Observation of Long-Range, Near-Side Angular Correlations in Proton-Proton Collisions at the LHC

The CMS Collaboration

I. 2-Particle correlation functions

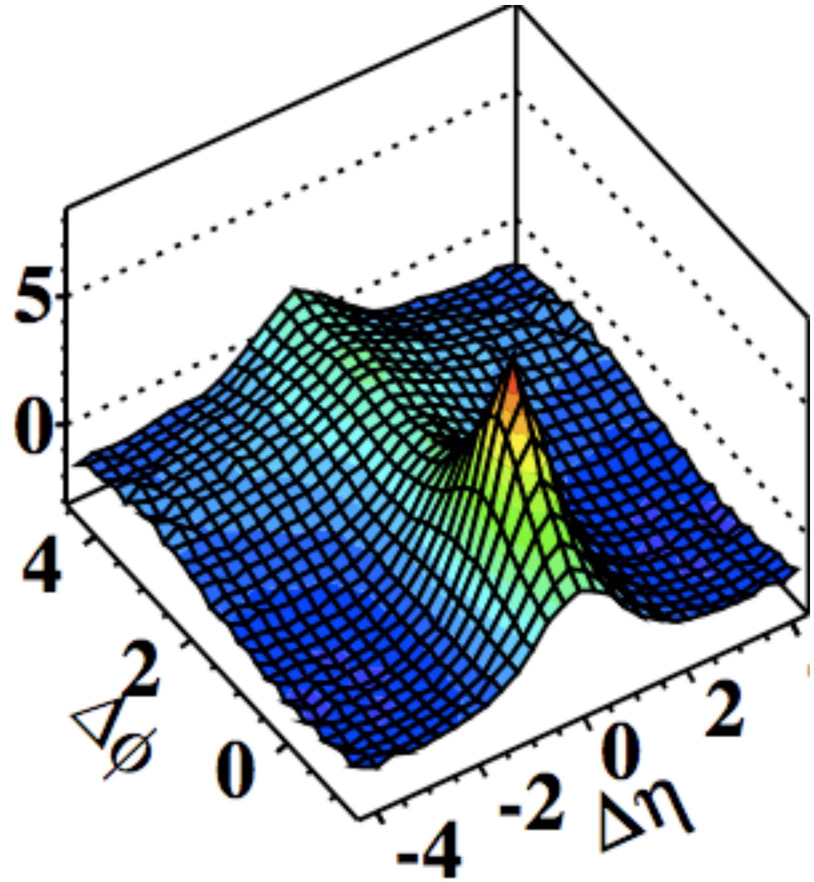
II. Minimum bias results

III. High multiplicity results

IV. Cross-checks

Gunther Roland/MIT

Angular Correlation Functions



Correlation Functions:

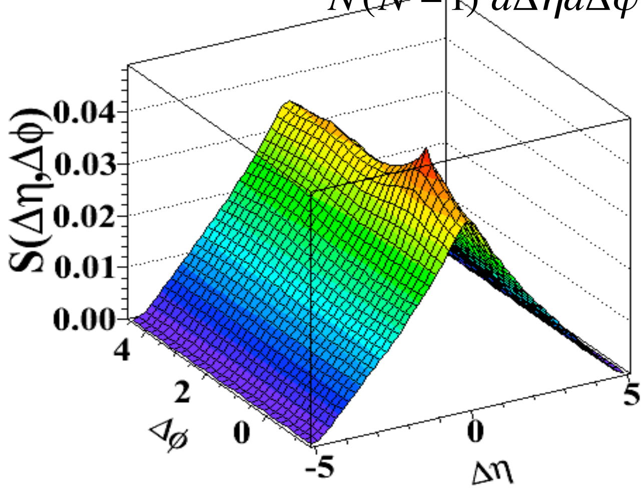
I. Definition

II. Anatomy

Correlation Function Definition

Signal distribution:

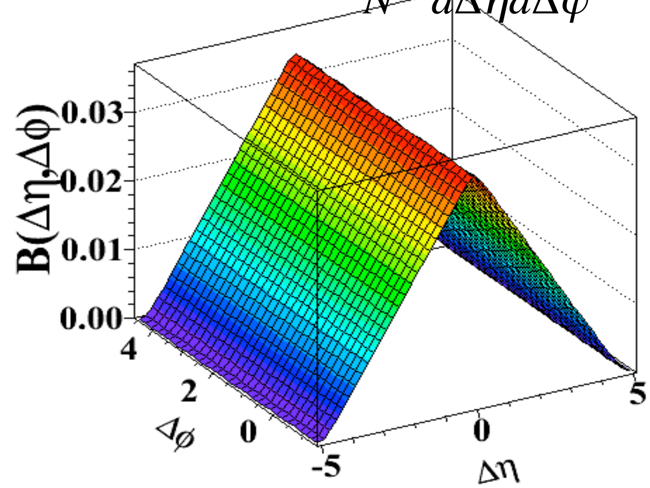
$$S_N(\Delta\eta,\Delta\varphi) = \frac{1}{N(N-1)}\frac{d^2N^{signal}}{d\Delta\eta d\Delta\varphi}$$



Same event pairs

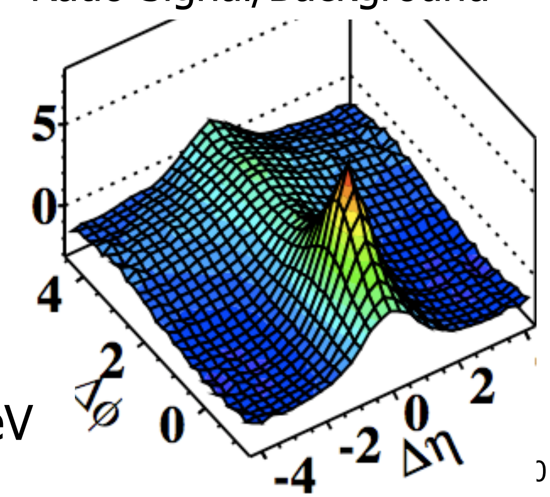
Background distribution:

$$B_N(\Delta\eta,\Delta\varphi) = \frac{1}{N^2}\frac{d^2N^{bkg}}{d\Delta\eta d\Delta\varphi}$$



Mixed event pairs

Ratio Signal/Background



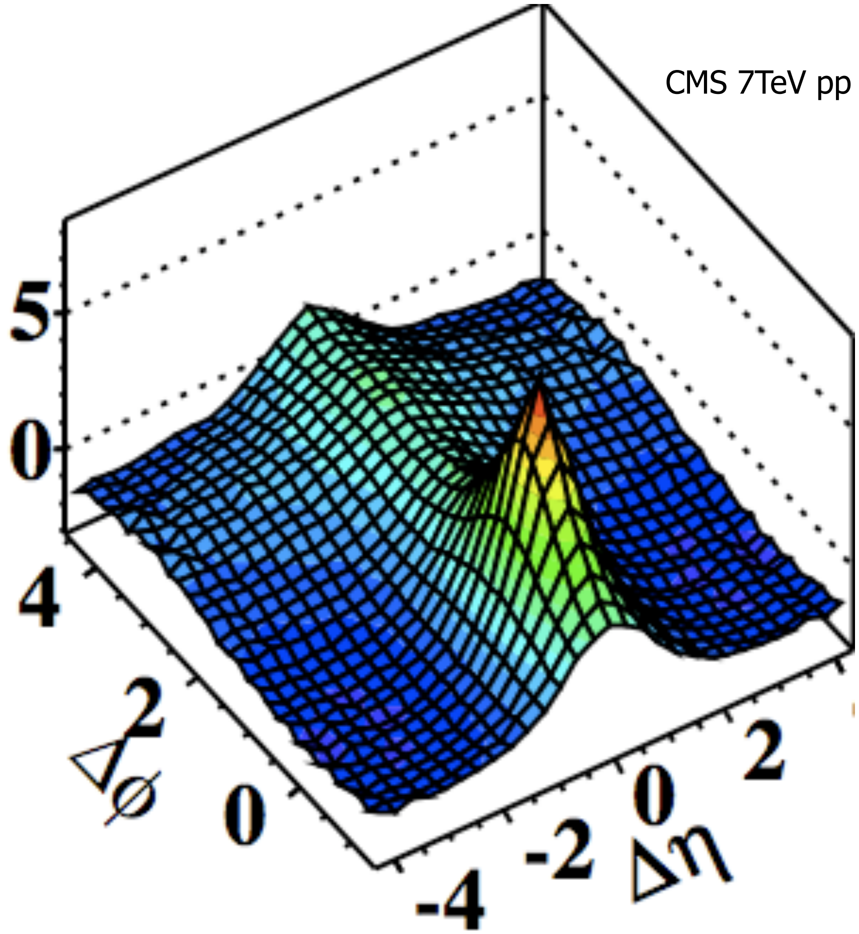
$$R(\Delta\eta,\Delta\varphi) = \left\langle (N-1)\left(\frac{S_N(\Delta\eta,\Delta\varphi)}{B_N(\Delta\eta,\Delta\varphi)} - 1\right)\right\rangle_N$$

$$\Delta\eta = \eta_1 - \eta_2$$
$$\Delta\varphi = \varphi_1 - \varphi_2$$

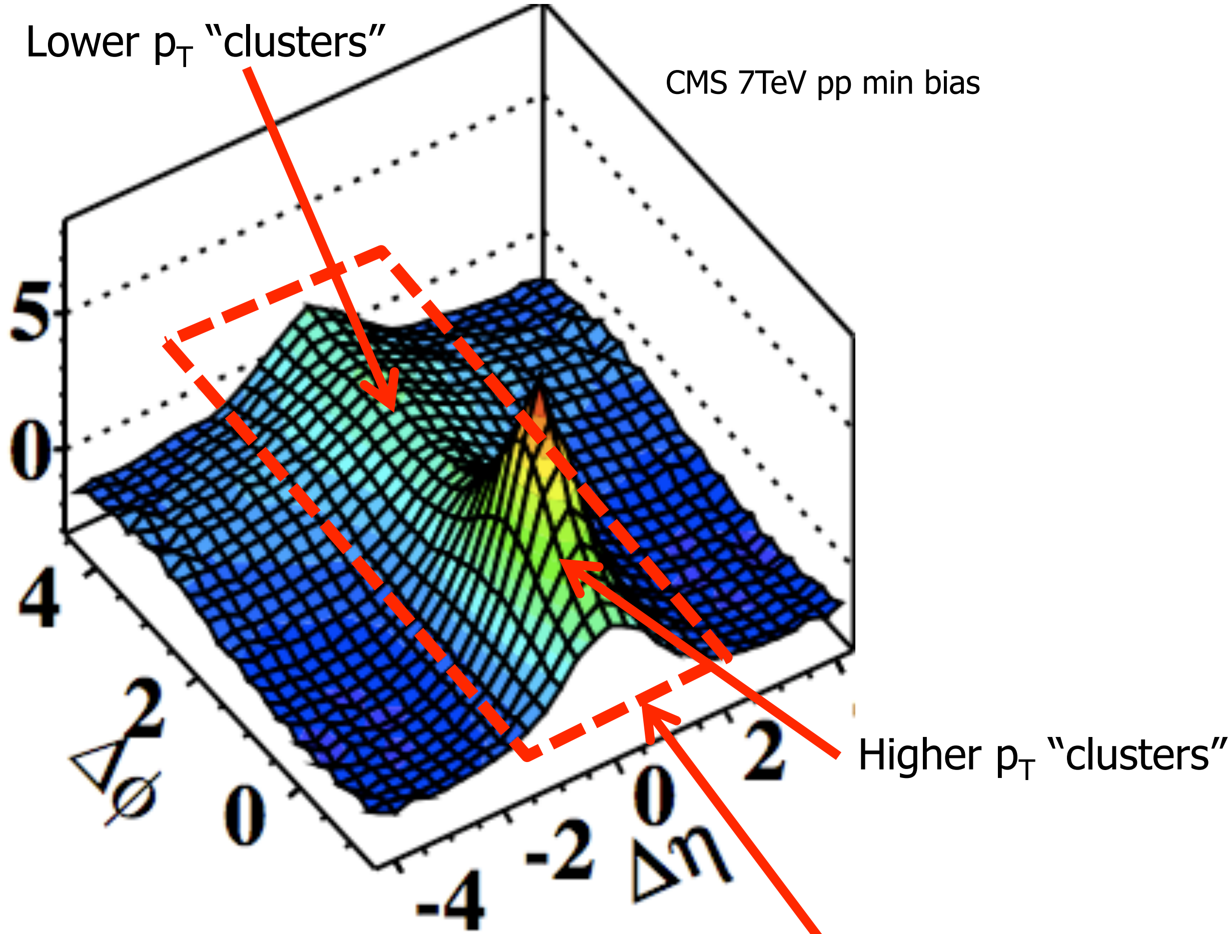
CMS pp 7TeV

p_T-inclusive two-particle angular correlations in min bias collisions

Angular Correlation Functions



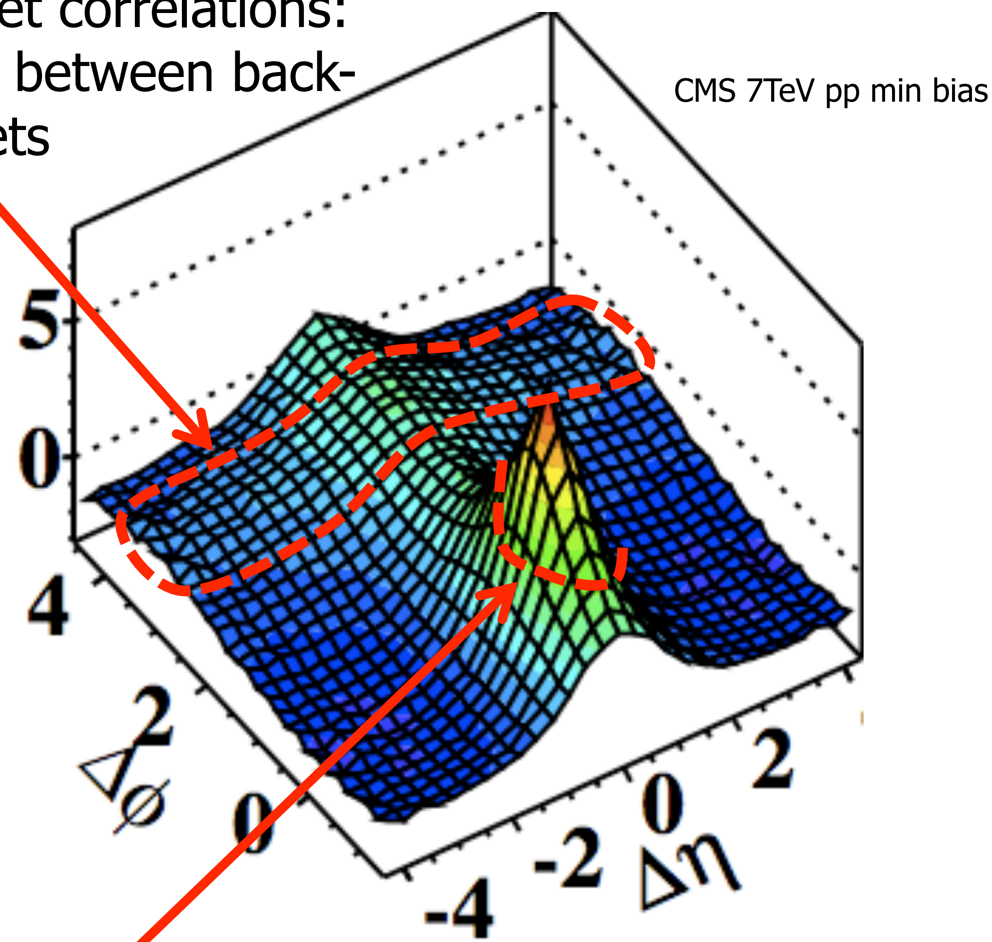
Angular Correlation Functions



Short-range correlations ($\Delta\eta$ < 2):
Resonances, string fragmentation, "clusters"

Angular Correlation Functions

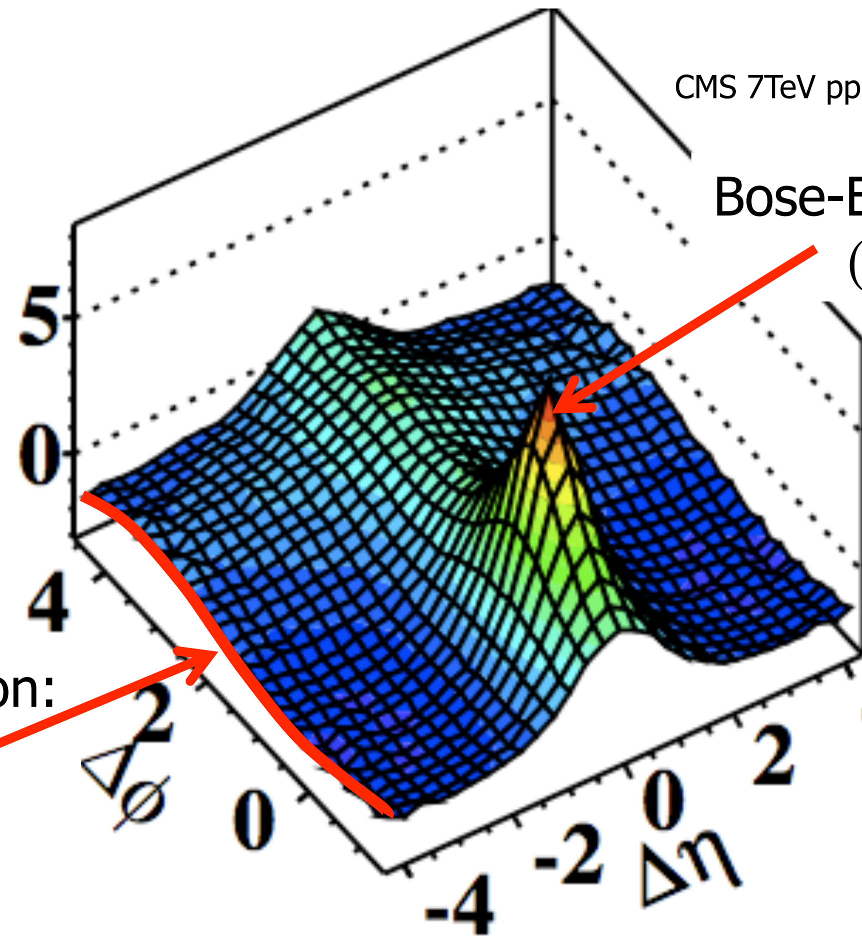
"Away-side" ($\Delta\phi \sim \pi$) jet correlations: Correlation of particles between back-to-back jets



"Near-side" ($\Delta\phi \sim 0$) jet peak: Correlation of particles within a single jet

Angular Correlation Functions

CMS 7TeV pp min bias

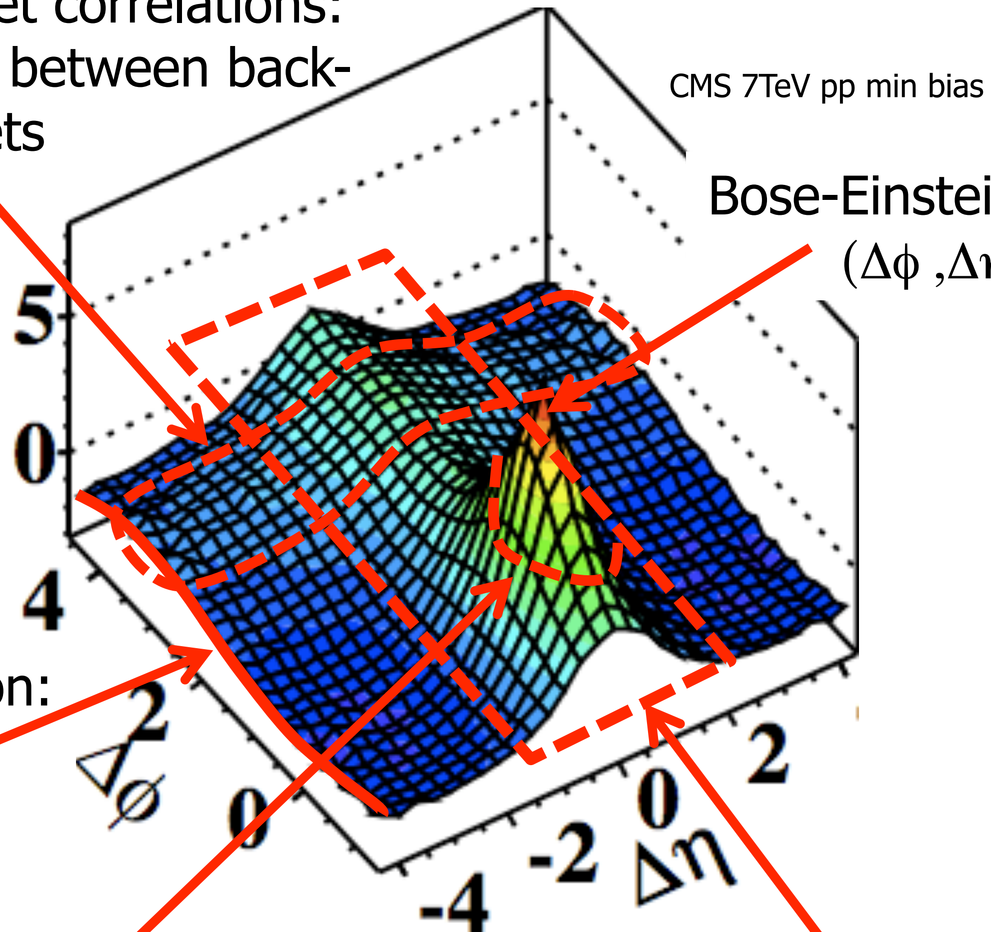


Bose-Einstein correlations:
$(\Delta\phi, \Delta\eta) \sim (0,0)$

Momentum conservation:
$\sim -\cos(\Delta\phi)$

Angular Correlation Functions

"Away-side" ($\Delta\phi \sim \pi$) jet correlations: Correlation of particles between back-to-back jets



