Experimental results on collective flow and correlation at RHIC and LHC

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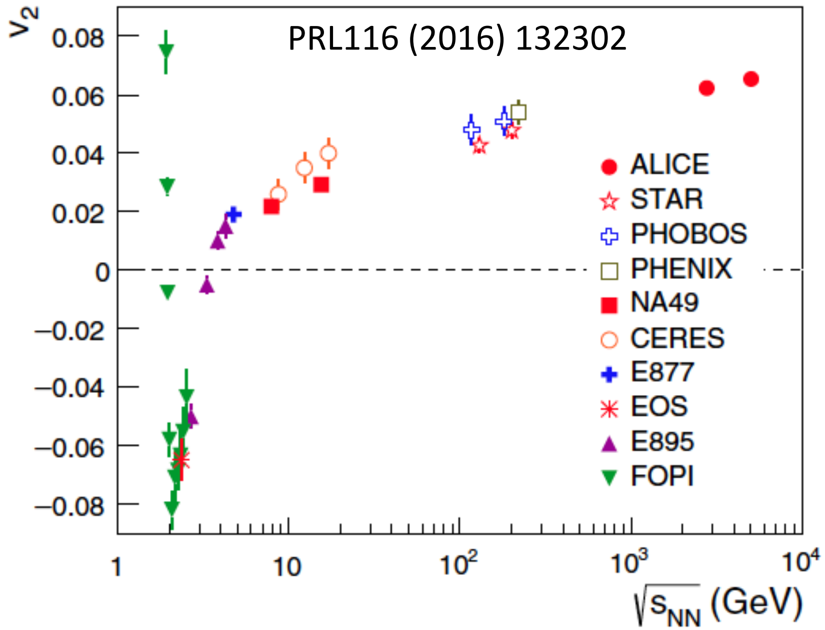
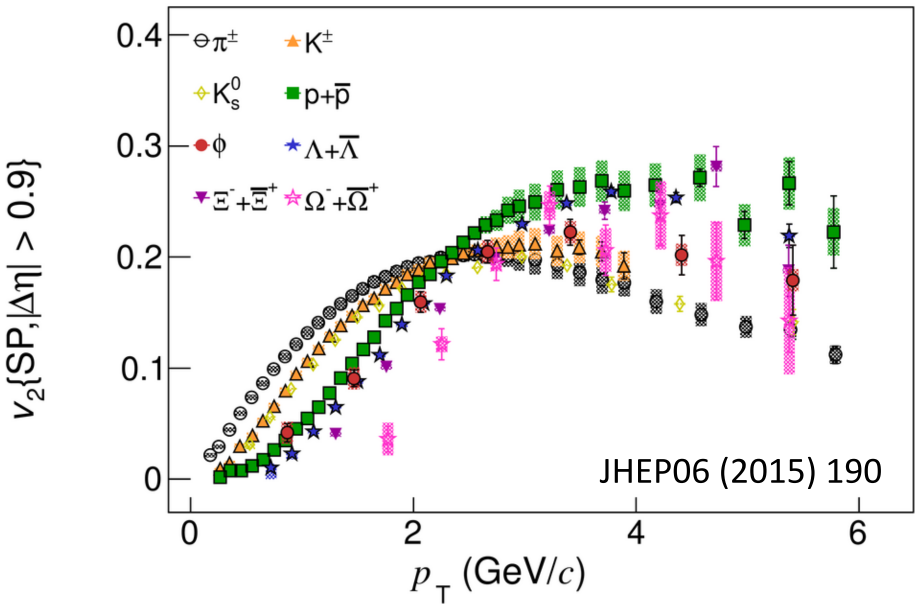
Contents

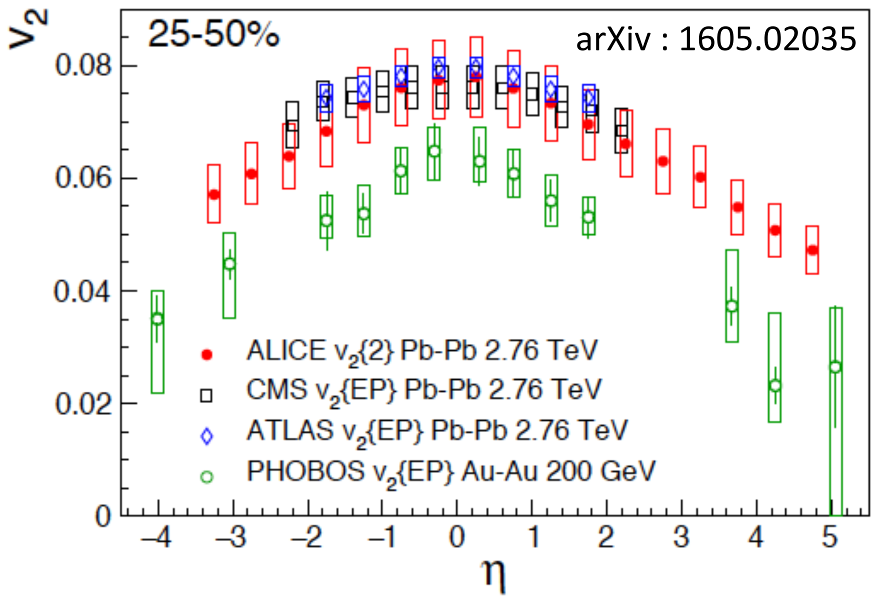
- Flow and fluctuation in AA
- Flow in small systems; pp, pA, dA…
- From partonic to hadronic world

Elliptic flow

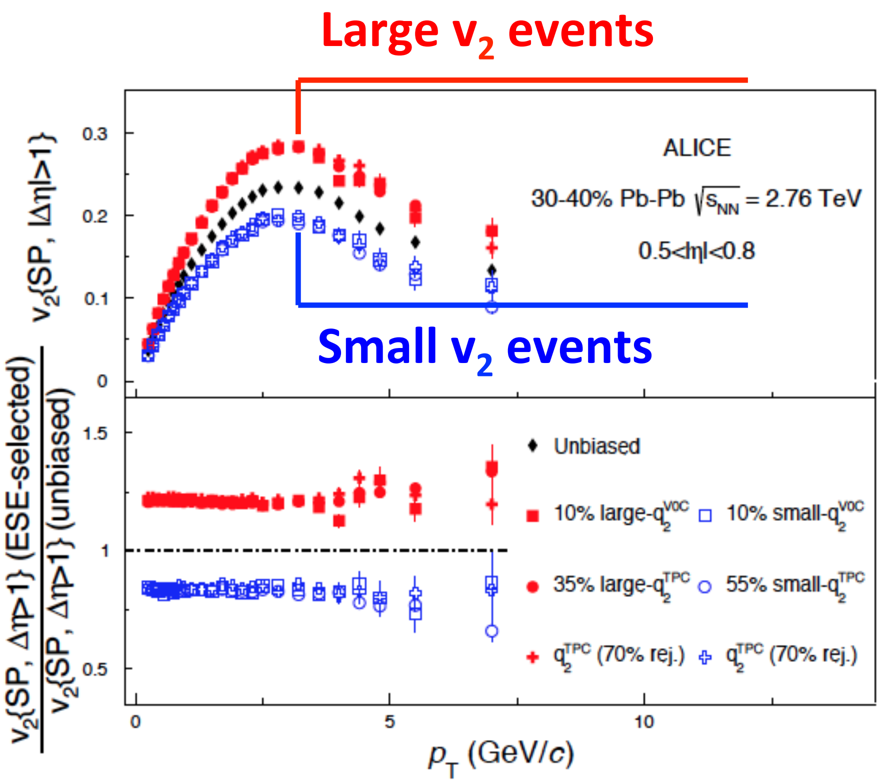
- Mass dependence
- Baryon/Meson
- p_T, rapidity dependence
- Beam energy dependence



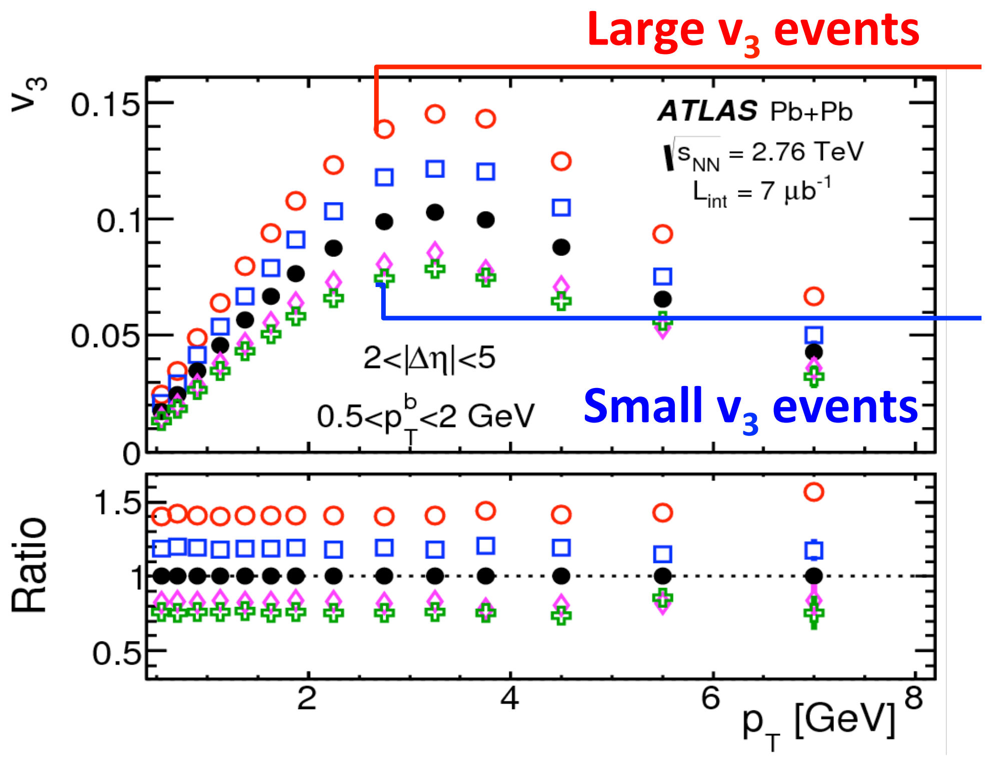




Event Shape Engineering (ESE), Event Shape Selection
--- for a given centrality ---



PRC93 (2016) 034916

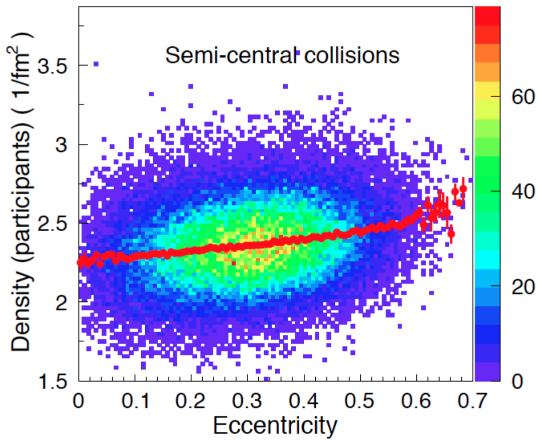


PRC92 (2015) 034903

flat p_T dependence -> indicative for an initial geometry

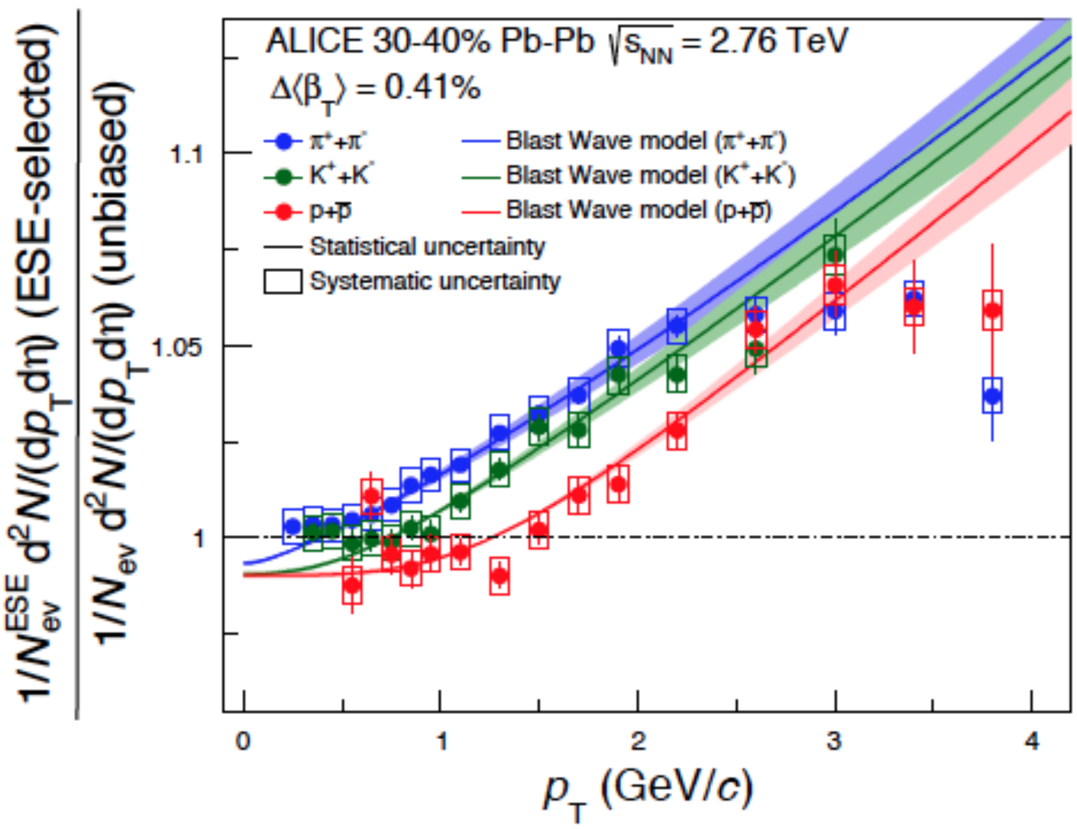
Applications of ESE

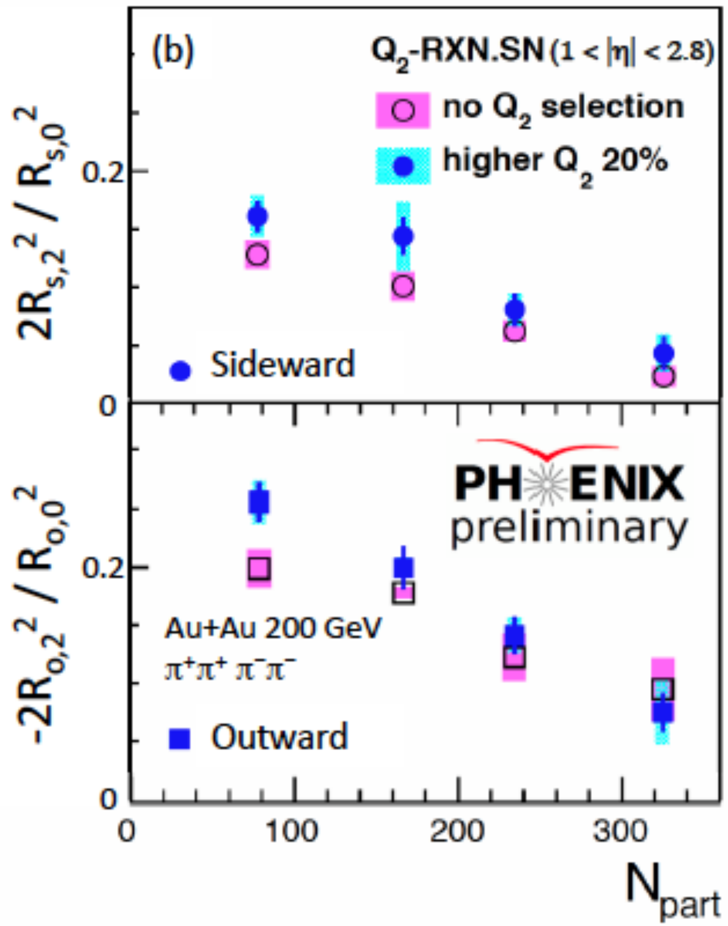
- **correlation between radial (β_T) and elliptic (v_2) flows**
- **correlation between HBT eccentricity (ε_2^{final}) and v_2**



PHENIX, QM14

PRC93 (2016) 034916





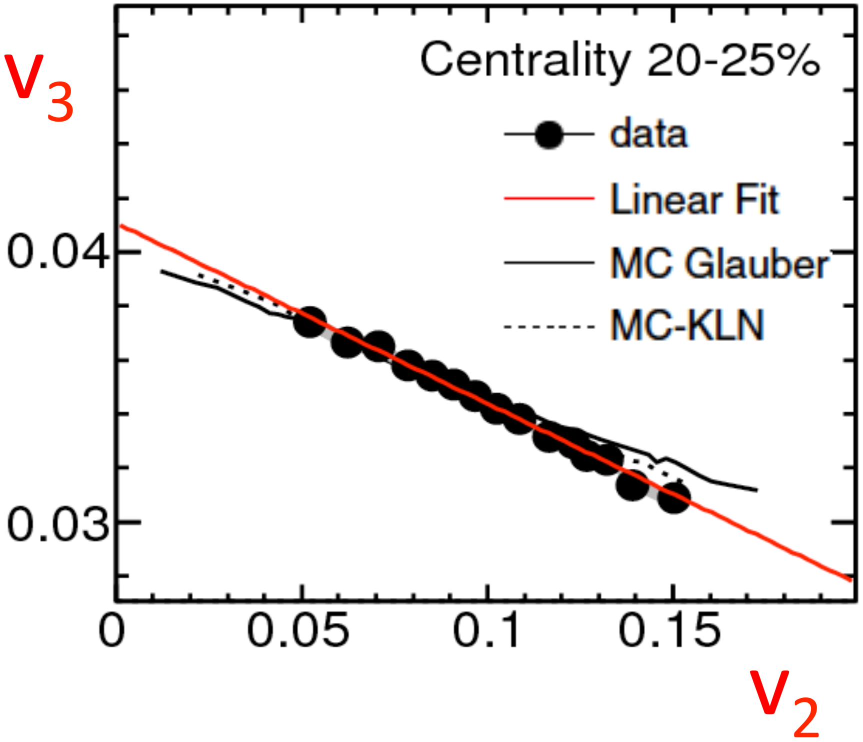
$$\langle\langle \cos(m\varphi_1 + n\varphi_2 - m\varphi_3 - n\varphi_4)\rangle\rangle_c = \langle\langle \cos(m\varphi_1 + n\varphi_2 - m\varphi_3 - n\varphi_4)\rangle\rangle - \langle\langle \cos[m(\varphi_1 - \varphi_2)]\rangle\rangle \langle\langle \cos[n(\varphi_1 - \varphi_2)]\rangle\rangle = \langle v_m^2 v_n^2\rangle - \langle v_m^2\rangle \langle v_n^2\rangle ,$$

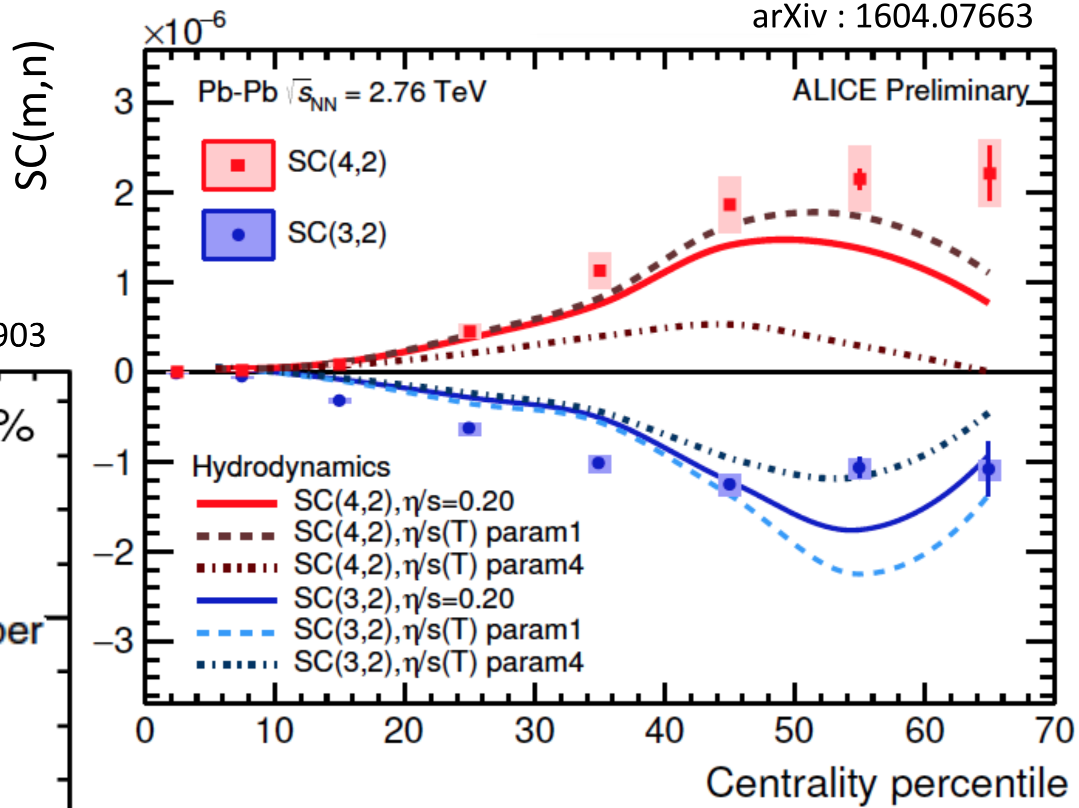
SC(m,n)

