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

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CMS Collaboration

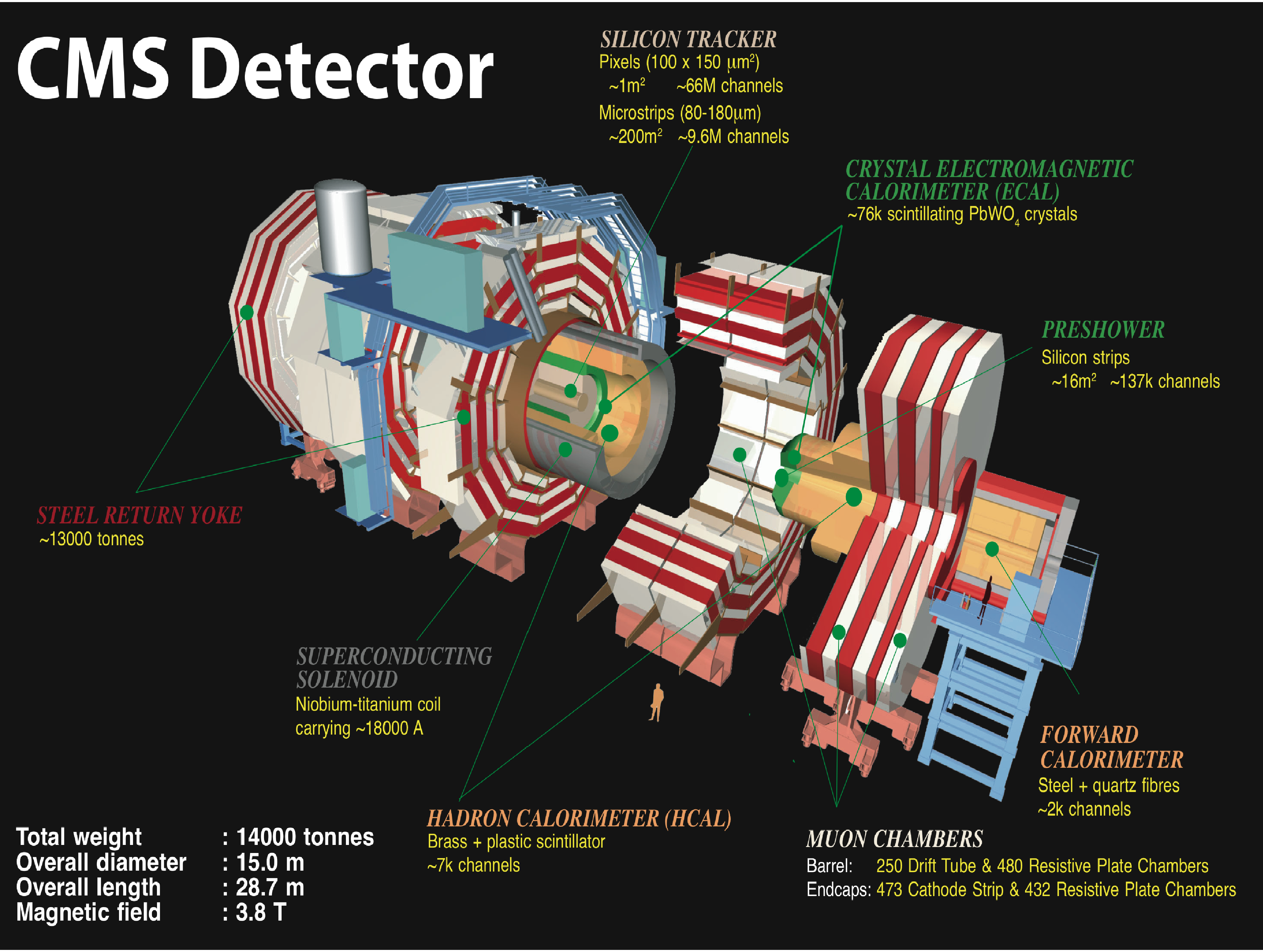
- **The CMS detector**
- **Two-particle correlation functions**
- **Results in minimum bias collisions**
- **Results in high multiplicity collisions**
- **Cross-checks**

Based on:

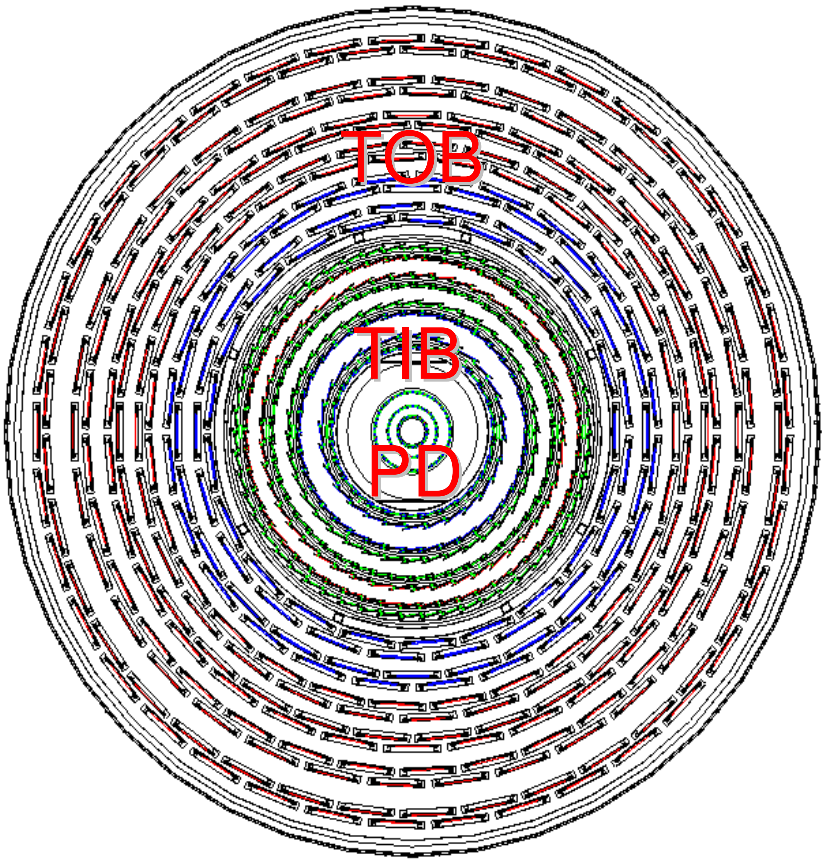
- JHEP 1009:091,2010

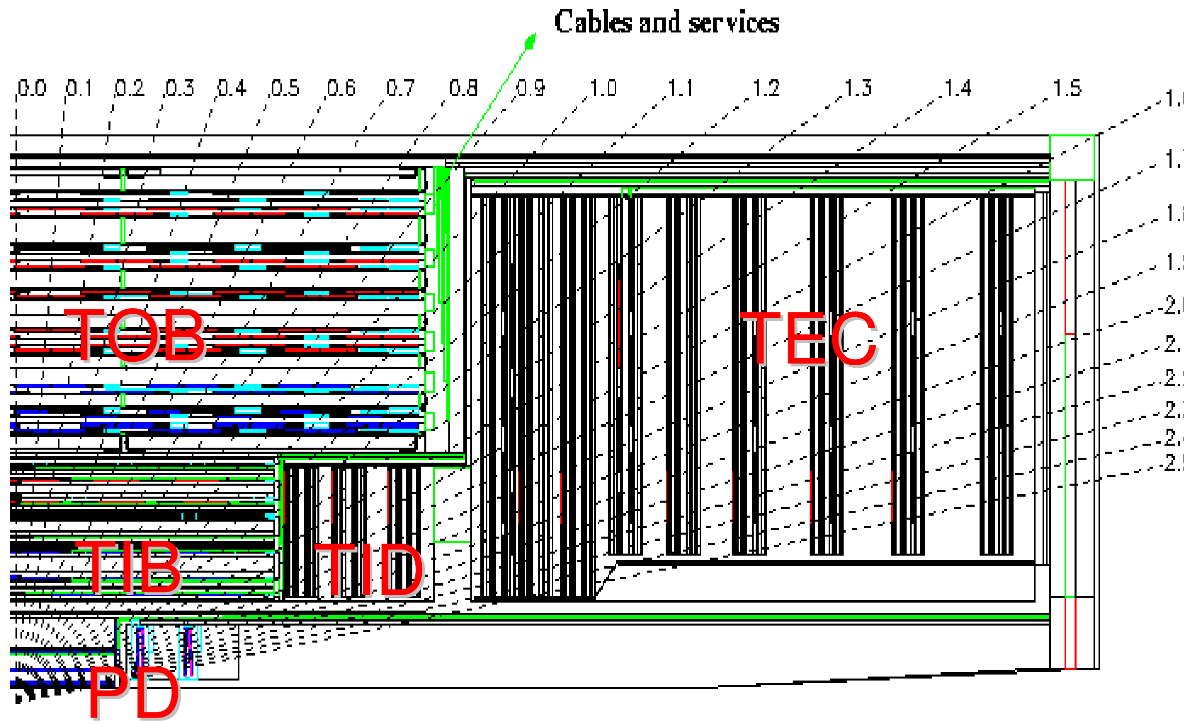
- My talk at ECT Trento: QCD at the LHC, September 28, 2010*

- CERN seminar talks by Gunther Roland and Guido Tonelli, Sept. 21, 2010


CMS Detector
SILICON TRACKER
Pixels (100 x 150 μm²)
~1m² ~66M channels
Microstrips (80-180μm)
~200m² ~9.6M channels
CRYSTAL ELECTROMAGNETIC CALORIMETER (ECAL)
~76k scintillating PbWO₄ crystals
PRESHOWER
Silicon strips
~16m² ~137k channels
STEEL RETURN YOKE
~13000 tonnes
SUPERCONDUCTING SOLENOID
Niobium-titanium coil carrying ~18000 A
FORWARD CALORIMETER
Steel + quartz fibres
~2k channels
HADRON CALORIMETER (HCAL)
Brass + plastic scintillator
~7k channels
MUON CHAMBERS
Barrel: 250 Drift Tube & 480 Resistive Plate Chambers
Endcaps: 473 Cathode Strip & 432 Resistive Plate Chambers
Total weight : 14000 tonnes
Overall diameter : 15.0 m
Overall length : 28.7 m
Magnetic field : 3.8 T

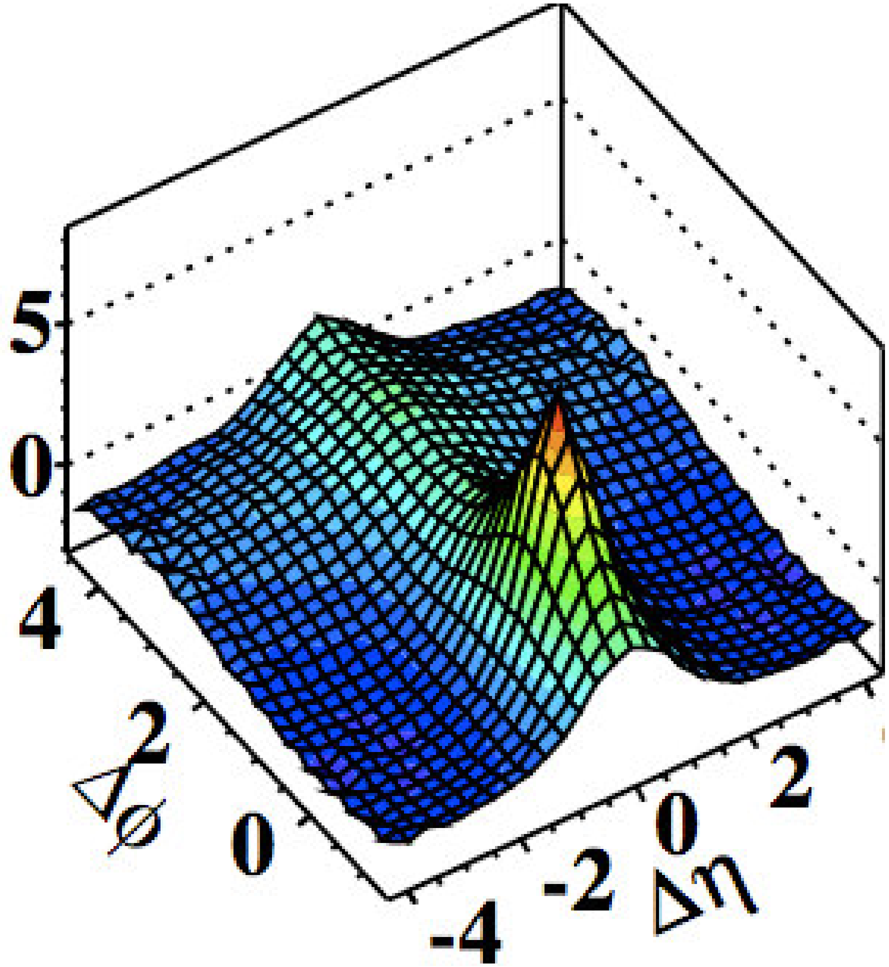
The CMS Silicon Tracker





- Coverage up to **|η|<2.5**; extremely high granularity, to keep low occupancy (~ a few%) also at LHC nominal luminosity.
- Largest Silicon Tracker ever built: Strips: 9.3M channels; Pixels: 66M channels. **Operational fractions: strips 98.1%; pixel 98.3%**

Angular Correlation Functions



Correlation Functions:

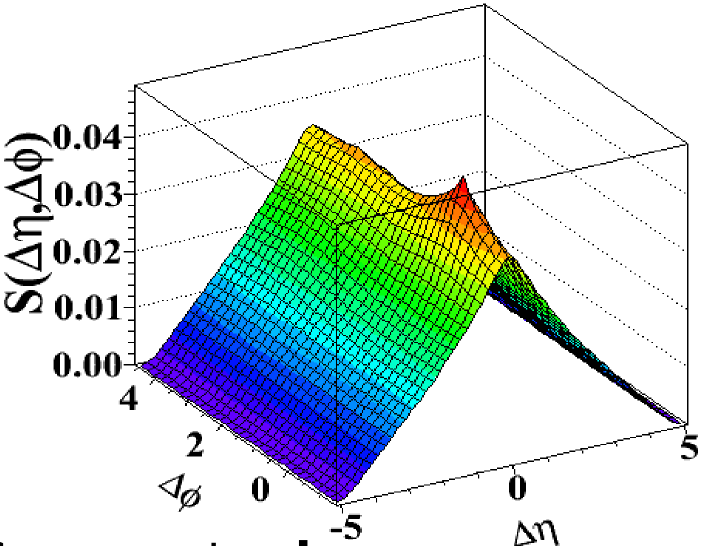
I. Definition

II. Anatomy

Correlation Function Definition

Signal distribution:

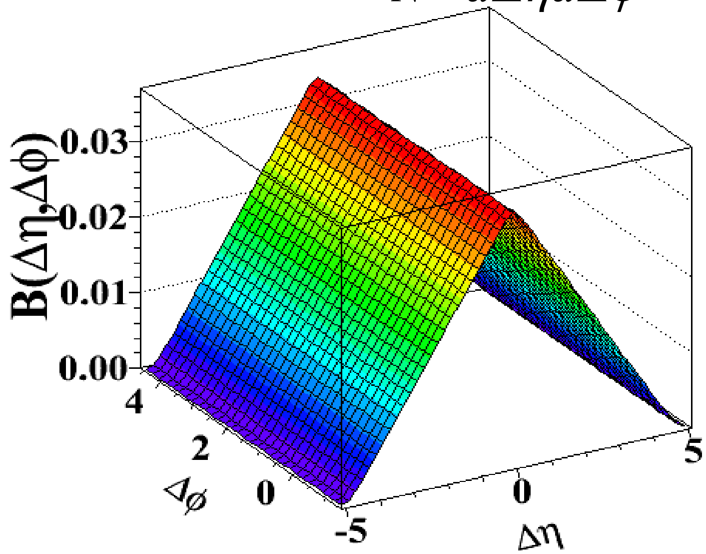
$$S_N(\Delta\eta,\Delta\varphi)=\frac{1}{N(N-1)}\frac{d^2N^{signal}}{d\Delta\eta d\Delta\varphi}$$



