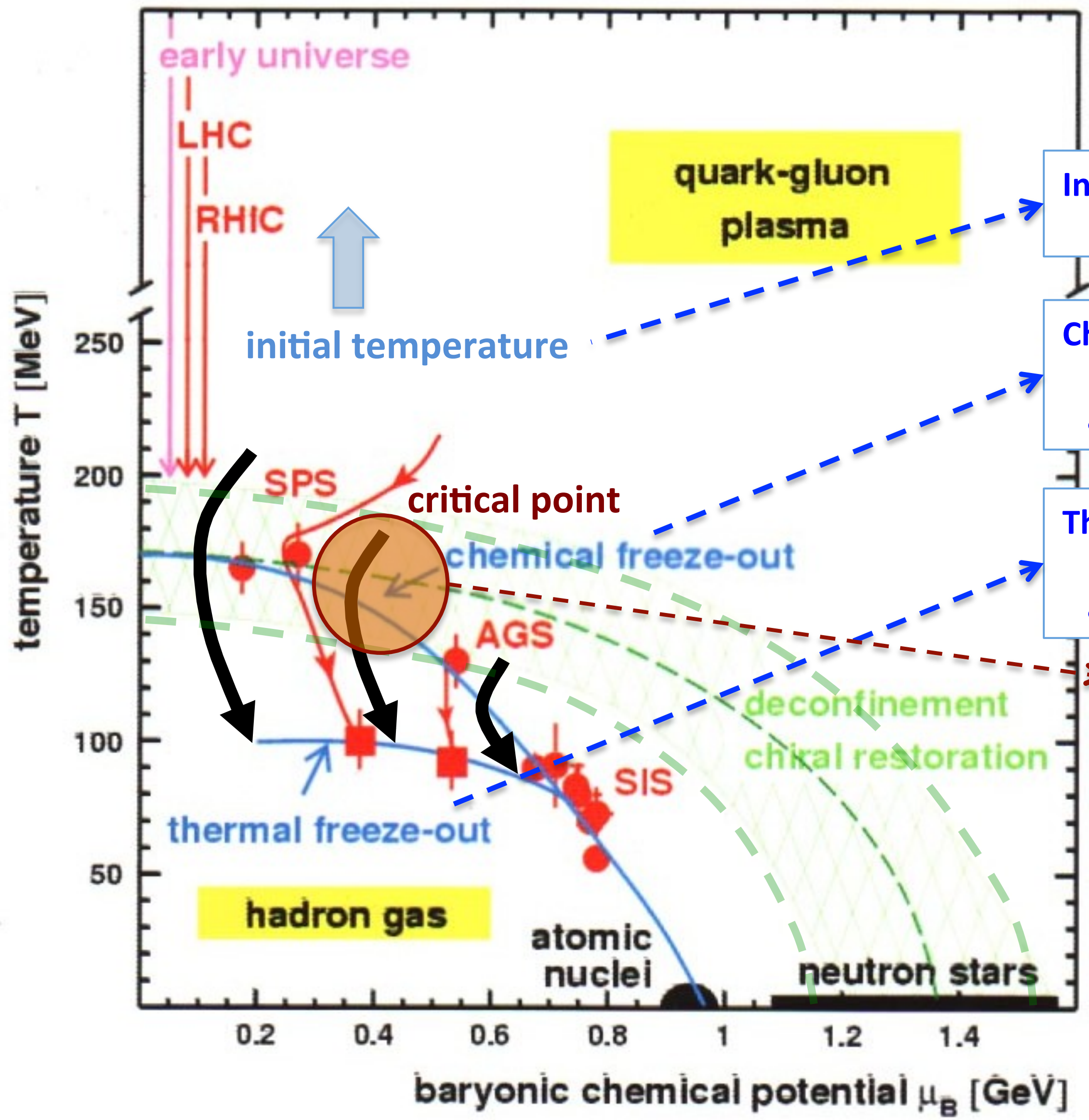
フロー（粒子相関）とゆらぎ

横方向運動量分布、半径方向膨張
反応平面と指向的方位角異方性（v_1）
楕円的方位角異方性（ハドロン、光子v_2）
多粒子相関（ridge、ゆらぎ）

チュートリアル研究会
「重イオン衝突の物理：基礎から最先端まで」

筑波大物理、江角晋一

History of temperature before/after the phase transition



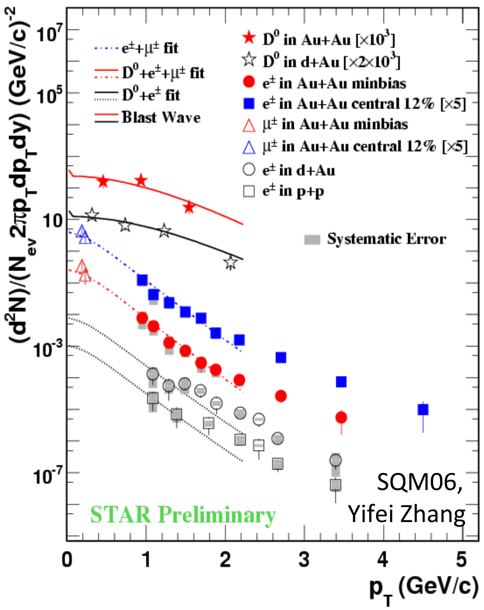
Initial temperature :
Direct thermal photon measurement

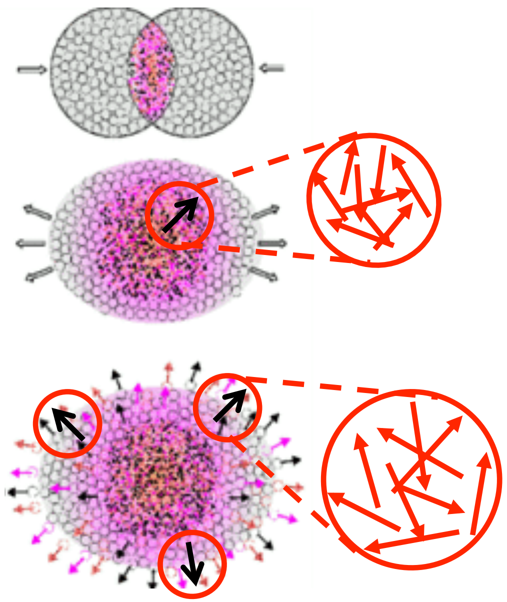
Chemical Freeze-out temperature :
Particle species, ratios are fixed
at the end of inelastic interactions

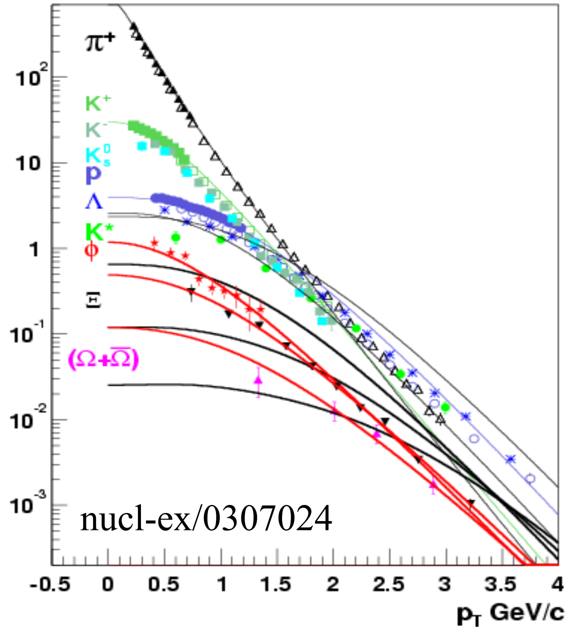
Thermal Freeze-out temperature :
Particle spectra are fixed
at the end of elastic interactions

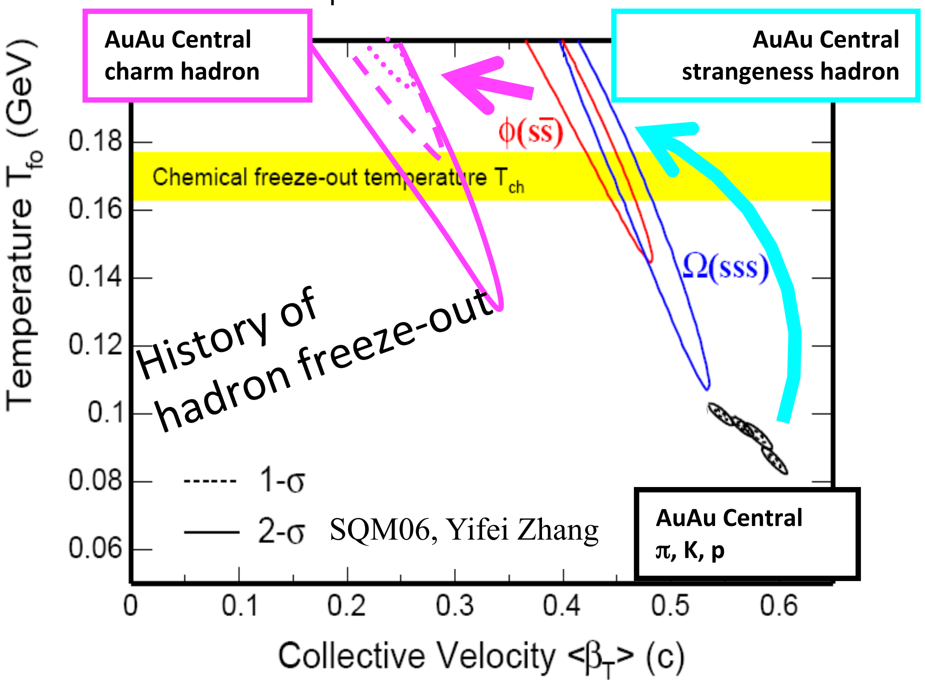
Critical Point :
1^{st} order phase transition
non-monotonic behavior
expected fluctuation to diverge

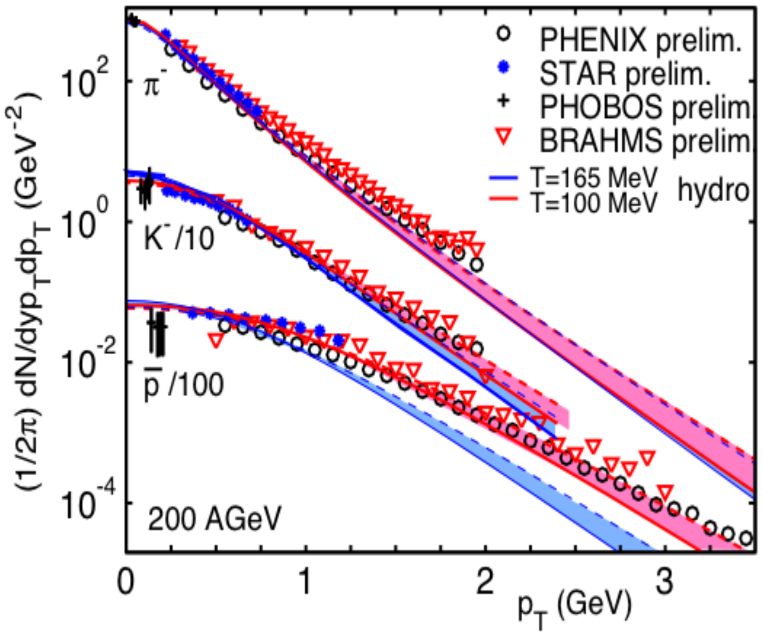
Blast Waveモデル（流体計算に基づいたフィット関数）





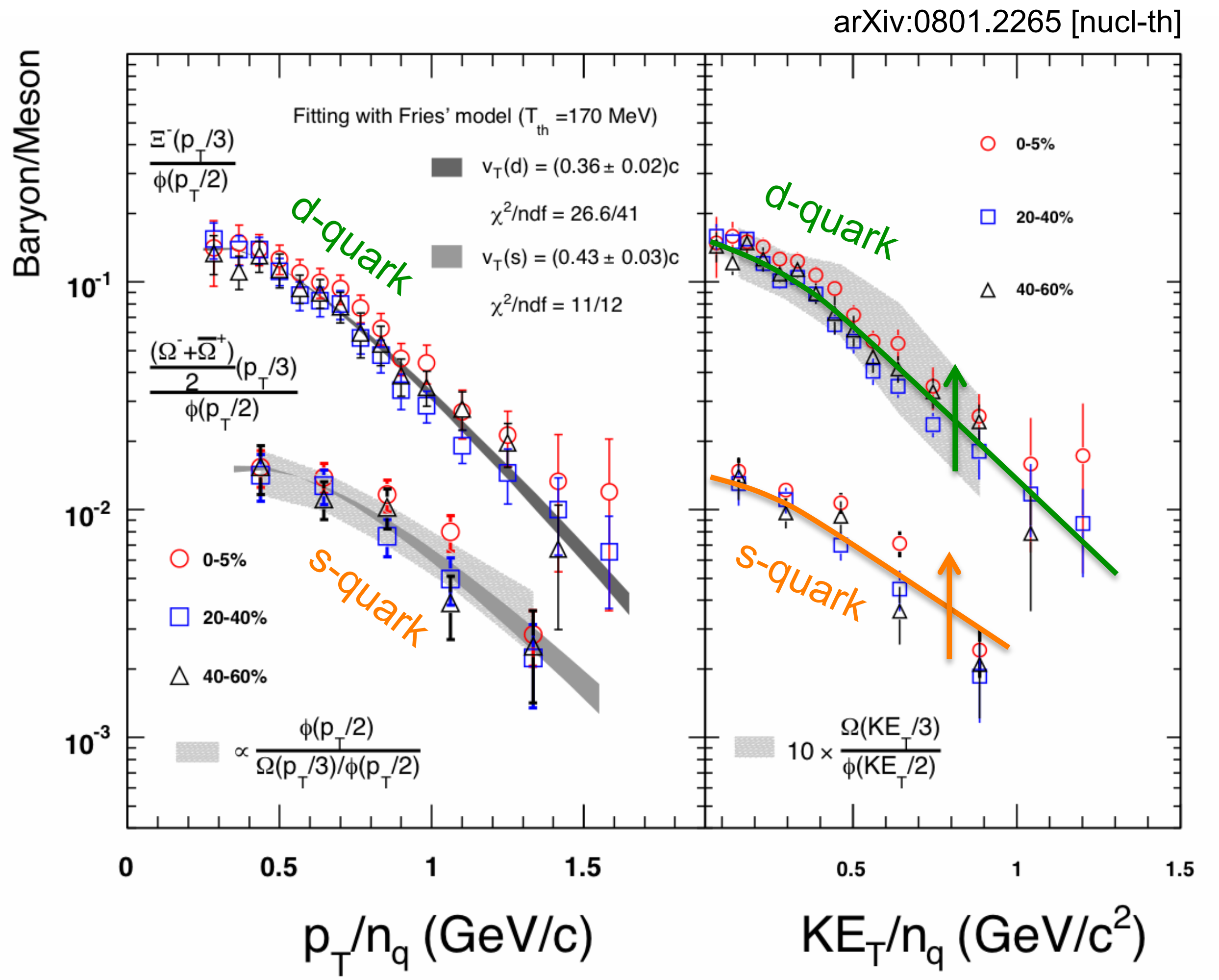


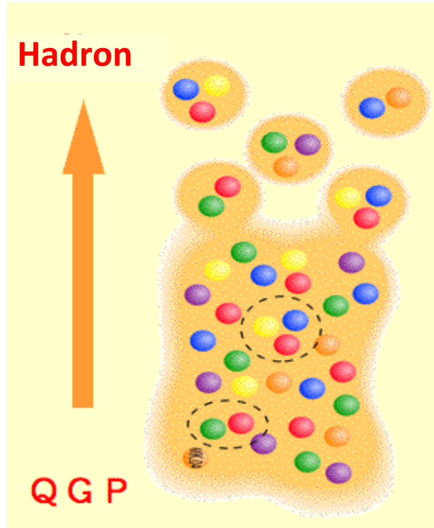




Quark momentum distribution

--- extracted from multi-strange hadron ratio ---

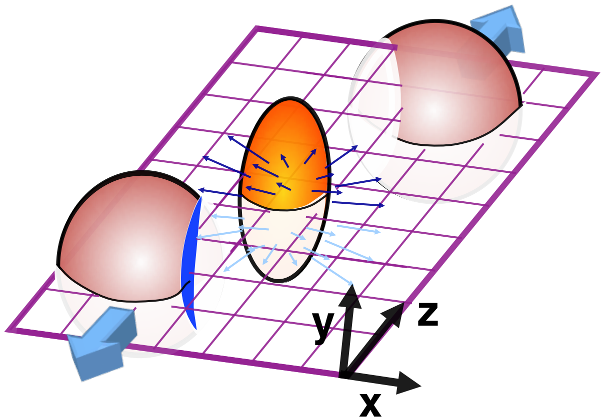




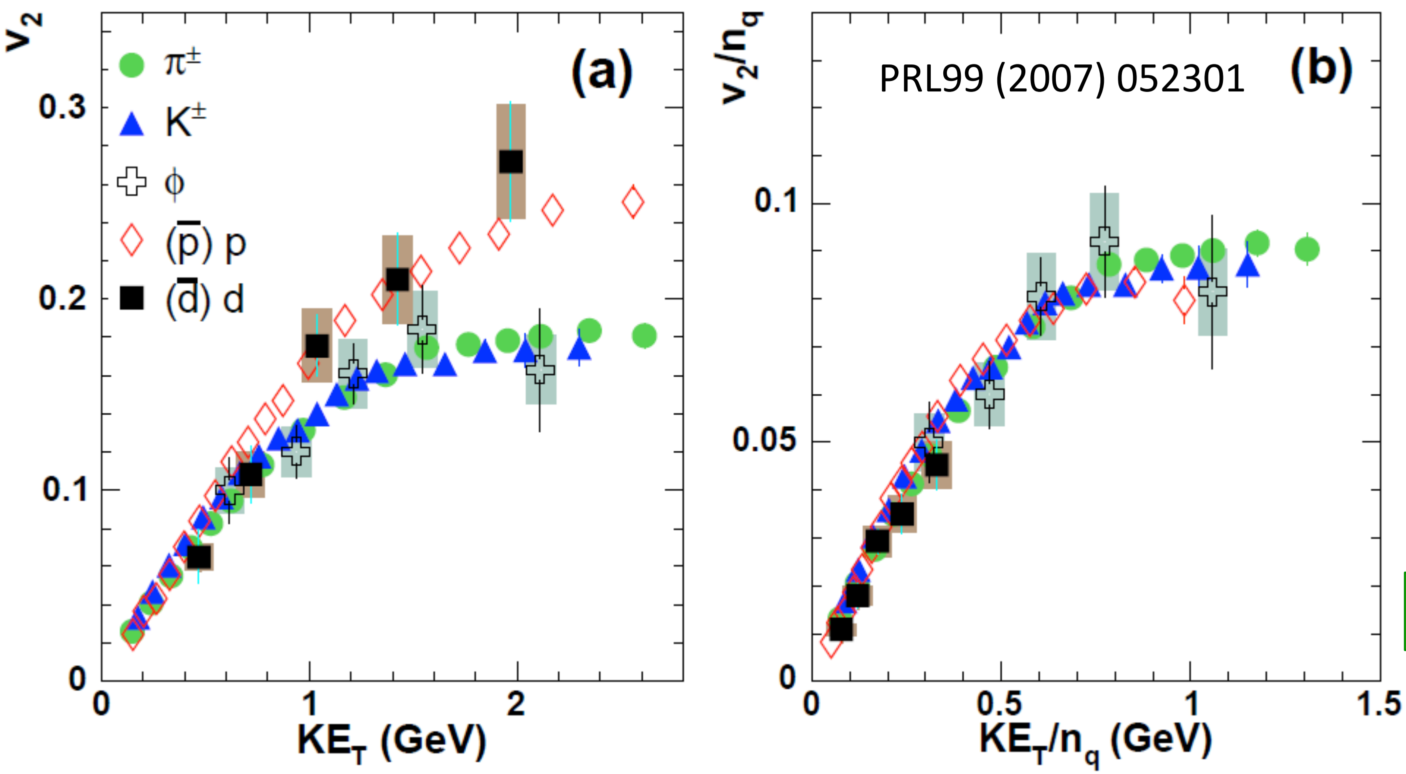
Collective radial expansion
-during the partonic phase
-before the hadronic phase

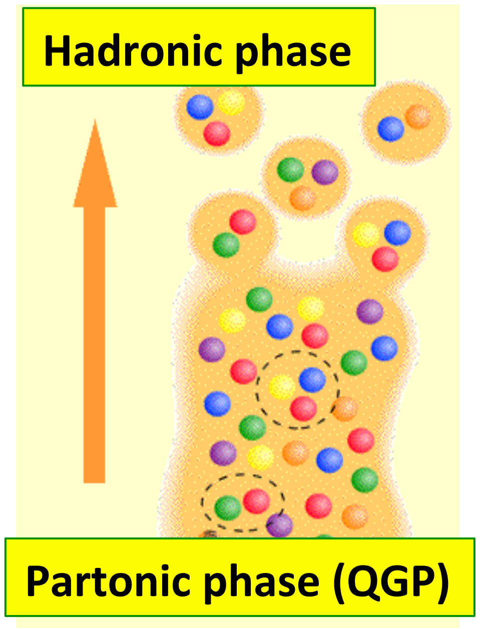
Quark coalescence or
recombination mechanism
for the hadronization

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



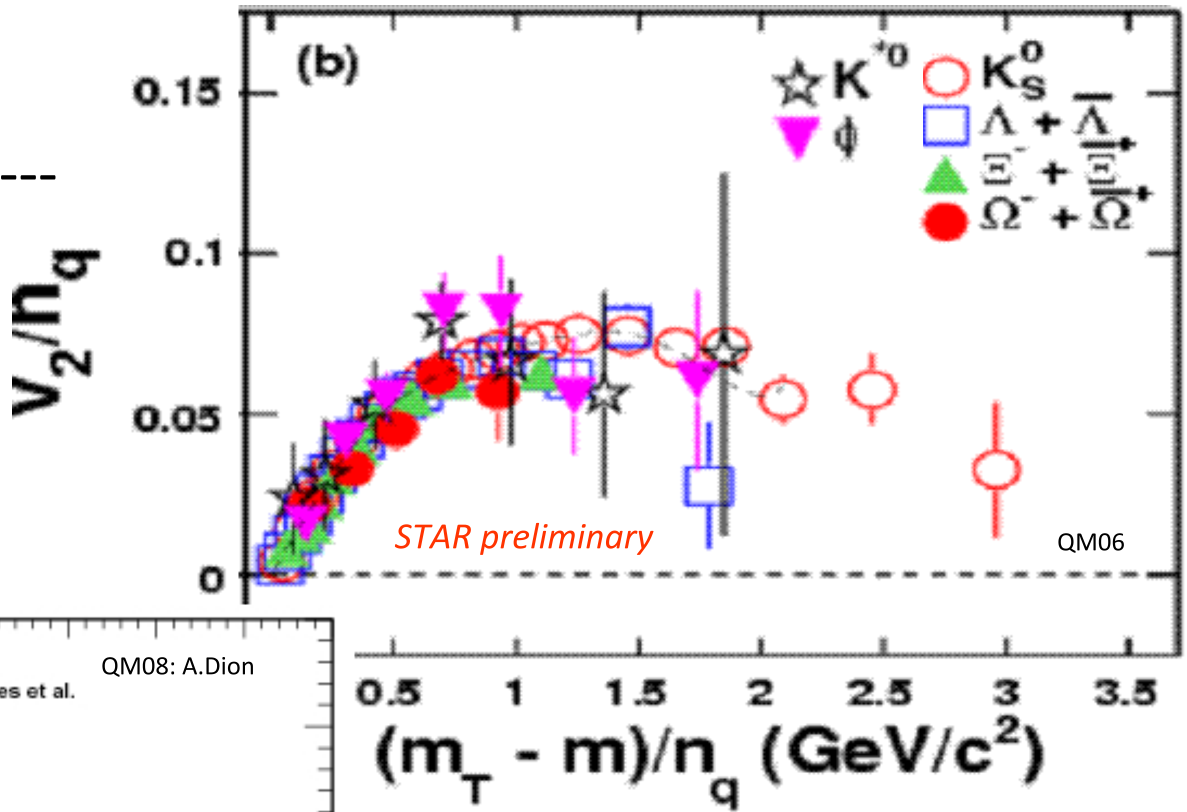
Indication of quark flow (in partonic phase)

