

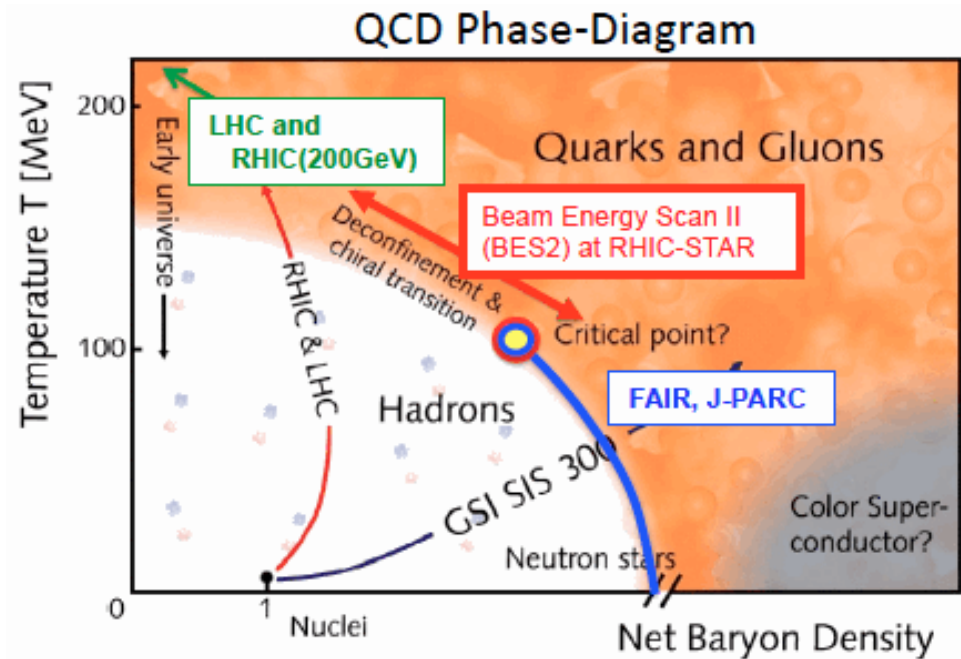
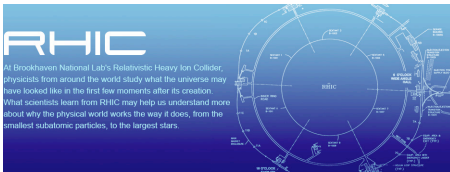
Experimental studies on QCD phase transition to search for a critical point at RHIC energies



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

Contents

- Freeze-out and radial flow
- Energy loss and elliptic flow
- Re-distribution of lost energy
- Heavy-quark dE/dx and flow
- Flow in small system
- Beam energy scan

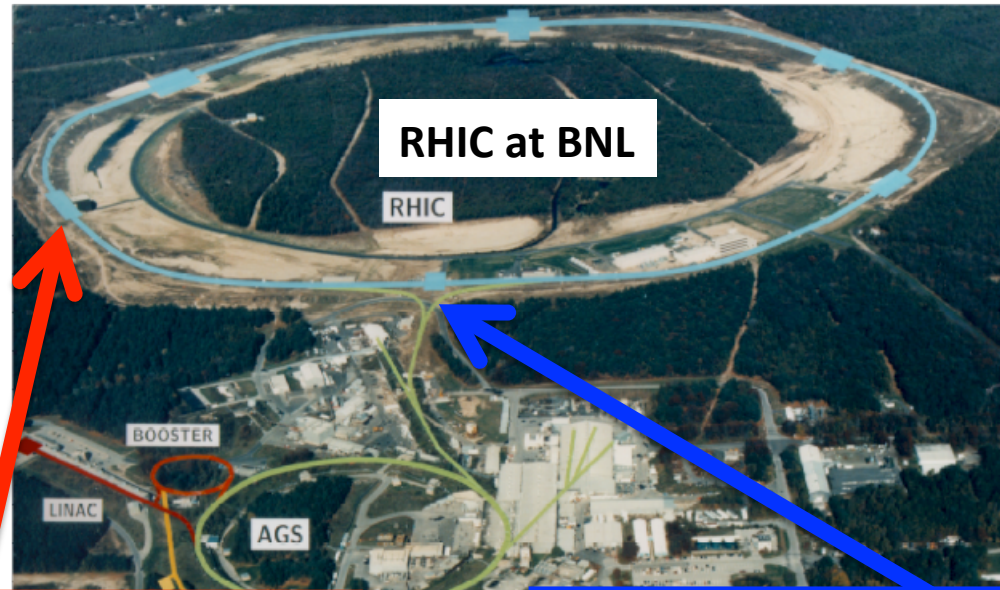


Relativistic Heavy-Ion Collider at Brookhaven National Laboratory

RHIC has started with 4 experiments :

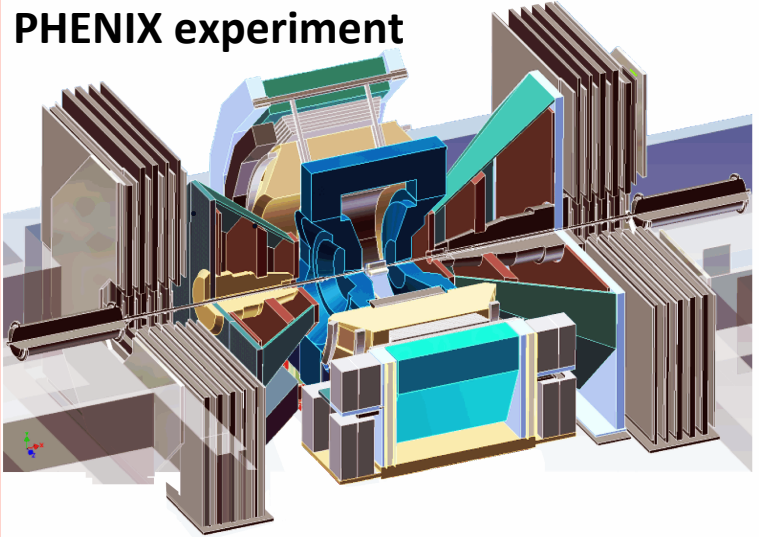
- STAR
- PHENIX
- BRAHMS
- PHOBOS

(2001 - 2016)

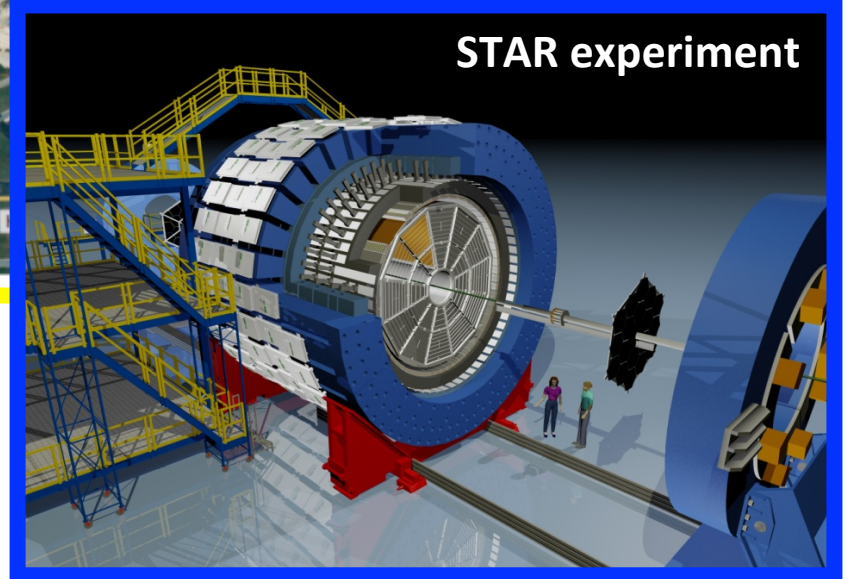


(2001 - 2020 -)

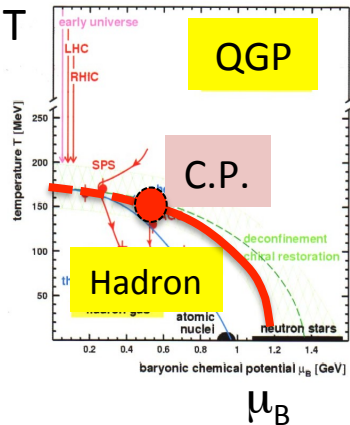
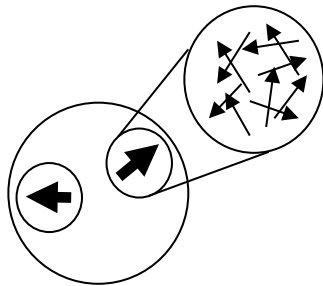
PHENIX experiment



STAR experiment

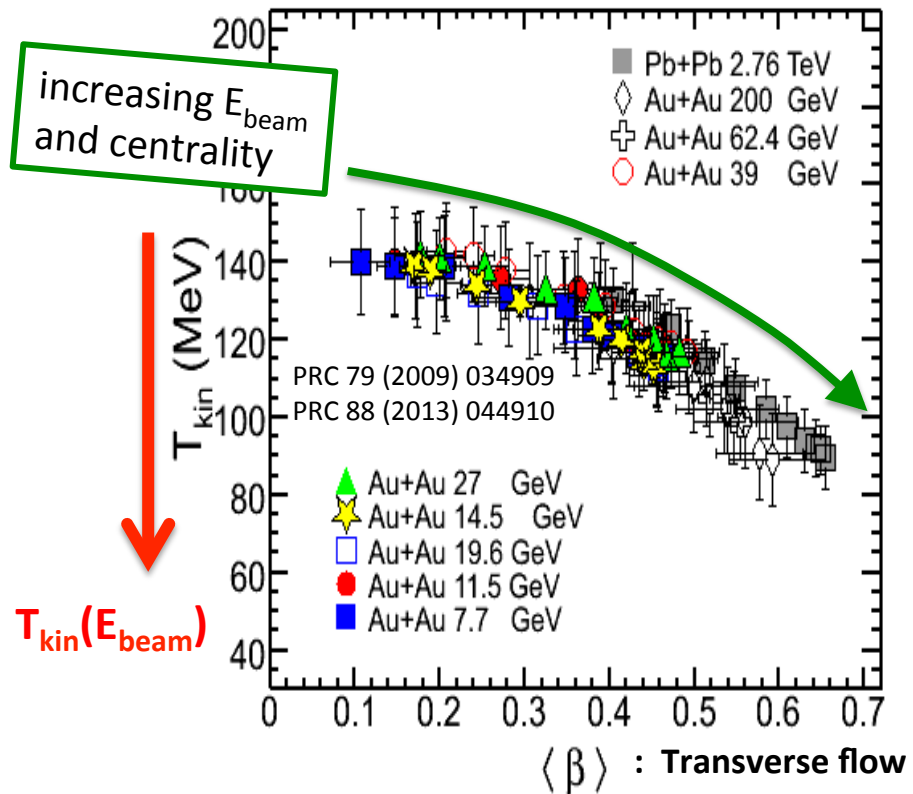
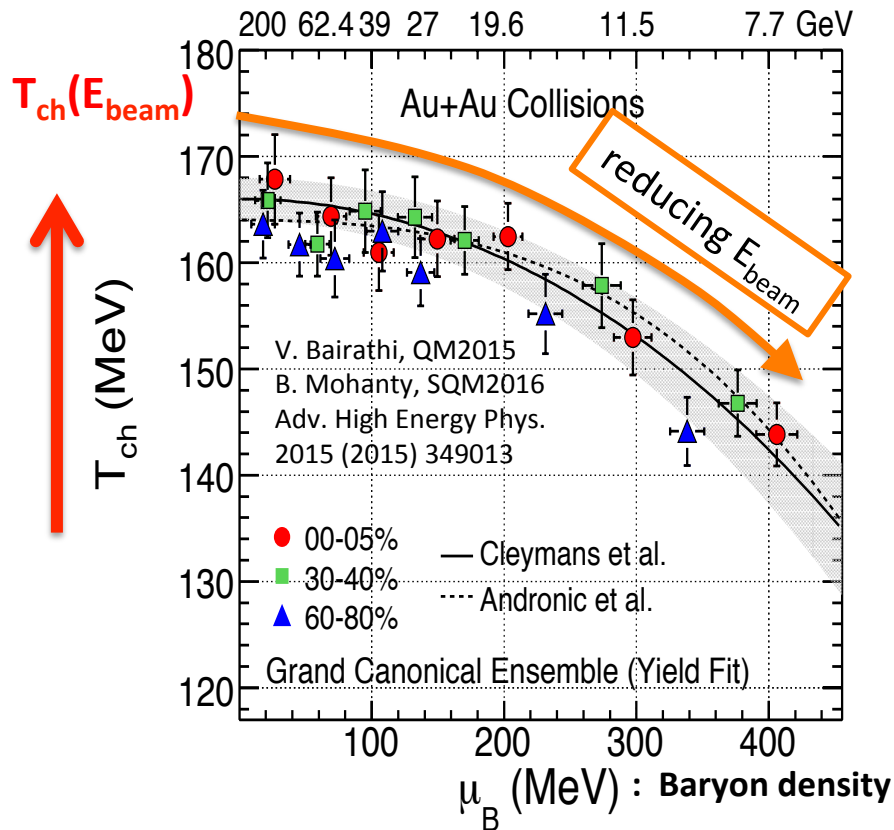


