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Universiteit Antwerpen

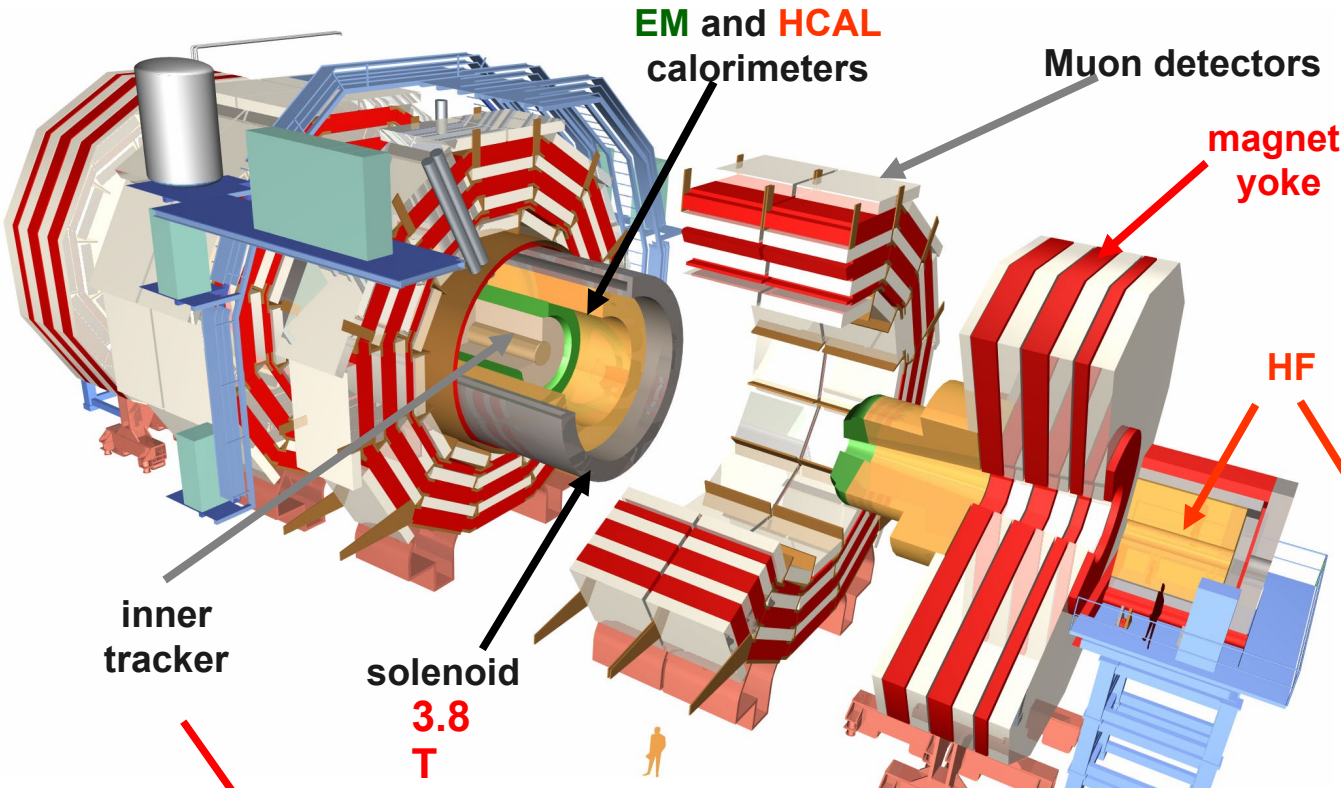
Observation of long-range, near-side two particle angular correlations in pp collisions at the LHC

Xavier Janssen
(On behalf of the CMS Collaboration)

MPI@LHC 2010: 2nd International Workshop on
Multiple Partonic Interactions at the LHC

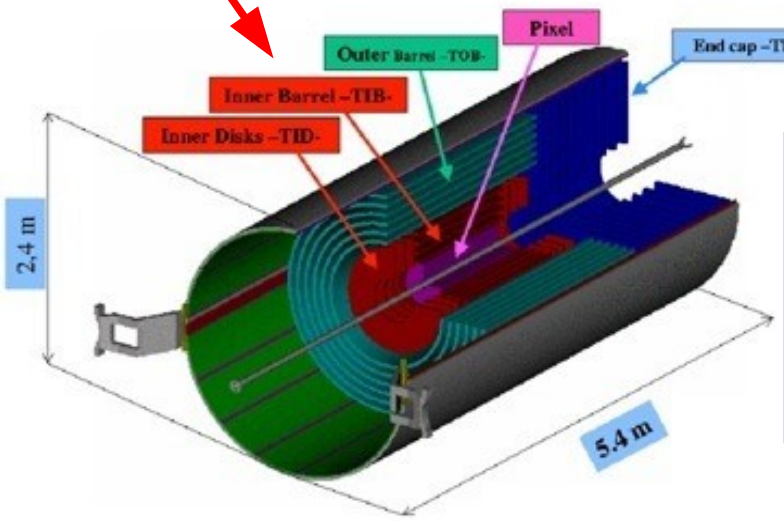
Glasgow, 29th of November to the 3rd of December 2010

The CMS Detector

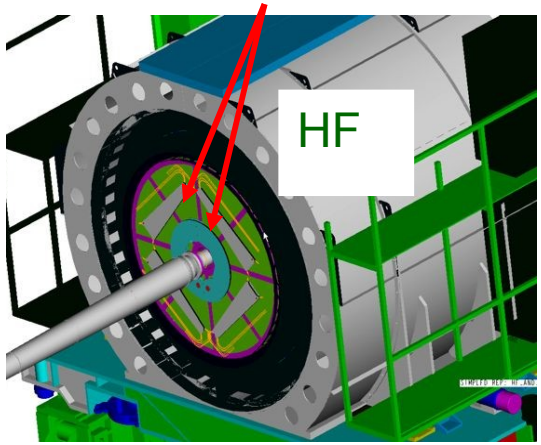


Total weight	12500 t
Overall diameter	15 m
Overall length	21.6 m

"Inclusive" (MinBias) Trigger: Scintillators around Beam Pipe (BSC)



BSC



CMS η coverage:

Tracker (Pixel + Strip)	$\|\eta\| < 2.4$
Calorimeters (EM+HCAL)	$\|\eta\| < 3.0$
HF Calorimeter	$3 < \|\eta\| < 5$
Muon Detectors	$\|\eta\| < 2.4$

Data Selection and Efficiencies

Event Selection

- **MinBias trigger** events
  (*or High Multiplicity trigger, see later*)
- At least 1 HF tower > 3 GeV on each side
  → Non Single Diffractive (**NSD**) selection
- At least **one primary vertex** with:
  $|z_{vtx}| < 4.5$ cm & $\rho_{xy}(BS) < 0.15$ cm

→ 168k events @ 900 GeV (3.3 μb^{-1})
→ 10k events @ 2.36 TeV (0.2 μb^{-1})
→ 150k events @ 7 TeV (3.0 μb^{-1})

Event Selection Efficiency

$$\varepsilon^{evtSel}(N_{trk}^{true}) = \frac{N_{gen}^{NSD}(N_{trk}^{true})}{N_{gen}^{evtSel}(N_{trk}^{true})}$$

→ ε^{evtSel} = 50% (100%) at N_{trk}^{true} = 6 (15)

→ Data (**each track pair**) weigthed by:

$$1/\varepsilon^{evtSel}(N_{trk}^{corrected})$$

Track Selection

- **$0.1 < p_T < 5$ GeV/c** and **$|\eta| < 2.4$**
- **Primary** particle (primary vertex link):
  - $d_z(vtx)/\sigma(d_z) < 3$
  - $d_{xy}(vtx)/\sigma(d_{xy}) < 3$
- **Good quality** tracks:
  - $\sigma(p_T)/p_T < 0.1$
  - CMS "High Purity" tracks only

Matching tracks to primary vertex with a resolution O(100 μm)

Tracking Efficiency

$$\varepsilon^{trk}(\eta, p_T, z_{vtx}) = \frac{N_{reco,MC}^{trk}(\eta, p_T, z_{vtx})}{N_{gen,MC}^{trk}(\eta, p_T, z_{vtx})}$$

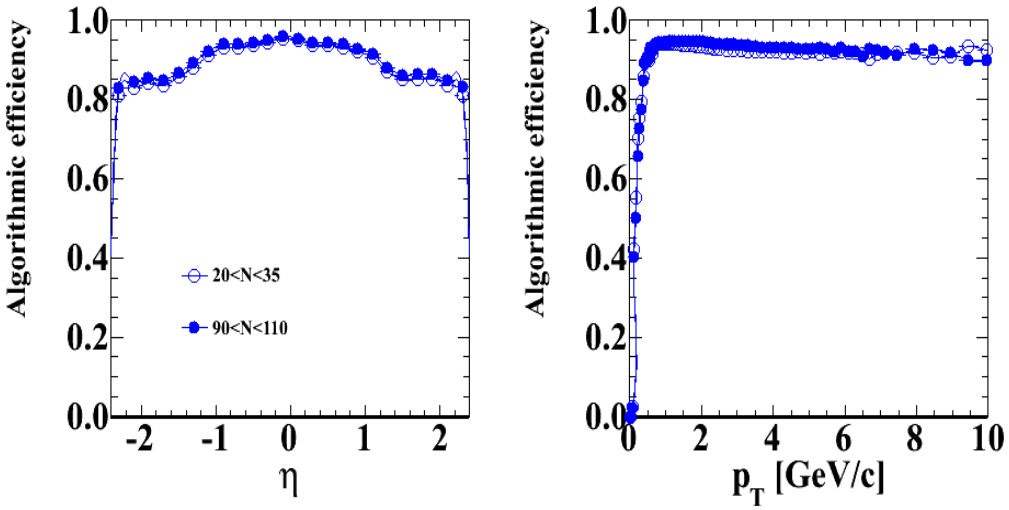
- ε^{trk} = 50% for $p_T \approx 0.1$ GeV/c
- ε^{trk} > 90% for $|\eta|<1$ and $p_T > 0.6$ GeV/c
- Fake rate below 2% for $p_T > 0.2$ GeV/c

→ Data (**each track**) weigthed by:

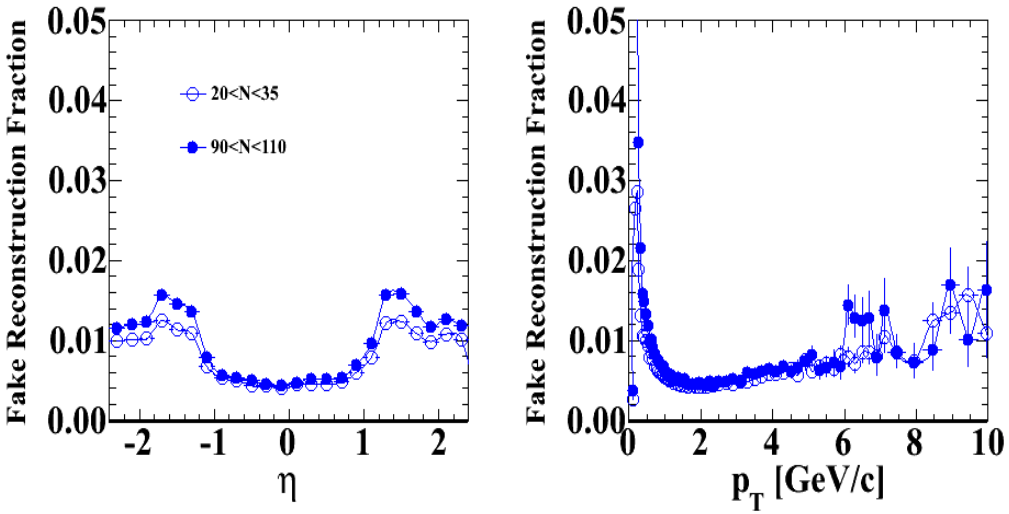
$$1/\varepsilon^{trk}(\eta, p_T, z_{vtx})$$

Data Selection and Efficiencies

Tracking Efficiency



Fake Rate



Efficiencies and Fake rate similar for low and high multiplicities

Track Selection

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- Fake rate below 2% for $p_T > 0.2$ GeV/c

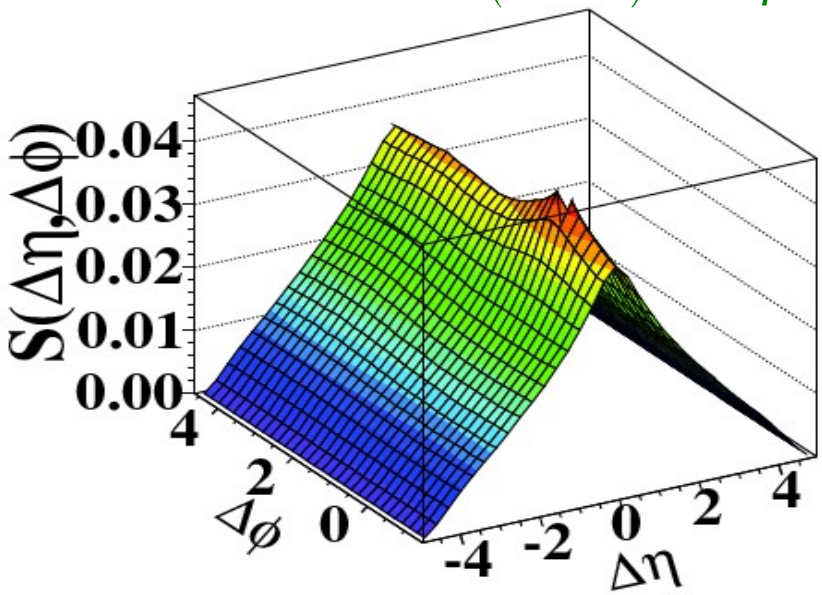
→ Data (**each track**) weigthed by:

$$1/\varepsilon^{trk}(\eta, p_T, z_{vtx})$$

Analysis Technique

Signal distribution
= Correlated and uncorrelated pairs
from same event

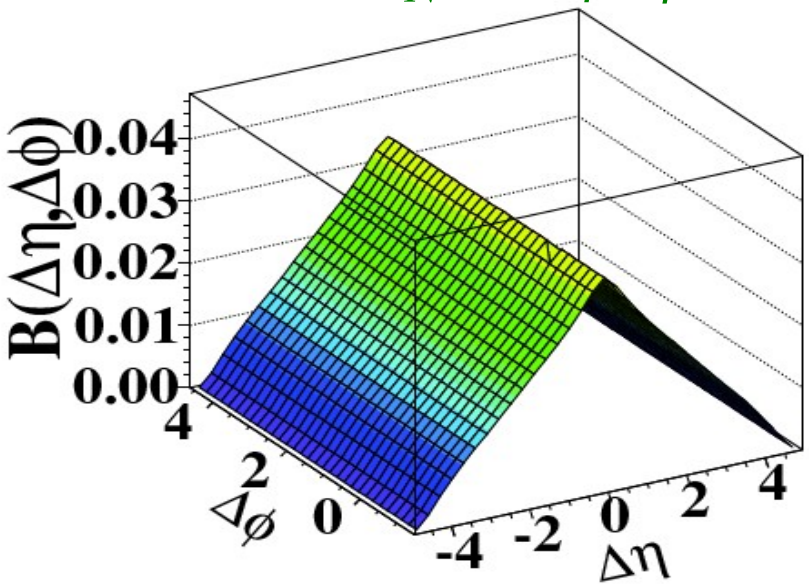
$$S(\Delta\eta,\Delta\phi)=\frac{1}{N(N-1)}\frac{d^2N}{d\Delta\eta\,\Delta\phi}$$



$$\Delta\eta=\eta_1-\eta_2$$
$$\Delta\phi=\phi_1-\phi_2$$

Background distribution
= Uncorrelated pairs
from mixing 2 events

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



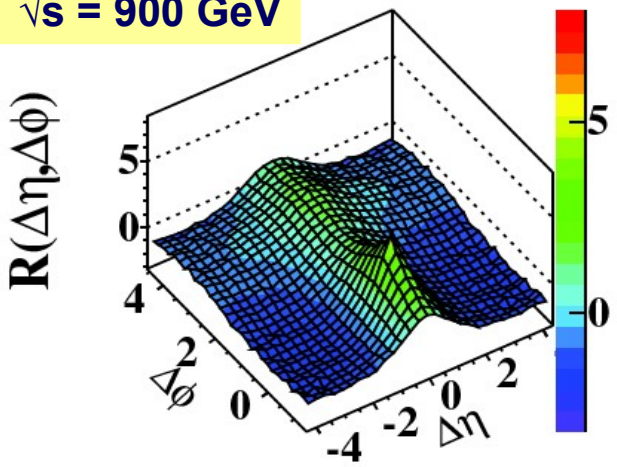
Two-particle correlation

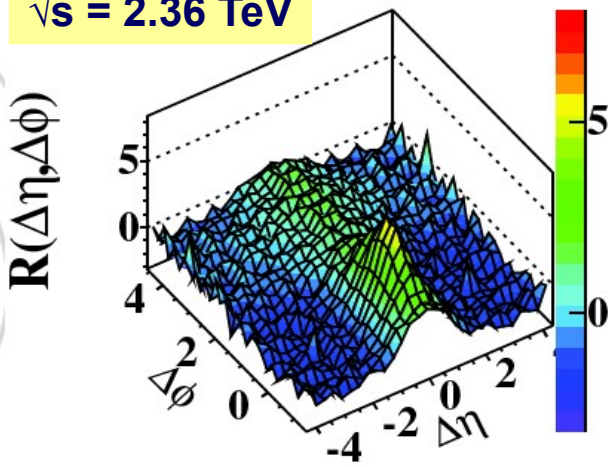
$$R(\Delta\eta,\Delta\phi)=\left\langle (N-1)\left(\frac{S_N(\Delta\eta,\Delta\phi)}{B_N(\Delta\eta,\Delta\phi)}-1\right)\right\rangle_N$$

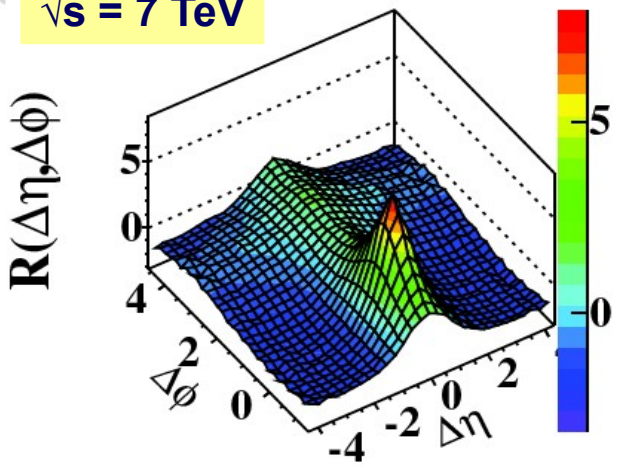
N.B.: – S & B constructed in bins of multiplicity N and of vertex position prior to average
– $|\Delta\eta|<0.06$ and $|\Delta\phi|<0.06$ region excluded both in S and B (avoid residual secondary effects)

MinBias Results: 2D Two-particle Correlations

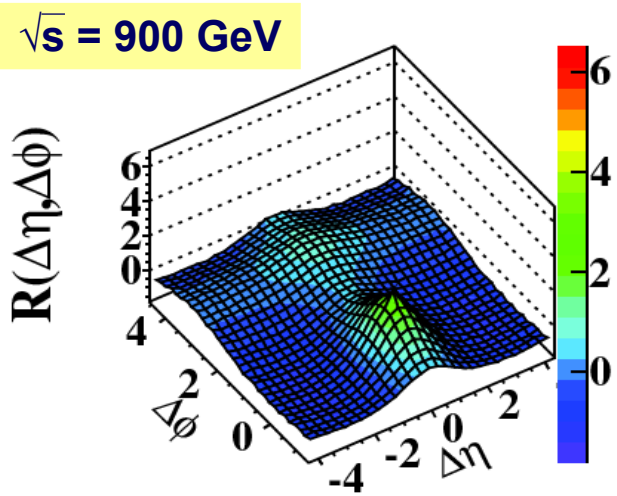
DATA

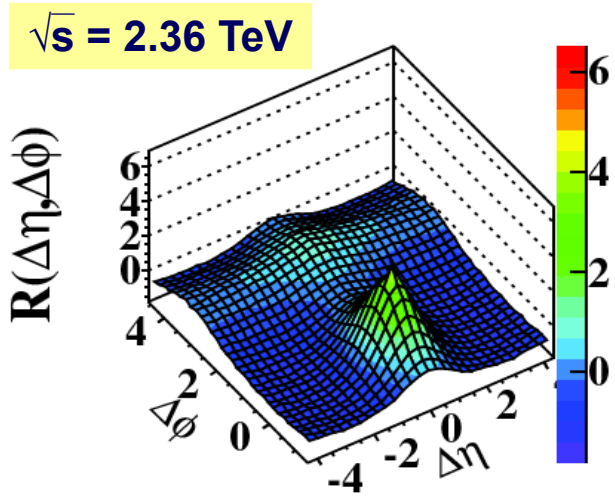


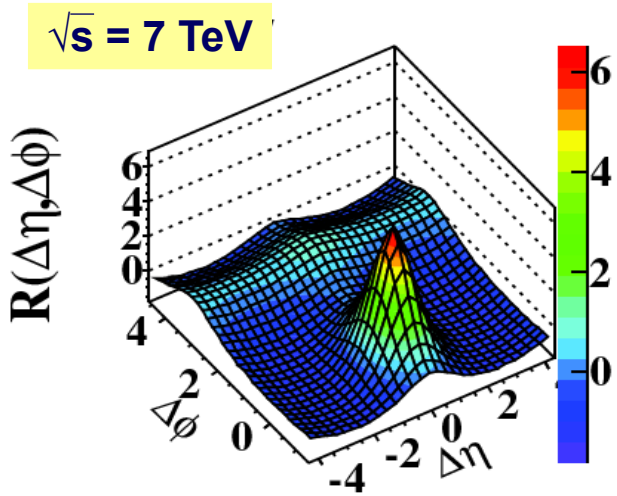




PYTHIA D6T





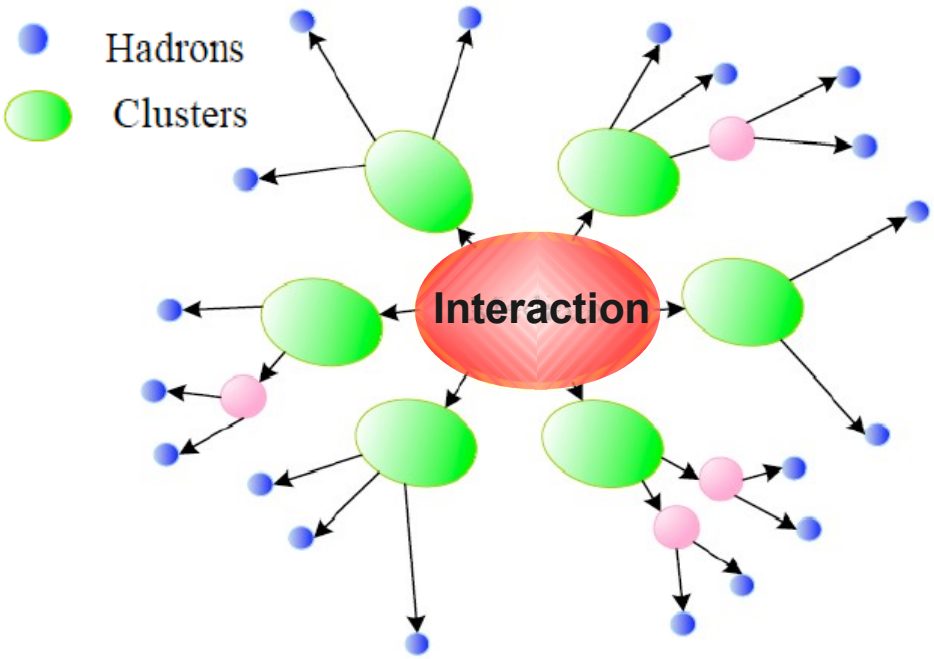


DATA:

