Di-hadron correlations from CMS

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Thanks to the CMS Collaboration

e-Forum on High-energy Nuclear Physics in China

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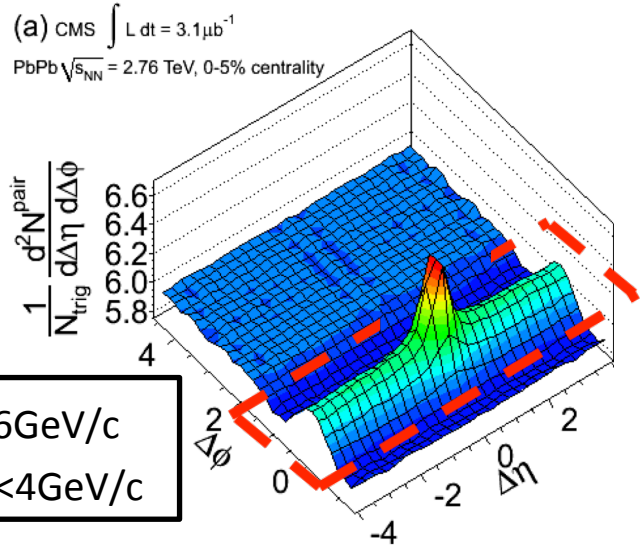
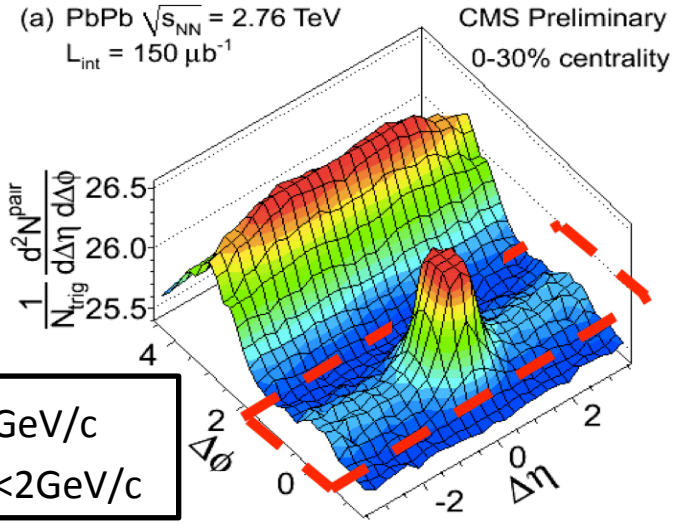
Motivation

Di-hadron correlations:

Low p_T (a couple GeV/c) → High p_T (tens of GeV/c)



$4<p_T^{trig}<6$GeV/c
$2<p_T^{assoc}<4$GeV/c



$p_T^{trig}>20$GeV/c
$1<p_T^{assoc}<2$GeV/c

Motivation

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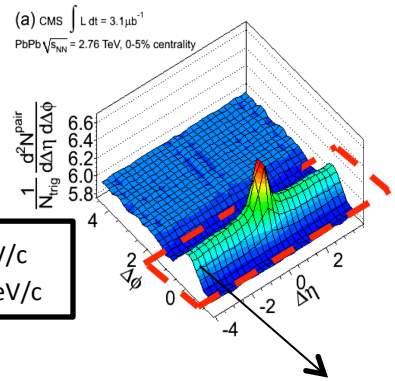
Low p_T (a couple GeV/c) → High p_T (tens of GeV/c)



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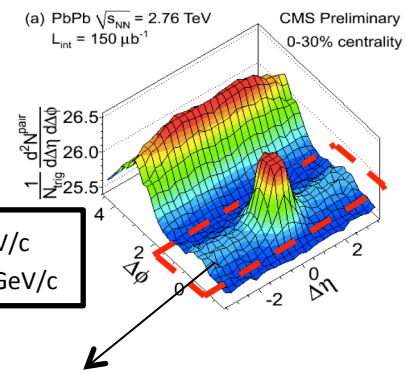
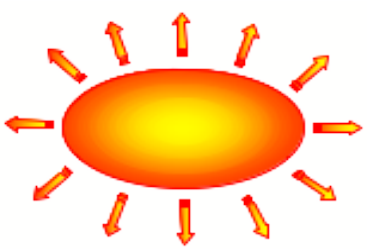
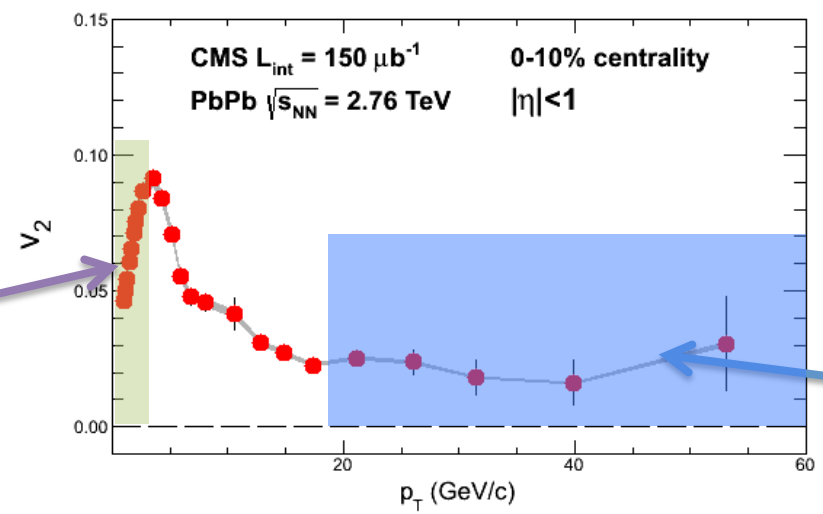
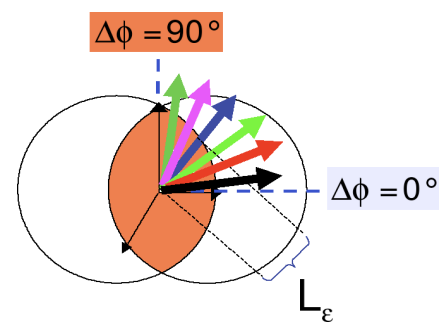


$p_T^{trig}>20$GeV/c
$1<p_T^{assoc}<2$GeV/c

Single-particle azimuthal anisotropy (v_n)







Flow dominant
- **η/s**
- **Initial condition**

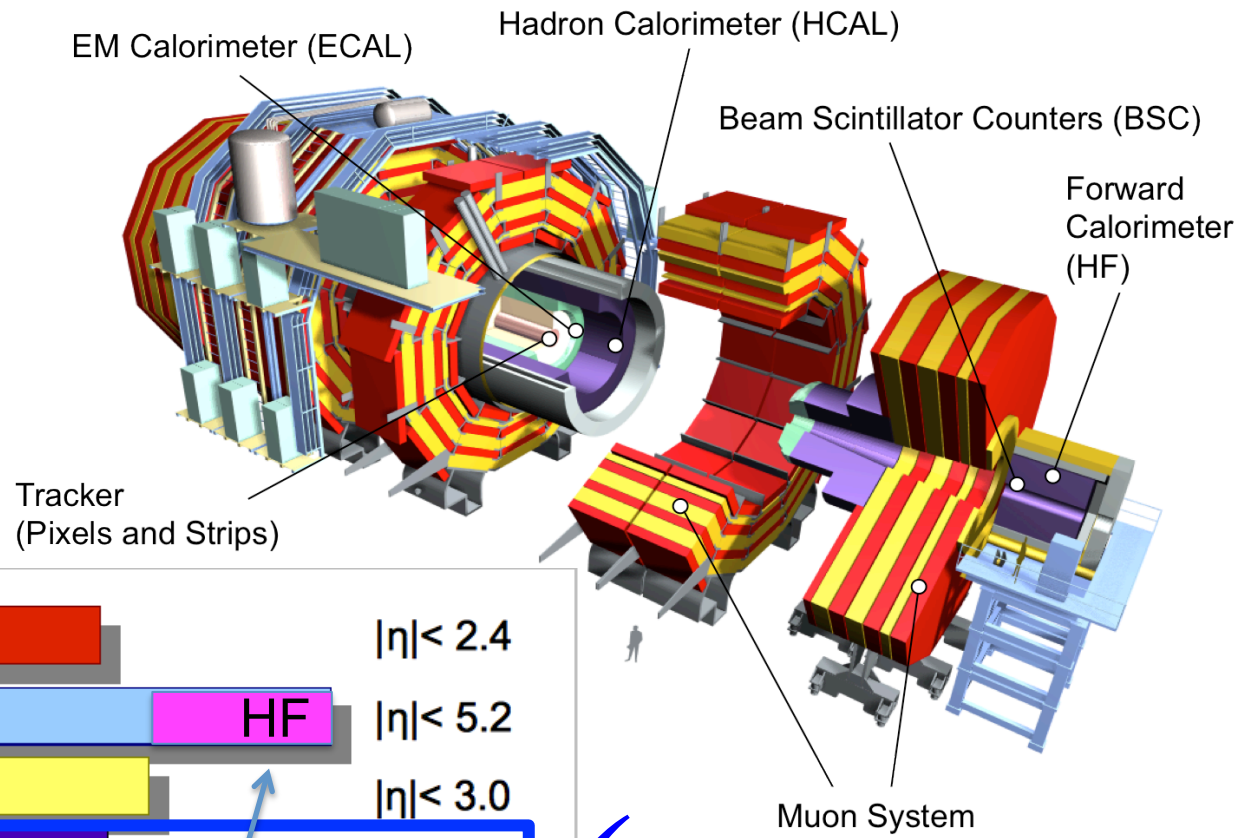
Jet quenching dominant
- **Energy loss**
- **Initial condition**

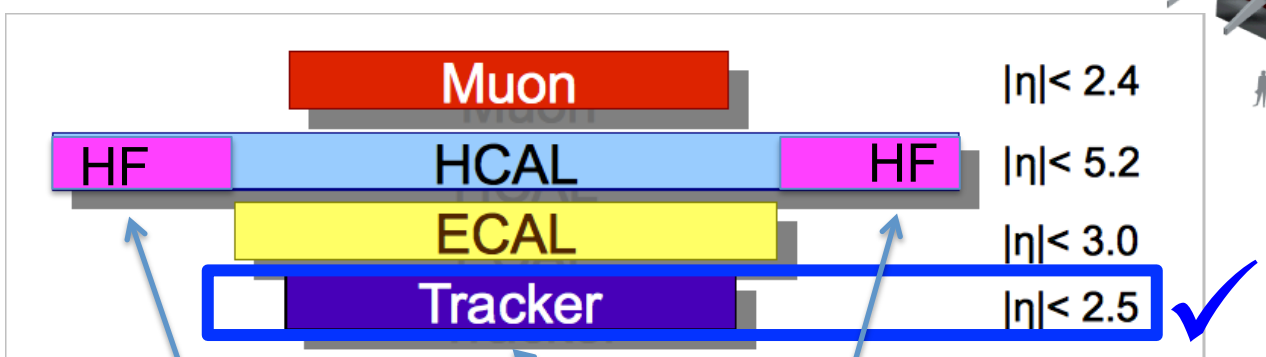
And ridge/correlations in pPb, pp colisions; CGC/hydrodynamics

CMS di-hadron correlations measurements

- PbPb collisons
  - Centrality dependence study (low p_T)
  - Very high p_T correlations
  - Correlations in ultra-central (0-0.2%) collisions
- pPb collisions (Ridge yield, $v_2\{2\}$, $v_2\{4\}$, $v_3\{2\}$)
- pp collisions (Ridge yield)

CMS experiment at LHC





Charged particle tracks
(p_T > 0.2 GeV/c)
Event-plane determination

Di-hadron correlations

Reconstructed tracks with |η|<2.4

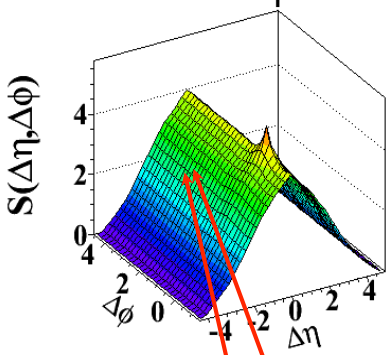
Signal pair distribution:

$$S(\Delta\eta,\Delta\varphi) = \frac{1}{N_{trig}} \frac{d^2N^{same}}{d\Delta\eta d\Delta\varphi}$$

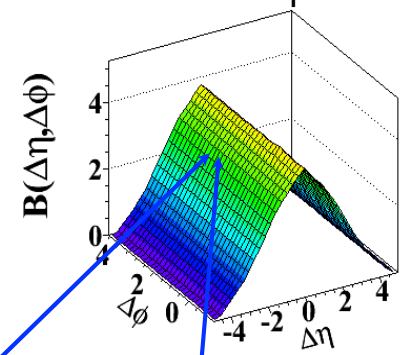
Background pair distribution:

$$B(\Delta\eta,\Delta\varphi) = \frac{1}{N_{trig}} \frac{d^2N^{mix}}{d\Delta\eta d\Delta\varphi}$$

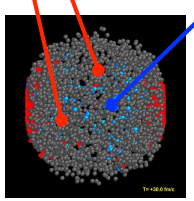
same event pairs



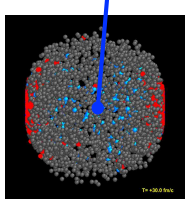
mixed event pairs



Event 1:



Event 2:

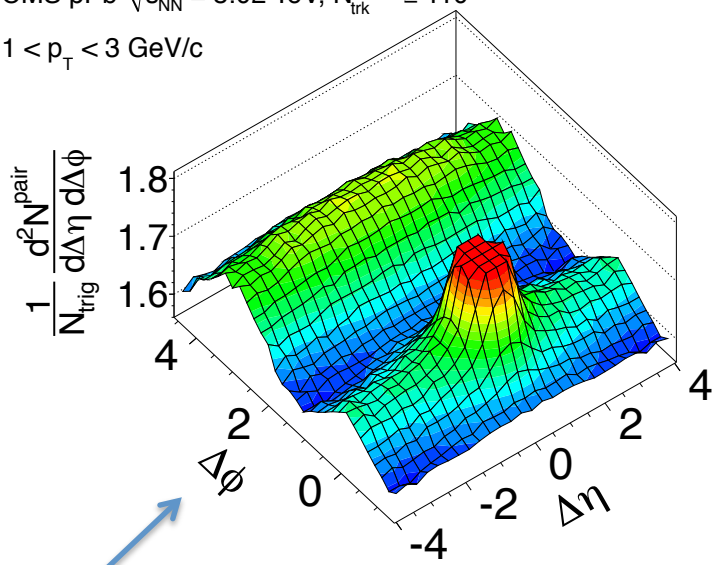


$\Delta\eta = \eta^{assoc} - \eta^{trig}$

$\Delta\phi = \phi^{assoc} - \phi^{trig}$

CMS pPb $\sqrt{s_{NN}}$ = 5.02 TeV, $N_{trk}^{offline} \geq 110$

$1 < p_T < 3$ GeV/c

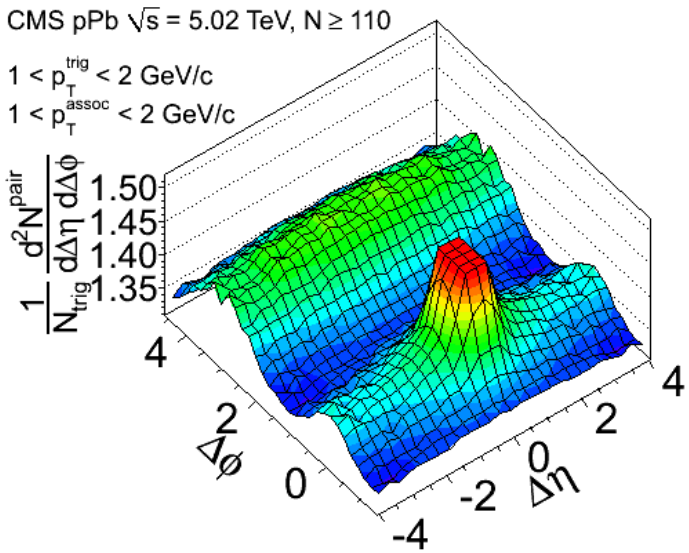


Physics Letters B
718 (2013) 795–814

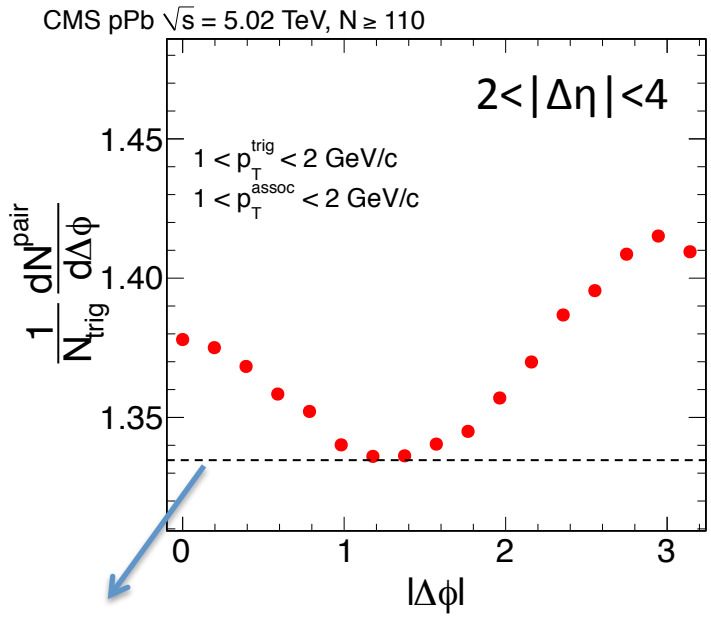
Associated hadron yield per trigger:

$$\frac{1}{N_{trig}} \frac{d^2N^{pair}}{d\Delta\eta d\Delta\phi} = B(0,0) \times \frac{S(\Delta\eta,\Delta\phi)}{B(\Delta\eta,\Delta\phi)}$$

Δϕ-projected correlation functions and yield

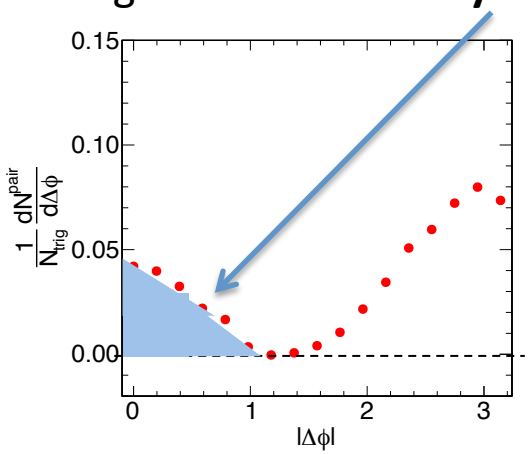


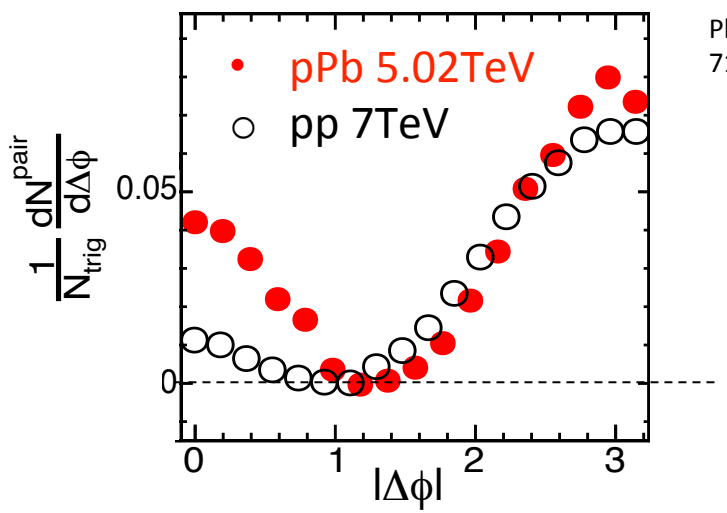
Average over ridge region (2<|Δη|<4)



Shift the distribution to zero yield at minimum (ZYAM)

Integrated associated **yield**





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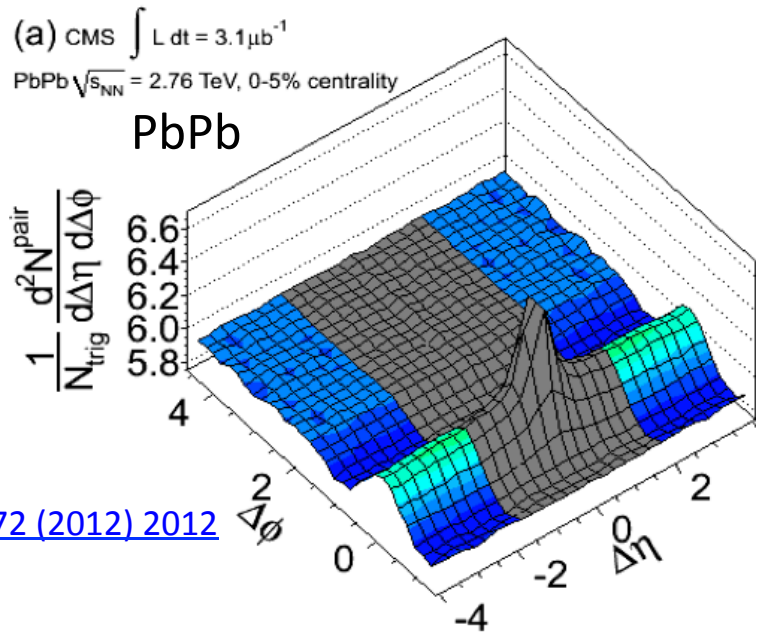
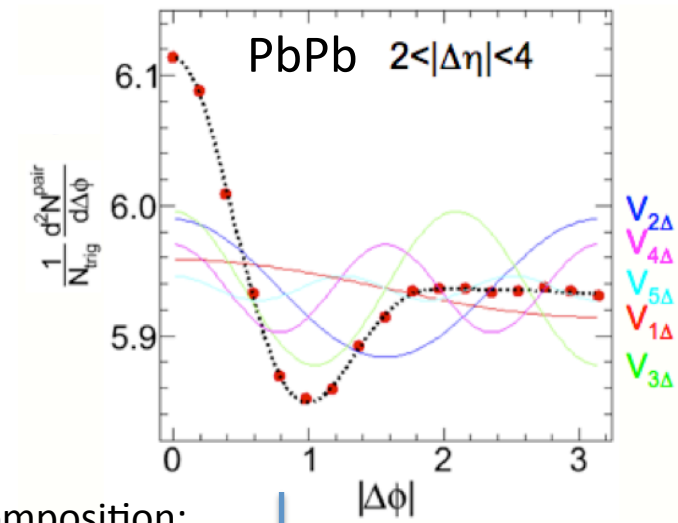
Fourier harmonic decomposition