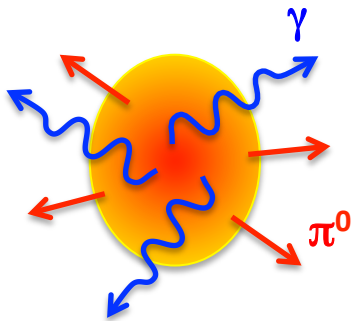
Chemical and Thermal kinetic freeze-out with radial flow



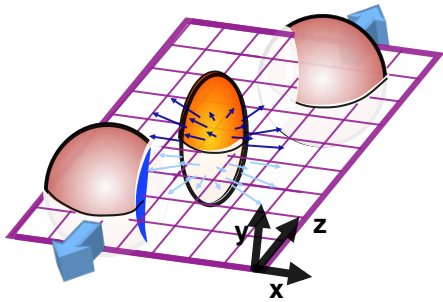
Hadron yields are fitted with chemical thermal model in order to extract (T_{ch}, μ_B) parameters.

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



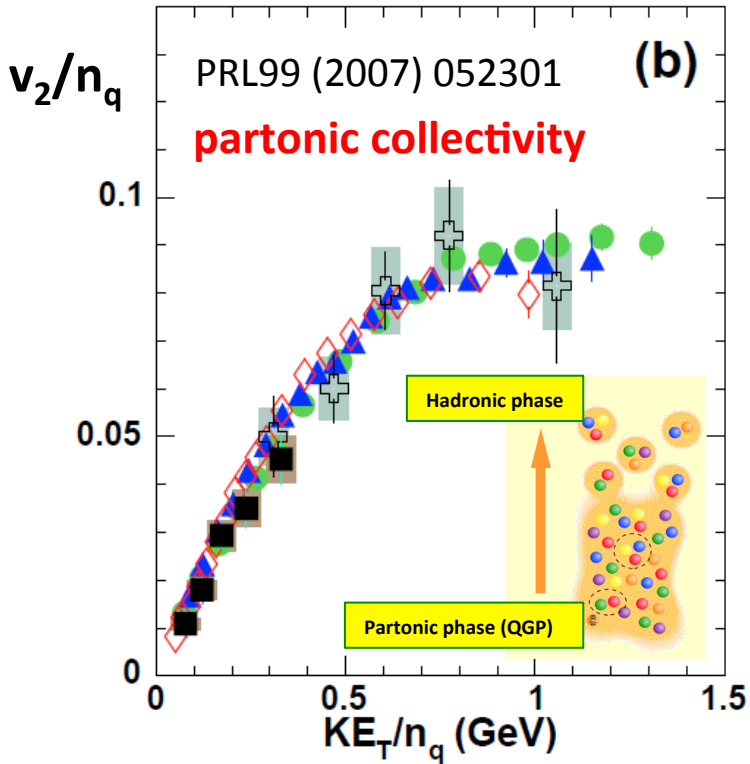
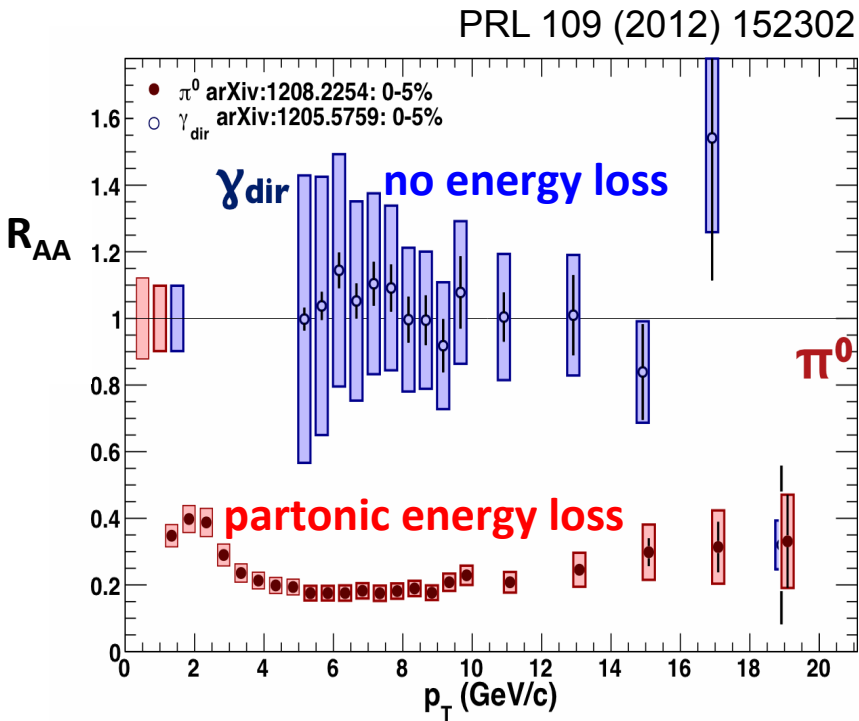


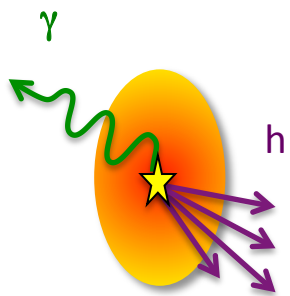
Energy loss and Elliptic flow in partonic phase



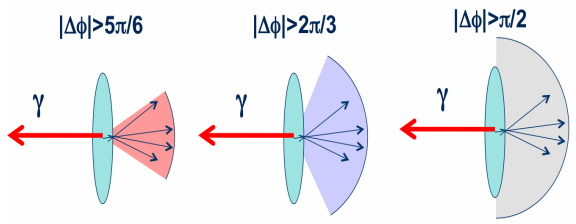
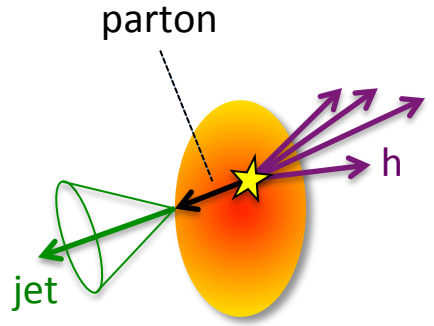
(relative yield w.r.t. p+p superposition : R_{AA})

(elliptic event anisotropy : v_2)

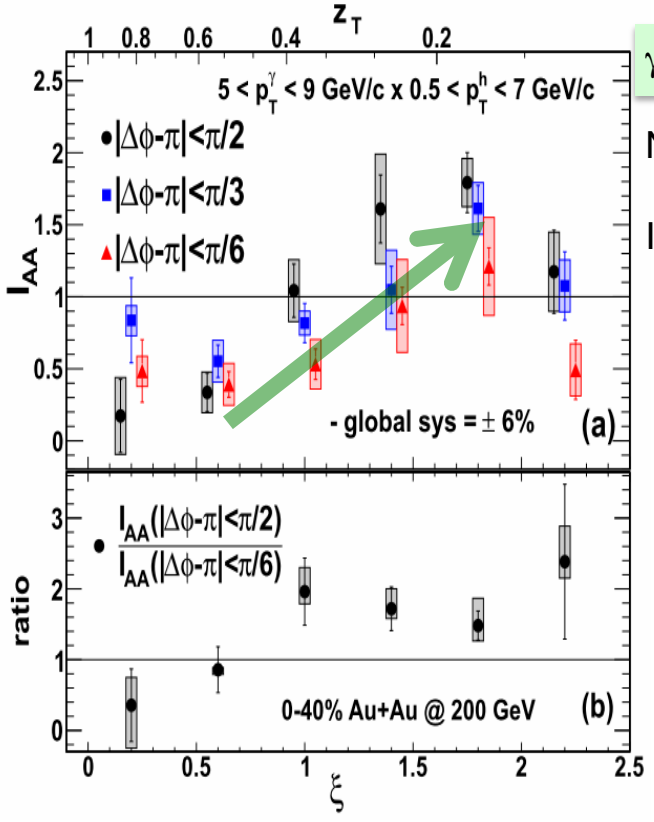




$\gamma^{\text{dir.}}$ -hadron and Jet-hadron correlation --- re-distribution of the lost energy ---



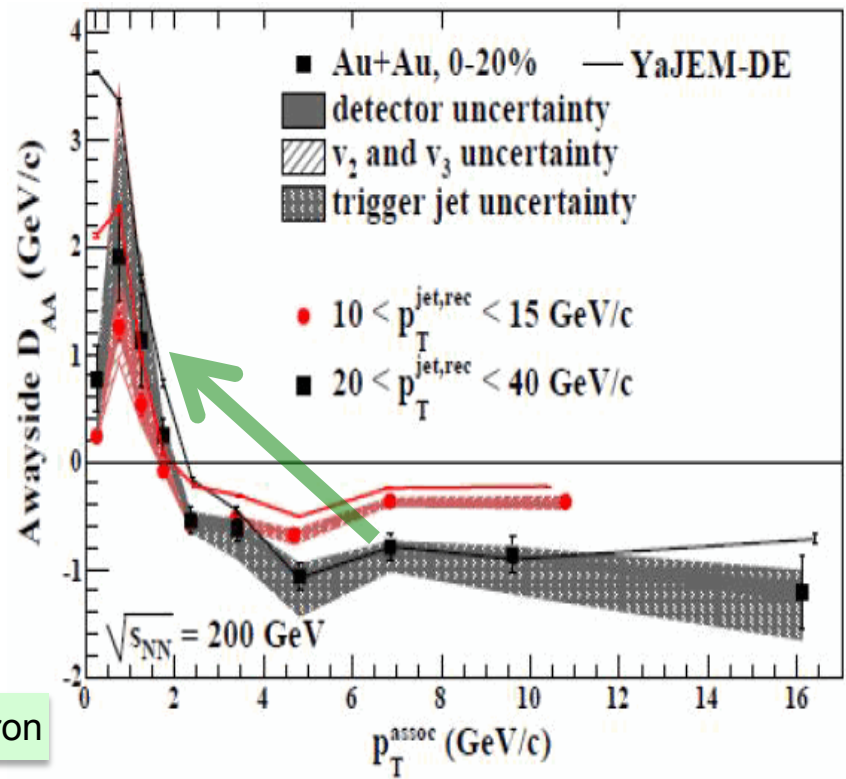
PRL 111 (2013) 032301



$\gamma^{\text{dir.}}$ - hadron

$N_{\text{PTY}} =$ associate hadron yield per trigger γ
 $I_{AA} = N_{\text{PTY}}(\text{AA}) / N_{\text{PTY}}(\text{pp})$

