

Low P_t Physics with CMS



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On behalf of the CMS Collaboration



*LHC Days in Split
October 4-9 2010*



Low-Pt Physics: the full CMS Menu



Underlying Event
Activity



Underlying Event
from JetArea/
Median

Charged Hadron
spectra



Charged Hadron
Multiplicities



Long-Range
Near-Side Angular
Correlations



Bose-Einstein
Correlations



Strangeness
Production



Forward Energy
Flow



Observation of
Diffraction





My trimmed Menu for today



Underlying
Event Activity



Charged
Hadron
Multiplicities



Charged
Hadron
Multiplicities



Long-Range
Near-Side Angular
Correlations



Observation
of Diffraction





Ingredients for these measurements



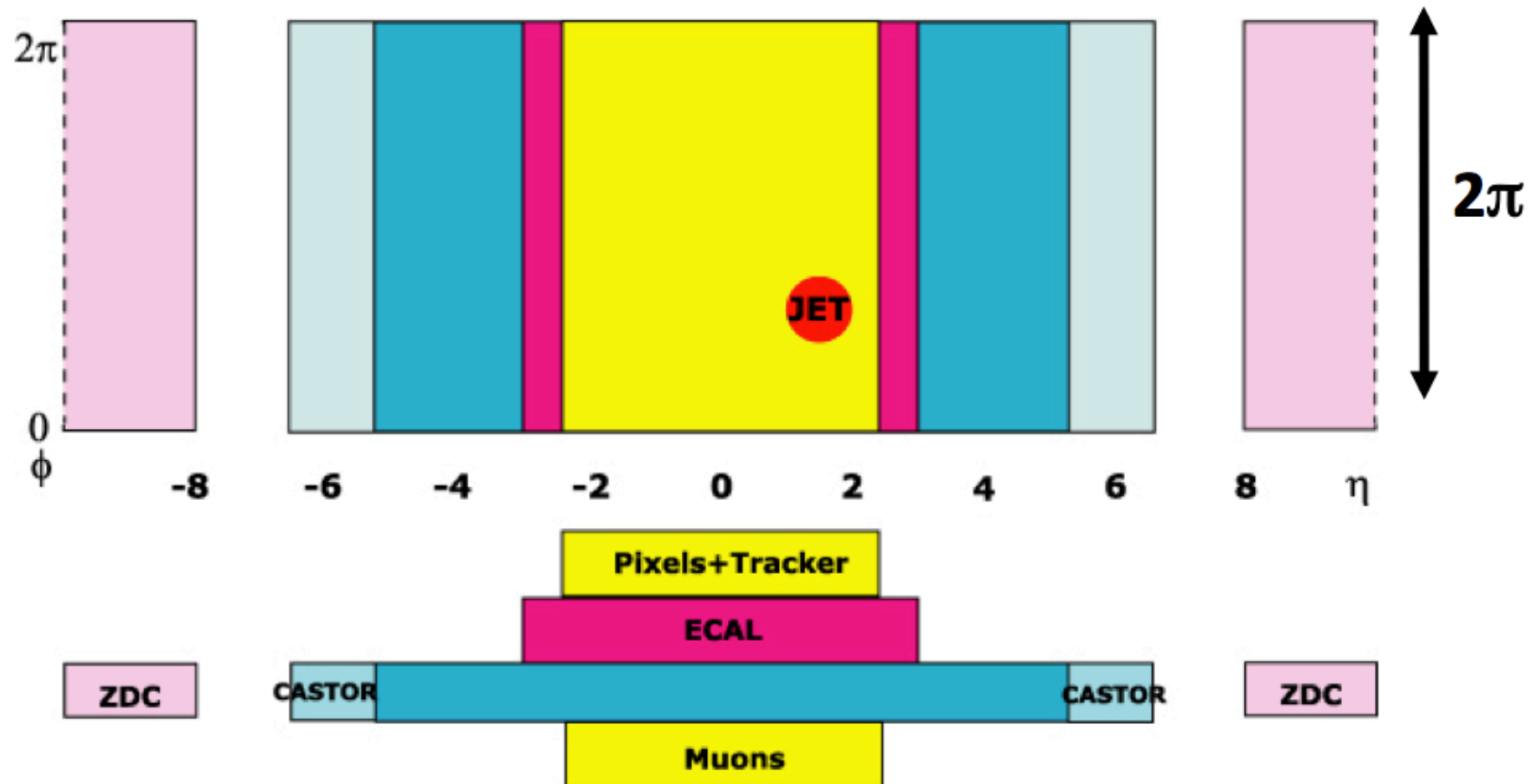
The CMS coverage

Full azimuthal calorimetric coverage for CMS

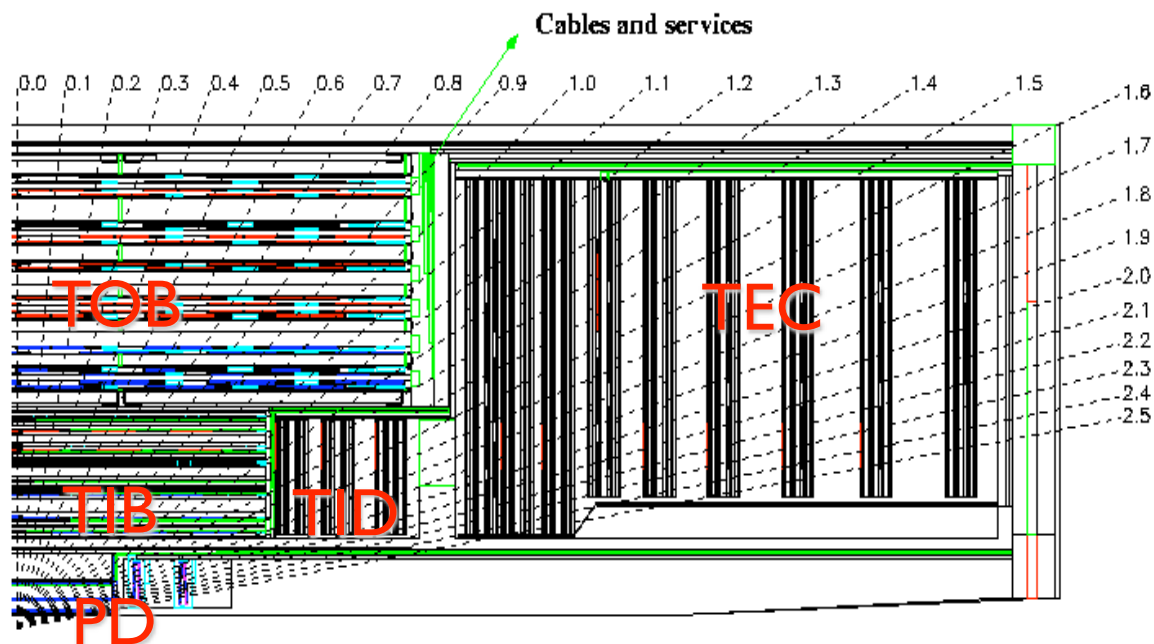
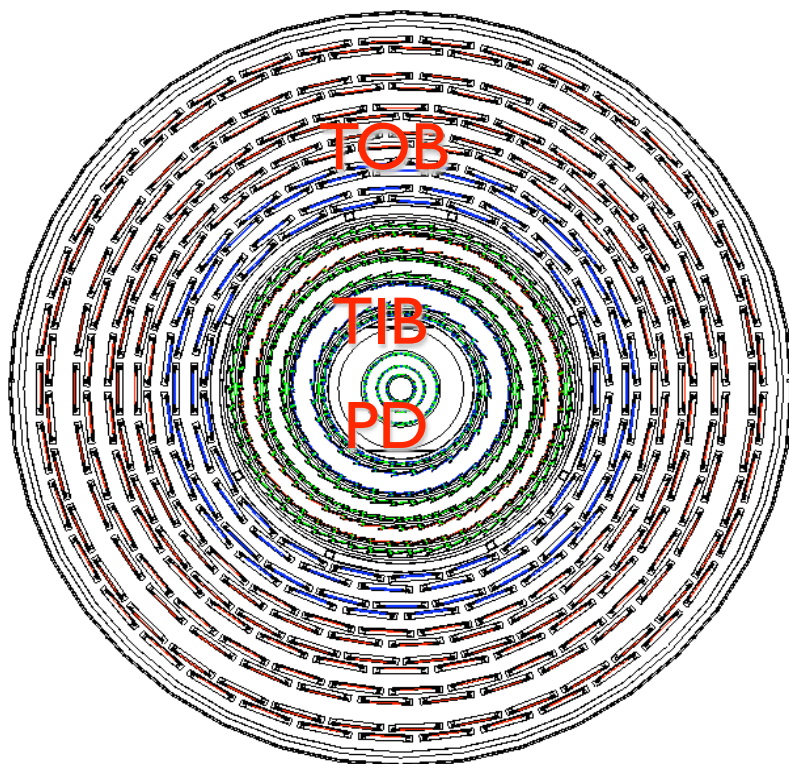
$\Delta\eta = 10$ for Calorimetry



$\Delta\eta = 5$ for Si tracker

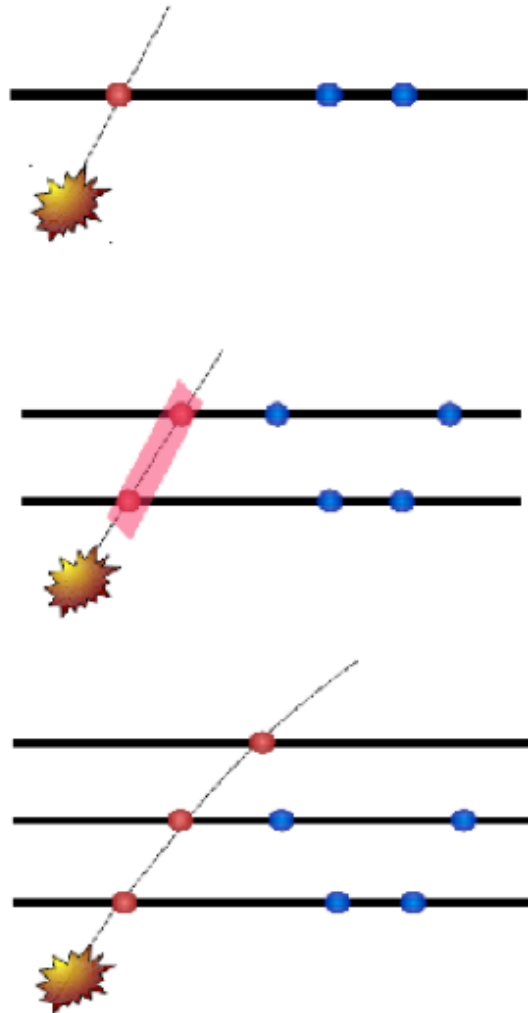


The CMS All Silicon Tracker



- ★ Coverage up to $|\eta| < 2.5$; extremely high granularity, due to the small cell size and high longitudinal segmentation, to keep low occupancy (\sim a few%) also at LHC nominal luminosity.
- ★ It is the largest Silicon Tracker ever built: Strips: 9.3M channels; Pixels: 66M channels. **Operational fractions: strips 98.1%; pixel 98.3%**

Track Pt Resolution
 For 1 GeV tracks:
 0.7 % @ $|\eta| \sim 0$
 2.5 % @ $|\eta| \sim 2.5$



- Pixel hit counting (1 hit)

- Using the primary vertex, calculate η for each cluster
- Immune to detector mis-alignment, simplest
- $p_T > 30 \text{ MeV}/c$, $|\eta| < 2$

- Tracklets (2 hits)

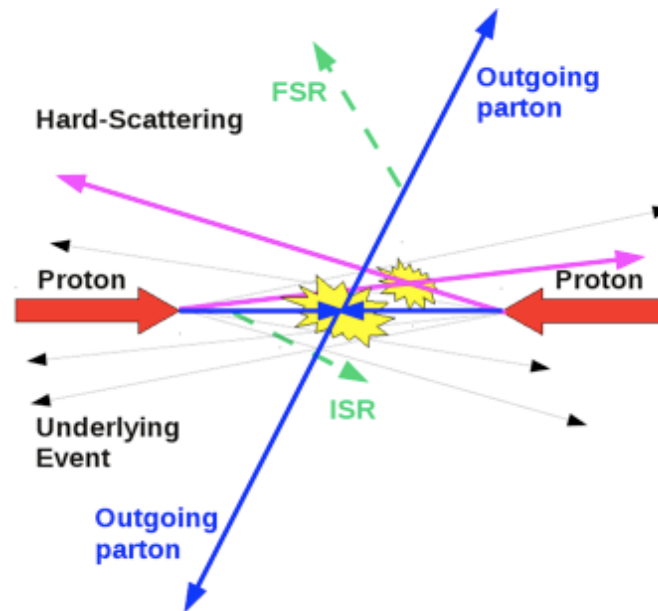
- Form hit pairs, calculate η
- Data-driven background subtraction
- $p_T > 50 \text{ MeV}/c$, $|\eta| < 2$

- Full tracks

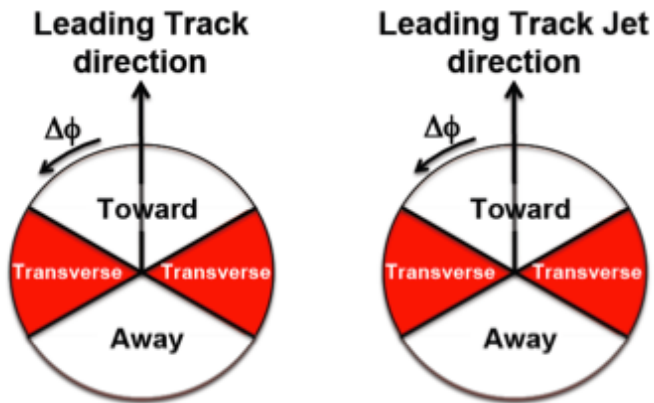
- Use all pixel and strip hits, provide η and p_T
- Sensitive, most complex
- $p_T > 100 \text{ MeV}/c$, $|\eta| < 2.4$

Measure η and p_T of charged hadrons with the silicon tracker

Underlying Event



UE: Products from hadronization of Multiple-Parton Interactions (MPI) and Beam-Beam remnants (BBR)

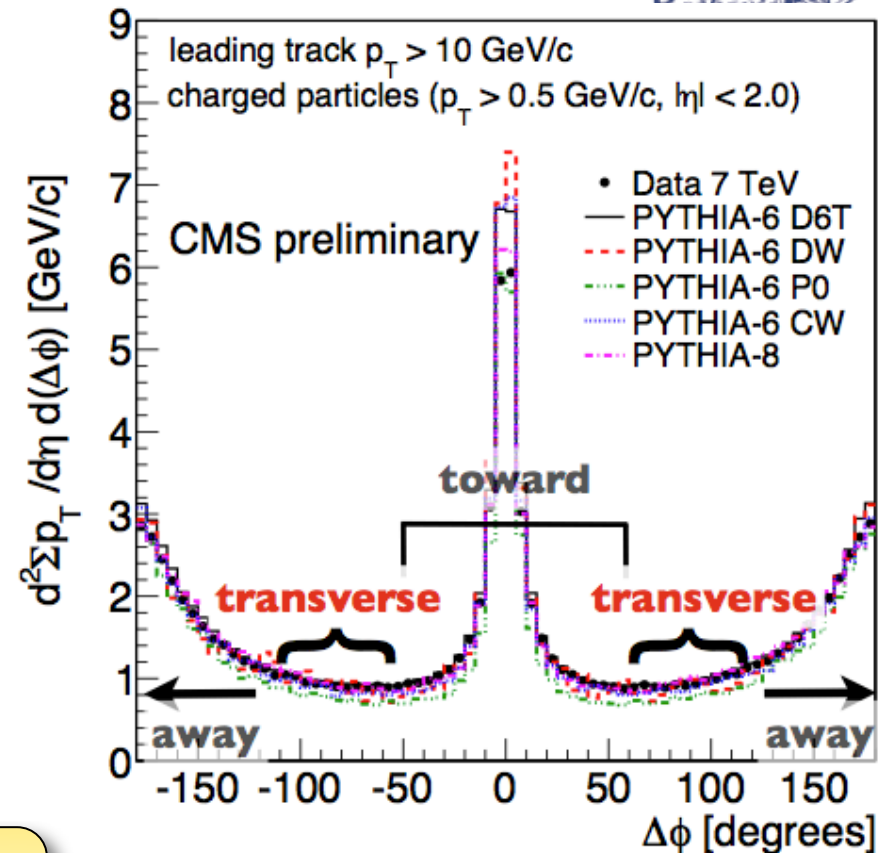


- Traditional approach (R. Field)
- **Leading Track or Leading Track-Jet** define a direction in the phi plane
- Track or Track-jet p_T provide an energy scale

Main observables, built from Tracks:

$d^2N_{ch}/d\eta d\Phi$ charged mult. density
 $d^2\text{Sum}(PT)/d\eta d\Phi$ energy density

