CMS results on diffraction *and low-x*

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(CERN)
on behalf of
CMS Collaboration

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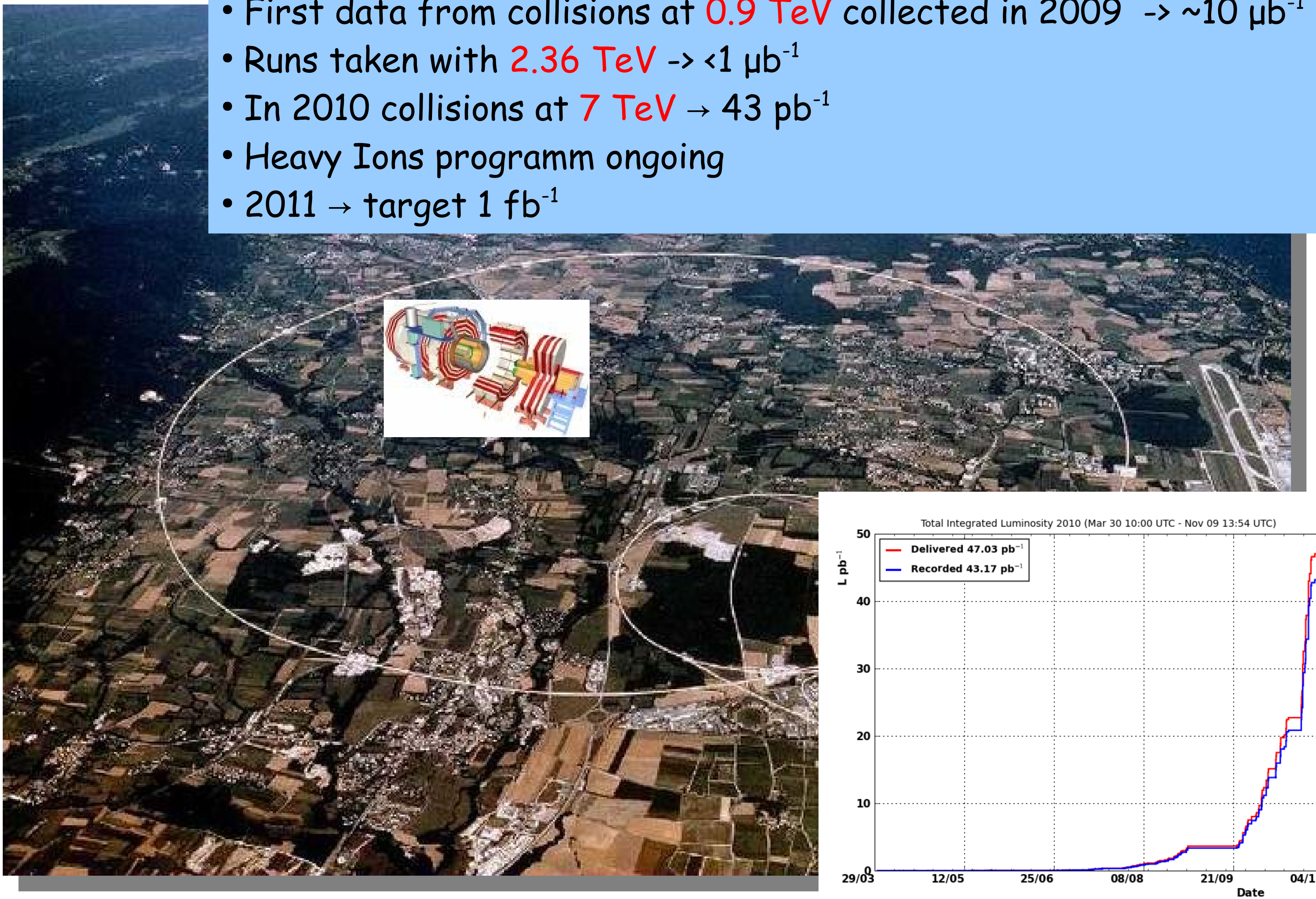
MPI@LHC 2010:
2nd International Workshop
on Multiple Partonic Interactions at the LHC

The Outline

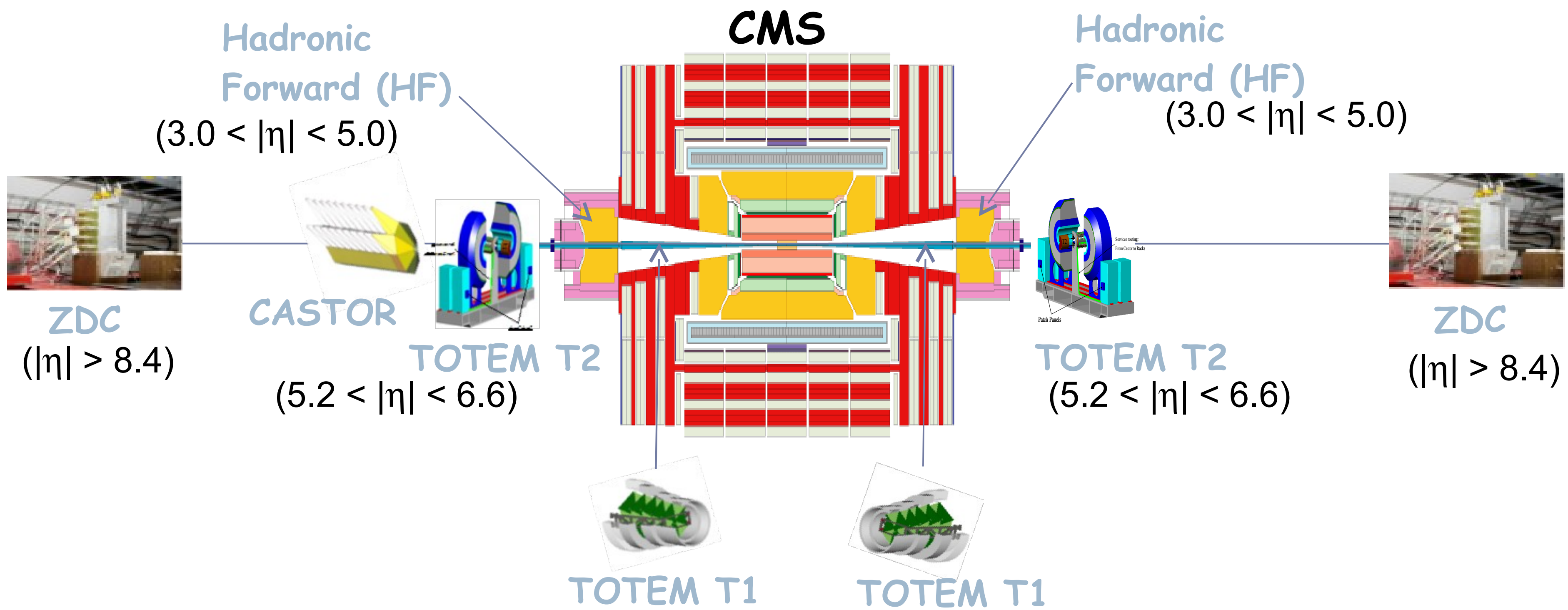
- Apparatus
- Observation of inclusive diffraction
- Observation of hard diffraction
- Energy flow in the forward region
- Forward jets spectrum
- Outlook and Summary

CMS and LHC

- First data from collisions at 0.9 TeV collected in 2009 -> ~10 μb^{-1}
- Runs taken with 2.36 TeV -> <1 μb^{-1}
- In 2010 collisions at 7 TeV → 43 pb^{-1}
- Heavy Ions programm ongoing
- 2011 → target 1 fb^{-1}



The CMS detector



- **Hadronic Forward** calorimeters (HF)
- **Zero Degree Calorimeter** (ZDC)
- **Centauro And STrange Objects Research** (CASTOR) – calorimeter

- **TOTEM** – separate experiment:
  - T1 – in front of the HF, 7.5 m from IP
  - T2 – in front of CASTOR, 13.6 m from IP
  - RP – 147 & 149 and 216 & 220 m from IP

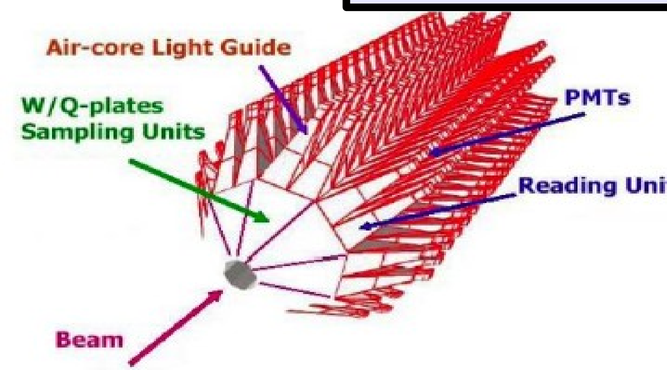
The CMS forward detectors

HF

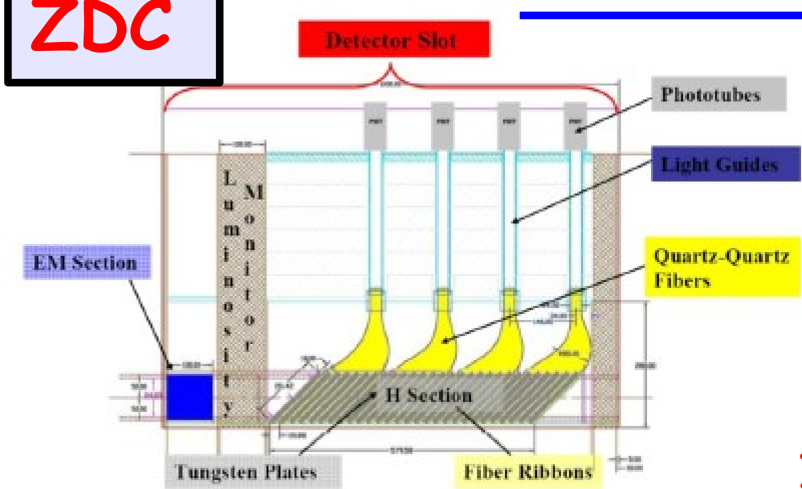
- Located at 11.2 m from IP
- Rapidity coverage: 3 < |η| < 5
- 0.175x0.175 segmentation in η and ϕ
- Steel absorbers and embedded radiation-hard quartz fibers for fast collection of Cherenkov light

CASTOR

- Located at 14.3 m from IP
- Rapidity coverage: -6.6 < η < -5.2
- Segmentation in ϕ (16 sectors)
- 14 modules (2EM+12HAD)
- Alternate tungsten absorbers and quartz plates



ZDC



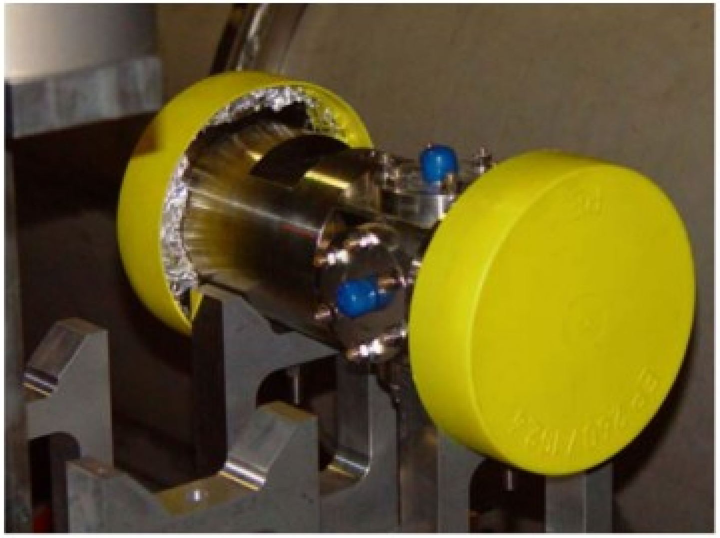
- Located at 140 m from IP
- Rapidity coverage: |η| > 8.1
- Tungsten/quartz Cherenkov calorimeter with separated EM and HAD sections
- Detection of neutrals (γ, π^0, n)

In the presented analyses CASTOR and ZDC not used

Minimum Bias Triggers

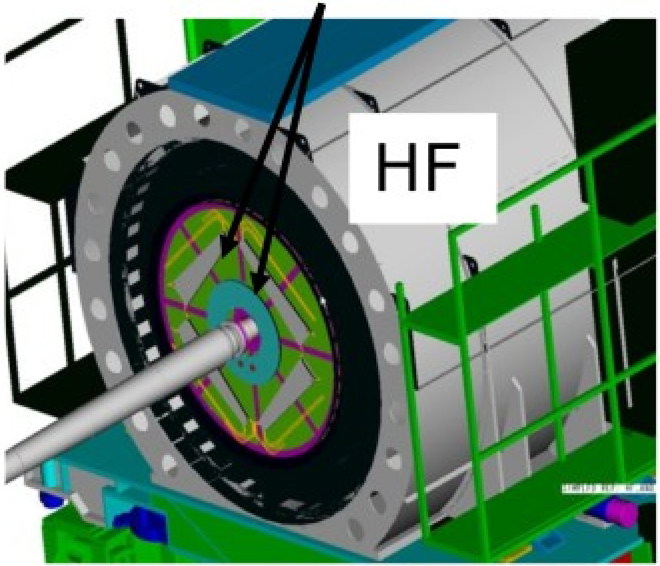
- Beam Pick-up Timing for eXperiments - BPTX
- 175 m from interaction point (both sides)
- Designed to provide precise info on the bunch structure and timing of the incoming beam
- Trigger formed if one (two bunches) present

BPTX



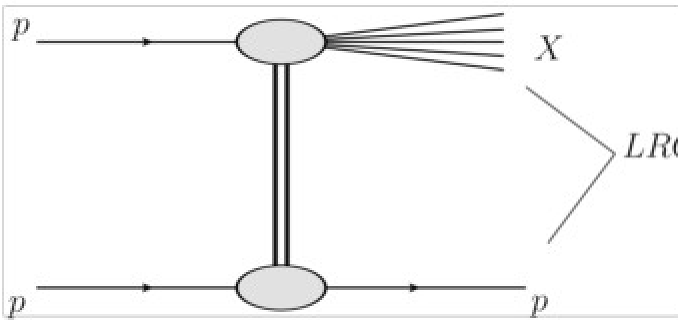
- Beam Scintillator Counters – BSC
- 10.86 m from interaction point (both sides)
- Each BSC is a set of 16 tiles
- Designed to provide hits and coincidence rates

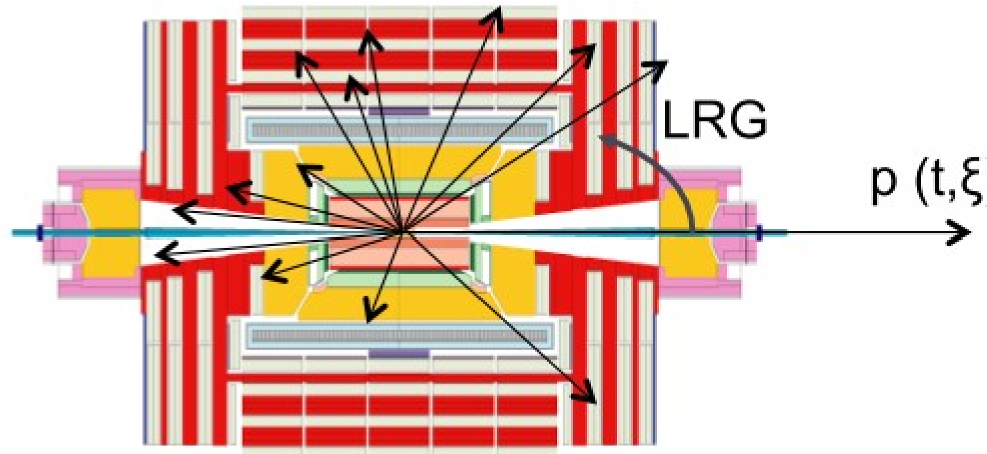
BSC



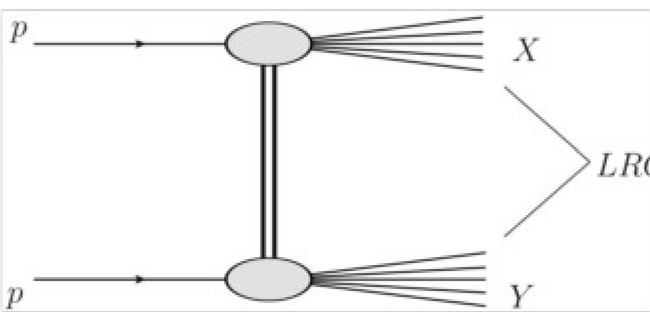
Diffraction at CMS

Single-diffractive dissociation SD

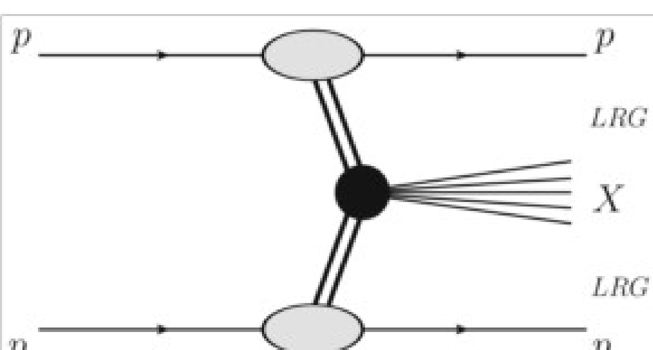




Double-diffractive dissociation DD



Central-diffractive dissociation CD



- Diffractive events are an important fraction of MB events
- Without hard scale set – soft diffraction
- Large differences between the models implemented in Monte Carlo generators
- Observation and measurement of soft diffraction characteristic an important ingredient of models testing and tuning

Event selection

Selection on trigger

- Coincidence of signals in BPTX (presence of two proton bunches)
- Activity at least in one BSC (at one side of CMS)