Bose-Einstein correlations: $(\Delta\phi, \Delta\eta) \sim (0,0)$

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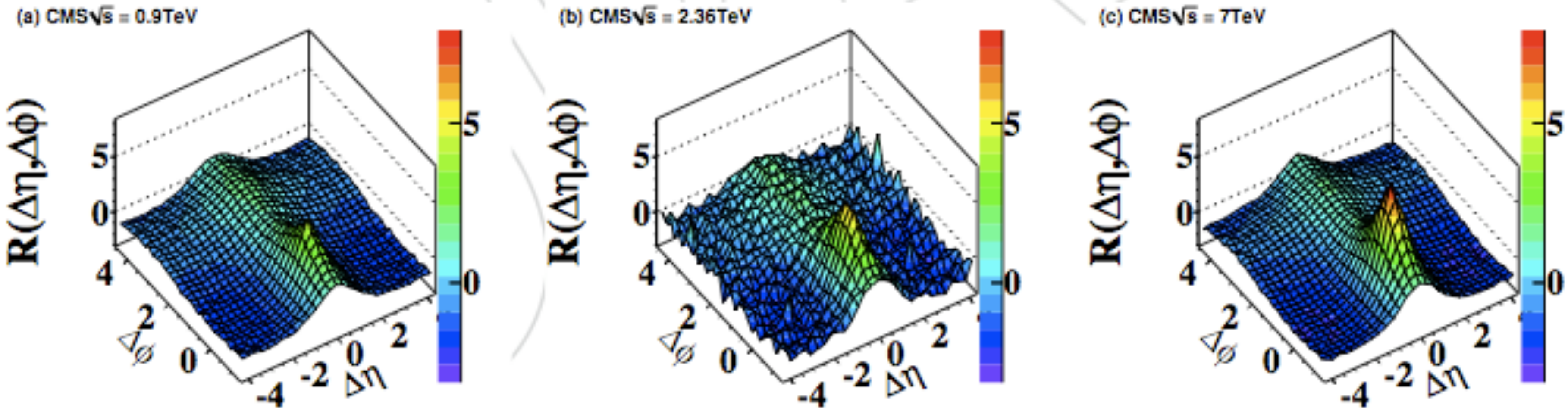
"Near-side" ($\Delta\phi \sim 0$) jet peak: Correlation of particles within a single jet

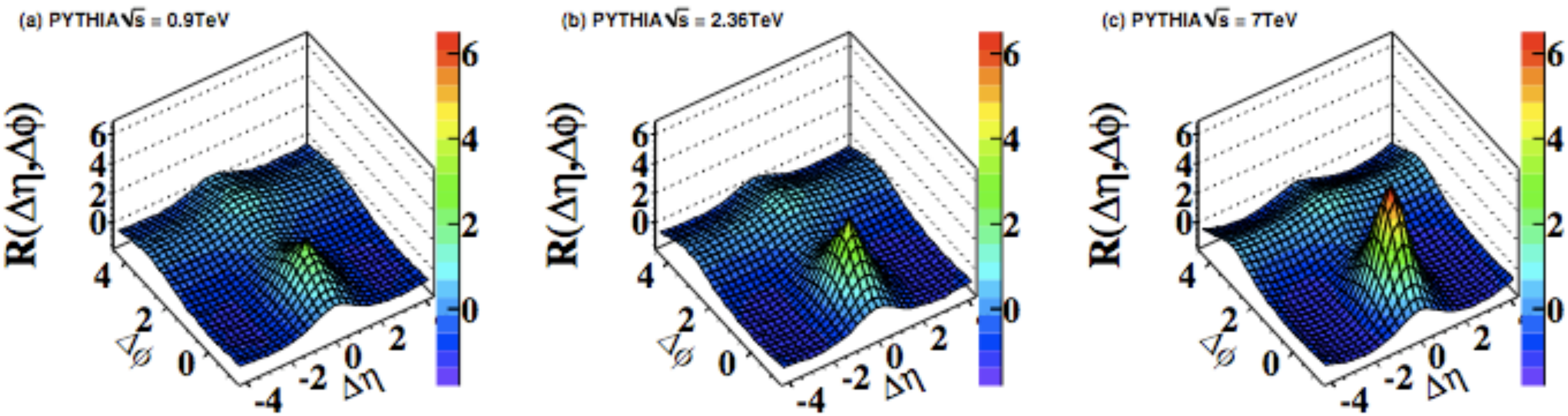
Short-range correlations ($\Delta\eta < 2$): Resonances, string fragmentation, "clusters"

Correlations in Min Bias pp

CMS pp Data

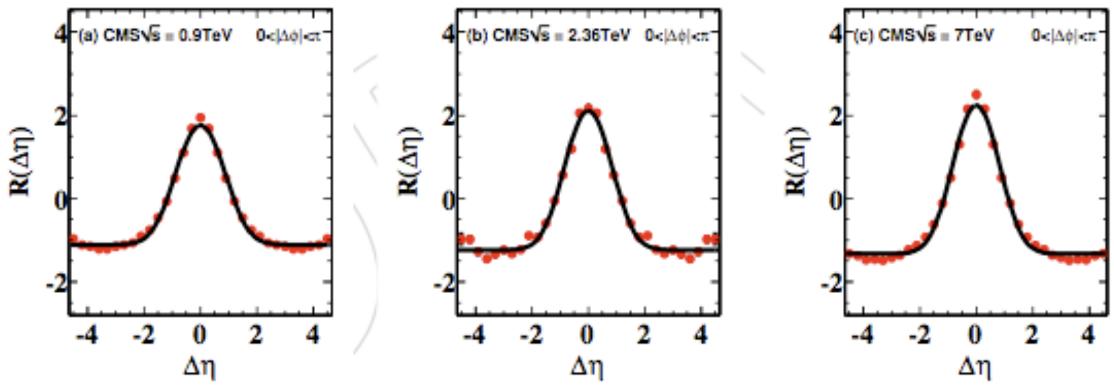


Pythia D6T

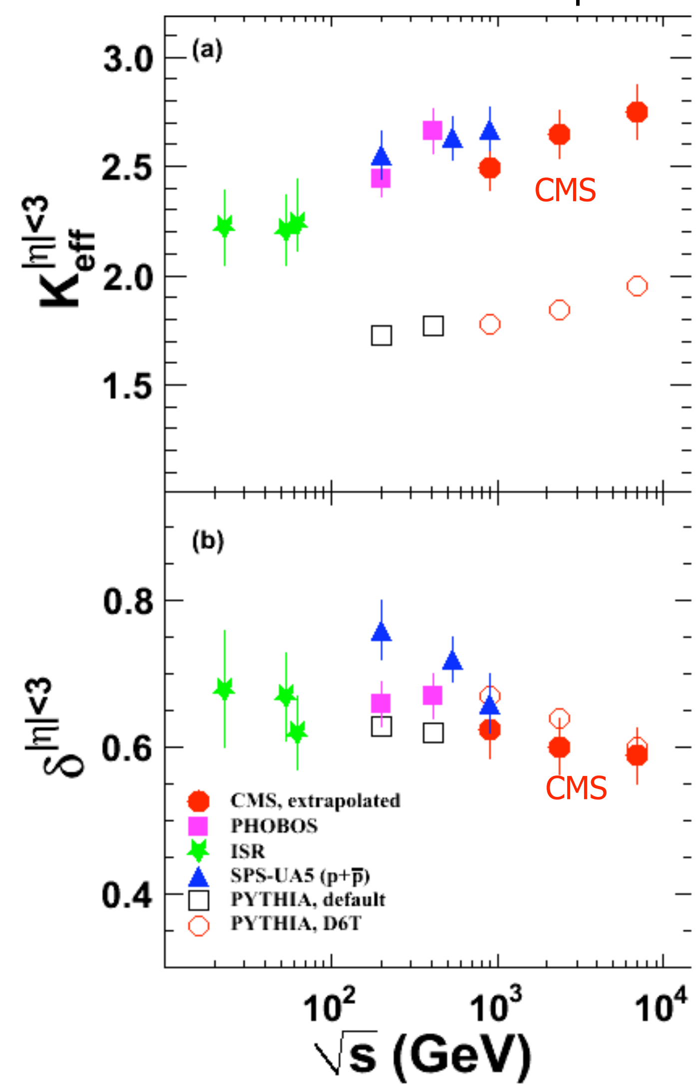


Short-Range Correlations vs sqrt(s)

1D "Projection" to Δη axis



K_{eff}: Number of correlated particles
δ: Extent of correlation in Δη

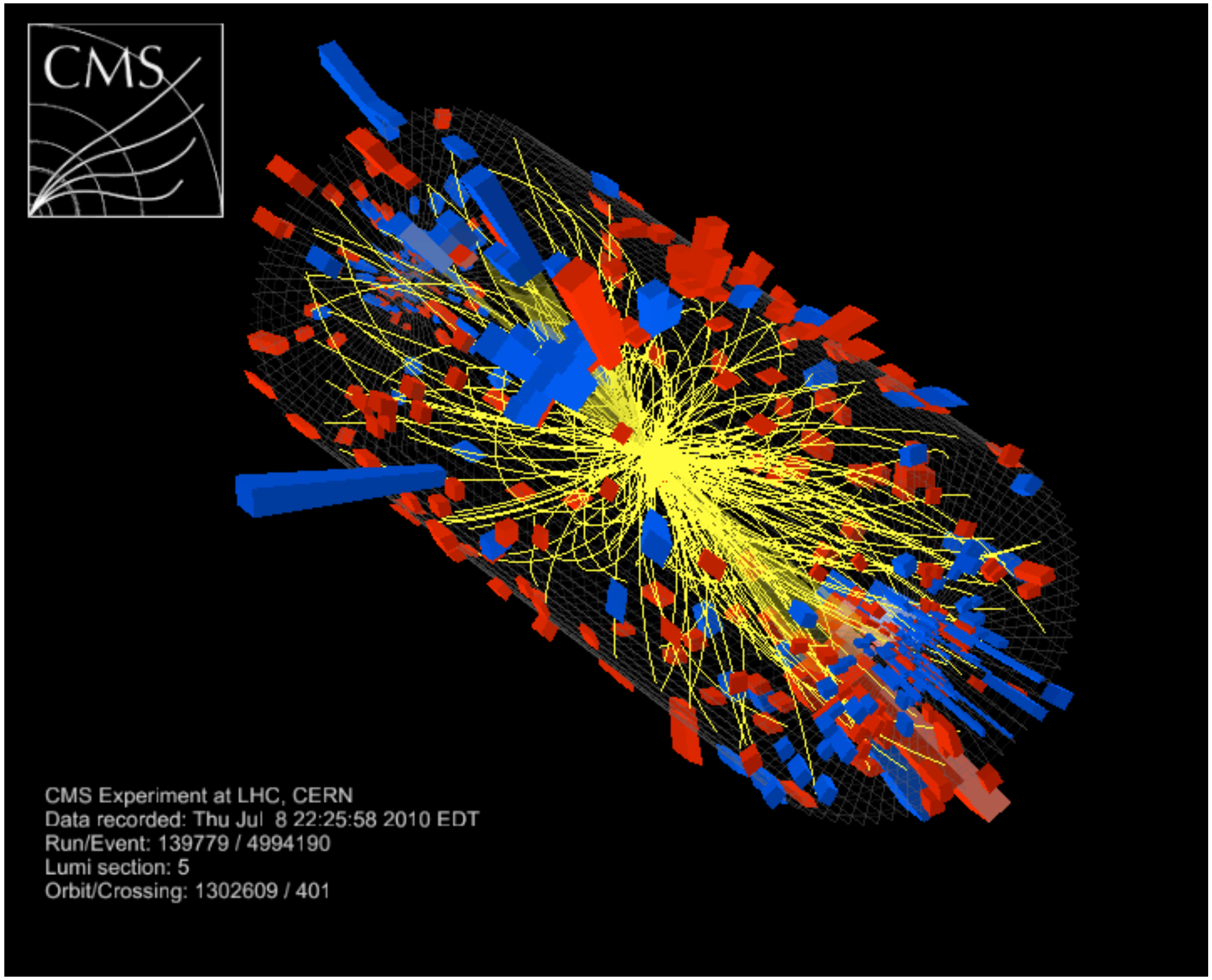


PYTHIA describes the energy dependence

Matches cluster width δ in data

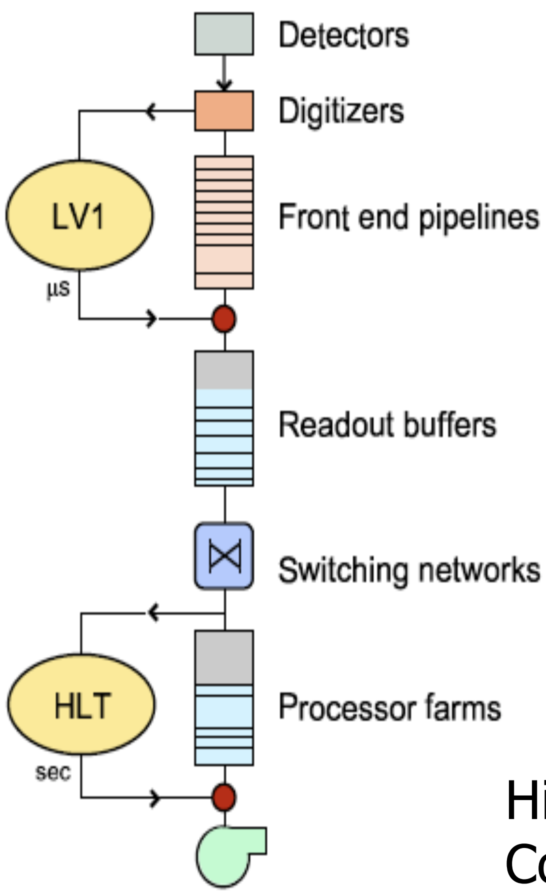
Underestimates the cluster size K_{eff}

High Multiplicity Events

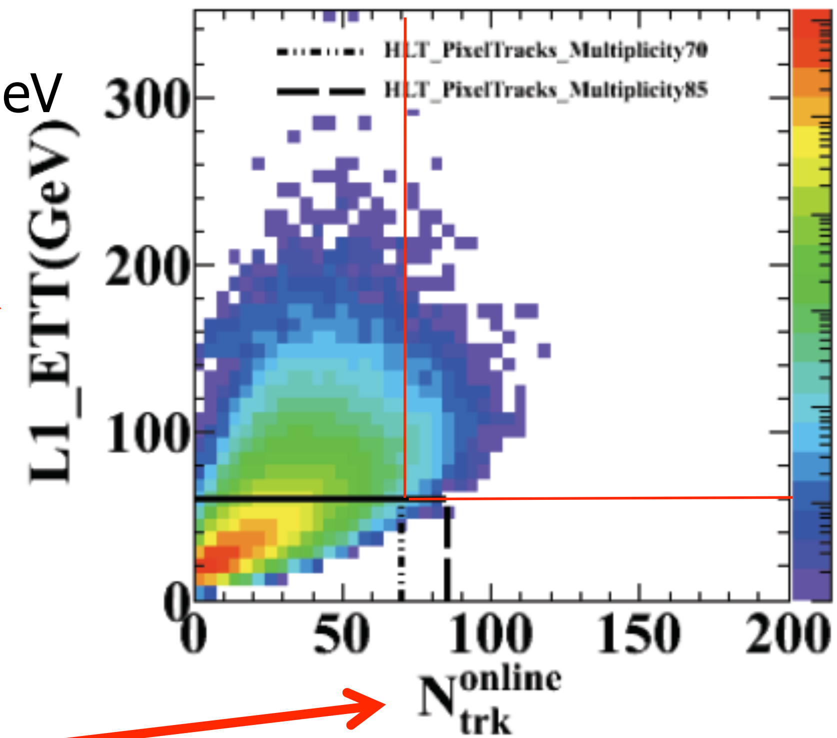


High Multiplicity Events

Dedicated trigger needed to record highest multiplicities

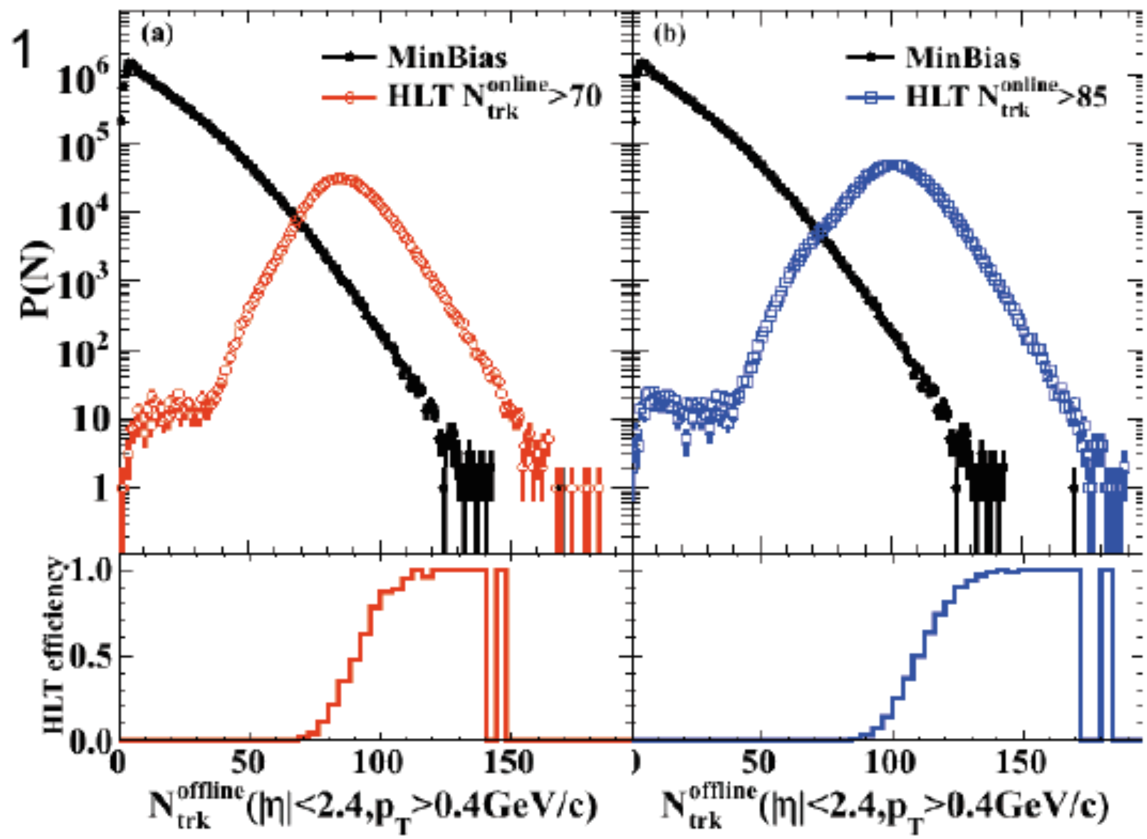


Level-1:
Require E_T> 60 GeV
in calorimeters



High-Level trigger:
Count number of tracks with p_T > 0.4 GeV/c, $|\eta|$ < 2,
within dz < 0.12cm of a **single** vertex with z <10cm