- Transverse region expected to be particularly sensitive to the UE



Note : so far data were not corrected for detector effects. Efforts in this direction under way

see QCD-10-001
and QCD-10-010



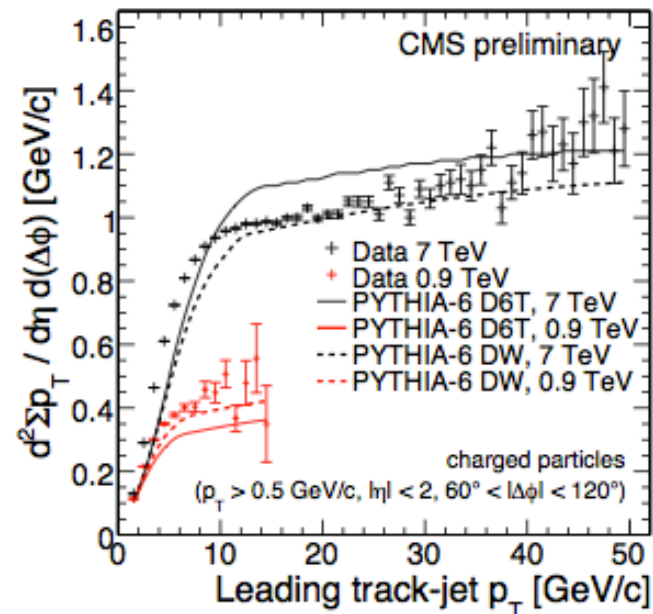
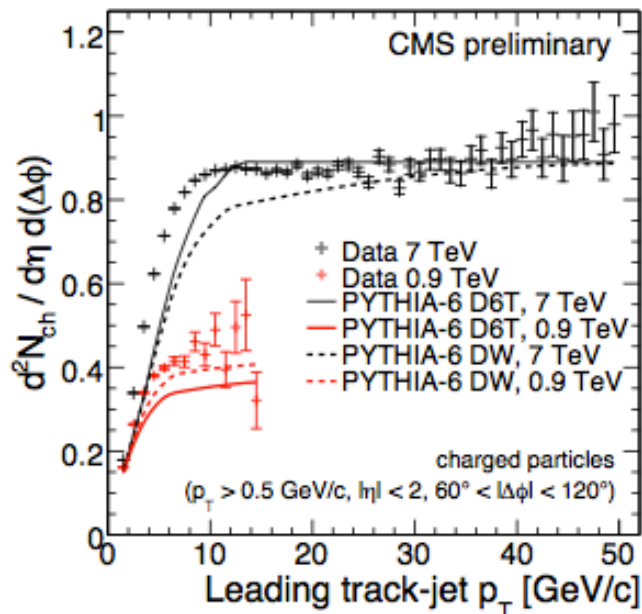
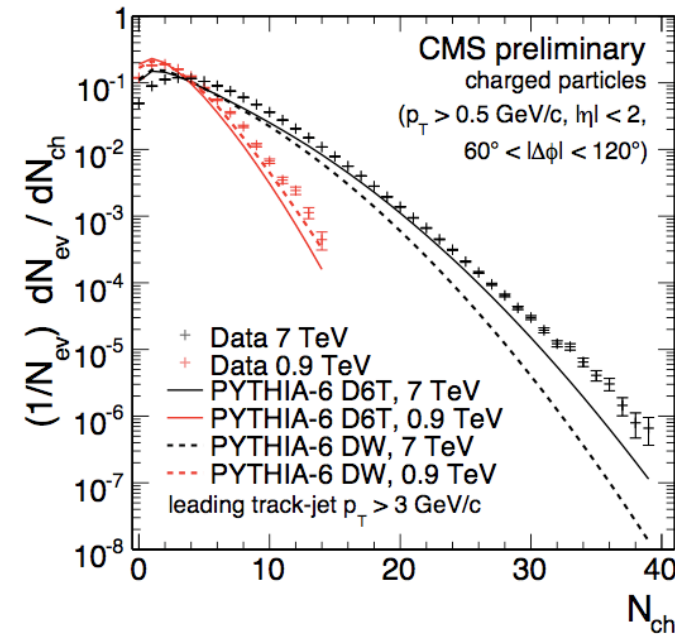
E_{cm} Dependence : Transverse Region



Track multiplicities in transverse region:

- ✓ Compare 0.9 vs 7 TeV
- ✓ Compare with several MC tunes

- ➔ Large growth of UE activity @ 7 TeV
- ➔ Rise in general poorly described by MC





Charged Hadron Multiplicities



Pseudo-rap. density (NSD)



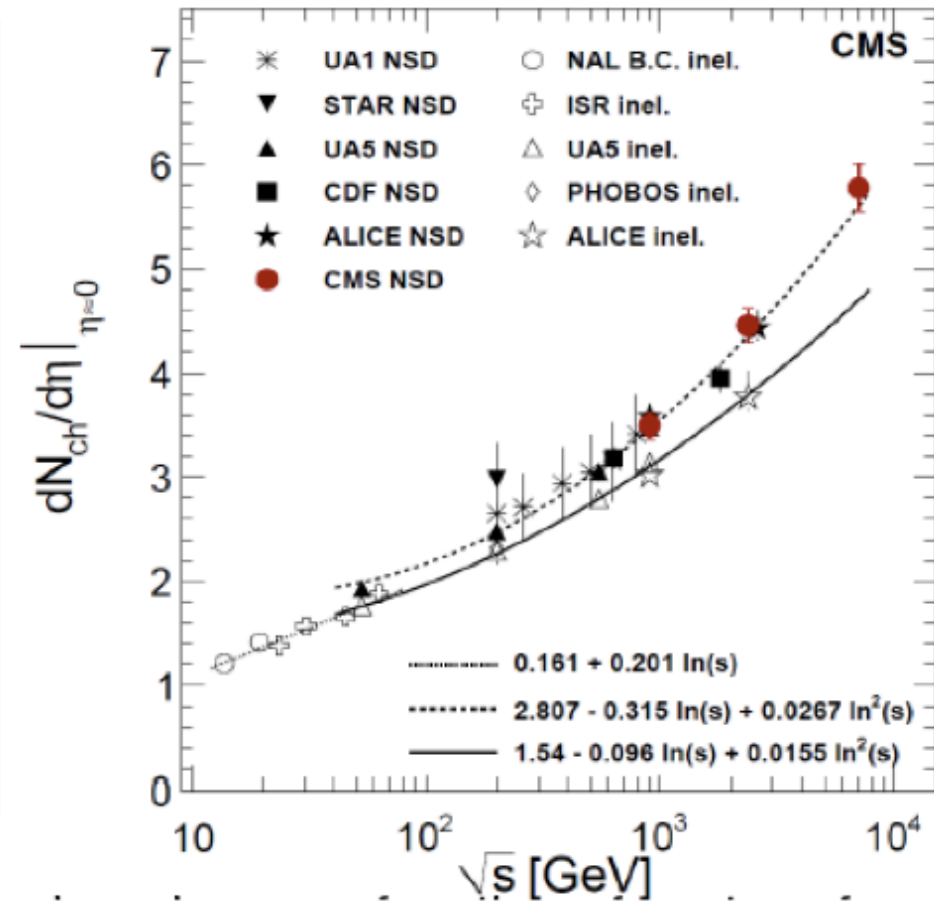
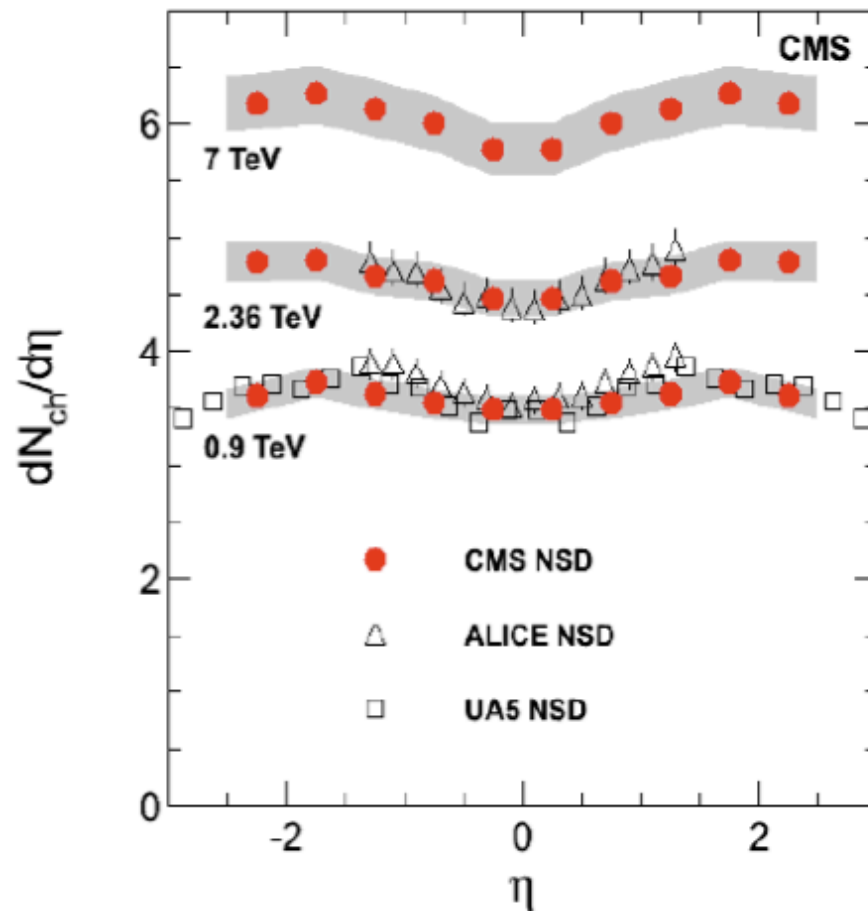
Minimum bias events

Non single-diffractive event selection (correction 6%→2.5% systematic error)

Really soft QCD (p_T tracks dow to 50MeV)

V. Khachatryan et al., JHEP 02 (2010) 041

V. Khachatryan et al., Phys. Rev. Lett. 105 (2010) 022002



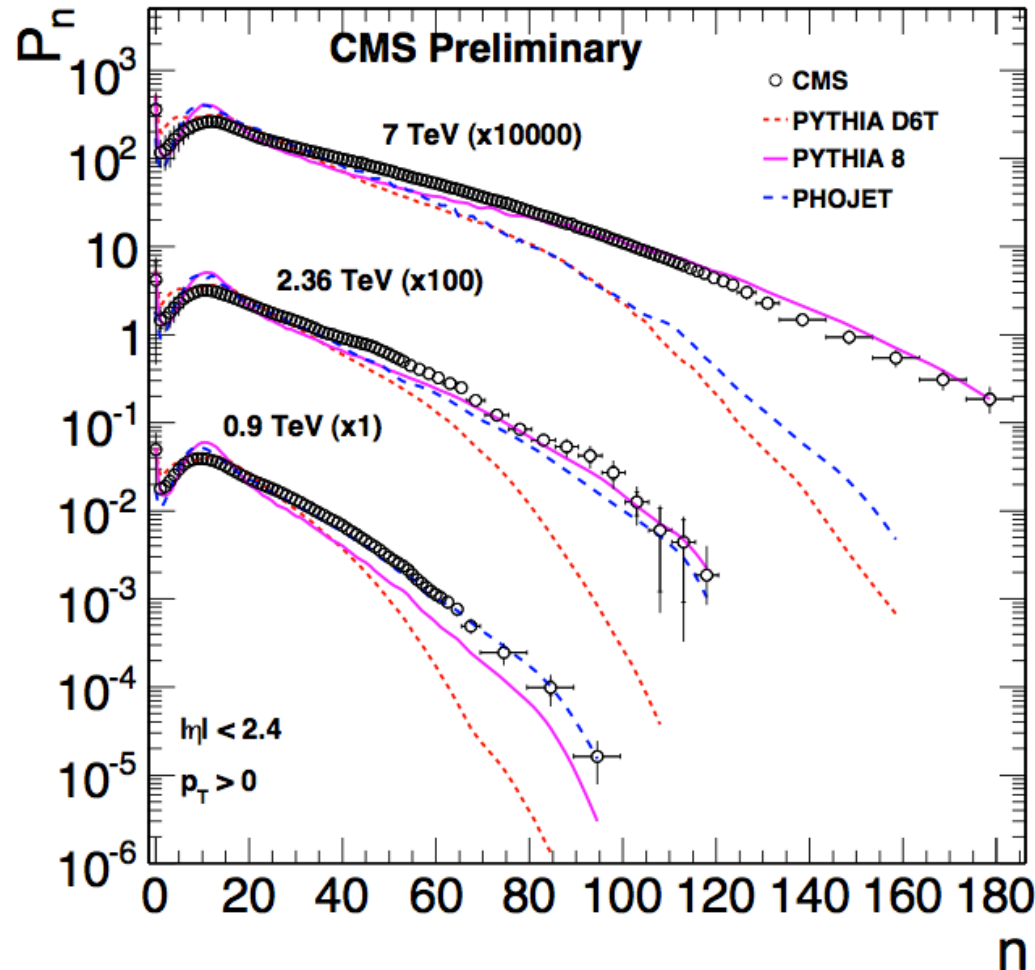
Rise with \sqrt{s} :
steeper than predicted by most MC models, with up to 40% difference



Charged particle multiplicities



QCD-10-004



Unfolded up to primary hadron level
Extrapolated to $p_T > 0$ (2% correction)
Normalization to NSD

- shows need to improve (tuning of) models
- so far no model which is able to describe well, simultaneously, multiplicity and p_T distributions, over whole range and at diff. E_{cm}
- biggest discrepancies seen for $p_T < 500$ MeV



Observation of Long-range, Near-side Angular Correlations



Recently published

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.

CERN-PH-EP-2010-031

arXiv:1009.4122v1

JHEP09(2010)091

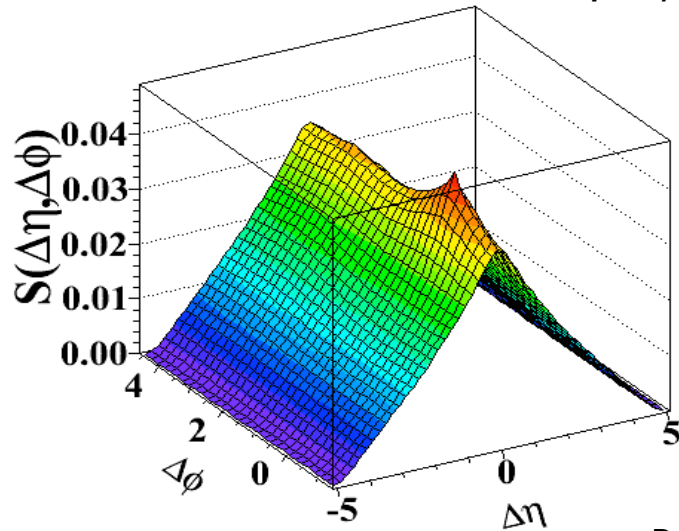


Correlation Function Definition



Signal distribution:

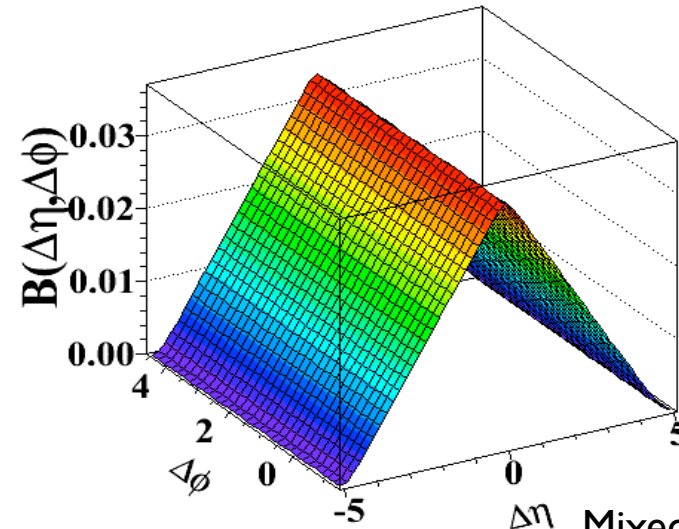
$$S_N(\Delta\eta, \Delta\phi) = \frac{1}{N(N-1)} \frac{d^2 N^{signal}}{d\Delta\eta d\Delta\phi}$$



Same event pairs

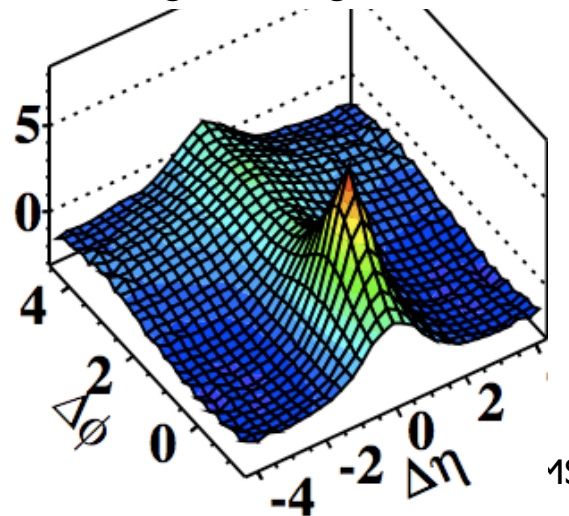
Background distribution:

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



Mixed event pairs

Ratio Signal/Background



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

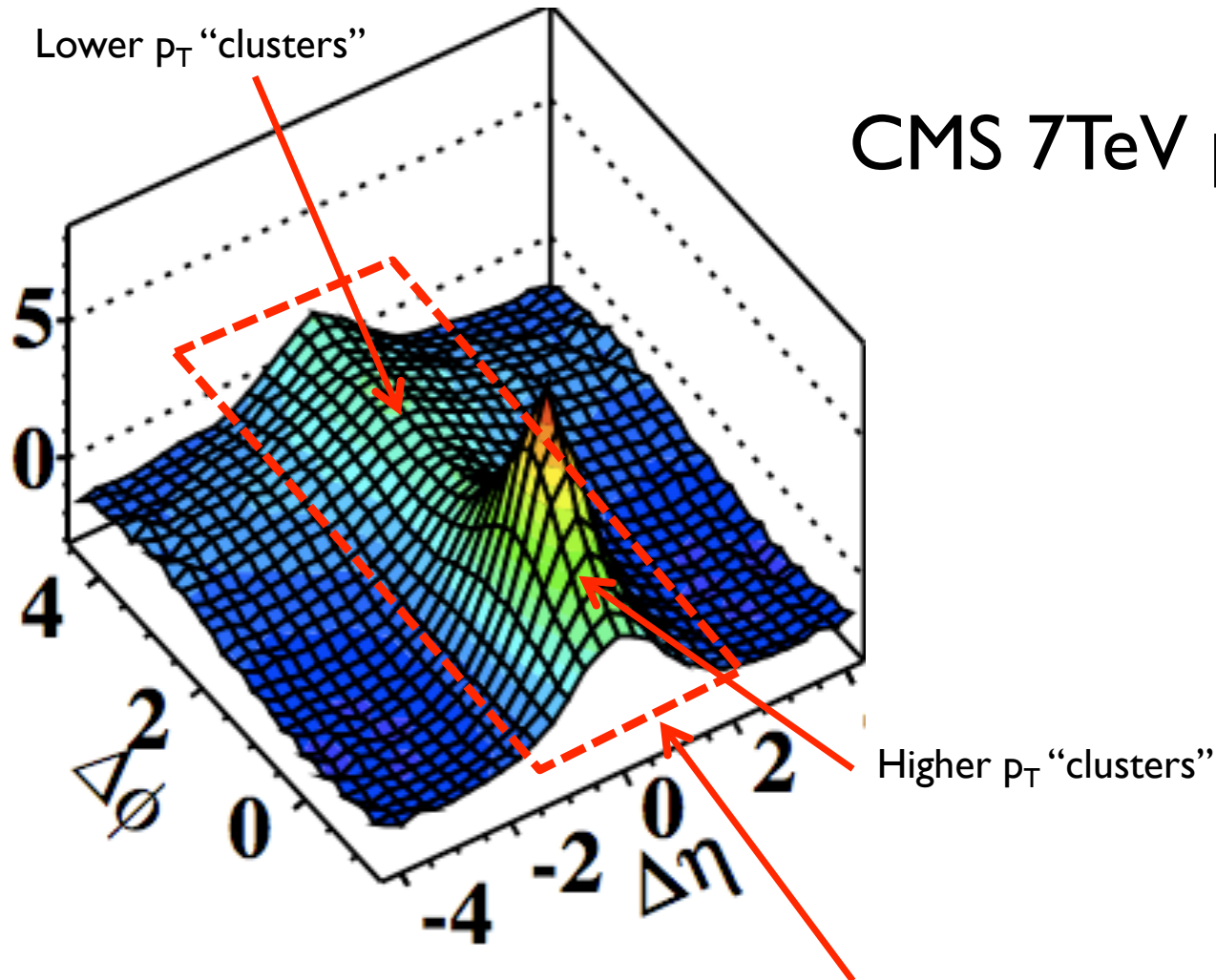
p_T -inclusive two-particle angular correlations in min bias collisions

$$\Delta\eta = \eta_1 - \eta_2$$

$$\Delta\phi = \phi_1 - \phi_2$$

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CMS pp 7TeV



CMS 7TeV pp min bias

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

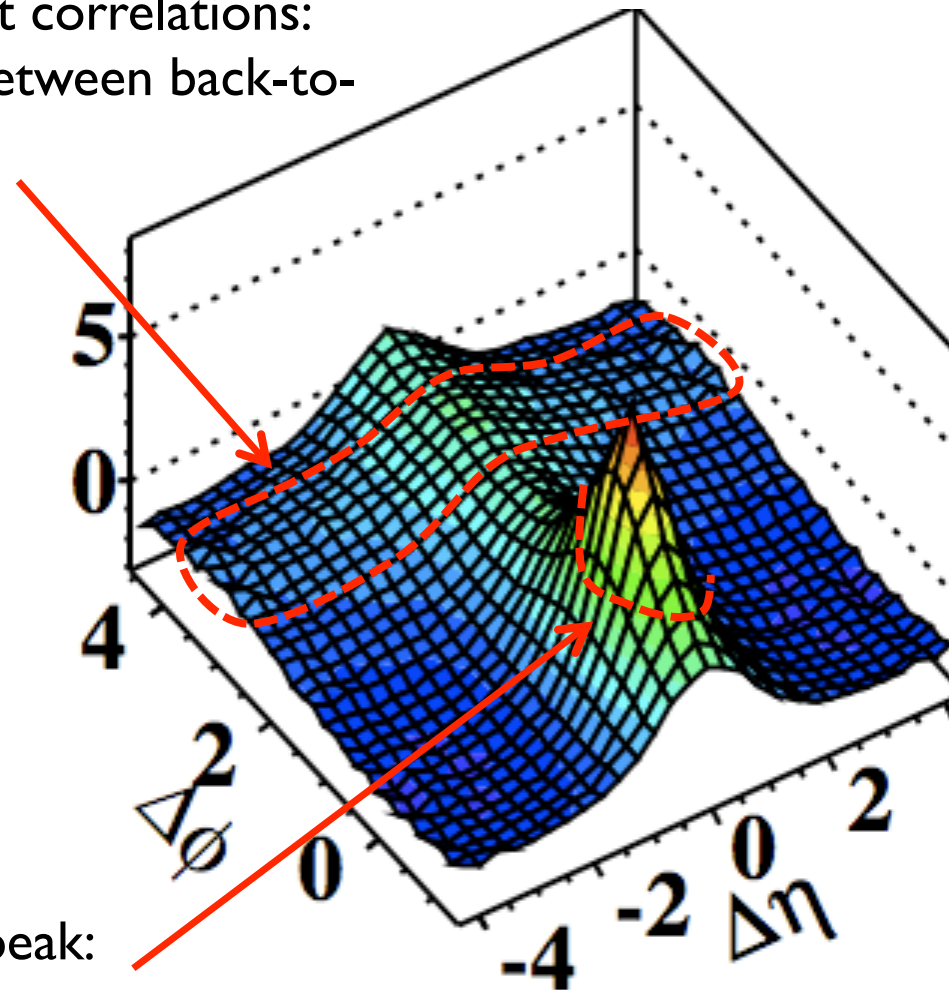


Angular Correlation Functions



CMS 7TeV pp min bias

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



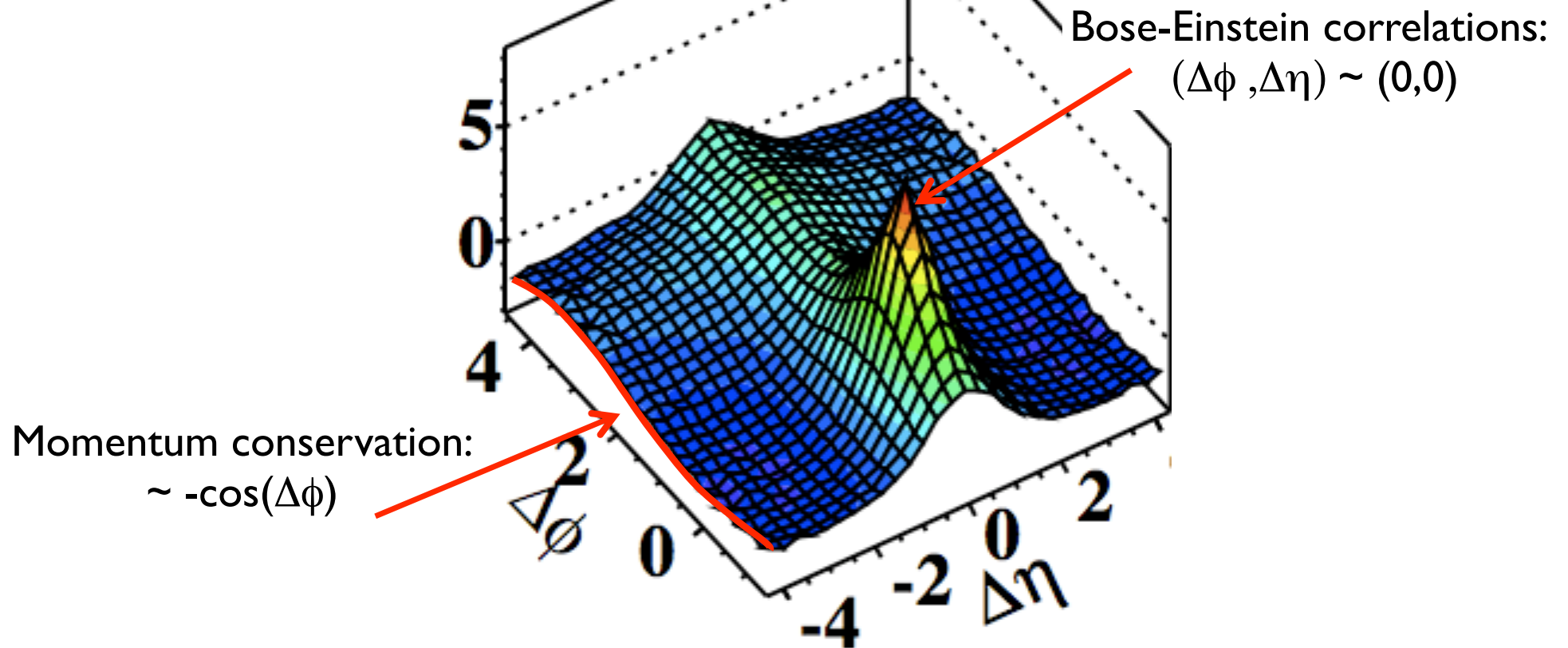
“Near-side” ($\Delta\phi \sim 0$) jet peak:
Correlation of particles
within a single jet



Angular Correlation Functions



CMS 7TeV pp min bias





Angular Correlation Functions

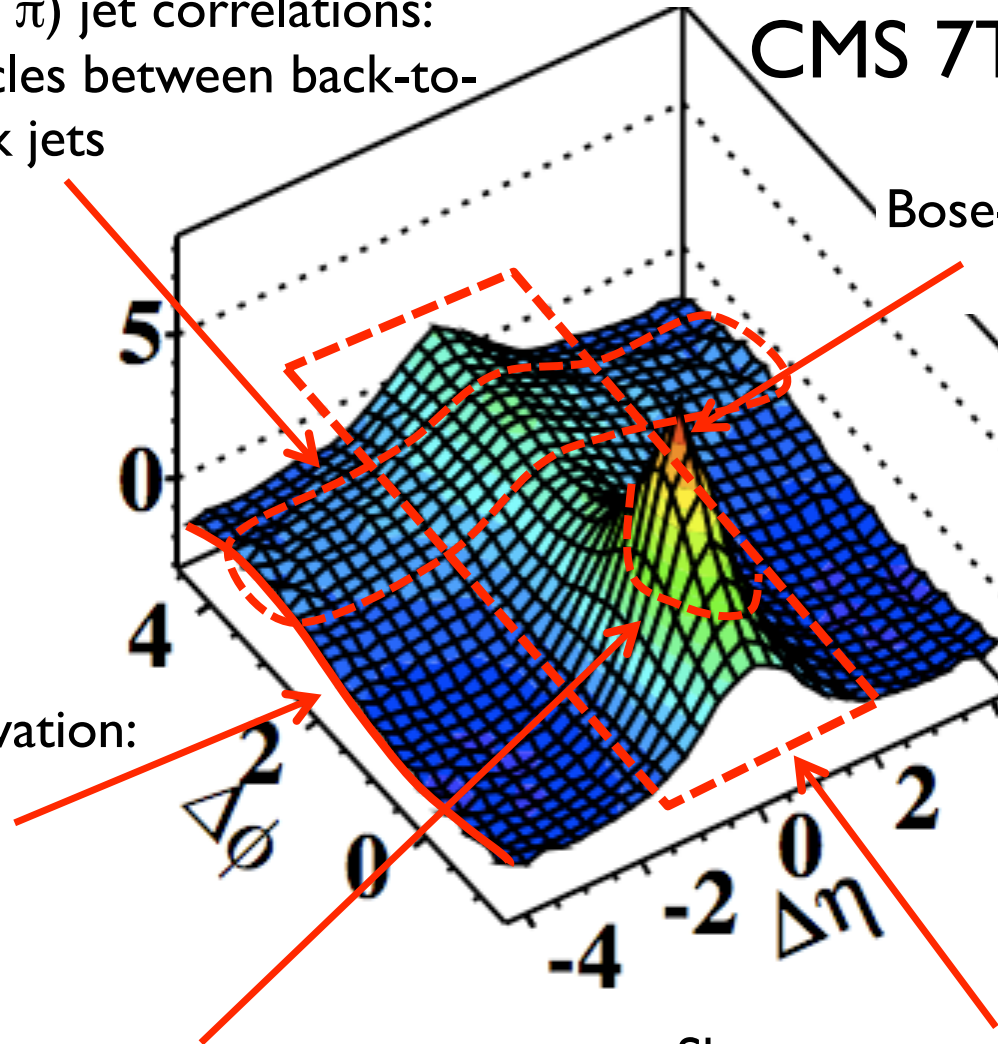


“Away-side” ($\Delta\phi \sim \pi$) jet correlations:
Correlation of particles between back-to-back jets

CMS 7TeV pp min bias

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

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



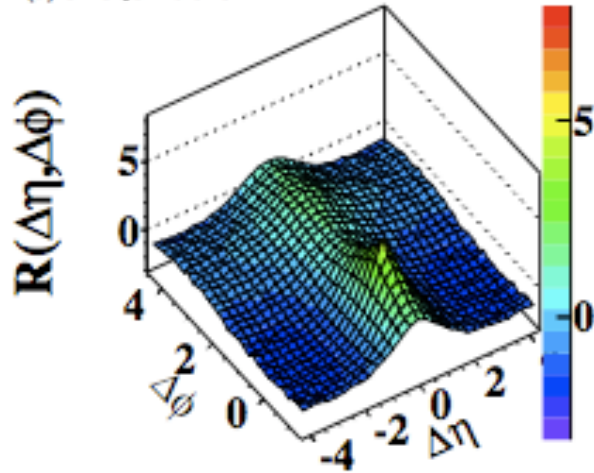
“Near-side” ($\Delta\phi \sim 0$) jet peak:
Correlation of particles
within a single jet

