CMS Minimum Bias Results

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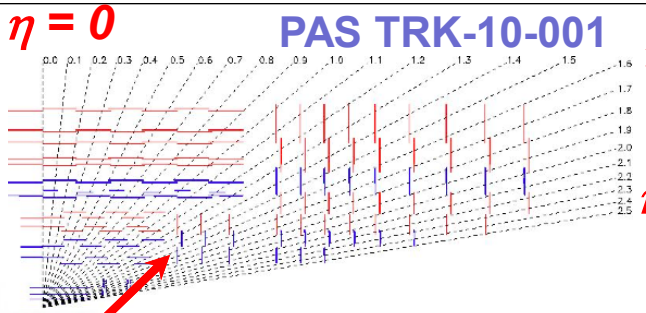
Outline…

- Low-p_T Physics
  - Particle correlations
  - Particle Production in MB events
  - Underlying Event studies
- Forward/Diffractive results
- Conclusion

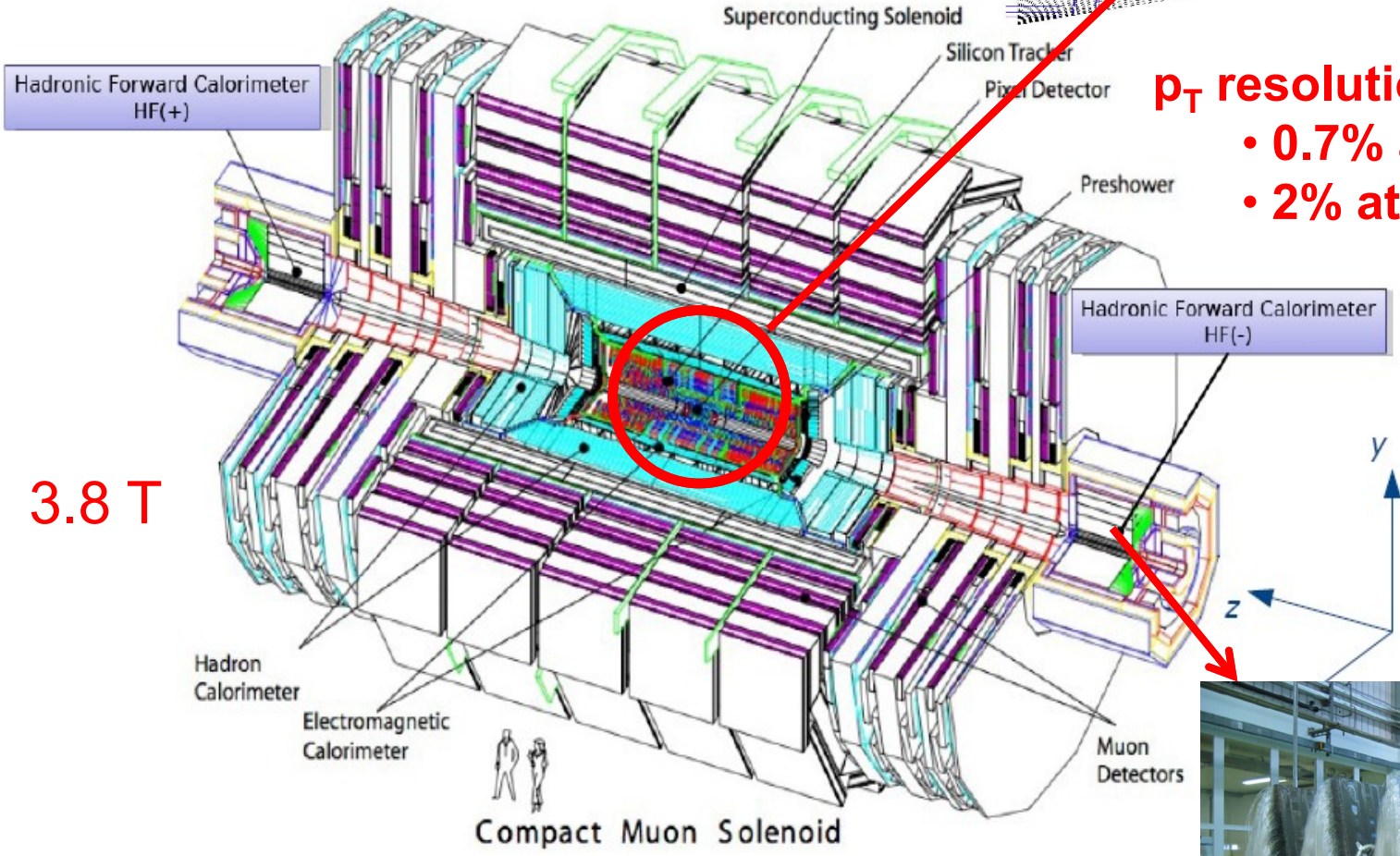
CMS Detector

CMS Tracker



p_T resolution @ 1 GeV/c:

- 0.7% at $\eta = 0$
- 2% at $|\eta| = 2.5$

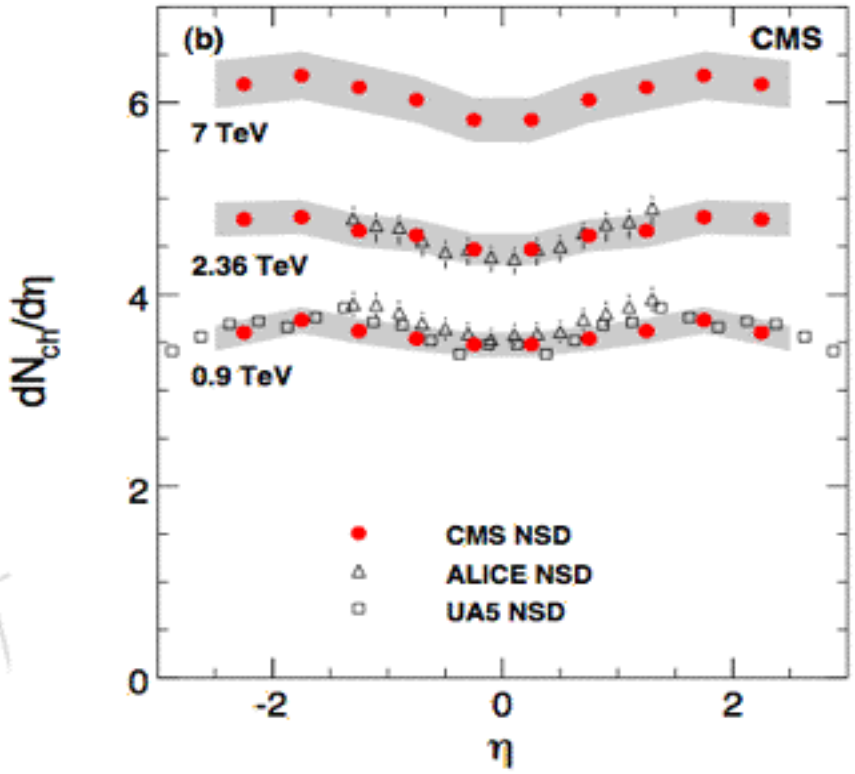


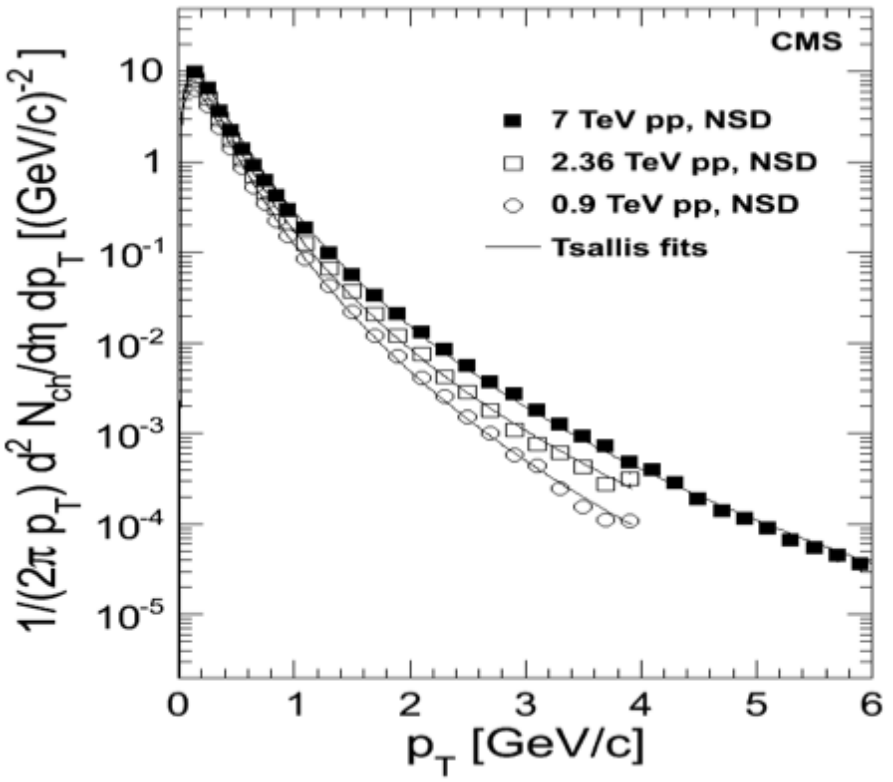
Early measurements of Pseudorapidity and Charge Multiplicity Production @ CMS

First CMS physics results

Single particle spectra

$dN/d\eta \sim \ln \sqrt{s}$





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

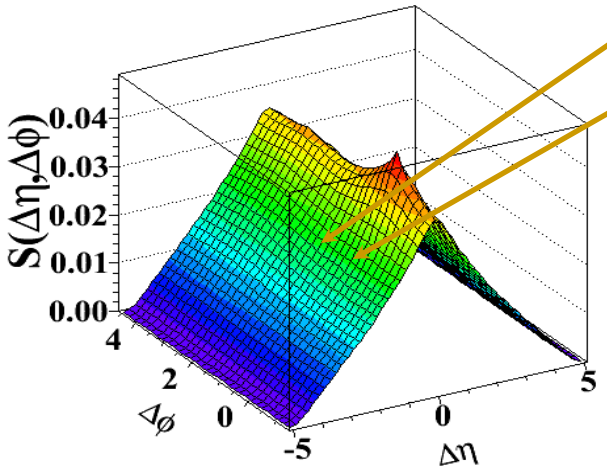
Sep. 21st , 2010

arXiv:1009.4122 ➔ JHEP 1009:091, 2010

Angular Correlation Technique

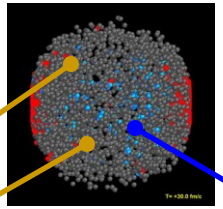
Signal distribution:

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

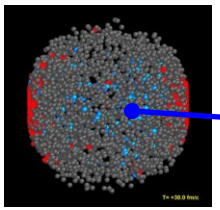


same event pairs

Event 1

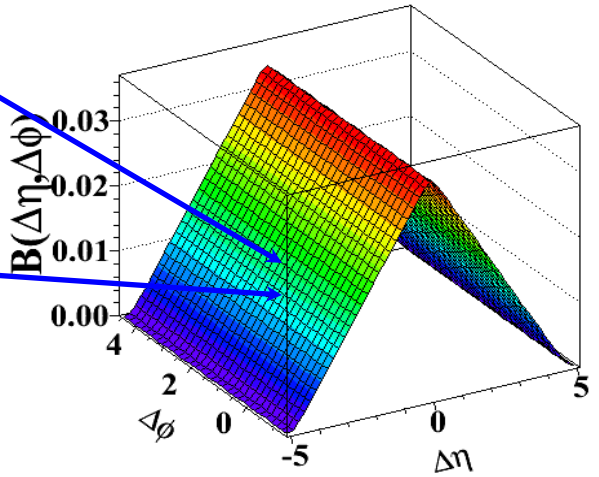


Event 2



Background distribution:

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



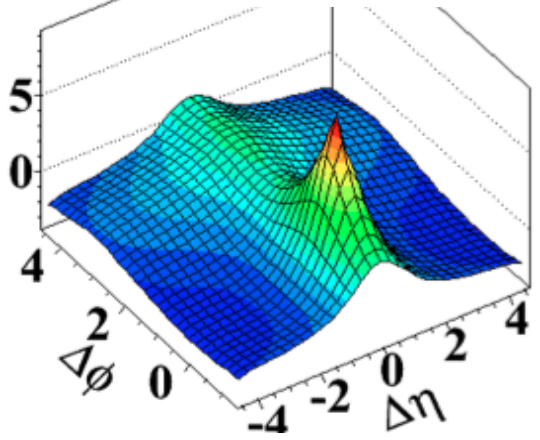
mixed event pairs

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

$$\Delta\varphi = \varphi_1 - \varphi_2$$

Charged primary tracks

CMS pp 7TeV



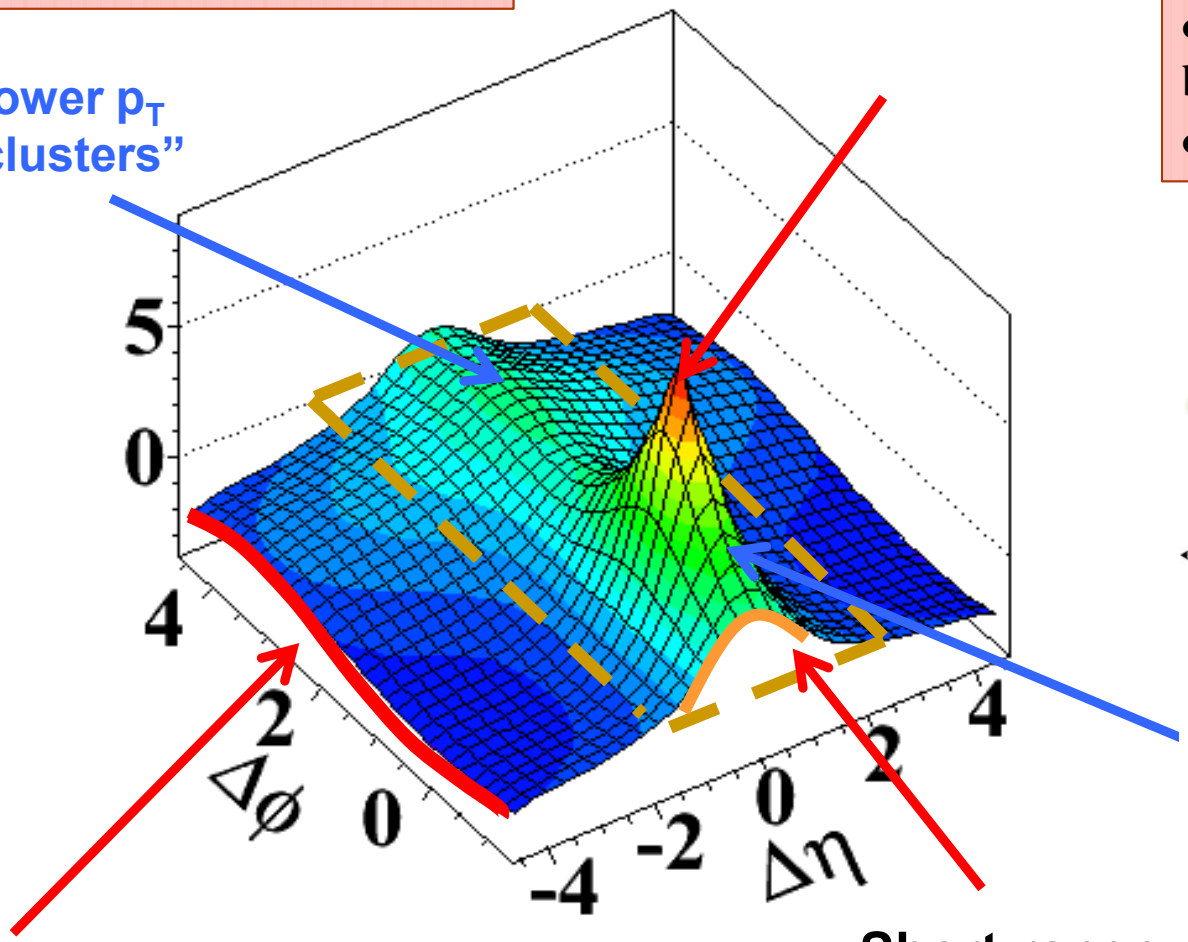
$$R(\Delta\eta,\Delta\varphi) = \left\langle (N-1)\left(\frac{S_N(\Delta\eta,\Delta\varphi)}{B_N(\Delta\eta,\Delta\varphi)} - 1\right)\right\rangle_N$$

p_T-inclusive two-particle angular correlations in Minimum Bias collisions

Two Particle Angular Correlation (1)

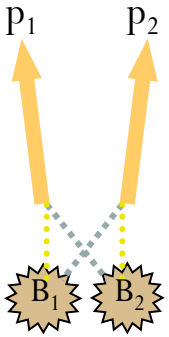
CMS 7 TeV pp minimum bias

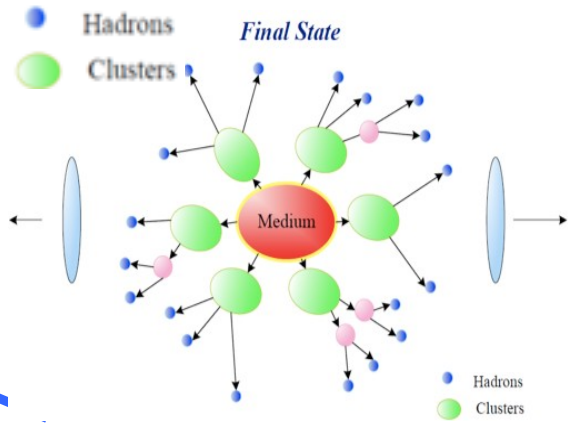
Lower p_T "clusters"



Higher p_T "clusters"

