"High-p_T" correlations in CMS

Wei Li

Massachusetts Institute of Technology

for the CMS Collaboration

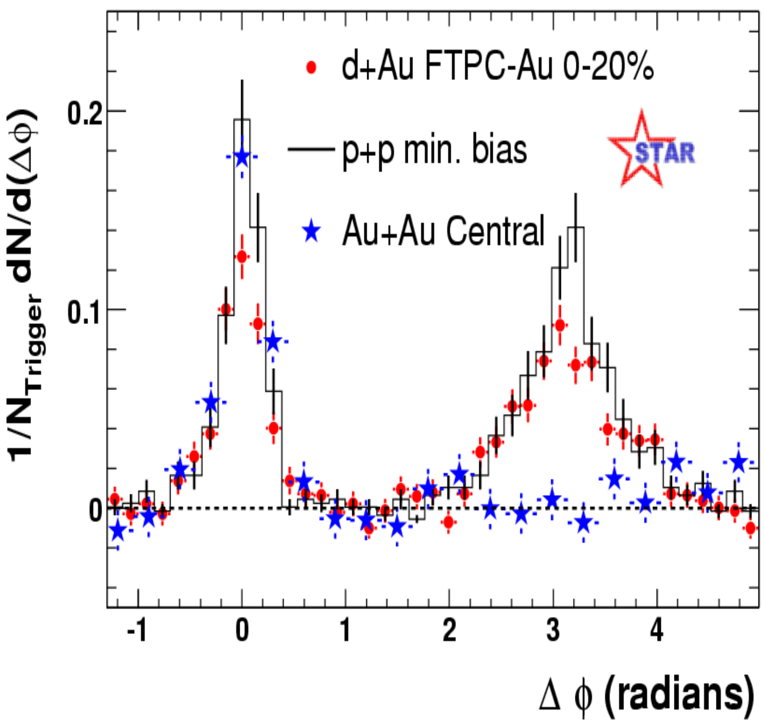
Introduction

Dihadron correlations in AA at RHIC:

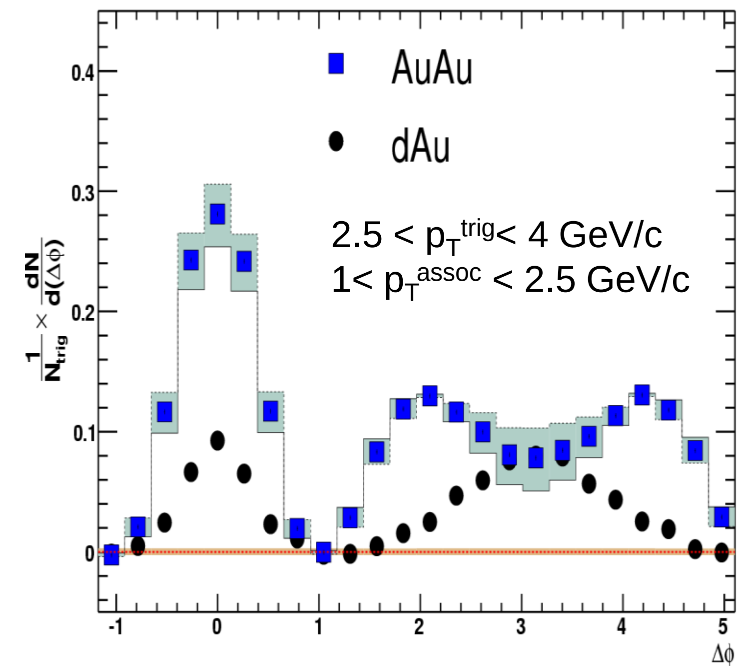
- Disappearance of back-to-back high p_T hadrons
- Broadening of away side

p_{TIp} : 4 - 6 GeV/c
p_{Tasoc} : 2 GeV/c - p_{TIp}

Jet quenching



Away-side modification



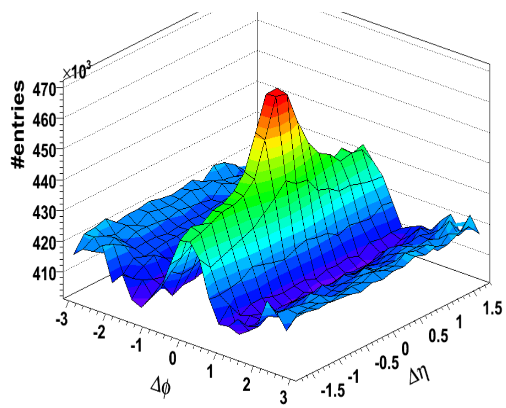
Introduction

Dihadron correlations in AA at RHIC:

- Disappearance of back-to-back high p_T hadrons
- Broadening of away side
- Long-range, near-side ridge structure

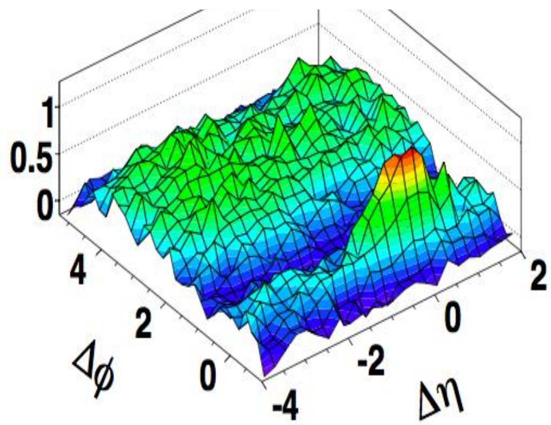
Intriguing ridge structure at RHIC

STAR Au+Au 0-10%



PRC 80 (2009) 64912

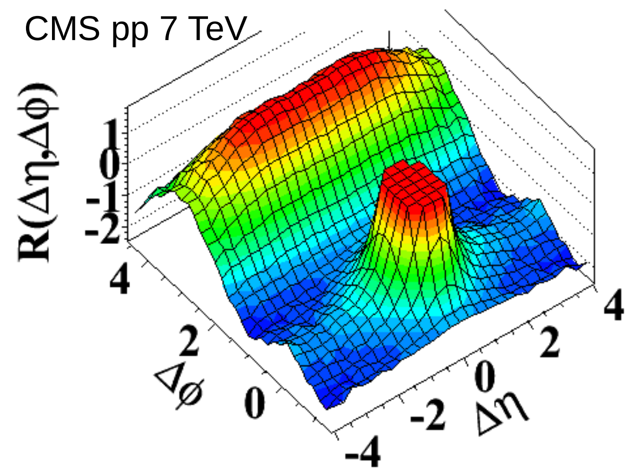
PHOBOS Au+Au 0-30%



PRL 104, 062301 (2010)

Ridge in pp at LHC!

CMS pp 7 TeV



JHEP 09 (2010) 091

Introduction

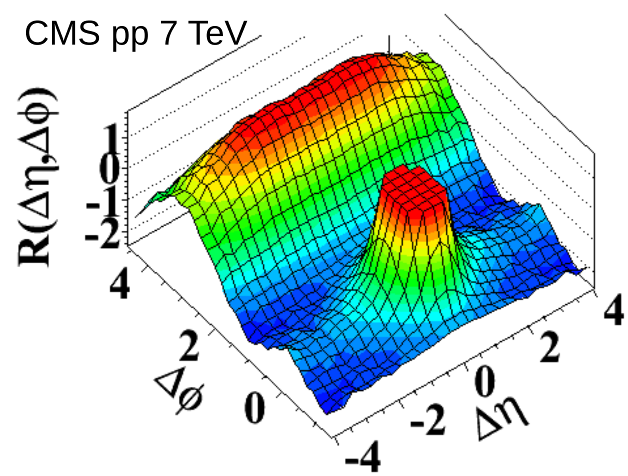
Dihadron correlations in AA at RHIC:

- Disappearance of back-to-back high p_T hadrons
- Broadening of away side
- Long-range, near-side ridge structure

LHC and CMS provide:

- Higher density system
- Unprecedented η and p_T reach

Ridge in pp at LHC!

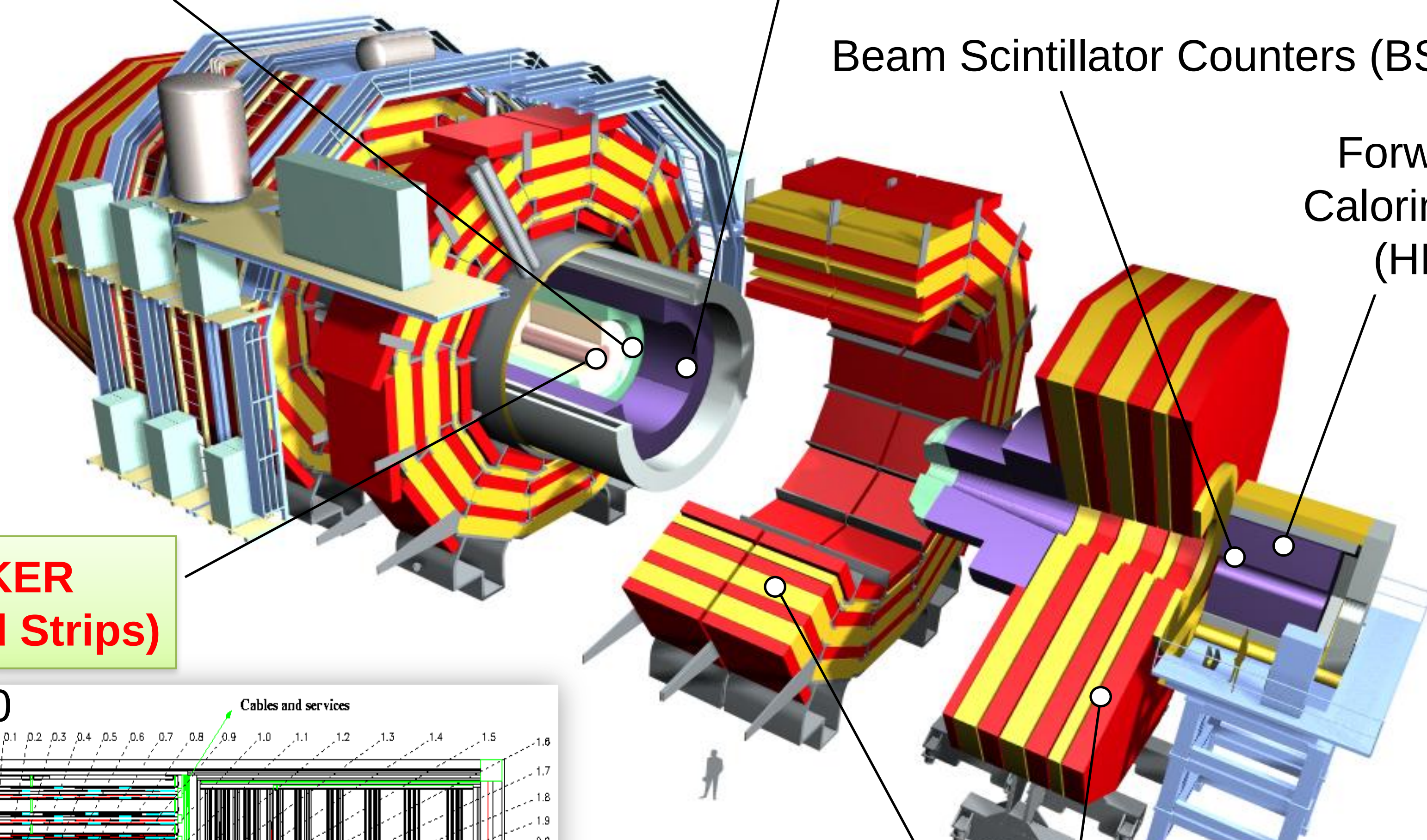


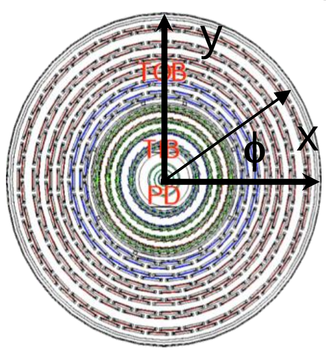
JHEP 09 (2010) 091

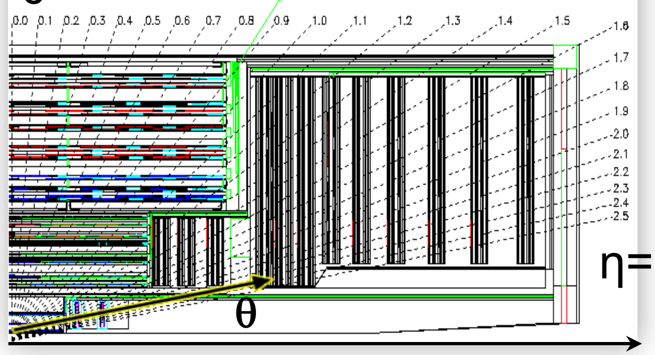
Outline:

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

CMS experiment







Very large coverage (|Δη| < 5.0)!

Dihadron correlation technique in CMS

Signal distribution:

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

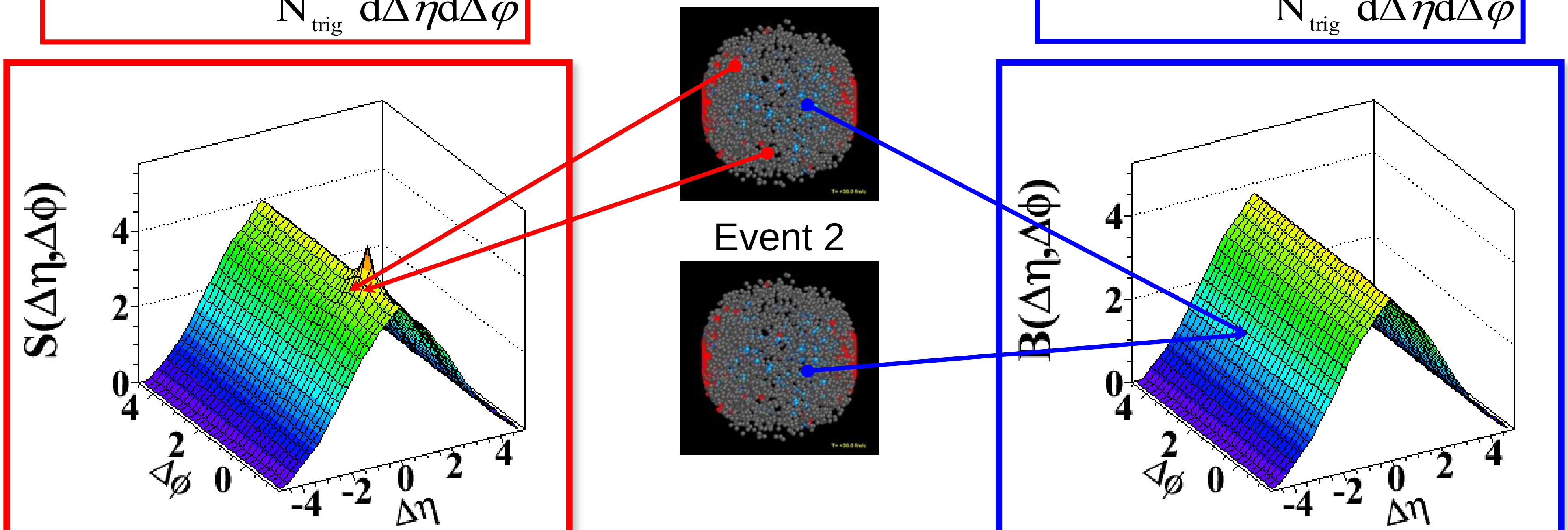
Particle 1: trigger

Particle 2: associated

Background distribution:

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

Event 1



same event pairs

mixed event pairs

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

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

Associated hadron yield per trigger:

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

Correlations in minimum bias pp

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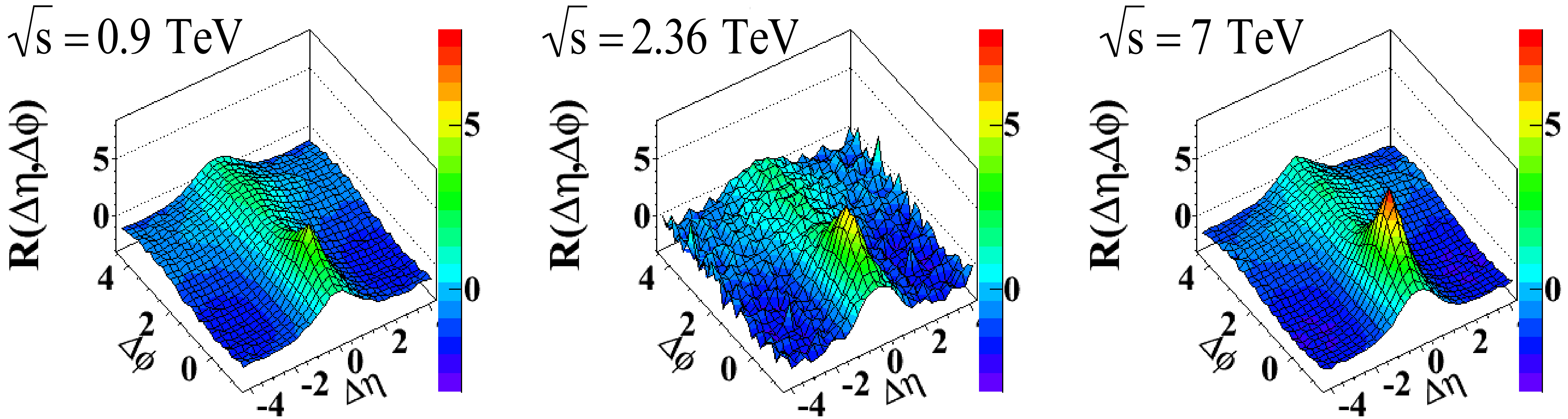
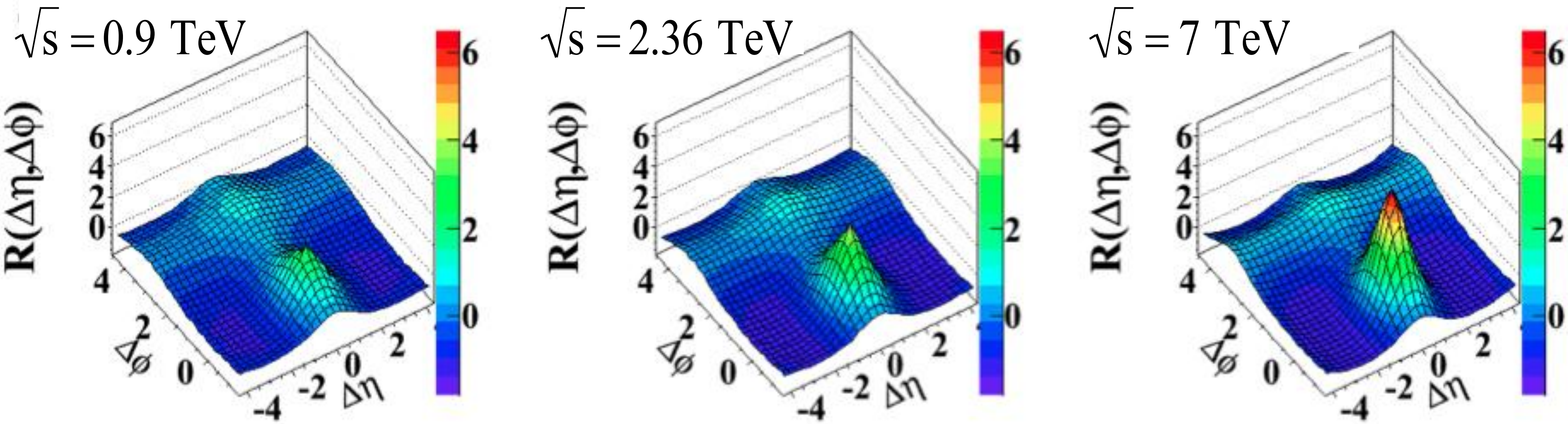
CMS pp Data

