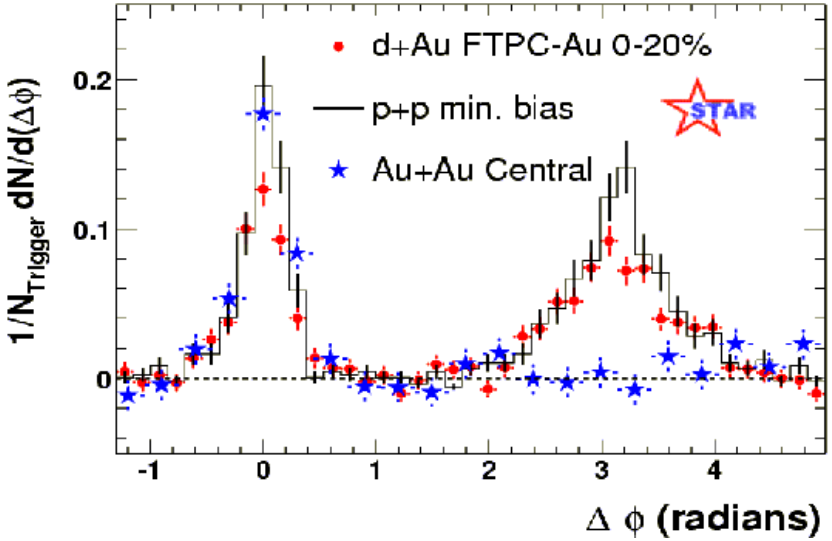
Jet quenching (high p_T suppression)



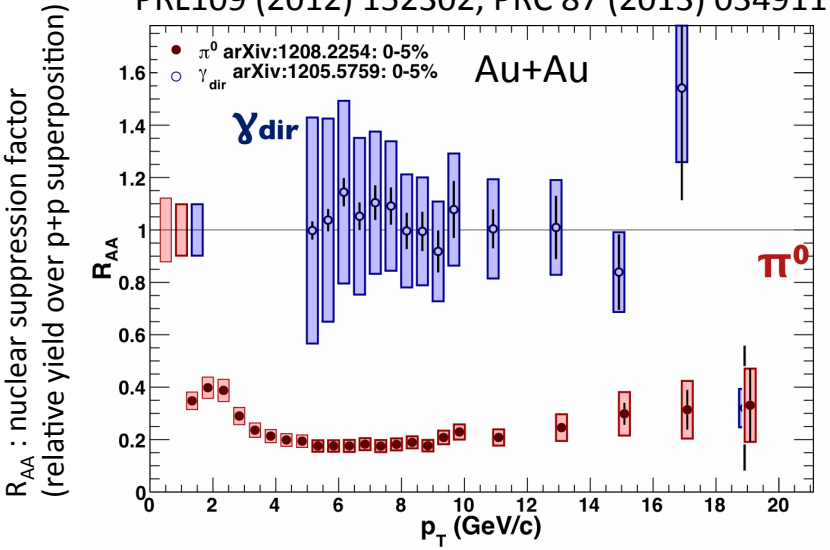
--- partonic energy-loss : $R_{AA}(\pi^0)<1$ ---
--- penetration of direct photon : $R_{AA}(\gamma^{dir.})=1$ ---



PRL 91 (2003) 072304

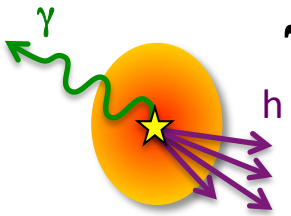


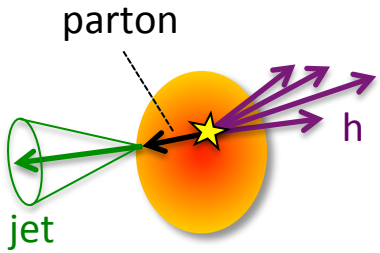
PRL109 (2012) 152302, PRC 87 (2013) 034911

