Beam Energy Scan studies at RHIC
Flow studies in small system

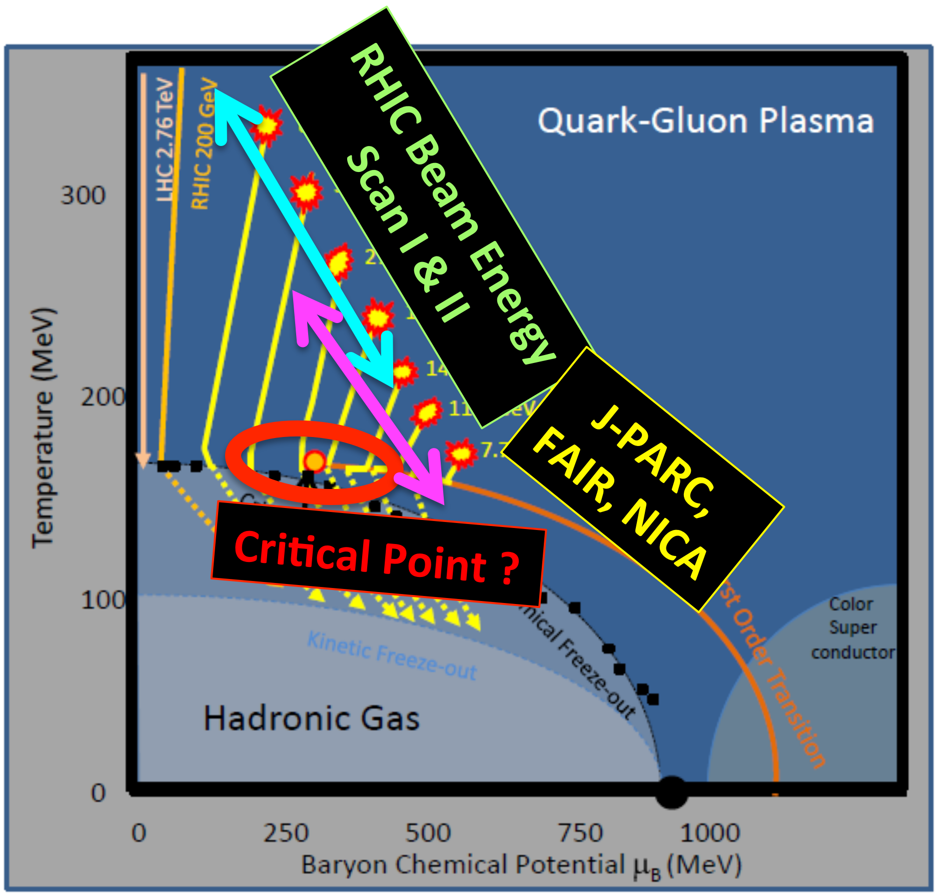
ShinIchi Esumi
Inst. of Physics, Univ. of Tsukuba
Center for Integrated Research in
Fundamental Science and Engineering (CiRfSE)

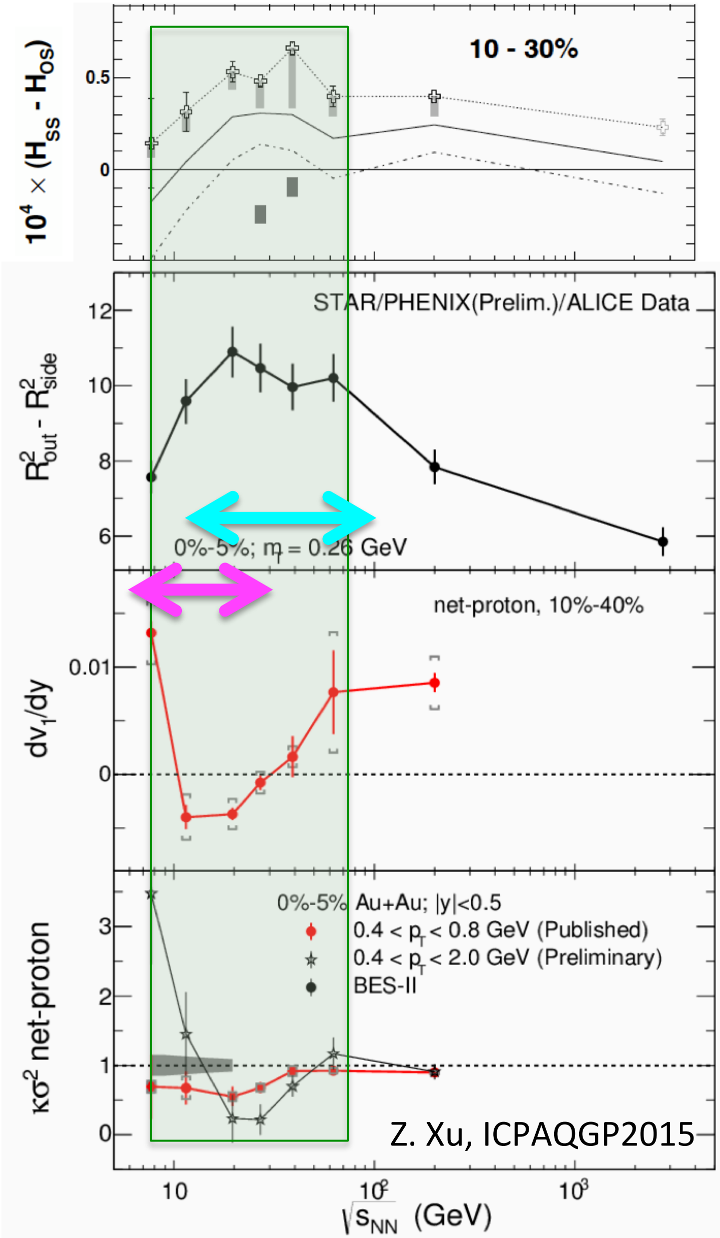
for "**Heavy-Ion Meeting (HIM : force)**" just after KPS2016 fall meeting
in **Chonnam National University, Gwangju, Korea**

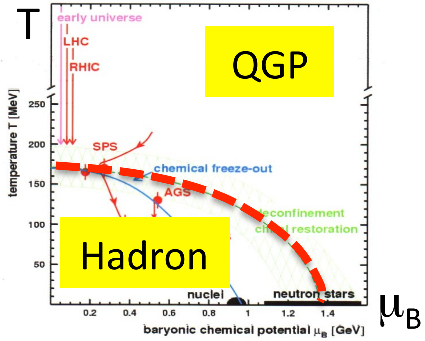
Heavy-Ion Café meeting : in Tokyo-Tsukuba-KEK area (East side of Japan)
Heavy-Ion Pub meeting in Hiroshima-Osaka-Nara-Nagoya area (West side of Japan)

RHIC beam energy scan (BES) program from phase I to phase II

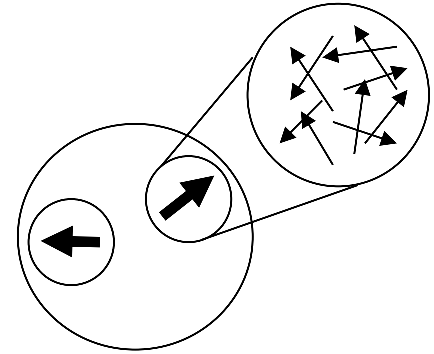
~ 2016 2019 ~





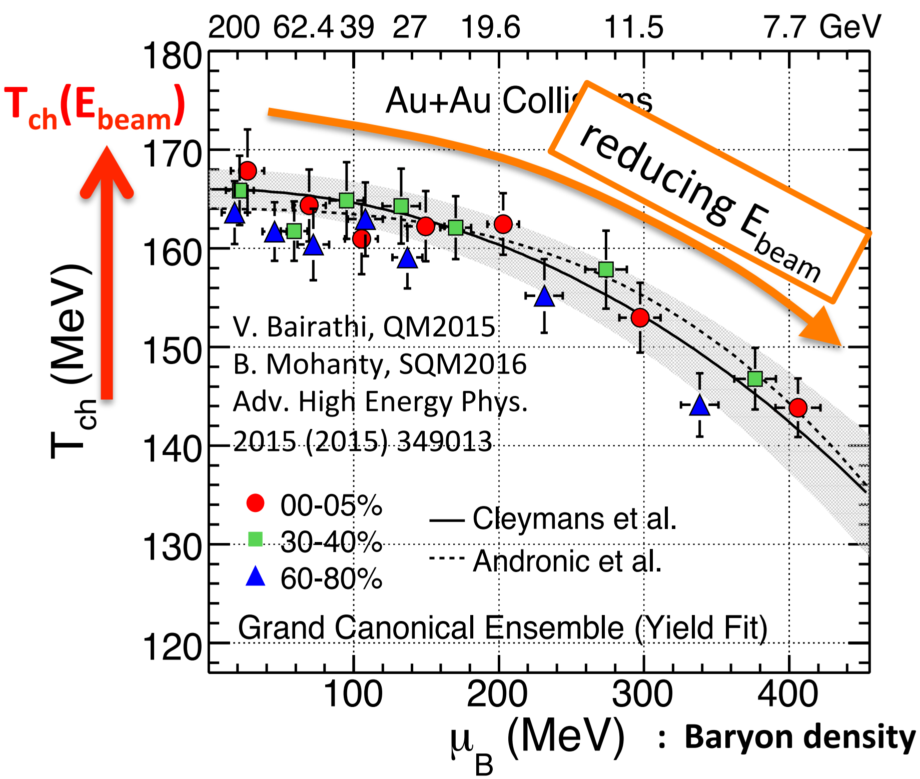


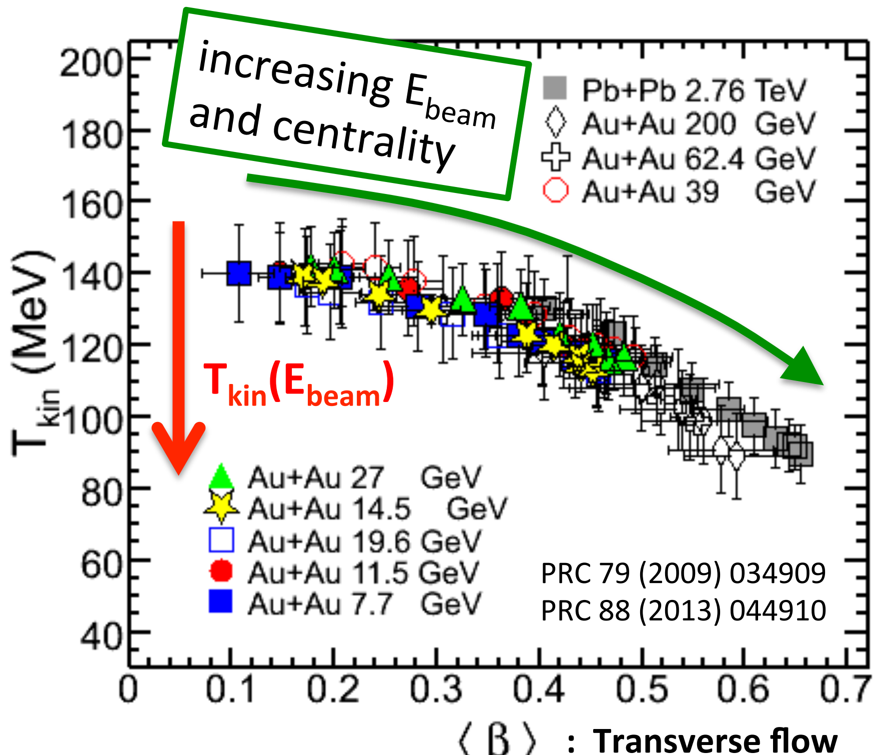
Chemical and Thermal kinetic freeze-out with radial flow

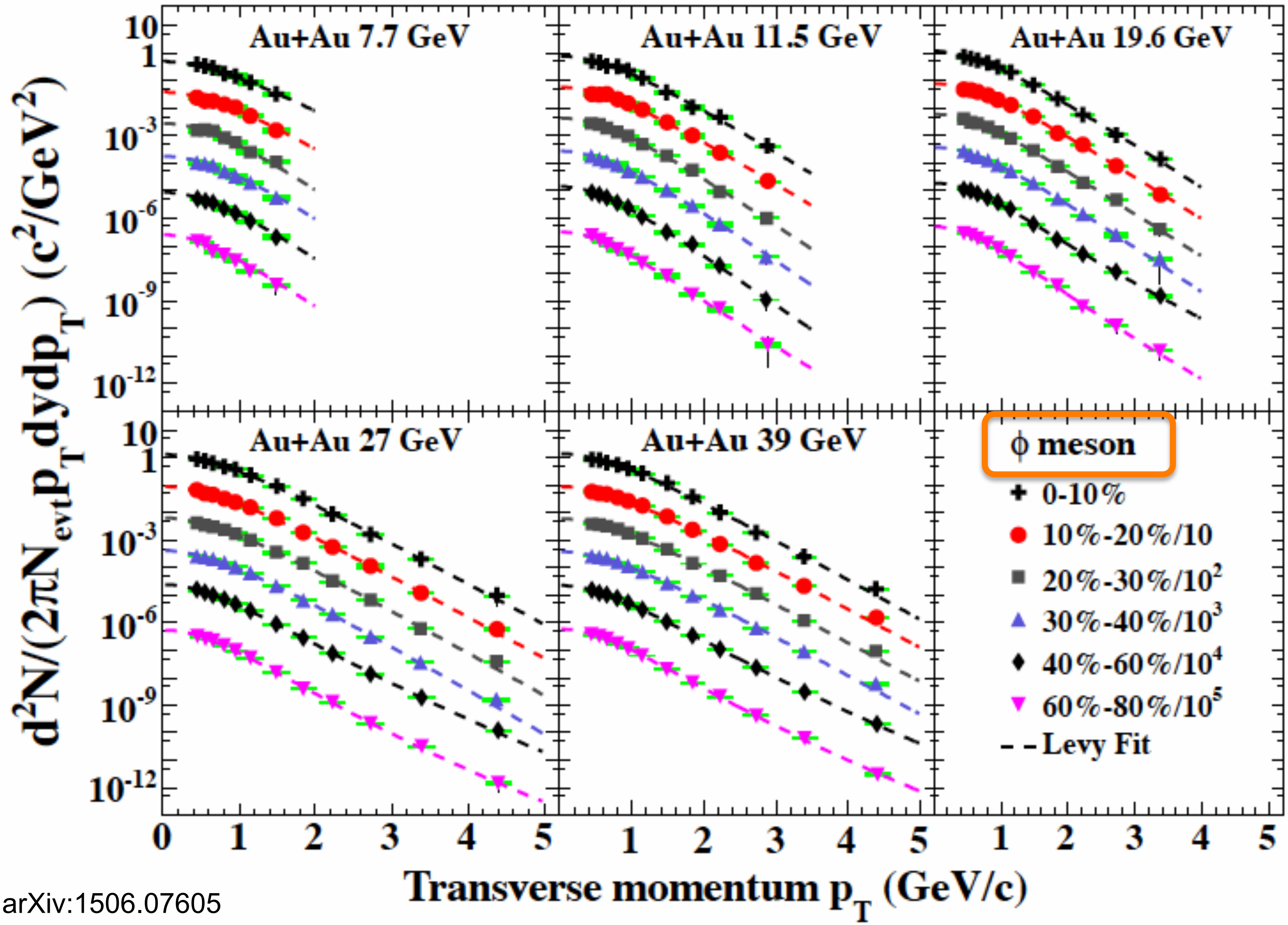


Hadron yields are fitted with chemical thermal model in order to extract (T_{ch}, μ_B) parameters.

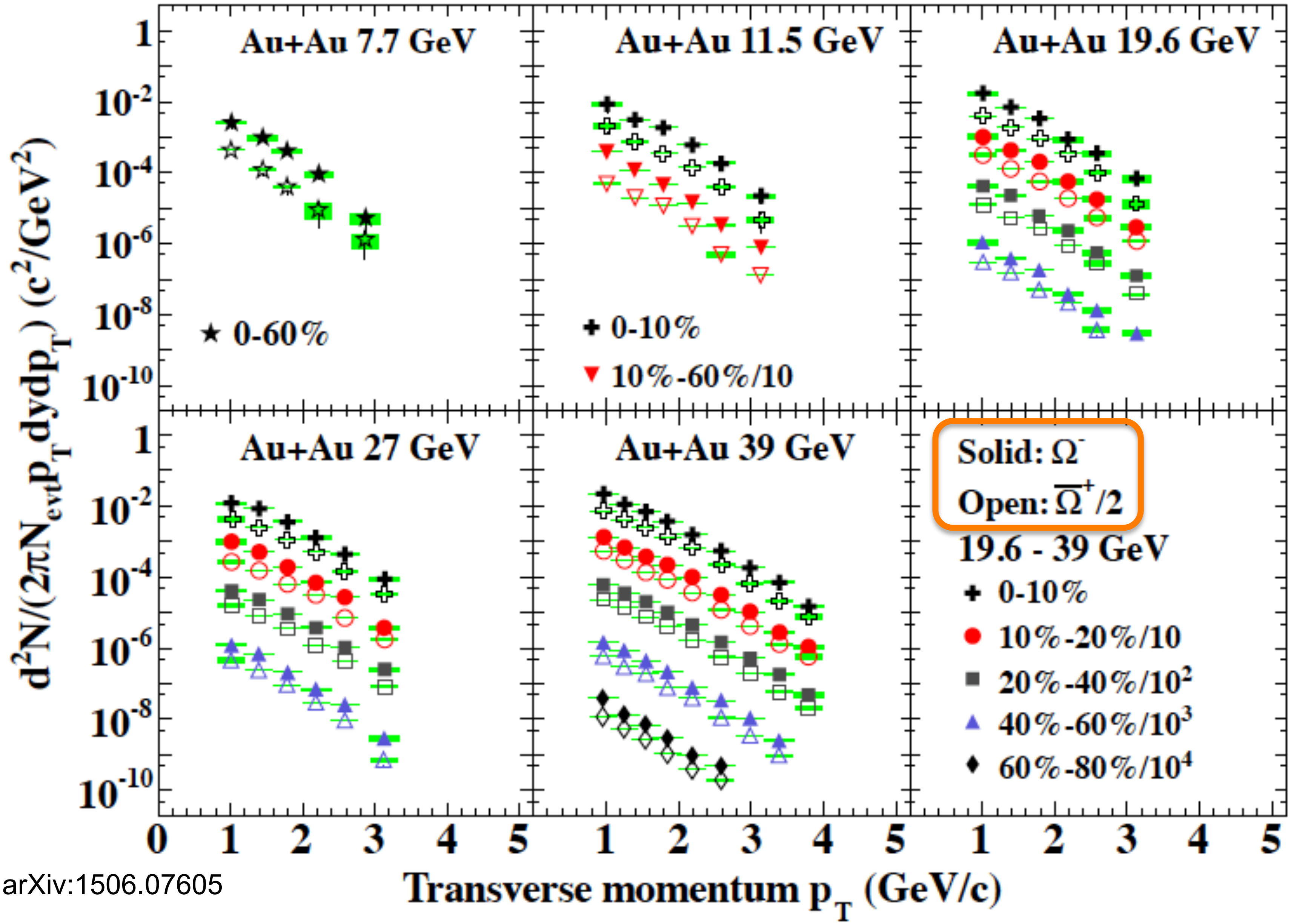
Hadron pT spectra are fitted with Blast-wave model in order to extract (T_{kin}, β_T) parameters.







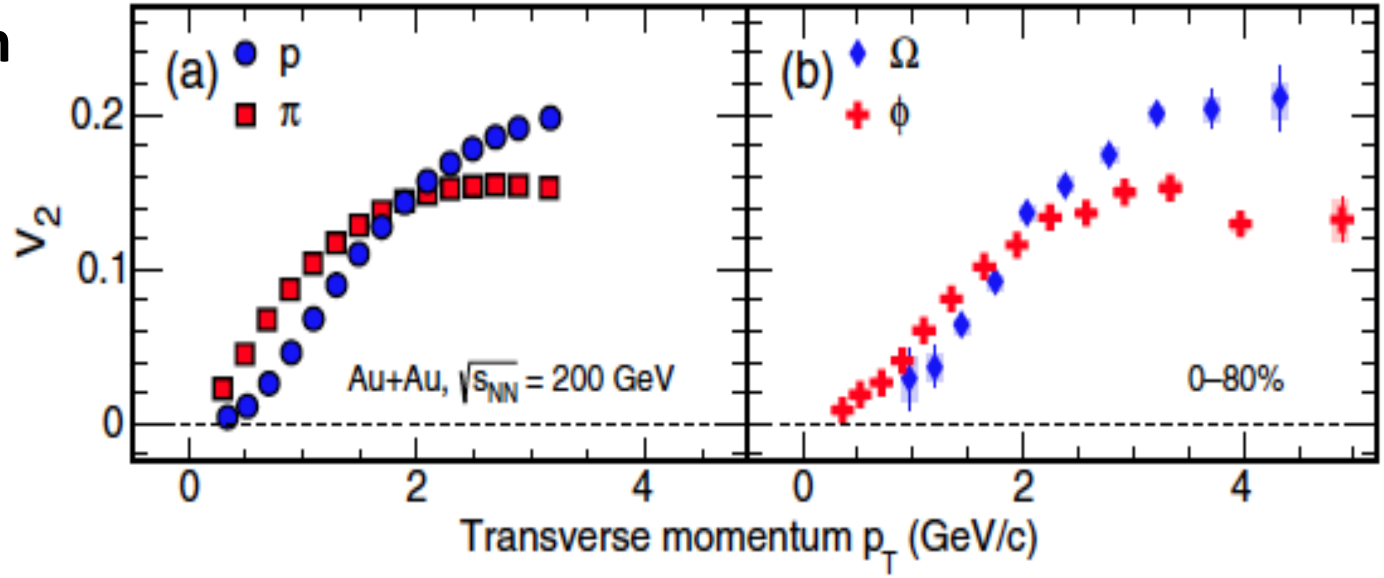
arXiv:1506.07605



arXiv:1506.07605

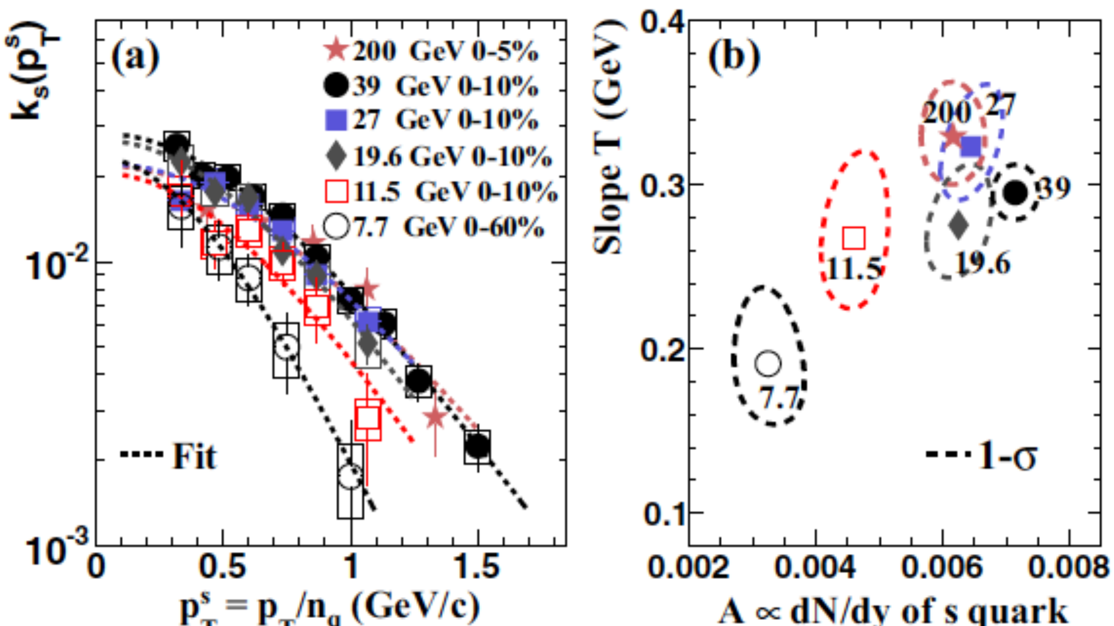
System Evolution from Partonic to Hadronic Phase

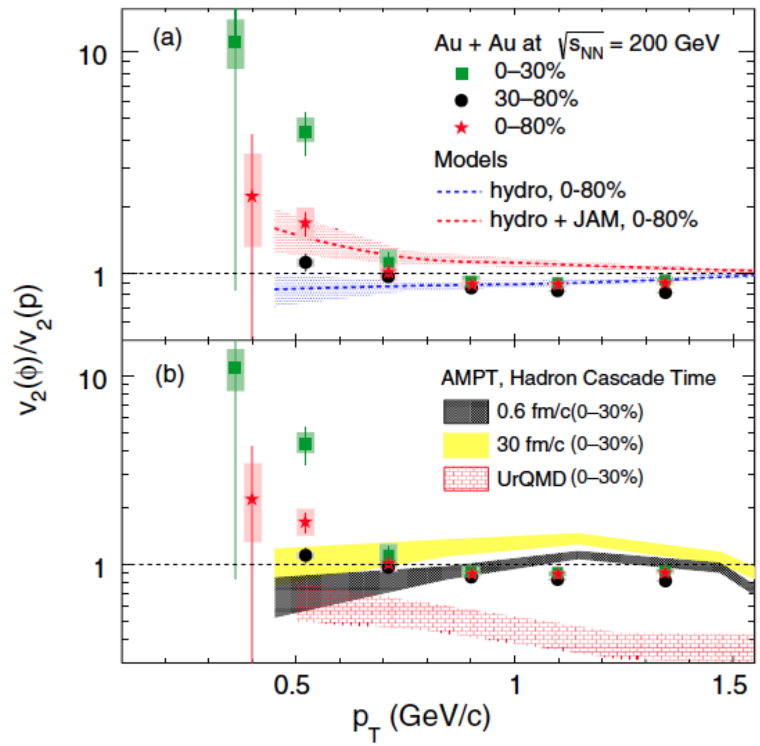
PRL116 (2016) 162301



$k_s = N(\Omega)/N(\phi)$

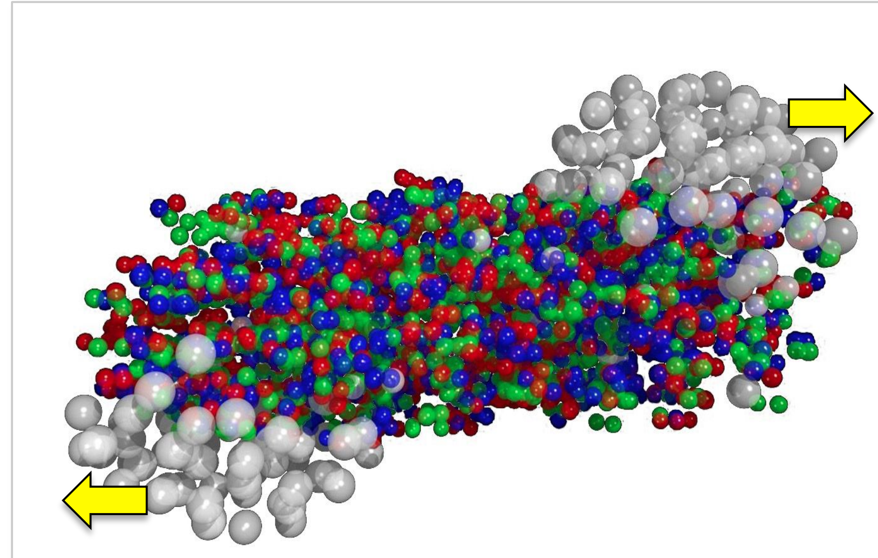
PRC93 (2016) 021903R



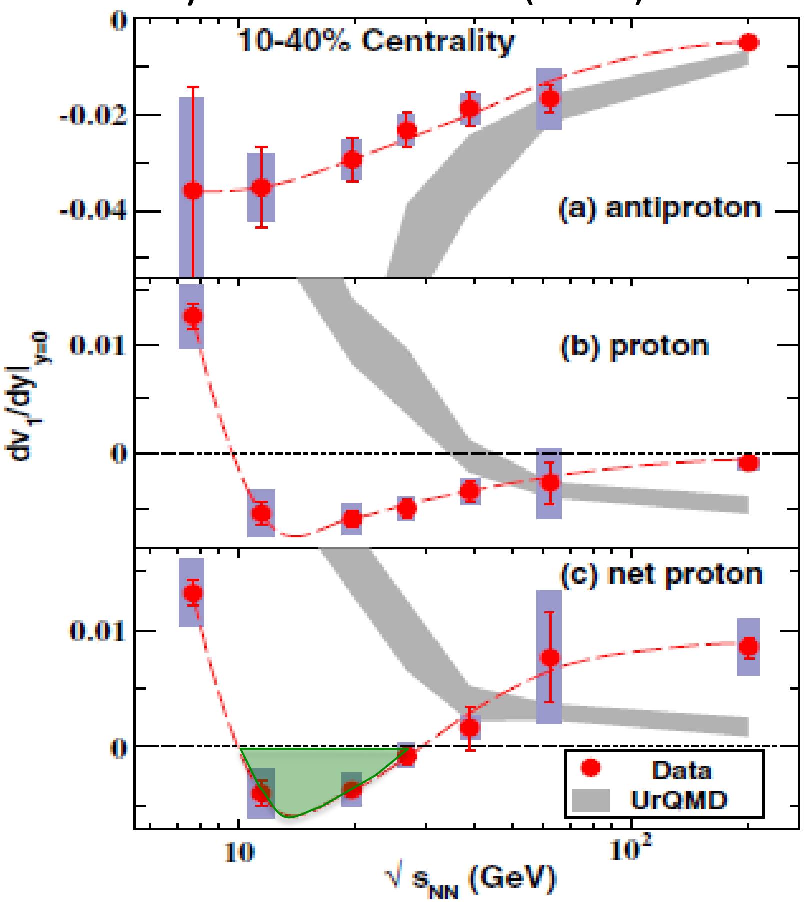


Directed flow (v_1)

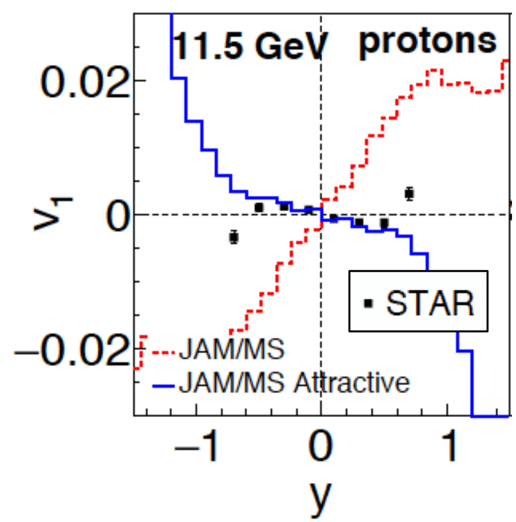
negative slope of dv_1/dy for net-proton
softening of Equation of State