High Multiplicity Trigger



Multiplicity binning uses
p_T > 0.4 GeV/c
$|\Delta\eta|$ < 2.4

Multiplicity bin ($N_{trk}^{offline}$)	Event Count	$\langle N_{trk}^{offline} \rangle$
MinBias	21.43M	15.9
$N_{trk}^{offline} < 35$	19.36M	13.0
$35 \leq N_{trk}^{offline} < 90$	2.02M	45.3
$90 \leq N_{trk}^{offline} < 110$	302.5k	96.6
$N_{trk}^{offline} \geq 110$	354.0k	117.8

out of 5×10^{10} collisions

Two different HLT thresholds:
$N^{online} > 70$ and $N^{online} > 85$

HLT85 trigger range un-prescaled
for full $980nb^{-1}$

Event and Track Selection

Vertex selections:

- OfflinePrimaryVertices
- NDOF>4
- |vz|<10cm

Event-selection and analysis done with tracks pointing to primary vertex with O(100μm) resolution

Track quality selections:

- *highPurity* bit
- $dxy/\sigma(dxy)<3$ & $dz/\sigma(dz)<3$, relative to primary vertex
- $\sigma(p_T)/p_T<0.1$

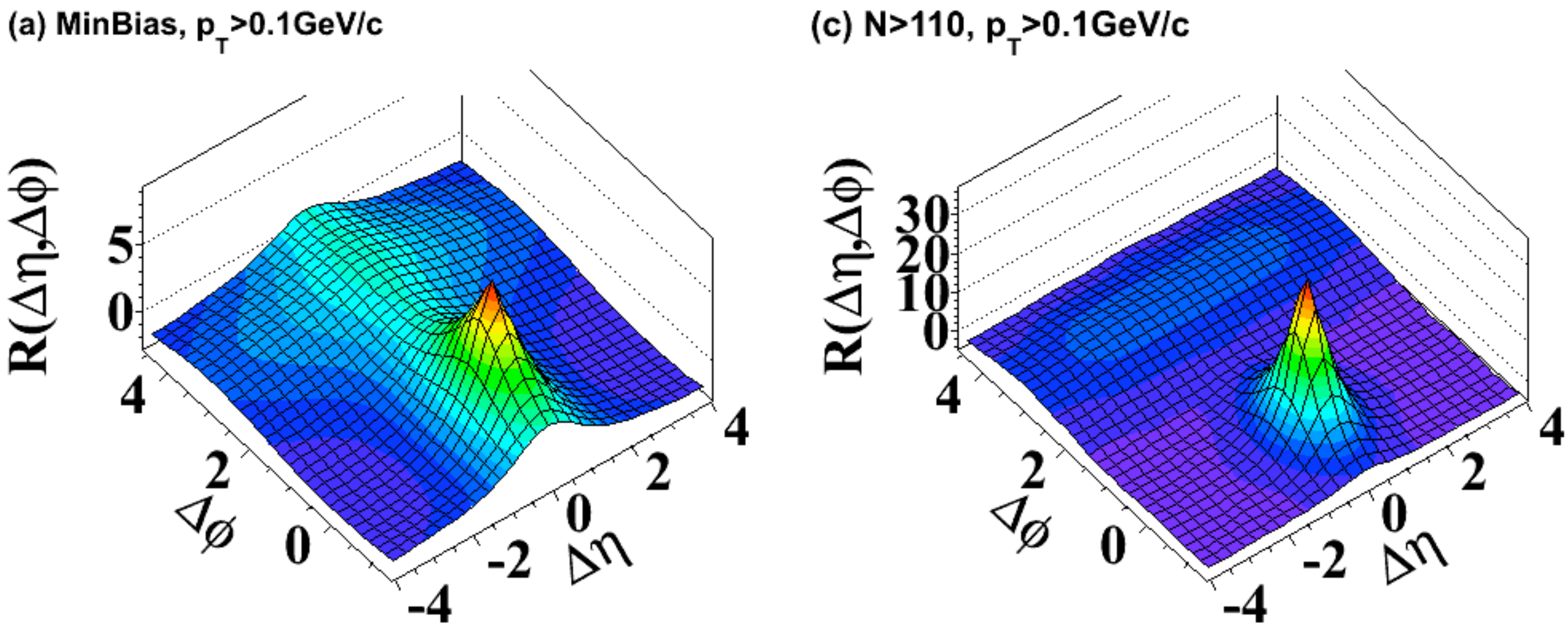
Main corrections:

- Tracking/acceptance efficiency, fake rate
- HLT triggering efficiency - data driven

Results

Inclusive p_T

MinBias | high multiplicity (N>110)



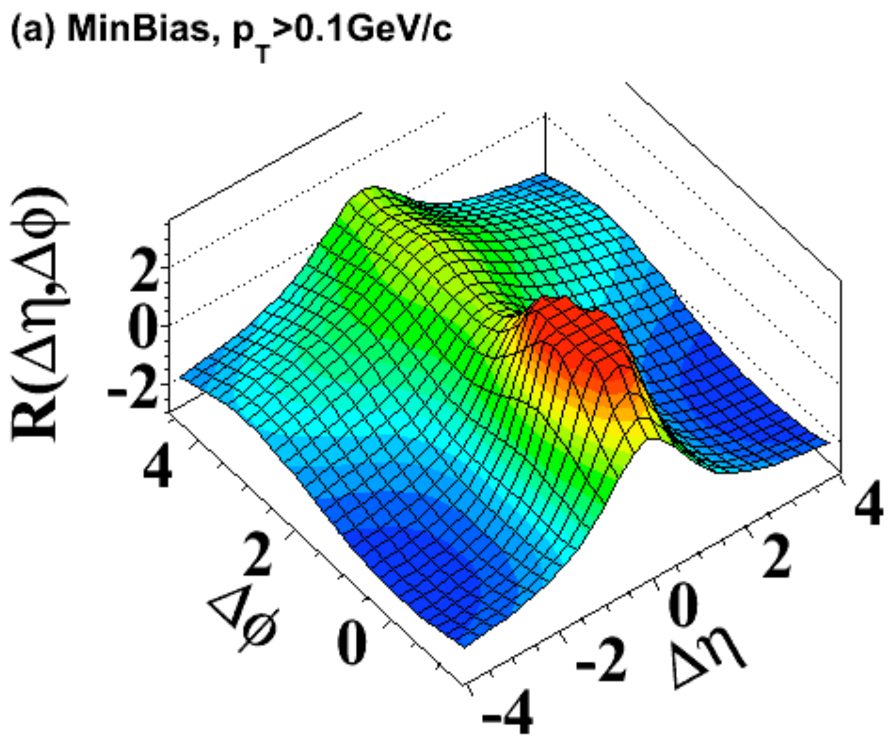
Jet peak/away-side correlations enhanced in high multiplicity events

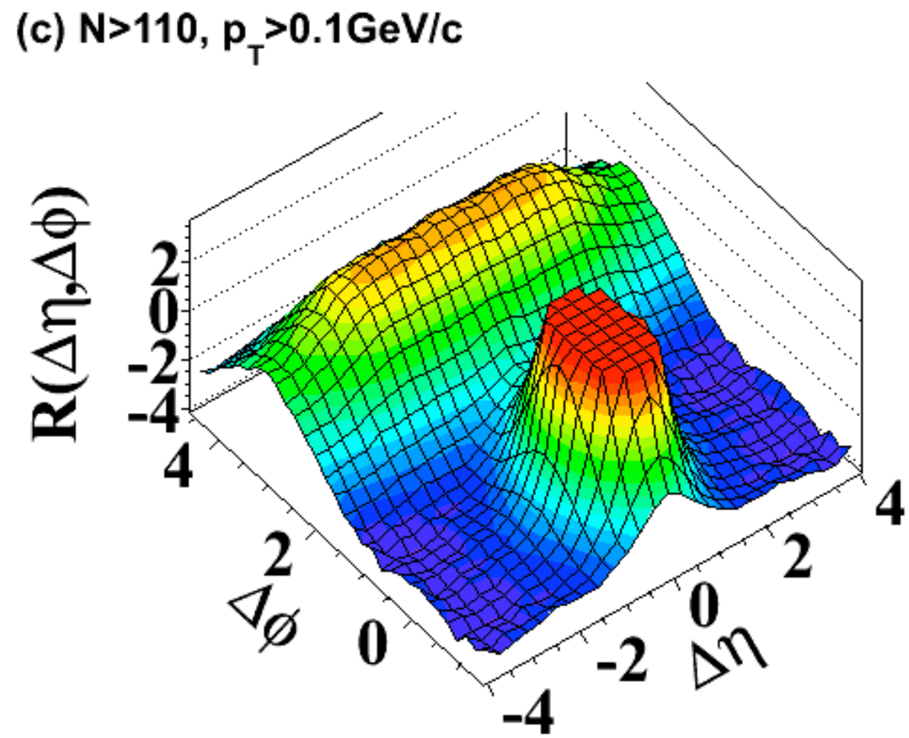
Abundant jet production in high multiplicity sample

Results

Inclusive p_T

MinBias | high multiplicity (N>110)





Cut off peak at (0,0):

Shows structure of away-side ridge (back-to-back jets)

Small change for large $\delta\eta$ around $\delta\phi \sim 0$?

Results

Intermediate p_T: 1-3 GeV/c

MinBias

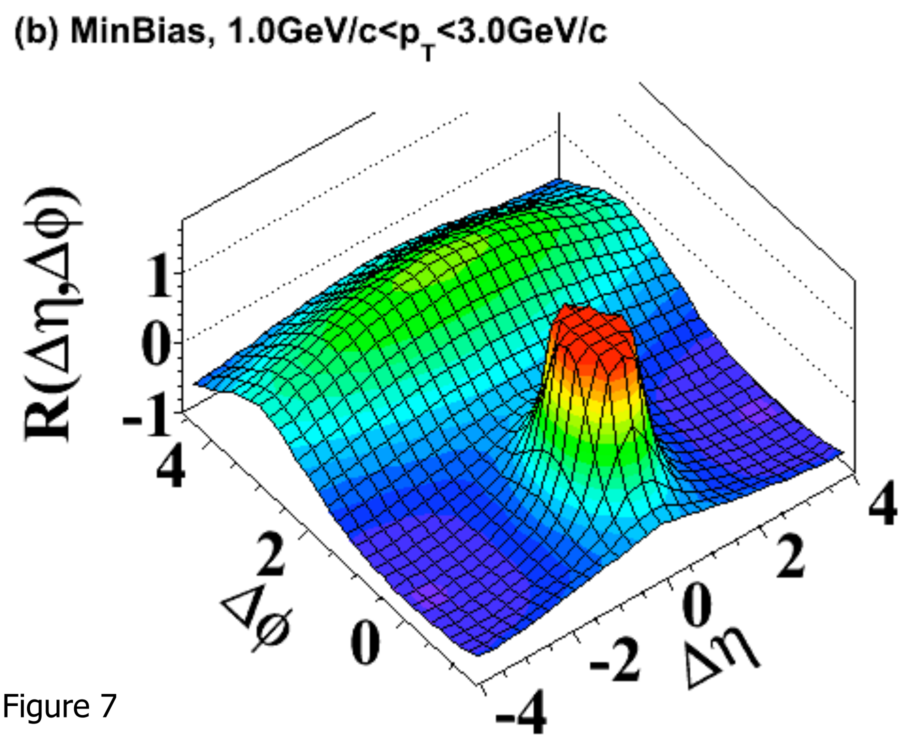
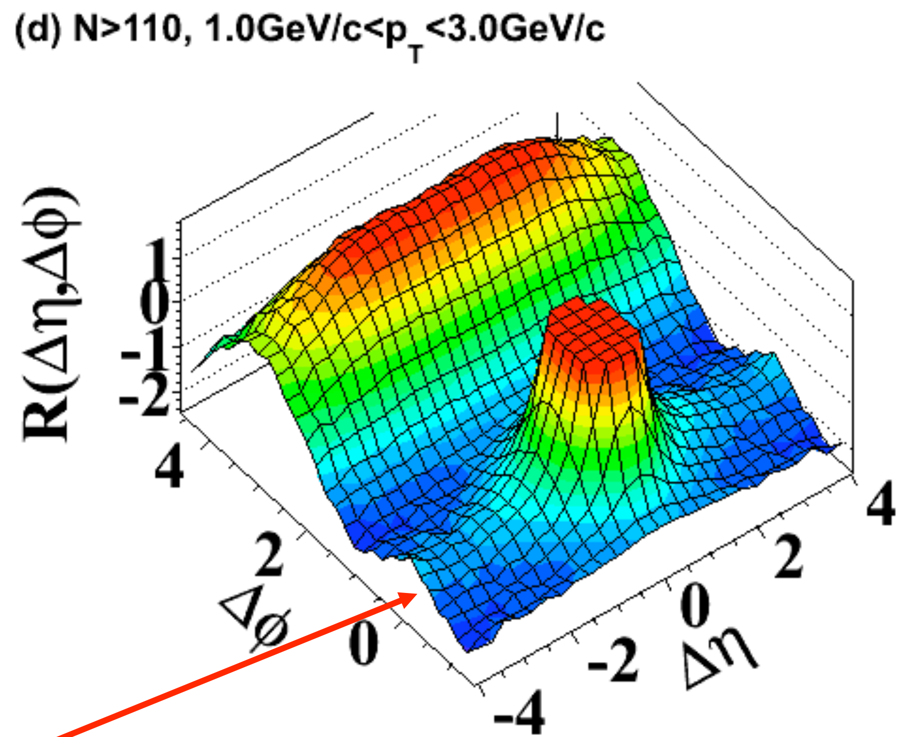


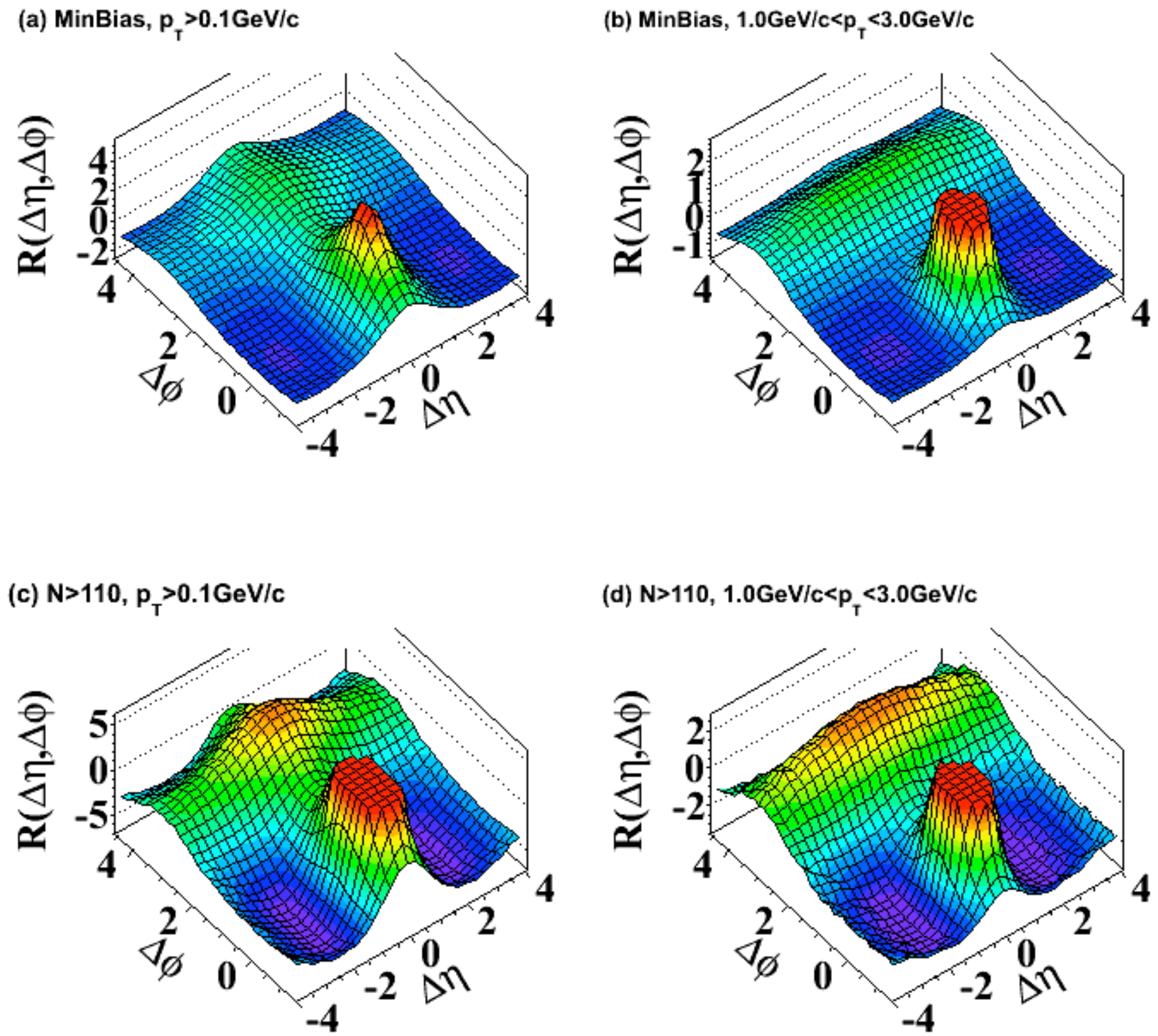
Figure 7

high multiplicity (N>110)



Pronounced structure at large $\delta\eta$ around $\delta\phi \sim 0$!

Results



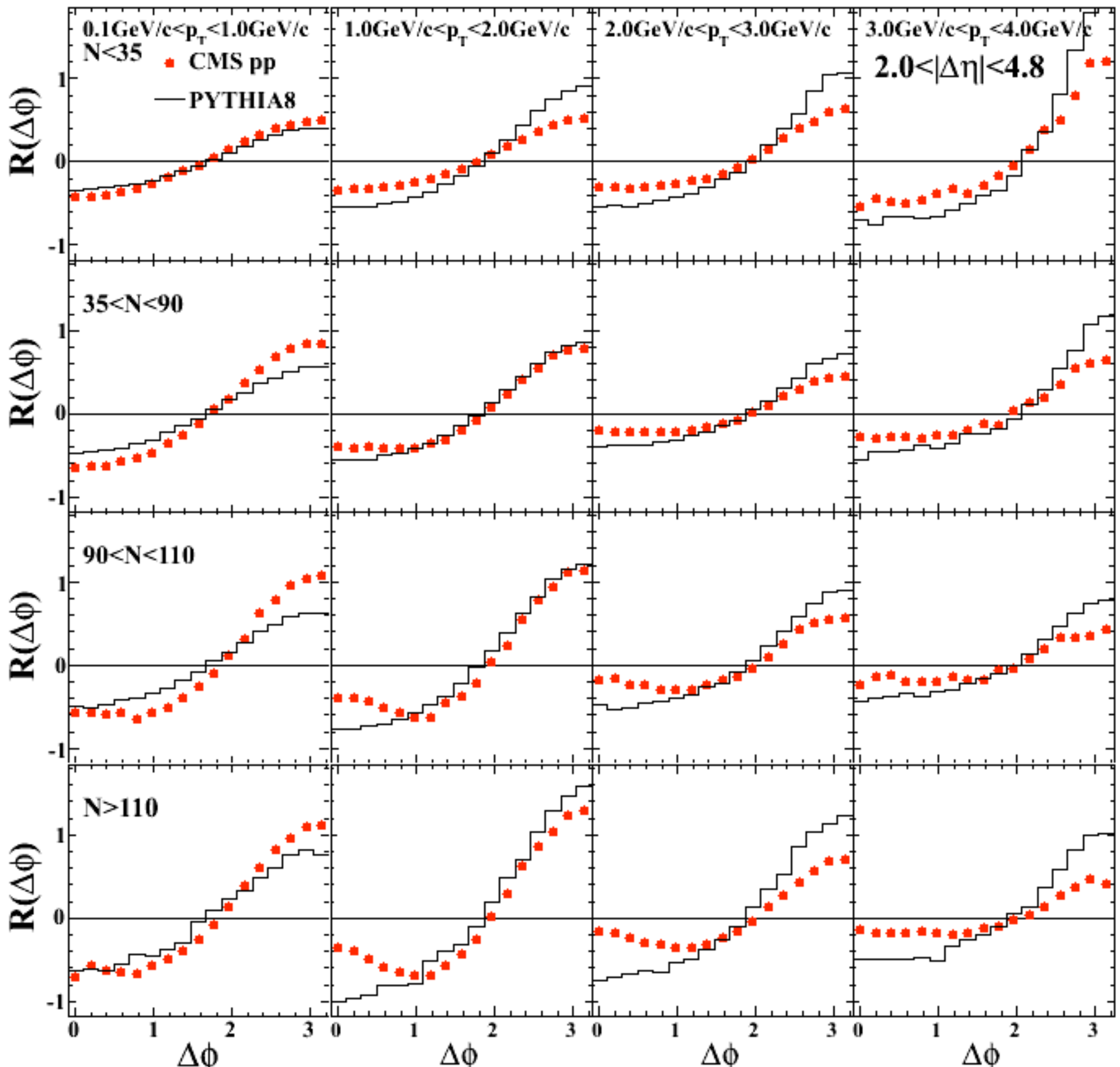
No $\delta\phi \sim 0$ structure in PYTHIA 8 at large $\delta\eta$

