Post QM17 : Flow

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Contents

- pp 13TeV at LHC
- p/d/^{3}He+Au at RHIC
- Longitudinal direction
  -Event plane de-correlation
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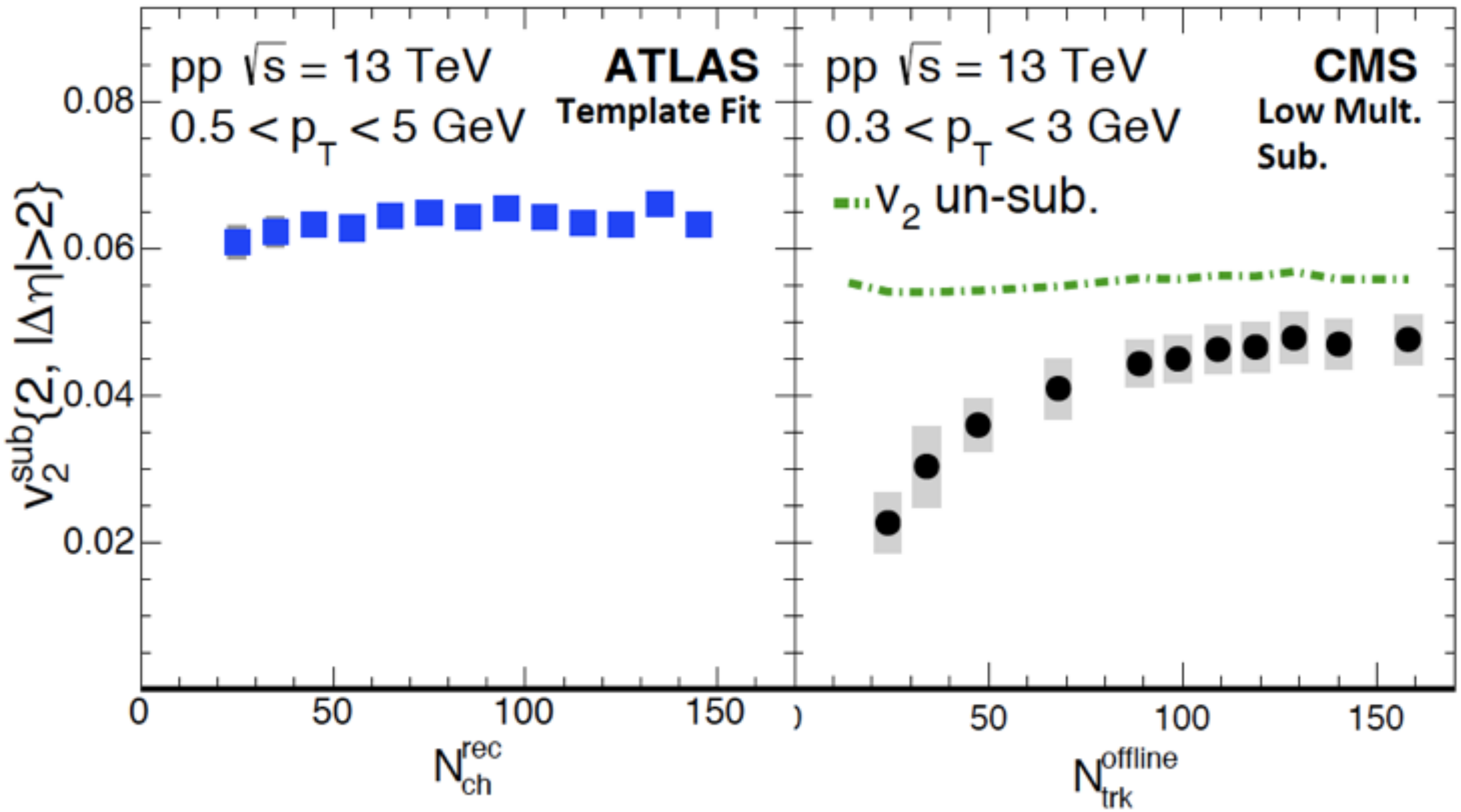
  -HBT
- Event shape engineering
  -HBT
- Low energy(Fixed target HADES)
  -v_3 w.r.t Psi_1

v_2 in p+p 13 TeV

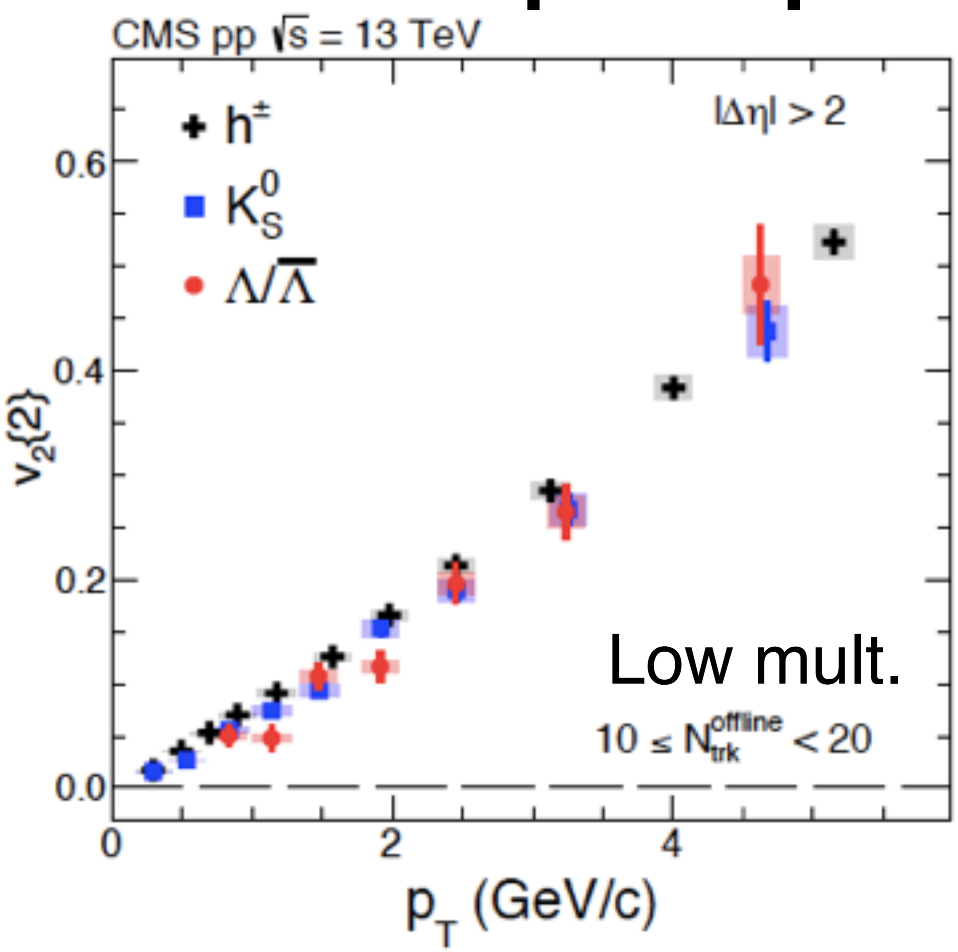
CMS Zhenyu Chen

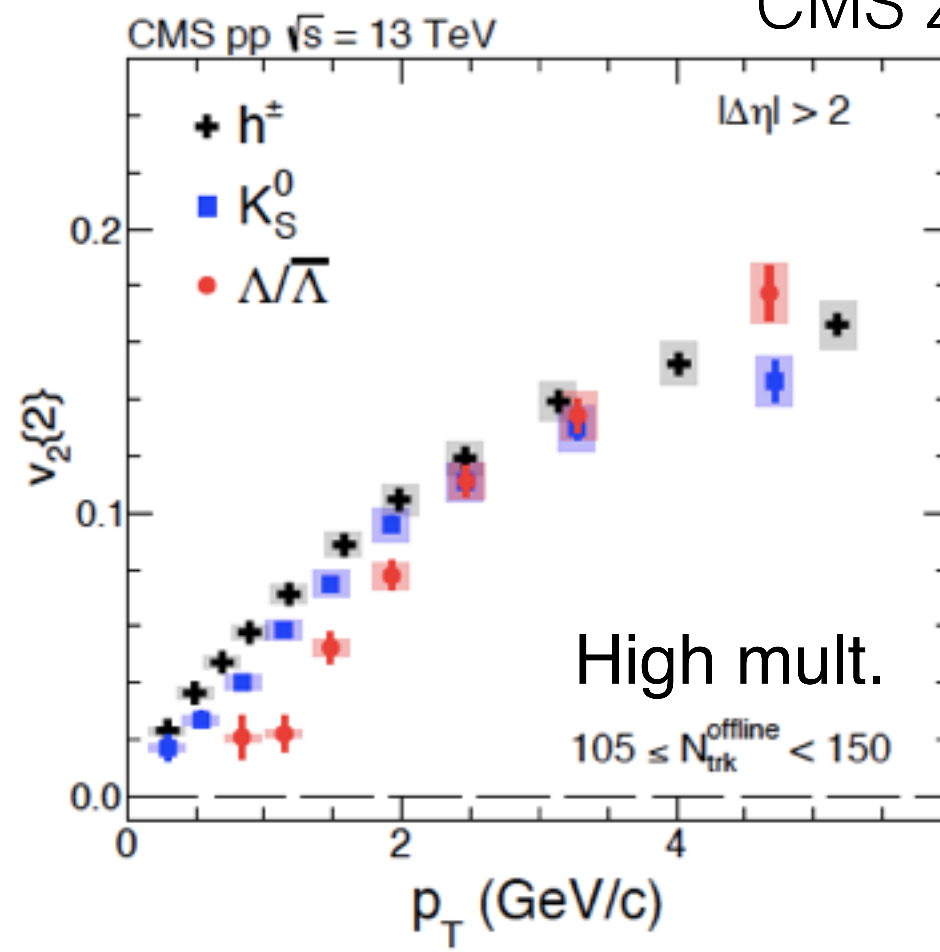


- ATLAS Template fit
  - -Template function using low mult.
  - -Assume $v_2 \neq 0$ in low mult.
  - -No multiplicity dependence
- CMS Low mult. subtraction method
  - -Subtract low mult. from high mult.
  - -Assume $v_2 = 0$ in low mult.
  - -Strong multiplicity dependence

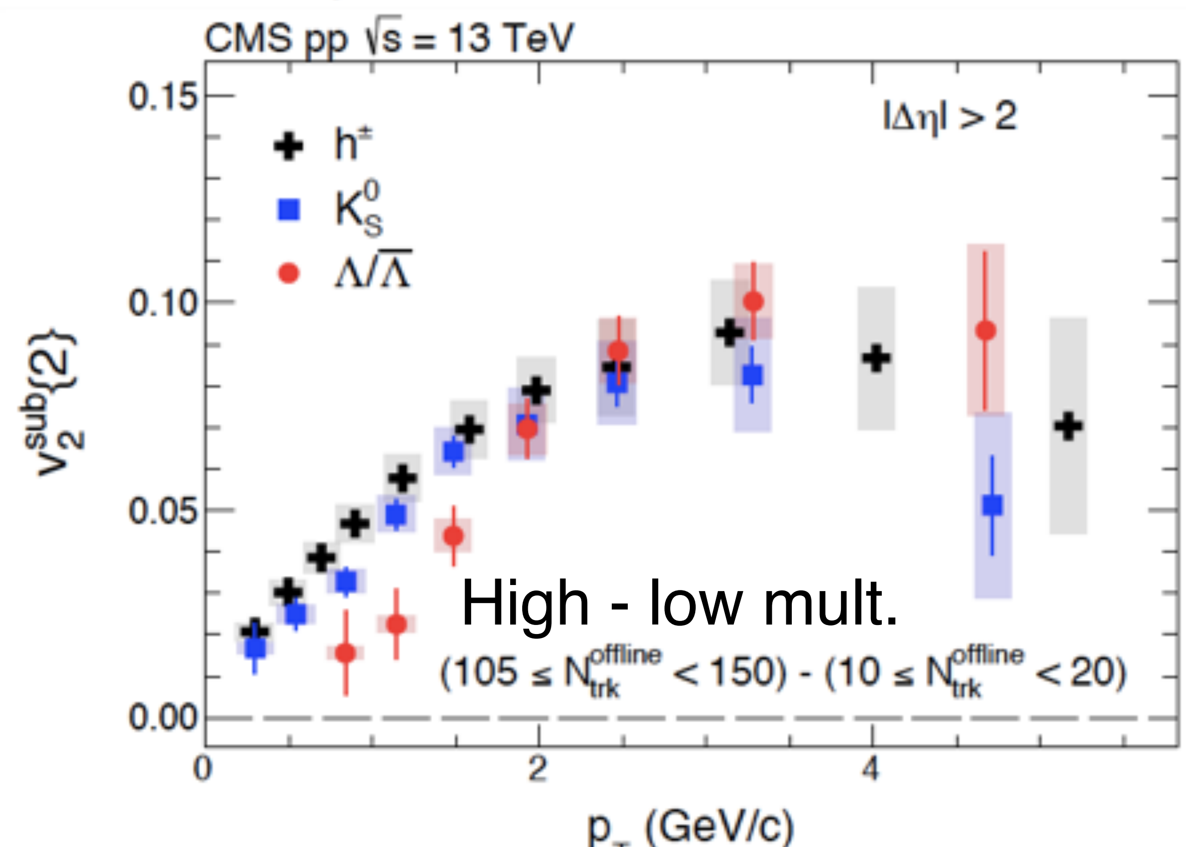
PID v_2 in p+p 13 TeV

CMS Zhenyu Chen





- $v_2\{2\}$ without subtraction
  - -Non-flow is included
  - -Low mult. does not show mass ordering
  - -Mass ordering at high mult.
- $v_2\{2\}$ with subtraction
  - -Suppress non-flow
  - -Mass ordering is still seen



$c_2\{4\}$ in p+p 13 TeV(CMS)

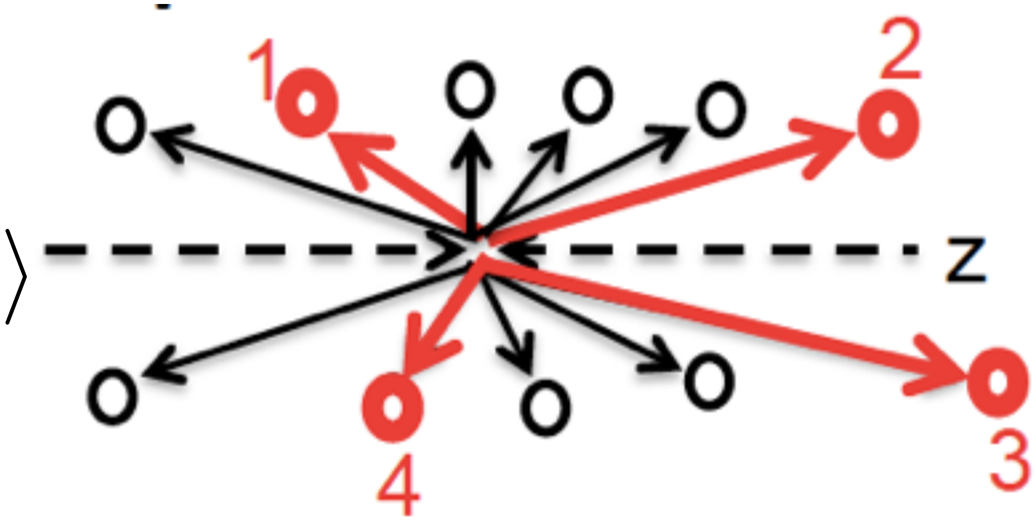
- Four particle correlation

$$c_n\{4\} = \langle\langle\cos[n(\phi_1+\phi_2-\phi_3-\phi_4)]\rangle\rangle - 2\langle\langle\cos[n(\phi_1+\phi_2)]\rangle\rangle^2$$

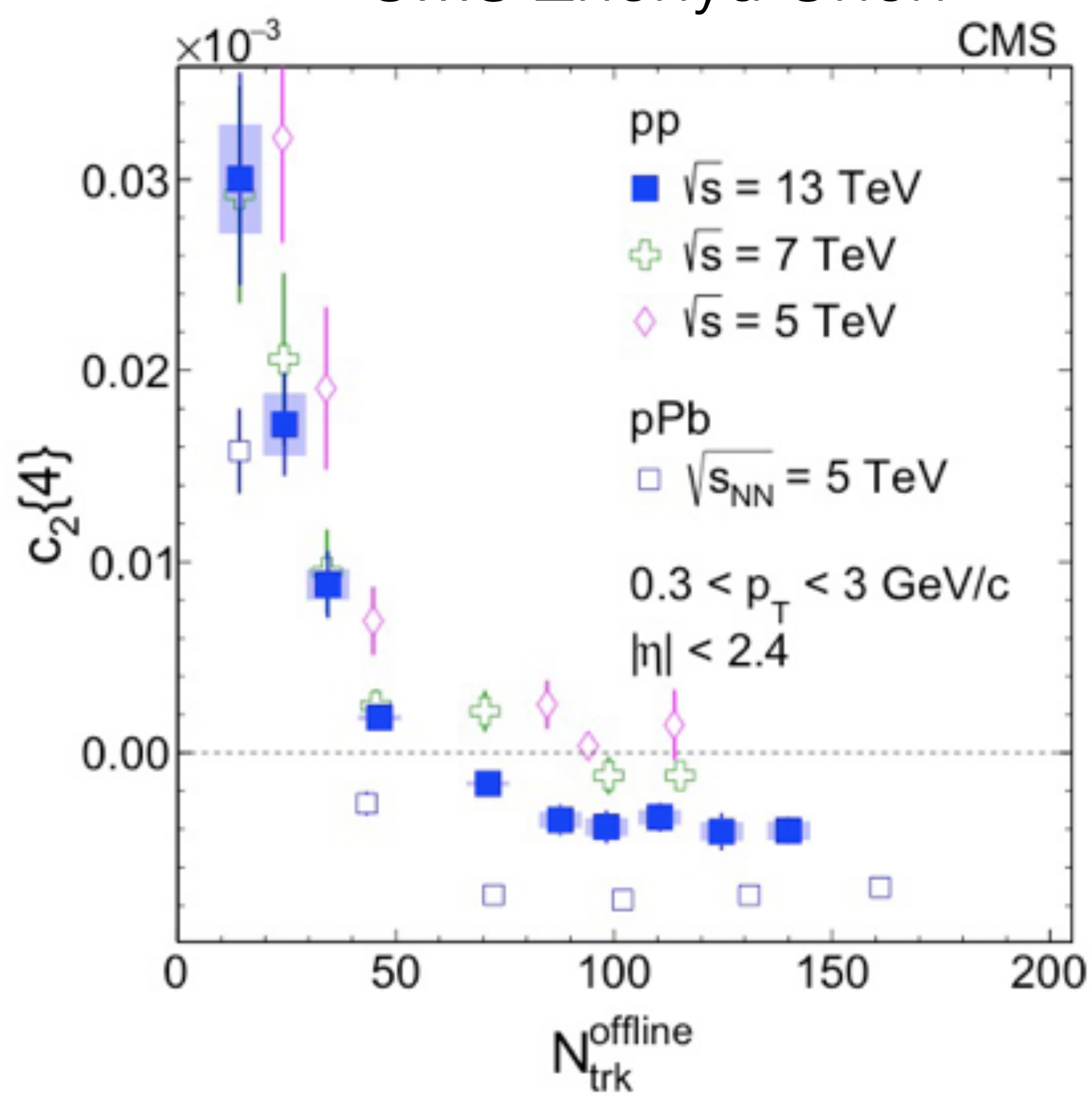
$$v_2\{4\} = \sqrt[4]{-c_n\{4\}}$$

-Negative $c_n\{4\}$ →positive $v_n\{4\}$
-Suppress non-flow, fluctuation

- pp 13 TeV shows negative $c_2\{4\}$
  -Indicate positive v_2
  -Energy dependence
  - Collectivity ?

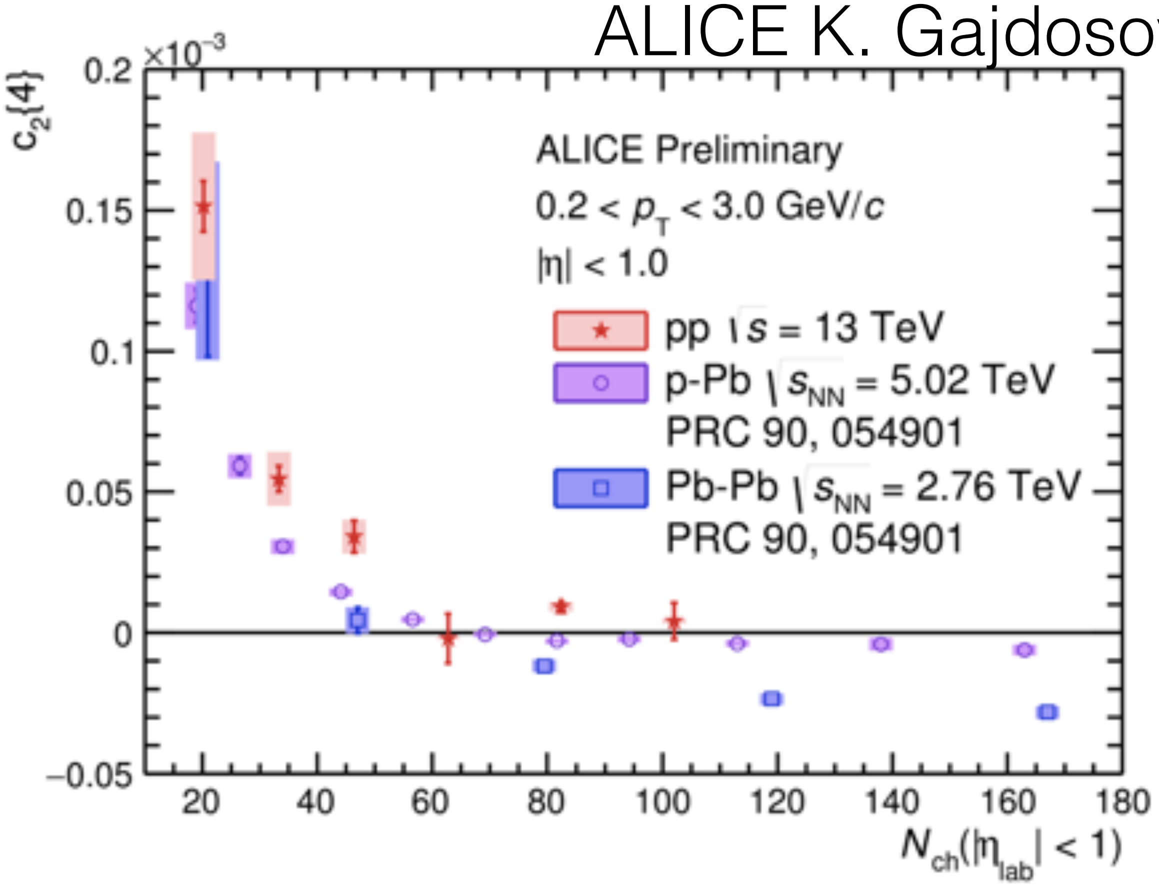


CMS Zhenyu Chen



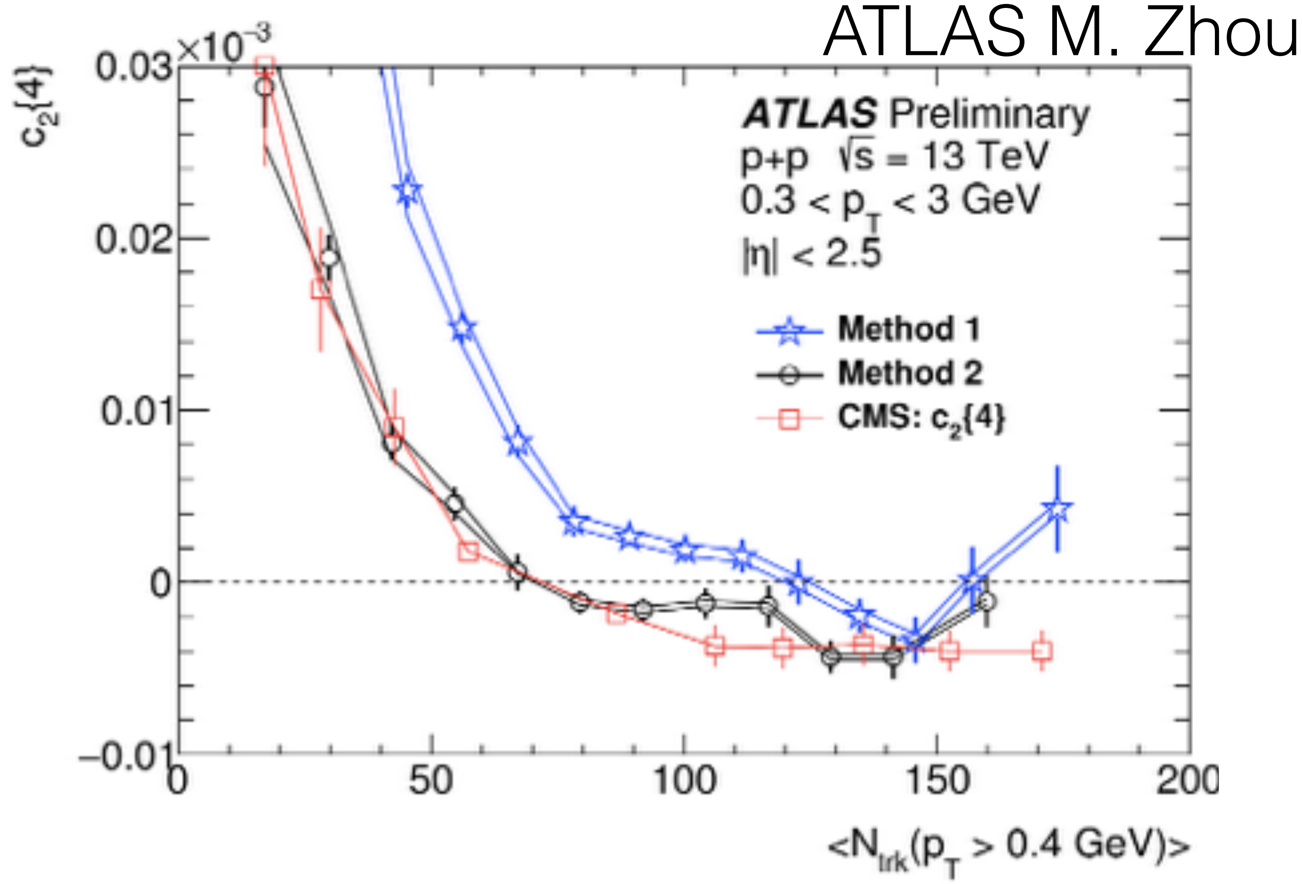
$c_2\{4\}$ in p+p 13 TeV(ALICE,ATLAS)

ALICE K. Gajdosova



Event classification with 0.2<pT<3.0 GeV

ATLAS M. Zhou

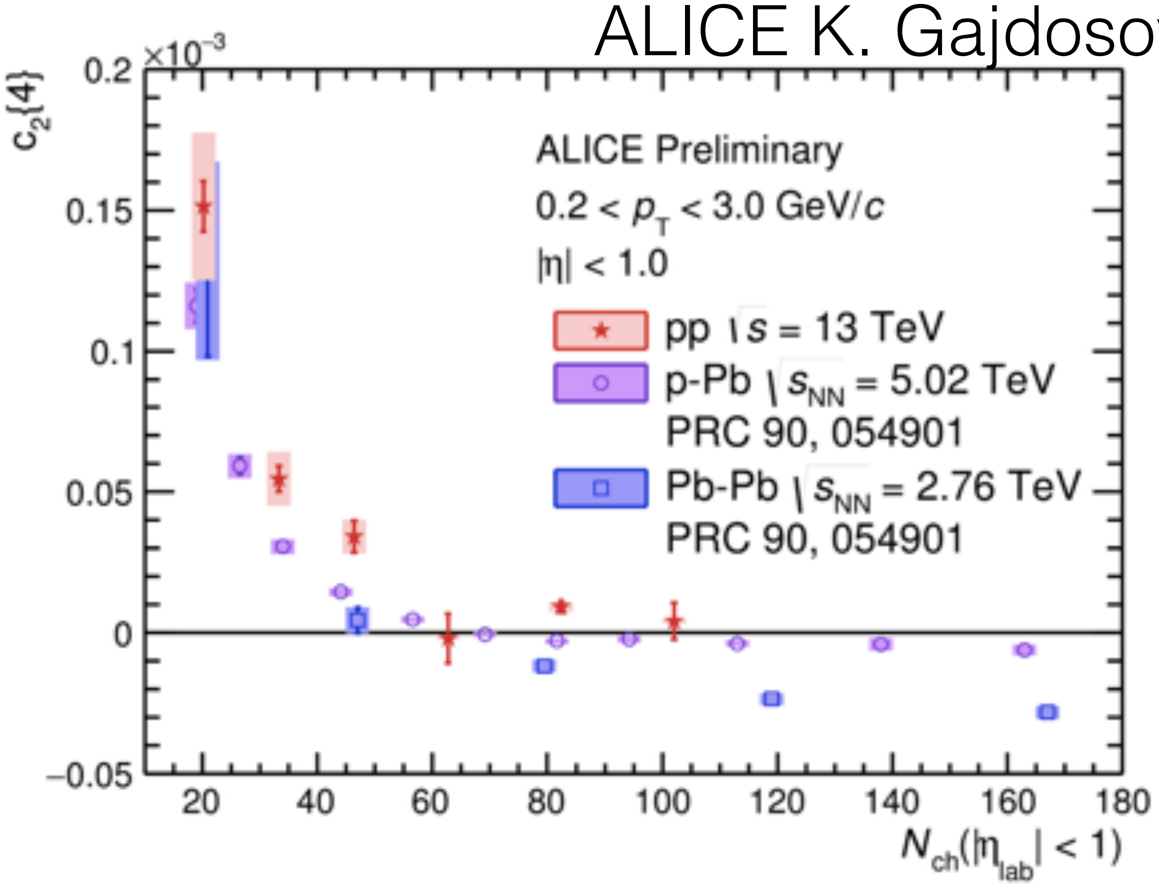


Method1:Event classification with 0.3<pT<3.0 GeV
Method2:Event classification with pT>0.4GeV(=CMS)

- ALICE/ATLAS(Method1)
  - $c_2\{4\}$ and event classification with same pT range
  - $c_2\{4\}$ shows no negative sign
- ATLAS(Method2)
  - $c_2\{4\}$ shows negative sign, consistent with CMS result
  - $c_2\{4\}$ depends on event classification(multiplicity fluctuation)