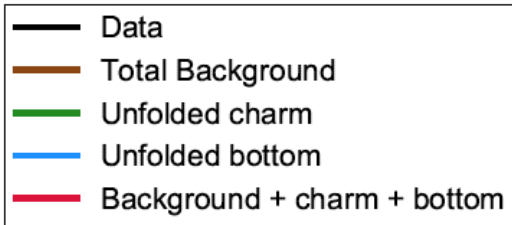
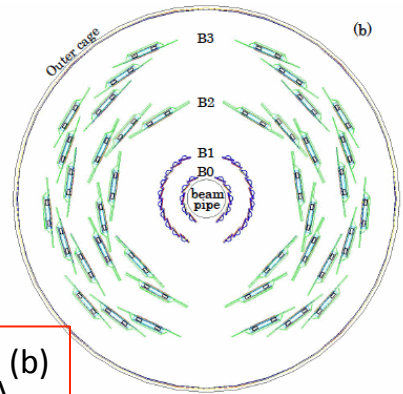
PRL 112 (2014) 122301



jet - hadron

$S_{\text{PT}} =$ associate hadron p_T sum per jet
 $D_{AA} = S_{\text{PT}}(\text{AA}) - S_{\text{PT}}(\text{pp})$

Charm / Bottom energy-loss with Silicon Vertex Detector (VTX)



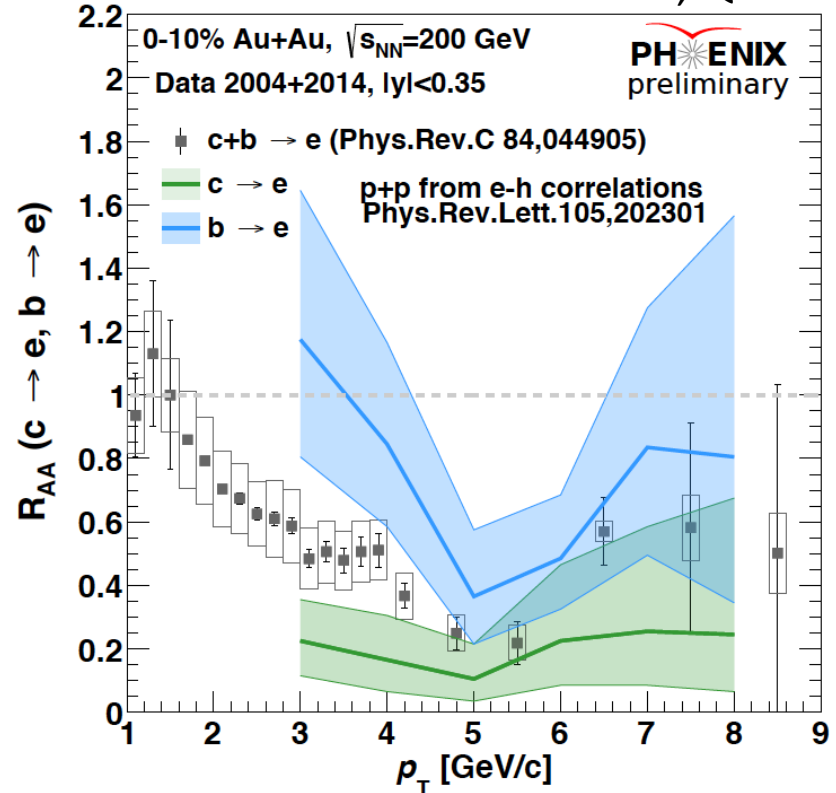
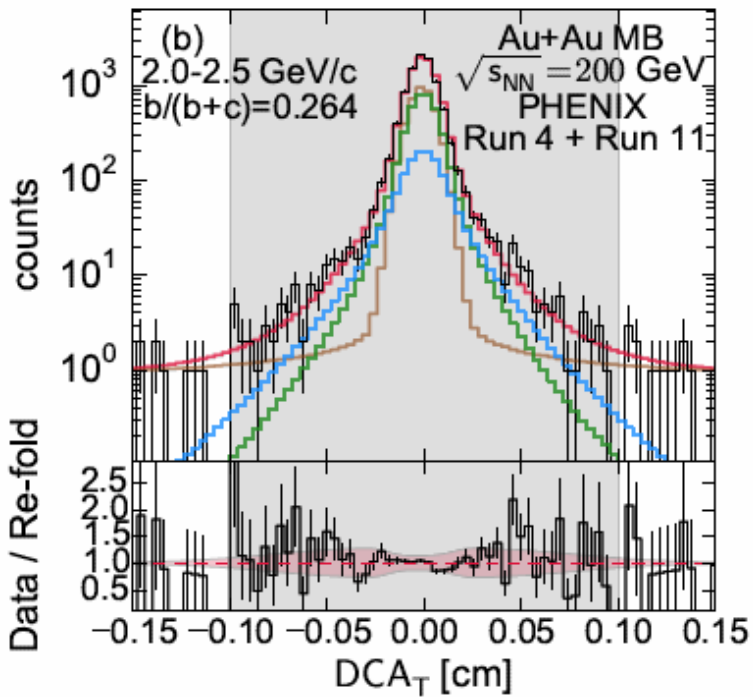
DCA distribution
of electrons from
heavy flavor decays
(charm and bottom
contributions)

$$R_{AA}^{(u,d,s)} \leq R_{AA}^{(c)} \leq R_{AA}^{(b)}$$

$$v_2^{(u,d,s)} \geq v_2^{(c)} \geq v_2^{(b)}$$

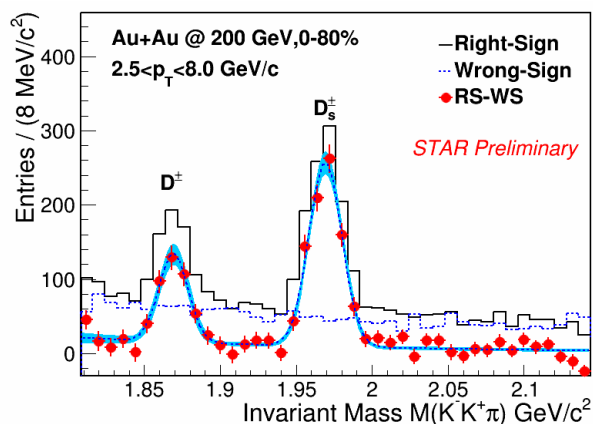
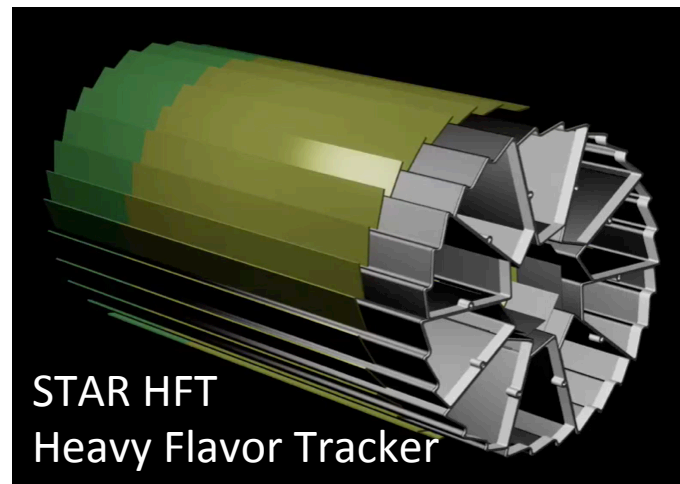
PHENIX, QM17

PRC 93 (2016) 034904



Charm flows together

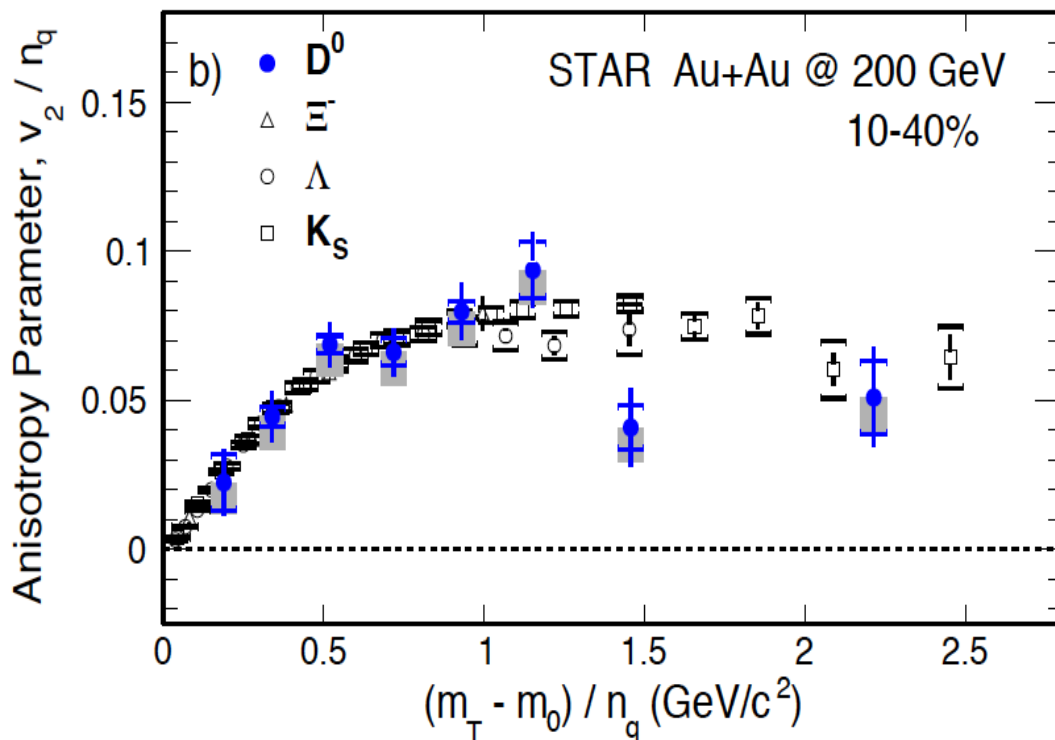
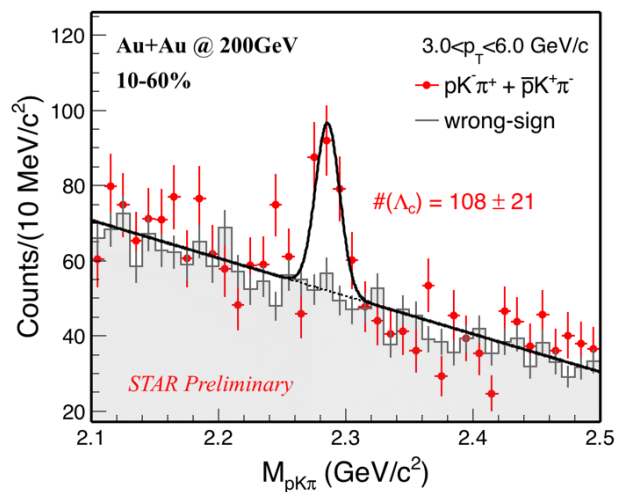
--- quark coalescence including charm quarks ---
 --- first measurement of Λ_c in A+A ---



$$R_{AA}(u,d,s) \sim R_{AA}(c)$$

$$v_2(u,d,s) \sim v_2(c)$$

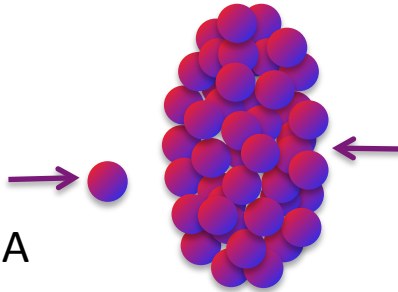
STAR, QM17



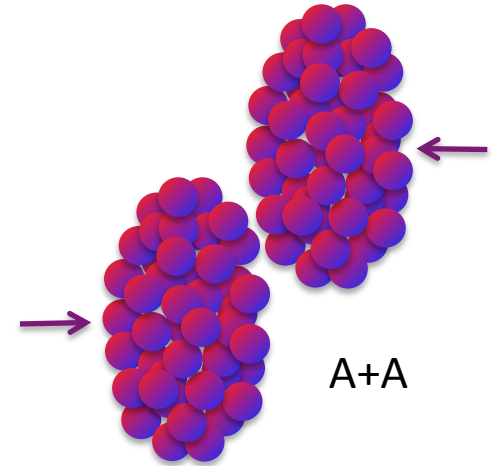
Small vs Large system
 --- indication of **elliptic flow** evolution ---



p+p (high mult.)