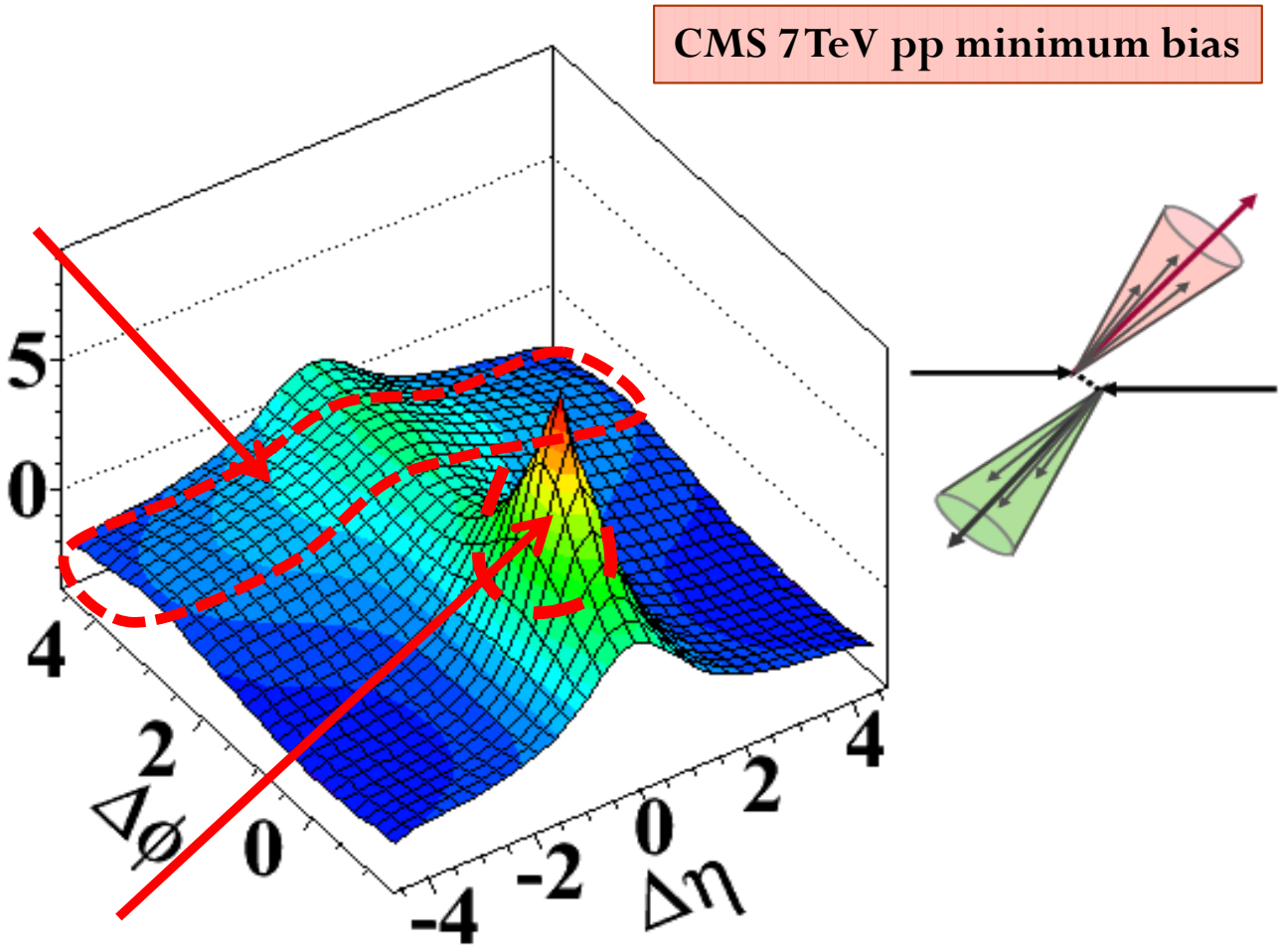
Wave-func. of identical bosons overlaps …





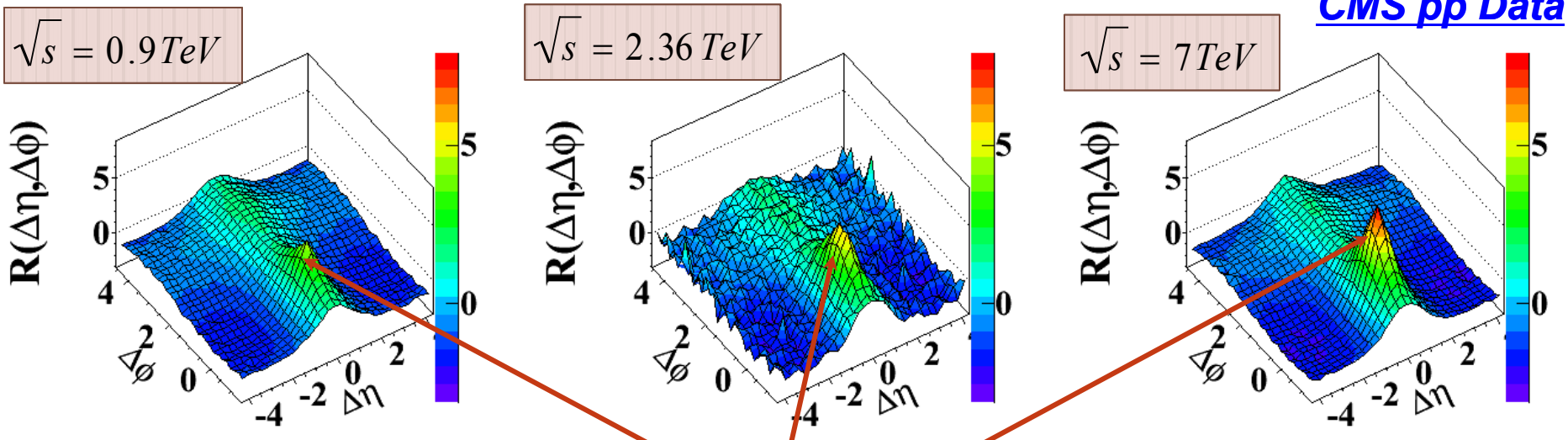
Short-range correlations ($\Delta\eta < 2$): Resonances, string fragmentation, "clusters"

Two Particle Angular Correlation (2)

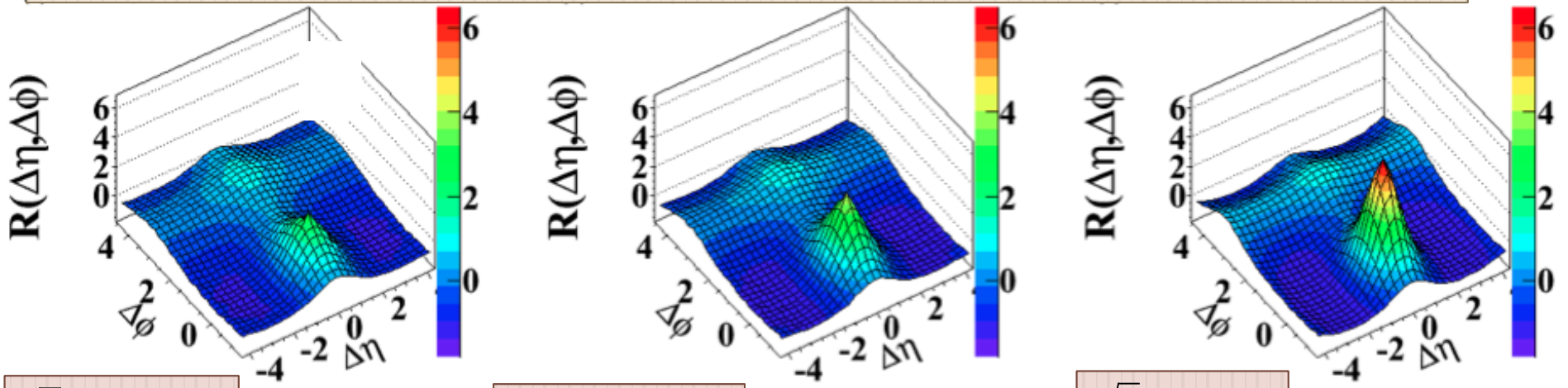


Data & MC as a function of Energy

CMS pp Data



"Jet-like" component grows with collision energy ($\sqrt{s}$)



$\sqrt{s} = 0.9\,TeV$

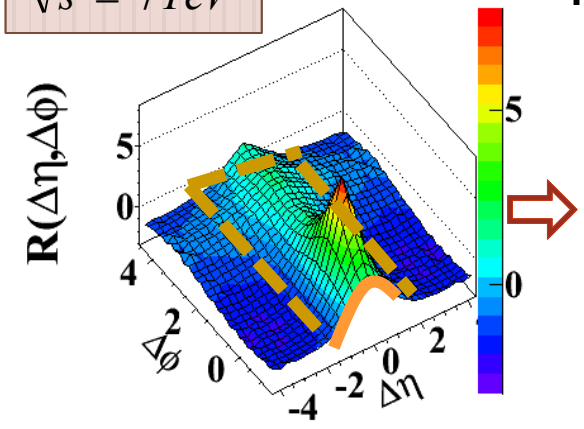
$\sqrt{s} = 2.36\,TeV$

$\sqrt{s} = 7\,TeV$

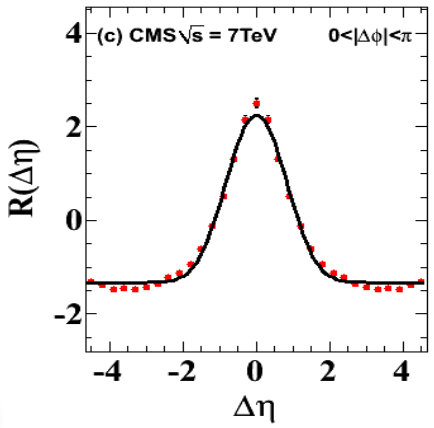
PYTHIA D6T

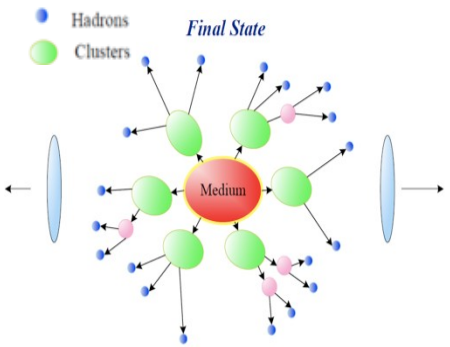
Short-Range Correlation ($\Delta\eta < 2$) vs Energy

$\sqrt{s} = 7TeV$

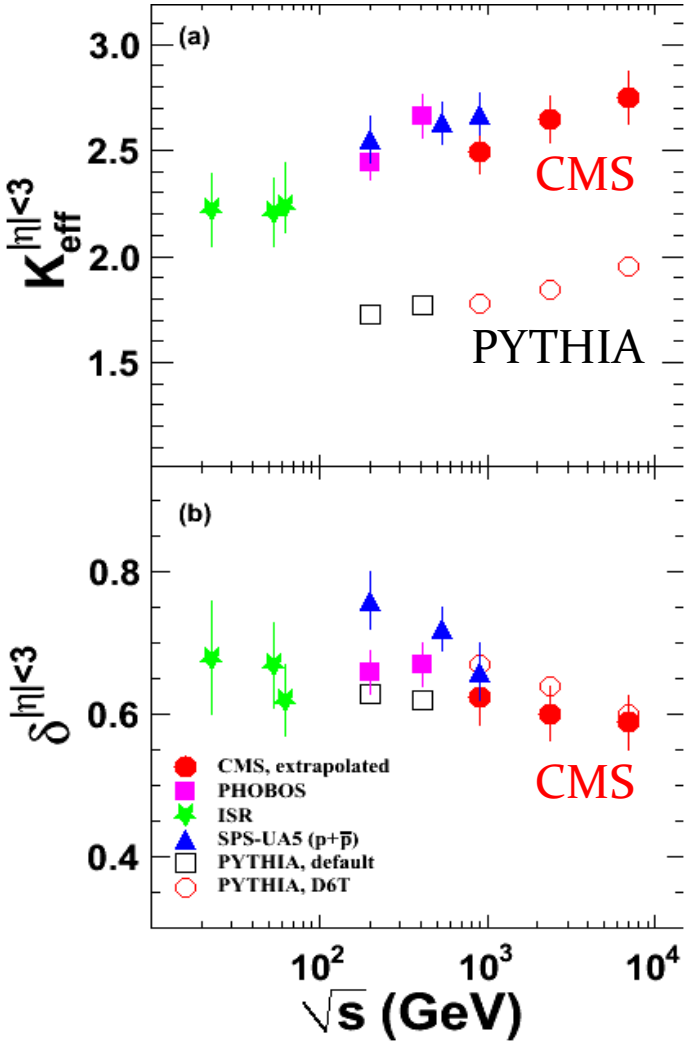


1-D "projection" to $\Delta\eta$ axis





K_{eff}: # of correlated particles
δ: extent of correlation in η



PYTHIA describes energy dependence

→ Matches cluster width δ

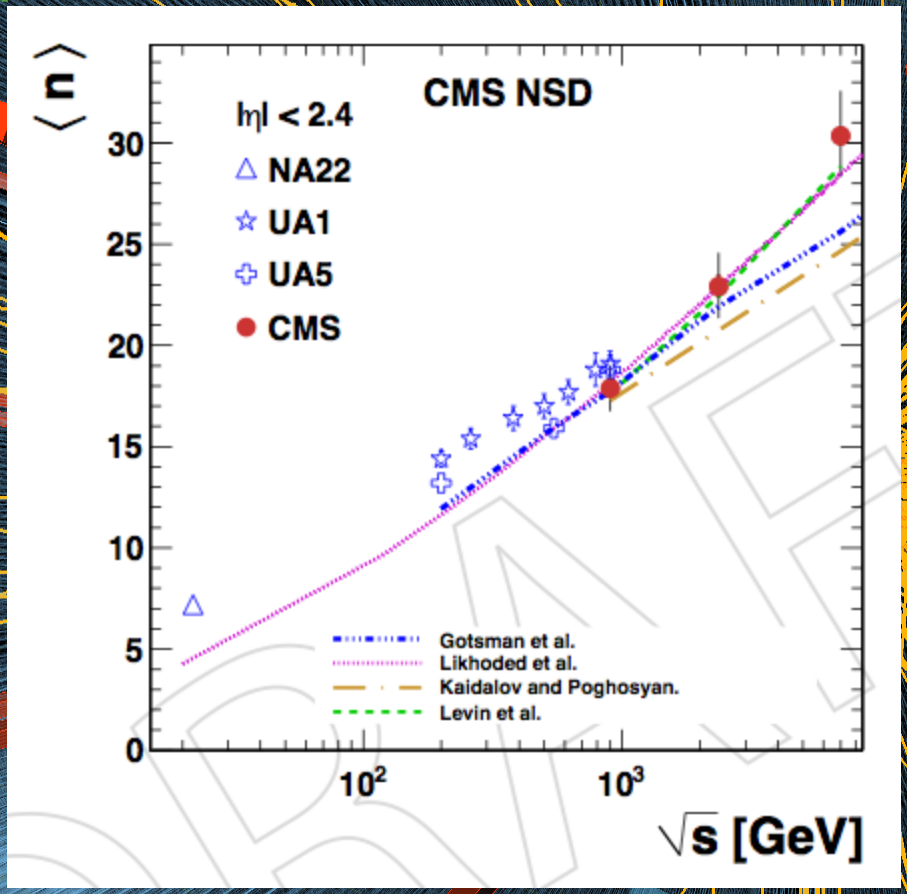
→ Underestimates the cluster size K_{eff}

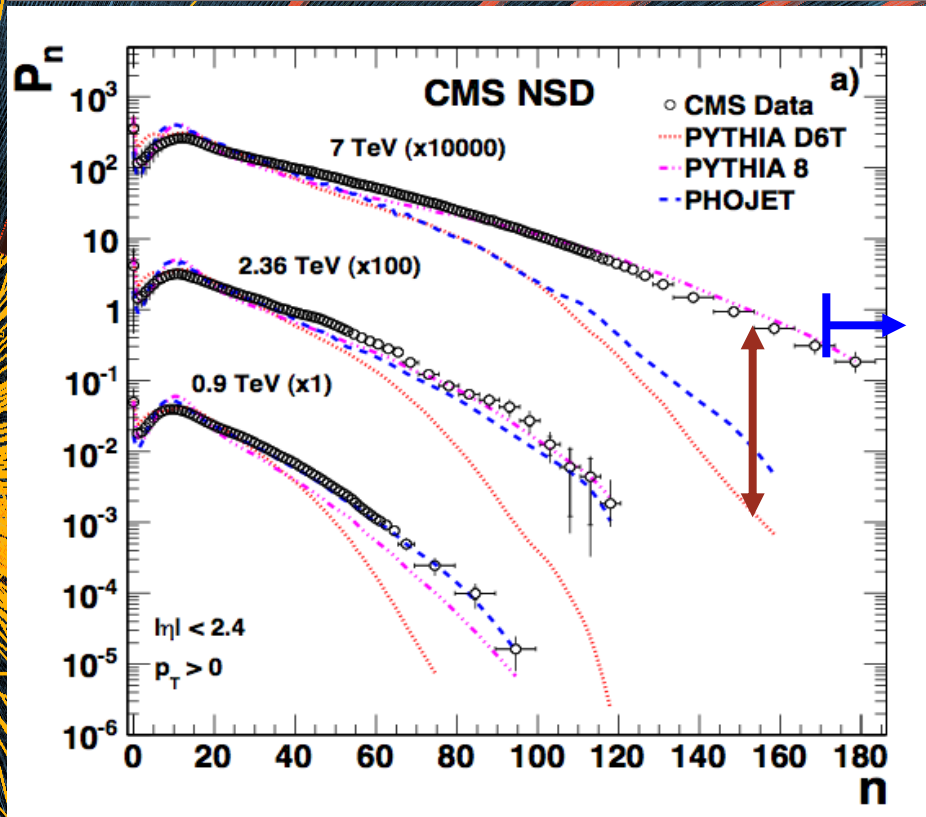
Mean & High Multiplicity pp collisions

CMS Experiment at the LHC, CERN

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

High Multiplicity events are rare in nature



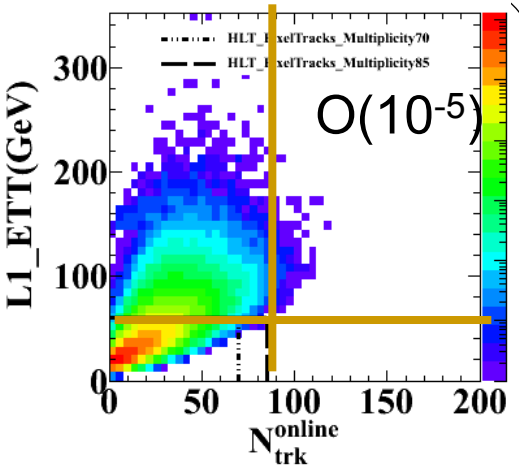


Very high particle density regime

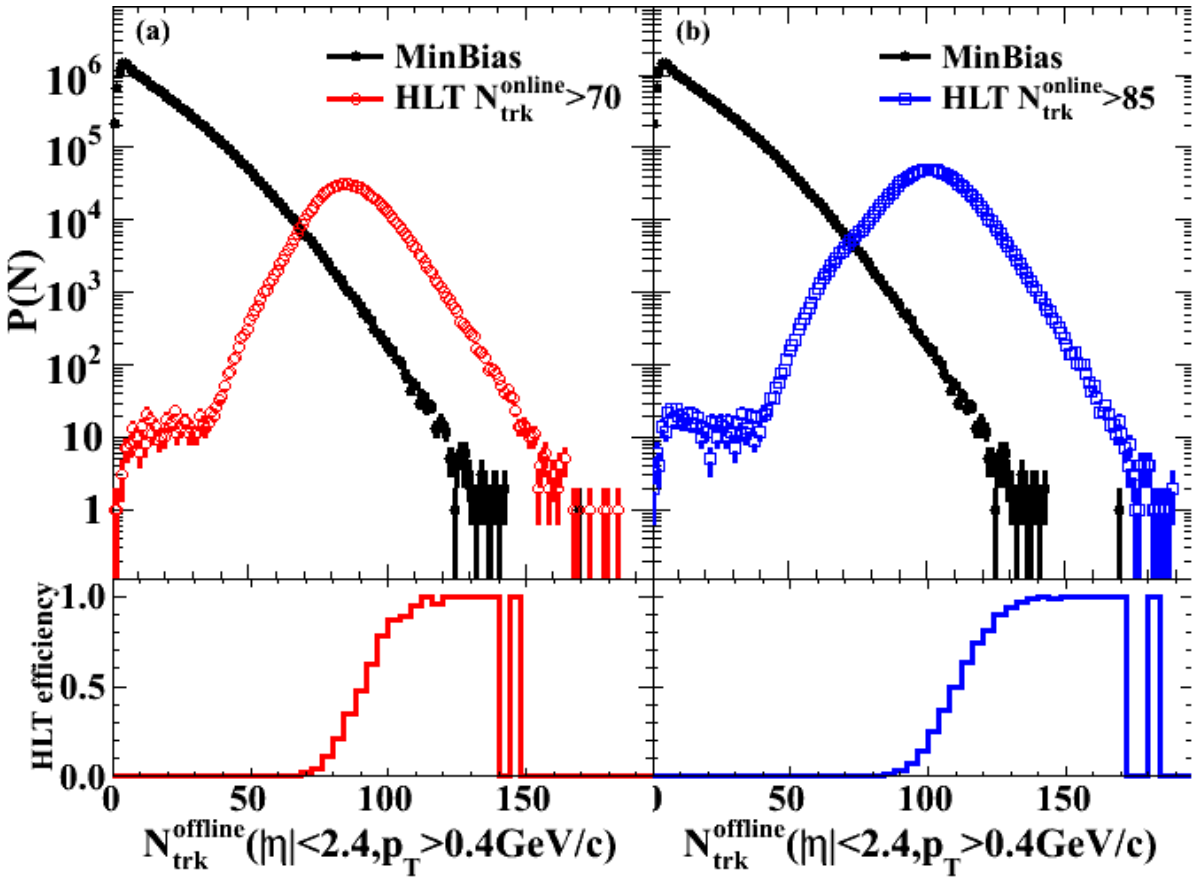
Is there anything peculiar happening there?

