High p_T EWK and QCD in CMS

Preliminary measurements at $\sqrt{s} = 7$ TeV

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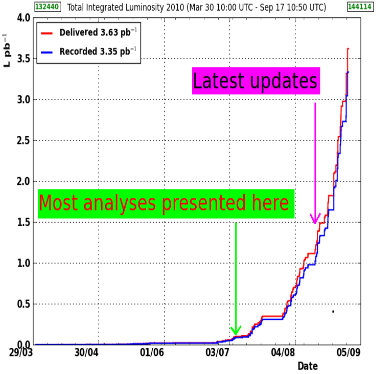
Outline

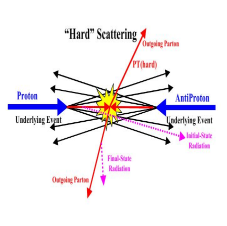


132440
Total Integrated Luminosity 2010 (Mar 30 10:00 UTC - Sep 17 10:50 UTC)
144114
Delivered 3.63 pb⁻¹
Recorded 3.35 pb⁻¹
Latest updates
Most analyses presented here
L pb⁻¹
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
29/03
30/04
01/06
03/07
04/08
05/09
Date

QCD and EWK in Proton-Proton Physics at 7 TeV

Test further perturbative QCD and the Standard Model

- e.g. measure α_S, PDF. Larger phase-space accessible.
- characterise better gluon and heavy-flavours : gg processes much more important than at Tevatron.
- study impact of non-perturbative effects: e.g. underlying event, multi-parton interactions, hadronisation. More data $\Rightarrow$ better modelling.
- $\Rightarrow$ importance of Collinear- and IR-safe jet algorithms.



Commissioning of detector and objects:

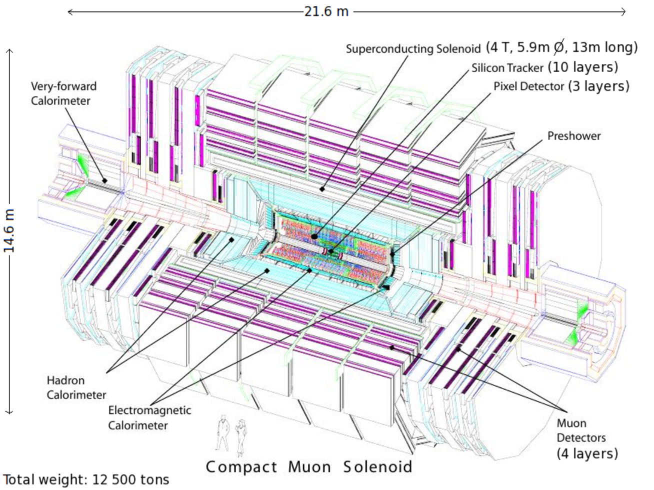
- dijet, γ+jets balance $\Rightarrow$ measure jet energy scale and resolution
- W,Z candles $\Rightarrow$ calibrate EM response

Backgrounds to new physics:

- "QCD" multijet background, W/Z+jets, $t\bar{t}$, γ+X
- fine-tuning of MC required.
- NLO/NNLO calculations required.

The CMS Detector

The CMS collaboration: 39 countries, 169 institutes, 3170 members.

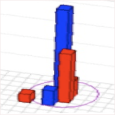


Jet and MET Reconstruction in CMS
Different inputs ⇒ cross-check of systematics

- Standard jet reconstruction: collinear and IR safe anti-k_T clustering algorithm, size 0.5 or 0.7.
- Four different jet types, leading to three different MET types:

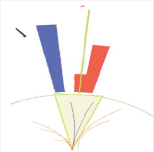
Calorimeter-based

- caloJets/caloMET
- calorimeter towers only



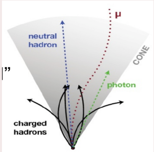
Track-corrected

- Jet Plus Track (JPT) and tcMET
- calo complemented with track informations



Particle Flow (PF): generator-level like

- PFJets and PFMET
- clustering starts from a list of “identified particles”

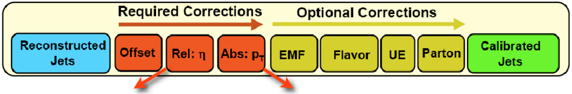


Purely Track-based

- track jets

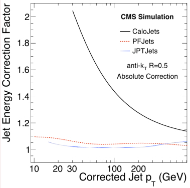
Jet Energy Corrections and Uncertainties

MC-based (current situation) vs data-driven (with O(10 pb^{-1}) data)



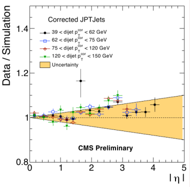
Absolute p_T scale

- γ+Jet, Missing E_T Projection Fraction $\Rightarrow$ syst. 10% (5%) calo (JPT/PF)



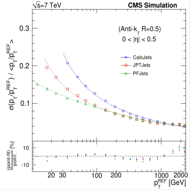
Relative η dependence

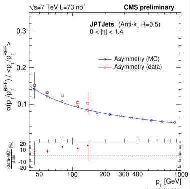
- Dijet balance $\Rightarrow$ syst. 2% $\times$ $|\eta|$