Same event **pairs**

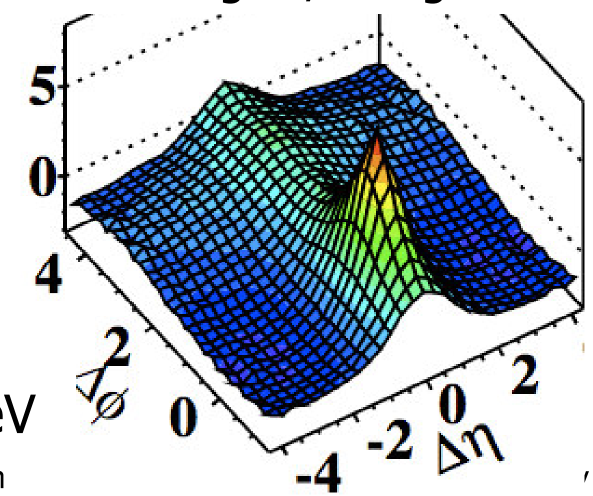
Background distribution:

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



Mixed event **pairs**

Ratio Signal/Background



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

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

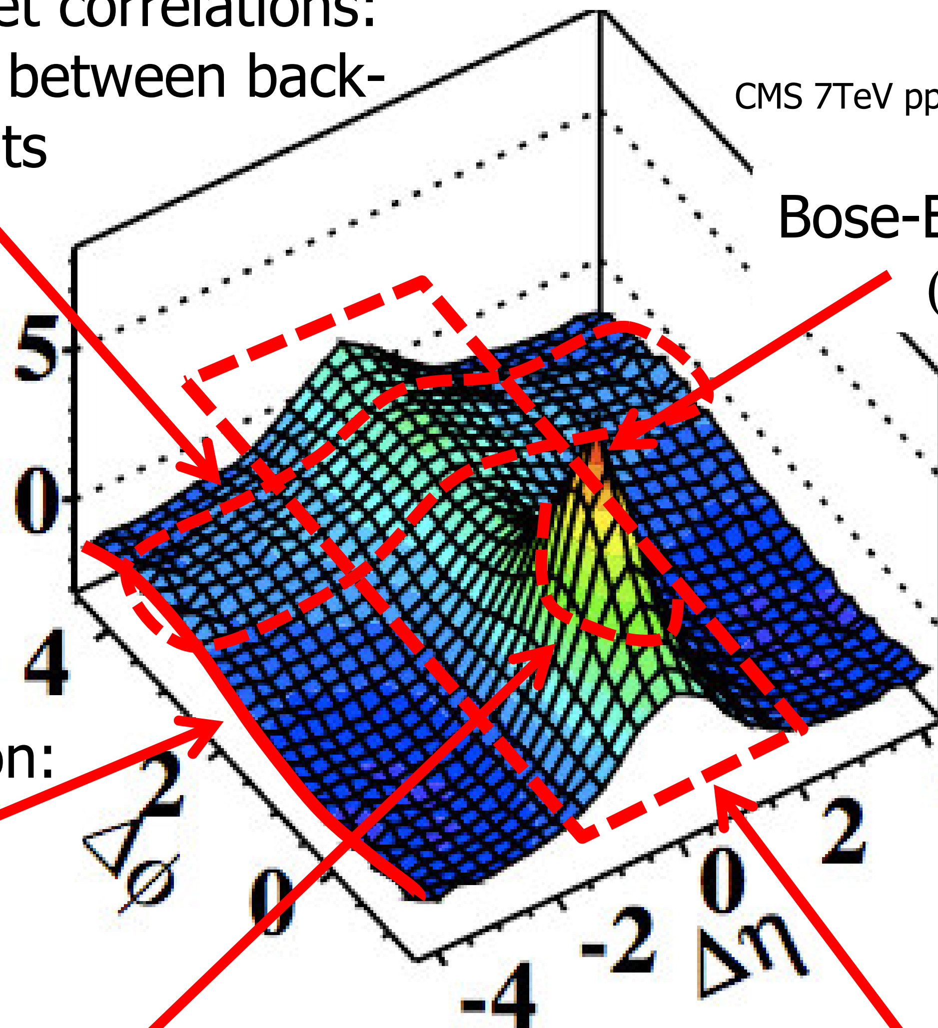
CMS pp 7TeV

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

Angular Correlation Functions

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

CMS 7TeV pp min bias



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

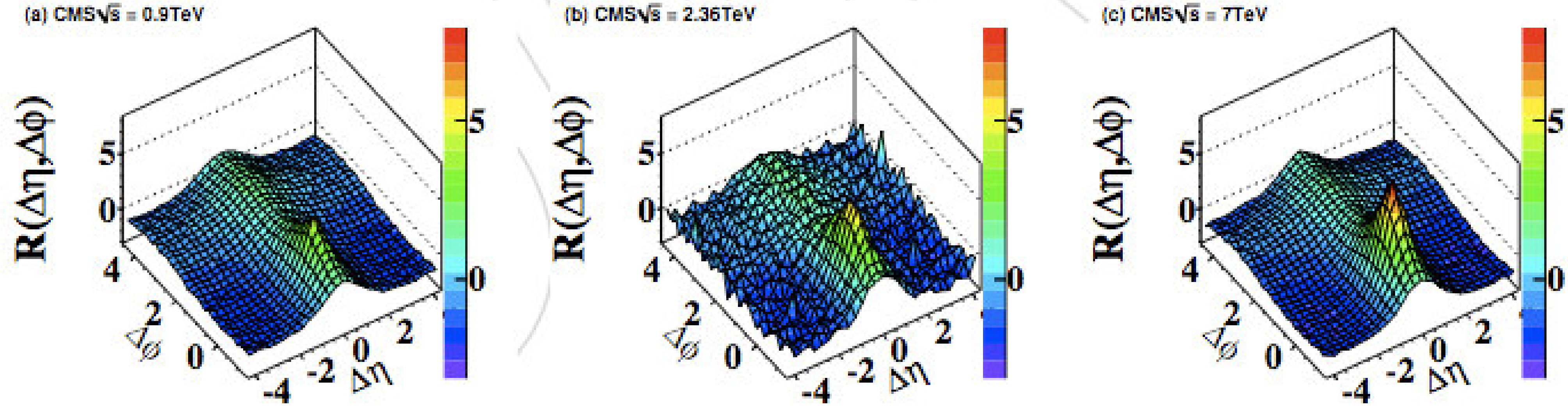
Momentum conservation: $\sim -\cos(\Delta\phi)$

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

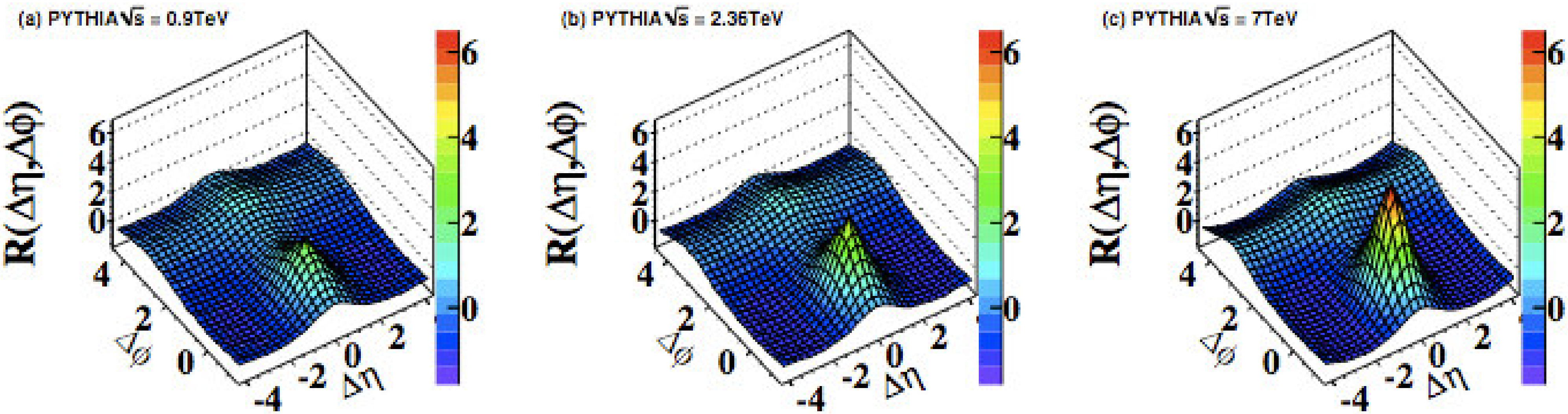
Short-range correlations ($\Delta\eta$ < 2): Resonances, string fragmentation, "clusters"