Trigger on High Multiplicity pp

$\sum E_T$> 60 GeV in calorimeters



Total integrated luminosity: 980nb^{-1}



Two HLT thresholds:

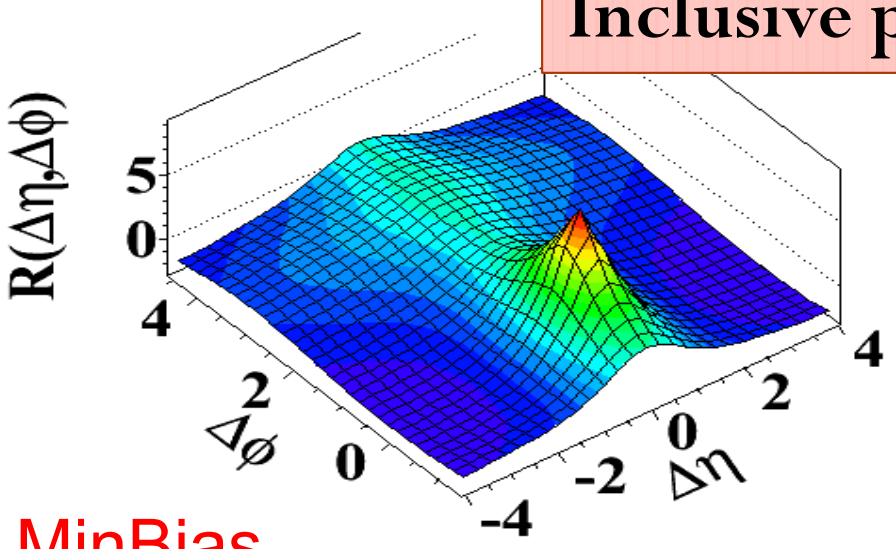
- $N^{online} > 70$
- $N^{online} > 85$

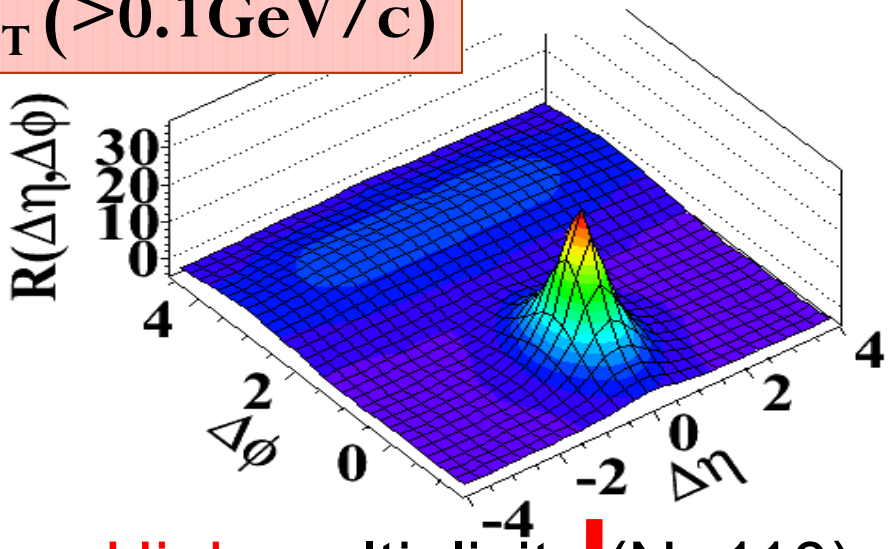
Yield & high multiplicity Events increased by a factor of 1000

~350K top multiplicity events (N>110) out of 50 Billion collisions!

Correlation in High Multiplicity Events

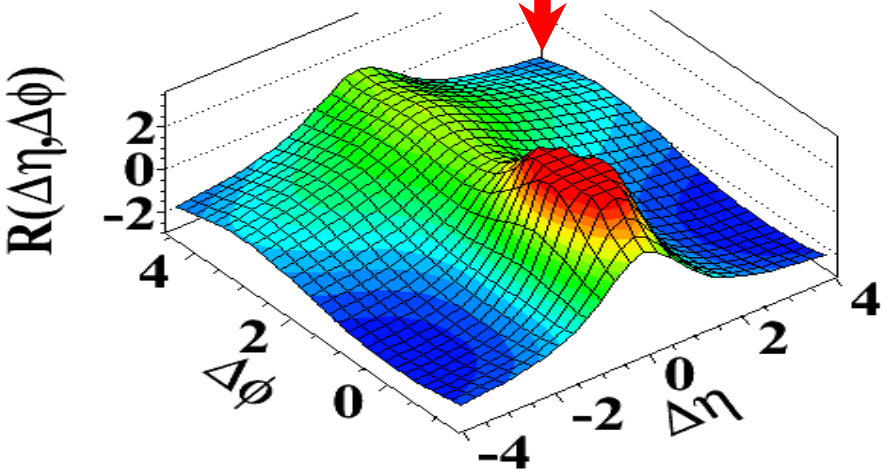
Inclusive p_T (>0.1GeV/c)

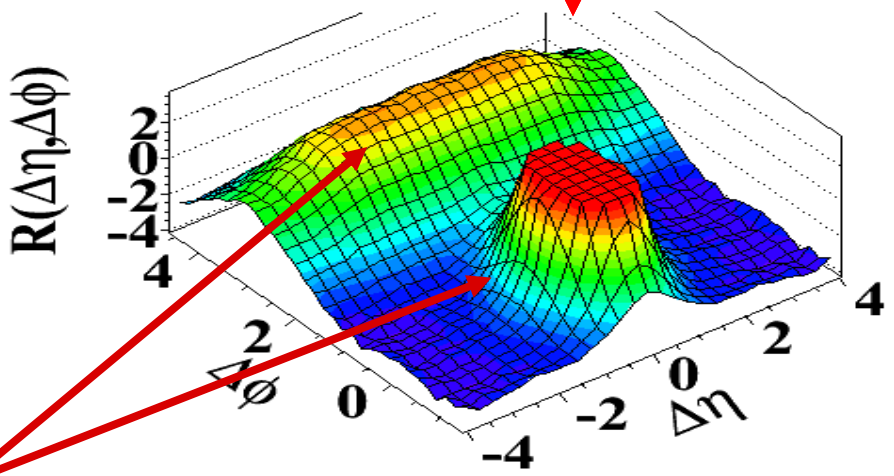




MinBias

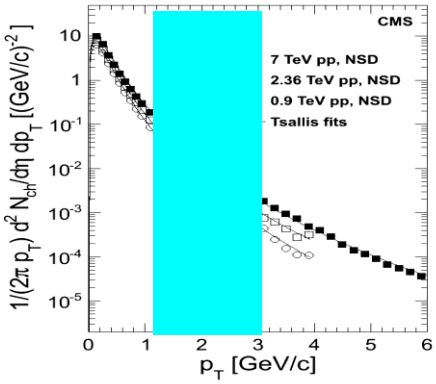
High multiplicity (N>110)





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

Correlations in High Multiplicity pp… momentum range

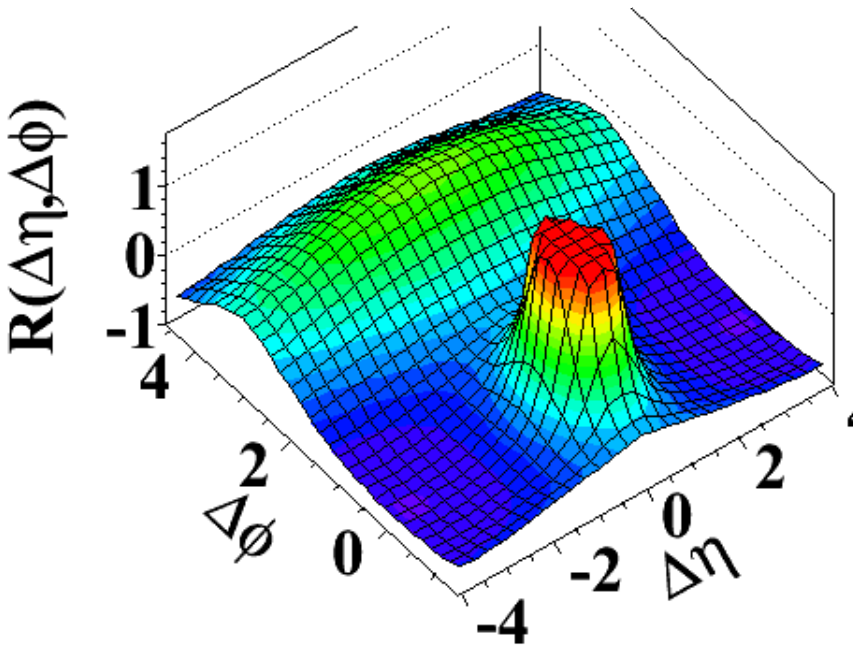


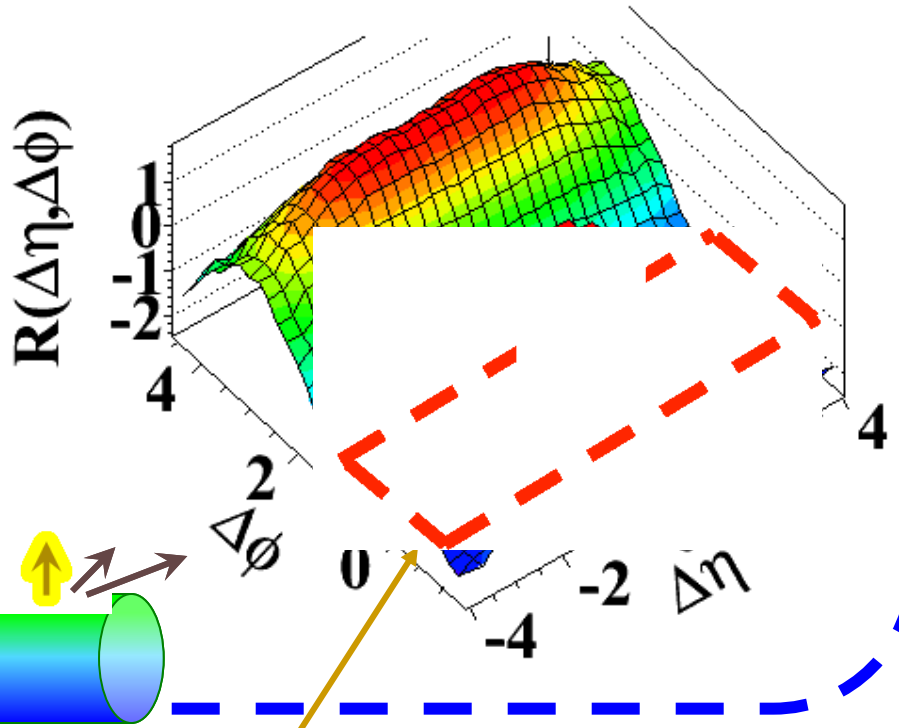
Minimum Bias pp

Higher p_T: 1-3 GeV/c

"Discovery"

High multiplicity pp (N>110)



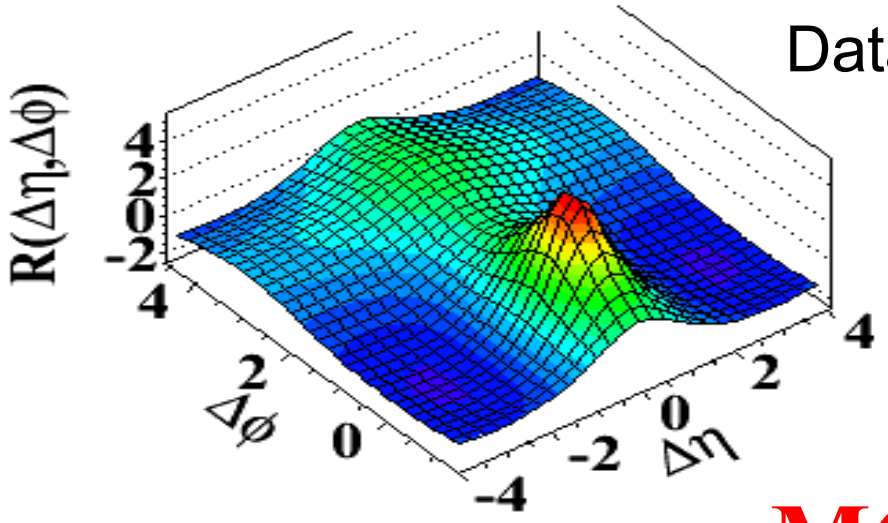


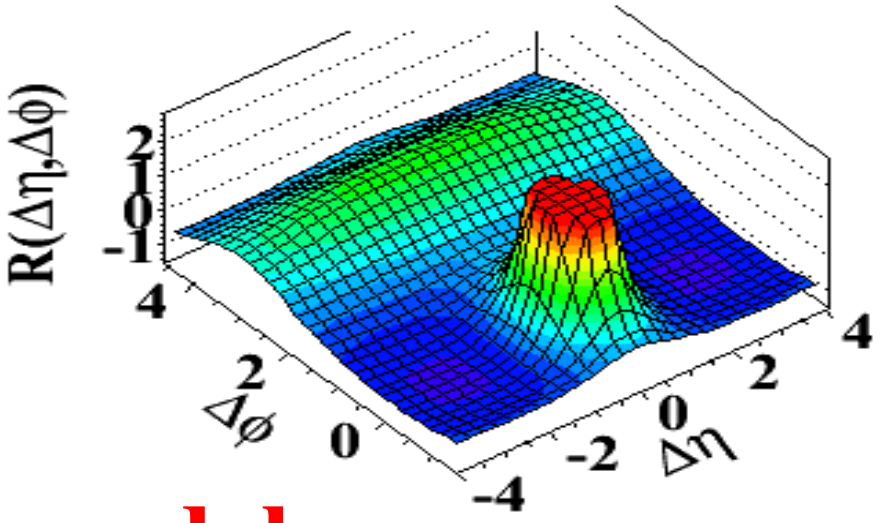
"ridge-like" structure extending over $\Delta\eta$ at $\Delta\phi \sim 0$

(a) MinBias, p_T>0.1GeV/c

(b) MinBias, 1.0GeV/c<p_T<3.0GeV/c

Data



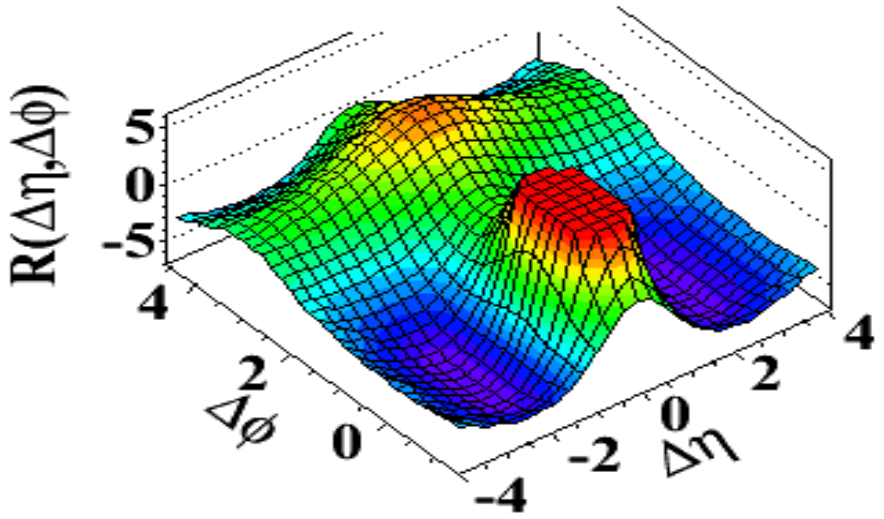


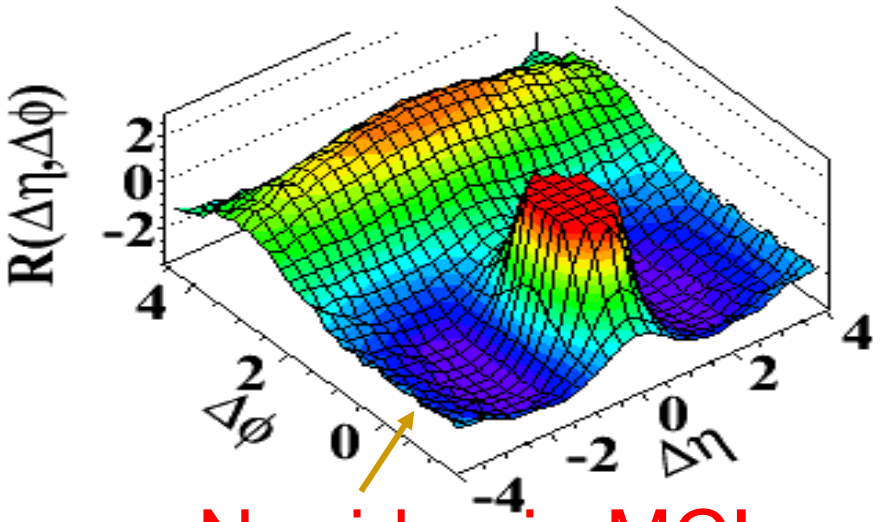
MC model

PYTHIA8, v8.135

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

(d) N>110, 1.0GeV/c<p_T<3.0GeV/c

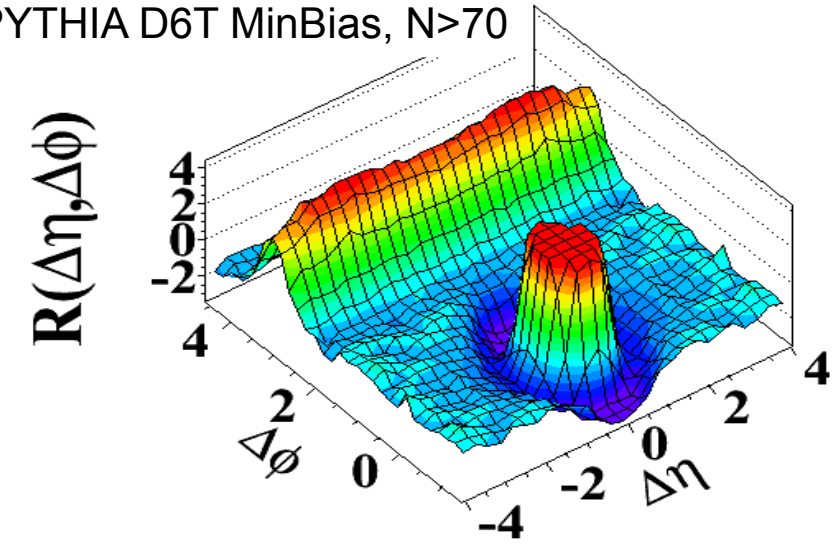




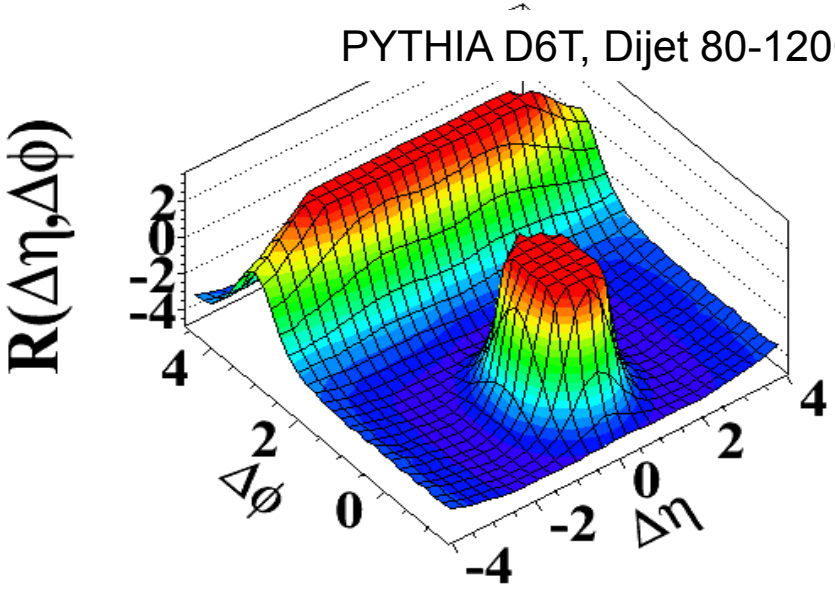
No ridge in MC!

