

Correlations and fluctuations measured by the CMS experiment in pp and PbPb collisions

Wei Li



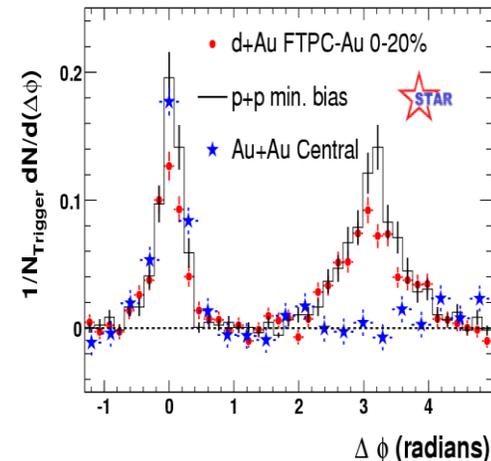
for the CMS Collaboration

Introduction

Correlation measurements are powerful tools to:

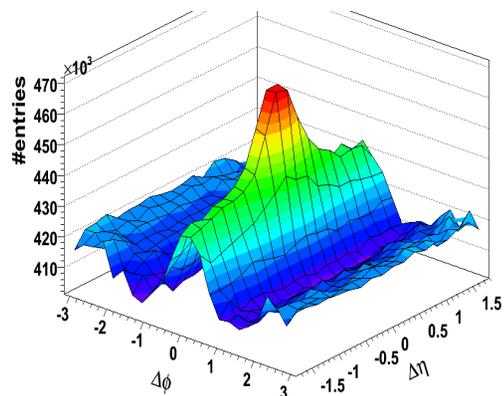
- Study the mechanism of hadron production
- Probe the jet-medium interactions in AA
- Explore the bulk properties of the medium

Jet quenching



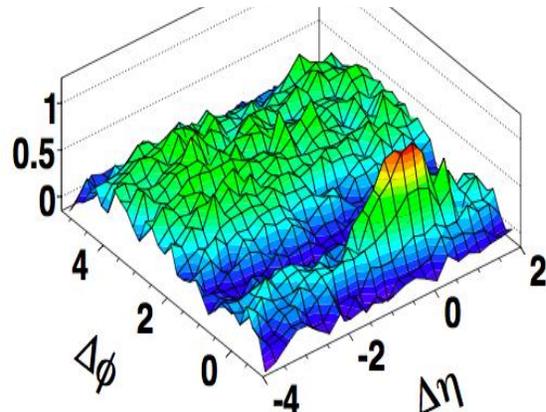
Intriguing ridge structure at RHIC

STAR Au+Au 0-10%



PRC 80 (2009) 64912

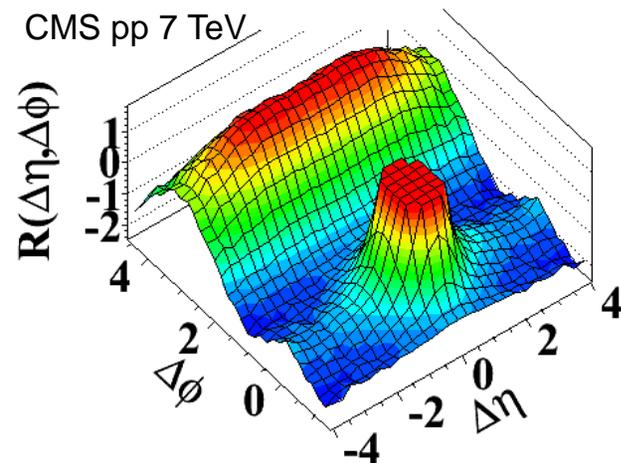
PHOBOS Au+Au 0-30%



PRL 104, 062301 (2010)

Ridge in pp at LHC!

CMS pp 7 TeV



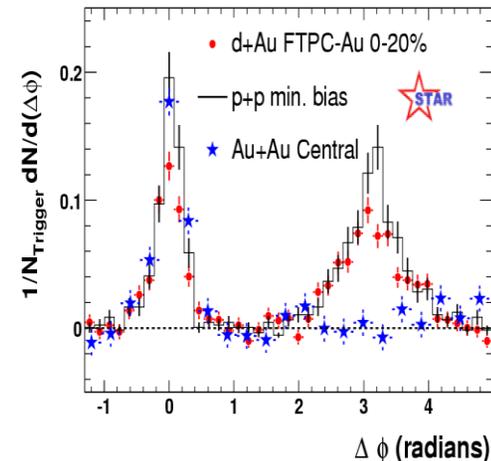
JHEP 09 (2010) 091

Introduction

Correlation measurements are powerful tools to:

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- Probe the jet-medium interactions in AA
- Explore the bulk properties of the medium

Jet quenching

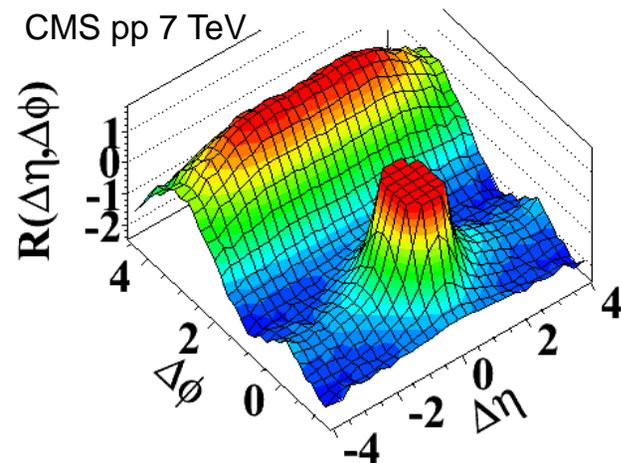


Outline:

- Correlations in high multiplicity pp at 7 TeV
- Correlations in PbPb at 2.76 TeV

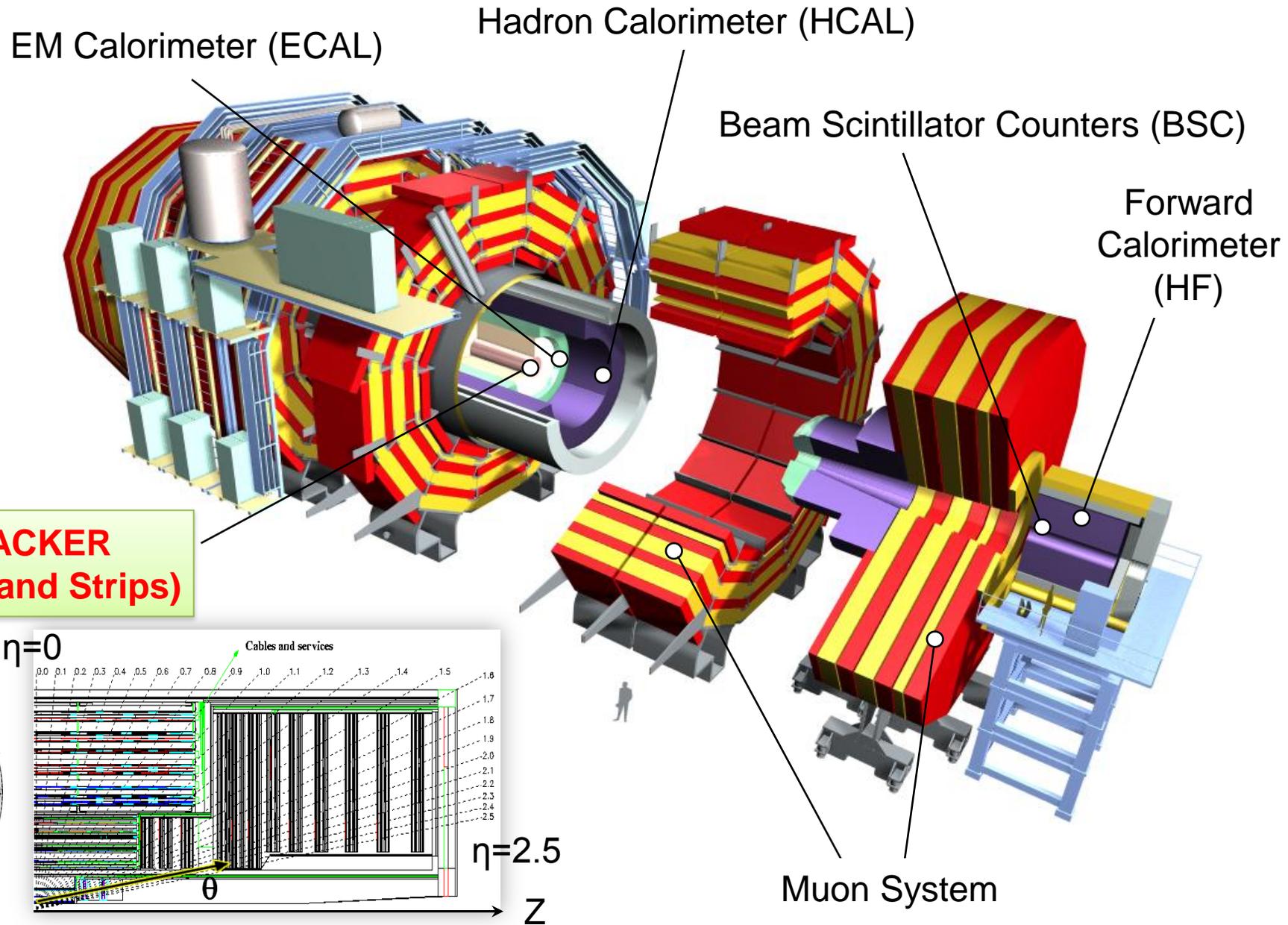
Ridge in pp at LHC!

CMS pp 7 TeV



JHEP 09 (2010) 091

CMS experiment



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

Dihadron correlation technique in CMS

Signal distribution:

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

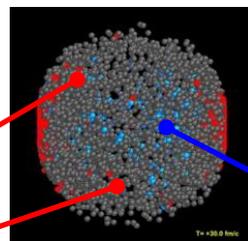
Particle 1: trigger

Particle 2: associated

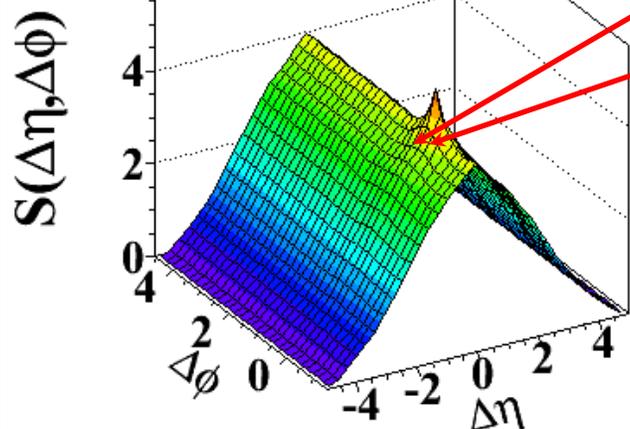
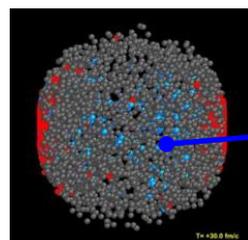
Background distribution:

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

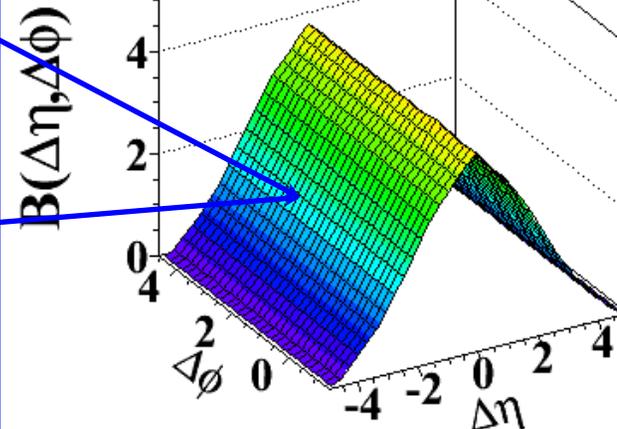
Event 1



Event 2



same event pairs



mixed event pairs

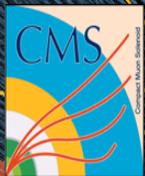
$$\Delta\eta = \eta^{\text{assoc}} - \eta^{\text{trig}}$$

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

Associated hadron yield per trigger:

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

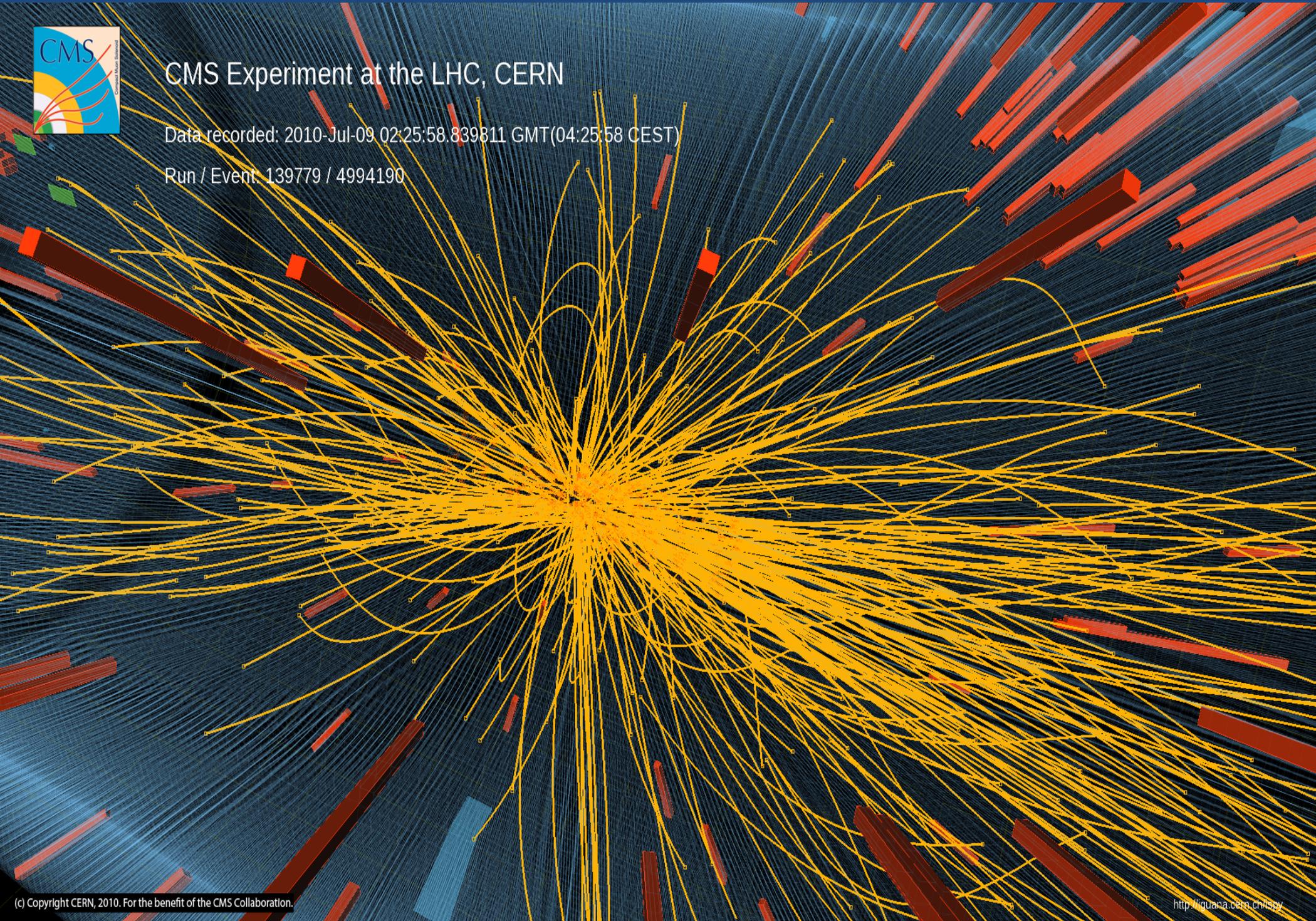
High multiplicity pp collisions



CMS Experiment at the LHC, CERN

Data recorded: 2010-Jul-09 02:25:58.839811 GMT(04:25:58 CEST)

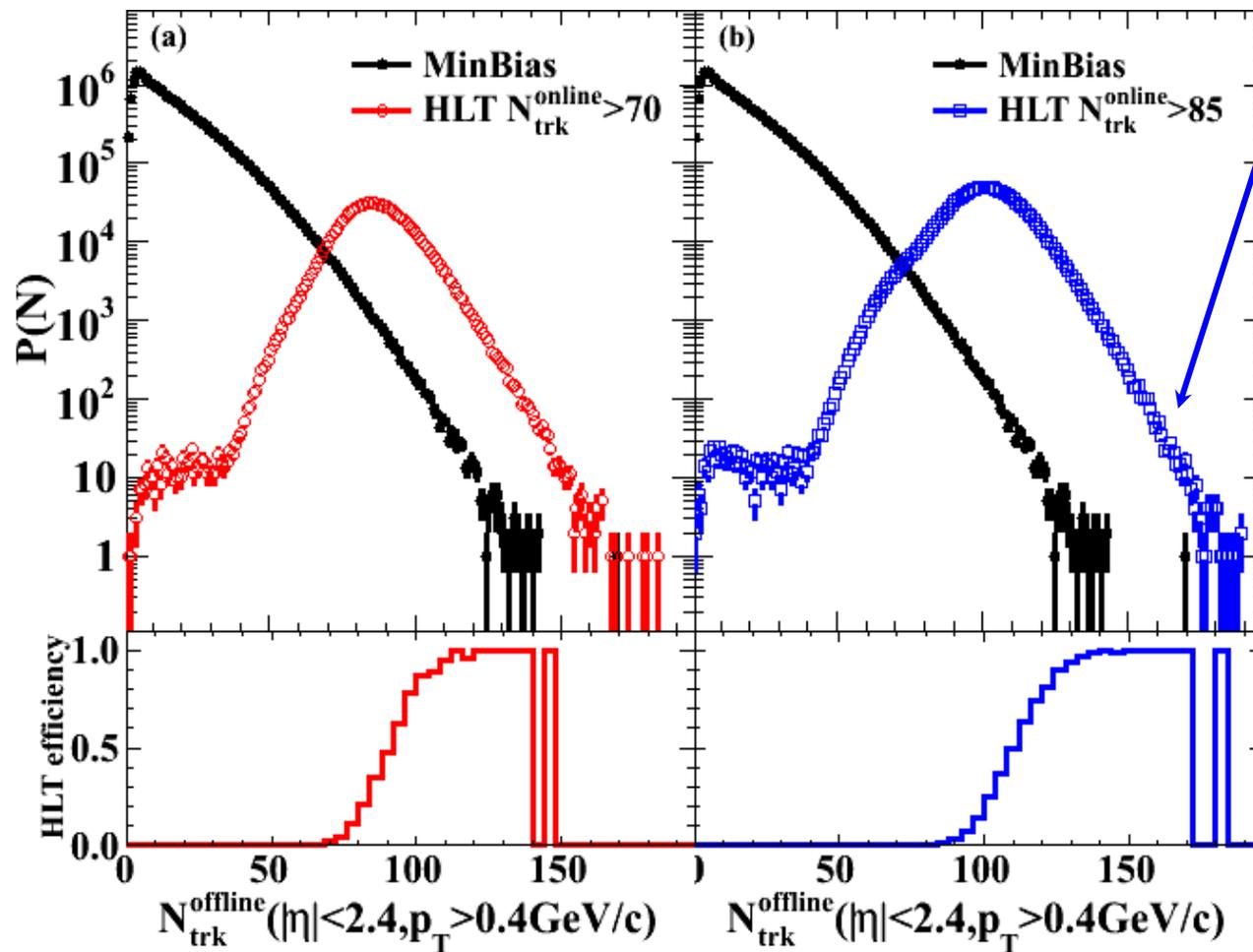
Run / Event: 139779 / 4994190



High multiplicity pp collisions

See talk by Dragos Velicanu
(05/23, 3:00pm)

Very high particle density regime
Is there anything interesting happening?



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

$N_{\text{online}} > 85$ trigger
un-prescaled for
full 980nb^{-1} data set

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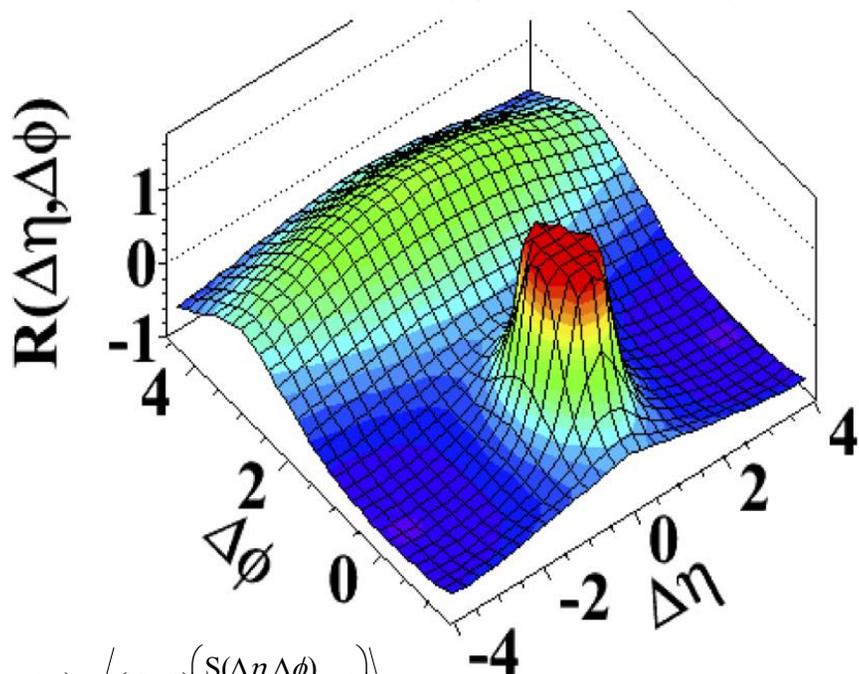
~350K top multiplicity events ($N > 110$) out of 50 billion collisions!