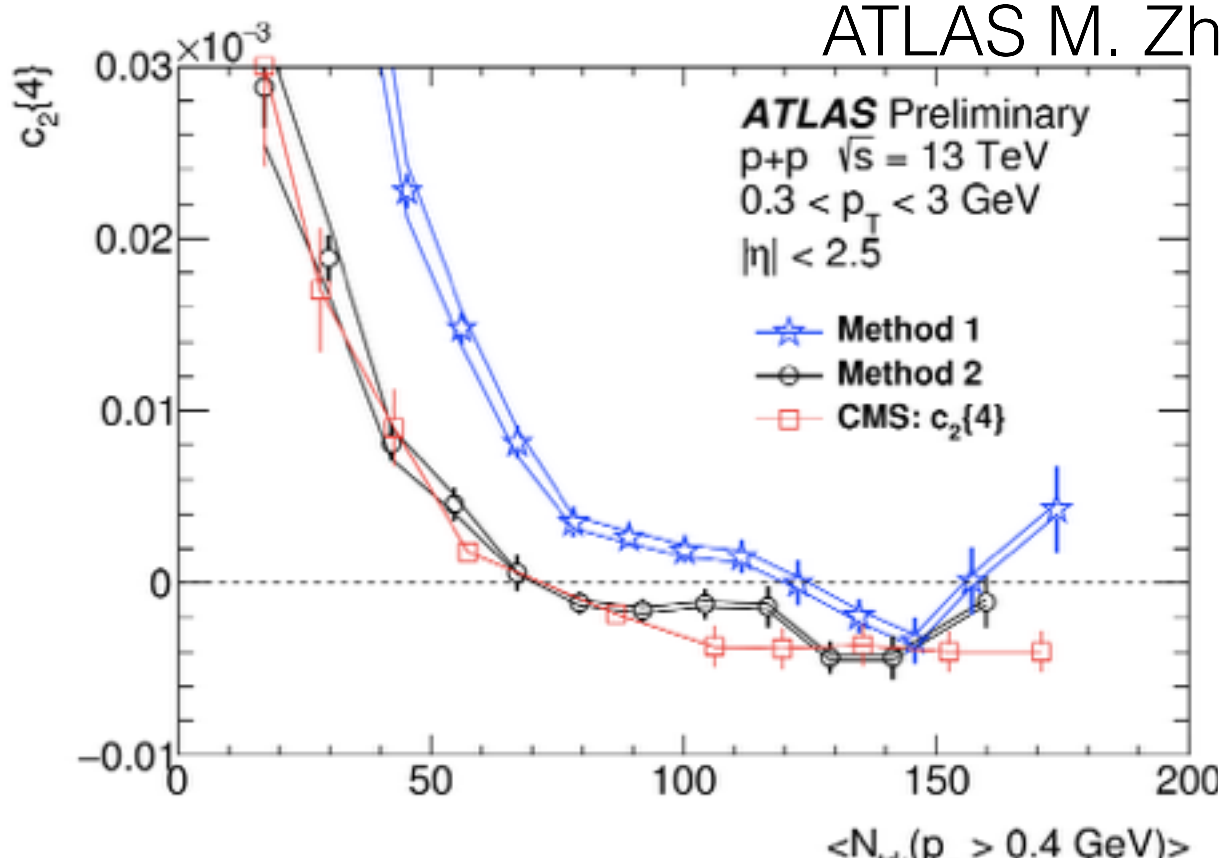
$c_2\{4\}$ in p+p 13 TeV(ALICE,ATLAS)

ALICE K. Gajdosova



Event classification with 0.2<pT<3.0 GeV

ATLAS M. Zhou

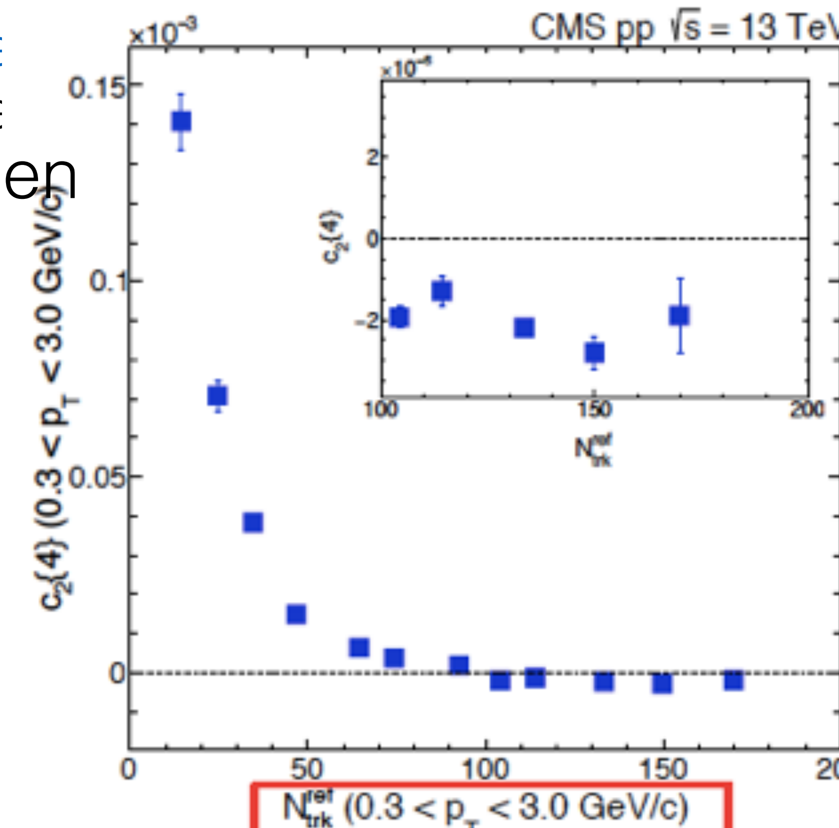


Method1:Eve

Method2:Eve

S)

CMS Zhenyu Chen

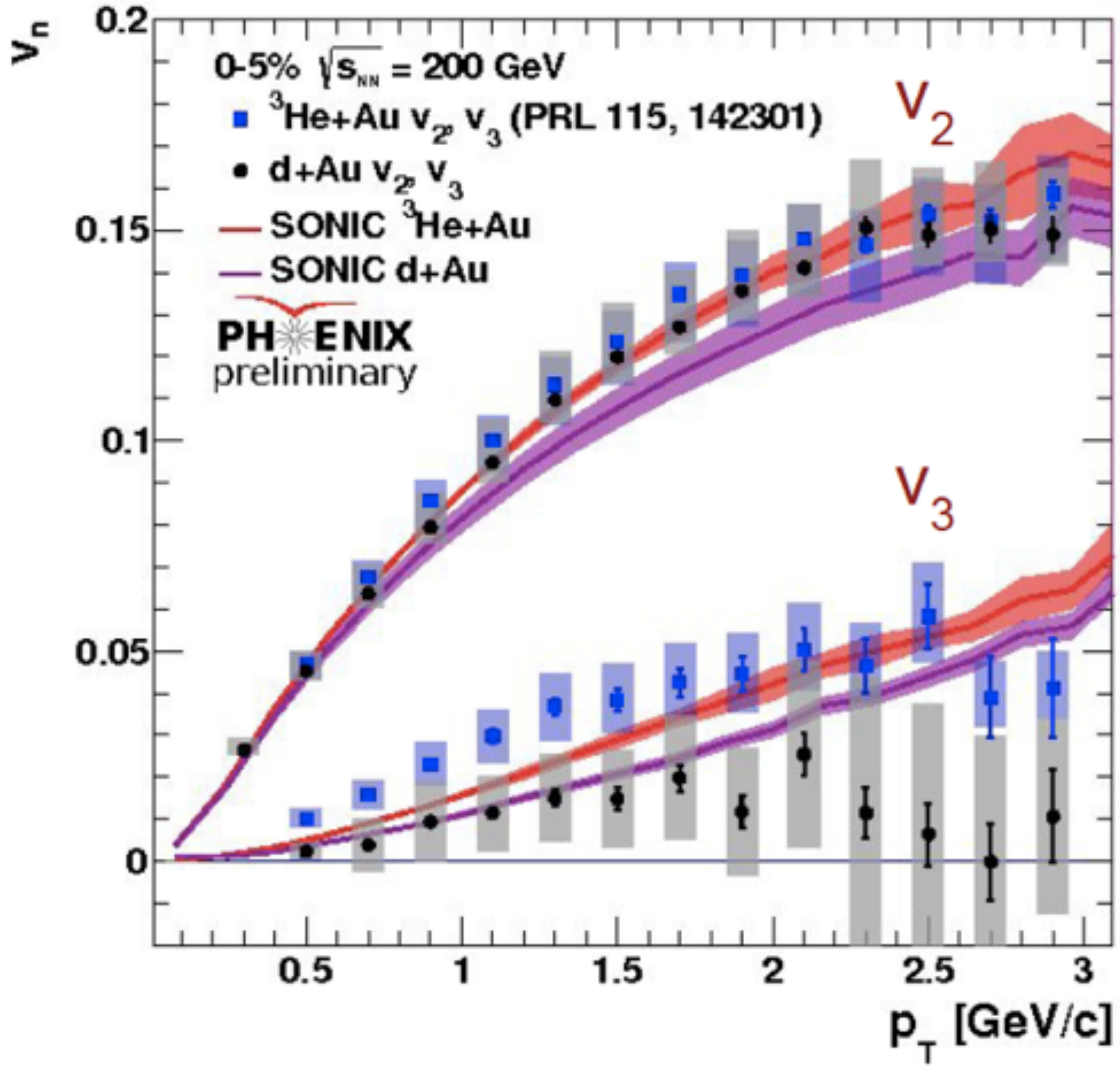


- CMS
  - $c_2\{4\}$ and event classification with same pT range
  - c2{4} shows negative sign

  →CMS does not agree with ATLAS(Method1)/ALICE

d+Au v_3

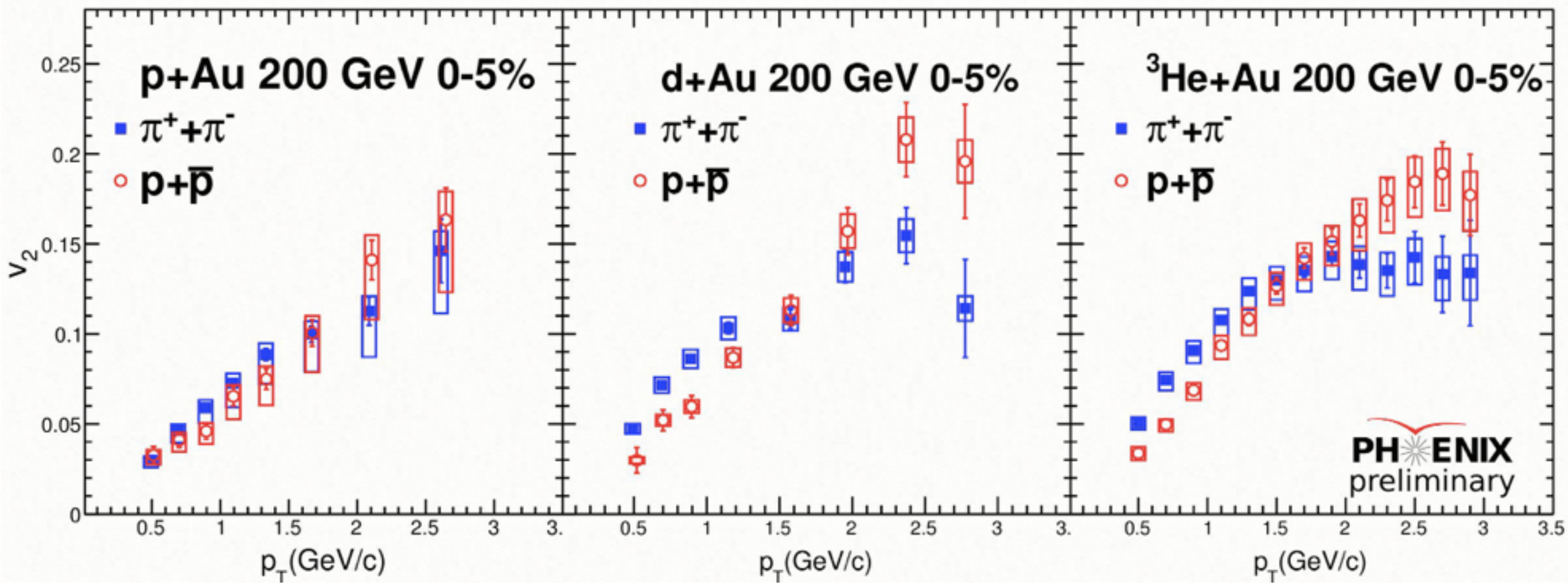
PHENIX Q. Xu



- v_3 in d+Au is observed
  - -Event plane method
- Hydrodynamics reproduces ordering of v_3
  - -v_3 (^{3}He+Au) > v_3 (d+Au)

PID v_2 in p/d/^{3}He+Au

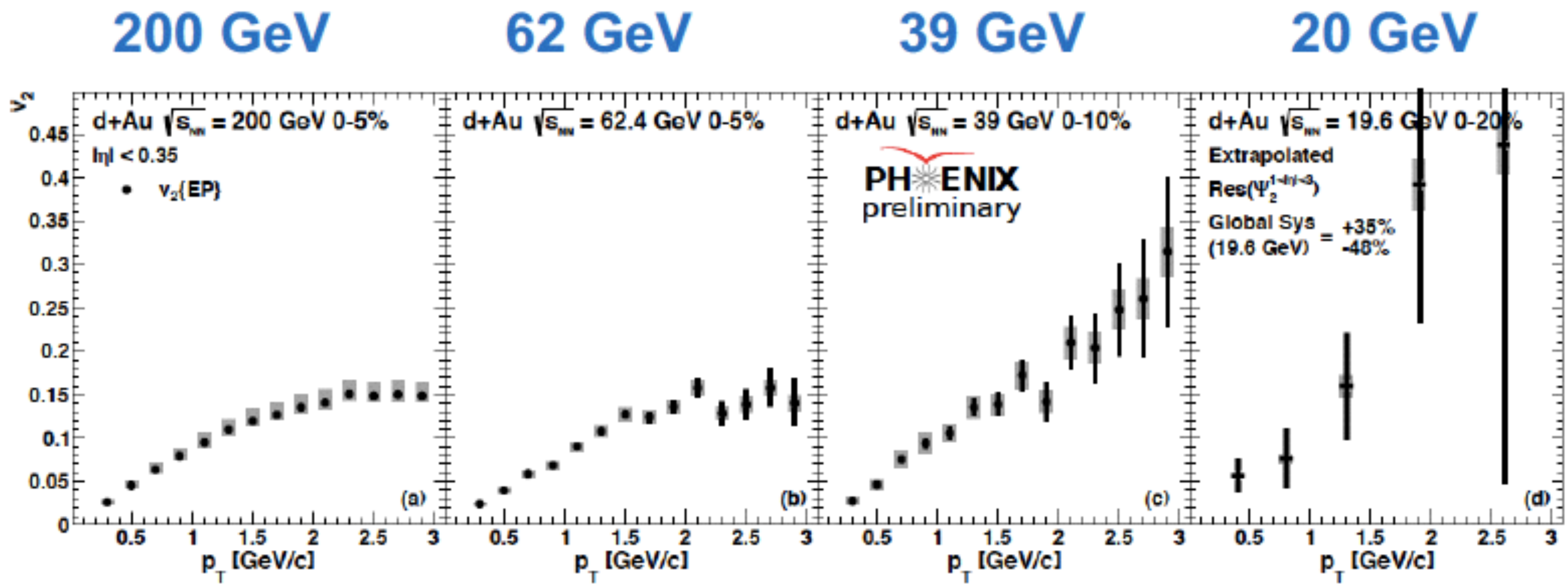
PHENIX Q. Xu



- Charged π and p v_2 in p/d/^{3}He+Au is observed
  - Event plane method
- Mass-ordering feature is seen
  - Less pronounced in p+Au

d+Au BES: v_2 vs p_T

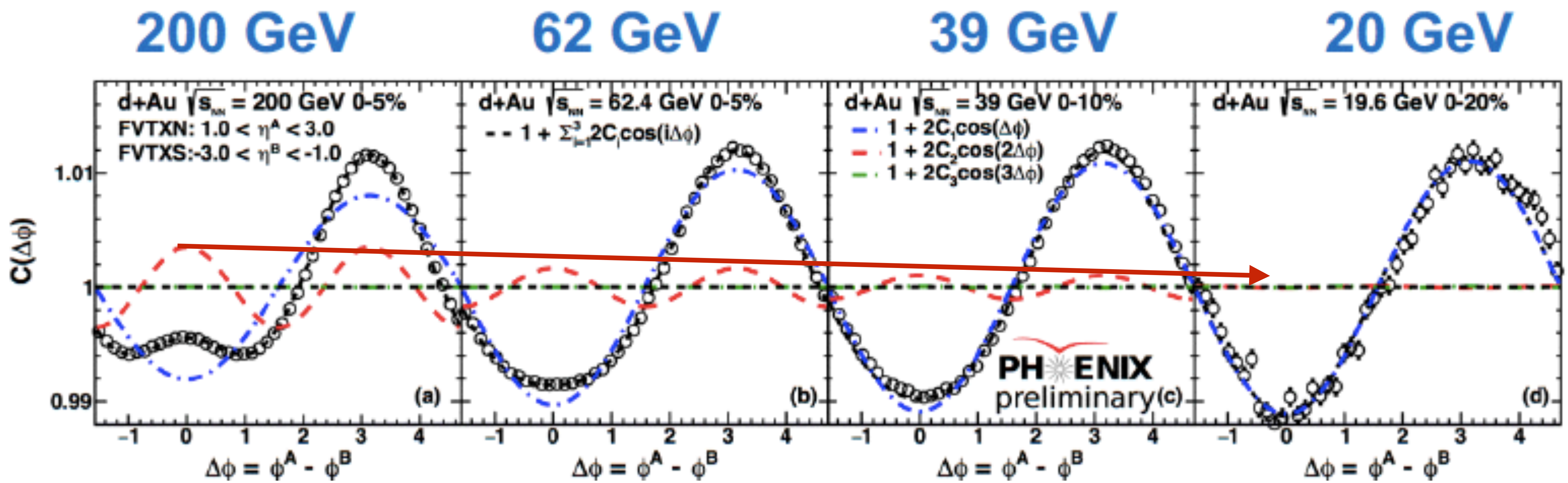
PHENIX J. Velkovska



- v_2 at 200 and 62 GeV shows a similar p_T dependence
- v_2 at 39 and 20 GeV increase at high p_T
  - Non flow ?

d+Au BES: Ridge

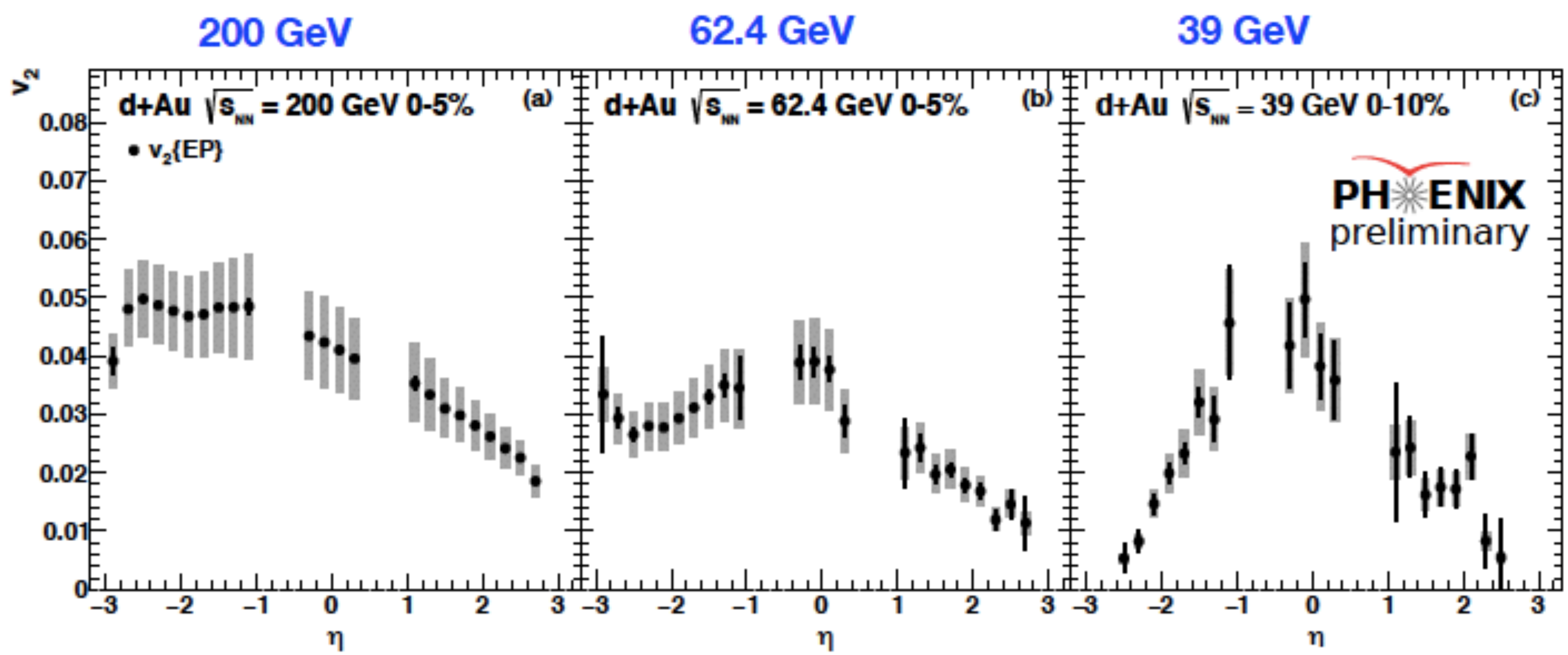
PHENIX J. Velkovska



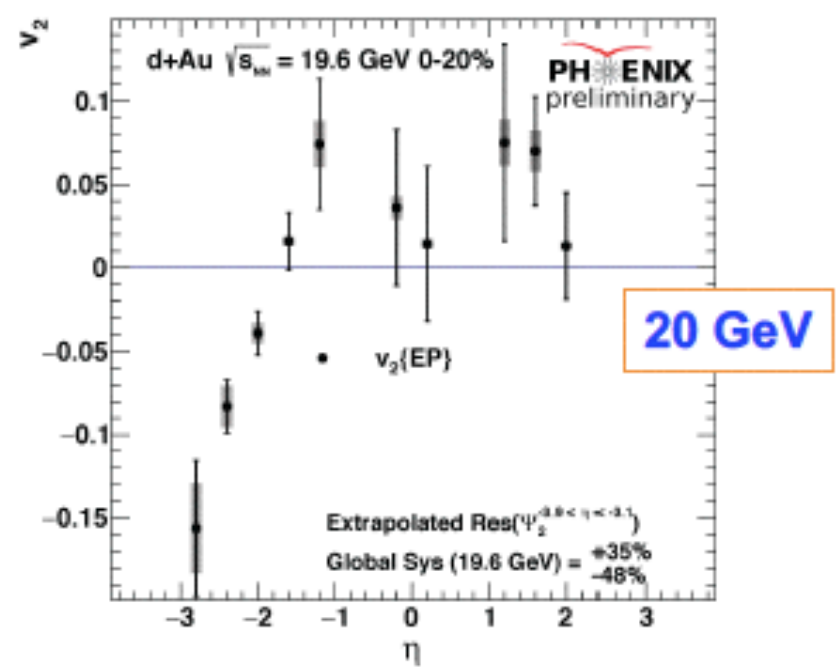
- Long range correlation is observed in d+Au BES
  - p_T>0, $|\Delta\eta|$>2, charged hadrons (Forward vertex detector)
- Elliptic component decreases with decreasing energy

d+Au BES: v_2 vs η

elkovska



- Forward: similar values at all $\sqrt{s_{NN}}$
- Backward: decrease with $\sqrt{s_{NN}}$
  -Au-going side v_2 drastically
  changed below 39GeV

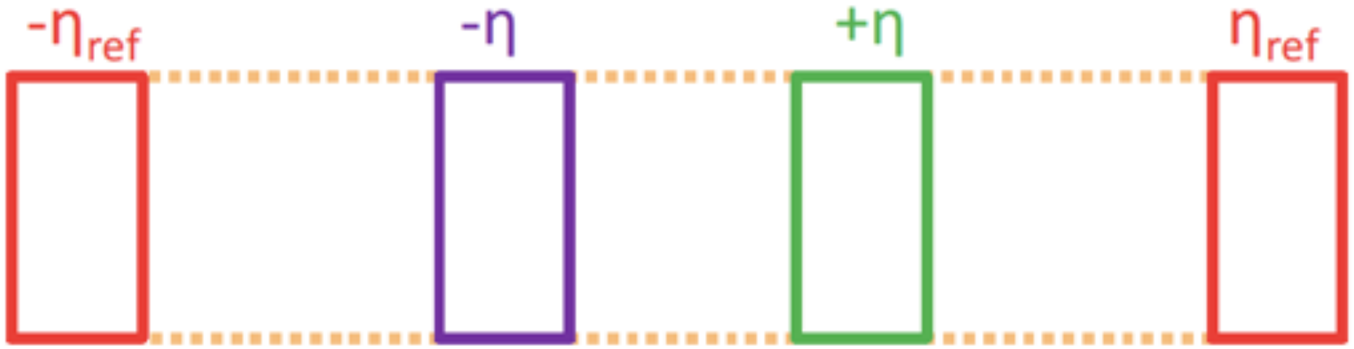


PHENIX

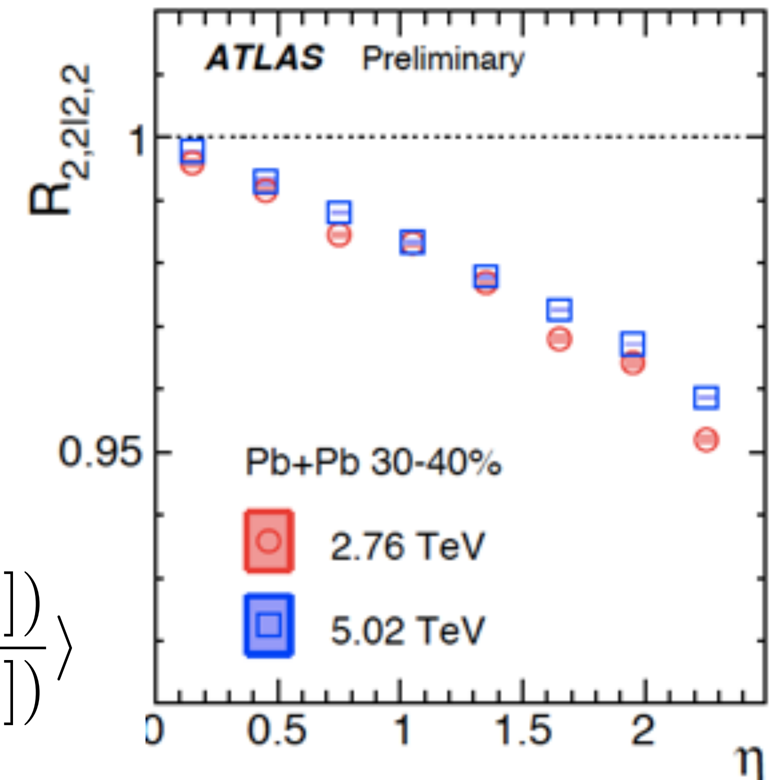
Julia Velkovska, QM 2017

Event plane de-correlation

ATLAS M.Soumya
P. Huo



$$R_{n,n|n,n} = \frac{\langle q_n(-\eta_{\rm ref})q_n(-\eta)q_n^*(+\eta)q_n^*(+\eta_{\rm ref})\rangle}{\langle q_n(-\eta_{\rm ref})q_n^*(-\eta)q_n(+\eta)q_n^*(+\eta_{\rm ref})\rangle}$$
$$\sim \langle \frac{\cos(n[\Psi_n(-\eta_{\rm ref}) - \Psi_n(\eta_{\rm ref}) + (\Psi_n(-\eta) - \Psi_n(\eta))])}{\cos(n[\Psi_n(-\eta_{\rm ref}) - \Psi_n(\eta_{\rm ref}) - (\Psi_n(-\eta) - \Psi_n(\eta))])}\rangle$$

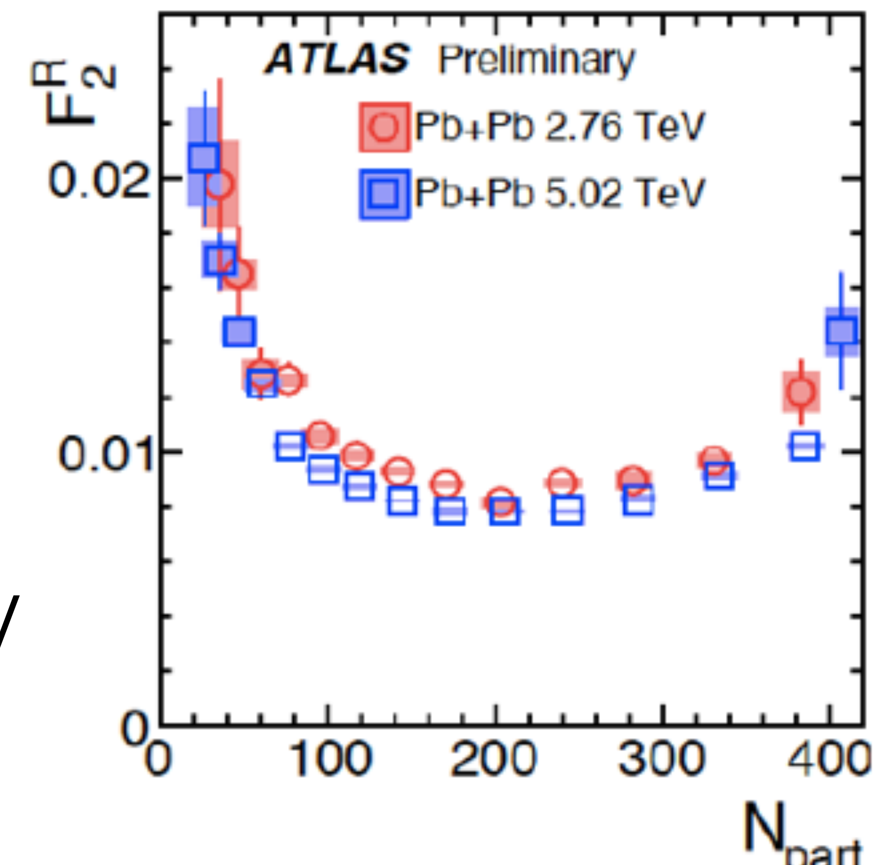


$R_{n,n|n,n} \approx 1 - 4F^{twi}_{n;2}\eta$

$R_{n,n|n,n} = 1$:η independent Ψ_n

$$\Psi_n(-\eta_{\rm ref}) = \Psi_n(\eta) = \Psi_n(-\eta) = \Psi_n(\eta_{\rm ref})$$

