First Jet and QCD Results from CMS

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On behalf of the CMS Collaboration

Low-X Meeting
Kavala, Greece

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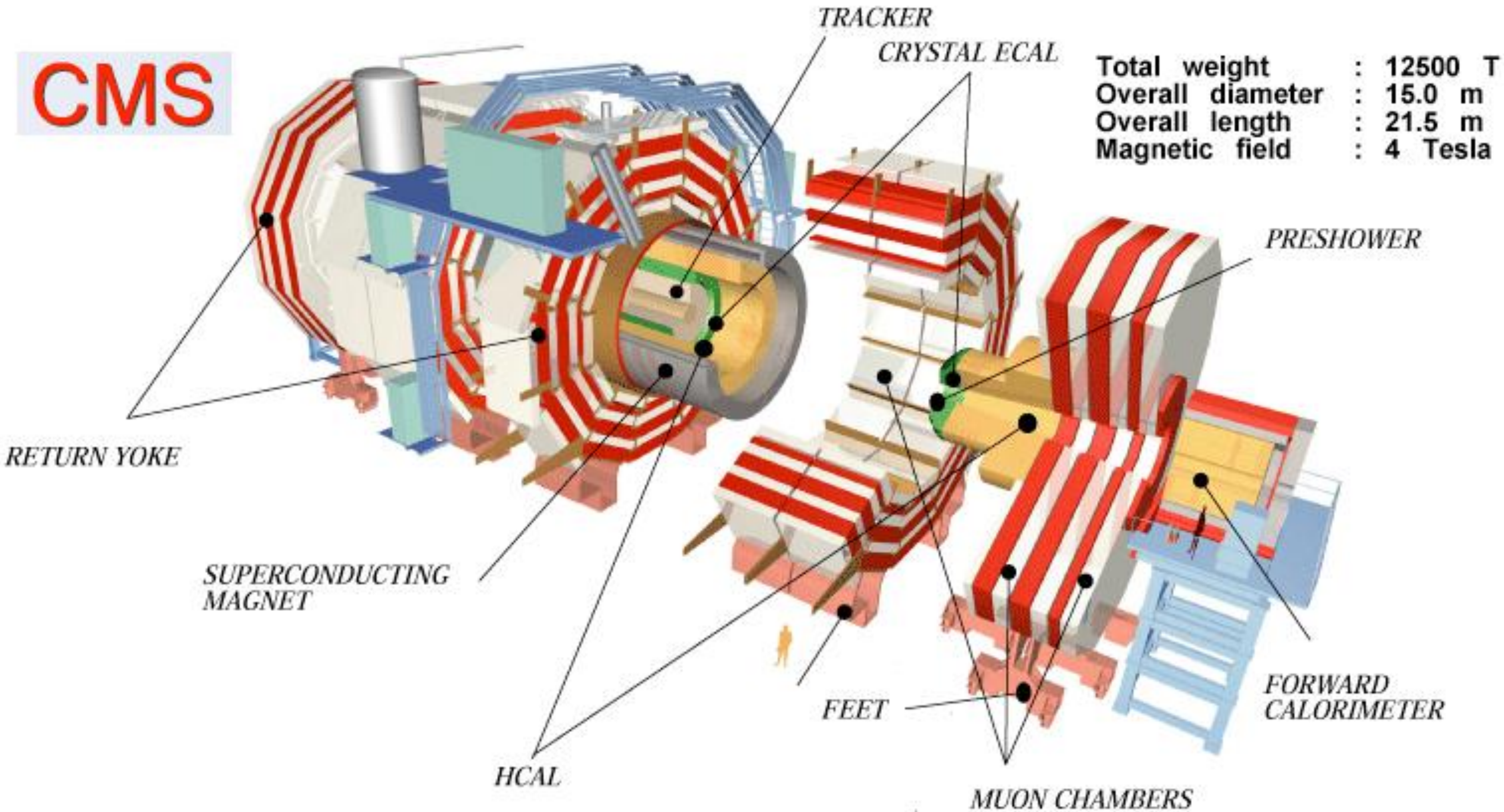
The CMS Detector



Jets and Missing Transverse Energy (MET)

- Use collected data at three energy points: $\sqrt{s}$=0.9, 2.36, 7.0 TeV to commission Jet and MET algorithms
- Compare results with MC

Data Samples for Jet/MET Commissioning

Two types of samples considered:

- Di-jet sample
  - High purity jet sample
  - Allows inclusion of jets with looser quality requirements

	Jet plots	MET plots
$p_T(1^{st}$ jet)	>25 GeV	>25 GeV
$p_T(2^{nd}$ jet)	>25 GeV	>10 GeV
$\Delta\phi=\|\phi_{1st} - \phi_{2nd}\|$	> 2.1	
η	$\|\eta\| < 3$	

(selection for the 7 TeV sample shown)

- Inclusive sample
  - Higher statistics
  - Examines jet properties independent of event topology
  - Probe bulk and tails of MET

The studies were performed for $\sqrt{s}$=0.9, 2.36, 7 TeV;
Consistent results.
In the following show distributions from the $\sqrt{s}$=7 TeV sample.

Jet Reconstruction and Clustering

Jet reconstruction techniques (based on detector use):

- Calorimeter jets (CaloJet)
  - use calorimeter towers from combined ECAL and HCAL information,
- Track-corrected calorimeter jets (jet plus tracks, JPT)
  - replace charged-particle calorimeter response with tracker measurements
- Particle Flow Jets (PF Jets)
  - Use all detector systems to reconstruct and categorize particles
- Track jets (not discussed here)
  - Use only charged particles to form jets

Jet clustering algorithms:

- A range of algorithms and cone sizes available, applicable to all reconstruction methods
- Default at the beginning: anti-k_T with size R=0.5 (AK5); used for all results in this presentation

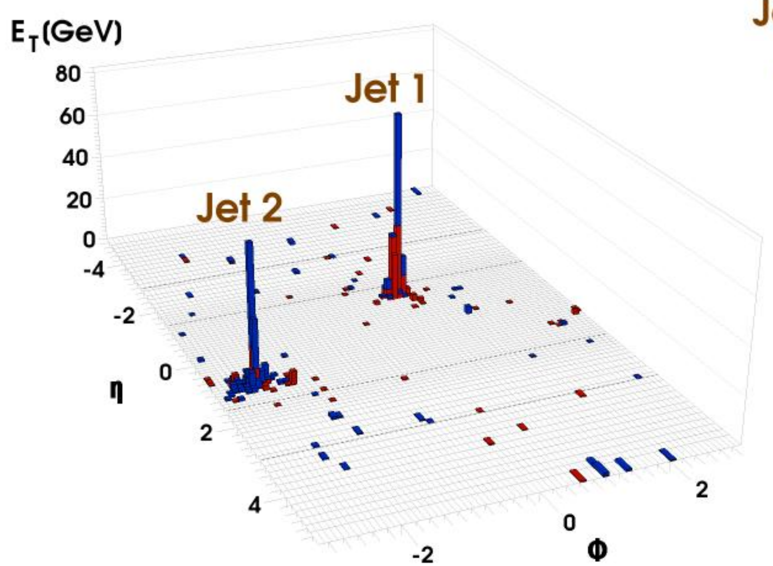
Jet correction applied in these studies:

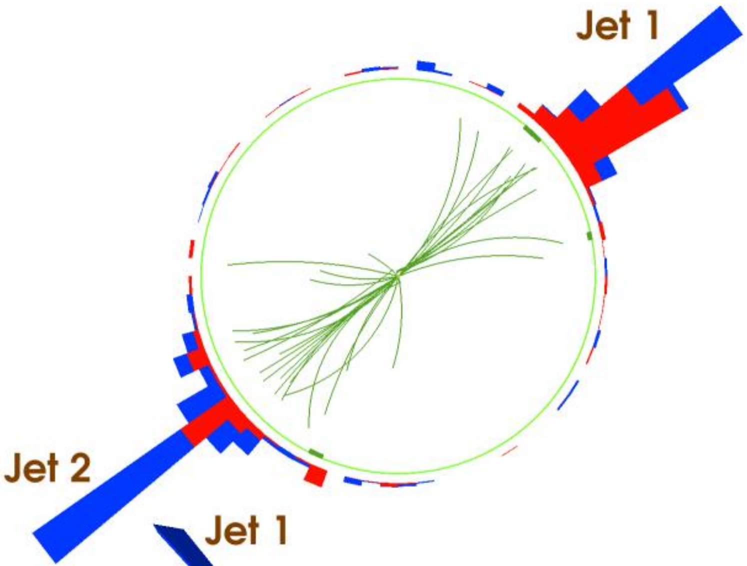
- Equalize response in η
- Equalize response in p_T

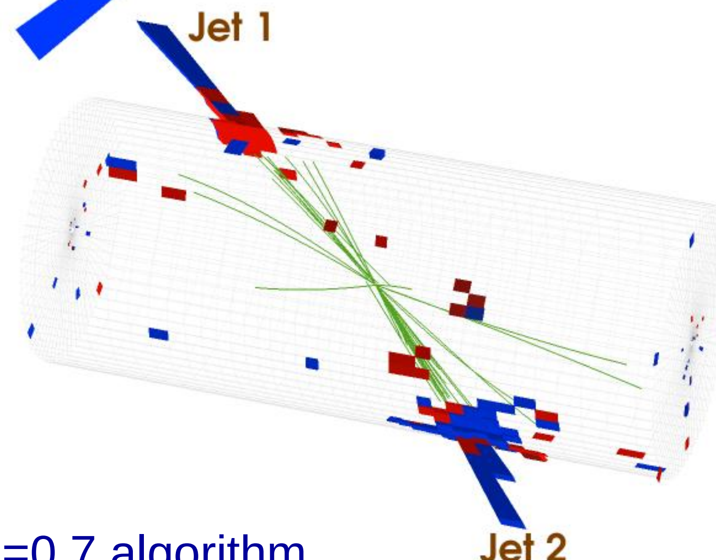
Di-jet Event from 7 TeV Collisions

CMS Experiment at LHC, CERN
Run 133450 Event 16358963
Lumi section: 285
Sat Apr 17 2010, 12:25:05 CEST