General selection

- Vertex with at least 3 tracks and with $|z| < 15$ cm
- Rejection of beam halo events
- Rejection of beam background events
- Rejection of events with large signals consistent with noise in HCAL

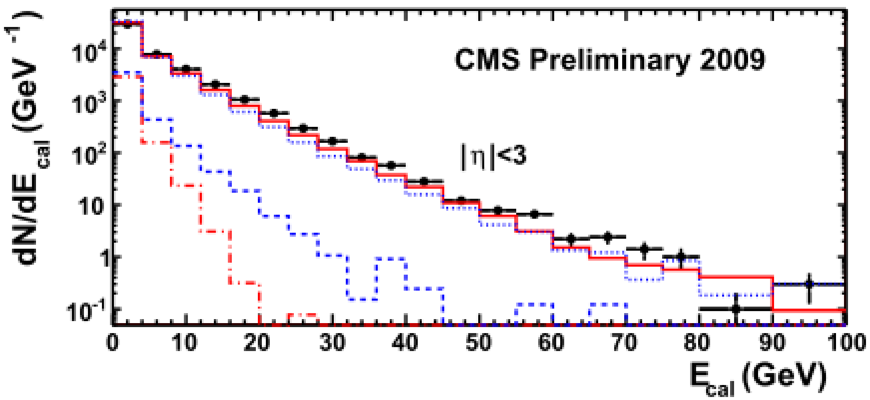
At 0.9 TeV : 207 000 events selected

At 2.36 TeV : 11 800 events selected

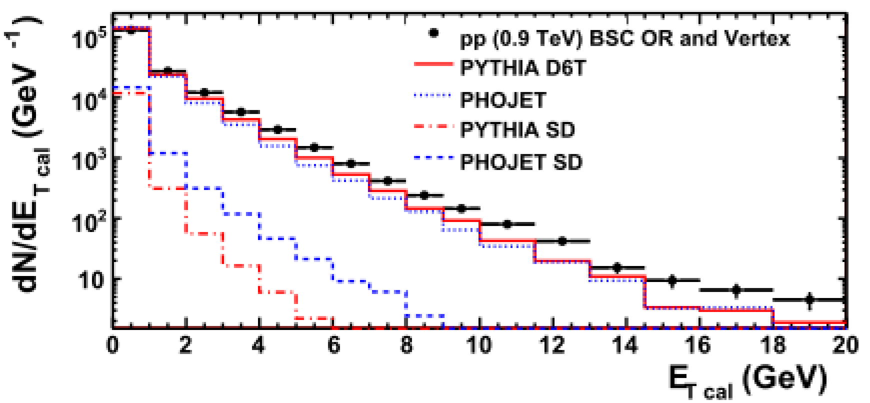
with residual contamination of beam-gas < 1% (estimated from non-colliding bunches)

Control plots

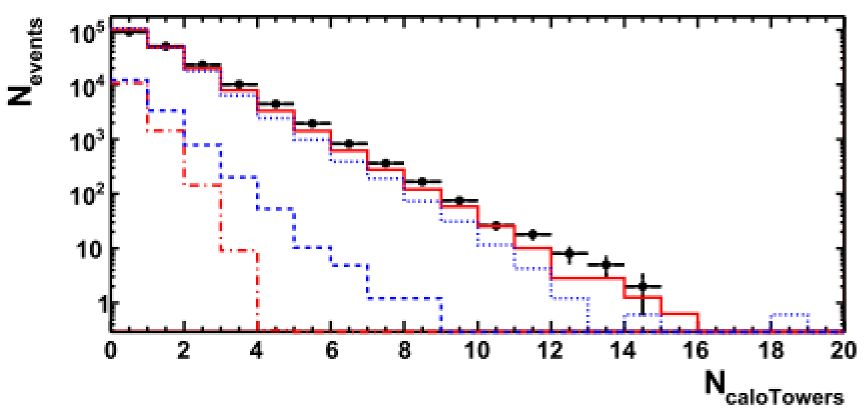
0.9 TeV



Energy distribution in calotowers in central CMS calorimeters (excl. HF)



Transverse energy distribution in calotowers in central CMS calorimeters (excl. HF)



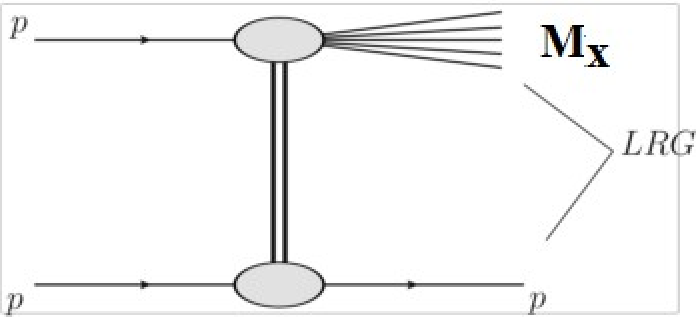
Multiplicity of calotowers in central CMS calorimeters (excl. HF) , treshold of 3 GeV

All distributions – uncorrected

MC normalised to data

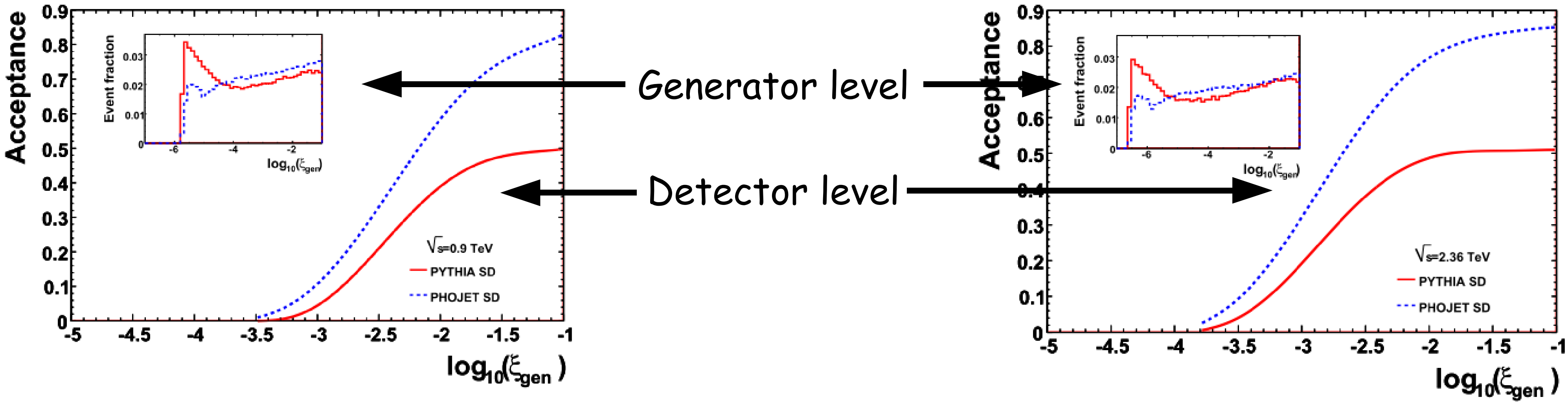
Acceptance for SD

Acceptance as a function of ξ (fractional momentum loss of the scattered p):



$$\xi = (M_x)^2 / S$$

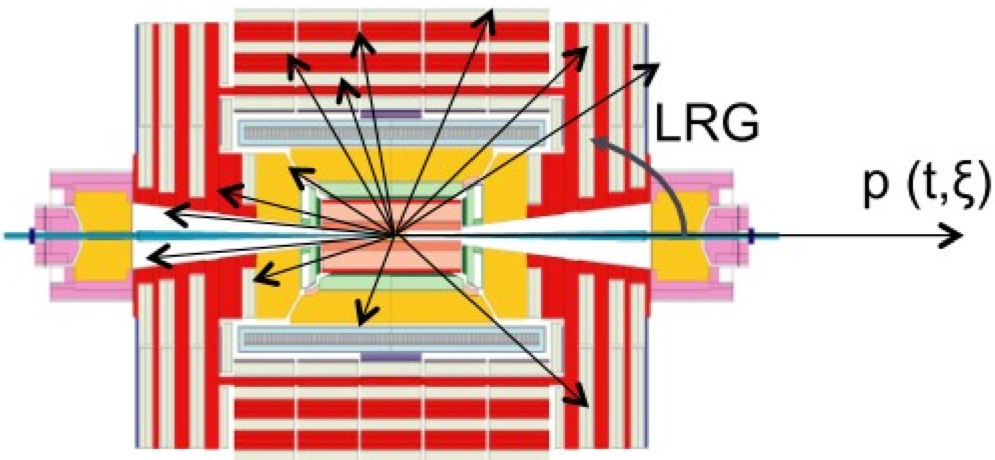
PYTHIA and PHOJET different modeling of diffraction
→ different selection efficiency



Inefficiencies for: low ξ → escape undetected
low charge activity

SD efficiency: 0.9 TeV → 18% (PYTHIA), 32% (PHOJET)
2.36 TeV → 20% (PYTHIA), 37% (PHOJET)

Observation of diffraction



Variables:

1) $\sum (E_i \pm p_{z,i})$

where sum runs over all calotowers including HF, $p_{z,i} = E_i \cos\theta_i$
approx. twice the pomeron energy
for diffraction peaks at small values

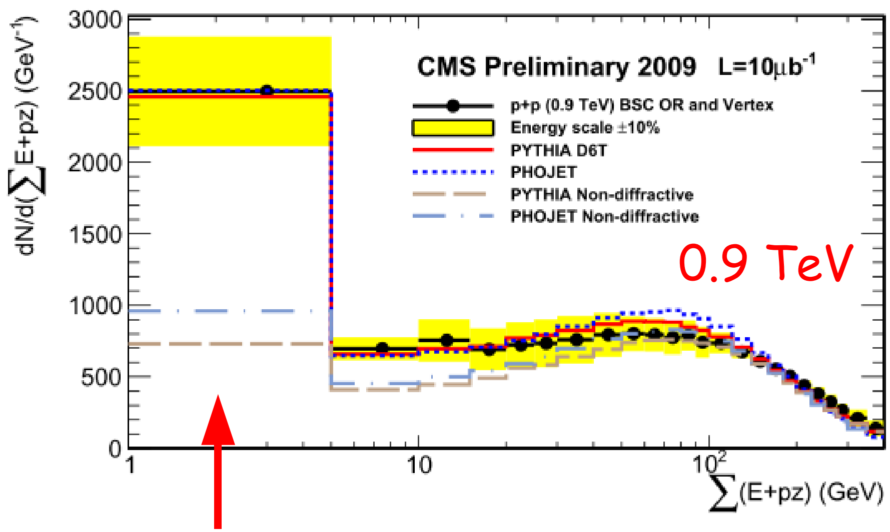
2) E_{HF} – total energy deposit in HF
diffractive events with rapidity gap extending over HF appears in the first bin of this distribution

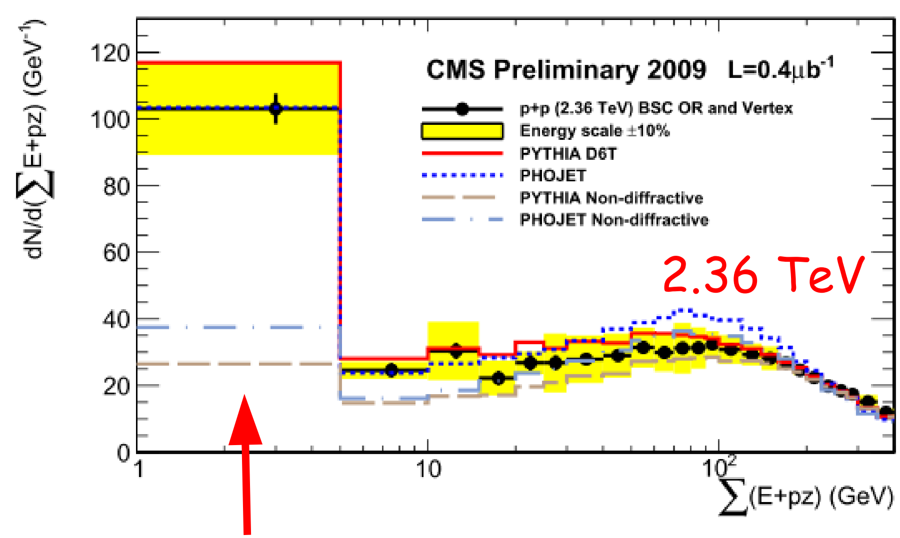
3) N_{HF} – multiplicity of the towers above threshold of 4 GeV
diffractive events cluster at zero multiplicities

All variables are sensitive to the calorimeter energy scale uncertainty → 10%

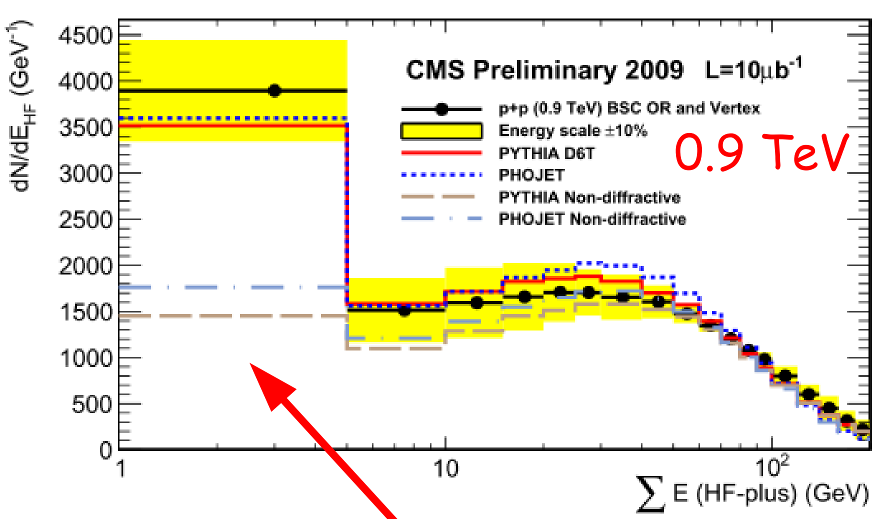
Observation of diffraction

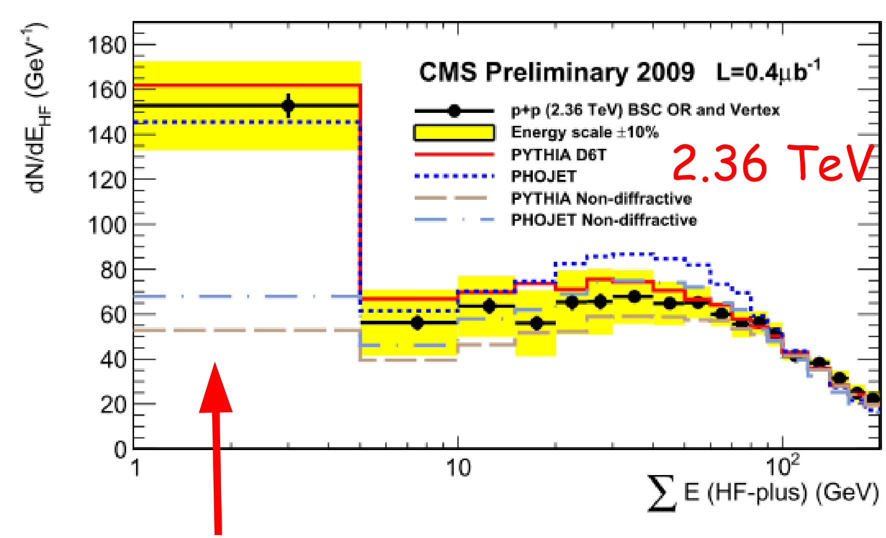
Comparison with PYTHIA-6 (D6T tune) and PHOJET





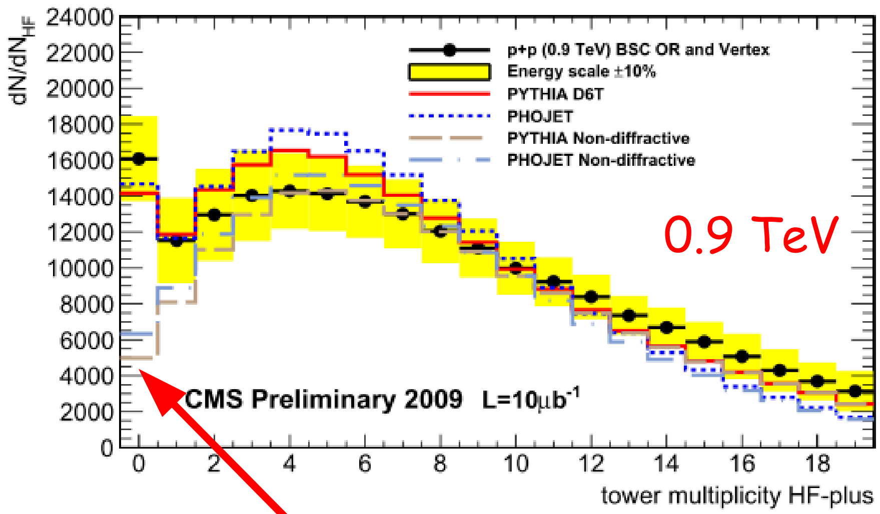
Clear sign of diffraction at both energies, in agreement with PYTHIA and PHOJET