EPJC 72 (2012) 2012

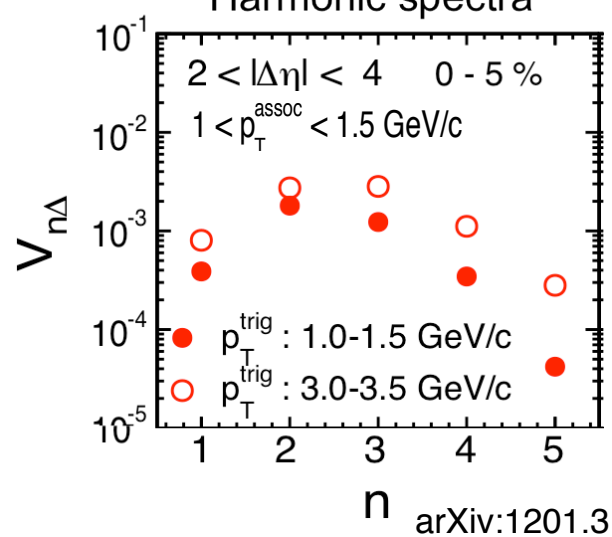
Average over ridge region (2<|Δη|<4)



Fourier decomposition:

$$\frac{dN^{pair}}{d\Delta\phi} \sim 1 + 2\sum_{n=1} V_{n\Delta} \cos(n\Delta\phi)$$

Harmonic spectra



arXiv:1201.3158

Assuming factorization:

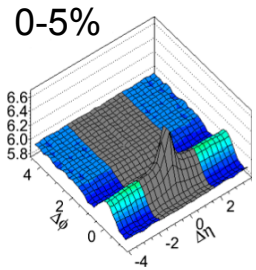
$$V_{n\Delta} = v_n(p_T^{trig}) \times v_n(p_T^{assoc})$$

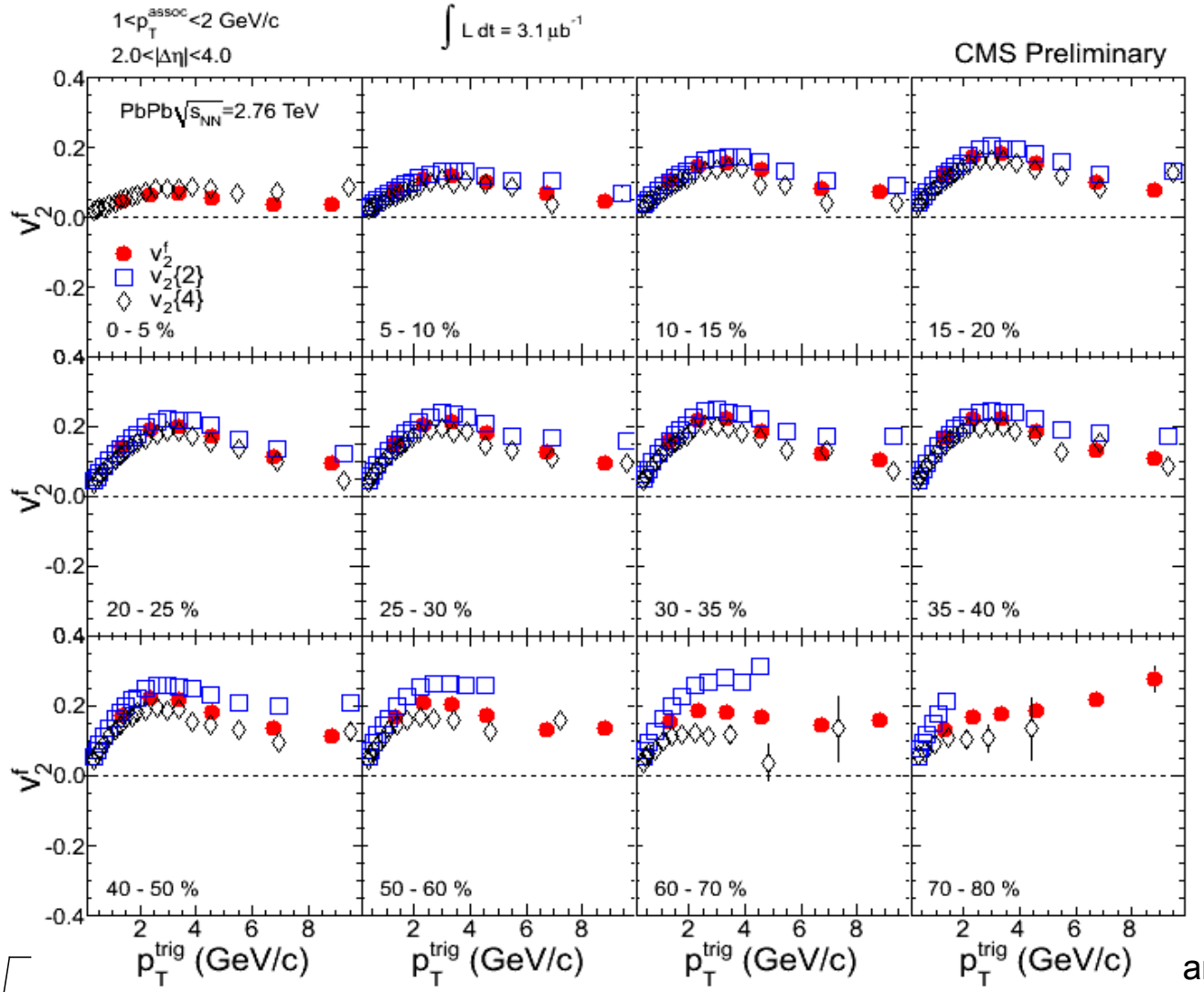
$$v_n\{2, |\Delta\eta| > 2\}(p_T) = \frac{V_{n\Delta}(p_T, p_T^{ref})}{\sqrt{V_{n\Delta}(p_T^{ref}, p_T^{ref})}}$$

Take low reference p_T bin (e.g.: 0.3-3 GeV/c)

v_2 from long-range correlations

0-5%

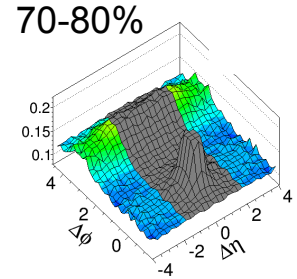




v_2^f with $2<|\Delta\eta|<4$

No η gap for $v_2\{2\}$

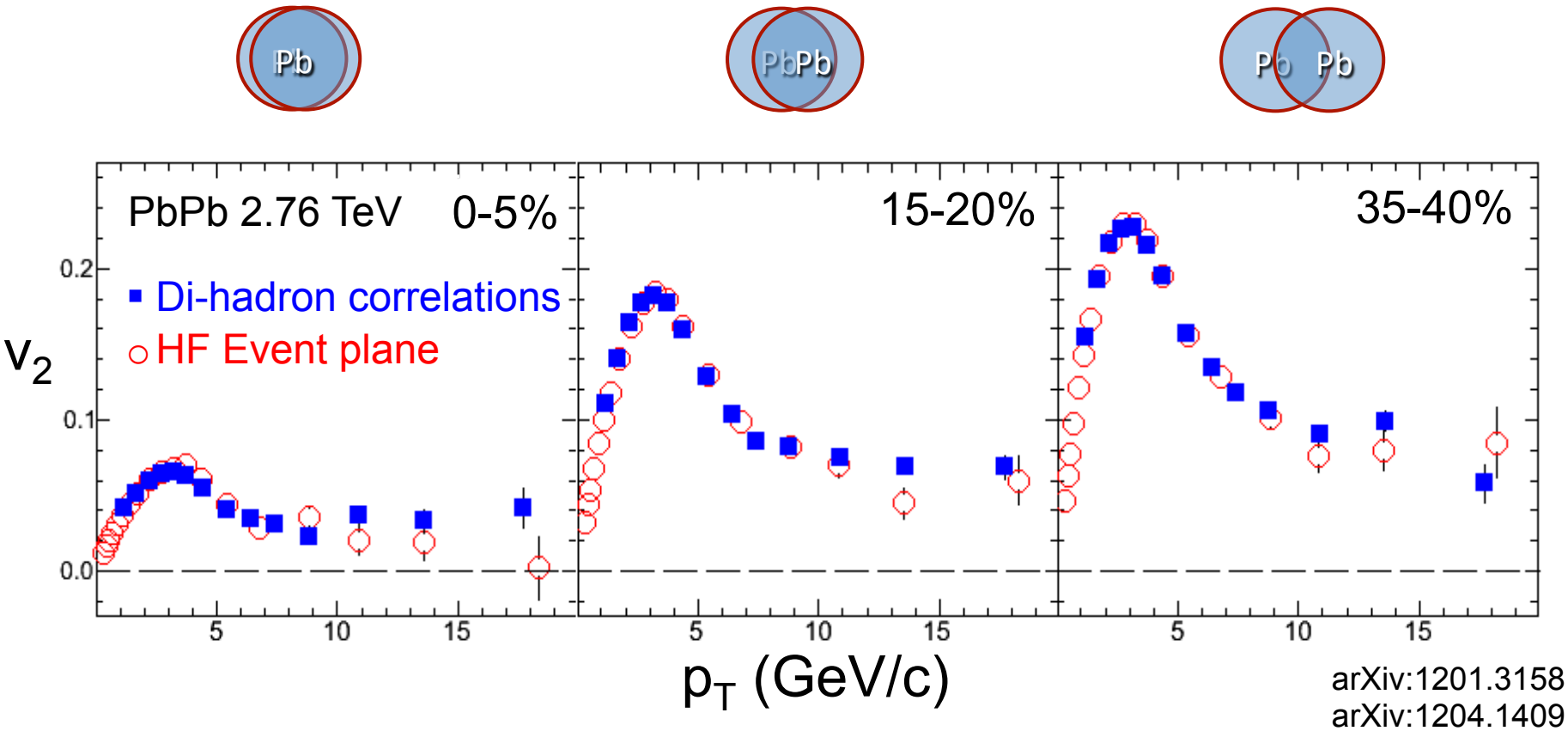
70-80%



arXiv:1201.3158

$V_n^f(\text{Fourier}) \xrightarrow{\sqrt{\ }} v_n^f(\text{flow})$

Comparing with v_2 from Event Plane method

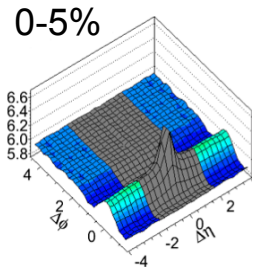


arXiv:1201.3158
arXiv:1204.1409

$v_2(p_T)$ from correlation method derived by assuming factorization agrees well with EP method

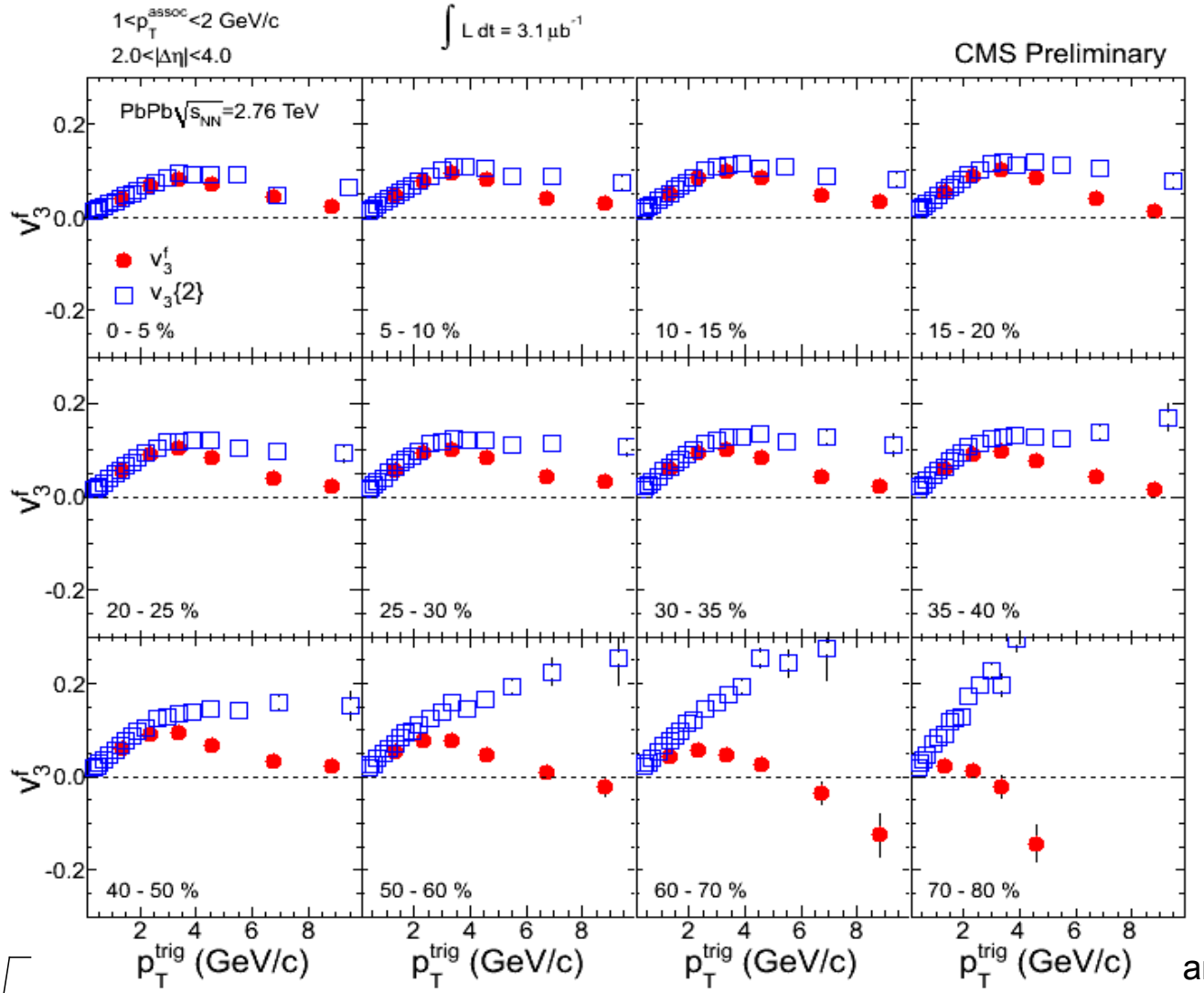
v_3 from long-range correlations

0-5%



● v_3^f

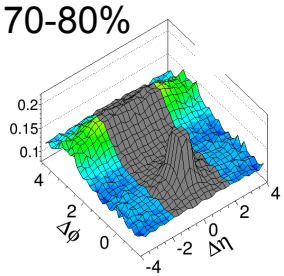
□ $v_3\{2\}$



v_3^f with $2<|\Delta\eta|<4$

No η gap for $v_3\{2\}$

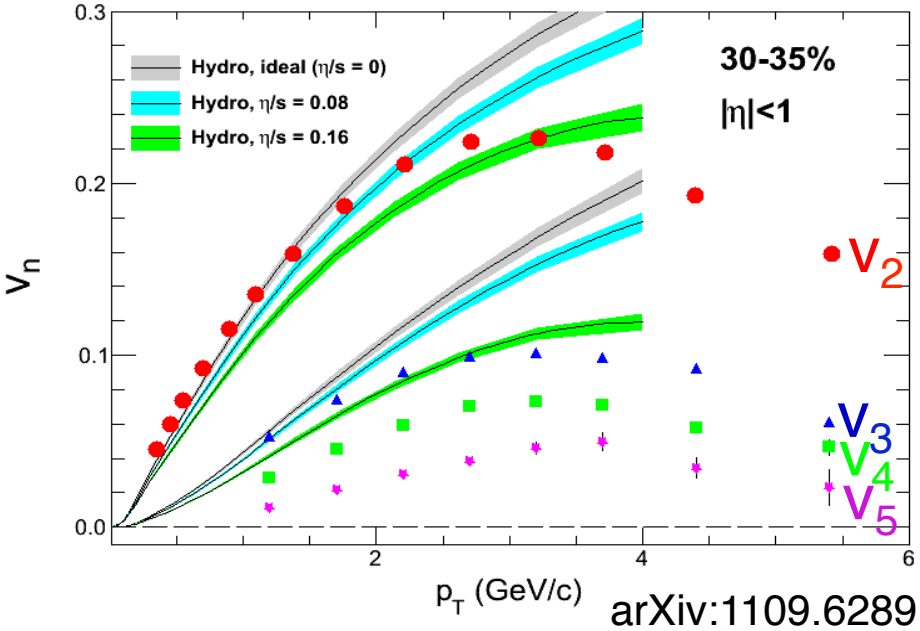
70-80%



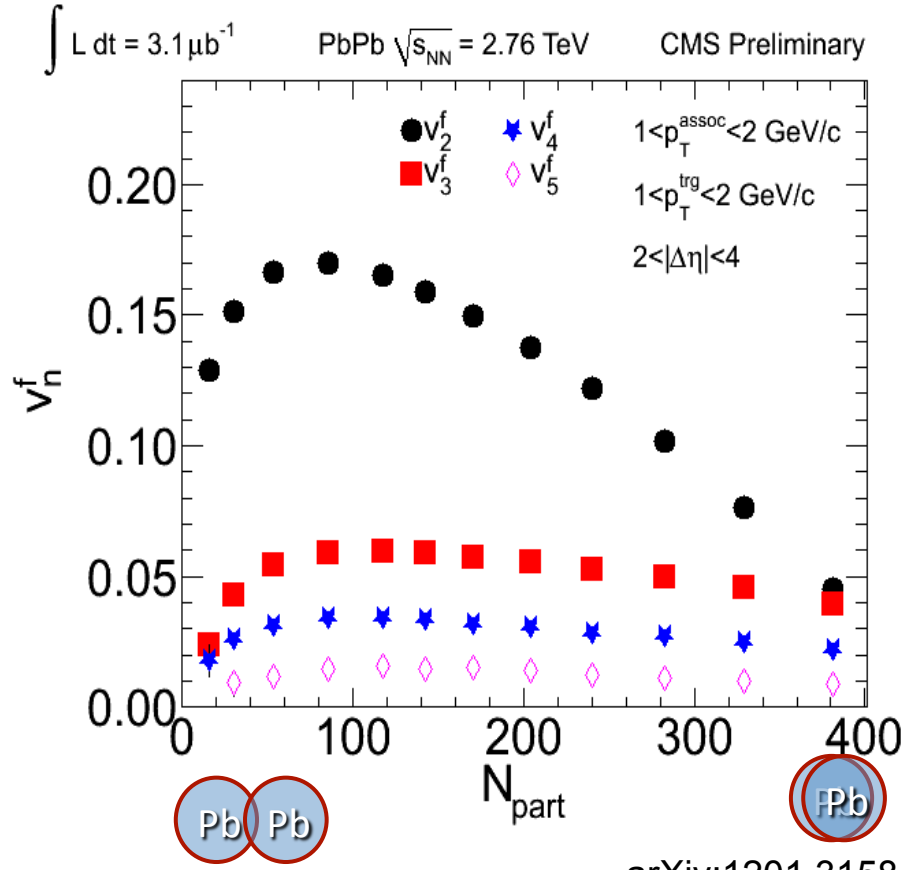
arXiv:1201.3158

$V_n^f(\text{Fourier}) \xrightarrow{\sqrt{\ }} v_n^f(\text{flow})$

Full flow harmonics (v_2, v_3, …)



arXiv:1109.6289



arXiv:1201.3158

Measure all v_n to constrain the hydro calculations

✧ η/s

✧ Initial conditions (Glauber vs CGC)

High p_T di-hadron correlations

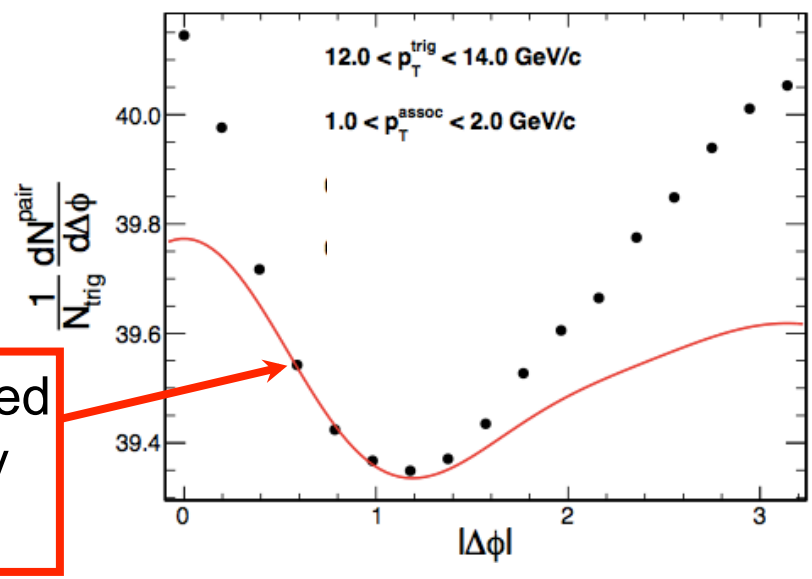
The ZYAM Procedure:

The 2D correlations are averaged over $\Delta\eta$ and projected onto the $\Delta\phi$-axis to get 1D correlations.

v_n Subtraction via the Zero-Yield-At-Minimum procedure

$$\frac{1}{N_{trig}}\frac{dN^{pair}_{sub}}{d\Delta\phi} = \frac{1}{N_{trig}}\frac{dN^{pair}}{d\Delta\phi} - a\left(1+2\sum_n v_n(p_T^{trig})v_n(p_T^{assoc})\cos(n\Delta\phi)\right)$$

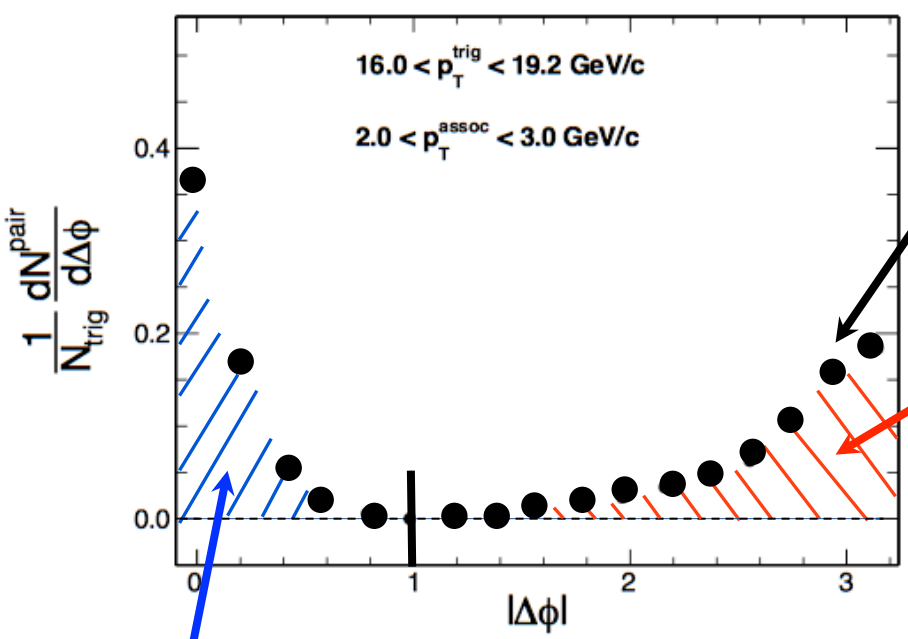
- Find "a" such that the minimum of the difference is around 0 at $\Delta\phi=\Delta\phi_{ZYAM}$