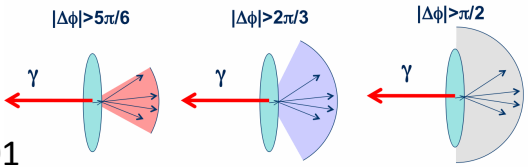


$\gamma^{dir.}$-hadron and Jet-hadron correlation

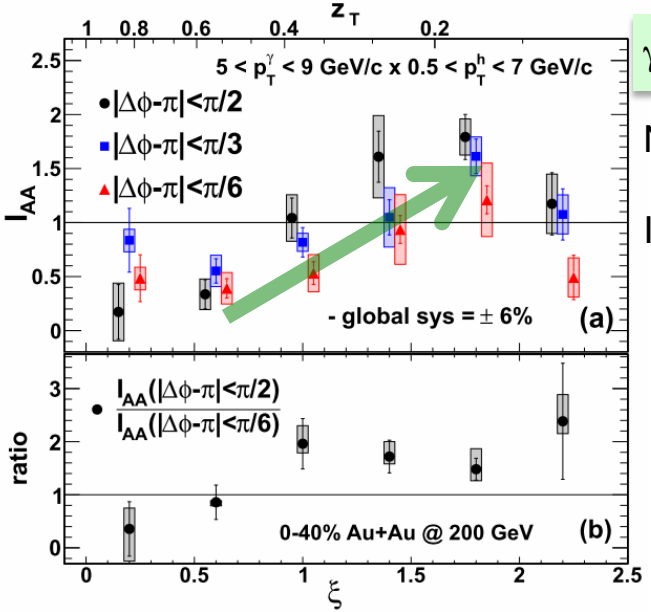
--- re-distribution of the lost energy ---







