Heavy-Ion Meeting (HIM2011-12)
Yonsei University, Seoul, Korea, 10 December, 2011

Dihadron Correlations and Flow from CMS

Byungsik Hong
(Korea University)

For the CMS Collaboration

Outline

1. Introduction
   - Physics motivation
   - LHC and the CMS detector
2. First experimental data from CMS
   - We concentrate only on the correlation and flow results in this presentation.
   - Correlations in pp at 7 TeV and PbPb at 2.76 TeV
   - Flow in PbPb at 2.76 TeV
   - Comparison to Hydro
3. Summary

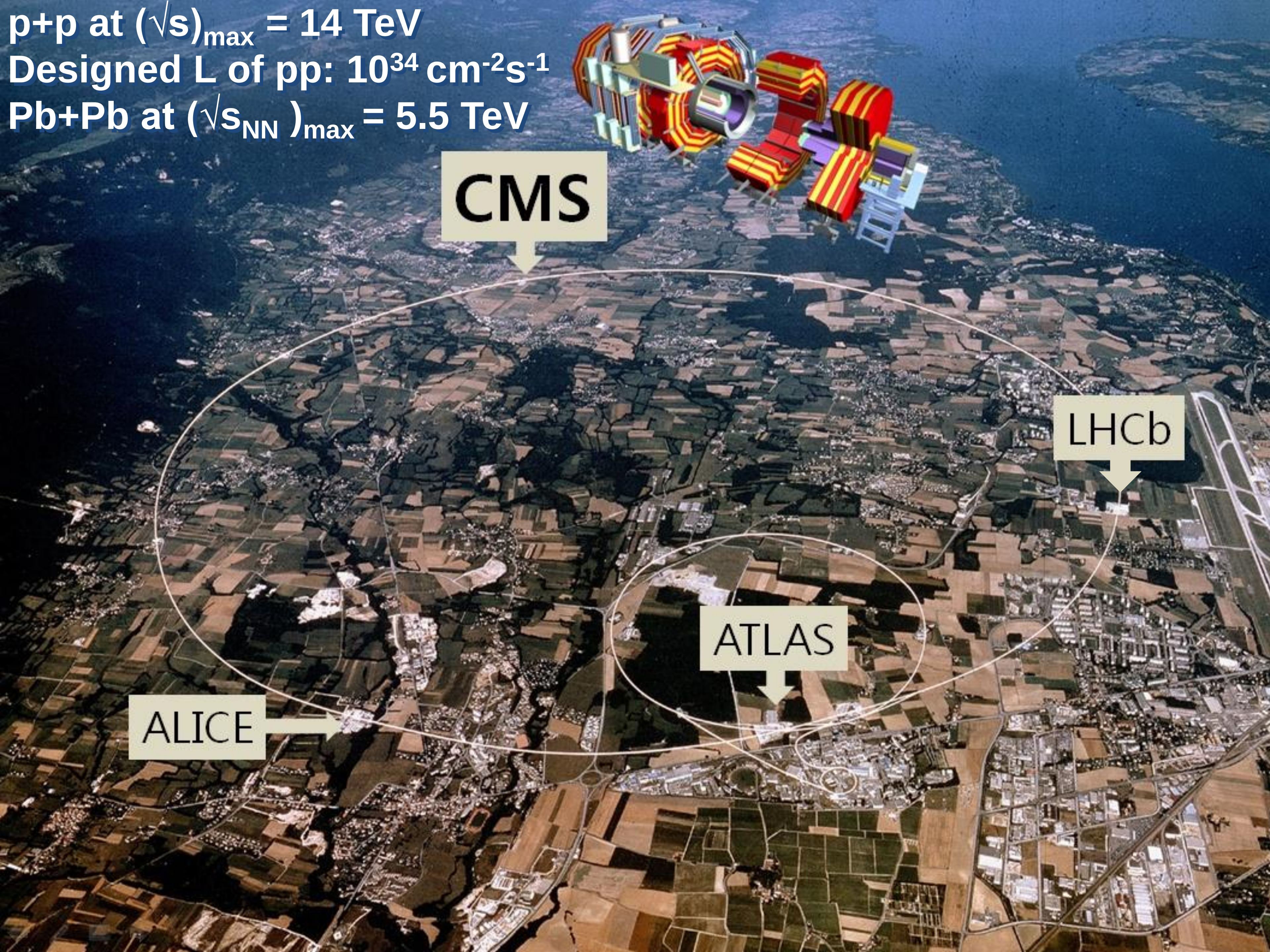
Motivation

- Correlation is a powerful tool to study
  - Hadron production mechanism
  - Jet-medium interactions in heavy-ion collisions
  - Bulk properties of the produced medium (sQGP)
- Flow is a powerful tool to address
  - Equation-of-state
  - Viscosity of the medium
  - Fluctuations and initial conditions

p+p at $(\sqrt{s})_{max}$ = 14 TeV

Designed L of pp: 10^{34} $cm^{-2}s^{-1}$

Pb+Pb at $(\sqrt{s_{NN}})_{max}$ = 5.5 TeV



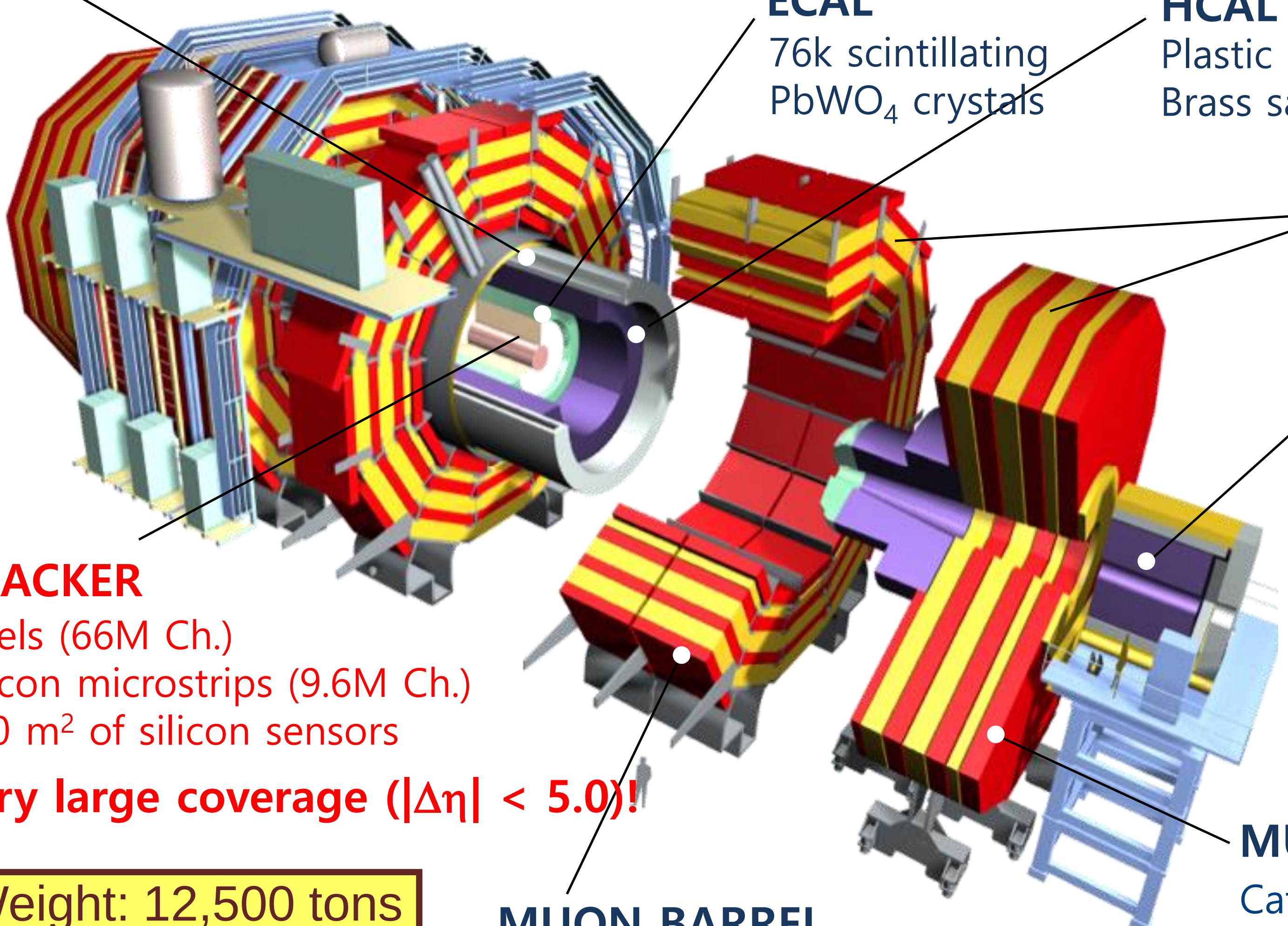
CMS Detector

Superconducting Coil (3.8 T)

CALORIMETERS

ECAL
76k scintillating
$PbWO_4$ crystals

HCAL
Plastic scintillator/
Brass sandwich



Steel YOKE

HF
Centrality in
heavy-ion events
for 2010 run

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

Very large coverage ($|\Delta\eta| < 5.0$)!

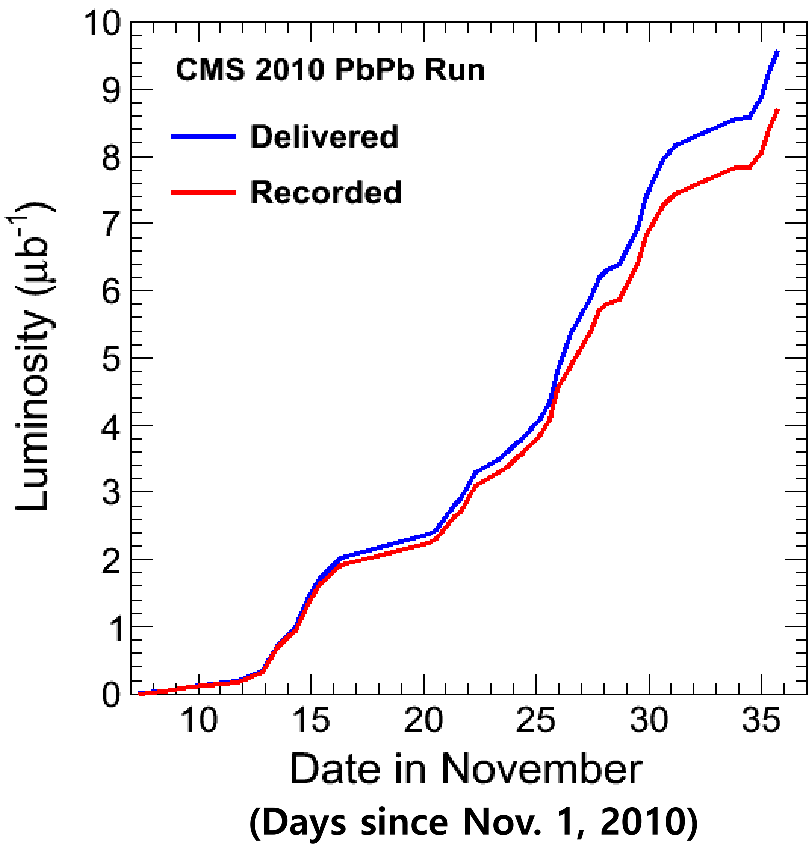
Weight: 12,500 tons
Diameter: 15 m
Length: 22 m

MUON BARREL
Drift Tube Chambers
Resistive Plate Chambers

MUON ENDCAPS
Cathode Strip Chambers
Resistive Plate Chambers

Summary of 2010 PbPb Run

- A dedicated heavy-ion mode
  - Turn off zero suppression
  - Taking data at up to 220 Hz
  - 12 MB event size
- Triggering on minimum bias, jets, muons and photons
  - ALL rare probes written to tape
  - ~half of minimum bias written
- **Recorded luminosity**
  - PbPb @ $\sqrt{s_{NN}}$ = 2.76 TeV: 8.7 μb^{-1}
- **Reference pp data**
  - pp @ $\sqrt{s}$ = 2.76 TeV: 241 nb^{-1}
  - pp @ $\sqrt{s}$ = 7 TeV: > 5 fb^{-1}
- Total volume of PbPb data
  - ~0.89 PetaByte



- Note: luminosities will be rescaled by few % after complete analysis of Van der Meer scans