Jet1 p_T : 253 GeV
Jet2 p_T : 244 GeV
Dijet Mass : 764 GeV







Jets reconstructed with the anti-k_T R=0.7 algorithm

Jet Quality Criteria

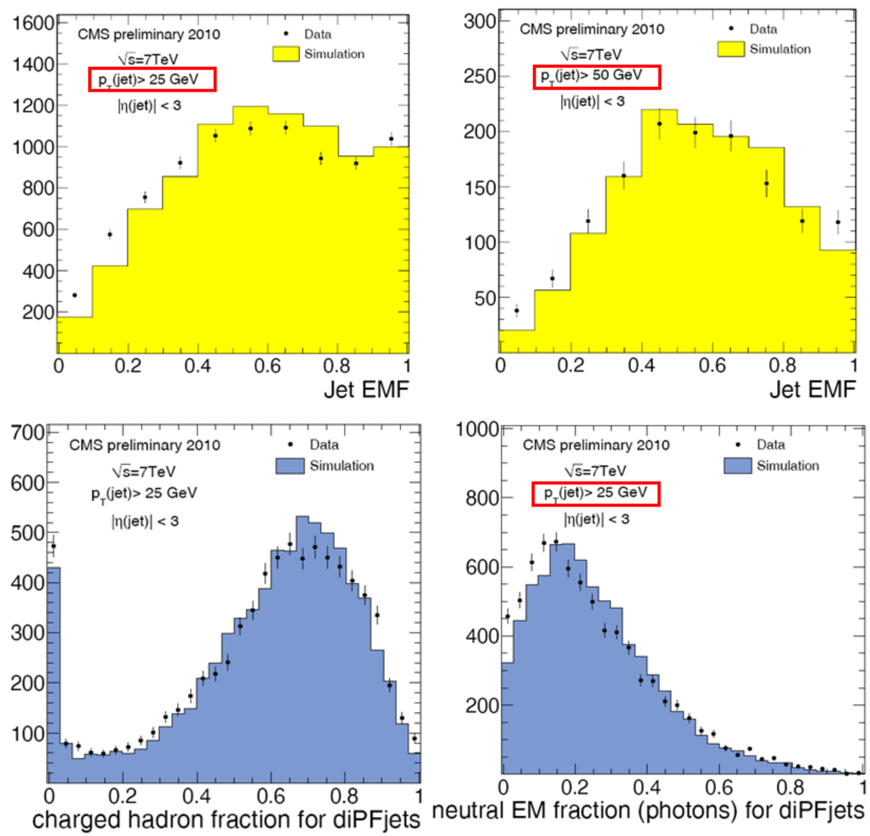
Criteria applied to remove objects due to electronics noise and detector malfunction

CaloJets, JPT

variable	$\|\eta\|$	loose	tight
EMF	< 2.6	> 0.01	> 0.01
n_{hits}^{90}	-	> 1	> 4
f_{HPD}	-	< 0.98	< 0.98
f_{RBX}	-	-	< 0.98
σ_η	-	-	> 0.01
σ_φ	-	-	> 0.01

PF Jets

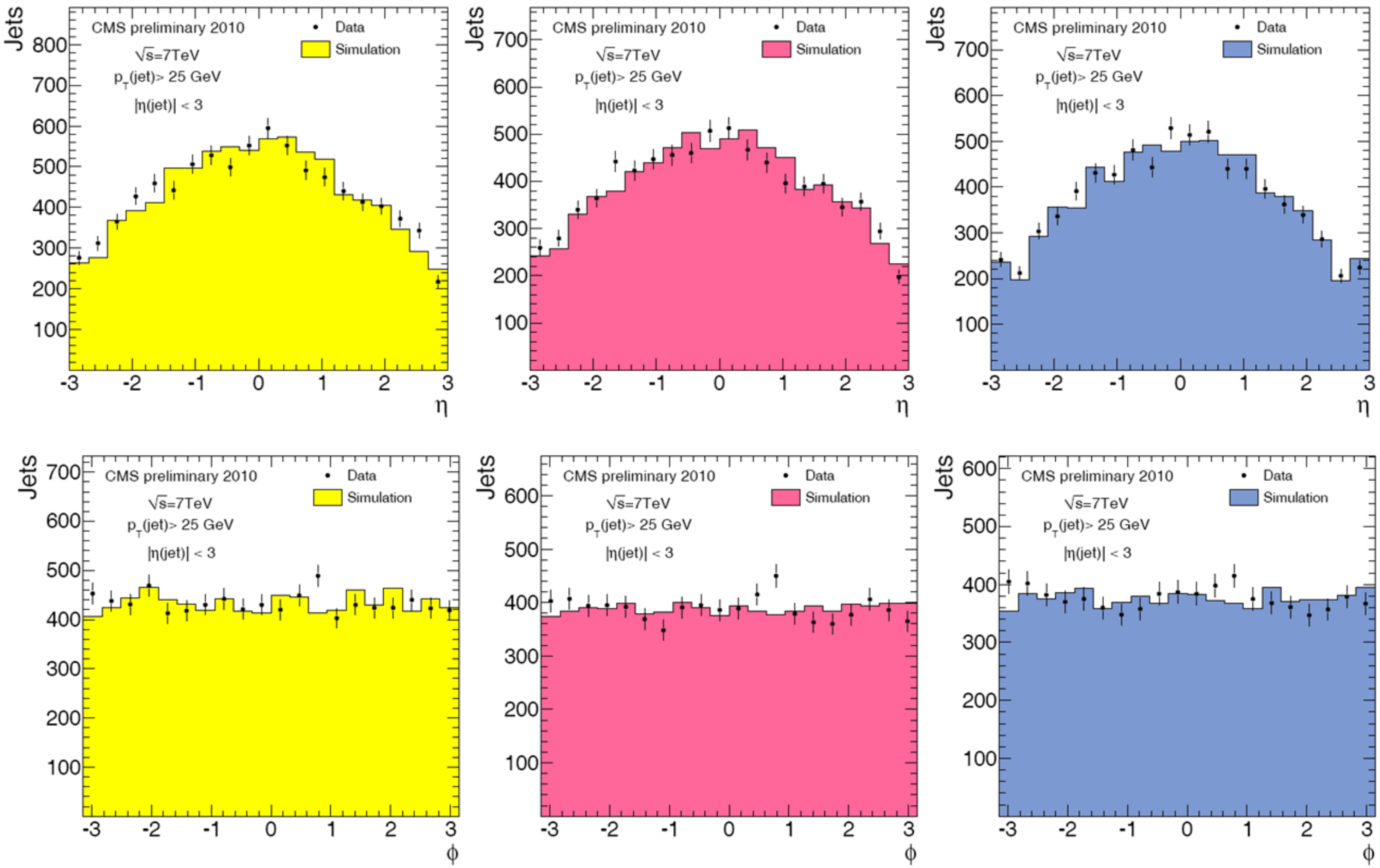
variable	$\|\eta\|$	loose	tight
CHF	< 2.4	> 0.0	> 0.0
NHF	-	< 1.0	< 0.9
CEF	-	< 1.0	< 1.0
NEF	-	< 1.0	< 0.9



Distributions of quality parameters are reasonably well described in MC.
No major differences near cut values.

Jet Commissioning (7 TeV)

Calo Jets | **JPT Jets** | **PF Jets**



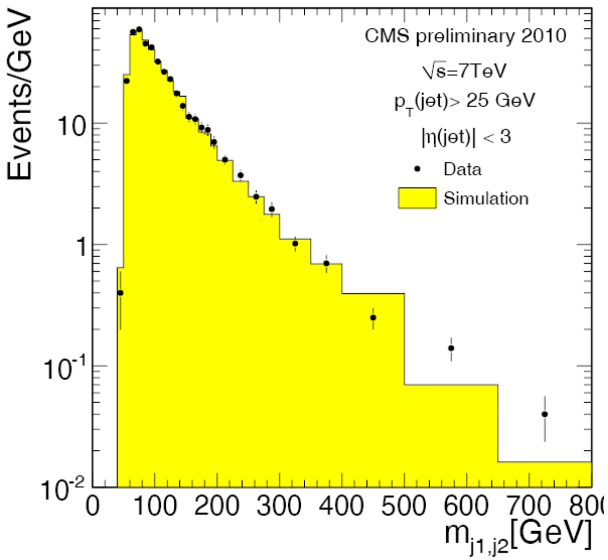
η

ϕ

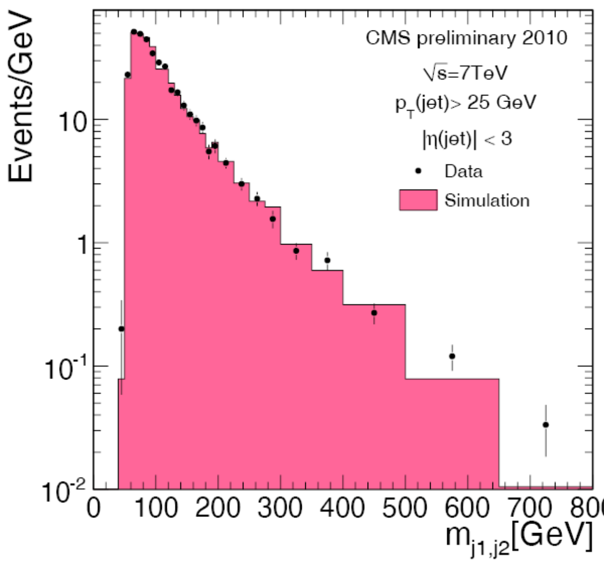
Jet Commissioning (7 TeV)

Comparison of Di-jet mass distributions in data and MC (di-jet sample)

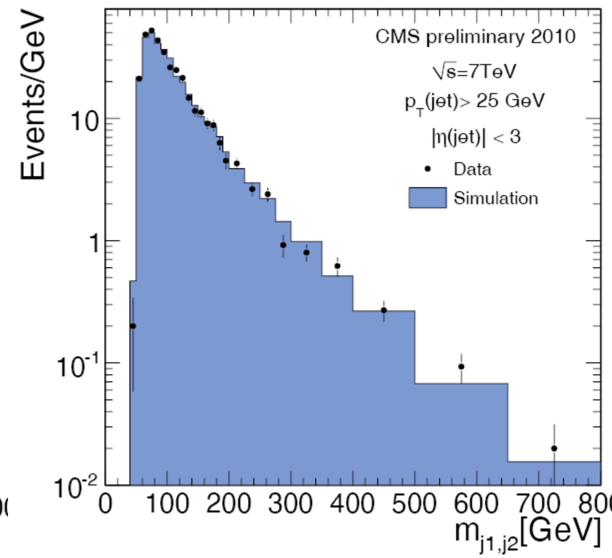
Calo Jets



JPT Jets



PF Jets



Good agreement between data and MC for all three jet algorithms

MET Reconstruction

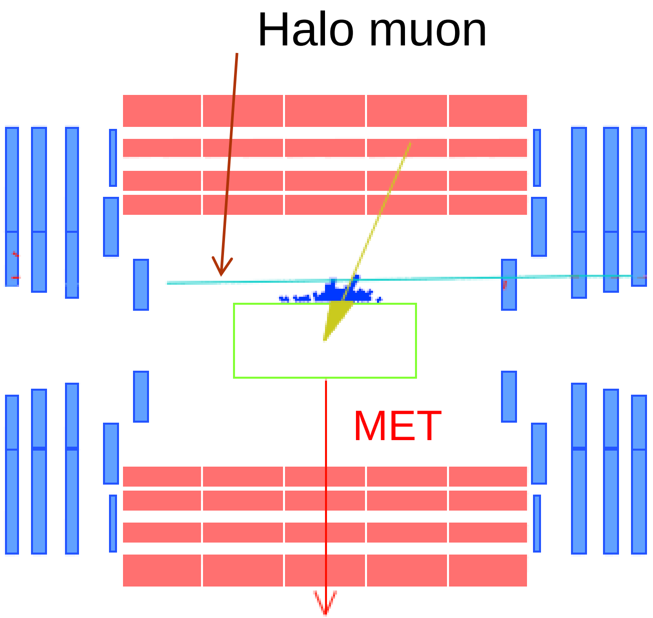
MET reconstruction techniques similar to Jet Reco:

- Calorimeter (CaloMET)
- Track-corrected MET (tcMET)
- Particle Flow MET (PF MET)

All algorithms employ event clean-up: remove contributions from

- Instrumental anomalous signals
- Beam induced signal

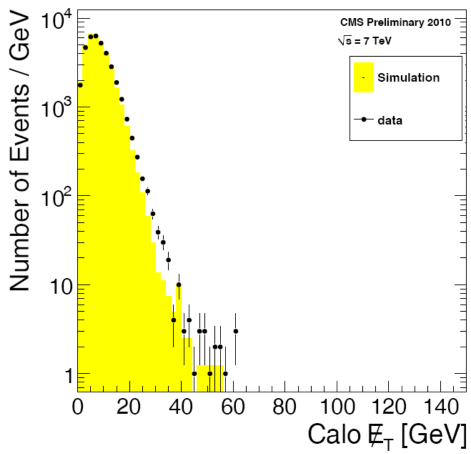
- The algorithms evolve as detector understanding improves; rely on:
  - Timing
  - Information from neighbors
  - Trigger information
  - …

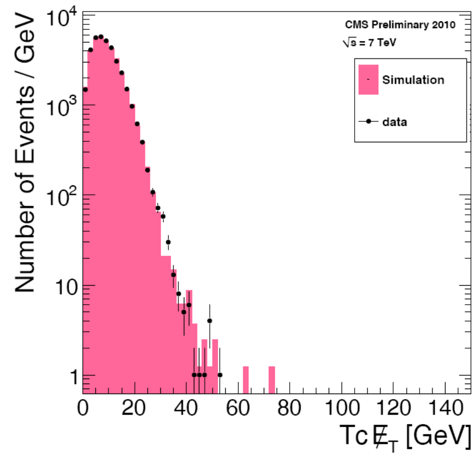


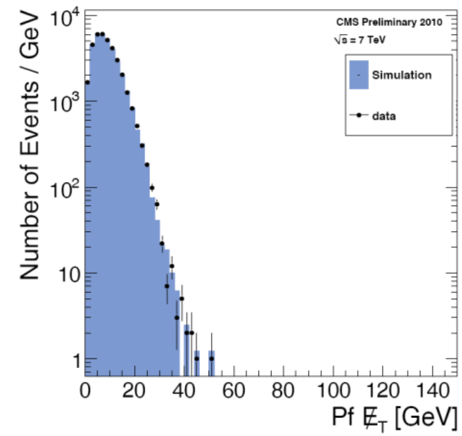
MET Commissioning (7 TeV)

CaloMET | **tcMET** | **PF MET**

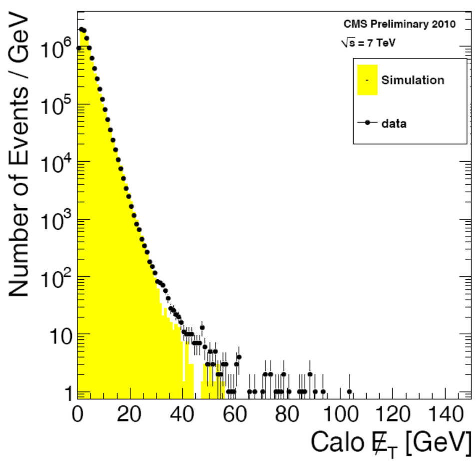
Inclusive sample

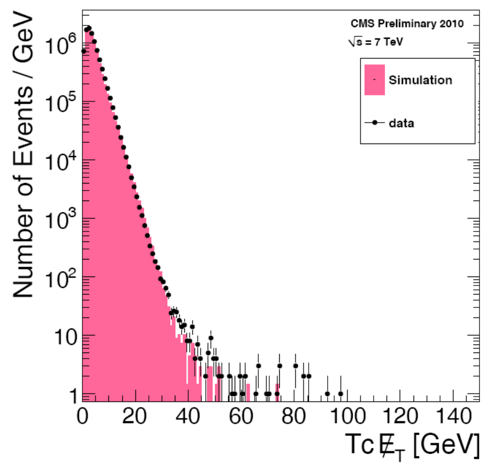


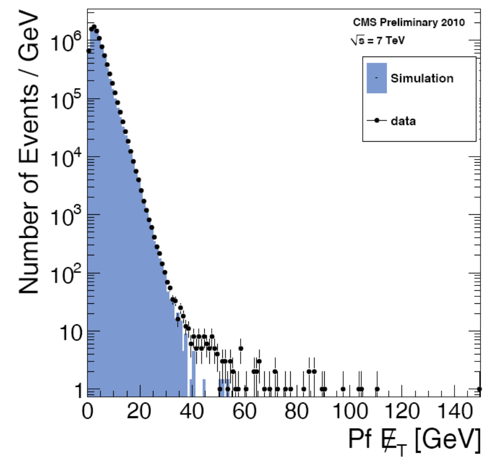




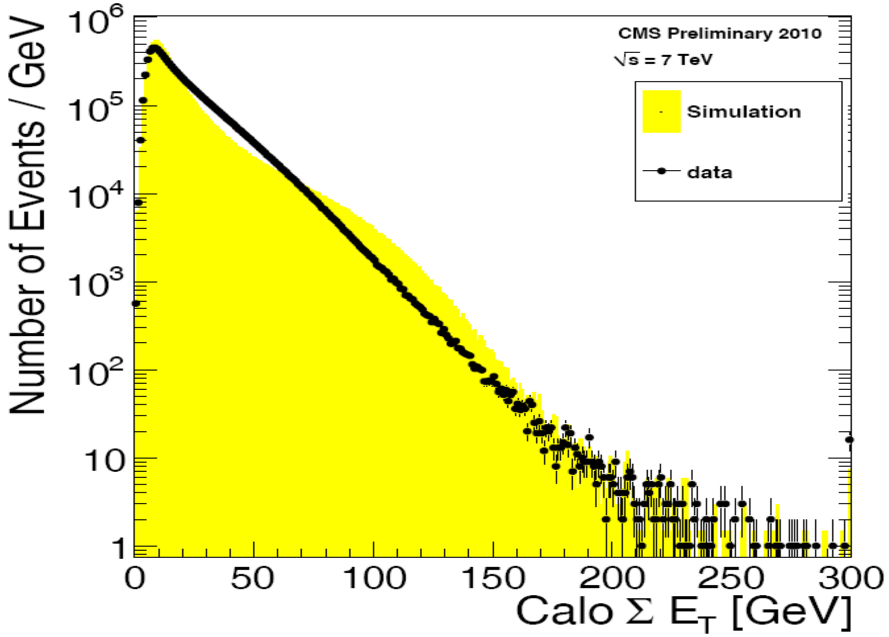
Di-jet sample

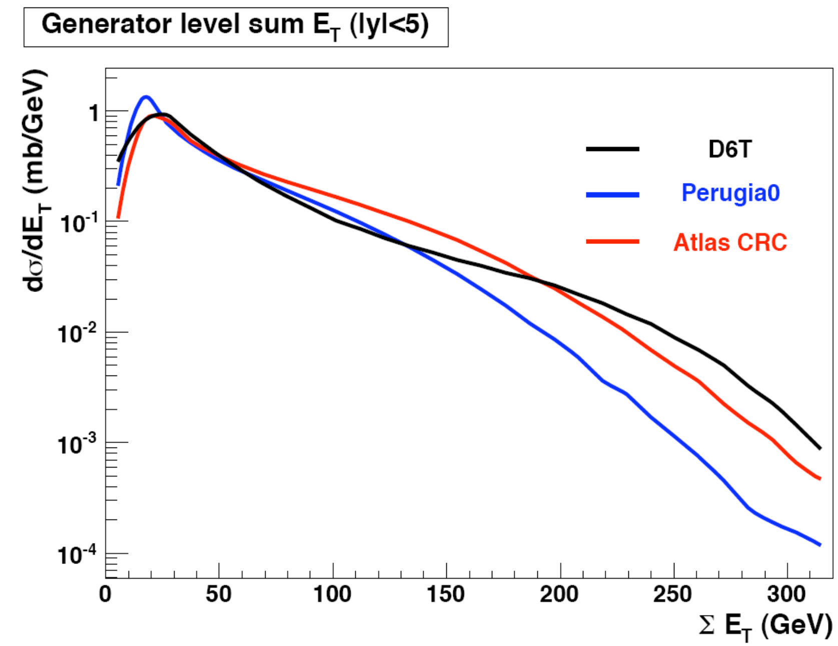






$\sum E_T$ and PYTHIA Parameters





- Disagreement in $\sum E_T$ seen for all MET reconstruction methods
- This is an event generation issue: $\sum E_T$ distribution depends strongly on PYTHIA "tunes" $\Rightarrow$ CMS MC needs to be optimized

As shown, distributions related to Jet/MET reconstruction are in good agreement.

