Measurements of two-particle correlations in pp collisions with the CMS detector

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(On behalf of the CMS Collaboration)

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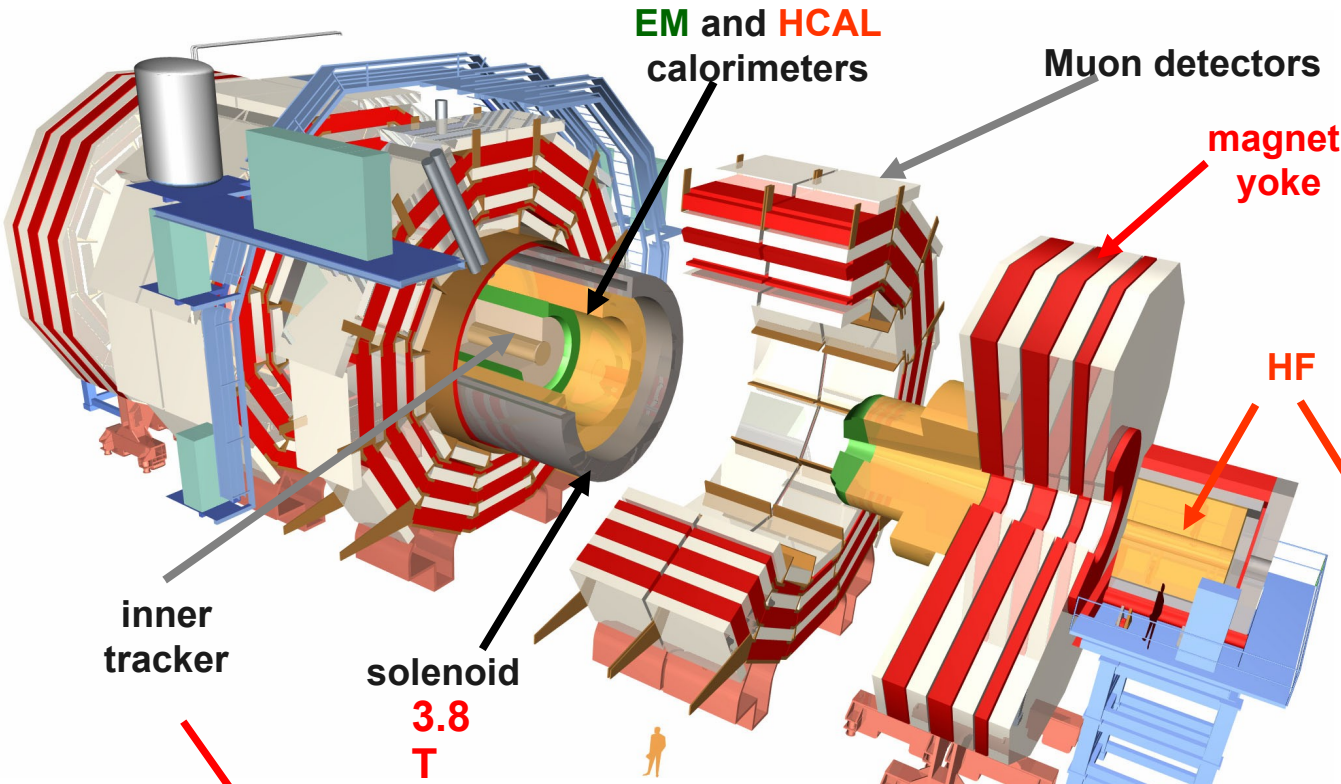
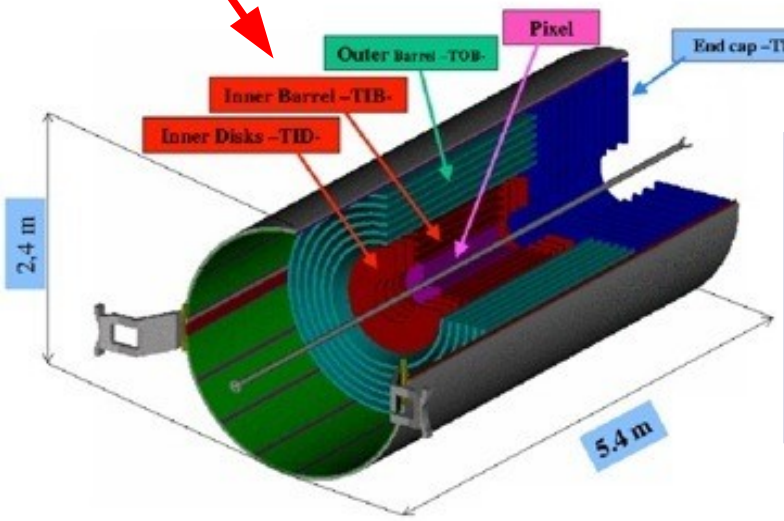
The CMS Detector

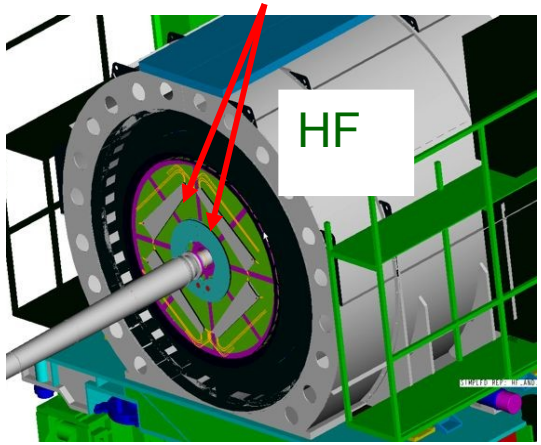


Total weight	12500 t
Overall diameter	15 m
Overall length	21.6 m

"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	$\|\eta\| < 2.4$

Bose–Einstein Correlations in proton-proton Collisions at $\sqrt{s}$ = 0.9 and 2.36 TeV at the LHC

Phys. Rev. Lett. 105 (2010) 032001

Bose-Einstein Correlations

When wave-function of identical bosons overlaps, Bose-Einstein statistic changes their dynamics

→ **Production probability enhancement for identical light boson with similar momenta.**

→ **BEC measurements give information about size, shape and space-time development of emitting source**

→ First observation in pion-production from $p\bar{p}$ annihilations – Phys. Rev. 120 (1960) 300

→ Many experimental resutls: e^+e^- @ PETRA, SLAC, LEP / $p\bar{p}$ @ SPS / ep @ HERA / fix target: NaXX, NOMAD, ...

Observable: $$R = \frac{P(p_1, p_2)}{P(p_1)P(p_2)}$$

$P(p_1,p_2)$: Joint probability of emission of a pair of bosons

$P(p_1)$, $P(p_2)$: Individual probability of emission

→ **Need to define a reference sample of non interfering boson pairs !**

$$\rightarrow R(Q) = \frac{dN/dQ}{dN/dQ_{ref}}$$

Assuming particle are mostly pions, Q is:

$$Q = \sqrt{-(p_1 - p_2)^2} = \sqrt{M_{inv}^2 - 4m_\pi^2}$$

Parametrization: $$R(Q) = C[1 + \lambda\,\Omega(Qr)](1 + \delta Q)$$

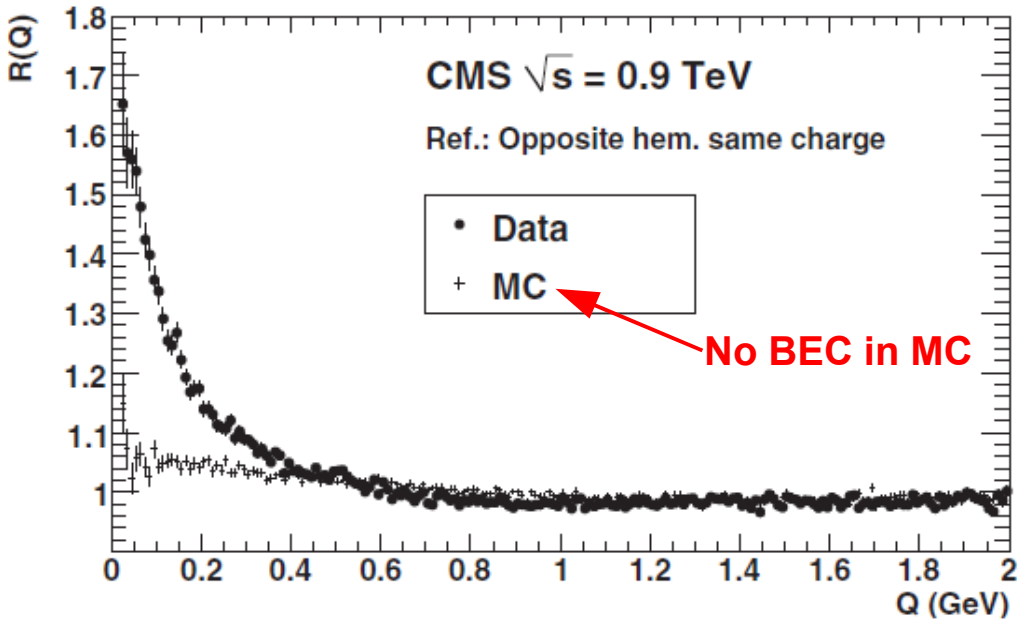
$\Omega(Qr)$: Fourier transform of emission region of effective size ***r***

λ : BEC strength δ : Long distance correlations

Data S`election and Reference Samples

Data Selection:

- **Minbias trigger events** with a primary vertex
  → 240 k events @ 900 GeV
  → 13.5 k events @ 2.36 TeV
- Study all **tracks** (charged particles) with:
  - **p_T > 200 MeV/c** and **|η| < 2.4**
  - **Good quality** tracks: > 5 hits , χ^2/ndof < 5
  - **Primary** particle: |dxy|<0.15 cm, hits close to beam axis (1st hit less than 20 cm)



Signal → All same sign track pairs in the event

7 reference samples

- Track pairs from same events:
  - Opposite charge (ρ,η resonances !)
  - Opposite charge / Opposite hemisphere
  - Same charge / Opposite hemisphere
  - Same charge with $\bar{p}$ rotated (transv. Plane)
- Tracks pairs from different events:
  - Random mixing
  - Similar dN/dη
  - Similar total invariant mass

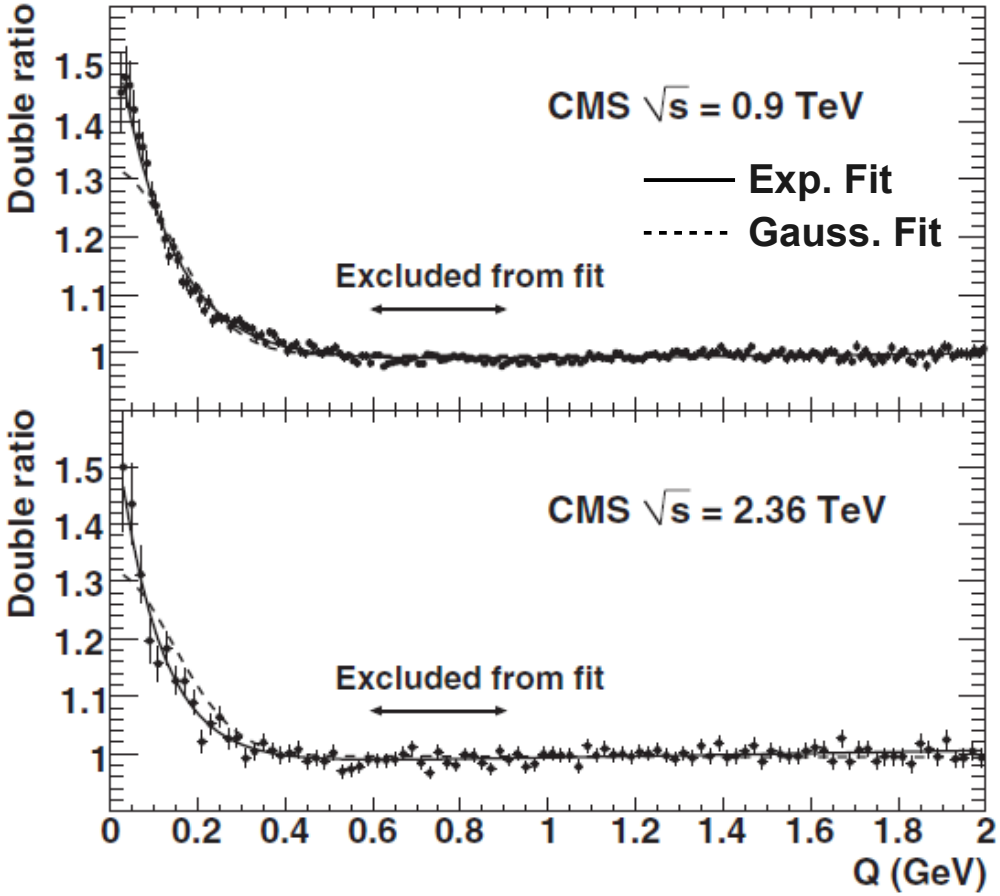
→ **BEC observed at small Q values**
→ **Use Double Ratio (no BEC in MC):**

$$R/R_{MC} = \left(\frac{dN/dQ}{dN/dQ_{ref}}\right) / \left(\frac{dN/dQ_{MC}}{dN/dQ_{MC,ref}}\right)$$

→ **Build a combined reference sample to reduce individual biases**

BEC Results: Double Ratio and Parametrization

First observation of Bose-Einstein correlations in proton-proton collisions at the c.m. energy of 0.9 and 2.36 TeV



→ **Fit with $\Omega(Qr) = exp(-Qr)$:**

900 GeV pp collisions

r = 1.59 ± 0.05 (stat.) ± 0.19 (syst.) fm

λ = 0.625± 0.021 (stat.) ± 0.046 (syst.)

2.36 TeV pp collisions

r = 1.99 ± 0.18 (stat.) ± 0.24 (syst.) fm

λ = 0.663 ± 0.073 (stat.) ± 0.048 (syst.)

→ Systematics mostly from spread of 7 references samples

→ ρ resonance region excluded from fit

→ Exponential form $\Omega(Qr) = exp(-Qr)$ fits better data than widely used Gaussian form $\Omega(Qr) = exp(-Qr)^2$

Long-Range, Near-Side Angular Correlations in Proton-Proton Interactions in CMS

CERN-PH-EP-2010-031
arXiv:1009.4122
Submitted to JHEP

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

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

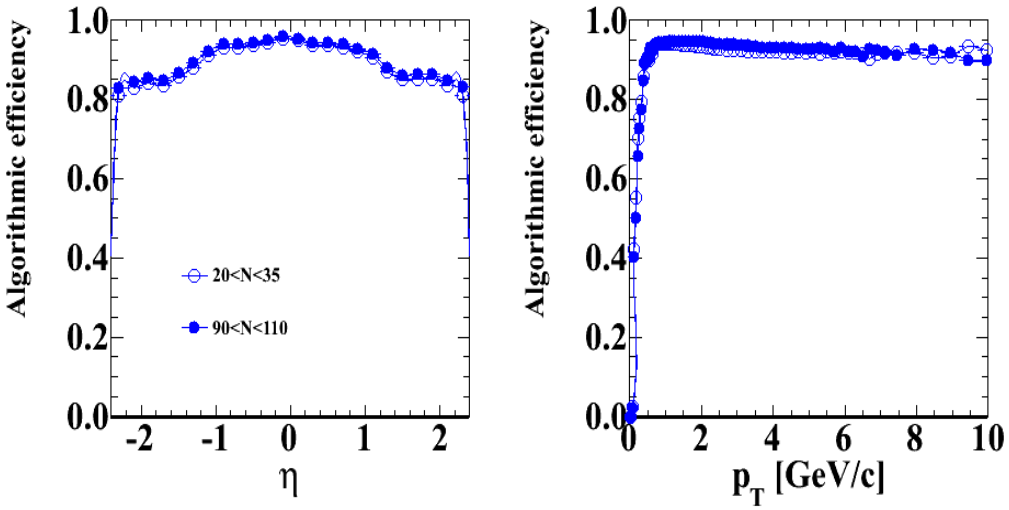
- ε^{trk} = 50% for $p_T \approx 0.1$ GeV/c
- ε^{trk} > 90% for $|\eta|<1$ and $p_T > 0.6$ GeV/c
- Fake rate below 2% for $p_T > 0.2$ GeV/c

→ Data (**each track**) weigthed by:

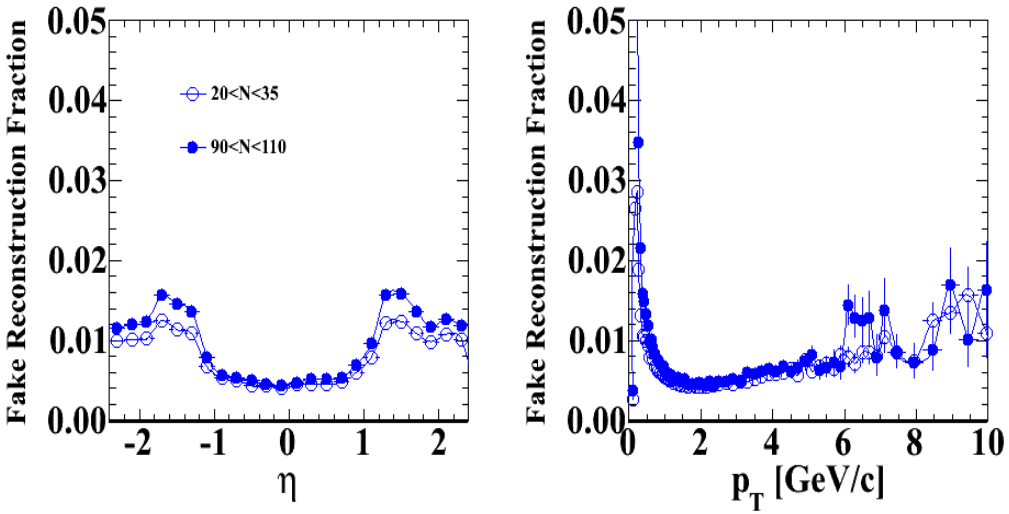
$$1/\varepsilon^{trk}(\eta, p_T, z_{vtx})$$

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

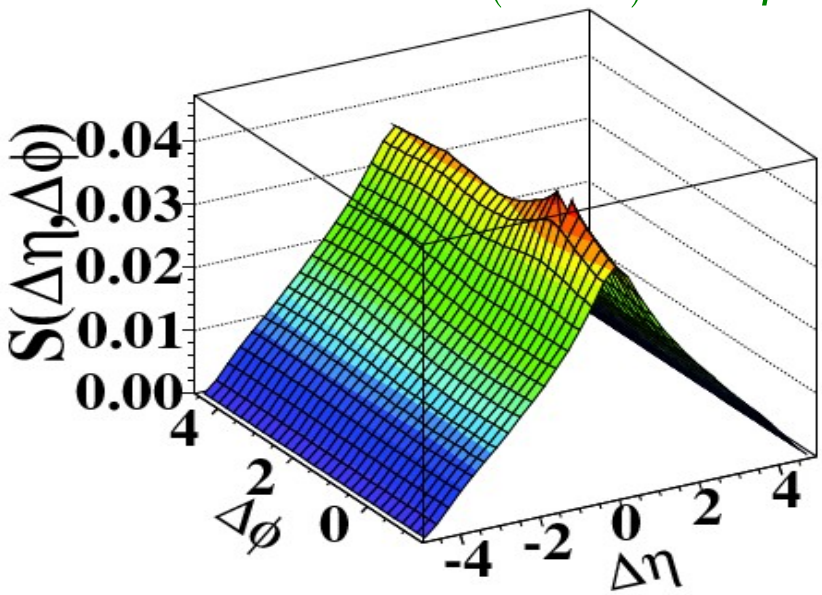
→ Data (**each track**) weigthed by:

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

Analysis Technique

Signal distribution
= Correlated and uncorrelated pairs
from same event

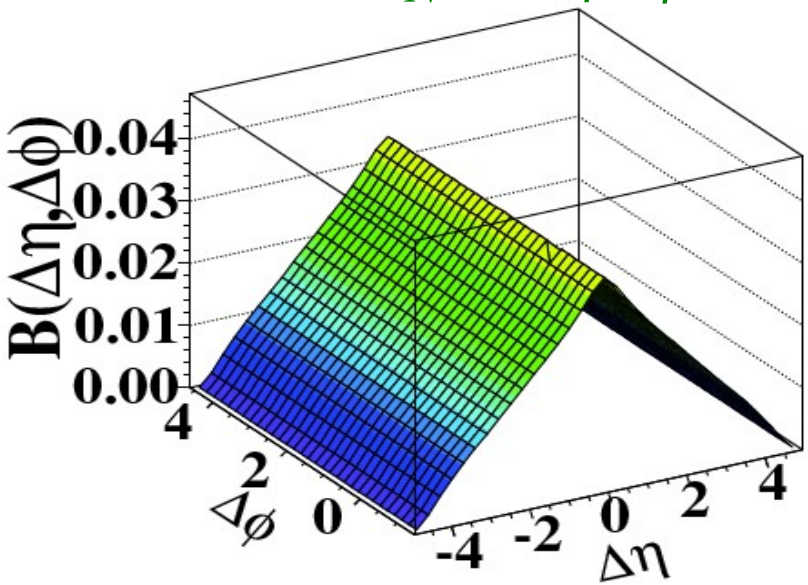
$$S(\Delta\eta,\Delta\phi)=\frac{1}{N(N-1)}\frac{d^2N}{d\Delta\eta\,\Delta\phi}$$



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

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

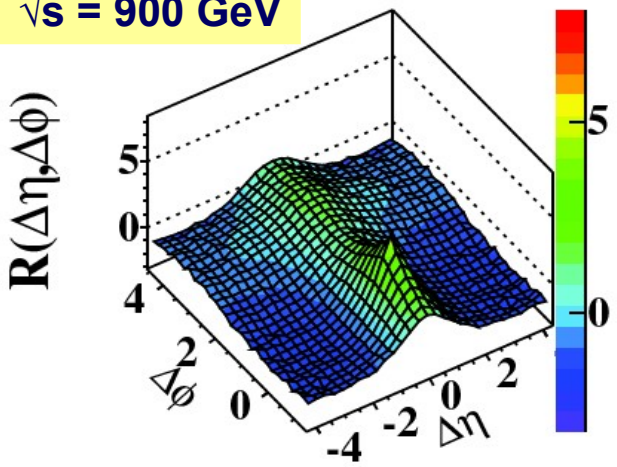
$$R(\Delta\eta,\Delta\phi)=\left\langle (N-1)\left(\frac{S_N(\Delta\eta,\Delta\phi)}{B_N(\Delta\eta,\Delta\phi)}-1\right)\right\rangle_N$$

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)

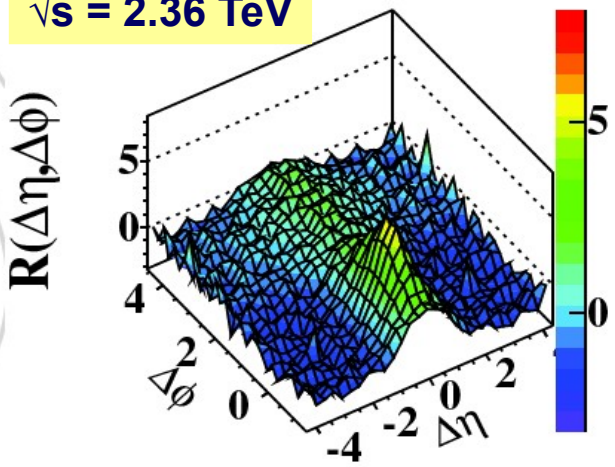
MinBias Results: 2D Two-particle Correlations