Correlations in Min Bias pp

CMS pp Data

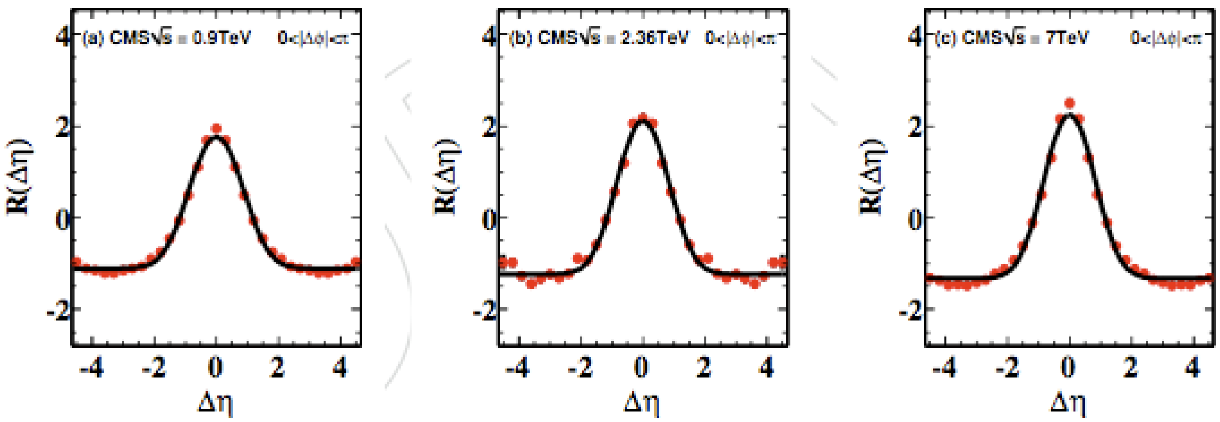


Pythia D6T

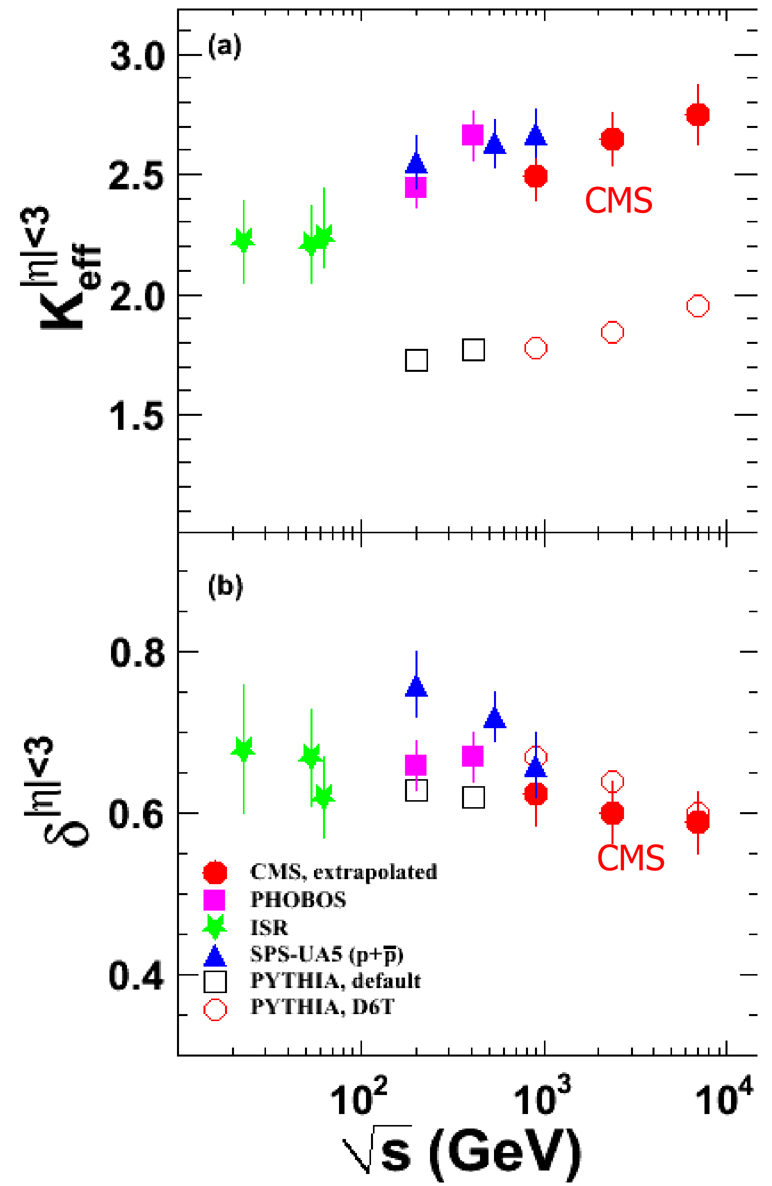


Short-Range Correlations vs. $\sqrt{s}$

1D "Projection" to $\Delta\eta$ axis

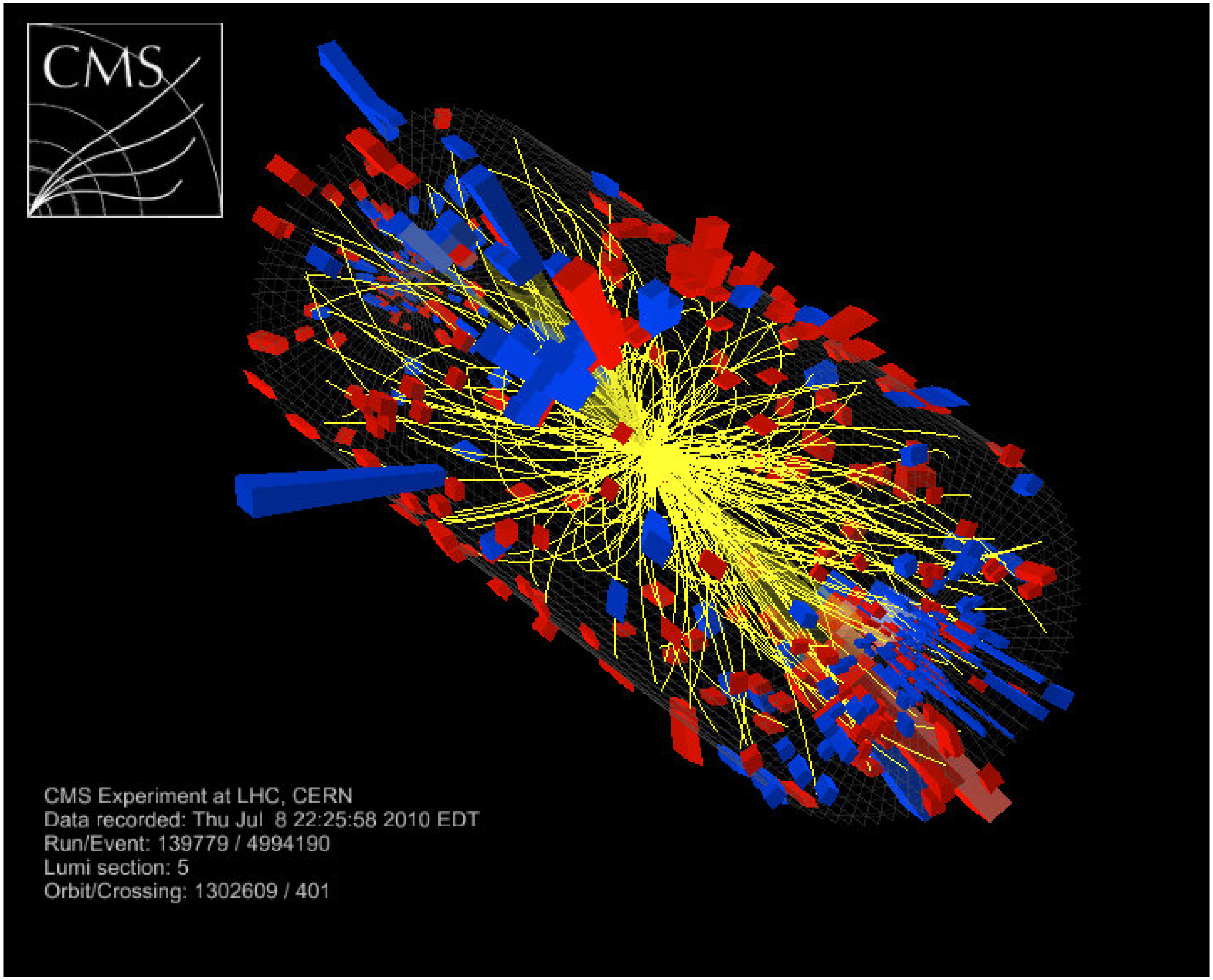


K_{eff}: Number of correlated particles
δ: correlation width in $\Delta\eta$



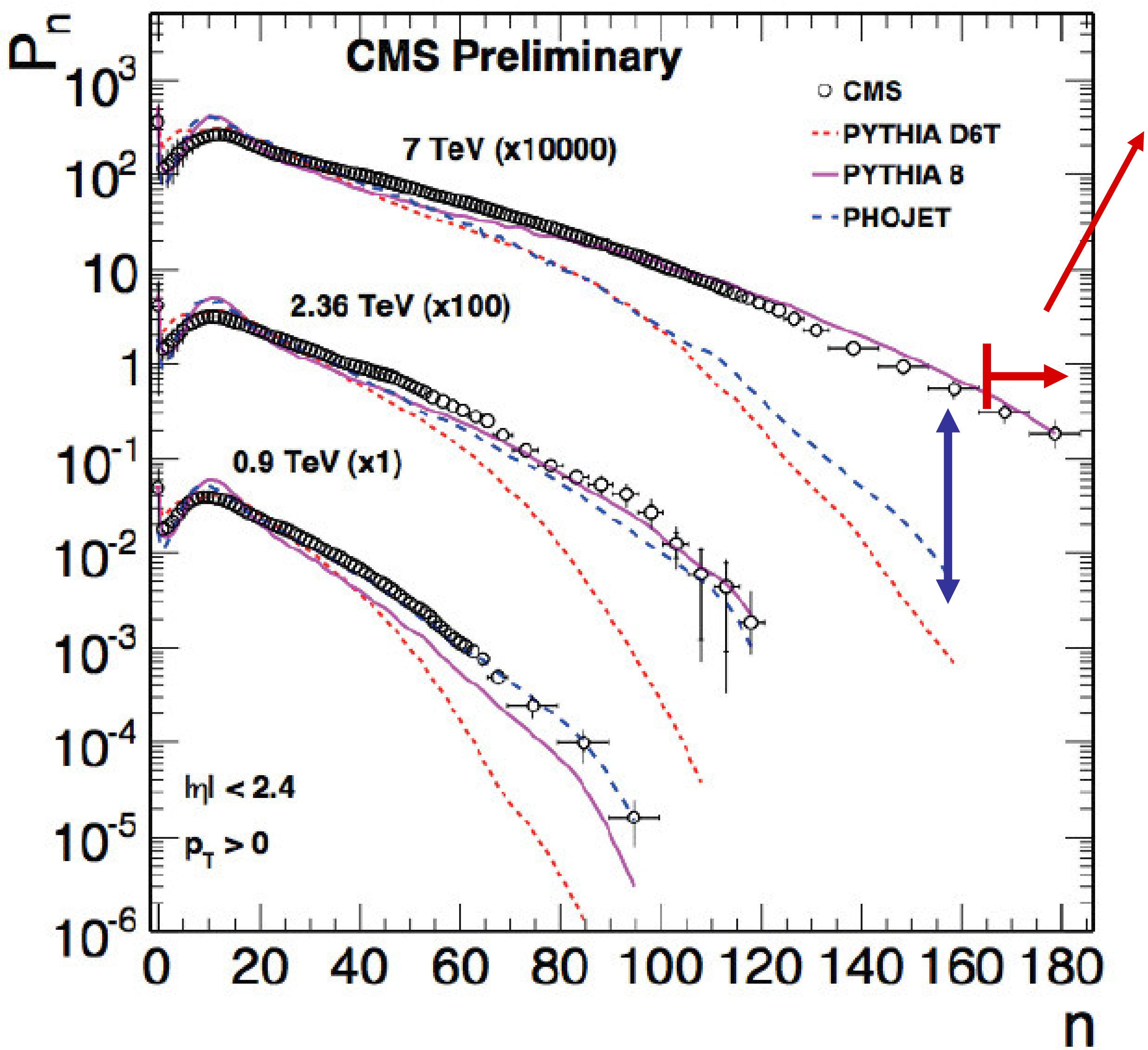
PYTHIA describes the energy dependence, matches cluster width δ in data, but underestimates the cluster multiplicity K_{eff}

High Multiplicity Events



268 reconstructed particles in the tracker in a single pp collision:
the highest multiplicity event in ~70 billion inelastic events sampled (1/pb)

Why study extreme multiplicities?



Our most recent correlation studies focus on the tail of the distribution, where several MC generators severely under-estimate the data (an exception: PYTHIA8).

Motivations:

→ Trying to find (more) unexpected effects in this regime

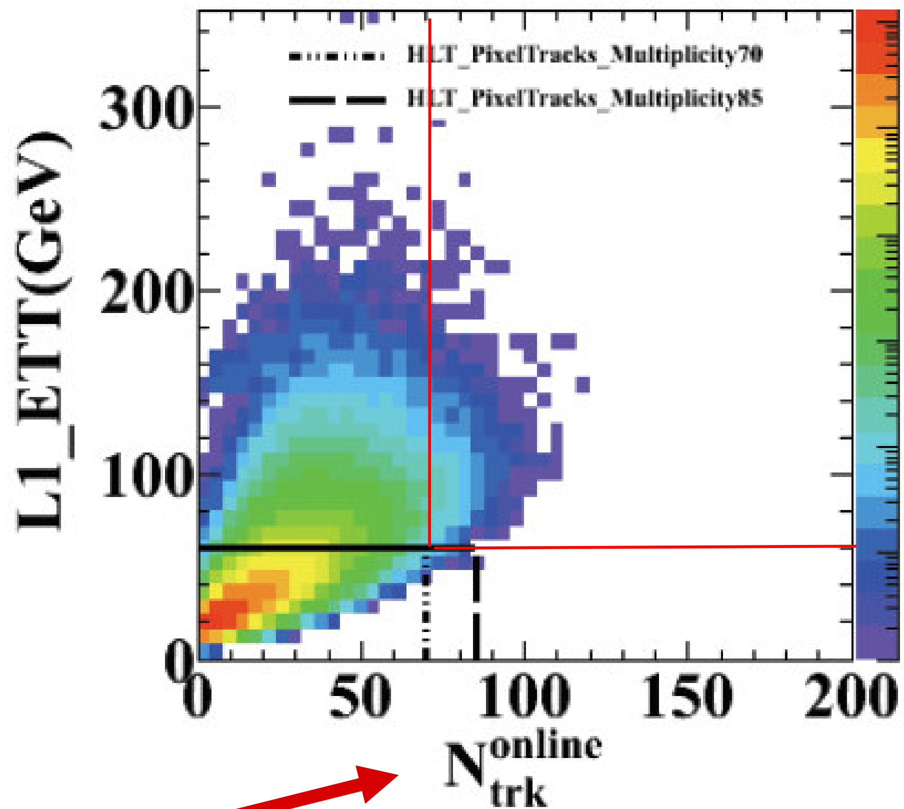
→ Learn more about (soft) QCD and particle production mechanisms with more differential measurements

→ Highest multiplicities in pp begin to approach those in ion collisions; can we learn something about similarities or differences?

High Multiplicity Trigger

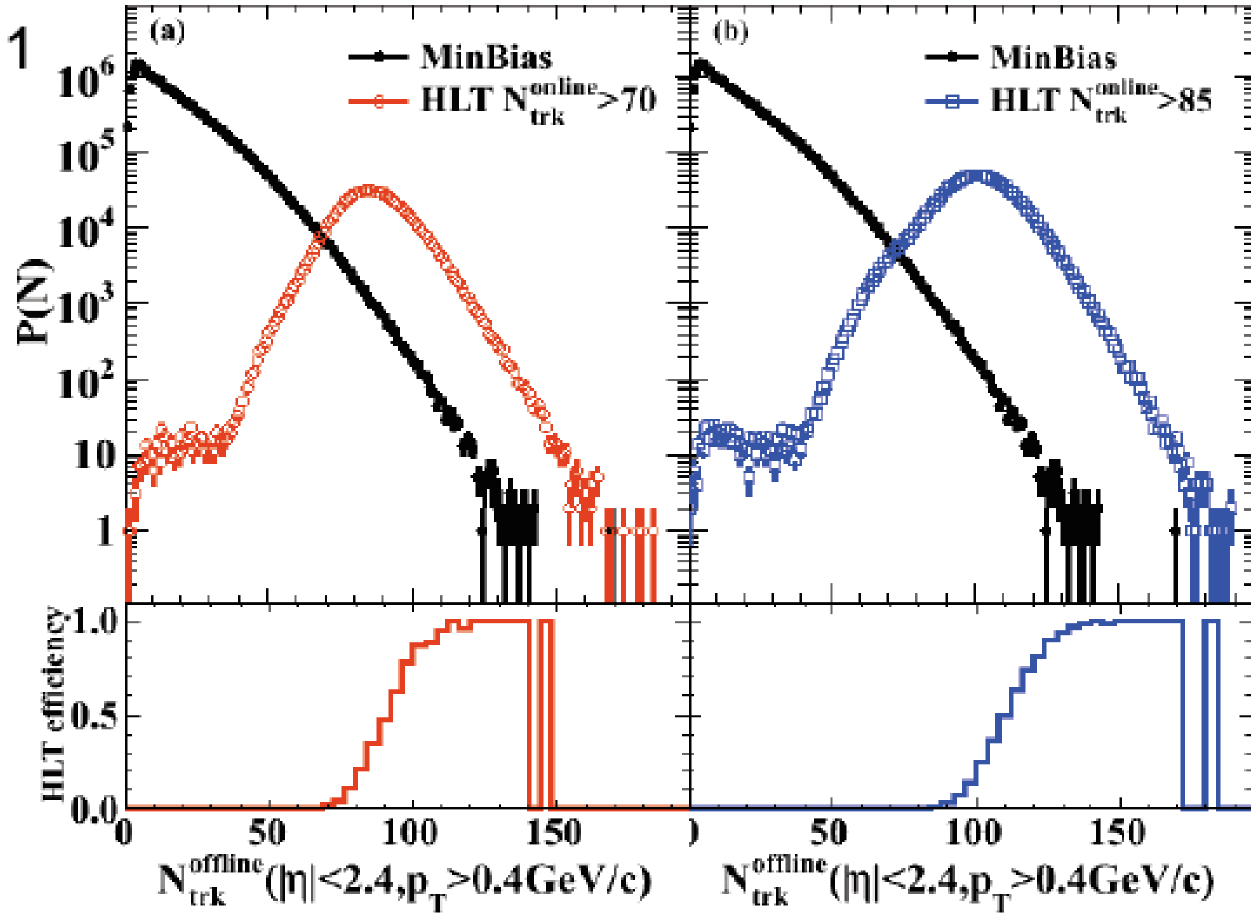
Dedicated trigger was needed to record highest multiplicities

Level-1 (hardware):
Requires E_T> 60 GeV
in calorimeters



High-Level trigger (software):
More than 70 (85) tracks with p_T > 0.4 GeV/c, $|\eta|$ < 2,
within dz < 0.12 cm of a **single** vertex with z < 10 cm.
~50% CPU usage of the HLT

High Multiplicity Event Statistics



1000 times more high multiplicity events recorded with the trigger compared to Min. Bias

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

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

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

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

out of 5×10^{10} collisions

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:

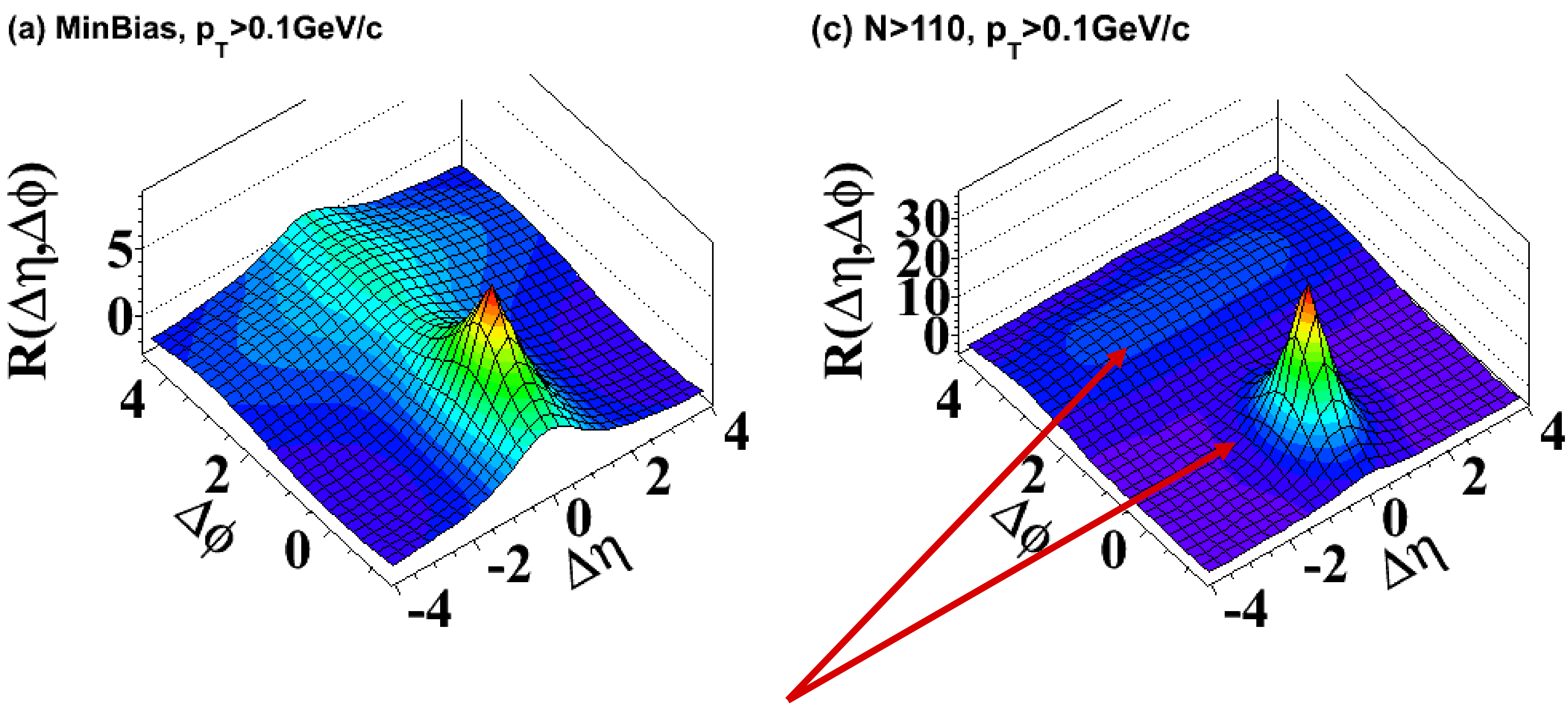
- *highPurity* bit
- dxy/σ(dxy)<3 & dz/σ(dz)<3, relative to primary vertex
- $\sigma(p_T)/p_T<0.1$

Main corrections:

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

Results : data, inclusive p_T

MinBias | high multiplicity (N>110)