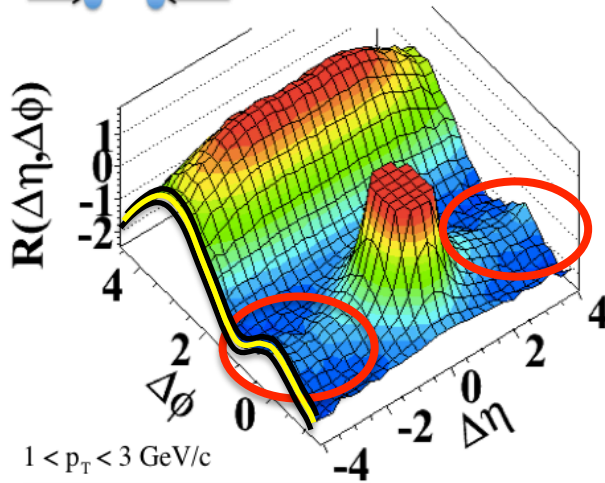
p+A



A+A

CMS, QM15

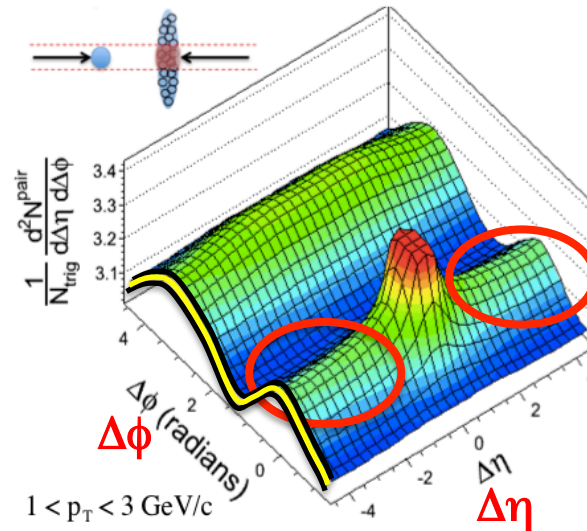
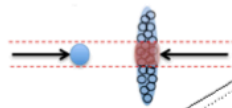
(a) pp $\sqrt{s} = 7$ TeV, $N_{\text{trk}}^{\text{offline}} \geq 110$



$1 < p_T < 3$ GeV/c

JHEP 09 (2010) 091

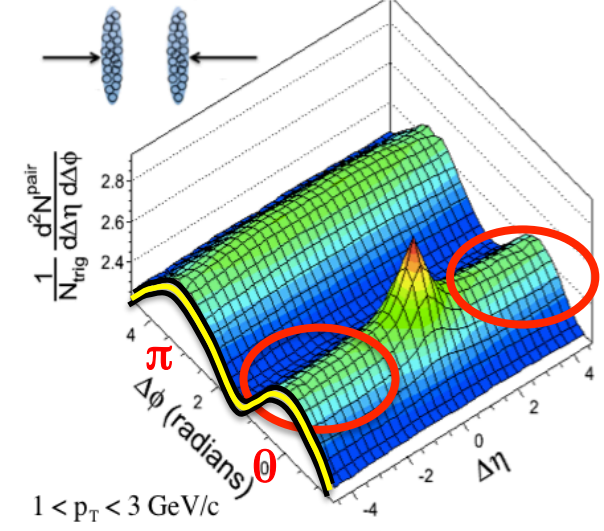
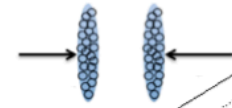
(b) pPb $\sqrt{s_{NN}} = 5.02$ TeV, $220 < N_{\text{trk}}^{\text{offline}} \leq 260$



$1 < p_T < 3$ GeV/c

PLB 724 (2013) 213

(c) PbPb $\sqrt{s_{NN}} = 2.76$ TeV, $220 < N_{\text{trk}}^{\text{offline}} \leq 260$



$1 < p_T < 3$ GeV/c

PLB 724 (2013) 213

Beam Energy Scan in d+Au collisions

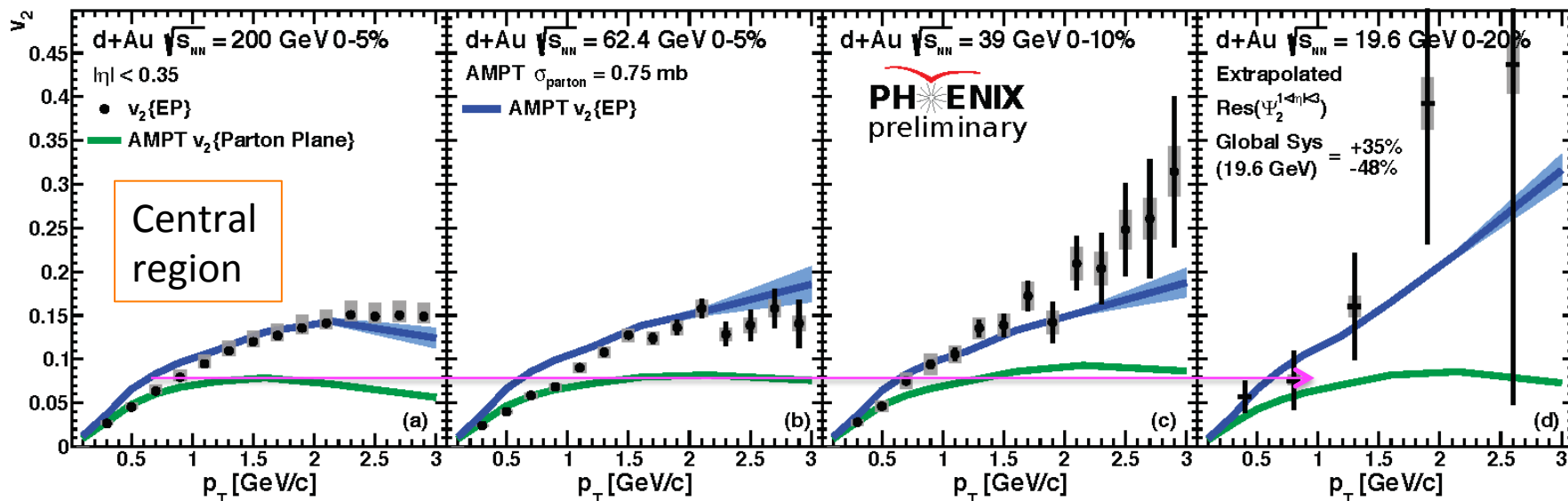
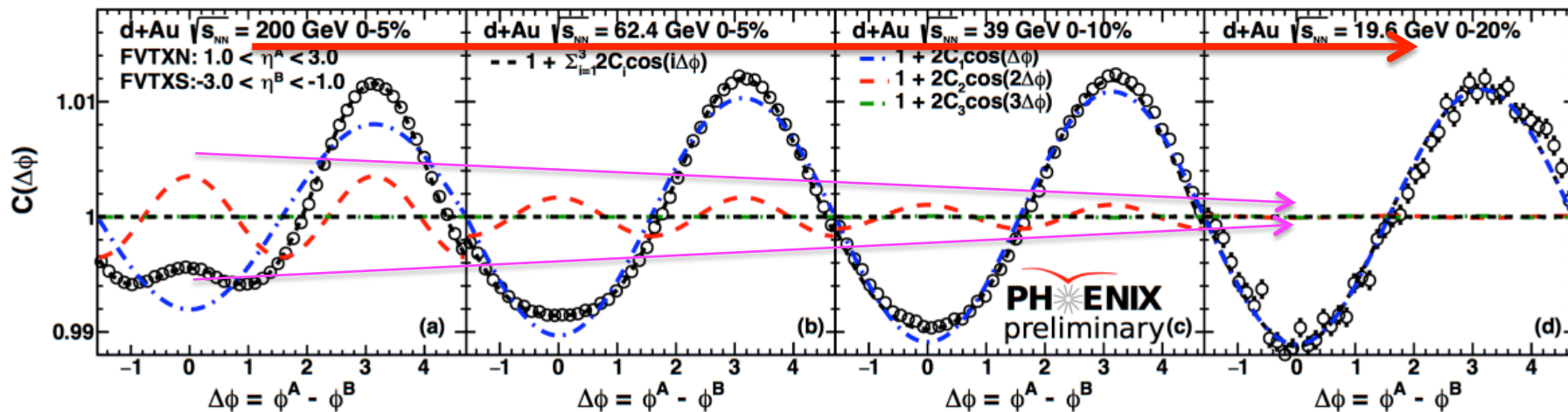
Forw.-Back.
correlation

200 GeV

62 GeV

39 GeV

20 GeV

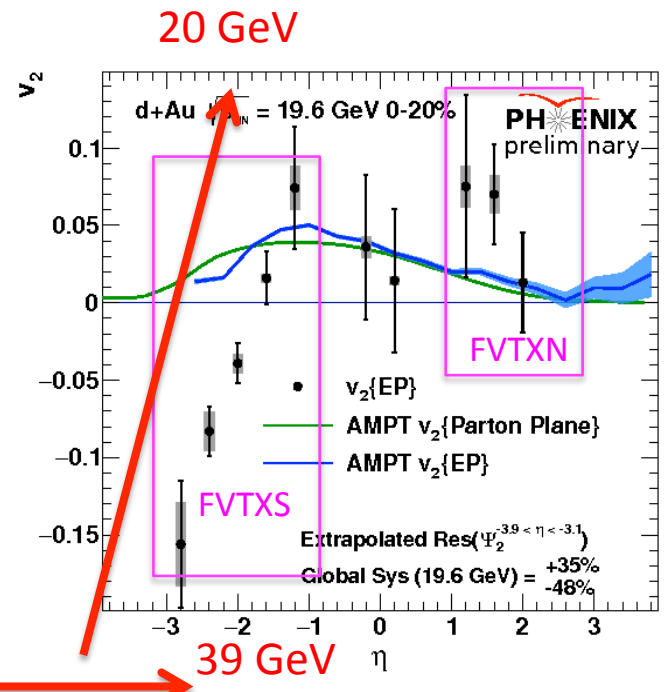


PHENIX, QM17

Beam Energy Scan in d+Au collisions --- rapidity dependence ---

p_T and rapidity dependences have been studied,
the centrality (multiplicity) dependence IS the key...!
A new insight of forward/backward v_n from Cu+Au