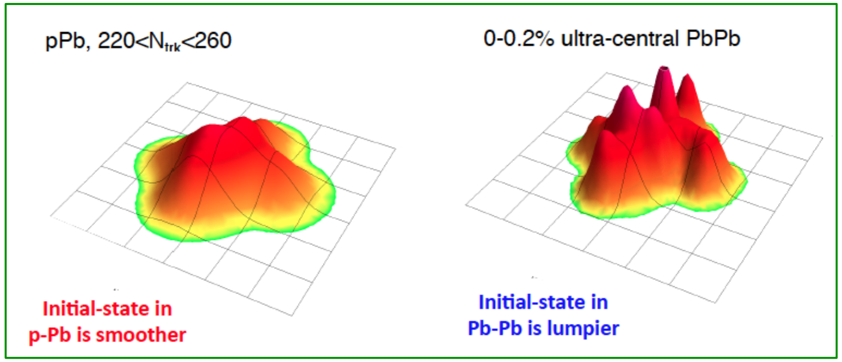
arXiv : 1604.07663

Correlation between different harmonics

PRC92 (2015) 034903







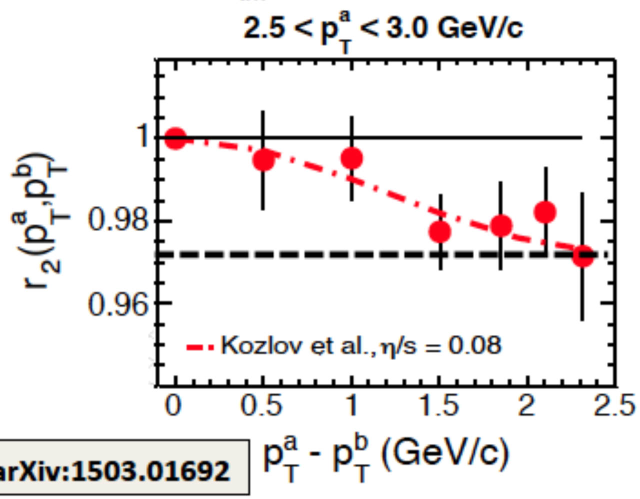
p_T dependent event plane fluctuation (breaking of factorization)

Due to EP $\Psi_n(p_T)$ caused by lumpy initial state:

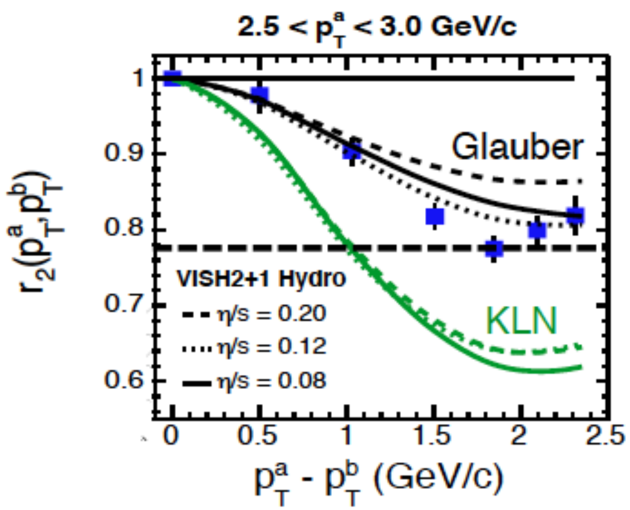
$$V_{n\Delta}(p_T^a, p_T^b) \neq v_n(p_T^a) \times v_n(p_T^b)$$

$$r_n(p_T^a, p_T^b) \equiv \frac{V_{n\Delta}(p_T^a, p_T^b)}{\sqrt{V_{n\Delta}(p_T^a, p_T^a)}\sqrt{V_{n\Delta}(p_T^b, p_T^b)}} \sim \langle cos\left[n(\Psi_n(p_T^a) - \Psi_n(p_T^b))\right]\rangle$$

pPb, 220<N_{trk}<260



0-0.2% ultra-central PbPb

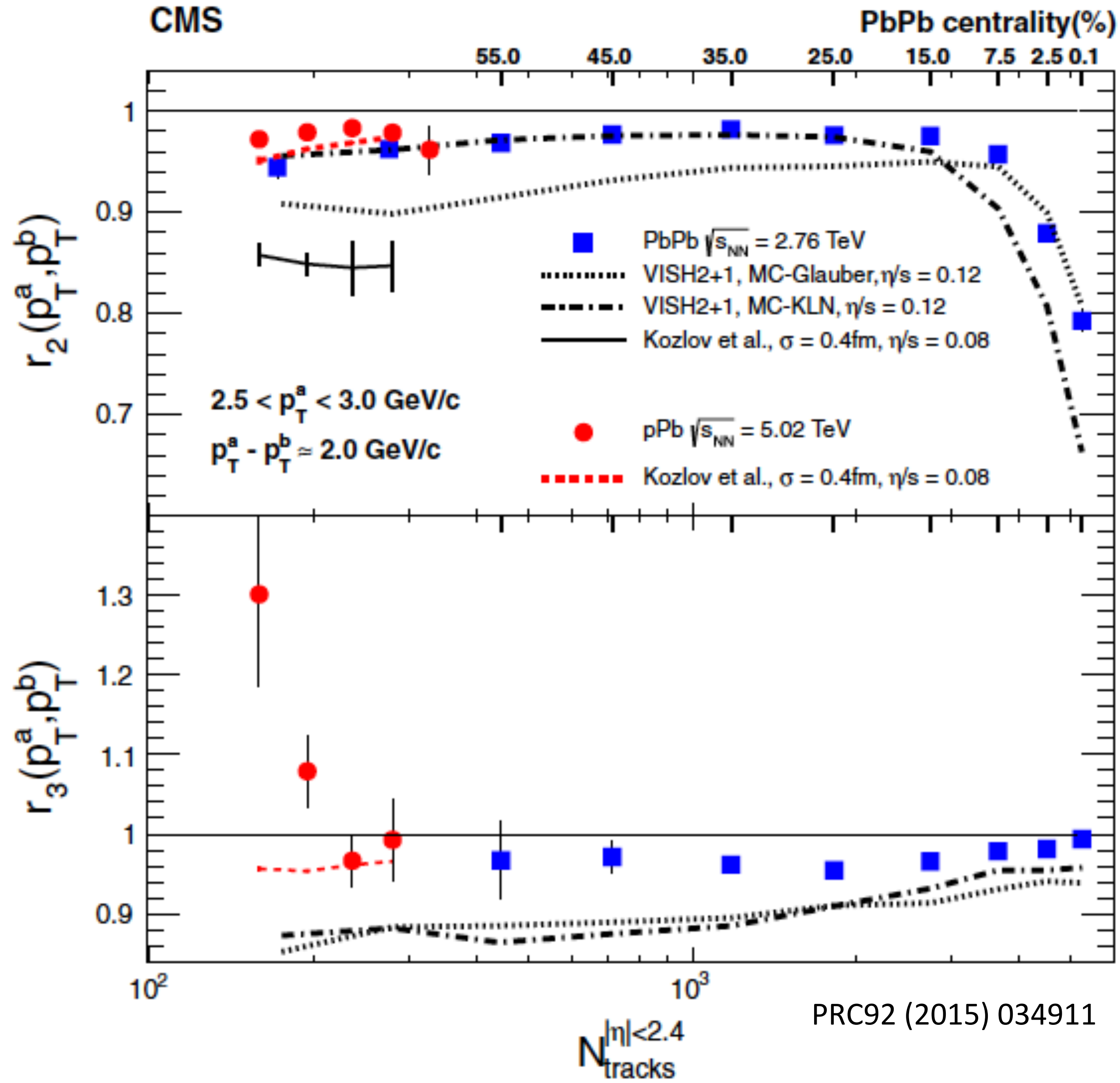


arXiv:1503.01692

|Δη|>2

CMS, QM15

breaking of factorization



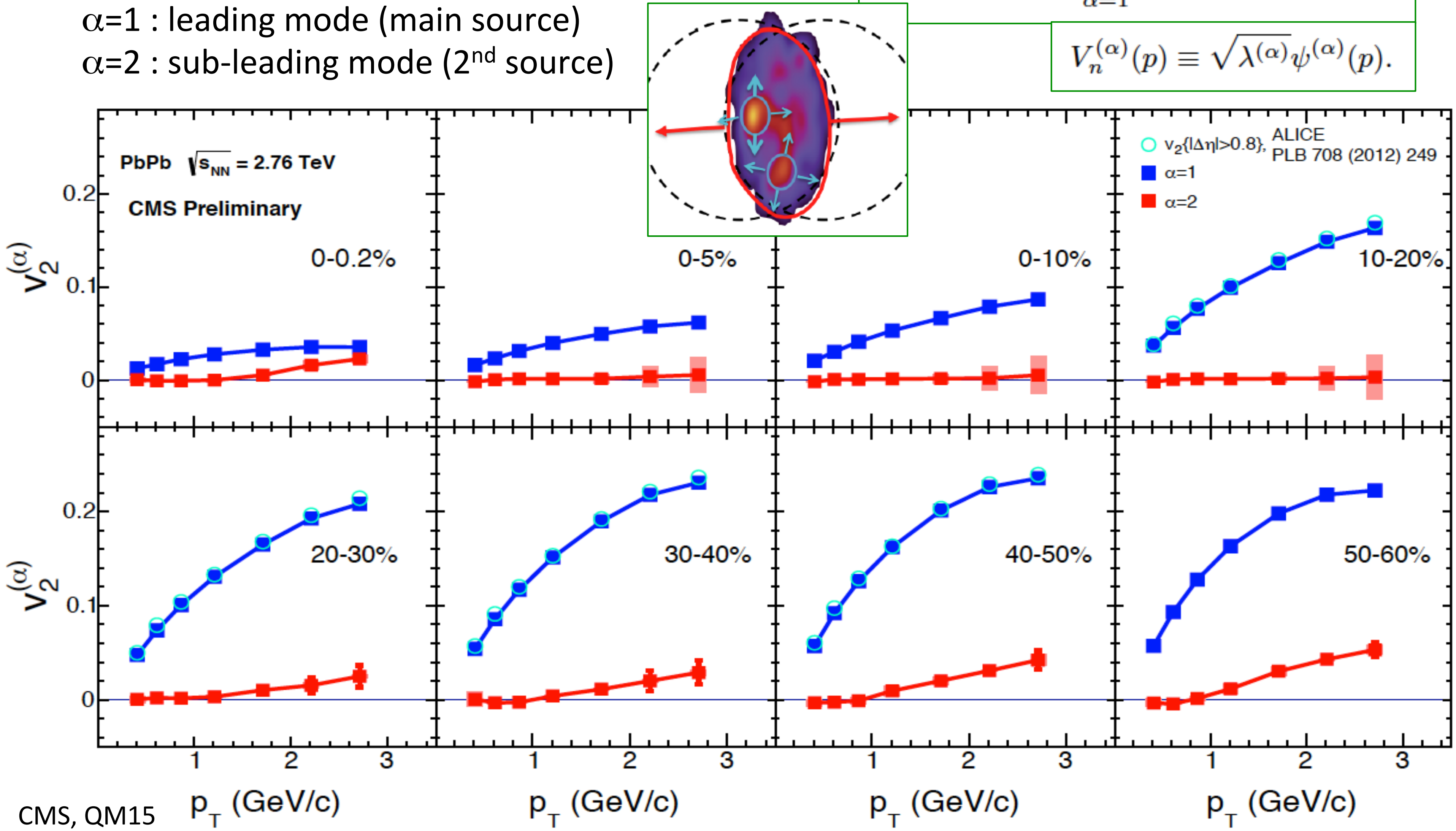
PRC92 (2015) 034911

Principle Component Analysis in v_2

$$V_{n\Delta}(p_1,p_2) \approx \sum_{\alpha=1}^{k} V_n^{(\alpha)}(p_1)V_n^{(\alpha)*}(p_2),$$

$$V_n^{(\alpha)}(p) \equiv \sqrt{\lambda^{(\alpha)}}\psi^{(\alpha)}(p).$$

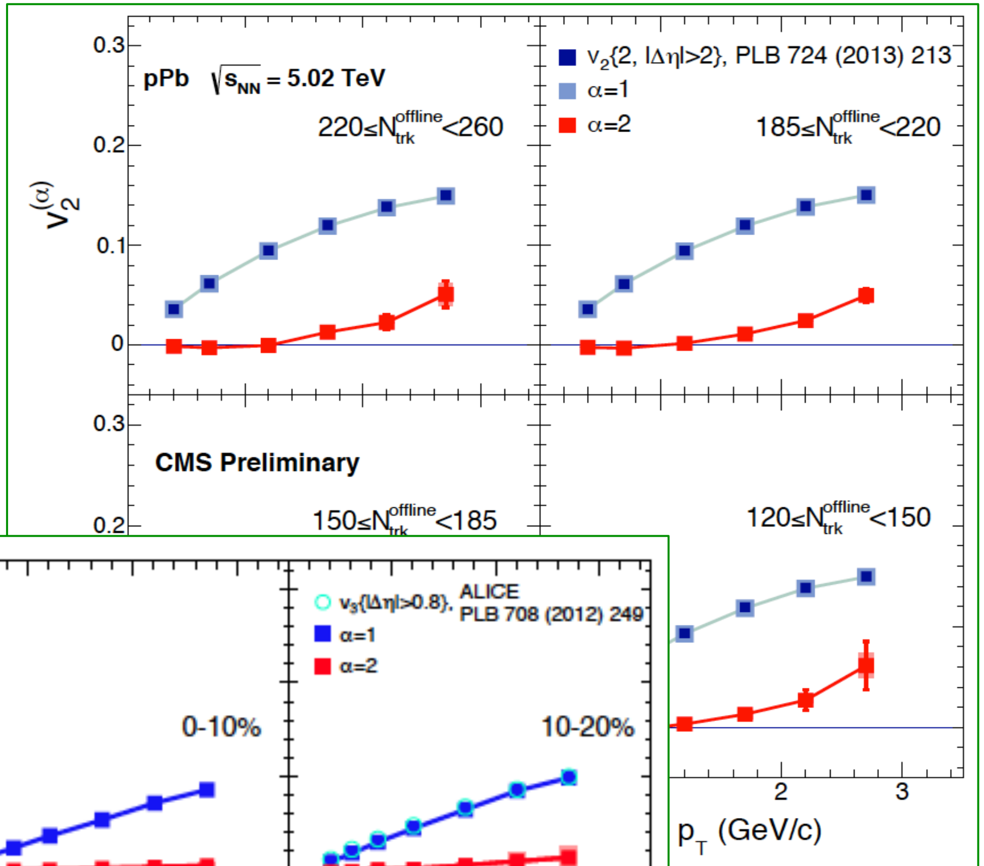
α=1 : leading mode (main source)
α=2 : sub-leading mode (2nd source)

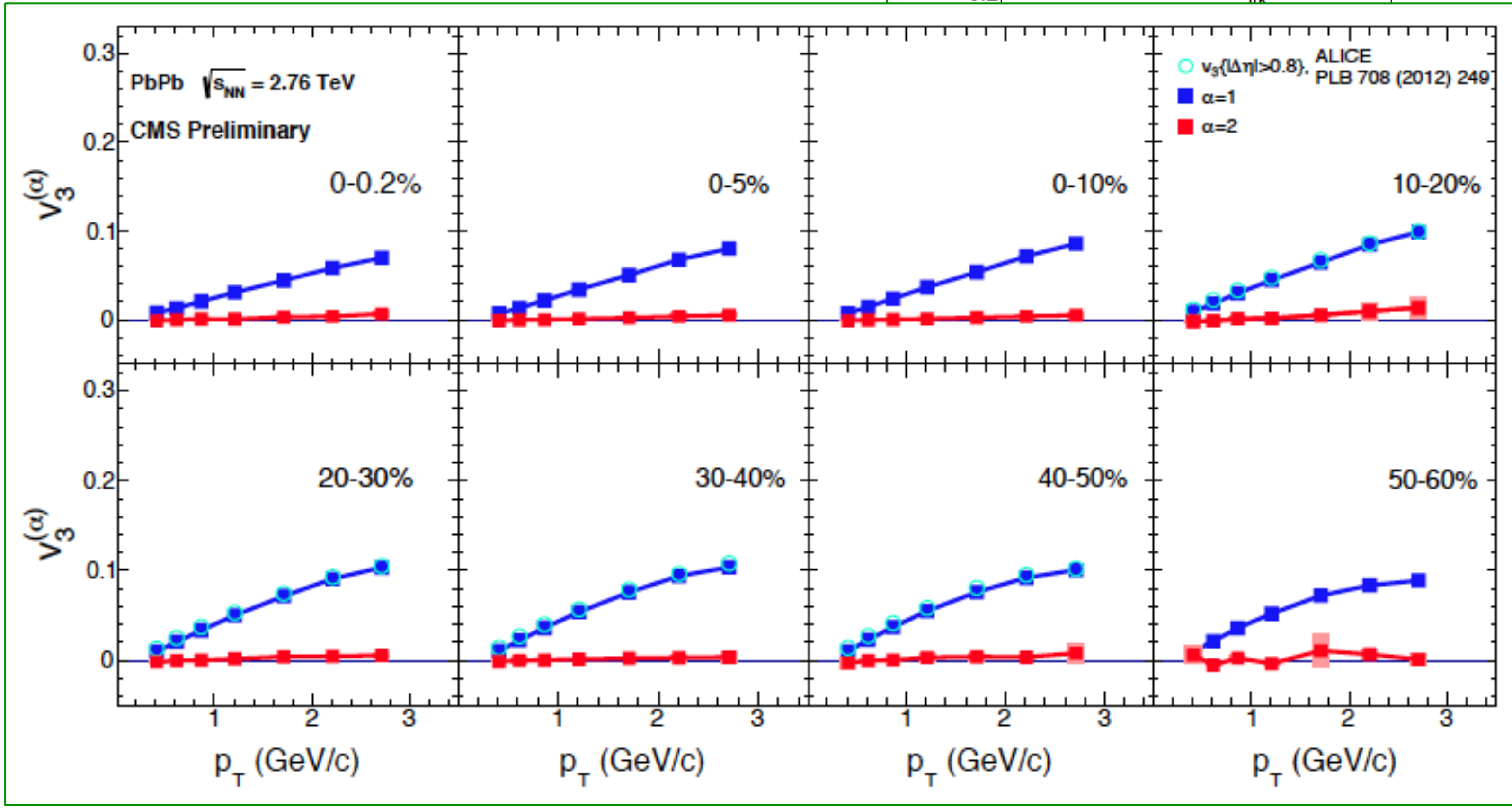


CMS, QM15

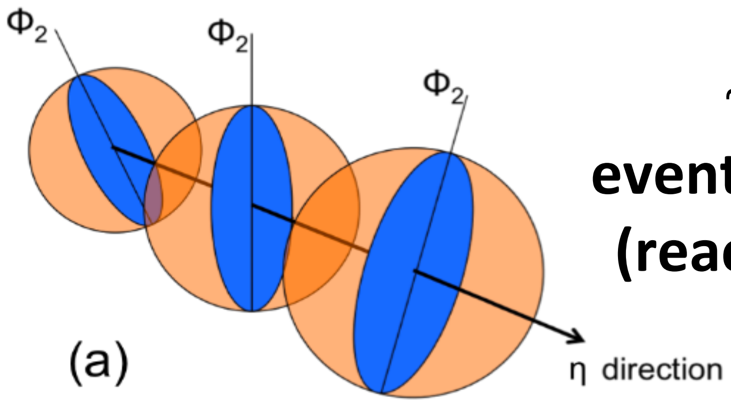
p+Pb : similar sub-leading mode in v_2 as peripheral Pb+Pb