- Gaussian ridge" @ $|\Delta\eta| < 2$ → clusters fragmentation (short range correlations)
- Near-side peak @ $\Delta\eta, \Delta\phi \approx 0$ → Near-side "jet"/ higher p_T clusters (+Bose-Einstein)
- Broad ridge @ $\Delta\phi \approx \pi$ → Away-side "jet" / lower p_T clusters
- Cos ($\Delta\phi$) modulation → Momentum conservation

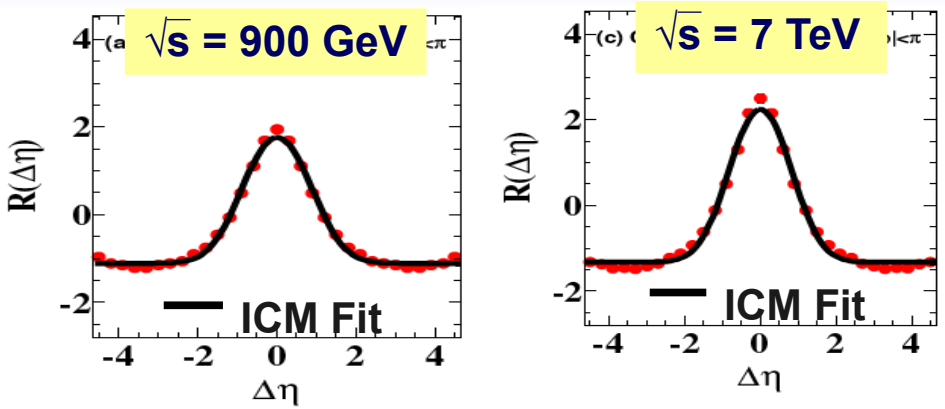
PYTHIA D6T: Simulation qualitatively similar to data (but not in magnitude for each component)

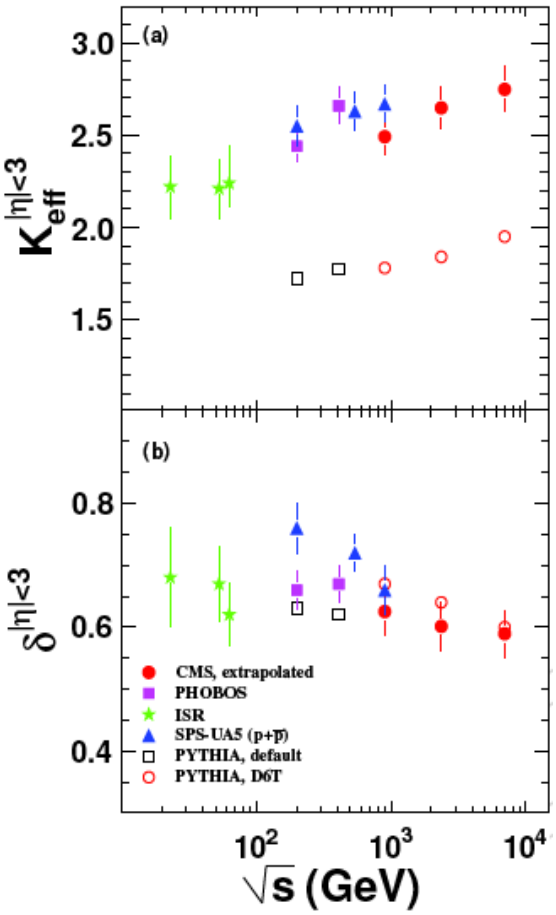
MinBias Results: Independent Cluster Model



Independent Cluster Model (ICM)

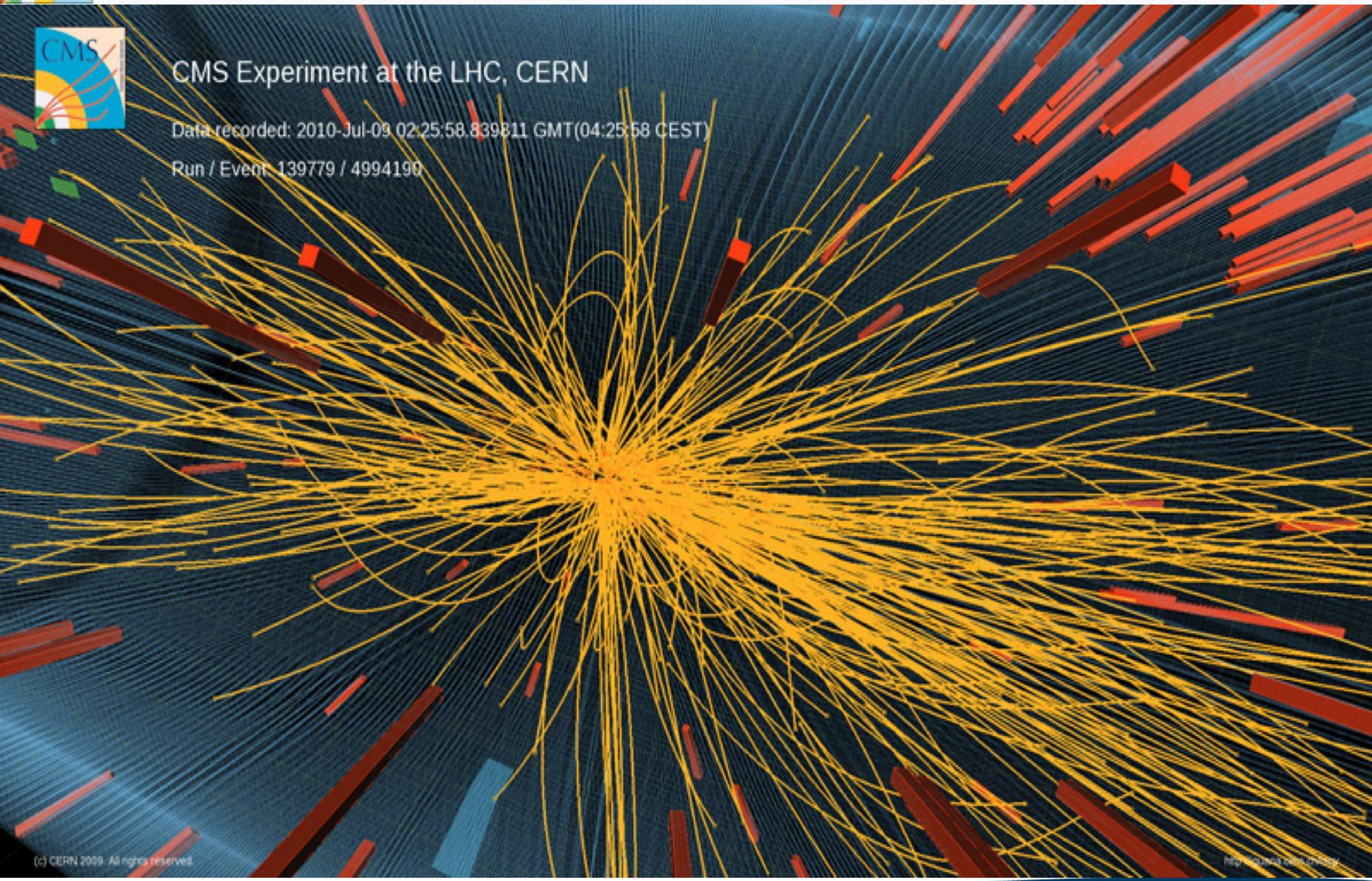
- Clusters are produced independently
- Each cluster decay isotropically into hadrons in its own c.m.s.
- Short range correlations in $\Delta\eta$ can be characterized by 2 parameters:
  - cluster size K → # correlated particles
  - cluster width δ → $\Delta\eta$ correlation size





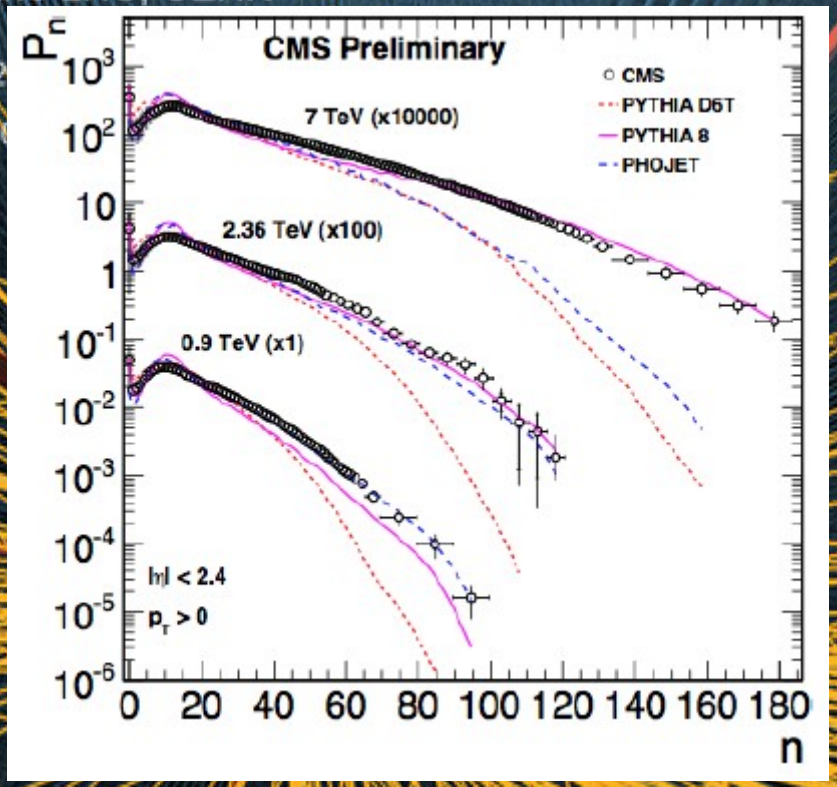
- K_{eff} increase with $\sqrt{s}$ (more jets at high $\sqrt{s}$?)
- δ constant with $\sqrt{s}$ (isotropic cluster decay)
- CMS results follow trend from lower $\sqrt{s}$ data
- PYTHIA (D6T) shows similar energy dependencies for K_{eff} and δ as data
- PYTHIA (D6T) predicts too low K_{eff}

High Multiplicity Analysis at $\sqrt{s} = 7$ TeV



N = 268

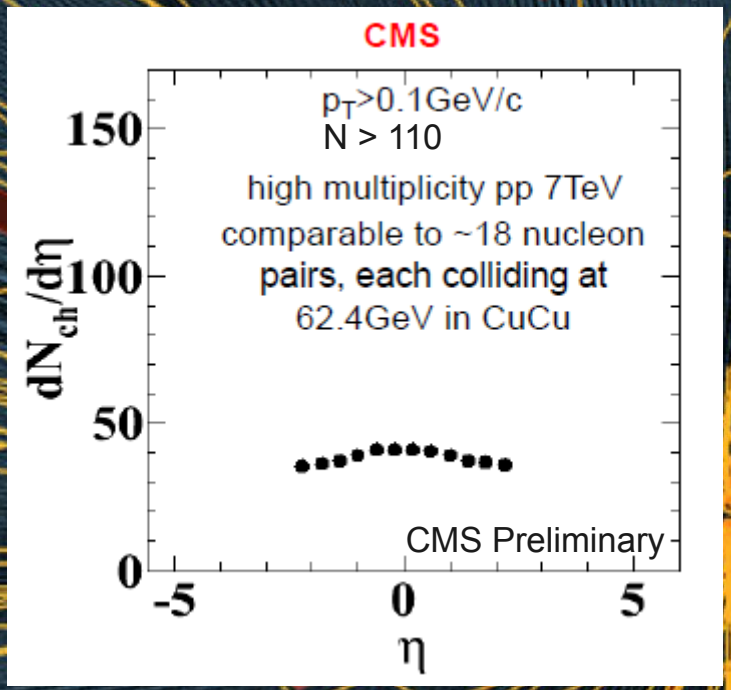
High Multiplicity Analysis at $\sqrt{s} = 7$ TeV

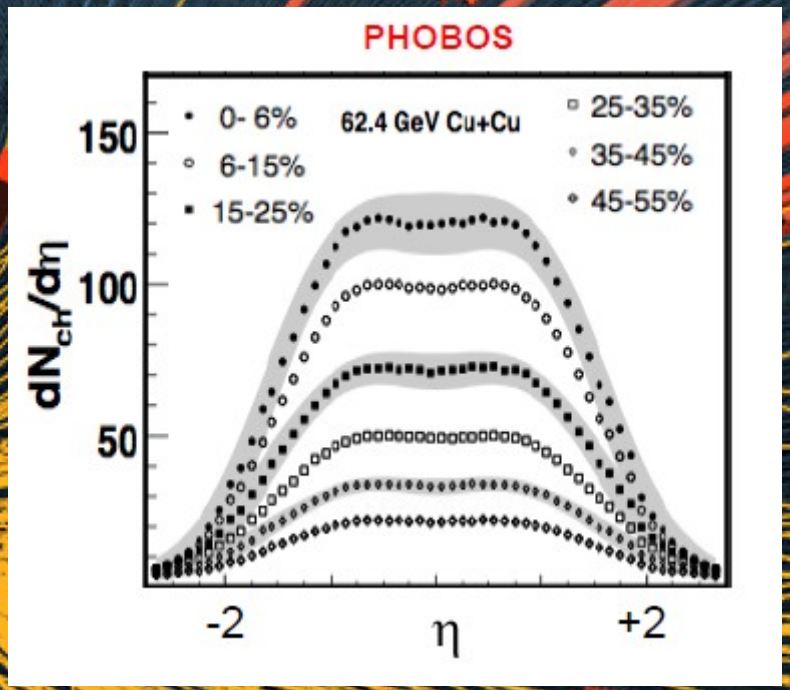


Large multiplicities observed in 7 TeV data
→ Detailed studies of the properties of these events

N = 268

High Multiplicity Analysis at $\sqrt{s} = 7$ TeV



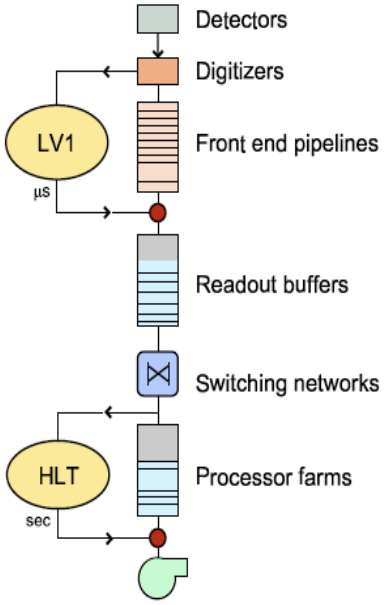


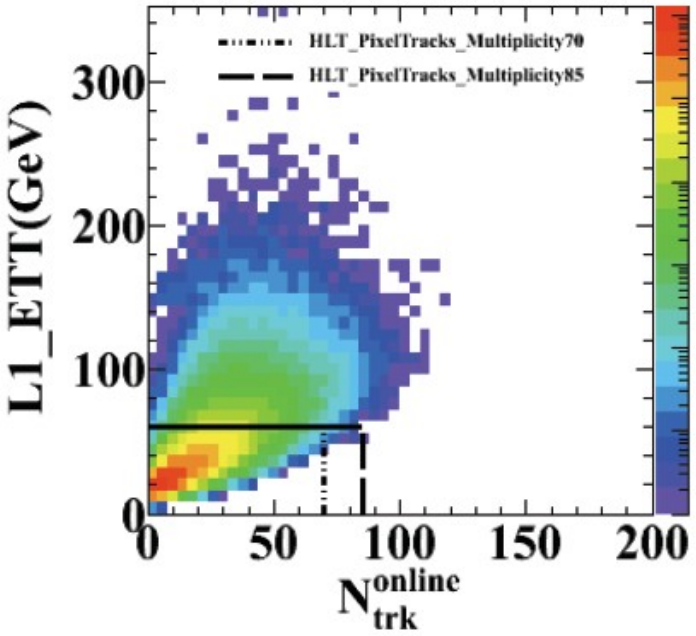
Large multiplicities observed in 7 TeV data
→ Detailed studies of the properties of these events

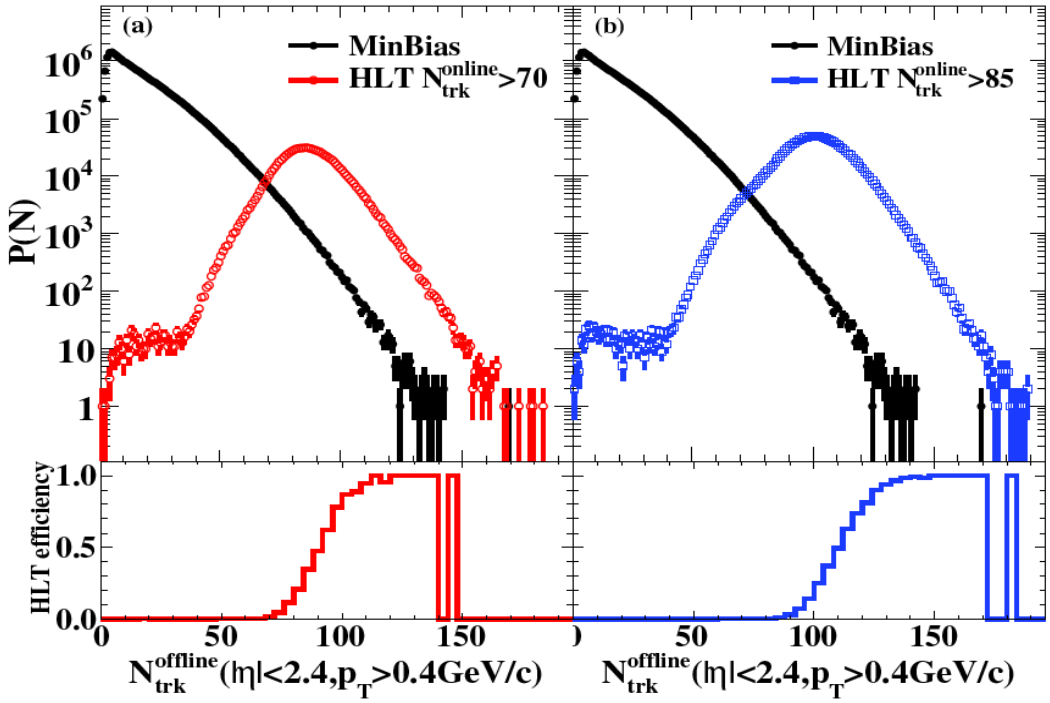
The particle densities in the high multiplicity events of proton-proton collisions at 7TeV begin to approach those in high-energy collisions of nuclei such as Copper
→ Benchmark / reference for Heavy Ion run

N = 268

High Multiplicity Trigger







High Multiplicity Trigger

- **L1 :** ΣE_T(Calo) > 60 GeV
  → 100% efficient for $N_{trk}^{offline} > 90$
- **HLT :** $N_{trk}^{online} > 70$ (85)
  Primary (vertex link) pixel tracks for $|\eta| < 2$ and $p_T > 0.4$ GeV/c
  → Good efficiencies at high $N_{trk}^{offline}$
  → Pairs weighted by $1/\varepsilon_{event}^{HLT}(N_{trk}^{offline})$

Multiplicity Definition

$$N_{trk}^{offline} \rightarrow N_{trk}^{corrected}$$

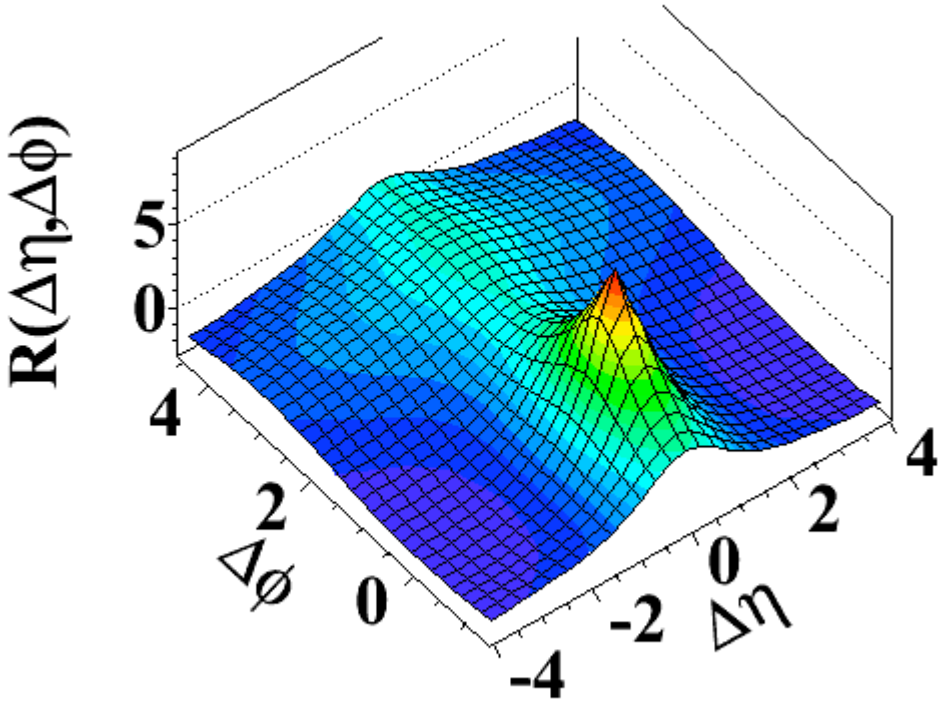
Primary tracks in full tracker for **$|\eta| < 2.4$** and **$p_T > 0.4$ GeV/c**

→ 980 nb^{-1} analyzed @ 7 TeV
→ ~1000 more statistics from high multiplicity trigger than MinBias one (pre-scaled) at high multiplicity
→ **Differential analysis in N and p_T**