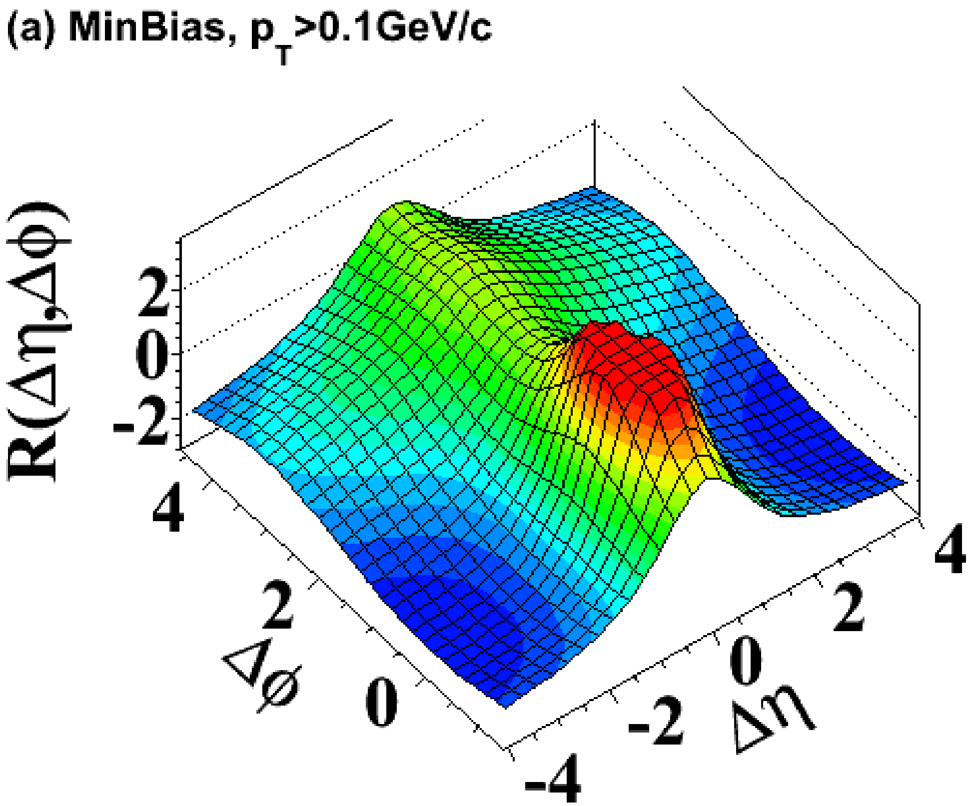


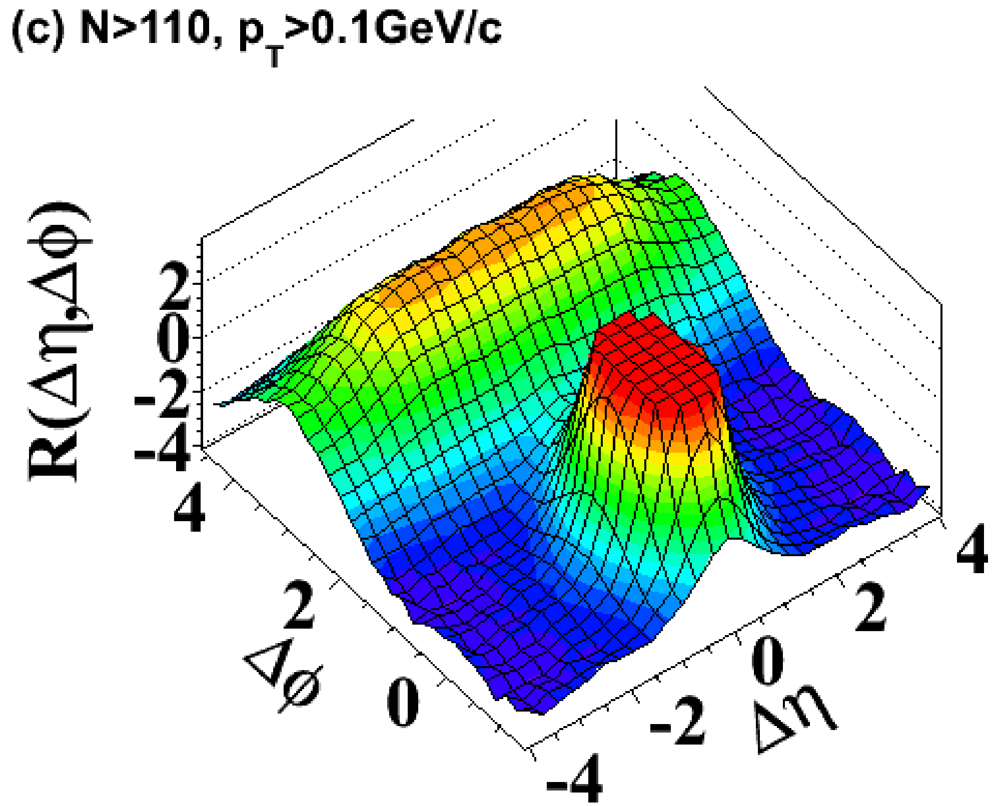
Jet peak/away-side correlations enhanced in high multiplicity events
Abundant jet production in high multiplicity sample

Results: data, inclusive p_T

MinBias

high multiplicity (N>110)





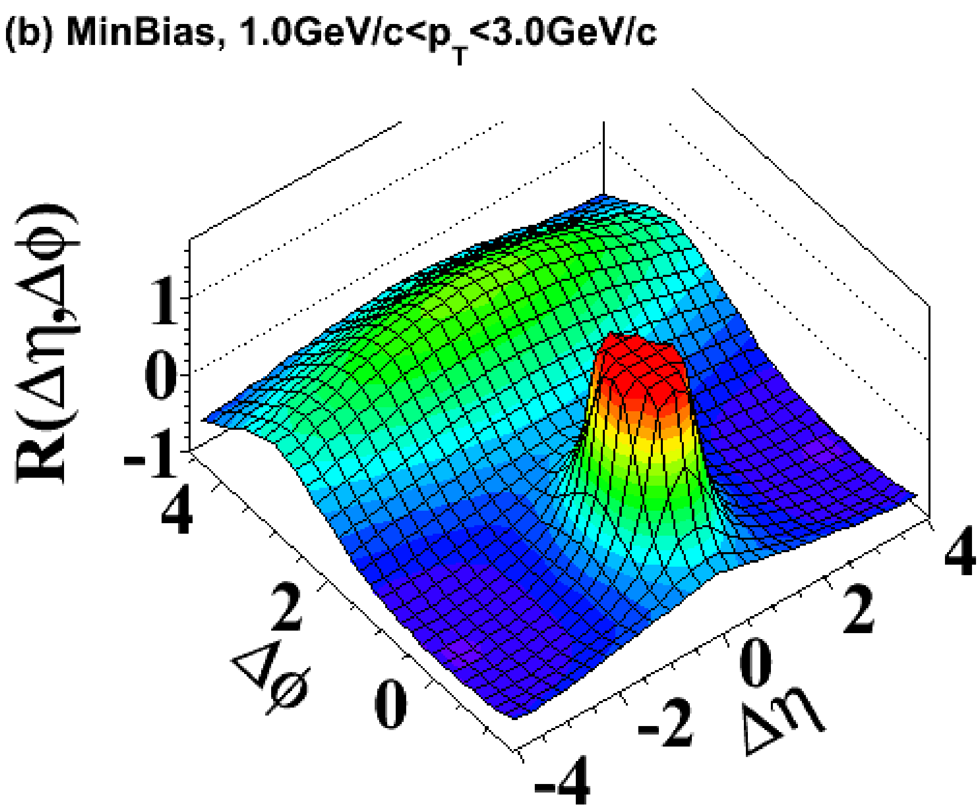
After cuting off the jet peak at (0,0) we can observe:

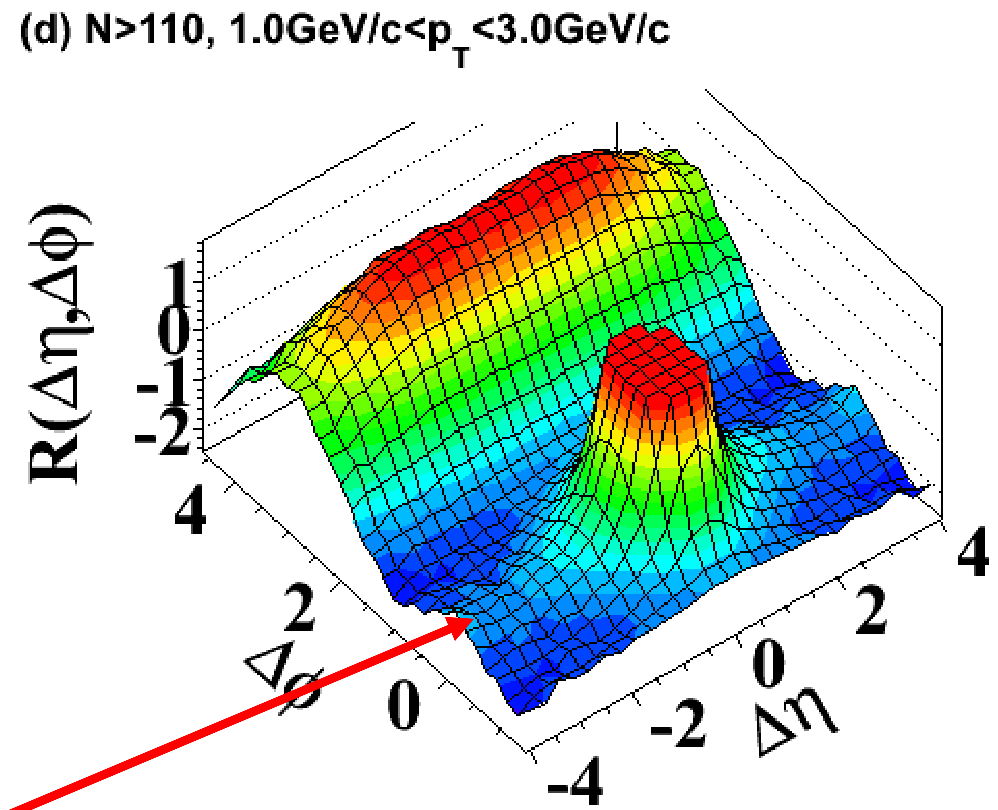
Structure of away-side ridge (back-to-back jets)

Small change for large δη around δϕ ~ 0 ?

Results: data, p_T: 1-3 GeV/c

MinBias | high multiplicity (N>110)

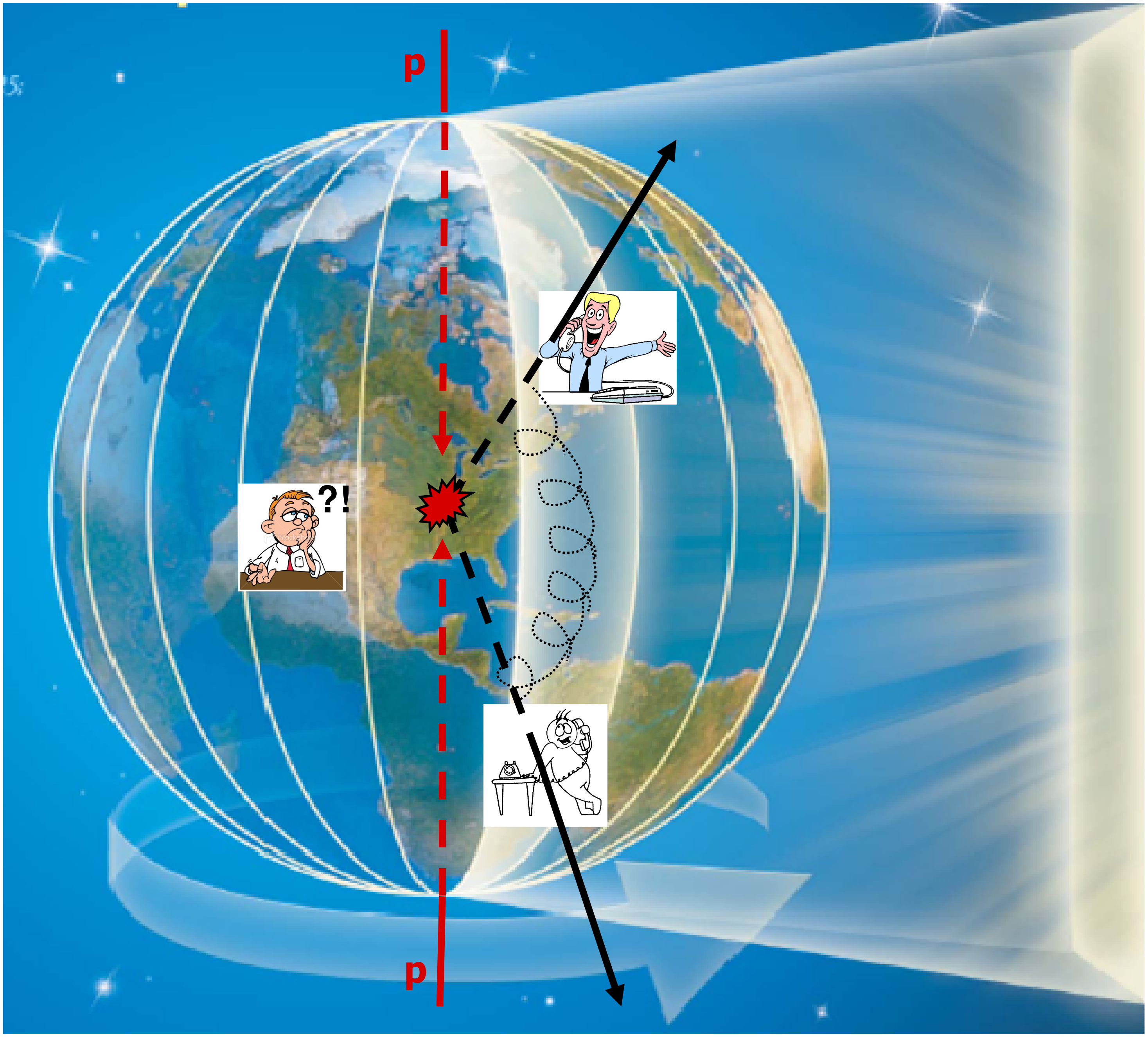




Pronounced new structure at large $\delta\eta$, around $\delta\phi \sim 0$!

CMS Collab., **JHEP 1009:091,2010,** arXiv:1009:4122

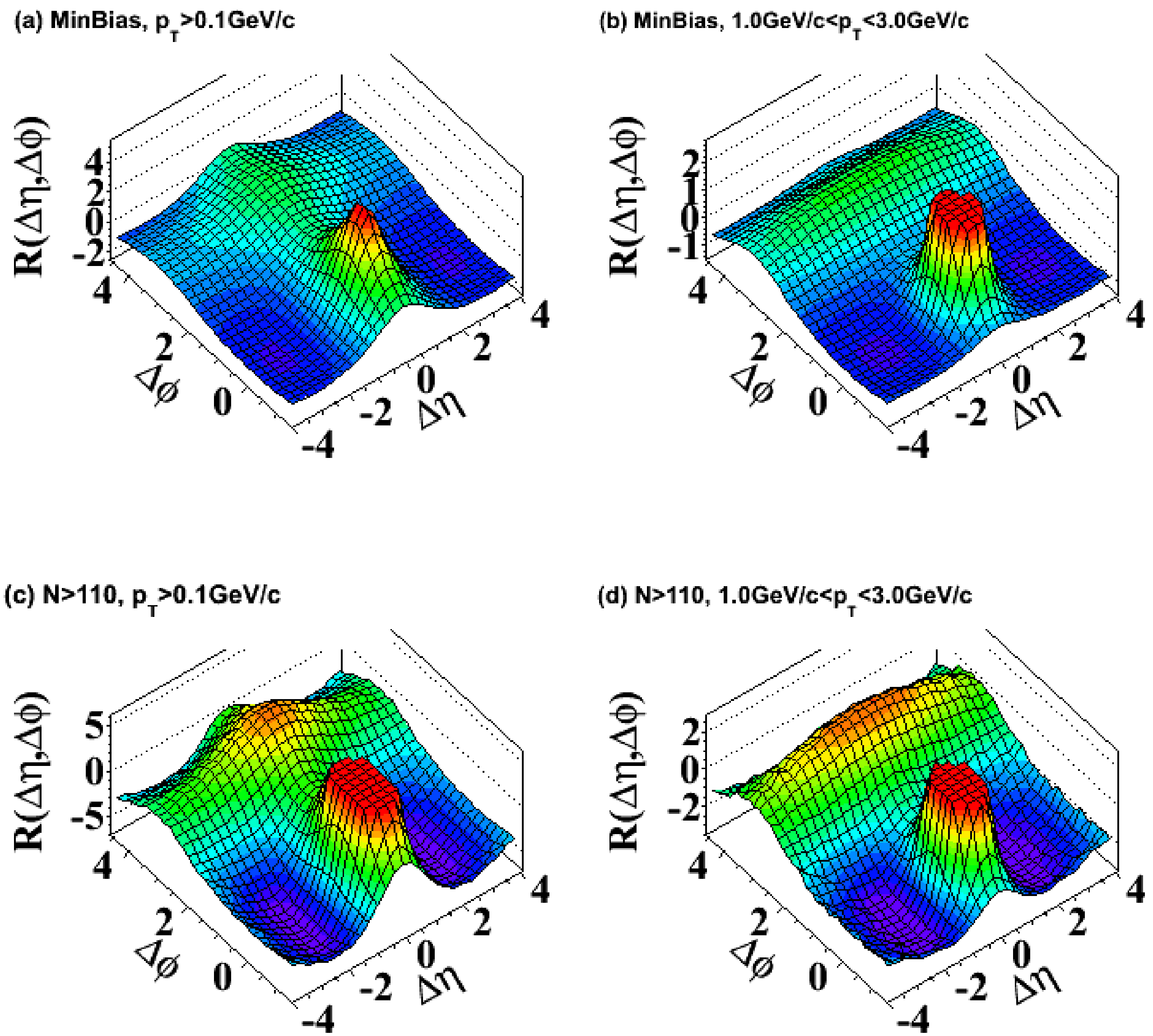
Illustration of the effect



Particles surfacing in the same *time zone*, but far away in latitude, *talk to* each other…

…What mechanism is the "telephone line"?