Pb+Pb : (better factorization in v_3) small sub-leading mode in v_3

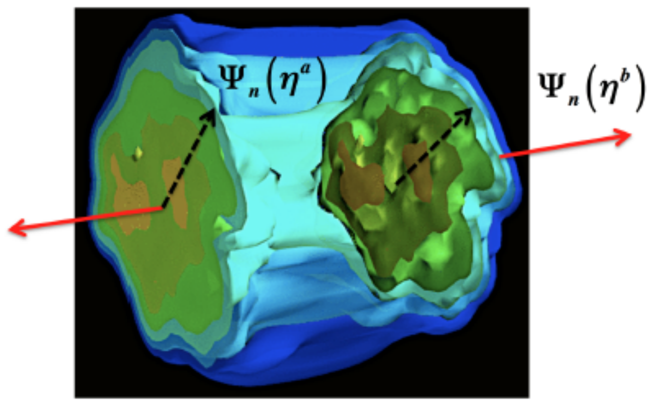




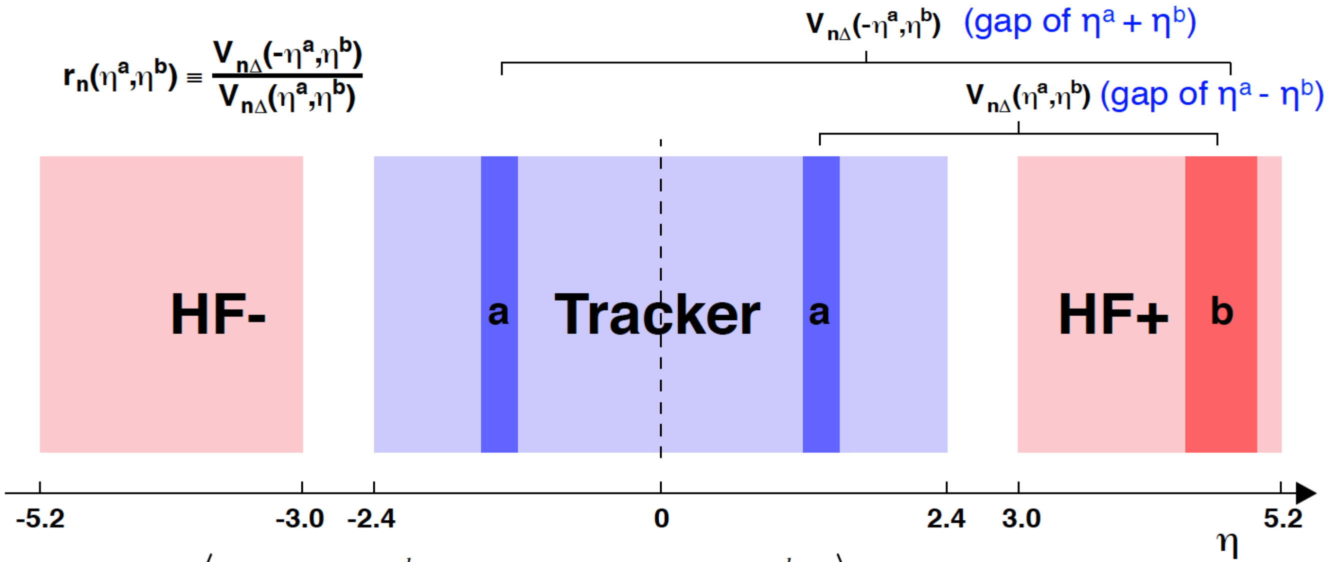
CMS, QM15



η dependent event plane fluctuation (reaction plane twist)



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

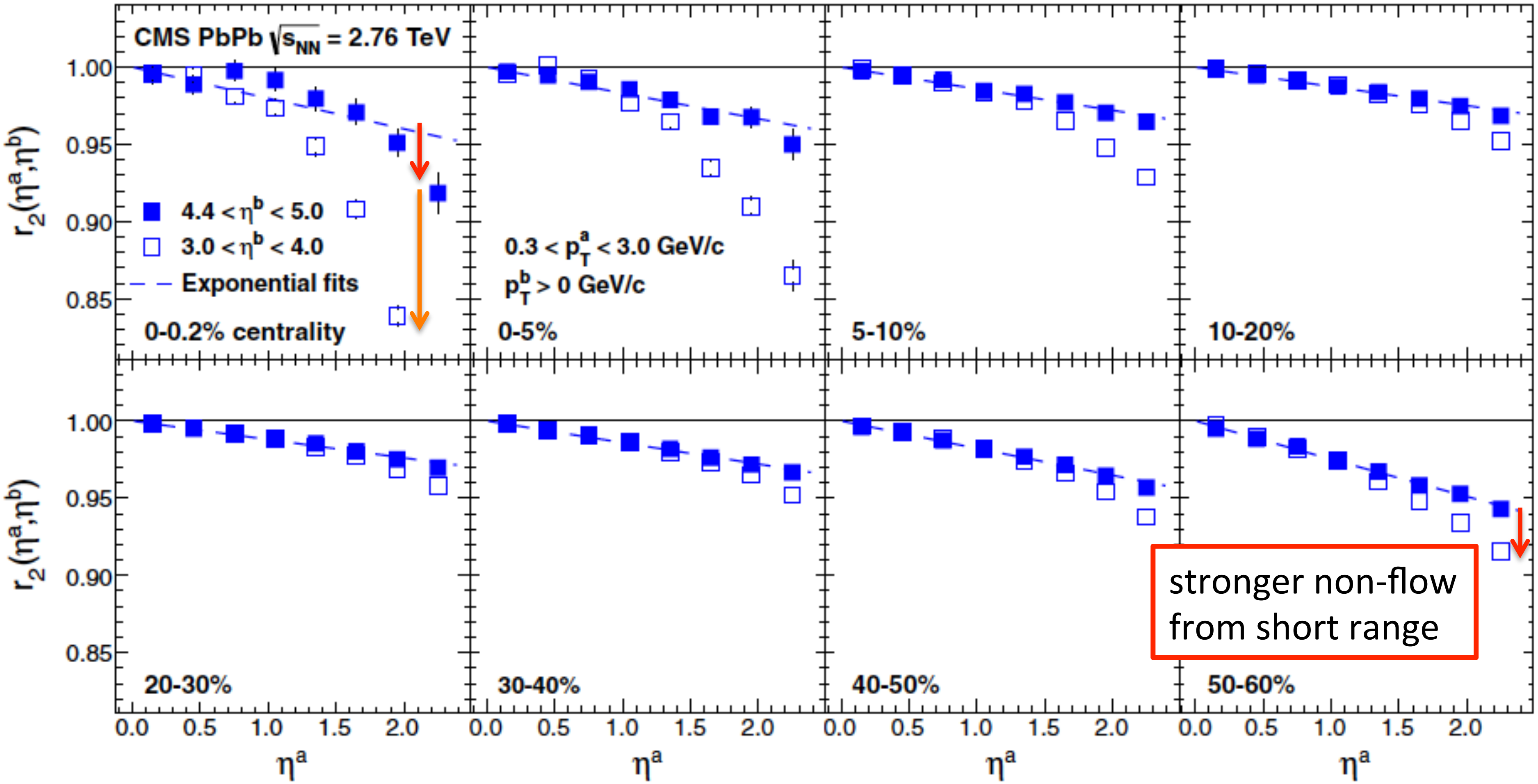


$$r_n(\eta^a,\eta^b)=\frac{\langle v_n(-\eta^a)v_n(\eta^b)\cos[n(\Psi_n(-\eta^a)-\Psi_n(\eta^b))]\rangle}{\langle v_n(\eta^a)v_n(\eta^b)\cos[n(\Psi_n(\eta^a)-\Psi_n(\eta^b))]\rangle}\sim\langle\cos[n(\Psi_n(\eta^a)-\Psi_n(-\eta^a))]\rangle$$

CMS, QM15

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

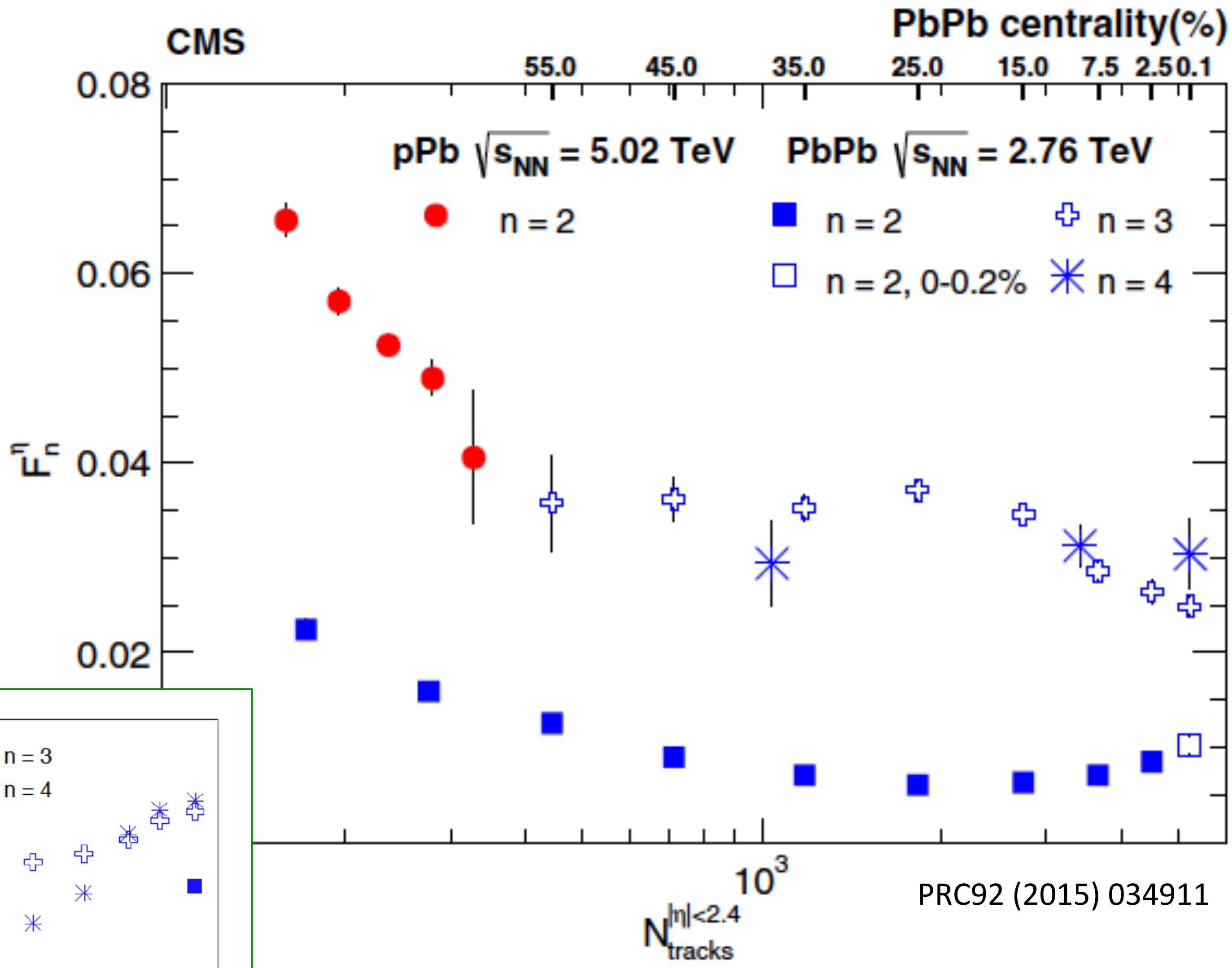
PRC92 (2015) 034911



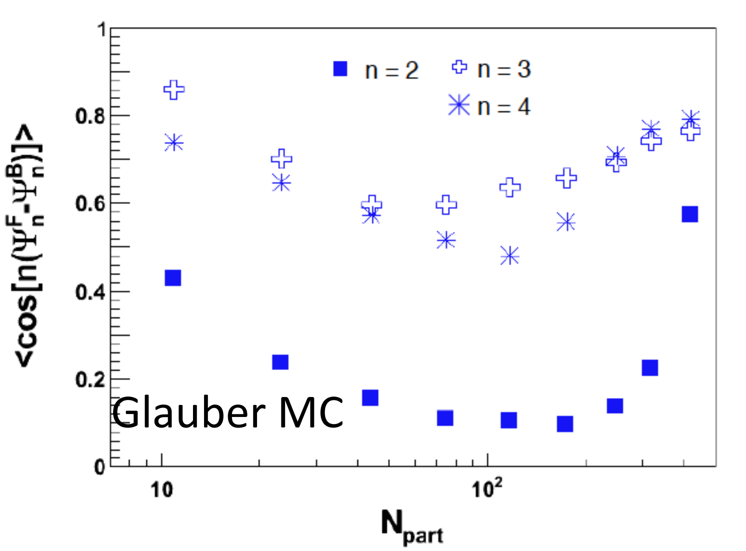
$$r_n(\eta^a, \eta^b) = e^{-2F_n^\eta \eta^a} \sim 1 - 2F_n^\eta \eta^a$$

extract : F_n^η

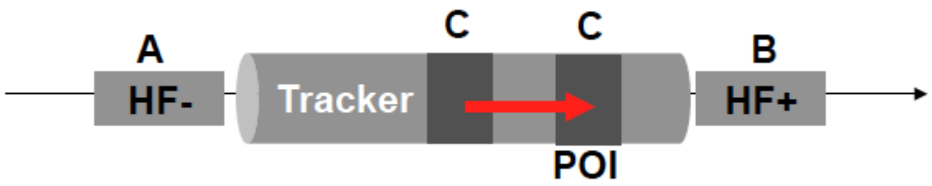
Extracted F_n^{η} Parameter



PRC92 (2015) 034911



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



POI :
particle of interest

➢ Decorrelation effects [arXiv:1503.01692]