Jet Energy Resolution

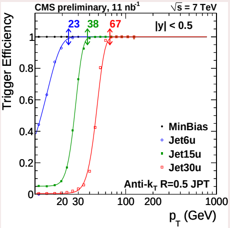
- Dijet Asymmetry $\Rightarrow$ syst. 10%



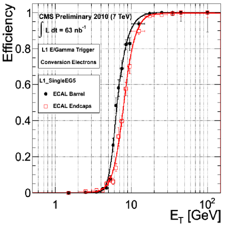


Leptons, Jets and MET: an extract of performance results

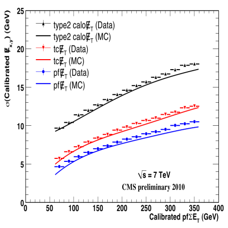
Single jet turn-ons



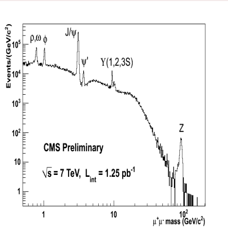
L1 EM turn-on



MET resolution



$\mu^+\mu^-$ resonances

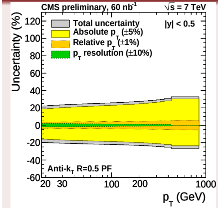


- Lepton isolation, based on $\sum p_{T_{trk}}$, $\sum E_{T_{ECAL}}$, $\sum E_{T_{HCAL}}$ in $\Delta R = 0.3$ cone around the lepton. Relative+combined for μ analysis, absolute for e analysis.
- Electron identification: cut-based, using cluster width and track-cluster matching. Tight (loose) selection: eff = 75% (90%).
- Muon identification: cut-based, good consistency between tracker and muon chambers.

Inclusive Jet Analysis : the Method

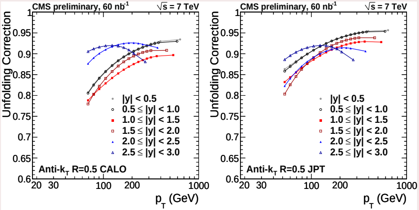
- Calo, JPT and PF Jets: cross-check of systematics
- Beam background + noise cleaning
- Minimum bias + single jet triggers
- 6 rapidity regions $0 < |y| < 3$
- Data $\Leftrightarrow$ NLO pQCD @ hadron level: data - detector effects, NLO + non-pertubative effects.

Main systematics



- Luminosity: 11%.
- Absolute p_T scale: 5% on JES $\Rightarrow$ 25% on cross-section.

Unfolding Method (DØ Ansatz fit)

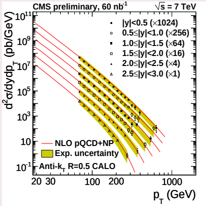


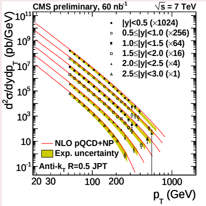
- Theory-motivated function: $f(p_T) = Np_T^{-a}\left(1 - \frac{2\cosh(y_{min})p_T}{\sqrt{s}}\right)^b \exp\frac{-\gamma}{p_T}$
- Gaussian resolution $R(p_T^{gen}, p_T^{reco})$
- Data $F(p_T) = \int_0^\infty f(x)R(x, p_T)dx$
- $C_{res} = f(p_T)/F(p_T)$
- $\frac{d^2\sigma}{dp_T dy} = \frac{C_{res}N_{jets}}{\mathcal{L}\epsilon\Delta p_T \Delta y}$

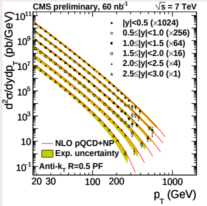
Inclusive Jet Analysis : the Results

Comparison between 3 algorithms: systematics well under control.

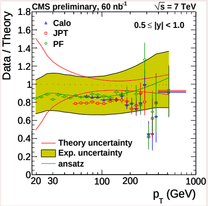
p_T spectrum for CALO jets — JPT jets — PF jets

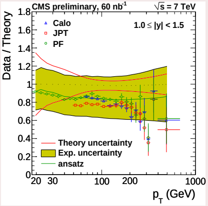


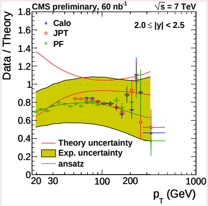




Data/Theory for $0.5 < |y| < 1$ — $1 < |y| < 1.5$ — $2 < |y| < 2.5$



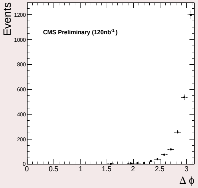




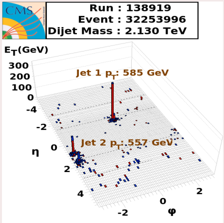
Dijet Mass Spectrum

No surprise... Yet ...

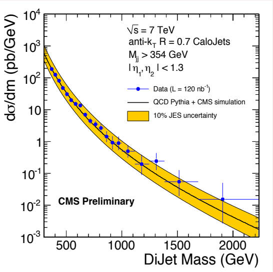
Selection



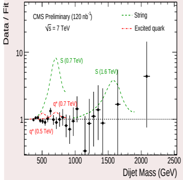
- Same data cleaning as inclusive jet analysis,
- Calojets, anti k_T size 0.7,
- Two jets in barrel region: $|\eta| < 1.3$,
- Trigger selection: $\epsilon_{trig} > 0.99$ for $M_{jj} > 354$ GeV.