Ridge in high multiplicity pp

Intermediate p_T : 1-3 GeV/c

350K events

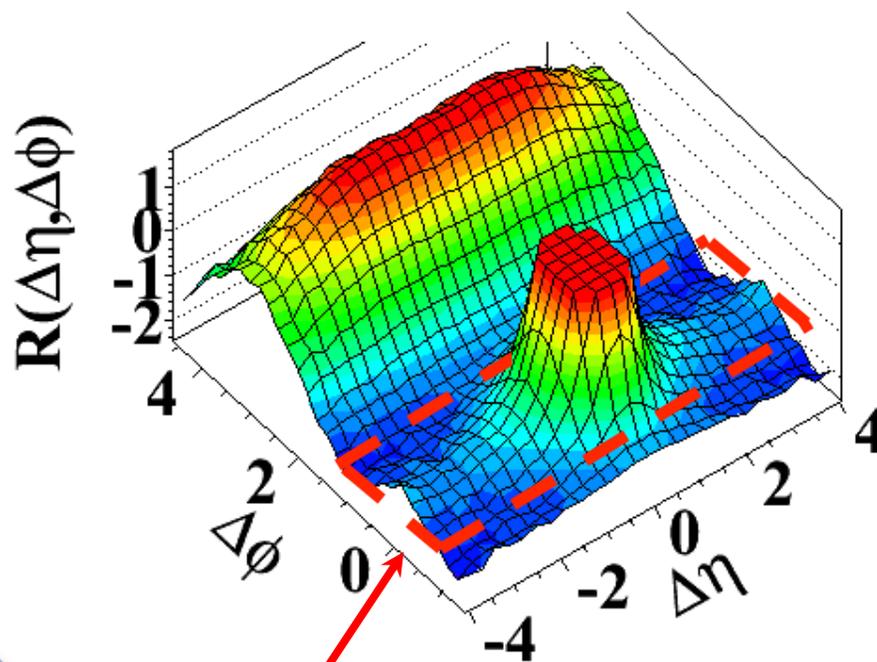
Minimum Bias pp ($\langle N \rangle \sim 15$)



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

peak truncated

High multiplicity pp ($N \geq 110$)

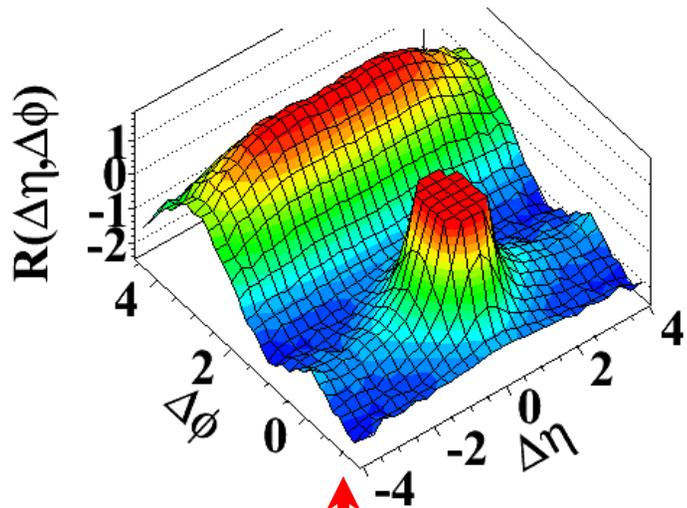


JHEP 09 (2010) 091

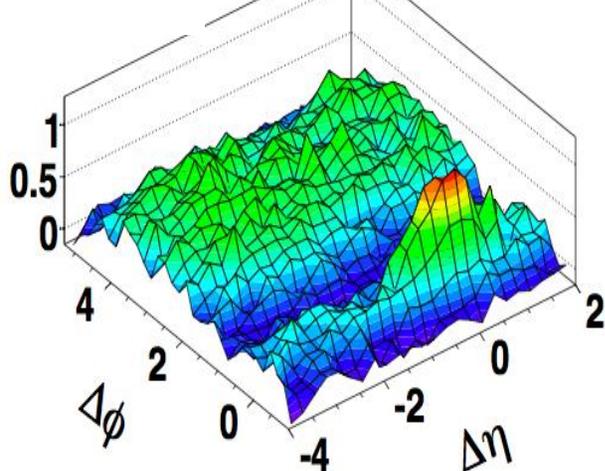
Striking **“ridge-like”** structure extending over $\Delta\eta$ at $\Delta\phi \sim 0$
(not observed before in hadron collisions or MC models)

Ridge in high multiplicity pp

CMS pp 7 TeV, $N \geq 110$



PHOBOS AuAu 200 GeV 0-30%



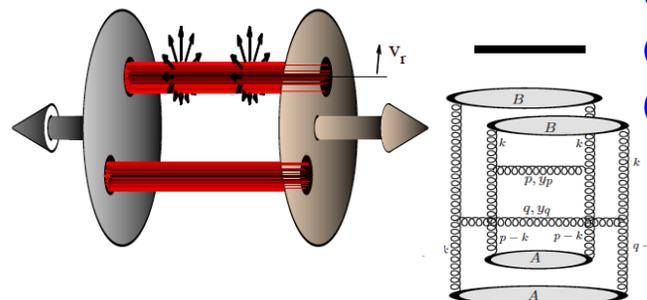
Interpretations:

48 citations

- Multi-jet correlations
- Jet-Jet color connections
- Jet-proton remnant color connections

} **Jet**

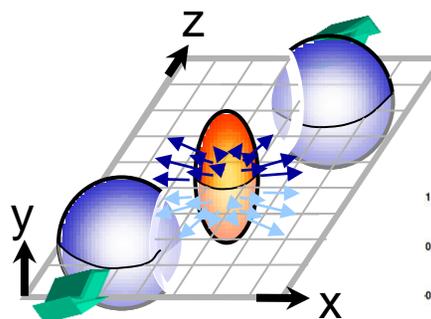
Glasma tube



**Color
Glass
Condensate**

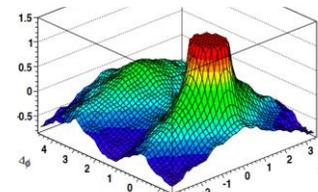
Phys. Lett. B697:21-25, 2011

Hydrodynamic flow



**Quark
Gluon
Plasma**

EPOS model: pp



K. Werner, WWND2011

Ridge in high multiplicity pp

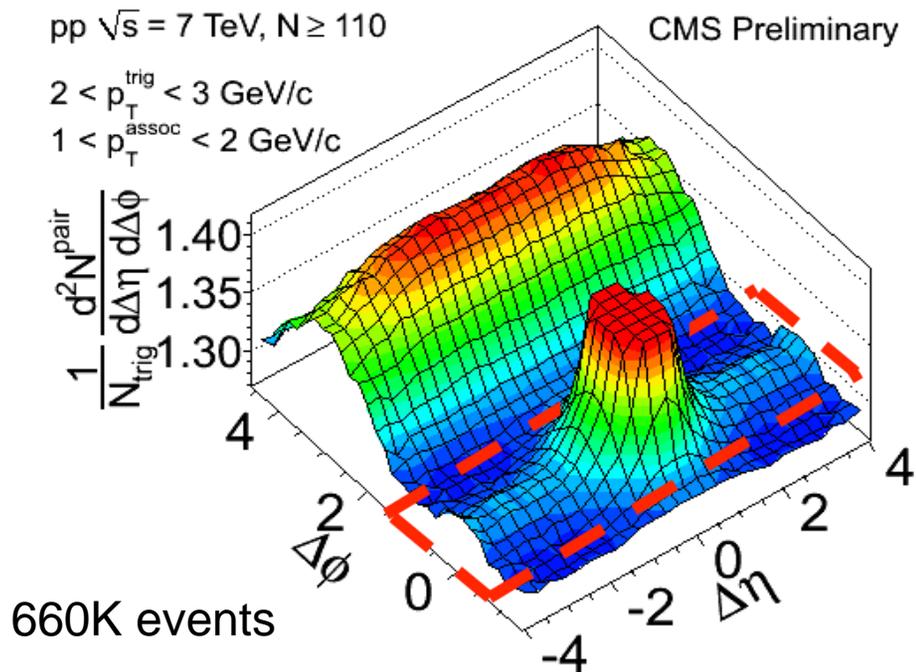
Updated new results:

- ~ 2 x statistics of previous results
- Extend multiplicity reach
- Detailed ($p_T^{\text{trig}}, p_T^{\text{assoc}}$) dependence

Associated hadron yield per trigger:

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

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



Ridge in high multiplicity pp

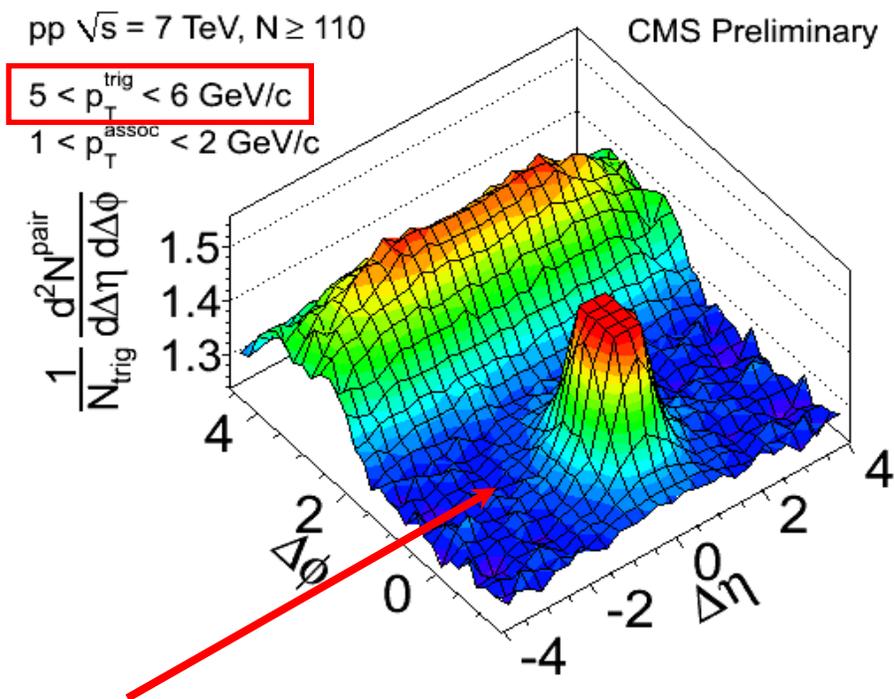
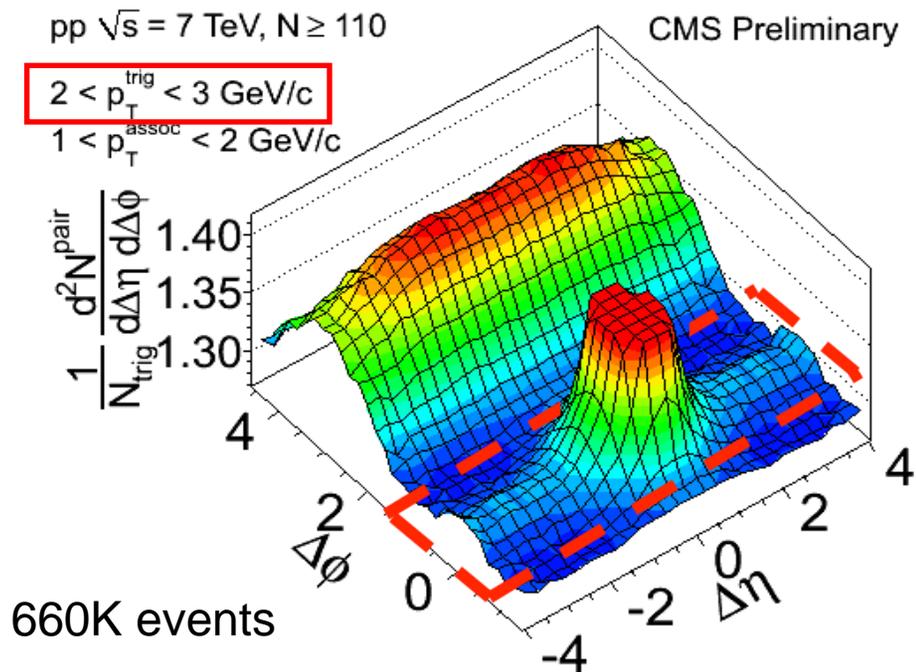
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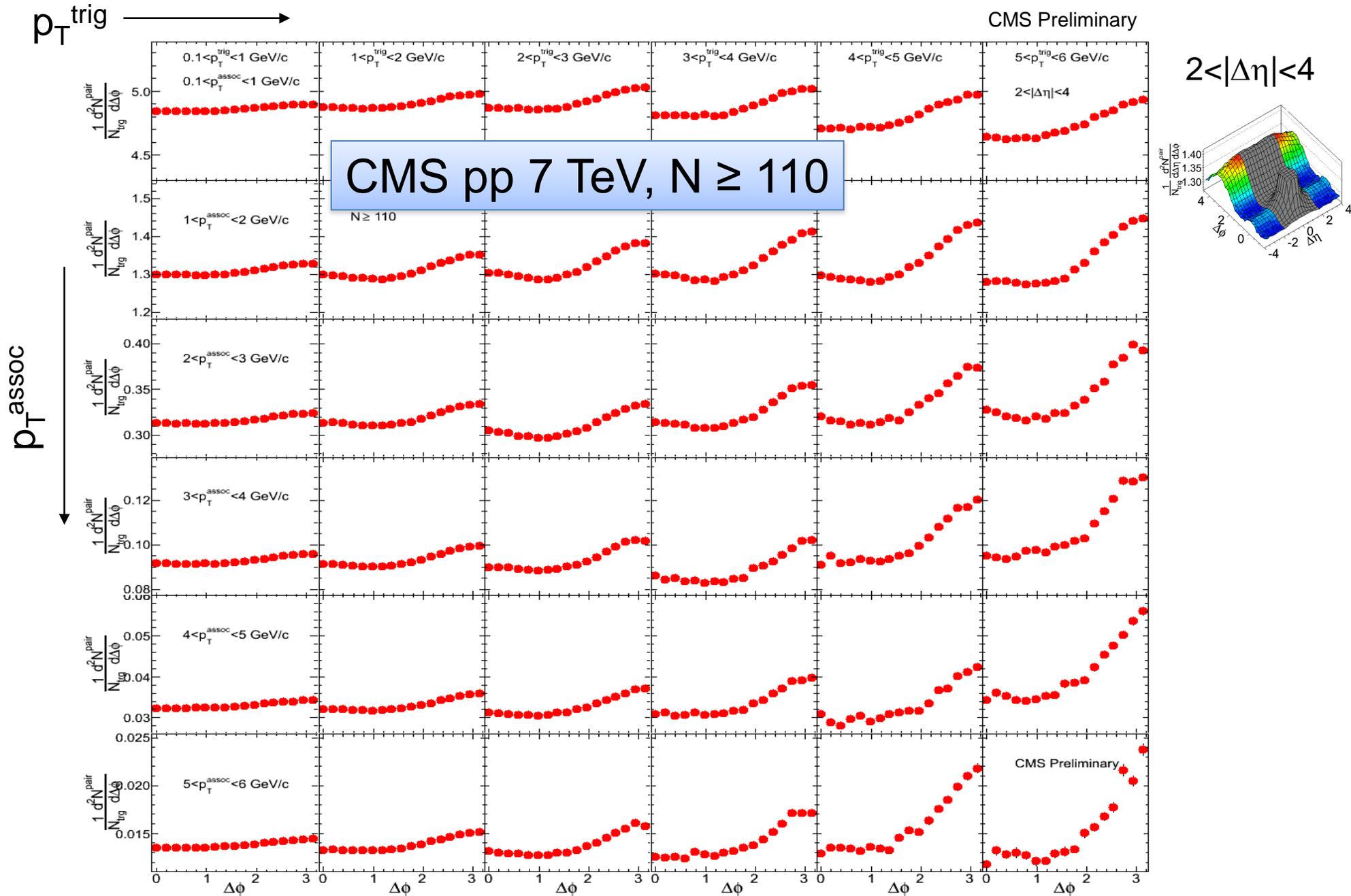
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No ridge when correlating to high p_T particles!

$\Delta\phi$ projections in various p_T ranges



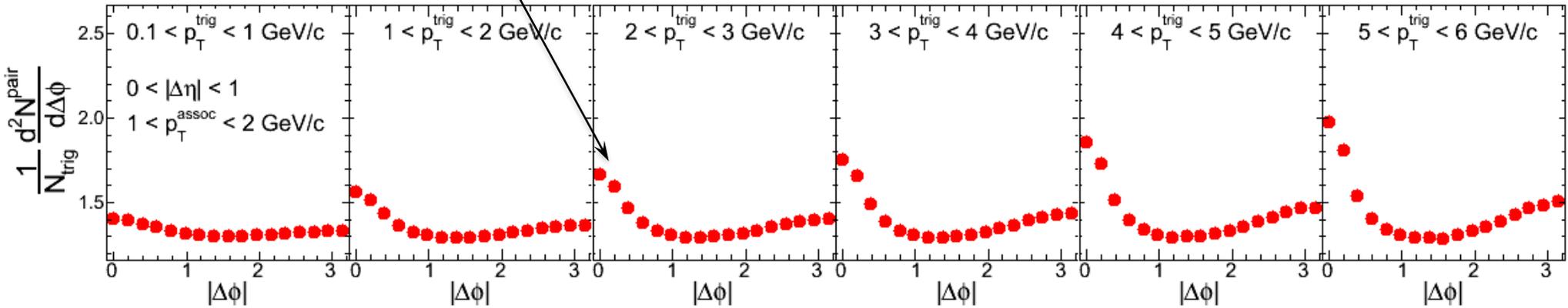
$\Delta\phi$ projections in various p_T ranges

CMS pp 7 TeV, $N \geq 110$

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

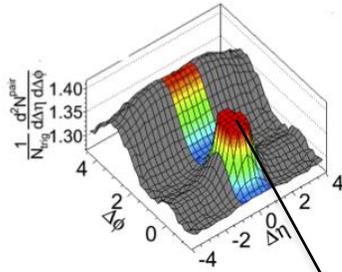
p_T

CMS Preliminary



$\Delta\phi$ projections in various p_T ranges

CMS pp 7 TeV, $N \geq 110$

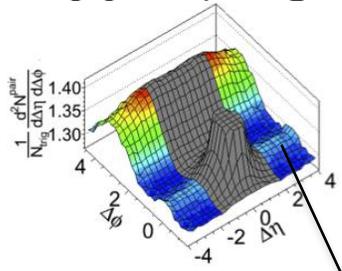
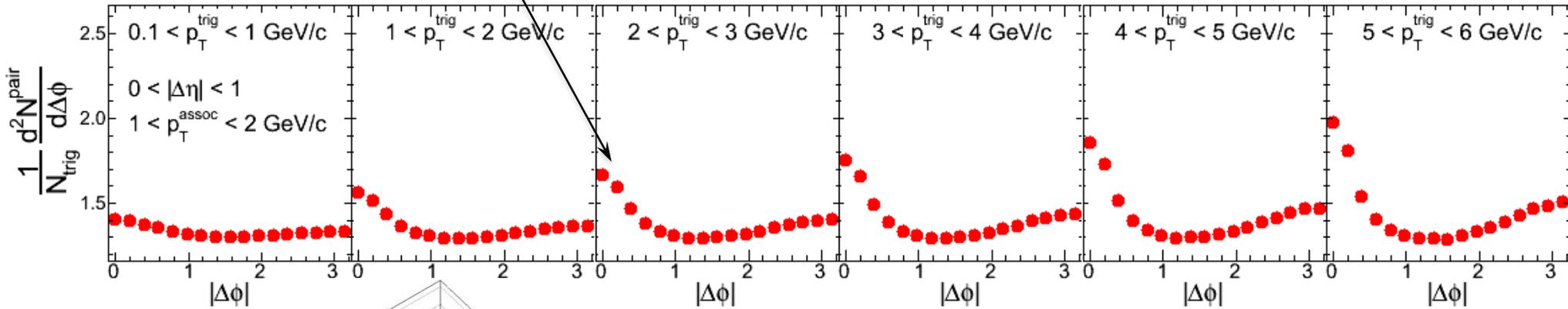


Jet region ($|\Delta\eta| < 1$)

p_T



CMS Preliminary

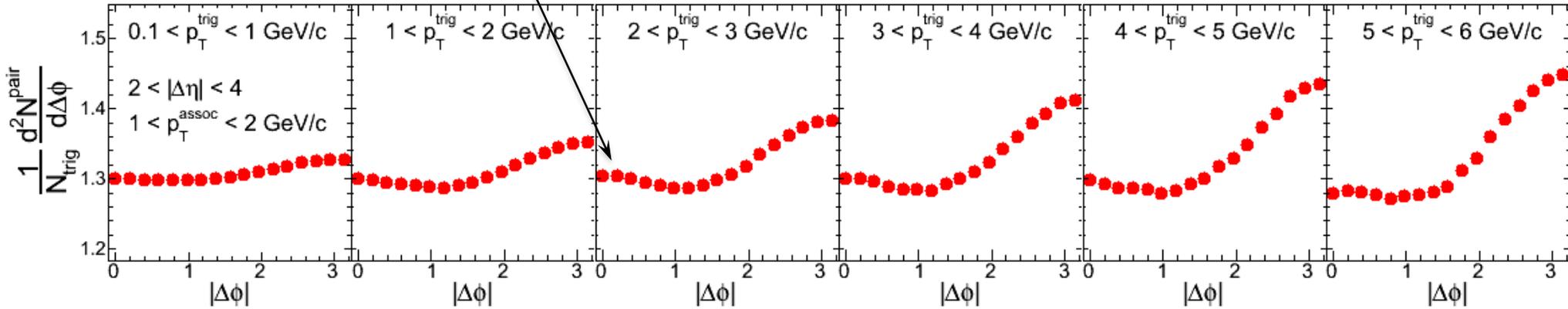


Ridge region ($2 < |\Delta\eta| < 4$)

