Heavy-Ion Meeting (HIM 2014-12)
Haeundae Grand Hotel, Busan, Korea, 5-6 December, 2014

Long-Range Correlations and Implication to Collectivity in pPb & PbPb from CMS

Byungsik Hong
(Korea University)

for the CMS Collaboration

Outline

1. Introduction
   - A brief history of near-side ridge and away-side conical emission in long-range correlations in heavy-ion collisions
   - CMS detector system and heavy-ion runs
2. Recent experimental data
   - Long-range correlations in pPb and PbPb
   - Elliptic and triangular flows in pPb and PbPb
     - Pseudo-rapidity dependence of flow parameters in pPb
     - Flow of identified particles (K_S^0 and $\Lambda/\overline{\Lambda}$)
3. Summary

Dihadron Correlation Technique

Signal distribution

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

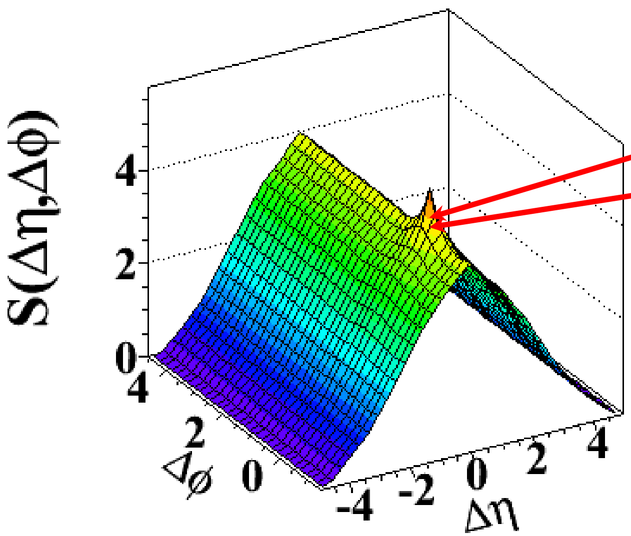
Particle 1: Trigger

Particle 2: Associated

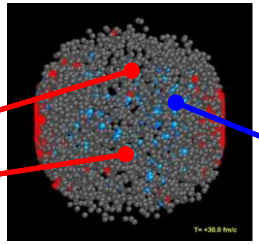
Background distribution

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

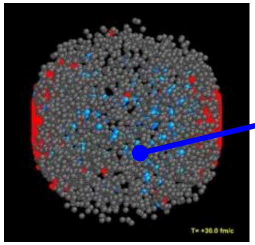
Same event pairs



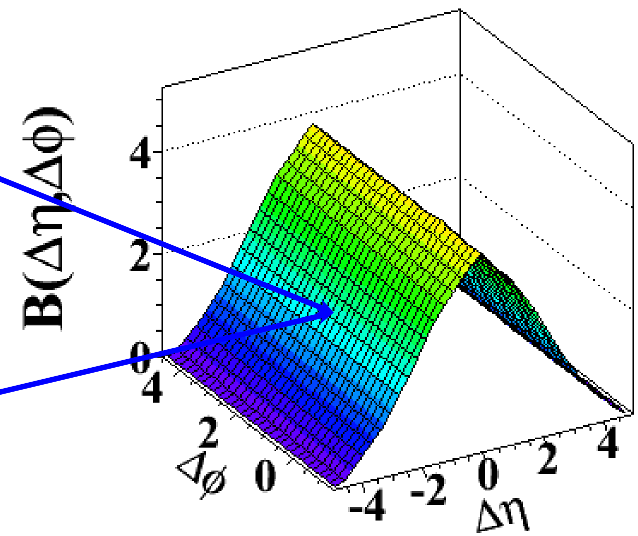
Event #1



Event #2



Mixed event pairs



Associated hadron yield per trigger:

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

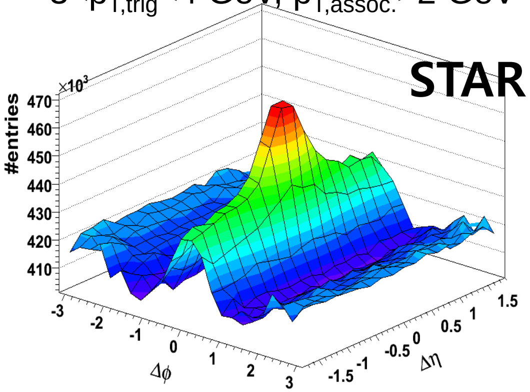
$\Delta\eta = \eta^{assoc} - \eta^{trig}$

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

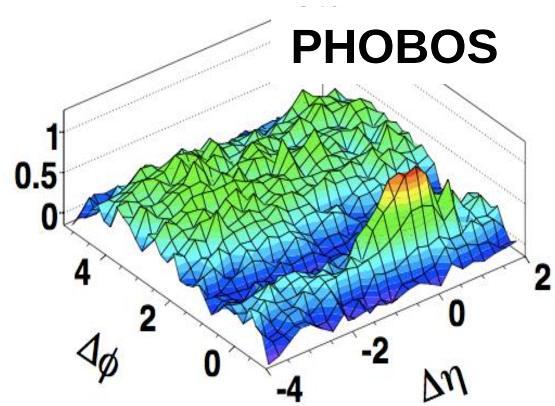
Discovery of Ridge @ RHIC

- First observation of near-side ridge in central Au+Au at 200 GeV in QM2006 in Shanghai by two-particle correlations

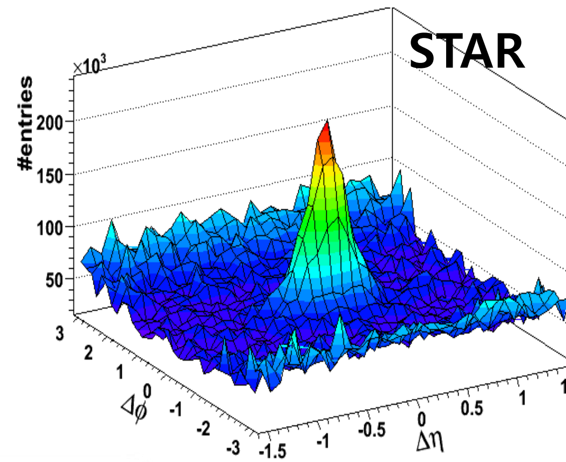
Au+Au @ 200 GeV (0-10%)
$3<p_{T,trig}<4$ GeV, $p_{T,assoc.}>2$ GeV

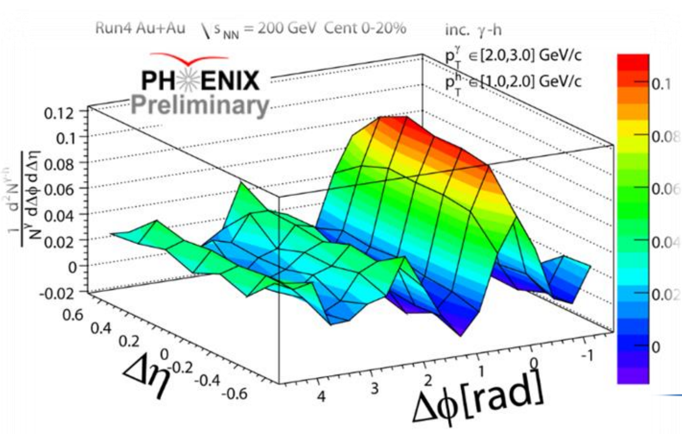


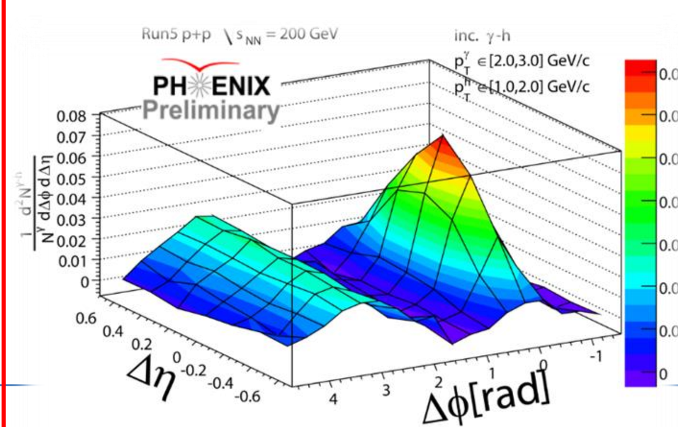
Au+Au (0-30%)
PRL 104, 062301 (2010)



d+Au @ 200 GeV (0-10%)





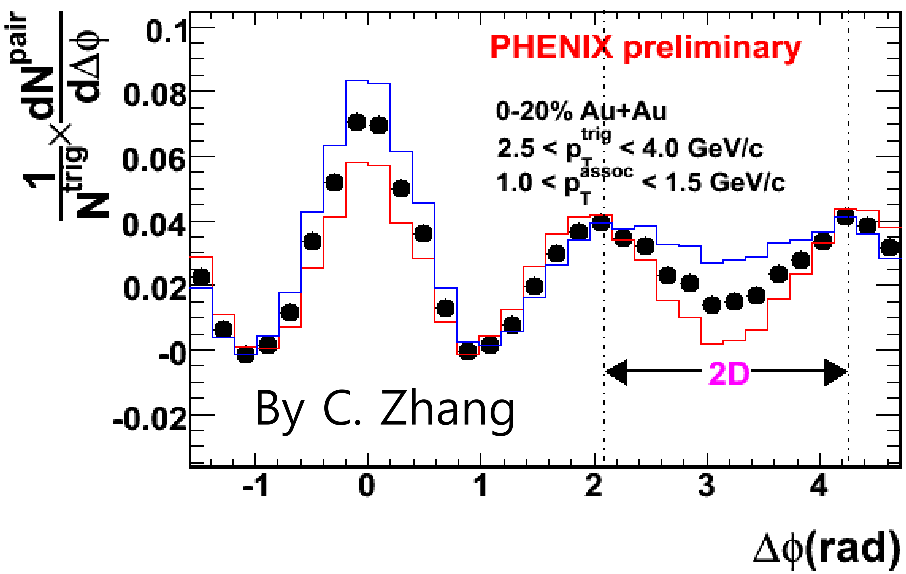


Ridge was absent in pp and dAu

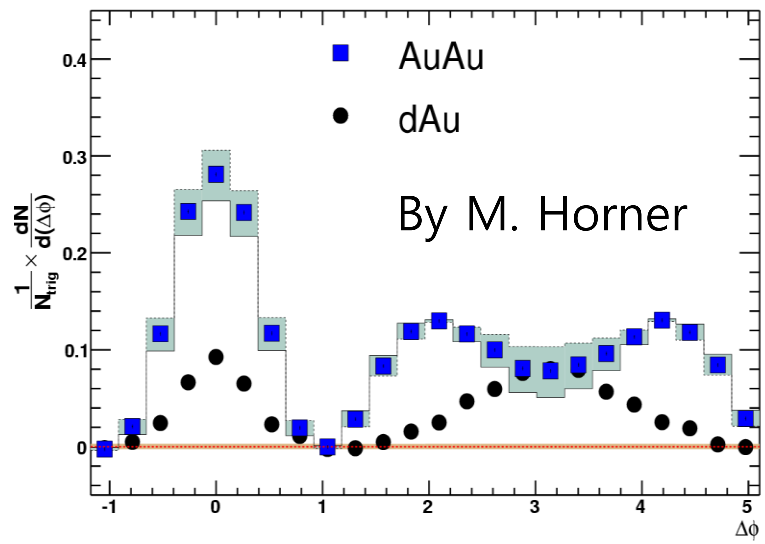
Conical Emission @ RHIC

- First observation of away-side conical emission in central Au+Au at 200 GeV in QM2006 in Shanghai by two-particle correlations

PHENIX

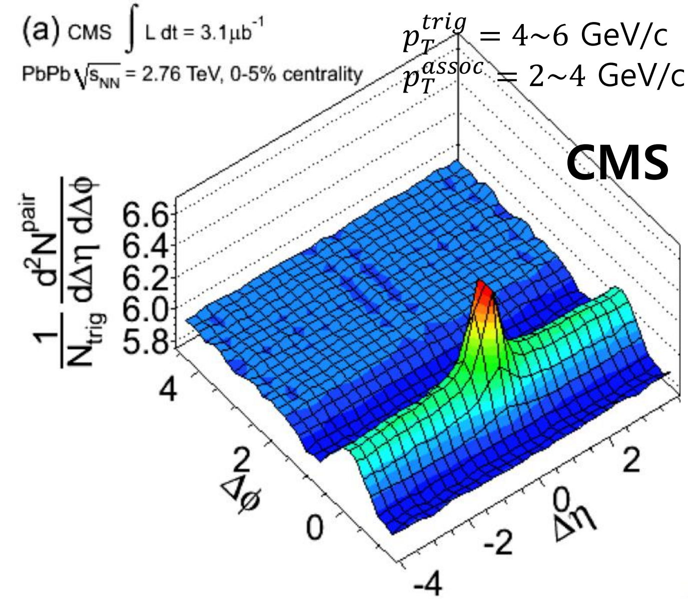


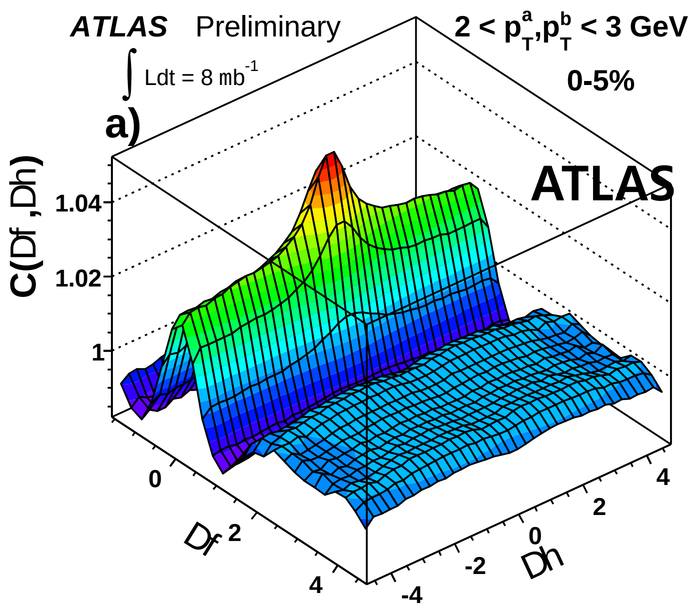
STAR

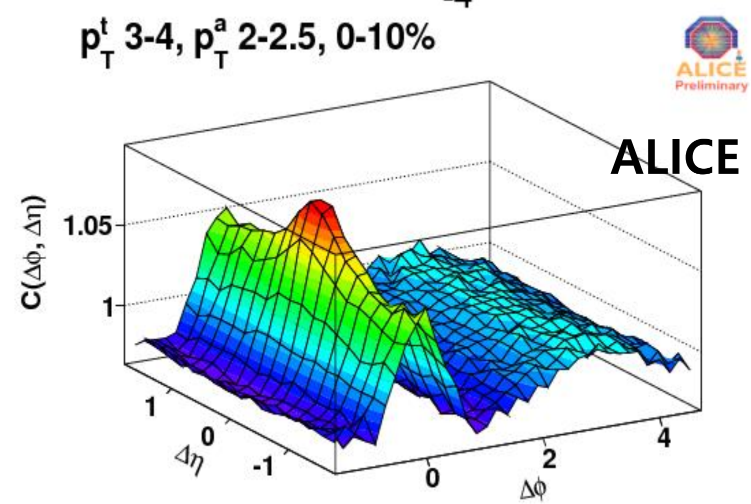


Ridges in PbPb @ LHC

- LHC experiments observed near-side ridge and away-side conical emission in central PbPb at 2.76 TeV in QM2011 in Annecy



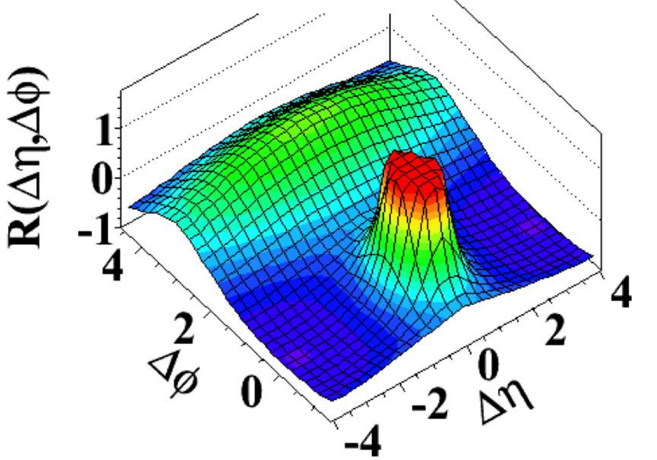




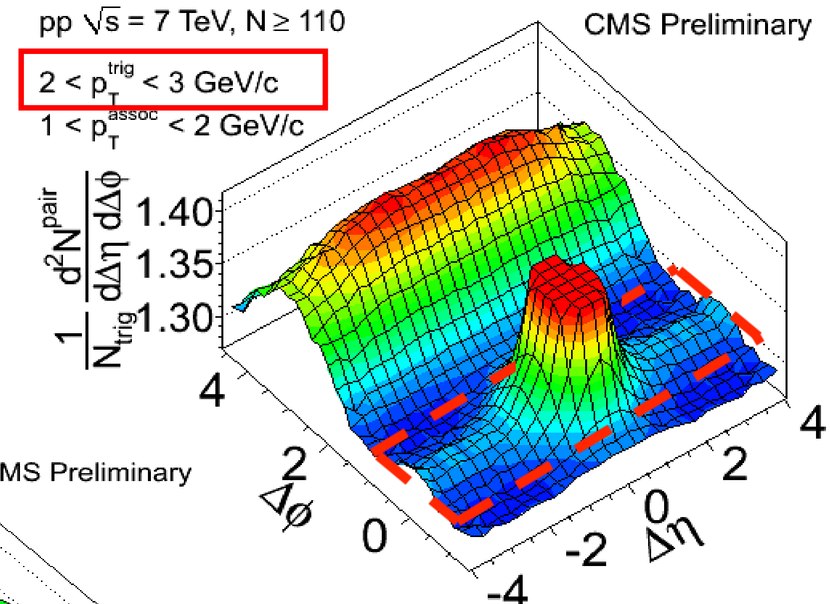
Ridge in pp @ LHC

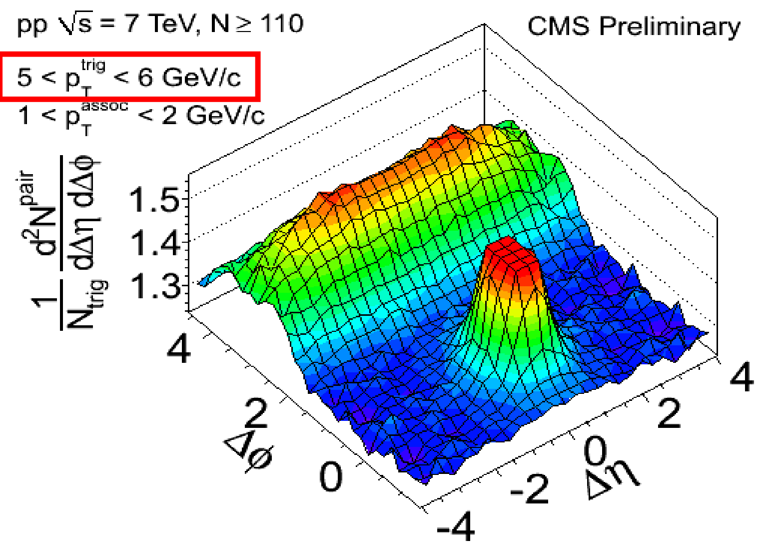
- Striking near-side ridge in high-multiplicity pp events
  - Not observed before in either hadron collisions or MC models