Dihadron Correlation Technique

Same event pairs

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

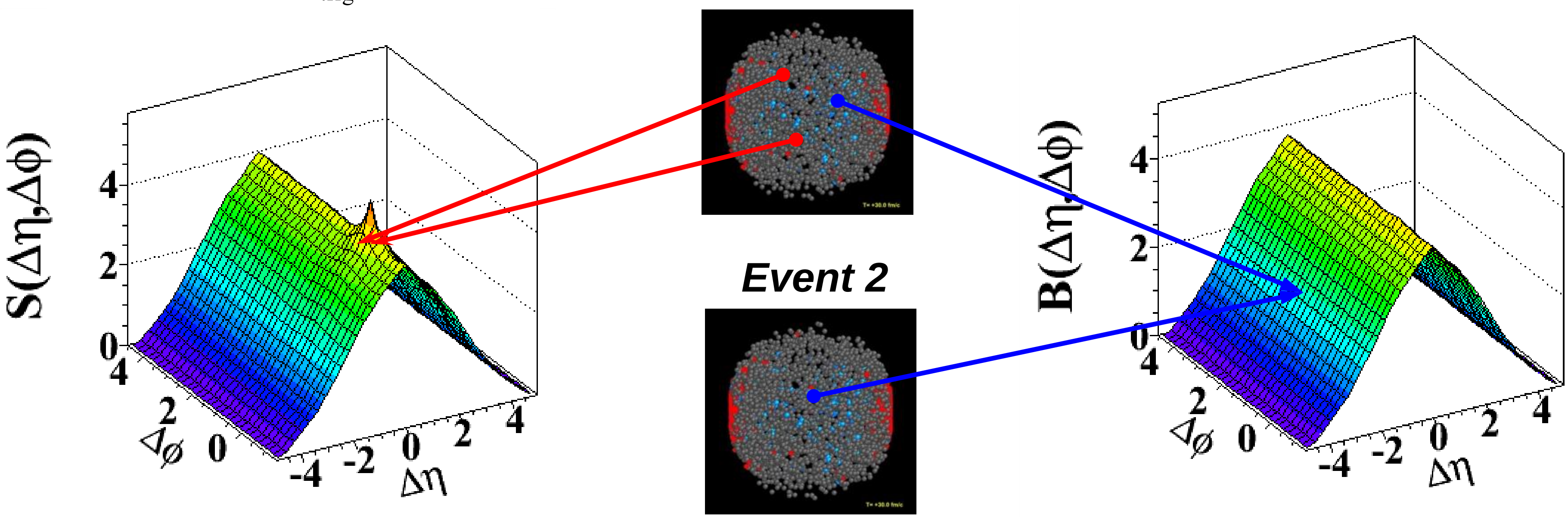
1: Trigger particle

2: Associated particle

Mixed event pairs

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

Event 1



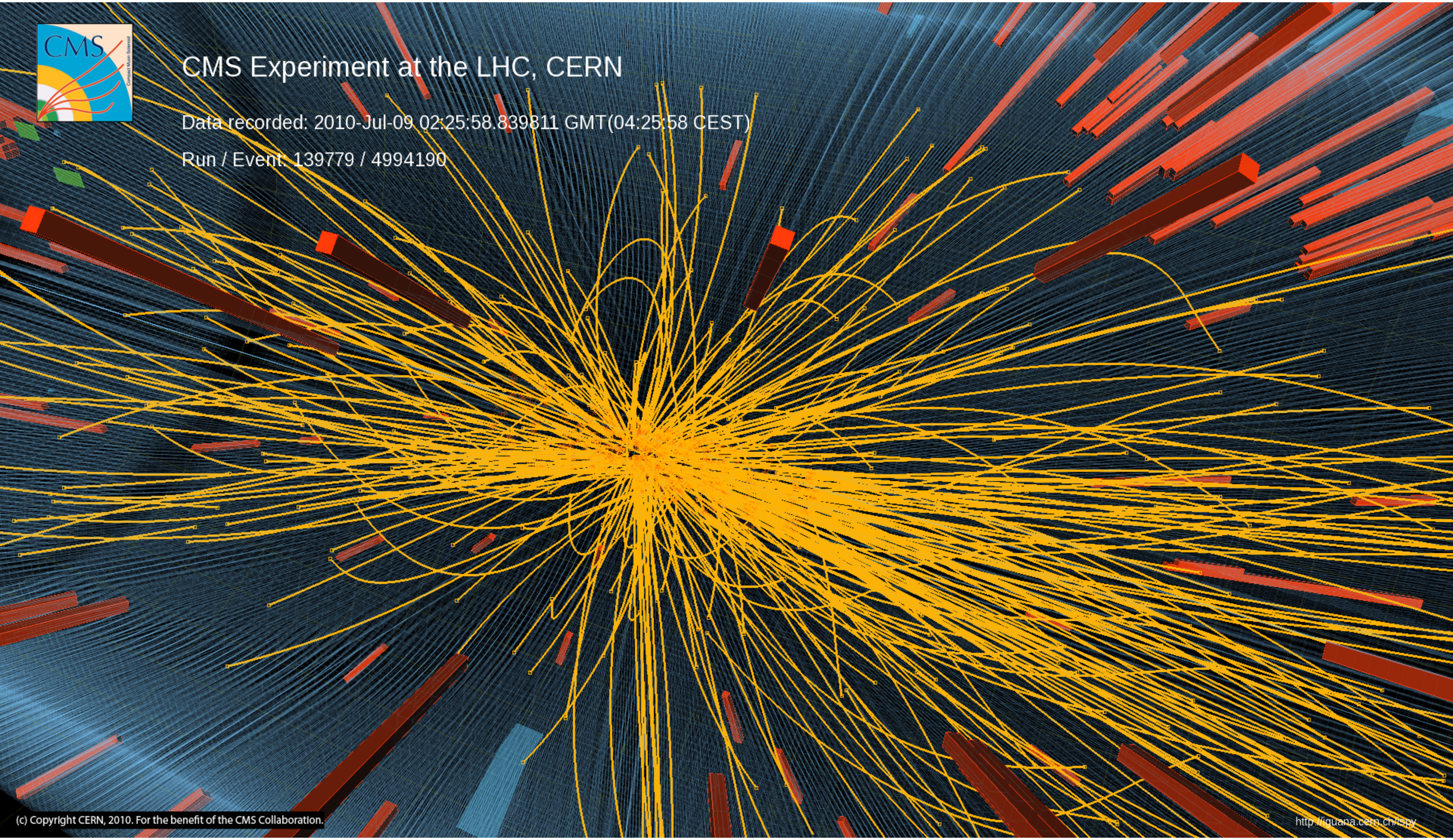
Associated hadron yield per trigger

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

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

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

High-Multiplicity pp Event



Ridge in High-Multiplicity pp

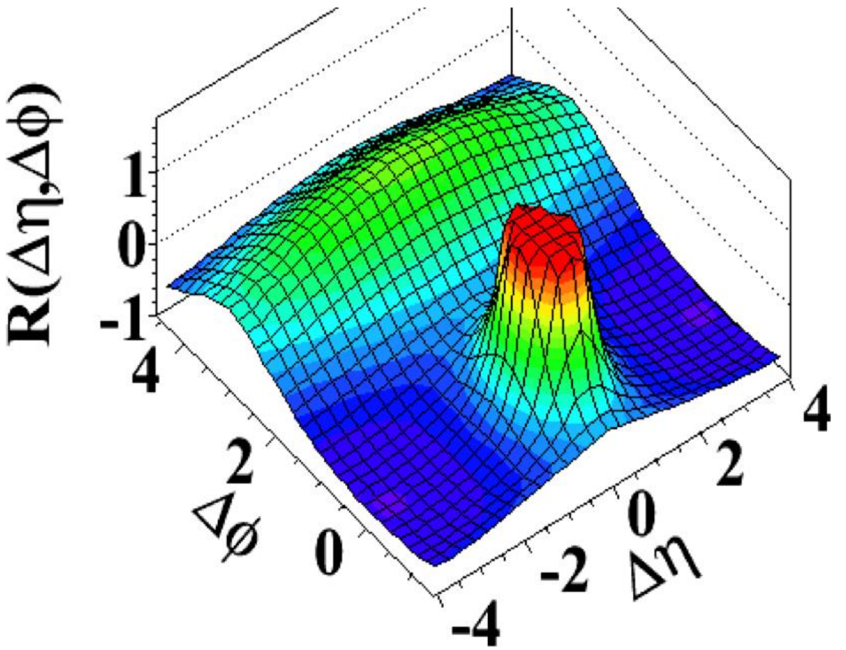
JHEP09, 091 (2010)

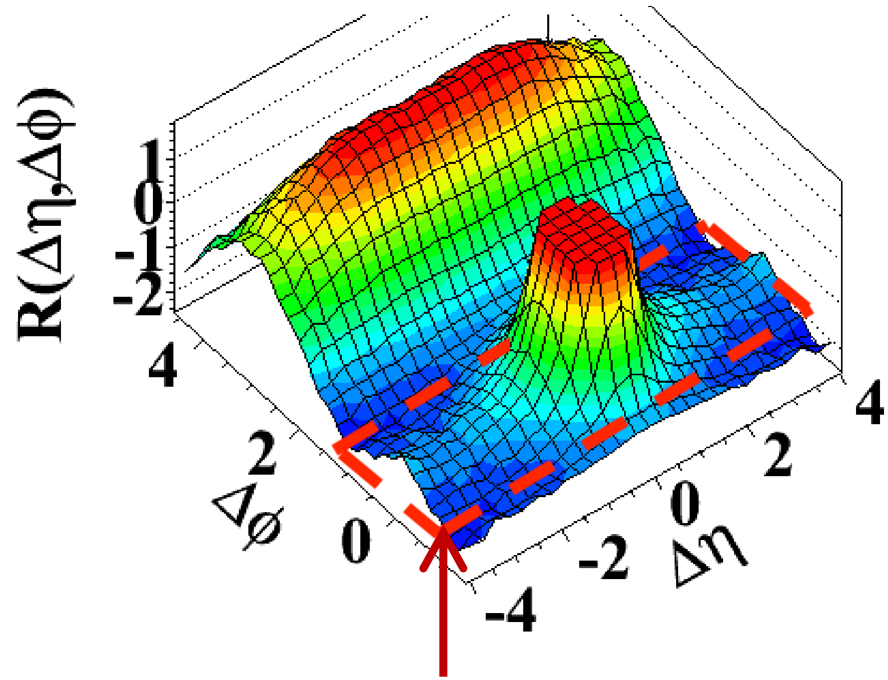
Intermediate p_T: 1-3 GeV/c

350K top multiplicity events out of 50 billion collisions

Minimum bias pp (<N>~15)

High multiplicity pp (N ≥ 110)



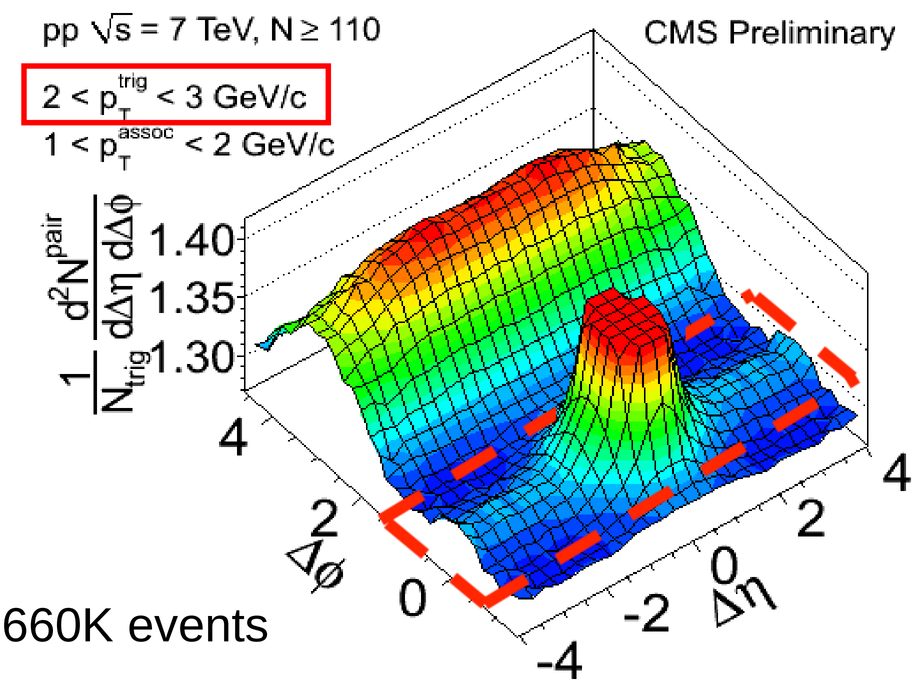


$$R(\Delta\eta,\Delta\phi) = \left\langle (N-1)\left(\frac{S(\Delta\eta,\Delta\phi)}{B(\Delta\eta,\Delta\phi)} - 1\right)\right\rangle_N$$

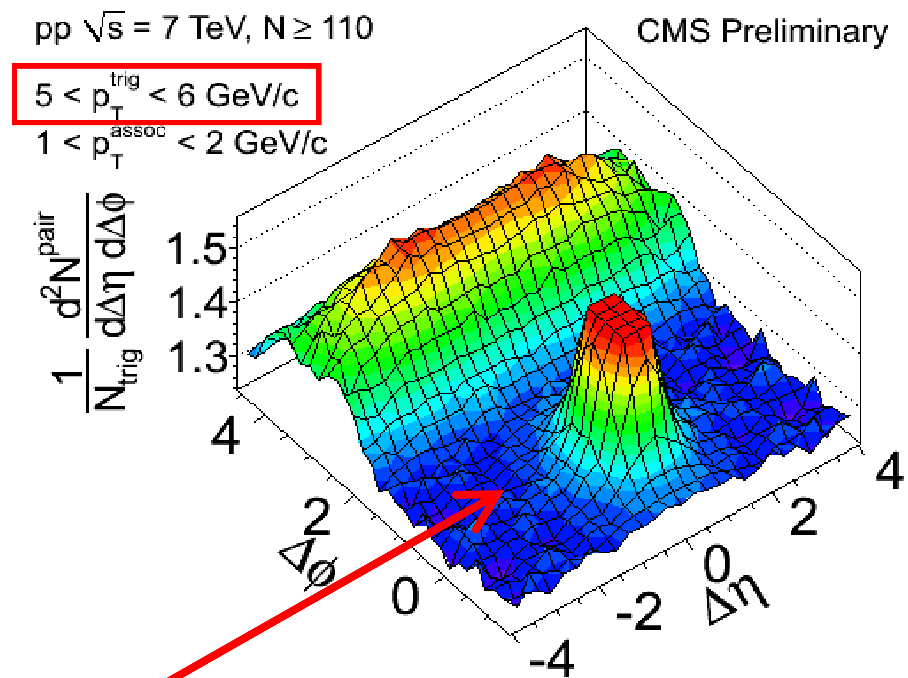
Striking "**ridge-like**" structure extending over Δη at Δϕ ~ 0

p_T Dependence in pp

100 billion (1.78 pb^{-1}) sampled minimum-bias events from high-multiplicity trigger



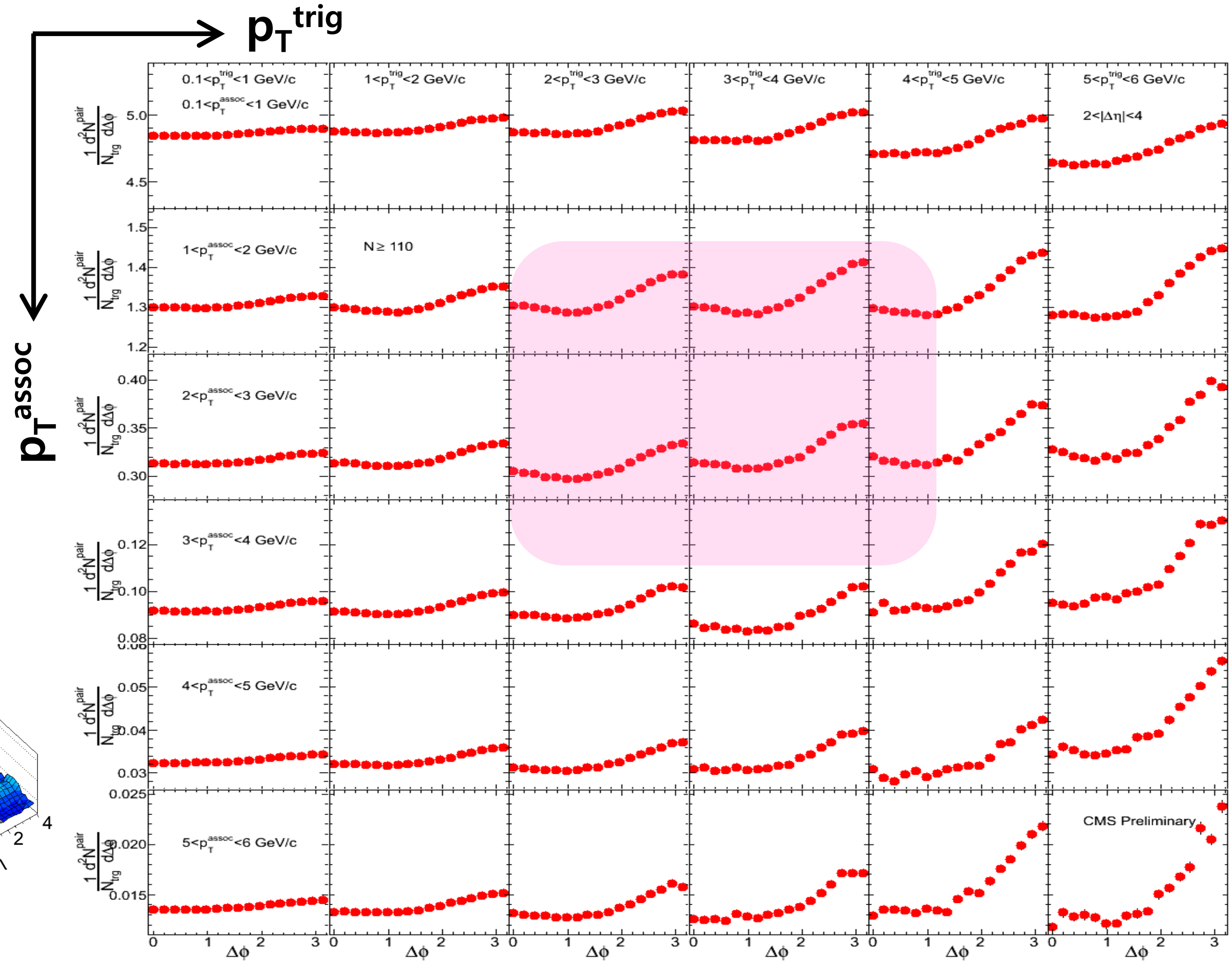
660K events



No ridge when correlating to high p_T particles!

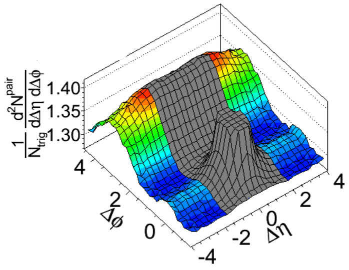
Differential Δϕ Projection

CMS Preliminary



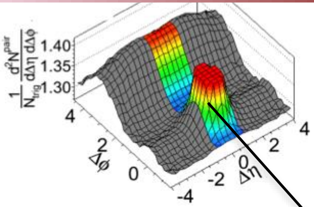
CMS pp 7 TeV, N ≥ 110

2<|Δη|<4



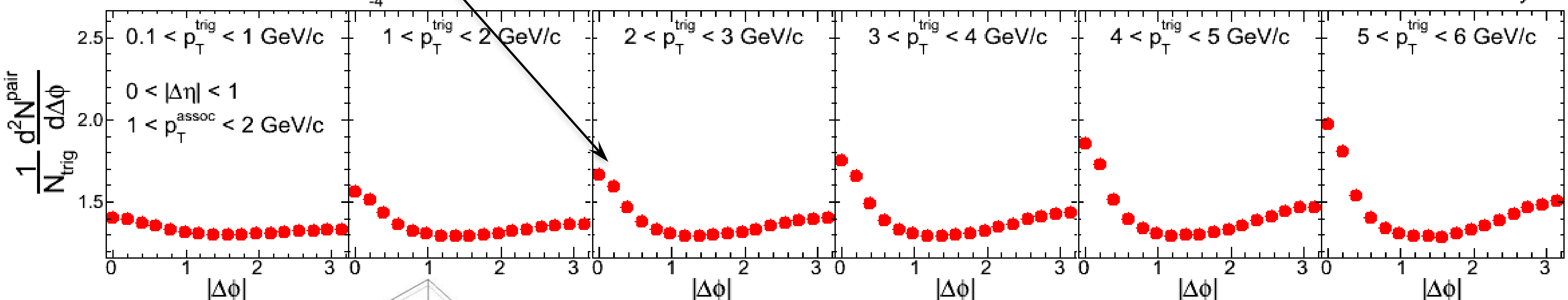
Differential Δϕ Projection

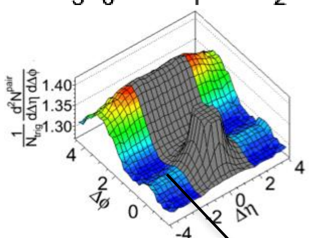
CMS pp 7 TeV, N ≥ 110



Jet region (|Δη|<1)