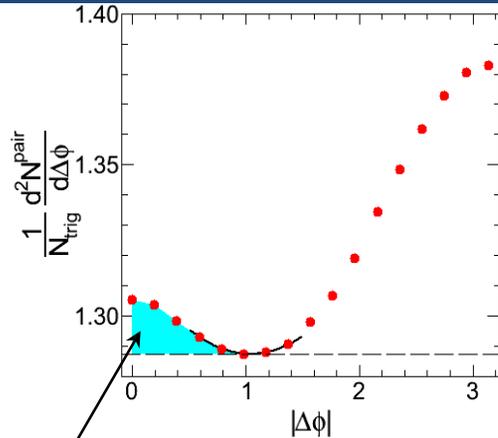
p_T



CMS Preliminary



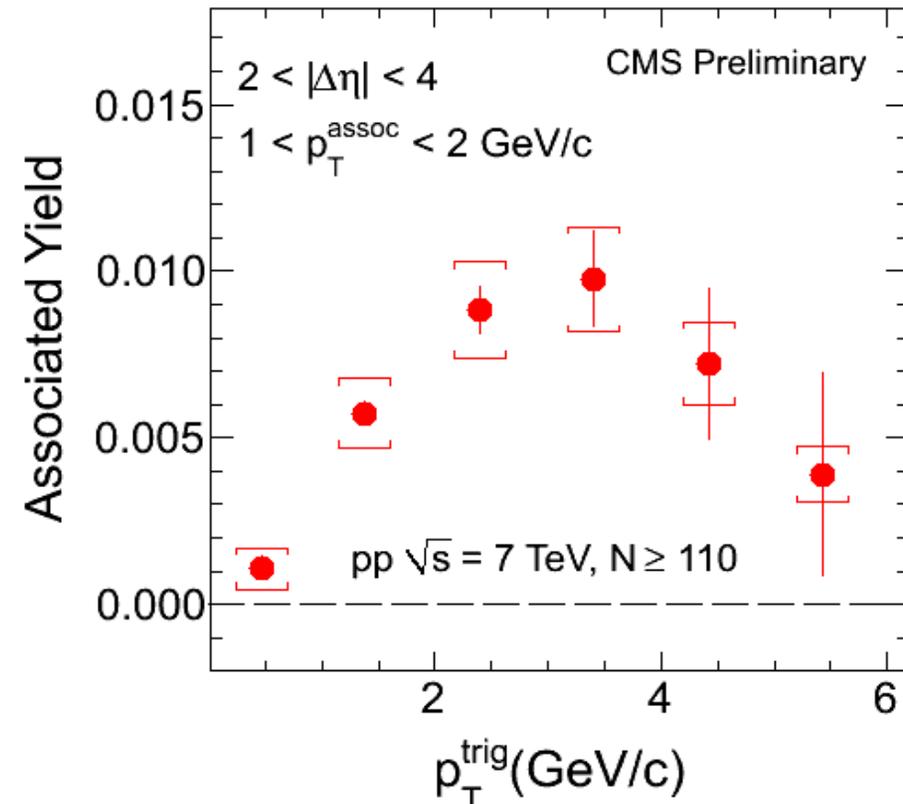
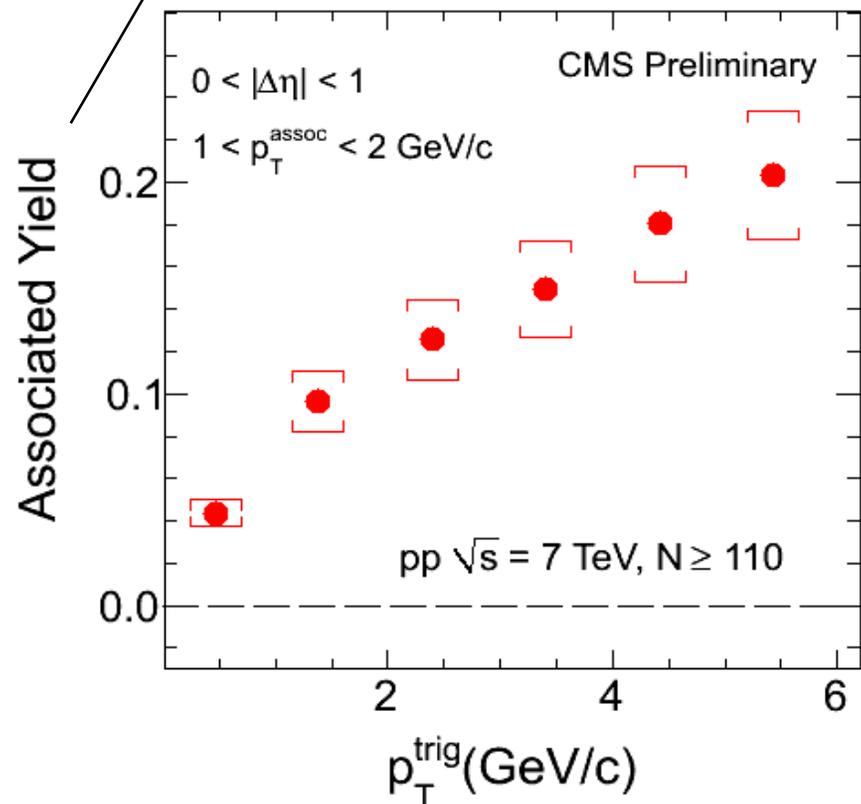
Near-side yield vs p_T in pp ($N \geq 110$)



Zero-Yield-At-Minimum (ZYAM)

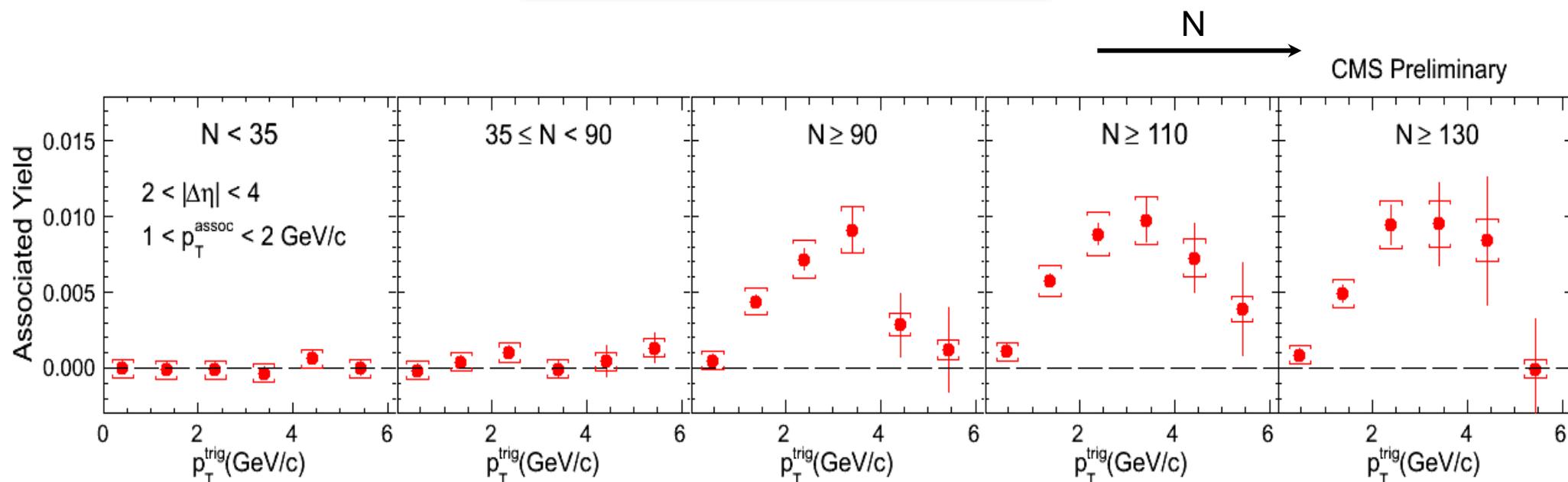
Jet region ($|\Delta\eta| < 1$)

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



Near-side yield vs p_T in pp

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

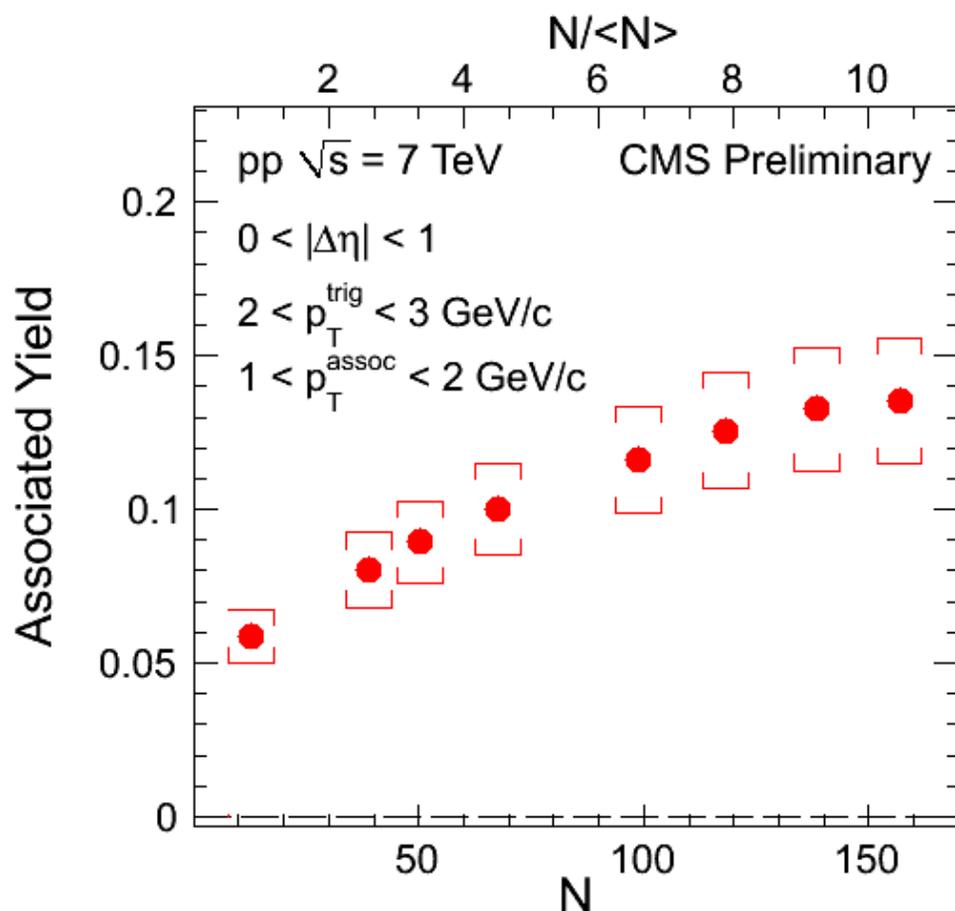


Significant ridge effect for $N \geq 90$ in pp

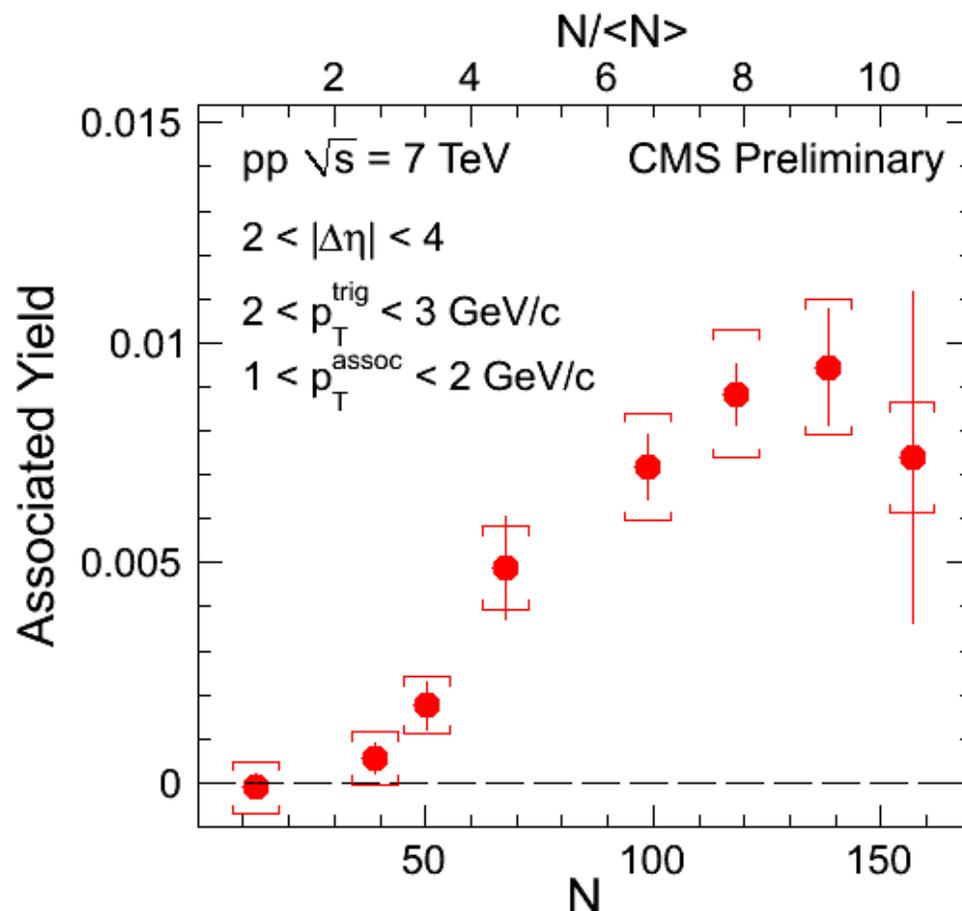
Ridge first rises with p_T , and then drops at high p_T

Near-side yield vs multiplicity in pp

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



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



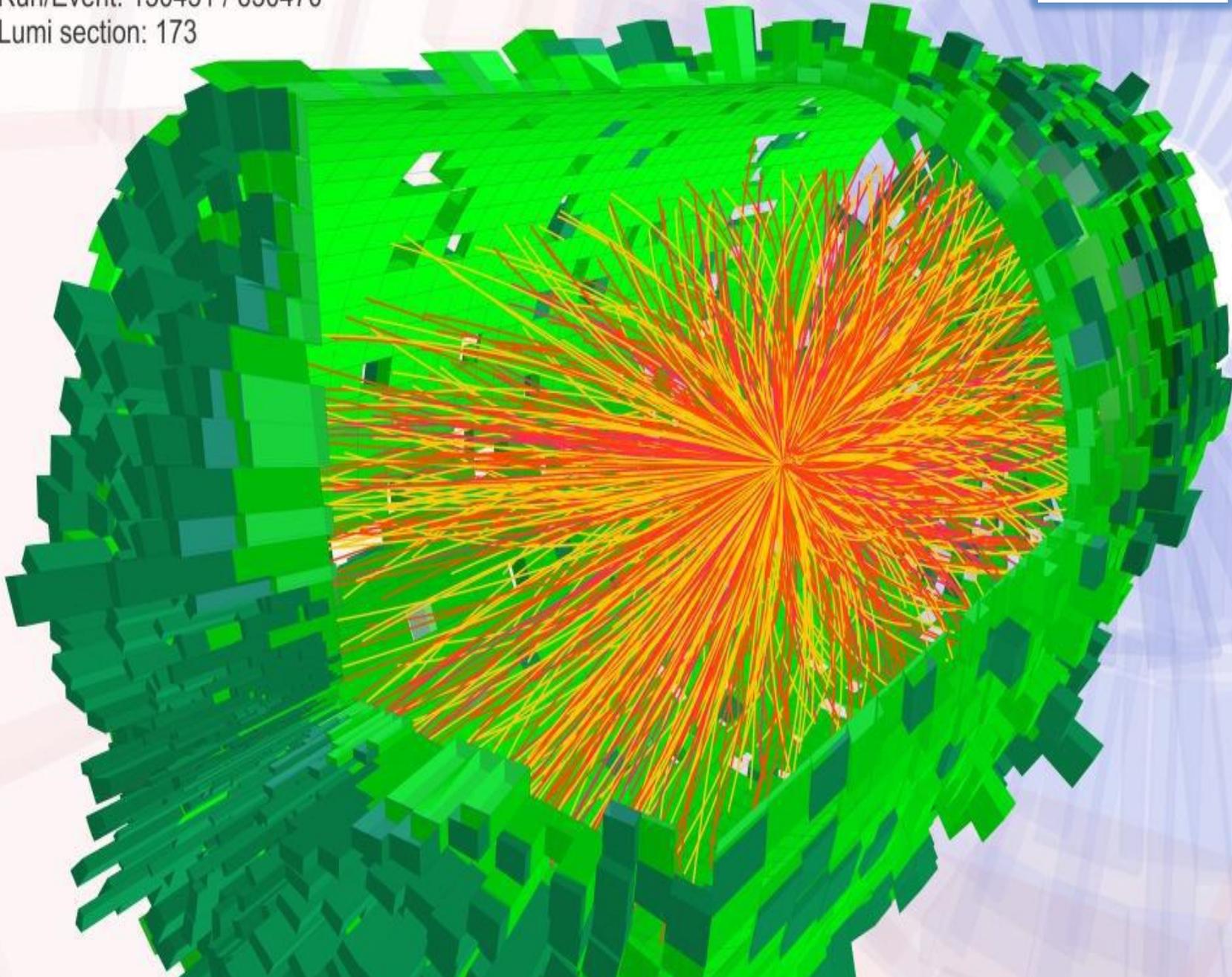
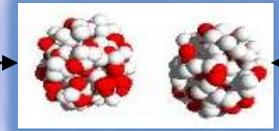
- Jet yield in pp monotonically increases with N
- Ridge in pp turns on around $N \sim 50 - 60$ (4 x MinBias) smoothly ($\langle N \rangle \sim 15$ in MinBias pp events)

PbPb collisions at the LHC



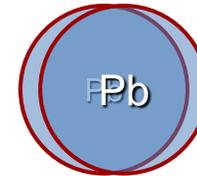
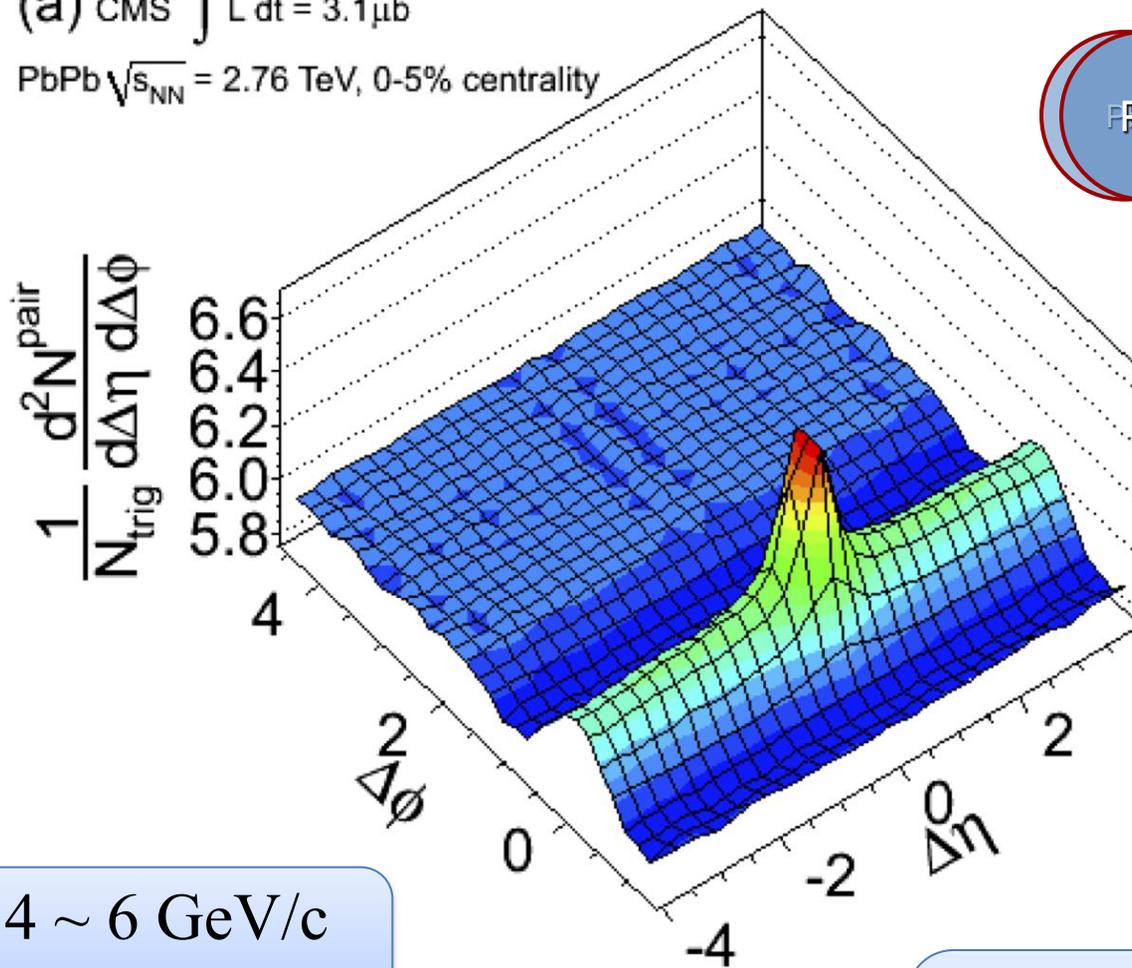
CMS Experiment at LHC, CERN
Data recorded: Mon Nov 8 11:30:53 2010 CEST
Run/Event: 150431 / 630470
Lumi section: 173

PbPb at 2.76 TeV
(14 x RHIC energy)



Heavy-ion “ridge” at LHC

(a) CMS $\int L dt = 3.1 \mu\text{b}^{-1}$
 PbPb $\sqrt{s_{\text{NN}}} = 2.76 \text{ TeV}$, 0-5% centrality



0-5% most central

arXiv:1105.2438

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

See talk by Jeremy Callner
 (05/24, 3:20pm)

Associated hadron yield per trigger:

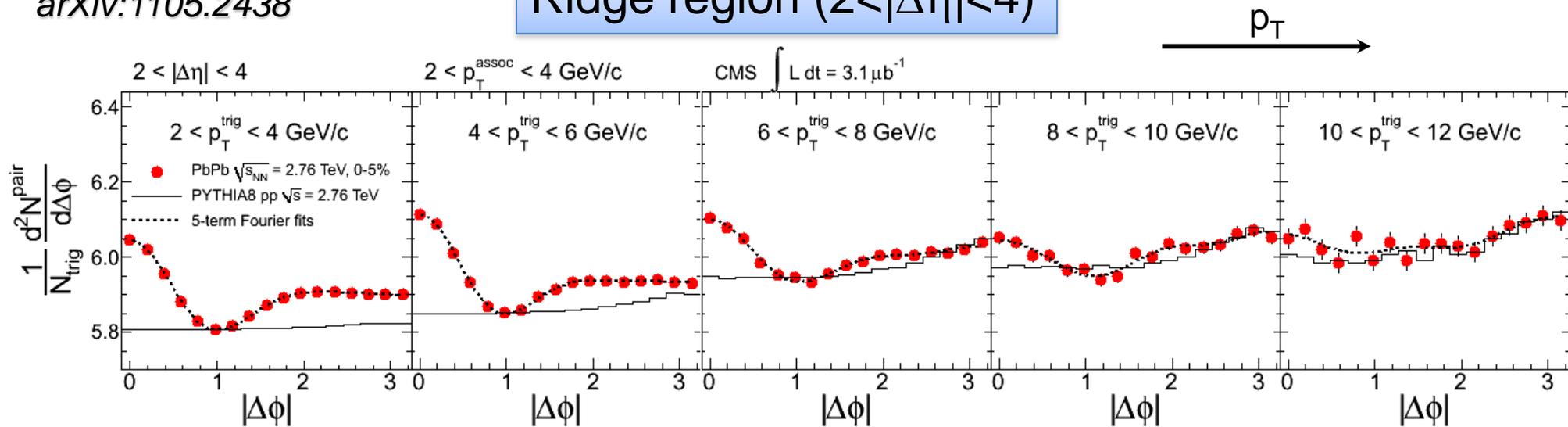
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Ridge vs p_T in PbPb

arXiv:1105.2438

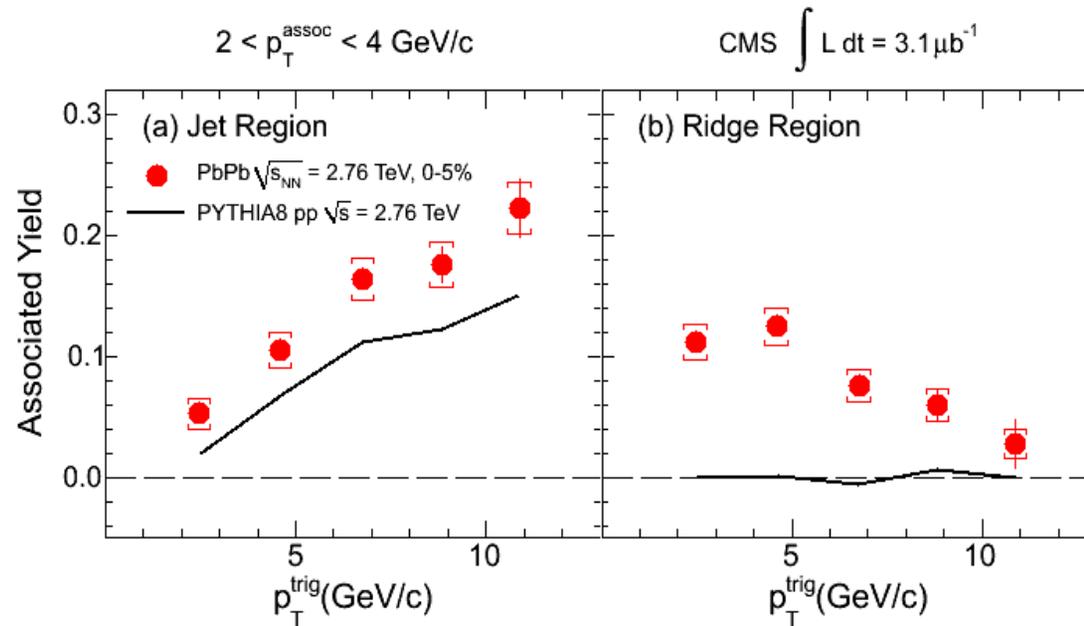
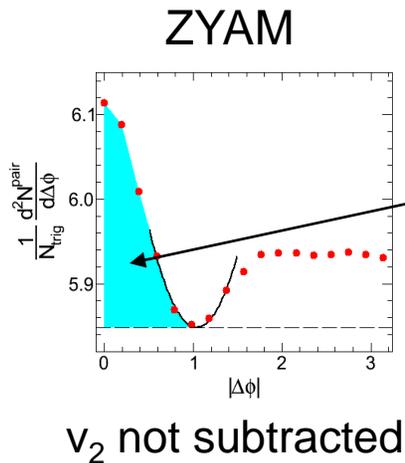
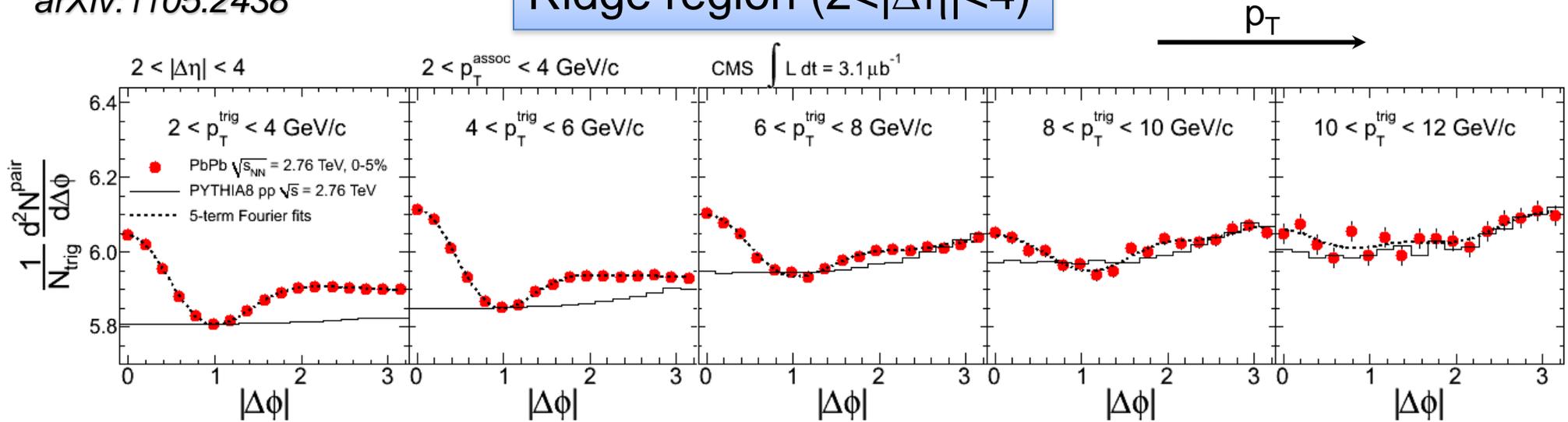
Ridge region ($2 < |\Delta\eta| < 4$)



Ridge vs p_T in PbPb

arXiv:1105.2438

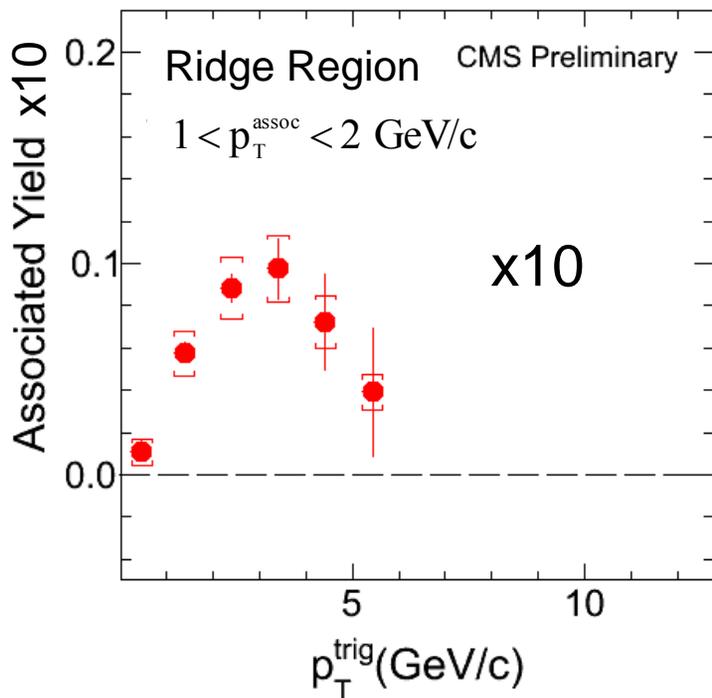
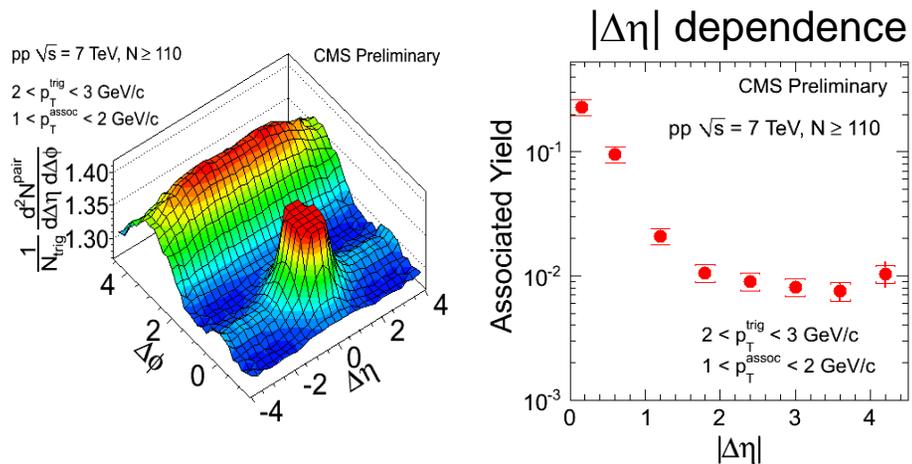
Ridge region ($2 < |\Delta\eta| < 4$)



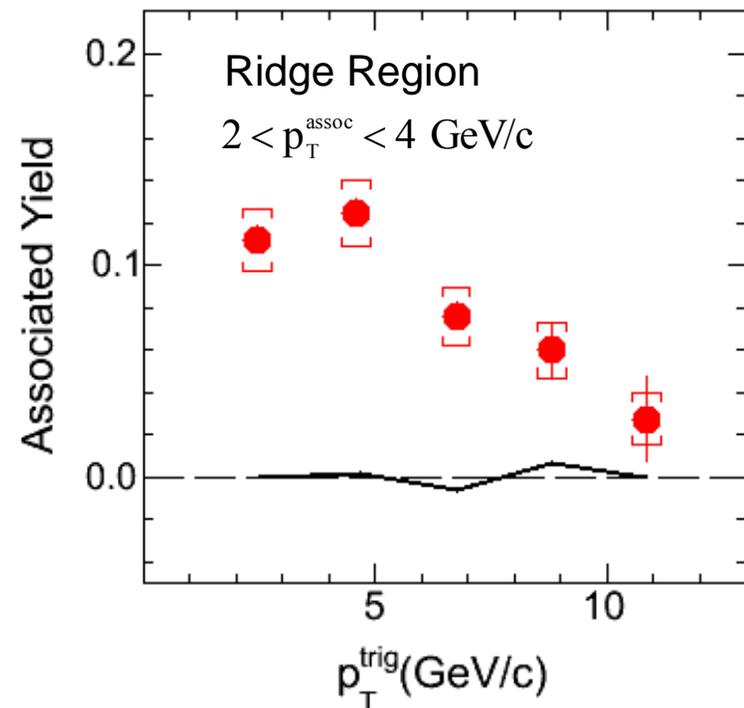
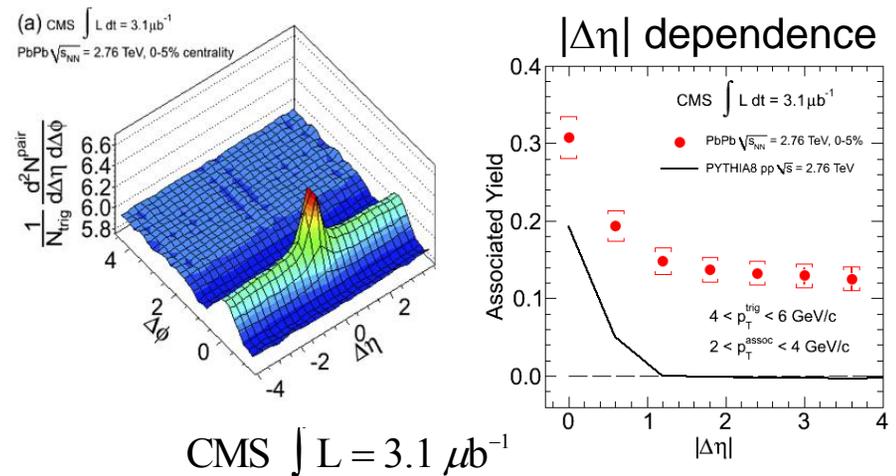
Ridge in PbPb collisions tends to diminish at high p_T

Ridge in pp and PbPb

CMS pp 7 TeV, $N \geq 110$



CMS PbPb 2.76 TeV, 0-5%

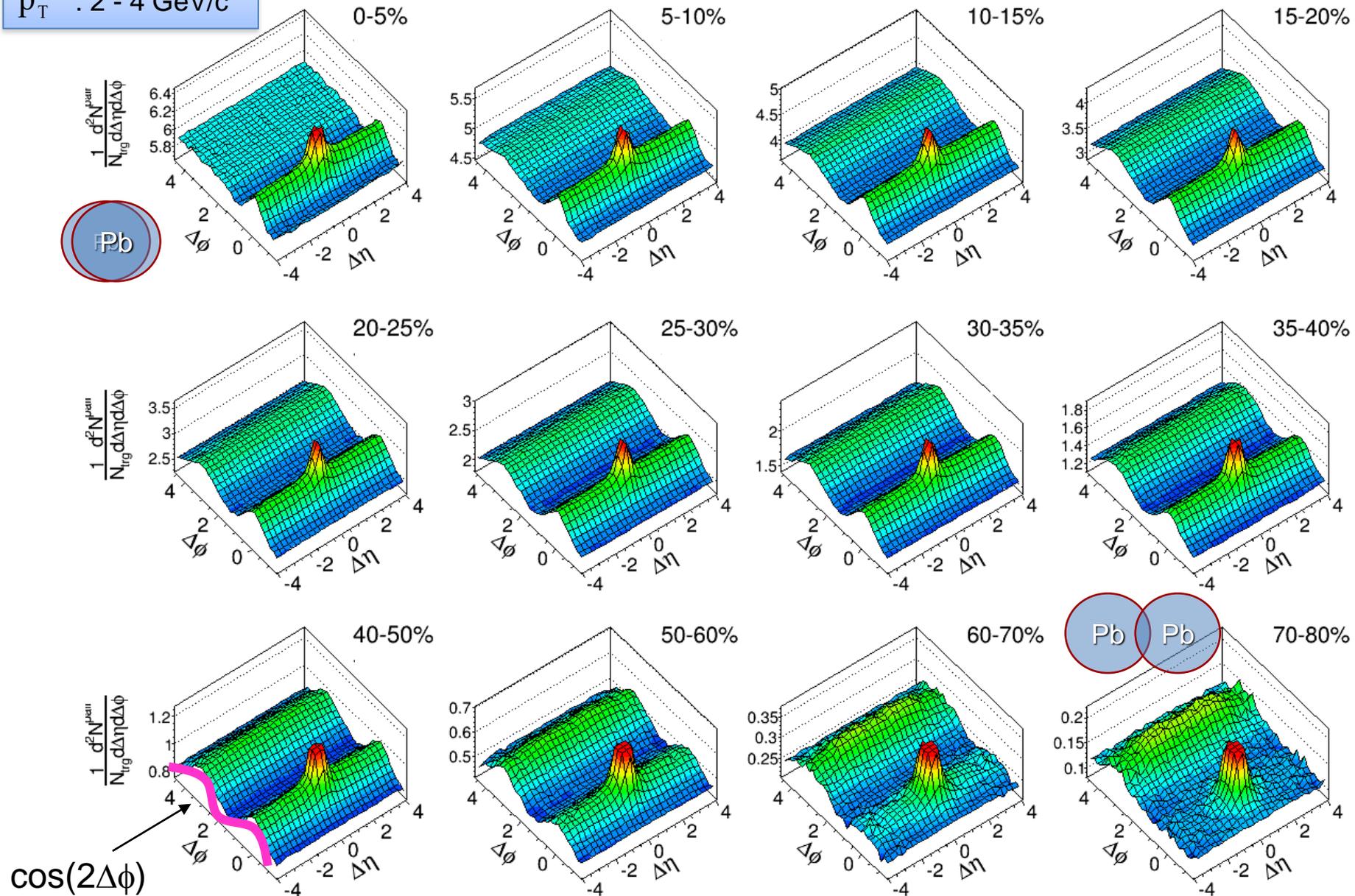


Centrality dependence in PbPb

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

PbPb 2.76 TeV

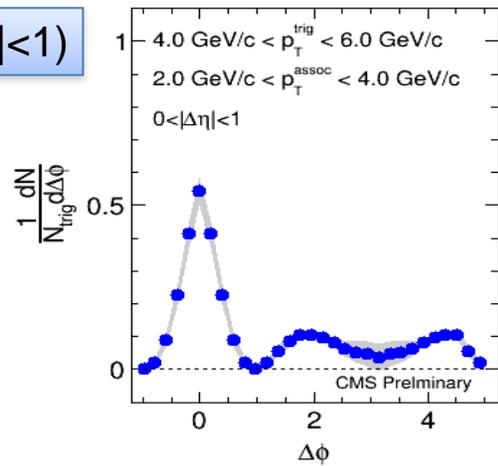
CMS Preliminary



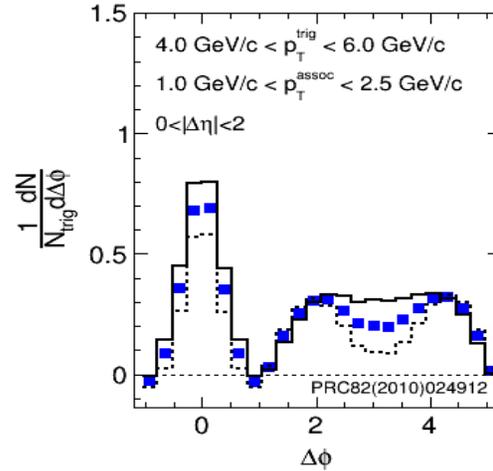
v_2 -subtracted associated yield in PbPb

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

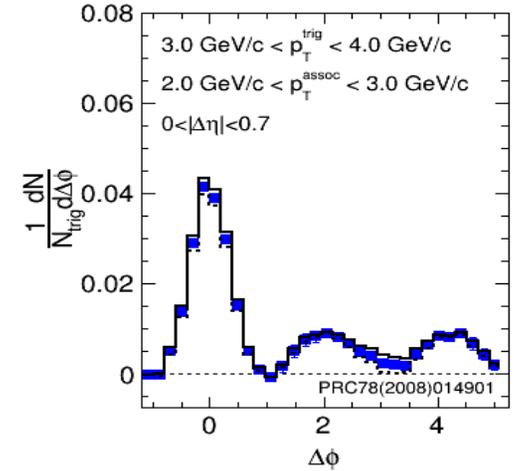
CMS Preliminary
 PbPb $\sqrt{s_{NN}} = 2.76$ TeV
 5-10% Centrality



STAR/RHIC
 AuAu $\sqrt{s_{NN}} = 0.2$ TeV
 0-12% Centrality

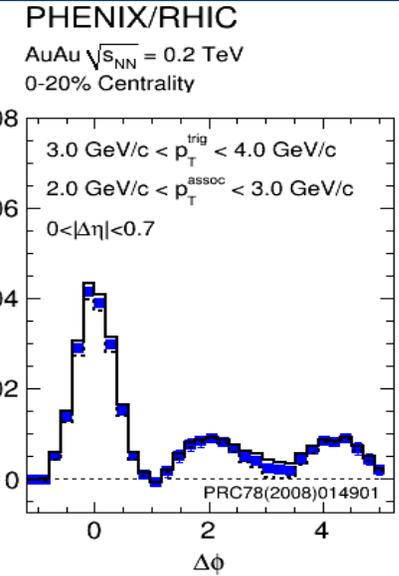
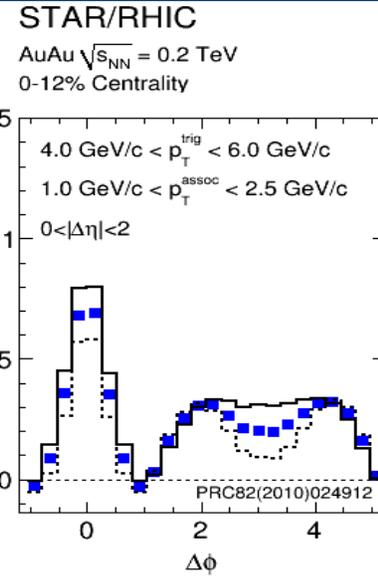
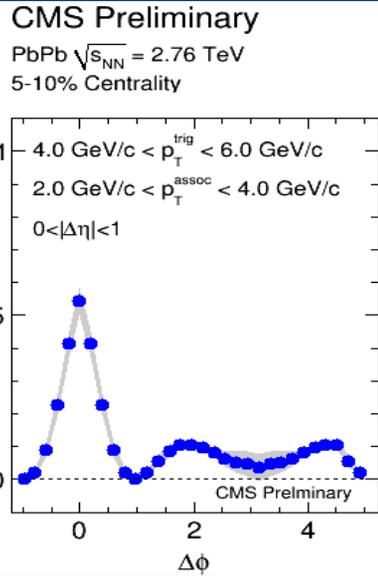


