Stony Brook University | The State University of New York

Correlations and fluctuations in high-energy nuclear collisions

-- a "flow" centric review

Jiangyong Jia

- Ridge in small systems
- Collective phenomena in A+A

XXIV QUARK MATTER DARMSTADT 2014

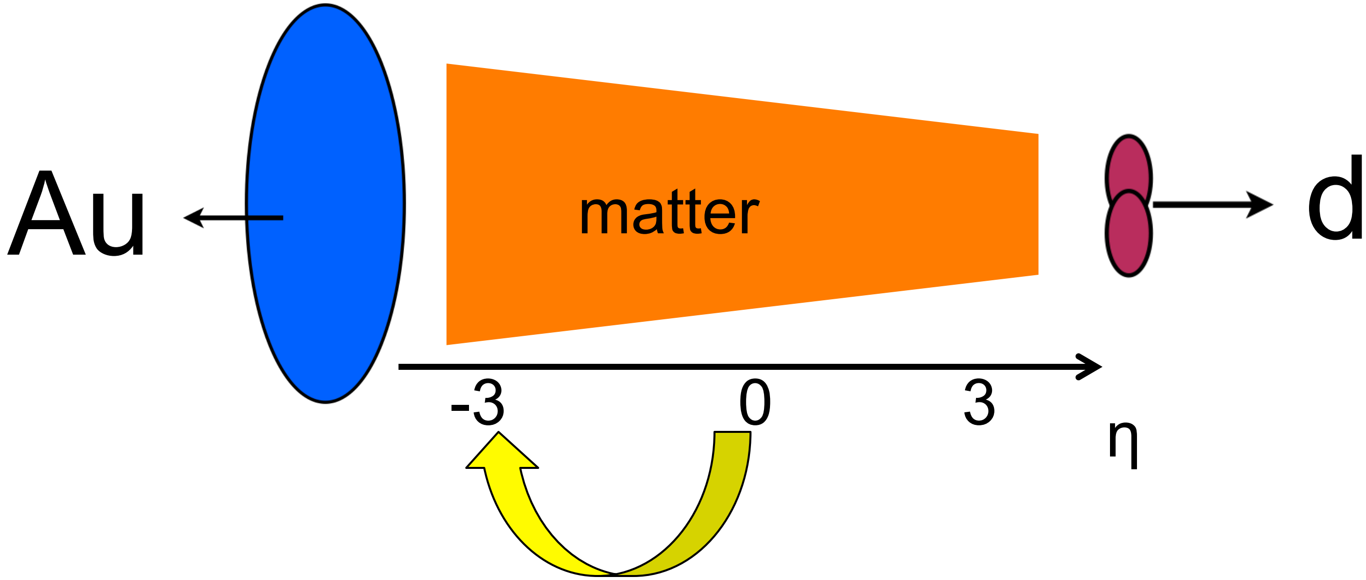
Refer to Alex Shmah for other topics

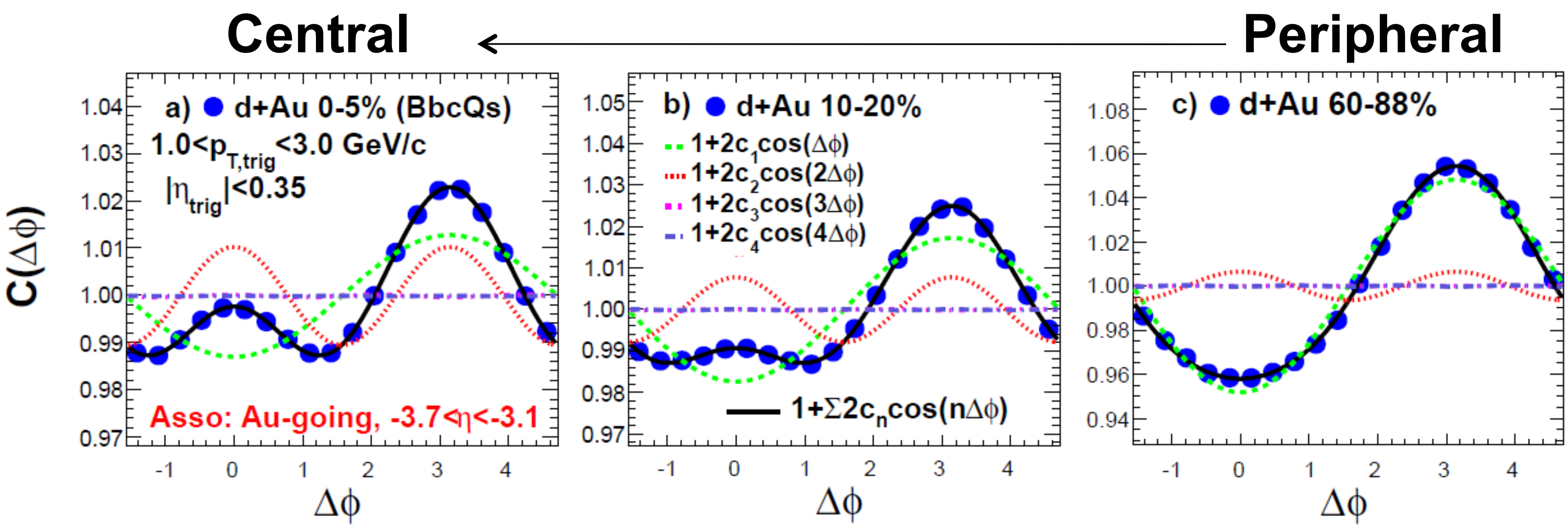
Brookhaven National Laboratory
Office of Science | U.S. Department of Energy

5/19-5/24, 2014

BROOKHAVEN NATIONAL LABORATORY

The PHENIX d+Au ridge





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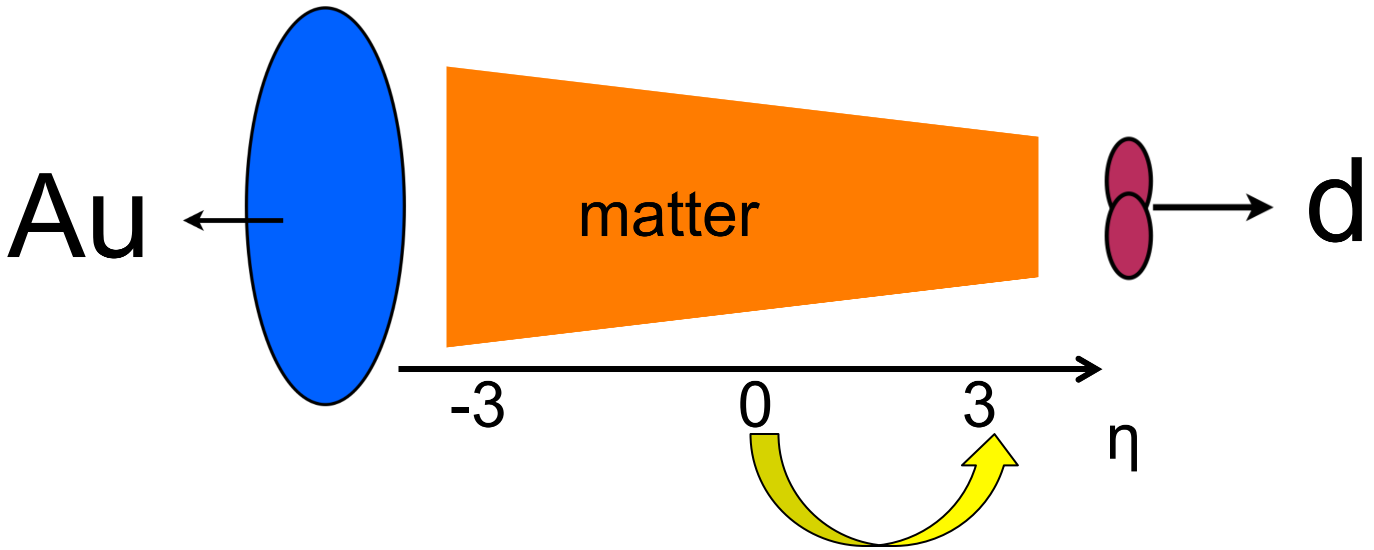
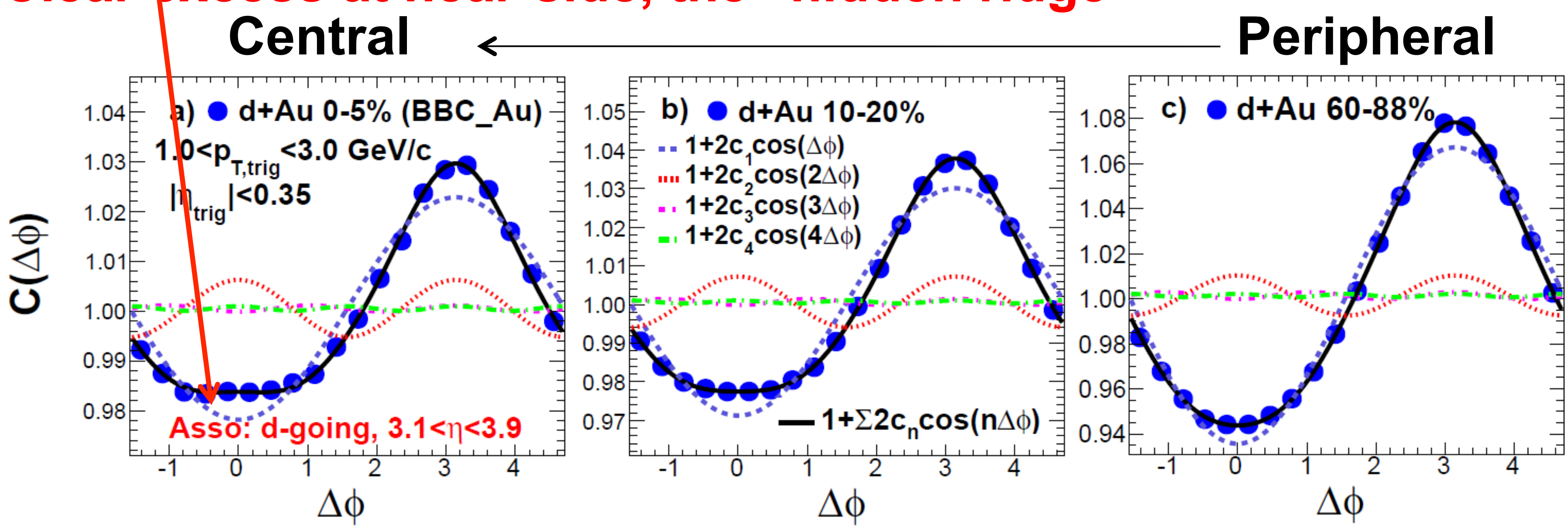
The PHENIX "hidden" d+Au ridge



Clear excess at near-side, the "hidden ridge"



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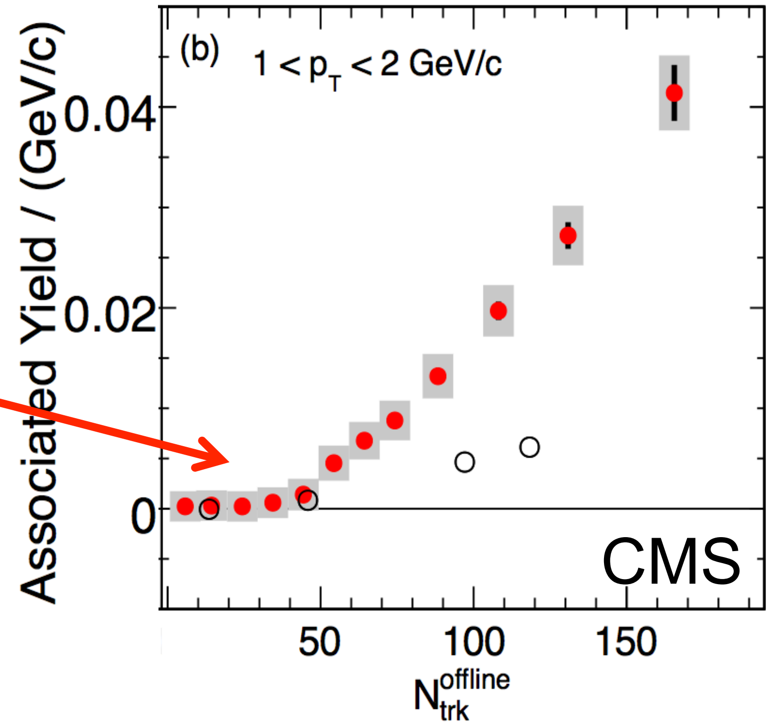
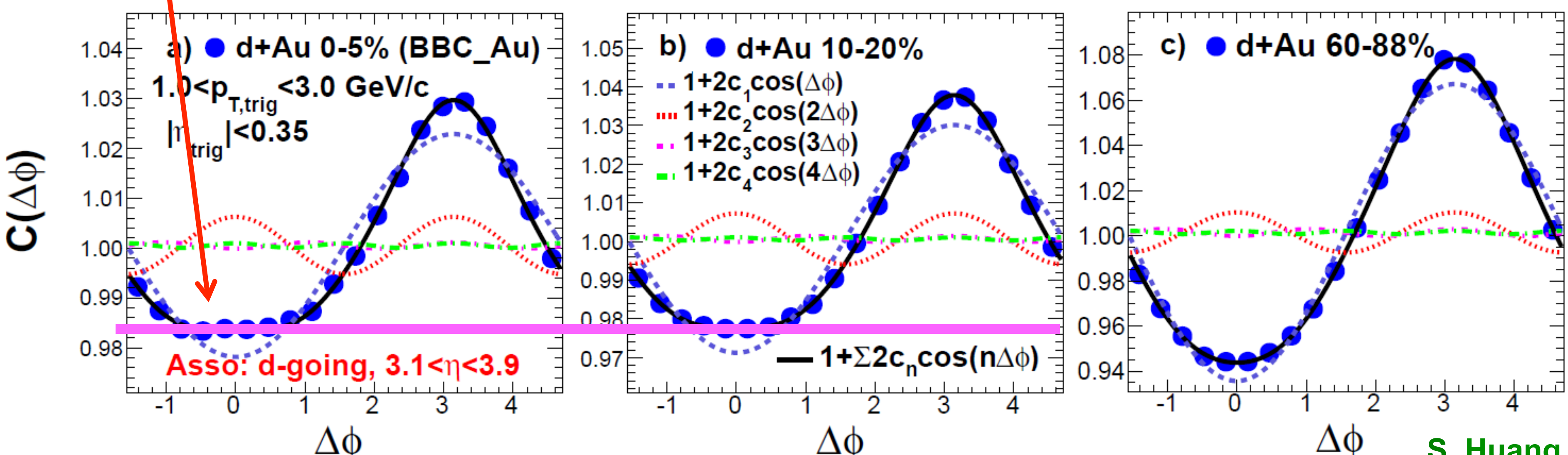
Be careful about Per-trigger yield…

Step structure here is simply a ZYAM anomaly

ZYAM can't see the ridge if the near-side shape is concave





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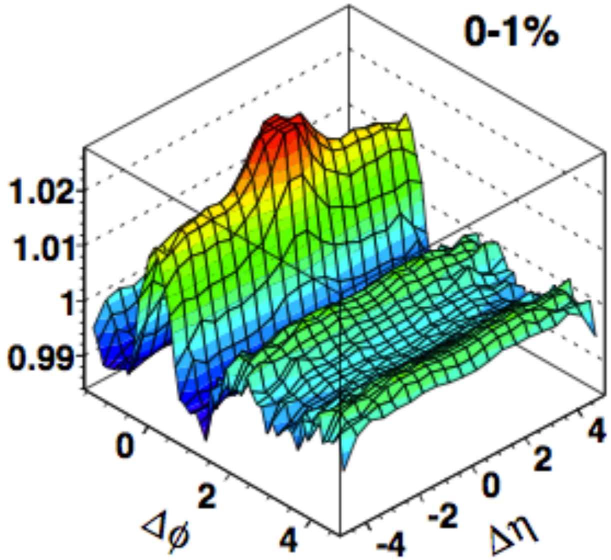
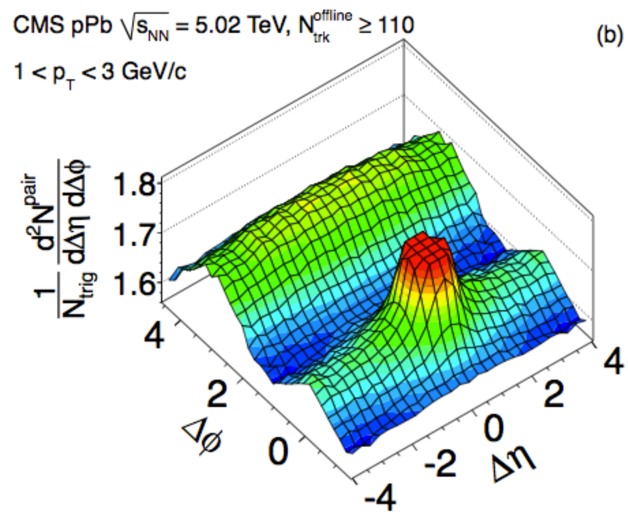
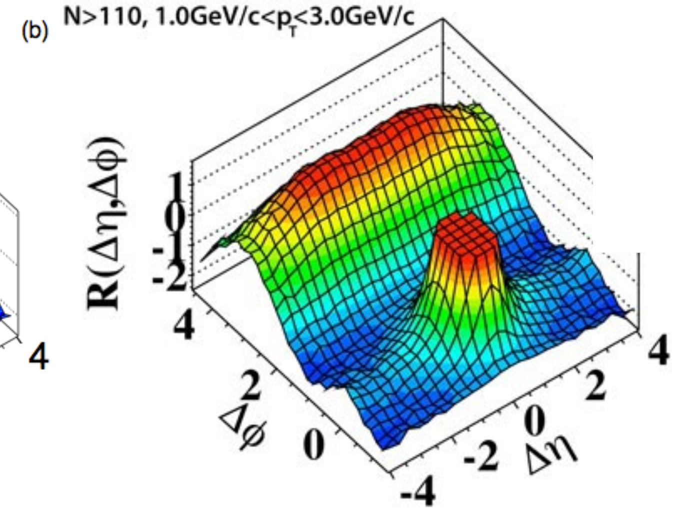
The tale of three ridges….



Pb+Pb ridge



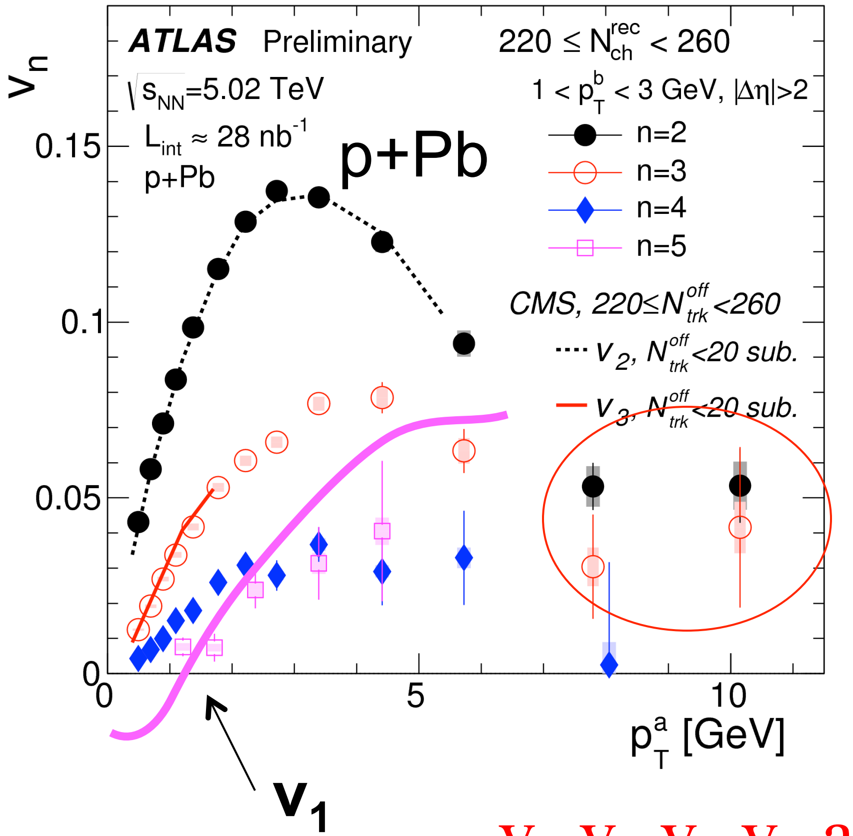
p+Pb ridge

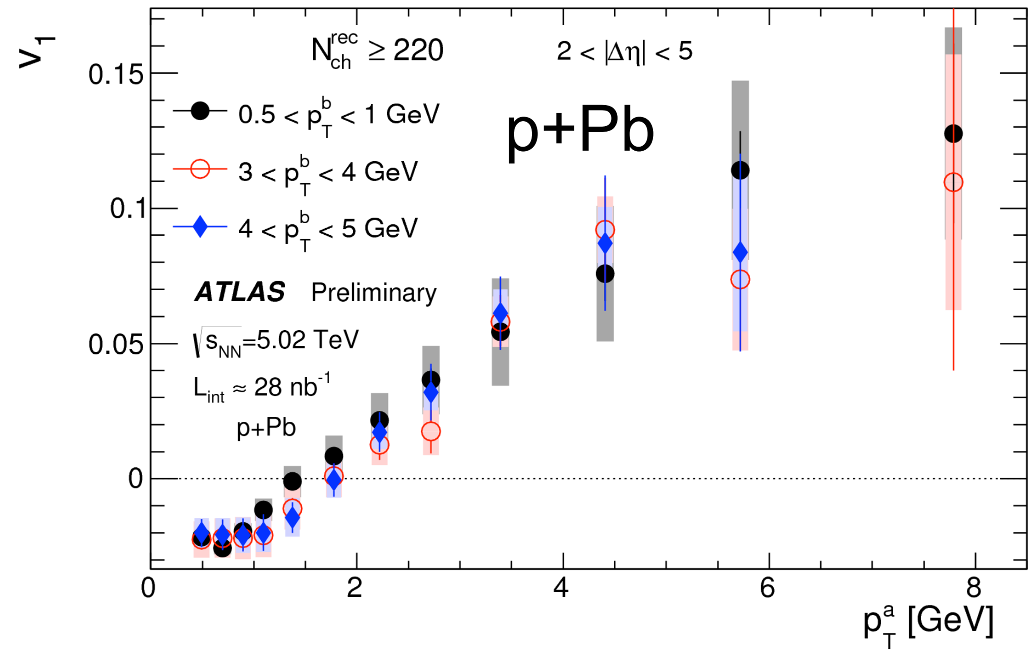


p+p ridge

- Manifestation of QCD in different high density systems
- But is there an effective mechanism that rules them all? Is it initial state effect, final state effect or both?
- What is its detailed p_T, η, and centrality dependence? How these dependences compare between different systems?

pPb ridge properties summarized by harmonics



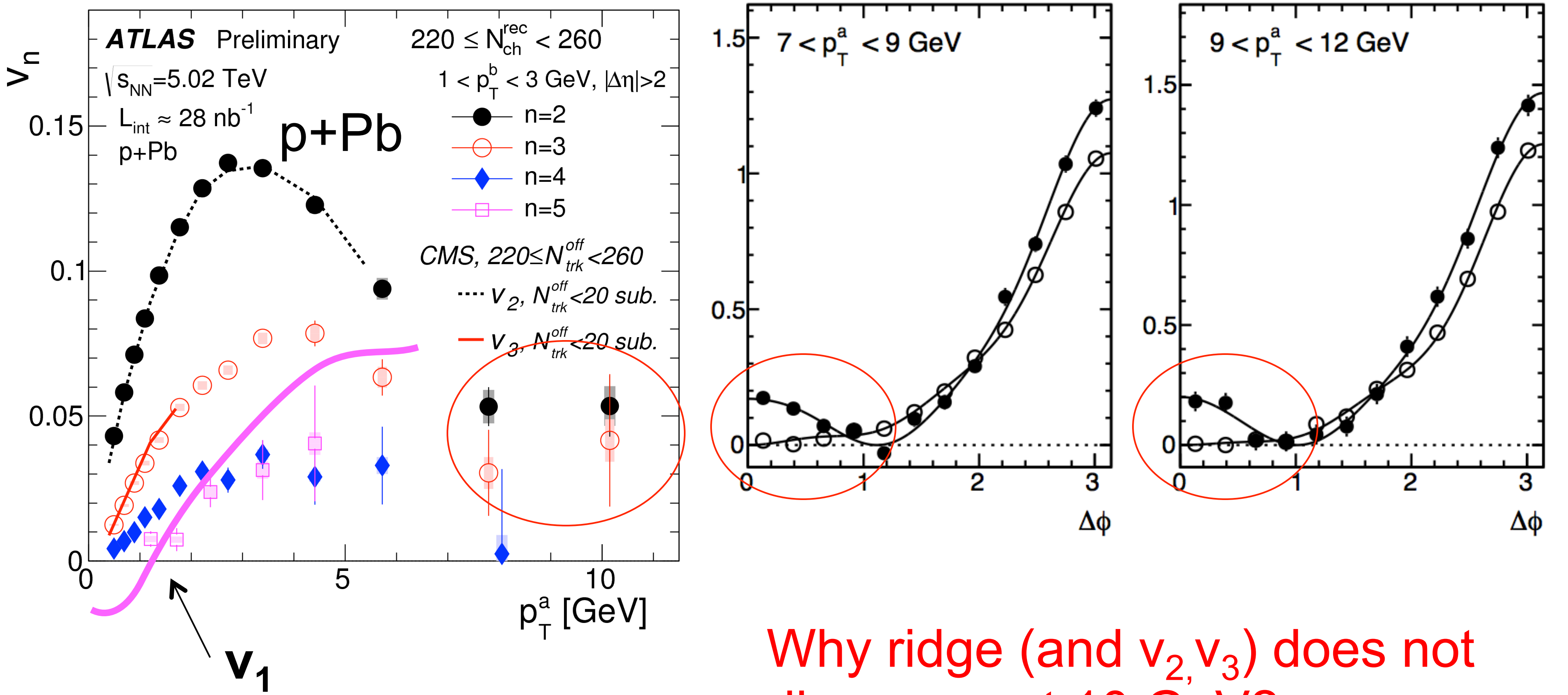


v_1, v_2, v_3, v_4 and v_5 has been measured in pPb!