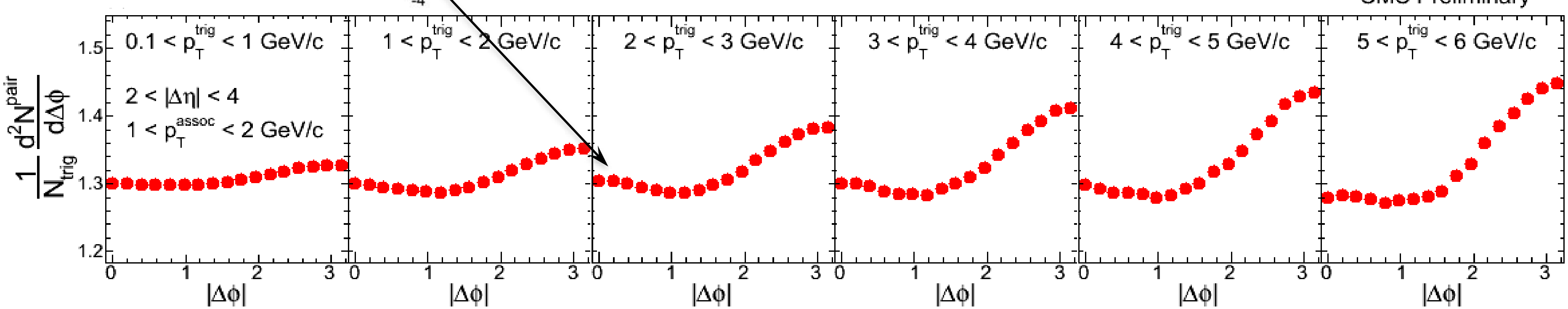
p_T^{trig} →



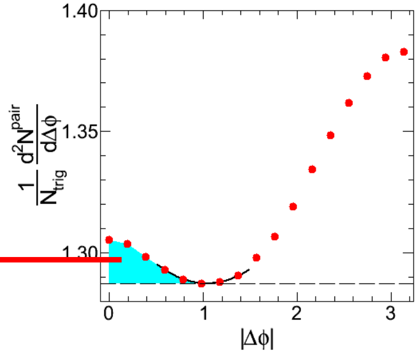


Ridge region (2<|Δη|<4)

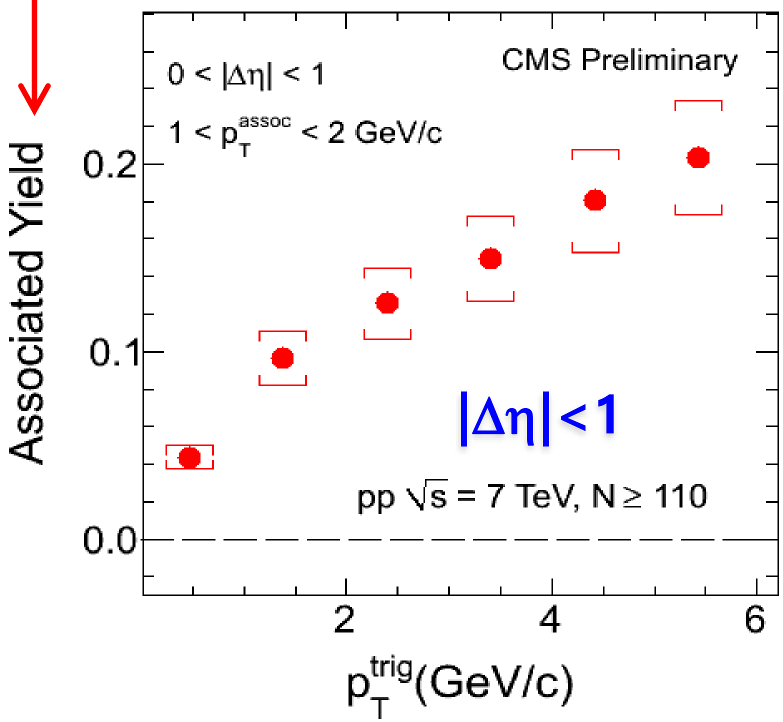
p_T^{trig} →

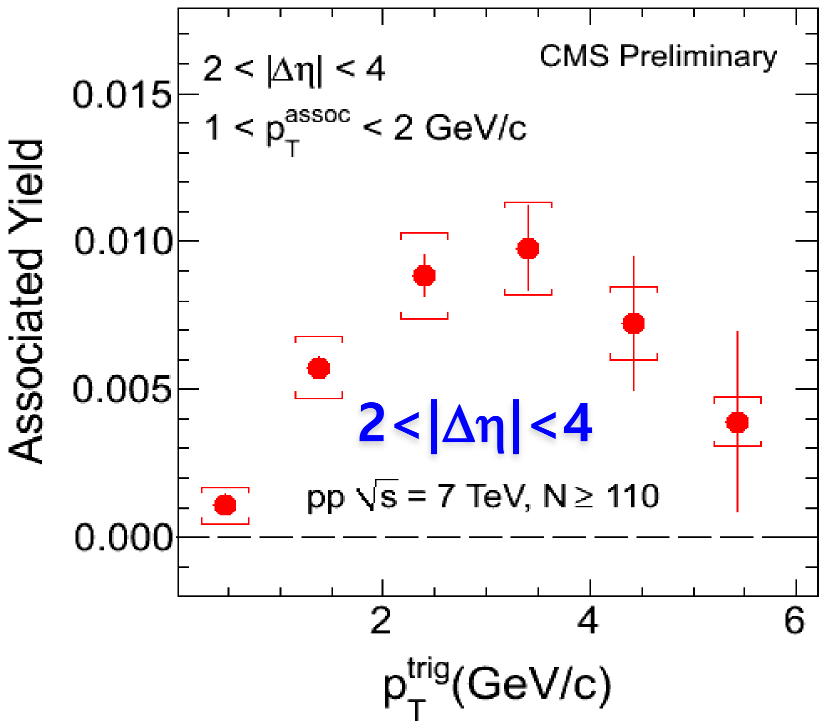


Near-Side Yields for N≥110

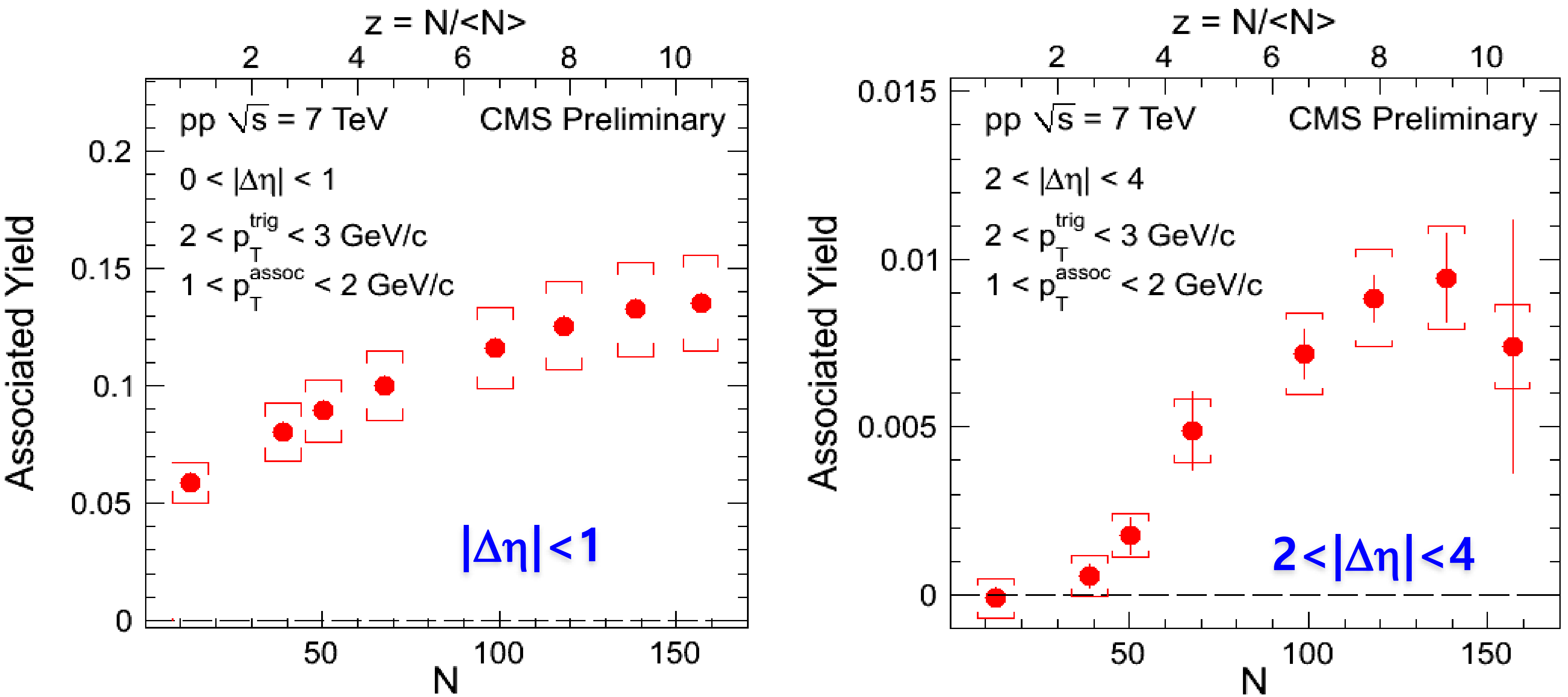


Zero-Yield-At-Minimum (ZYAM)





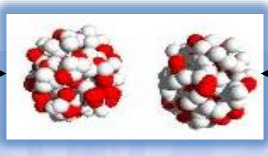
Near-Side Yields for N≥110

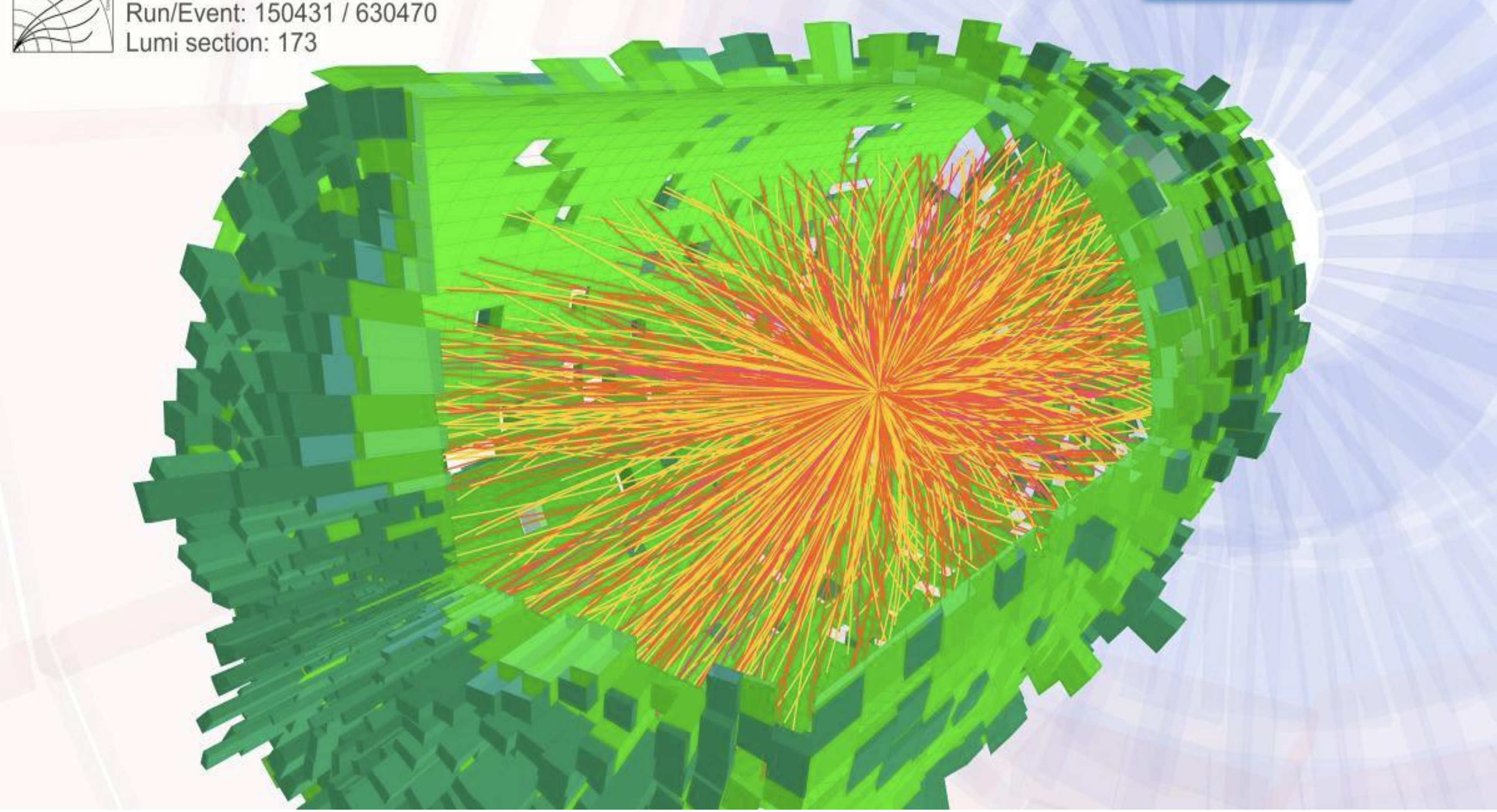


- Jet yield in pp monotonically increases with N
- Ridge in pp turns on around N~50-60 (4XMB) smoothly

PbPb Event

PbPb at $\sqrt{s_{NN}}$ = 2.76 TeV
(14 X RHIC energy)

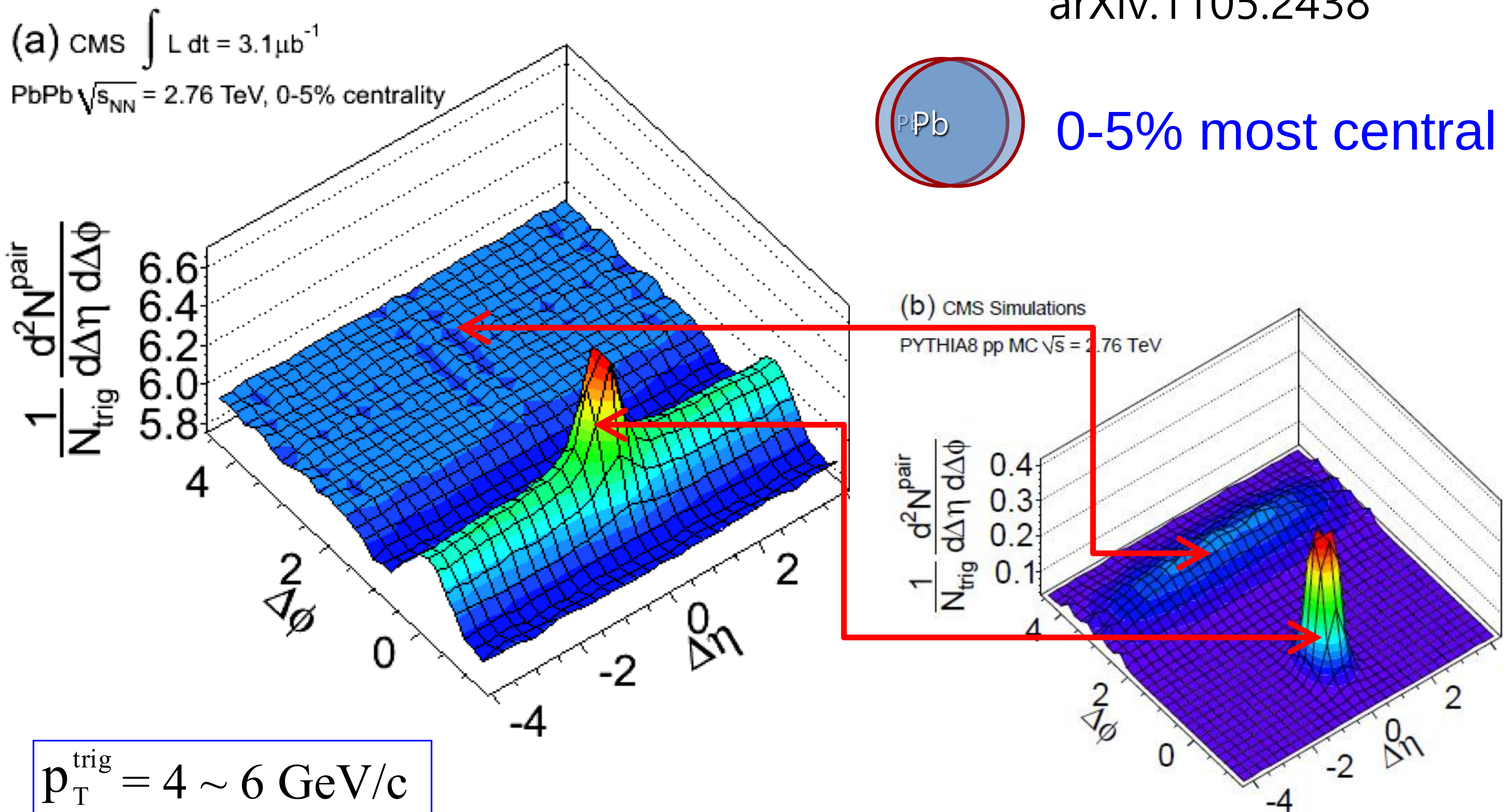




Ridge in Heavy-Ion Collisions

arXiv:1105.2438

0-5% most central



$$p_T^{trig} = 4 \sim 6\ \text{GeV/c}$$
$$p_T^{assoc} = 2 \sim 4\ \text{GeV/c}$$

PYTHIA8 simulation

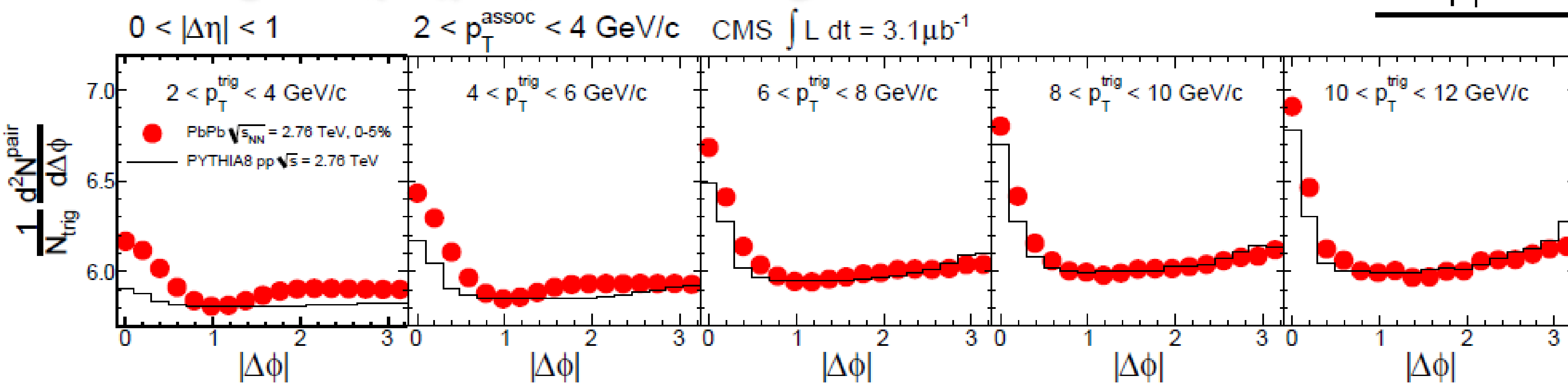
Differential Δφ Projection

(0-5% most central PbPb)