PHENIX/RHIC
 AuAu $\sqrt{s_{NN}} = 0.2$ TeV
 0-20% Centrality

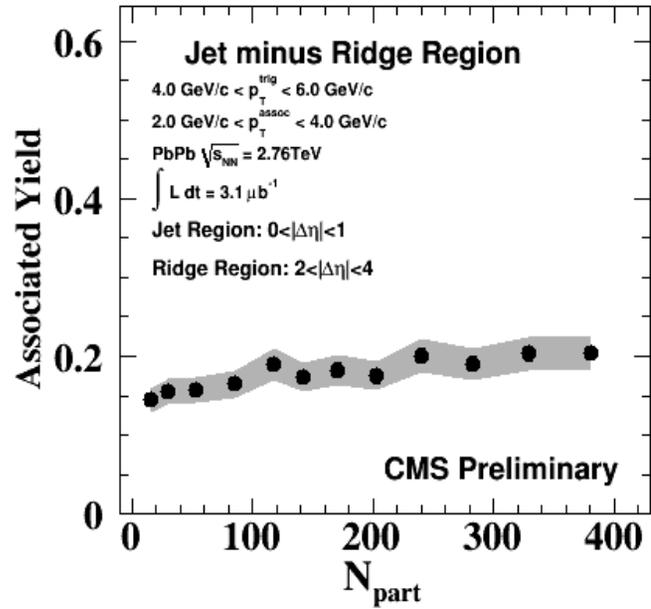


v_2 -subtracted associated yield in PbPb

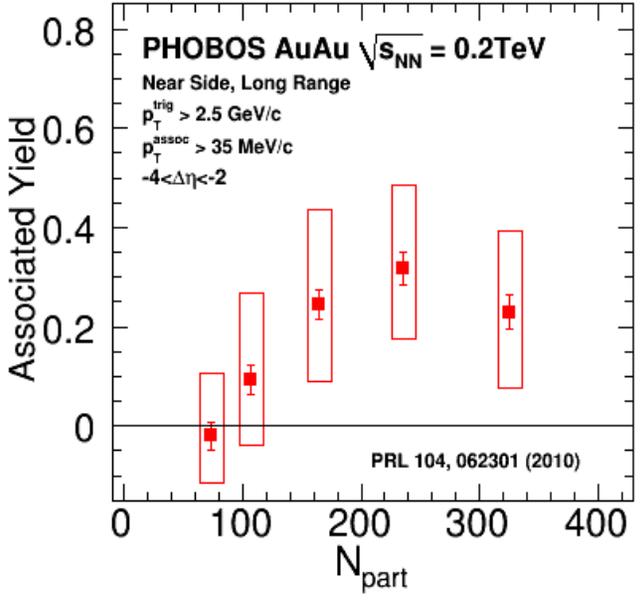
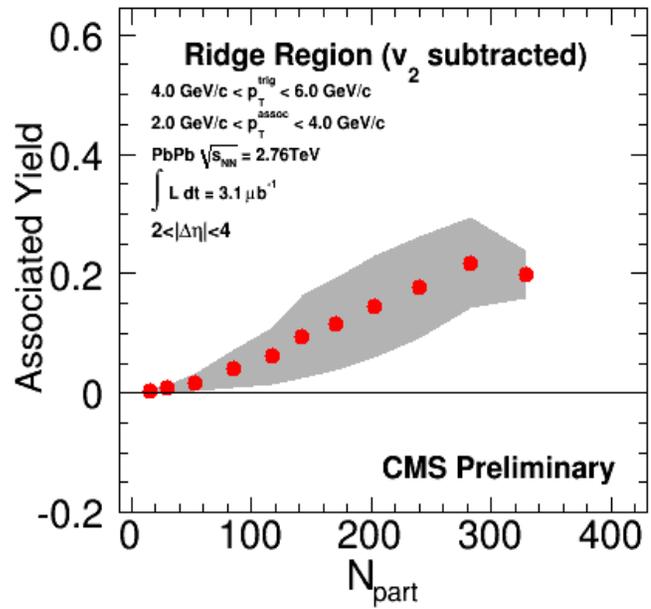
Jet region ($|\Delta\eta| < 1$)



Jet minus ridge region



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

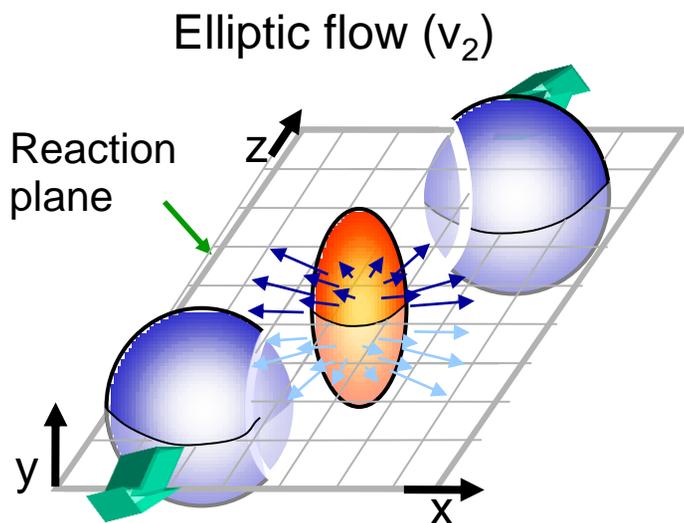


Qualitatively, similar trend in centrality to RHIC results

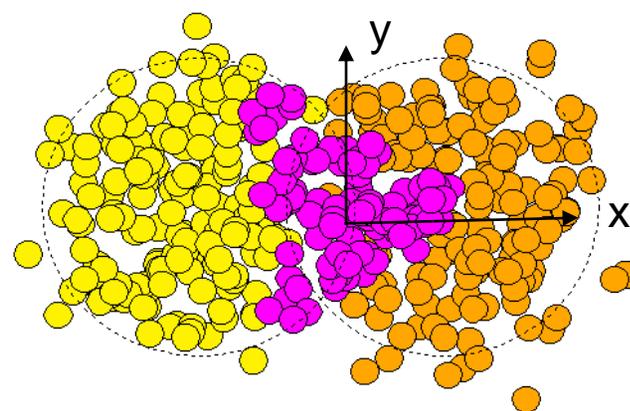


Alternative approach: Fourier analysis

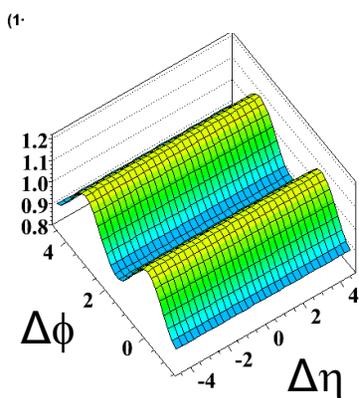
It was recently realized that the ridge may be induced just by higher order flow terms ($v_2, v_3, v_4, v_5, \dots$)



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

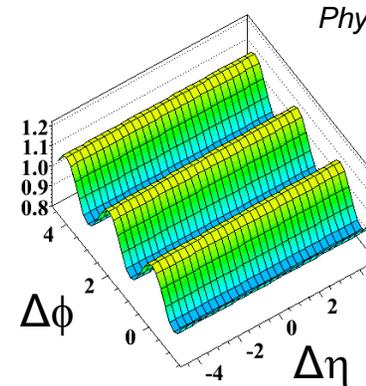
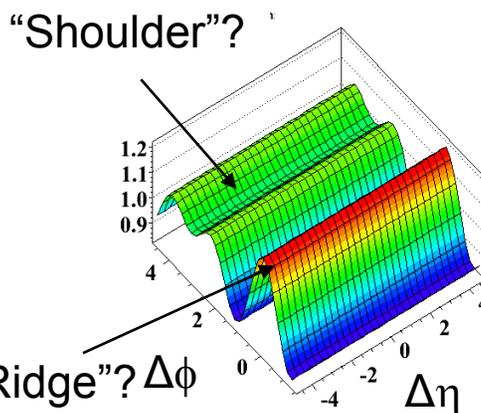


Phys. Rev. C81:054905, 2010



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

Add V_2 and V_3

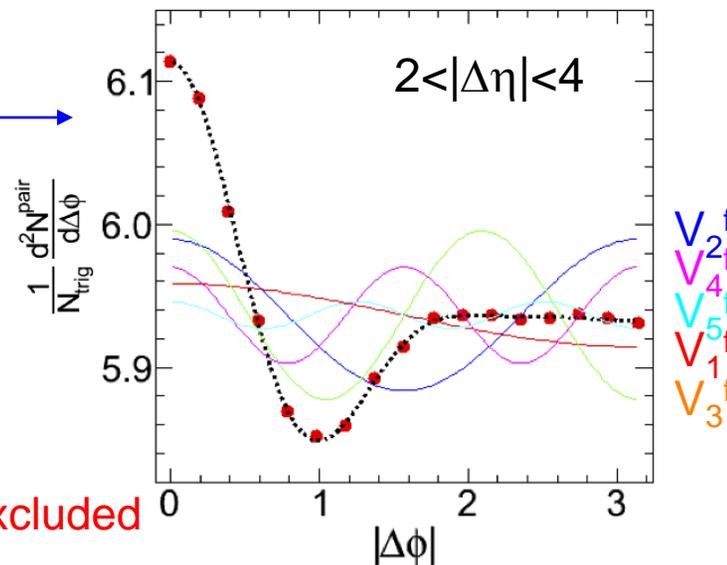
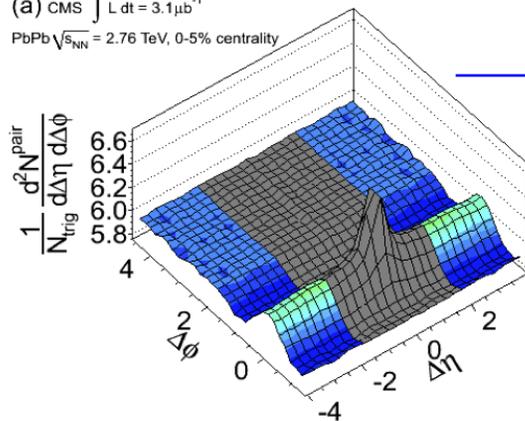


$\sim V_3 \cos(3\Delta\phi)$

Fourier analysis of $\Delta\phi$ correlations

$$\text{Fourier decomposition: } \frac{1}{N_{\text{trig}}} \frac{d^2 N^{\text{pair}}}{d\Delta\eta d\Delta\phi} = \frac{N_{\text{assoc}}}{2\pi} \left(1 + 2 \sum_{n=1} V_n^f \cos(n\Delta\phi) \right)$$

(a) CMS $\int L dt = 3.1 \mu\text{b}^{-1}$
PbPb $\sqrt{s_{\text{NN}}} = 2.76 \text{ TeV}$, 0-5% centrality



Flow driven correlations:

$$V_n^f = v_n^f(p_T^{\text{trig}}) \times v_n^f(p_T^{\text{assoc}})$$

(f: Fourier analysis of long-range dihadron correlations)

Short-range non-flow effects excluded

Complementary to standard flow methods (EP, cumulants, LYZ)

See talks by:

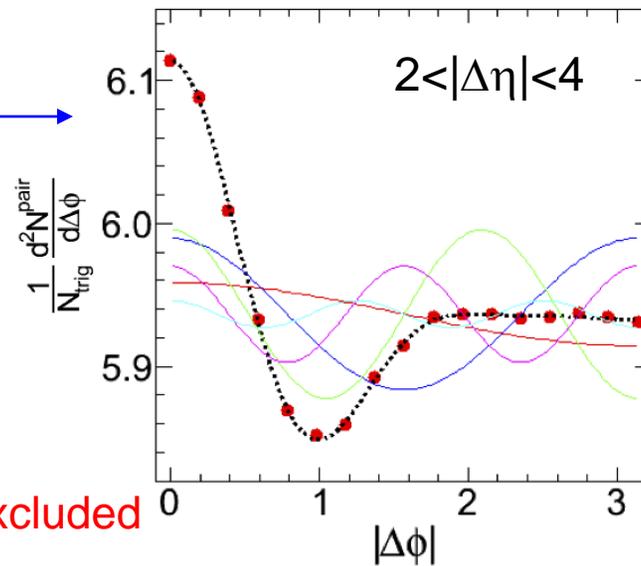
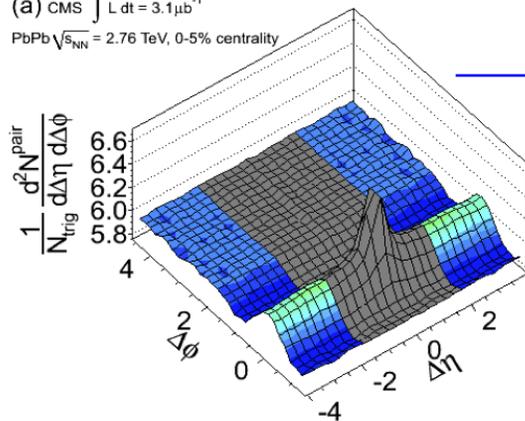
Julia Velkovska (05/24, 11:05am)

Victoria Zhukova (05/23, 5:50pm)

Fourier analysis of $\Delta\phi$ correlations

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

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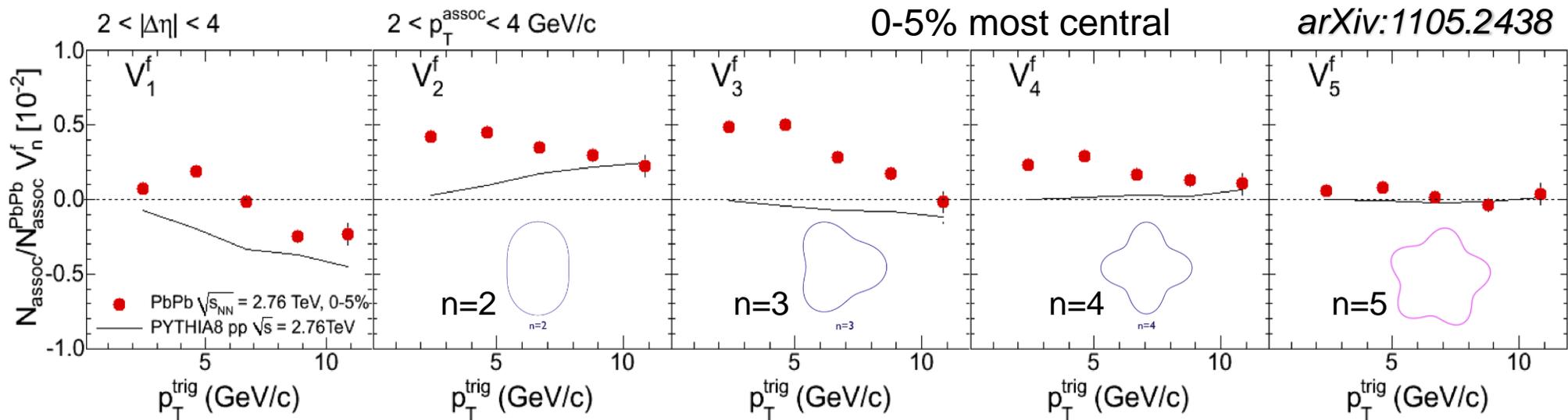


Flow driven correlations:

$$V_n^f = v_n^f(p_T^{\text{trig}}) \times v_n^f(p_T^{\text{assoc}})$$

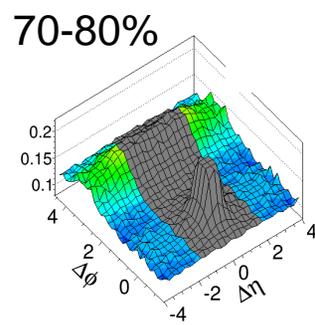
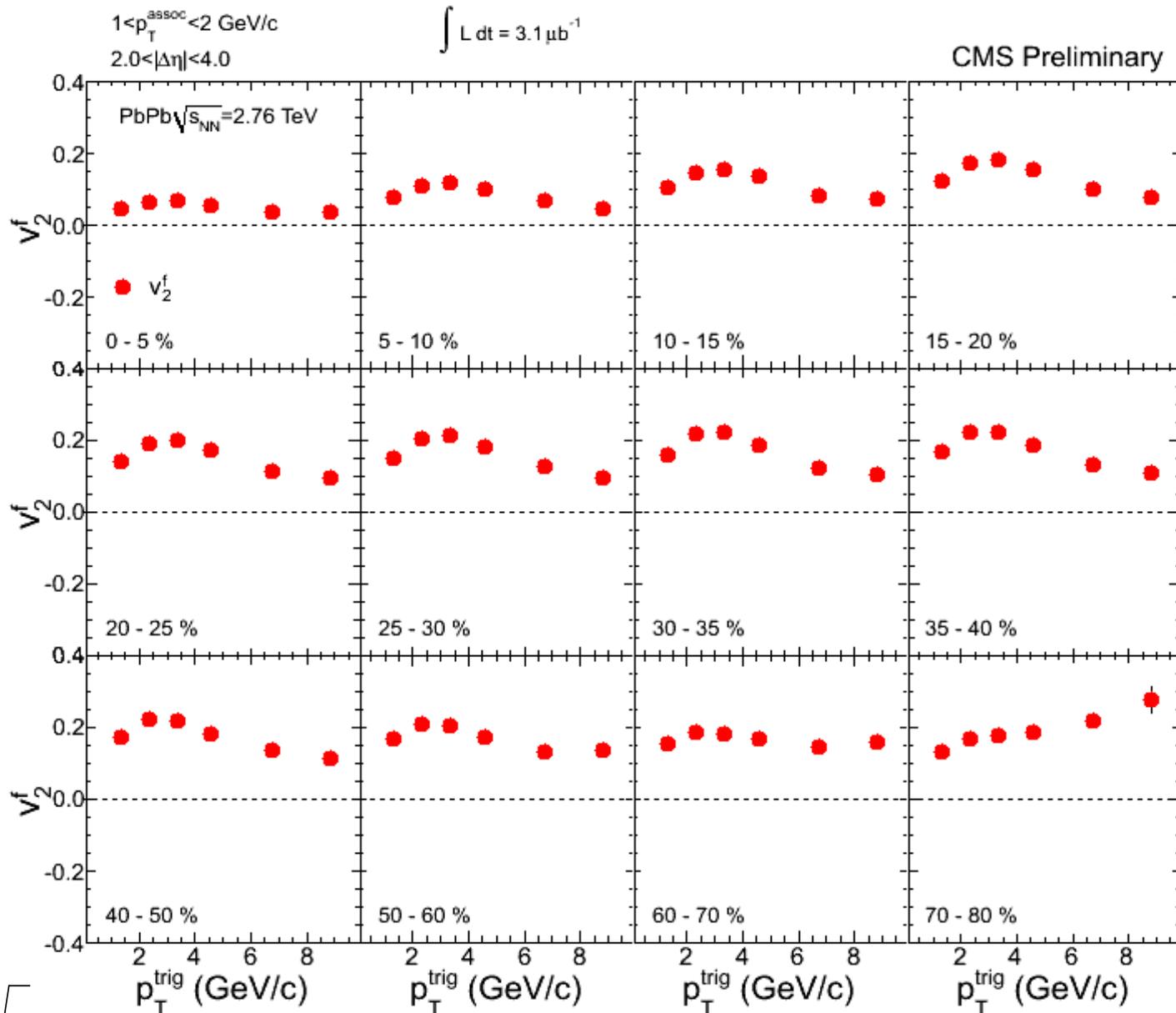
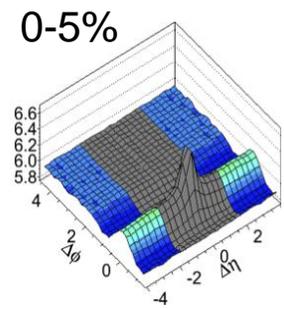
(f: Fourier analysis of long-range dihadron correlations)

Short-range non-flow effects excluded



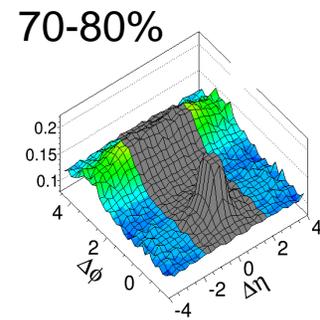
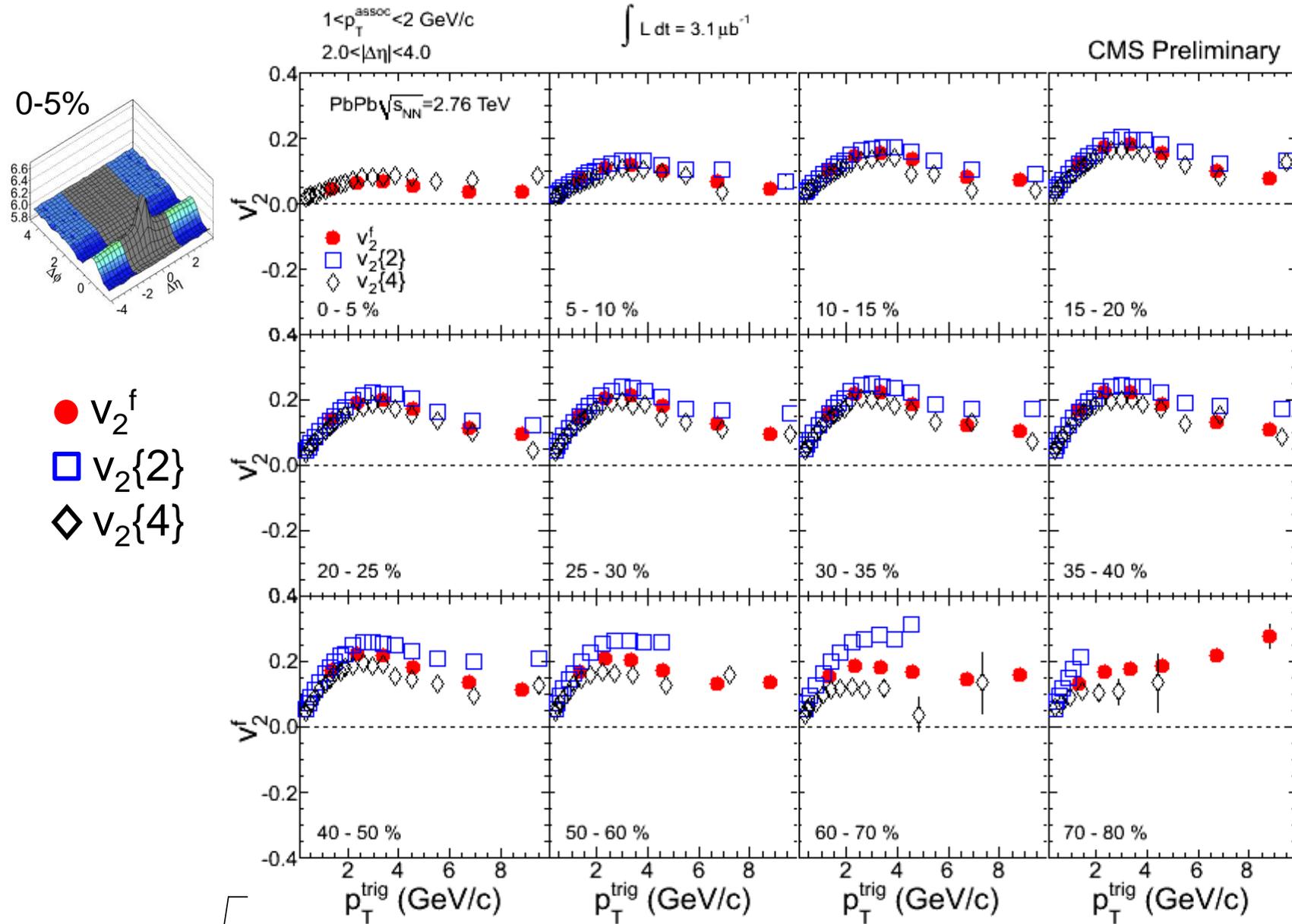
arXiv:1105.2438

