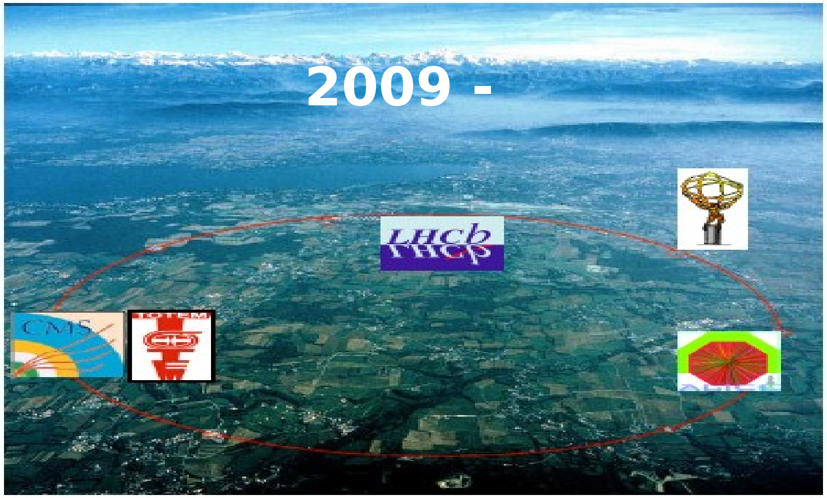
Hadron Collider Physics

Lecture 2

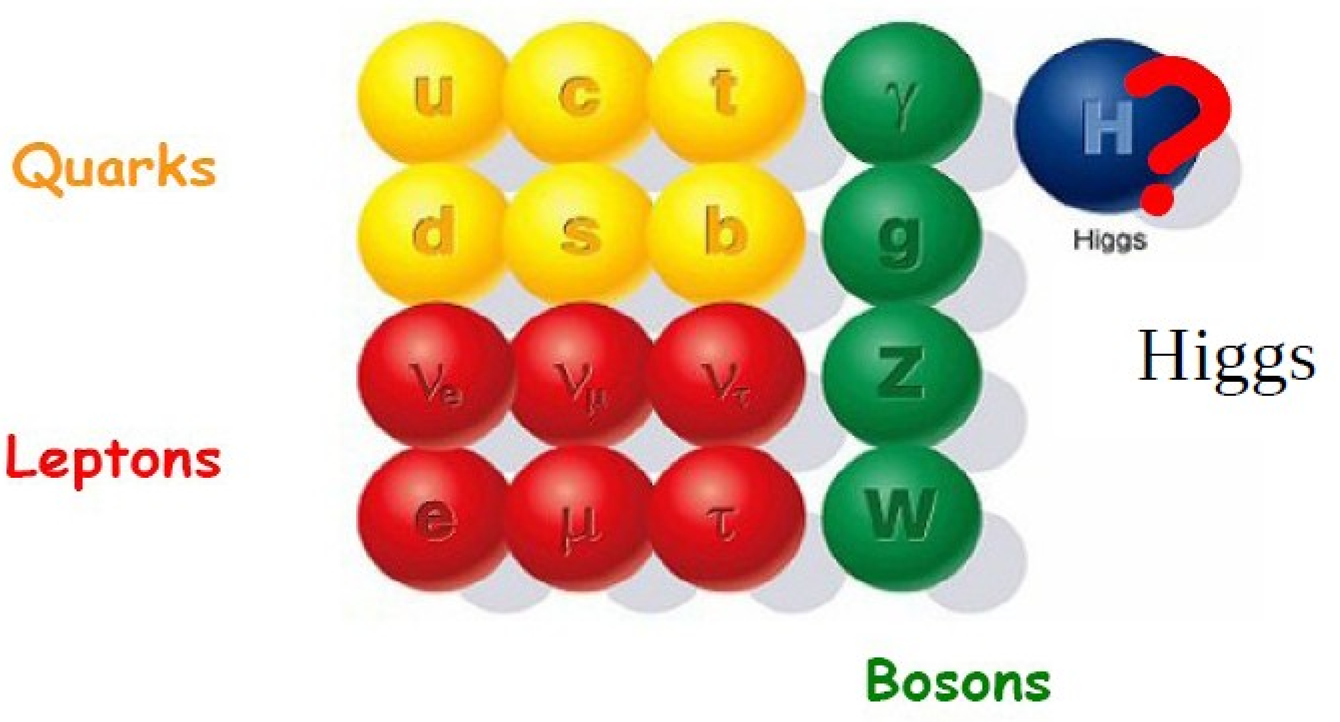
- QCD jets
- W, Z bosons

Disclaimer:

- **shown results based on 2010-2011 data for LHC**
- **the 2012 news left to topical lectures of the next week**



Standard Model



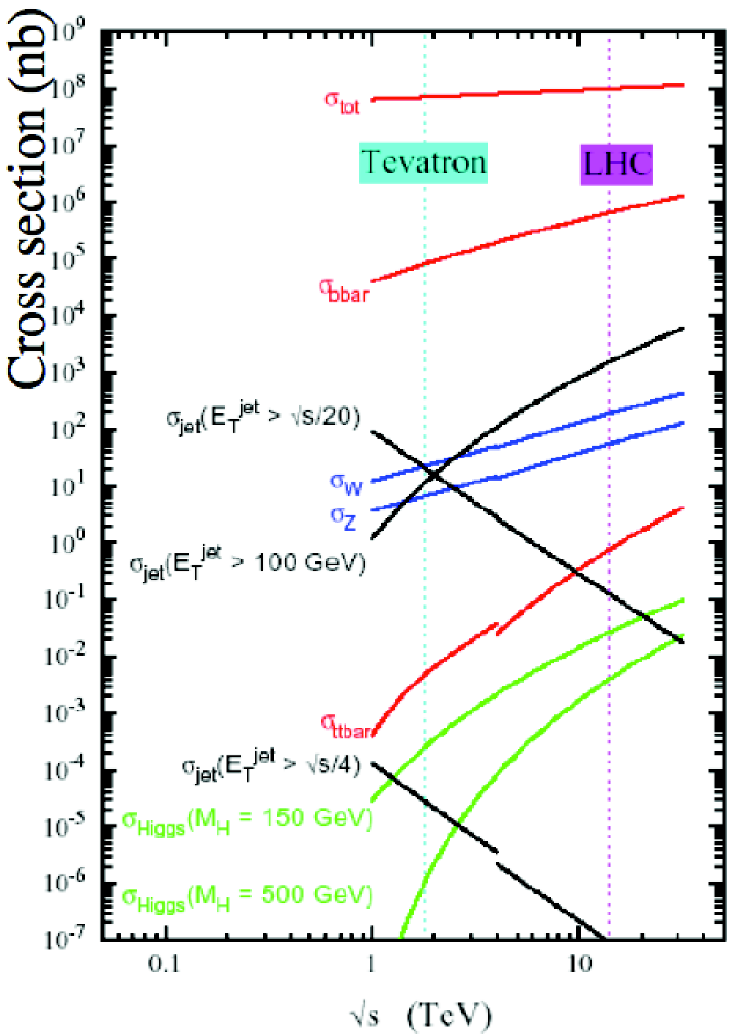
- Most quarks/leptons/bosons deeply scrutinised already
- Neutrinos not really testable at hadron colliders
- Many open issues about top quark
- Higgs (?)

Cross -section

- Differential cross section: $d\sigma/d\Omega$:
  - Probability of a scattered particle in a given quantum state per solid angle $d\Omega$
    - E.g. Rutherford scattering experiment
- Other differential cross sections: $d\sigma/dE_T$(jet)
  - Probability of a jet with given E_T
- Integrated cross section
  - Integral: $\sigma = \int d\sigma/d\Omega \, d\Omega$

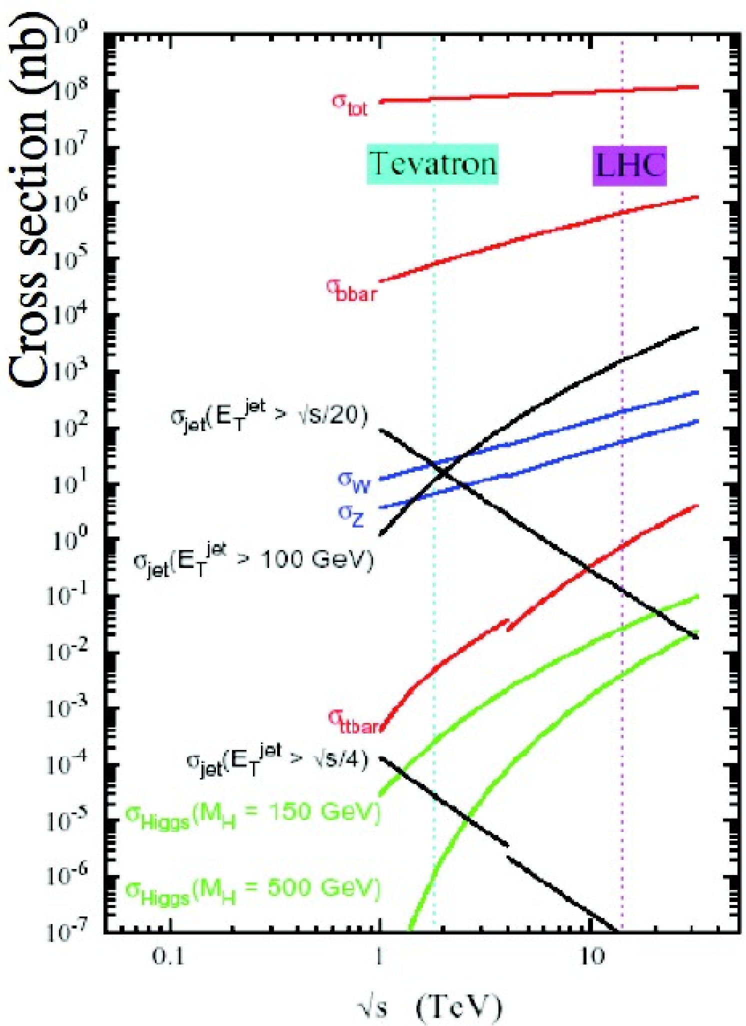
Measurement: $\sigma=(N_{obs}-N_{bg})/(\varepsilon L)$

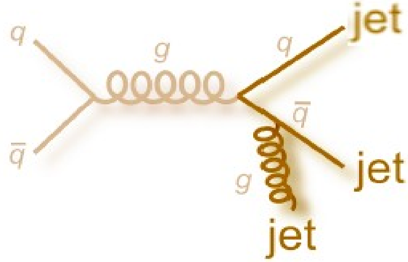
Cross-section



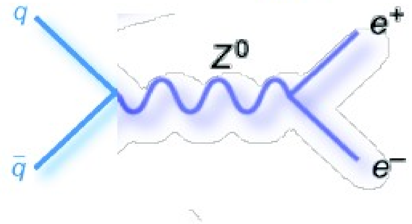
- a lot more "uninteresting" than "interesting" processes, at design luminosity ($L=10^{34}$ $cm^{-2}s^{-1}$):
  - any event: 10^9 / second
  - W boson: 150 / second
  - top quark: 8 / second
  - Higgs (150 GeV): 0.2 / second
- "interesting" events get selected by
  - trigger: online selection to find events with hard jets, leptons etc.
  - physics analysis: offline selection to enhance signal over background ratio