Comparison to pQCD



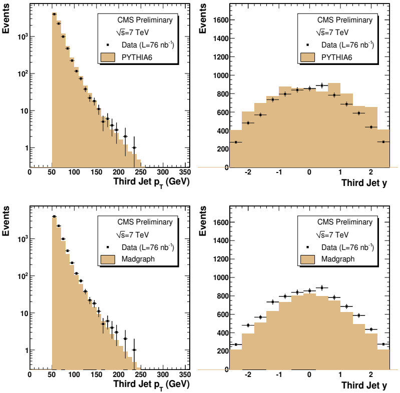
Comparison to exotica models

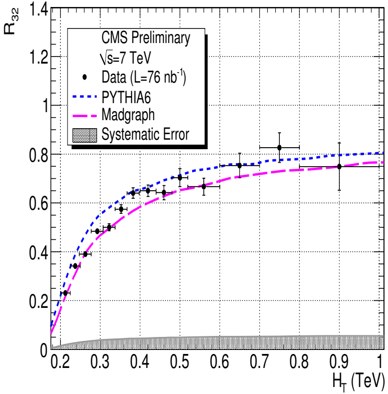


- New limit on string resonances: $M < 1.67$ TeV
- With O(5 pb^{-1}): expect new world limits in many models.

3-jet to 2-jet cross-section ratio
Good agreement with MC within uncertainties

- Ratio: eliminate JES and luminosity uncertainty.
- Selection: $|y| < 2.5$, $\epsilon_{trig} > 0.99 \Rightarrow p_T > 50$ GeV.
- Total transverse Jet Energy: $0.2 < H_T < 1.0$ TeV.
- $R_{32} = \frac{d\sigma_3/dH_T}{d\sigma_2/dH_T}$, plateau sensitive to α_S.



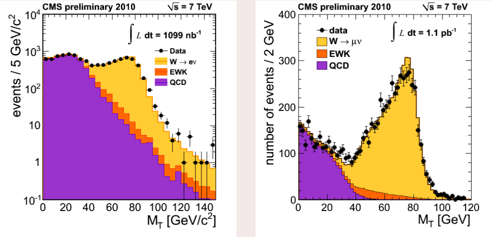


$W^{\pm}$ and Z Analyses - Global picture

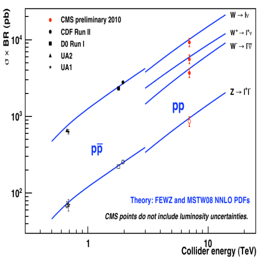
Selection

- Trigger $E_T > 9$ (15) GeV, p_T>20 GeV, $|\eta| < 2.1(2.5)$ for μ (e)
- W (Z): Tight (loose) isolation and identification requirements
- W analyses: veto 2nd μ (e) $p_T > 10(20)$ GeV

Transverse Mass for $W \to e\nu$ and $W \to \mu\nu$

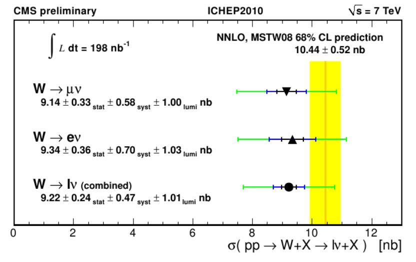


- W yield: binned likelihood fit to M_T distribution
- Z yield: number of events in $60 < M_{ee} < 120$ GeV (bkg negligible)
- QCD background shape: data-driven, based on inverted isolation.
- EWK+signal shape: MC
- Full analysis: 0.198 pb^{-1}. Latest mass distributions: 1.1 pb^{-1}.

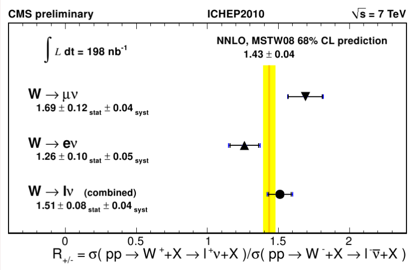


$W^{\pm}$ cross-section and charge asymmetry

Cross-section vs SM predictions

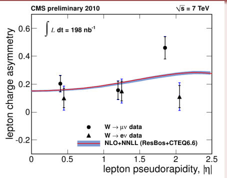


W^+/W^- ratio vs SM predictions



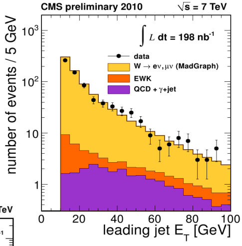
Lepton charge asymmetry

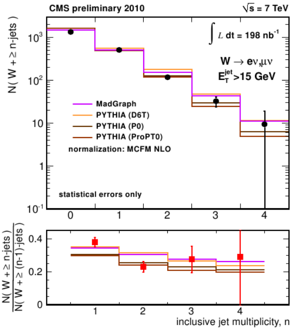
- pp collisions: $u >> d \Rightarrow W^+ > W^-$, sensitive to PDFs.
- $A(\eta) = \frac{d\sigma^+/d\eta - d\sigma^-/d\eta}{d\sigma^+/d\eta + d\sigma^-/d\eta}$, SM predictions $\Rightarrow A(\eta) \simeq 0.2$
- Raw measurement: without e/μ acceptance corrections.
- With O(10 pb^{-1}), $\sigma(A) \simeq 0.03 \Leftrightarrow 0.04$ PDF variations.