PRL 111 (2013) 032301

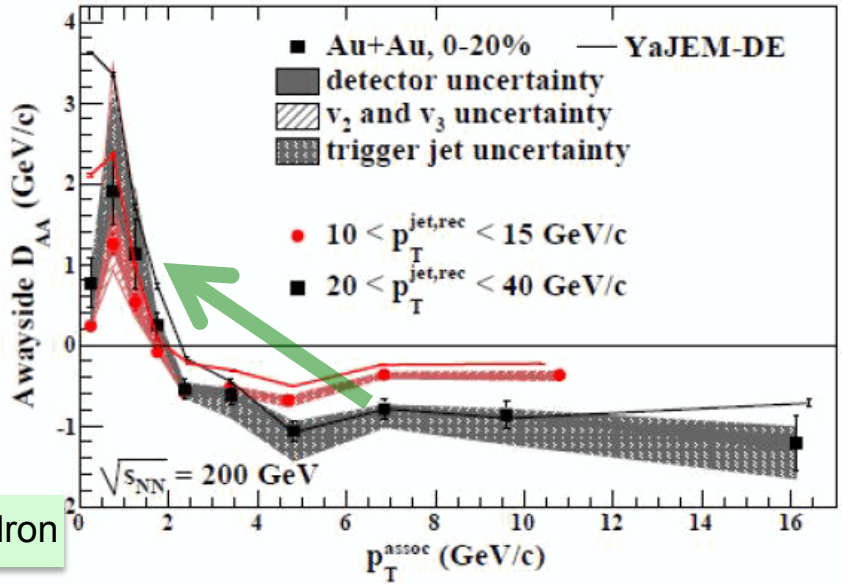


$\gamma^{dir.}$ - hadron

N_{PTY} = associate hadron yield per trigger γ

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

PRL 112 (2014) 122301



jet - hadron

S_{PT} = associate hadron p_T sum per jet

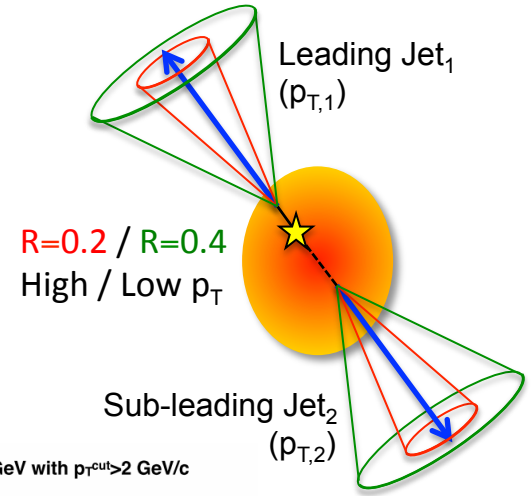
$D_{AA} = S_{PT}(AA) - S_{PT}(pp)$

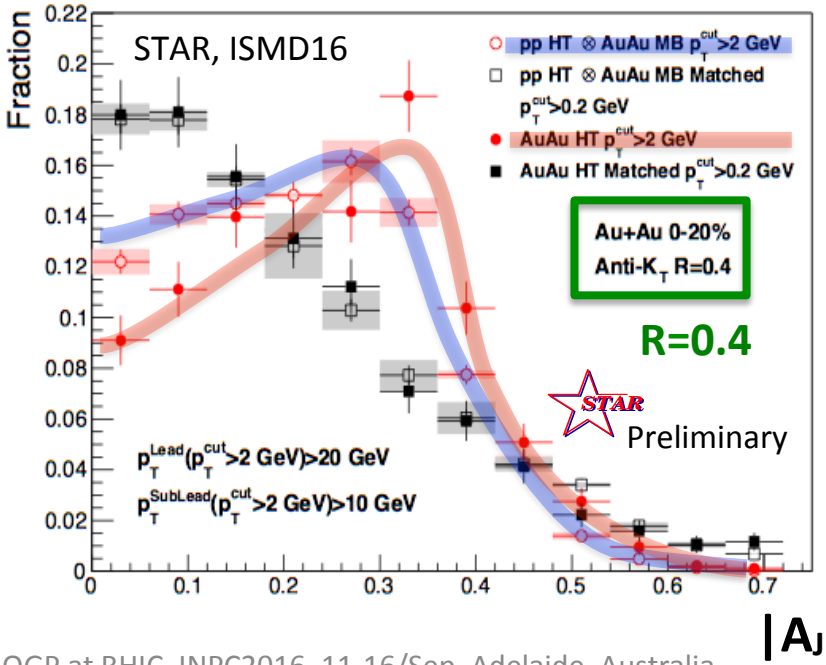
Jet energy imbalance via energy-loss

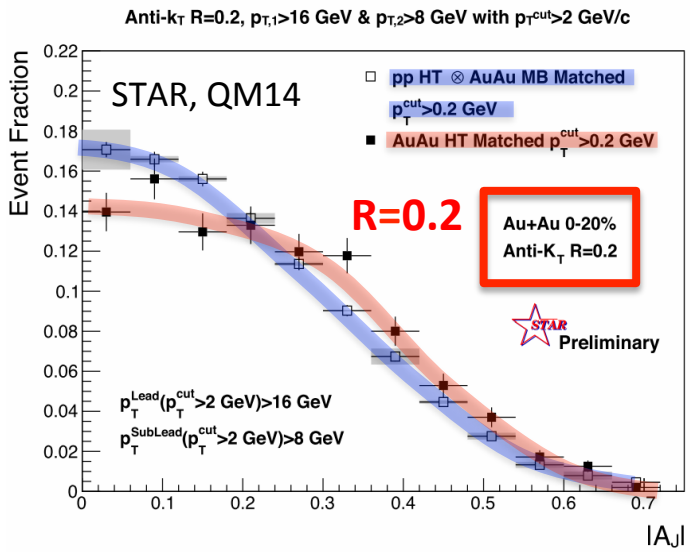
--- visible, but smaller than at LHC ---

Jet with higher p_T cut : visible
Jet with smaller cone : visible
Jet with larger cone + lower p_T : not