Minimum Bias pp (<N>~15)



High-multiplicity events (N>110)

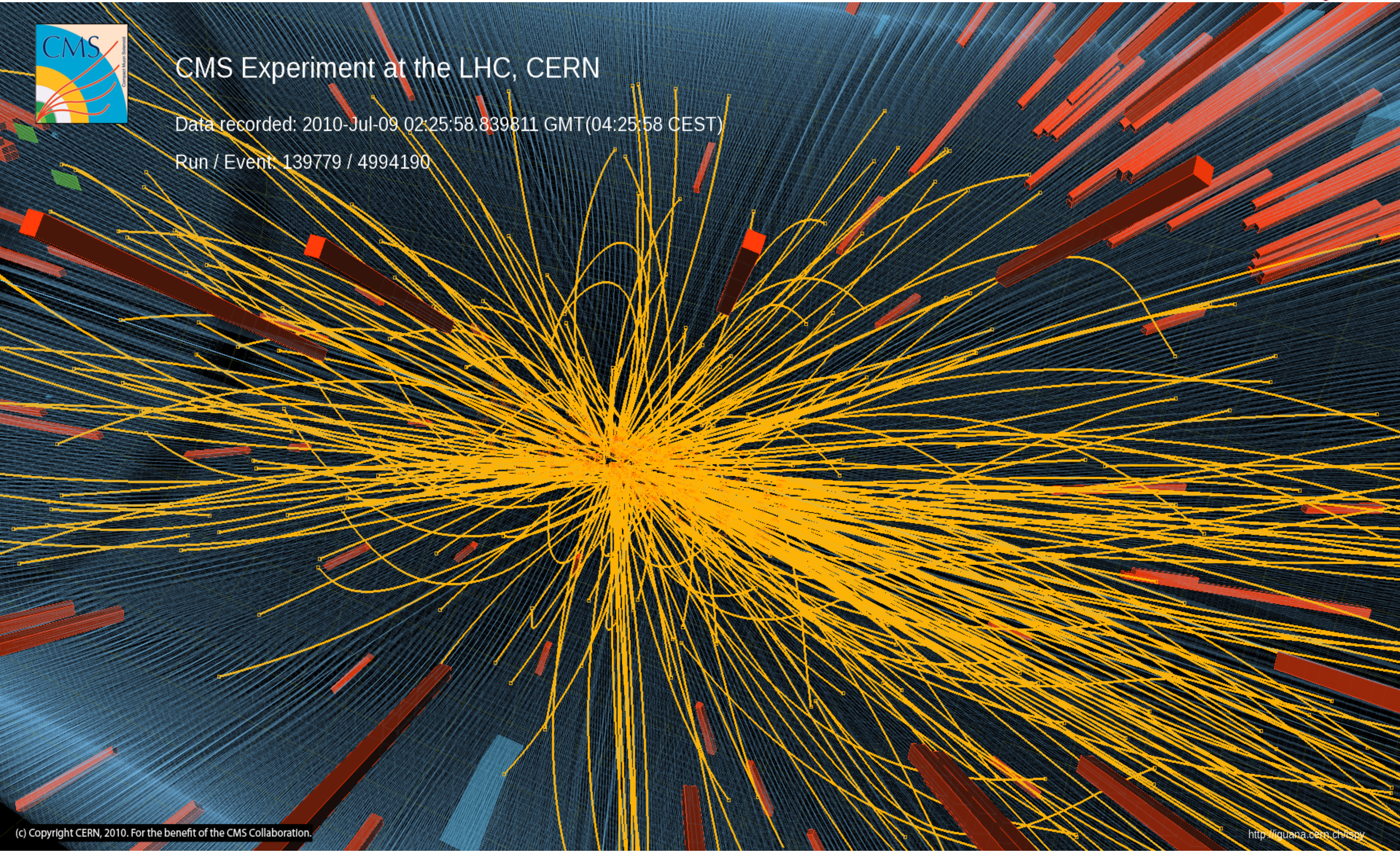




CMS,
JHEP 09, 091 (2010)
PAS HIN-11-006

No ridge when correlating to high p_T particles!

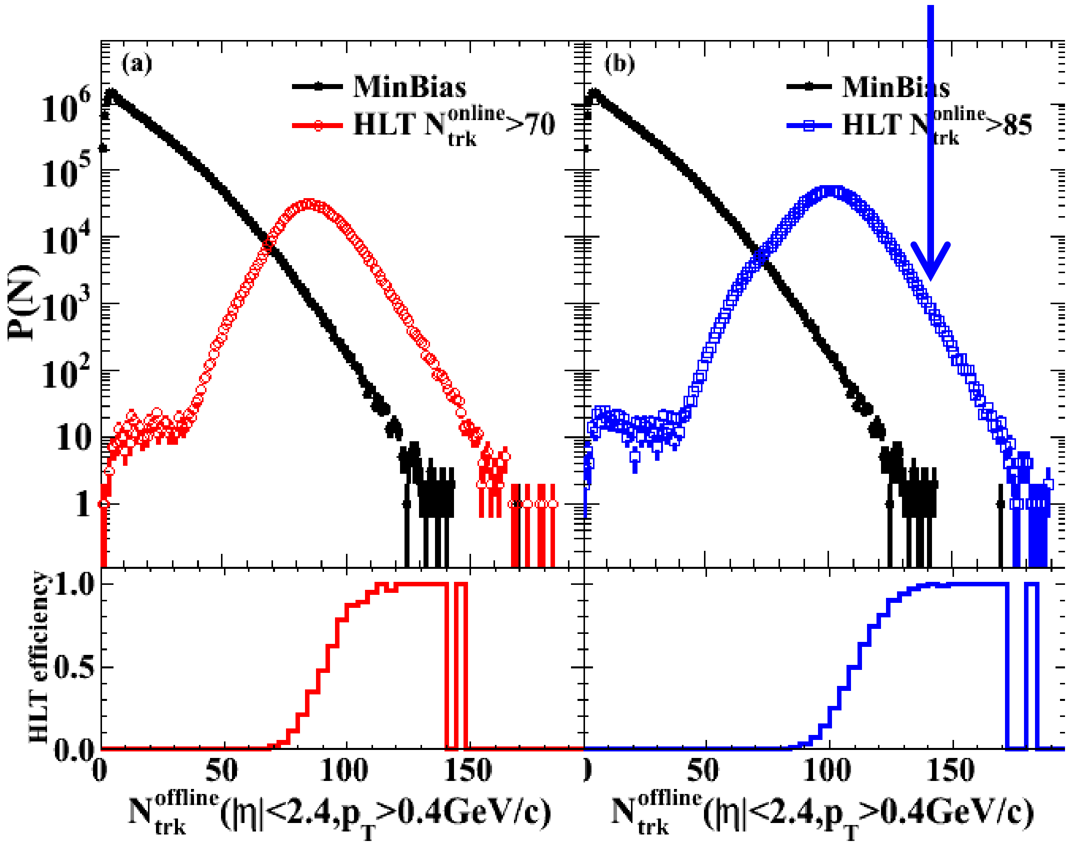
High-Multiplicity pp Event



High-Multiplicity pp Events

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 un-prescaled for full 980 nb^{-1} data set

JHEP 09, 091 (2010)

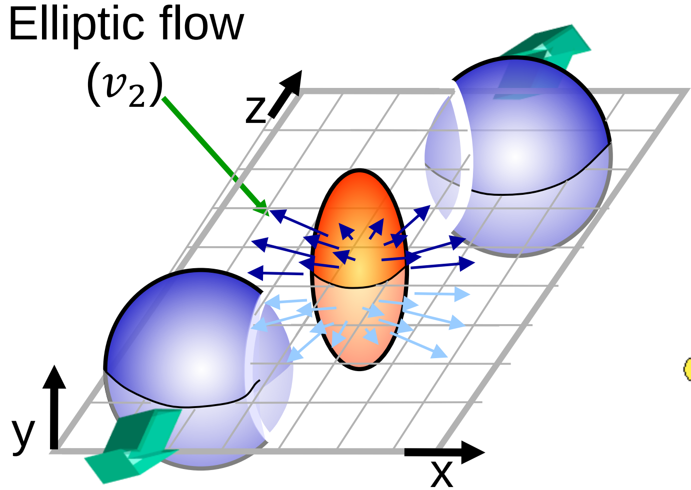
~350k top multiplicity events (N>110) out of 50 billion collisions!

Proposed Interpretations ~06’

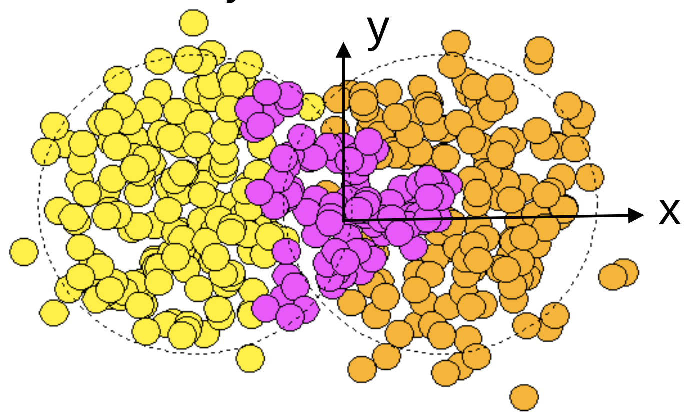
- Ridge
  - QCD bremsstrahlung radiation boosted by transverse flow
  - In-medium radiation and longitudinal flow push
  - Broadening of quenched jets in turbulent color fields
  - Recombination between thermal and shower partons at intermediate p_T
  - Momentum kick model
- Conical emission
  - Shock-wave excitation by supersonic partons (QCD Mach cone)
    - Hydrodynamics, Colored plasma, AdS/CFT, etc.
  - Cherenkov gluon radiation
  - Jet deflection
  - And more …

Alternative Interpretation

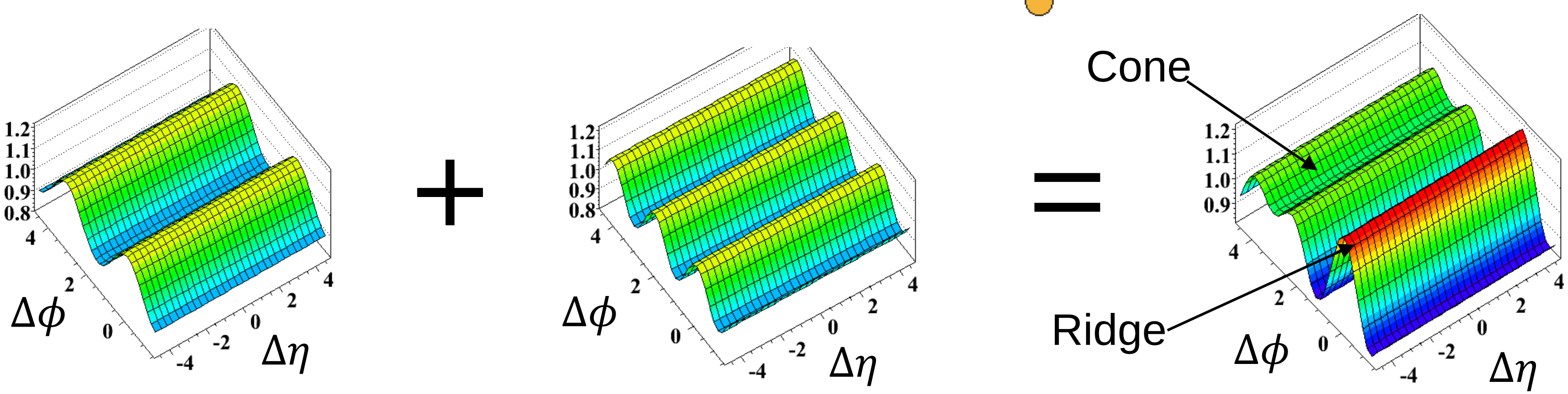
Fluctuation+Higher-order flow terms (v_2, v_3, v_4, v_5, …)



Triangular flow (v_3) from event-by-event fluctuation



B. Alver & G. Roland, Phys. Rev. C 81, 054905 (2010)



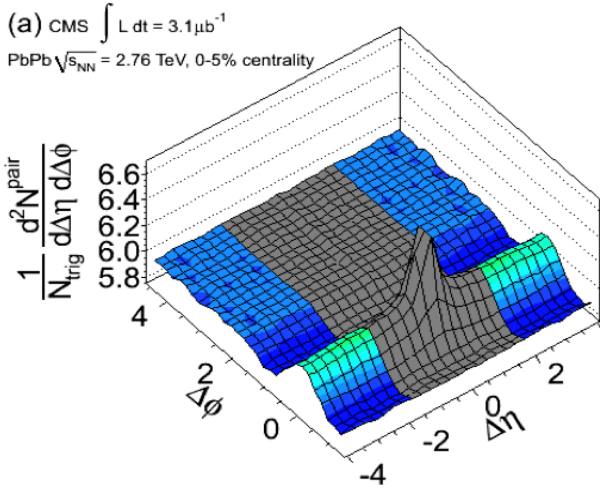
$\sim v_2 \cos(2\Delta\phi)$

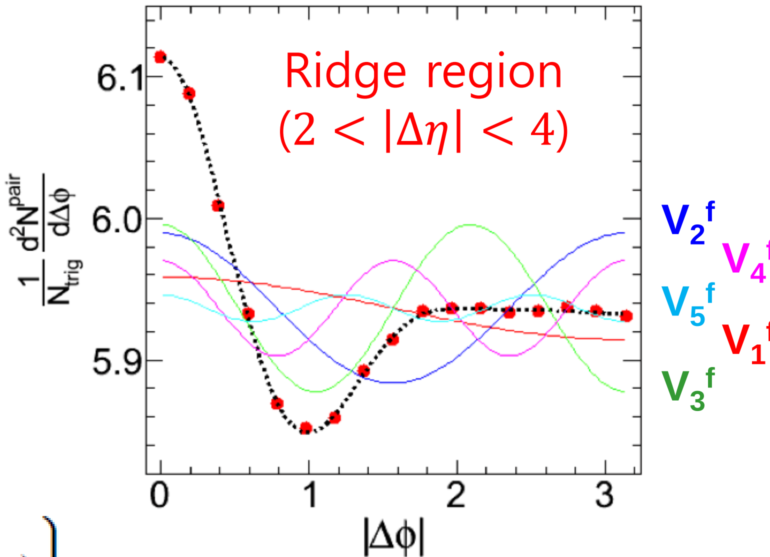
$\sim v_3 \cos(3\Delta\phi)$

Application to PbPb Data

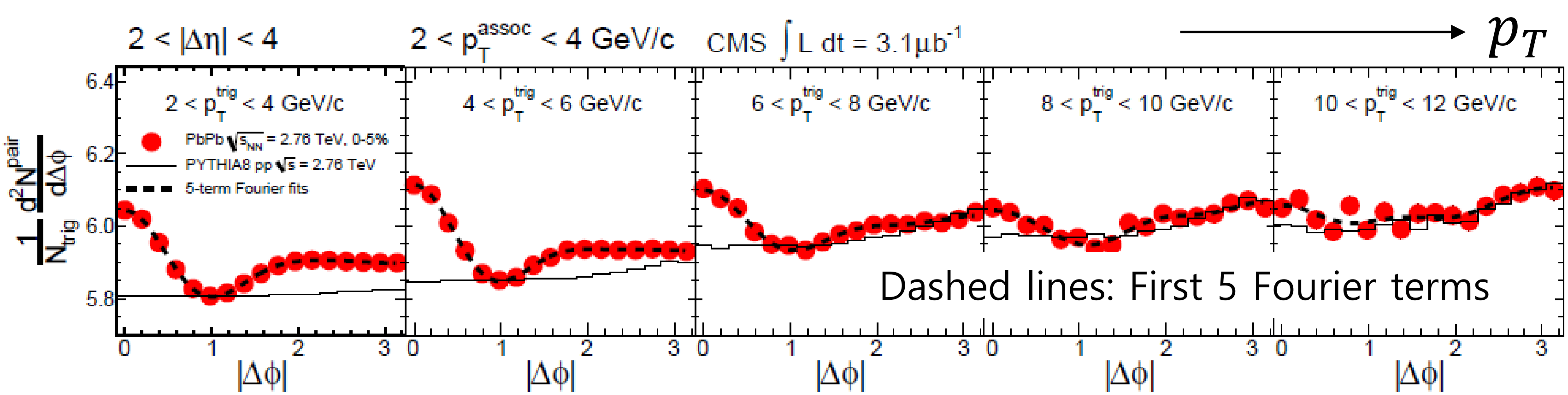
JHEP07, 076 (2011)