Correlations in PYTHIA8



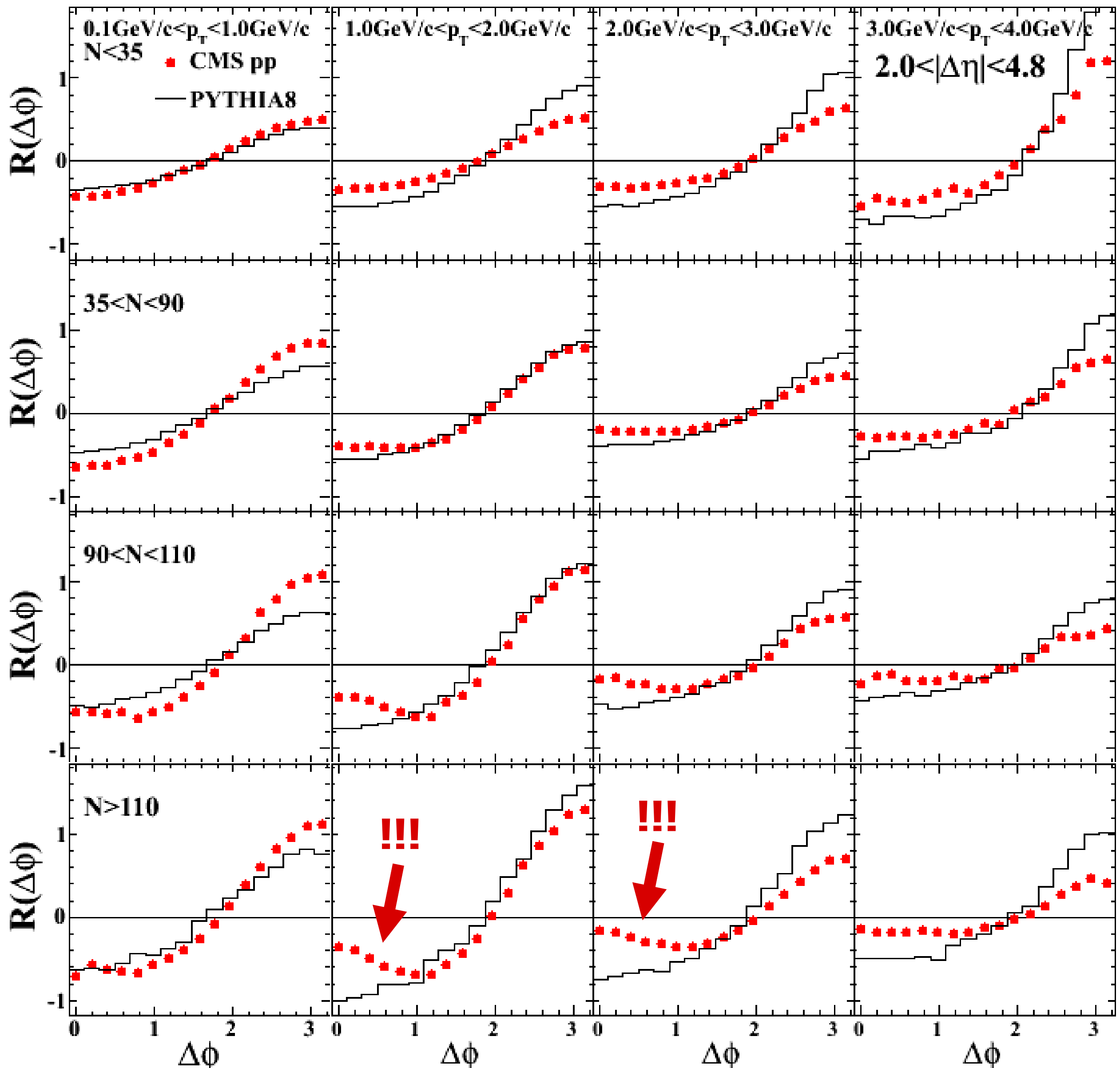
No $\delta\phi \sim 0$ structure at large $\delta\eta$

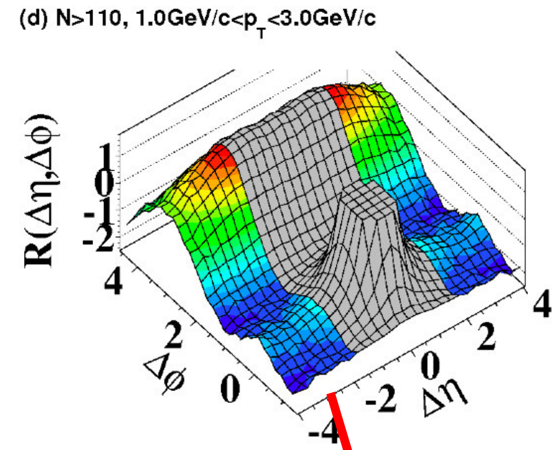
→ Same for Herwig++, madgraph, PYTHIA6

Multiplicity- and p_T -Dependence

Increasing p_T

Increasing multiplicity





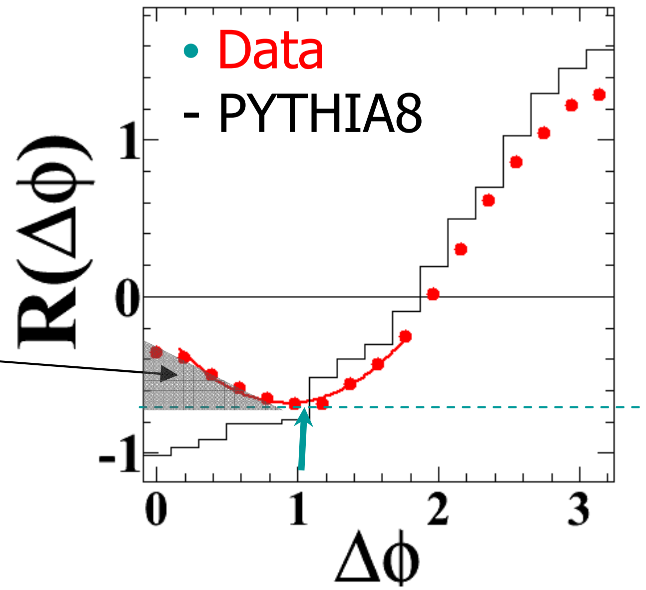
Project $|\Delta\eta| > 2$ onto $\Delta\phi$

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

Quantifying the associated yield

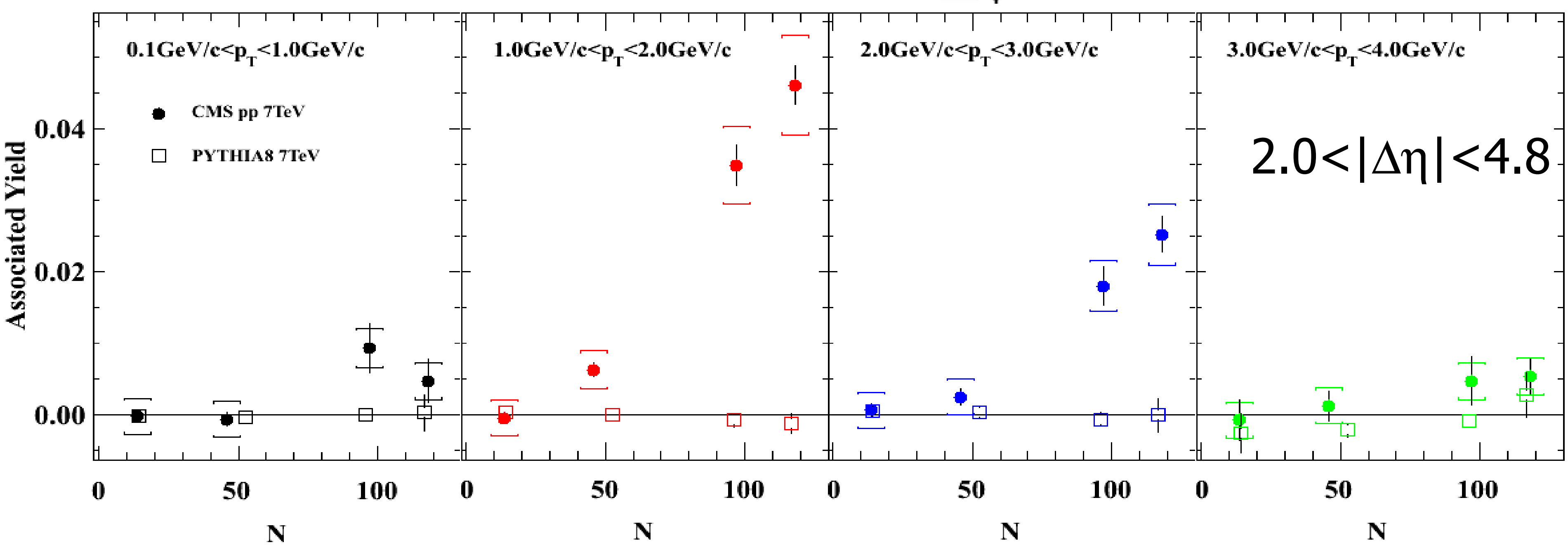
Zero Yield At Minimum (ZYAM)

Associated yield:
correlated multiplicity per particle



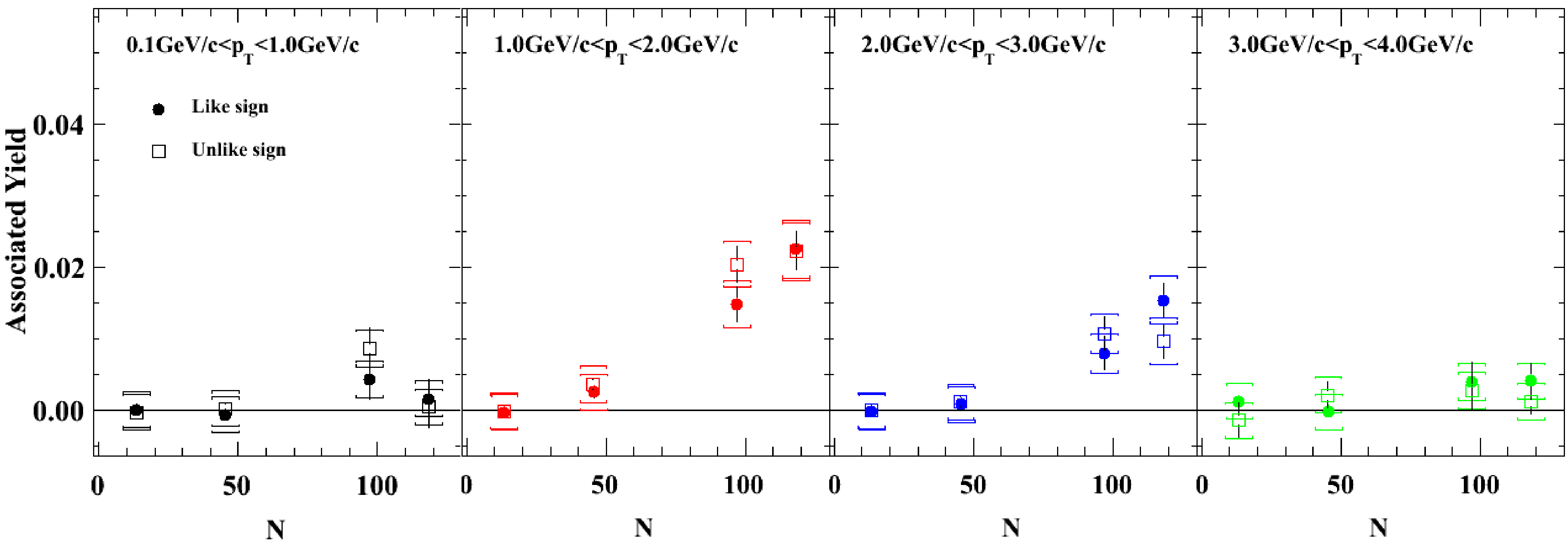
N>110
$2.0<|\Delta\eta|<4.8$
$1GeV/c<p_T<2GeV/c$

Minimum of R



Associated yield grows with increasing multiplicity

Like-Sign vs. Unlike-Sign Pairs



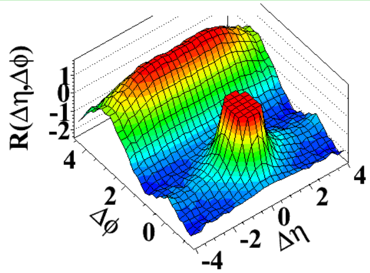
No dependence on relative charge sign

Systematic Uncertainties, Checks

- 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

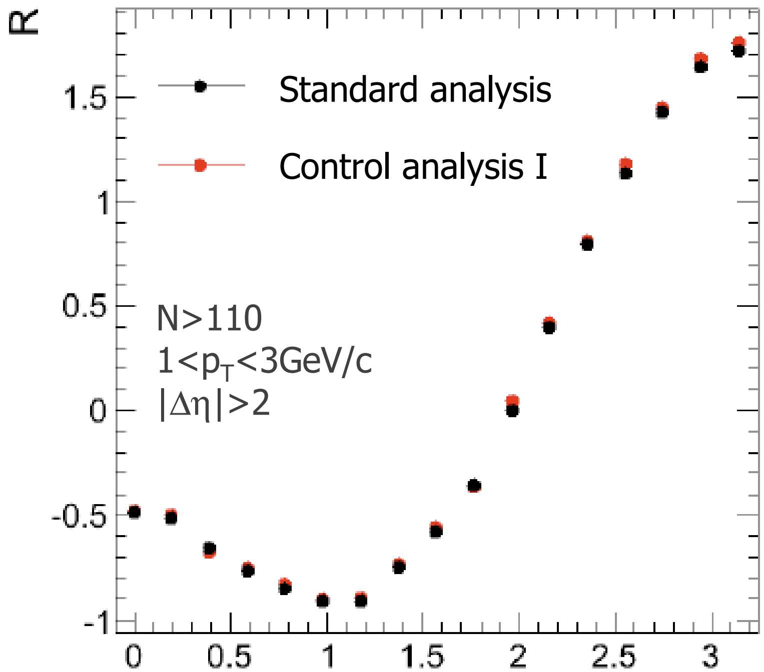
CMS Event

Physics

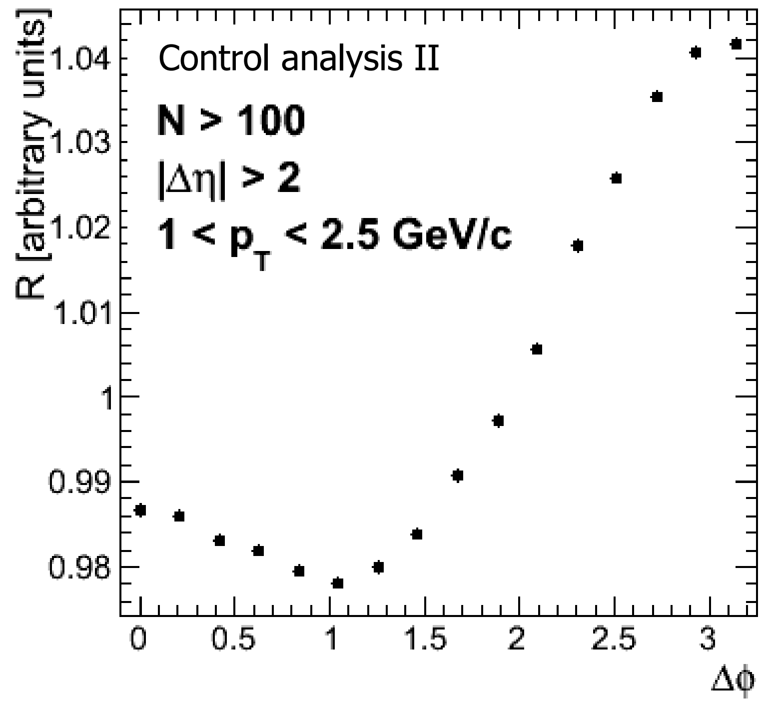
Collision

Test the complete chain with data-driven checks!