QCD Results

Comprehensive QCD program at CMS

- Many analyses are near completion
- Most results targeted for release in summer 2010

In this presentation:

- Bose-Einstein correlations
- Two-particle correlations
- Charged track distributions
- Observation of Single Diffraction events
- Underlying event studies

Events used in these analyses are triggered using

- Beam timing information from BPTX
- Hit(s) in the Beam Scintillation Counters (BSC)

Bose-Einstein Correlations (BEC)

- Manifestation of BEC: enhanced emission of identical boson pairs with small relative momenta
- Provide information on the space-time structure of the emission source
- Measure of the effect $R = P(p_1, p_2)/[P(p_1)P(p_2)]$
- Look for dependence on $Q = \sqrt{-(p_1 - p_2)^2} = \sqrt{M_{\pi\pi}^2 - 4m_\pi^2}$:

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

Parameterization:

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

C - Normalization constant
λ - BEC strength for incoherent boson emission
Ω(Qr) – Fourier transform of the emission region
δ - Long range momentum correlations

Bose-Einstein Correlations (BEC)

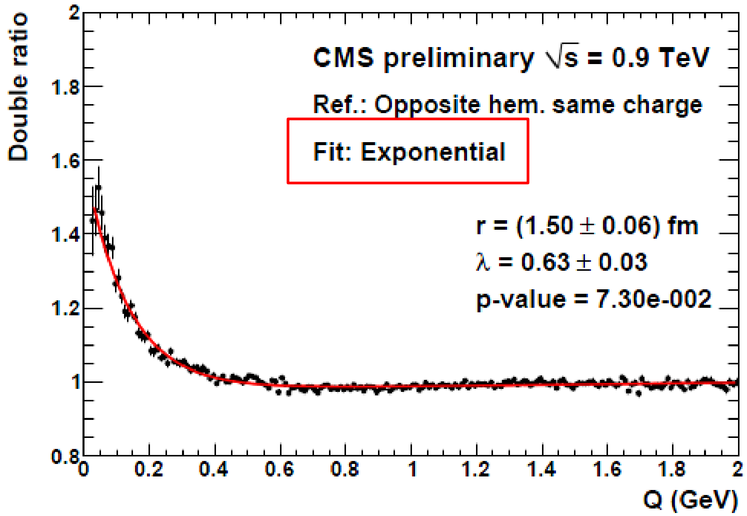
Selection:

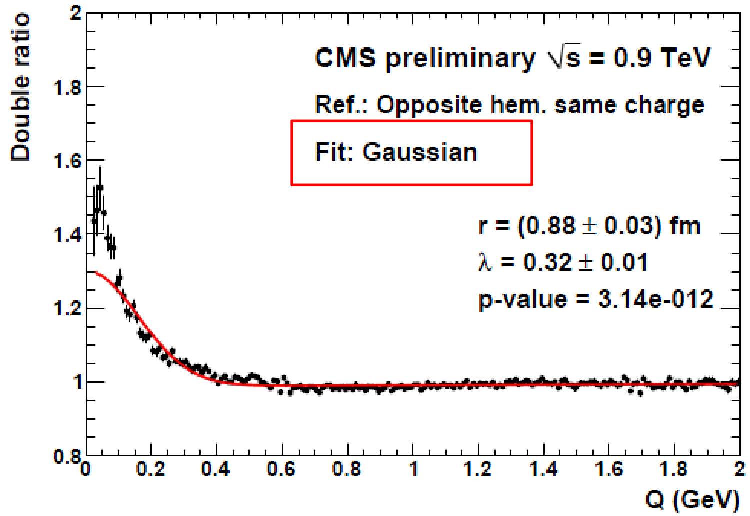
- p_T> 200 MeV
- $|\eta|$<2.4
- Good quality
- Veto conversions, long-lived particles

Reference samples

- Opposite-sign pairs
- Opposite hemisphere pairs, for one track replace $(p_x,p_y,p_z) \rightarrow (-p_x,-p_y,-p_z)$; use same and opposite charge pairs
- Rotated pair: for one track replace $(p_x,p_y,p_z) \rightarrow (-p_x,-p_y,p_z)$
- Mixing events: Random; same multiplicity; same mass
- Use double ratio: $R=R_{data}/R_{MC}$ (no BEC in MC) to reduce bias in reference construction

Fit region: $0.02 < Q < 2$ GeV; test $\Omega(Qr) = \exp[-Qr]$ and $\Omega(Qr) = \exp[-(Qr)^2]$

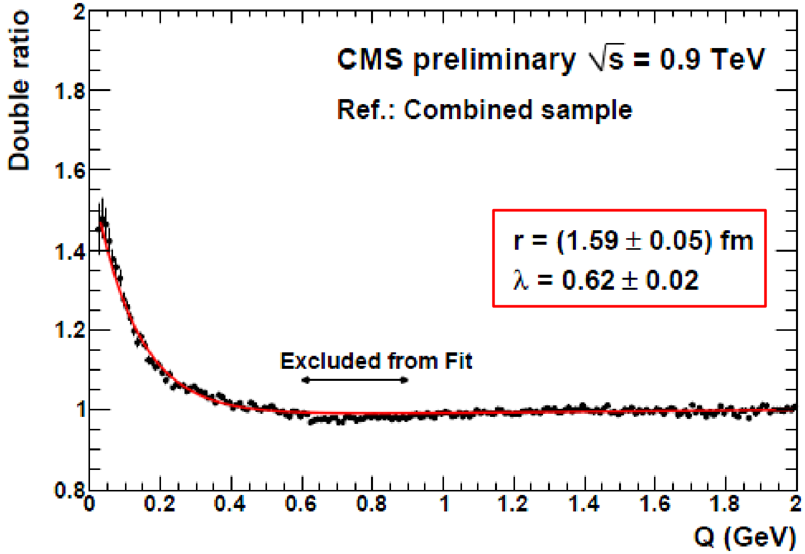


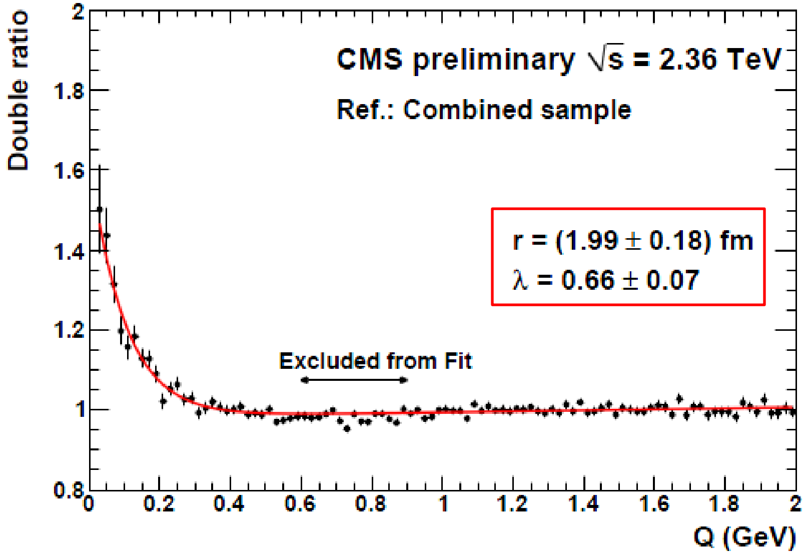


Bose-Einstein Correlations (BEC)

Parameter extraction:

- No reference sample is “perfect”: use all, interpret spread as systematic uncertainty

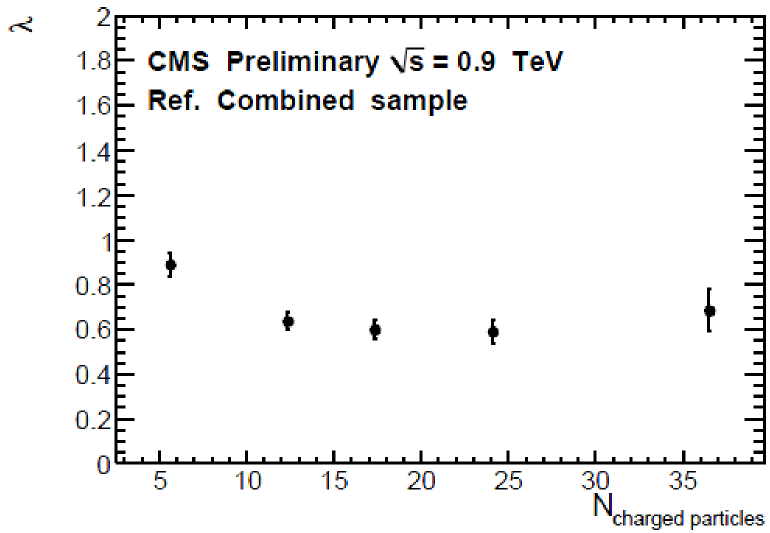


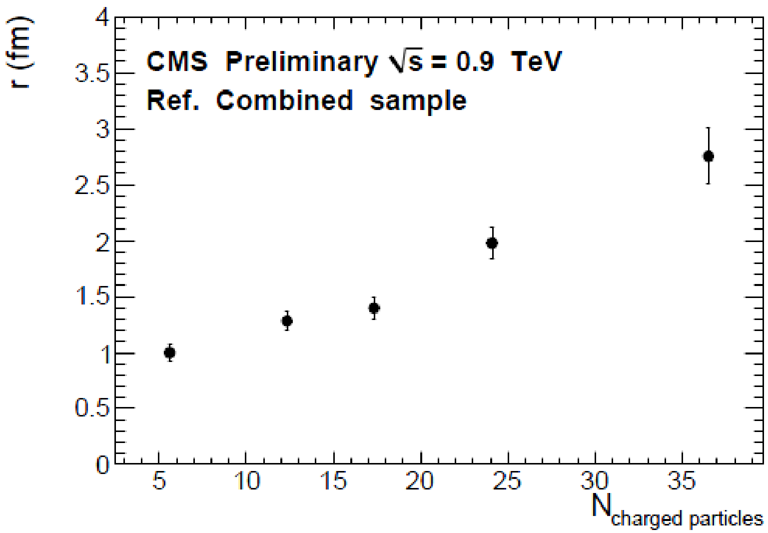


$r = 1.59 \pm 0.05$ (stat.) ± 0.19 (syst.) fm and $\lambda = 0.625 \pm 0.021$ (stat.) ± 0.046 (syst.) for 0.9 TeV data;
$r = 1.99 \pm 0.18$ (stat.) ± 0.24 (syst.) fm and $\lambda = 0.663 \pm 0.073$ (stat.) ± 0.048 (syst.) for 2.36 TeV data.