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

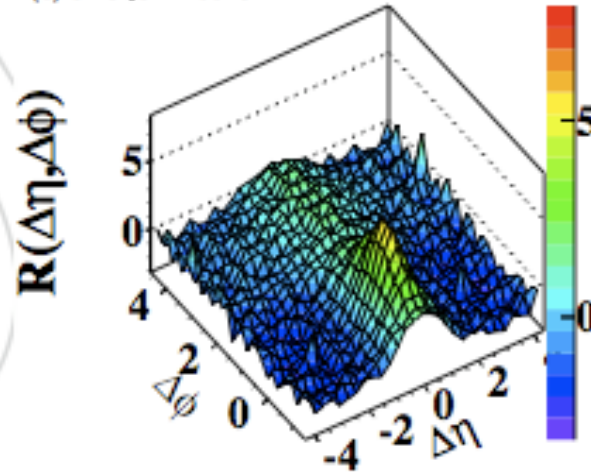
Correlations in Min Bias pp

CMS pp Data

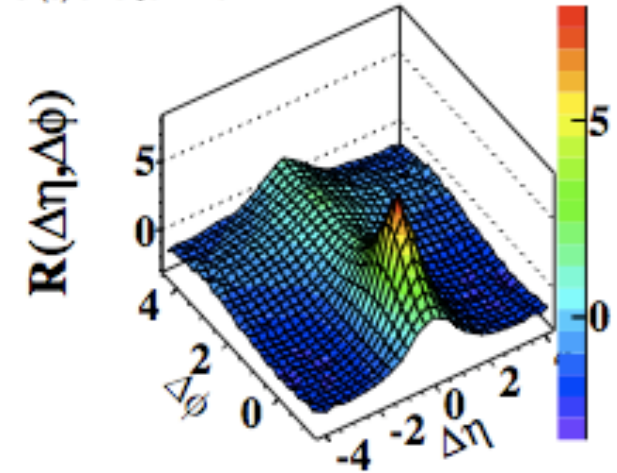
(a) CMS $\sqrt{s} = 0.9\text{TeV}$



(b) CMS $\sqrt{s} = 2.36\text{TeV}$

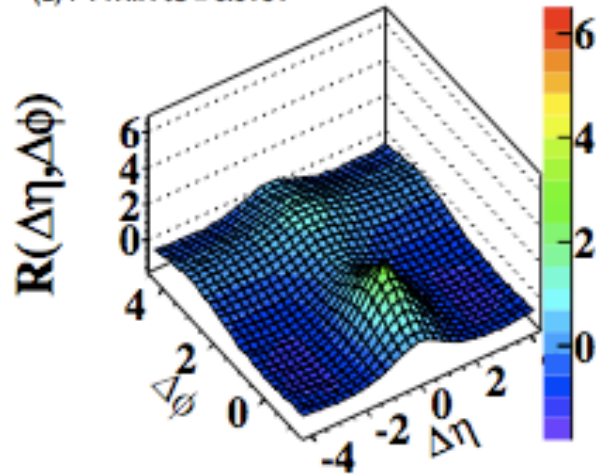


(c) CMS $\sqrt{s} = 7\text{TeV}$

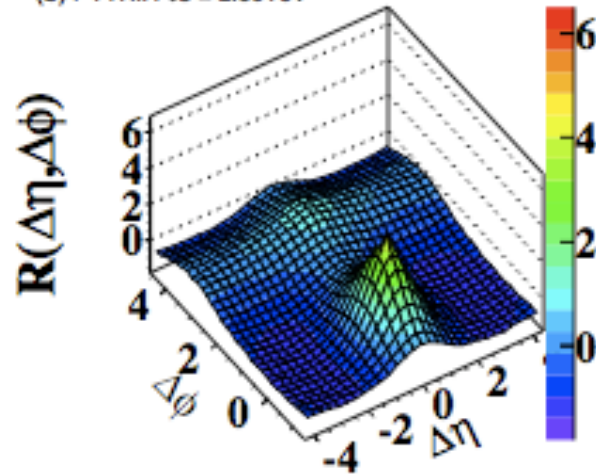


Pythia D6T

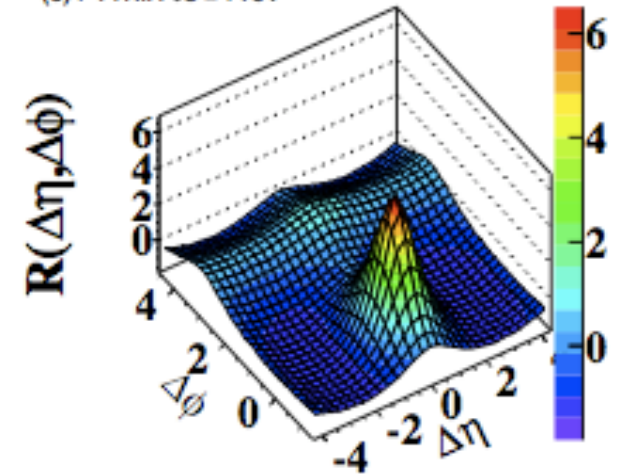
(a) PYTHIA $\sqrt{s} = 0.9\text{TeV}$



(b) PYTHIA $\sqrt{s} = 2.36\text{TeV}$



(c) PYTHIA $\sqrt{s} = 7\text{TeV}$

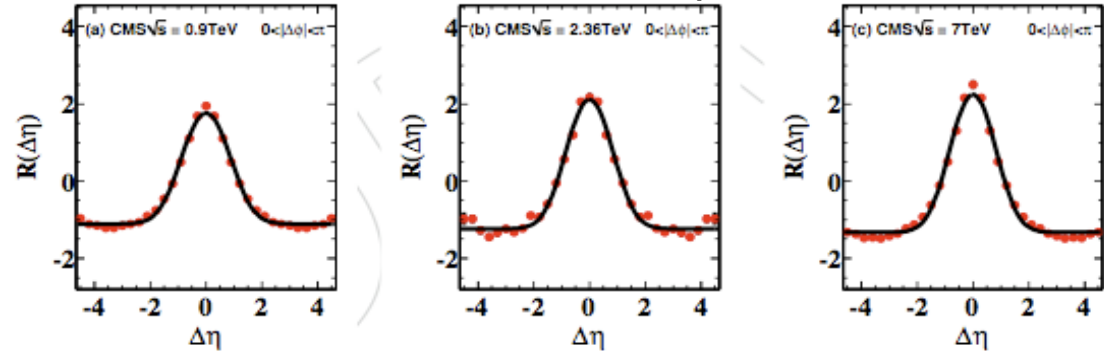
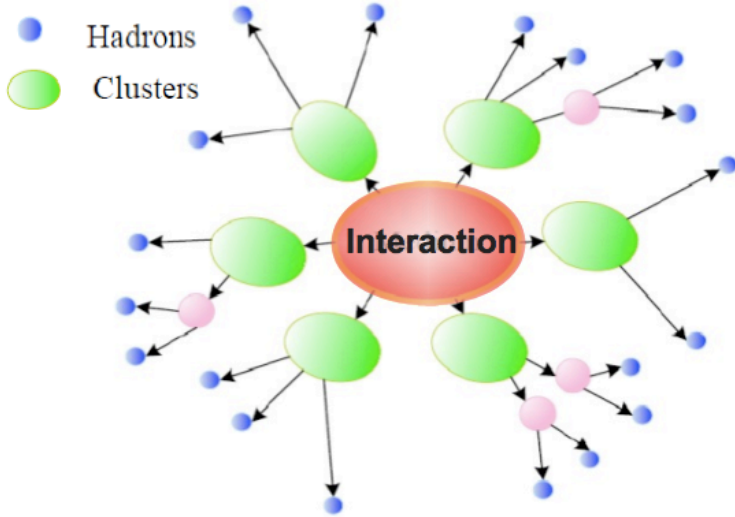




Short-Range Correlations vs \sqrt{s}

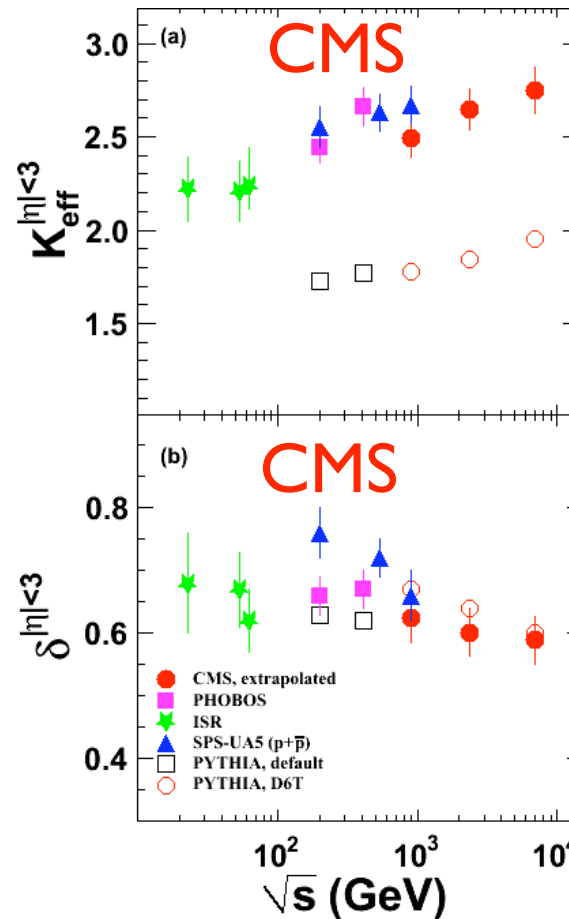


1D "Projection" to $\Delta\eta$ axis



Independent Cluster Model

- ✓ Clusters produced independently
- ✓ Each cluster decays isotropically into hadrons in its own c.m.s.
- ✓ Short range correlations in $\Delta\eta$ characterized by 2 parameters:
 - ▶ cluster size K : # correlated particles
 - ▶ cluster width δ : $\Delta\eta$ correlations size

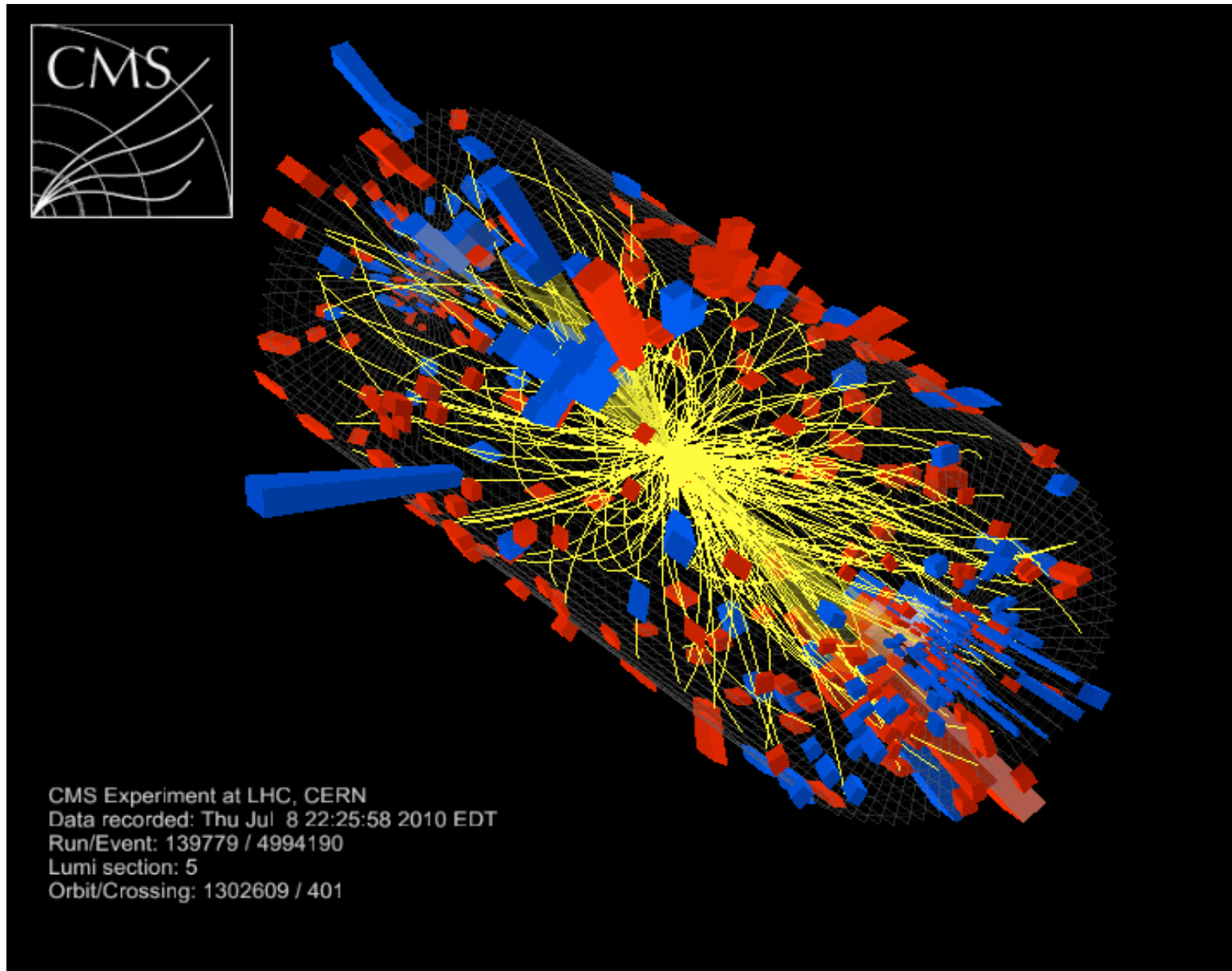


PYTHIA:

- ✓ describes the energy dependence
- ✓ Matches cluster width δ in data
- ✓ Underestimates the cluster size K_{eff}

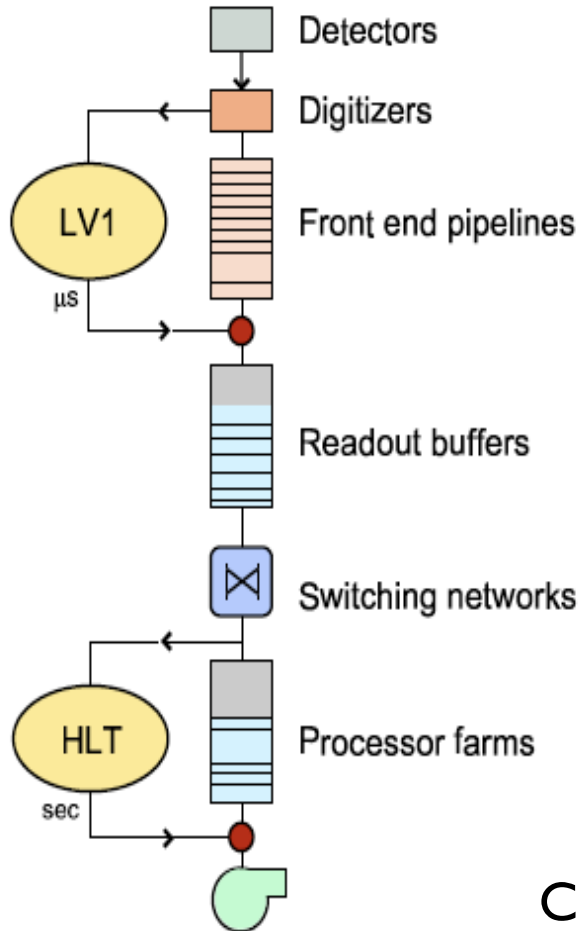


High Multiplicity Events

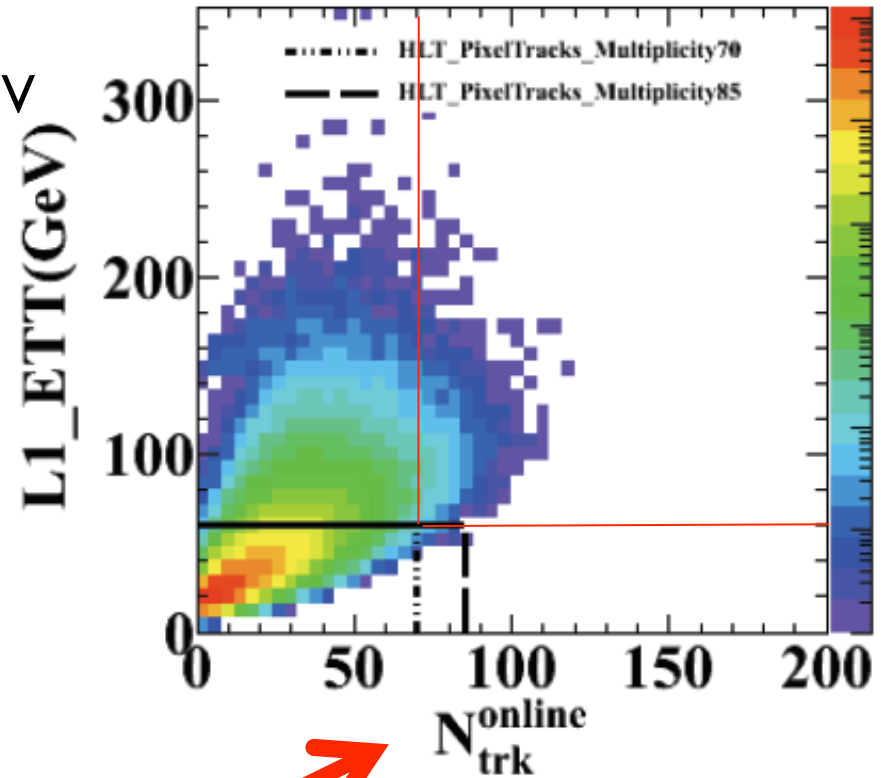
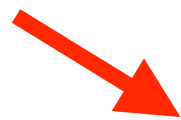