Analysis Code



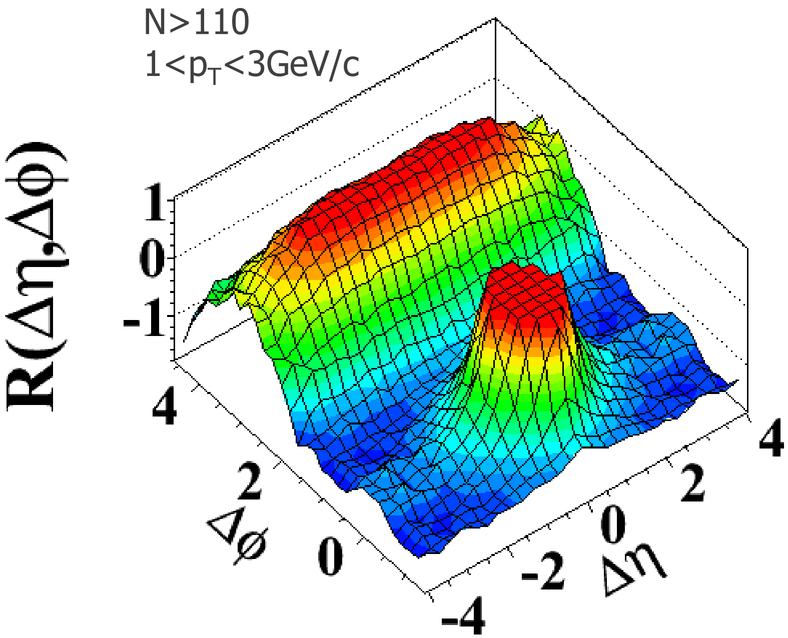
Independent code
Same definition of *R*
Same input file (skim)



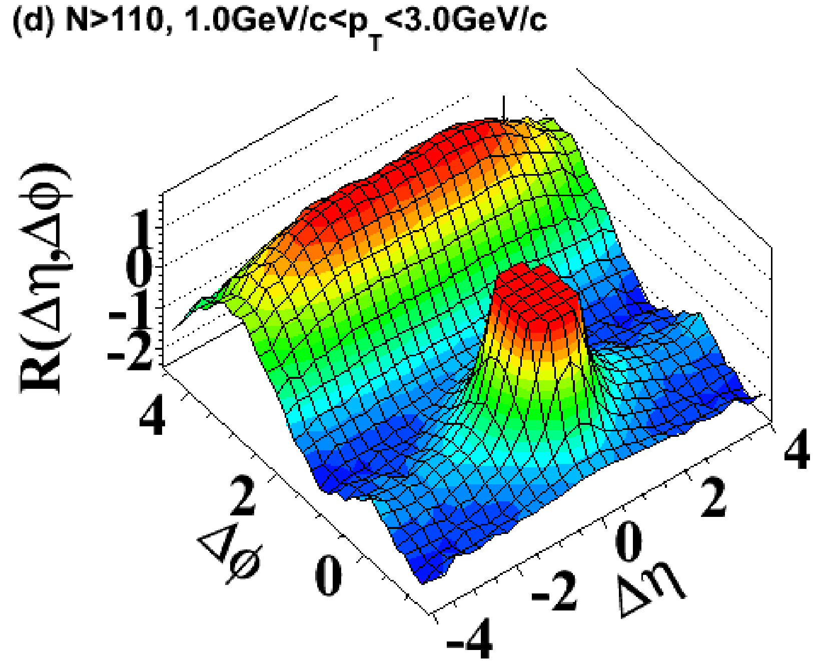
Independent code
Different definition of *R*
Different input file (skim)

Ridge is seen with three independent analysis codes

Reconstruction Code



Pixel-only tracks
3 hits in pixel detector

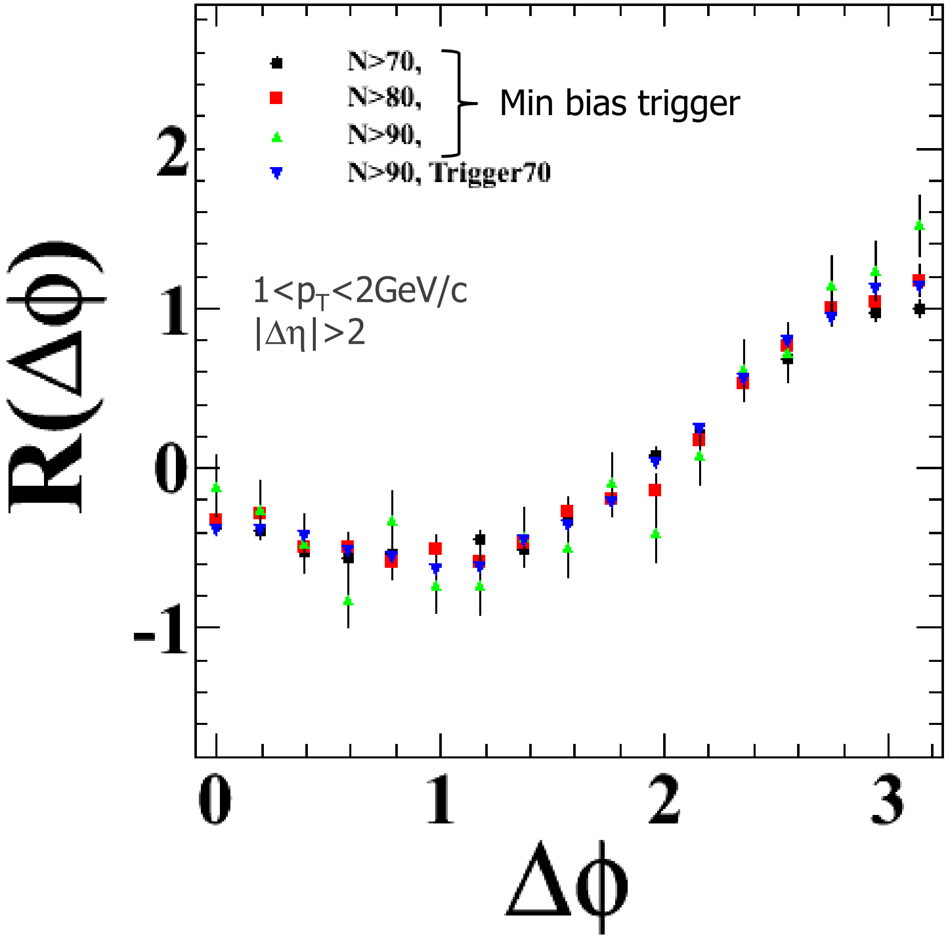


"HighPurity" tracks
Pixel + Silicon Strip tracker

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

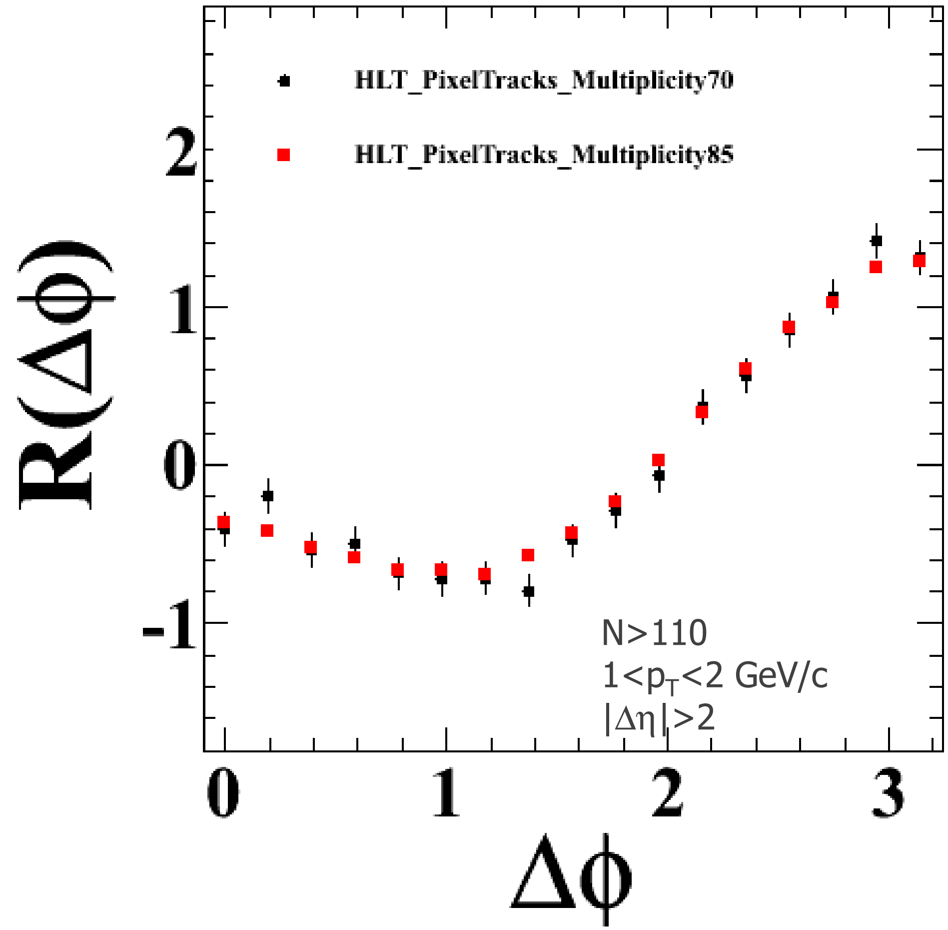
Trigger bias

Min-bias trigger vs. high mult trigger



Ridge is seen using
min bias trigger + offline selection

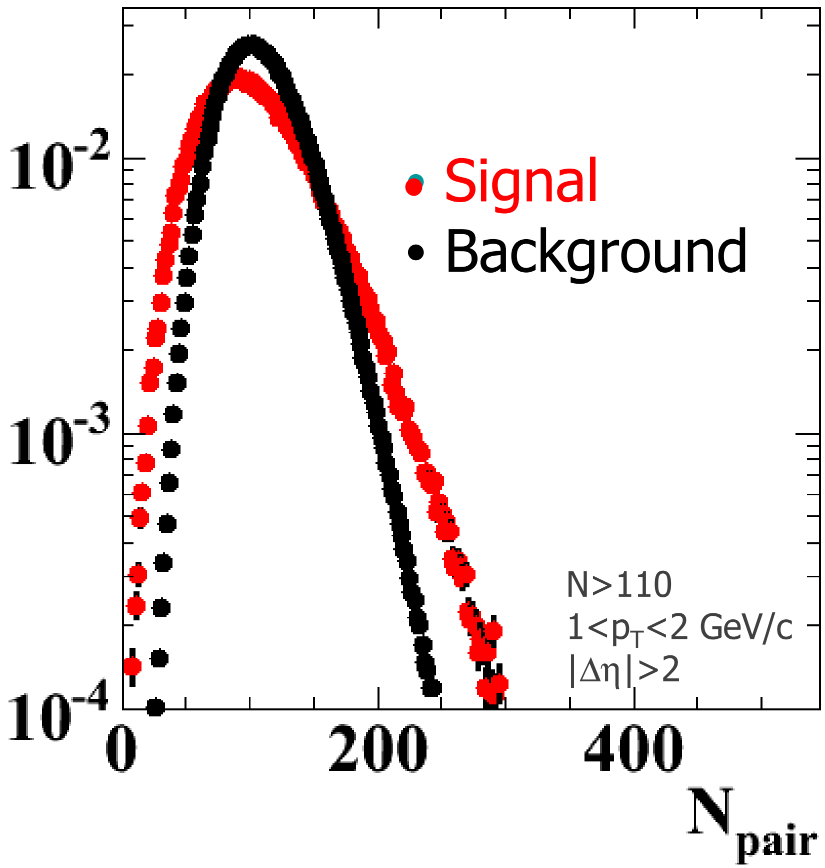
HLT 70 vs. HLT 85 for N > 110



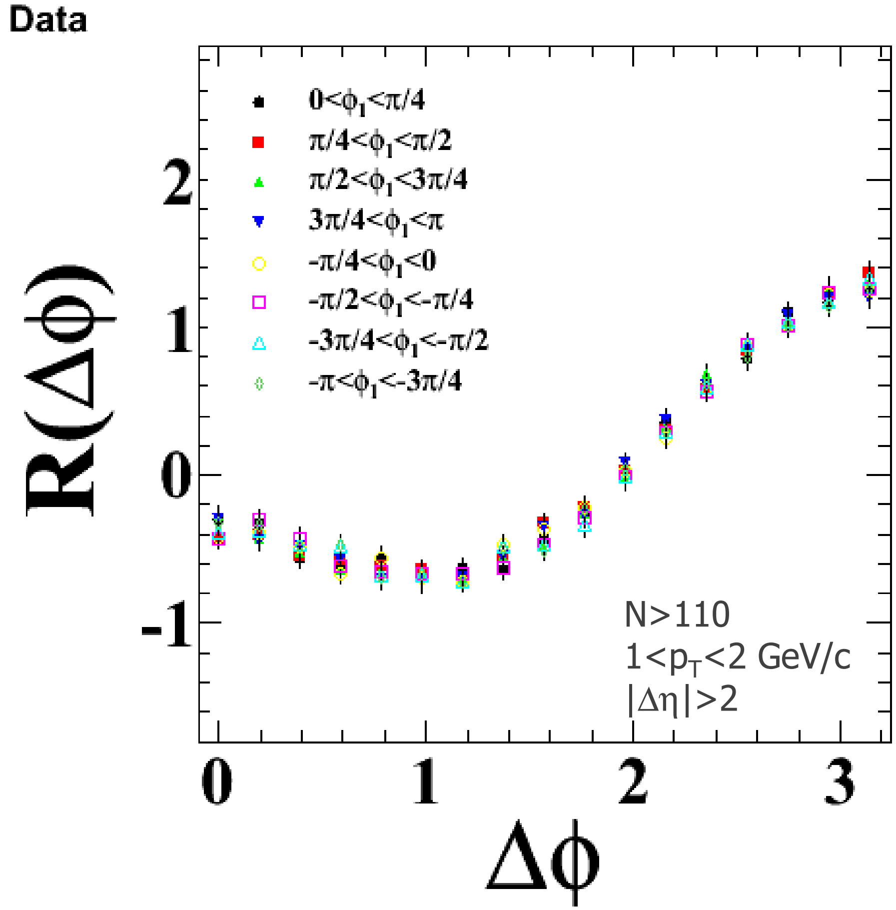
No trigger bias seen from
comparison of trigger paths