- v_1, v_2, v_3, v_4 and v_5, made possible with recoil subtraction
  - v_2, v_3 out to 10 GeV, remain 3-5%, small jet modifications?
  - v_n decrease with n for n=2-5
  - Significant v_1 comparable with v_3 at 4 GeV.

S. Radhakrishnan

pPb ridge properties summarized by harmonics



Why ridge (and v_2, v_3) does not disappear at 10 GeV?

- v_1, v_2, v_3, v_4 and v_5, made possible with recoil subtraction
  - v_2, v_3 out to 10 GeV, remain 3-5%, small jet modifications?
  - v_n decrease with n for n=2-5
  - Significant v_1 comparable with v_3 at 4 GeV.

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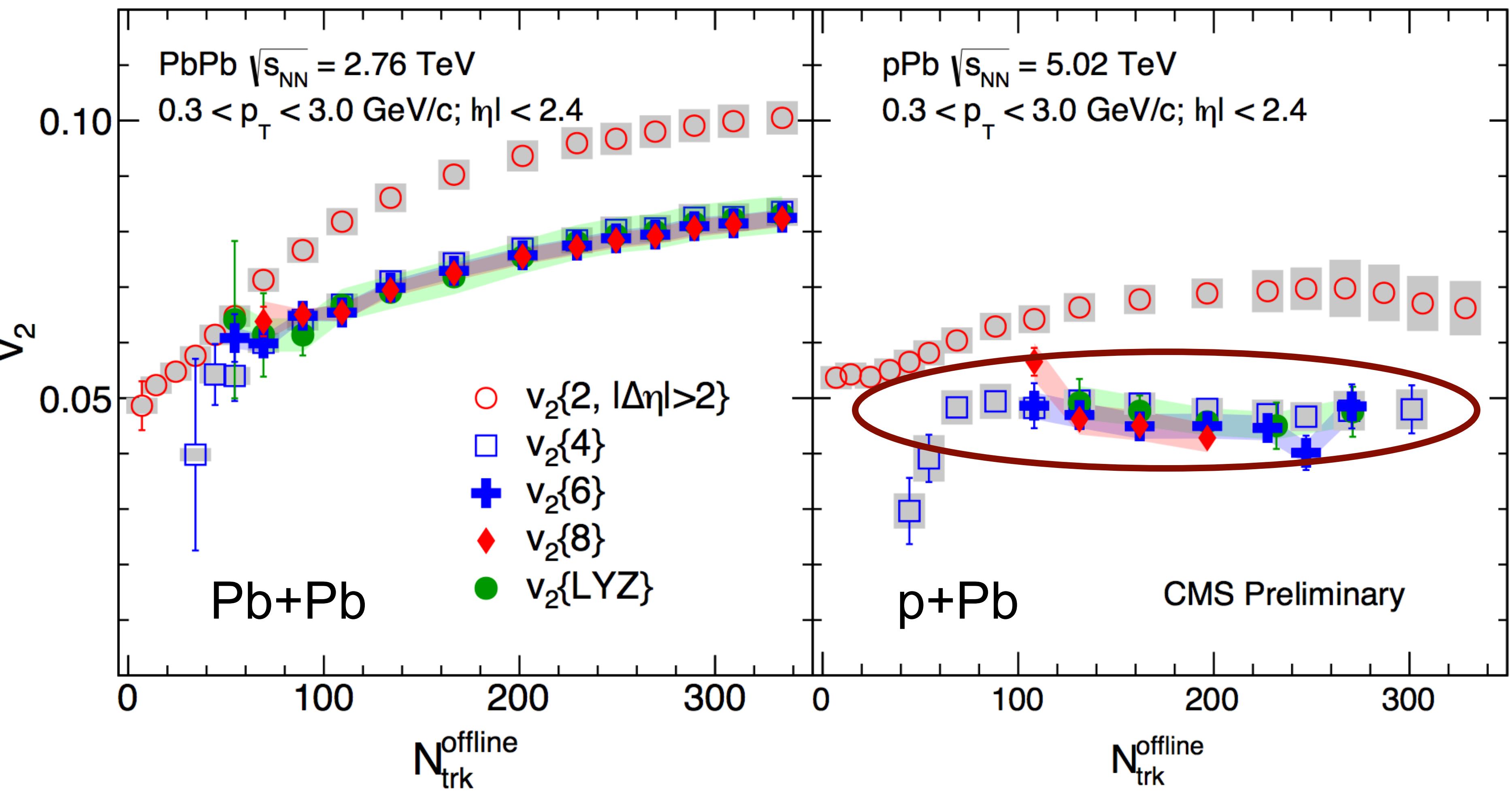
Is there global correlation in p+Pb system?



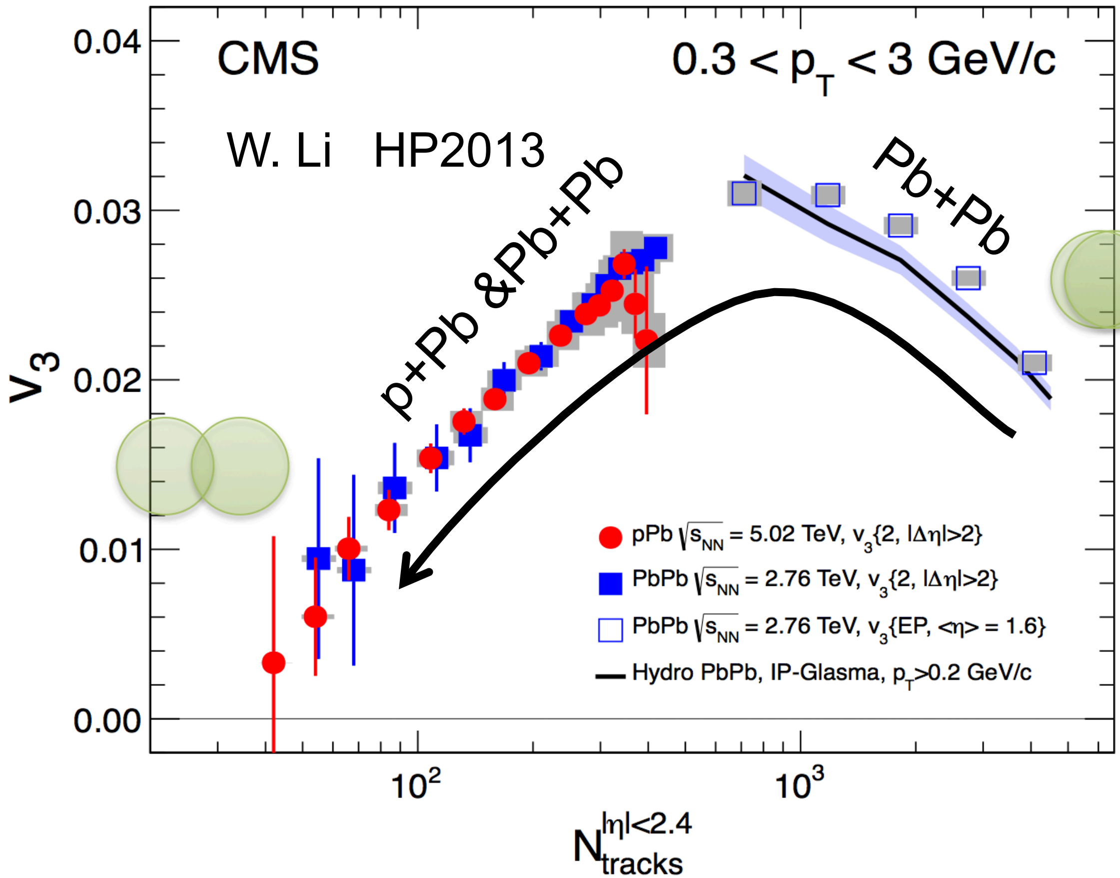
Multi-particle and all particle correlation signal remain remarkably large in high-multiplicity events!!

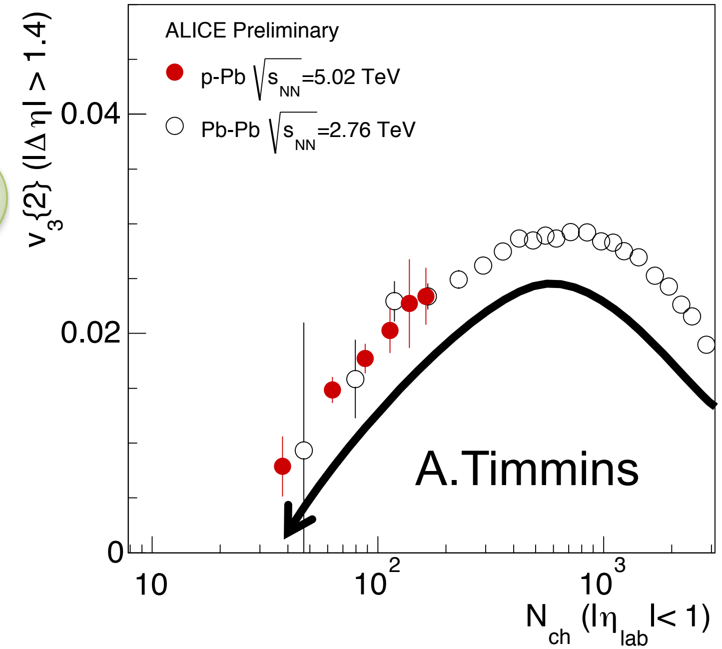
Collective behavior!

Q. Wang

Comparison p+Pb with Pb+Pb

- Collectivity increase and decrease with system size.





Where and how the hydro-picture breaks down?
What is the correct effective theory? CGC+transport?

Comparison of p+Pb with Pb+Pb

- Why extrapolation of hydro prediction works so well? e.g. conformal scaling

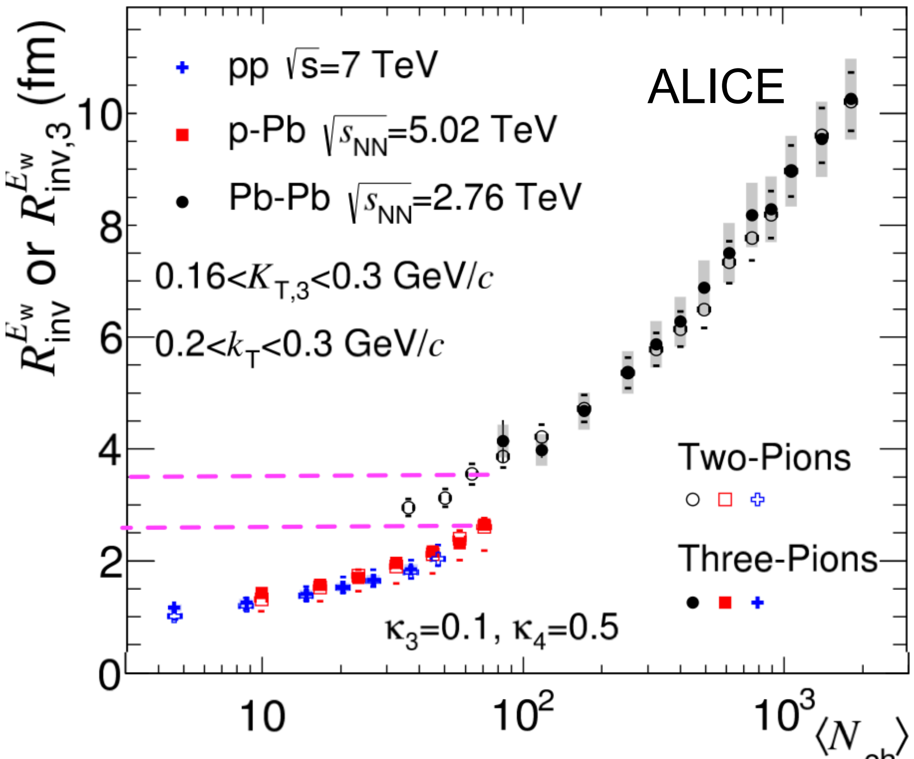
G. Basar & Teaney

- From the confomal analysis

$$\frac{L_{AA}}{L_{pA}} = \frac{\langle p_T \rangle_{pA}}{\langle p_T \rangle_{AA}} = 1.3$$

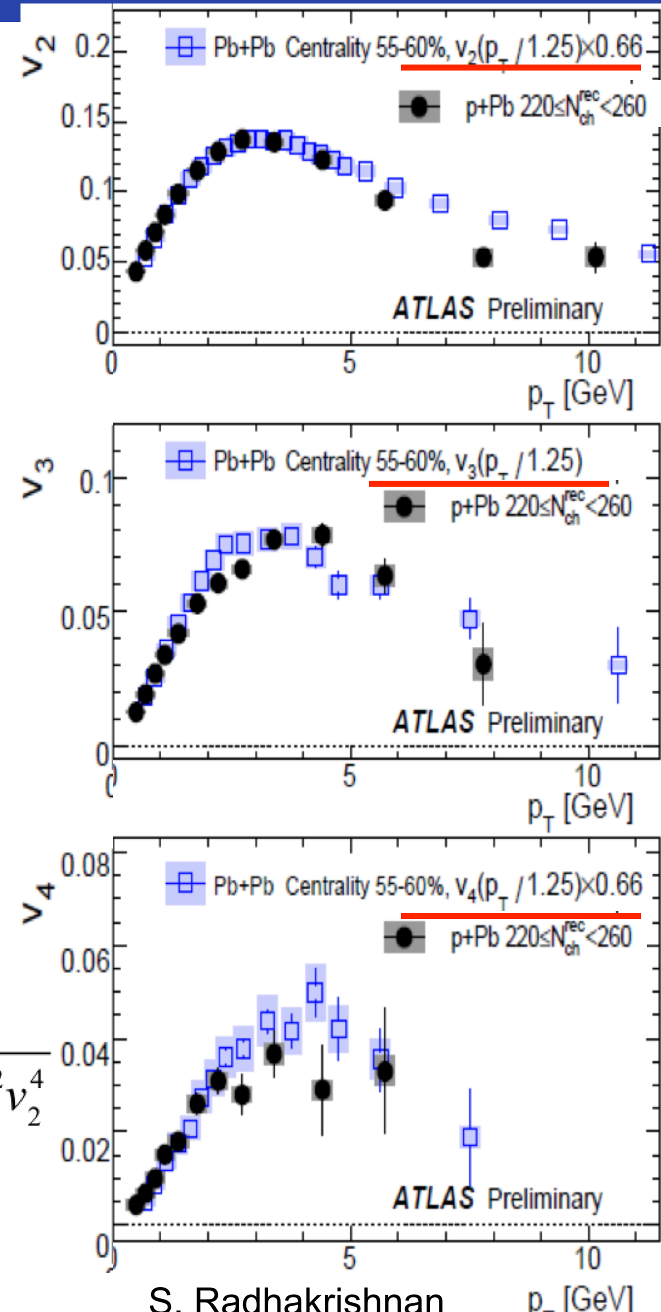
- Find:

$$\frac{R_{AA}}{R_{pA}} = \frac{3.5}{2.6} = 1.35$$



D.Gangadharan

$$v_4 = \sqrt{c_0^2 + c_1^2 v_2^4}$$



S. Radhakrishnan

Comparison of p+Pb with Pb+Pb

- Why extrapolation of hydro prediction works so well? e.g. conformal scaling

Detailed comparison between experiments are needed

- From the confomal analysis

$$\frac{L_{AA}}{L_{pA}} = \frac{\langle p_T \rangle_{pA}}{\langle p_T \rangle_{AA}} = 1.3$$

- Find:

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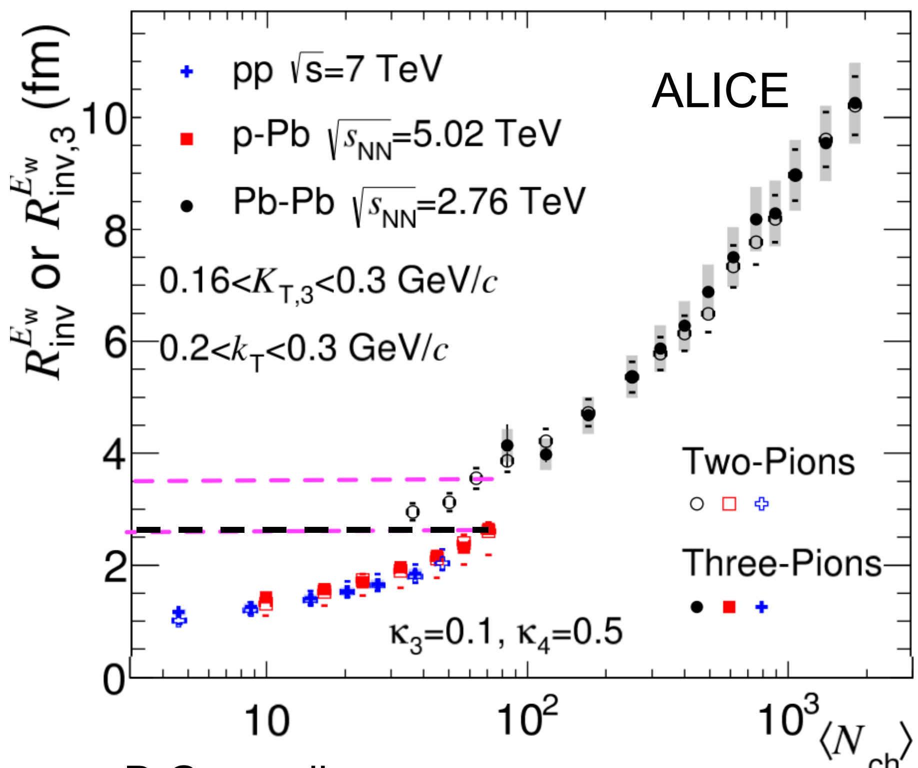

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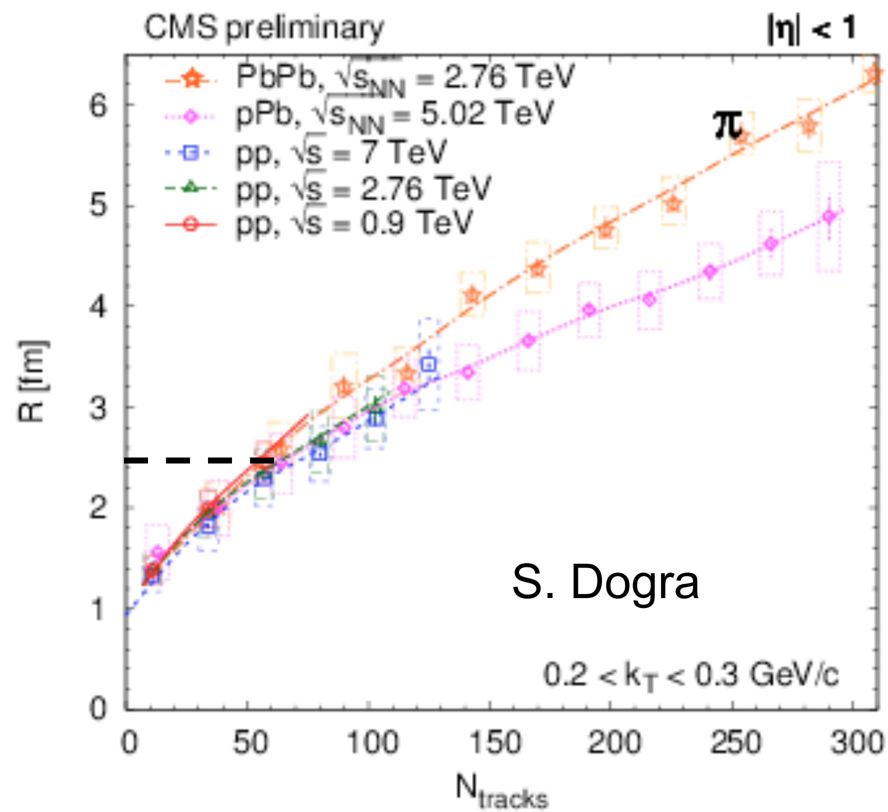
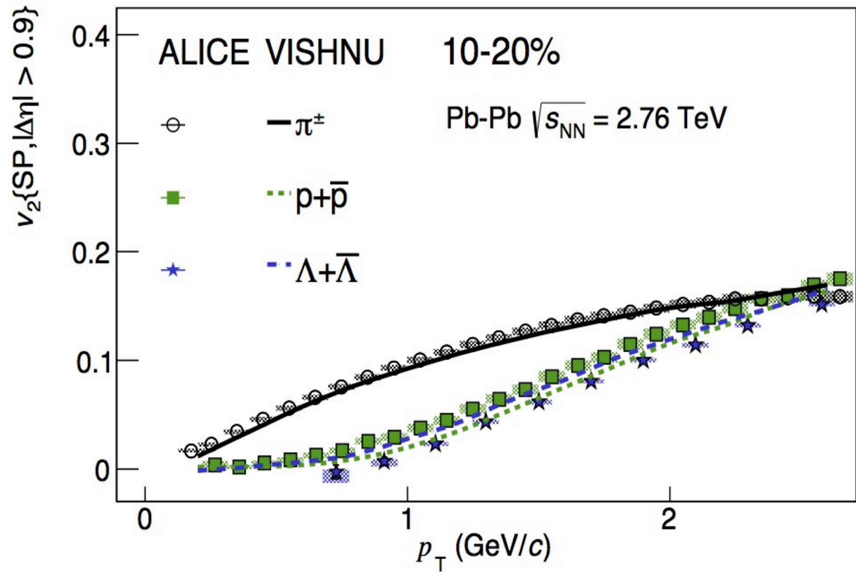


