New forward physics results from CMS

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On Behalf of the CMS Collaboration

Minimum Bias and Underlying Event Working Group

17. June 2011

Outline

In this presentation:

Focus:

- Forward energy flow for different processes
- Forward jet cross sections
- Info that can be used for MC tuning

Plots are taken from the following CMS analyses:

- **PAS FWD-10-001:** Observation of Diffraction in *pp* Collisions at 900 GeV and 2360 GeV com Energies at the LHC
- **PAS FWD-10-003:** Inclusive Forward Jet Production Cross Sections in Proton-Proton collisions at $\sqrt{s} = 7$ TeV
- **PAS FWD-10-006:** Cross section measurement for simultaneous production of a central and a forward jet in proton-proton collisions at $\sqrt{s} = 7$ TeV
- **PAS FWD-10-008:** Forward Energy Flow, Central Track Multiplicities and Large Rapidity Gaps in W and Z Boson Events at 7 TeV pp Collisions
- **PAS FWD-10-011:** Forward Energy Flow in the CMS Detector

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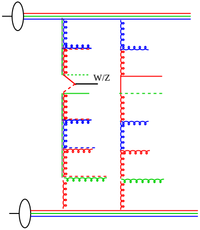
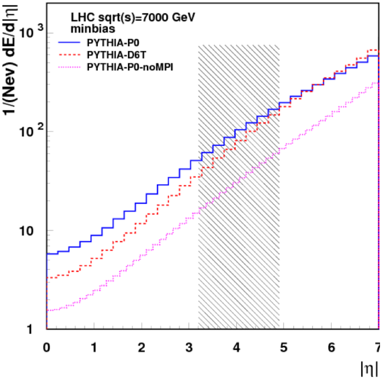
Introduction

- FWD energy flow is sensitive to:
  - physics of the UE
  - amount of parton radiation
  - multi parton interaction (MPI)
  - the scale of the process
- can be used to:
  - discriminate different MPI models
  - eventually determine MPI model parameters
- MPI: so far tuned to central observables
- expect differences in FWD region



On generator level:

Soft scale: Minimum bias



Introduction

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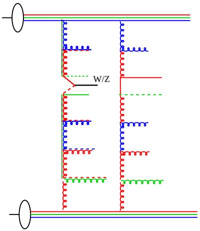
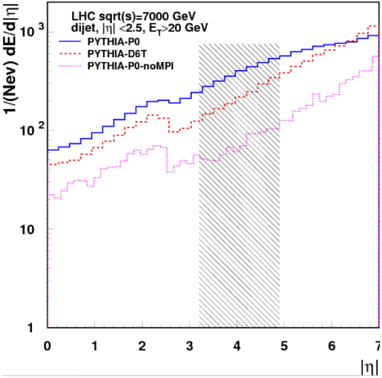
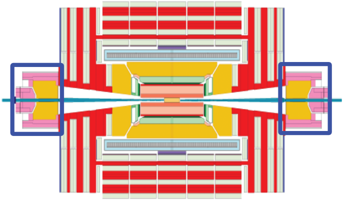


On generator level:

Hard scale: Di-jets



The Hadronic Forward Calorimeter



- coverage: $2.9 \leq |\eta| \leq 5.2$
- Distance from IP: 11.2 m
- Iron absorber + quartz fibers
- Able to distinguish electromagnetic and hadronic energy deposits
- $\approx 10\%$ energy scale uncertainty

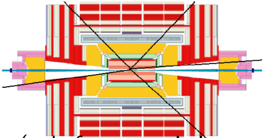
Variables used:

- Energy deposit in HF: $\sum E_{tower}$
  - Where E_{tower} above some threshold to remove noise
  - Energy in HF as function of η: $\frac{\mathrm{d}E}{\mathrm{d}\eta}$
  - Total energy in HF
- Central track multiplicity
  - $|\eta| < 2.5$
  - $p_t > 0.5/1$ GeV