Cross-section

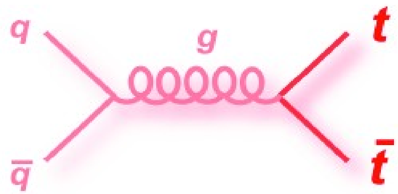




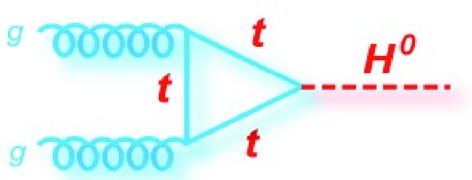
jets



W, Z bosons

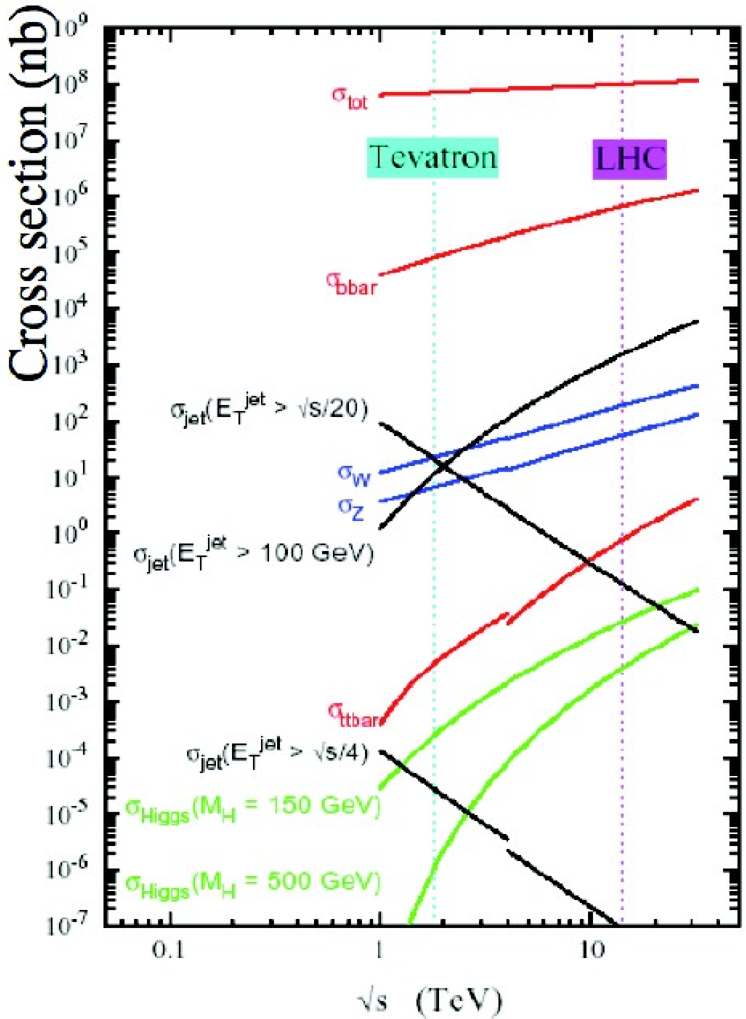


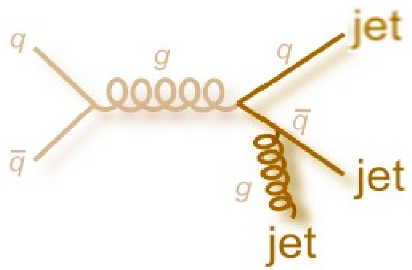
top quark



Higgs boson (?)

Cross-section





jets

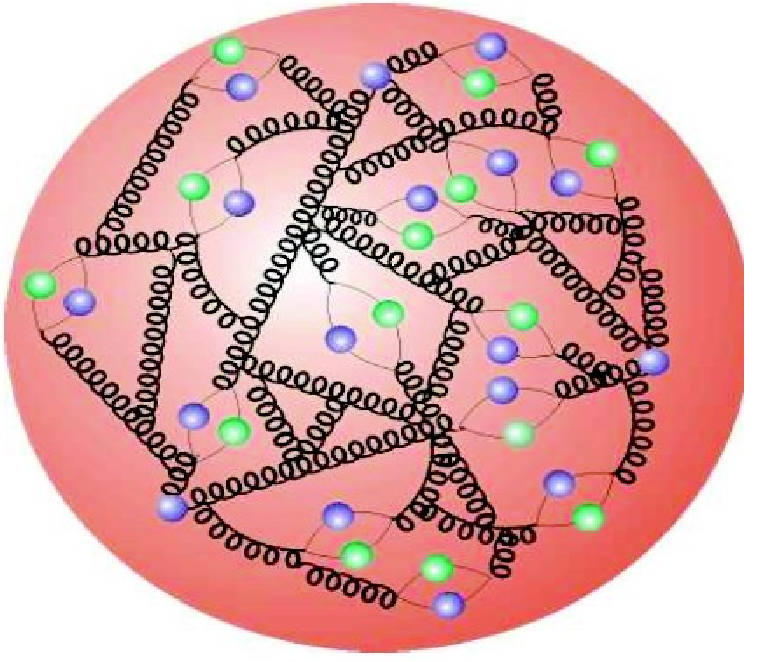
)

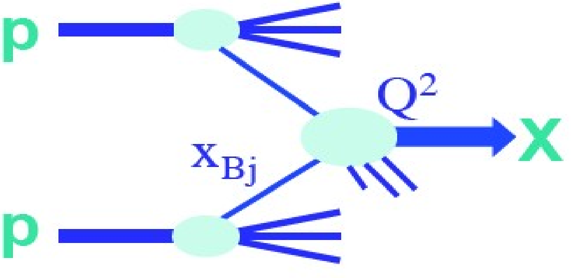
The proton composition

- It's complicated:
  - Valence quarks, Gluons, Sea quarks
- Exact mixture depends on:
  - Q^2: $\sim(M^2+p_T^2)$
  - Björken-x:
    - fraction or proton momentum carried by parton
- Energy of parton collision:

$$\hat{s} = x_p \cdot x_{\bar{p}} \cdot s$$

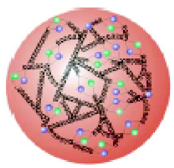
$$M_X = \sqrt{\hat{s}}$$

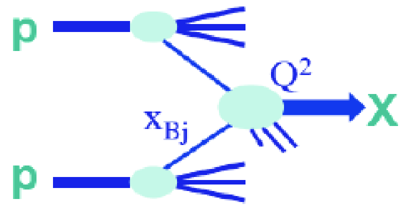




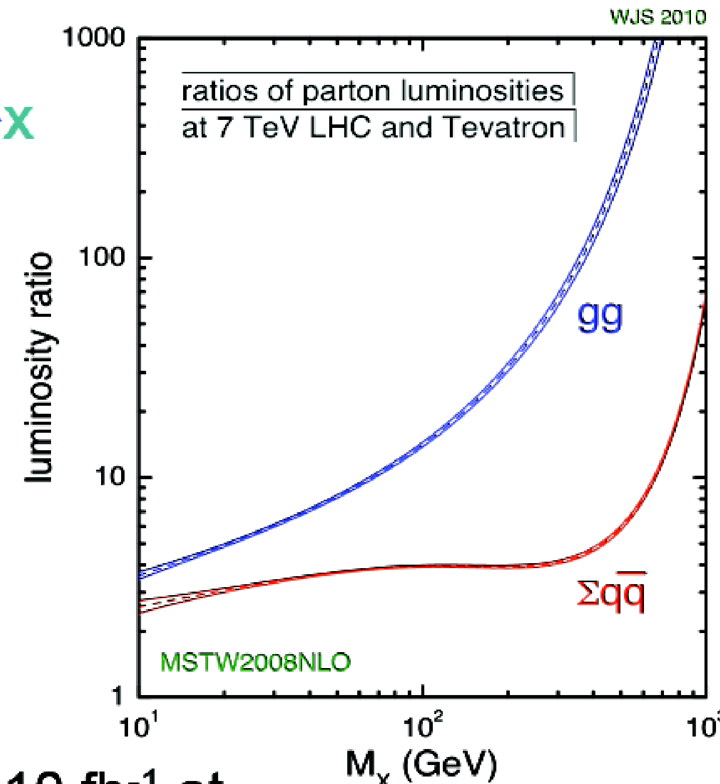
Physics cross-section

$$M_X = \sqrt{x_1 \cdot x_2 \cdot s}$$





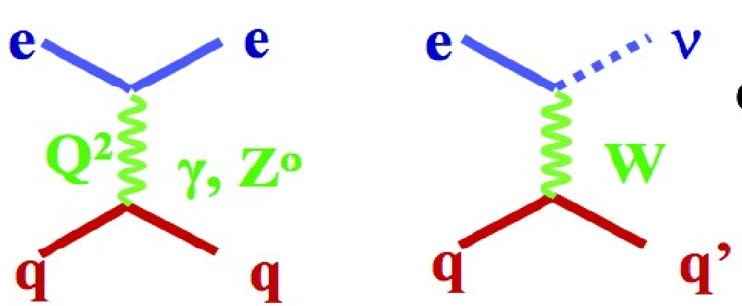
Process	M_X	σ(LHC @ 7 TeV) / σ(Tevatron)
$q\bar{q} \to W$	80 GeV	3
$q\bar{q} \to Z'_{SM}$	1 TeV	50
$gg \to H$	120 GeV	20
$q\bar{q}/gg \to t\bar{t}$	2x173 GeV	20
$gg \to \tilde{g}\tilde{g}$	2x400 GeV	1000

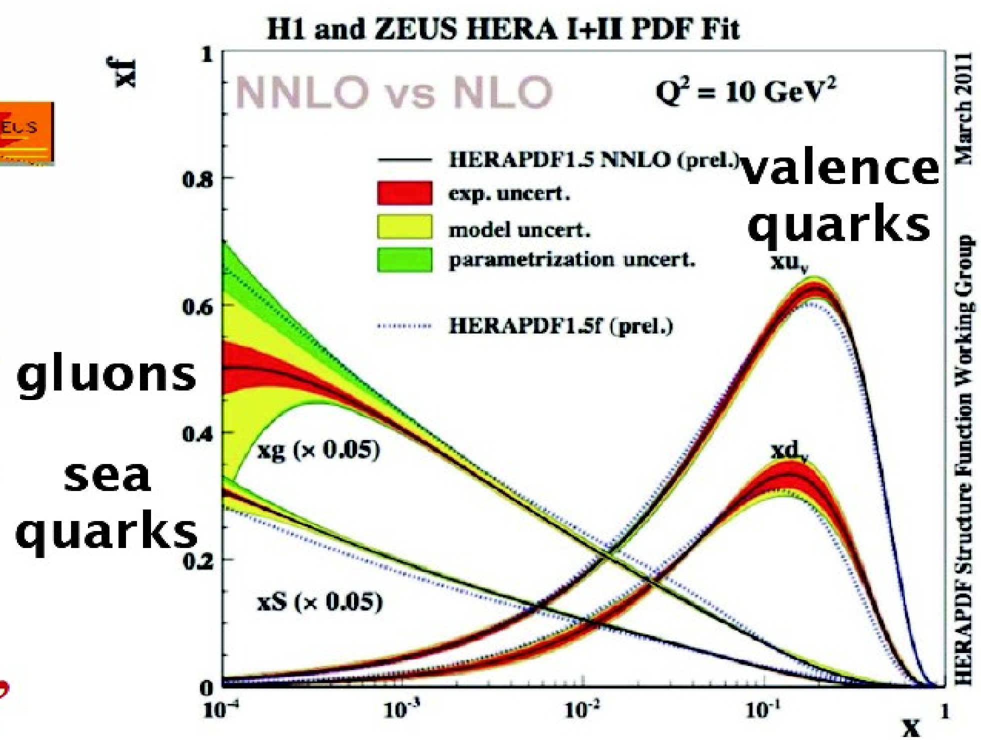


- $\int Ldt = 1\ fb^{-1}$ at LHC competitive with $10\ fb^{-1}$ at Tevatron for high mass processes
- $\int Ldt = 100\ pb^{-1}$ already interesting in some cases