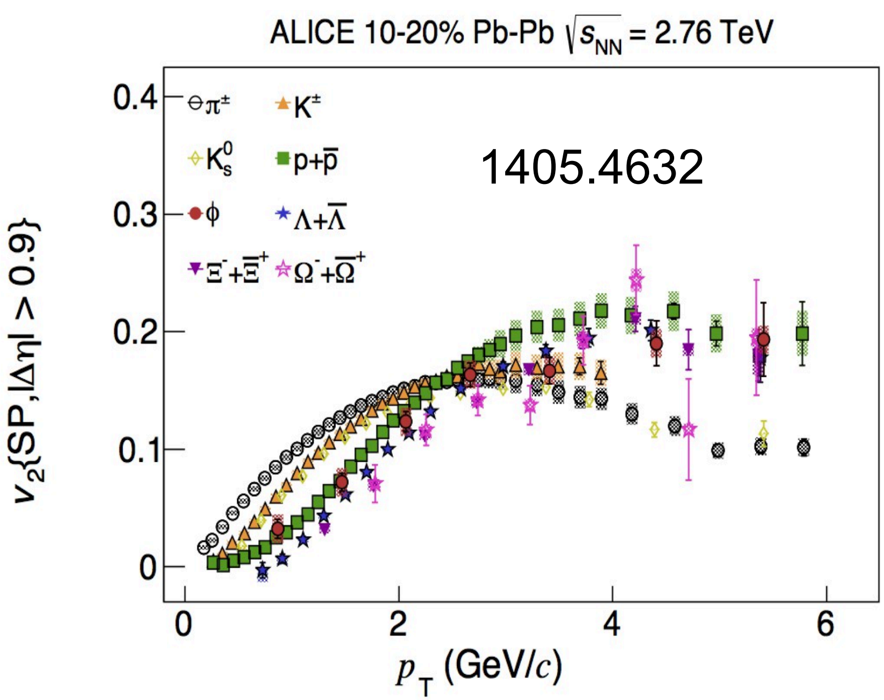
A few observations/comments about flow in A+A collisions

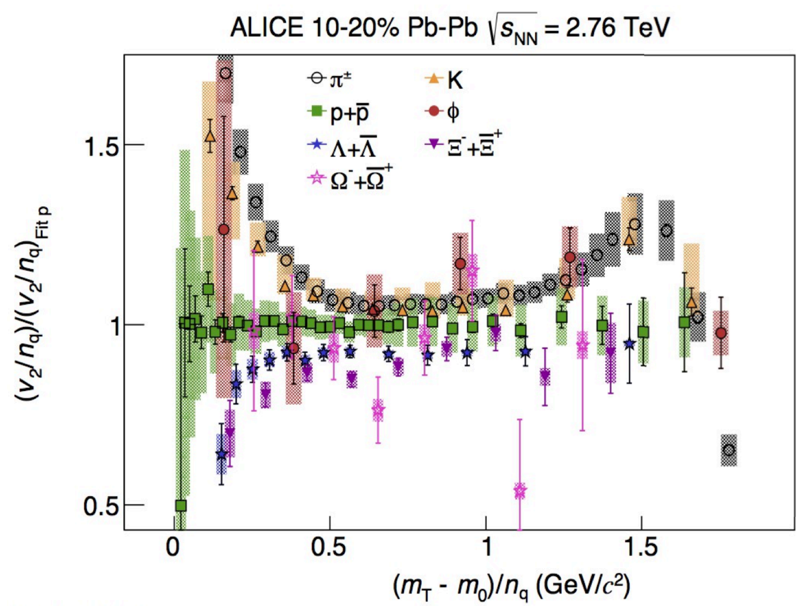
PID v_2 at LHC

- Compare to RHIC results,
  - Stronger radial flow and importance of hadronic rescattering.
  - Poorer NCQ scaling.
- ϕ flow like a baryon (central) and meson (mid-central)
  - Combination of mass and cross-section effects?

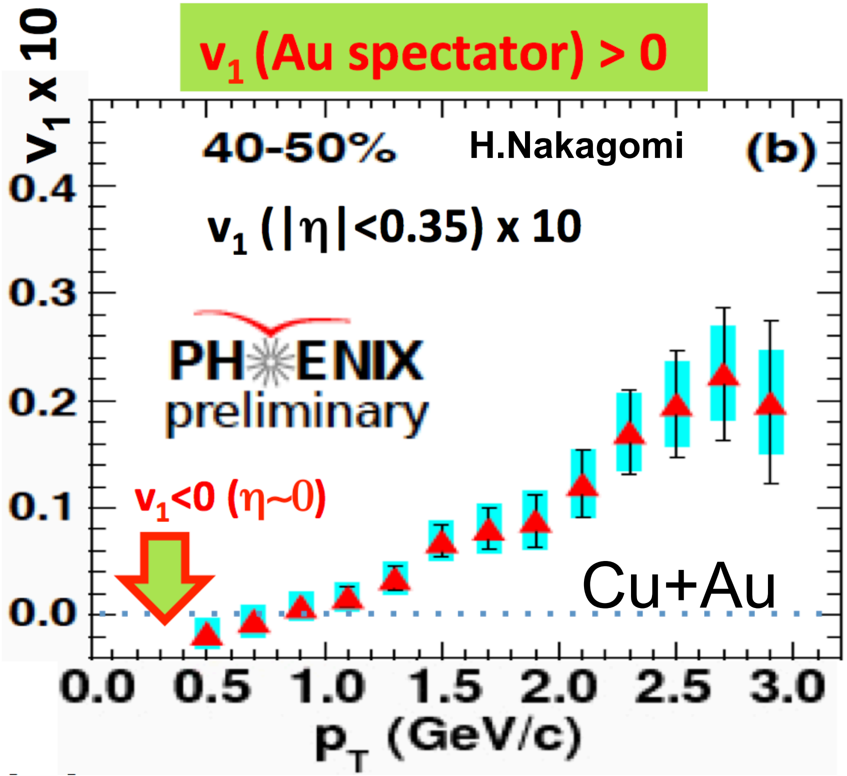


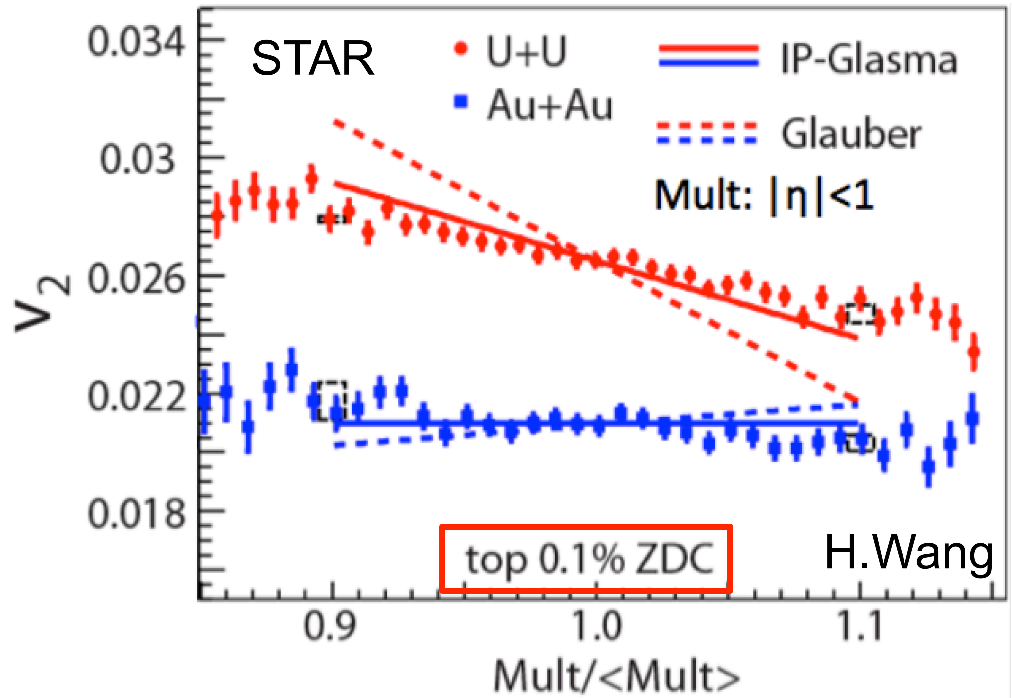
A. Dobrin & Jan





Cu+Au and U+U





- Cu+Au v_1 from average dipolar geometry
- U+U: see some sensitivity to the initial state geometry.

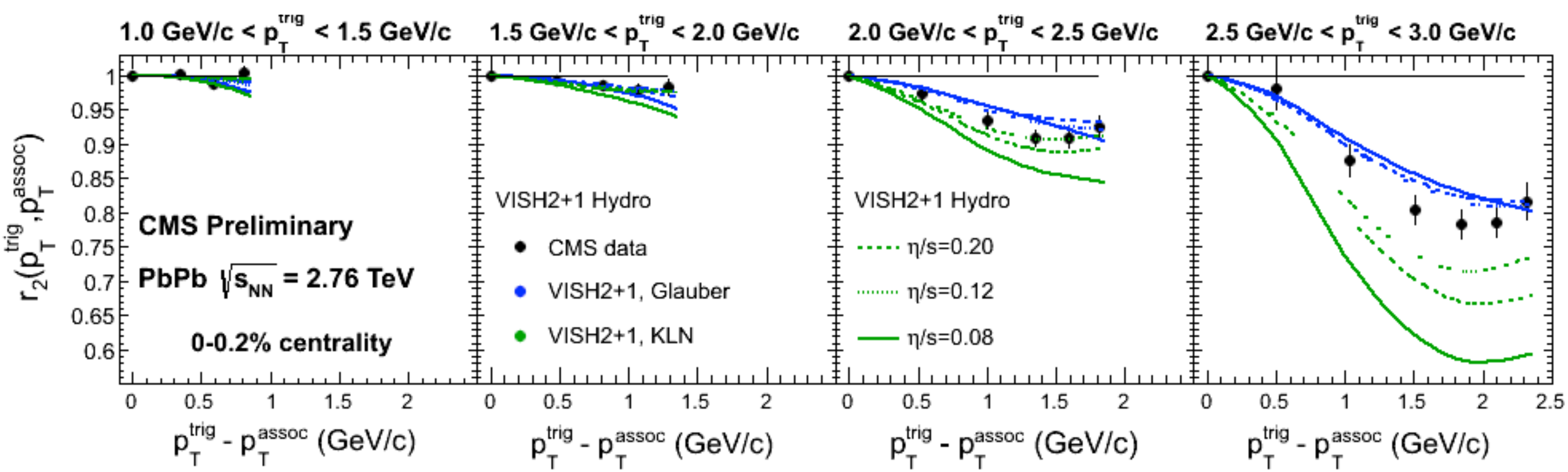
Each collision system introduces its own uncertainty in geometry!

Intra-event flow fluctuation and factorization

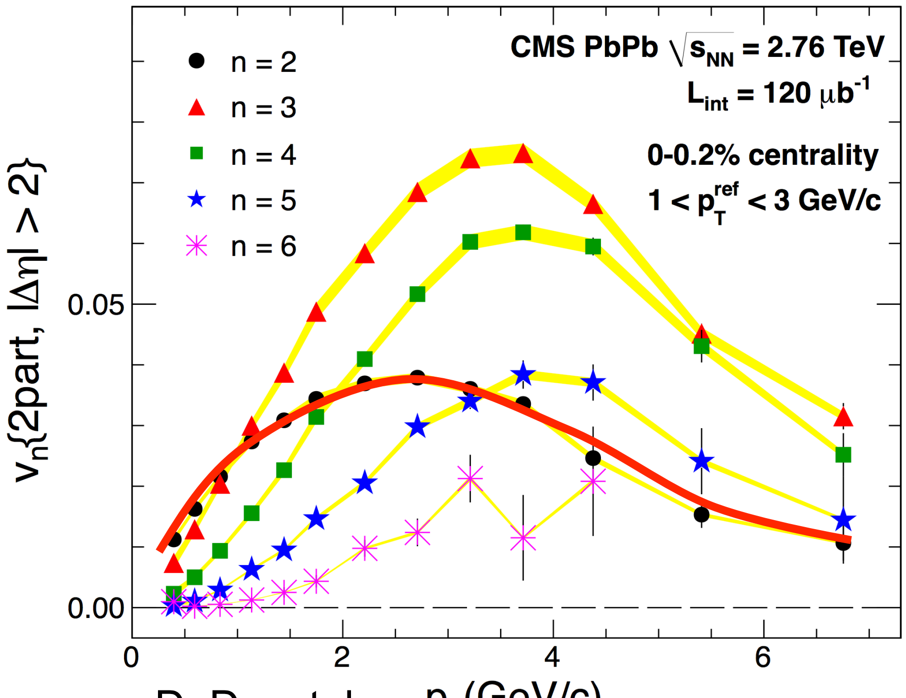
- Flow angle and amplitude fluctuates in p_T (and η) Ollitrault QM2012

$$\tilde{r}_n(p_{T1}, p_{T2}) := \frac{\langle v_n(p_{T1}) v_n(p_{T2}) \cos[n(\Psi_n(p_{T1}) - \Psi_n(p_{T2}))]\rangle}{\langle v_n(p_{T1}) v_n(p_{T2})\rangle}$$

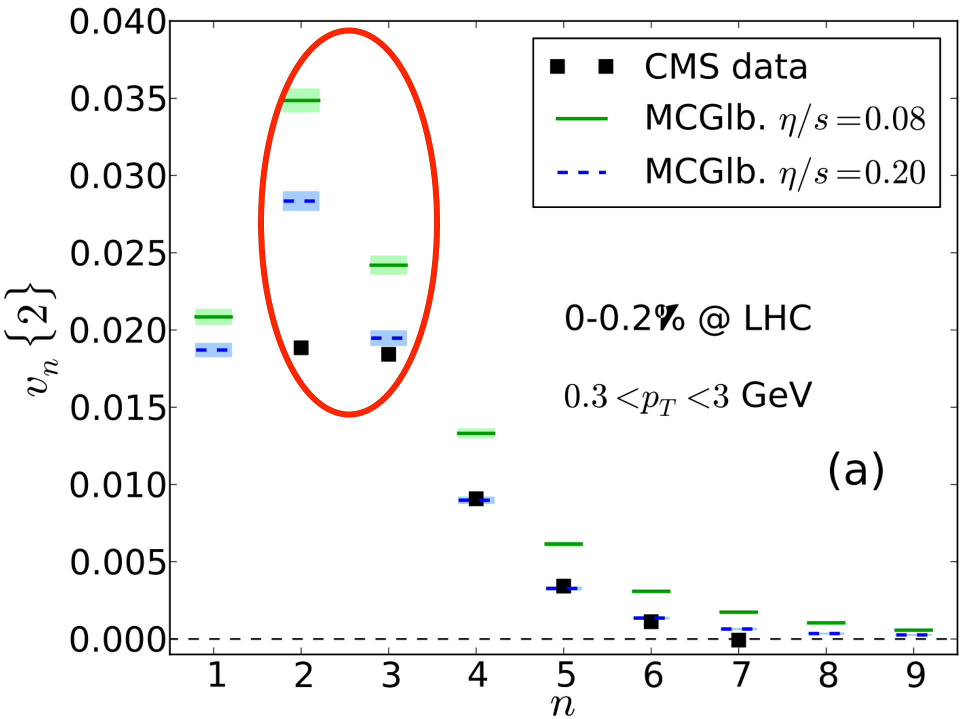
- Breaking is largest for v_2 in ultra-central Pb+Pb collisions
  - Much smaller for other harmonics and in other centralities (ALICE/ATLAS/CMS)
- Breaking of factorization p+Pb at a few % level D. Devetak also Y. Zhou



Ultra-central collisions



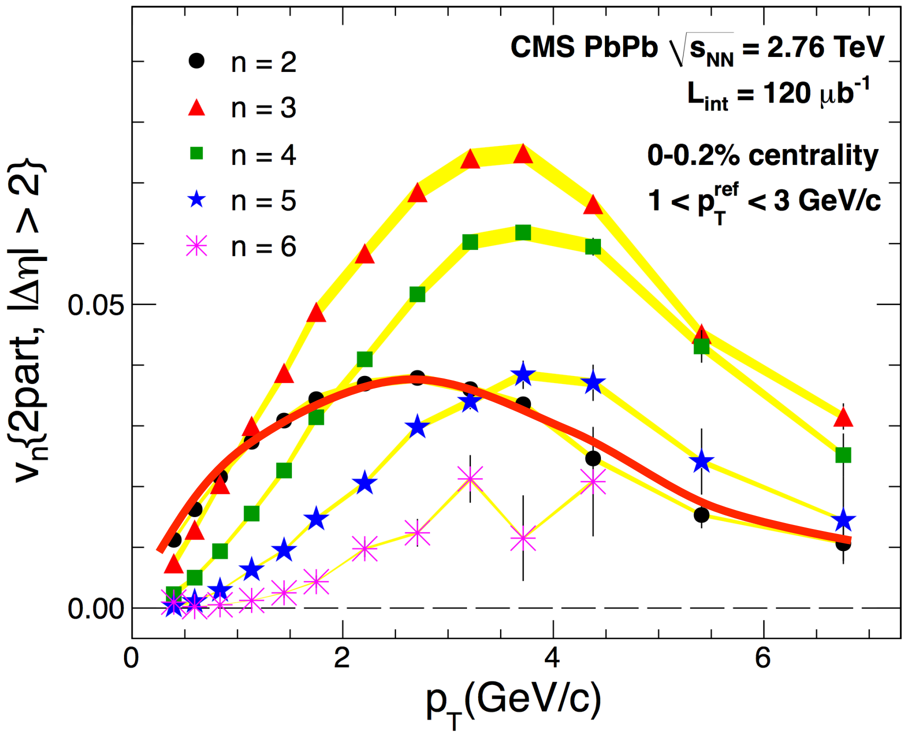
D. Devetak

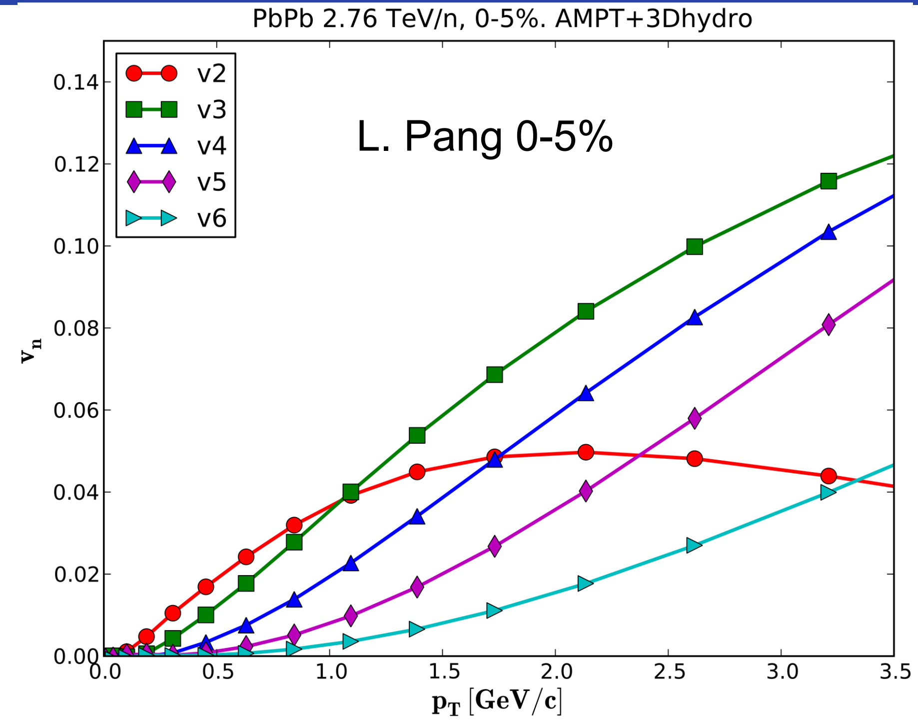


The strange $v_2(p_T)$ shape!

- Linear response dominates: $v_n \propto \varepsilon_n$ for all n
- Models have difficulty explain $v_2 \approx v_3$
  - Importance of nucleon-nucleon correlation and bulk viscosity? G.Denicol

Ultra-central collisions





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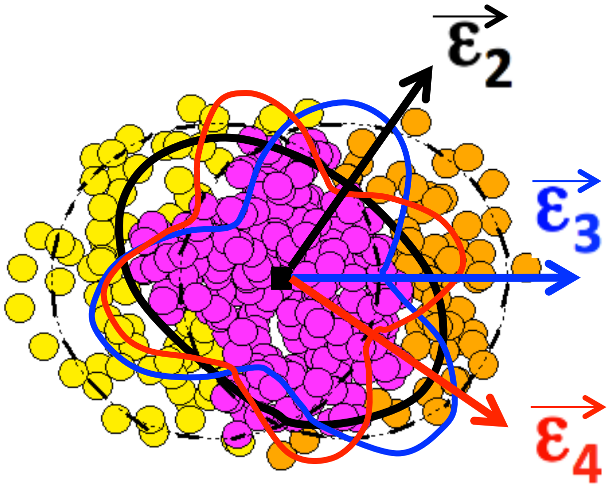
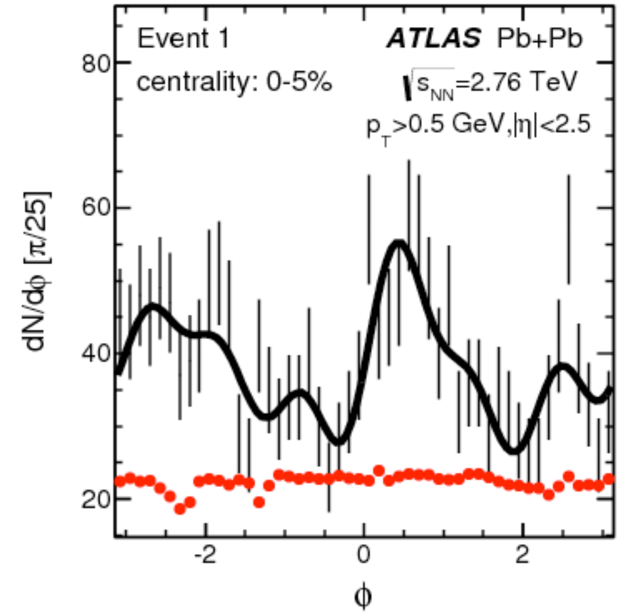
Event-by-Event fluctuations

Geometry and harmonic flow





$$\vec{\epsilon}_n \equiv \epsilon_n e^{in\Phi_n^*} \equiv -\frac{\langle r^n e^{in\phi}\rangle}{\langle r^n\rangle}$$

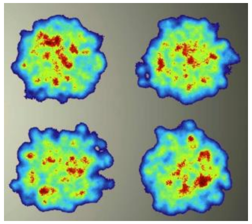
$$\frac{dN}{d\phi} \propto 1 + 2\sum_n v_n \cos n(\phi - \Phi_n)$$

$$\vec{v}_n \equiv v_n e^{in\Phi_n}$$

- How $(\varepsilon_n, \Phi_n^*)$ are transferred to (v_n, Φ_n)?
- What is the nature of final state (non-linear) dynamics?