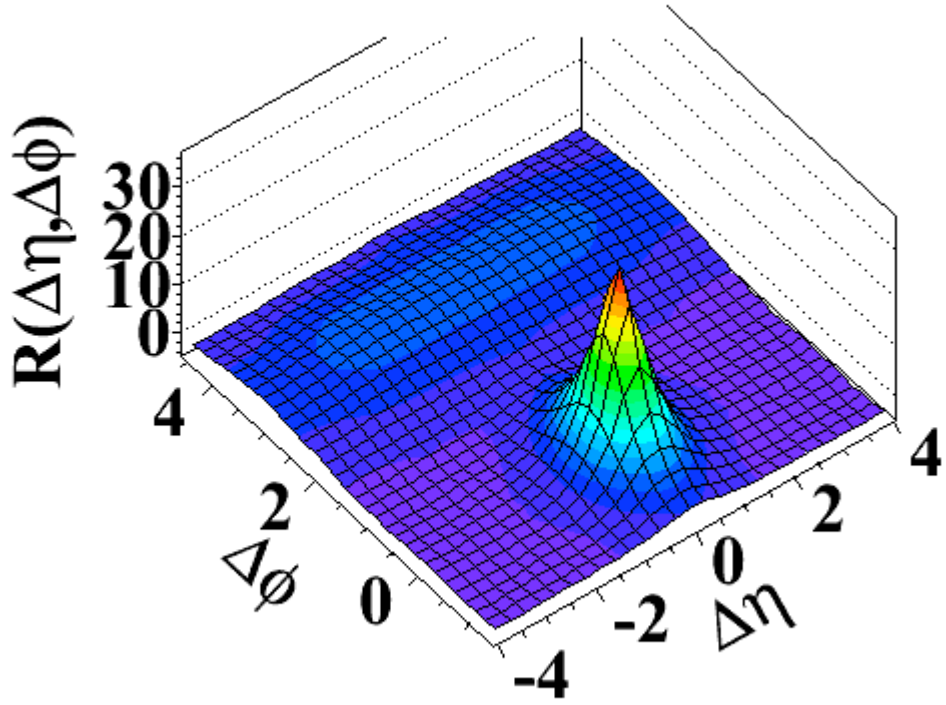
High Multiplicity Results

Inclusive p_T : p_T > 0.1 GeV/c

MinBias



High Multiplicity: N>110



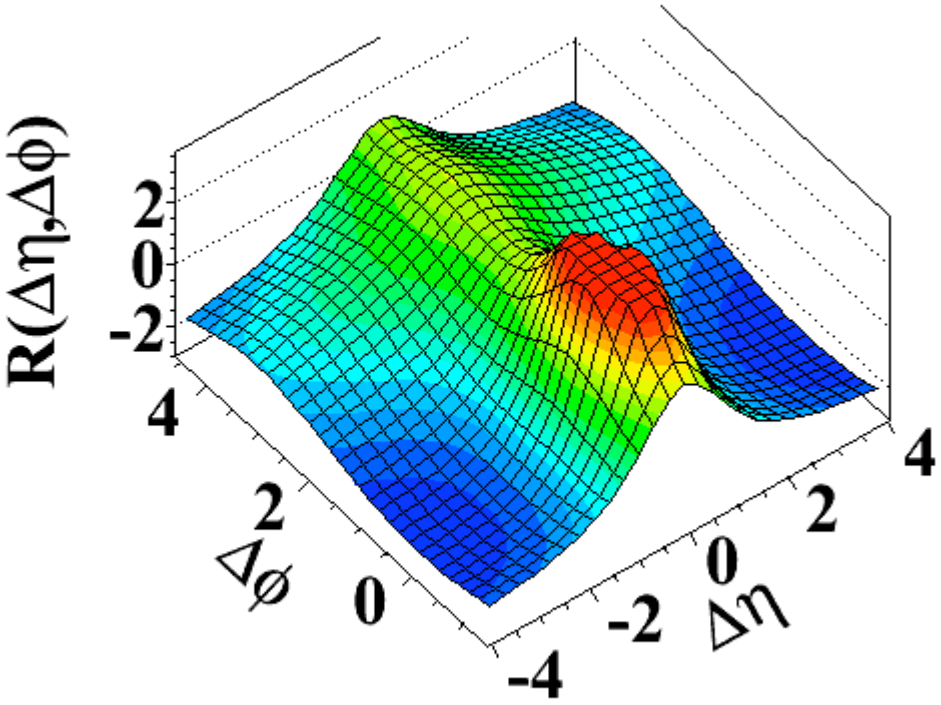
→ Jet peak/away-side correlations enhanced at high multiplicity
→ Abundant jet production in high multiplicity sample

High Multiplicity Results

Inclusive p_T : p_T > 0.1 GeV/c

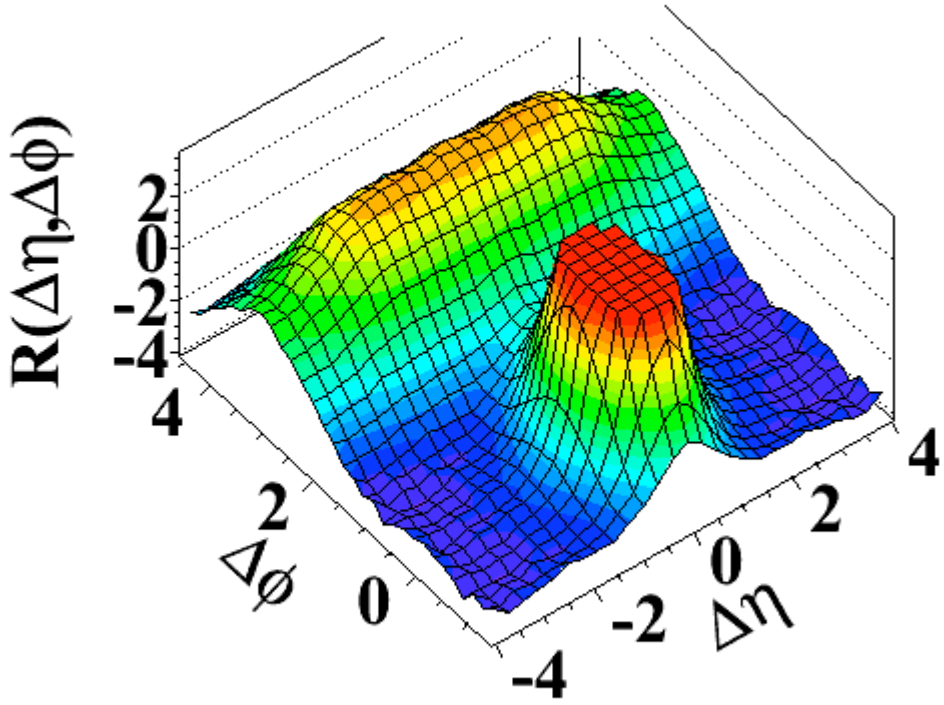
MinBias

(a) MinBias, p_T>0.1GeV/c



High Multiplicity: N>110

(c) N>110, p_T>0.1GeV/c



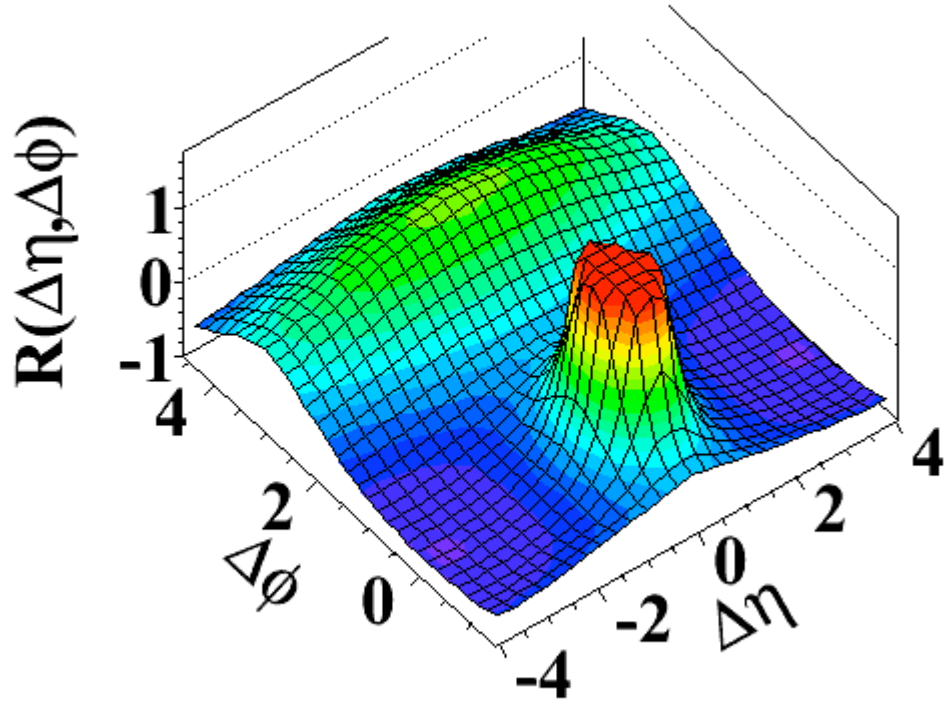
→ Jet peak/away-side correlations enhanced at high multiplicity
→ Abundant jet production in high multiplicity sample

→ Cut-off dominant peak at (Δη,Δφ) ≈ (0,0) to better see details !

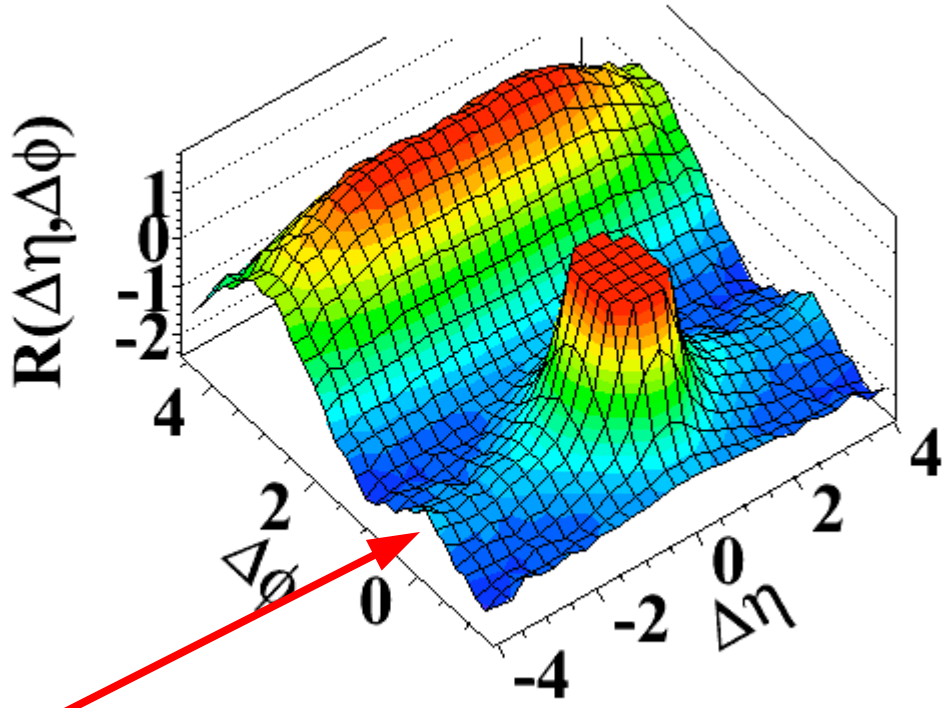
High Multiplicity Results

Intermediate pT : $1 < p_T < 3$ GeV/c

MinBias



High Multiplicity: N>110

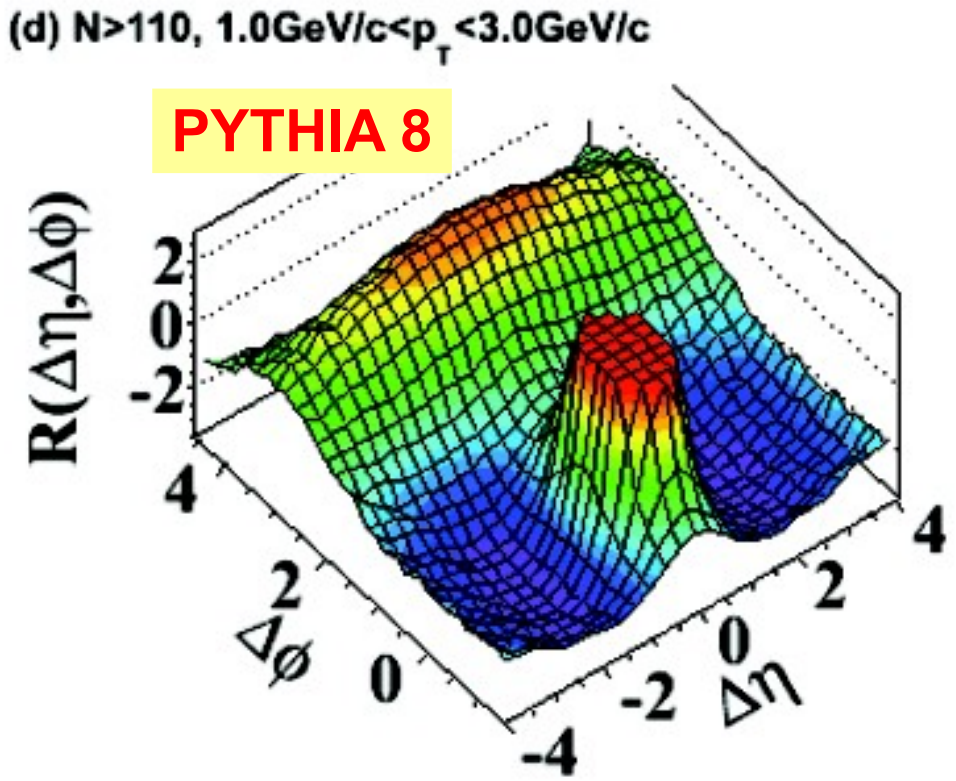


→ **Observation of a Long-Range, Near-Side angular correlations at high multiplicity in pp events at intermediate p_T (Ridge at $\Delta\phi \sim 0$)**

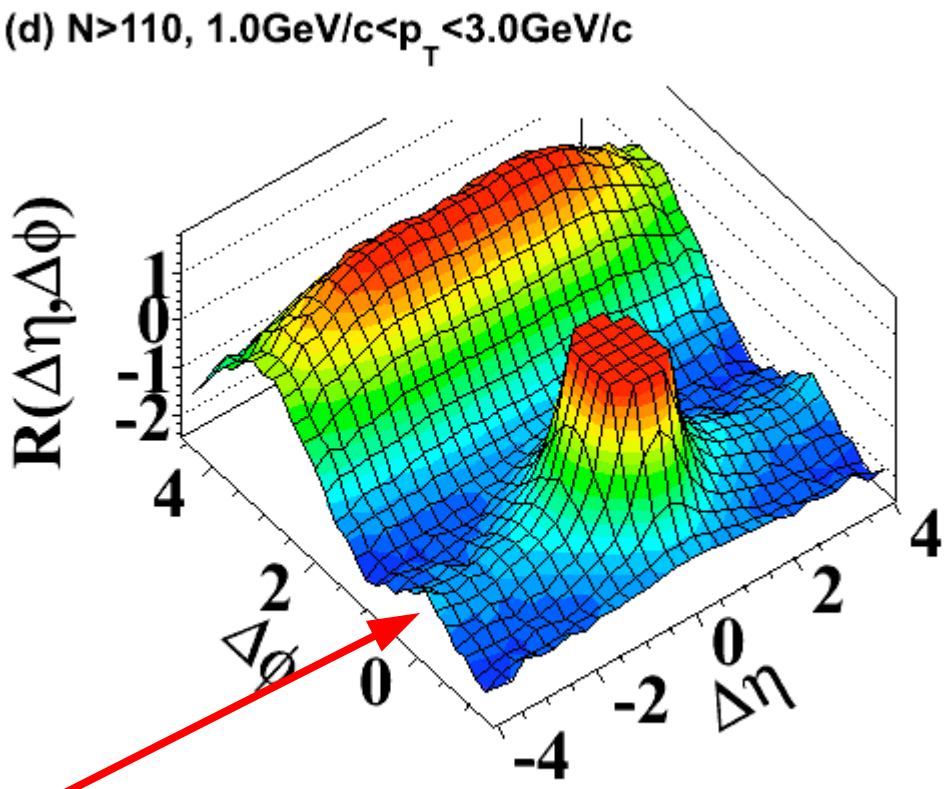
High Multiplicity Results

Intermediate pT : $1 < p_T < 3$ GeV/c

High Multiplicity: N>110



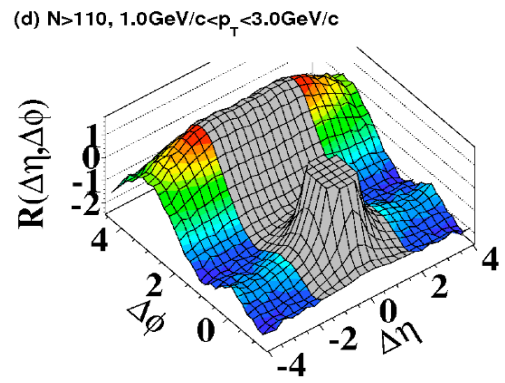
High Multiplicity: N>110



→ Observation of a Long-Range, Near-Side angular correlations at high multiplicity in pp events at intermediate p_T (Ridge at $\Delta\phi \sim 0$)

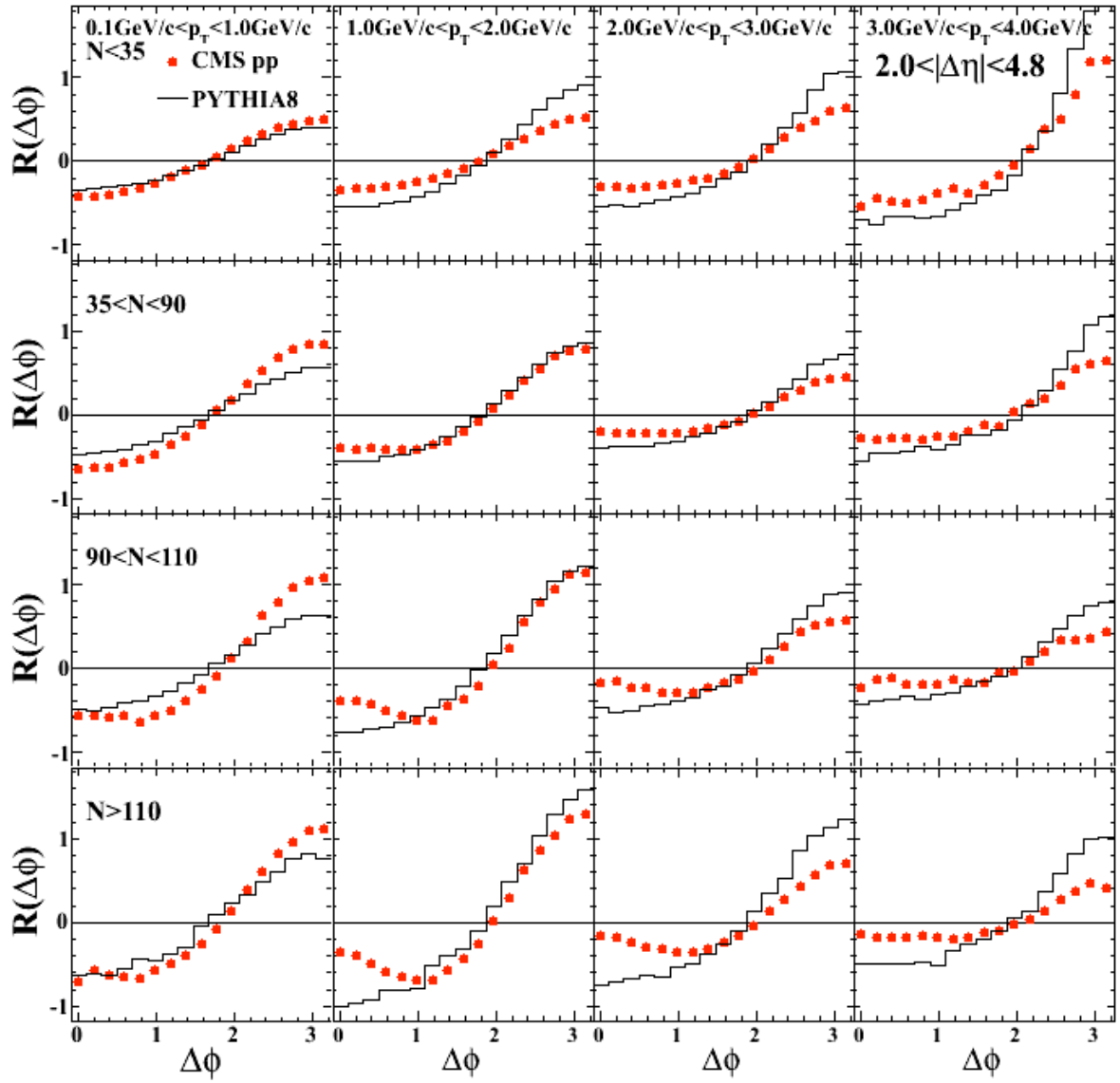
… not reproduced in PYTHIA 8 (and PYTHIA 6, HERWIG++, madgraph)

Multiplicity and p_T dependences



p_T range

Multiplicity



→ **Study dependence on p_T and multiplicity for $2 < |\Delta\eta| < 4.8$ for $R(\Delta\phi)$:**

$$R(\Delta\phi) = \left\langle (N-1)\left(\frac{\int_2^{4.8} S_N(\Delta\eta,\Delta\phi)\,d\Delta\eta}{\int_2^{4.8} B_N(\Delta\eta,\Delta\phi)\,d\Delta\eta} - 1 \right) \right\rangle_N$$

"Ridge" maximal for high multiplicity and intermediate p_T : $1 < p_T < 3$ eV/c

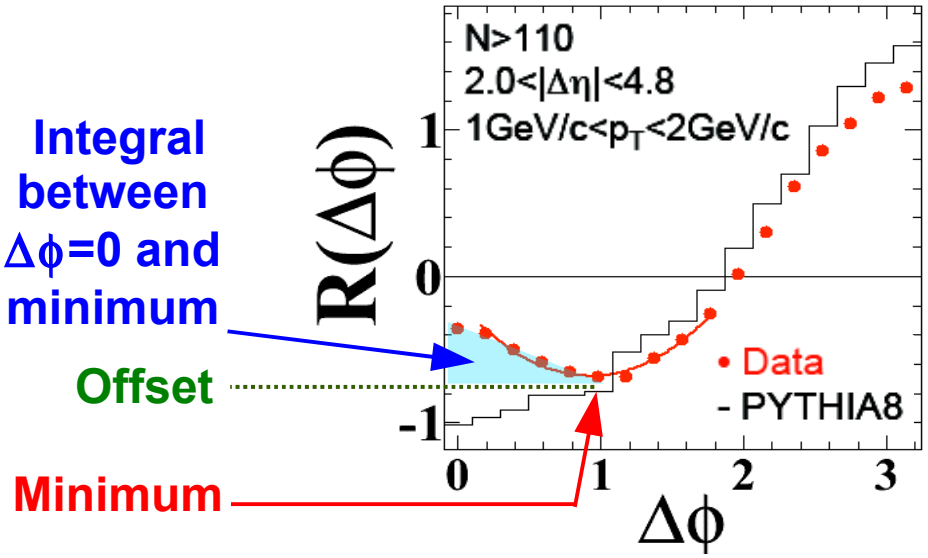
"Ridge" not reproduced by PYTHIA 8

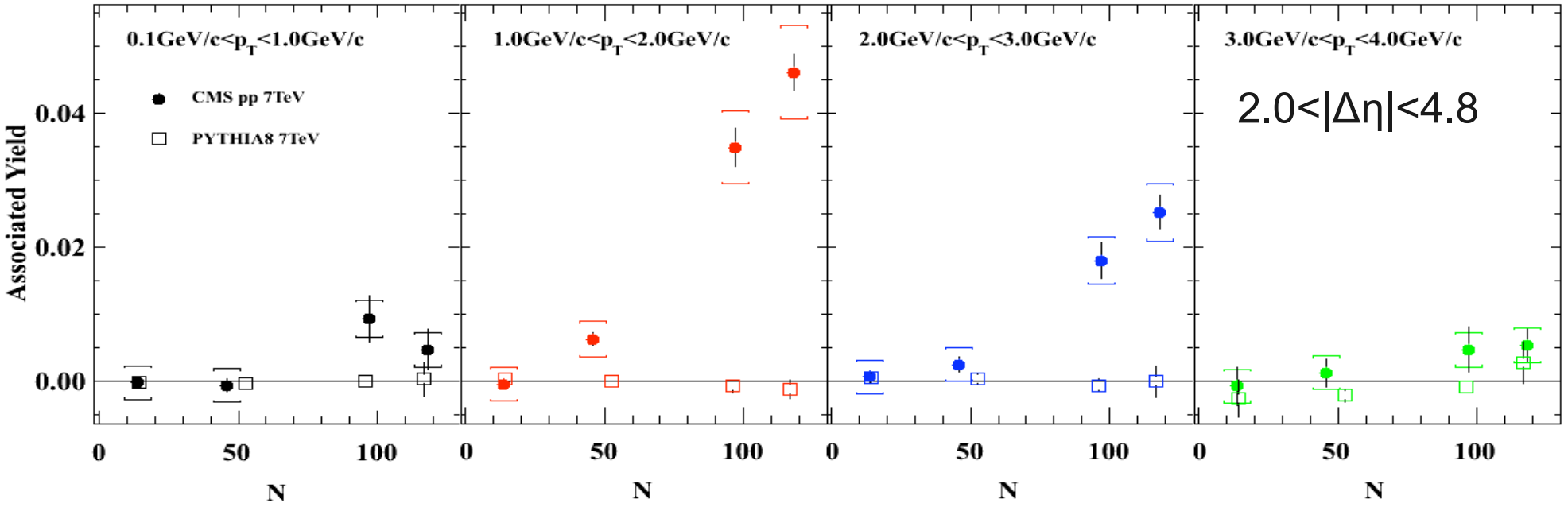
Quantifying the "Ridge": Associated Yield