Bose-Einstein Correlations (BEC)

- Topological dependence:
  - No statistically significant dependence of λ, r on $<p_T>$, pair rapidity, energy difference
  - Pronounced dependence of r on track multiplicity





The trend can be further probed with 7 TeV data

Two-particle Correlations

Angular correlations in soft particle productions in pp collisions:

- Probe the hadronization process in the context of a “cluster” description
- Provide baseline for studies in heavy ion collision

2D correlation function: $$R(\Delta\eta, \Delta\phi) = \left\langle (N-1)\left(\frac{S_N(\Delta\eta,\Delta\phi)}{B_N(\Delta\eta,\Delta\phi)} - 1\right)\right\rangle_N$$

$\Delta\phi = \phi1 - \phi2$
$\Delta\eta = \eta1 - \eta2$
N – track multiplicity
S_N – normalized signal density (correlated+uncorrelated)
B_N – normalized background density

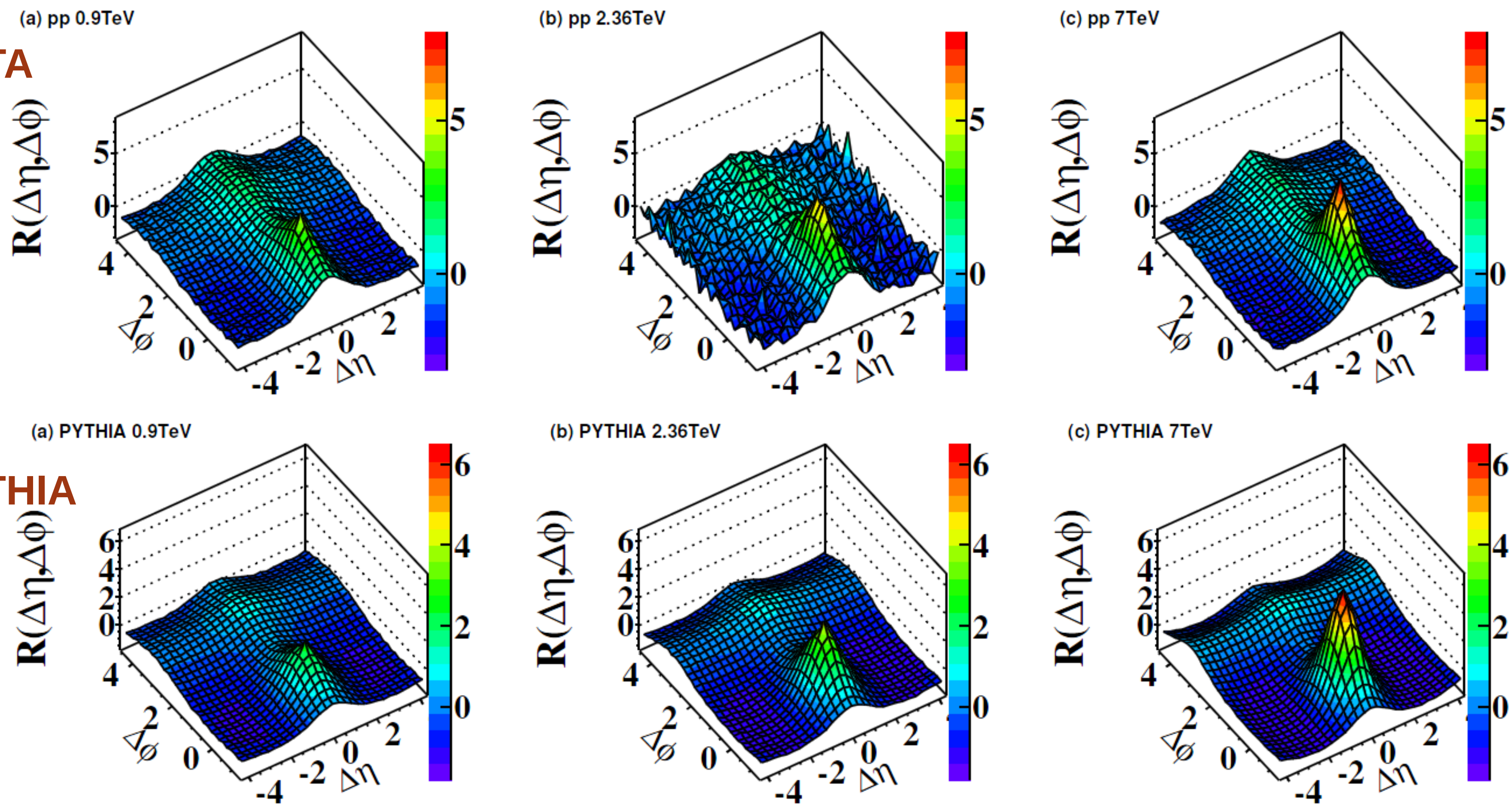
CMS has performed studies using collisions at $\sqrt{s}$=0.9, 2.36, 7 TeV

Two-particle Correlations

2D correlation functions measured at three CM energies

DATA

PYTHIA



PYTHIA qualitatively reproduces the shapes

Two-particle Correlations

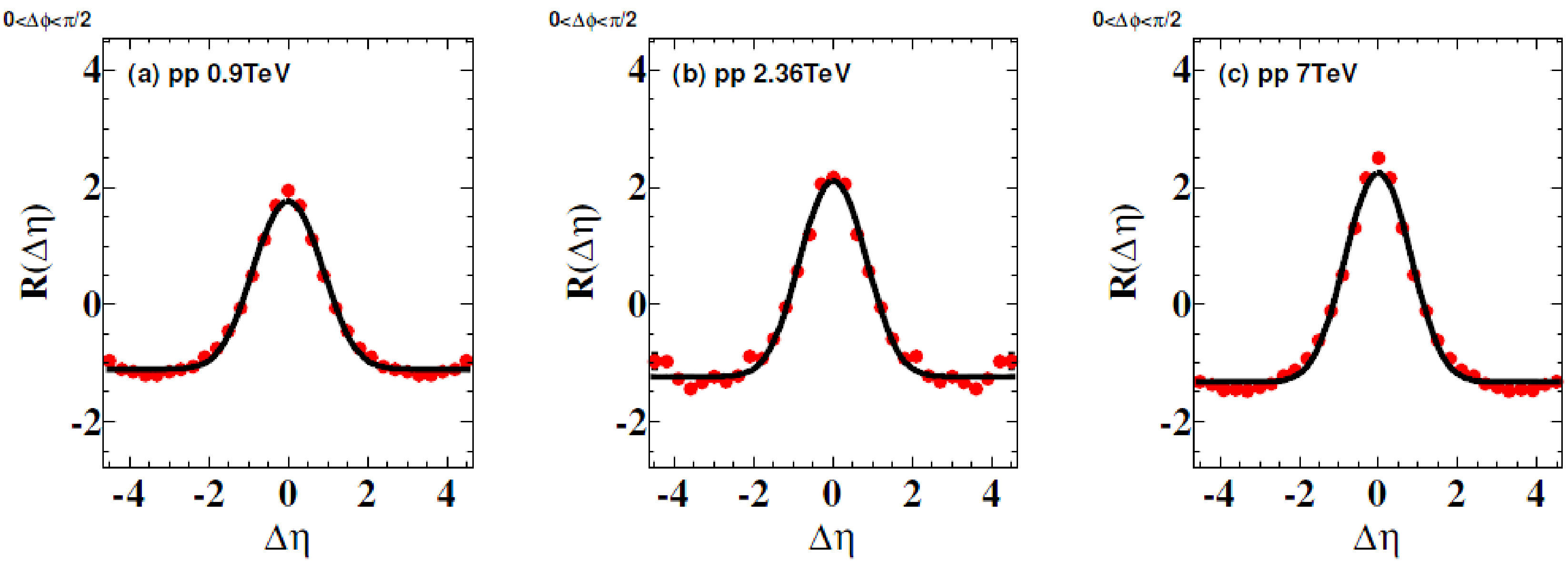
Parameterization after integration over ϕ:
(independent cluster model)

$$R(\Delta\eta) = (K_{eff} - 1)\left[\frac{\Gamma(\Delta\eta)}{B(\Delta\eta)} - 1\right]$$

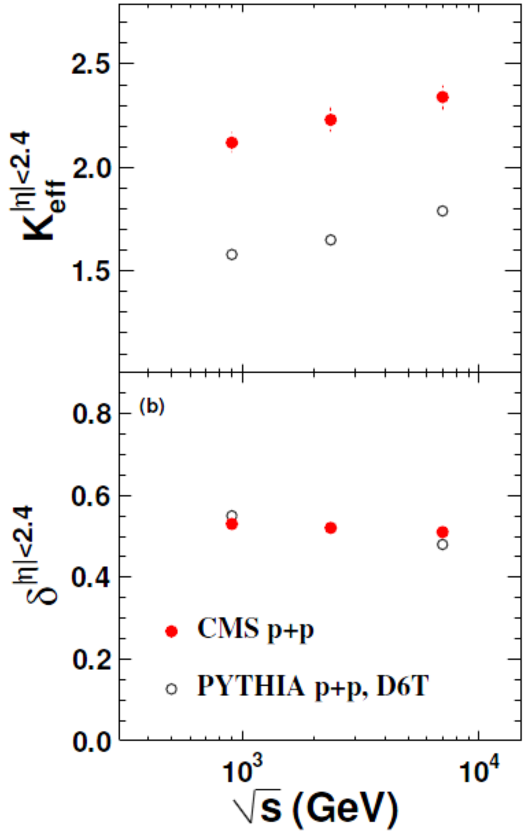
$$\Gamma(\Delta\eta) \propto \exp\left(-\frac{(\Delta\eta)^2}{4\delta^2}\right)$$

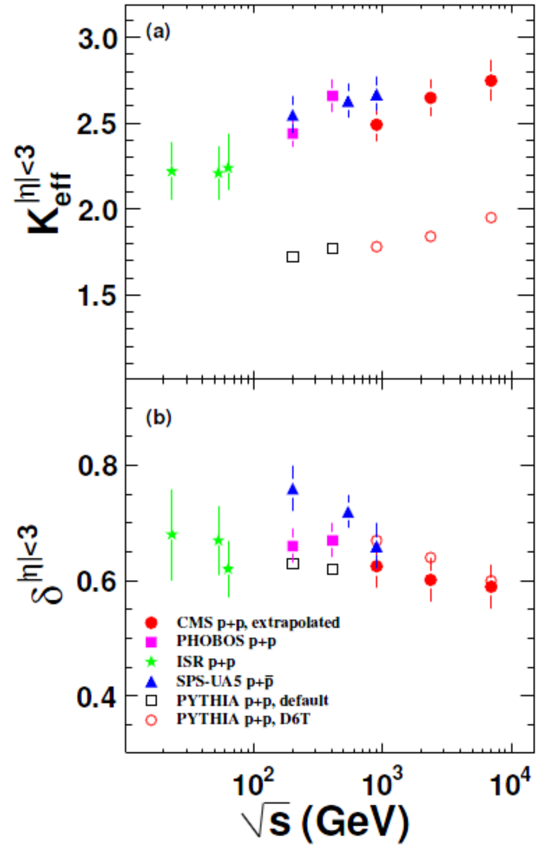
δ – cluster decay width
K_{eff} – effective cluster size

K_{eff} and *δ* can be extracted from the *$R(\Delta\eta)$* fits and provide a simple way to compare data and different models.