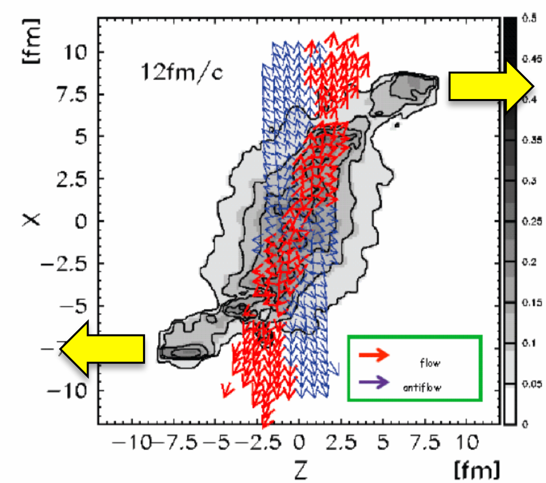


Phys. Rev. Lett. 112 (2014) 162301

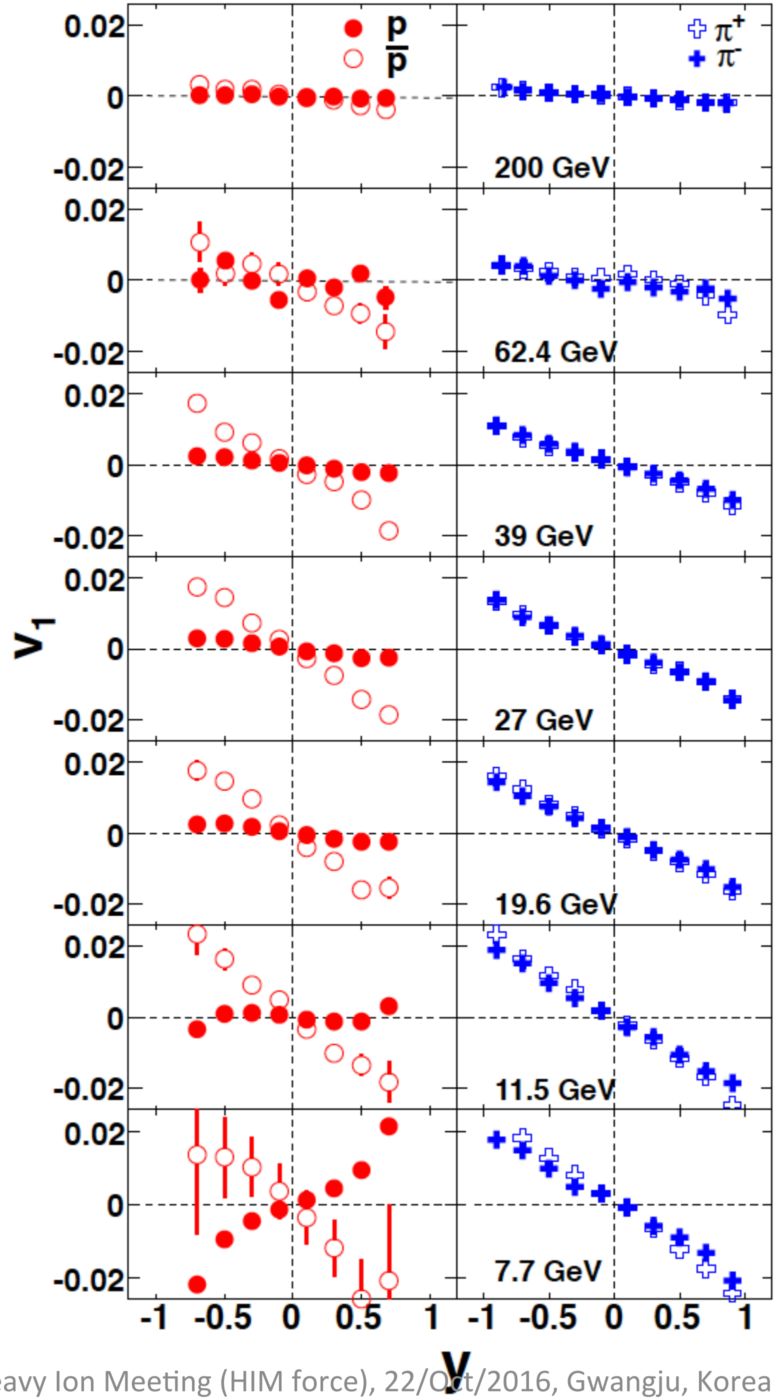


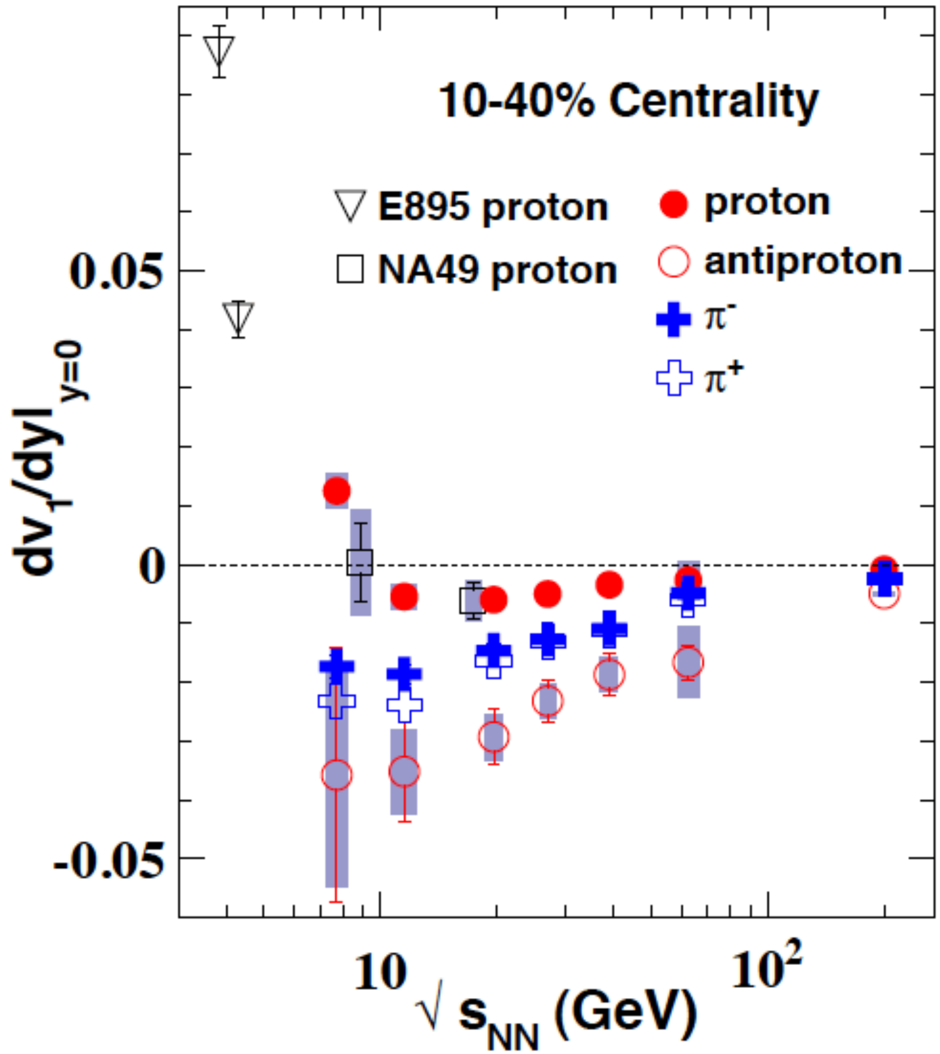
arXiv : 1601.07692





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





arXiv:1401.3043
PRL112 (2014) 16, 162301

arXiv : 1601.07692

Yasushi Nara,[1,2] Harri Niemi,[3] Akira Ohnishi,[4] and Horst Stöcker[2,3,5]

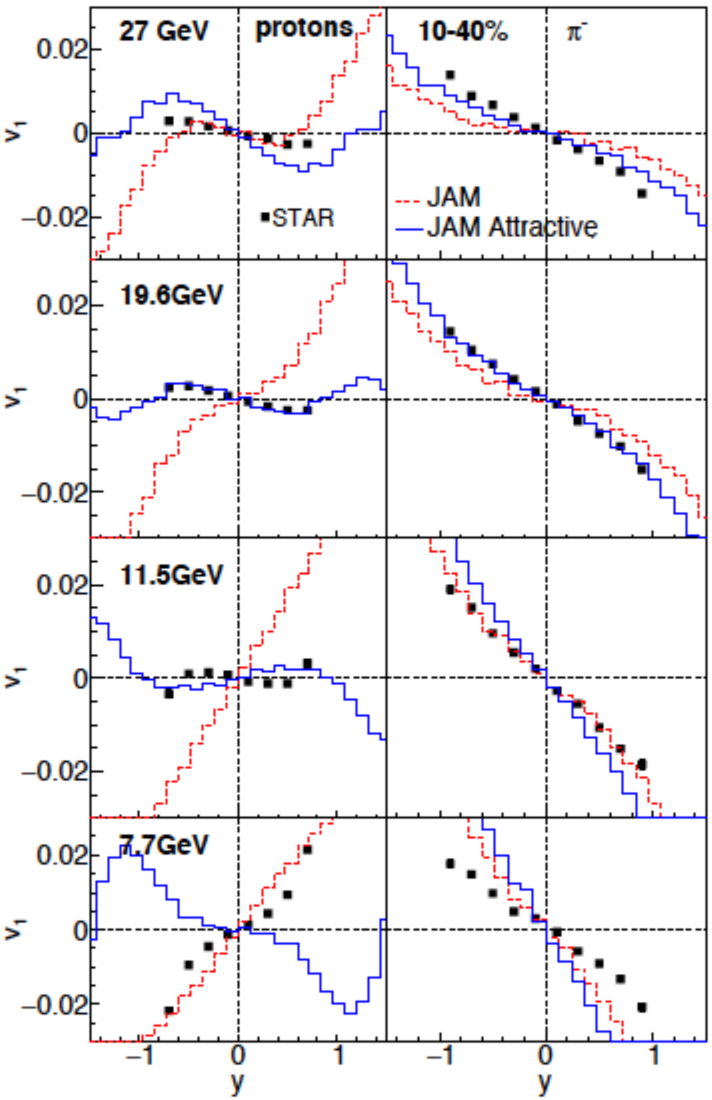


FIG. 1: Directed flows of protons and pions in mid-central Au+Au collisions (10-40%) at $\sqrt{s_{NN}} = 7.7 - 27$ GeV from JAM cascade mode (dashed lines), and JAM cascade with attractive orbits (solid lines) in comparison with the STAR data [1].

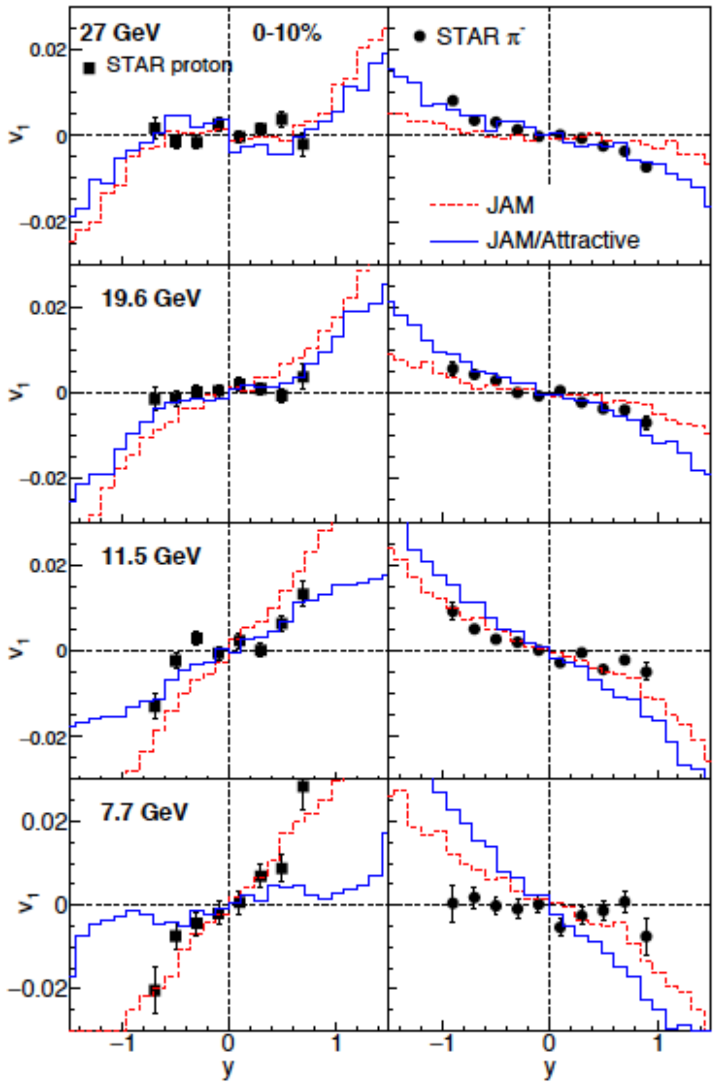
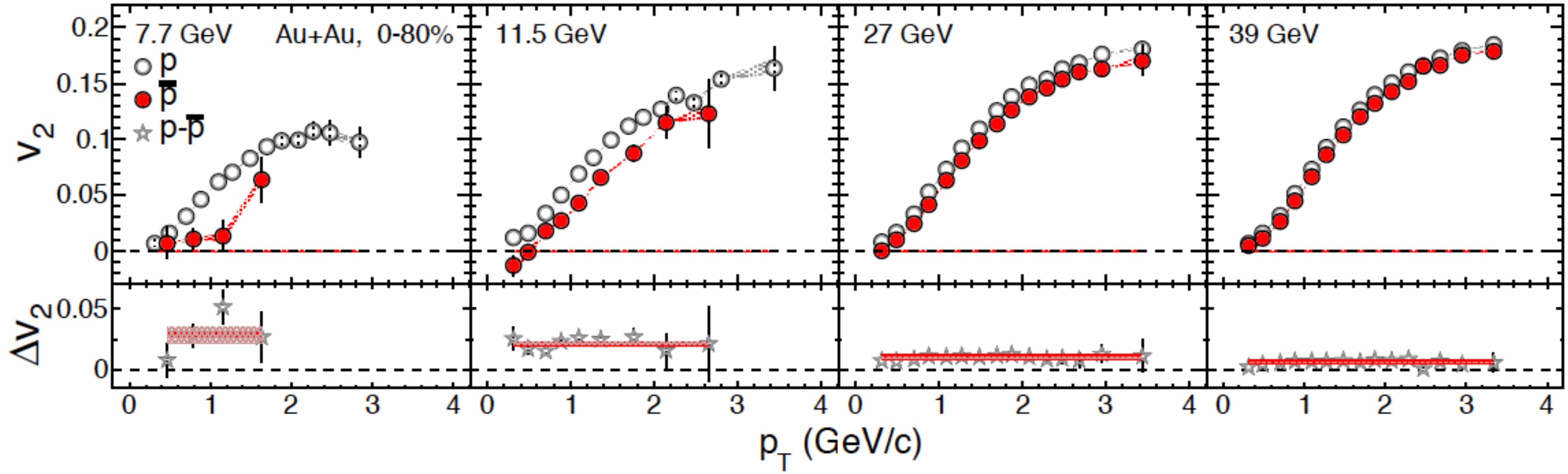
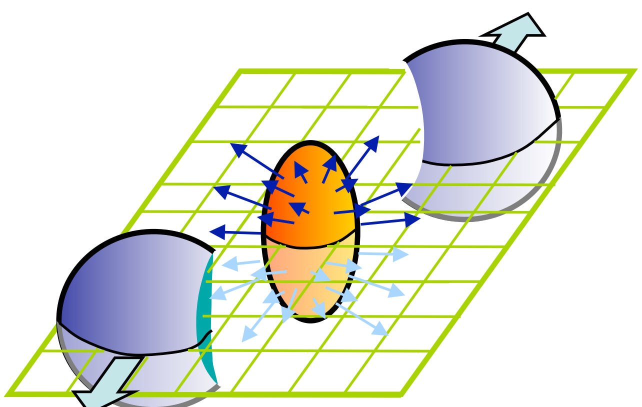
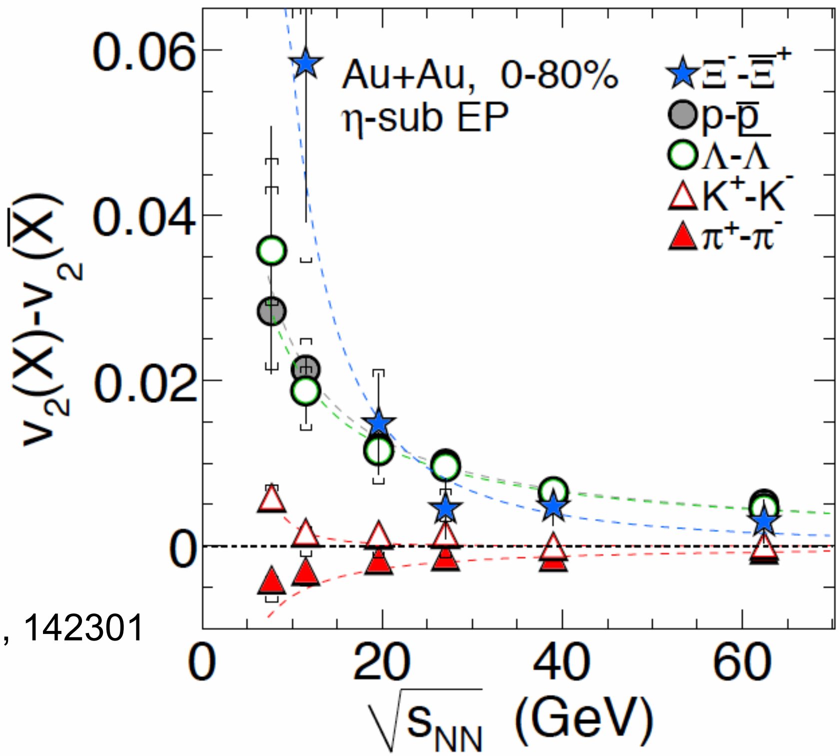


FIG. 2: Same as in Fig. 1, but for central collisions (0-10%).



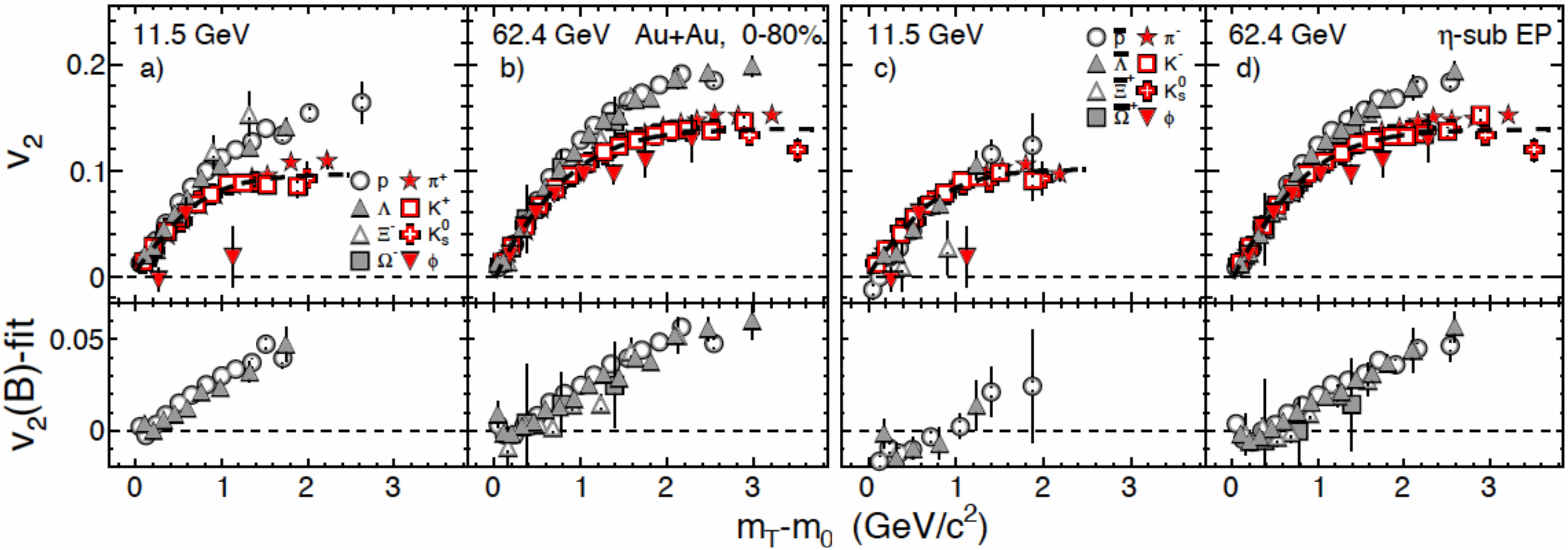
Elliptic Flow v_2

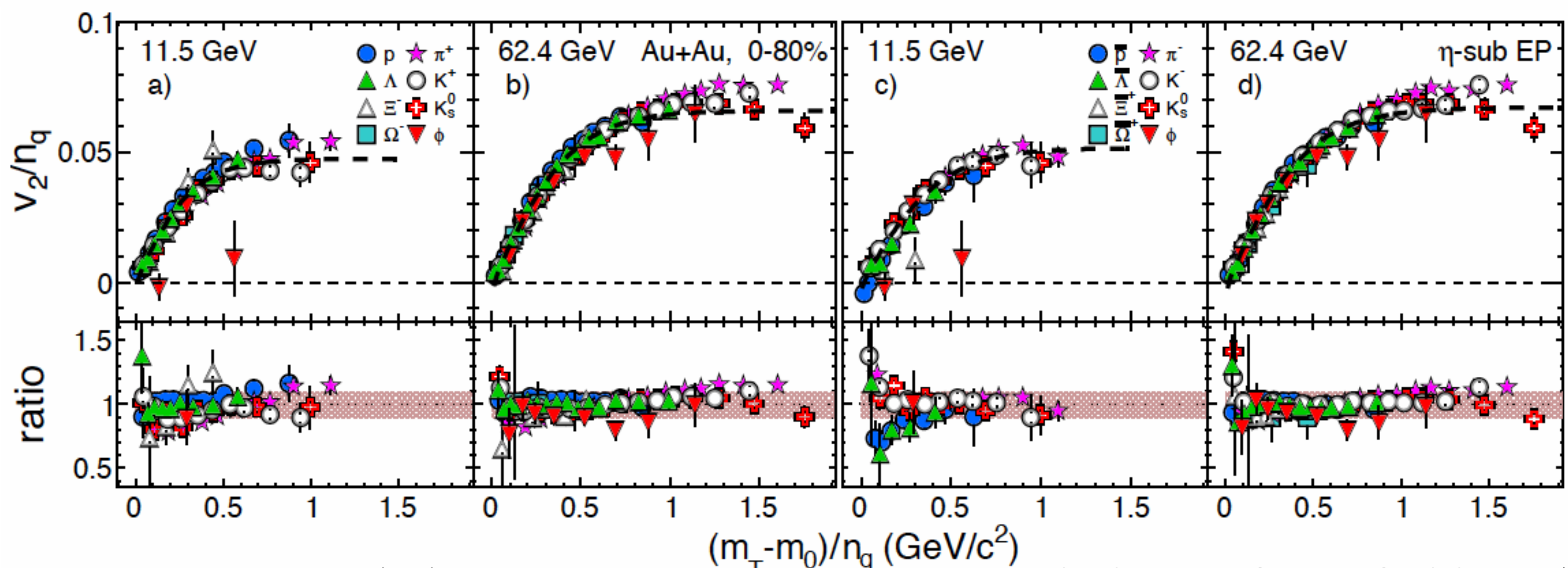




arXiv:1301.2347
PRL110 (2013) 14, 142301

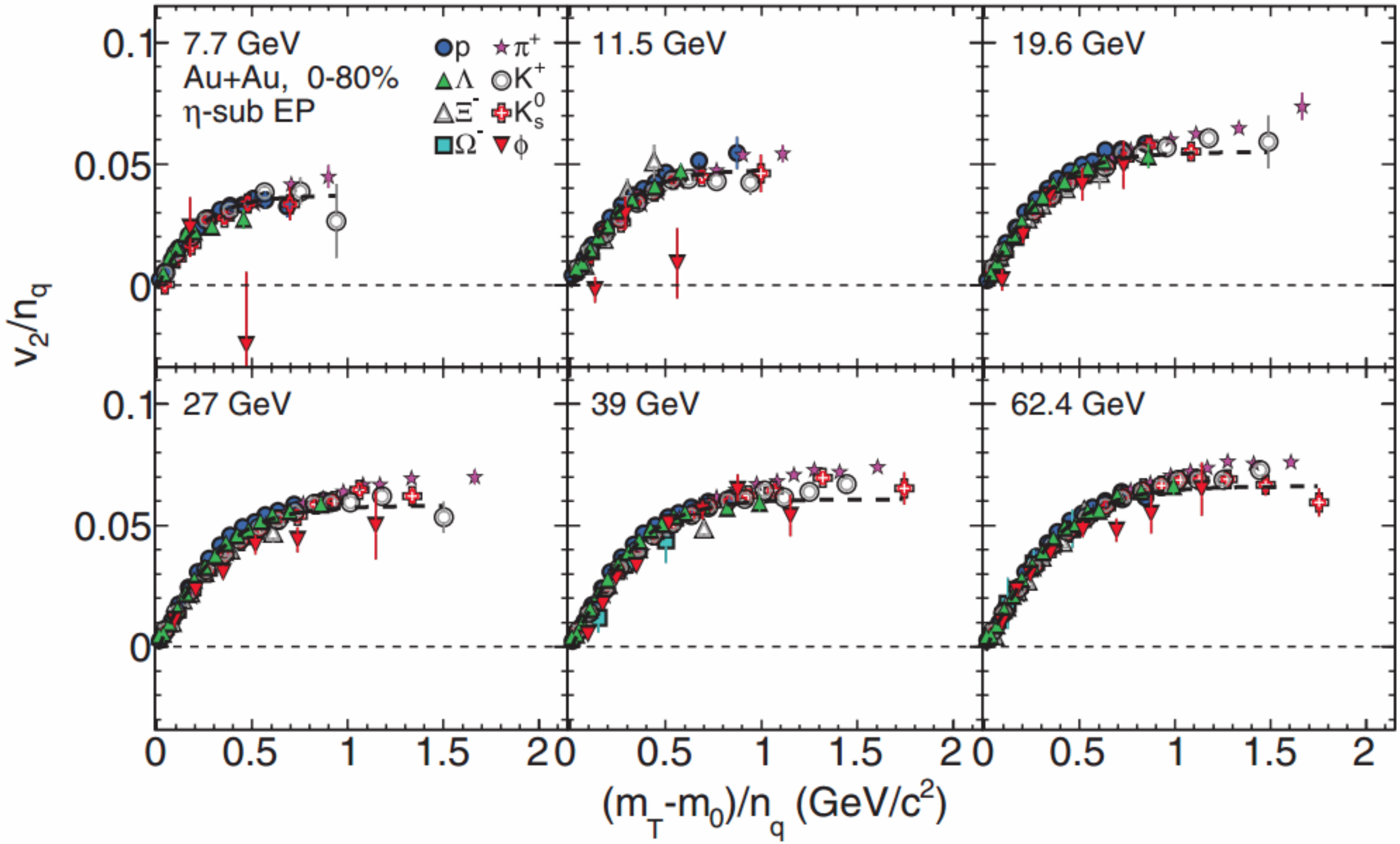
arXiv:1301.2347, PRL110 (2013) 14, 142301





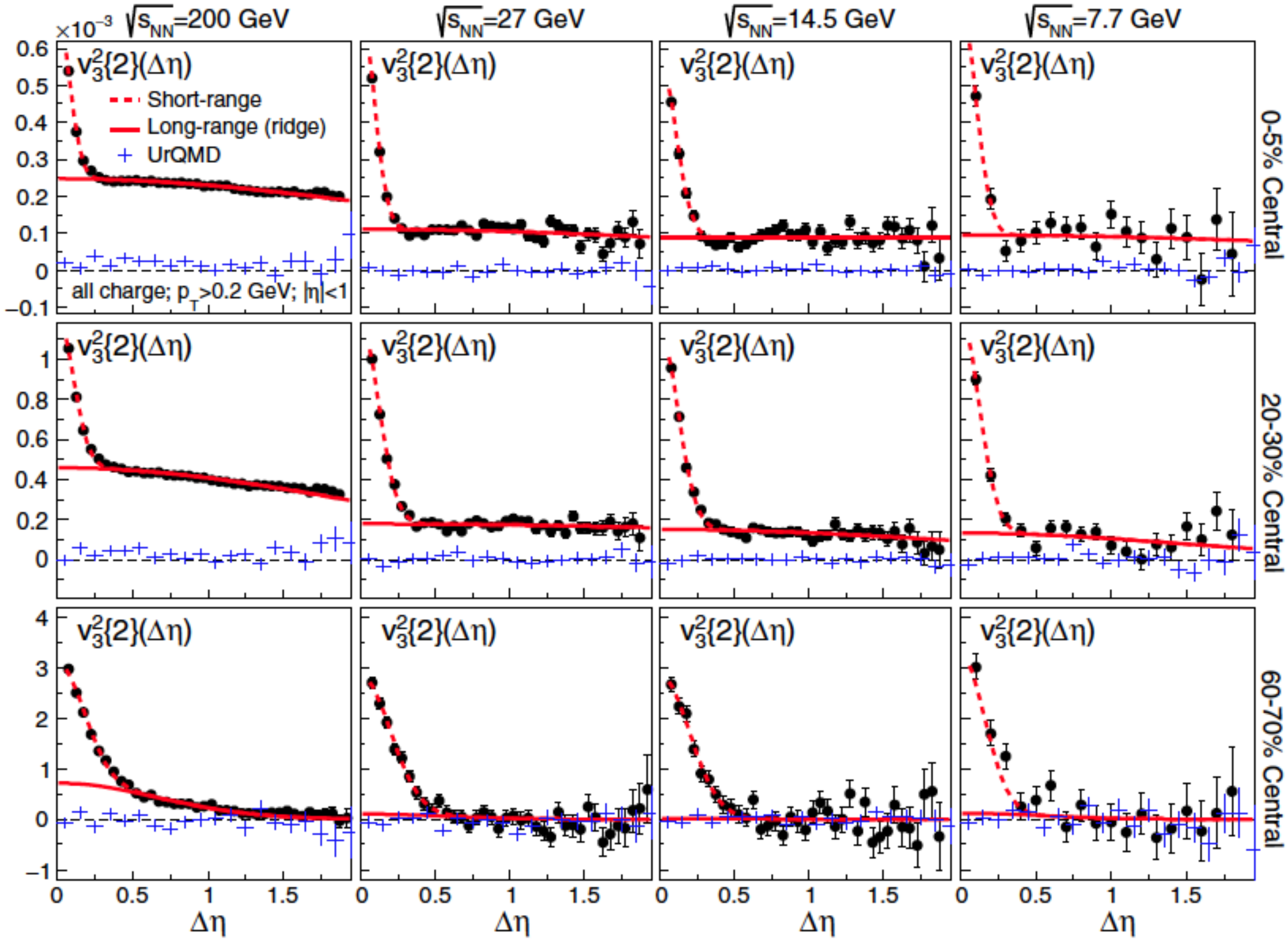
Elliptic Flow v_2 --- departure from quark number scaling ---