High Multiplicity Events

Dedicated trigger needed to record highest multiplicities



Level-1
Require $E_T > 60$ GeV
in calorimeters

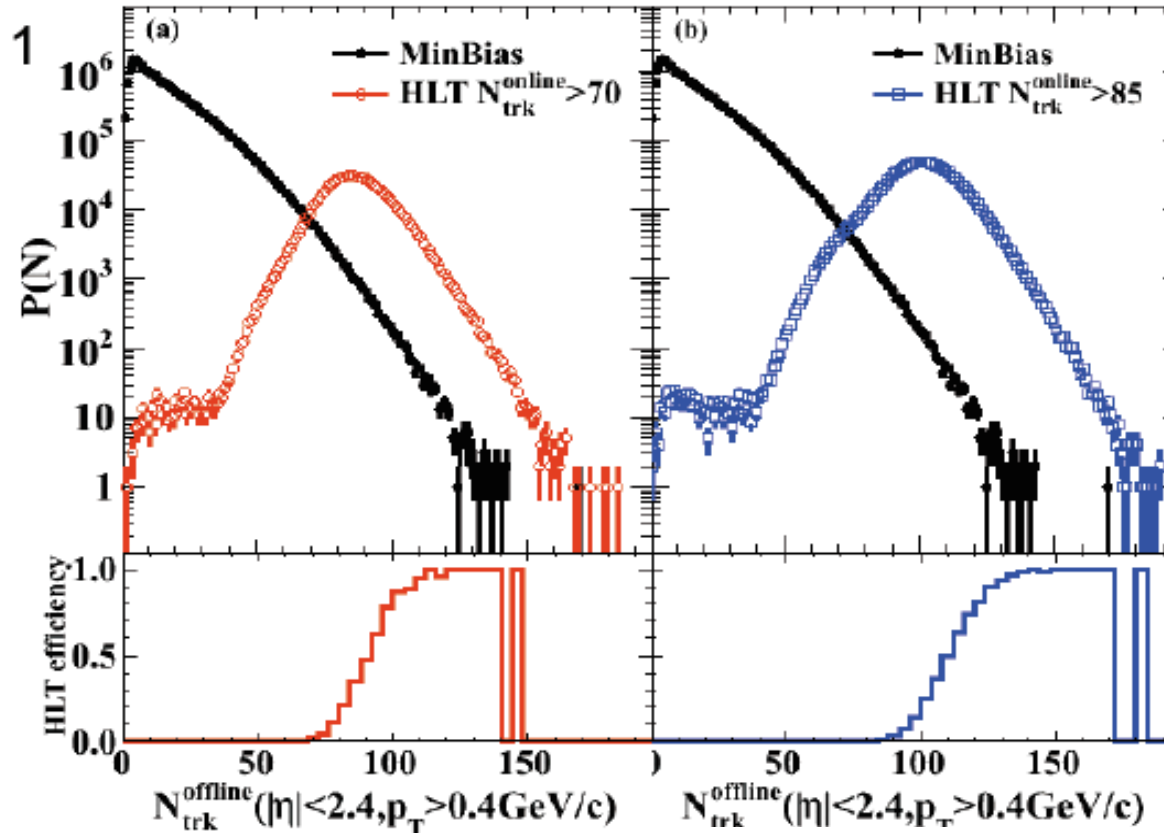


High-Level trigger

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



High Multiplicity Trigger



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



Two different HLT thresholds:
 $N_{\text{online}} > 70$ and $N_{\text{online}} > 85$

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

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

Results

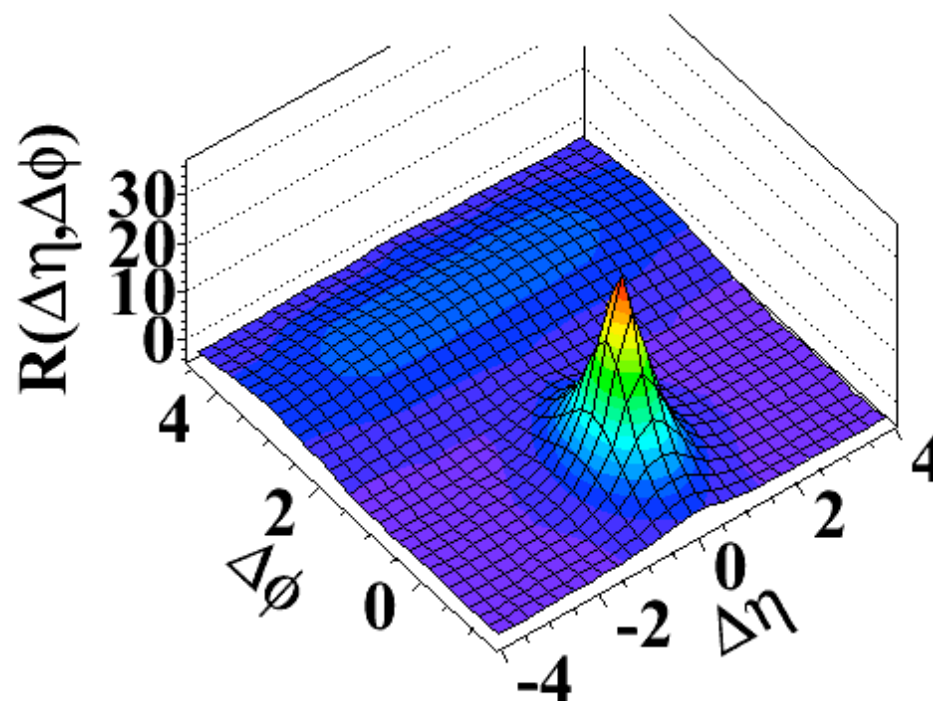
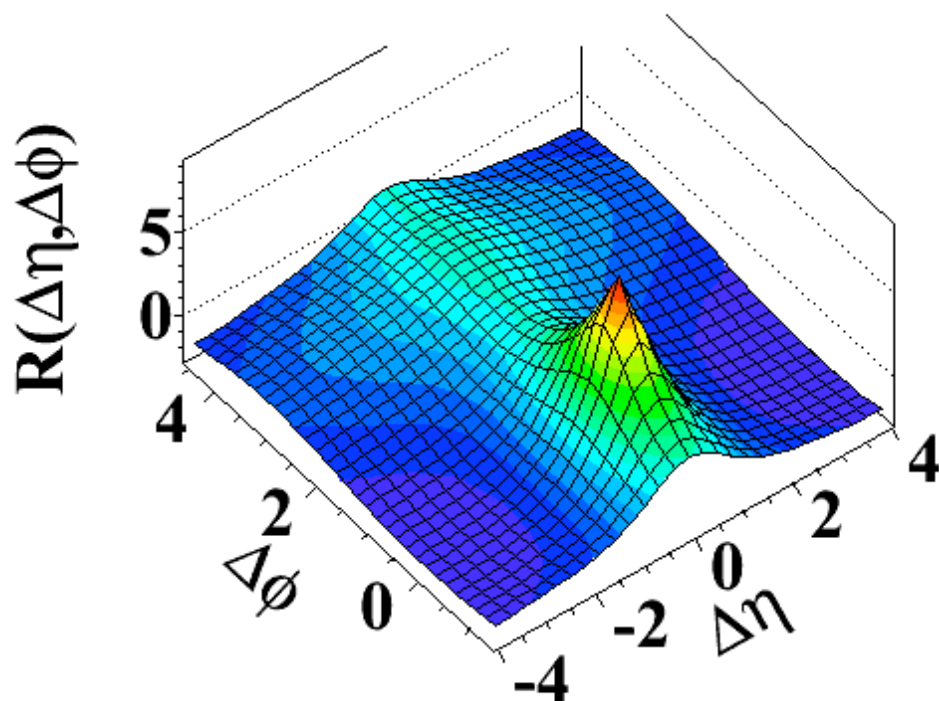
Inclusive p_T

MinBias

high multiplicity ($N > 110$)

(a) MinBias, $p_T > 0.1 \text{ GeV}/c$

(c) $N > 110$, $p_T > 0.1 \text{ GeV}/c$



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

Abundant jet production in high multiplicity sample

Results

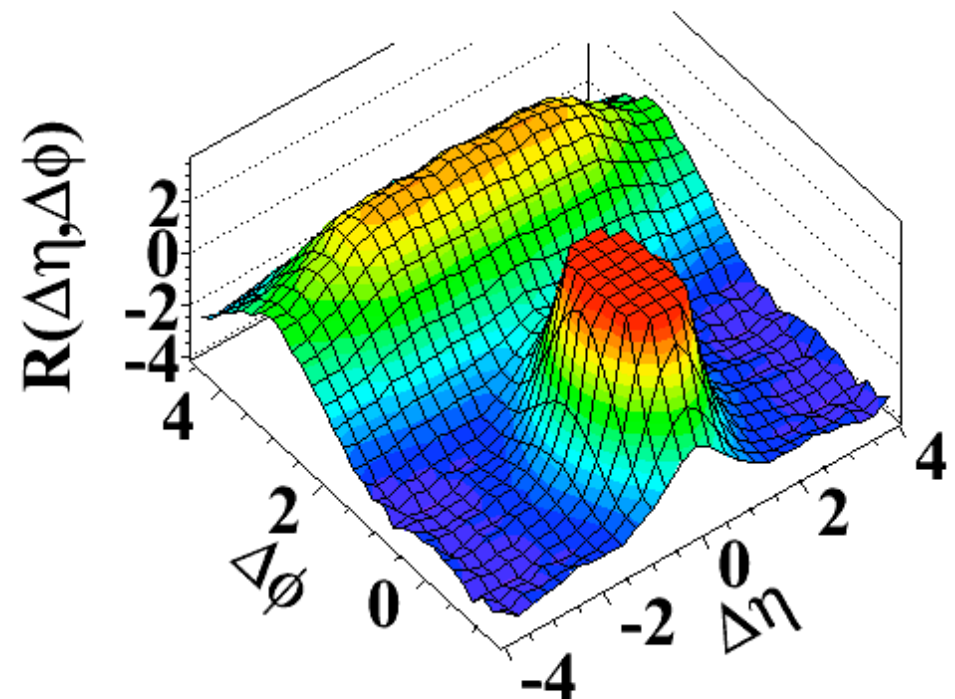
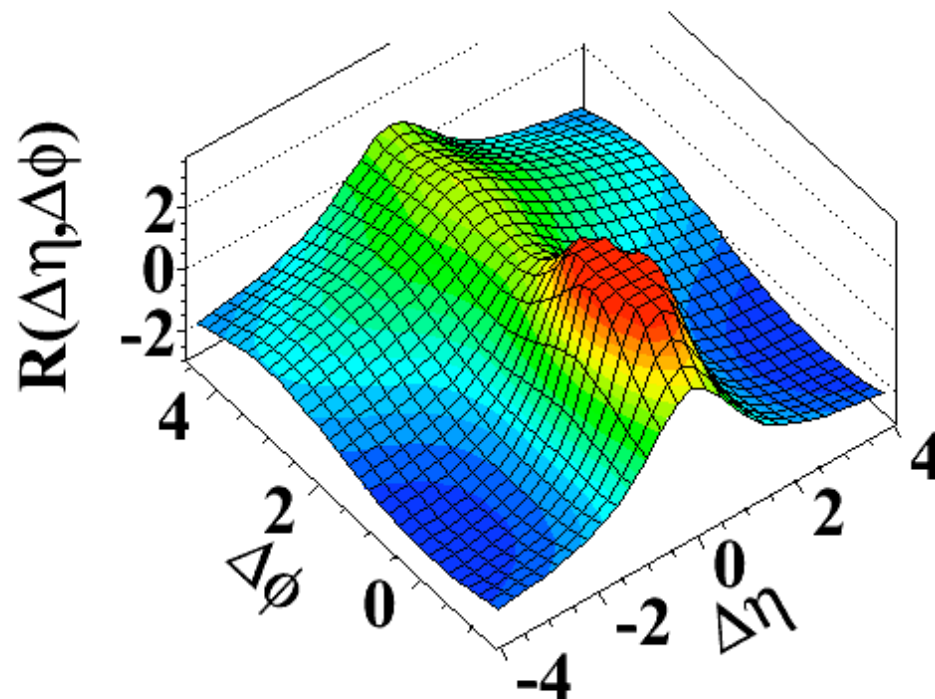
Inclusive p_T

MinBias

high multiplicity ($N > 110$)

(a) MinBias, $p_T > 0.1 \text{ GeV}/c$

(c) $N > 110$, $p_T > 0.1 \text{ GeV}/c$



Cut off peak at (0,0):

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

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

Results

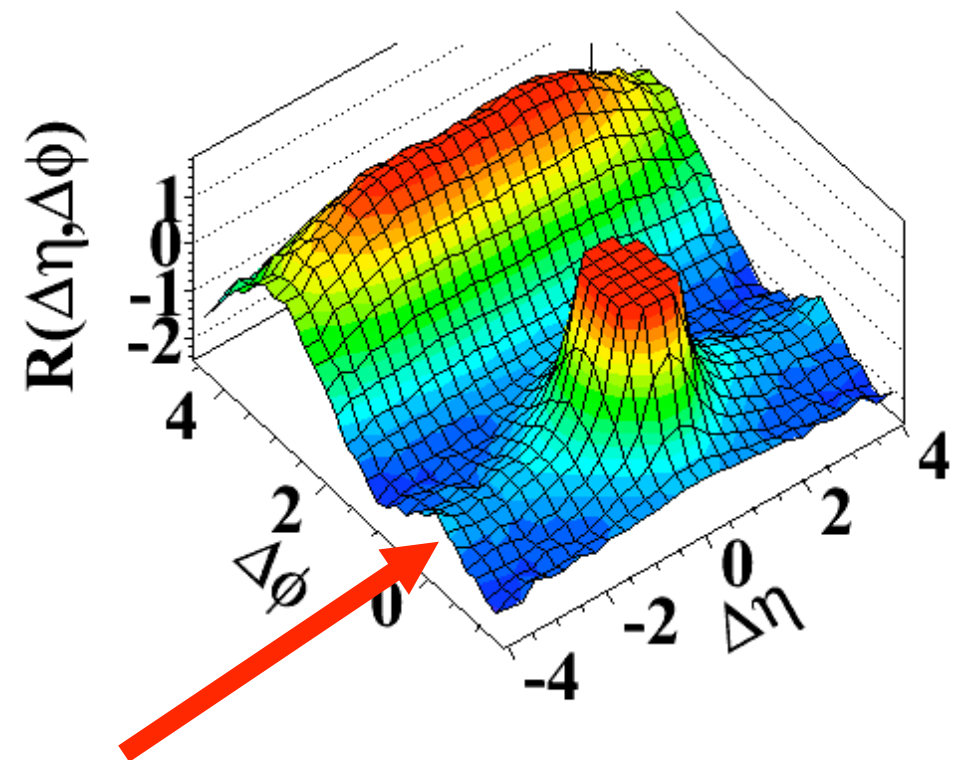
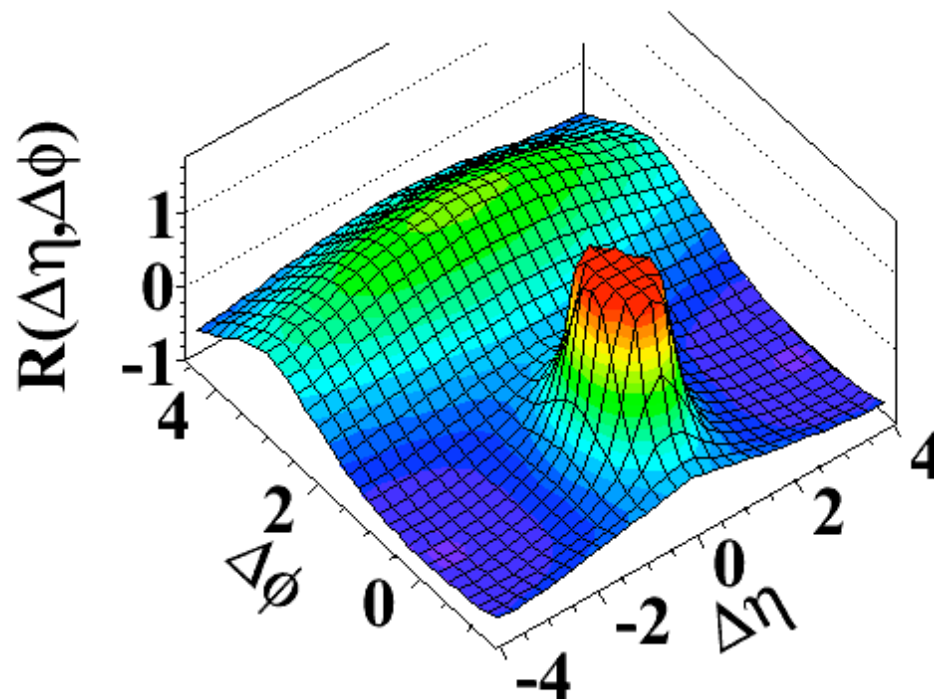
Intermediate p_T : 1-3 GeV/c

MinBias

high multiplicity ($N > 110$)

(b) MinBias, $1.0 \text{ GeV}/c < p_T < 3.0 \text{ GeV}/c$

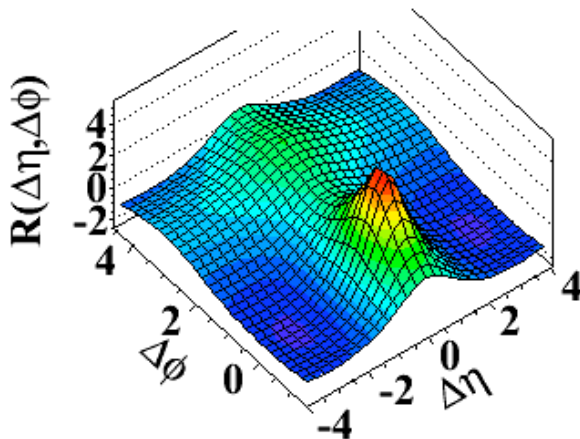
(d) $N > 110$, $1.0 \text{ GeV}/c < p_T < 3.0 \text{ GeV}/c$



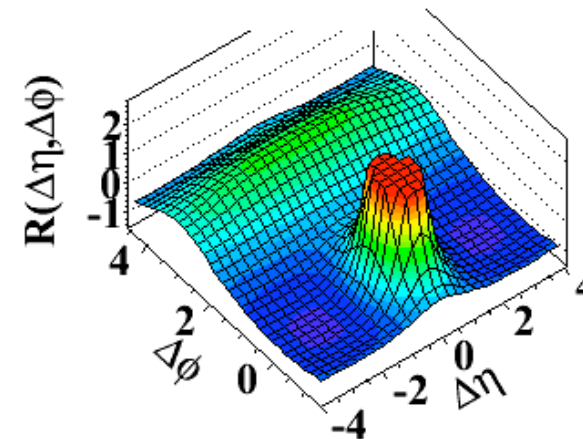
Pronounced structure at large $\Delta\eta$ around $\Delta\phi \sim 0$!

