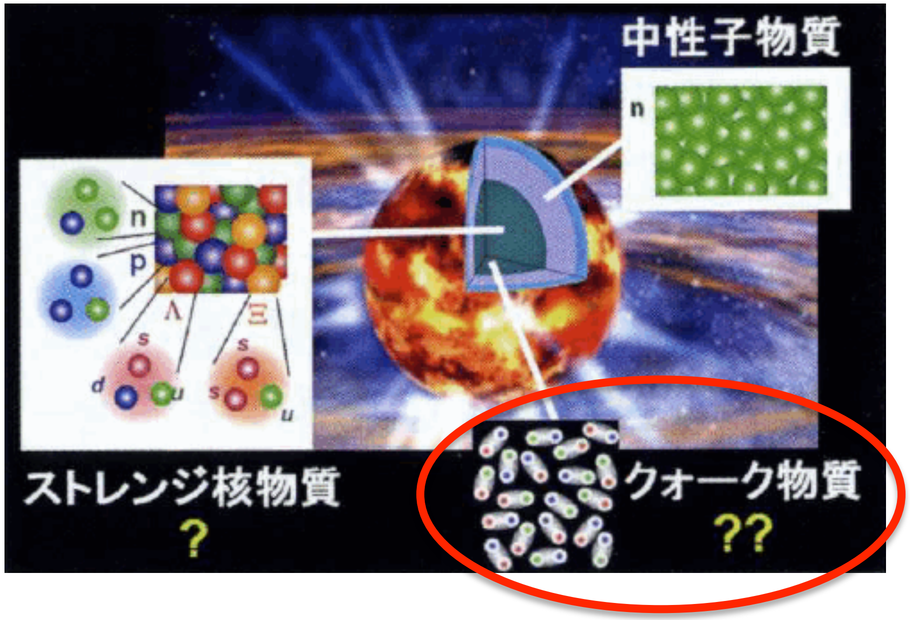
新学術領域「実験と観測で解き明かす中性子星の核物質」研究会

A02:公募研究「高温高密度クォーク物質のQCD臨界点探索」

----- 多粒子相関法（ハード領域のジェットとソフト領域の流体間の相関測定） -----

筑波大学、物理、江角晋一

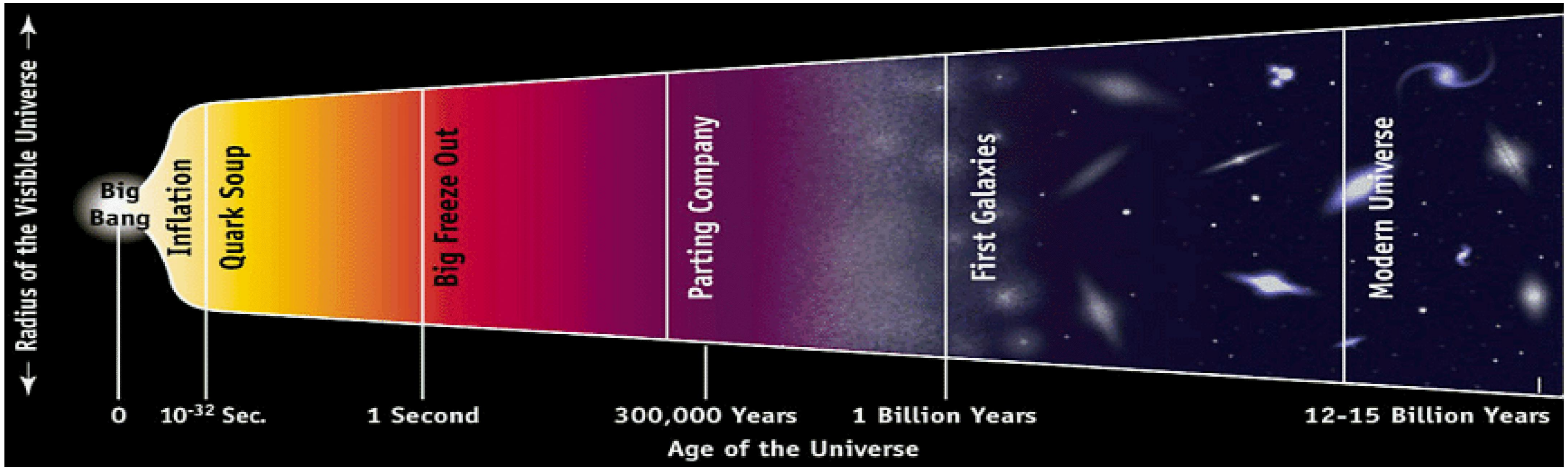


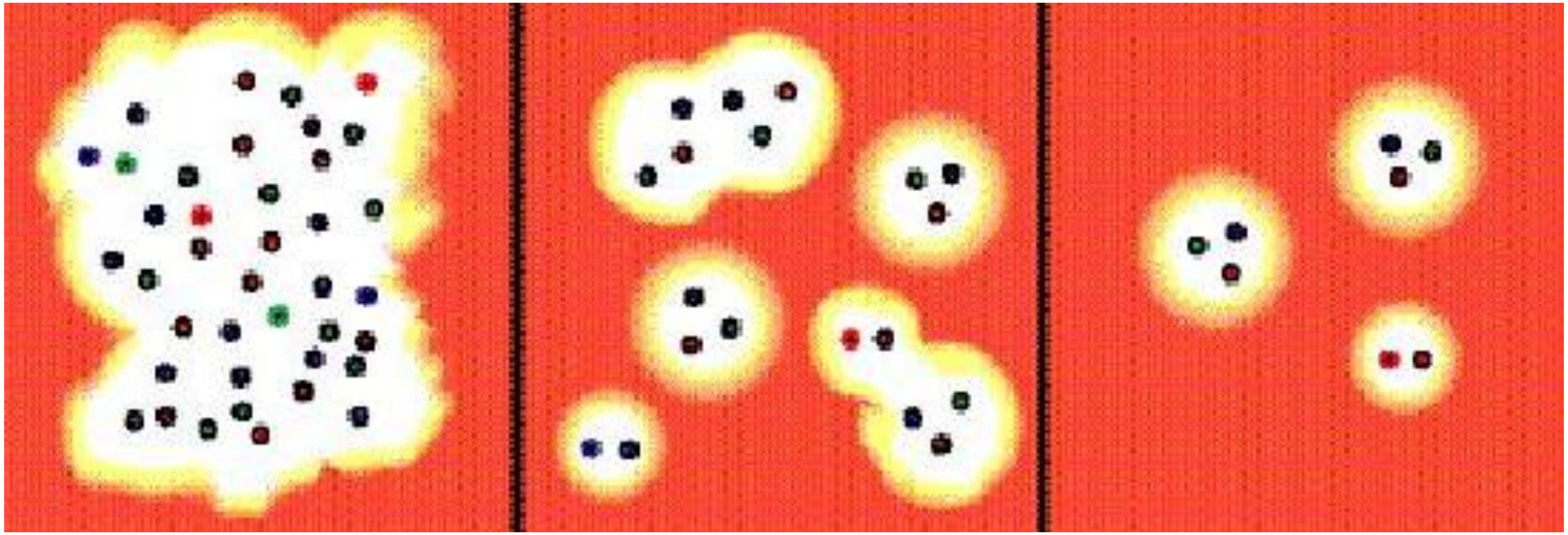
田村さん、大阪市立科学館発行 月刊「うちゅう」
2013年7月号より（画像の一部はNASAより。）

高温・高密度クォーク物質
クォーク・グルーオン・プラズマ（QGP）
ハドロン・QGP相転移
QCD臨界点

ジェットや光子等のハード物理
流体的、集団運動的なソフト物理
多粒子相関的手法を使い
これらの間の相互作用を研究

Quark Gluon Plasma (QGP)