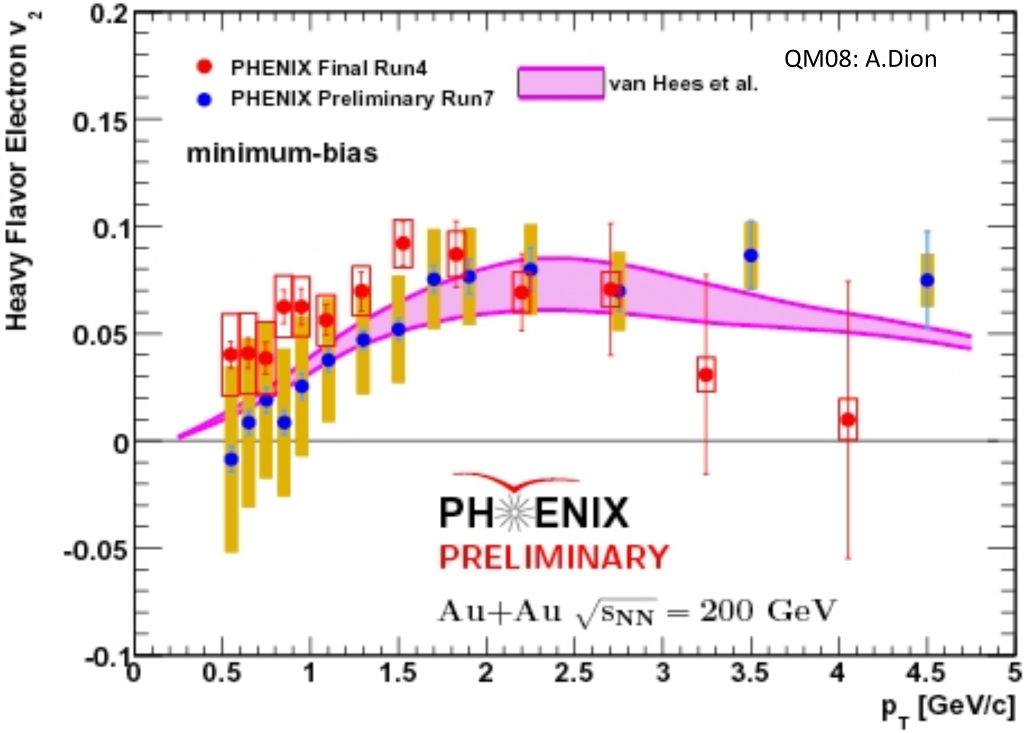




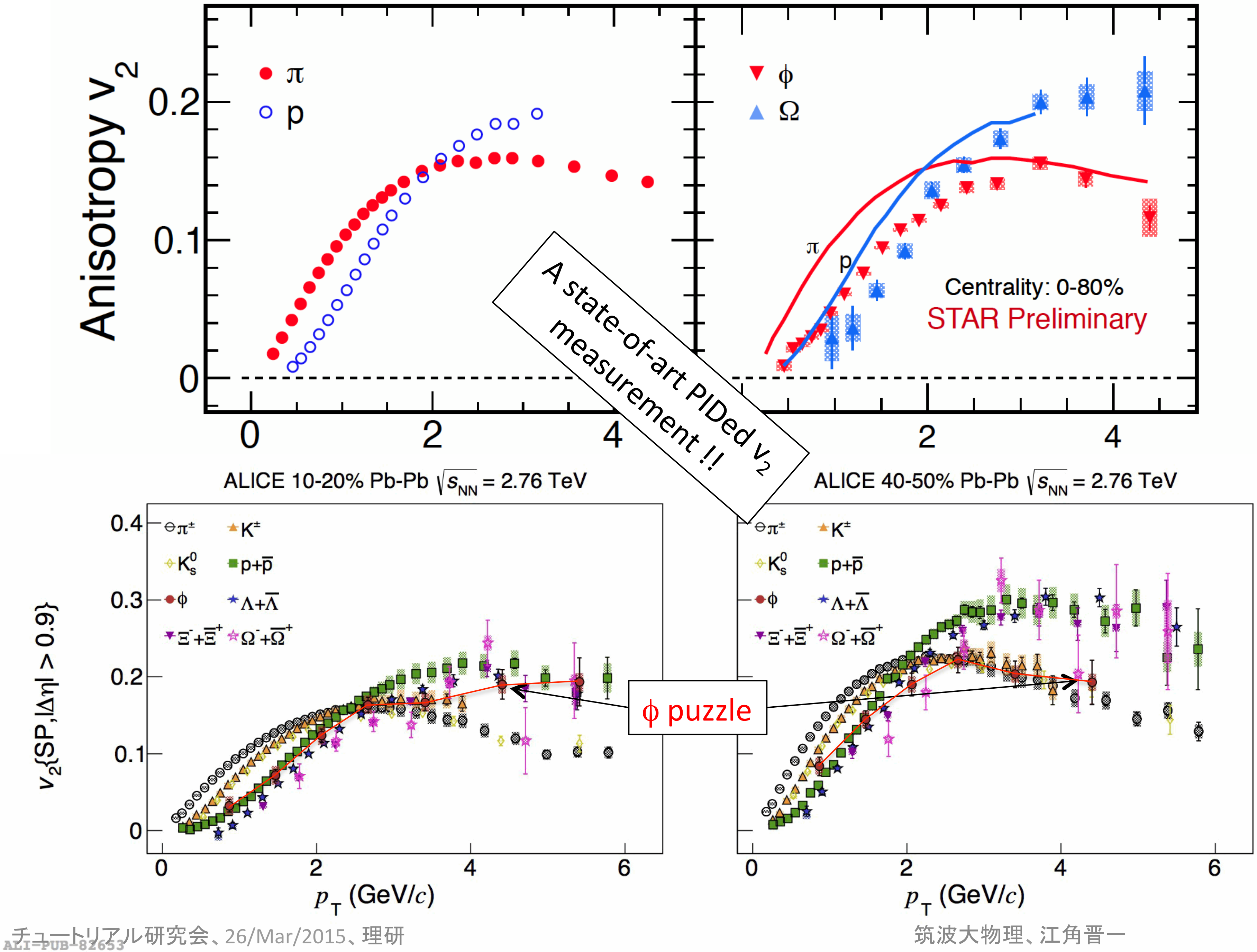
Partonic collectivity
--- particle identified v_2 ---

multi-strangeness and
charmed hadron

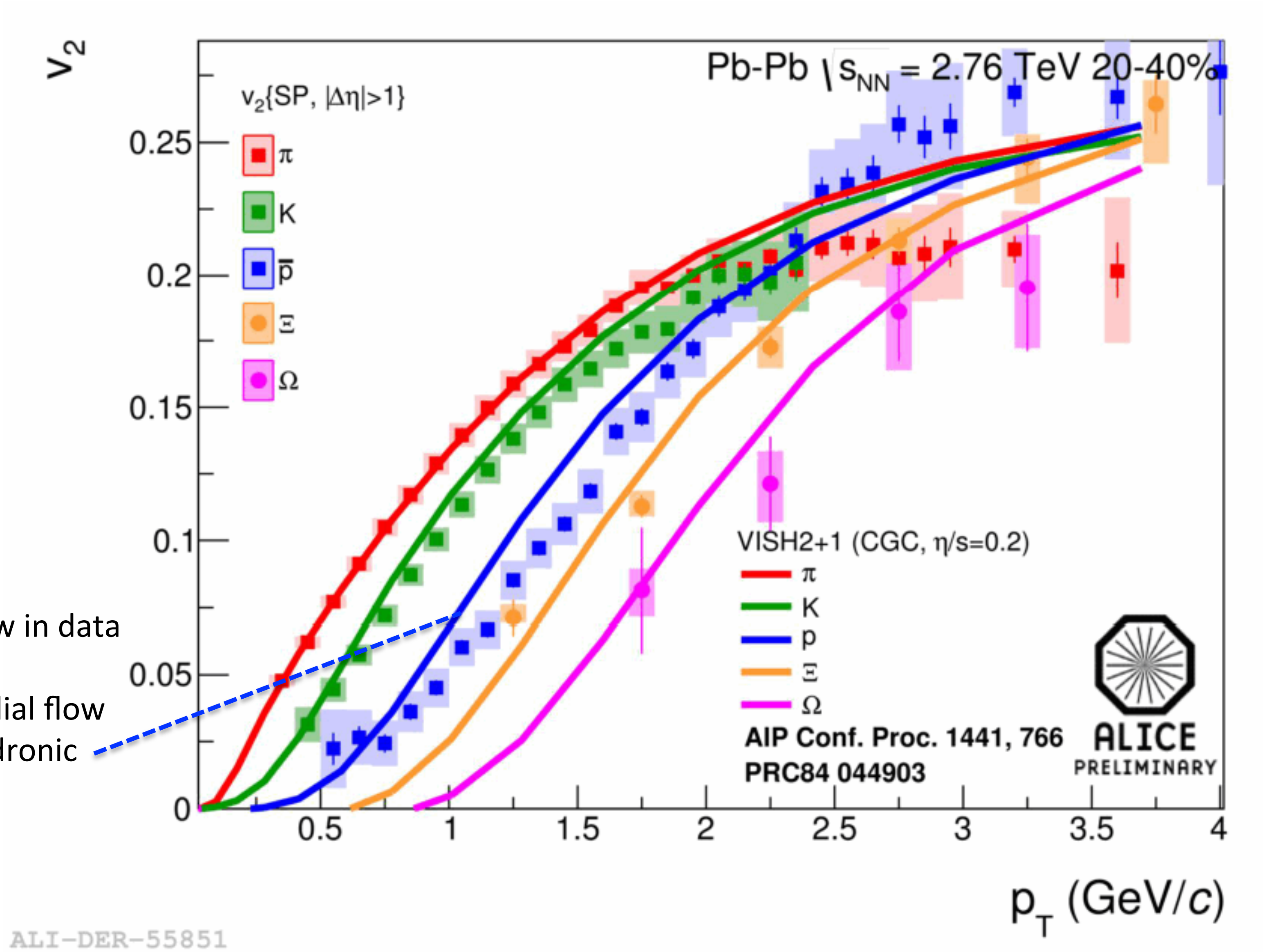




Number of constituent quark scaling in hadron v_2 as well as multi-strange baryon v_2: v_2 is already established during the quark phase before the hadronization. This seems to be true even for heavy quark like charm.


Anisotropy v_2
π
p
ϕ
Ω
Centrality: 0-80%
STAR Preliminary
A state-of-art PIDed v_2 measurement !!
ALICE 10-20% Pb-Pb $\sqrt{s_{NN}}$ = 2.76 TeV
ALICE 40-50% Pb-Pb $\sqrt{s_{NN}}$ = 2.76 TeV
$\pi^{\pm}$
$K^{\pm}$
K^0_s
$p+\bar{p}$
ϕ
$\Lambda+\bar{\Lambda}$
$\Xi^-+\bar{\Xi}^+$
$\Omega^-+\bar{\Omega}^+$
$v_2\{SP,|\Delta\eta| > 0.9\}$
p_T (GeV/c)
ϕ puzzle
ALI-PUB-82653

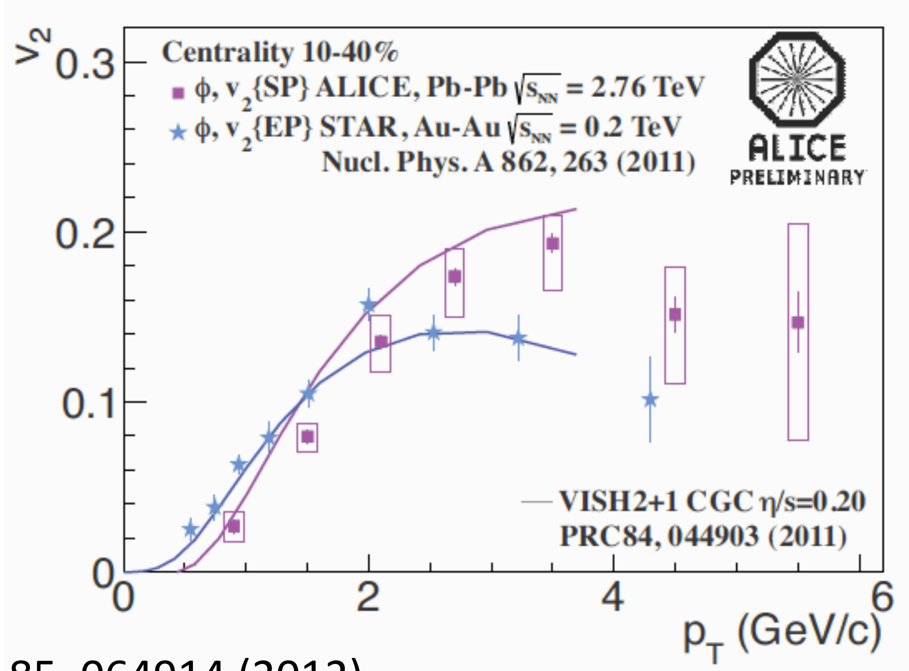
mass dependence of v_2 with hydro-model



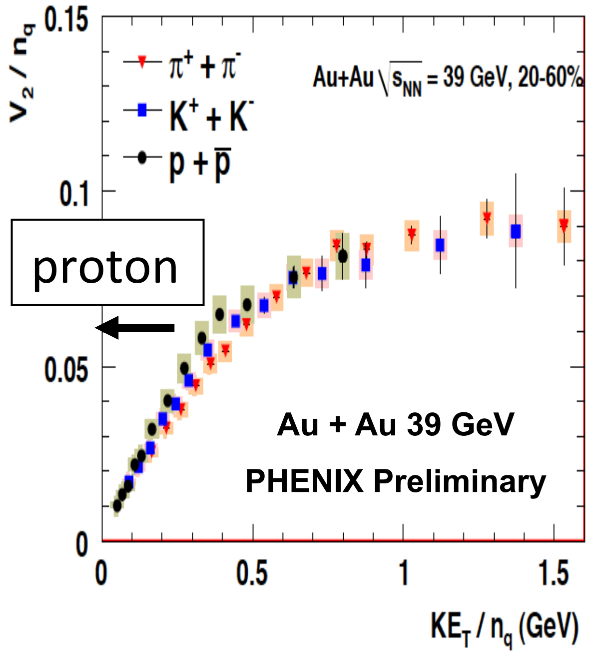
More radial flow in data

Not enough radial flow in hydro, or hadronic afterburner

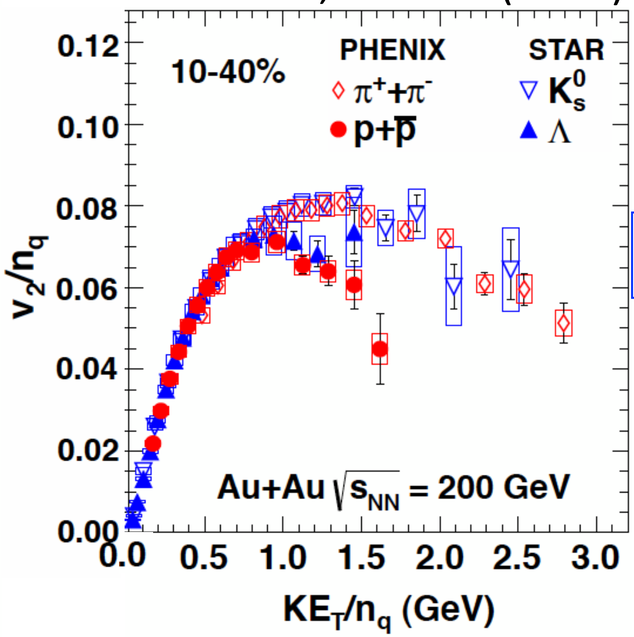
Beam energy dependence of v_2 (increased radial flow)

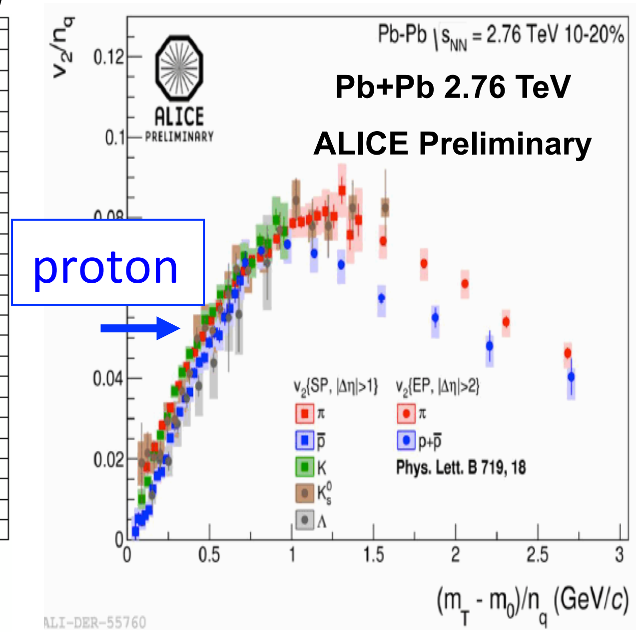


Relative momentum shift of heavier particles (protons) are larger than light hadrons (pions), which is consistent with an increased radial flow.



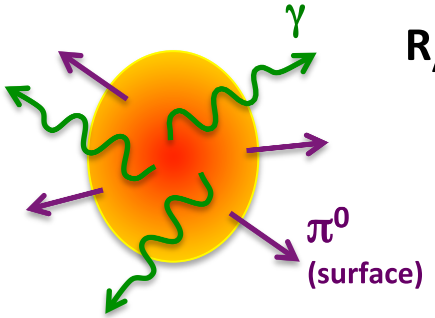
PRC 85, 064914 (2012)



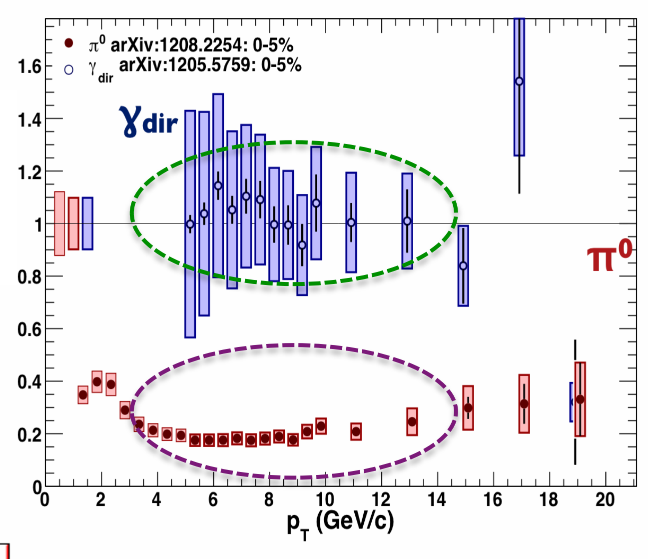


High p_T direct photon as penetrating probe

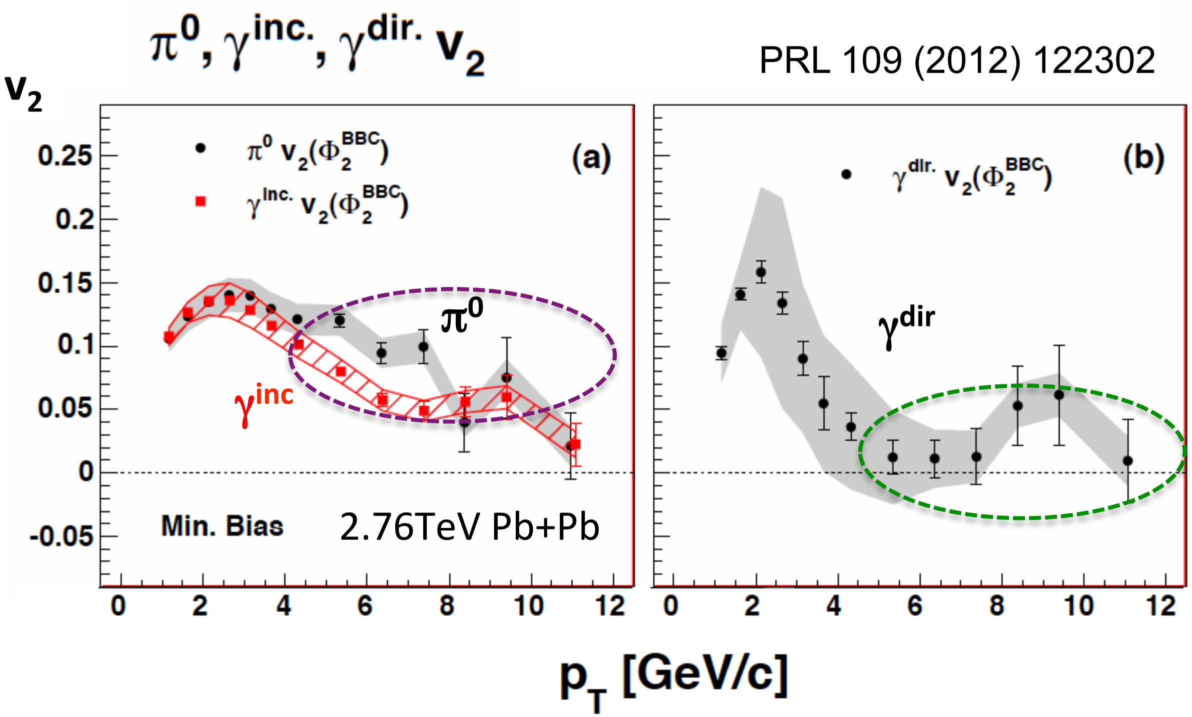
$p_T > 5$ GeV/c	hadron	γ^{dir}
R_{AA}	< 1	~ 1
v_2	> 0	~ 0