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

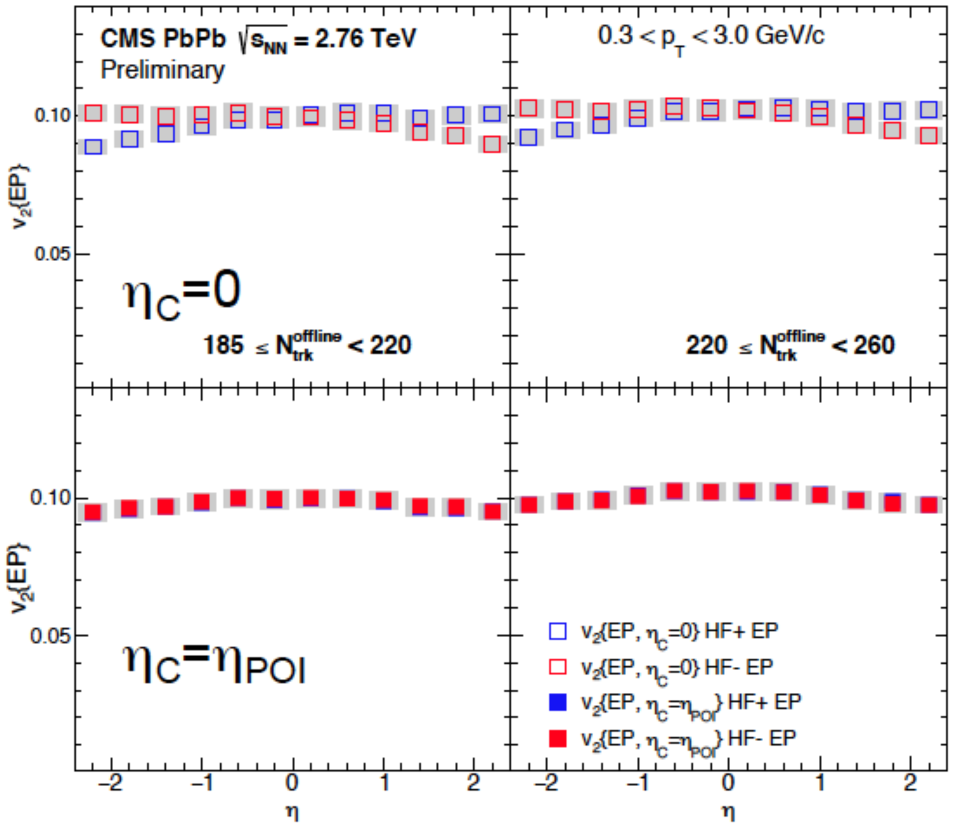
$(\eta_C=0)$

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

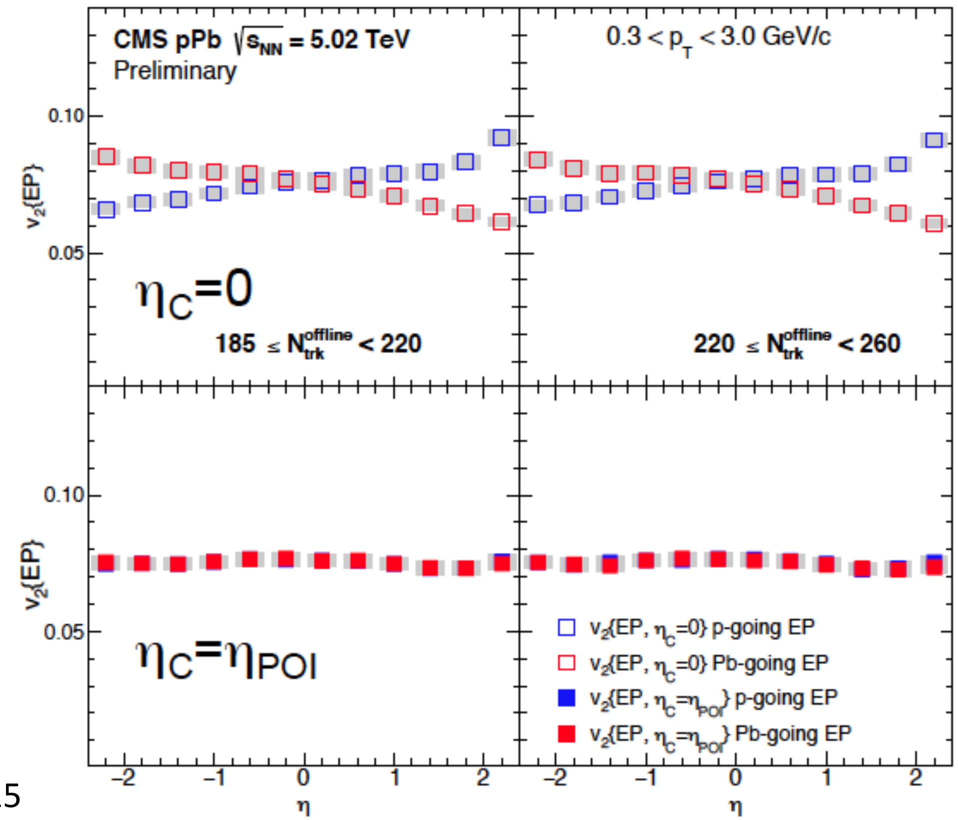
$(\eta_C=\eta_{POI})$

CMS, QM15

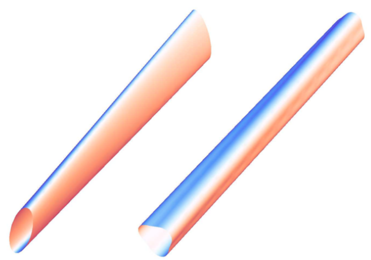
Pb+Pb



p+Pb



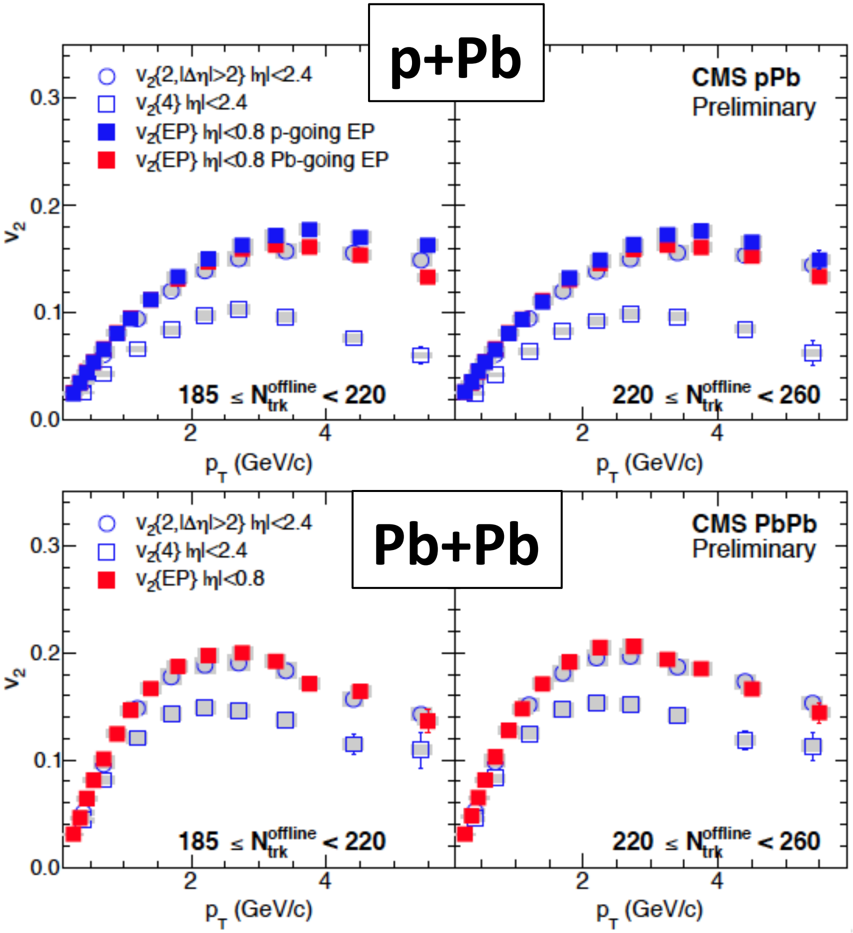
Torqued fireball



Bozek et.al., arXiv:1011.3354

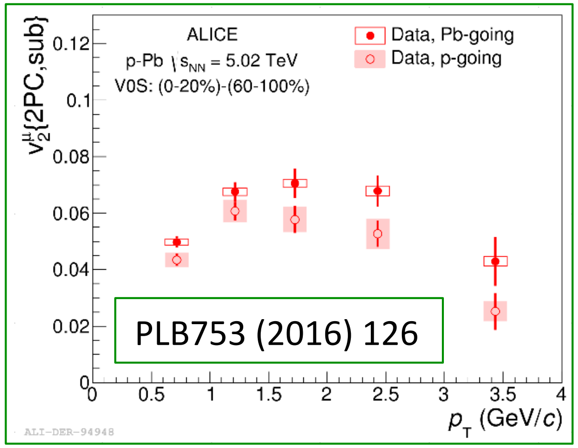
CMS, QM15

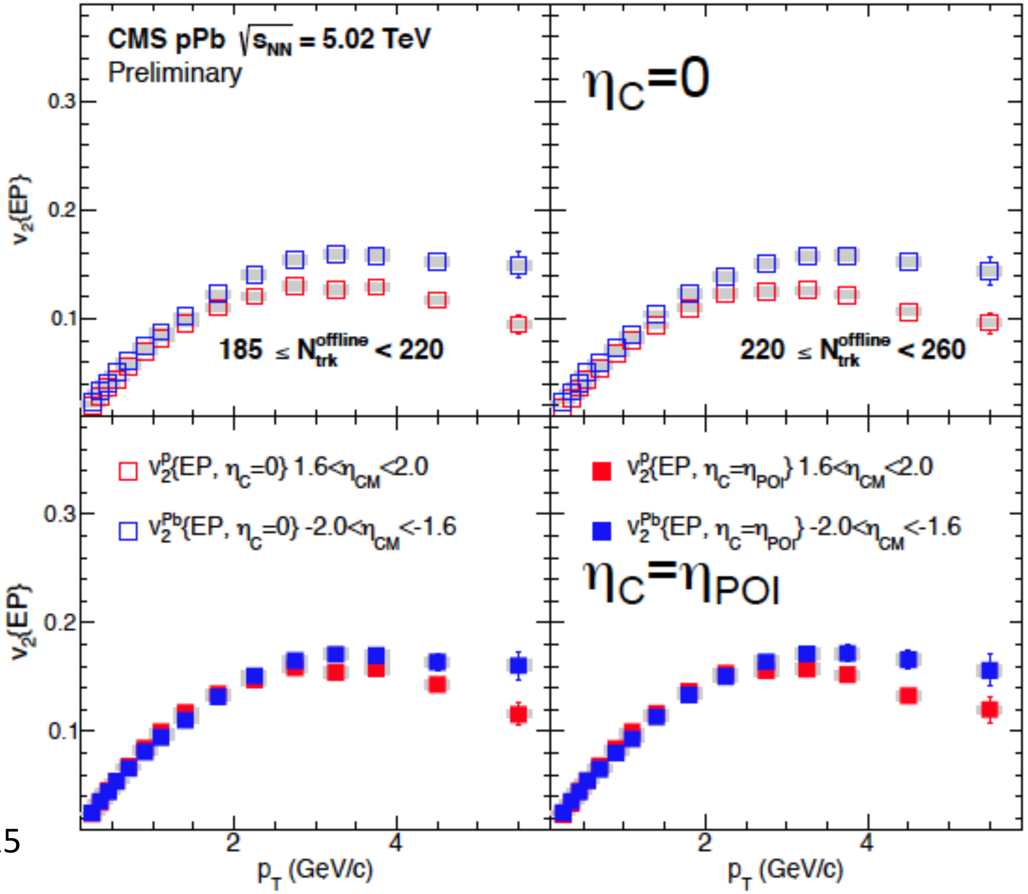
$v_2^{(|\eta|<0.8)}$



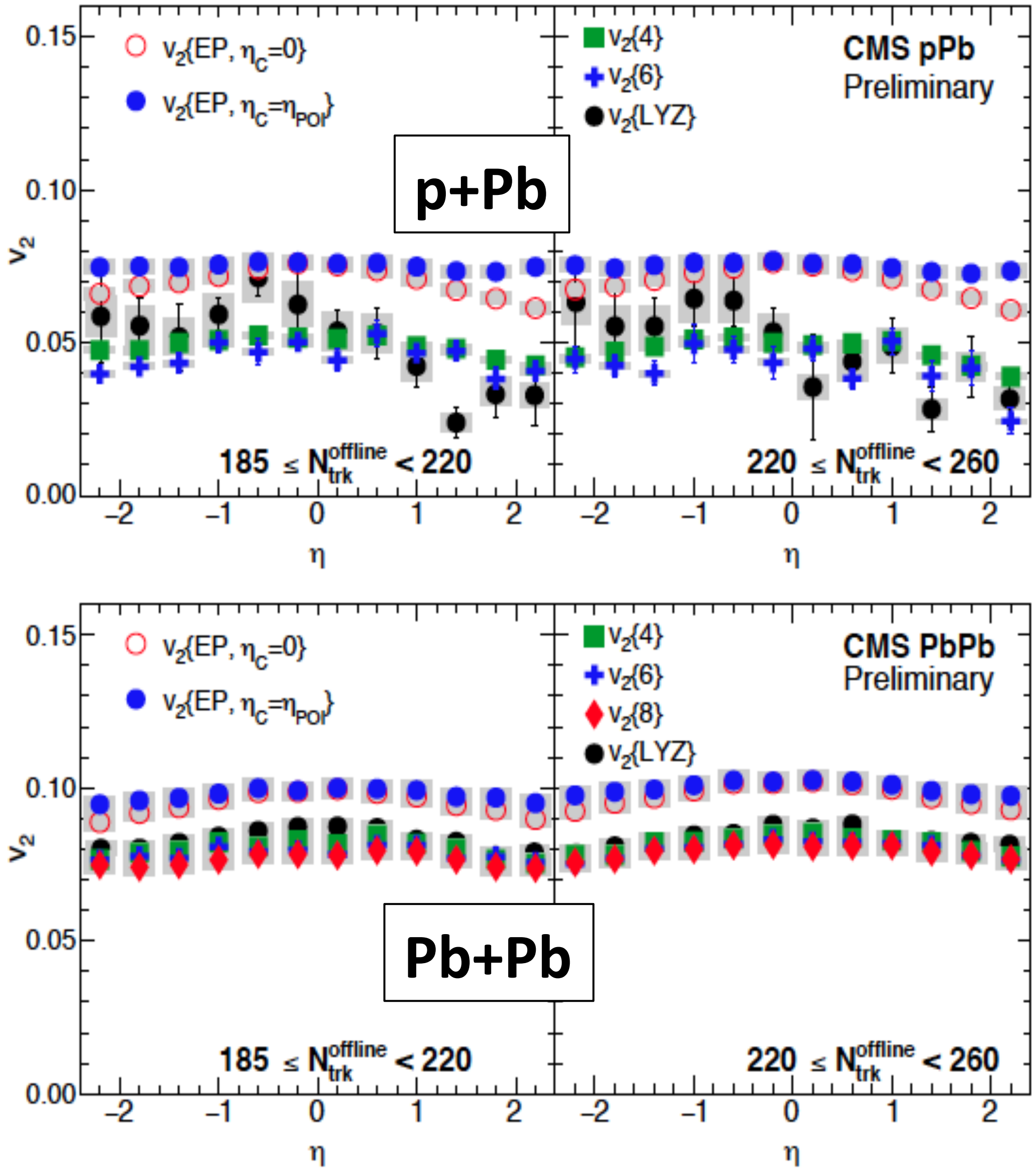
p+Pb

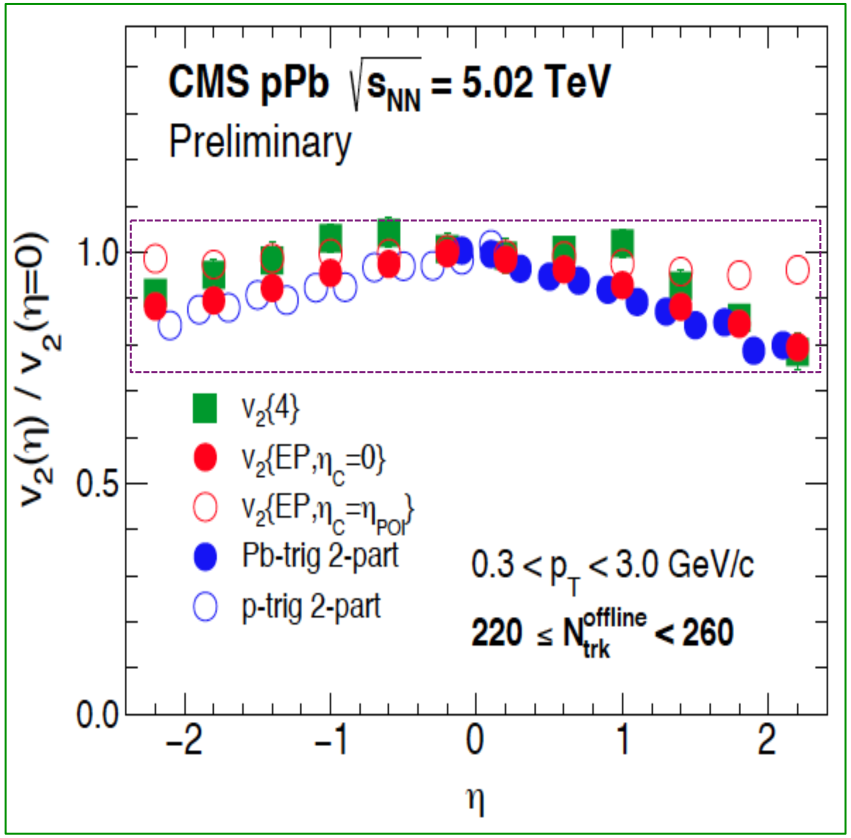
$v_2^{(1.6<|\eta|<2.0)}$





CMS, QM15

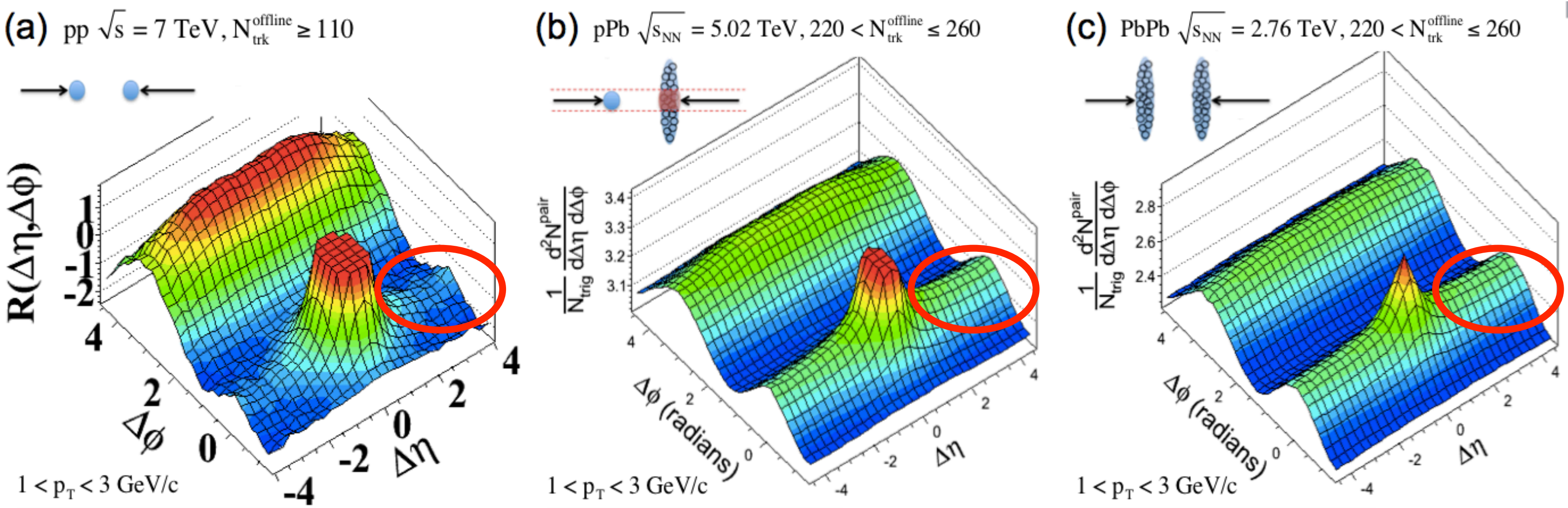




η dependence of v_2

CMS, QM15

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



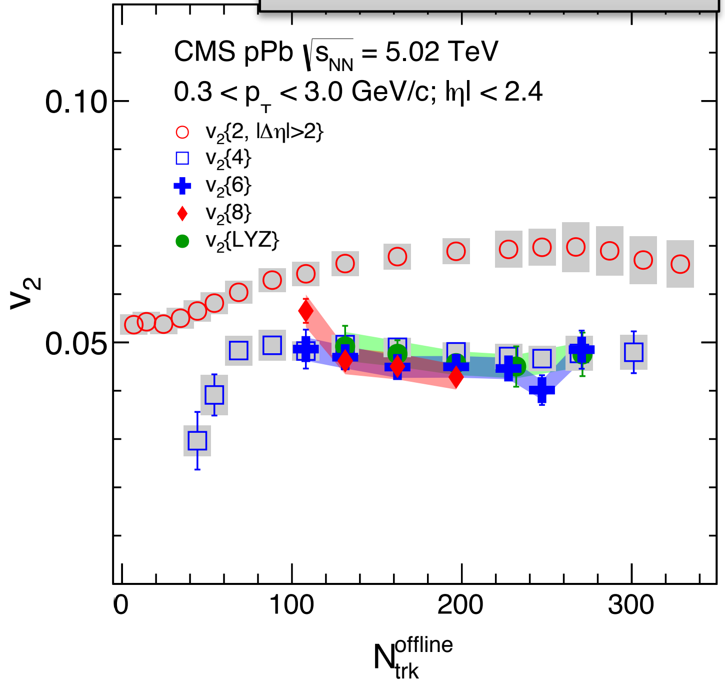
JHEP 09 (2010) 091

PLB 724 (2013) 213

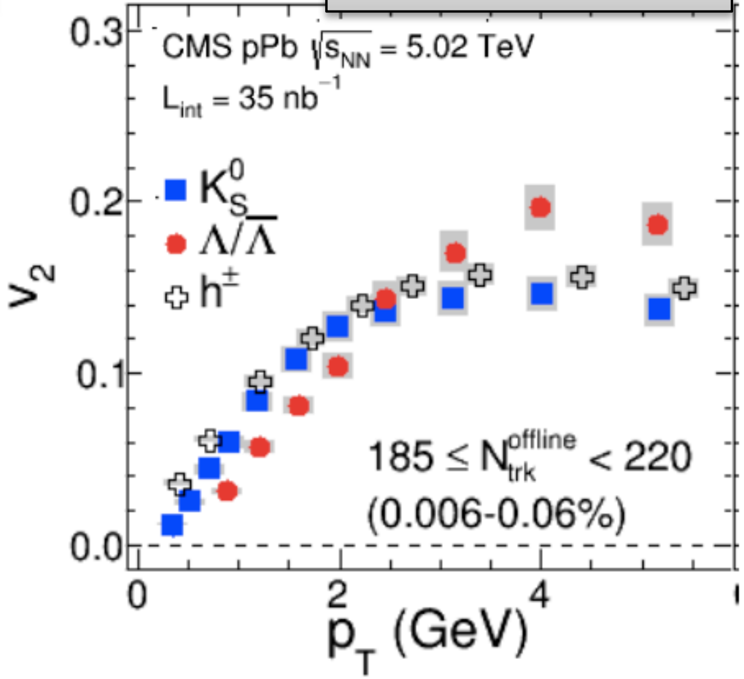
PLB 724 (2013) 213

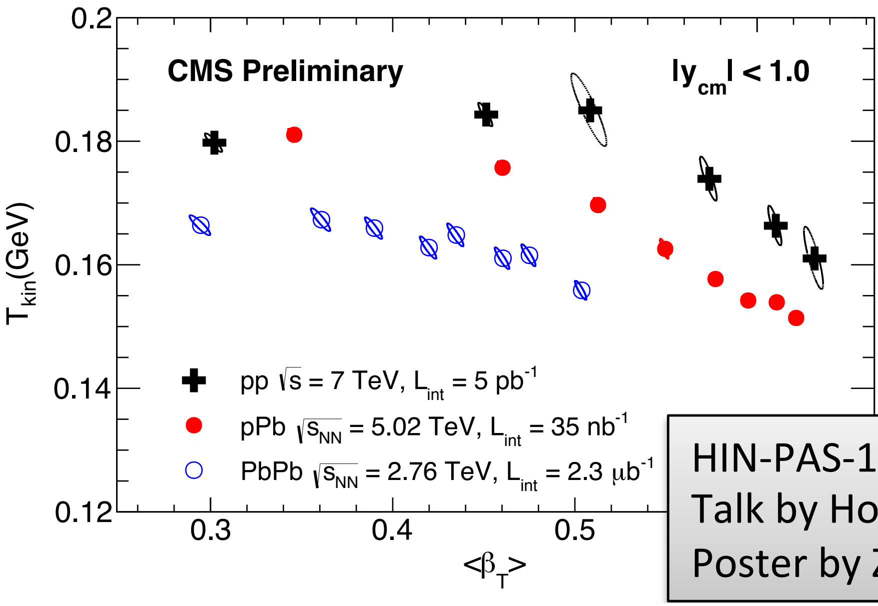
CMS, QM15

PRL 115 (2015) 012301



PLB 742 (2015) 200



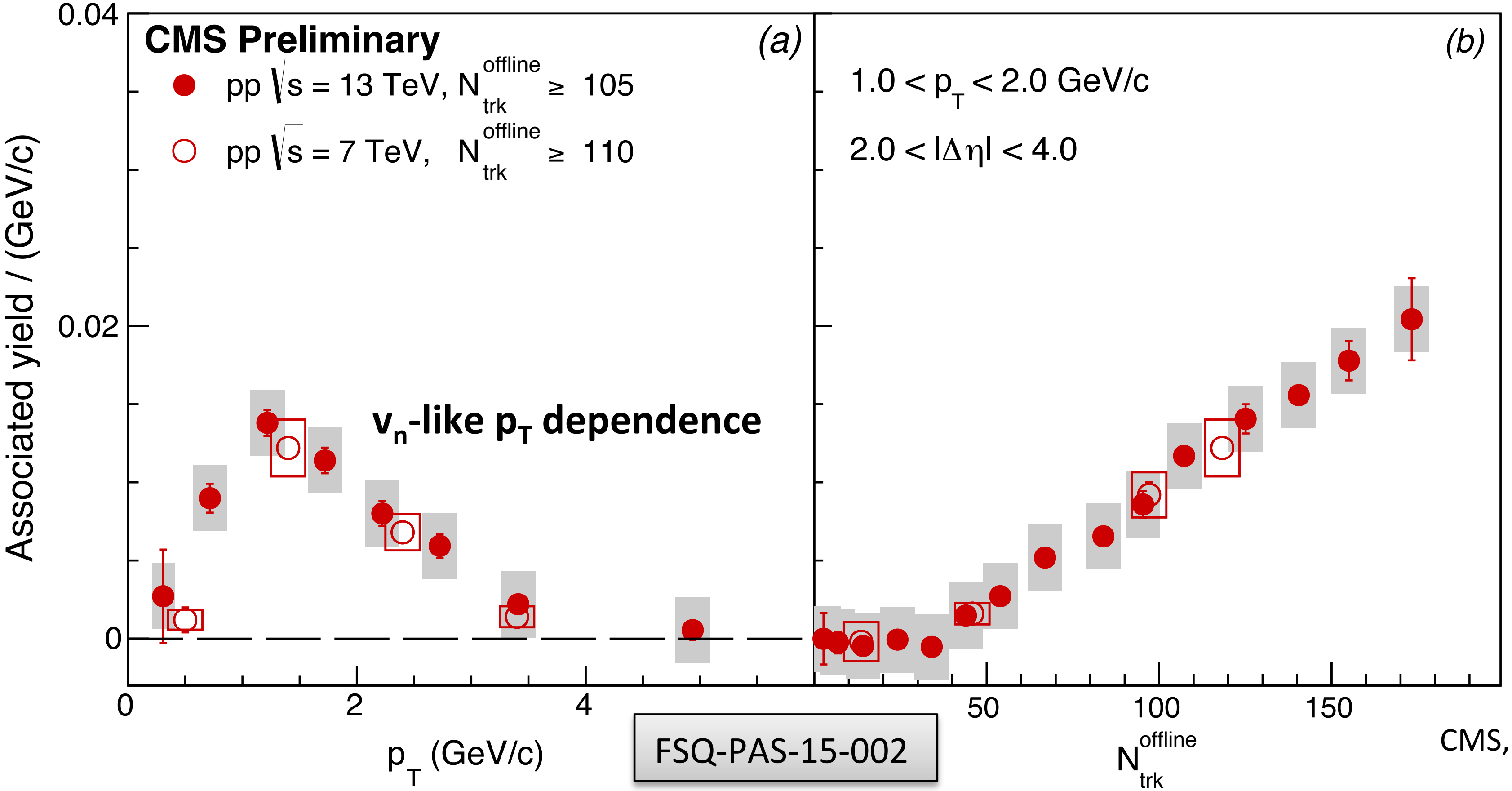


HIN-PAS-15-006
Talk by Hong Ni
Poster by Z. Tu (#0214)