"Flow (v_2-v_4)" Background expressed as a Fourier expansion and scaled by the ZYAM procedure

Note: v_1 is not included in flow background

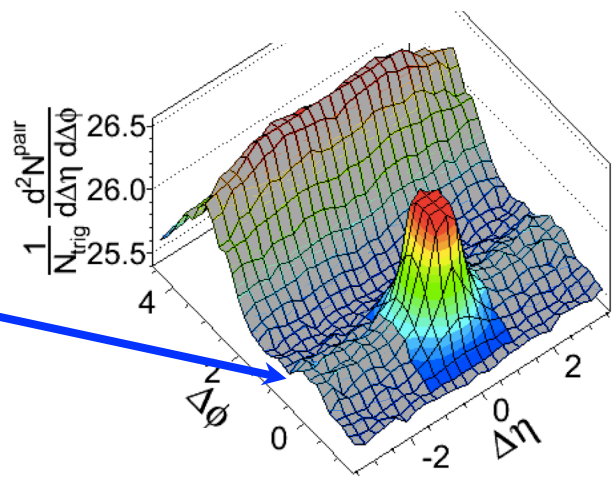
Calculating the Integrated Yield

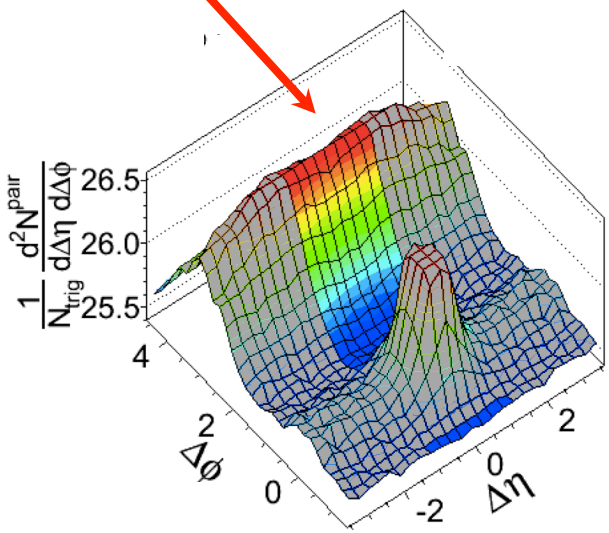


1D ZYAM Subtracted Correlation

Away-side integrated yield

Near-side integrated yield



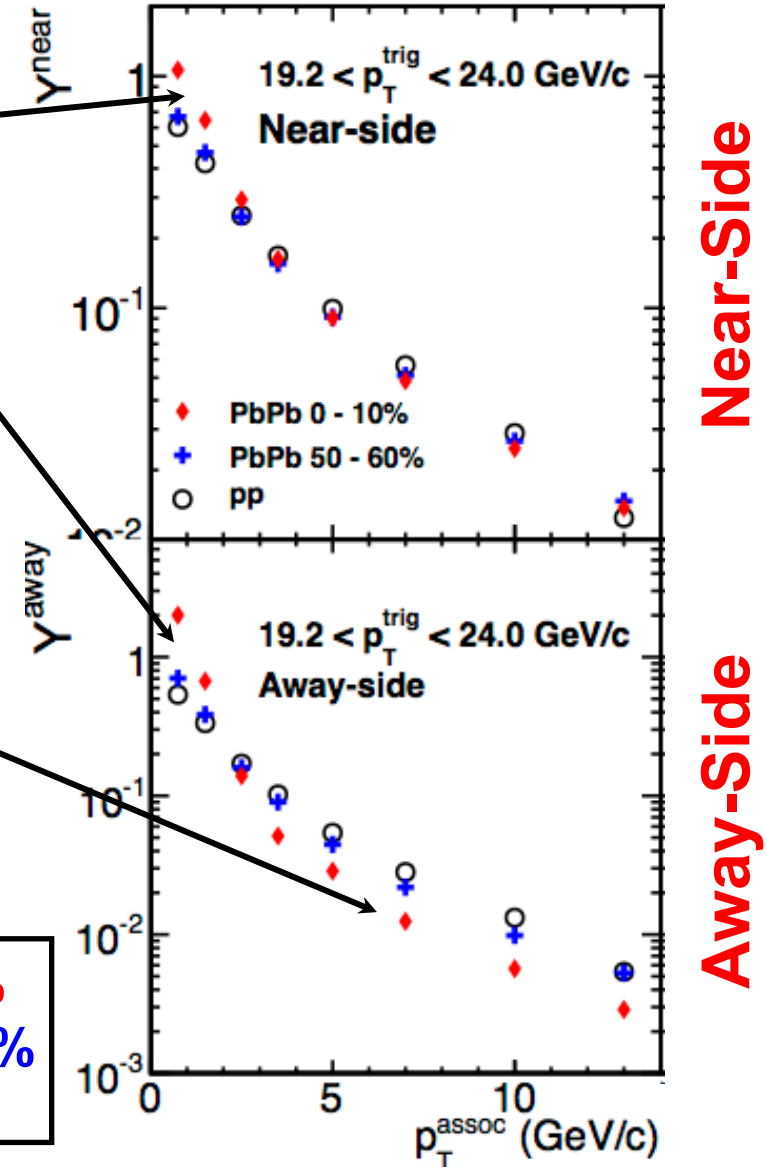


$|\Delta\eta| < 1$

Integrated Yields

Differences at low associated particle p_T are clearly visible on the near and away-side

The away-side also shows large discrepancies at high associated particle p_T



We use I_{AA} ratios to quantify any modifications from pp reference:

$$I_{AA}^{near} = \frac{Y_{PbPb}^{near}}{Y_{pp}^{near}}$$

$$I_{AA}^{away} = \frac{Y_{PbPb}^{away}}{Y_{pp}^{away}}$$

0-10%
50-60%
PP

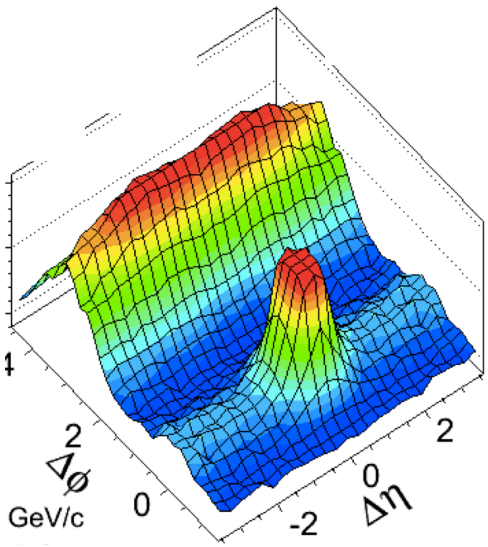
Long-Range Δη Subtraction

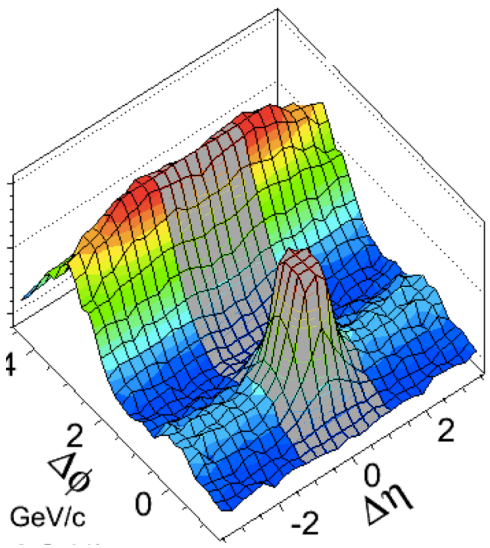
An alternate method is to use the long-range region to estimate the full flow background (including v_1)

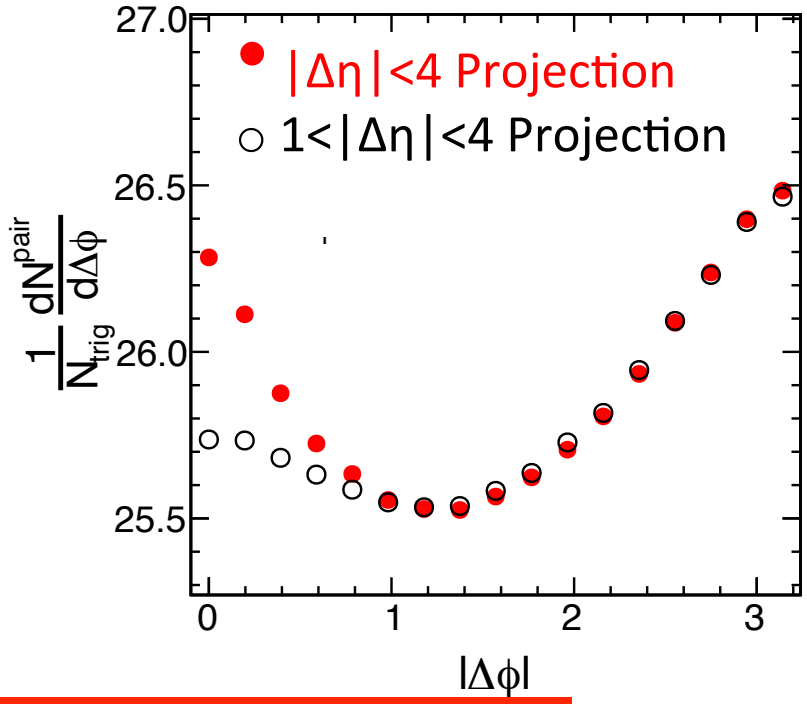
Full Range
$|\Delta\eta| < 4$

—

Long Range
$1 < |\Delta\eta| < 4$

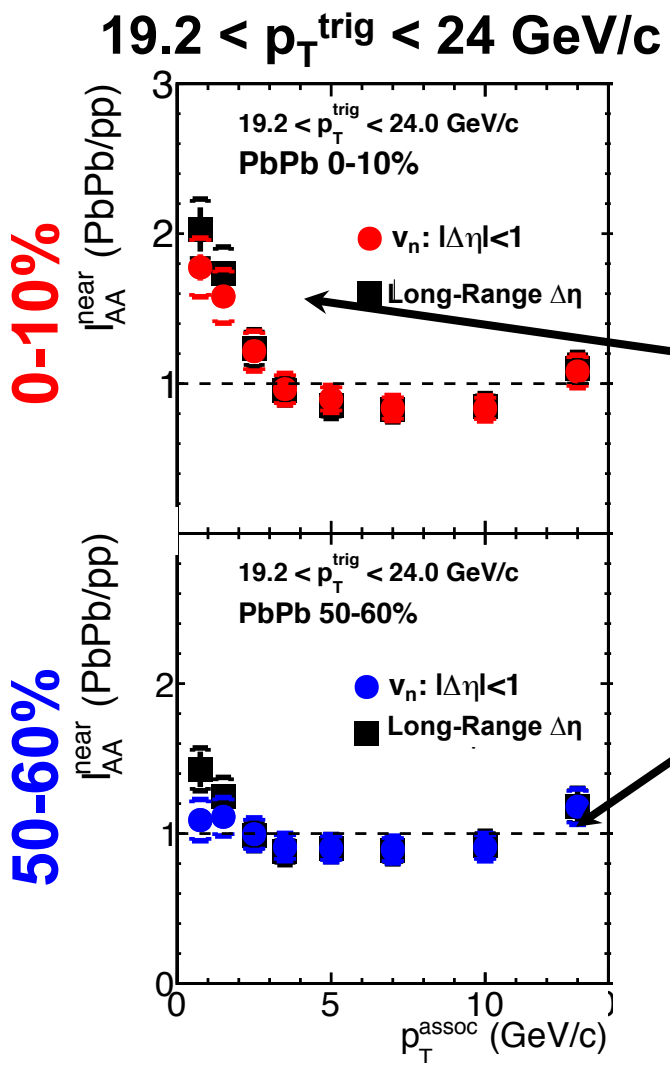






Note: This method can only be applied to the near-side

Near-Side I_{AA}

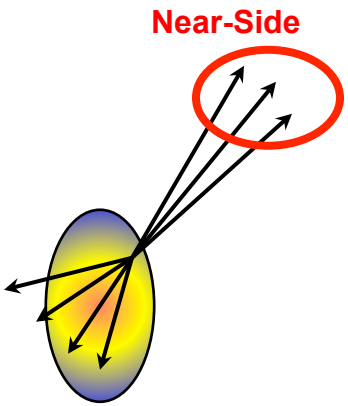


We can compare the near-side I_{AA} results from the ZYAM and the Long-Range Δη subtraction methods

Significant enhancement of low p_T particles

No significant suppression or enhancement at high p_T

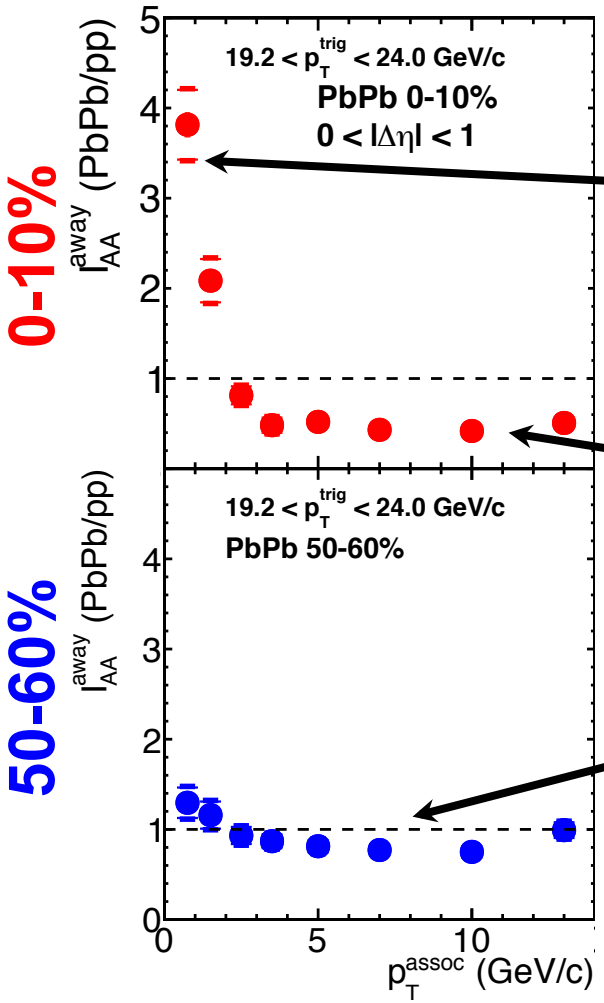
There is a slight difference between the two methods at low p_T, possibly due to a long-range cos(ΔØ) background term



CMS-PAS-HIN-12-010

Away-Side I_{AA}

$19.2 < p_T^{trig} < 24$ GeV/c

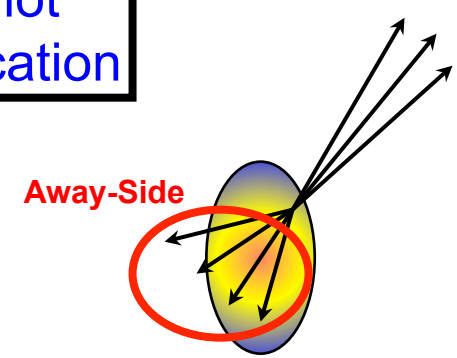


Factor of ~4 enhancement of low p_T particles in central collisions

Factor of ~2 suppression at high p_T in central collisions

Peripheral events do not show as much modification

Consistent with the jet quenching picture



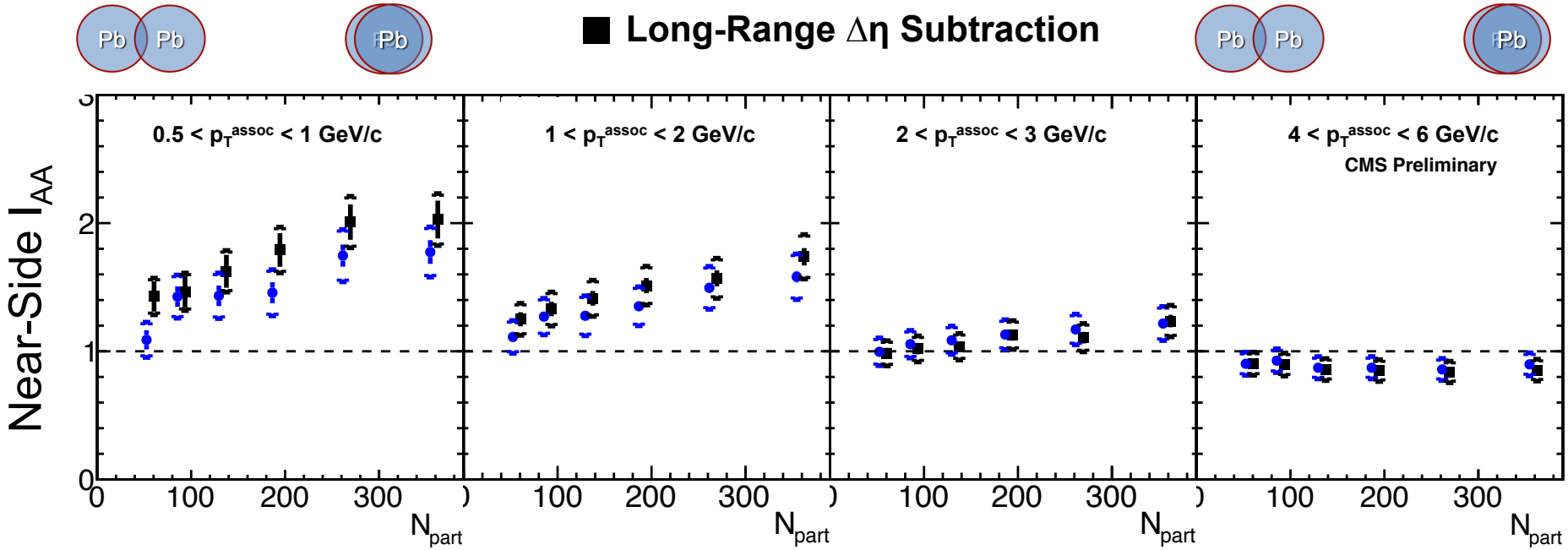
Note: the long-range $\Delta\eta$ method can only be applied to the near-side

Near-Side I_{AA} Centrality Dependence

$19.2 < p_T^{trig} < 24$ GeV/c

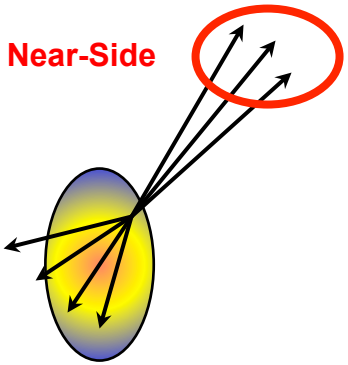
● **v_n Subtraction: $|\Delta\eta| < 1$**

■ **Long-Range $\Delta\eta$ Subtraction**



Enhancement at low p_T^{assoc}

Increases with N_{part}



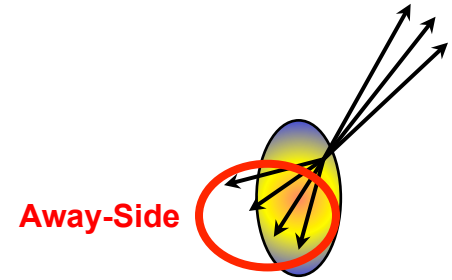
No enhancement for $p_T^{assoc} \sim 5$ GeV/c