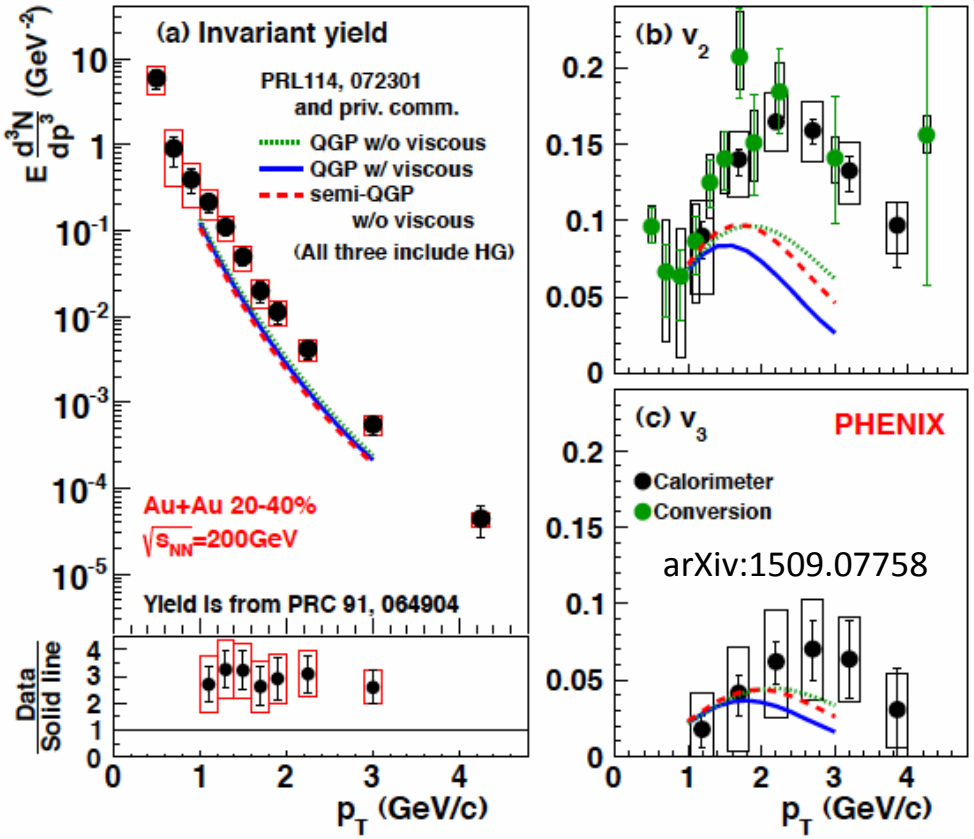
$$A_J = \frac{P_{T,1} - P_{T,2}}{P_{T,1} + P_{T,2}}$$