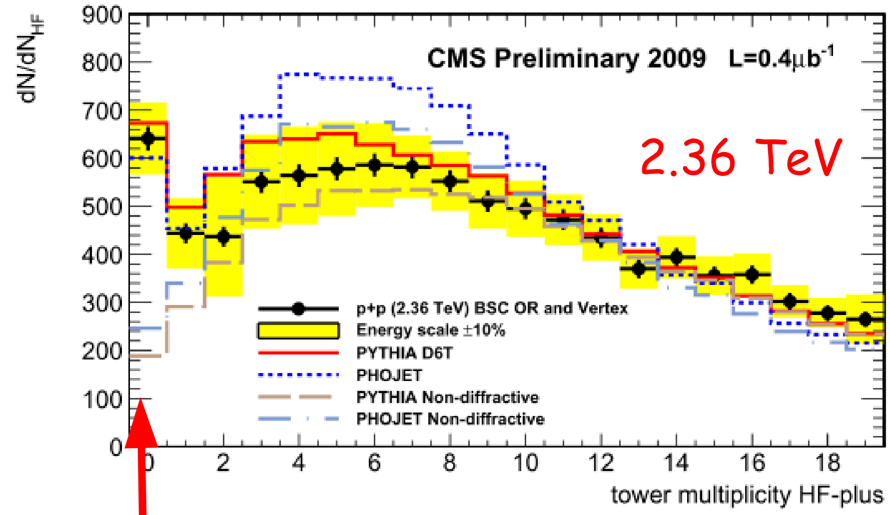




Rapidity gap extending over HF(plus)

Observation of diffraction





Rapidity gap extending over HF(plus)

Both – PYTHIA and PHOJET describes well inclusive spectra

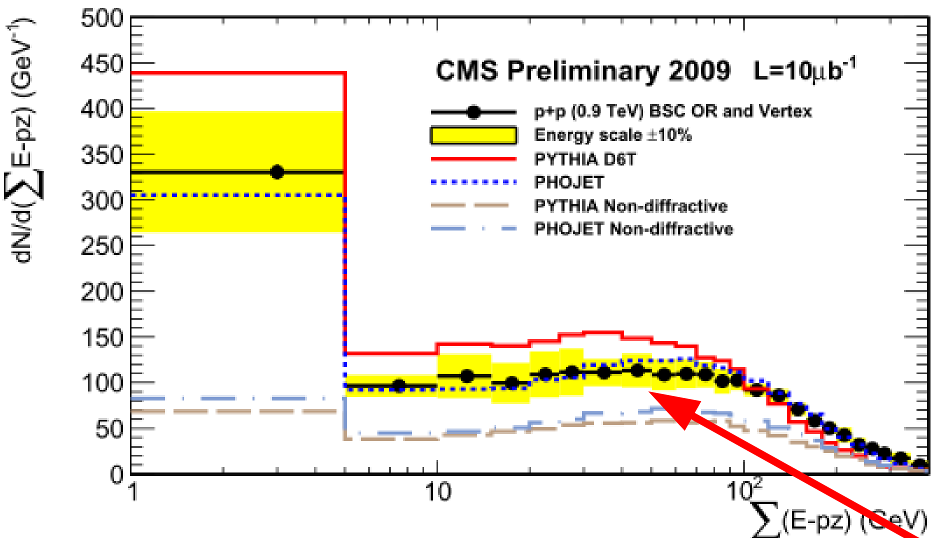
PYTHIA describes better higher-energy (non-diffractive) part of spectrum

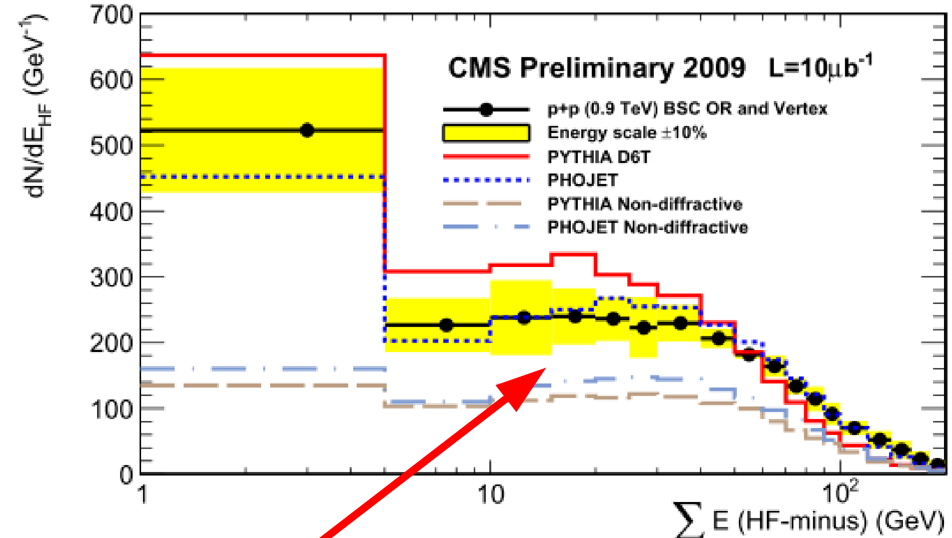
Enhancing diffractive component

Requirement: low activity at one side of HF calorimeter
→ SD component is enhanced in the Minimum Bias data

Test the SD diffractive component in Monte Carlo

$E_{HF(plus)} < 8$ GeV

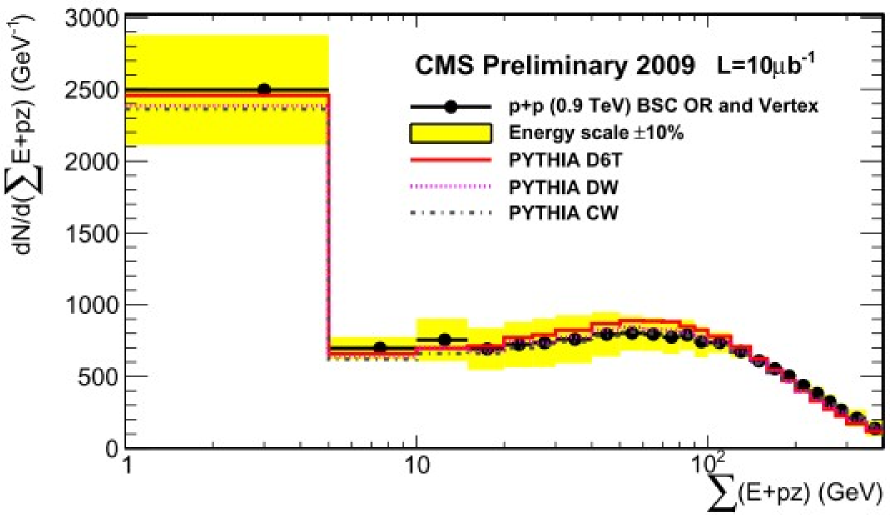


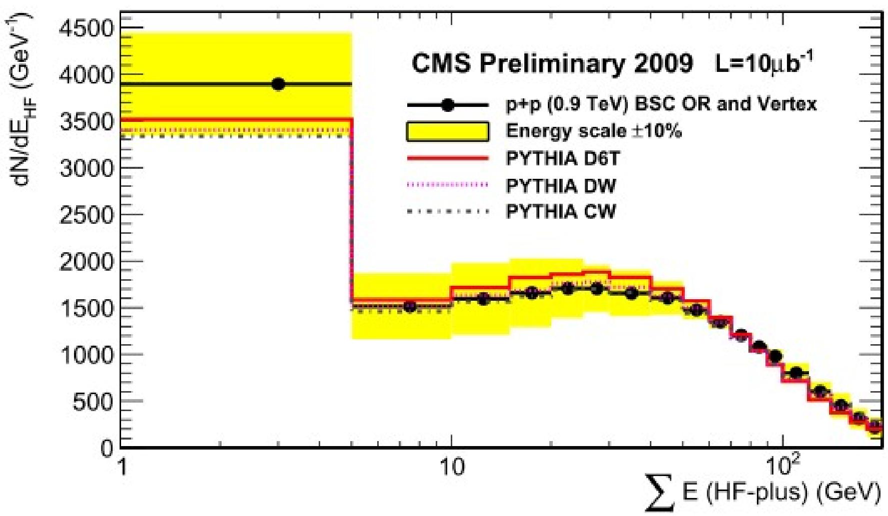


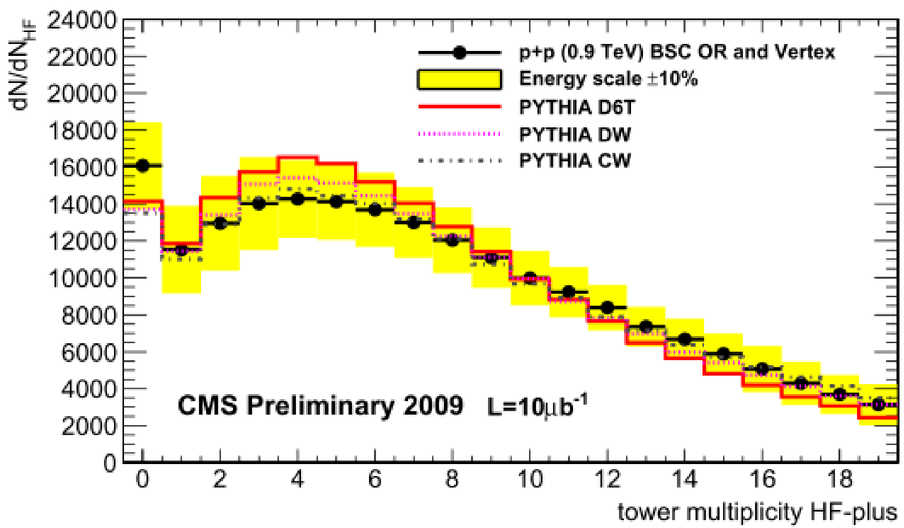
PHOJET agrees better with the data
→ especially for a high mass diffractive system
→ PYTHIA-6 shows a softer spectrum

Different UE tunes

Different PYTHIA tunes: DW and CW (comparison to D6T)





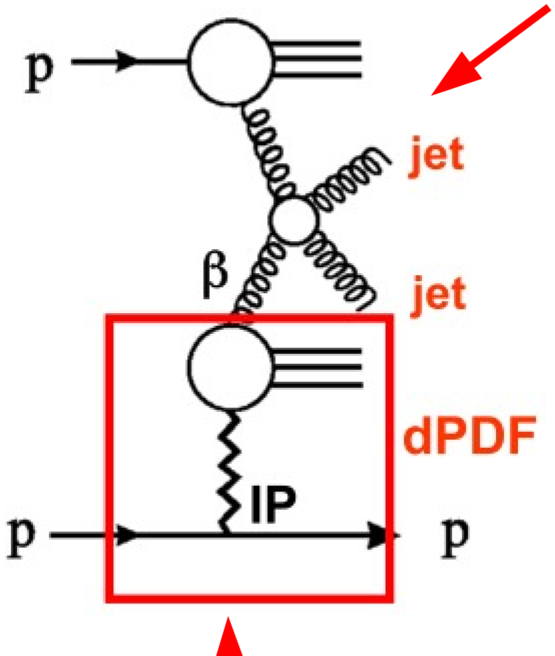


Given the present systematic uncertainties, the data cannot discriminate between tunes

Hard diffraction

Factorization:

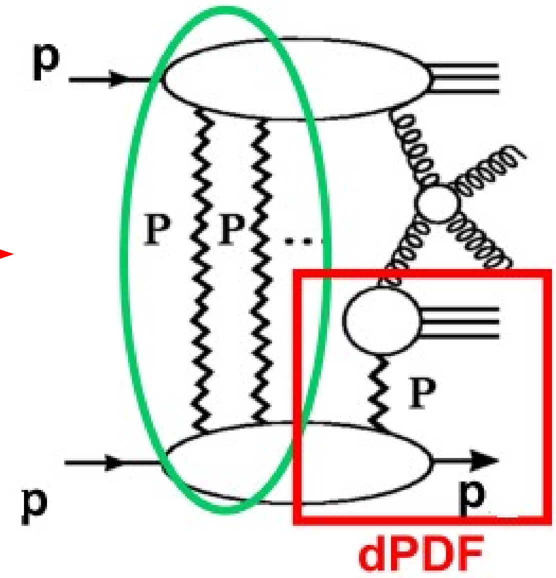
Hard scattering
(hard scale eg. jets)



Diffractive PDFs

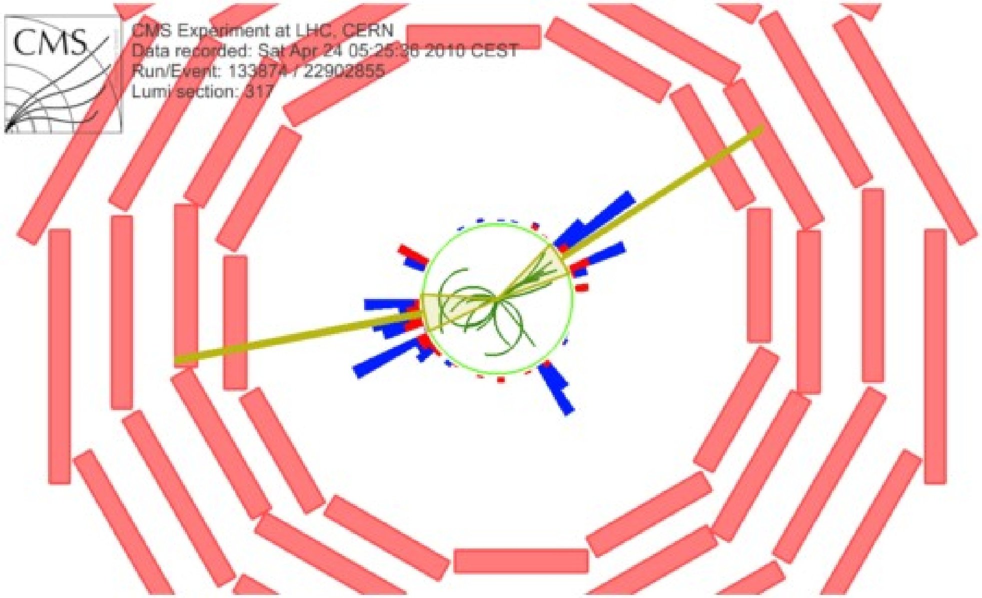
broken

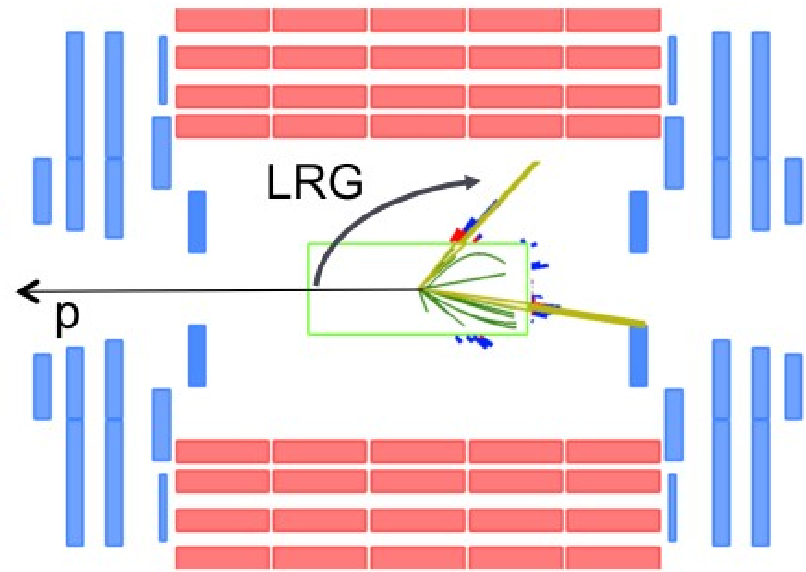
Soft interactions/rescatterings among spectator partons
- fill the rapidity gap
- suppress visible x-section

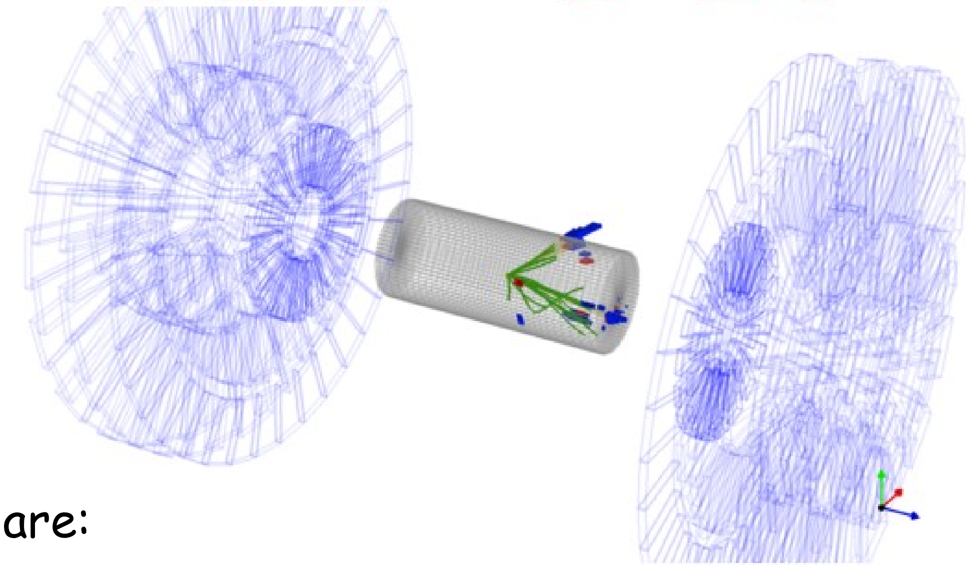


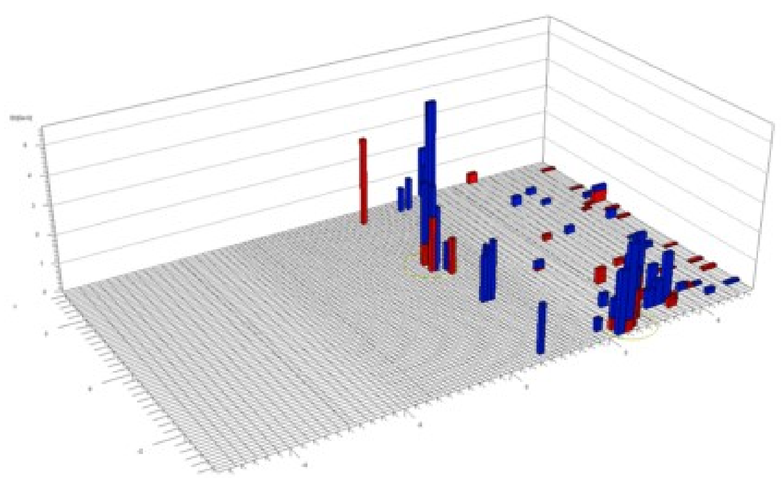
- At Tevatron suppresion of O(10%) with respect to HERA
- At LHC predictions between vary by order of magnitude
- An important measurement at early LHC