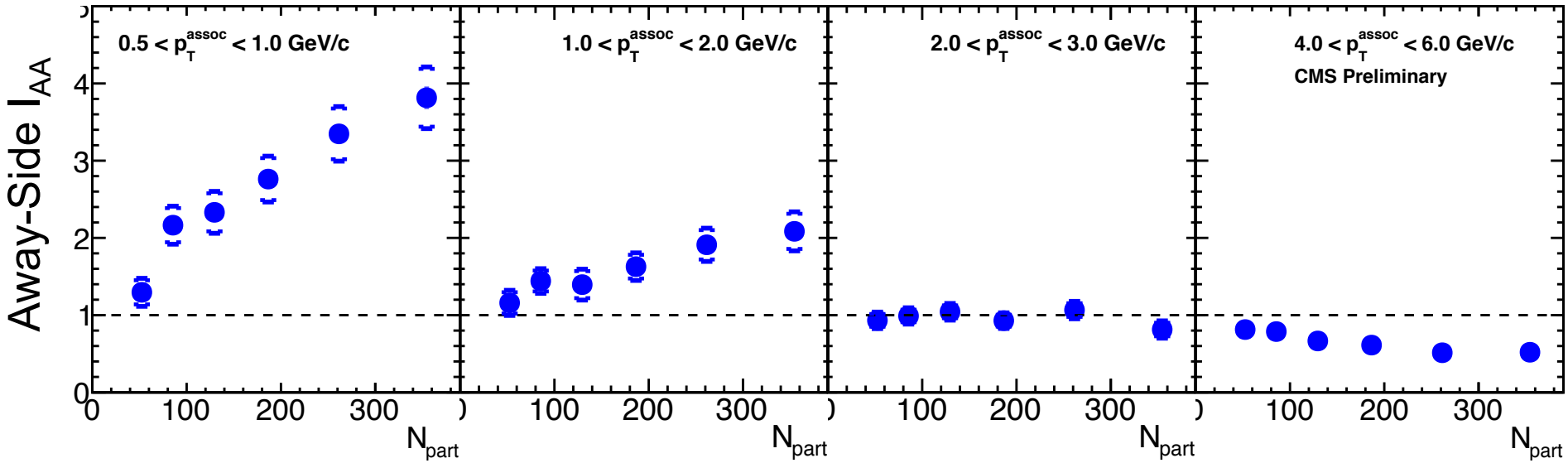
Constant with N_{part}

CMS-PAS-HIN-12-010

Away-Side I_{AA} Centrality Dependence

$19.2 < p_T^{trig} < 24$ GeV/c



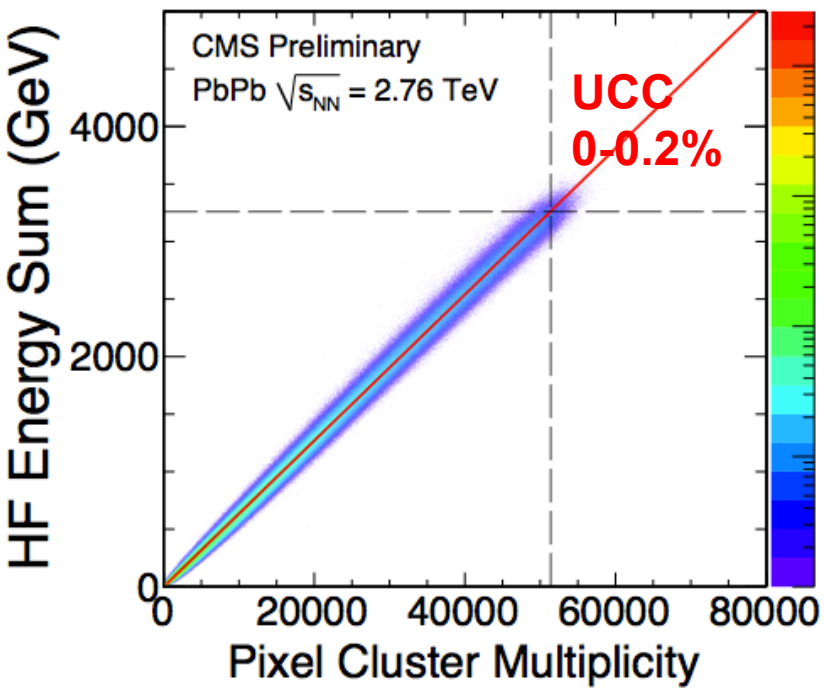


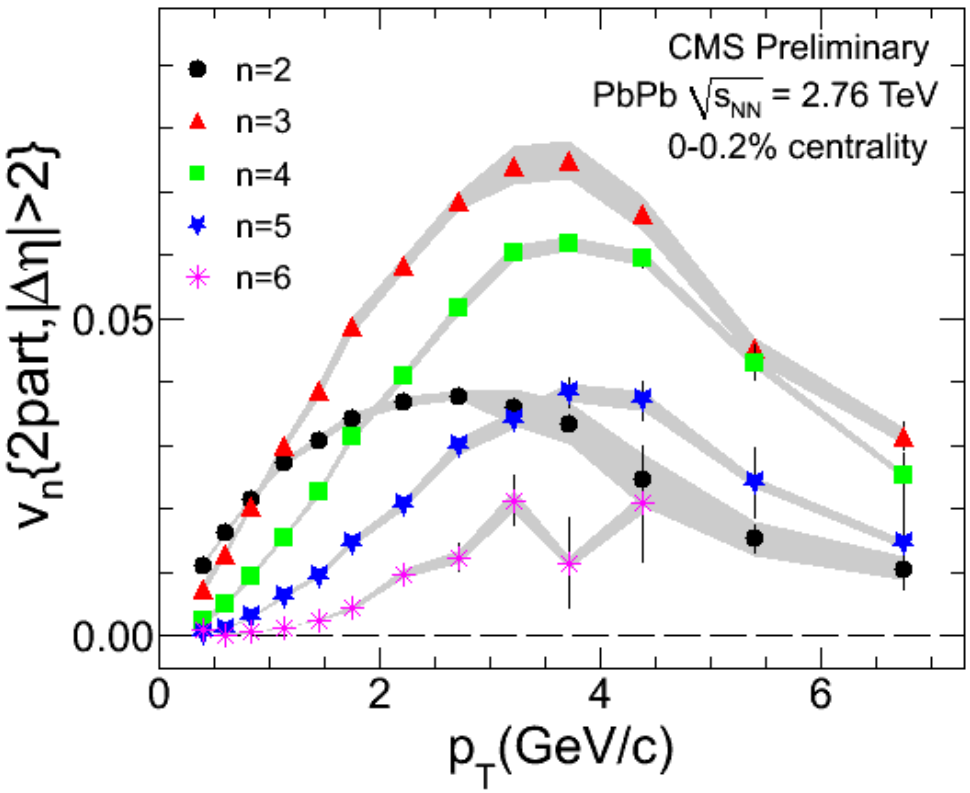
Enhancement Evolves with increasing p_T^{assoc} → **Suppresion**

There is a clear correlation between N_{part} and I_{AA} at different p_T^{assoc} consistent with the jet quenching picture

Ultra-central collisions (UCC)

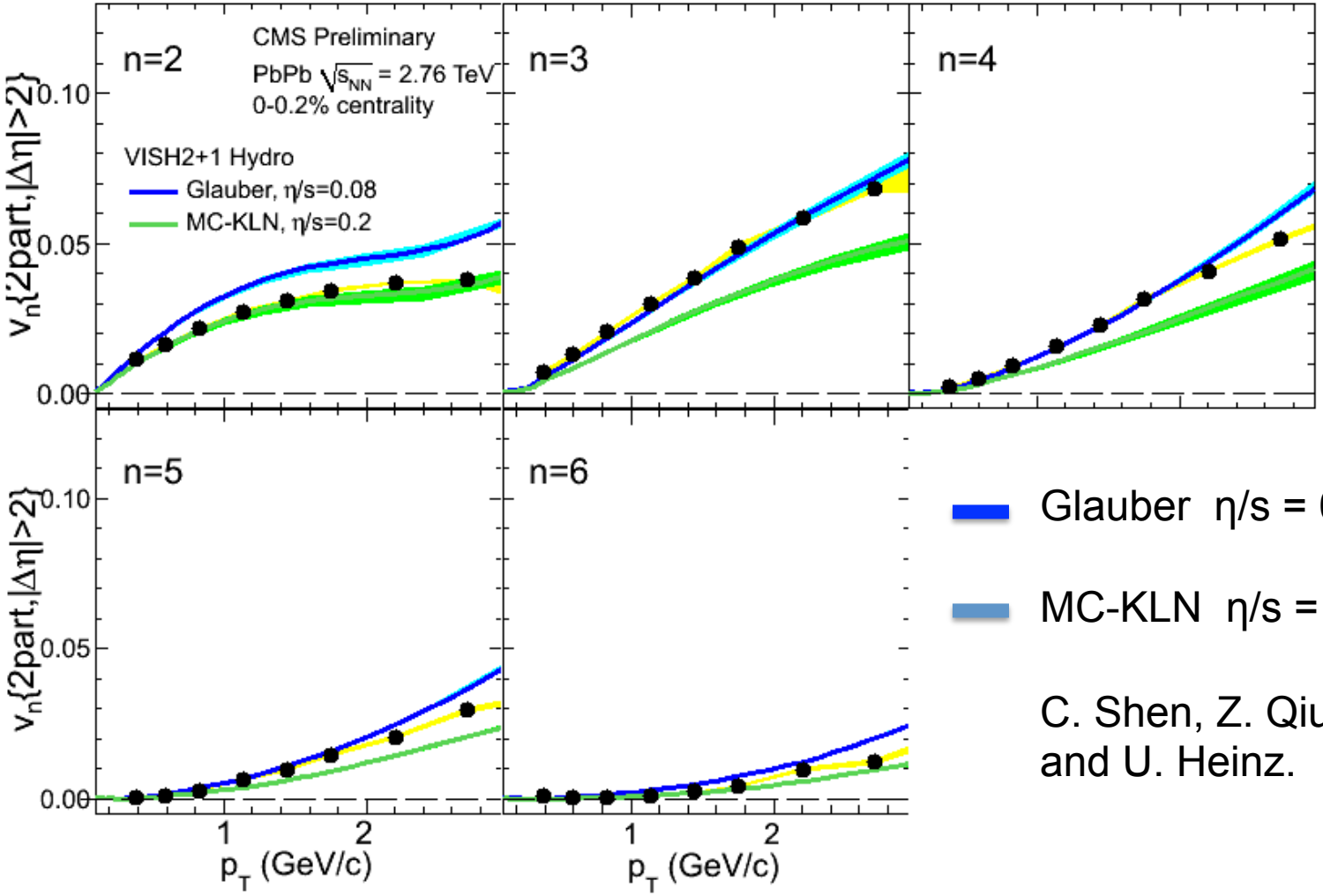
2011 UCC trigger.
~ 1.8 M events for 0-0.2%.





- v_3 larger than v_2 for p_T > 1 GeV/c
- v_5 > v_2 for p_T > 3 GeV/c

$v_n(p_T)$ comparison with hydro



Glauber η/s = 0.08

MC-KLN η/s = 0.2

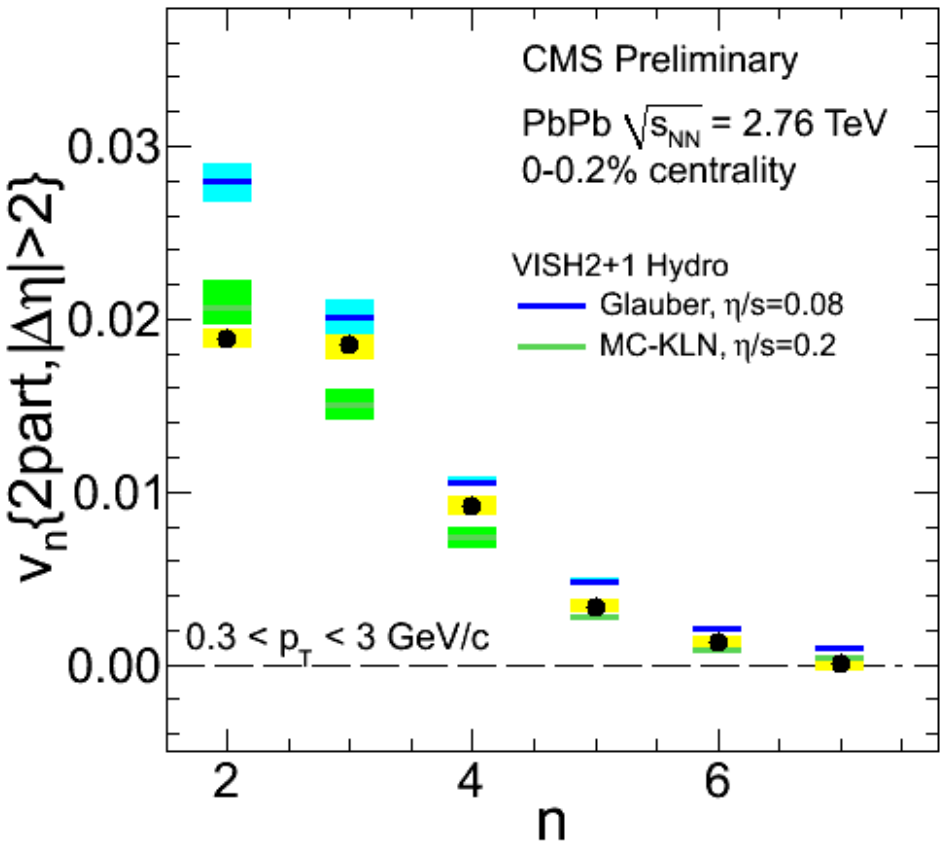
C. Shen, Z. Qiu, and U. Heinz.

η/s ~ 0.08-0.2 with the model

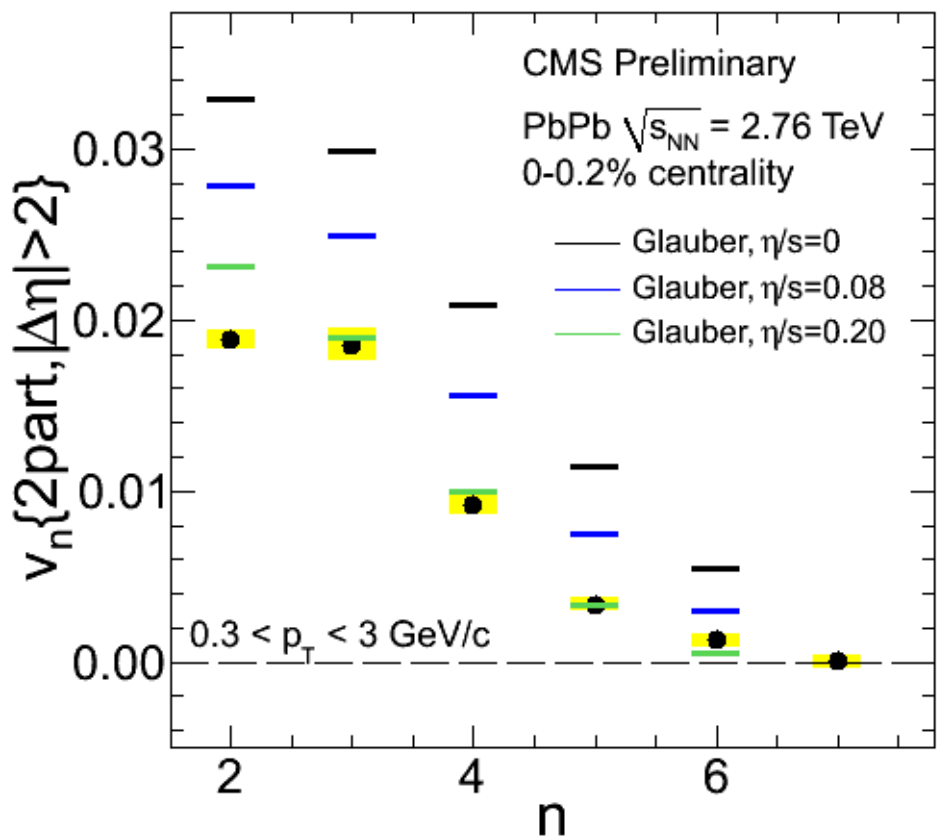
CMS-PAS-HIN-12-011

v_n vs. n comparison with hydro

C. Shen, Z. Qiu, and U. Heinz.



M. Luzum and J. Ollitrault.

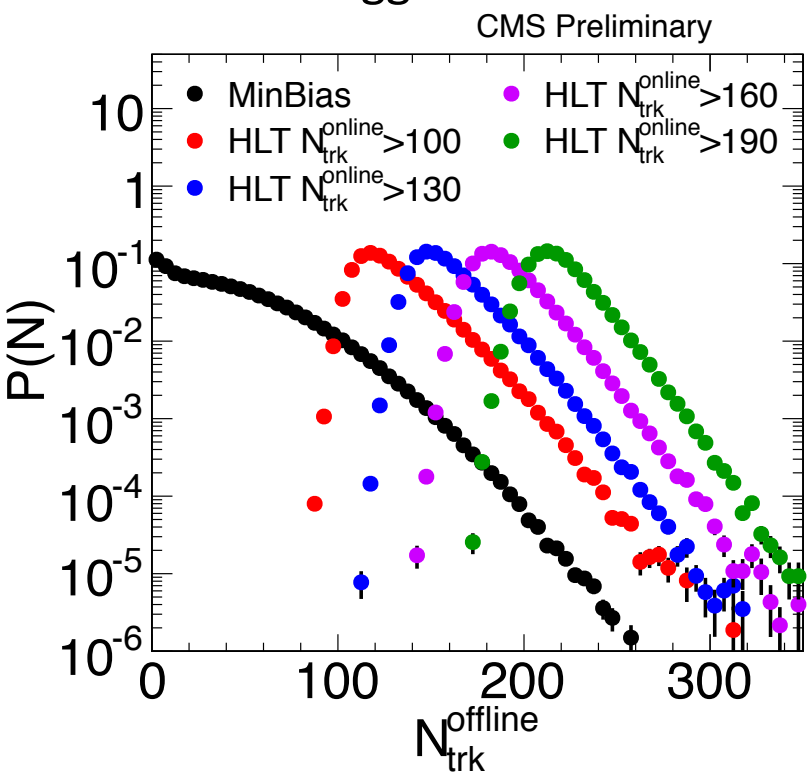


Theory reproduces ordering of harmonics with n > 2 quite well

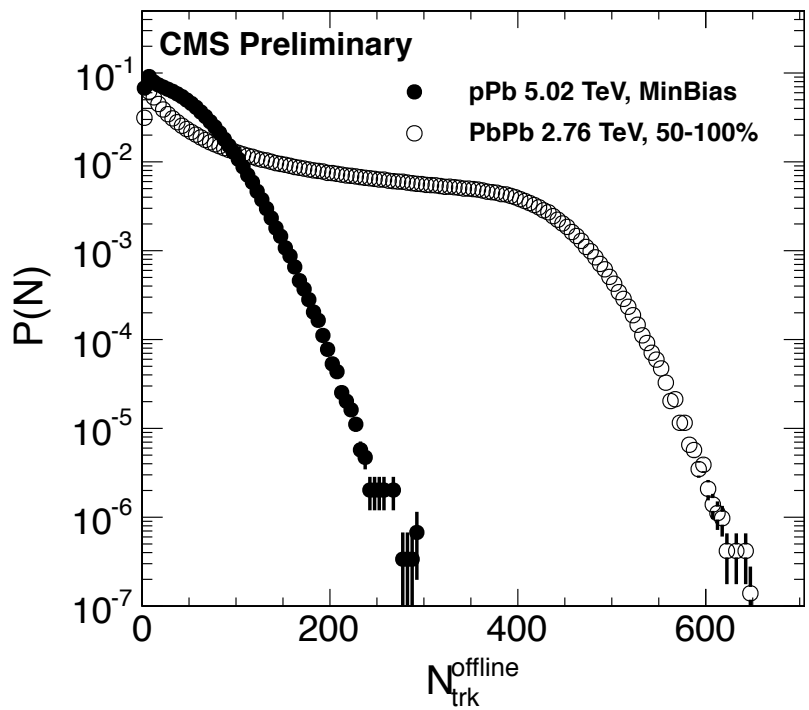
Di-hadron correlations in pPb

Multiplicity distribution:

Track (p_T>0.4 GeV/c, |η|<2.4) multiplicity distribution in pPb for different triggers



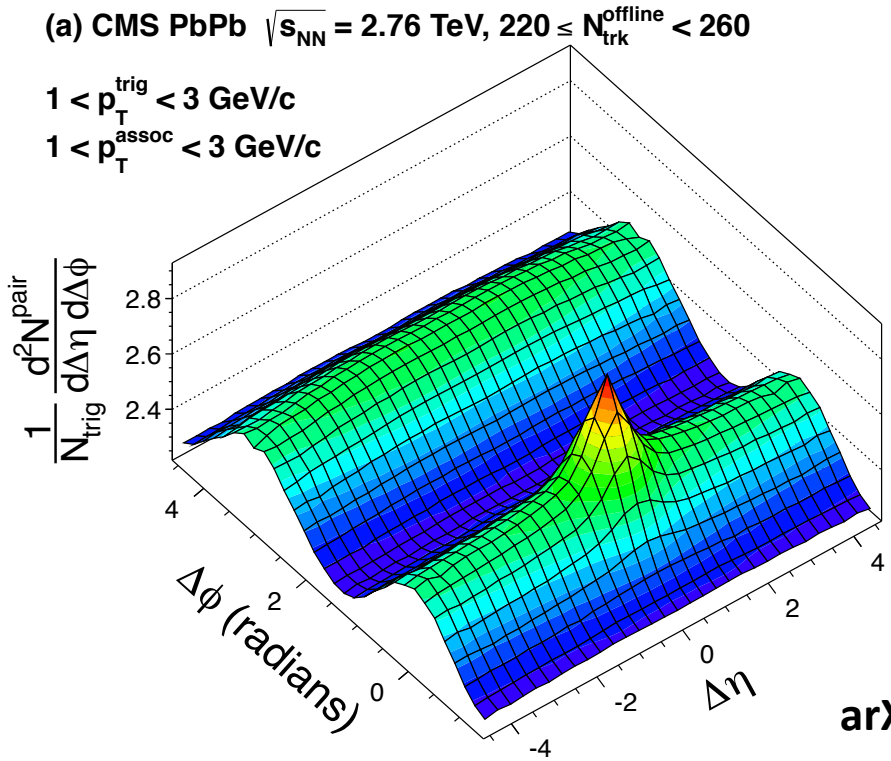
Track multiplicity distribution in MiniBias pPb and PbPb 50-100%



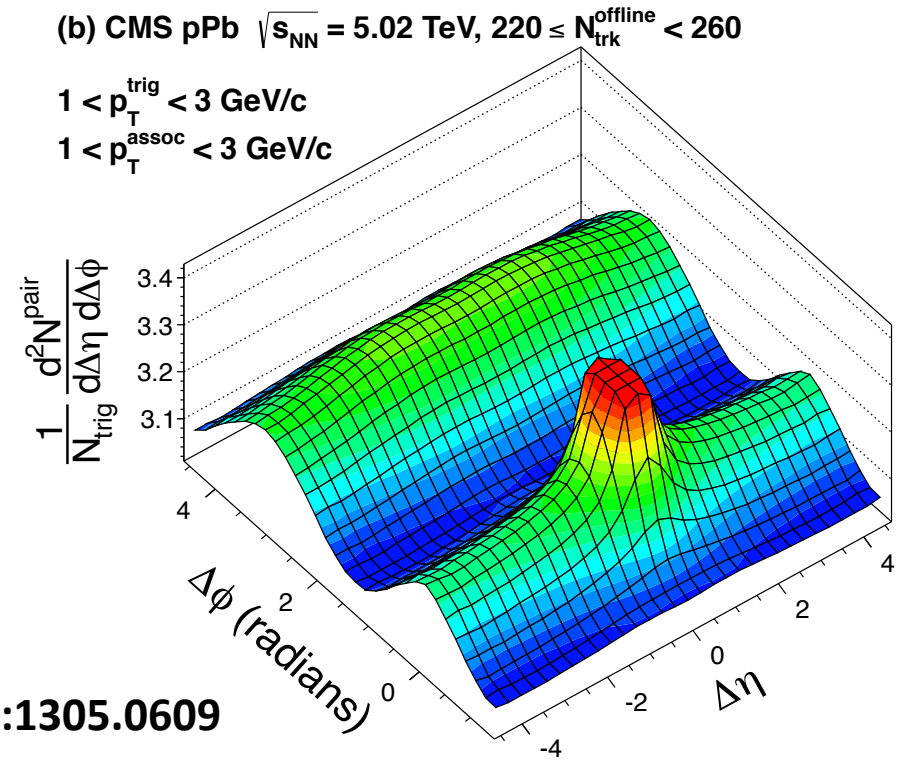
Reaches very high multiplicity (The fraction of events in 300=<$N_{trk}^{offline}$<350 is about 10^{-7} with respect to all MiniBias events. Very central !)