Associated yield:
Extra correlated multiplicity per particle

→ **Zero Yield At Minimum (ZYAM) :**

→ **ZYAM = 0 if no "Ridge"**

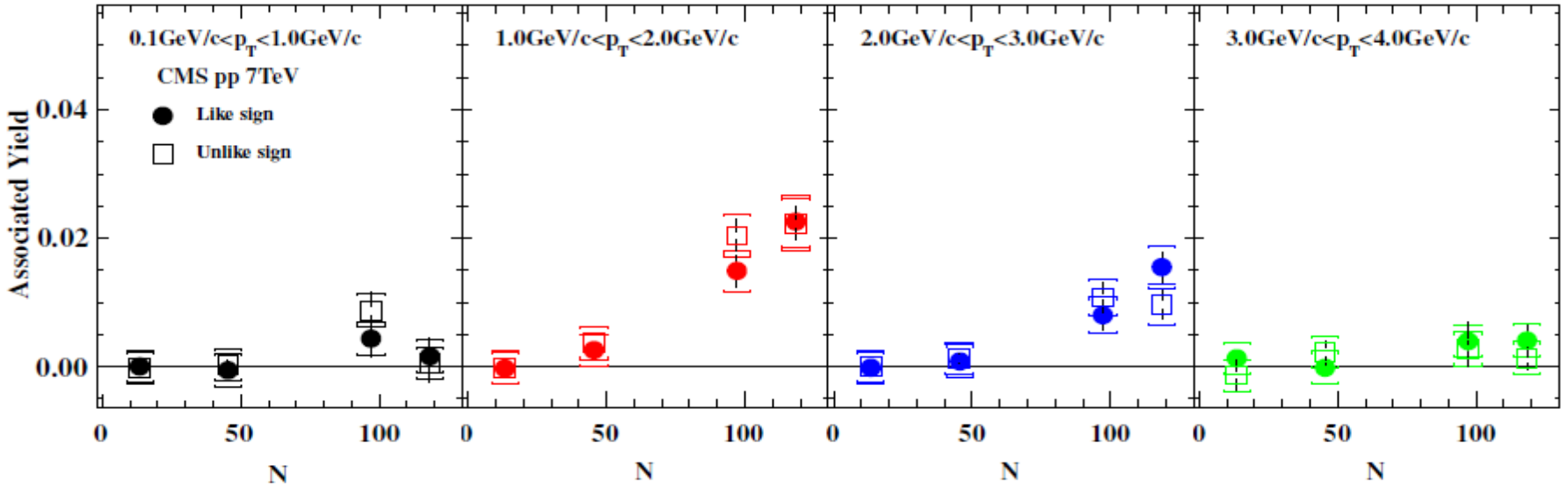




→ **Associated yield grows with increasing multiplicity**

→ **Maximum for 1< p_T < 2 GeV/c**

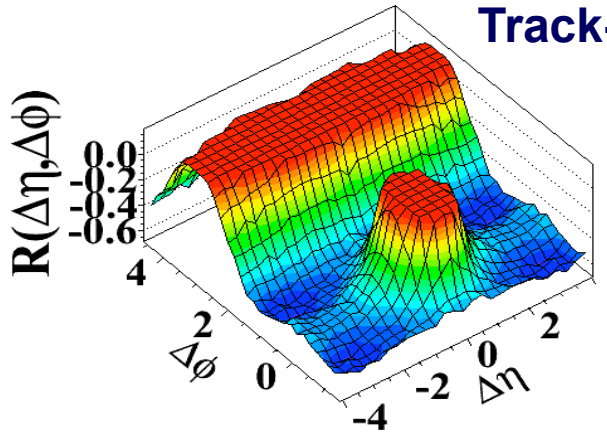
Like- and Unlike-charge pair / "Photons"

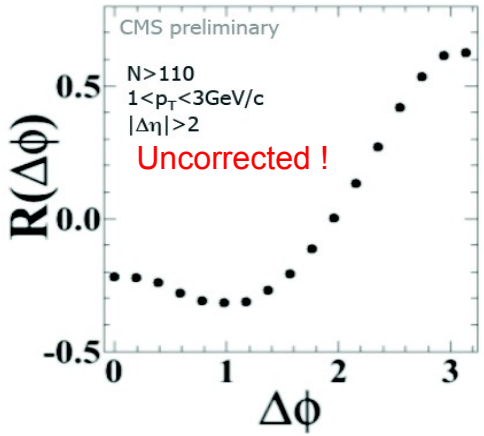


→ **Same effect for like- and unlike-charge pairs (factor 2 = normalisation)**

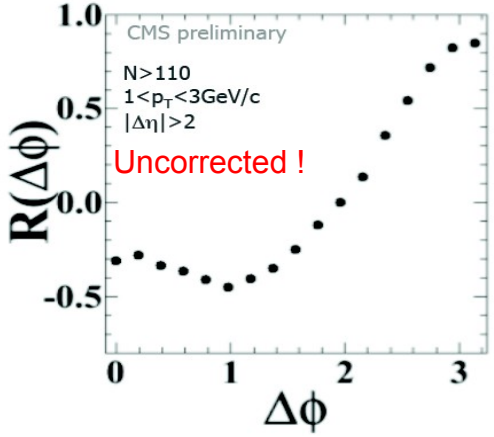
Use ECAL Object (Particle-flow "photons") = π^0 dominated

Track-"Photons"



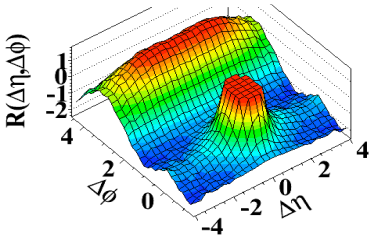


"Photons"-"Photons"



→ **Same effect seen for neutrals from Particle Flow (ECAL driven)**

Cross-Checks → Systematic Uncertainties



Analysis Code

Reconstruction

Trigger

Detector

CMS Event

Collision

"The new feature has appeared in our analysis around middle of July in the hottest days of the preparation for ICHEP. We have immediately set-up an independent analysis (control group) and organized a full set of tests and cross-checks to kill the effect." G. Tonelli

→ Many data driven cross-checks performed

→ No indication of effect that would fake ridge signal

→ Estimate Systematic Uncertainties:

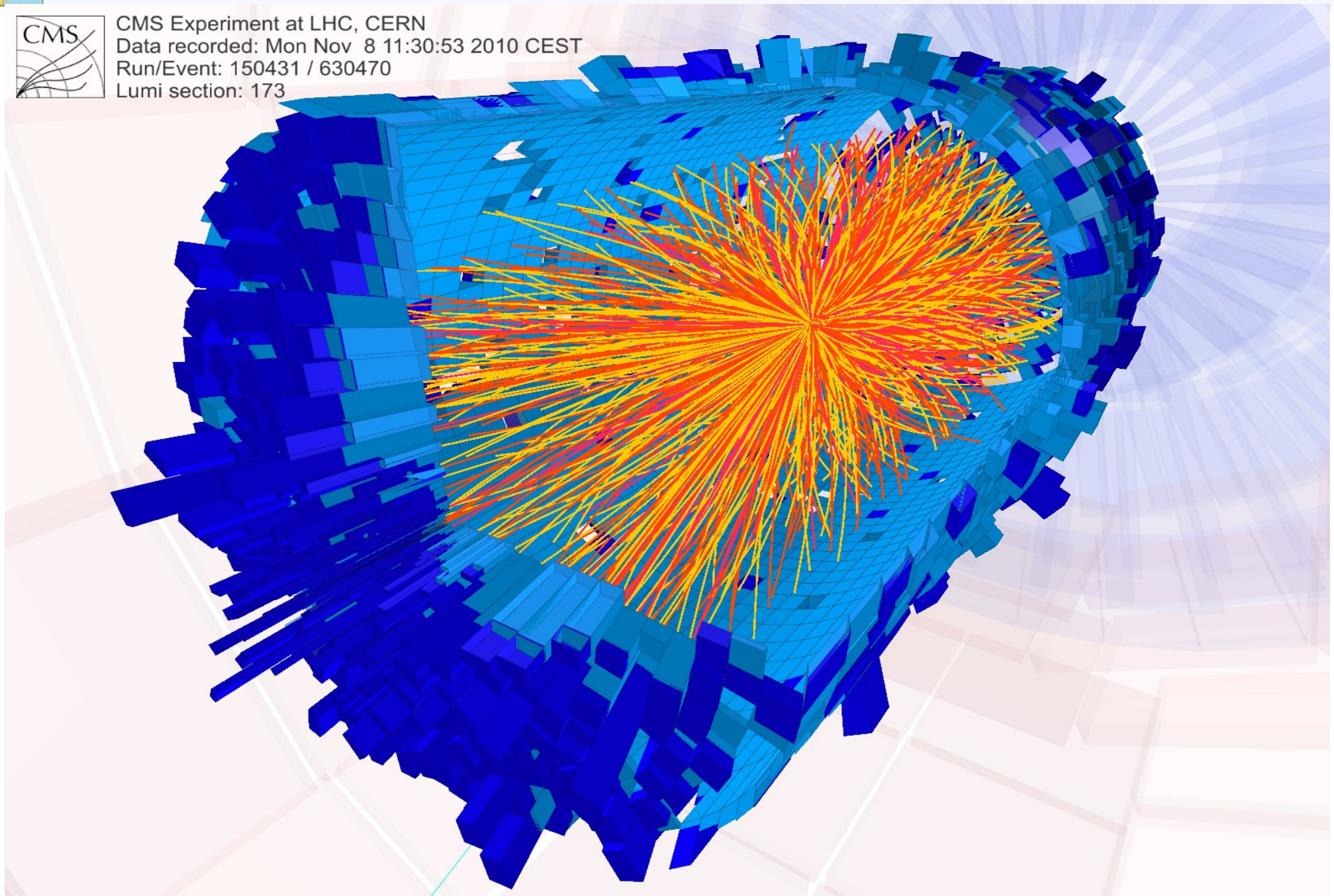
Sources	Syst. on ridge yield
Pileup	15%
HLT efficiency	4-5%
Tracking	1-2%
ZYAM	0.0025

CONCLUSIONS

Study of short-range and long-range angular correlations in pp collisions with CMS at LHC @ $\sqrt{s}$ = 0.9, 2.36 and 7 TeV

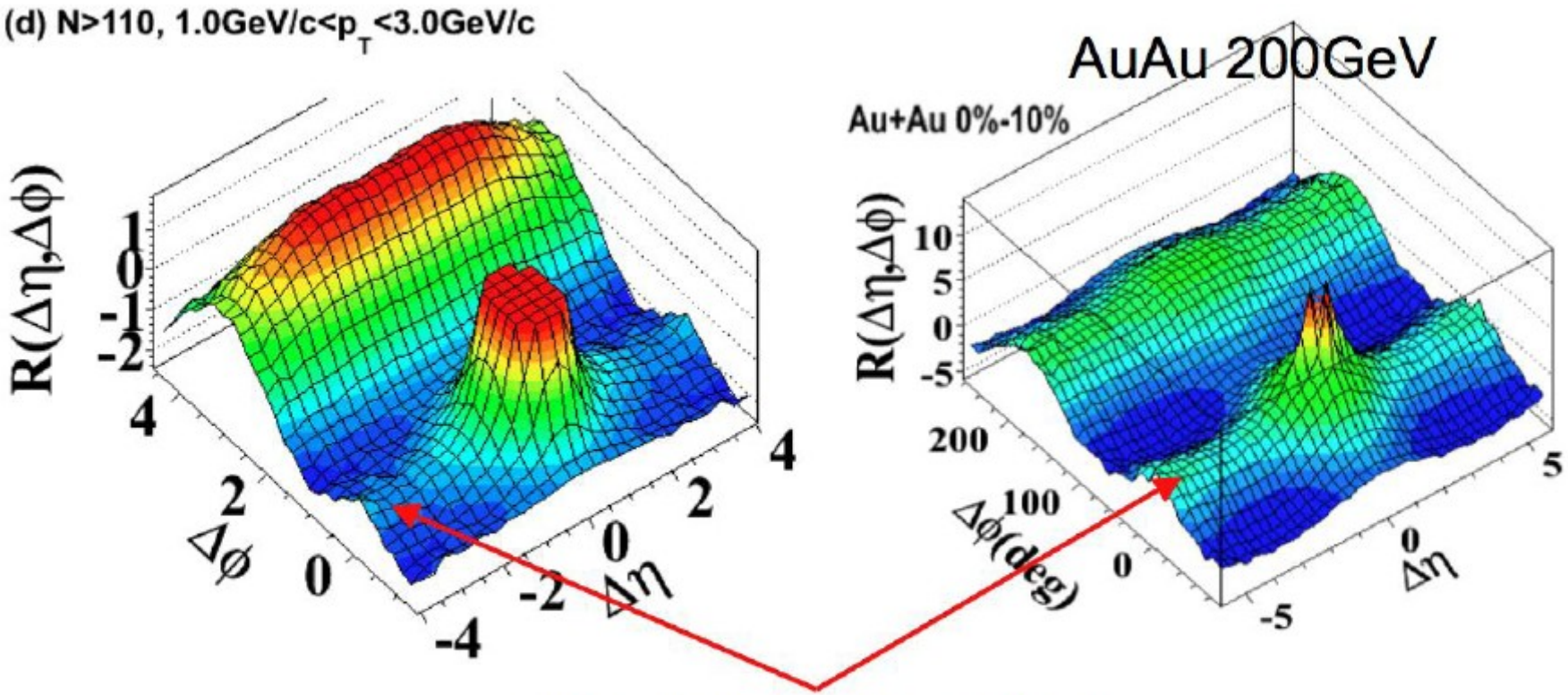
- **Short-range: cluster size and width compatible with previous experiments but not reproduced by PYTHIA**
- **Observation of long-range, near-side correlations in high multiplicity events**
  - → **Signal grows with event multiplicity**
  - → **Effect is maximal in the $1 < p_T < 3$ GeV/c range**
  - → **Seen in like- and unlike-sign pairs**
  - → **Seen for neutral (γ as proxy for π^0)**
- **Not seen at low multiplicity and generators (PYTHIA, HERWIG,MadGraph)**
- **This is a subtle effect in a complex environment careful work is needed to establish physical origin. The Heavy Ion run will be an additional important test bench.**

First Heavy Ion (Pb-Pb) Collisions at LHC



This is the first observation of such a long-range, near-side feature in two-particle correlation functions in pp or $p\bar{p}$ collisions.

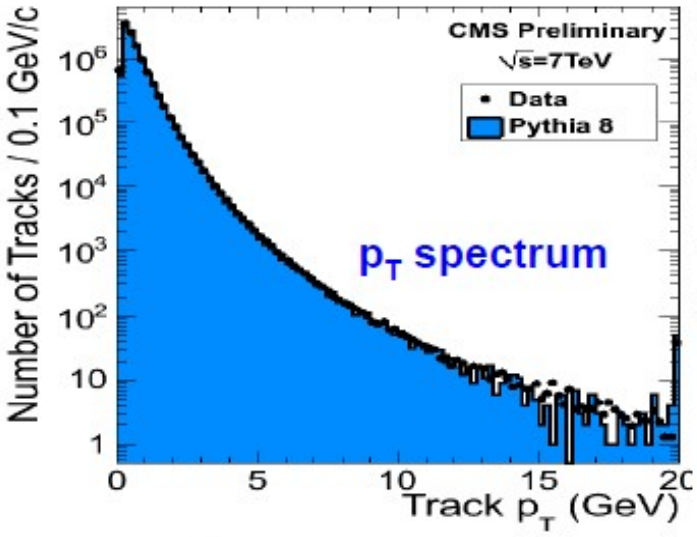
It is a small effect, however, very interesting. Although there are also differences, it resembles a similar feature observed at RHIC that was interpreted as being due to the hot and dense matter formed in relativistic heavy ion collisions

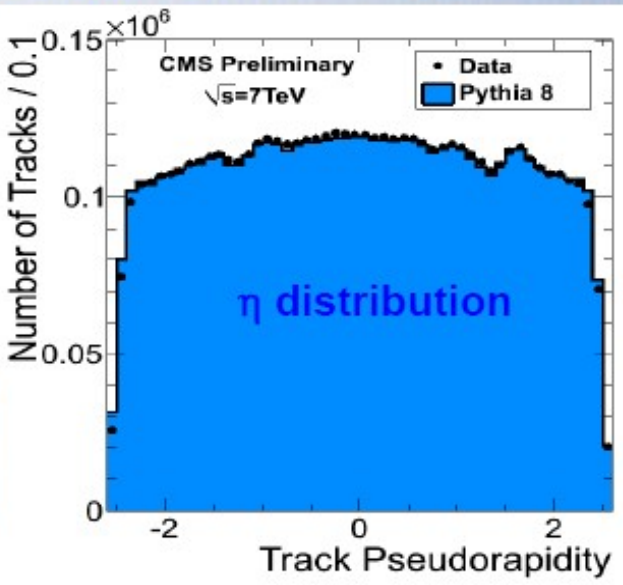


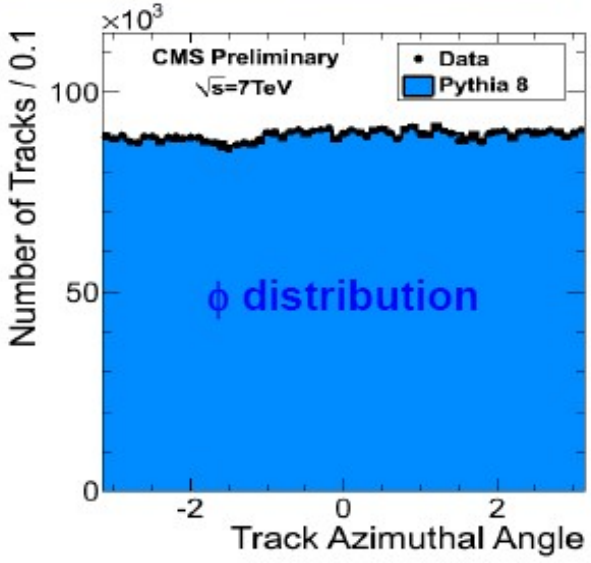
Similar "ridge" in high multiplicity pp
(even similar p_T dependence)

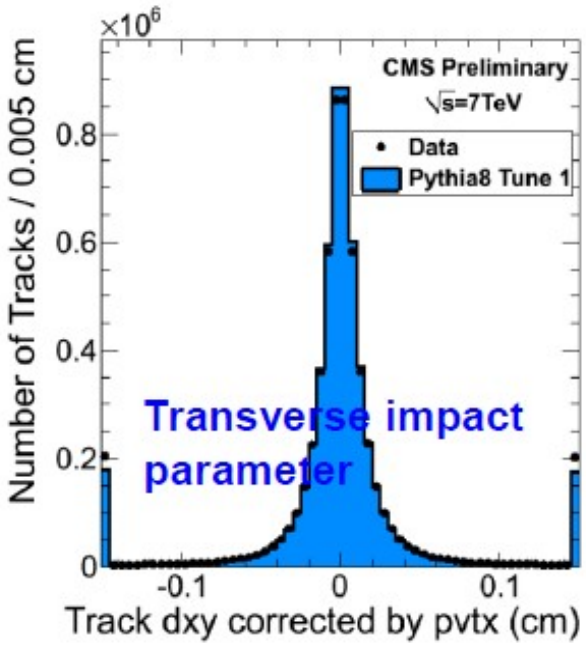
BACKUP SLIDES

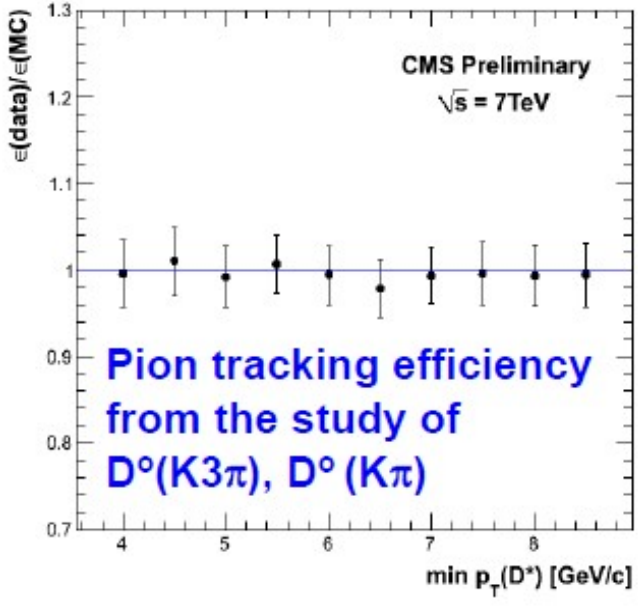
Tracker Performance are well understood

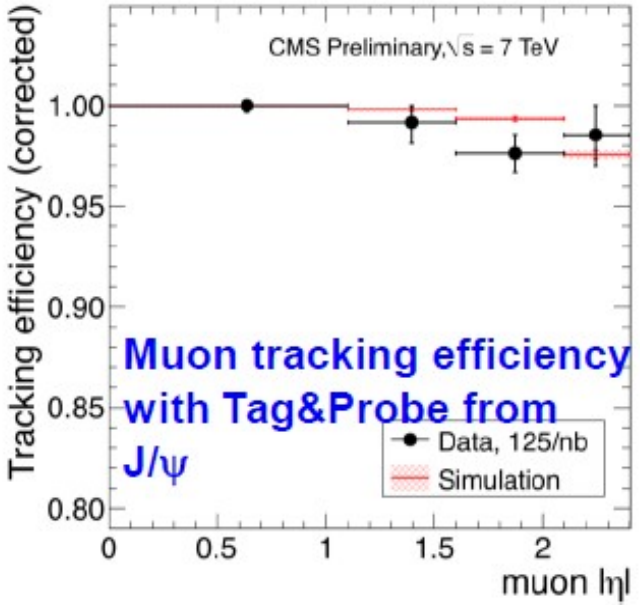






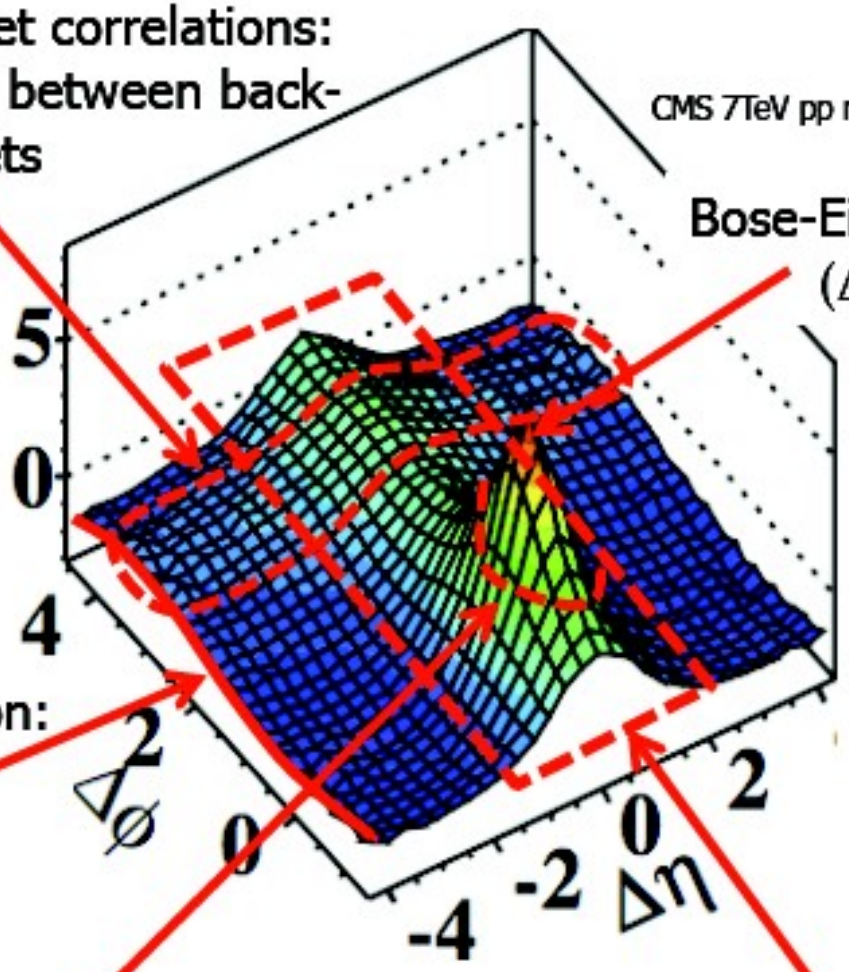






(MinBias) Angular Correlation Function

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



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

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

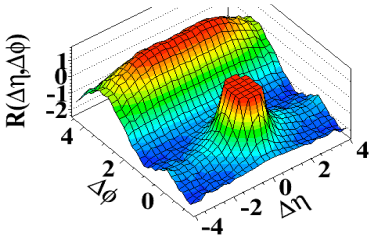
"Near-side" ($\Delta\phi \sim 0$) jet peak:
Correlation of particles within a single jet