arXiv:1105.2438

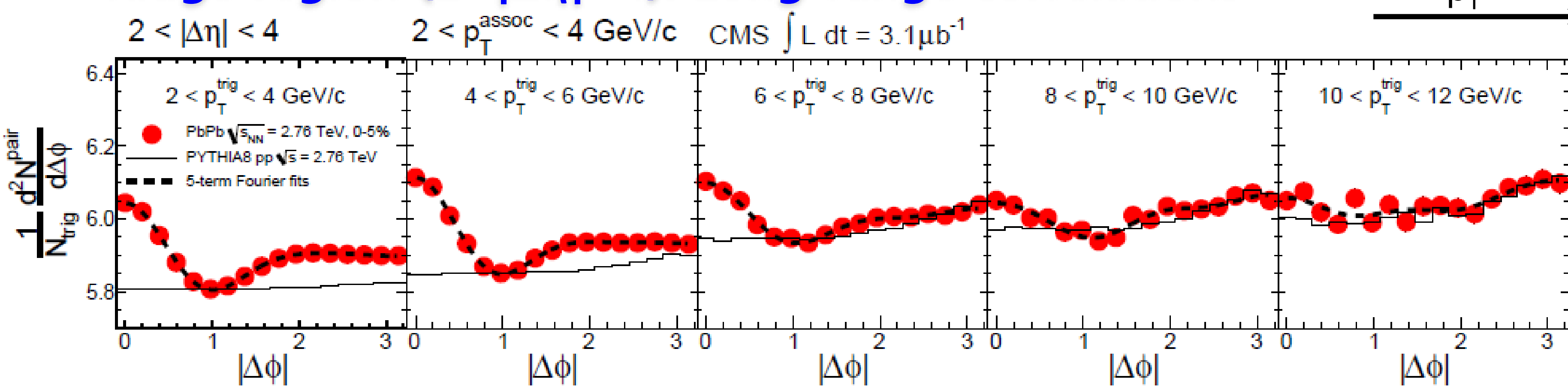
Jet region (|Δη|<1): Short-range correlations

p_T^{trig} →



Ridge region (2<|Δη|<4): Long-range correlations

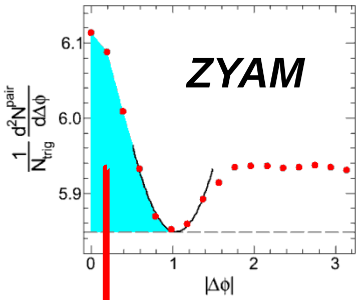
p_T^{trig} →



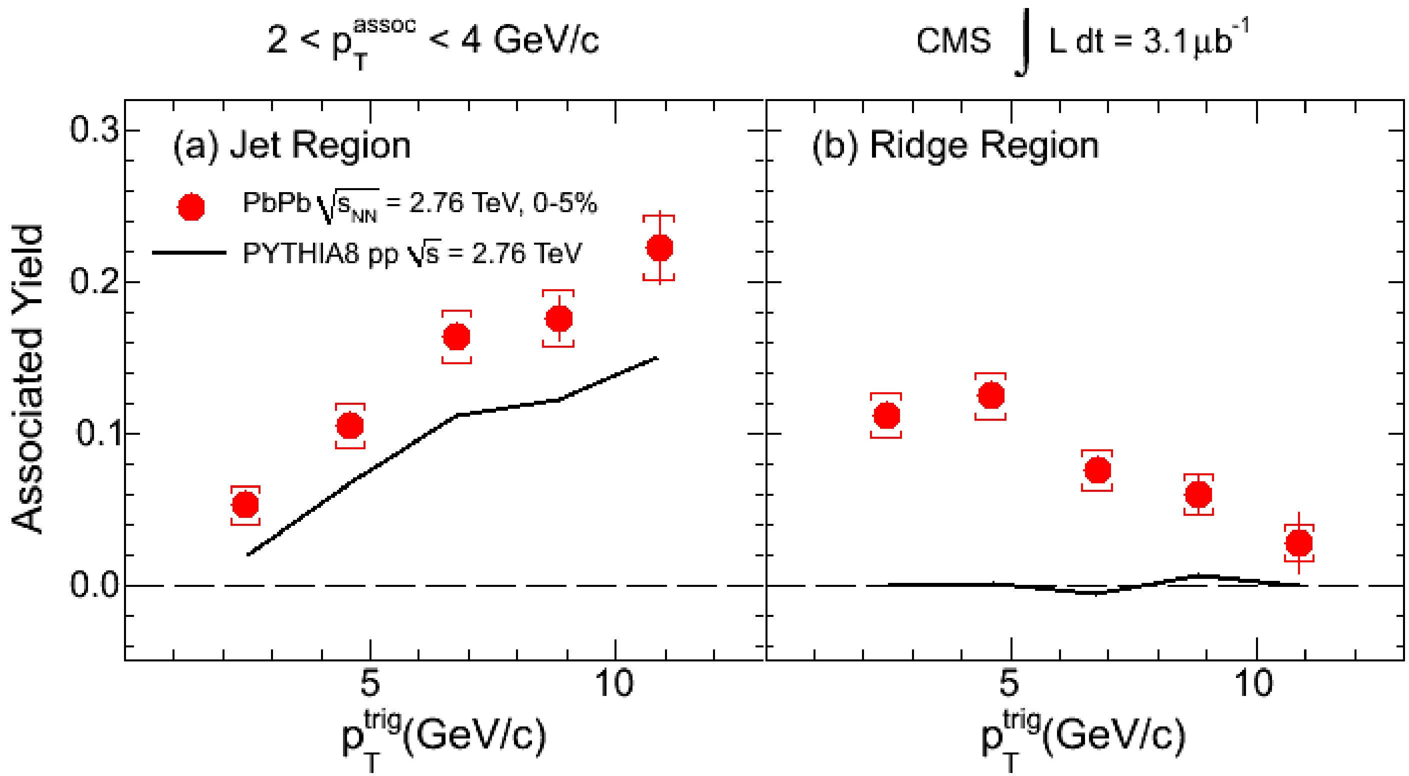
Integrated Associated Yield

(0-5% most central PbPb)

arXiv:1105.2438



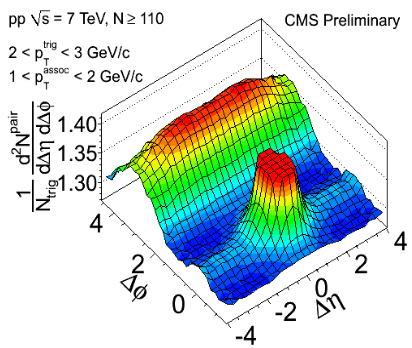
v_2 not subtracted: not significant in central collisions



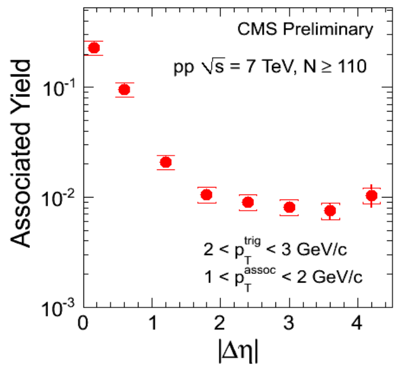
- Ridge-region yield: integration of the near-side enhancement
- Jet-region yield: sum of the near-side short- & long-range yields
- Ridge in PbPb diminishes at high p_T