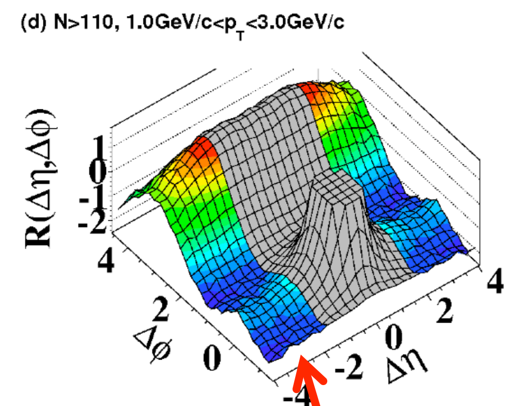
Same for Herwig++, madgraph, PYTHIA6

Multiplicity- and p_T -Dependence

Increasing p_T

Increasing multiplicity





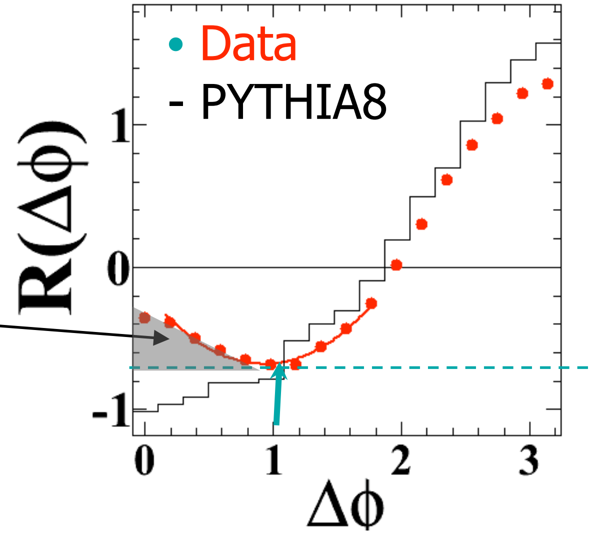
Project $|\Delta\eta| > 2$ onto $\Delta\phi$

"Ridge" maximal for highest multiplicity and $1 < p_T < 3$ GeV/c

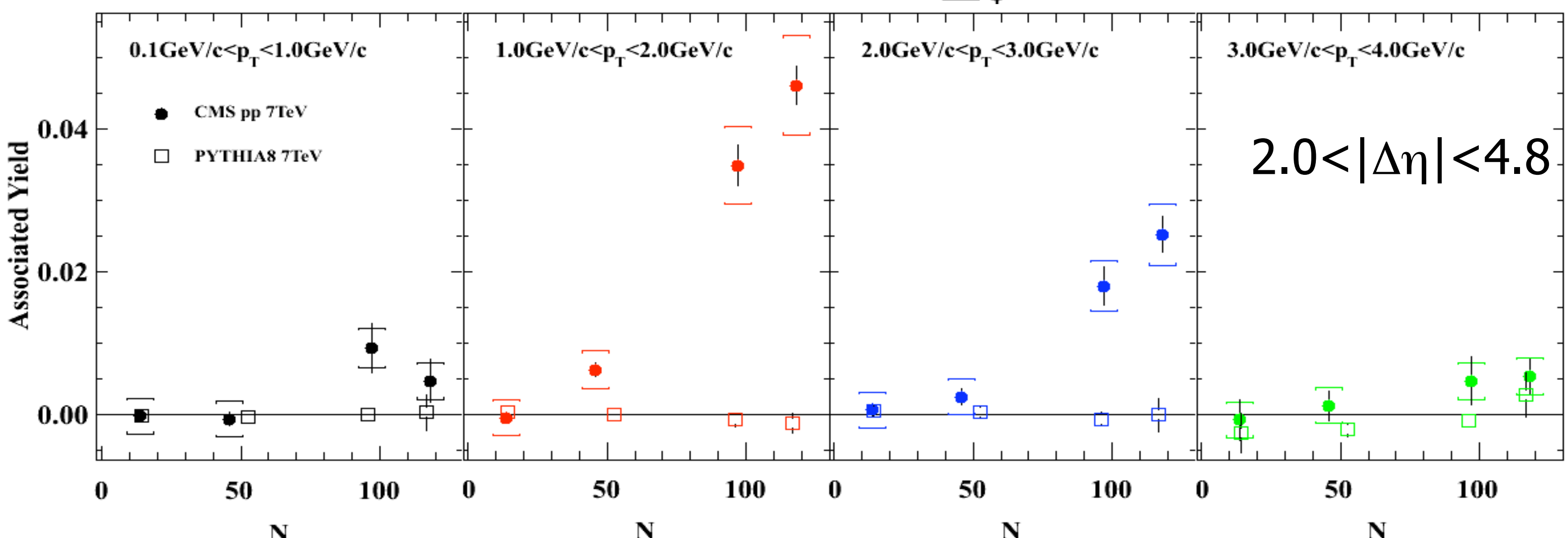
Multiplicity- and p_T -Dependence

Zero Yield At Minimum (ZYAM)

Associated yield:
correlated multiplicity per particle

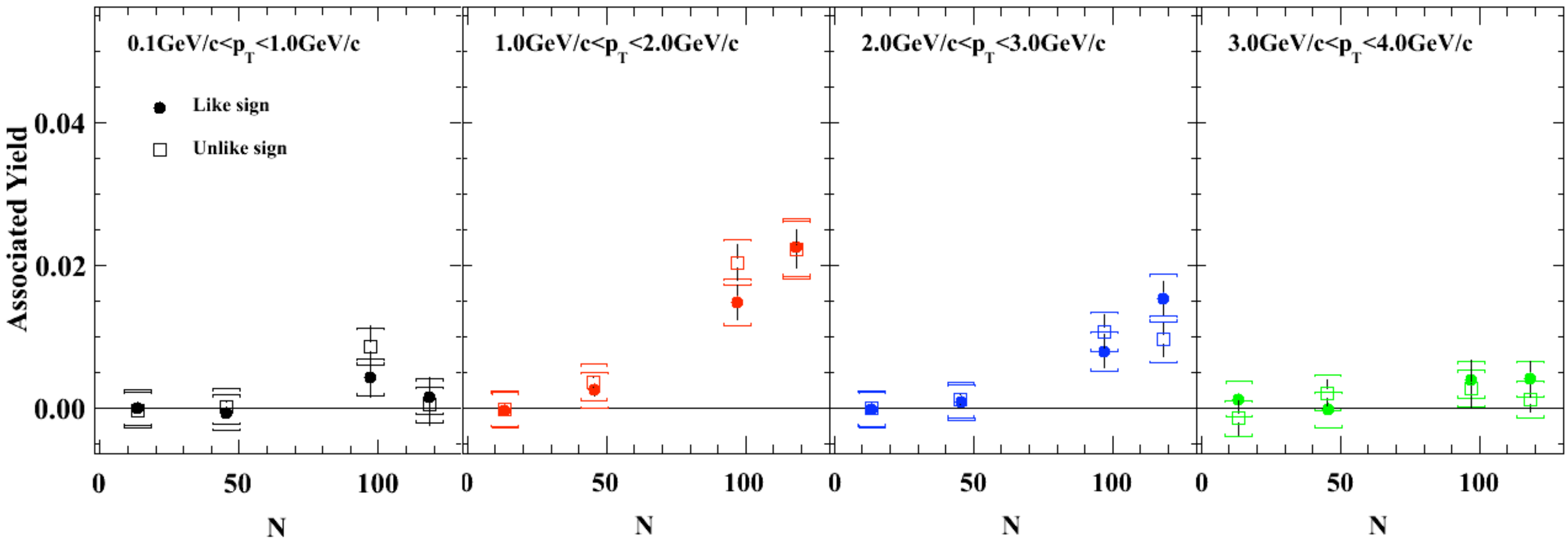


N>110
$2.0<|\Delta\eta|<4.8$
$1GeV/c<p_T<2GeV/c$



Associated yield grows with increasing multiplicity

Like-Sign vs Unlike-Sign



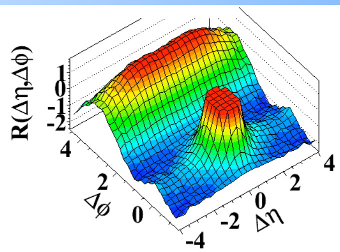
No dependence on relative charge sign

Systematic Uncertainties

- Statistical uncertainty negligibly small
- However, the signal is subtle and unexpected
- Estimate systematic uncertainties
- Is there a way to fake the signal *qualitatively*?

Systematic Uncertainties

+ bugs?



Analysis code

+ efficiency, fakes

Reconstruction

+ trigger efficiency, bias

Trigger

+ detector noise, acceptance, efficiency

Detector

+ pile-up, beam backgrounds

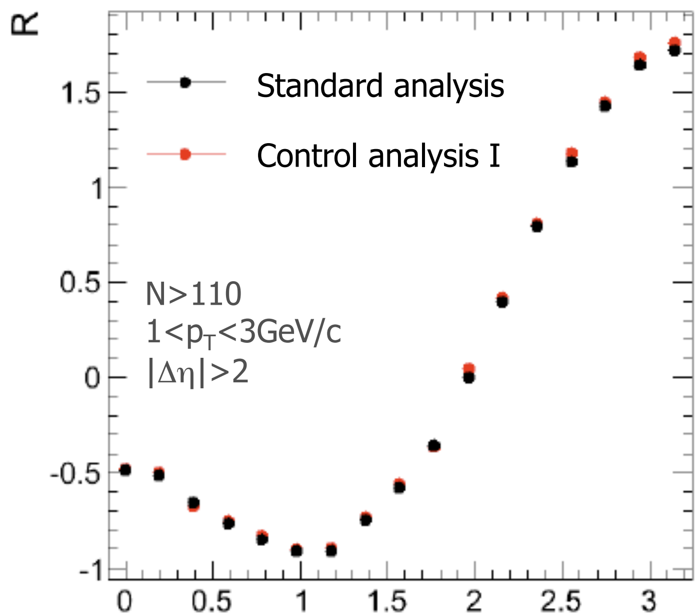
CMS Event

Physics

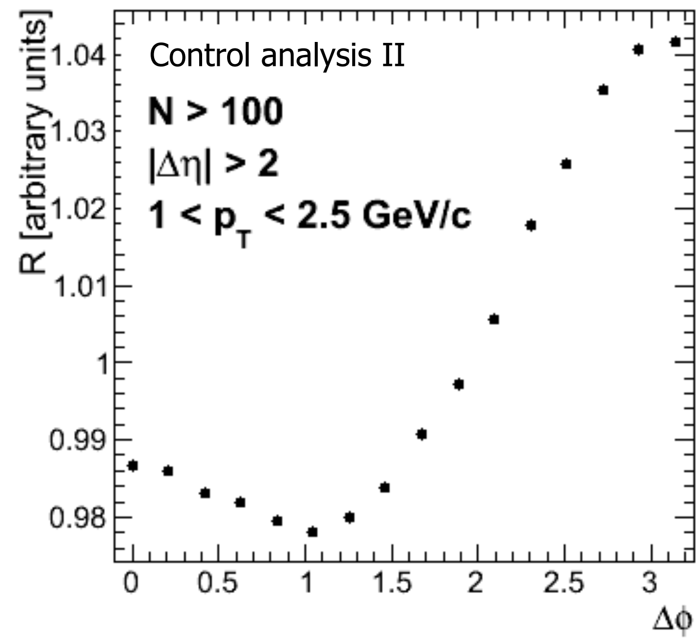
Collision

Test the complete chain with data-driven checks!

Analysis Code



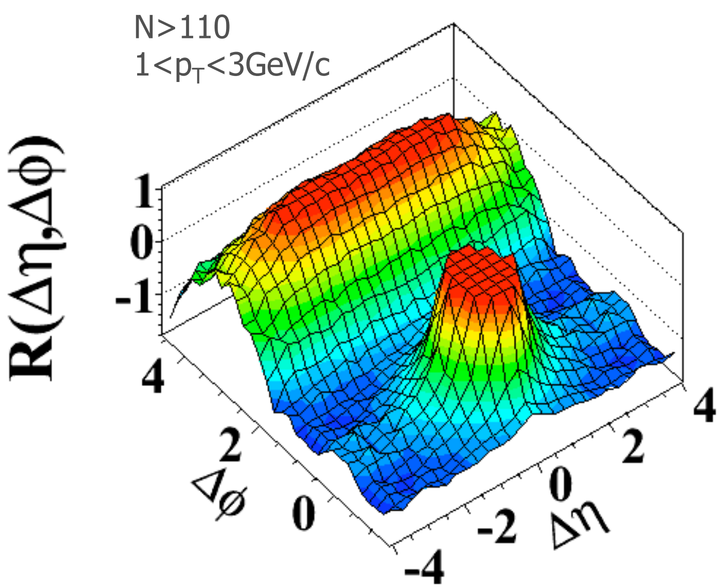
Independent code
Same definition of *R*
Same input file (skim)



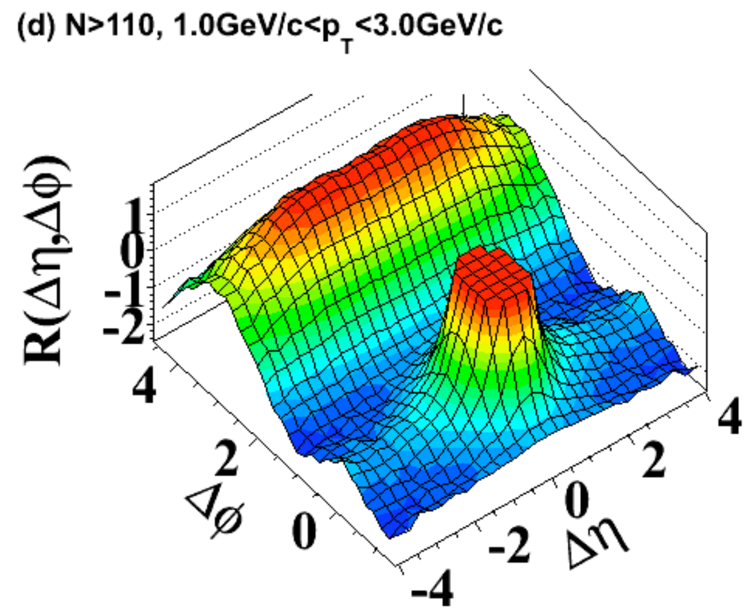
Independent code
Different definition of *R*
Different input file (skim)

Ridge is seen with three independent analysis codes

Reconstruction Code



Pixel-only tracks
3 hits in pixel detector

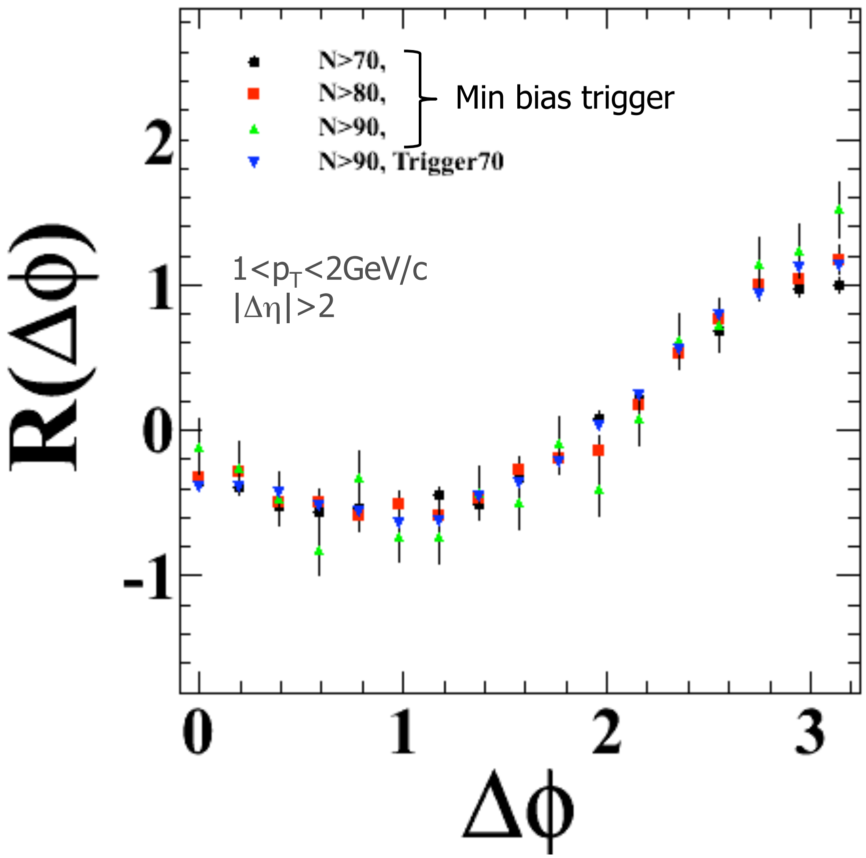


"HighPurity" tracks
Pixel + Silicon Strip tracker

(Largely) independent code
Independent detectors
Also: Variation of tracking +vertexing parameters