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

CERN Seminar September 21 2010

8

Cross-Checks



"The new feature has appeared in our analysis around middle of July in the hottest days of the preparation for ICHEP. We have immediately set-up an independent analysis (control group) and organized a full set of tests and cross-checks to kill the effect." **G. Tonelli**

→ Many data driven cross-checks performed

Analysis Code ← **Bugs ?**

Reconstruction ← **Reconstruction Algorithm + Efficiency + Fakes**

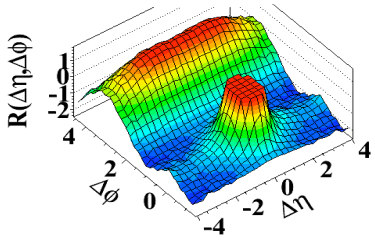
Trigger ← **Trigger Efficiency + Bias**

Detector ← **Detector Noise + Acceptance + Efficiency**

CMS Event ← **Pile-Up + Beam Backgrounds**

Collision ← **Physics**

Cross Checks (1)



Analysis Code

Reconstruction

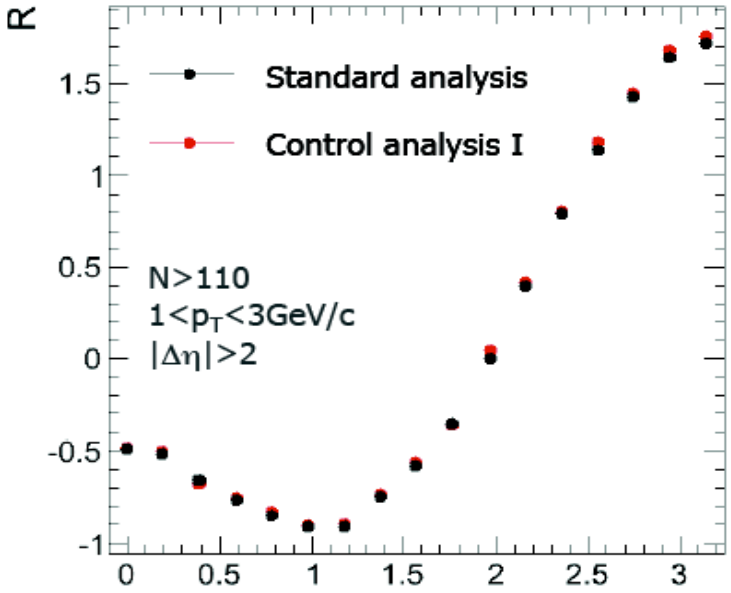
Trigger

Detector

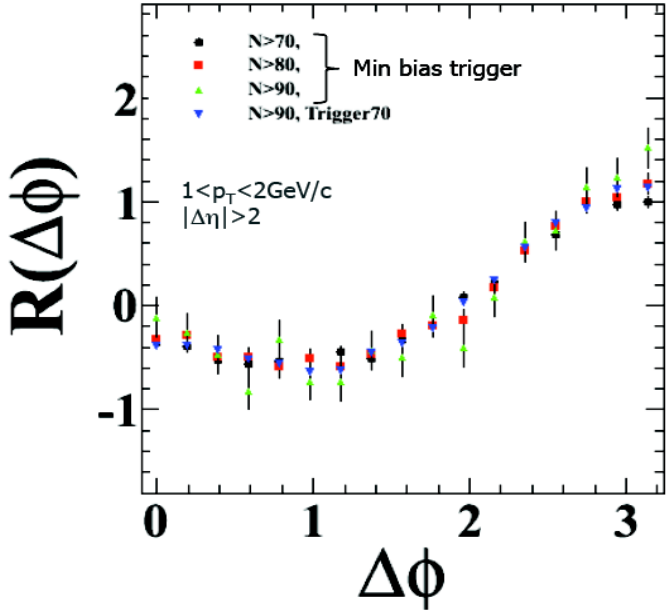
CMS Event

Collision

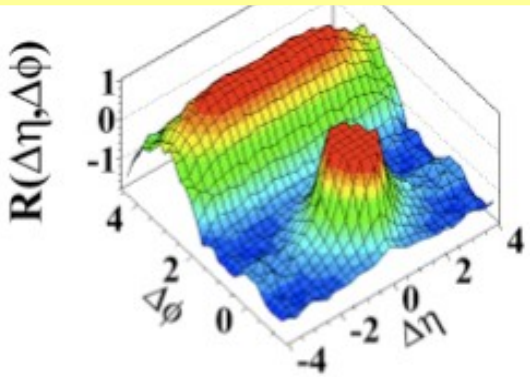
3 Independent Analysis (2 shown)



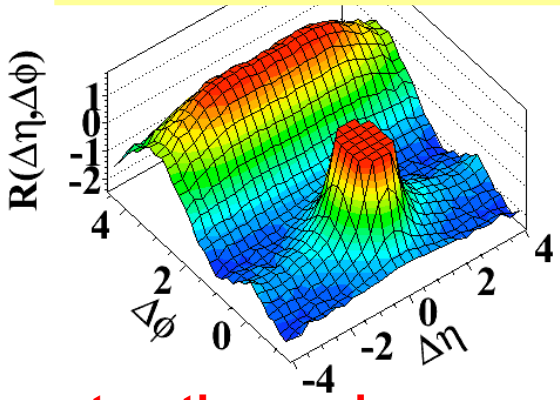
High Multiplicity vs MinBias Trigger



Pixel (Vtx Detector) Tracking

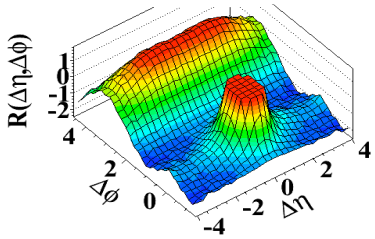


Full CMS Tracking



(Largely) independent reconstruction code

Cross Checks (2)



Analysis Code

Reconstruction

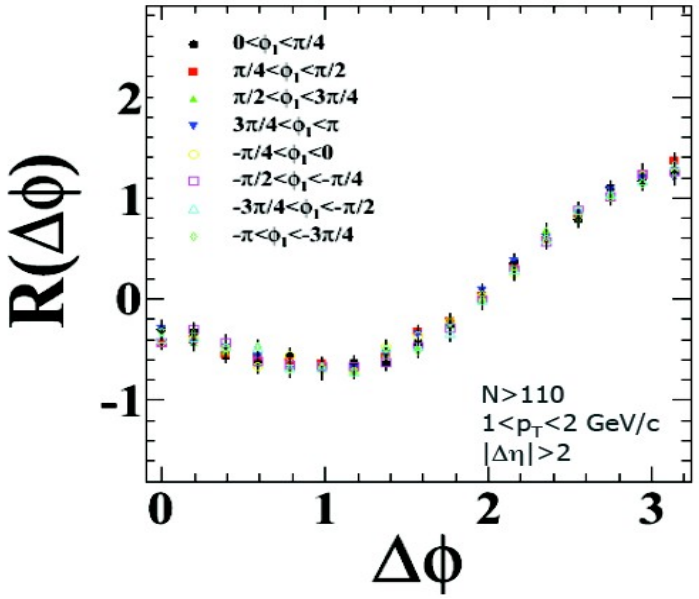
Trigger

Detector

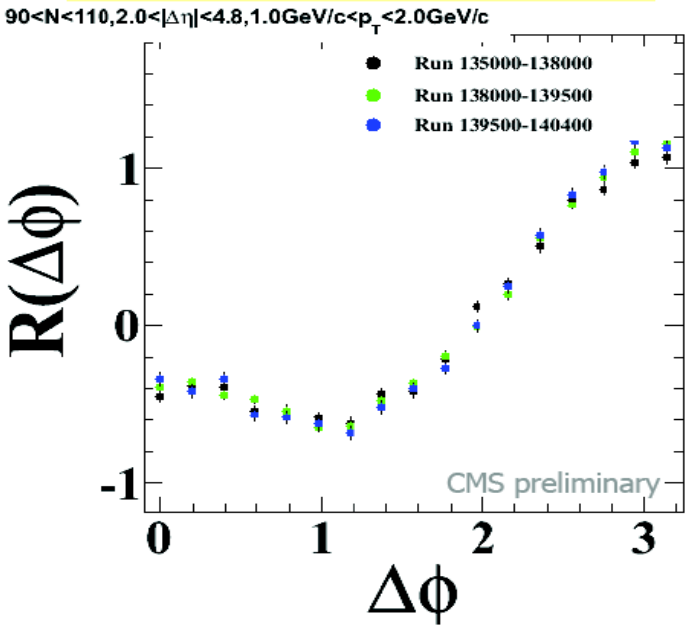
CMS Event

Collision

Ridge is Symmetric in ϕ

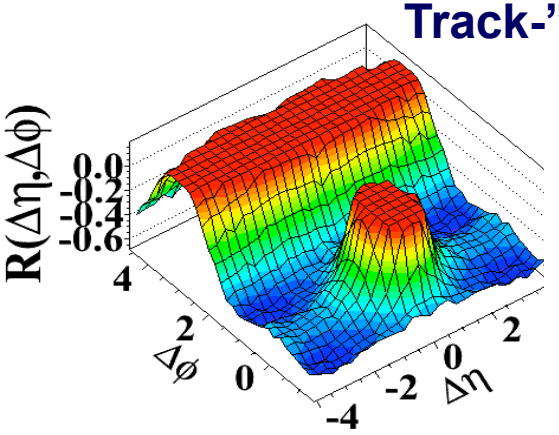


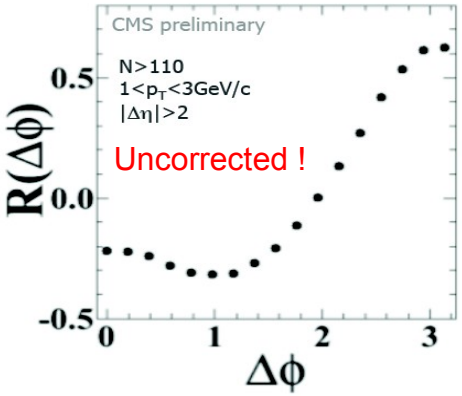
Pile-Up Effect Negligeable



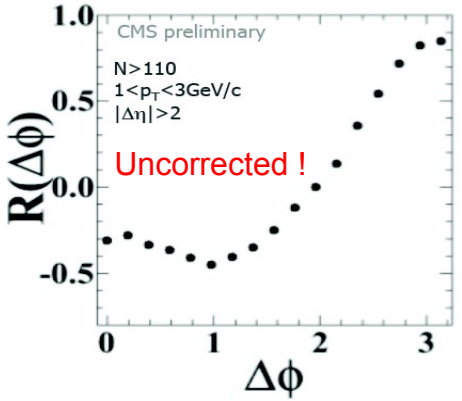
Use ECAL Object (Particle-flow "photons") = π^0 dominated

Track-"Photons"



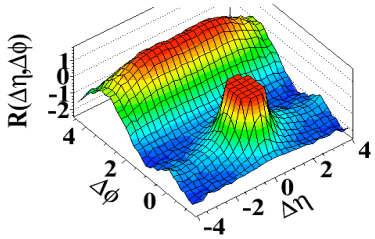


"Photons"-"Photons"



Cross Checks

Analysis Code



Analysis Code

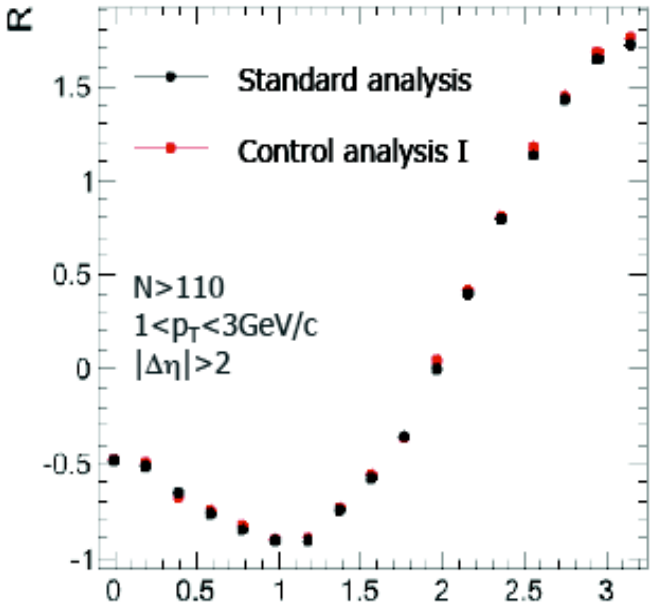
Reconstruction

Trigger

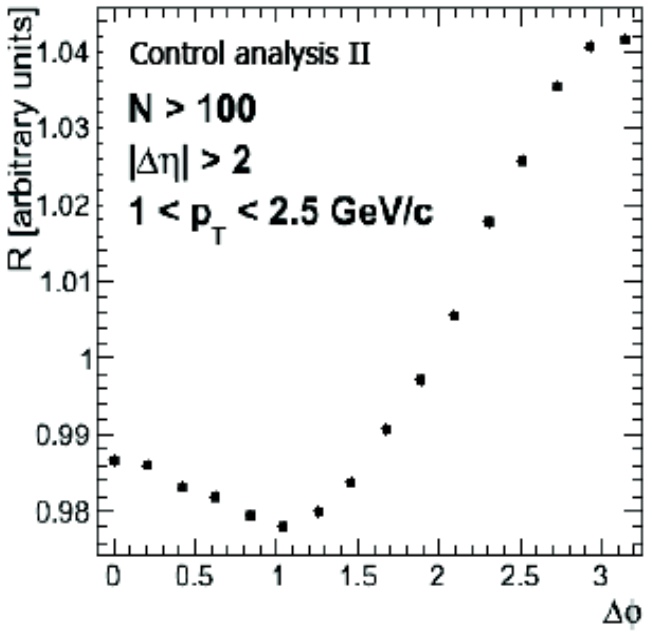
Detector

CMS Event

Collision



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

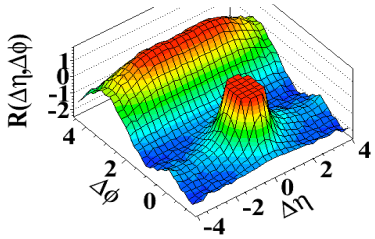


Independent code
Different definition of *R*
Different input file (skim)

Ridge is seen with three independent analysis codes

Cross Checks

Signal and Background



Analysis Code

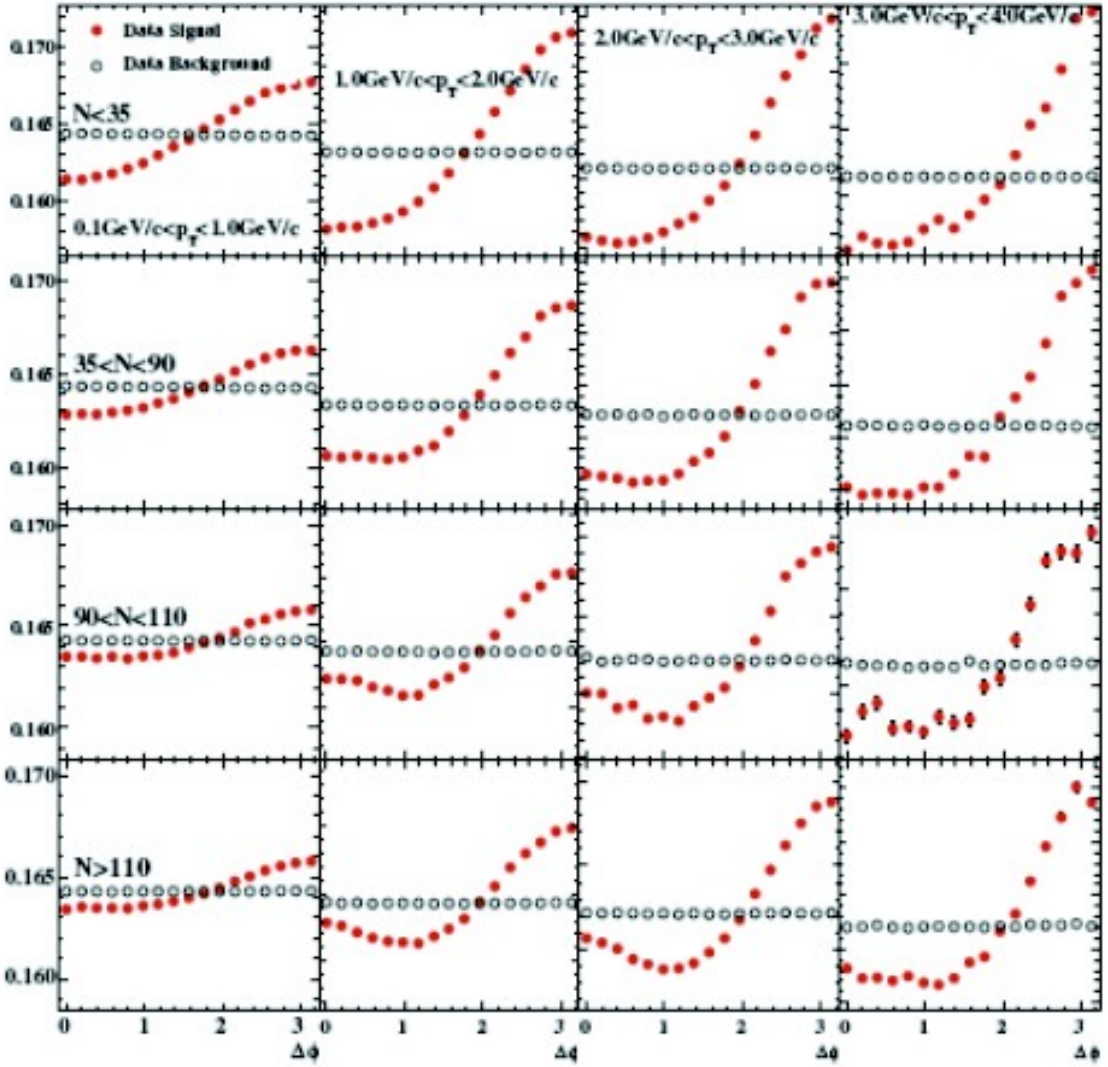
Reconstruction

Trigger

Detector

CMS Event

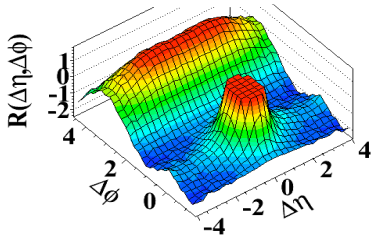
Collision



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

44

Cross Checks



Analysis Code

Reconstruction

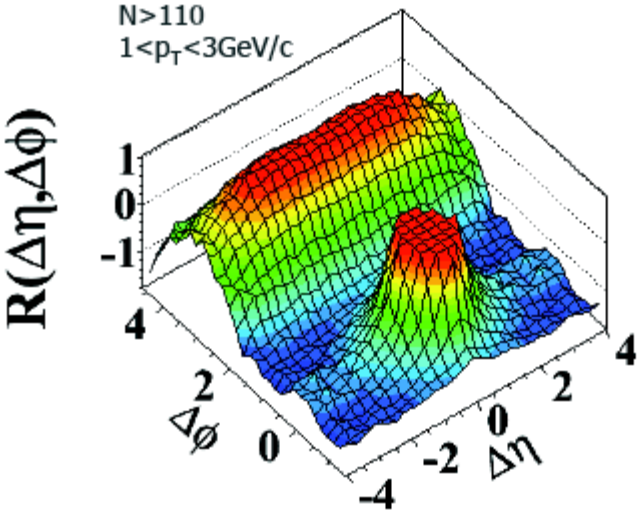
Trigger

Detector

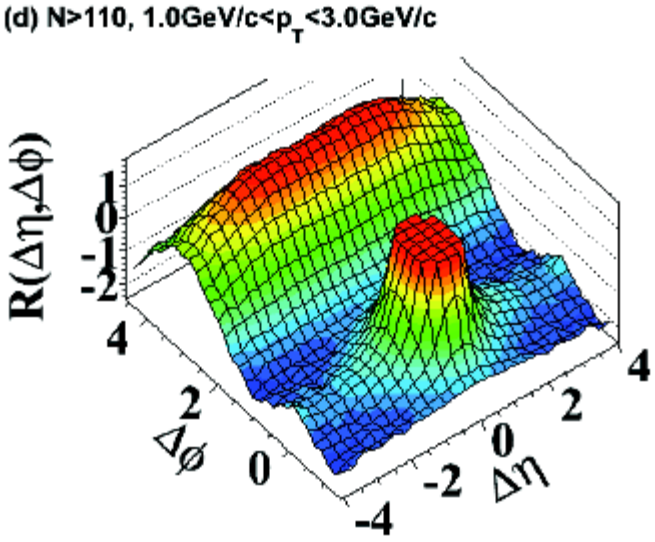
CMS Event

Collision

Reconstruction Code



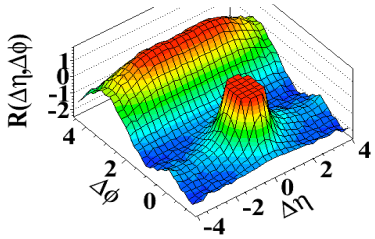
Pixel-only tracks
3 hits in pixel detector