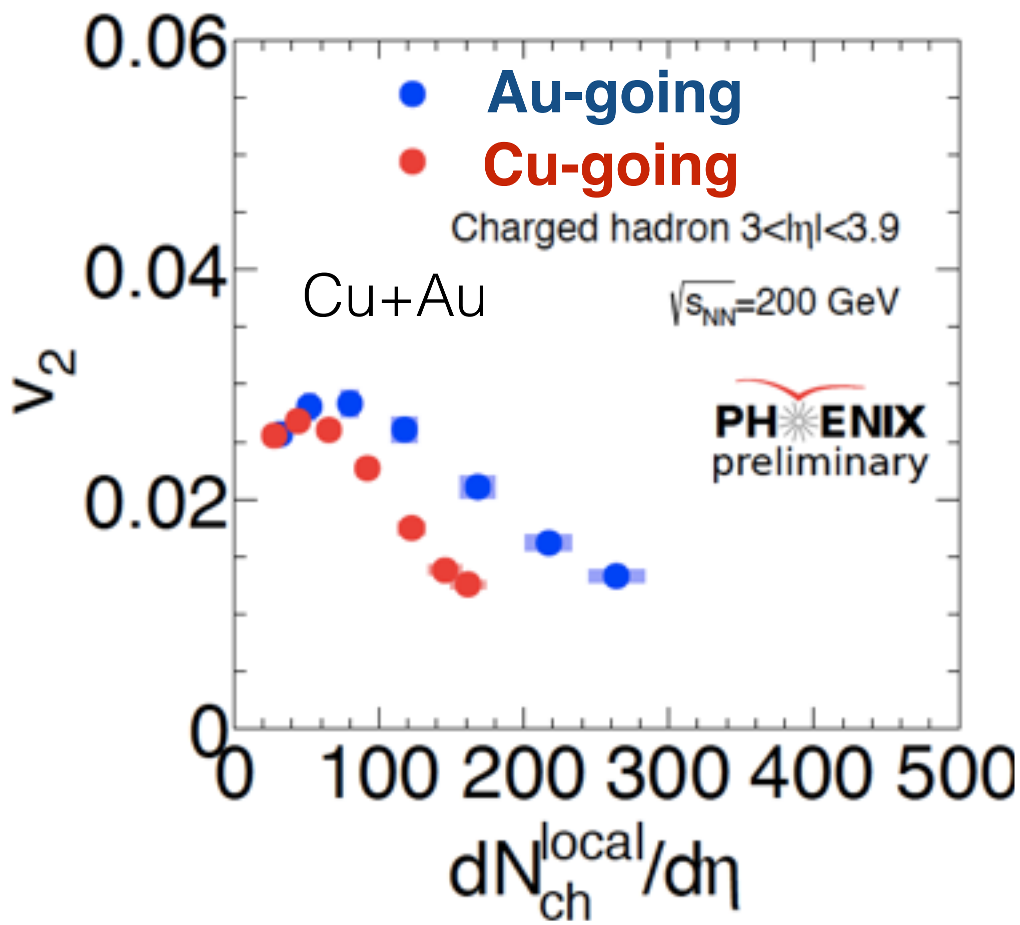
$R_{n,n|n,n} < 1$: η dependent Ψ_n

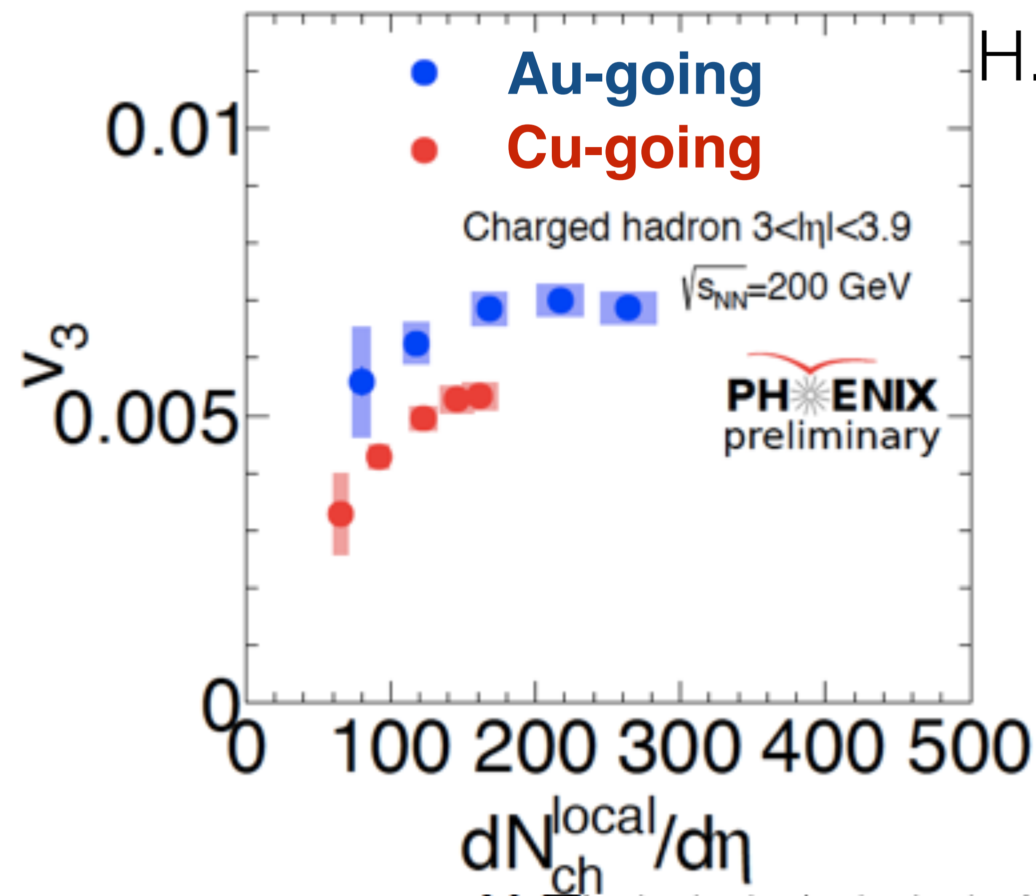


- De-correlation increasing linearly with increasing η gap
- De-correlation is smaller at lower energy
- De-correlation is smallest at mid-central

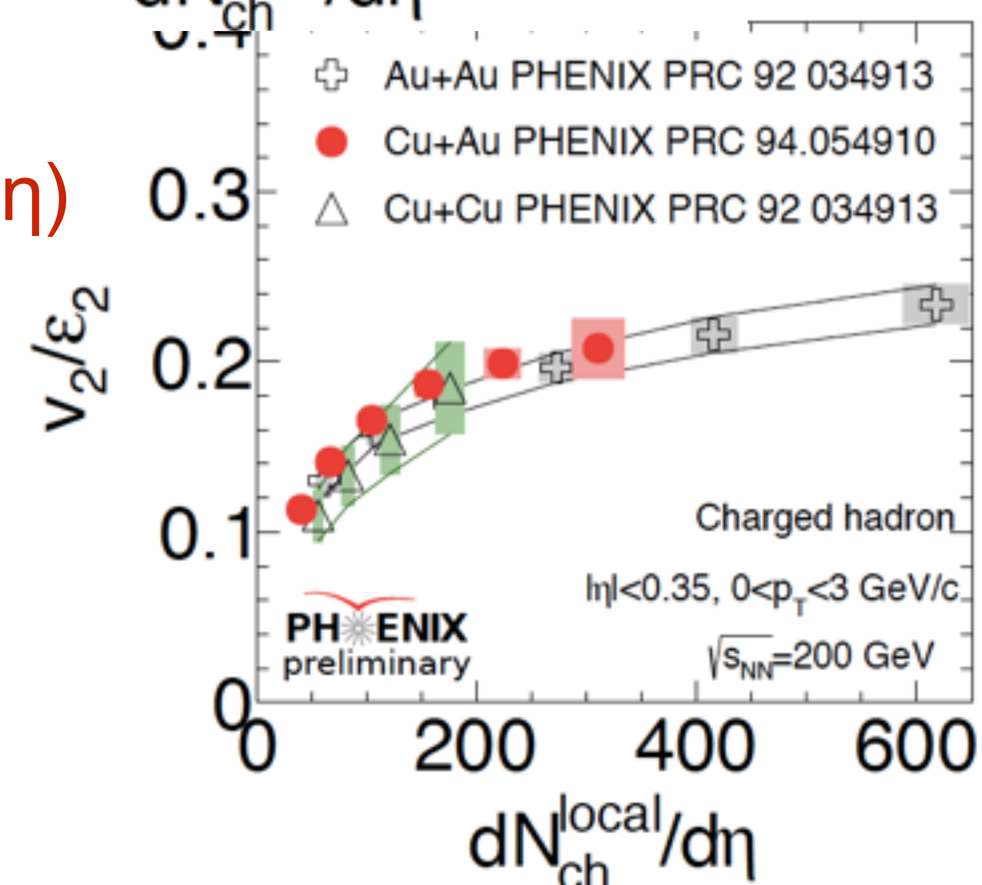
Forward/Backward asymmetry of v_n

PHENIX M. Shimomura
H. Nakagomi





- F/B v_n plotted as a function of F/B $dN_{ch}/d\eta$
  - Au-going v_n ($dN_{ch}/d\eta$) > Cu-going v_n ($dN_{ch}/d\eta$)
  - $\varepsilon_{n,\text{Au-going}} \neq \varepsilon_{n,\text{Cu-going}}$?
- Empirical relation among v_2, ε_2 and $dN/d\eta$ at mid-η
  - $v_2/\varepsilon_2 \propto f(dN/d\eta)$
  - Study of eccentricity

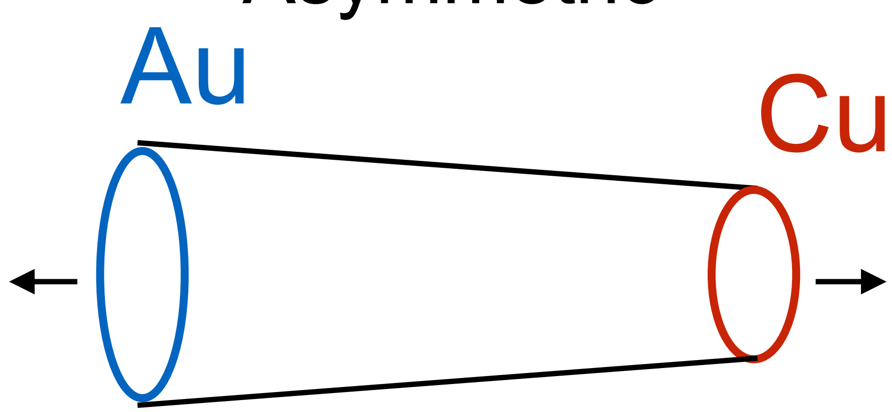


v_n/ε_n : Asymmetric initial eccentricity

PHENIX M. Shimomura
H. Nakagomi

Initial eccentricity

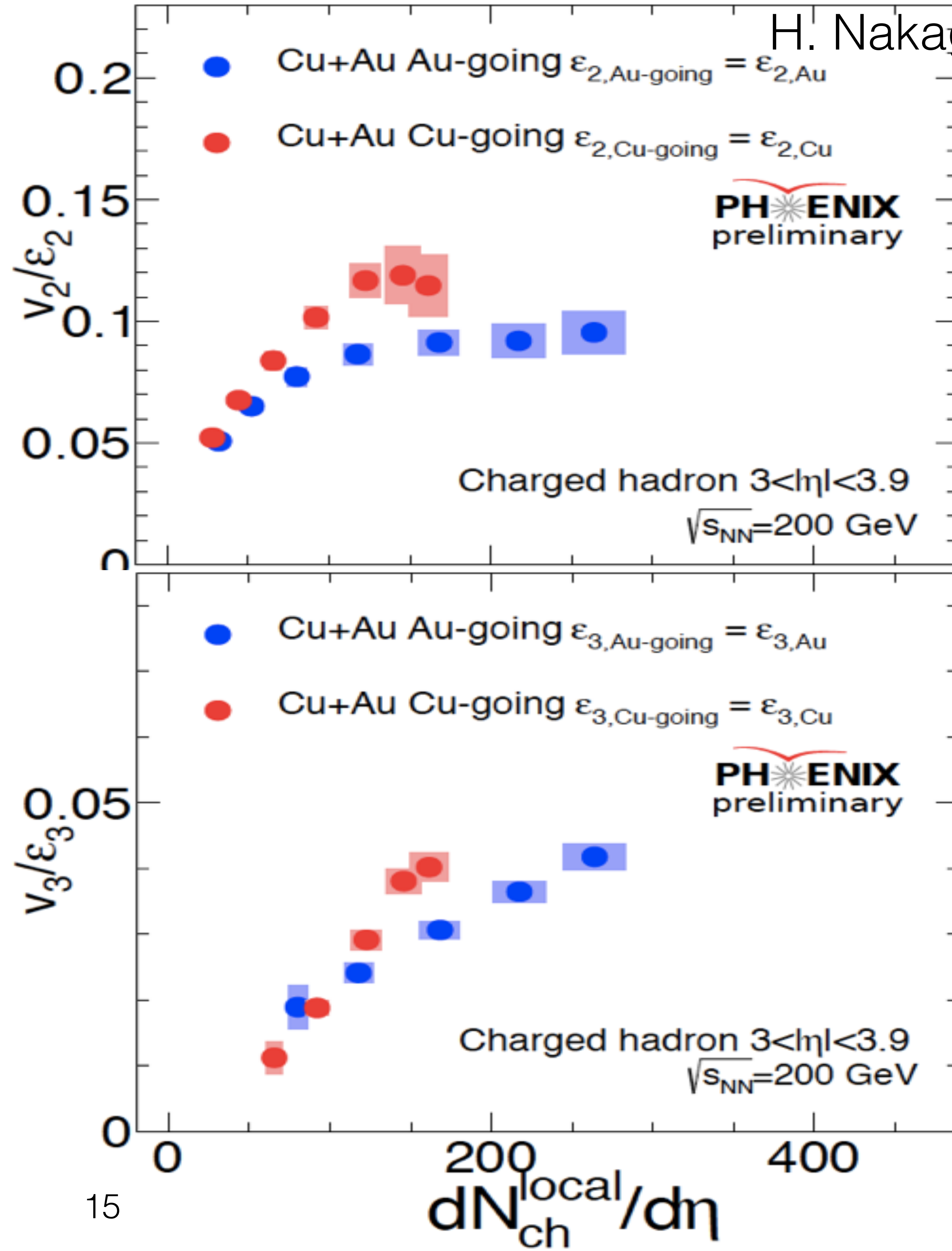
Asymmetric



$v_{n,\text{ Au-going}}/\varepsilon_{n,\text{Au}}$

$\neq$

$v_{n,\text{ Cu-going}}/\varepsilon_{n,\text{Cu}}$



v_n/ε_n : Symmetric initial eccentricity

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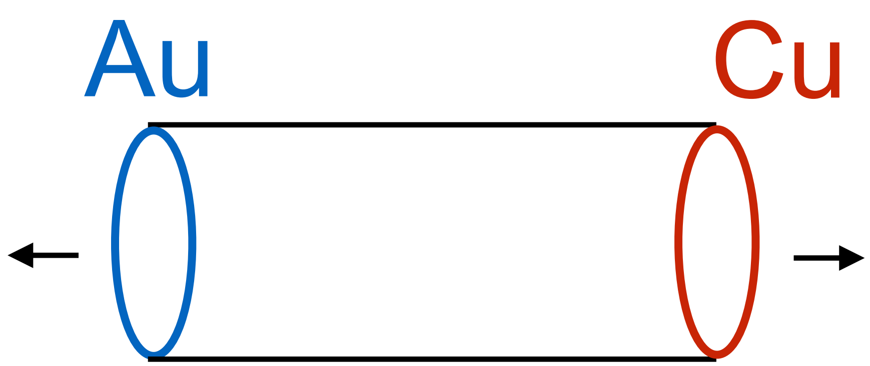
Initial eccentricity

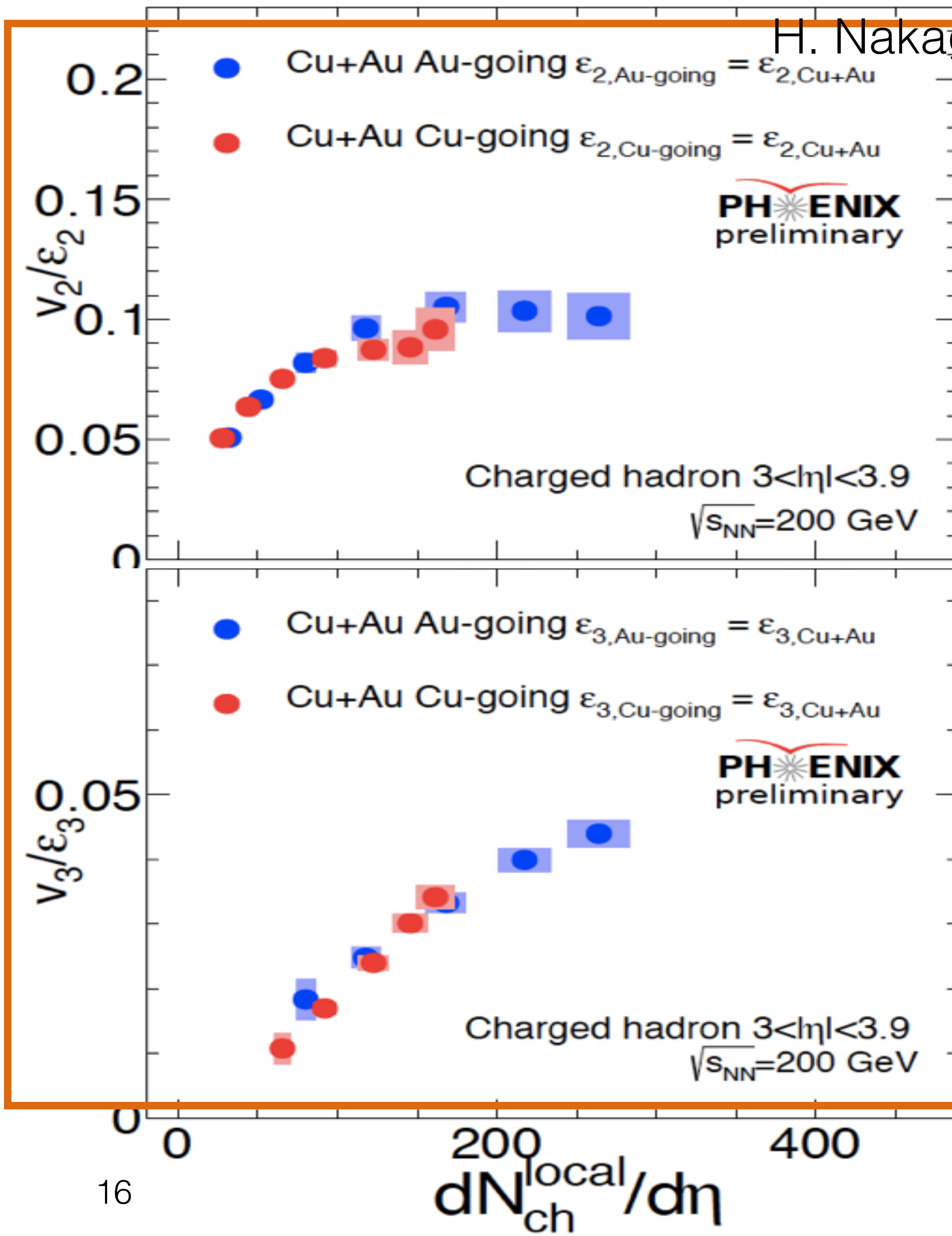
Symmetric



$v_{n,\text{ Au-going}}/\varepsilon_{n,\text{Cu+Au}}$

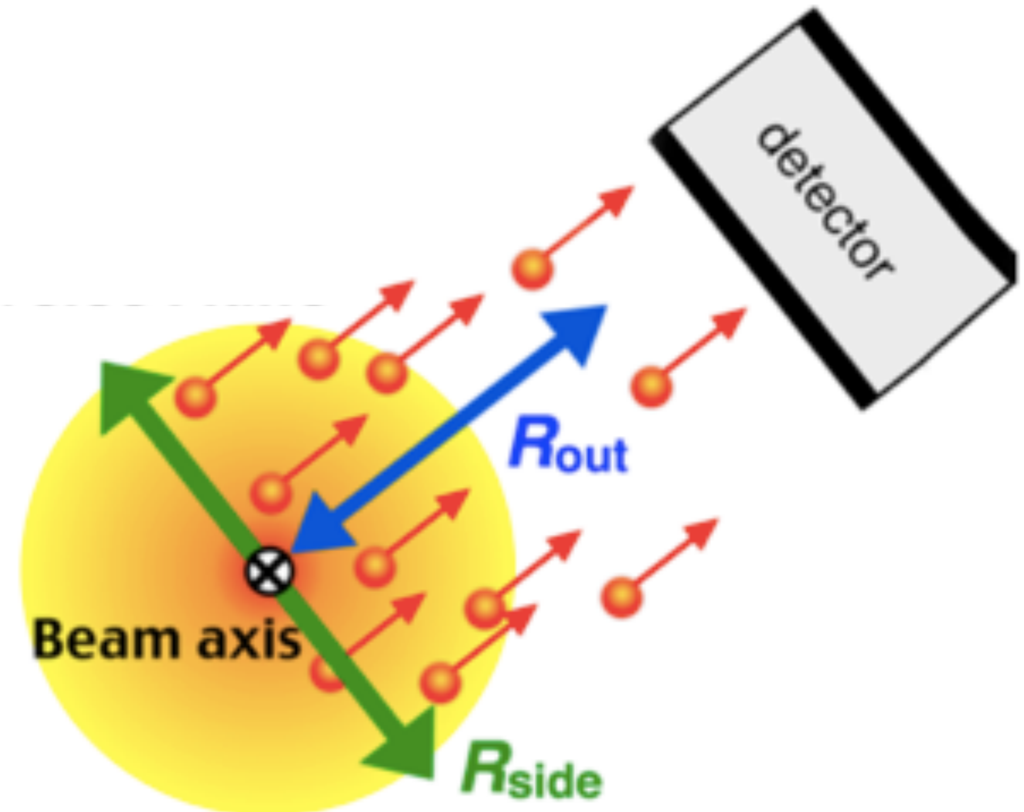
=

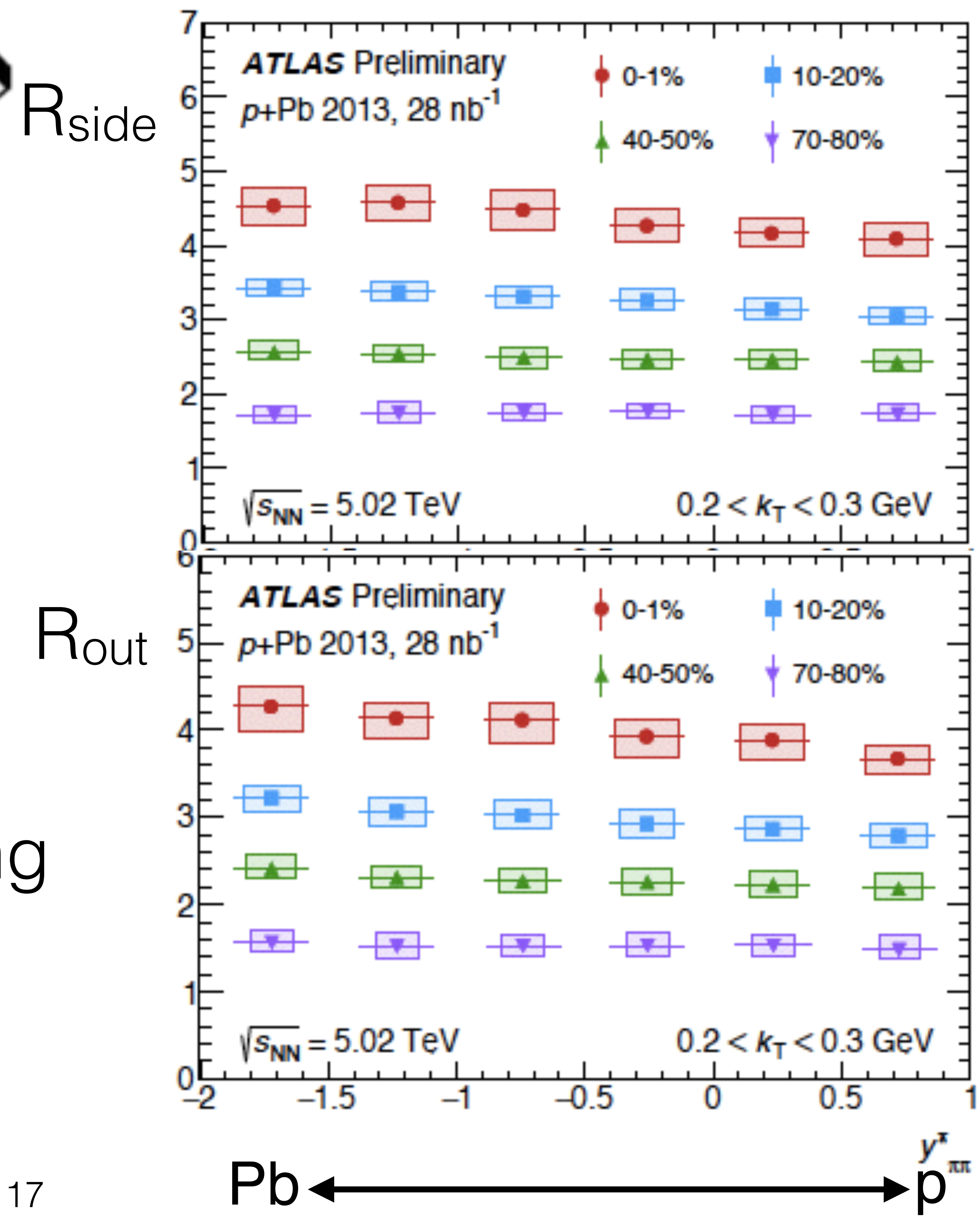
$v_{n,\text{ Cu-going}}/\varepsilon_{n,\text{Cu+Au}}$



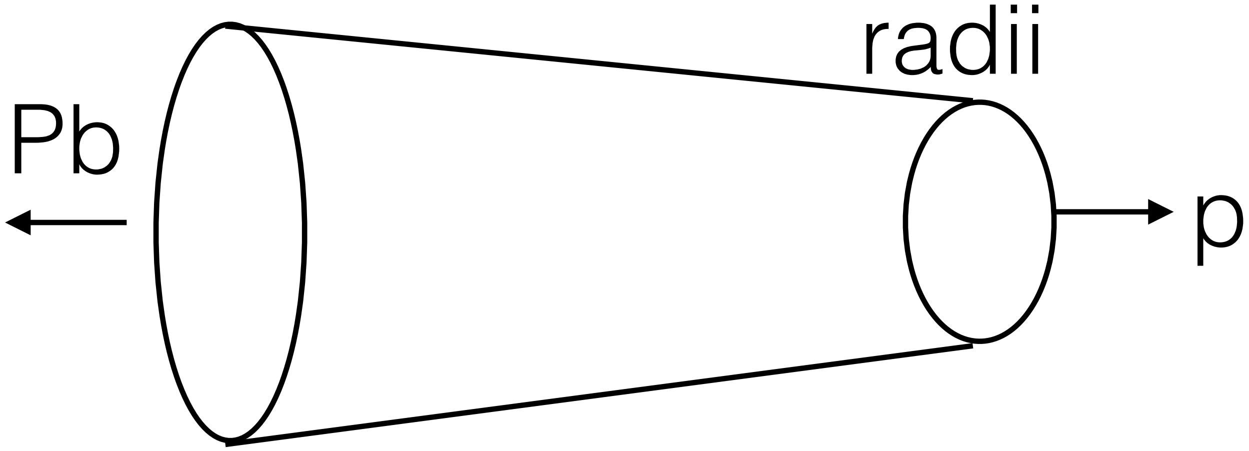
p+Pb HBT radii vs y(rapidity of pion pair)

ATLAS M. Clark





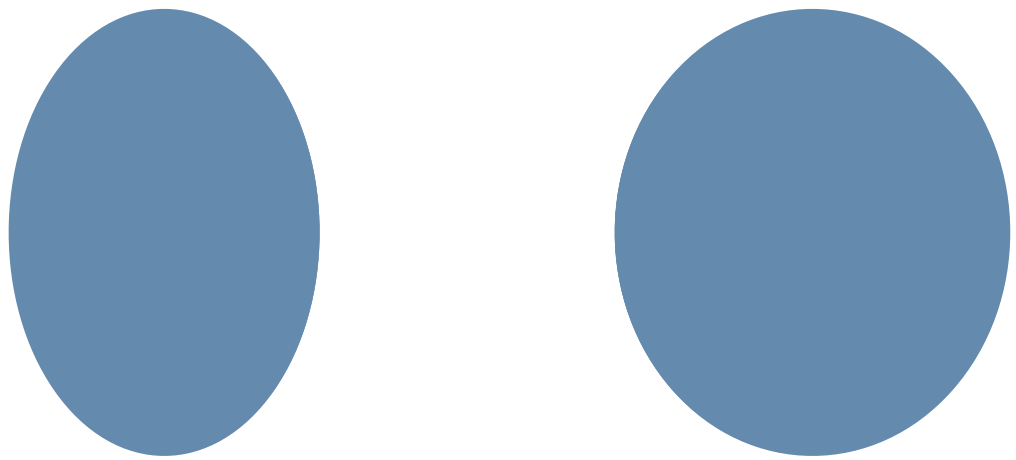
- y' = y - 0.465
  - -Center of momentum frame
- Central: Pb-going > p-going
- Peripheral : Pb-going~p-going radii



HBT w.r.t Ψ_n in Pb+Pb with event shape engineering

✓Event shape engineering

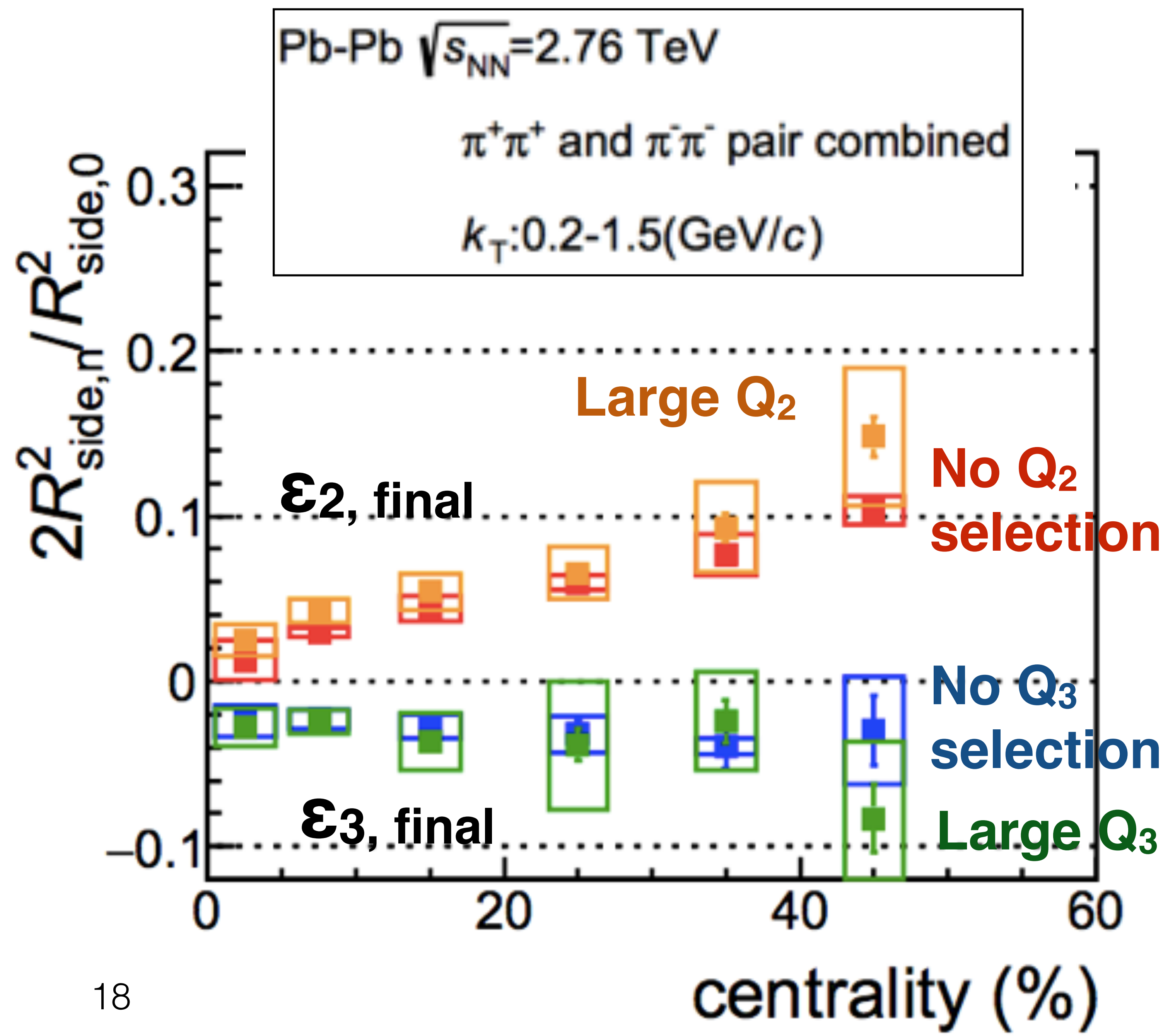
-Select larger flow vector $Q_n \propto v_n$