Comparing PbPb and pPb

PbPb



pPb



arXiv:1305.0609

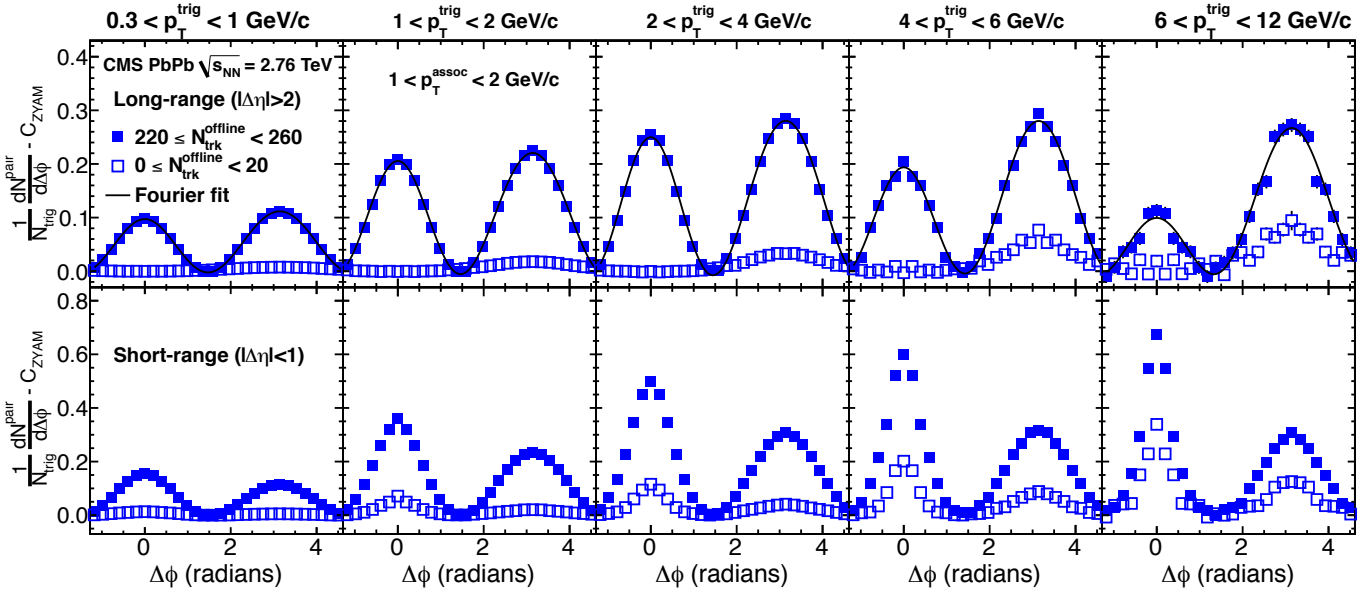
- PbPb and pPb use the same multiplicity selection, 220 =< $N_{trk}^{offline}$ <260
- Very strong long-range correlations in pPb

PbPb vs pPb: p_T dependence

PbPb

$|\Delta\eta| > 2$

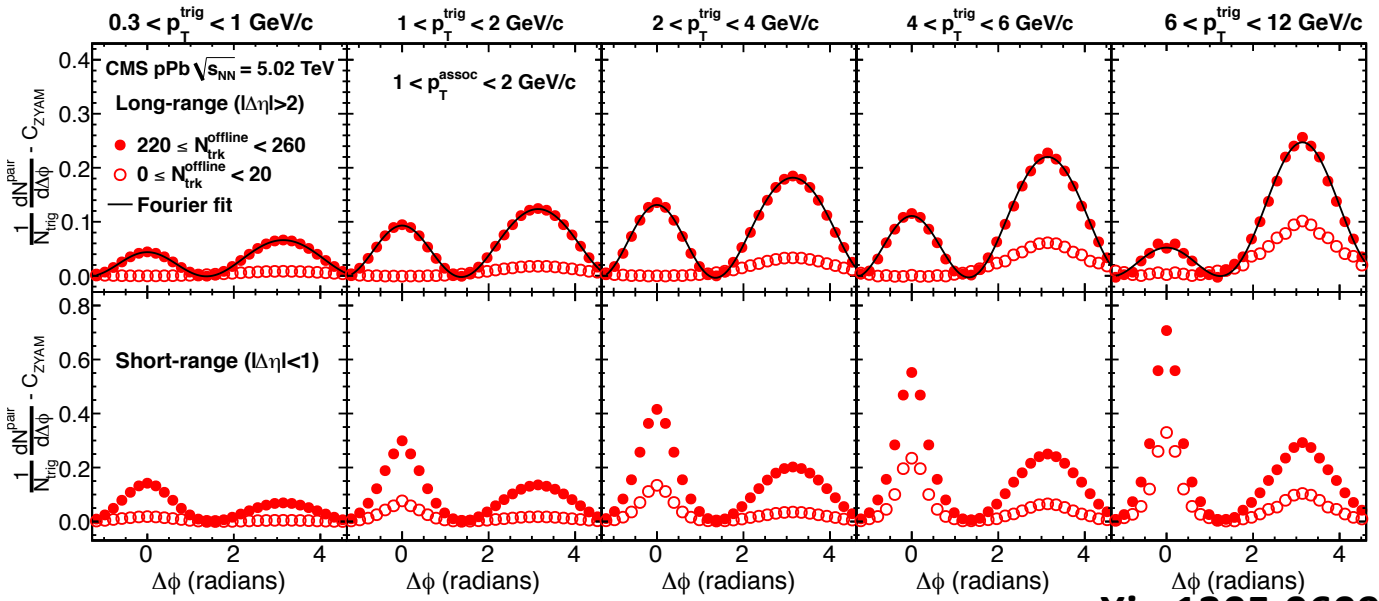
$|\Delta\eta| < 1$



pPb

$|\Delta\eta| > 2$

$|\Delta\eta| < 1$

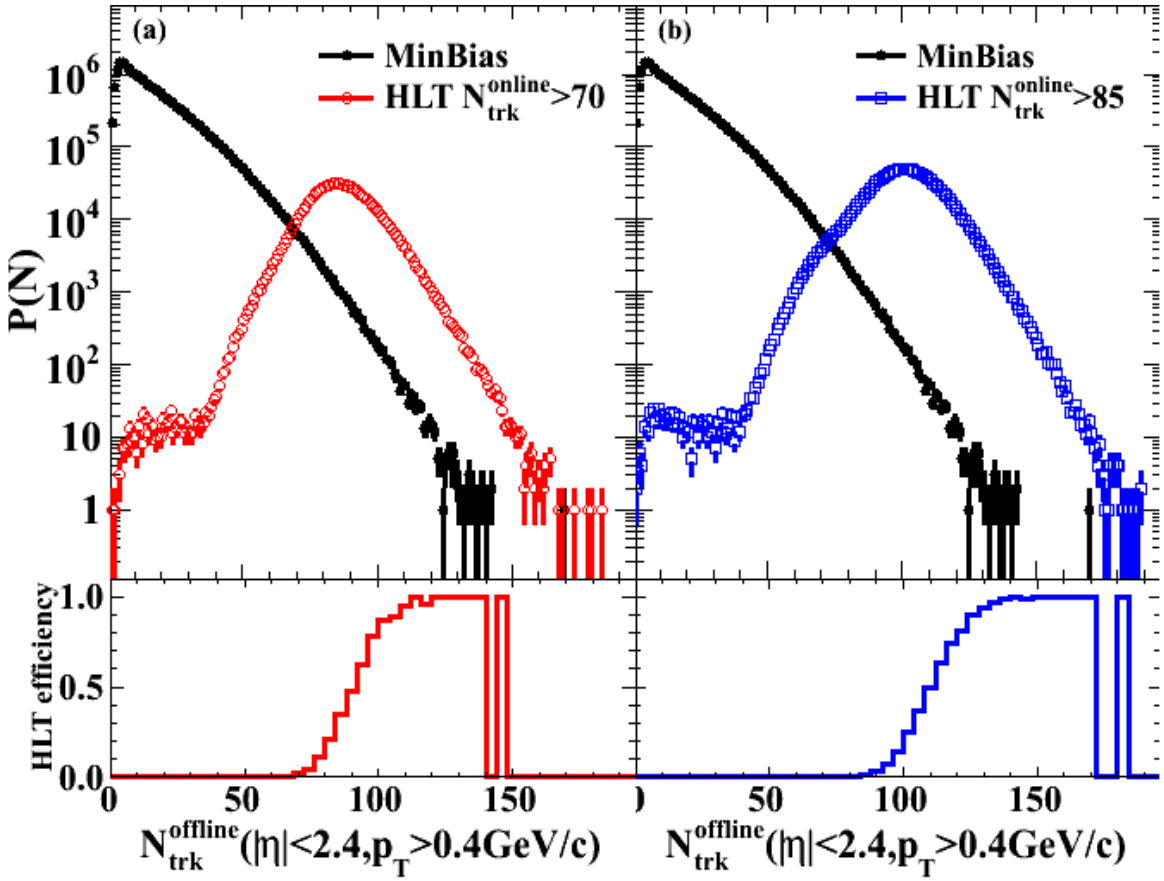


arXiv:1305.0609

Di-hadron correlations in high multiplicity pp collisions

Very high particle density regime

Is there anything interesting happening?



Dedicated triggers on high multiplicity events from a single collisions (not pileup!)

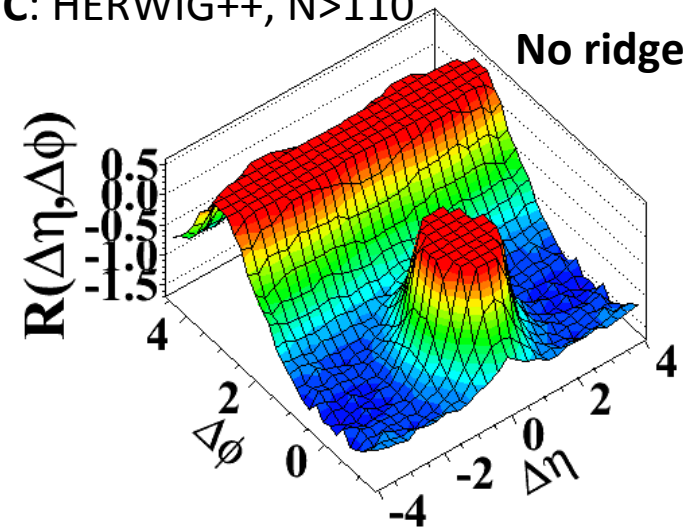
N^{online} > 85 trigger <u>un-prescaled</u> for full 980nb^{-1} data set

JHEP 09 (2010) 091

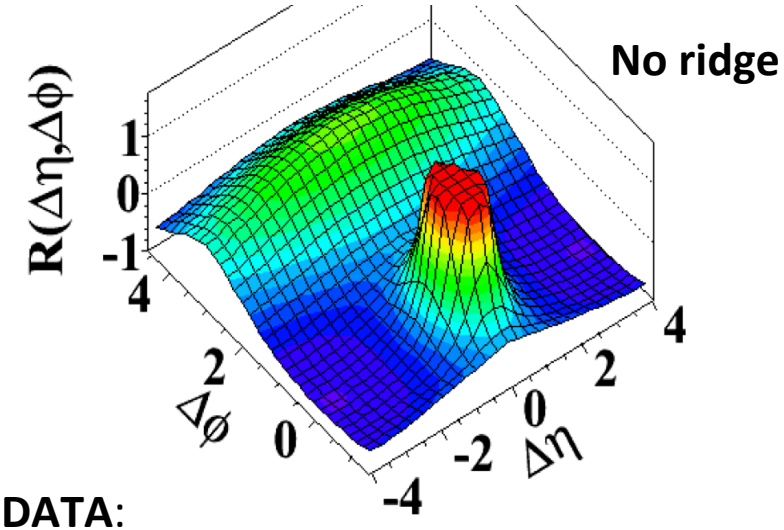
~350K top multiplicity events (N>110) out of 50 billion collisions!

Ridge in pp collisions

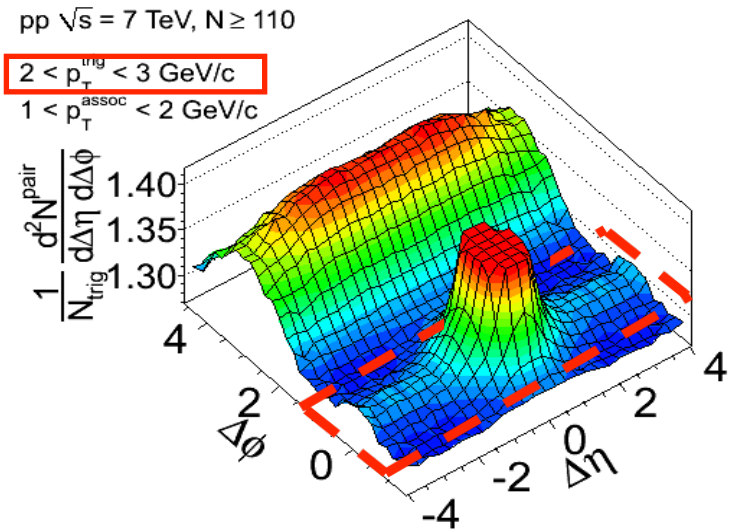
MC: HERWIG++, N>110



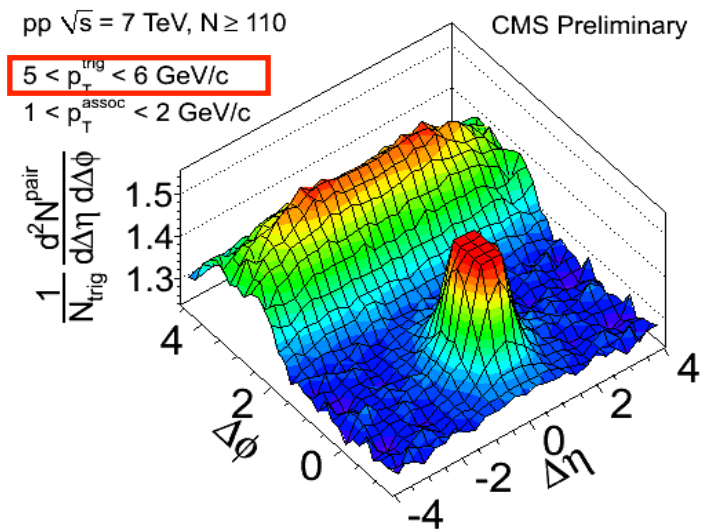
DATA: Minimum Bias pp (<N> ~ 15)



DATA:



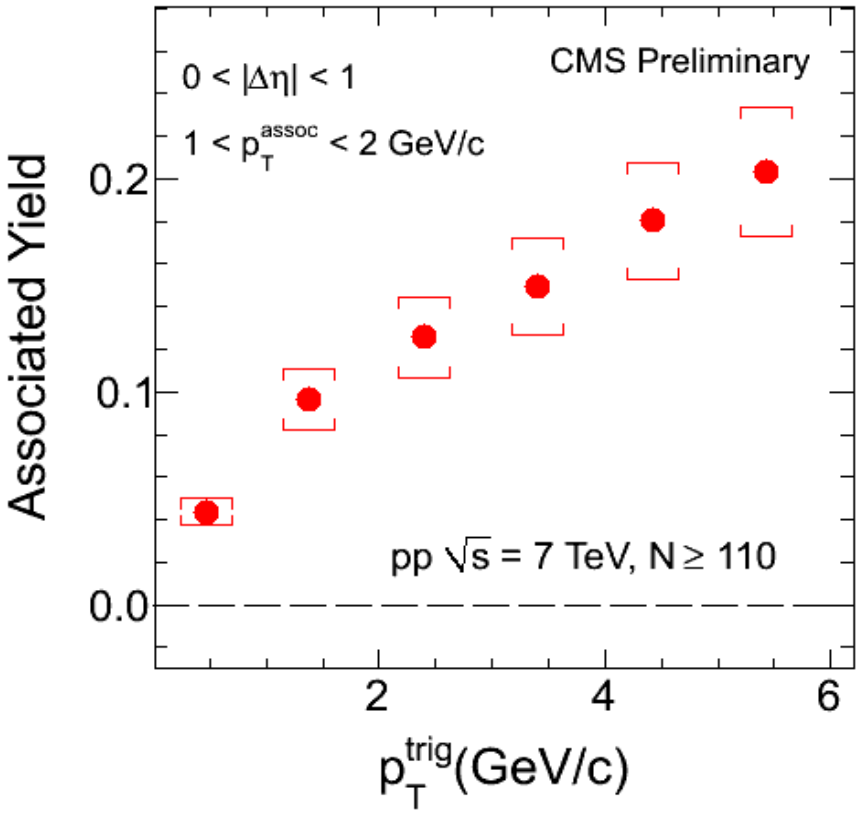
DATA:



No ridge when correlating to high p_T particles!

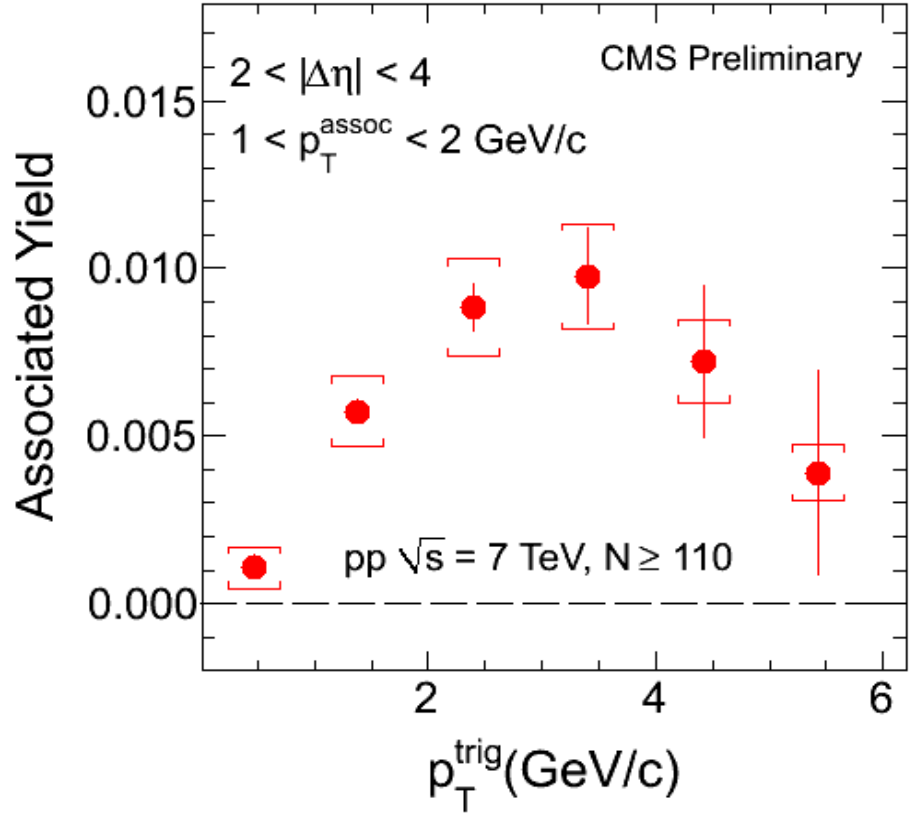
Near-side yield vs p_T in pp (N≥110)

Jet region (|Δη|<1)



Increase with p_T^{trig}

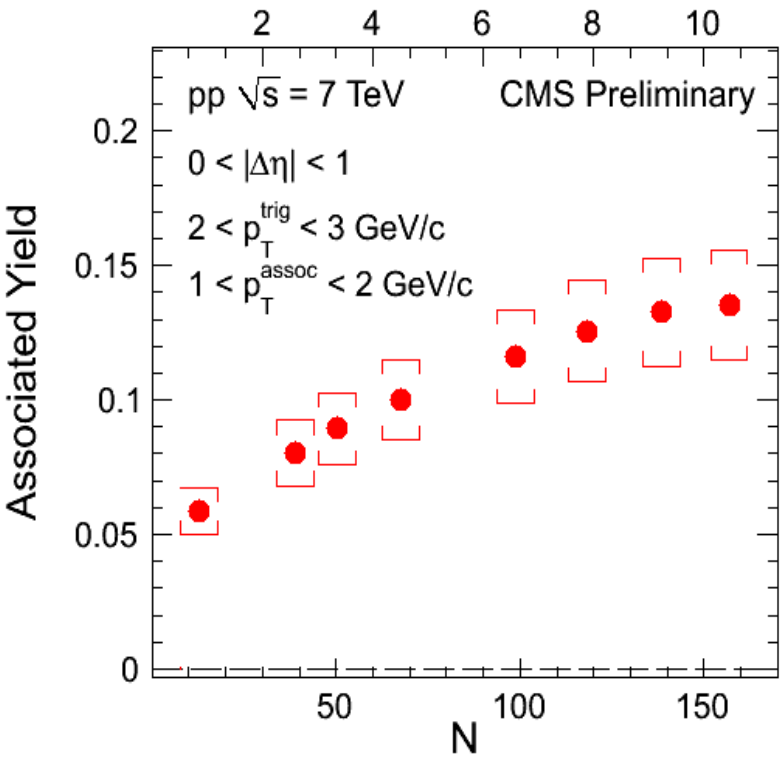
Ridge region (2<|Δη|<4)



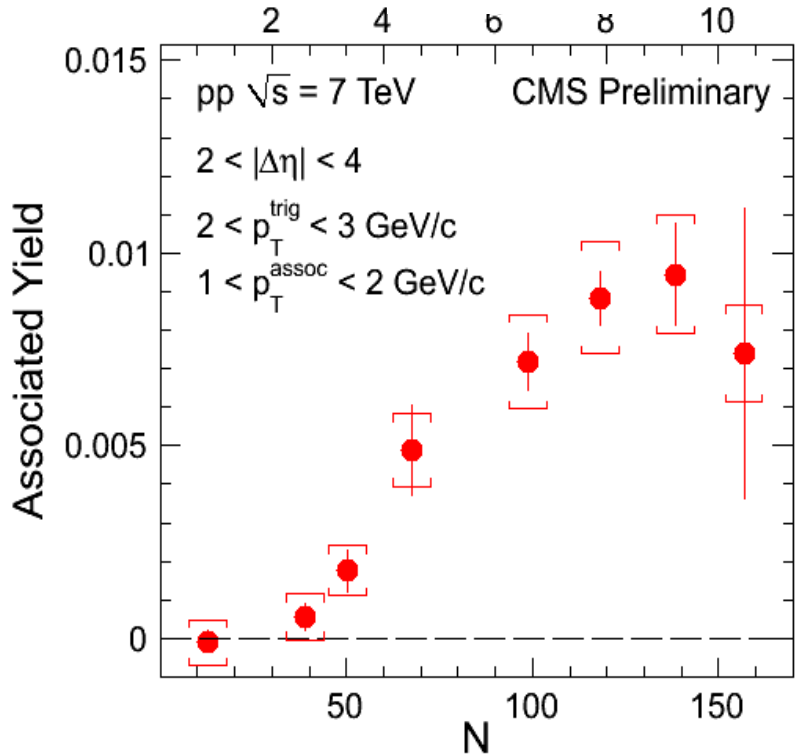
Increase, then decrease

Near-side yield vs multiplicity in pp

Jet region (|Δη|<1)



Ridge region (2<|Δη|<4)