41

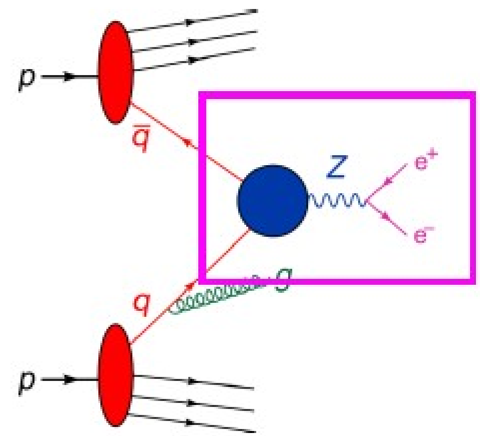
Parton density structure functions: HERA





QCD factorisation and parton model

- Asymptotic freedom guarantees that as short distances (large transverse momenta) partons in the proton are almost free
- Sampled "one at a time" in hard collisions
  - QCD improved parton shower model



Parton distribution function: prob. of finding parton *a* in proton 1, carrying fraction x_1 of its momentum

"suitable" final state

factorization scale ("arbitrary")

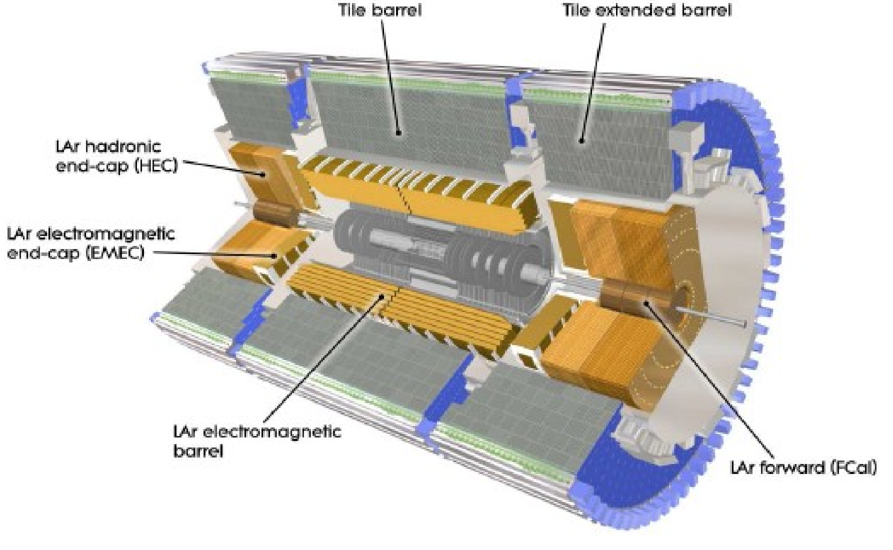
$$\sigma^{pp\to X}(s;\alpha_s,\mu_R,\mu_F) = \sum_{a,b}\int_0^1 dx_1\int_0^1 dx_2\, f_a(x_1,\alpha_s,\mu_F)\, f_b(x_2,\alpha_s,\mu_F) \times \hat{\sigma}^{ab\to X}(sx_1x_2;\alpha_s,\mu_R,\mu_F)$$

Partonic cross section, computable in perturbative QCD

partonic CM energy^2

renormalization scale ("arbitrary")

ATLAS Calorimeters



Electromagnetic and hadronic calorimeters

- Subsystem technology and granularity $\leftrightarrow$ shower characteristics
- Transverse and longitudinal sampling $\approx$ 200000 readout cells up to $|\eta| < 4.9$

Electromagnetic Calorimeters:

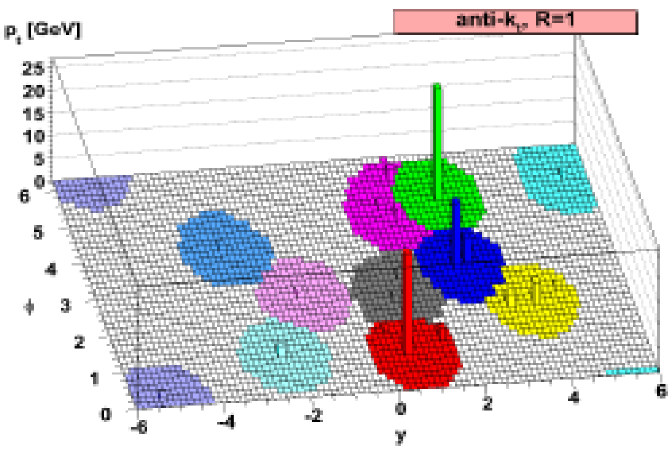
- Fine granularity $\Delta\eta \times \Delta\phi = 0.025 \times 0.025$ in central region
- Energy resolution $10\%/\sqrt{E}$

Hadronic Calorimeters:

- Granularity $\Delta\eta \times \Delta\phi = 0.1 \times 0.1$ in central region, less segmented in forward region
- Energy resolution $50\%/\sqrt{E} \oplus 0.03$

Jet reconstruction in ATLAS

- Jet finding: from partons/particles/energy deposits to jet

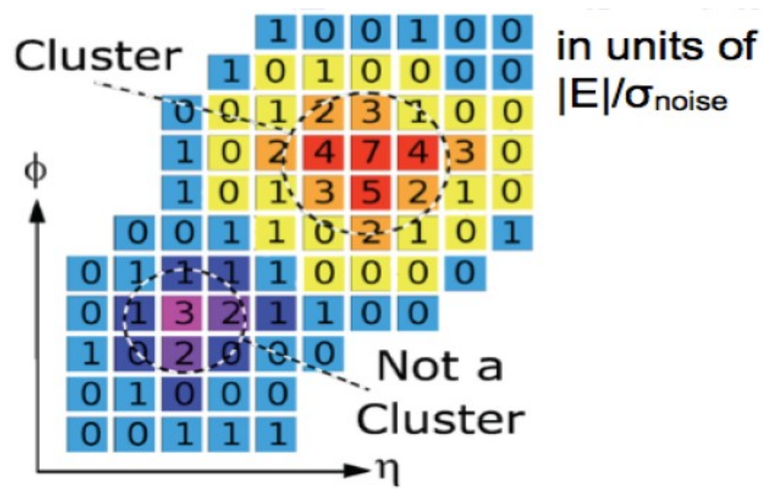


[Cacciari, Salam, Soyez JHEP 0804:063,2008]

Energy deposits → noise-suppressed 3D clusters:
exploit transverse and longitudinal calorimeter segmentation

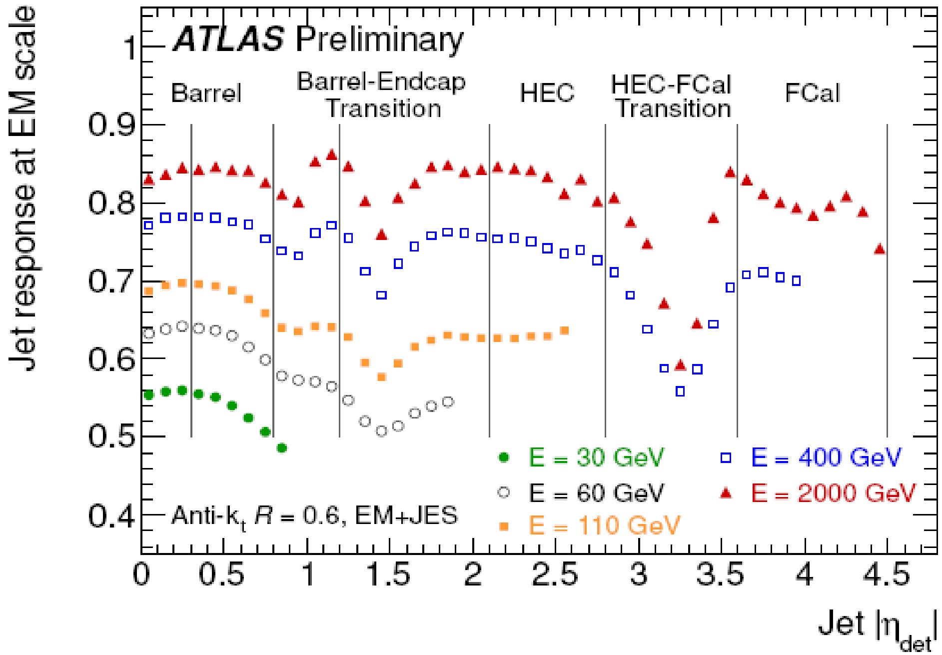
Jet inputs clustered with anti-k_T algorithm:

- Infrared safe, collinear safe (⇒ NLO comparisons)
- Regular, cone-like jets in calorimeters
- Distance parameter 0.4, 0.6



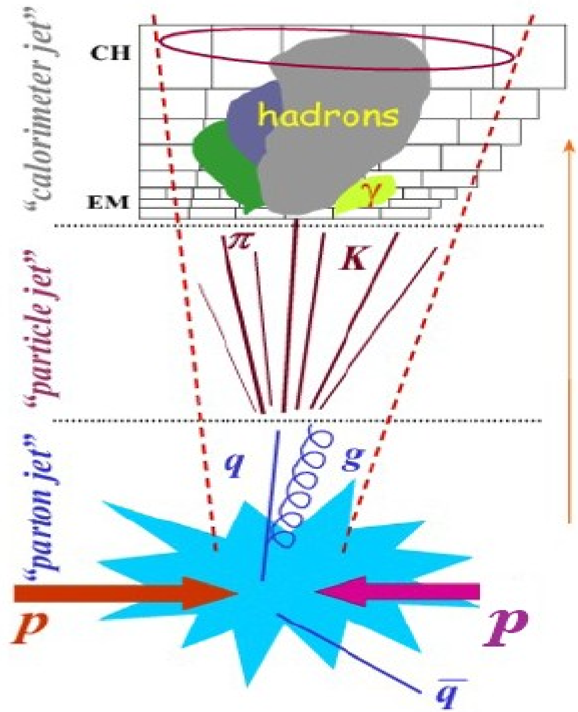
Jet reconstruction in ATLAS

- Jet calibration: restore the jet energy scale (JES) starting from the EM energy scale



Transitions between separate calorimeters evident.