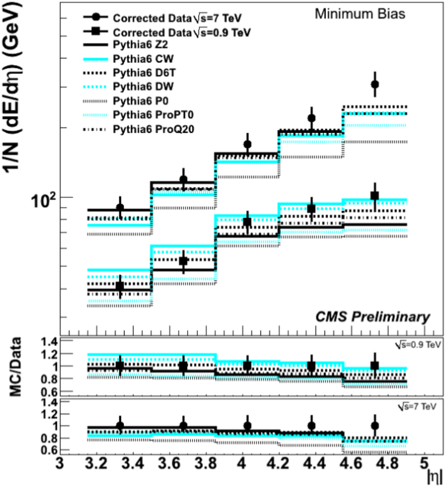
Soft scale	$\sqrt{s}$	Hard scale	$\sqrt{s}$	scale
Minimum Bias	900 GeV 7 TeV	Dijets	900 GeV 7 TeV	$p_t > 8$ GeV $p_t > 20$ GeV
		$W(Z)$ events	7 TeV	$m_{W(Z)}$

Differential FWD energy flow: $\frac{\mathrm{d}E}{\mathrm{d}\eta}$

FWD Energy Flow I



Minimum bias - $\sqrt{s} = 900$ GeV & 7 TeV



No hard scale (only few partonic interactions)
900 GeV vs. 7 TeV

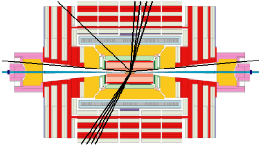
- Minimum bias trigger

PYTHIA 6

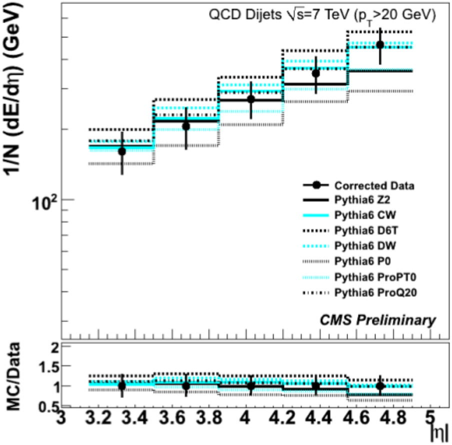
- increase with η
- $\sqrt{s}$ dependence
- tune Z2: shows the same energy dependence
- distinguish different tunes e.g. D6T, ProQ20:
- discrepancy for $\sqrt{s} = 7$ TeV at high η
- no significant difference between p_t or Q^2 ordered MC

Corrected to hadron level

FWD Energy Flow II



Dijet sample - $\sqrt{s} = 7$ TeV



With hard scale (high p_t partonic interactions)

- anti-k_t algo with $R = 0.5$
- $p_t > 8(20)$ GeV for $\sqrt{s} = 0.9(7)$ TeV

PYTHIA 6 - dijets @ 7 TeV

- higher energy flow than in min bias
- different MC more spread
- Z2: same behaviour as in min bias
- D6T: shifted to higher energy, independent of η (with respect to min bias)
- ProQ20: agrees with data! (also for 900 GeV)

Corrected to hadron level, only 7 TeV shown

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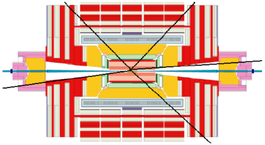
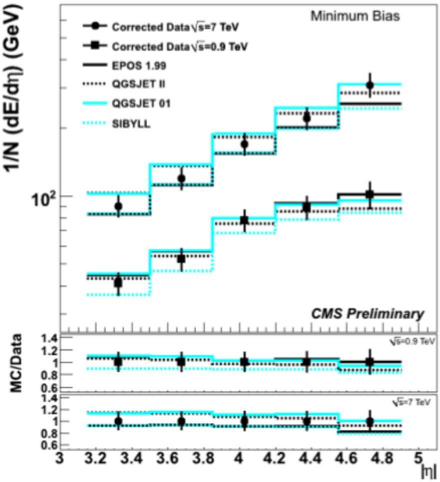
Remark: Cosmic Ray MC



Comparing to predictions from cosmic ray MC...



Minimum bias

Excellent agreement between data and MC!

-proton (cosmic rays) interactions with atmosphere
-based on Regge theory (Pomeron exchange)

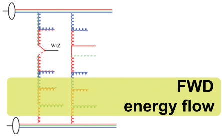
- EPOS
- QGSJET
- SIBYLL

Corrected to hadron level

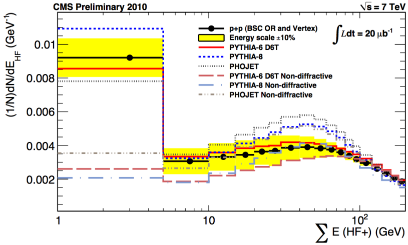
Total FWD energy flow deposited in HF: $\sum E$