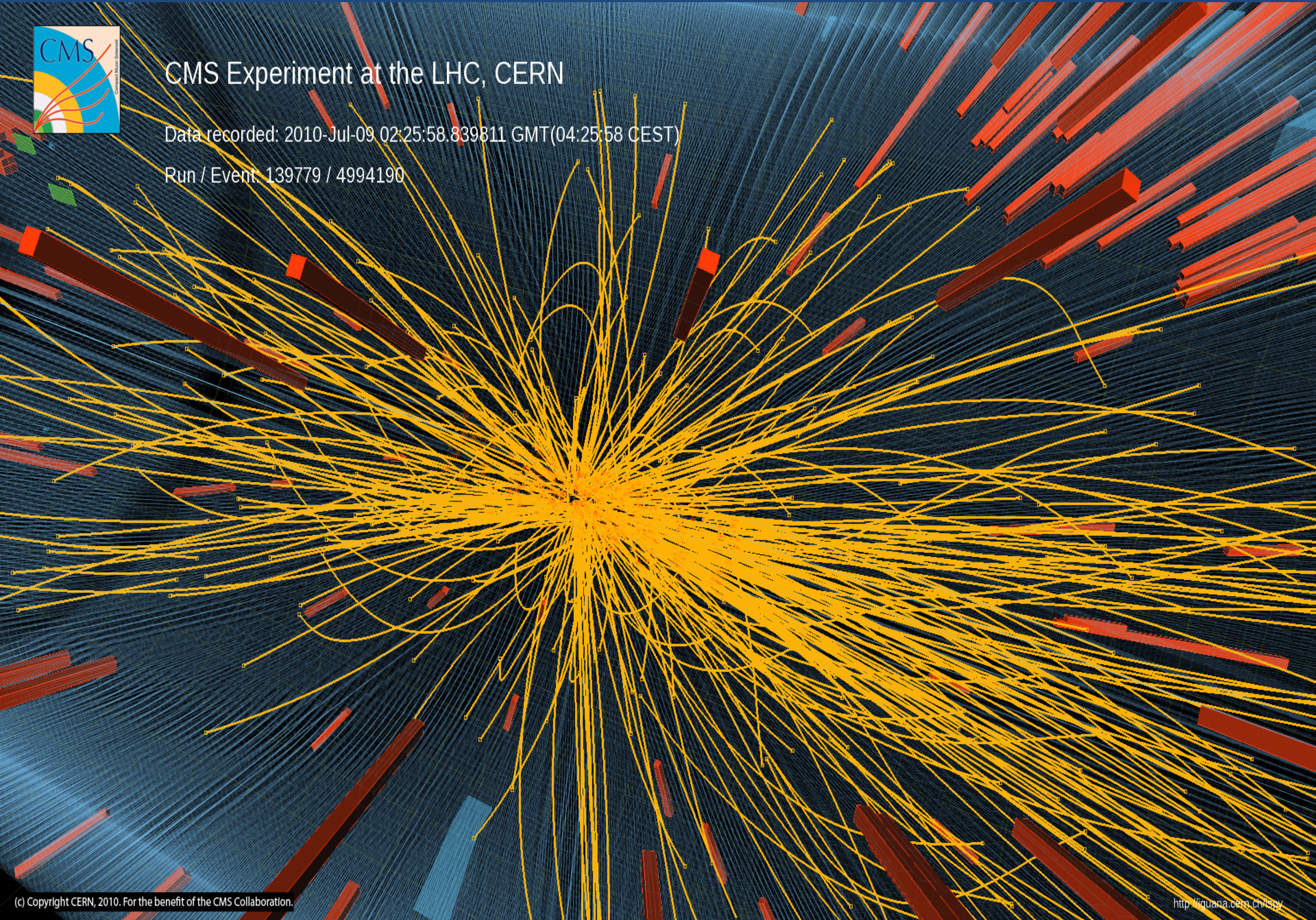
all charged, p_T>0.1 GeV/c



PYTHIA D6T



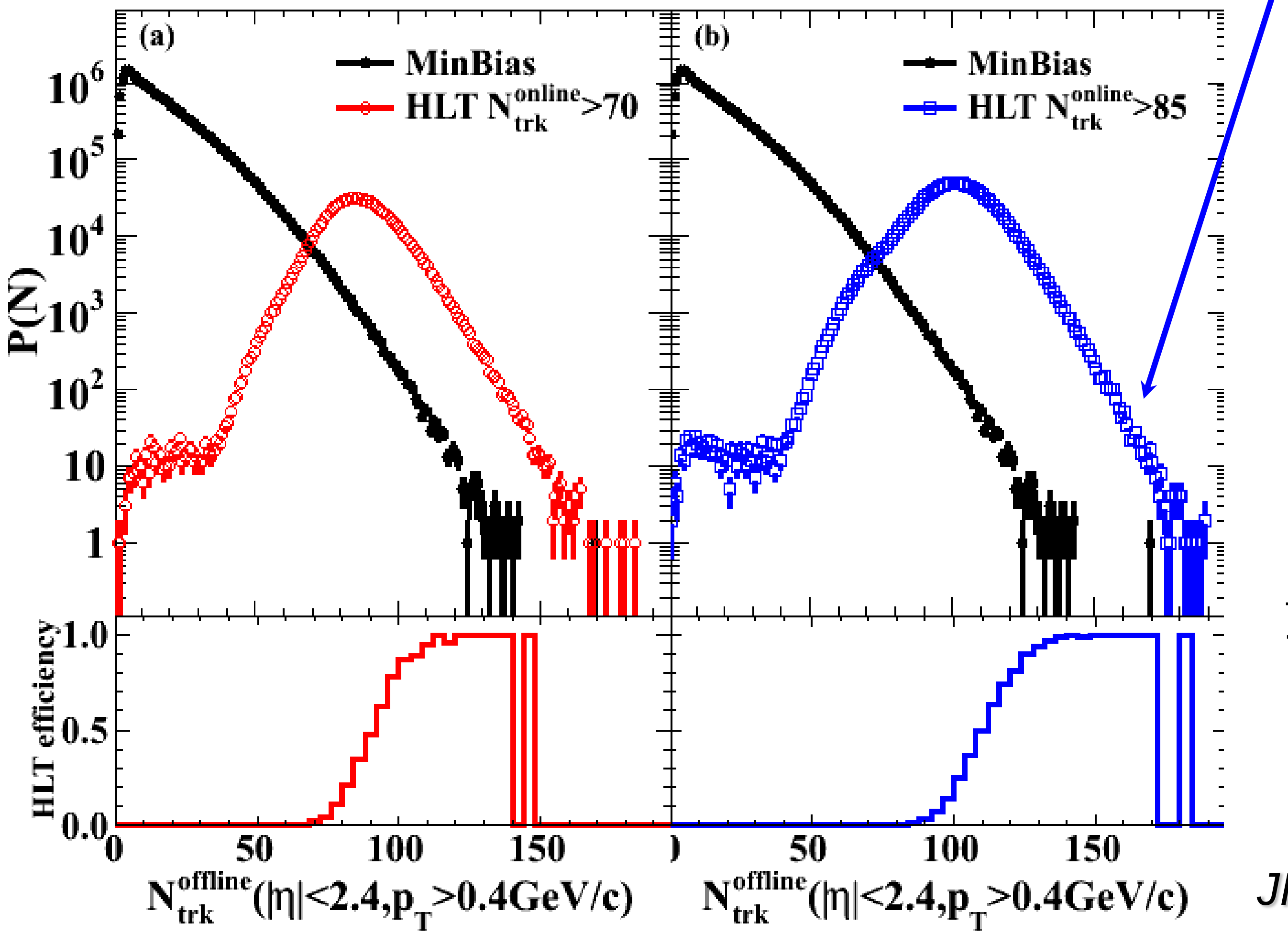
High multiplicity pp collisions



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

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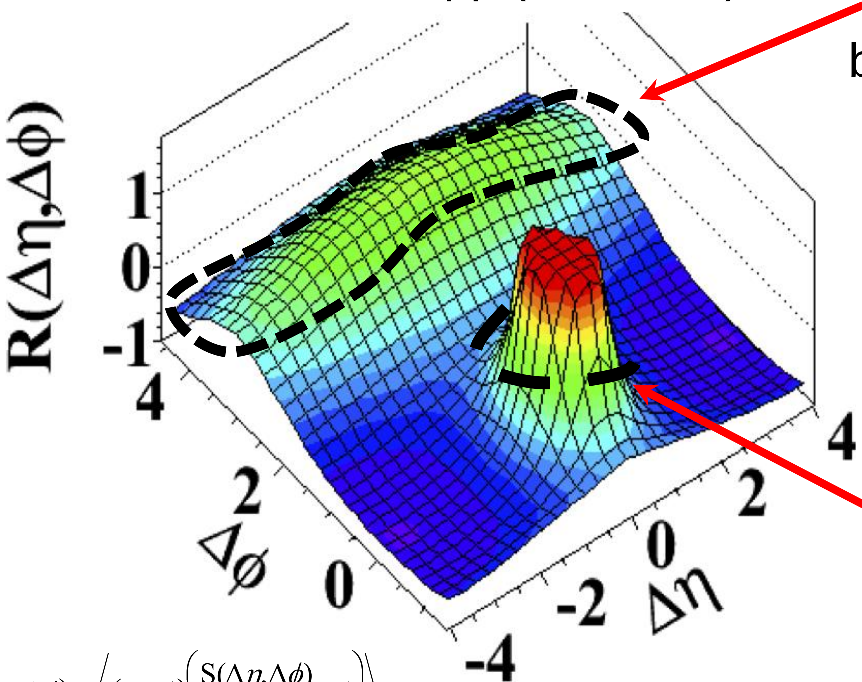
~350K top multiplicity events (N>110) out of 50 billion collisions!

Ridge in high multiplicity pp

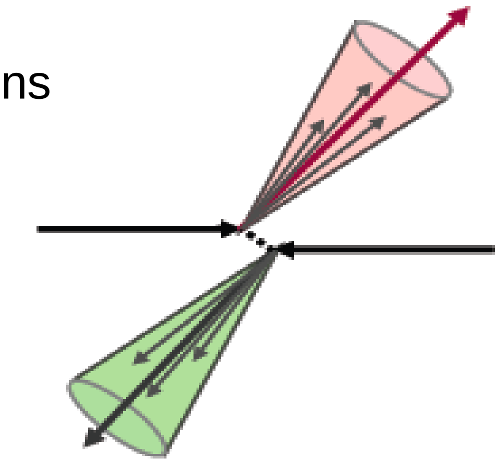
Intermediate p_T: 1-3 GeV/c

Minimum Bias pp (<N> ~ 15)



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

"Away-side" ($\Delta\phi \sim \pi$)
back-to-back jet correlations



"Near-side" ($\Delta\phi$, $\Delta\eta \sim 0$)
correlations from single jets

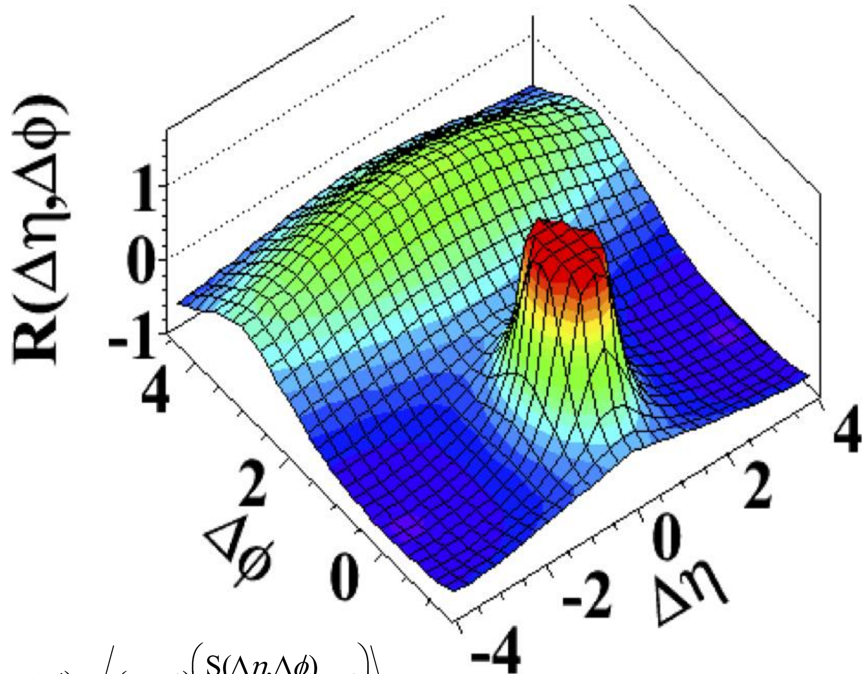
peak truncated

Ridge in high multiplicity pp

Intermediate p_T: 1-3 GeV/c

350K events

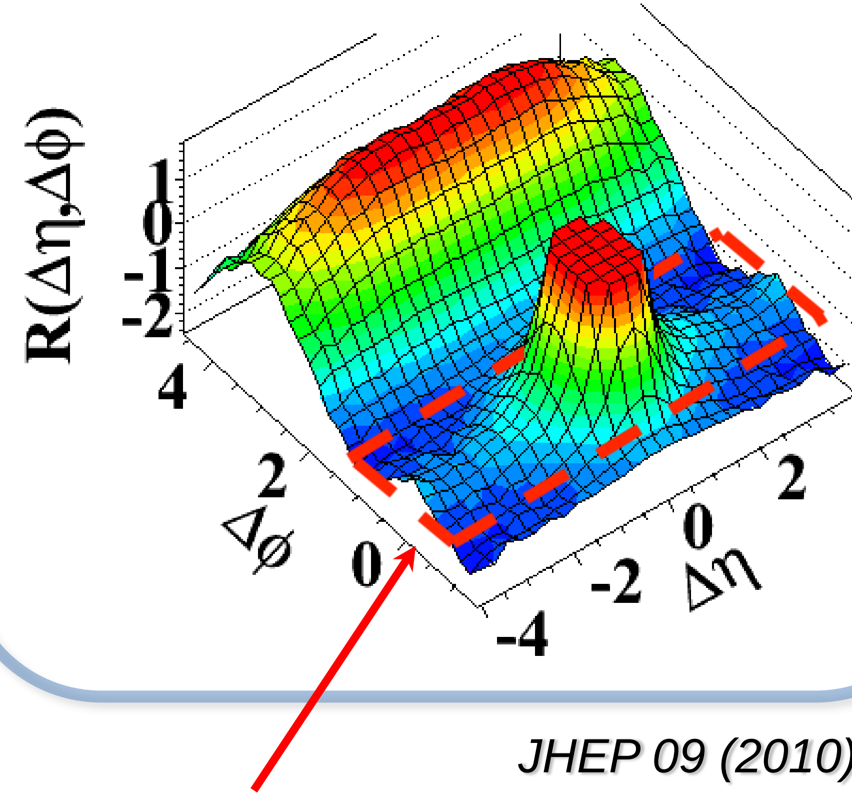
Minimum Bias pp (<N> ~ 15)



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

peak truncated

High multiplicity pp (N ≥ 110)



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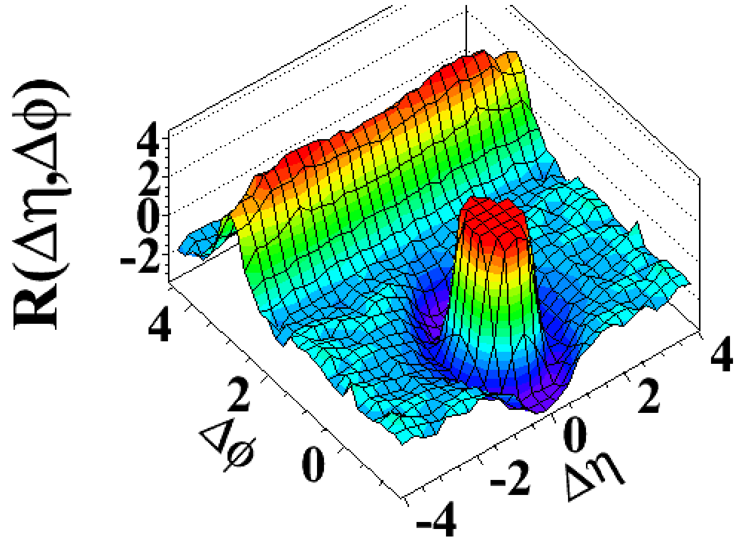
Striking "**ridge-like**" structure extending over $\Delta\eta$ at $\Delta\phi \sim 0$

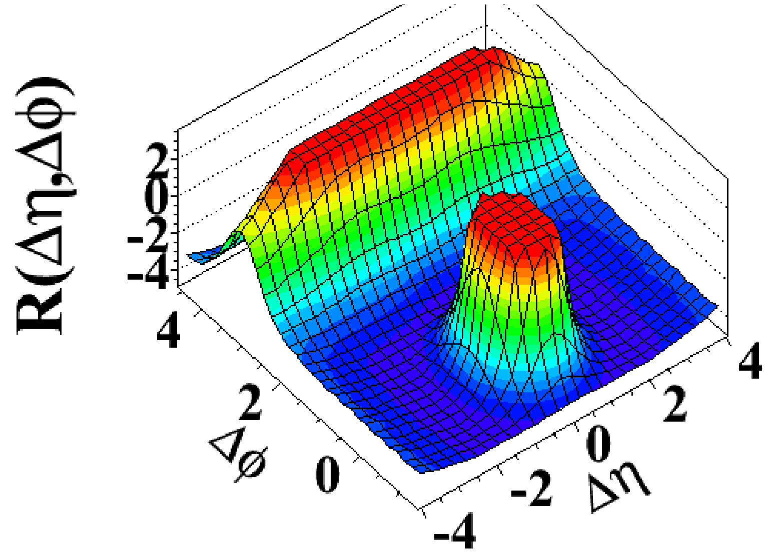
(not observed before in hadron collisions or MC models)

Some pp MC models

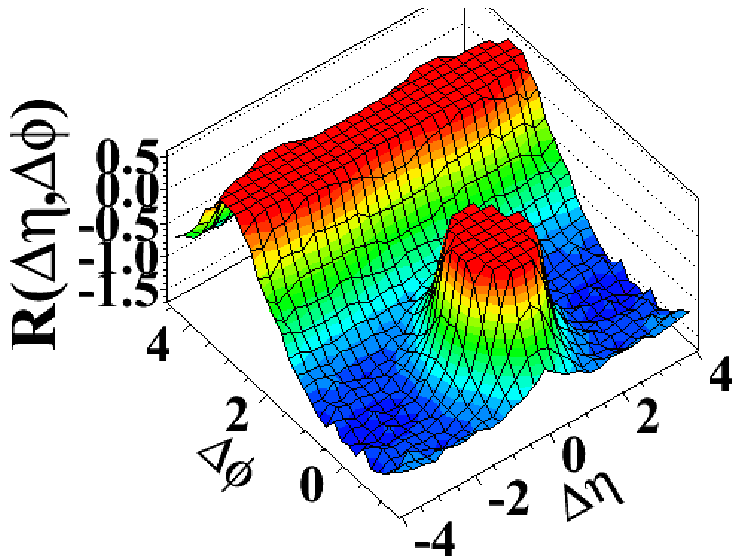
PYTHIA D6T MinBias, N>70



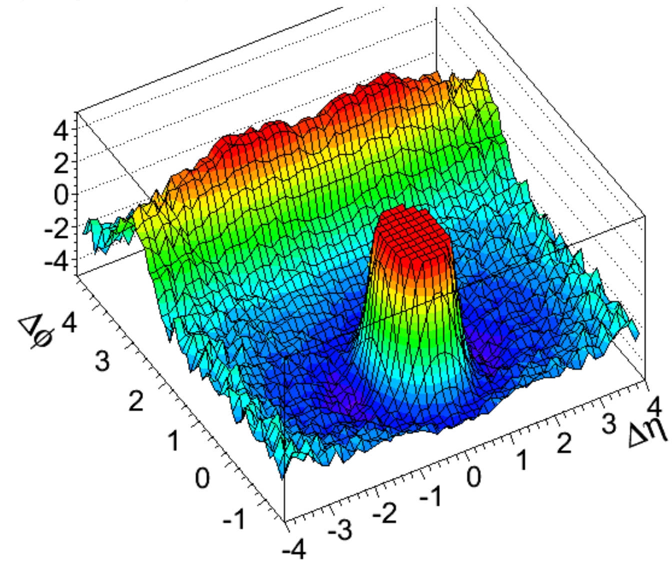
PYTHIA D6T, Dijet 80-120GeV



HERWIG++, N>110

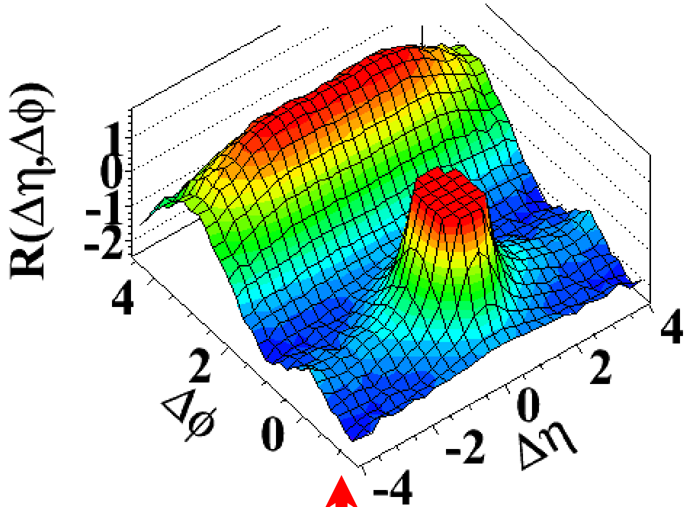


Madgraph, Dijet 100-250GeV, N>90



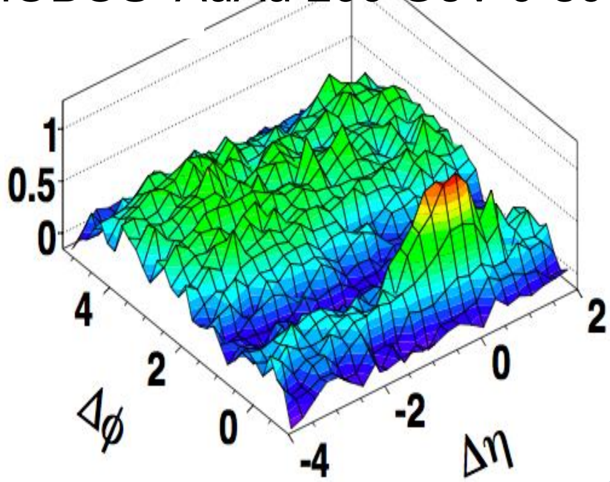
Ridge in high multiplicity pp

CMS pp 7 TeV, N ≥ 110

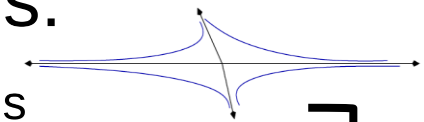


?

PHOBOS AuAu 200 GeV 0-30%



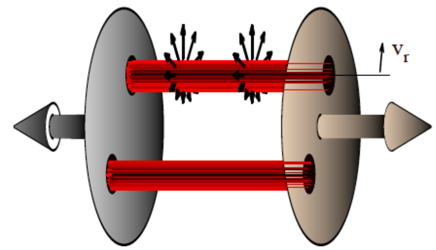
Interpretations:

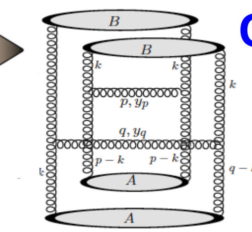


Multi-jet correlations
Jet-Jet color connections
Jet-proton remnant color connections

] **Jet**

Glasma tube

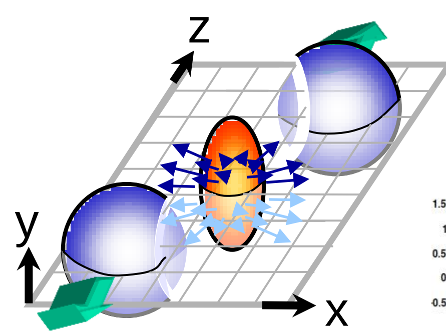




— **Color Glass Condensate**

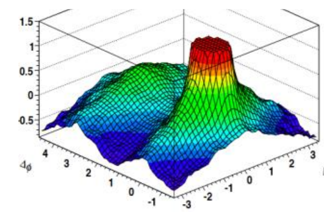
Phys. Lett. B697:21-25, 2011

Hydrodynamic flow



— **Quark Gluon Plasma**

EPOS model: pp



K. Werner, WWND2011

⋮

Ridge in high multiplicity pp

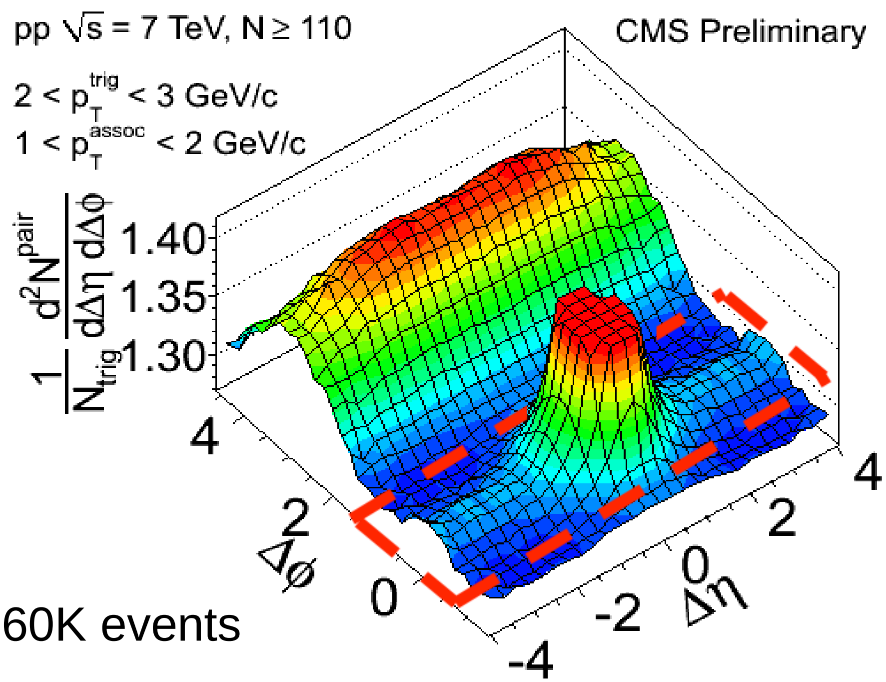
Updated new results:

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

Associated hadron yield per trigger:

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

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



660K events

Ridge in high multiplicity pp

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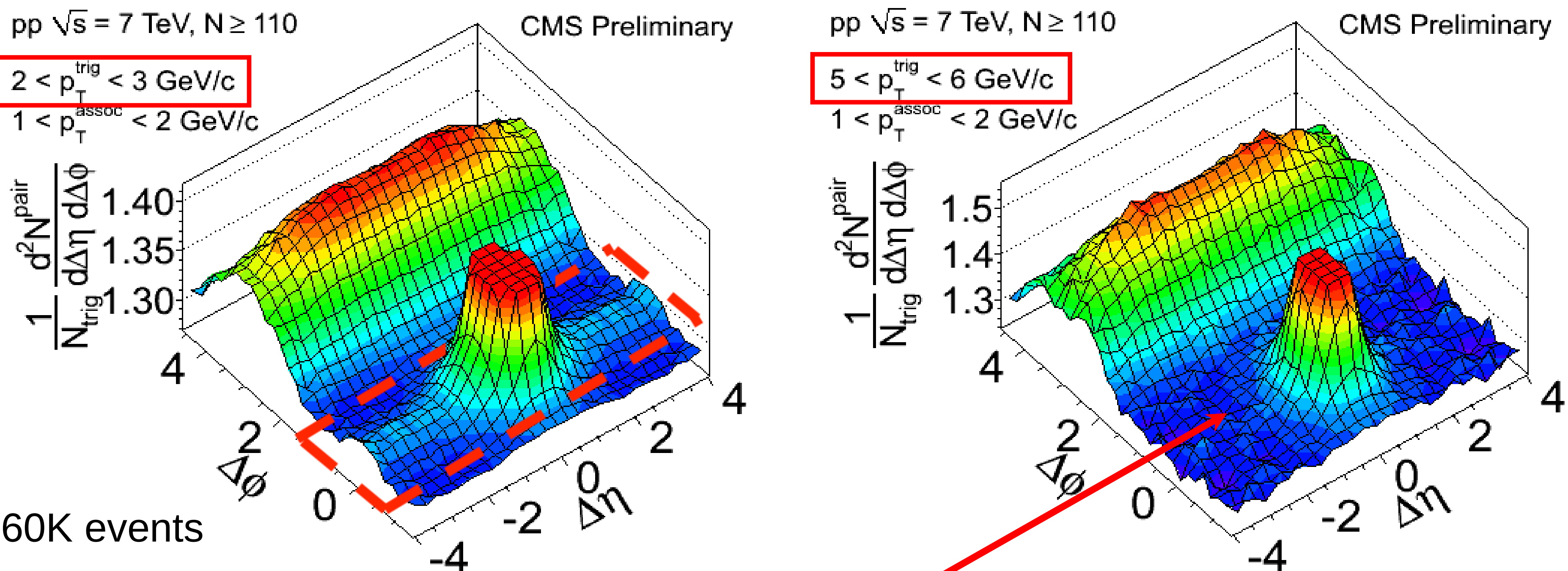
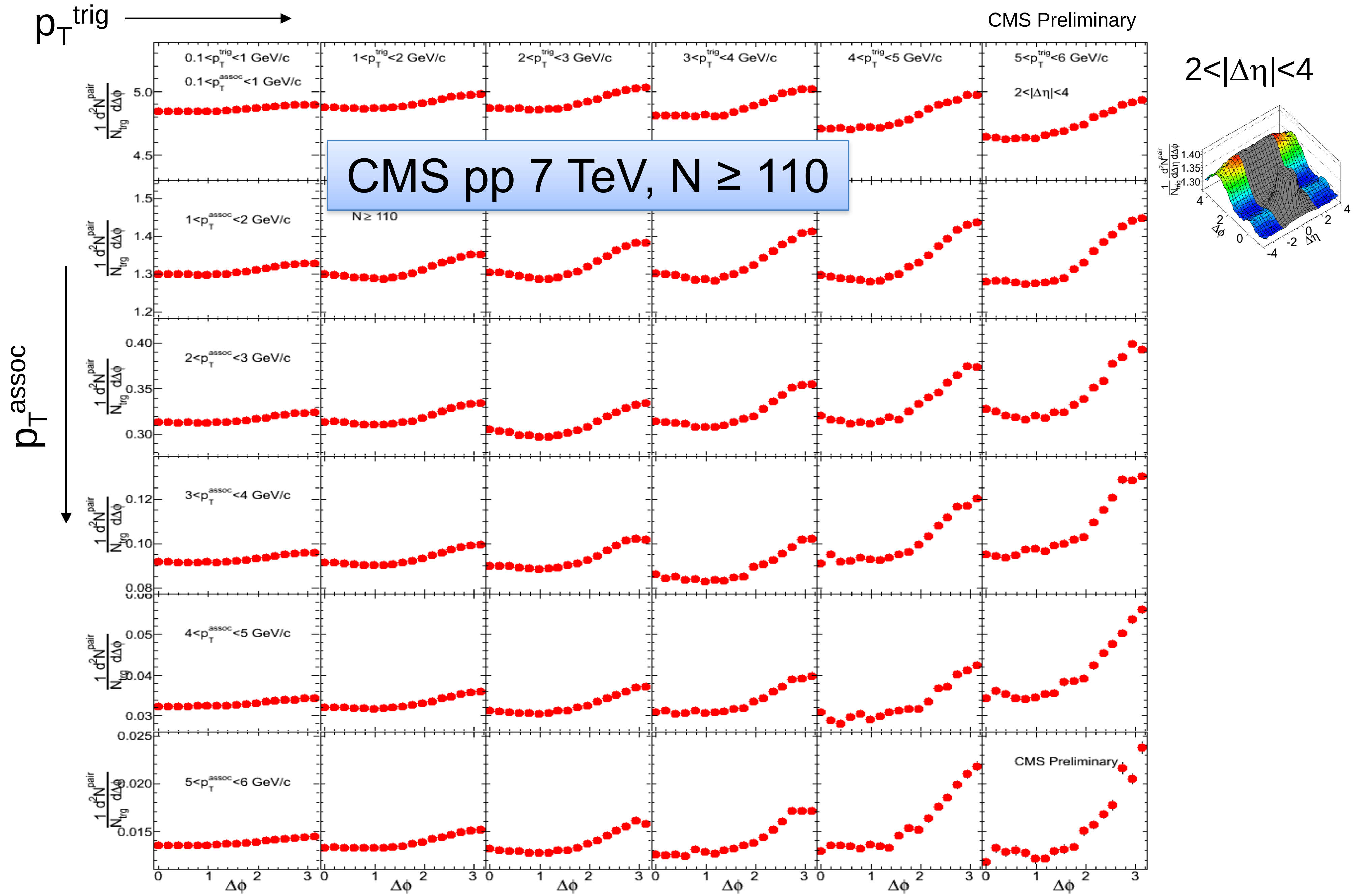


660K events

No ridge when correlating to high p_T particles!