DATA

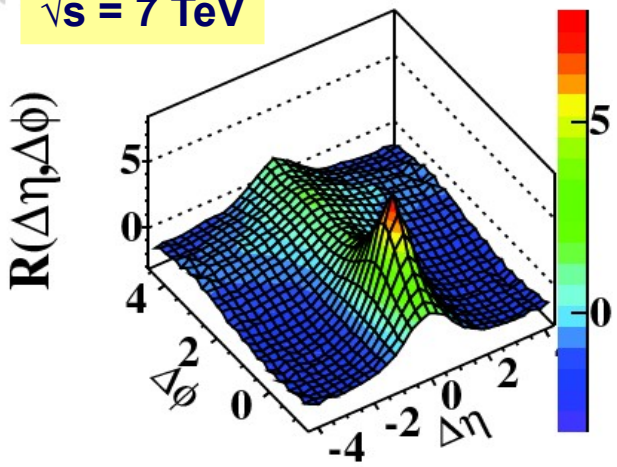
$\sqrt{s}$ = 900 GeV



$\sqrt{s}$ = 2.36 TeV

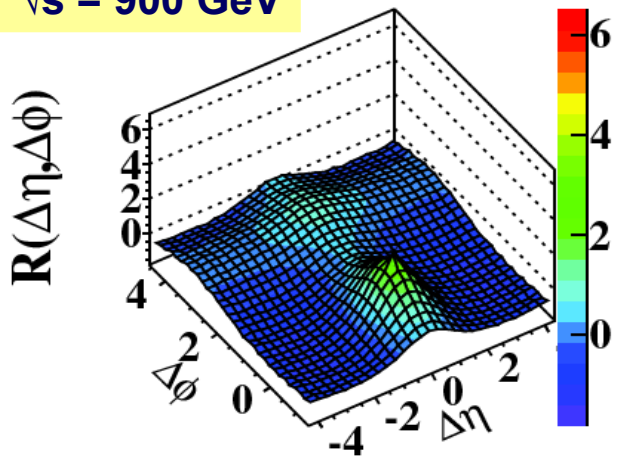


$\sqrt{s}$ = 7 TeV

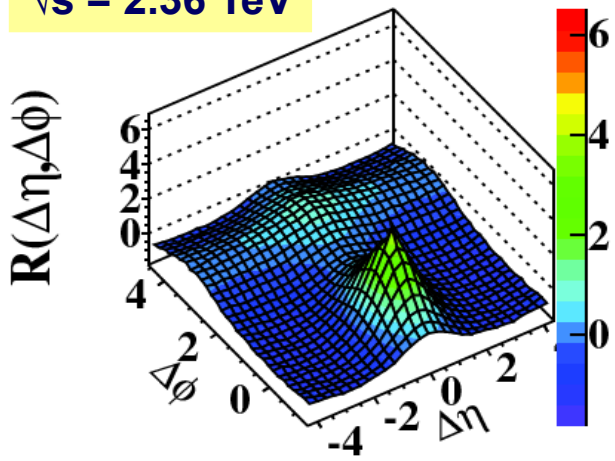


PYTHIA D6T

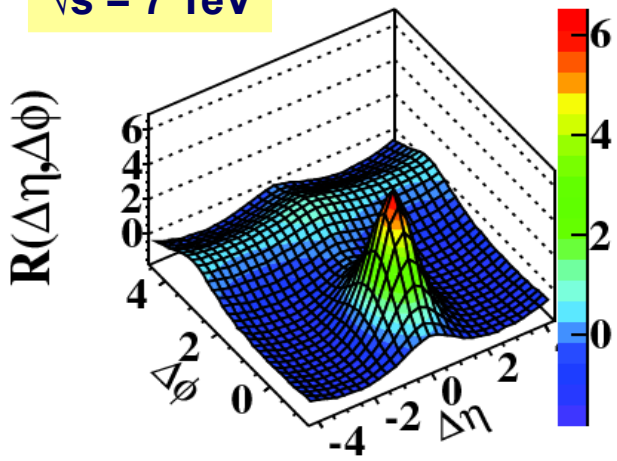
$\sqrt{s}$ = 900 GeV



$\sqrt{s}$ = 2.36 TeV



$\sqrt{s}$ = 7 TeV

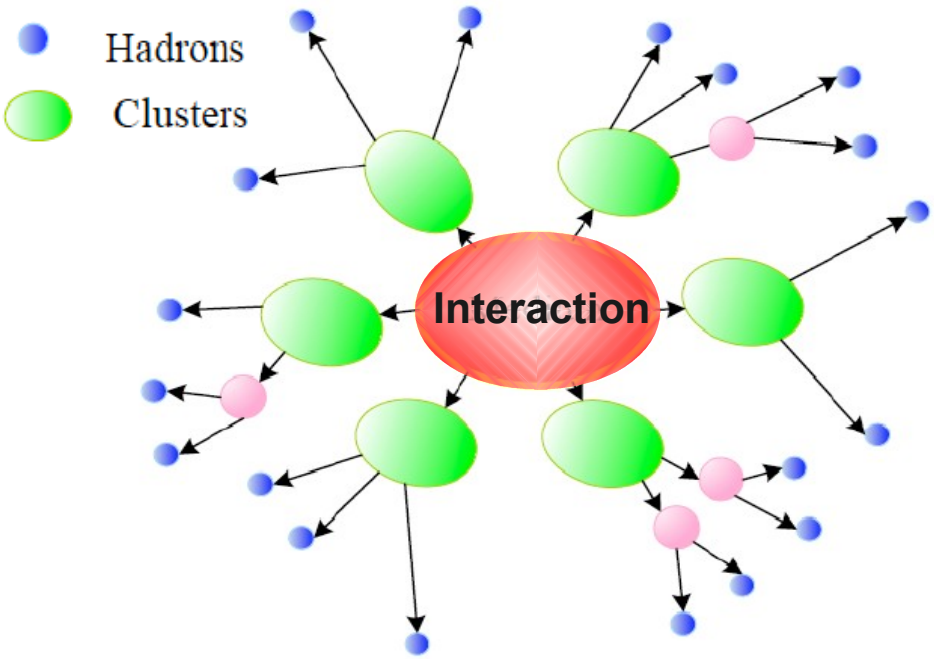


DATA:

- 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

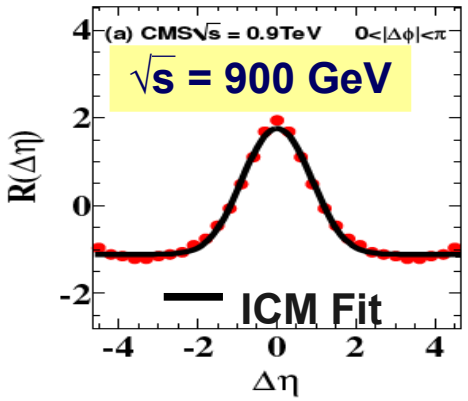
PYTHIA D6T: Simulation qualitatively similar to data (but not in magnitude for each component)

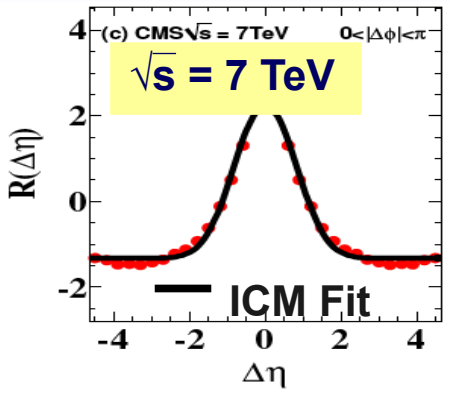
MinBias Results: Independent Cluster Model

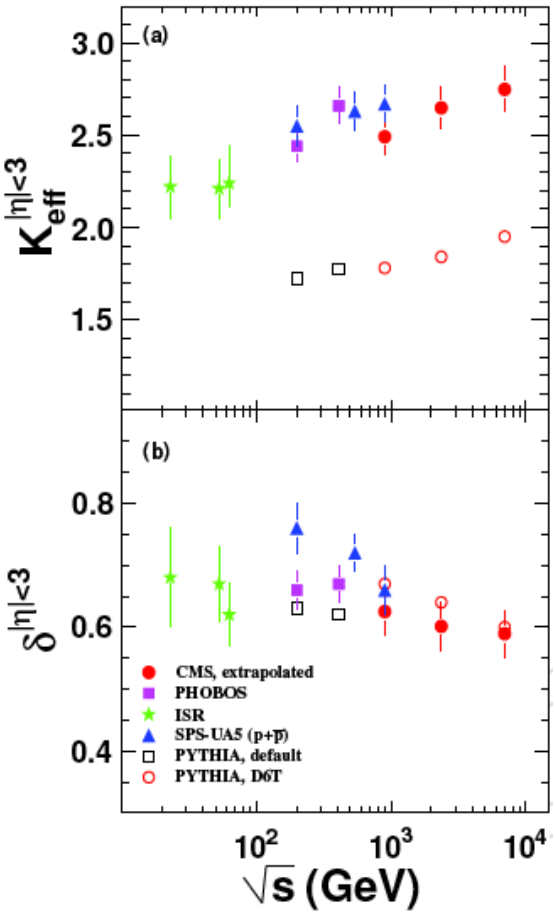


Independent Cluster Model (ICM)

- 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

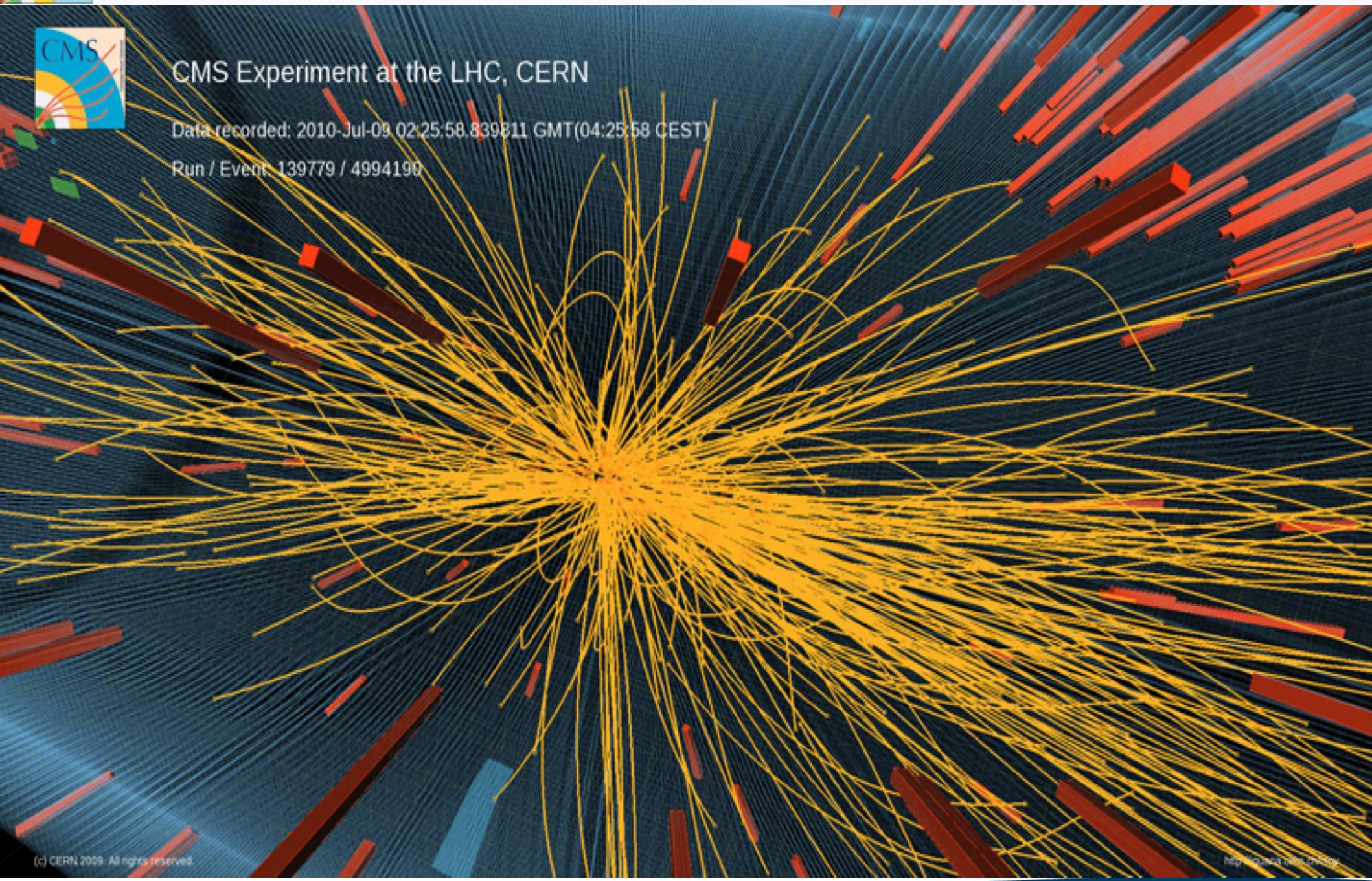






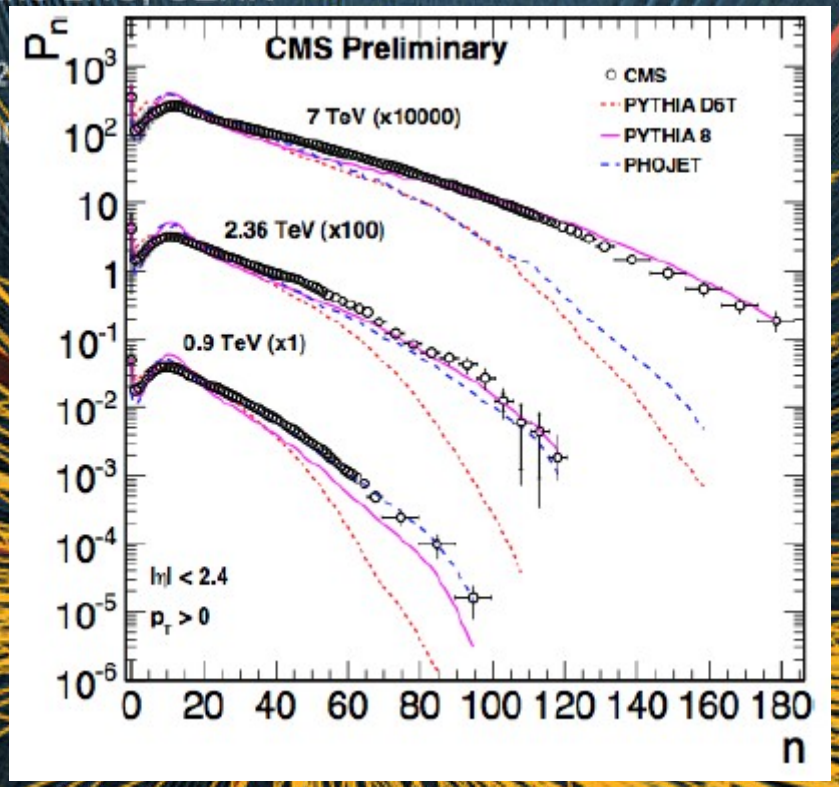
- K_{eff} increase with $\sqrt{s}$ (more jets at high $\sqrt{s}$?)
- δ constant with $\sqrt{s}$ (isotropic cluster decay)
- CMS results follow trend from lower $\sqrt{s}$ data
- PYTHIA (D6T) shows similar energy dependencies for K_{eff} and δ as data
- PYTHIA (D6T) predicts too low K_{eff}

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



N = 268

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



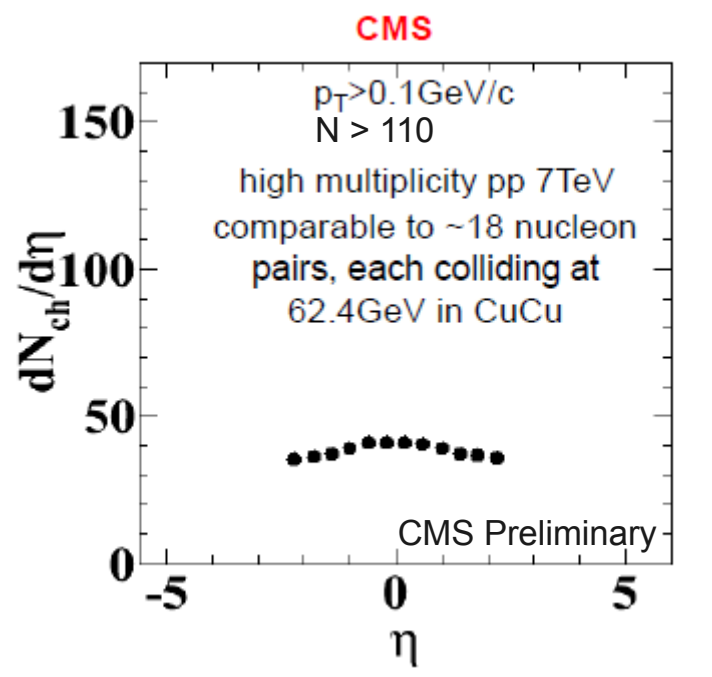
Large multiplicities observed in 7 TeV data
→ Detailed studies of the properties of these events

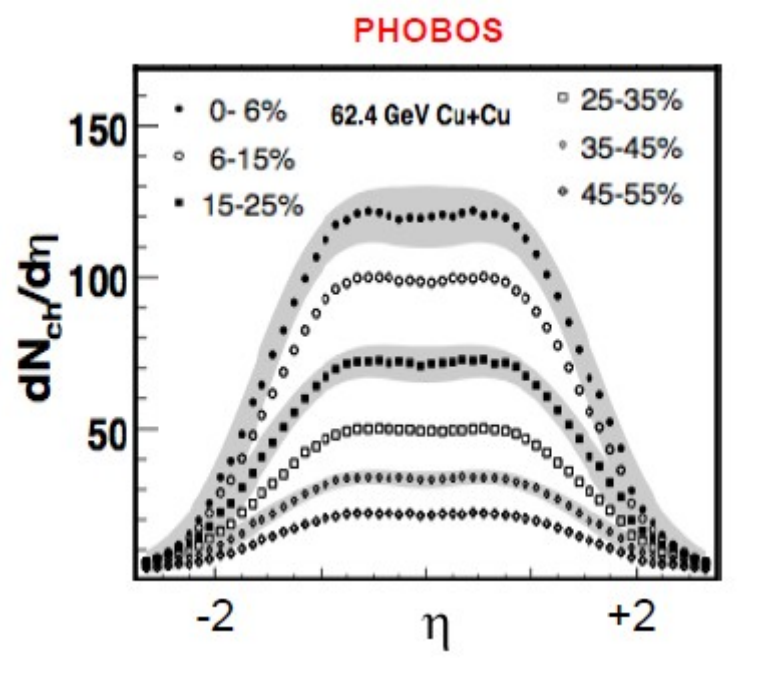
N = 268

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

CMS Experiment at the LHC, CERN

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





Large multiplicities observed in 7 TeV data

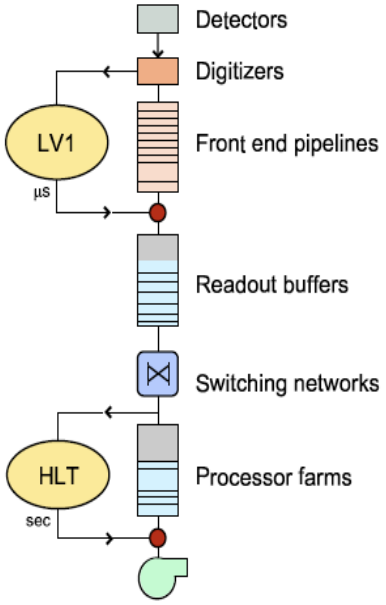
→ Detailed studies of the properties of these events

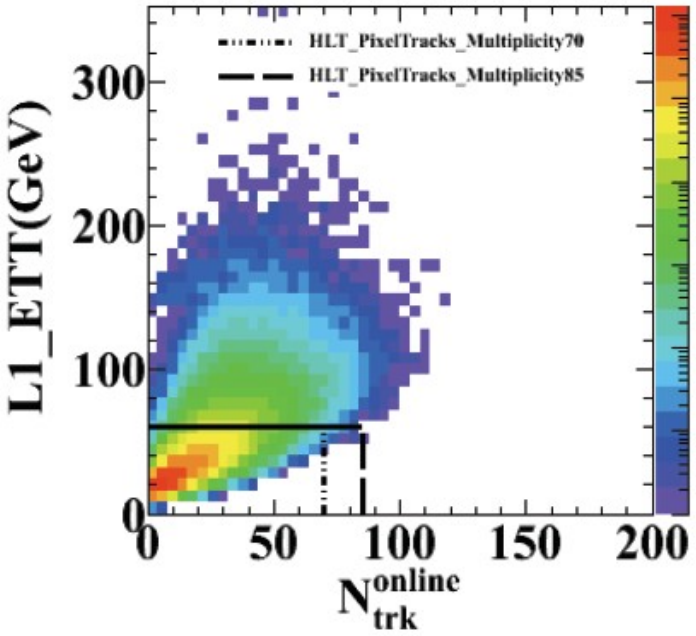
The particle densities in the high multiplicity events of proton-proton collisions at 7TeV begin to approach those in high-energy collisions of nuclei such as Copper

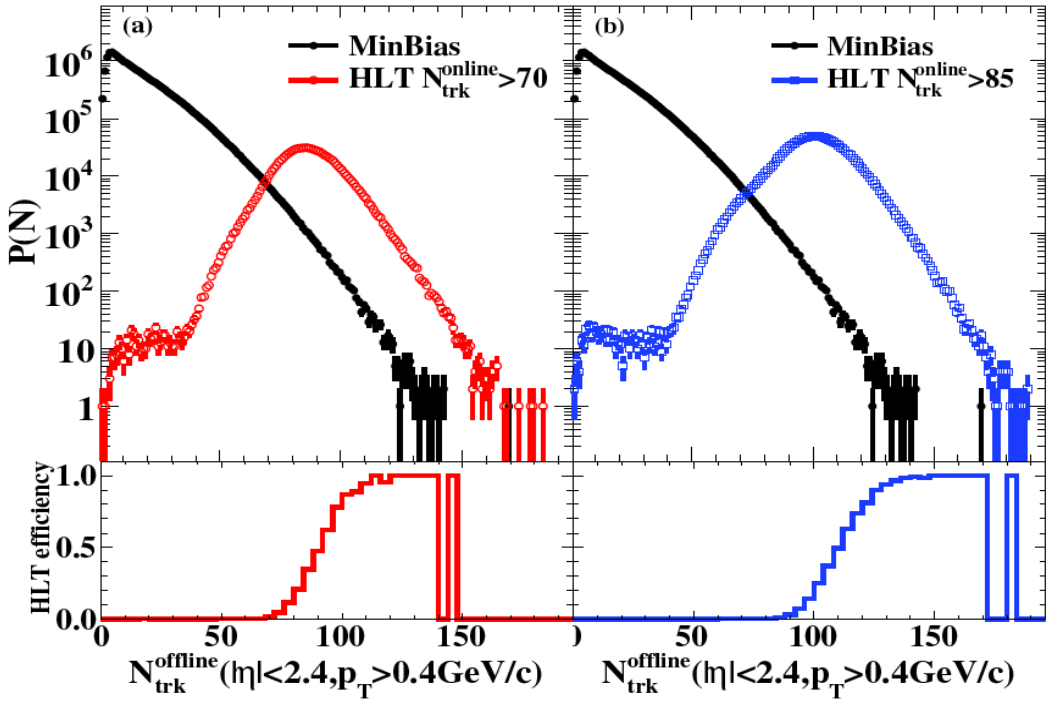
→ Benchmark / reference for Heavy Ion run

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

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

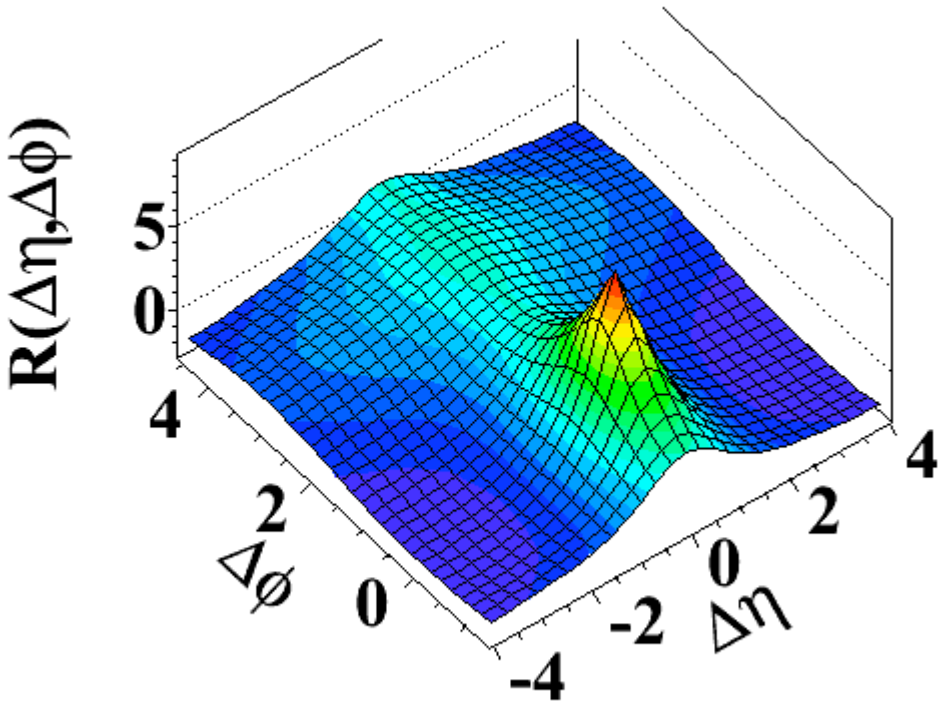
Primary tracks in full tracker for **$|\eta| < 2.4$** and **$p_T > 0.4$ GeV/c**