η-dependent jet calib corrects for response diffs in η



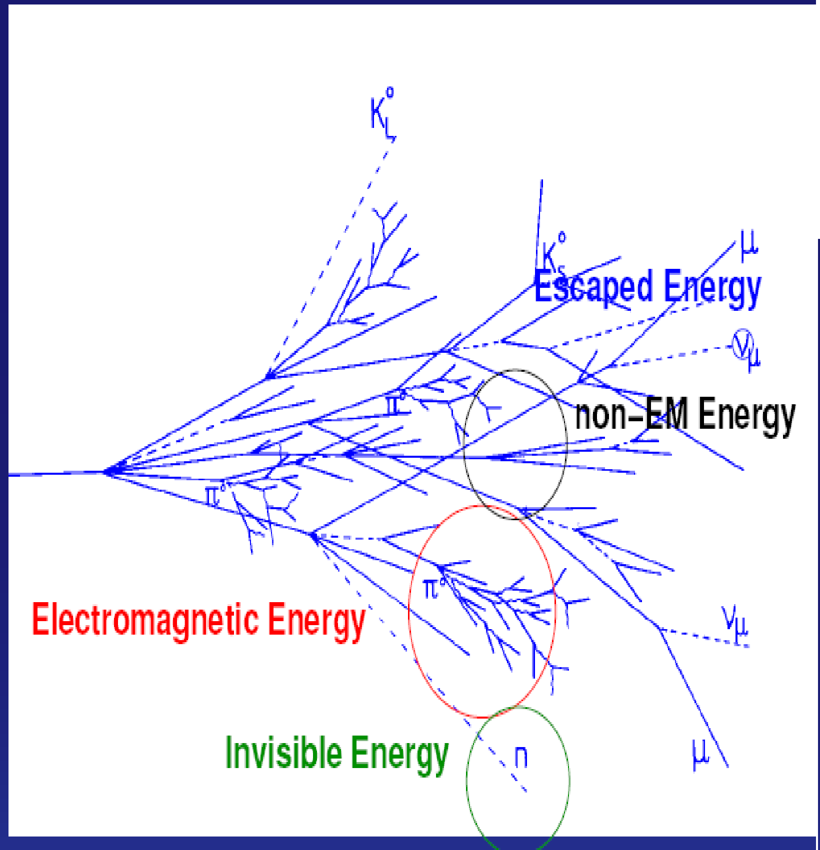
Calorimeter jet response needs to be corrected for :

- **Non-compensating** calorimeters
- **Inactive** material
- **Out-of-cone** effects

$\Rightarrow$ calibrate the jet kinematics to the hadronic scale

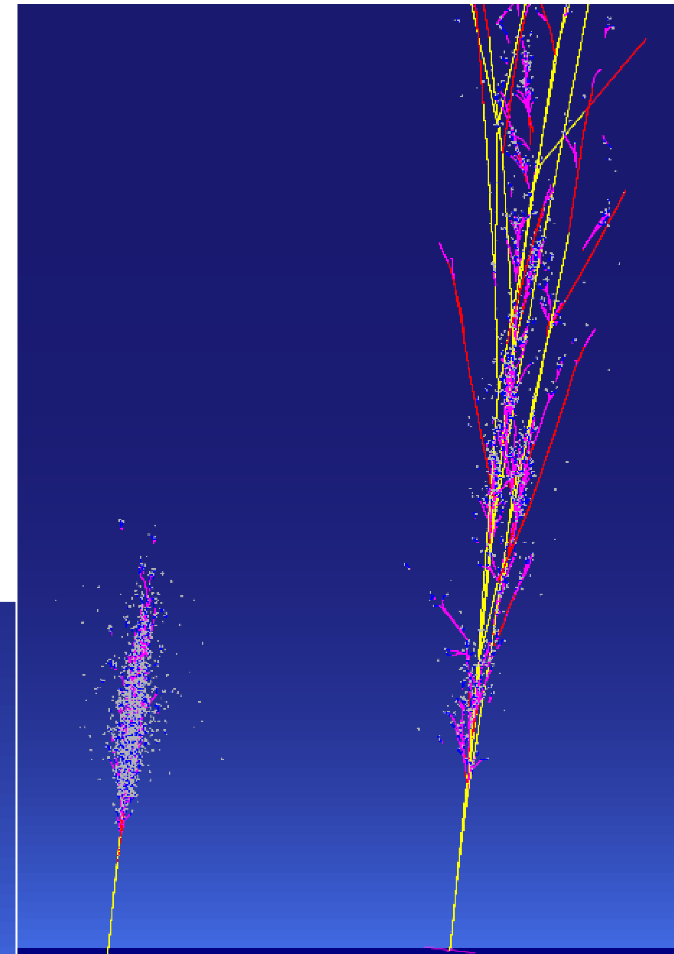
A hadronic shower consists of

- EM energy (e.g. $\pi^0 \to \gamma\gamma$) $O(50\,\%)$
- visible non-EM energy (e.g. dE/dx from $\pi^{\pm}, \mu^{\pm}$, etc.) $O(25\,\%)$
- invisible energy (e.g. breakup of nuclei and nuclear excitation) $O(25\,\%)$
- escaped energy (e.g. ν) $O(2\,\%)$



each fraction is energy dependent and subject to large fluctuations

50 GeV showers of electron (left) and pion (right) in iron

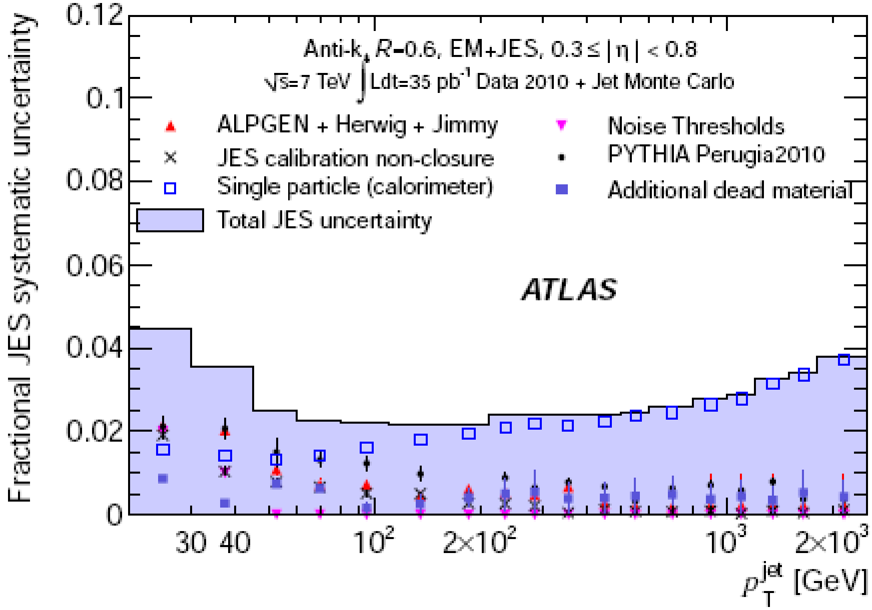


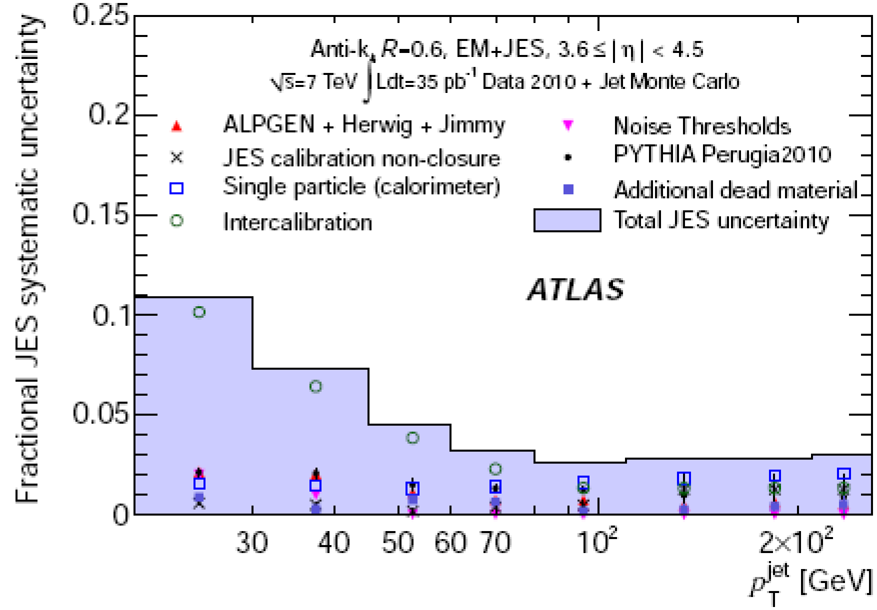
invisible energy is the main source of the non-compensating nature of hadron calorimeters

hadronic calibration has to account for the invisible and escaped energy and deposits in dead material and ignored calorimeter parts

Jet energy calibration

- Jet measurements require calibration of the jet energy scale
  - Derives a calibration which restores average JES with (η,E)-dependent calibration constants from MC





Central region $(|\eta| < 0.8)$, $60 < p_T < 800$ GeV $< 2.5\%$

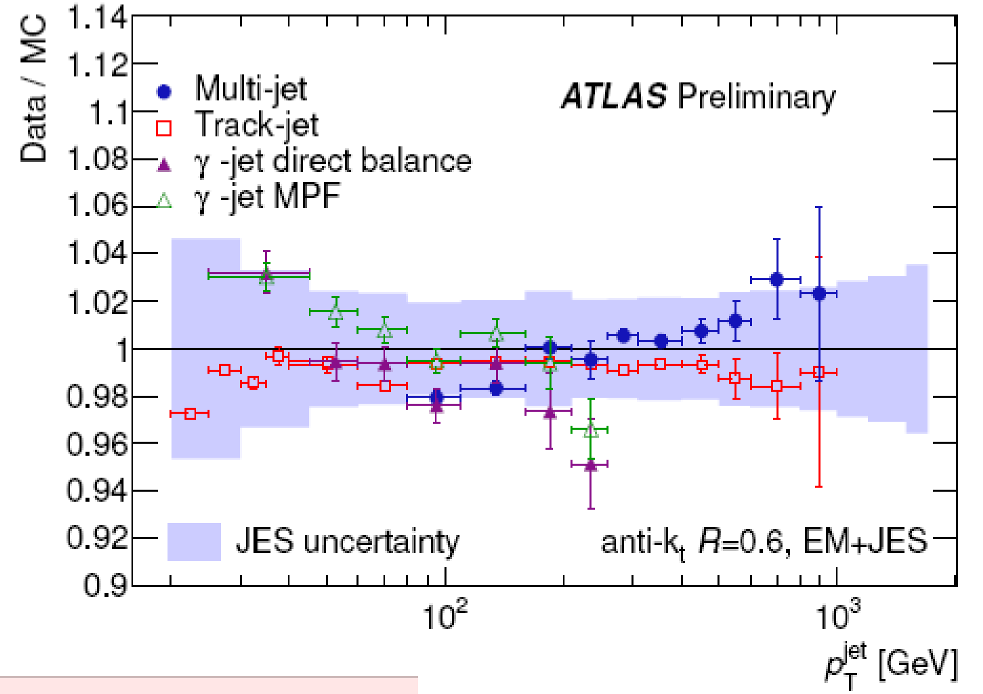
Forward region $(3.6 < |\eta| < 4.5)$, $p_T > 20$ GeV $< 12\%$

Jet energy calibration

- In-situ techniques used to validate JES and its uncertainty
  - Use well calibrated objects as reference for jet p_T
  - Compare calibrated JES in data and Monte Carlo simulation

Techniques used in ATLAS:

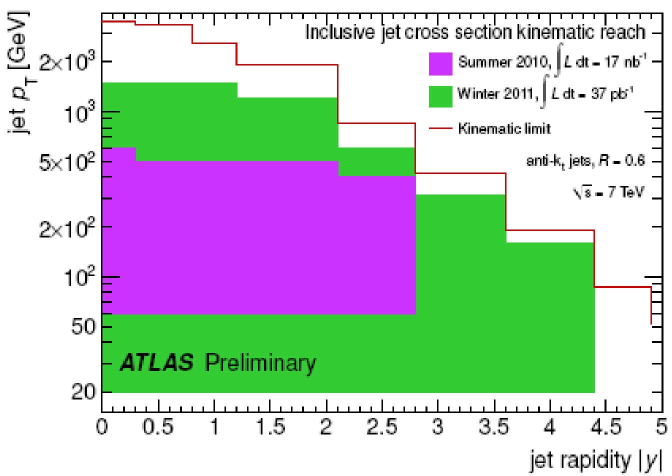
- Balance high p_T jet with recoil system (*Multi-jet / MJB*)
- γ-jet direct p_T balance
- Missing-E_T projection fraction (*MPF*)
- Compare calorimeter jets to track-jets
- $Z \rightarrow ee$-jet p_T balance (2011 only)