PbPb @ 2.76 TeV (0-5%)





$$\frac{1}{N_{\rm trig}} \frac{dN^{\rm pair}}{d\Delta\phi} = \frac{N_{\rm assoc}}{2\pi} \left\{ 1 + \sum_{n=1}^{\infty} 2V_n^{\rm f} \cos(n\Delta\phi) \right\}$$



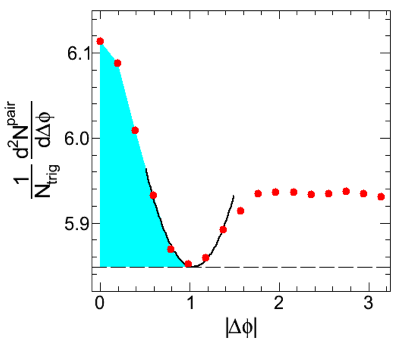
Application to PbPb Data

JHEP07, 076 (2011)

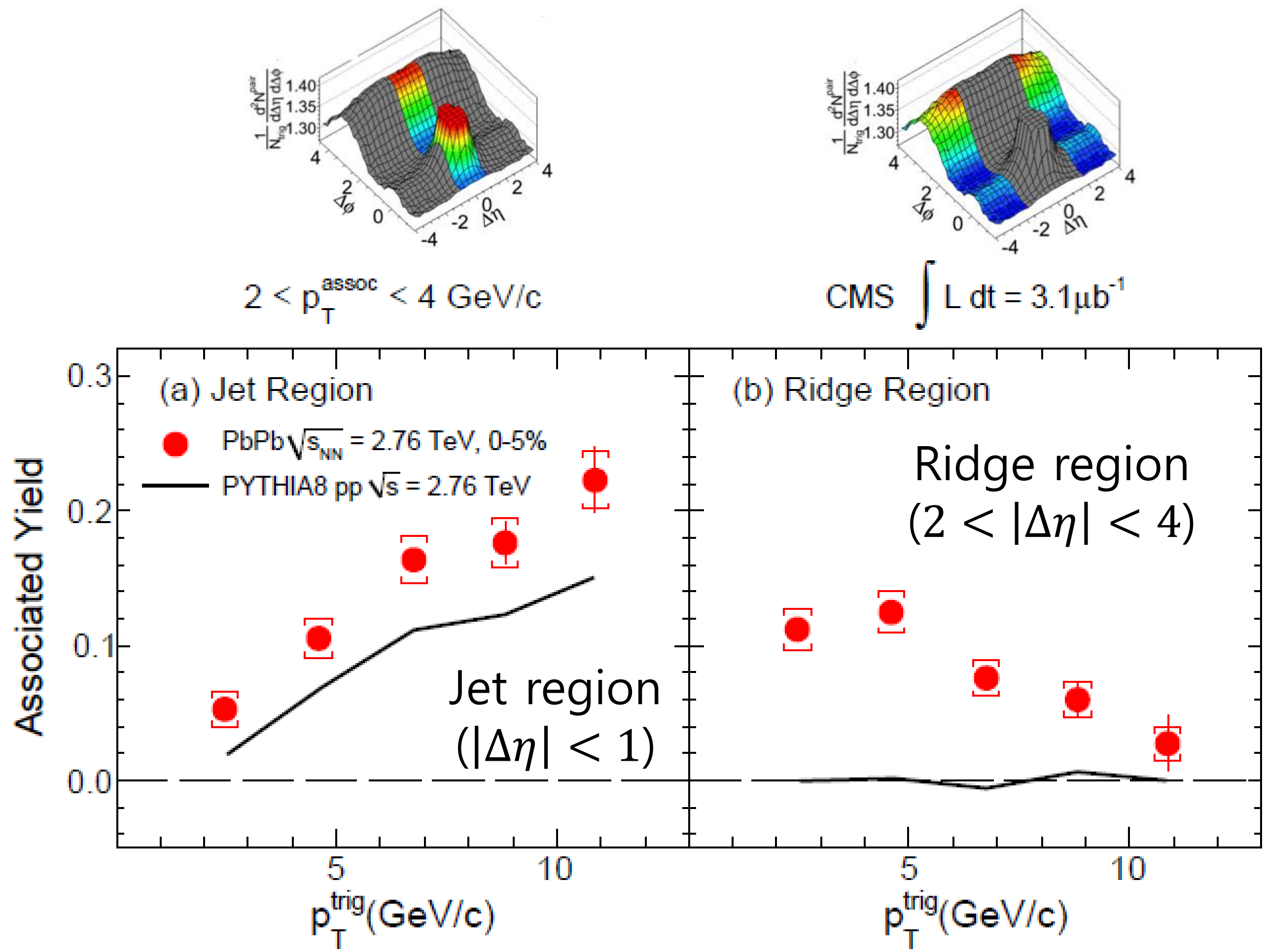
PbPb @ 2.76 TeV (0-5%)

Definition of the associated yield

ZYAM



v_2 not subtracted

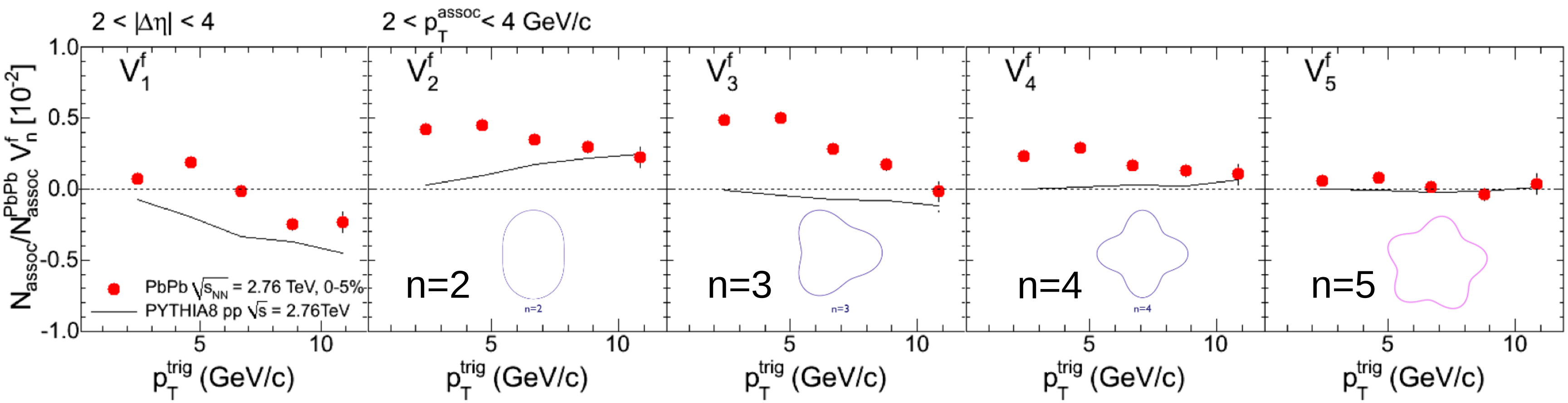


- Ridge in PbPb collisions tends to diminish at high p_T.

Application to PbPb Data

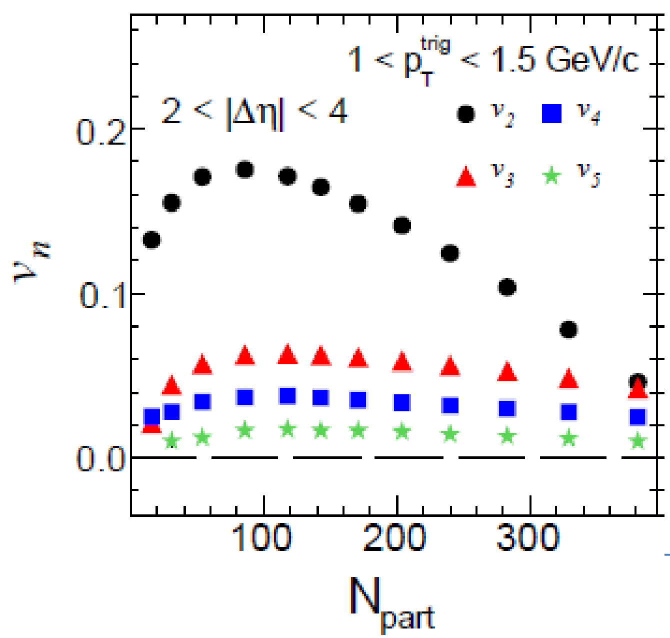
JHEP07, 076 (2011)

PbPb @ 2.76 TeV (0-5%)



- f: Fourier analysis of long-range dihadron correlations
- Flow driven correlations: $V_n^f(p_T^{trig}, p_T^{assoc}) = v_n^f(p_T^{trig}) v_n^f(p_T^{assoc})$
- Complimentary to other standard flow methods (EP, cumulants, LYZ)

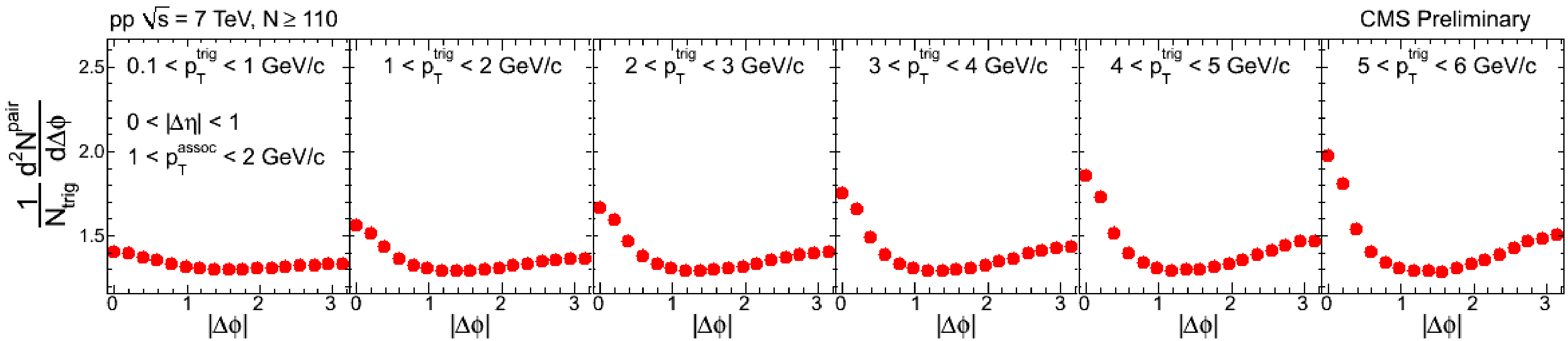
$1 < p_T^{assoc} < 3$ GeV/c



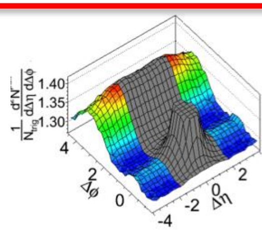
EPJC72, 2012 (2012)

Application to pp Data

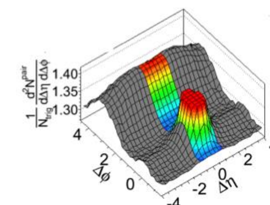
PAS HIN-11-006 pp @ 7 TeV, N ≥ 110

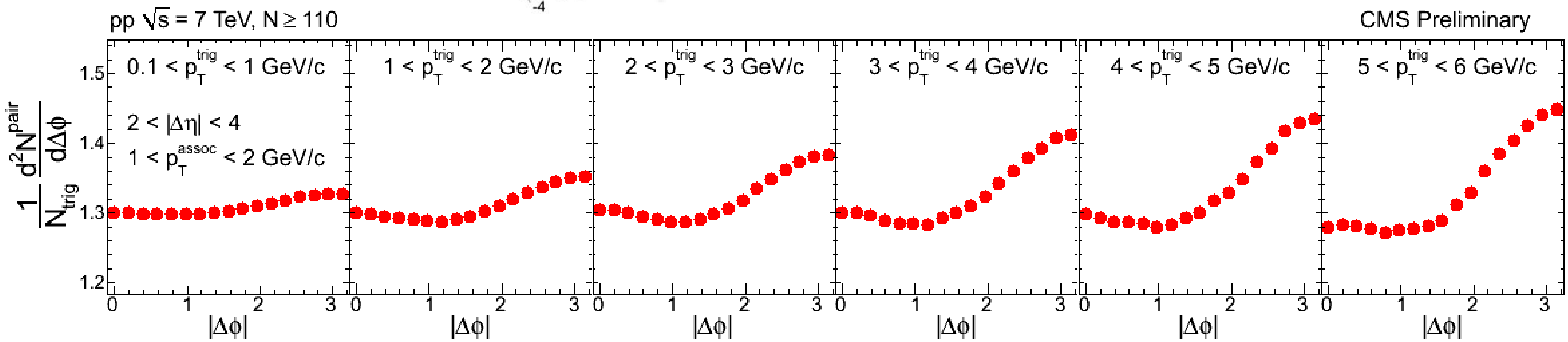


Ridge region
$(2 < |\Delta\eta| < 4)$



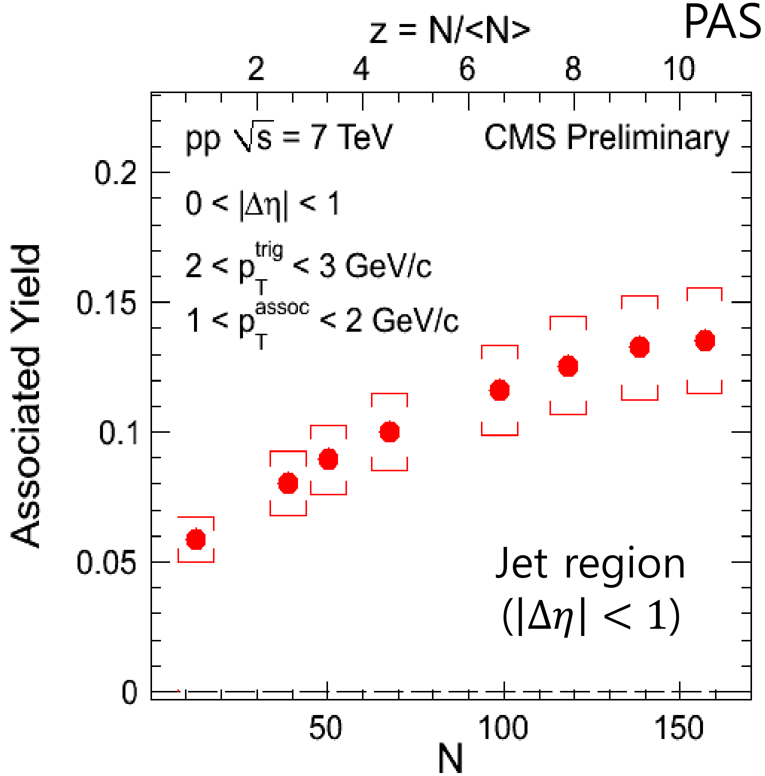
Jet region
$(|\Delta\eta| < 1)$

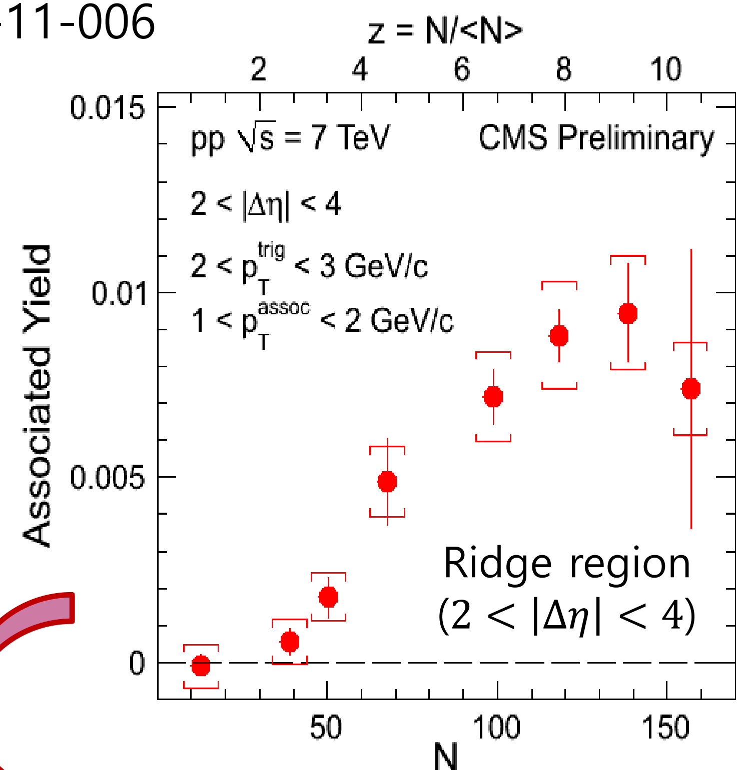




Application to pp Data

PAS HIN-11-006





For the rest of time,

- Recent detailed correlation results in pPb & PbPb from CMS
  - Long-range correlation (ridge)
  - Extracted flow parameters (v_2 & v_3)

- Ridge in pp turns on N~50 (<N>~15 for MinBias events)
- Origin is not yet clear
  - Multi-jet correlation
  - Color connection between jets
  - Hydrodynamic flow of QGP, etc.