Large Q_2 :20% Average Q_2

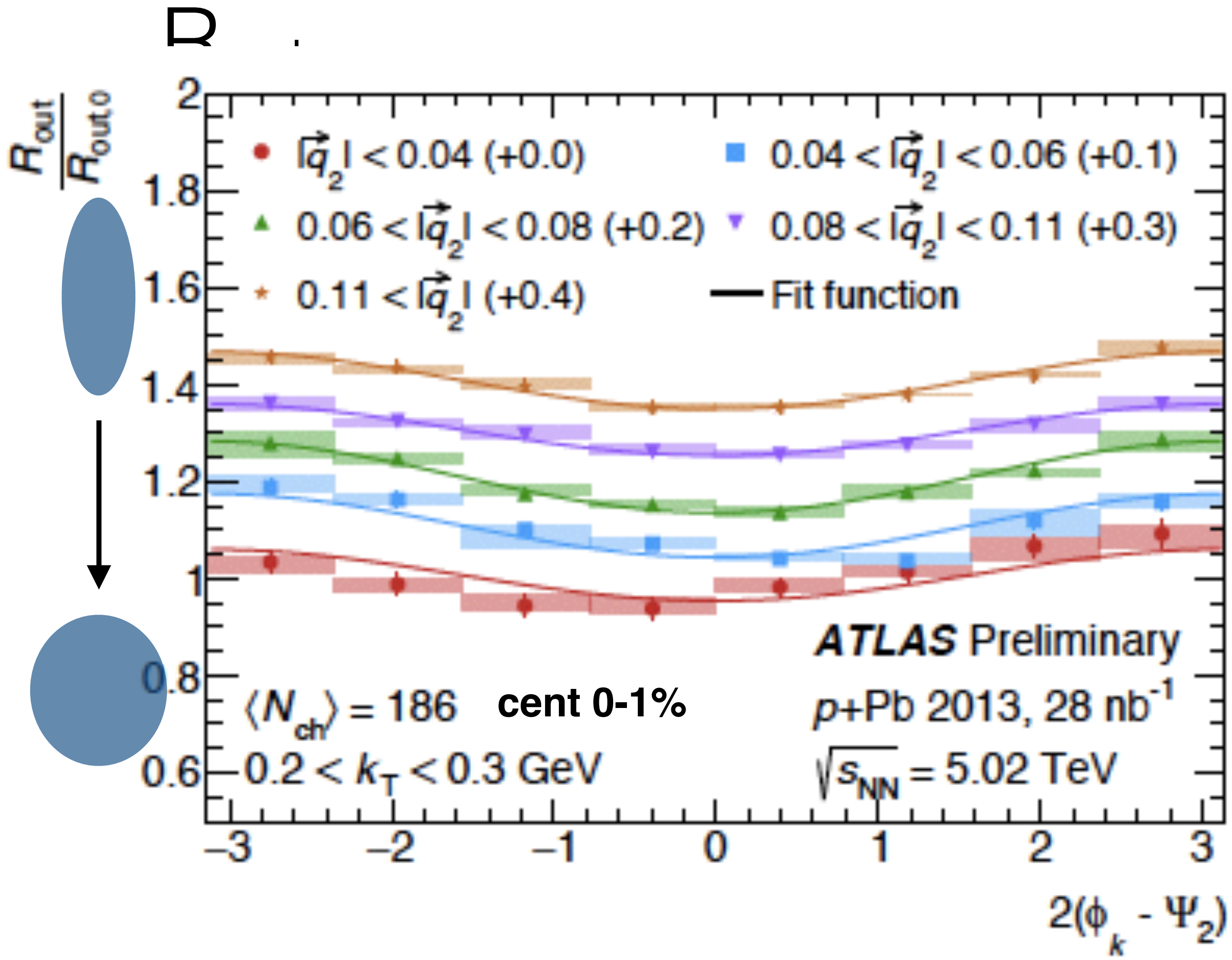
- Large q_2 selection
  - -20% larger v_2
  - -slightly enhance final eccentricity
- Large q_3 selection
  - -15% larger v_3
  - -Final eccentricity does not change

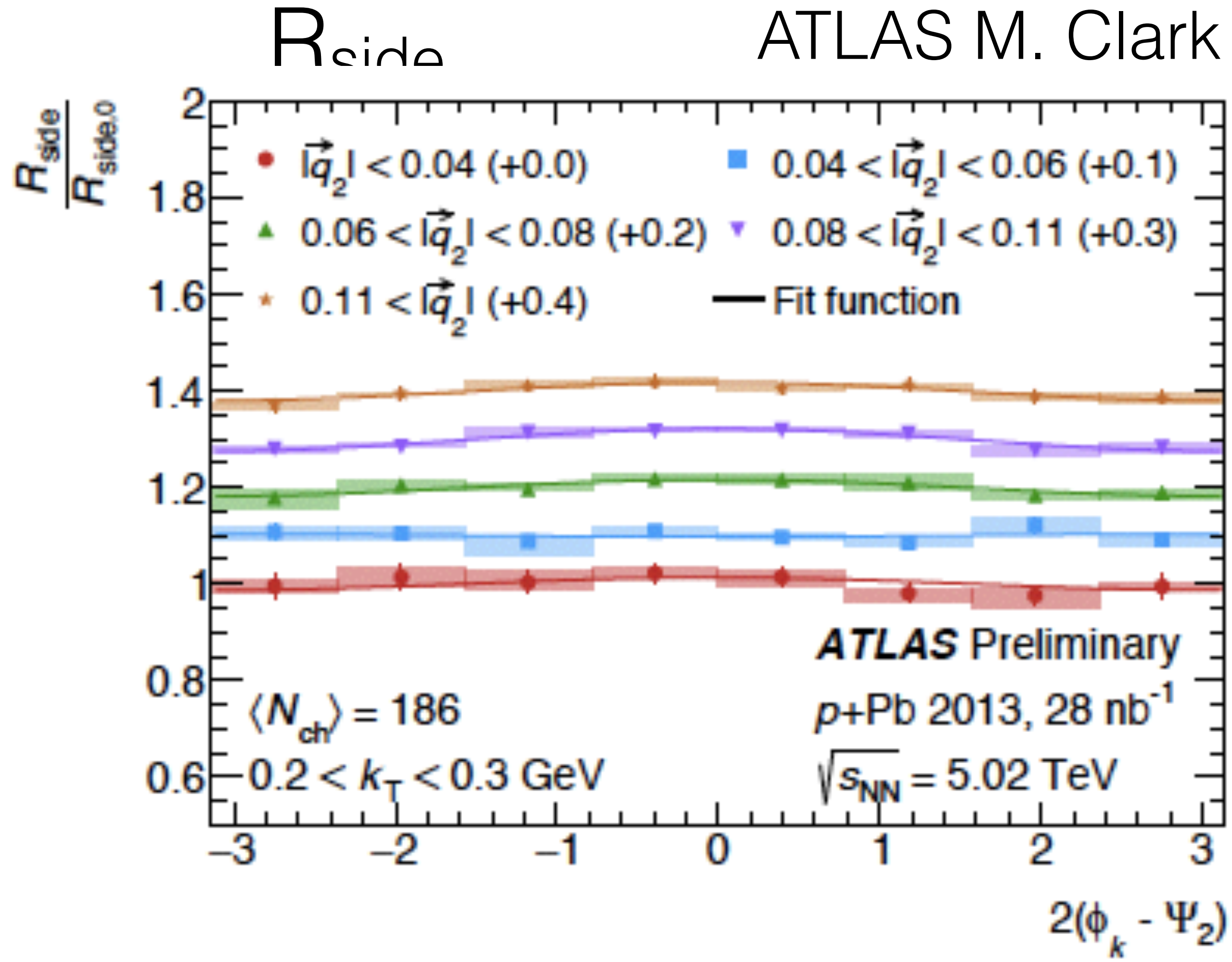
ALICE M. Saleh&N. Tanaka



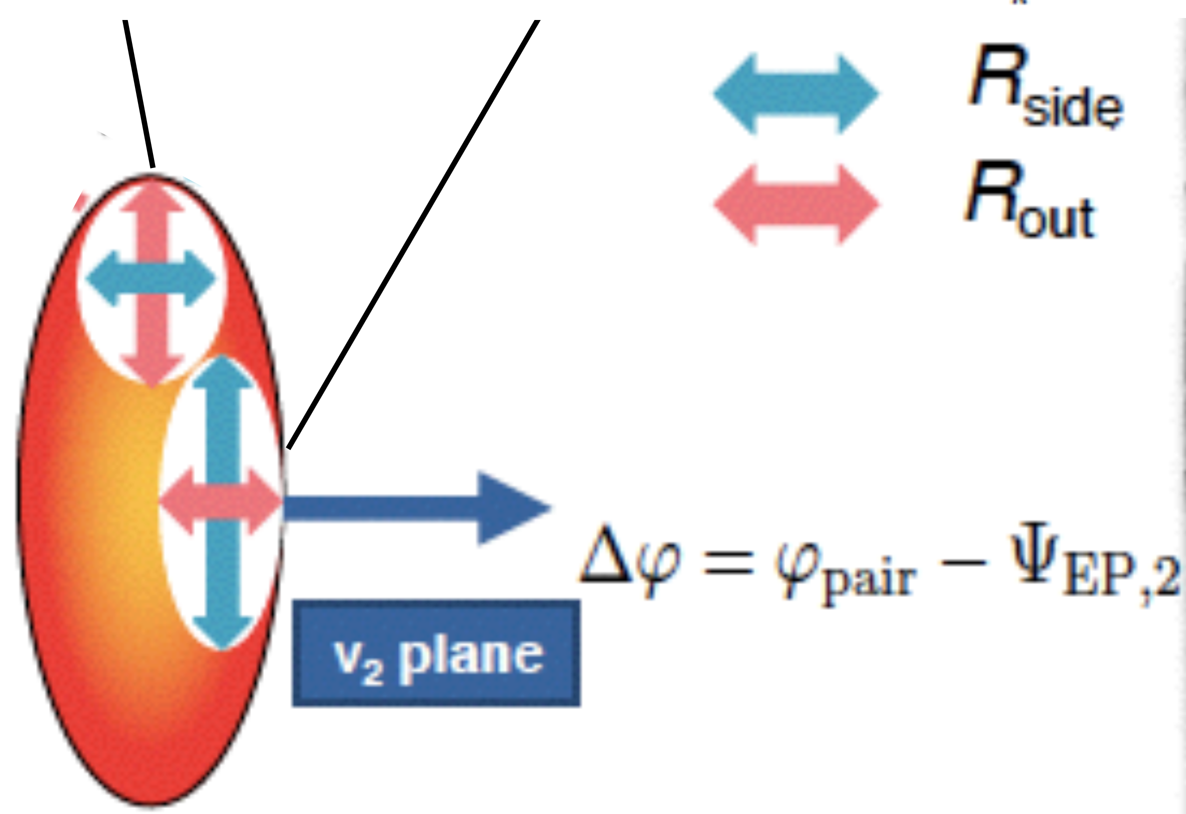
HBT w.r.t Ψ_2 in p+Pb with event shape engineering

ATLAS M. Clark





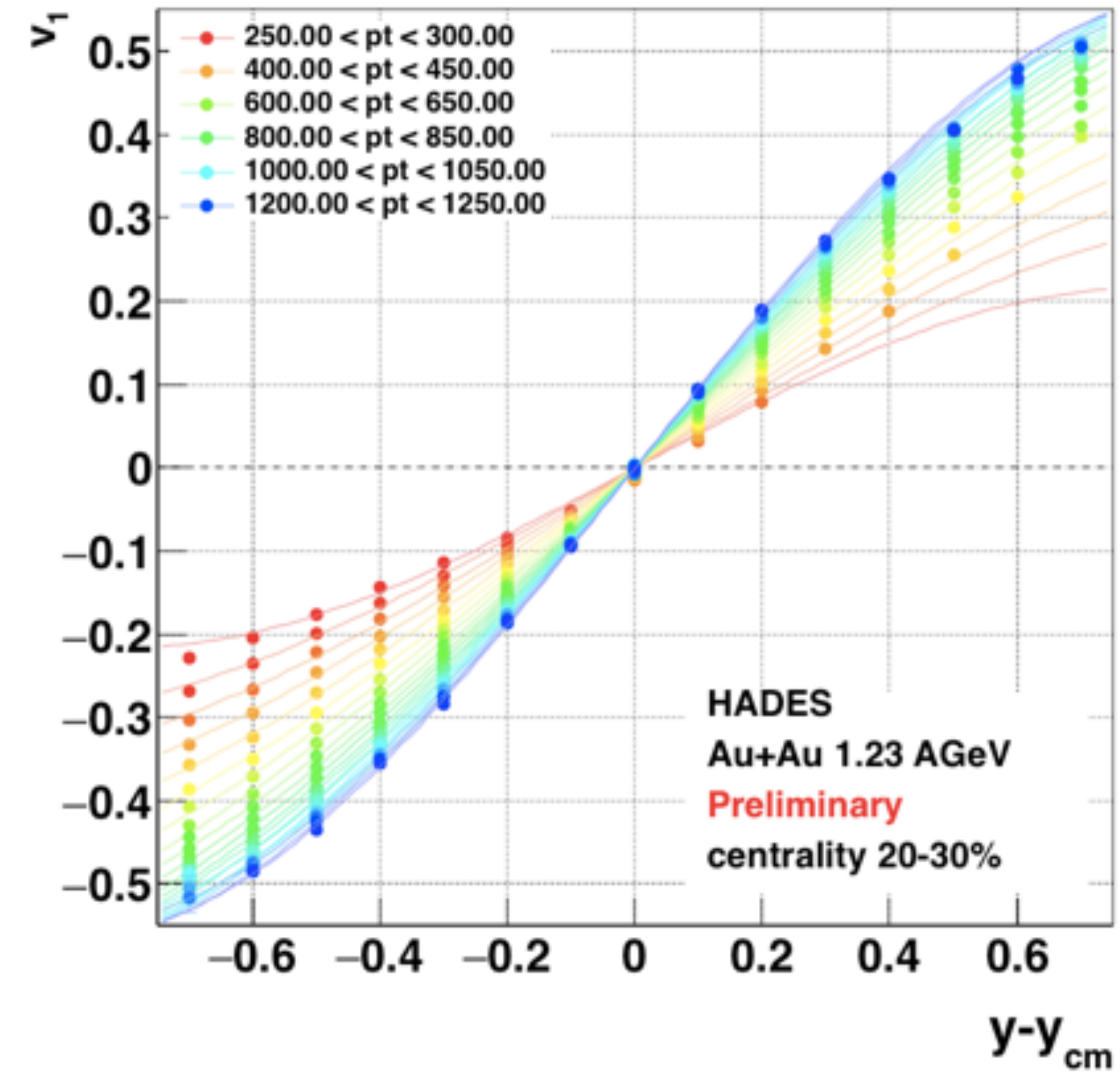
- R_{out}: Smaller in-plane size
- R_{side}: Larger in-plane size
- Same sign of modulation as seen in A+A
- Does not show strong dependence of Q selection

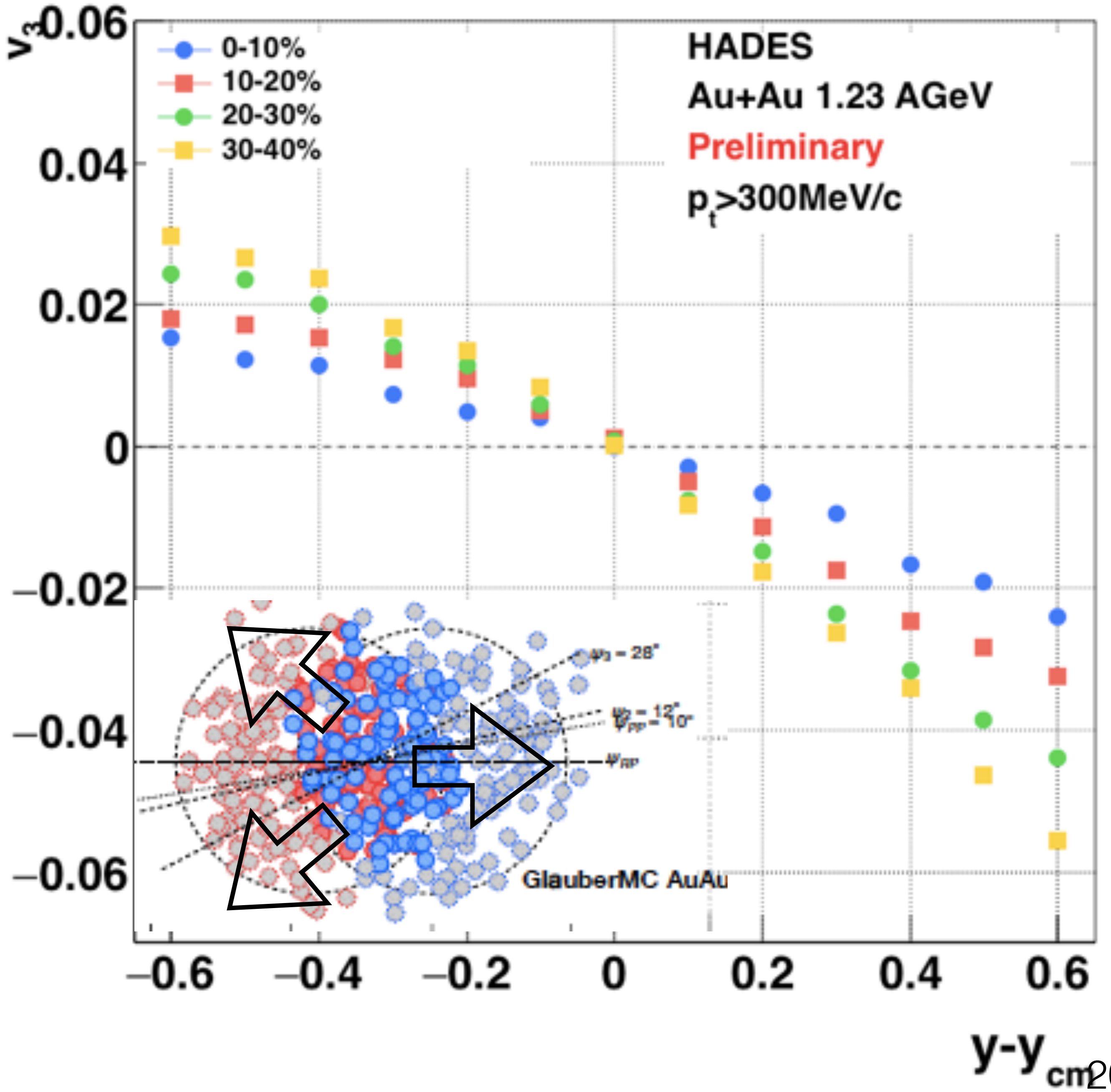


Proton v_3 w.r.t $\Psi_{1,spec}$ in Au+Au at 1.23AGeV

HADES Behruz Kardan

- Proton v_1 w.r.t spectator Ψ_1
  - -Forward :same direction as Ψ_1
  - -Backward:opposite direction as Ψ_1





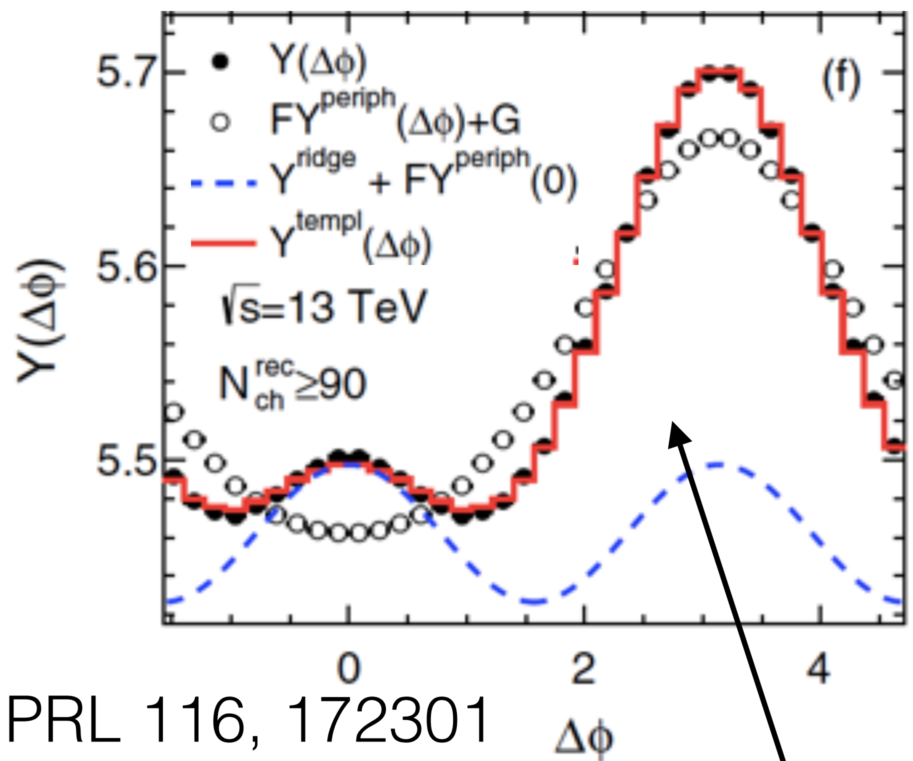
- Proton v_3 w.r.t spectator Ψ_1
  - -Never observed at collider energy
  - -Forward:opposite direction as Ψ_1
  - -Backward:same direction as Ψ_1

Summary

- pp 13TeV at LHC
  - $v_{2:}$ATLAS/CMS show different multiplicity dependence
  - v_2:mass ordering is observed as seen in A+A
  - c2{4}:Inconsistency between ATLAS/ALICE and CMS
- p/d/^{3}He+Au at RHIC
  - -mass ordering is less pronounced in p+Au
  - -d+Au BES pT and η dependence is changed between 39 and 62.4
- Longitudinal direction
  - -η dependent EP
  - -Initial geometry is almost η independent
  - -HBT radii is η dependent
- Event shape engineering
  - -PbPb:Unlike $\varepsilon_{2,Final}$, $\varepsilon_{3,Final}$ is less sensitive
  - -pPb: HBT radii w.r.t $\Psi_{2,}$ same oscillation as seen PbPb
- Low energy(Fixed target HADES)
  - -v_3 w.r.t Psi_1 is new observable at BES?

Template fit method (ATLAS)

- Extract flow component(v_2) via template function



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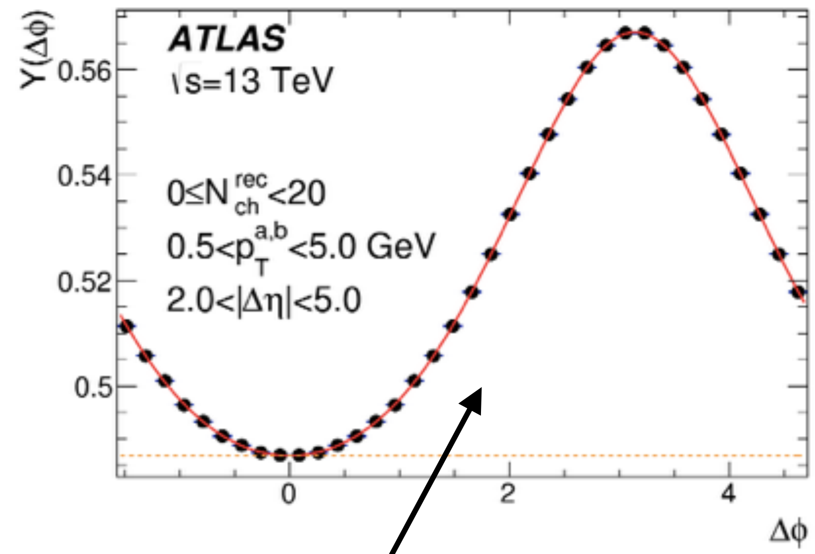
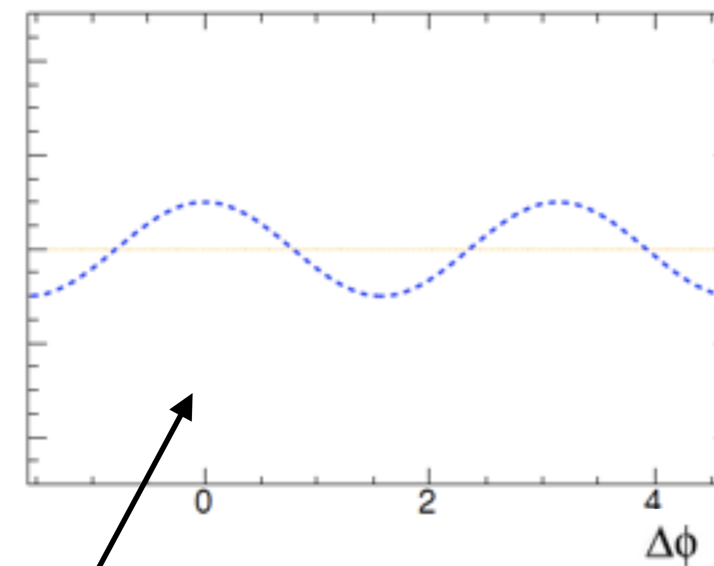
Low mult.



+

v_2 term



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

v_2 term

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

v_2 term

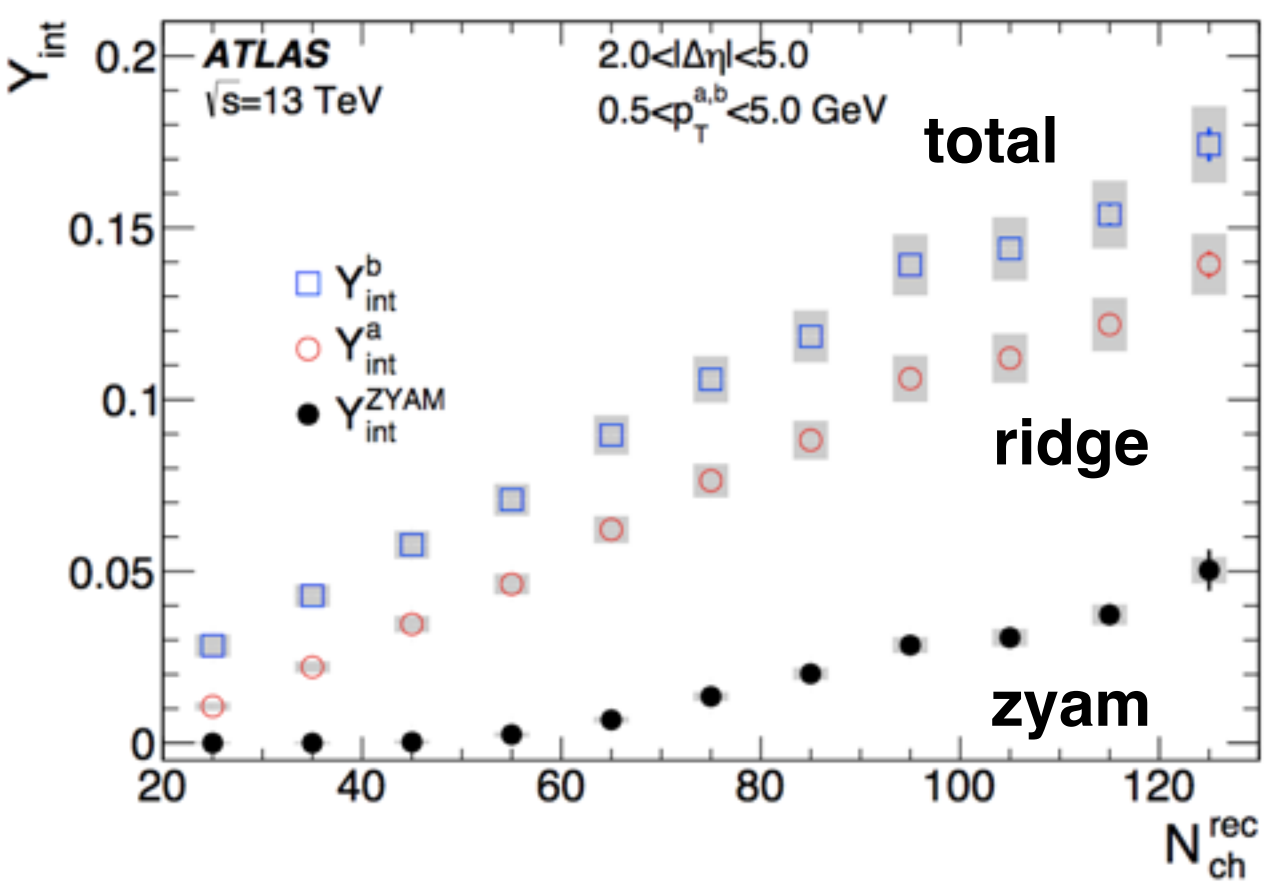
$$Y^{\mathrm{ridge}}(\Delta\phi) = G[1 + 2v_{2,2}\cos(2\Delta\phi)]$$

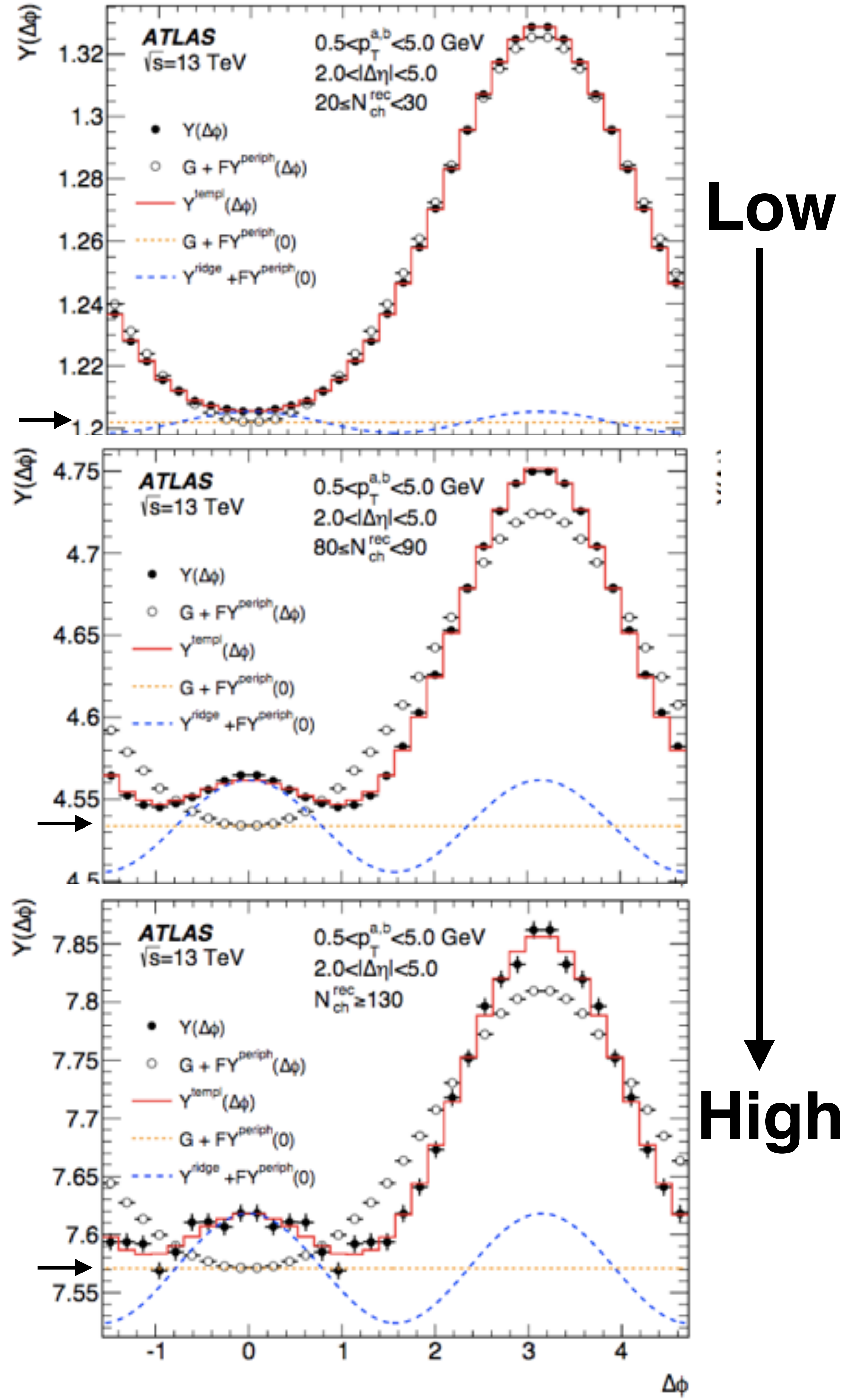
Ridge yield

- $v_{2,2}$ depends on baseline G

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

- G and Y^{ridge} increase with N_{ch}





Subtraction method (CMS)