Two-particle Correlations



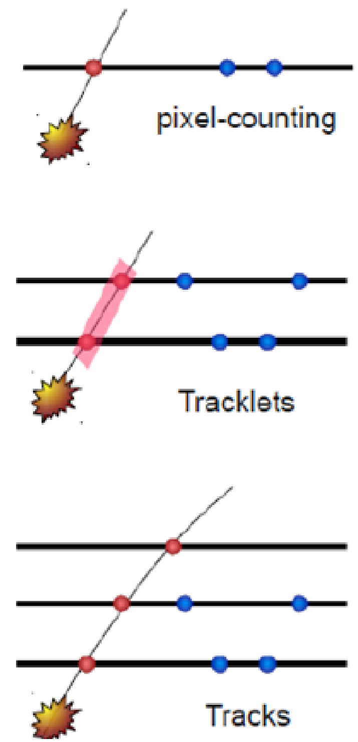


Comparison with other results (after extrapolation to |η|<3)

- The results are consistent with the trends from other measurements
- PYTHIA does not describe well the soft correlations

Charged Hadron Studies

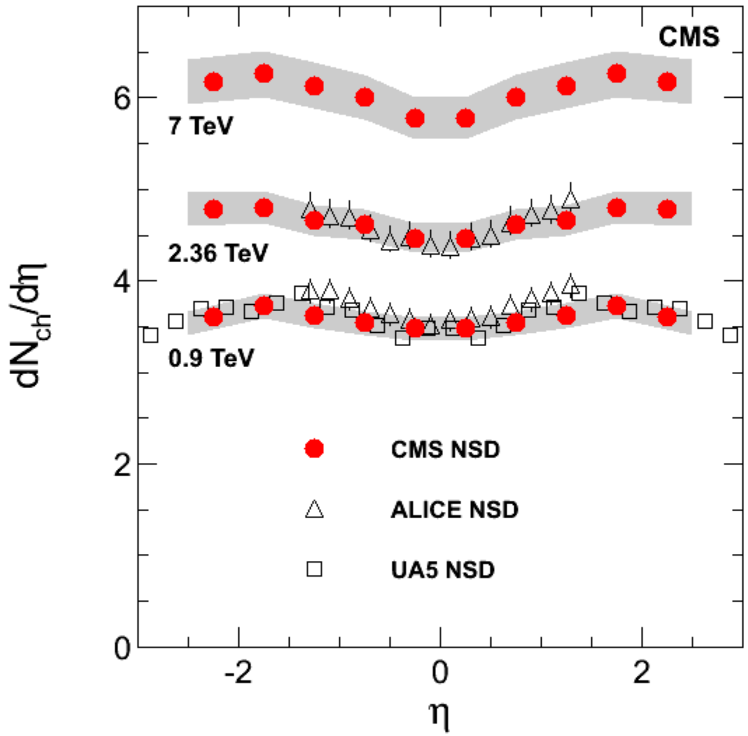
- Examine:
  - Charged particle multiplicity as a function of η
    - Use three techniques
      - Pixel counting
      - Primitive tracks (tracklets)
      - Fully reconstructed tracks
    - Combine: weight by uncorrelated uncertainties
  - p_T spectra
  - Dependence of $\langle p_T \rangle$ on η

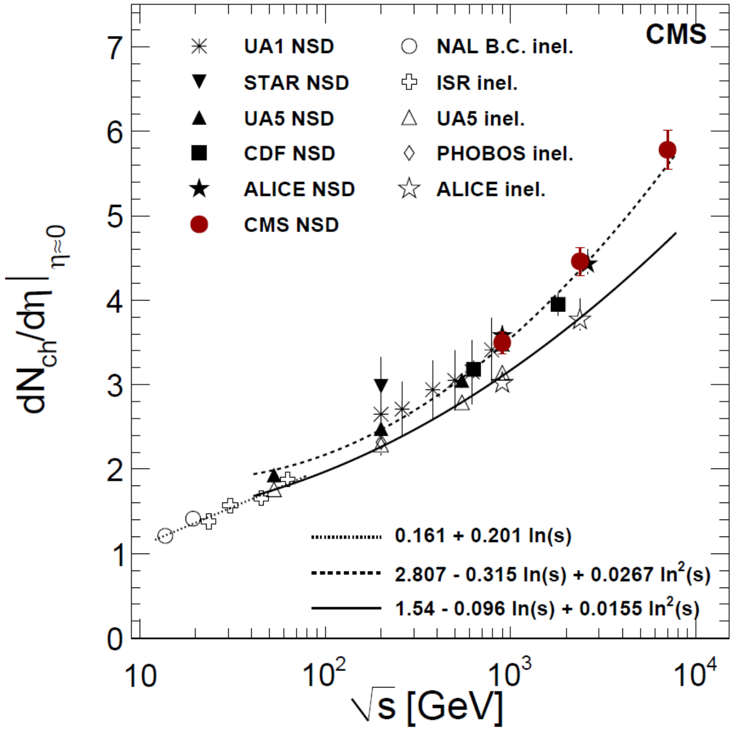


Select events with a good PV, activity in +/- sides of HF

These studies provide information on basic properties in Minimum Bias events at different CM energy. Useful for MC tuning.

Distributions of $dN_{ch}/d\eta$

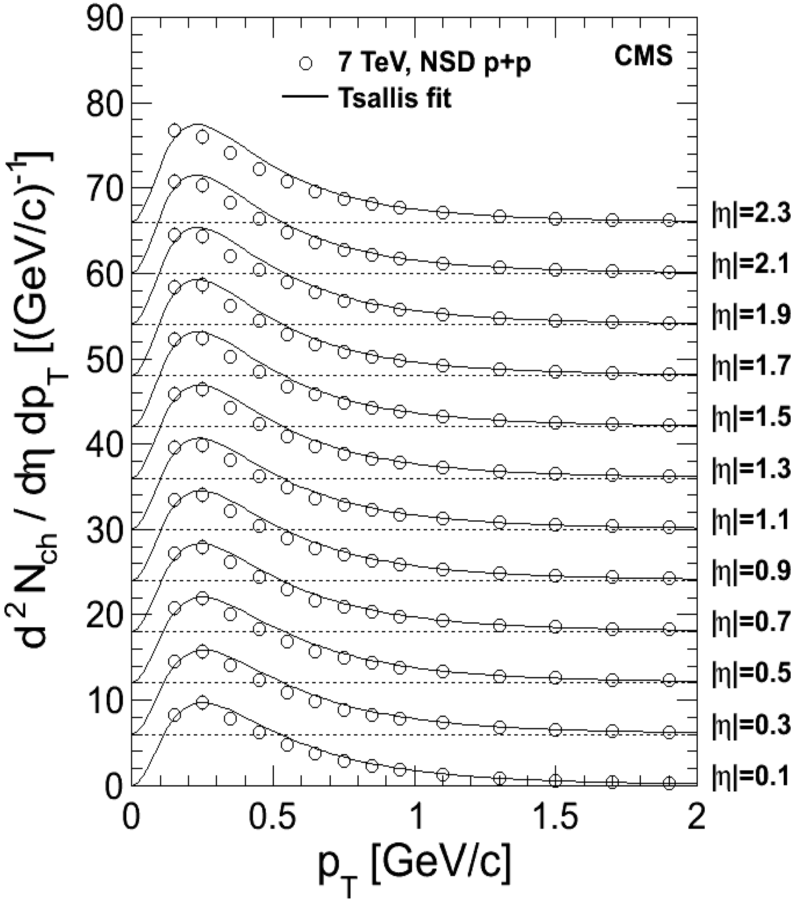




- The $dN_{ch}/d\eta$ results are in general agreement with other experiments
- Steeper particle multiplicity increase between 0.9-7 TeV than predictions from most models/tunes

Charged Hadron Spectra

Differential yield



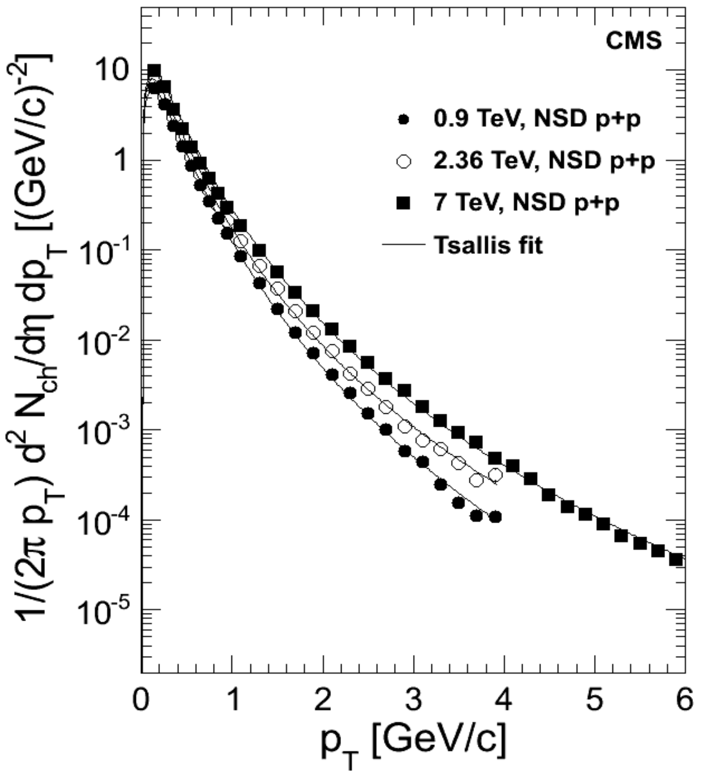
Fit with Tsallis function:

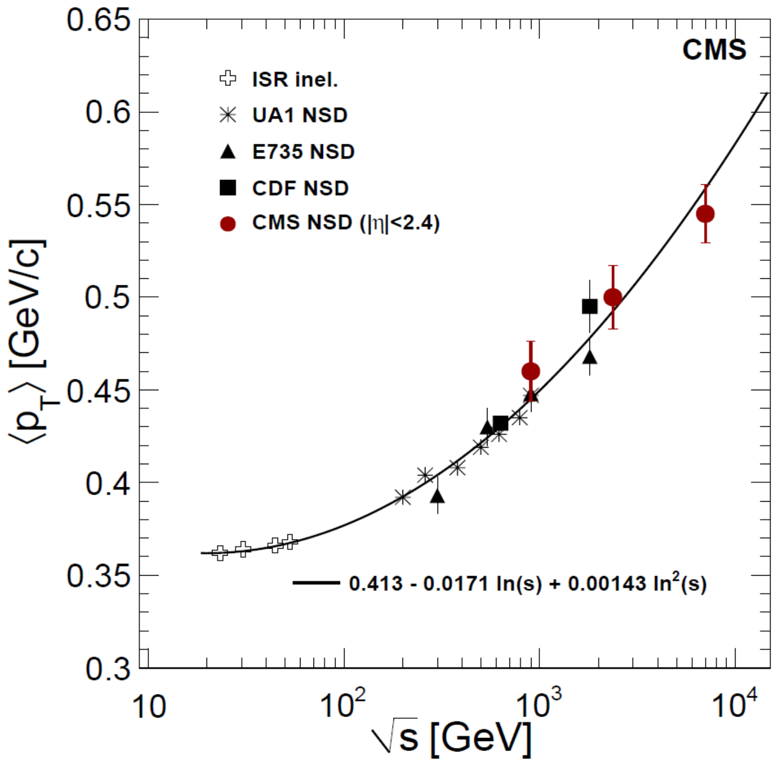
$$E\frac{d^3N_{\rm ch}}{dp^3} = \frac{1}{2\pi p_{\rm T}}\frac{E}{p}\frac{d^2N_{\rm ch}}{d\eta\, dp_{\rm T}} = C\frac{dN_{\rm ch}}{dy}\left(1+\frac{E_{\rm T}}{nT}\right)^{-n}$$

- Exponential at low p_T
- Power law at high p_T

The data for different η-bins on the plot are successively shifted by six units on the y-axis.