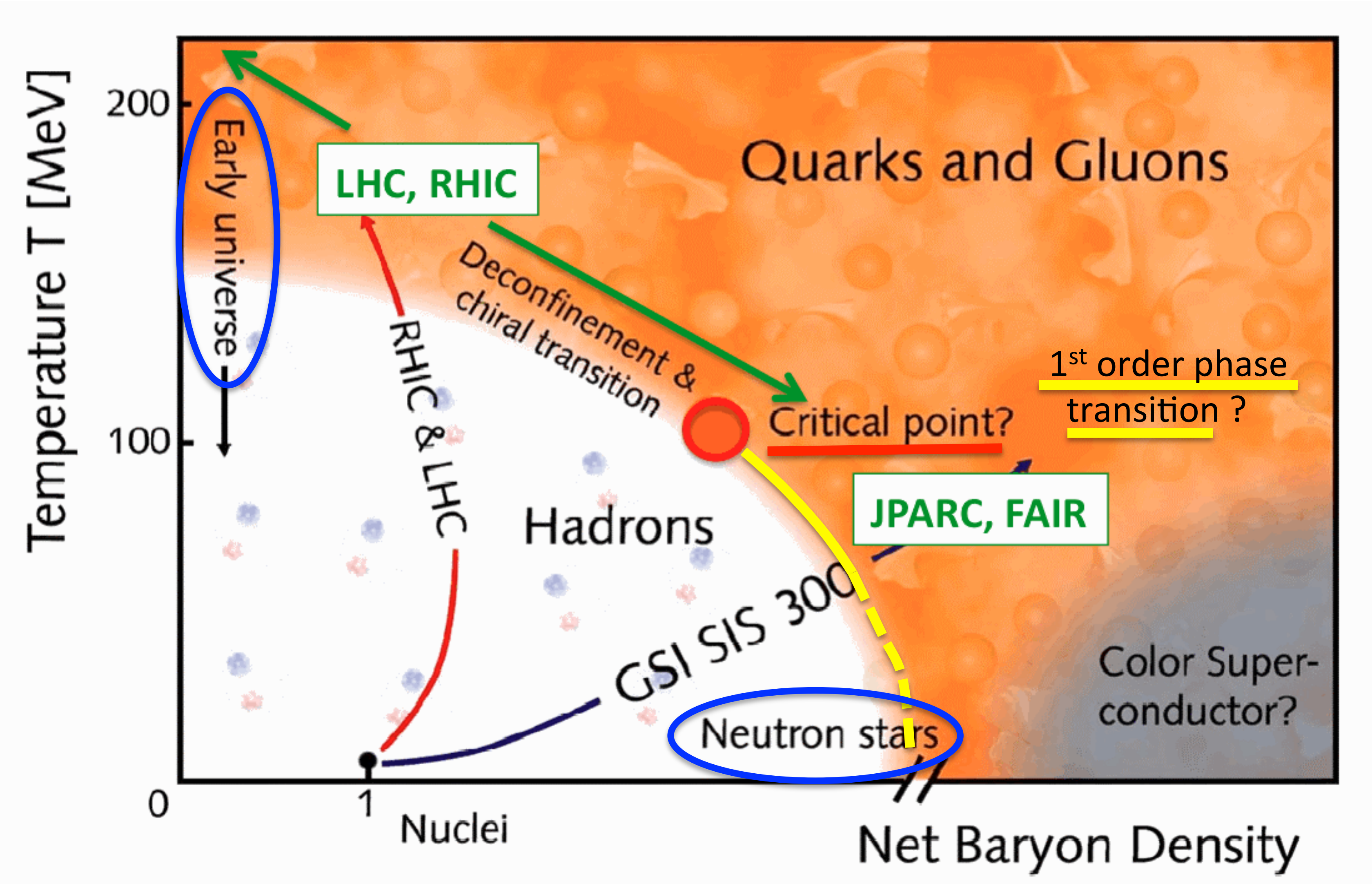




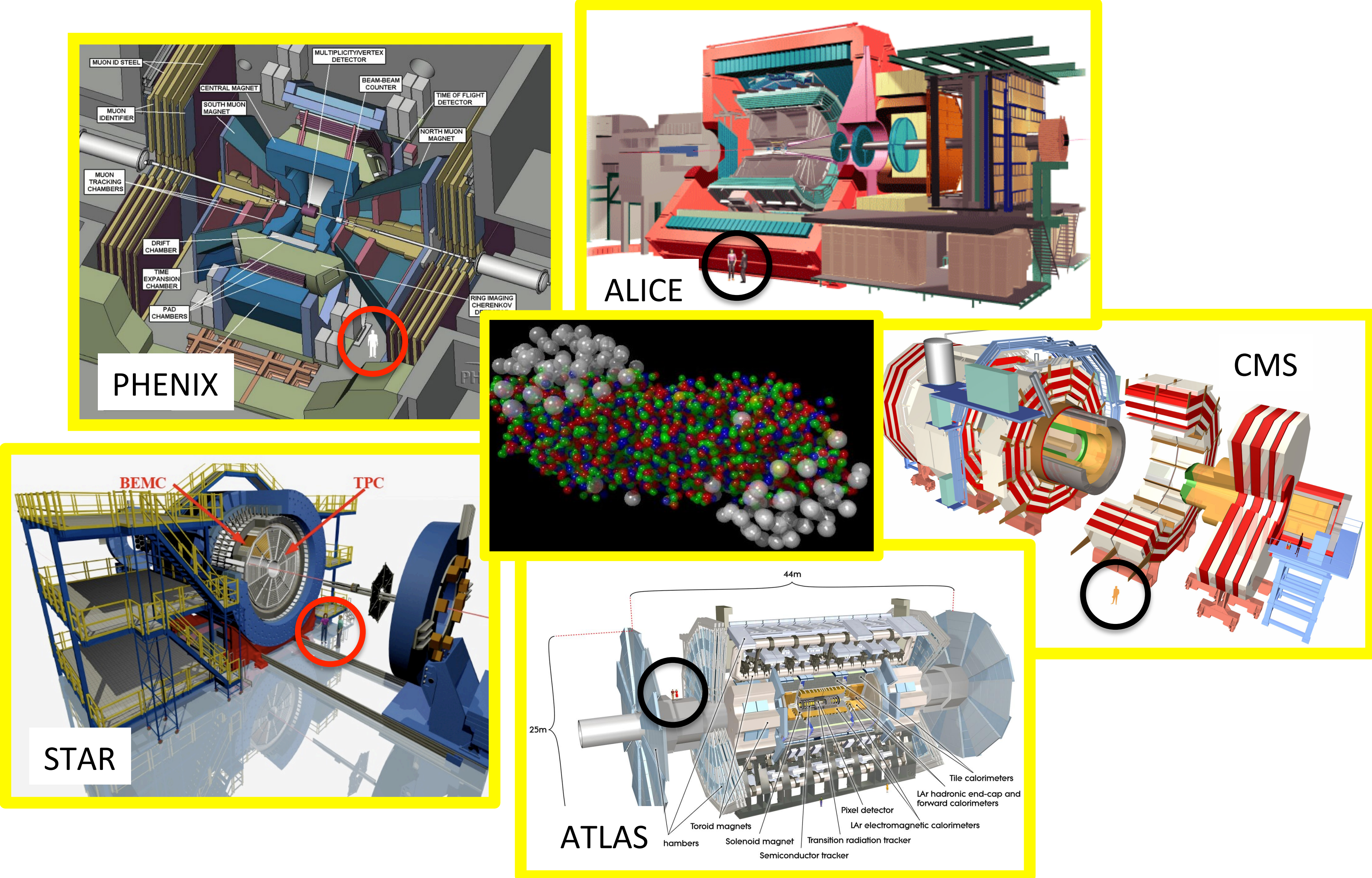
Quark Gluon Plasma   Hadrons

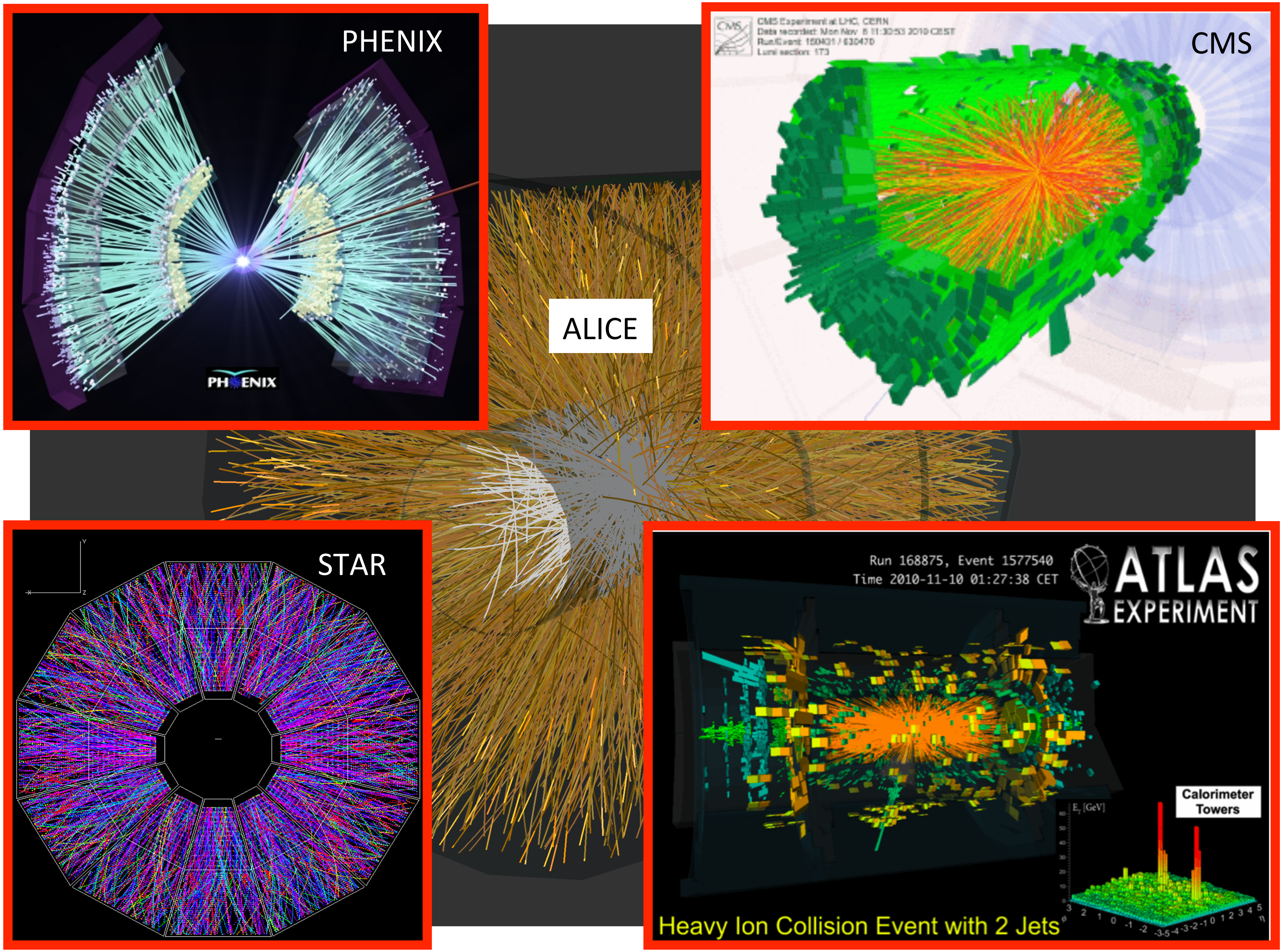
RHIC Beam Energy Scan program (BES)

to look for critical behaviors --- critical point and 1st order phase transition ---

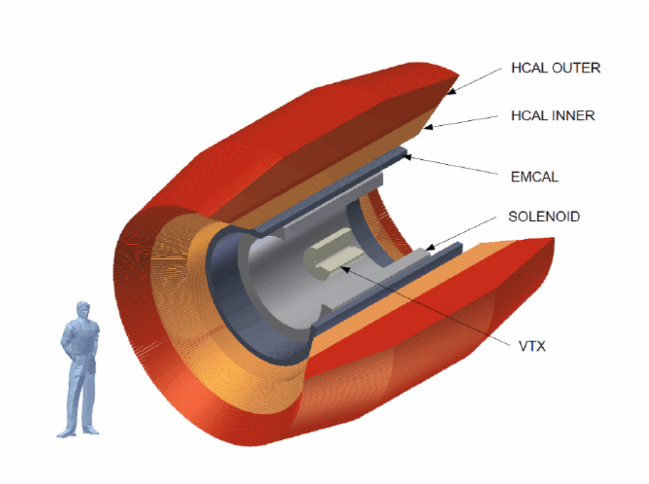


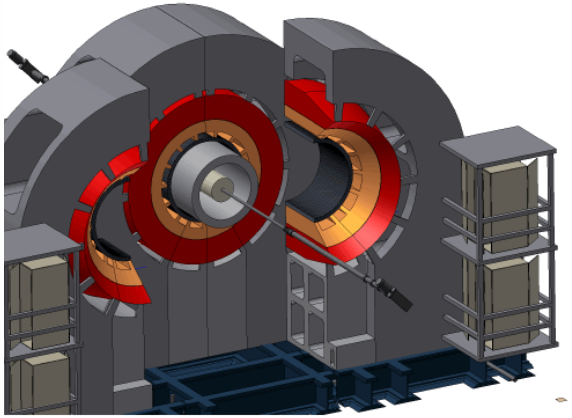
Relativistic Heavy-Ion Collider (RHIC) at Brookhaven National Laboratory (BNL)
Large Hadron Collider (LHC) at European Organization for Nuclear Study (CERN)

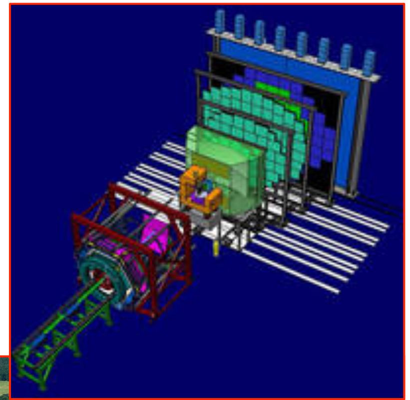



PHENIX
PHENIX
ALICE
CMS
STAR
Run 168875, Event 1577540
Time 2010-11-10 01:27:38 CET
ATLAS
EXPERIMENT
Calorimeter Towers
Heavy Ion Collision Event with 2 Jets

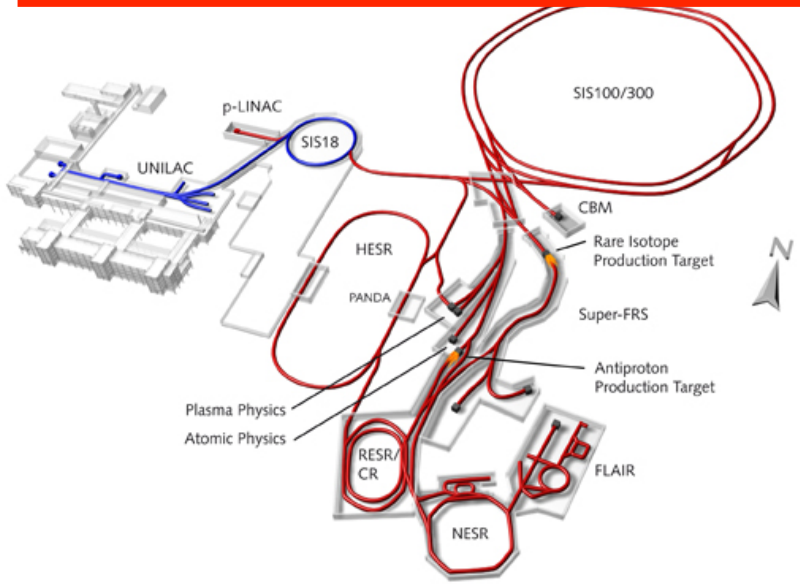
sPHENIX upgrade at RHIC, New York, USA





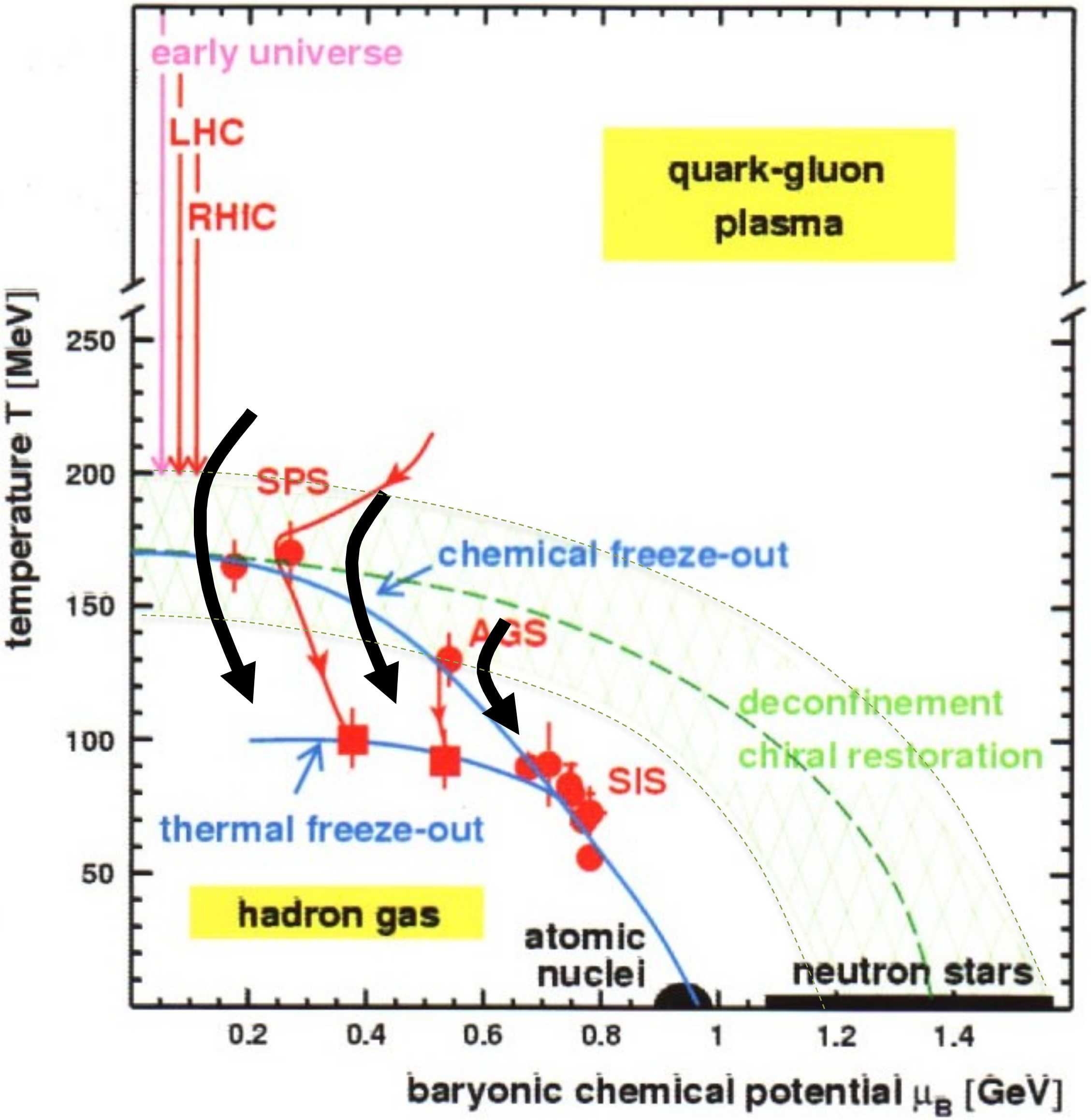


FAIR at GSI, Darmstadt, Germany



Heavy-Ion upgrade at J-parc, Tokai, Japan

化学的、熱的なフリーズアウト



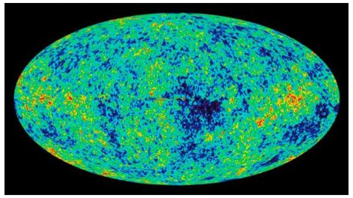
single particle p_T spectra, HBT measurements

- Thermal freeze-out
- $T_{fo}^{(Th)} \sim$ 100MeV
- end of elastic interaction among hadrons
- local thermalization
- Radial expansion, flow

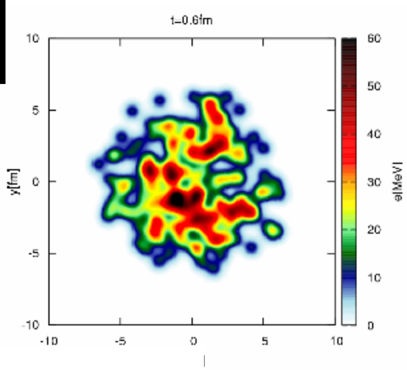
particle yield and ratio

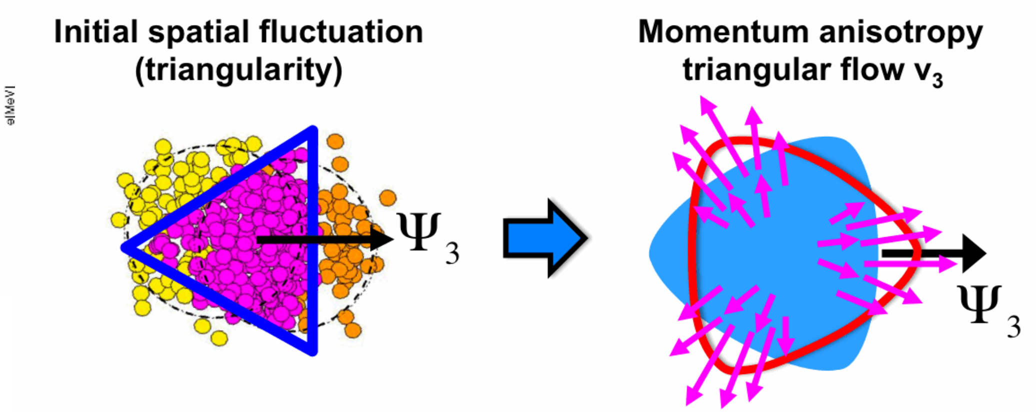
- Chemical freeze-out
- $T_{fo}^{(Ch)} \sim$ 170MeV
- end of inelastic interaction among hadrons
- close to the expected phase boundary