3 Supporting Facts of Collective Expansion in pA at LHC

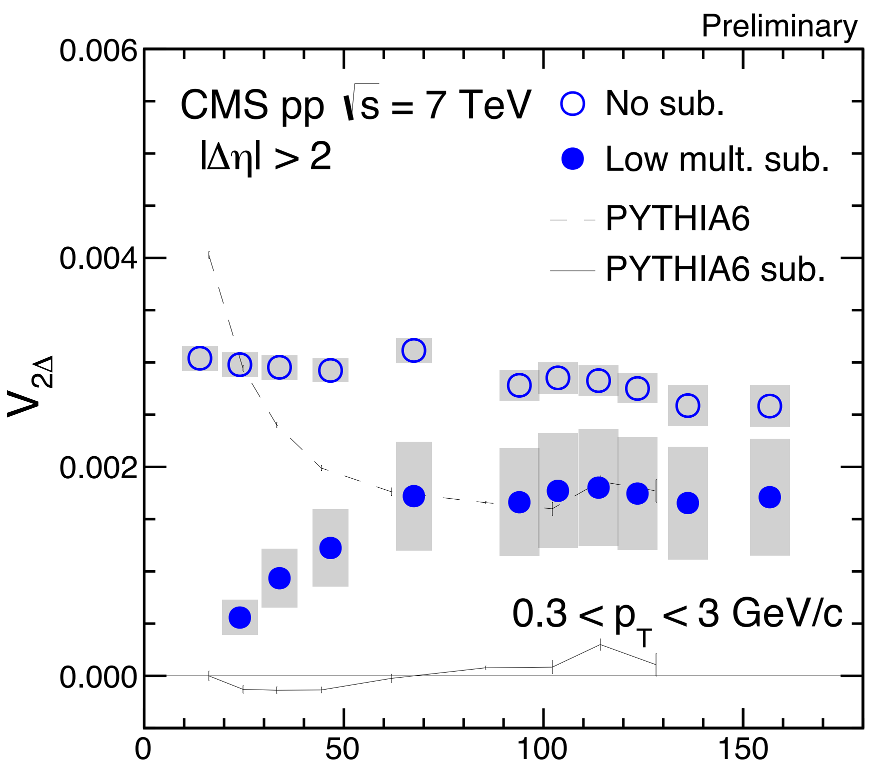
CMS, QM15

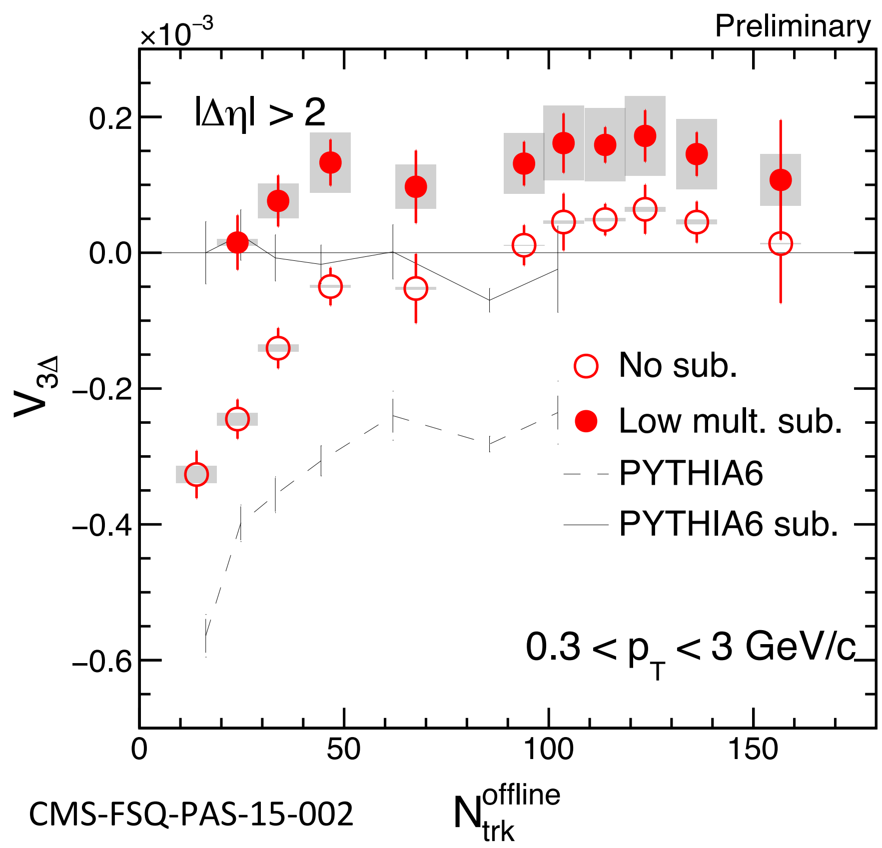
Ridge Yield vs (p_T, beam energy, multiplicity) in pp at LHC



FSQ-PAS-15-002

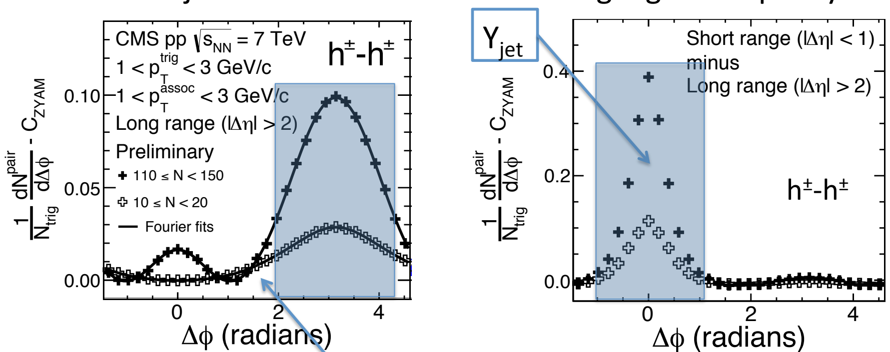
CMS, QM15





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:

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

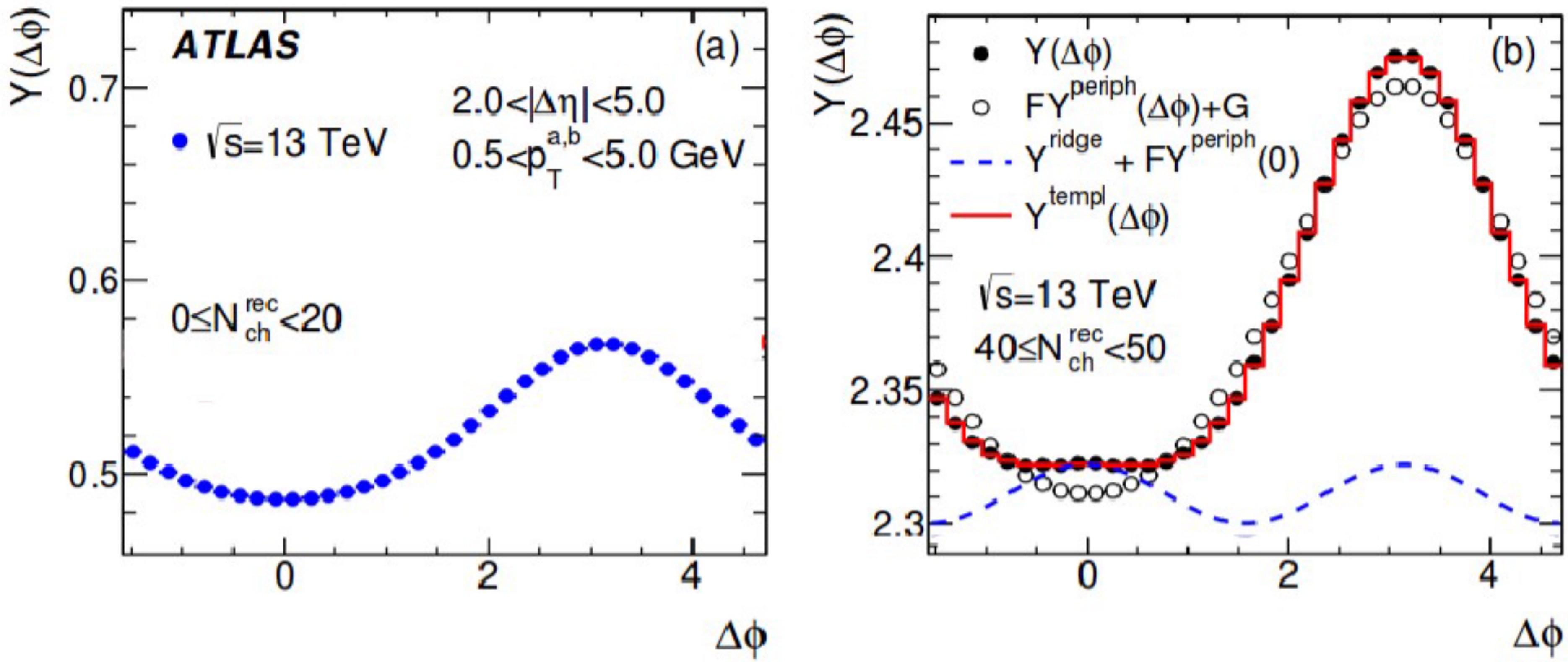
Multiplicity dependence of v_n with/without low mult. subtraction

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

CMS, QM15

ATLAS ways of pp analysis

arXiv:1509.04776
PRL116 (2016) 172301



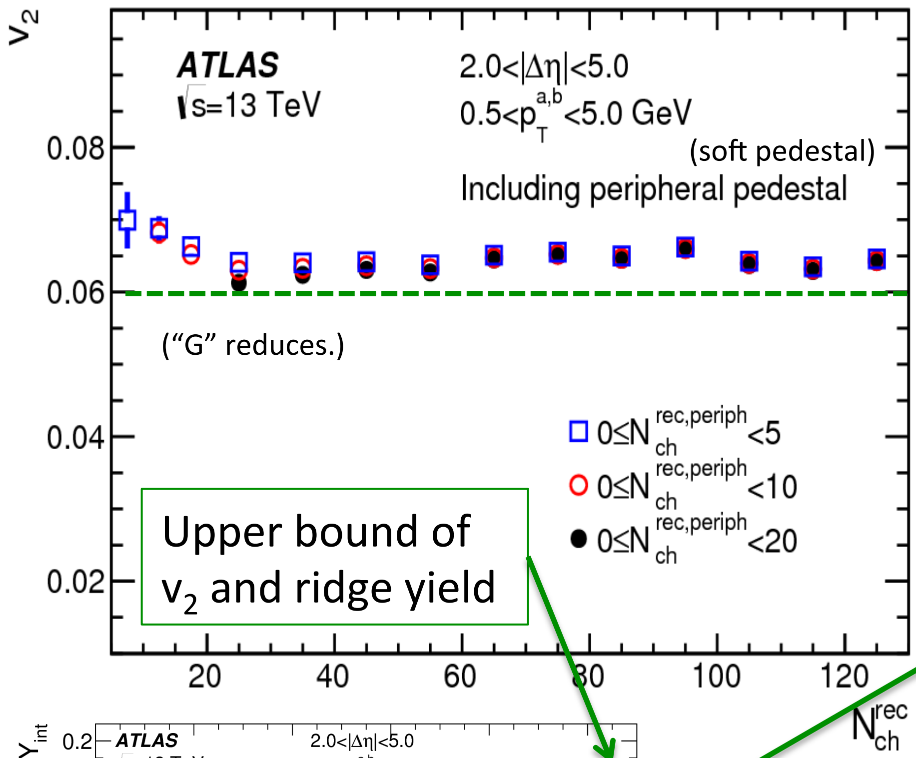
Template fitting

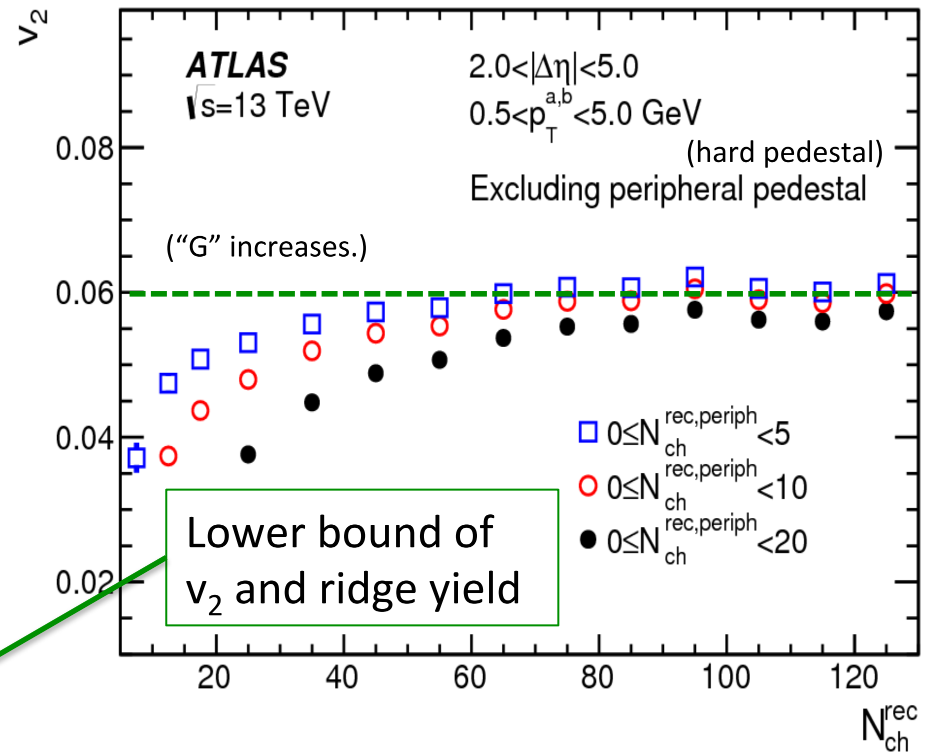
$$Y^{\mathrm{templ}}(\Delta\phi) = FY^{\mathrm{periph}}(\Delta\phi) + Y^{\mathrm{ridge}}(\Delta\phi),$$

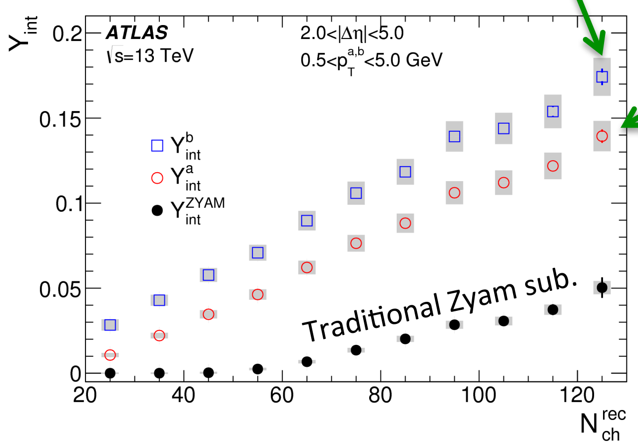
$$Y^{\mathrm{ridge}}(\Delta\phi) = G[1 + 2v_{2,2}\cos(2\Delta\phi)],$$

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

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



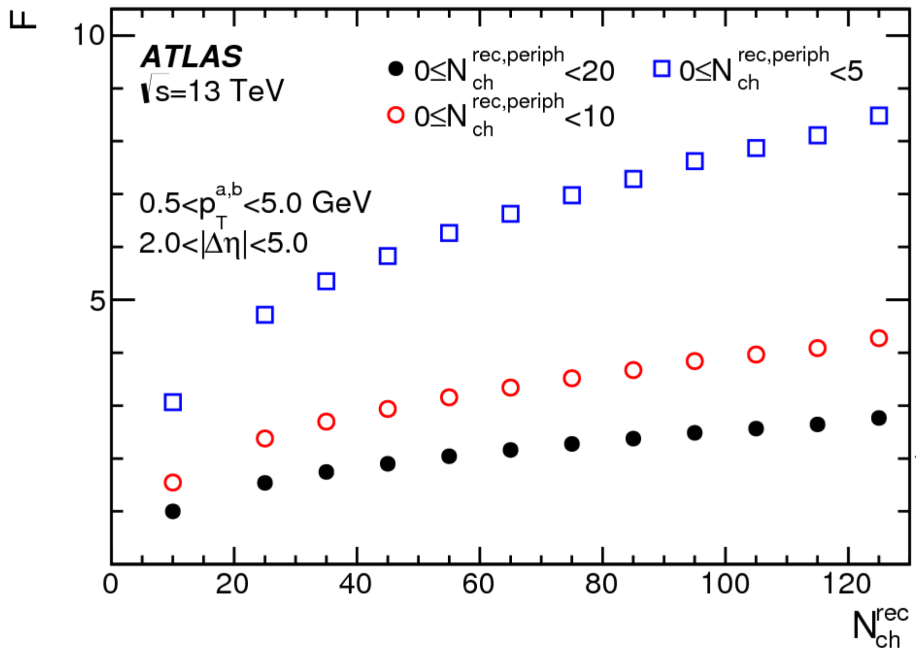


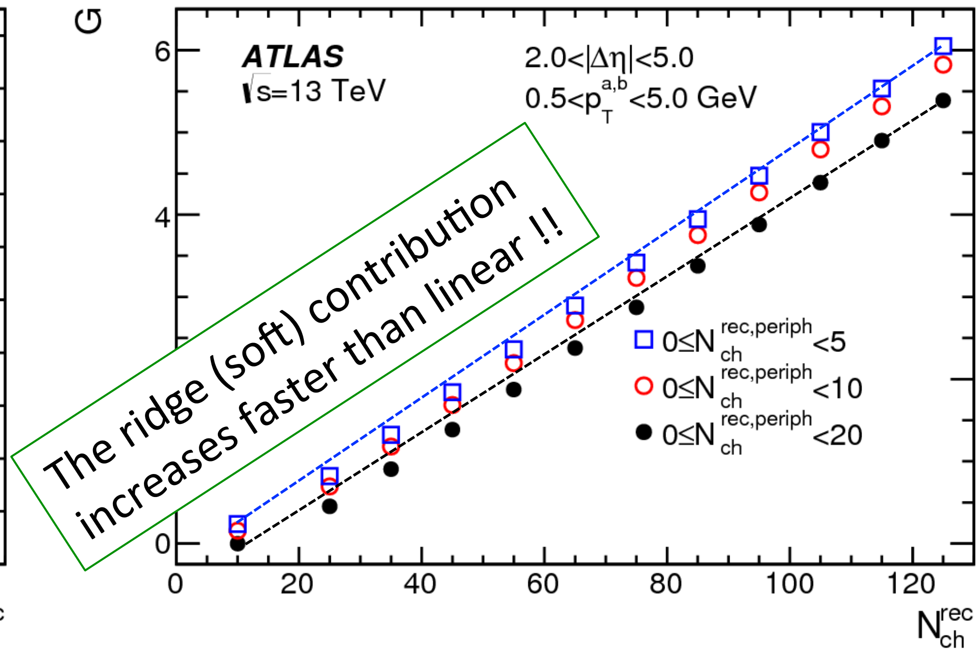


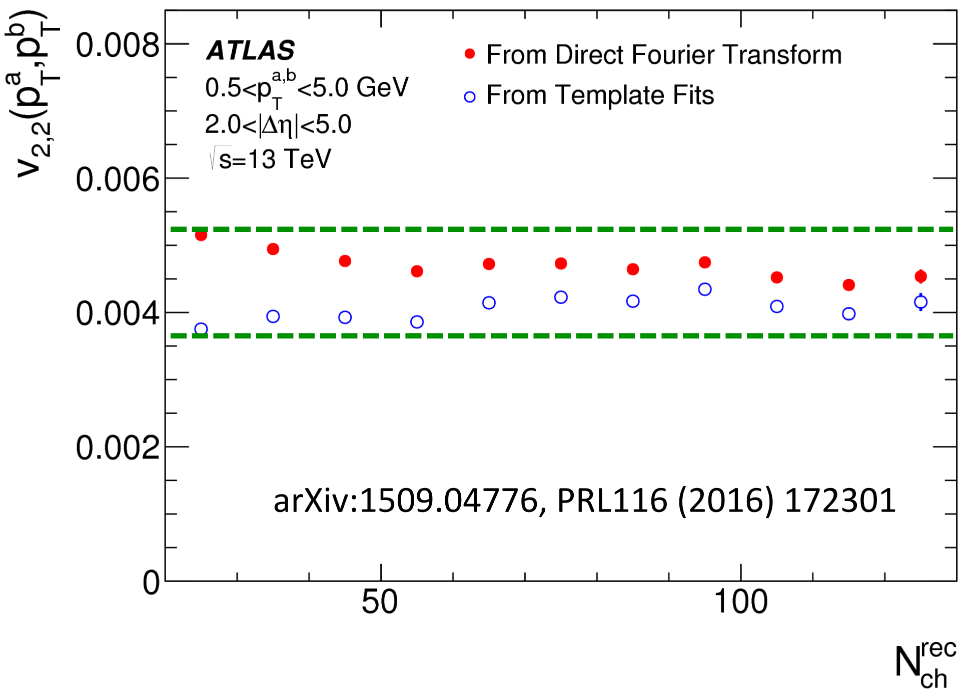
$$Y^{\mathrm{templ}}(\Delta\phi) = FY^{\mathrm{periph}}(\Delta\phi) + Y^{\mathrm{ridge}}(\Delta\phi),$$