→ 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**

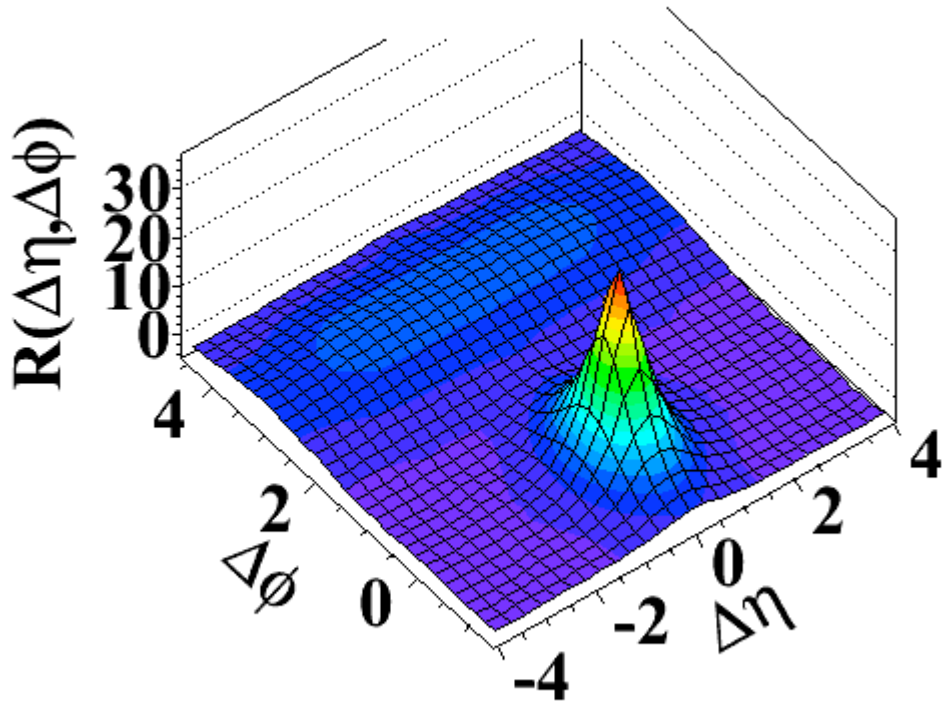
High Multiplicity Results

Inclusive p_T : p_T > 0.1 GeV/c

MinBias



High Multiplicity: N>110



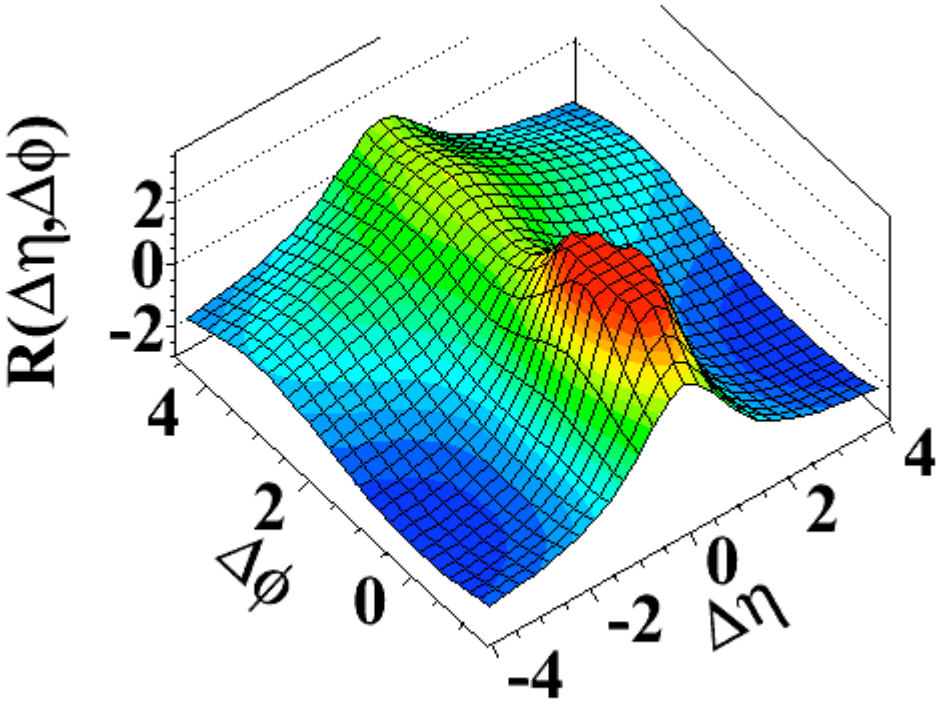
→ Jet peak/away-side correlations enhanced at high multiplicity
→ Abundant jet production in high multiplicity sample

High Multiplicity Results

Inclusive p_T : p_T > 0.1 GeV/c

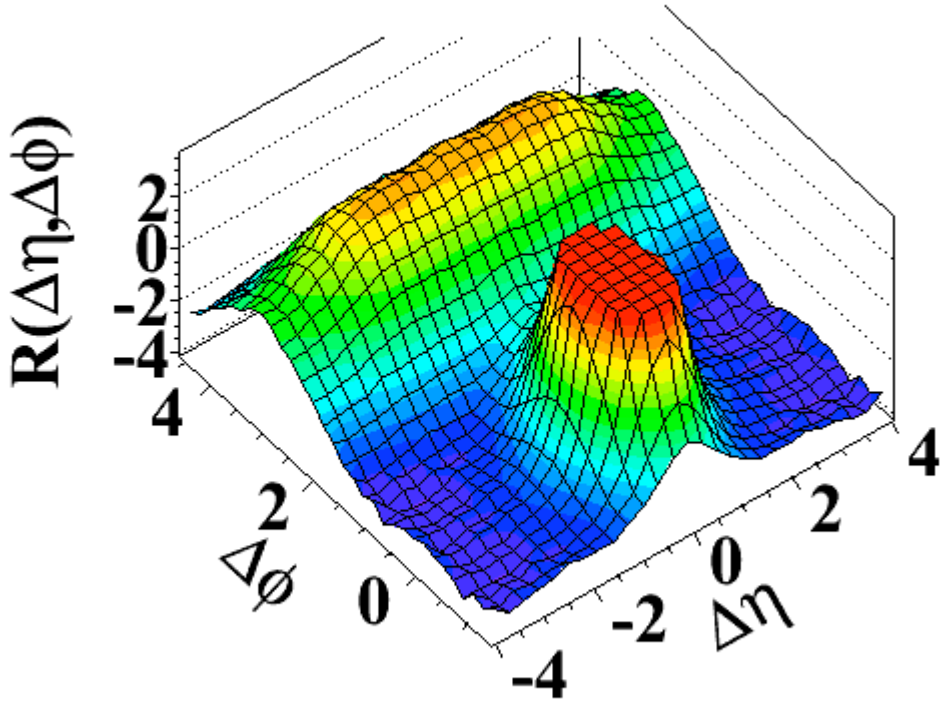
MinBias

(a) MinBias, p_T>0.1GeV/c



High Multiplicity: N>110

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



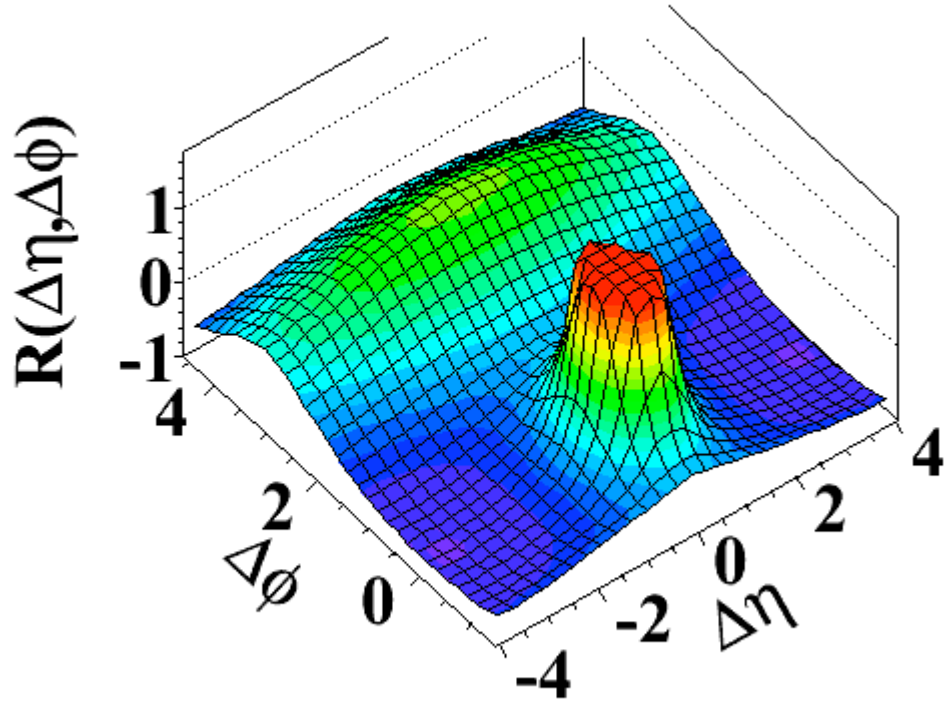
→ Jet peak/away-side correlations enhanced at high multiplicity
→ Abundant jet production in high multiplicity sample

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

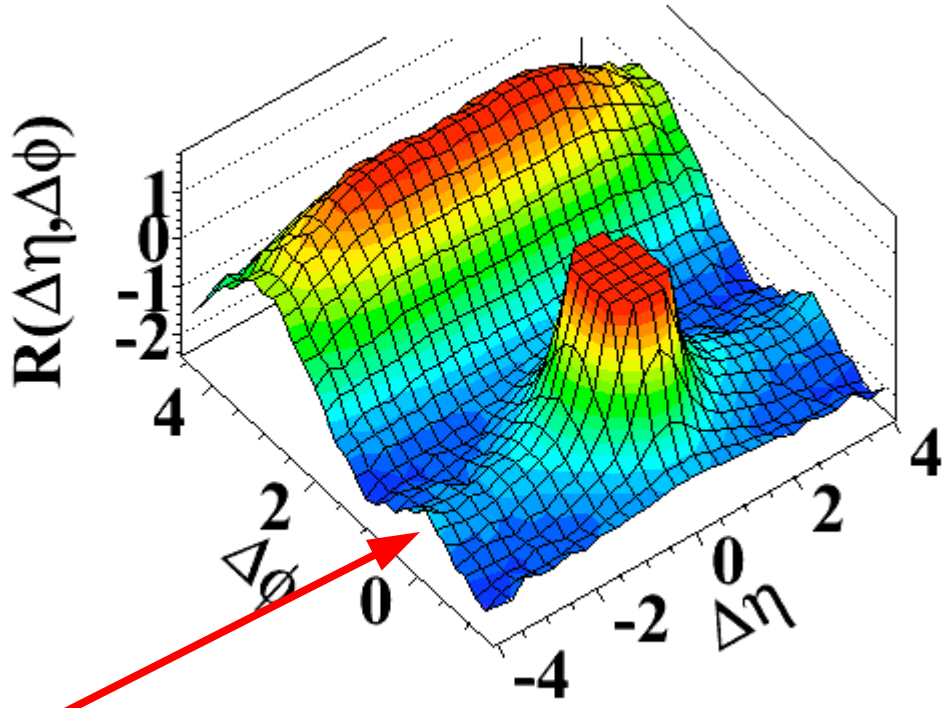
High Multiplicity Results

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

MinBias



High Multiplicity: N>110

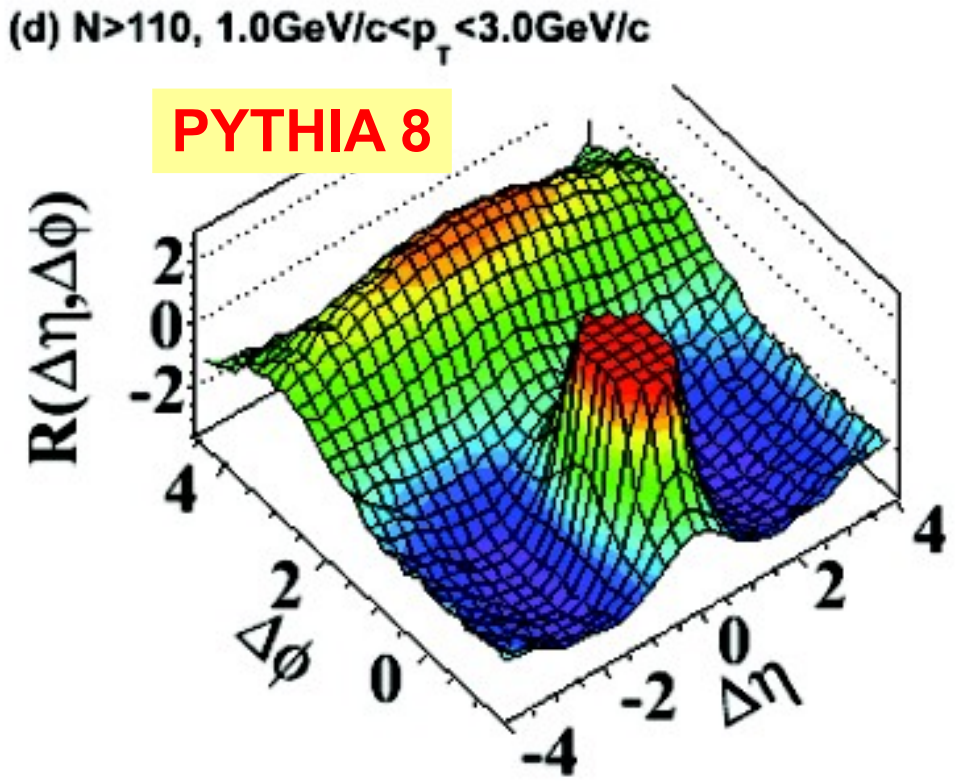


→ **Observation of a Long-Range, Near-Side angular correlations at high multiplicity in pp events at intermediate p_T (Ridge at $\Delta\phi \sim 0$)**

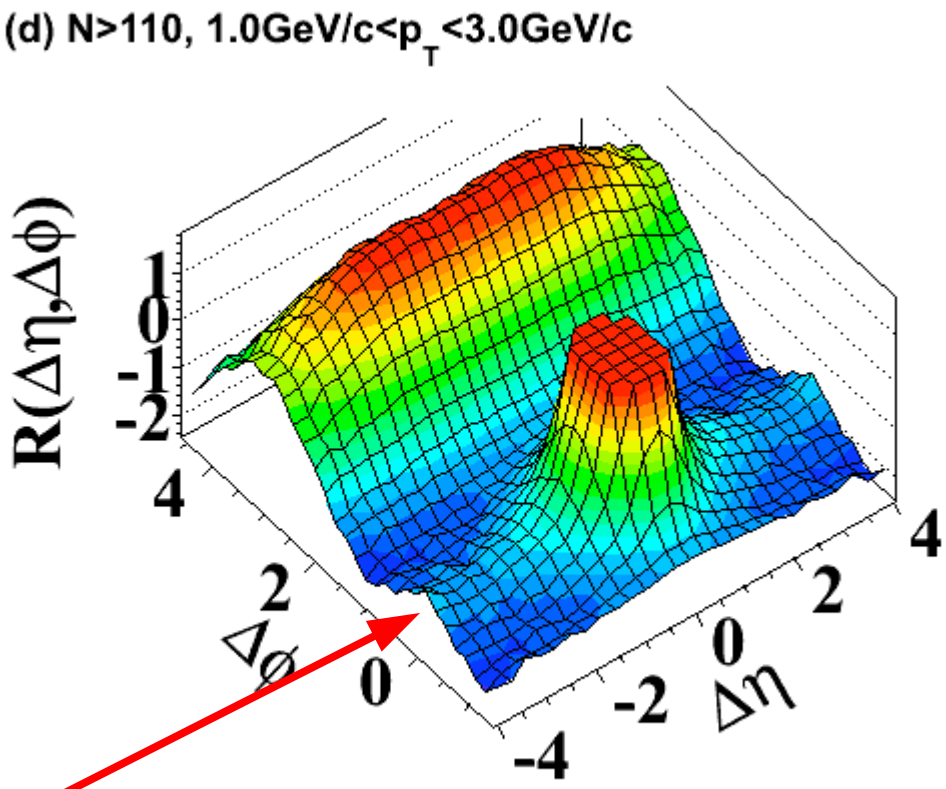
High Multiplicity Results

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

High Multiplicity: N>110



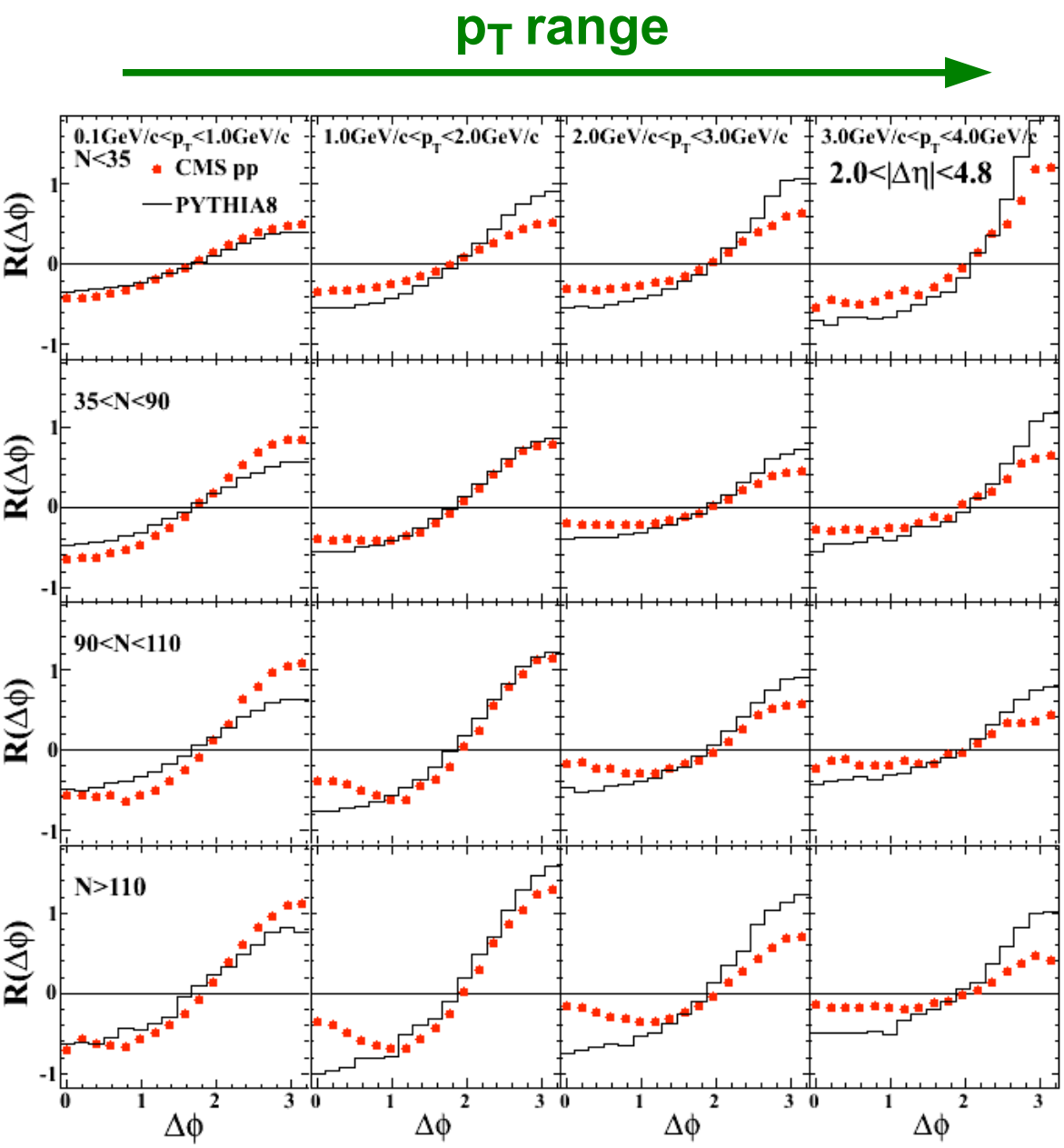
High Multiplicity: N>110

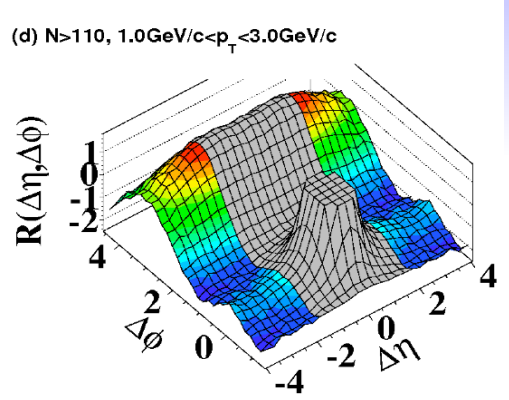


→ Observation of a Long-Range, Near-Side angular correlations at high multiplicity in pp events at intermediate p_T (Ridge at $\Delta\phi \sim 0$)

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

Multiplicity and p_T dependences





→ **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

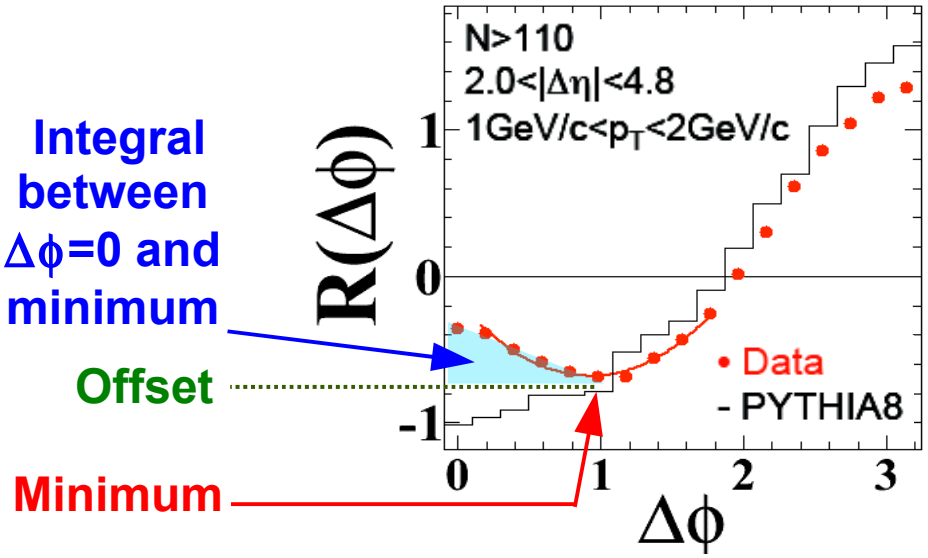
"Ridge" not reproduced by PYTHIA 8

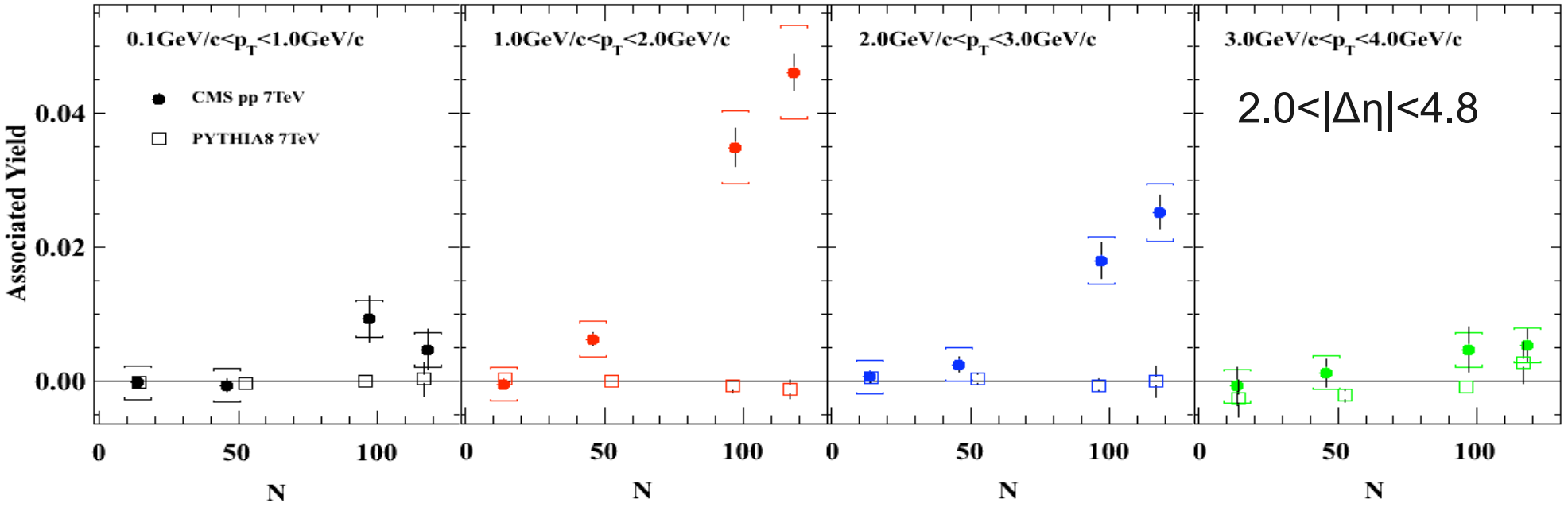
Quantifying the "Ridge": Associated Yield

Associated yield:
Extra correlated multiplicity per particle

→ **Zero Yield At Minimum (ZYAM) :**

→ **ZYAM = 0 if no "Ridge"**



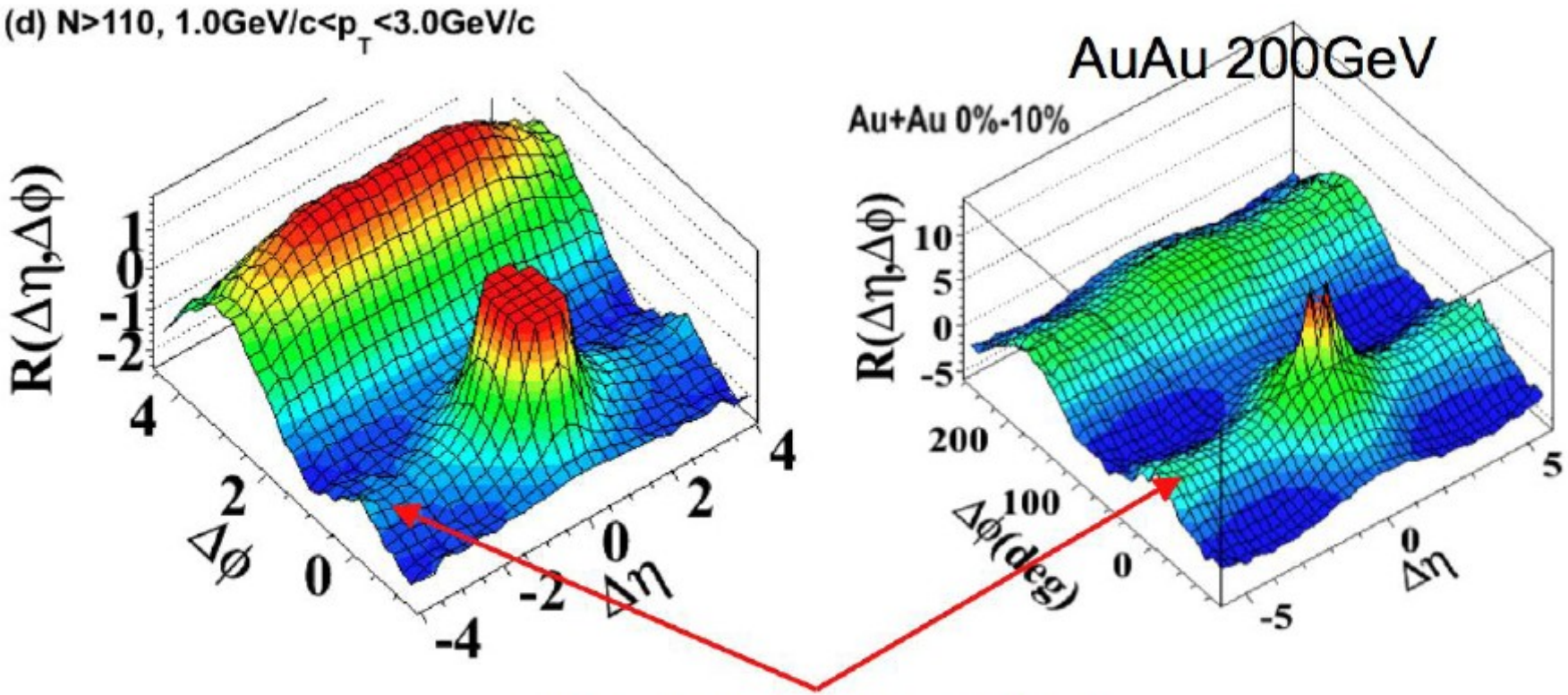


→ **Associated yield grows with increasing multiplicity**

→ **Maximum for 1< p_T < 2 GeV/c**

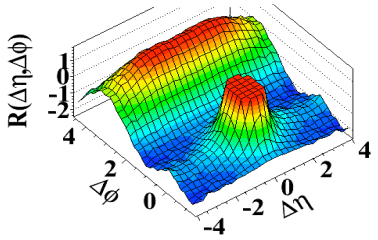
This is the first observation of such a long-range, near-side feature in two-particle correlation functions in pp or $p\bar{p}$ collisions.