- Extract flow component(v_2) via low mult. subtraction

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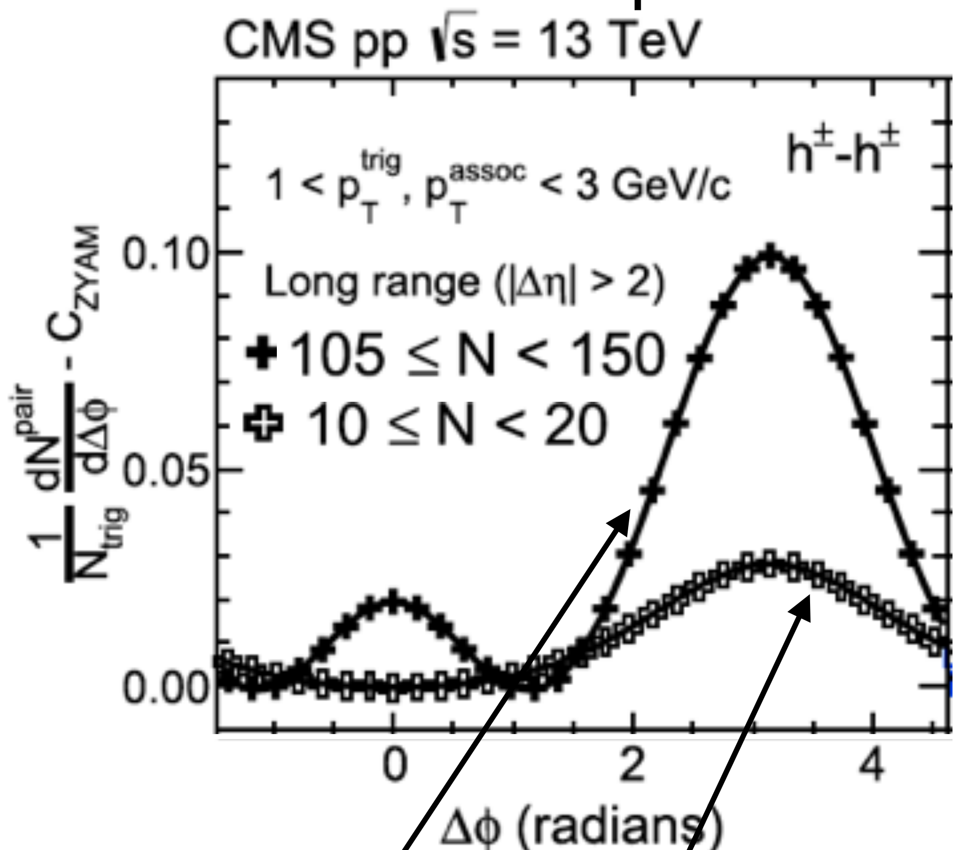
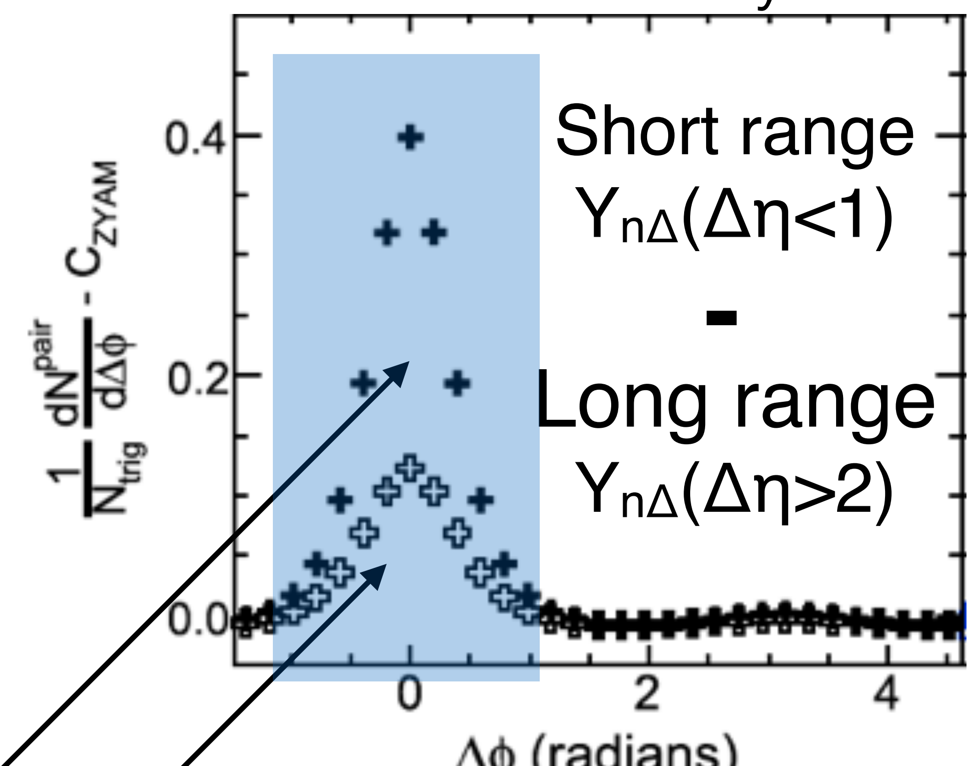
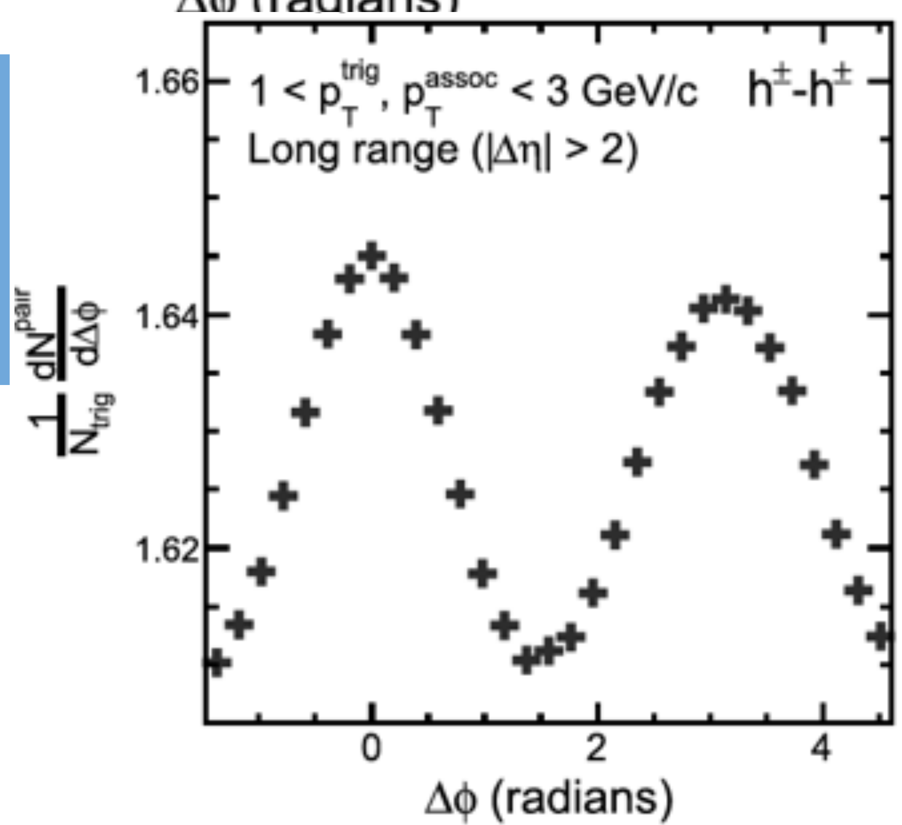






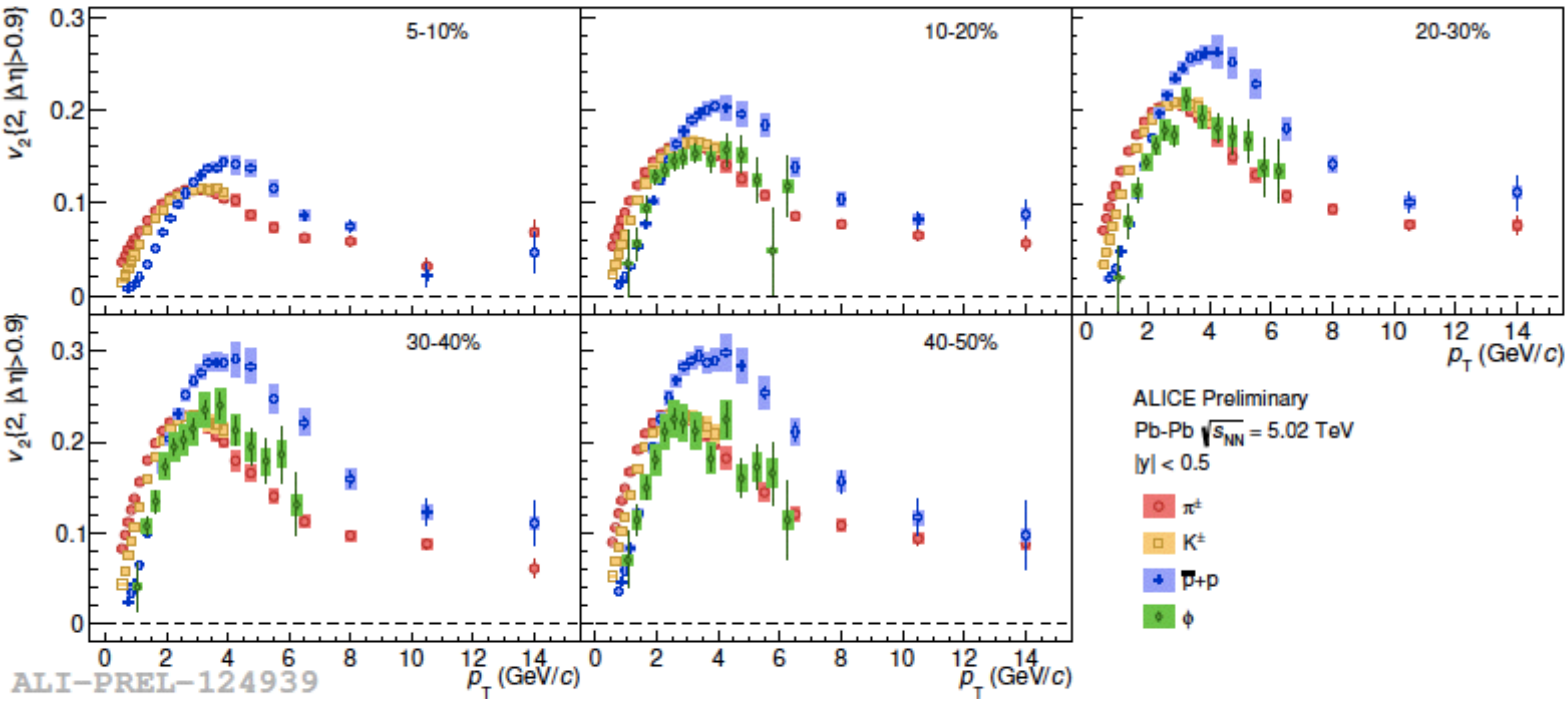
$$V_{n\Delta}^{\mathrm{sub}} = V_{n\Delta} - V_{n\Delta}^{\mathrm{per}} \frac{Y_{\mathrm{jet}}}{N_{\mathrm{asso}}} \Big/ \frac{Y_{\mathrm{jet}}^{\mathrm{per}}}{N_{\mathrm{asso}}^{\mathrm{per}}}$$

scale factor

-Scale factor is fraction of jet yield

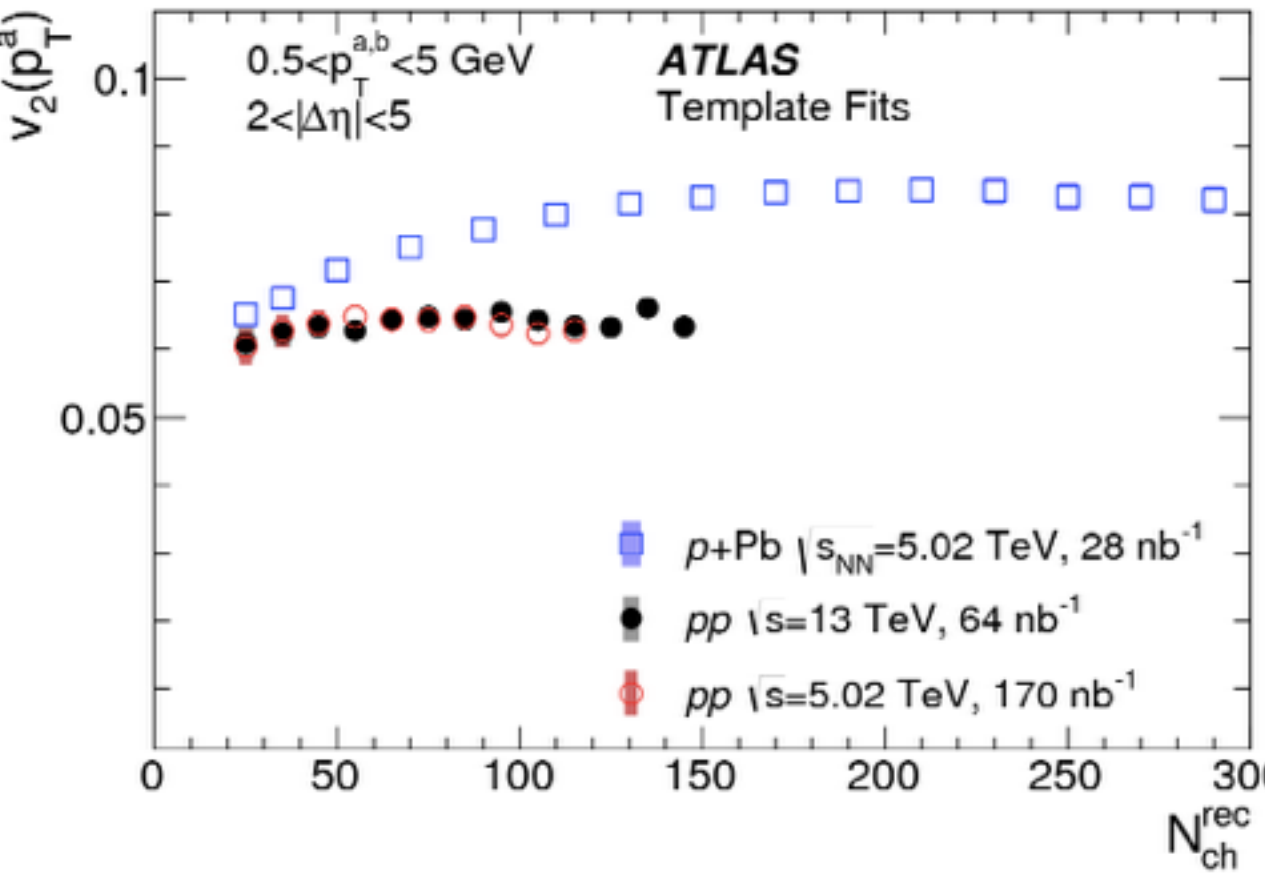
-Unlike ATLAS, CMS assumes $v_2=0$ at low mult.

PID v_2 in Pb+Pb at 5.02 TeV

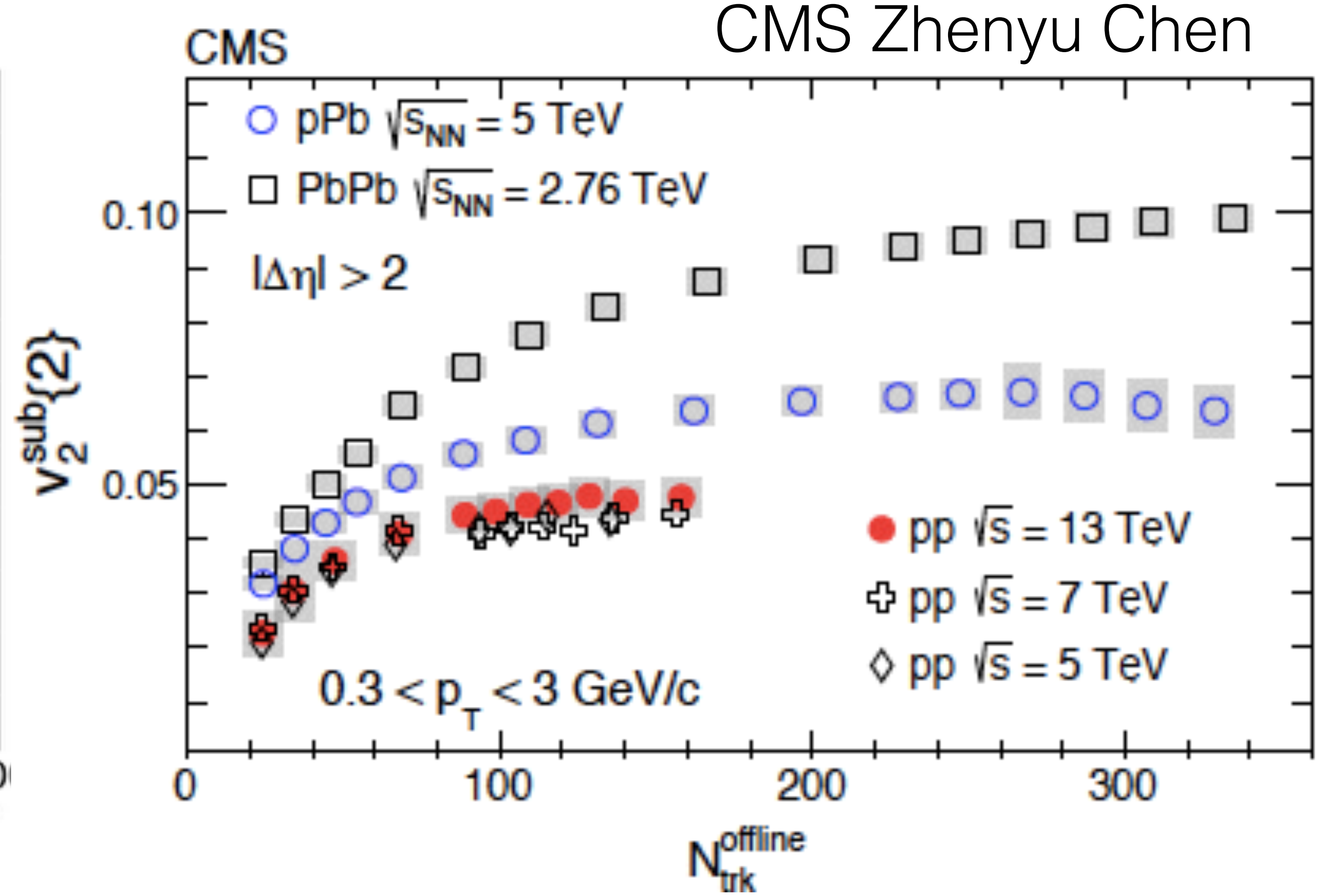


v_2 in p+p 13 TeV

ATLAS Adam Trzupek



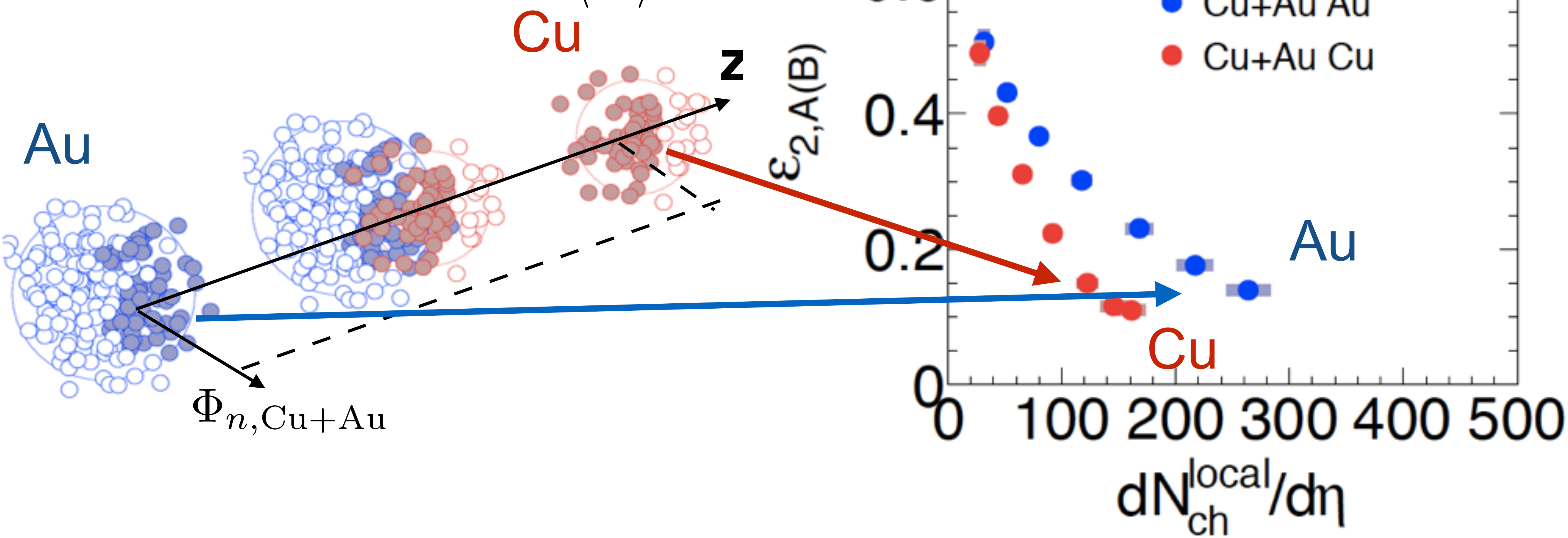
CMS Zhenyu Chen



ε_n : Asymmetric initial eccentricity

MC-Glauber model

$$\varepsilon_{n,\mathrm{Au(Cu)}} = \frac{\langle r^n \cos[n(\phi_{\mathrm{Au(Cu)}} - \Phi_{n,\mathrm{Cu+Au}})]\rangle}{\langle r^n \rangle}$$



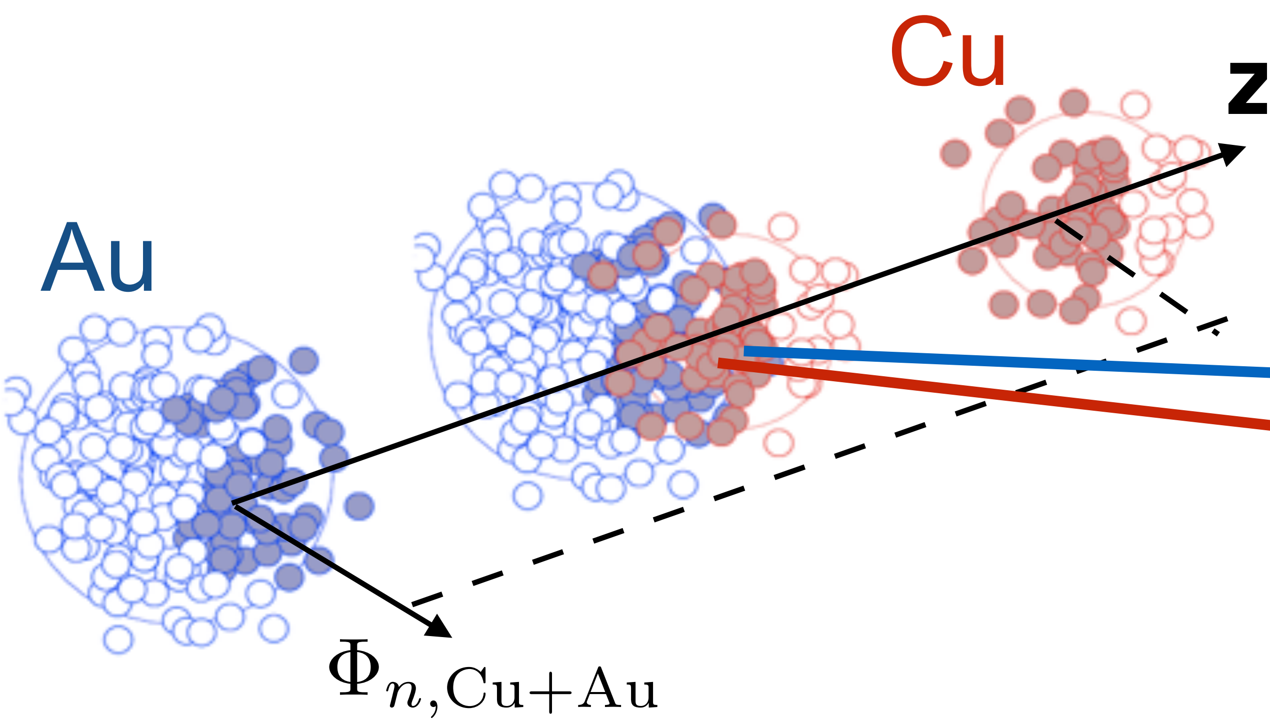
$\varepsilon_{n,\,\mathrm{Au}}$: Au participant eccentricity

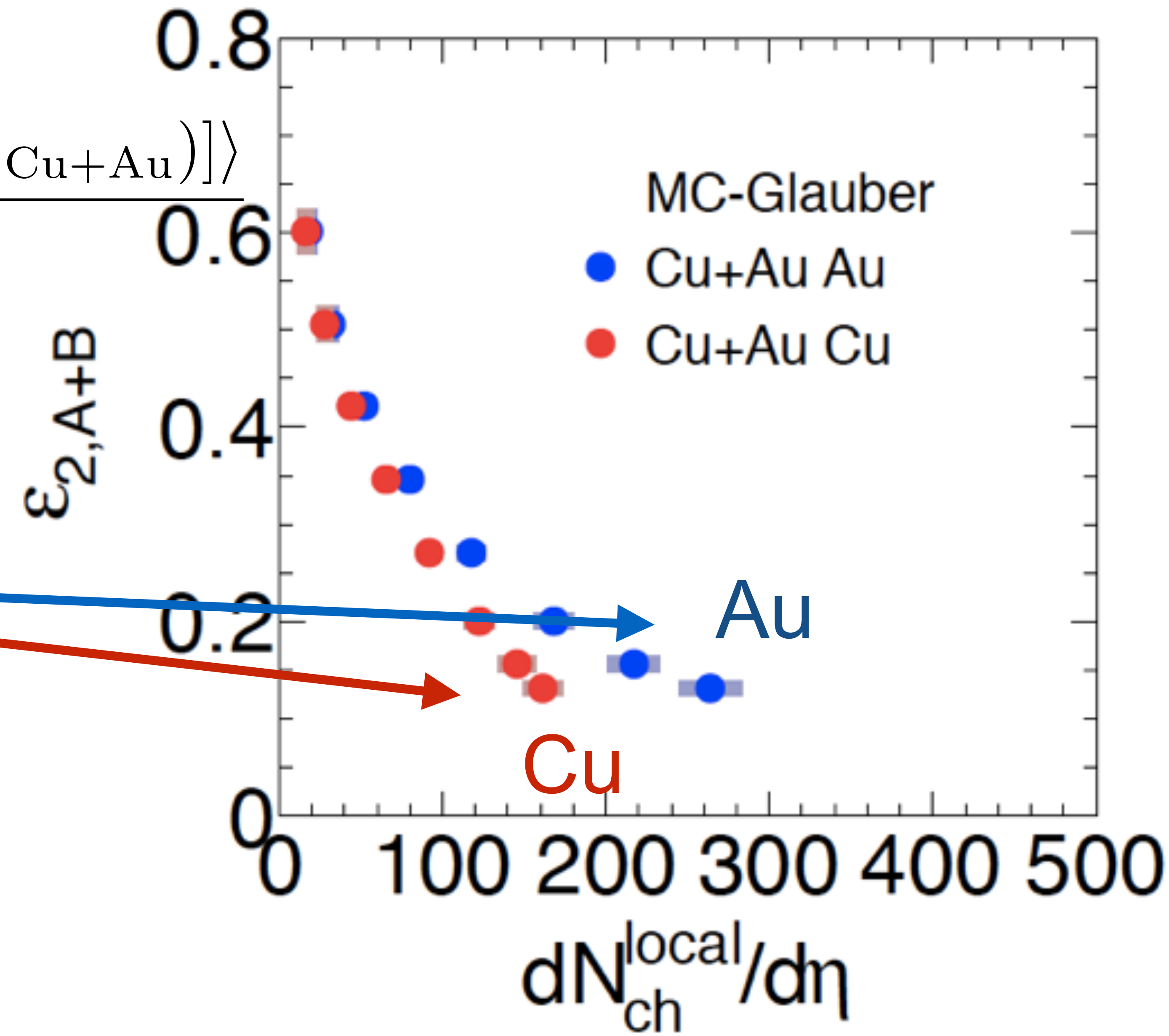
$\varepsilon_{n,\,\mathrm{Cu}}$: Cu participant eccentricity

ε_n :Symmetric initial eccentricity

MC-Glauber model

$$\varepsilon_{n,\mathrm{Au(Cu)}} = \frac{\langle r^n \cos[n(\phi_{\mathrm{Au(Cu)}} - \Phi_{n,\mathrm{Cu+Au}})] \rangle}{\langle r^n \rangle}$$