Forward Energy Flow

Total energy deposit in FWD calorimeter
on detector level

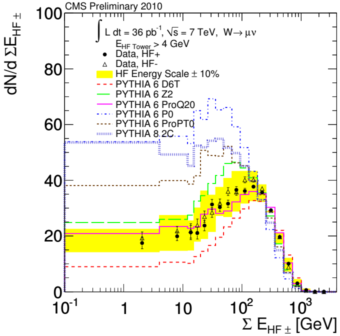


Minimum bias



PYTHIA 6 D6T: good agreement
PYTHIA 8 & PHOJET: good description at low *E*, but not total FWD energy flow

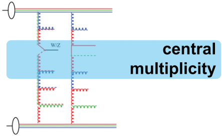
W events



No PYTHIA tune describes FWD energy spectrum
Large difference between tunes!

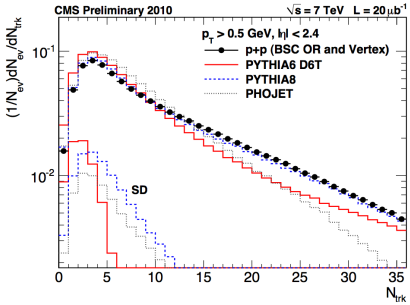
- Non-Diffractive PYTHIA 6 D6T: same behavior for min bias & *W* production!
- FWD energy flow strongly tune dependent for *W* production

Central Track Multiplicity

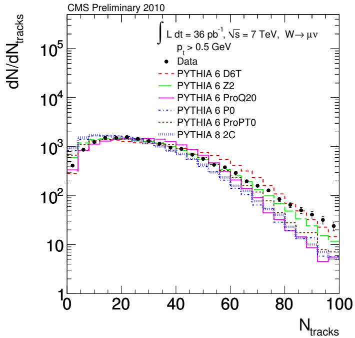


Track multiplicity in central region of the detector
on detector level

Minimum bias



W events



PYTHIA 8 (tune 1): good agreement
PYTHIA 6 D6T & PHOJET: too low track multiplicity

PYTHIA 8 2C: too low, but very good with 1 GeV p_t cut!
PYTHIA 6 Z2: good description

- Track multiplicity is less tune dependent and
- strongly track p_t cut dependent!

Overview of the different tunes / MCs

Minimum bias:

	D6T	Pythia 8	PHOJET
Tracks $p_t > 0.5$ GeV	disagreement	good agreement	disagreement
Forward Energy Flow	good agreement	decent agreement	decent agreement
Central Calorimetry	decent agreement	decent agreement	disagreement

W analysis:

	D6T	Z2	ProQ20	Pythia 8
Tracks $p_t > 0.5$ GeV	decent agreement	decent agreement	decent agreement	disagreement
Tracks $p_t > 1.0$ GeV	disagreement	decent agreement	disagreement	good agreement
Forward Energy Flow	disagreement	disagreement	good agreement	disagreement

Conclusion:
No single MC describes the data in their entirety

good agreement
decent agreement
disagreement

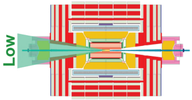
- Different PYTHIA tunes show same behavoiur for a soft and a hard scale
- For W events: overall energy flow strongly tune dependent
- Some tunes are able to describe central multiplicity others not (depending of track selection)
- No studied MC model can do both at the same time

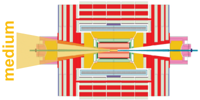
⇒ **Correlation Between Forward Energy Flow and Central Track Multiplicity in W Events**

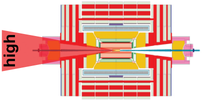
Correlation Studies in W events

To study differences and correlation of energy flow and track multiplicites in more detail, split in 3 HF energy ranges:

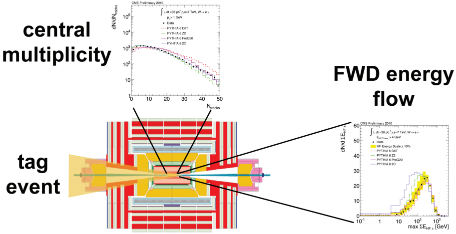
Low: 20 - 100 GeV	**Medium:** 200 - 400 GeV	**High:** >500 GeV
(region of largest discrepancy)	(peak region)	(high energy region)







Categorize event with HF− energy deposit
"Look" at opposite side (i.e. HF+) deposit and track multiplicities