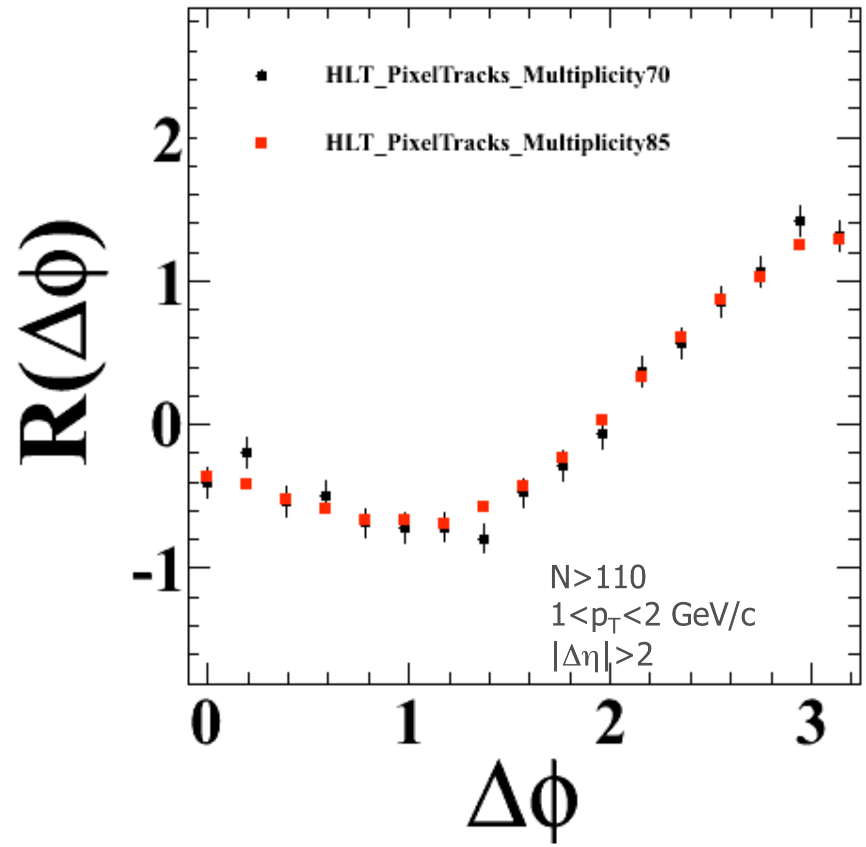
Trigger

Min-bias trigger vs high mult trigger



Ridge is seen using
min bias trigger + offline selection

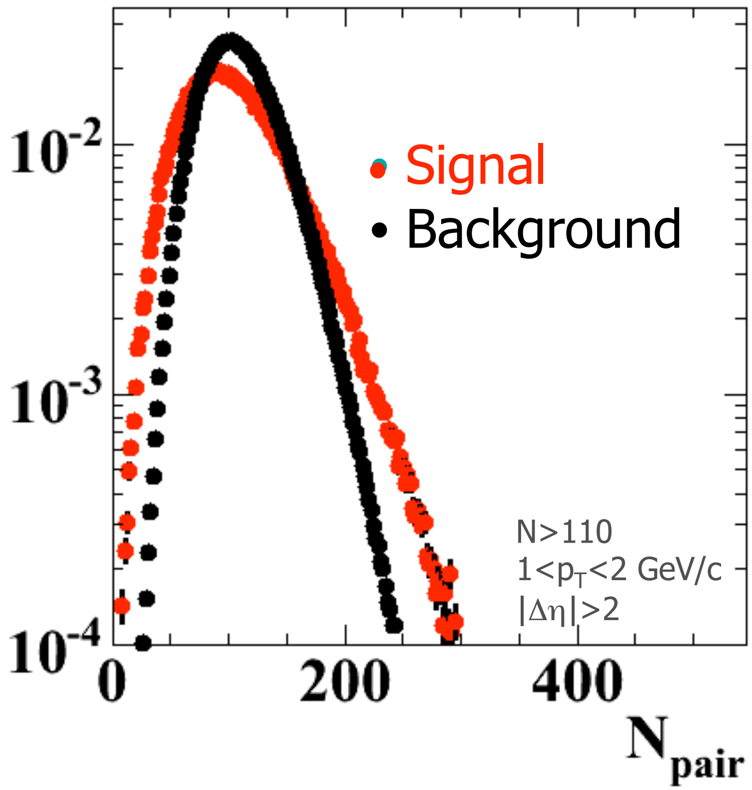
HLT 70 vs HLT 85 for N > 110



No trigger bias seen from
comparison of trigger paths

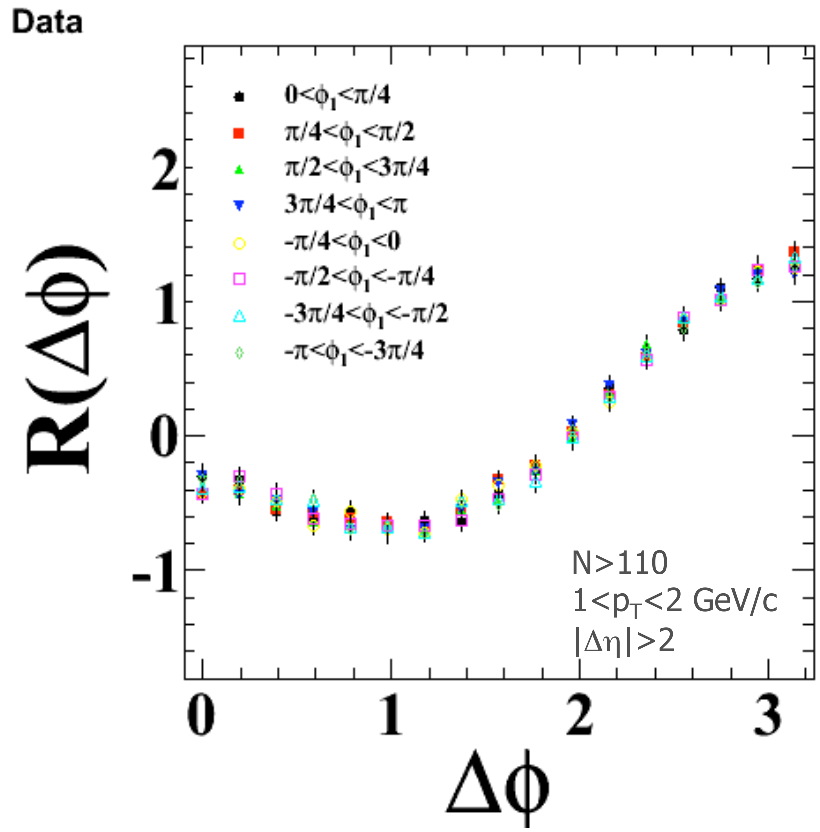
Detector

Pair multiplicity distribution for $|\Delta\eta|>2$ and $|\Delta\phi|<1$



Ridge is not caused by rare events with large # of pairs

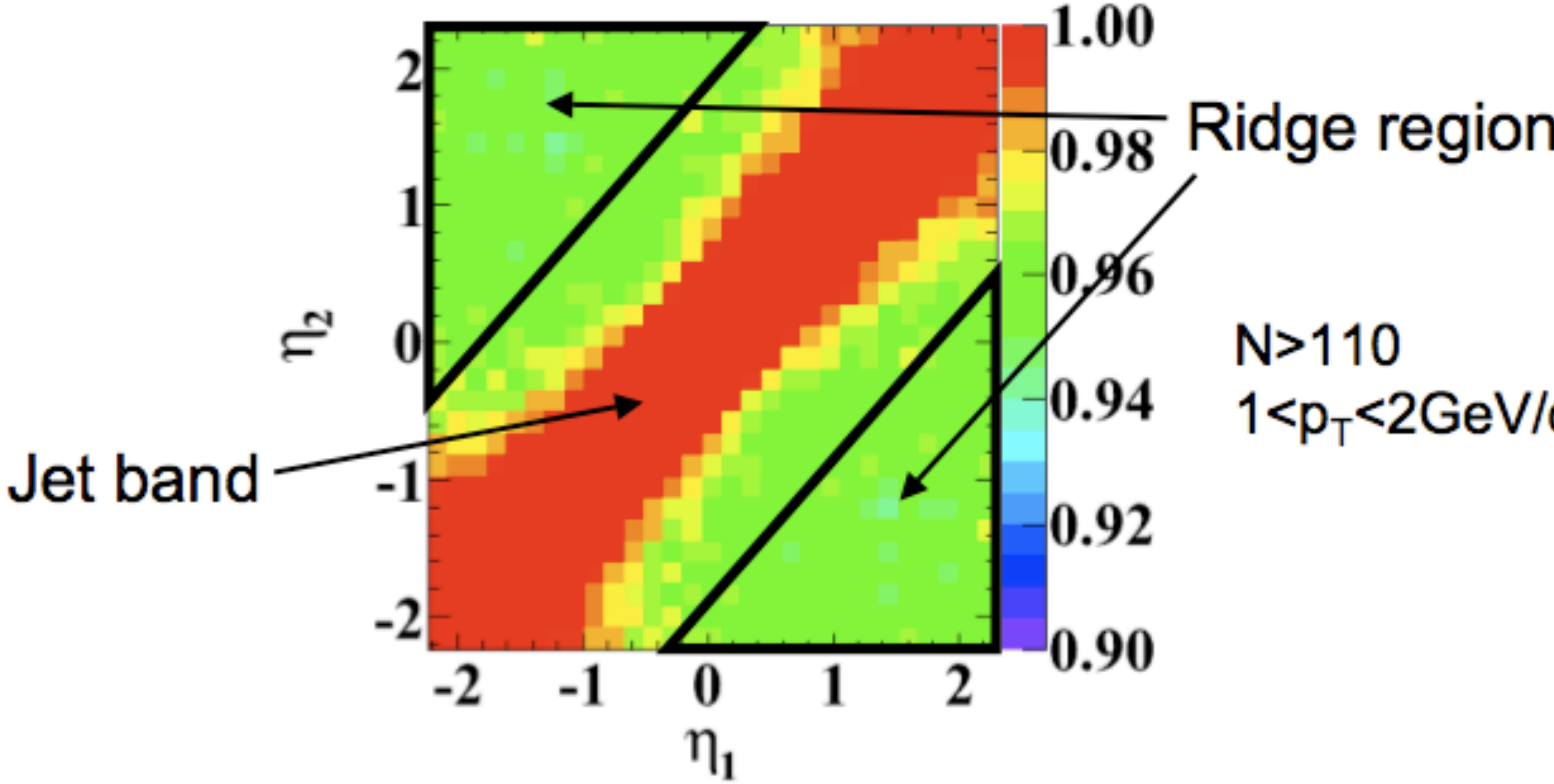
Constrain one track to one ϕ octant



Ridge is ϕ symmetric

Detector

η_1 vs η_2 correlations for near-side ($|\Delta\phi|<1$)

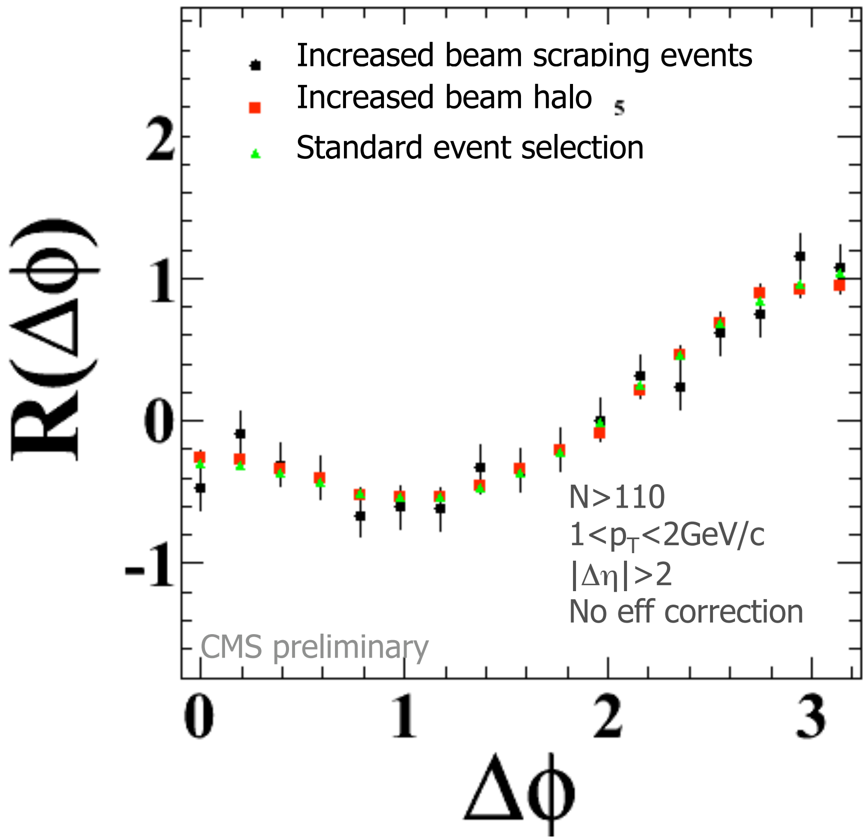


N>110
$1<p_T<2$GeV/c

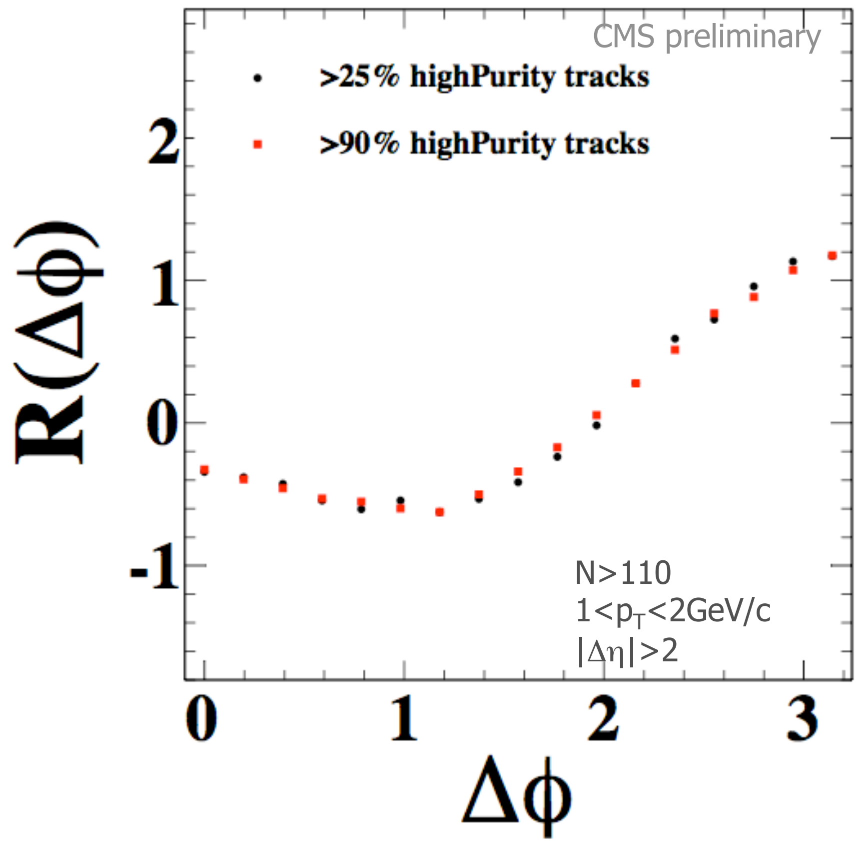
Ridge region shows no structure in η_1 vs η_2

Event Backgrounds

Select higher fraction of possible beam-gas or beam-scraping events



Reject beam background by veto on fraction of low quality tracks

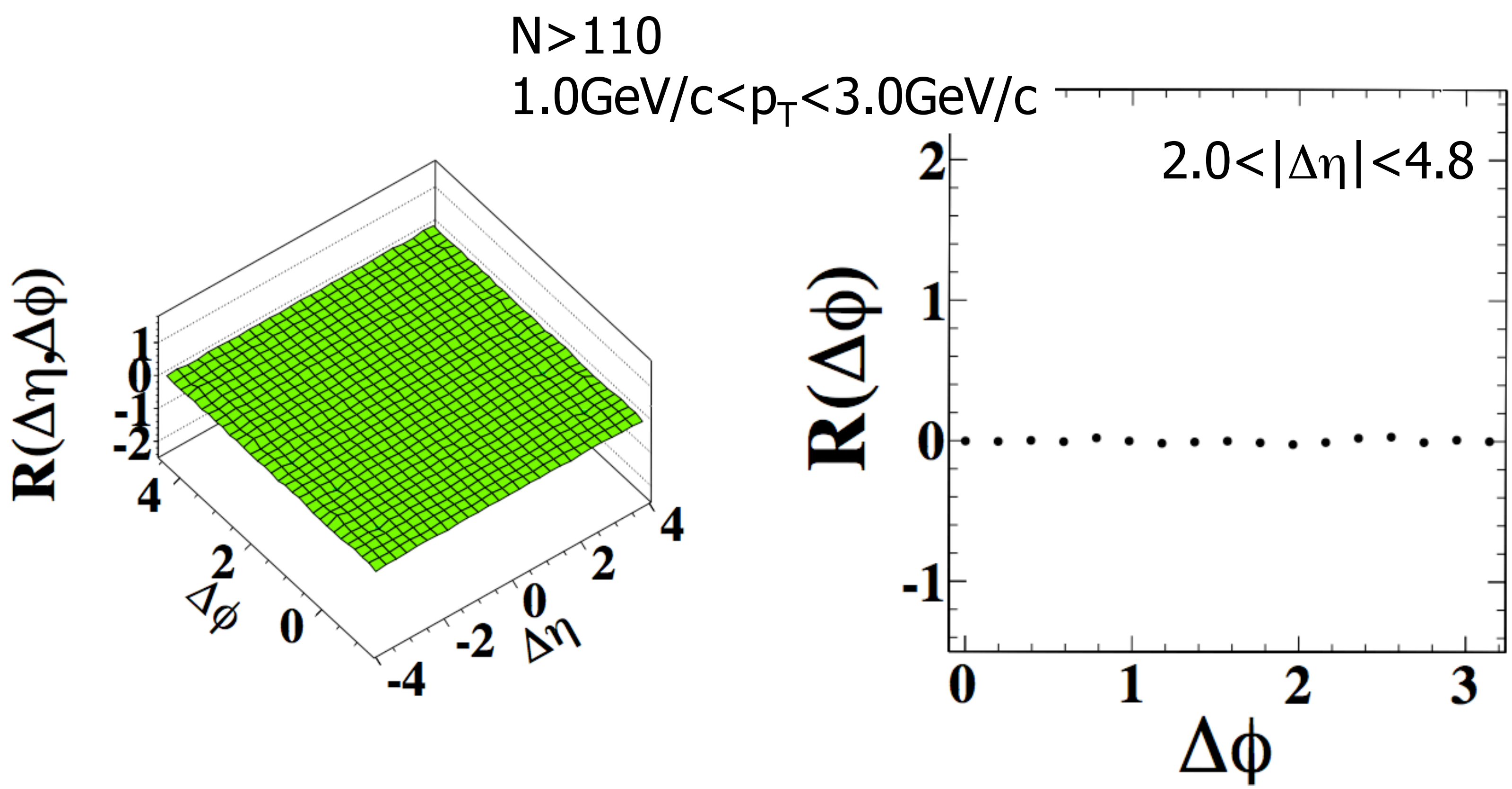


Ridge region shows no sensitivity to beam background

Note: Analysis is done on HighPurity tracks

Event Backgrounds

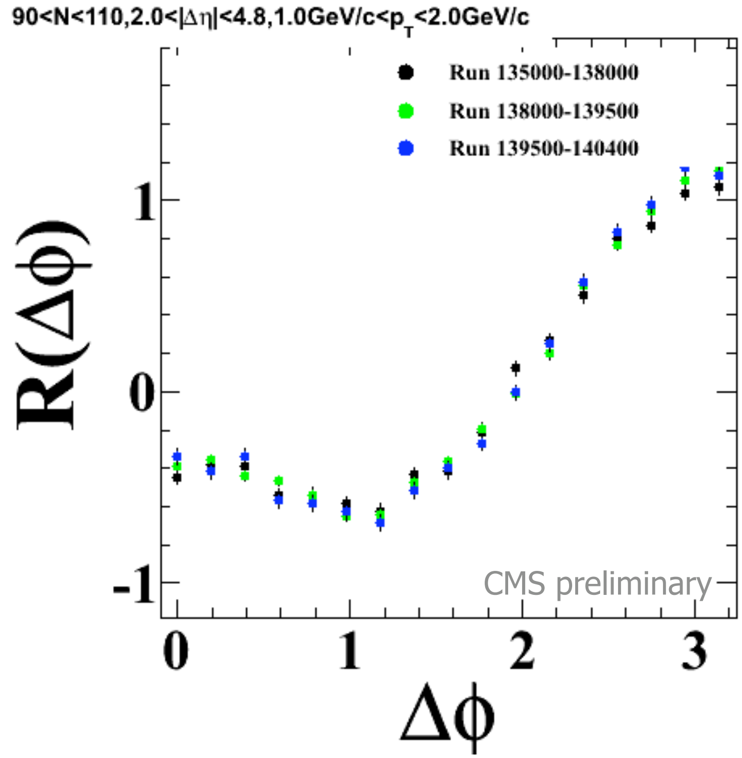
Correlate tracks from high multiplicity vertex with tracks from different collision (vertex) in same bunch crossing



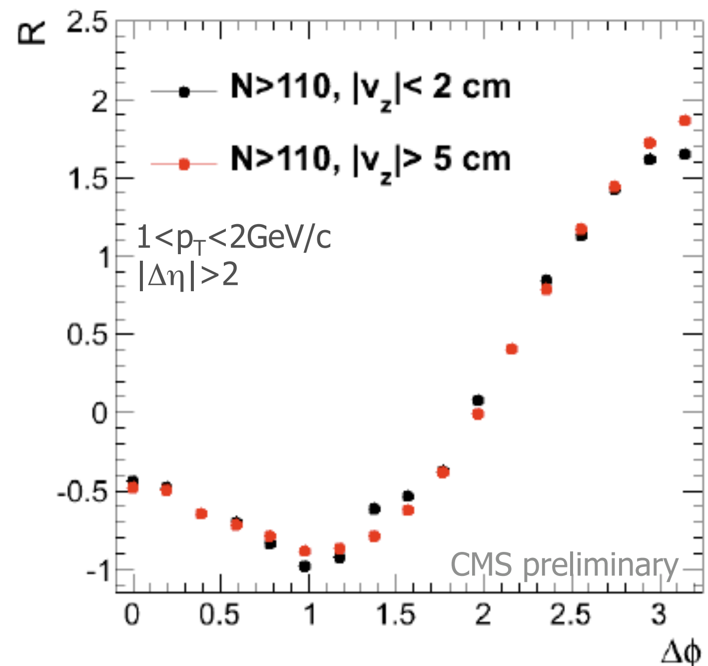
No background or noise effects seen in cross-collision correlations

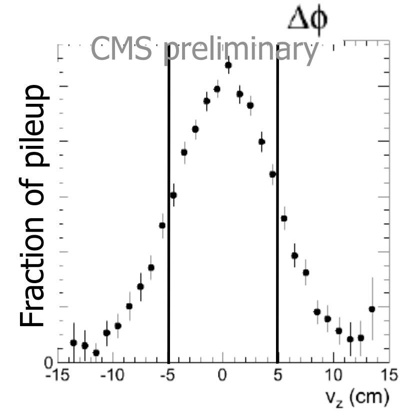
Event Pileup

Compare different run periods
(fraction of pileup varies by x4-5)



Compare different vertex regions
(fraction of pile-up ~ $dN/dvtx_z$)