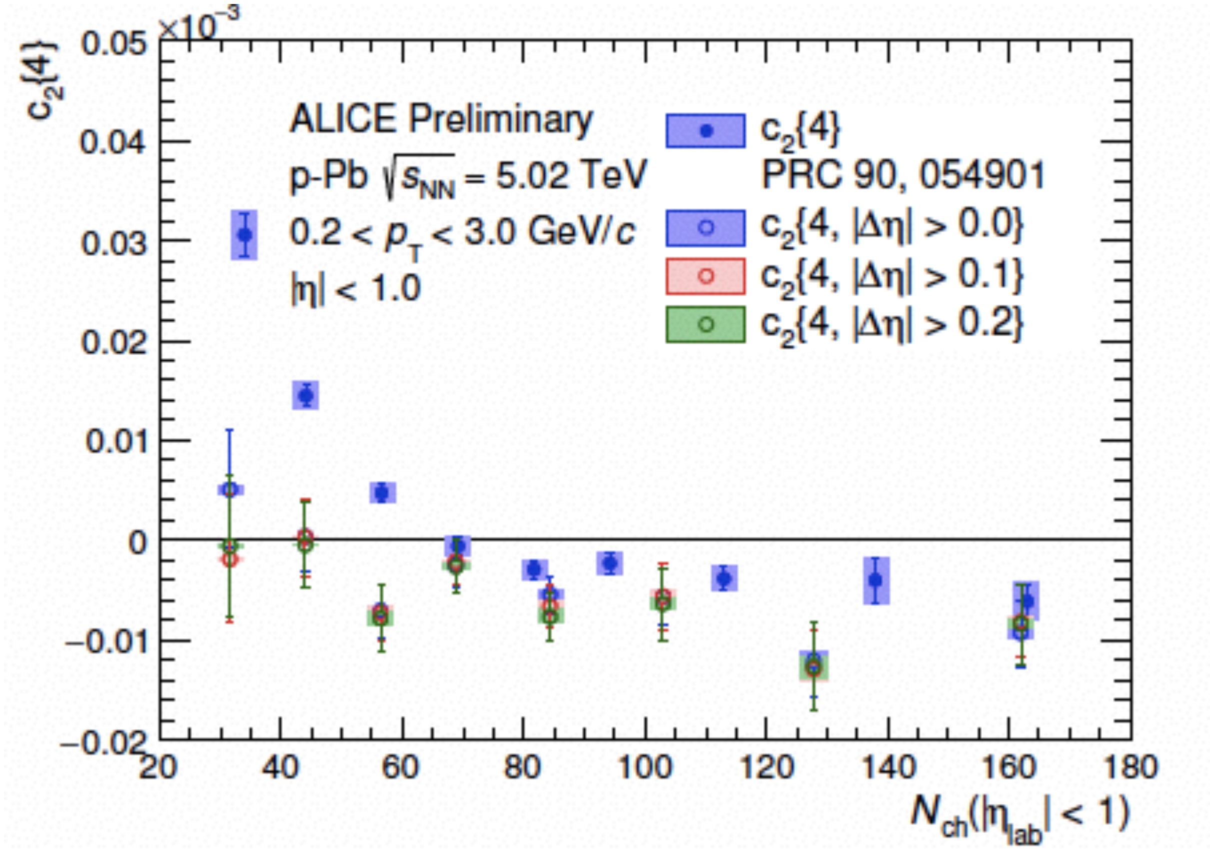


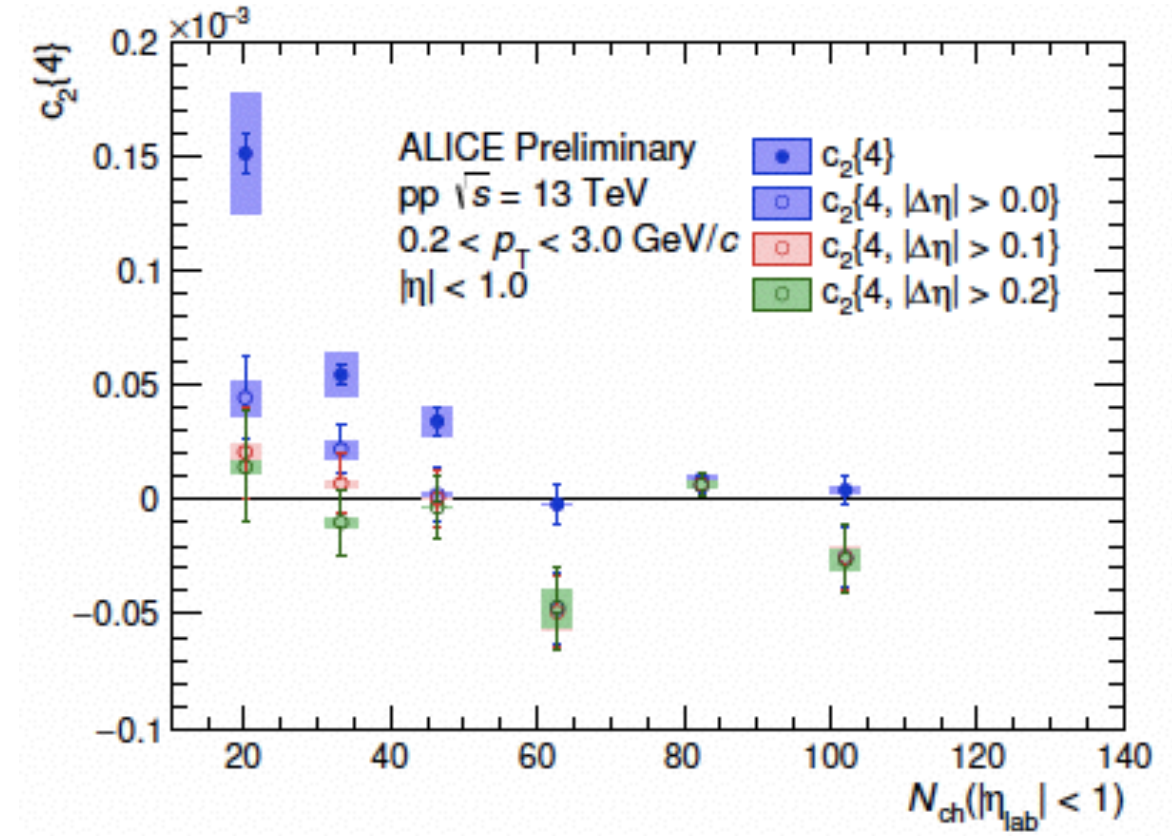


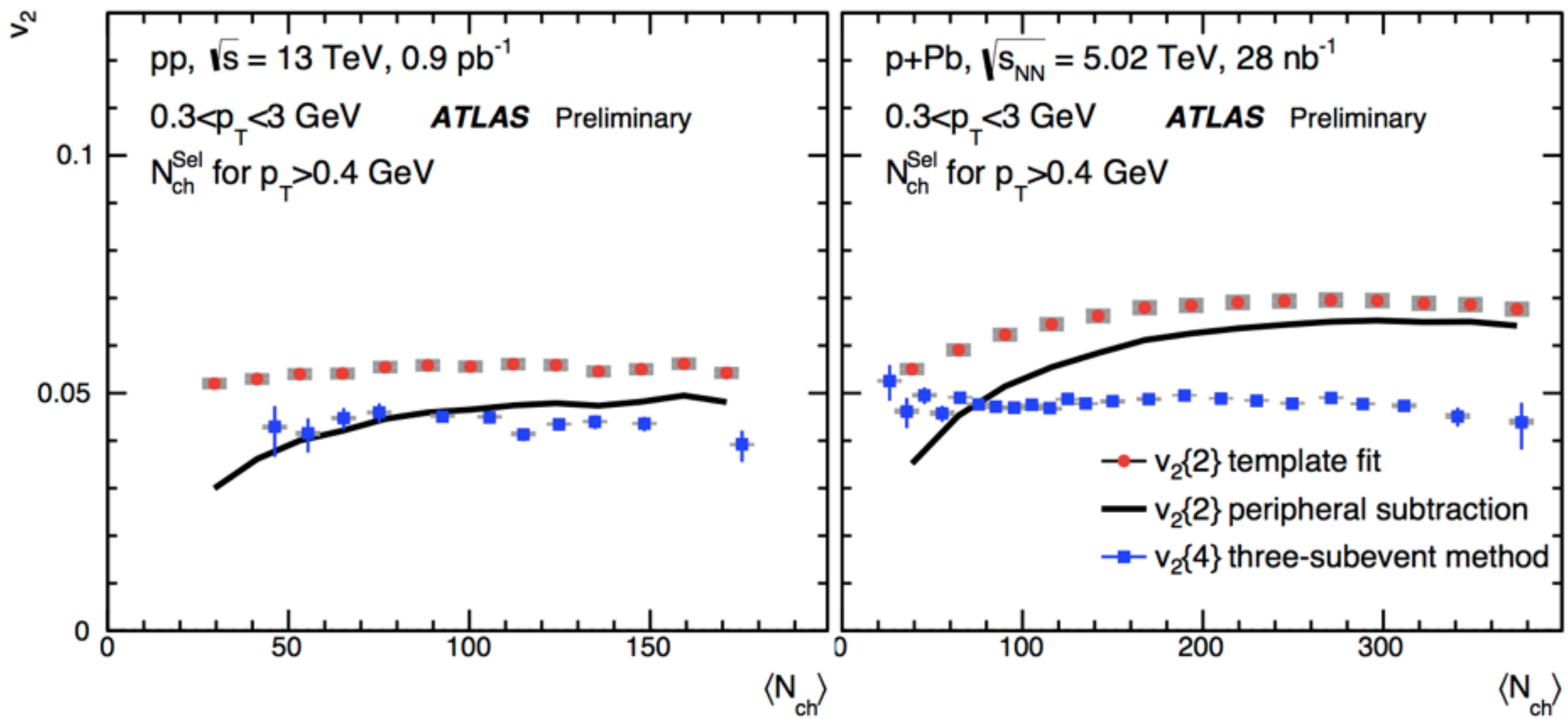
$\varepsilon_{n,\ \mathrm{Cu+Au}}$: Cu+Au participant eccentricity

$\varepsilon_{n,\ \mathrm{Cu+Au}}$: Cu+Au participant eccentricity

Additional removal of non-flow



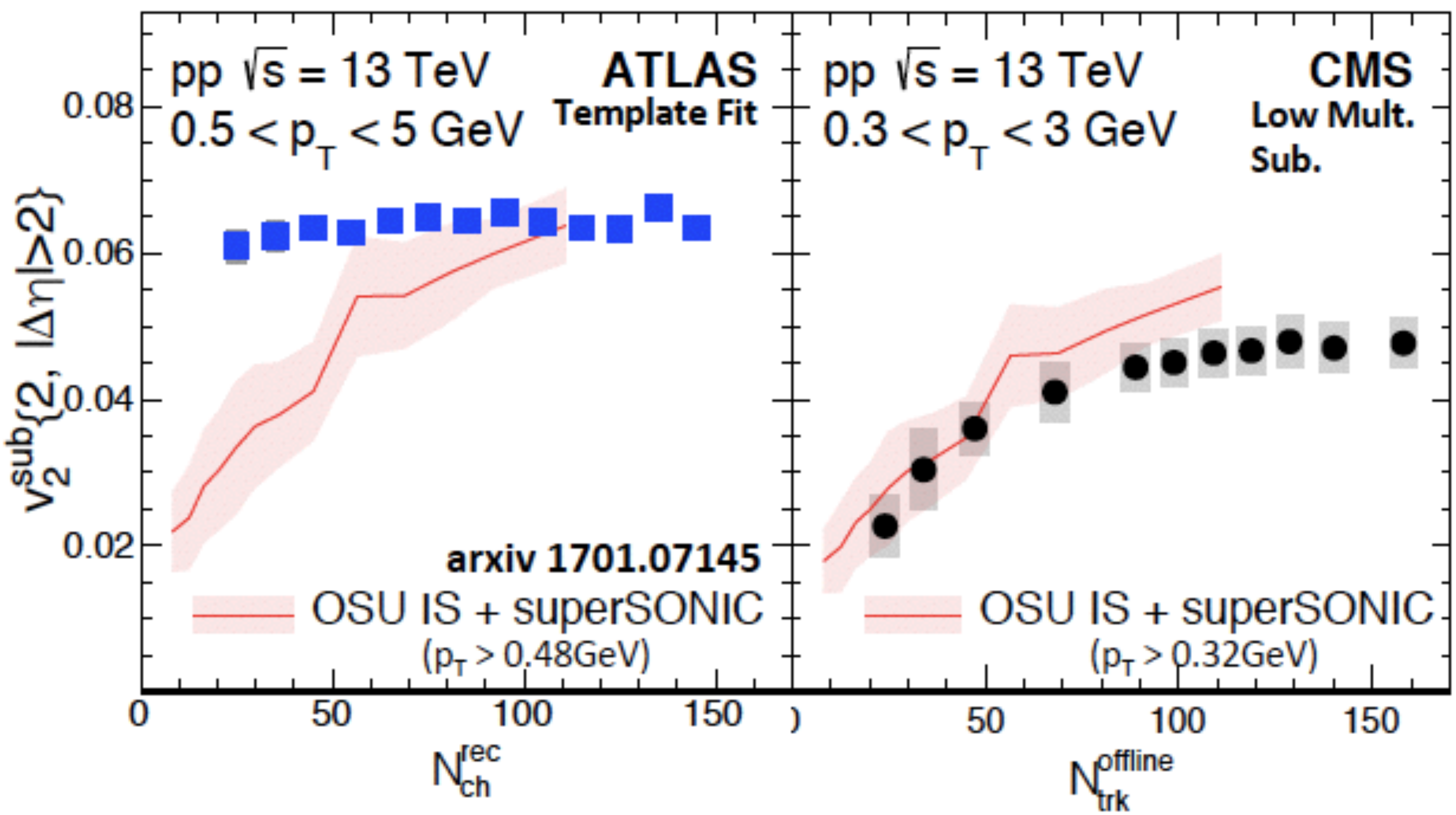




v2
pp, √s = 13 TeV, 0.9 pb-1
0.3<pT<3 GeV
ATLAS Preliminary
N_ch^Sel for pT>0.4 GeV
0.1
0.05
0
0
50
100
150
⟨Nch⟩
p+Pb, √sNN = 5.02 TeV, 28 nb-1
0.3<pT<3 GeV
ATLAS Preliminary
N_ch^Sel for pT>0.4 GeV
0
100
200
300
⟨Nch⟩
v2{2} template fit
v2{2} peripheral subtraction
v2{4} three-subevent method

v_2 in p+p 13 TeV

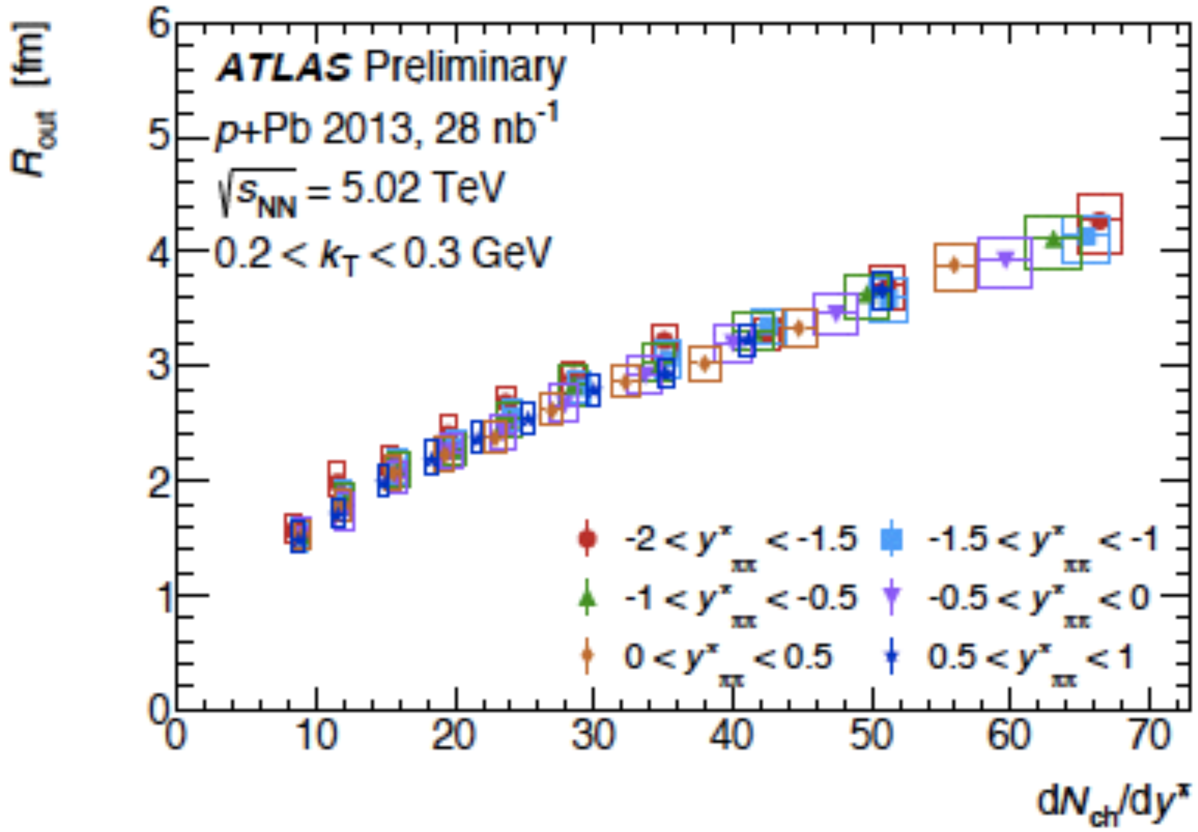
CMS Zhenyu Chen

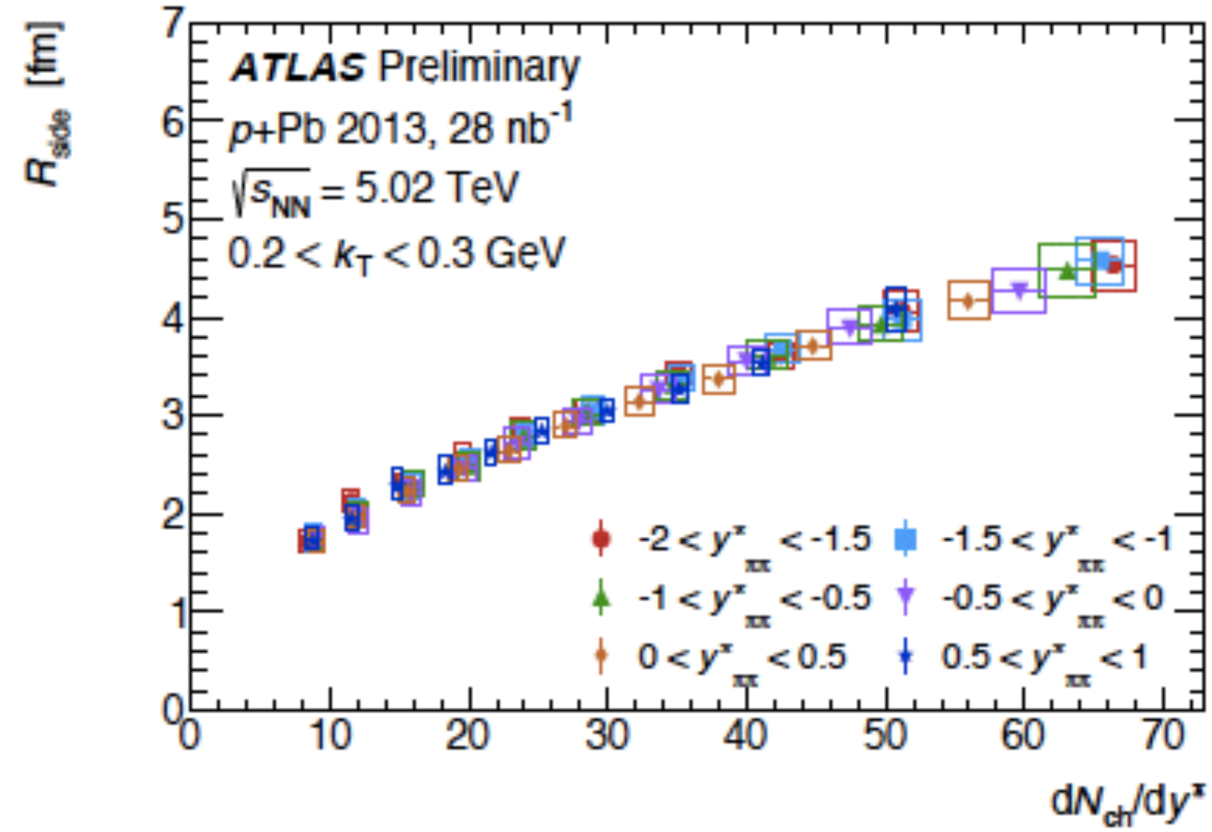


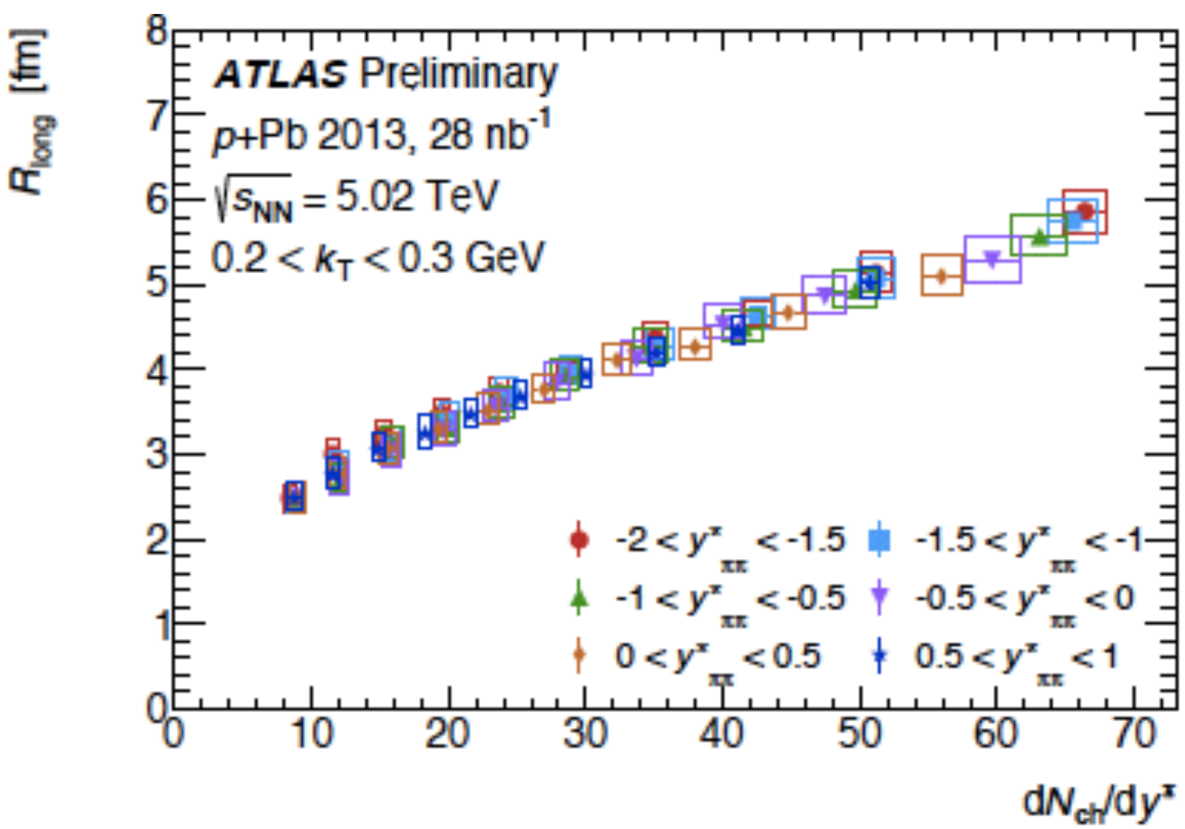
- ATLAS Template fit
  - -No multiplicity dependence
- CMS Low mult. subtraction method
  - -Strong multiplicity dependence
  - -Hydrodynamics well reproduce

→Results depend on

p+Pb HBT vs local dN/dy



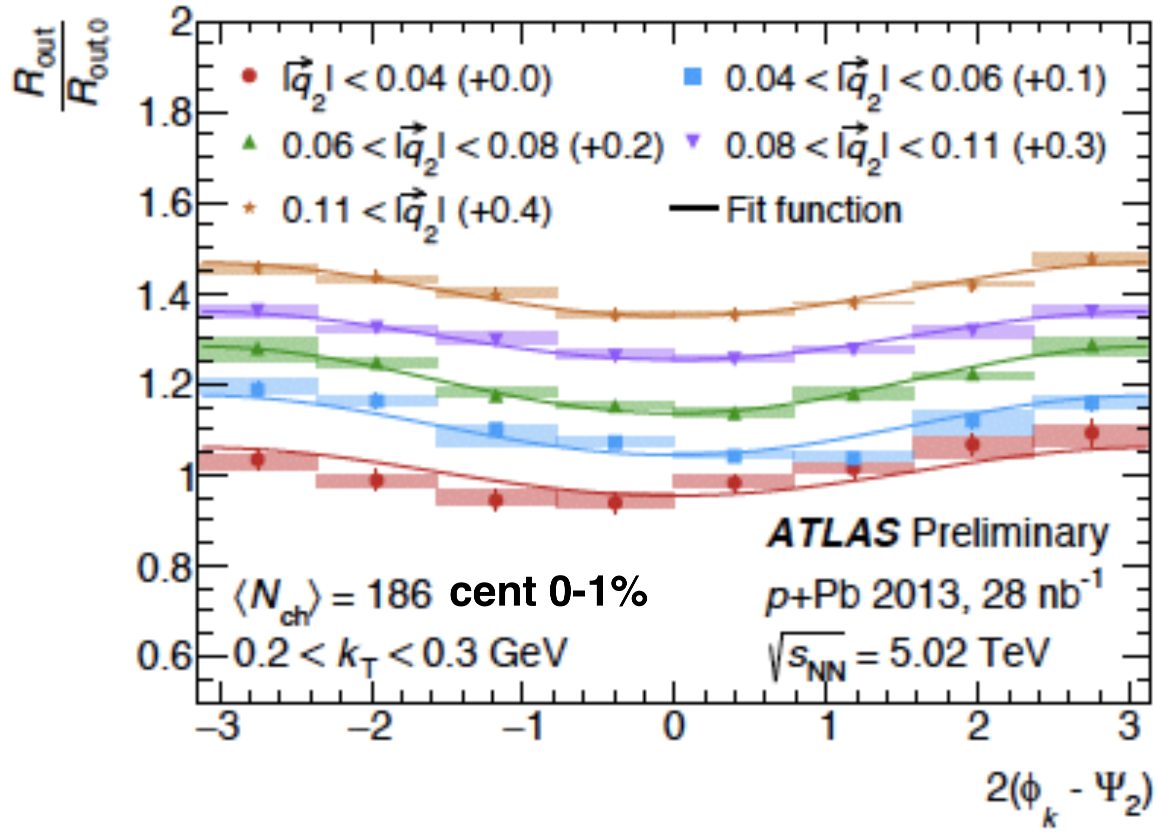


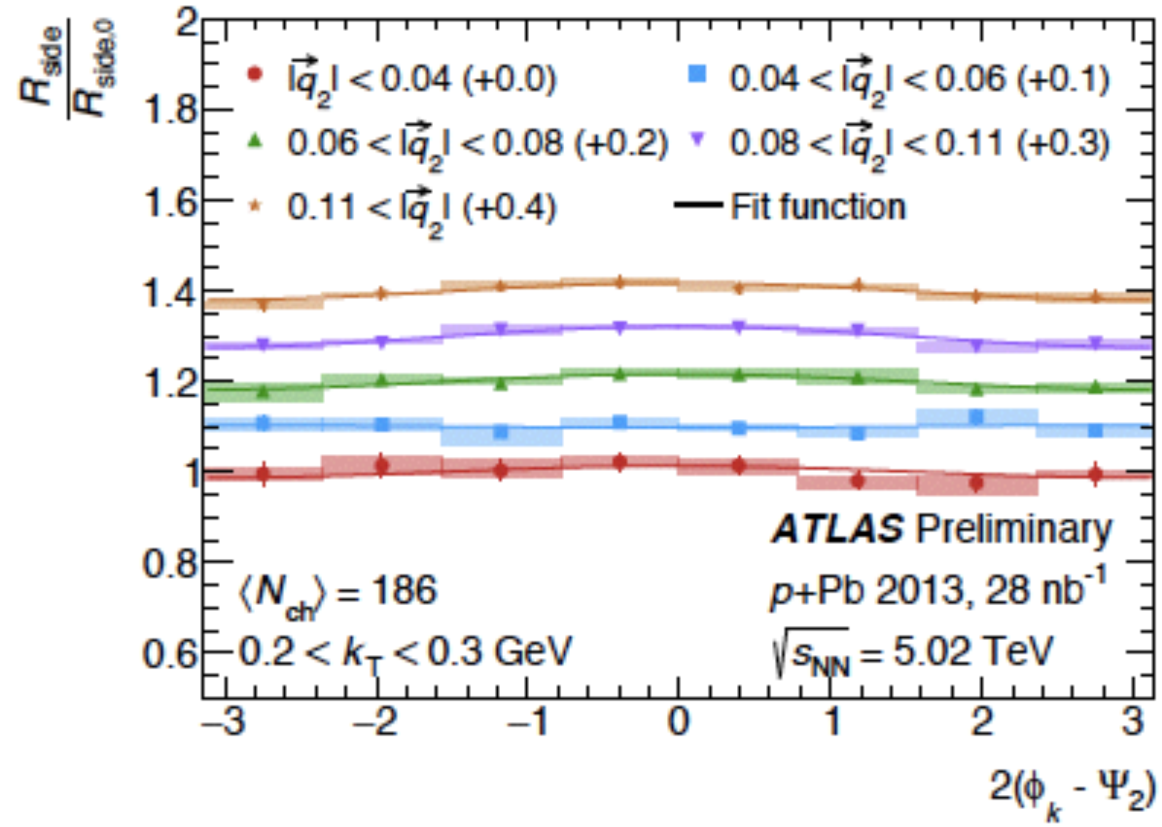


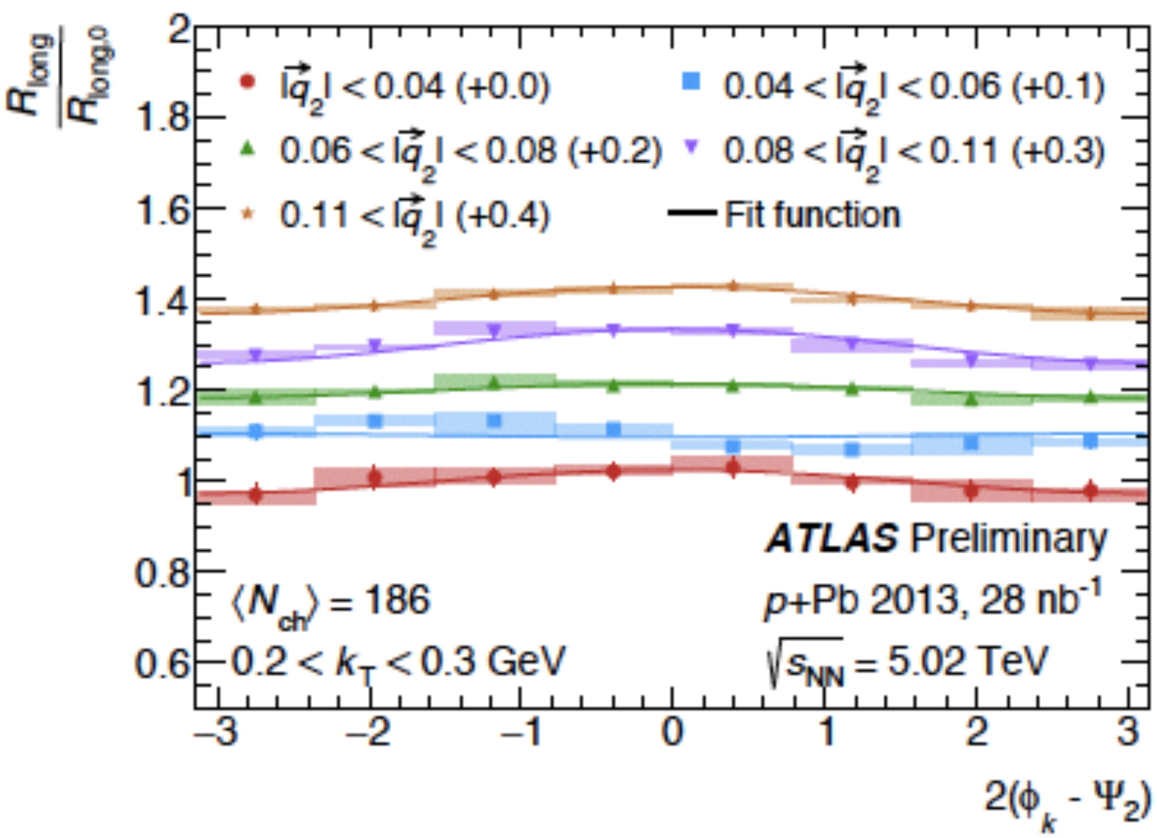
- HBT radii is highly correlated with local multiplicity