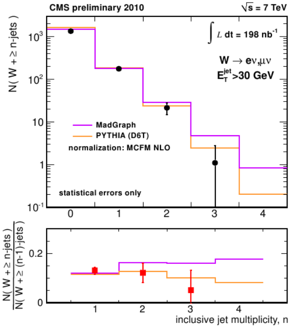


First look at jet multiplicity in W+jets events

- PF Jets $|\eta| < 2.5$, $\Delta R(jet - lepton) > 0.5$
- MC signal and backgrounds normalised to MCFM NLO cross-sections.
- Inclusive rates: $N(W+ \geq n - jets)$ and ratio: $\frac{N(W+\geq n-jets)}{N(W+\geq (n-1)-jets)}$
- Two jet E_T threshold analysed: 15 and 30 GeV.

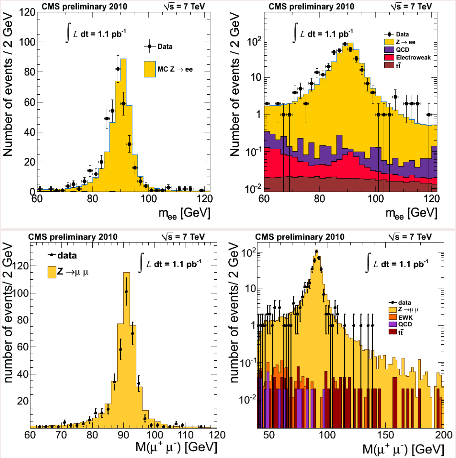




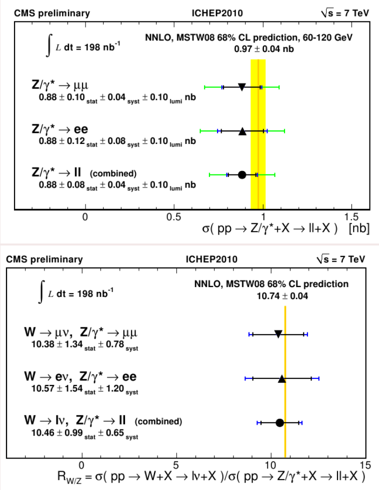


Z cross-section and W/Z ratios

M_{ee} and $M_{\mu\mu}$, linear and log



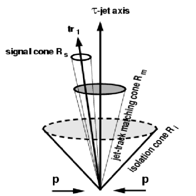
Z cross-sections and W/Z ratio

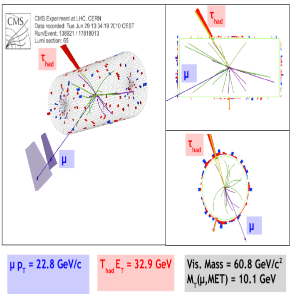


First Taus !

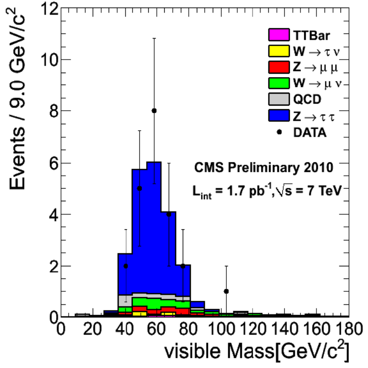
Study of $\tau_{had} + \mu$ final state

- 3 PF-based algorithms, one track-corrected, based on signal vs isolation cones.
- Main backgrounds: QCD, W.
- Exp. efficiency (MC): 60% for $p_T^{vis} > 50$ GeV.
- Fake rate (data 8.4 nb^{-1}) $\simeq 10^{-2}$.





Visible mass of the $Z \to \mu\tau$ candidates, $p_T^{\mu} > 15$ GeV, $p_T^{\tau} > 20$ GeV

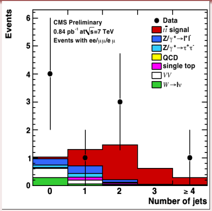


Top Measurements in One Slide

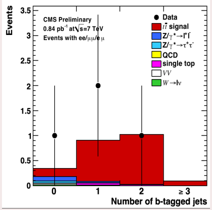
A complete exercise demonstrating excellent detector performance

Dilepton selections

- ≥ 2 e (μ) opp. charges, $p_T > 20$ GeV, $|\eta| < 2.4(2.5)$.
- W sel. identification and isolation cuts.
- $M_{ll} - 91 > 15$ GeV.
- tcMET > 30 GeV (20 for eμ).

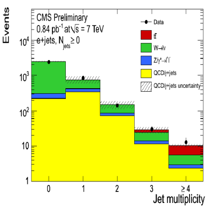


- JPT jets $p_T > 30$ GeV, $|\eta| < 2.4$, $\Delta R(l, jet) > 0.4$.
- track counting btag $\epsilon_b = 0.81$, $\epsilon_{c,l} = 0.10$.

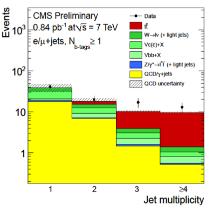


Lepton+jet selections

- $= 1$ e (μ) $p_T > 30(20)$ GeV, $|\eta| < 2.5(2.1)$.
- W sel. tight isolation, identification.