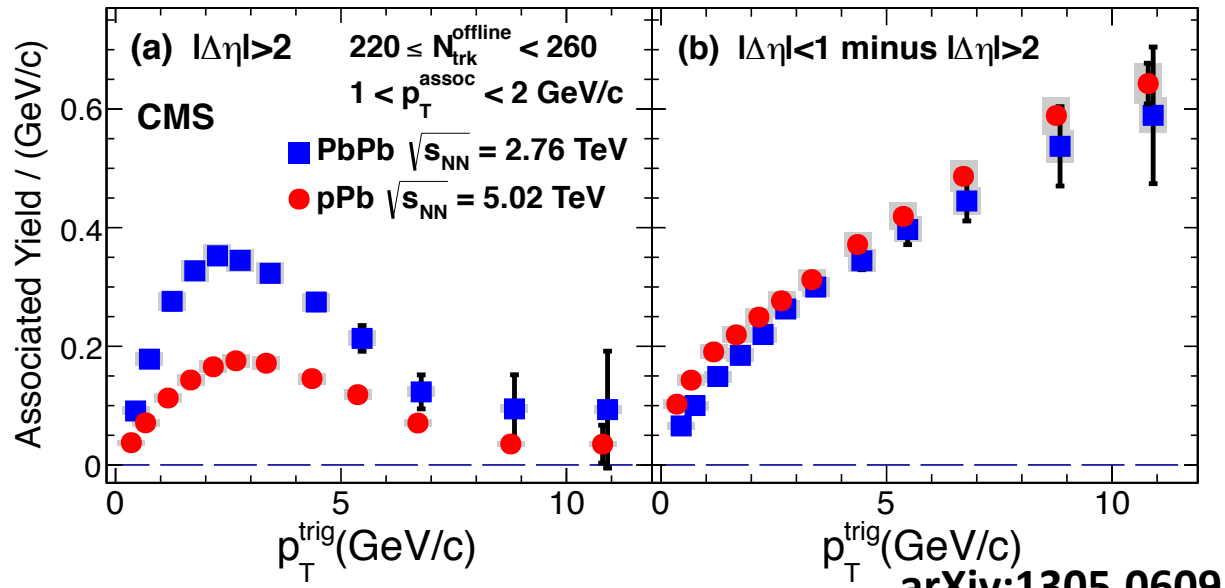
arXiv:1009.4122

- Jet yield in pp monotonically increases with N
- Ridge in pp turns on around N ~ 40 - 50 smoothly

Associated yield in PbPb, pPb and pp

Yield vs p_T

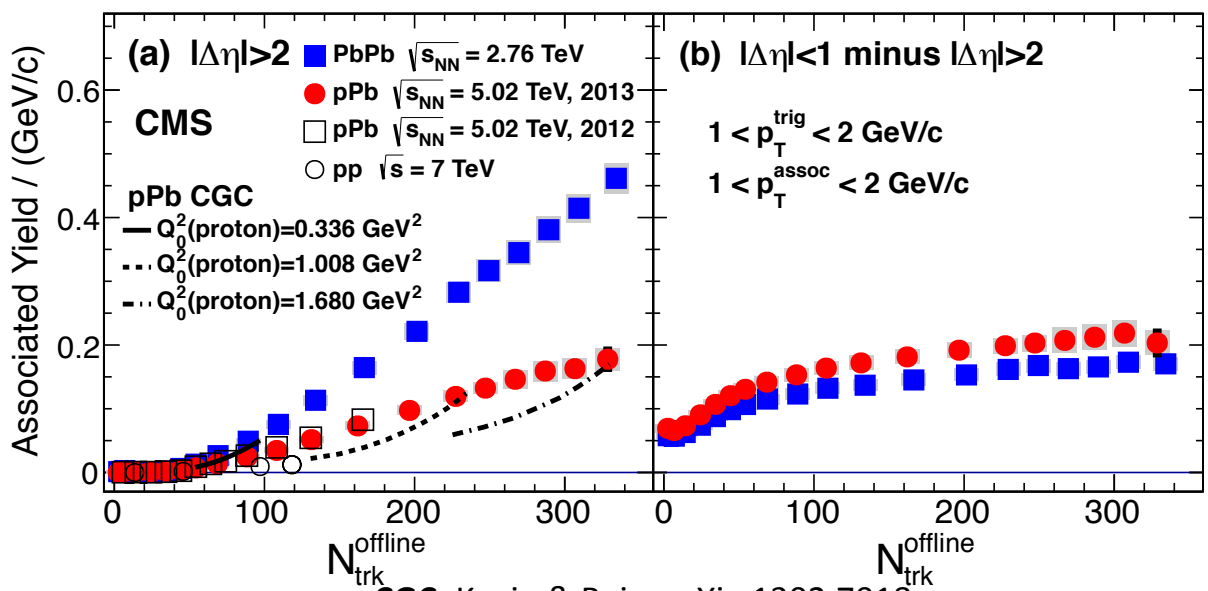
- Similar p_T dependence for PbPb and pPb
- Larger in PbPb ($|\Delta\eta|>2$)



arXiv:1305.0609

Yield vs N

- Yield becomes significant at N~40-50, followed by a monotonic rise
- Larger in PbPb ($|\Delta\eta|>2$)

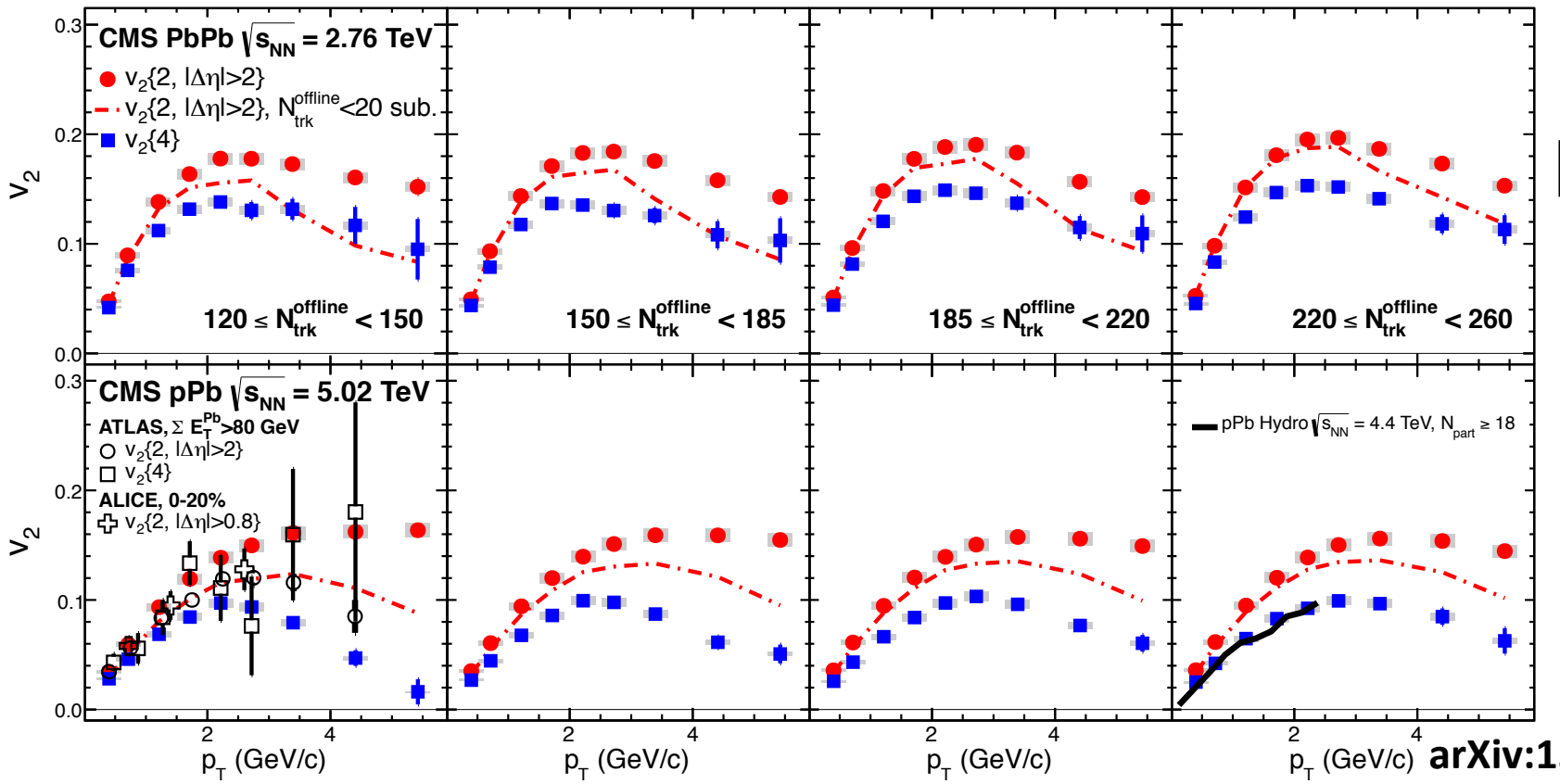


CGC: Kevin & Raju, arXiv:1302.7018

v_2 in PbPb and pPb

Dash-dot line: peripheral subtracted

multiplicity →



PbPb

pPb

arXiv:1305.0609

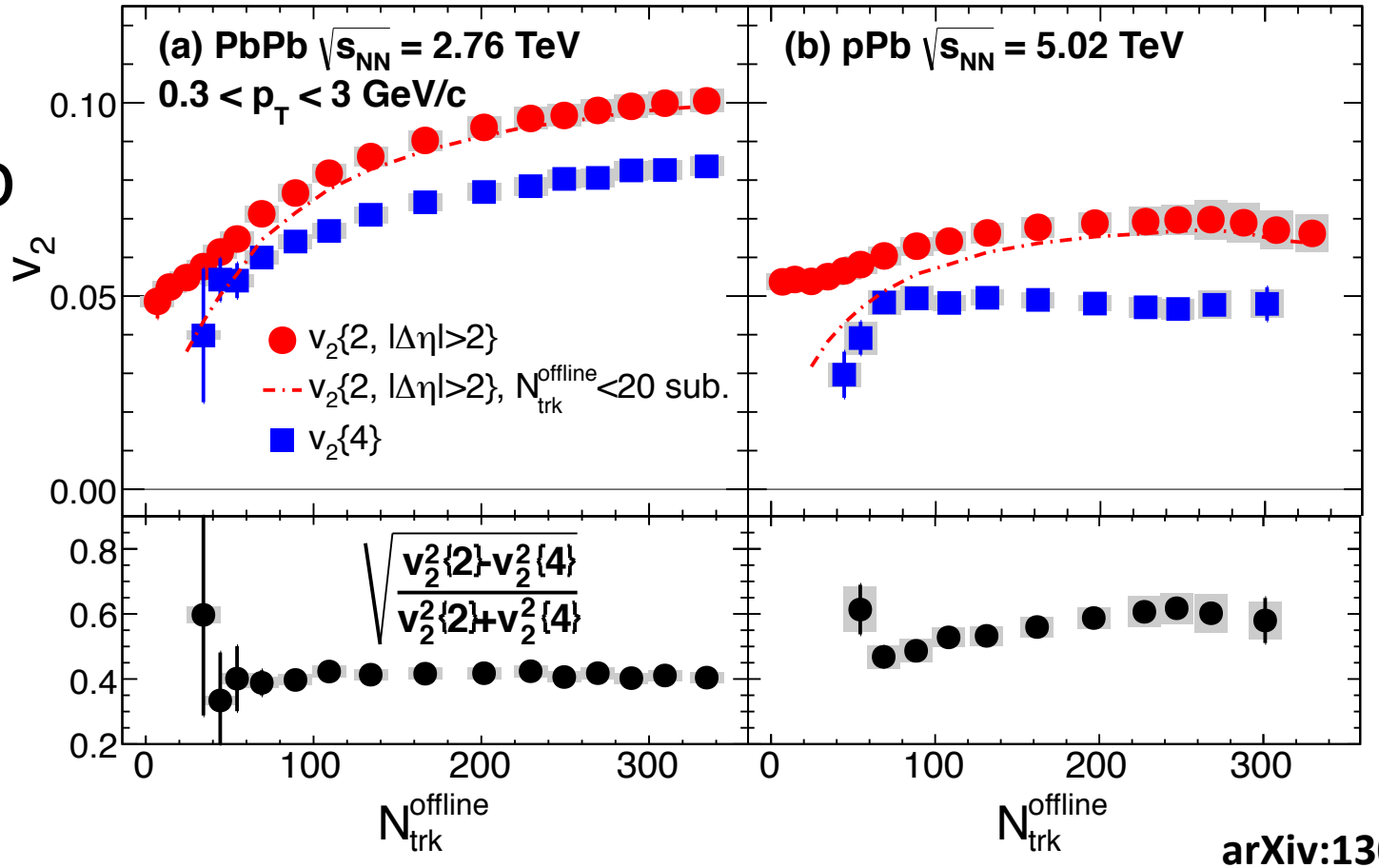
ATLAS: arXiv:1303.2084; ALICE: Phys. Lett. B 719 (2013) 29

Hydro: Phys. Rev. C 85 (2012) 014911

- v_2 shows similar shape in pPb and PbPb, but is smaller in pPb
- Peripheral subtraction has a small effect at high multiplicity
- Hydro prediction: $v_2\{PP\}$, not including fluctuations

v_2 in PbPb and pPb

PbPb



pPb

arXiv:1305.0609

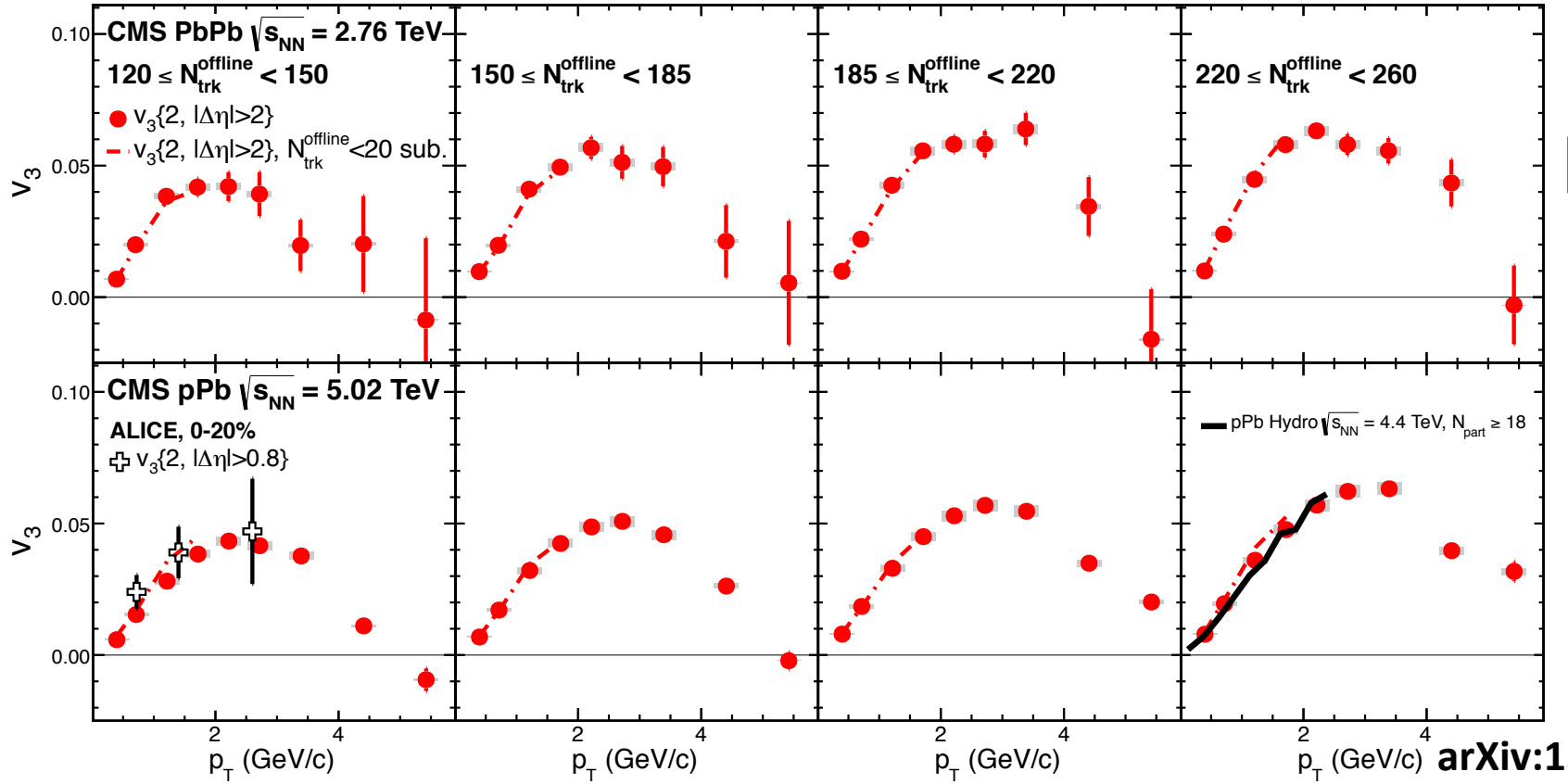
- v_2 is smaller in pPb than in PbPb
- Peripheral subtraction has a small effect at high multiplicity

$$v_2\{2\} = \sqrt{< v_2 >^2 + \sigma_{v_2}^2} \quad v_2\{4\} = \sqrt{< v_2 >^2 - \sigma_{v_2}^2}, \quad \frac{\sigma_{v_2}}{v_2} = \sqrt{\frac{v_2^2\{2\} - v_2^2\{4\}}{v_2^2\{2\} + v_2^2\{4\}}}.$$

v_3 in PbPb and pPb

Dash-dot line: peripheral subtracted

multiplicity →



PbPb

pPb

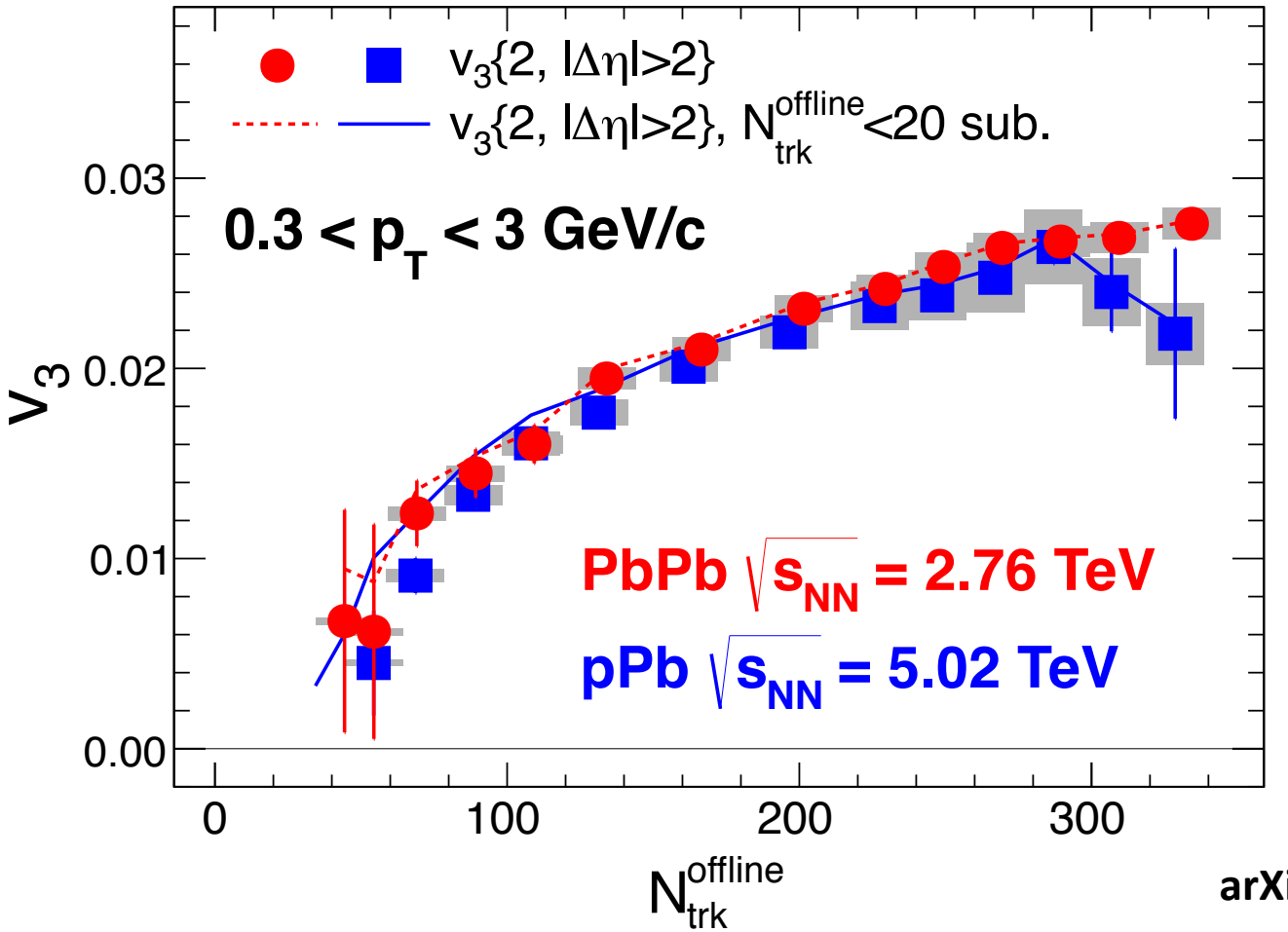
arXiv:1305.0609

ALICE: Phys. Lett. B 719 (2013) 29

Hydro: Phys. Rev. C 85 (2012) 014911

- v_3 shows similar shape in pPb and PbPb; magnitude comparable
- Peripheral subtraction makes essentially no difference
- Hydro prediction: $v_3\{PP\}$, not including fluctuations

v_3 in PbPb and pPb



arXiv:1305.0609

- v_3 is essentially the same in pPb and PbPb; turns on at N~40-50
- Peripheral subtraction makes almost no difference