Hard diffraction









Visible are:

calotowers with η<3.0 and E>1.5 GeV

η>3.0 and E>2.0 GeV

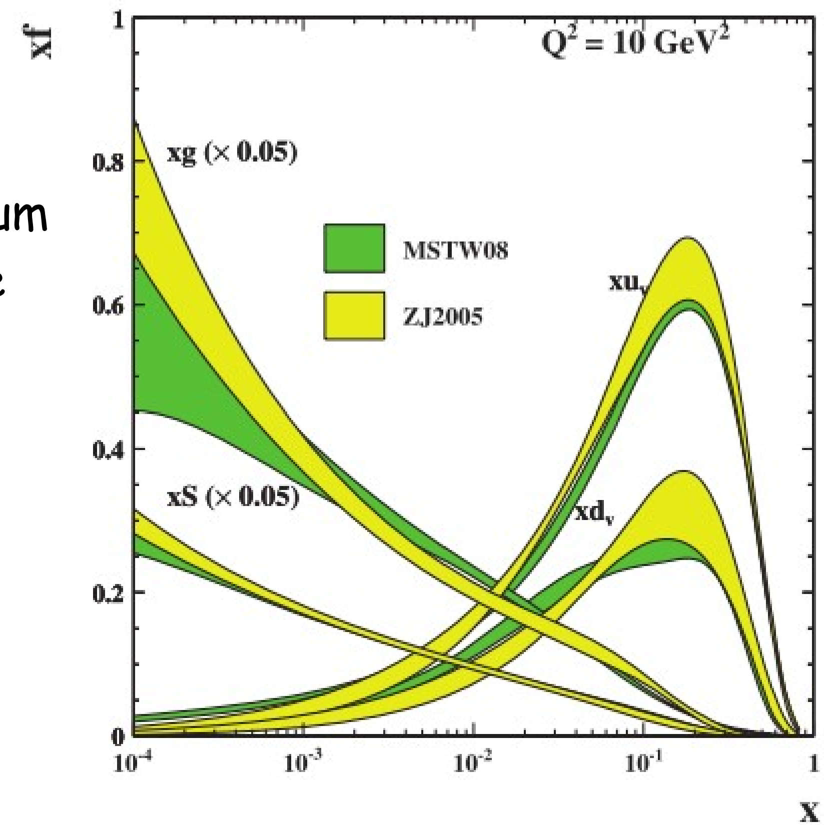
tracks with pT>0.5 GeV

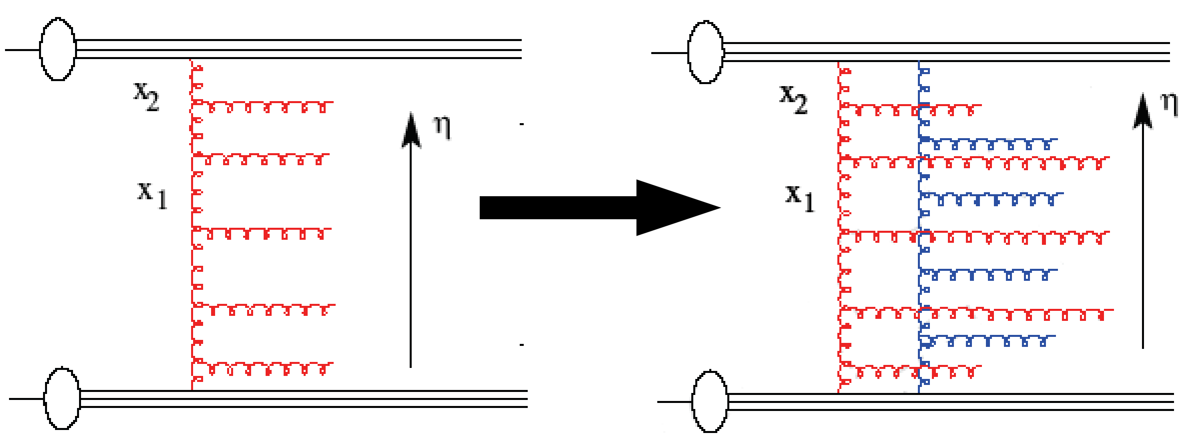
p_T(jet1) = 43.5 GeV η(jet1) = 0.83

p_T(jet2) = 36.9 GeV η(jet1) = 2.55

Energy flow in the forward region

- A logical step before going to jets studies
  - but also a meaningful, new physics result
- At very large centre of mass energies, the momentum fraction of the proton carried by the partons in the hard scattering (x_1, x_2) can become very small and the parton densities become very large.
- Probability for more than one partonic interaction per event increases.
- This approach is described in the models of multiparton interactions.
- Models implemented in Monte Carlo event generators need parameters to be adjusted to describe the measurement.
- Parameters tuned to data from Tevatron ($|\eta|<3$).





Energy flow in the forward region

- Measurement done with Hadronic Forward calorimeter: **3.152 < |η| < 4.903**
- Plans: extend it to CASTOR and to ZDC
- Three different cms energies included: 900 GeV, 2360 GeV, 7000 GeV
- The measurement done at the detector level – no factors correcting it to the hadron level applied
- A comparison with the Monte Carlo generators predictions at the detector level

- Distributions studied:

$$E_{FLOW}(dijet)=\frac{1}{N_{dijet}}\frac{\Delta E}{\Delta\eta}(dijet)$$

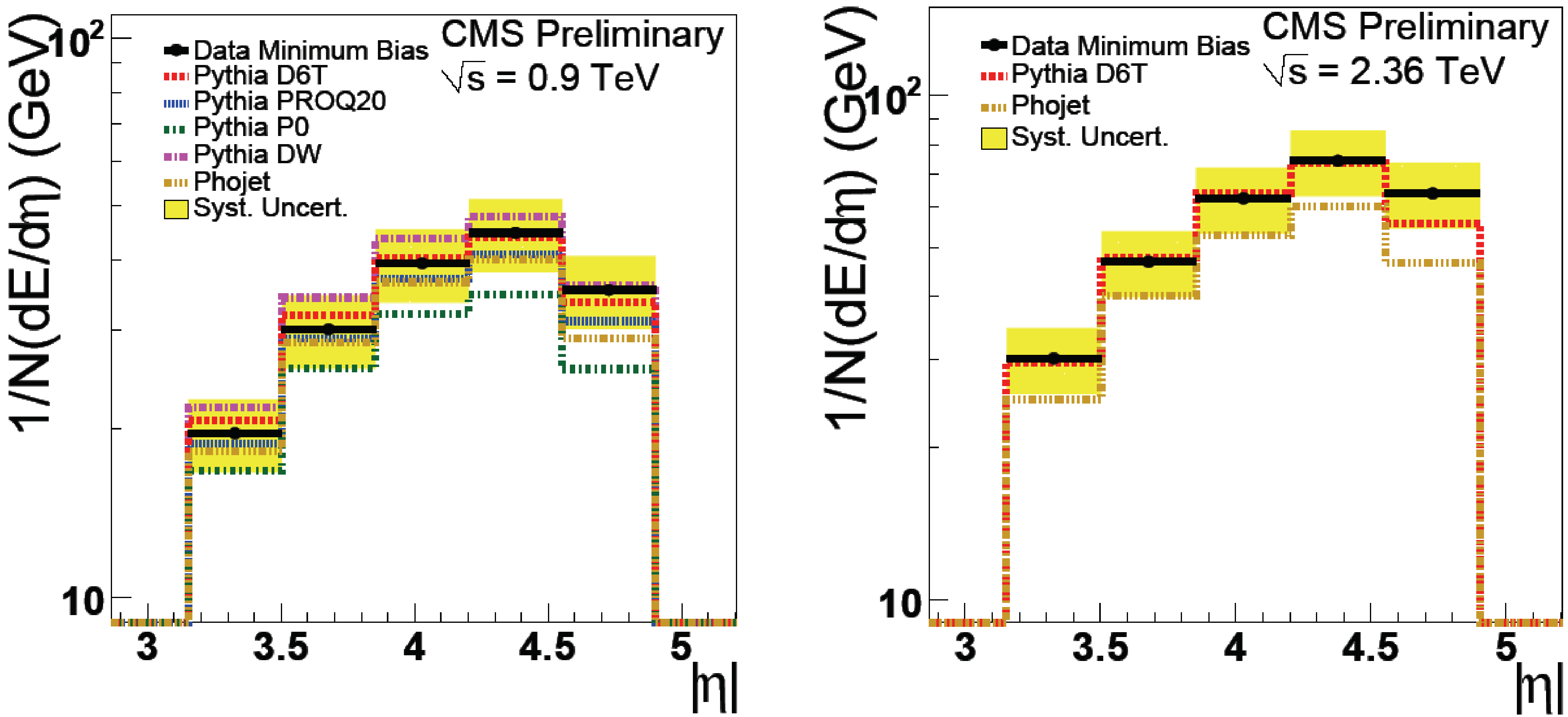
$$E_{FLOW}(minbias)=\frac{1}{N_{minbias}}\frac{\Delta E}{\Delta\eta}(minbias)$$

- Definition of Minimum Bias sample: all events trigger with MB trigger: activity at both sides of IP (coincidence between BSC) + vertex reconstructed
- Definition of Dijet sample: for 900/2360 GeV p_T>8 GeV, for 7000 GeV p_T>20 GeV, **|η|<2.5**

√s	900 GeV	2.36 TeV	7 TeV
MB sample	177475	10245	3713294
Dijet sample	433	86	4292

Energy flow in the forward region

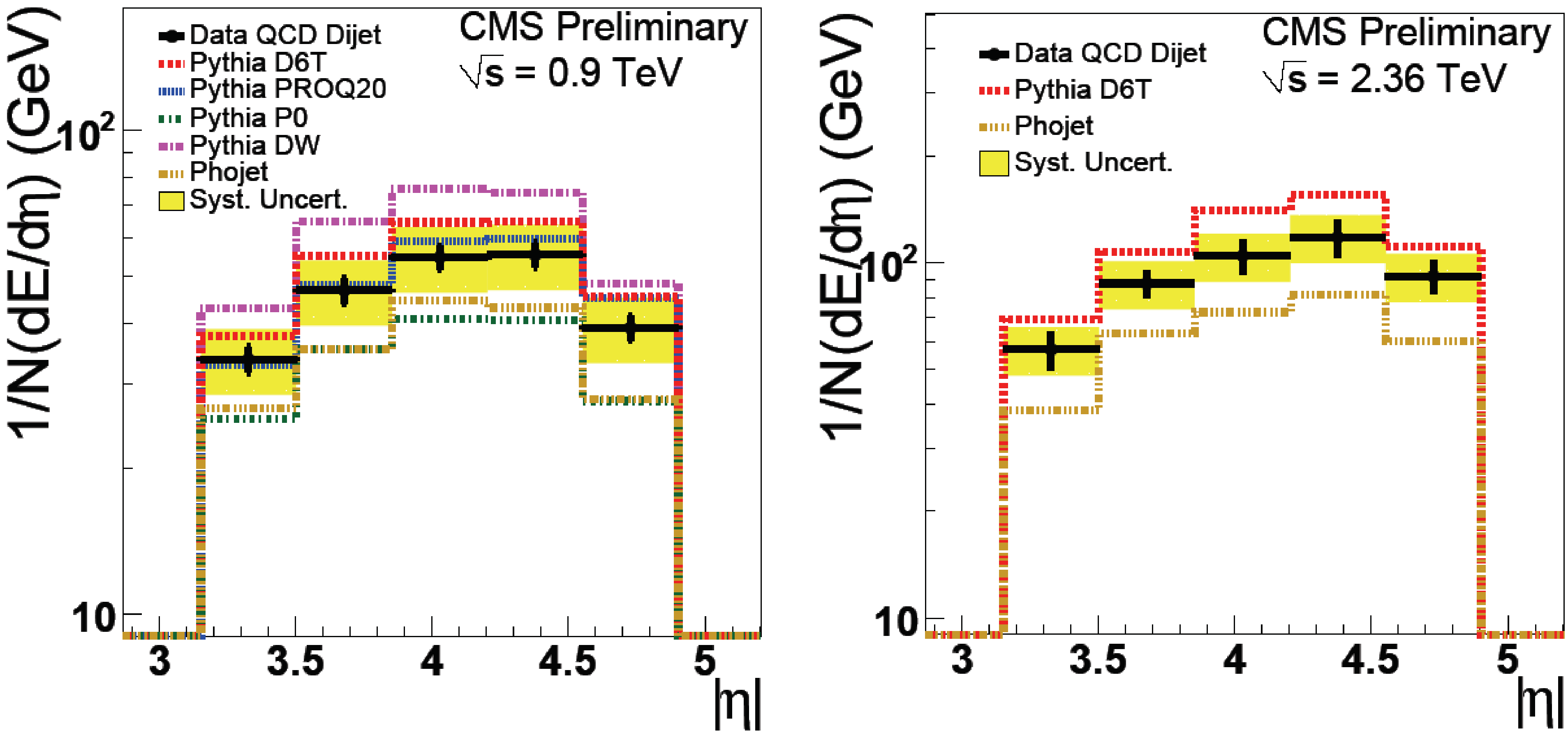
Energy flow in the Minimum Bias sample at 900/2360 GeV:



At 900 GeV the energy flow in minimum bias events is best described by the D6T tune, whereas the PROQ20, P0 tune and PHOJET is lower than the measurement.

Energy flow in the forward region

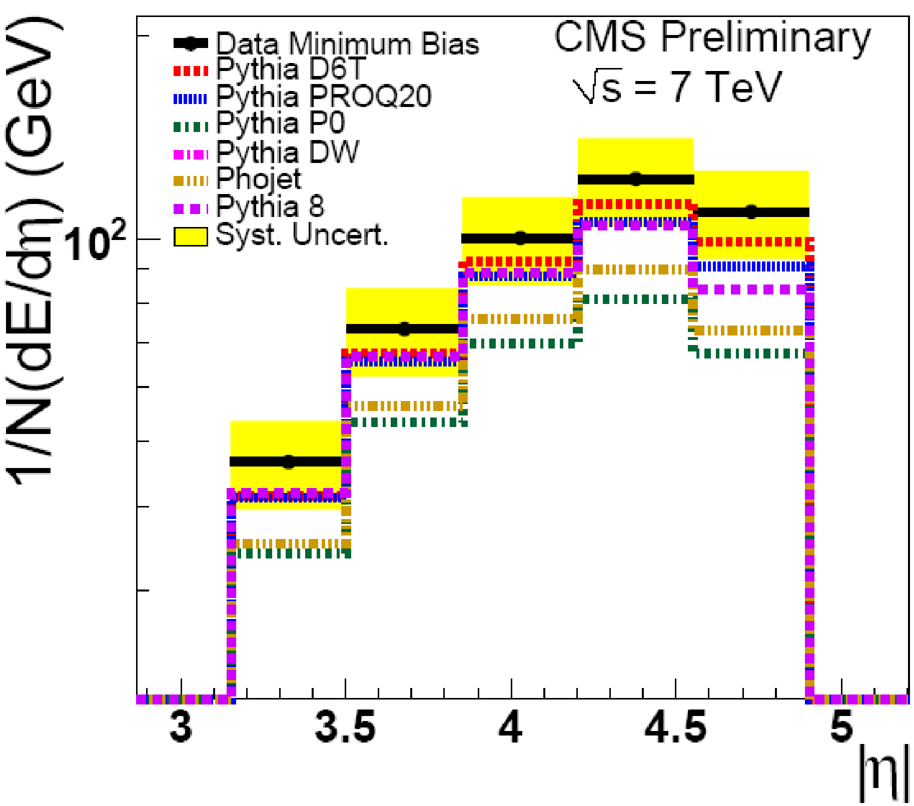
Energy flow in the Dijet sample at 900/2360 GeV:

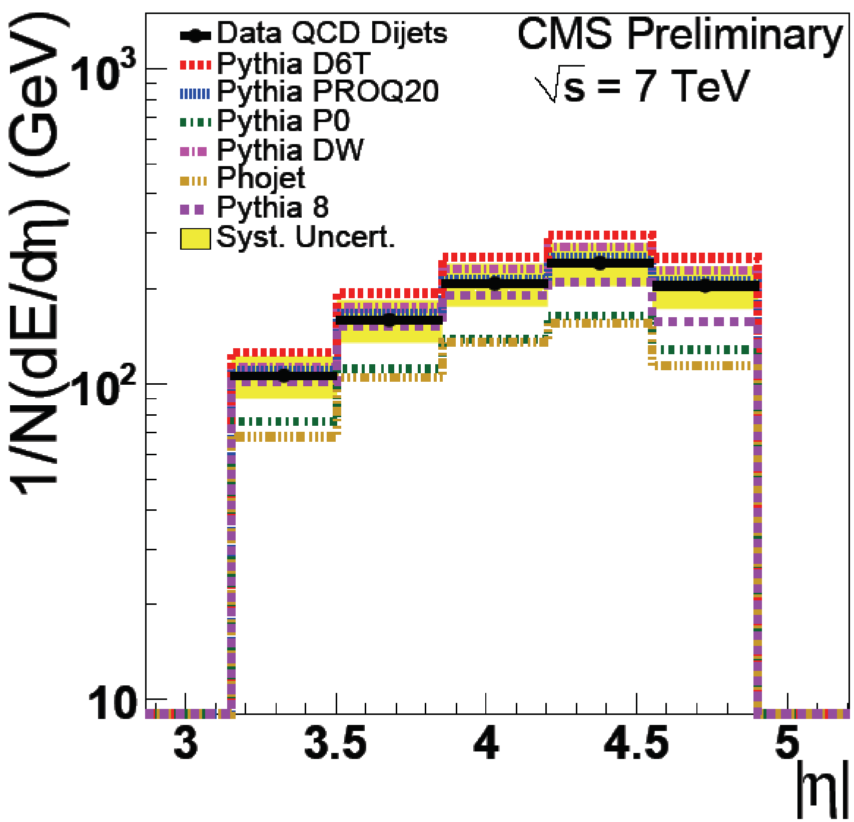


In dijet events the increase of energy flow with increasing centre-of-mass energy is reproduced by the simulations. Here, the D6T tune predicts too high energy flow, whereas the PROQ20 tune is best and the P0 tune and PHOJET is too low.