- $M_{ee} \notin [76, 106]$ GeV.
- calo jets $E_T > 30$ GeV, $|\eta| < 2.4$, $\Delta R(l, jet) > 0.4$.

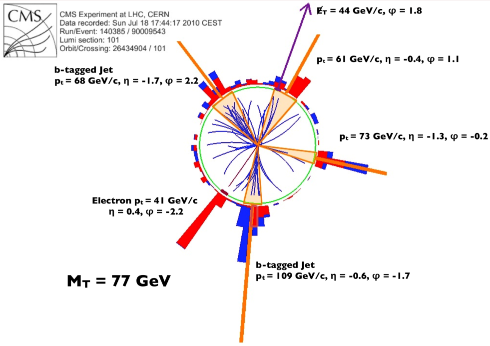


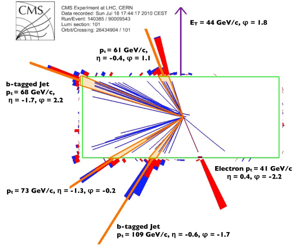
Conclusion

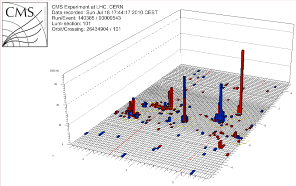
- Standard Model predictions confirmed at 7 TeV within current statistical and experimental uncertainties.
- CMS is delivering very good quality data: commissioning of the detectors well under way.
- Era of MC tuning has started: O(30) pb^{-1} of integrated luminosity by Christmas.
- Era of precision measurements: O(1) fb^{-1} in 2011.
- CMS is also getting ready for Heavy Ion collisions in November.
- More CMS results:
  - P. Katsas, Wednesday 12:10 "Studies of QCD jet production with the CMS detector in pp collisions at $\sqrt{s} = 7$ TeV"
  - X. Janssen, Wednesday 19:40 "Measurements of two-particle correlations in pp collisions with the CMS detector"
  - D. Piparo, Wednesday 20:50 "Measurements of Hadron Production and Underlying Event Studies at CMS"
  - D. S. Cerci, Thursday 11:20 "Forward energy and particle flow with CMS"
  - L. Benucci, Saturday 10:35 "Searches for physics beyond the Standard Model with CMS"

$t\bar{t} \rightarrow e + jets$ Candidate in Image

Special thanks to the LHC machine for working so smashingly well.







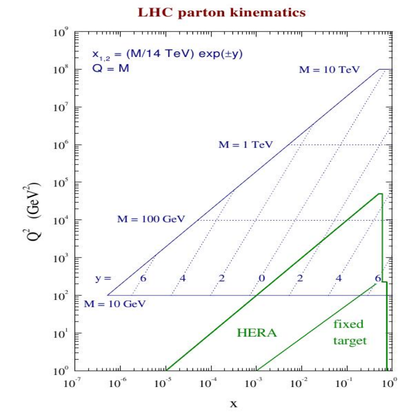
BACKUPS

The LHC

Collisions	pp		Heavy ions	
Parameter	Start-up	Nominal	Start-up	Nominal
Energy/nucleon (TeV)	5	7	2.76	2.76
Luminosity ($cm^{-2}s^{-1}$)	10^{31}-10^{32}	10^{34}	5×10^{25}	10^{27}
Bunch separation (ns)	25-50-75	25	1350	99.8
No. of bunches	43/156/936-2808	2808	62	592
particles/bunch	0.5×10^{11}	1.15×10^{11}	7.0×10^{7}	7.0×10^{7}
β-value at IP (m)	1-3	0.55	1.	0.5-0.55
RMS beam radius at IP (μm)	16.7	16.7	15.9	15.9
Luminosity lifetime (hour)	15	15	14/7.5/5.5	8/4.5/3
Collisions/crossing	$\simeq$3	$\simeq$20	-	-

PDF and α_S measurements

Parton kinematics

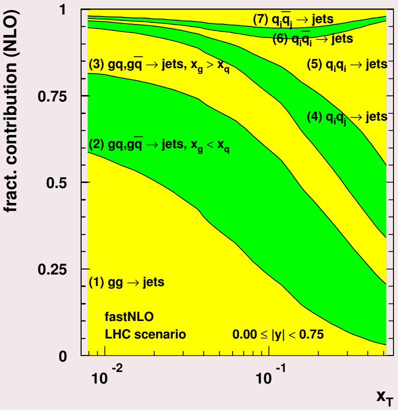


Rep. Prog. Phys. 70 (2007)

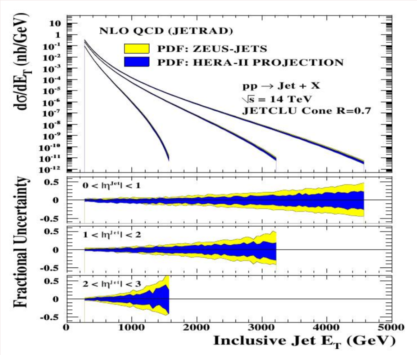
- Momentum fraction x = $\frac{M}{\sqrt{s}} \times e^{\pm y}$,
- Scale Q = Mass (dijet,Z,W,H,...),
- QCD factorisation theorem: fits to the inclusive jet cross-sections ⇒ PDF,
- Theoretical uncertainties due to factorisation and renormalisation scales,
- Test of DGLAP equations thanks to large range in Q^2,
- $\frac{\sigma(X+jet)}{\sigma(X)} \propto \alpha_S$

Jet production processes and HERA projections

Jet production processes



HERA projections



hep-ph/0601012, hep-ph/0601013.