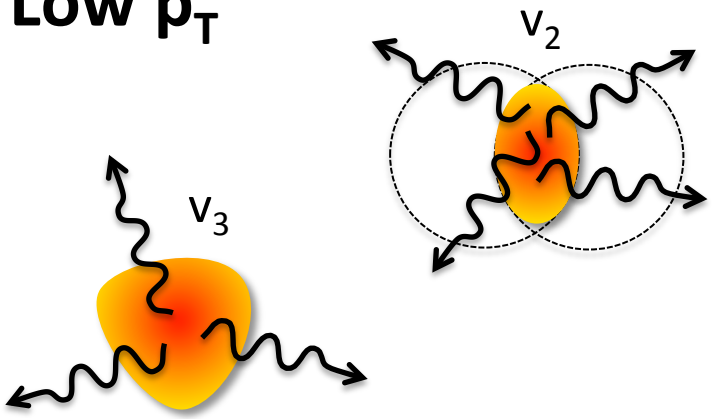






Thermal photon yield and flow at Low p_T

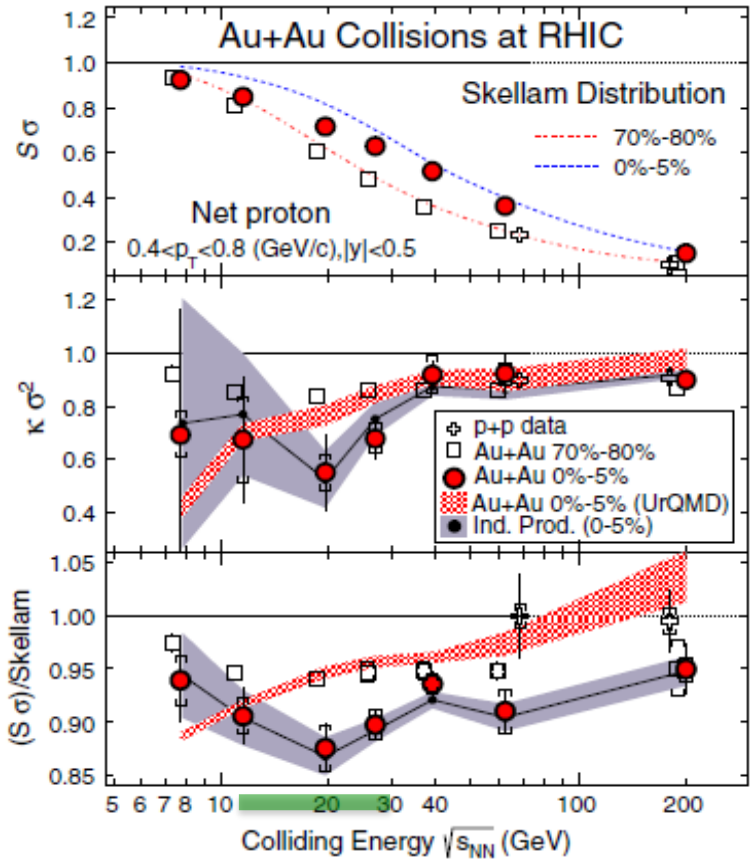




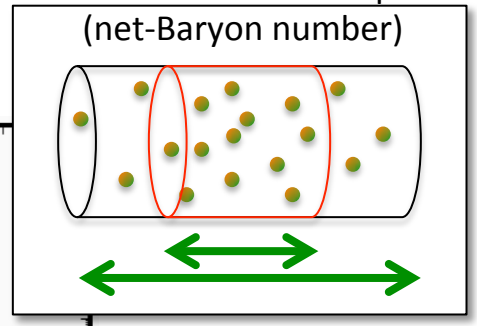
- R_{AA}~1 and v_2~0 at high p_T prompt photon
- Large photon yield from early stage
- Large photon flow from later stage
- Bremsstrahlung with early B-field…
- New data from STAR arXiv:1607.01447
  with somewhat smaller yield…