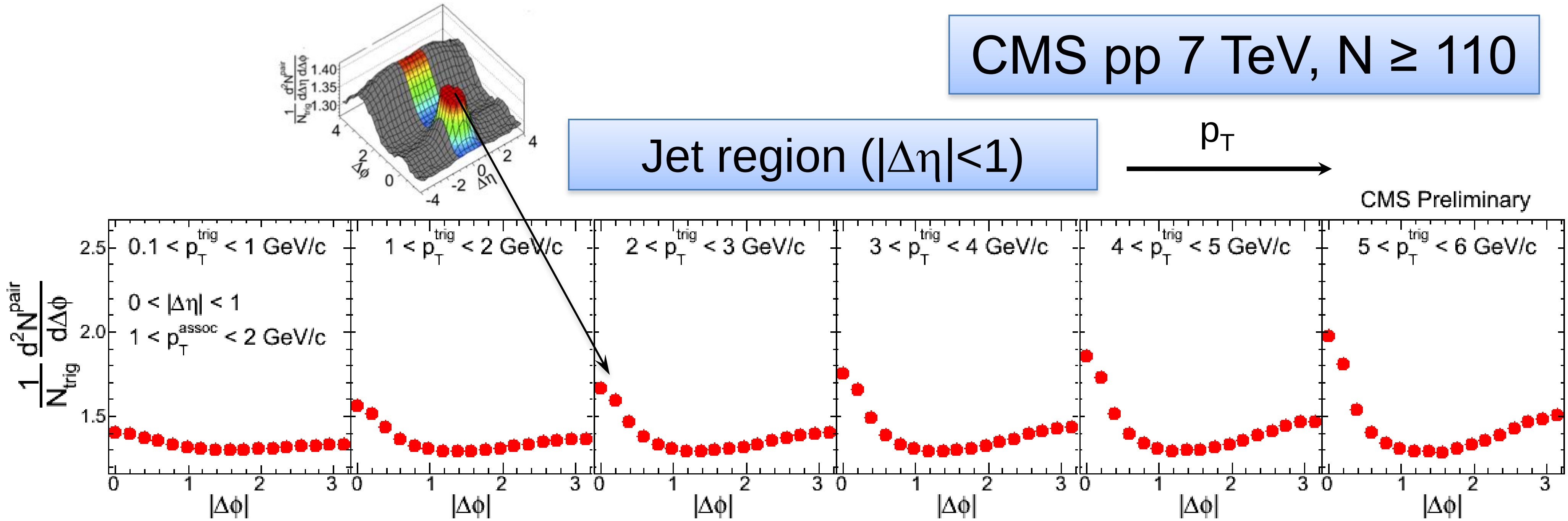
$\Delta\phi$ projections in various p_T ranges



$\Delta\phi$ projections in various p_T ranges

CMS pp 7 TeV, N ≥ 110

Jet region (|Δη|<1)



$\Delta\phi$ projections in various p_T ranges

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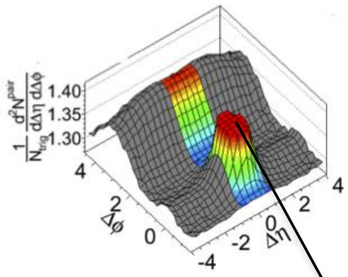
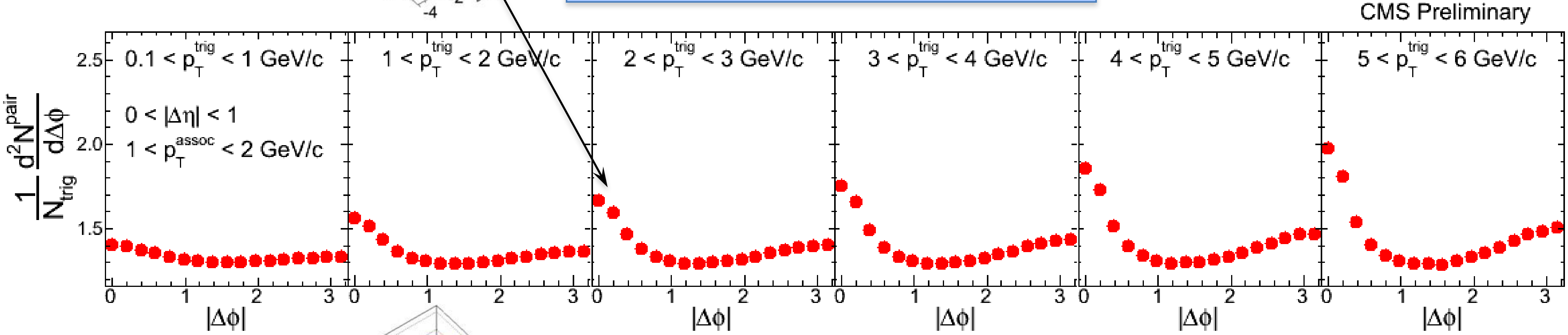
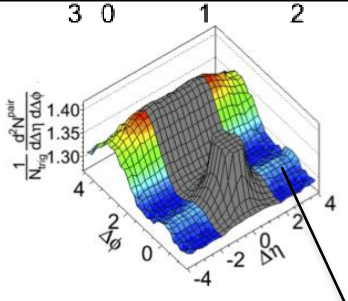


Jet region ($|\Delta\eta|<1$)

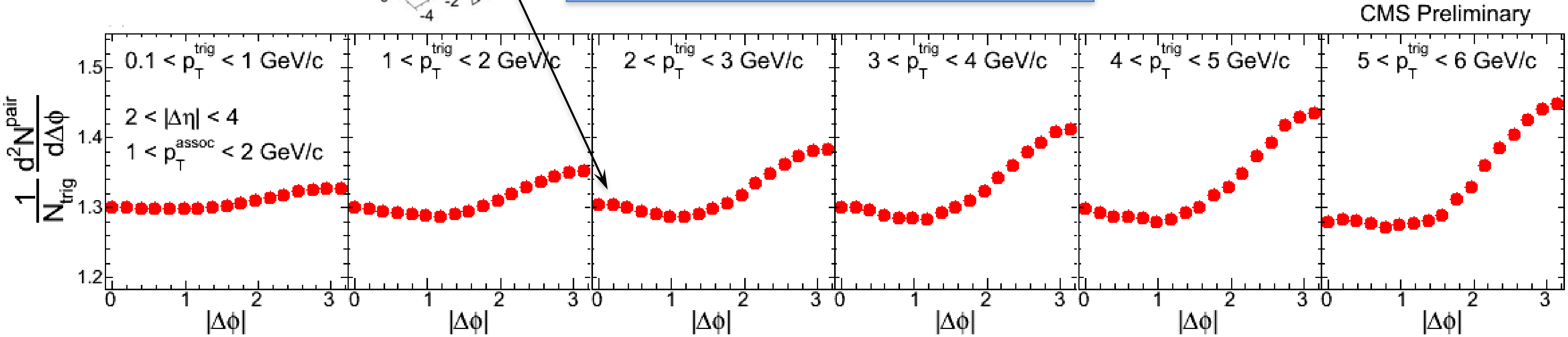
p_T →



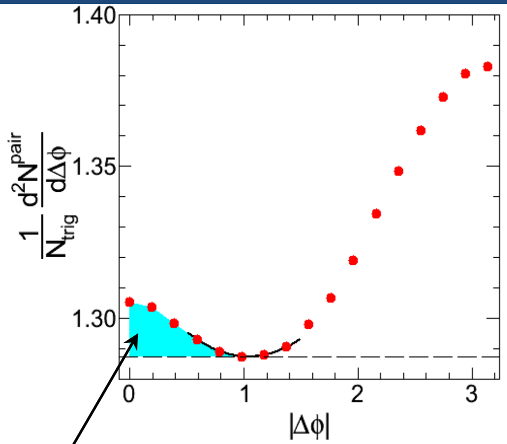


Ridge region ($2<|\Delta\eta|<4$)

p_T →

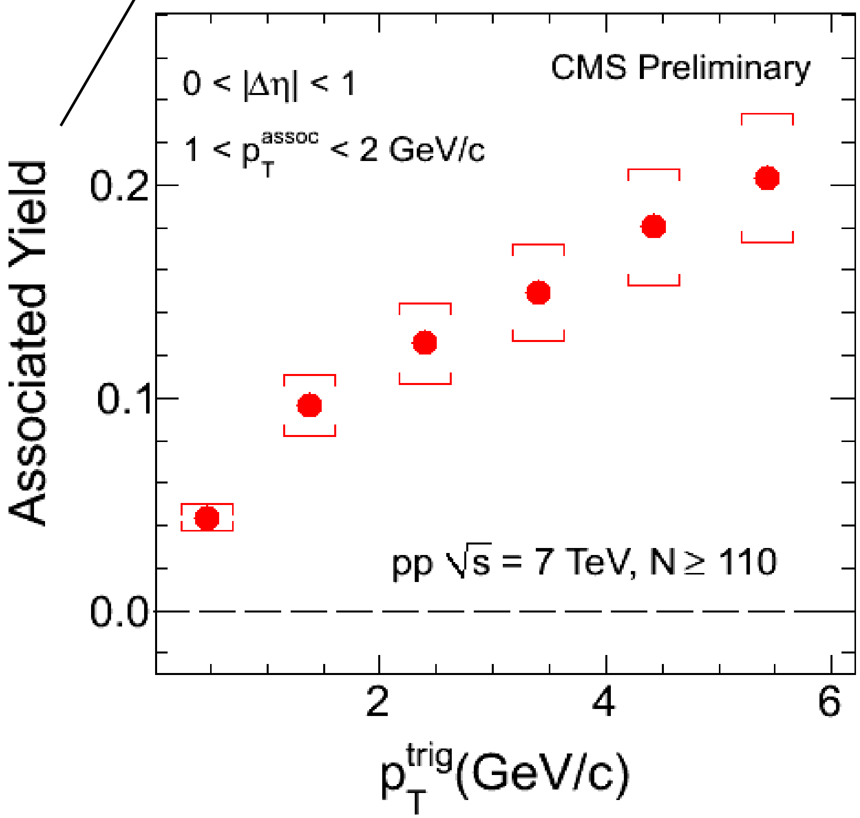


Near-side yield vs p_T in pp (N≥110)

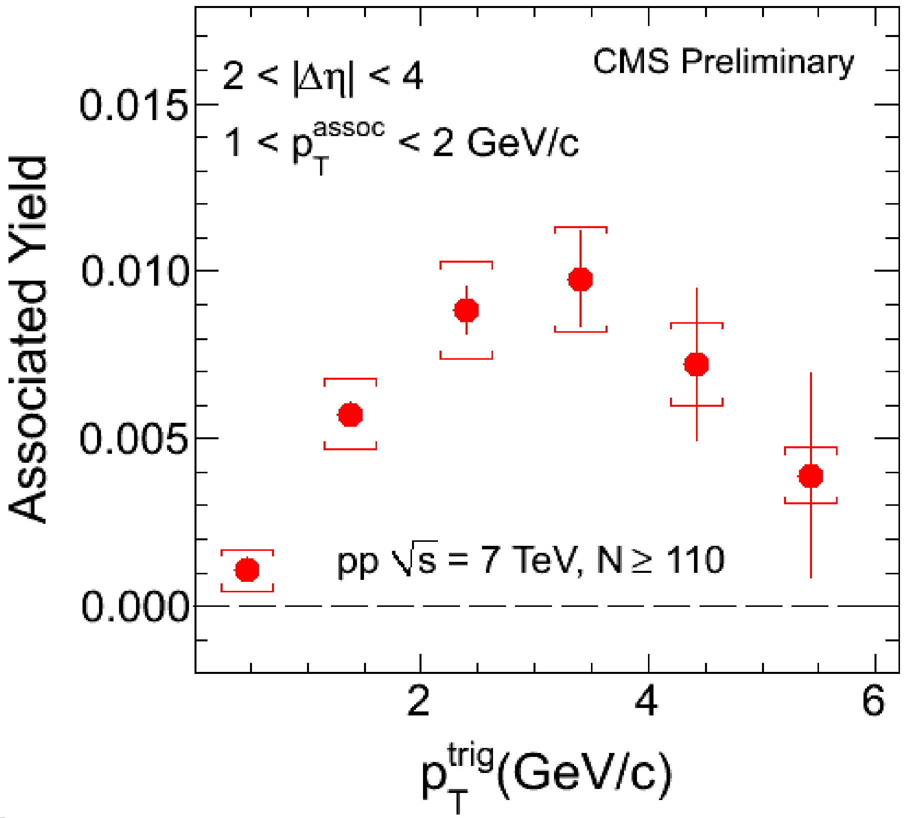


Zero-Yield-At-Minimum (ZYAM)

Jet region (|Δη|<1)

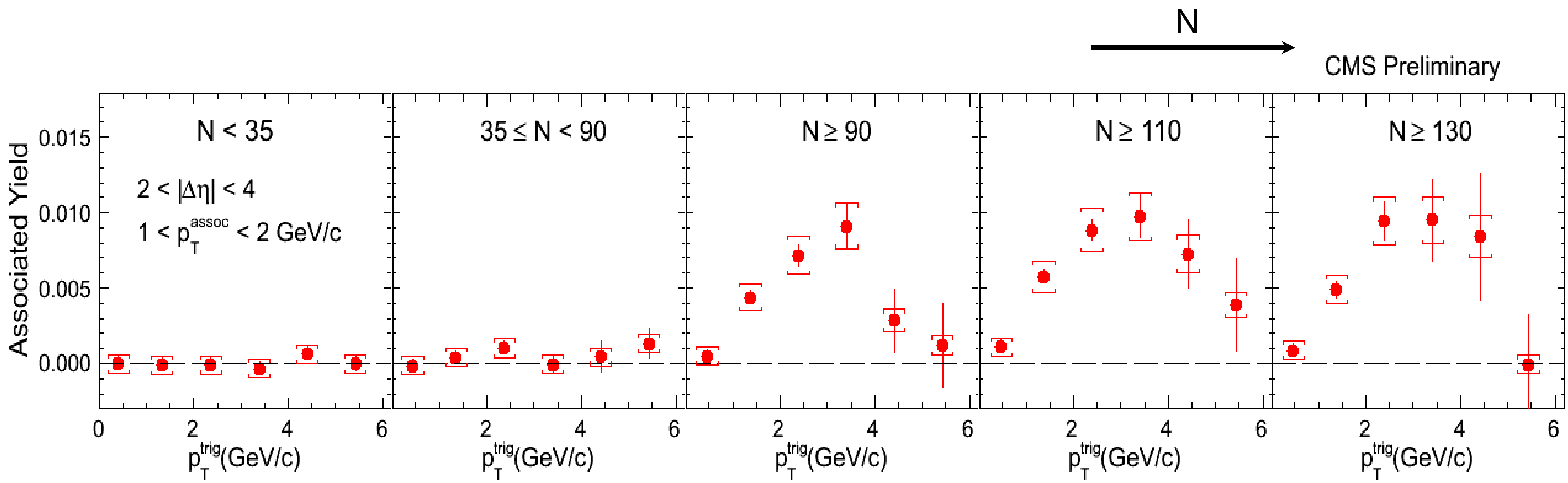


Ridge region (2<|Δη|<4)



Near-side yield vs p_T in pp

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



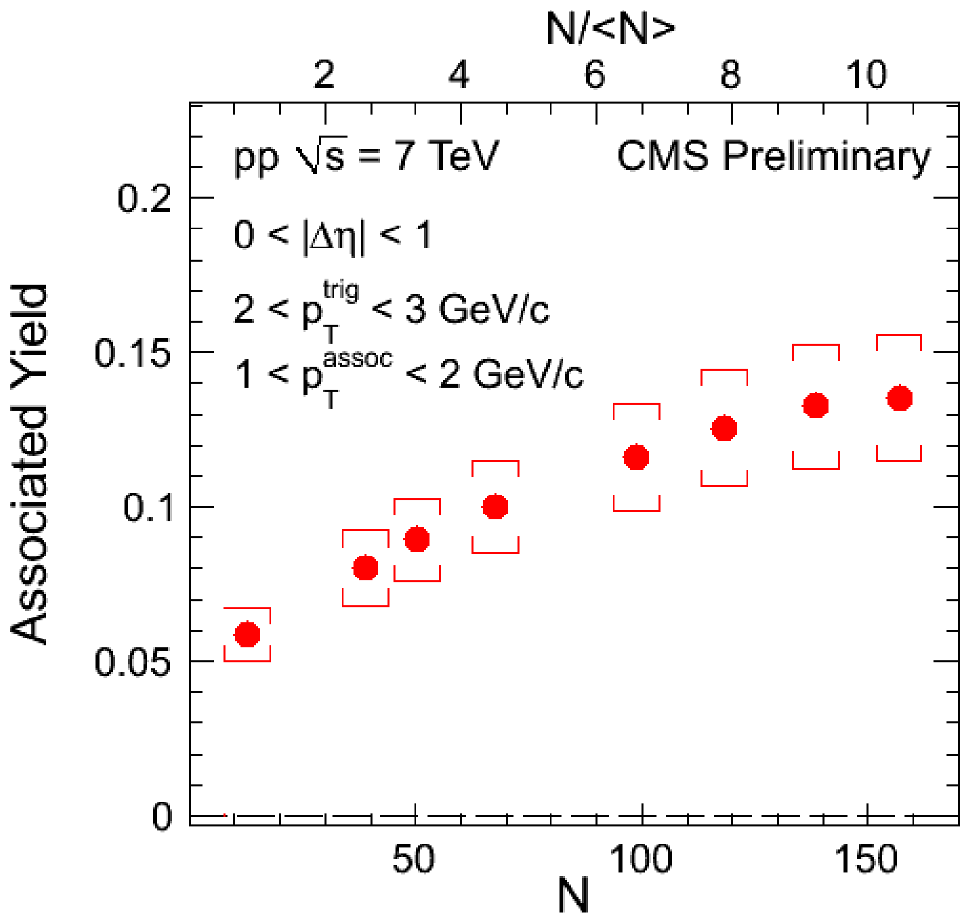
Significant ridge effect for $N \geq 90$ in pp

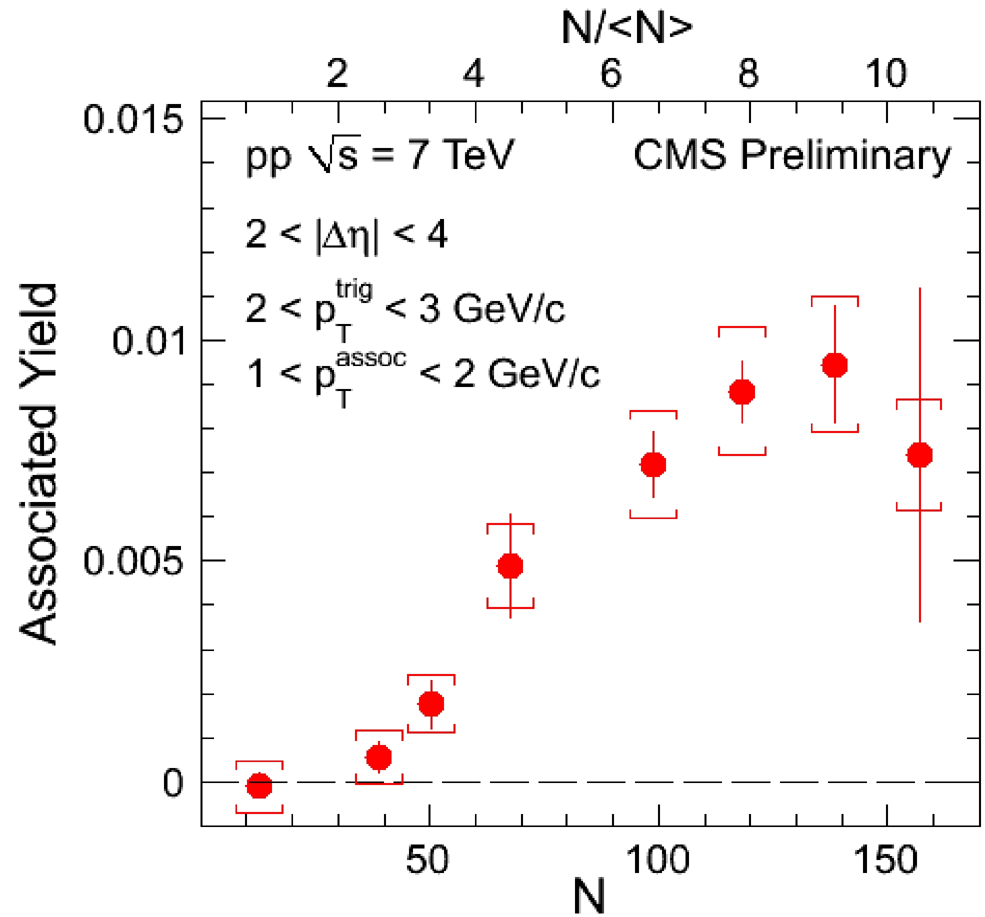
Ridge first rises with p_T, and then drops at high p_T

Near-side yield vs multiplicity in pp

Jet region (|Δη|<1)

Ridge region (2<|Δη|<4)