Energy flow in the forward region

Energy flow in the MB and Dijet samples at 7000 GeV:

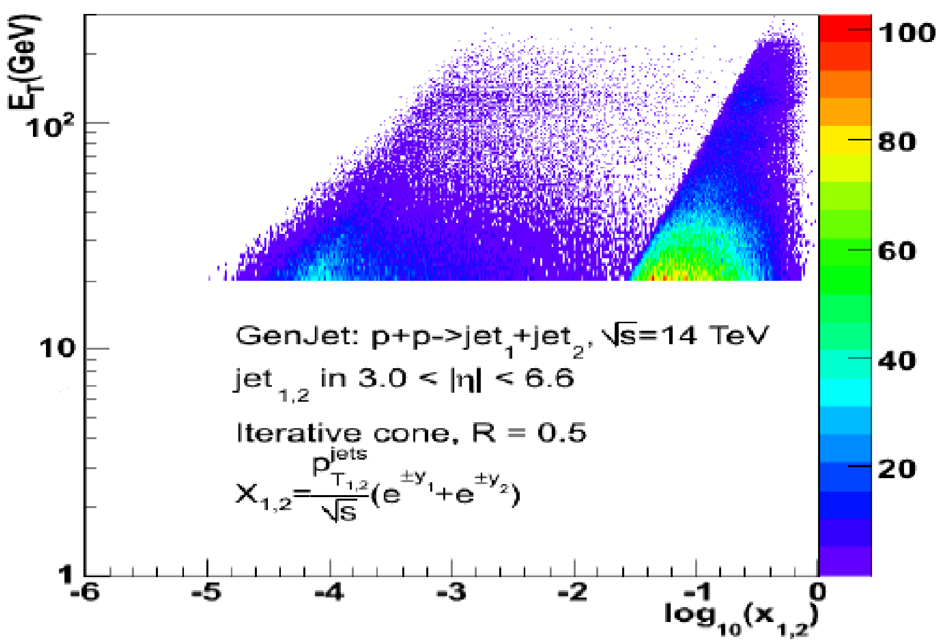




- At 7000 GeV the predicted energy flow in minimum bias events is below the measurement for all tunes, the prediction of PYTHIA8 is similar to the tune PROQ20.
- For dijet sample D6T tune predicts too high energy flow, whereas the PROQ20 tune and PYTHIA8 are best and the P0 tune and PHOJET is too low.

Jets in forward region

- Jets productions has never been investigated in such a forward region as the one covered by CMS HF calorimeter
- First measurement of forward jets in $3.2<|\eta|<4.7$
- Forward jets probe low x region
- First step: validate the jets reconstruction in the forward region
- Trigger selection → BSC coincidence
- Integrated luminosity 10 nb^{-1}



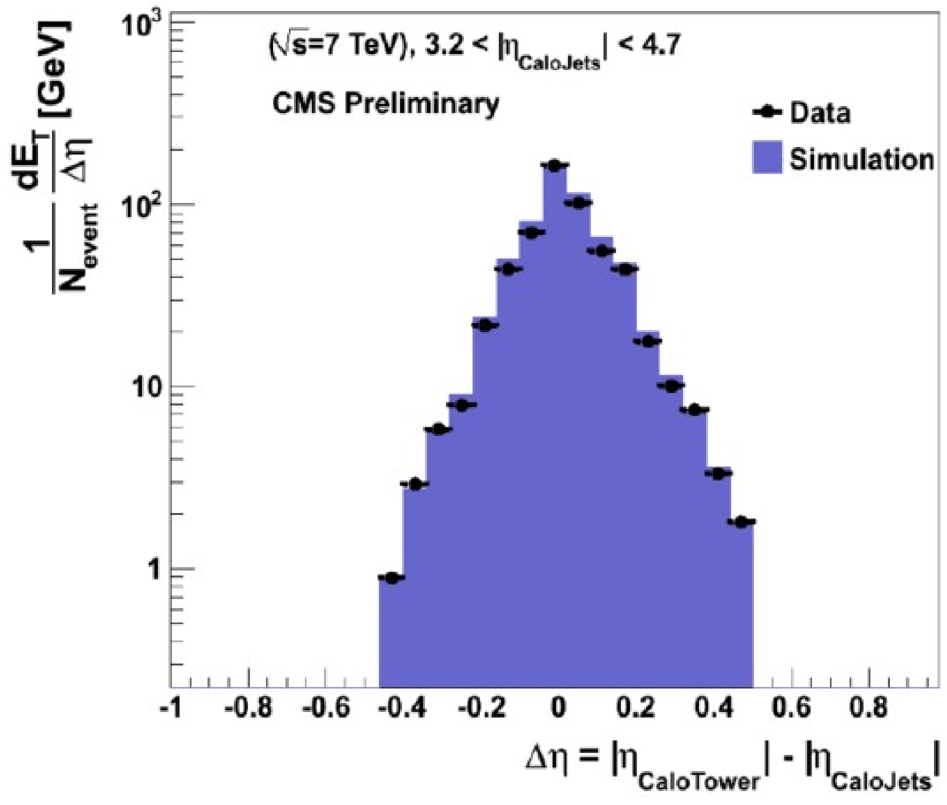
(PYTHIA default PDF: CTEQ5L)

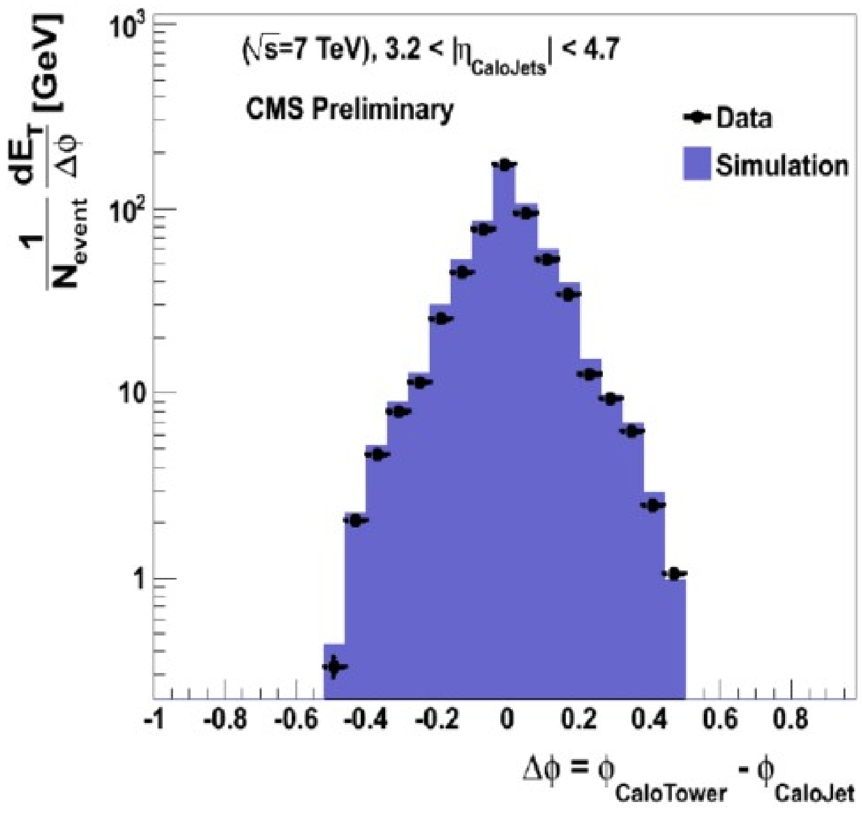
- Jets reconstructed with anti-kT (R=0.5) algorithm
- $35<E_T<120$ GeV (energy corrected for detector effects)

Jets in forward region

- Transverse energy E_T flow inside jet cone – size and shape of calorimeter jets in the forward region
- Test of the description of data by MC – PYTHIA-6 D6T

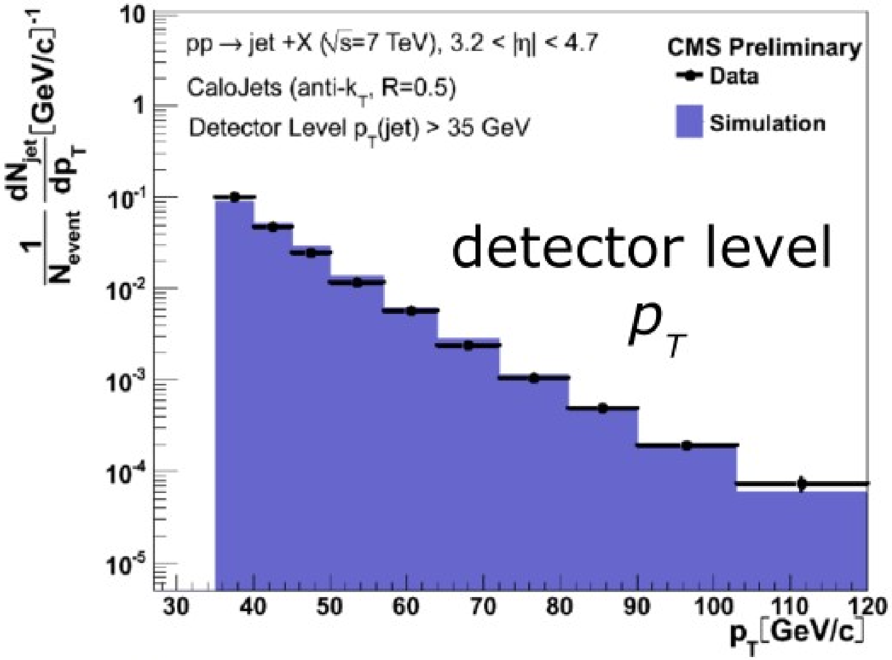
→ transverse energy flow well described by MC

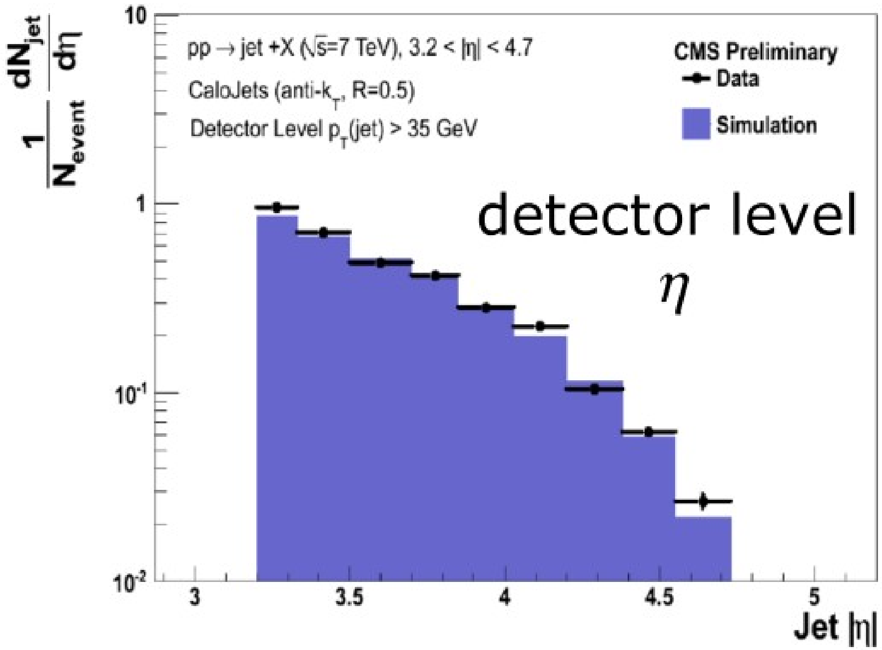




Jets in forward region

- p_T and η distributions at the detector level
- No unfolding back to hadron level applied
- No systematic uncertainty taken into account
- Fair agreement between the the data and PYTHIA-6 D6T tune

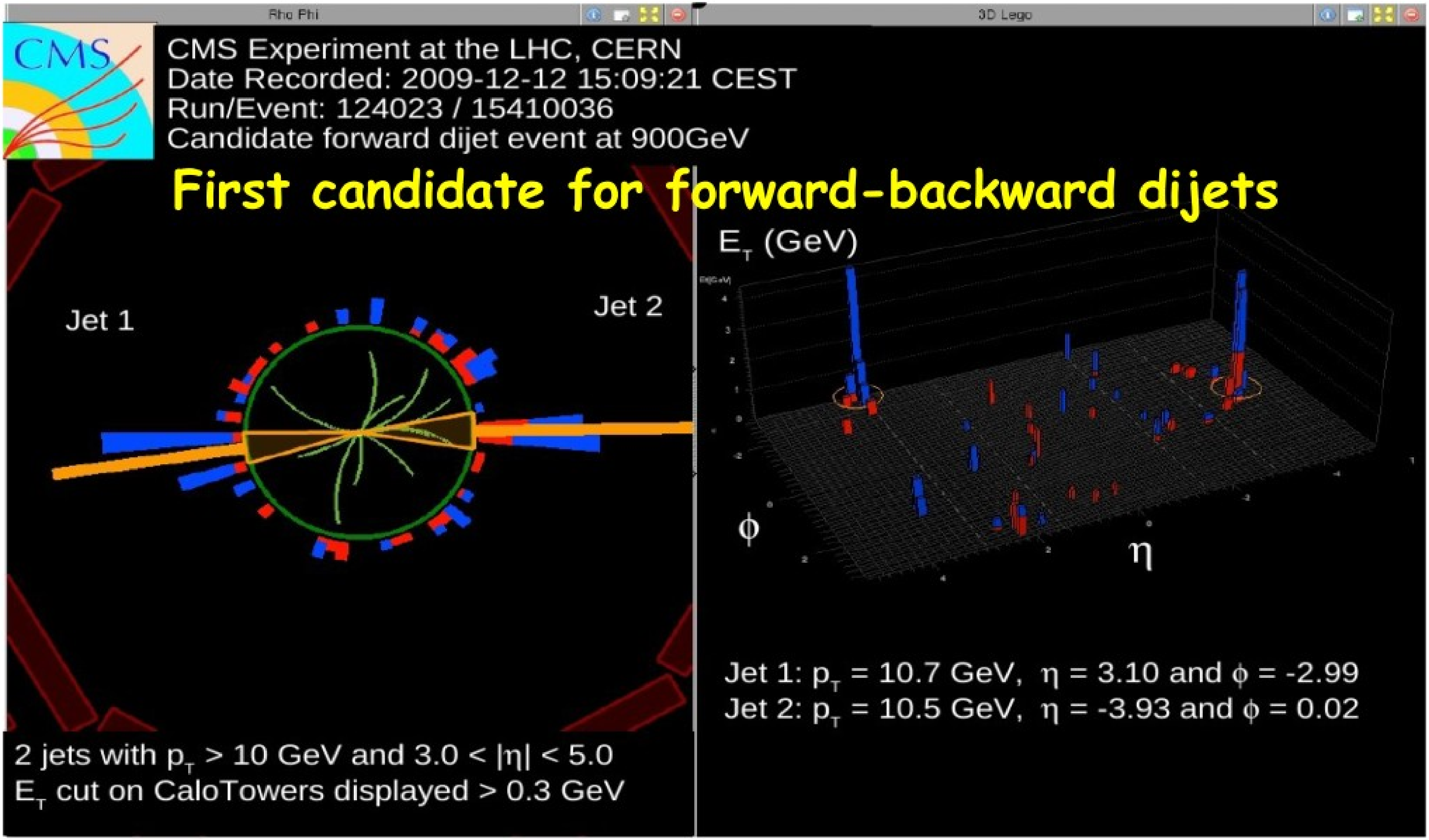




- Expected resolutions from MC:
  - $\sigma(p_T)/p_T$ ~ 15 % at 20 GeV, ~ 12 % at 100 GeV
  - $\sigma(\Delta\eta), \sigma(\Delta\varphi)$ ~ 0.035 at 20 GeV, ~ 0.025 at 100 GeV

Jets in forward region

First pairs of jets with large rapidity interval in-between observed (MN dijets)



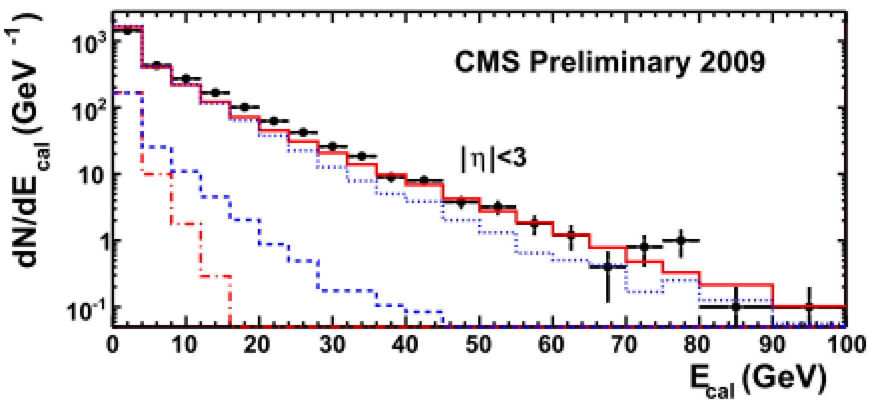
Conclusions

- Rediscovery of diffraction in the CMS minimum bias data: 0.9 and 2.36 TeV
- Fair agreement with the Monte Carlo models predictions
- First observation of diffractive events with a hard scale set by jets
- First measurement of the energy flow in $3.2<|\eta|<4.9$ for Minimum Bias sample and for events with a hard scale set by central jets
- None of the MC can describe the energy flow in all aspects, at 7 TeV the energy flow is larger than in any MC predictions
- First measurement of the jets in the $3.2<|\eta|<4.7$ range → validation of the forward jets reconstruction
- First measurement at 0.9, 2.36 and 7 TeV show very good performance of the CMS detector, especially its main forward calorimeter - HF