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)

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**

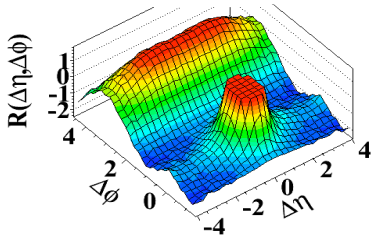
Trigger ← **Trigger Efficiency + Bias**

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

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

Collision ← **Physics**

Cross Checks (1)



Analysis Code

Reconstruction

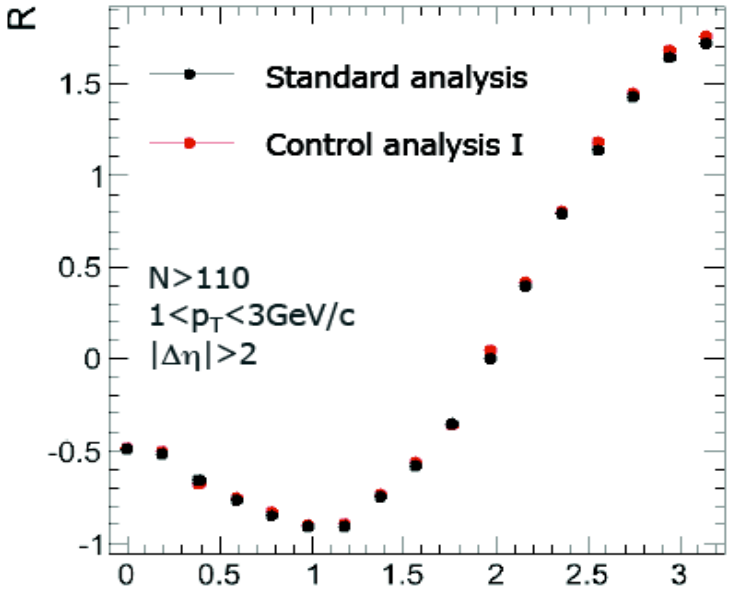
Trigger

Detector

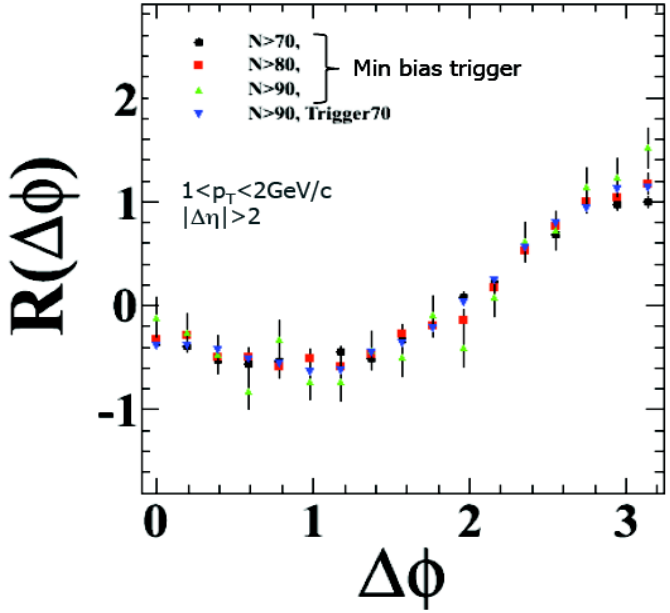
CMS Event

Collision

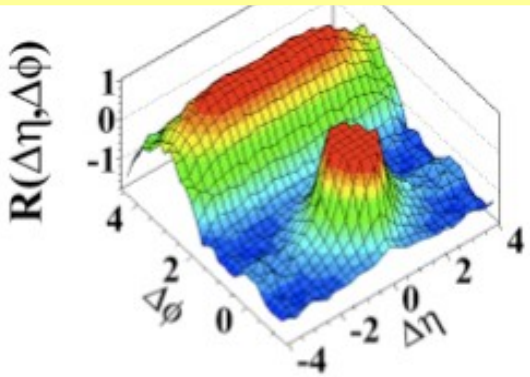
3 Independent Analysis (2 shown)



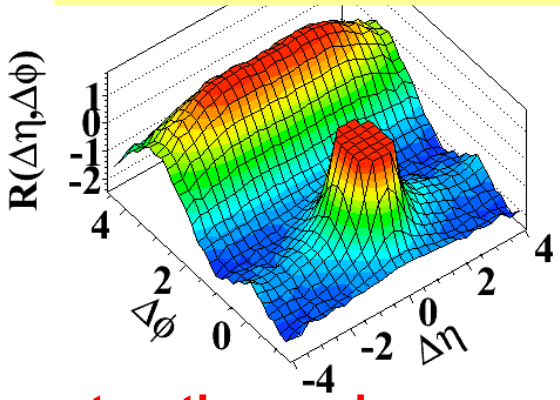
High Multiplicity vs MinBias Trigger



Pixel (Vtx Detector) Tracking

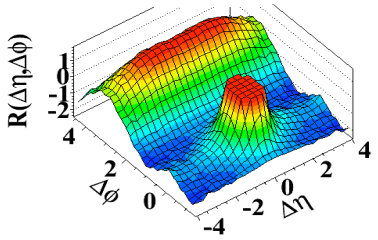


Full CMS Tracking



(Largely) independent reconstruction code

Cross Checks (2)



Analysis Code

Reconstruction

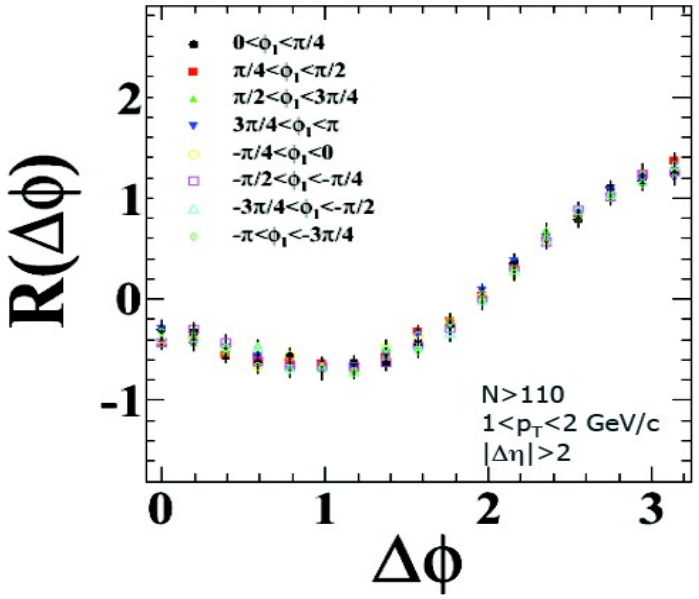
Trigger

Detector

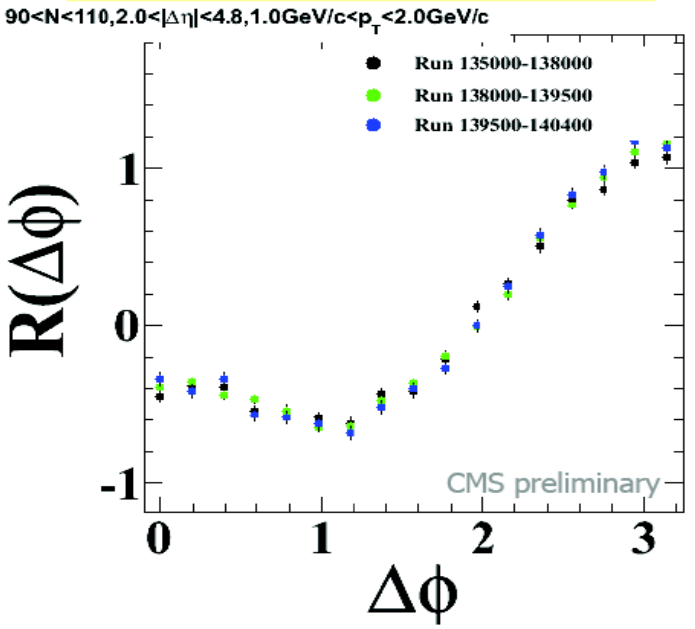
CMS Event

Collision

Ridge is Symmetric in ϕ

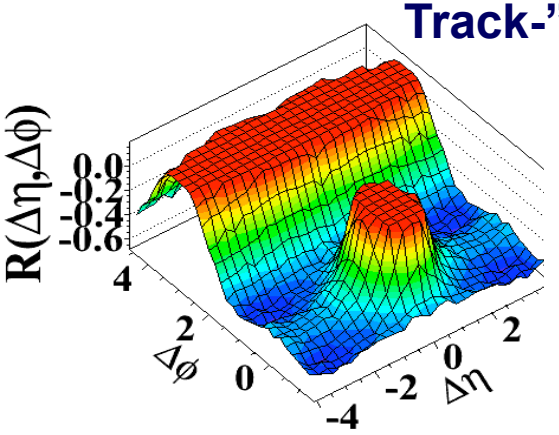


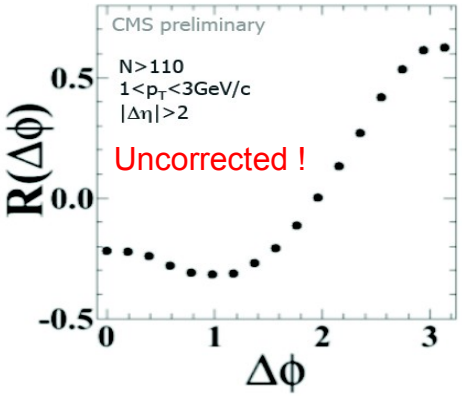
Pile-Up Effect Negligeable



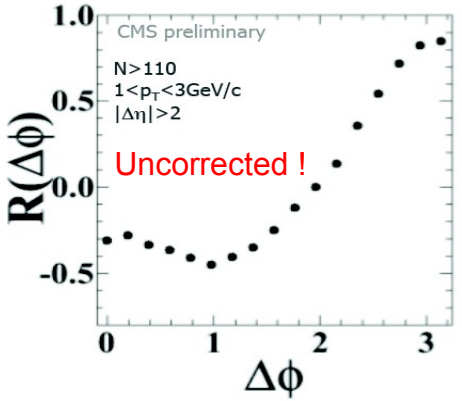
Use ECAL Object (Particle-flow "photons") = π^0 dominated

Track-"Photons"

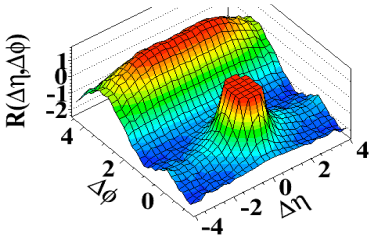




"Photons"-"Photons"



Cross-Checks → 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

First observation of Bose-Einstein Correlations in proton-proton @ $\sqrt{s}$ = 900 GeV and 2.36 TeV

- Used double ratio combining many reference samples
- Exponential shape fits better than Gaussian one

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
- 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 coming Heavy Ion run will be an additional important test bench.

Paper public since yesterday !

CERN-PH-EP-2010-031
arXiv:1009.4122
Submitted to JHEP

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

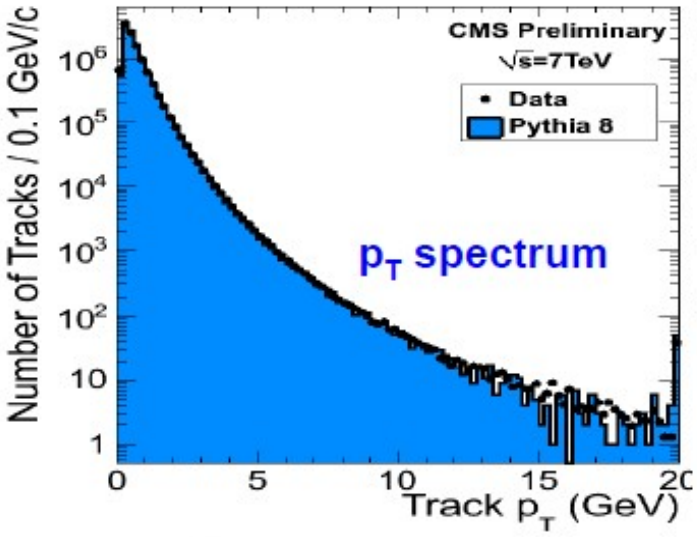
Abstract

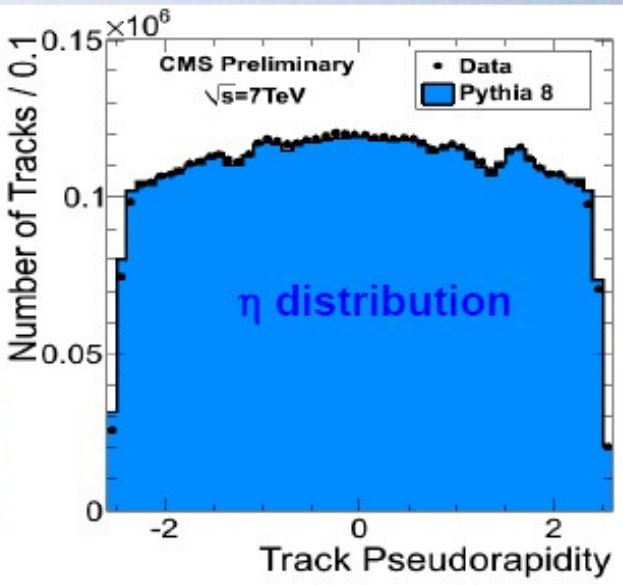
Results on two-particle angular correlations for charged particles emitted in proton-proton collisions at center-of-mass energies of 0.9, 2.36, and 7 TeV are presented, using data collected with the CMS detector over a broad range of pseudorapidity (η) and azimuthal angle (ϕ). Short-range correlations in $\Delta\eta$, which are studied in minimum bias events, are characterized using a simple "independent cluster" parametrization in order to quantify their strength (cluster size) and their extent in η (cluster decay width). Long-range azimuthal correlations are studied differentially as a function of charged particle multiplicity and particle transverse momentum using a 980 nb^{-1} data set at 7 TeV. In high multiplicity events, a pronounced structure emerges in the two-dimensional correlation function for particle pairs with intermediate p_T of 1–3 GeV/c, $2.0 < |\Delta\eta| < 4.8$ and $\Delta\phi \approx 0$. 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.

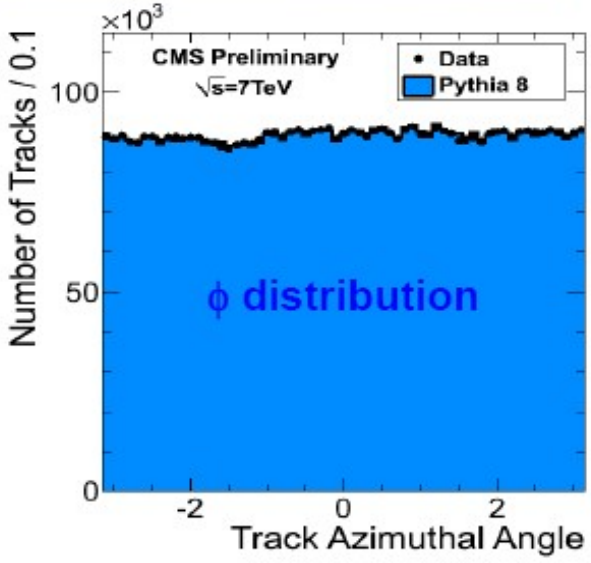
→ Since there are a number of potential explanations, today's presentation was focused on the experimental evidence in the interest of fostering a broader discussion on the subject

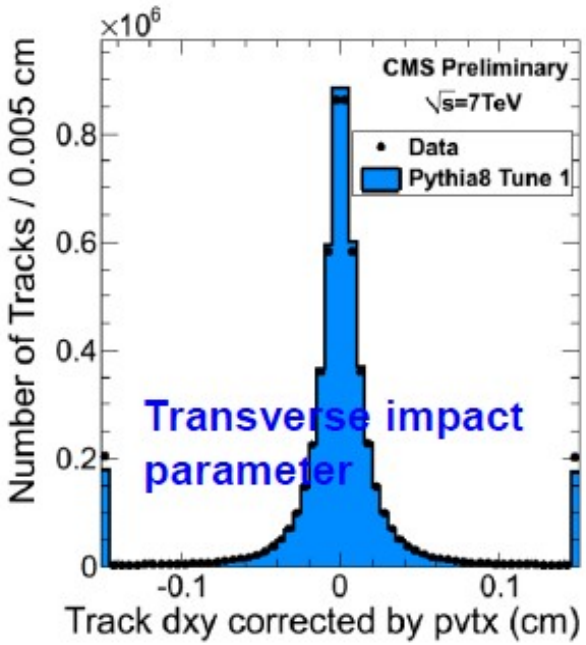
BACKUP SLIDES

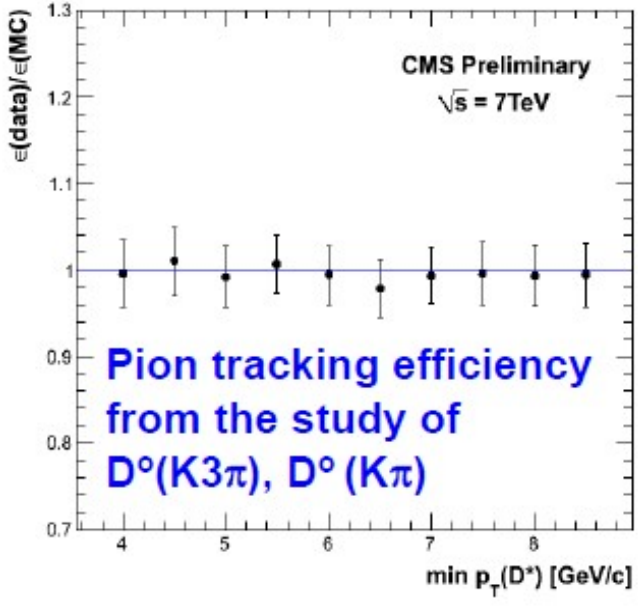
Tracker Performance are well understood

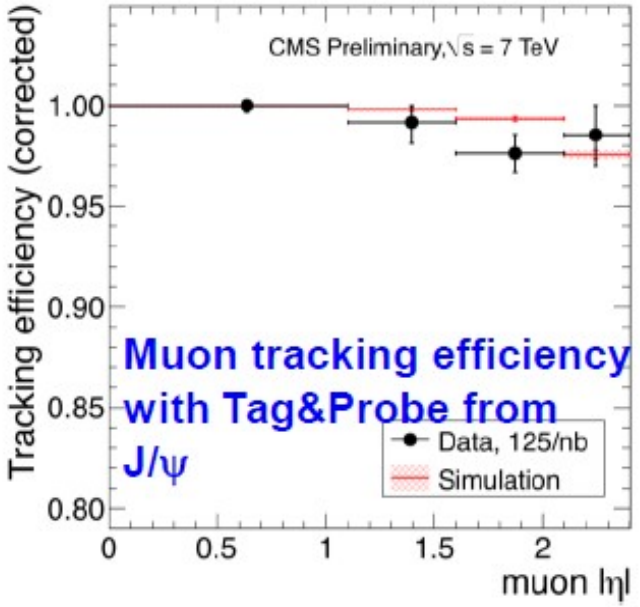






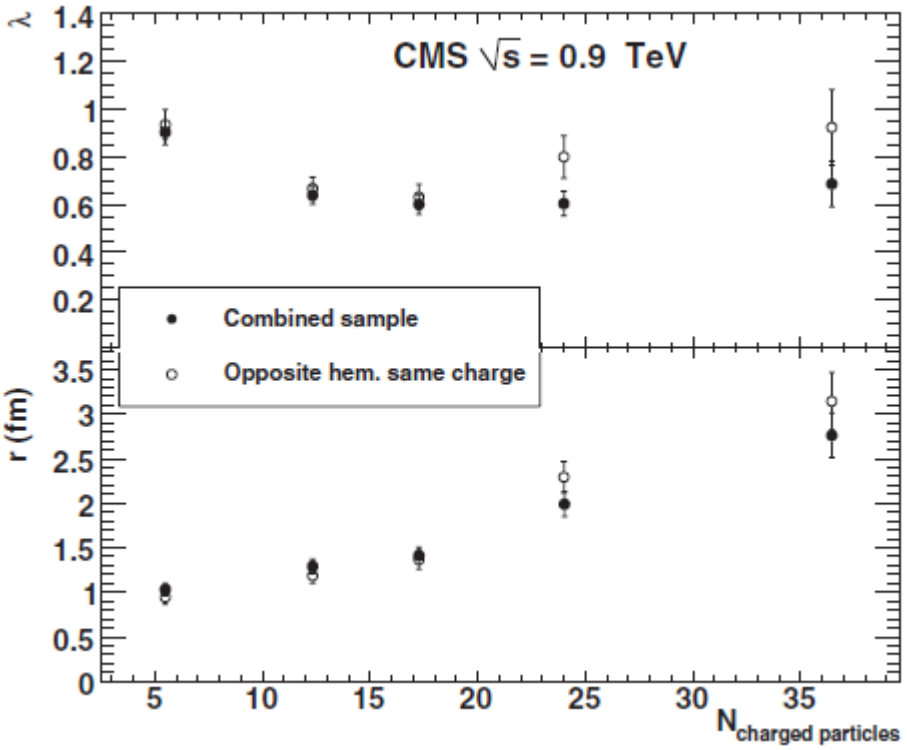






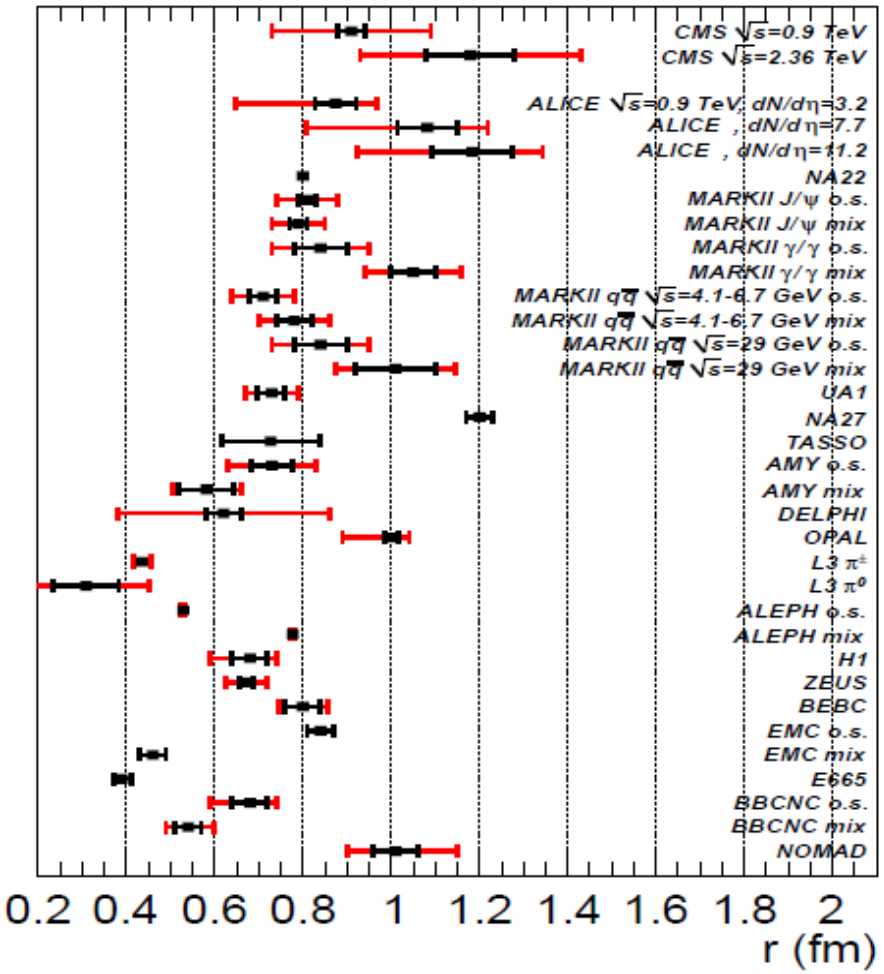
BEC: Dependence on Multiplicity and Previous Results