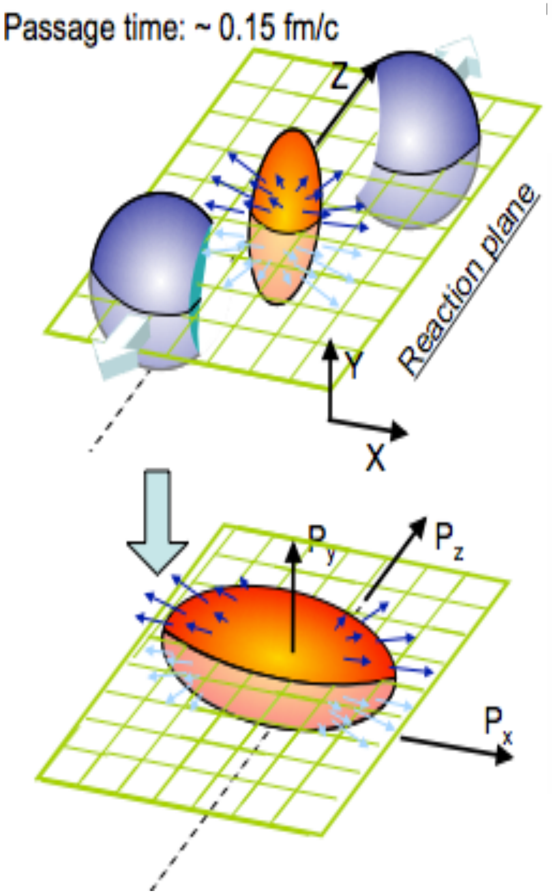
初期ゆらぎ、高次方位角異方性、集団運動的膨張

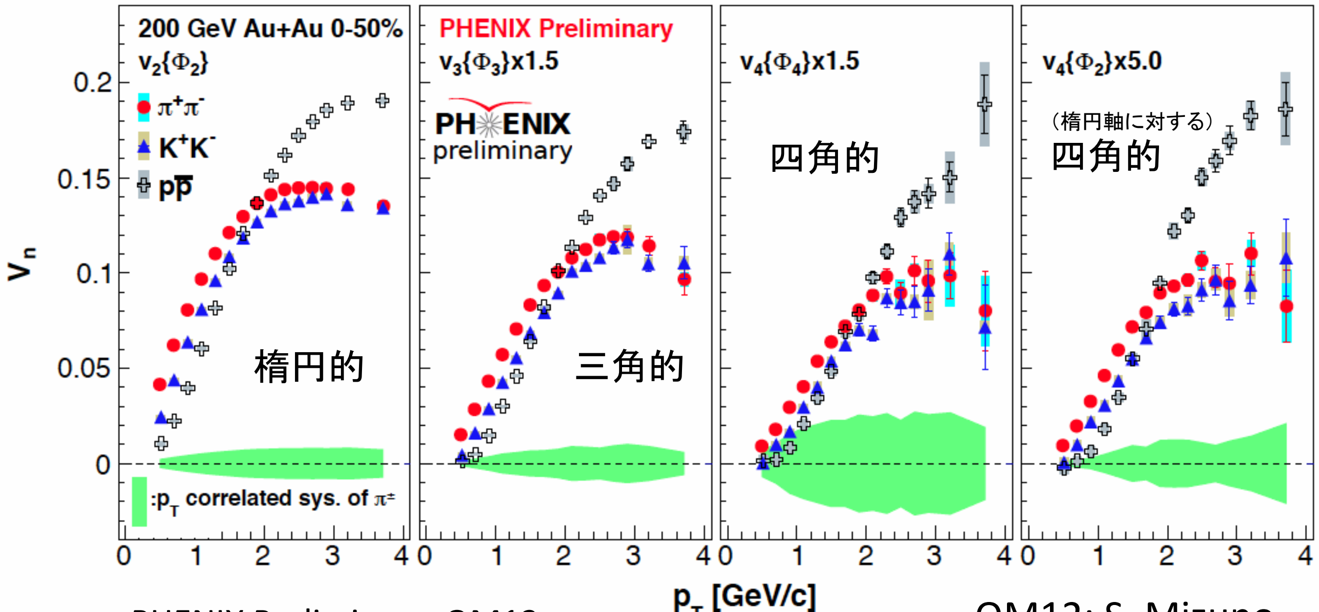


WMAP









PHENIX Preliminary, QM12

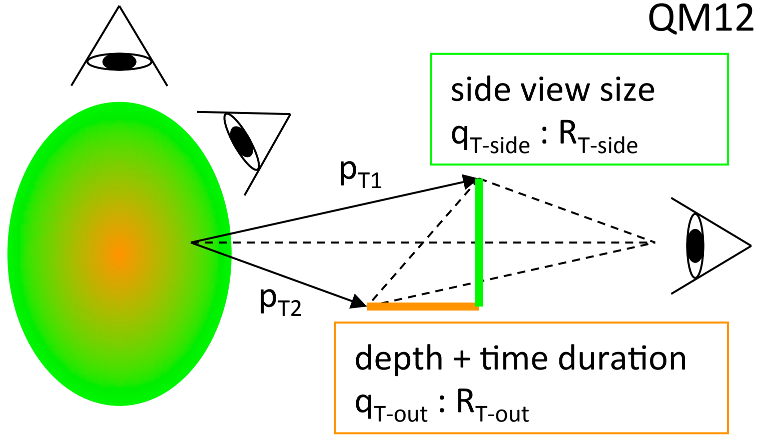
QM12: S. Mizuno

QM12: T. Niida

フリーズアウト時の

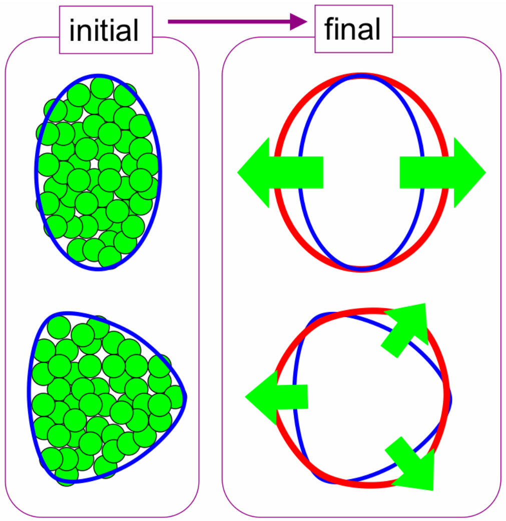
幾何学的形状、大きさ、時間幅

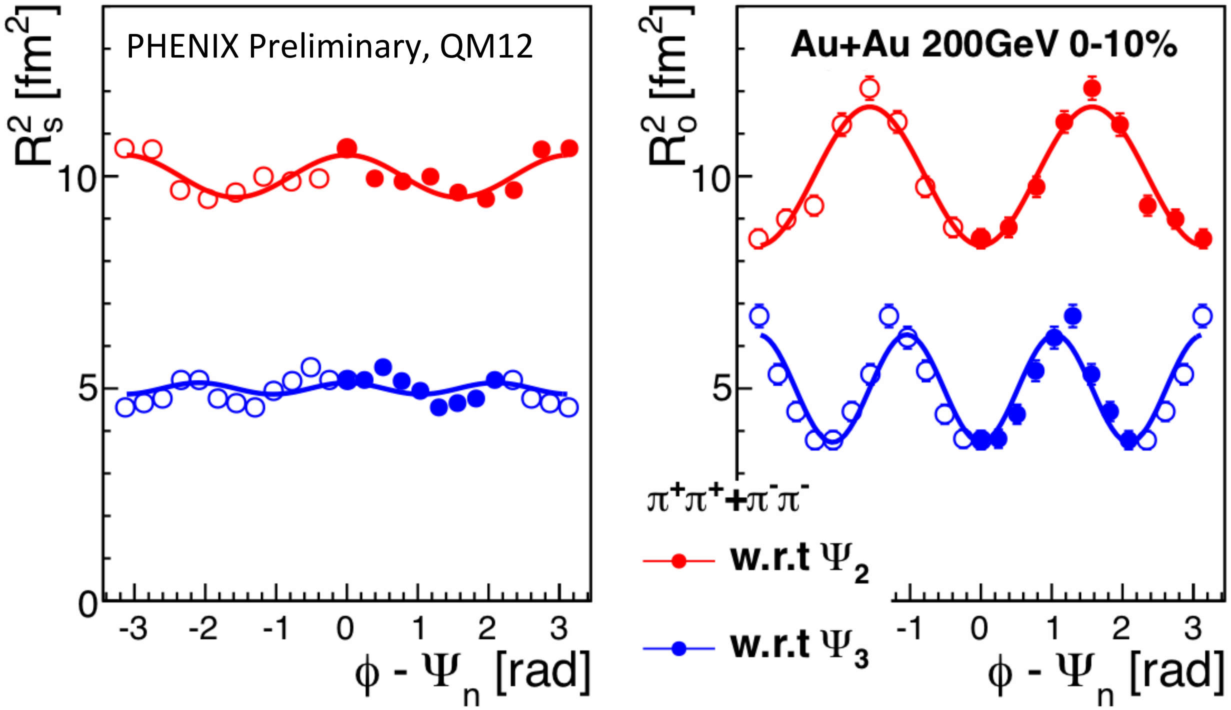
量子力学的二粒子相関（HBT相関）



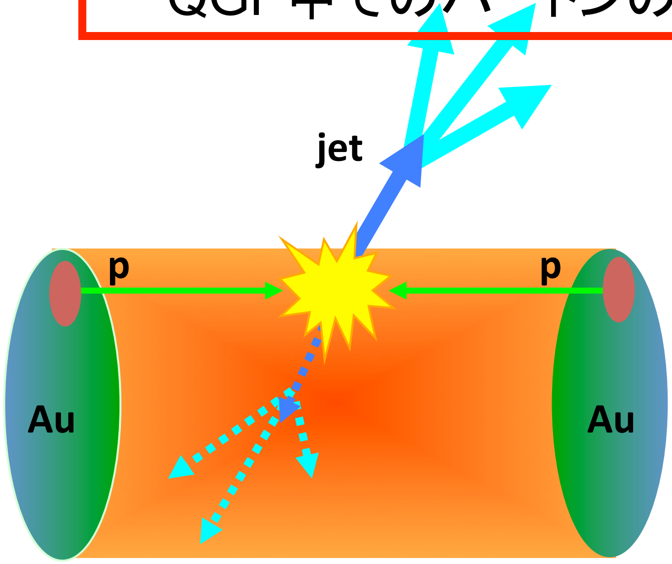
$R_{T\text{-side}}$, $R_{T\text{-out}}$ vs $(\phi-\Phi_2)$, $(\phi-\Phi_3)$
$R_{T\text{-side}}^{oscill.} < R_{T\text{-out}}^{oscill.}$ for n=2,3 (central)

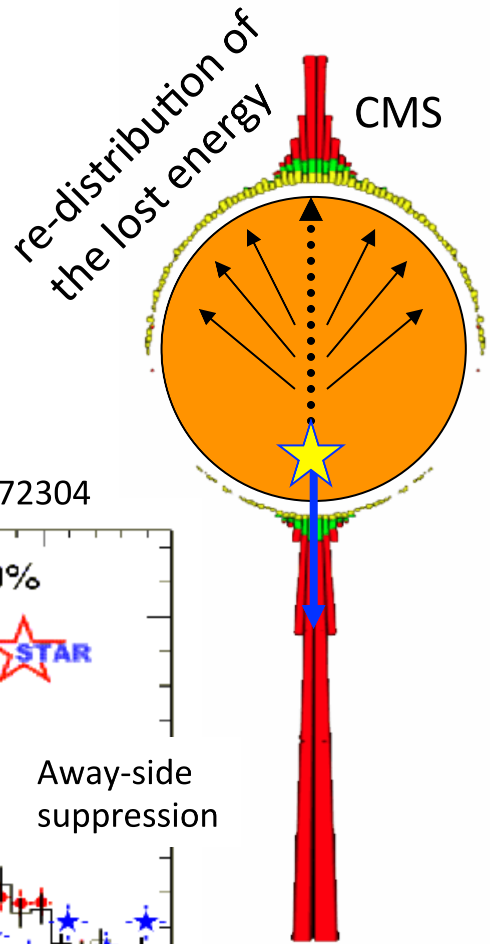
together with $v_n(p_T)^{PID}$
fitting with Blast Wave