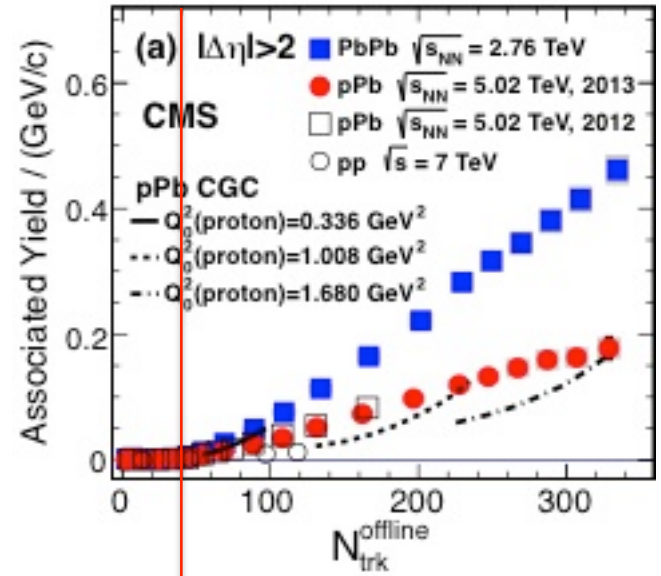
Summary I

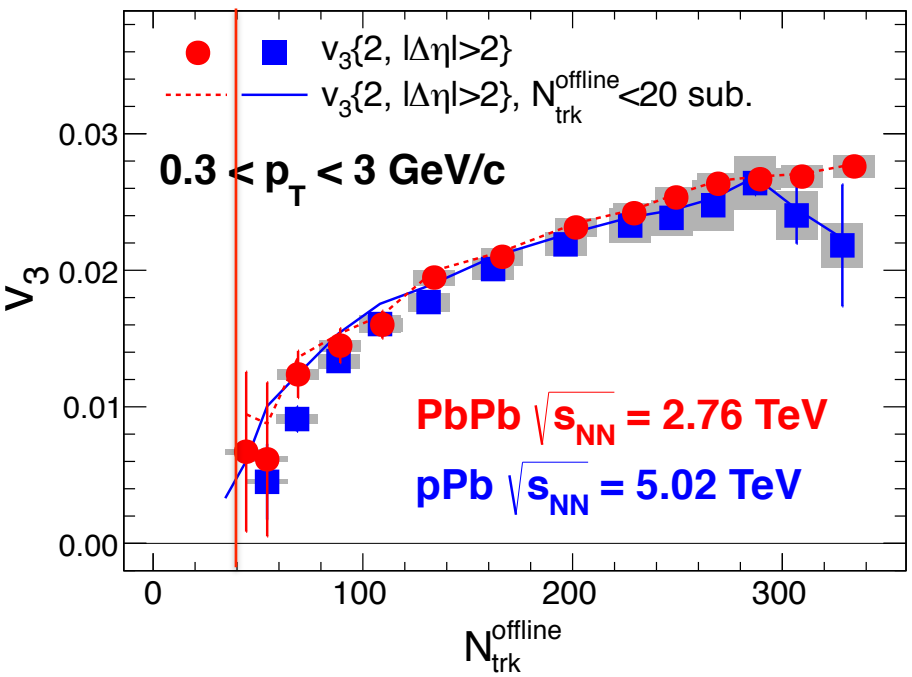
Comprehensive study of di-hadron correlations in PbPb (low and high p_T), pPb and high multiplicity pp

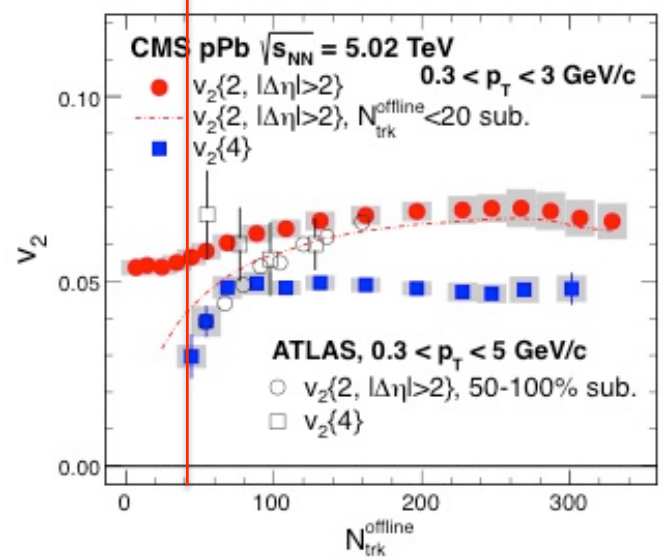
- v_n as a function of p_T and centrality
- High p_T correlations consistent with the jet quenching picture
- v_n exist in ultra-central PbPb collisions
- Re-analysis of peripheral PbPb using identical reconstruction, analysis code, …, for comparison with pPb
- Large $v_2\{2\}$ in pPb, larger in PbPb
- Large $v_2\{4\}$ in pPb, larger in PbPb
- Large $v_3\{2\}$ in pPb
- Ridge in pp

Summary II

- Associated yield, $v_2\{4\}$ and $v_3\{2\}$ become apparent at about the same multiplicity in pPb and PbPb
- $v_3\{2\}$ is essentially the same in pPb and PbPb at the same multiplicity

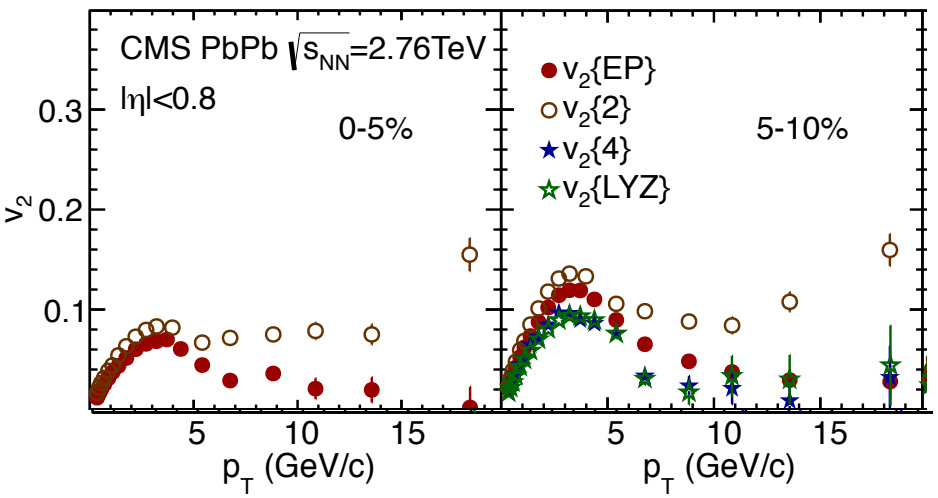




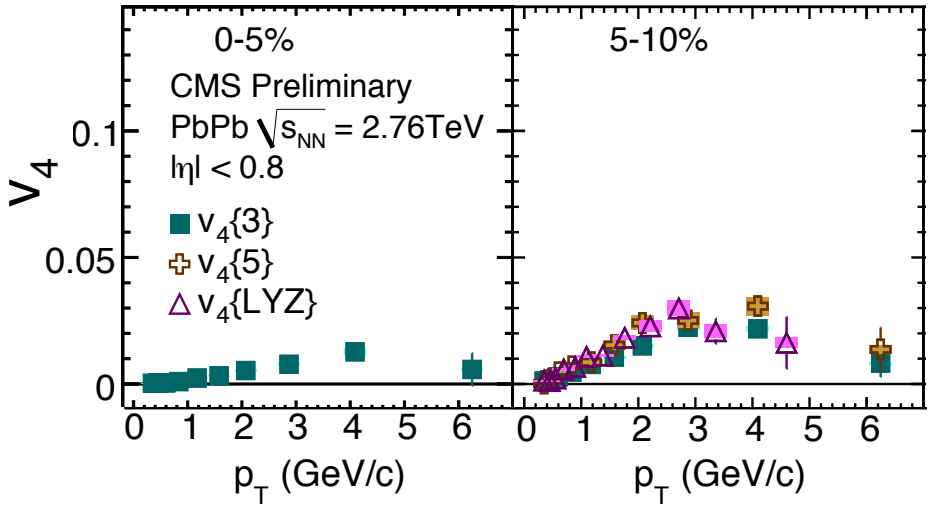


More CMS correlations/flow results

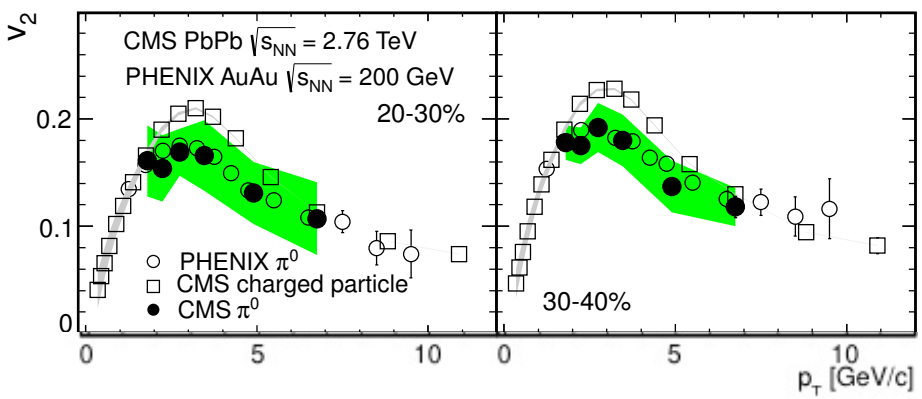
v_2 from different methods:



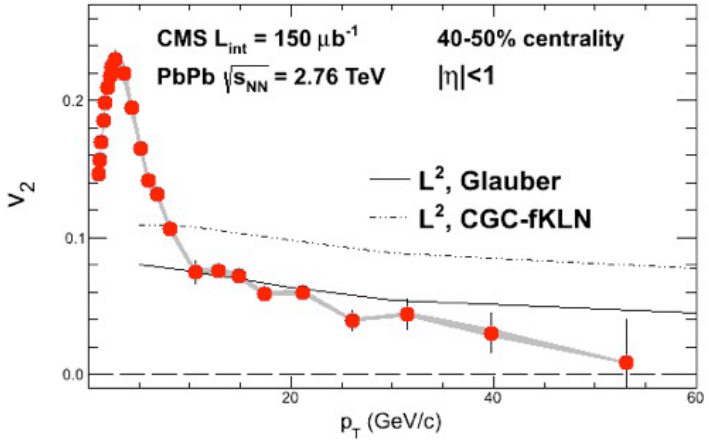
v_3, v_4, v_5 and v_6 from different methods:



π^0 v_2:



v_2 at very high p_T:

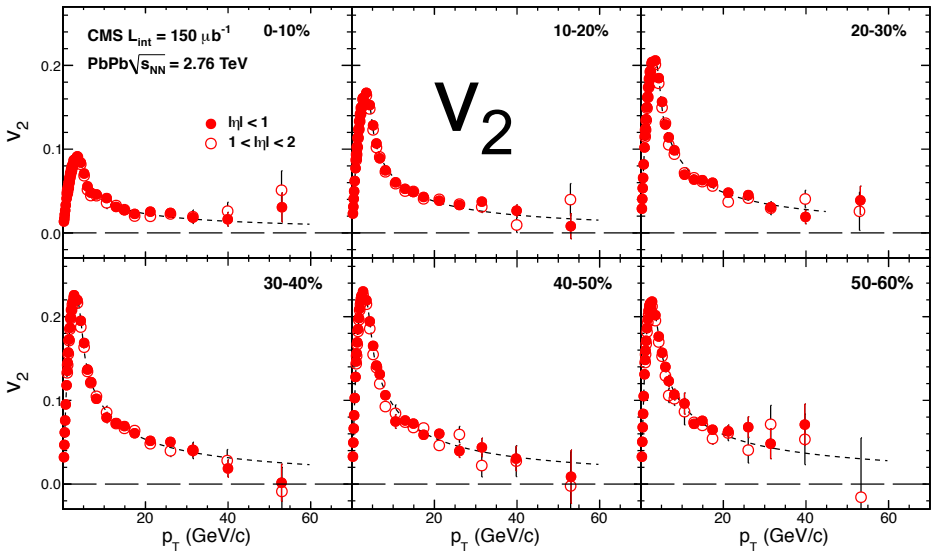


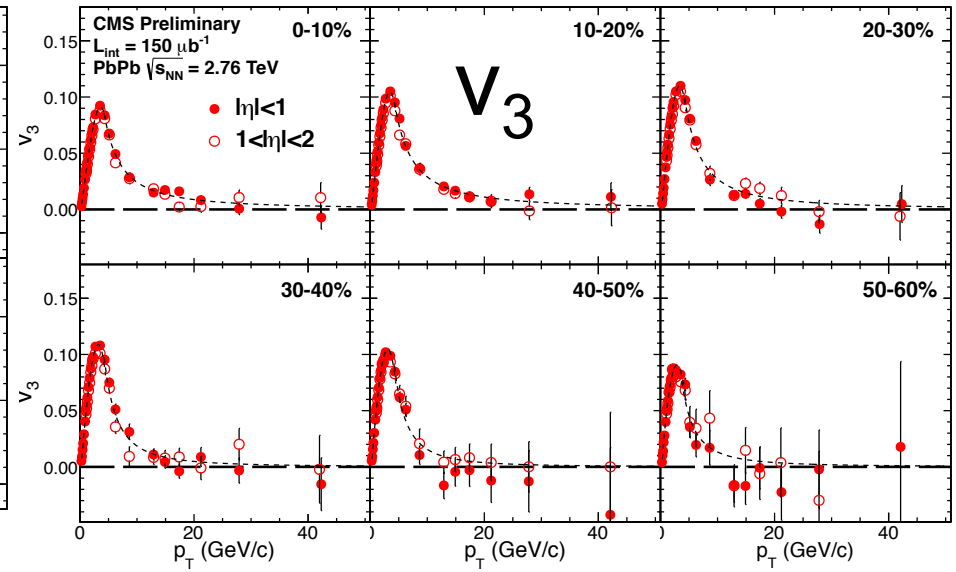
CMS correlations/flow papers

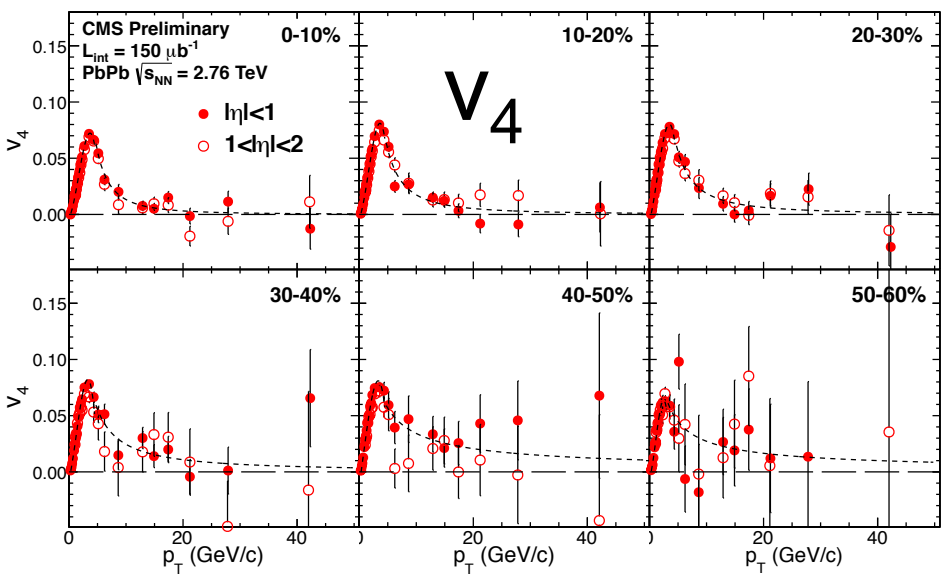
1. HIN-10-002: PbPb, v_2, different methods; arXiv:1204.1409
2. HIN-11-001: PbPb, correlations, most central; arXiv:1105.2438
3. HIN-11-005: PbPb, v_n, different methods; CMS-HIN-11-005
4. HIN-11-006: PbPb, correlations, centrality dep.; arXiv:1201.3158
5. HIN-11-009: PbPb, π^0 v_2, centrality dep.; arXiv:1208.2470
6. HIN-11-012: PbPb, v_2, very high p_T; arXiv:1204.1850
7. HIN-12-010: PbPb, correlations, very high p_T; CMS-HIN-12-010
8. HIN-12-011: PbPb, v_2, ultra-central; CMS-HIN-12-011
9. HIN-12-015: pPb, ridge, mult. dep.; arXiv:1210.5482
10. HIN-13-002: pPb, v_2, v_3, mult. dep.; arXiv:1305.0609
11. QCD-10-002: pp, ridge, high mult.; arXiv:1009.4122

Backup

High-p_T v_n Measurements





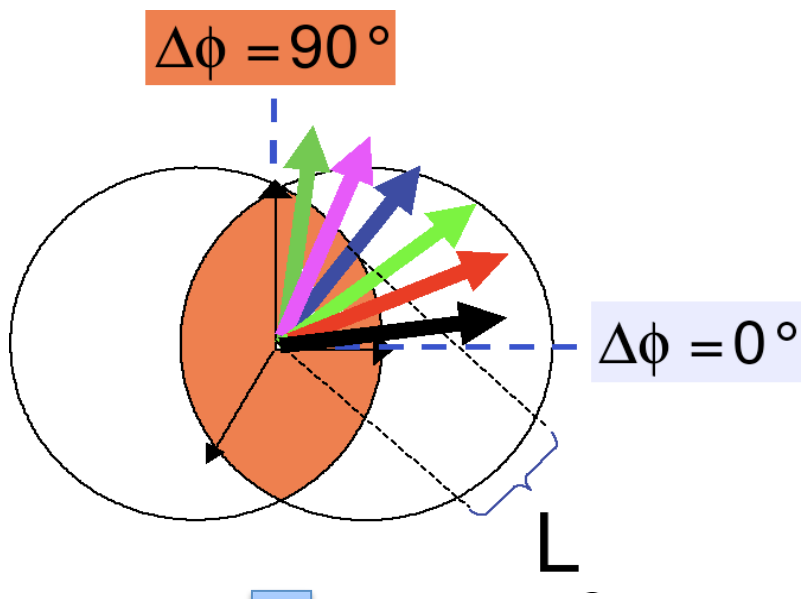


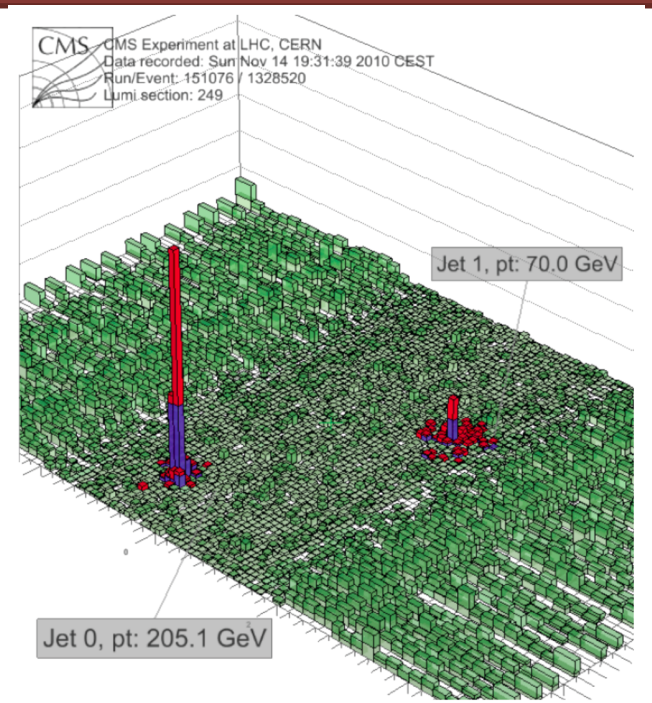
High-p_T v_n coefficients used in the flow background subtraction were measured using the HF event plane method

CMS-PAS-HIN-12-010

"Flow" at high p_T

Path length (L) dependence of jet energy loss (ΔE)





$\Delta E \sim L^{\alpha}$:

α = 1 for QCD, collisional

α = 2 for QCD, radiative

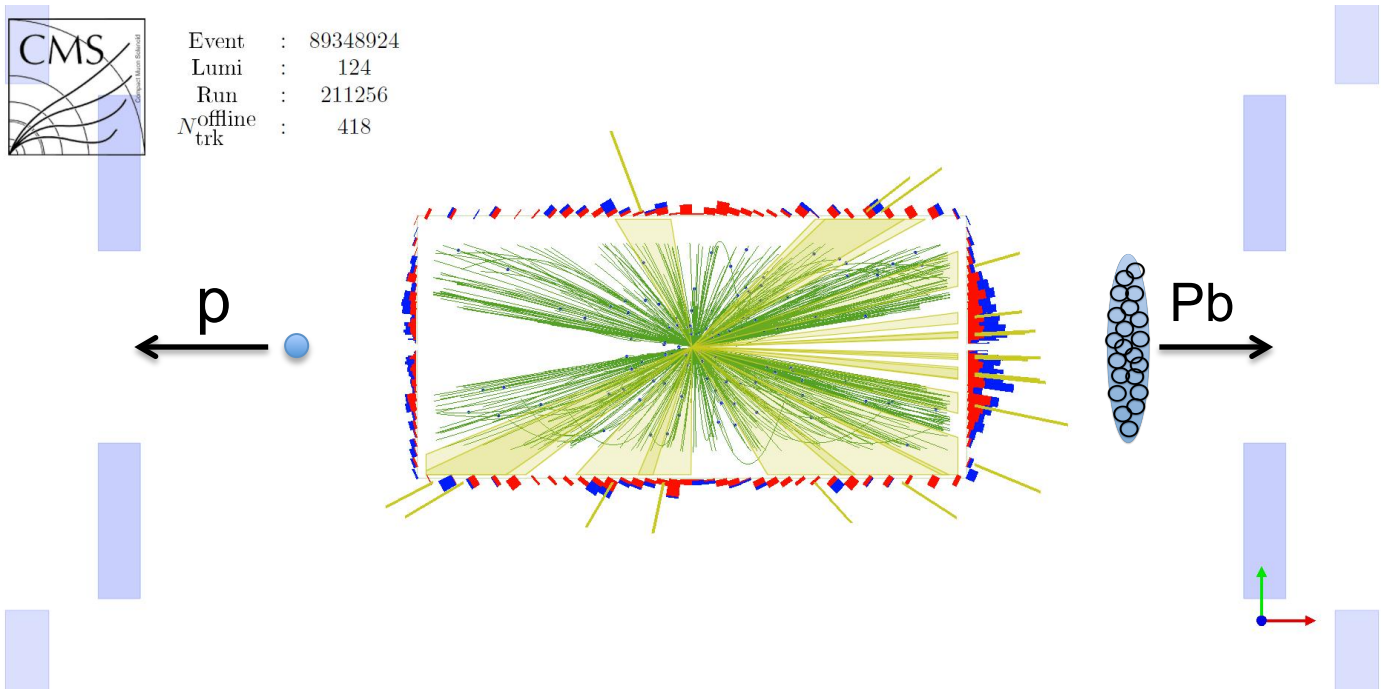
α = 3 for AdS/CFT

Azimuthal anisotropy (v_2) of jets

Also sensitive to initial geometry

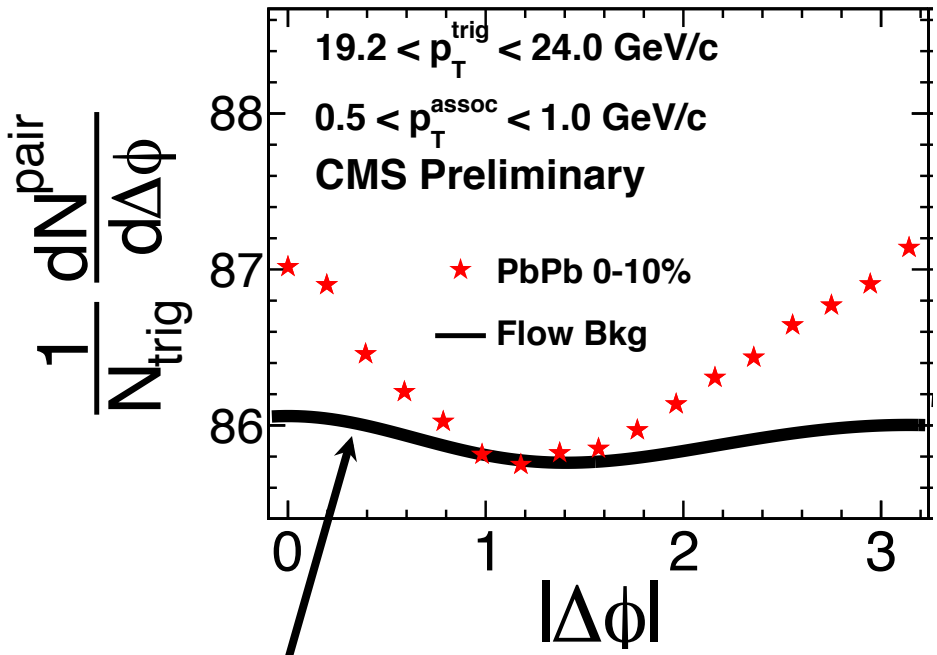
One pPb collision

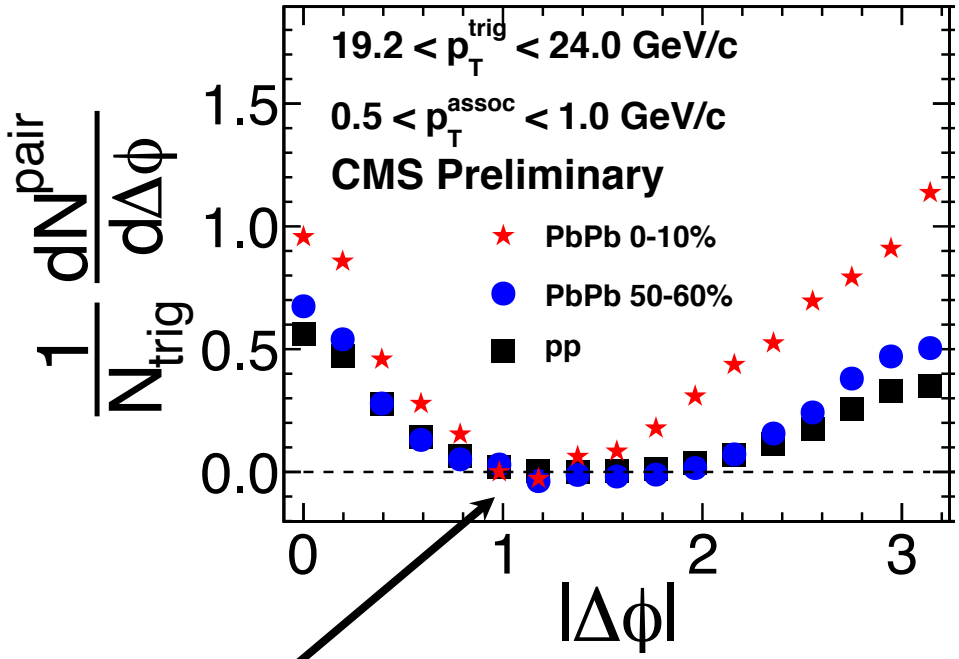
CMS preliminary, $N_{trk}^{offline}$=418