Spares

Control plots

2.36 TeV



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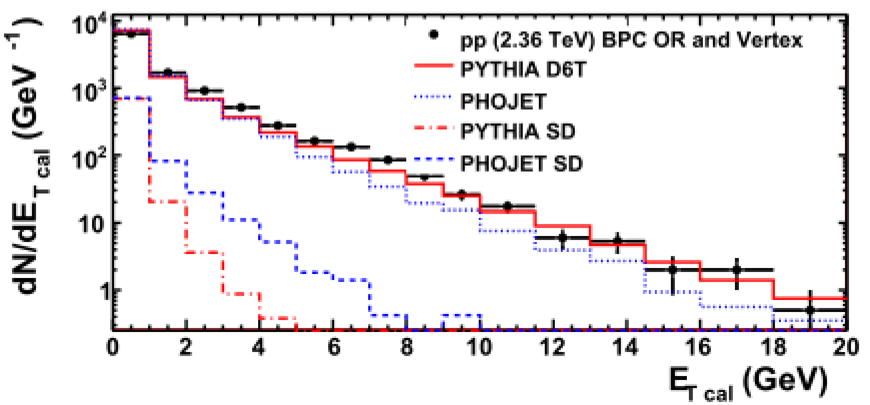
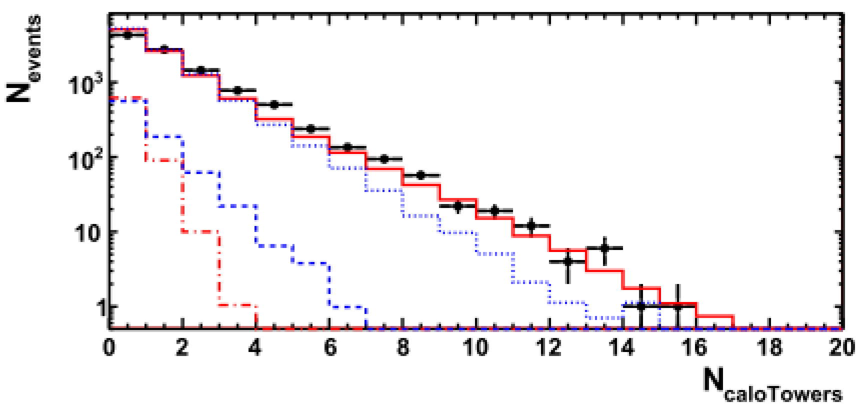


Transverse energy distribution in calotowers in central CMS calorimeters (excl. HF)



Multiplicity of calotowers in central CMS calorimeters (excl. HF) , treshold of 3 GeV

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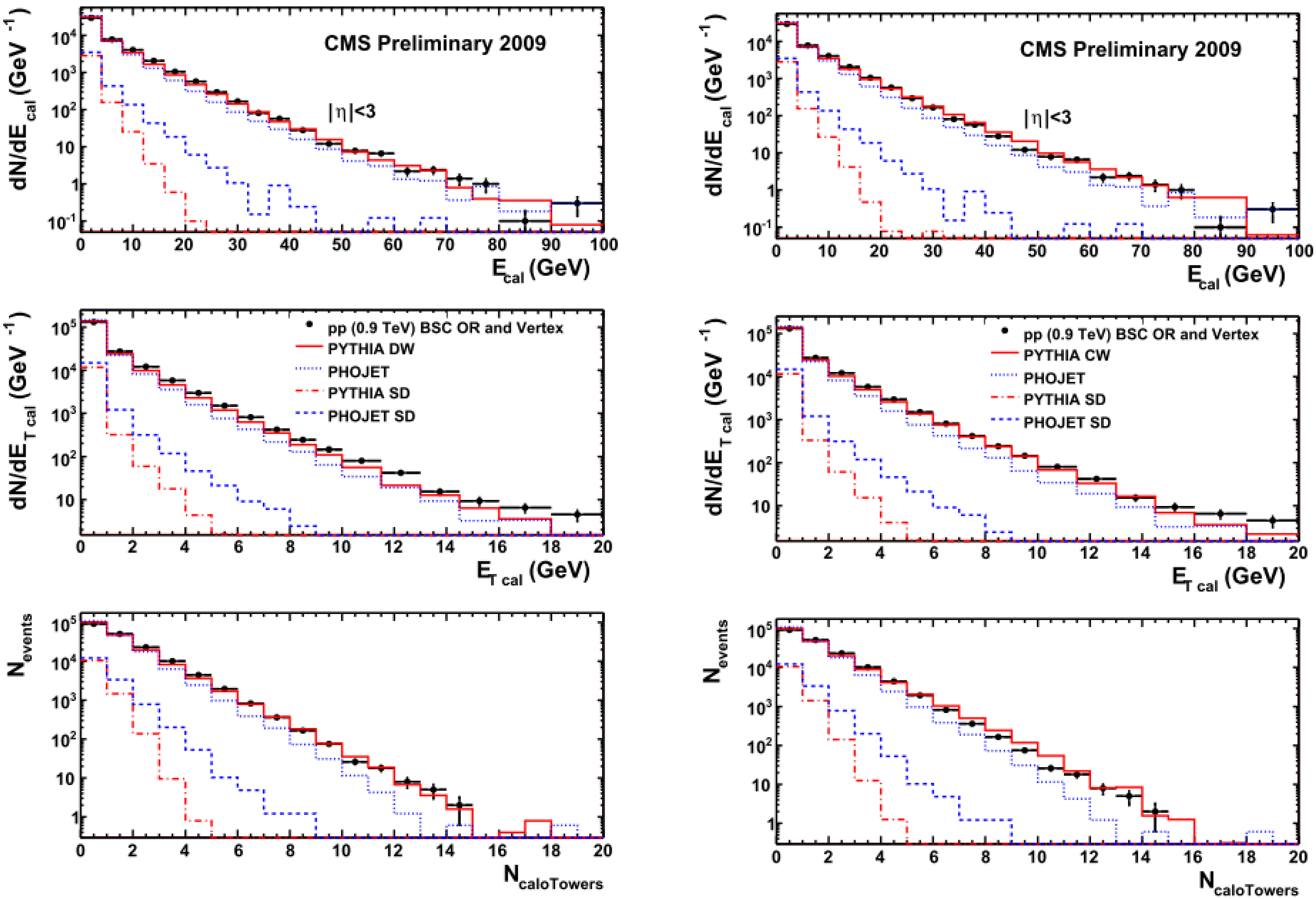
MC normalised to data

Control plots (tunes)



Tunes

- MPI model included in PYTHIA. The parameters of the model can be tuned – different sets of parameter values define different tunes.
- Avoid differgences in hard scattering and MPI: $$\frac{1}{p_T^4} \rightarrow \frac{1}{(p_T^2 + p_{T0}^2)^2}$$
- Where p_{T0} is parametrized: $$p_{T0}(\sqrt{s}) = p_{T0}(\sqrt{s_0})\left(\frac{\sqrt{s}}{\sqrt{s_0}}\right)^{\epsilon}$$
- Different pdfs, cuts for ISR and FSR, fragmentation model

		D6T (108)	DW (103)	Pro-Q20 (129)	P0 (320)
pdfs		CTEQ6L	CTEQ5L	CTEQ5L	CTEQ5L
p_{t0}	PARP(82)	1.84 GeV	1.9 GeV	1.9 GeV	2.0 GeV
E_0	PARP(89)	1.96 TeV	1.8 TeV	1.8 TeV	1.8 TeV
ϵ	PARP(90)	0.16	0.25	0.22	0.26
fragmentation	standard	standard	standard	professor LEP tune	professor LEP tune
Q^2_{max} factor (ISR)	PARP(67)	2.5	2.5	2.65	1.0
Q^2_{max} factor (FSR)	PARP(71)	4.0	4.0	4.0	2.0

Tunes

- Tunes of the PYTHIA generator (version 6.420): **D6T**, **DW**, **Perugia-0 (P0)**, **CW**
- **Pythia 8** (different model! only one tune along the lines of P0): version 8.135

PYTHIA **regularization** of the formal divergence of the leading order partonic scattering amplitude as the final state parton transverse momentum p_T approaches 0:

$$\begin{cases} 1/\hat{p}_T^{\,4} \to 1/(\hat{p}_T^{\,2}+\hat{p}_{T_0}^{\,2})^2 \\ \hat{p}_T(\sqrt{s}) = \hat{p}_{T_0}(\sqrt{s_0})\cdot(\sqrt{s}/\sqrt{s_0})^{\epsilon} \end{cases}$$

Regularization: can be interpreted as inverse of effective color screening length

energy dependence

Reference value: e.g. at CDF $\sqrt{s_0}=1.8\text{TeV}\,,\ \hat{p}_{T_0}=2.0\text{GeV}/c$

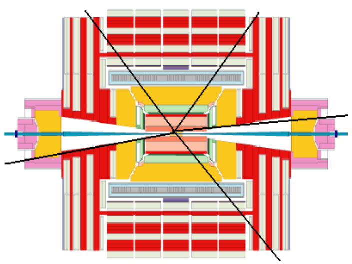
- Same parameter regularize **both MPI and hard scattering**: more MPI activity is predicted for smaller values of p_T^0

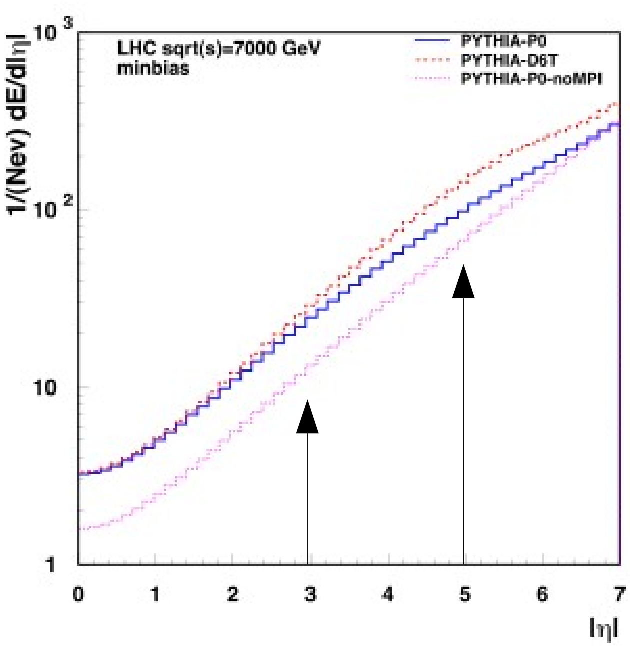
Tune	p_T^0(1.8TeV)	ϵ	details
D6T	**1.8 GeV/c**	**0.16**	**Consider ATLAS and LHCb studies on multiplicity at SPS; CTEQ6LL Parton distributions**
DW	1.9 GeV/c	0.25	Consider 630GeV & 1.8TeV CDF resultsCTEQ5L parton distributions
P0	**2 GeV/c**	**0.26**	**As above + New PYTHIA MPI model; PT ordered showers;**
CW	**1.8 GeV/c**	**0.3**	Ad hoc for 900GeV CMS data, maximizing MPI but still compatible with Tevatron; default PYTHIA color reconnection; Parton distributions CTEQ5L

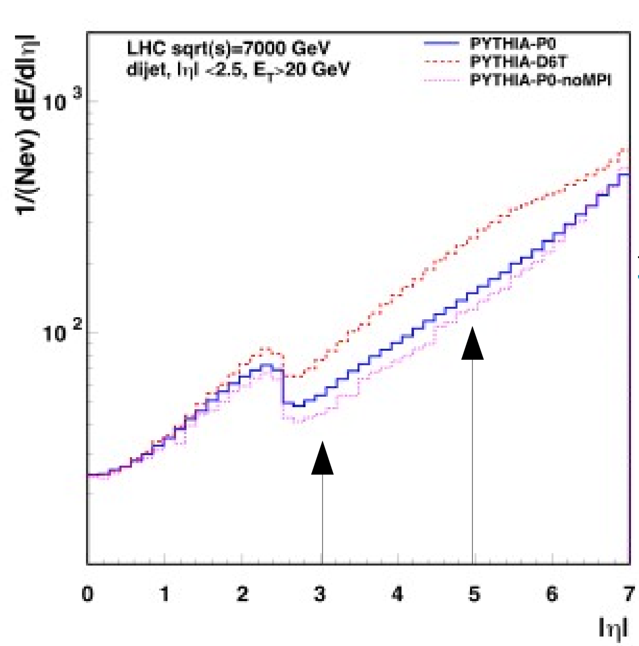
Energy flow in the forward region

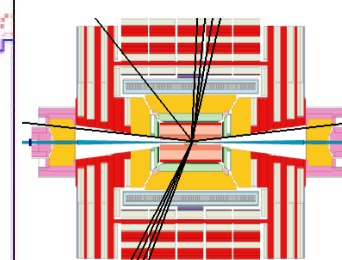
- The extrapolation of models to larger |η| is very uncertain, differences up to factors 5.
- The extrapolation of models to larger energies is also uncertain.
- Provide input to the determination of the parameters for the multiparton interaction models.

Predictions at generator level for two samples and for two Pythia6 tunes with MPI and no-MPI scenario









Energy flow in the forward region

Systematic effects on the measurement:

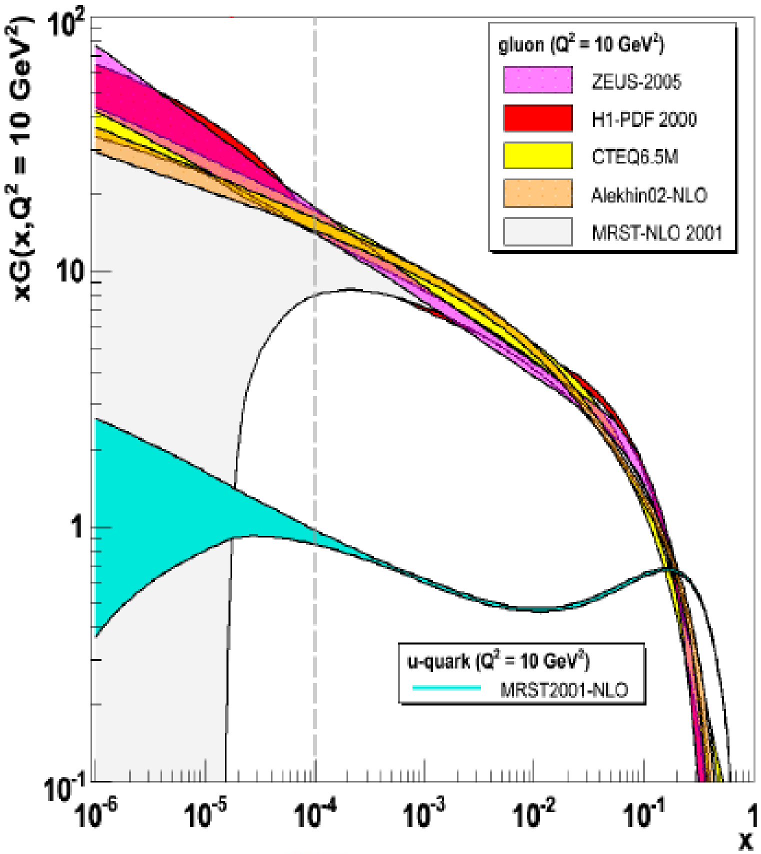
- Energy scale of HF (calibration → 15% - will improve in future)
- Position of interaction vertex
- Direct PMT hits → 3%
- Remaining noises in HF CaloTowers
- Random channel-by-channel miscalibration
- No beam-beam interactions

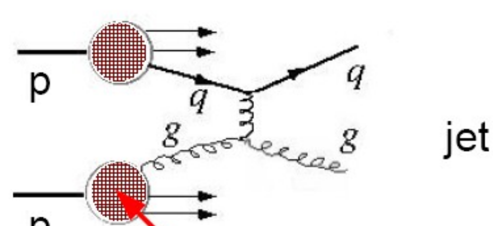
} Negligible with comparison to HF energy scale

Effect	Minimum bias sample	Dijet sample
Energy scale	15%	15%
Primary vertex z position	1%	1%
Photomultiplier hits	3%	3%
Energy deposit cut in calorimeter towers	2%	2%
Channel-by-channel miscalibration	1%	1%
Total	15%	15%