PRL 109 (2012) 152302



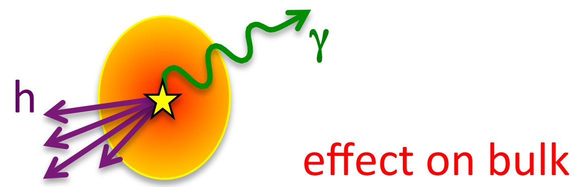
PRL 109 (2012) 122302

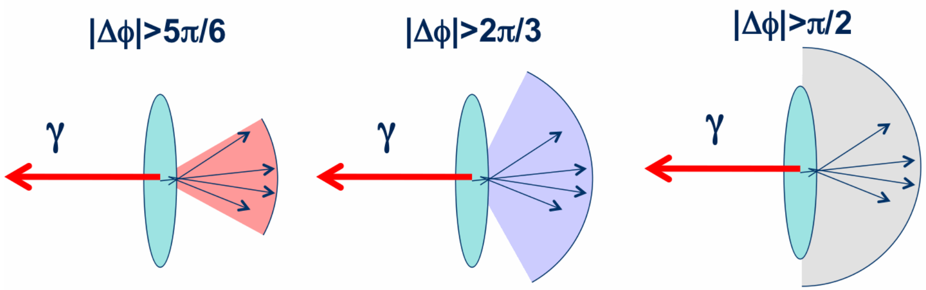


$$R_{AA} = \frac{N\,(A+A)}{N_{coll}\;N(p+p)}$$

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

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



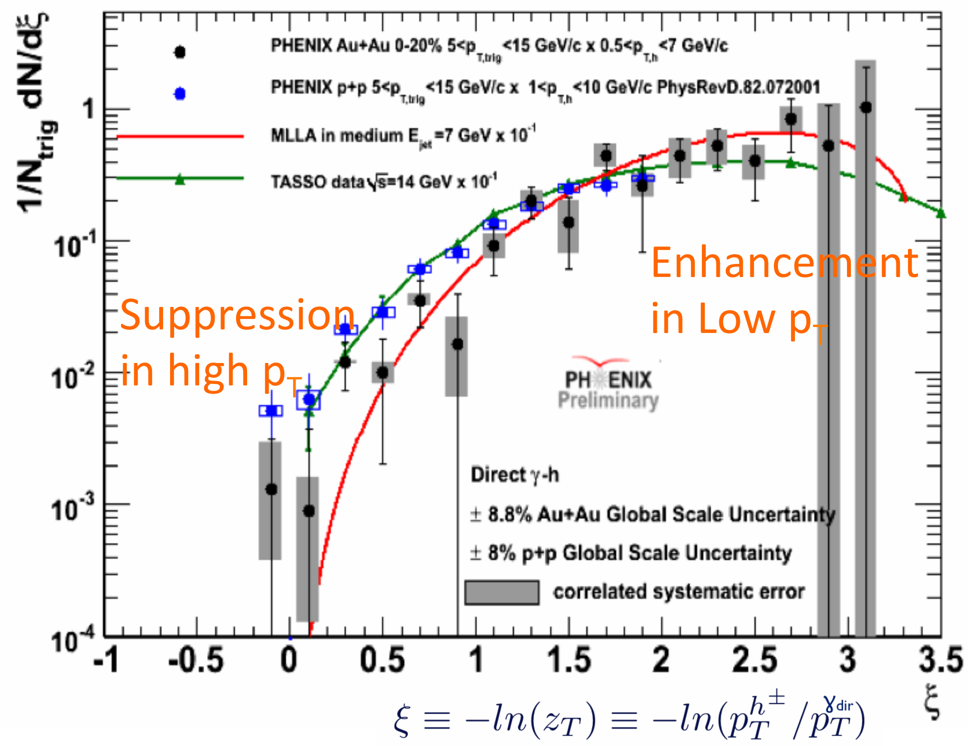


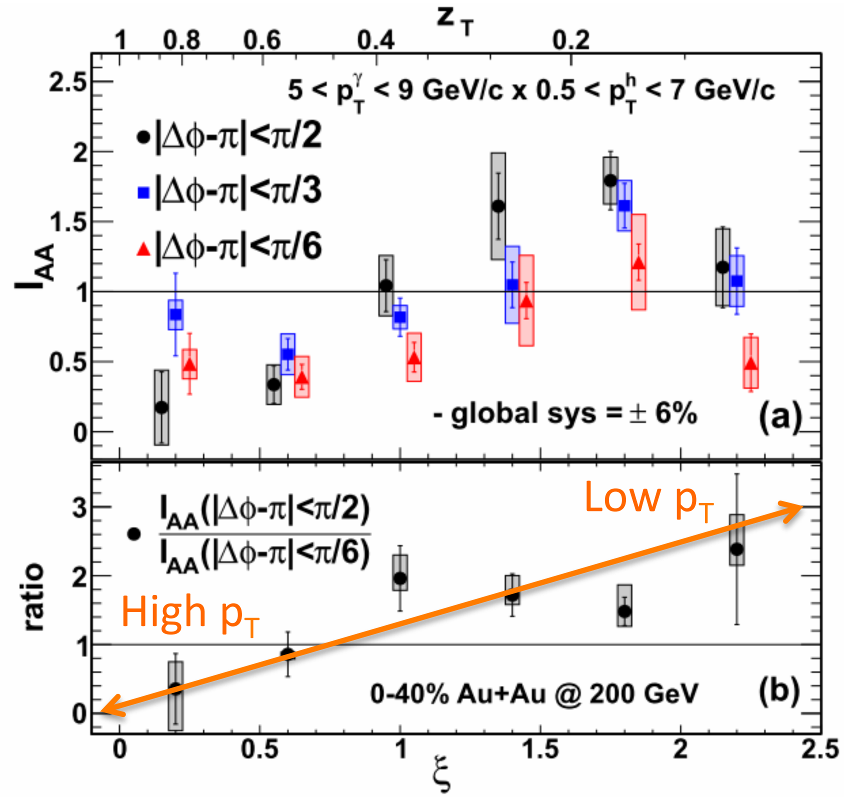
prompt photon - hadron correlation

N_{PTY} = associate hadron yield per trigger γ

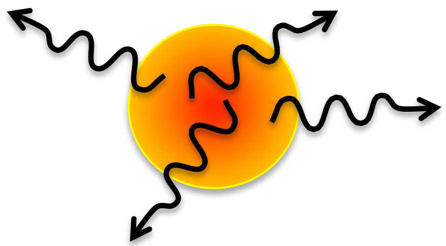
$I_{AA} = N_{PTY}(AA) / N_{PTY}(pp)$

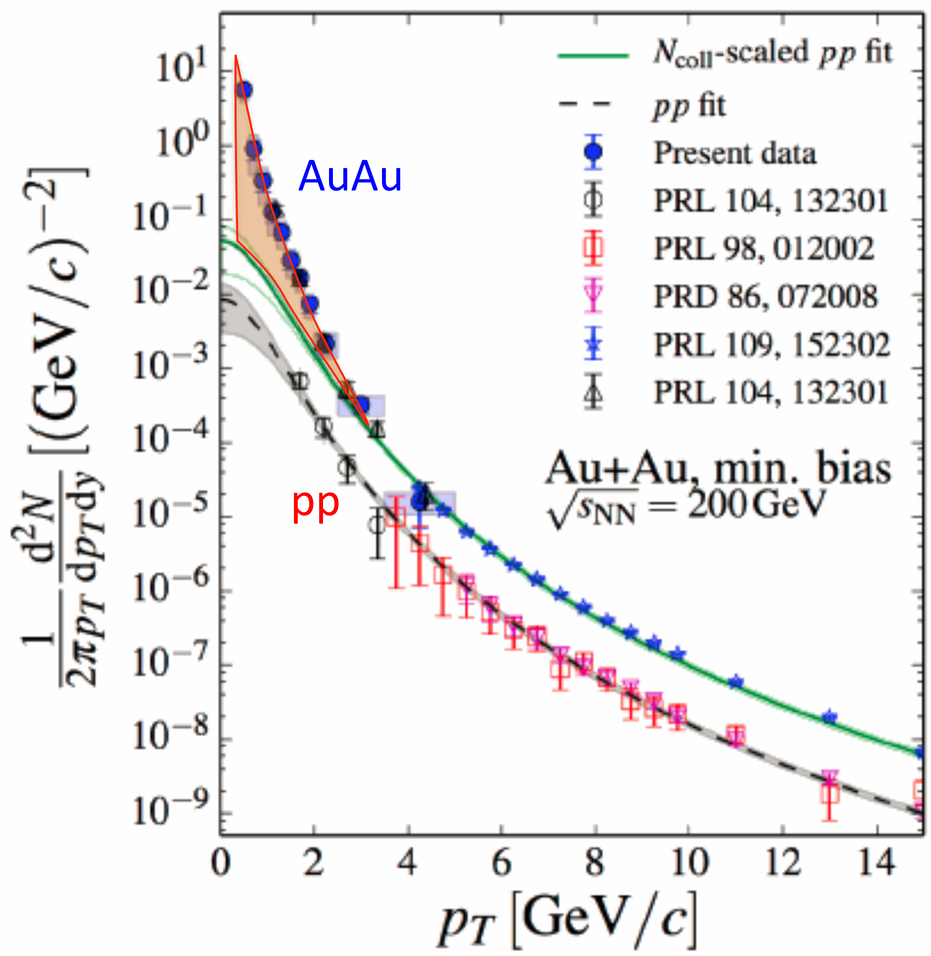
PRL 111 (2013) 032301





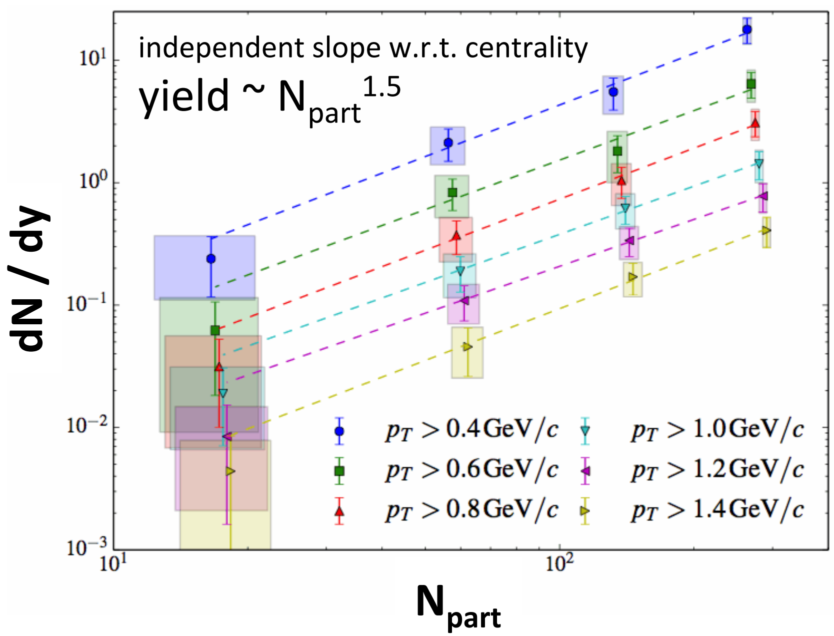
Enhanced thermal photon production at low p_T



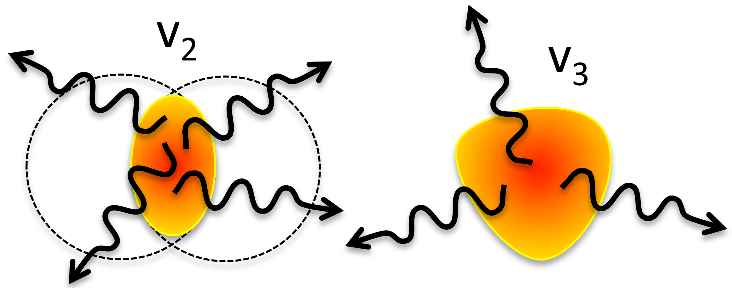


- Virtual and real photon measurements via internal and external conversion methods with electron pair measurements
- Real photon measurements with EMcal
- Initial temperature of 300~600MeV

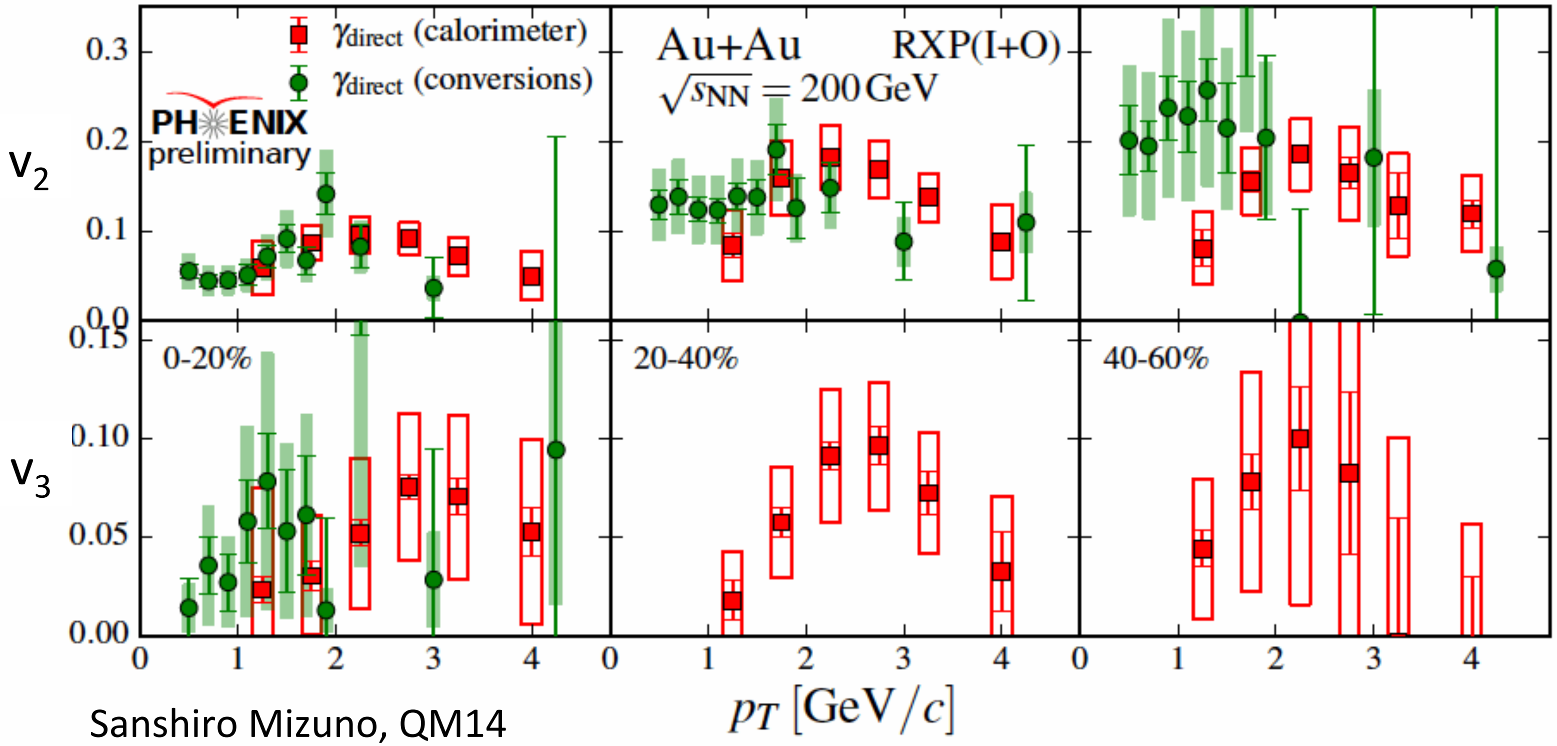
arXiv:1405.3940



Direct (thermal) photon v_2 and v_3



$v_n = < \cos n(\phi^{particle} - \Phi_n^{plane}) >$
(n=2 : elliptic flow), (n=3 : triangular flow)

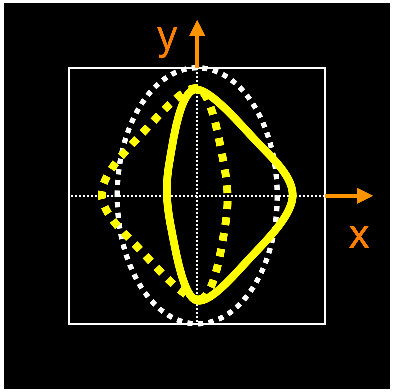


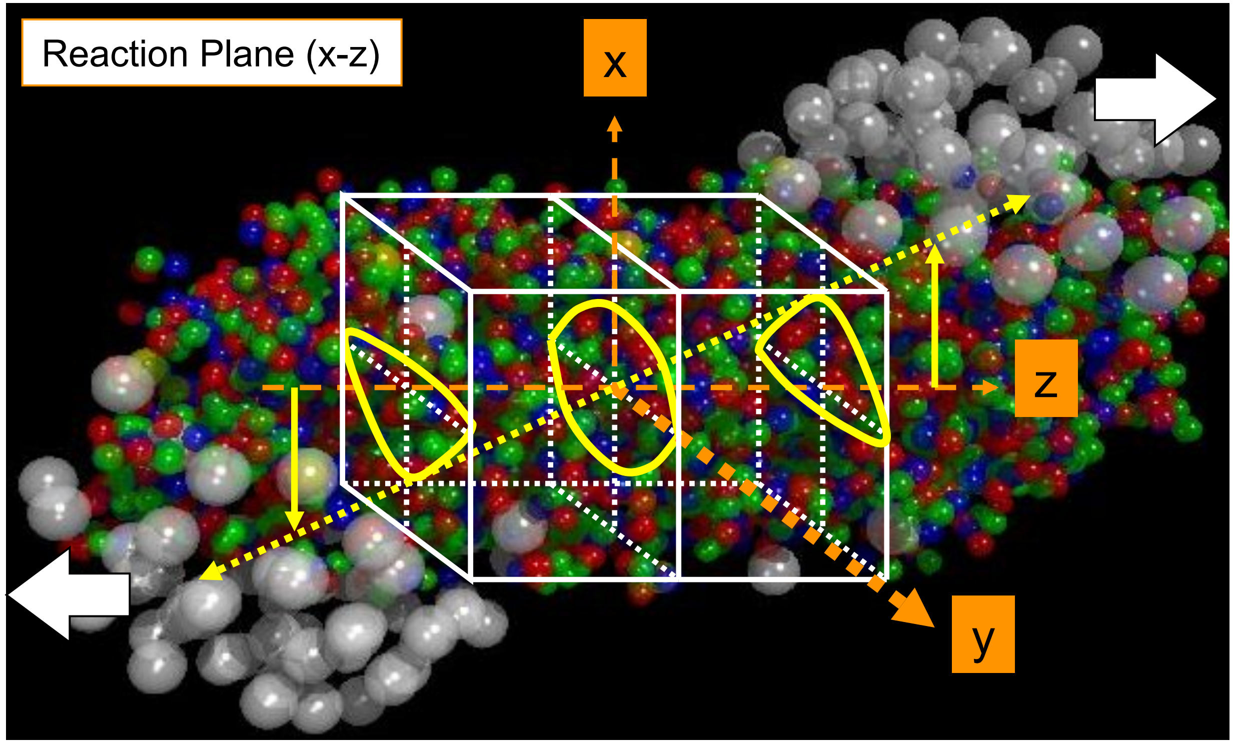
Sanshiro Mizuno, QM14

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

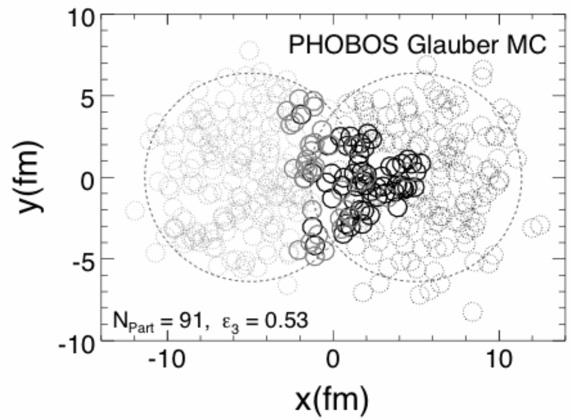
Higher order event anisotropy --- v_3 ---

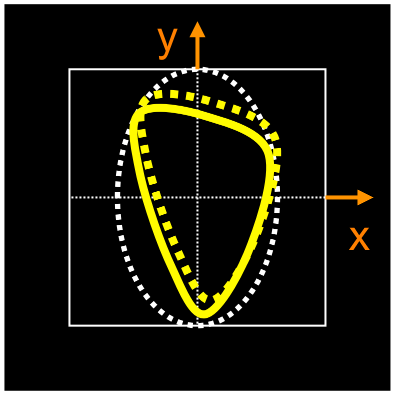
black-disk collision, sign-flipping v_3 like v_1
initial geometrical fluctuation, no-sign-flipping v_3

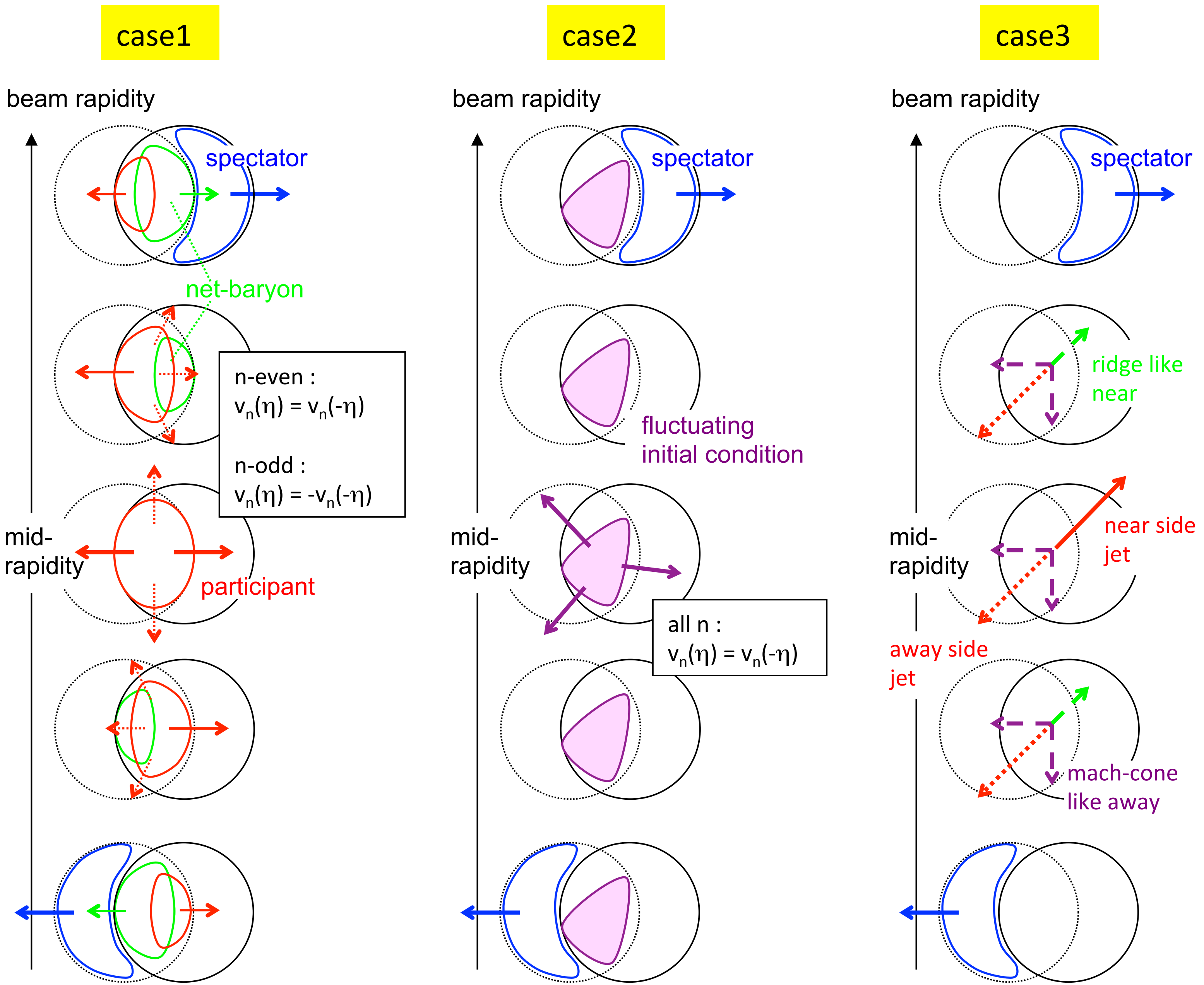




arXiv:1003.0194

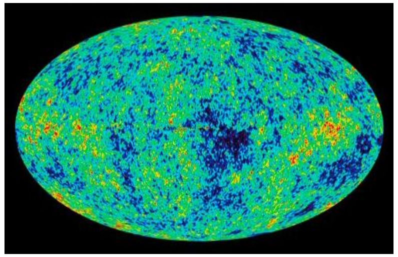


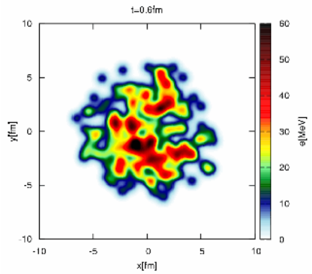


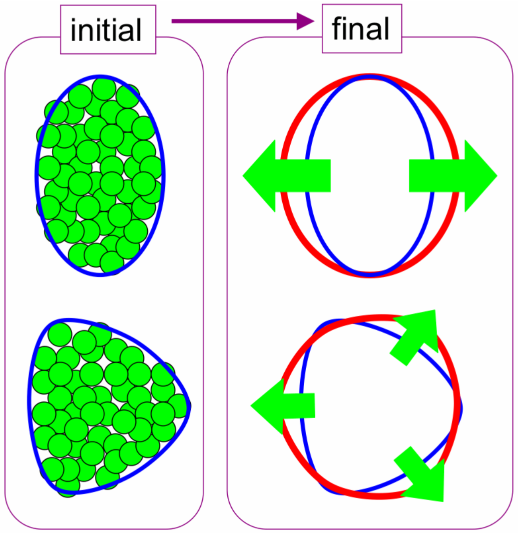


case1
case2
case3
beam rapidity
beam rapidity
beam rapidity
spectator
spectator
spectator
net-baryon
n-even :
$v_n(\eta) = v_n(-\eta)$
n-odd :
$v_n(\eta) = -v_n(-\eta)$
fluctuating
initial condition
ridge like
near
mid-
rapidity
participant
mid-
rapidity
all n :
$v_n(\eta) = v_n(-\eta)$
mid-
rapidity
near side
jet
away side
jet
mach-cone
like away

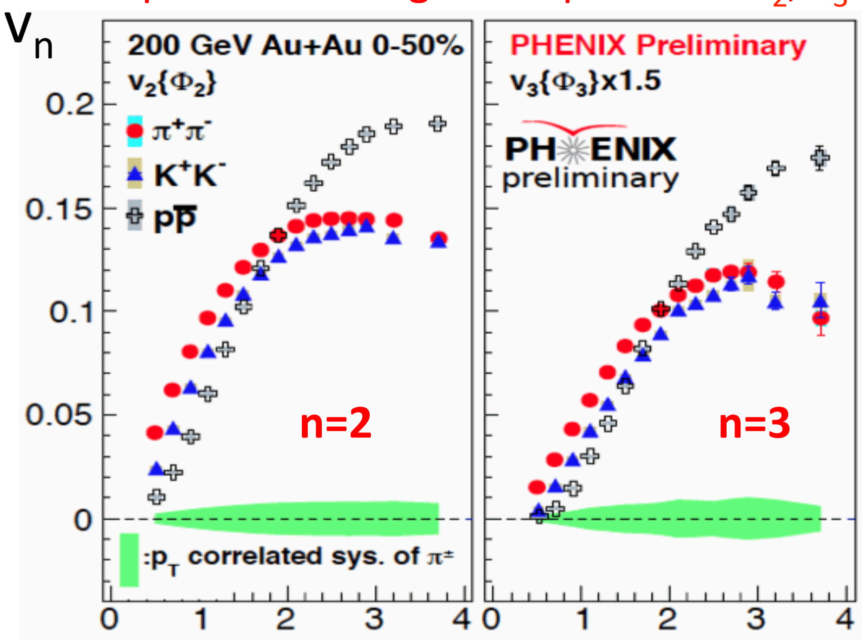
Elliptic and triangular expansion and freeze-out geometry