"HighPurity" tracks
Pixel + Silicon Strip tracker

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

Cross Checks



Analysis Code

Reconstruction

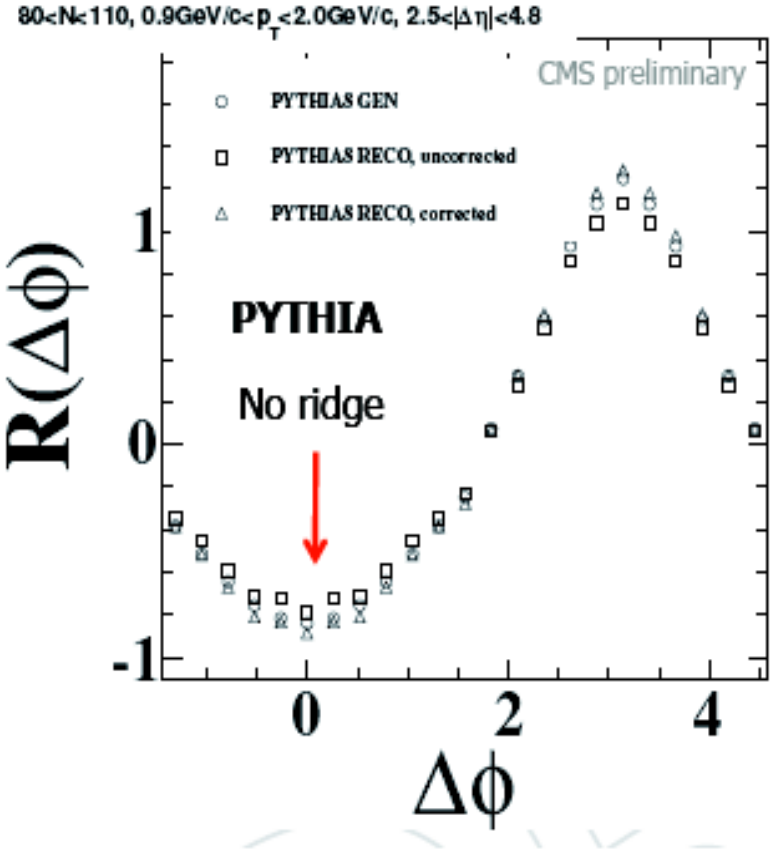
Trigger

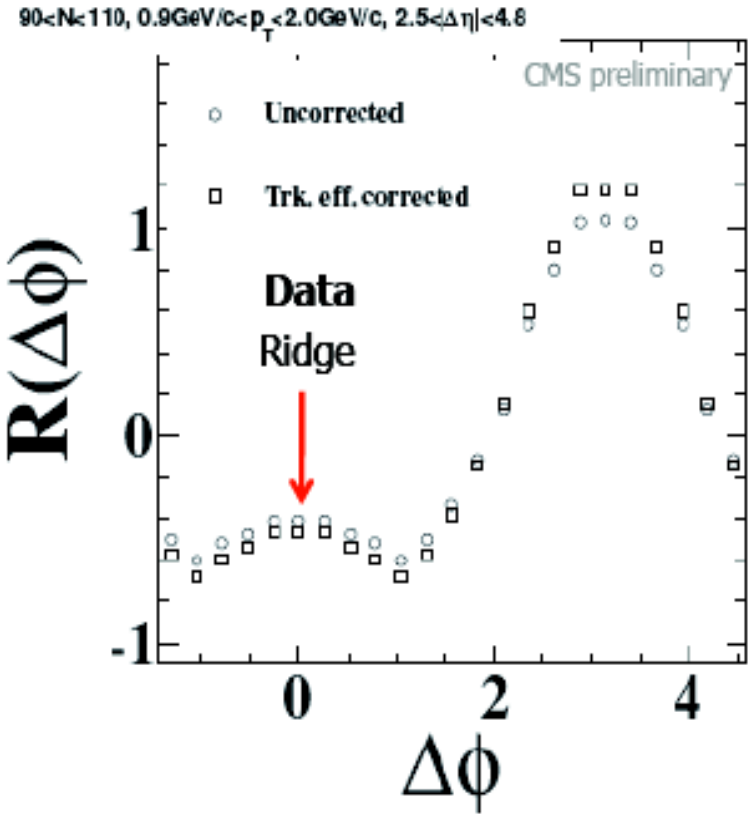
Detector

CMS Event

Collision

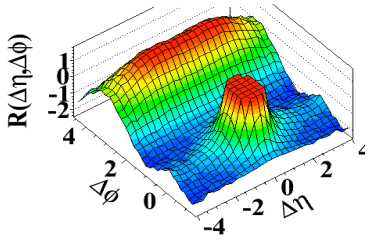
Efficiency Correction





Tracking efficiency correction has small effect on correlation function

Cross Checks



Analysis Code

Reconstruction

Trigger

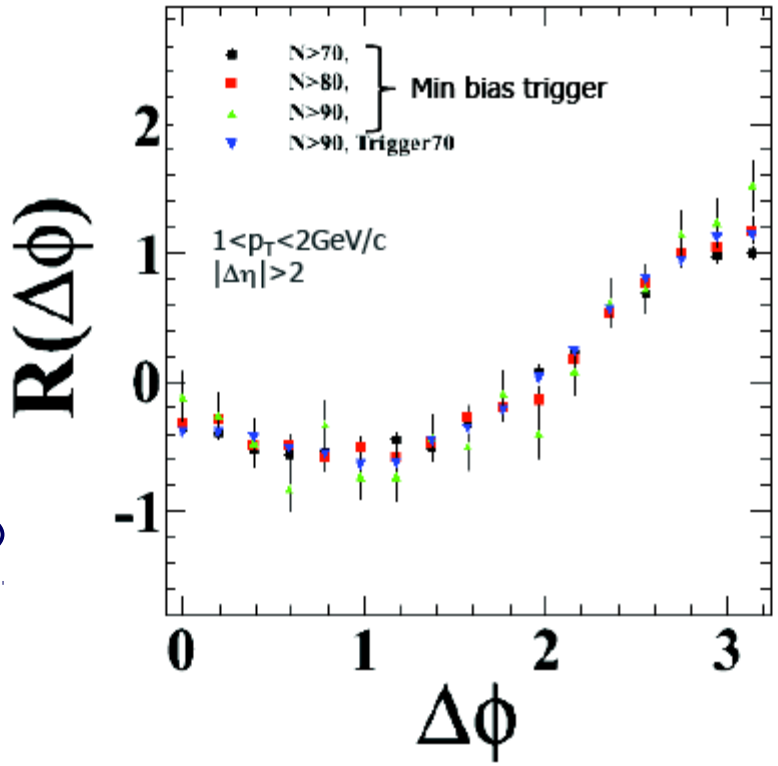
Detector

CMS Event

Collision

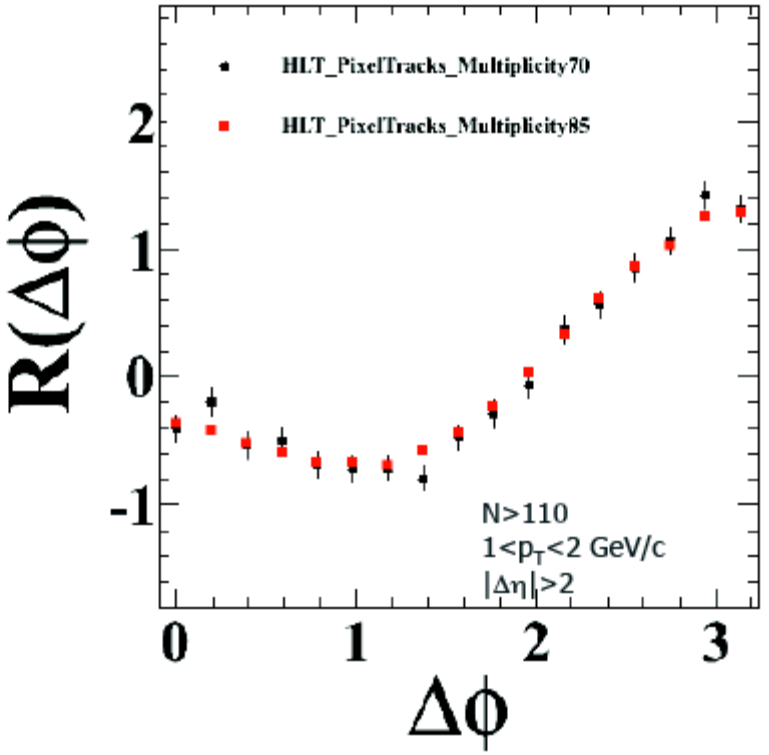
Trigger

Min-bias trigger vs high mult trigger



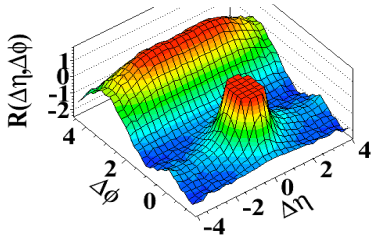
Ridge is seen using
min bias trigger + offline selection

HLT 70 vs HLT 85 for N > 110



No trigger bias seen from
comparison of trigger paths

Cross Checks



Analysis Code

Reconstruction

Trigger

Detector

CMS Event

Collision

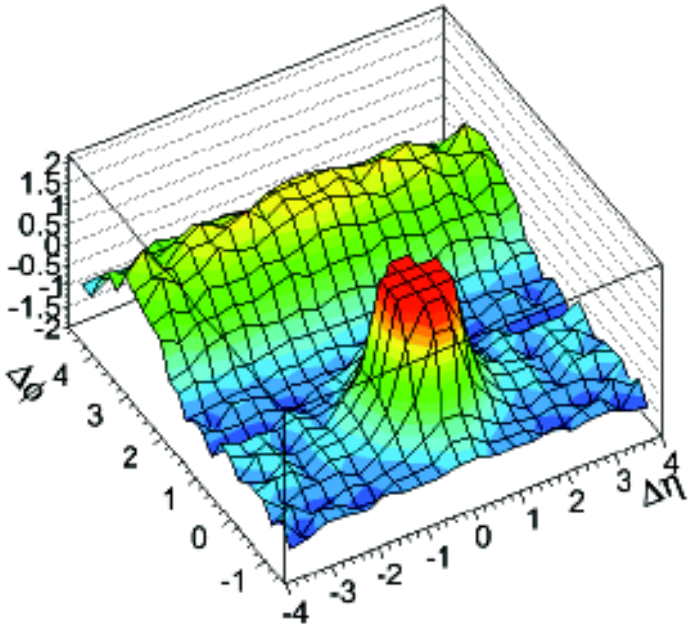
BSC High Multiplicity Trigger

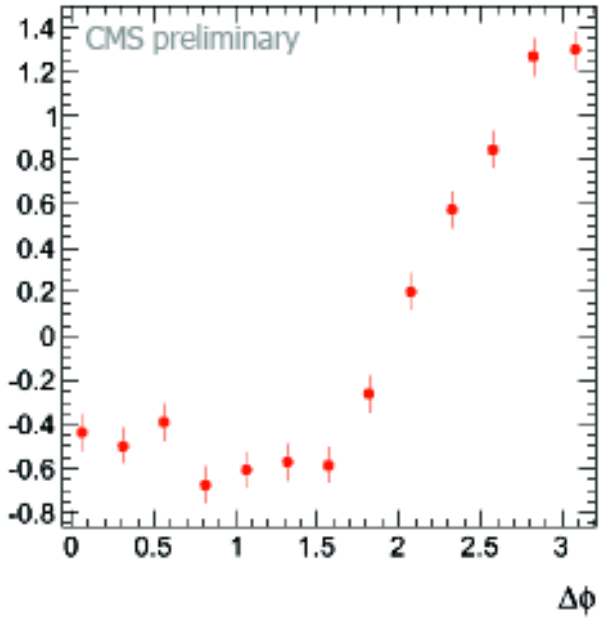
Preliminary results from BSC high multiplicity trigger

N>65

$|\Delta\eta|>2.0$

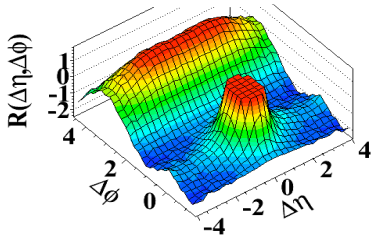
$1.0\text{GeV/c}<p_T<3.0\text{GeV/c}$





Agreement with standard results within statistical uncertainty

Cross Checks



Analysis Code

Reconstruction

Trigger

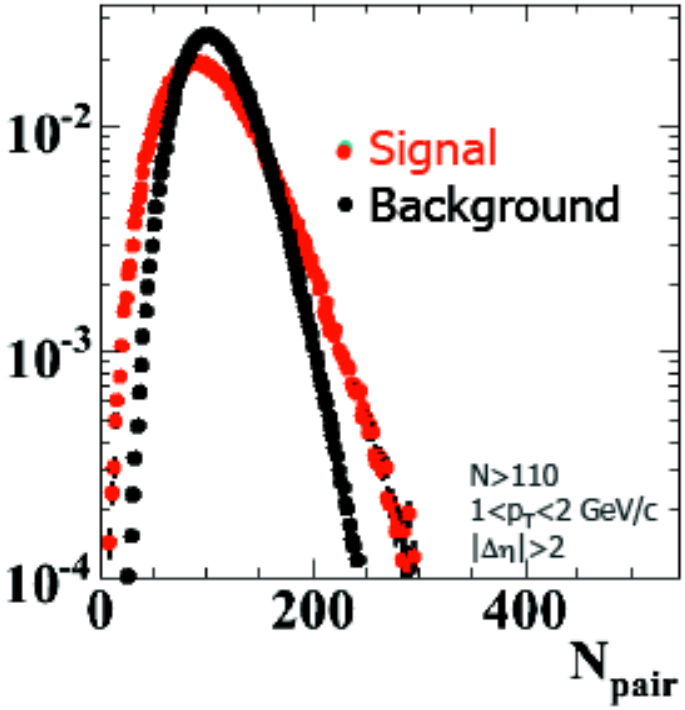
Detector

CMS Event

Collision

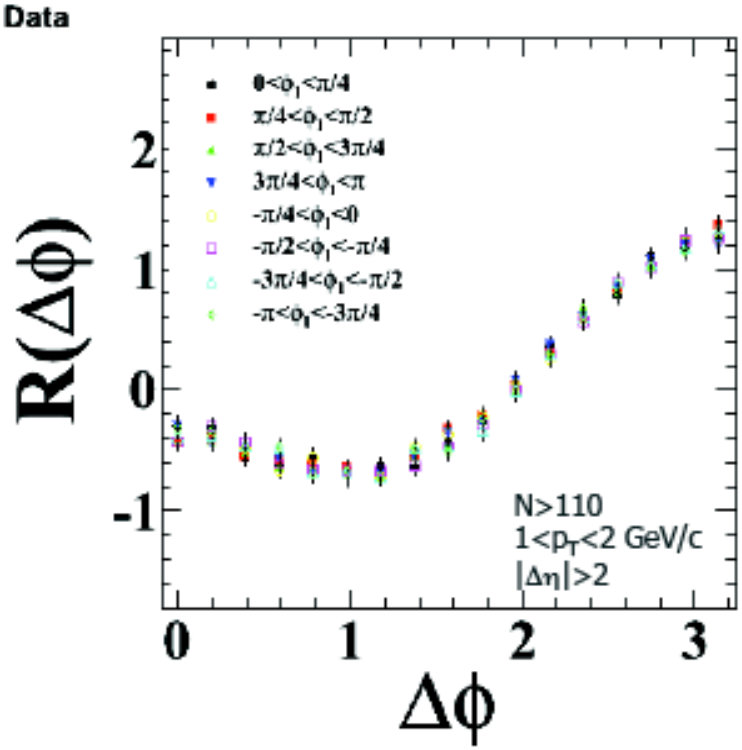
Detector

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



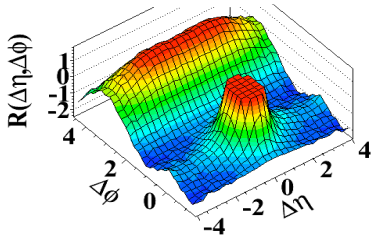
Ridge is not caused by rare events with large # of pairs