Experimental observables

Many little bangs



$$p(v_n, v_m, ..., \Phi_n, \Phi_m, ...) = \frac{1}{N_{\text{evts}}} \frac{dN_{\text{evts}}}{dv_n dv_m ... d\Phi_n d\Phi_m ...}$$

Angular component captured by cosines

$$\frac{dN_{\text{evts}}}{d\Phi_1 d\Phi_2 ... d\Phi_l} \propto \sum_{c_n=-\infty}^{\infty} a_{c_1,c_2,...,c_l} \cos(c_1\Phi_1 + c_2\Phi_2 ... + c_l\Phi_l)$$

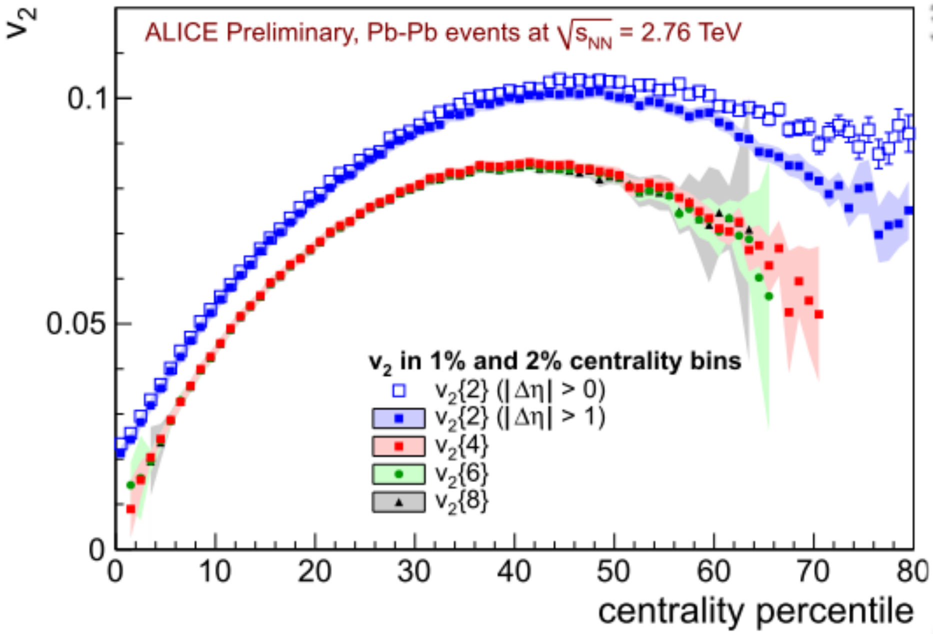
$$a_{c_1,c_2,...,c_l} = \langle \cos(c_1\Phi_1 + c_2\Phi_2 + ... + c_l\Phi_l)\rangle$$

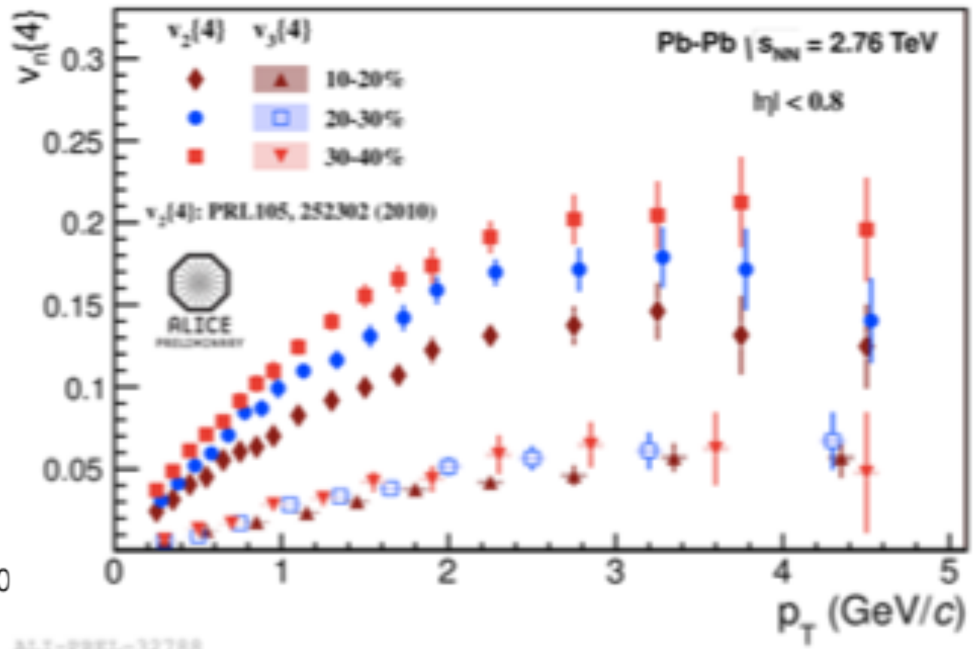
$$\langle \cos(c_1\Phi_1 + 2c_2\Phi_2 ... + lc_l\Phi_l)\rangle \,, c_1 + 2c_2 ... + lc_l = 0$$

1104.4740, 1209.2323, 1203.5095 ,1312.3572

	Probability distribution	Cumulants
Flow amplitudes	$p(v_n), p(v_n, v_m)$	$v_n\{2k\}, \langle v_n^2 v_m^2\rangle - \langle v_n^2\rangle\langle v_m^2\rangle$
Event-plane correlation	$p(\Phi_n, \Phi_m, ...)$	$\langle \vec{v}_n \vec{v}_m ...\rangle$ or $\langle \cos(c_1\Phi_1 + ... + lc_l\Phi_l)\rangle$

$v_n\{2k\}$ in Pb+Pb collisions



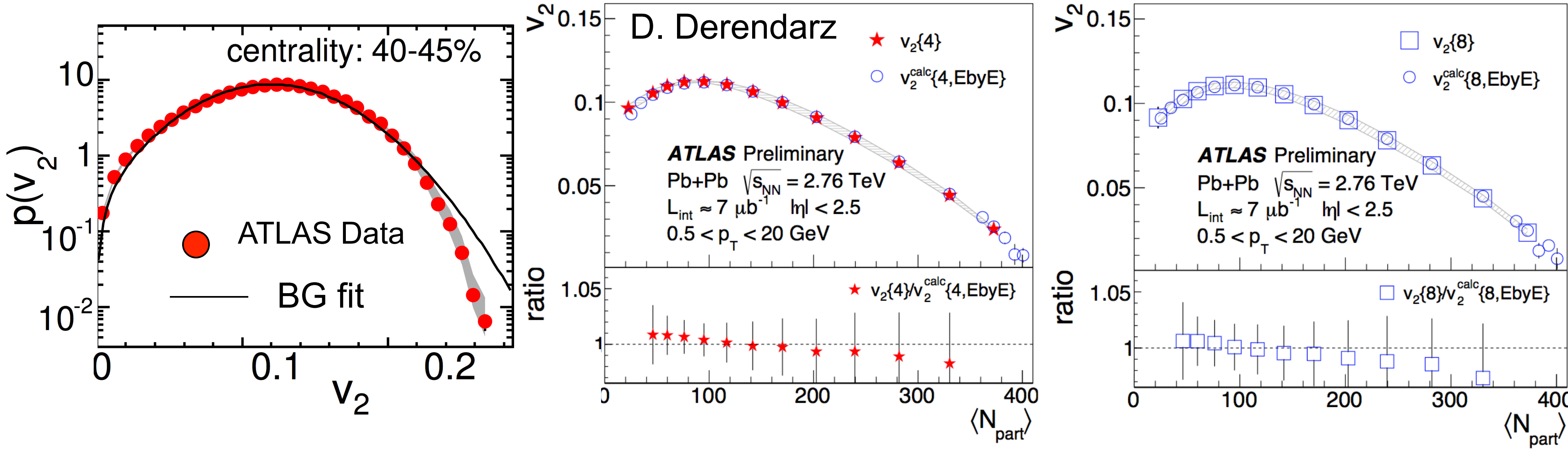


- Provide information about the underlying $p(v_n)$ distribution
- $v_2\{4\} \sim v_2\{6\} \sim v_2\{8\}$ ➔ Gaussian fluctuation around mean v_2^{RP}:

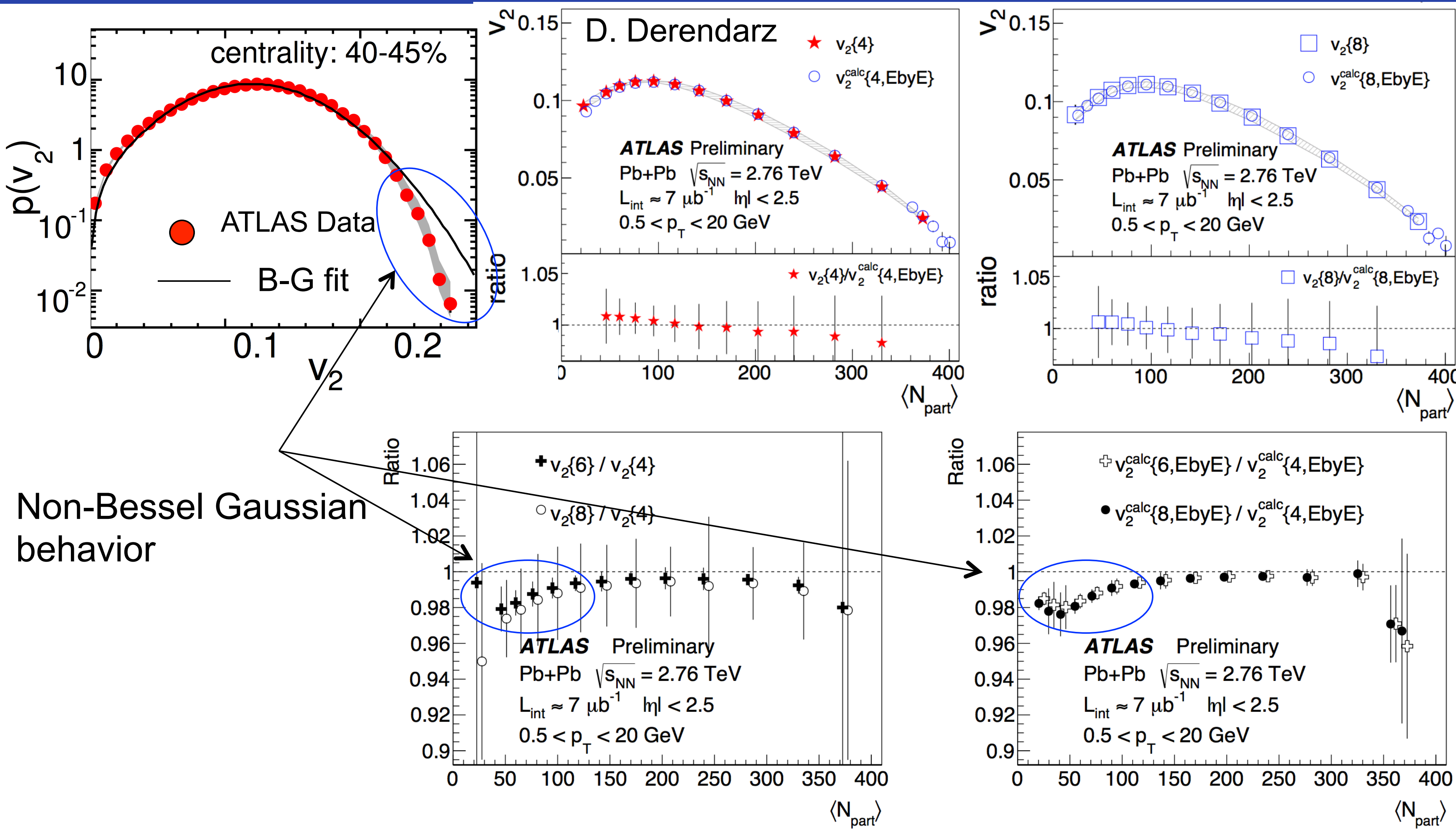
$$p(\vec{v}_n) = \frac{1}{2\pi\delta_{v_n}^2} e^{-\left(\vec{v}_n - \vec{v}_n^{\,RP}\right)^2 / \left(2\delta_{v_n}^2\right)}$$

- Non-zero $v_3\{4\}$ (ALICE) and also $v_4\{4\}$ (ATLAS)

Cumulants from traditional method and from $p(v_2)$



Cumulants from traditional method and from $p(v_2)$



- Measuring $p(v_2)$ is equivalent to cumulants, more intuitive and simpler systematics
- Non-Bessel Gaussian is reflected by a 2% change beyond 4th order cumulants

How (ε_n,Φ_n^*) are transferred to (v_n, Φ_n)?

- Flow response is linear for v_2 and v_3: $v_n \propto \varepsilon_n$ and $\Phi_n \approx \Phi_n^*$ i.e.

$$v_2 e^{-i2\Phi_2} \propto \epsilon_2 e^{-i2\Phi_2^*}, \quad v_3 e^{-i3\Phi_3} \propto \epsilon_3 e^{-i3\Phi_3^*}$$

How (ε_n, Φ_n^*) are transferred to (v_n, Φ_n)?

- Flow response is linear for v_2 and v_3: $v_n \propto \varepsilon_n$ and $\Phi_n \approx \Phi_n^*$ i.e.

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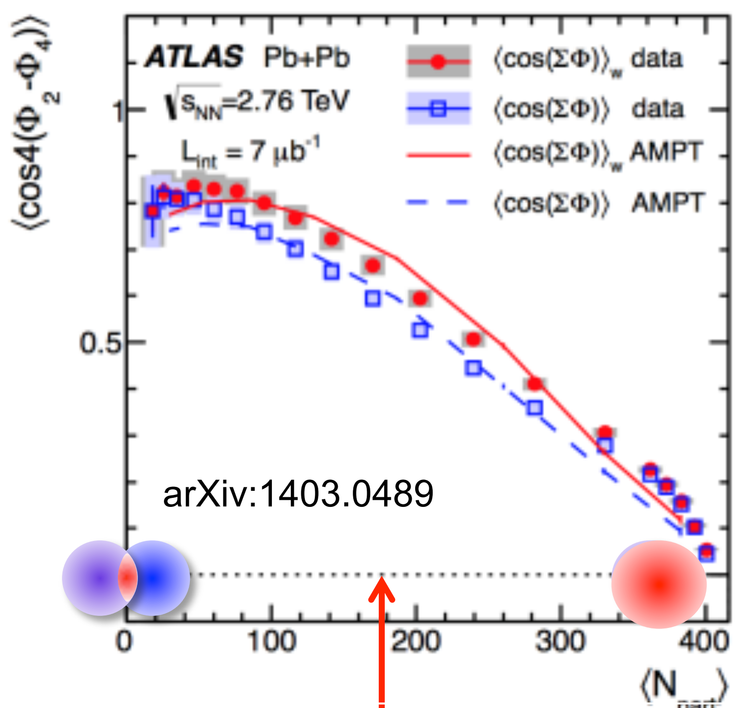
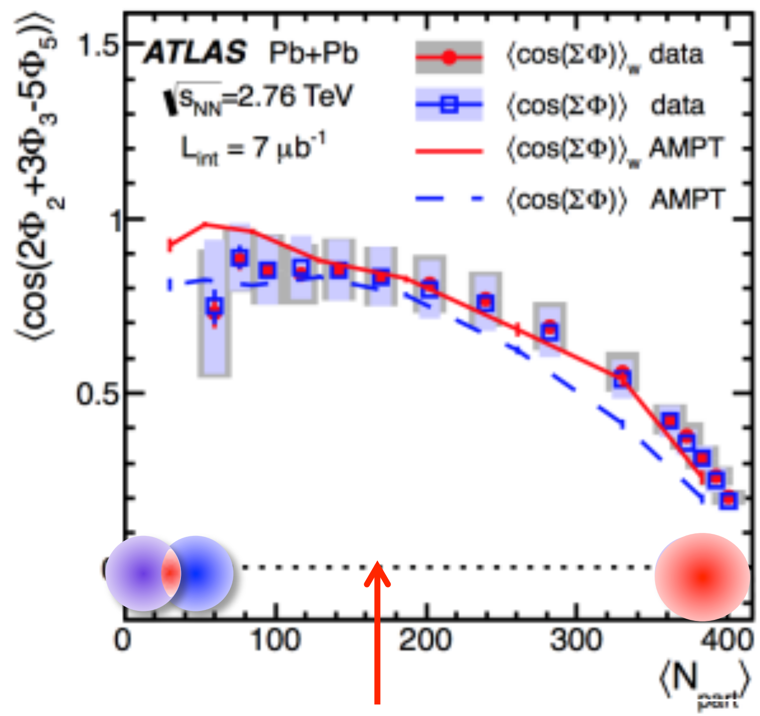
- Higher-order flow arises from EP correlations., e.g. :

Ollitrault, Luzum, Teaney, Li, Heinz,Chun….

$\langle \cos 4(\Phi_2 - \Phi_4) \rangle$



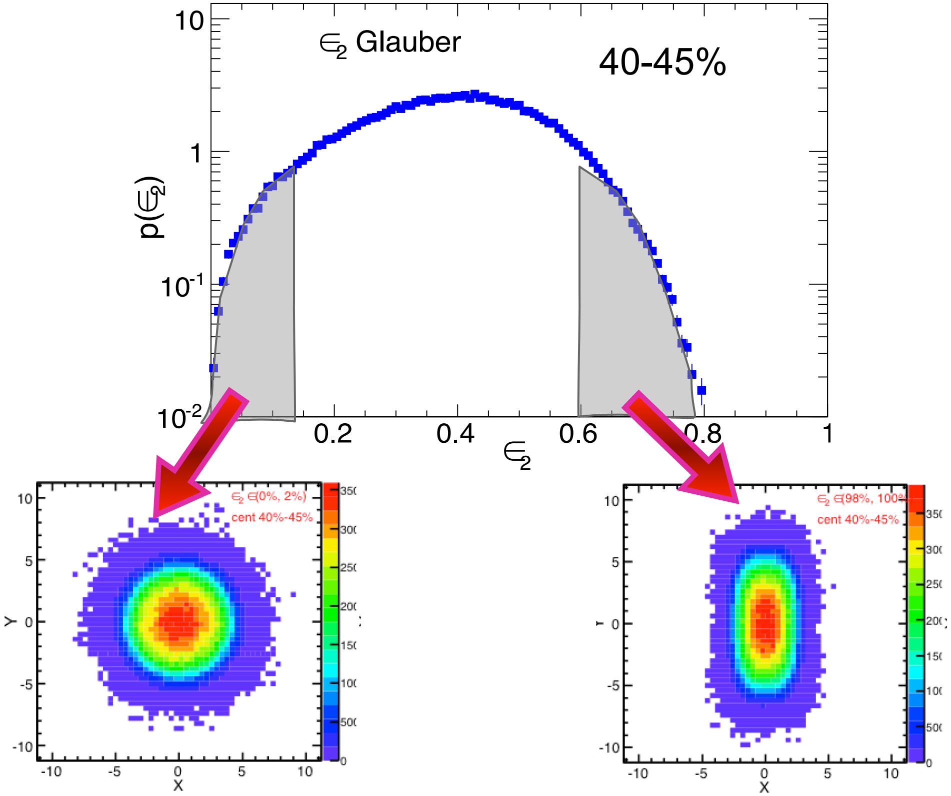
$\langle \cos(2\Phi_2 + 3\Phi_3 - 5\Phi_5) \rangle$



$$v_4 e^{-i4\Phi_4} \propto \varepsilon_4 e^{-i5\Phi_4^*} + c v_2^2 e^{-i4\Phi_2} + \ldots$$

$$v_5 e^{-i5\Phi_5} \propto \varepsilon_5 e^{-i5\Phi_5^*} + c v_2 v_3 e^{-i(2\Phi_2 + 3\Phi_3)} + \ldots$$

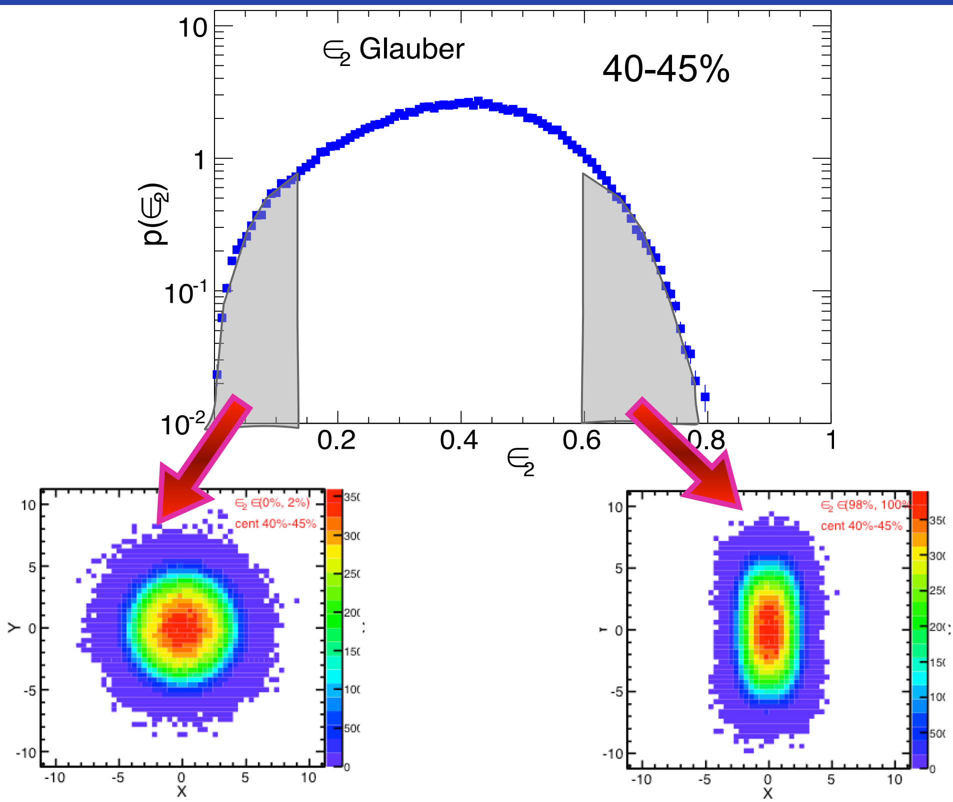
More info by selecting on event-shape

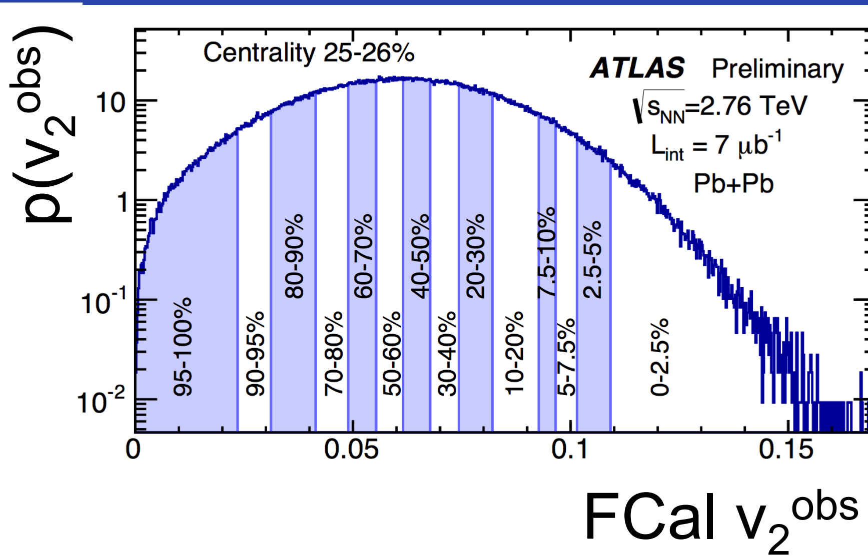


arXiv:1208.4563
arxiv:1311.7091

- Select events with certain v_2^{obs} in Forward Rapidity:

More info by selecting on event-shape





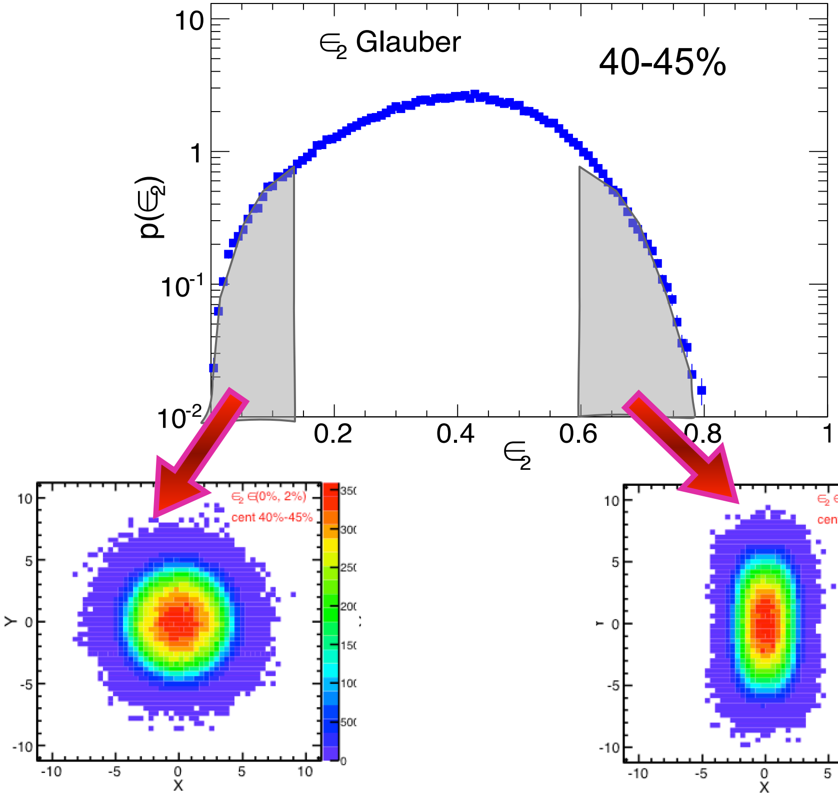
arXiv:1208.4563
arxiv:1311.7091

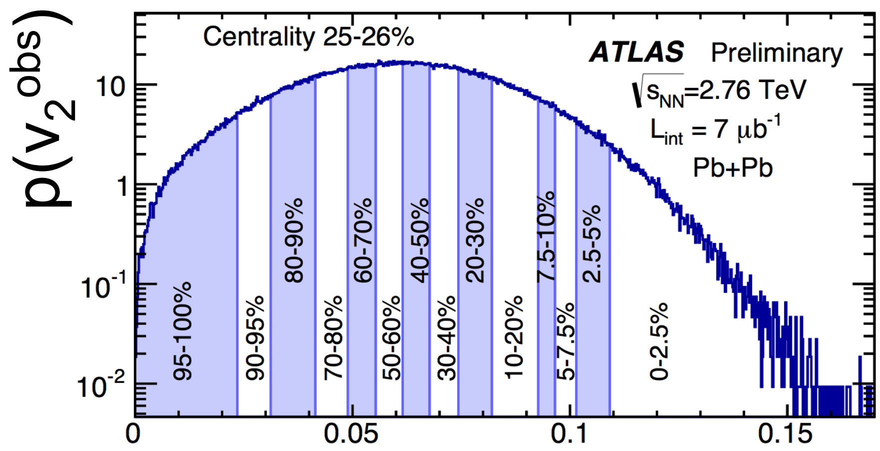
- Fix centrality, then select events with certain v_2^{obs} in Forward rapidity:

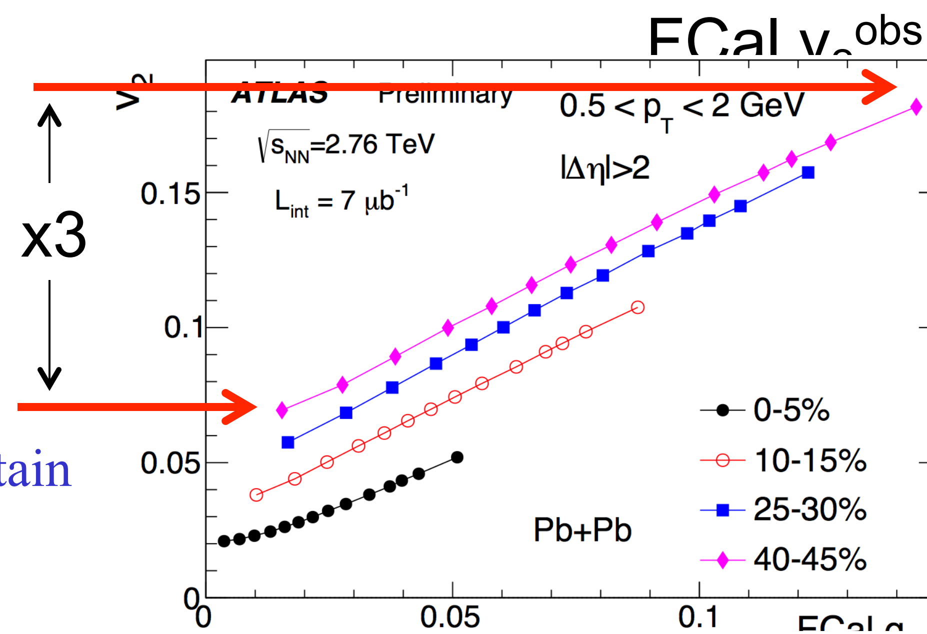
➔ATLAS: measure v_n via two-particle correlations in $|\eta|< 2.5$

Fix system size and change ellipticity!!

More info by selecting on event-shape







FCal v_2^{obs}

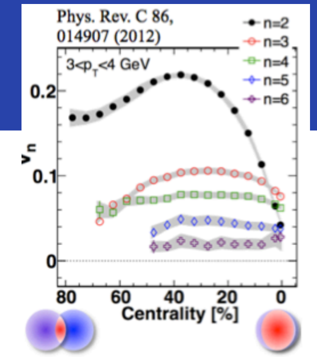
- Fix centrality, then select events with certain v_2^{obs} in Forward rapidity:

➔ATLAS: measure v_n via two-particle correlations in $|\eta| < 2.5$

Vary ellipticity by a factor of 3!

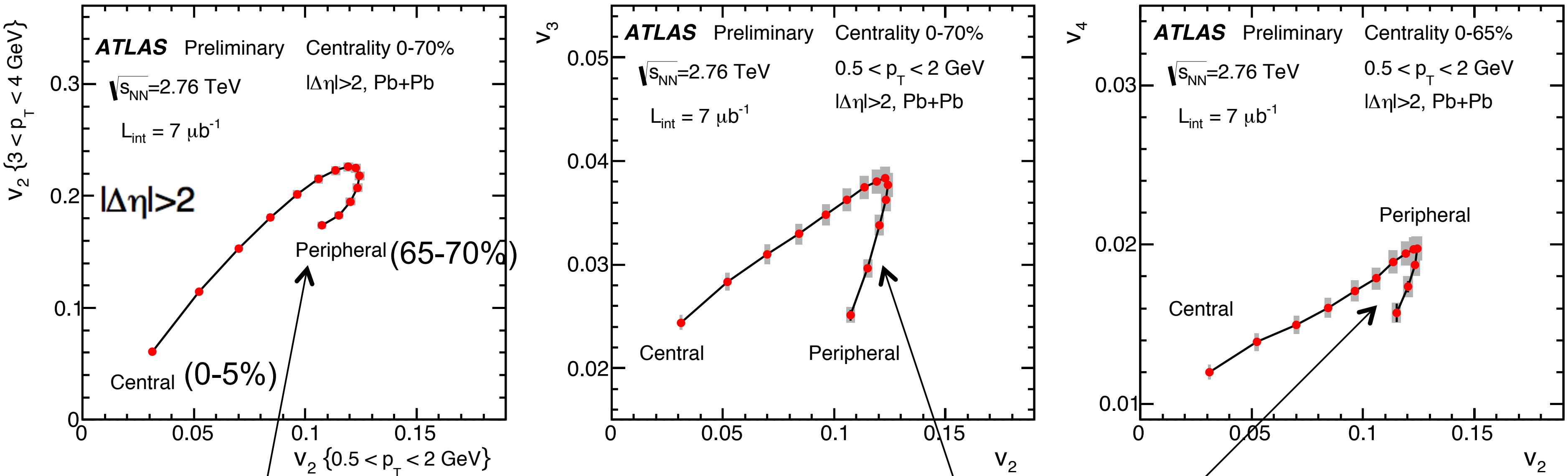
S. Mohapatra

v_n-v_2 correlations: centrality dependence



- First correlation without event v_2-selection, 5% steps

v_2 (higher p_T) | v_3 | v_4



"Boomerang" reflects stronger viscous damping at higher p_T and peripheral

"Boomerang" reflects reflects different centrality dependence, which is also sensitive to the viscosity effect.

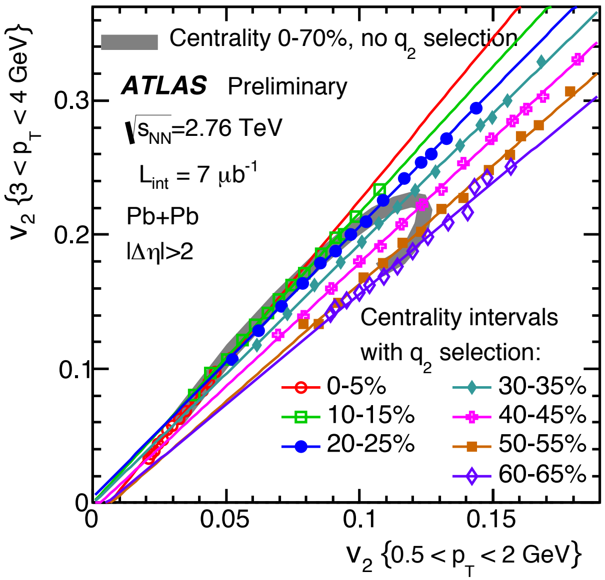
S. Mohapatra

v_n-v_2 correlations: within fixed centrality

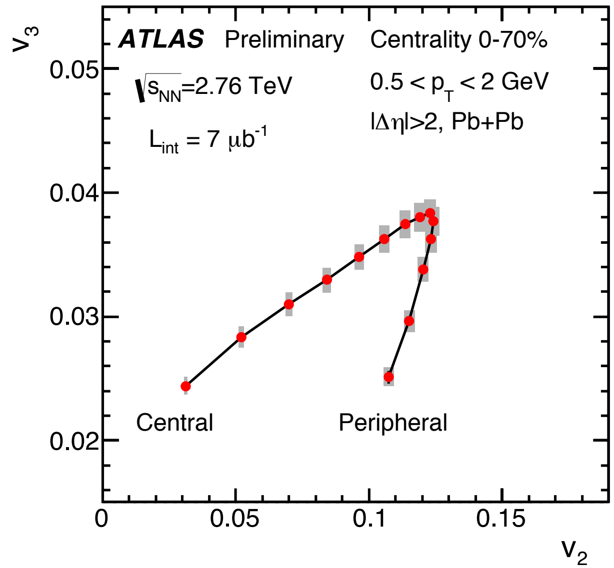
- Fix system size and vary the ellipticitiy!

Probe $p(v_n,v_2)$

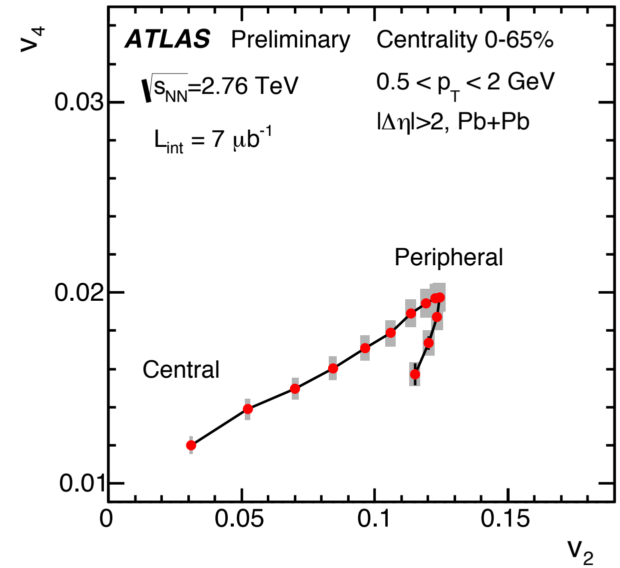
v_2 (higher p_T)



v_3



v_4



Linear correlation for forward v_2-selected bin→viscous damping controlled by system size, not shape

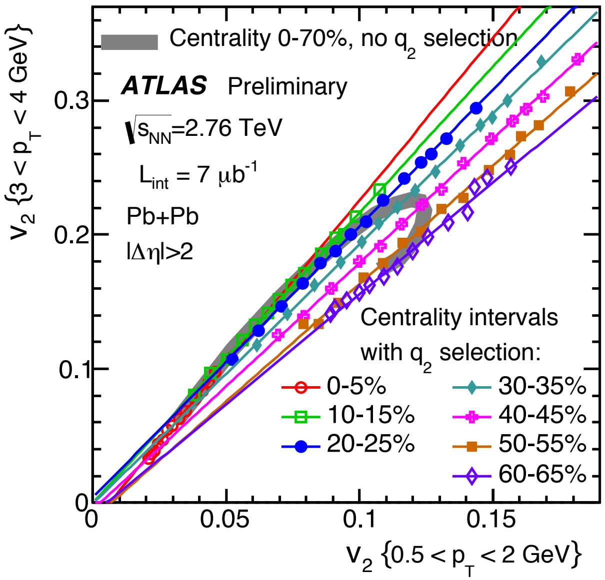
S. Mohapatra

v_n-v_2 correlations: within fixed centrality

- Fix system size and vary the ellipticitiy!
- Overlay ε_3-ε_2 and ε_4-ε_2 correlations, rescaled

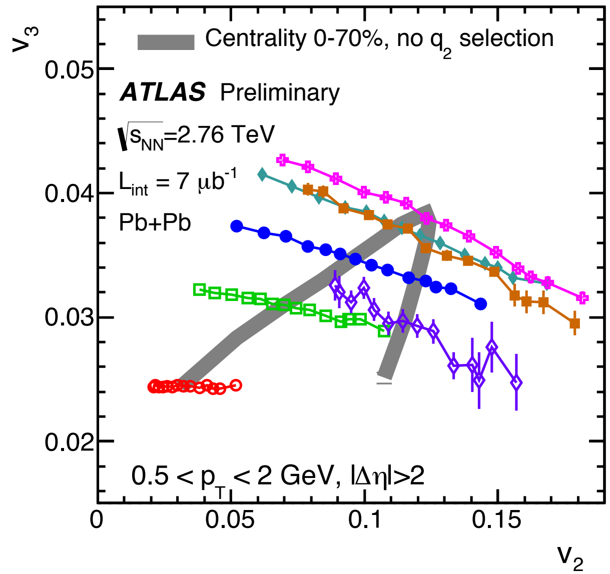
Probe $p(v_n,v_2)$

v_2 (higher p_T)



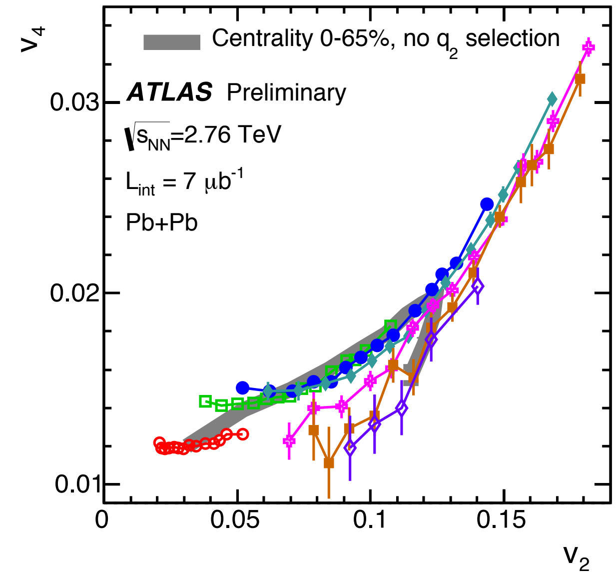
Linear correlation for forward v_2-selected bin→viscous damping controlled by system size, not shape

v_3



Clear anti-correlation,

v_4



quadratic rise from non-linear coupling to v_2^2

S. Mohapatra

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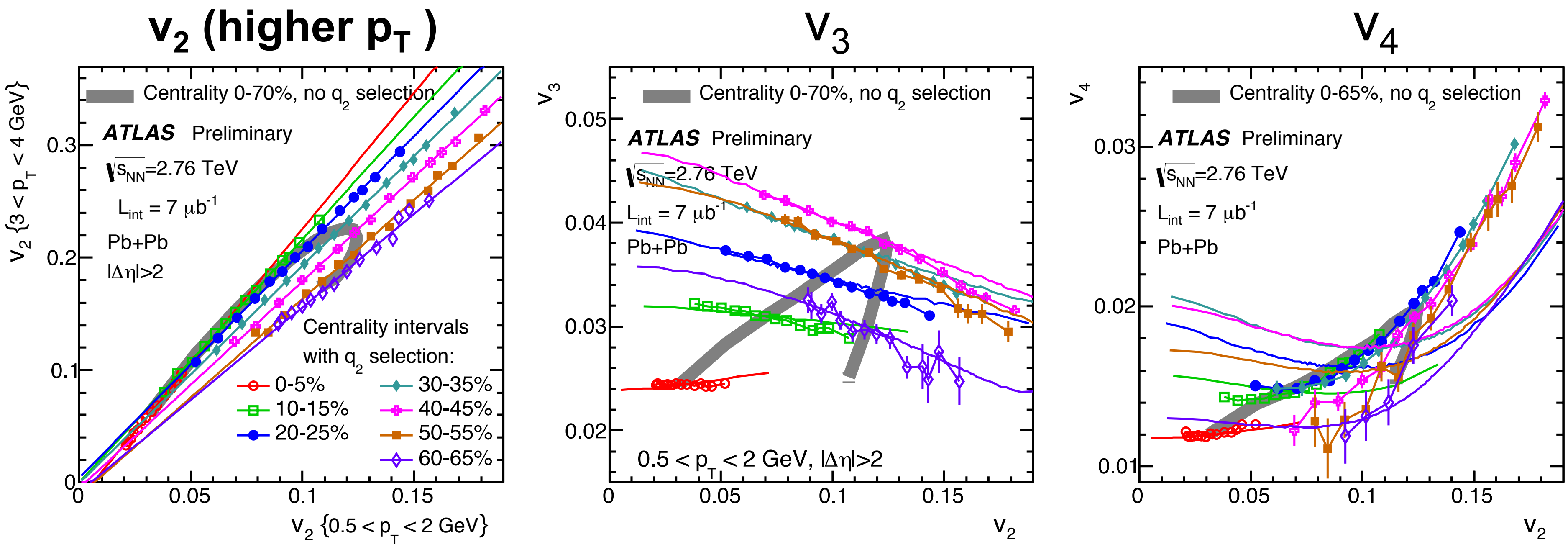


Linear correlation for forward v_2-selected bin→viscous damping controlled by system size, not shape

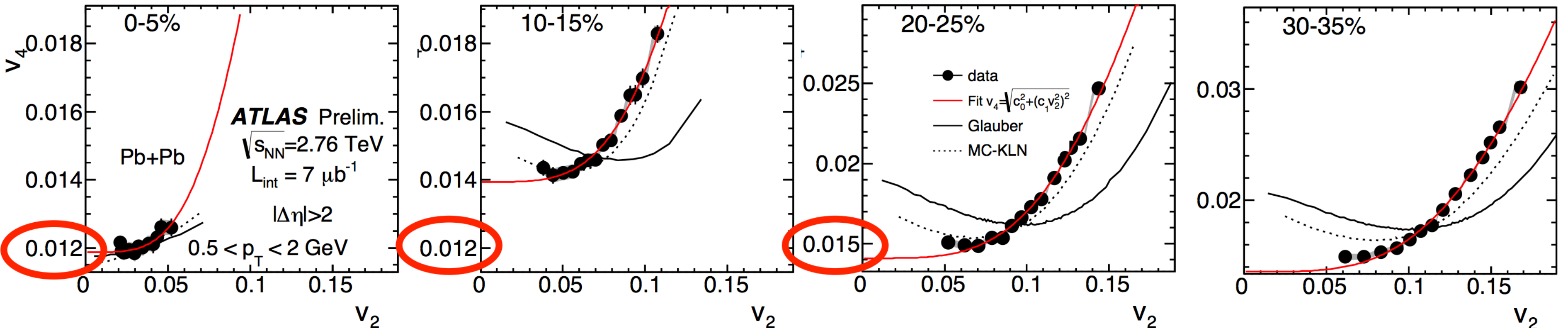
Clear anti-correlation, mostly initial geometry effect!!

quadratic rise from non-linear coupling to v_2^2 initial geometry do not work!!

Initial geometry describe v_3-v_2 but fails v_4-v_2 correlation S. Mohapatra

linear (ε_4) and non-linear (v_2^2) component of v_4

- v_4-v_2 correlation for fixed centrality bin $v_4 e^{i4\Phi_4} = c_0 e^{i\Phi_4^*} + c_1 \left(v_2 e^{i2\Phi_2}\right)^2 \Rightarrow$ Fit by $v_4 = \sqrt{c_0^2 + c_1^2 v_2^4}$



- Fit $v_4 = \sqrt{c_0^2 + c_1^2 v_2^4}$ to separate linear (ε_4) and non-linear (v_2^2) component

S. Mohapatra

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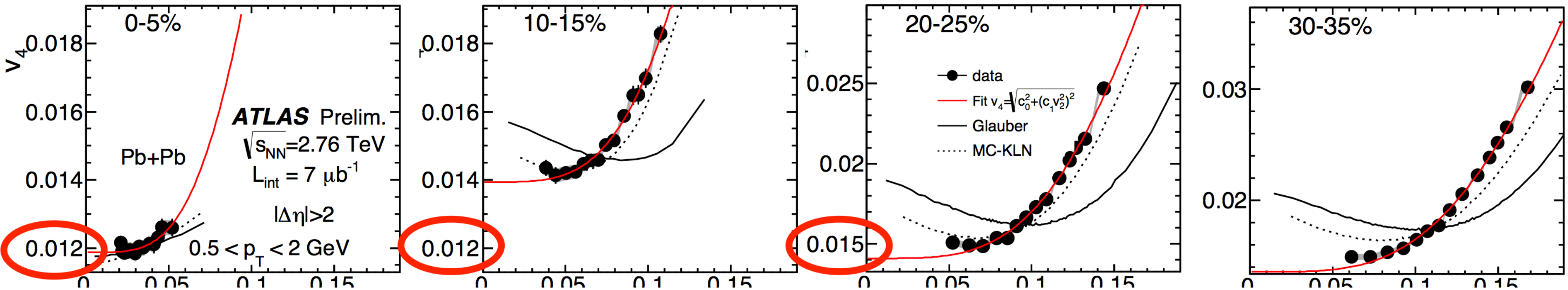
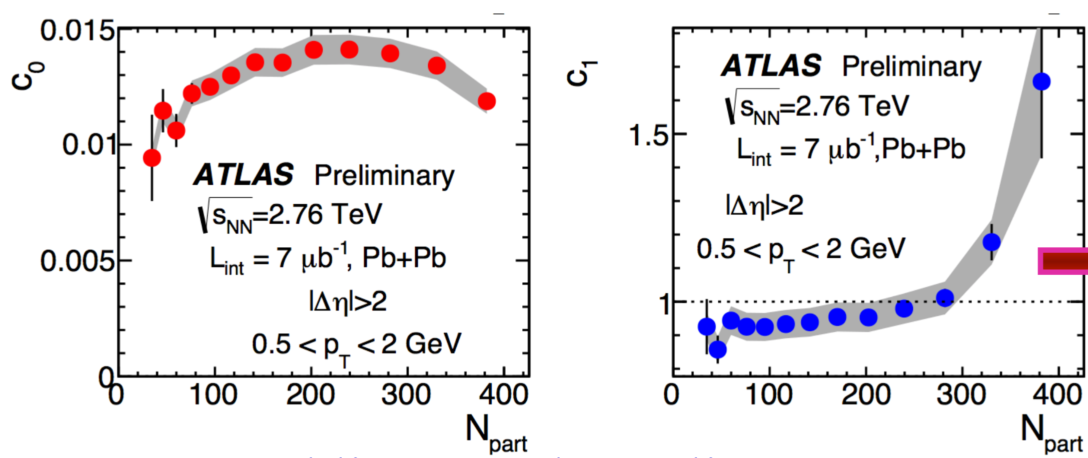
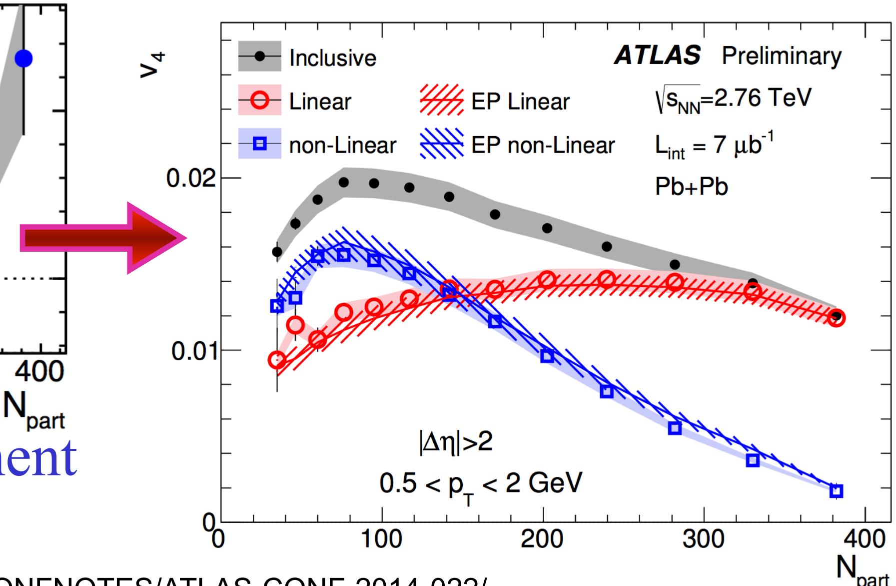