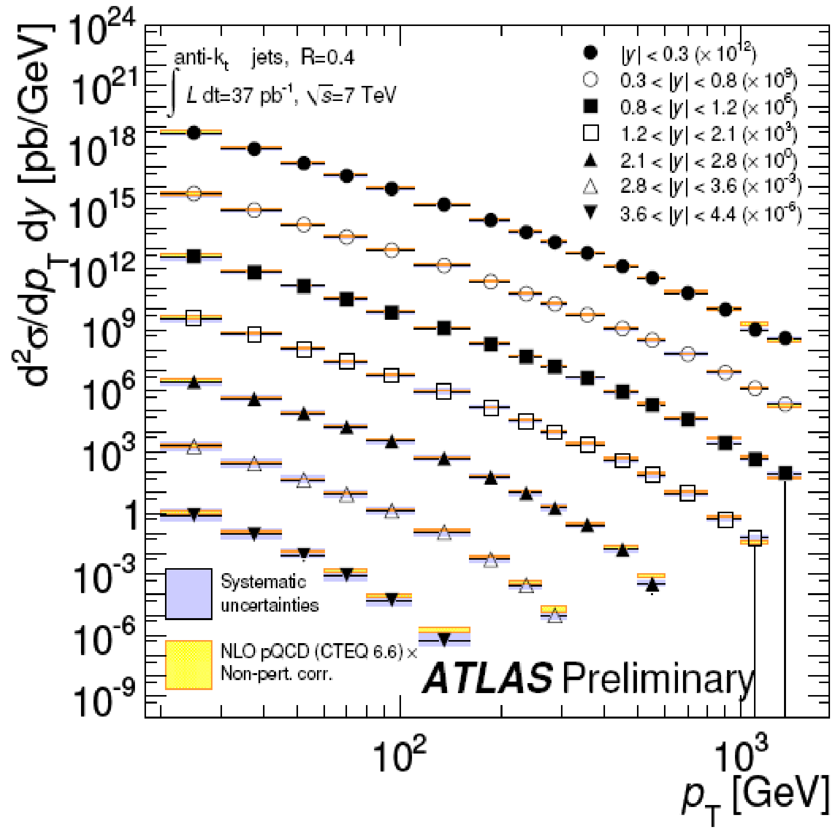


ATLAS goal for jet energy scale uncertainty: **1%**

Inclusive jet cross-section

Using 37 pb^{-1} pb of data, increasing the kinematic range of previous measurements

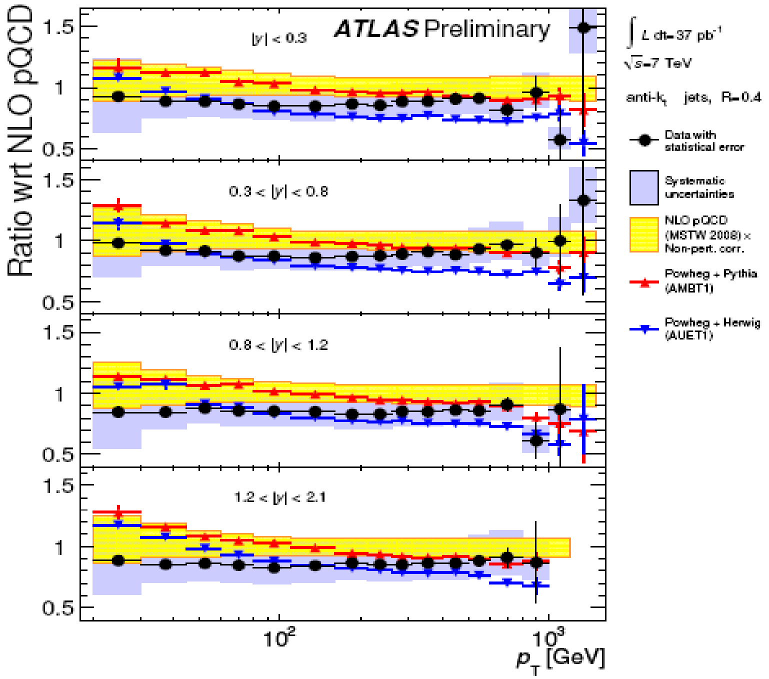


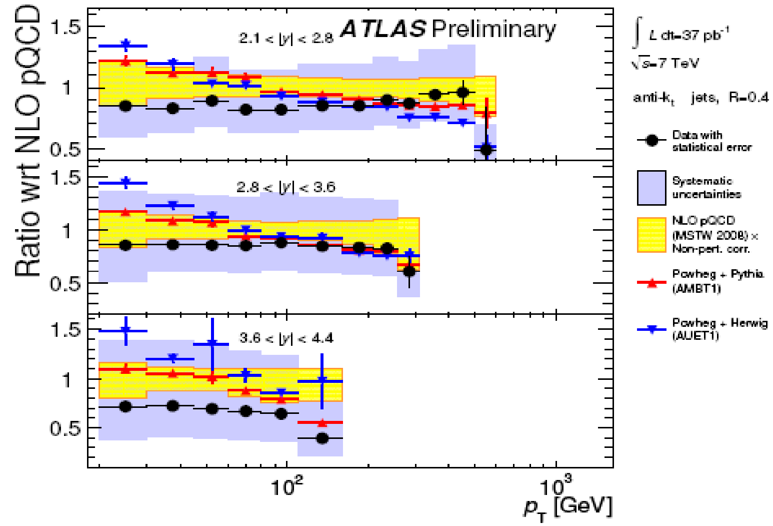


- Cross section out to $|y| < 4.4$
- p_T up to 1.5 TeV

Comparison of data to NLO pQCD predictions with CTEQ 6.6.

Inclusive jet cross-section





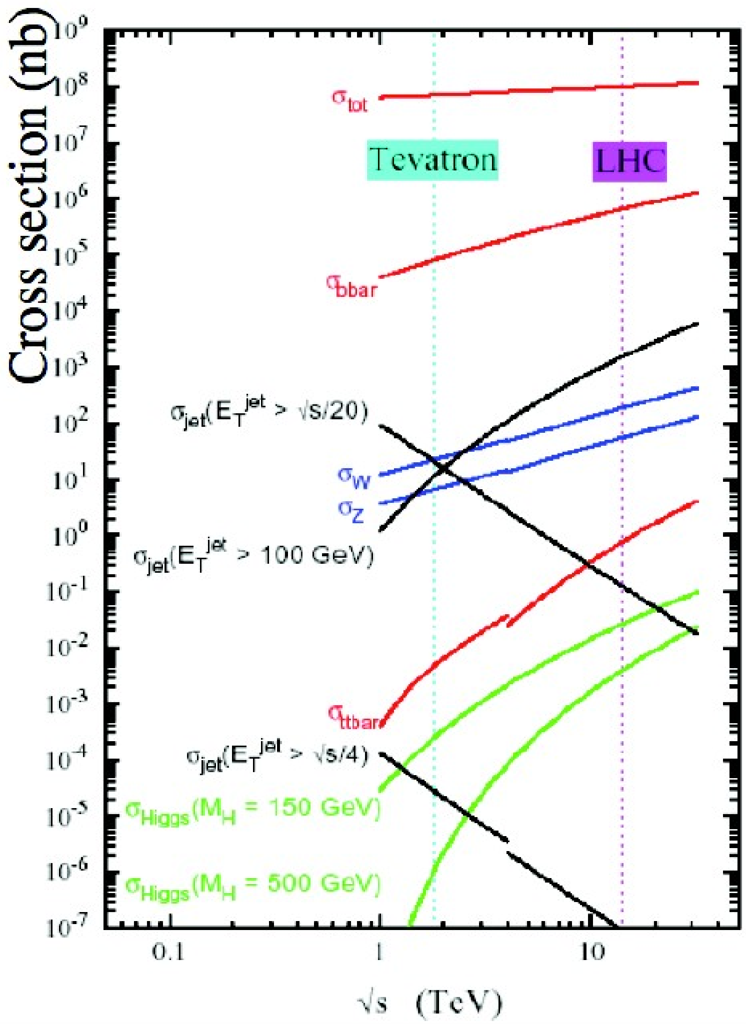
Prediction w.r.t NLOJet++ MC

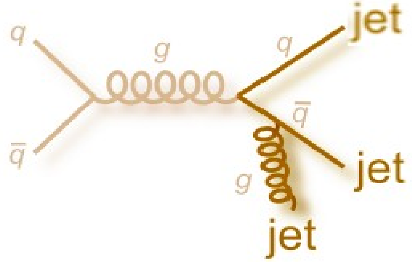
$AMBT1$, $AUET1$ are different detector tunes

Powheg predictions are consistent with data and NLOJet++, with present uncertainties

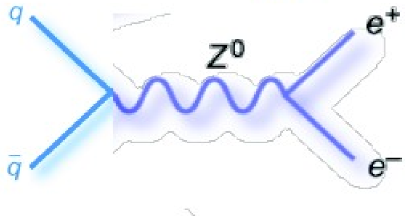
Trend for Powheg to predict different slope to cross section