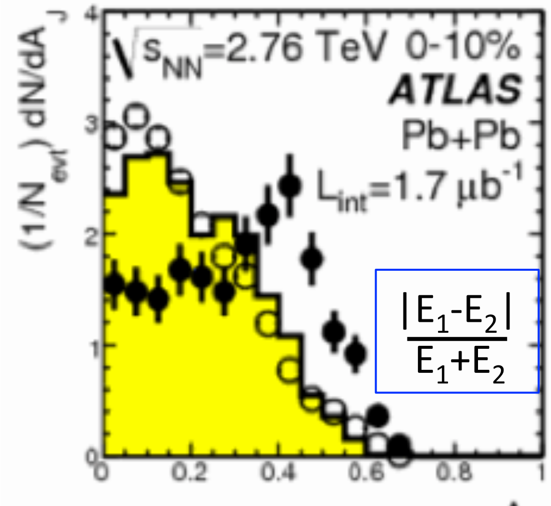


QGP中でのパートンのエネルギー損失　---jet quenching---

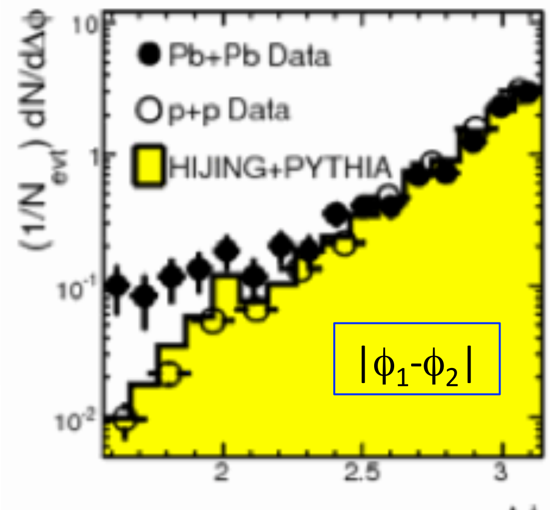




Phys. Rev. Lett. 105 (2010) 252303

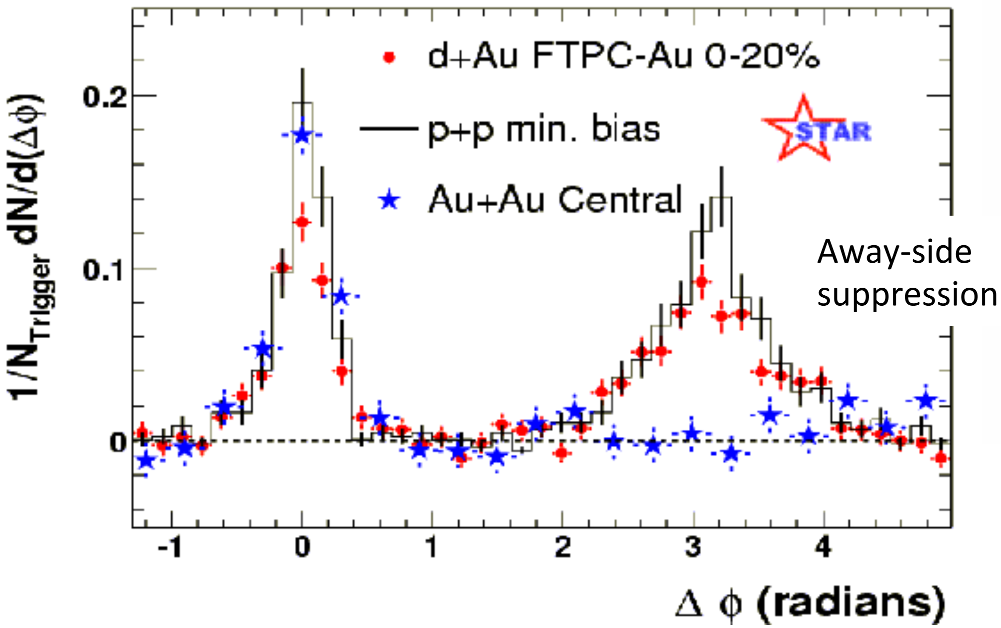


di-jet energy asymmetry



di-jet relative angle

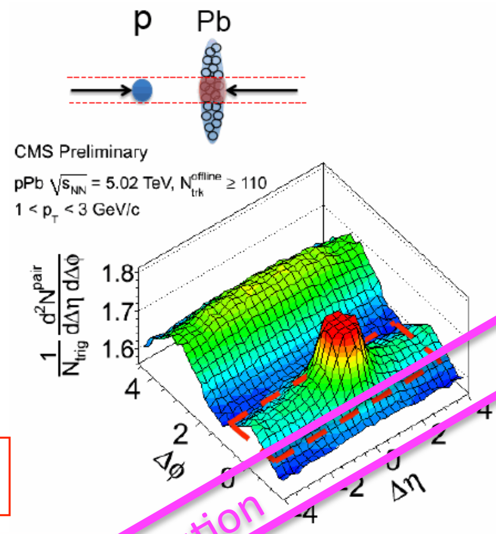
Phys. Rev. Lett. 91 (2003) 072304



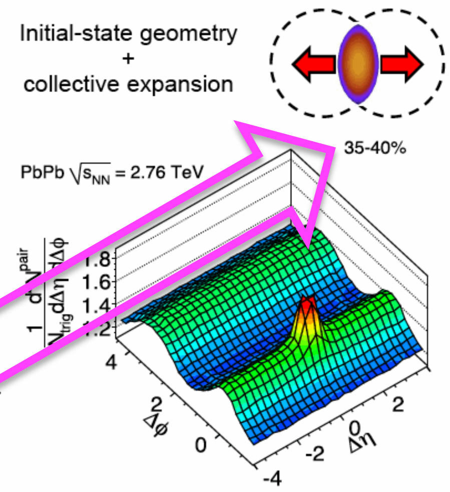
リッジ構造か、高次異方的な流体か

ppやpA衝突のような小さい衝突系でも、
特に、高多重度衝突事象においては、
高温・高密度状態の生成の可能性がある。
--- 集団運動的な膨張があるのか？ ---
--- 中心衝突度依存性、多重度依存性 ---

High mult. p+A

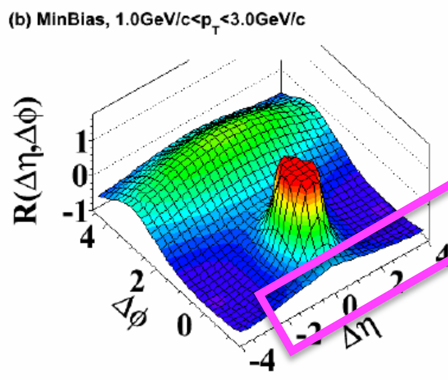


A+A



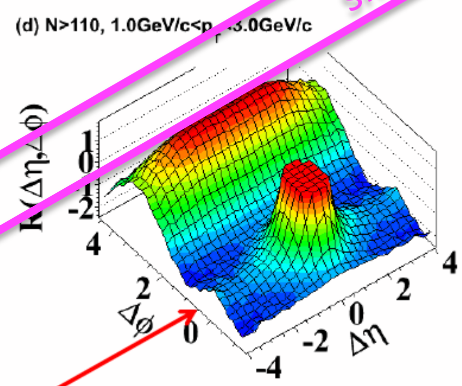
Min. bias p+p

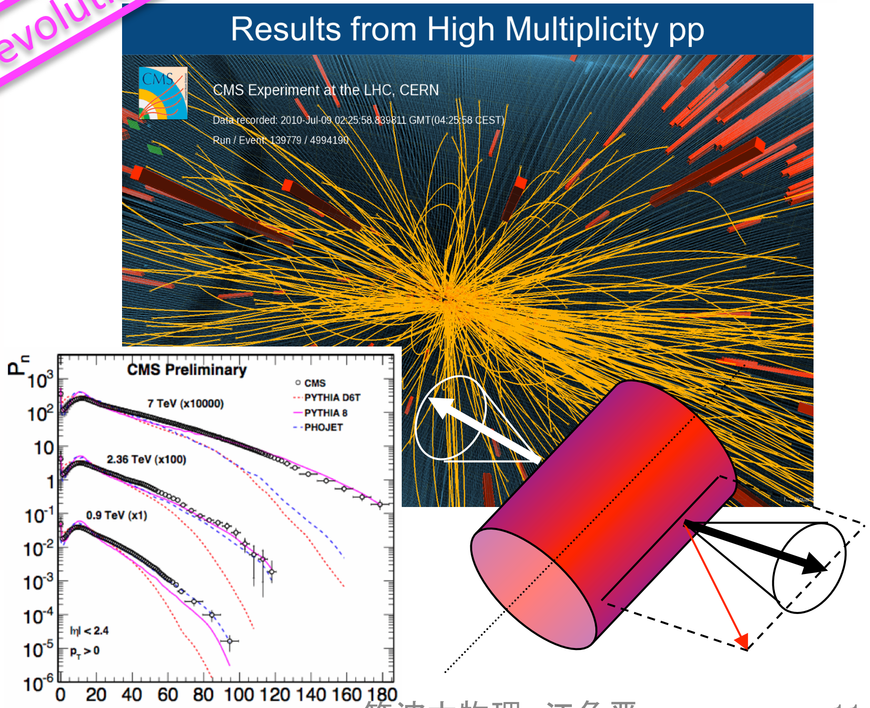
Minimum Bias
no cut on multiplicity



High mult. p+p

High multiplicity data set
and N>110





New “ridge-like” structure extending to large Δη at Δφ ~ 0

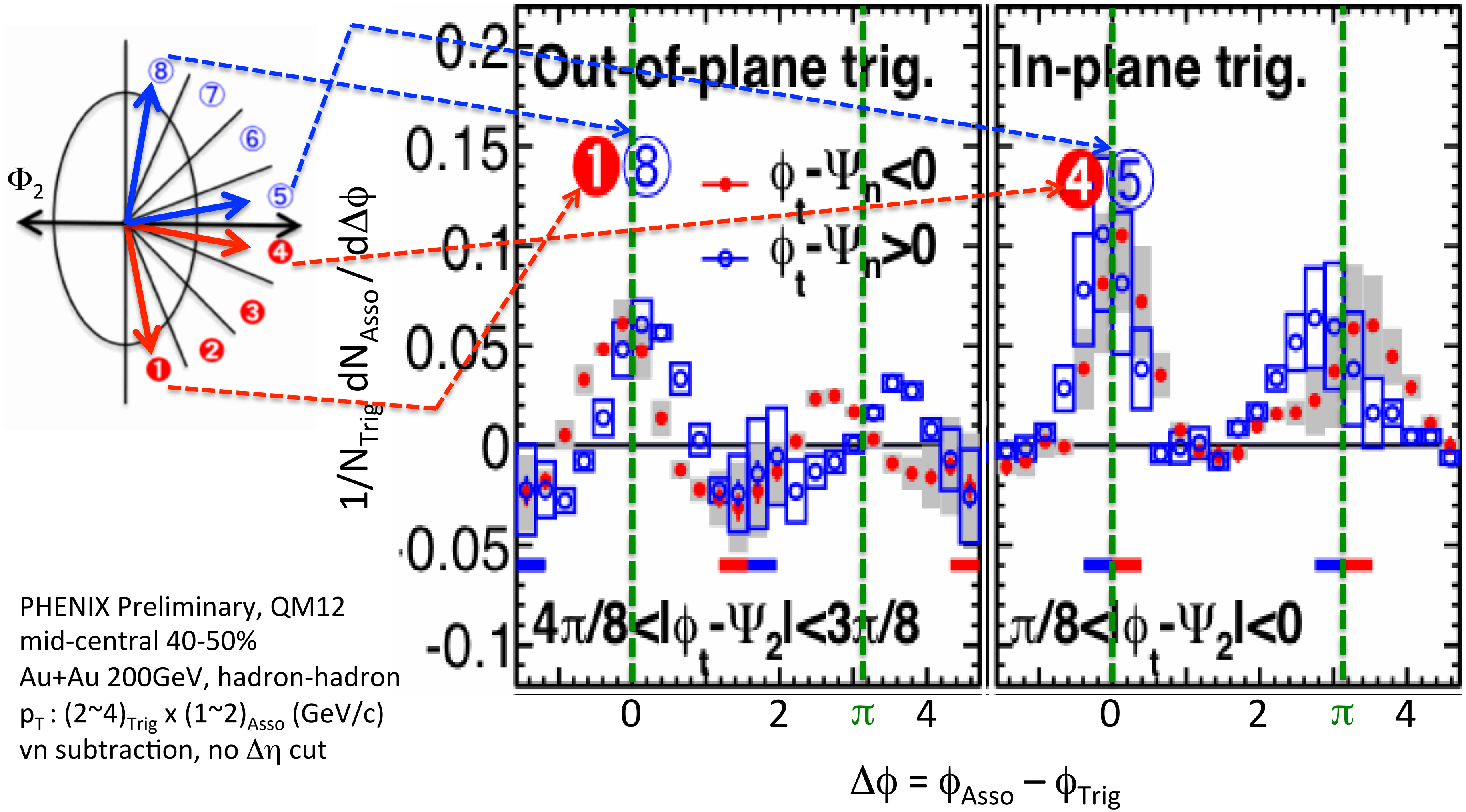
JHEP 09 (2010) 091,   Eur. Phys. J. C 72 (2012) 2012
Phys. Lett. B 718 (2013) 795-814

CMS

ジェット相関の角度・左右非対称性　--- ハード・ソフト間の相互作用 ---

QM12: T. Todoroki

- strong Φ_2 dependence and left/right asymmetry (coupled with energy loss and collective flow)
- broader out-of-plane correlation than in-plane correlation (re-distribution of lost energy)
- some weak Φ_3 dependence (in back-up slides)

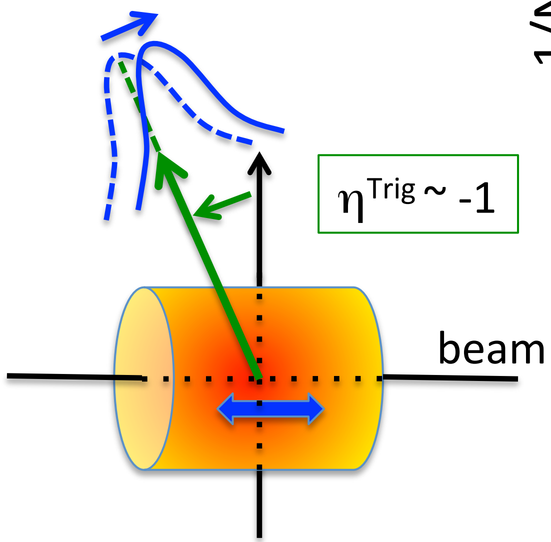


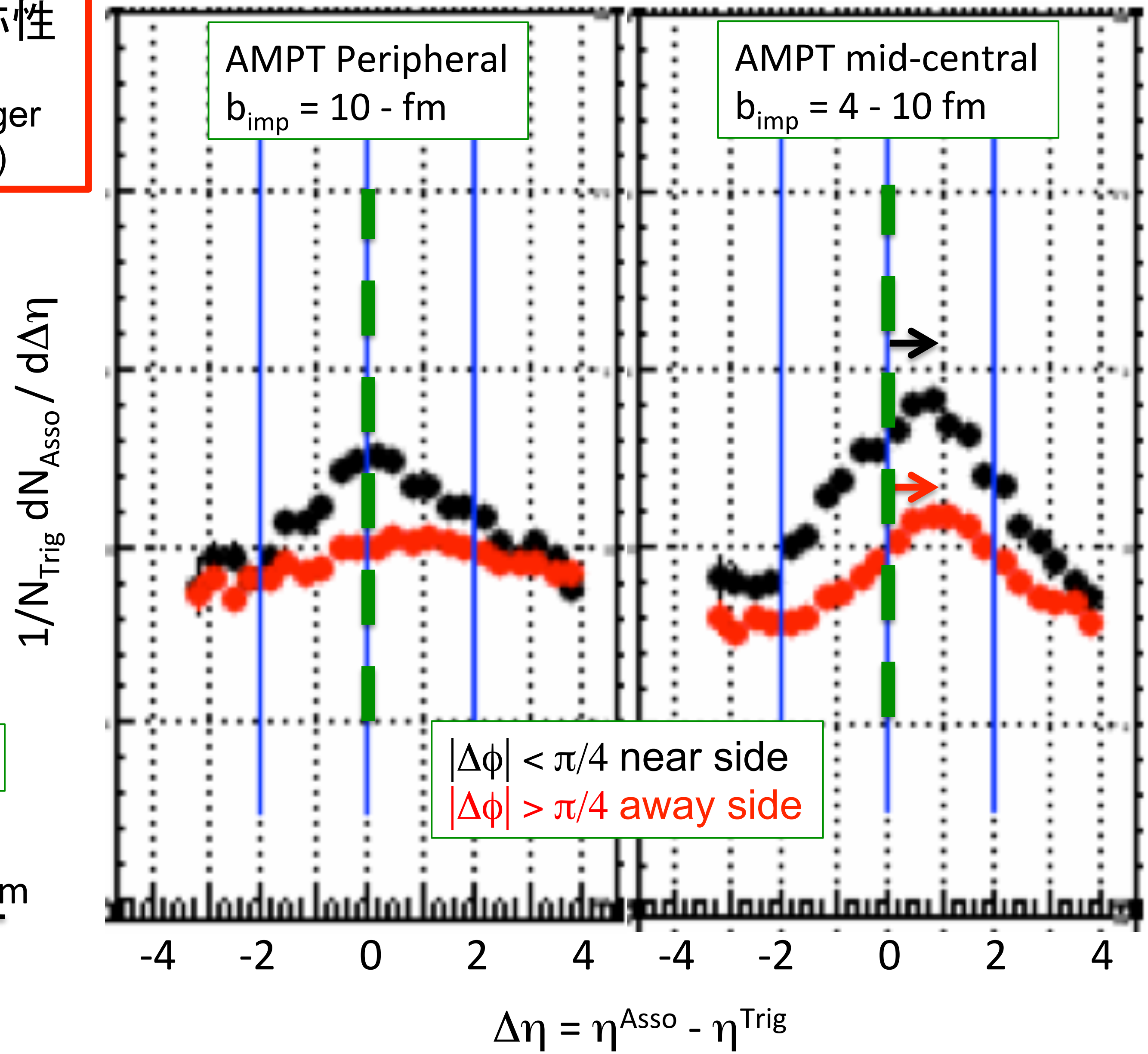
PHENIX Preliminary, QM12
mid-central 40-50%
Au+Au 200GeV, hadron-hadron
p_T : $(2\sim4)_{Trig}$ x $(1\sim2)_{Asso}$ (GeV/c)
vn subtraction, no $\Delta\eta$ cut