PRC88 (2013) 014902



Beam energy dependence of v_3^2

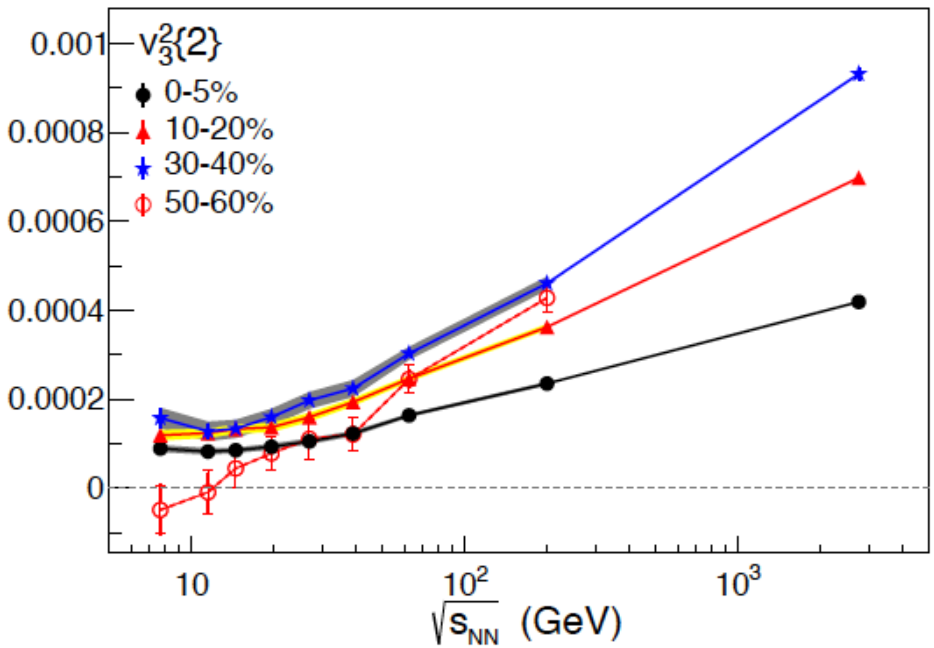
PRL116 (2016) 112302

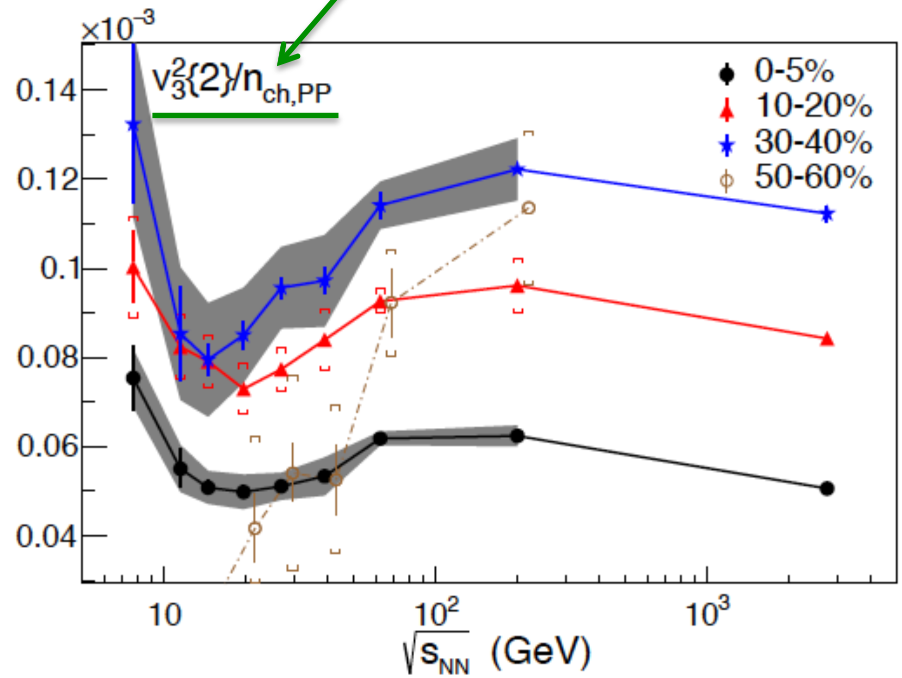


Beam energy dependence of $v_3^2/n_{ch,PP}$

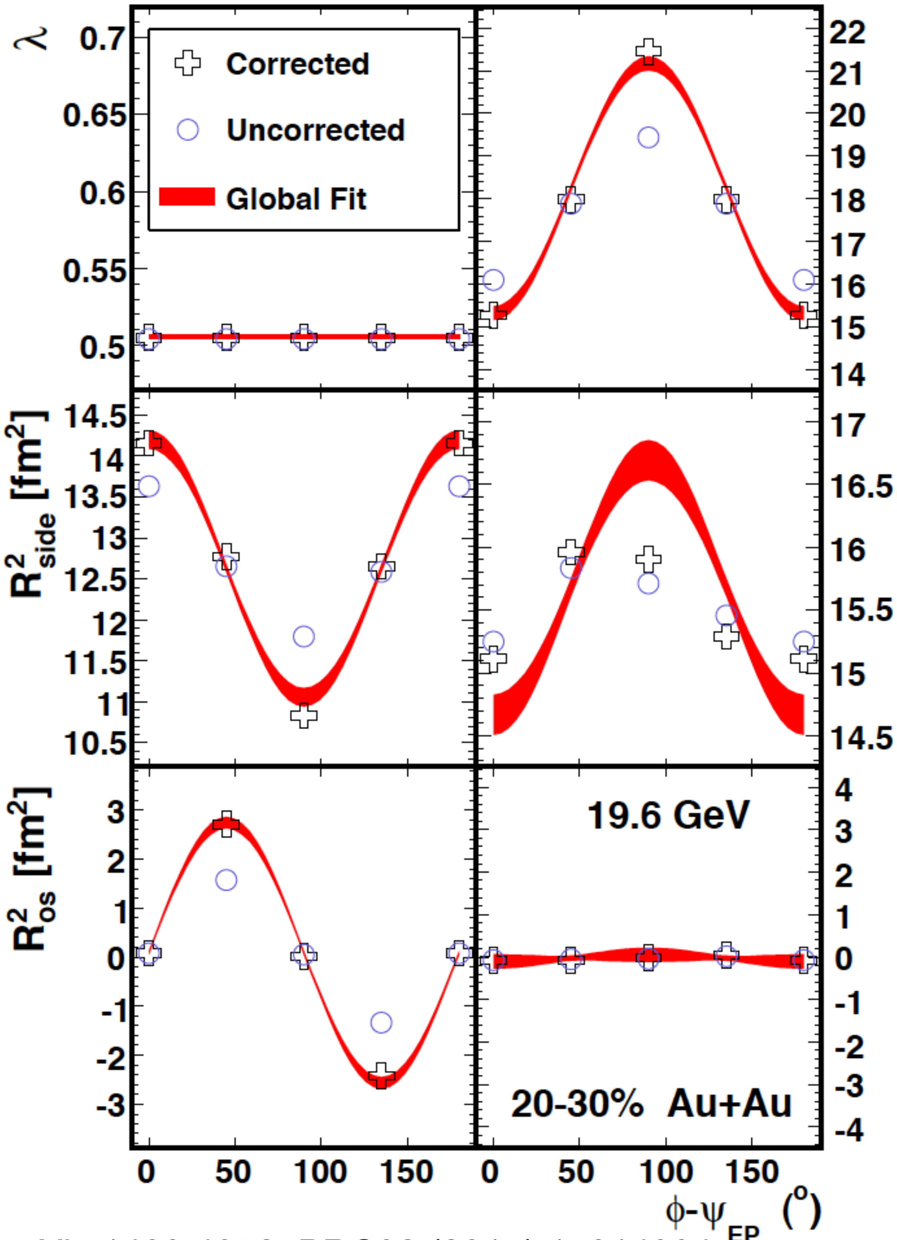
PRL116 (2016) 112302

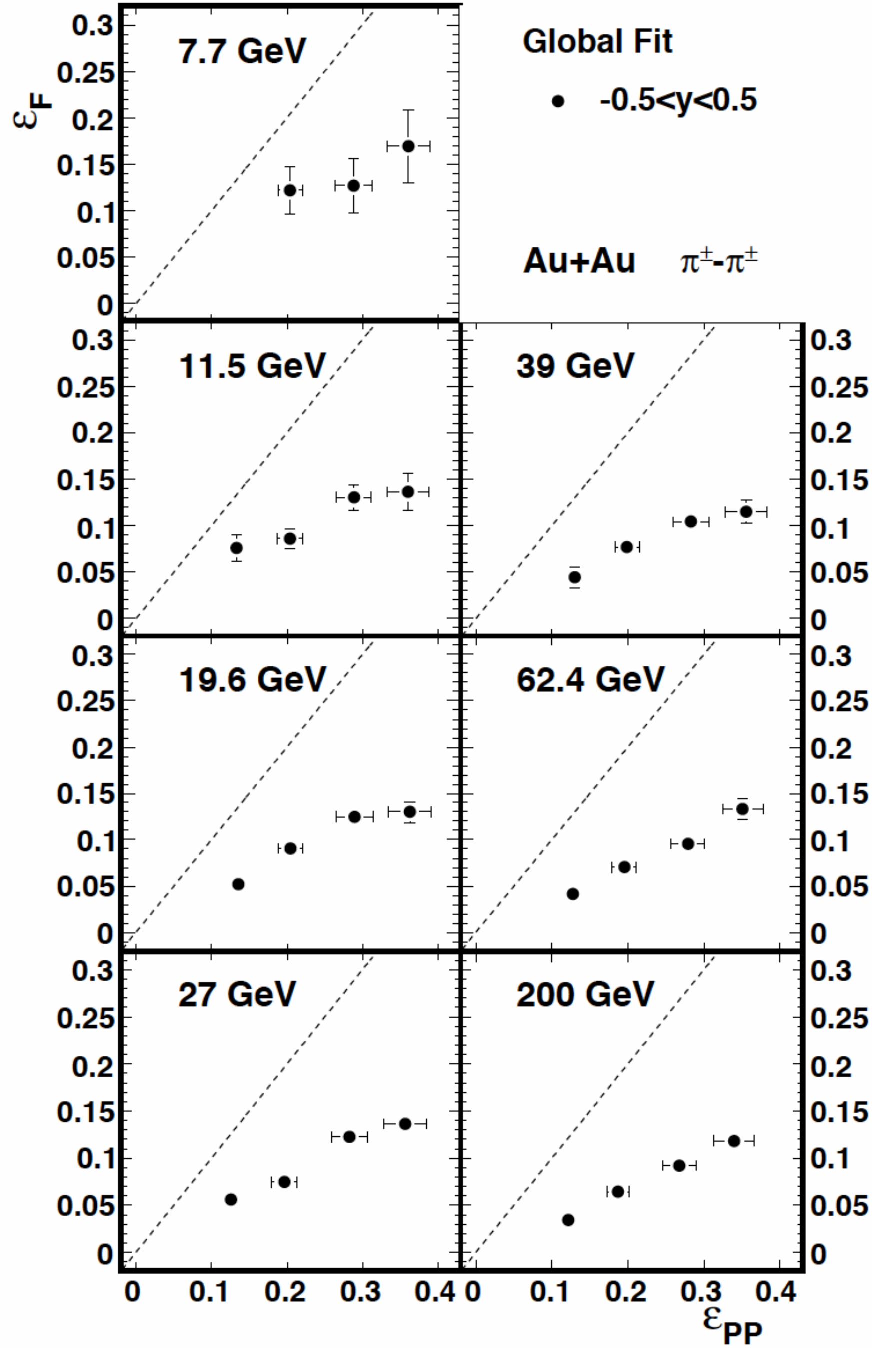
$$n_{\mathrm{ch,PP}} = \frac{2}{N_{\mathrm{part}}} dN_{\mathrm{ch}}/d\eta.$$





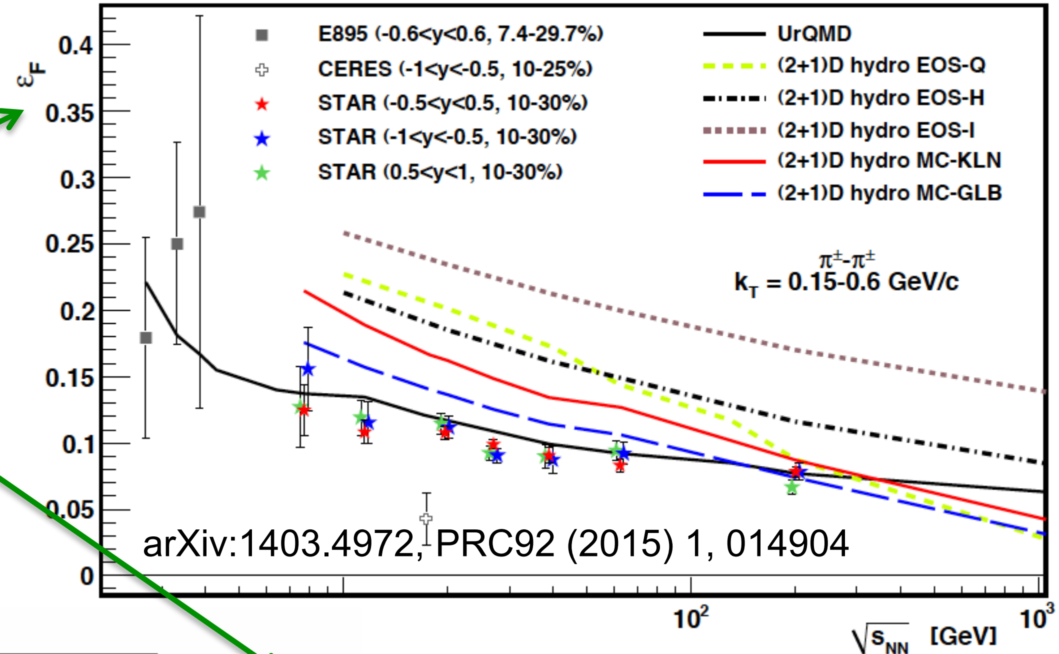
extraction of freeze-out eccentricity

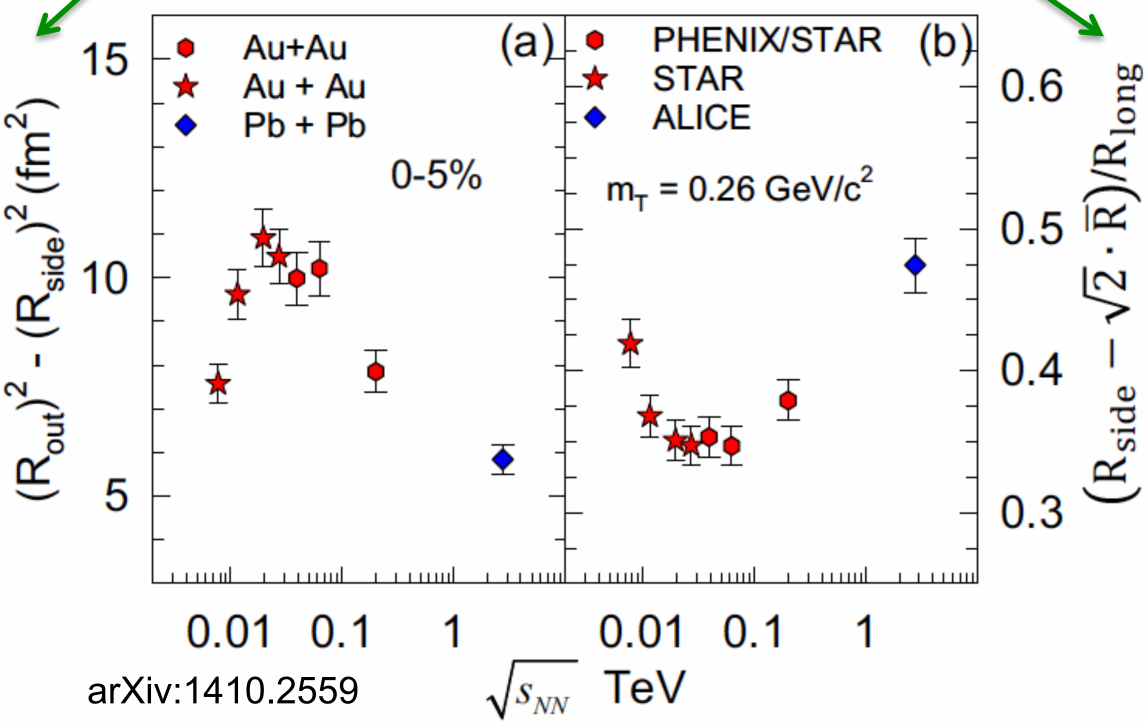




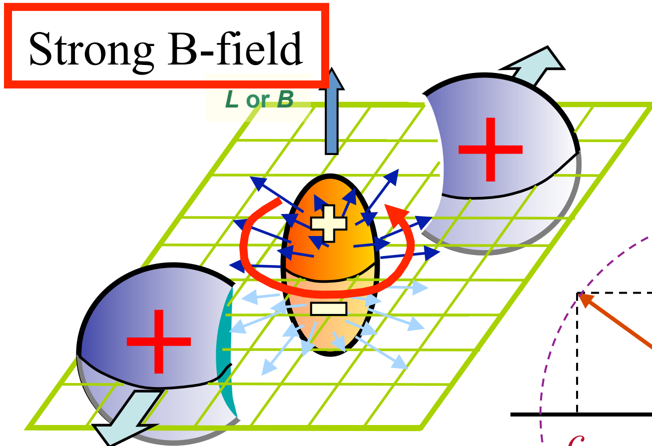
arXiv:1403.4972, PRC92 (2015) 1, 014904

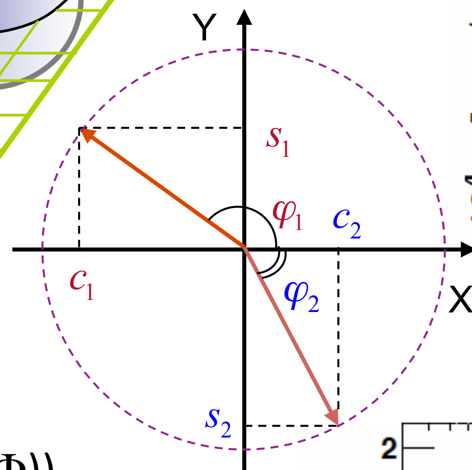
Energy dependence of
(1) freeze-out shape ε_{Final}
(2) duration time
(3) expansion velocity
from HBT data

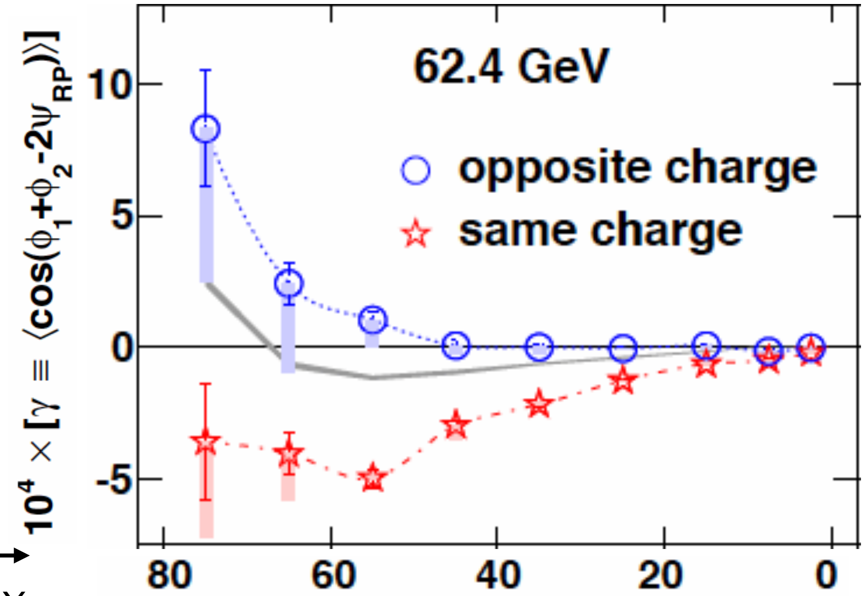




charge separation signal w.r.t. reaction plane from local parity violation

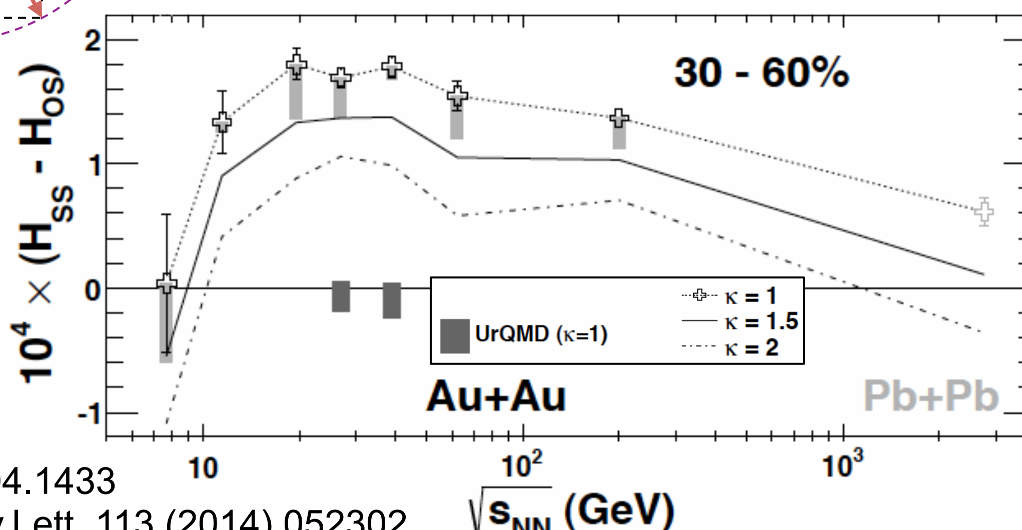






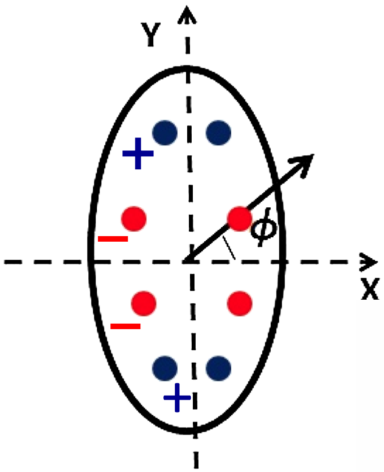
$dN/d\phi \sim 1 + 2v_n\cos(n(\phi-\Phi))$
$+ 2a_{+/-}\sin(\phi-\Phi)$
$<\cos(\phi_1+\phi_2-2\Phi)> \sim -<a_1a_2>$

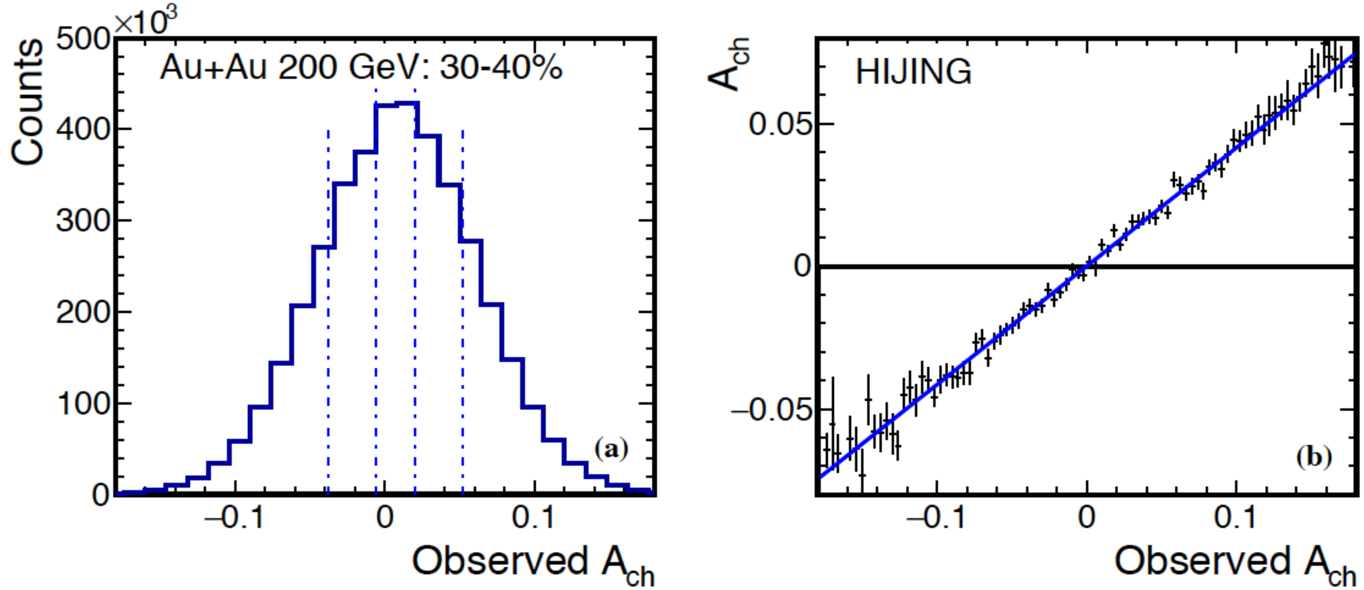
$$\gamma \equiv \langle\cos(\phi_1+\phi_2-2\Psi_{\rm RP})\rangle = \kappa v_2 F - H$$
$$\delta \equiv \langle\cos(\phi_1-\phi_2)\rangle = F + H,$$

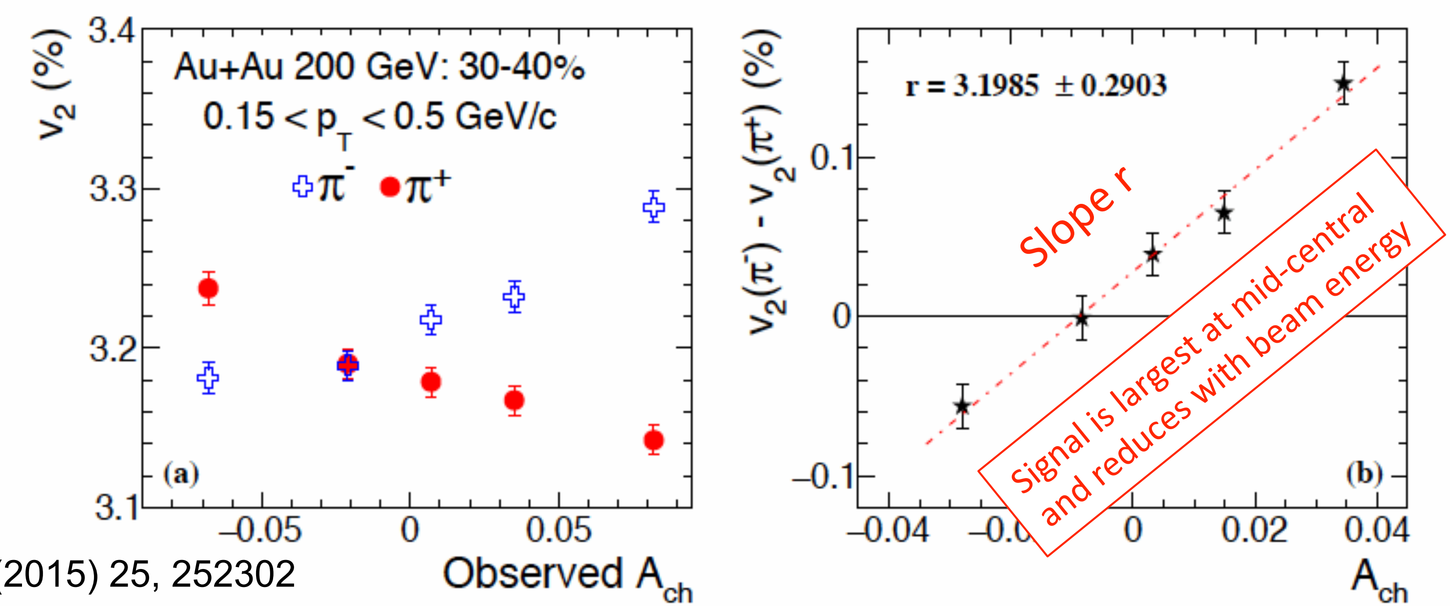


arXiv:1404.1433
Phys.Rev.Lett. 113 (2014) 052302

charge dependent v2 w.r.t. charge asymmetry



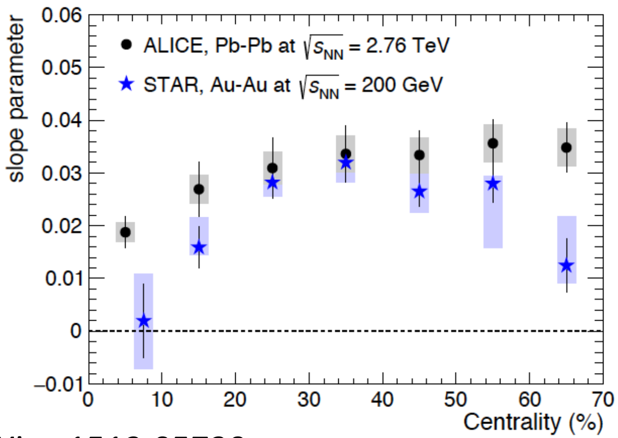




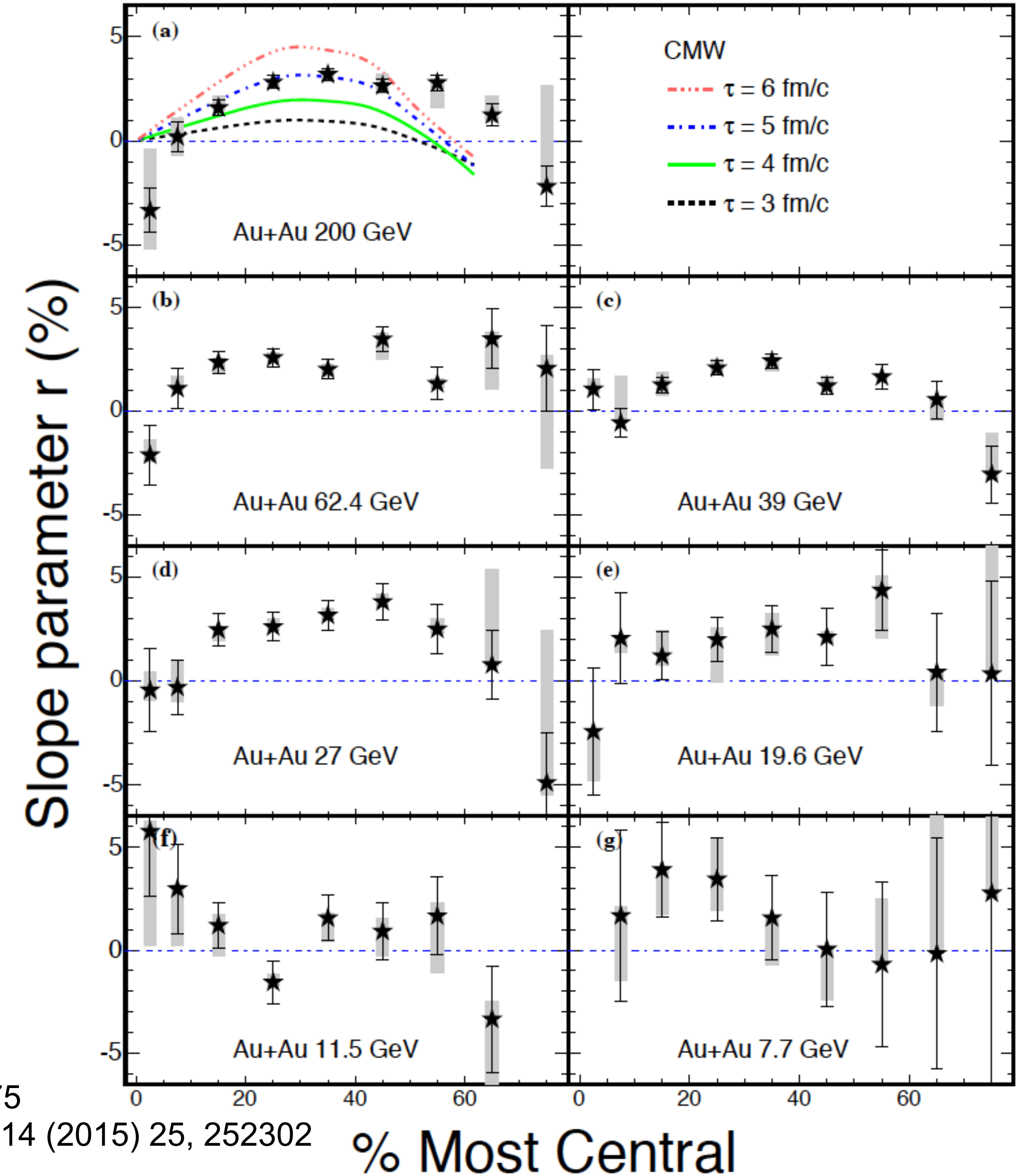
arXiv:1504.02175
Phys.Rev.Lett. 114 (2015) 25, 252302

Slope :