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

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







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

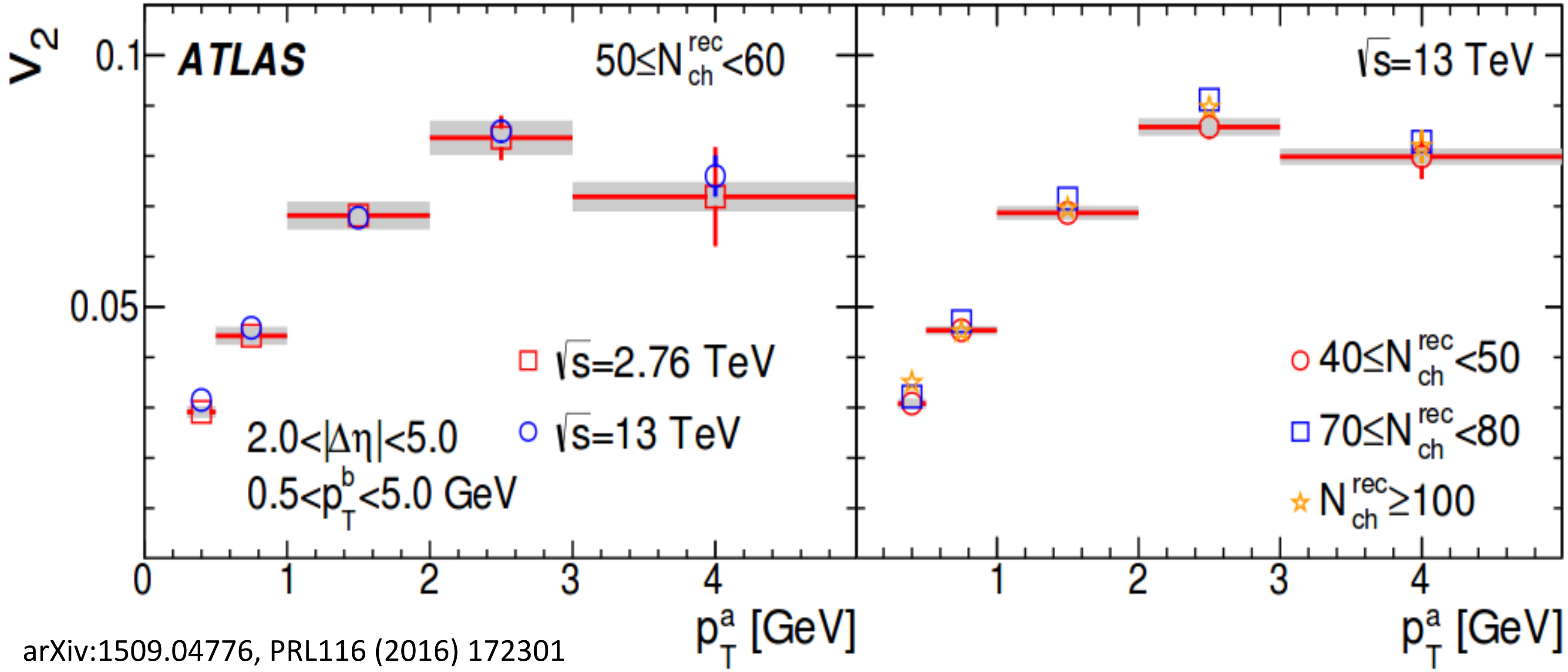
$$Y^{\mathrm{ridge}}(\Delta\phi) = G[1 + 2v_{2,2}\cos(2\Delta\phi)],$$

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

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

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

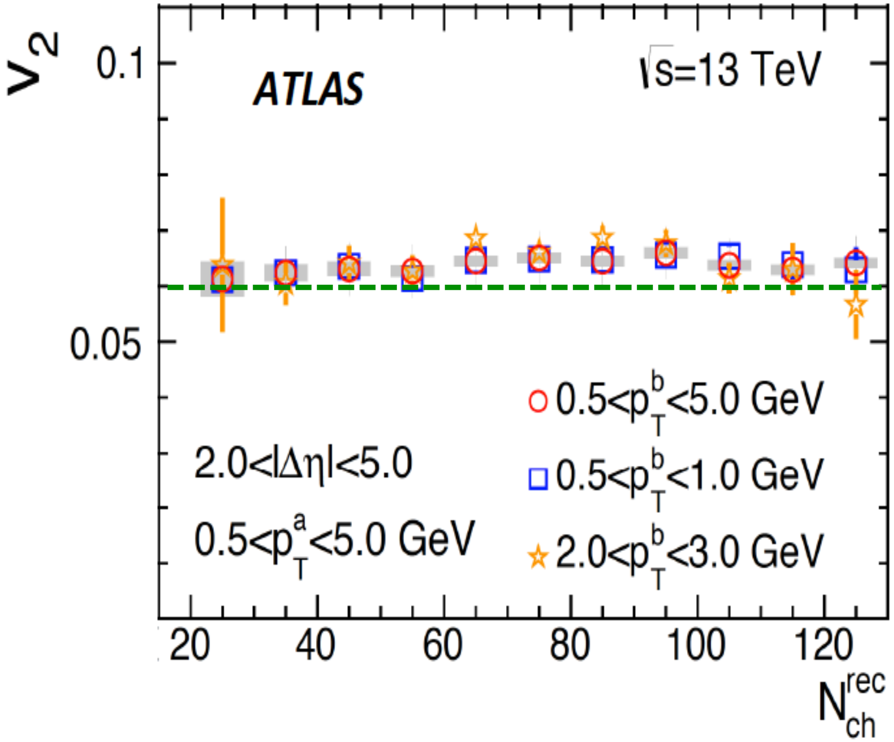
similar p_T dependence of v_2 to the larger systems
no (or very weak) dependence of v_2 on energy and multiplicity



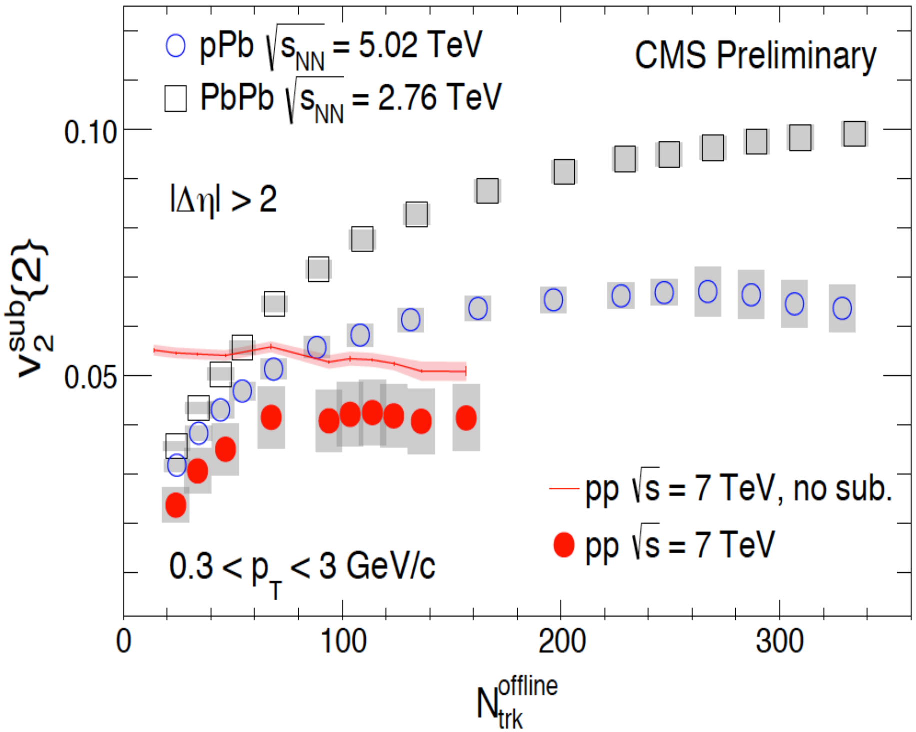
arXiv:1509.04776, PRL116 (2016) 172301

Multiplicity dependence of v_2 in pp at LHC with various methods

arXiv:1509.04776, PRL116 (2016) 172301



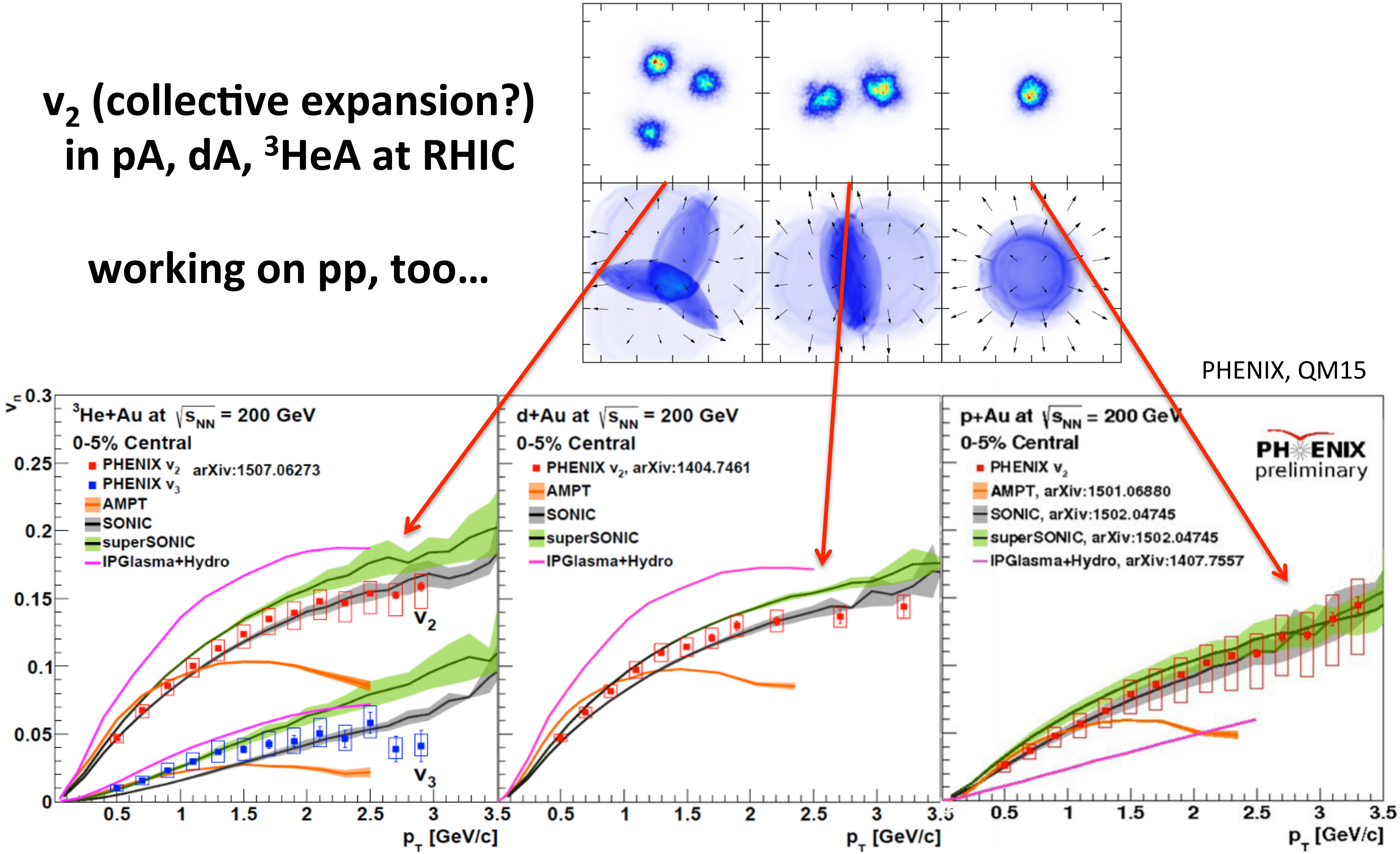
CMS, QM15



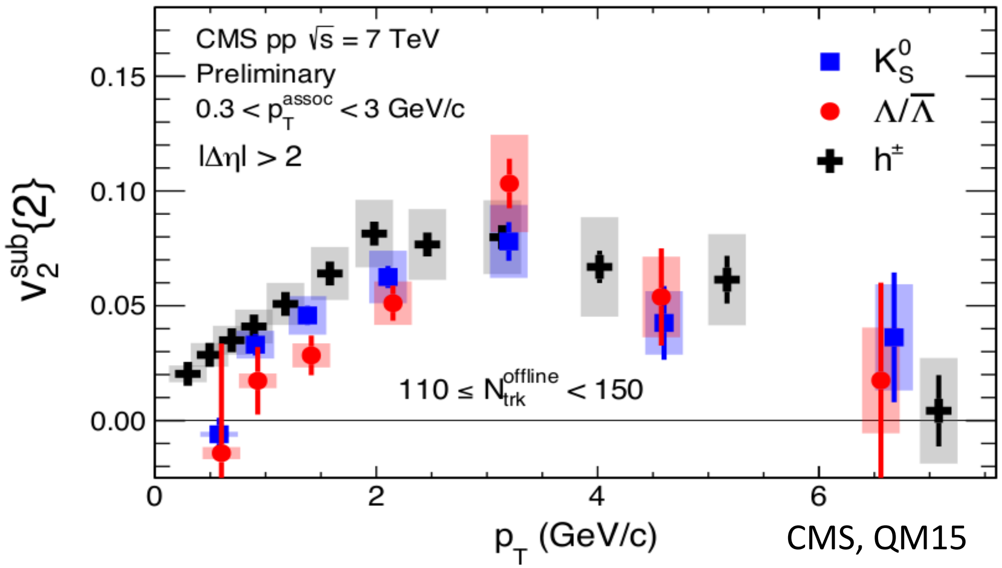
v_2 (collective expansion?) in pA, dA, ^{3}HeA at RHIC

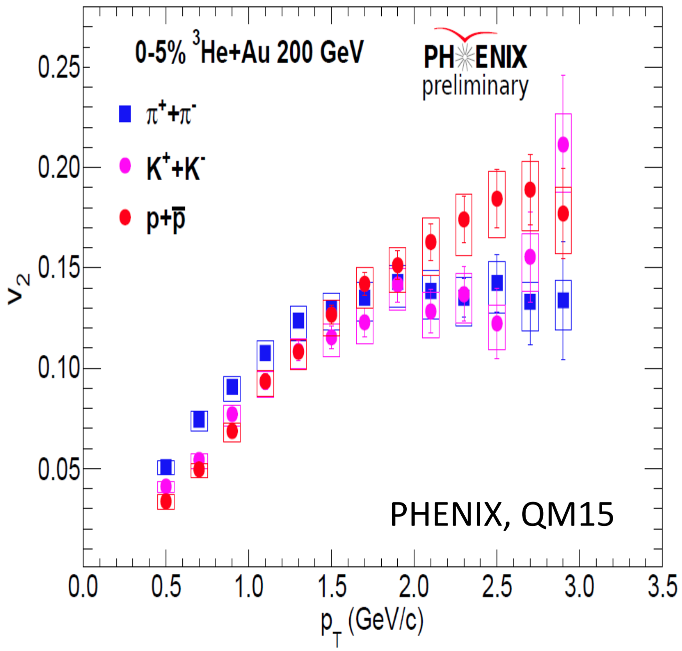
working on pp, too…

PHENIX, QM15

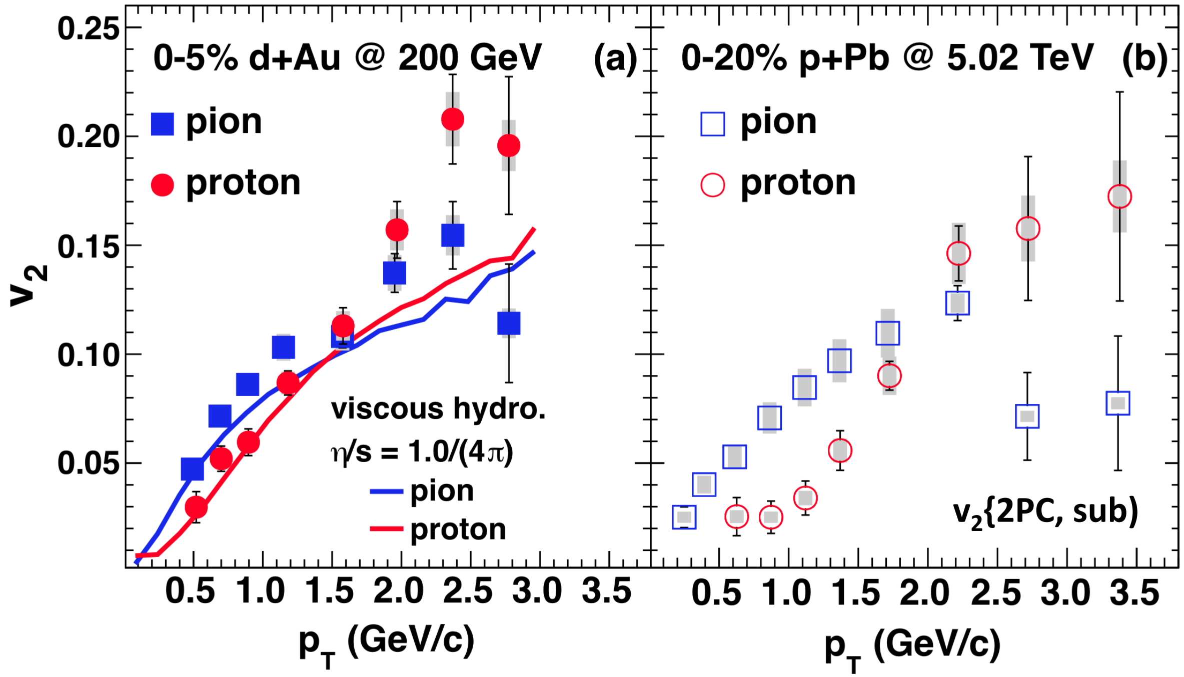


Mass dependence and Baryon/Meson splitting of v_2 in small systems at RHIC/LHC (pp, pA, dA and ^{3}HeA)