On the following slides, only the track multiplicity plots with $p_t > 0.5$ GeV cut are shown. The 1 GeV cut plots can be found in the backup

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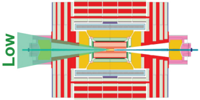
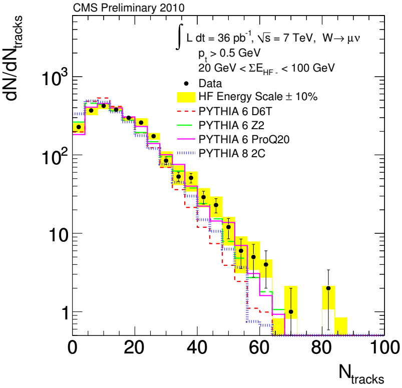
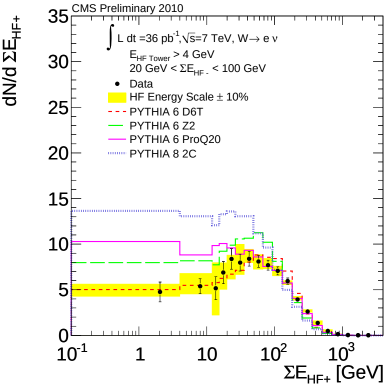
Low - 20 – 100 GeV







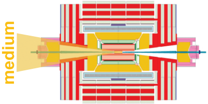
Multiplicity $p_t > 0.5$ GeV, Muons

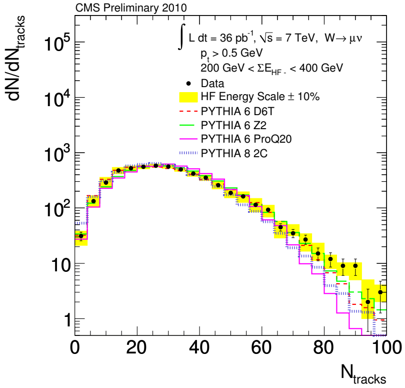
- good: PYTHIA 6: ProQ20, Z2
- slightly low: PYTHIA 6 D6T, PYTHIA 8 2C

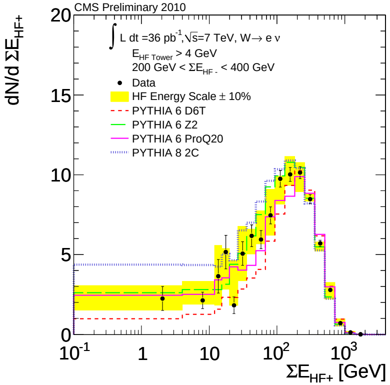
Energy Flow, Electrons

- too low: PYTHIA 6: ProQ20, Z2, PYTHIA 8 2C
- slightly high: PYTHIA 6 D6T

Medium - 200 – 400 GeV







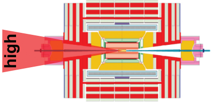
Multiplicity $p_t > 0.5$ GeV, Muons

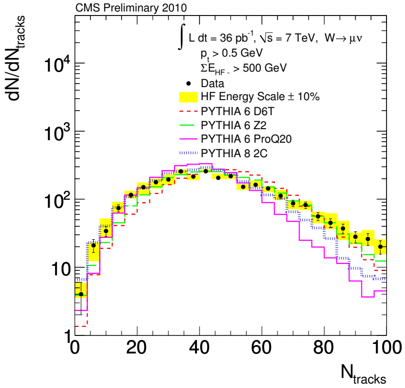
- good: PYTHIA 6: D6T, Z2
- slightly low: PYTHIA 8 2C
- shape: PYTHIA 6 ProQ20

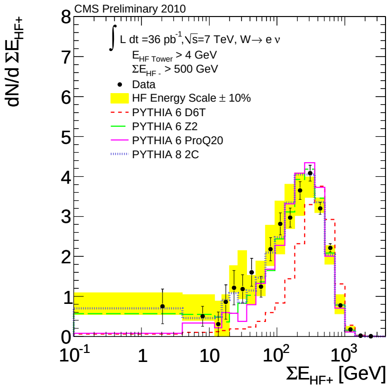
Energy Flow, Electrons

- good: PYTHIA 6 Z2
- too hard: PYTHIA 6: D6T, ProQ20
- too soft: PYTHIA 8 2C

High - $>$ 500 GeV







Multiplicity $p_t > 0.5$ GeV, Muons

- good: PYTHIA 8 2C
- higher: PYTHIA 6: D6T, Z2
- shape: PYTHIA 6 ProQ20

Energy Flow, Electrons

- good: PYTHIA 6: Z2, ProQ20, PYTHIA 8 2C
- too hard: PYTHIA 6 D6T

Overview of the different tunes - W Analysis

It's impossible to give a short overview,
and very subjective...