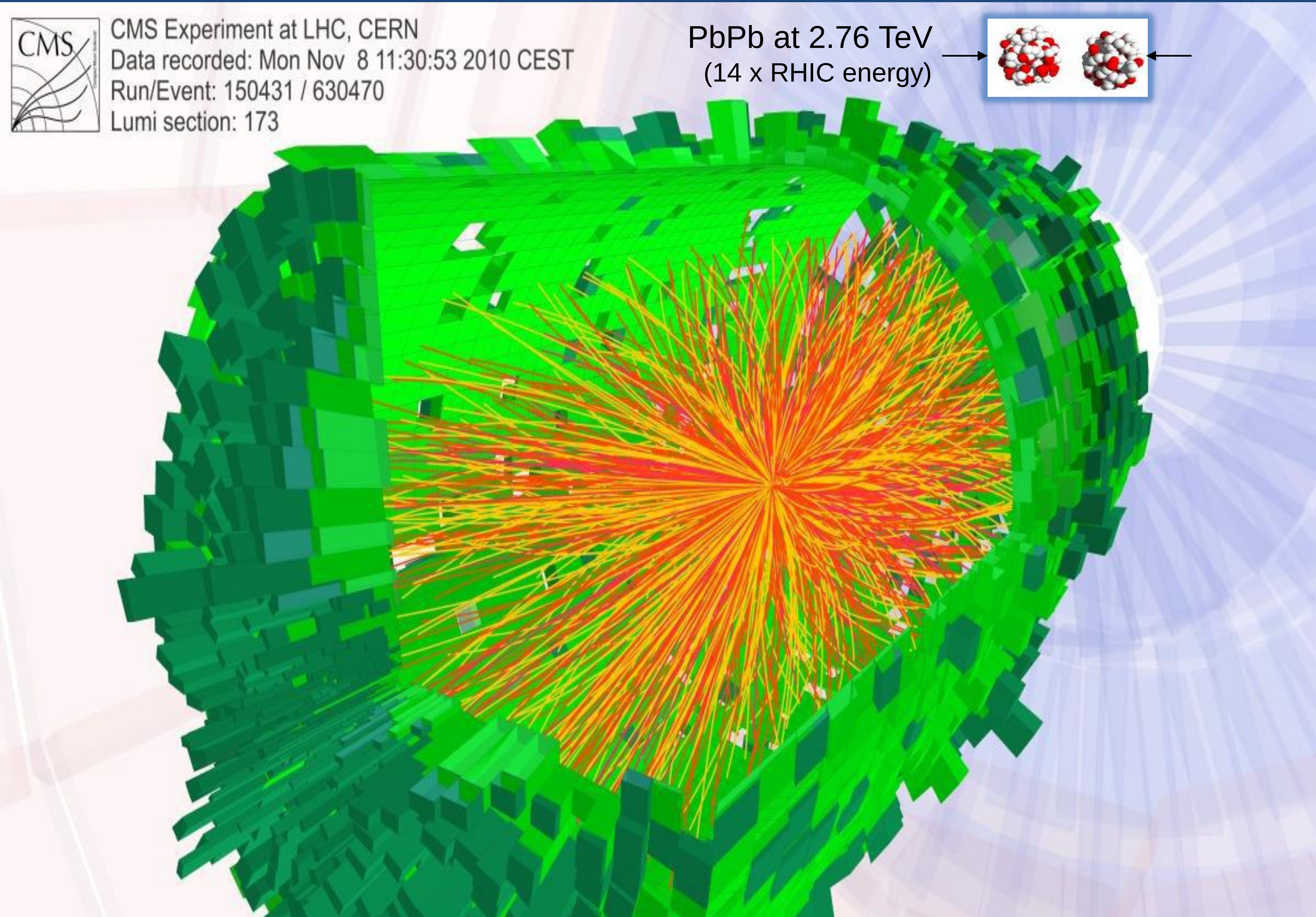




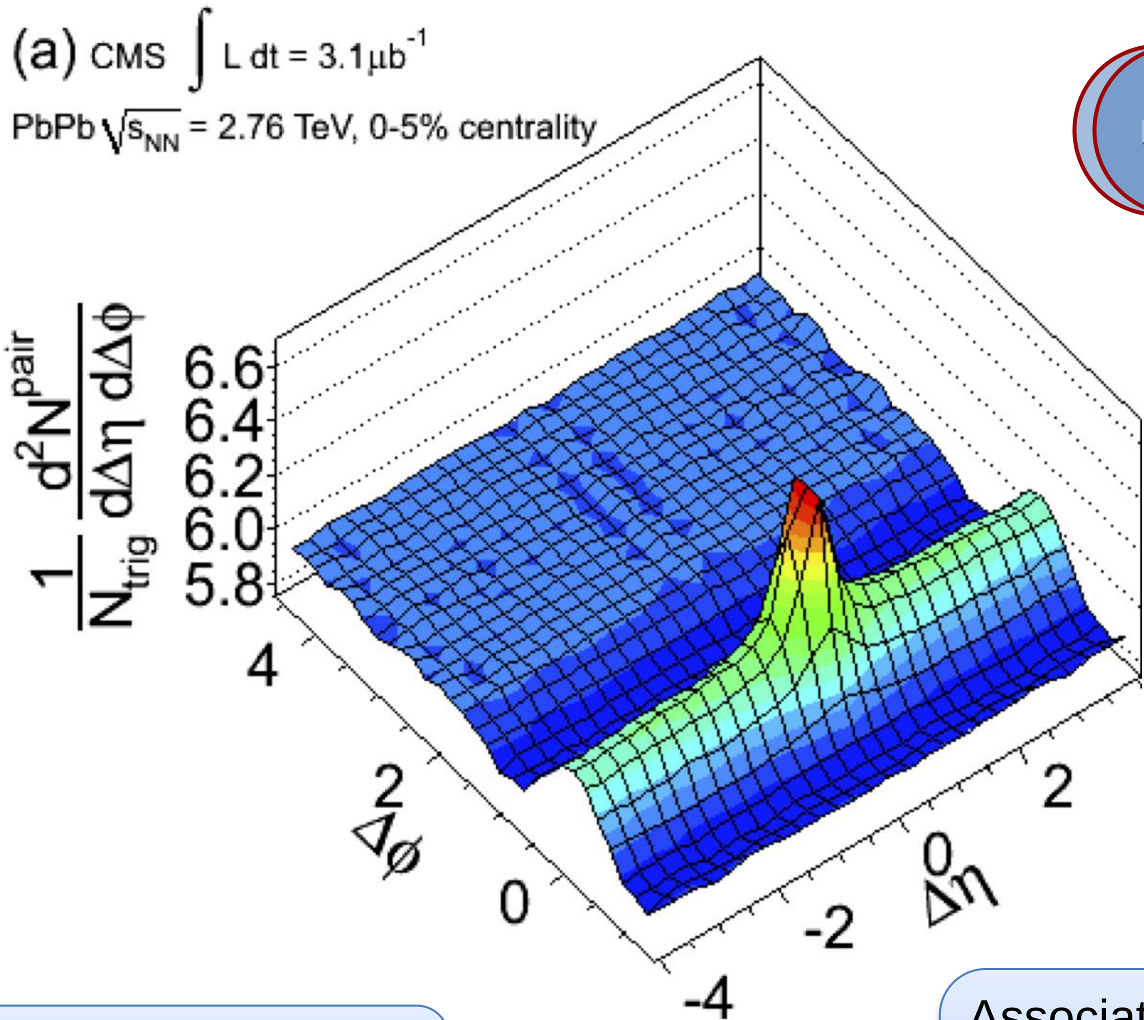
- Jet yield in pp monotonically increases with N
- Ridge in pp turns on around N ~ 50 – 60 (4 x MinBias) smoothly

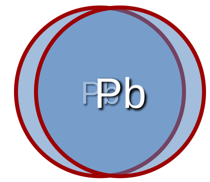
(<N> ~ 15 in MinBias pp events)

PbPb collisions at the LHC



Heavy-ion "ridge" at LHC





0-5% most central

arXiv:1105.2438

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

Associated hadron yield per trigger:

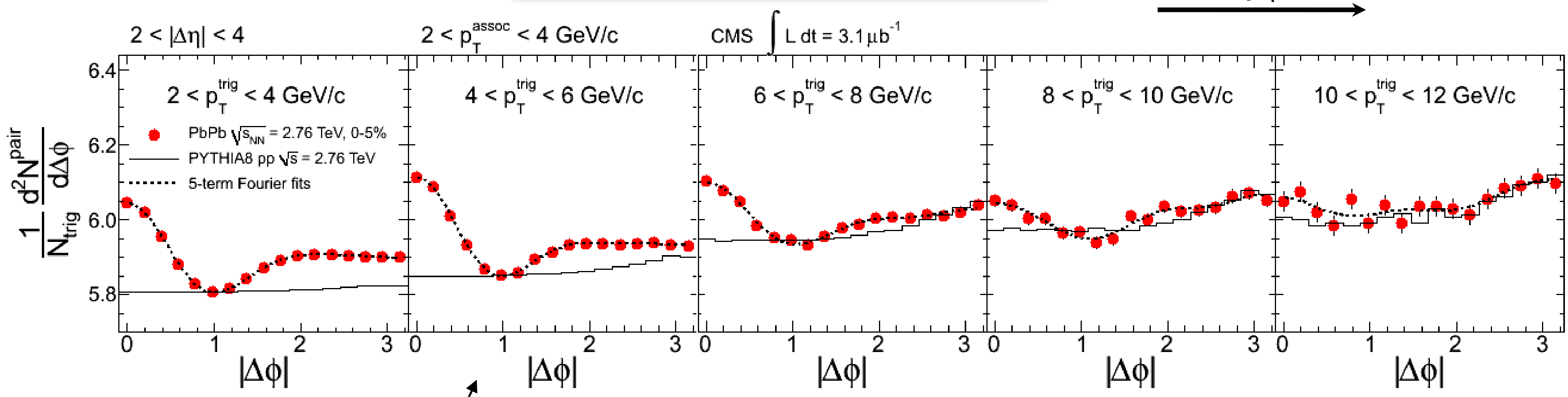
$$\frac{1}{N_{trig}} \frac{d^2N^{pair}}{d\Delta\eta d\Delta\phi} = B(0,0) \times \frac{S(\Delta\eta,\Delta\phi)}{B(\Delta\eta,\Delta\phi)}$$

Ridge vs p_T in PbPb

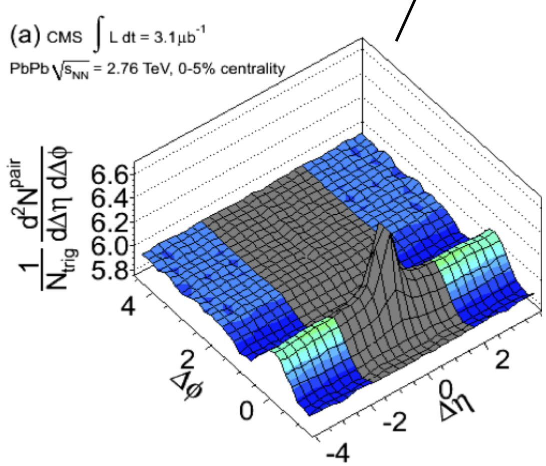
arXiv:1105.2438

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

p_T →



projection



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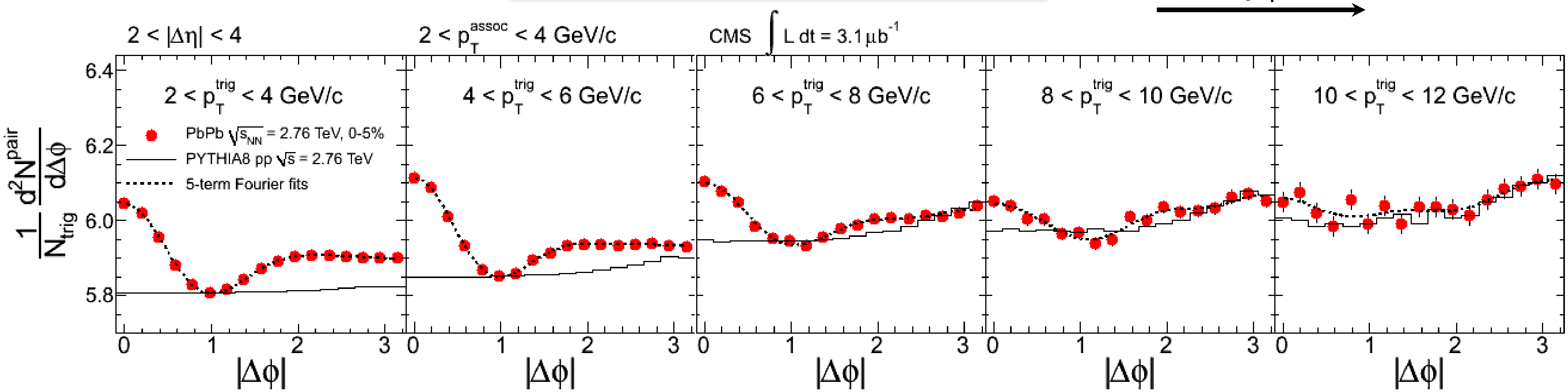
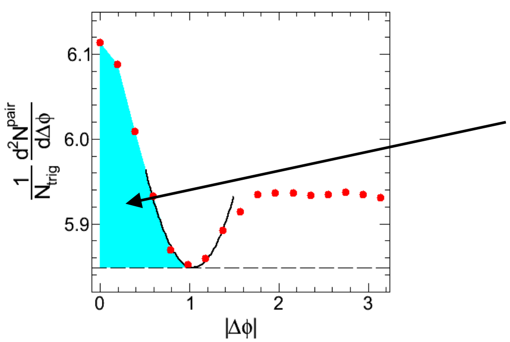
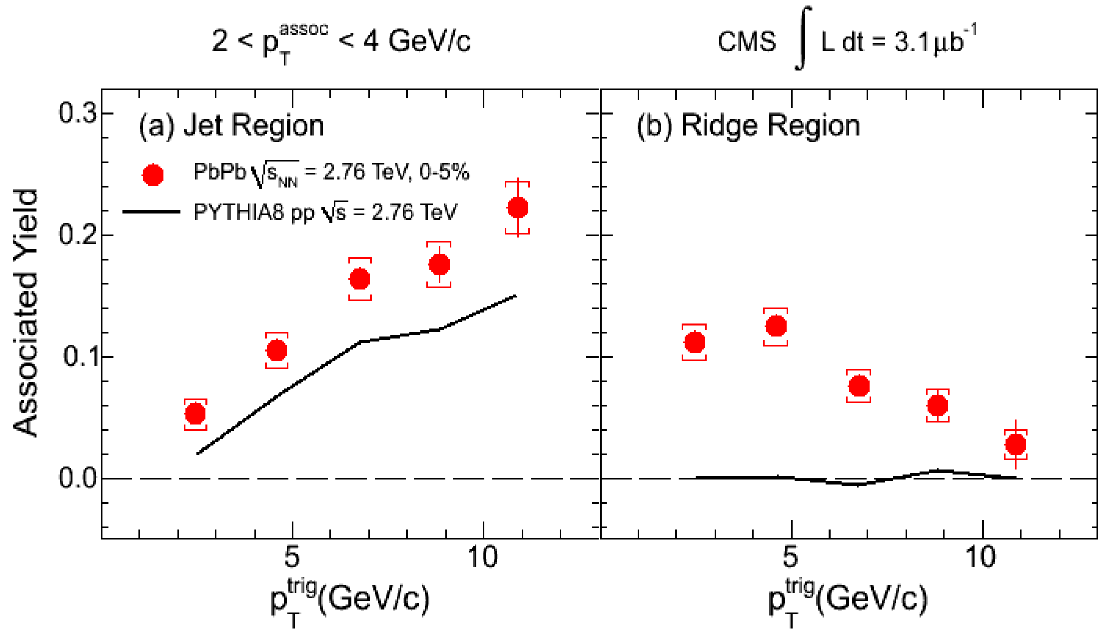
p_T →



ZYAM



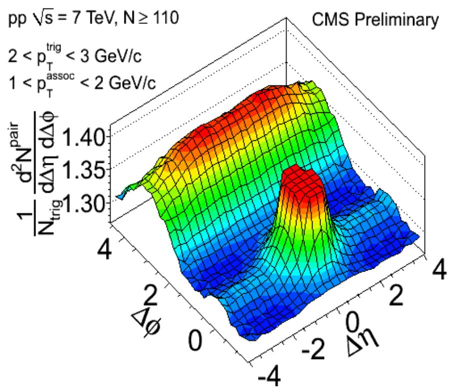
v_2 not subtracted



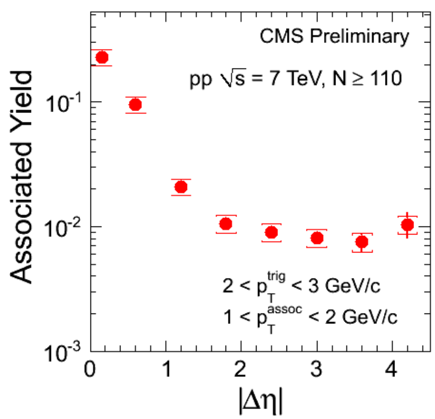
Ridge in PbPb collisions tends to diminish at high p_T

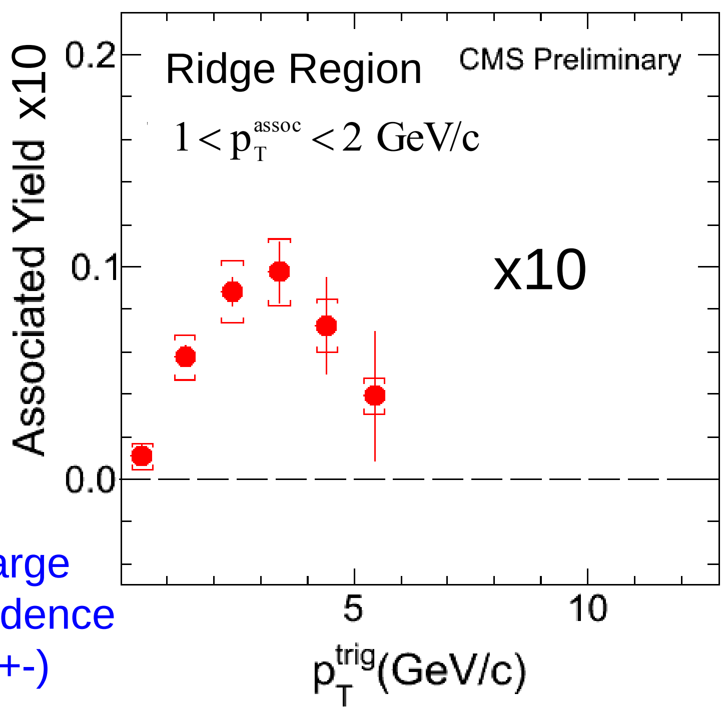
Ridge in pp and PbPb

CMS pp 7 TeV, N ≥ 110



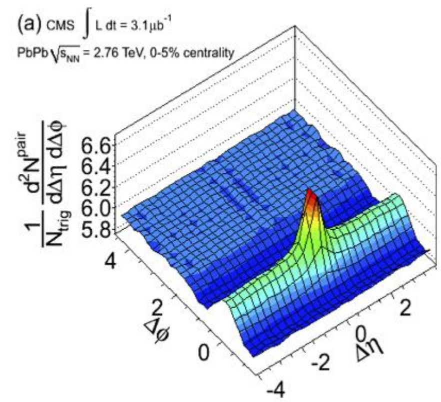
|Δη| dependence



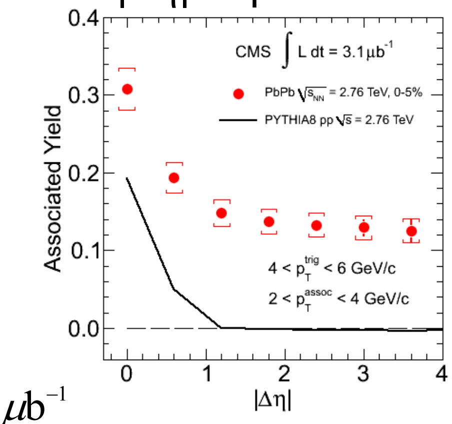


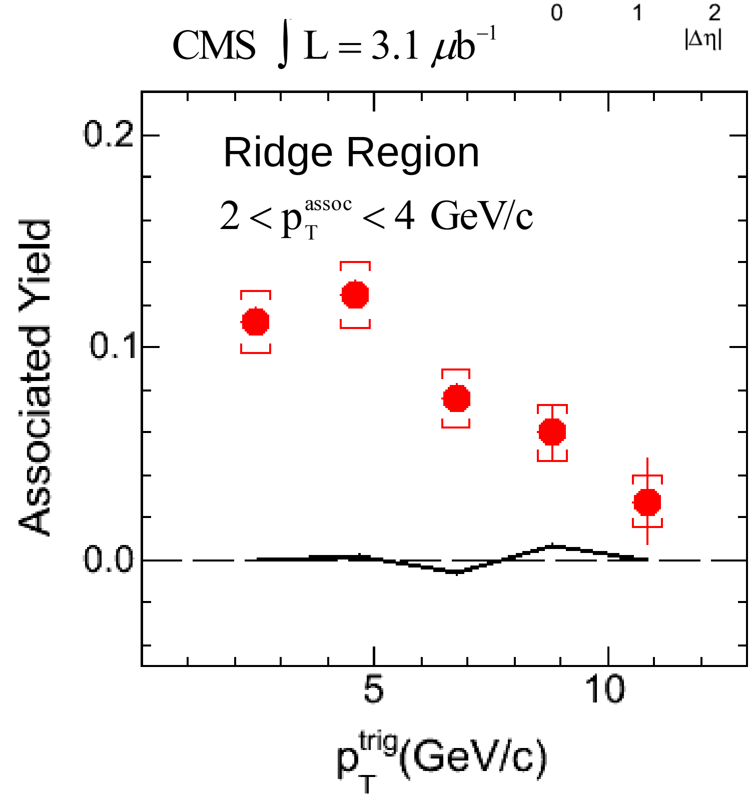
no charge dependence (++,--,+-)