v_2 from long-range correlations



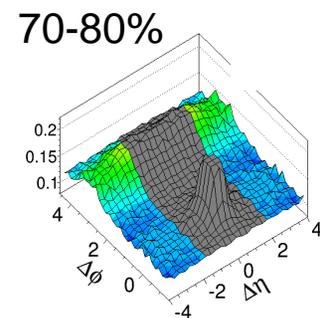
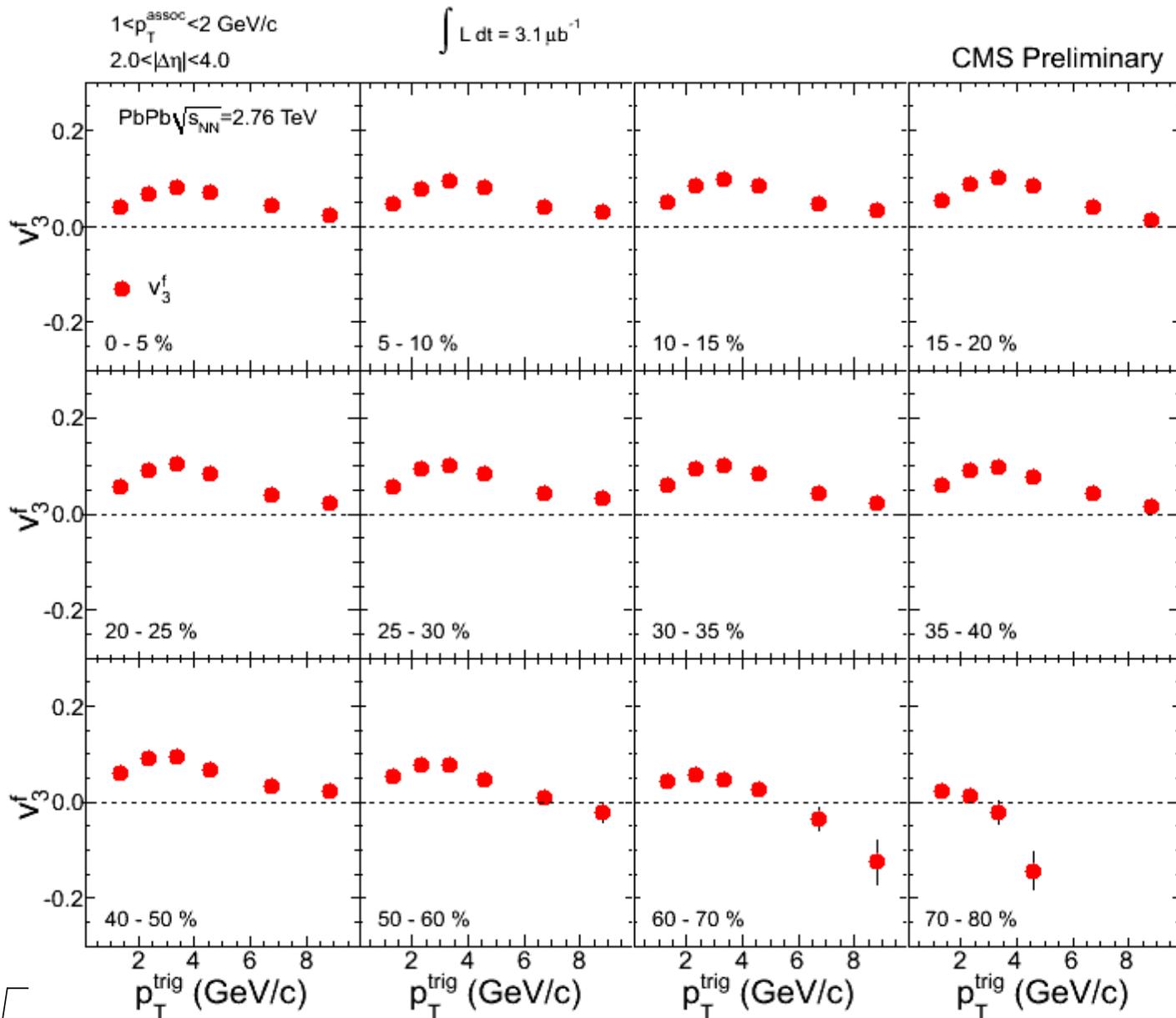
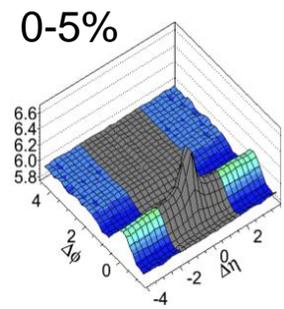
$V_n^f \text{ (Fourier)} \xrightarrow{\sqrt{}} v_n^f \text{ (flow)}$

v_2 from long-range correlations



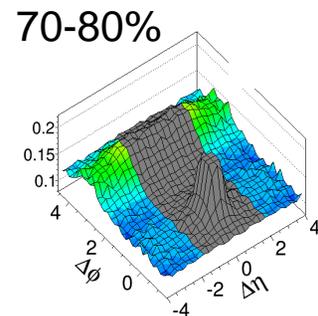
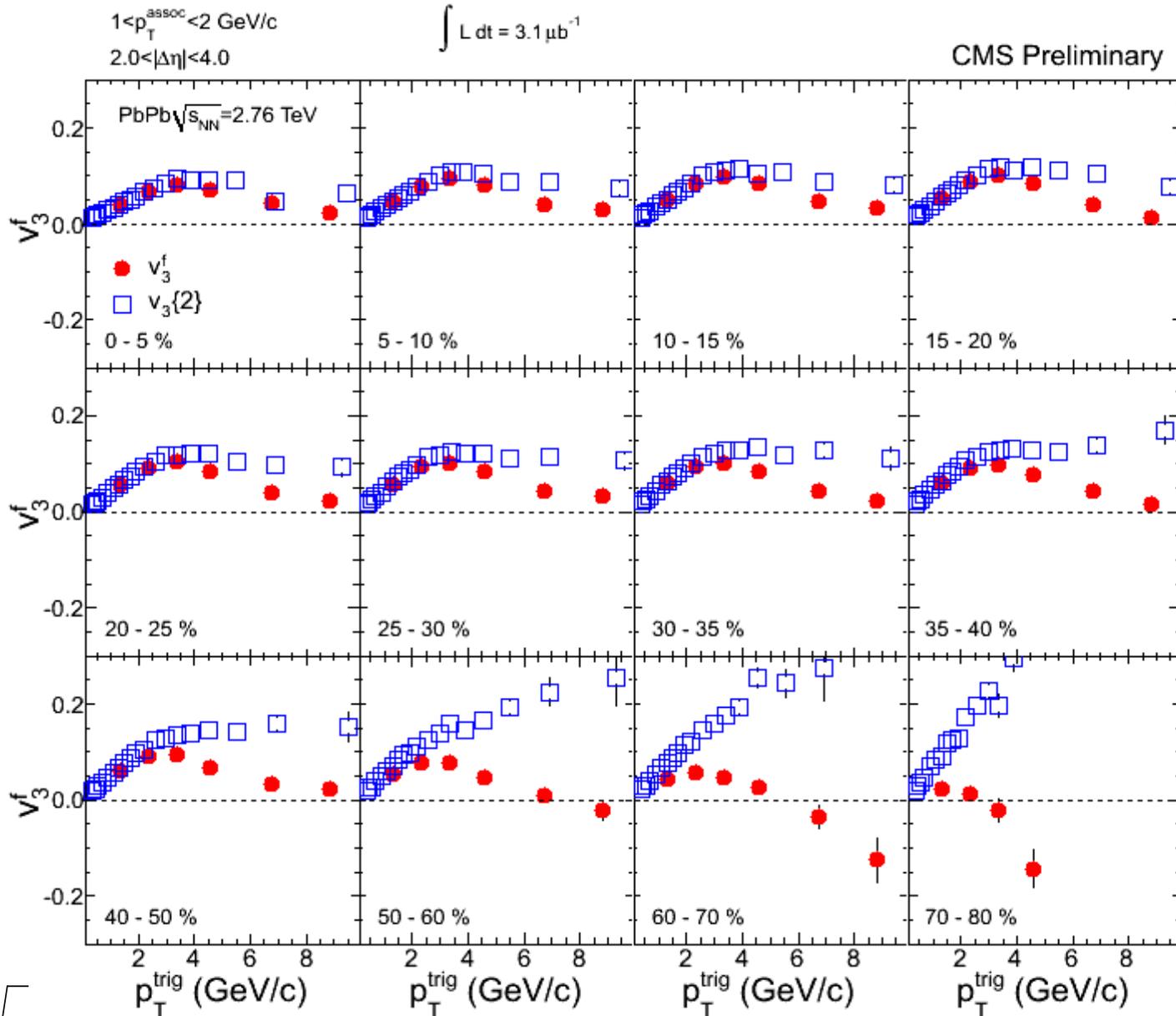
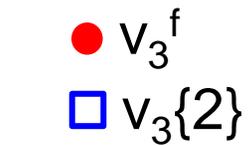
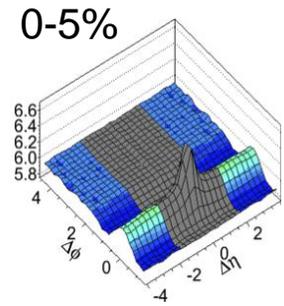
$V_n^f \text{ (Fourier)} \xrightarrow{\sqrt{}} v_n^f \text{ (flow)}$

v_3 from long-range correlations



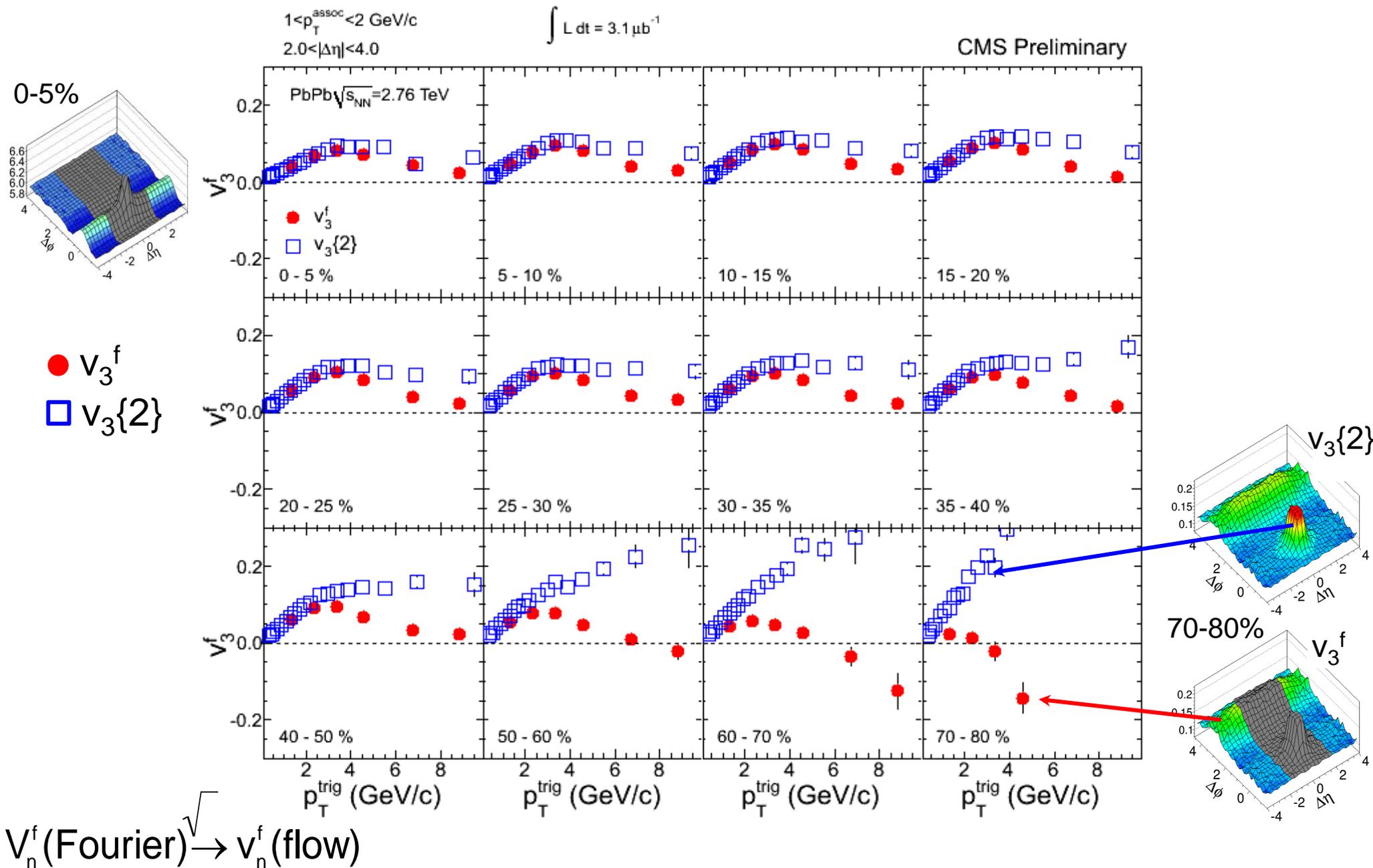
V_n^f (Fourier) $\xrightarrow{\sqrt{}}$ v_n^f (flow)

v_3 from long-range correlations

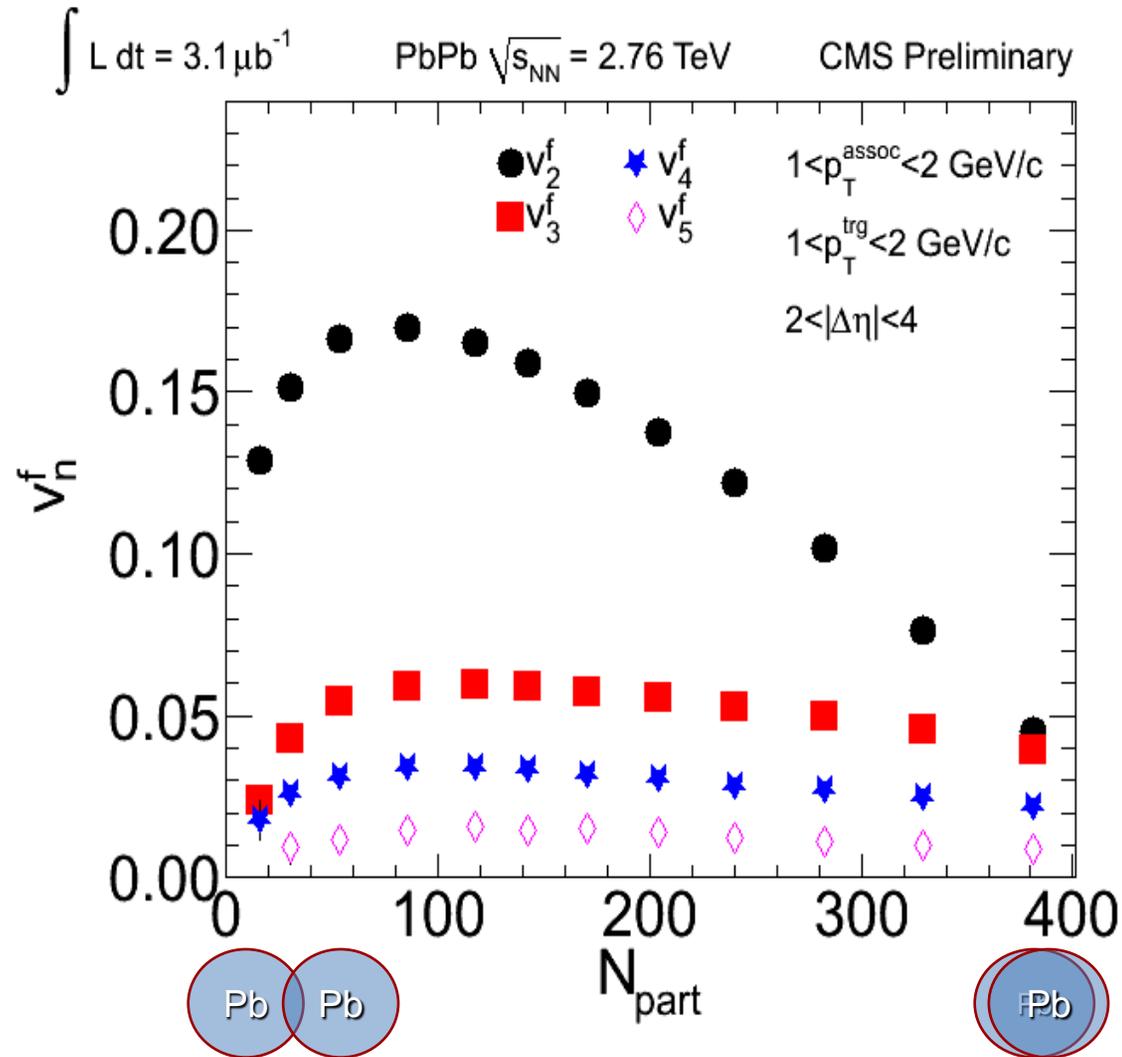


$V_n^f(\text{Fourier}) \xrightarrow{\sqrt{}} v_n^f(\text{flow})$

v_3 from long-range correlations



Flow coefficients (v_n^f) vs centrality



- Powerful constraints on the viscous property of the medium
- Additional handle on the initial condition of heavy-ion collisions

Summary

Observation of a ridge correlation structure in high multiplicity pp

- Not observed before in pp or pp MC
- Resembles similar effect in heavy-ion collisions

Detailed multiplicity and p_T dependence of the ridge in pp

- Increases linearly at low p_T and tends to vanish at high p_T
- Ridge emerges at $N \sim 50 - 60$ (4 times of $\langle N \rangle$ in MinBias)

Comprehensive studies of dihadron correlations in 2.76 TeV PbPb

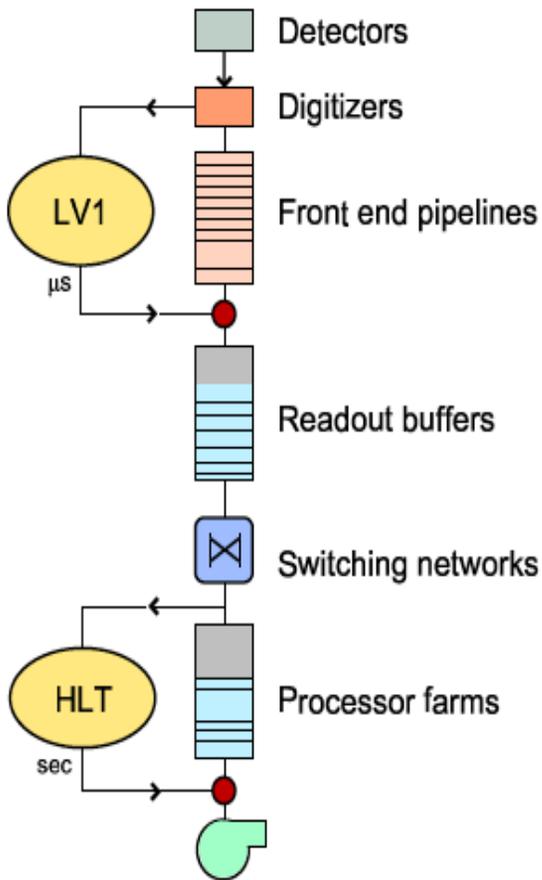
- In central PbPb, ridge yield significantly drops toward high p_T
- Higher order flow from a Fourier analysis of long-range correlations

New territory of high-density QCD at LHC!