Charged Hadron Spectra

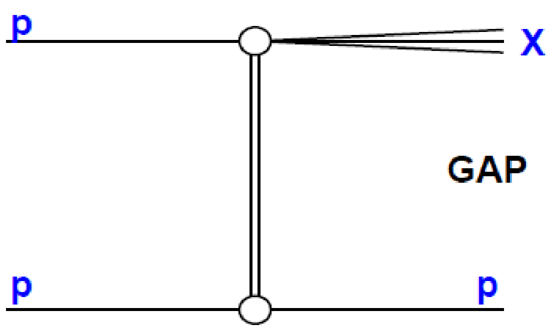




- The Tsallis function describes the data quite well
- The spectrum becomes harder as $\sqrt{s}$ increases (as expected)

Observation of Diffractive Events

Diffraction:
• pp→XY described by colorless exchange, vacuum quantum numbers
• Final states with large rapidity gap (LRG)
Single Diffraction (SD):
• pp→pX
• Can be observed at CMS
• Acceptance: very model dependent

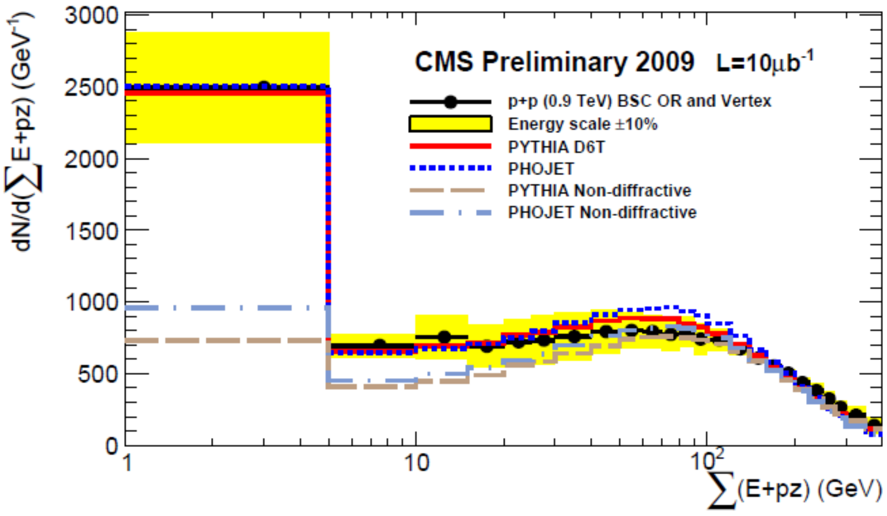


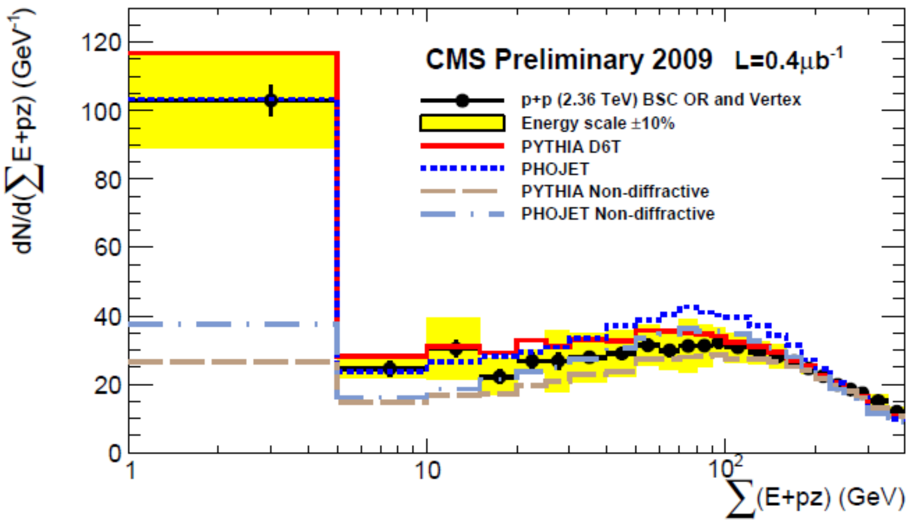
The CMS analysis uses 0.9 TeV (L_{int}=10 μb^{-1}) and 2.36 TeV (L_{int}=0.4 μb^{-1}) events

Hit in either +/- BSC (SD will be suppressed if coincidence is required)

- Look for evidence for SD events:
  - $\sum(E+p_z)$ (sum over all calorimeter towers): diffractive events peak at low values
  - Alternatively, use the forward calorimeter HF ($2.9<|\eta|<5.2$)
    - E_{HF} sum of energy in either +/- side
    - N_{HF}: multiplicity of towers in +/- side above threshold

Observation of Diffraction



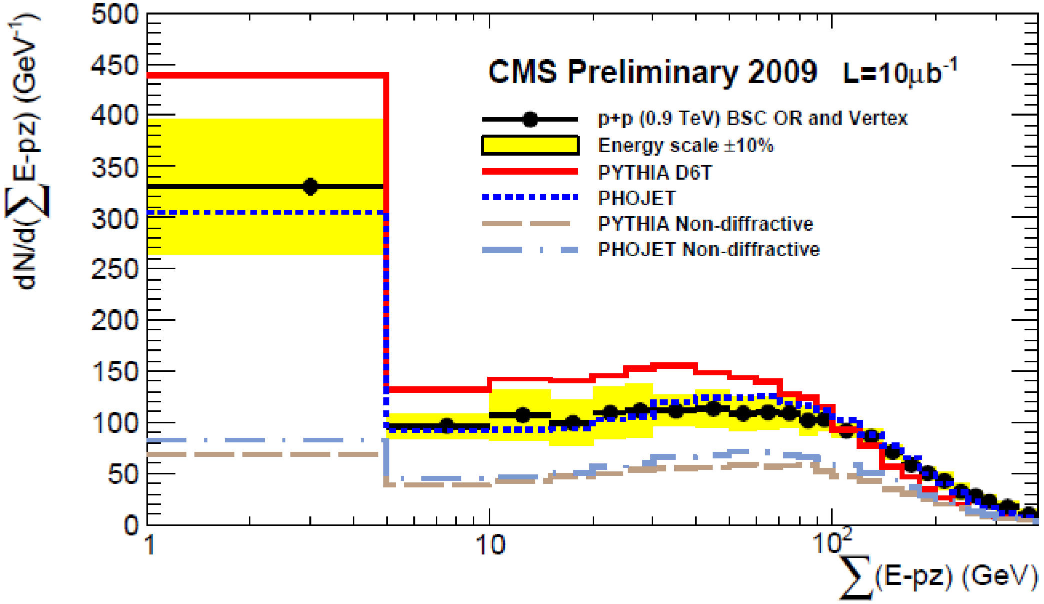


The yellow band indicates a 10% uncertainty on the energy scale.

- Observe clear presence of SD events
- PYTHIA describes better the non-diffractive part

Observation of Diffraction

Enriched sample of SD events: require a gap in HF+ (E_{HF+}< 8 GeV)



- PHOJET describes better the SD–enriched sample

Studies with 7 TeV data are in progress

Underlying Event Studies (0.9 TeV)

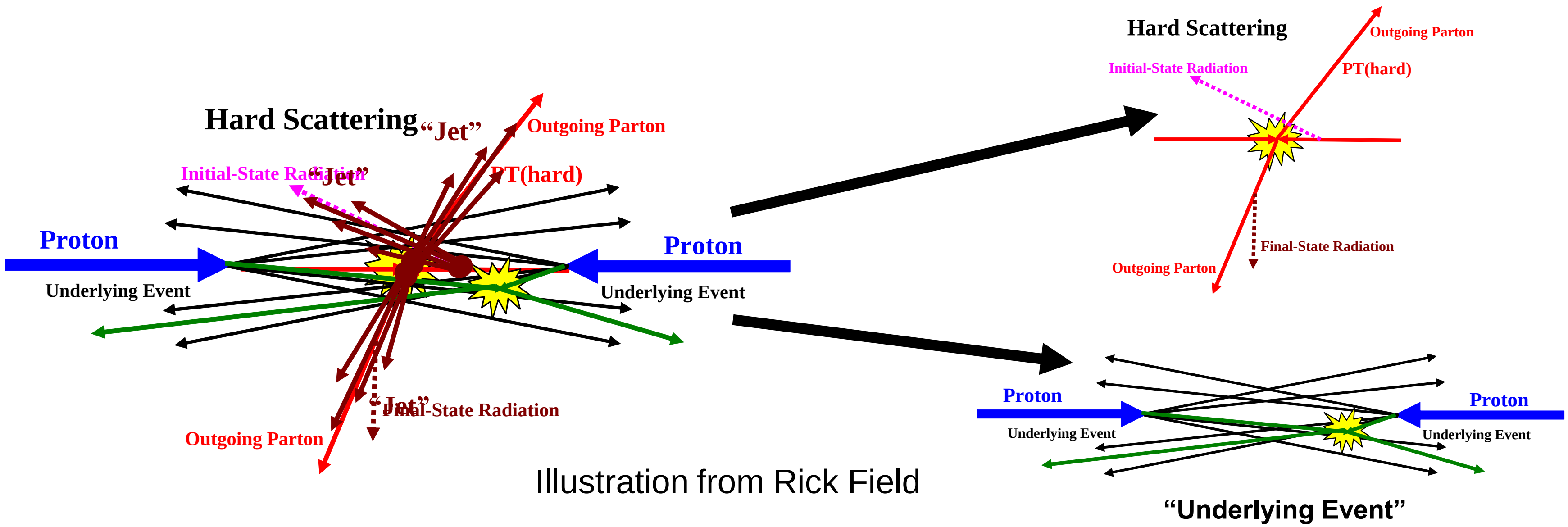


Illustration from Rick Field

Underlying event (UE):

- Beam-beam remnants (BBR) + multiple parton interactions (MPI)
- Background to most collider observables
- Need to be well understood for precision measurements

UE Modeling and PYTHIA "Tunes"

MPI modeling is included in PYTHIA, adjustable through a set of parameters. Different set of parameters define "tunes".