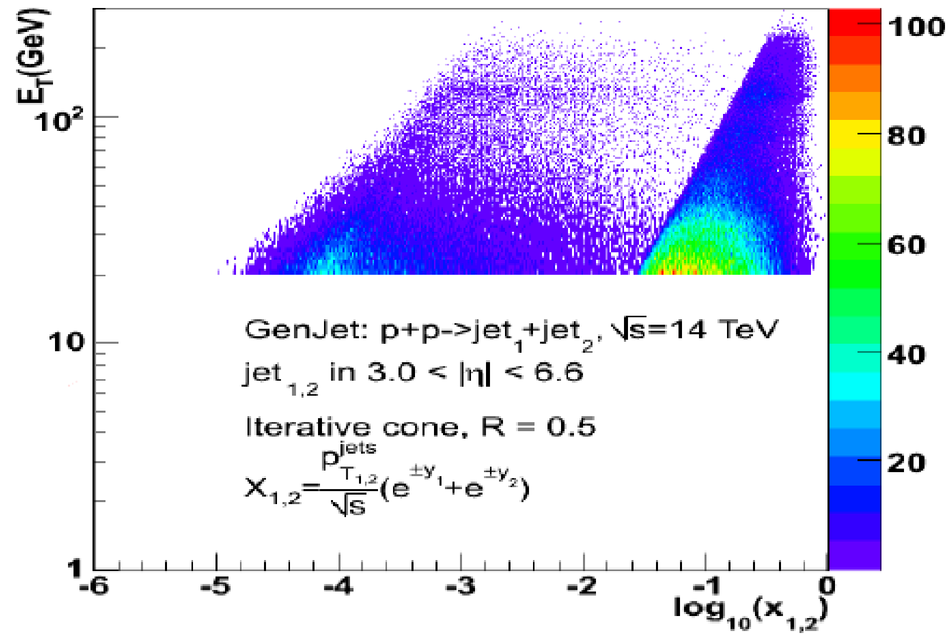
Forward Jets at CMS

Small x gluon density poorly constrained:

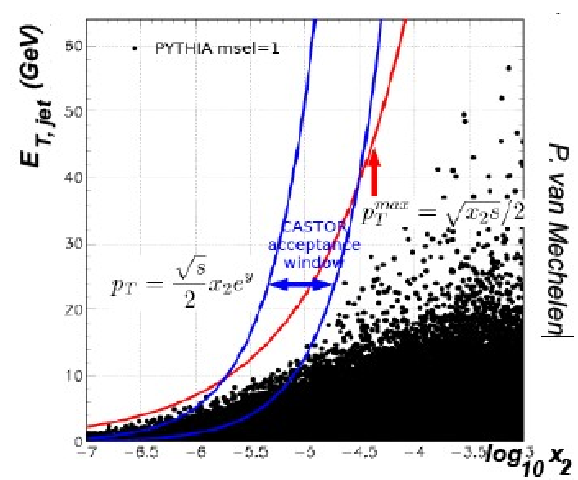




dσ(pp->jet)=PDF(x_1,Q^2)⊗PDF(x_2,Q^2)⊗dσ(qg->jet)



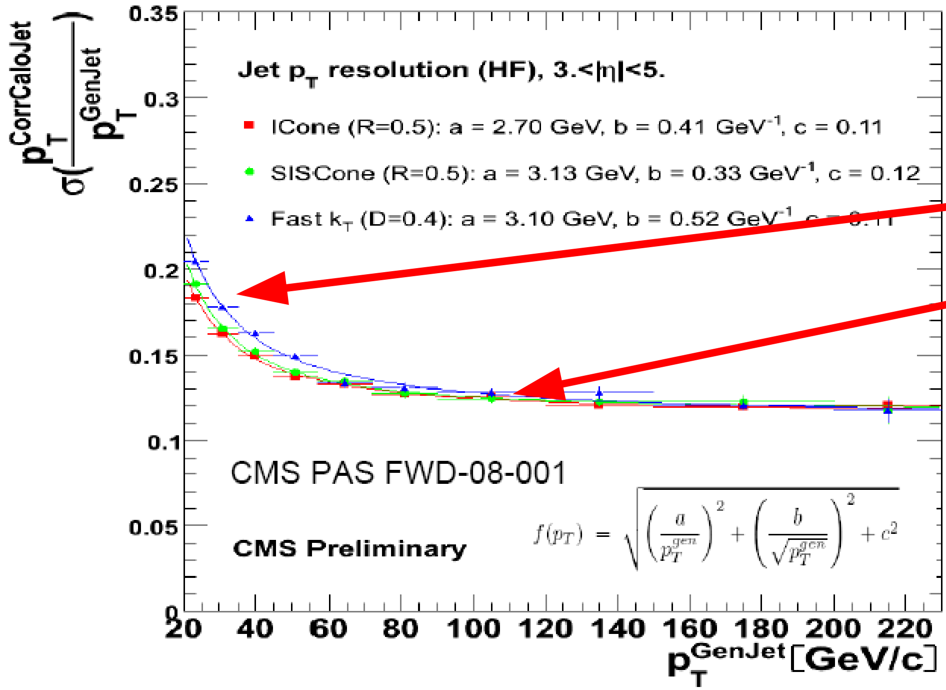
(PYTHIA default PDF: CTEQ5L)



Studies done with MC for 14 TeV

Forward Jets at CMS

Studies done with MC for 14 TeV



p_T resolution:

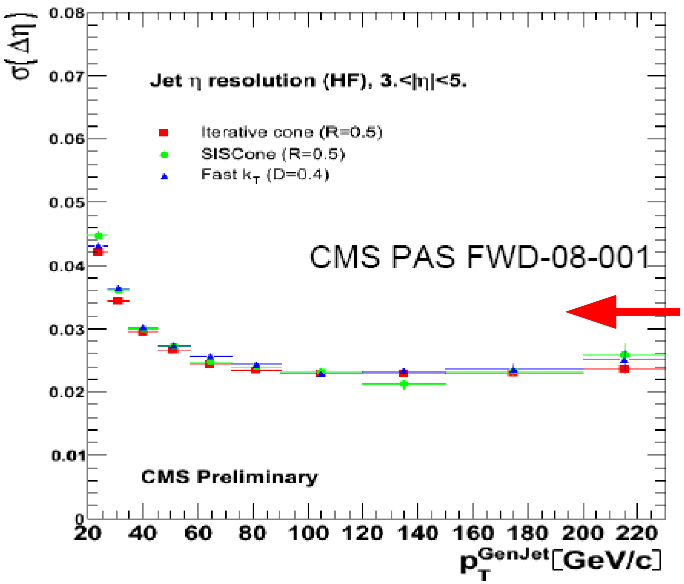
~20% for p_T~20 GeV

~12% for p_T>100 GeV

φ resolution:

~0.05 for p_T~20 GeV

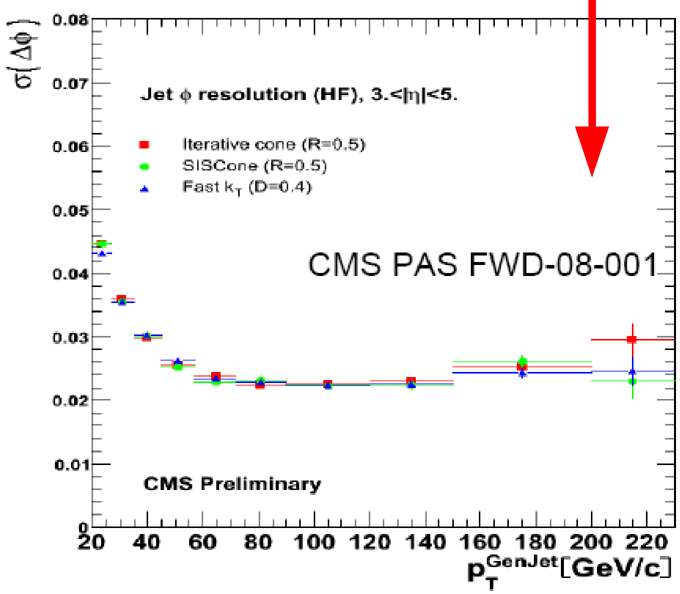
~0.02 for p_T>100 GeV



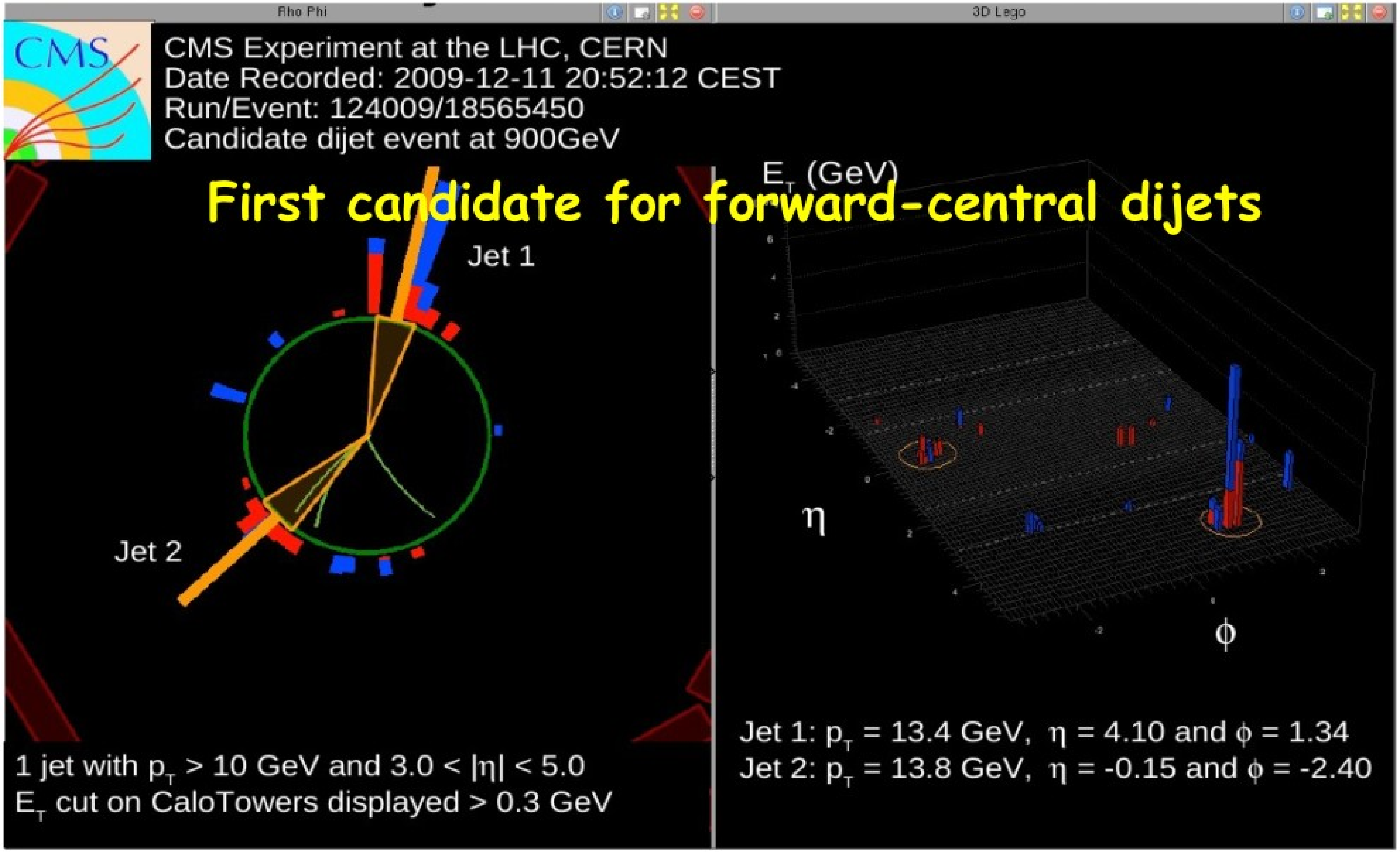
η resolution:

~0.05 for p_T~20 GeV

~0.02 for p_T>100 GeV

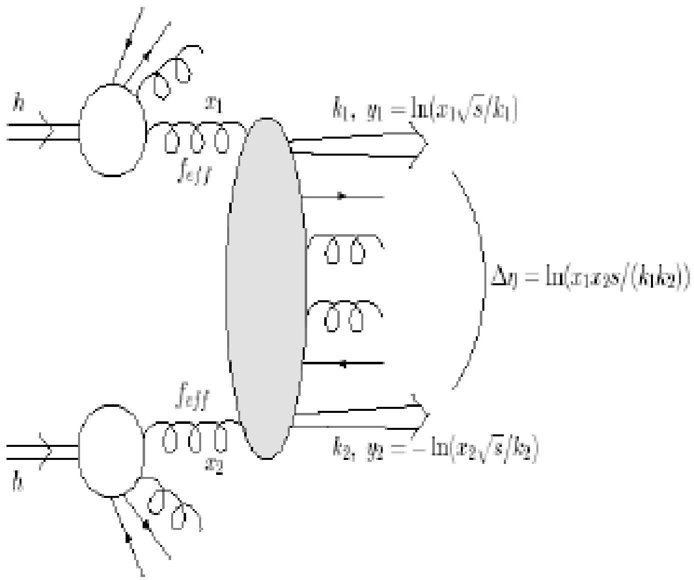


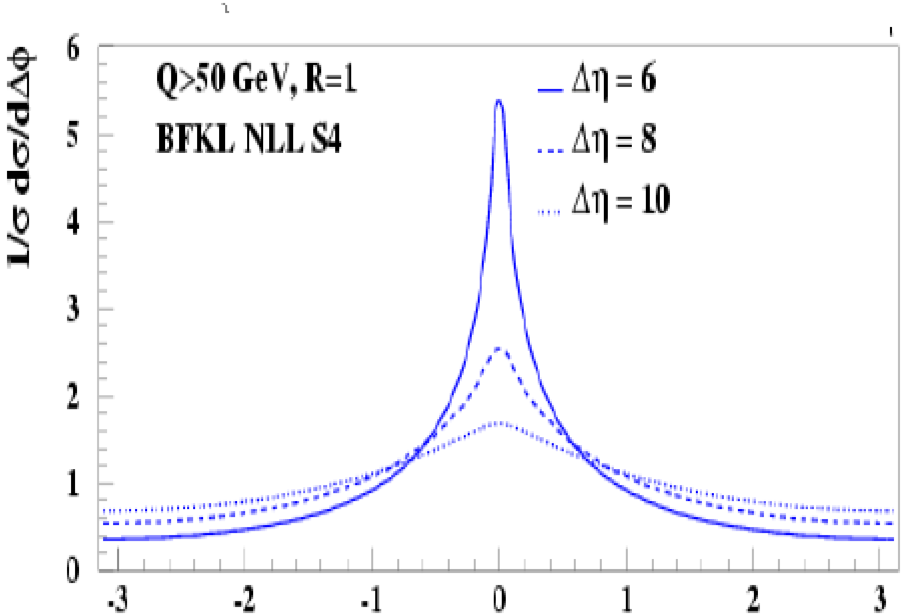
First Forward Jets from CMS



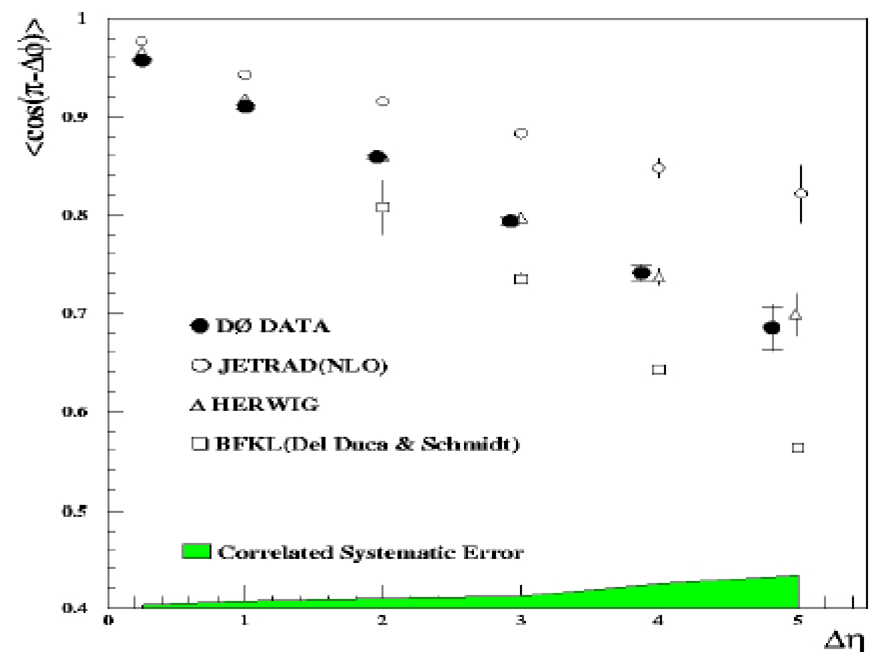
Jets correlations

- Mueller-Navelet dijets → large Δη separation
- Testing BFKL evolution
- Extra radiation between two jets will smear back-to-back correlation
- 6-10 units in Δη for HF





[A.Sabio-Vera, F.Schwennsen]
[C.Marquet, Royon]



S. Abachi et al. [DO Collaboration]
Phys. Rev. Lett. 77, 595 (1996).

A new CMS trigger will select dijet events with large Δη

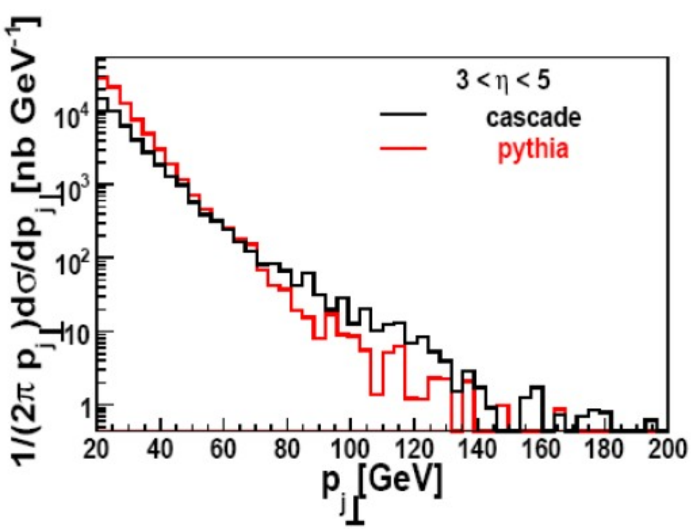
Jets correlations

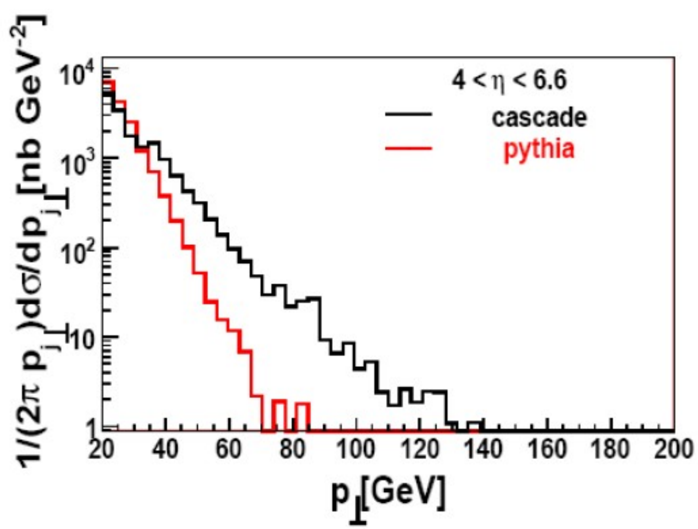
Other possible observables:

1. Dijet K-factor = inclusive dijet / "exclusive" dijet
Inclusive dijet V.Kim & G. Pivovarov (96-98)
Most forward/backward dijet A.Mueller & H.Navelet (87)

2.