$r = \Delta v_2 / \Delta A_{ch}$



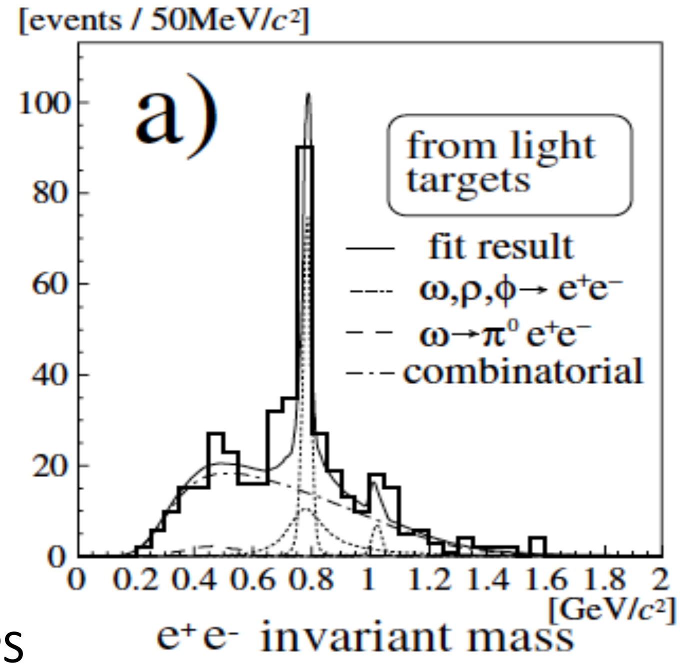
arXiv : 1512.05739

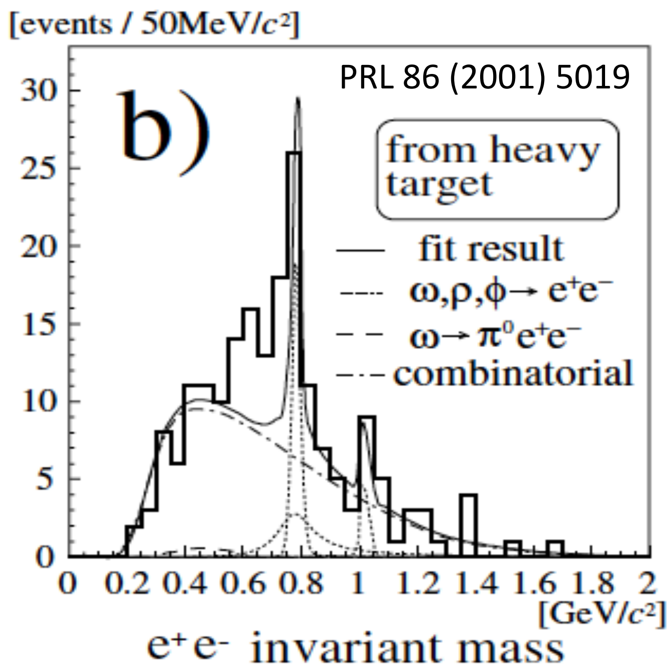


arXiv:1504.02175

Phys.Rev.Lett. 114 (2015) 25, 252302

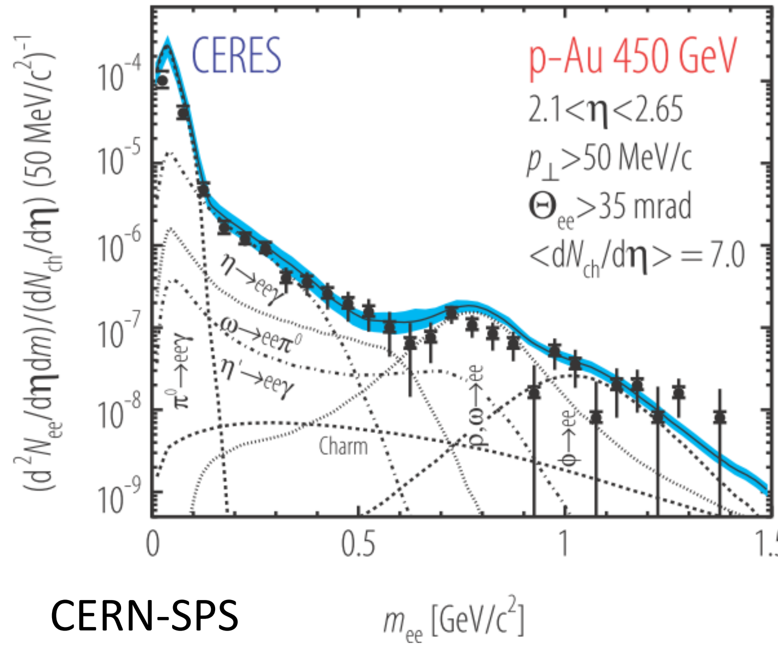
KEK-PS



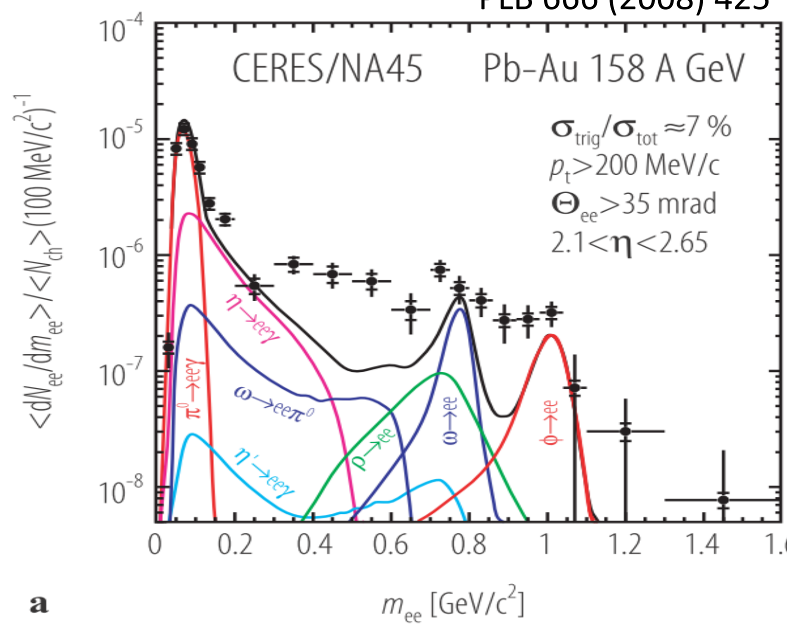


PRL 86 (2001) 5019

CERN-SPS



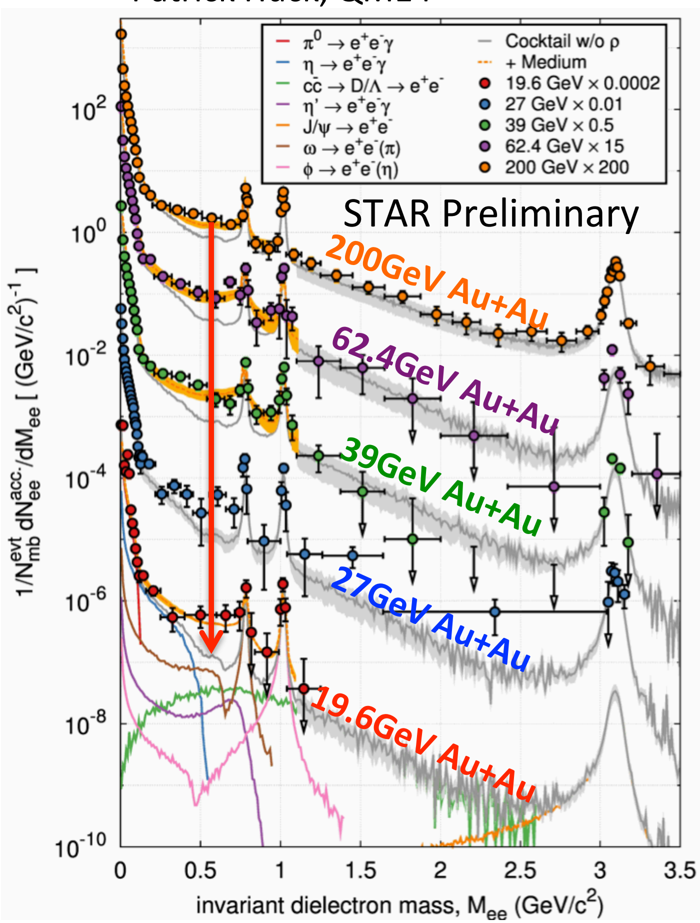
PLB 666 (2008) 425



Low-mass ee-pair excess

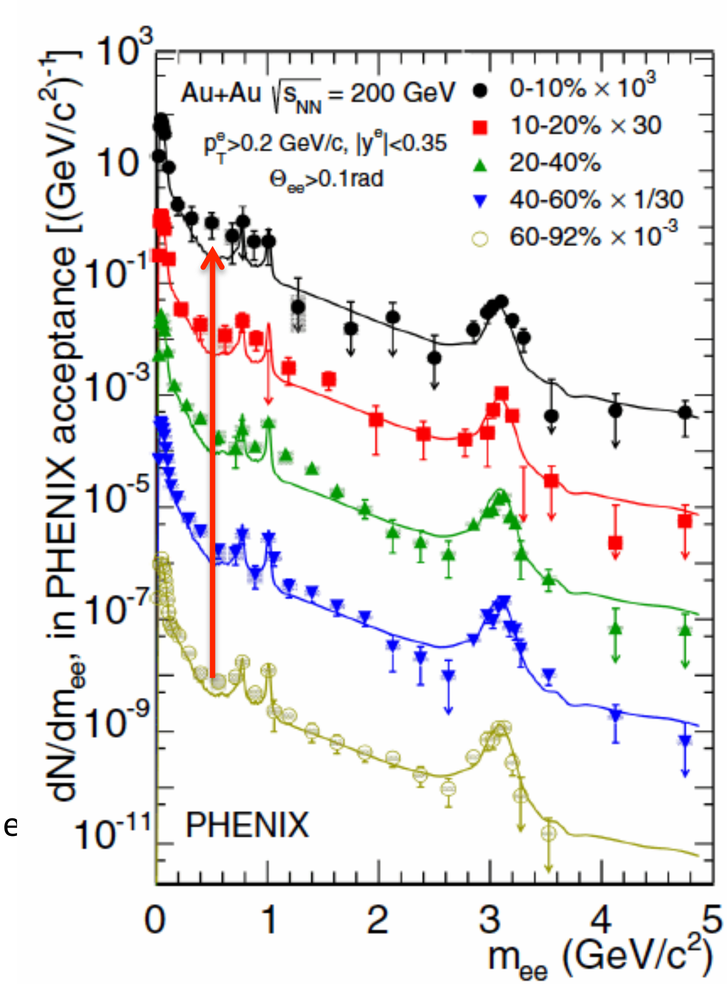
--- ρ shape modification ---
--- duration time of QGP ---

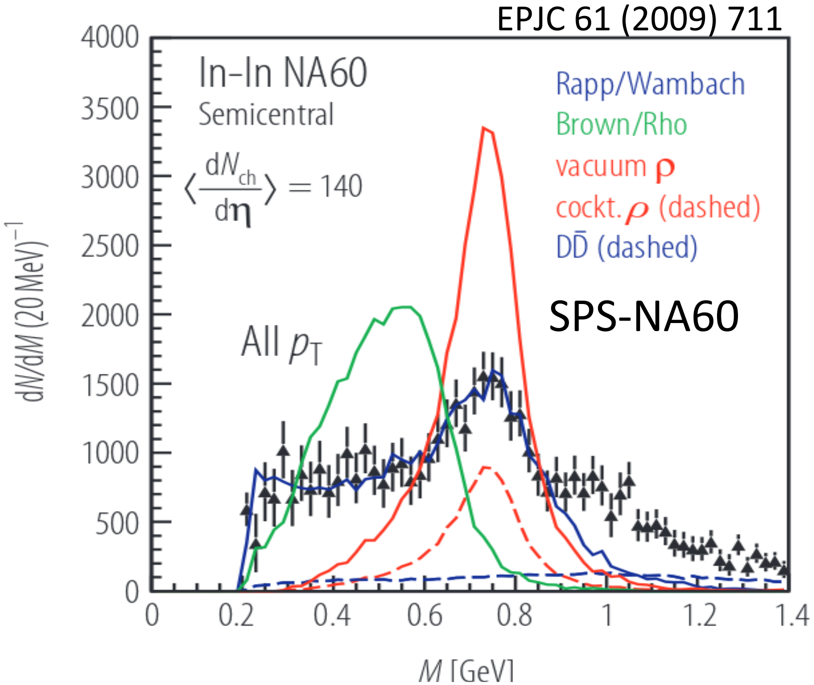
Patrick Huck, QM14

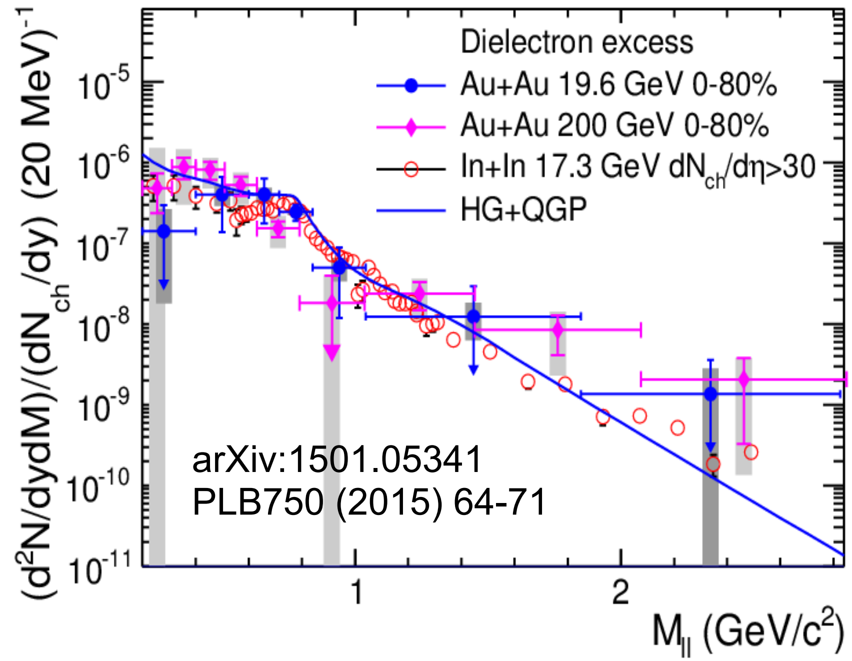


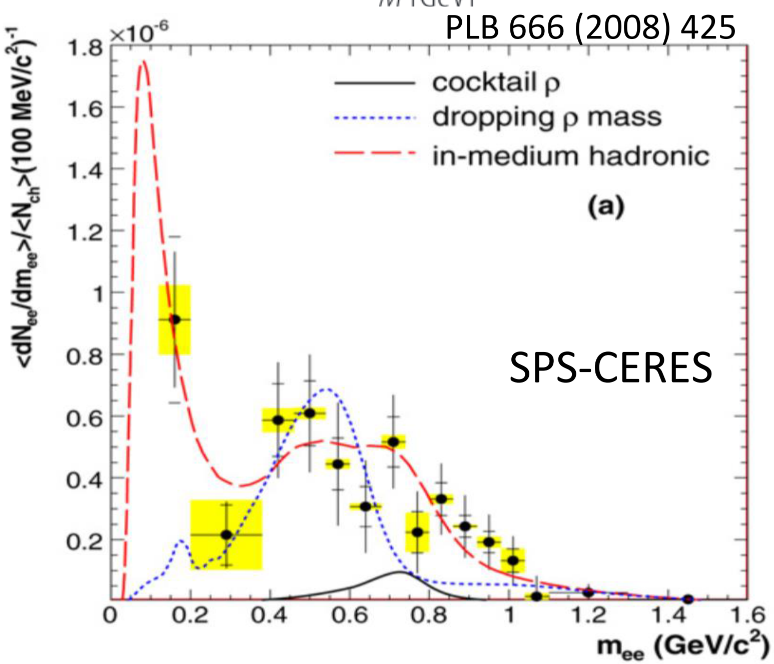
Long standing discrepancy between star and phenix has been resolved with an improved and updated analysis with Hadron Blind Detector (HBD) in phenix : Phys. Rev. C 93 (2016) 014904

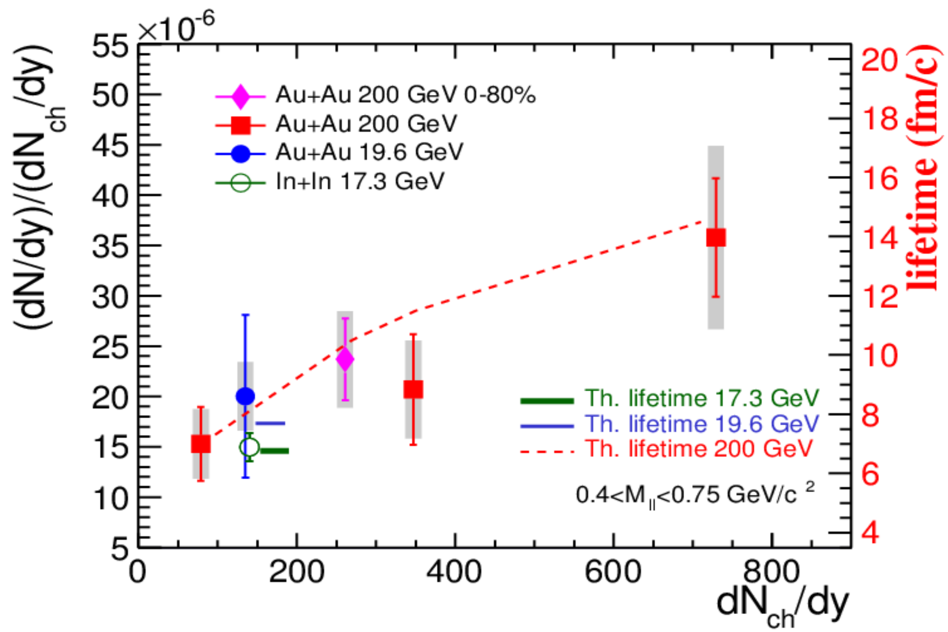
final results for 19.6, 200 Ge
and comparison to SPS at
Phys. Lett. B 750 (2015) 64




EPJC 61 (2009) 711
In-In NA60
Semicentral
All p_T
Rapp/Wambach
Brown/Rho
vacuum ρ
cockt. ρ (dashed)
DD̄ (dashed)
SPS-NA60
dN/dM (20 MeV)$^{-1}$
M [GeV]

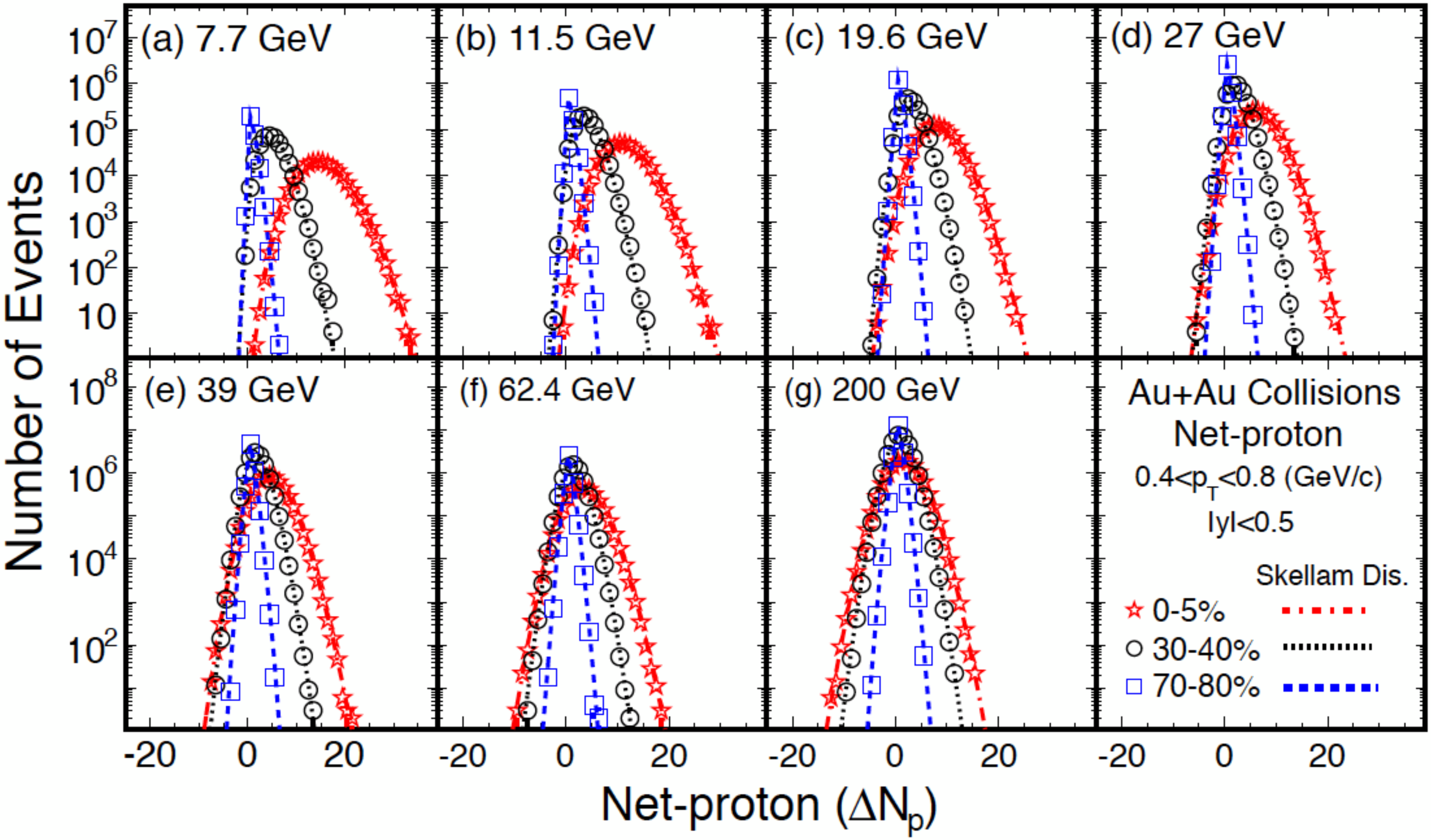

Dielectron excess
Au+Au 19.6 GeV 0-80%
Au+Au 200 GeV 0-80%
In+In 17.3 GeV $dN_{ch}/d\eta>30$
HG+QGP
arXiv:1501.05341
PLB750 (2015) 64-71
$(d^2N/dydM)/(dN_{ch}/dy)$ (20 MeV)$^{-1}$
M_{ll} (GeV/c^2)


PLB 666 (2008) 425
cocktail ρ
dropping ρ mass
in-medium hadronic
(a)
SPS-CERES
$<dN_{ee}/dm_{ee}>/<N_{ch}>$(100 MeV/$c^2$)$^{-1}$
m_{ee} (GeV/c^2)


Au+Au 200 GeV 0-80%
Au+Au 200 GeV
Au+Au 19.6 GeV
In+In 17.3 GeV
Th. lifetime 17.3 GeV
Th. lifetime 19.6 GeV
Th. lifetime 200 GeV
$0.4<M_{ll}<0.75$ GeV/c^2
$(dN/dy)/(dN_{ch}/dy)$
lifetime (fm/c)
dN_{ch}/dy

Shape of net-proton distribution

arXiv:1309.5681
Phys.Rev.Lett. 112 (2014) 032302



Observables: Higher Moments (fluctuations)

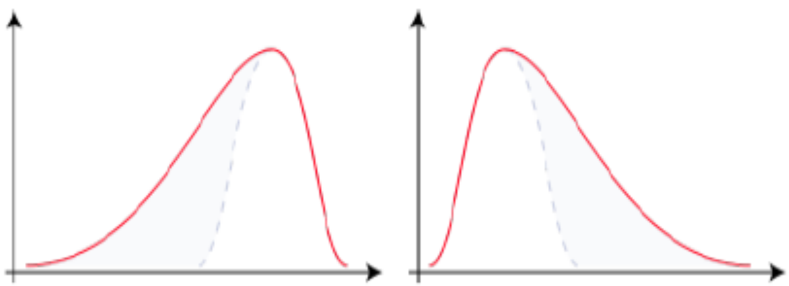
"Shape" of the fluctuations can be measured: non-Gaussian moments.

$$C_{1,x} = < x >, C_{2,x} = < (\delta x)^2 >,$$

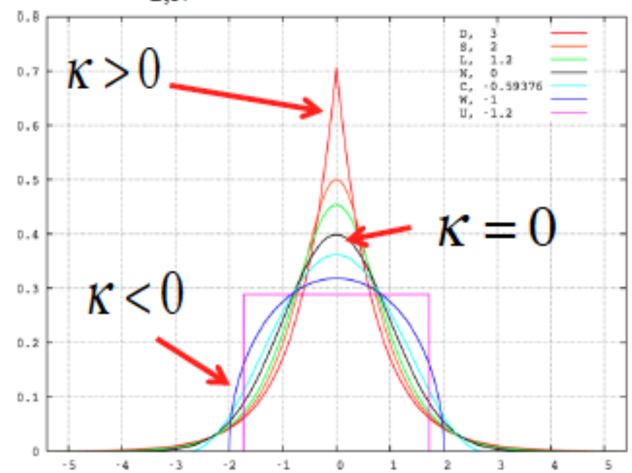
$$C_{3,x} = < (\delta x)^3 >, C_{4,x} = < (\delta x)^4 > - 3 < (\delta x)^2 >^2$$

$$S = \frac{C_{3,N}}{(C_{2,N})^{3/2}} = \frac{< (N - < N >)^3 >}{\sigma^3}$$

$$\kappa = \frac{C_{4,N}}{(C_{2,N})^2} = \frac{< (N - < N >)^4 >}{\sigma^4} - 3$$



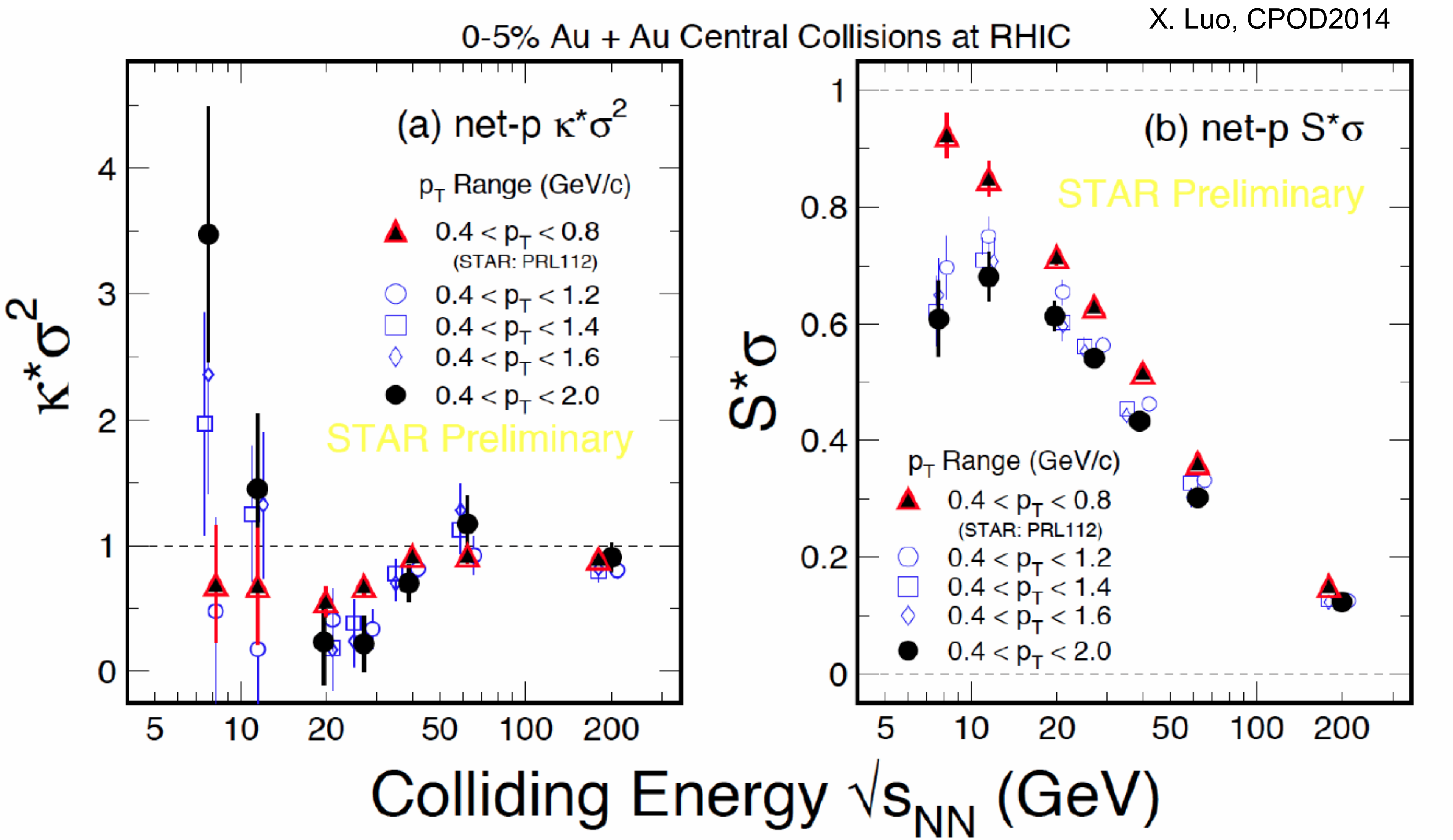
Negative Skew Positive Skew

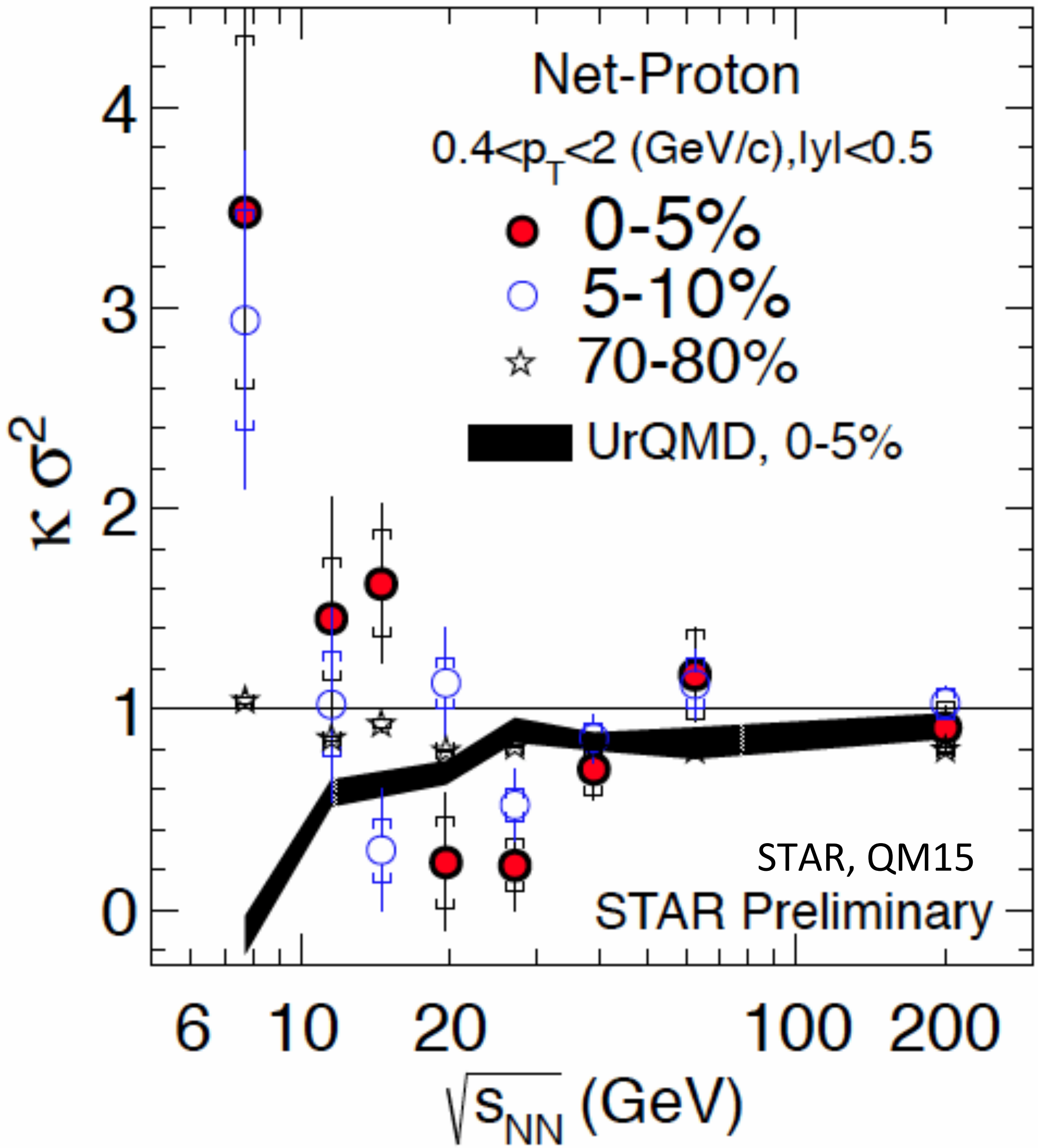


➢ **Susceptibility ratios ⇔ Cumulant Ratios (Cancel V dependence)**

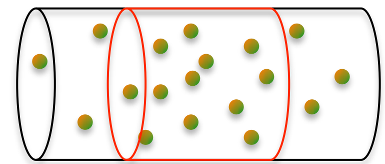
$$\frac{\chi_q^4}{\chi_q^2} = \kappa\sigma^2 = \frac{C_{4,q}}{C_{2,q}} \qquad \frac{\chi_q^3}{\chi_q^2} = S\sigma = \frac{C_{3,q}}{C_{2,q}}, \qquad \textbf{(q=B, Q, S)}$$

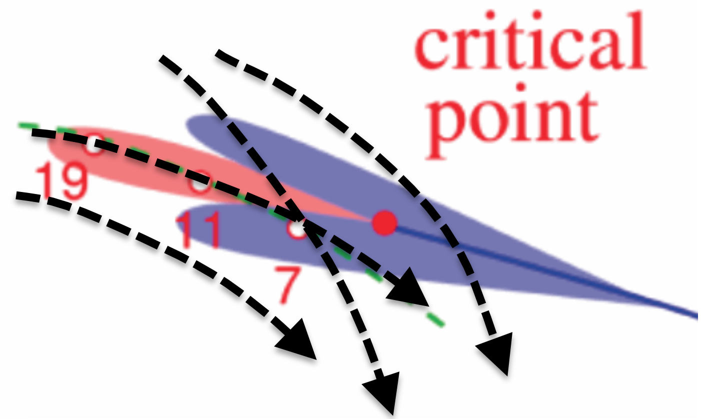
Xiaofeng Luo CiRfSE workshop, Jan. 19, 2016 @ Tsukuba University. 17 / 40


X. Luo, CPOD2014
0-5% Au + Au Central Collisions at RHIC
(a) net-p κ*σ²
pT Range (GeV/c)
0.4 < pT < 0.8
(STAR: PRL112)
0.4 < pT < 1.2
0.4 < pT < 1.4
0.4 < pT < 1.6
0.4 < pT < 2.0
STAR Preliminary
κ*σ²
(b) net-p S*σ
STAR Preliminary
S*σ
Colliding Energy √sNN (GeV)



Possible critical signature





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

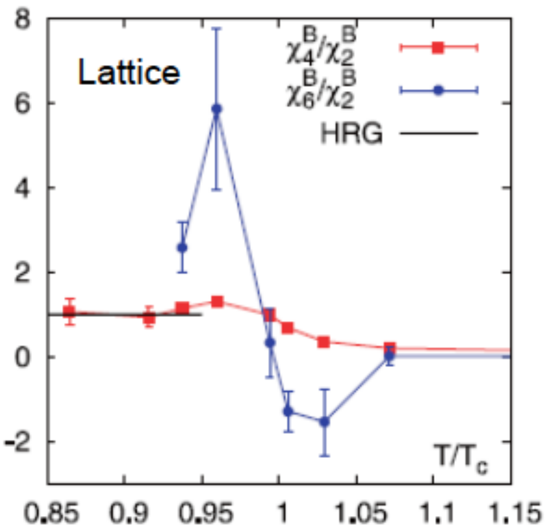
Higher Order Fluctuations of Conserved Quantities

1. Higher sensitivity to correlation length (ξ) and probe non-gaussian fluctuations near the Critical Point.

$$\left\langle (\delta N)^3 \right\rangle_c \approx \xi^{4.5}, \quad \left\langle (\delta N)^4 \right\rangle_c \approx \xi^{7}$$

M. A. Stephanov, Phys. Rev. Lett. 102, 032301 (2009).
M. A. Stephanov, Phys. Rev. Lett. 107, 052301 (2011).
M. Asakawa, S. Ejiri and M. Kitazawa, Phys. Rev. Lett. 103, 262301 (2009).