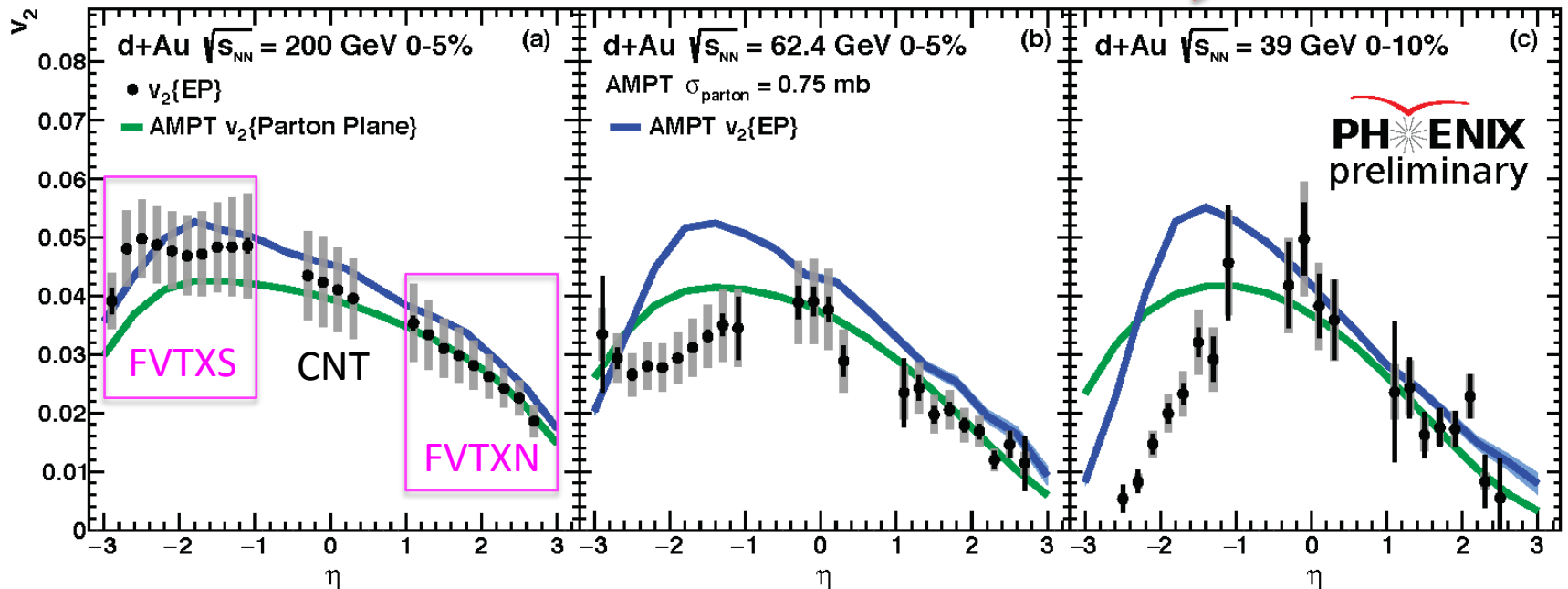
PHENIX, QM17



200 GeV

62 GeV

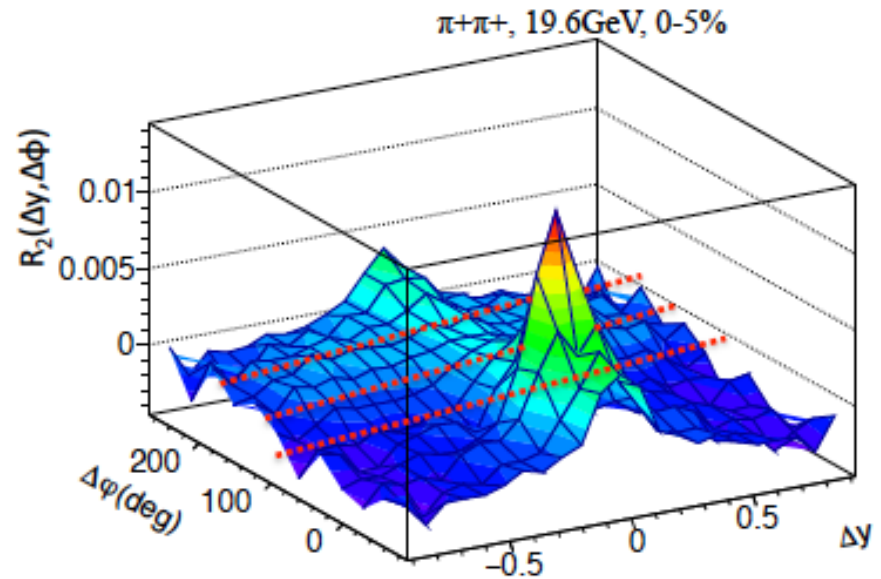
39 GeV



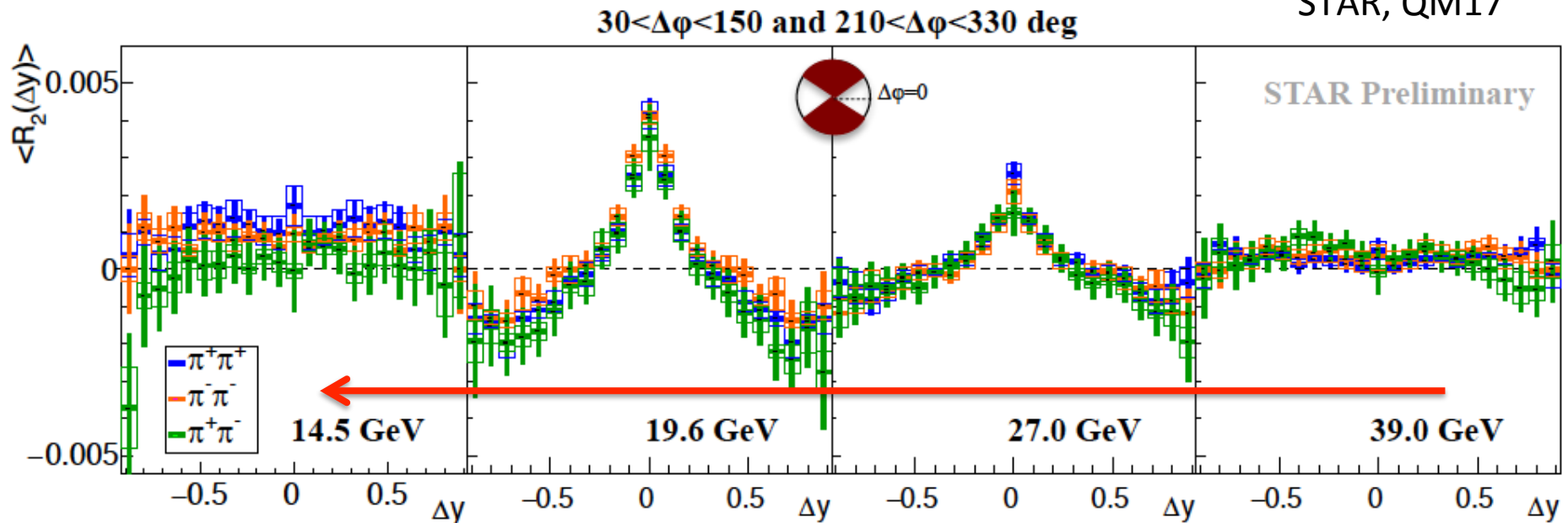
Ridge structure in $\Delta\phi$ direction

--- significant at 20-30GeV ---

A new structure along $\Delta\phi$ has appeared at 20~30GeV central AuAu collisions, where similar structure has been seen in pp at lower pT region in wide colliding energies at RHIC and LHC.

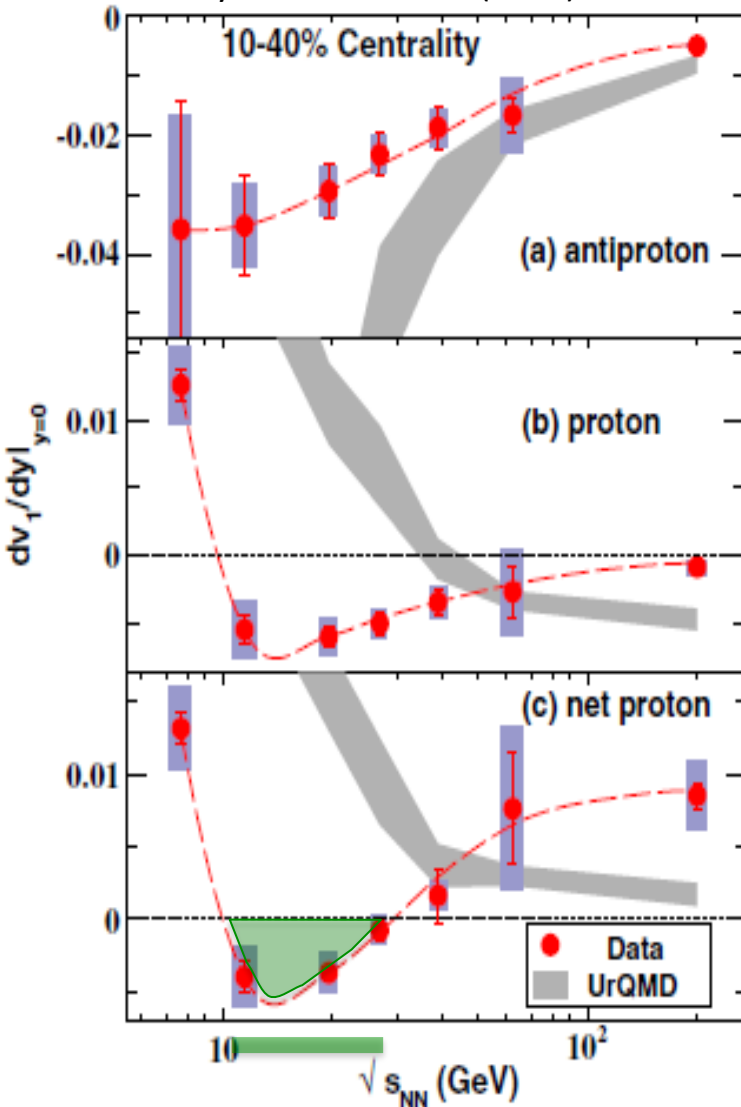


STAR, QM17

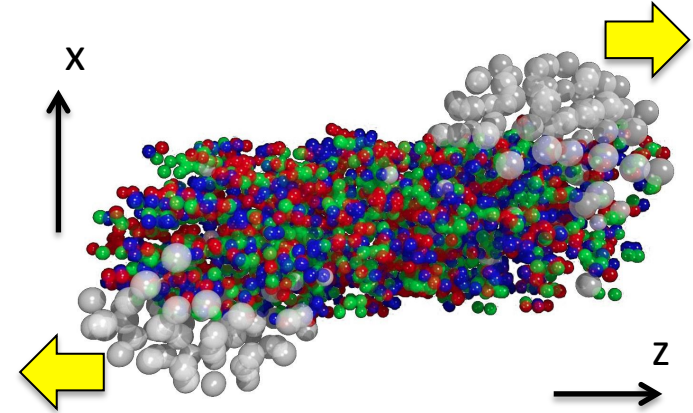


Equation of state from Directed flow (v_1)

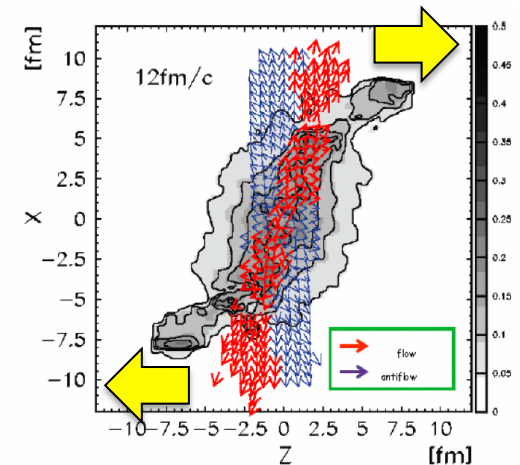
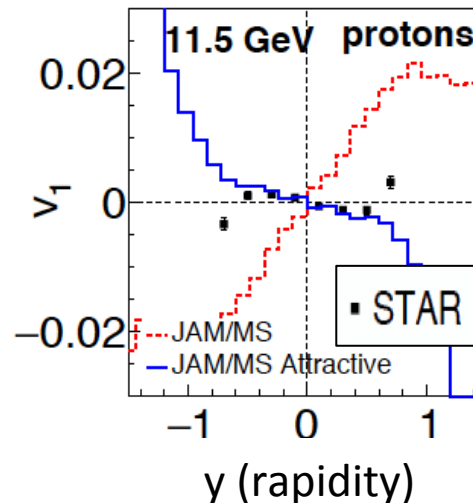
Phys. Rev. Lett. 112 (2014) 162301