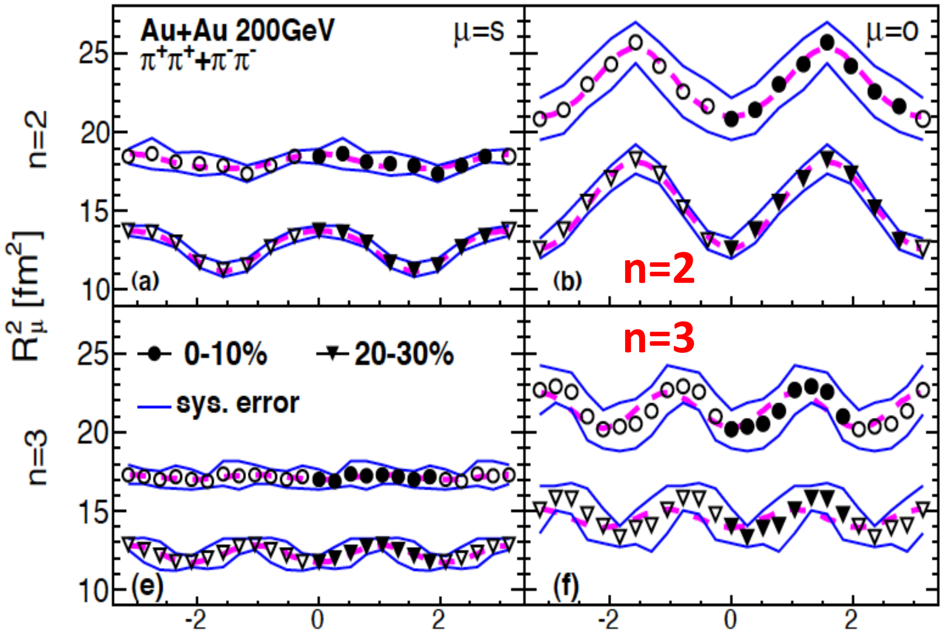
Elliptic and Triangular expansion : v_2, v_3



arXiv:1412.1038

p_T [GeV/c]

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



PRL112 (2014) 222301

$\phi - \Psi_n$ [rad]

Event plane (E.P.) method

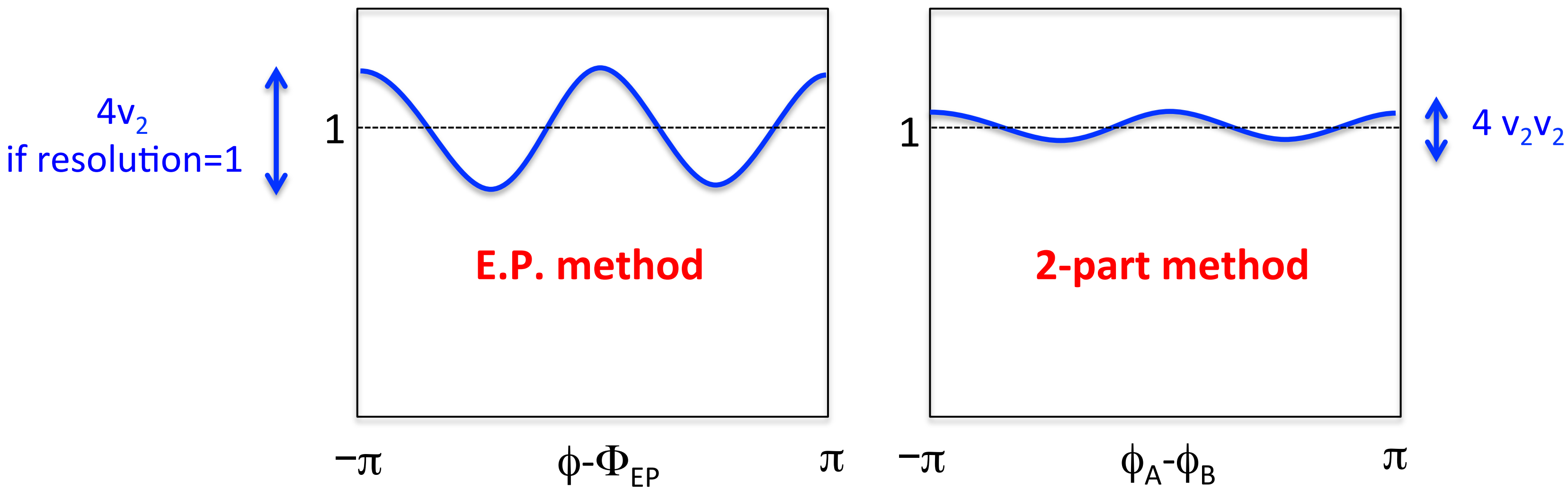
$F(x) = 1 + \Sigma\, [2\, p_n \cos(n\, x)]$

$$v_n^{measured} = \langle \cos n(\phi - \Phi_{EP}) \rangle$$
$$= \langle \cos n(\phi - \Phi_{RP}) \rangle \langle \cos n(\Phi_{RP} - \Phi_{EP}) \rangle$$
$$= v_n^{True} \times \text{resolution}_{(n\text{-th order})}$$

2-particle correlation method

$$p_n^{\{2\text{-part}\}} = \langle \cos n(\phi_A - \Phi_{RP}) \rangle \langle \cos n(\phi_B - \Phi_{RP}) \rangle$$
$$= v_n^{\{A\}} \times v_n^{\{B\}}$$

- Rapidity-gap
- Scaler Product (S.P.) method
- 2(4,6,8,) particle cumulant
- Lee Yang Zero



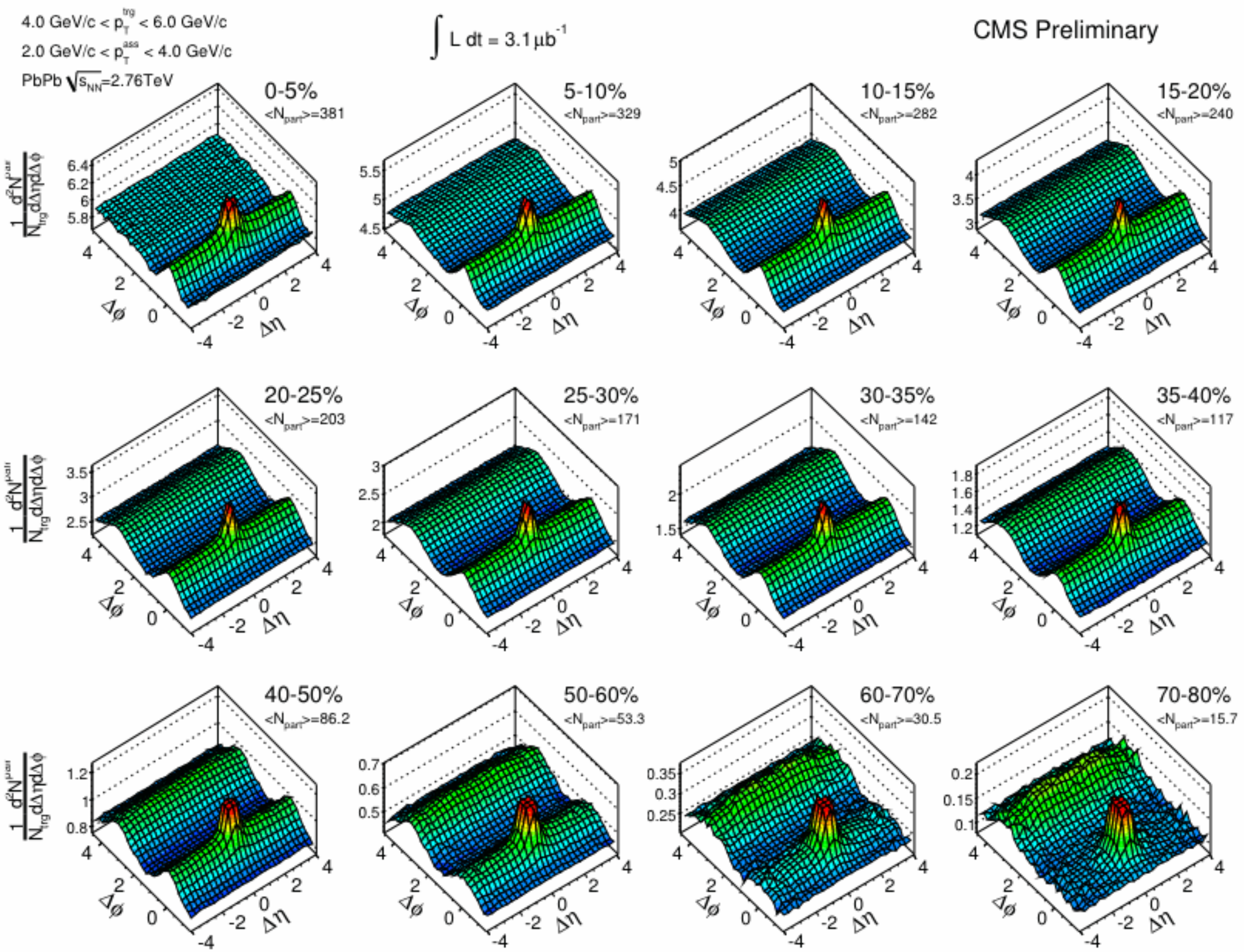
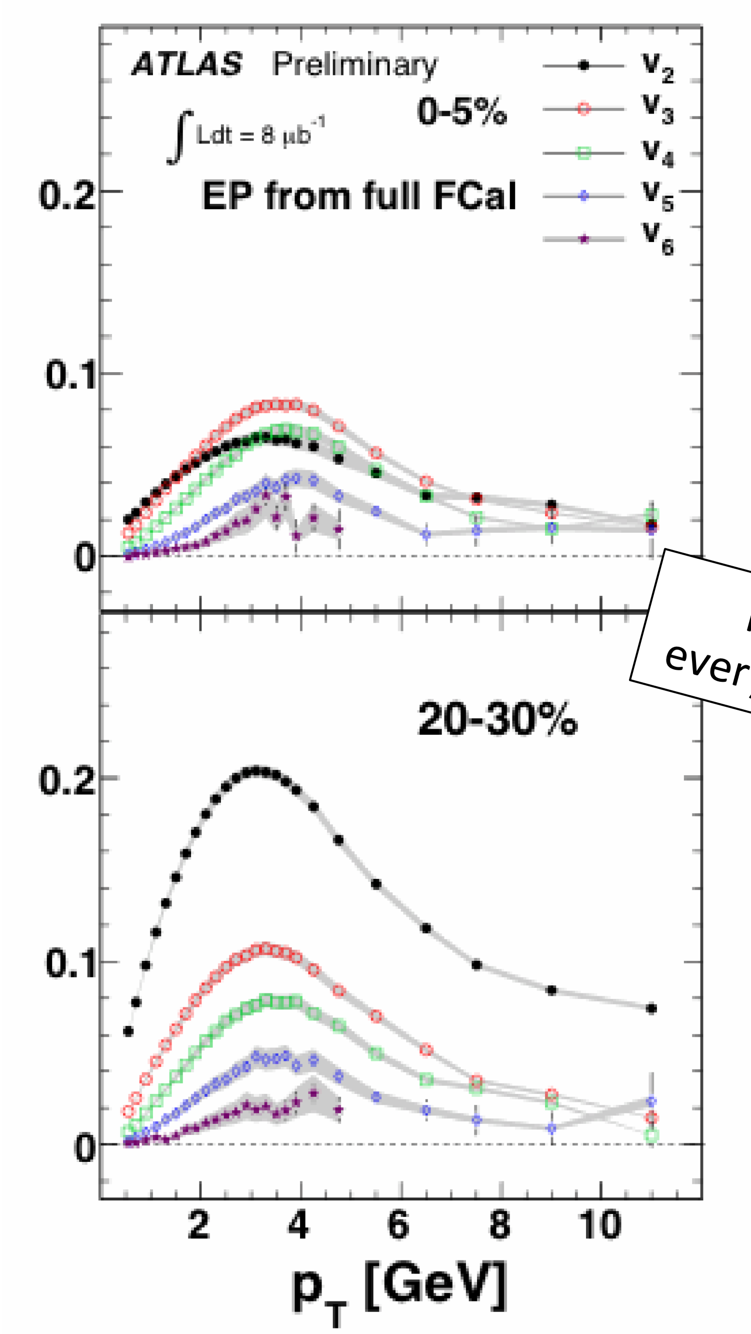
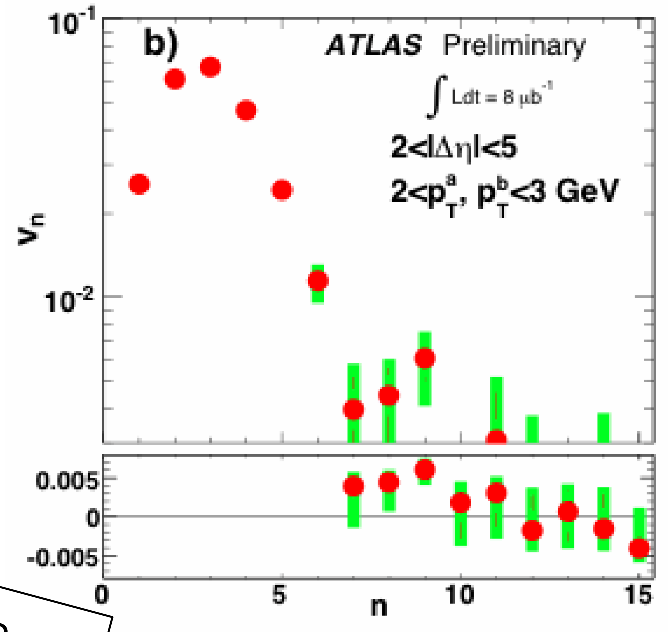
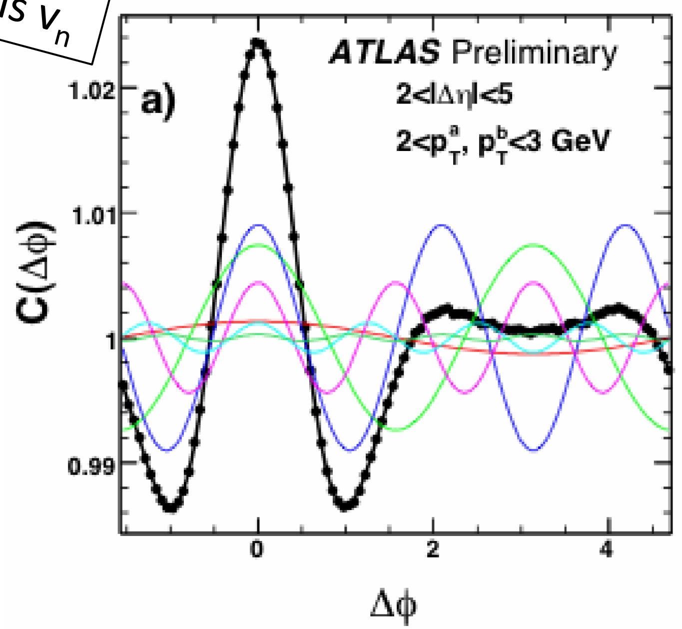


Figure 5: Two-dimensional (2-D) per-trigger-particle associated yield of charged hadrons as a function of $\Delta\eta$ and $\Delta\phi$ for $4 < p_T^{trig} < 6$ GeV/c and $2 < p_T^{assoc} < 4$ GeV/c in 12 centrality classes of PbPb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. The centrality labeling is such that 0-5% is the most central five percent of PbPb collisions.



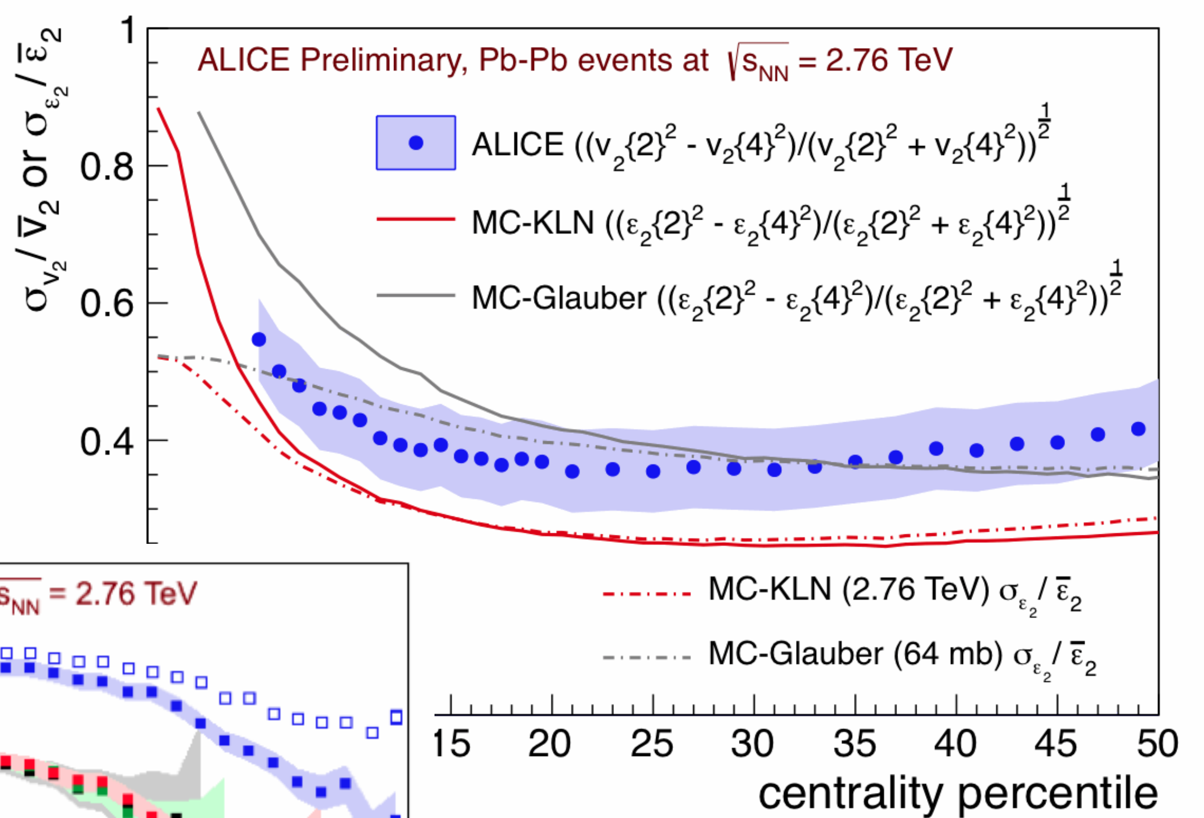
no ridge
everything is v_n

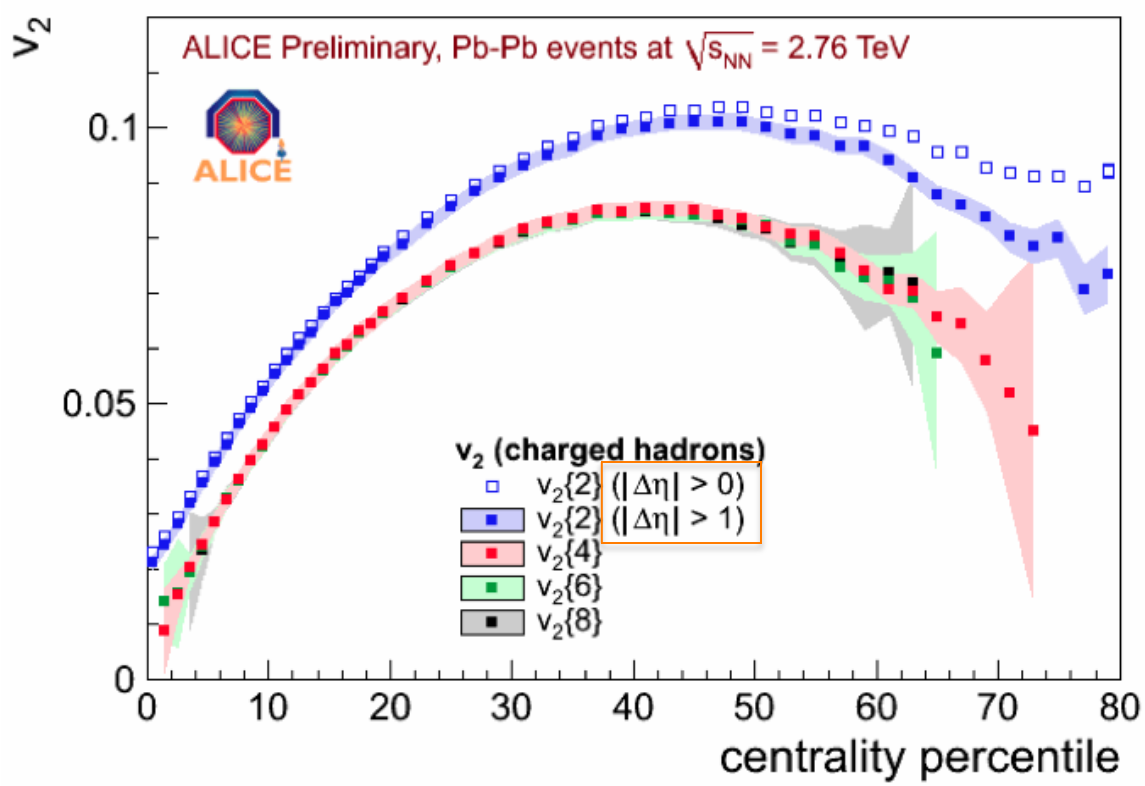




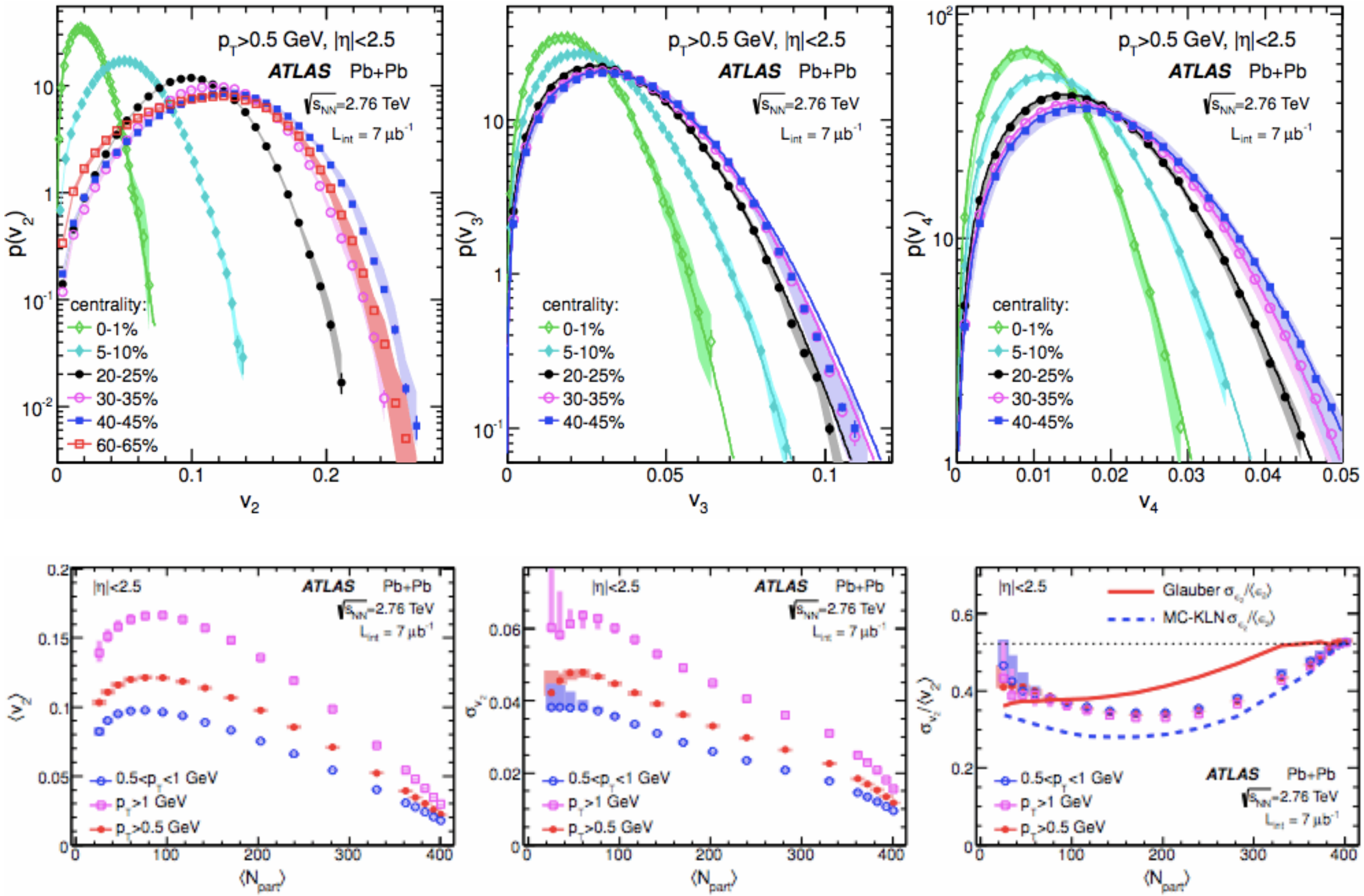
Measurement of v2 fluctuation

--- via v2{2} and v2{4} difference ----





The next page show the same v2 fluctuation measurement of event-by-event directly