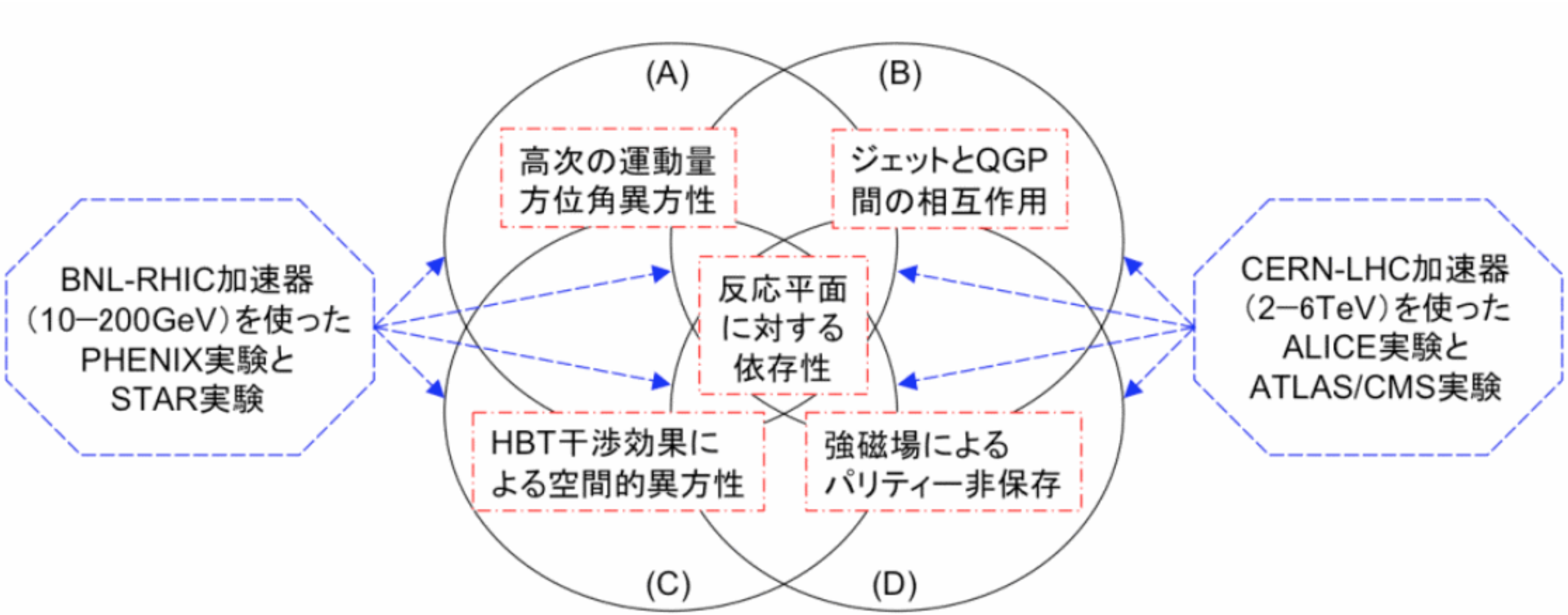
ジェット軸に対するη分布の前方・後方−非対称性

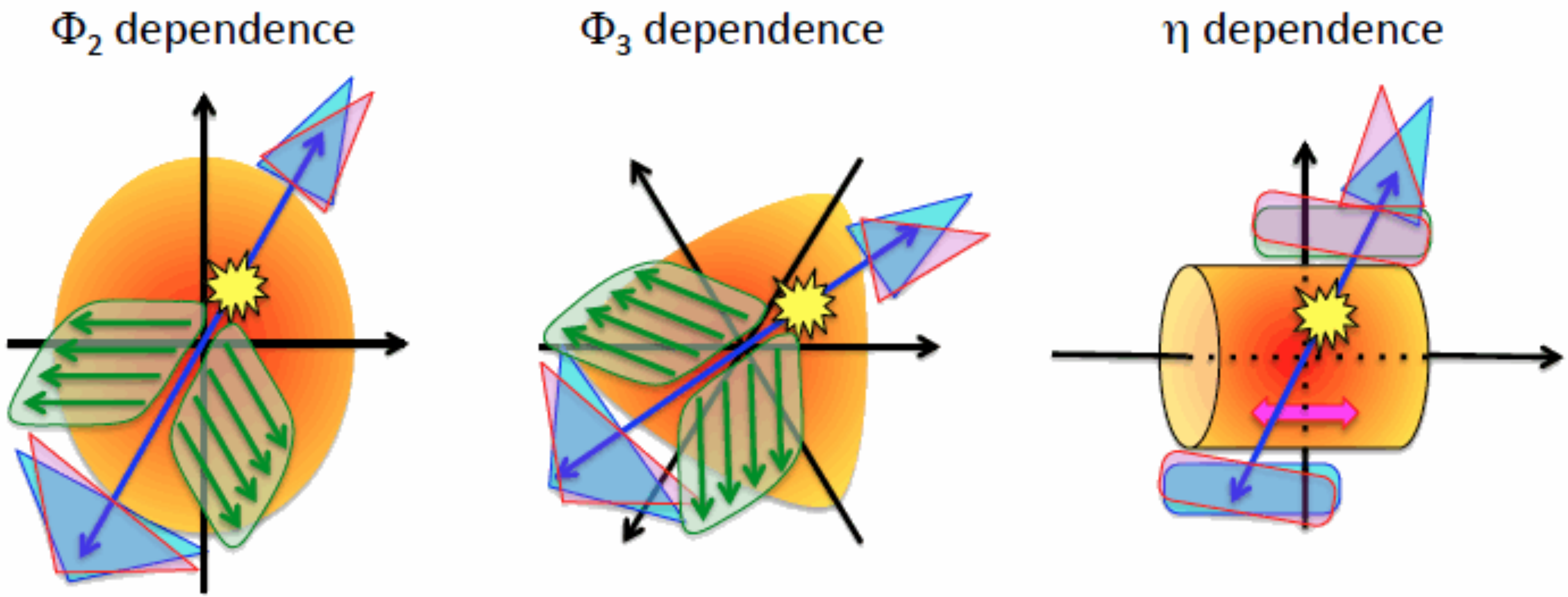
(associate yield per trigger with AMPT simulation)

Forward-backward asymmetry is visible at least in AMPT.
Near side Δη peak is backward shifted w.r.t. trigger η direction.






(A)
(B)
高次の運動量
方位角異方性
ジェットとQGP
間の相互作用
BNL-RHIC加速器
(10−200GeV)を使った
PHENIX実験と
STAR実験
反応平面
に対する
依存性
CERN-LHC加速器
(2−6TeV)を使った
ALICE実験と
ATLAS/CMS実験
HBT干渉効果に
よる空間的異方性
強磁場による
パリティー非保存
(C)
(D)


Φ2 dependence
Φ3 dependence
η dependence

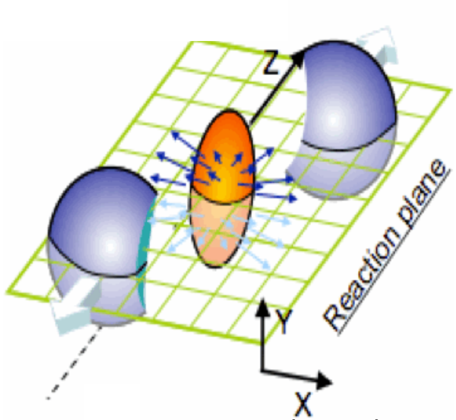
まとめと今後の展望

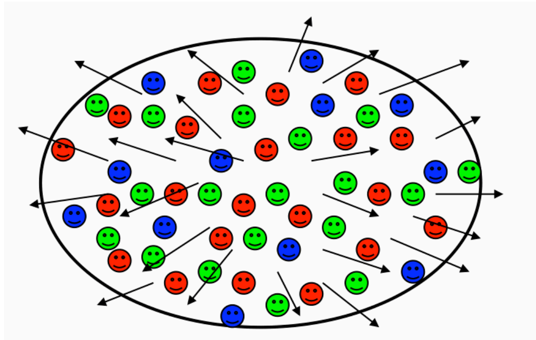
- RHIC,LHC加速器、PHENIX,ALICE実験での衝突実験、解析
  $\mathrm{sqrt}(s_{NN})$ = 200 GeV at RHIC, $\mathrm{sqrt}(s_{NN})$ = 2.76 TeV at LHC
- PHENIX-STAR実験データの共同解析、多粒子相関解析

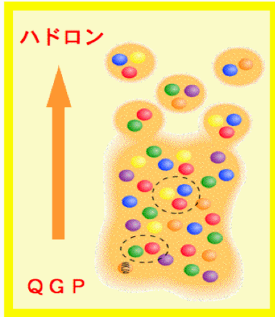
- LHC加速器での$\mathrm{sqrt}(s_{NN})$ = 5.5TeV鉛・鉛衝突実験
- RHIC加速器でのビーム・エネルギー走査実験
  RHIC Beam Energy Scan (BES) program $\mathrm{sqrt}(s_{NN})$ = 5 - 20GeV
- RHIC,LHC加速器でのpp, pA, dA, HeAu, CuAu, UU

- sPHENIX, ePHENIX(for eIC), ALICE アップグレード
- FAIR, J-parc 重イオン衝突アップグレード

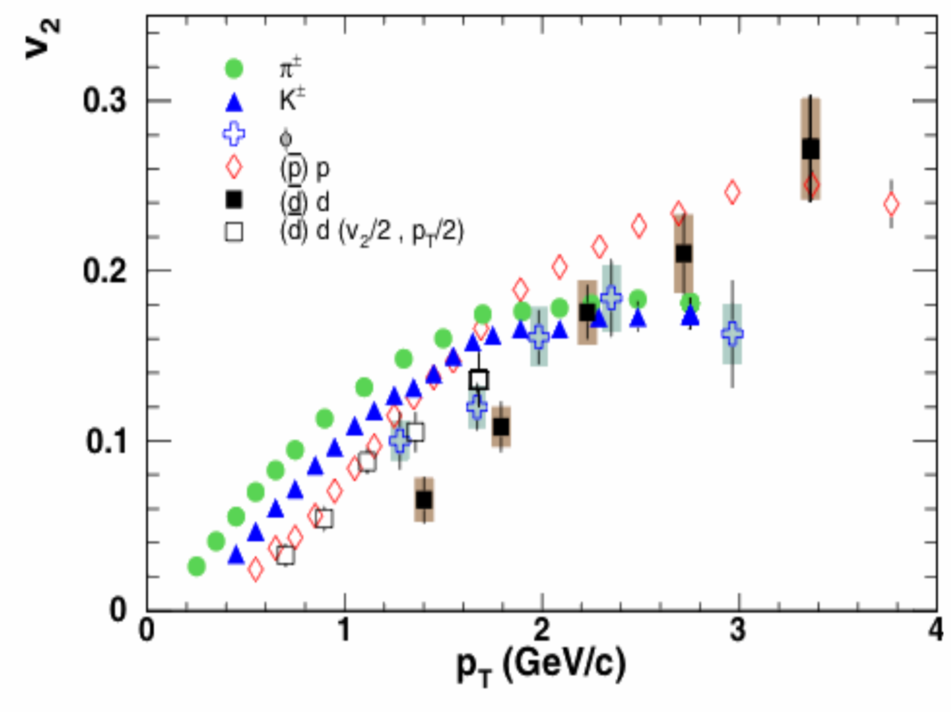
Elliptic expansion in pre-hadronic phase



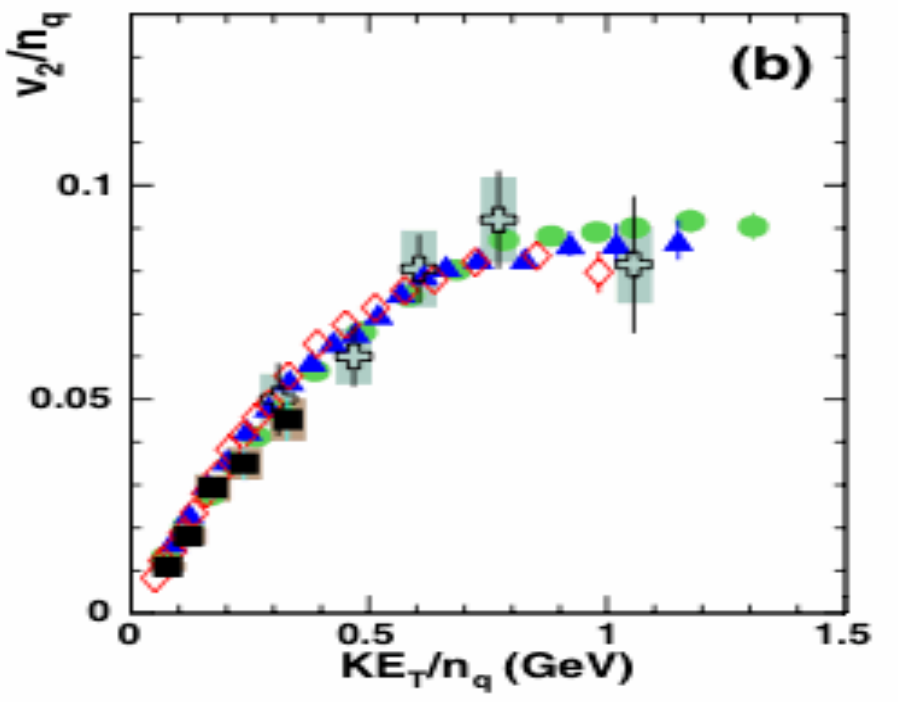




Phys. Rev. Lett. 99, 052301 (2007), PHENIX

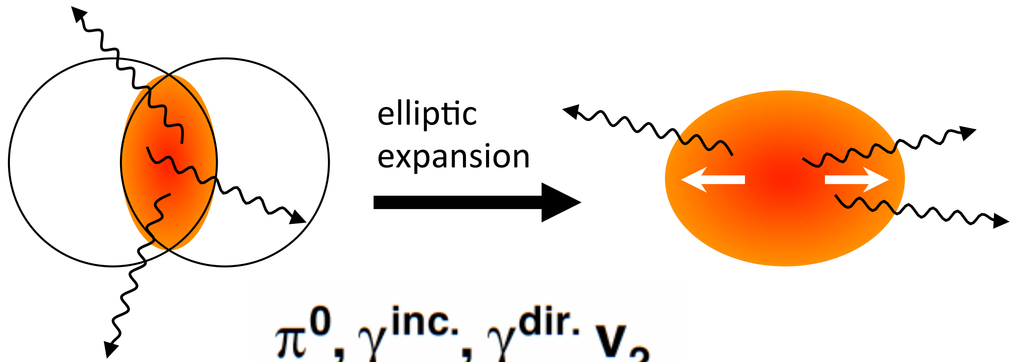


Phys. Rev. Lett. 99, 052301 (2007), PHENIX



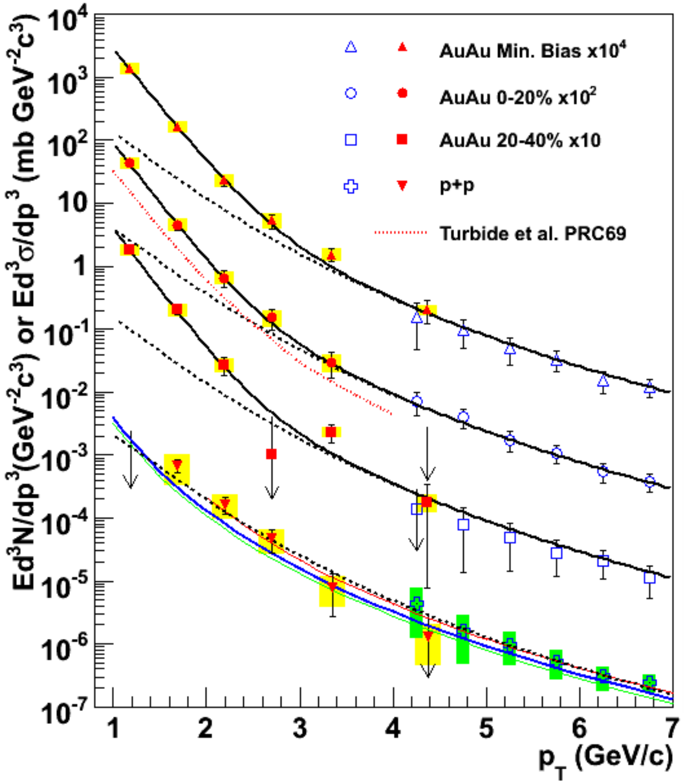
Thermal photon radiation and collective flow