Cross-section





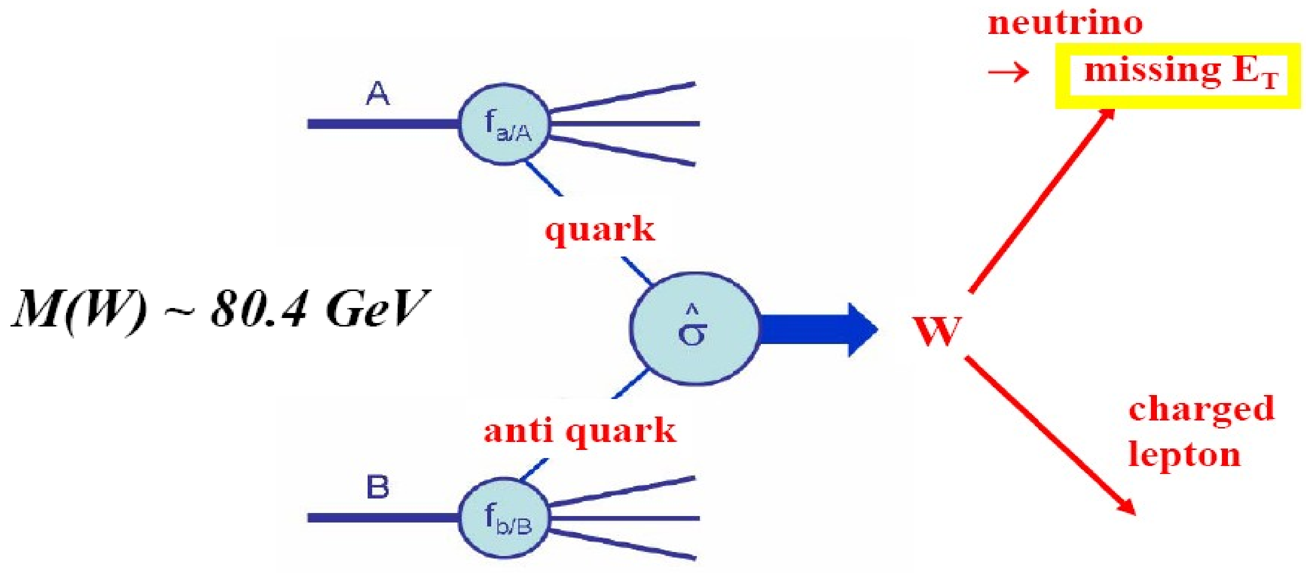
jets



W, Z bosons

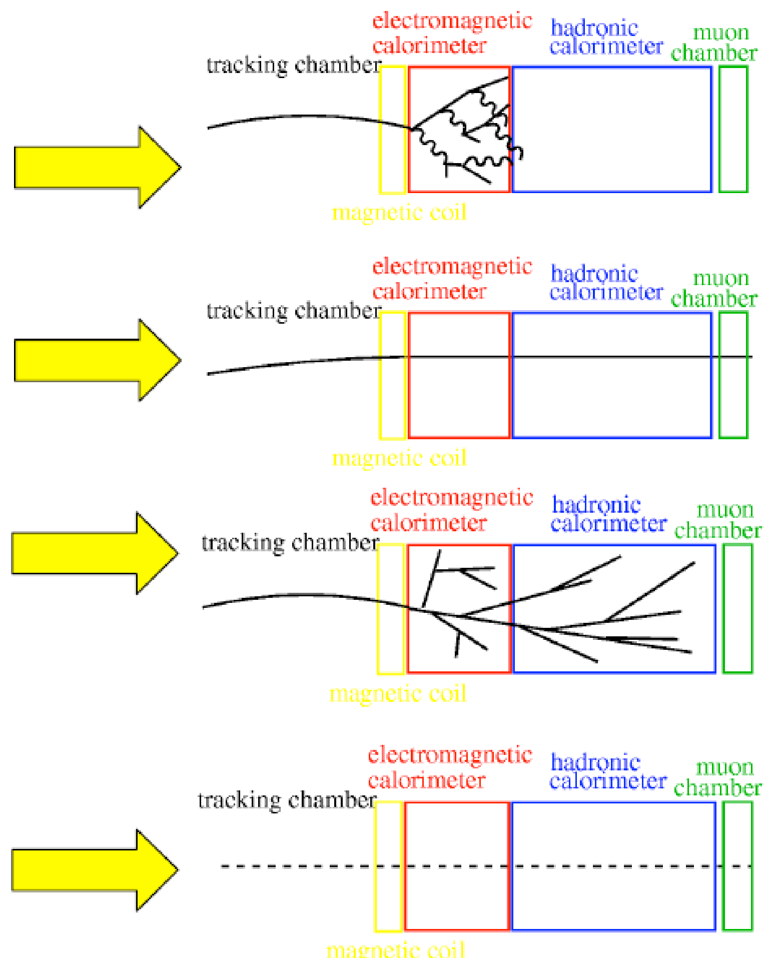
Measurement: W → l ν

- Signature:
  - Single charged lepton and missing transverse energy (MET)
  - Leptons are high p_T and isolated
  - MET from neutrino
  - Peaking at transverse invariant mass



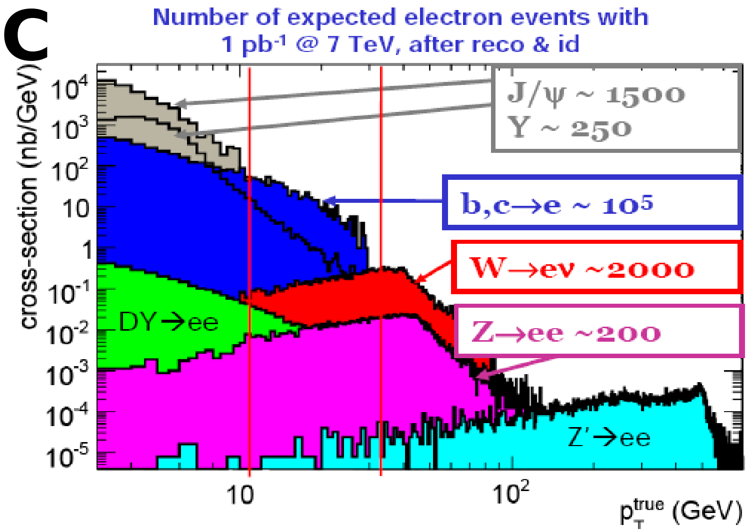
Lepton identification

- Electron:
  - Compact electromagnetic cluster in calorimeter
  - Matched to track
- Muons:
  - Track in the muon chambers
  - Matched to track
- Taus:
  - Narrow jet
  - Matched to one or three tracks
- Neutrinos
  - Imbalanse in transverse momentum
  - Inferred from total transverse energy in detector



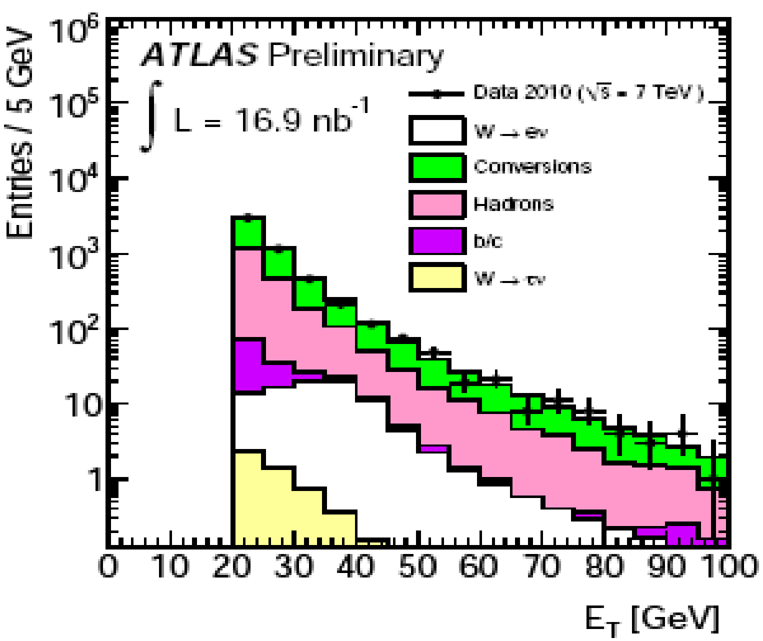
Electrons and jets

MC



- There is also lot of true electrons from semileptonic decays inside jets

DATA: loose electron ID



- Jets can look like electrons
  - Photon conversion from π^0's
  - Early showering charged pions
- And there is lot of jets
- Difficult to model in Monte Carlo
  - Detailed simulation in tracking and calorimeter volume

W selection

Electrons:

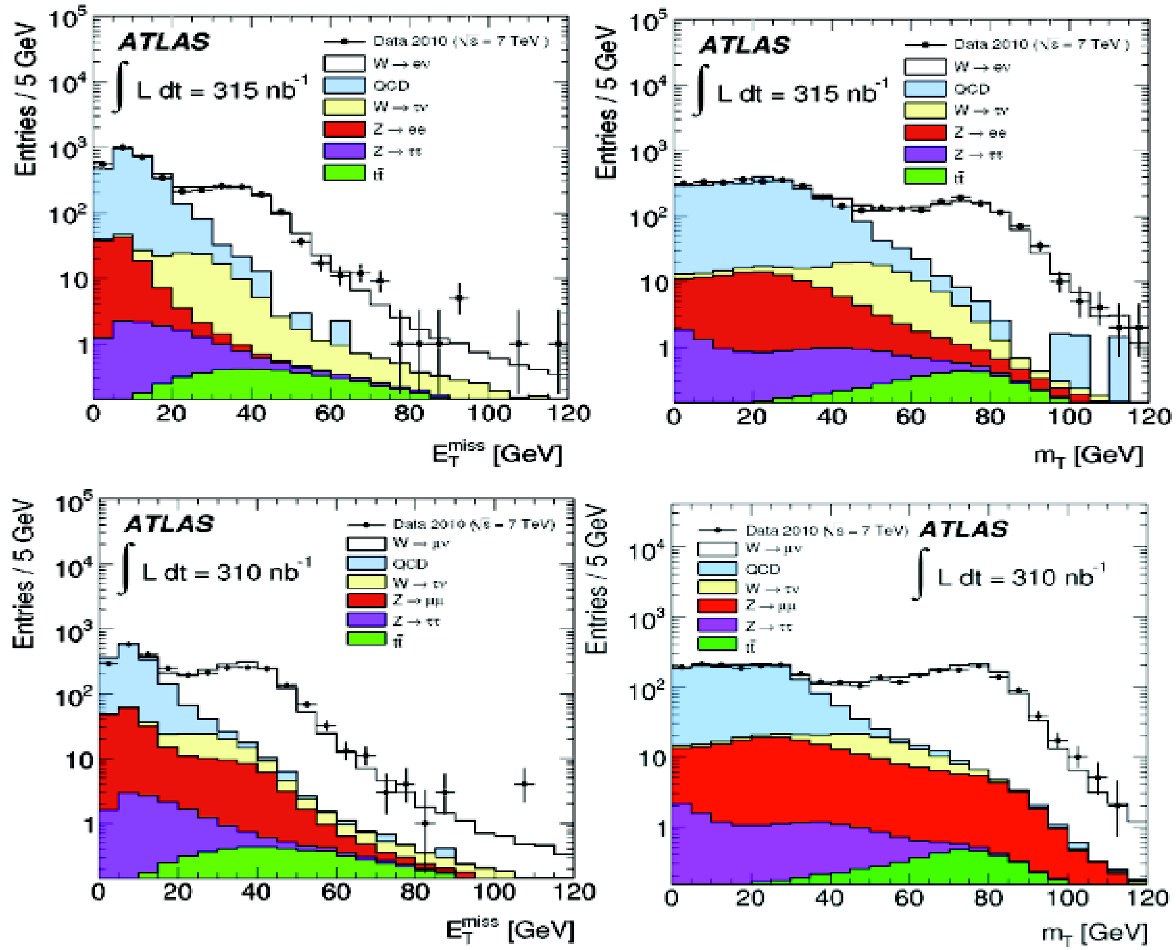
- $E_T > 20$ GeV
- *Tight ID*
- *Missing* $E_T > 25$ GeV
- $m_T > 40$ GeV

➢ *1069 Candidates*

Muons:

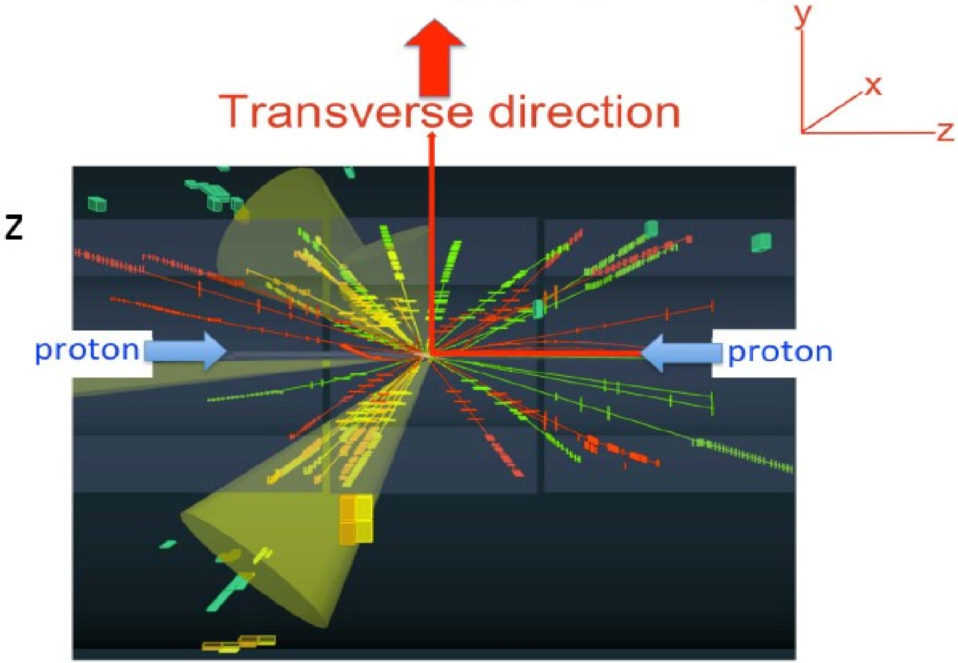
- $p_T > 20$ GeV
- *Track isolation*
- *Missing* $E_T > 25$ GeV
- $m_T > 40$ GeV

➢ *1181 Candidates*



Missing transverse energy

- In pp collisions at the LHC, a significant, unmeasured amount of energy escapes in z direction
- Total initial and final momentum is zero in transverse direction
- Imbalance of energy in transverse direction signals presence of weakly or non-interacting particles such as neutrinos



$$E_T^{miss} = \sqrt{(E_x^{miss})^2 + (E_y^{miss})^2}$$

$$E_{x(y)}^{miss} = - \sum_{particles} E_{x(y)}$$

$$\sum E_T = \sum_{particles} E_T$$

2

W backgrounds

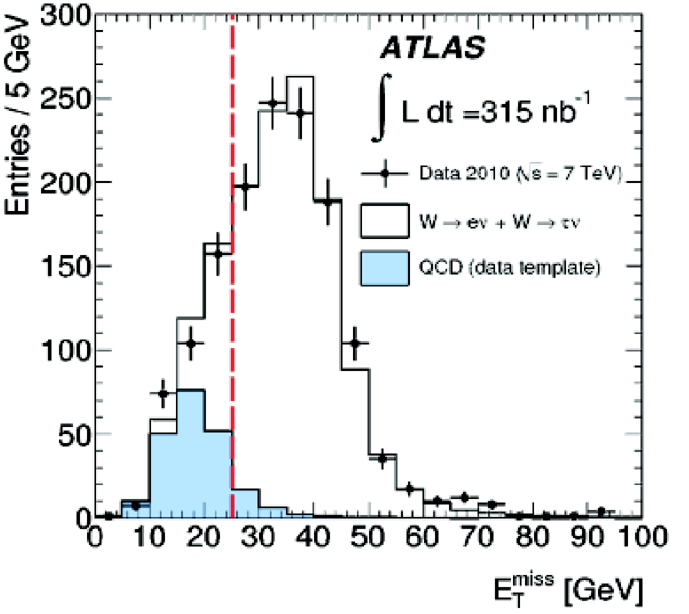
Electrons:

- EW + top background: $W \rightarrow \tau\ \nu\ + Z \rightarrow e^+e^- + t\bar{t}$

  $N_{EW+TOP} = 33.5 \pm 0.2(stat) \pm 3.0(syst)$

- QCD background is estimated with the template method using the missing energy distribution.

  $N_{QCD} = 28.0 \pm 3.0(stat) \pm 10.0(syst)$



Muons:

- EW + top background: $Z \rightarrow \mu^+\mu^- + W \rightarrow \tau\ \nu^- + t\bar{t}$

  $N_{EW+TOP} = 77.6 \pm 0.3(stat) \pm 5.4(syst)$

- QCD background estimated from comparison of events seen in data after the full selection to number of events observed if the isolation is not applied.

  $N_{QCD} = 22.8 \pm 4.6(stat) \pm 8.7(syst)$

$$N_{loose} = N_{nonQCD} + N_{QCD}$$
$$N_{iso} = \epsilon^{iso}_{nonQCD} N_{nonQCD} + \epsilon^{iso}_{QCD} N_{QCD}$$

Cross-section measurement

$$\sigma = \frac{N_{\mathrm{obs}} - N_{\mathrm{bkg}}}{A \cdot C \cdot \int dt\, \mathcal{L}}$$

N_{obs}: number of observed events in the signal region

N_{bkg}: estimated number of background events

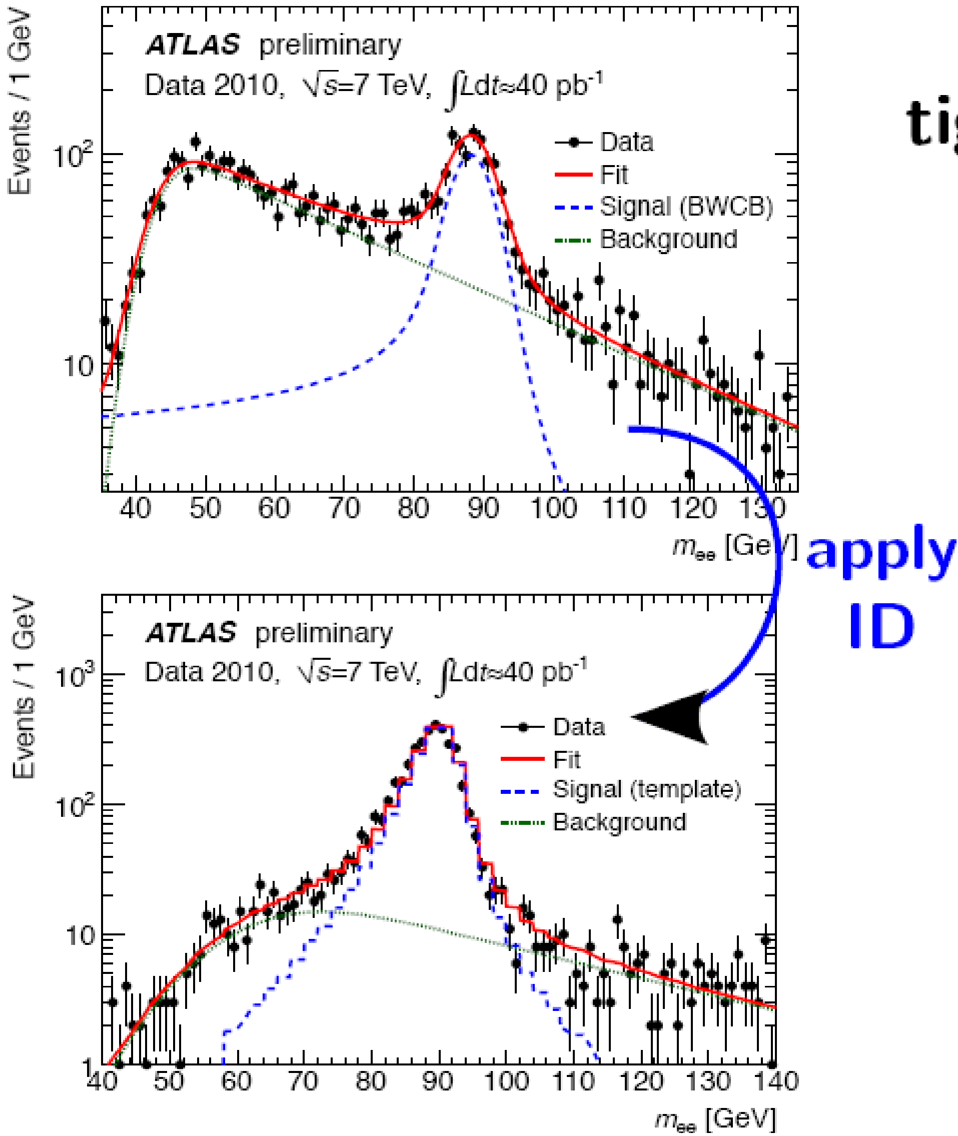
- EW backgrounds are estimated with Monte Carlo, constrained to data with performance scale factors.
- QCD backgrounds are estimated with **data-driven** methods.

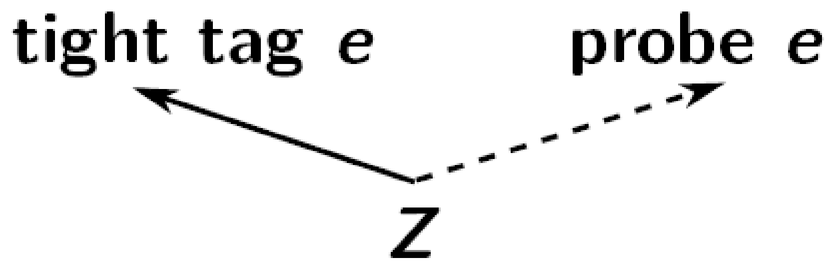
A: kinematic acceptance factor, estimated with generator-level Monte Carlo.

C: summarizes reconstruction efficiency, estimated with reconstructed Monte Carlo, corrected with **scale factors**.

$\int dt\, \mathcal{L}$: integrated luminosity.

Scale factor: tag-and-probe studies





- **"Tag"** events with sufficient purity, leaving an unbiased **"probe"** object.
- Measure probe ID efficiency *in situ*.
- Constrains the performance of our object identification.
- Derive **scale factors** for correcting our simulation.

W cross-section measurements

The total cross section for each lepton channel can be obtained by:

$$\sigma_W \times BR(W \to l\nu) = \frac{N_W^{obs} - N^{bkg}}{A_W C_W L_{int}}$$

A_W is the geometrical acceptance calculated at generator level:

$$A_W = \left(\frac{N^{acc}}{N^{all}}\right)_{gen}$$

MC	A_W $W^+ \to e^+\nu$	A_W $W^- \to e^-\nu$	A_W $W \to e\nu$	A_W $W^+ \to \mu^+\nu$	A_W $W^- \to \mu^-\nu$	A_W $W \to \mu\nu$
PYTHIA MRST LO*	0.466	0.457	0.462	0.484	0.475	0.480
PYTHIA CTEQ6.6	0.479	0.458	0.471	0.499	0.477	0.490
PYTHIA HERAPDF1.0	0.477	0.461	0.470	0.496	0.479	0.489
MC@NLO HERAPDF1.0	0.475	0.454	0.465	0.494	0.472	0.483
MC@NLO CTEQ6.6	0.478	0.452	0.465	0.496	0.470	0.483

C_W components and uncertainties

$$\sigma_W \times BR(W \to l\nu) = \frac{N_W^{obs} - N^{bkg}}{A_W C_W L_{int}}$$

- C_W is a factor correcting for reconstruction, identification and trigger efficiencies of the lepton.