CMS Detector

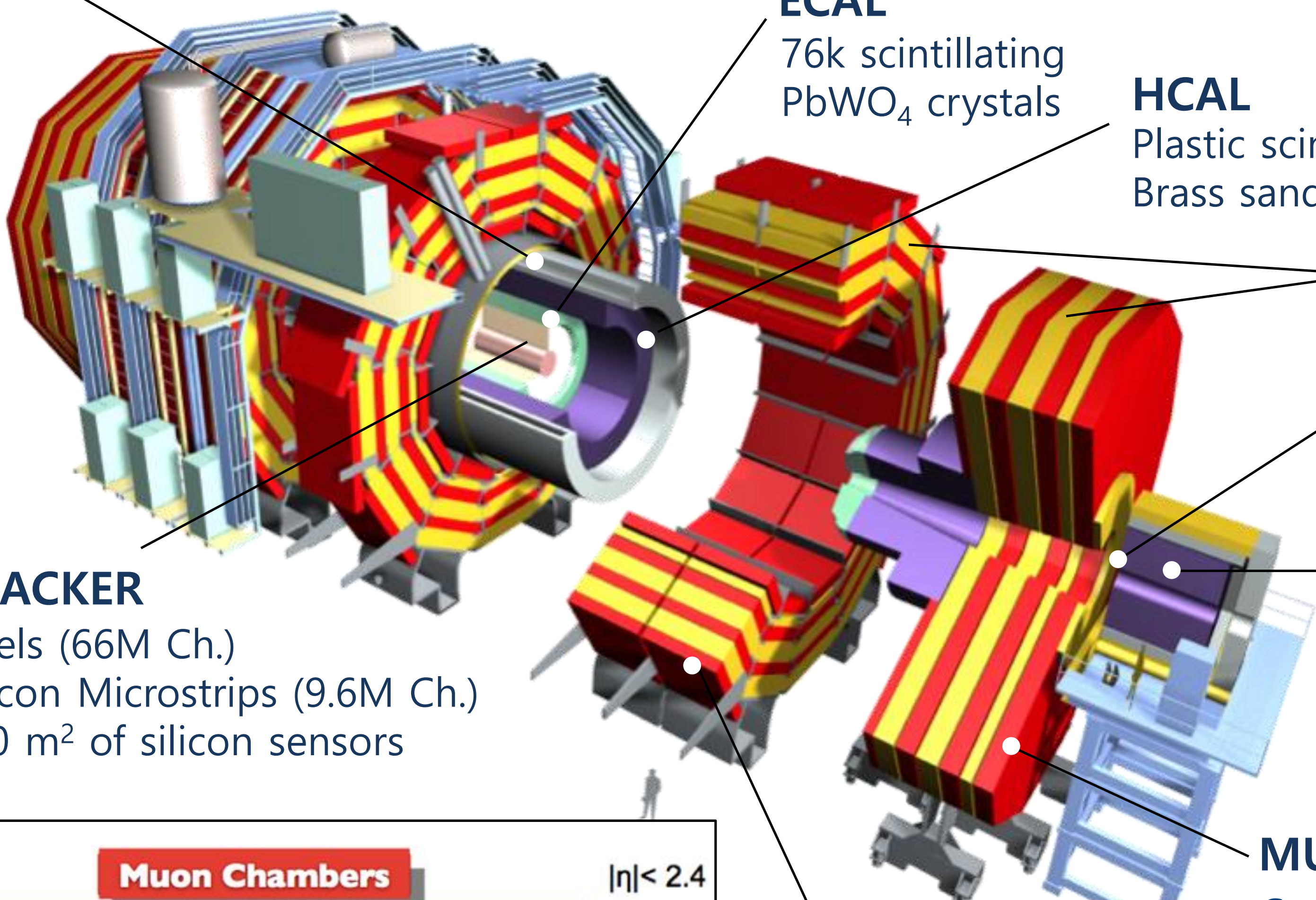
Superconducting Coil (3.8 T)

CALORIMETERS

ECAL
76k scintillating
$PbWO_4$ crystals

HCAL
Plastic scintillator/
Brass sandwich

Weight: 12,500 tons
Diameter: 15 m
Length: 22 m



Steel YOKE

BSC
MB trigger

HF
MB trigger
Centrality in HI

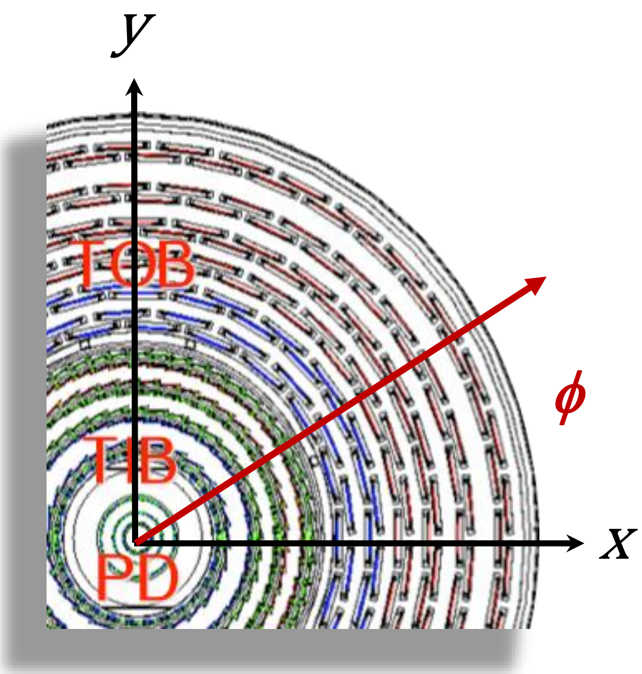
TRACKER
Pixels (66M Ch.)
Silicon Microstrips (9.6M Ch.)
220 m^2 of silicon sensors

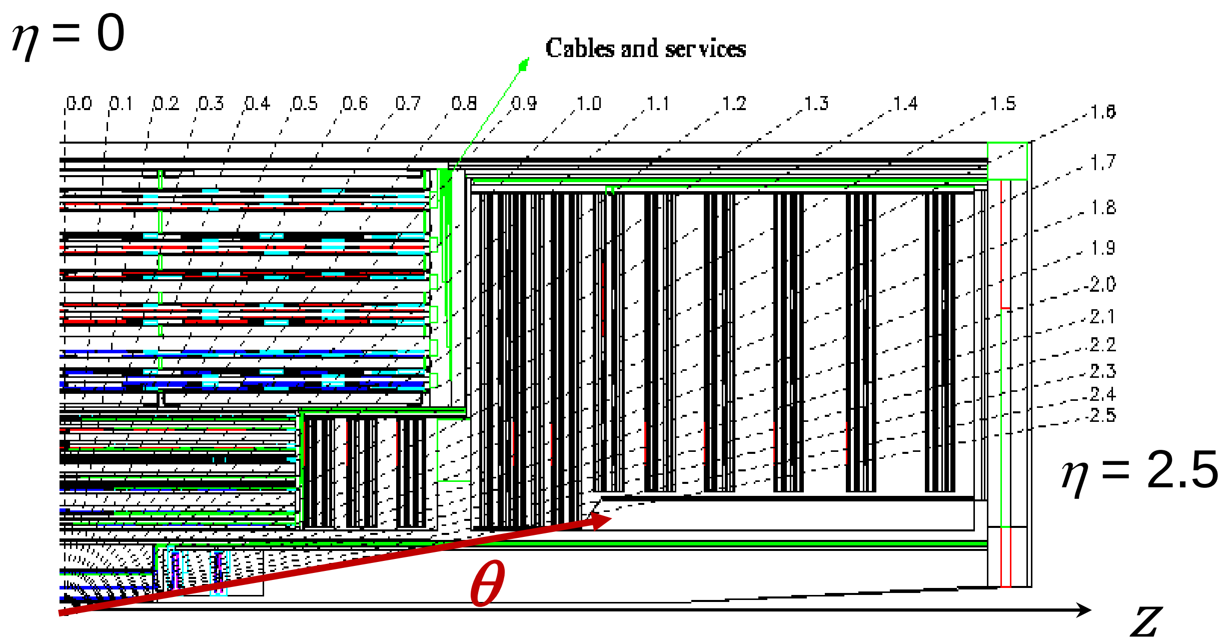
MUON BARREL
Drift Tube Chambers
Resistive Plate Chambers

MUON ENDCAPS
Cathode Strip Chambers
Resistive Plate Chambers

CMS Trackers

Large coverage (|$\Delta\eta$| < 2.5)!



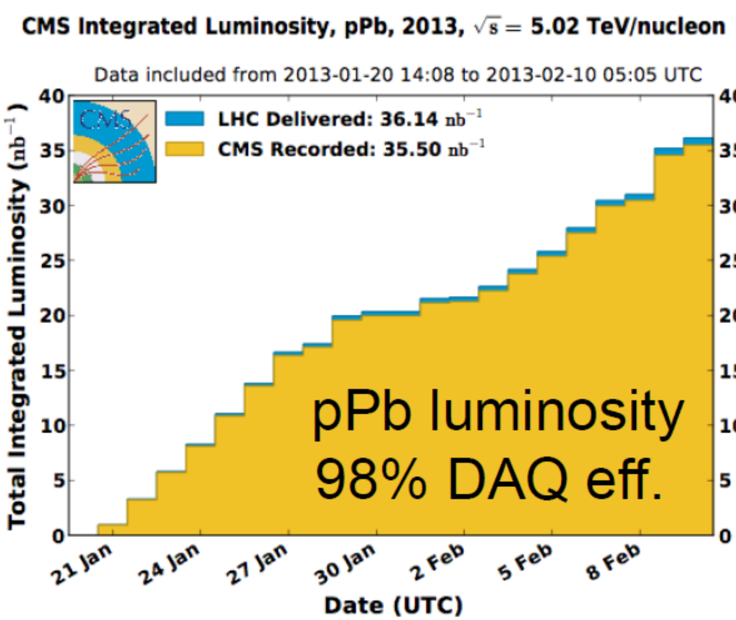


- Pixels (66M channels) + Silicon Microstrips (9.6M channels)
- 220 m^2 of silicon sensors

Heavy-Ion Related Data Samples

Period	System	$\sqrt{s_{NN}}$ (TeV)	Int. $\mathcal{L}$	Comment
Dec. 2010	Pb+Pb	2.76	7 μb^{-1}	
Dec. 2011	Pb+Pb	2.76	150 μb^{-1}	
Mar. 2011	p+p	2.76	230 nb^{-1}	Reference
Jan. 2013	p+Pb	5.02	35 nb^{-1}	
Feb. 2013	p+p	2.76	5.4 pb^{-1}	Reference

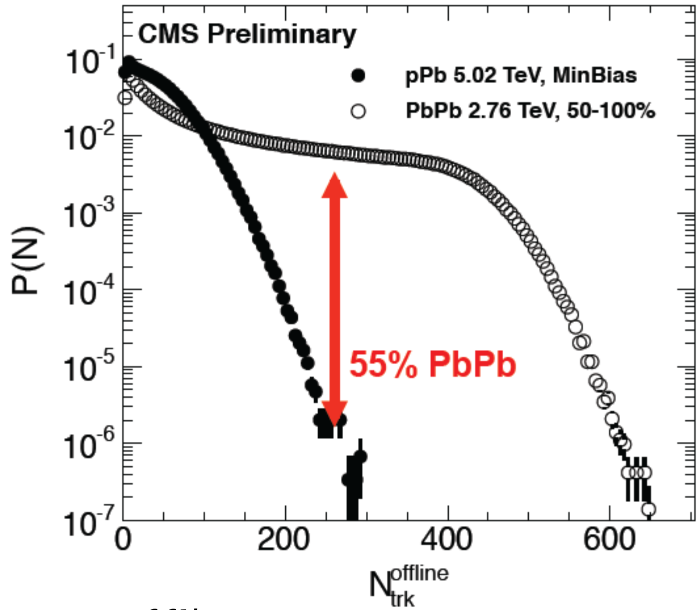
- Almost same N_{coll} scaled luminosities for pp, pPb & PbPb
  - As many as Z's and W's
- Recent improvements (compared to QM2012)
  - PbPb results updated with 20 times more pp reference data
  - New pPb results



Ridges in pPb @ LHC

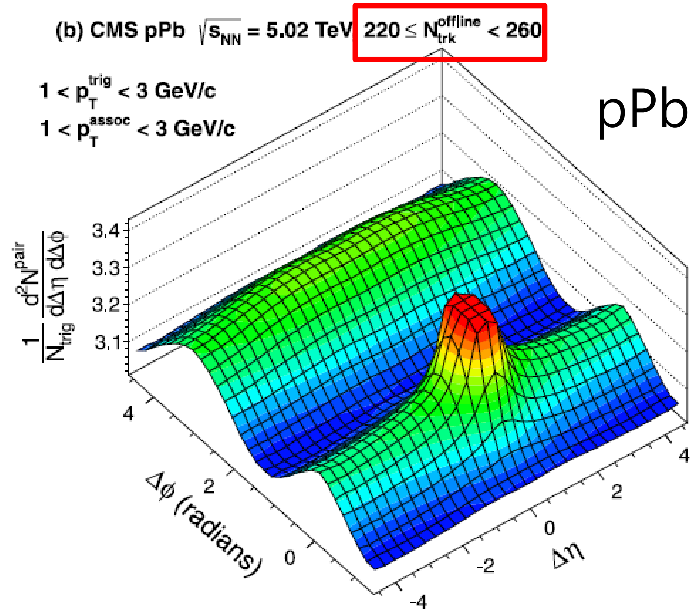
CMS, PLB 724, 213 (2013)

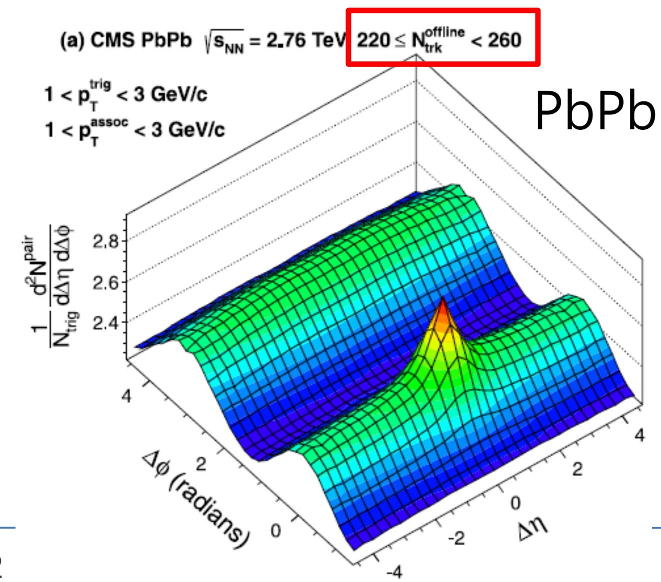
p_T > 0.4 GeV/c, $|\eta|$ < 2.4



($N_{trk}^{offline}$: Offline track multiplicity)

- Ridge structure in pPb was also found by other LHC experiments
  - ALICE, PLB 719, 29 (2013)
  - ATLAS, PLB 725, 60 (2013)



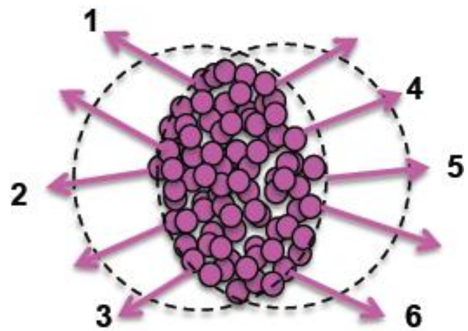


Same $N_{trk}^{offline}$ range

Relevant Formulae

- Cumulants formed from v_n moments

$$c_n\{2\} = \langle\langle 2\rangle\rangle$$
$$c_n\{4\} = \langle\langle 4\rangle\rangle - 2\langle\langle 2\rangle\rangle^2$$
$$c_n\{6\} = \langle\langle 6\rangle\rangle - 9\langle\langle 4\rangle\rangle\langle\langle 2\rangle\rangle + 12\langle\langle 2\rangle\rangle^3,$$ etc.



where, for example,

$$\langle 6\rangle \equiv \left\langle e^{in(\phi_1+\phi_2+\phi_3-\phi_4-\phi_5-\phi_6)}\right\rangle$$
$$\equiv \frac{1}{P_{M,6}} \sum_{i\neq j\neq k\neq l\neq m\neq n}^{M} e^{in\left(\phi_i+\phi_j+\phi_k-\phi_l-\phi_m-\phi_n\right)}$$

and $\langle\langle\cdot\rangle\rangle$ means the average of over all particles from all events within a given multiplicity range

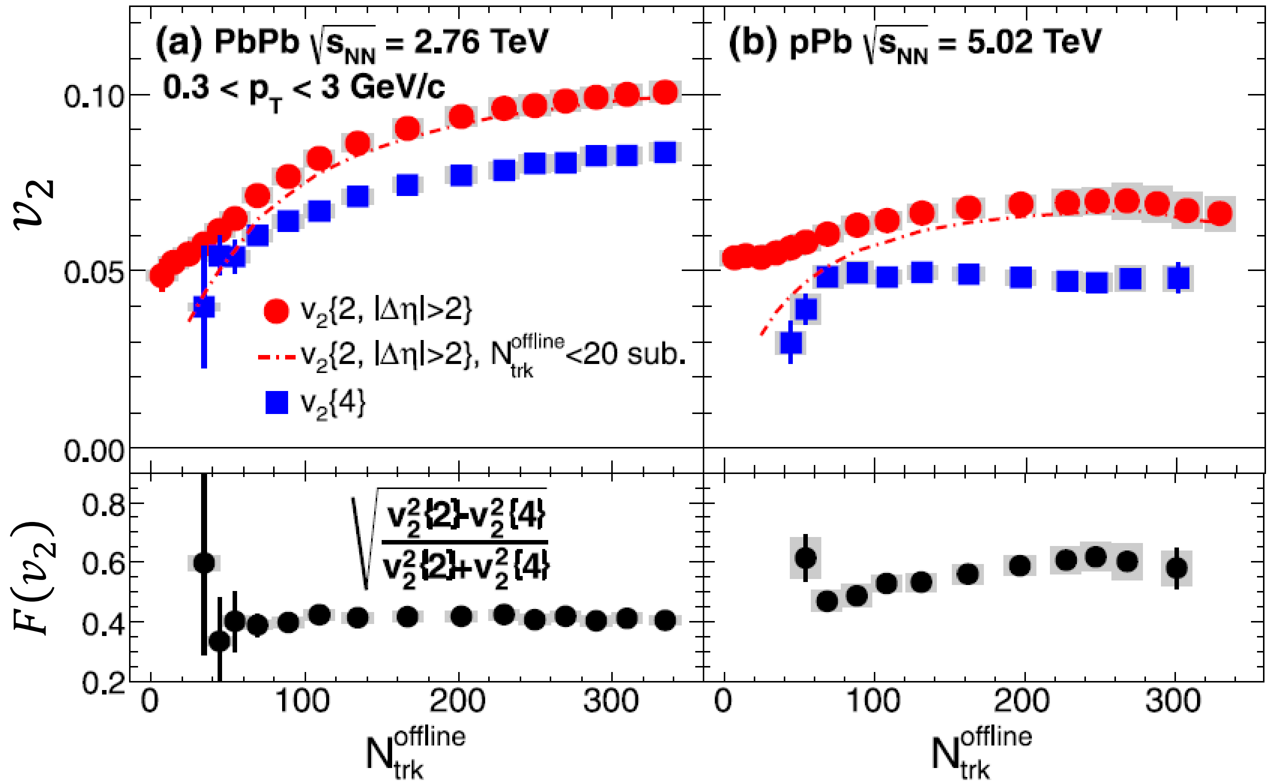
- Flow coefficients from cumulants

$$v_n\{2\} = \sqrt{c_n\{2\}},\ v_n\{4\} = \sqrt[4]{-c_n\{4\}},\ v_n\{6\} = \sqrt[6]{\frac{1}{4}c_n\{6\}},$$
$$v_n\{8\} = \sqrt[8]{-\frac{1}{33}c_n\{8\}},$$ etc.