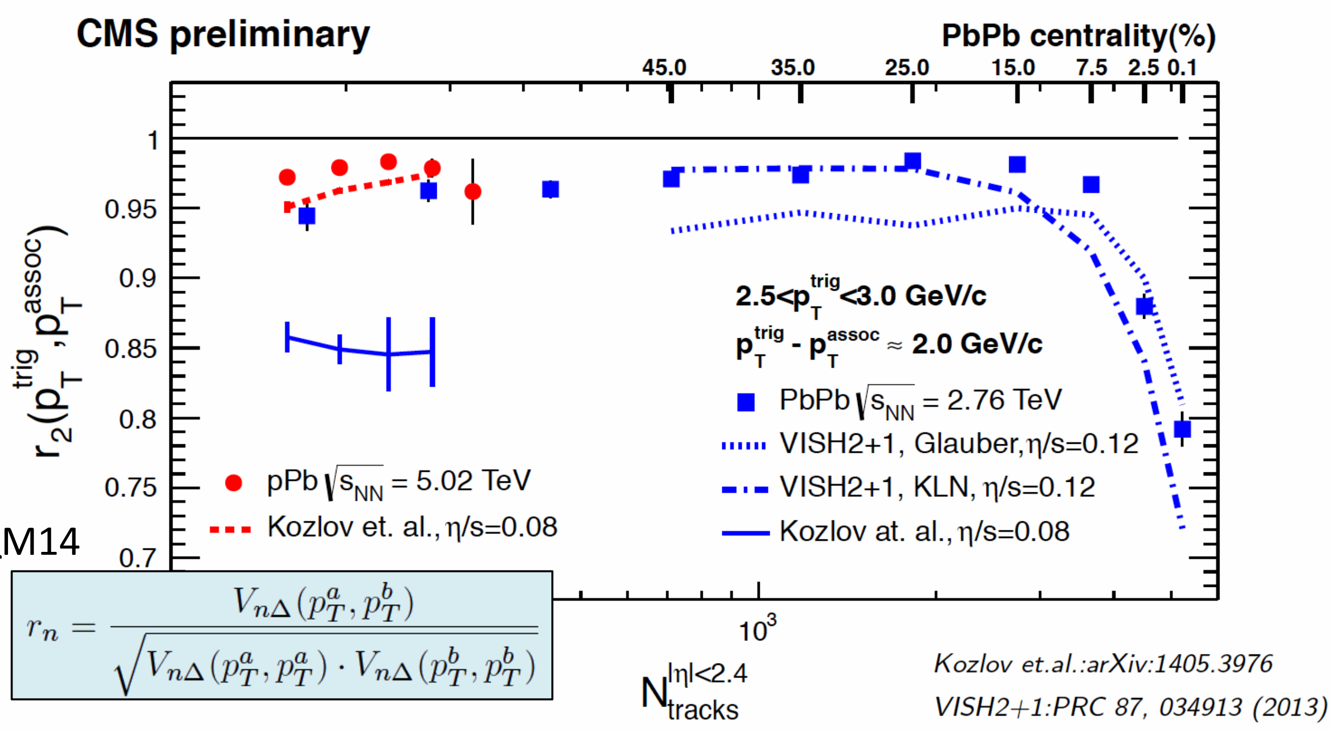


p_T>0.5 GeV, |η|<2.5
ATLAS Pb+Pb
√s_NN=2.76 TeV
L_int = 7 μb^-1
centrality:
0-1%
5-10%
20-25%
30-35%
40-45%
60-65%
p(v_2)
v_2
p(v_3)
v_3
p(v_4)
v_4
|η|<2.5
⟨v_2⟩
σ_v2
σ_v2/⟨v_2⟩
⟨N_part⟩
0.5<p_T<1 GeV
p_T>1 GeV
p_T>0.5 GeV
Glauber σ_ε2/⟨ε_2⟩
MC-KLN σ_ε2/⟨ε_2⟩

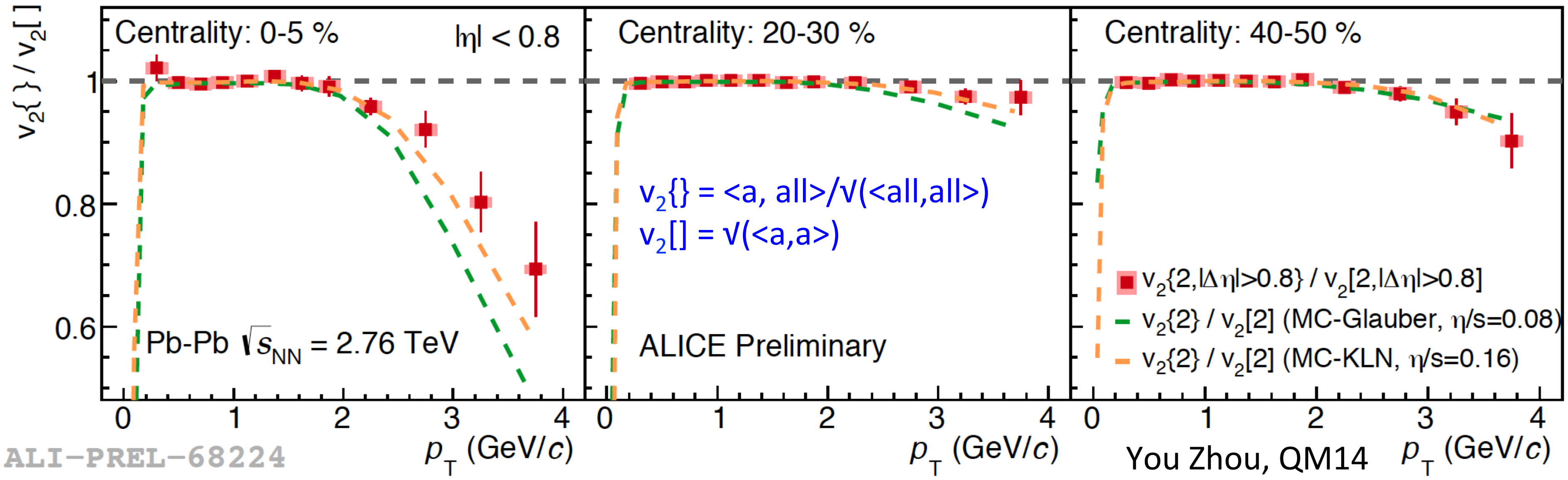
p_T dependent flow fluctuation

amazing similarity
in hydro-models
especially at mid-pT
and in central…

Damir Devetak, QM14



$$r_n = \frac{V_{n\Delta}(p_T^a, p_T^b)}{\sqrt{V_{n\Delta}(p_T^a, p_T^a) \cdot V_{n\Delta}(p_T^b, p_T^b)}}$$



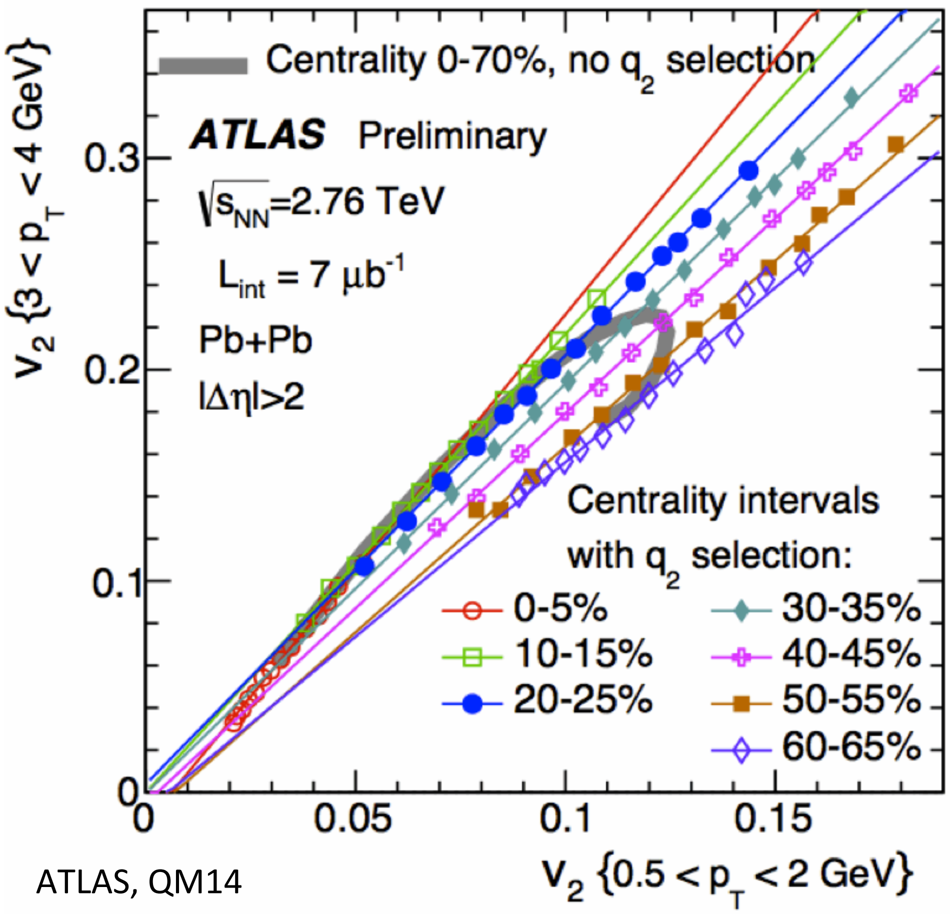
$v_2\{\} = <a, all>/\sqrt{(<all,all>)}$

$v_2[] = \sqrt{(<a,a>)}$

You Zhou, QM14

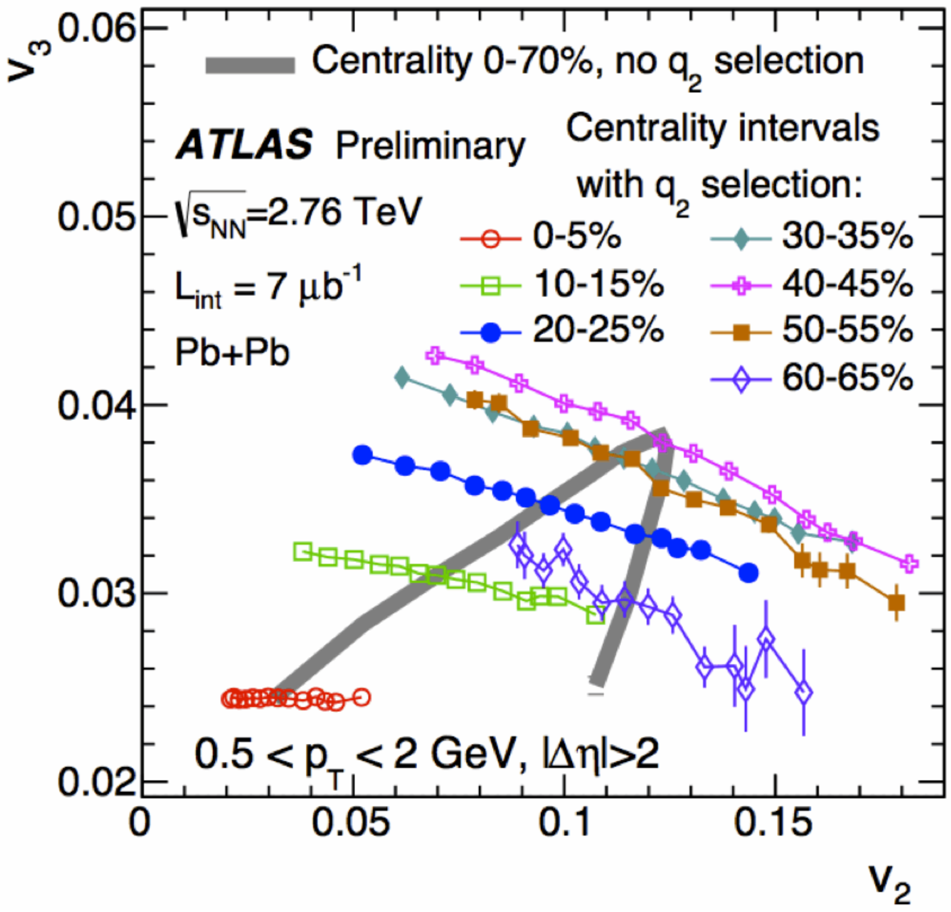
Cross harmonics correlation with Q_2 selection (v_nゆらぎの相関)

$v_2^{(\text{Low pT})}$ vs $v_2^{(\text{high pT})}$



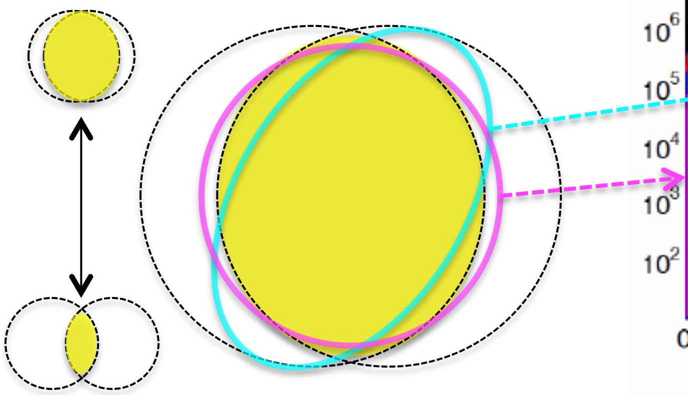
ATLAS, QM14

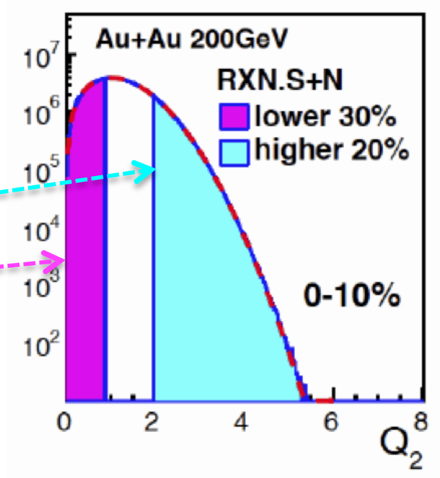
v_2 vs v_3



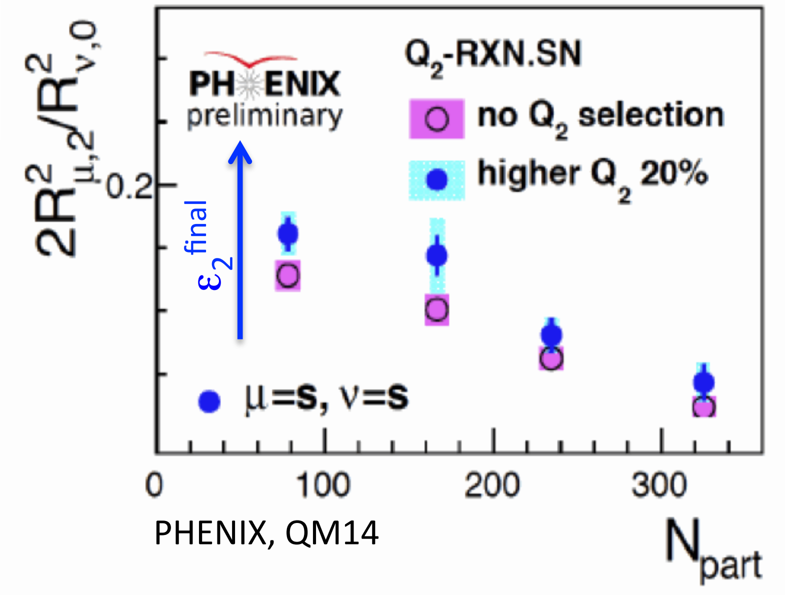
Event shape selection Q_2 (~v_2)

relation of $\varepsilon_2^{initial} - v_2 - \varepsilon_2^{final}$
for a given centrality



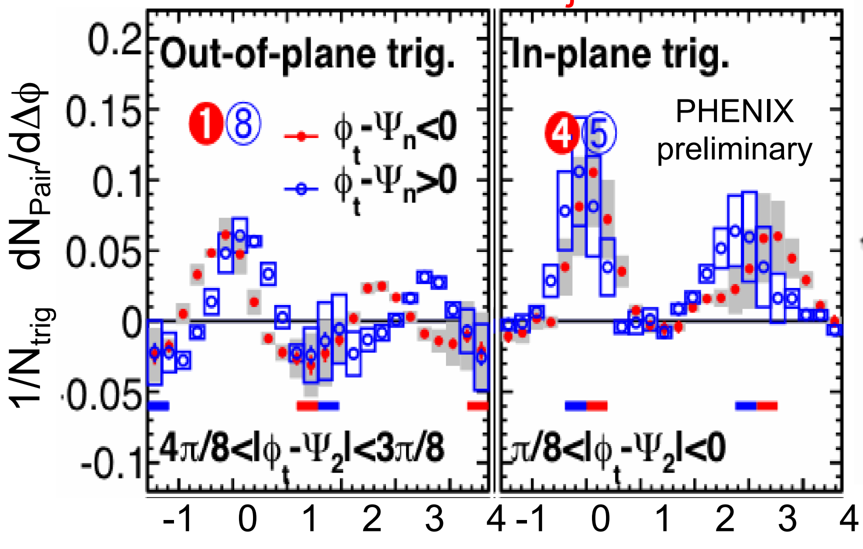


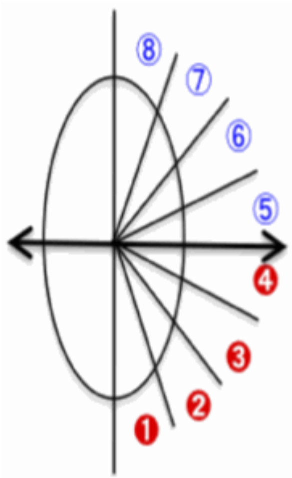
ε_{final} via HBT interferometry



PHENIX, QM14

flow BG subtracted jet correlation

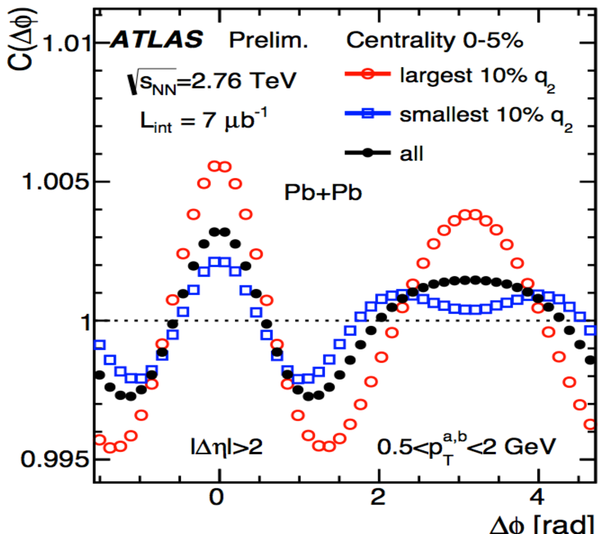




PHENIX, QM12

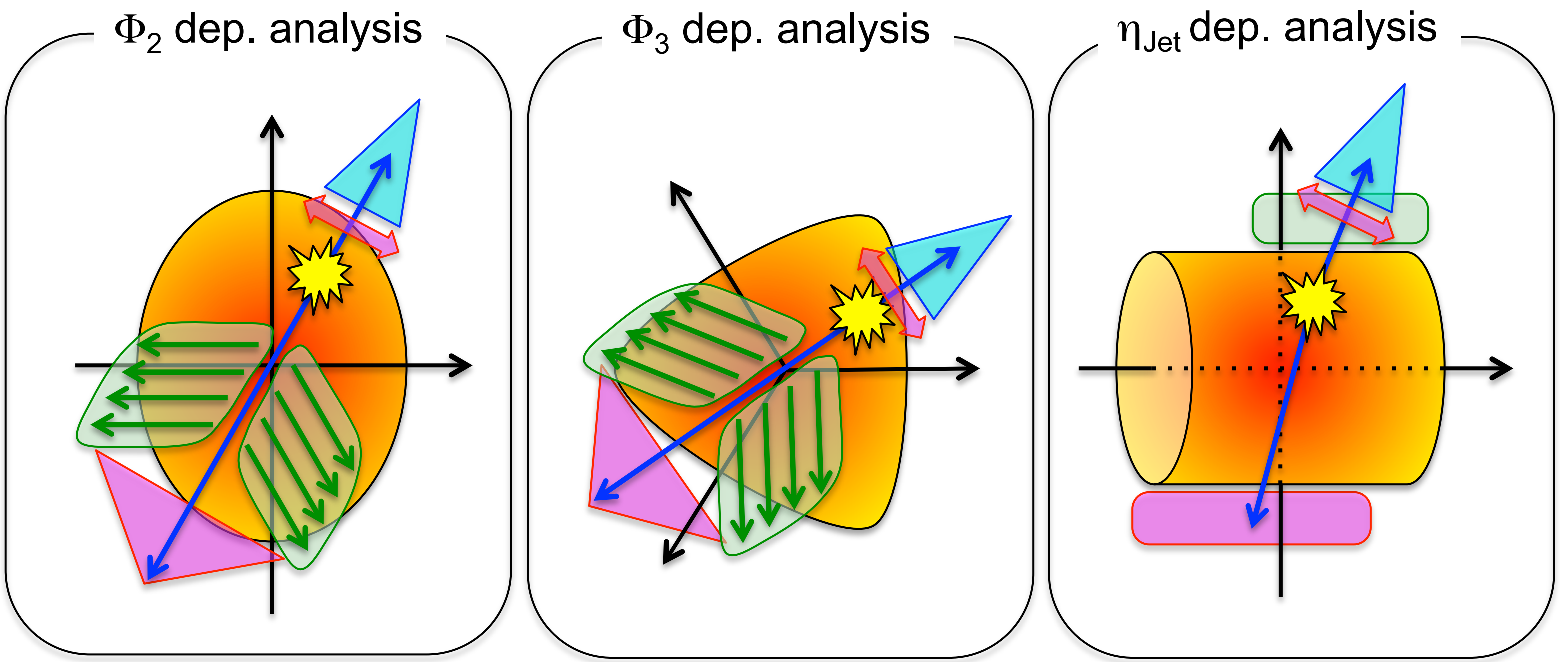
$\Delta\phi = \phi_{Asso.} - \phi_{Trig.}$

2-particle correlation



ATLAS, QM14

Further tests of hard-soft interplay using correlation between jet modification and geometry/expansion of QGP



methods

- Multi-particle correlation
- Jet-hadron / γ-hadron correlation
- Jet fragmentation function
- Di-jet distribution

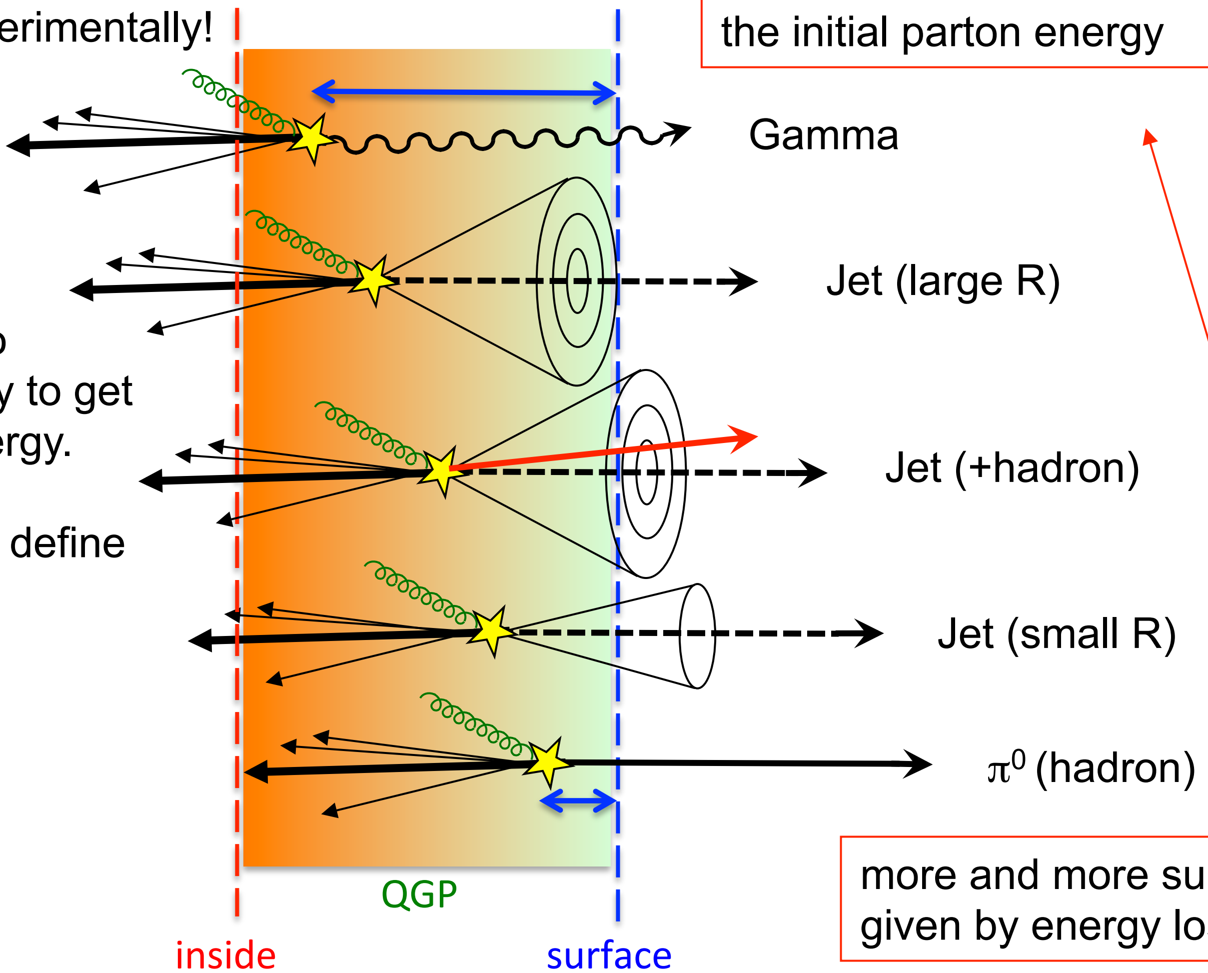
Yet another axis as a control parameter
to define path length, geometry and expansion.