Study dependence of BEC on the charged particle multiplicity



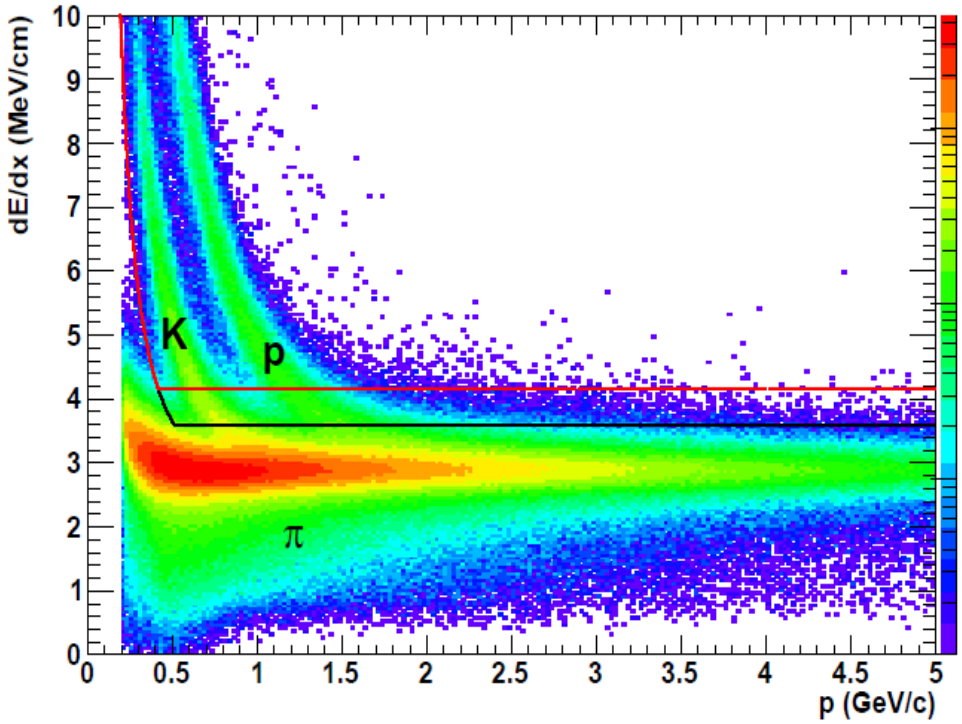
→ **Increase of the effective size of the BEC emission region with charged particle multiplicity**

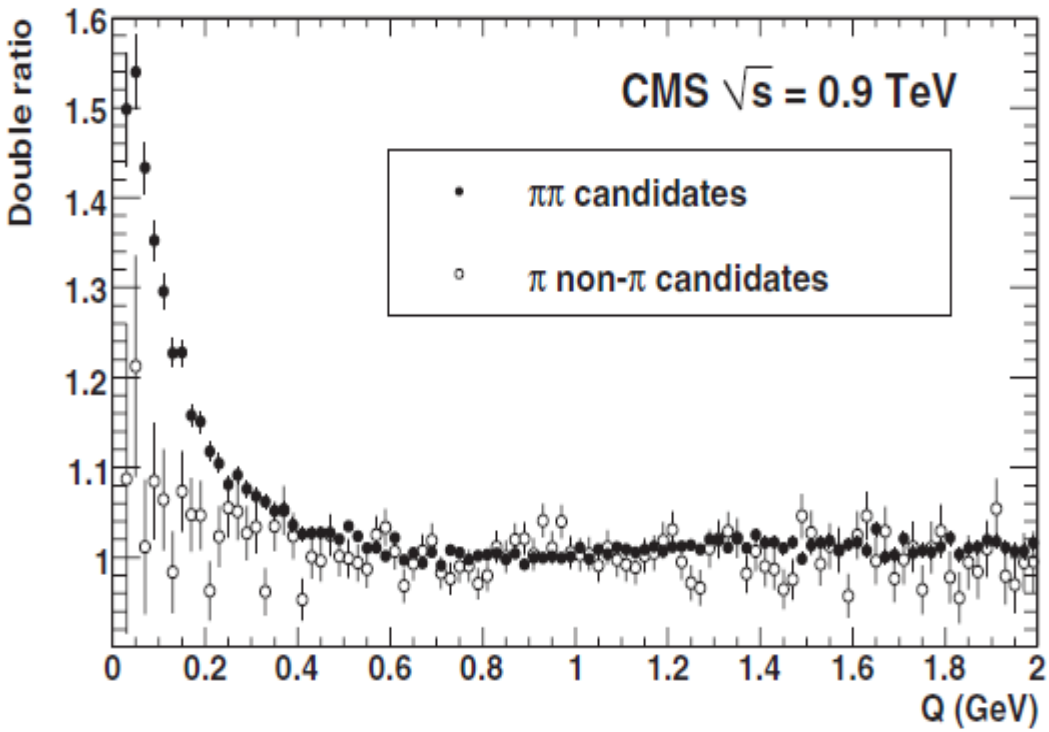
Comparison with (some) previous experiments by rescaling CMS fit results by $1/\sqrt{\pi}$ to translate from exponential to Gaussian parametrization (first moments)



BEC: Cross-check with dE/dx PID

Cross-check BEC by explicatively constructing two samples with either 2 identified π or with an identified π and another particle from dE/dx measurement in CMS tracker





→ **BEC observed only in π–π candidates, not in π-non π !**

→ **Small π–π contamination in π-non π sample (low momentum)**

→ **dE/dx PID not used to construct reference sample**

BEC: Results from each reference sample

Parametrization: $R(Q) = C[1 + \lambda\,\Omega(Qr)](1 + \delta Q)$

$\Omega(Qr)$: Fourier transform of emission region of effective size ***r***

λ : BEC strength δ : Long distance correlations

→ Fit with $\Omega(Qr) = exp(-Qr)$:

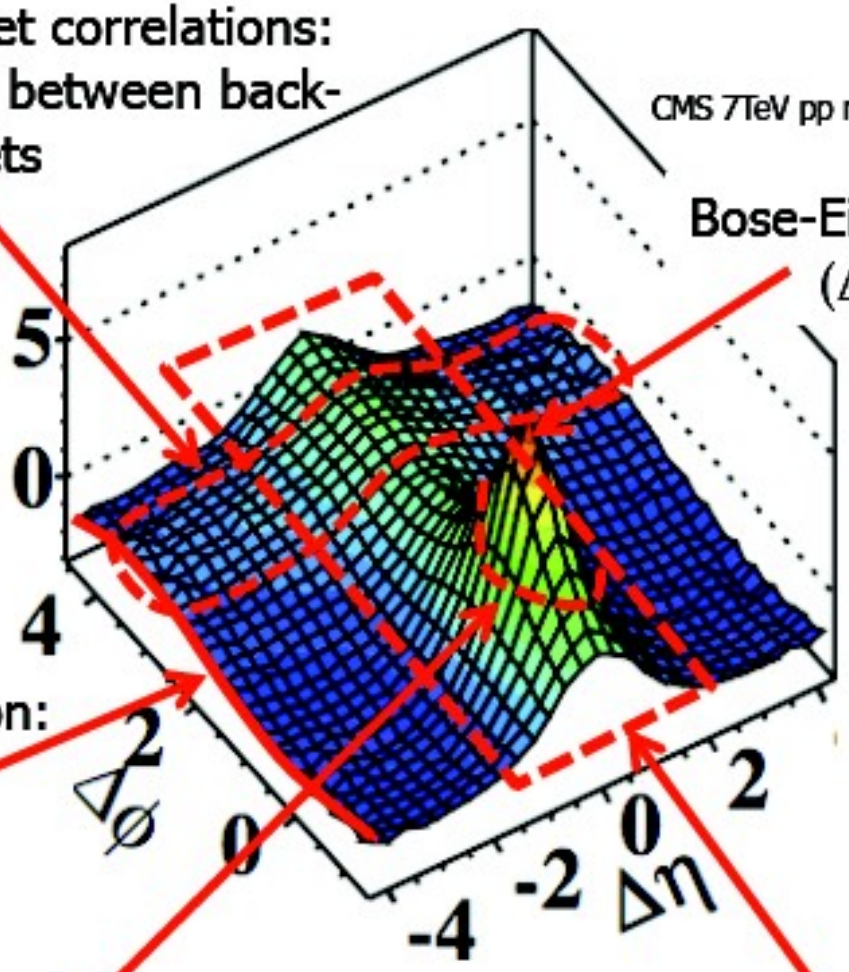
TABLE I. Results of fits to the double ratios $\mathcal{R}(Q)$ for several reference samples, using the parametrization of Eq. (2) with the exponential form, for 0.9 TeV data (left) and 2.36 TeV data (right). Errors are statistical only, and quoted as if independent.

	Results of fits to 0.9 TeV data					Results of fits to 2.36 TeV data				
Reference sample	p value (%)	C	λ	r (fm)	δ (10^{-3} GeV^{-1})	p value (%)	C	λ	r (fm)	δ (10^{-3} GeV^{-1})
Opposite charge	21.9	0.988 ± 0.003	0.56 ± 0.03	1.46 ± 0.06	−4 ± 2	57	1.004 ± 0.008	0.53 ± 0.08	1.65 ± 0.23	−16 ± 6
Opposite hemisphere same charge	7.3	0.978 ± 0.003	0.63 ± 0.03	1.50 ± 0.06	11 ± 2	42	0.977 ± 0.006	0.68 ± 0.11	1.95 ± 0.24	15 ± 5
Opposite hemisphere opposite charge	11.9	0.975 ± 0.003	0.59 ± 0.03	1.42 ± 0.06	13 ± 2	46	0.969 ± 0.005	0.70 ± 0.11	2.02 ± 0.23	24 ± 5
Rotated	0.02	0.929 ± 0.003	0.68 ± 0.02	1.29 ± 0.04	58 ± 3	42	0.933 ± 0.007	0.61 ± 0.07	1.49 ± 0.15	58 ± 6
Mixed events (random)	1.9	1.014 ± 0.002	0.62 ± 0.04	1.85 ± 0.09	−20 ± 2	23	1.041 ± 0.005	0.74 ± 0.15	2.78 ± 0.36	−40 ± 4
Mixed events (same multiplicity)	12.2	0.981 ± 0.002	0.66 ± 0.03	1.72 ± 0.06	11 ± 2	35	0.974 ± 0.005	0.63 ± 0.10	2.01 ± 0.23	20 ± 5
Mixed events (same mass)	1.7	0.976 ± 0.002	0.60 ± 0.03	1.59 ± 0.06	14 ± 2	73	0.964 ± 0.005	0.73 ± 0.11	2.18 ± 0.23	28 ± 5
Combined	2.9	0.984 ± 0.002	0.63 ± 0.02	1.59 ± 0.05	8 ± 2	89	0.981 ± 0.005	0.66 ± 0.07	1.99 ± 0.18	13 ± 4

√s = 900 GeV **√s = 2.36 TeV**

(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

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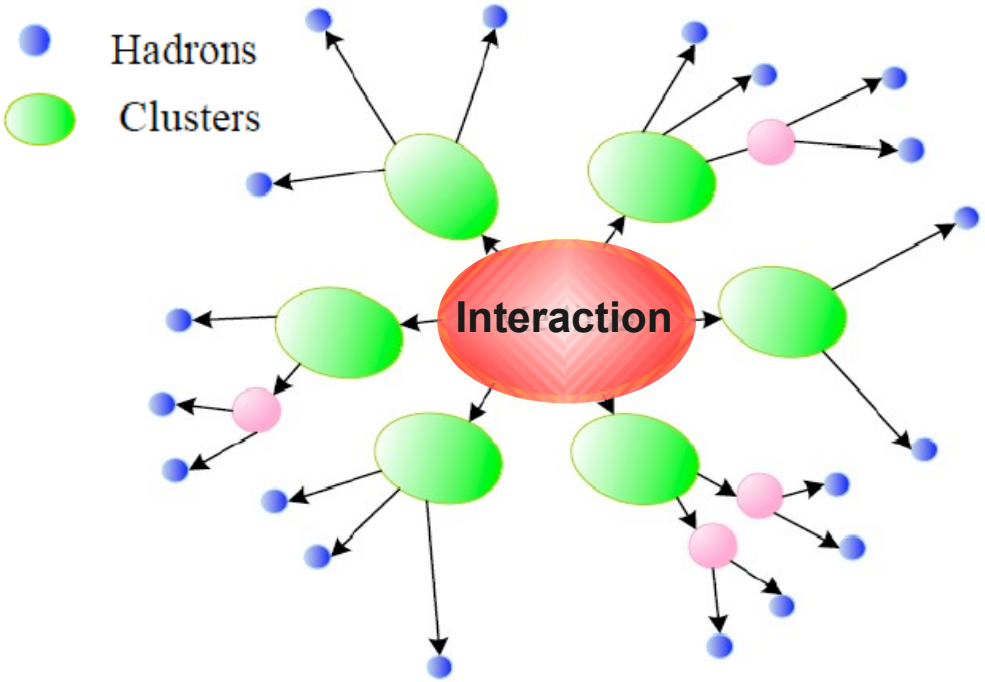
MinBias Results: Independent Cluster Model



Independent Cluster Model (ICM)

- Clusters are produced independently
- Each cluster decay isotropically into hadrons in its own c.m.s.
- Short range correlations can be characterized by 2 parameters:
  - cluster size (K)
  - cluster width (δ)

Functional cluster parametrization vs Δη:

$$\alpha = \frac{\langle K(K-1)\rangle}{K}$$ correlation strength depending of cluster size K distribution

$$R(\Delta\eta) = \alpha\left[\frac{\Gamma(\Delta\eta)}{B(\Delta\eta)} - 1\right]$$ with: $$\Gamma(\Delta\eta) \propto \exp\left[-(\Delta\eta)^2/(4\delta)^2\right]$$ δ : Spread of particles originating from 1 cluster

$B(\Delta\eta)$ Background from mixed events

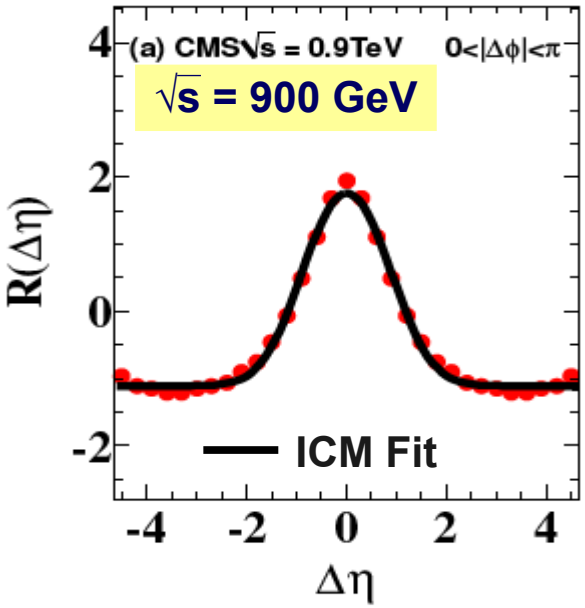
N.B.: ICM is not a fundamental model but provides simple way to quantitatively compare two-particle correlations among experiments and vs MC

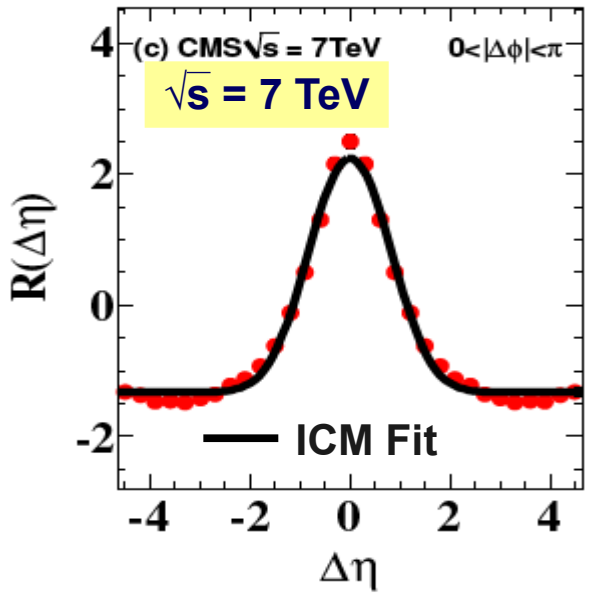
MinBias Results: K_{eff} and δ from ICM Fits

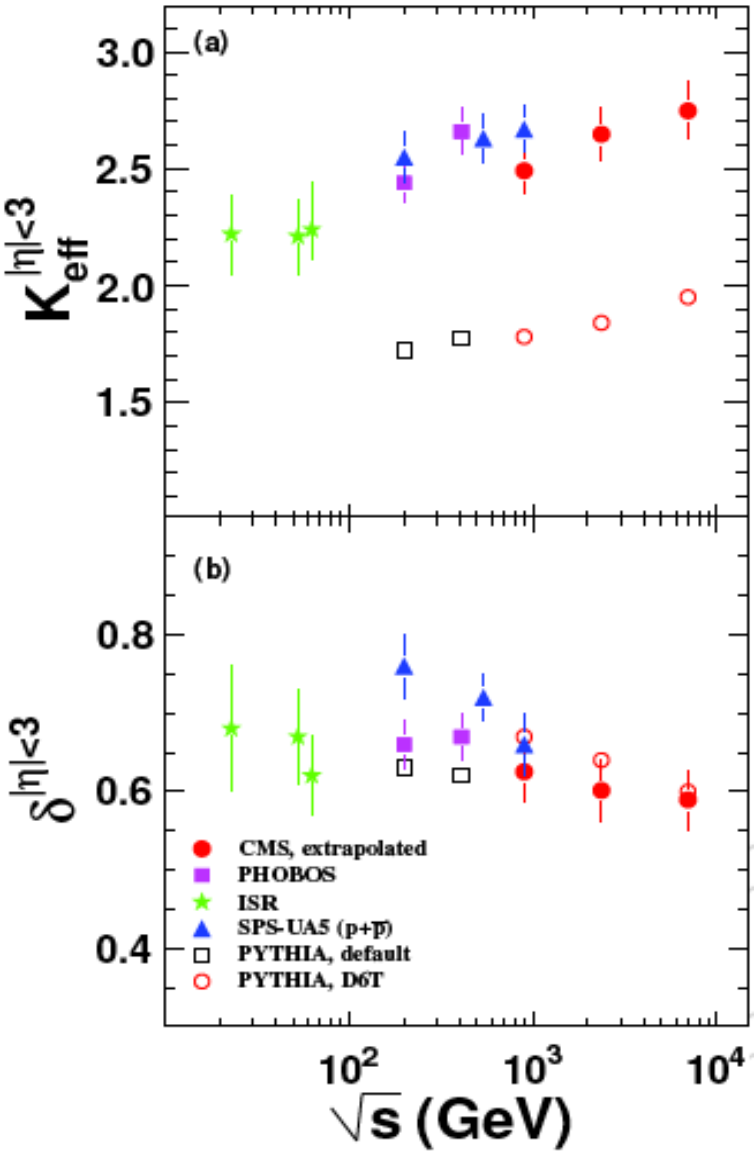
$$R(\Delta\eta)=\left\langle (N-1)\left(\frac{\int S_N(\Delta\eta,\Delta\phi)\,d\Delta\phi}{\int B_N(\Delta\eta,\Delta\phi)\,d\Delta\phi}-1\right)\right\rangle_N$$

$$K_{eff}=\alpha+1=\frac{\langle K(K-1)\rangle}{\langle K\rangle}+1=\langle K\rangle+\frac{\sigma_K^2}{\langle K\rangle}$$

+ extrapolation to $|\Delta\eta|<3$ and $p_T>0$



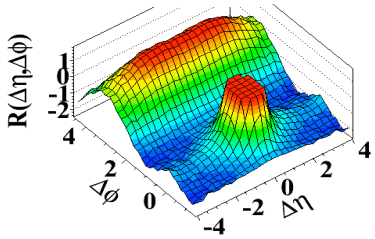




- K_{eff} increase with $\sqrt{s}$ (more jets at high √s ?)
- δ constant with $\sqrt{s}$
- CMS results follow trend from lower $\sqrt{s}$ data
- PYTHIA (D6T) shows similar energy dependencies for K_{eff} and δ as data
- PYTHIA (D6T) predicts too low K_{eff}

Cross Checks

Analysis Code



Analysis Code

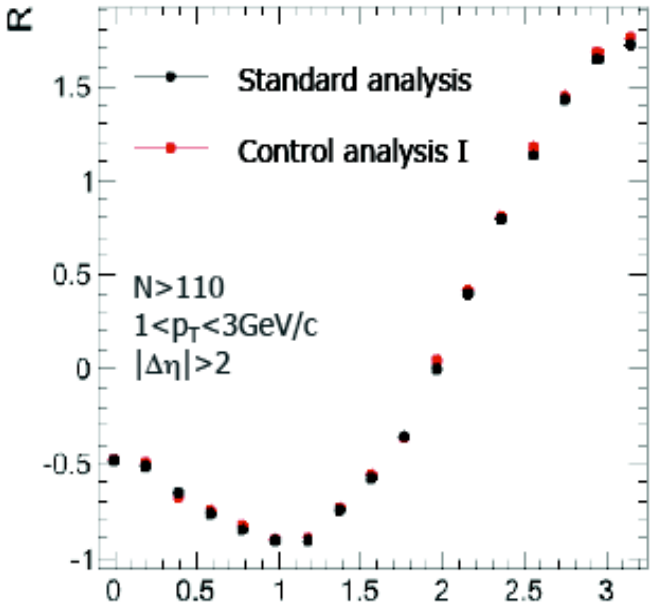
Reconstruction

Trigger

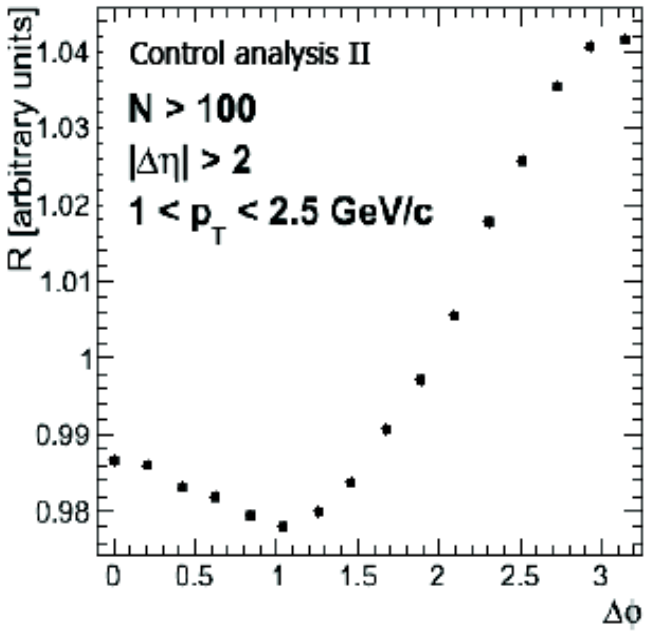
Detector

CMS Event

Collision



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

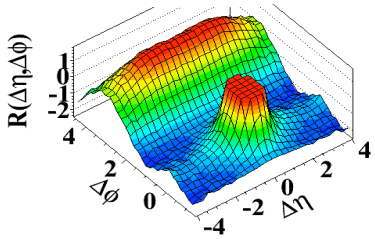


Independent code
Different definition of *R*
Different input file (skim)