- negative slope of dv_1/dy for net-proton
- softening of equation of state



arXiv : 1601.07692

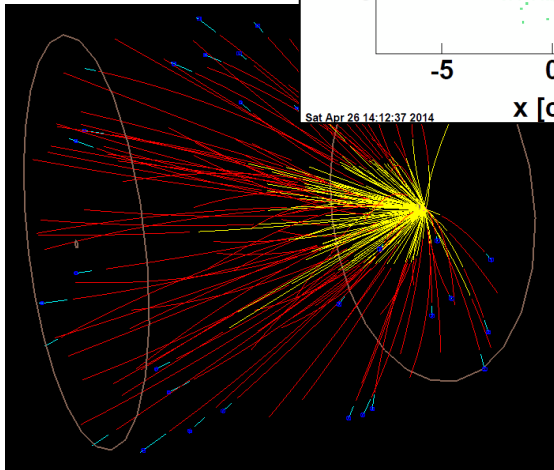
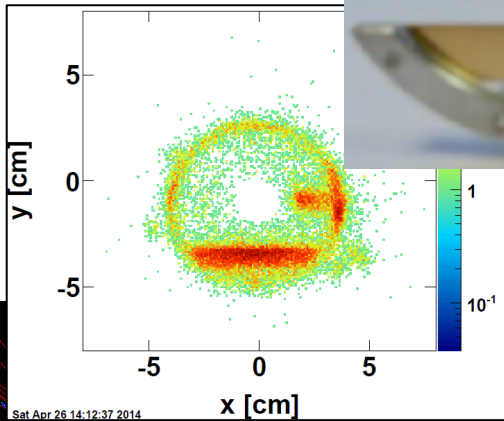
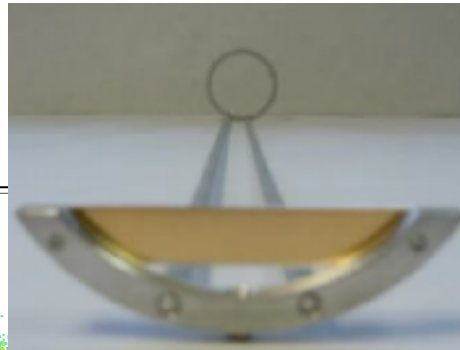


J. Brachmann et al., PRC 61, 24909 (2000).

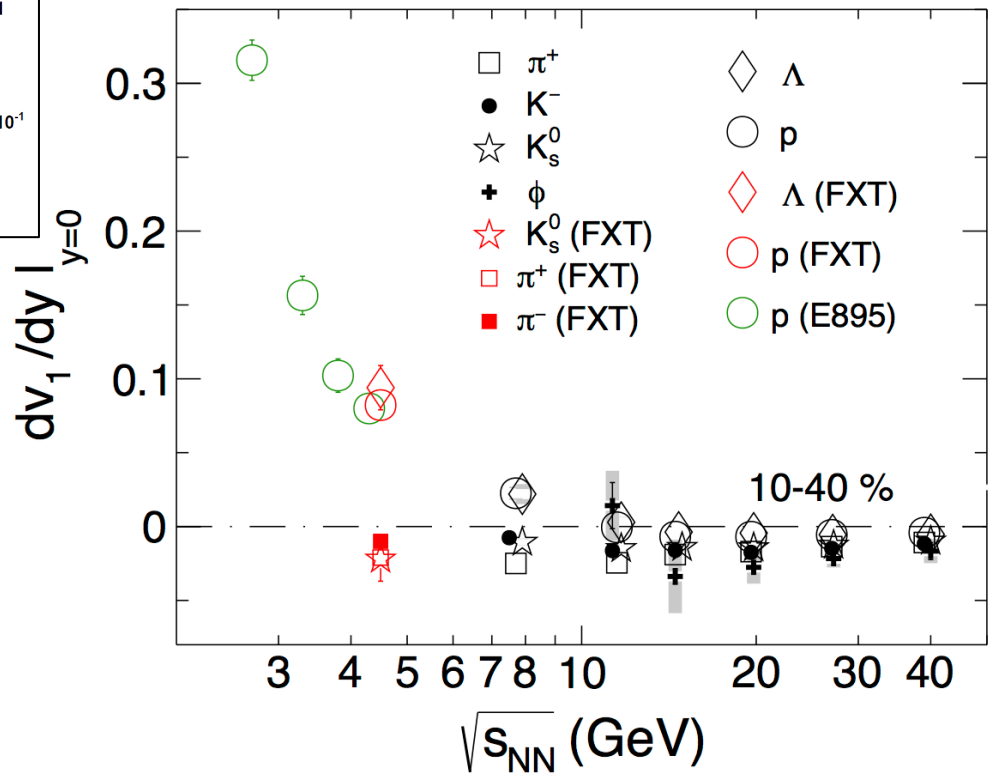
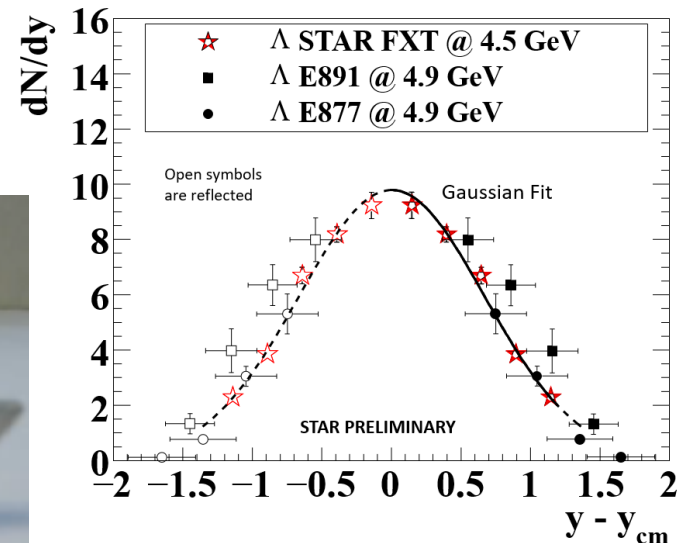
Fixed-target mode in STAR

Dedicated fixed-target run
already taken at STAR in 2015 :
 $\sqrt{s_{NN}} = 4.5 \text{ GeV}$ (2 M events/h)

target in beam pipe

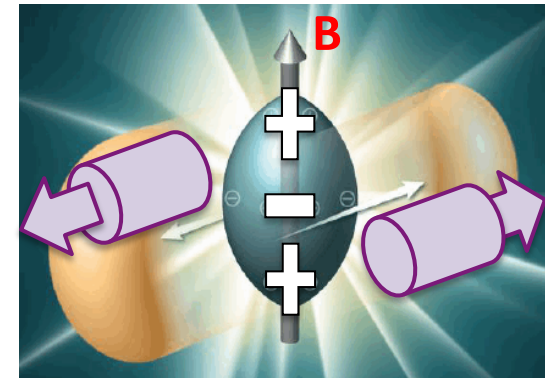
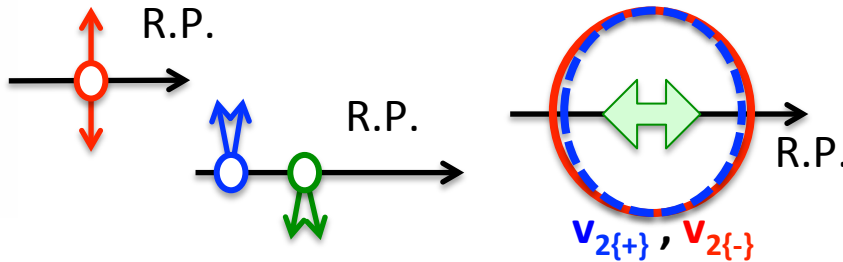
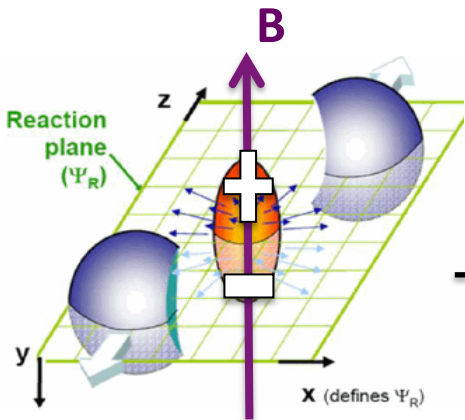


MRPC-TOF at End-cap from CBM
experiment in FAIR in next few years

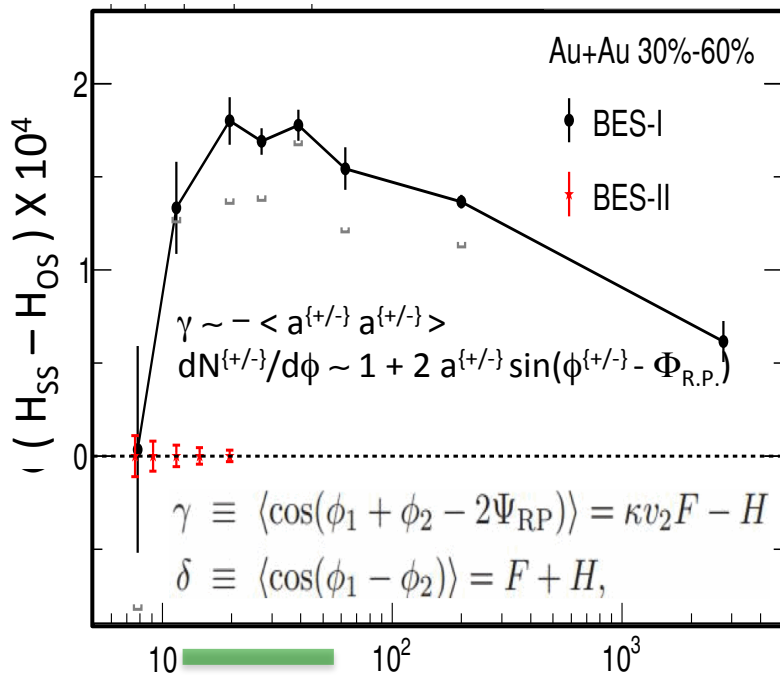


Chiral magnetic effect/wave

--- via strong B-field ---



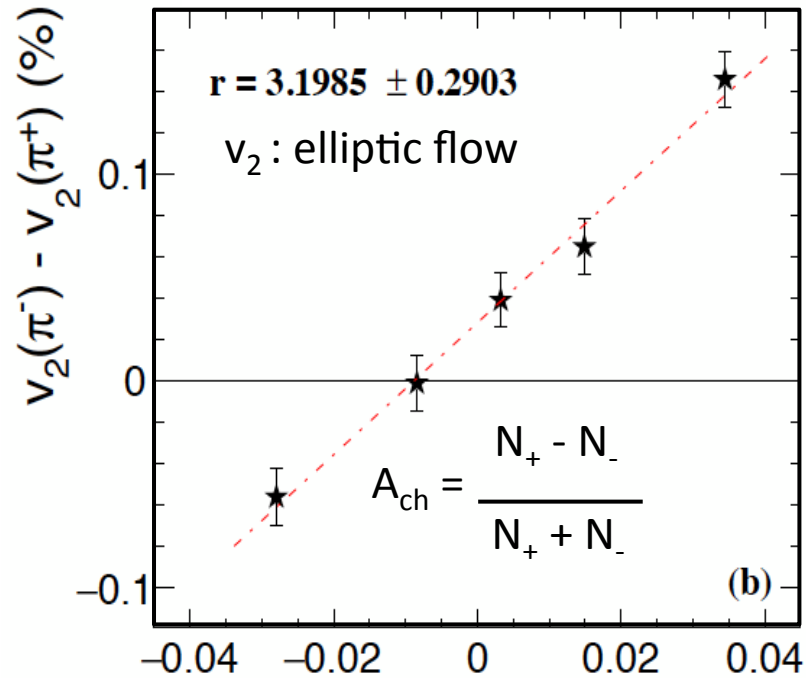
Phys. Rev. Lett. 113 (2014) 052302



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

$\sqrt{s_{NN}}$ (GeV)