Systematic test of energy loss and redistribution with photons, jets and hadrons

These two effects (energy loss and redistribution) can not be clearly separated experimentally!

Jet reconstruction is to recover the lost energy to get the original parton energy.

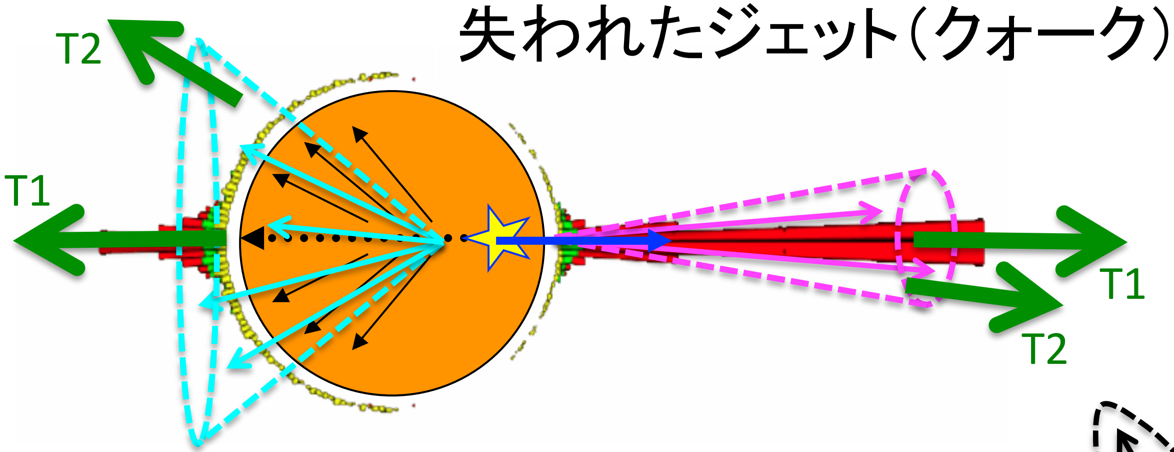
Jet as a control tool to define path length



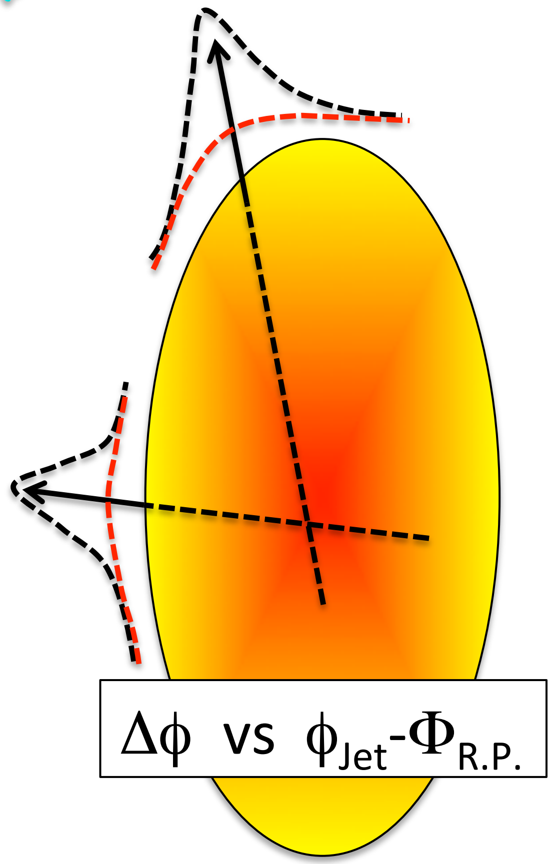
Closer and closer to the initial parton energy

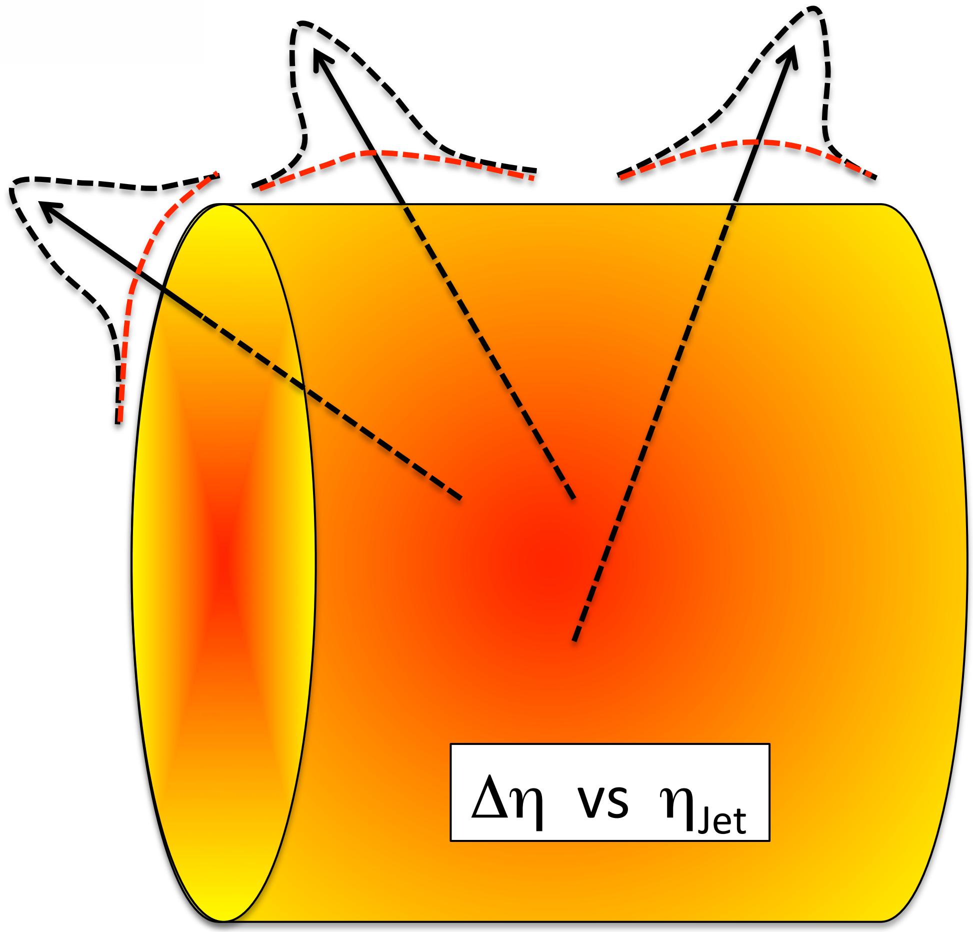
more and more surface bias given by energy loss

失われたジェット（クォーク）のエネルギーはどこへ？

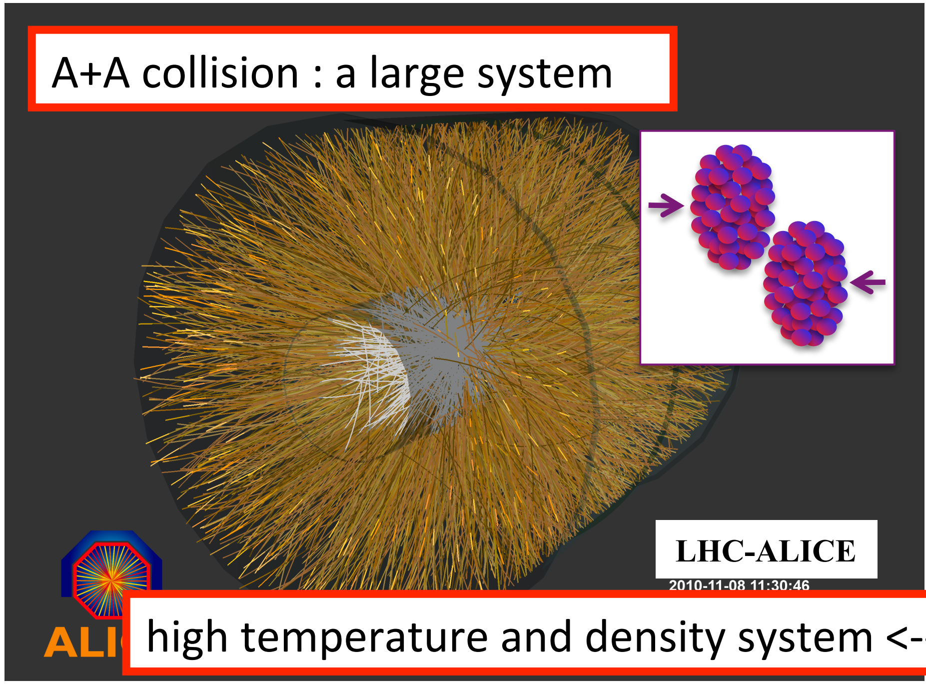


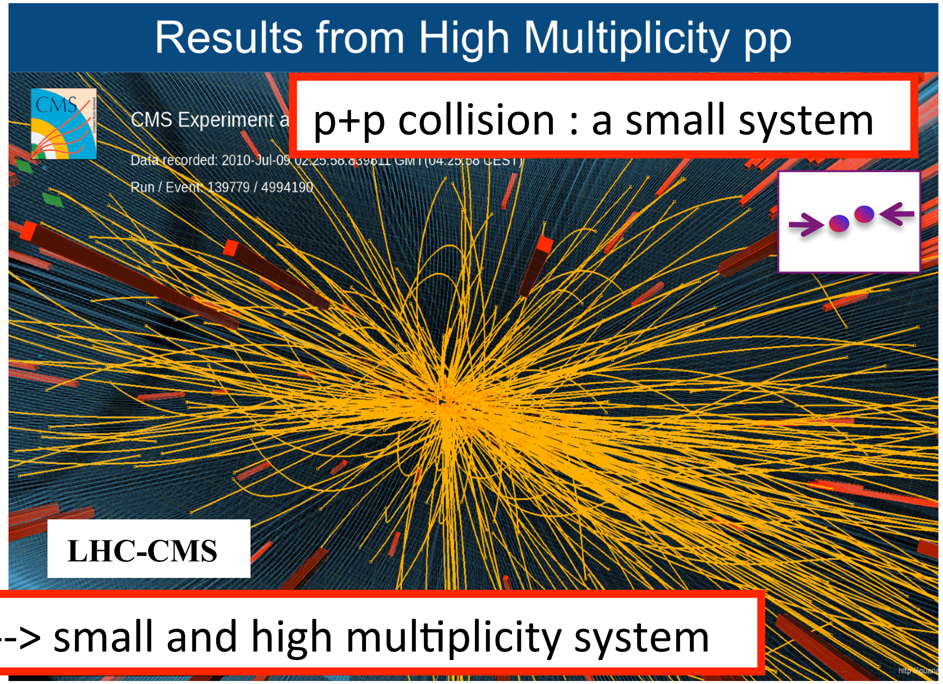
ジェット軸に対する
粒子相関分布の変化





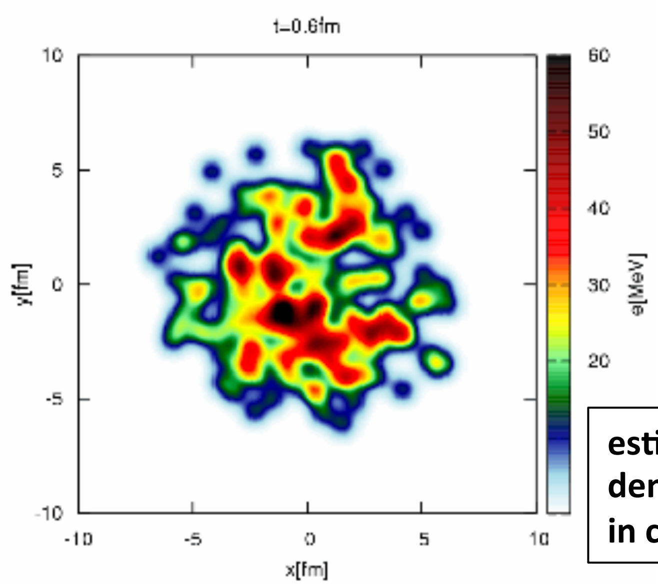
A+A collision : a large system





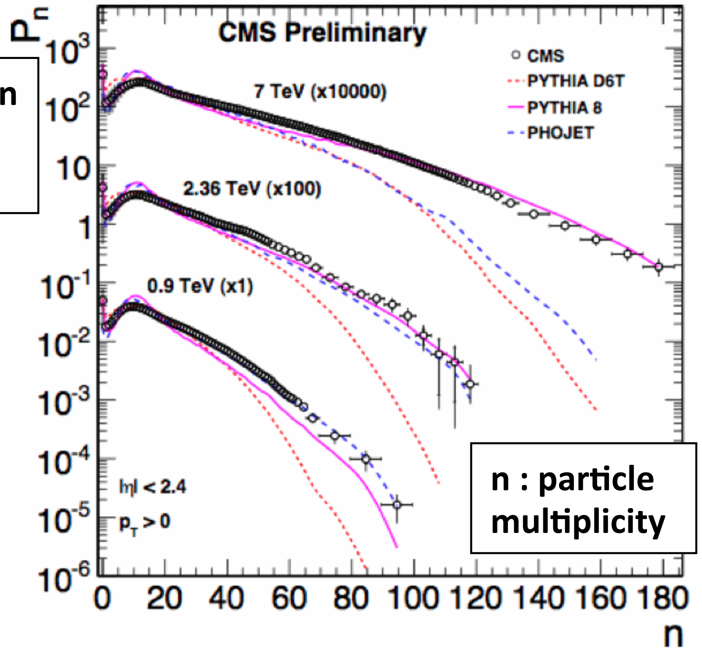
p+p collision : a small system

high temperature and density system <---> small and high multiplicity system

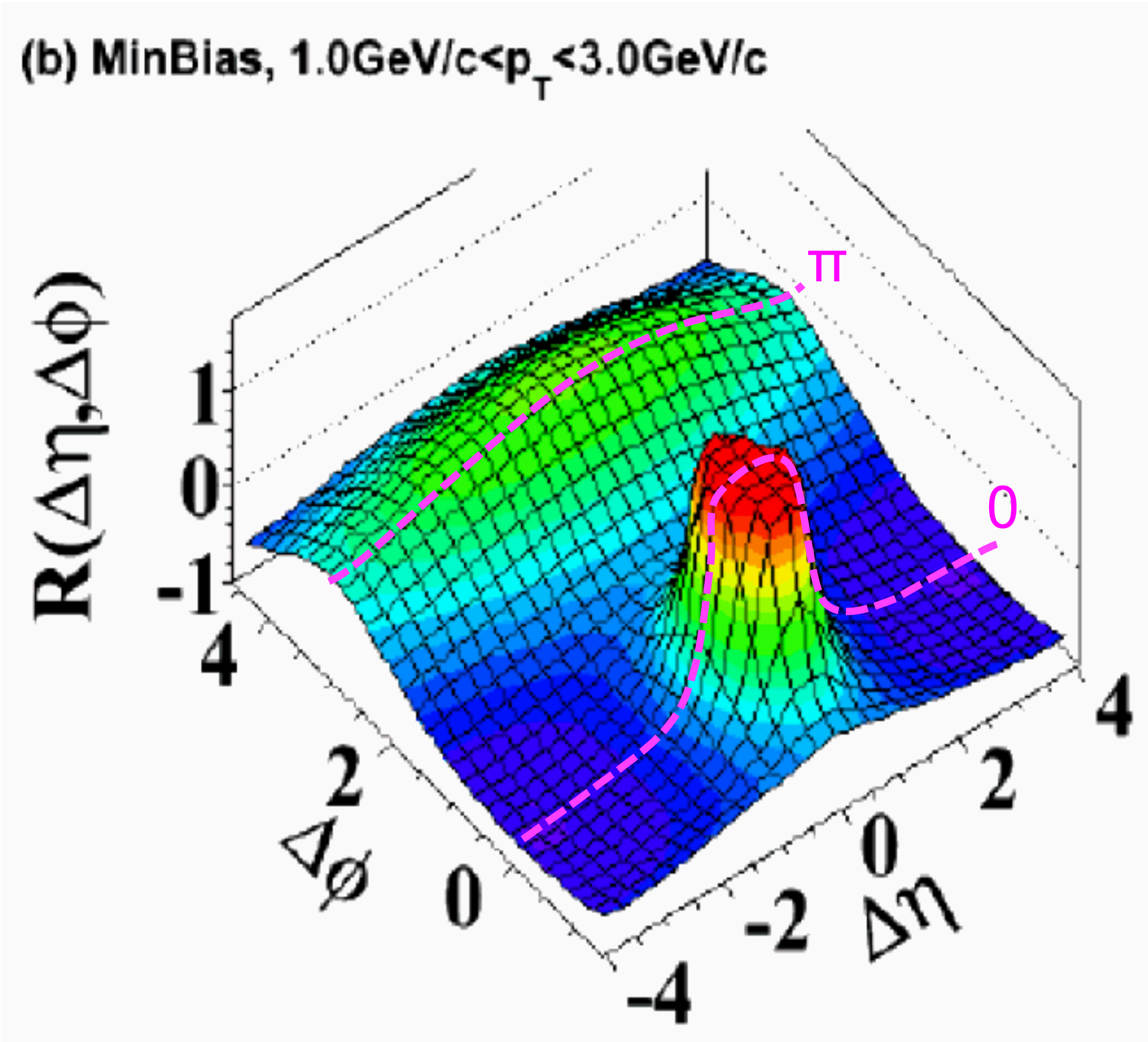


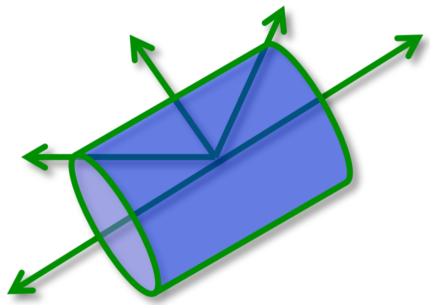
estimated initial energy density distribution in central A+A collision

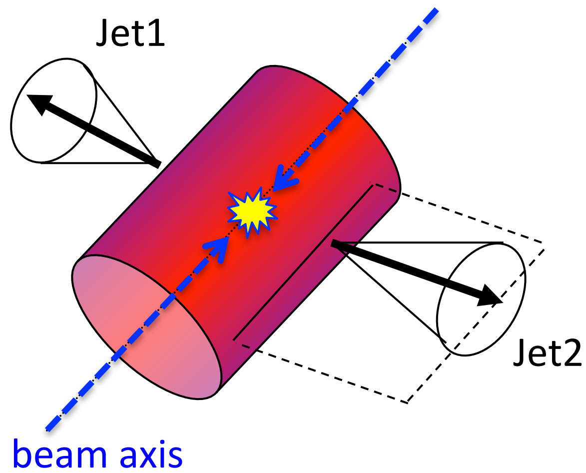
Probability distribution of event with "n" particles production