Central jet	Forward jet	Central jet	Forward jet
$\lvert y_j \rvert < 2$	$3 < y_j < 5$	$\lvert y_j \rvert < 2$	$4. < y_j < 6.6$
$p_{jt} > 20\mathrm{GeV}$	$p_{jt} > 20\mathrm{GeV}$	$p_{jt} > 20\mathrm{GeV}$	$p_{jt} > 20\mathrm{GeV}$

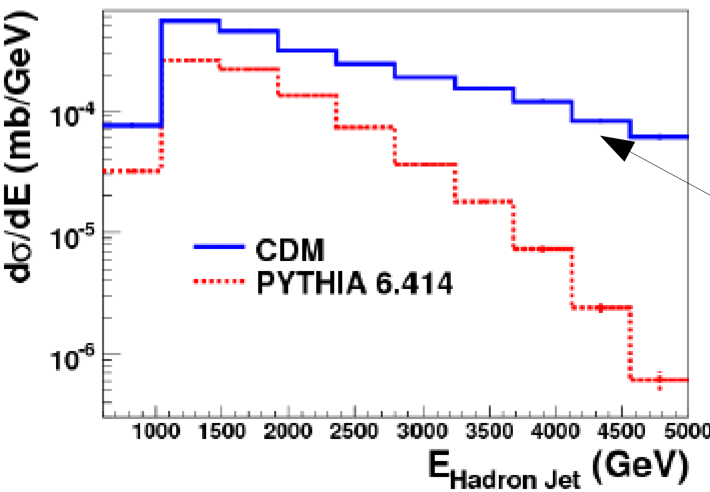




Jets with CASTOR

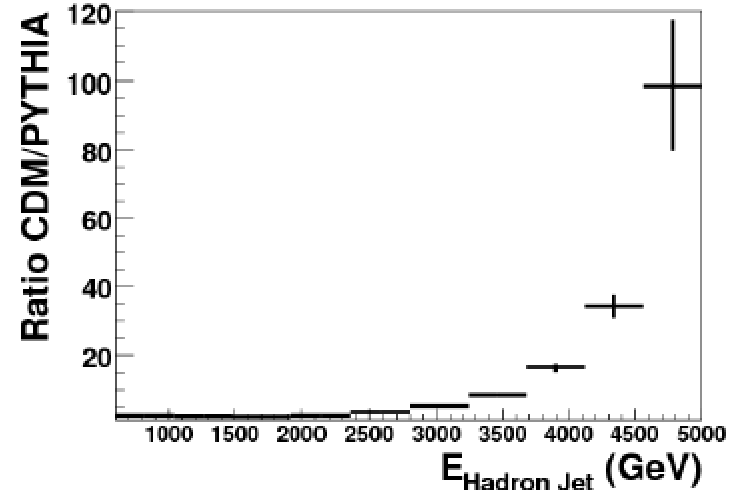
Selection: 2 central jets, Et>50 GeV
1 jet in CASTOR region, Et>10 GeV

Generator level



More hard jets predicted by Color Dipole Model

Generator level



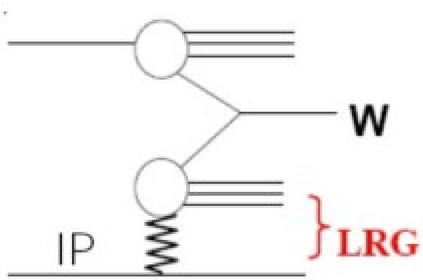
Both PYTHIA and ARIADNE are run together with Multiparton Interactions Tune A. (Tune A = to TEVATRON data.)

- A good tool to distinguish between DGLAP and non-DGLAP types of QCD evolution
- Also extend Mueller-Navelet studies into CASTOR acceptance

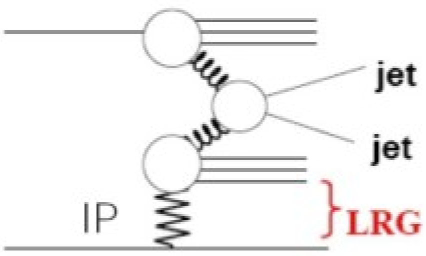
SD production of W and dijets

• Both are hard diffractive processes characterized by the presence of a hard scale and a Large Rapidity Gap in the final state.

• Sensitive to the diffractive structure function of the proton



sensitive to the quark component of the proton



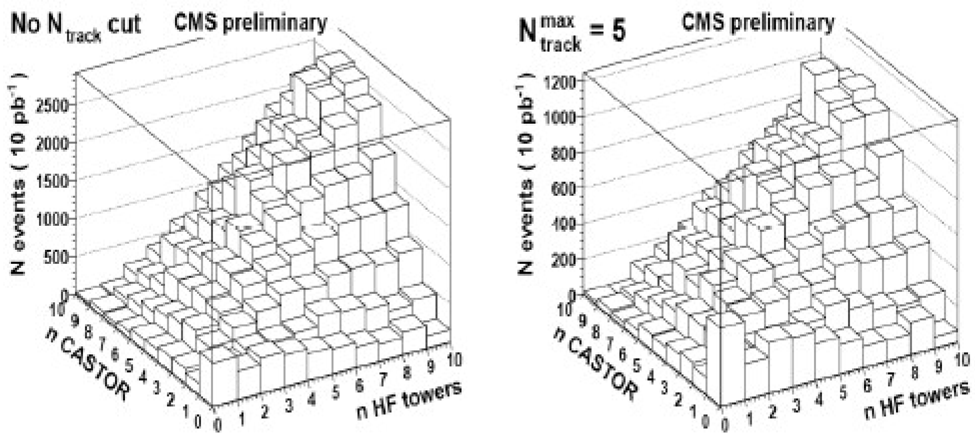
sensitive to the gluon component of the proton

• selection of diffractive candidates using the multiplicity distributions in the central tracker and HF/CASTOR: diffractive events on average have lower multiplicity in the central region and in the "gap side"

SD production of W and dijets

- **Dijets production:**

O(300) evts/10 pb^{-1} in
[n(Castor), n (HF)] = [0,0] bin



Diffractive events peak at zero

Next step: measurement of the ratio of SD to the total yields for W and dijet production giving an access to the estimation of:

- the rapidity gap survival probability
- the quark/gluon component in the diffractive PDFs of the proton

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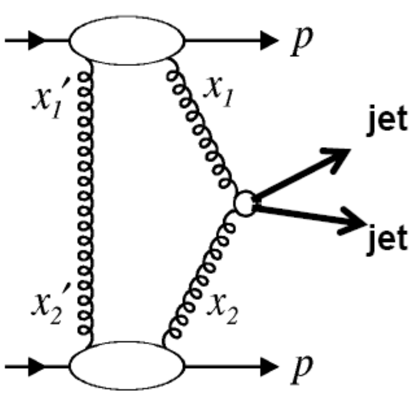
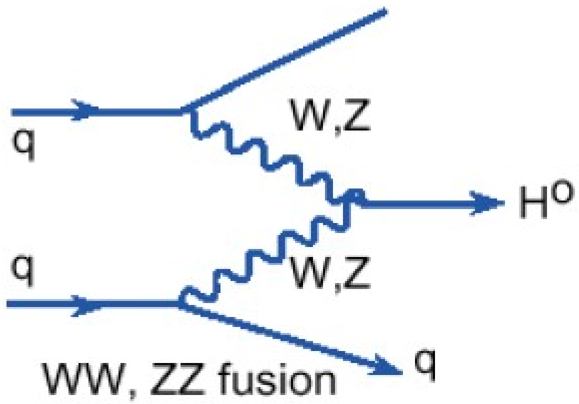


- Two jets produced exclusively
- $R_{jj} = M_{jj}/M_X$ variable (for CEP close to ~1)
- Observation at Tevatron (Phys. Rev. D77, 05, 2004)
- σ ~ O(10) pb at LHC energies (large sample)
- Central two – three jets production can be used to constrain Sudakov factor

Long term plans



Leptonic H decay:

qqH → jj WW → jj lνlν

Low activity in central region, forward jets

Graviton production in trans-Planckian regime

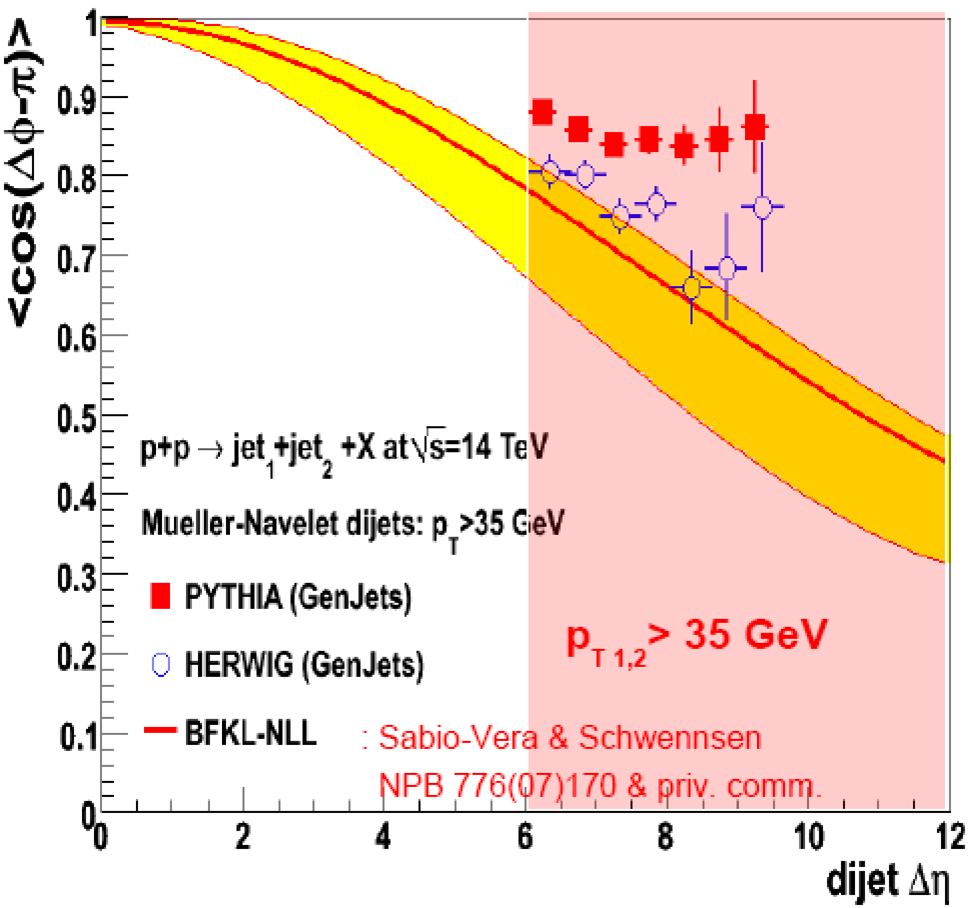
G. Giudice, R. Ratazzi & J. Wells (99,02)

t-channel gravition contribution

large mass dijet with large rapidity interval

few hundred pb^{-1}

Jets correlations



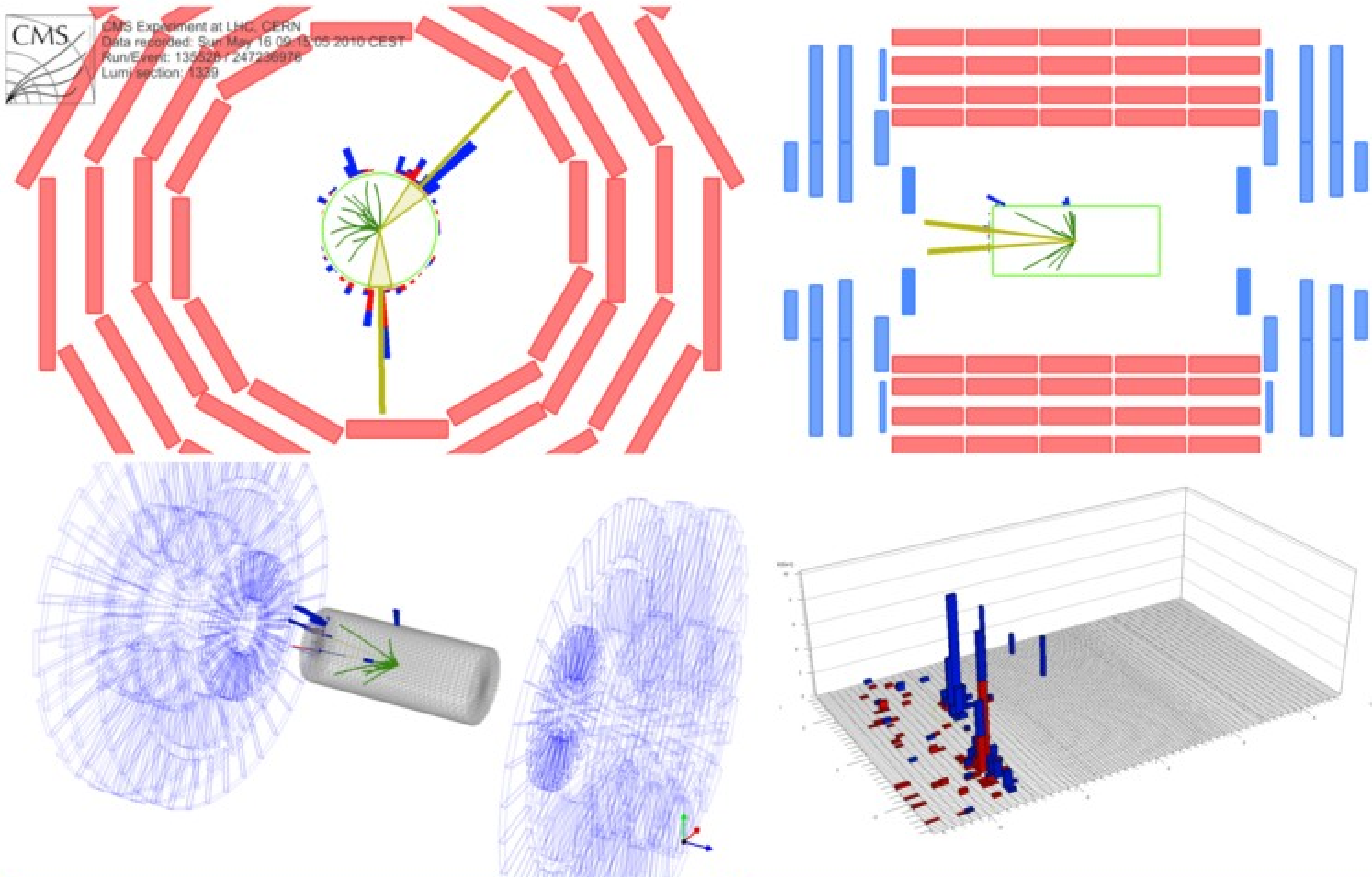
Average cos(Δφ-π) as a function of Δη

HERWIG shows ~15% more decorrelation than PYTHIA and ~20% less than BFKL analytical estimates

Parton showering & hadronization has to be taken into account

Yet another candidate...

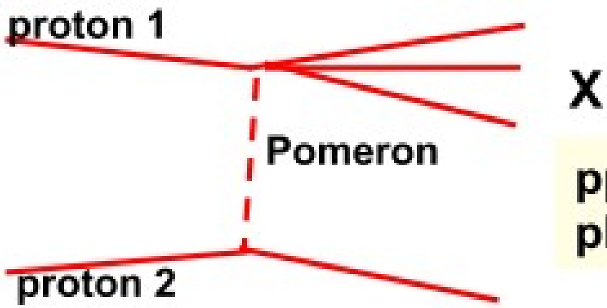
Diffractive dijet candidate at 7 TeV



$E(\eta < 3.0) > 1.5$ 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, η (jet2) = -3.3

Variable E+pz



pp --> pX
pPomeron --> X

- $\Sigma(E \pm p_z)$ runs over all calo towers
- Measure for the momentum of the Pomeron = momentum loss of the proton

Momentum and energy conservation:
E(Pomeron) + E(proton 1) = E(X)
p_z(Pomeron) + p_z(proton 1) = p_z(X)

Recall: in SD events proton loses almost none of its initial momentum.

If proton 1 moves in positive z direction: E(proton 1) - p_z(proton 1) ≈ 0 (and proton 2, and Pomeron, move in the negative z direction)

Hence:
E(Pomeron) - p_z(Pomeron) ≈ 2E(Pomeron) ≈ E(X) + p_z(X)

i.e. $\xi = 2E(\text{Pomeron})/\sqrt{s} \approx (E(X) + p_z(X))/\sqrt{s}$