- significant low p_T photon excess
  with much higher temperature than T_f
- comparable v_2 with hadrons



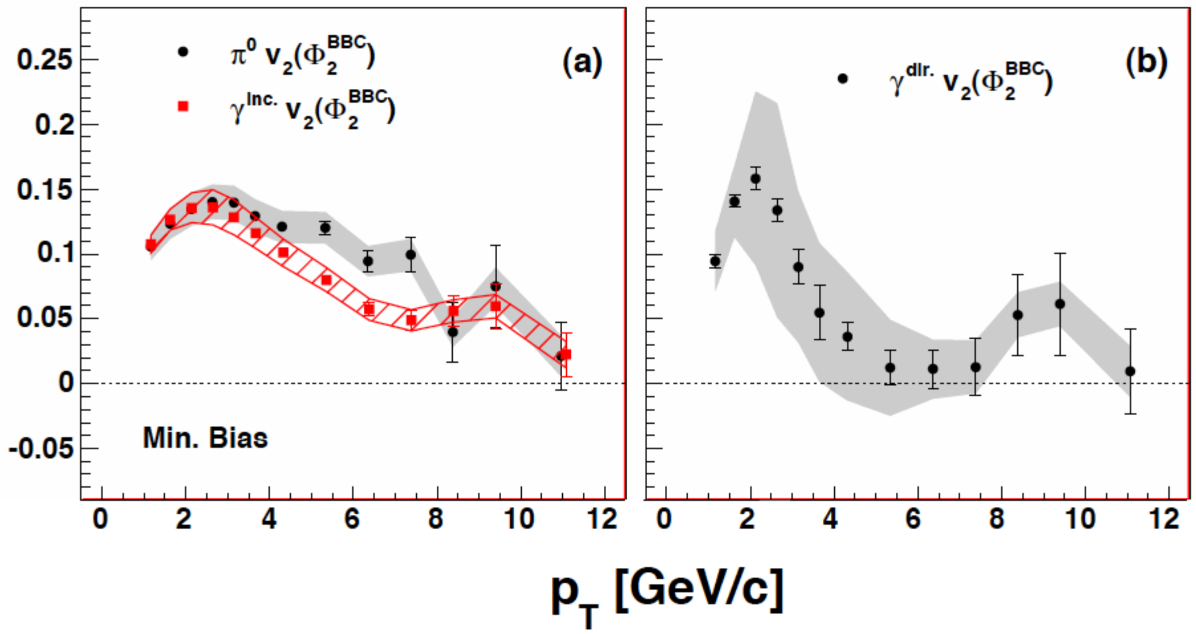
$\pi^0, \gamma^{inc.}, \gamma^{dir.}$ v_2

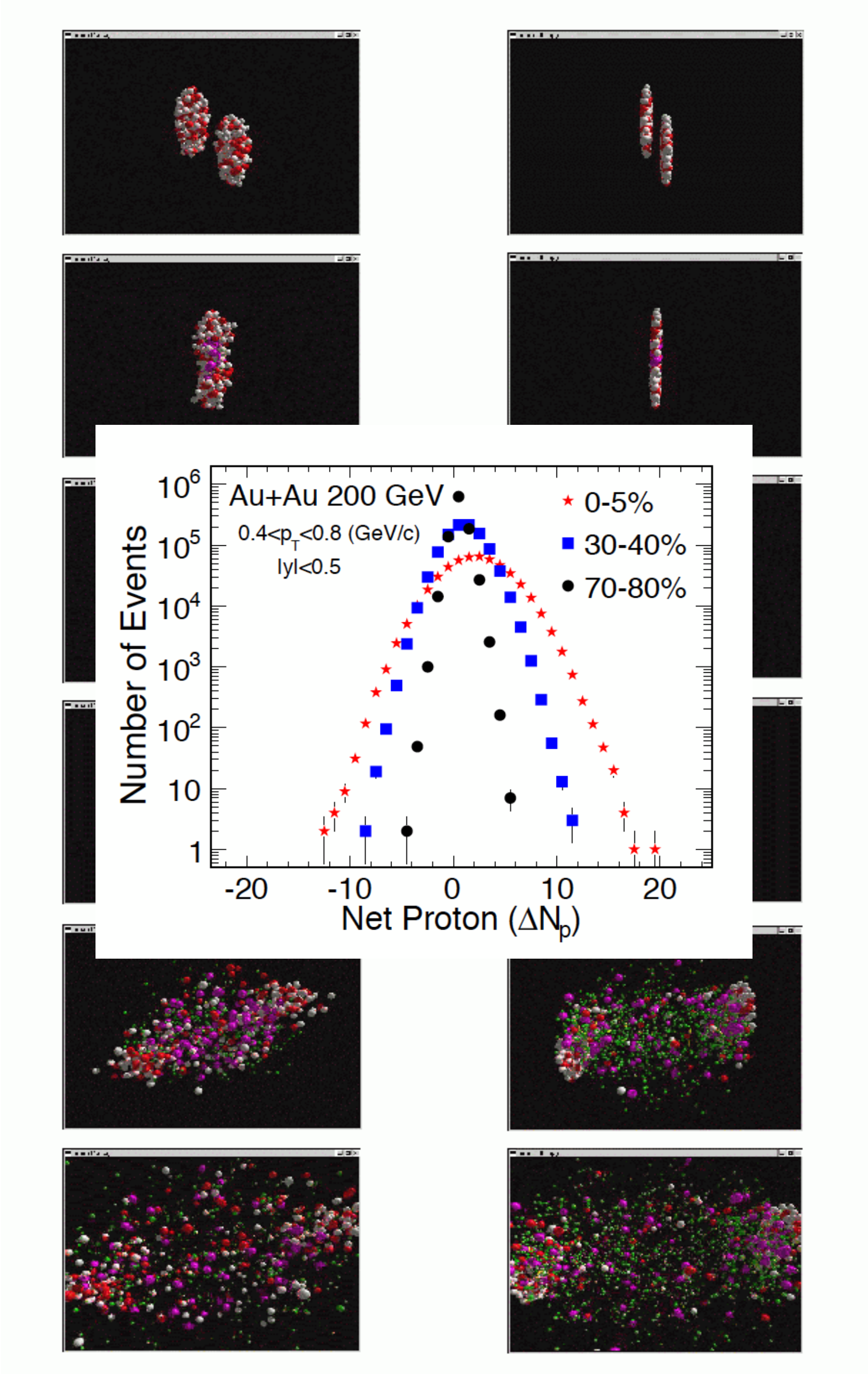
Phys. Rev. Lett. 104, 132301 (2010)



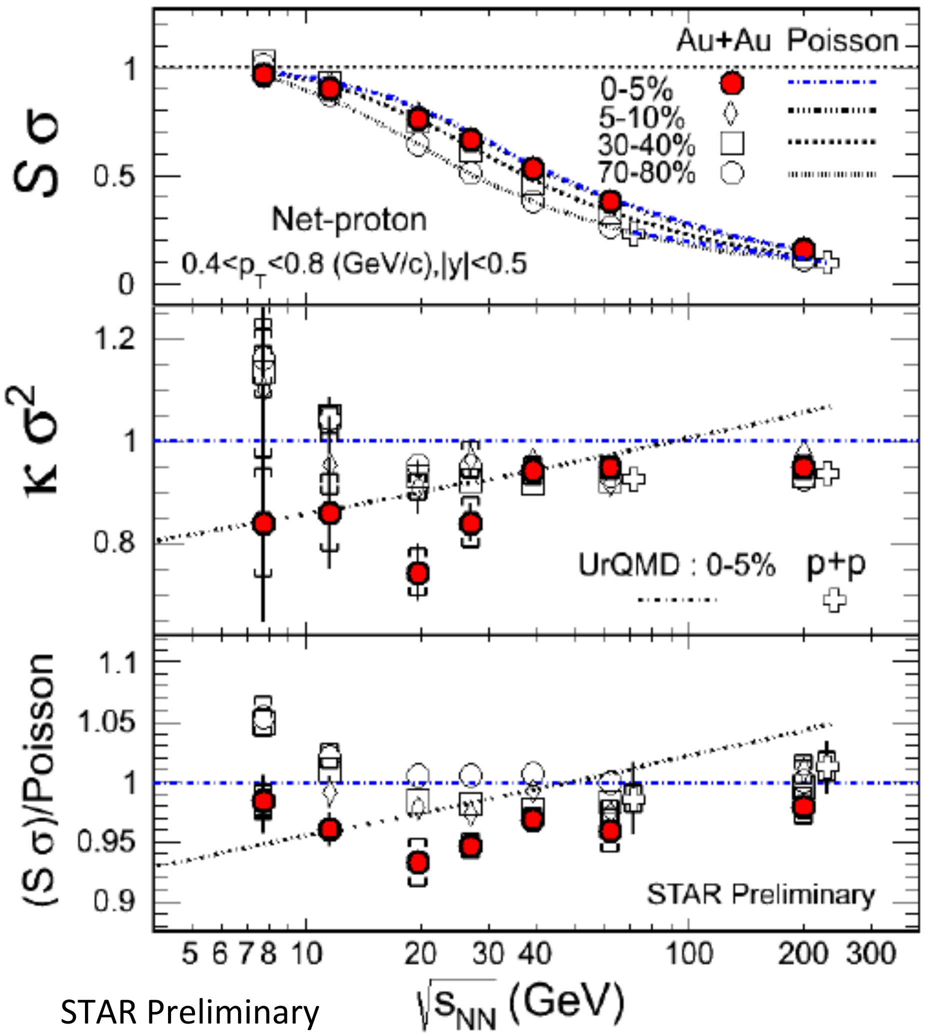
arXiv: 1105.4126

Phys. Rev. Lett. 109, 122302 (2012)

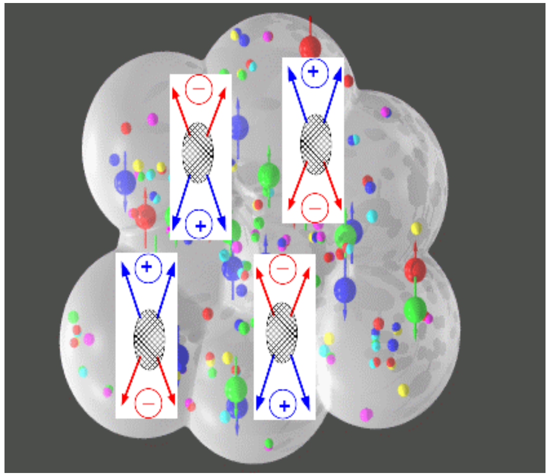




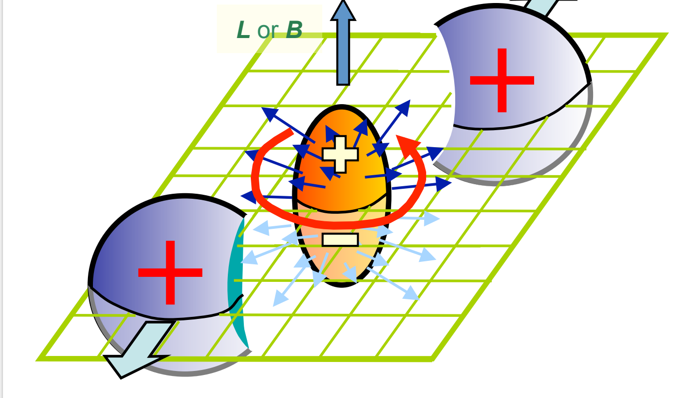
net-Baryon number fluctuation is expected to reflect the critical point as a non-monotonic behavior

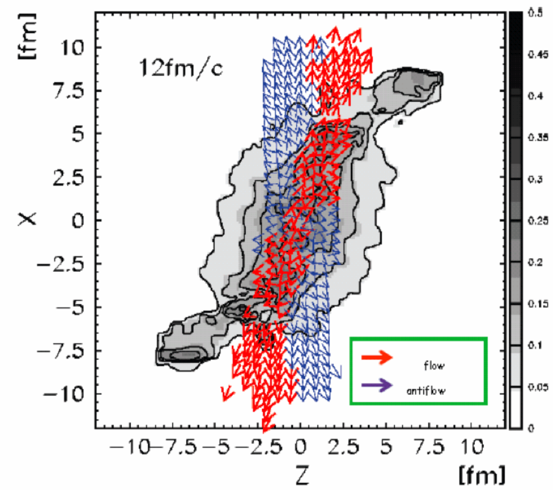


STAR Preliminary
QM12

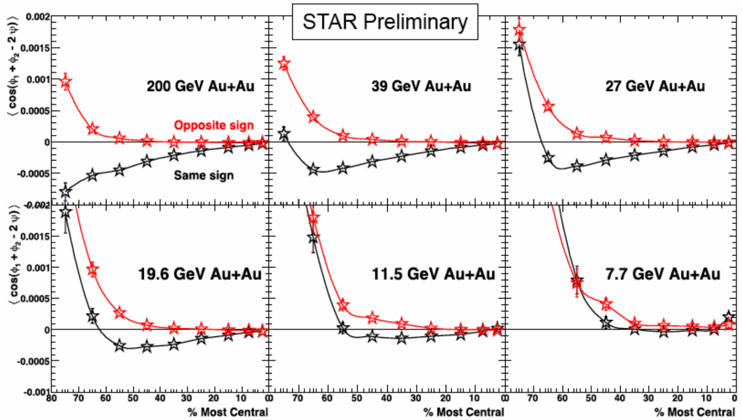


Strong magnetic field

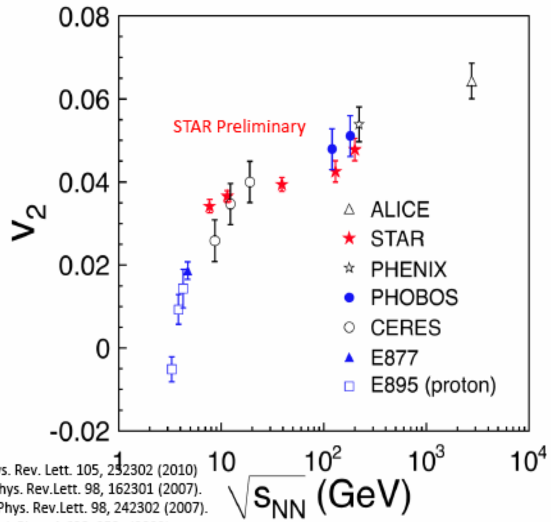




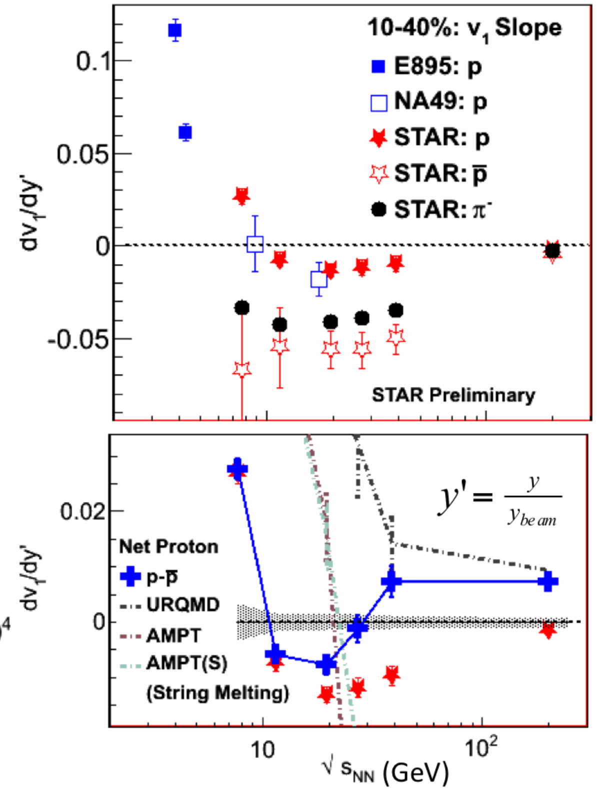
J. Brachmann et al., PRC 61, 24909 (2000).