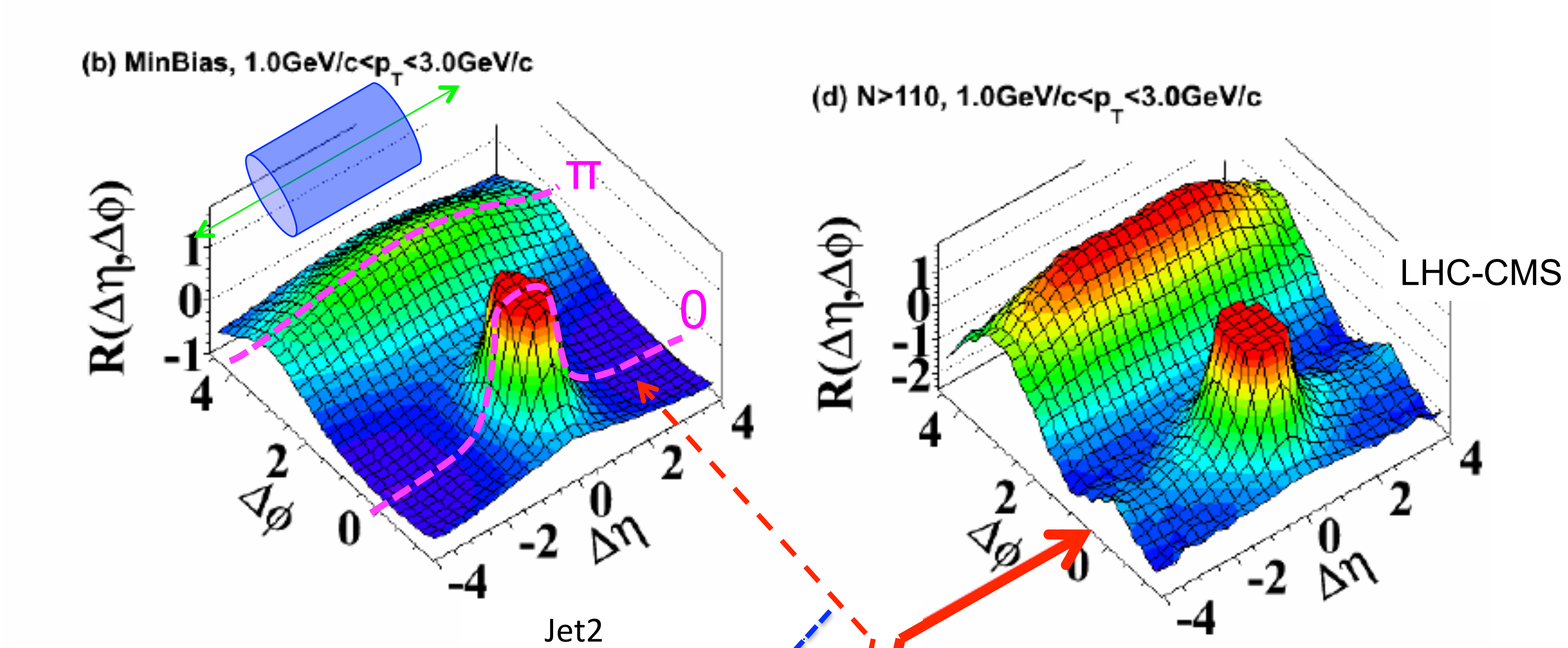
n : particle multiplicity

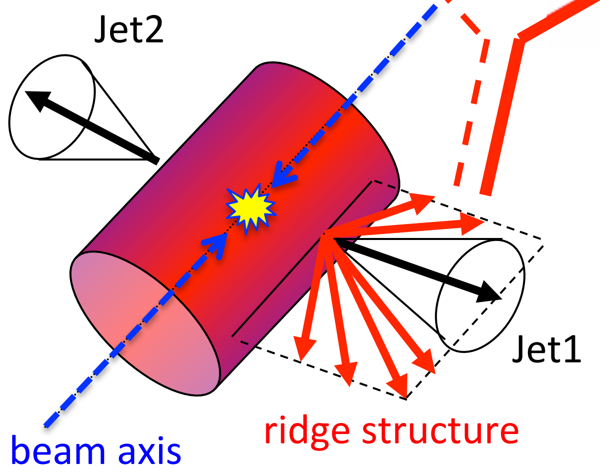

(b) MinBias, 1.0GeV/c<p_T<3.0GeV/c
R(Δη,Δφ)
1
0
-1
4
2
Δφ
0
-4
-2
0
Δη
2
4
π
0




Jet1
Jet2
beam axis

minimum bias p+p events ⟷ high multiplicity p+p events

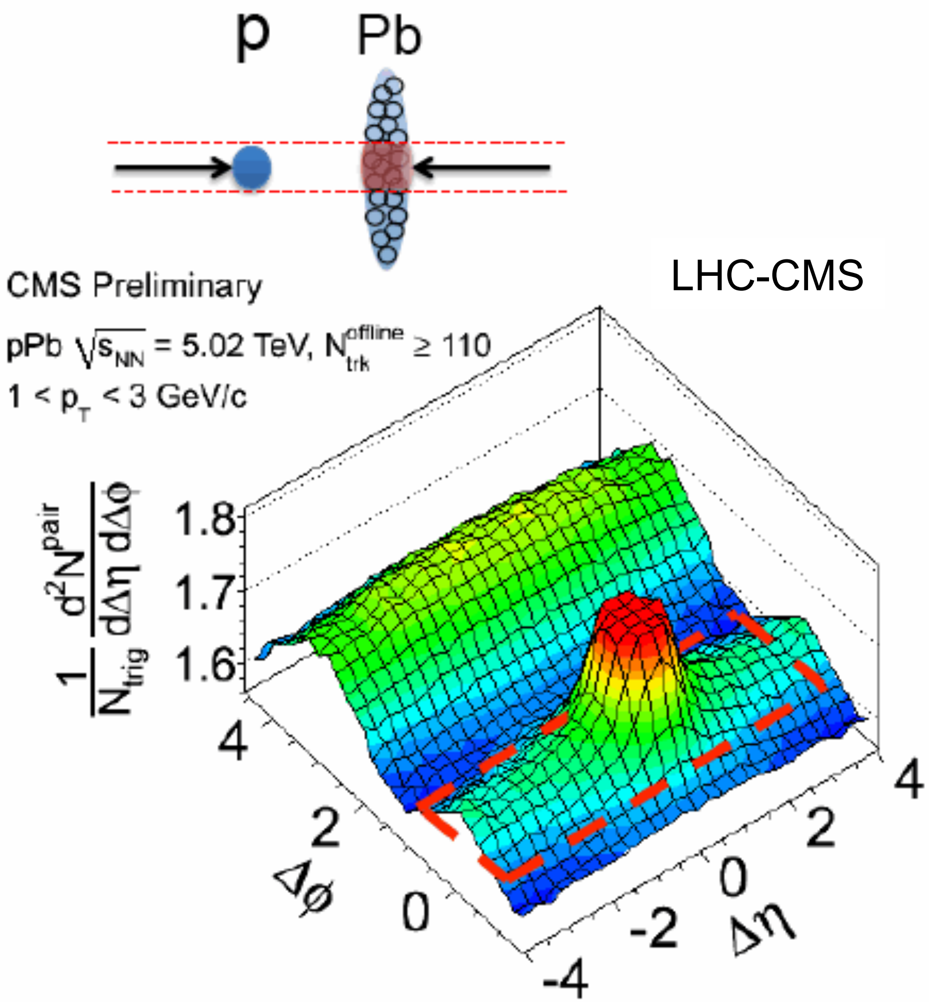


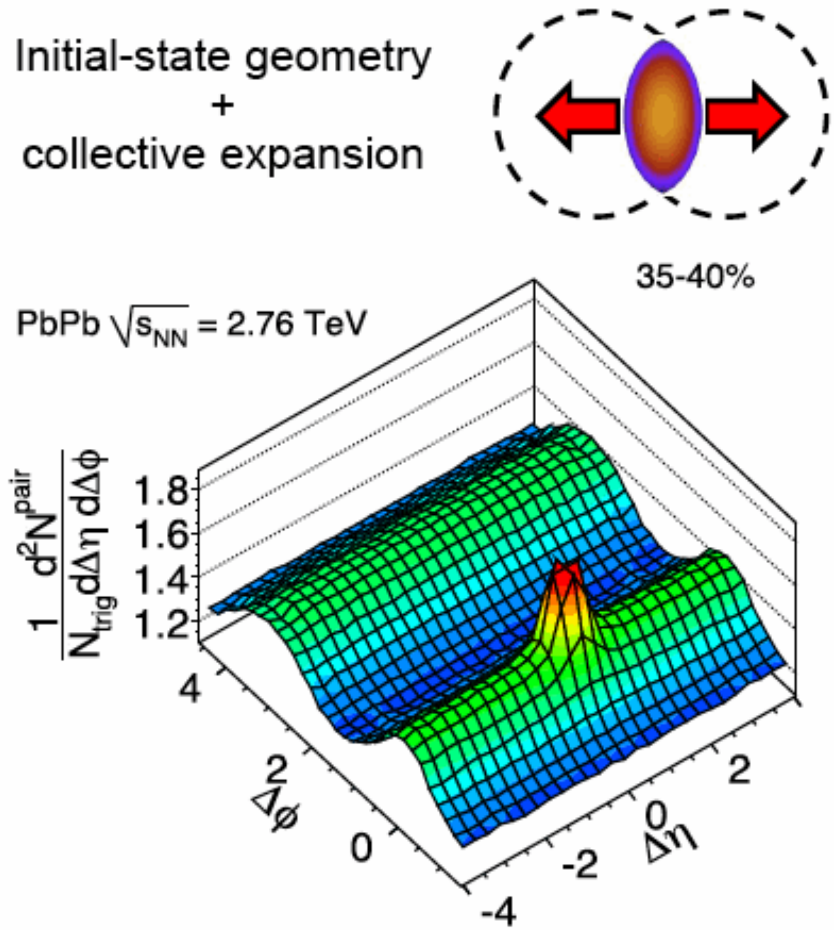


- inter-correlation between di-jets
- correlated multi-parton interactions
- collective behavior in small and dense system

p+A collisions

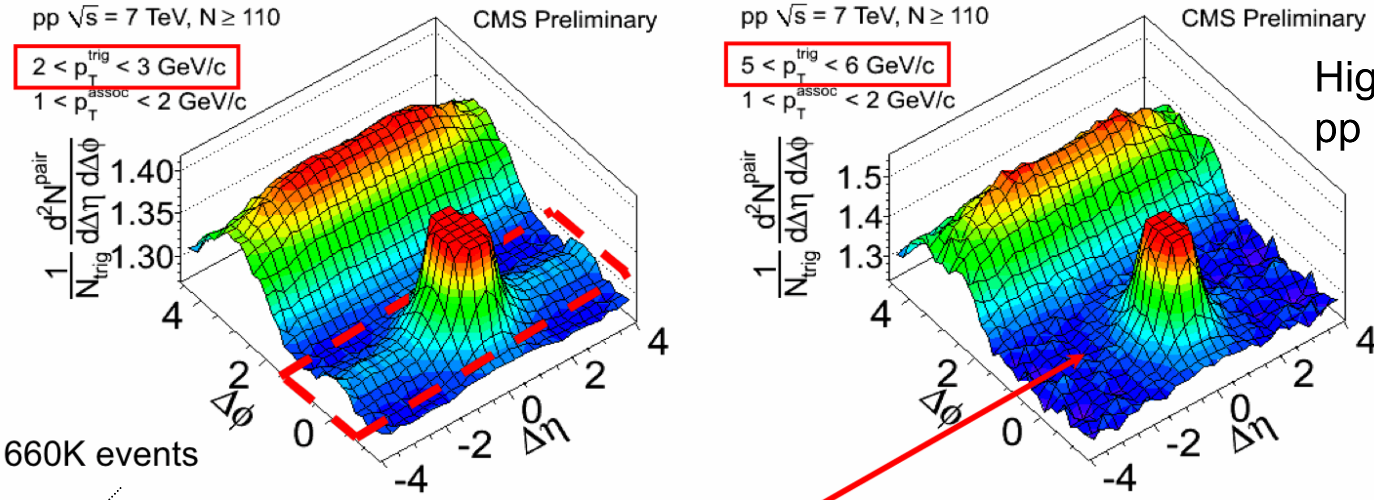
A+A collisions





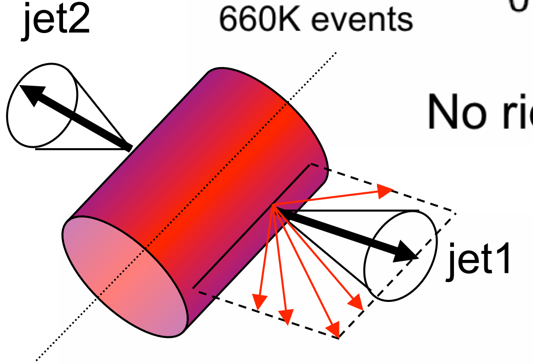
100 billion (1.78 pb^{-1}) sampled minimum bias events from high-multiplicity trigger

LHC-CMS



High multiplicity
pp collisions

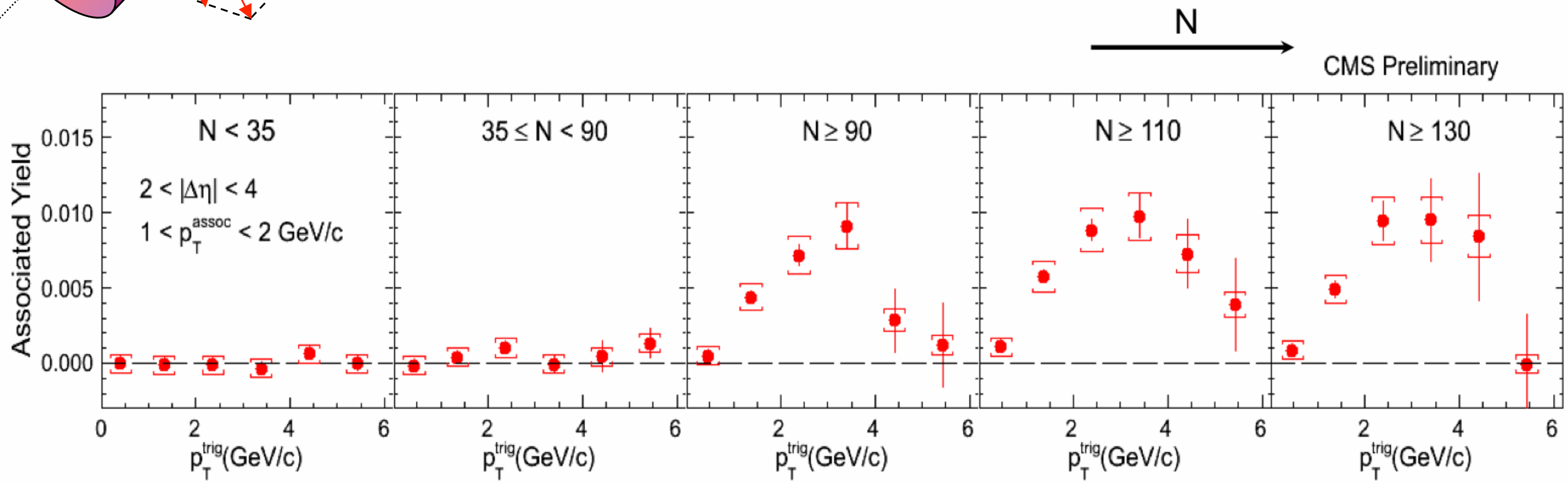
660K events



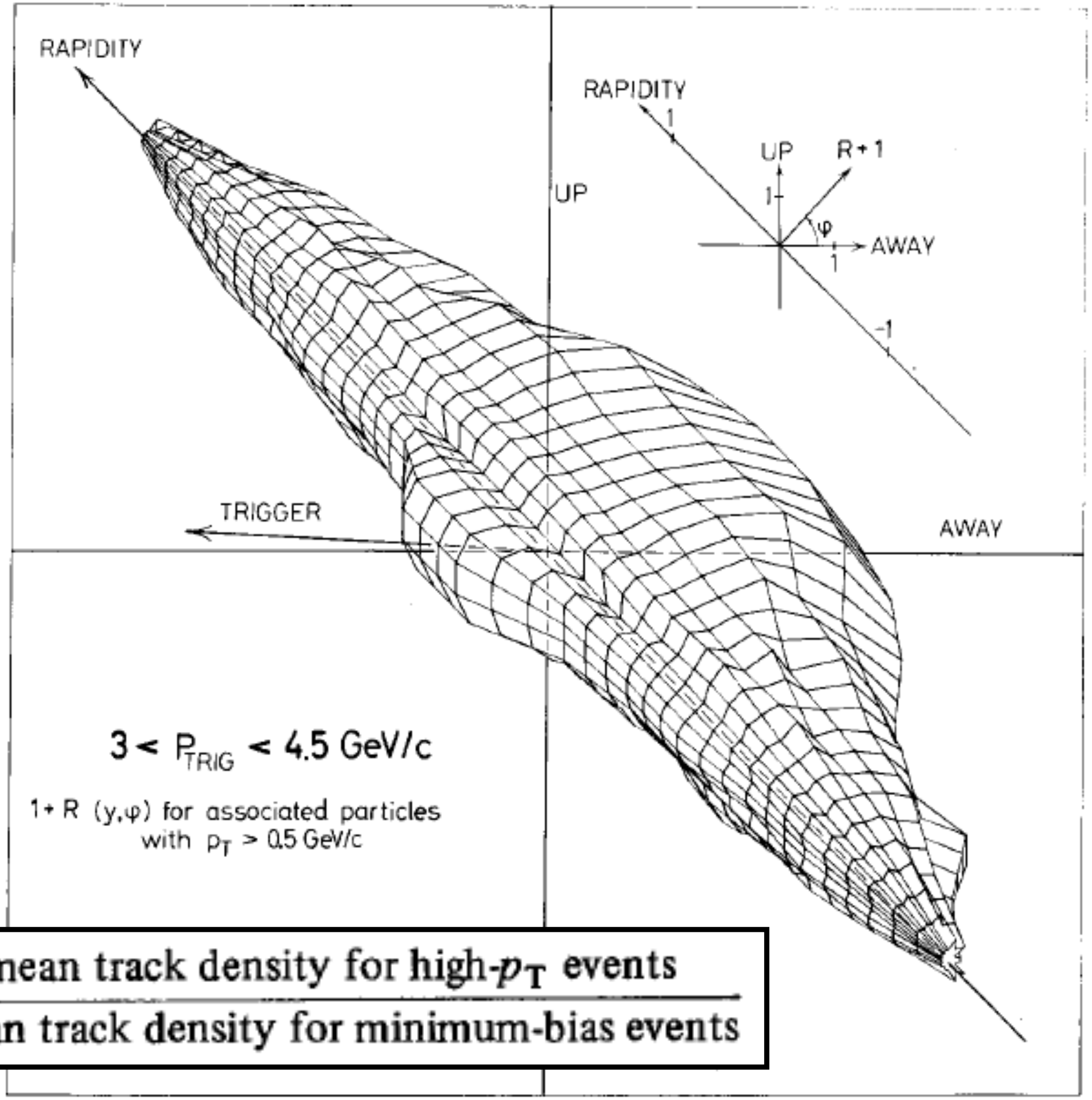
No ridge when correlating to high p_T particles!

Ridge region ($2<|\Delta\eta|<4$)

Only around
p_T = 2~4GeV/c



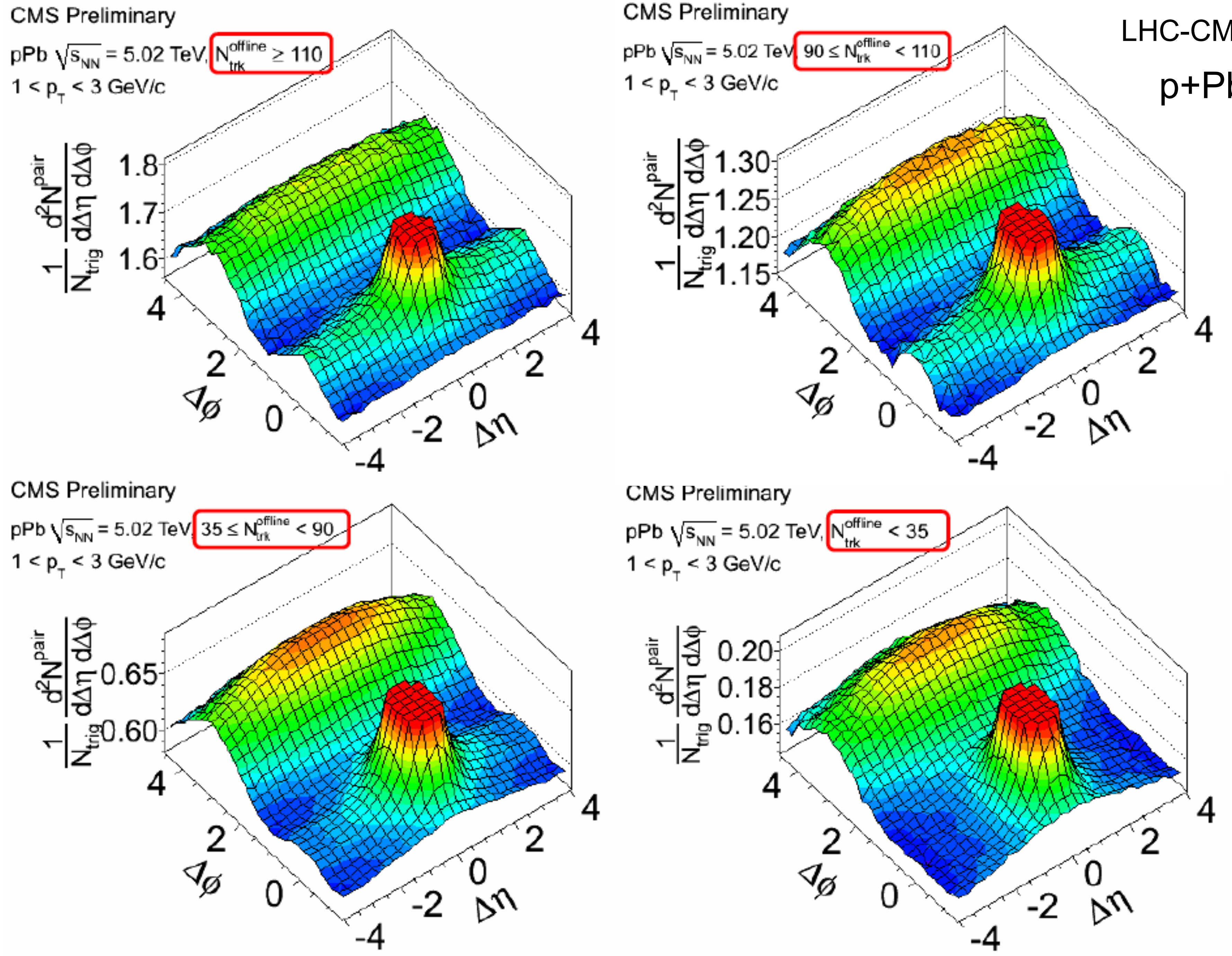
CERN-ISR
Nucl. Phys. B145
(1978) 305-348



$$R + 1 \approx \frac{\text{mean track density for high-}p_T\text{ events}}{\text{mean track density for minimum-bias events}}$$

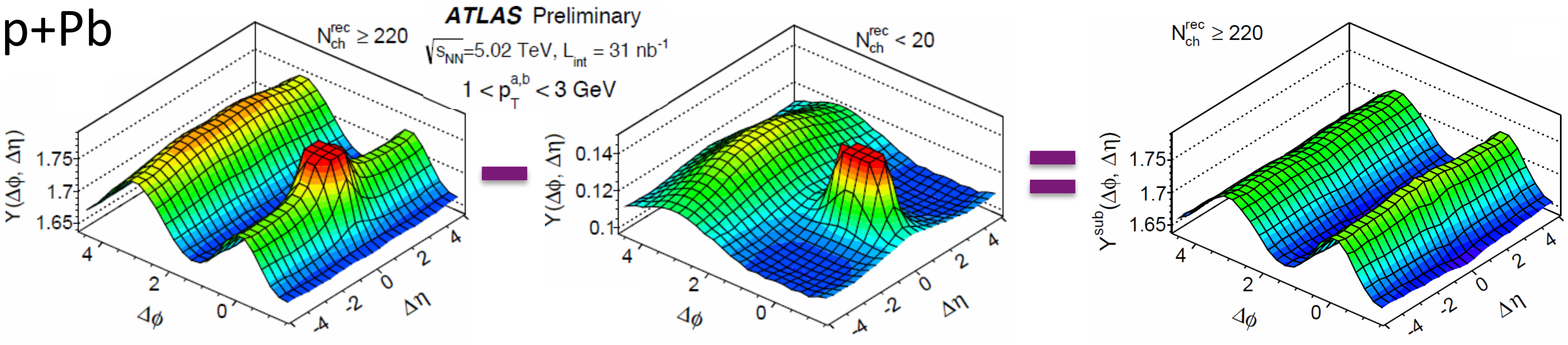
LHC-CMS

p+Pb

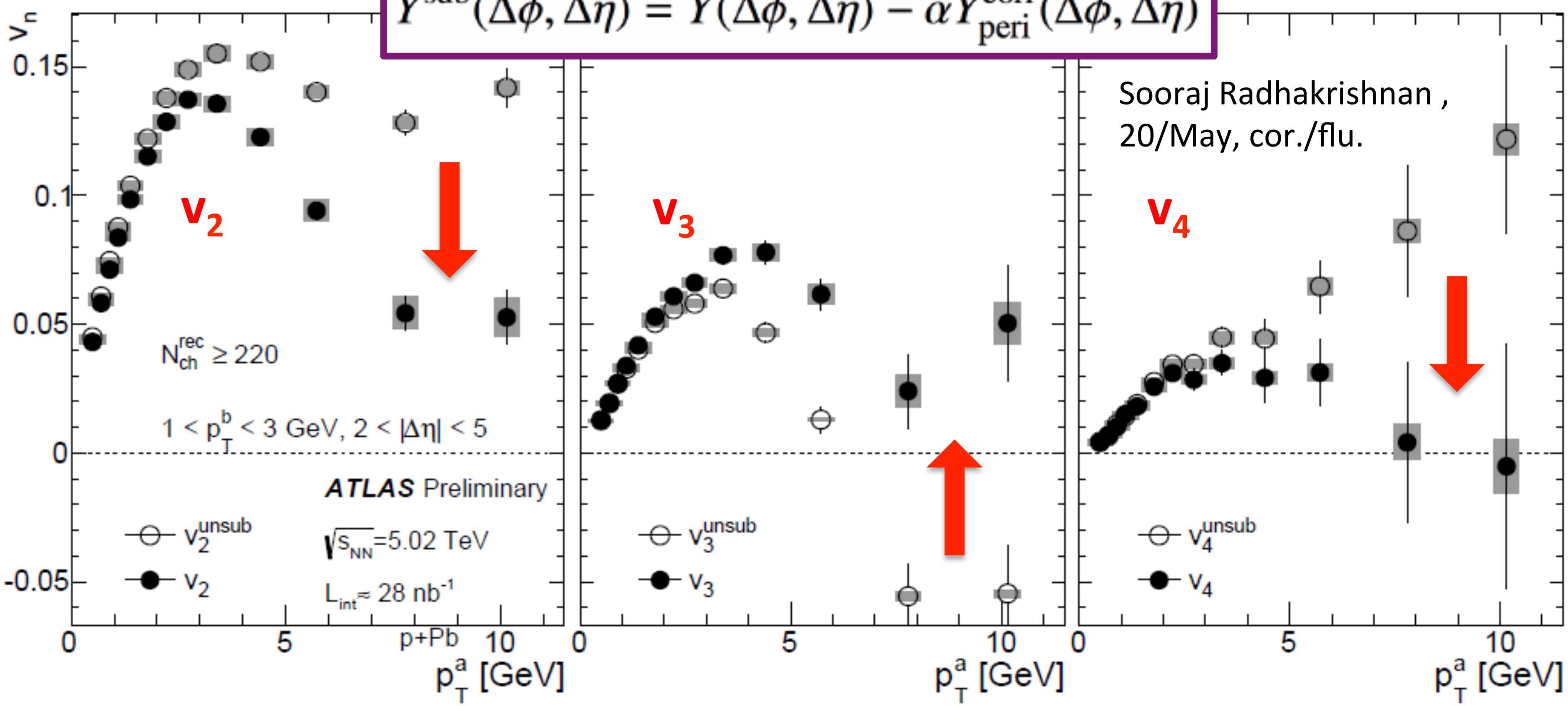


CMS Preliminary
pPb $\sqrt{s_{NN}}$ = 5.02 TeV, $N_{trk}^{offline} \geq 110$
1 < p_T < 3 GeV/c
CMS Preliminary
pPb $\sqrt{s_{NN}}$ = 5.02 TeV, $90 \leq N_{trk}^{offline} < 110$
1 < p_T < 3 GeV/c
CMS Preliminary
pPb $\sqrt{s_{NN}}$ = 5.02 TeV, $35 \leq N_{trk}^{offline} < 90$
1 < p_T < 3 GeV/c
CMS Preliminary
pPb $\sqrt{s_{NN}}$ = 5.02 TeV, $N_{trk}^{offline} < 35$
1 < p_T < 3 GeV/c
$\frac{1}{N_{trig}} \frac{d^2N^{pair}}{d\Delta\eta\, d\Delta\phi}$
$\Delta\phi$
$\Delta\eta$

p+Pb

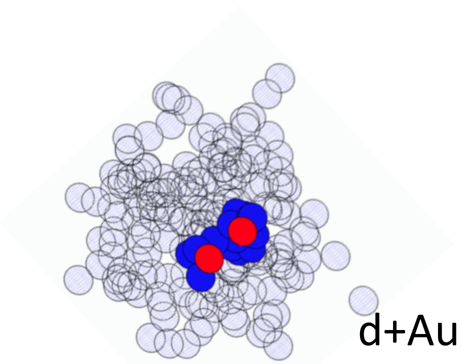


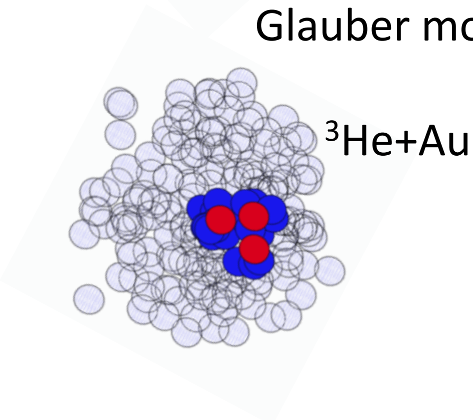
$$Y^{\rm sub}(\Delta\phi,\Delta\eta) = Y(\Delta\phi,\Delta\eta) - \alpha Y^{\rm corr}_{\rm peri}(\Delta\phi,\Delta\eta)$$



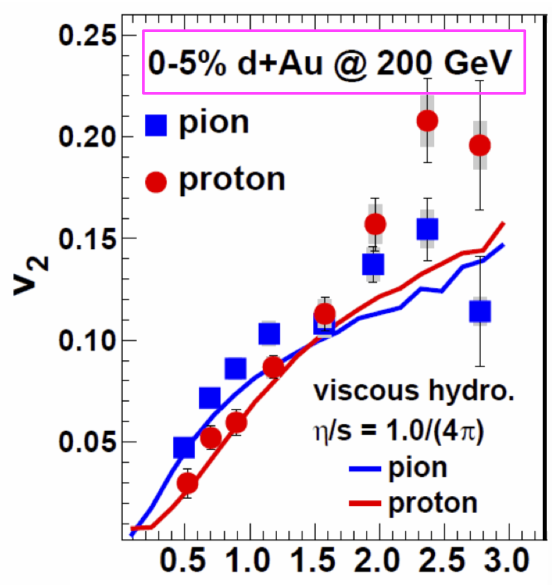
Sooraj Radhakrishnan ,
20/May, cor./flu.