A. Bilandzic, et al.,
Phys. Rev. C 83, 044913 (2011)

Elliptic Flow: PbPb vs. pPb

CMS, PLB 724, 213 (2013)



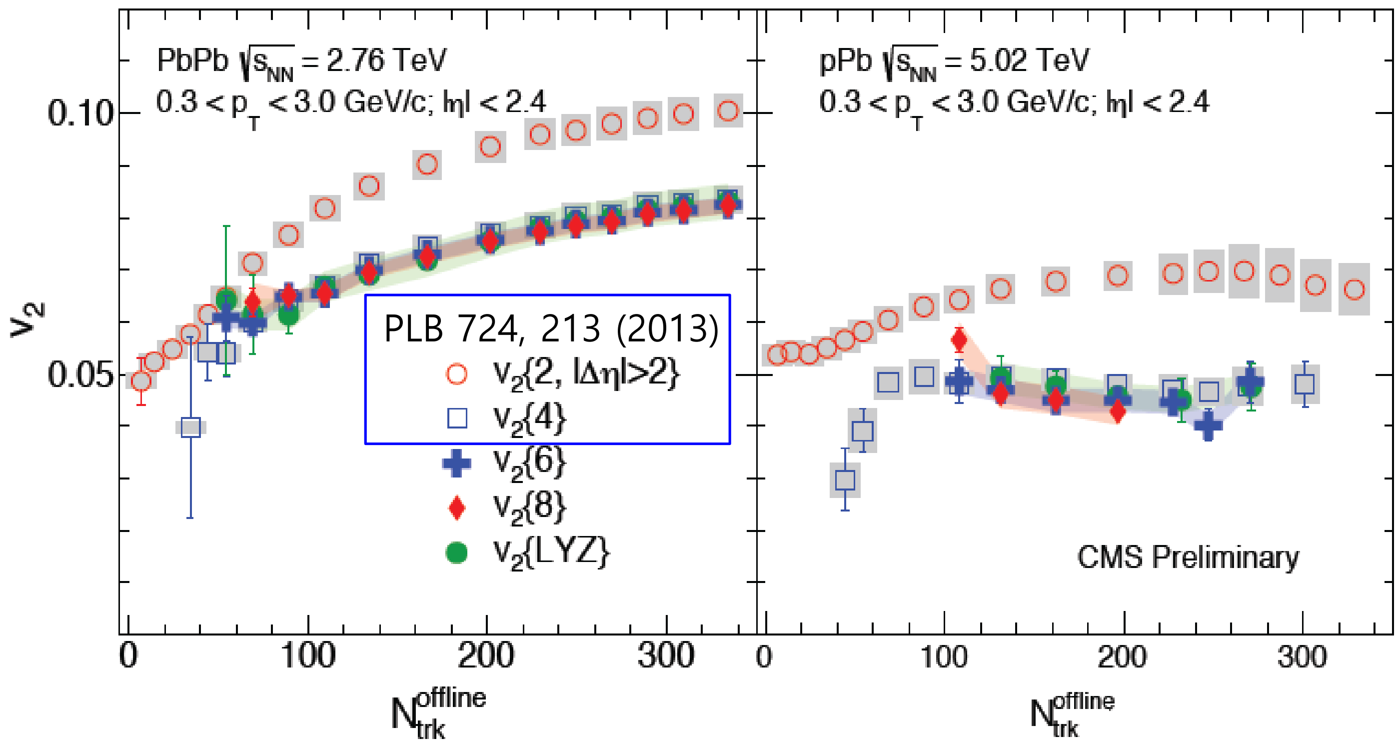
Relative fluctuation
N. Borghini, P. M. Dinh, J.-Y. Ollitrault, arXiv:nucl-ex/0110016

- Fourier expansion also works well for the long-range correlations in pPb.
- $v_2\{2\}$ contains some non-flow components.

Elliptic Flow: PbPb vs. pPb

PAS HIN-14-006

- 6- & 8-particle cumulants: Insensitive to non-flow contributions
- Lee-Yang Zeros (LYZ): All particle correlations

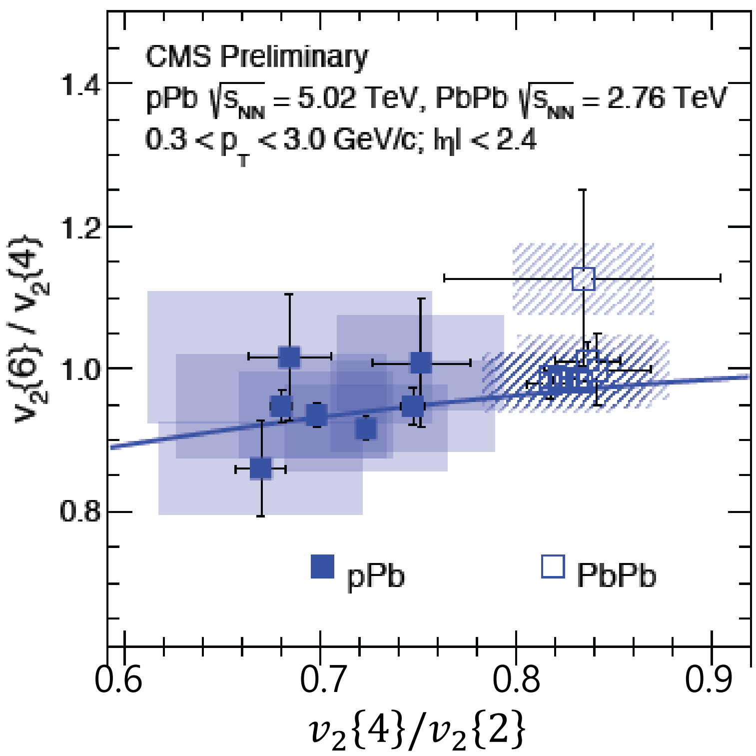


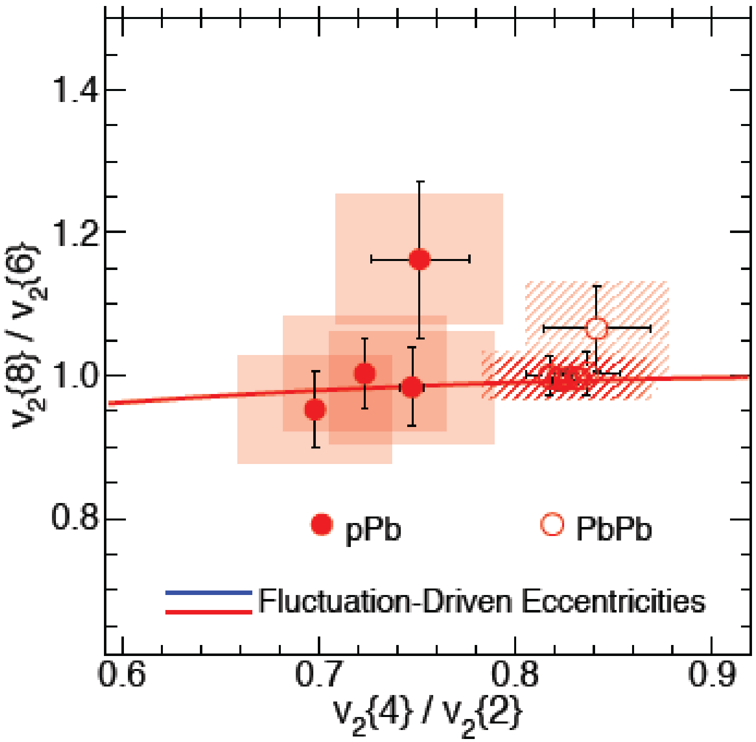
- $v_2\{4\}$, $v_2\{6\}$, $v_2\{8\}$ and $v_2\{LYZ\}$ are in good agreement within ±10%
- True collectivity observed in pPb!

Elliptic Flow: PbPb vs. pPb

PAS HIN-14-006

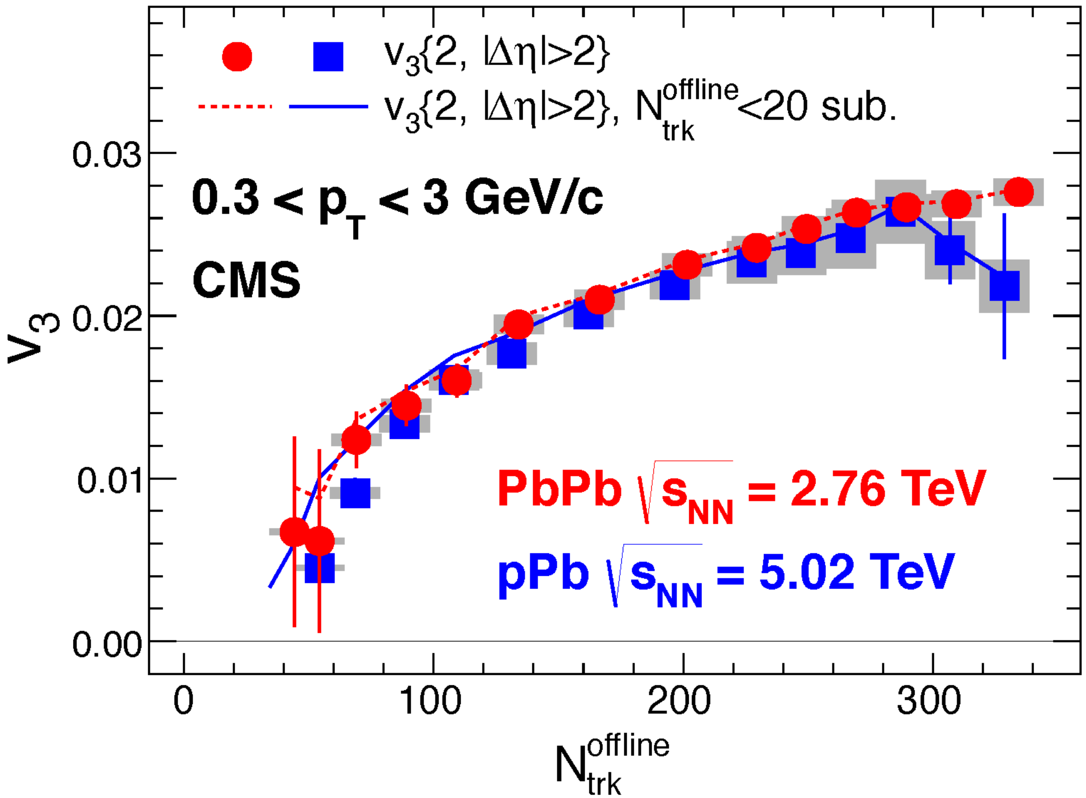
- Fluctuation-driven initial-state eccentricity in hydrodynamics in pPb
  - A. Bzdak, P. Bozek, and L. McLerran, arXiv: 1311.7325
  - L. Yan and J.-Y. Ollitrault, PRL 112, 082301 (2014)

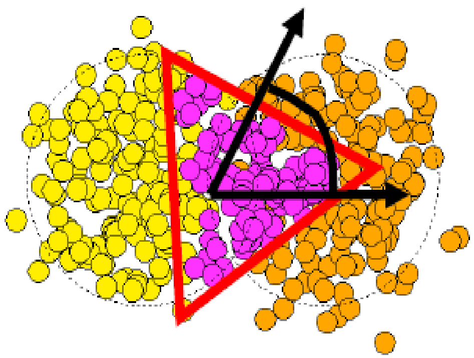




Triangular Flow: PbPb vs. pPb

CMS, PLB 724, 213 (2013)



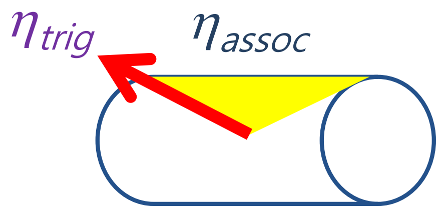


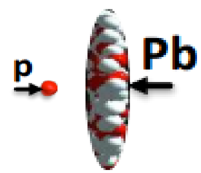
- Remarkable similarity in the v_3 signal as a function of multiplicity in pPb and PbPb

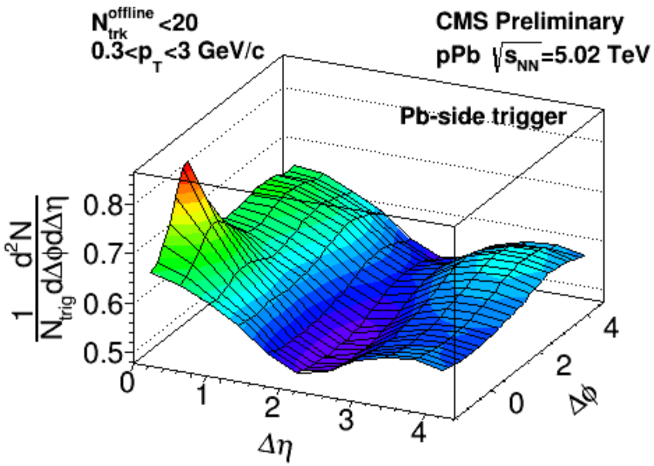
η-Dependence of v_n in pPb

$-2.4 < \eta_{trig} < 2.0$ (Pb-going trigger)

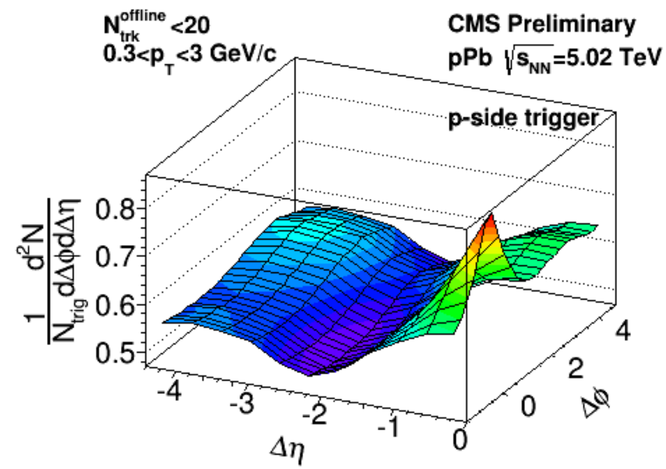
$2.0 < \eta_{trig} < 2.4$ (p-going trigger)

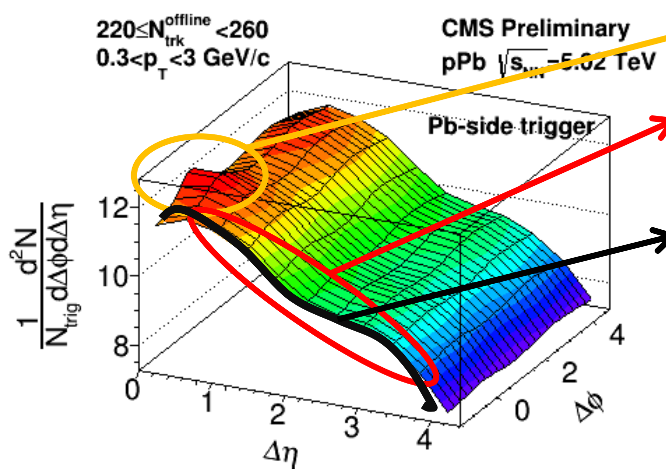






$$S(\Delta\eta, \Delta\phi) = \frac{1}{N_{trig}} \frac{d^2N^{same}}{d\Delta\eta\Delta\phi}$$