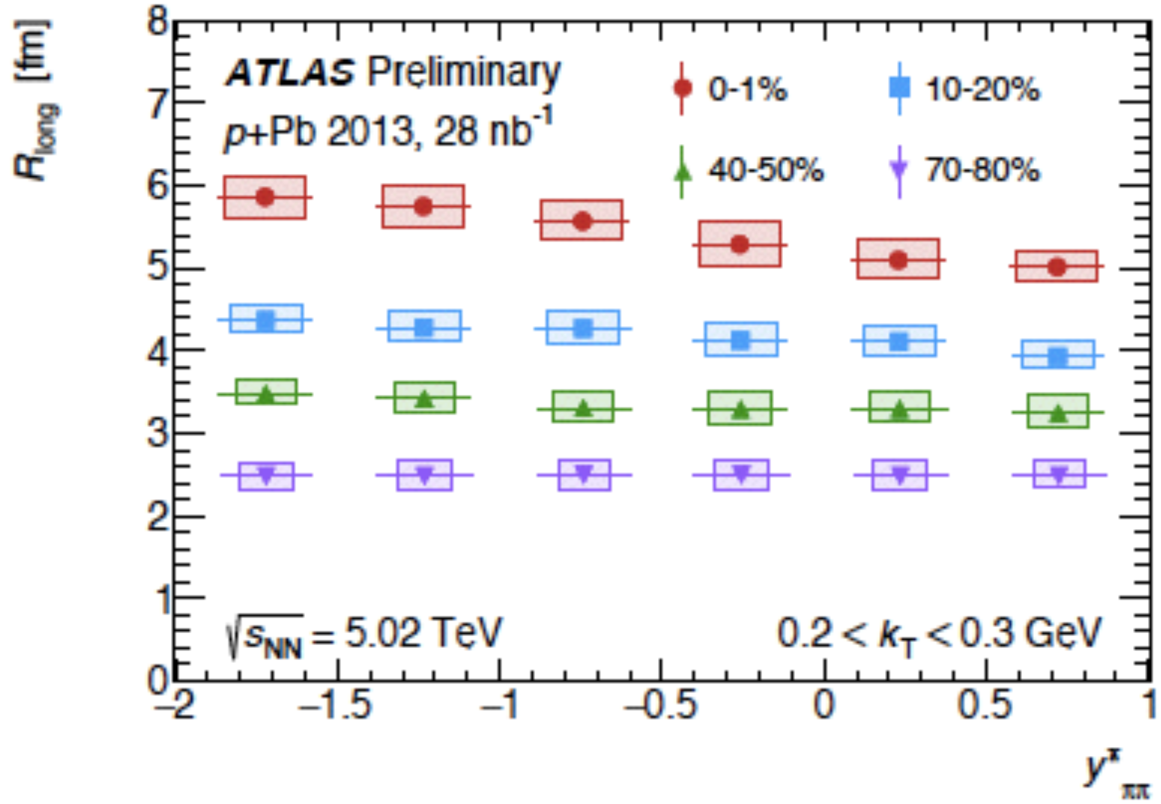
HBT w.r.t Ψ_2 in p+Pb with event shape engineering

ATLAS M. Clark



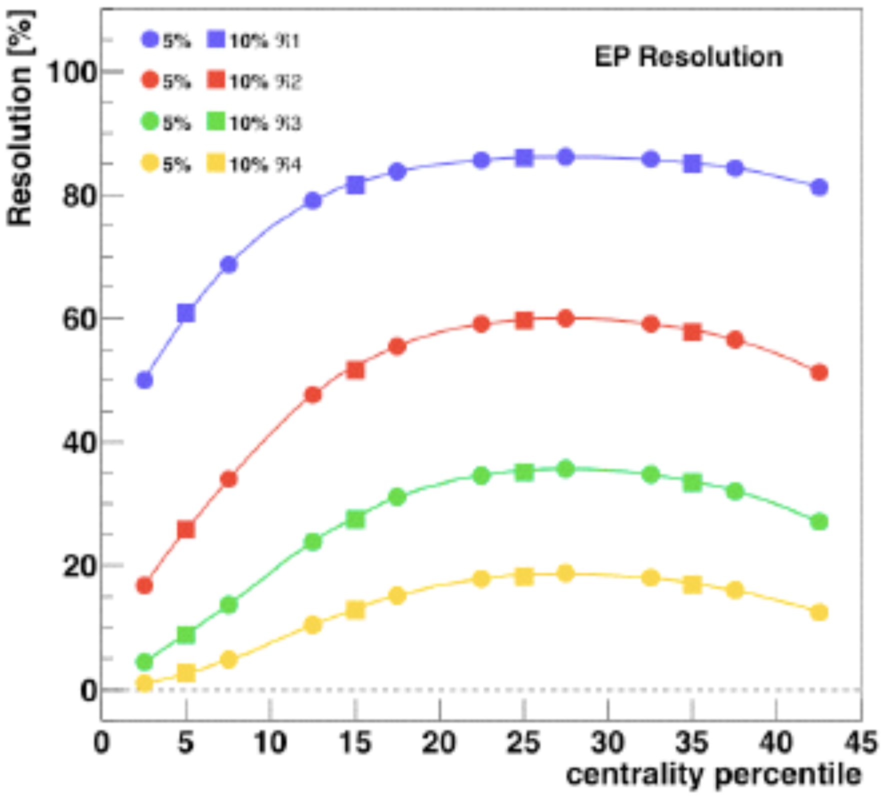


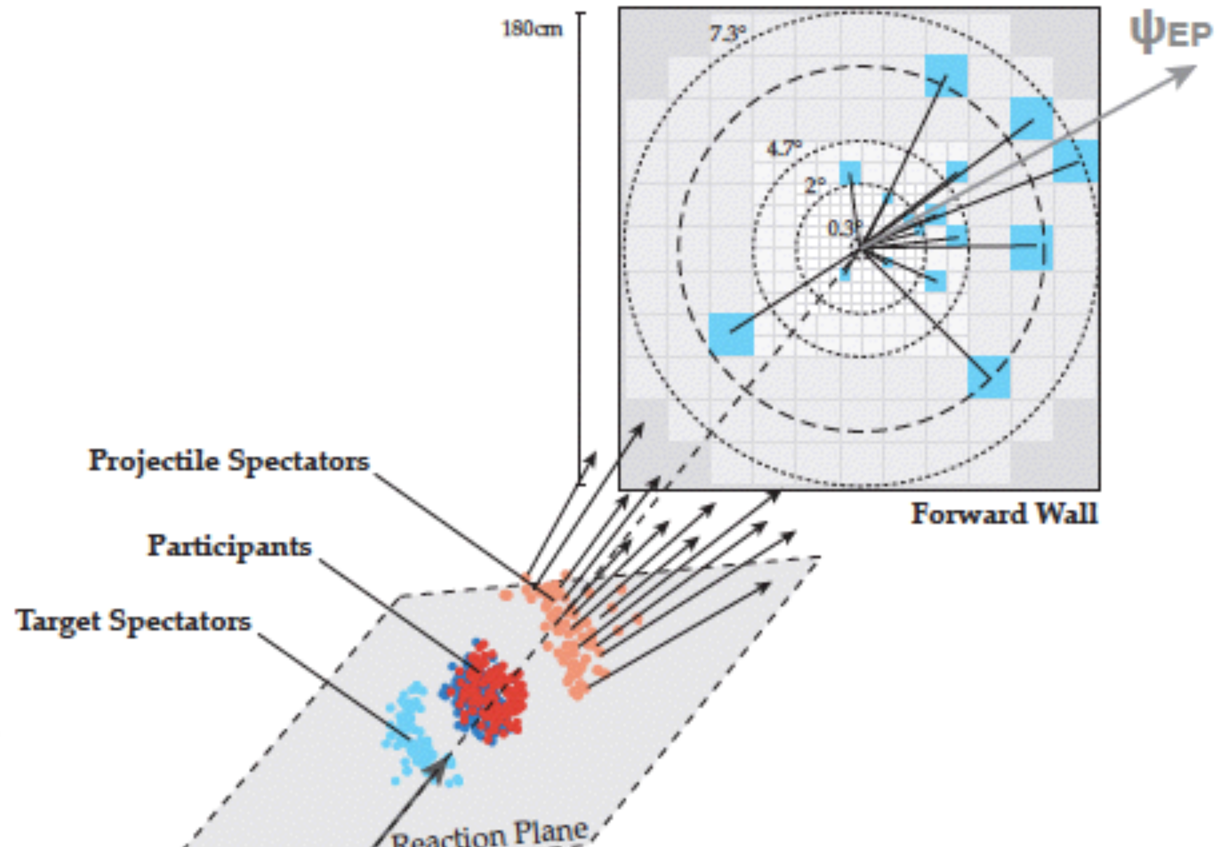




ATLAS Preliminary
p+Pb 2013, 28 nb-1
0-1%
10-20%
40-50%
70-80%
$\sqrt{s_{NN}}$ = 5.02 TeV
0.2 < k_T < 0.3 GeV
R_{long} [fm]
$y^*_{\pi\pi}$

Event Plane Reconstruction





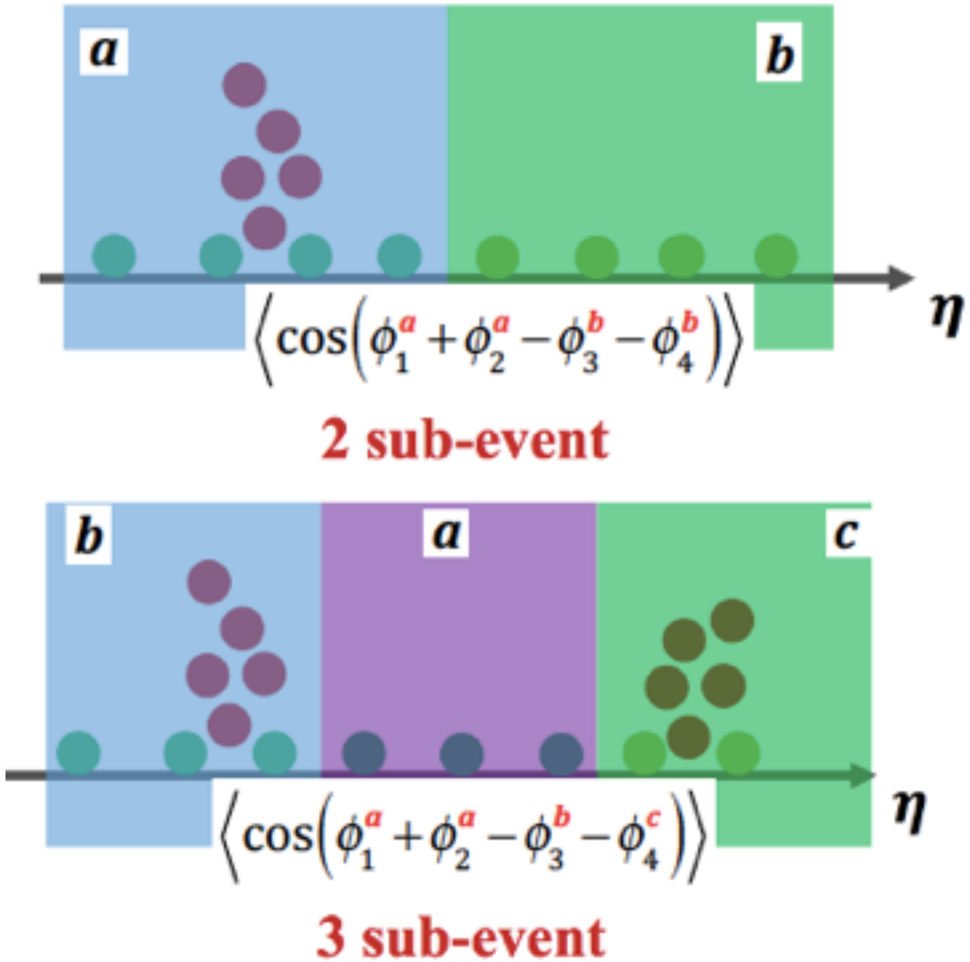
- Event plane based on projectile spectators
- Resolution determined with two sub-event method and corrected with method described in J.-Y. Ollitrault, arXiv:nucl-ex/9711003

$$v_n = v_n^{obs} \,/\, \mathfrak{R}_n$$

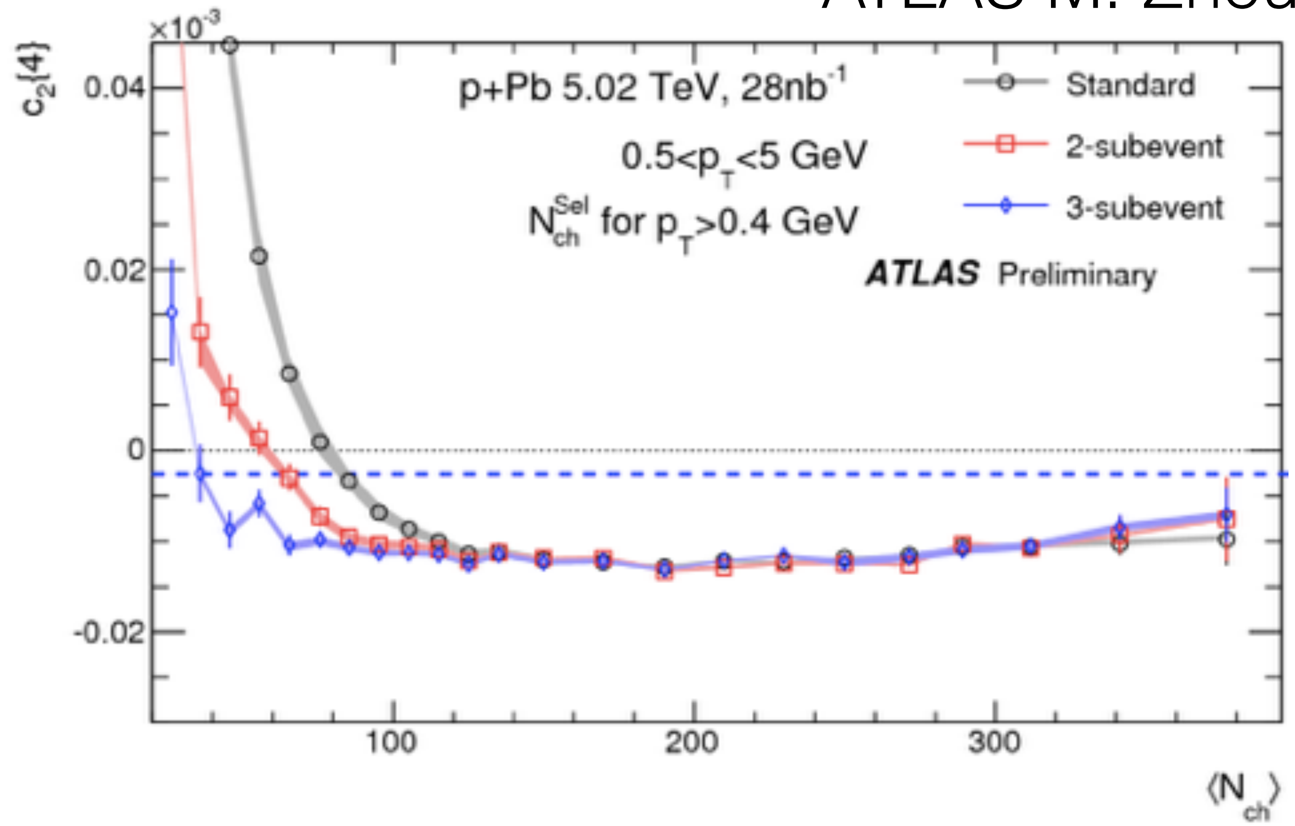
$$\mathfrak{R}_n = \langle \cos[n(\Psi_n - \Psi_{RP})] \rangle$$

$$= \sqrt{2\,\langle \cos[n(\Psi_n^A - \Psi_n^B)] \rangle}$$

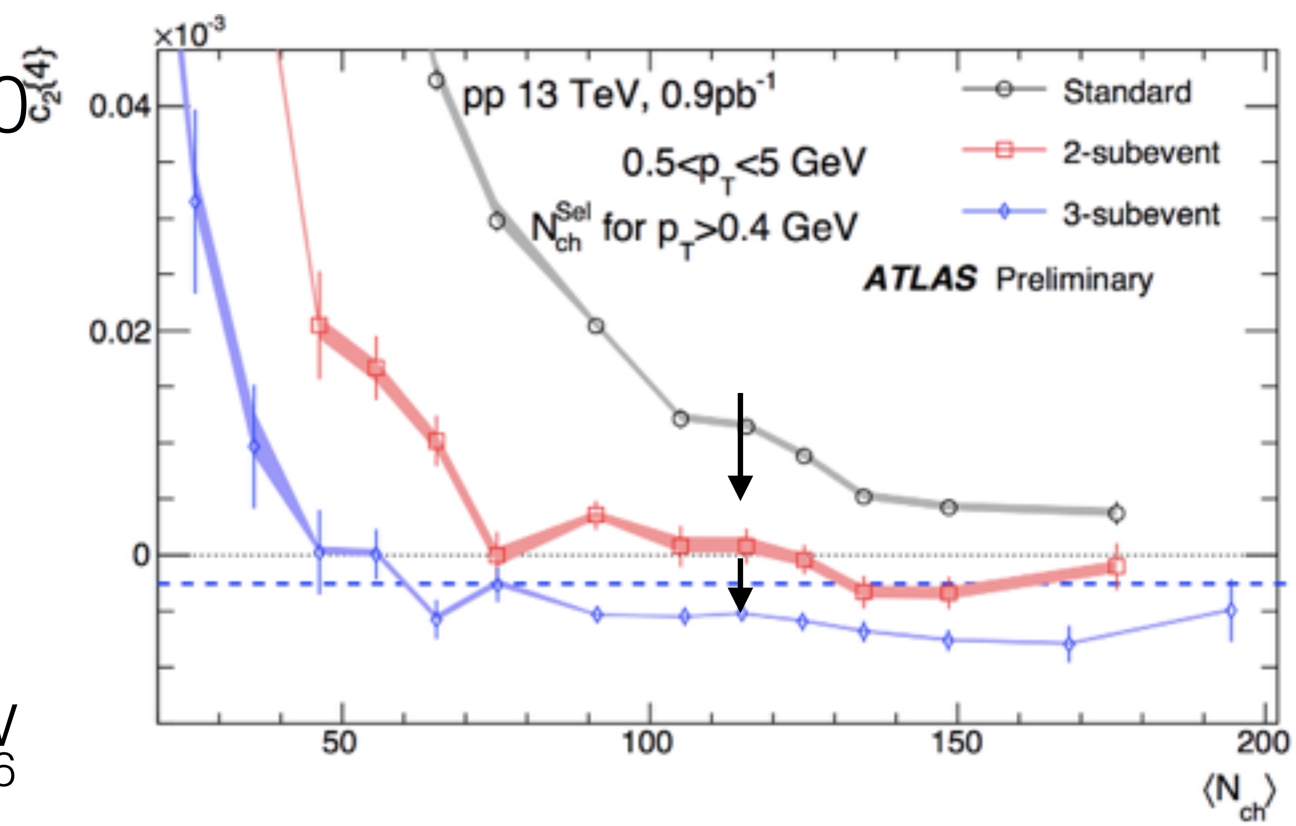
Additional removal of non-flow:3sub method



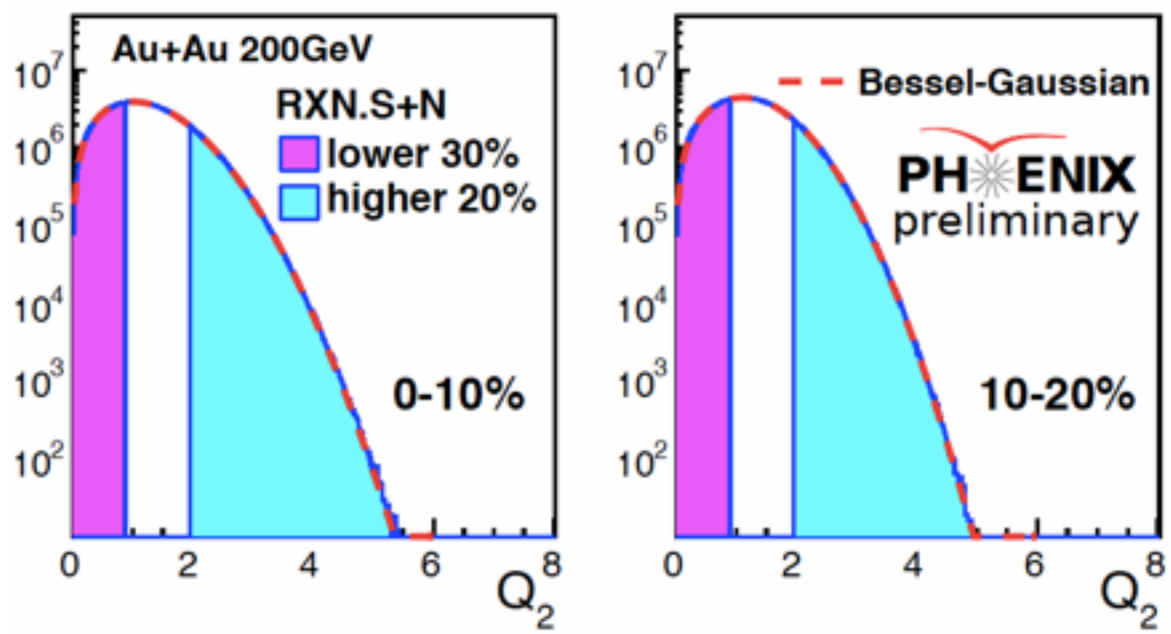
ATLAS M. Zhou

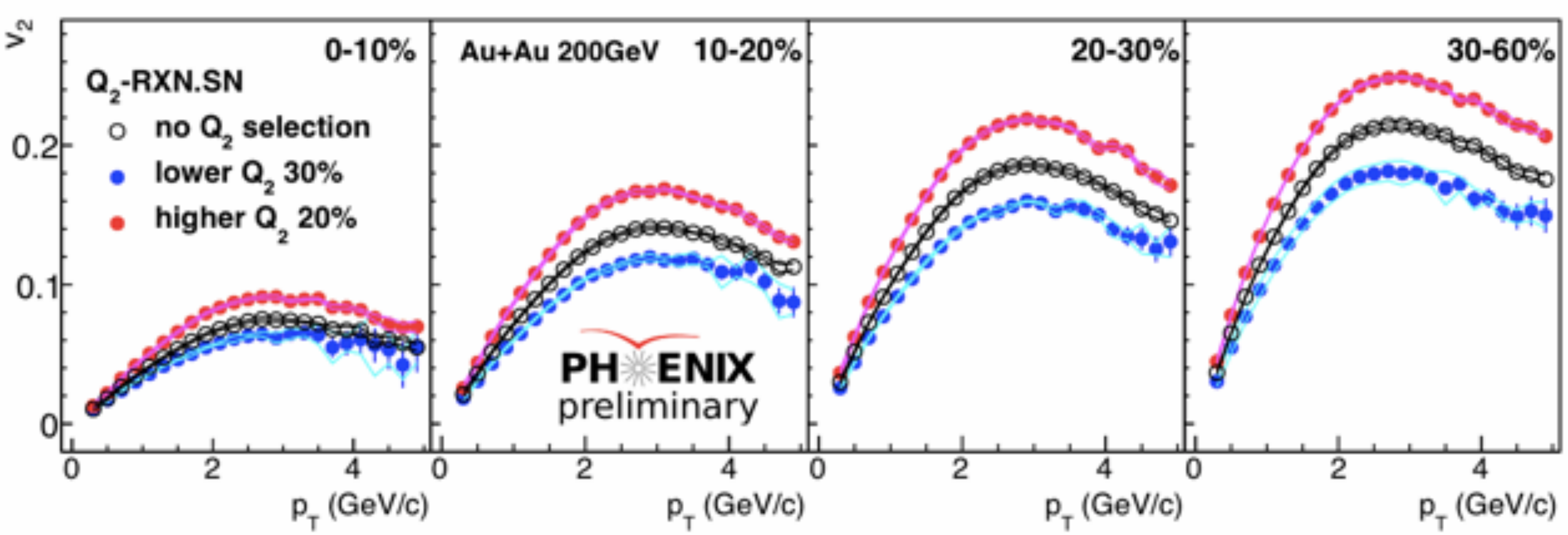


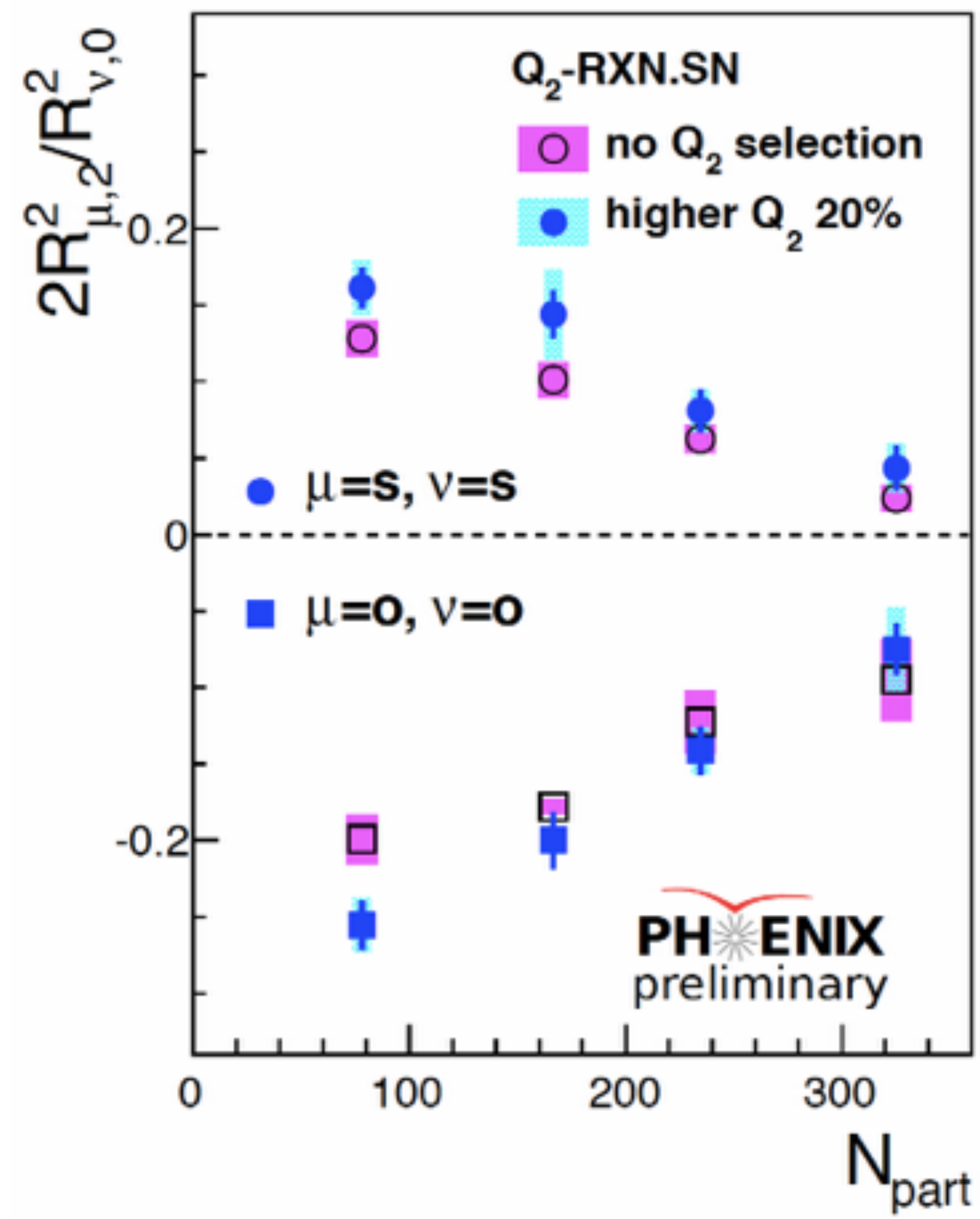
- Sub-event method arXiv:1701. 03830
- p+Pb
  -Larger Nch:non-flow is small
  -Smaller Nch:3sub method reduce non-flow
- p+p
  -Sub event method reduces non-flow



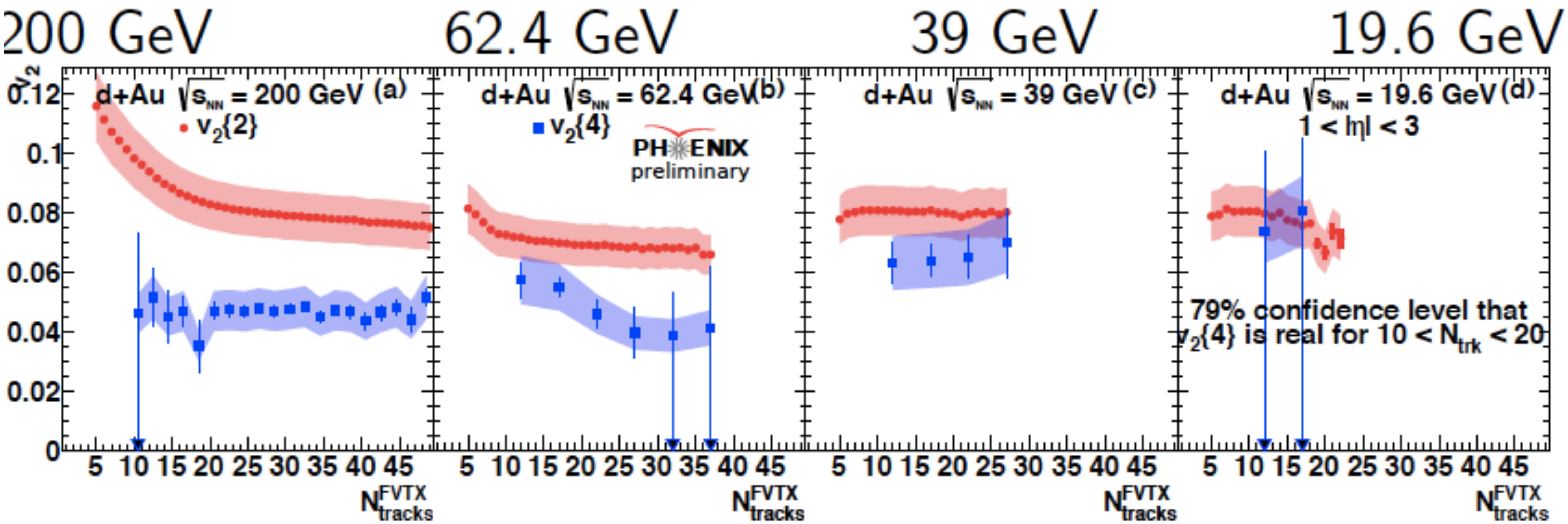
Final eccentricity with ESE





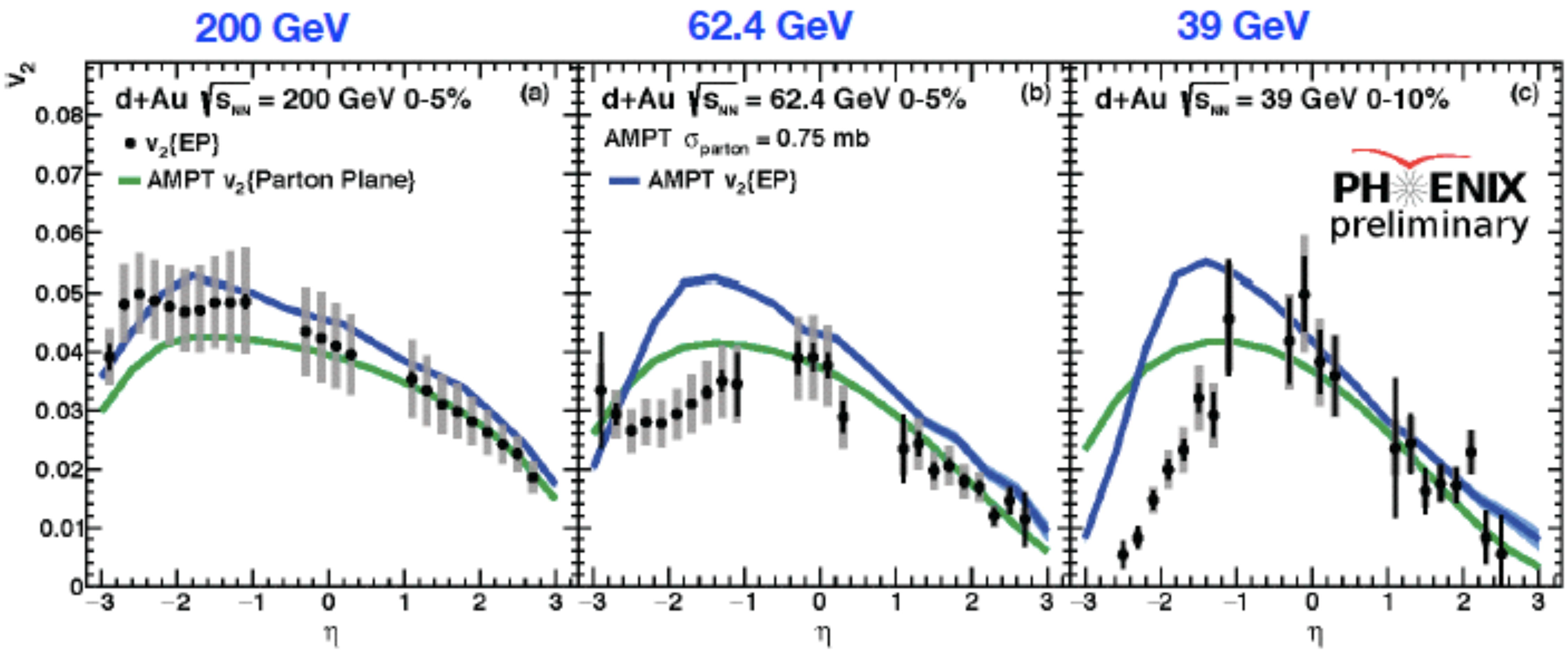


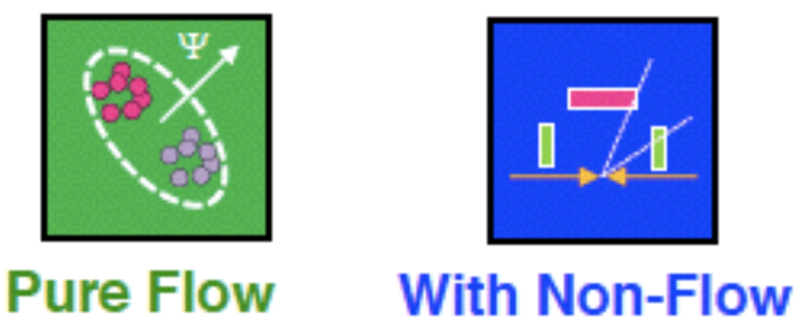
$v_2\{2\}$ and $v_2\{4\}$ in the d+Au beam energy scan