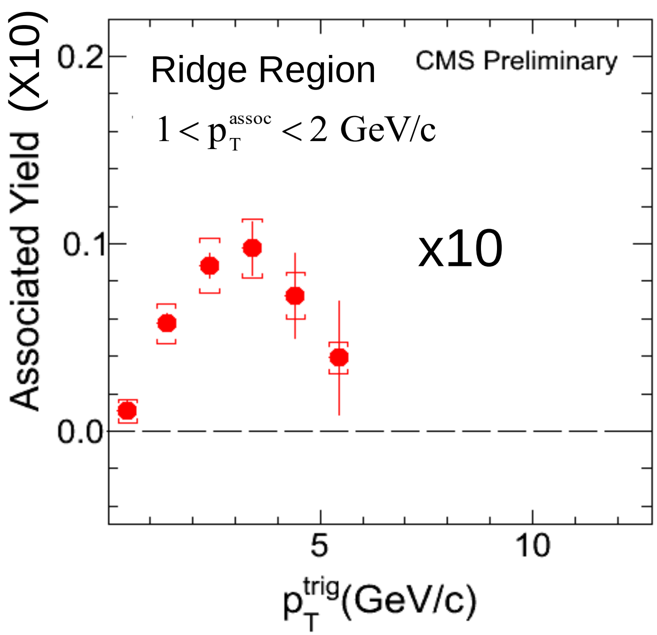
PbPb vs. pp

CMS pp 7 TeV, N ≥ 110

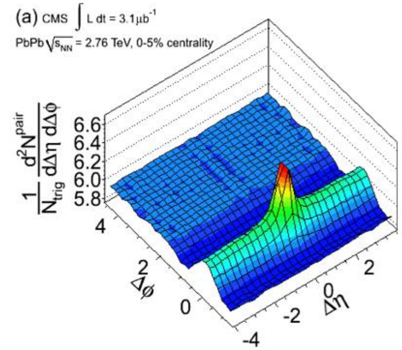


|Δη| dependence

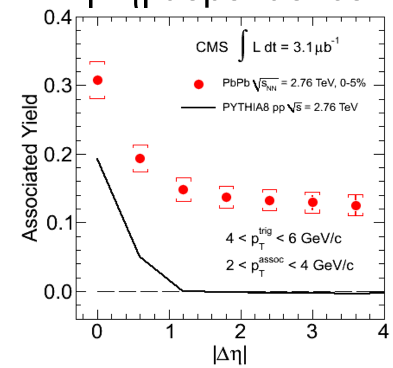


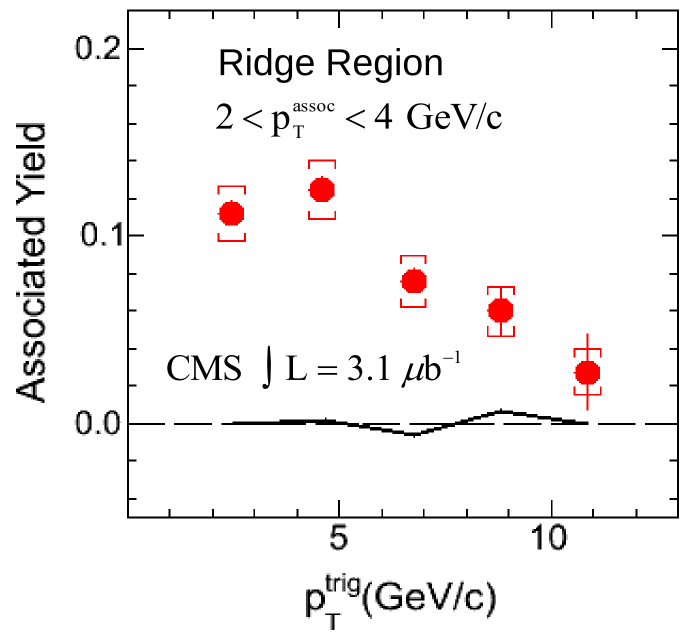


CMS PbPb 2.76 TeV, 0-5%



|Δη| dependence

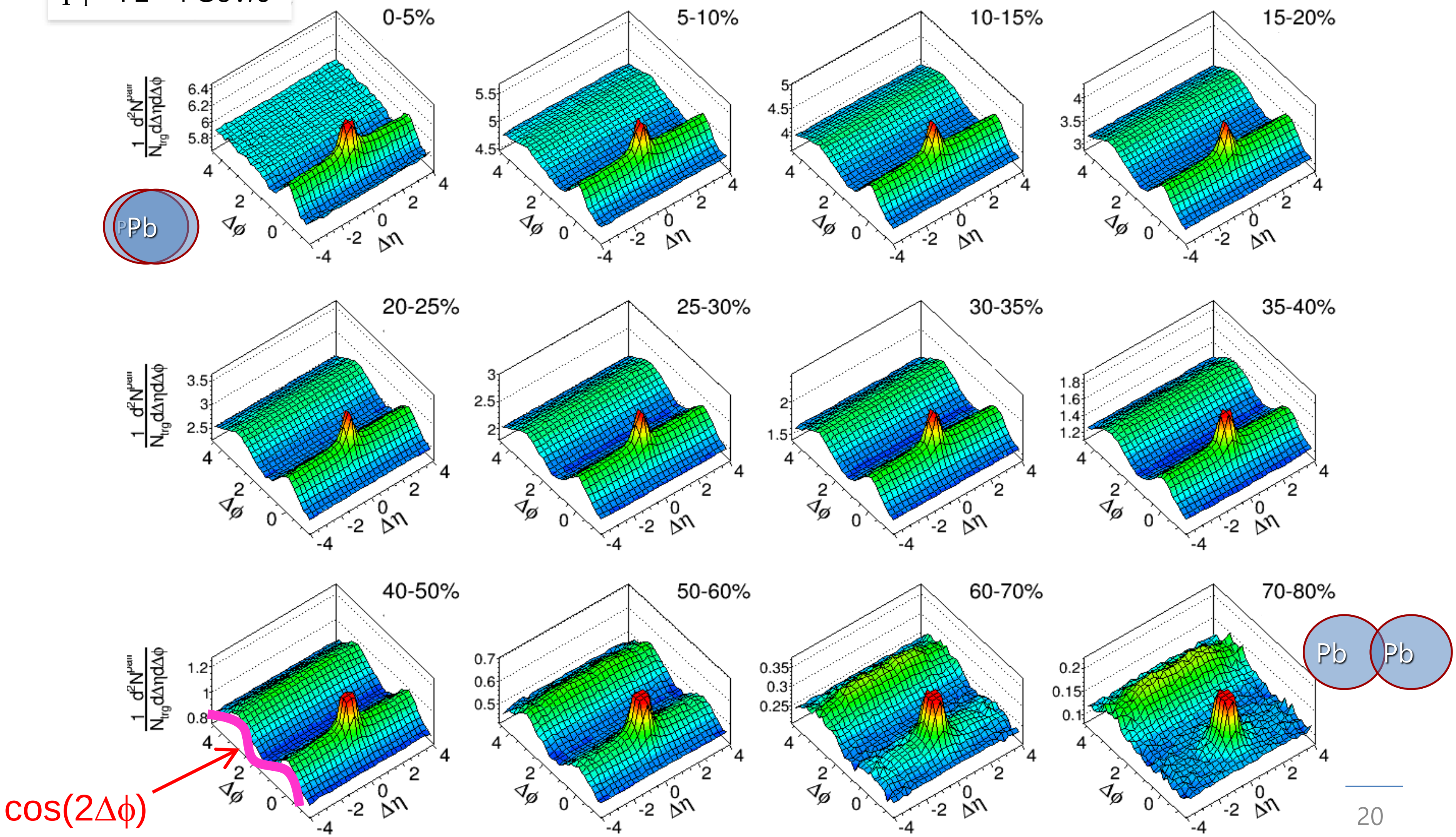




Centrality Dependence in PbPb

p_T^{trig} : 4 - 6 GeV/c
p_T^{assoc} : 2 - 4 GeV/c

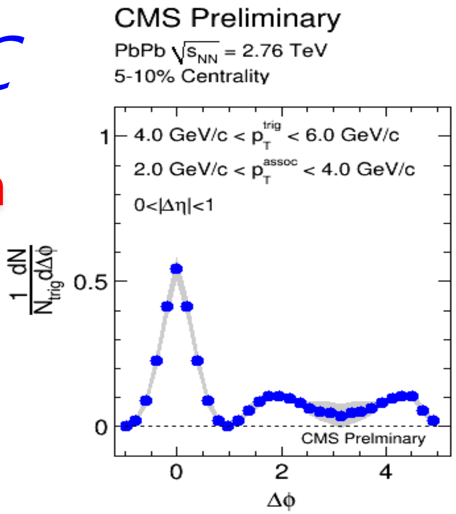
PbPb at 2.76 TeV

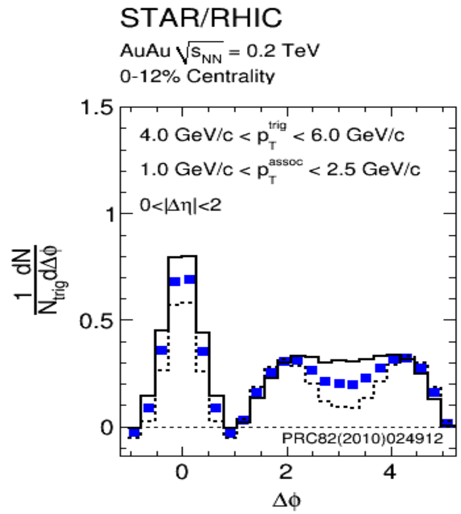


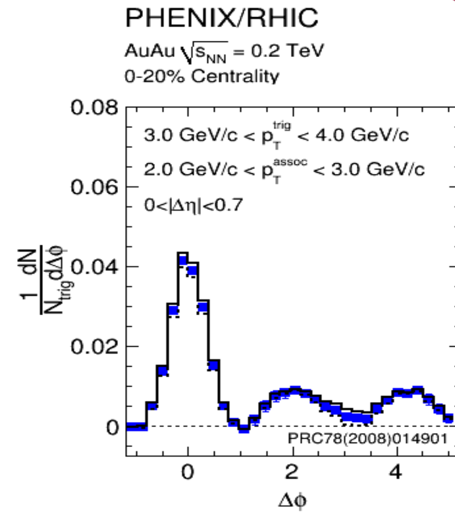
v_2-Subtracted Yields in PbPb

vs. RHIC

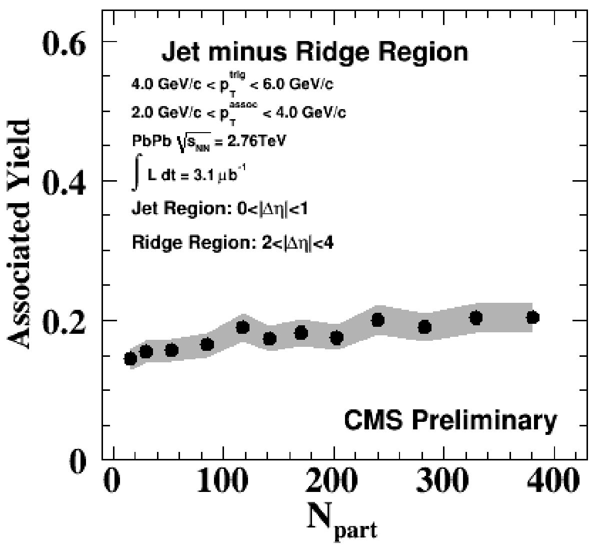
Jet region ($|\Delta\eta|<1$)



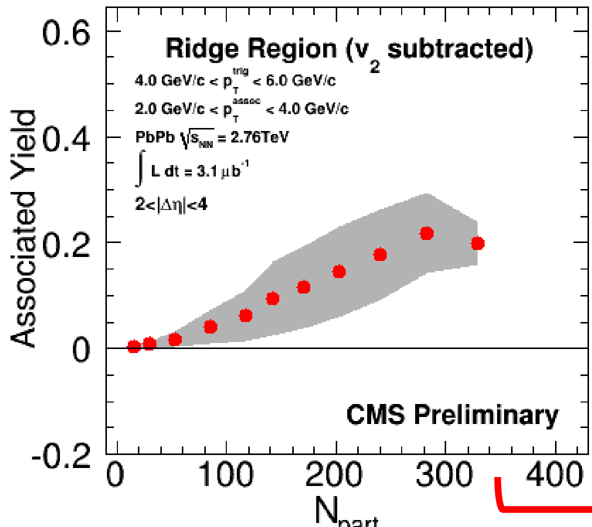


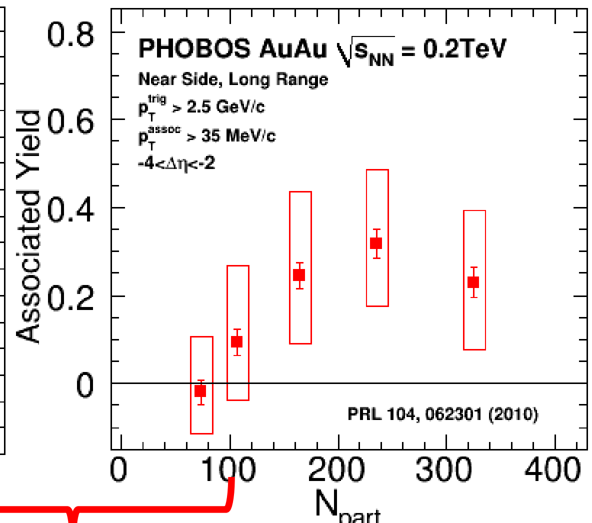


Jet minus ridge region



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



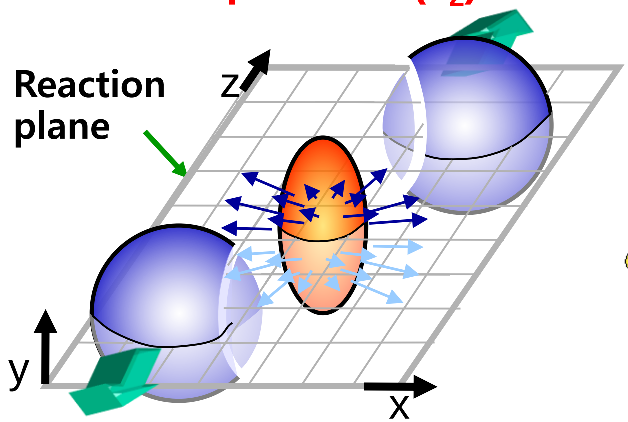


Similar trend in centrality to RHIC results!

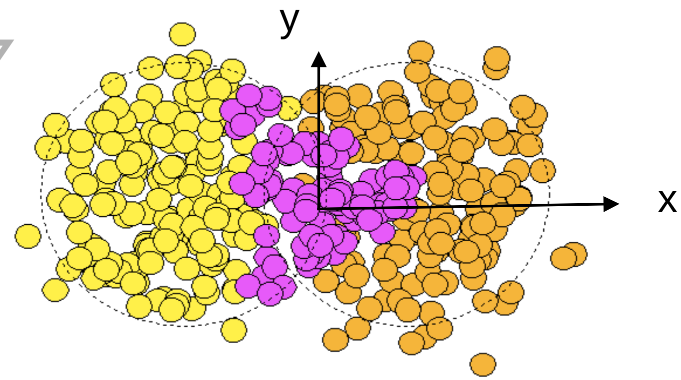
Possible Origin of Ridge

The ridge & Mach-cone like emission may be induced by higher order flow terms!

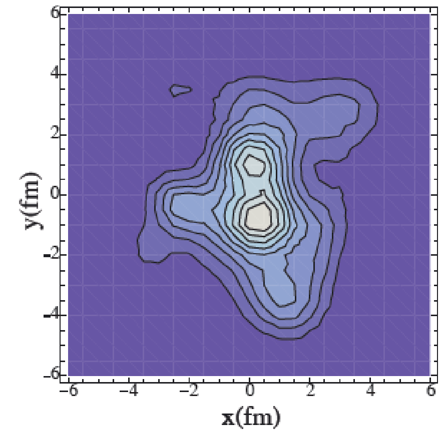
Elliptic flow (v_2)



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

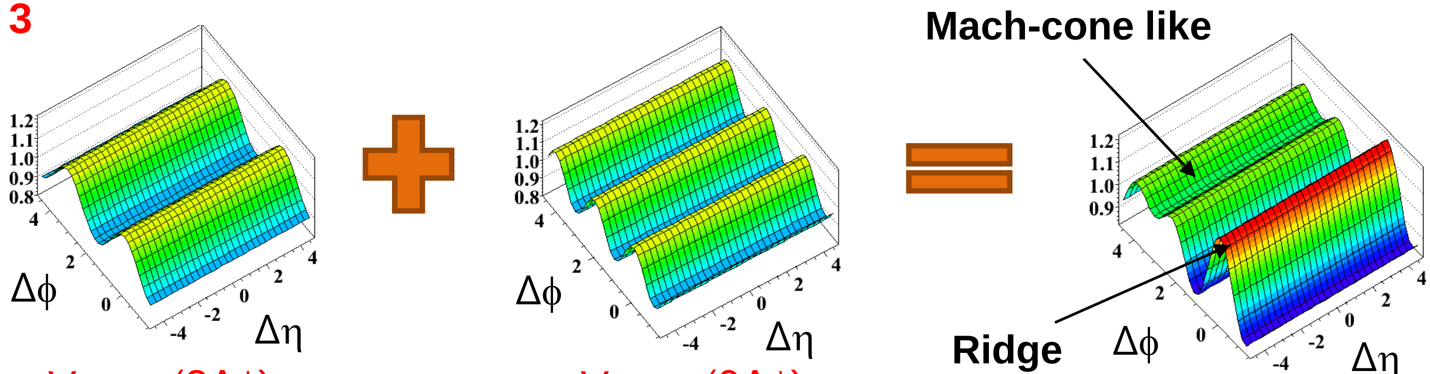


PRC81, 054905 (2010)



G. Qin, H. Peterson
S. Bass, B. Müller

$V_2 + V_3$

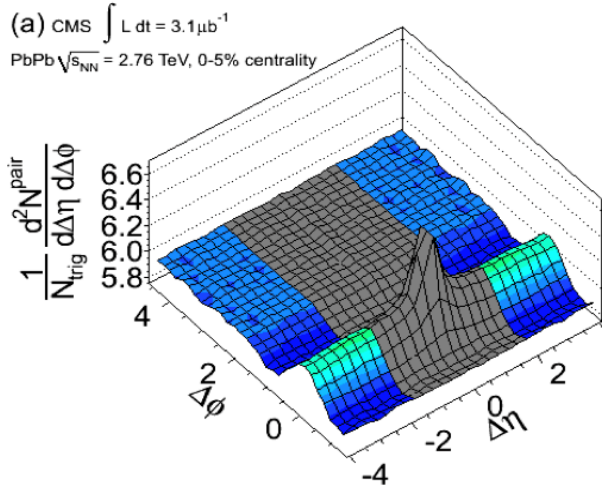


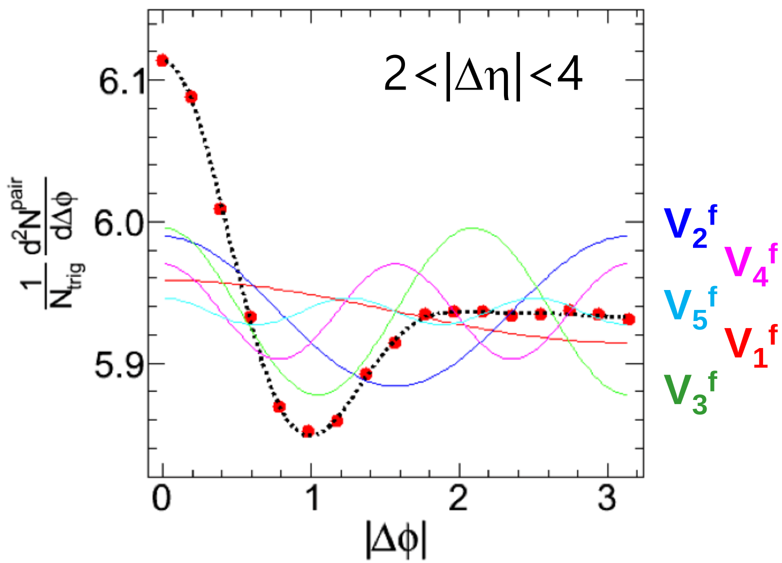
~ $V_2 \cos(2\Delta\phi)$

~ $V_3 \cos(3\Delta\phi)$

Fourier Decomposition

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





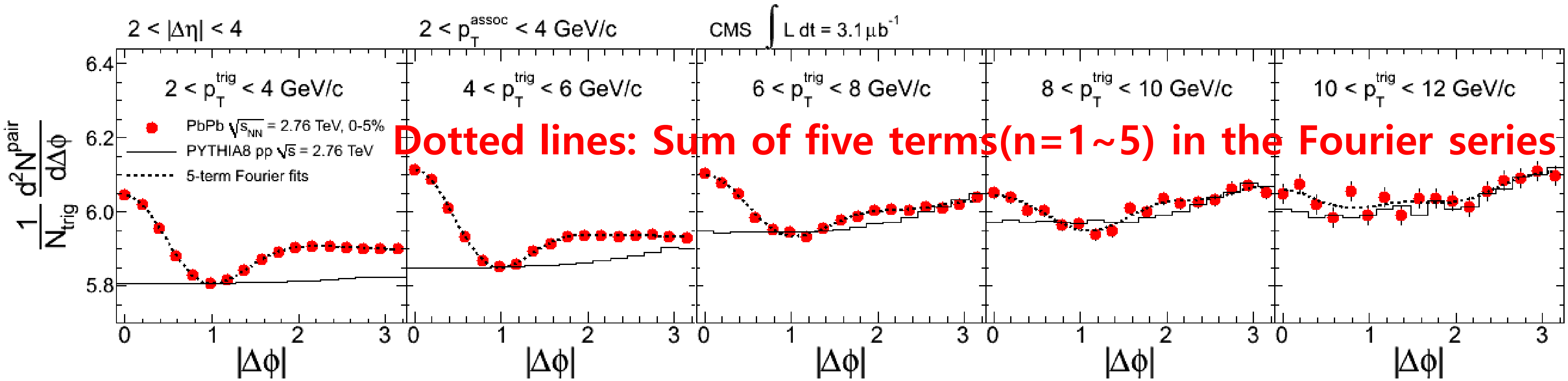
- Fourier analysis of long-range dihadron correlation
  - Short-range non-flow effects are excluded.
  - Complementary to standard flow analysis methods (EP, cumulants, LYZ)

Fourier Decomposition

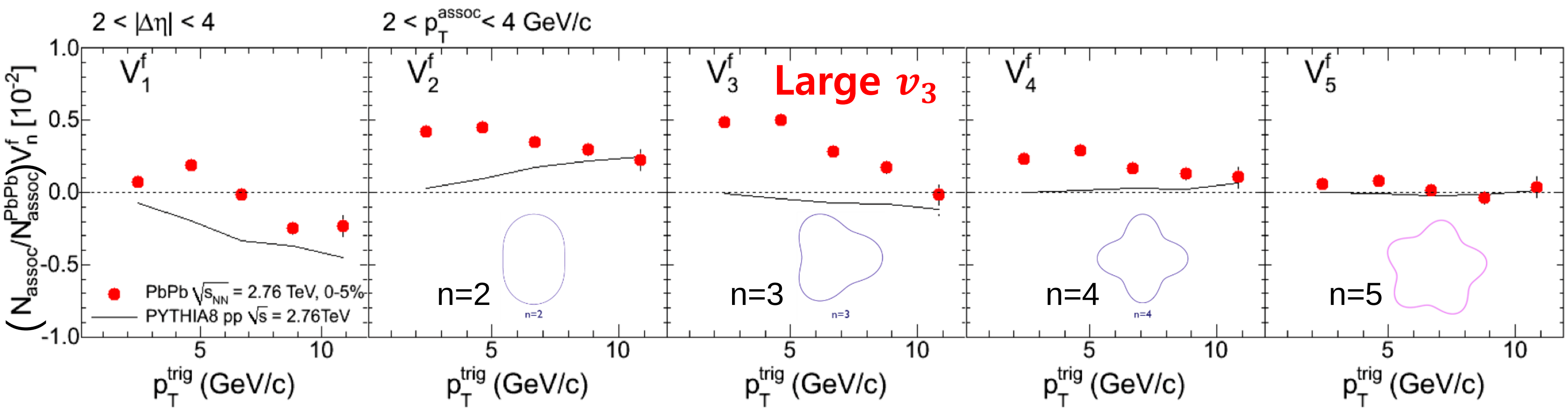
(0-5% most central PbPb)