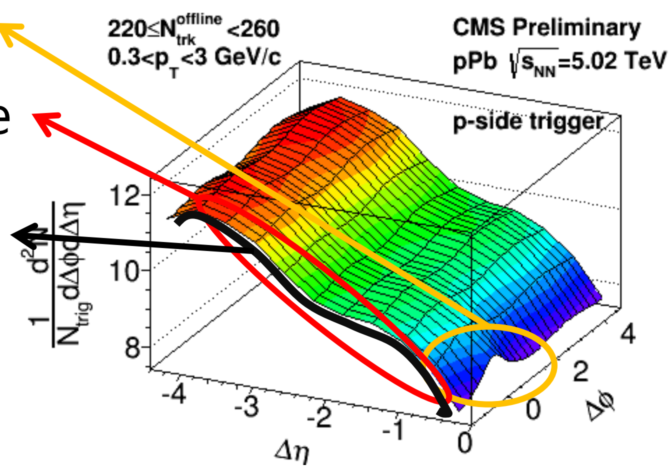




Near-side jet

Near-side ridge

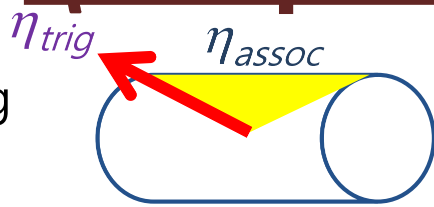
Shape~dN/dη

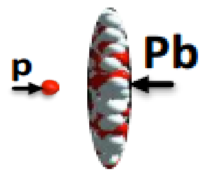


PAS HIN-14-008

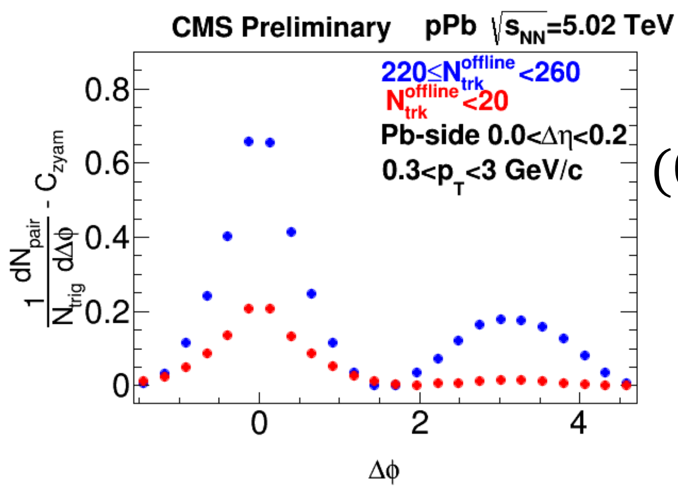
η-Dependence of v_n in pPb

Pb-going trigger



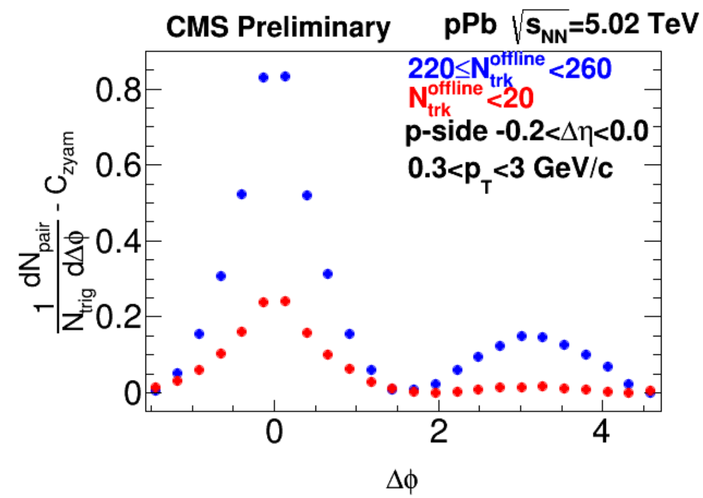


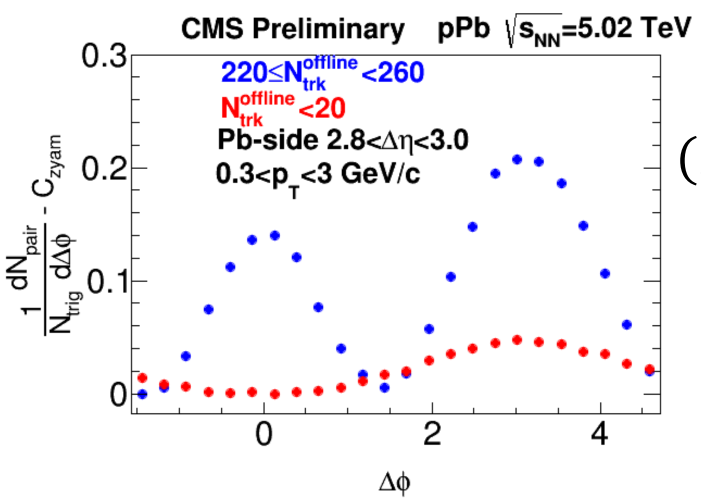
p-going trigger



Jet region

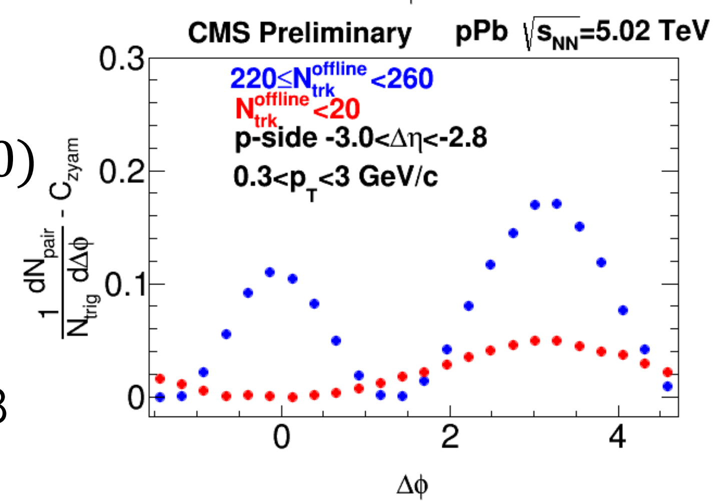
$(0 < |\Delta\eta| < 0.2)$





Ridge region

$(2.8 < |\Delta\eta| < 3.0)$

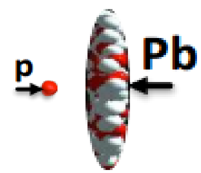


PAS HIN-14-008

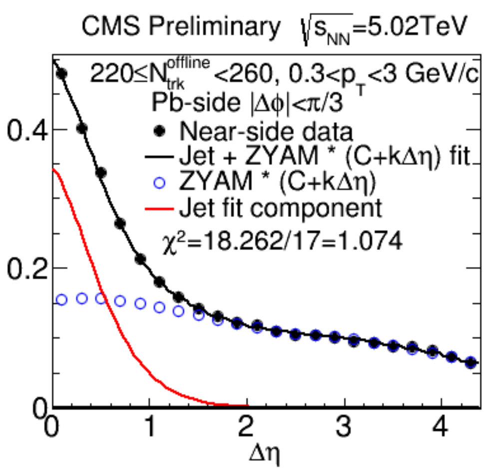
η-Dependence of v_n in pPb

- Comparison of the near-side ridge yields for both direction triggers

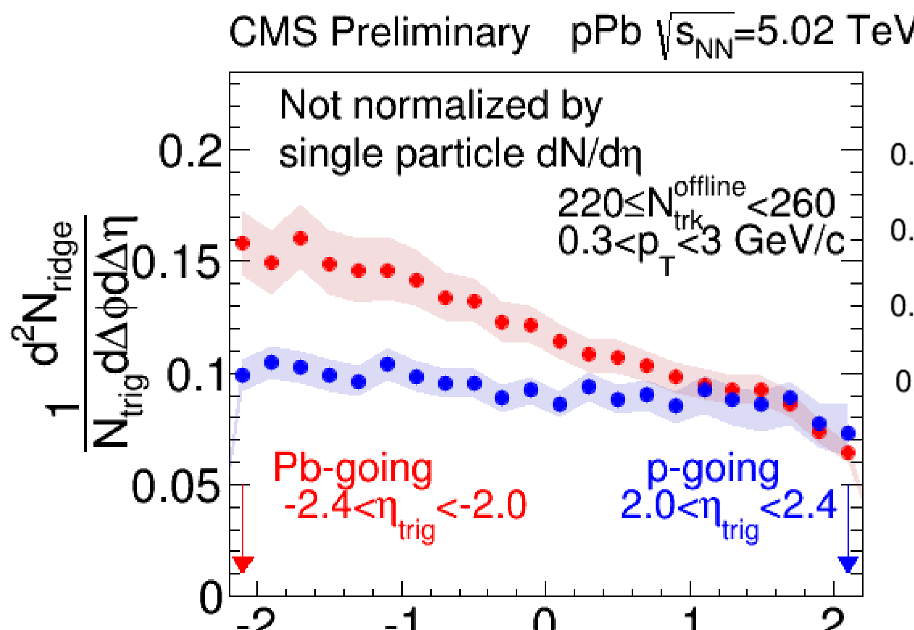
Pb-going



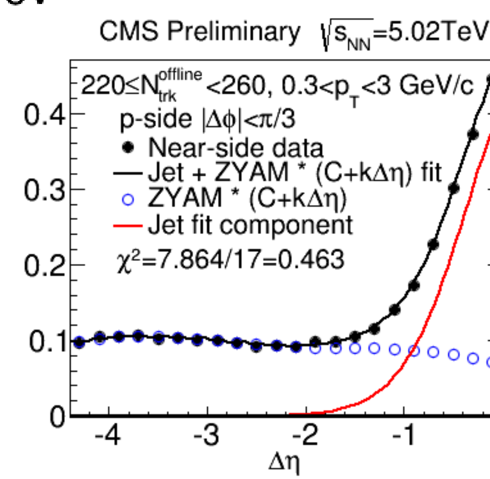
p-going



After jet subtraction



Shifted to single particle $\eta_{assoc}=\Delta\eta+<\eta_{trig}>$



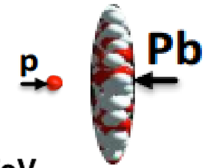
PAS HIN-14-008

Near-side ridge yields show different η dependences for both triggers.

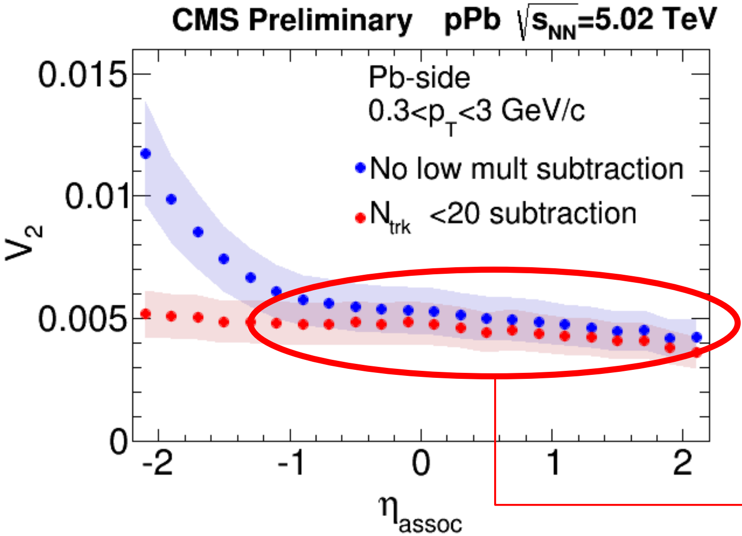
η-Dependence of v_n in pPb

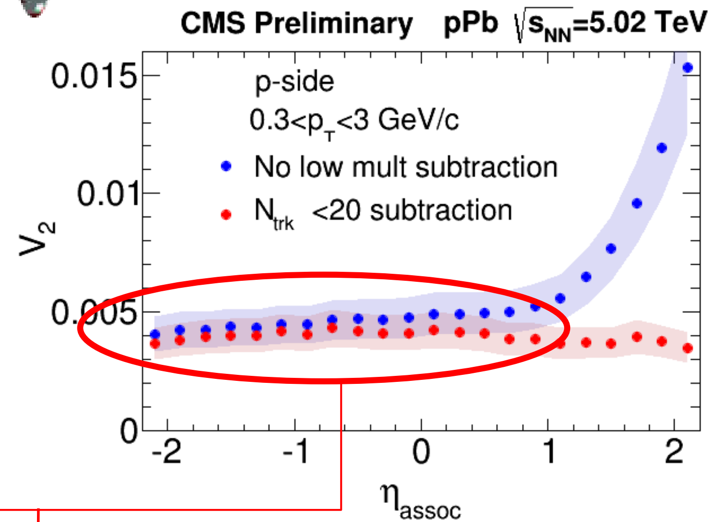
PAS HIN-14-008

Pb-going



p-going





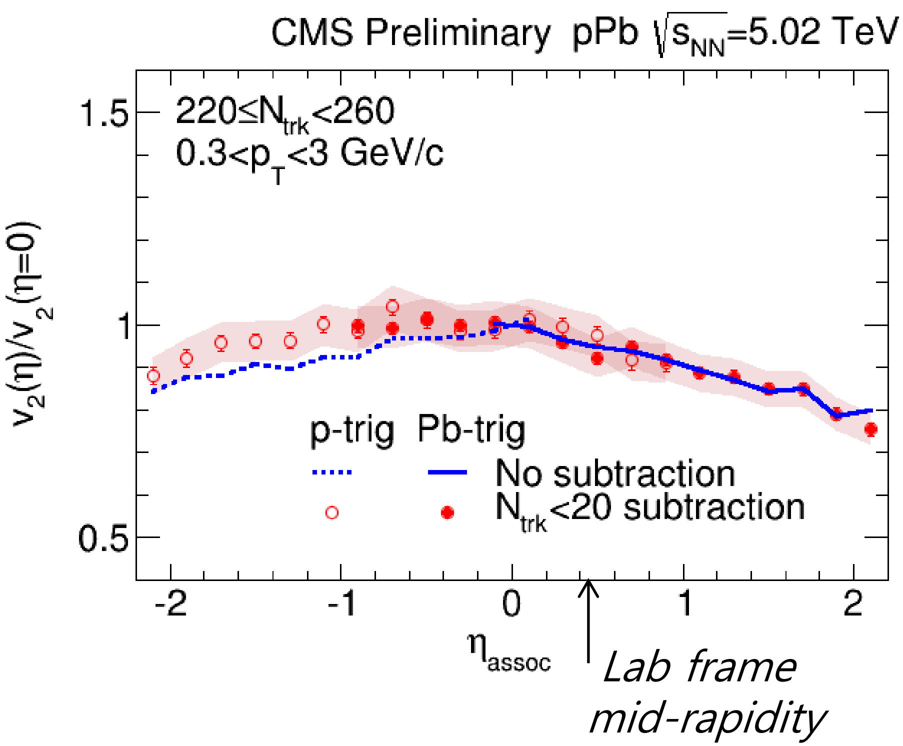
Red symbols: Low-multiplicity subtraction to minimize jet contribution [CMS, PLB 724, 213 (2013)]

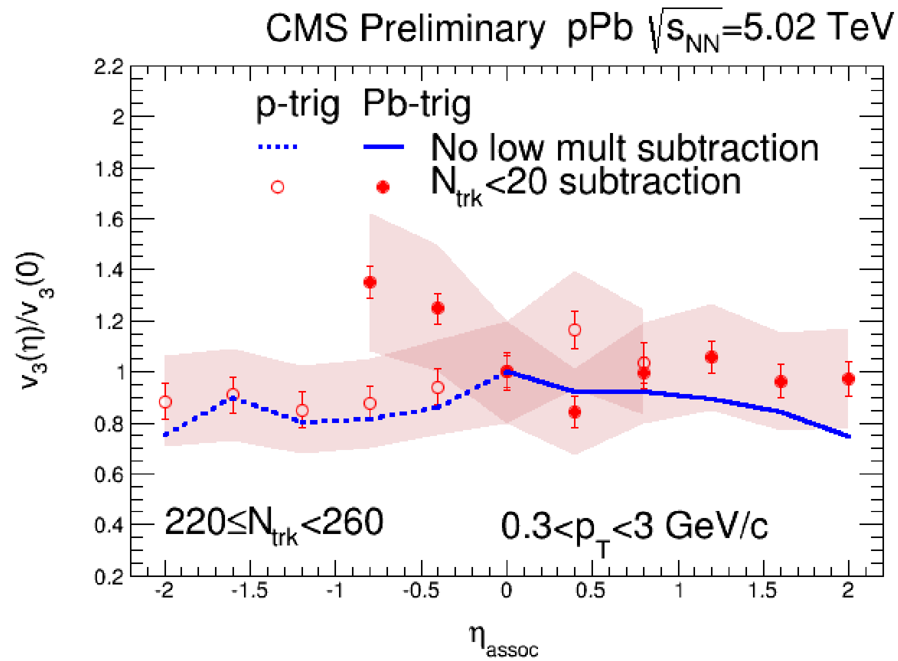
Long range data used for single $v_n(\eta_{assoc})/v_n(0)$

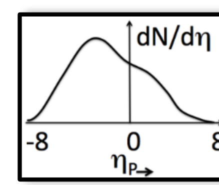
- Extract V_2 and V_3 from the Fourier decomposition
- Assuming factorization, $V_n(\eta_{trig}, \eta_{assoc}) = v_n(\eta_{trig}) v_n(\eta_{assoc})$
- Self-normalized single particle flow parameter $v_n(\eta_{assoc})/v_n(0)$
- Practically, $v_n(\eta_{assoc})/\, v_n(0) = V_n(\eta_{trig}, \eta_{assoc})/V_n(\eta_{trig}, 0)$