CMS PbPb 2.76 TeV, 0-5%



|Δη| dependence



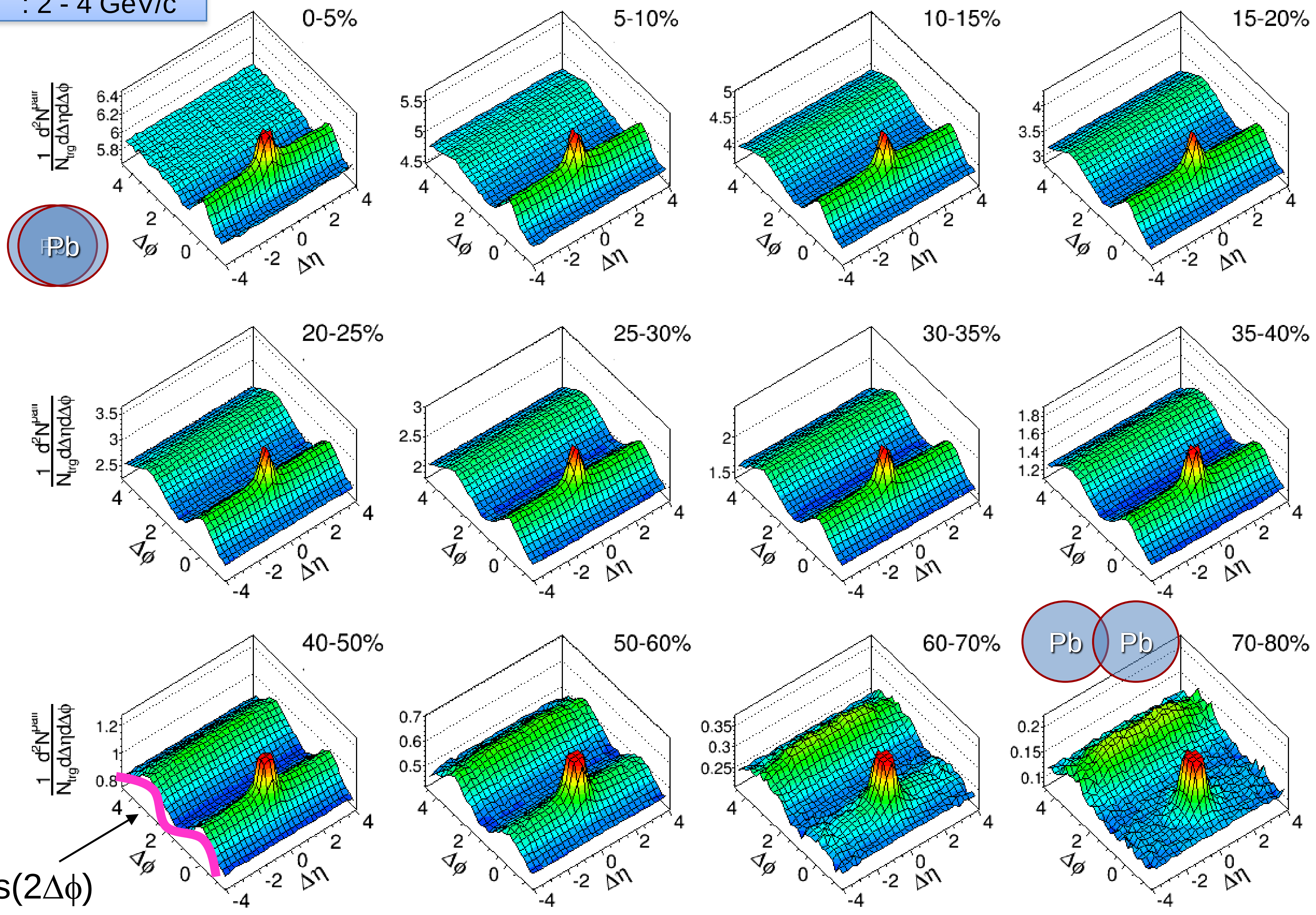


Centrality dependence in PbPb

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

PbPb 2.76 TeV

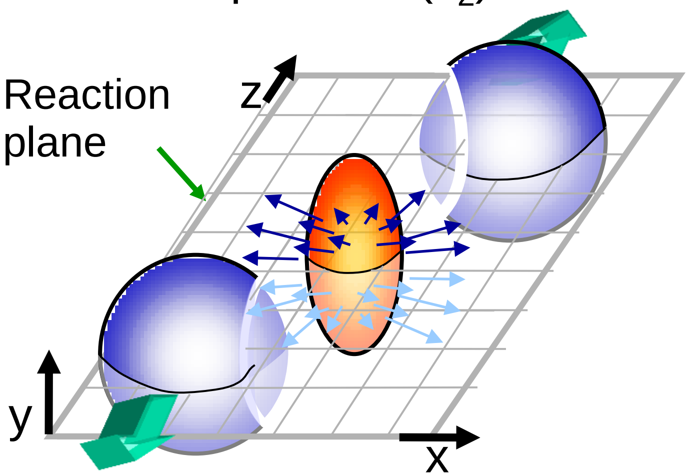
CMS Preliminary



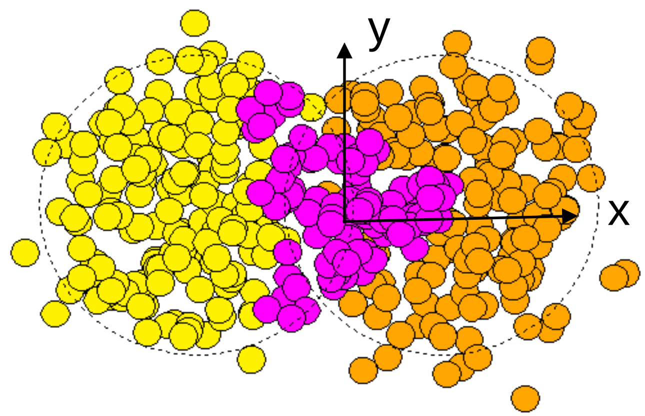
Fourier analysis of $\Delta\phi$ correlations

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

Elliptic flow (v_2)

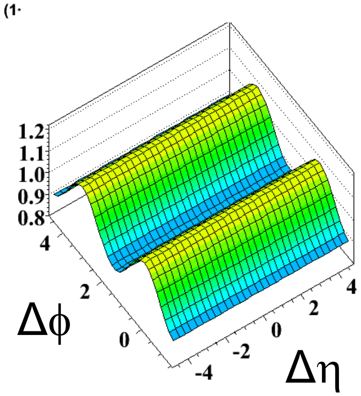


Triangular flow (v_3) from event-by-event fluctuation

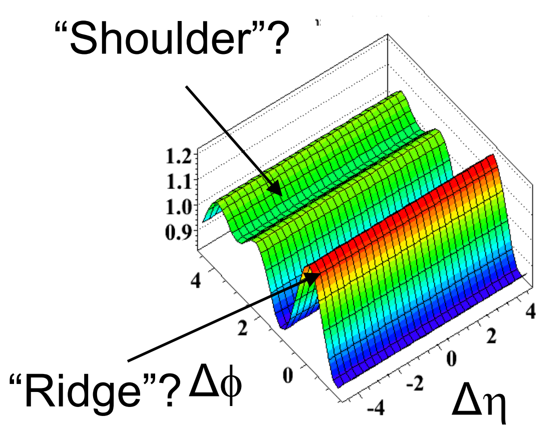


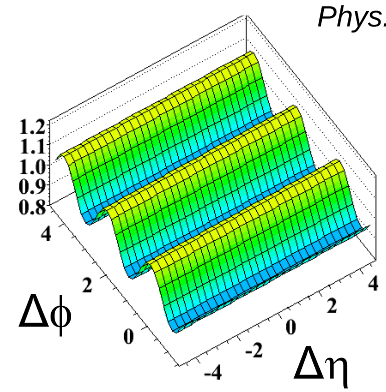
Phys. Rev. C81:054905, 2010

Add V_2 and V_3



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



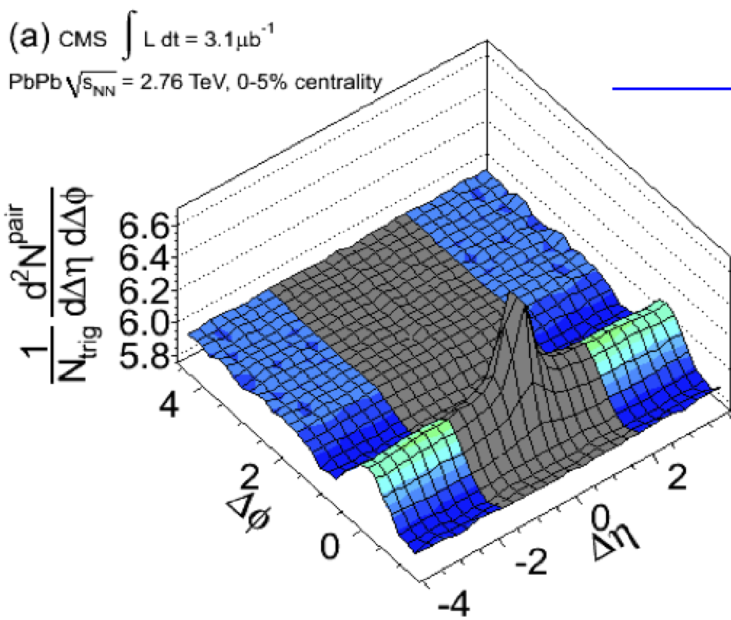


~ $V_3 \cos(3\Delta\phi)$

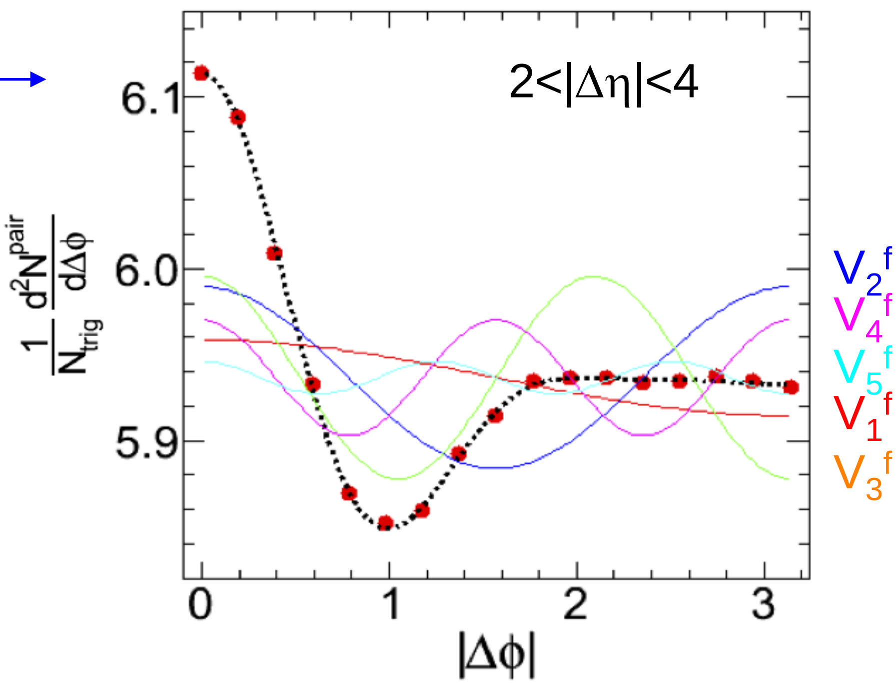
Fourier analysis of Δφ correlations

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

$$\frac{N_{assoc}}{2\pi}(1+2V_1^f\cos(\Delta\phi)+2V_2^f\cos(2\Delta\phi)+2V_3^f\cos(3\Delta\phi)+2V_4^f\cos(4\Delta\phi)+2V_5^f\cos(5\Delta\phi)+...)$$

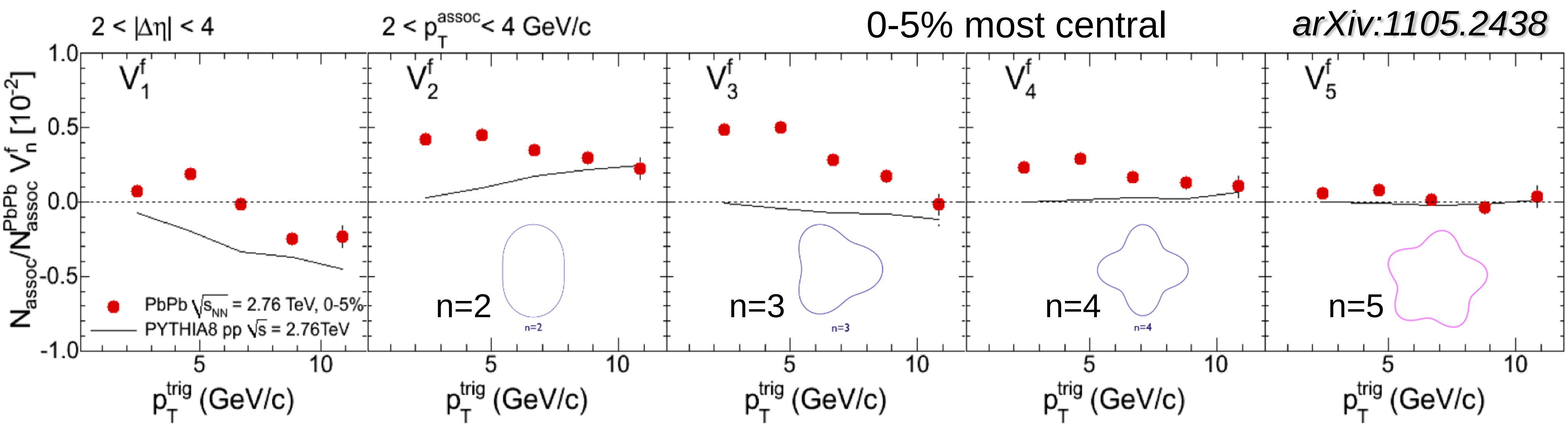


Short-range non-flow effects excluded

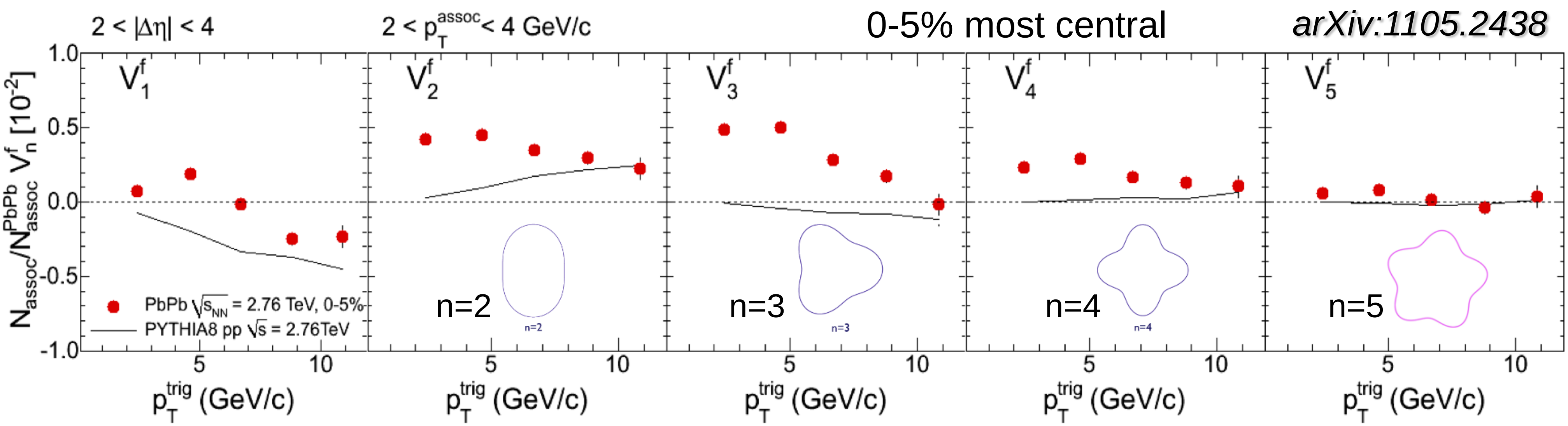


Very hot topic in QM2011!

Fourier analysis of Δϕ correlations



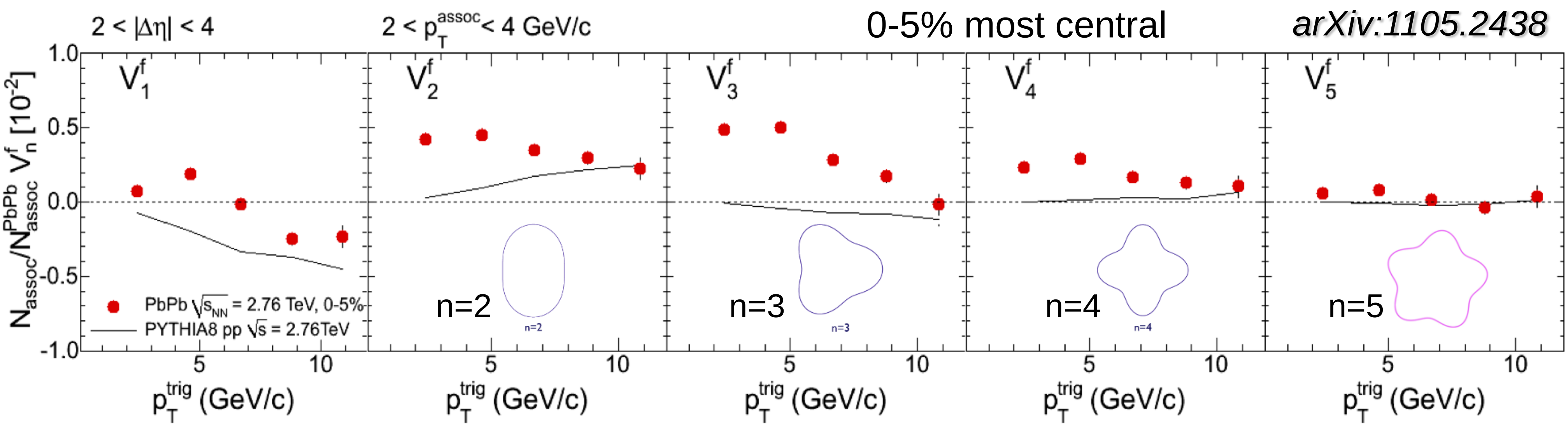
Fourier analysis of Δϕ correlations



For flow driven correlations, factorization:

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

Fourier analysis of $\Delta\phi$ correlations



For flow driven correlations, factorization:

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

Deriving flow harmonics (v_n^f)

Off-diagonal terms

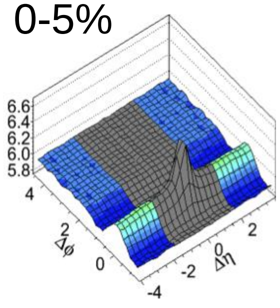
$$\frac{V_n^f(p_T^{trig}, p_T^{assoc})}{\sqrt{V_n^f(p_T^{assoc}, p_T^{assoc})}} = \frac{v_n(p_T^{trig}) \times v_n(p_T^{trig})}{\sqrt{v_n(p_T^{assoc}) \times v_n(p_T^{assoc})}} = v_n(p_T^{trig})$$