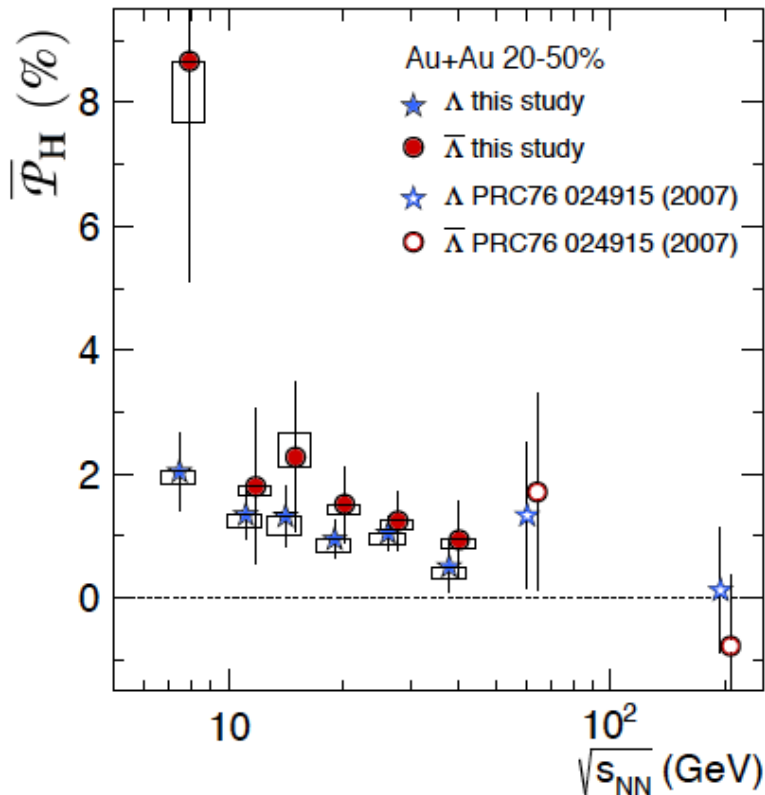
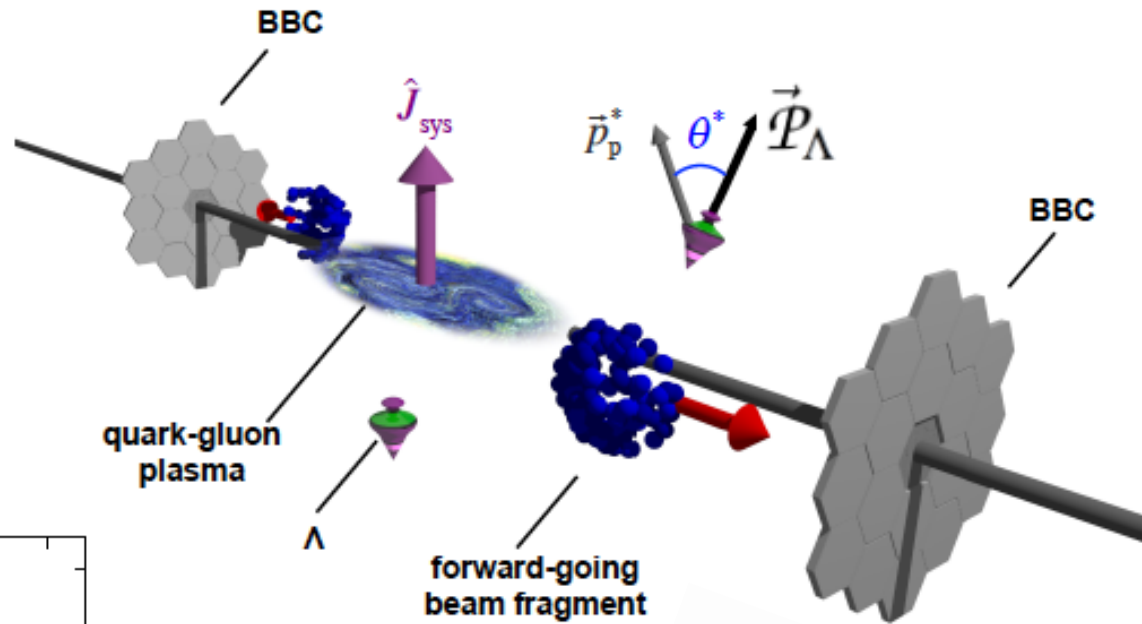
Phys. Rev. Lett. 114 (2015) 252302



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

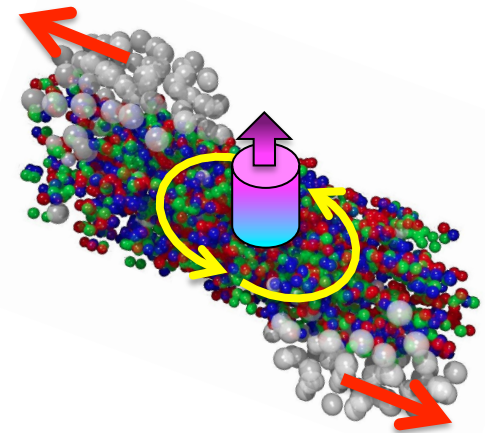
Angular momentum and/or B-field in non-central heavy-ion collisions

--- via Λ polarization ---



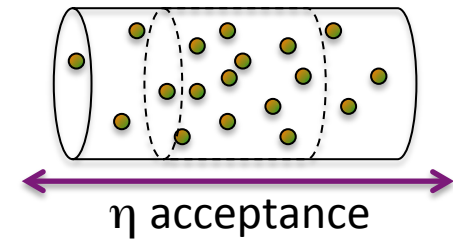
$\Lambda, \bar{\Lambda}$ signals

- Average : angular momentum
- Difference : B-field

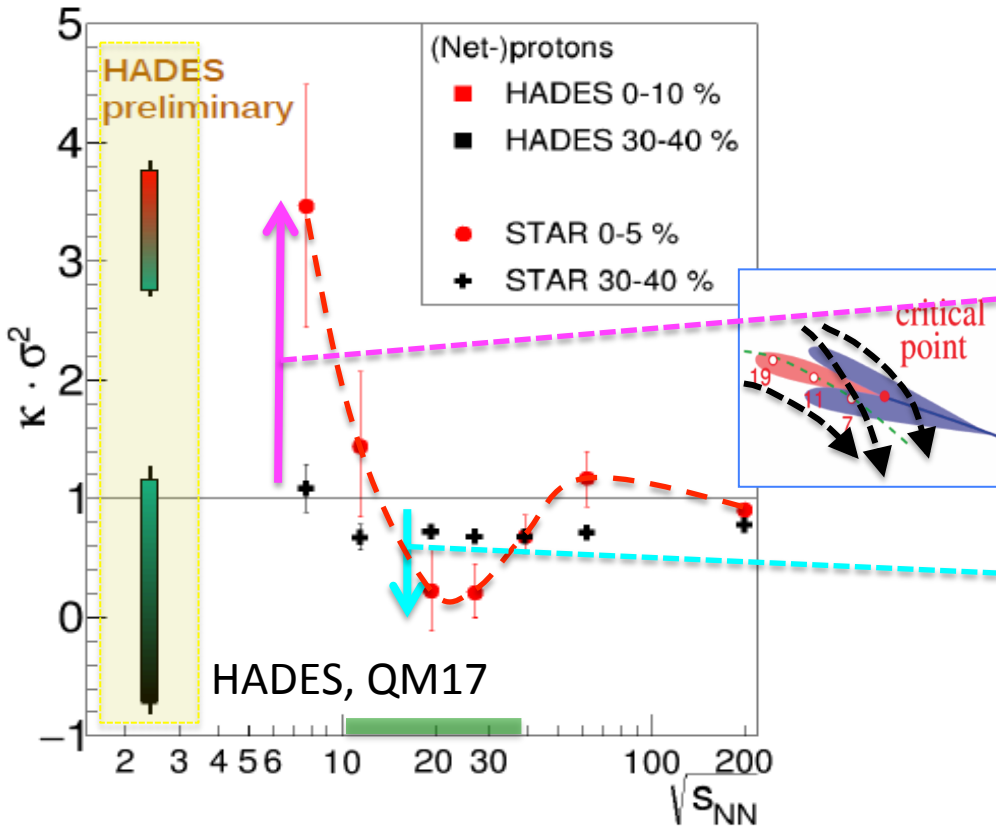


Directed flow v_1 event plane Φ_1 from spectator beam fragments are measured by BBC detector

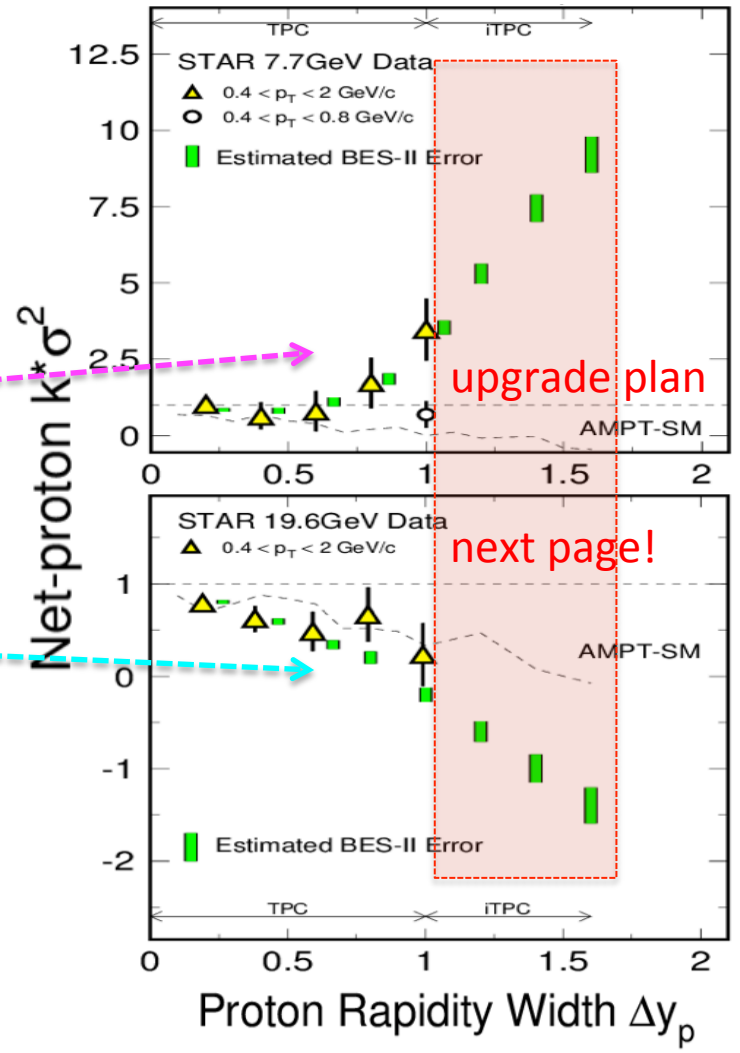
Fluctuation of conserved quantity in Au+Au (net-proton as a proxy of net-Baryon)



arXiv:1503.02558v2 RHIC-BES1 (2010-2011)



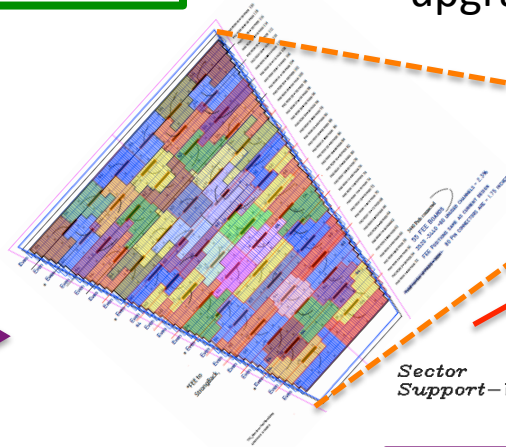
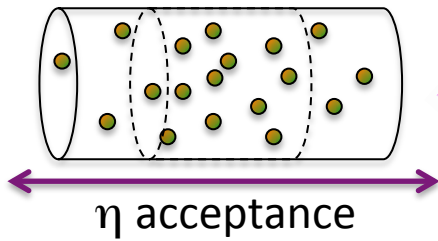
Note : different $\Delta y_p \sim 0.2$ window compared to STAR (~ 1.0)
: different assumption in volume fluctuation correction