Ridge is seen with three independent analysis codes

Cross Checks

Signal and Background



Analysis Code

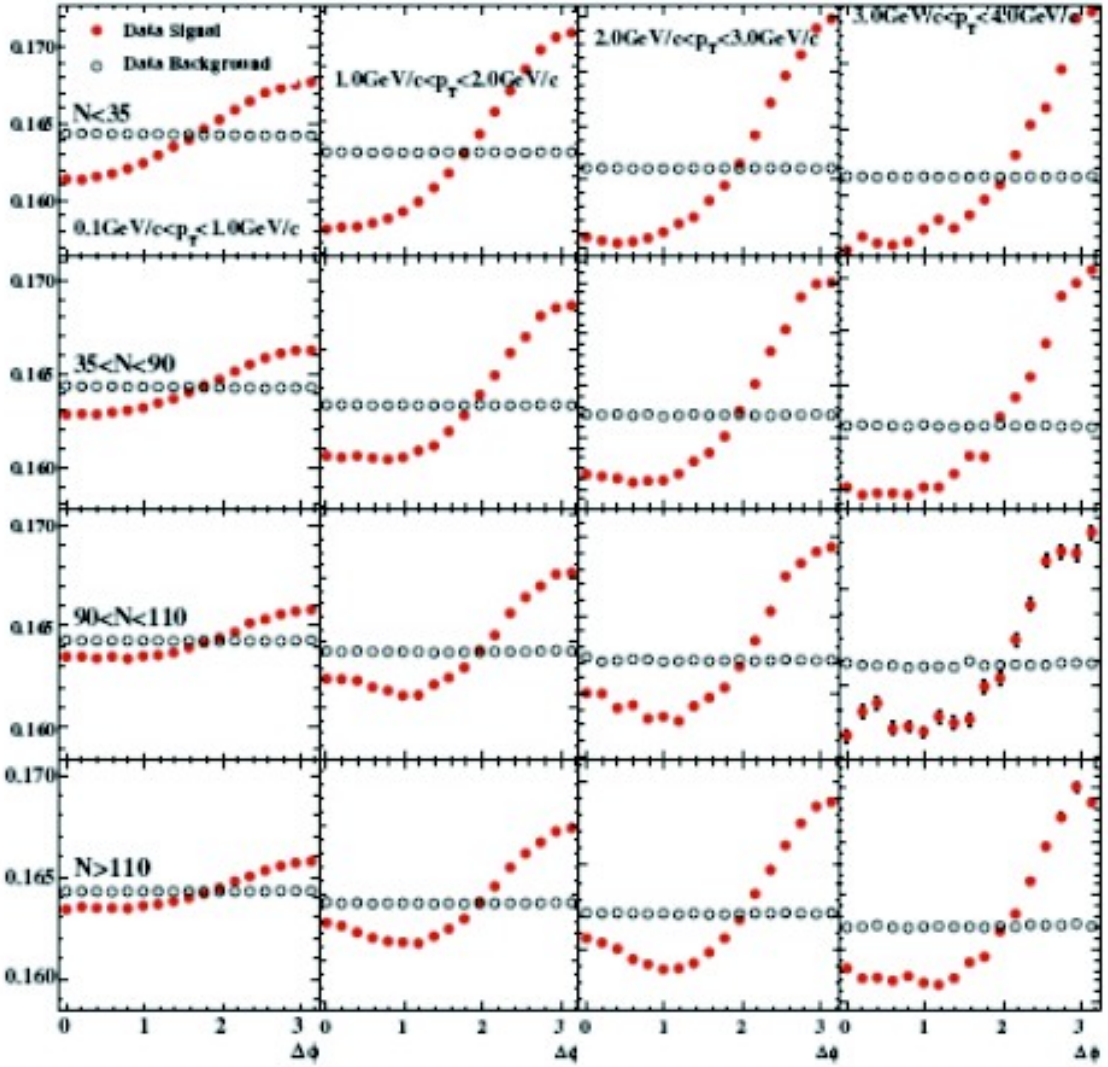
Reconstruction

Trigger

Detector

CMS Event

Collision



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

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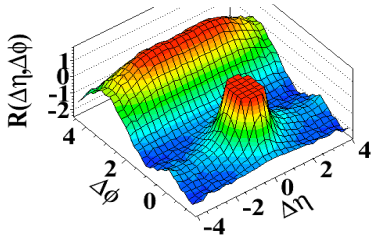
Cross Checks

Reconstruction Code



Analysis Code

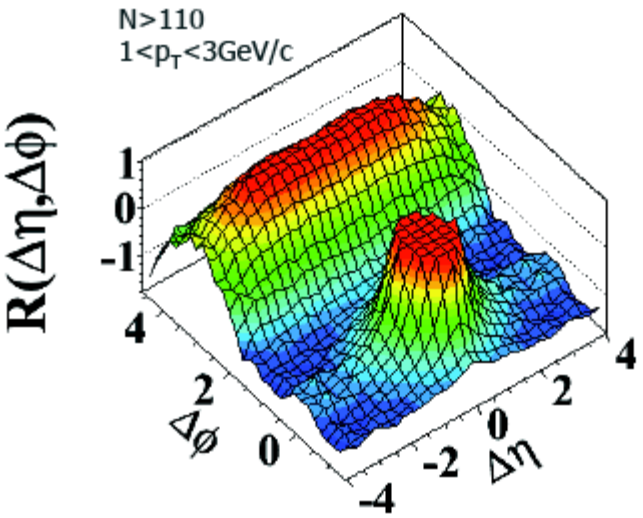
Reconstruction

Trigger

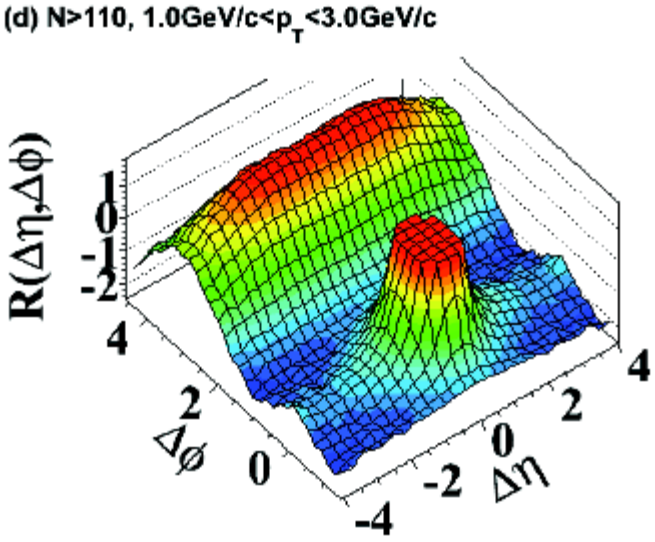
Detector

CMS Event

Collision



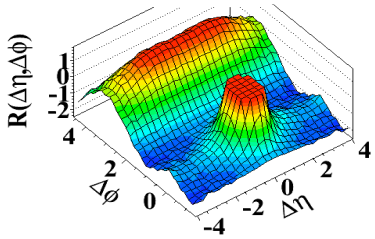
Pixel-only tracks
3 hits in pixel detector



"HighPurity" tracks
Pixel + Silicon Strip tracker

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

Cross Checks



Analysis Code

Reconstruction

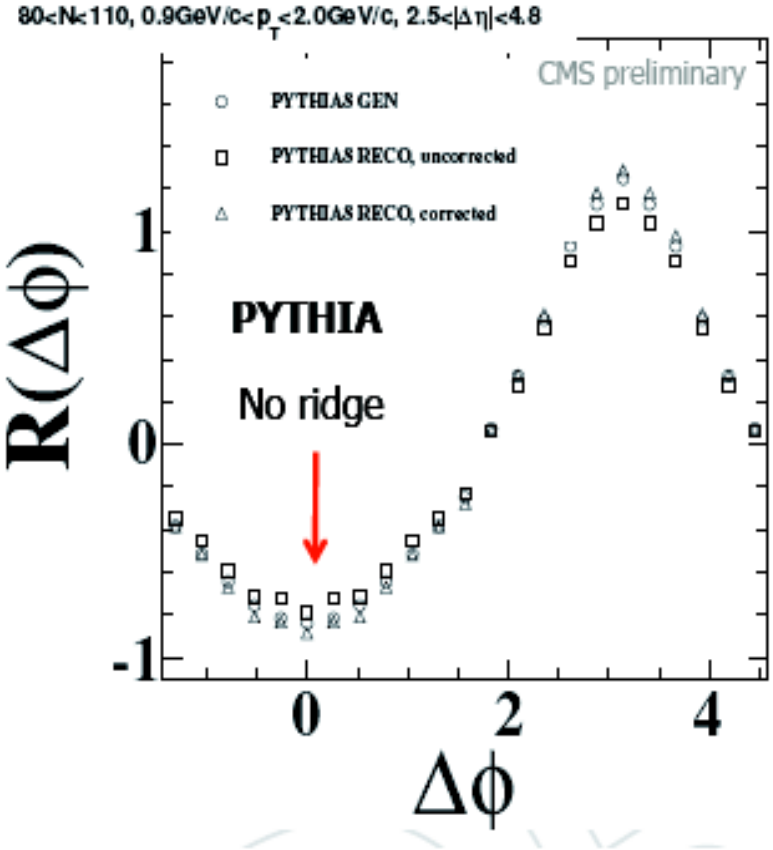
Trigger

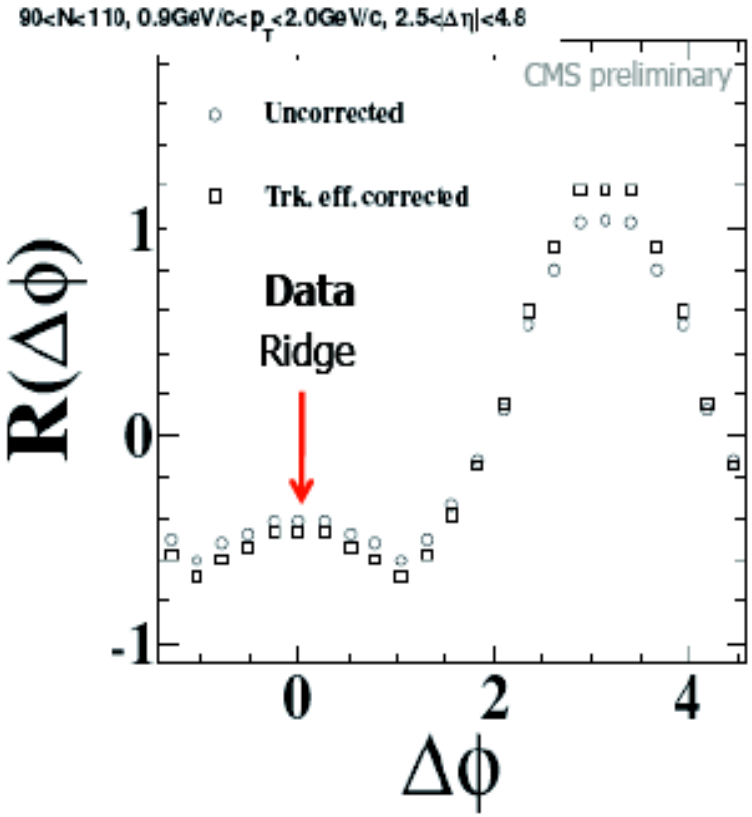
Detector

CMS Event

Collision

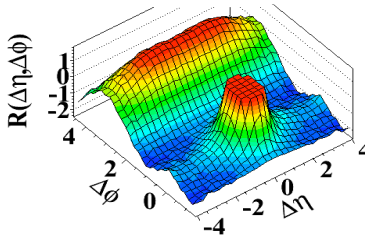
Efficiency Correction





Tracking efficiency correction has small effect on correlation function

Cross Checks



Analysis Code

Reconstruction

Trigger

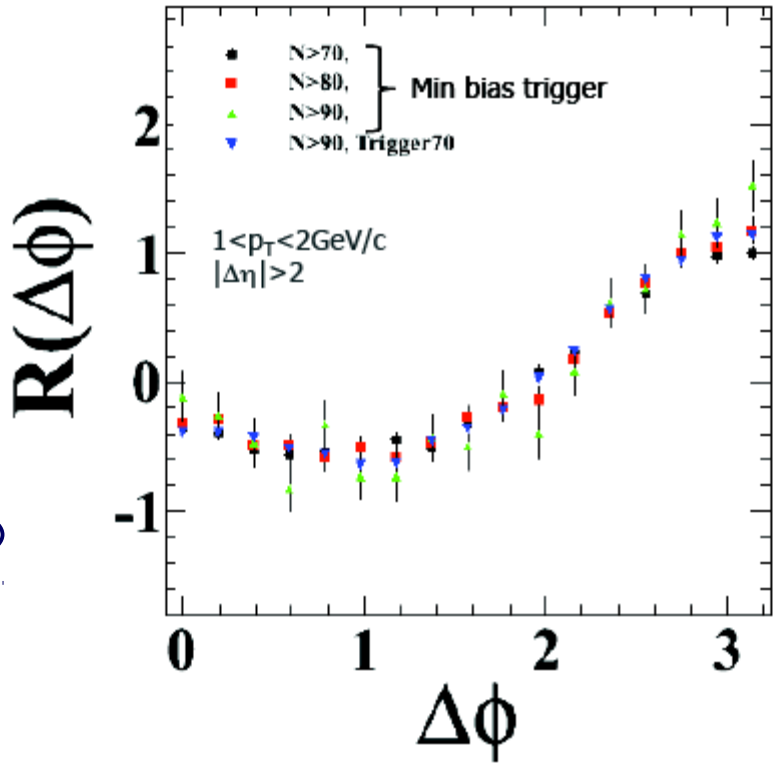
Detector

CMS Event

Collision

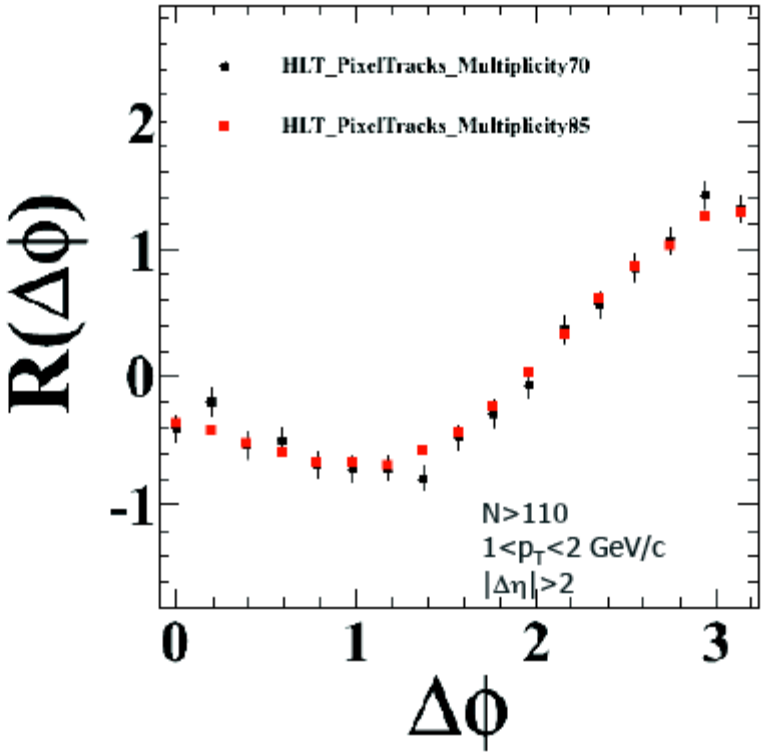
Trigger

Min-bias trigger vs high mult trigger



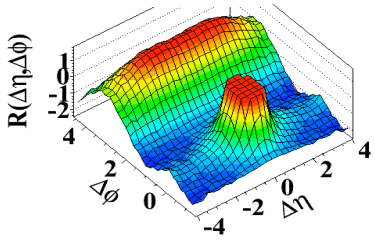
Ridge is seen using
min bias trigger + offline selection

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

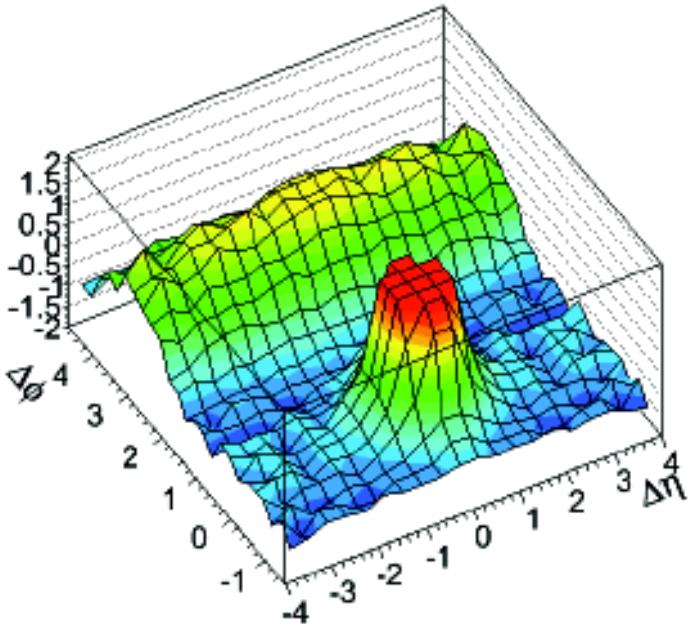
BSC High Multiplicity Trigger

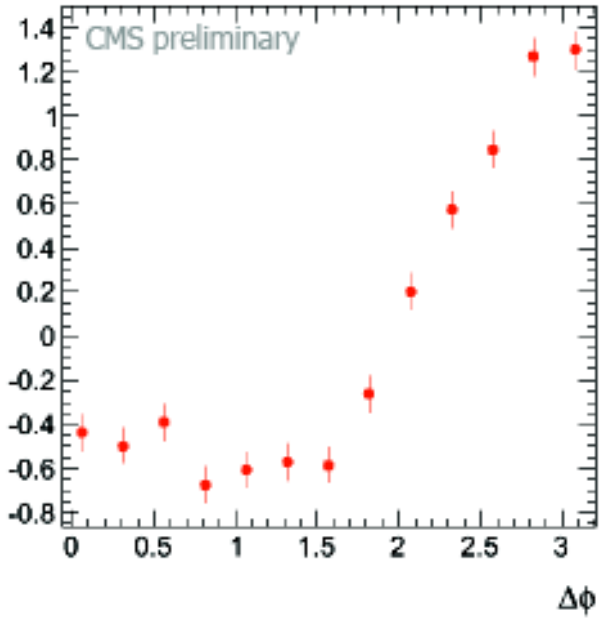
Preliminary results from BSC high multiplicity trigger

N>65

$|\Delta\eta|>2.0$

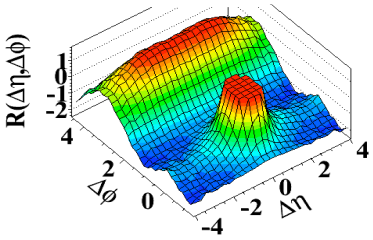
$1.0\text{GeV/c}<p_T<3.0\text{GeV/c}$





Agreement with standard results within statistical uncertainty

Cross Checks



Analysis Code

Reconstruction

Trigger

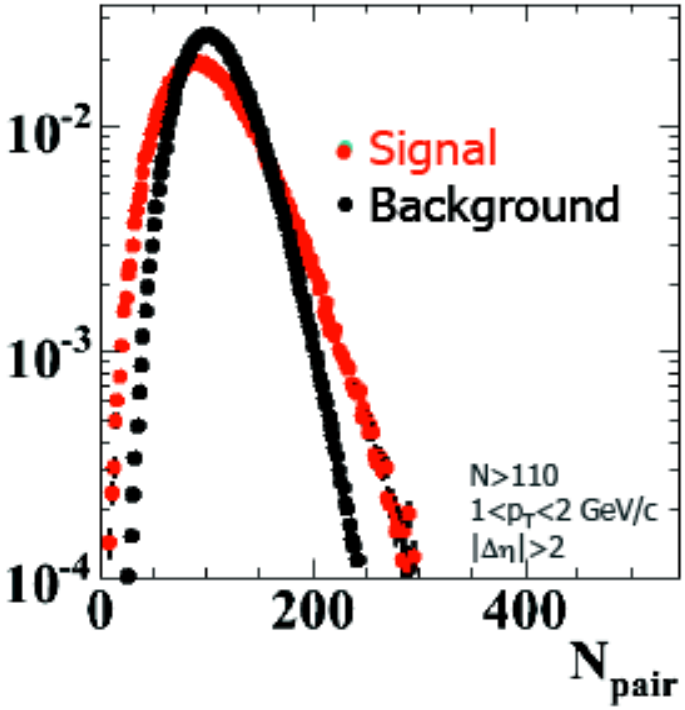
Detector

CMS Event

Collision

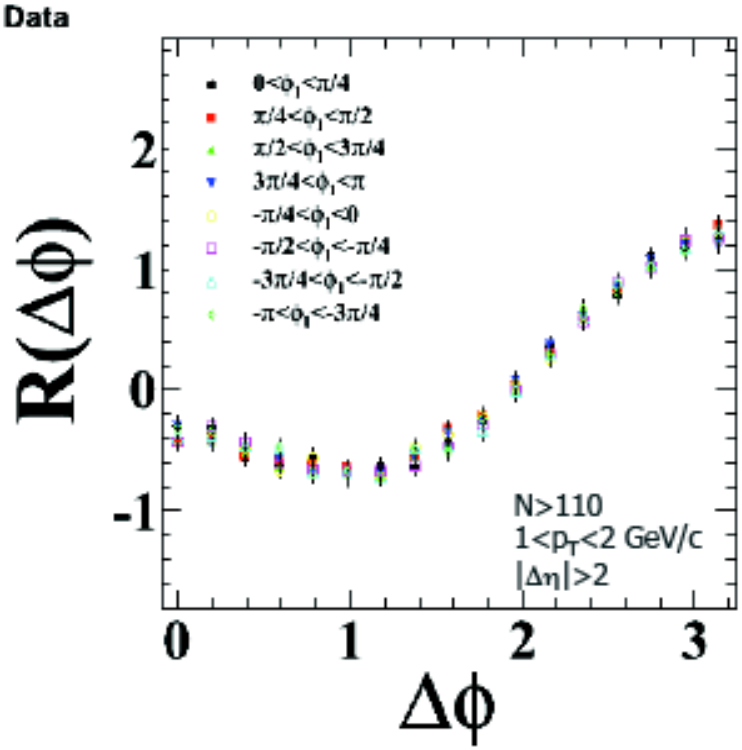
Detector

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



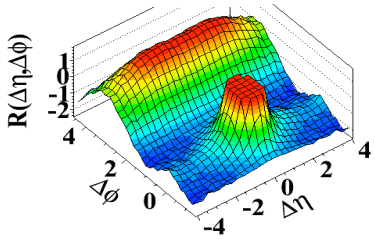
Ridge is not caused by rare events with large # of pairs