Backups

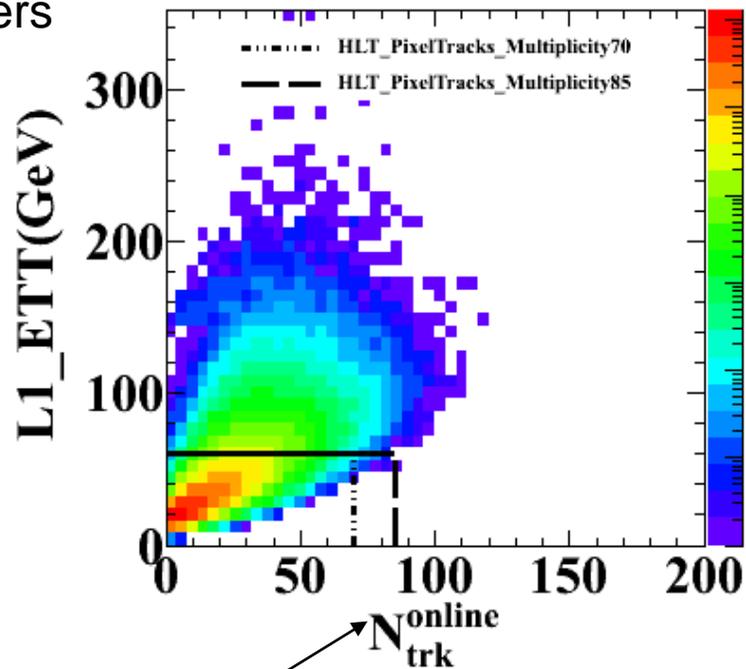
Trigger on High Multiplicity pp

CMS trigger and DAQ



Level-1:

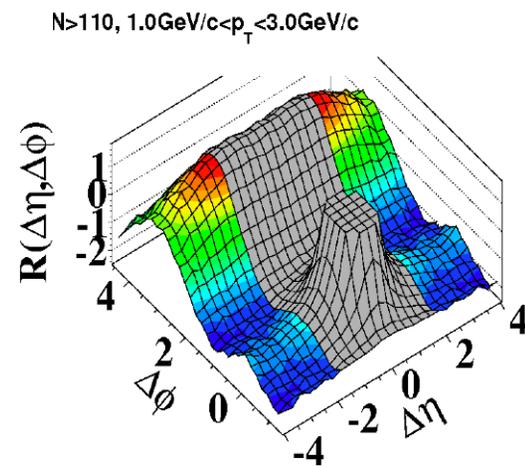
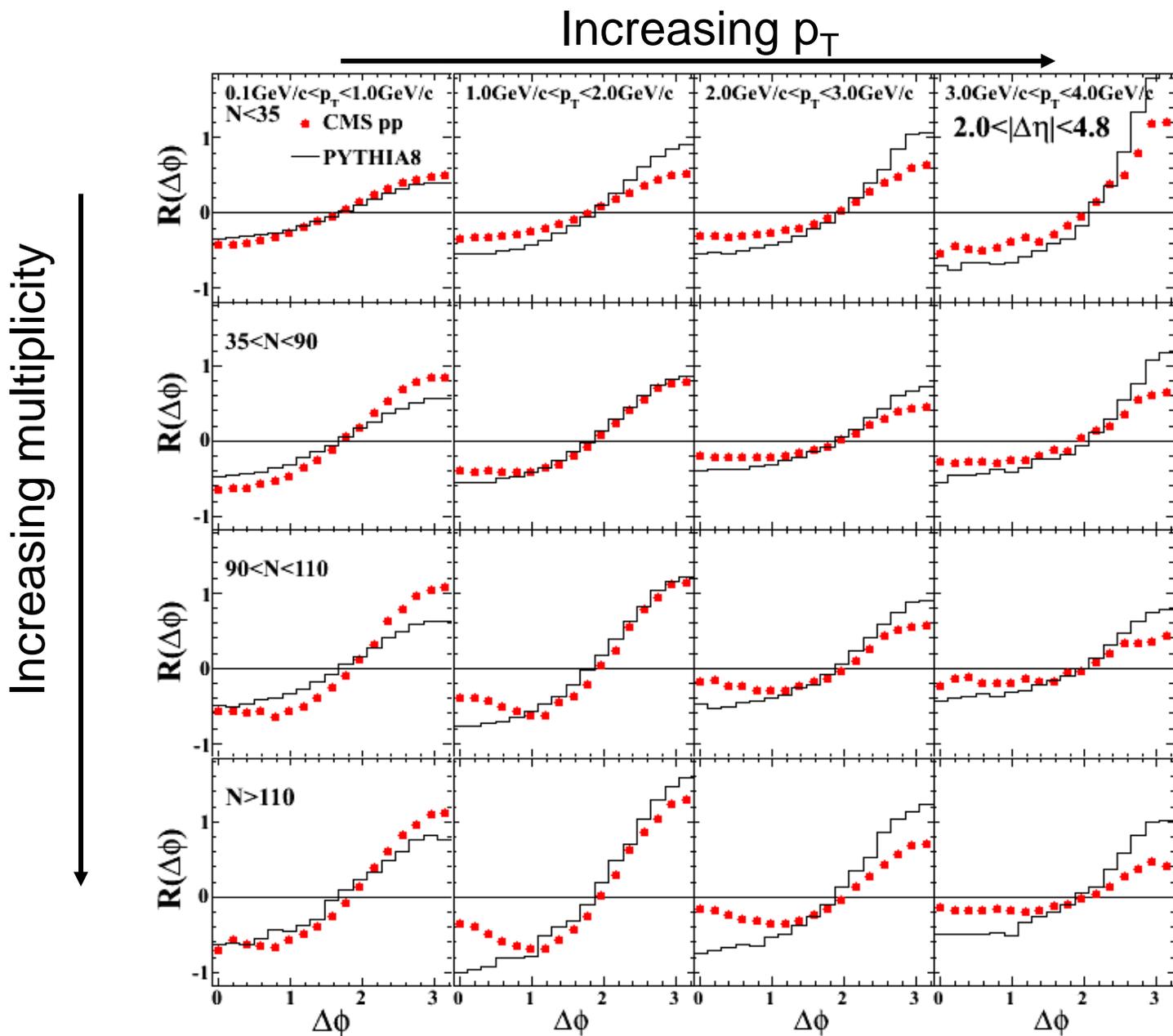
$\Sigma E_T > 60 \text{ GeV}$
in calorimeters



High-Level trigger:

number of tracks with $p_T > 0.4 \text{ GeV}/c$, $|h| < 2$ from a **single** vertex

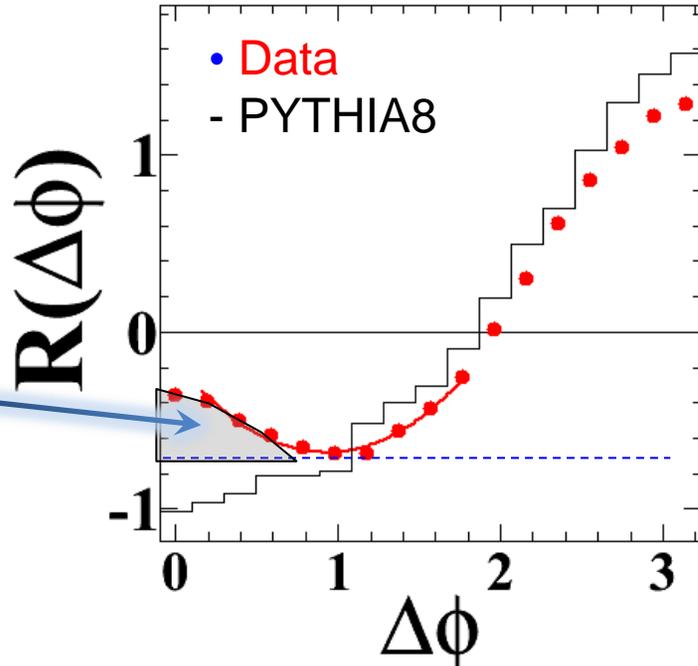
1-D projected $R(\Delta\phi)$ at large $\Delta\eta$



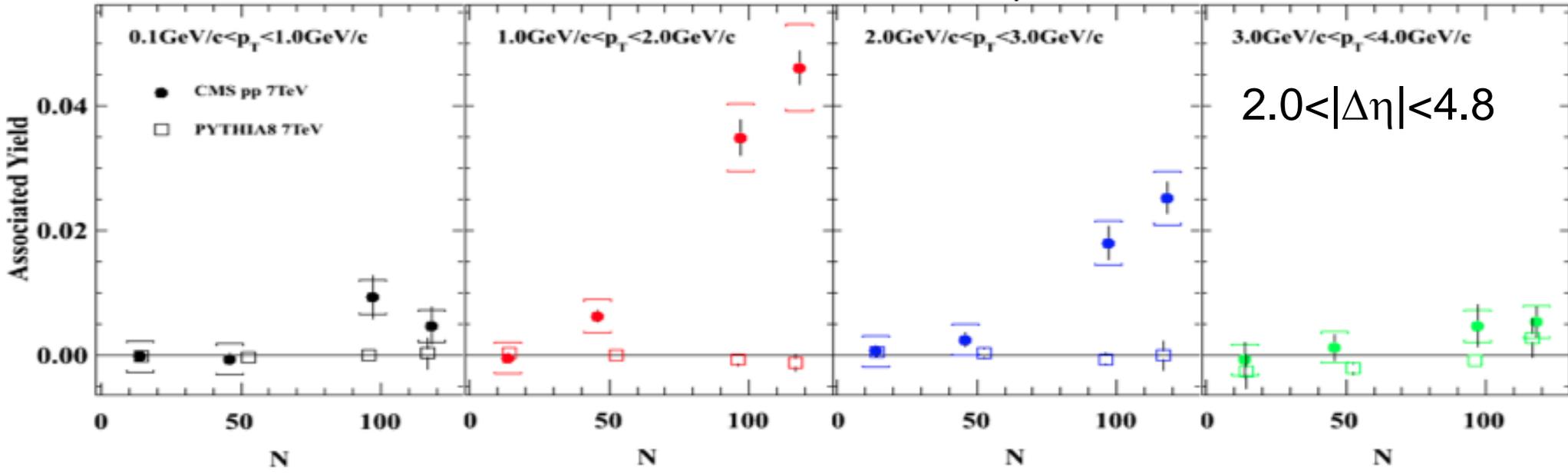
Quantify the Ridge

Zero Yield At Minimum (ZYAM)

Associated yield:
correlated multiplicity per particle

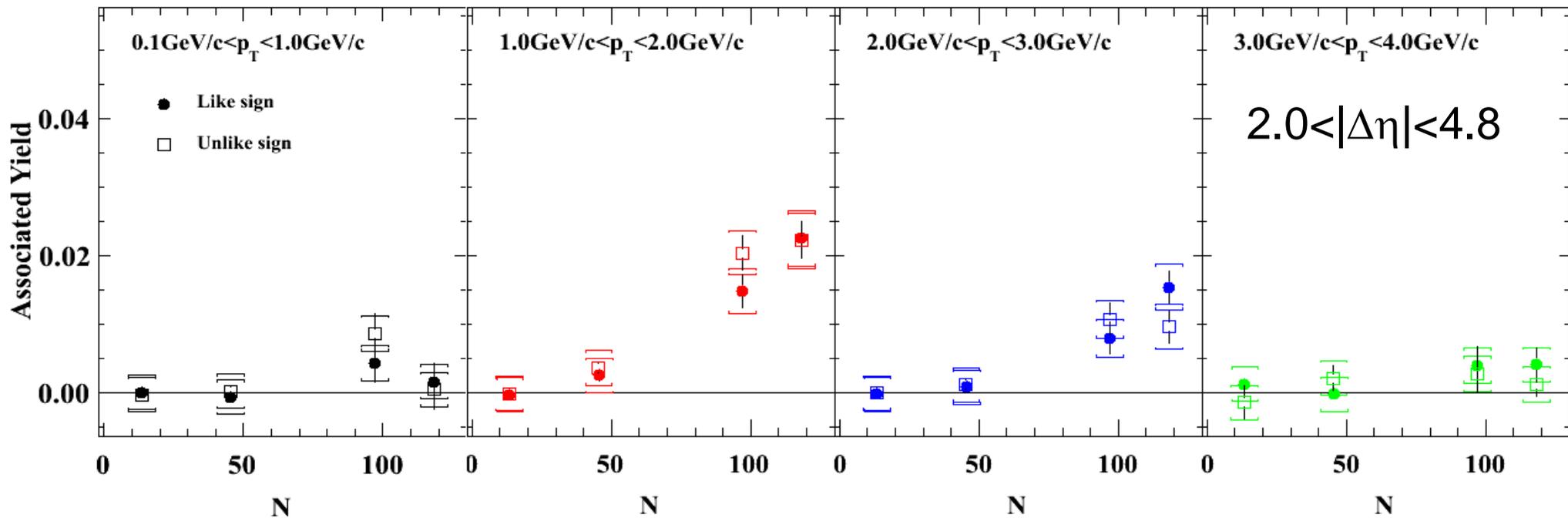


$N > 110$
 $2.0 < |\Delta\eta| < 4.8$
 $1 \text{ GeV}/c < p_T < 2 \text{ GeV}/c$



Charge Dependence of the Ridge

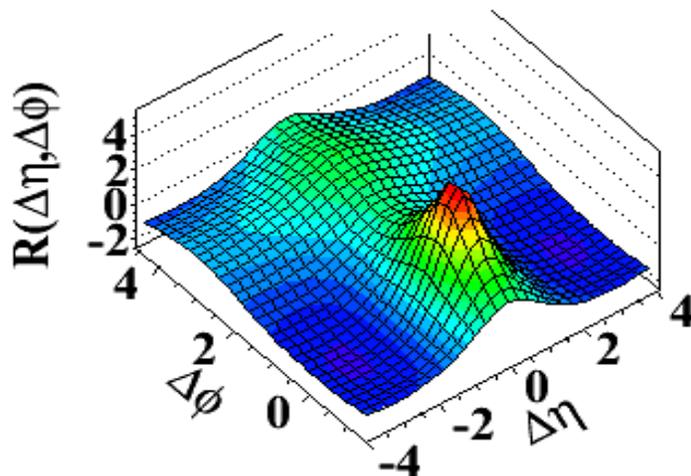
Like-sign ($++$, $--$) and unlike-sign ($+-$) pair correlations:



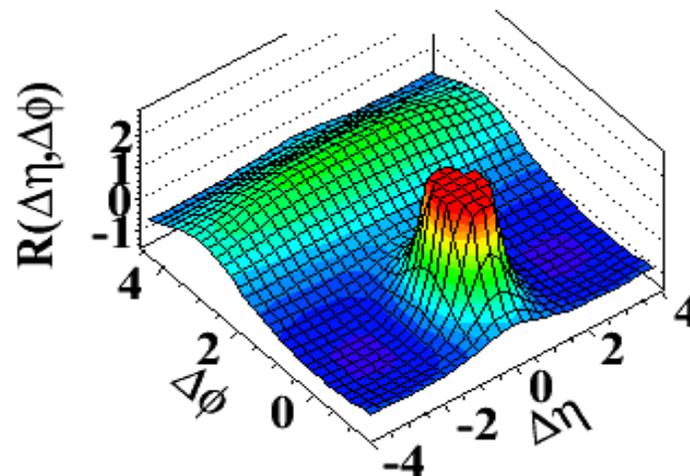
No charge sign dependence of the ridge!

Comparing to various MC

(a) MinBias, $p_T > 0.1 \text{ GeV}/c$

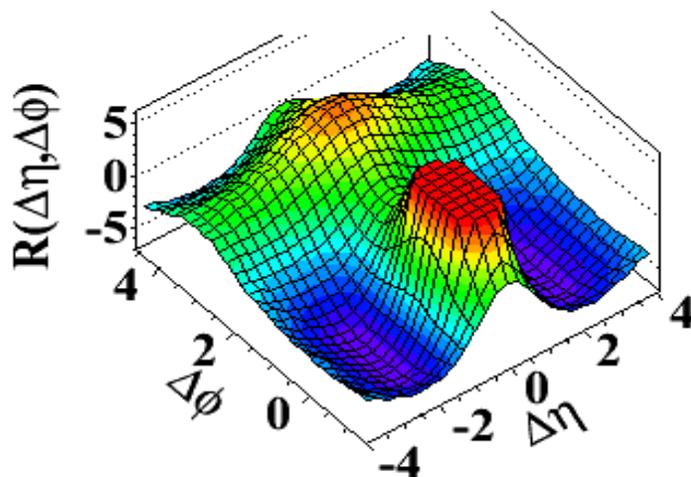


(b) MinBias, $1.0 \text{ GeV}/c < p_T < 3.0 \text{ GeV}/c$

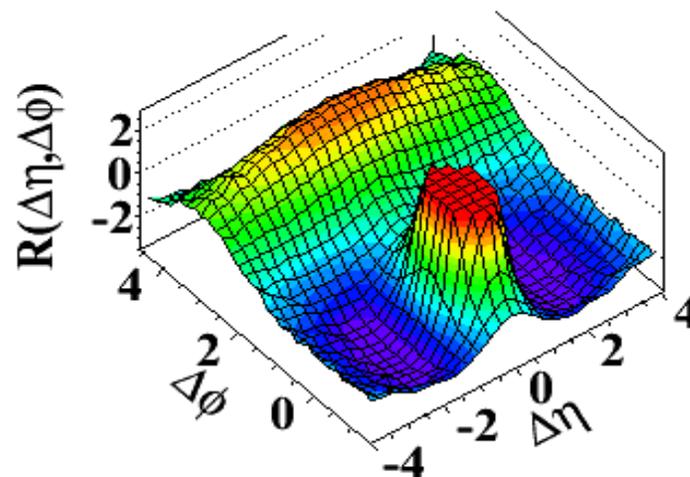


PYTHIA8, v8.135

(c) $N > 110$, $p_T > 0.1 \text{ GeV}/c$

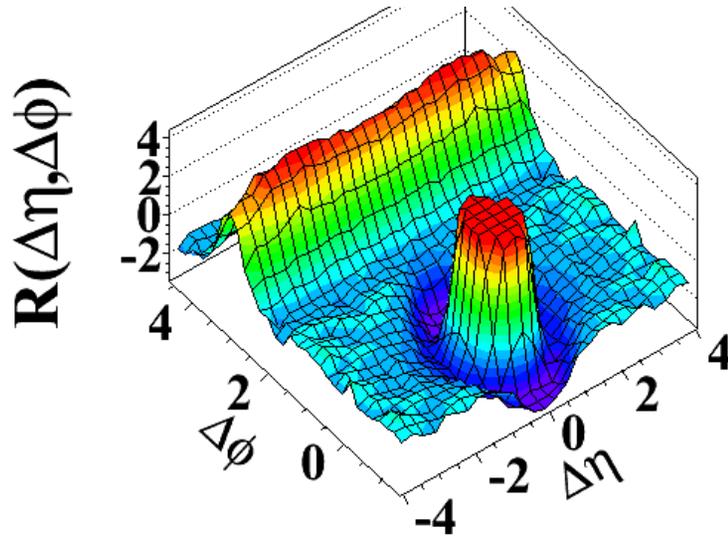


(d) $N > 110$, $1.0 \text{ GeV}/c < p_T < 3.0 \text{ GeV}/c$

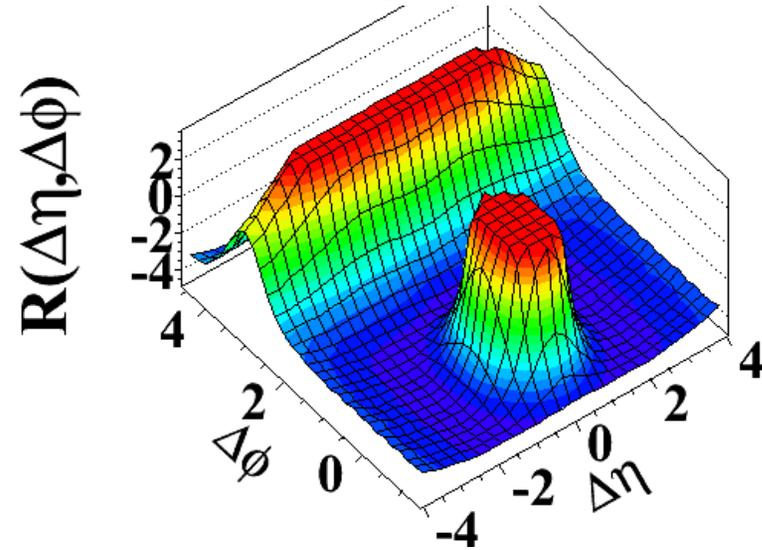


More MC models

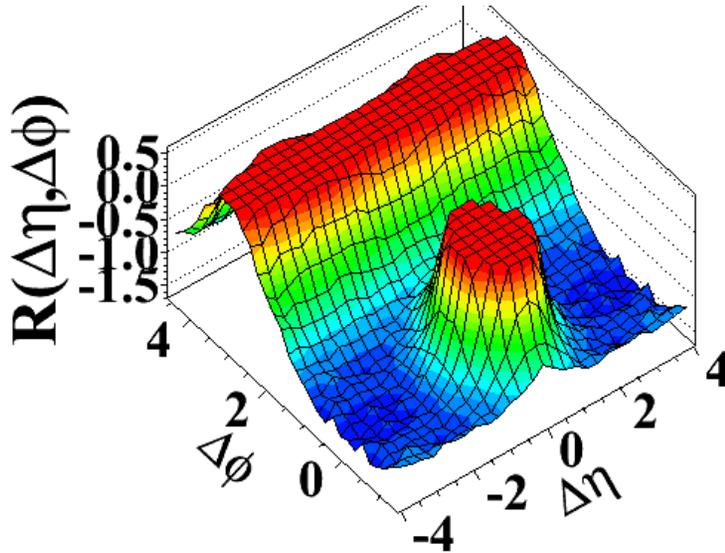
PYTHIA D6T MinBias, $N > 70$



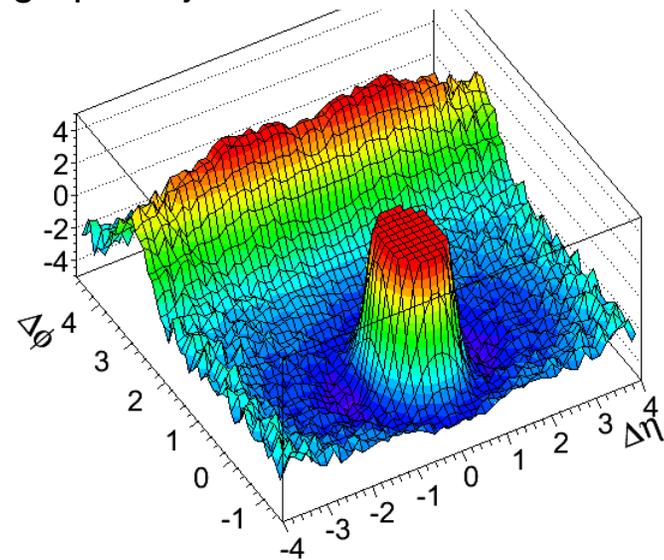
PYTHIA D6T, Dijet 80-120GeV



HERWIG++, $N > 110$



Madgraph, Dijet 100-250GeV, $N > 90$

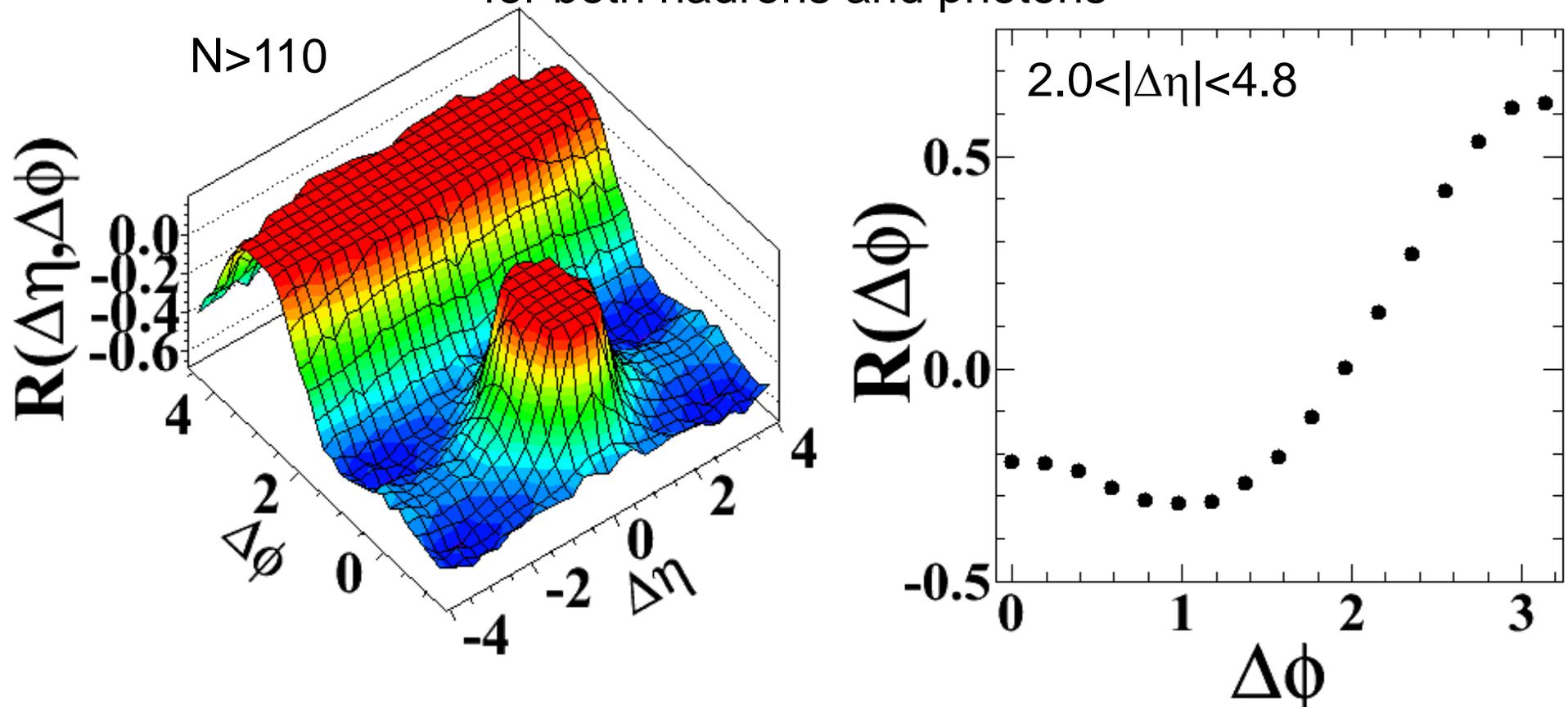


Cross check: ECAL Photons

Charged hadron - photon correlations

(photons are mostly from π^0 decay)