Constrain one track to one ϕ octant



Ridge is ϕ symmetric

Cross Checks



Analysis Code

Reconstruction

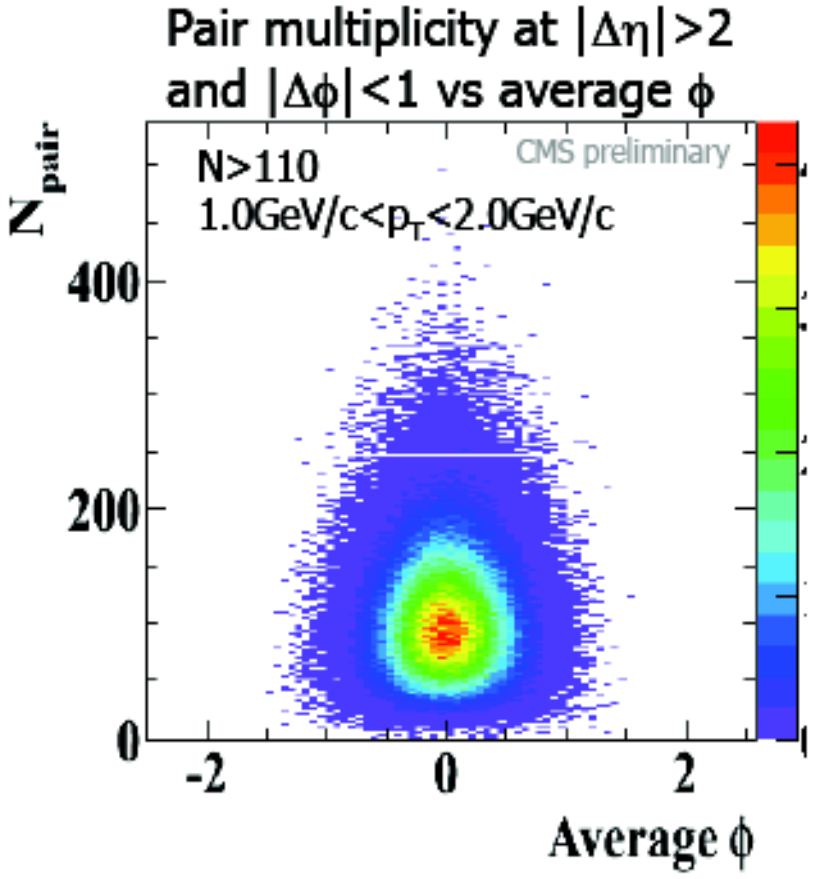
Trigger

Detector

CMS Event

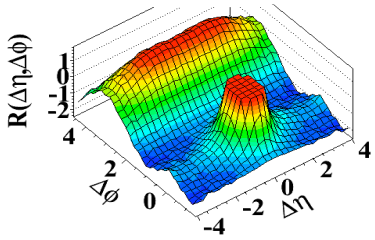
Collision

ϕ Symmetry



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

Cross Checks



Analysis Code

Reconstruction

Trigger

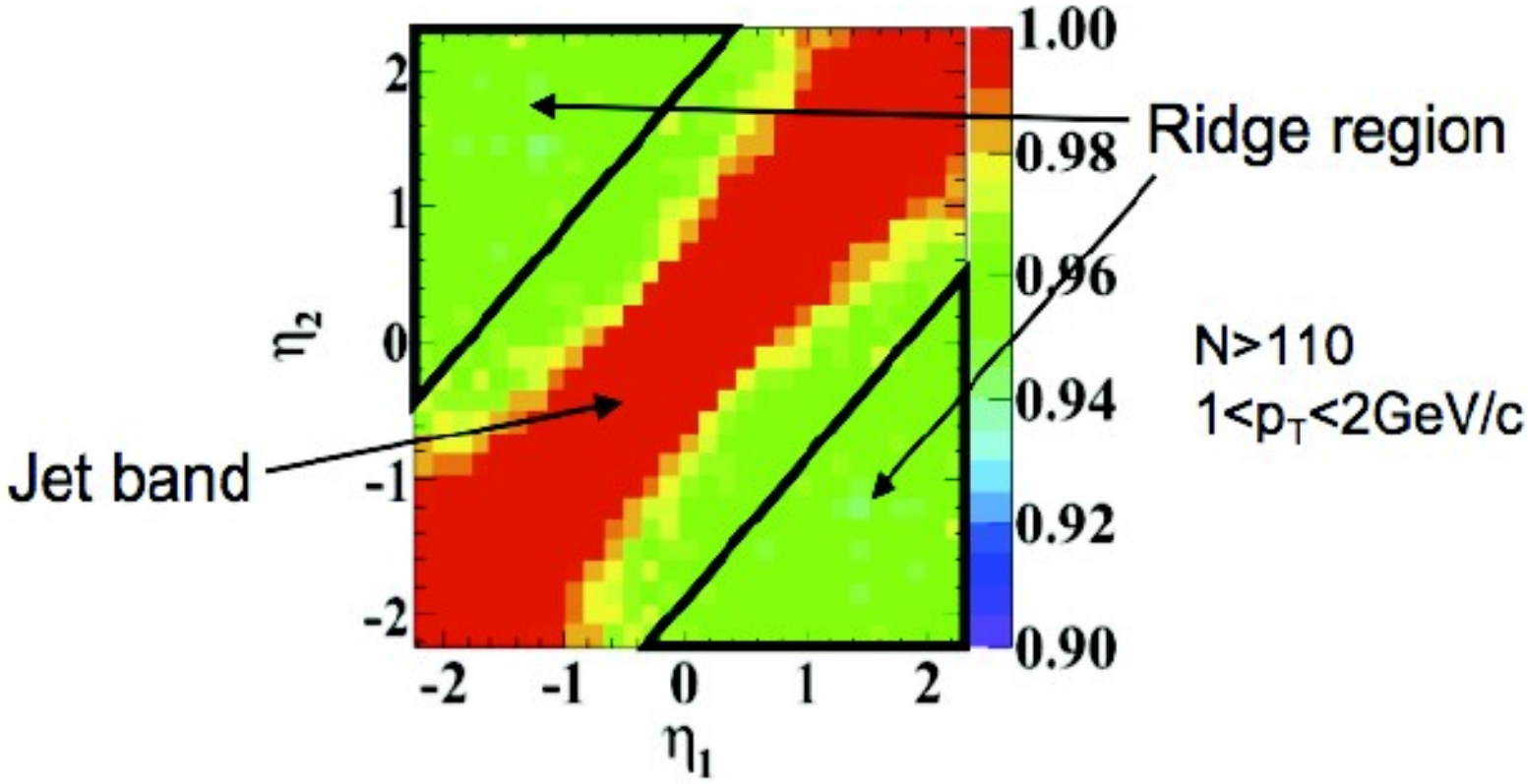
Detector

CMS Event

Collision

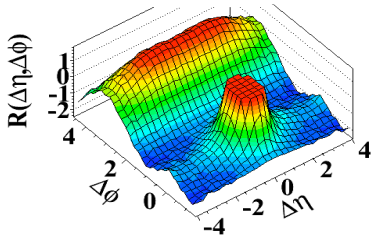
Detector

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



Ridge region shows no structure in η_1 vs η_2

Cross Checks



Analysis Code

Reconstruction

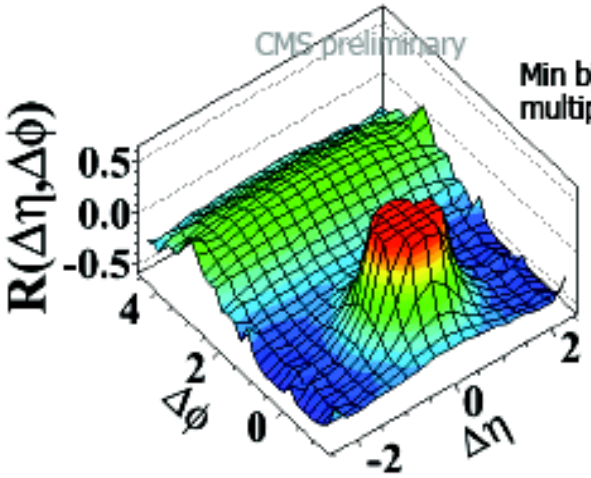
Trigger

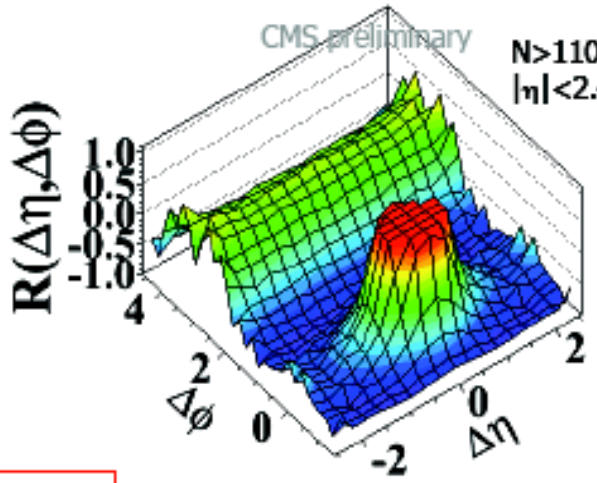
Detector

CMS Event

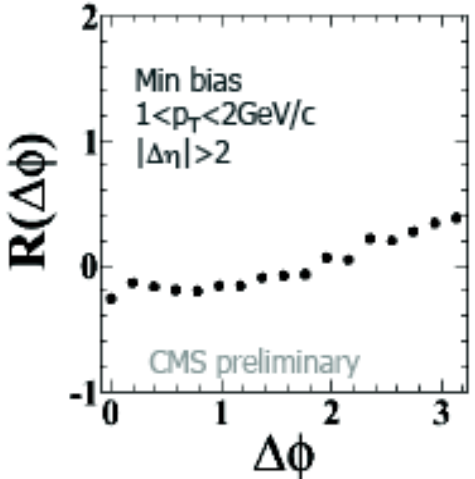
Collision

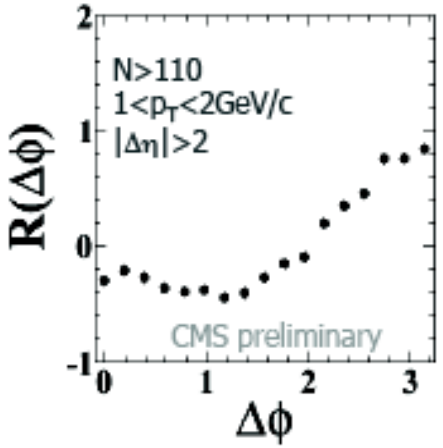
Acceptance Variation





$|\eta| < 1.2$

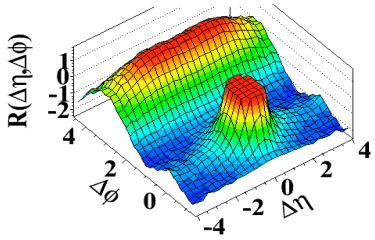




Ridge also seen in reduced acceptance
(but with larger statistical uncertainty)

Cross Checks

Event Backgrounds



Analysis Code

Reconstruction

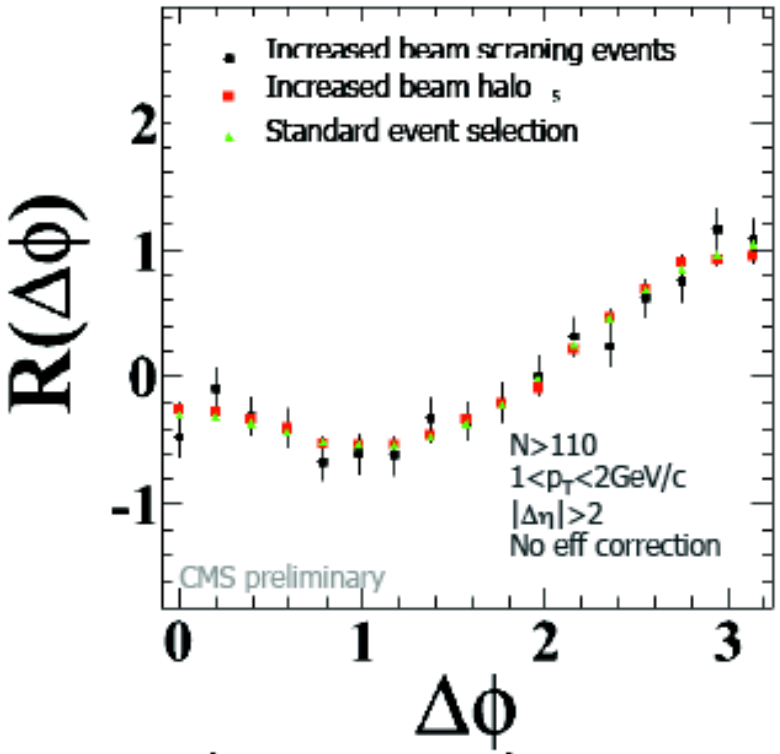
Trigger

Detector

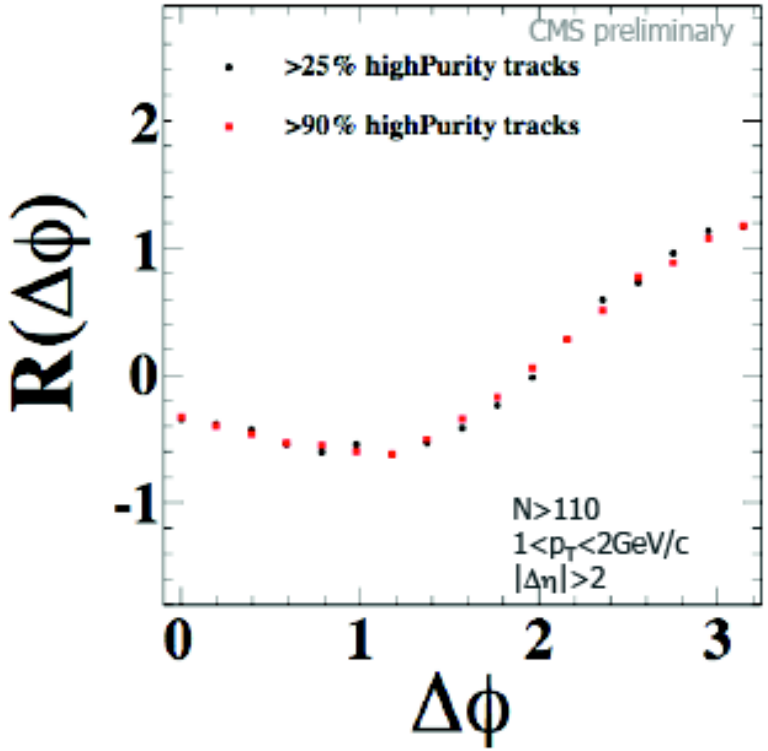
CMS Event

Collision

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



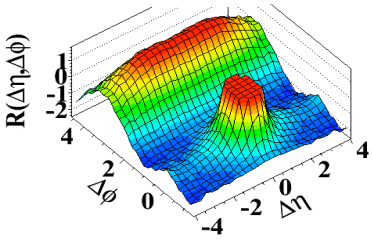
Reject beam background by veto on fraction of low quality tracks



Ridge region shows no sensitivity to beam background

Note: Analysis is done on HighPurity tracks

Cross Checks



Analysis Code

Reconstruction

Trigger

Detector

CMS Event

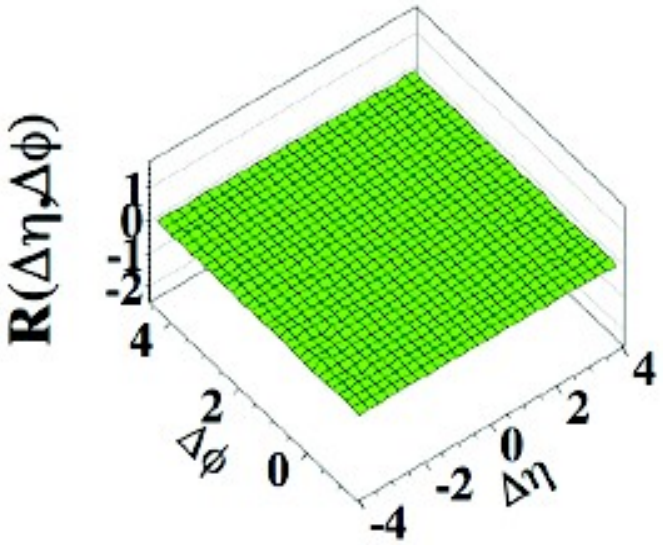
Collision

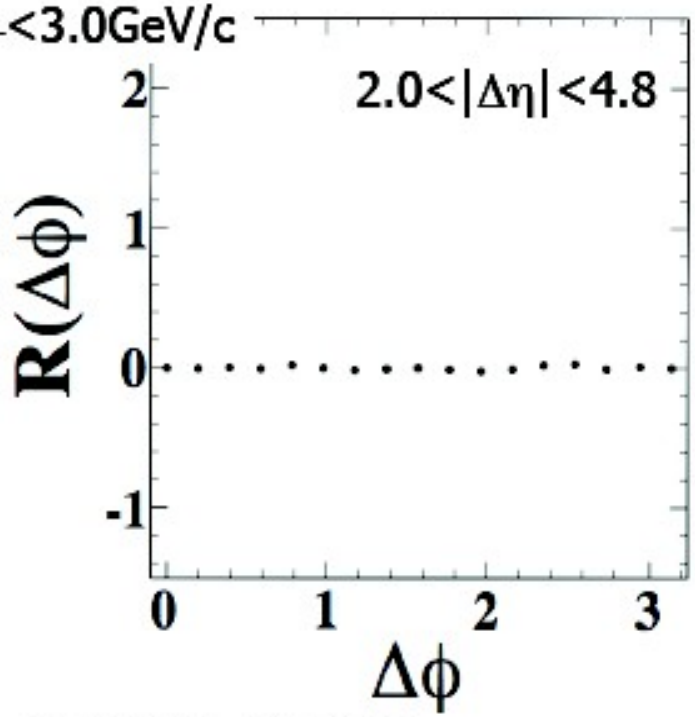
Event Backgrounds

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

N>110

1.0GeV/c<p_T<3.0GeV/c

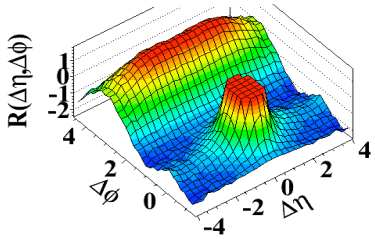




No background or noise effects seen in cross-collision correlations

Cross Checks

Event Pileup



Analysis Code

Reconstruction

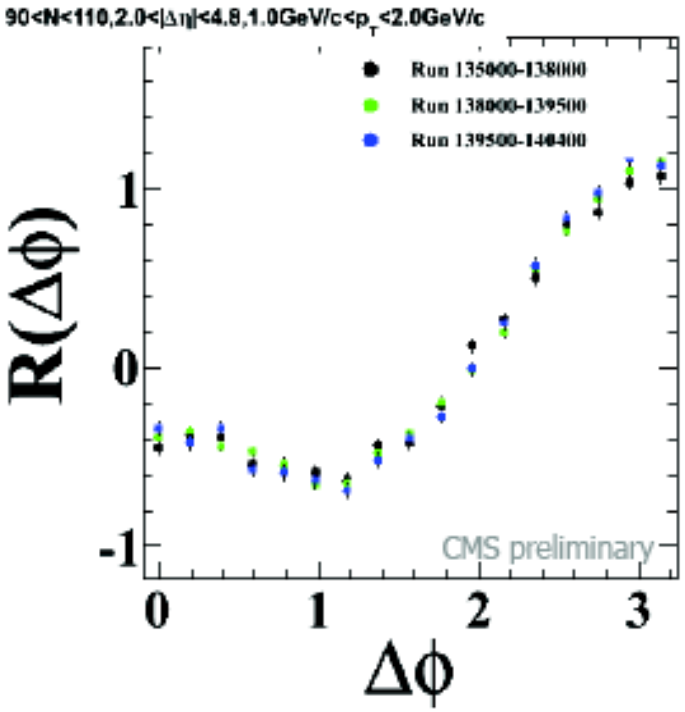
Trigger

Detector

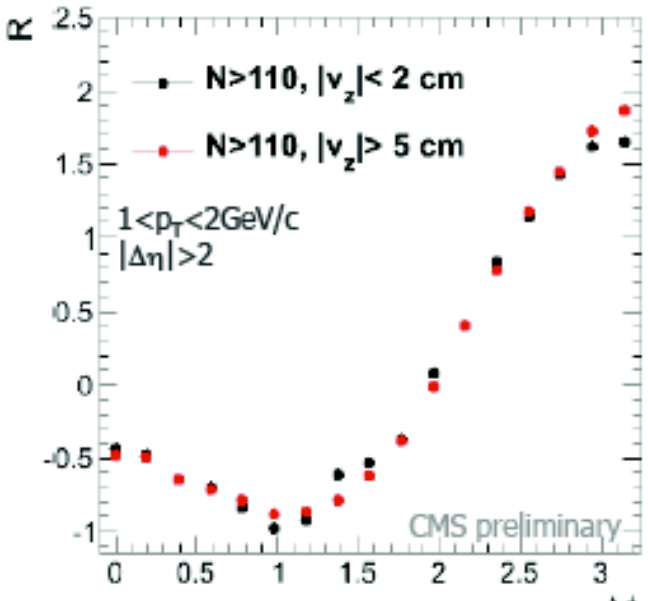
CMS Event

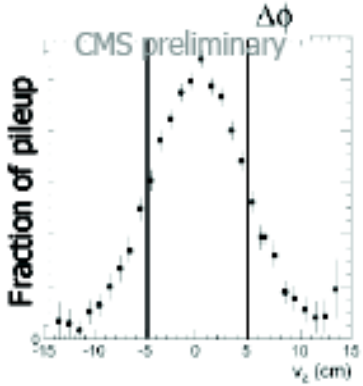
Collision

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



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

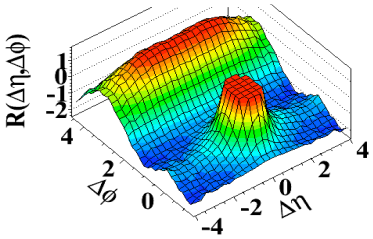




Change in pileup fraction by factor 2-4
has almost no effect on ridge signal

Cross Checks

Event Pileup



Analysis Code

Reconstruction

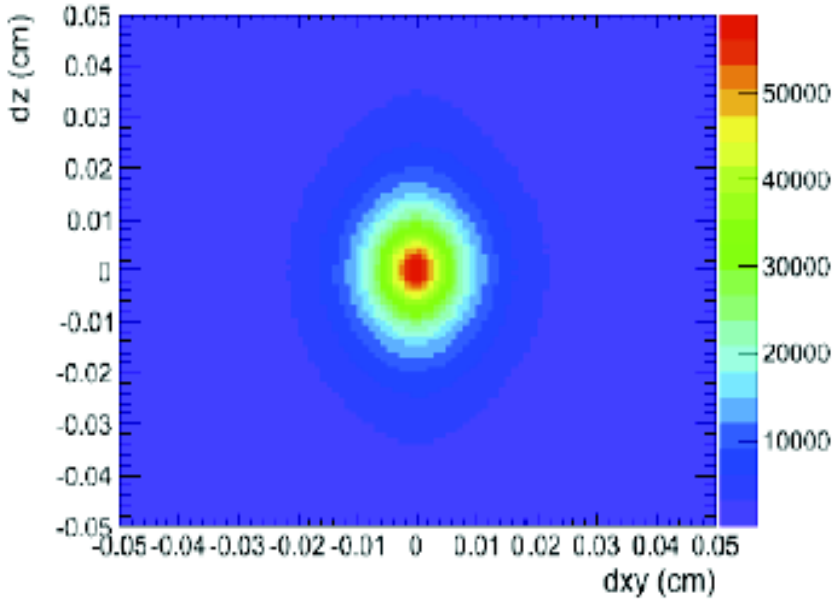
Trigger

Detector

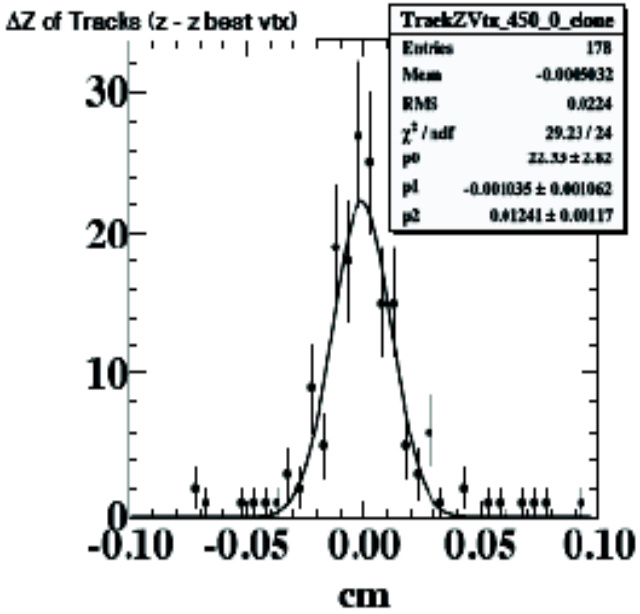
CMS Event

Collision

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



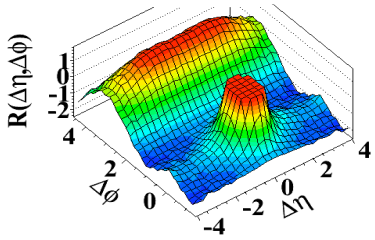
Single-event track dz distribution



Pileup effects are suppressed due to excellent resolution

Track counting done with σ_{dz}, σ_{dxy} of O(100μm)

Cross Checks



Analysis Code

Reconstruction

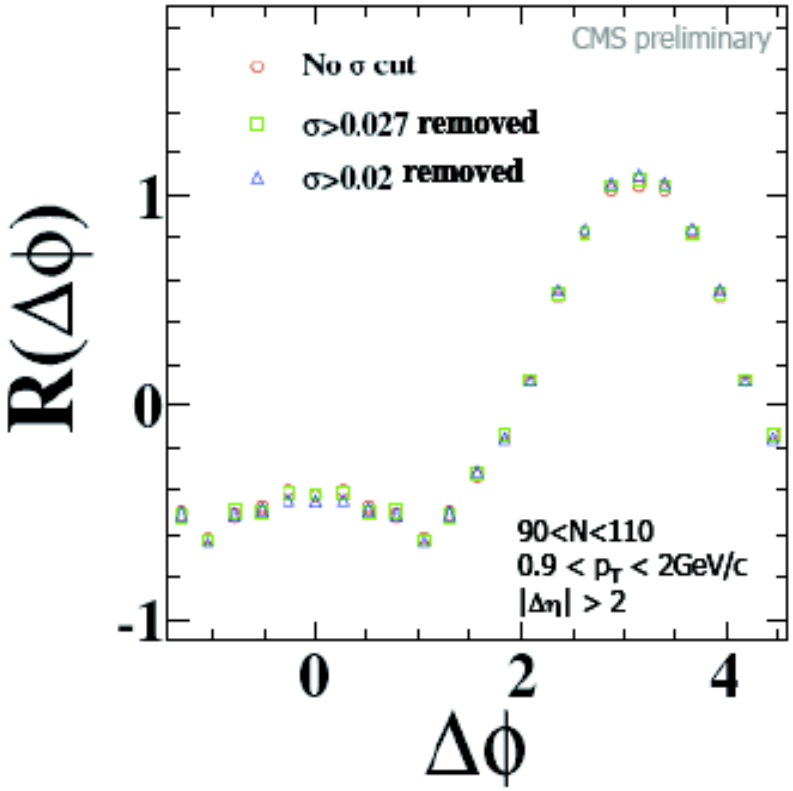
Trigger

Detector

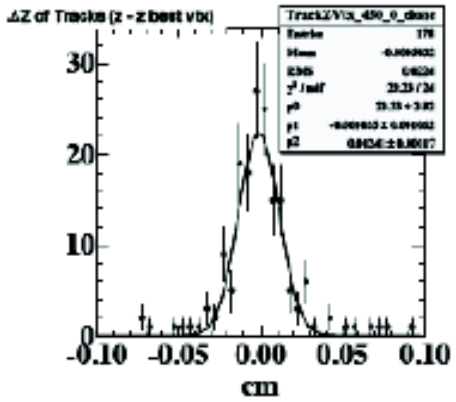
CMS Event

Collision

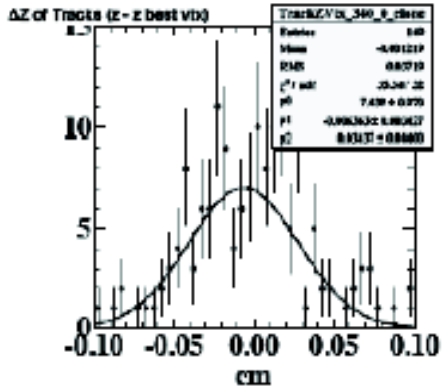
Rejection of "Wide Vertices"



Keep

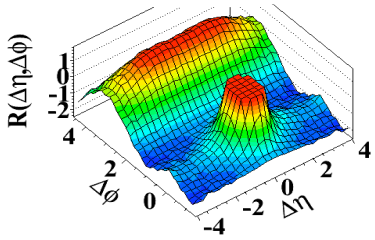


Remove



Removing events with "suspicious" vertex distributions does not change result

Cross Checks



Analysis Code

Reconstruction

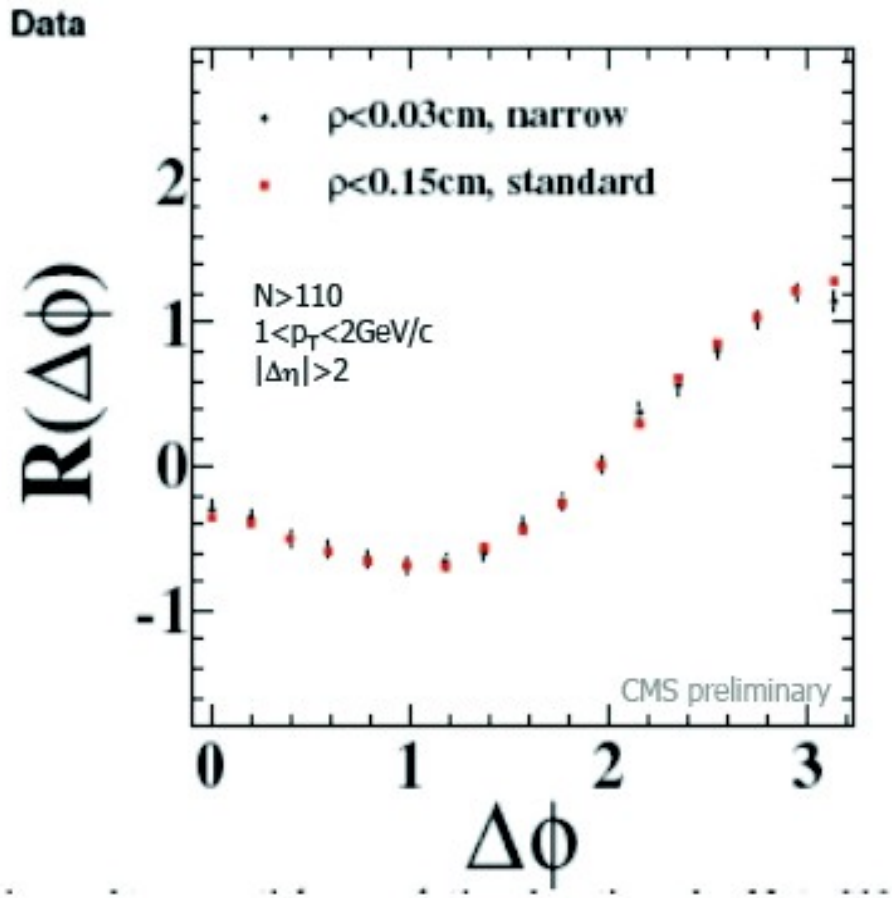
Trigger

Detector

CMS Event

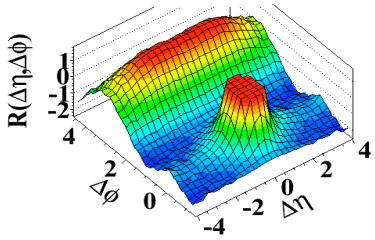
Collision

Select Beamspot "Core"