Results: Pythia8

(a) MinBias, $p_T > 0.1 \text{ GeV}/c$

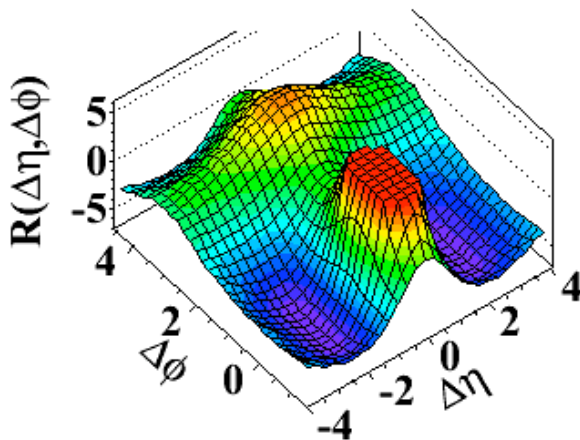


(b) MinBias, $1.0 \text{ GeV}/c < p_T < 3.0 \text{ GeV}/c$

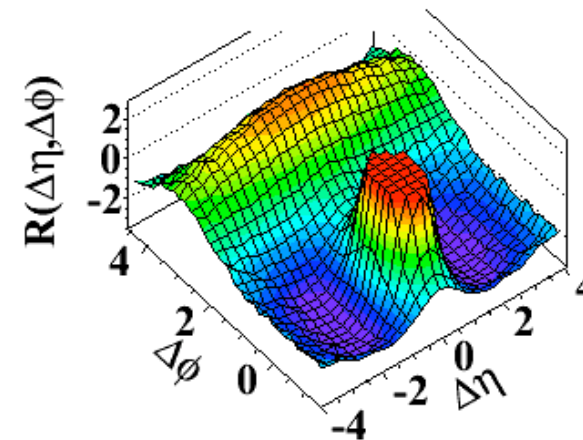


Pythia8

(c) $N > 110$, $p_T > 0.1 \text{ GeV}/c$



(d) $N > 110$, $1.0 \text{ GeV}/c < p_T < 3.0 \text{ GeV}/c$



No $\delta\phi \sim 0$ structure in PYTHIA 8 at large $\delta\eta$
 Same for Herwig++, madgraph, PYTHIA6

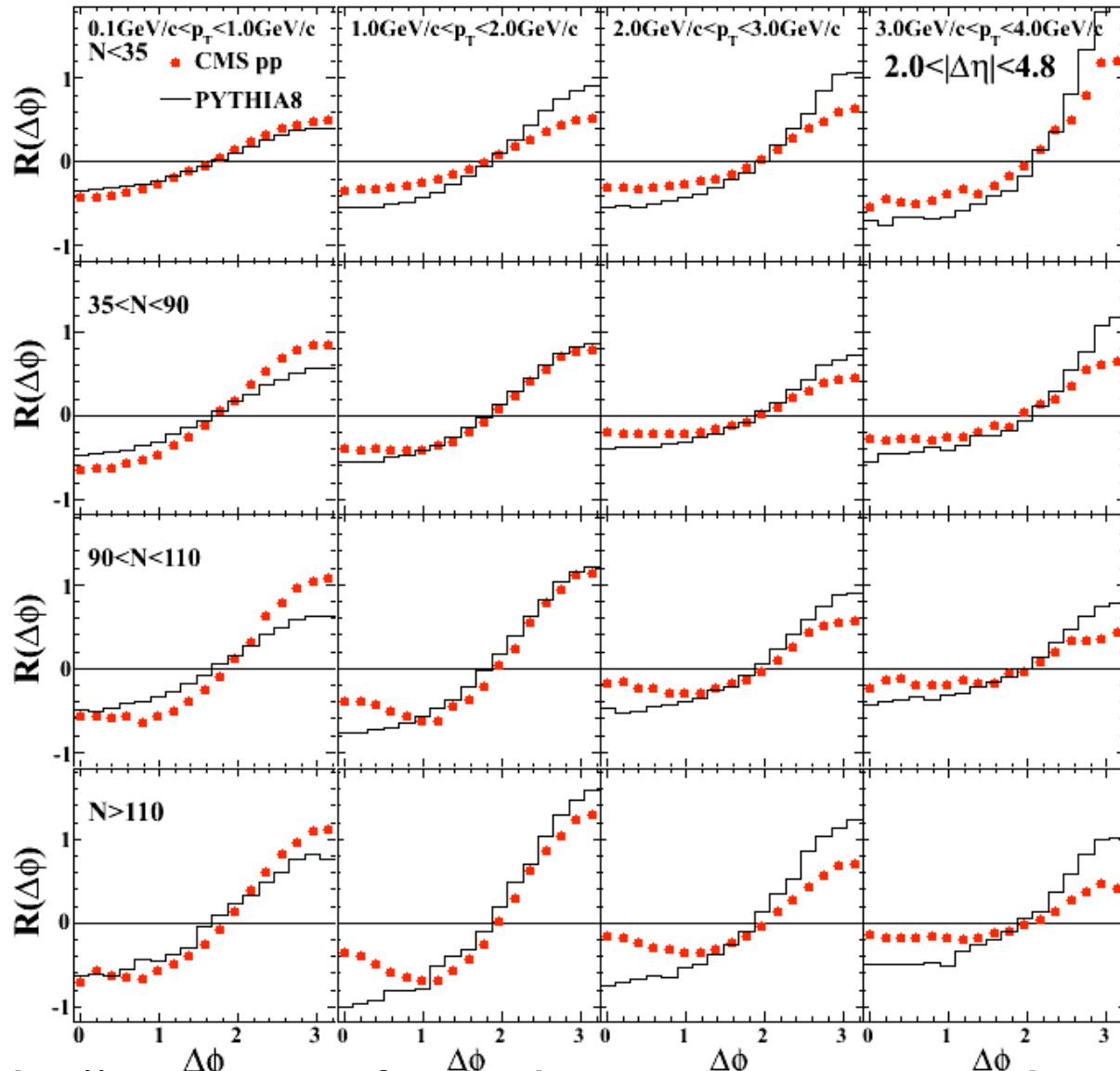


Multiplicity- and p_T -Dependence

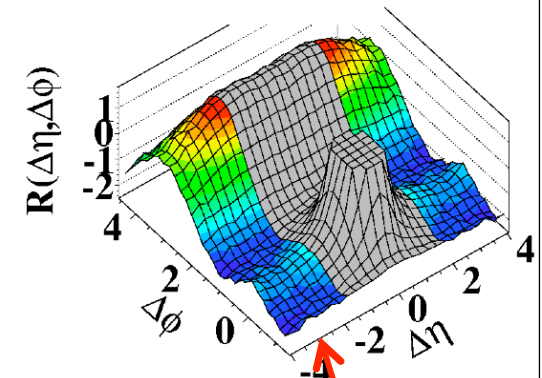


Increasing p_T →

Increasing multiplicity ↓



(d) $N > 110, 1.0 \text{ GeV}/c < p_T < 3.0 \text{ GeV}/c$



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

“Ridge” maximal for highest multiplicity and $1 < p_T < 3 \text{ GeV}/c$



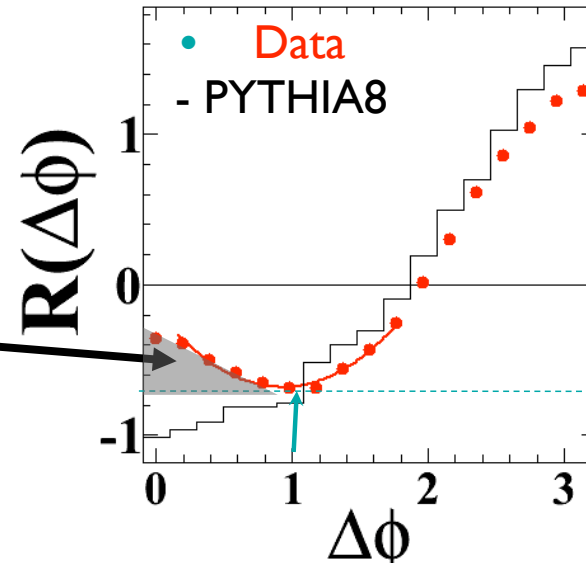
Quantifying the “ridge”: Associated Yield



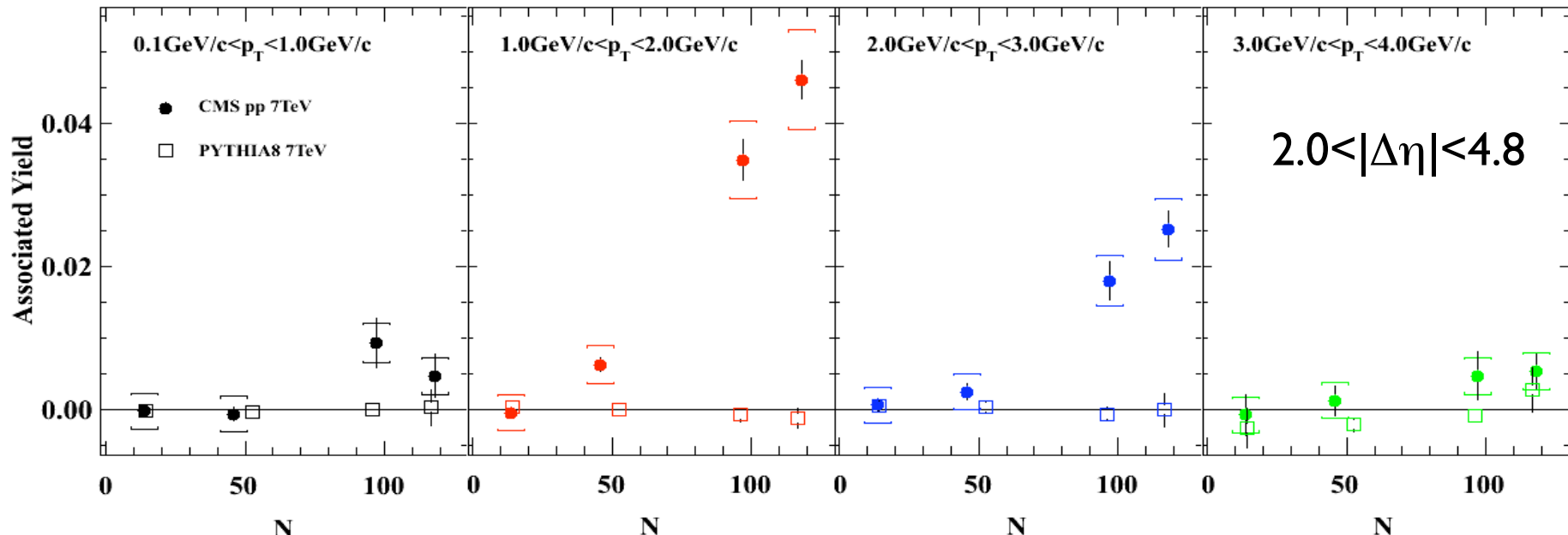
Zero Yield At Minimum (ZYAM)

Associated yield:
extra correlated multiplicity per particle

ZYAM = 0 if no “ridge”



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



Associated yield grows with increasing multiplicity

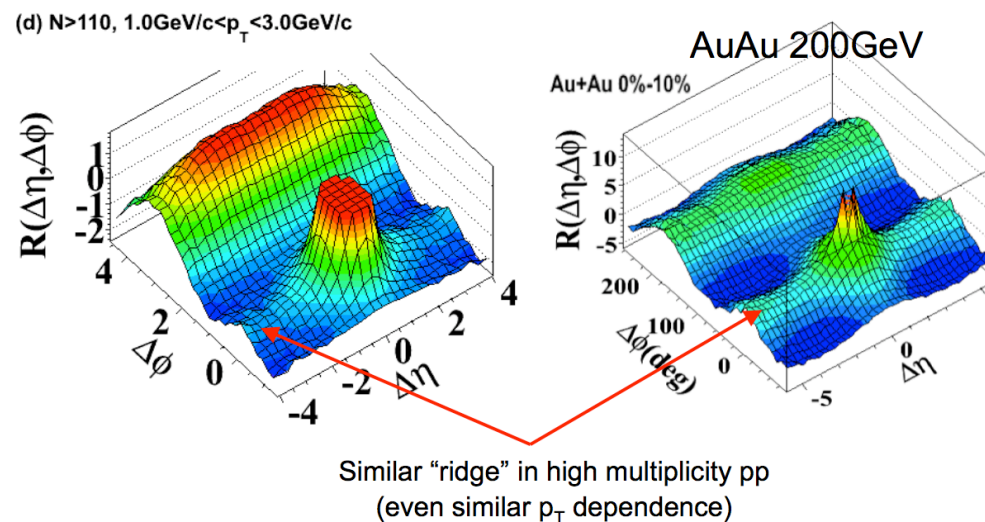


First observation of a ridge-like structure in pp-collisions



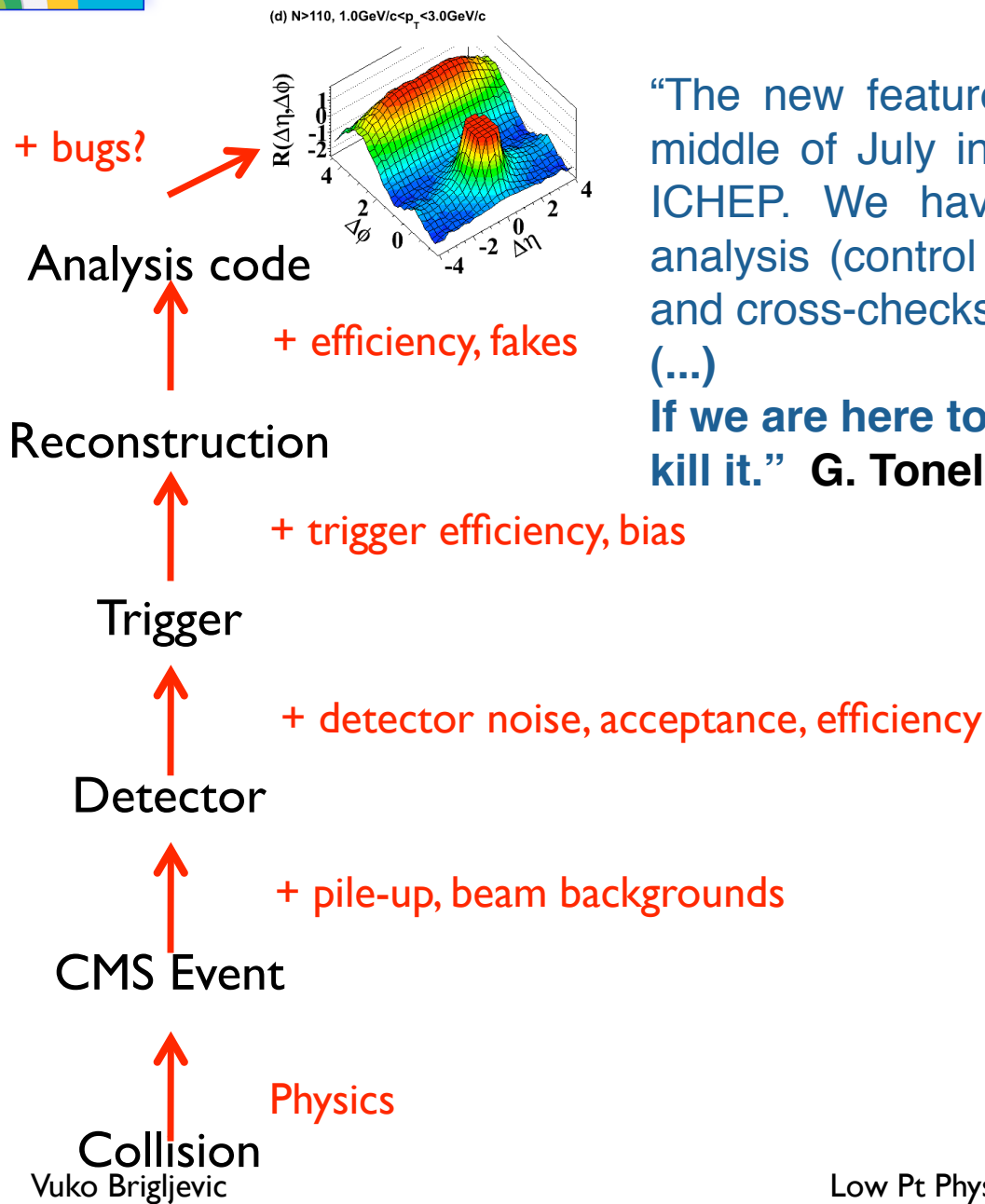
This is the first observation of such a long-range, near-side feature in two-particle correlation functions in pp or p-pbar collisions.