η-Dependence of v_n in pPb

$v_2(\eta)/v_2(0)$ PAS HIN-14-008 $v_3(\eta)/v_3(0)$



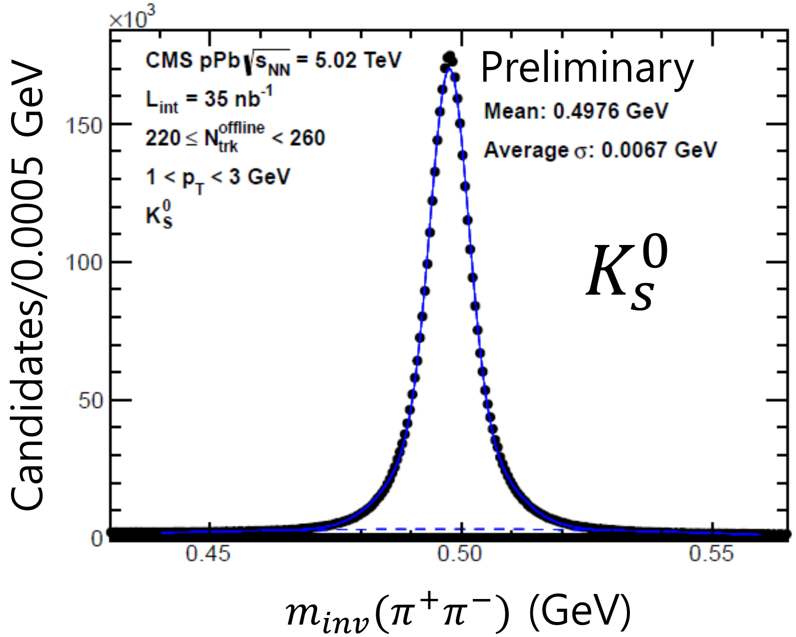


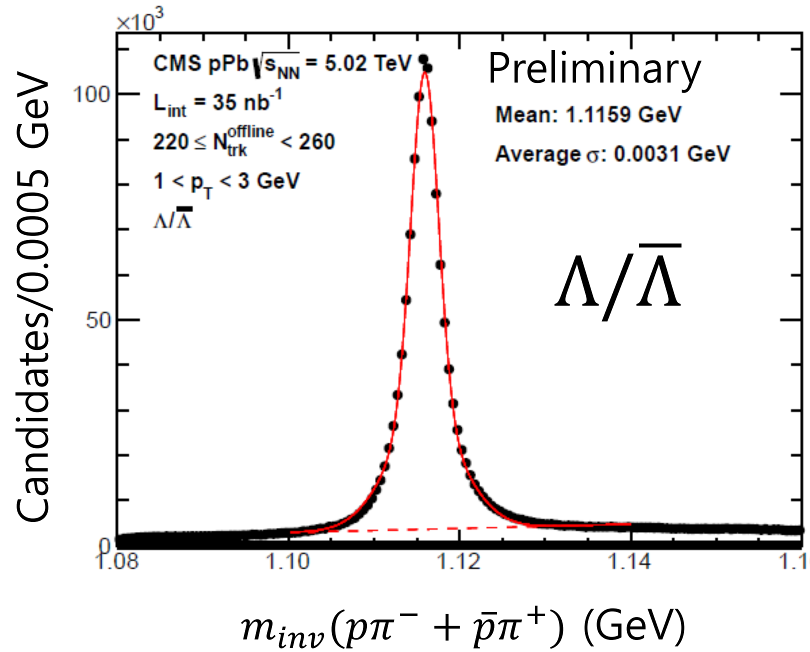


- v_2 is η dependent: Larger v_2 with higher particle density
- v_2 from low-multiplicity subtraction: asymmetric about mid-rapidity
- With large errors, we cannot draw any conclusion yet for v_3.

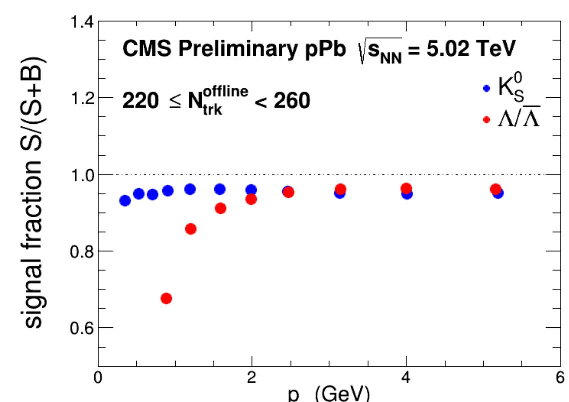
Elliptic Flow of Identified Particles

PAS HIN-14-002



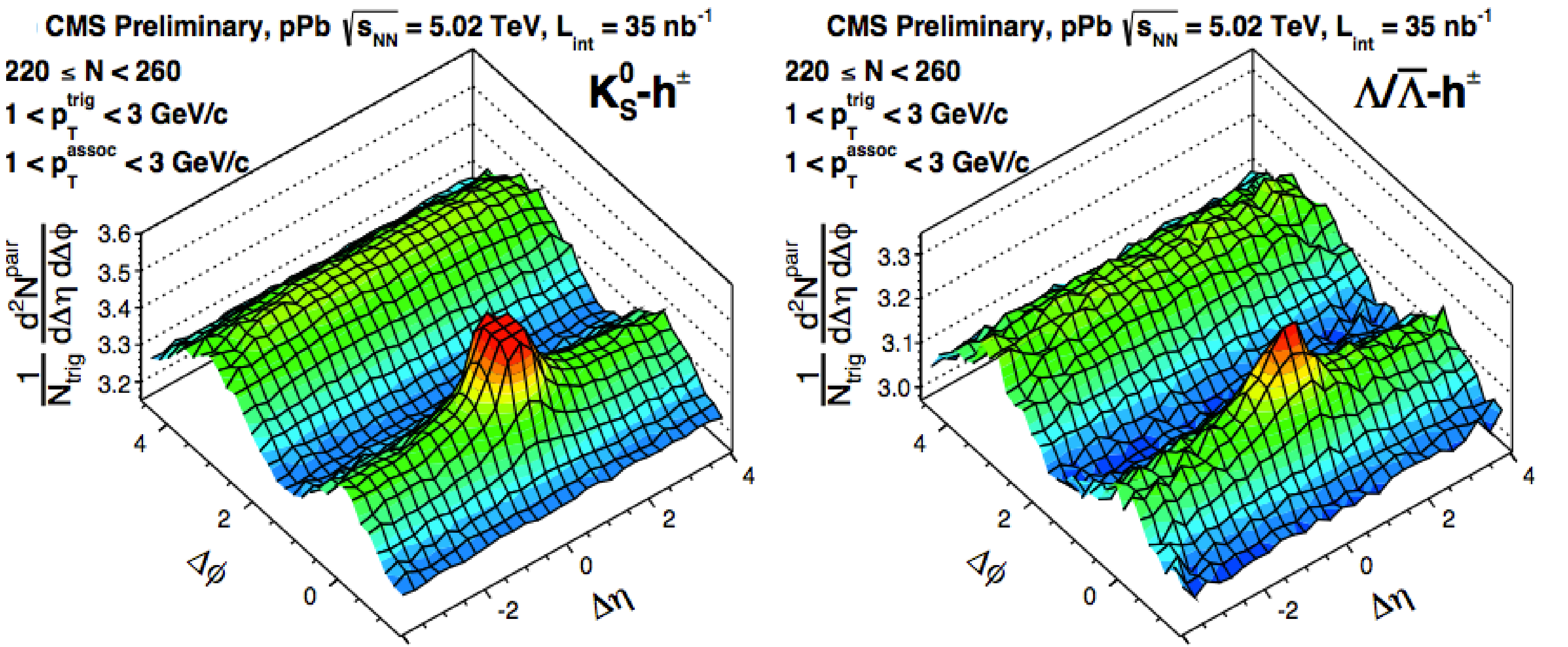


- Clean signal of K_s^0 and Λ reconstructed over a wide range of p_T and η.
- Masses are very close to PDG values.



Elliptic Flow of Identified Particles

PAS HIN-14-002



- Two-particle correlation functions are constructed for
  - $K_s^0 - h^{\pm}$: K_s^0 as trigger, the charged hadrons as associated
  - $\Lambda - h^{\pm}$: Λ as trigger, the charged hadrons as associated

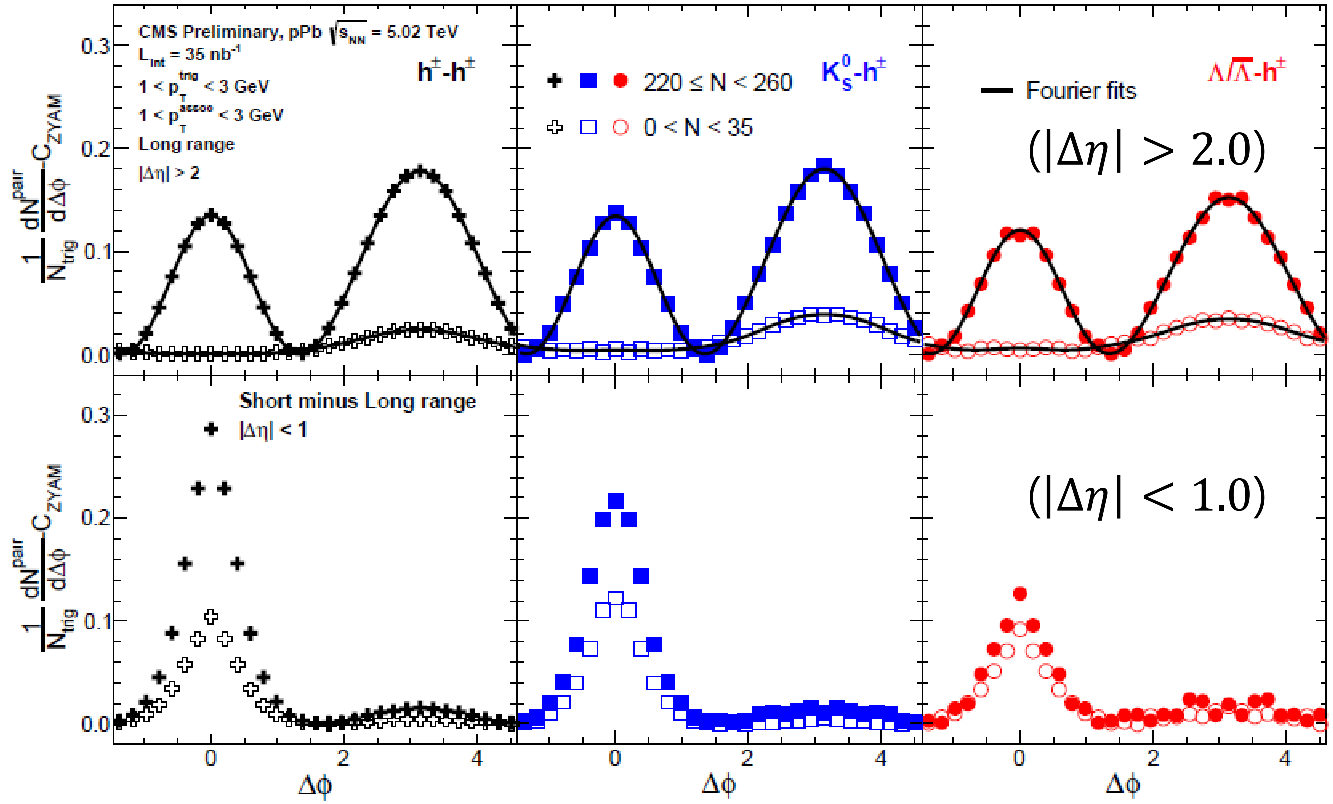
Elliptic Flow of Identified Particles

- Two-particle long-range correlation functions projected
- Fitted by the Fourier series function to extract V_n
- Extracted single particle v_n, assuming factorization:

$$v_n^{K_S^0} = V_n^{K_S^0-h}/v_n^h, \qquad v_n^{\Lambda} = V_n^{\Lambda-h}/v_n^h$$

Ridge region

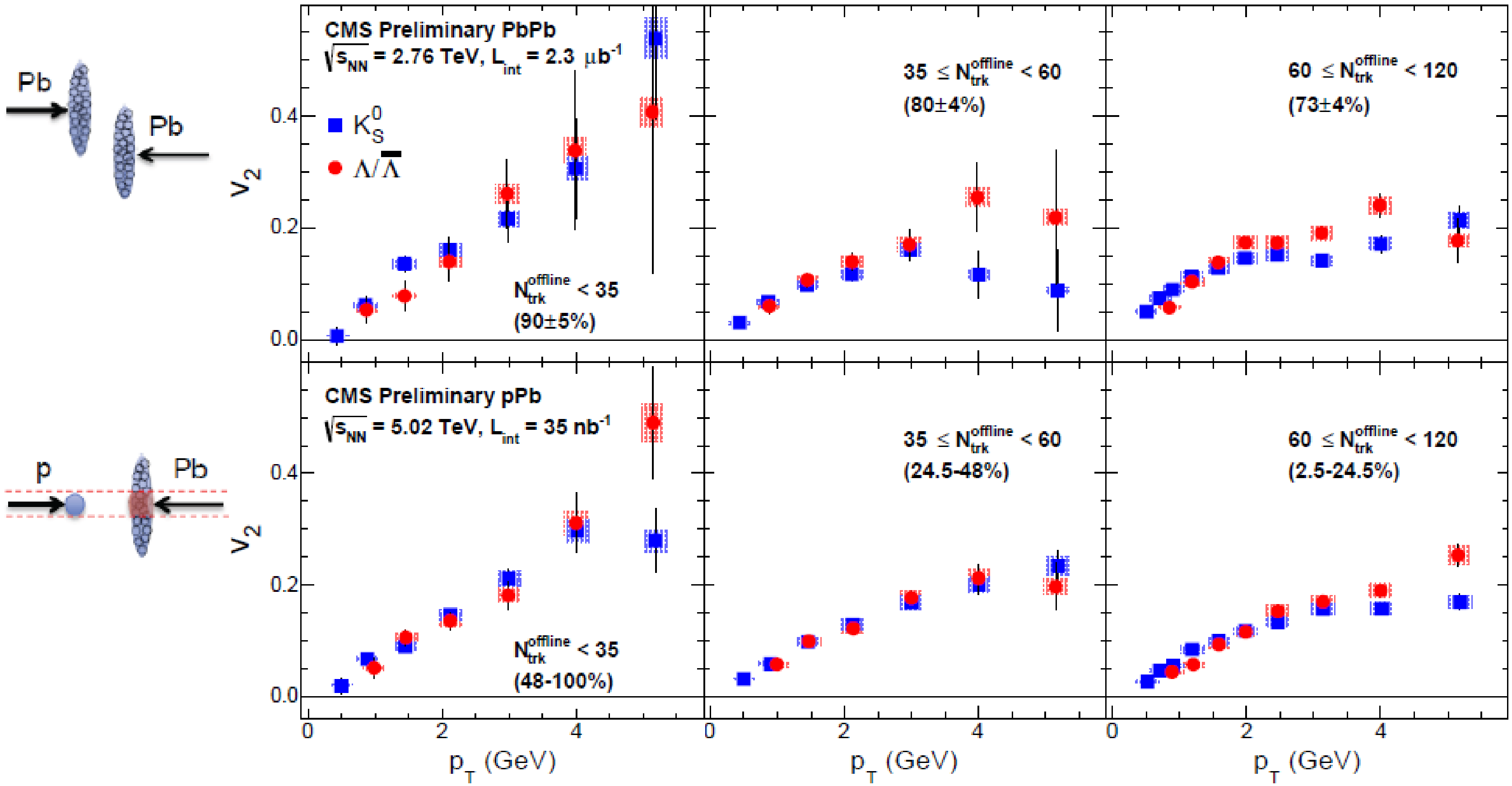
Jet region



PAS HIN-14-002

Elliptic Flow of Identified Particles

(Minbias events) → $N_{trk}^{offline}$



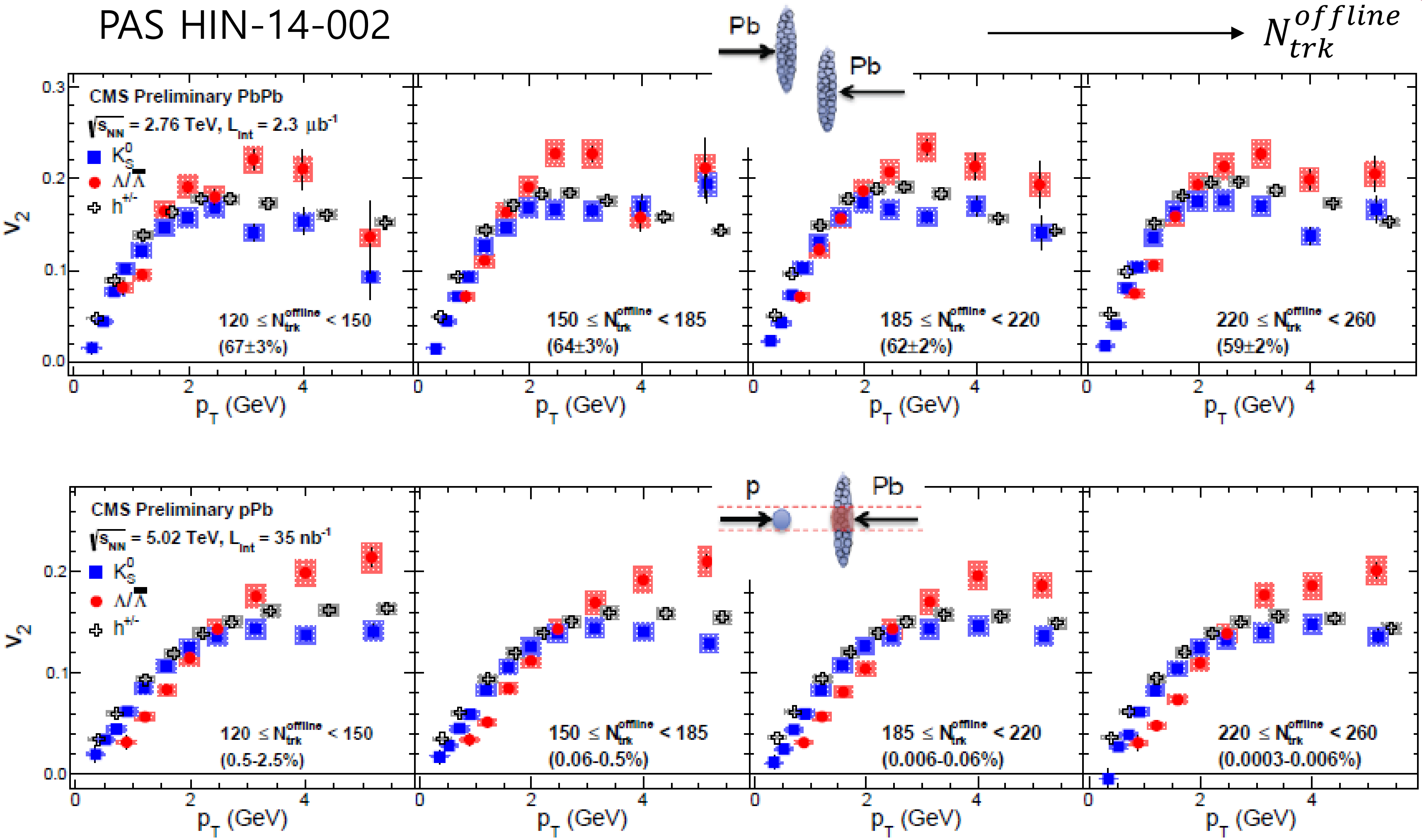
PAS HIN-14-002

v_2 patterns almost the same for K_s^0 & Λ at low multiplicity in both collision systems