More MC models …

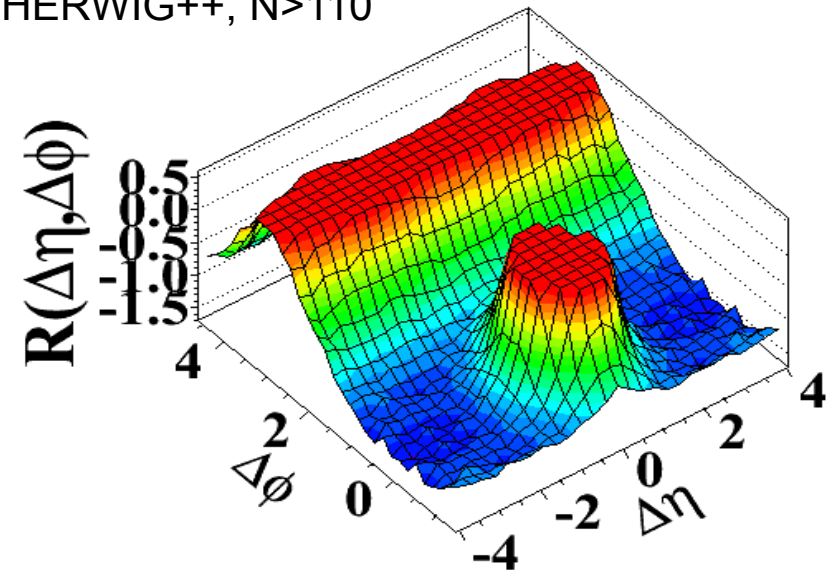
PYTHIA D6T MinBias, N>70



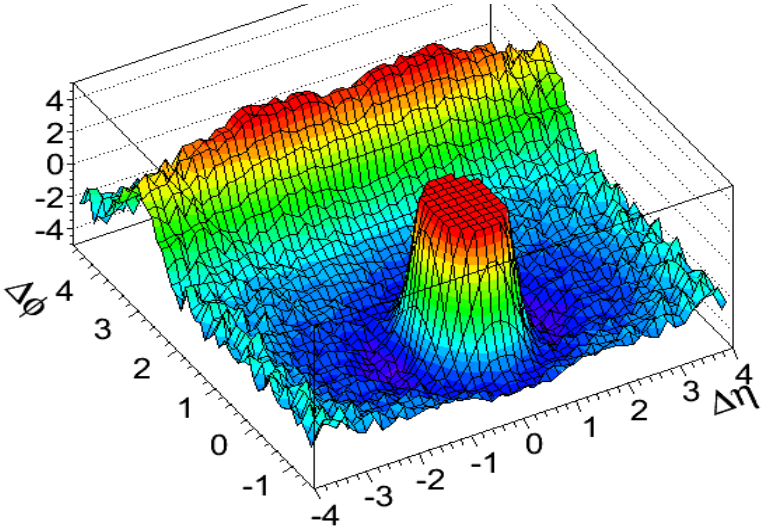
PYTHIA D6T, Dijet 80-120GeV



HERWIG++, N>110

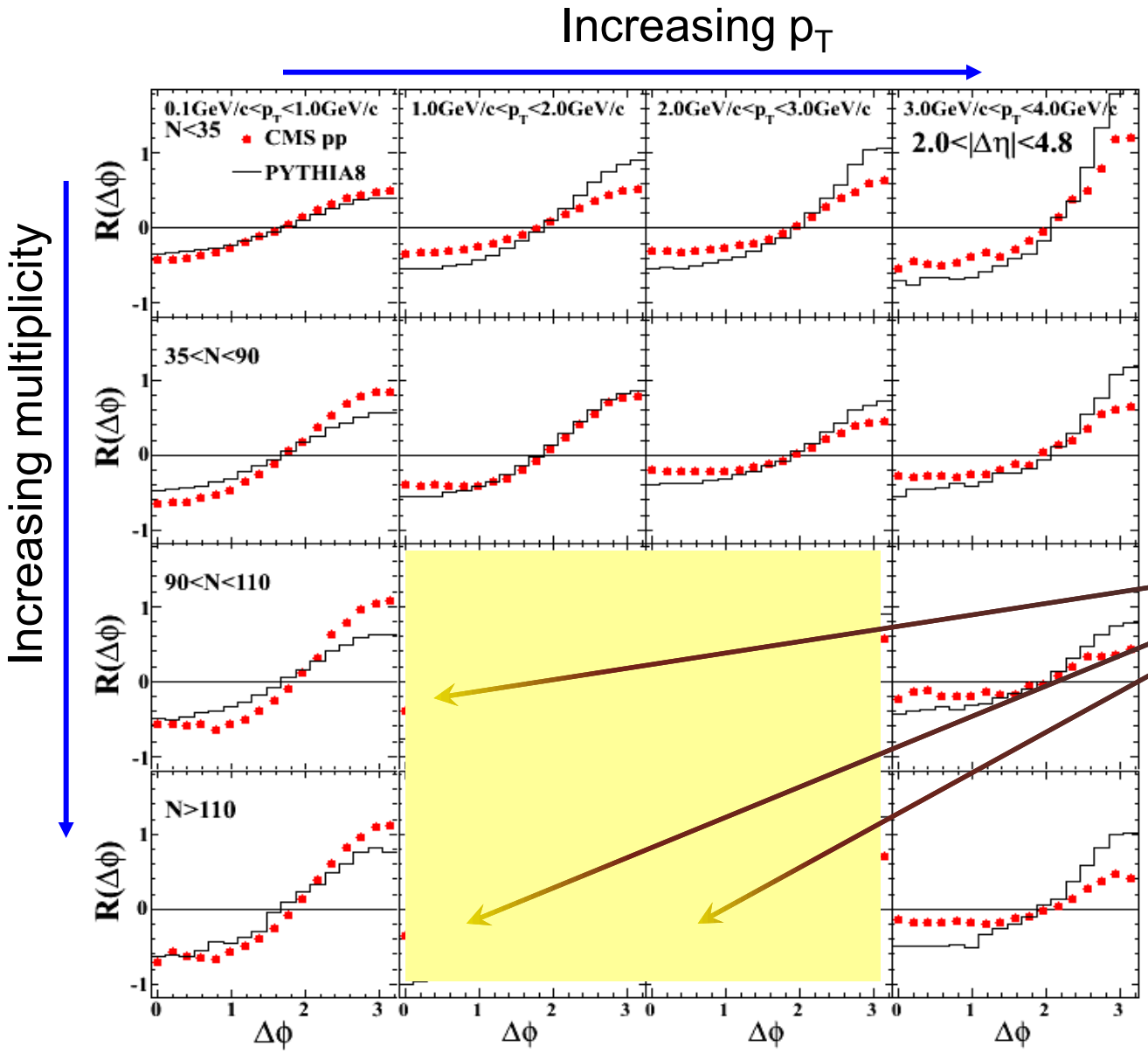


Madgraph, Dijet 100-250GeV, N>90

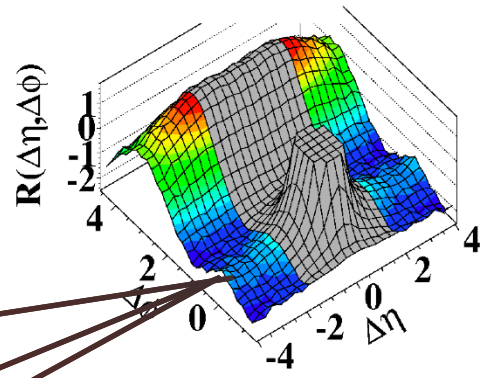


No PRE-diction of the effect in existing theoretical pp models!

1-D projected R(Δϕ) at large Δη



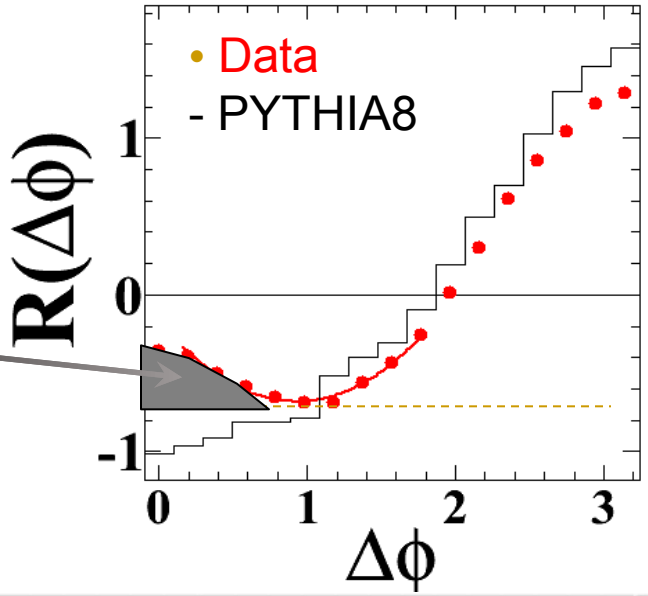
"Ridge" maximal for highest multiplicity & $1 < p_T < 3$ GeV/c



Also:
No charge dependence from like- (++,--) and unlike- (+-) sign correlations

Quantify the Ridge

Zero Yield At Minimum (ZYAM)

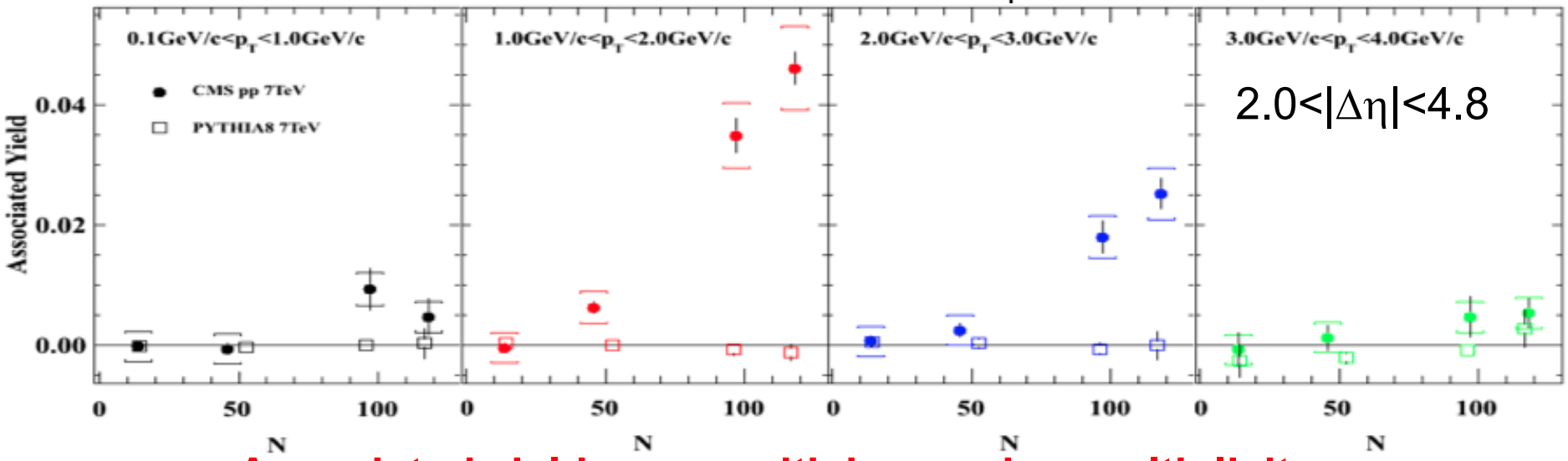


N>110
2.0<|Δη|<4.8
1GeV/c<p_T<2GeV/c

Associated yield:

correlated multiplicity per particle

Minimum of R

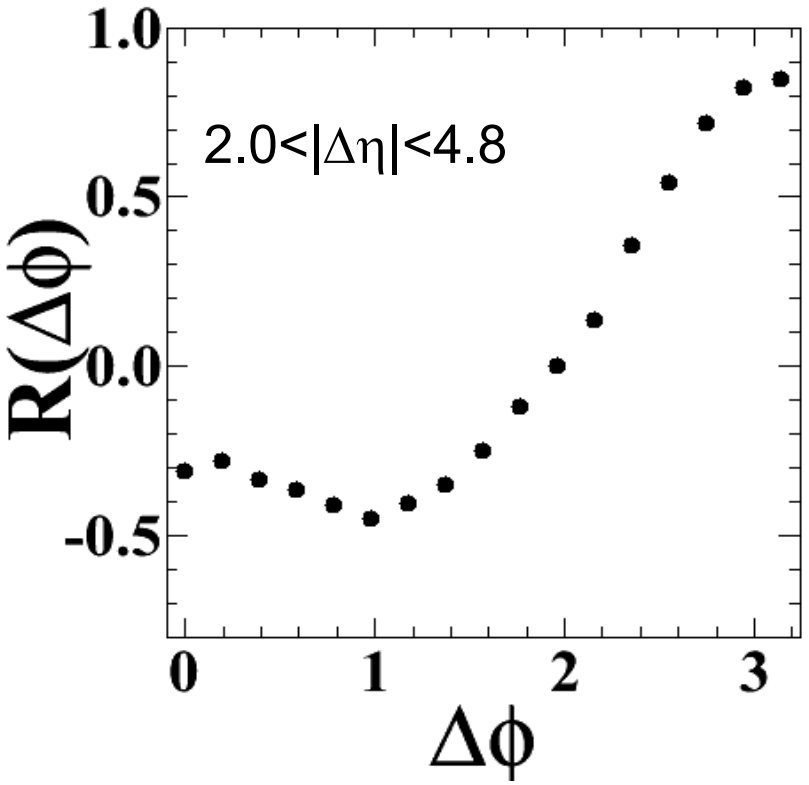


Associated yield grows with increasing multiplicity

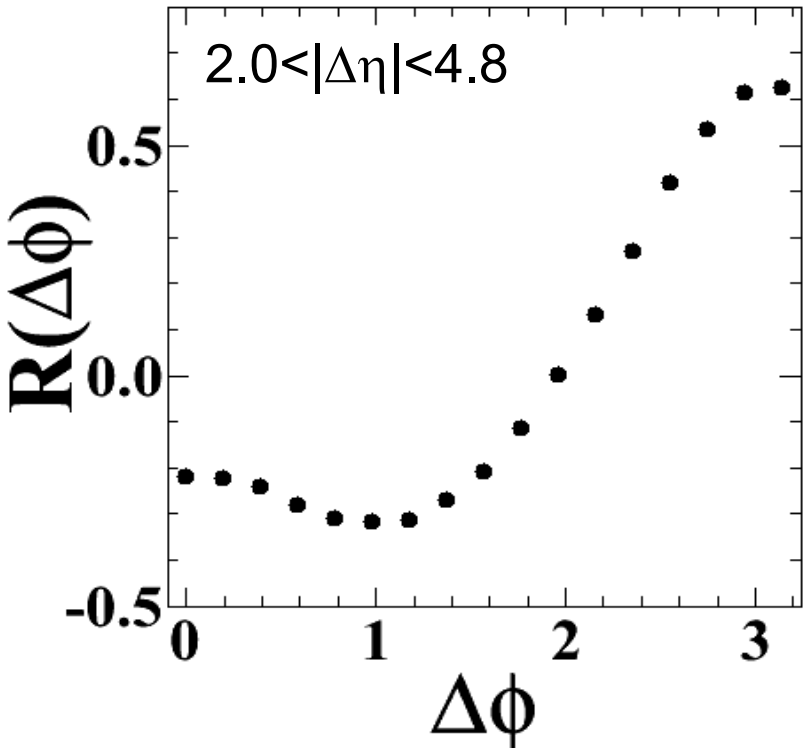
Cross check: Calorimeter information

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

$\gamma\gamma$



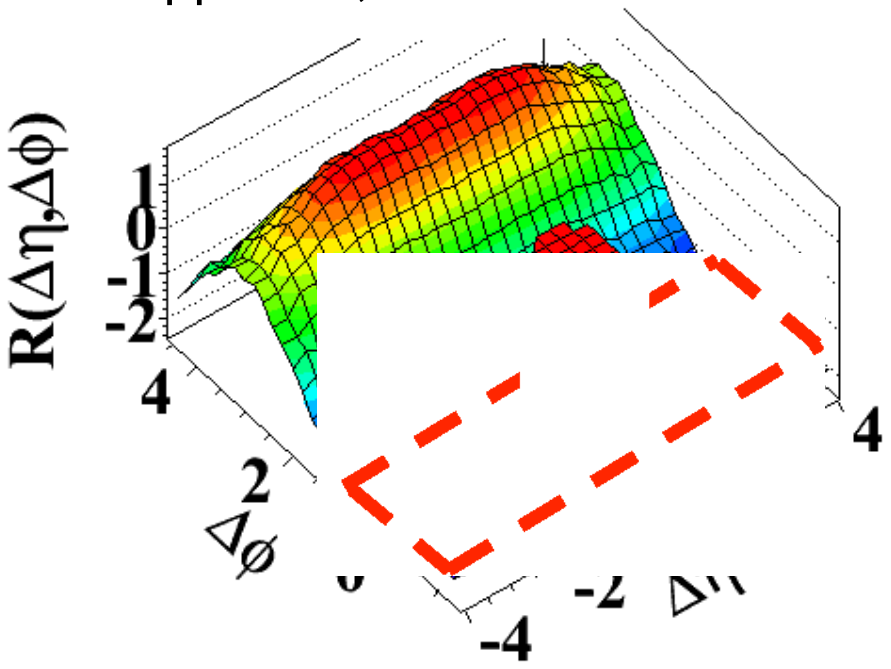
$\pi^{\pm}\gamma$



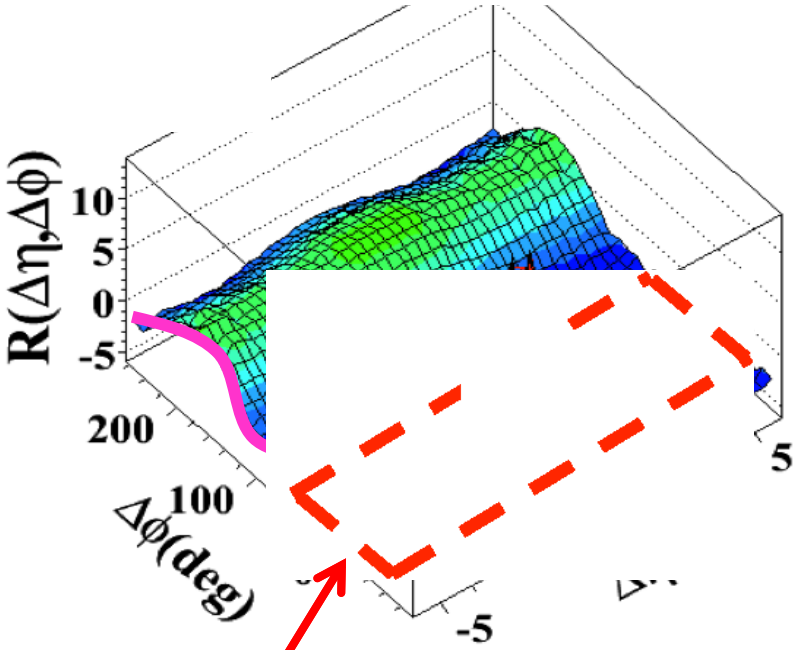
Independent detector, independent reconstruction!