STAR Preliminary, QM12



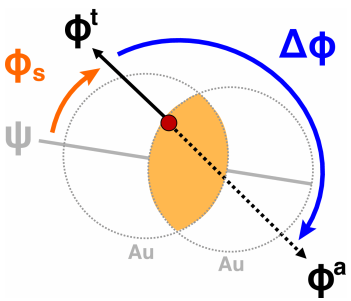
ALICE: Phys. Rev. Lett. 105, 252302 (2010)
PHENIX: Phys. Rev.Lett. 98, 162301 (2007).
PHOBOS: Phys. Rev.Lett. 98, 242302 (2007).
CERES: Nucl. Phys. A 698, 253c (2002).
E877: Nucl. Phys. A 638, 3c(1998).
E895: Phys. Rev. Lett. 83, 1295 (1999).
STAR 130 and 200 GeV: Phys. Rev. C 66,873 034904 (2002); Phys. Rev. C 72,790 014904 (2005)



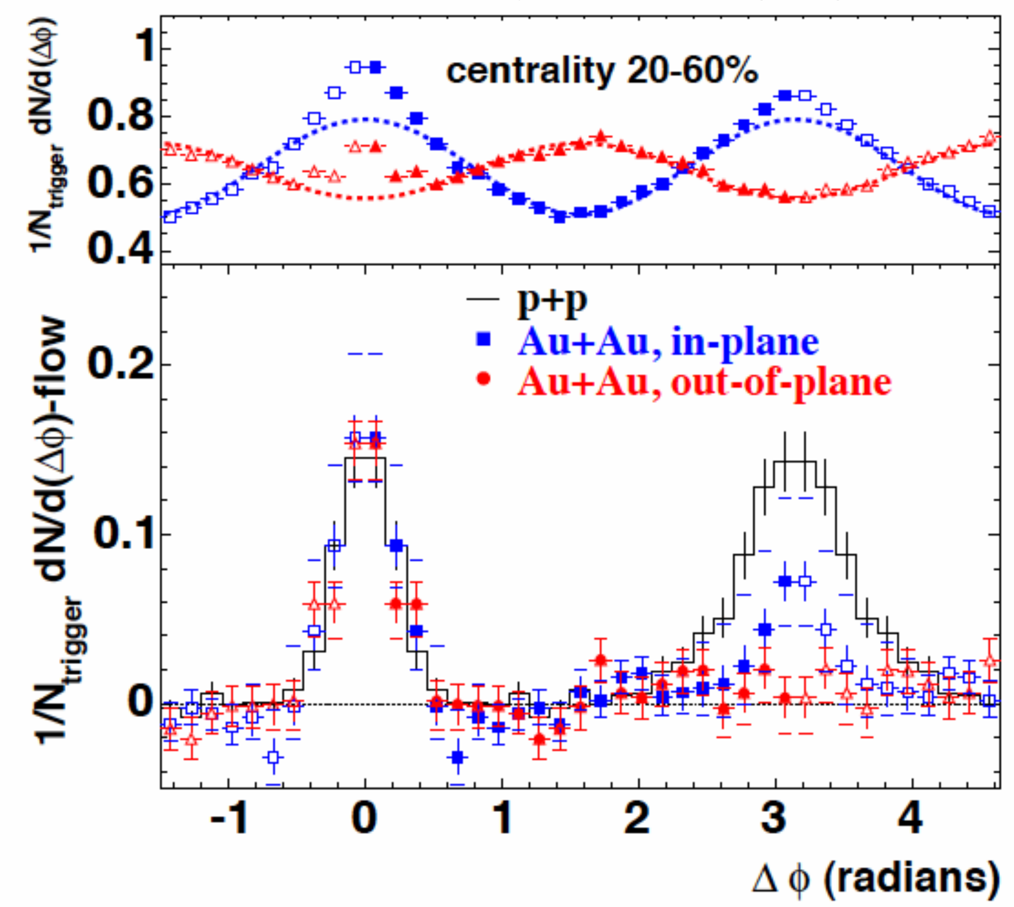
Beam energy dependence of charge asymmetry and flow (v_1, v_2, v_n...) signals in order to look for any non-monotonic behavior

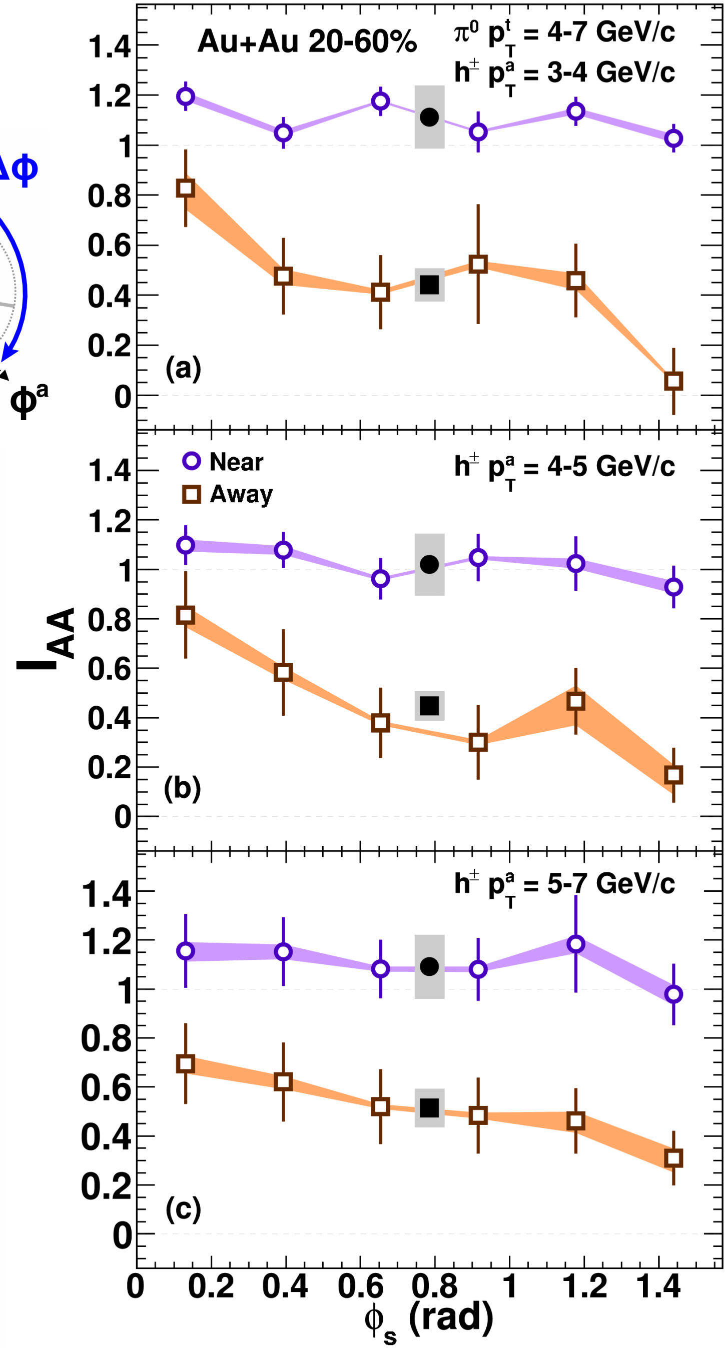
Angle (Length) dependence of di-hadron correlation

- high p_T single/jet suppression
- high p_T di-hadron/di-jet suppression
- High p_T v_2



Phys. Rev. Lett. 93 (2004) 252301





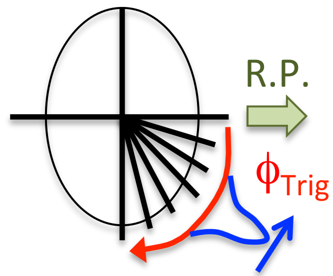
Phys. Rev. C 84 (2011) 024904

Left/right asymmetry in ridge/mach-cone

QM09: J. Konzer

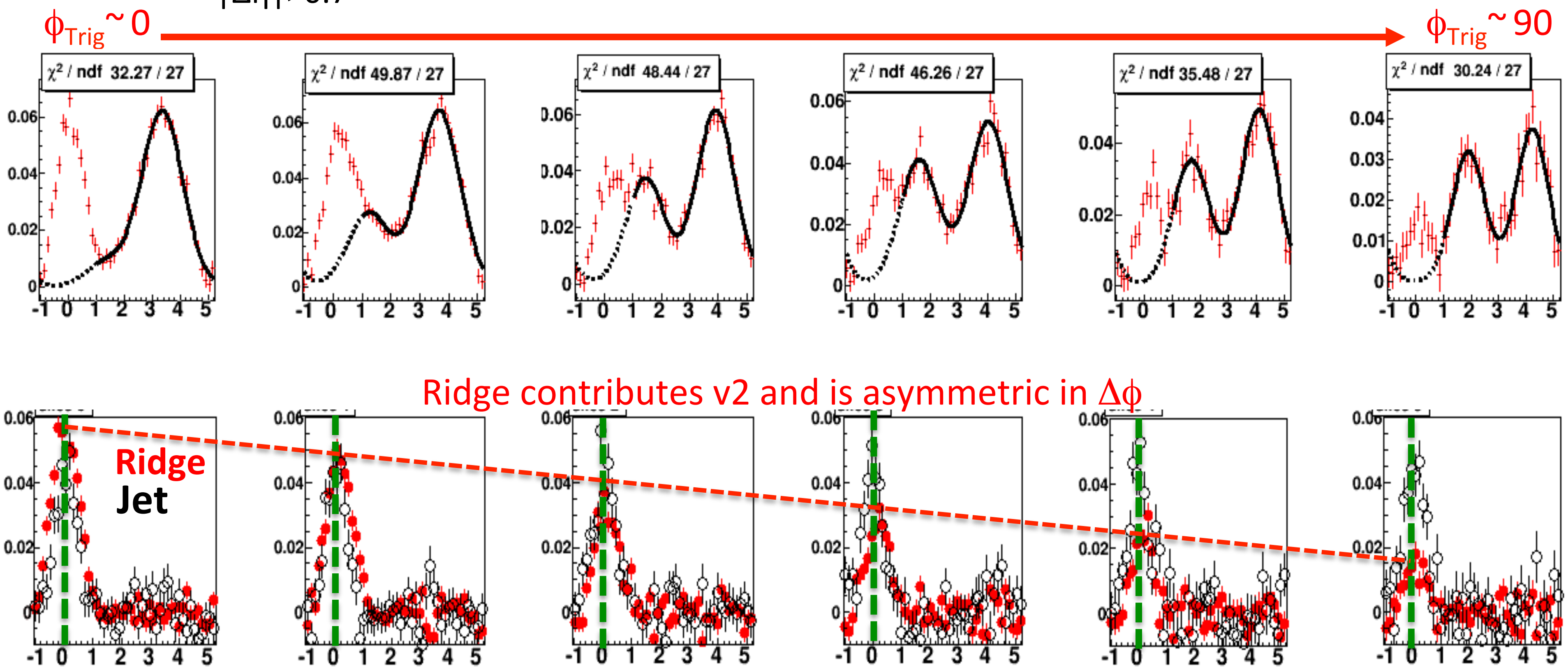
Y(|Δη|>0.7) = **Ridge** + away-side two-Gaussian

Jet = Y(|Δη|<0.7) – Acceptance*Y(|Δη|>0.7)