		D6T	Z2	ProQ20	Pythia 8
Tracks $p_t > 0.5$ GeV	all	decent agreement	decent agreement	decent agreement	disagreement
	low	decent agreement	decent agreement	good agreement	decent agreement
	medium	good agreement	decent agreement	decent agreement	decent agreement
	high	disagreement	decent agreement	disagreement	decent agreement
Tracks $p_t > 1.0$ GeV	all	disagreement	decent agreement	disagreement	good agreement
	low	disagreement	disagreement	disagreement	disagreement
	medium	decent agreement	decent agreement	disagreement	good agreement
	high	disagreement	good agreement	decent agreement	good agreement
Forward Energy Flow	all	disagreement	disagreement	good agreement	disagreement
	low	decent agreement	disagreement	decent agreement	disagreement
	medium	disagreement	good agreement	decent agreement	decent agreement
	high	disagreement	decent agreement	decent agreement	good agreement

Conclusion:
No PYTHIA tune is able to describe FWD energy flow and central track multiplicity simultaneously.

- good agreement
- decent agreement
- disagreement

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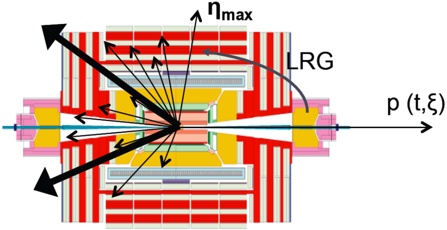
Size of rapidity gaps

Use Particle Flow to measure the gap size (with respect to the beam)

- LRGs mostly from multiplicity fluctuations
- ND MC can have large gaps too!



The largest (smallest) η_{max} (η_{min}) gives the size of the gap

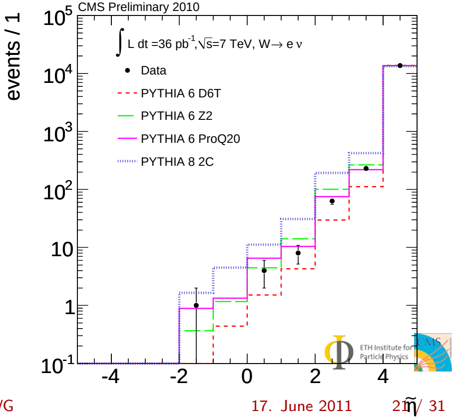
$$\tilde{\eta} = \min(\eta_{max}, -\eta_{min})$$

$$\Delta\eta^{4.9}_{gap} = 4.9 - \tilde{\eta}$$

with a too soft FWD energy spectrum or a too low track mutliplicity, one can get too large gaps.

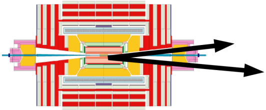
remark: $\tilde{\eta} < 0 \Rightarrow$ "empty" hemisphere

Large differences between different tunes!



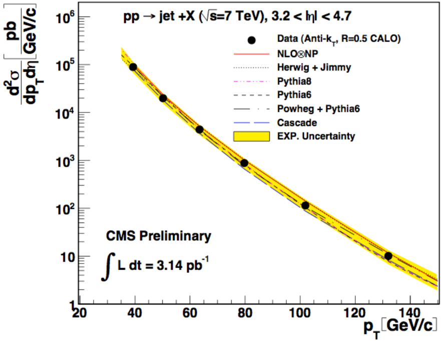
- Inclusive FWD jet cross section
- Central-FWD jet cross section

Inclusive FWD Jet Cross Section



Jet production sensitive to UE, parton radiation & PDFs
small x processes: $\approx 10^{-5}$
$x_2 \ll x_1 \Rightarrow$ expect differences

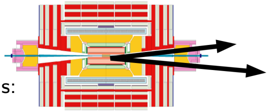
Measurement of the inclusive FWD jet cross section