1D Projected Correlation Functions

Before ZYAM Subtraction → **After ZYAM Subtraction**





Flow Background

"Zero Yield At Minimum"

$|\Delta\eta|<1$

0-10%
50-60%
pp

CMS-PAS-HIN-12-010

Peripheral subtraction (pPb)

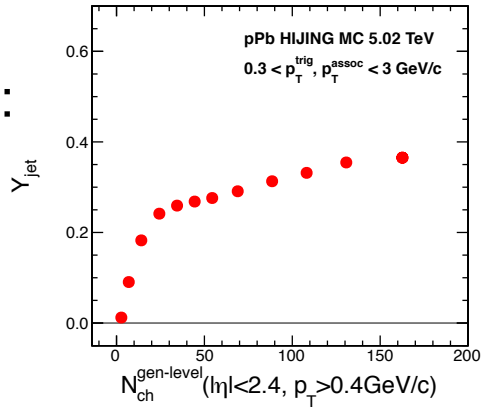
- Away-side correlations contain non-flow effects
- Subtract the data for high multiplicity by low multiplicity to correct for this

Fourier decomposition:

$$\frac{1}{N_{\mathrm{trig}}}\frac{\mathrm{d}N^{\mathrm{pair}}}{\mathrm{d}\Delta\phi} = \frac{N_{\mathrm{assoc}}}{2\pi}\left\{1+\sum_{n} 2V_{n\Delta}\cos(n\Delta\phi)\right\}$$

Subtracting peripheral correlations in v_2, v_3 calculations:

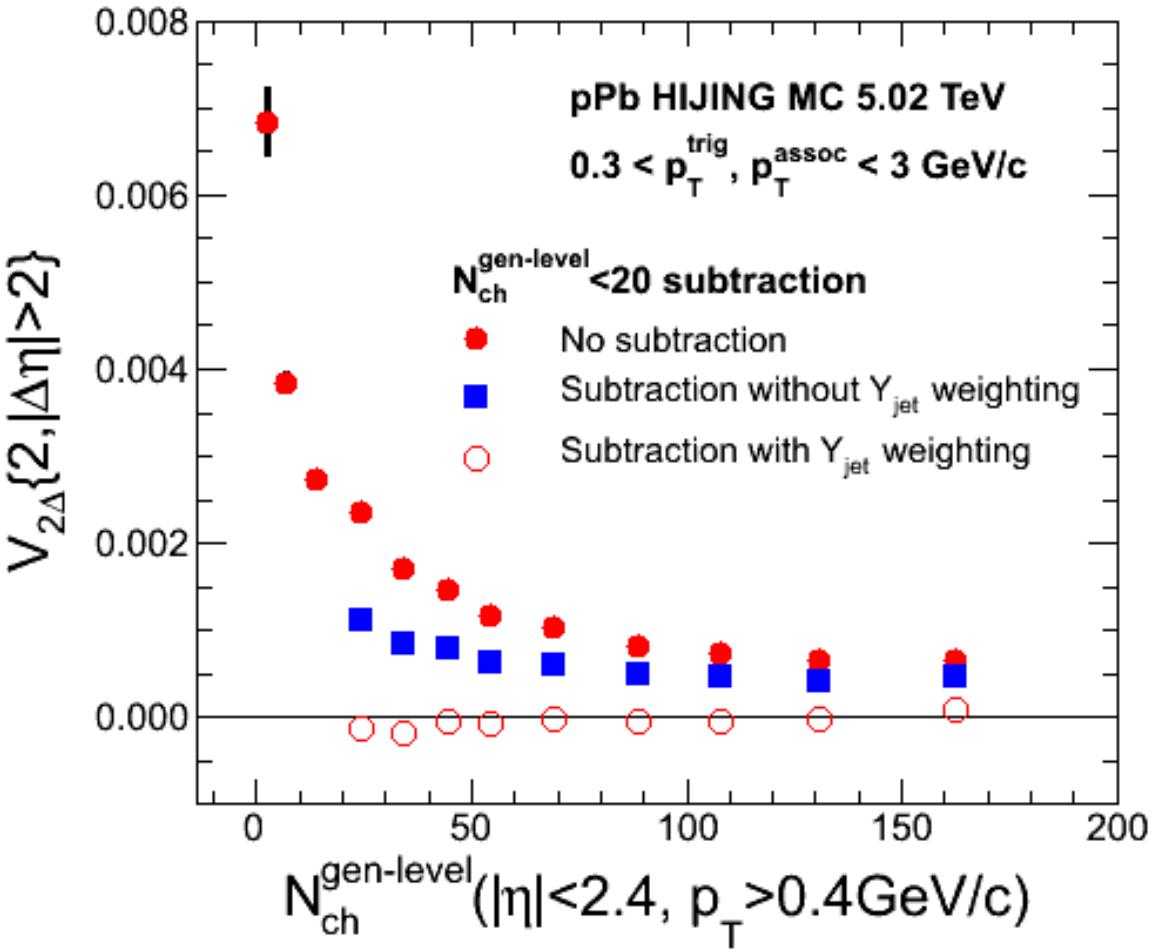
$$V_{n\Delta}(\mathrm{cent}) - V_{n\Delta}(\mathrm{peri}) \times \frac{N_{\mathrm{assoc}}(\mathrm{peri})}{N_{\mathrm{assoc}}(\mathrm{cent})} \times \frac{Y^{\mathrm{jet}}(\mathrm{cent})}{Y^{\mathrm{jet}}(\mathrm{peri})}$$



Subtract $N_{trk}^{offline}$<20 (70-100%) to avoid removing signal ($N_{trk}^{offline}$ ~ 40)

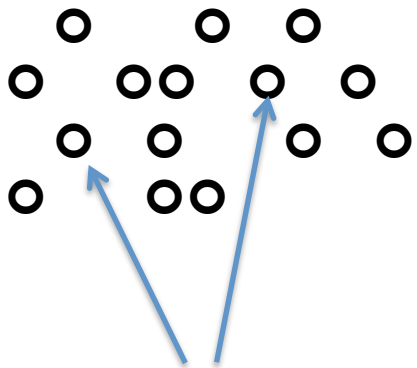
Account for the fact that jet correlation increases with multiplicity

Test our procedure in HIJING

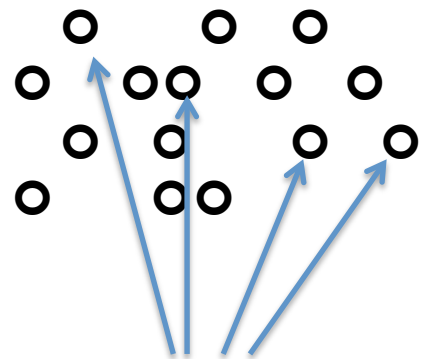


Weighted by near-side jet yield, most of non-flow correlations are subtracted

Multi-particle correlations

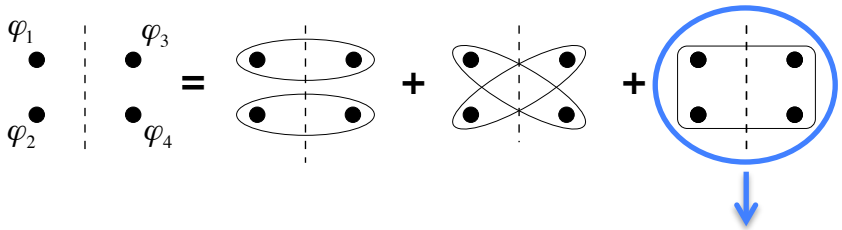


$$\left\langle e^{in(\varphi_1-\varphi_2)} \right\rangle$$



$$\left\langle e^{in(\varphi_1+\varphi_2-\varphi_3-\varphi_4)} \right\rangle$$

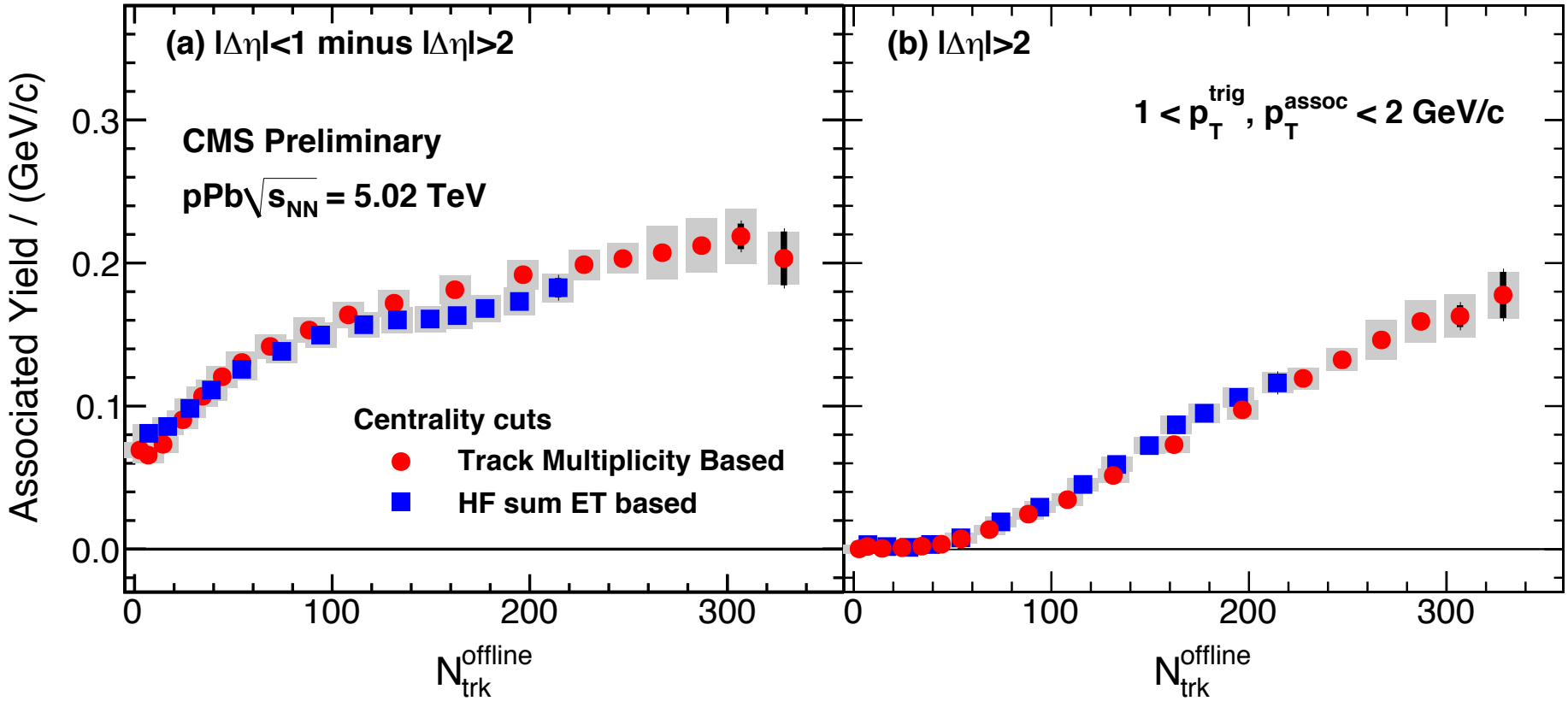
Four particle correlations (Q-cumulant method): remove 2 and 3 particle correlations



$$c_n\{4\} = \langle\langle 4 \rangle\rangle - 2 \cdot \langle\langle 2 \rangle\rangle^2$$

$$\left\langle e^{in(\varphi_1+\varphi_2-\varphi_3-\varphi_4)} \right\rangle - \left\langle e^{in(\varphi_1-\varphi_3)} \right\rangle \left\langle e^{in(\varphi_2-\varphi_4)} \right\rangle - \left\langle e^{in(\varphi_1-\varphi_4)} \right\rangle \left\langle e^{in(\varphi_2-\varphi_3)} \right\rangle$$

Yield from HF based triggers



- Reach much higher multiplicity for multiplicity triggers
- Difference between multiplicity and HF based triggers for jet yield is expected

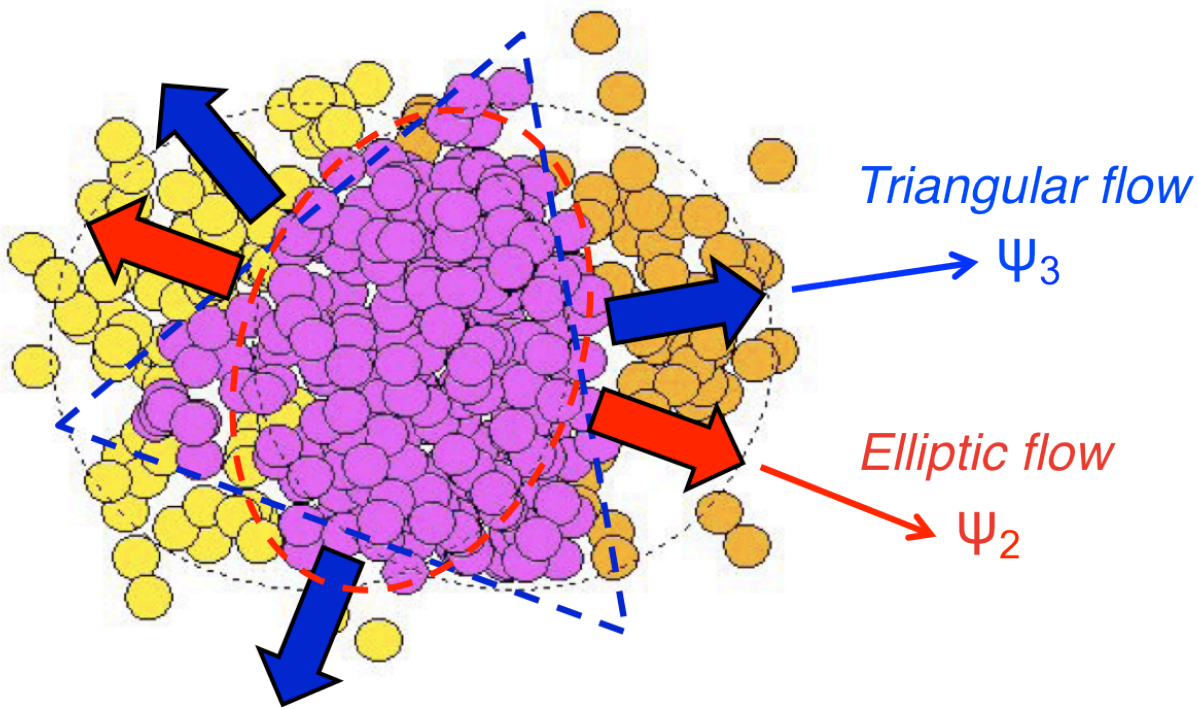
Multiplicity bins in the analysis

arXiv:1305.0609

Table 1: Fraction of MB triggered events after event selections in each multiplicity bin, and the average multiplicity of reconstructed tracks per bin with $|\eta| < 2.4$ and $p_T > 0.4\,\mathrm{GeV}/c$, before ($N_{\mathrm{trk}}^{\mathrm{offline}}$) and after ($N_{\mathrm{trk}}^{\mathrm{corrected}}$) efficiency correction, for 2.76 TeV PbPb and 5.02 TeV pPb data.

	PbPb data			pPb data		
$N_{\mathrm{trk}}^{\mathrm{offline}}$ bin	$\langle$Centrality$\rangle$ $\pm$ RMS (%)	$\langle N_{\mathrm{trk}}^{\mathrm{offline}} \rangle$	$\langle N_{\mathrm{trk}}^{\mathrm{corrected}} \rangle$	Fraction	$\langle N_{\mathrm{trk}}^{\mathrm{offline}} \rangle$	$\langle N_{\mathrm{trk}}^{\mathrm{corrected}} \rangle$
$[0, \infty)$				1.00	40	50±2
$[0, 20)$	92±4	10	13±1	0.31	10	12±1
$[20, 30)$	86±4	24	30±1	0.14	25	30±1
$[30, 40)$	83±4	34	43±2	0.12	35	42±2
$[40, 50)$	80±4	44	55±2	0.10	45	54±2
$[50, 60)$	78±3	54	68±3	0.09	54	66±3
$[60, 80)$	75±3	69	87±4	0.12	69	84±4
$[80, 100)$	72±3	89	112±5	0.07	89	108±5
$[100, 120)$	70±3	109	137±6	0.03	109	132±6
$[120, 150)$	67±3	134	168±7	0.02	132	159±7
$[150, 185)$	64±3	167	210±9	4×10^{-3}	162	195±9
$[185, 220)$	62±2	202	253±11	5×10^{-4}	196	236±10
$[220, 260)$	59±2	239	299±13	6×10^{-5}	232	280±12
$[260, 300)$	57±2	279	350±15	3×10^{-6}	271	328±14
$[300, 350)$	55±2	324	405±18	1×10^{-7}	311	374±16

Anisotropic azimuthal distributions

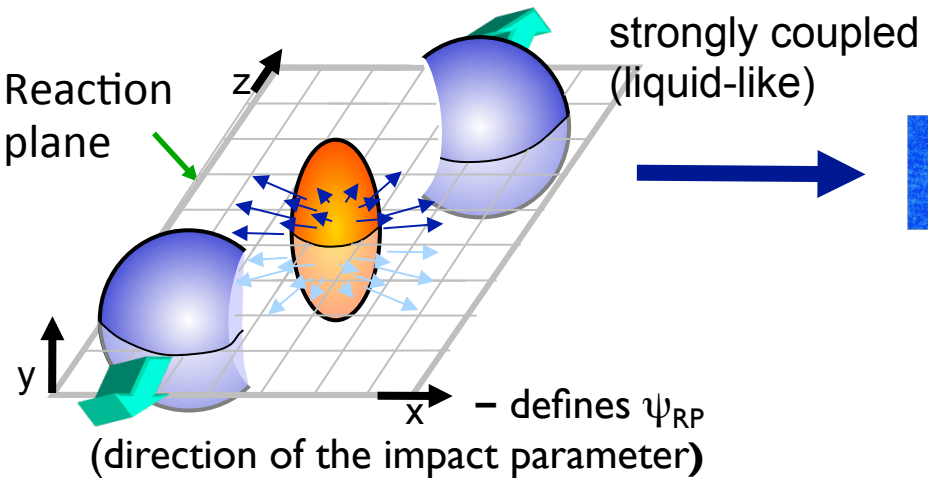


$$\frac{dN}{d\phi} \sim 1 + 2v_2 \cos 2(\phi - \psi_2) + 2v_3 \cos 3(\phi - \psi_3) + \ldots$$

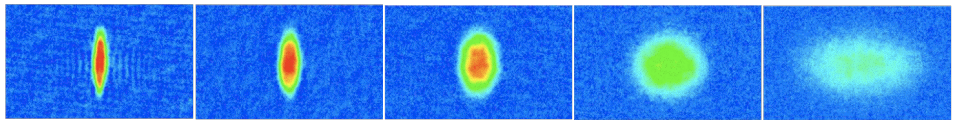
v_2: Elliptic flow v_3: Triangular flow

Hydrodynamic flow in HI collisions

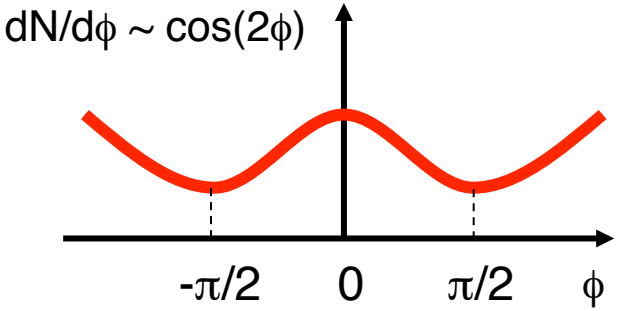
Initial anisotropy



Pressure driven expansion



Ultracold ^{6}Li fermi gas



Initial-state eccentricity:

$$\varepsilon_{std} = \frac{\sigma_y^2 - \sigma_x^2}{\sigma_y^2 + \sigma_x^2}$$

Initial condition
Transport coefficients
Equation of state