STAR Preliminary
Au+Au 20-60%
$3<p_T^{Trig}<4$ GeV/c
$1<p_T^{Assoc}<1.5$ GeV/c

|Δη|>0.7

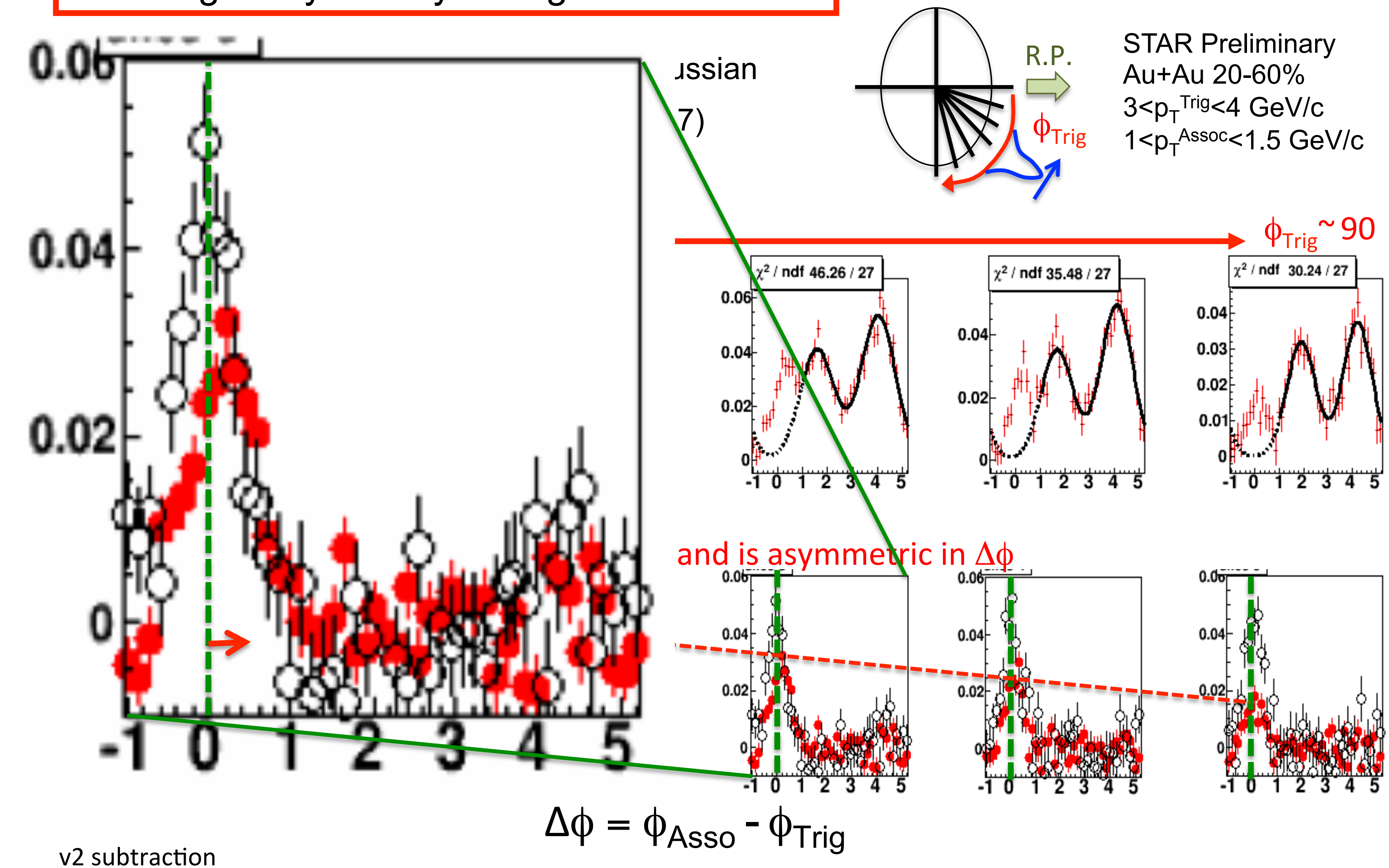


$$\Delta\phi = \phi_{Asso} - \phi_{Trig}$$

v2 subtraction

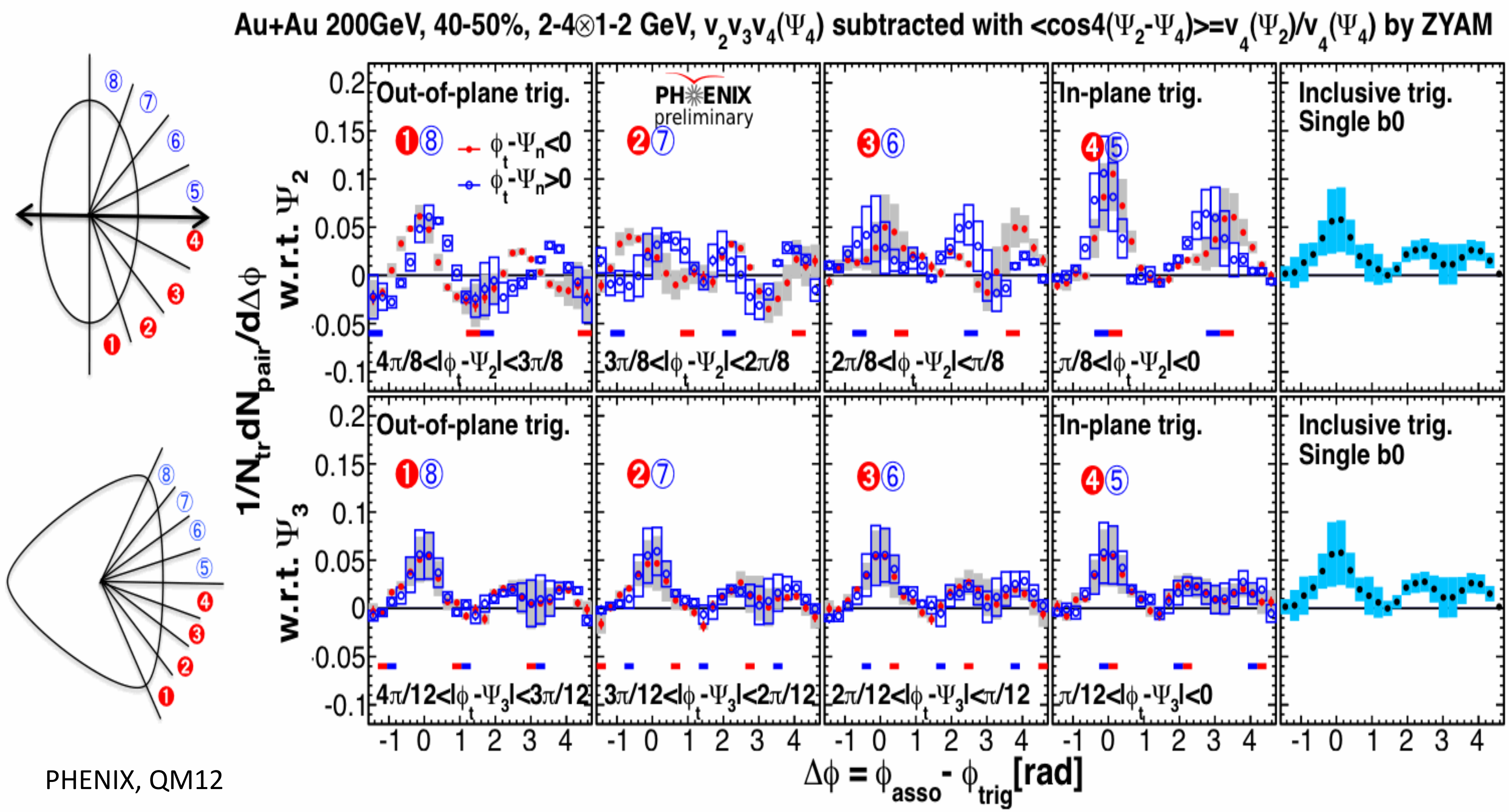
Left/right asymmetry in ridge/mach-cone

QM09: J. Konzer



v2 subtraction

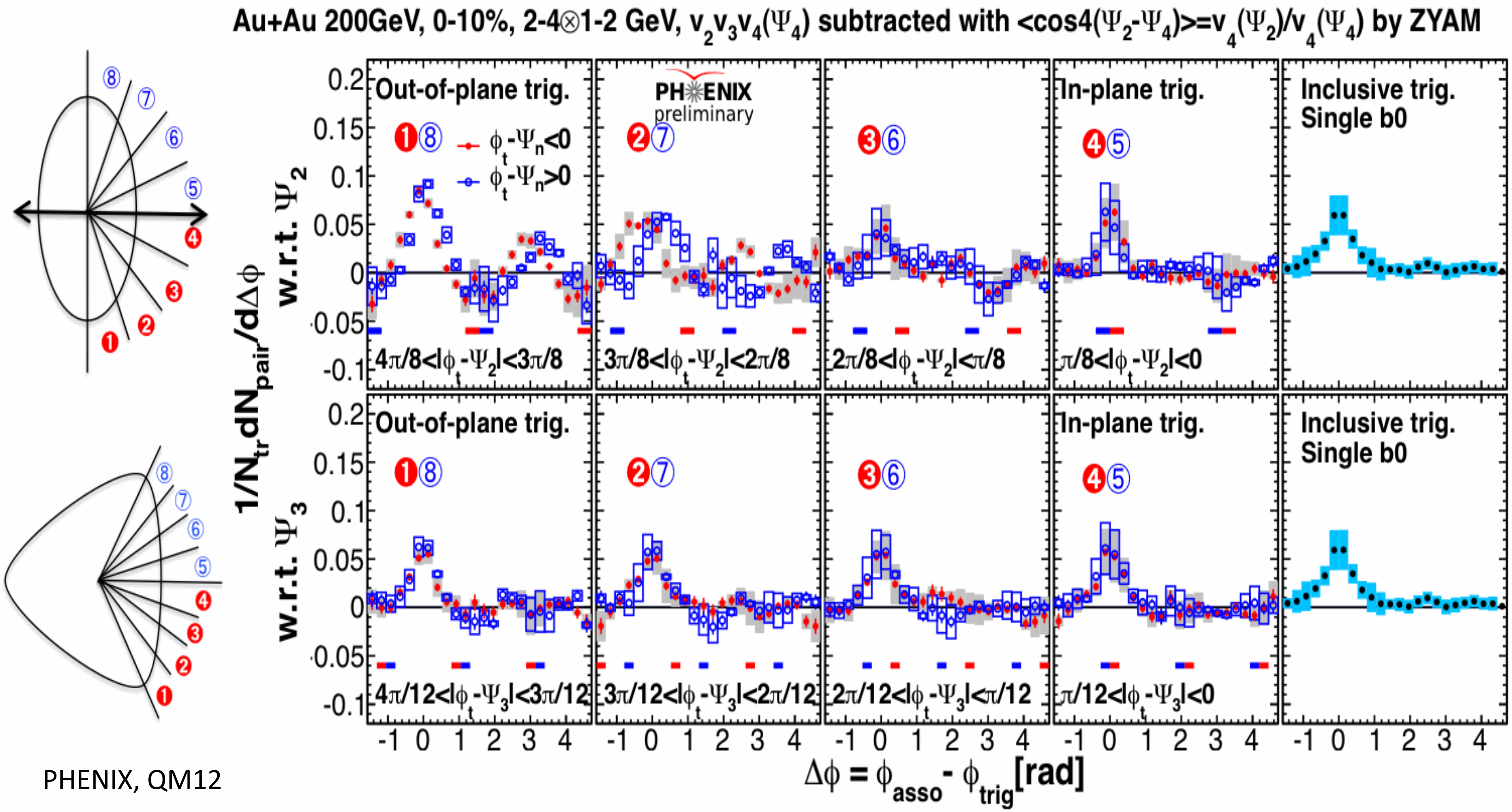
Correlations relative to Ψ_2 & Ψ_3, 40-50%



PHENIX, QM12

mid-central collisions	- driving force of v_2 (enhances v_2) - almost no Φ_3 dependence (poor Φ_3 resolution)

Correlations relative to Ψ_2 & Ψ_3, 0-10%



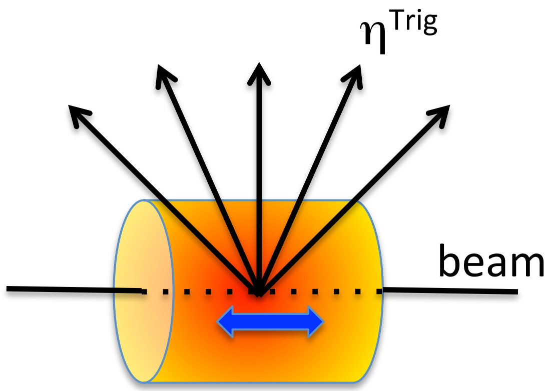
PHENIX, QM12

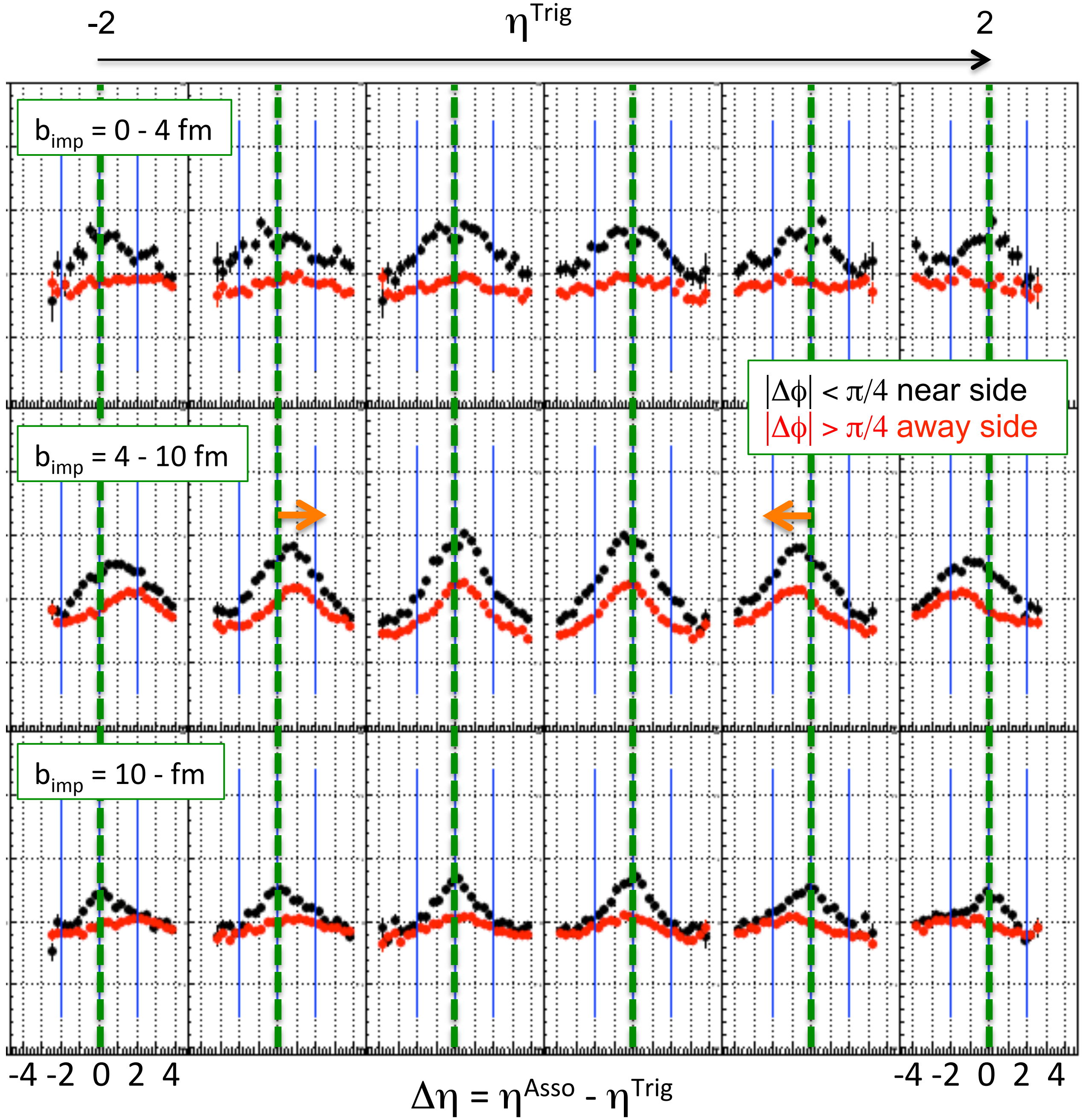
central collisions

- stopping force of v_2 (suppresses v_2)
- some weak Φ_3 dependence

Trigger η dependence of $\Delta\eta$ distribution

(associate yield per trigger with AMPT simulation)





look at the asymmetry in $\Delta\eta = \eta^{Asso} - \eta^{Trig}$ (associate η distribution with respect to trigger η) in order to see the hard-soft coupling with longitudinal density profile and/or expansion