Constrain one track to one ϕ octant



Ridge is ϕ symmetric

Cross Checks



Analysis Code

Reconstruction

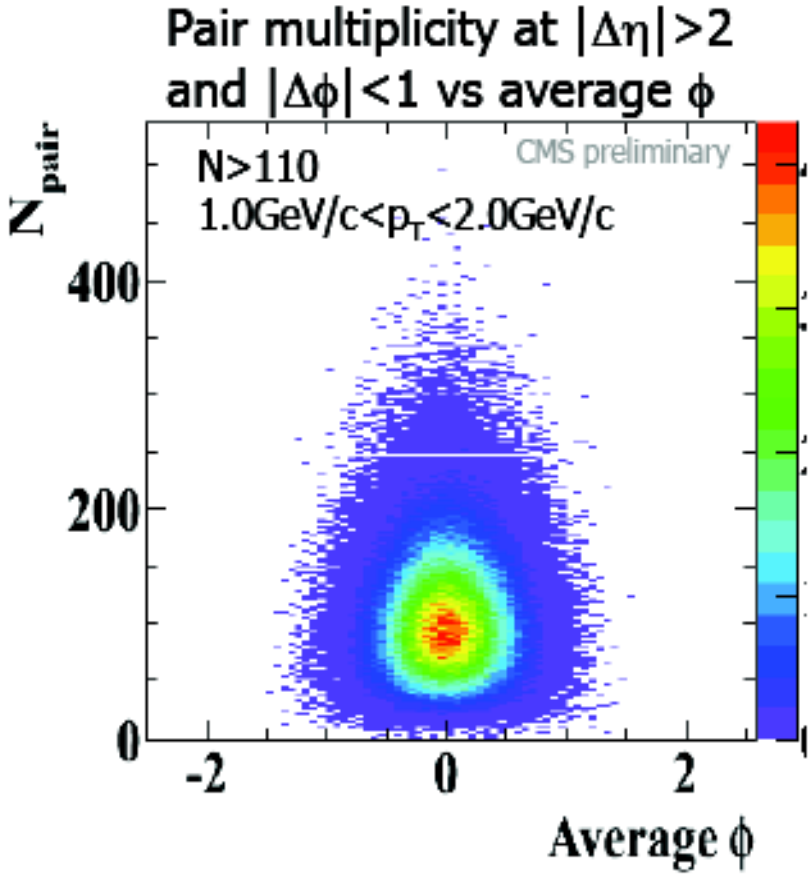
Trigger

Detector

CMS Event

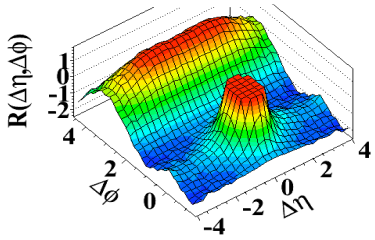
Collision

ϕ Symmetry



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

Cross Checks



Analysis Code

Reconstruction

Trigger

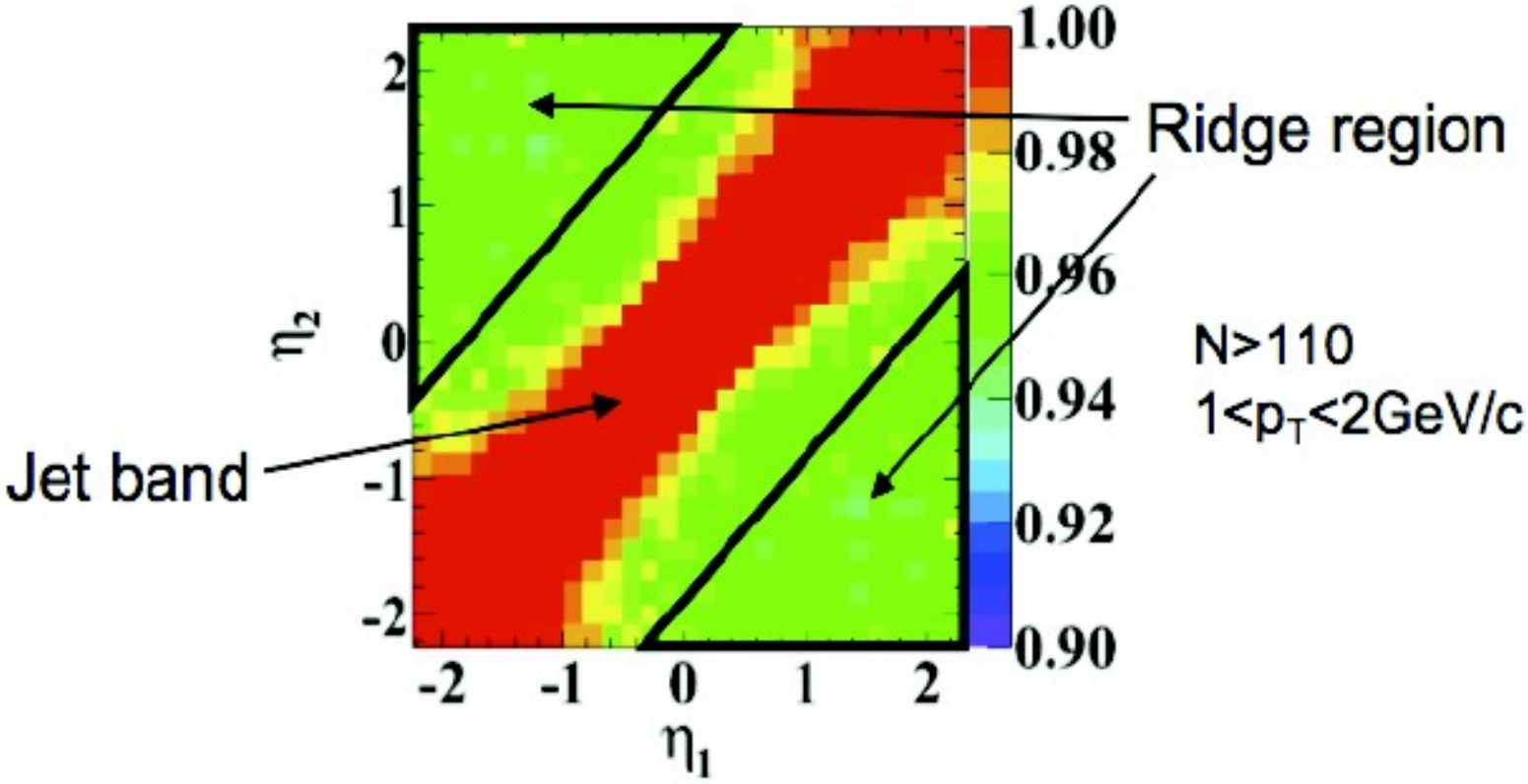
Detector

CMS Event

Collision

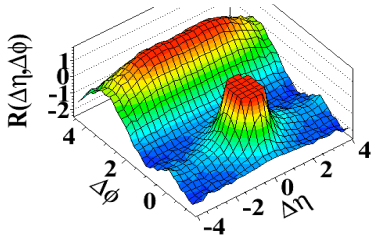
Detector

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

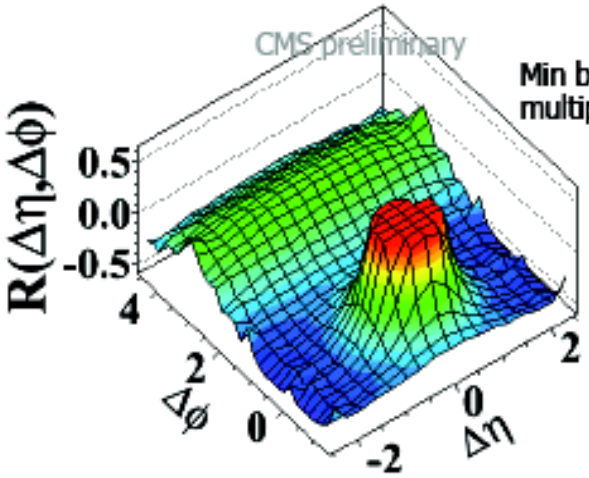
Trigger

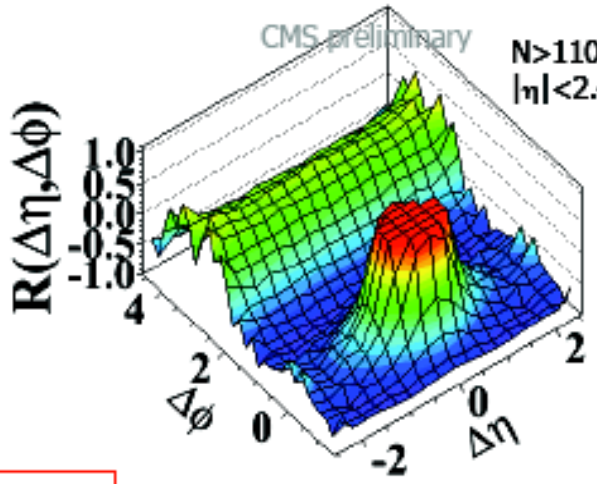
Detector

CMS Event

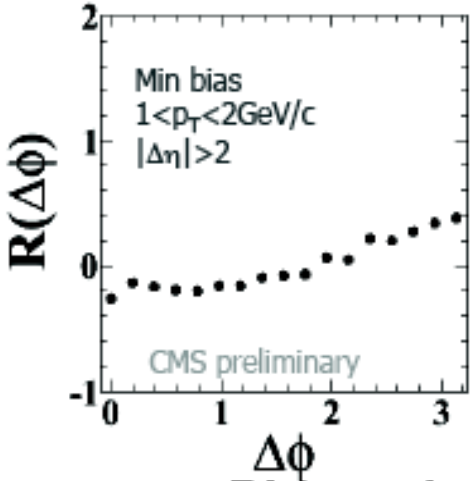
Collision

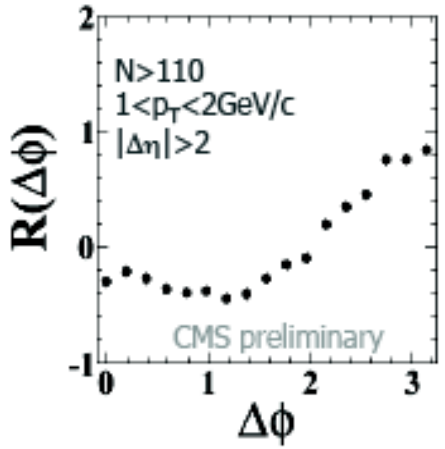
Acceptance Variation





$|\eta| < 1.2$

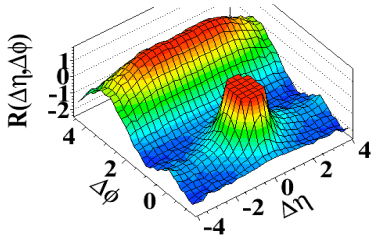




Ridge also seen in reduced acceptance
(but with larger statistical uncertainty)

Cross Checks

Event Backgrounds



Analysis Code

Reconstruction

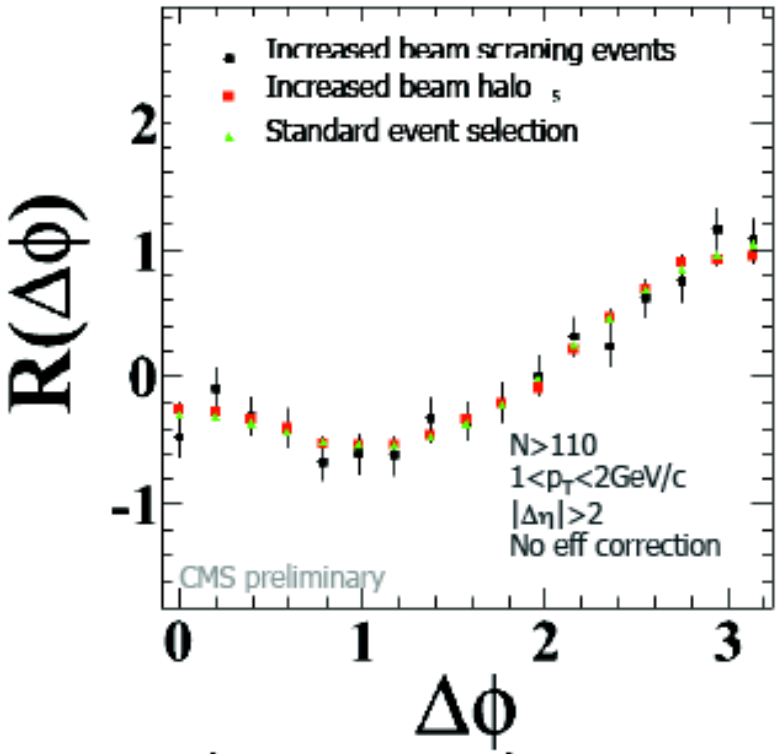
Trigger

Detector

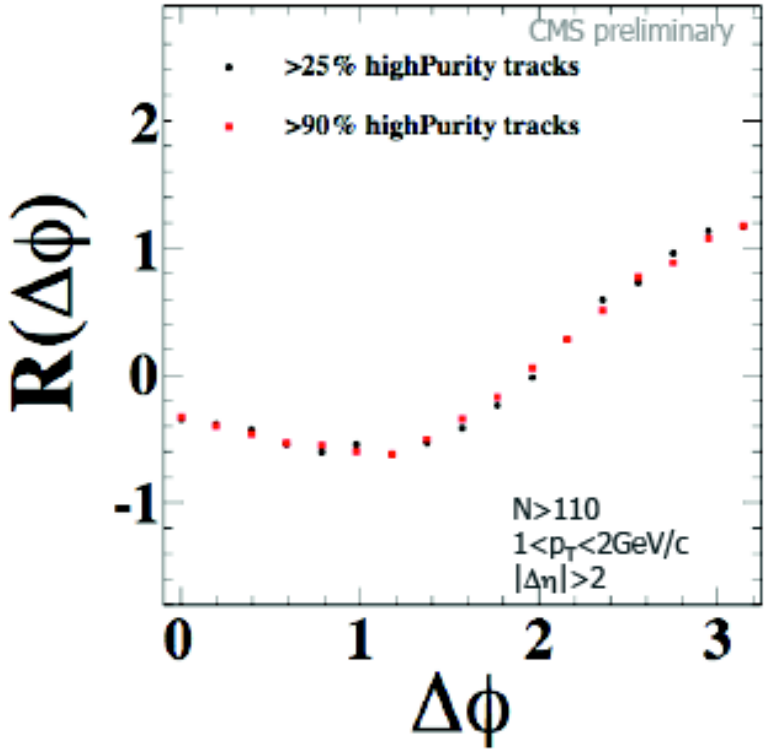
CMS Event

Collision

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



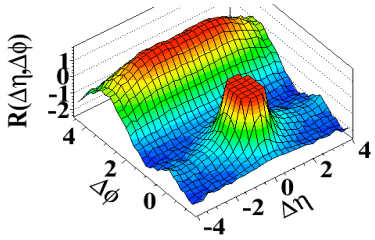
Reject beam background by veto on fraction of low quality tracks



Ridge region shows no sensitivity to beam background

Note: Analysis is done on HighPurity tracks

Cross Checks



Analysis Code

Reconstruction

Trigger

Detector

CMS Event

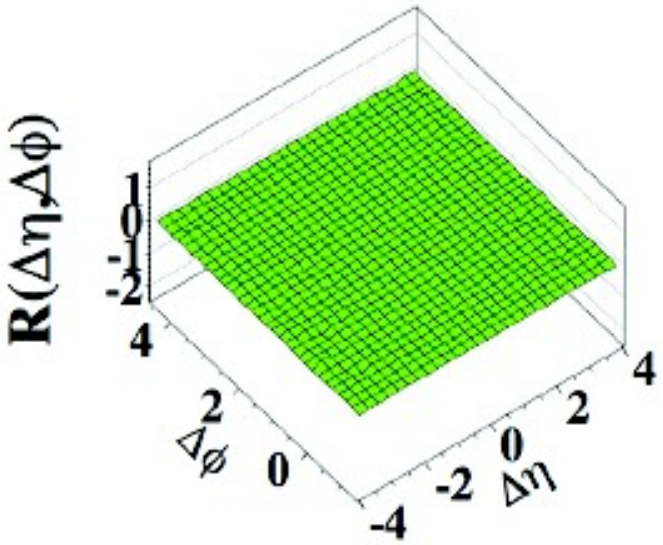
Collision

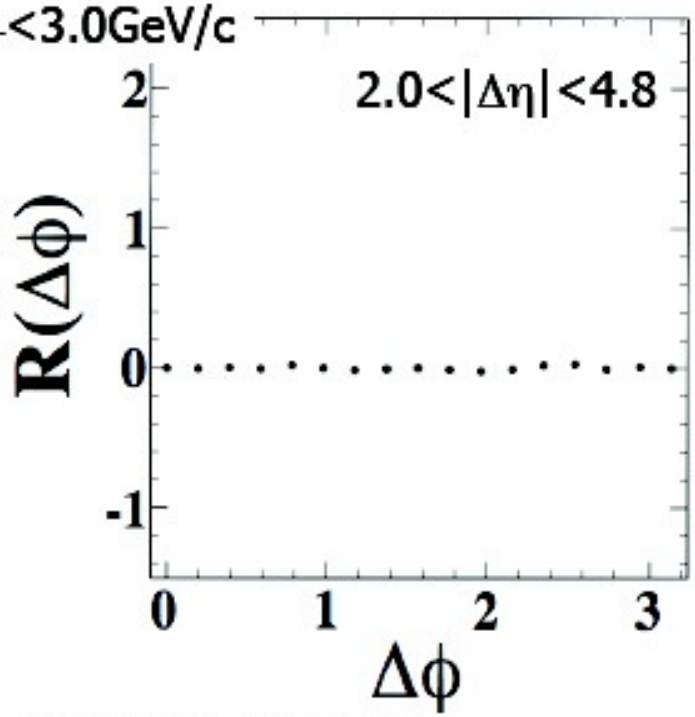
Event Backgrounds

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

N>110

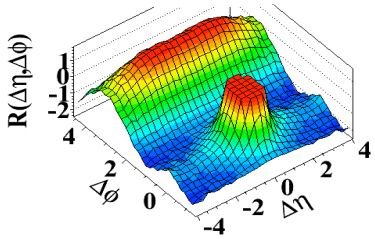
1.0GeV/c<p_T<3.0GeV/c





No background or noise effects seen in cross-collision correlations

Cross Checks



Analysis Code

Reconstruction

Trigger

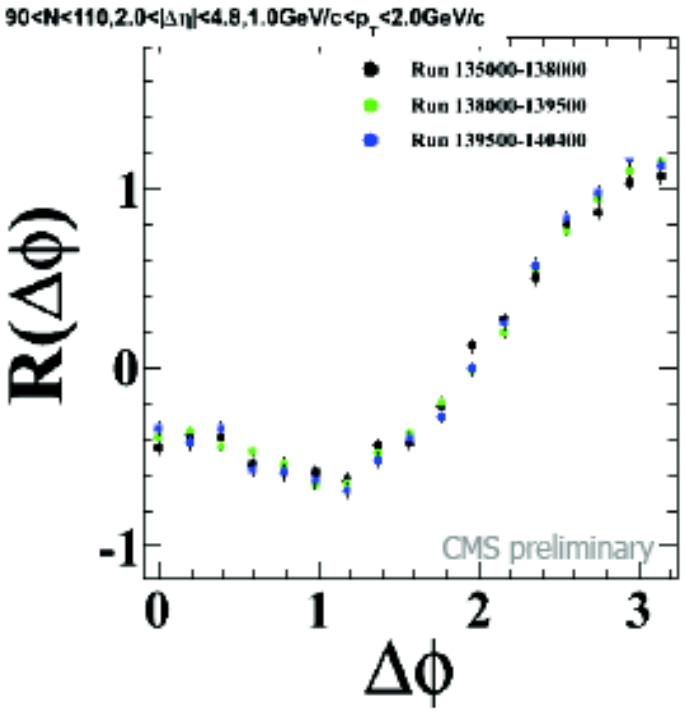
Detector

CMS Event

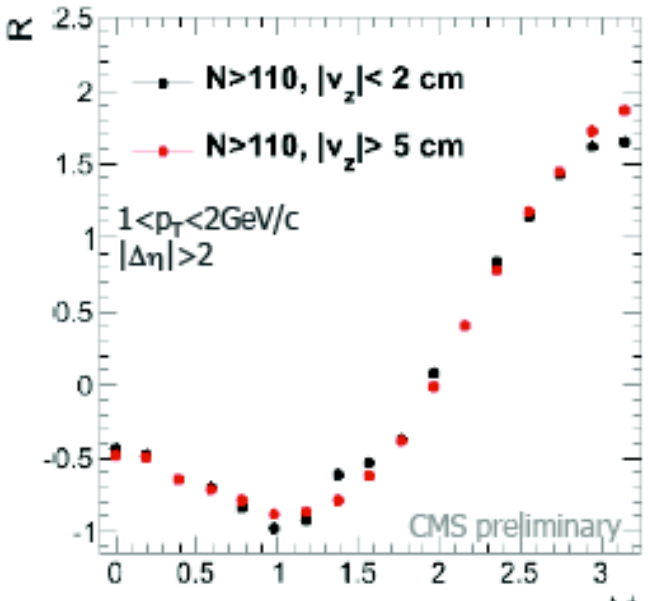
Collision

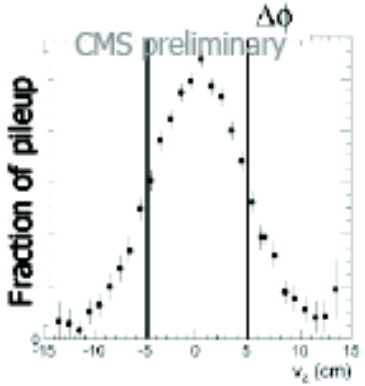
Event Pileup

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



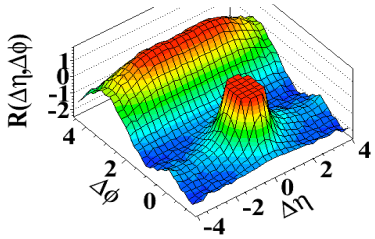
Compare different vertex regions
(fraction of pile-up ~ $dN/dvtx_z$)





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

Cross Checks



Analysis Code

Reconstruction

Trigger

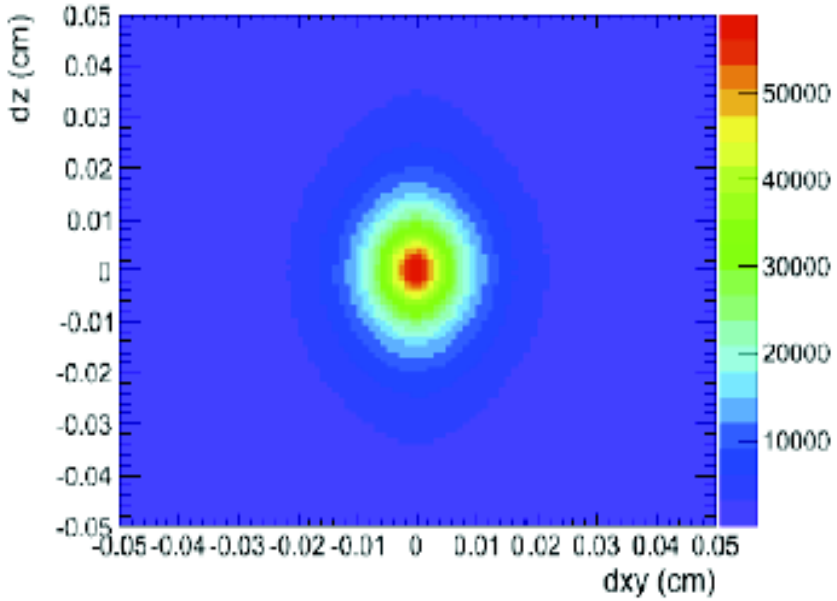
Detector

CMS Event

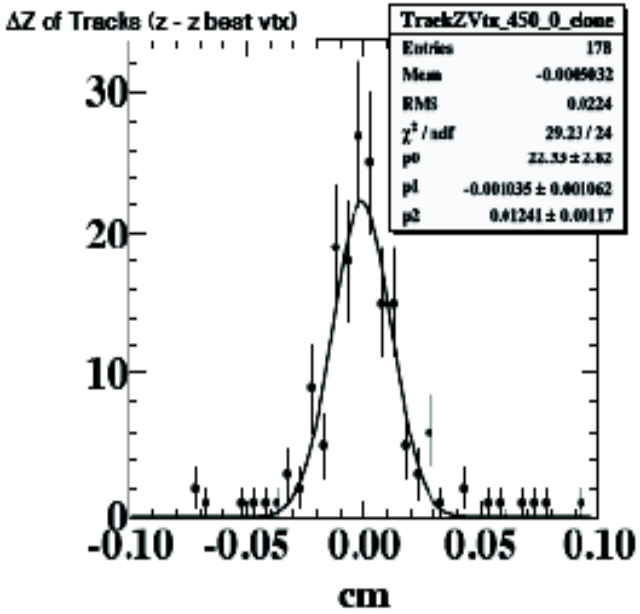
Collision

Event Pileup

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



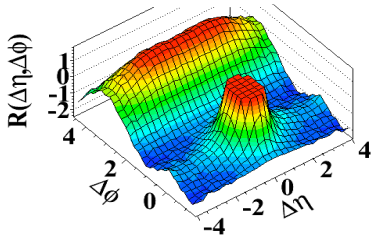
Single-event track dz distribution



Pileup effects are suppressed due to excellent resolution

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

Cross Checks



Analysis Code

Reconstruction

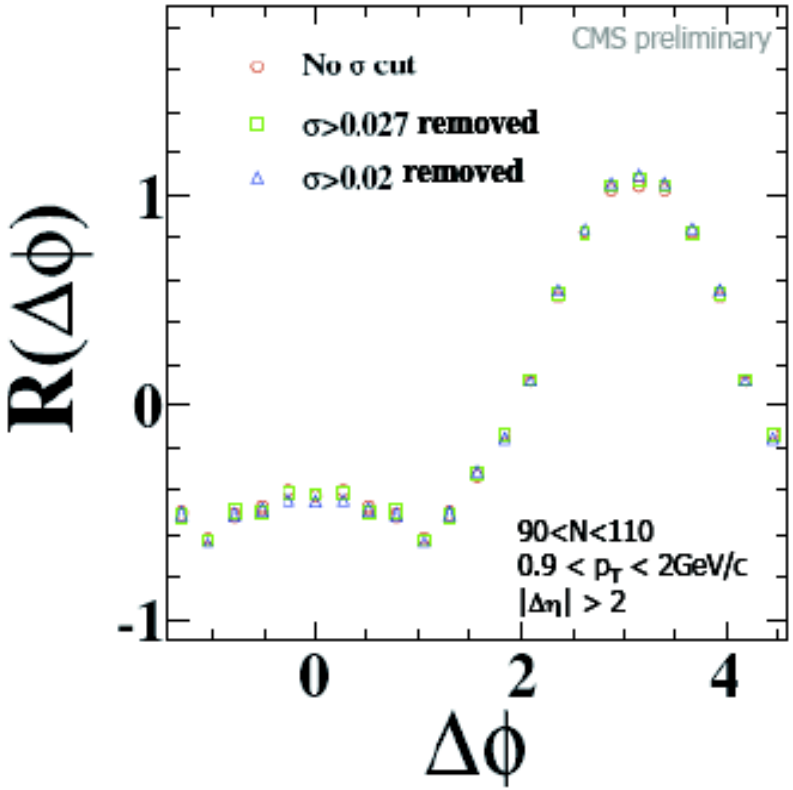
Trigger

Detector

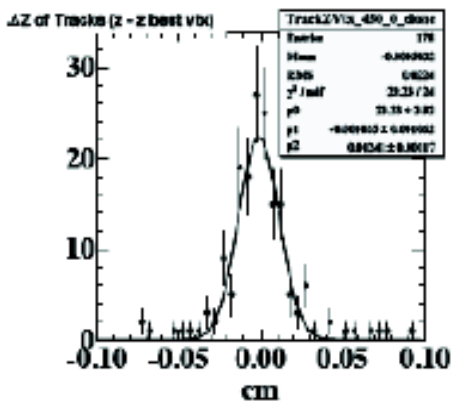
CMS Event

Collision

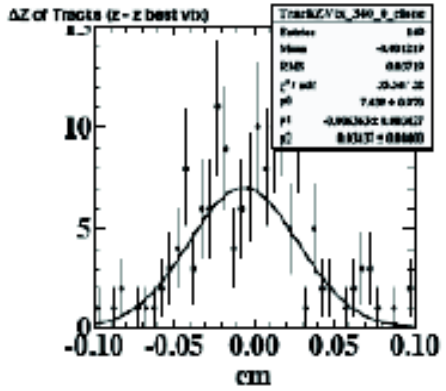
Rejection of "Wide Vertices"