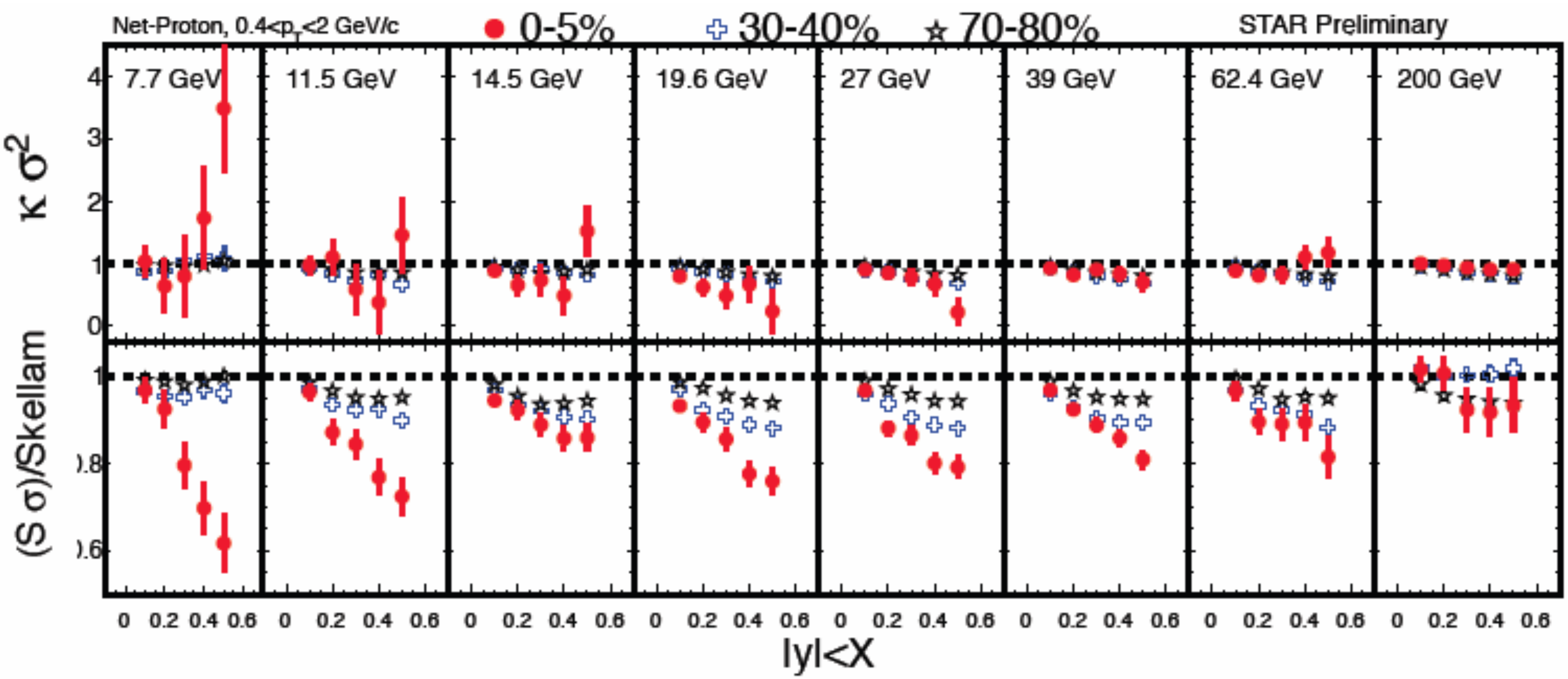
2. Direct connection to the susceptibility of the system.



$$\chi_q^{(n)} = \frac{1}{VT^3} \times C_{n,q} = \frac{\partial^n (p/T^4)}{\partial (\mu_q)^n}, q = B, Q, S$$

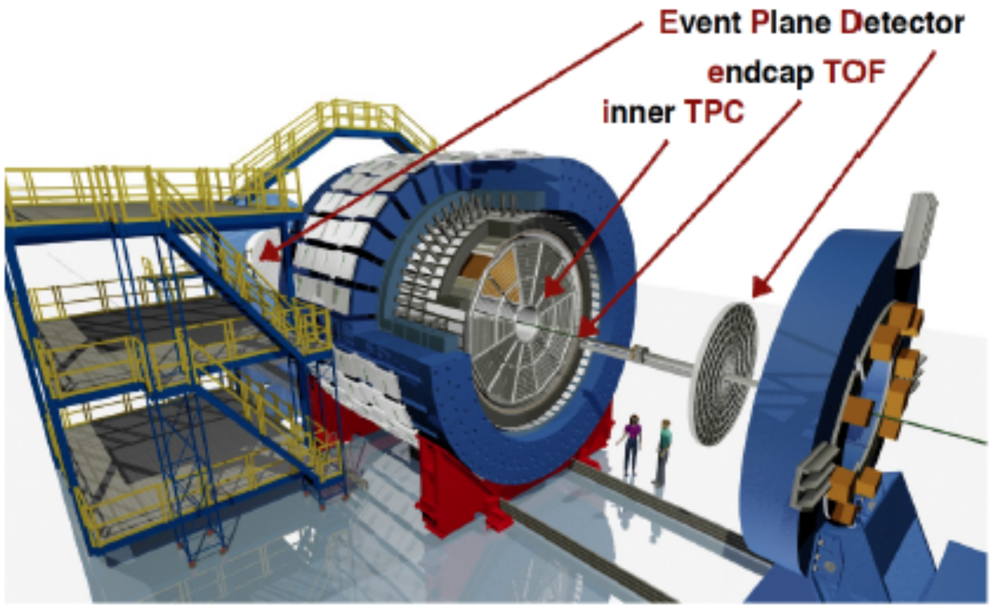
S. Ejiri et al, Phys.Lett. B 633 (2006) 275.
Cheng et al, PRD (2009) 074505. B. Friman et al., EPJC 71 (2011) 1694.
F. Karsch and K. Redlich , PLB 695, 136 (2011).
S. Gupta, et al., Science, 332, 1525(2012).
A. Bazavov et al., PRL109, 192302(12) // S. Borsanyi et al., PRL111, 062005(13) // P. Alba et al., arXiv:1403.4903

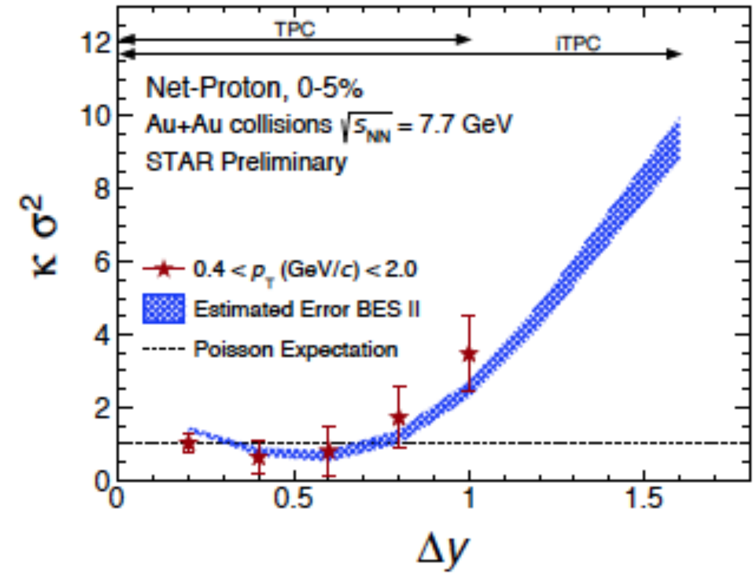
Rapidity Window Dependence



Significant rapidity window dependence are observed.
Large acceptance is crucial for the fluctuation measurement.

STAR Upgrades and BES Phase-II (2019-2020)





iTPC proposal: http://drupal.star.bnl.gov/STAR/starnotes/public/sn0619
BES-II whitepaper: http://drupal.star.bnl.gov/STAR/starnotes/public/sn0598

Larger rapidity acceptance crucial for further critical point search with net-protons

- Electron cooling upgrade will provide increased luminosity ~ 3-10 times.
- Inner TPC(iTPC) upgrade : $|\eta| < 1$ to $|\eta| < 1.5$. Better dE/dx resolution.
- Forward Event Plane Detector (EPD): Centrality and Event Plane Determination. $1.8 < |\eta| < 4.5$

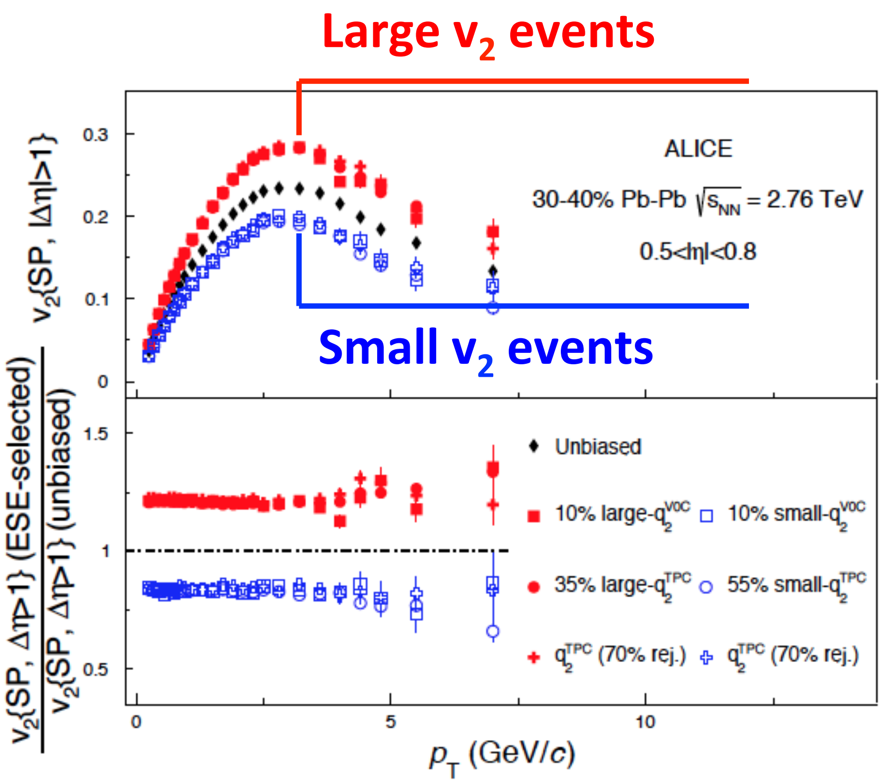
End Cap MRPC-TOF from Fair-CBM (fixed target and coll. modes)

Xiaofeng Luo   CiRfSE workshop, Jan. 19, 2016 @ Tsukuba University.   38 / 40

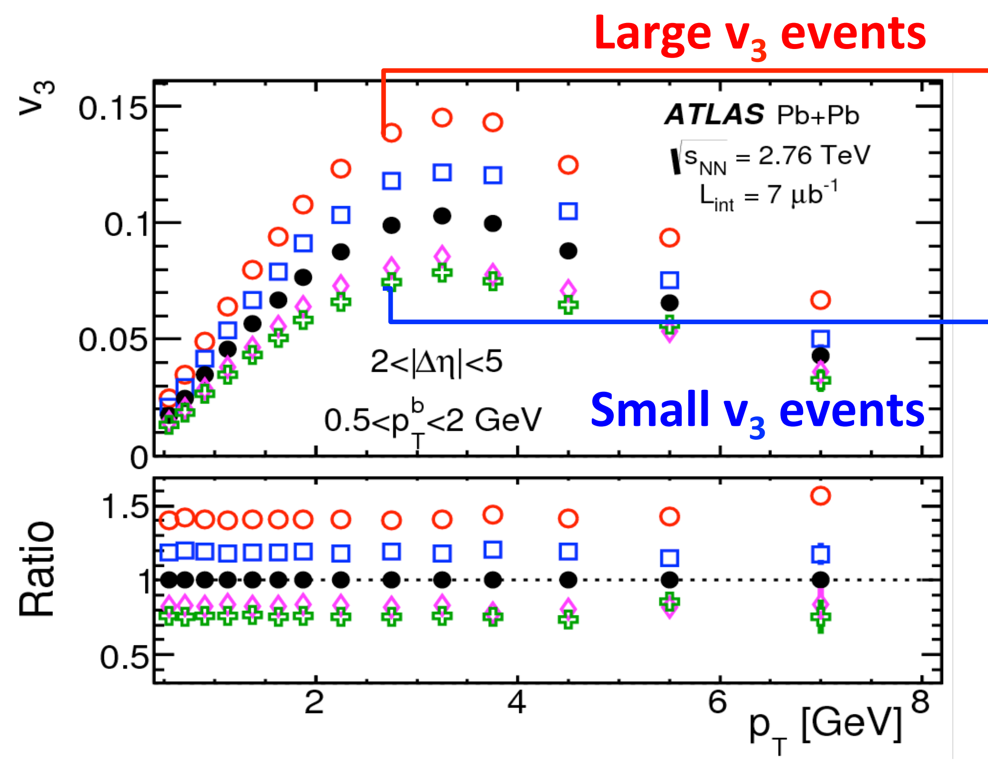
2^{nd} half starts here, on flow and correlation studies including small systems…

Event Shape Engineering (ESE), Event Shape Selection

--- for a given centrality ---



PRC93 (2016) 034916



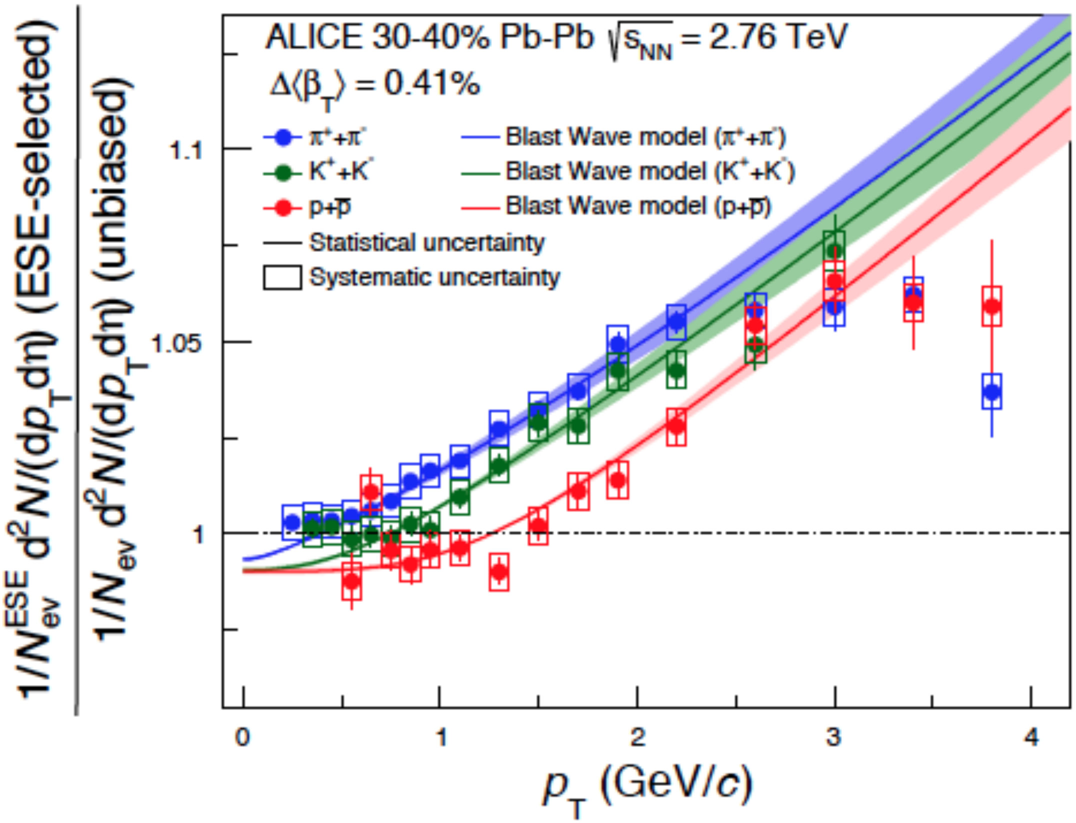
PRC92 (2015) 034903

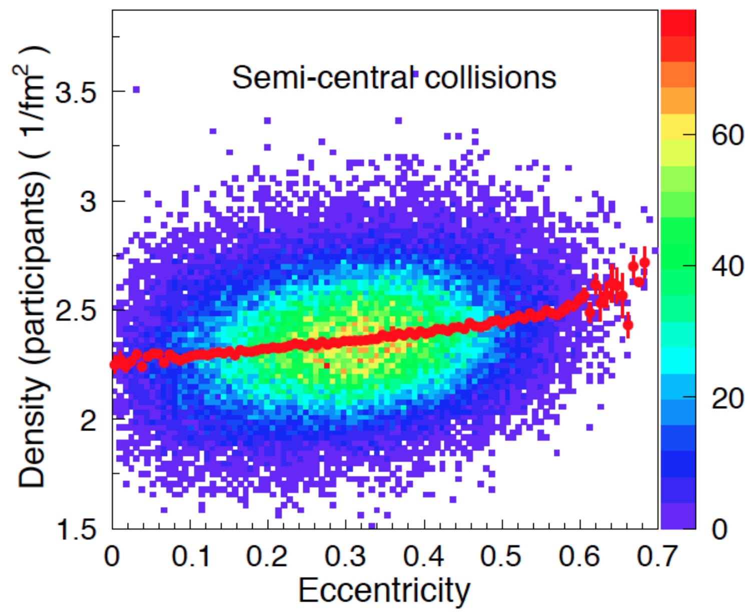
flat p_T dependence -> indicative for an initial geometry

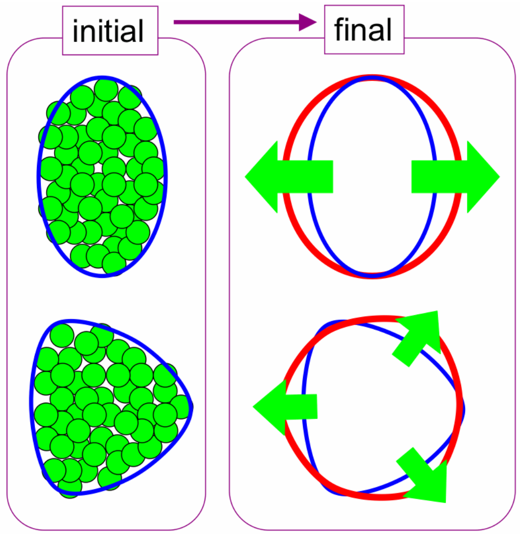
Applications of ESE

- correlation between radial (β_T) and elliptic (v_2) flows
- correlation between HBT eccentricity (ε_2^{final}) and v_2
- correlation between di-jet w.r.t. Φ_2 and v_2

PRC93 (2016) 034916

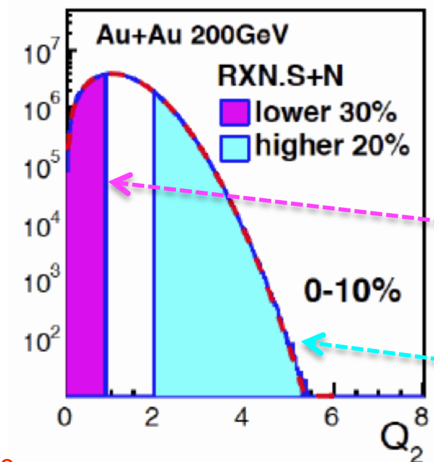


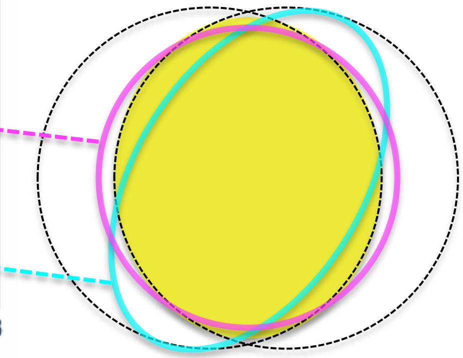




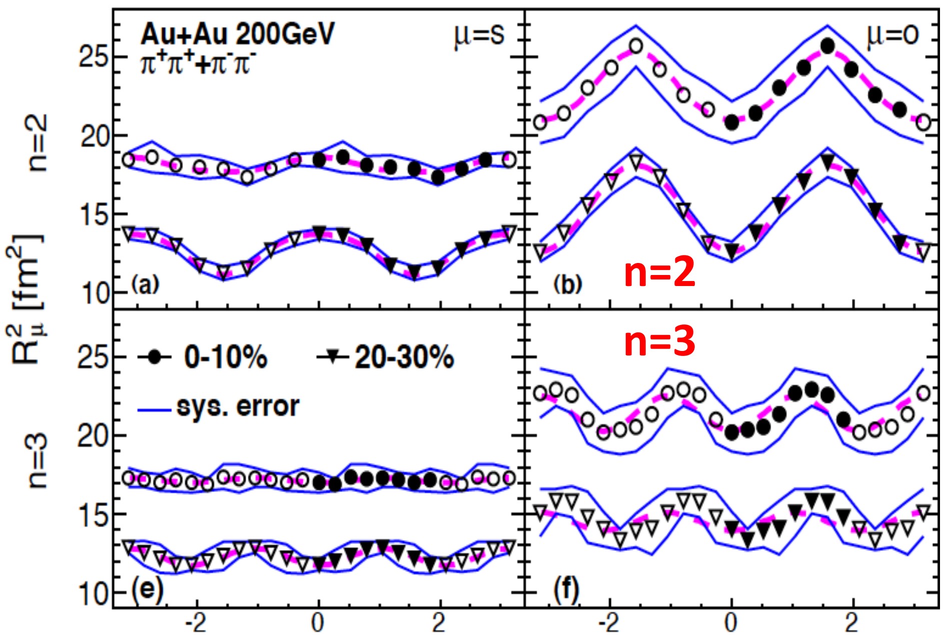
ESE application to HBT

relation : $\varepsilon_2^{initial} - v_2 - \varepsilon_2^{final}$



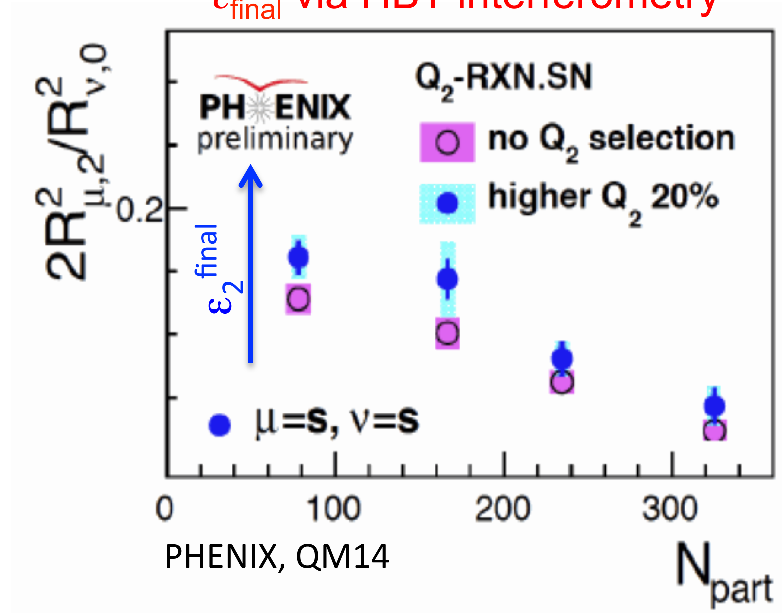


Elliptic and Triangular shape : $R^{HBT}_{\Phi 2}$, $R^{HBT}_{\Phi 3}$



PRL112 (2014) 222301

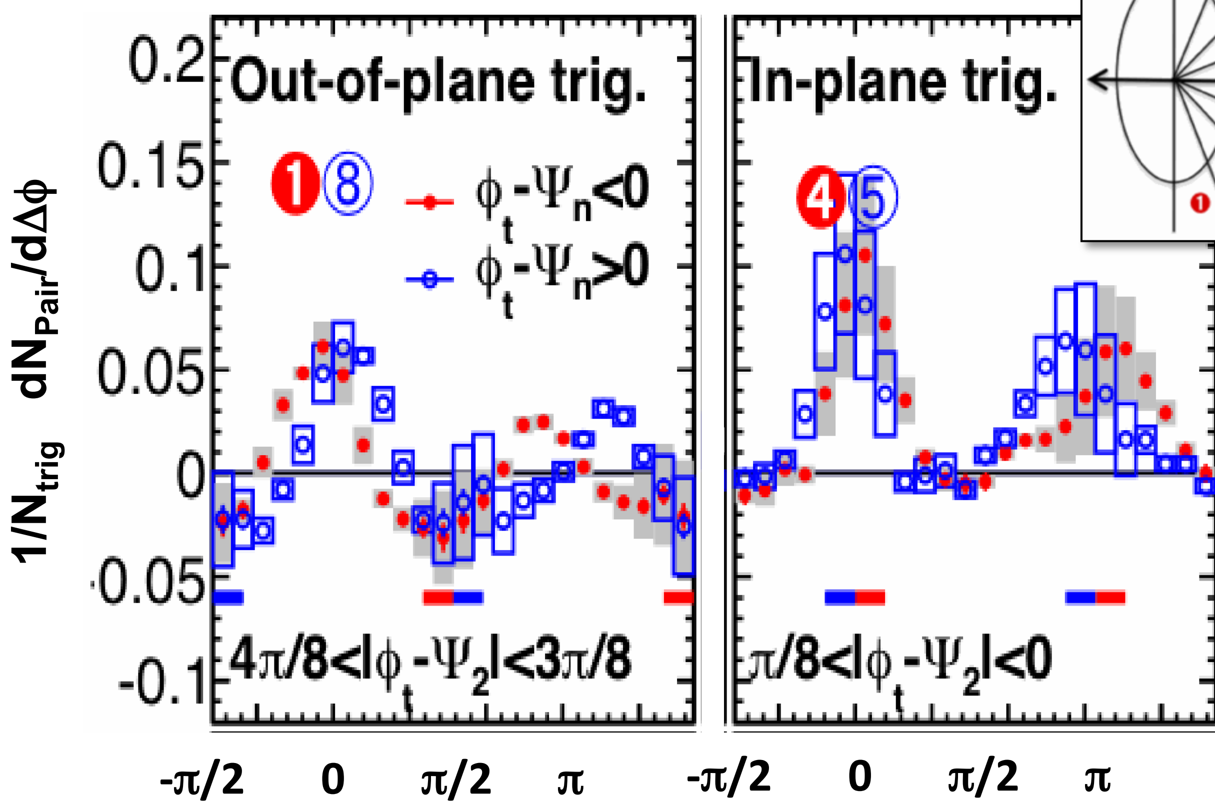
ε_{final} via HBT interferometry

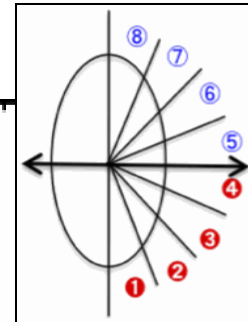


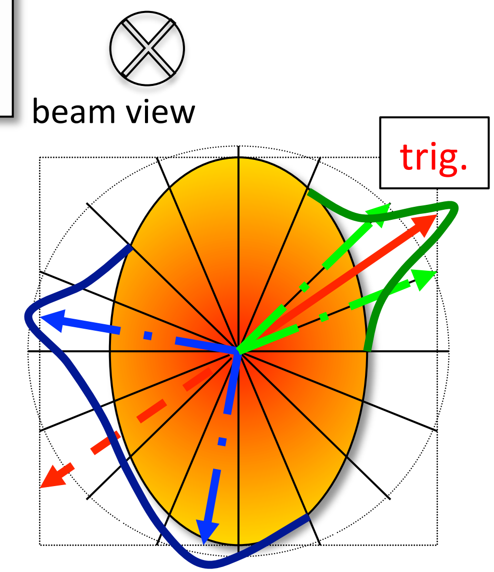
PHENIX, QM14

Possible application (on going) of ESE
Shape and flow relation to the jet modification

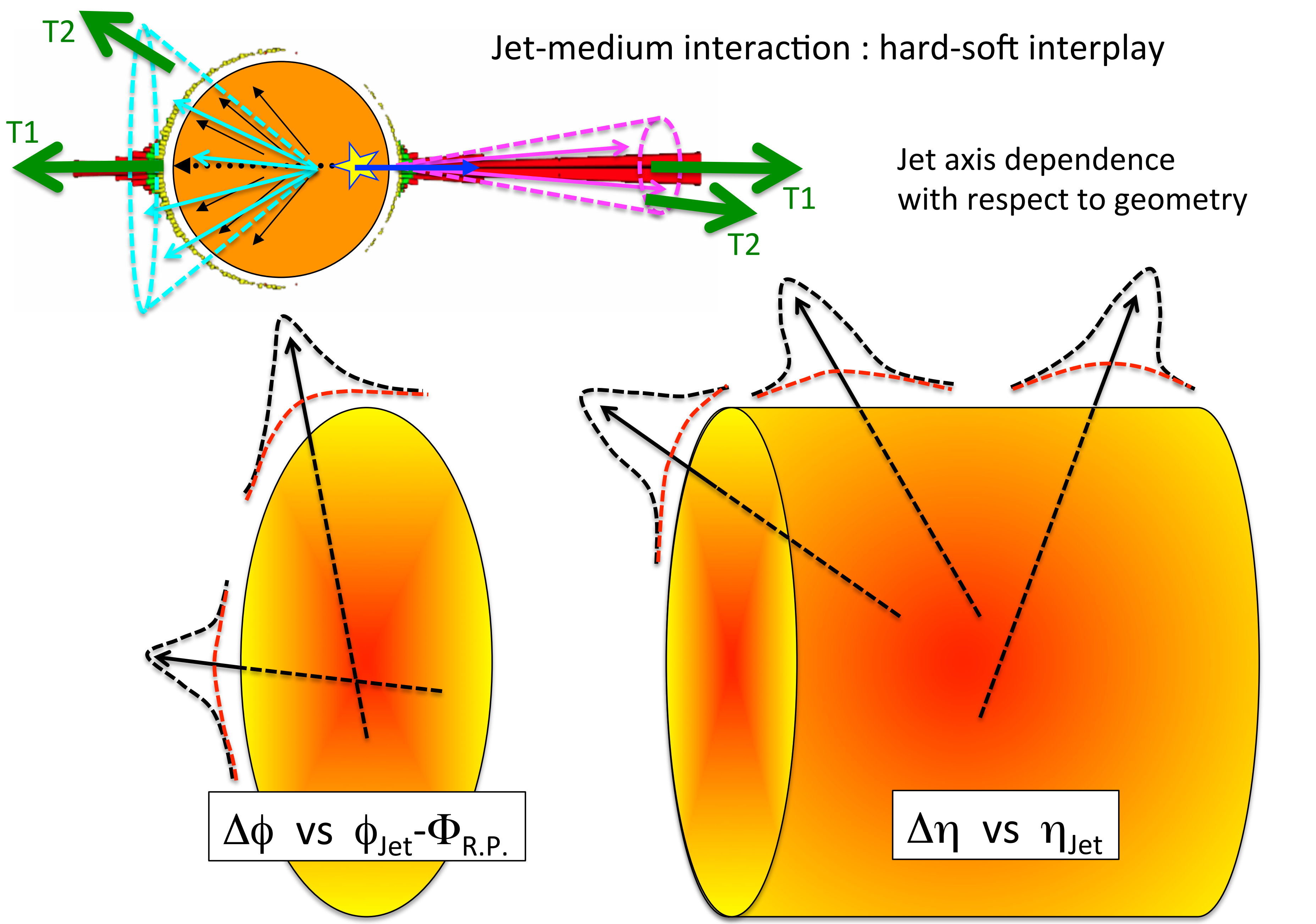
PHENIX preliminary







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

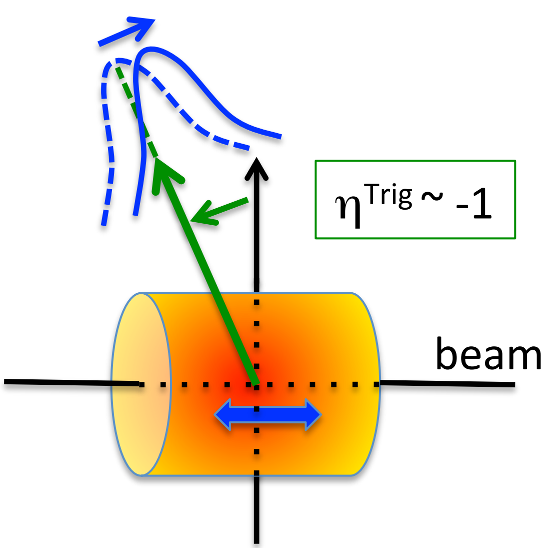


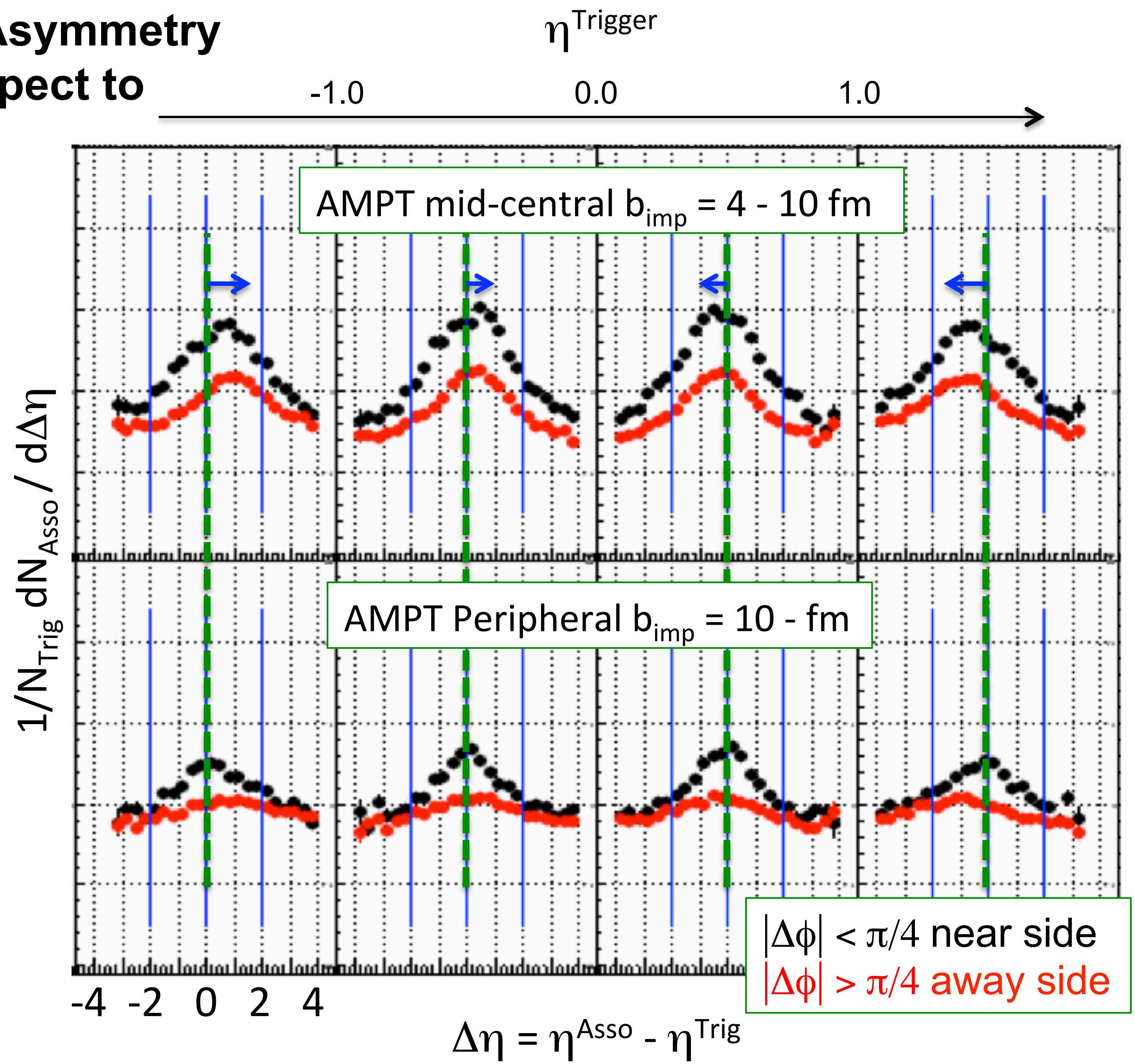
T2
T1
T1
T2
Jet-medium interaction : hard-soft interplay
Jet axis dependence
with respect to geometry
$\Delta\phi$ vs ϕ_{Jet}-$\Phi_{R.P.}$
$\Delta\eta$ vs η_{Jet}