arXiv:1105.2438

Ridge region ($2<|\Delta\eta|<4$): Long-range correlations



Dotted lines: Sum of five terms(n=1~5) in the Fourier series



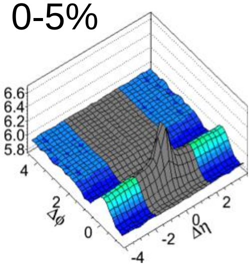
Large v_3

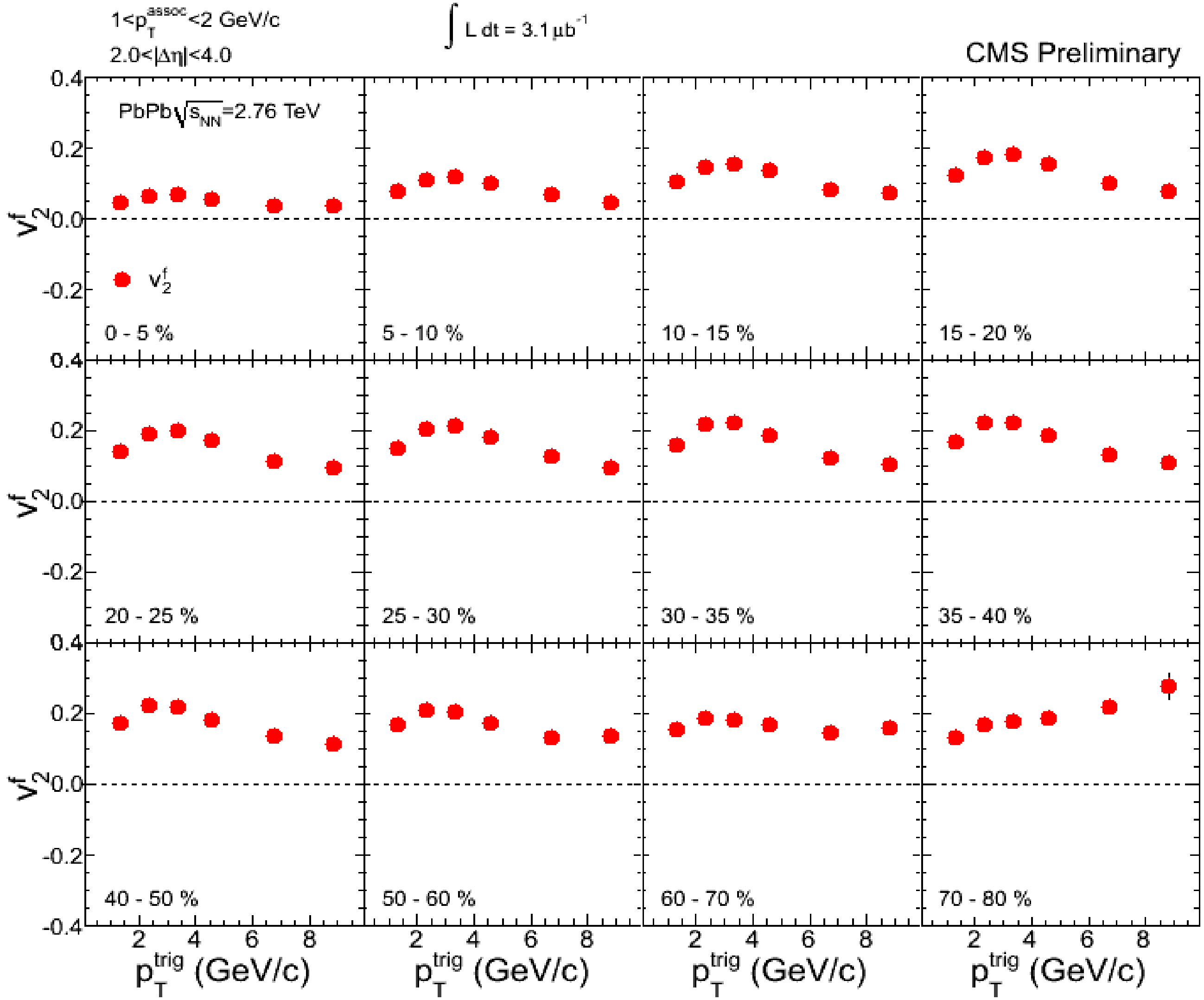
v_2 from Long-Range Correlations

$$V_n^f = v_n^f(p_T^{trig}) \times v_n^f(p_T^{assoc}) \Rightarrow V_n^f(\text{Fourier}) \xrightarrow{\sqrt{\ }} v_n^f(\text{flow})$$

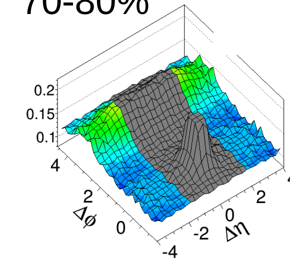
ZPC70, 665 (1996)
PRC81, 054905 (2010)

0-5%





70-80%

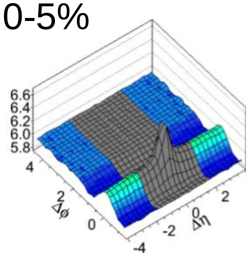


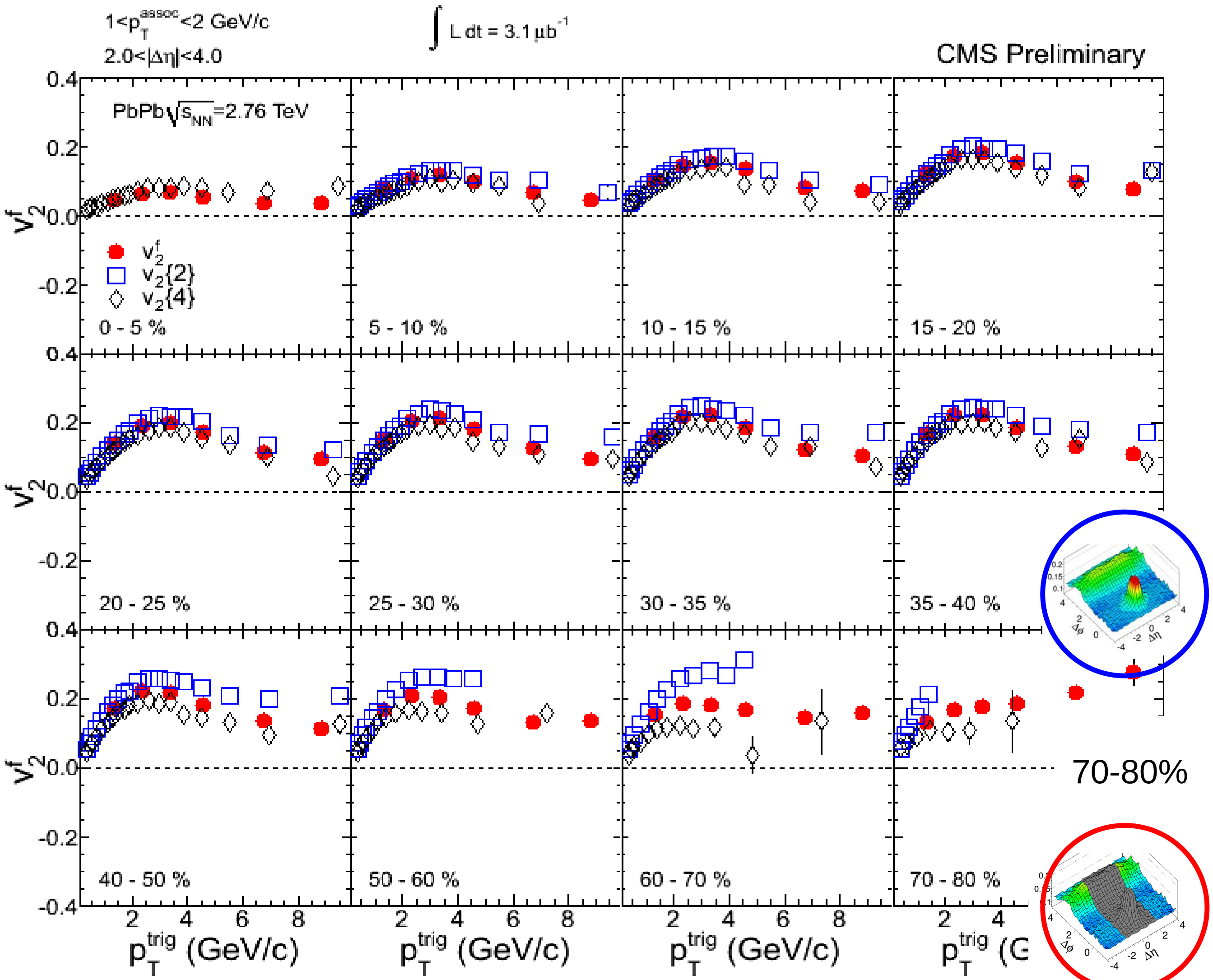
v_2 from Long-Range Correlations

$$V_n^f = v_n^f(p_T^{trig}) \times v_n^f(p_T^{assoc}) \Rightarrow V_n^f\,(\text{Fourier}) \xrightarrow{\sqrt{\ }} v_n^f\,(\text{flow})$$

ZPC70, 665 (1996)
PRC81, 054905 (2010)

0-5%





- ● v_2^f
- □ $v_2\{2\}$
- ◇ $v_2\{4\}$

$$v_n^2\{2\} = \overline{v_n}^2 + \sigma_v^2$$
$$v_n^2\{4\} = \overline{v_n}^2 - \sigma_v^2$$

for small fluctuation

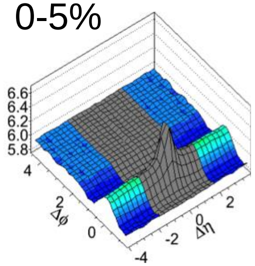
Borghini, Dhin, Ollitrault
PRC64, 054901 (2001)

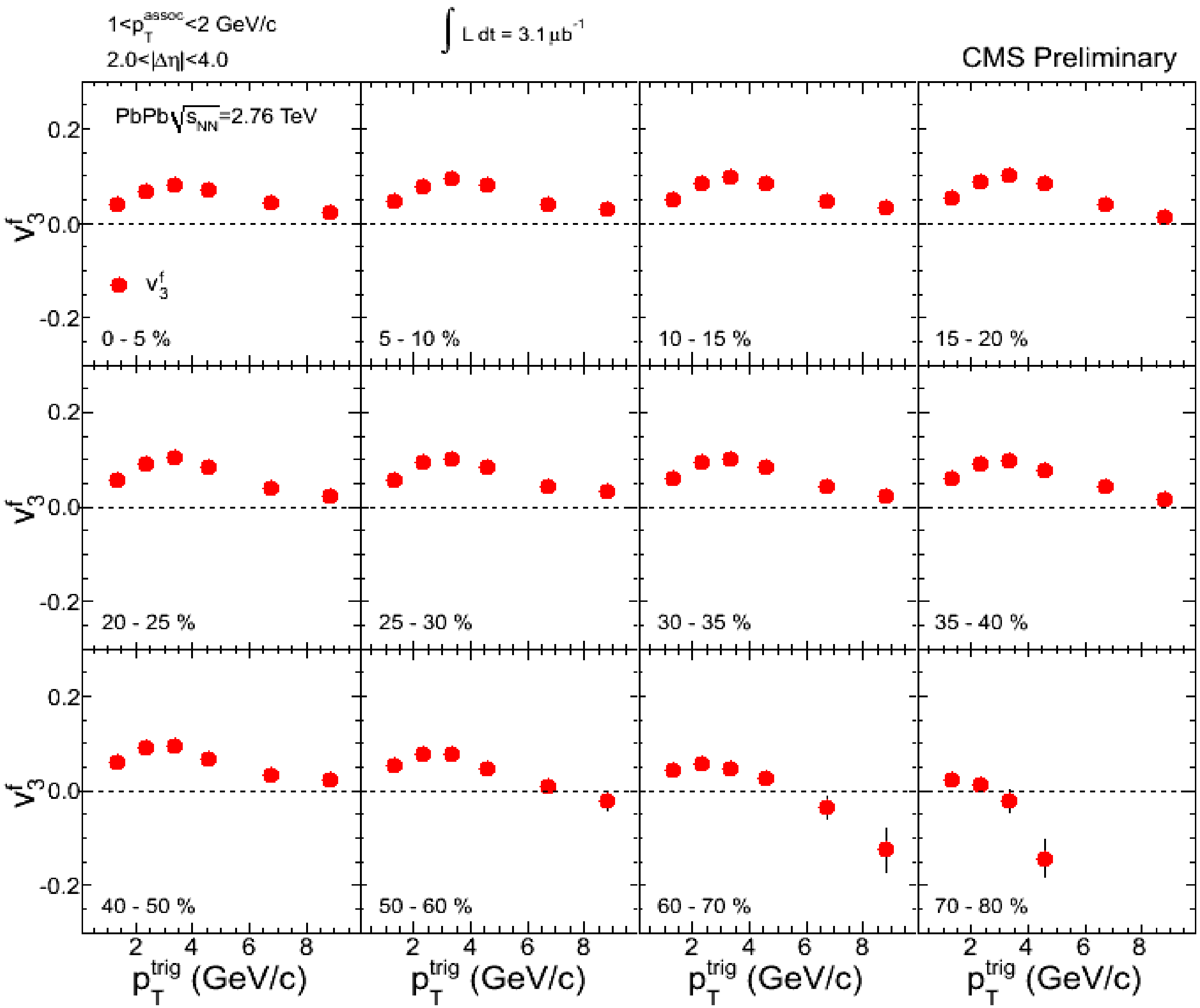
v_3 from Long-Range Correlations

$$V_n^f = v_n^f(p_T^{trig}) \times v_n^f(p_T^{assoc}) \Rightarrow V_n^f\,(\text{Fourier}) \xrightarrow{\sqrt{\;}} v_n^f\,(\text{flow})$$

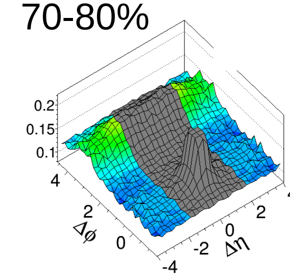
ZPC70, 665 (1996)
PRC81, 054905 (2010)

0-5%





70-80%

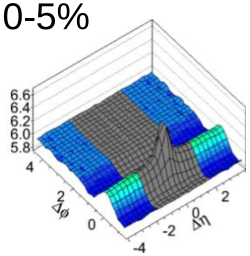


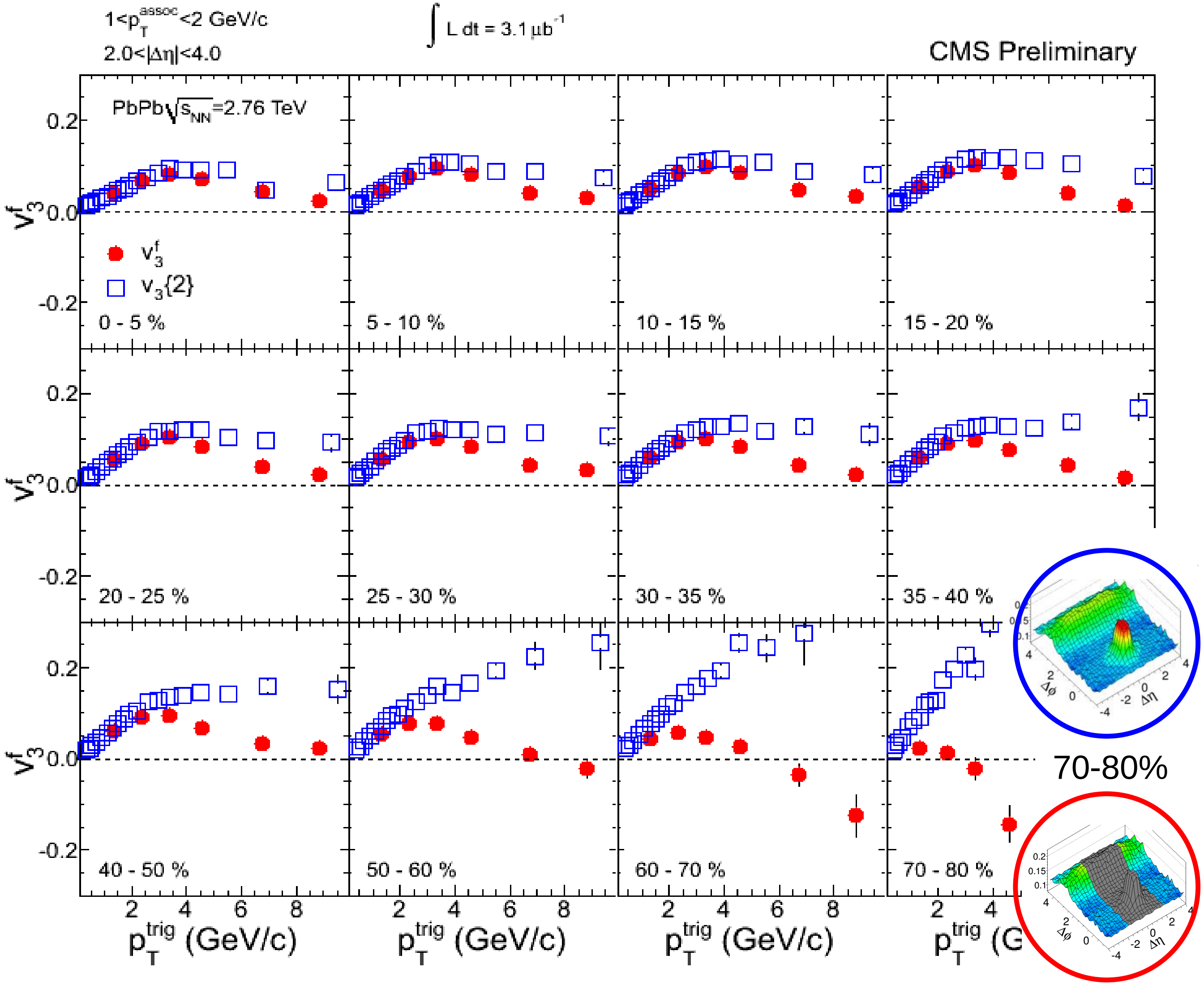
v_3 from Long-Range Correlations

$$V_n^f = v_n^f(p_T^{trig}) \times v_n^f(p_T^{assoc}) \Rightarrow V_n^f\,(\text{Fourier}) \xrightarrow{\sqrt{\ }} v_n^f\,(\text{flow})$$

ZPC70, 665 (1996)
PRC81, 054905 (2010)