The CMS calorimeters

- EM : $|\eta| < 3$,
  - $PbWO_4$ cristals,
  - 24.7-25.8 X_o, 1.1 λ,
  - 1 longitudinal section + preshower (3 X_o),
  - $\Delta\eta \times \Delta\Phi = 0.0175 \times 0.0175$,
  - $\sigma/E \simeq 2 - 5\%/\sqrt{E}$.
- HCAL : $|\eta| < 3$,
  - Brass/Scintillator sampling calorimeter,
  - 6-10 λ
  - 2 longitudinal sections + Outer HCAL (3 λ for $|\eta| < 1.4$)
  - $\Delta\eta \times \Delta\Phi \geq 0.0875 \times 0.0875$,
  - $\sigma/E \simeq 100\%/\sqrt{E} \oplus 0.05$.
- HF : $3 < |\eta| < 5$,
  - Fe/Quartz fibers, Cerenlov light
  - EM 90 X_o, HAD 9.5 λ
  - 1 EM + 1 HAD longitudinal sections

Relative JEC: dijet p_T balance

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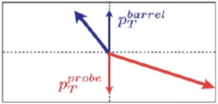
Relative JEC removes jet response variation in η
A priori estimate of uncertainty: ±2% x |η|

Barrel Jet



Probe Jet

$$p_T^{dijet} = \frac{p_T^{probe} + p_T^{barrel}}{2}$$

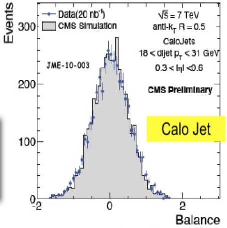
$$B = \frac{p_T^{probe} - p_T^{barrel}}{p_T^{dijet}}$$

$$r = \frac{2 + \langle B \rangle}{2 - \langle B \rangle}$$

r:= relative response in a given (p_T^{dijet}, |η|) bin

- Require at least 2 jets, one jet in the barrel region |η|<1.3
- Azimuthal separation ΔΦ > 2.7
- Third jet veto $p_T^{3rd}/p_T^{dijet} < 0.2$

=> Measure distributions of balance variable B in representative (p_T^{dijet}, |η|) bins for all jet types



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Relative JEC: Data/MC

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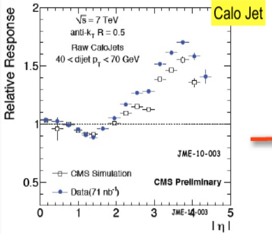
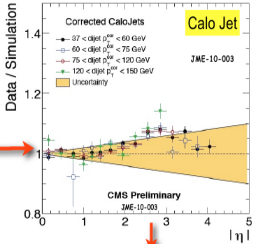
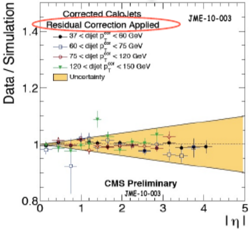


- Good agreement up to |η| =2
- Relative response in data ~10% higher compared to simulation for |η| > 2





=> Data/MC close to unity after the residual correction
=> Data/MC deviations are covered by conservative η-dependent systematic uncertainty of **±2% x |η|**

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Absolute JEC: photon+jet balance

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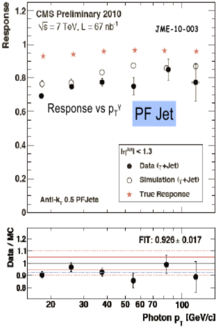
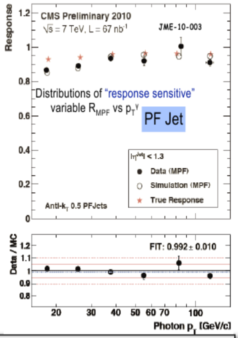
Photon+jet balance: Bias due to soft veto on second jet → Missing-E_T projection fraction method (**MPF**, from D0) uses MET to measure the balance and is less sensitive to QCD radiation





=> Mostly good agreement when same method applied to MC and Data
=> Direct evidence from MPF supports **5%/10% JEC uncertainty** as conservative

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Jet p_T resolutions

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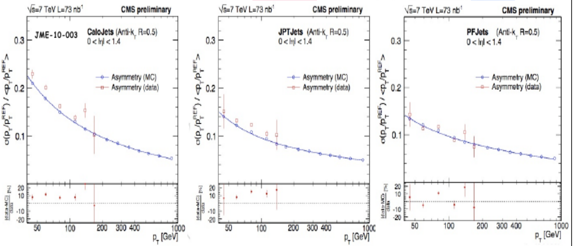
Extracted from Pythia QCD sample (MC) and Dijet Asymmetry method (In Situ)

- Define pT asymmetry of the two leading jets in back-to-back dijet events: $A = \frac{p_T^{jet1} - p_T^{jet2}}{p_T^{jet1} + p_T^{jet2}}$
- For approximately equal value of the jet p_T's: $\frac{\sigma(p_T)}{p_T} = \sqrt{2}\,\sigma_A$