Crossing over at p_T~2 GeV/c for $60 \leq N_{trk}^{offline} < 120$

Elliptic Flow of Identified Particles

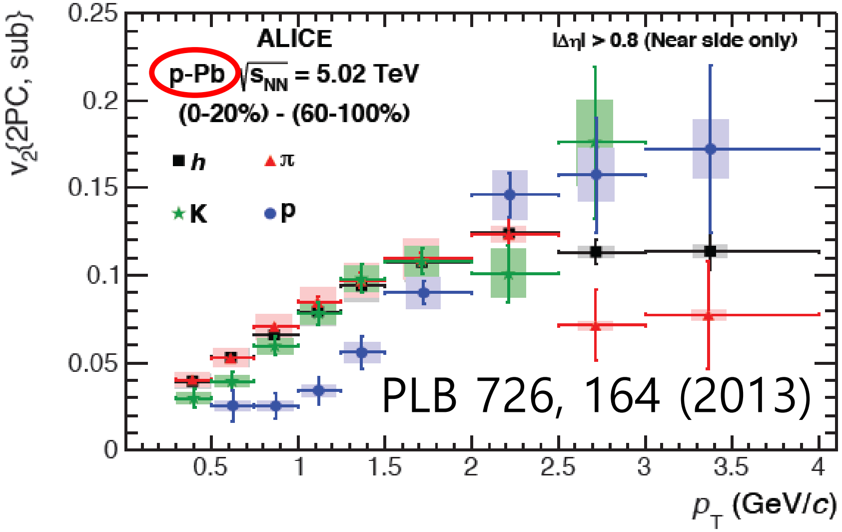
PAS HIN-14-002

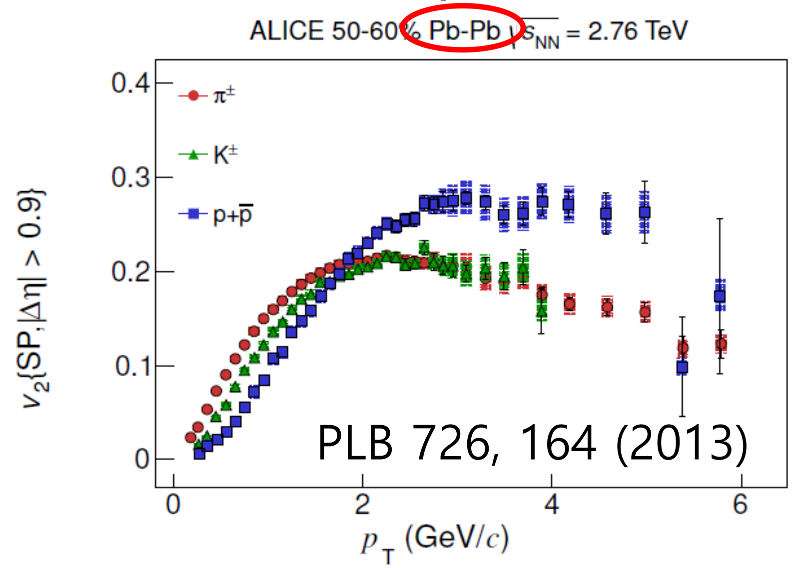


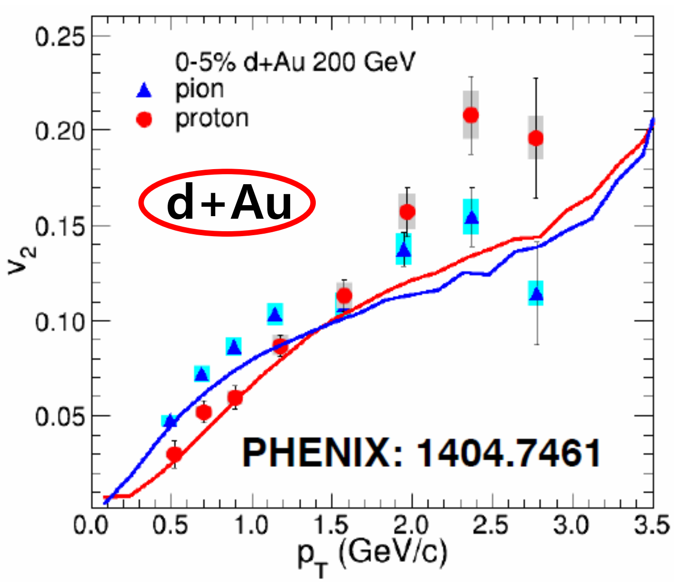
Mass ordering in p_T < 2 GeV/c and crossover in p_T > 2 GeV/c

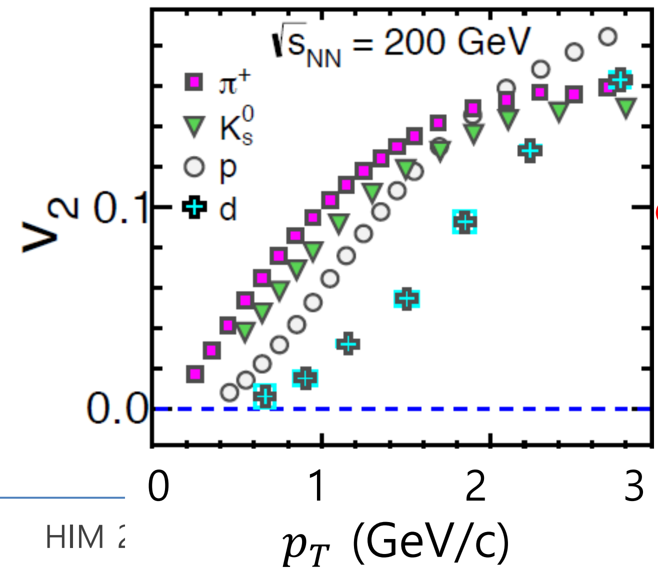
Mass Ordering & Crossover

Also observed by other RHIC and LHC experiments





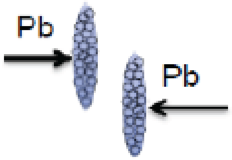


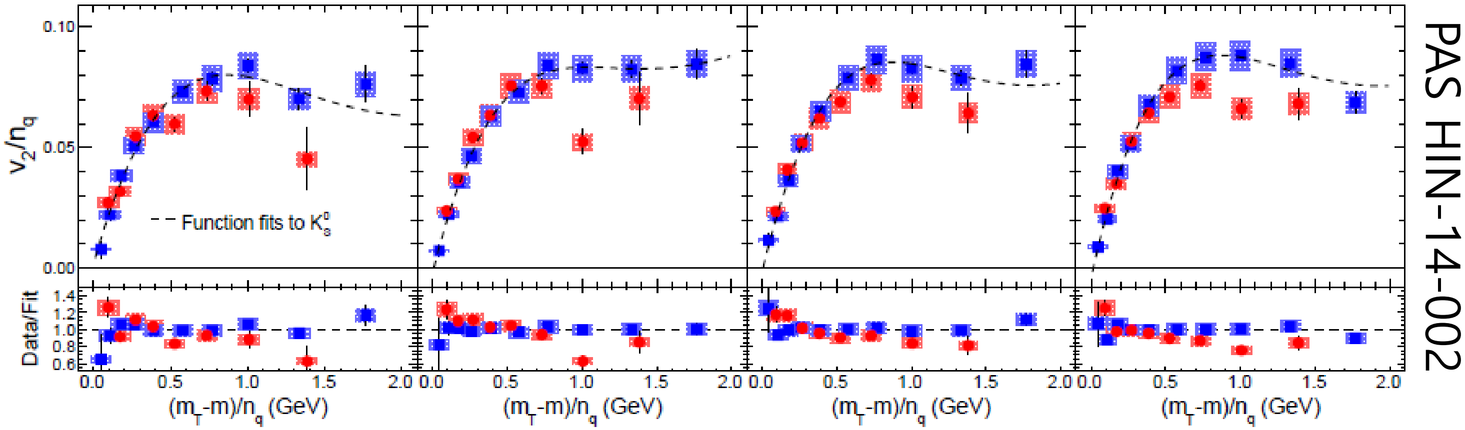


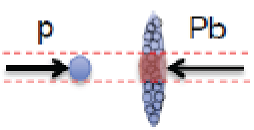
STAR
Au+Au, 0-80%
QM2014
Preliminary

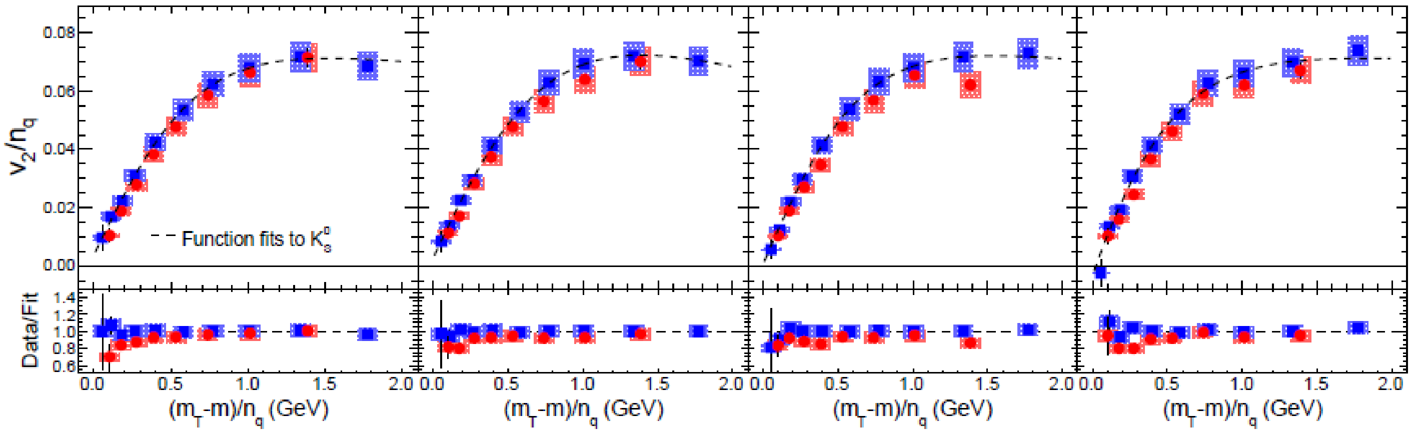
NCQ Scaling in High-Mult. Events

$N_{trk}^{offline}$: (120, 150) (150, 185) (185, 220) (220, 260)





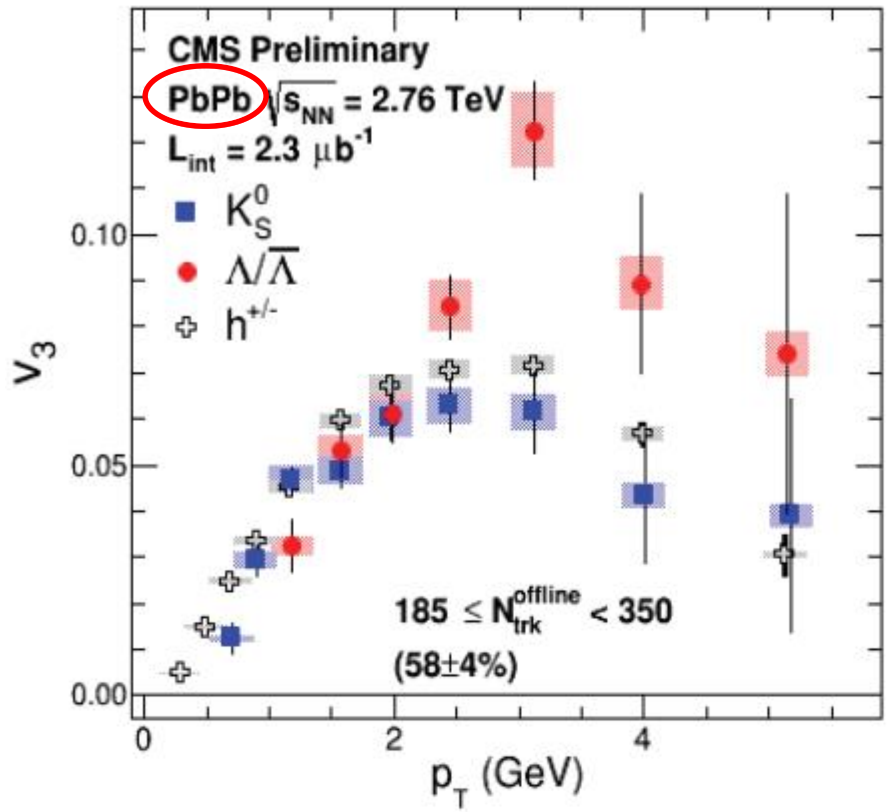


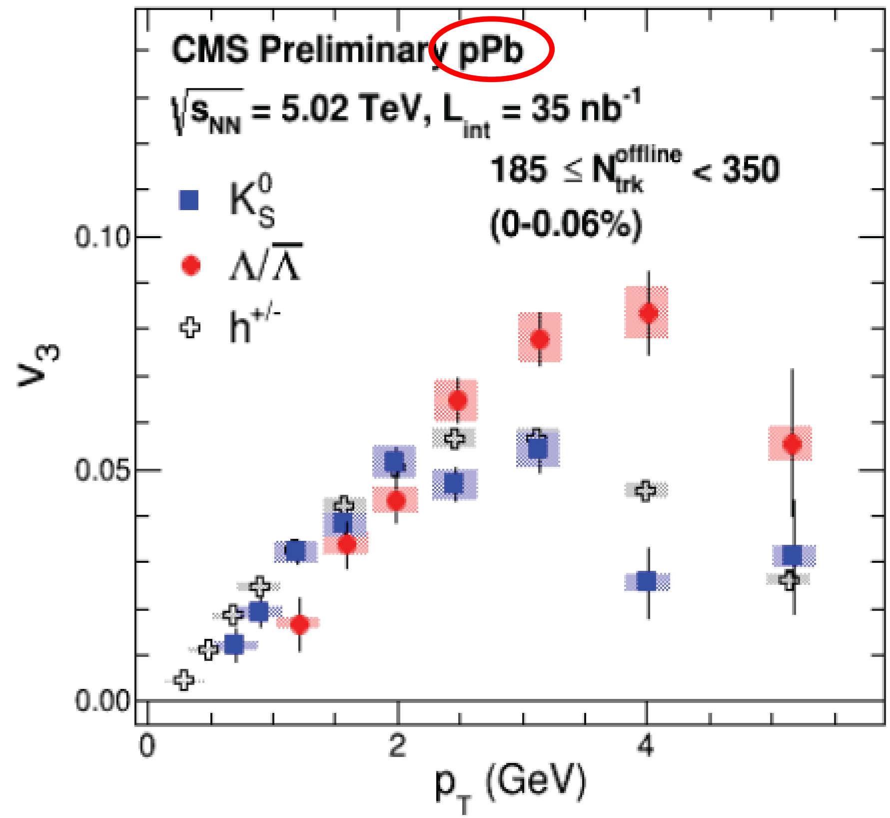


- Constituent quark scaling works better in pPb.
- Azimuthal anisotropy develops at the partonic level in pPb?

v_3 of K_s^0 and Λ

PAS HIN-14-002





Mass ordering and crossover also exist for v_3 at p_T ~ 2 GeV/c.

Summary

1. Long-range correlation
   - Near-side ridge structures exist in high-multiplicity pp, pPb and PbPb at LHC.
   - Ridges can be caused by the initial-state geometry fluctuations in pPb as well as PbPb.
     - *What about pp?*
2. Flow
   - Strong elliptic and triangular flows exist in pPb and PbPb
   - Elliptic flow depends on pseudo-rapidity η in pPb:
     - No conclusion yet on the triangular flow due to large errors.
   - Mass ordering and crossover were observed in v_2 and v_3 for identified hadrons.
3. High-multiplicity pPb events show collectivity!

   - *Are these results in pPb related to hydrodynamic flow as in PbPb?*