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.





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.

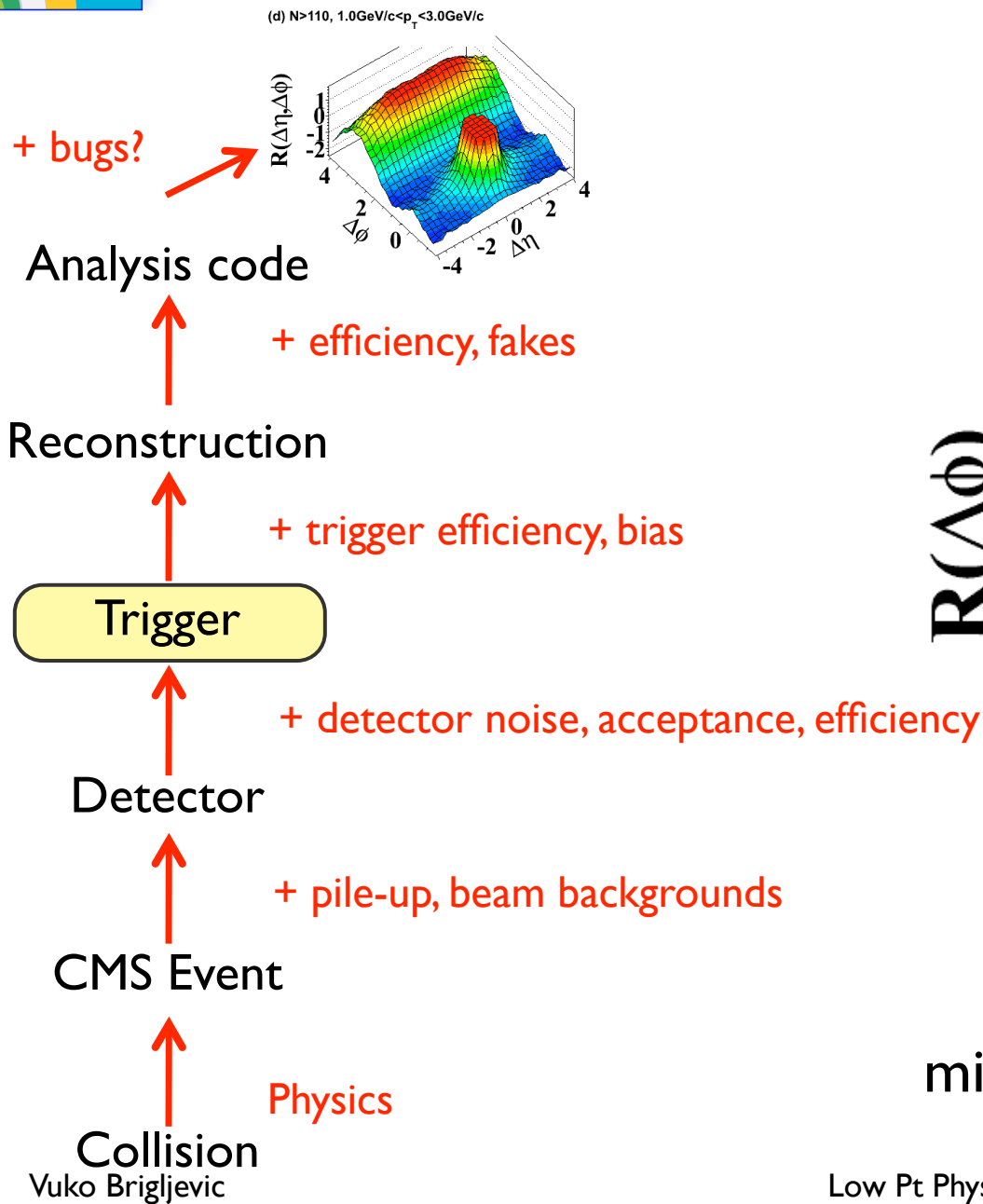
(...)

If we are here today it is because we didn't succeed to kill it.” G. Tonelli

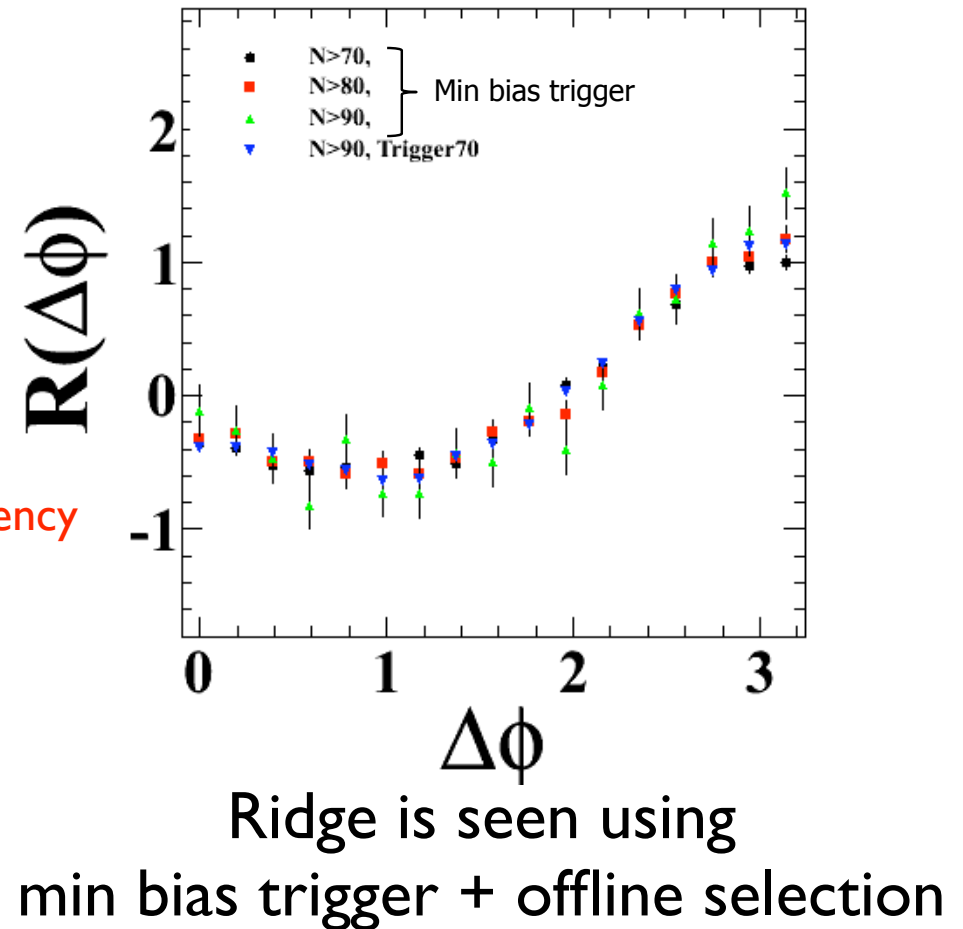
Test the complete chain with data-driven checks!



Cross-checks: Trigger



Min-bias trigger vs high mult trigger

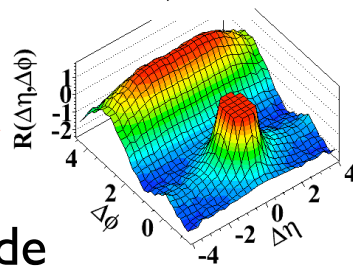




Cross-checks: Event Pile-Up



(d) $N > 110, 1.0 \text{ GeV}/c < p_T < 3.0 \text{ GeV}/c$



+ bugs?

Analysis code

+ efficiency, fakes

Reconstruction

+ trigger efficiency, bias

Trigger

+ detector noise, acceptance

Detector

+ pile-up, beam backgrounds

CMS Event

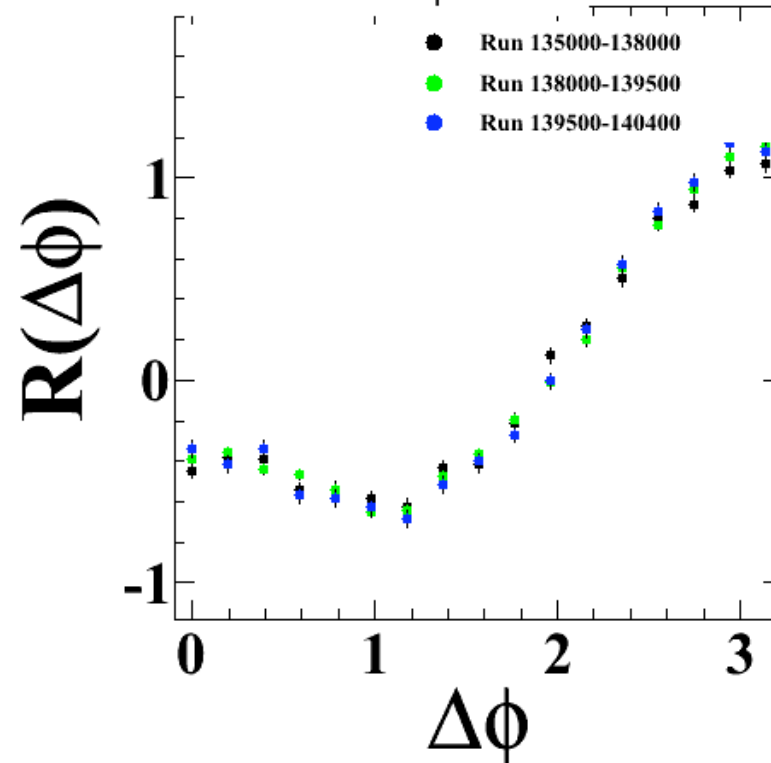
Collision

Physics

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

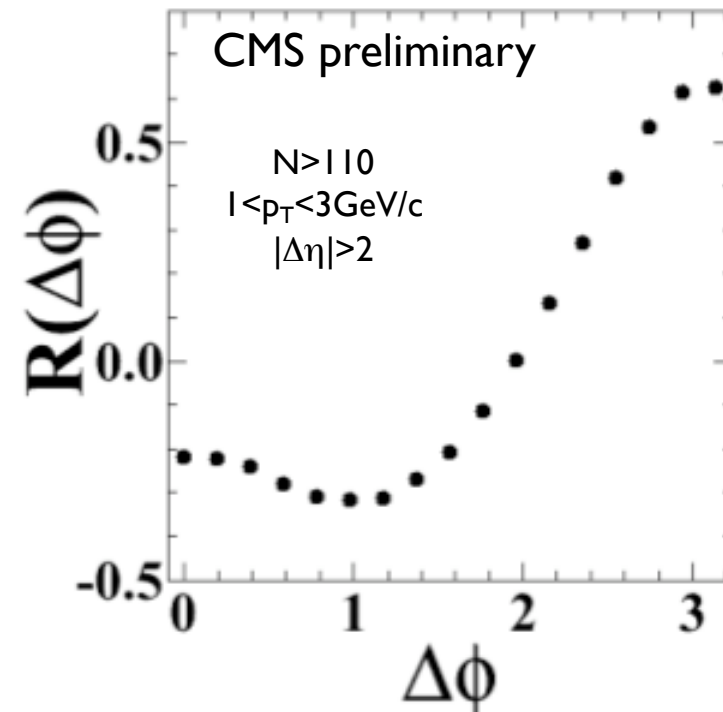
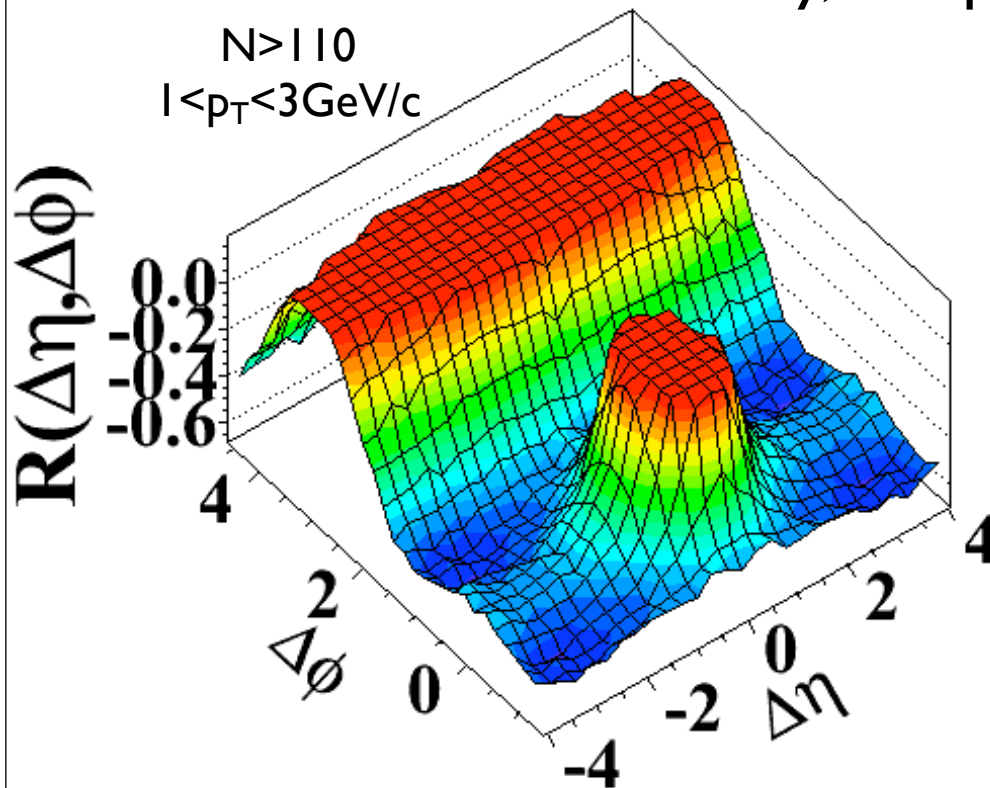
$90 < N < 110, 2.0 < |\Delta\eta| < 4.8, 1.0 \text{ GeV}/c < p_T < 2.0 \text{ GeV}/c$