The "Ridge" in pp and Heavy Ion

CMS pp 7TeV, N>110



PHOBOS AuAu 200GeV



cos(2Δφ)

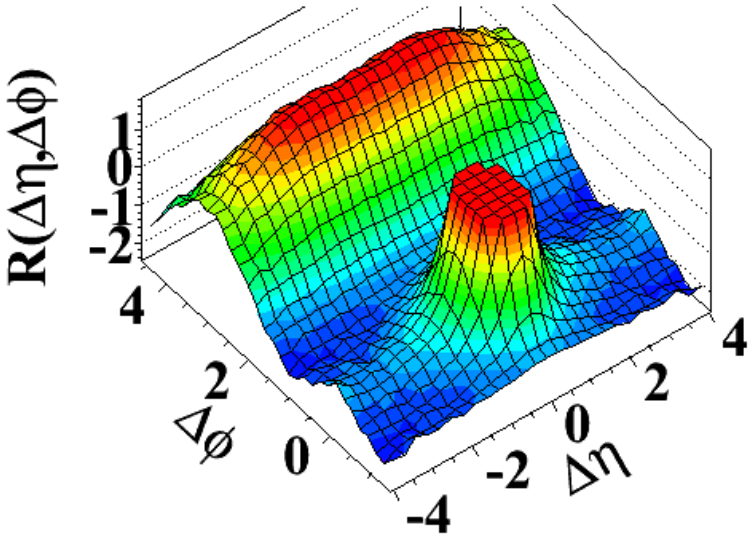
Hydrodynamic flow

QGP model

Similar "ridge" in high multiplicity pp and Heavy Ion! (even p_T dependence)

Interpreting "Ridge" requires more work

CMS pp 7TeV, N>110



Observed long-range, near-side correlations in high multiplicity events

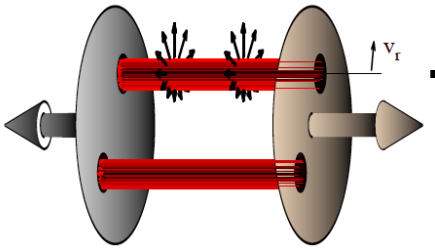
- Signal grows with multiplicity
- Effect maximal in $1 < p_T < 3$ GeV
- Not reproduced by generators
- Resembles effects seen in heavy-ion collisions at high energies

Interpretation:

Multi-jet correlations
Jet-Jet color connections
Jet-proton remnant color connections
Jet-remnant connections + medium

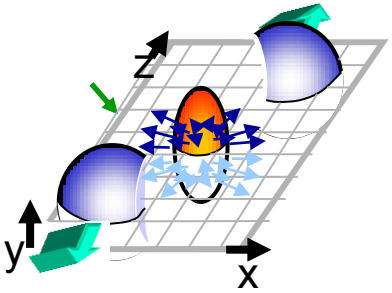
Jet

Glasma (+ radial flow)



Color Glass Condensate

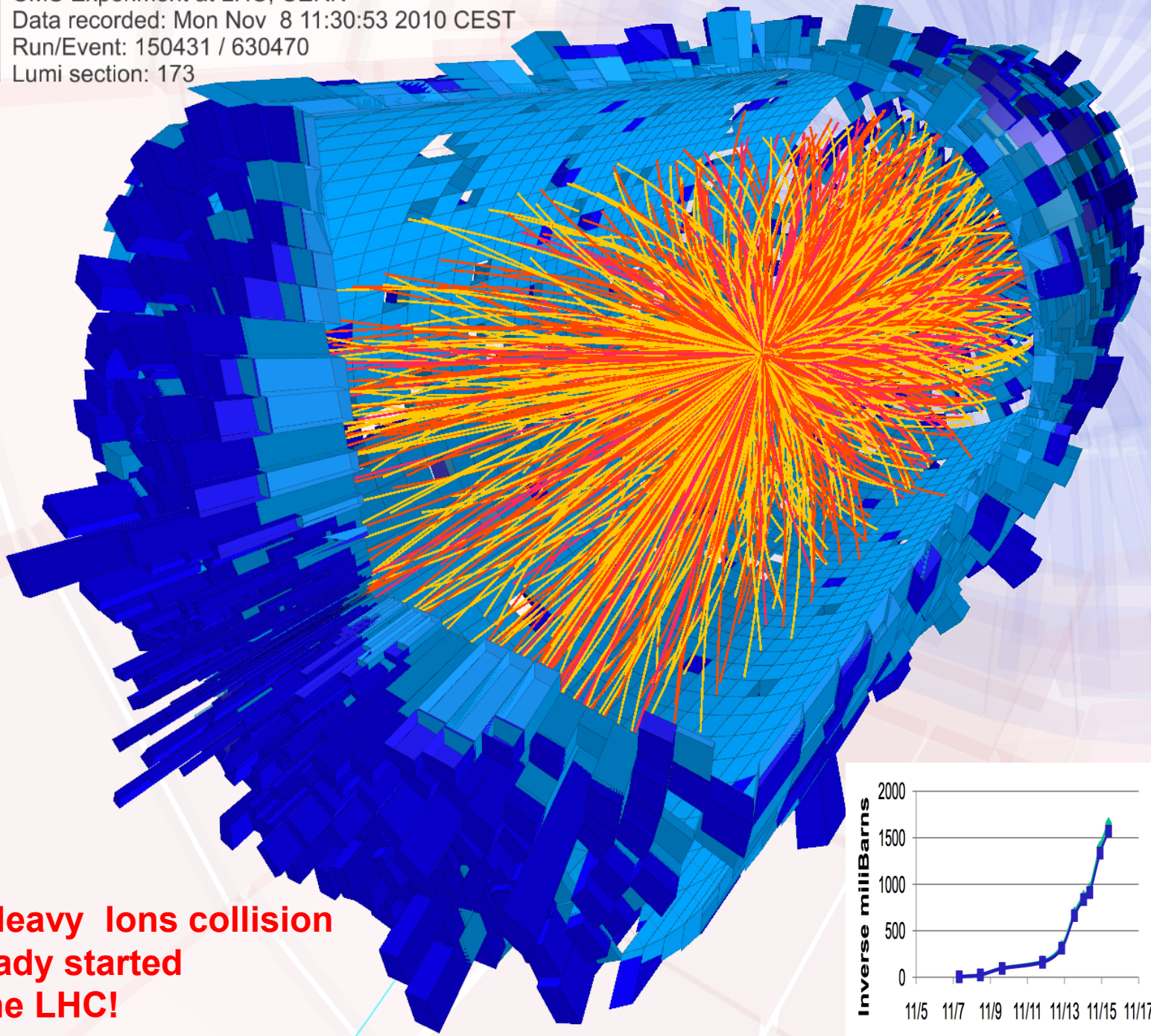
Hydrodynamic flow



Quark Gluon Plasma

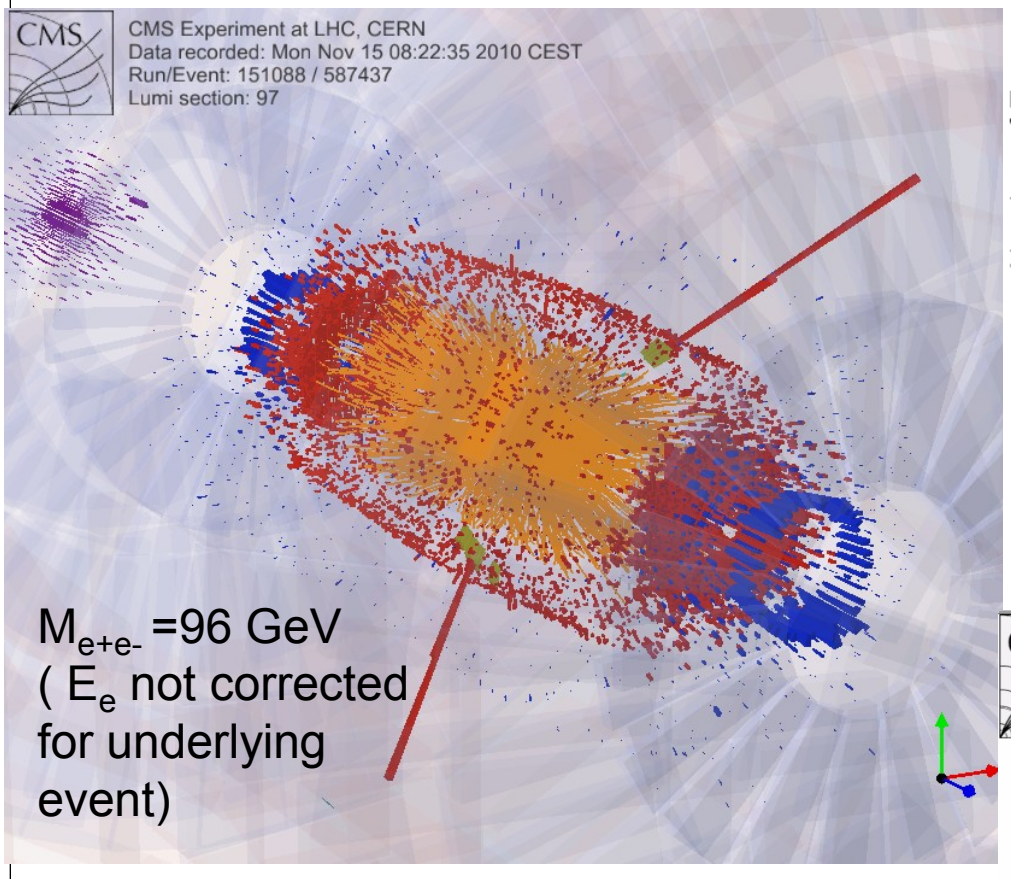
➔ **Complementary data from Heavy Ions runs**

CMS Experiment at LHC, CERN
Data recorded: Mon Nov 8 11:30:53 2010 CEST
Run/Event: 150431 / 630470
Lumi section: 173

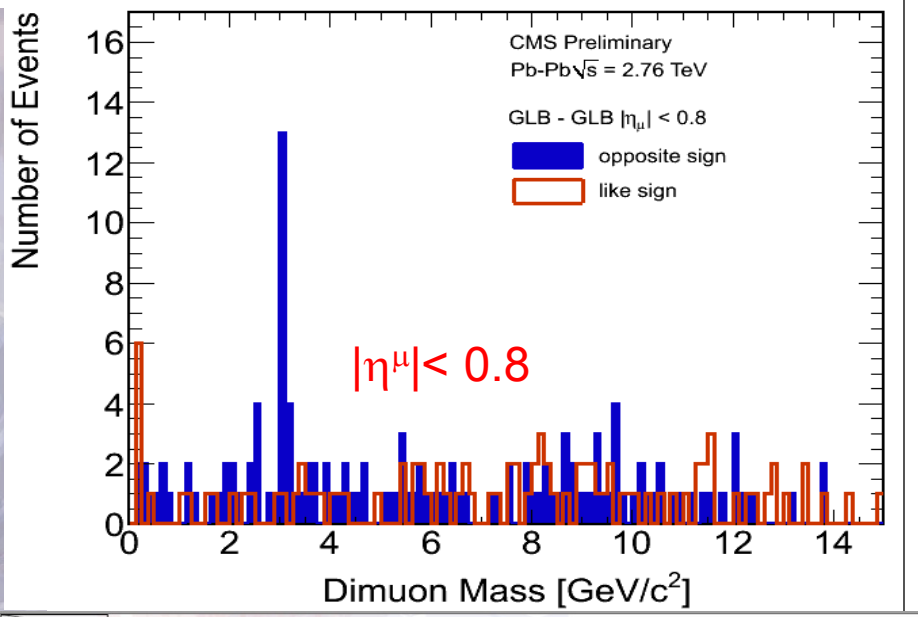


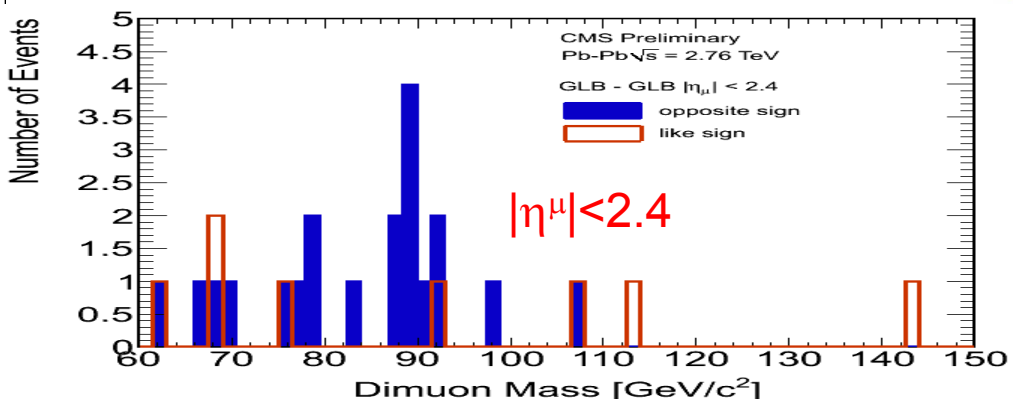
1st Heavy Ions collision already started at the LHC!

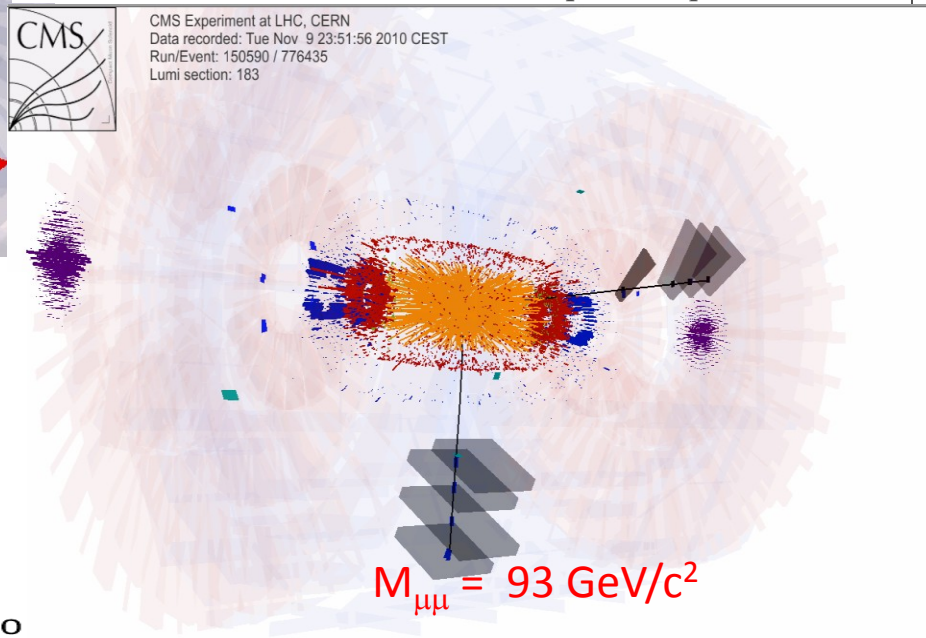
Heavy Ions: $Z \rightarrow e^+e^-, \mu^+\mu^-$ & $J/\psi \rightarrow \mu^+\mu^-$



M_{e+e-} =96 GeV
(E_e not corrected for underlying event)





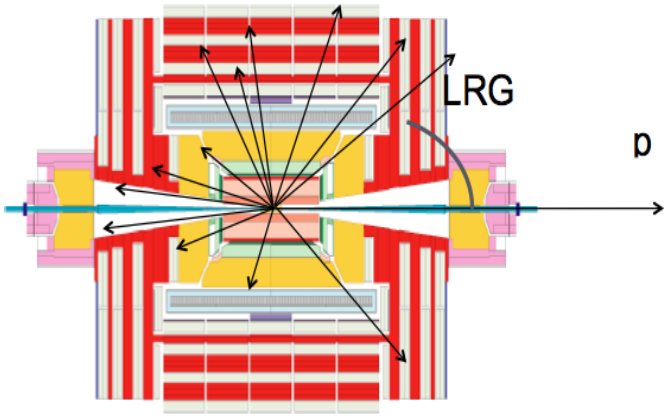


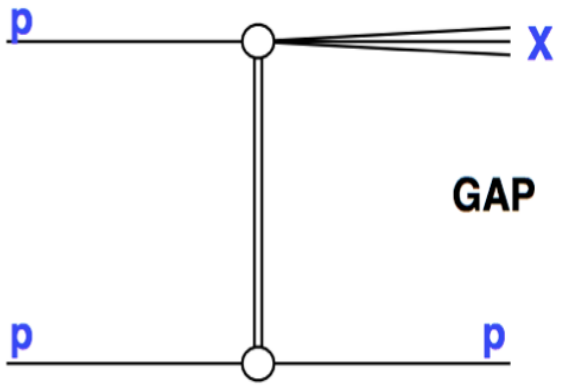
Observation of diffraction in proton-proton collisions at 900 and 2360 GeV