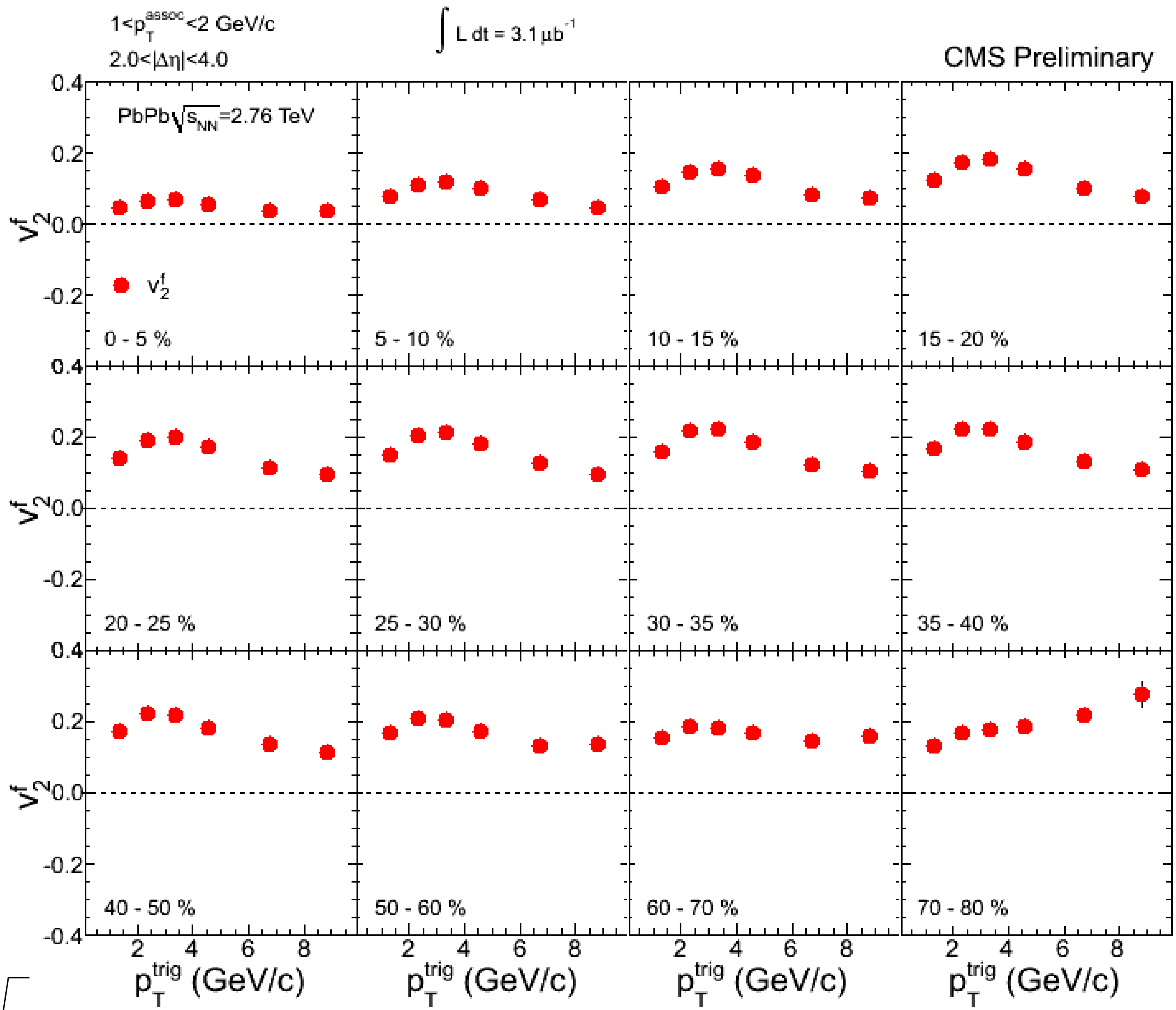
Diagonal terms

Keep low p_T^{assoc} to minimize non-flow

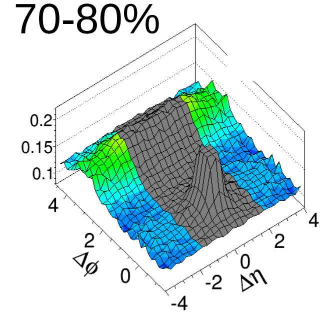
v_2 from long-range correlations

0-5%





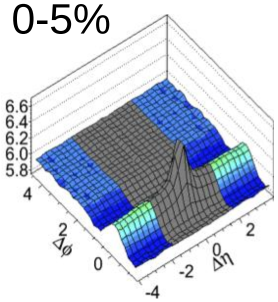
70-80%

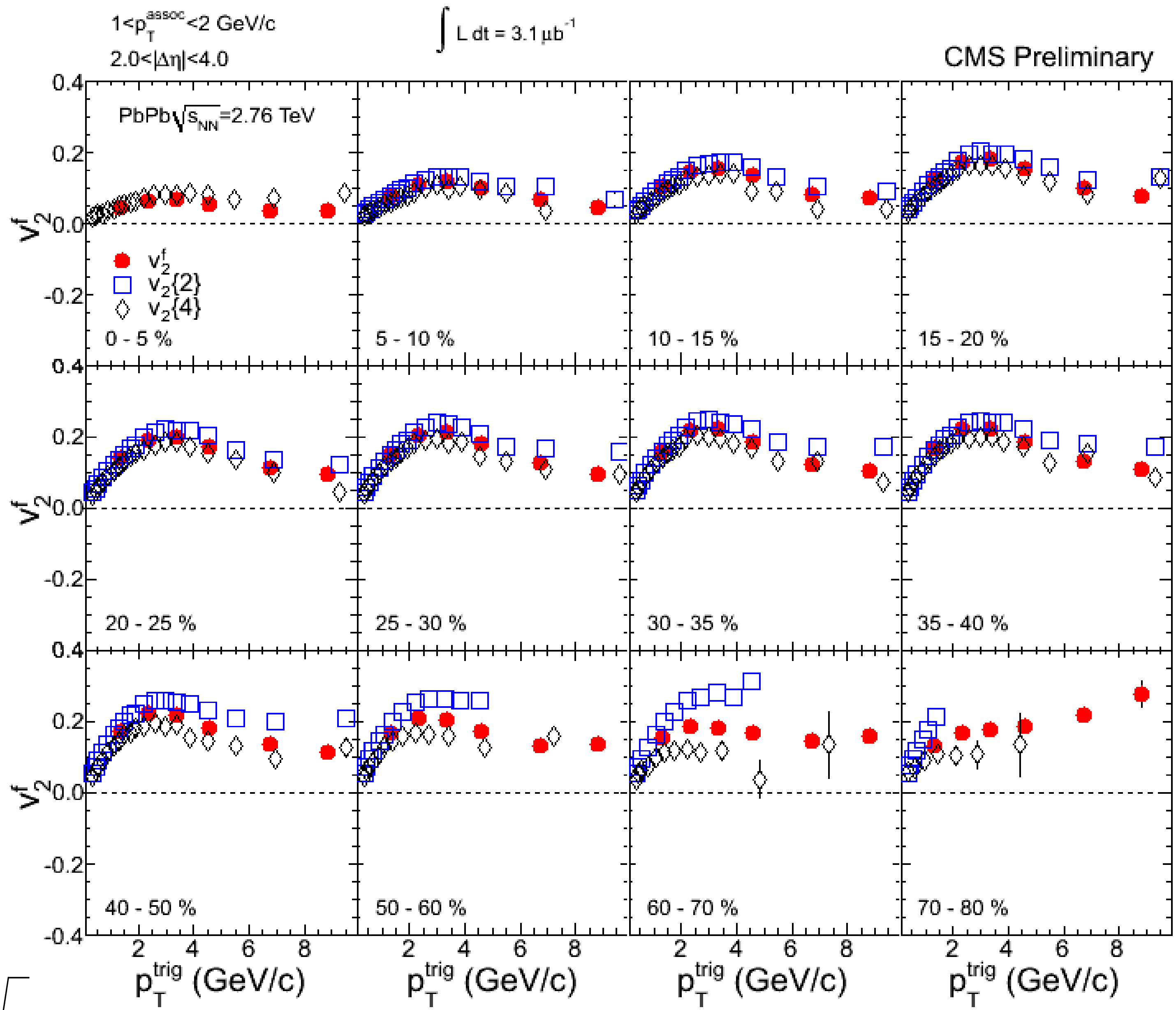


$V_n^f(\text{Fourier}) \xrightarrow{\sqrt{\ }} v_n^f(\text{flow})$

v_2 from long-range correlations

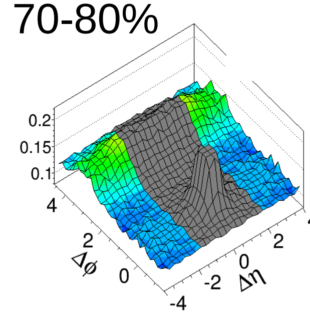
0-5%





- v_2^f
- $v_2\{2\}$
- $v_2\{4\}$

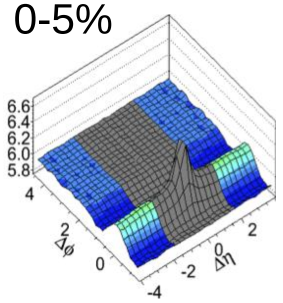
70-80%

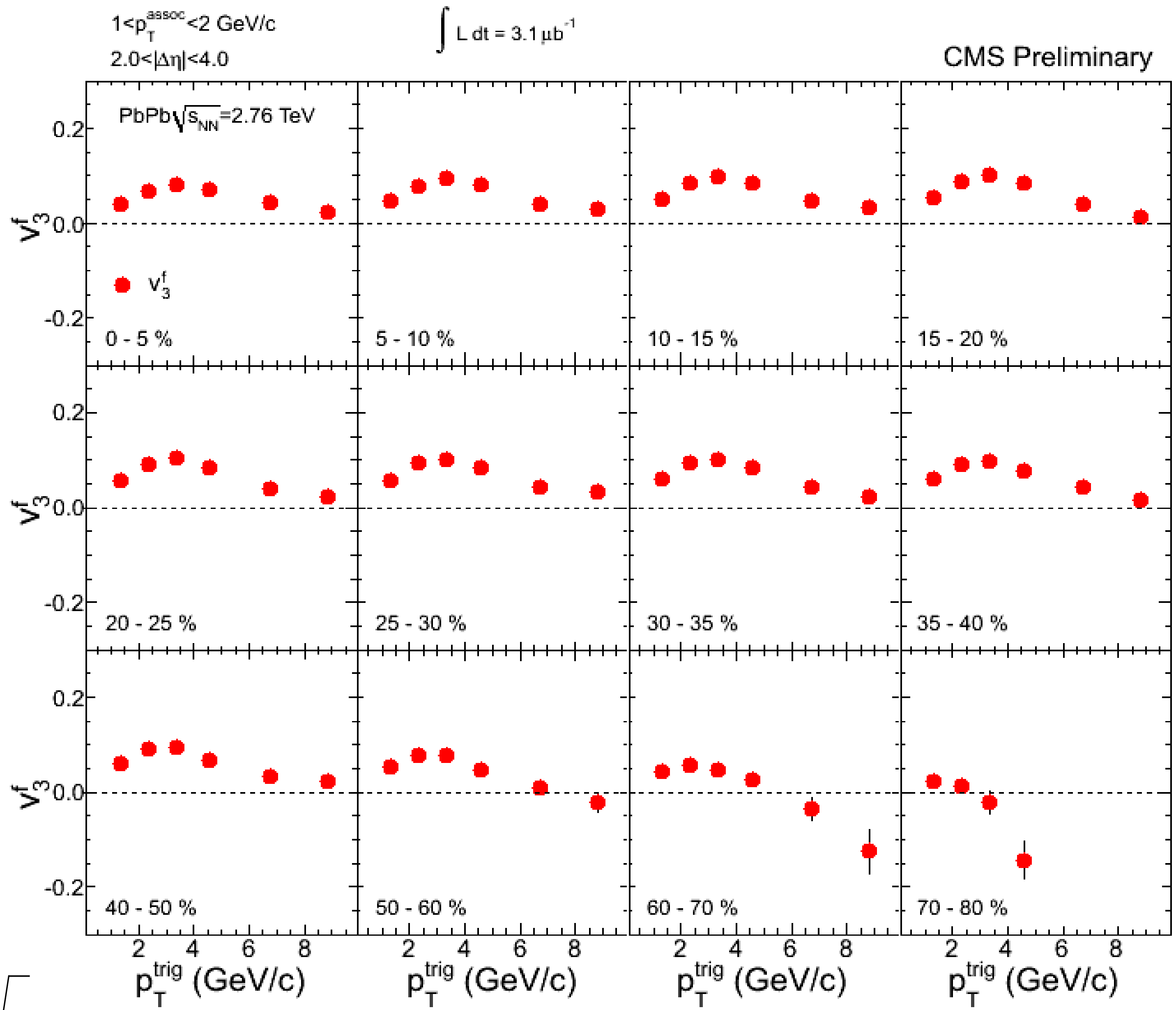


$V_n^f(\text{Fourier}) \xrightarrow{\sqrt{\ }} v_n^f(\text{flow})$

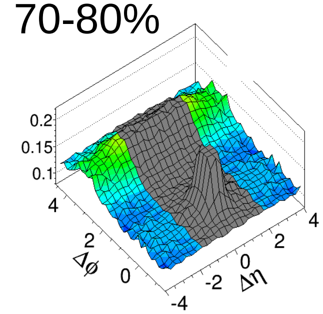
v_3 from long-range correlations

0-5%





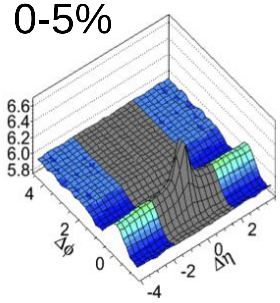
70-80%

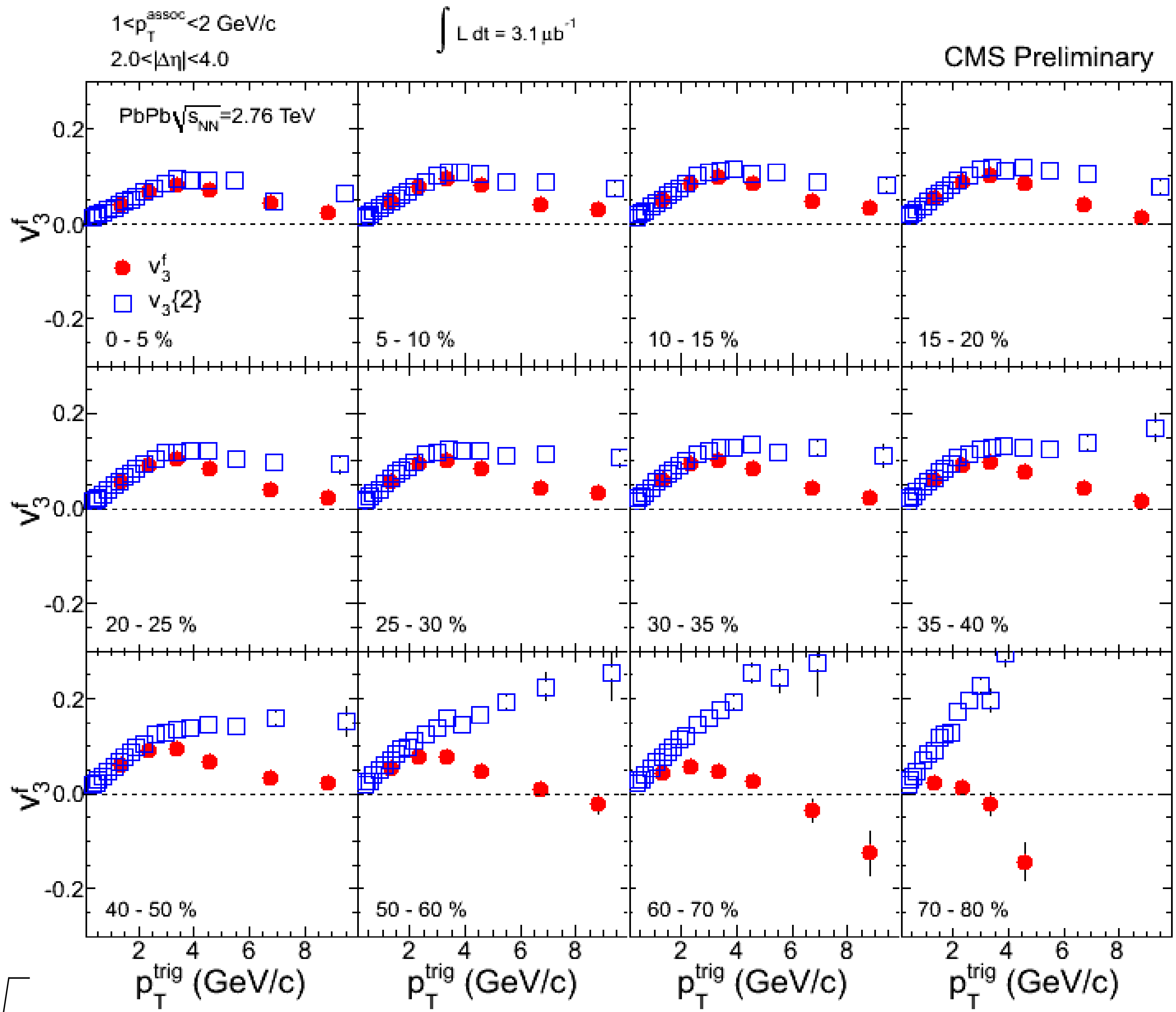


V_n^f(Fourier) $\xrightarrow{\sqrt{\ }}$ v_n^f(flow)

v_3 from long-range correlations

0-5%

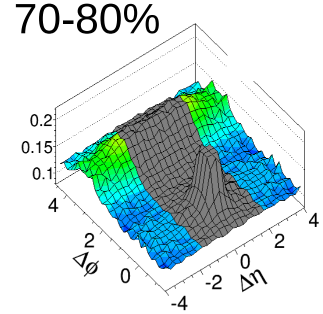




● v_3^f

□ $v_3\{2\}$

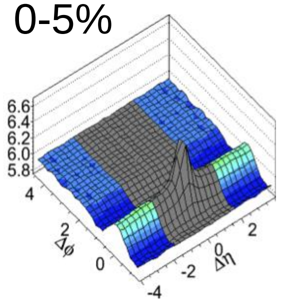
70-80%

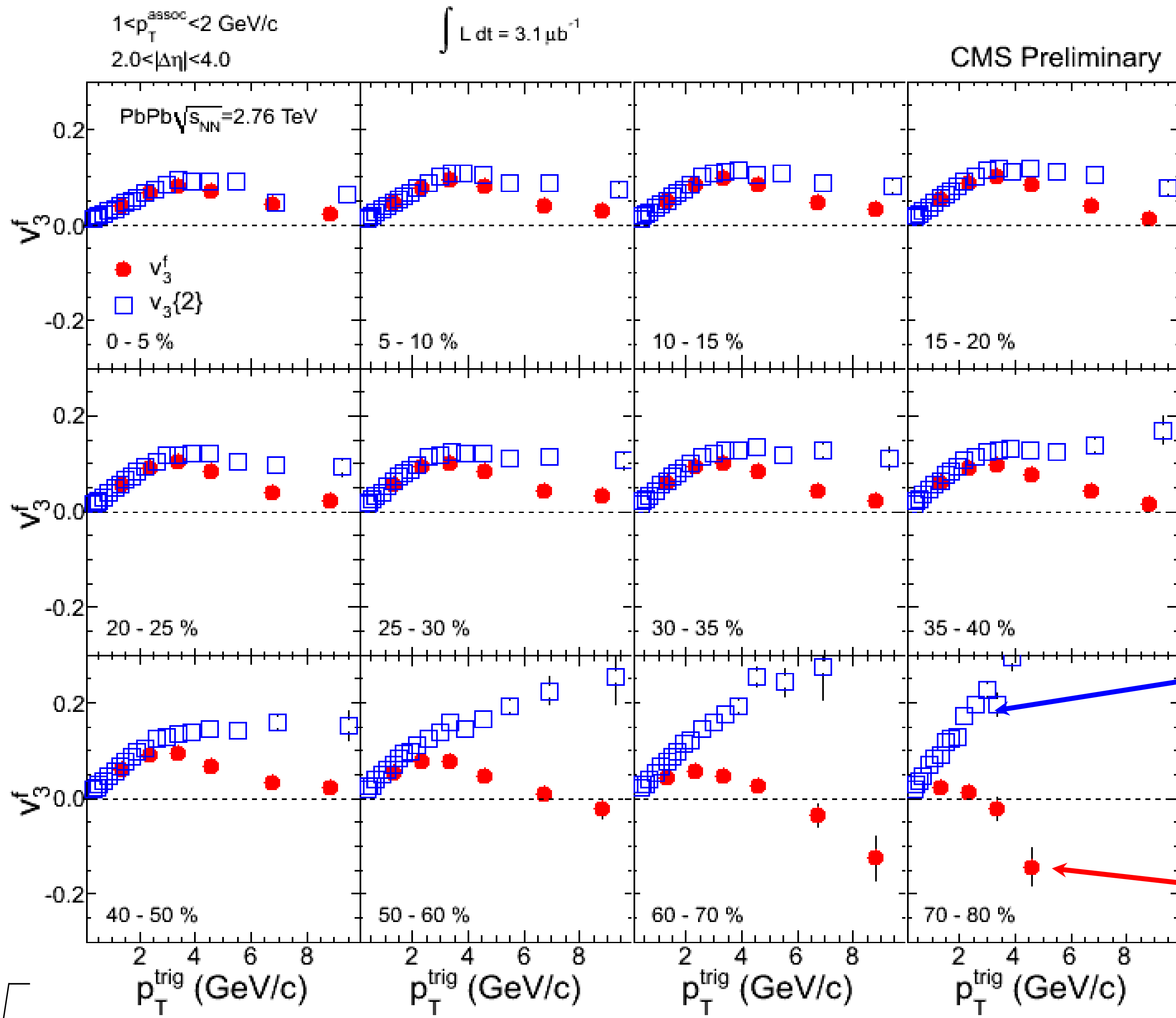


V_n^f(Fourier) $\xrightarrow{\sqrt{\ }}$ v_n^f(flow)

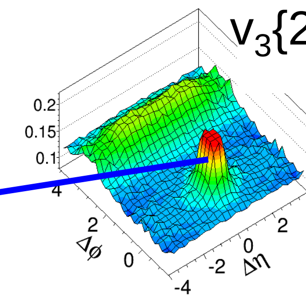
v_3 from long-range correlations

0-5%



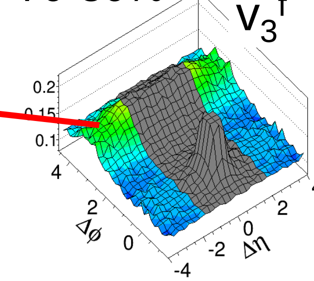


- v_3^f
- $v_3\{2\}$



$v_3\{2\}$

70-80%

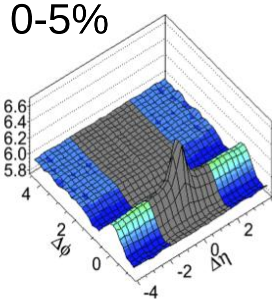


v_3^f

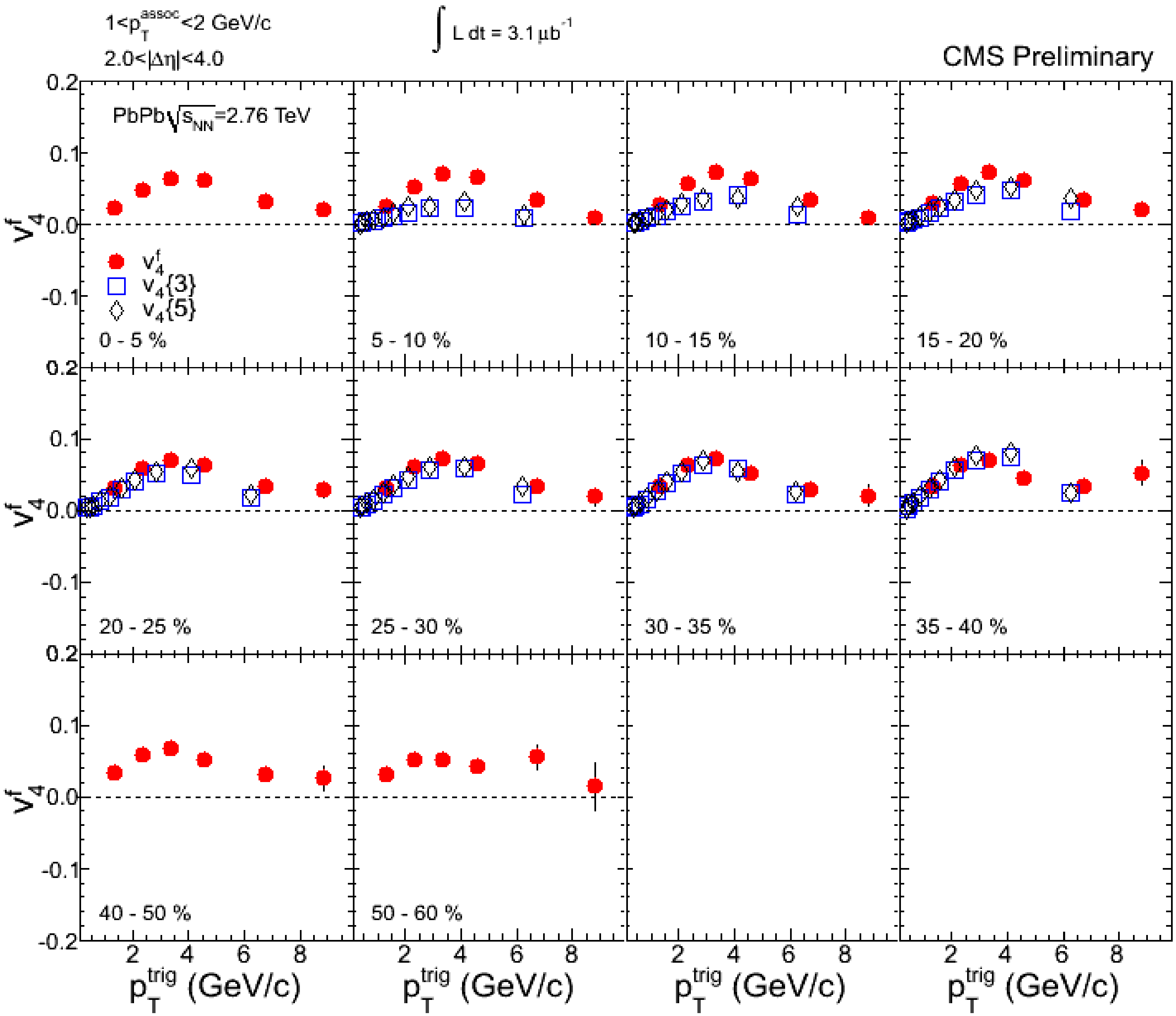
$V_n^f\text{(Fourier)} \xrightarrow{\sqrt{\ }} v_n^f\text{(flow)}$

v_4 from long-range correlations

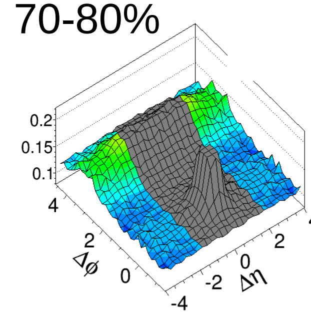
0-5%



● v_4^f
□ $v_4\{3\}$
◇ $v_4\{5\}$

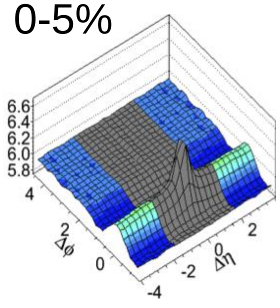


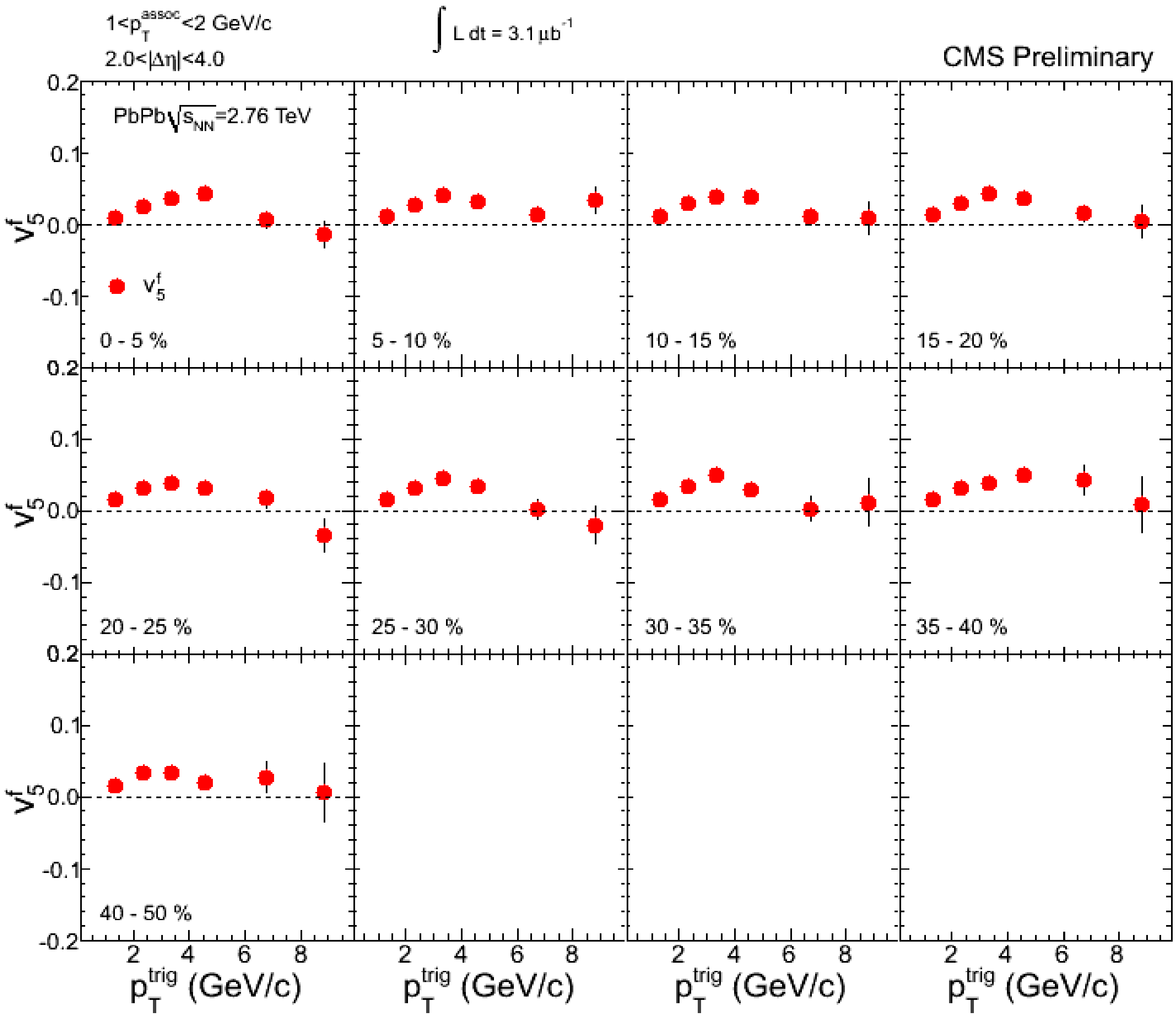
70-80%



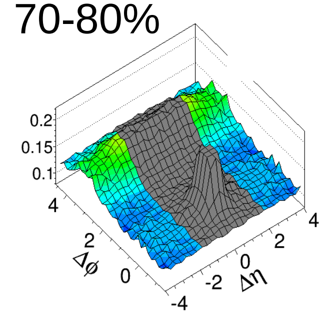
v_5 from long-range correlations

0-5%

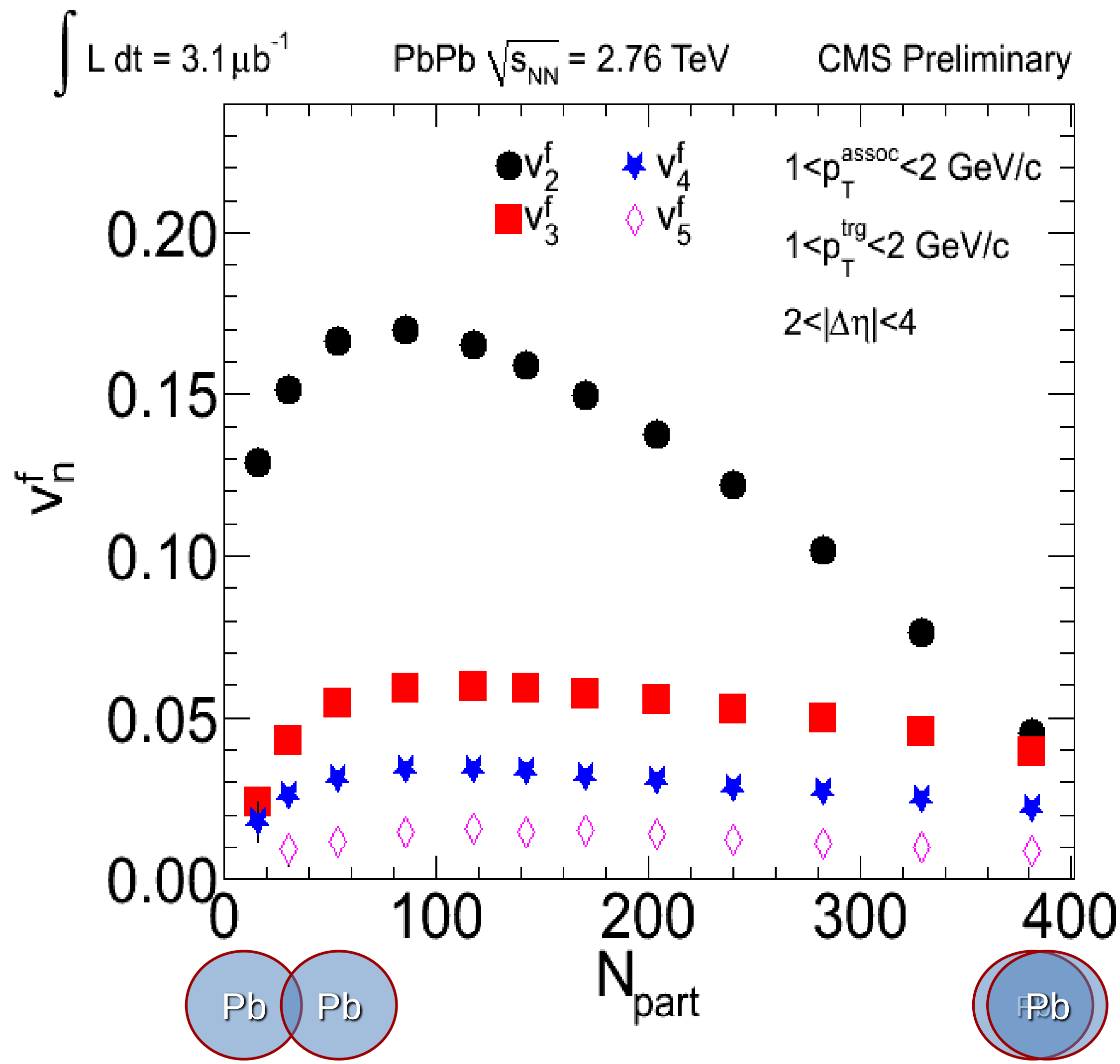




70-80%



Flow coefficients (v^f_n) 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 models but resembles similar effect in heavy-ion collisions
- Increases at low p_T (up to 3GeV/c) and tends to vanish at high p_T
- Ridge emerges at N ~ 50 – 60 (4 times of <N> in MinBias)
- *New opportunity of high-density QCD physics in a small system*