Calo Jet | JPT Jet | PF Jet



- Full chain of Dijet Asymmetry method applied to data and MC to extract jet p_T resolutions

=> Observed data/MC agreement within a priori **~10% uncertainty**

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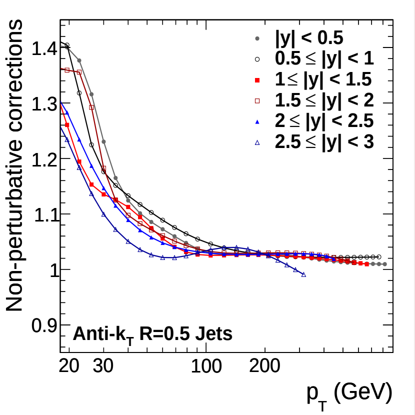
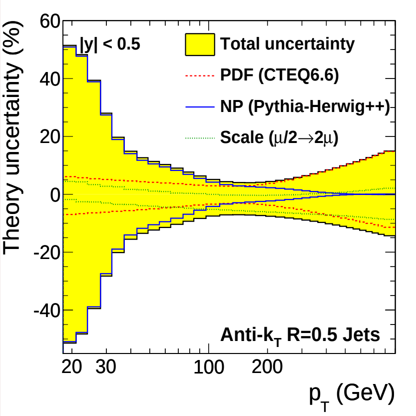
Inclusive Jet Analysis : Theoretical uncertainties

Non-perturbative corrections from Pythia and Herwig++



Uncertainties on final cross-section



Systematic uncertainties on W cross-section

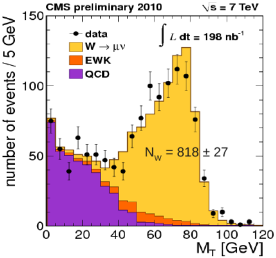
- Efficiencies and scales studied in Z events and recoil studies
- Background uncertainties from cut inversion studies and control samples
- PDF uncertainties evaluated via CTEQ66, MSTW08NLO, NNPDF2.0 sets

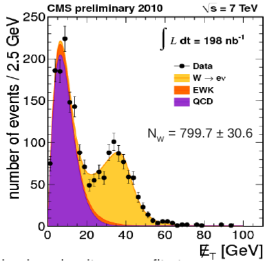
Source	$W \to \mu\nu$ (%)	$W \to e\nu$ (%)
Lepton reconstruction	3.0	6.1
Trigger Efficiency	3.2	0.6
Isolation Efficiency	0.5	1.1
Momentum/energy scale	1.0	2.7
MET scale and resolution	1.0	1.4
Background subtraction	3.5	2.2
PDF uncertainty in acceptance	2.0	2.0
Other theoretical uncertainties	1.4	1.3
Total systematic error	6.3	7.7
Luminosity uncertainty	11.0	11.0

Systematic uncertainties on Z cross-section

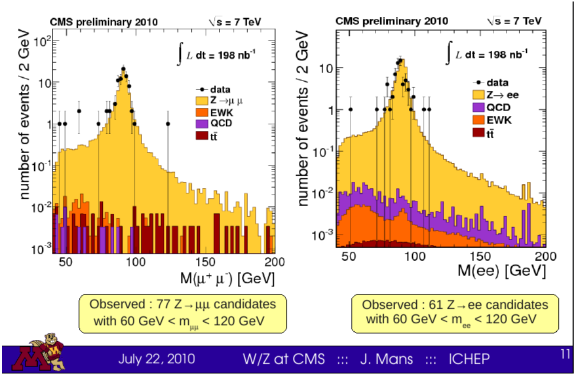
Source	$Z \to \mu\mu$ (%)	$Z \to ee$ (%)
Lepton reconstruction	2.5	7.2
Trigger Efficiency	0.7	-
Isolation Efficiency	1.0	1.2
Momentum/energy scale	0.5	-
PDF uncertainty in acceptance	2.0	2.0
Other theoretical uncertainties	1.6	1.3
Total systematic error	3.8	7.7
Luminosity uncertainty	11.0	11.0

W events leading to cross-section measurement



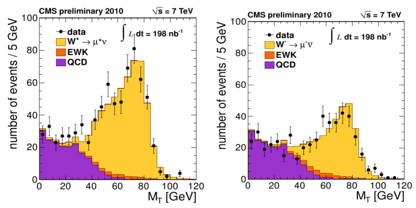


Z events leading to cross-section measurement

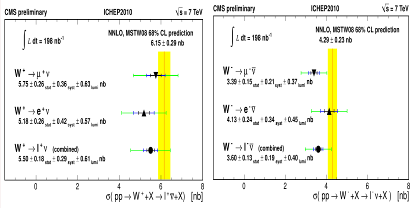


W cross-section by charge

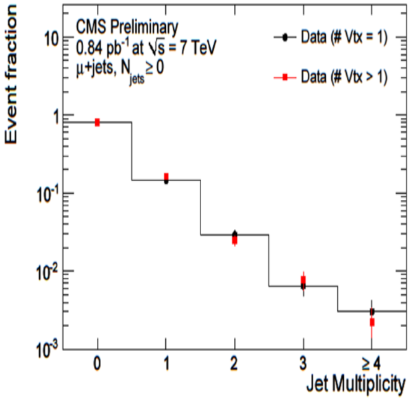
Transverse Mass



Cross-sections



Top-quark pair-production: influence of pile-up



Event Yields for $t\bar{t} \rightarrow ll$ channel

Table 1: Event yields (from simulation) for signal and background contributions, compared to the number of events in 0.84 ± 0.09 pb^{-1} of 7 TeV collision data. Also shown are the data-driven background estimates. The event selection includes the requirements of two opposite sign, high-p_T, isolated leptons, the Z-boson veto, and N(jets) > 1, but no requirement of missing transverse energy. For details, e.g. on the event selection or the systematic uncertainties included in this table, see the description in CMS-PAS-TOP-10-004.