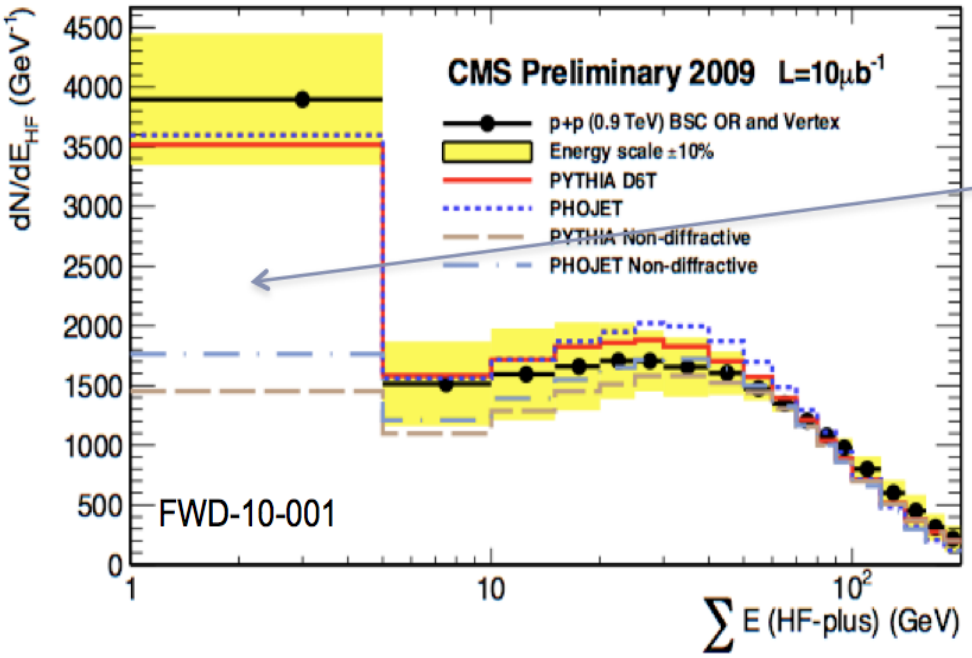
CMS PAS FWD-10-001

Diffraction in pp Collisions

Sketch of single-diffractive event:



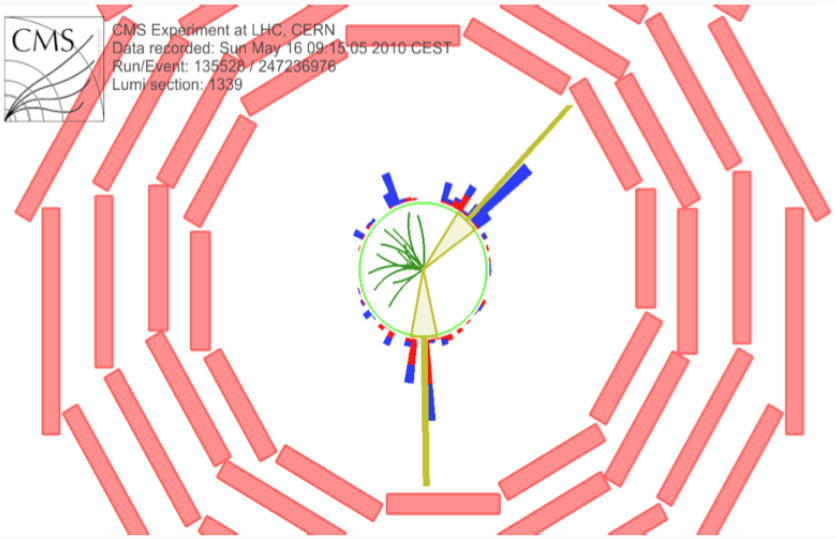


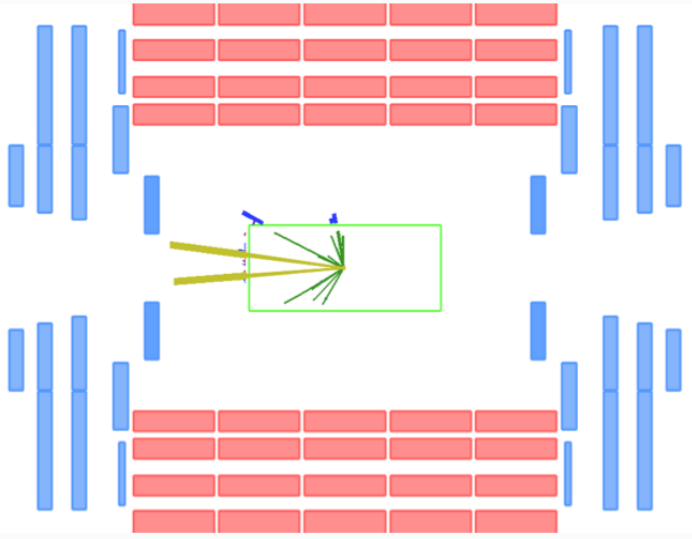


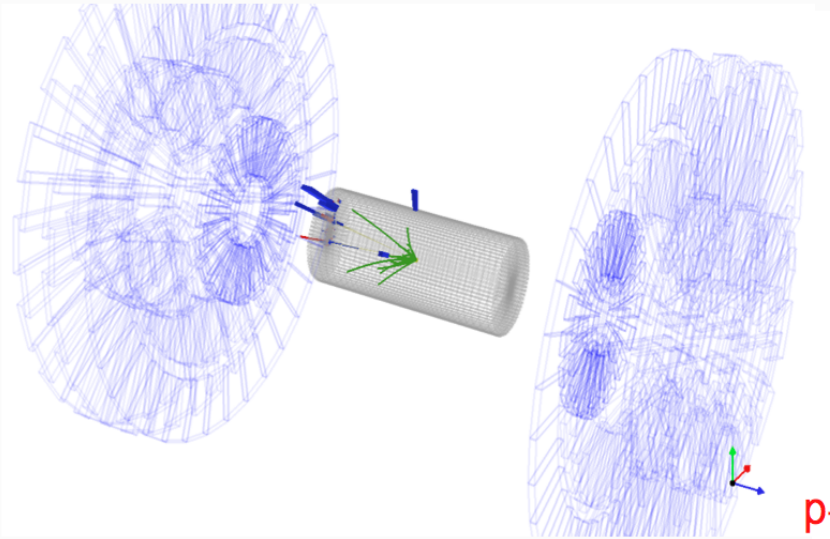
Σ E related to the momentum loss of the scattered proton. One expects a (diffractive) peak at low values of this variable ($\sigma \sim 1/\xi$).

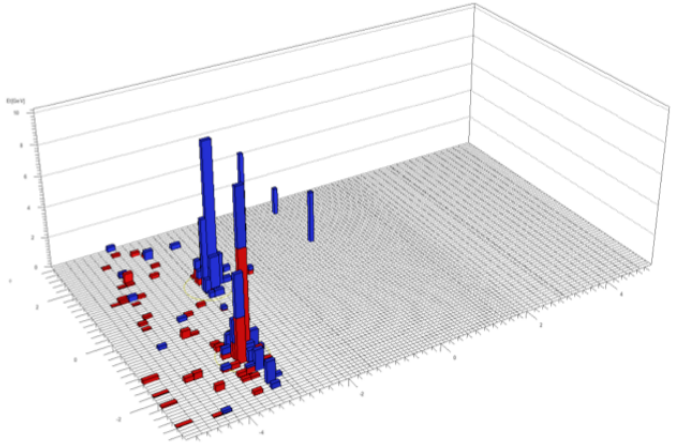
N.B. All plots are uncorrected

Diffractive Di-Jet Candidate at 7 TeV









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

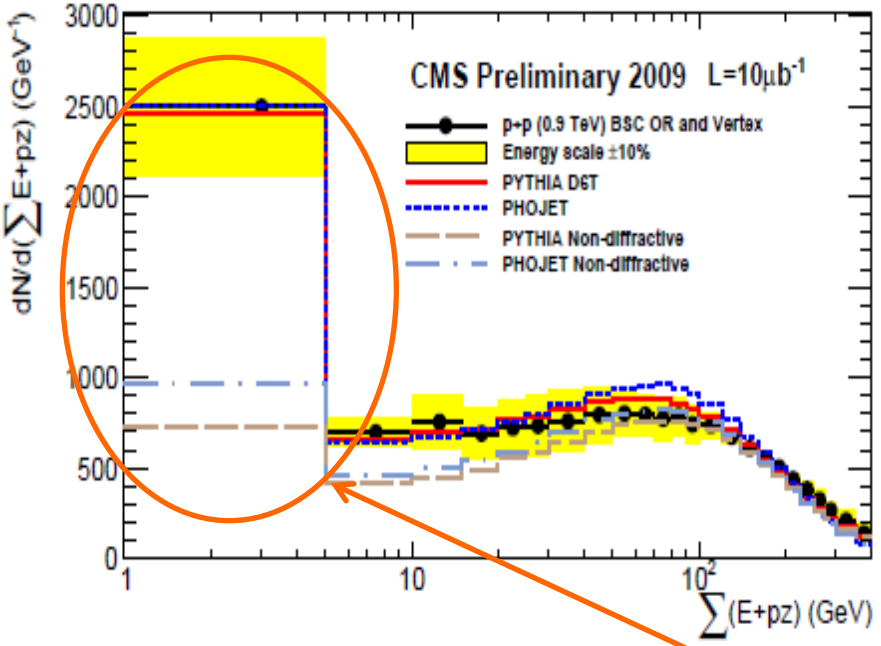
$E(\eta \geq 3.0) > 2.0$ GeV

p_T (jet1) = 41.2 GeV, p_T (jet2) = 31.9 GeV

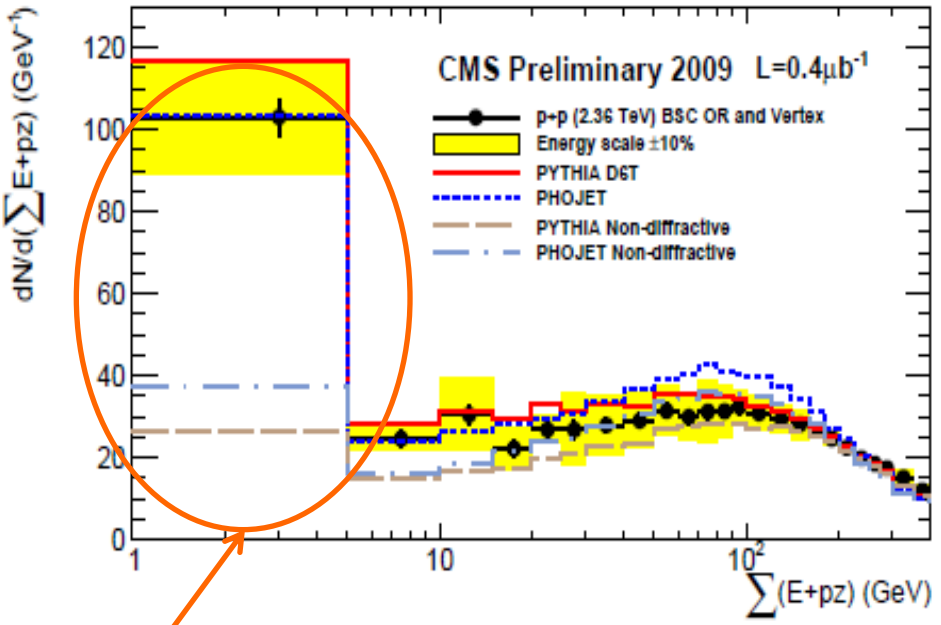
η (jet1) = -2.8, $\quad \eta$ (jet2) = -3.3

Observation of Single Diffraction at CMS

900 GeV (10 μb^{-1})



2360 GeV (0.4 μb^{-1})

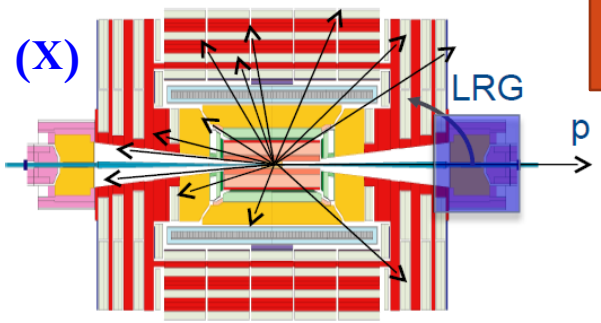


ystematic uncertainty dominated by energy scale

Acceptance for SD ~ 20%
For NSD ~80% (PYTHIA)

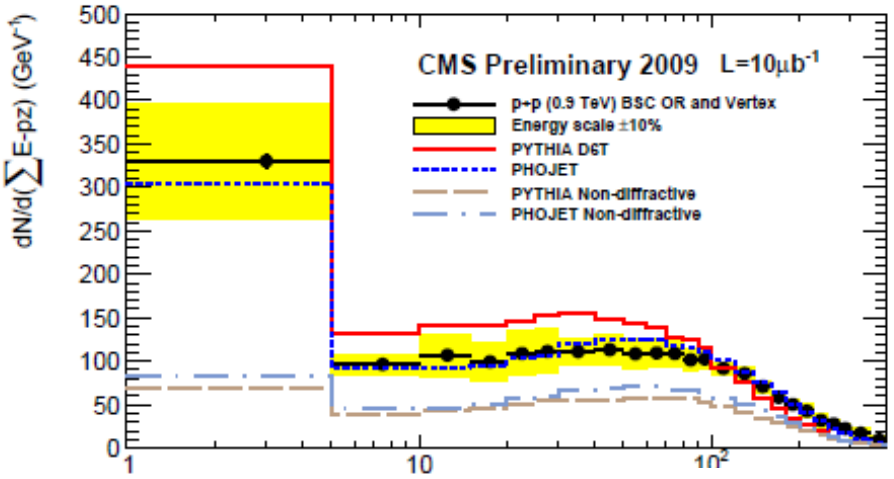
SD seen in Σ E+pz distribution due to cross section peaking at small values of ξ

Enriched SD Sample ➔ E(HF+) < 8 GeV

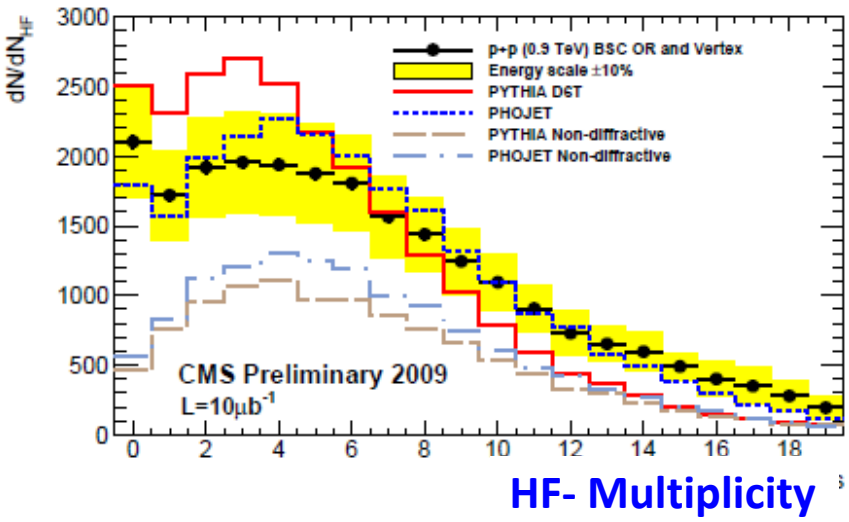


Requirement of low Activity in one side of CMS

SD component of the data
LRG in z+ direction
Concentrating on the fragmenting object
(X) boosted in z- direction