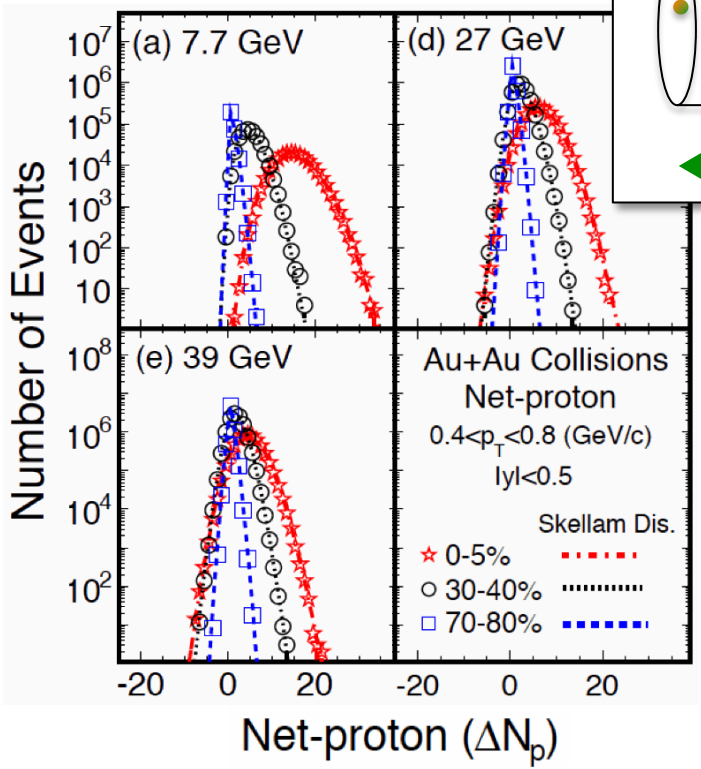
Net-proton distribution

Phys. Rev. Lett. 112 (2014) 032302



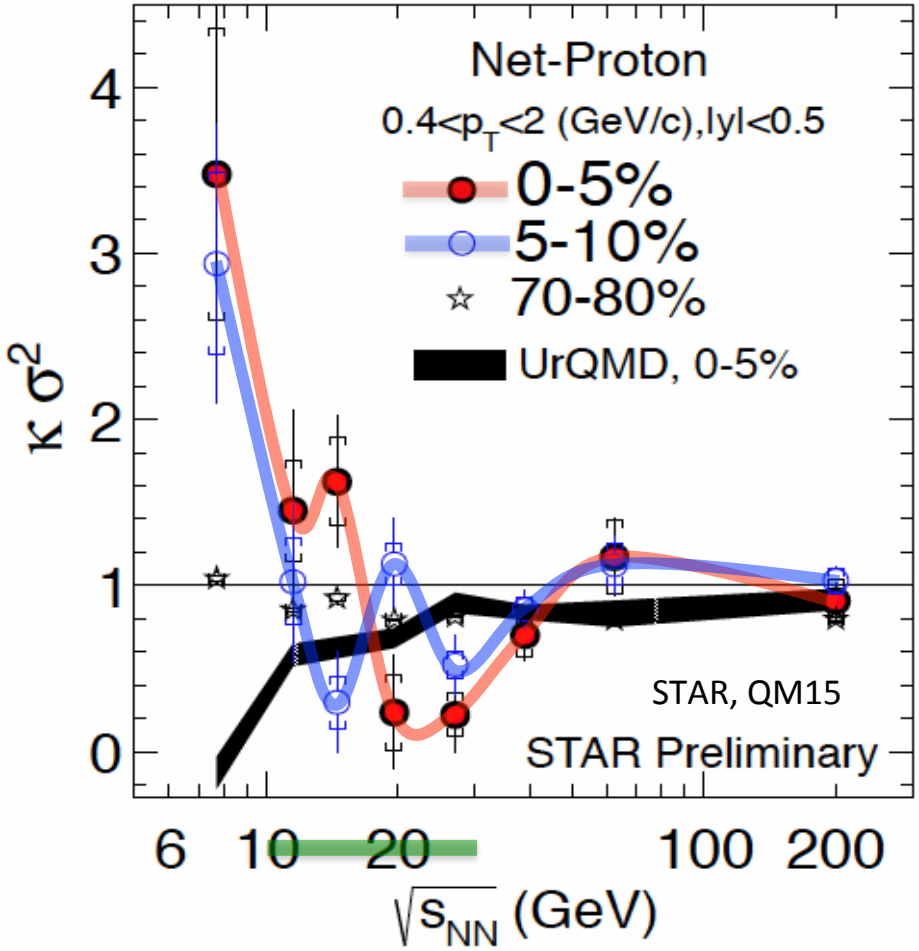
fluctuation of conserved quantity (net-Baryon number)



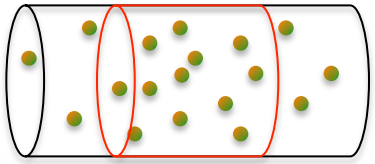


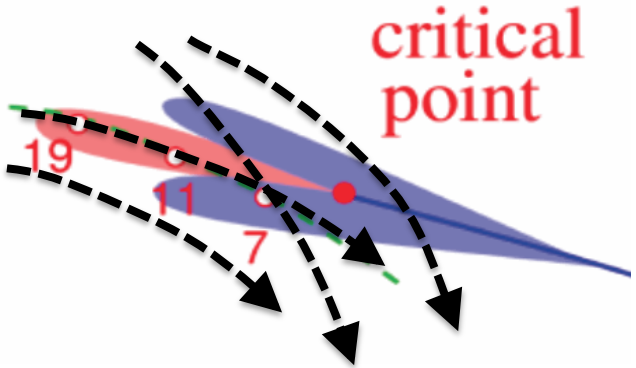
Sudden change of correlation length is expected at phase boundary close to critical point.