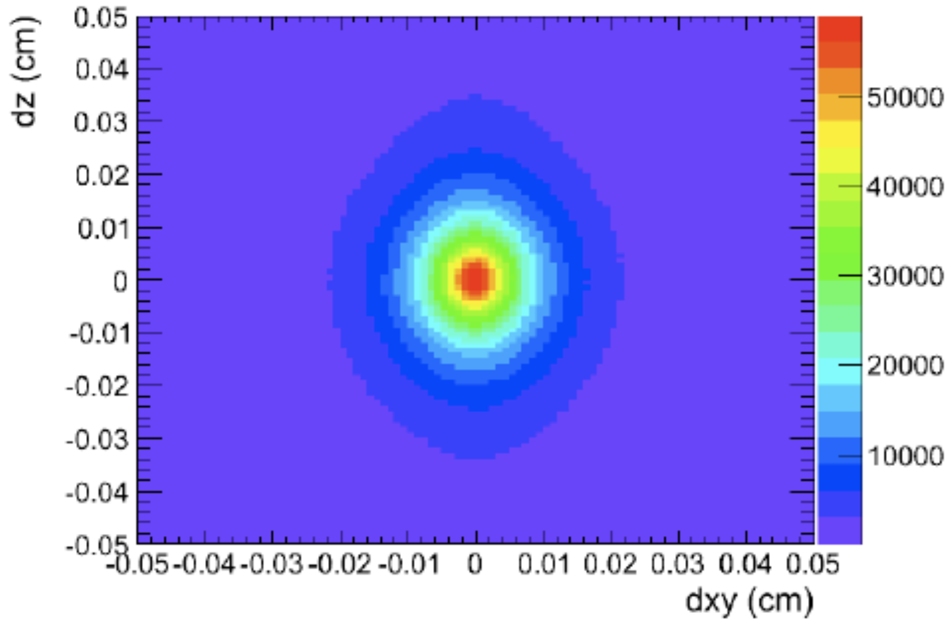




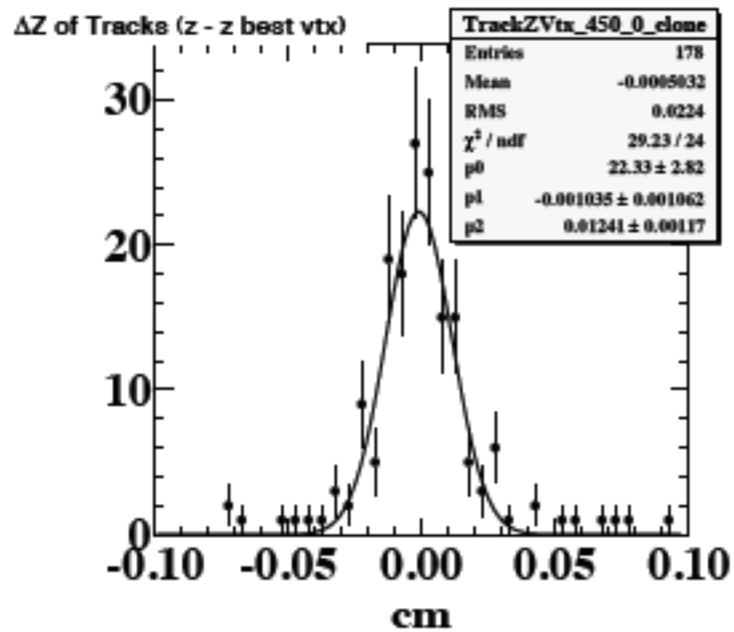
Change in pileup fraction by factor 2-4 has almost no effect on ridge signal

Event Pileup

Track longitudinal and transverse impact parameter
(p_T > 0.4 GeV/c)



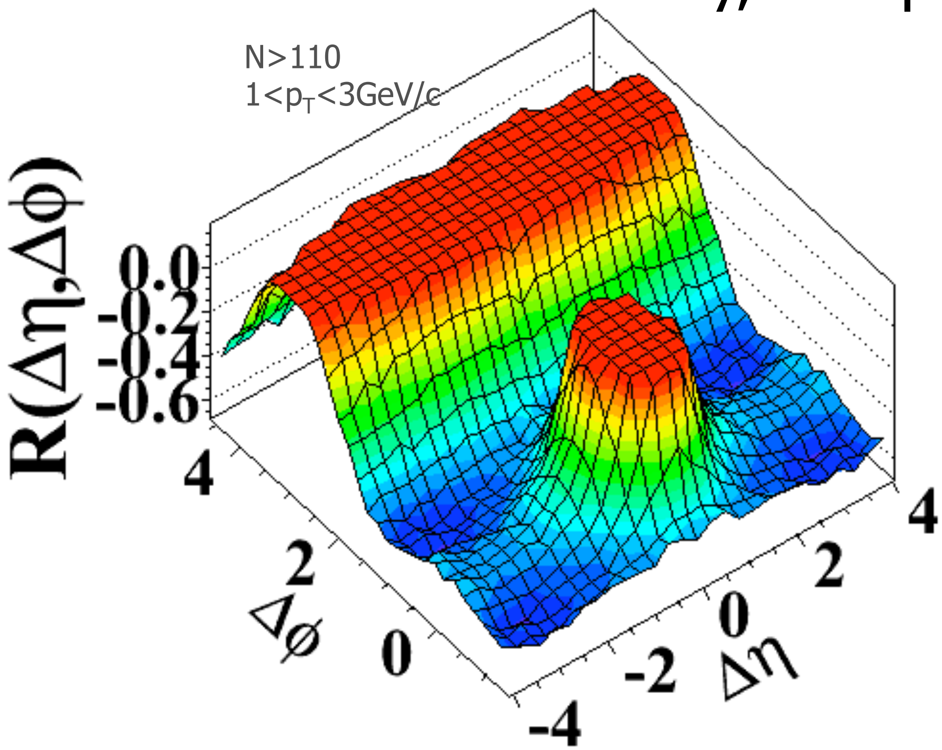
Single-event track dz distribution

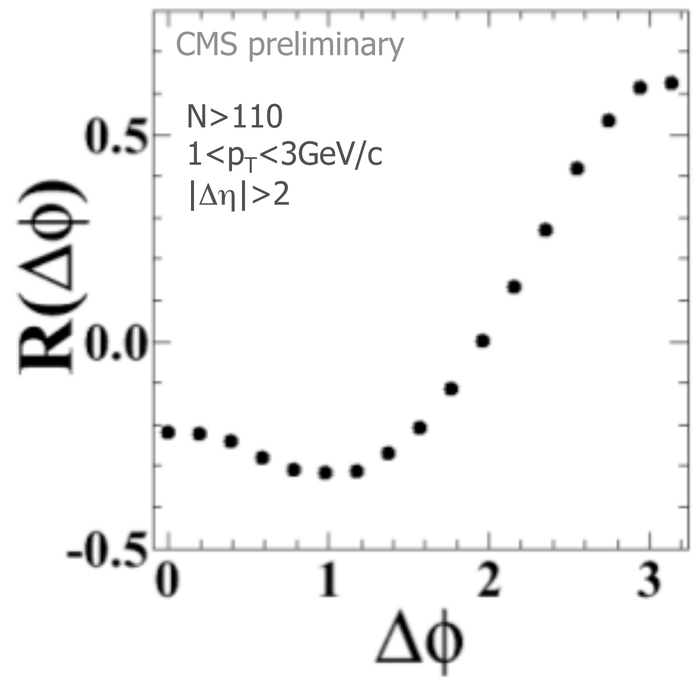


Pileup effects are suppressed due to excellent resolution
Track counting done with σ_{dz}, σ_{dxy} of O(100μm)

Final Test: ECAL photons

Use ECAL "photon" signal
Mostly single photons from π^0's
No efficiency, and p_T, ϕ smearing corrections



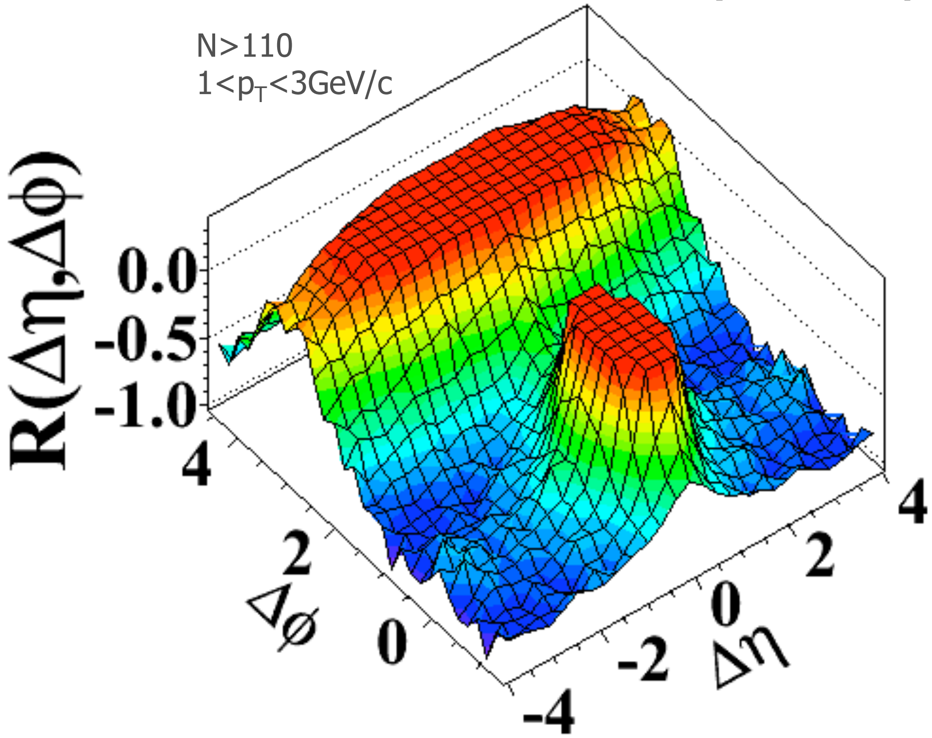


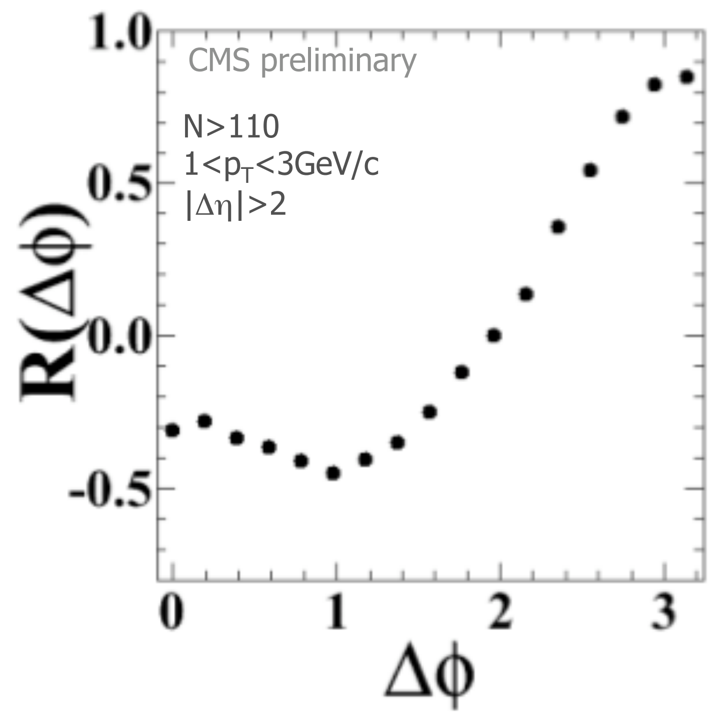
Track-photon correlations

Note: photons reconstructed using "particle flow" event reconstruction technique

Final Test: ECAL photons

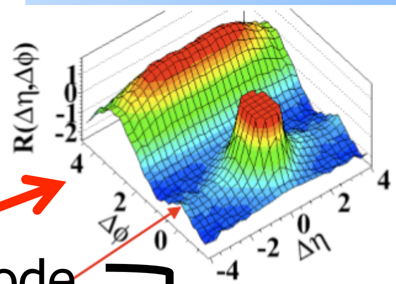
Use ECAL "photon" signal
Mostly single photons from π^0's
No efficiency, and p_T, ϕ smearing corrections





Photon-photon correlations
Qualitative confirmation
Independent detector, independent reconstruction

Systematic Uncertainties



Analysis code

↑

Reconstruction

↑

Trigger

↑

Detector

↑

CMS Event

↑

Collision

Each step tested with data-based checks

No indication of effect that would fake ridge signal (irrespective of magnitude)

Sources	Syst. on ridge yield
Pileup	15%
HLT efficiency	4-5%
Tracking	1-2%
ZYAM	0.0025

Conservative estimates of uncertainties on ridge associated yield

Summary

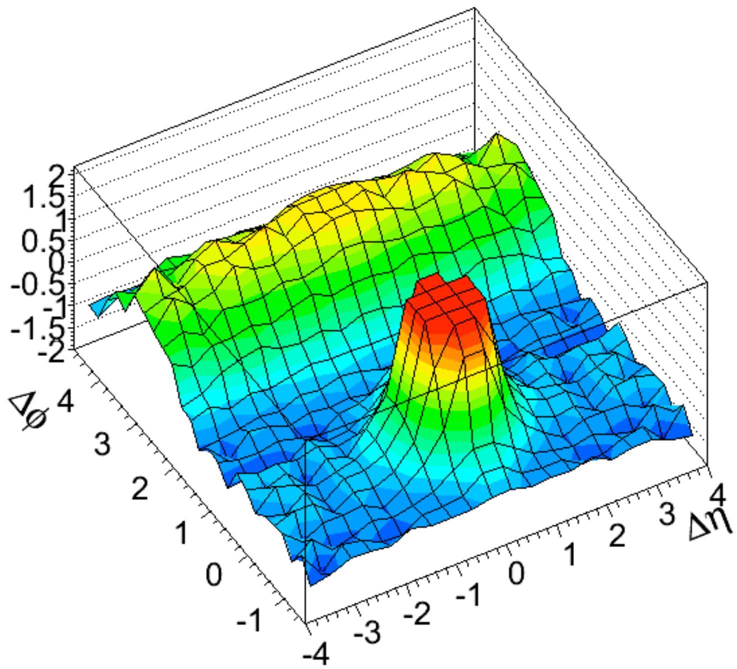
- **Study of short-range and long-range angular correlations in pp collisions with CMS at LHC**
- **Observation of long-range, near-side correlations in high multiplicity events**
  - Signal grows with event multiplicity
  - Effect is maximal in the $1 < p_T < 3$ GeV/c range
- **Long-range, near-side correlation is not seen in low multiplicity events and generators, but resembles effects seen in heavy-ion collisions at high energies**
- **This is a subtle effect in a complex environment – careful work is needed to establish physical origin**

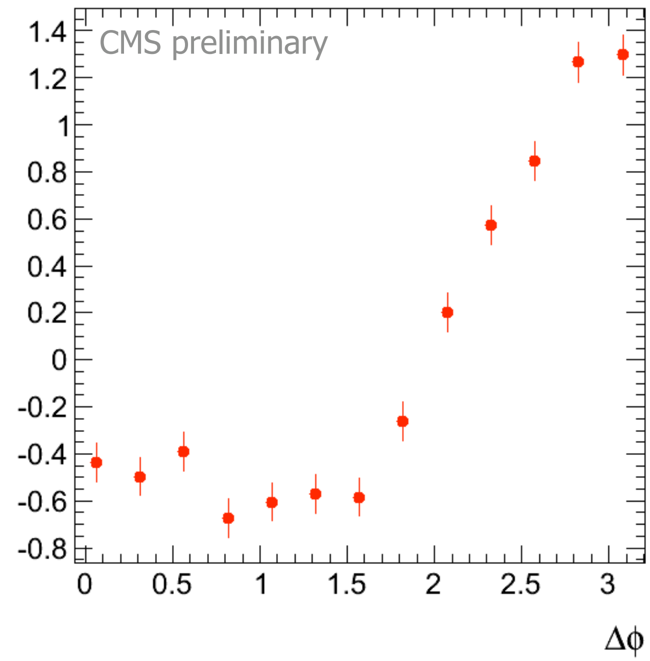
Backup slides

BSC High Multiplicity Trigger

Preliminary results from BSC high multiplicity trigger

N>65
$|\Delta\eta|>2.0$
$1.0\text{GeV/c}<p_T<3.0\text{GeV/c}$

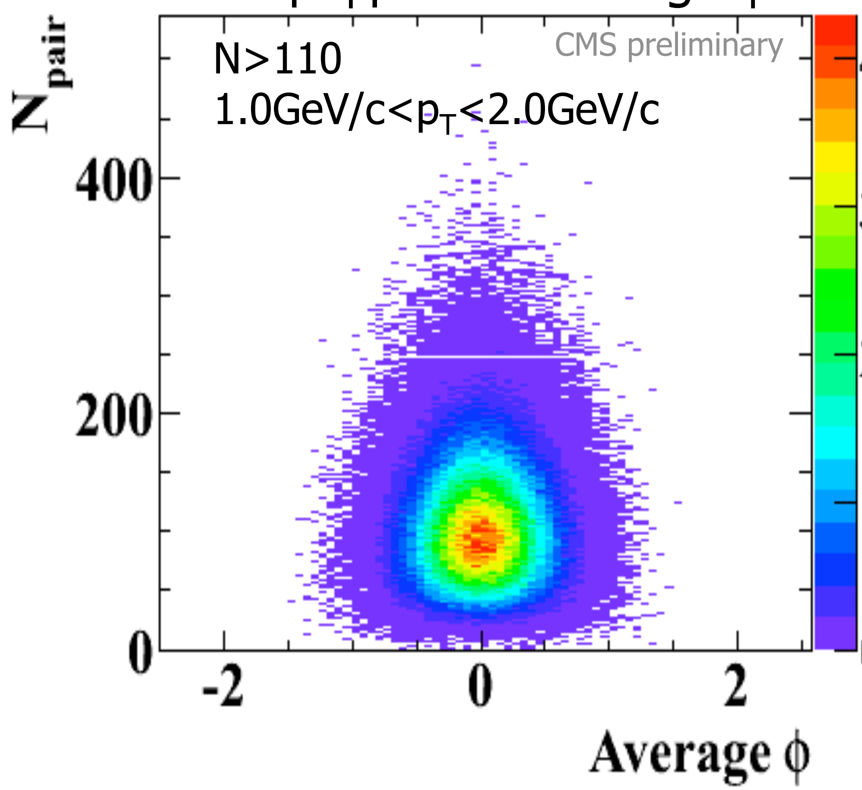




Agreement with standard results within statistical uncertainty

ϕ Symmetry

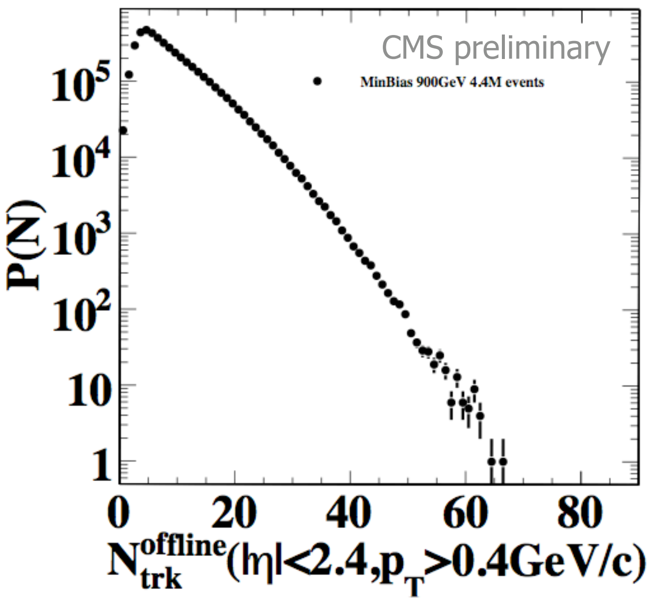
Pair multiplicity at $|\Delta\eta|>2$
and $|\Delta\phi|<1$ vs average ϕ