Linear-component provide independent constraints on viscosity

- Fit $v_4 = \sqrt{c_0^2 + c_1^2 v_2^4}$ to separate linear (ε_4) and non-linear (v_2^2) component

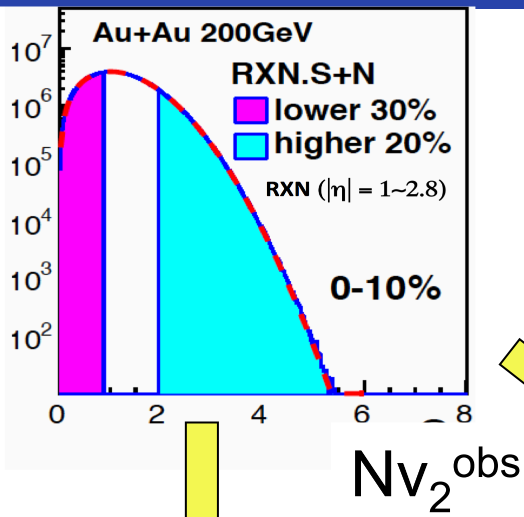


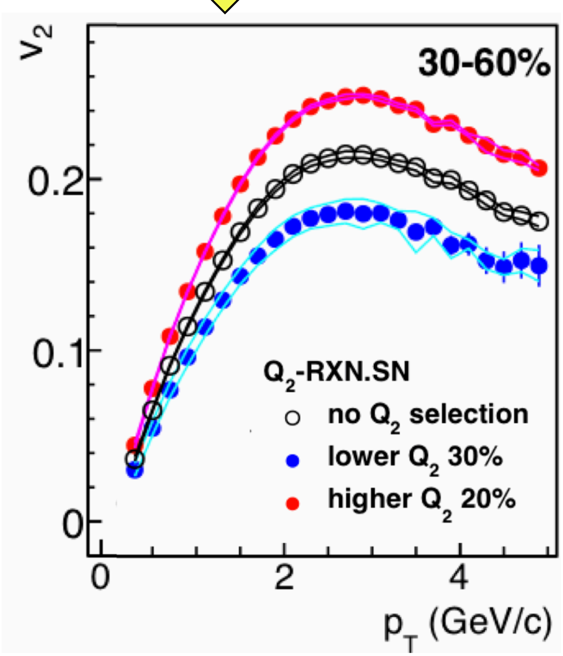


- Extracted linear and non-linear component as a function of centrality

See details at https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2014-022/

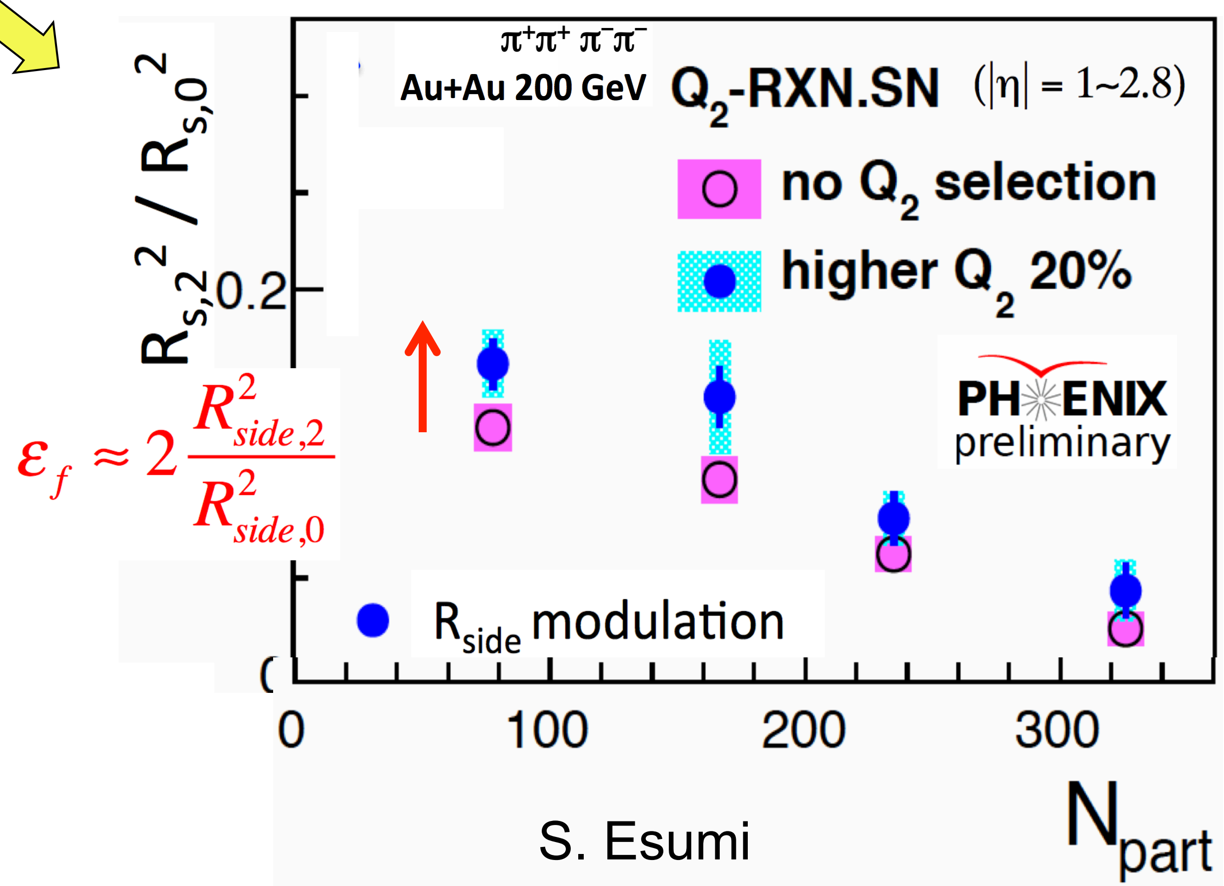
Event-shape (v_2) selected HBT





Freeze-out eccentricity show clear sensitivity to change of v_2 or initial ellipticity!

Large v_2 → large ε_2 → large ε_f.



S. Esumi

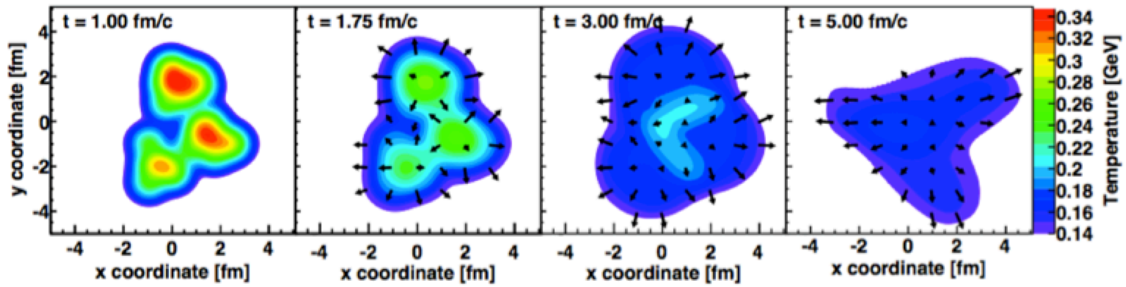
Future prospects:
my humble opinion

(I) : Precision event-shape selection

- Different collision system e.g. He^3+Au, June 16th!

P. ROMATSCHKE

Intrinsic trangularity



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P. ROMATSCHKE

Nagle, et al (MM), arXiv:1312.4565

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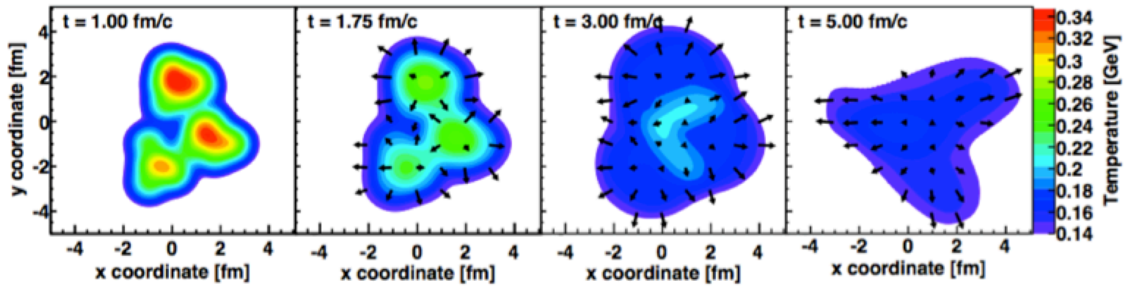
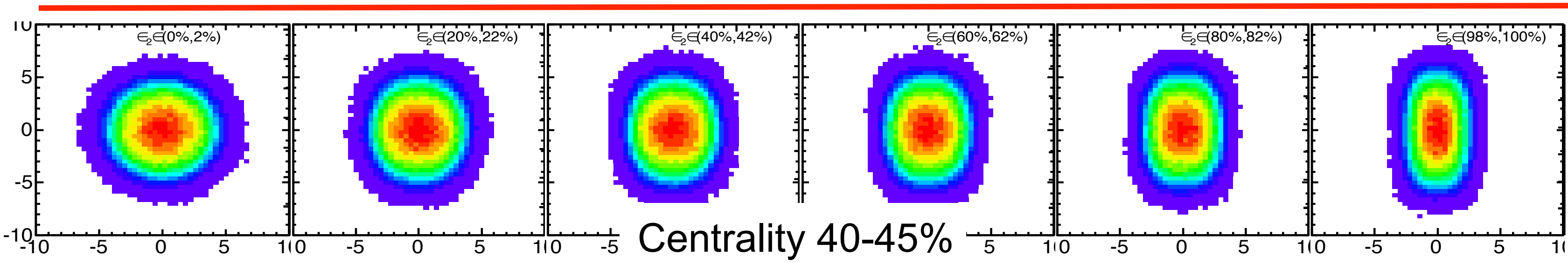


- Event-shape selections on v_2 and/or v_3 → Fix size, change ε_2 and ε_3
  - v_n, HBT, R_{AA},CME etc..

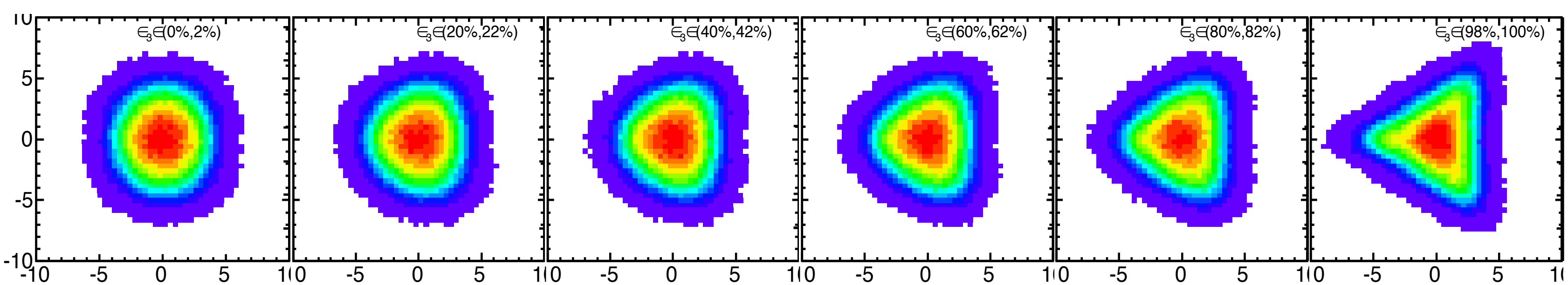
Schukraft, Timmins, and Voloshin, arXiv:1208.4563

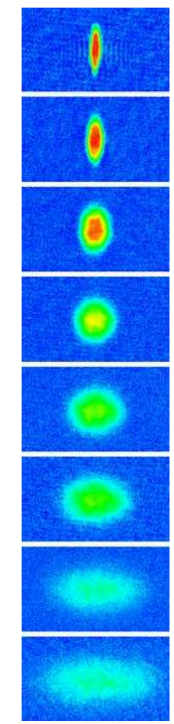
Huo, Mohapatra, JJ arxiv:1311.7091

Increasing ε_2



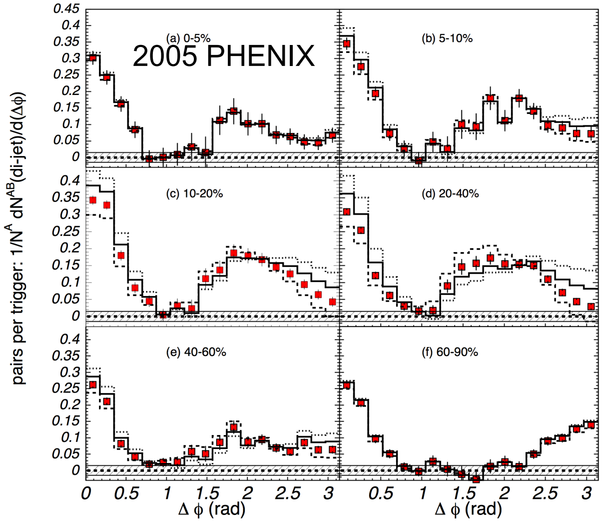
Increasing ε_3





(II) : understand jet-medium interaction

- How (mini)-jet are thermalized in medium?
  - Difficult due to dominance of collective flow
    - Until 2010, triangular flow was interpreted as "Mach-cone"
- Event-shape selection technique can help!
  - Require events to have small v_n, less flow subtraction.



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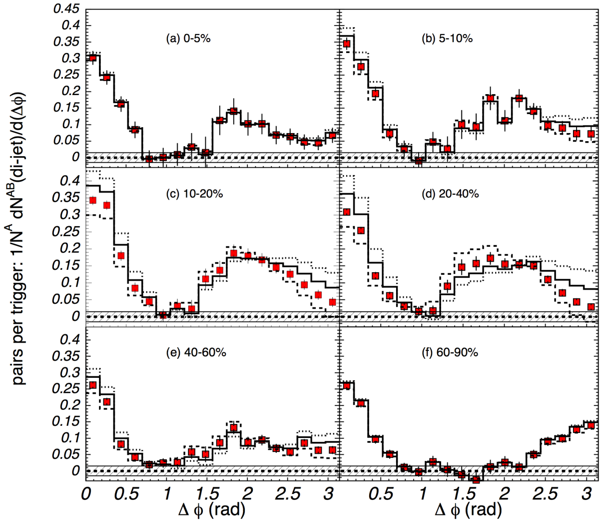
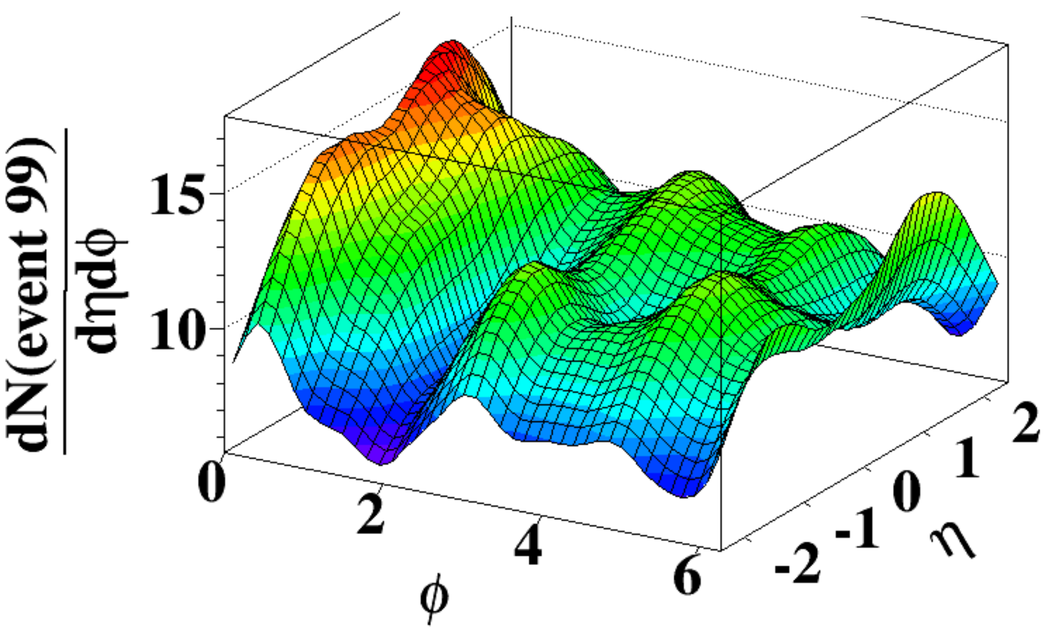


No boost invariance!!



Curtsey of L.Pang and X.N Wang, EbyE 3D hydro+AMPT condition

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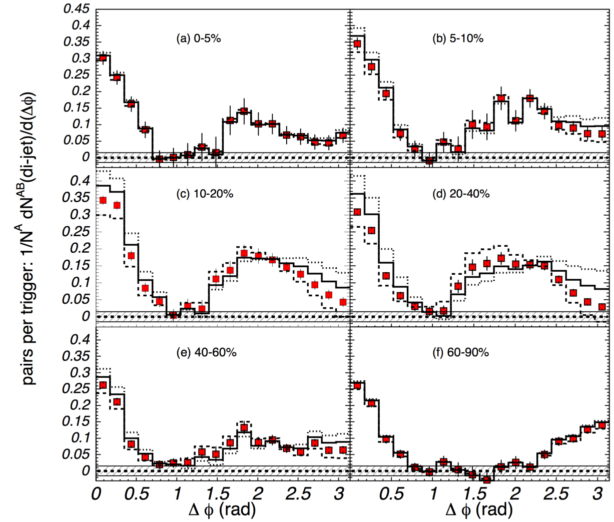
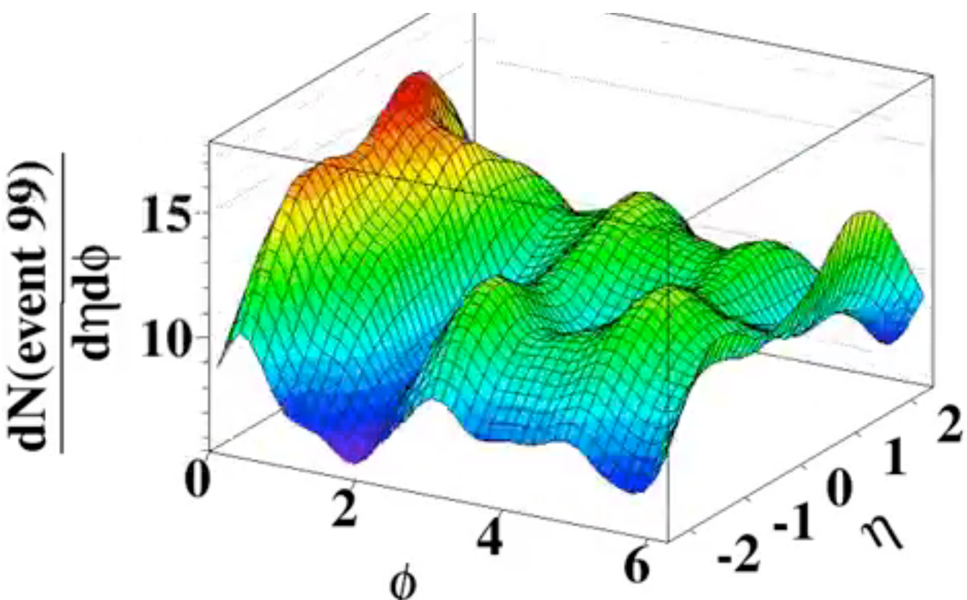
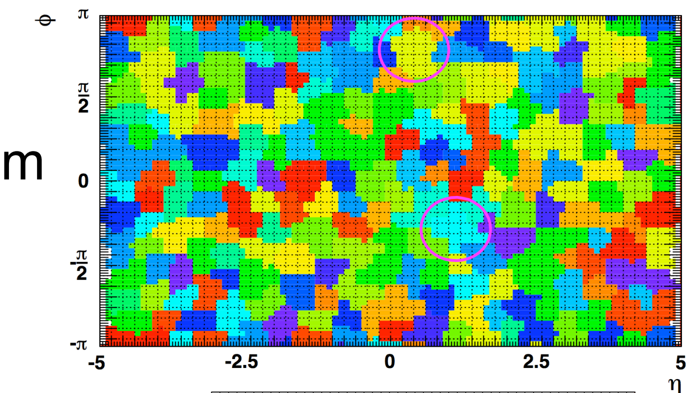
  - Require events to have small v_n, less flow subtraction.
- $\eta \times \phi$ space are dominated by fake-jets or "hydro-jets"
  - They can be found by jet-reco algorithm (vetoing good jets)

Then analysis spectrum or study substructure?