Fluctuation (shape of the distribution) will be affected especially for the higher order.



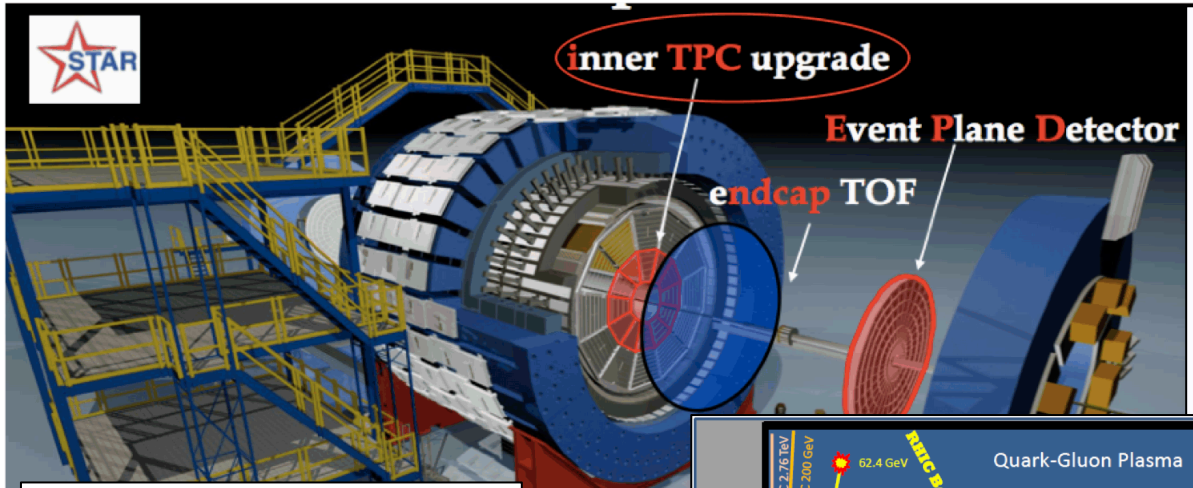
Possible critical signature





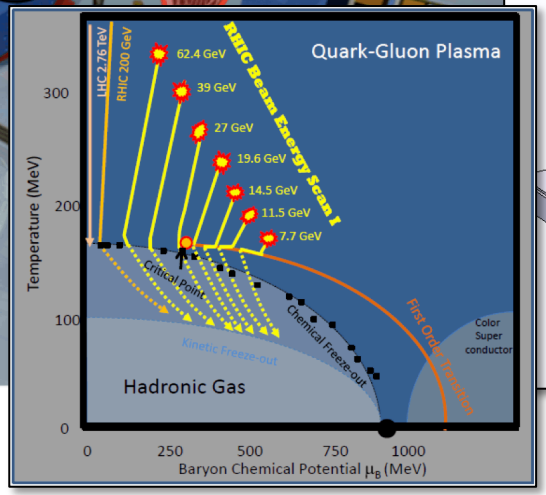
large errors : comparable to the critical signal
need for Beam Energy Scan Phase 2 (2019-)