0-5%





● v_3^f
□ $v_3\{2\}$

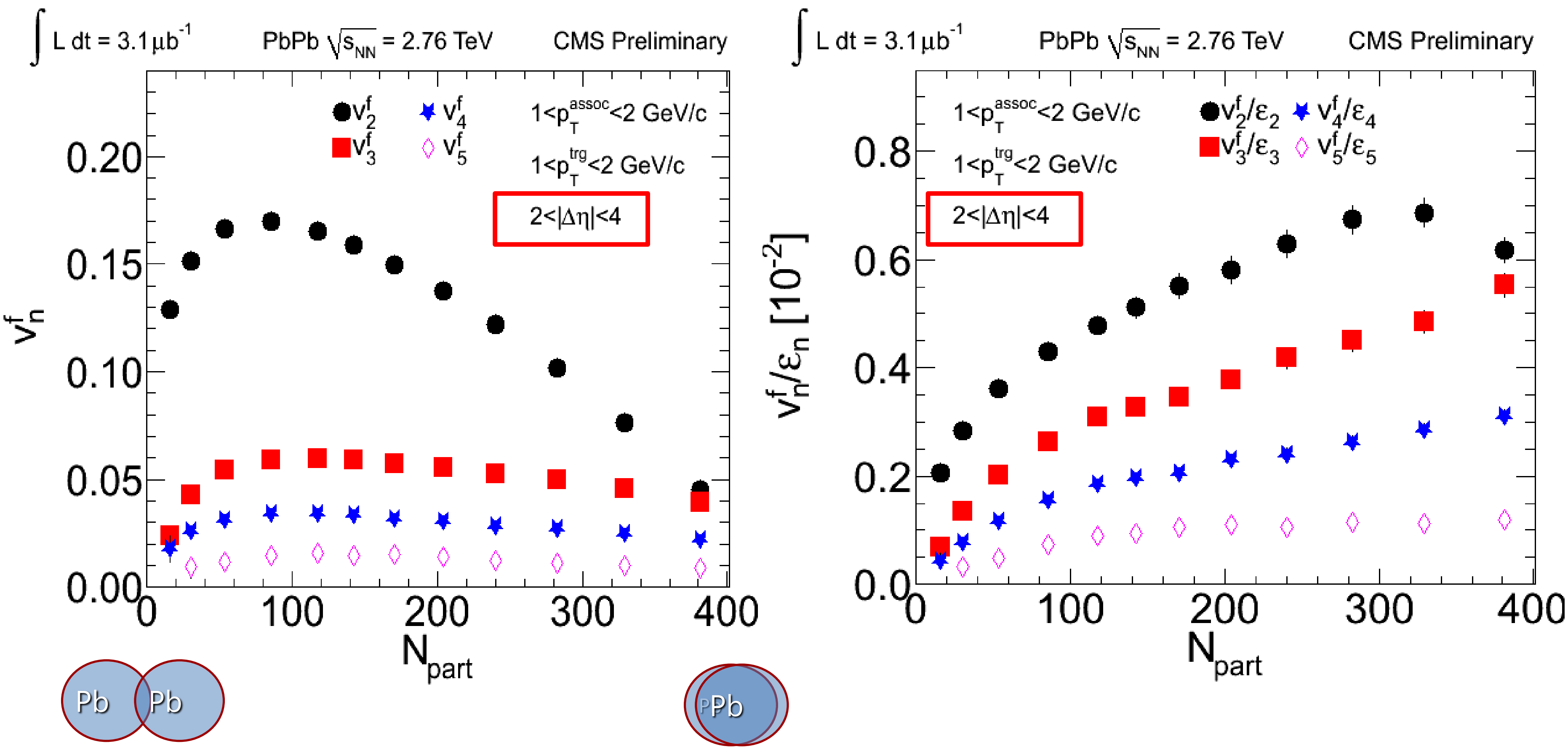
$$v_n^2\{2\} = \overline{v_n}^2 + \sigma_v^2$$
$$v_n^2\{4\} = \overline{v_n}^2 - \sigma_v^2$$

for small fluctuation

Borghini, Dhin, Ollitrault
PRC64, 054901 (2001)

70-80%

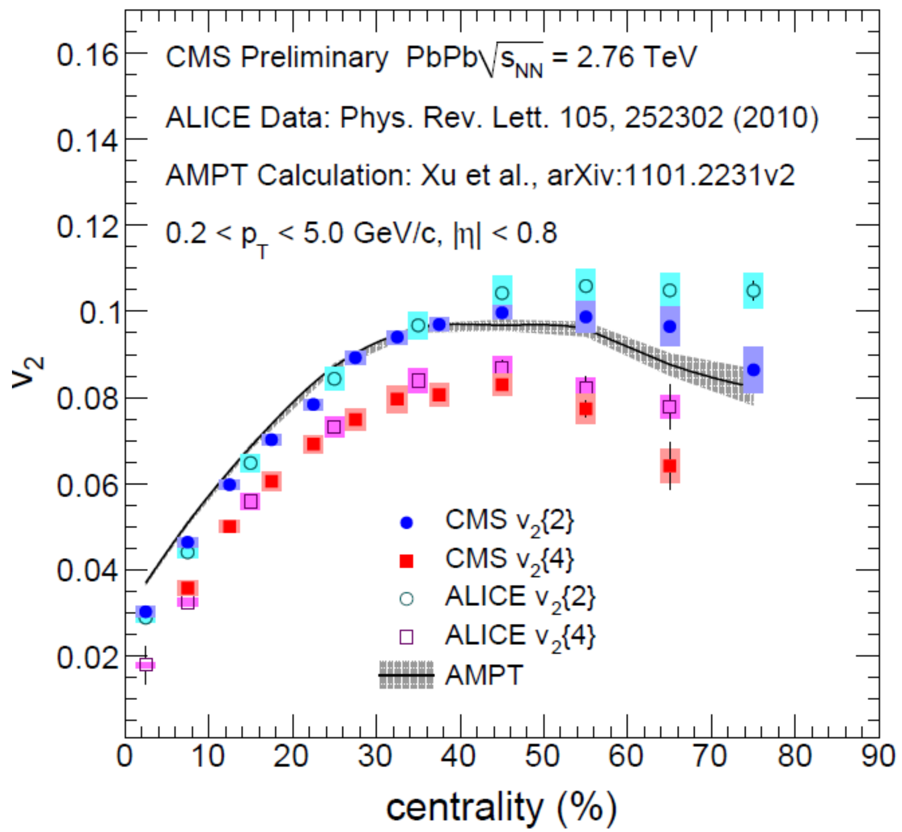
v^f_n vs. Centrality



- Powerful constraints on the viscosity of the medium
- Sensitive to the initial conditions

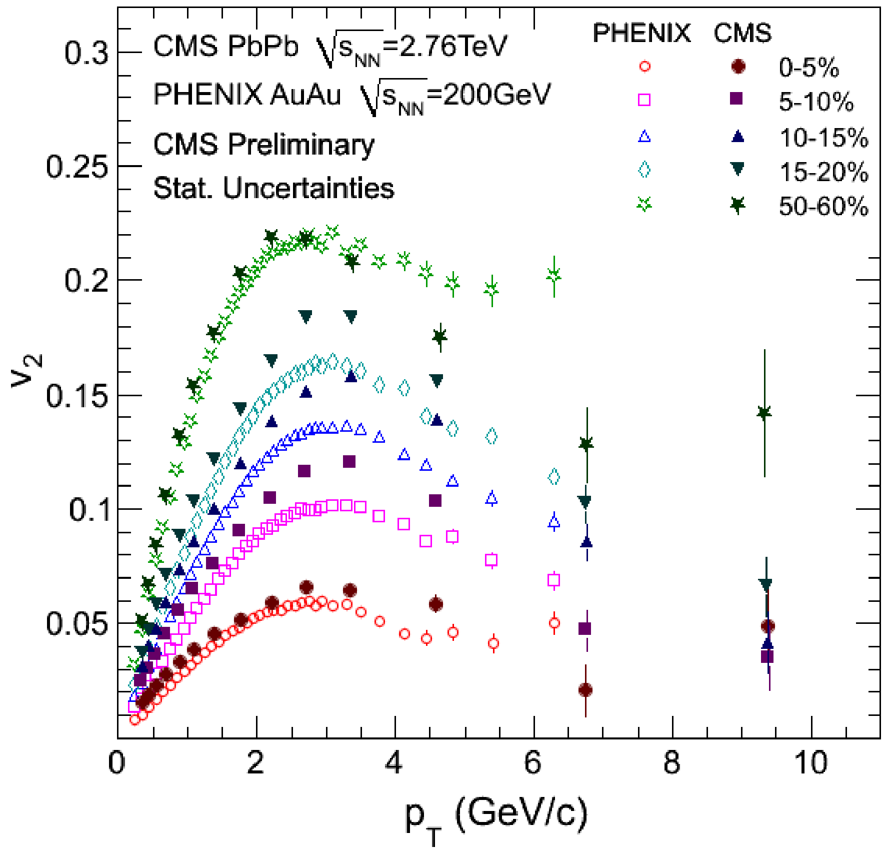
More on v_2

CMS vs. ALICE ($|\eta| < 0.8$)



CMS and ALICE agree in general except in most peripheral events

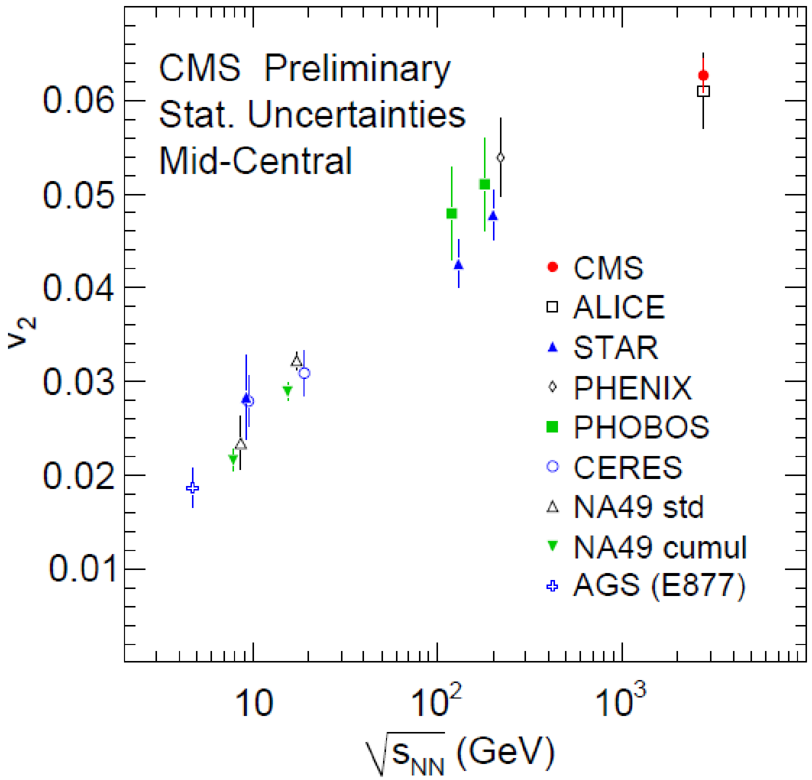
LHC vs. RHIC ($|\eta| < 0.8$)



PHENIX > CMS at high p_T for centrality > 30%

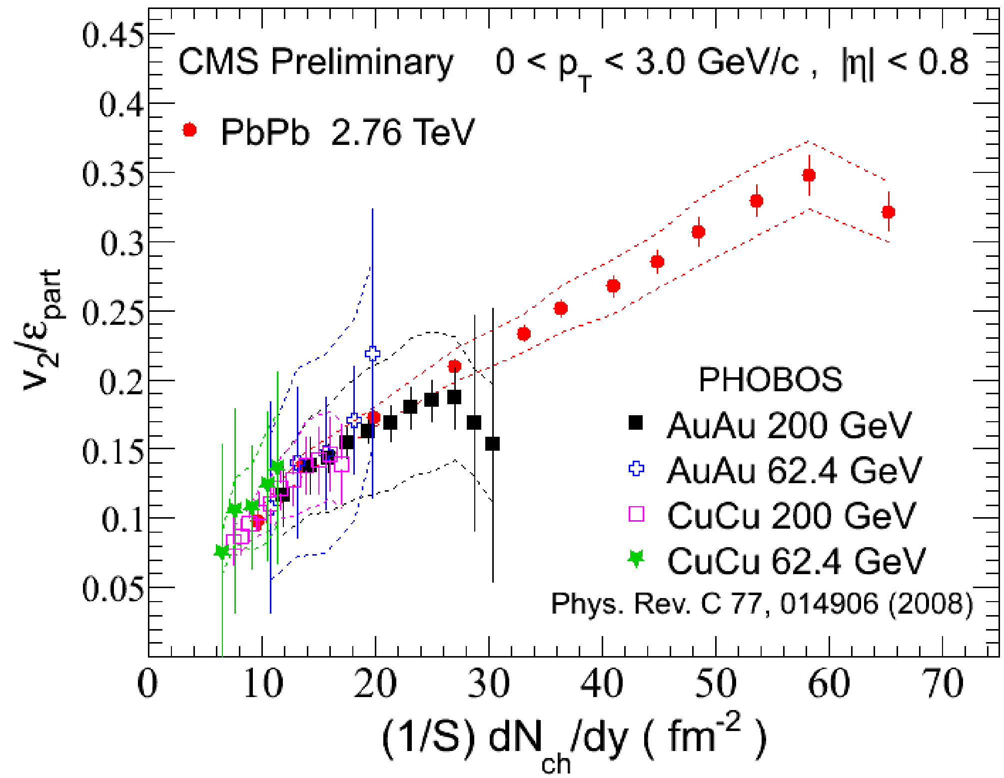
Systematics on v_2

Excitation function at mid η



Smooth increase from RHIC to LHC by 15-20%

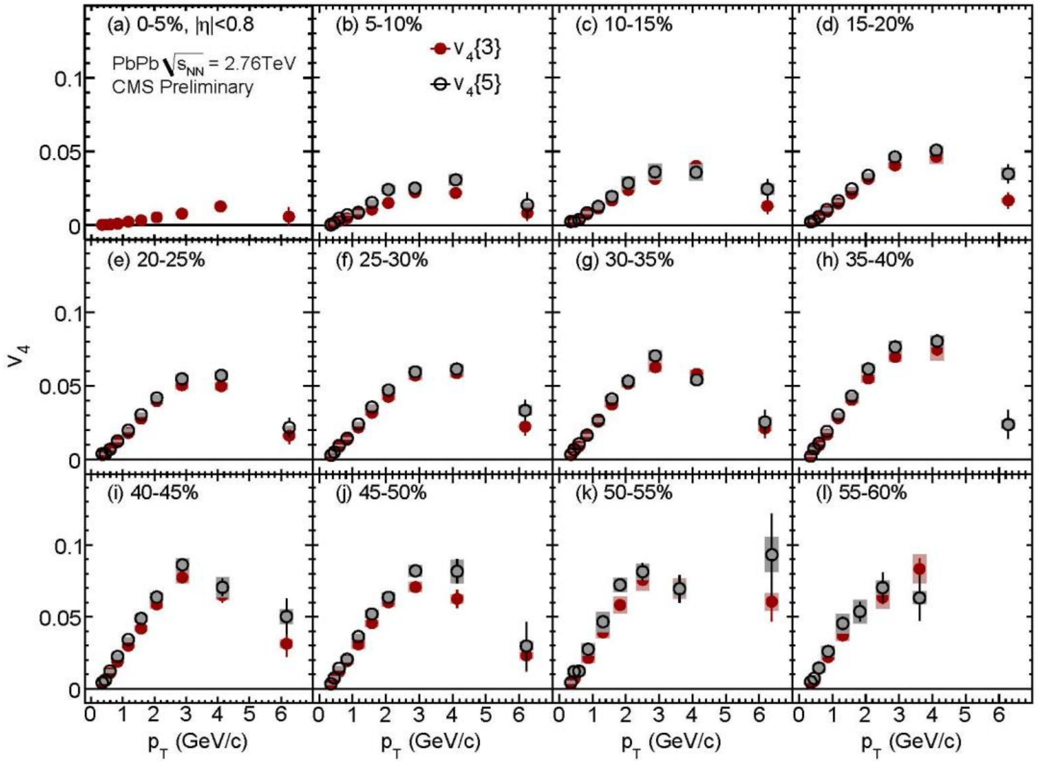
v_2/ε_{part} scaling



- **Scaling with transverse density across systems & $\sqrt{s_{NN}}$**
- **Constraint on η/s**