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

Final Test: ECAL photons

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



Track-photon correlations

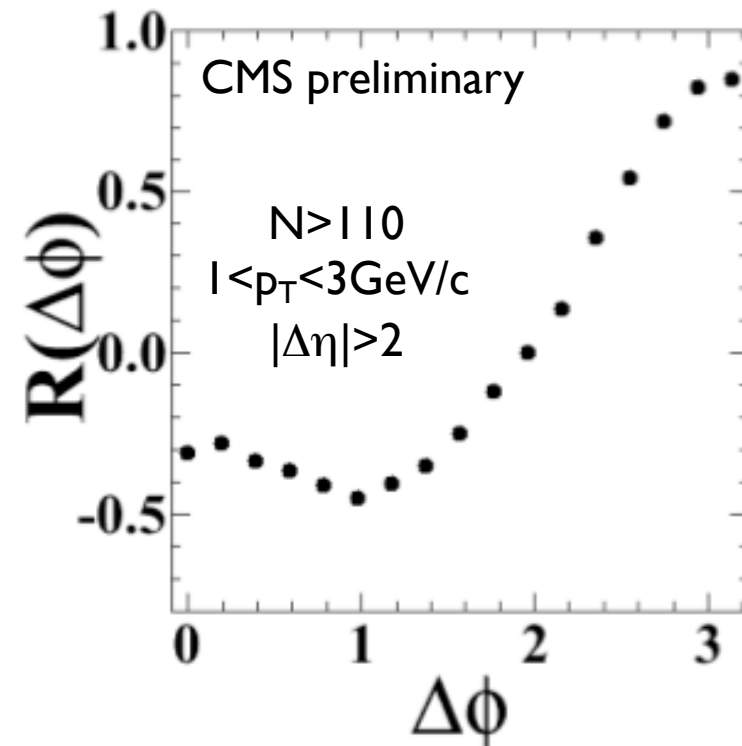
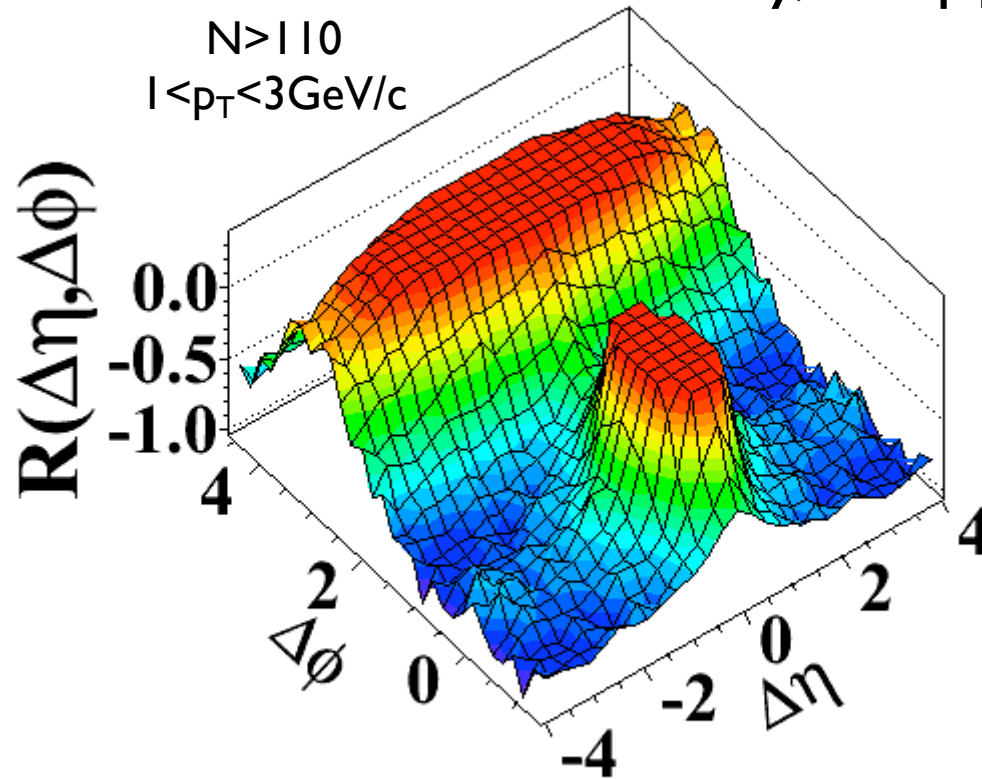
Note: photons reconstructed using “particle flow”
 event reconstruction technique

Final Test: ECAL photons

Use ECAL “photon” signal

Mostly single photons from π^0 's

No efficiency, and p_T , ϕ smearing corrections

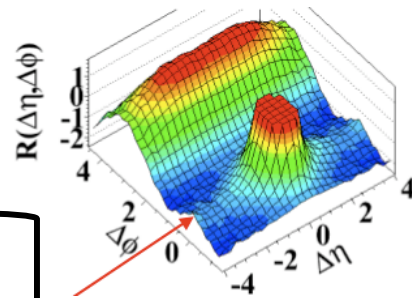


Photon-photon correlations

Qualitative confirmation

Independent detector, independent reconstruction

Systematic Uncertainties



Analysis code

Reconstruction

Trigger

Detector

CMS Event

Collision

Vuko Brigljevic

Each step tested with data-based checks

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

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

Conservative estimates of uncertainties on ridge associated yield



Summary on this observation



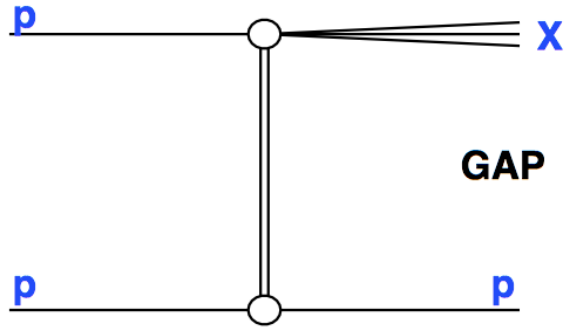
- ▶ Observation of long-range, near-side correlations in high multiplicity events
 - * Signal grows with event multiplicity
 - * Effect is maximal in the $1 < p_T < 3$ GeV/c range
- ▶ Long-range, near-side correlation is not seen in low multiplicity events and generators, but resembles effects seen in heavy-ion collisions at high energies
- ▶ Very extensive systematic checks performed.
 - * We are confident in the measurement as such
- ▶ This is a subtle effect in a complex environment – careful work is needed to establish physical origin



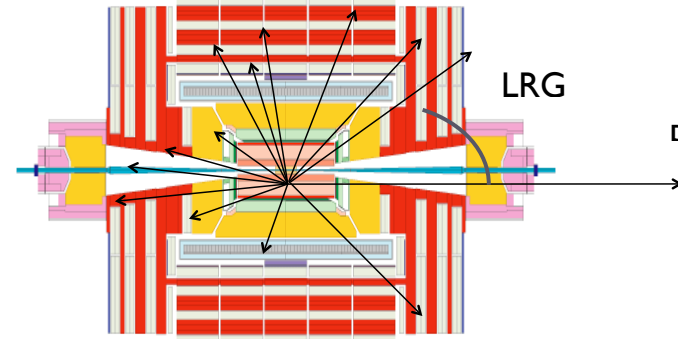
Forward Physics



Observation of Diffraction



Sketch of single-diffractive event:



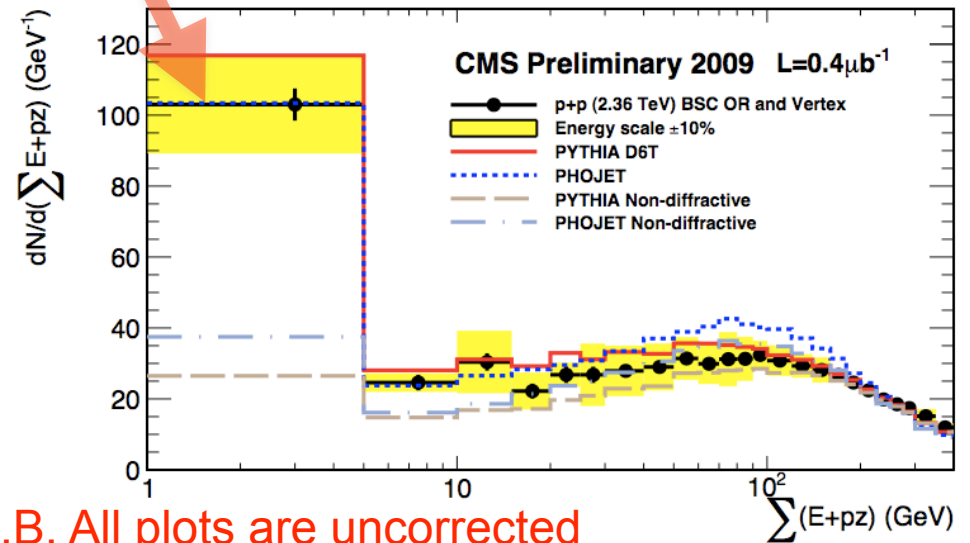
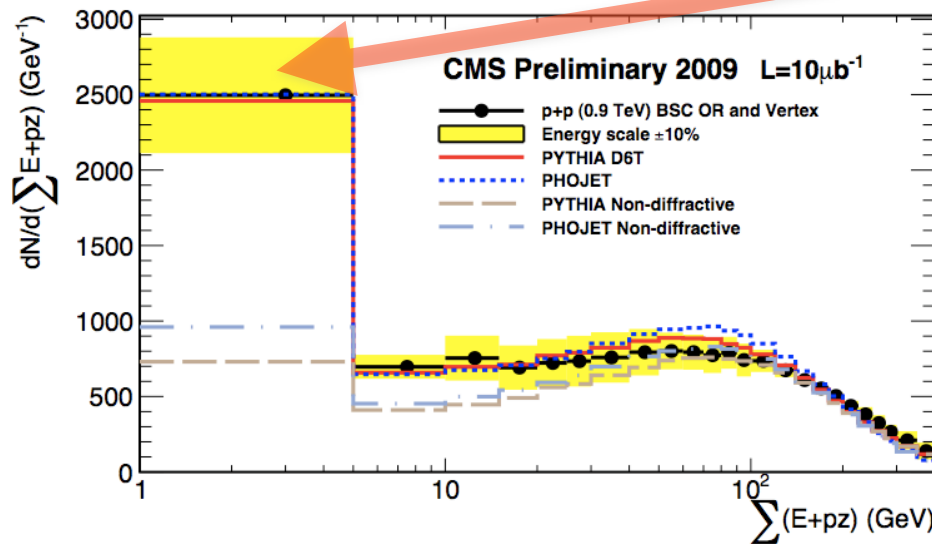
$$\xi = M_X^2 / s$$

$$\sigma \approx 1 / \xi$$

$$\Delta y \approx - \ln \xi$$

$$\xi \approx \sum_i (E_i \pm p_{z,i})$$

$\Sigma (E+p_z)$ related to the fractional energy loss of the scattered proton. One expects a (diffractive) peak at low values of this variable ($\sigma \sim 1/\xi$).



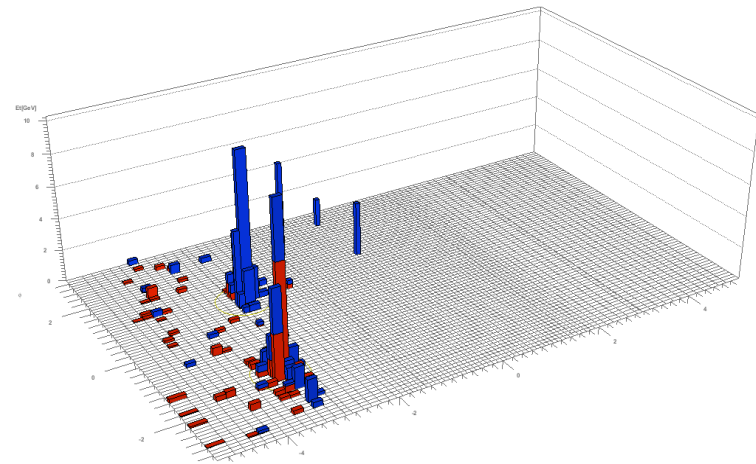
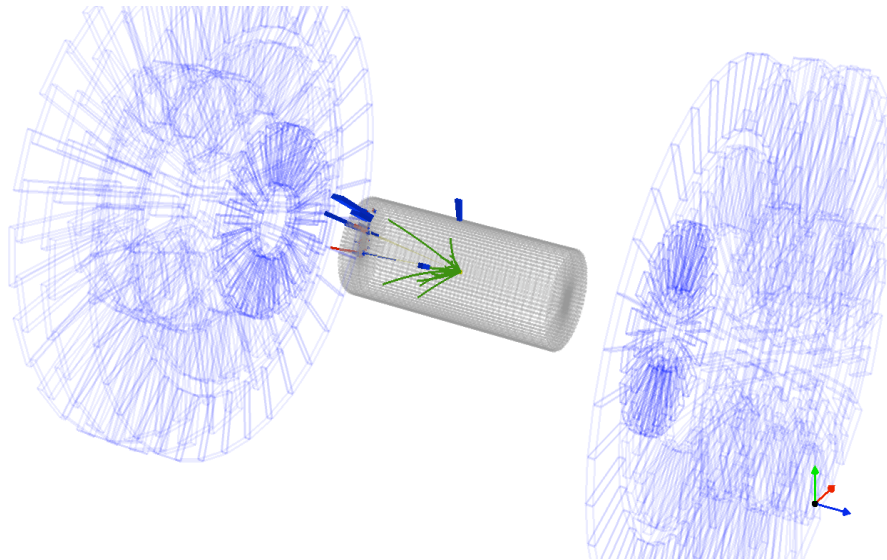
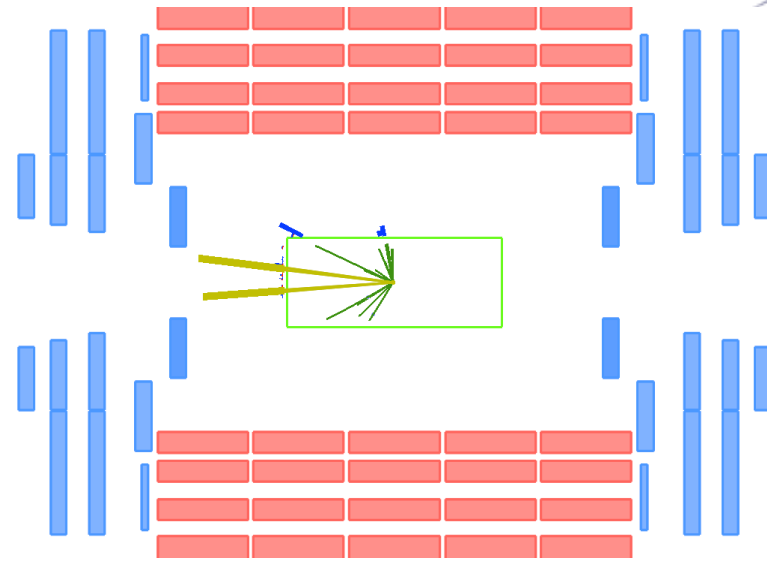
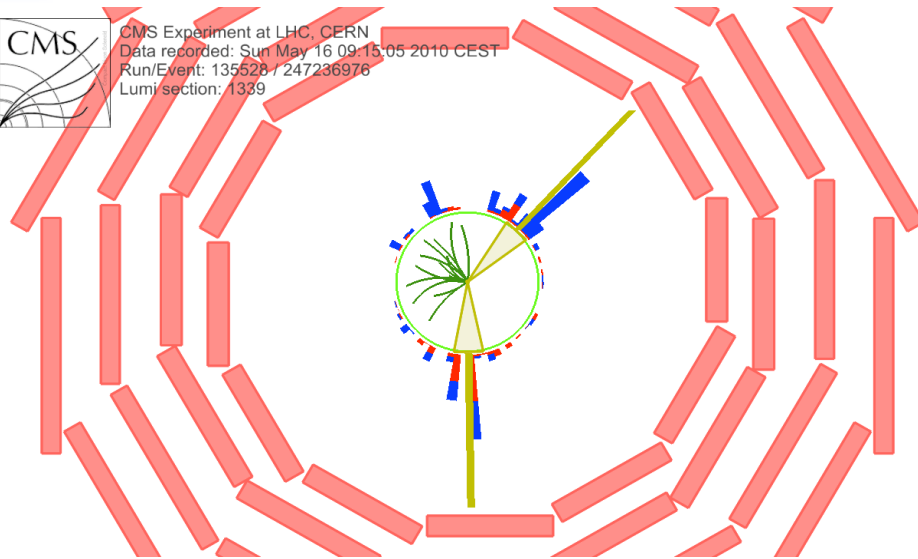
N.B. All plots are uncorrected



Diffractive Di-Jet Candidate at 7 TeV



CMS Experiment at LHC, CERN
Data recorded: Sun May 16 09:15:05 2010 CEST
Run/Event: 135628 / 247236976
Lumi section: 1339



$E(\eta < 3.0) > 1.5 \text{ GeV}$ $p_T(\text{track}) > 0.5 \text{ GeV}$
 $E(\eta \geq 3.0) > 2.0 \text{ GeV}$

$p_T(\text{jet1}) = 41.2 \text{ GeV}$, $p_T(\text{jet2}) = 31.9 \text{ GeV}$
 $\eta(\text{jet1}) = -2.8$, $\eta(\text{jet2}) = -3.3$



Summary



Some conclusions

- ▶ CMS Data @ 0.9, 2.36 and 7 TeV
 - Many low Pt-Studies made possible through excellent performance of Trigger, Calorimetry and in particular Tracking system
- ▶ Underlying Event Activity
 - Strong dependence on \sqrt{s}
 - Already many handles for MC tuning
- ▶ Charge Particle Production
 - Diverse tracking strategies established
 - General MC deficit
- ▶ First unexpected observation of long-range, near-side angular correlations
 - Physics origin needs to be understood
- ▶ Forward Processes
 - Single-diffractive peak observed



Some References



Gateway to collection of all CMS Results:
<https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResults>

- QCD-09-010 Charged hadrons @ 0.9/2.36 TeV [pub.]
- QCD-10-006 Charged hadrons @ 7 TeV [pub.]
- QCD-10-004 Charged particle multiplicities
- QCD-10-003 Bose-Einstein Correlations [pub.]
- QCD-10-001 Underlying Event @ 0.9TeV [pub.]
- QCD-10-010 Underlying Event @ 7 TeV
- QCD-10-005 Underlying Event from JetArea/Median
- QCD-10-002 Observation of Long-Range, Near-Side Angular Correlations [pub.]
- QCD-10-007 Strangeness production
- QCD-10-008 Charged hadron Pt spectra
- FWD-10-001 Observation of Diffraction
- FWD-10-002 Forward Energy Flow