Comprehensive studies of dihadron correlations in 2.76 TeV PbPb

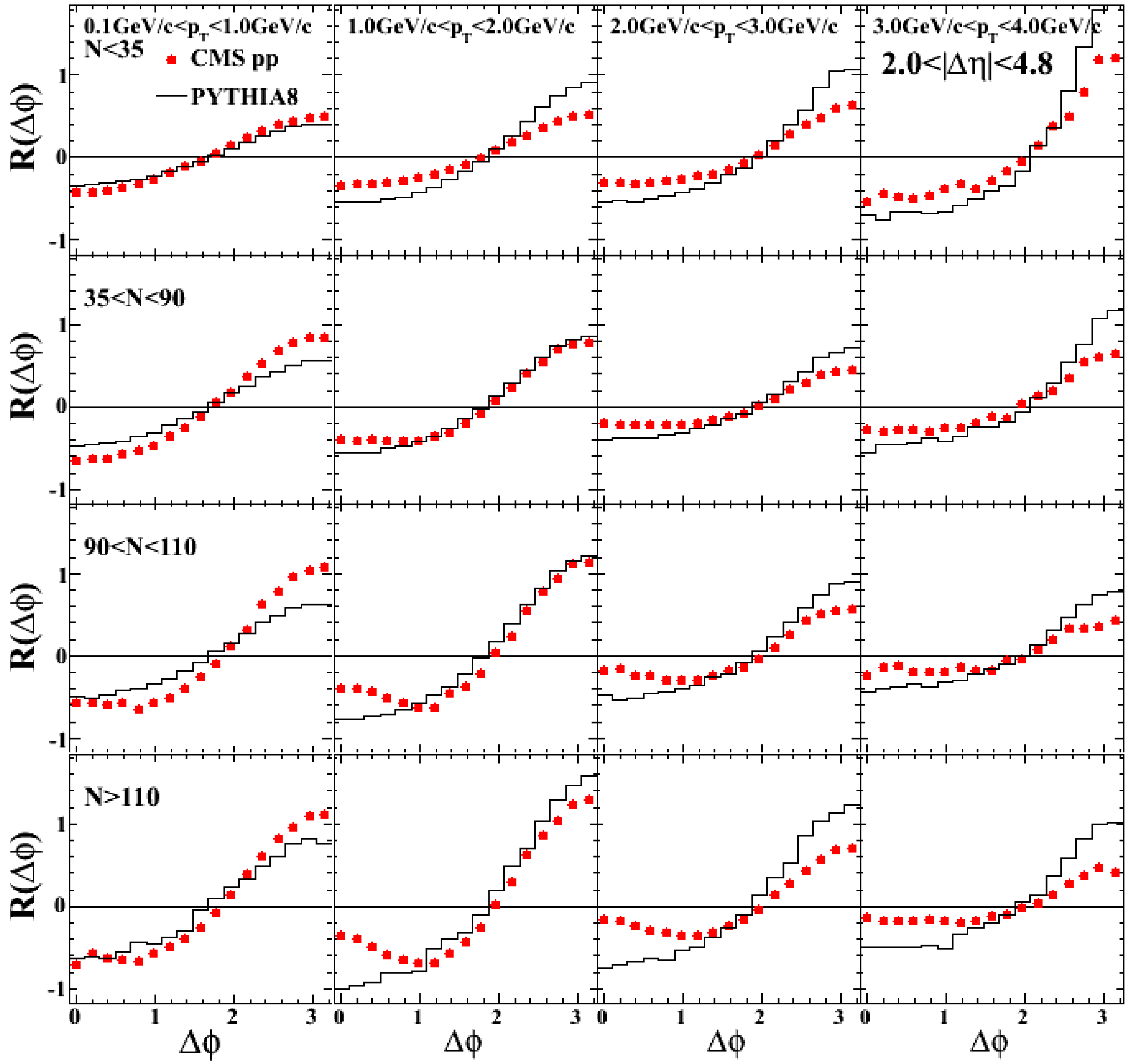
- In central PbPb, ridge yield significantly drops toward high p_T
- Higher order flow from a Fourier analysis of long-range correlations
  - Factorization of V_n^f: $V_n^f = v_n^f(p_T^{trig}) \times v_n^f(p_T^{assoc})$
  - Consistent with standard flow methods
  - Trend in centrality and p_T follows hydrodynamic expectation

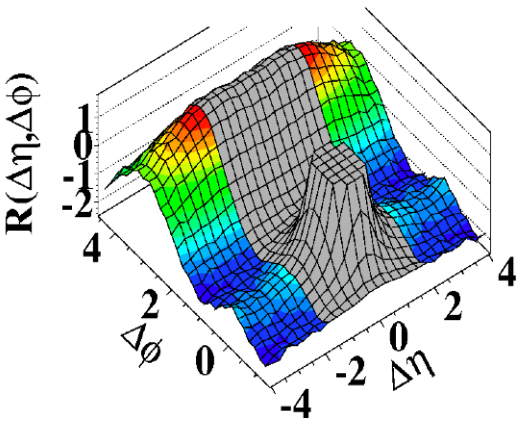
Backups

1-D projected R(Δφ) at large Δη

Increasing p_T

Increasing multiplicity



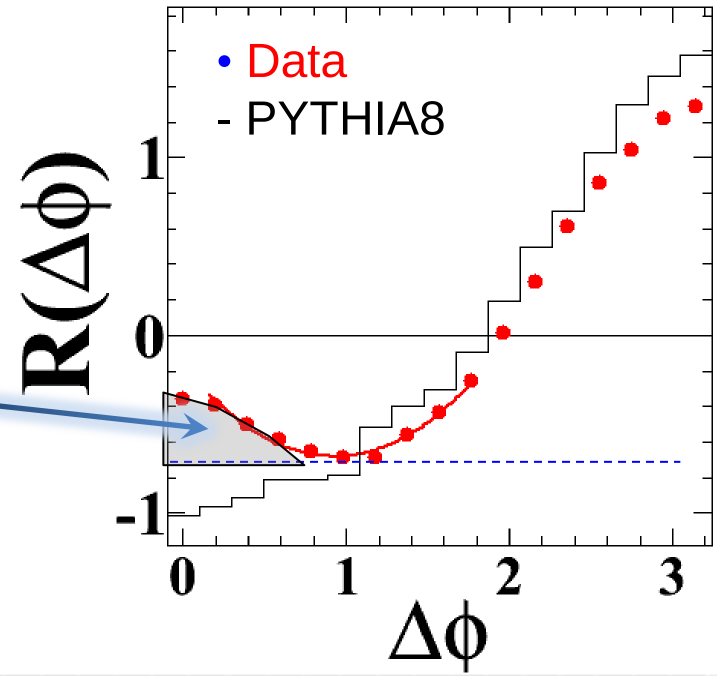


Quantify the Ridge

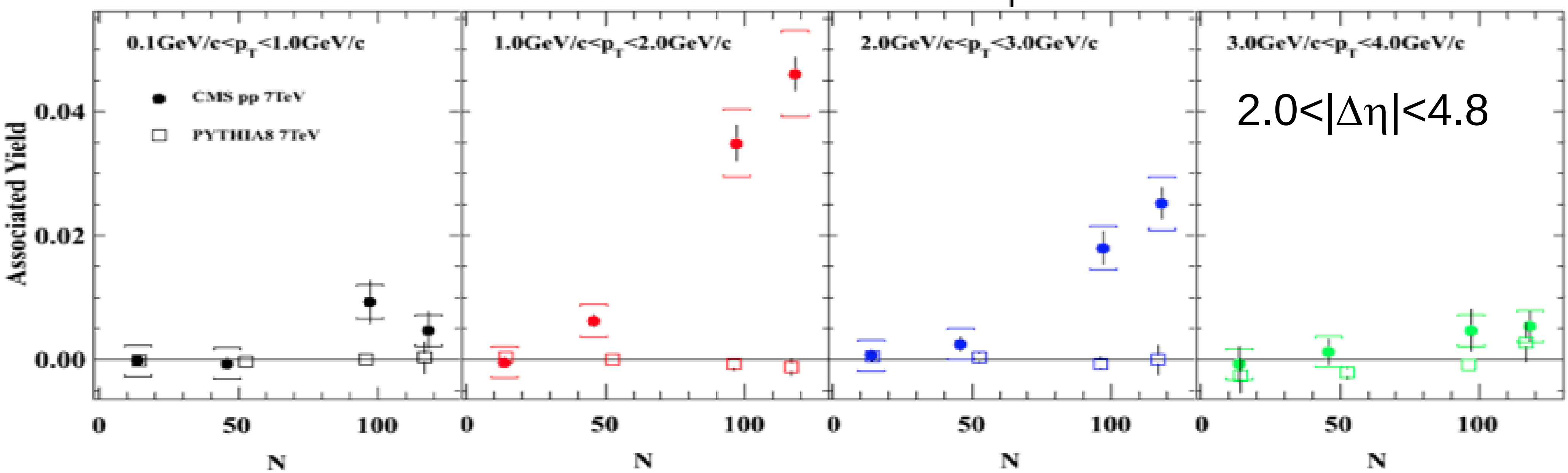
Zero Yield At Minimum (ZYAM)

Associated yield:

correlated multiplicity per particle

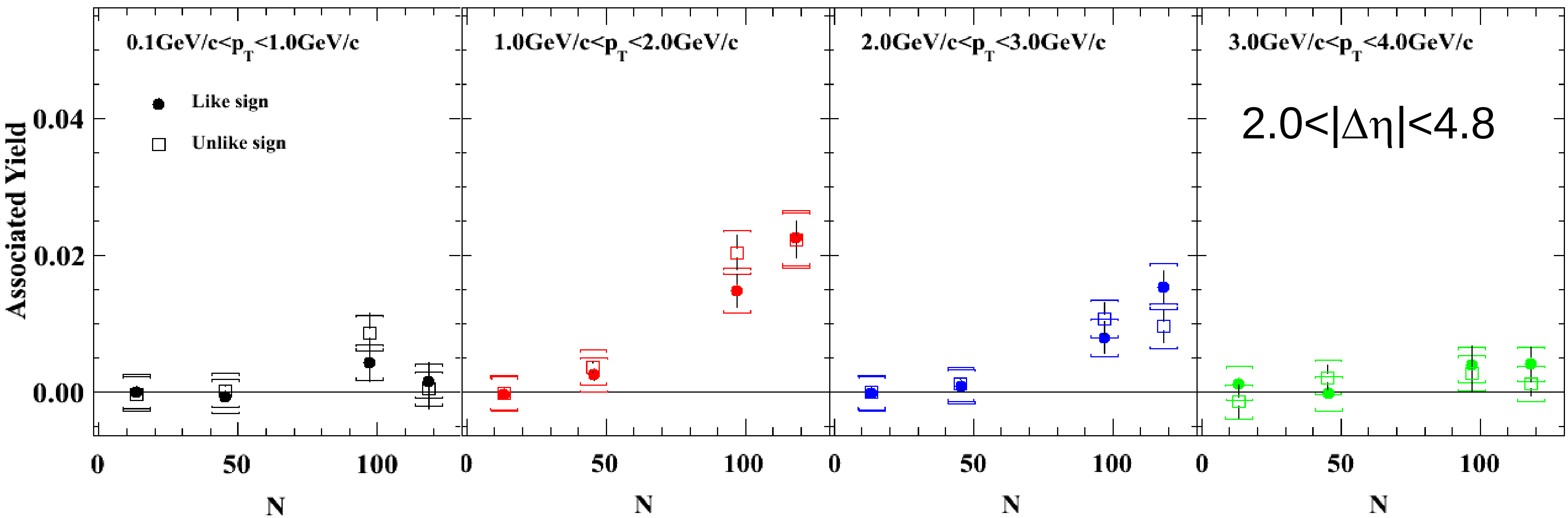


N>110
$2.0<|\Delta\eta|<4.8$
$1\,\mathrm{GeV}/c<p_T<2\,\mathrm{GeV}/c$



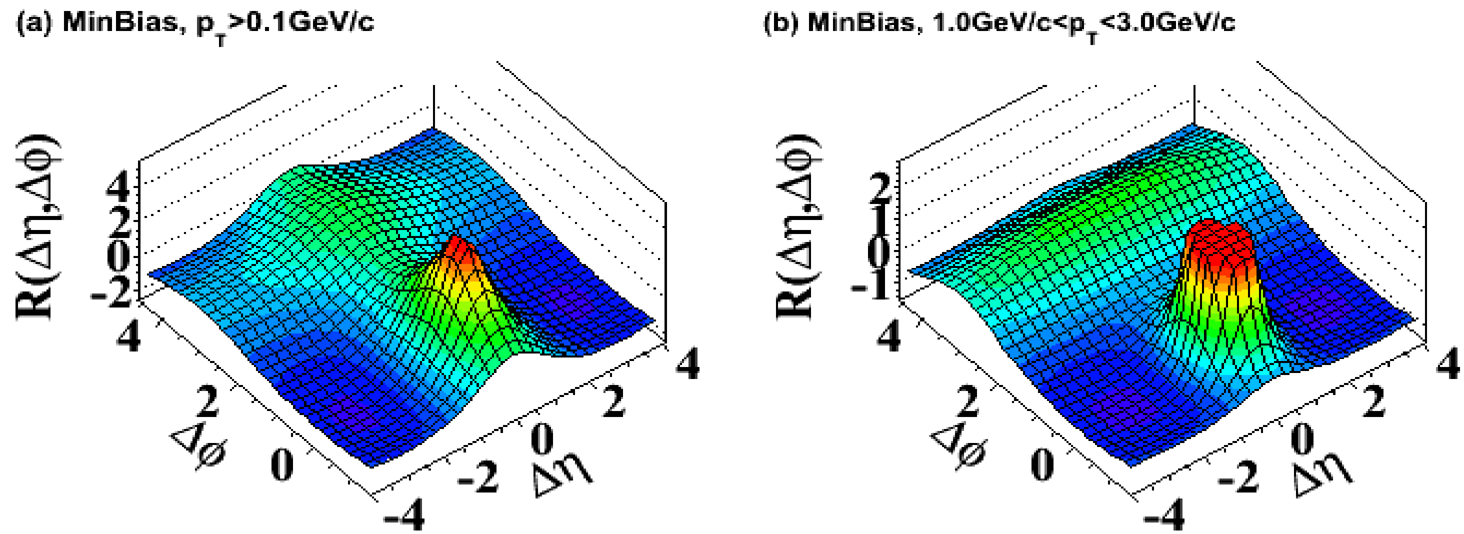
Charge Dependence of the Ridge

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

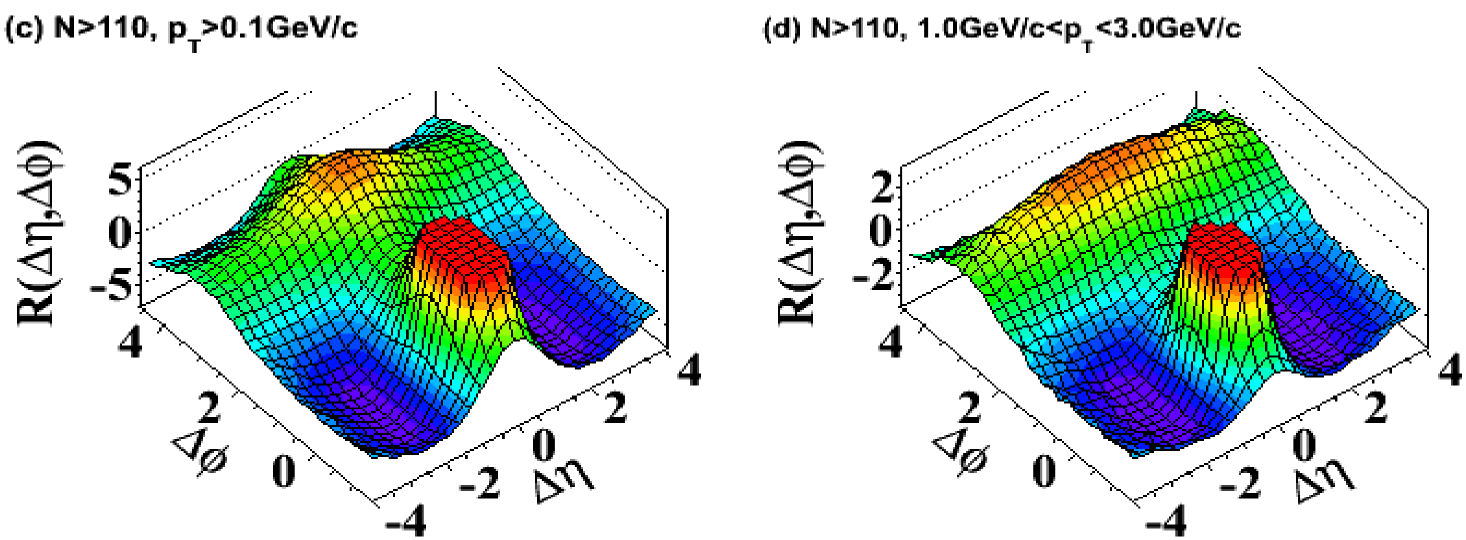


No charge sign dependence of the ridge!

Comparing to various MC



PYTHIA8, v8.135

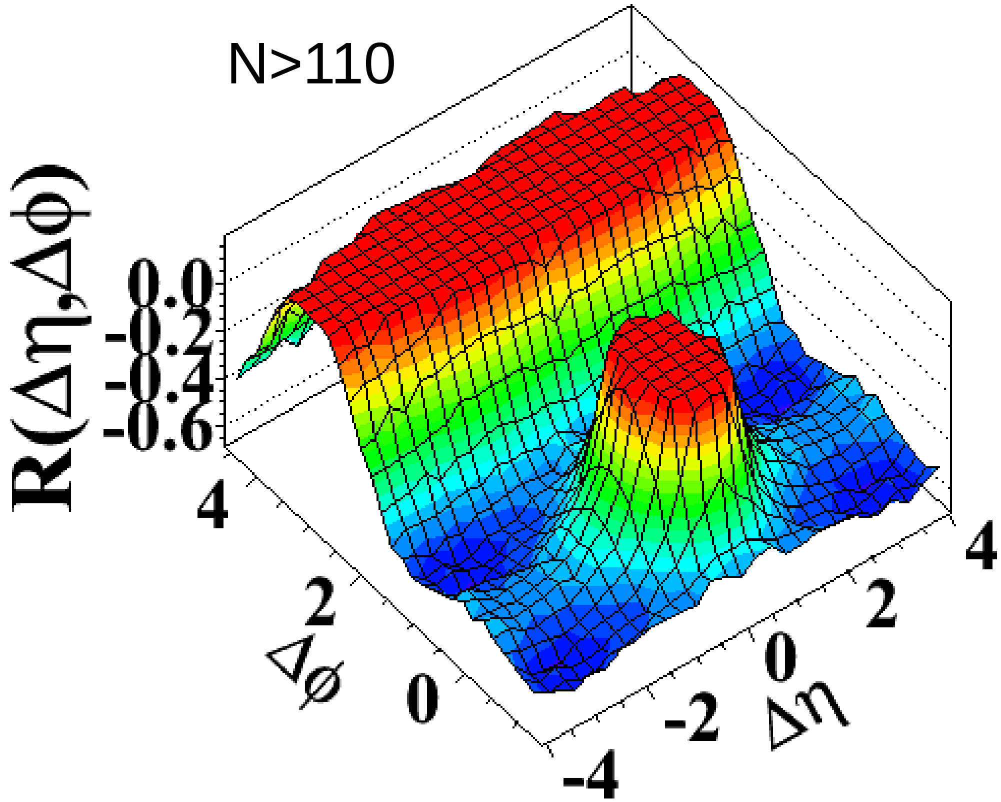


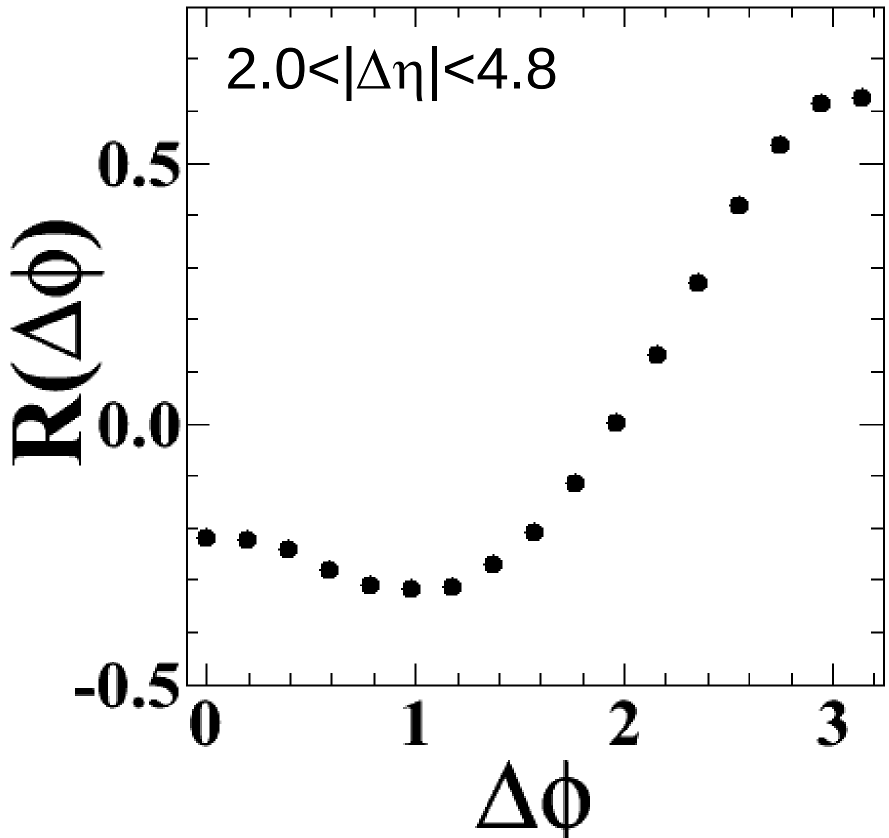
Cross check: ECAL Photons

Charged hadron - photon correlations

(photons are mostly from π^0 decay)

$1.0GeV/c<p_T<3.0GeV/c$
for both hadrons and photons





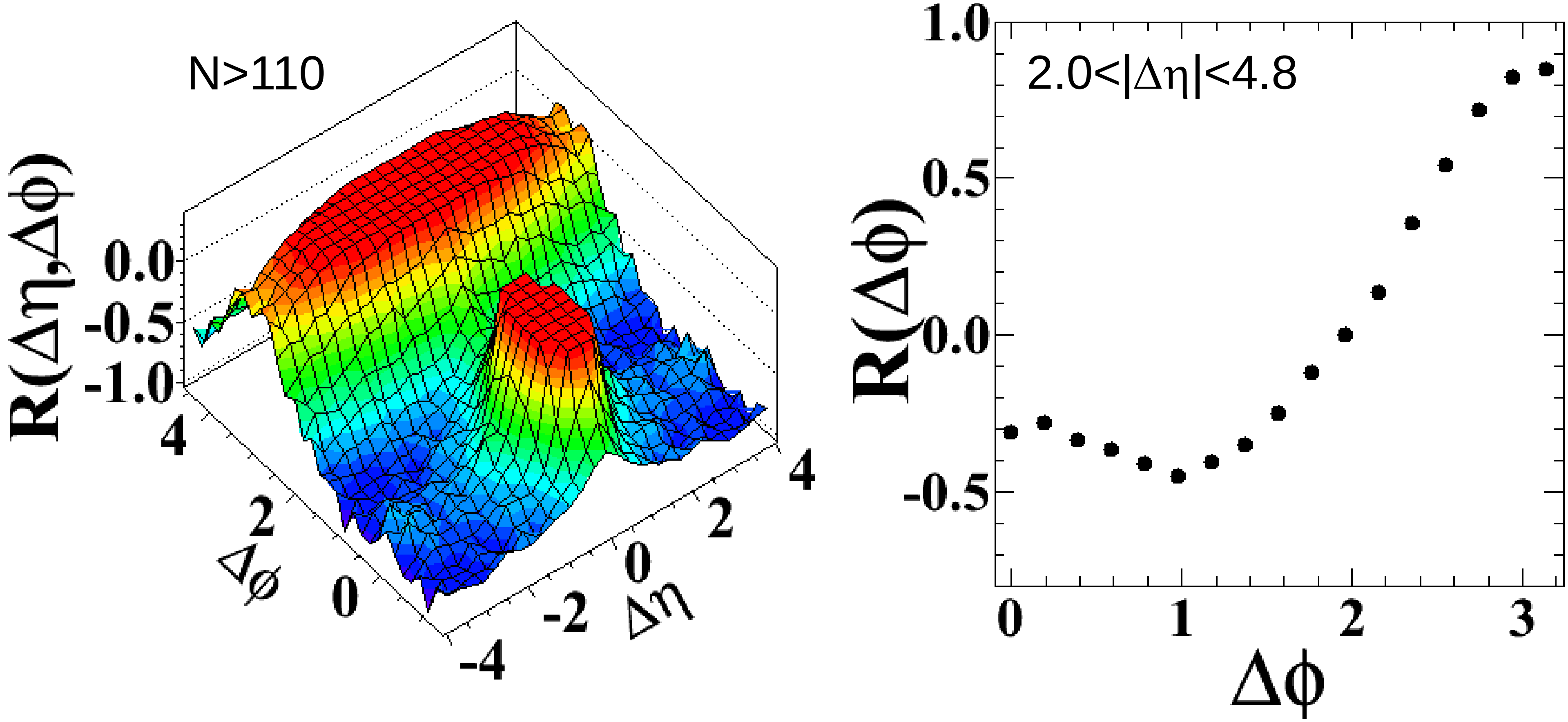
Independent detector, independent reconstruction!