Keep

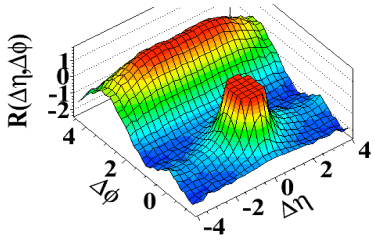


Remove



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

Cross Checks



Analysis Code

Reconstruction

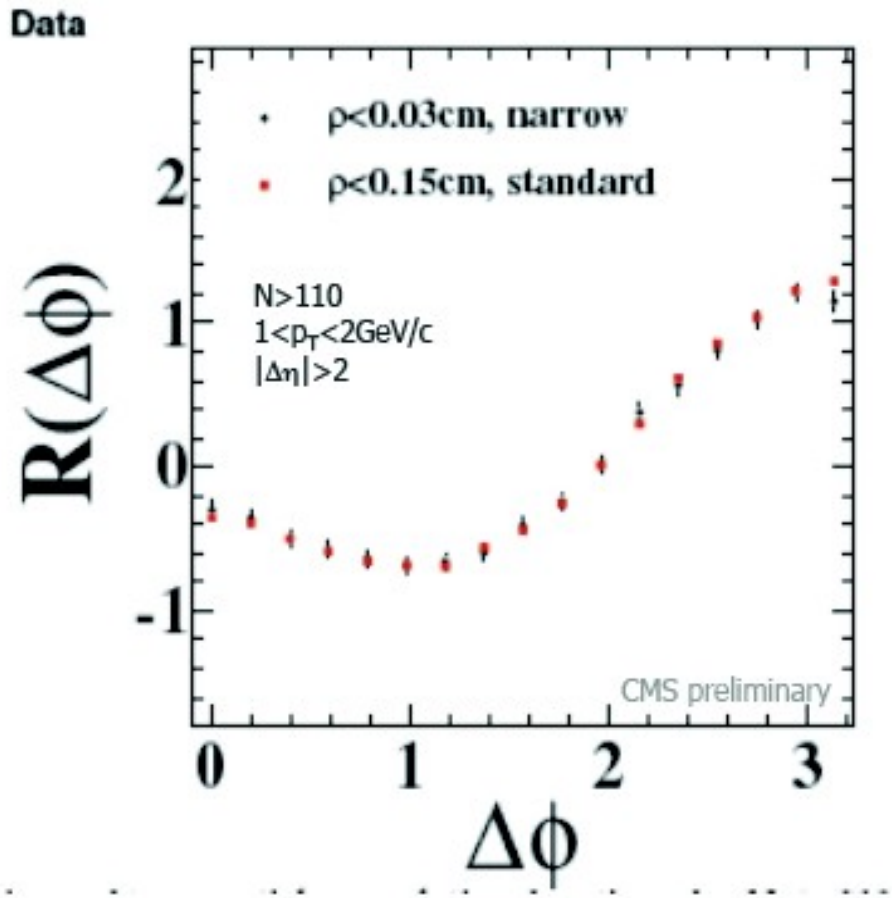
Trigger

Detector

CMS Event

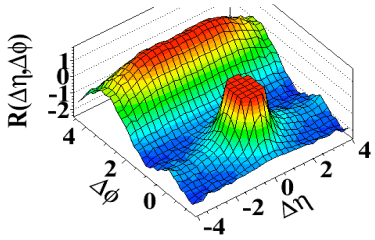
Collision

Select Beamspot "Core"



No dependence on radial distance from center of beam

Cross Checks



Analysis Code

Reconstruction

Trigger

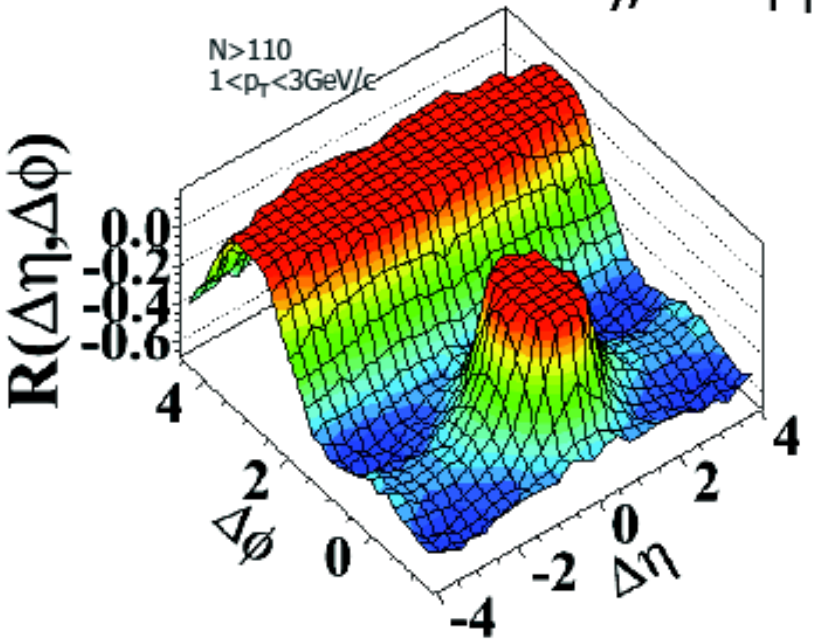
Detector

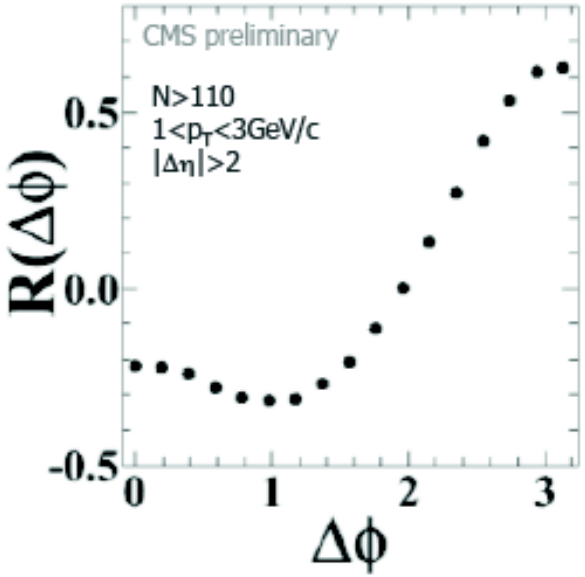
CMS Event

Collision

Final Test: ECAL photons

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

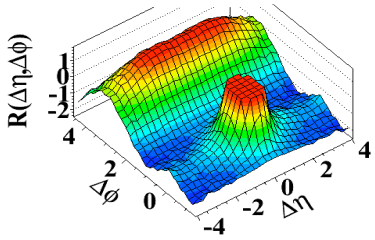




Track-photon correlations

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

Cross Checks



Analysis Code

Reconstruction

Trigger

Detector

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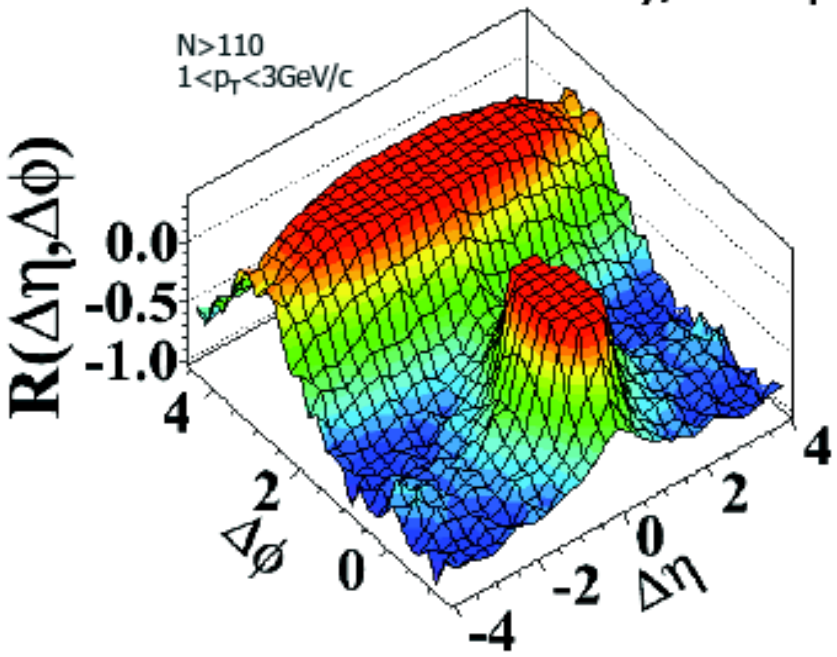
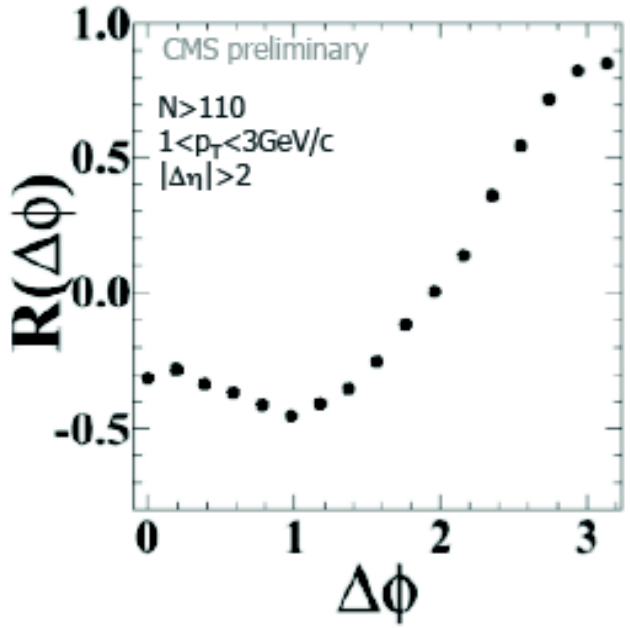
Collision

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

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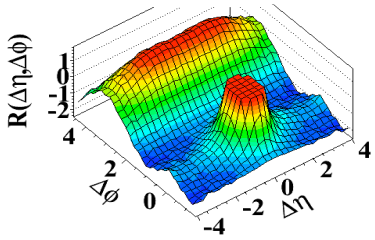
Cross Checks



Analysis Code

Reconstruction

Trigger

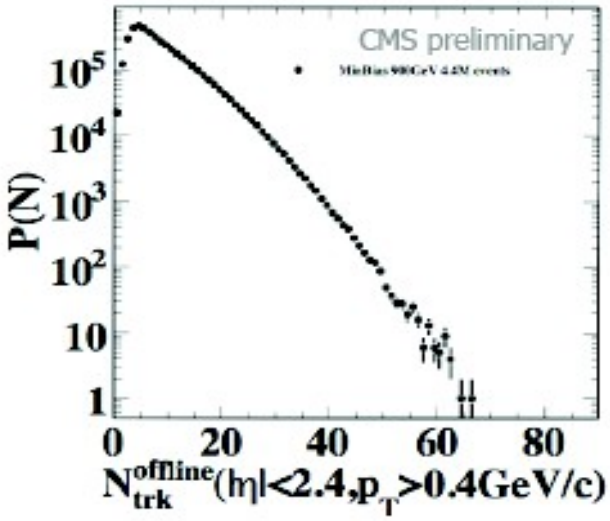
Detector

CMS Event

Collision

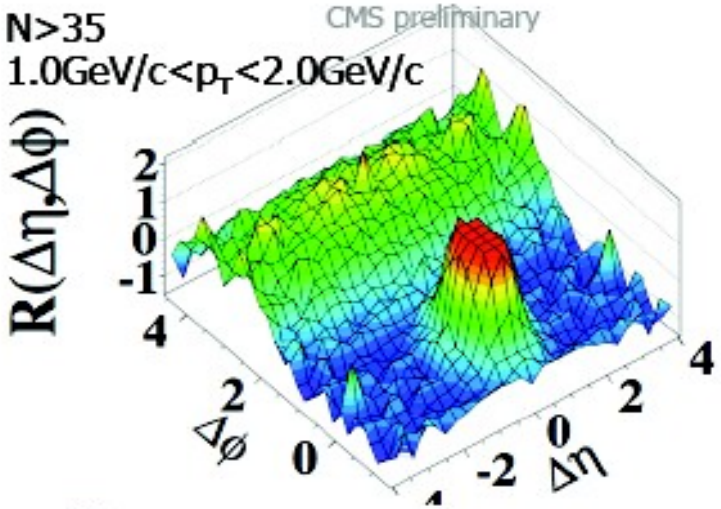
Preliminary 900 GeV Analysis

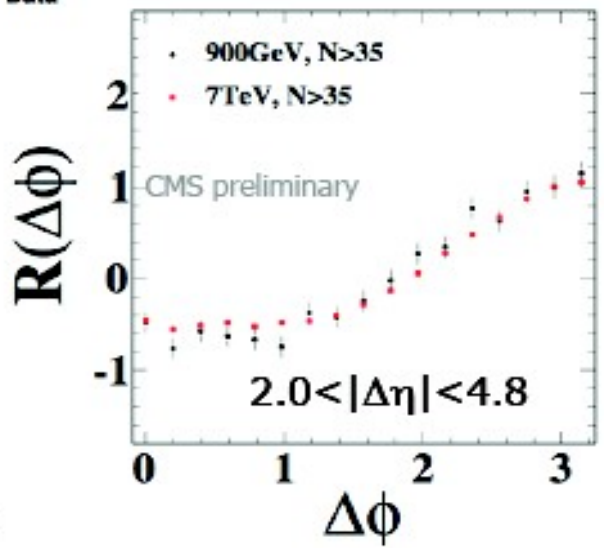
Run 134721, 134725



Limited statistics for high multiplicity events in 900GeV

Two energies agree within large uncertainties





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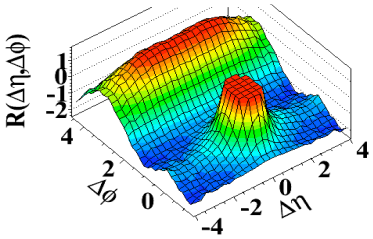
40

Cross Checks



Analysis Code

Reconstruction

Trigger

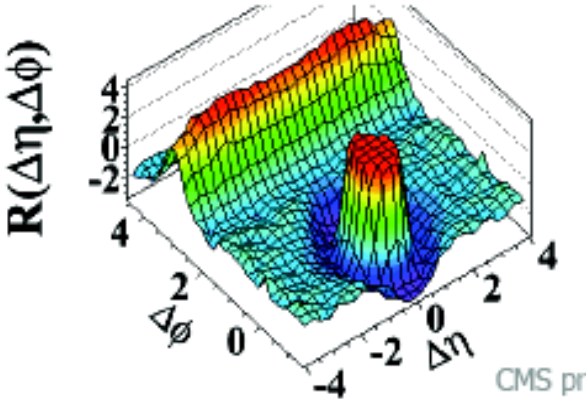
Detector

CMS Event

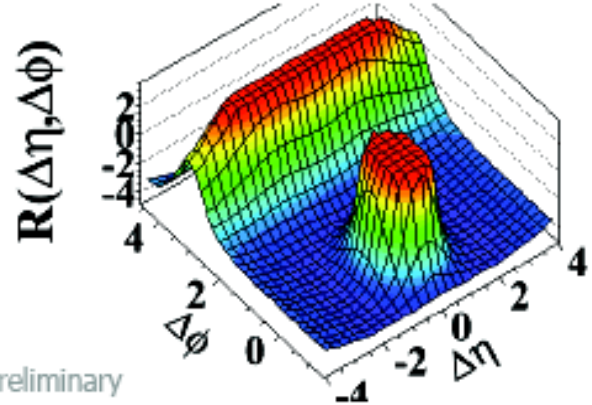
Collision

Other pp Event Generators

PYTHIA D6T MinBias, N>70



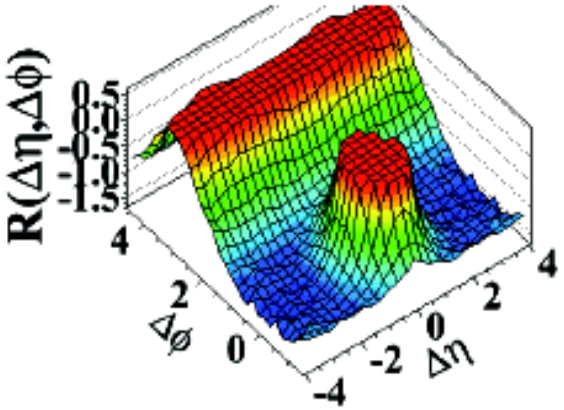
PYTHIA D6T, Dijet 80-120GeV



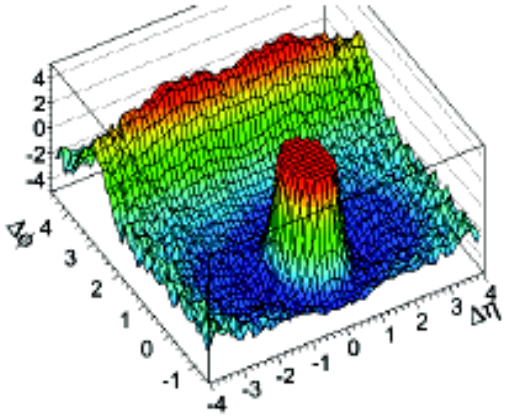
CMS preliminary

$1<p_T<3$GeV/c

HERWIG++, N>110

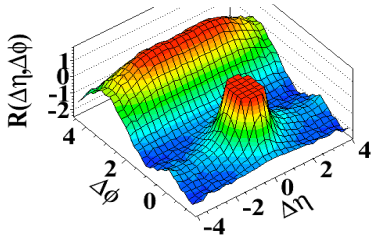


Madgraph, Dijet 100-250GeV, N>90



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

Cross Checks



Analysis Code

Reconstruction

Trigger

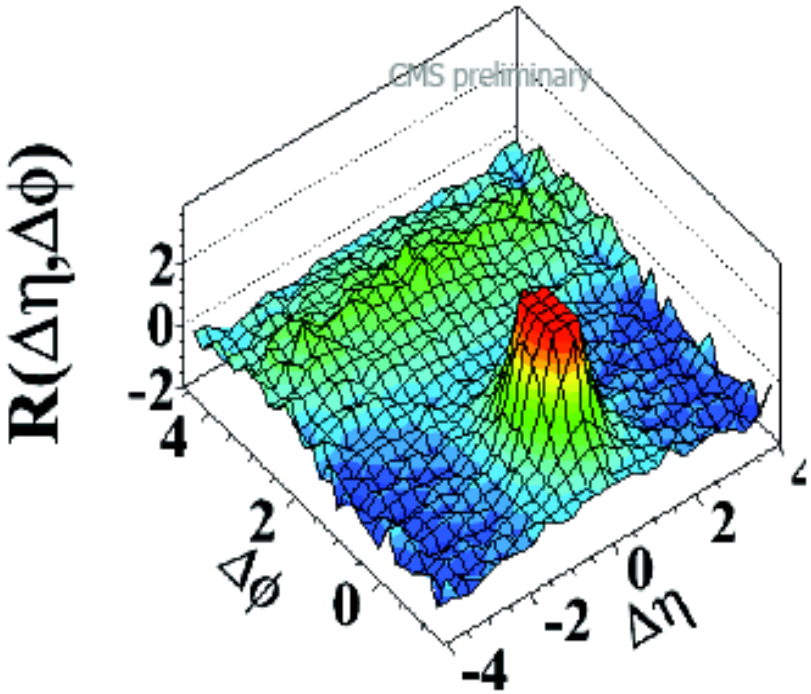
Detector

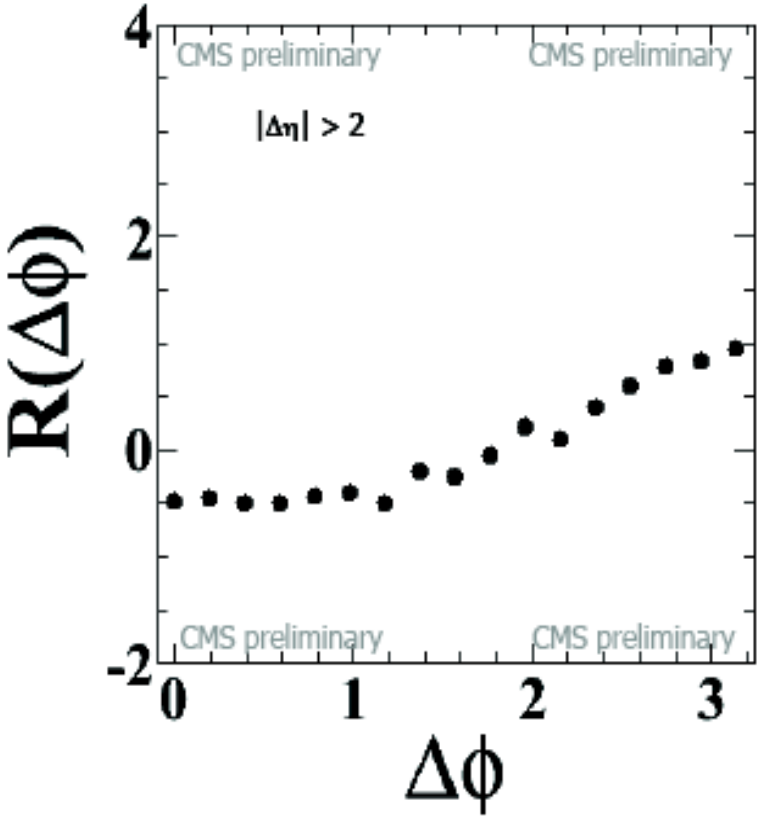
CMS Event

Collision

(Multi-) Jet Events

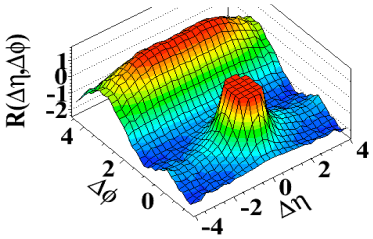
$N_{jet}>=4$, $N_{trk}<50$, $1<p_T<2$GeV/c





More work needed to explore connection to jet correlations

Cross Checks



Analysis Code

Reconstruction

Trigger

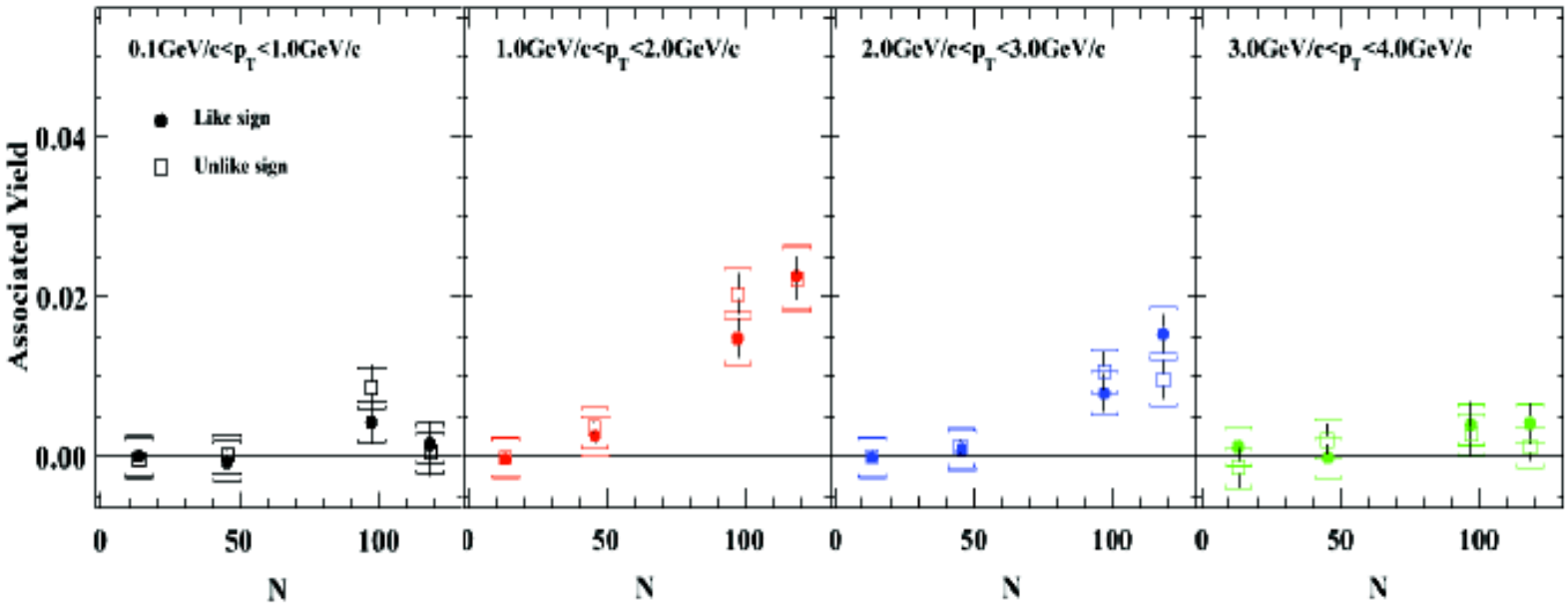
Detector

CMS Event

Collision

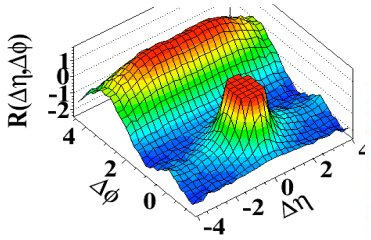
Like-Sign vs Unlike-Sign

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



No dependence on relative charge sign

Cross Checks



Analysis Code

Reconstruction

Trigger

Detector

CMS Event

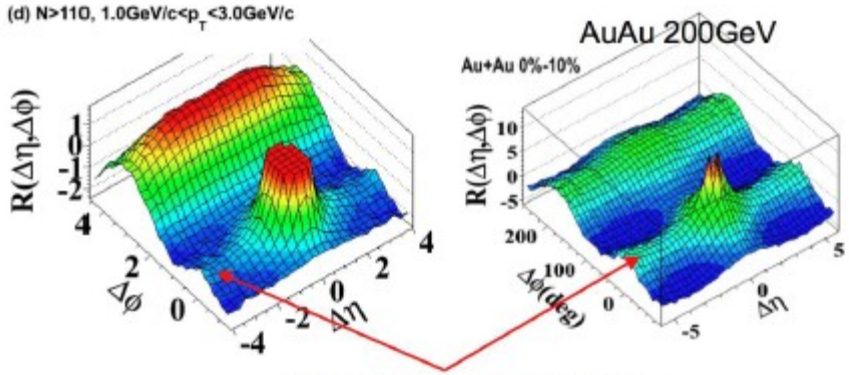
Collision

First observation of a ridge-like structure in pp collisions

The new feature is clearly seen for large rapidity differences $2 < |\Delta\eta| < 4.8$ in events with N ~ 90 or higher. The enhancement is most evident in the intermediate p_T range $1 < p_T < 3$ GeV/c.

This is the first observation of such a long-range, near-side feature in two-particle correlation functions in pp or p-pbar 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)