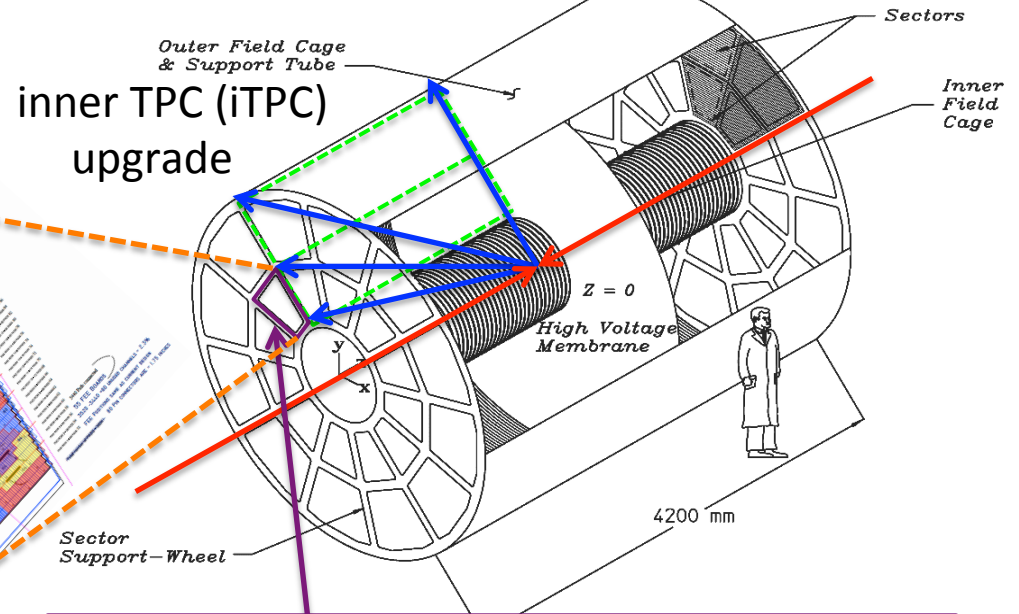
STAR upgrade for BES2

--- iTPC + eTOF + EPD ---

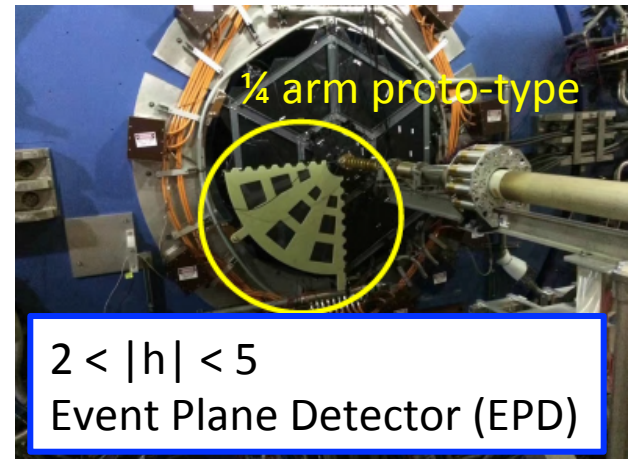
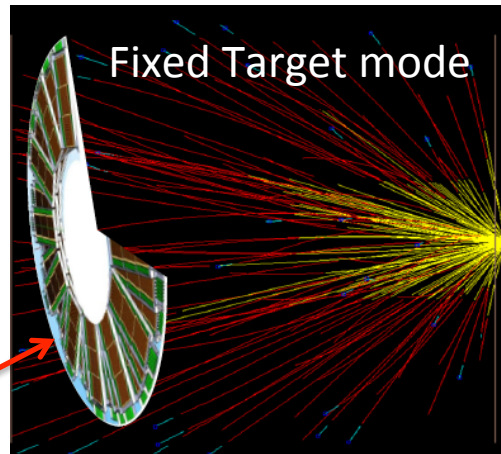
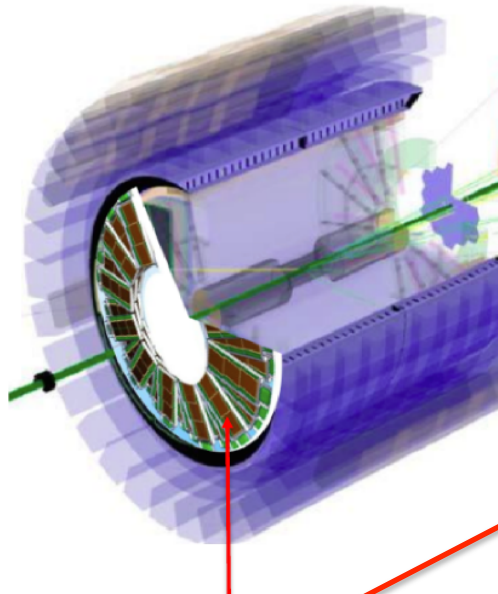
--- electron cooling at RHIC ---



Time Projection Chamber (TPC)



new inner pad/wire planes with full readout

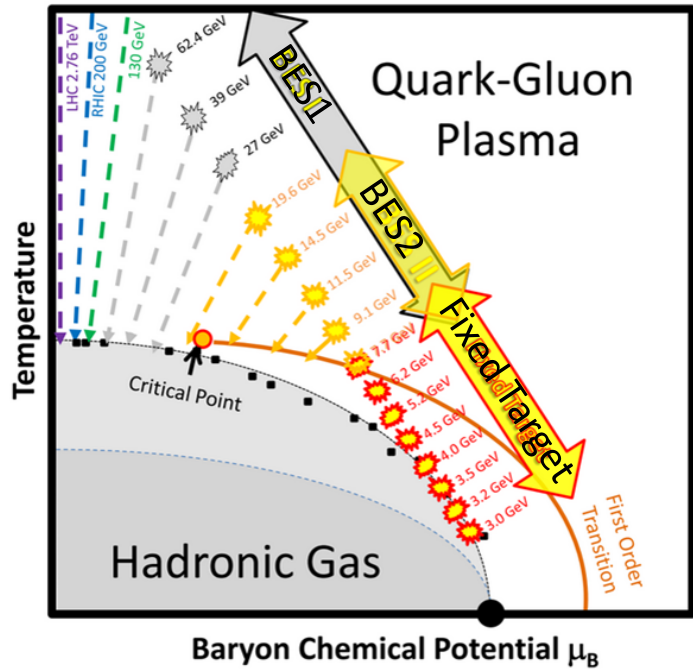


$2 < |h| < 5$
Event Plane Detector (EPD)

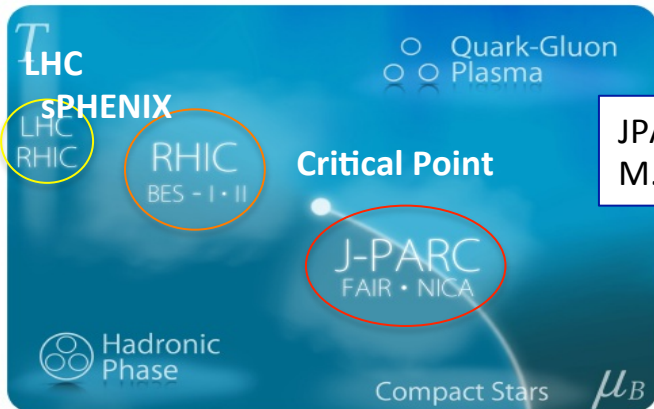
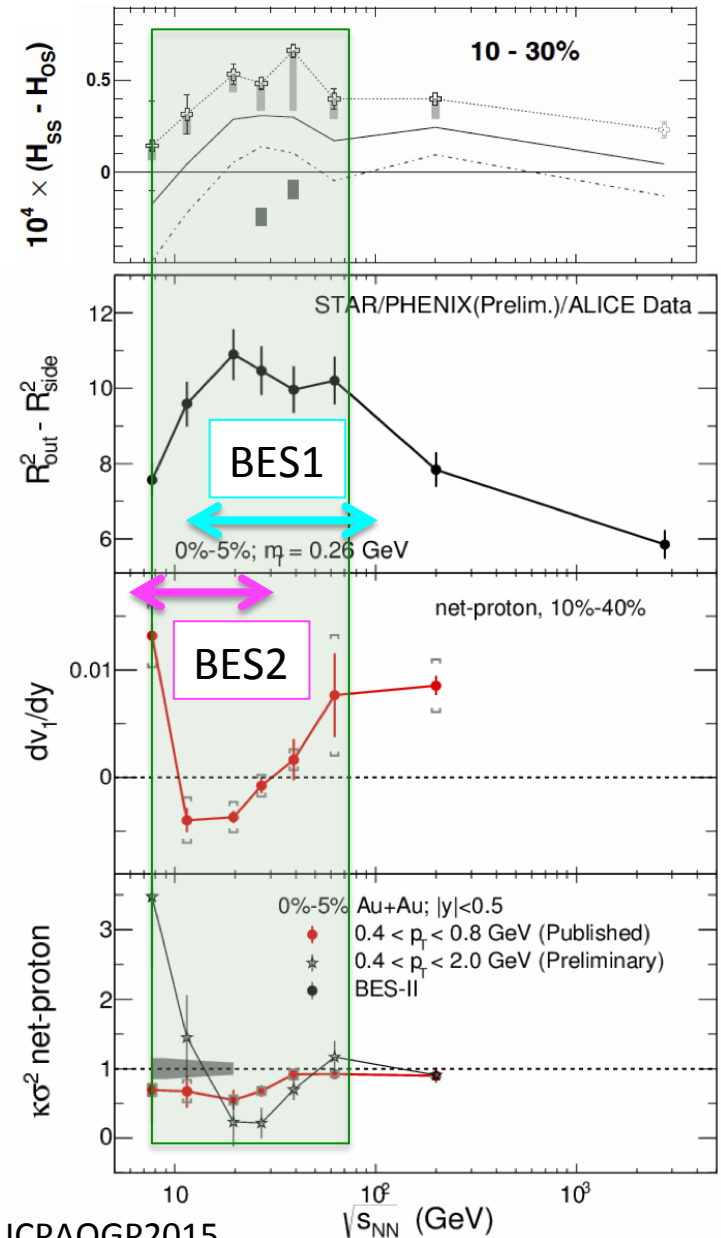
end-cap Time of Flight from CBM (Fair-GSI)

We've started working on EPD.

Beam Energy Scan 2 (BES2) and future programs



Phase diagram, Critical point, High-density nuclear matter



JPARC-HI LOI, H. Sako, M. Kitazawa, et. al.

Z. Xu, ICPAQGP2015

Shinichi Esumi, Univ. of Tsukuba, CiRFSE

Summary and Outlook

- High enough initial temperature
- Large elliptic flow in partonic stage and radial flow at the end of freeze-out
- Energy loss inside QGP and re-distribution of the lost energy
- Energy loss and flow of heavy-quarks

(recent results)

- Flow and correlation in small system (pp, pA and dAu energy scan 20-200GeV)
- Beam energy scan to search for critical behavior (cons. fluctuation, dv_1/dy , CME, CVE, ESE correlation)

RUN17 RUN18	500GeV p+p 200GeV Zr+Zr, Ru+Ru 27GeV Au+Au
RUN19 RUN20	14.5-20 GeV Au+Au 7-11 GeV Au+Au Fixed target mode
RUN21 RUN22	200GeV Au+Au sPHENIX (jet, γ ,upsilon)

2017年3月物理学会におけるRHIC加速器を用いた原子核実験講演

3月17日(金) 17pK24

4. 山口頼人(理研) for the sPHENIX collaboration
「sPHENIXに向けたシリコン飛跡検出器開発の現状」
5. 中川格(理研) for the sPHENIX collaboration
「sPHENIXに向けたシリコン飛跡検出器の冷却システム開発の状況」

3月18日(土) 18aH22

5. 野中俊宏(筑波大数理) for the STAR collaboration
「STAR実験金+金衝突 $v_{s_{NN}}=200\text{GeV}$ における陽子数分布を用いた6次キュムラントの中心衝突度およびアクセプタンス依存性の測定」
9. 杉浦哲郎(筑波大数理) for the STAR collaboration
「RHIC-STAR実験衝突における net-charge揺らぎの $\Delta\eta$ 依存性」
10. 武田明莉(奈良女大理) for the PHENIX collaboration
「Measurement of azimuthal anisotropy for high pT charged hadron at $v_{s_{NN}}=200\text{GeV}$ in Au+Au at RHIC-PHENIX」

3月19日(日) 19pK24

8. 工藤咲子(筑波大数理) for the PHENIX collaboration
「RHIC-PHENIX実験 $3\text{He}+\text{Au}$ 衝突における高運動量の荷電ハドロン生成量の測定」
9. 永嶋和也(広大院理) for the PHENIX collaboration
「Nuclear modification factor of bottom and charm in Au+Au collisions at $v_{s_{NN}}=200\text{GeV}$ in the PHENIX」
11. 江角晋一(筑波大数理) for the STAR collaboration
「RHICビームエネルギー走査実験とSTAR実験のアップグレード計画」