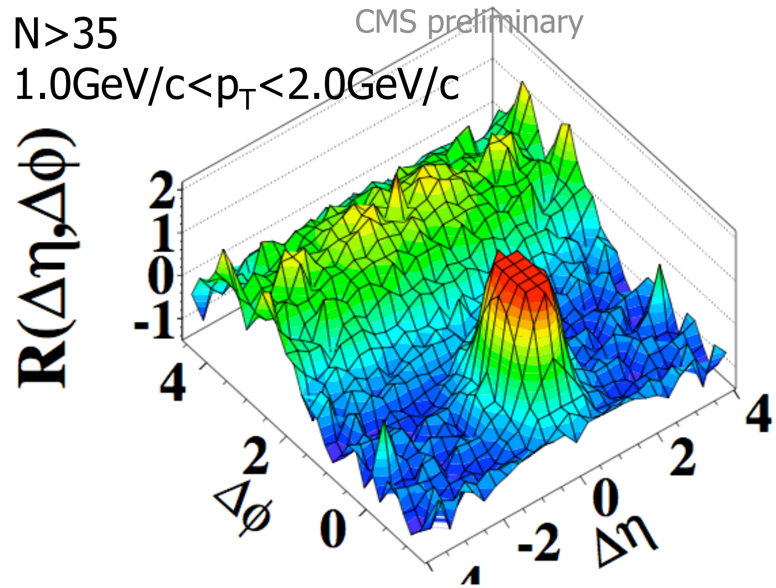


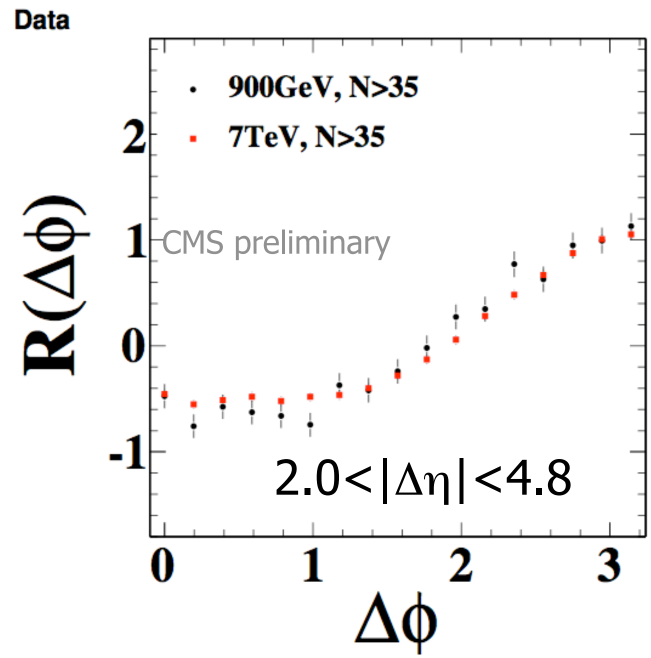
No indication of "hot spots" in event-by-event ϕ distribution

Preliminary 900 GeV Analysis

Run 134721, 134725





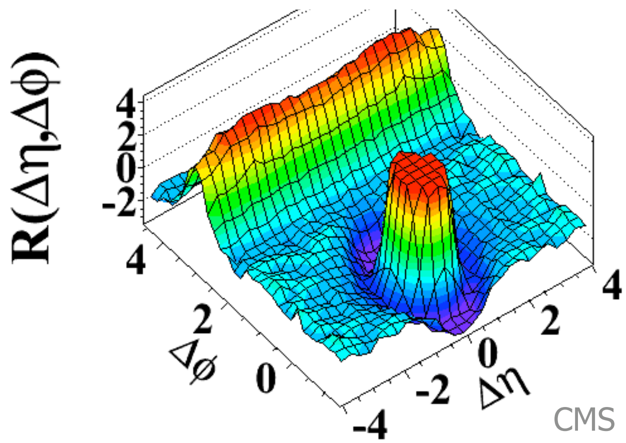


Limited statistics for high multiplicity events in 900GeV

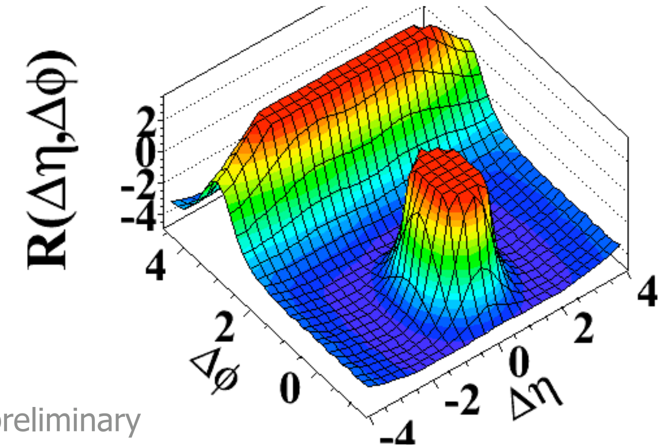
Two energies agree within large uncertainties

Other pp Event Generators

PYTHIA D6T MinBias, N>70



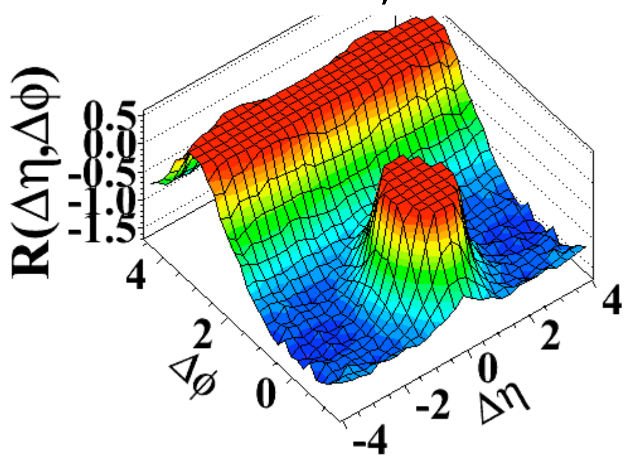
PYTHIA D6T, Dijet 80-120GeV



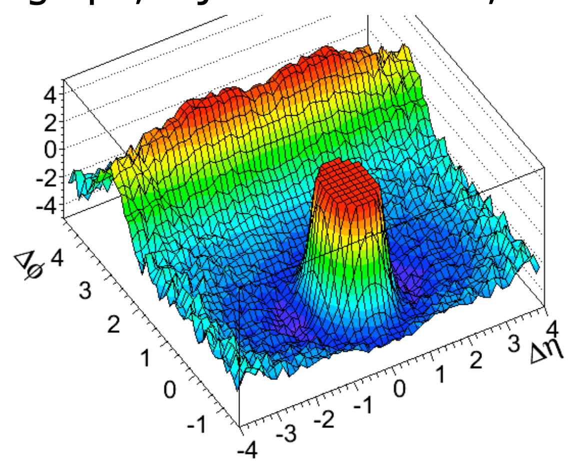
CMS preliminary

$1<p_T<3$GeV/c

HERWIG++, N>110



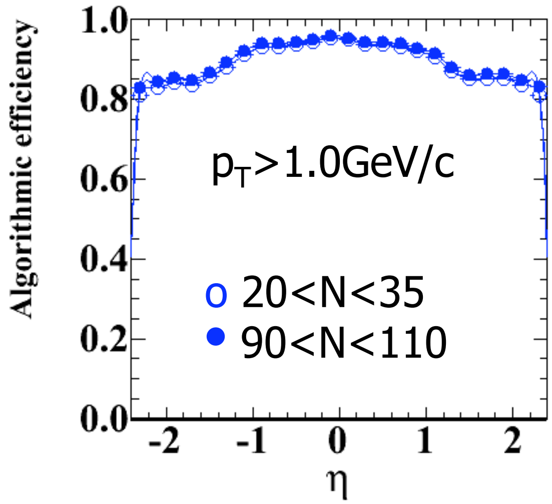
Madgraph, Dijet 100-250GeV, N>90

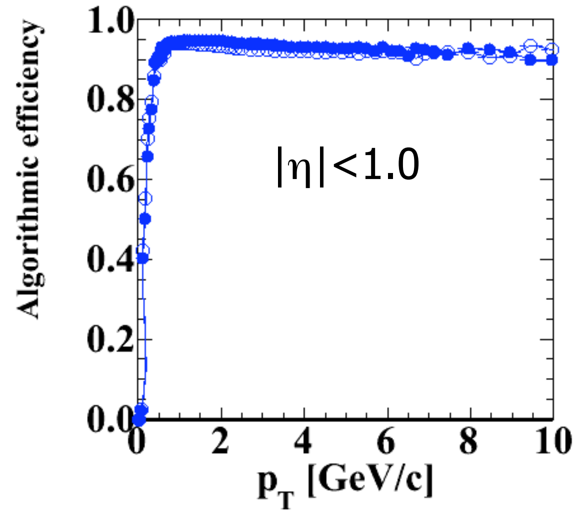


No ridge effect in these models (with the tunes used)

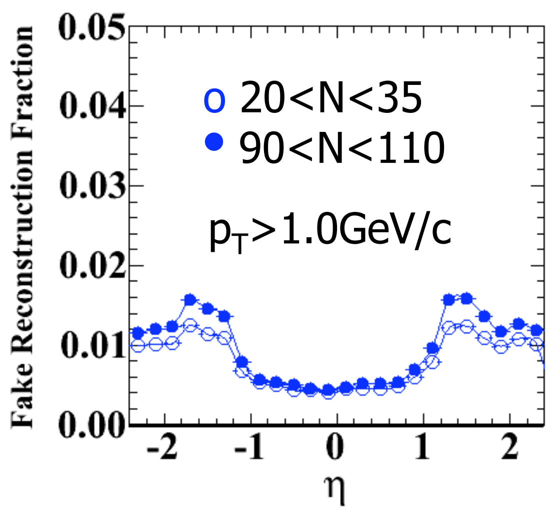
Tracking Performance

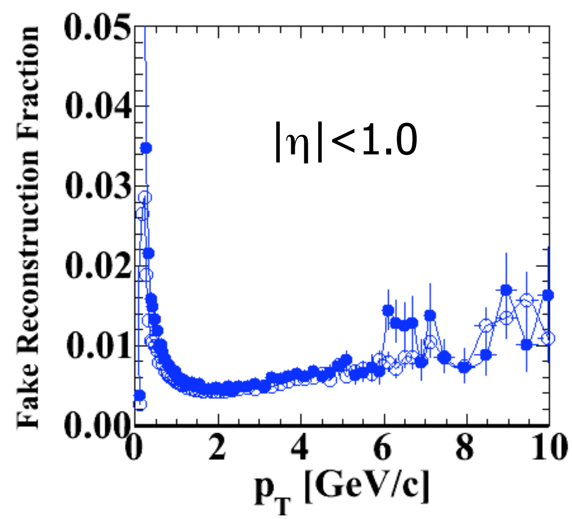
Tracking Algorithmic Efficiency:



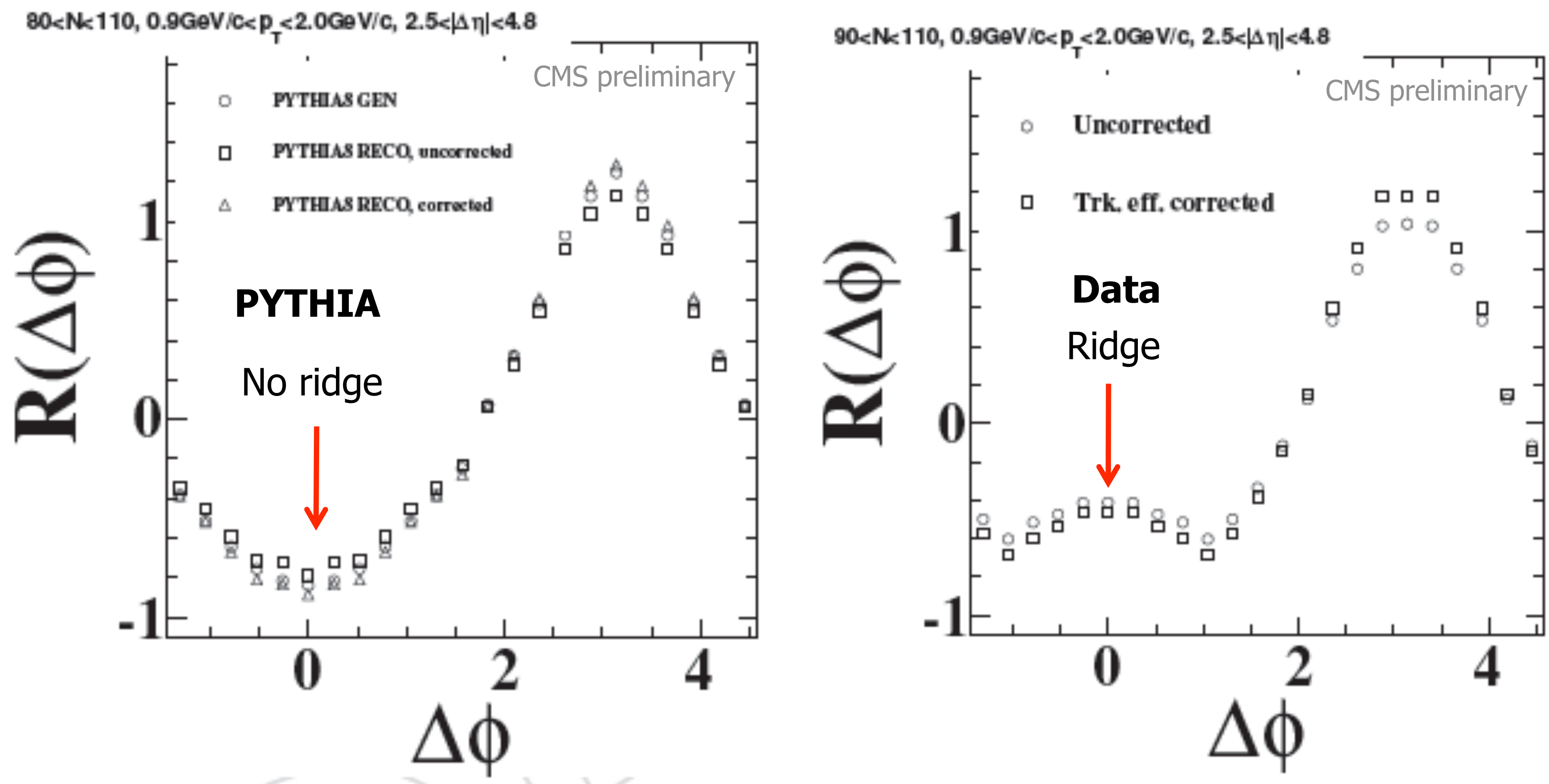


Fake rate:



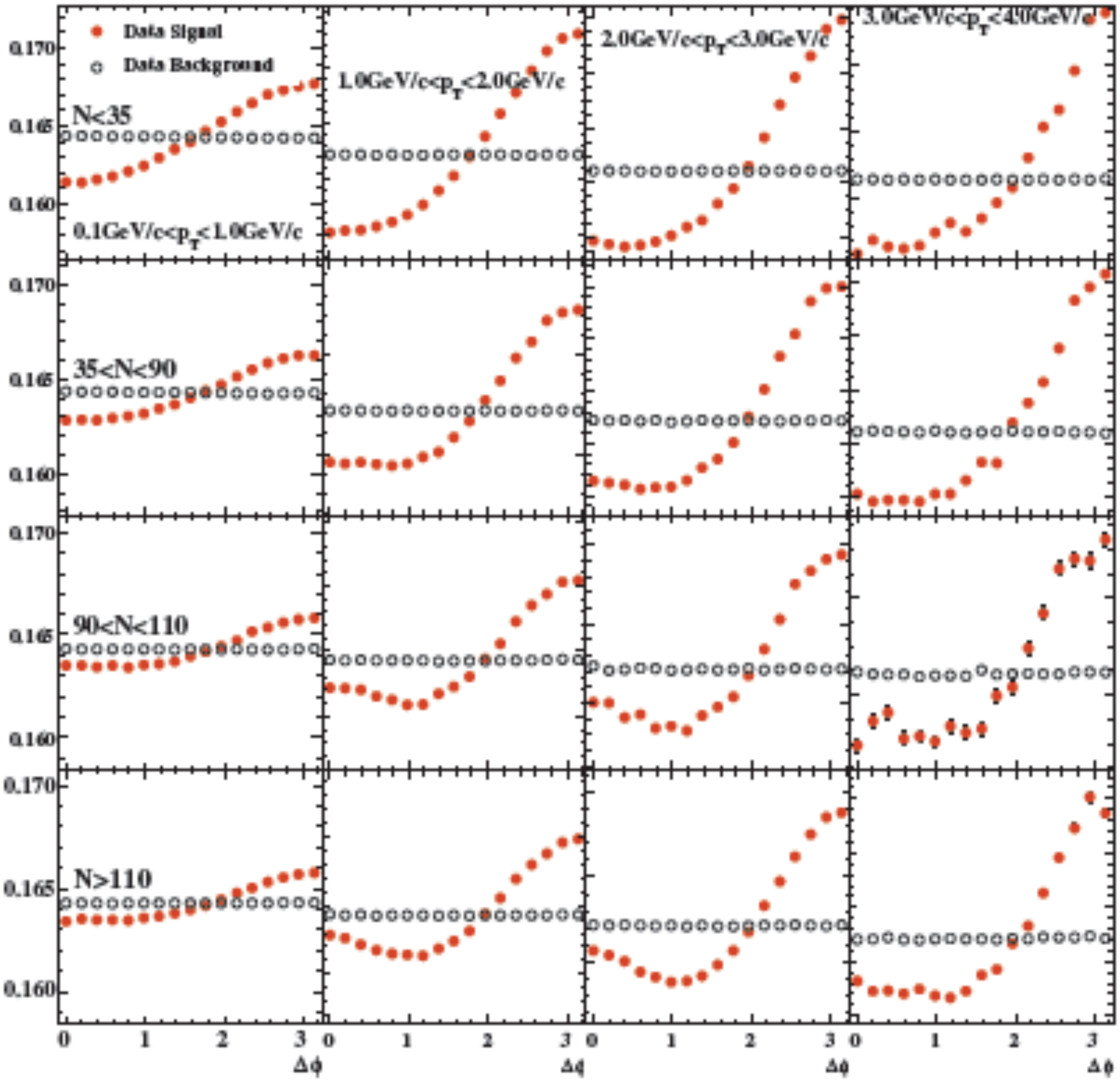


Efficiency Correction



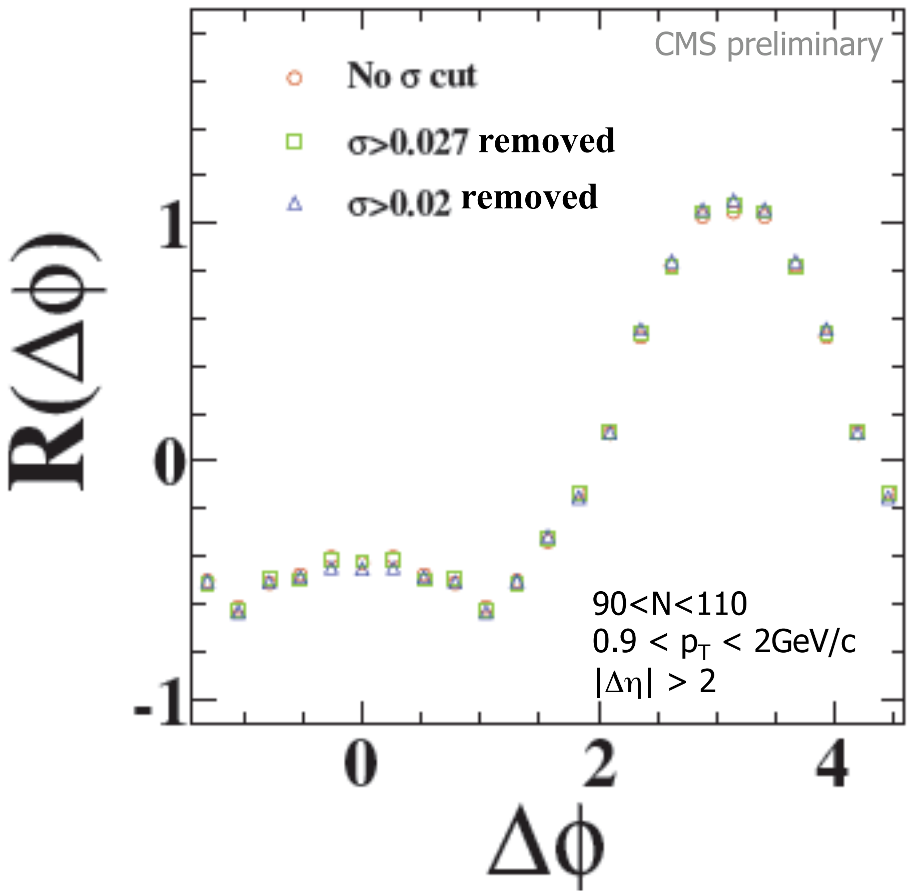
Tracking efficiency correction has small effect on correlation function