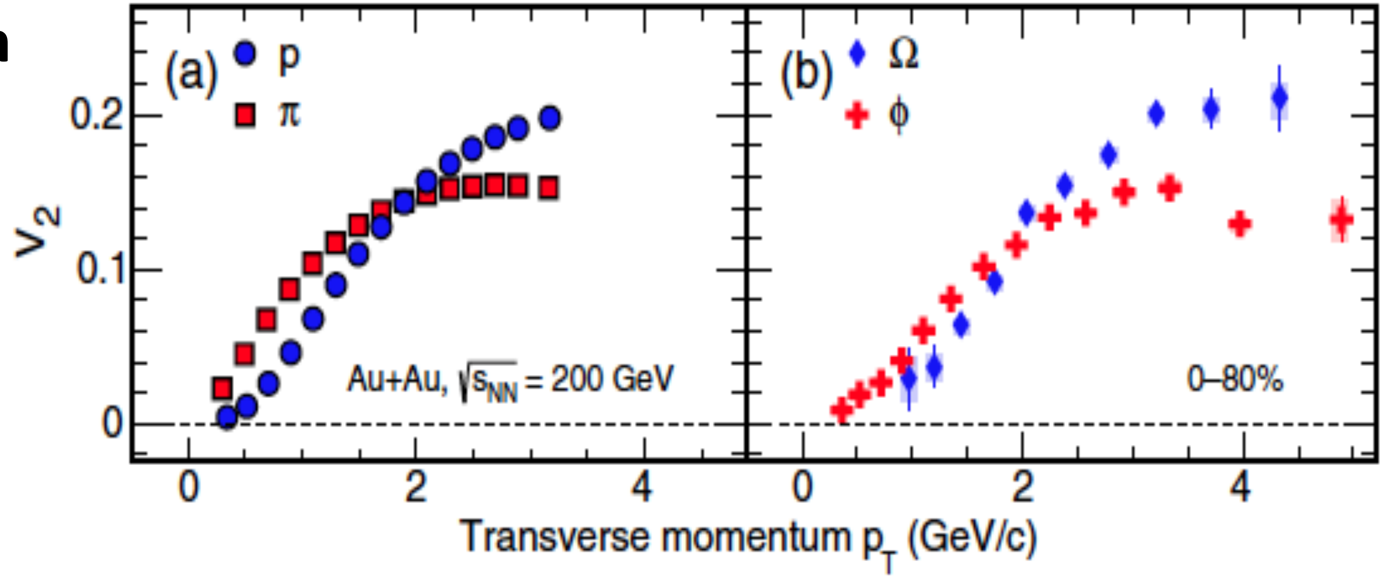


PRL114 (2015) 192301



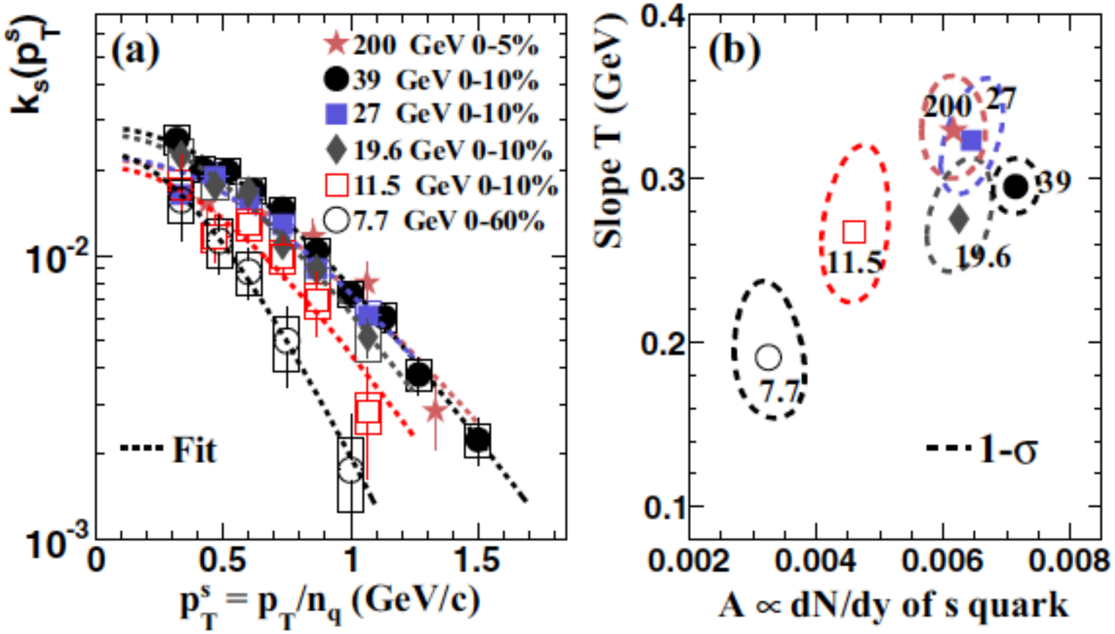
PRL116 (2016) 162301

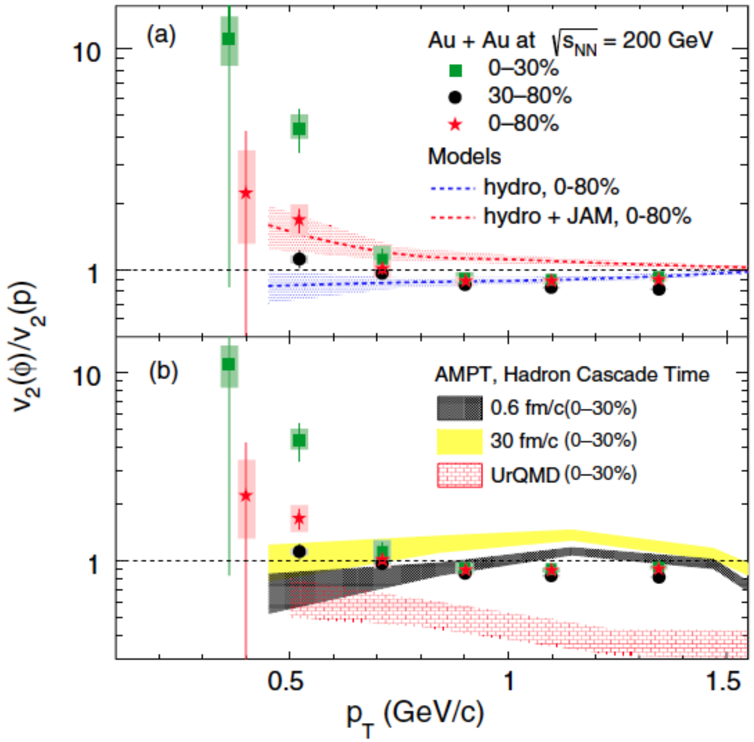
System Evolution from Partonic to Hadronic Phase



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

PRC93 (2016) 021903R





Beam energy dependence of net-proton v_1 and $v_3^2/n_{ch,PP}$

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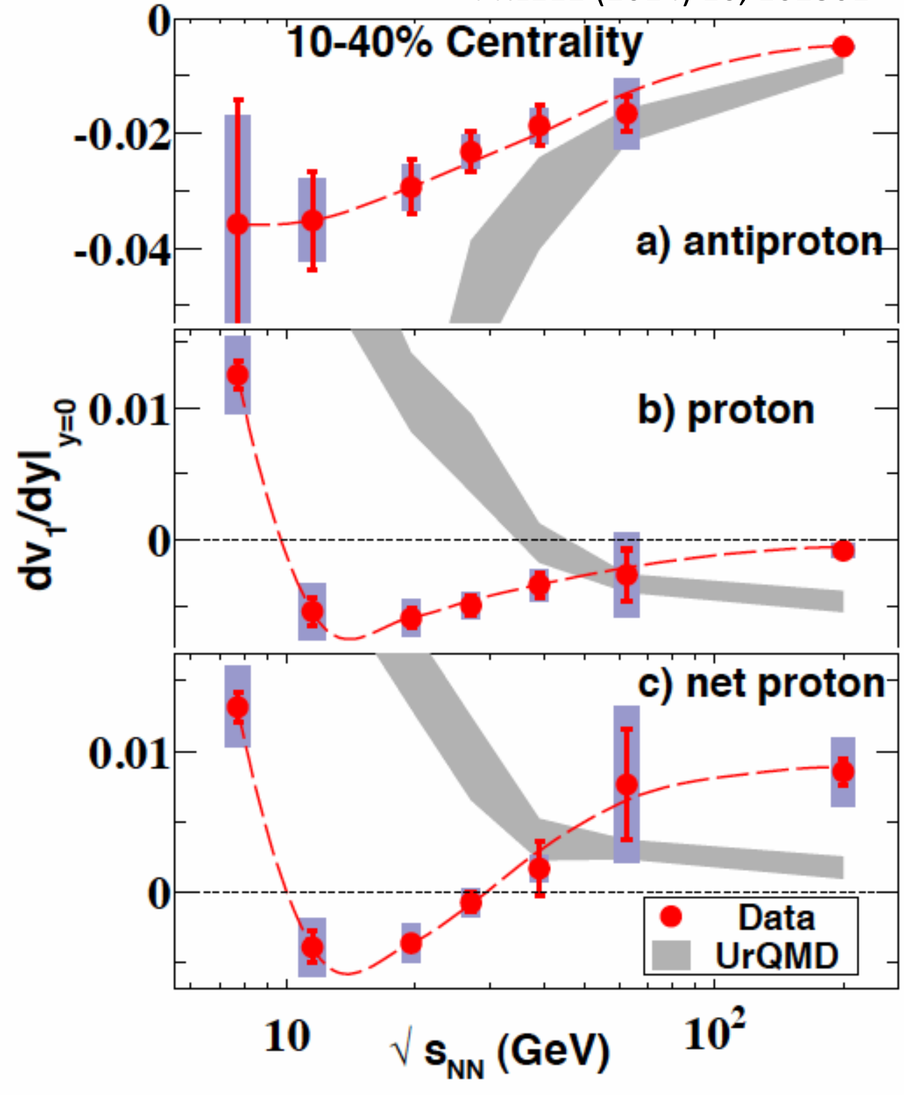
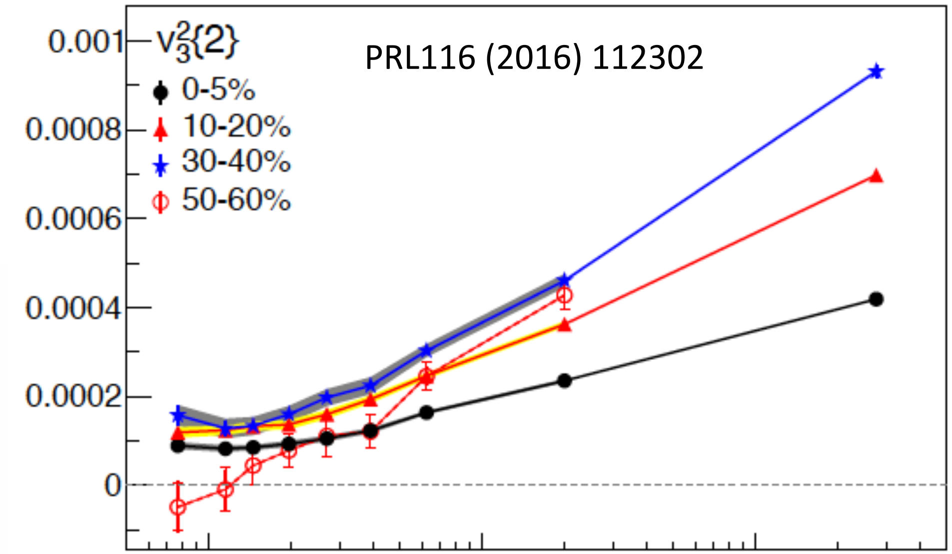
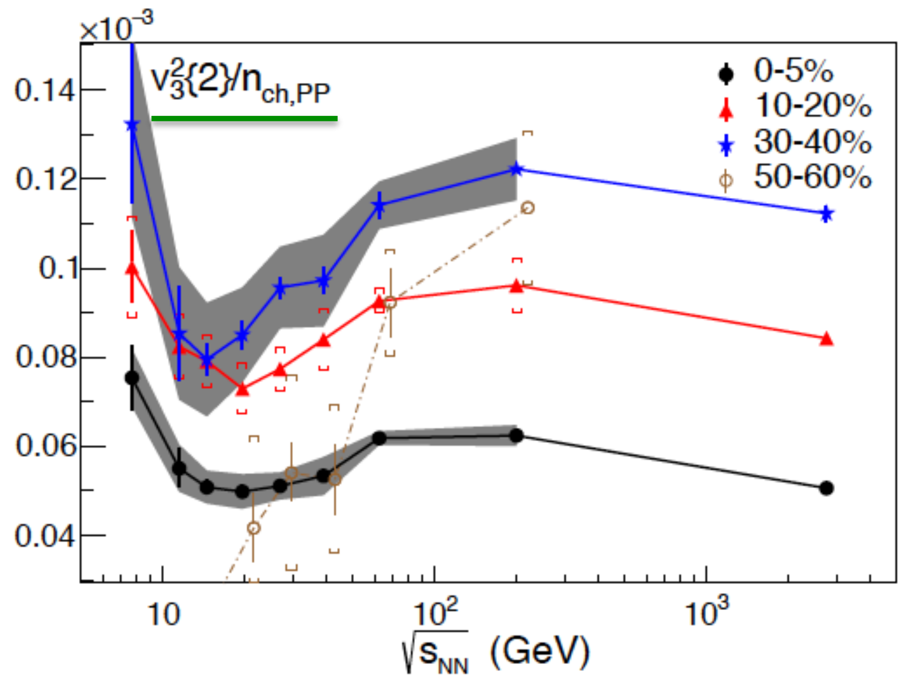
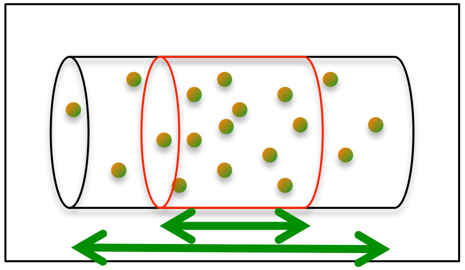


PRL116 (2016) 112302



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

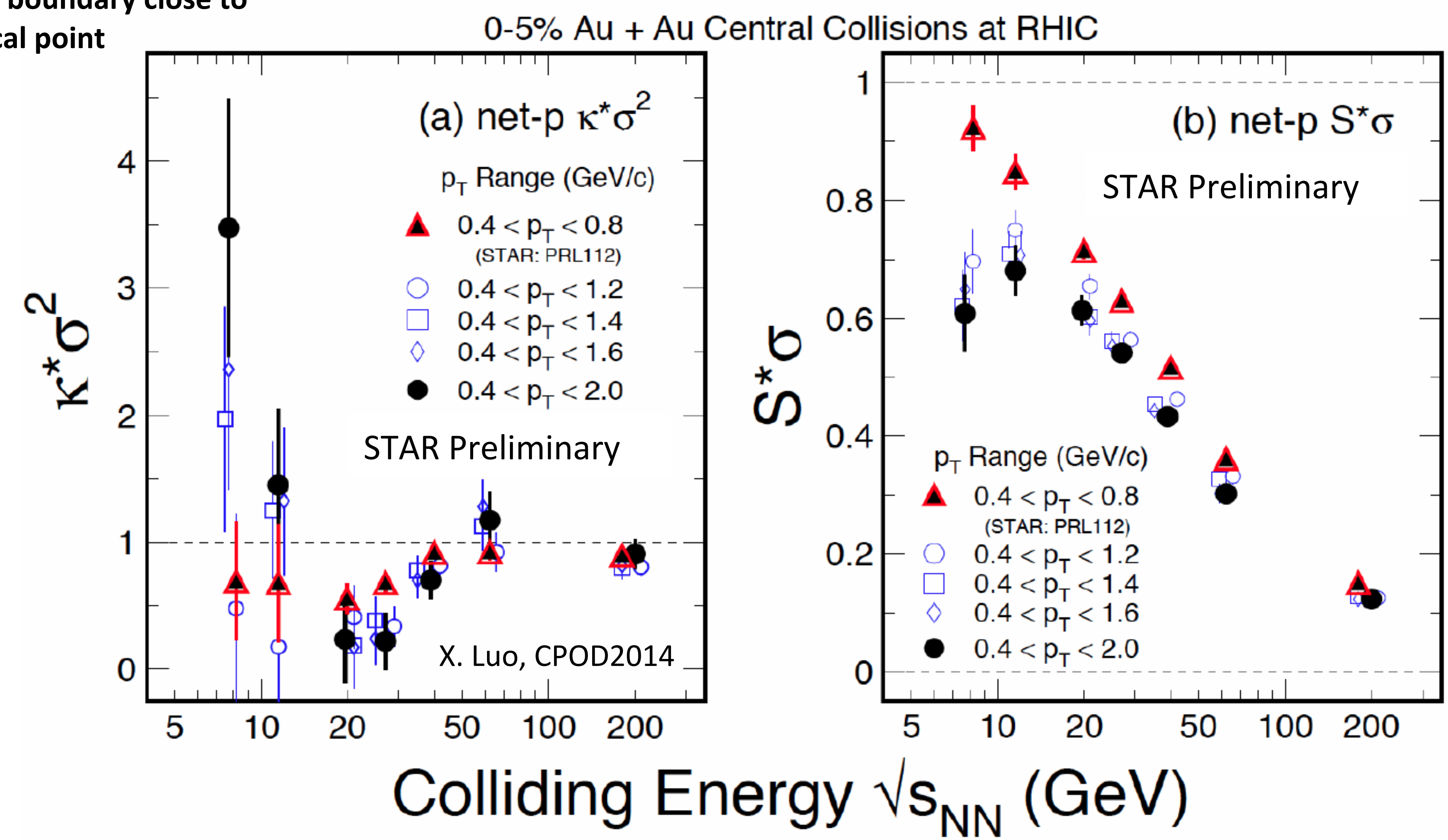




Fluctuation of conserved quantity

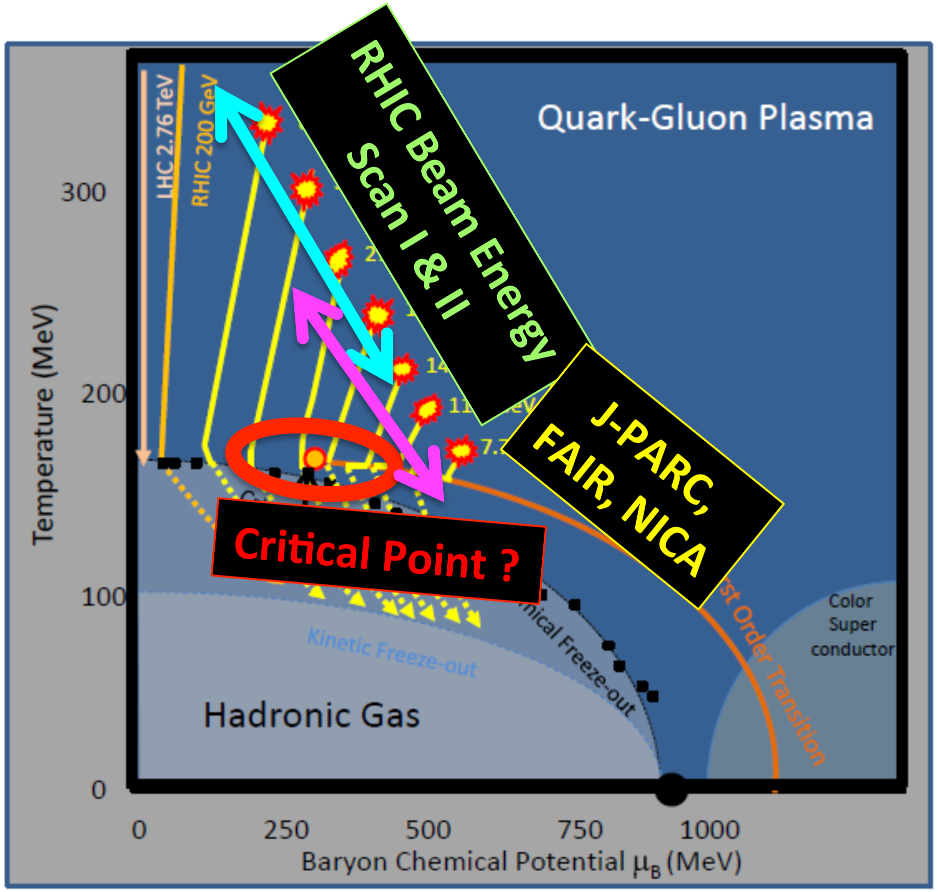
--- higher order moment of net-proton distribution as a proxy of net-Baryon distribution ---