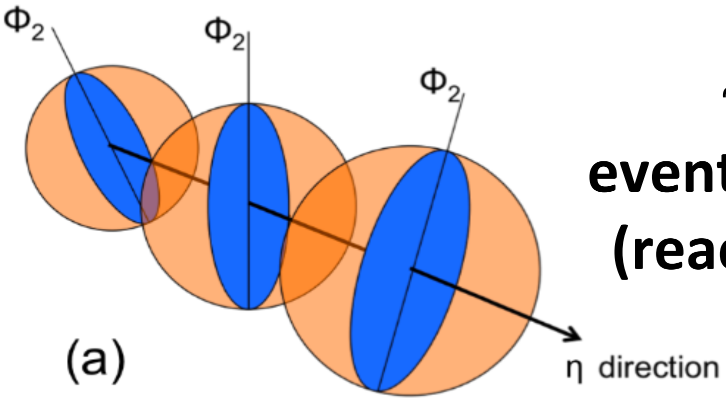
Forward-Backward Asymmetry in $\Delta\eta$ Shape with respect to Trigger η

(associate yield per trigger with AMPT simulation)

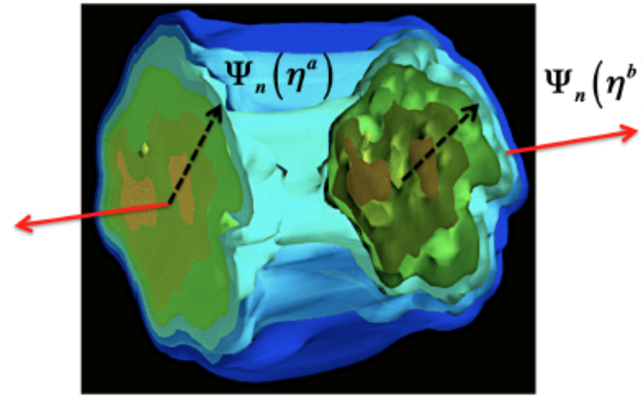
Forward-backward asymmetry is visible in AMPT simulation. Near side $\Delta\eta$ peak is backward shifted w.r.t. trigger η direction.





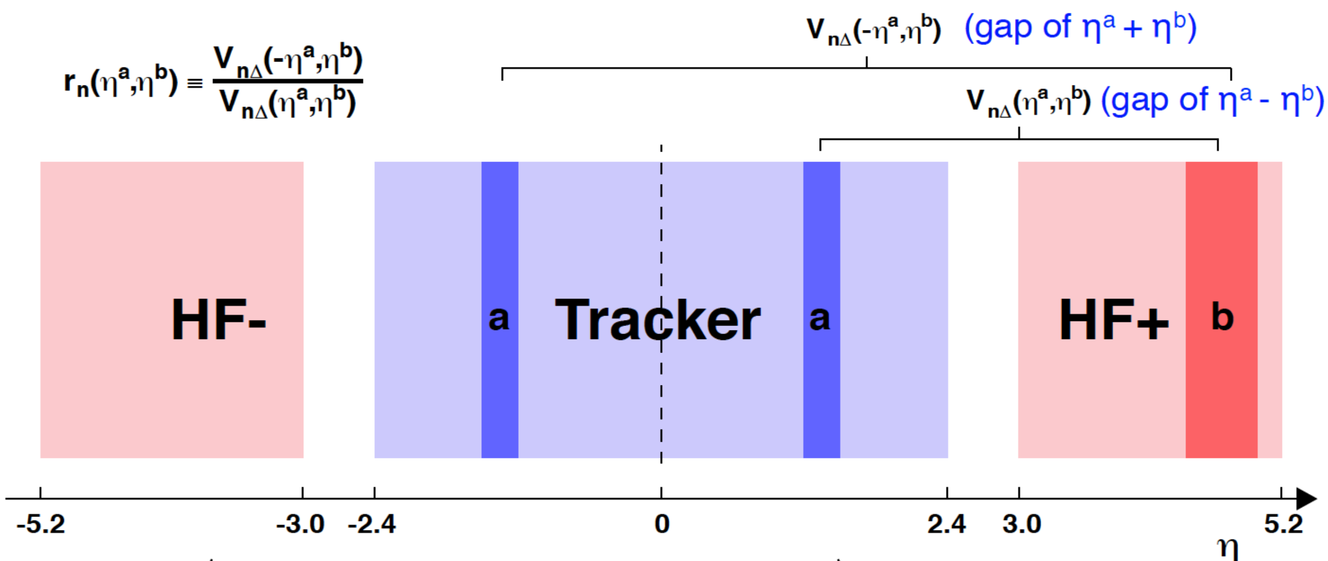


η dependent event plane fluctuation (reaction plane twist)



$$v_{n\Delta}(\eta^a,\eta^b)=\left\langle v_n(\eta^a)v_n(\eta^b)\right\rangle \rightarrow v_{n\Delta}(\eta^a,\eta^b)=\left\langle v_n(\eta^a)v_n(\eta^b)\cos\left(n\Psi_n(\eta^a)-n\Psi_n(\eta^a)\right)\right\rangle$$

$$r_n(\eta^a,\eta^b)\equiv\frac{V_{n\Delta}(-\eta^a,\eta^b)}{V_{n\Delta}(\eta^a,\eta^b)}$$

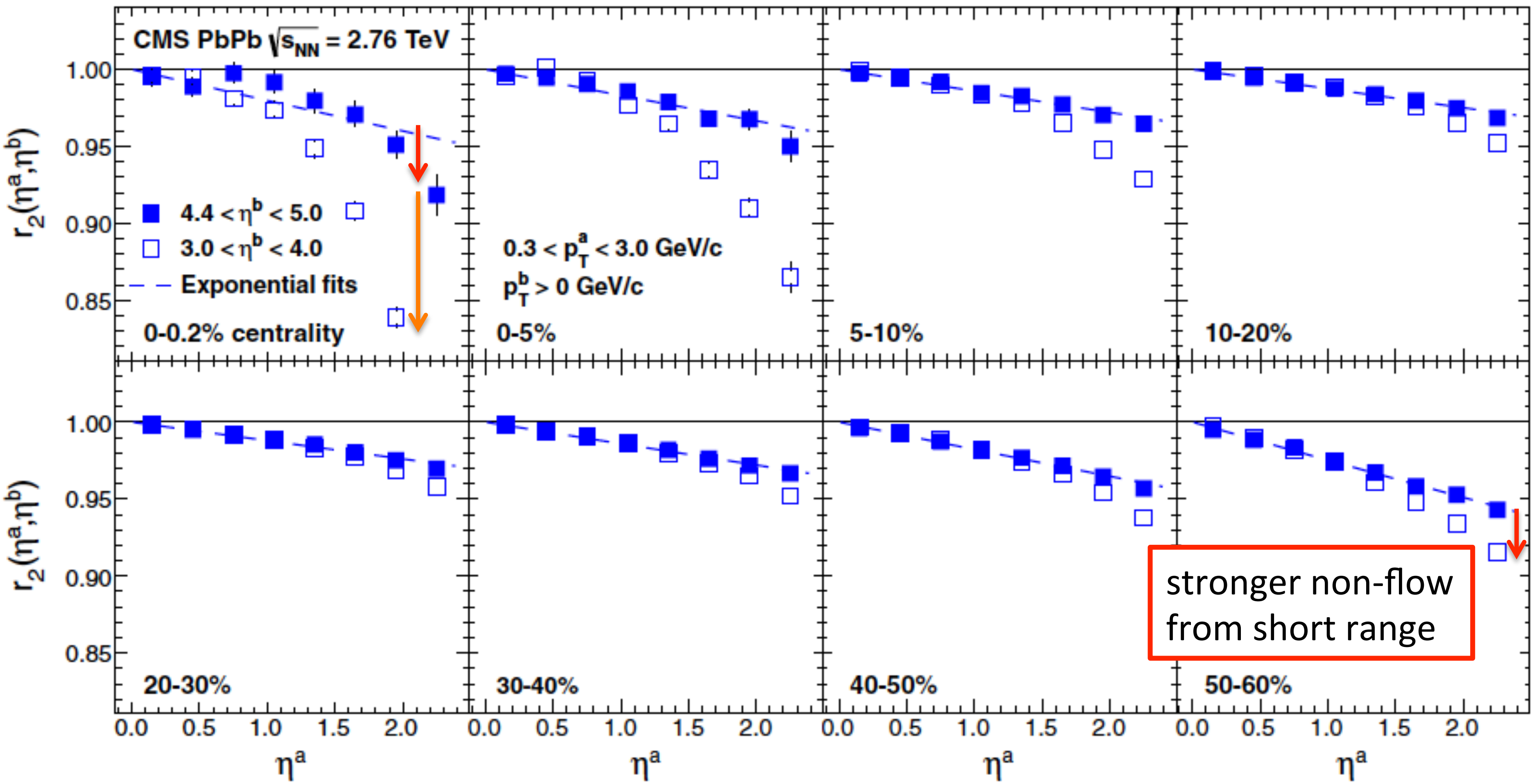


$$r_n(\eta^a,\eta^b)=\frac{\left\langle v_n(-\eta^a)v_n(\eta^b)\cos[n(\Psi_n(-\eta^a)-\Psi_n(\eta^b))]\right\rangle}{\left\langle v_n(\eta^a)v_n(\eta^b)\cos[n(\Psi_n(\eta^a)-\Psi_n(\eta^b))]\right\rangle}\sim\left\langle\cos[n(\Psi_n(\eta^a)-\Psi_n(-\eta^a))]\right\rangle$$

CMS, QM15

Stronger de-correlation of E.P. with η-gap

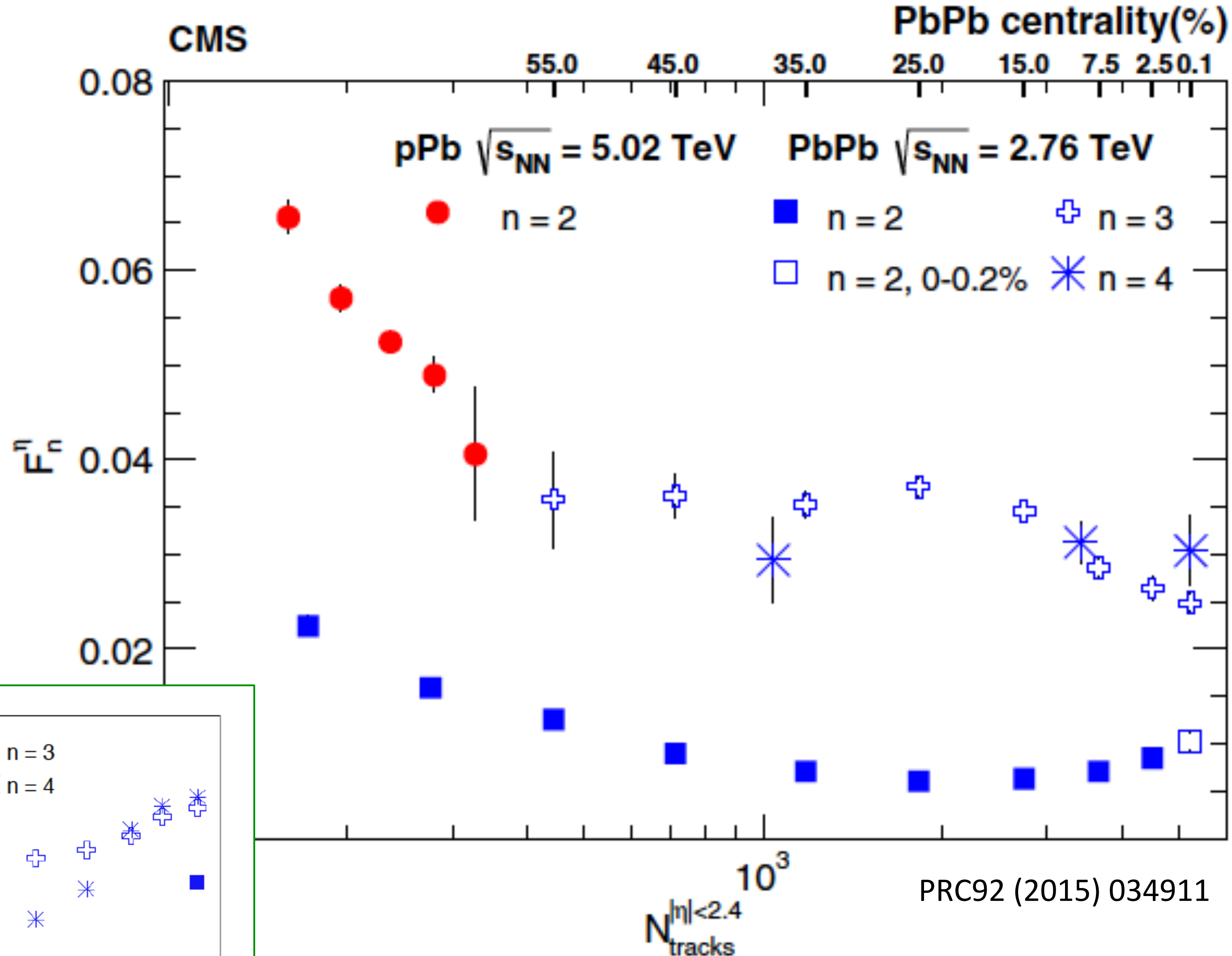
PRC92 (2015) 034911



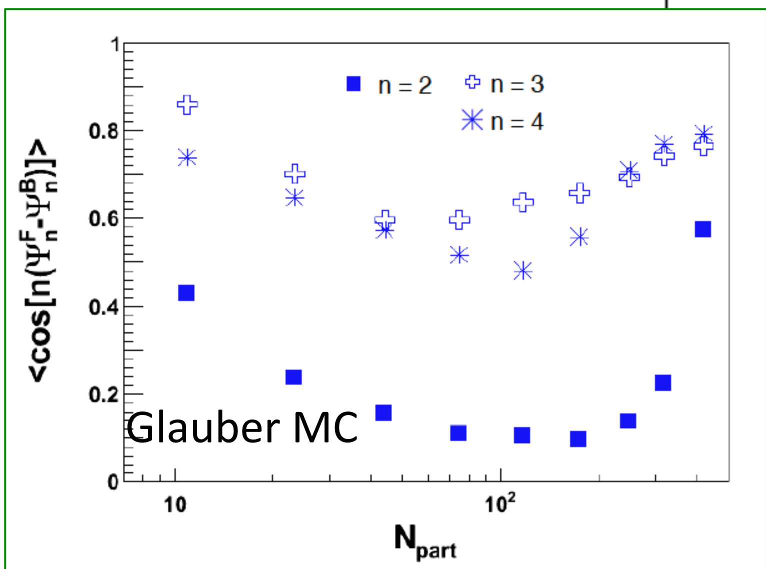
$$r_n(\eta^a, \eta^b) = e^{-2F_n^\eta \eta^a} \sim 1 - 2F_n^\eta \eta^a$$

extract : F_n^η

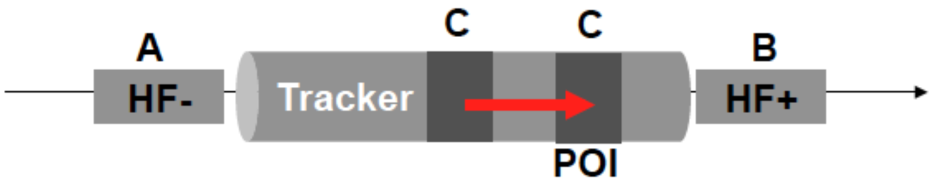
Extracted F_n^{η} Parameter



PRC92 (2015) 034911



η dependence of v_n or de-correlation of E.P.



➢ Decorrelation effects [arXiv:1503.01692]

$$\cos\left[2\left\{\Psi_n(\eta_1)-\Psi_n(\eta_2)\right\}\right]=e^{-F_n^{\eta}|\eta_1-\eta_2|}$$

POI :
particle of interest

2-par correlation 3-sub method gives vn at A/B, or look at resolution of A/B, that would vary with C location…

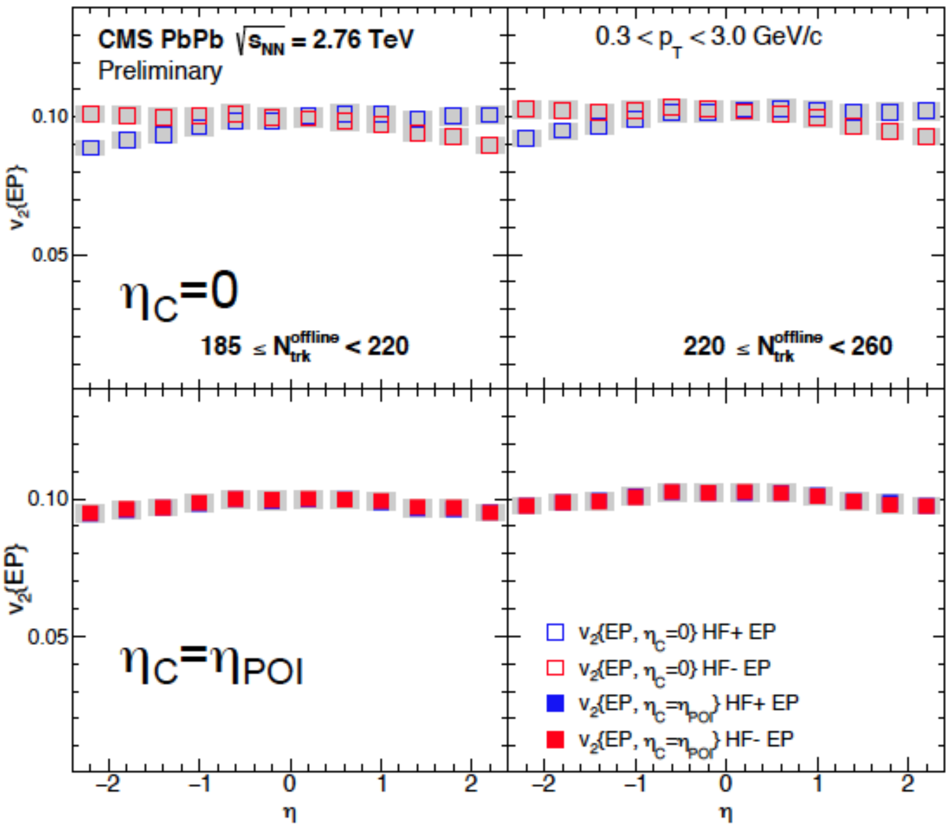
$(\eta_C=0)$

$$R_A(\eta_{POI})=\sqrt{\frac{\left\langle\cos[n(\Psi_n^A-\Psi_n^B)]\right\rangle\left\langle\cos[n(\Psi_n^A-\Psi_n^C)]\right\rangle}{\left\langle\cos[n(\Psi_n^B-\Psi_n^C)]\right\rangle}}$$