Sample	ee	$\mu\mu$	$e\mu$
Dilepton $t\bar{t}$	$0.63 \pm 0.09 \pm 0.12$	$0.70 \pm 0.11 \pm 0.13$	$1.70 \pm 0.26 \pm 0.32$
VV	0.05 ± 0.03	0.05 ± 0.03	0.12 ± 0.06
Single top - tW	0.04 ± 0.02	0.05 ± 0.03	0.12 ± 0.06
Drell-Yan $\tau\tau$	0.08 ± 0.04	0.13 ± 0.07	0.19 ± 0.09
Drell-Yan $ee, \mu\mu$	4.2 ± 1.1	5.0 ± 1.2	0.04 ± 0.02
Non-dilepton $t\bar{t}$	0.02 ± 0.01	0.003 ± 0.002	0.03 ± 0.02
W+jets	0.06 ± 0.03	$0.000\ ^{+0.002}_{-0.000}$	0.07 ± 0.04
QCD multijets	$0\ ^{+10}_{-0}$	$0\ ^{+10}_{-0}$	$0\ ^{+10}_{-0}$
Total simulated	5.1 ± 1.1	5.9 ± 1.2	2.3 ± 0.4
QCD data-driven	$0.0\ ^{+0.1}_{-0.0}\ ^{+0.1}_{-0.0}$	$0.0\ ^{+0.2}_{-0.0}\ ^{+0.2}_{-0.0}$	$0.0\ ^{+0.1}_{-0.0}\ ^{+0.1}_{-0.0}$
W+jets data-driven	$0.2\ ^{+0.2}_{-0.0}\ ^{+0.1}_{-0.0}$	$0.0\ ^{+0.4}_{-0.0}\ ^{+0.2}_{-0.0}$	$0.0\ ^{+0.4}_{-0.0}\ ^{+0.2}_{-0.0}$
Drell-Yan data-driven	$3.6 \pm 0.6 \pm 1.8$	$4.3 \pm 0.7 \pm 2.1$	N/A
Data	6	6	2

Event Yields for $t\bar{t} \rightarrow l + jet$ channel

Table 2: Event yields (from simulation) for signal and background contributions for the e+jets channel, compared to the number of events in 0.84 ± 0.09 pb^{-1} of 7 TeV collision data. For details, e.g. on the event selection or the uncertainties included in this table, see the description in CMS-PAS-TOP-10-004.

Jet multiplicity	ttbar	single top	W+jets	Z+jets	QCD	Sum MC	Data
$N_{jets} \geq 0$	12 ± 2	3.4 ± 0.4	2619 ± 317	180 ± 21	658 ± 73	3472 ± 326	3434
$N_{jets} \geq 1$	12 ± 2	3.1 ± 0.4	419 ± 77	92 ± 11	436 ± 62	962 ± 99	1022
$N_{jets} \geq 2$	11 ± 2	1.9 ± 0.3	74 ± 18	19 ± 5	85 ± 22	191 ± 29	183
$N_{jets} \geq 3$	8.9 ± 1.8	0.70 ± 0.14	13 ± 4	3.3 ± 1.0	14 ± 5	40 ± 7	43
$N_{jets} \geq 4$	4.8 ± 1.2	0.21 ± 0.06	2.6 ± 1.1	0.60 ± 0.23	2.3 ± 1.1	11 ± 2	13

Table 2: Event yields (from simulation) for signal and background contributions for the μ+jets, compared to the number of events in 0.84 ± 0.09 pb^{-1} of 7 TeV collision data. For details, e.g. on the event selection or the uncertainties included in this table, see the description in CMS-PAS-TOP-10-004.

Jet multiplicity	ttbar	single top	W+jets	Z+jets	QCD	Sum MC	Data
$N_{jets} \geq 0$	13 ± 3	4.2 ± 0.4	3708 ± 448	192 ± 29	223 ± 25	4140 ± 450	4142
$N_{jets} \geq 1$	13 ± 3	3.9 ± 0.4	552 ± 106	42 ± 12	79 ± 17	690 ± 108	789
$N_{jets} \geq 2$	13 ± 2	2.3 ± 0.3	92 ± 24	7.1 ± 4.4	10 ± 3	124 ± 25	153
$N_{jets} \geq 3$	10 ± 2	0.82 ± 0.15	16 ± 5	1.3 ± 0.9	1.3 ± 0.5	29 ± 5	40
$N_{jets} \geq 4$	5.6 ± 1.4	0.24 ± 0.06	3.1 ± 1.2	0.25 ± 0.18	0.15 ± 0.07	9.3 ± 1.9	11