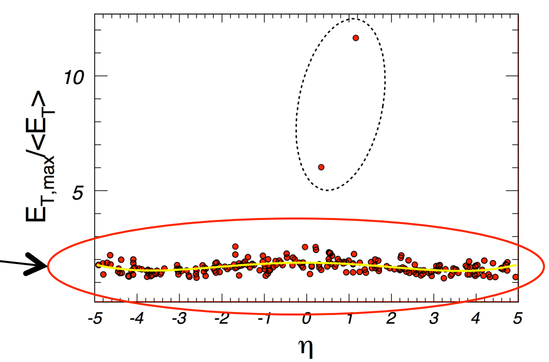




k_T algorithm

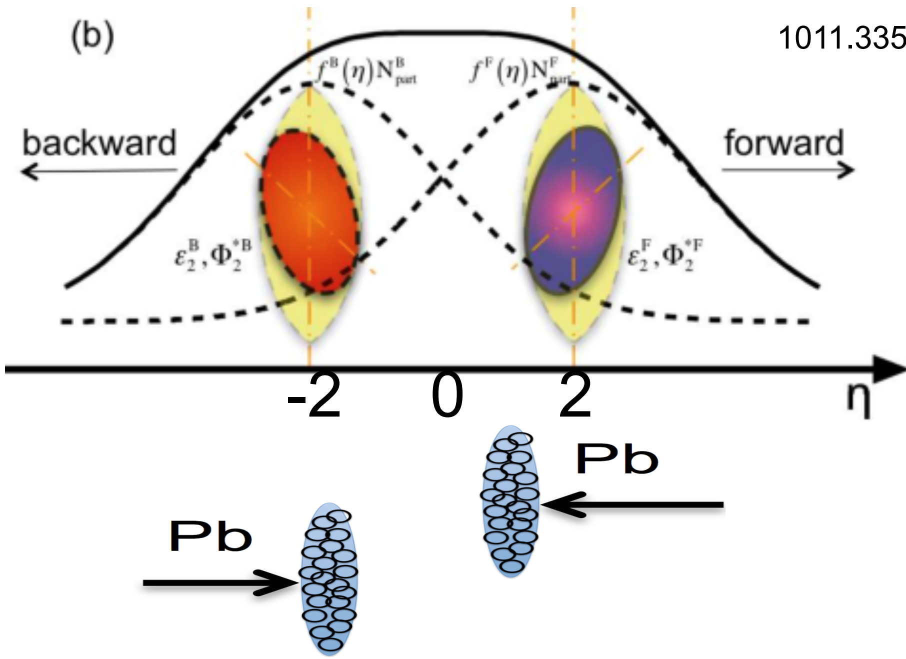


Interesting stuff

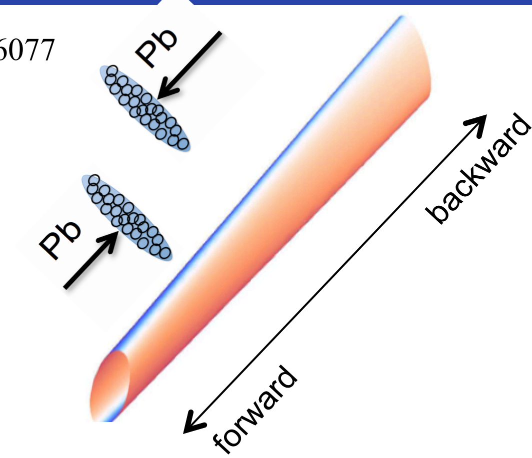


Curtsey of L.Pang and X.N Wang, EbyE 3D hydro+AMPT condition

(III) : flow longitudinal dynamics



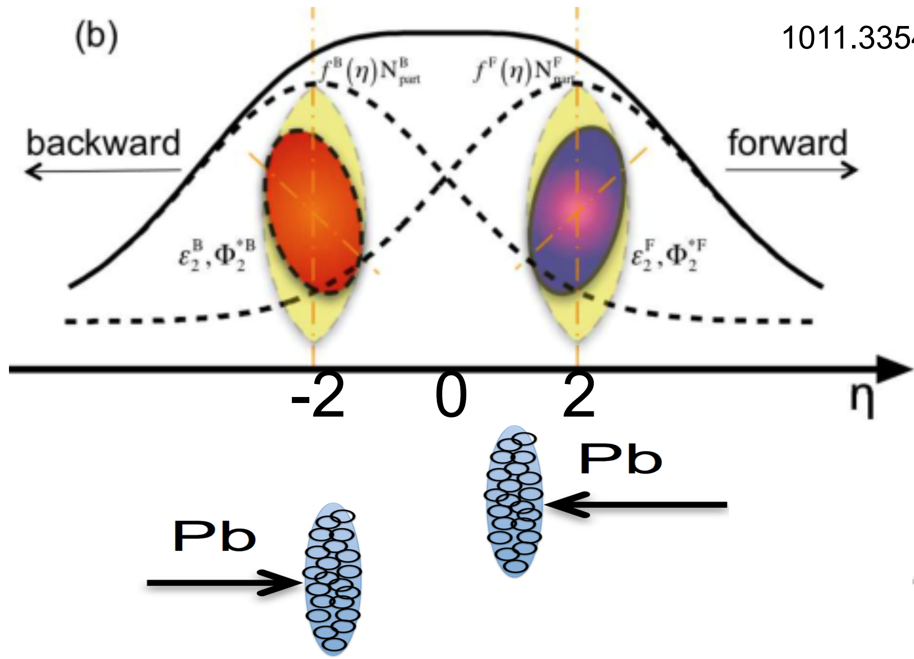
1011.3354, 1403.6077



- Shape of participants in two nuclei not the same due to fluctuation $\varepsilon_n^F, \Phi_n^{*F} \neq \varepsilon_n^B, \Phi_n^{*B}$
- Particles are produced by independent fragmentation of wounded nucleons, emission function f (η) not symmetric in η→ Wounded nucleon model

P. Huo Poster

(III) : flow longitudinal dynamics



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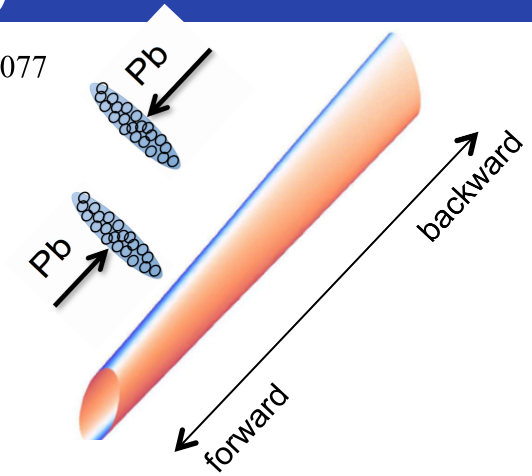


$$\varepsilon_n^F, \Phi_n^{*F} \neq \varepsilon_n^B, \Phi_n^{*B}$$

- Eccentricity vector interpolates between $\vec{\epsilon}_n^{F}$ and $\vec{\epsilon}_n^{B}$

$$\vec{\epsilon}_n^{tot}(\eta) \approx \alpha(\eta)\vec{\epsilon}_n^{F} + (1-\alpha(\eta))\vec{\epsilon}_n^{B} \equiv \epsilon_n^{tot}(\eta)e^{in\Phi_n^{*tot}(\eta)}$$

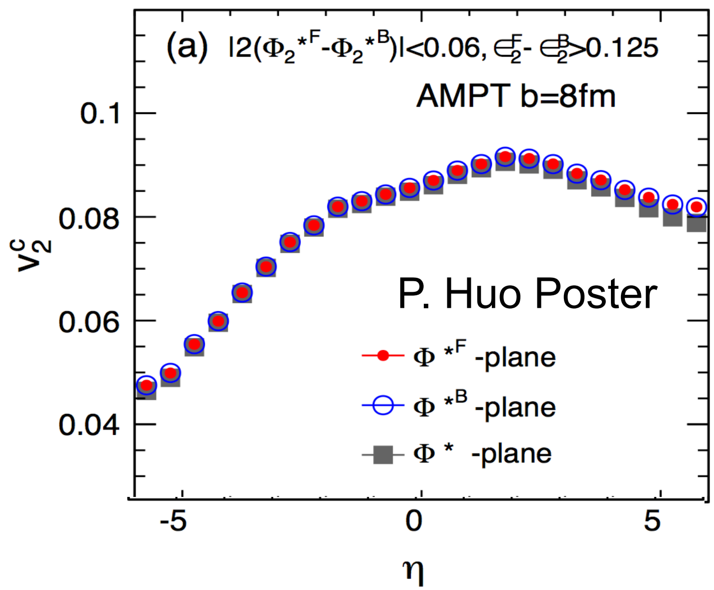
α(η) determined by f(η)

Asymmetry:	$\varepsilon_n^F \neq \varepsilon_n^B$
Twist:	$\Phi_n^{*F} \neq \Phi_n^{*B}$

- Hence $\vec{v}_n(\eta) \approx c_n(\eta)\left[\alpha(\eta)\vec{\epsilon}_n^{F} + (1-\alpha(\eta))\vec{\epsilon}_n^{B}\right]$ for n=2,3
  - Picture verified in AMPT simulations, magnitude estimated 1403.6077

P. Huo Poster

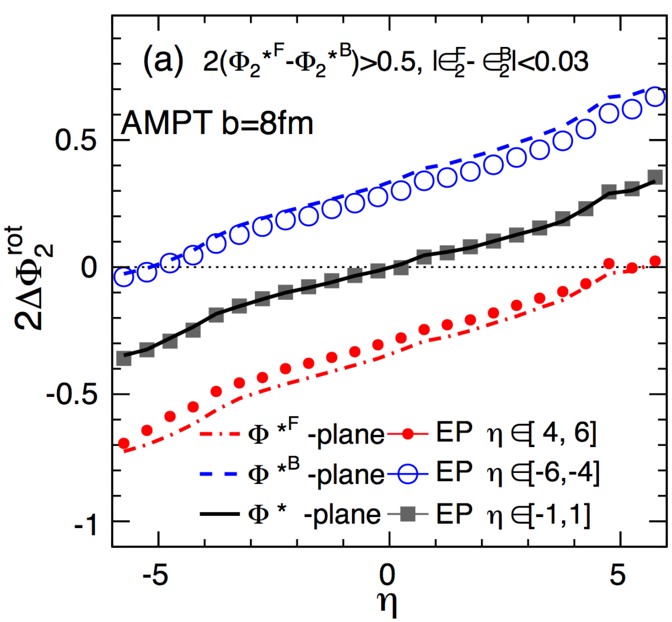
Require $\varepsilon_2^{F} > \varepsilon_2^{B}$ see $v_2(+\eta) > v_2(-\eta)$

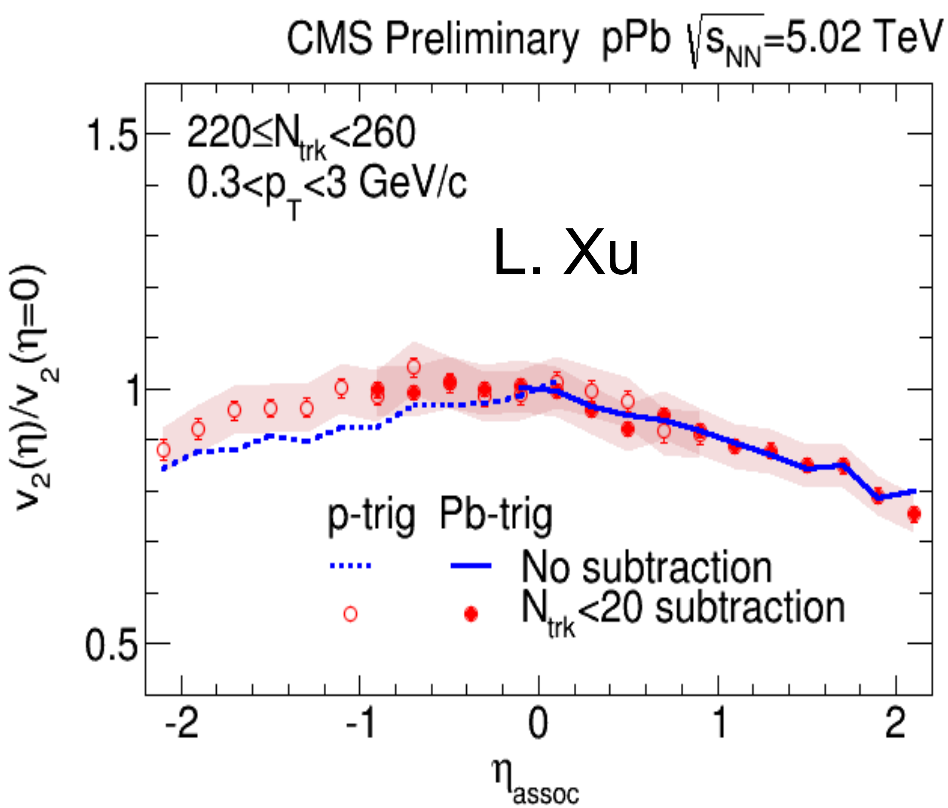


Initial state twist and asymmetry survives collective expansion

Play a bigger role for Cu+Au, U+U and p+A system

Require $\Phi_n^{*F} > \Phi_n^{*B}$ see $\Phi_2(+\eta) > \Phi_2(-\eta)$





Backup

Elliptic flow of identified particles

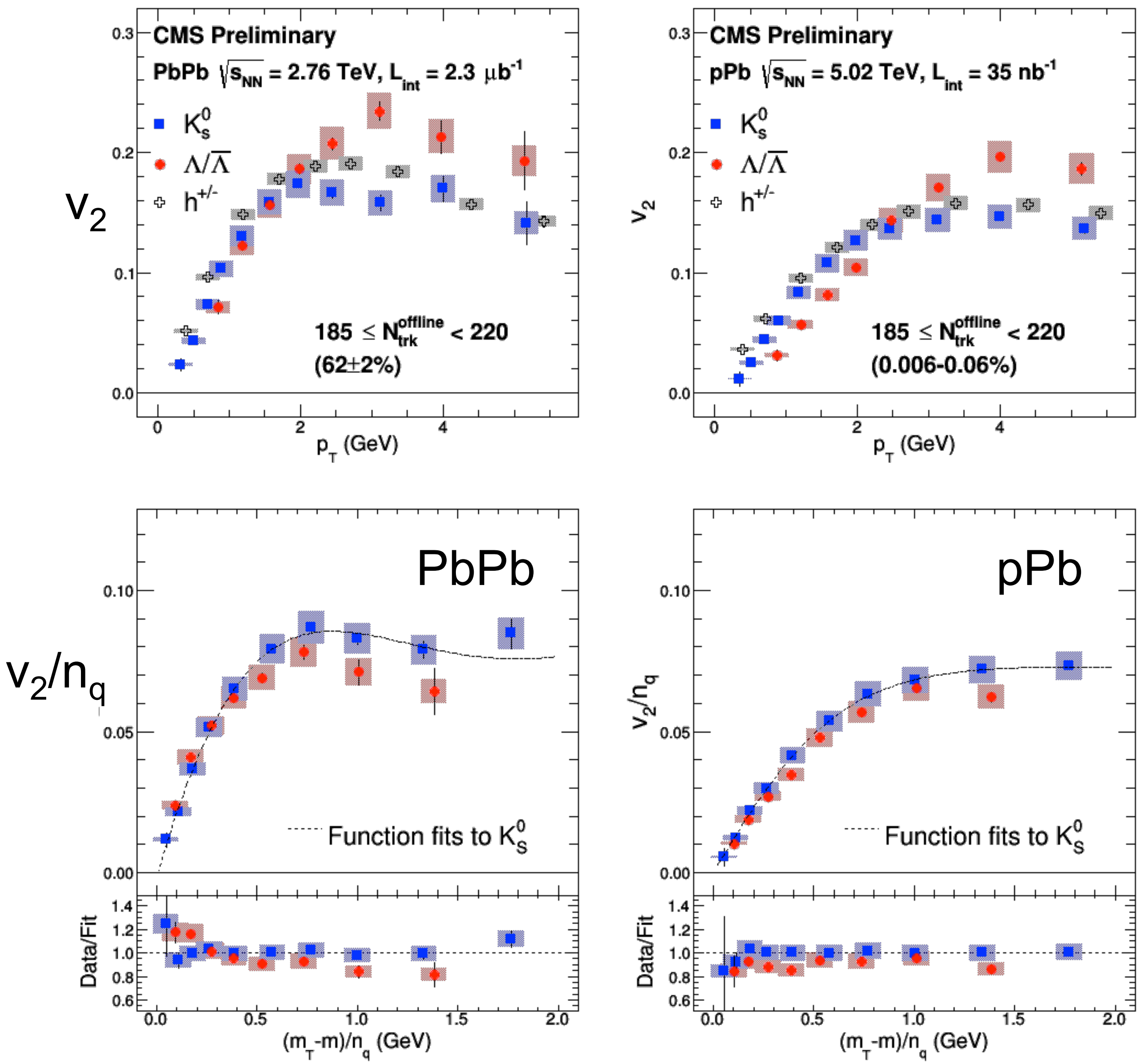
Identified K_S and Λ
& charged hadrons

v_2 (and v_3) from
2-particle correlations

show mass ordering
In pPb and PbPb
(stronger in pPb)

and ≈ quark scaling
(better in pPb)

Talk by Sharma
Poster by Chen
PAS-HIN-14-002



Linear and non-linearity example

- Hadrons freezeout from exponential distribution of the flow field

$$E\frac{d^3N}{d^3\vec{p}} \approx \frac{g}{(2\pi)^3}\int_{\Sigma} \exp(-\frac{p\cdot u(x)}{T})p\cdot d^3\sigma(x)$$

- Flow field u(x) has a harmonic modulation driven by geometry

$$u(\phi) = u_0(1+2\sum \beta_n \cos(\phi - \Phi_n))$$

- Quadratic term in saddle-point expansion leads to mode-mixing

$$e^{-p_{\rm T}u(\phi)} \approx 1 - p_{\rm T}u(\phi) + 1/2p_{\rm T}^2u^2(\phi)...$$

Borghini, Ollitrault 2005
Teaney, Yan 2012
Lang, Borghini 2013

$$I(p_t) \equiv \frac{\bar{u}_{\rm max}}{T}(p_t - m_t\bar{\rm v}_{\rm max})$$

$$v_2(p_{\rm T}) \approx I(p_{\rm T})\beta_2, v_3(p_{\rm T}) \approx I(p_{\rm T})\beta_3$$

$$v_4(p_{\rm T}) \approx I(p_{\rm T})\beta_4 + \frac{I(p_{\rm T})^2}{2}\beta_2^2 \longrightarrow v_2^2$$

$$v_5(p_{\rm T}) \approx I(p_{\rm T})\beta_5 + I(p_{\rm T})^2\beta_2\beta_3 \longrightarrow v_2v_3$$

$$v_6(p_{\rm T}) \approx I(p_{\rm T})\beta_6 + \frac{I(p_{\rm T})^3}{6}\beta_2^3 + \frac{I(p_{\rm T})^2}{2}\beta_3^2 + I(p_{\rm T})^2\beta_2\beta_4$$

v_2^3 , v_2^2, v_2v_4

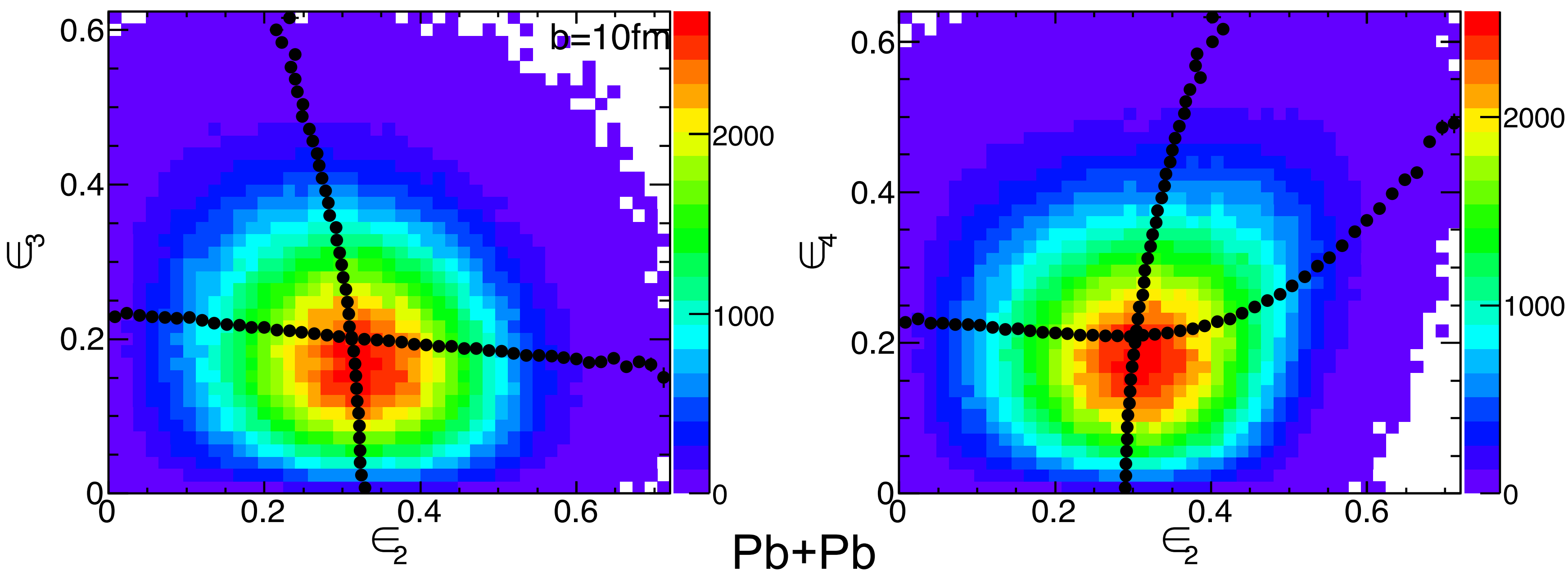
$p(v_m,v_n)$ or v_m-v_n correlations

- Evolution of v_n correlated with v_m via
  - Non-linearities from hydro evolution and freeze-out
  - But also initial correlation

See also talk by S. Floerchinger

anti-correlation between ε_2 and ε_3.

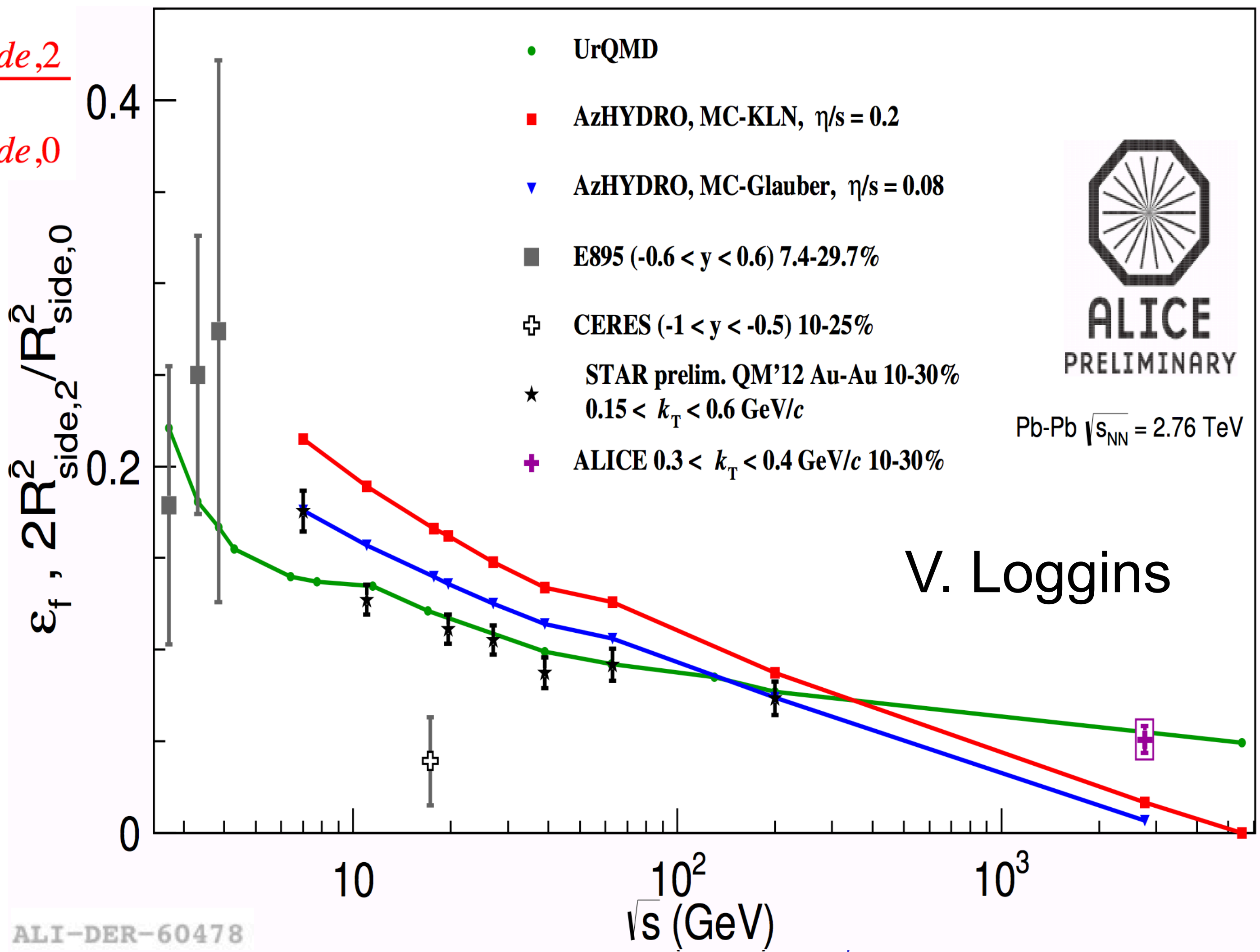
positive-correlation between ε_2 and ε_4.