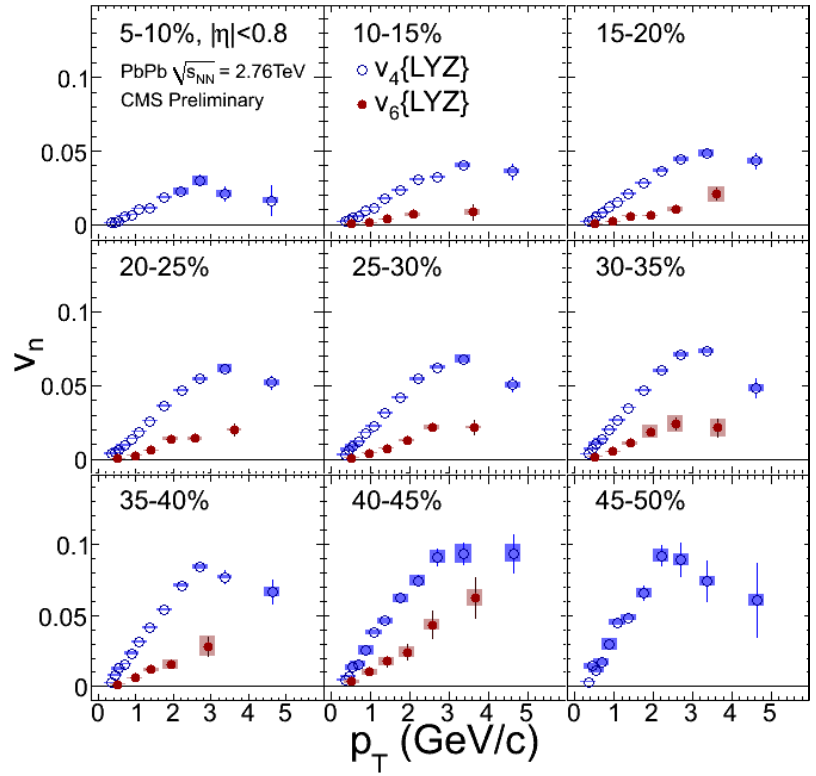
v_4 and v_6

Different methods for v_4 ($|\eta| < 0.8$)



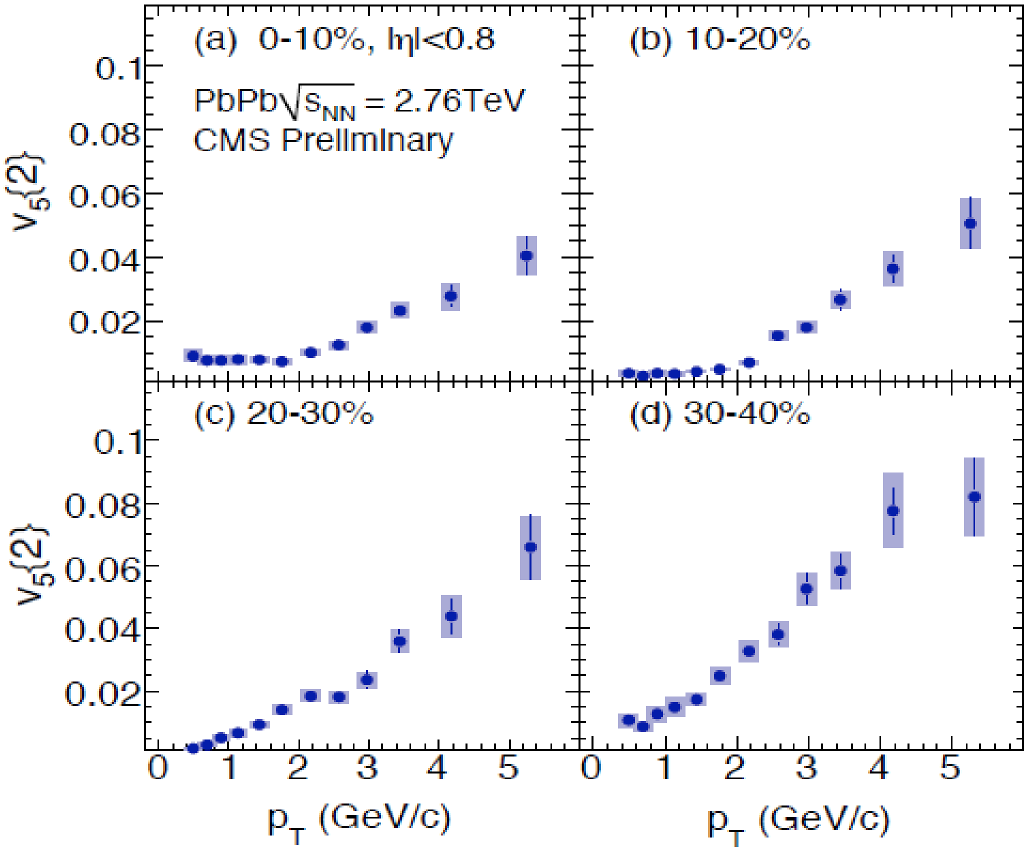
- Signals are sizable, reaching ~7%
- Compatible $v_4\{3\}$ and $v_4\{5\}$

v_4 vs. v_6 ($|\eta| < 0.8$) from LYZ

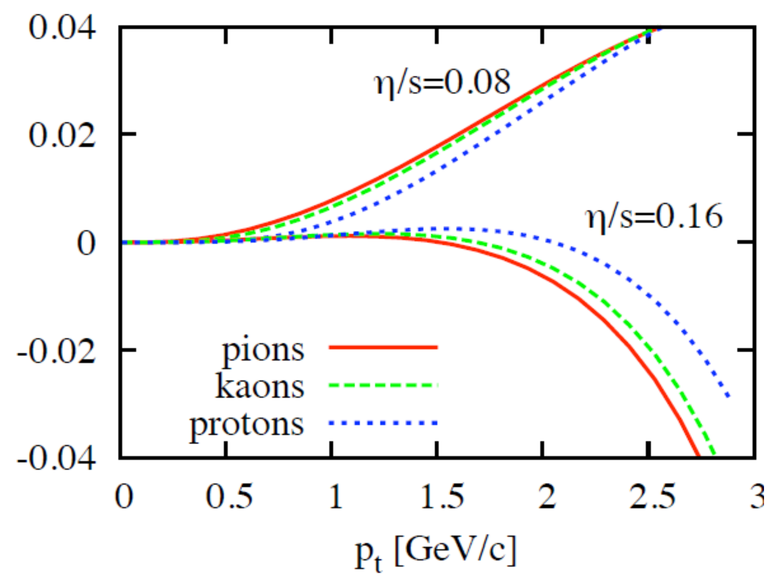


v_6 signal is small, but finite, reaching ~2% at mid-cent.

v_5

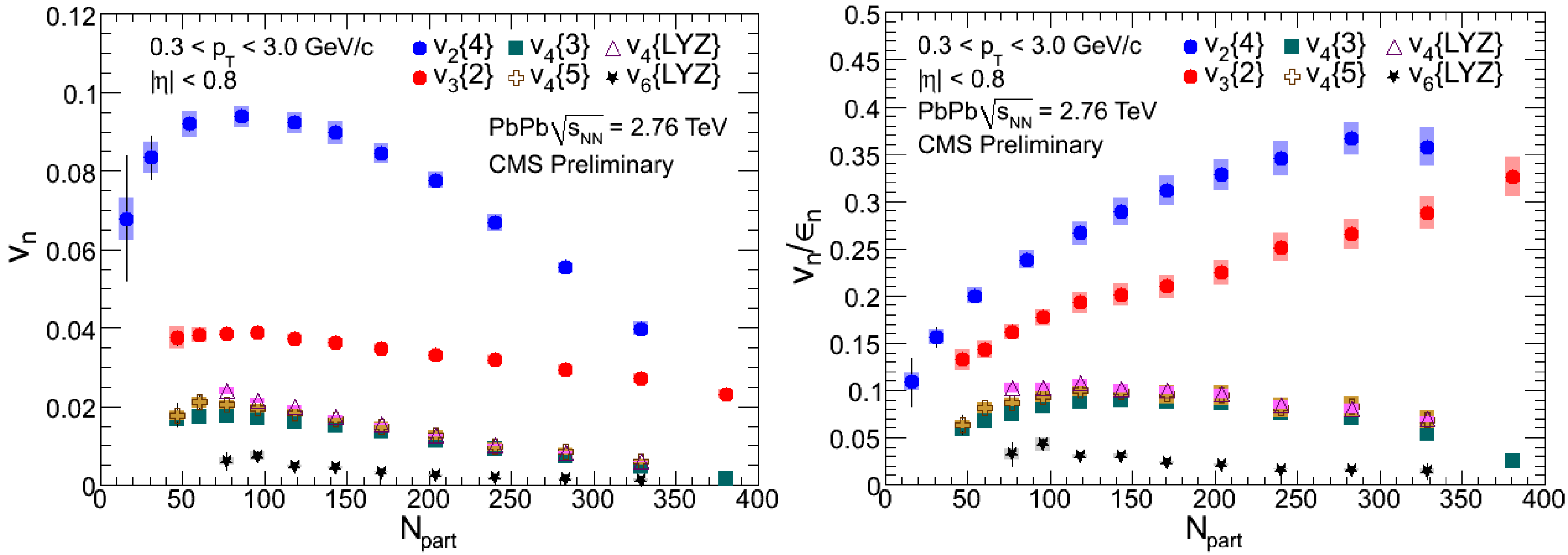


Alver et al., PRC82, 034913 (2010)
Prediction for RHIC, 0-5% centrality



- v_5 increases quadratically with p_T
  in contrast with other flow harmonics.

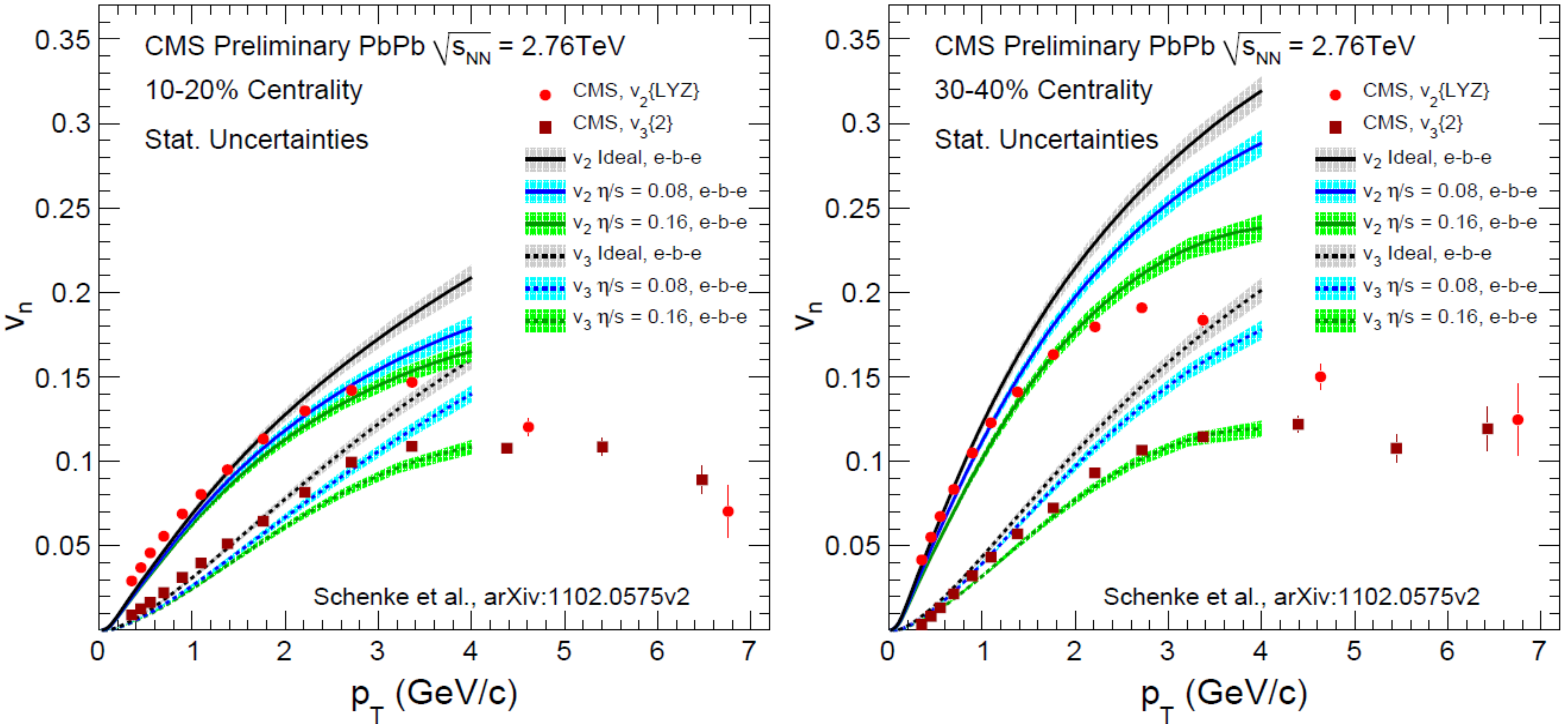
Full Harmonic Spectra



- v_n vs N_{part} shows different trends:
  - Even orders decrease and diminish with increasing N_{part}.
  - v_3 depends weakly on centrality & finite for central collisions.

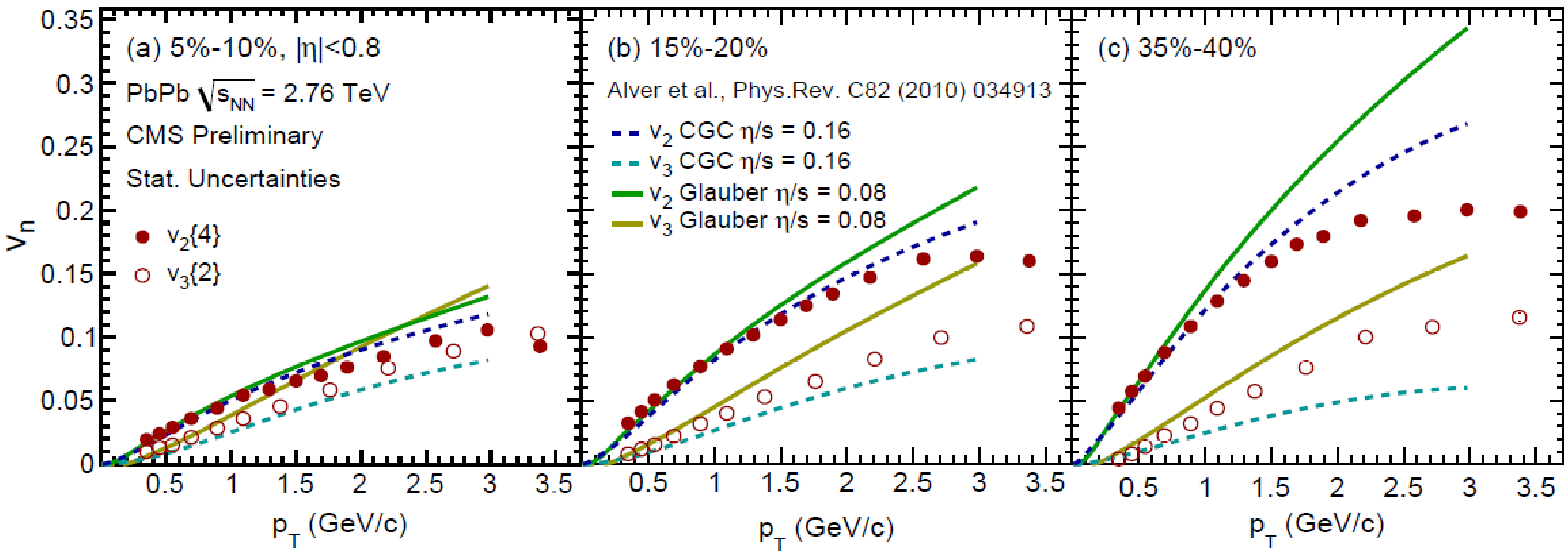
Comparisons to Hydro

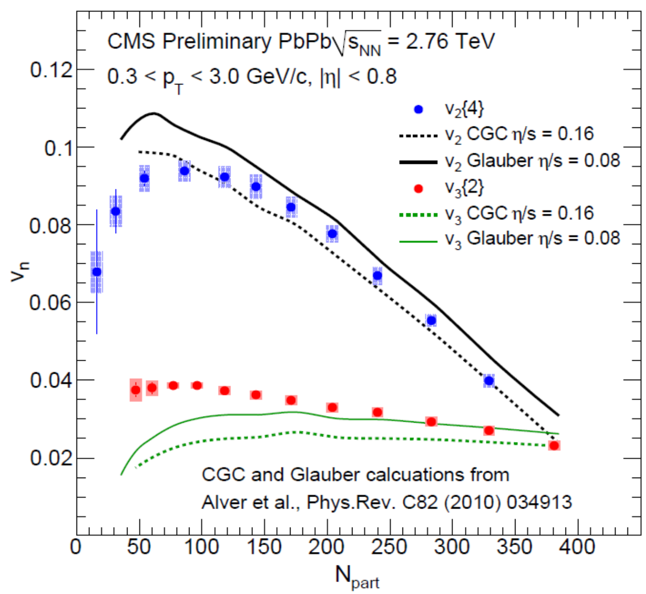
For Glauber initial conditions



- v_2 and v_3 together have better sensitivities on η/s.
- The centrality dependence adds further constraints.

Initial Conditions & η/s





- Different initial conditions add another parameter space
- Quantitative comparison requires further tuning
- Yet to be determined which set of parameters works best

Summary

1. Long-range ridge correlations observed in high-multiplicity pp
   – Ridge yield increases in low p_T and vanished at high p_T

2. Systematic study of dihadron correlations in PbPb
   – In central events, the ridge yield significantly drops at high p_T
   – Extracted flow parameters are consistent with other results done by the cumulant and LYZ methods

3. Flow parameters
   – v_2 is compatible with RHIC data
   – v_3 is sizable and weakly depends on the centrality
   – (v_4/v_2^2 is higher than at RHIC)
   – v_5 and v_6 are finite
   – Important basis for the initial conditions and η/s of sQGP