$1.0\text{GeV}/c < p_T < 3.0\text{GeV}/c$
for both hadrons and photons



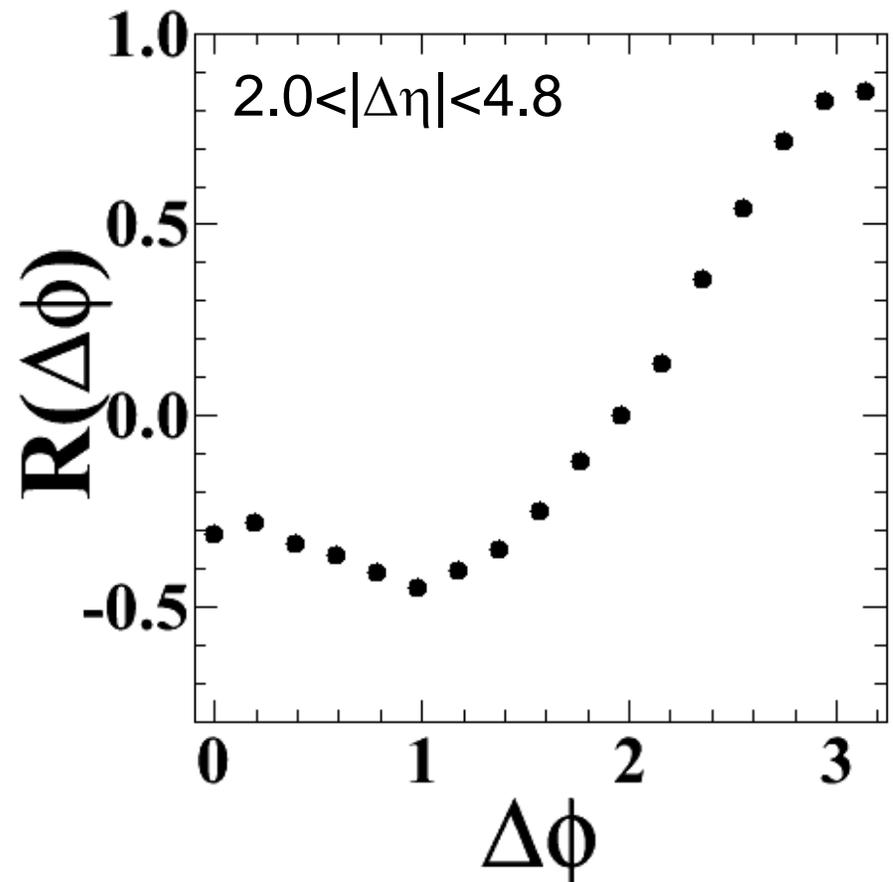
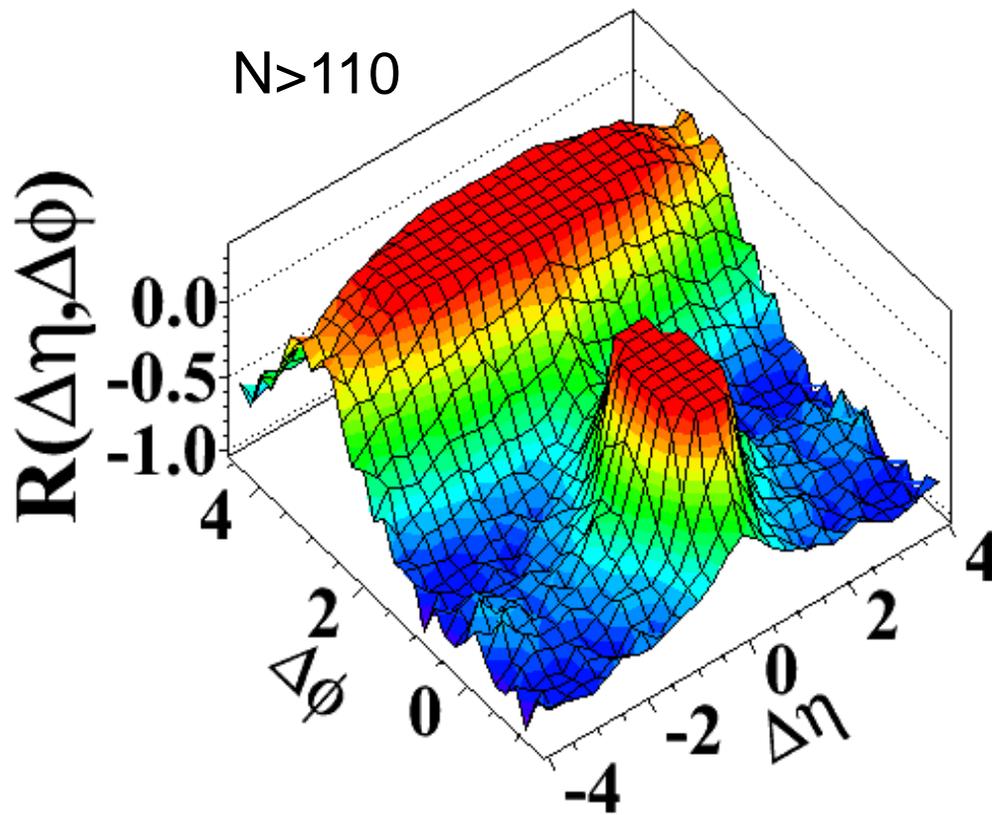
Independent detector, independent reconstruction!

Cross check: ECAL Photons

photon - photon correlations

(photons are mostly from π^0 decay)

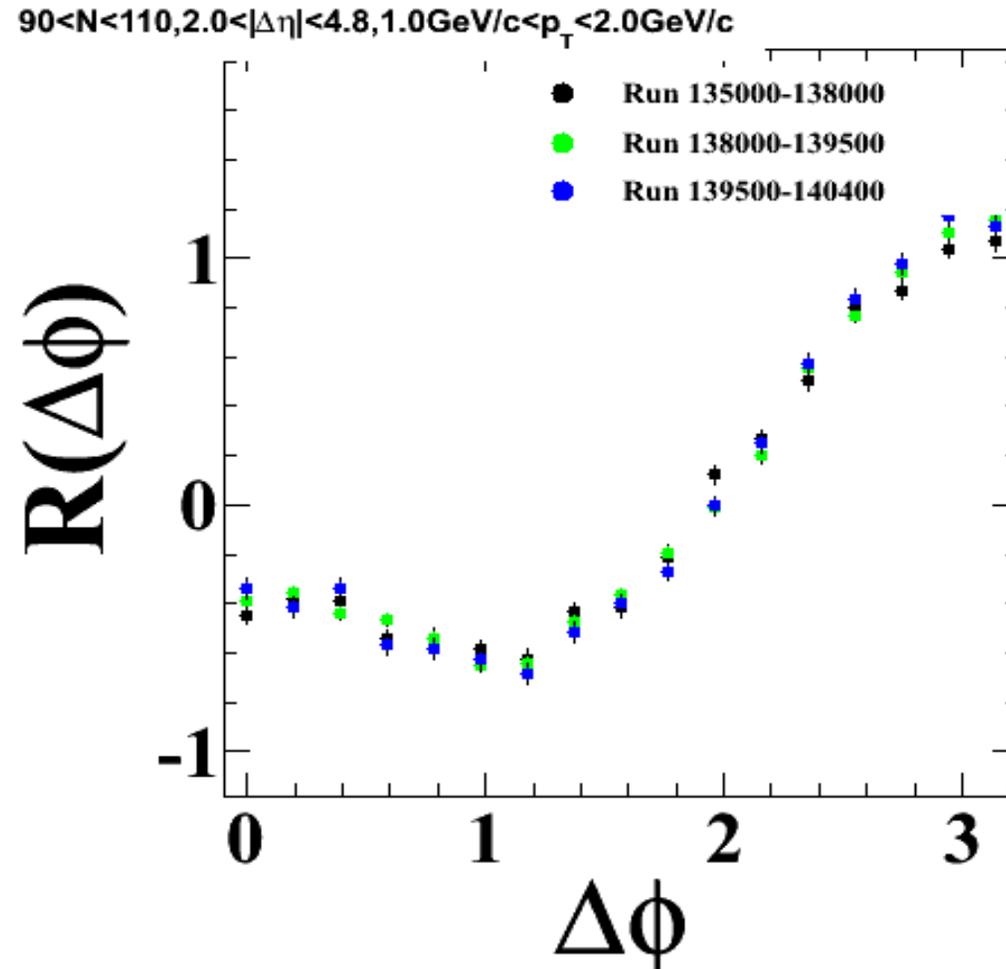
$1.0\text{GeV}/c < p_T < 3.0\text{GeV}/c$



Independent detector, independent reconstruction!

Cross Check: Event Pileup

Compare different run periods

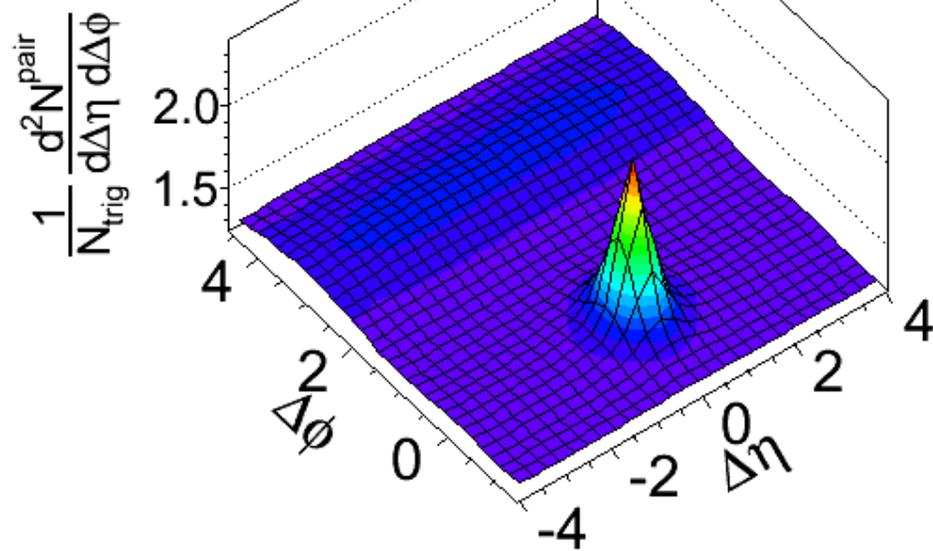


Change in pileup fraction by factor 4-5
has almost no effect on ridge signal

pp $\sqrt{s} = 7$ TeV, $N \geq 110$

$2 < p_T^{\text{trig}} < 3$ GeV/c

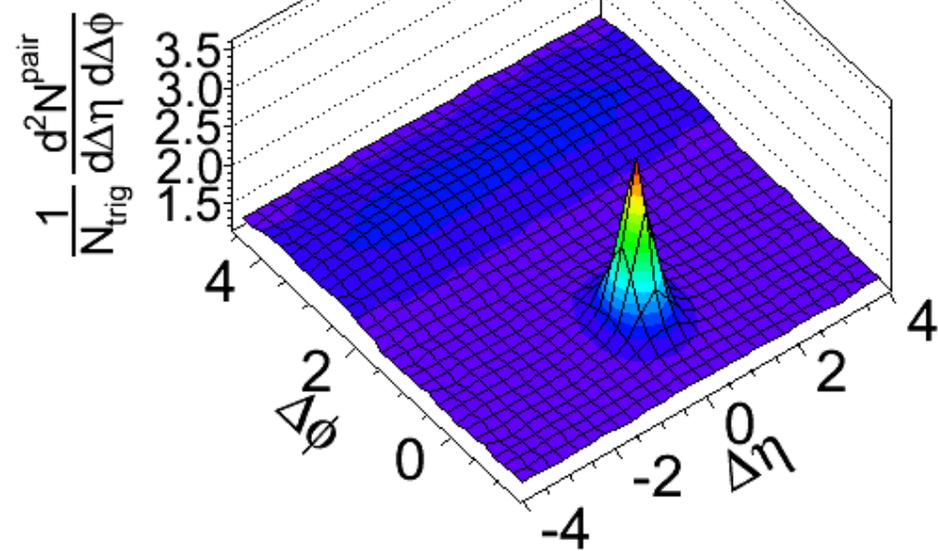
$1 < p_T^{\text{assoc}} < 2$ GeV/c



pp $\sqrt{s} = 7$ TeV, $N \geq 110$

$5 < p_T^{\text{trig}} < 6$ GeV/c

$1 < p_T^{\text{assoc}} < 2$ GeV/c



Turning V_n^f into flow coefficients v_n^f by assuming:

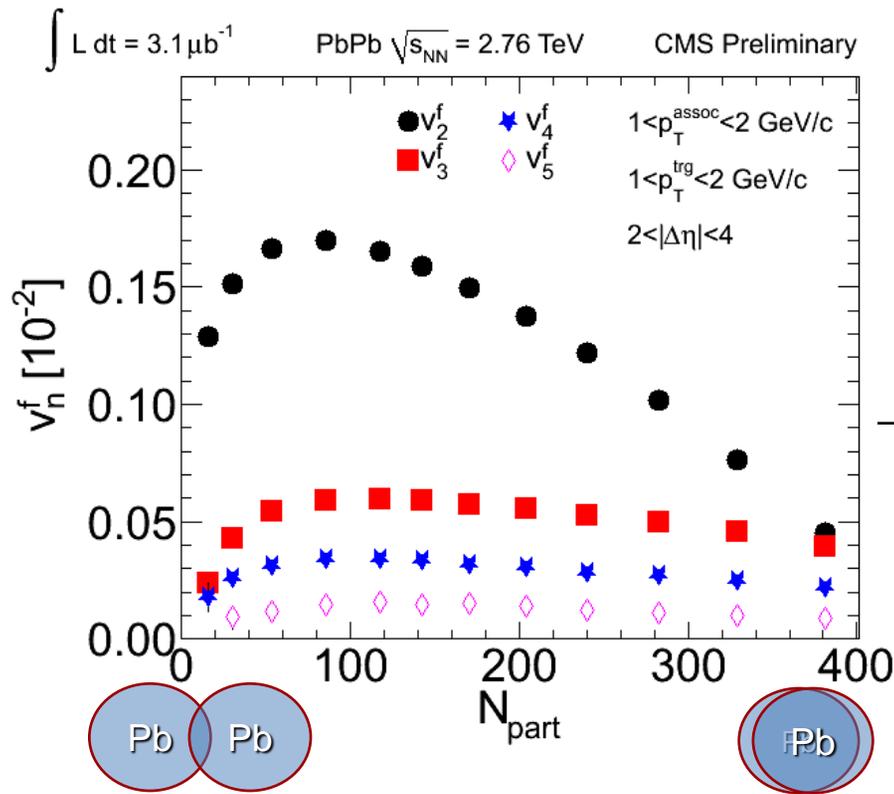
$$V_n^f(p_T^{\text{trig}}, p_T^{\text{assoc}}) = v_n^f(p_T^{\text{trig}}) \times v_n^f(p_T^{\text{assoc}})$$

We can get:

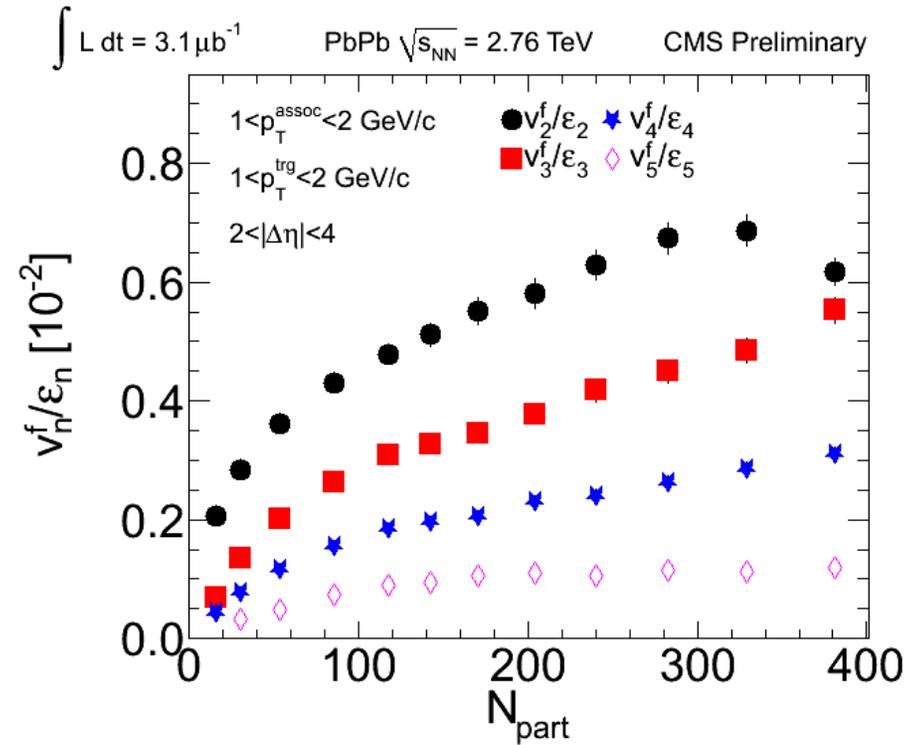
$$v_n^f(p_T^{\text{trig}}) = \frac{V_n^f(p_T^{\text{trig}}, p_T^{\text{assoc}})}{v_n^f(p_T^{\text{assoc}})}$$

$\sqrt{V_n^f(p_T^{\text{trig}}, p_T^{\text{assoc}})}$ for both $1 < p_T^{\text{trig}} < 2$ GeV/c and $1 < p_T^{\text{assoc}} < 2$ GeV/c to minimize non-flow effect.

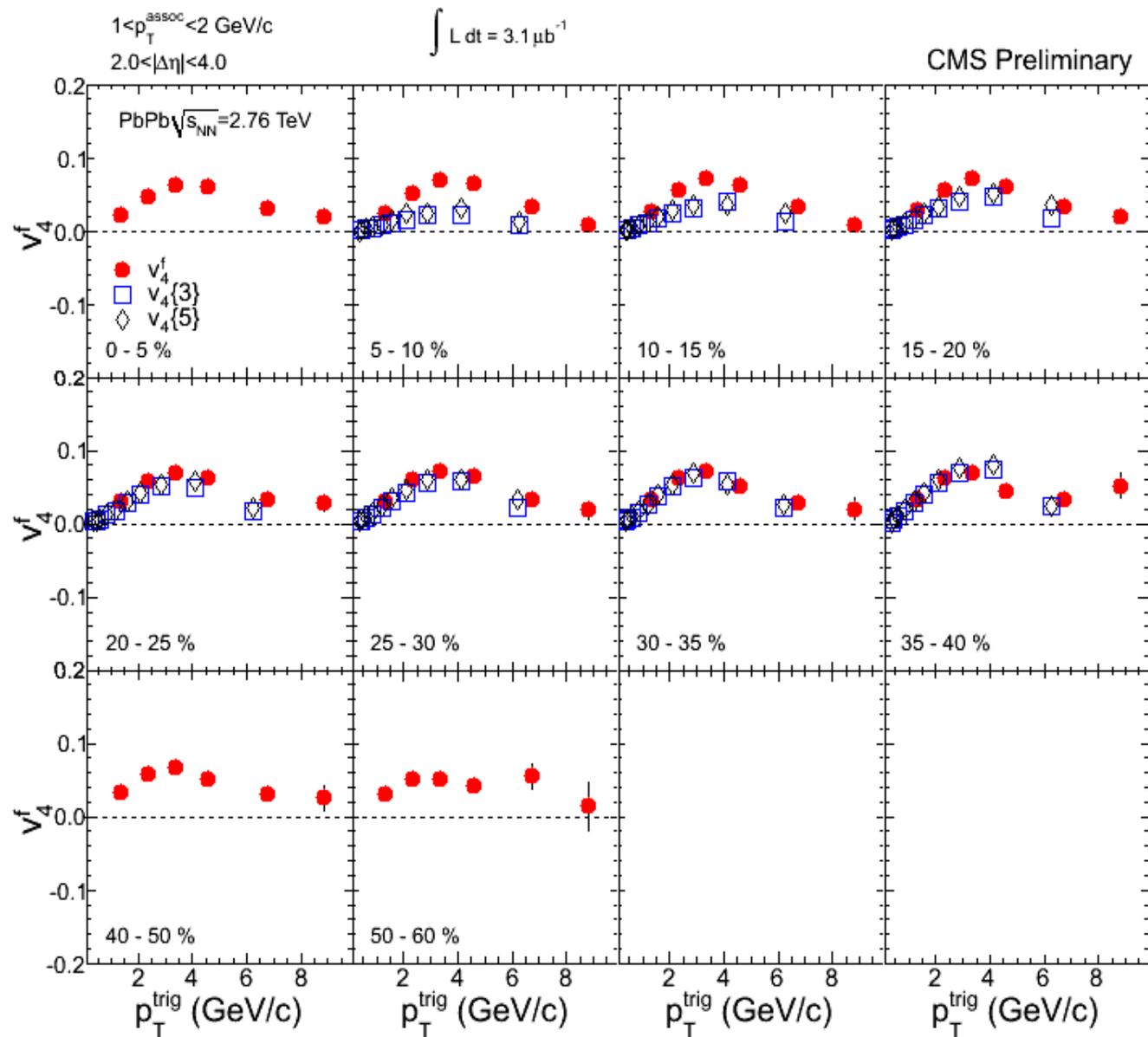
Flow coefficients (v_n^f) vs centrality



$\xrightarrow{1/\epsilon_n}$



v_4 from long-range correlations



v_5 from long-range correlations