Detector: φ -symmetry

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



Constrain one track to one ϕ-octant

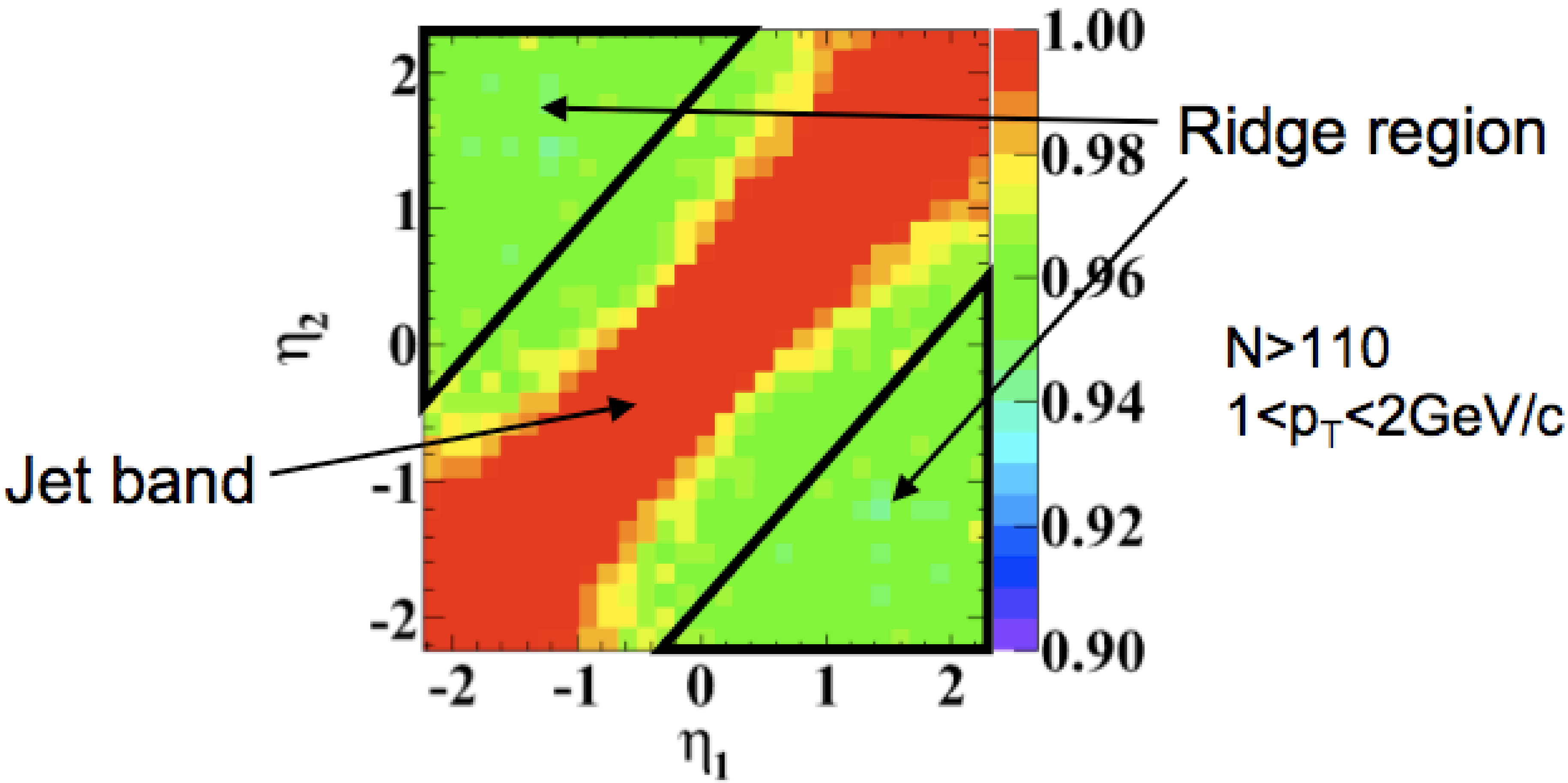


Ridge is not caused by rare events with large # of pairs

Ridge is invariant under ϕ rotation

Detector: uniformity in η

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

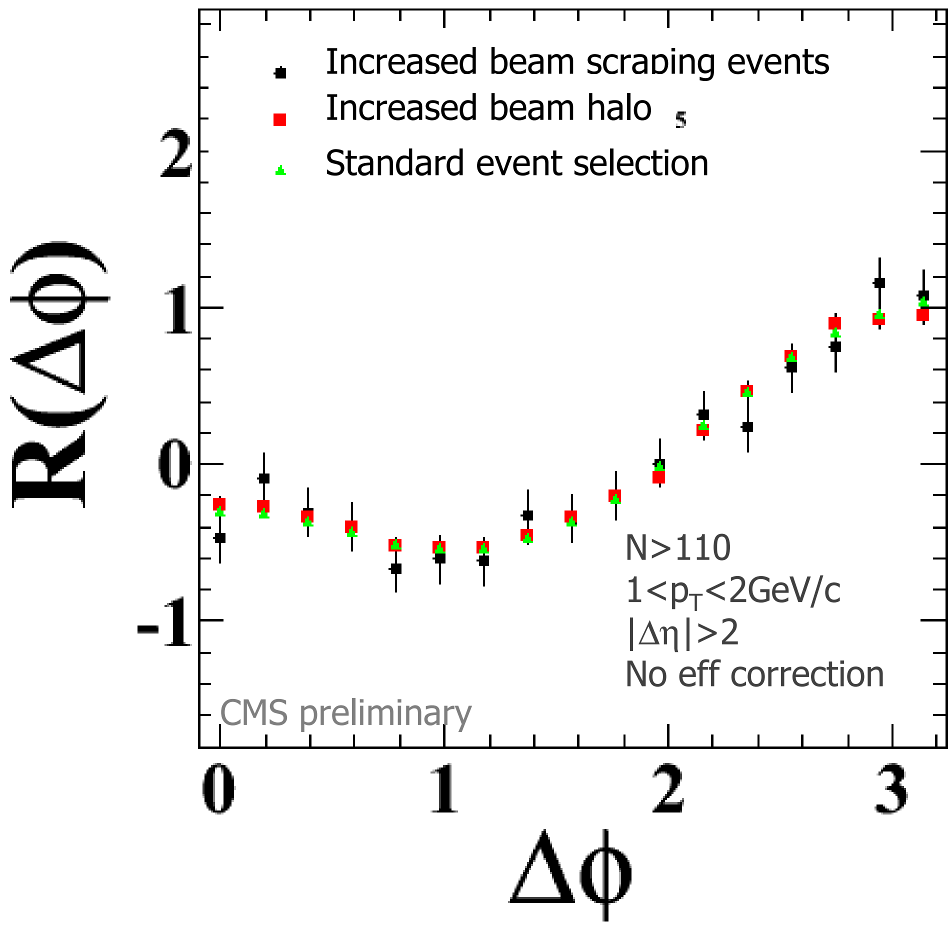


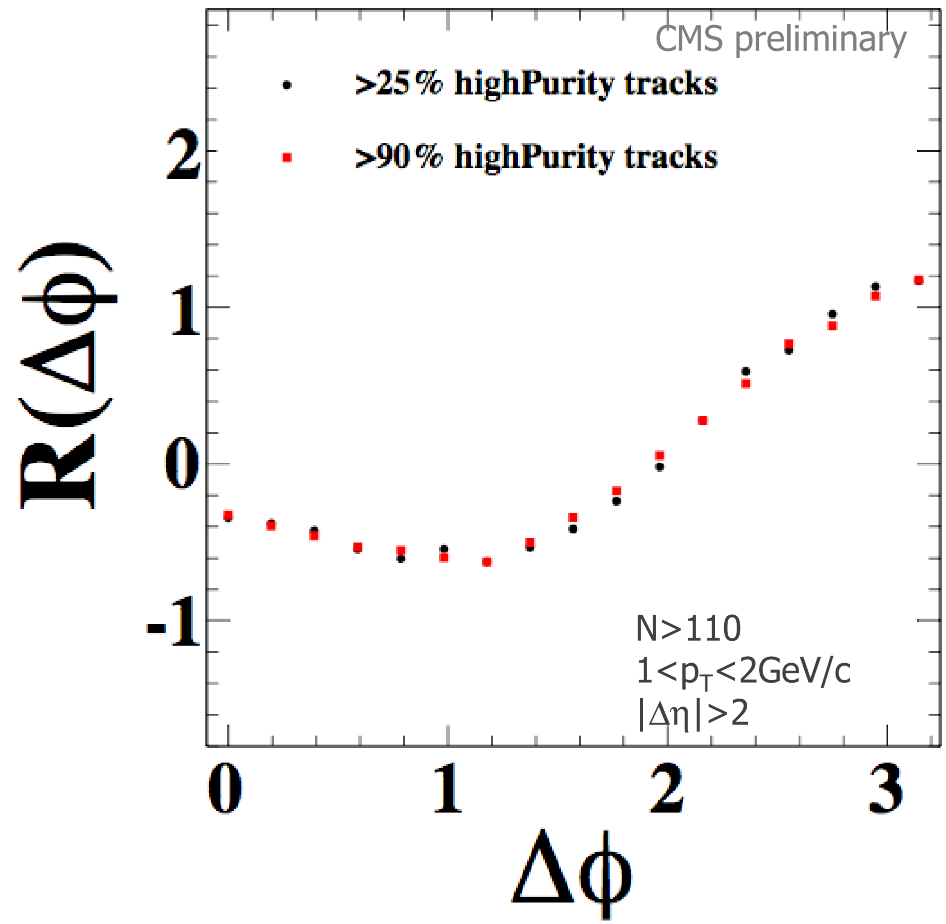
Ridge region shows no structure in η_1 vs η_2

Event Backgrounds

Enrich the sample with beam-gas and beam-scraping events

Reject beam background by veto on fraction of low quality tracks





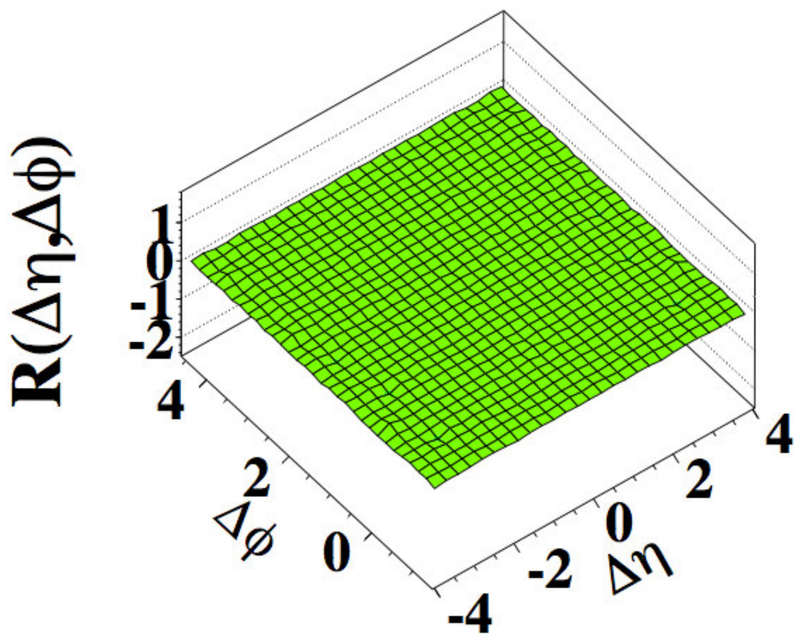
Ridge region shows no sensitivity to beam background

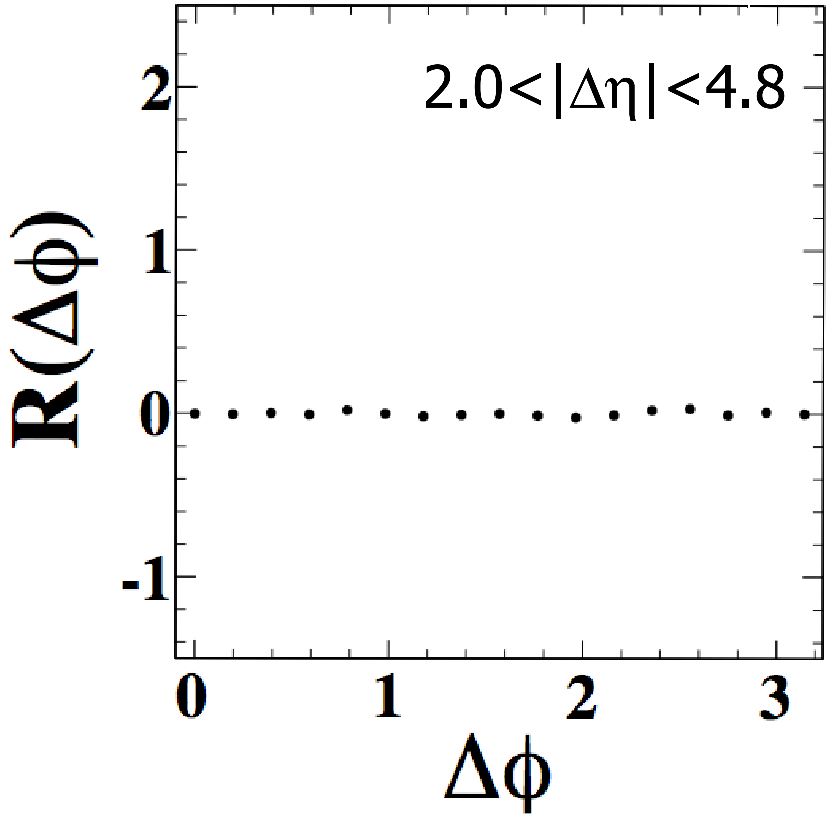
Note: Analysis is done on HighPurity tracks

Pileup collision events

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

N>110; 1 GeV/c<p_T<3 GeV/c

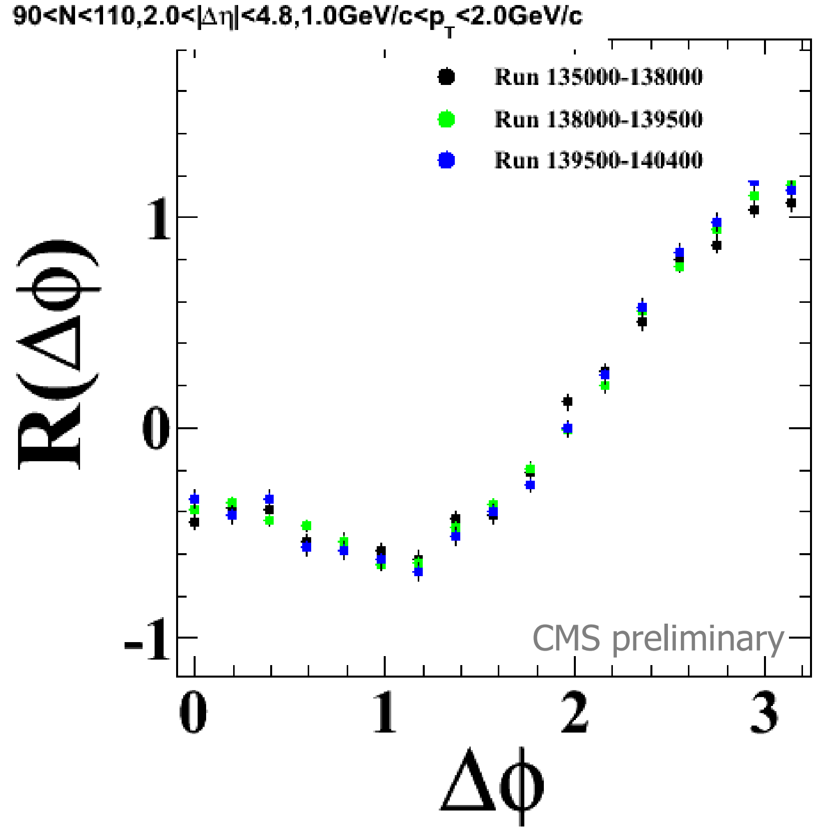




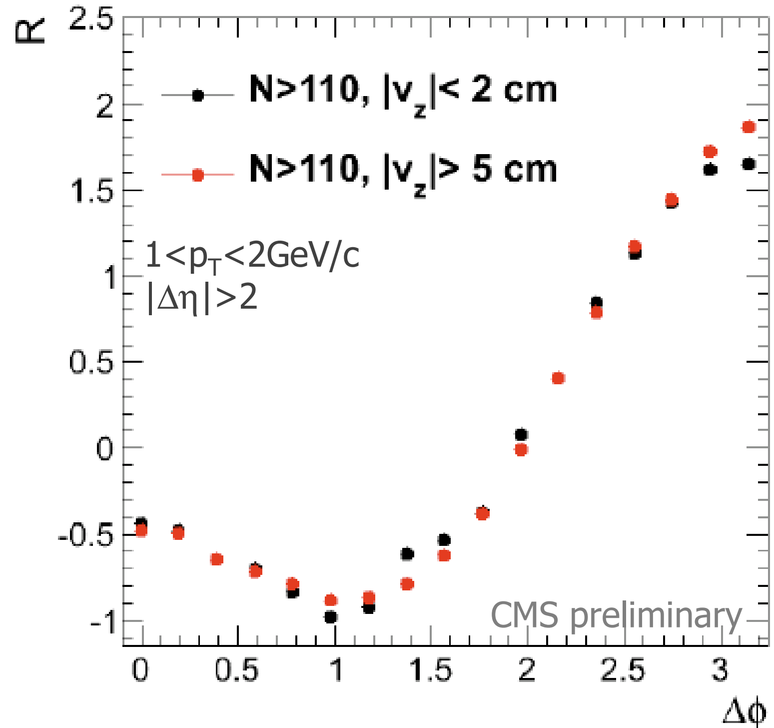
No background or noise effects seen in cross-collision correlations