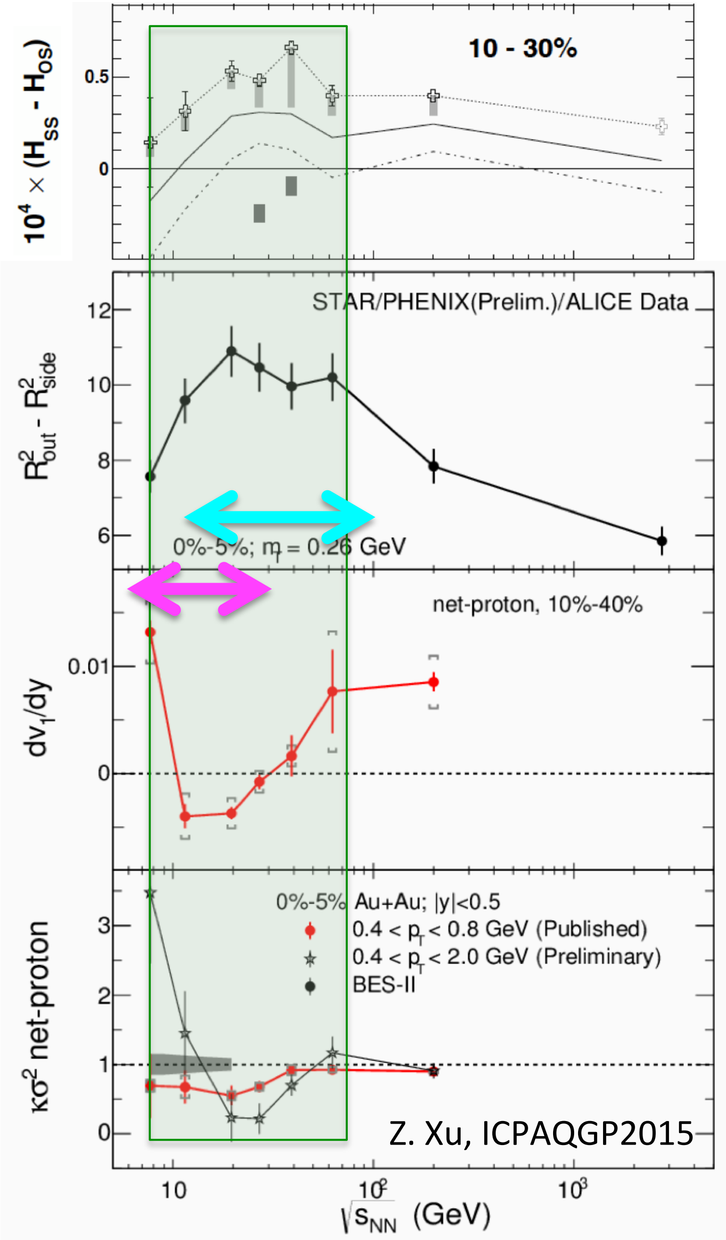
Change of correlation length at phase boundary close to the critical point



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

~ 2016 2019 ~

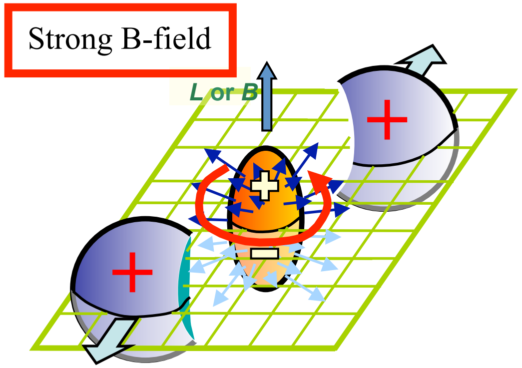


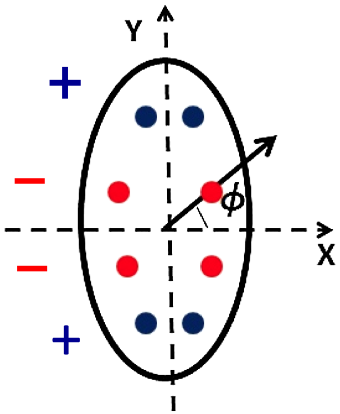


Summary

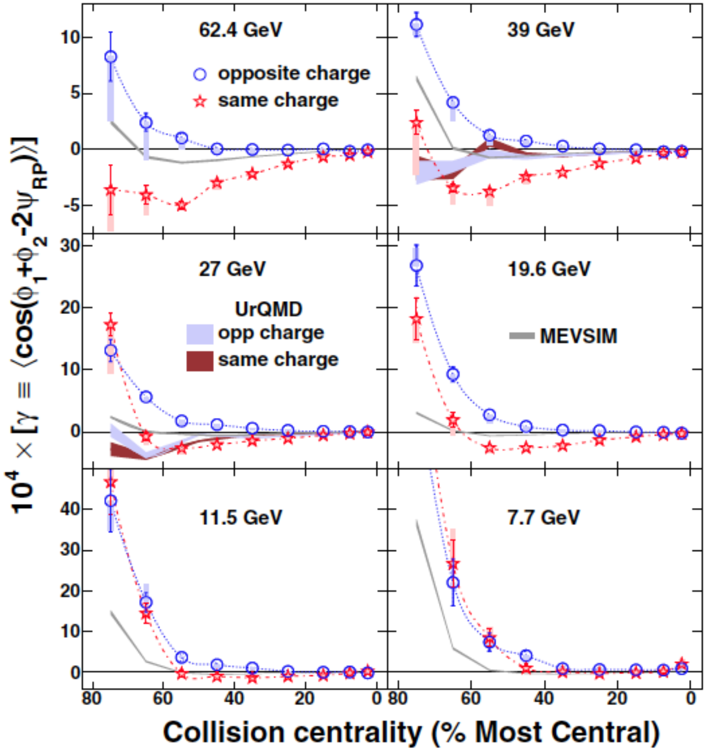
- **Flow and fluctuation in AA**
- **Flow in small systems; pp, pA, dA…**
- **From partonic to hadronic world**

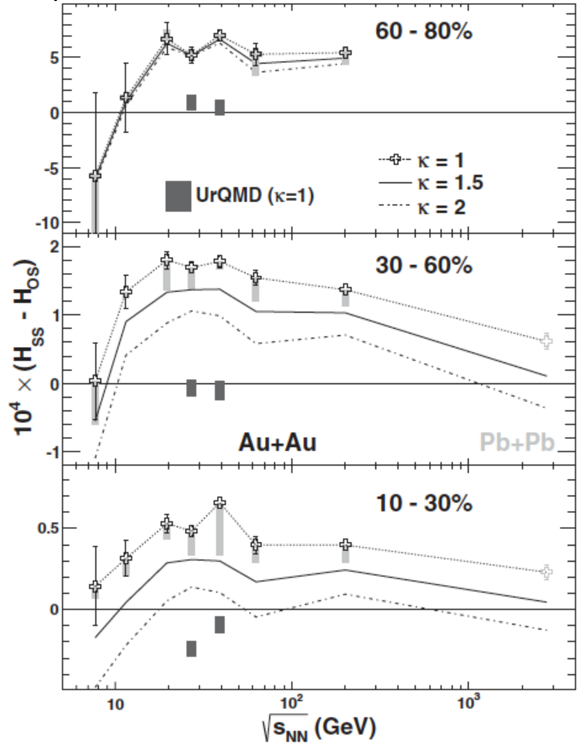
Thank you very much for your attention!
Please help us to setup "宇宙史国際研究拠点" in CiRfSE@筑波大学
Some back-up slides follow…



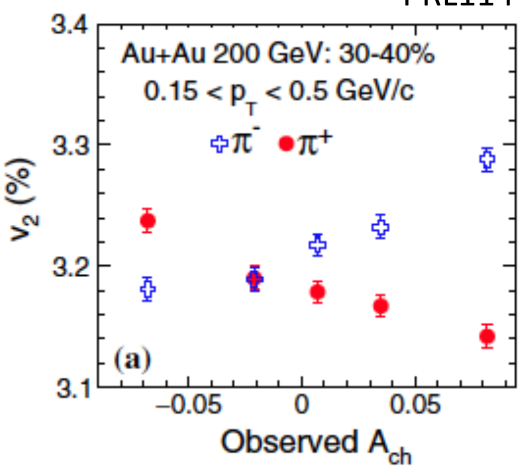


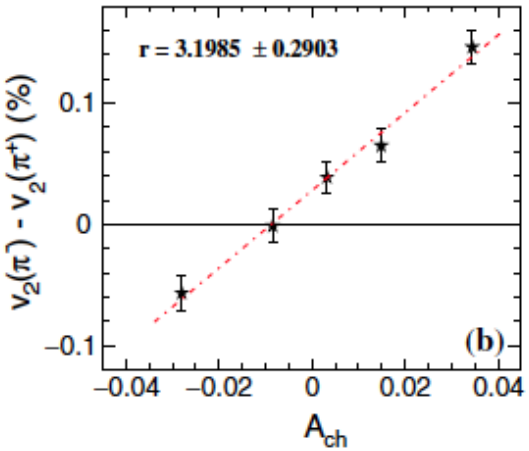
PRL113 (2014) 052302



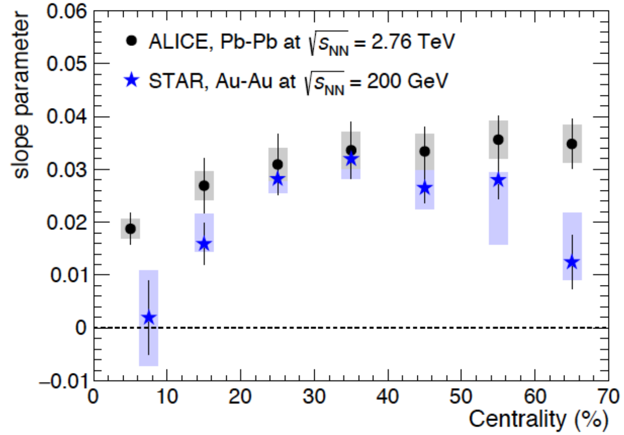


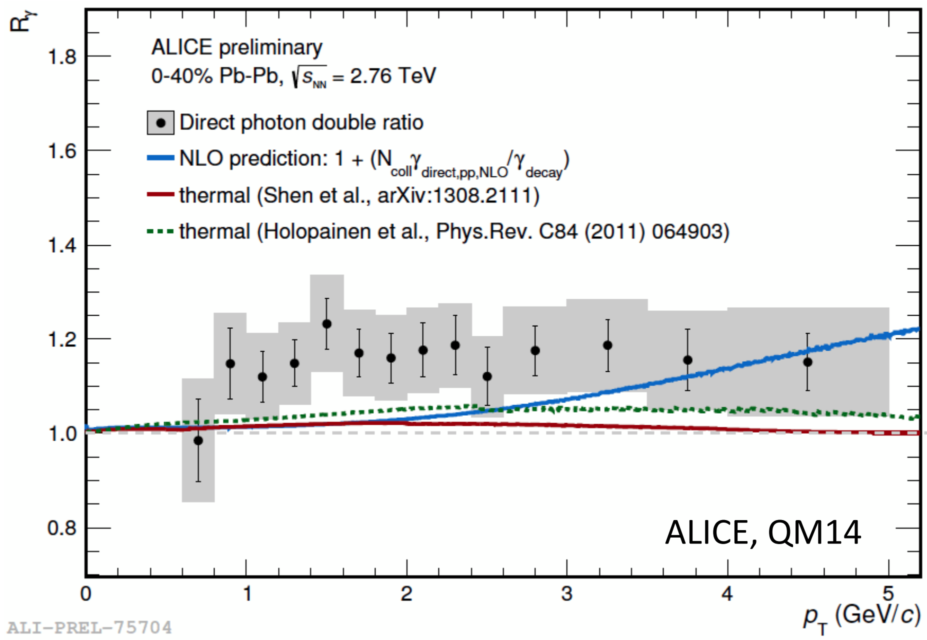
PRL114 (2015) 252302

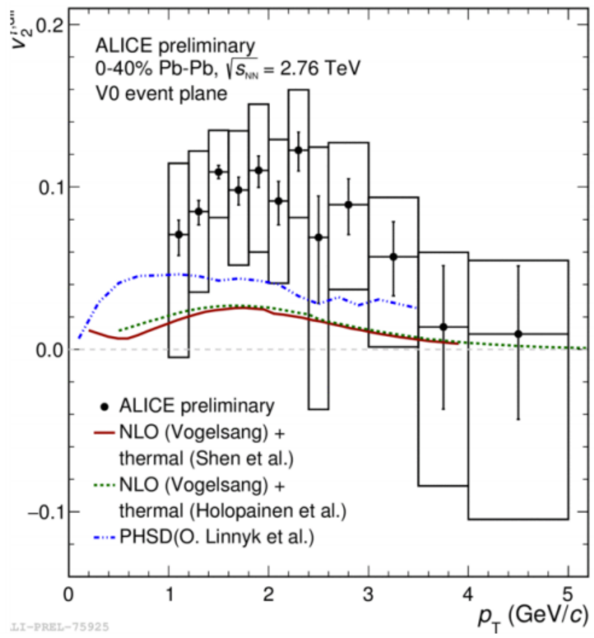


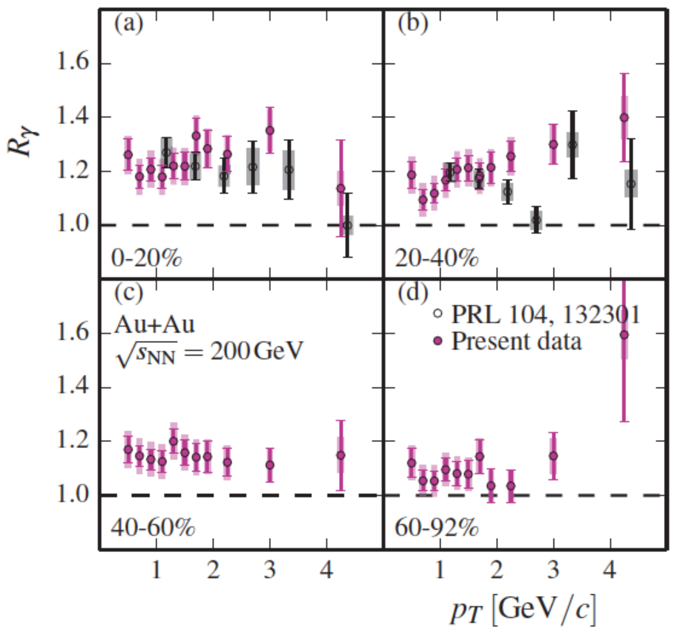


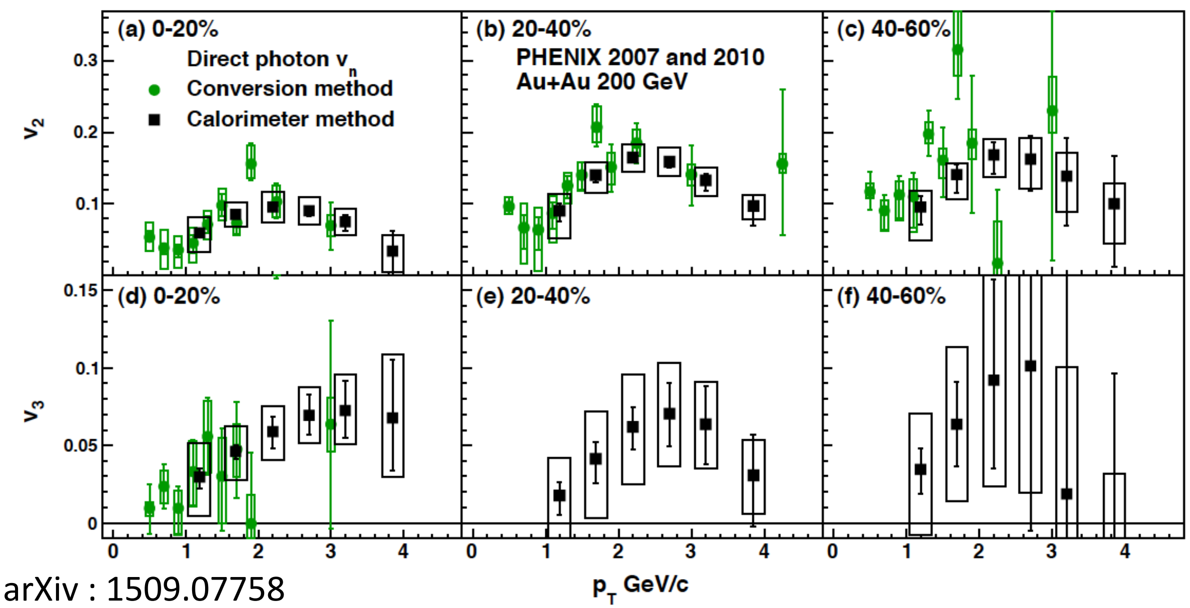
arXiv : 1512.05739





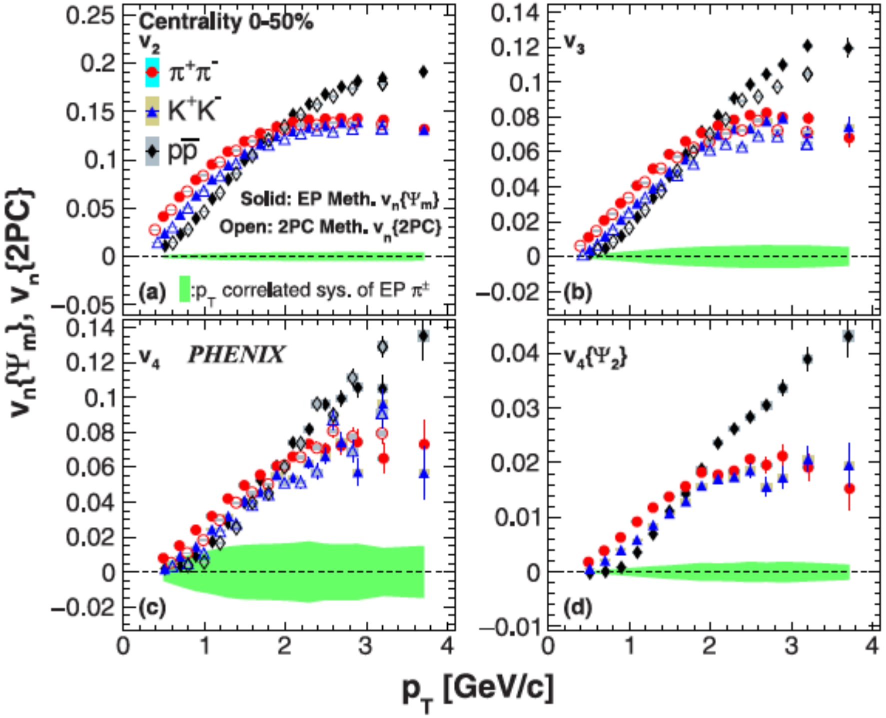


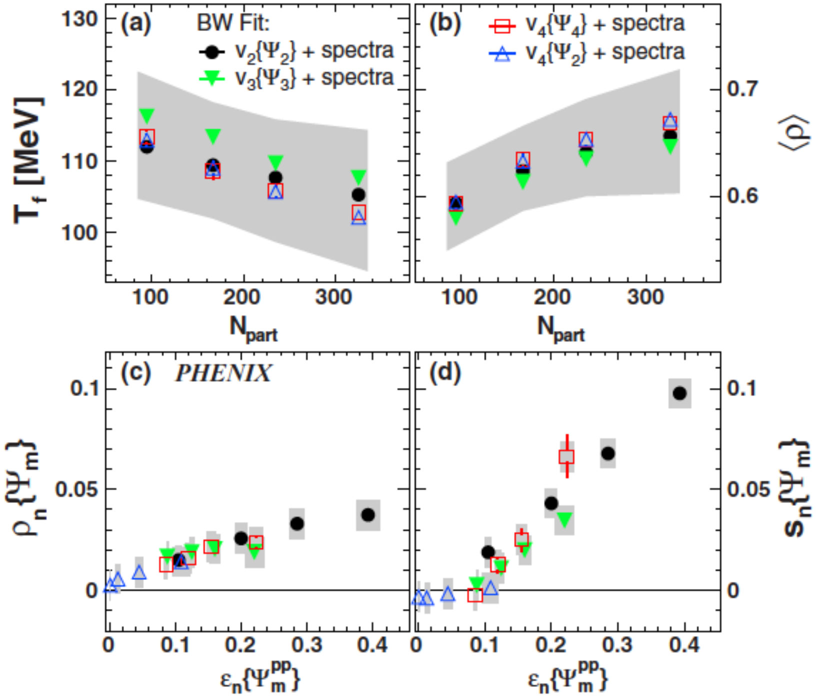




arXiv : 1509.07758

PRC93 (2016) 051902R





PRL112 (2014) 222301