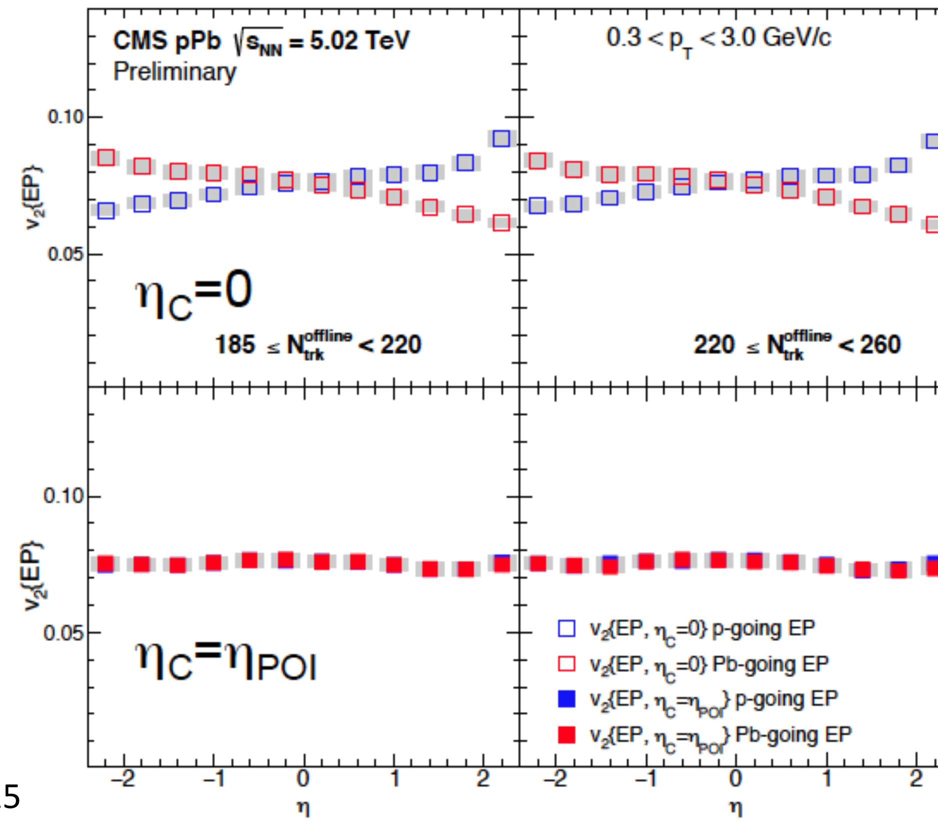
$(\eta_C=\eta_{POI})$

CMS, QM15

Pb+Pb

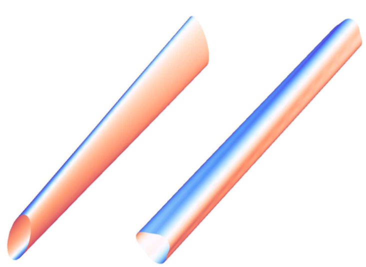


p+Pb



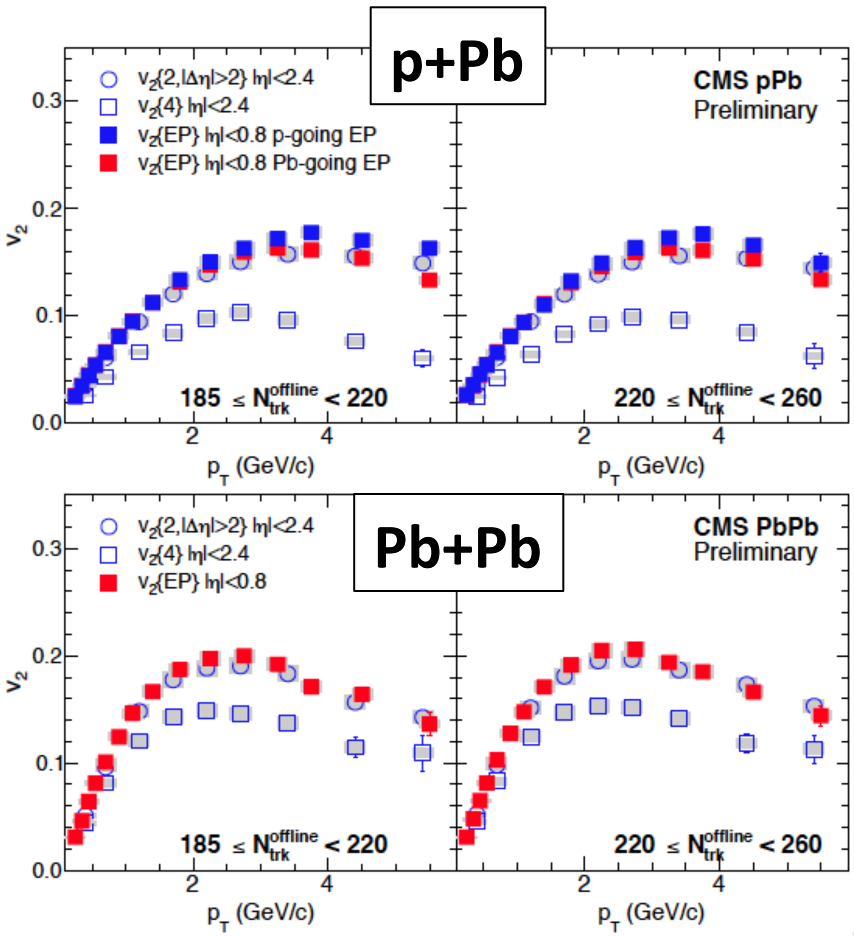
CMS, QM15

Torqued fireball



Bozek et.al., arXiv:1011.3354

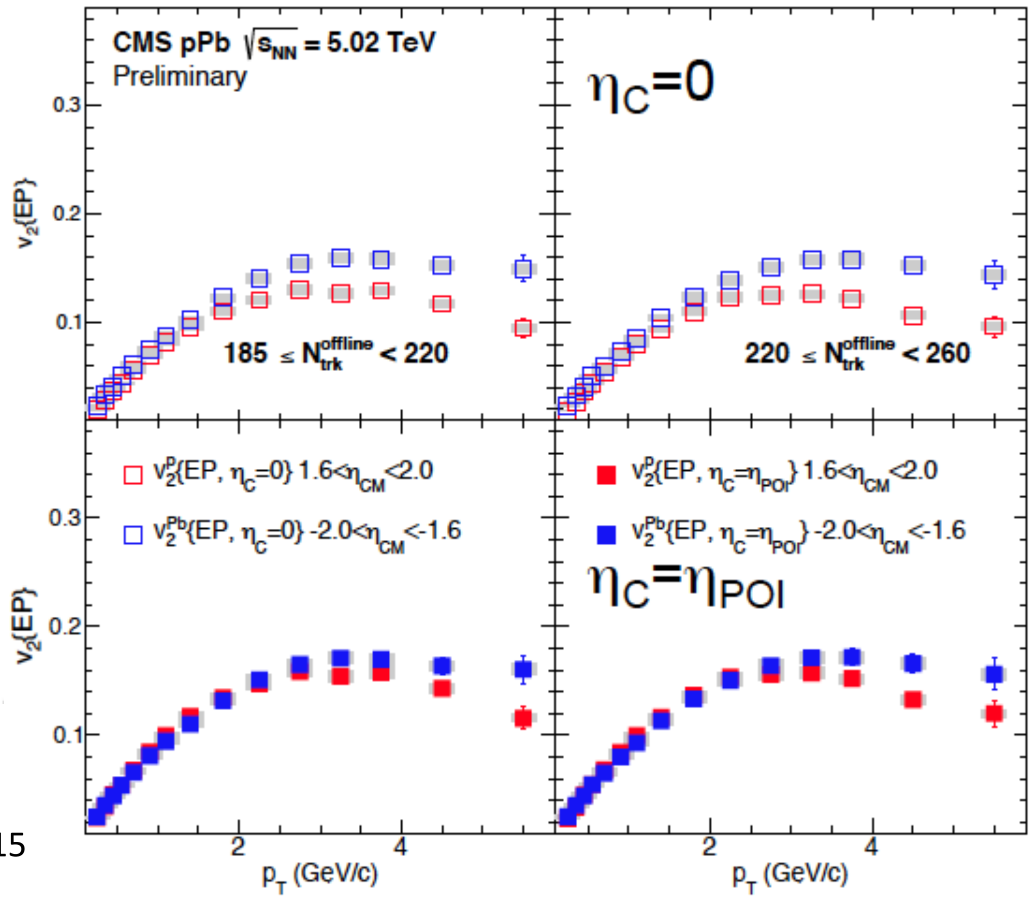
$v_2^{(|\eta|<0.8)}$

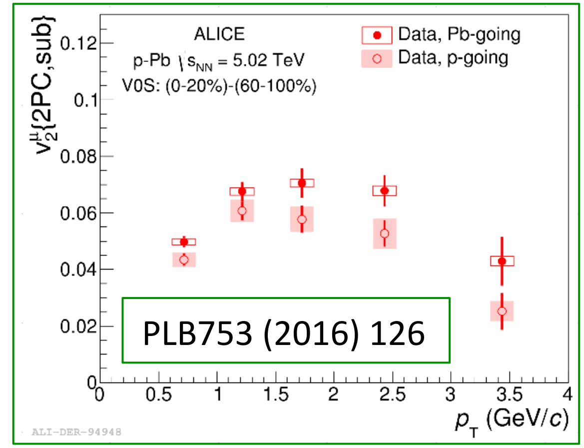


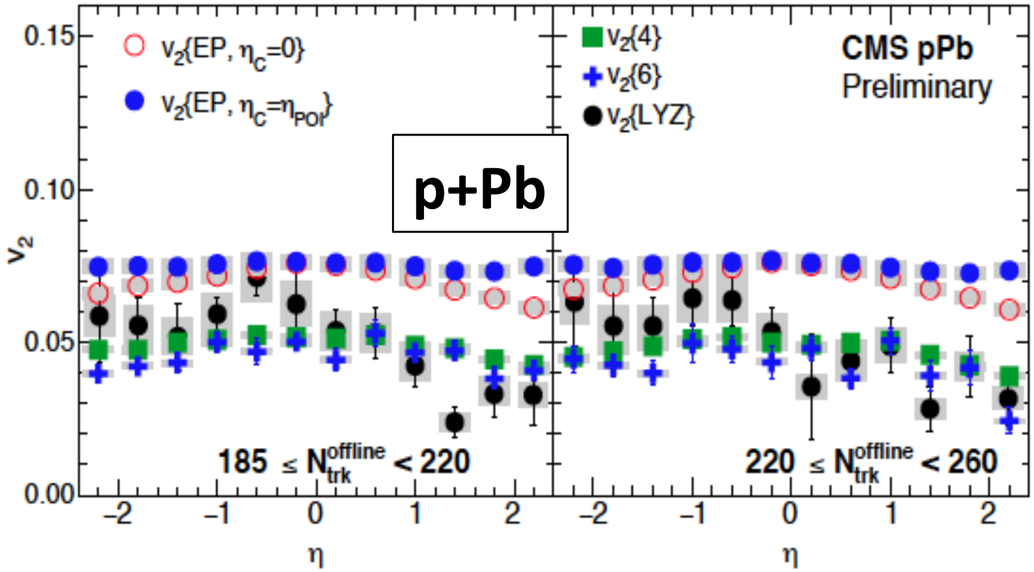
CMS, QM15

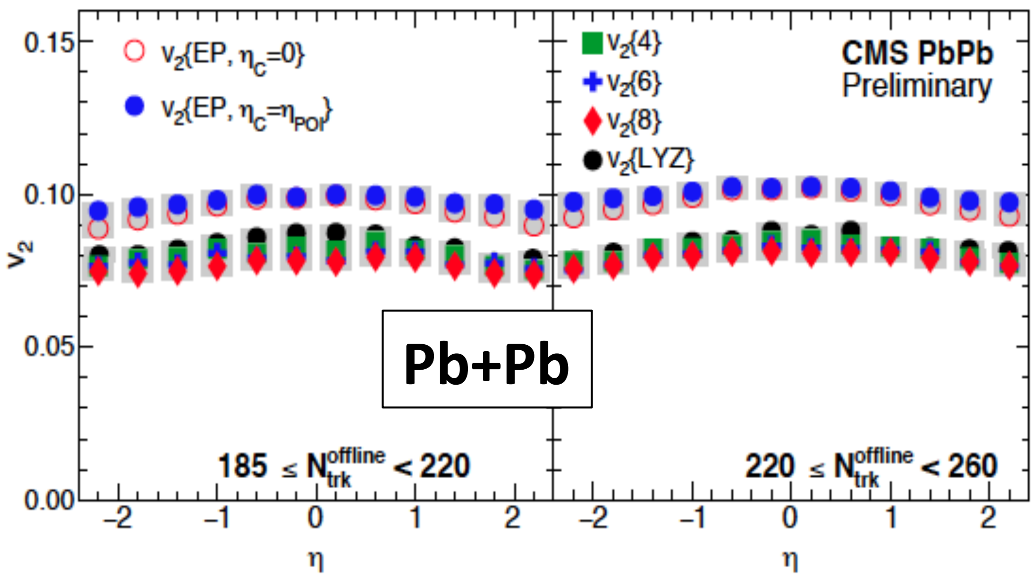
p+Pb

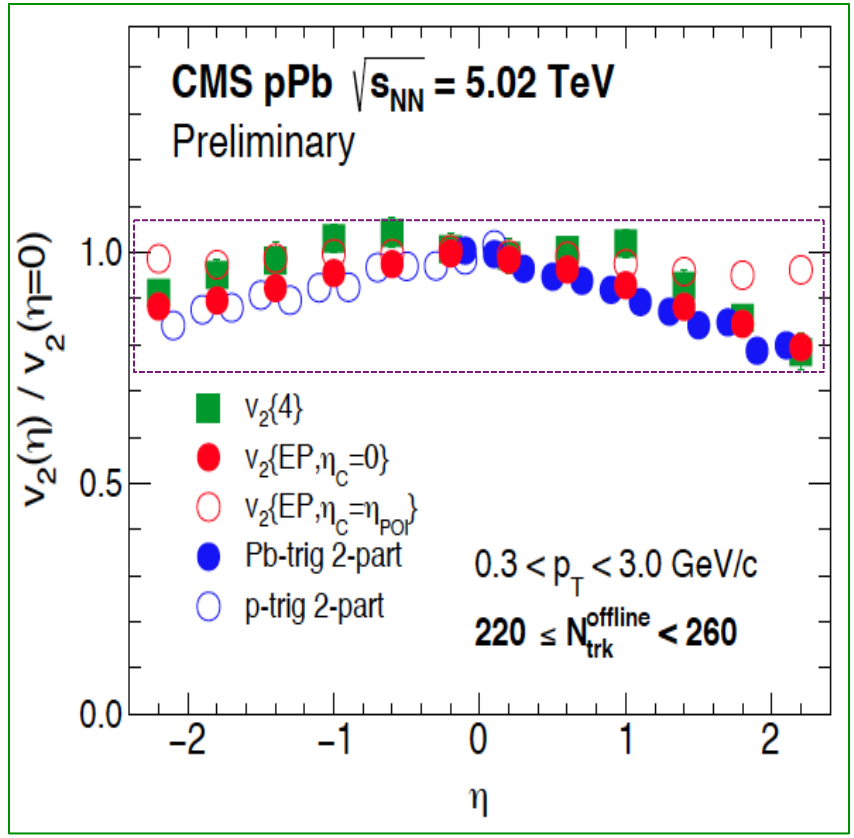
$v_2^{(1.6<|\eta|<2.0)}$







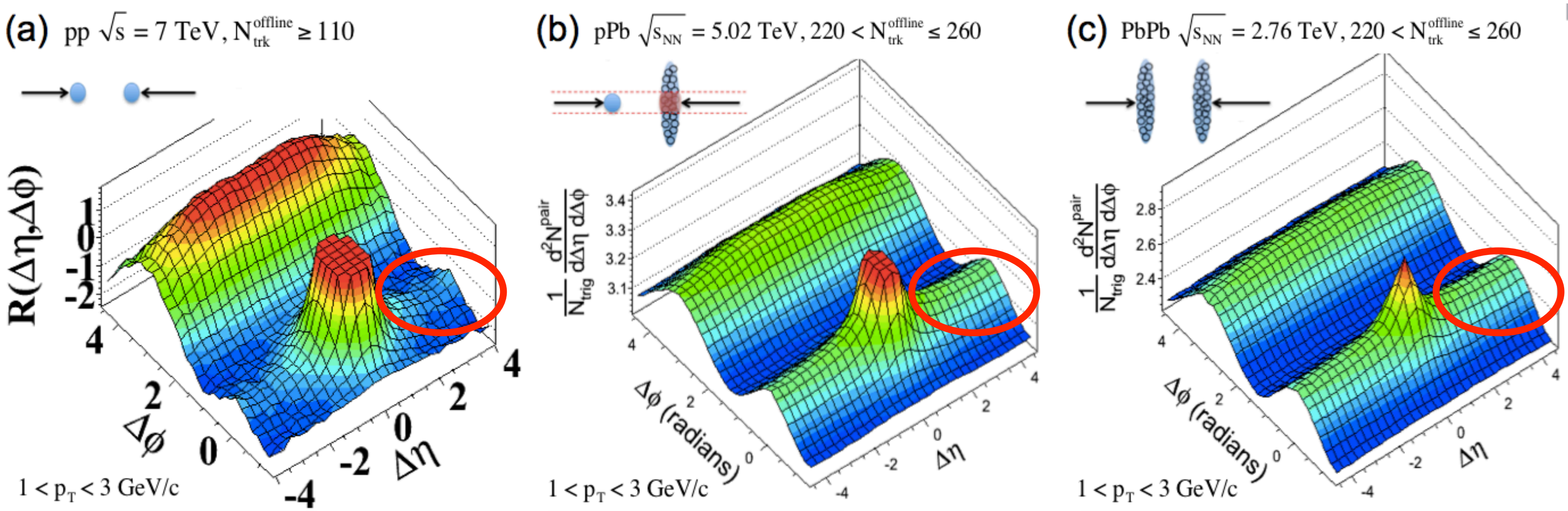




η dependence of v_2

CMS, QM15

Ridge/v_n (collective expansion?) in pp$^{(\text{high mult.})}$, pA, AA at LHC

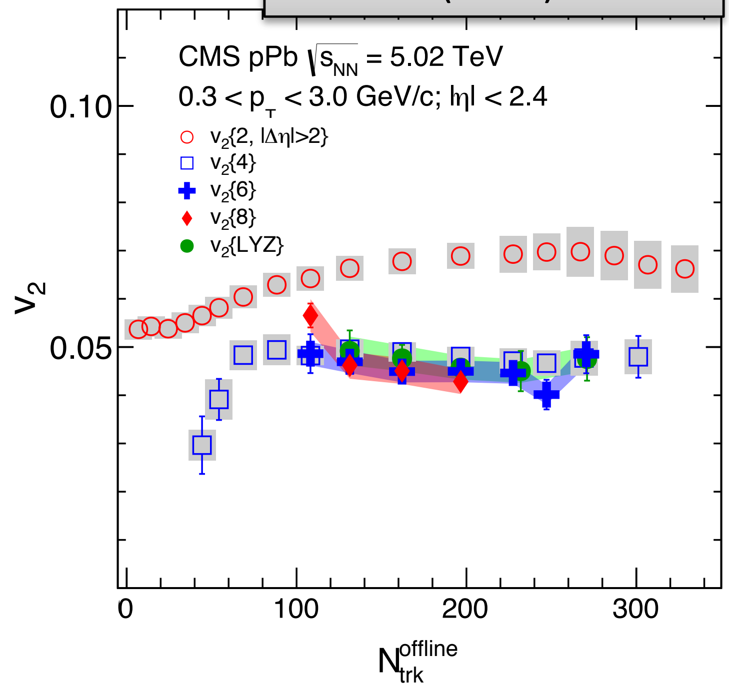


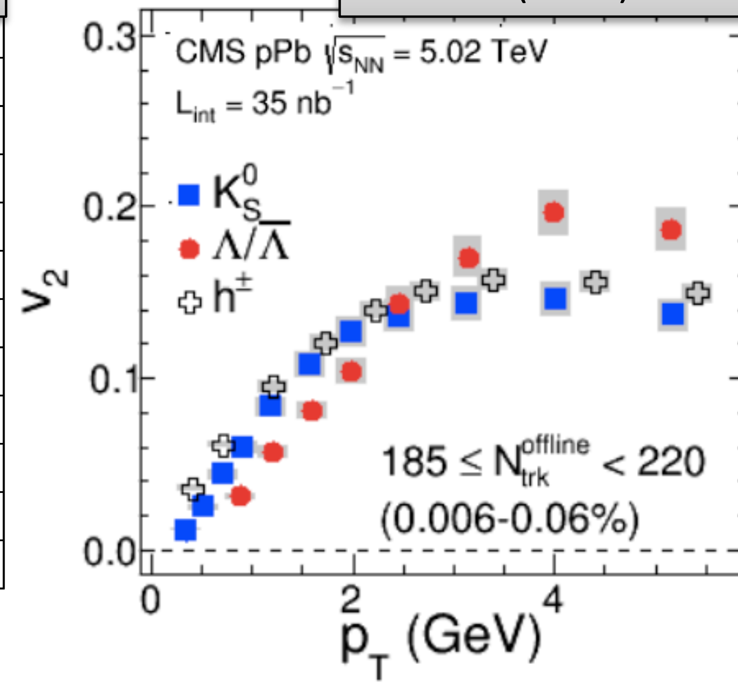
JHEP 09 (2010) 091

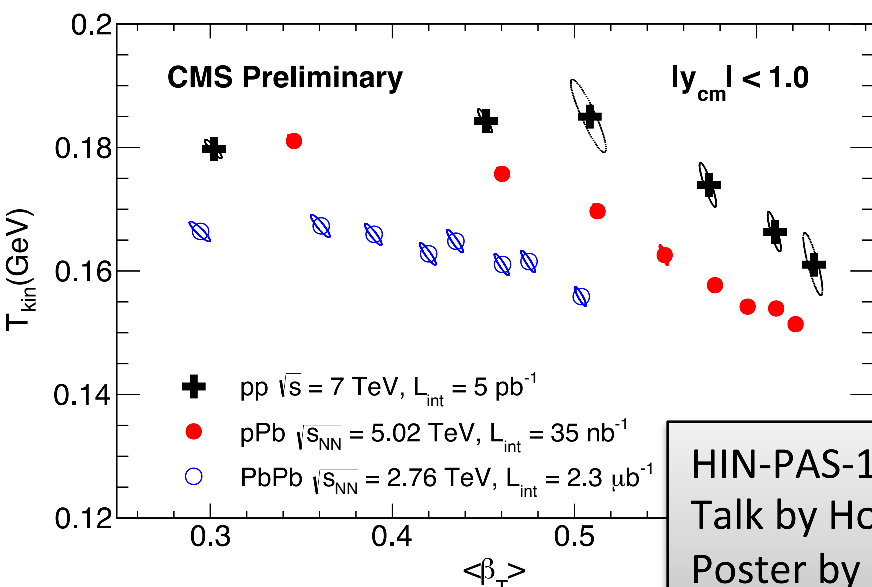
PLB 724 (2013) 213

PLB 724 (2013) 213

CMS, QM15





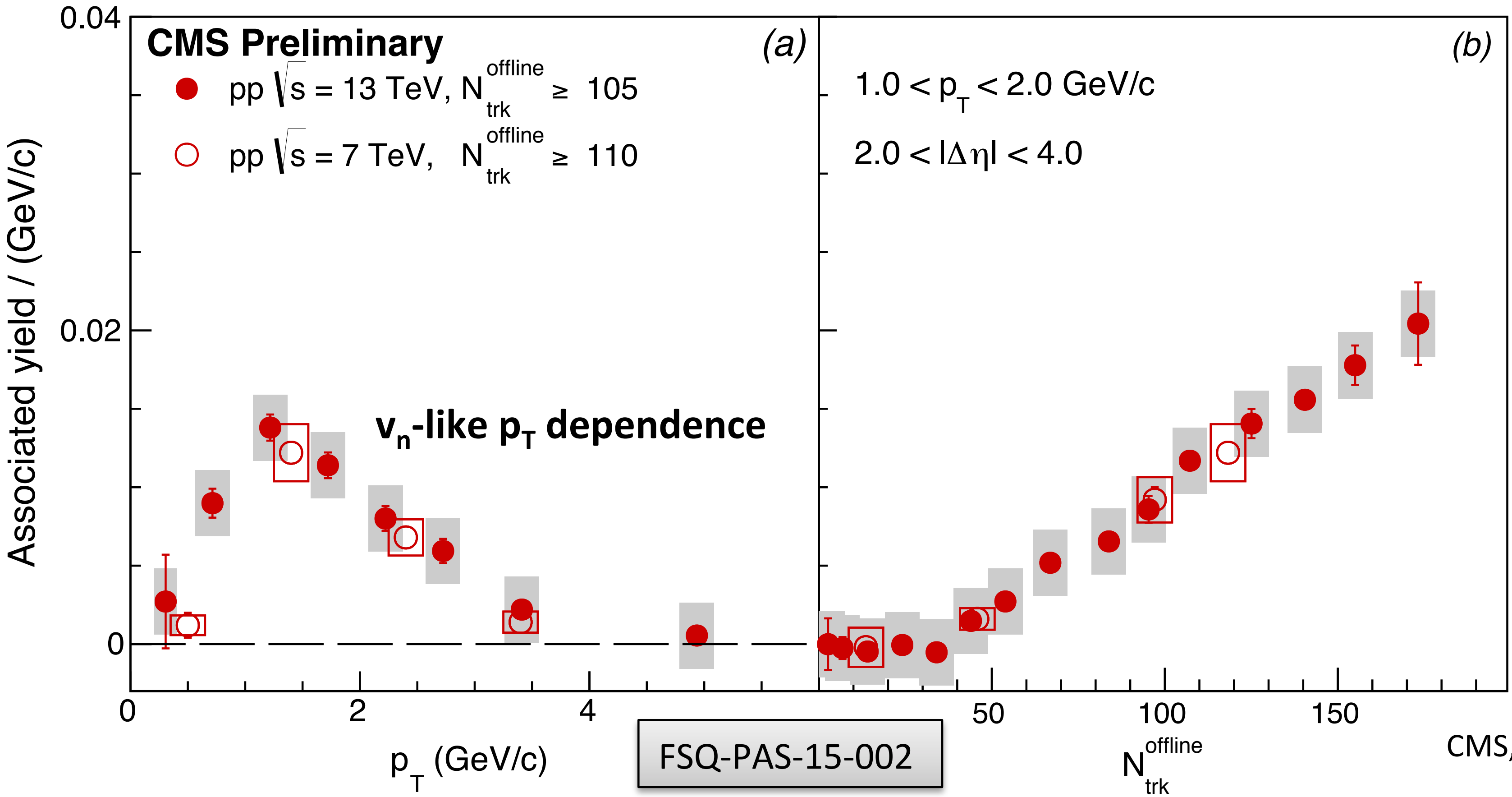


HIN-PAS-15-006
Talk by Hong Ni
Poster by Z. Tu (#0214)

3 Supporting Facts of Collective Expansion in pA at LHC

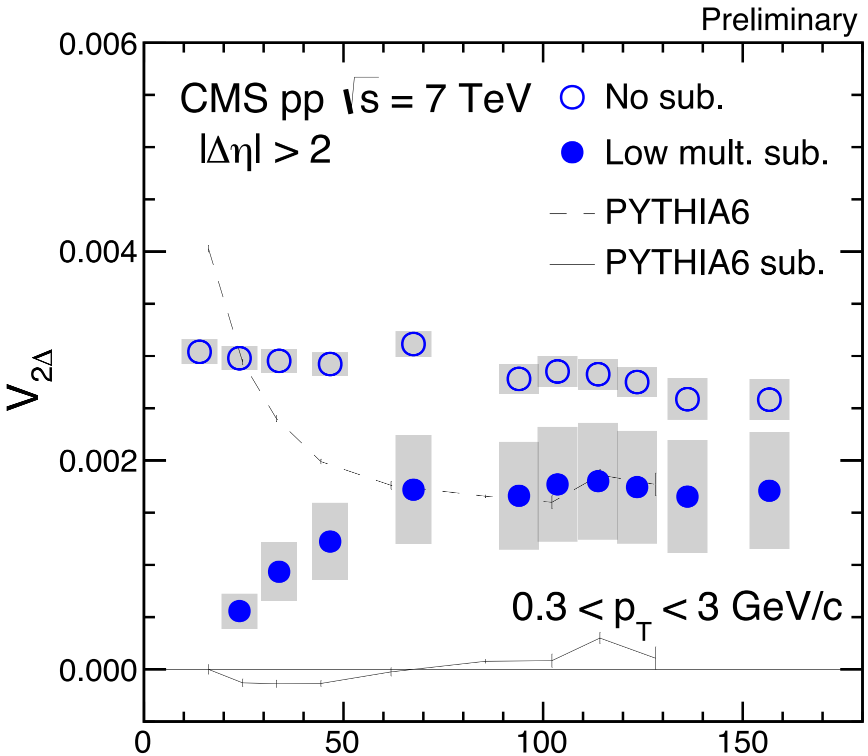
CMS, QM15

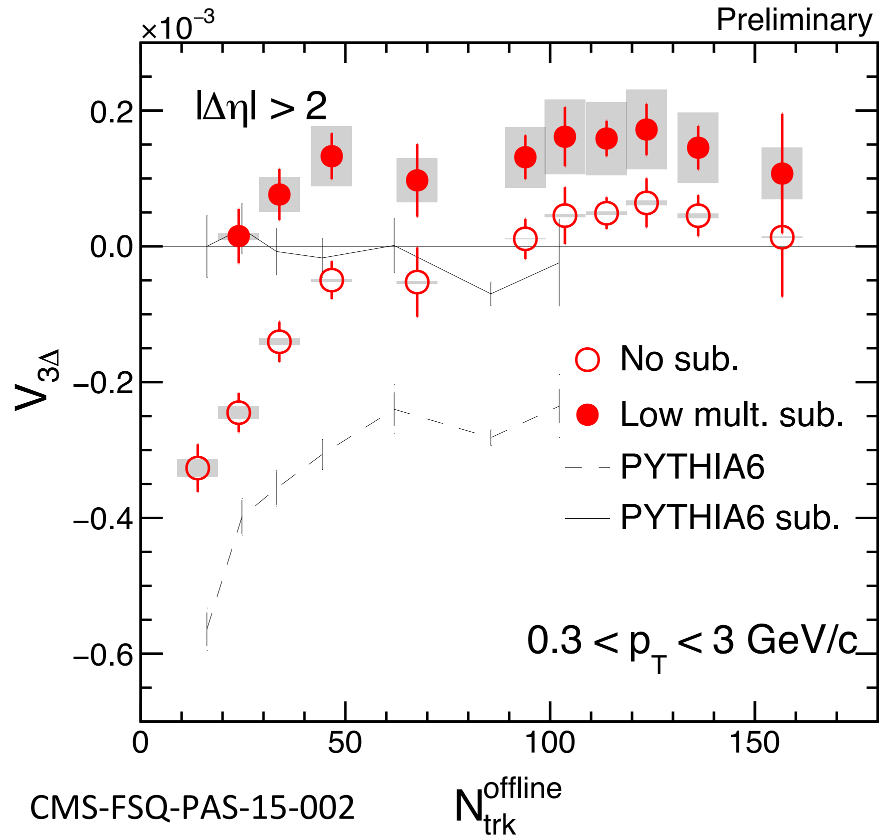
Ridge Yield vs (p_T, beam energy, multiplicity) in pp at LHC



FSQ-PAS-15-002

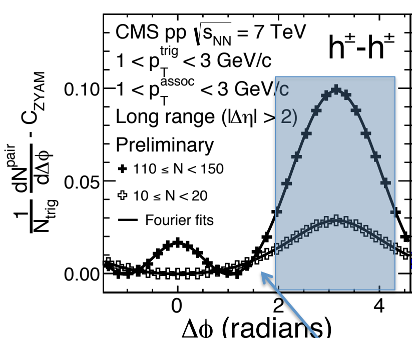
CMS, QM15

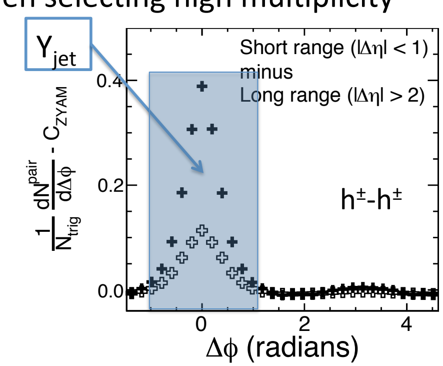




CMS-FSQ-PAS-15-002

- Bias to more jet contribution when selecting high multiplicity





- Calibrating the bias by near-side jet yield Y_{jet}, low multiplicity subtraction to remove jet contribution:

$$V_{n\Delta}^{sub} \times N_{assoc}^{high} = V_{n\Delta}^{high} \times N_{assoc}^{high} - V_{n\Delta}^{low} \times N_{assoc}^{low} \times \frac{Y_{jet}^{high}}{Y_{jet}^{low}}$$

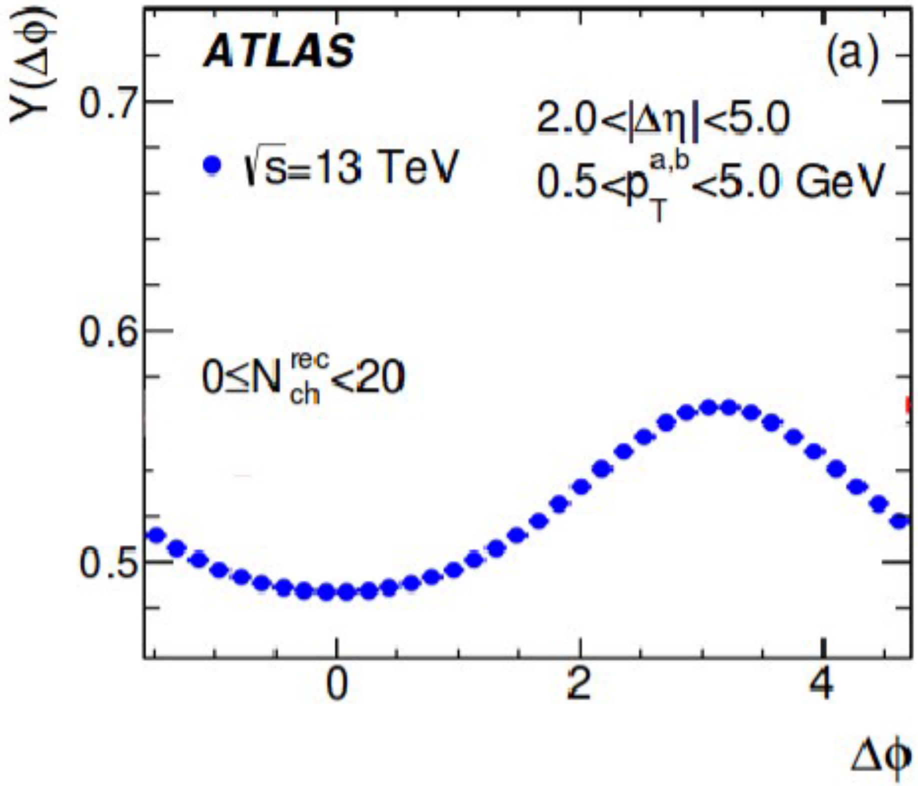
Multiplicity dependence of v_n with/without low mult. subtraction

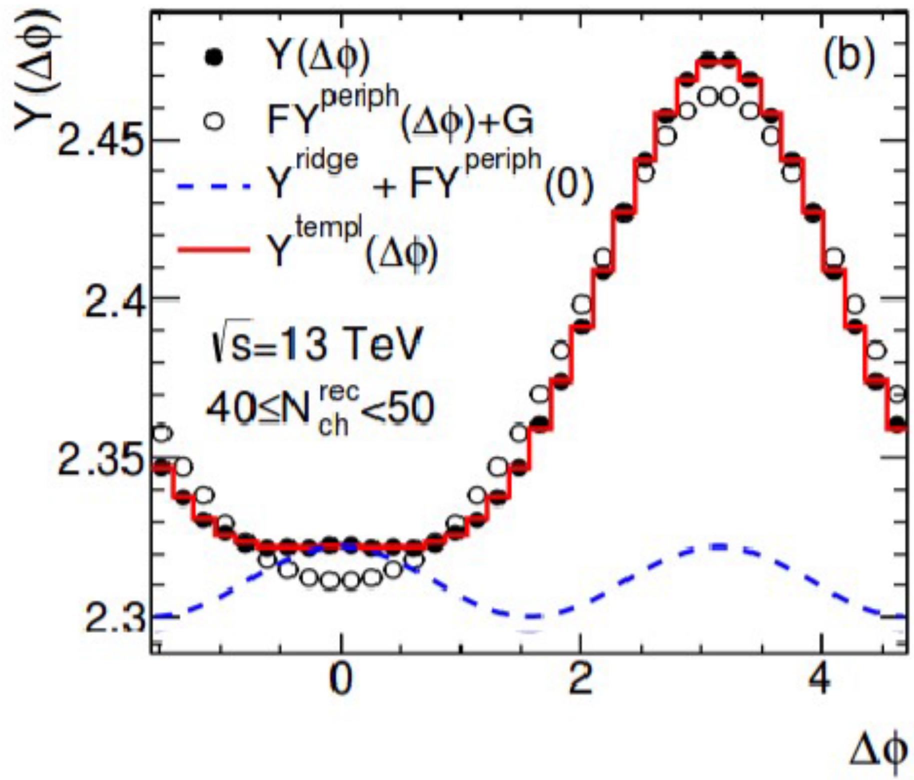
--- comparison with pythia6 M.C. ---

CMS, QM15

ATLAS ways of pp analysis

arXiv:1509.04776
PRL116 (2016) 172301





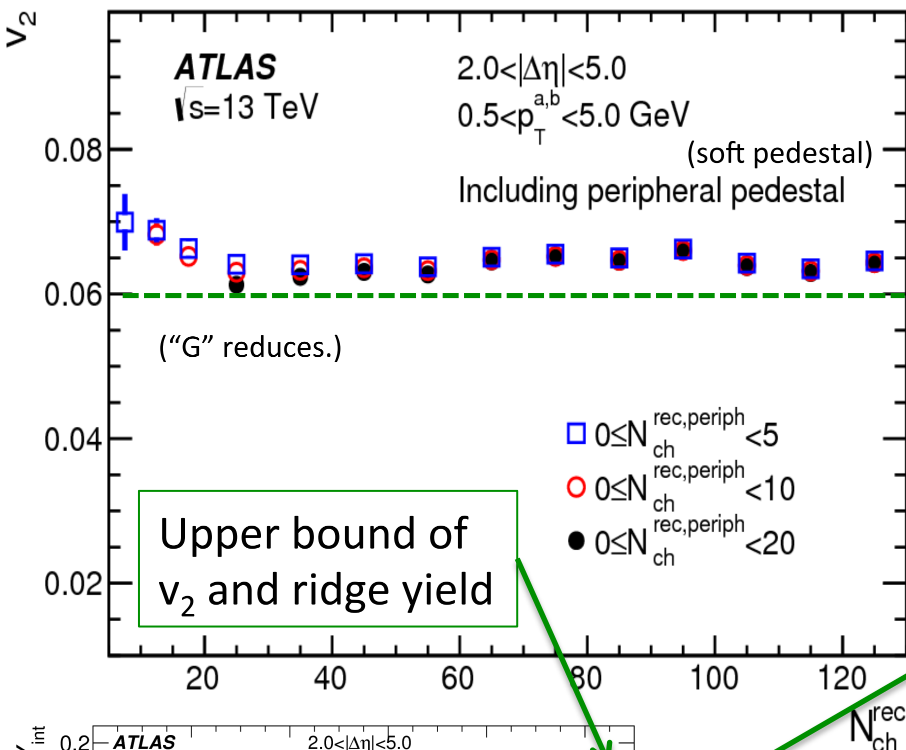
Template fitting

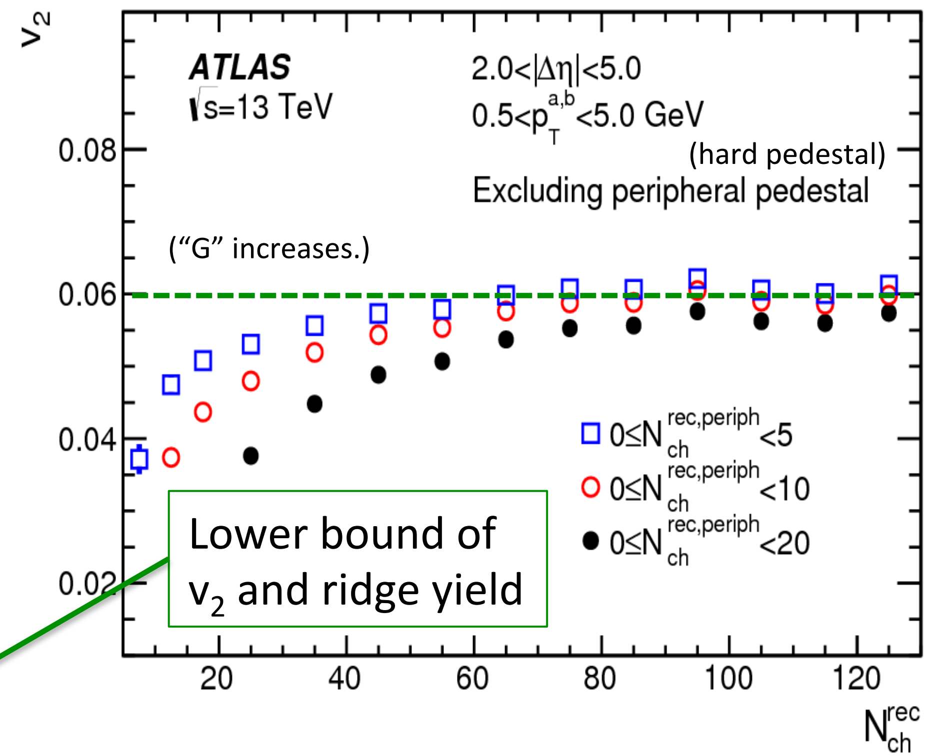
$$Y^{\text{templ}}(\Delta\phi) = FY^{\text{periph}}(\Delta\phi) + Y^{\text{ridge}}(\Delta\phi),$$

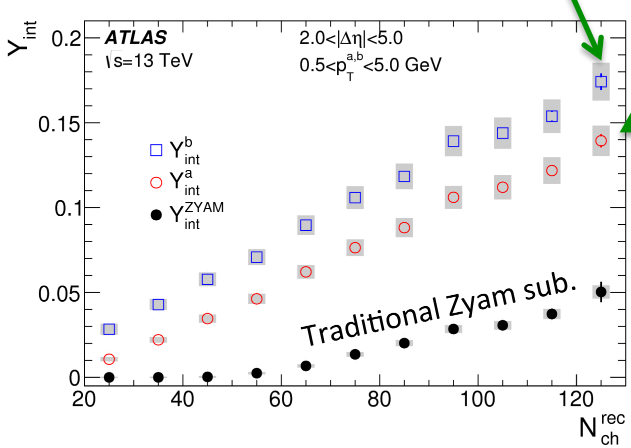
$$Y^{\text{ridge}}(\Delta\phi) = G[1 + 2v_{2,2}\cos(2\Delta\phi)],$$

$$Y^{\text{periph}}(\Delta\phi) = Y^{\text{hard}}(\Delta\phi) + G_0[1 + 2v_{2,2}^{0}\cos(2\Delta\phi)],$$

arXiv:1509.04776
PRL116 (2016) 172301, +supplementary material
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/HION-2015-09/