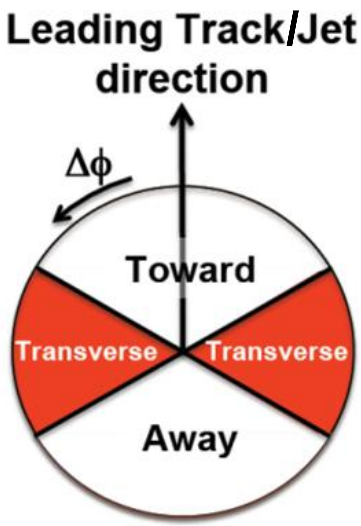
Significant impact from the

- p_{T0} : cut-off parameter that regularize both hard scattering and MPI $1/\hat{p}_T^4 \rightarrow 1/(\hat{p}_T^2 + p_{T_0}^2)^2$
- ε : enters the scaling of p_{T0} with CM energy $p_{T_0}(\sqrt{s}) = p_{T_0}(\sqrt{s_0}) \cdot (\sqrt{s} / \sqrt{s_0})^{\epsilon}$

Tune	p_{T0} (GeV/c) at √s=1.8TeV	ε	Motivation
D6T	1.84	0.16	Energy dependence of charged particle multiplicity by UA5
DW	1.9	0.25	CDF data @ √s=1.8, 0.630 TeV
Pro-Q20	2.1	0.25	CDF data @ √s=1.8, 0.630 TeV
Perugia-0	2.0	0.25	CDF data @ √s=1.8, 0.630 TeV
CW	1.8	0.30	Modification of DW, maximize UE activity at √s=0.9 TeV

Other differences in the tunes: fragmentation model, PDFs, MPI modeling (P0),…

UE Studies



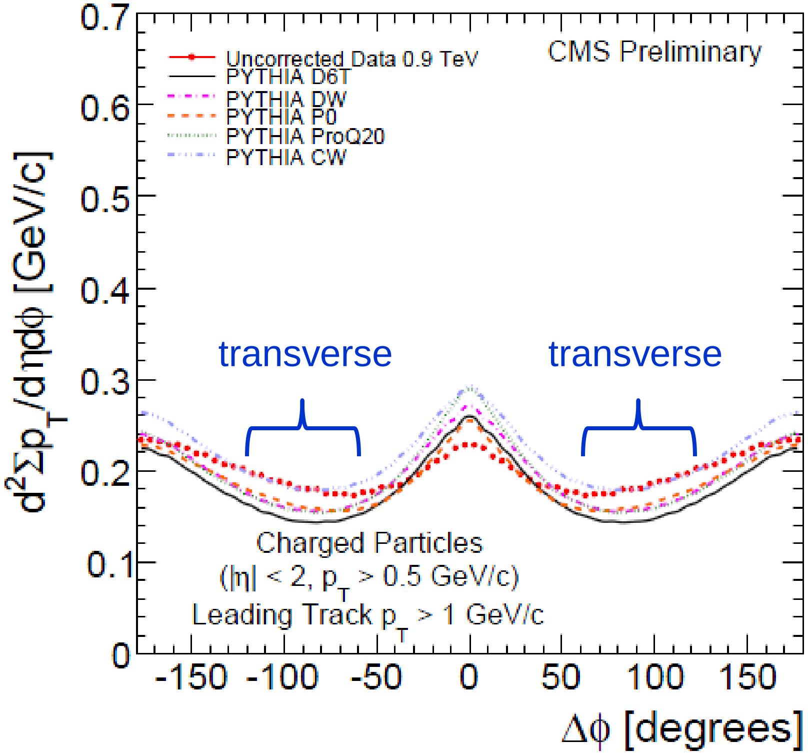
- Define regions in the transverse plane wrt the leading track/jet
  - Toward: $|\Delta\phi|<60^o$
  - Away: $|\Delta\phi|>120^o$
  - Transverse: $120^o<|\Delta\phi|<60^o$ - most useful for UE studies
- Examine track activity in data and compare with MC tunes: $d^2N_{ch}/d\eta d\phi$, $d^2\Sigma pT/d\eta d\phi$, $dN_{ch}/dp_{T,...}$
- Compare uncorrected data with full detector simulation MC

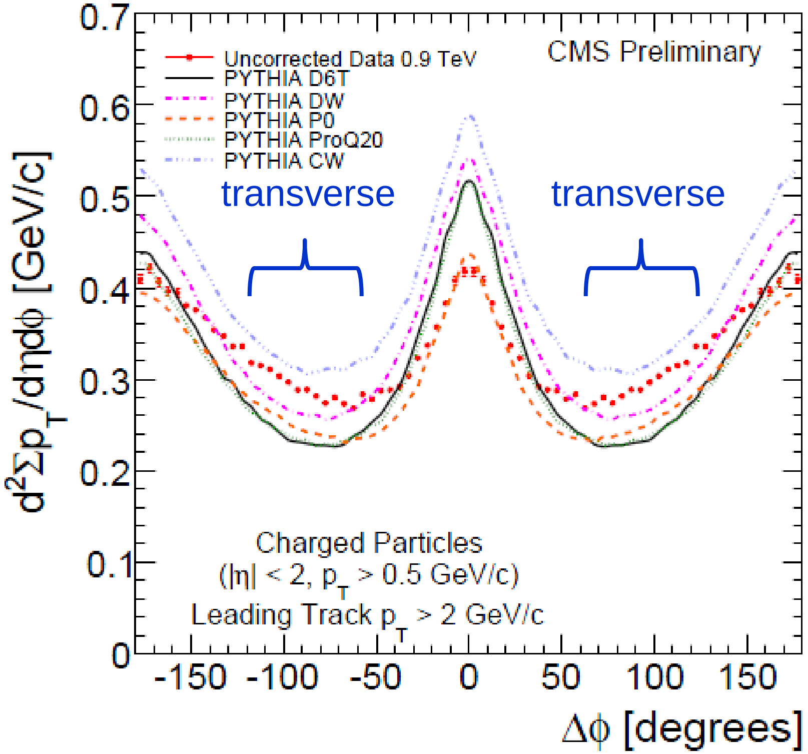
Basic selections criteria

- Hits in both Beam Shower Counters: ~255k triggered events
- Good primary vertex, ≥3 tracks; $|z_{PV}|<15$ cm
- Consider good tracks with $p_T>0.5$ GeV, $|\eta|<2.0$ (2.5 for jets)
- Jets: SysCone, R=0.5
- Leading jet (track) p_T > 3 (1) GeV/c

All data in this analysis was collected at $\sqrt{s}=0.9$ TeV

UE Studies

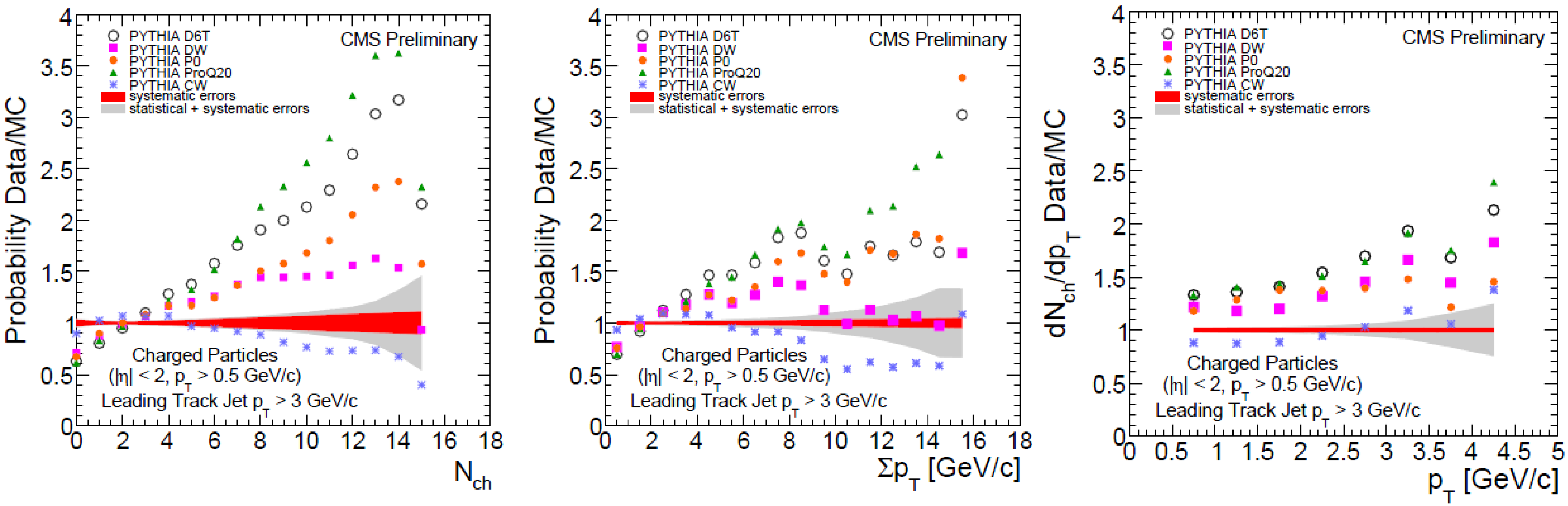




- DW and CW are the best performing tunes in the transverse region.
- Perugia-0 (P0) good along the leading track direction.
- No tune gives a good description in the entire range

UE Studies

Distributions in the transverse region: 120^o<|$\Delta\phi$|<60^o



General observations:

- Most of the tunes underestimate activity in the transverse region; CW, DW give the best agreement
- Data favors a strong energy dependence of the cut-off on CM energy (ε~0.25-0.30)

Better MC tunes wanted!

Summary

- CMS has set the foundation for a good understanding of jets and MET reconstruction in data and MC

- QCD physics results are rolling out:
  - ✓ Bose-Einstein correlations
  - ✓ Two-particle correlations
  - ✓ Charged track multiplicity distributions
  - ✓ Observation of single diffraction events
  - ✓ Underlying event studies
  - ➢ Many new results are on the way for ICHEP

References for presented results

- Jets in 0.9 and 2.36 TeV pp Collisions / CMS Collaboration (CMS PAS JME-10-001)
- Performance of Missing Transverse Energy Reconstruction in √s = 900 and 2360 GeV pp Collision Data / CMS Collaboration (CMS PAS JME-10-002)
- Transverse momentum and pseudorapidity distributions of charged hadrons in pp collisions at √ s = 0.9 and 2.36 TeV / CMS Collaboration (CMS PAS QCD-09-010; J. High Energy Phys. 02 (2010) 041)
- Transverse-momentum and pseudorapidity distributions of charged hadrons in pp collisions at √ s = 7 TeV / CMS Collaboration (CMS PAS QCD-10-006, accepted by PRL)
- First Measurement of Bose-Einstein Correlations in proton-proton Collisions at √s =0.9 and 2.36 TeV at the LHC / CMS Collaboration (CMS PAS QCD-10-003, accepted by PRL)
- Two-particle correlations and cluster properties from two-particle angular correlations in p+p collisions at √s = 0.9, 2.36TeV and 7 TeV / CMS Collaboration (CMS PAS QCD-10-002)
- Observation of diffraction at 0.9 TeV and 2.36 TeV (CMS PAS FWD-10-001)
- First Measurement of the Underlying Event Activity in Proton-Proton Collisions at 900 GeV at the LHC / CMS Collaboration (CMS PAS QCD-10-001)