Beam Energy Scan 2 @ STAR

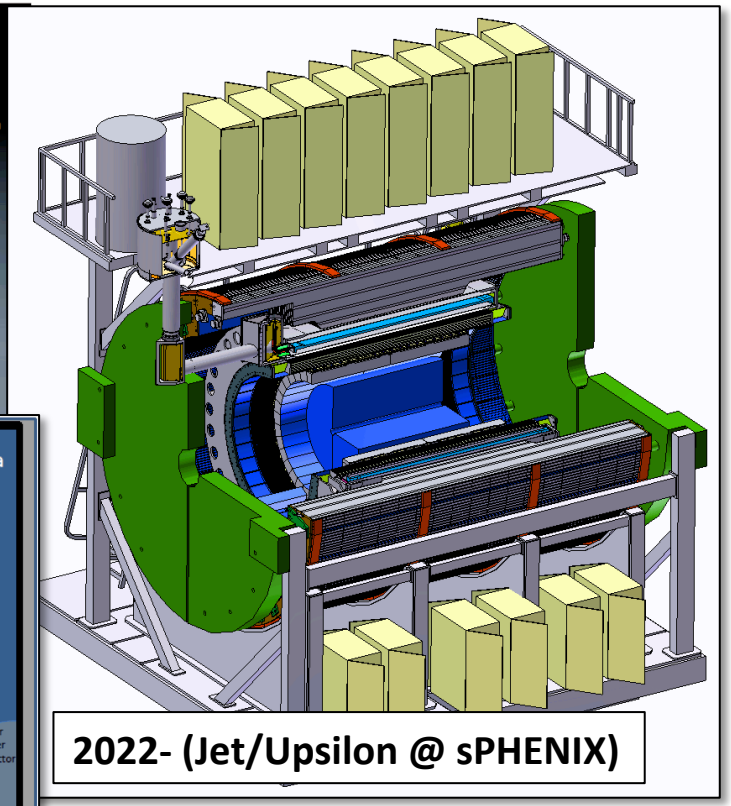


2019-2020 (BES2 @ STAR)

- New forward trigger + Event Plane Detector
- Very important for flow and fluctuation analyses
  → independent from main detector
  → reduces systematics (non-flow, centrality)!
- iTPC upgrade
  → increases TPC acceptance to ~1.5 in η
  → improves dE/dx resolution



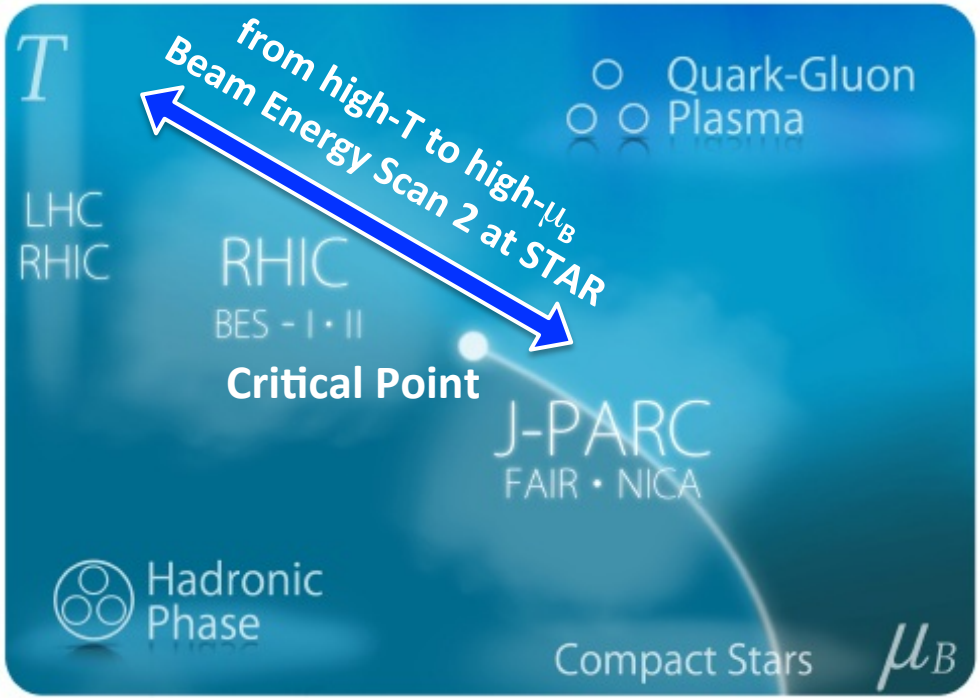
Jet @ sPHENIX



2022- (Jet/Upsilon @ sPHENIX)

Summary

- Collective flow
- Jet quenching
- Correlation & fluctuation
- Beam energy dependence (Critical point : 10~40GeV?)



M. Kitazawa, H. Sako, et. al. (J-PARC-HI LOI)