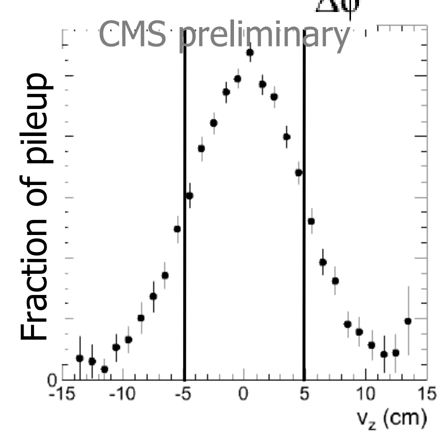
Pileup of collision events

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



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

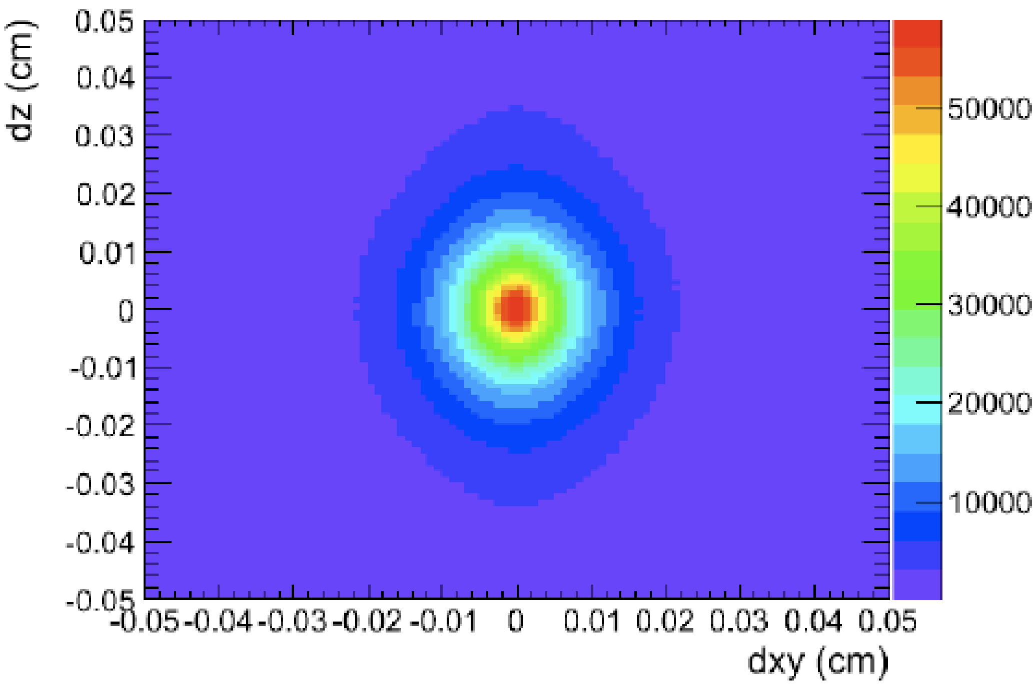




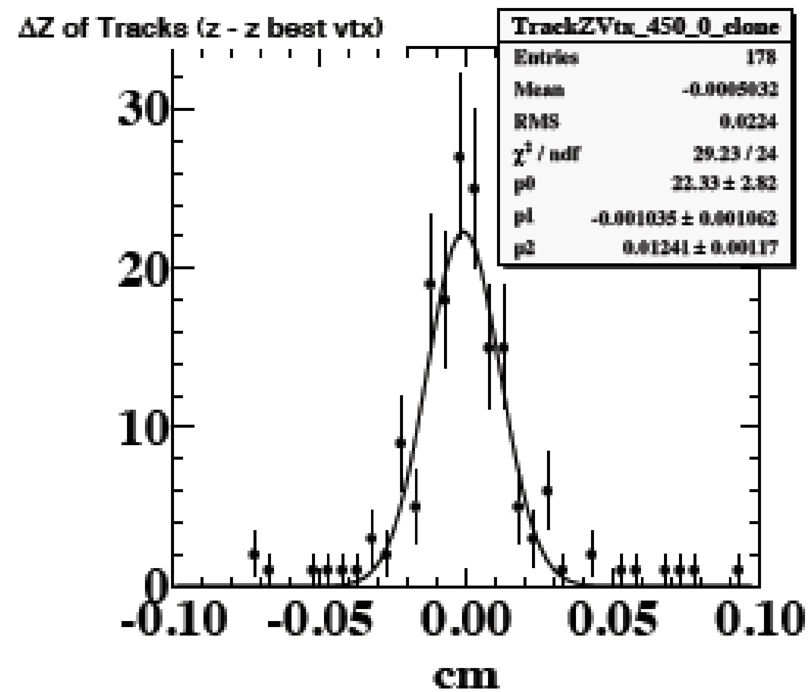
Change in pileup fraction by factor 2-4
has almost no effect on ridge signal

Event Pileup

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



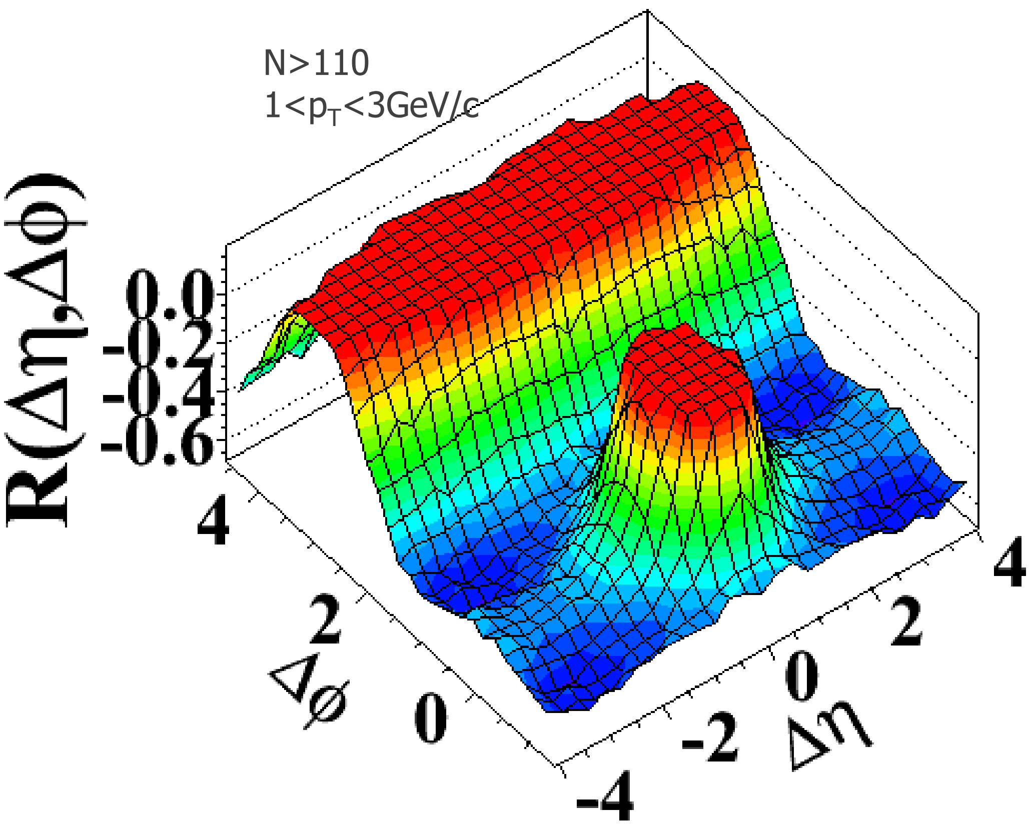
Single-event track dz distribution

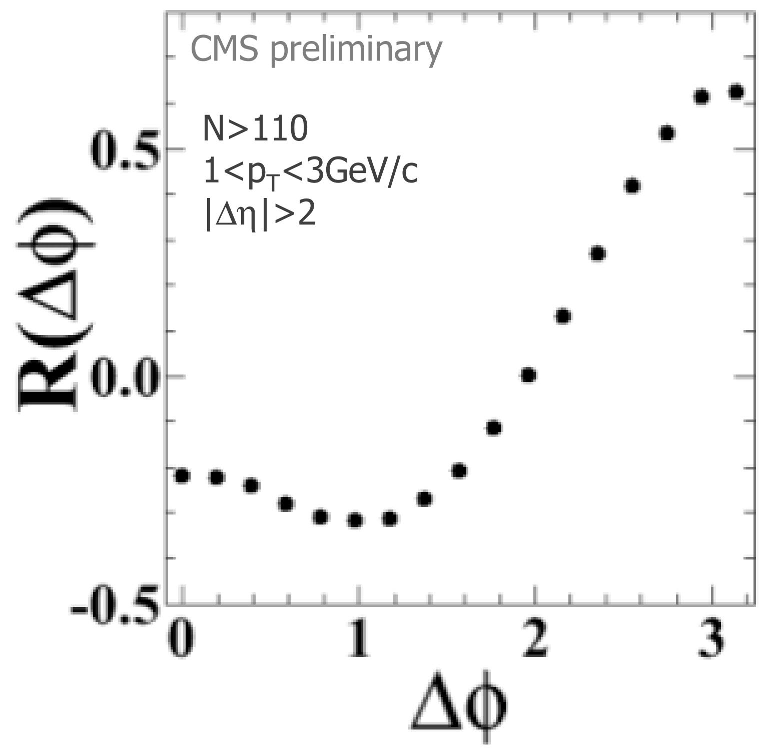


Pileup effects are suppressed due to excellent resolution
Track counting done with σ_{dz}, σ_{dxy} of O(100μm)

Track-Photon Correlations

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





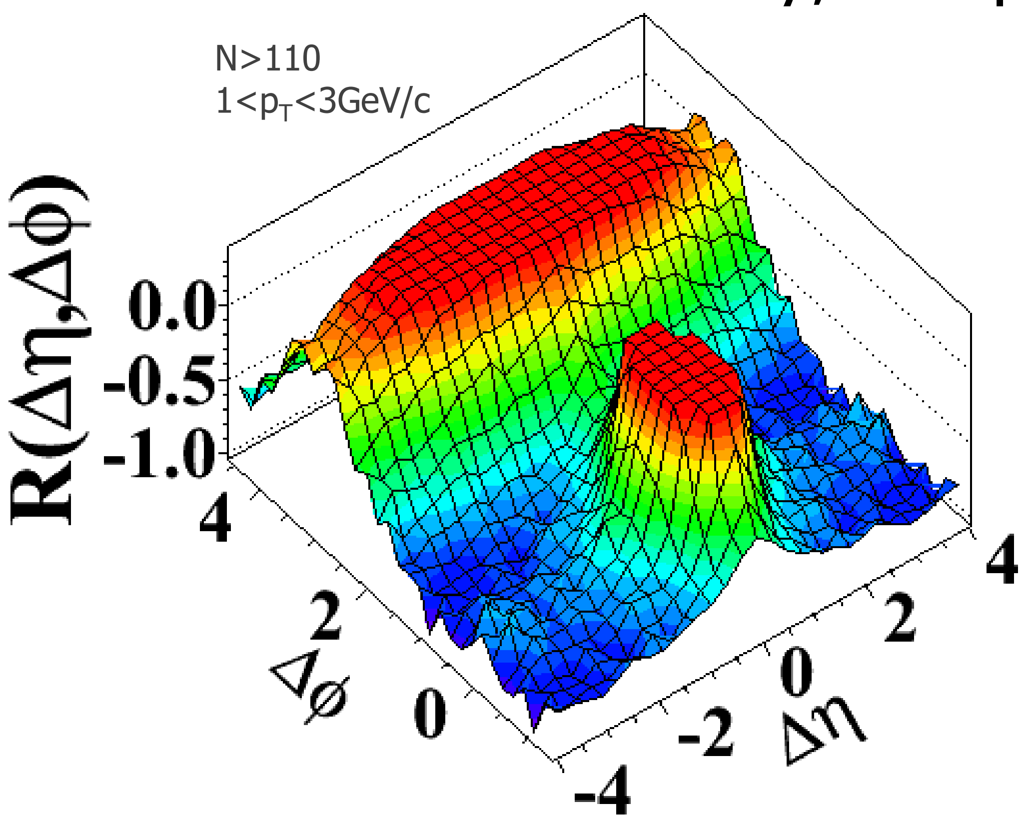
Note: photons reconstructed using "particle flow" event reconstruction technique

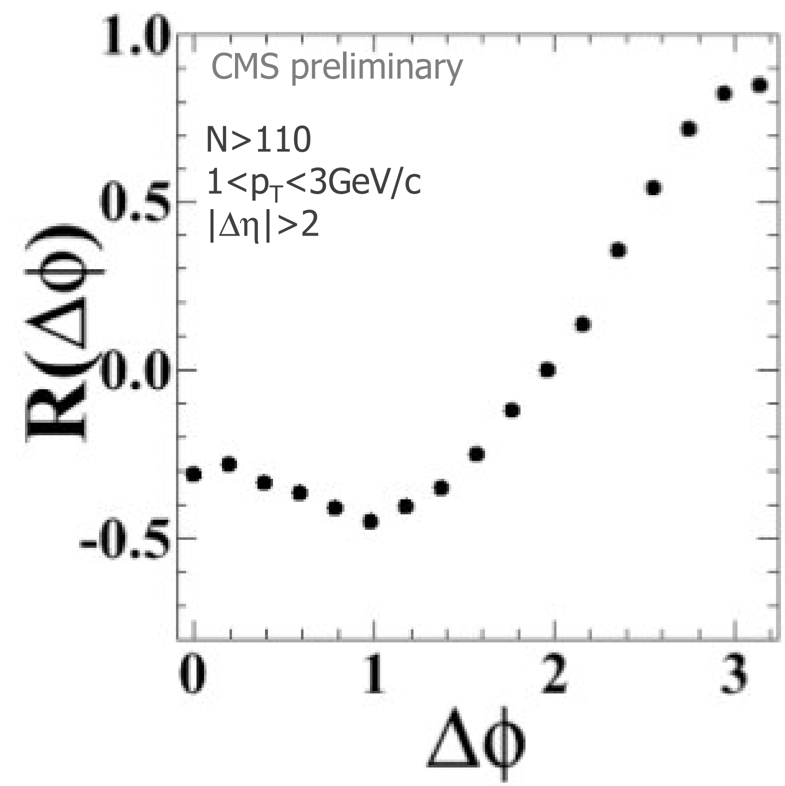
Photon-Photon Correlations

Use ECAL “photon” signal

Mostly single photons from π^0’s

No efficiency, and p_T, ϕ smearing corrections

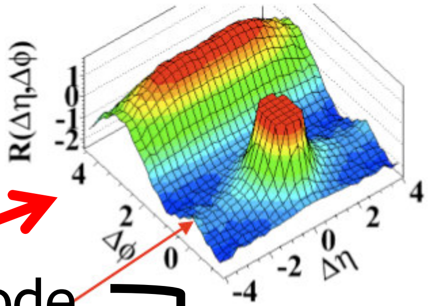




Qualitative confirmation

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

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
  - Not observed in low multiplicity events
  - Not observed in MC generators
- **This is a subtle effect in a complex environment – careful work is needed to establish physical origin**

Reconstructed high multiplicity pp event