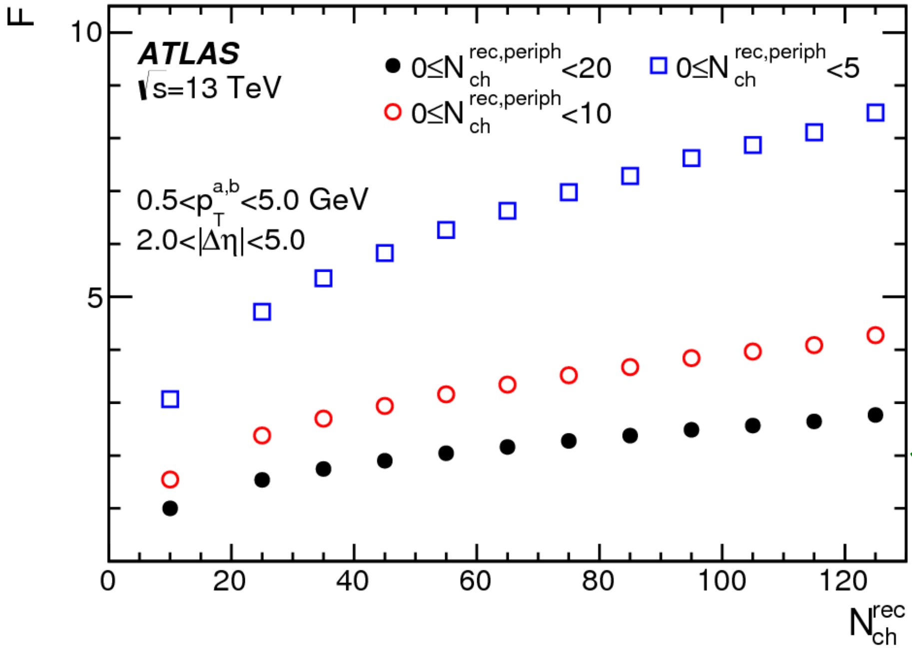


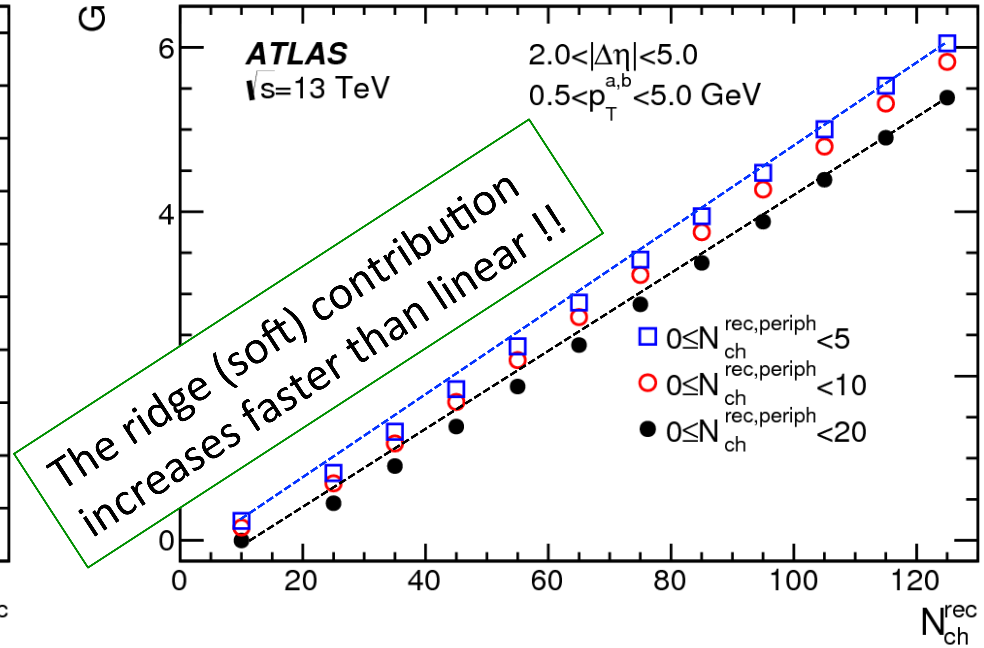


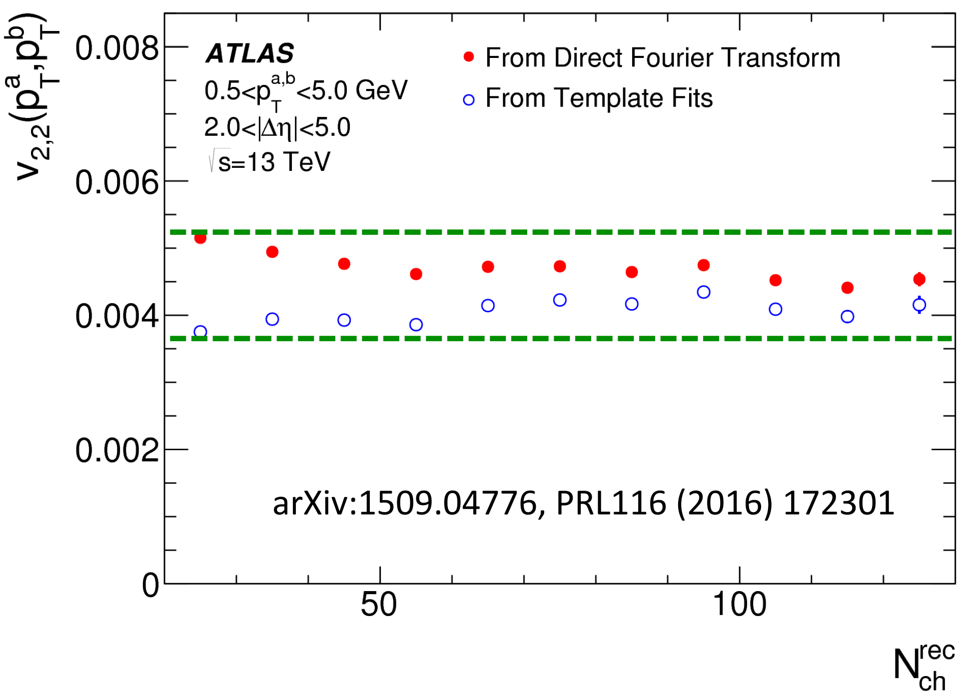
$$Y^{\mathrm{templ}}(\Delta\phi) = FY^{\mathrm{periph}}(\Delta\phi) + Y^{\mathrm{ridge}}(\Delta\phi),$$

$$Y^{\mathrm{ridge}}(\Delta\phi) = G[1 + 2v_{2,2}\cos(2\Delta\phi)],$$

$$Y^{\mathrm{periph}}(\Delta\phi) = Y^{\mathrm{hard}}(\Delta\phi) + \boxed{G_0[1 + 2v_{2,2}^{0}\cos(2\Delta\phi)],}$$







$$Y^{\mathrm{templ}}(\Delta\phi) = F\,Y^{\mathrm{periph}}(\Delta\phi) + Y^{\mathrm{ridge}}(\Delta\phi),$$

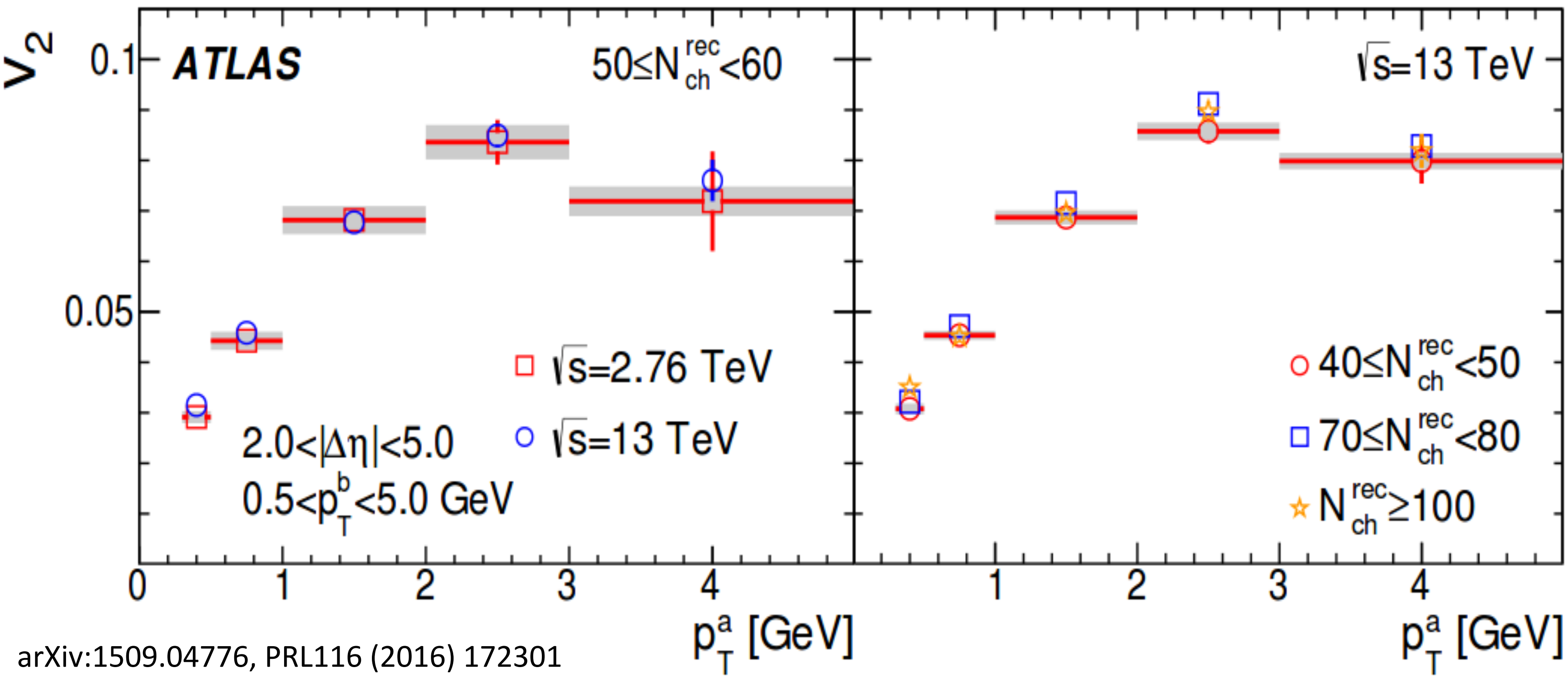
$$Y^{\mathrm{ridge}}(\Delta\phi) = G[1 + 2v_{2,2}\cos(2\Delta\phi)],$$

$$Y^{\mathrm{periph}}(\Delta\phi) = Y^{\mathrm{hard}}(\Delta\phi) + G_0[1 + 2v_{2,2}^{0}\cos(2\Delta\phi)],$$

- Reference fitting ($C_2 - C_{Ref.} + 1$)

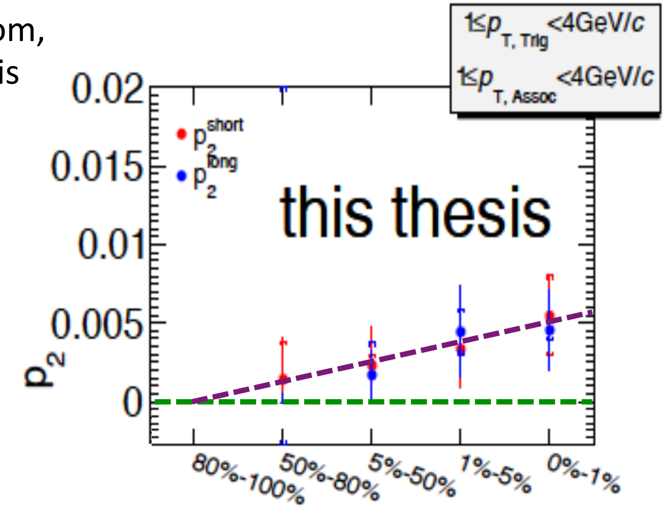
v_2 is defined w.r.t. the total integral based on no separation btw. hard/soft.?

similar p_T dependence of v_2 to the larger systems
no (or very weak) dependence of v_2 on energy and multiplicity



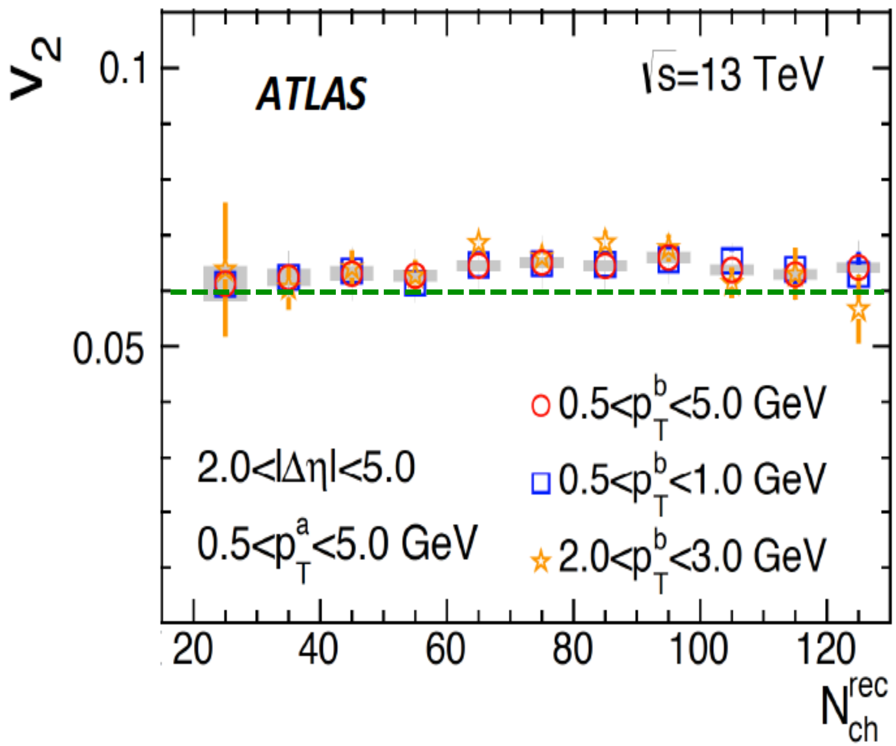
arXiv:1509.04776, PRL116 (2016) 172301

Jihyun Bhom, Ph.D. thesis

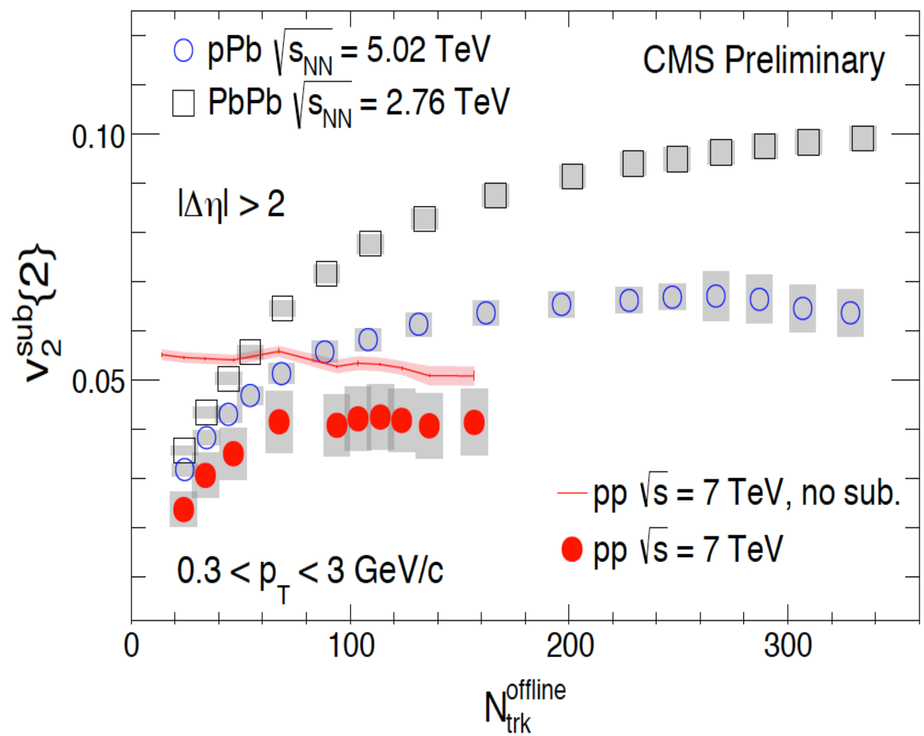


Multiplicity dependence of v_2 in pp at LHC with various methods

arXiv:1509.04776, PRL116 (2016) 172301

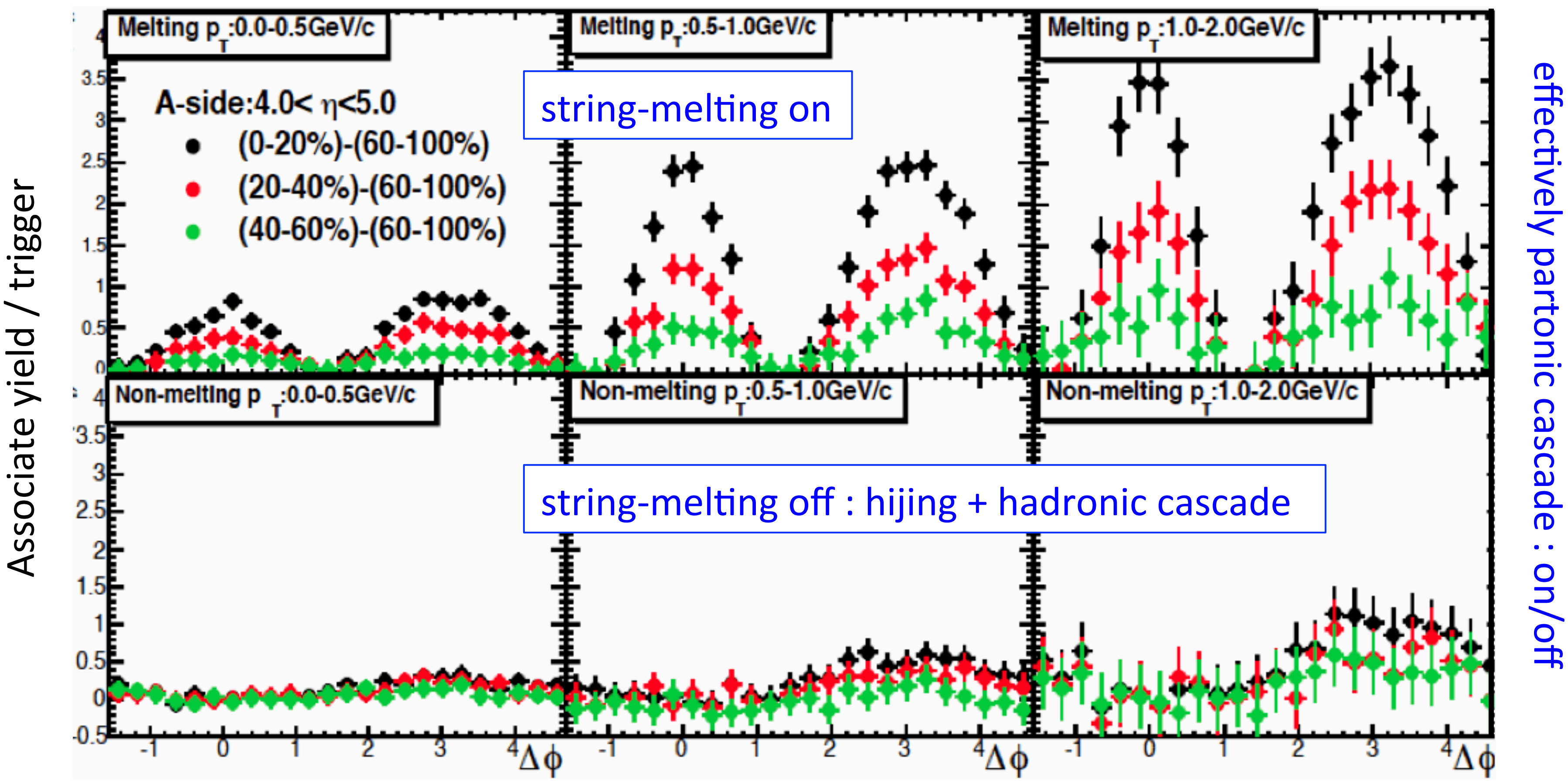


CMS, QM15



AMPT simulation p+Pb 5TeV (string-melting on/off)

for ALICE backward-central $\Delta\phi$ correlation ($|\Delta\eta|$=3~6)



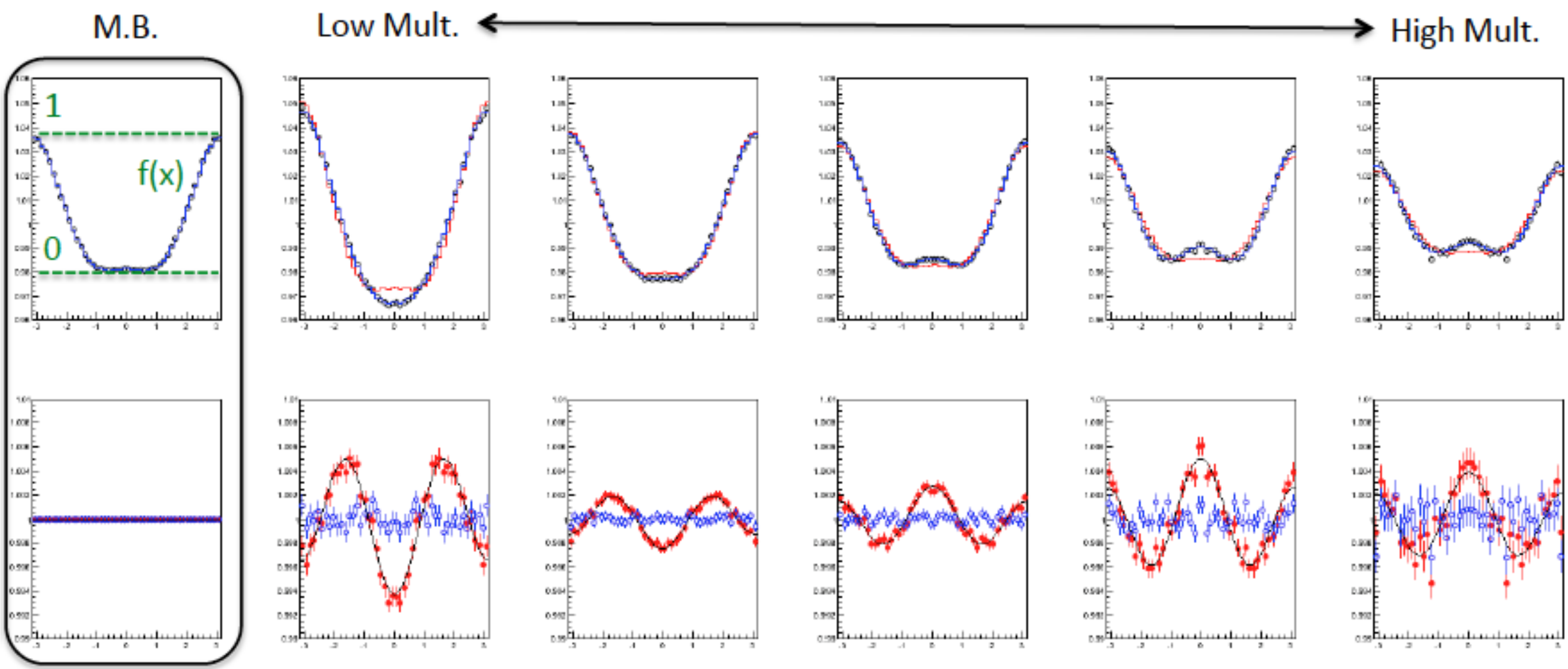
JPS 2014/Mar,
Kazuki Oshima,
Univ. of Tsukuba

p_T/η cuts are chosen for ALICE TPC-V0A acceptance.

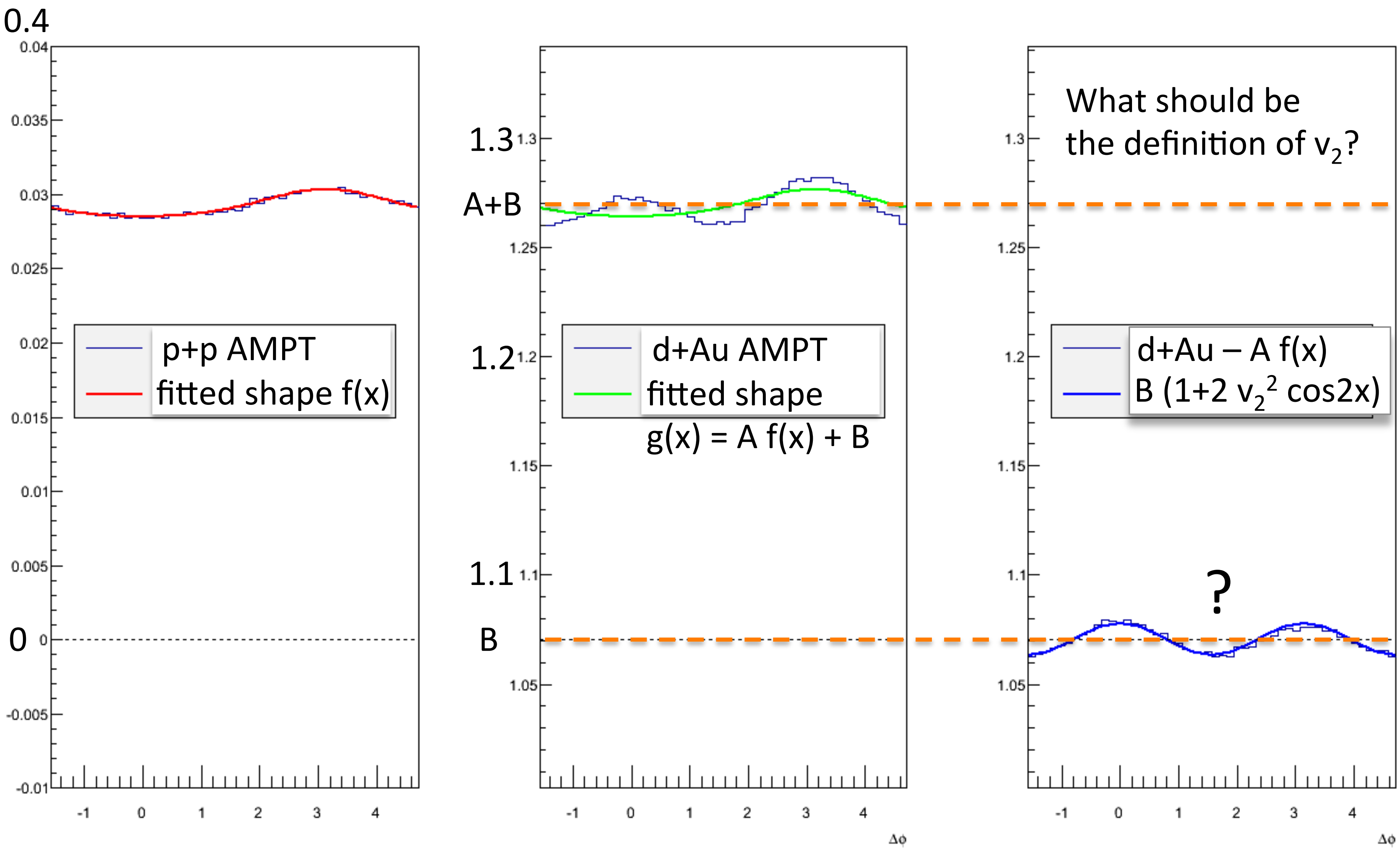
TPC : $|\eta|<1$
V0A: $3<\eta<5$ (Pb-going side)
V0C : $-4<\eta<-2$ (p-going side)

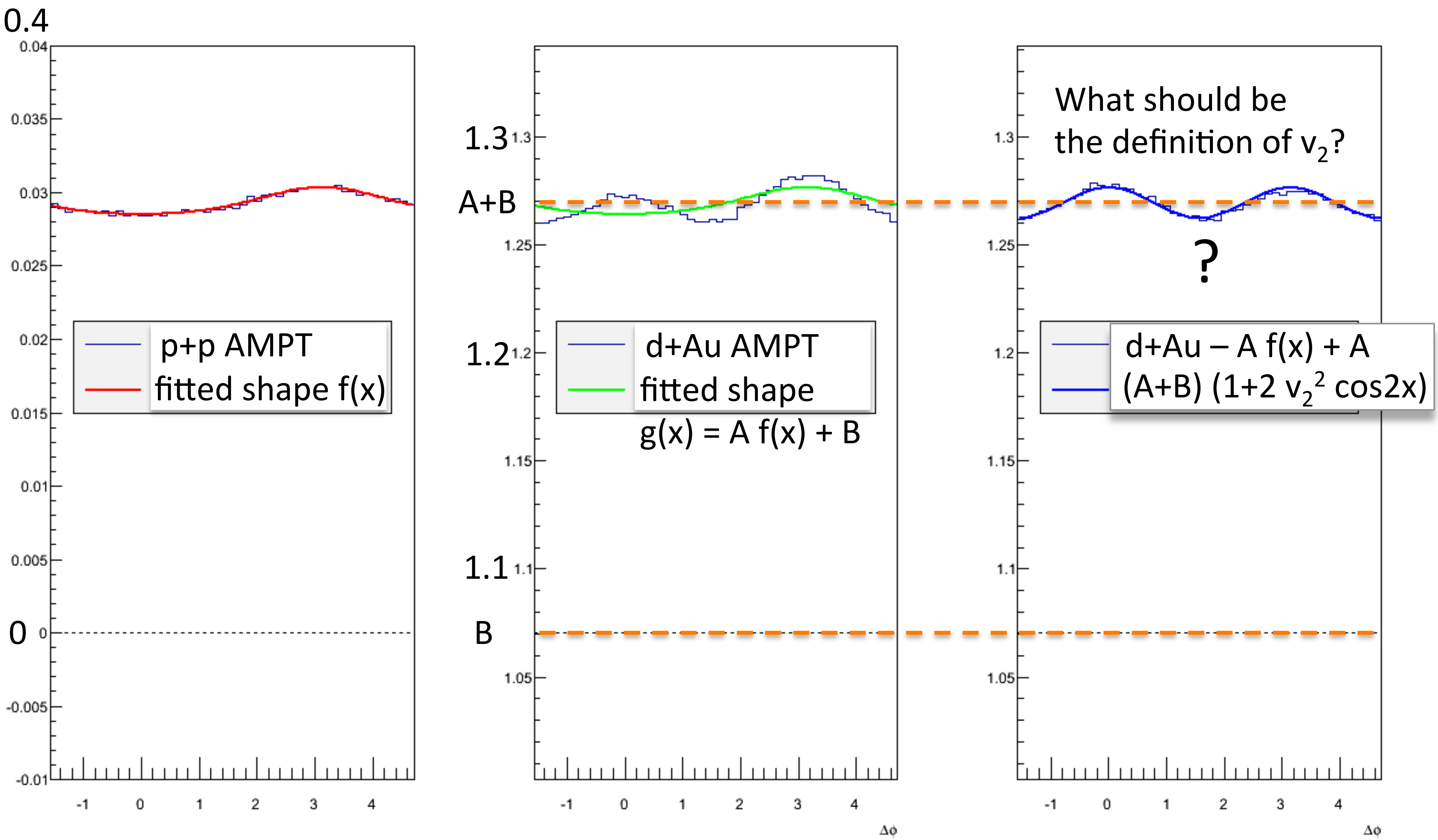
AMPT pp test with reference fitting method

- AMPT data
- Reference fitting : $F(x) = a + b f(x)$
- Reference fitting + v2 term : $F(x) = a + b f(x) + 2 c \cos(2x)$



- AMPT data - Reference fitting + 1
- AMPT data - (Reference fitting + v2 term) + 1


0.4
0
p+p AMPT
fitted shape f(x)
1.3
A+B
1.2
1.1
B
d+Au AMPT
fitted shape
g(x) = A f(x) + B
What should be the definition of v_2?
d+Au – A f(x)
B (1+2 v_2^2 cos2x)
?
Δφ



0.4
0
p+p AMPT
fitted shape f(x)
1.3
A+B
1.2
1.1
B
d+Au AMPT
fitted shape
g(x) = A f(x) + B
What should be the definition of v_2?
?
d+Au – A f(x) + A
(A+B) $(1+2\ v_2^2 \cos 2x)$
Δφ

Thank you very much
for our current and continuing fruitful collaboration !