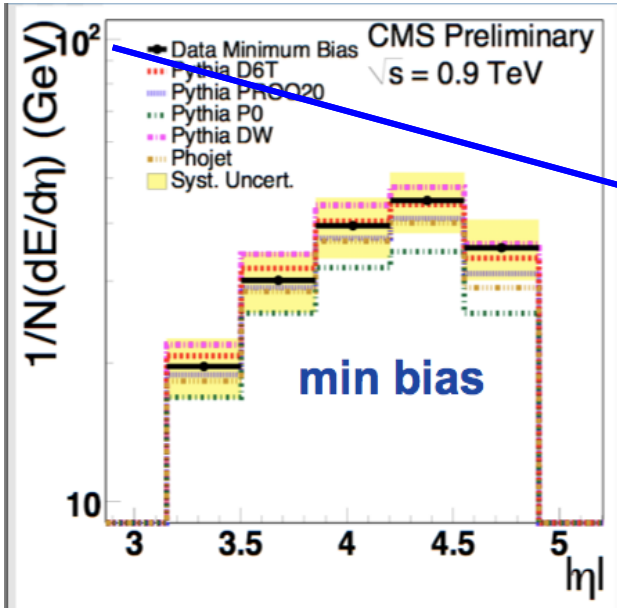
$\xi = \Sigma_i (E_i \pm p_{z,i})$

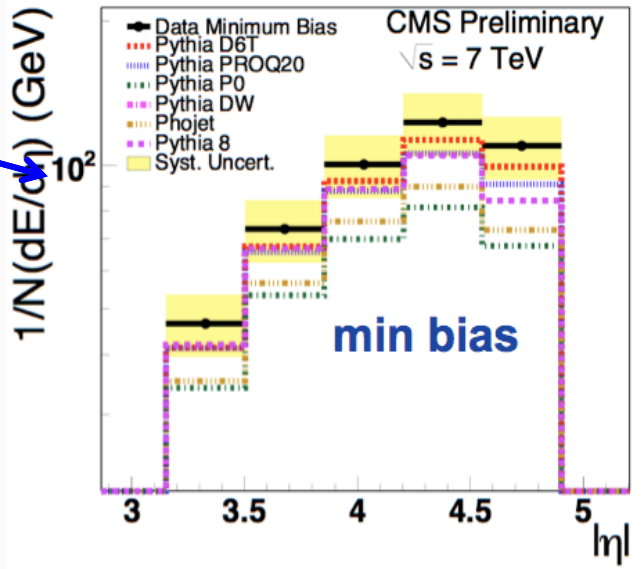


HF- Multiplicity

➔ *Now fit the data better than DT6*

Measurement of forward energy flow

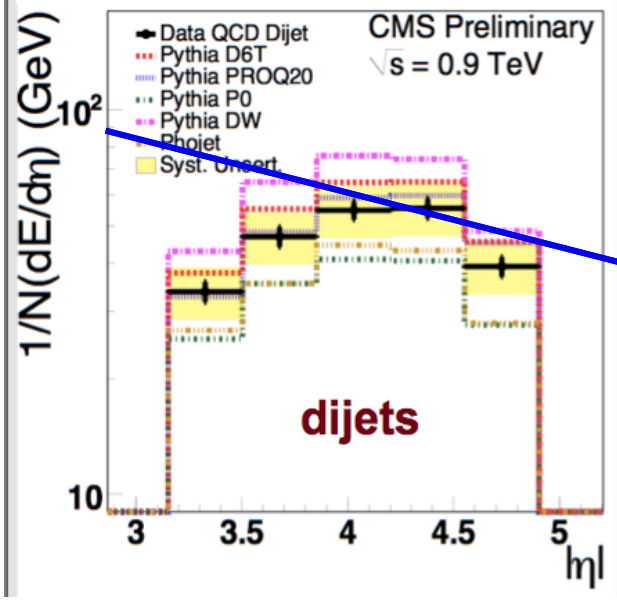


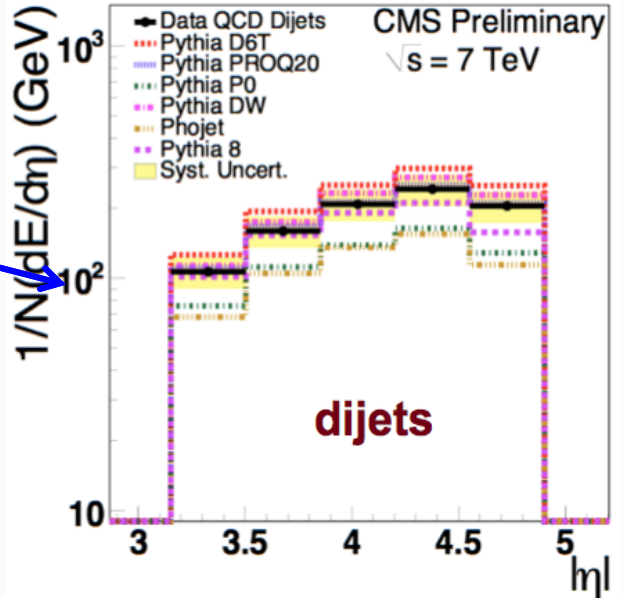


FWD-10-002

Forward Energy flow: sensitive to parton radiation and MPI

Energy flow increases from 0.9TeV to 7 TeV by factor ~ 3





Energy flow in dijet events significantly larger than in minbias

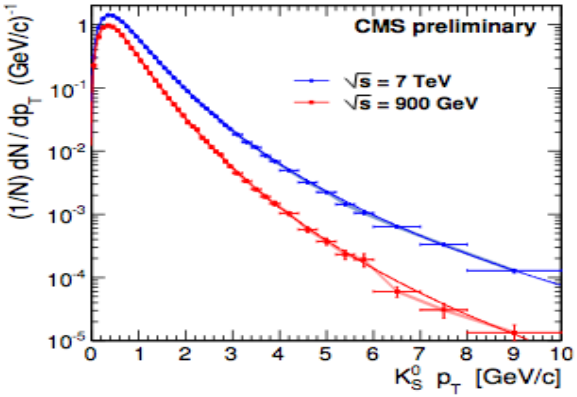
Strange Particle Production

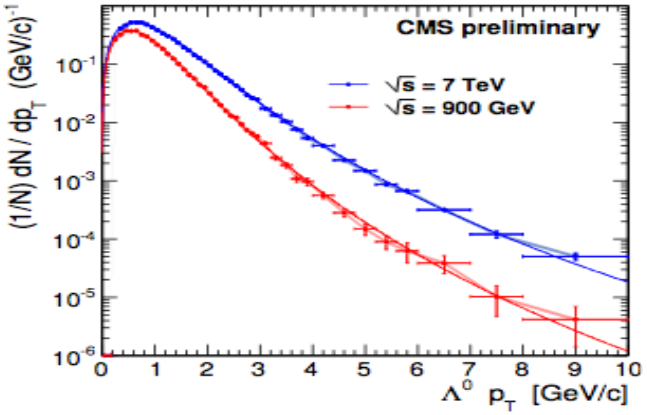
Ks, Λ & Ξ

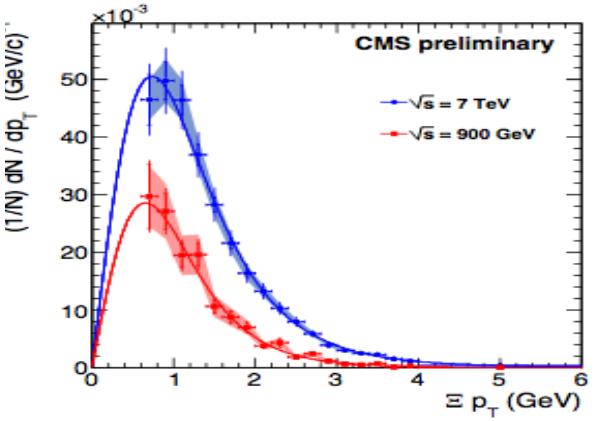
CMS PAS QCD-10-007

➔ Proper interaction for Anti-Proton needed in Physics list before ratios of Λ / Anti-Λ , etc can be reported

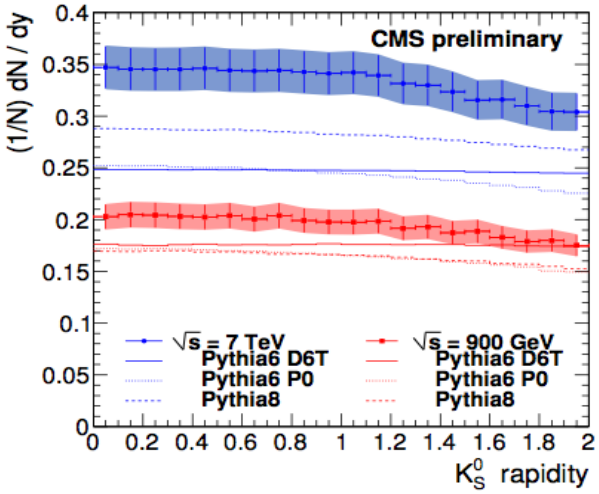
Strange Hadron Spectra

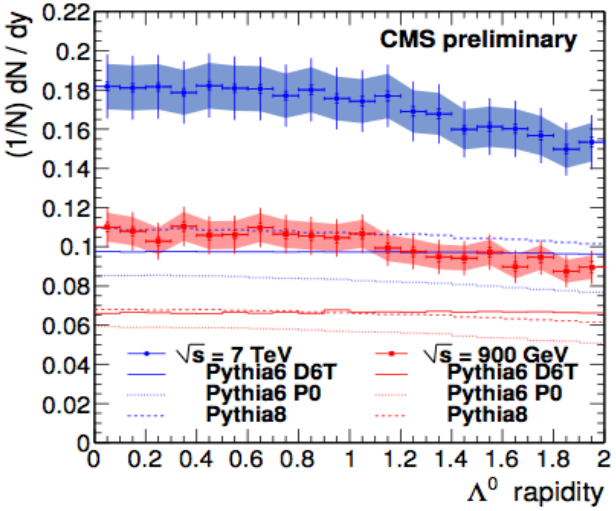


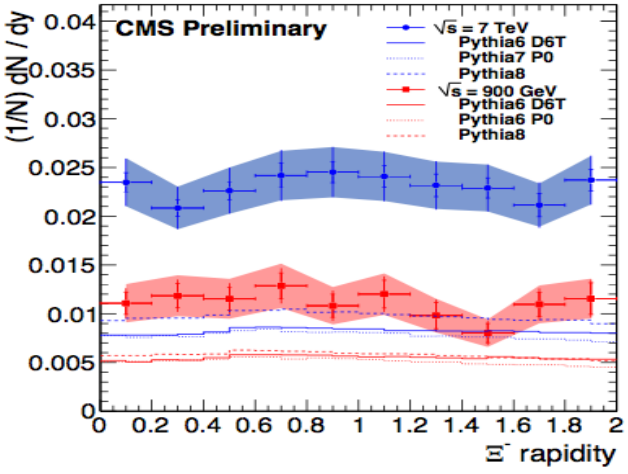




- **All generators underestimate the amount of Strange Particles produces at both 0.9 and 7 TeV**







Comparison with previous experiments & event Generator

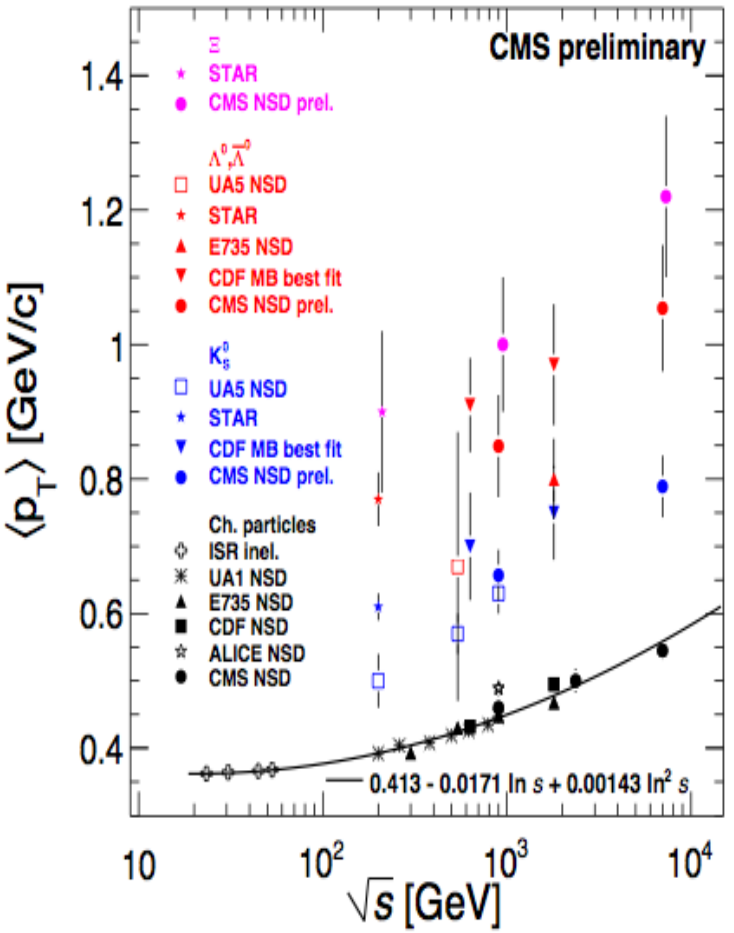
Simulation

Particle	$\sqrt{s} = 0.9$ TeV				$\sqrt{s} = 7$ TeV			
	T (GeV)	n	$\langle p_T \rangle_{\text{Tsallis}}$ (GeV/c)	$\langle p_T \rangle_{\text{true}}$ (GeV/c)	T (GeV)	n	$\langle p_T \rangle_{\text{Tsallis}}$ (GeV/c)	$\langle p_T \rangle_{\text{true}}$ (GeV/c)
PYTHIA 6 (D6T) K^0_S	0.156	7.41	0.581	0.579	0.183	5.71	0.753	0.754
PYTHIA 8 K^0_S	0.141	6.93	0.550	0.550	0.171	5.67	0.713	0.711
PYTHIA 6 (P0) K^0_S	0.150	6.73	0.585	0.582	0.168	5.39	0.730	0.726
PYTHIA 6 (D6T) Λ^0	0.152	6.07	0.756	0.756	0.216	5.11	1.064	1.069
PYTHIA 8 Λ^0	0.112	5.04	0.666	0.669	0.168	4.68	0.933	0.928
PYTHIA 6 (P0) Λ^0	0.124	5.33	0.695	0.694	0.163	4.64	0.921	0.910
PYTHIA 6 (D6T) Ξ^-	0.123	4.90	0.759	0.763	0.213	4.70	1.167	1.162

Simulation & Data

Particle	$\frac{dN}{dy}\|_{y=0}(7\text{ TeV}) / \frac{dN}{dy}\|_{y=0}(0.9\text{ TeV})$		$\frac{dN}{dy}\|_{y=0}(\text{PYTHIA D6T}) / \frac{dN}{dy}\|_{y=0}(\text{Data})$	
	Data	PYTHIA D6T	0.9 TeV	7 TeV
K^0_S	$1.71 \pm 0.02 \pm 0.20$	1.41	$0.87 \pm 0.01 \pm 0.07$	$0.72 \pm 0.01 \pm 0.06$
Λ^0	$1.65 \pm 0.04 \pm 0.26$	1.48	$0.60 \pm 0.01 \pm 0.07$	$0.54 \pm 0.01 \pm 0.06$
Ξ^-	$2.09 \pm 0.09 \pm 0.27$	1.47	$0.48 \pm 0.05 \pm 0.09$	$0.33 \pm 0.02 \pm 0.05$

Data

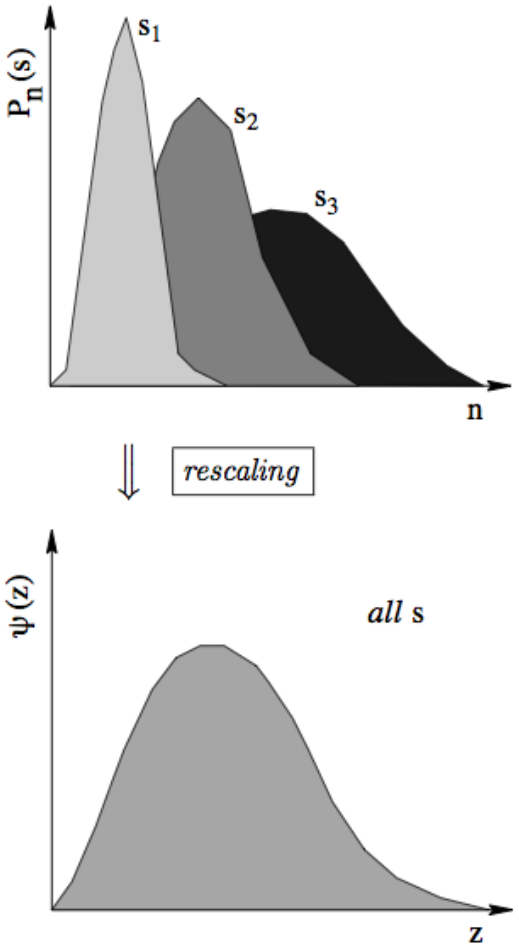


Bigger discrepancies in Baryons than Mesons

Charge Multiplicities

CMS PAS QCD-10-004

KNO Scaling and C_q Moments



- Probability distributions $P_n(s)$ of producing n particles at collision energy s :

$$P_n(s) = \frac{1}{\langle n(s) \rangle} \psi\left(\frac{n}{\langle n(s) \rangle}\right)$$

- Scaling function:

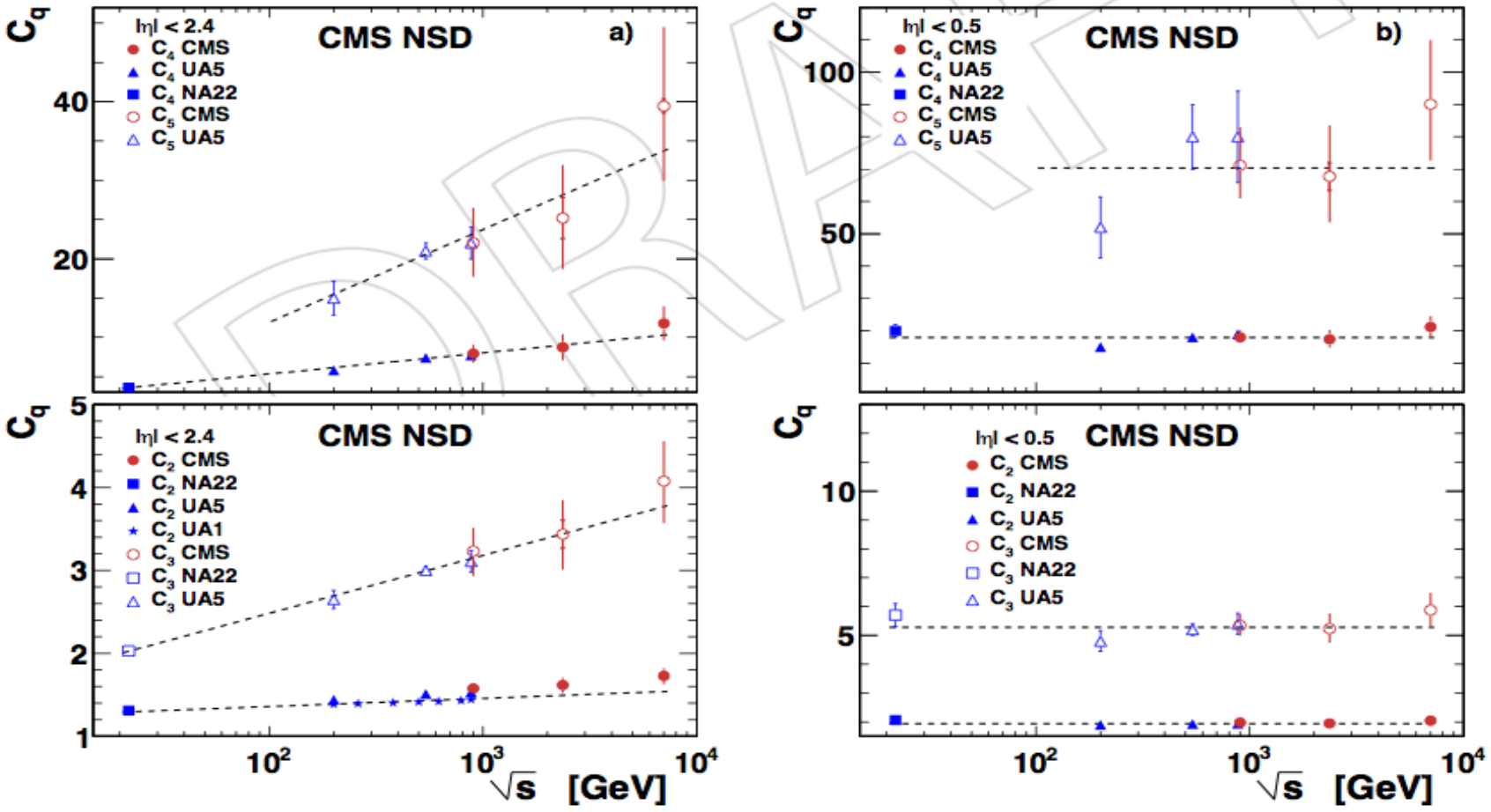
$$\Psi(z) = \langle n \rangle P_n, \text{ with } z = n/\langle n \rangle$$

- Moments:

$$C_q = \langle n^q \rangle / \langle n \rangle^q$$

C_q Energy Dependence - Scaling Violations

➔ Correlations between particles produced



C_q moments increase nearly linearly with log ($\sqrt{s}$) for $0.5 < |\eta| < 2.4$