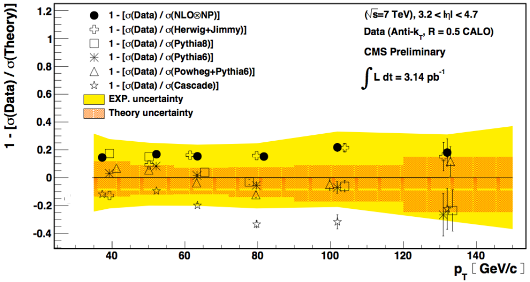
- Single jet trigger ($\approx$100% eff.)
- $3.2 < |\eta| < 4.7$, $p_t > 35$ GeV
- anti-k_t algo with $R = 0.5$
- good quality jets

good agreement, within uncertainties, between calculated and measured cross section!

Inclusive FWD Jet Cross Section



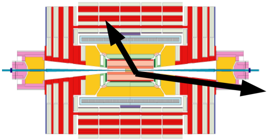
Comparison of measured x-sec with different model predictions:



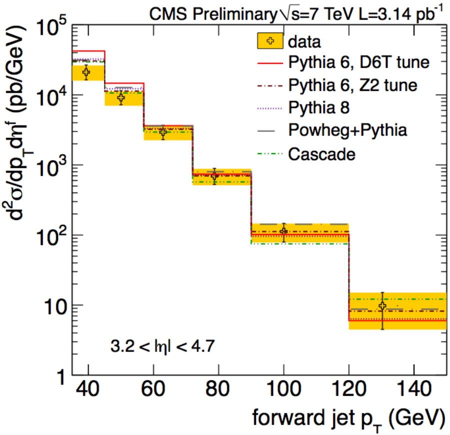
Systematic uncertainties (on final x-sec):

- Jet energy scale: $\approx 20 - 30\%$
- Jet energy resolution: $\approx 3 - 6\%$
- Luminosity: 4%
- HF calibration: $3 - 6\%$
- Model dependence: 3%

Central-FWD Jet Cross Section



One central and one FWD jet



- Dijet trigger (≈100% eff.)
- anti-k_t algo with $R = 0.5$
- central: $|\eta| < 2.8$
- fwd: $3.2 < |\eta| < 4.7$
- both: $p_t > 35$ GeV
- good quality jets

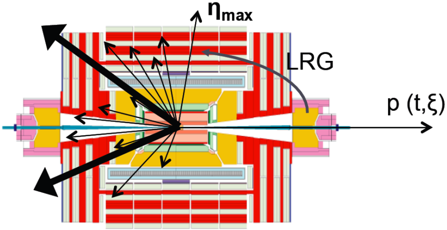
- MC over predicts data
- MC spectrum steeper
- Max discrepancy at low p_t

Summary

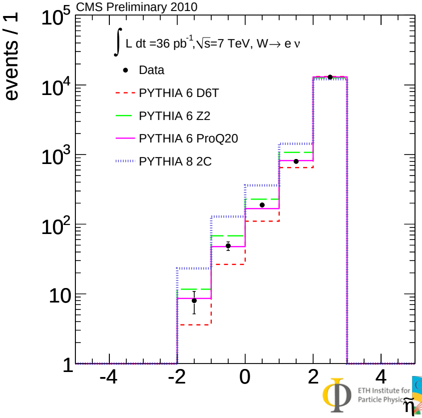
- Measurements of FWD energy flow were shown:
  - for different processes with different scales
  - compared to predictions from different MC models
- The FWD energy flow is:
  - strongly model dependent
- The correlation between FWD energy flow and central track multiplicity was studied:
  - for W events
  - none of the studied tunes describes FWD energy flow and central multiplicity simultaneously
- A measurement of the FWD jet cross section was shown:
  - for inclusive fwd jets
  - and central fwd jets
  - the predictions agree within uncertainties to the measurement

Backup Slides

Size of the Gap II



- Ignoring HF ⇒get information about more central LRGs
- LRGs mostly from multiplicity fluctuations (strongly tune dependent)
- ND MC can have large gaps too!