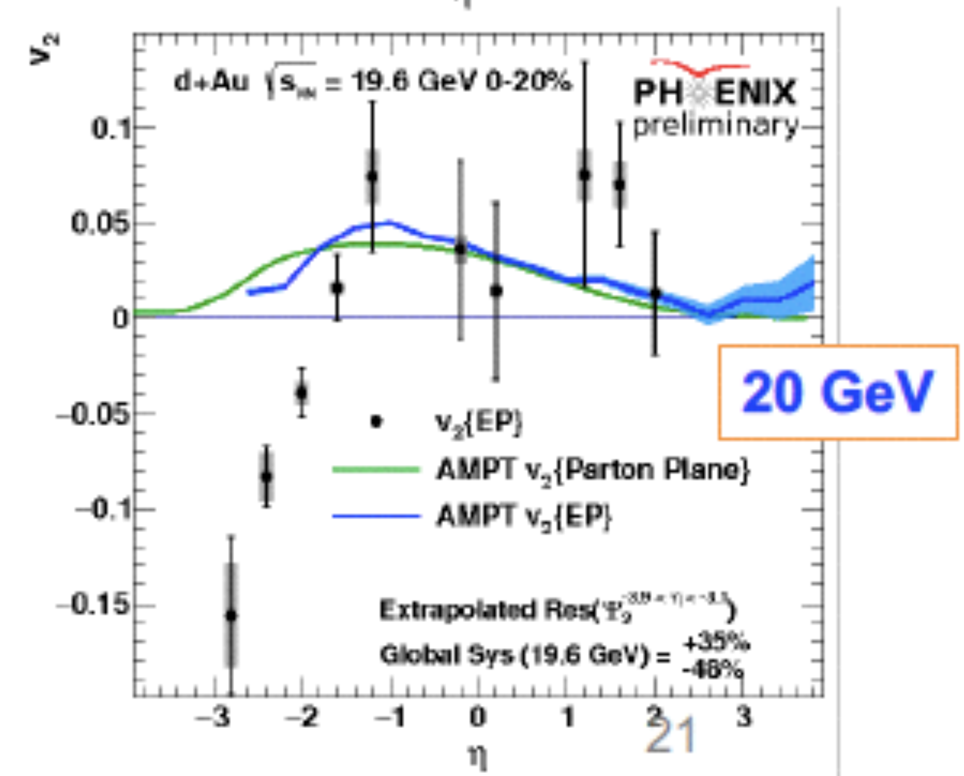


- $v_2\{2\}$ relatively constant with N_{tracks}^{FVTX} and collision energy
- **Observation of real $v_2\{4\}$ in d+Au at all energies!!!**
- **Strong evidence for collectivity**

Insights from AMPT







- Flow dominates at forward and middle pseudorapidity

PHENIX

Julia Velkovska, QM 2017

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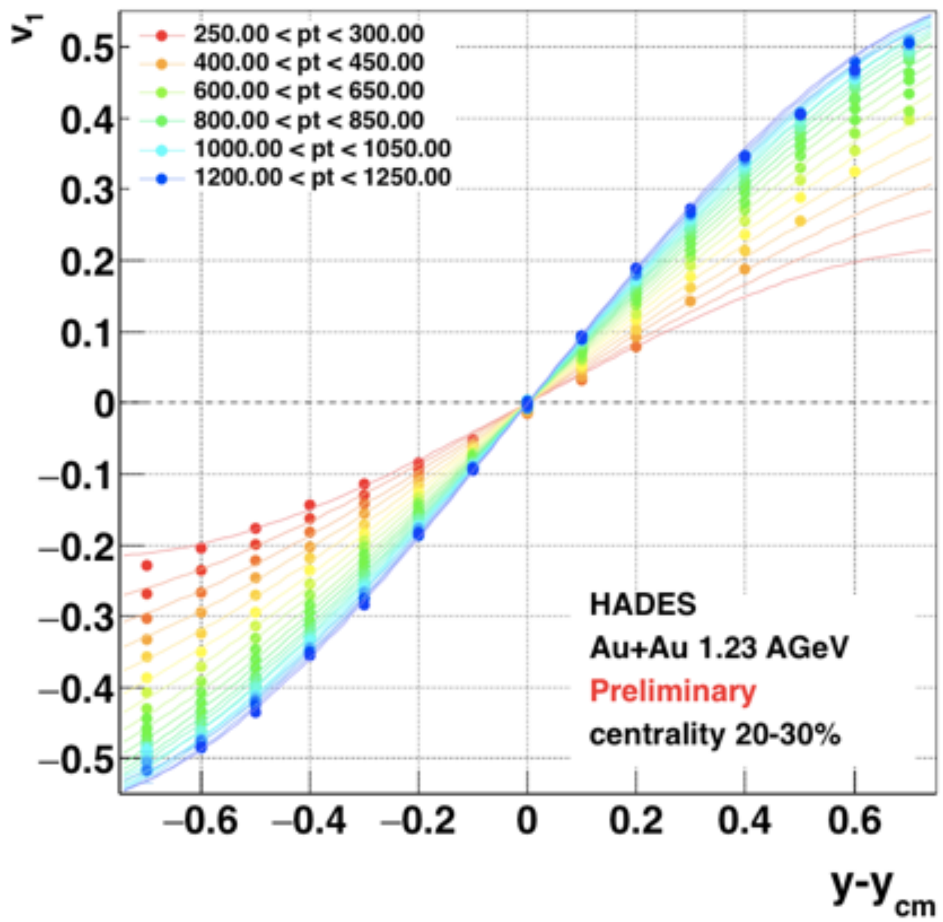
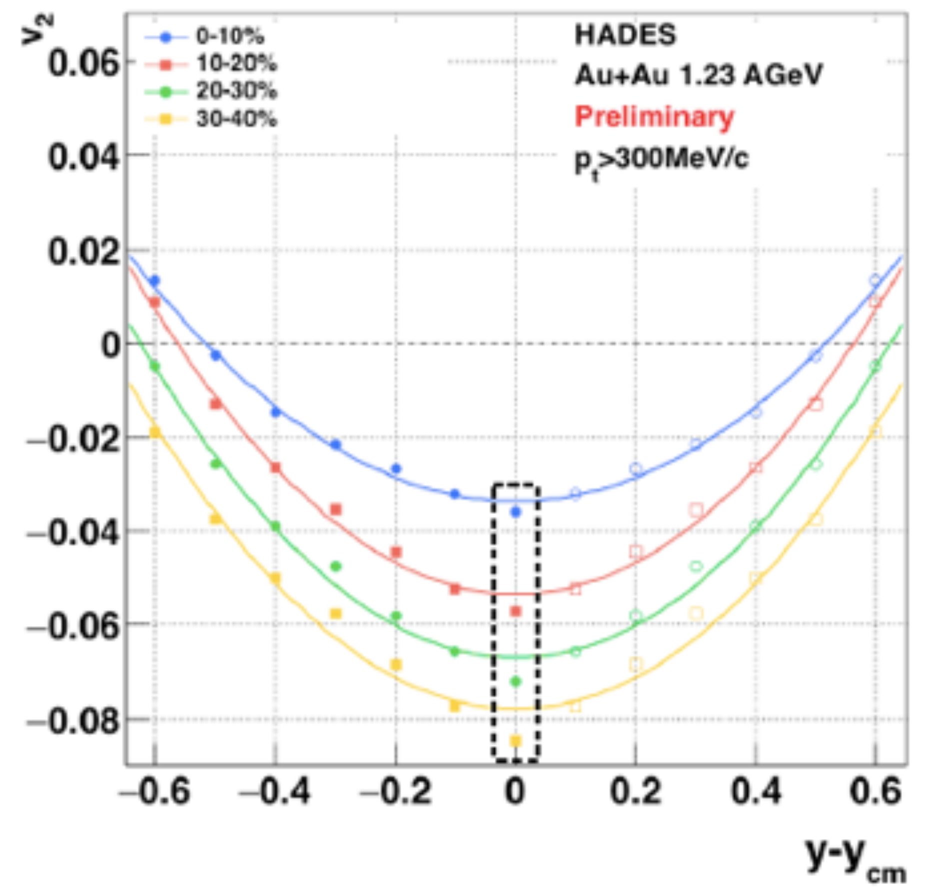
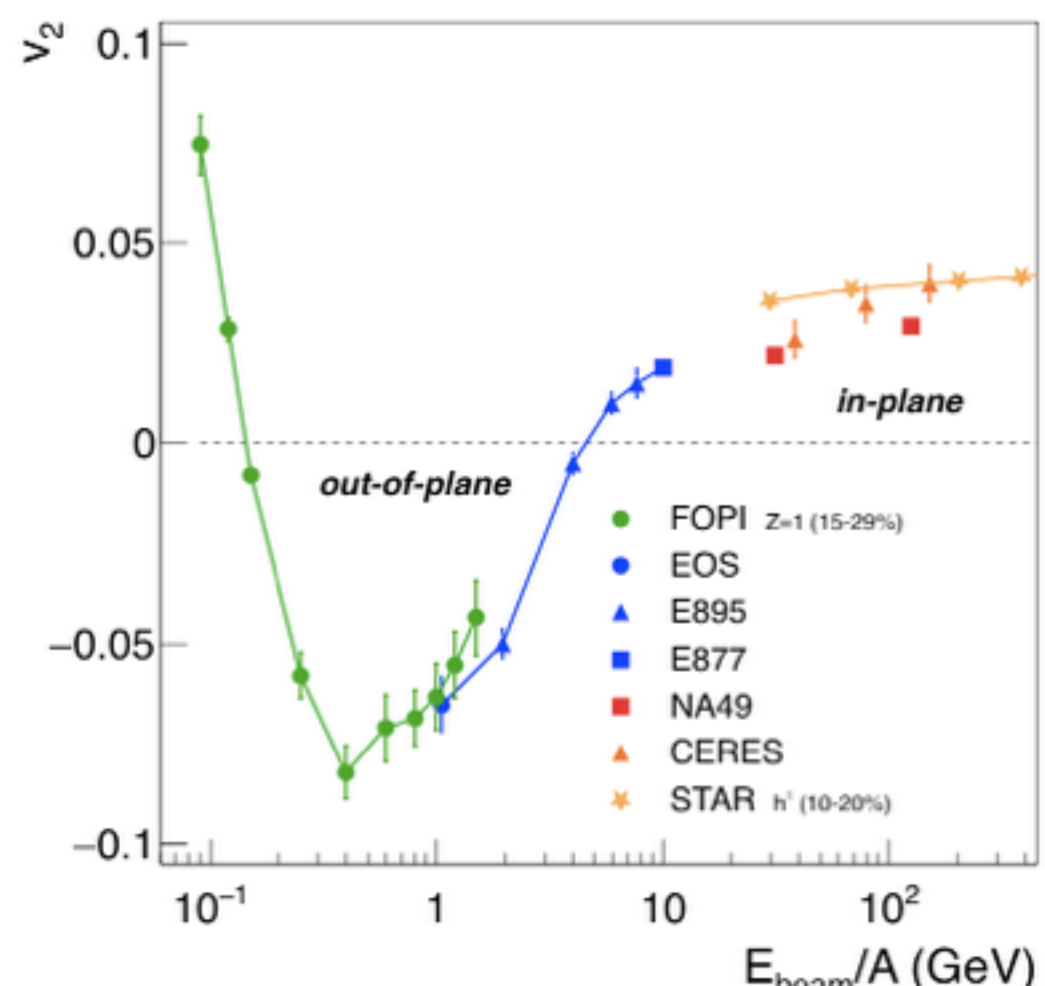


v1
250.00 < pt < 300.00
400.00 < pt < 450.00
600.00 < pt < 650.00
800.00 < pt < 850.00
1000.00 < pt < 1050.00
1200.00 < pt < 1250.00
HADES
Au+Au 1.23 AGeV
Preliminary
centrality 20-30%
y-ycm

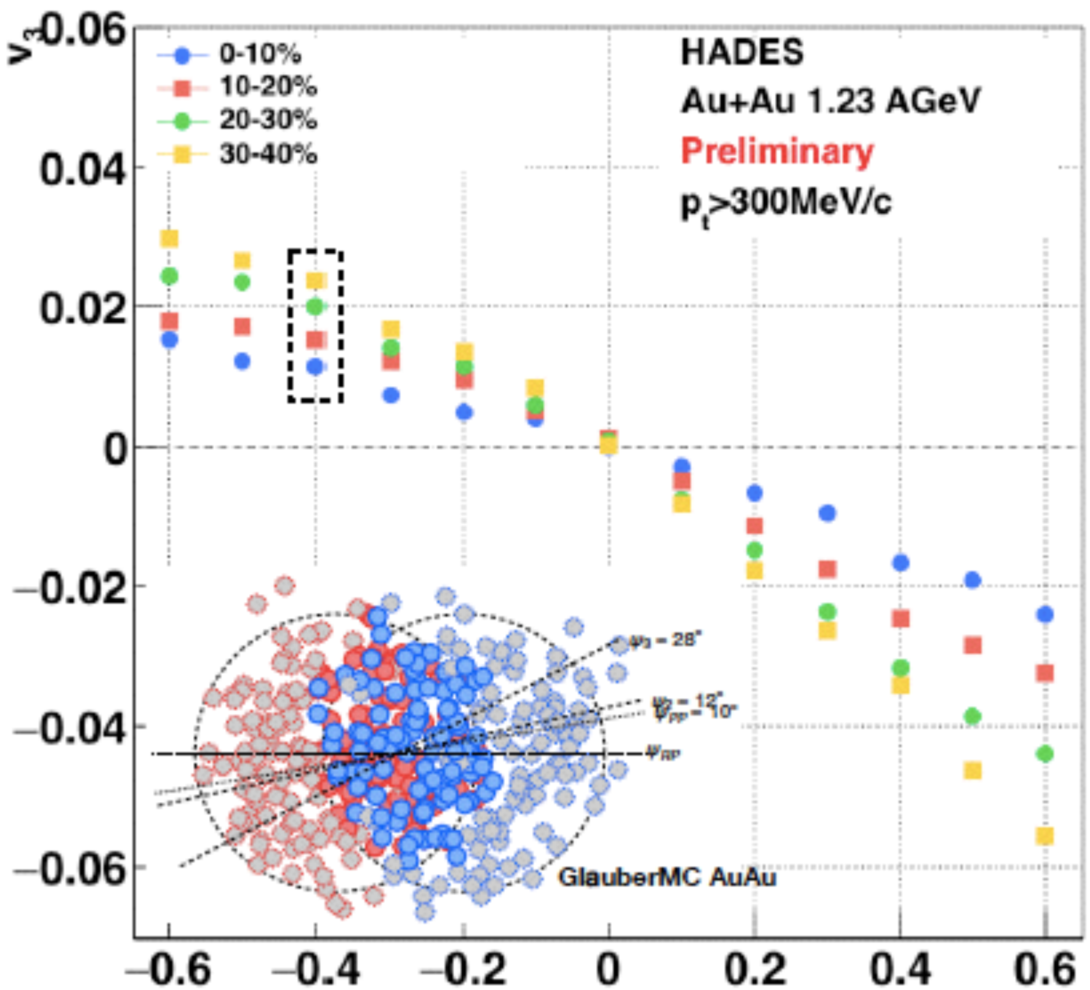


v2
0-10%
10-20%
20-30%
30-40%
HADES
Au+Au 1.23 AGeV
Preliminary
pt>300MeV/c
y-ycm

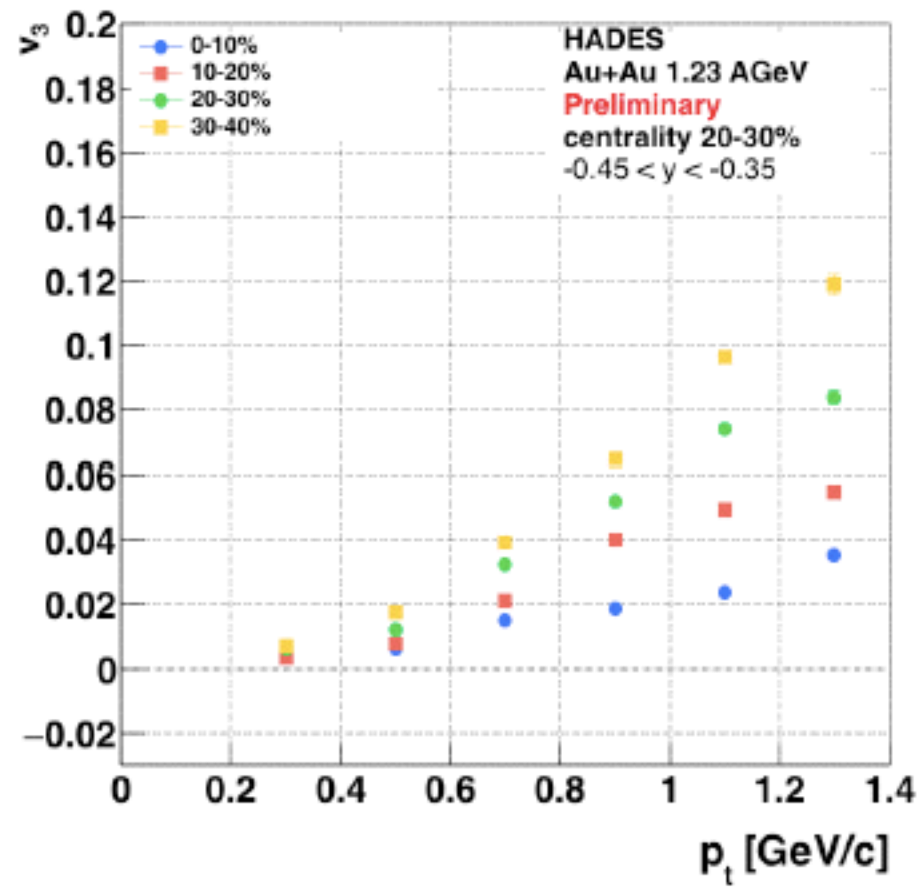


v2
out-of-plane
in-plane
FOPI Z=1 (15-29%)
EOS
E895
E877
NA49
CERES
STAR h± (10-20%)
Ebeam/A (GeV)

Proton $v_3\{\Psi_{RP}\}$



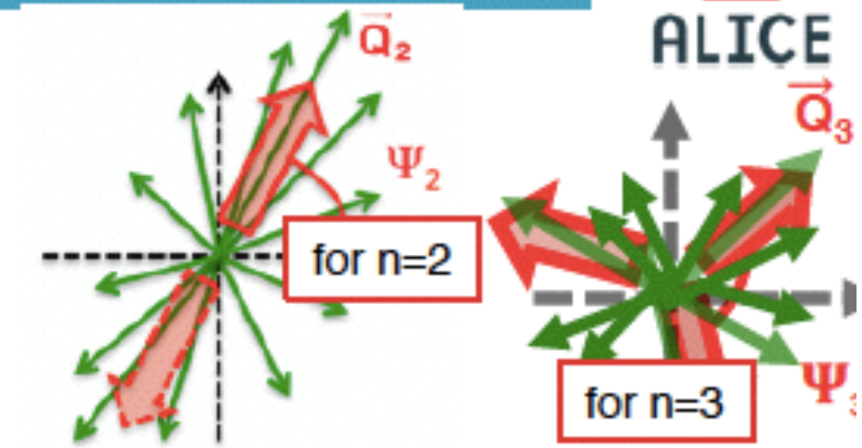
$$v_3\{\Psi_{RP}\} = \langle\langle \cos 3(\varphi - \Psi_{RP})\rangle\rangle$$
$$= \langle\langle \cos 3(\varphi - \Psi_3) \cos 3(\Psi_3 - \Psi_{RP})\rangle\rangle$$
$$= \langle v_3\{\Psi_3\} \quad \langle \cos 3(\Psi_3 - \Psi_{RP})\rangle\rangle$$



- Note: $v_3\{\Psi_{RP}\}$ w.r.t reaction plane
- Convolution of fluctuation of initial state (Ψ_3) and spectator plane

25 Event shape engineering

- New tool to select the initial source geometry [1]
  - by the magnitude of the flow vector $\boldsymbol{Q}_n$



$$|Q_n| = \sqrt{Q_{n,x}^2 + Q_{n,y}^2}$$

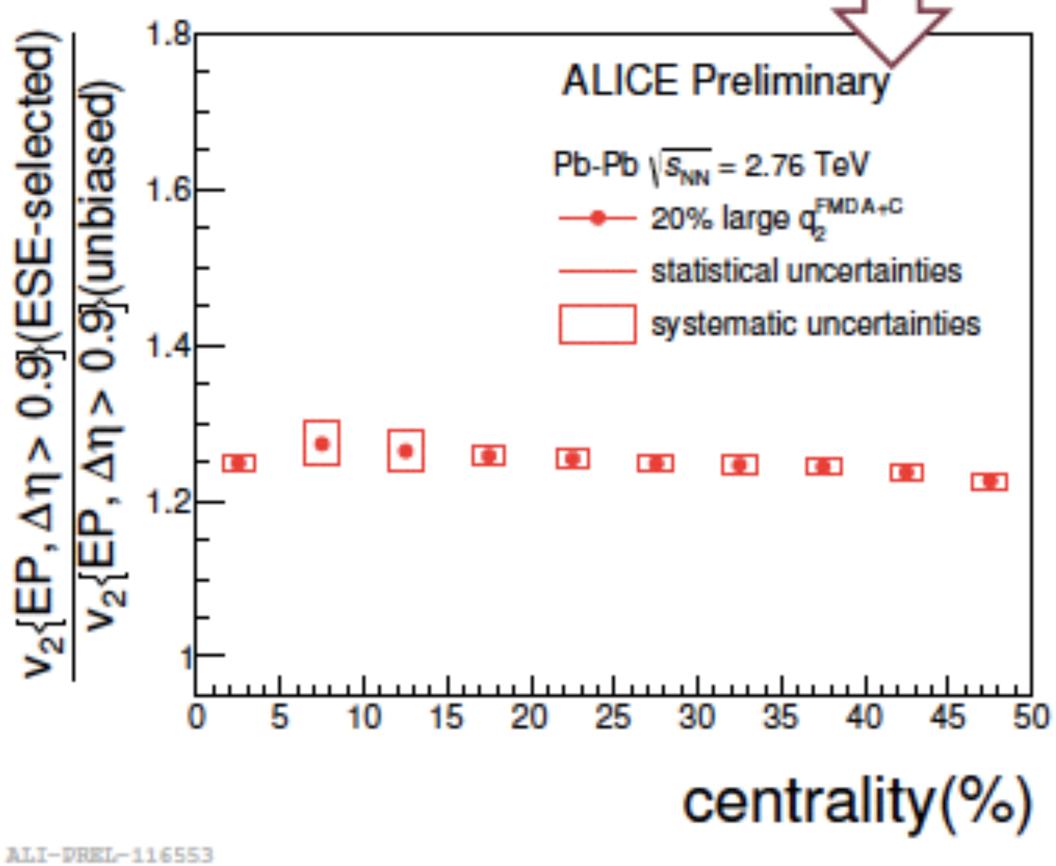
$$Q_{n,x} = \sum w_i \cos n\varphi_i$$

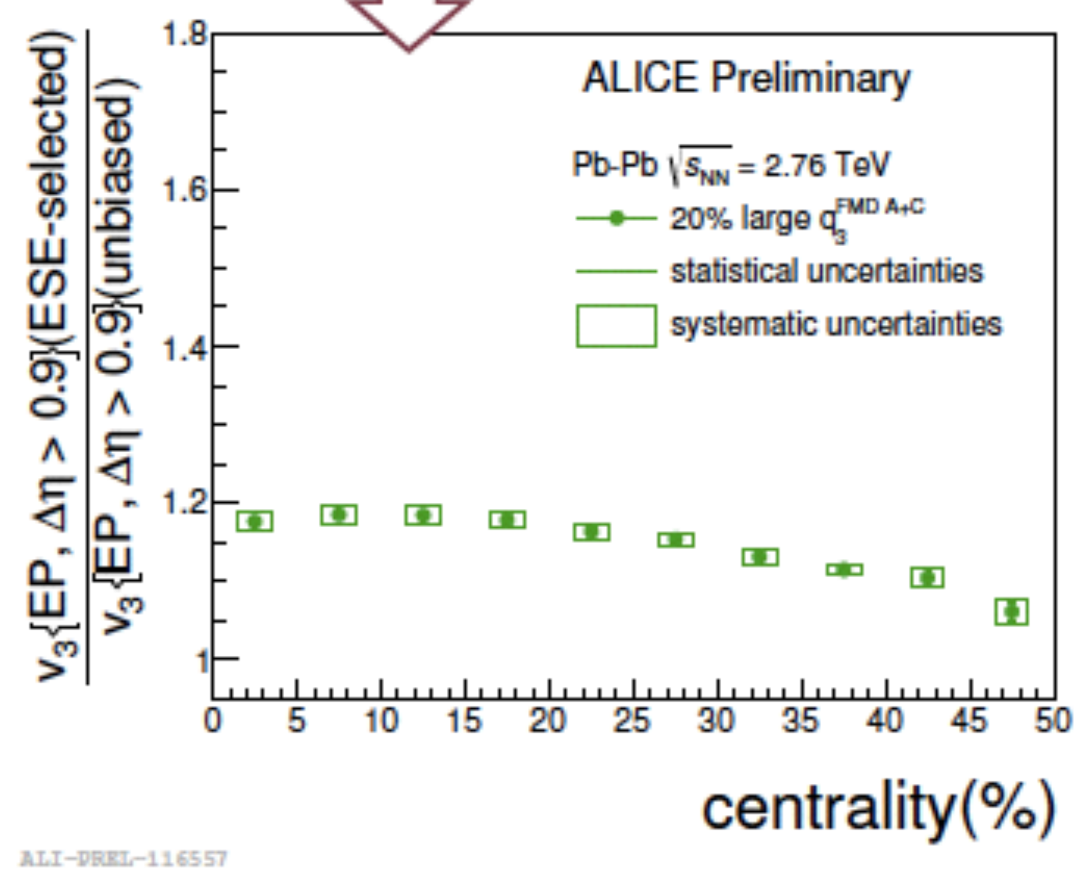
$$Q_{n,y} = \sum w_i \sin n\varphi_i$$

$$q_n = \frac{|Q_n|}{\sqrt{M}}$$

M: the multiplicity of the events

Effect of large q_n selection on v_n



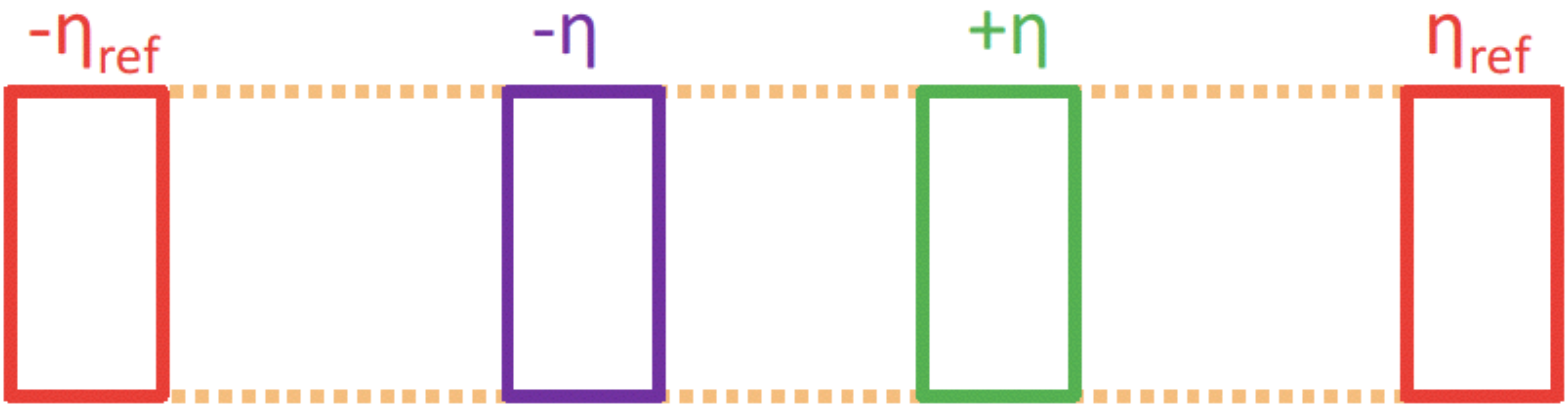


In selected events v_2 is increased about 25% and v_3 about 15%

[1] J. Schukraft, A. Timmins, and S. A. Voloshin, Phys.Lett. B719 (2013)

How to measure twist only

Flow Vector $\boldsymbol{q}_n \equiv \frac{\sum_i w_i e^{in\phi_i}}{\sum_i w_i} \equiv q_n \, e^{in\Psi_n}$



$$R_{n,n|n,n} = \frac{\left\langle q_n(-\eta_{ref}) q_n(-\eta) q_n^*(+\eta) q_n^*(\eta_{ref}) \right\rangle}{\left\langle q_n(-\eta_{ref}) q_n(+\eta) q_n^*(-\eta) q_n^*(\eta_{ref}) \right\rangle}$$

$$R_{n,n|n,n} \approx 1 - 4F_{n;2}^{twi}\eta$$

This correlator is sensitive only to the event-plane twist