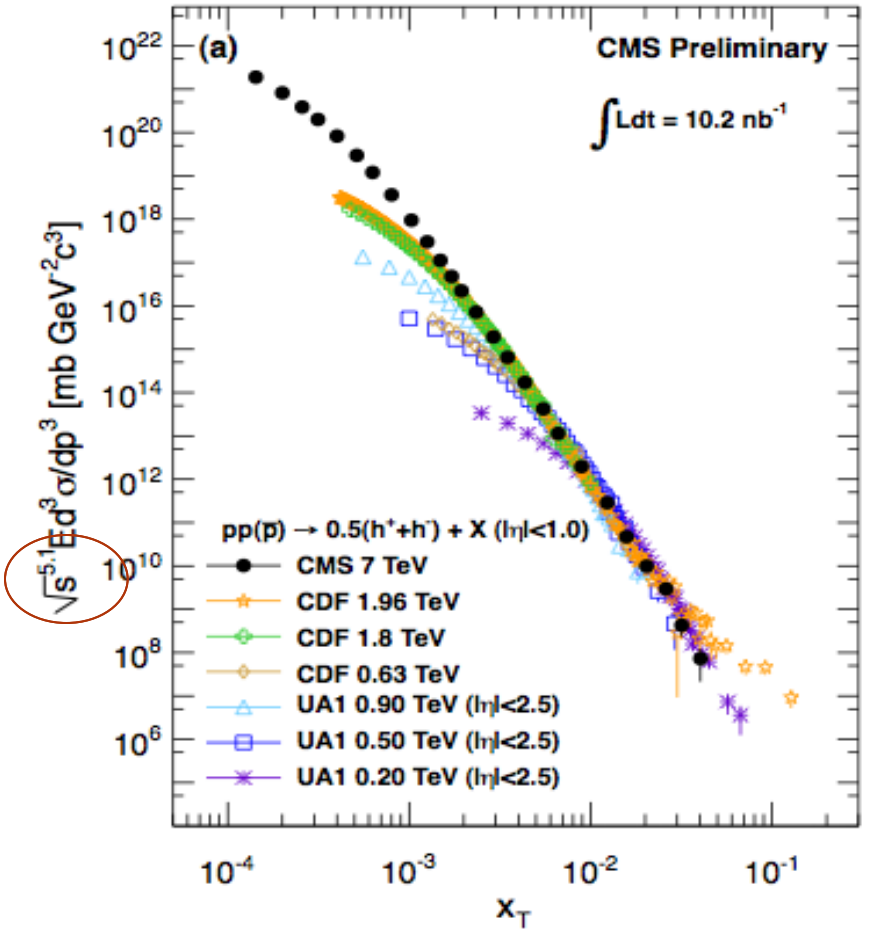
Charged particle transverse momentum spectra

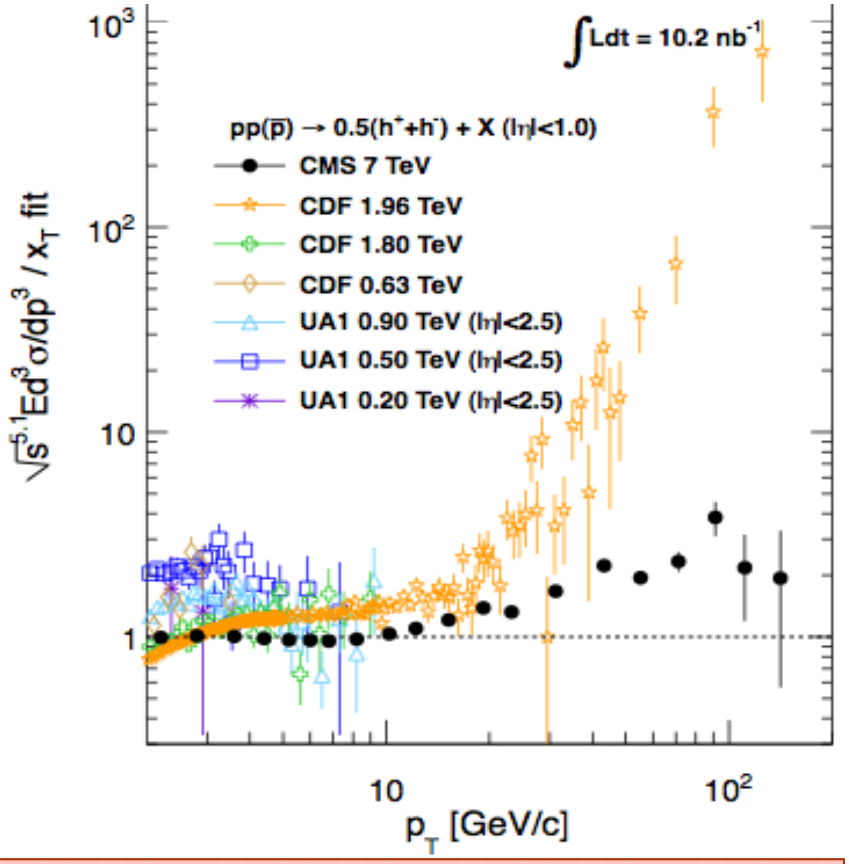
Jet Triggered: CMS PAS QCD-10-008

Minimum Bias: CMS PAPER QCD-10-006 (PRL)

Comparison of Differential Yield with Previous Experiments:

$$E\frac{d^3\sigma}{dp^3} = F(x_T)/p_T^{n(x_T,\sqrt{s})} = F'(x_T)/\sqrt{s}^{n(x_T,\sqrt{s})}$$

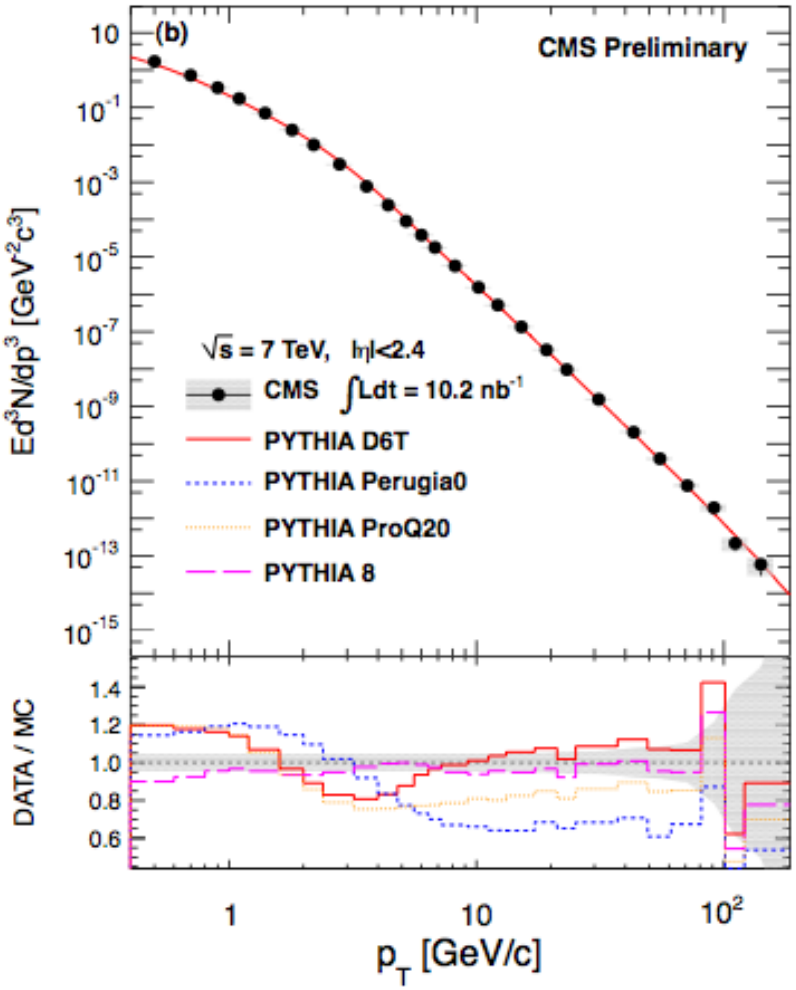




A robust prediction of pQCD hard processes is the power-law scaling of the inclusive invariant cross section with $x_T \equiv 2p_T/\sqrt{s}$

➔ Expected to be valid for $p_T > 2$GeV

Comparison of Differential Yield with Generators including the low p_T



- **The gray band corresponds to statistical plus systematic errors in quadrature.**
- **Pythia – 8 in reasonable agreement**
- **Jet Triggered data note: CMS PAS QCD-10-008**

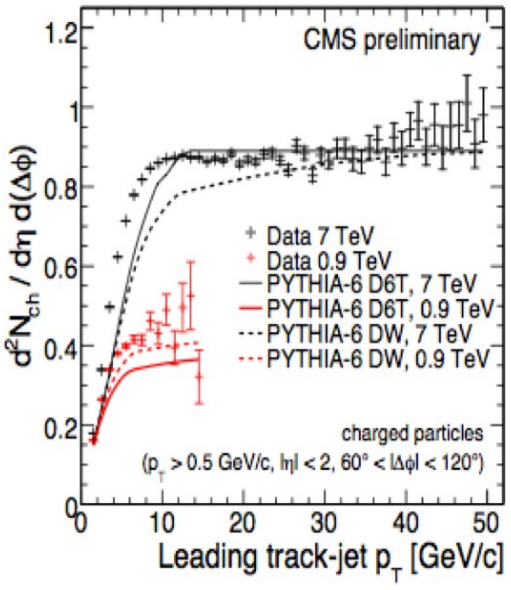
Underlying Event

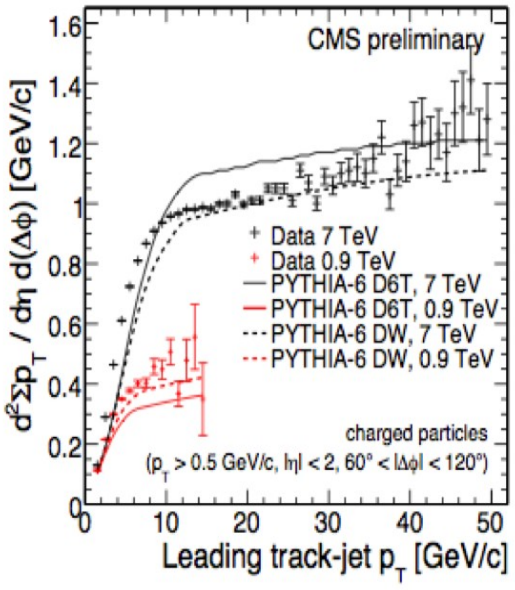
PAS-QCD-10-001

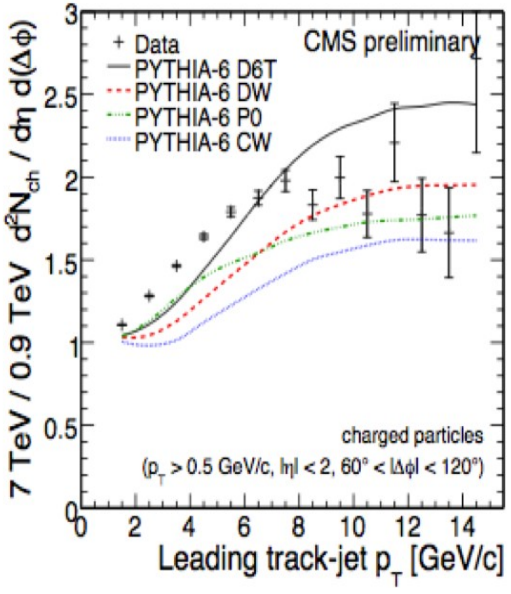
PAS-QCD-10-010

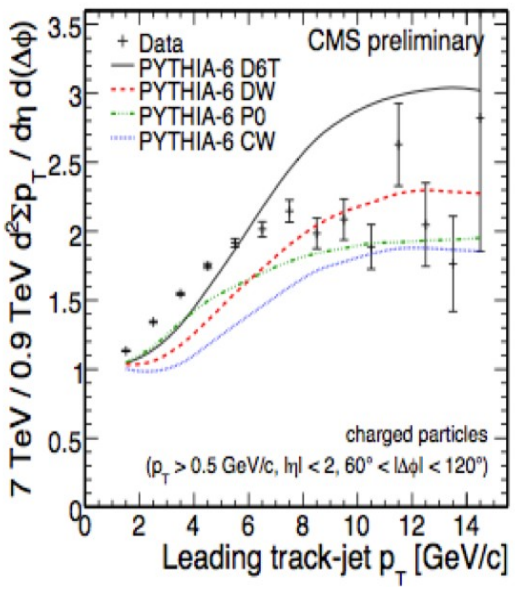
➔ See P. Skands talk

Transverse Region



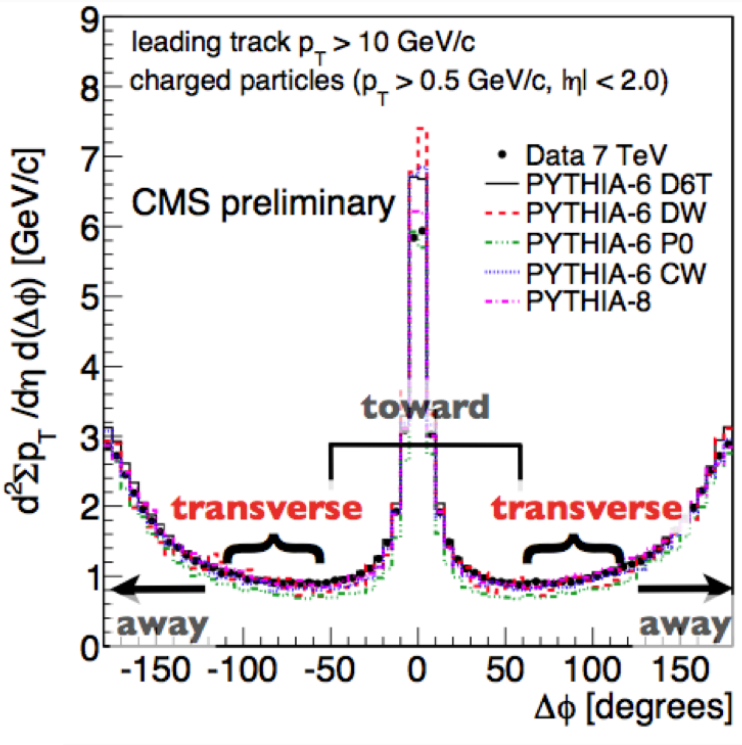




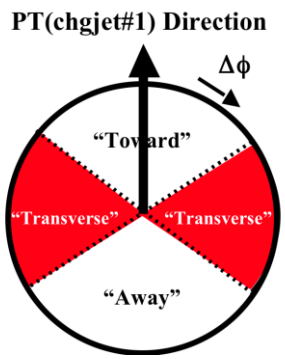


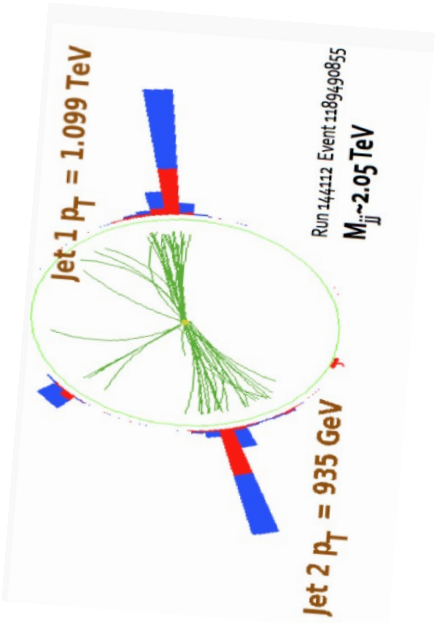
In general: Poor description by these generators.

Now we have better alternatives …

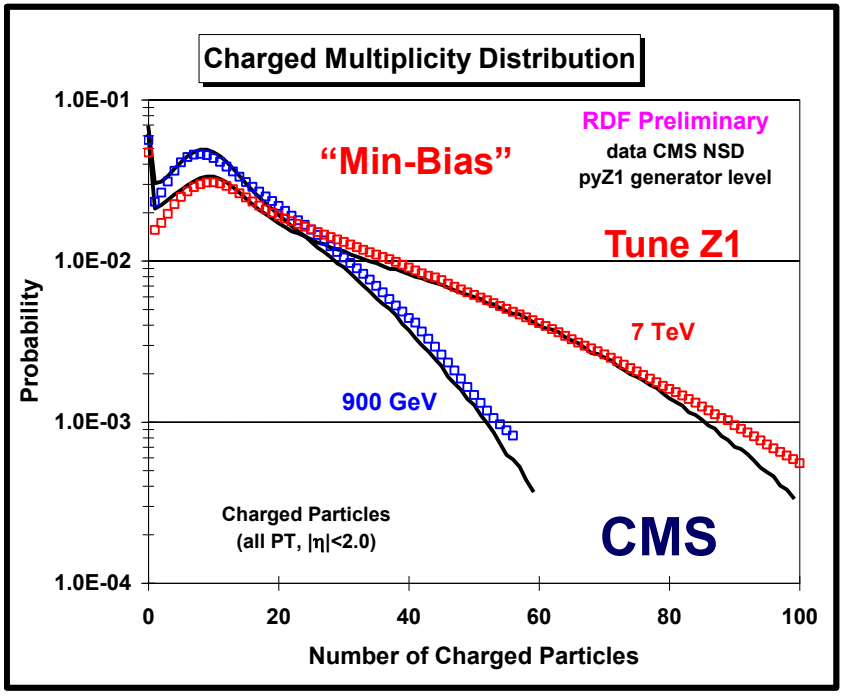


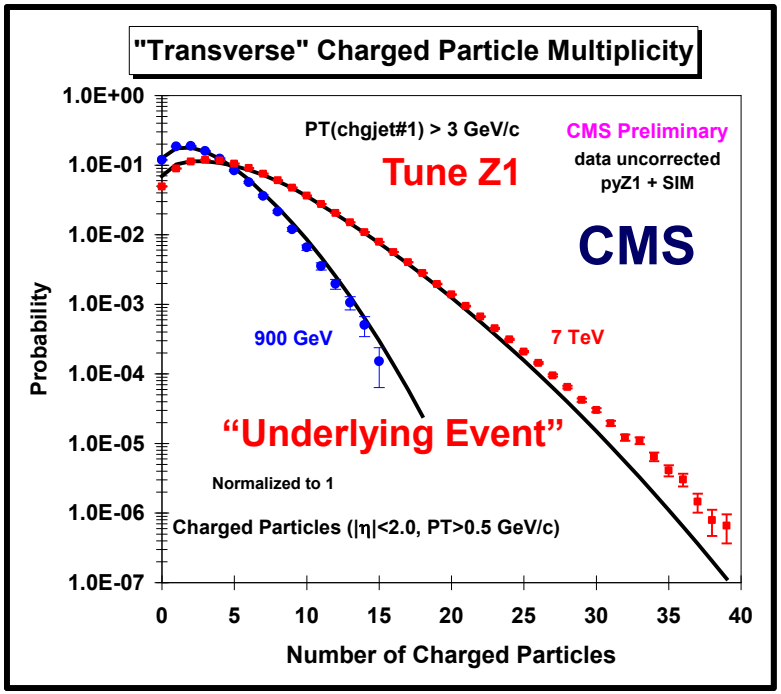
Low-pT QCD results 6 months later....





New well tune physics Generators provided by theorist like Rick Fields, *et.al*





Conclusion

- CMS working well
- Low pT measurements already showing unexpected results
- Latest PYTHIA Tunes incorporating our early measurements are better
- More to come…

Bibliography

- The underlying event in proton - proton collisions at 900 GeV, CMS PAS QCD-10-001
- Two-particle correlations and cluster properties from two-particle angular correlations in p+p collisions at sqrt(s) = 0.9, 2.36TeV and 7 TeV, CMS PAS QCD-10-002
- Measurement of Bose-Einstein correlations with first CMS data, CMS PAS QCD-10-003
- Charged particle multiplicities at sqrt(s)=0.9, 2.36 and 7 TeV, CMS PAS QCD-10-004
- Underlying Event with Jet Area at 900 GeV, CMS PAS QCD-10-005
- Transverse-momentum and pseudorapidity distributions of charged hadrons in pp collisions at sqrt(s) = 7 TeV, CMS PAS QCD-10-006
- Strange Particle Production in pp Collisions at sqrt(s) = 0.9 and 7 TeV, CMS PAS QCD-10-007
- Charged hadron transverse momentum spectra in pp collisions, CMS PAS QCD-10-008
- Measurement of the Underlying Event Activity at the LHC with sqrts=7 TeV, CMS PAS QCD-10-010