Signal and Background

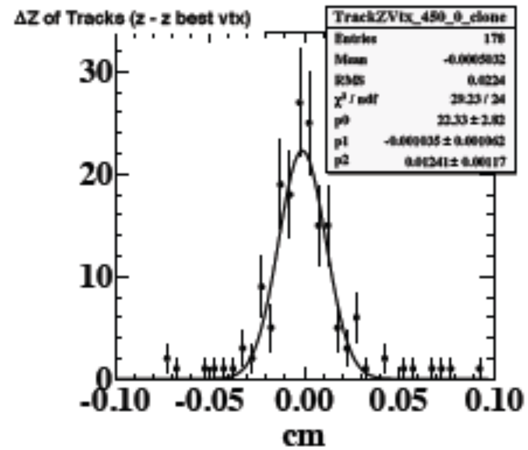


Signal is visible in raw data before dividing by (flat) background

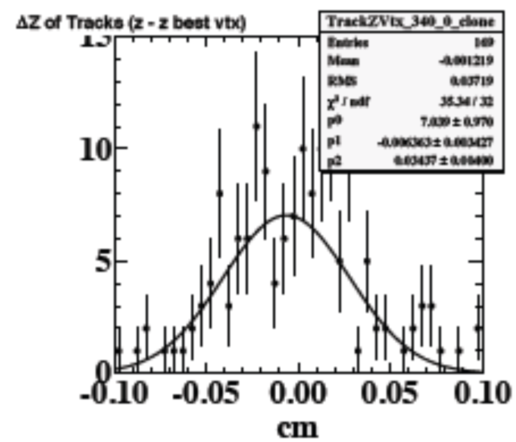
Rejection of “Wide Vertices”



Keep

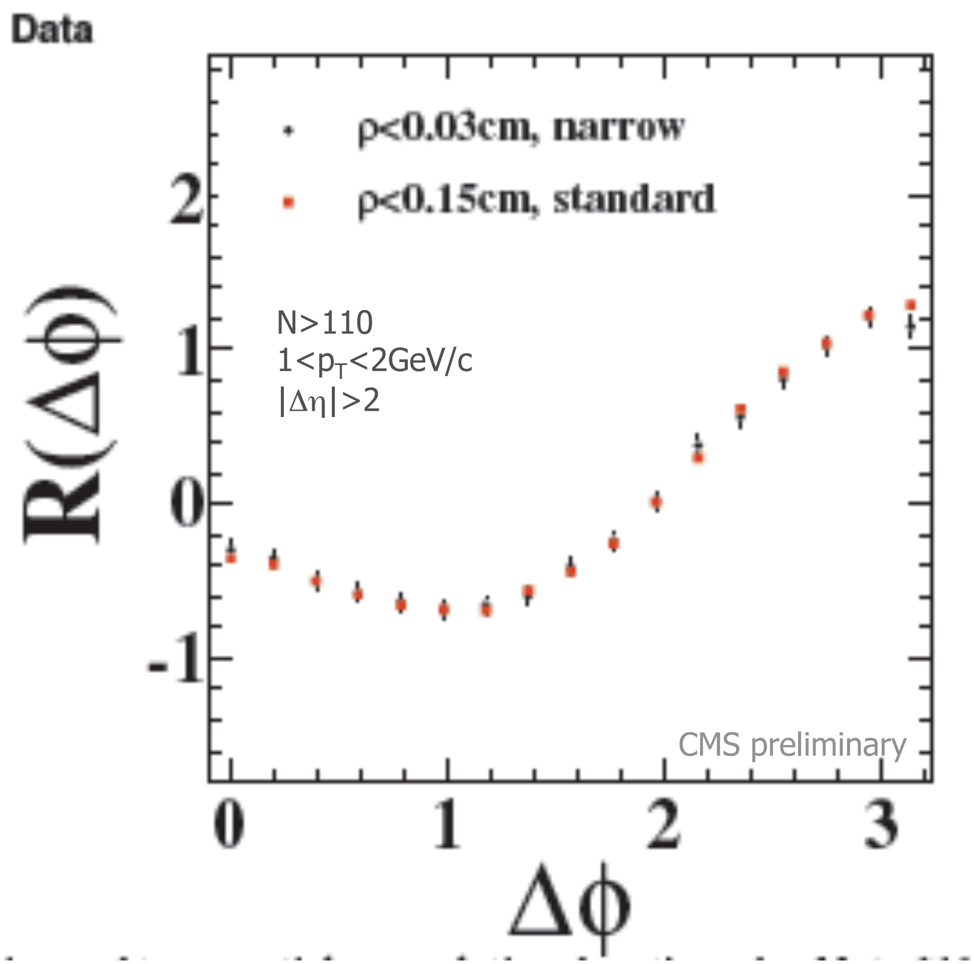


Remove



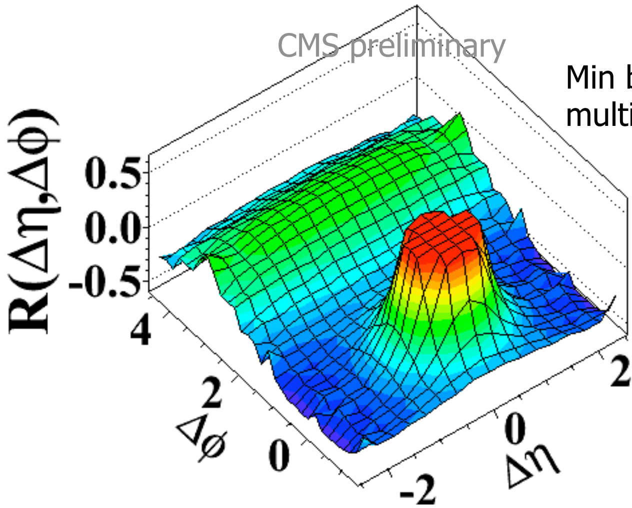
Removing events with “suspicious” vertex distributions does not change result

Select Beamspot "Core"

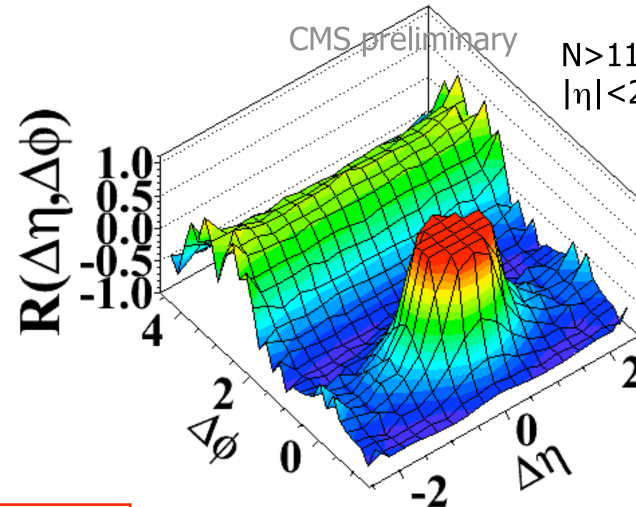


No dependence on radial distance from center of beam

Acceptance Variation

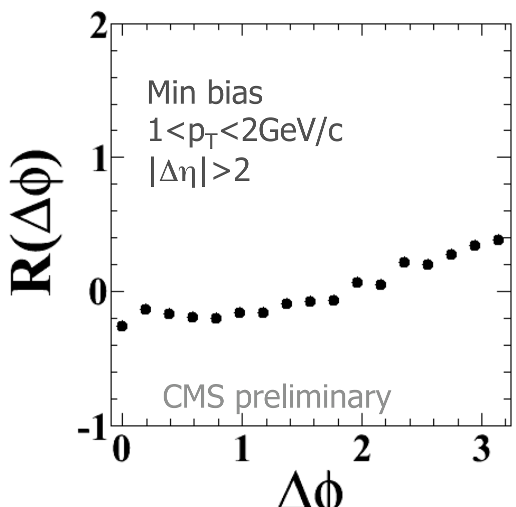


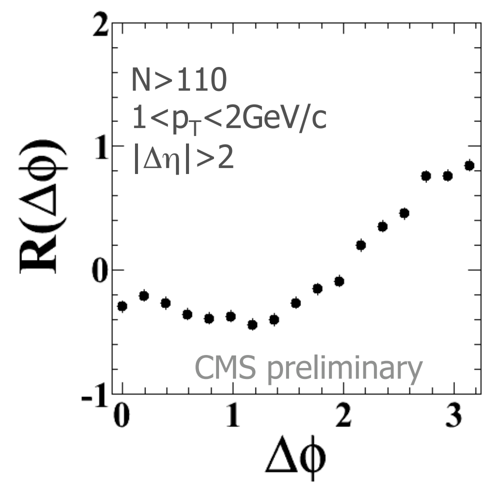
Min bias, no multiplicity selection



N>110 (counted for $|\eta|<2.4$, $p_T>0.4$ GeV/c)

$|\eta| < 1.2$

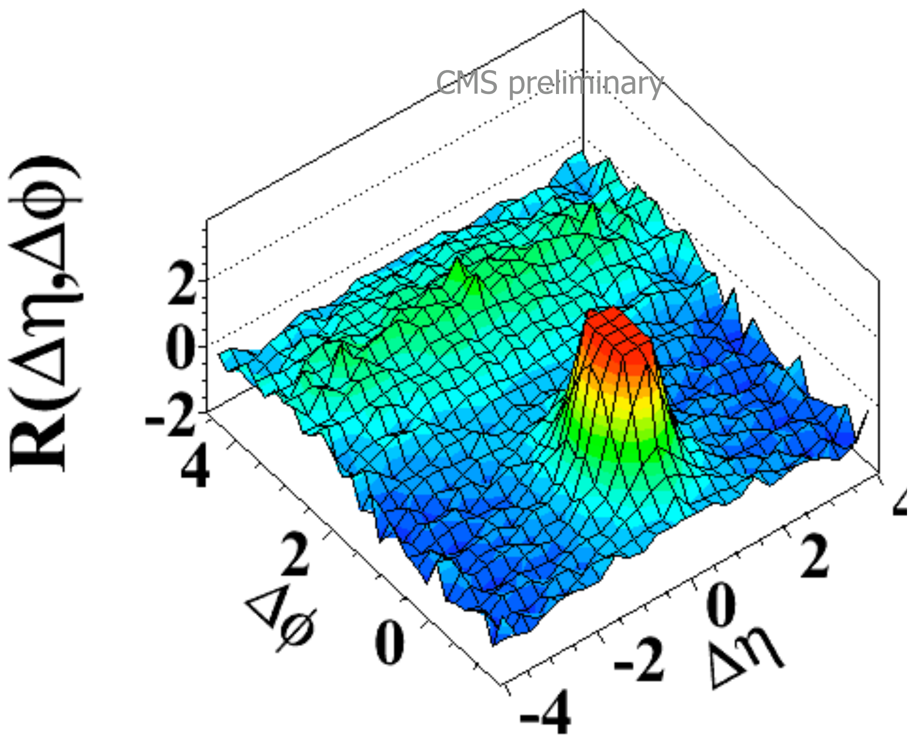


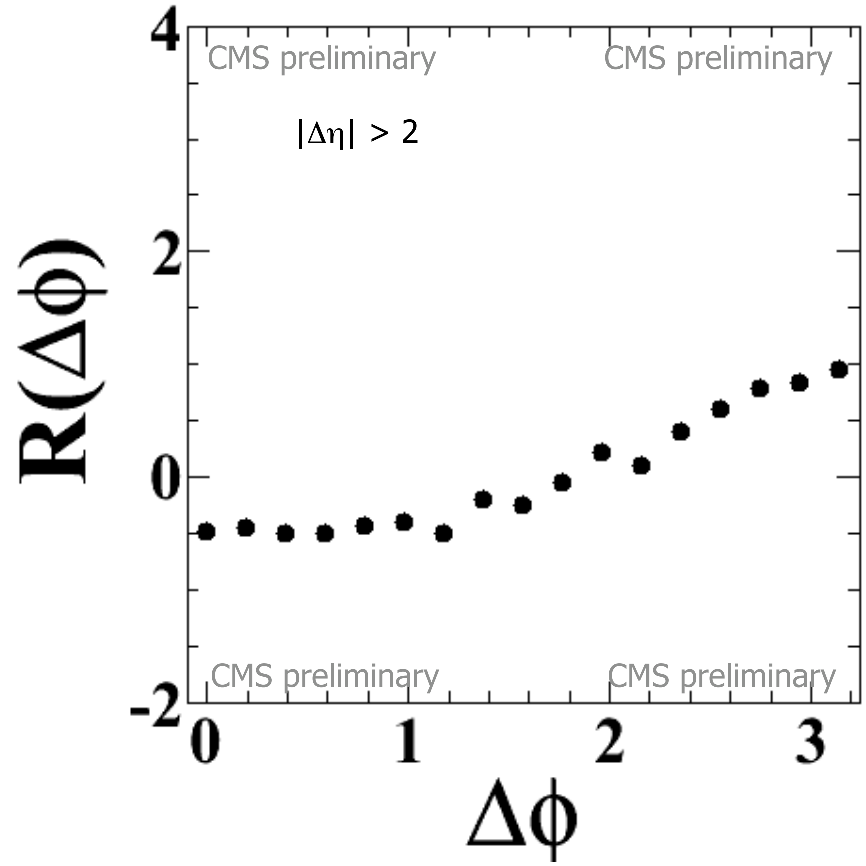


Ridge also seen in reduced acceptance
(but with larger statistical uncertainty)

(Multi-) Jet Events

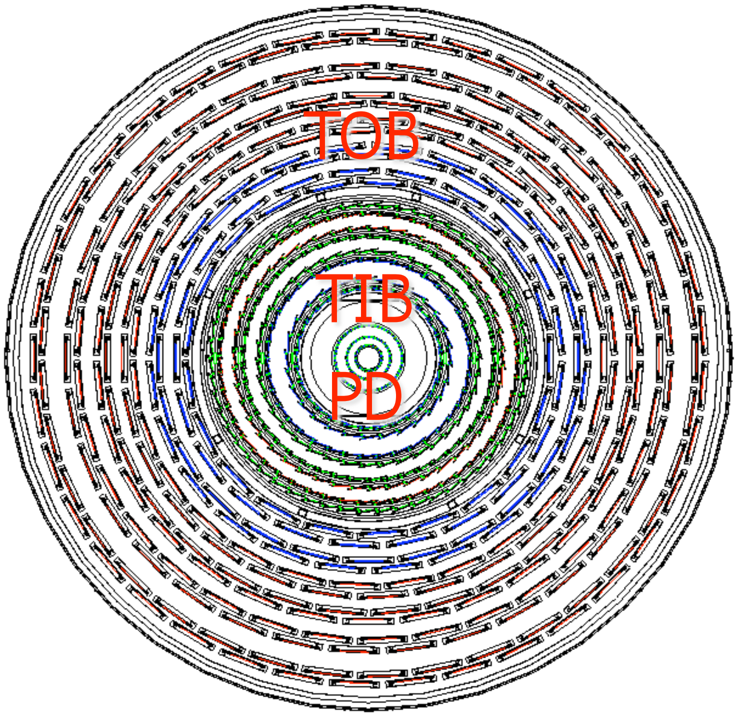
N_{jet}>=4, N_{trk}<50, 1<p_T<2GeV/c



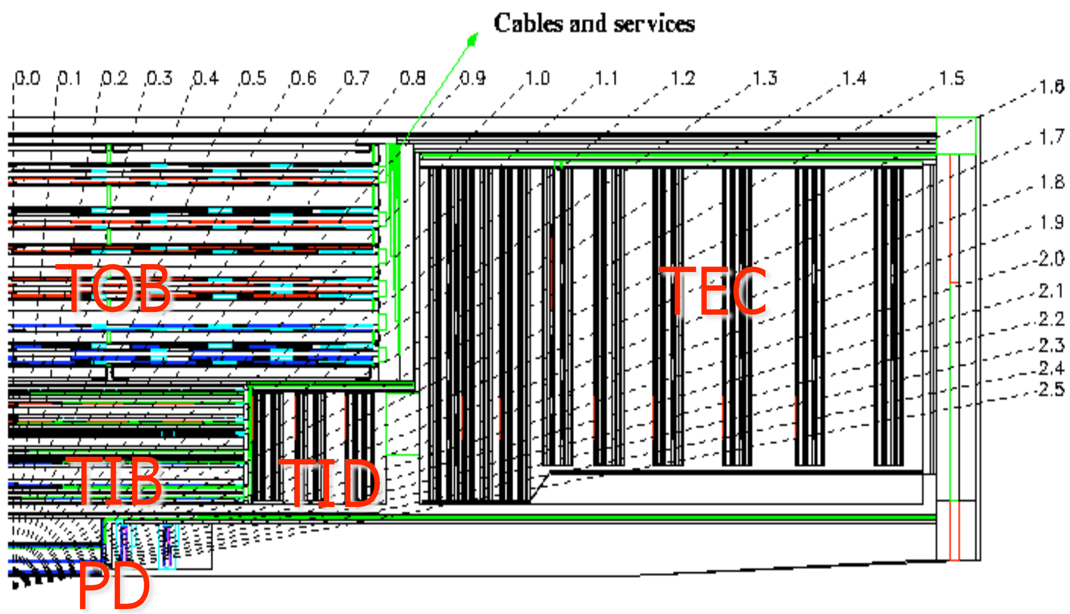


More work needed to explore connection to jet correlations

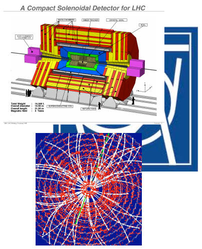
CMS Tracker



TOB
TIB
PD



Cables and services
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
1.1
1.2
1.3
1.4
1.5
1.6
1.7
1.8
1.9
2.0
2.1
2.2
2.3
2.4
2.5
TOB
TEC
TIB
TID
PD

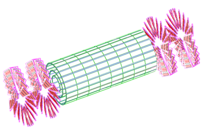


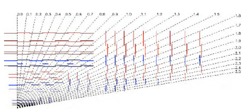
B

CMS detector: L=21.6m, D=14.6m, weight=12500tons

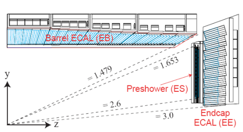
Time between bunch crossings: 25 ns (pp)
Event rate: 10^9 events/s (pp)

Magnetic field: 4T (L=13m, D_{in}=5.9m)



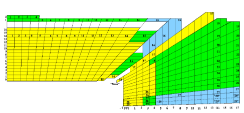


Silicon tracker: L=5.8m, D_{in}=2.6m, thickness=320, 500μm, operating T=-20^{0}C
Pixel: 3 barrel (768 modules) and 2 endcap (672 modules) layers, S_{tot}=1m^2, R_{barrel}=4.4, 7.3, 10.2cm, Z_{endcap}=34.5, 46.5cm, S_{pix}=100x150 μm^2, occupancy 10^{-4}(pp) – 1%(PbPb), single point resolution 10μm in r-f and 20μm in z direction
Silicon strip: 10 barrel and 9 endcap layers, S_{tot}=200m^2, 15,400 modules
Inner silicon strip: R=20-55cm, S=10cm x 80-120mm, occupancy 2-3% , single point resolution 23-34μm in r-f and 230μm in z direction
Outer silicon strip: R>55cm, S=25cm x 180μm, occupancy 1%(pp)-20%(PbPb) , single point resolution 35-52μm in r-f and 530μm in z direction

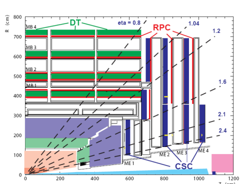


EM calorimeter: homogeneous $PbW0_4$ crystals, |η|<3.0, thickness ~25 X_0
Resolution: S=3.63±0.1%, N=124MeV, C=0.26±0.01%.
Barrel: 61200 crystals, |η|<1.479, R_{in}=129cm, 22x22x230 mm^3, 25.8 X_0
Endcups: 7324 crystals in each endcap, 1.479<|η|<3.0, 28.6x28.6x220 mm^3, 24.7 X_0

$$\left(\frac{\sigma}{E}\right)^2 = \left(\frac{S}{\sqrt{E}}\right)^2 + \left(\frac{N}{E}\right)^2 + C^2$$



Hadron calorimeter: sampling brass/scintilator, |η|<3.0, thickness 7-11 l_I
Hadron barrel: |η|<1.4, 2304 towers (ΔηxΔφ=0.087x0.087)
Hadron outer calorimeter: inside muon system, |η|<1.26
Hadron endcap: 1.3<|η|<3.0, 2304 towers (0.087-0.35 η segmentation, 5-10^0 φ segmentation)
Hadron forward: iron/quartz-fibre Cherenkov, 3.0<|η|<5.0, 900 towers (ΔηxΔφ=0.175-0.3x10-20^0)



Muon system: |h|<2.4, S>25,000m^2, ~10^6 electronic channels
Barrel: 250 chambers in 4 layers R=4.0m, 4.9m, 5.9m, 7.0m, Single point resolution: ~200 μm, space and direction resolution along f-angle <100mm and ~1mrad.
Endcap: 468 CSCs, Single point resolution 100-200μm, direction resolution along φ-angle 10mrad.