- Naturally studied via event-shape selection technique
  - E.g. select events with different v_2 and study v_n. in FIXED centrality

√s dependence of final spatial eccentricity

$$\varepsilon_f \approx 2\frac{R^2_{side,2}}{R^2_{side,0}}$$



- Gradual decrease of ε_f as function of √s.
  - Hydro predicts stronger decrease,
  - UrQMD works but it probably under-predicts the flow.

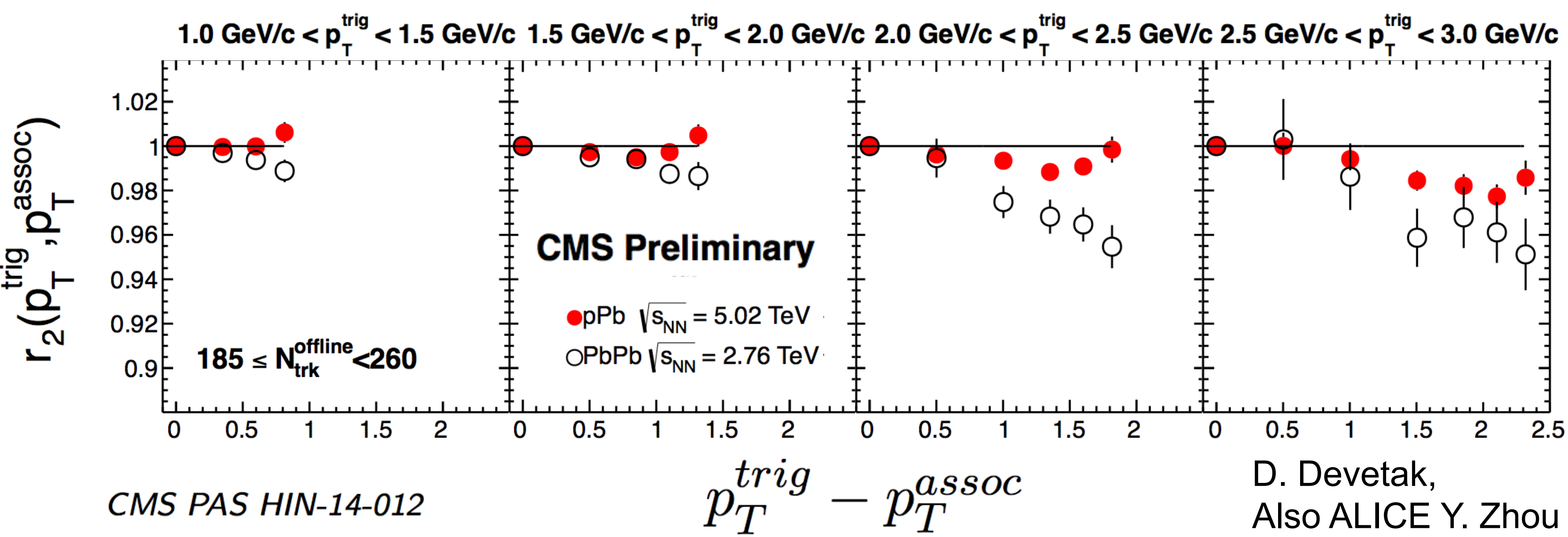
Intra-event flow fluctuation and factorization

- Flow angle and amplitude fluctuates in p_T (and η)

Ollitrault QM2012

$$\tilde{r}_n(p_{T1}, p_{T2}) := \frac{\langle v_n(p_{T1}) v_n(p_{T2}) \cos[n(\Psi_n(p_{T1}) - \Psi_n(p_{T2}))]\rangle}{\langle v_n(p_{T1}) v_n(p_{T2})\rangle}$$

- Breaking is largest for v_2 in ultra-central Pb+Pb collisions
- Much smaller for other harmonics and in other centralities
- Very small (2-3%) breaking for high-multiplicity pPb collisions
  - Be aware of non-flow bias from di-jets, recoil subtraction is necessary in



CMS PAS HIN-14-012

D. Devetak,
Also ALICE Y. Zhou

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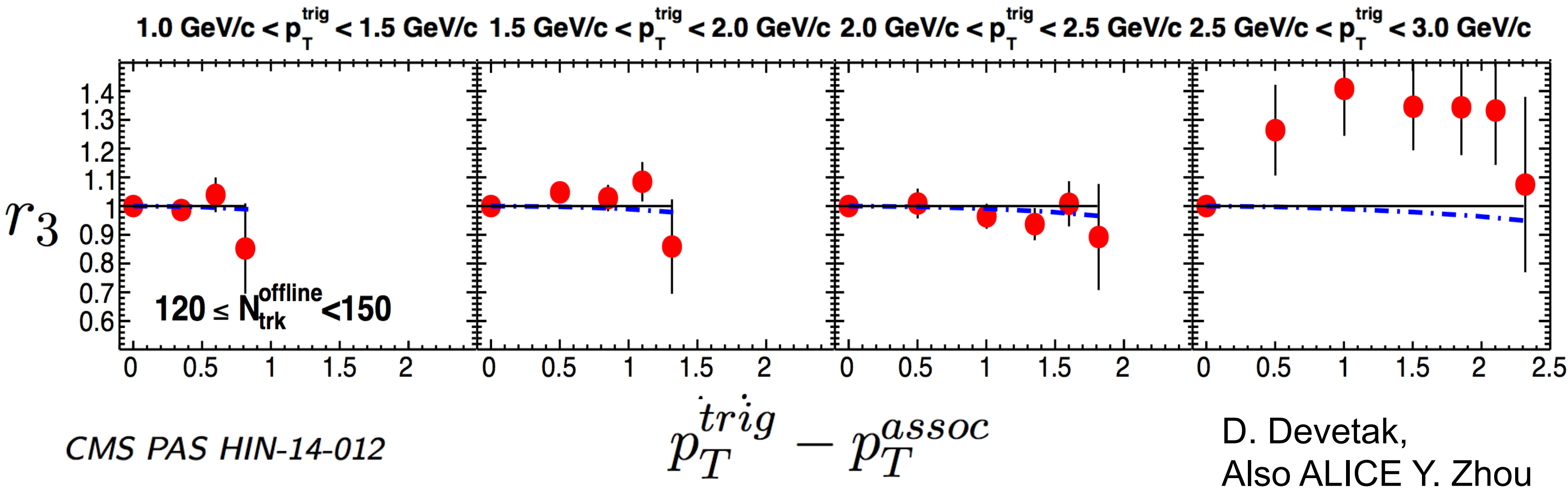
  - Be aware of non-flow bias from di-jets, recoil subtraction is necessary in order to compare with theory

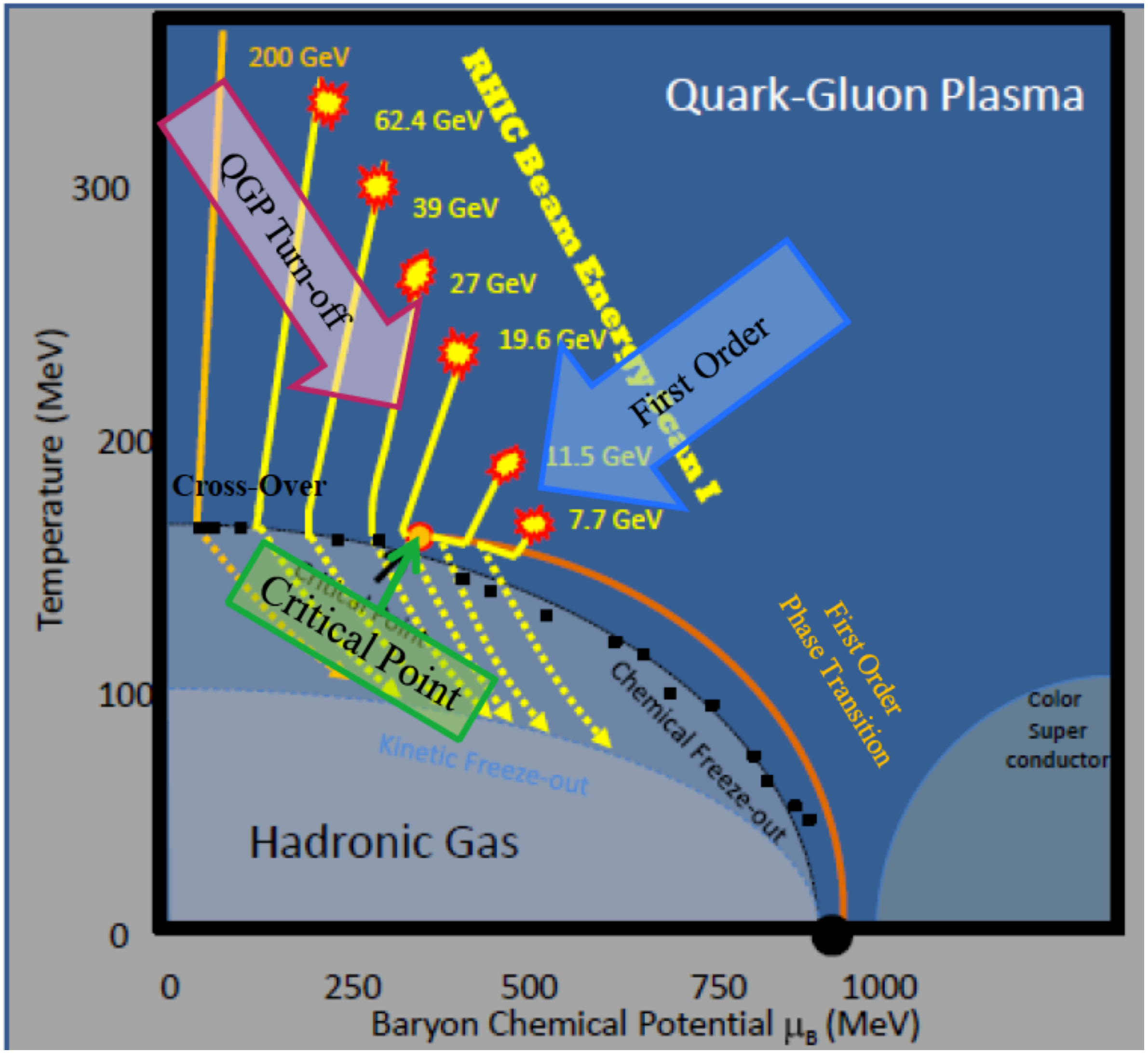
Kozlov et.al.:arXiv:1405.3976



CMS PAS HIN-14-012

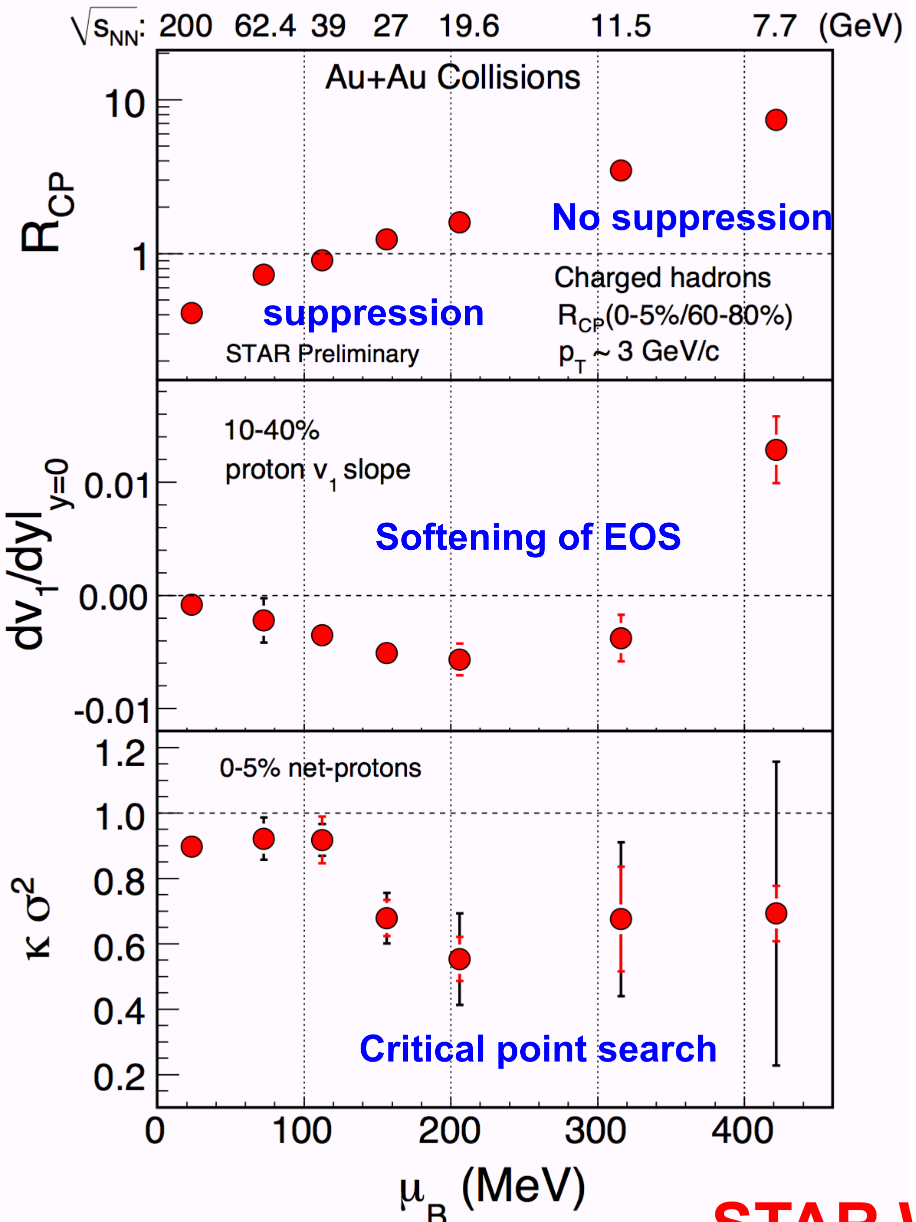
D. Devetak,
Also ALICE Y. Zhou

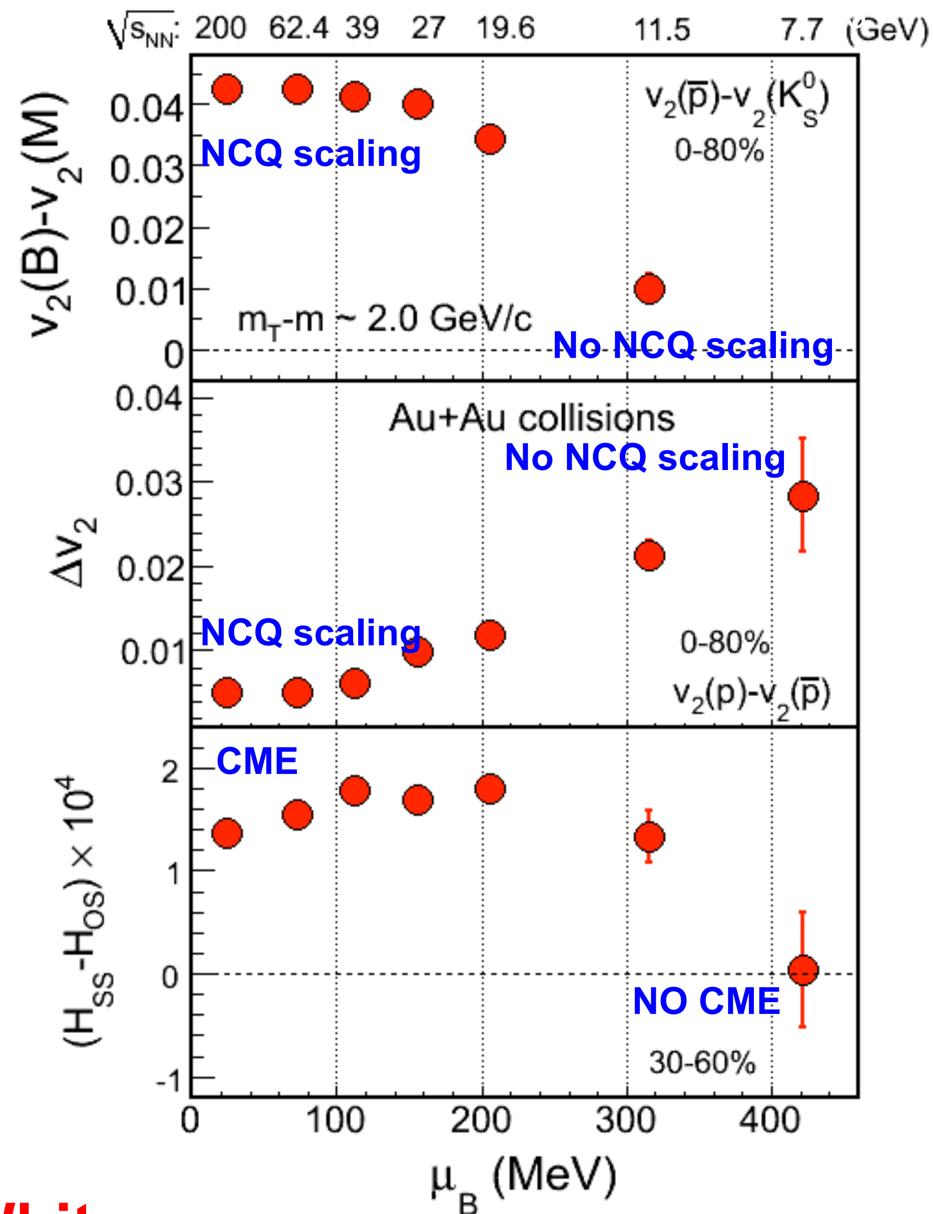
Beam Energy scan: search for CEP



- Looking for non-monotonic change with $\sqrt{s}$

Looking for non-monotonic change with √s





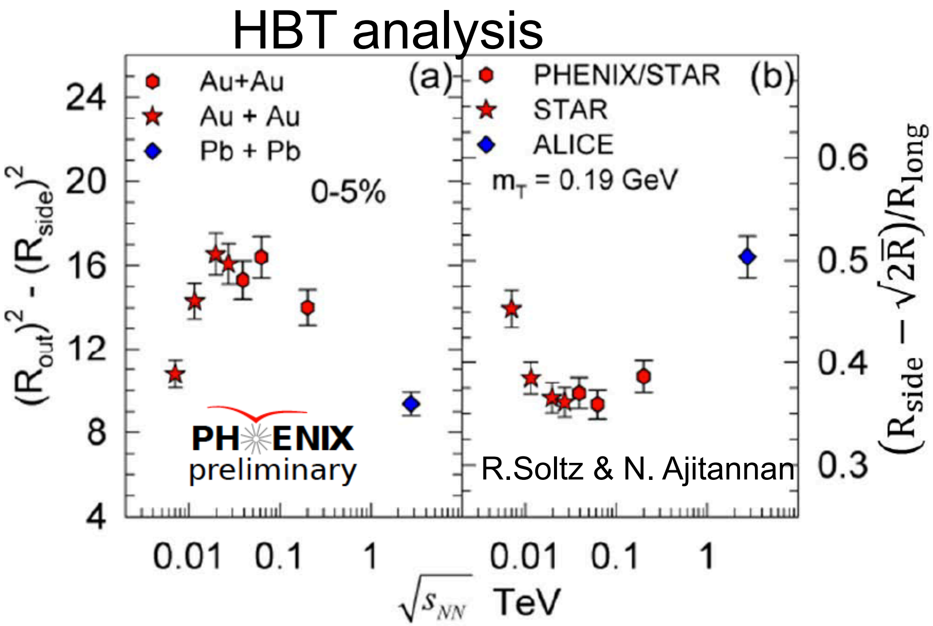
G. Wang & B. Mohanty

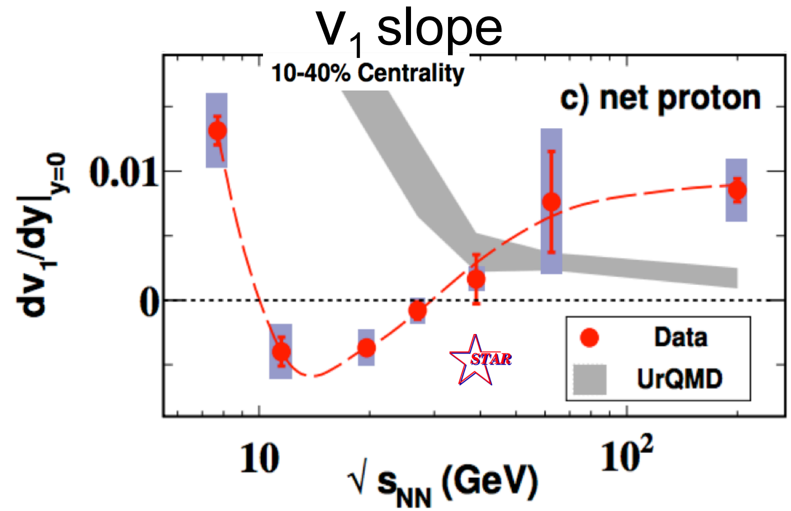
STAR White paper

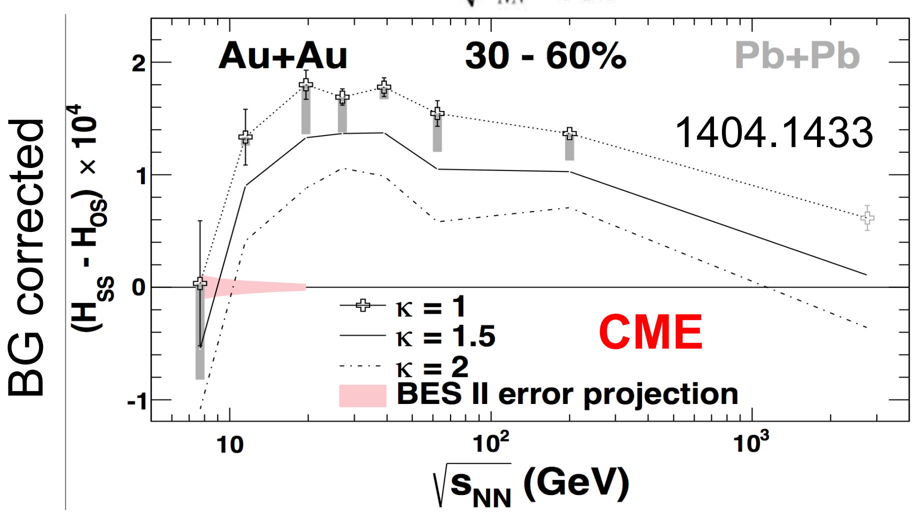
Caveat: qualitative picture

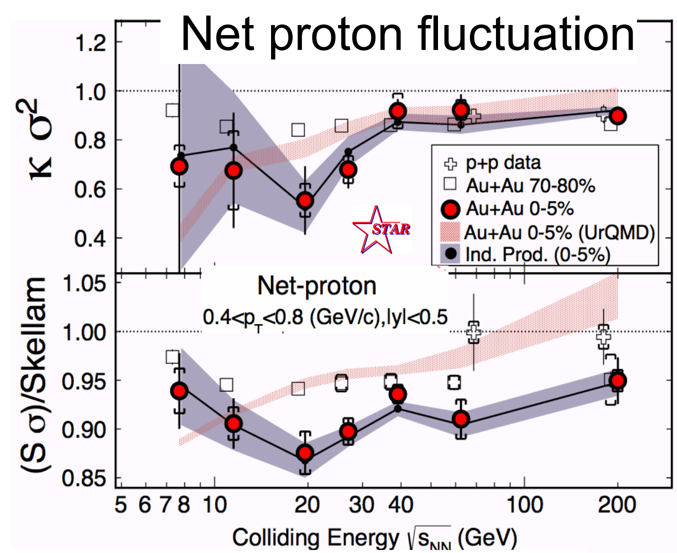
Looking for non-monotonic change with √s

- Shallow dips observed at ~ 10-20 GeV for several observables









More refined measurements with BES II and theory input!!