The largest (smallest) η_{max} (η_{min}) gives the size of the gap

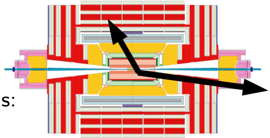
$$\tilde{\eta} = \min(\eta_{max}, -\eta_{min})$$

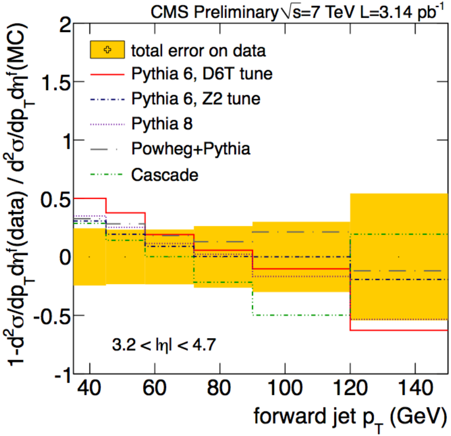
$$\Delta\eta_{gap}^{2.85} = 2.85 - \tilde{\eta}$$

e.g.:
D6T: too high multiplicity ⇒ smaller gaps
2C: too low multiplicity ⇒ larger gaps

Central-FWD Jet Cross Section

Comparison of measured x-sec with different model predictions:





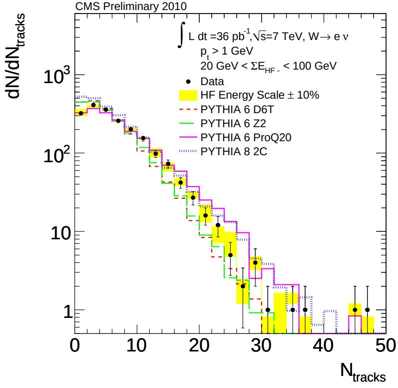
Systematic uncertainties (on final x-sec):

- Jet energy scale: $\approx 25\%$
- Jet energy resolution: $\approx 3.5\%$
- Pile up: $\approx 5\%$
- Luminosity: 4%
- Model dependence: 3%

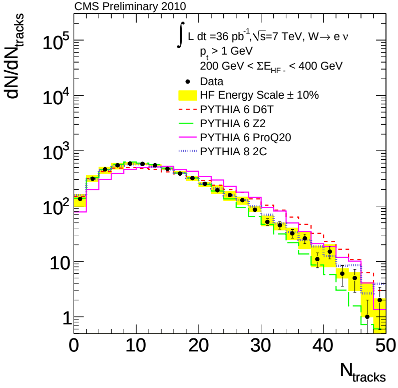
Track Multiplicity - Low & Medium - Electrons

Electron plots only (i.e. $p_t > 1$ GeV), muon plots in the talk:

Low Range



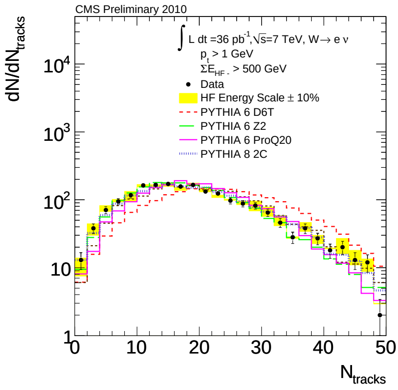
Medium Range



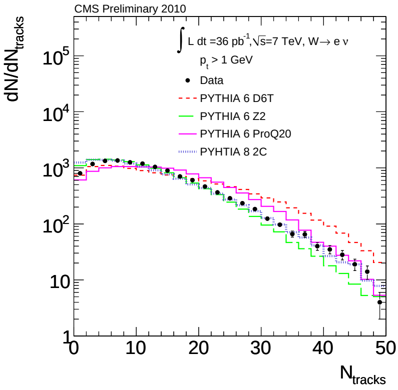
Track Multiplicity - High & Inclusive - Electrons

Electron plots only (i.e. $p_t > 1$ GeV), muon plots in the talk:

High Range



Inclusive



Asymmetry in signed η_{lepton} in LRG W Events

Electron and muon channel combined

- signed $\eta_{lepton} < 0 \Rightarrow$ lepton in opposite hemisphere than the gap
- ND: signed η_{lepton} is flat
- SD: tends to negative
- **Counting asymmetry:** -0.21 ± 0.06 (W) and -0.2 ± 0.16 (Z)
- Fraction f_{SD} of SD component from binned maximum likelihood fit
- $f_{SD} \approx 50\%$ independent from the tune
- PYTHIA 6 ProQ20 + POMPYT
- for the other tunes, only the ND fraction is shown

$$f_{SD} = 50 \pm 9.3(stat.) \pm 5.2(syst.)\%$$

NB: for higher FWD energy deposits, the asymmetry disappears!