Elliptic flow in small system?

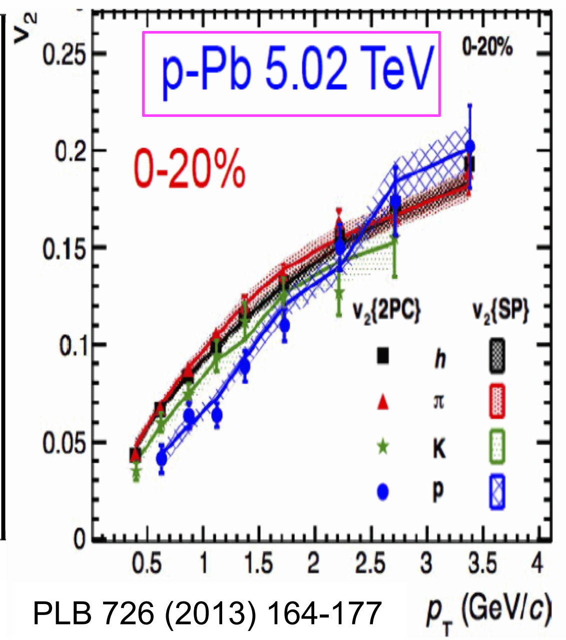




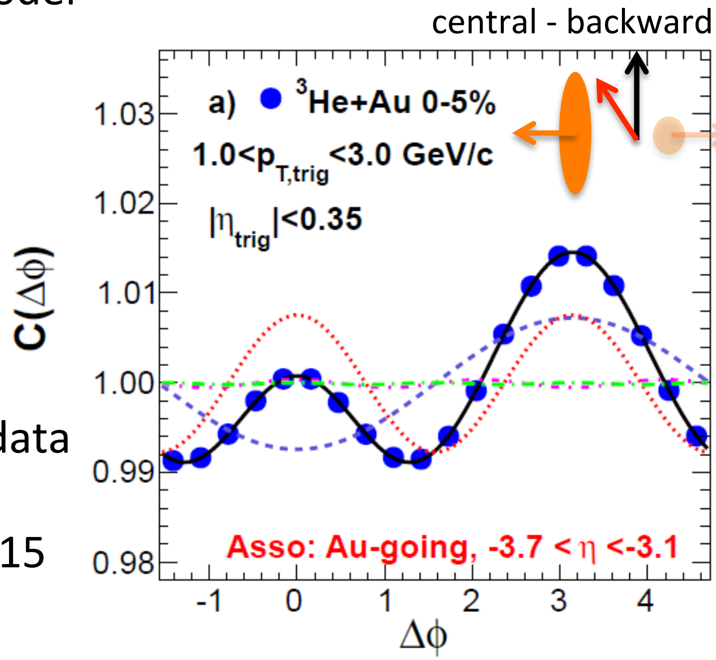
Glauber model

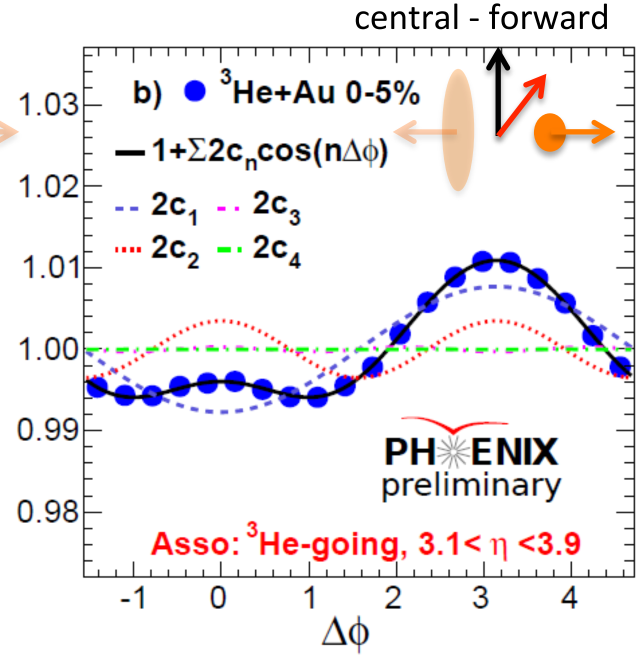


arXiv:1404.7461



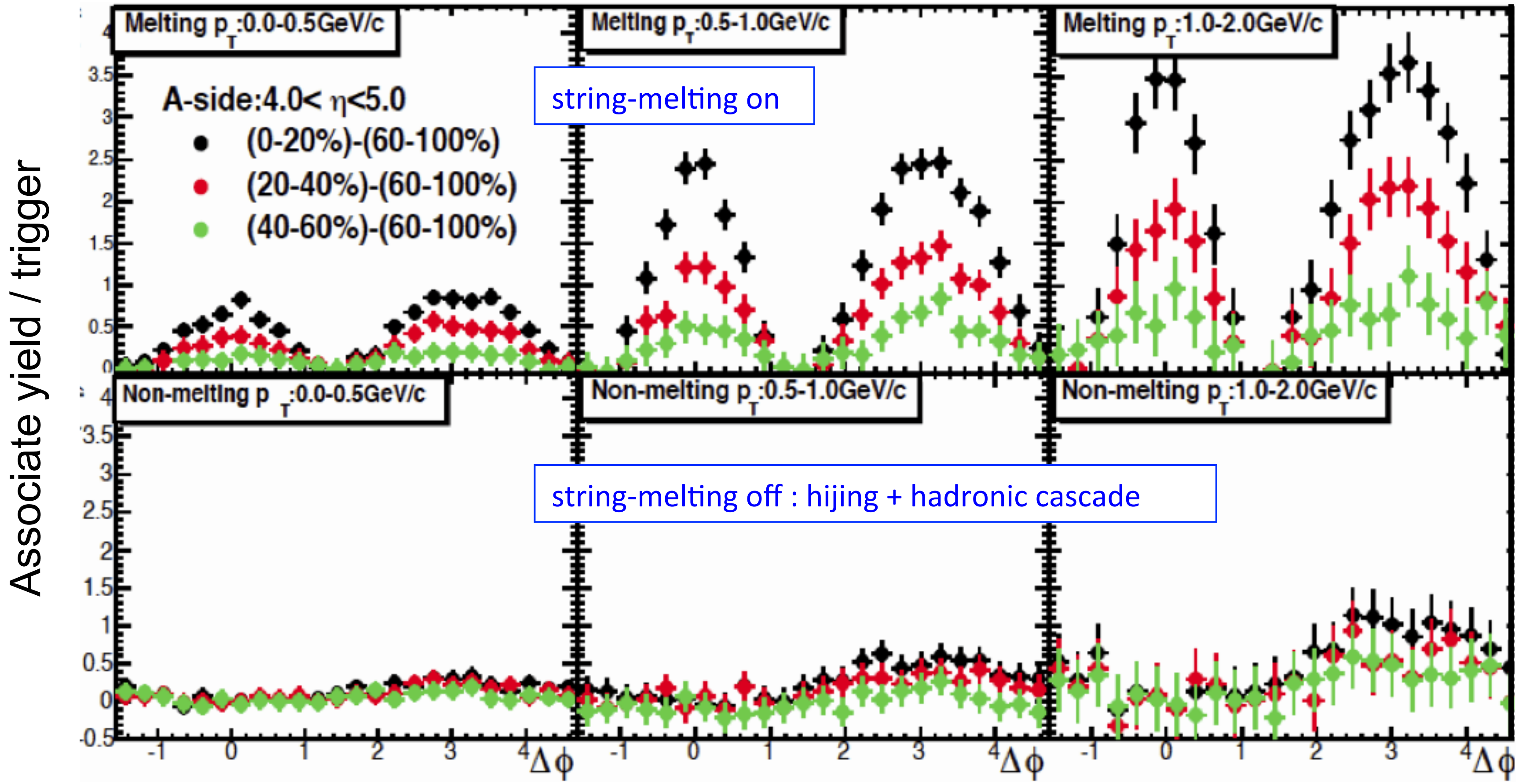
PLB 726 (2013) 164-177





* New ^{3}He+Au collision data from RHIC-RUN14
* p+p, p+Al, p+Pb in Run15 will come

AMPT simulation p+Pb 5TeV (string-melting on/off)
for ALICE backward-central Δφ correlation (|Δη|=3~6)



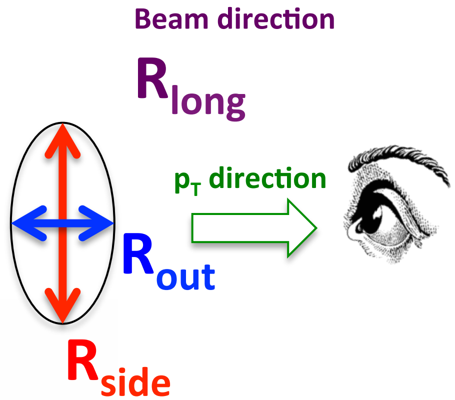
effectively partonic cascade : on/off

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

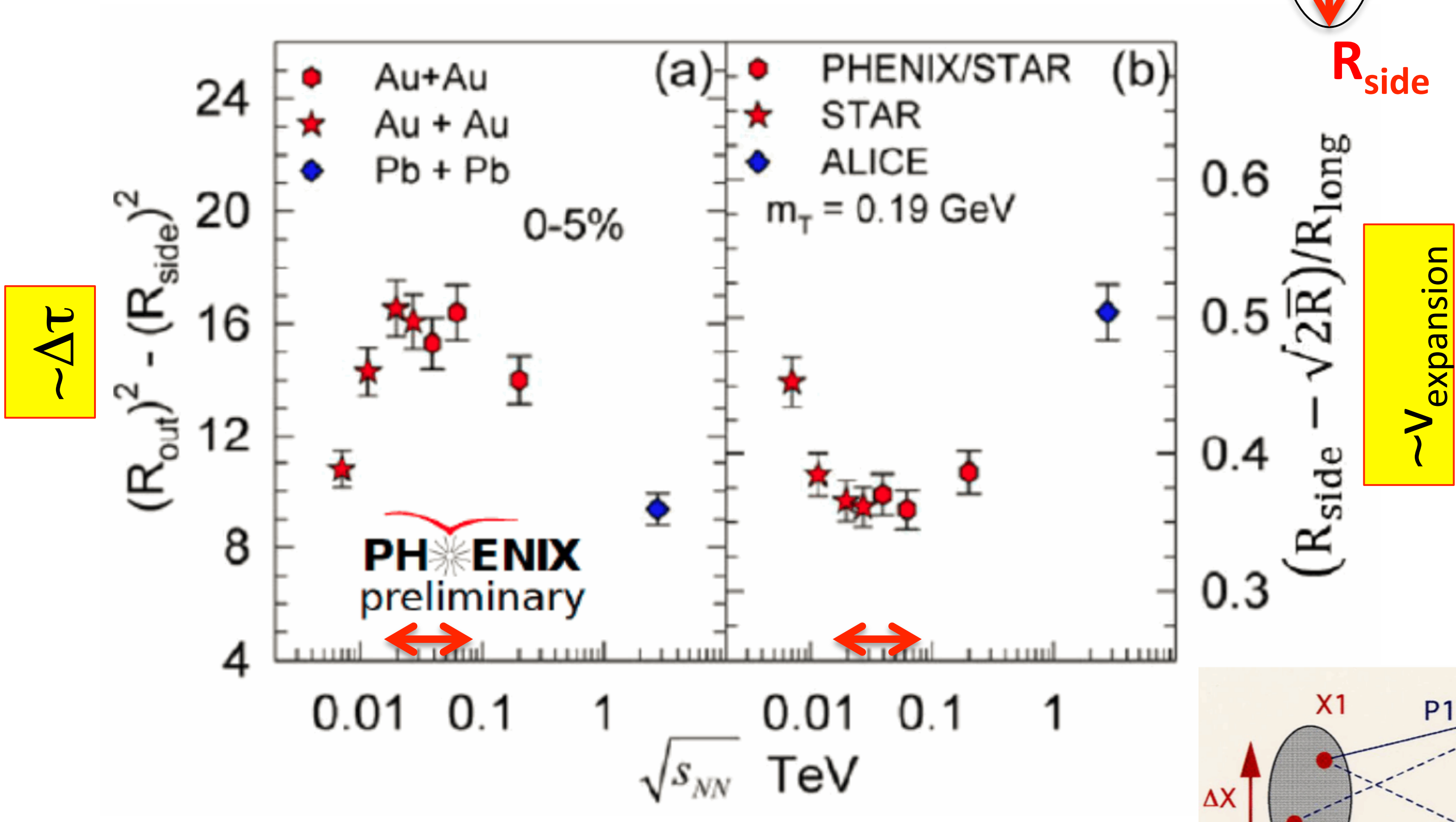
p_T/η cuts are chosen for ALICE TPC-V0A acceptance.

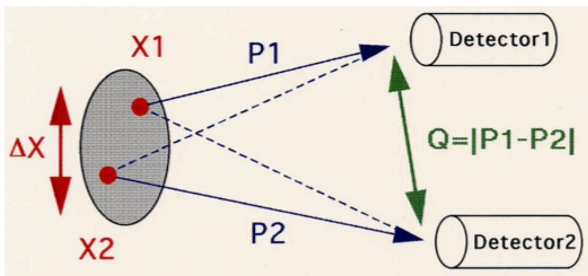
TPC : |η|<1
V0A: 3<η<5 (Pb-going side)
V0C : -4<η<-2 (p-going side)

Beam energy dependence of 2-particle interferometry measurement (HBT effect)



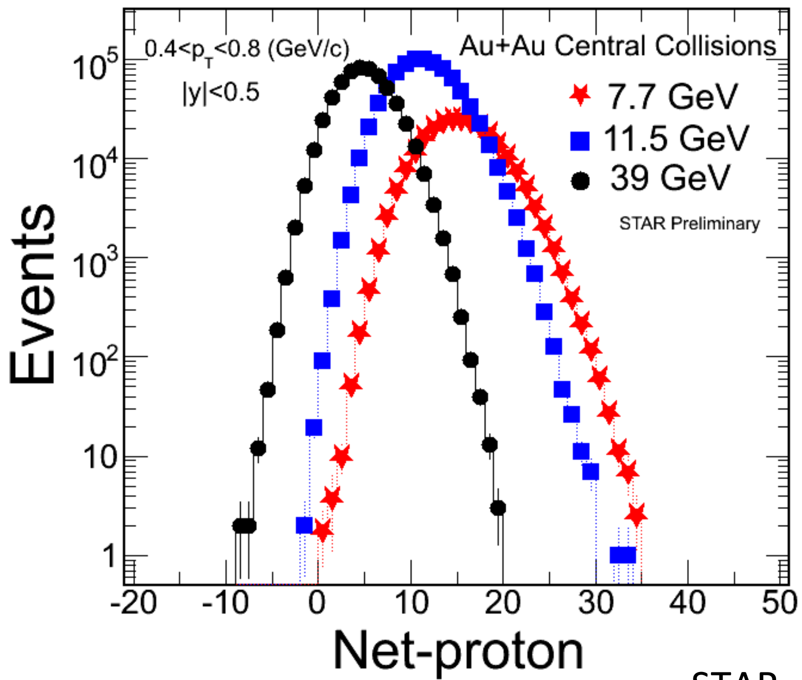
arXiv:1410.2559



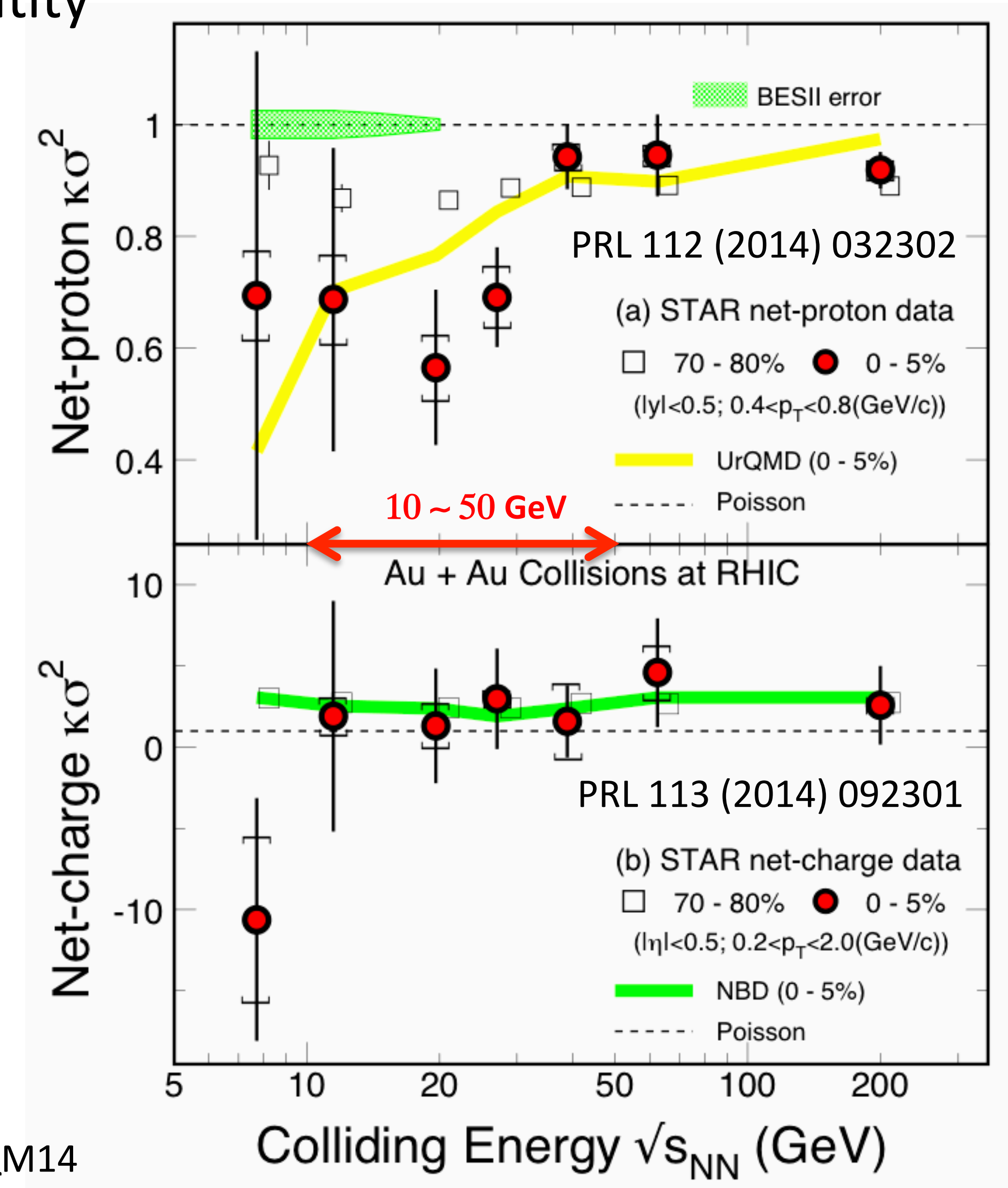


Fluctuation of conserved quantity vs beam energy

- Higher order moments (σ, S, κ) of net-baryon (net-proton) and net-charge distribution
- Non-monotonic behavior is expected around Critical Point.



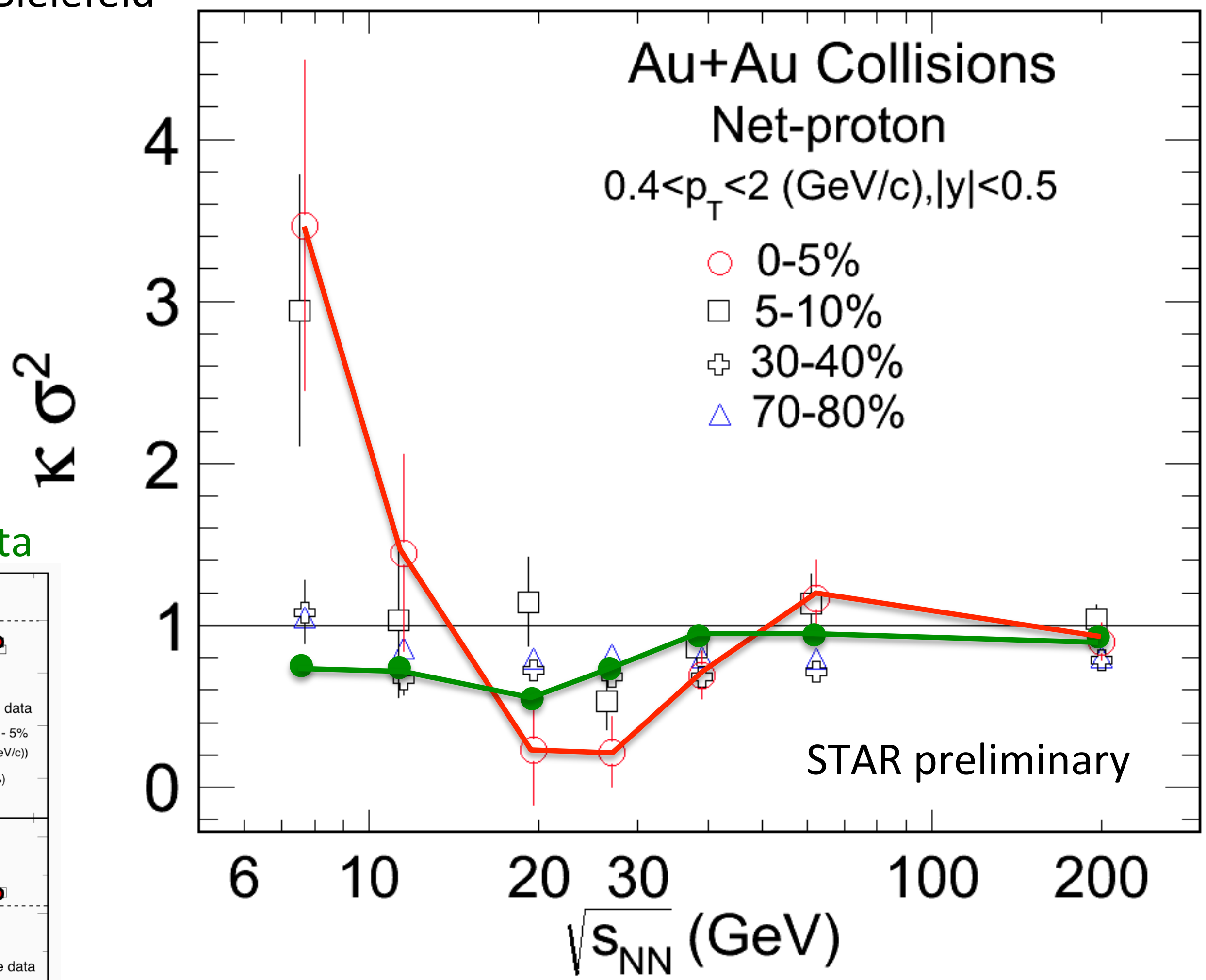
STAR, QM14



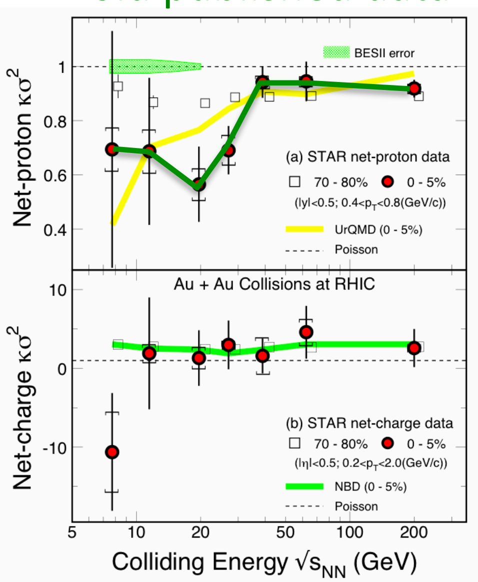
New data from STAR with improved PID

CPOD, 2014/Nov, Bielefeld

new preliminary data



old published data



フロー（粒子相関）とゆらぎ

横方向運動量分布、半径方向膨張
反応平面と指向的方位角異方性（v_1）
楕円的方位角異方性（ハドロン、光子v_2）
多粒子相関（ridge、ゆらぎ）