No dependence on radial distance from center of beam

Cross Checks



Analysis Code

Reconstruction

Trigger

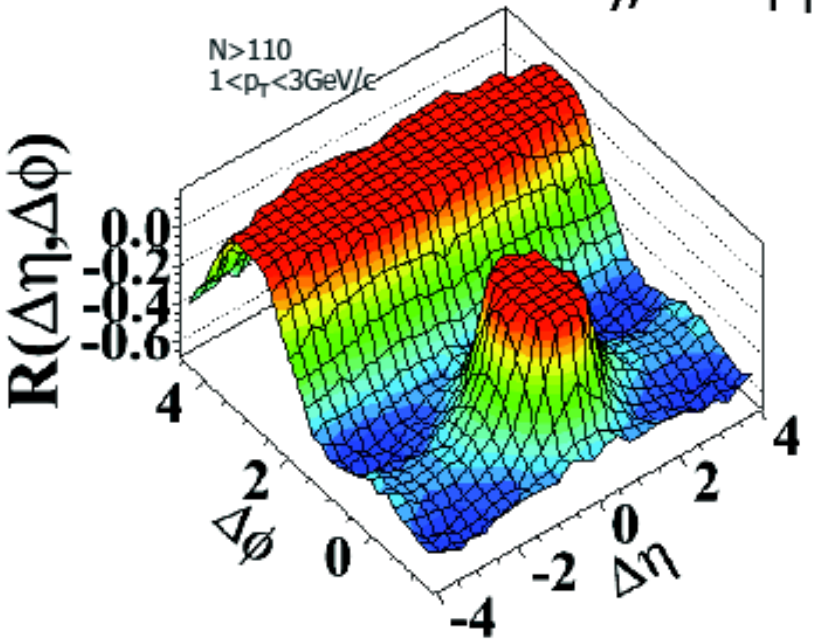
Detector

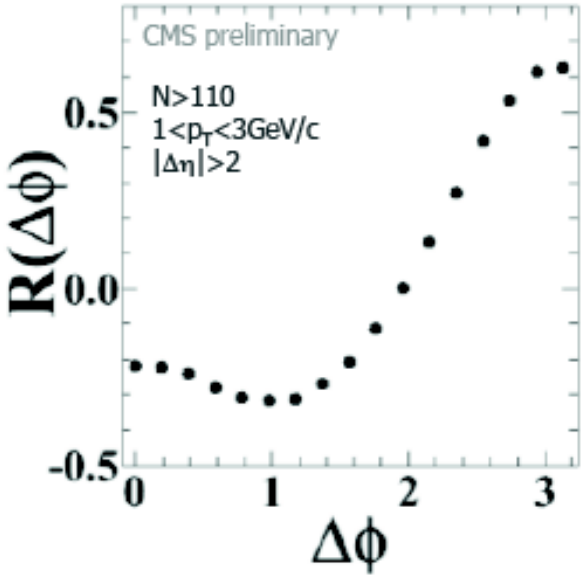
CMS Event

Collision

Final Test: ECAL photons

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

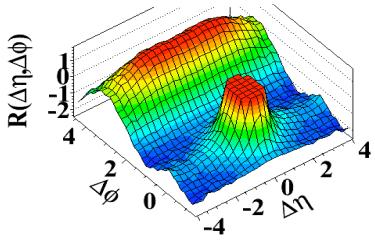




Track-photon correlations

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

Cross Checks



Analysis Code

Reconstruction

Trigger

Detector

CMS Event

Collision

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Mostly single photons from π^0's

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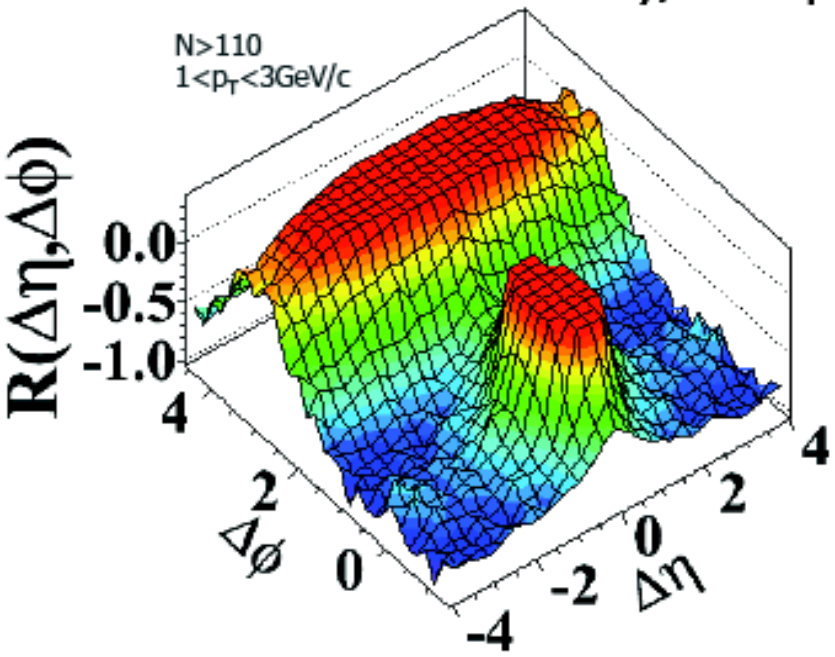
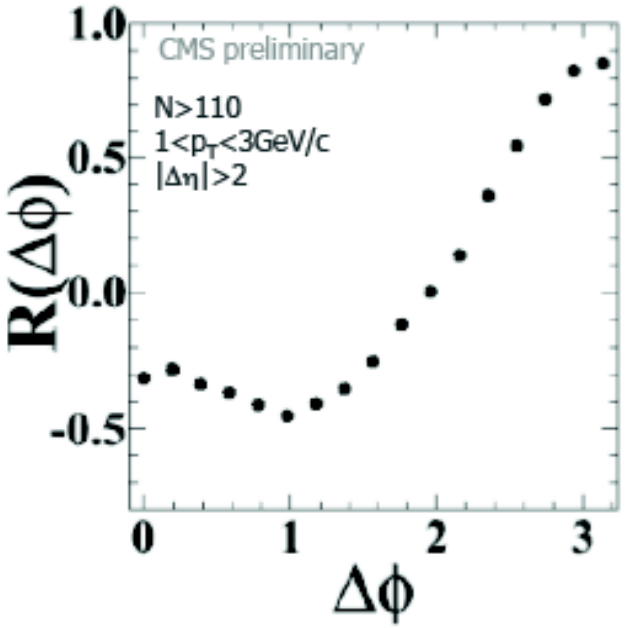


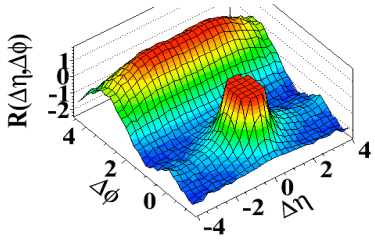


Photon-photon correlations

Qualitative confirmation

Independent detector, independent reconstruction

Cross Checks



Analysis Code

Reconstruction

Trigger

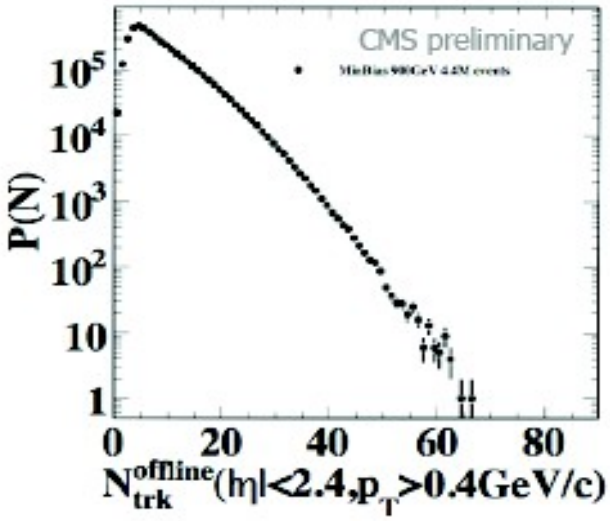
Detector

CMS Event

Collision

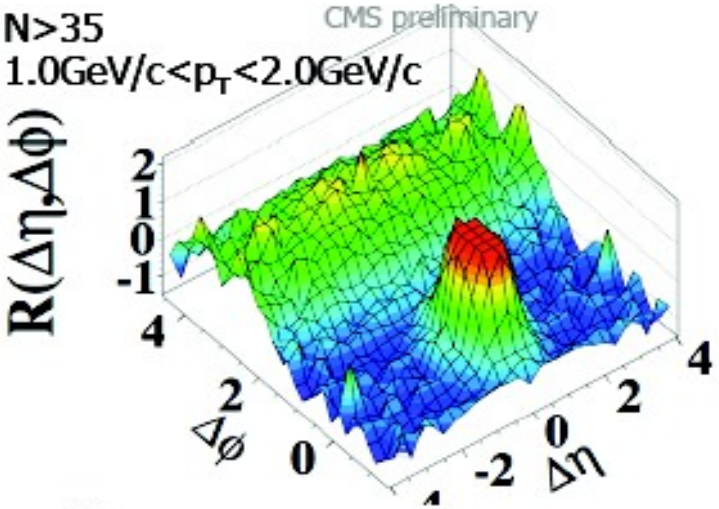
Preliminary 900 GeV Analysis

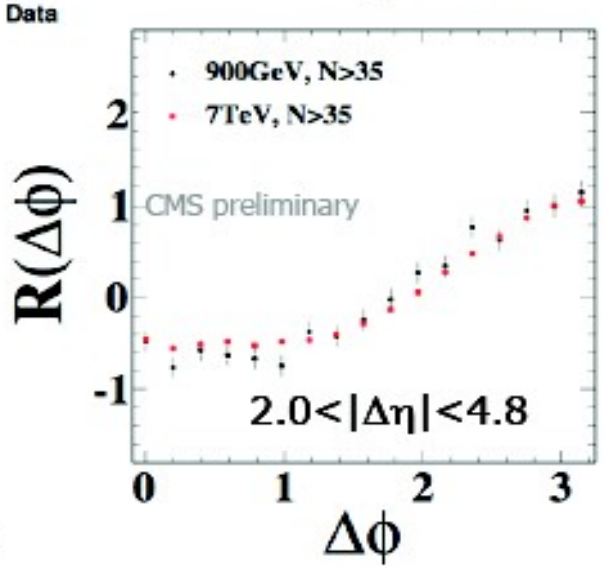
Run 134721, 134725



Limited statistics for high multiplicity events in 900GeV

Two energies agree within large uncertainties

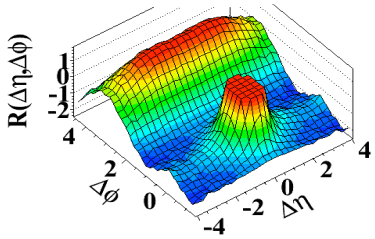




CERN Seminar Se

40

Cross Checks



Analysis Code

Reconstruction

Trigger

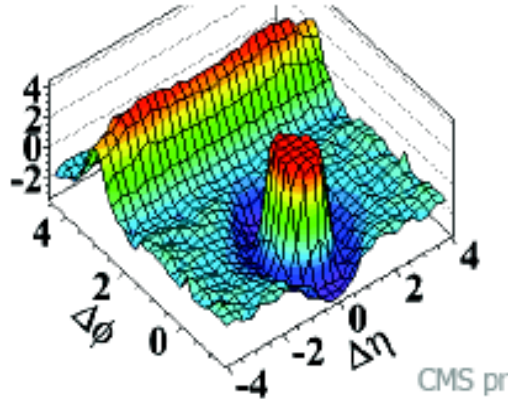
Detector

CMS Event

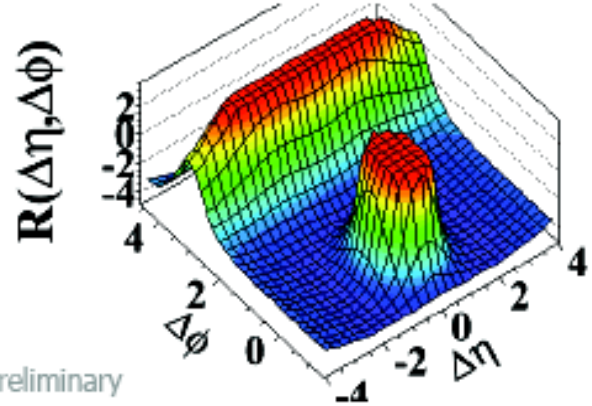
Collision

Other pp Event Generators

PYTHIA D6T MinBias, N>70



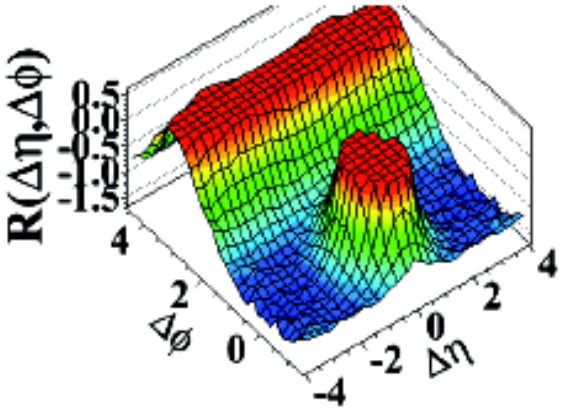
PYTHIA D6T, Dijet 80-120GeV



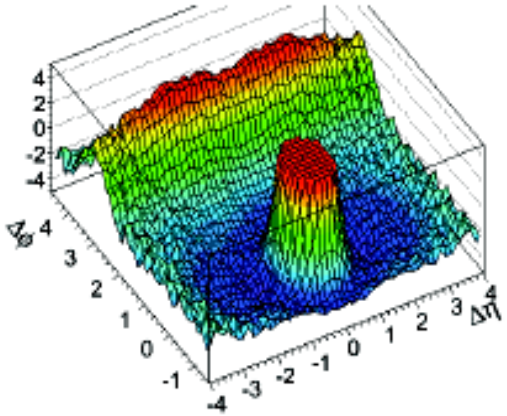
CMS preliminary

$1<p_T<3$GeV/c

HERWIG++, N>110

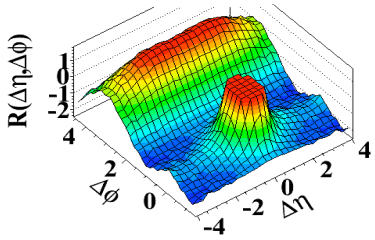


Madgraph, Dijet 100-250GeV, N>90



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

Cross Checks



Analysis Code

Reconstruction

Trigger

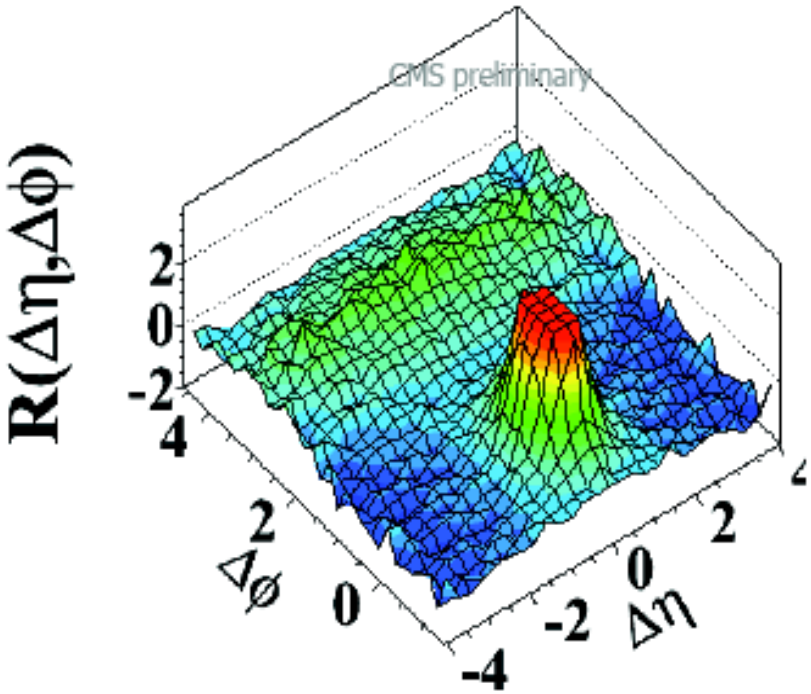
Detector

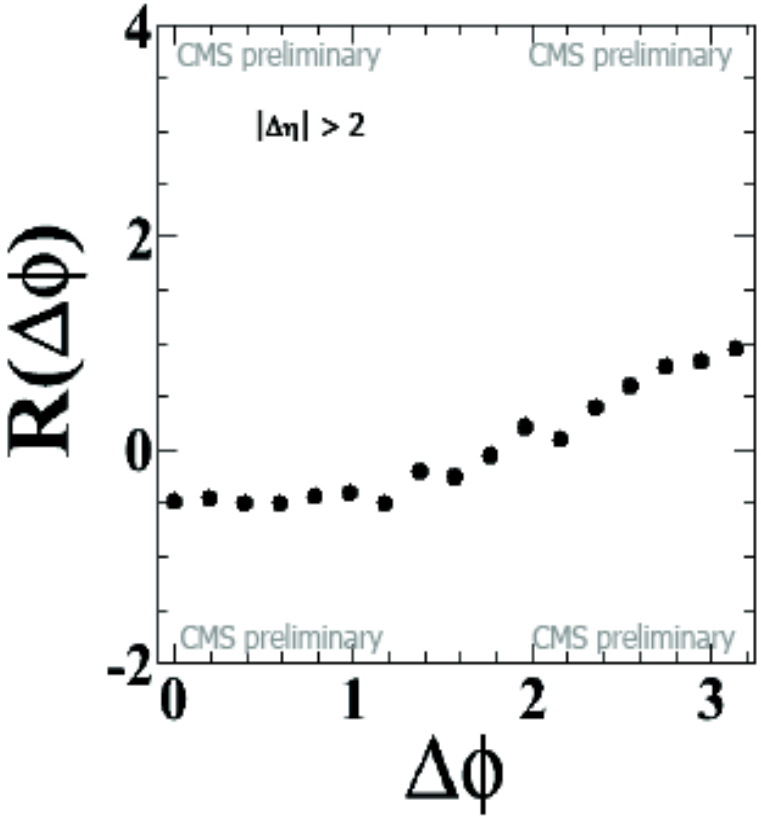
CMS Event

Collision

(Multi-) Jet Events

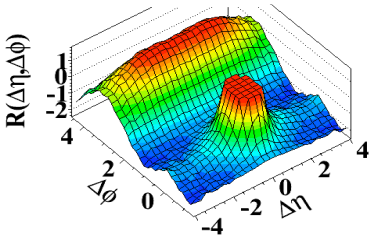
$N_{jet}>=4$, $N_{trk}<50$, $1<p_T<2$GeV/c





More work needed to explore connection to jet correlations

Cross Checks



Analysis Code

Reconstruction

Trigger

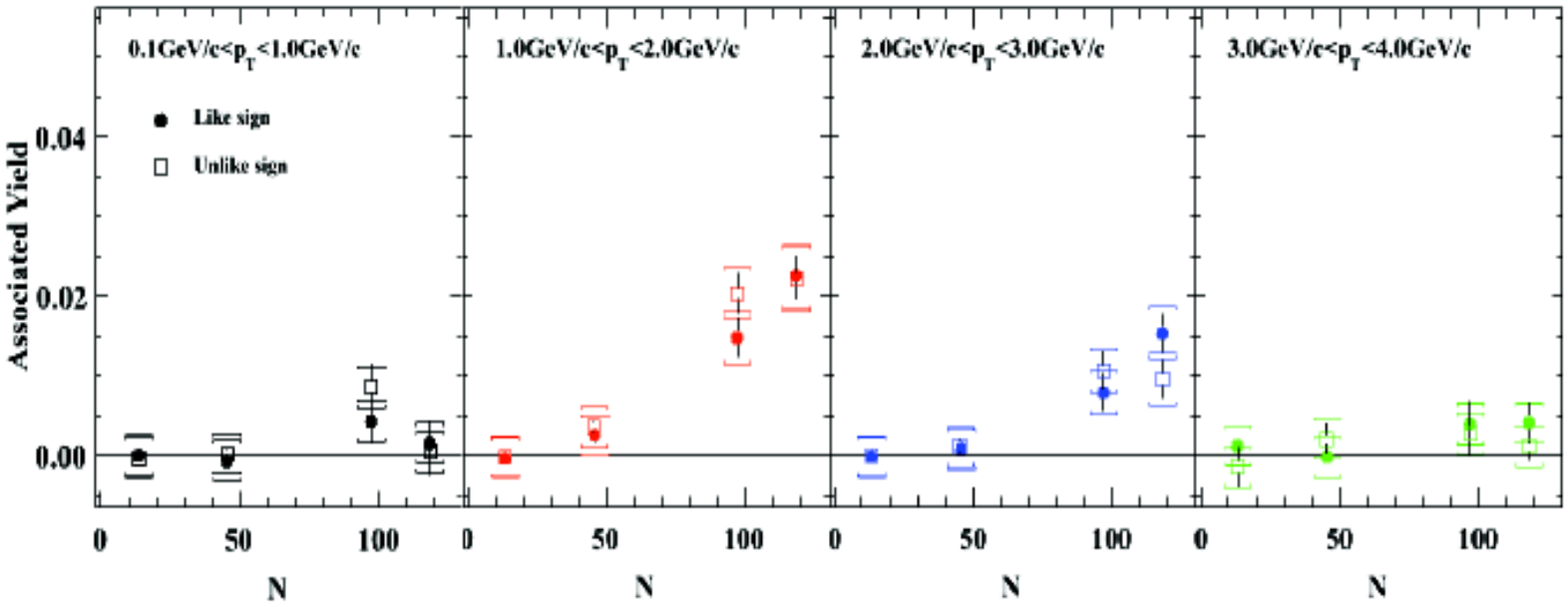
Detector

CMS Event

Collision

Like-Sign vs Unlike-Sign

Factor 2 lower → Associated yield normalized to all particles in the event



No dependence on relative charge sign