Cross check: ECAL Photons

photon - photon correlations

(photons are mostly from π^0 decay)

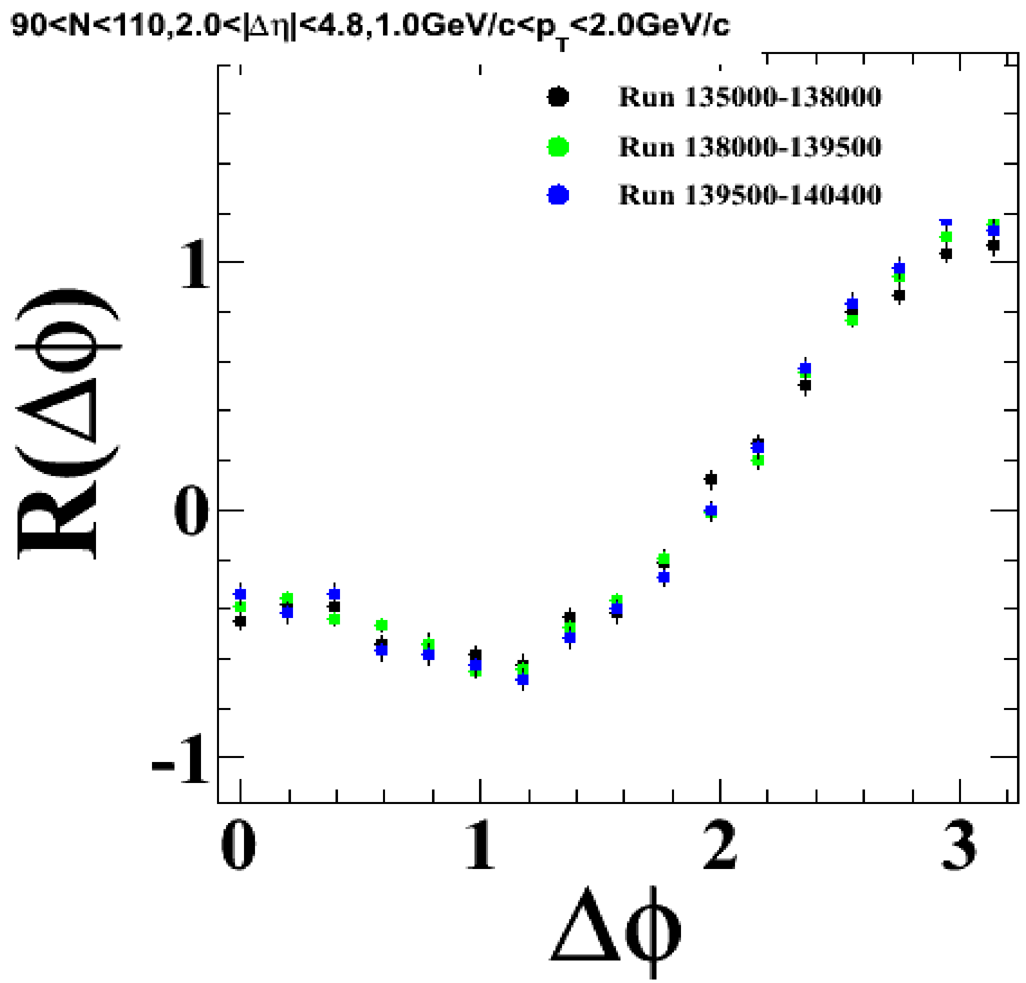
$1.0GeV/c<p_T<3.0GeV/c$



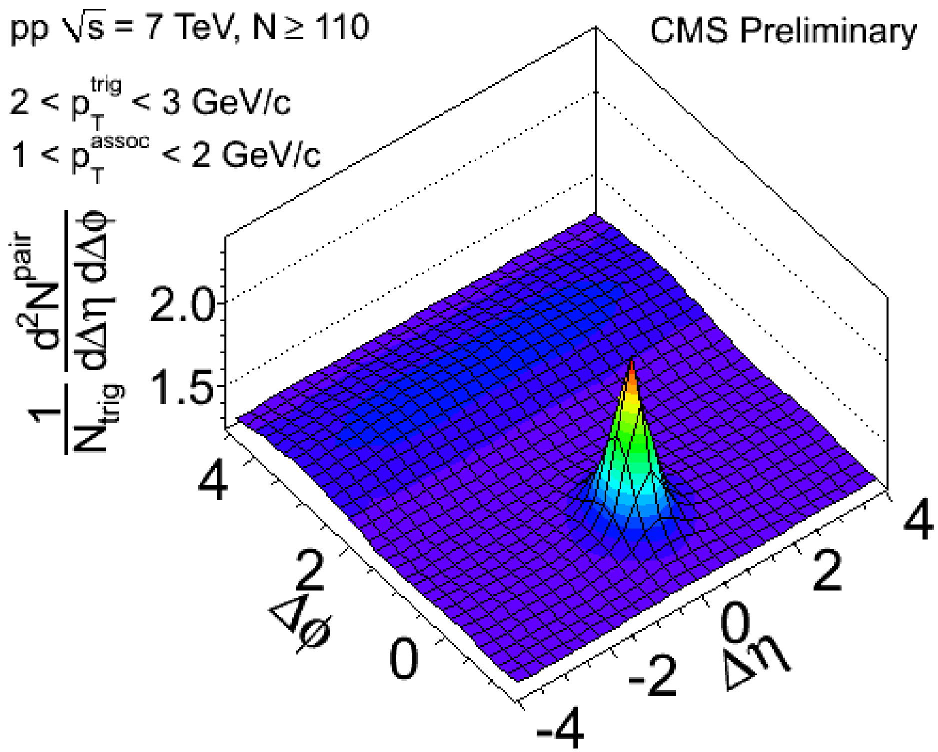
Independent detector, independent reconstruction!

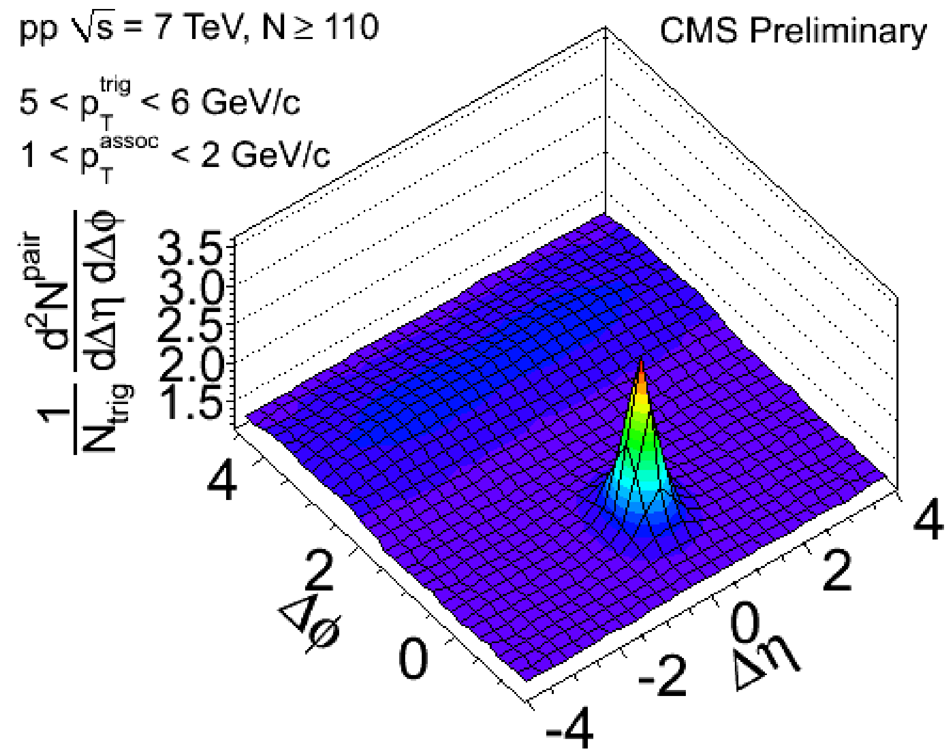
Cross Check: Event Pileup

Compare different run periods



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


pp √s = 7 TeV, N ≥ 110
CMS Preliminary
2 < p_T^trig < 3 GeV/c
1 < p_T^assoc < 2 GeV/c
1/N_trig d²N^pair/dΔη dΔφ
Δφ
Δη


pp √s = 7 TeV, N ≥ 110
CMS Preliminary
5 < p_T^trig < 6 GeV/c
1 < p_T^assoc < 2 GeV/c
1/N_trig d²N^pair/dΔη dΔφ
Δφ
Δη

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

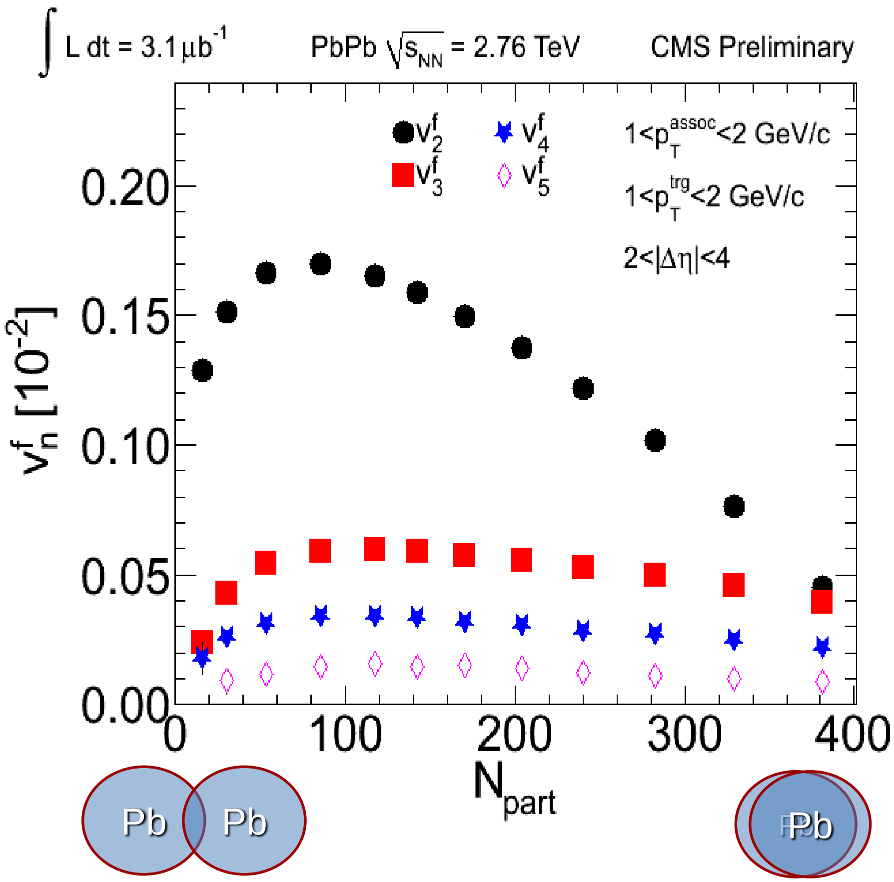
$$V_n^f(p_T^{trig}, p_T^{assoc}) = v_n^f(p_T^{trig}) \times v_n^f(p_T^{assoc})$$

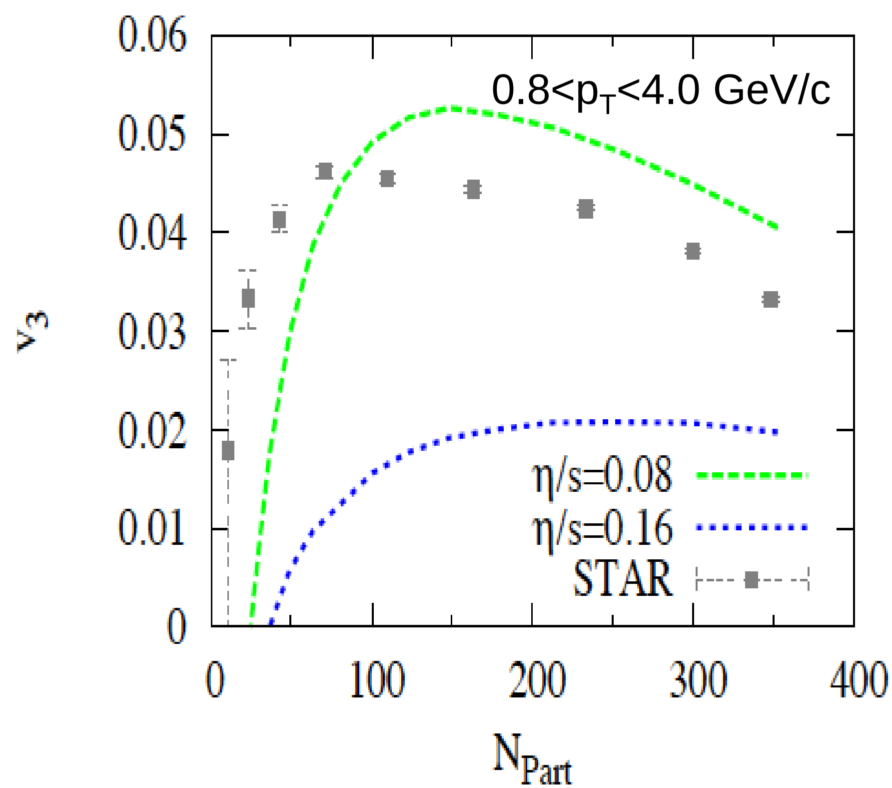
We can get:

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

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

Flow coefficients (v^f_n) vs centrality





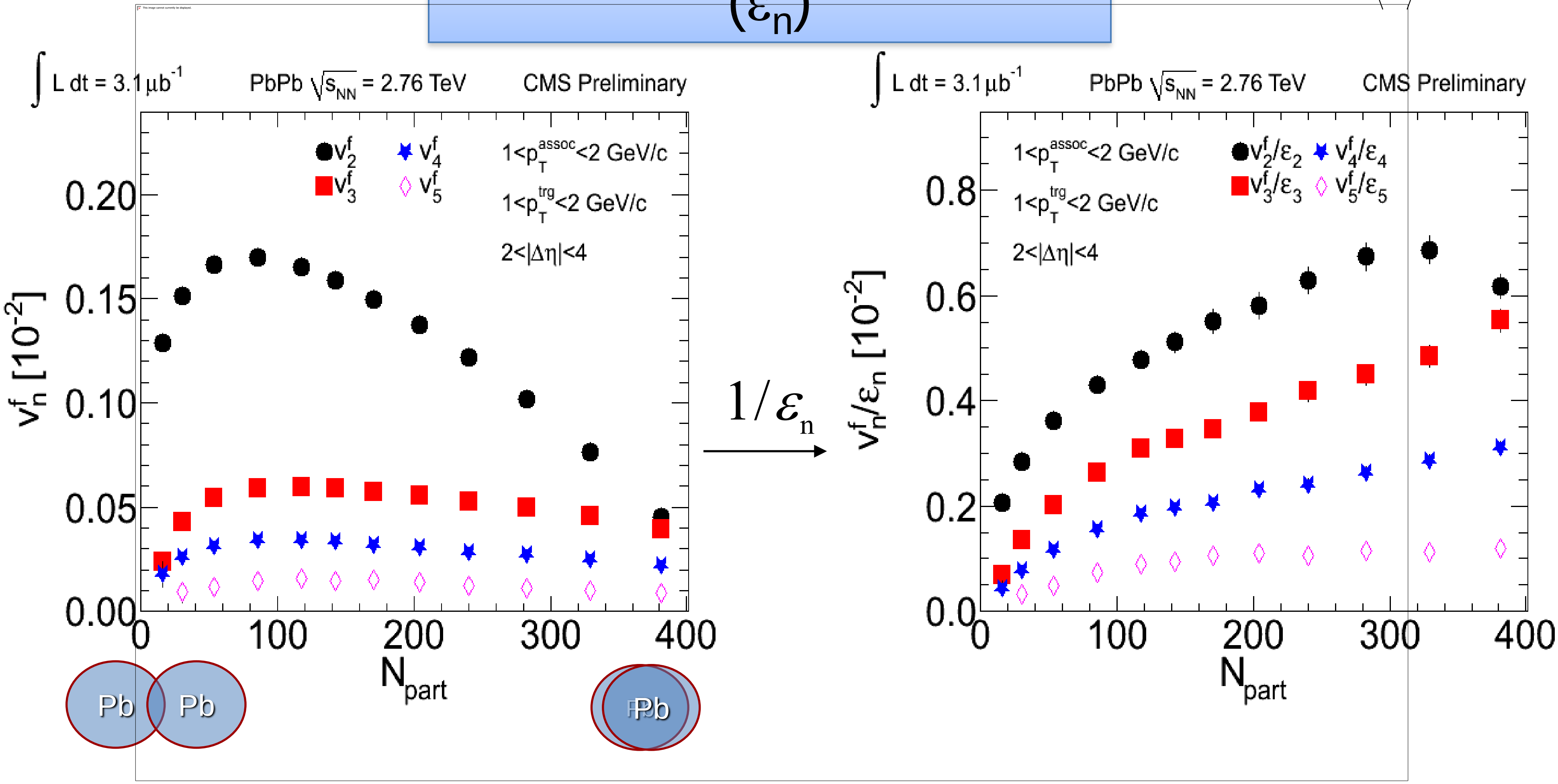
Phys. Rev. C 82, 034913 (2010)

Powerful constraints to the viscous property of the medium

Flow coefficients (v^f_n) vs centrality

Scaled by eccentricity (ε_n)

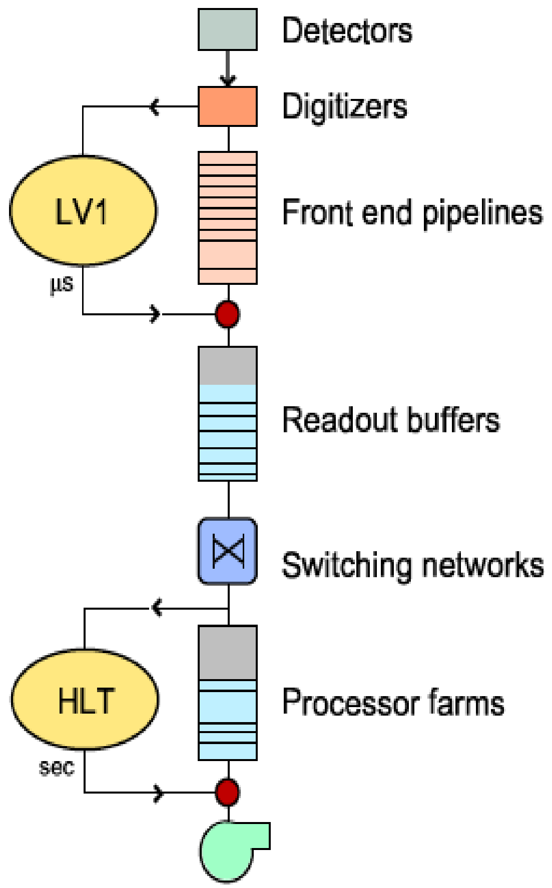
$$\varepsilon_n \equiv \frac{\sqrt{\langle r^2 \cos[n(\phi-\psi_n)]\rangle^2 + \langle r^2 \sin[n(\phi-\psi_n)]\rangle^2}}{\langle r^2 \rangle}$$



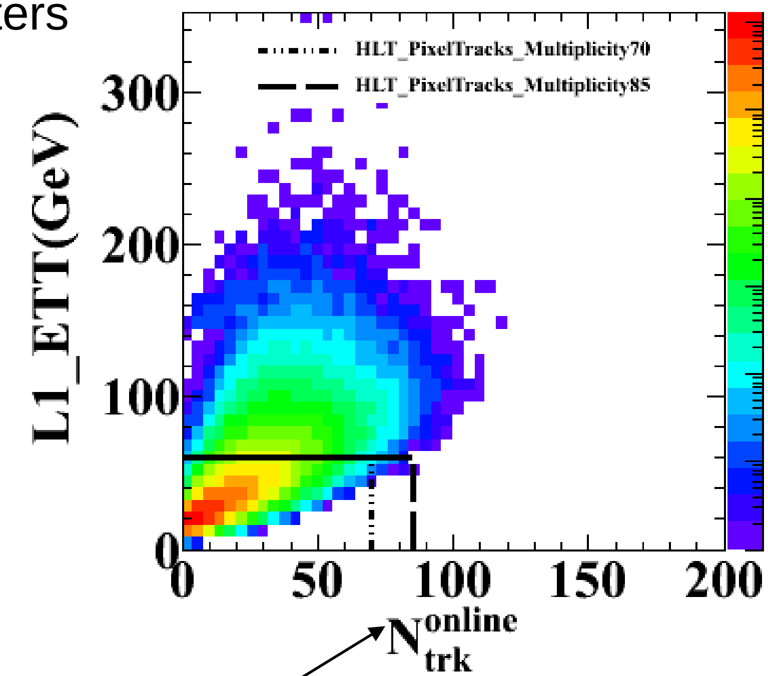
Powerful constraints to the viscous property of the medium

Trigger on high multiplicity pp

CMS trigger and DAQ



Level-1:
$\sum E_T > 60$ GeV
in calorimeters



High-Level trigger:
number of tracks with p_T>0.4 GeV/c, $|\eta|$<2 from a **single** vertex

Particle density in high Mult pp

- Similar particle densities in these pp collisions as were seen in CuCu at RHIC