	$W \to e\nu$	$W \to \mu\nu$
C_W	0.66	0.76

- Components to systematic uncertainties, are summarized below:

Parameter	$\delta C_W / C_W (\%)$
Trigger efficiency	<0.2
Material effects, reconstruction and identification	5.6
Energy scale and resolution	3.3
E_T^{miss} scale and resolution	2.0
Problematic regions in the calorimeter	1.4
Pile-up	0.5
Charge misidentification	0.5
FSR modelling	0.3
Theoretical uncertainty (PDFs)	0.3
Total uncertainty	7.0

Electrons

Parameter	$\delta C_W / C_W (\%)$
Trigger efficiency	1.9
Reconstruction efficiency	2.5
Momentum scale	1.2
Momentum resolution	0.2
E_T^{miss} scale and resolution	2.0
Isolation efficiency	1.0
Theoretical uncertainty (PDFs)	0.3
Total uncertainty	4.0

Muons

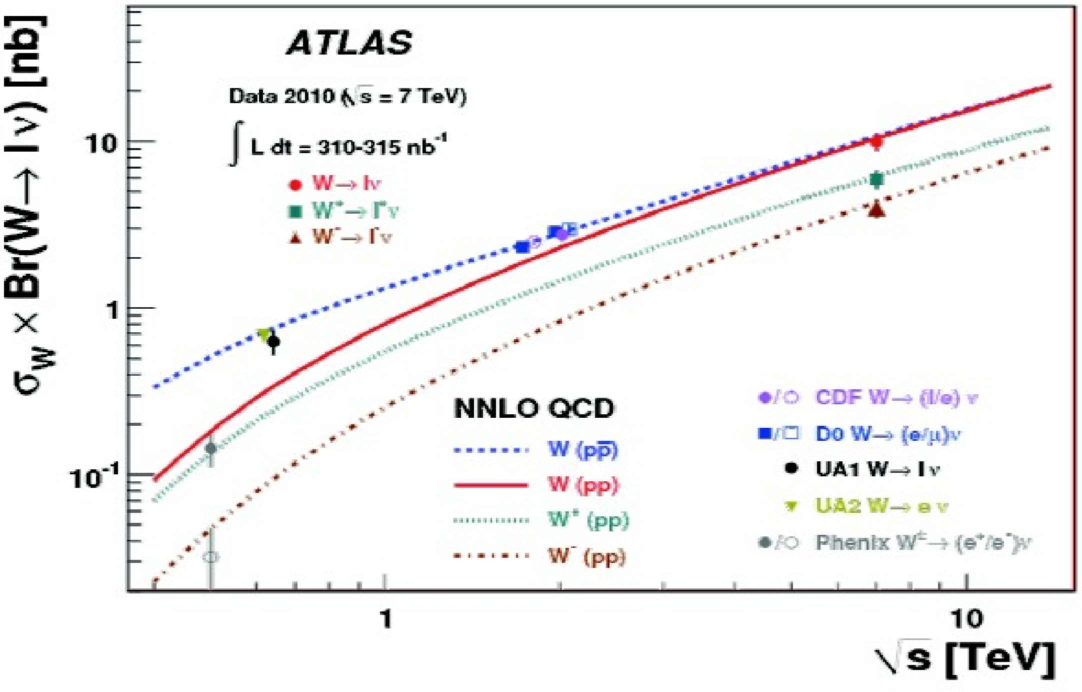
W cross-section results

$L \approx 310$ - $315\ nb^{-1}$

$$\text{Theory prediction}: 10.46 \pm 0.42 \text{ nb}$$

$$\sigma_W \times BR(W \to e\nu) = [10.51 \pm 0.34(stat) \pm 0.81(sys) \pm 1.16(lumi)]\, nb$$

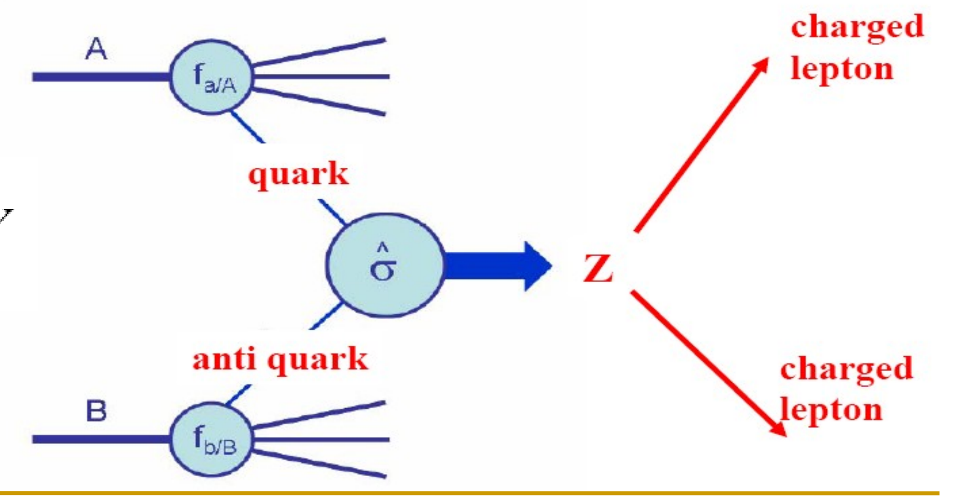
$$\sigma_W \times BR(W \to \mu\nu) = [9.58 \pm 0.30(stat) \pm 0.50(sys) \pm 1.05(lumi)]\, nb$$



Z cross-section measurement

- Signature:
  - Pair of charged leptons with opposite-charge
    - Leptons are high pT and isolated
    - Peak in l^+l^- invariant mass

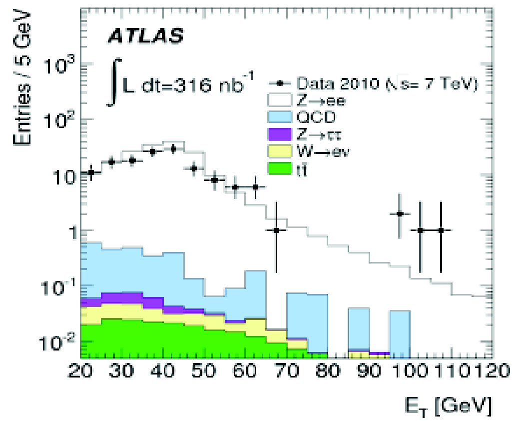
M(Z) ~ 91.2 GeV

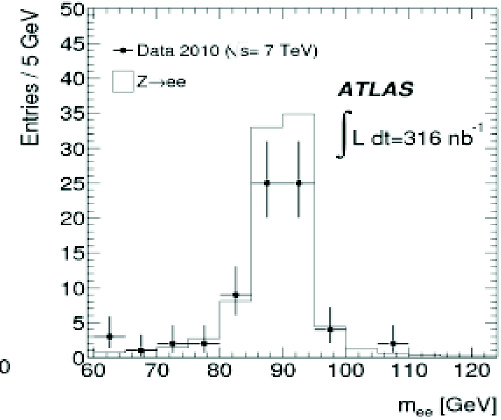


Z events selection

2 Electrons :

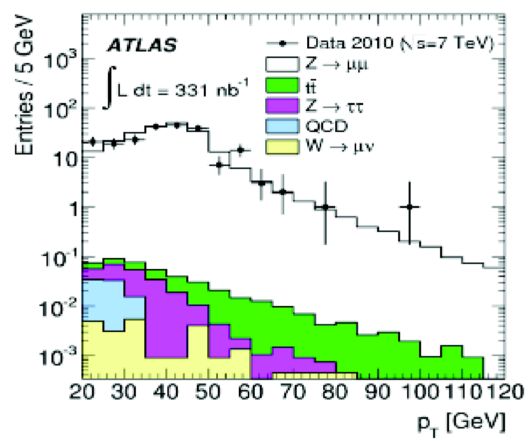
- $E_T > 20\ GeV$
- *Opposite charge*
- *Medium ID*
- $66 < m_{ee} < 116\ GeV$
- *70 Candidates*

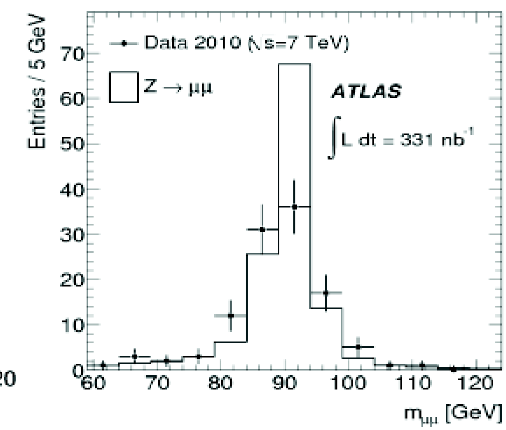




2 Muons :

- $p_T > 20\ GeV$
- *Track isolation*
- *Opposite charge*
- $66 < m_{\mu\mu} < 116\ GeV$
- *109 Candidates*





Z backgrounds and cross-section within 66 GeV < m_{ll} < 116 GeV

Electron background:

- EW + top background: $N_{EW+TOP} = 0.27 \pm 0.00(stat) \pm 0.03(syst)$
- QCD background estimate: $N_{QCD} = 0.91 \pm 0.11(stat) \pm 0.41(syst)$

Muon background:

- EW + top background: $N_{EW+TOP} = 0.21 \pm 0.01(stat) \pm 0.01(syst)$
- QCD background estimate: $N_{QCD} = 0.04 \pm 0.01(stat) \pm 0.04(syst)$

Cross section measurement

- Similar method as for the W
- The correction factor C_Z
  - Electron: 65.1% ± 6.1%
  - Muon: 77.3% ± 4.3%
  - A_Z *(table)*

$$\sigma \times BR(Z \to ll) = \frac{N_Z^{obs} - N^{bkg}}{A_Z C_Z L_{int}}$$

MC	A_Z $Z \to e^+e^-$	A_Z $Z \to \mu^+\mu^-$
PYTHIA MRST LO*	0.446	0.486
PYTHIA CTEQ6.6	0.455	0.496
PYTHIA HERAPDF1.0	0.451	0.492
MC@NLO HERAPDF1.0	0.440	0.479
MC@NLO CTEQ6.6	0.445	0.485

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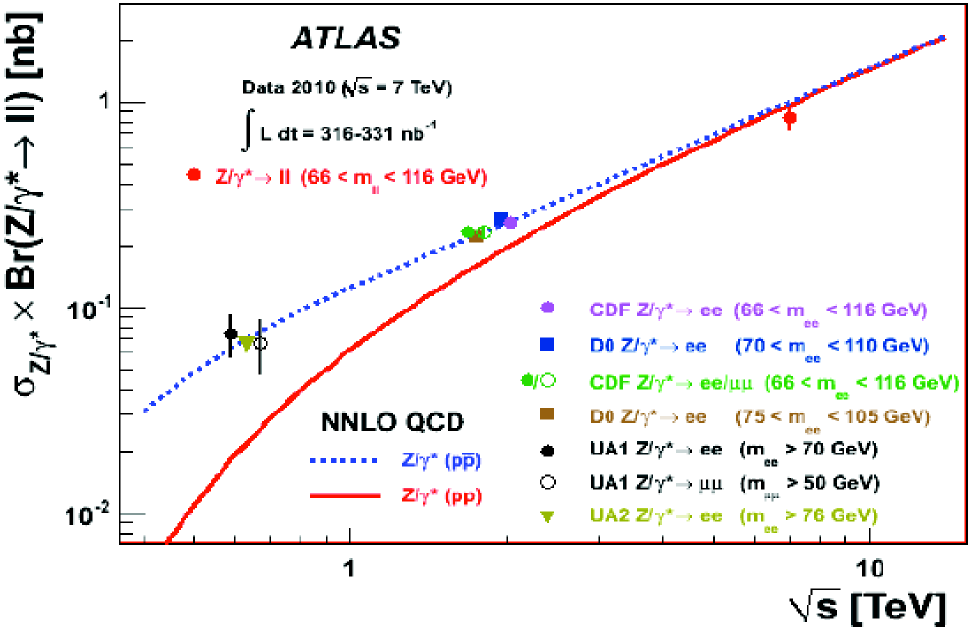
Z/γ* cross-section results

Theory prediction : 0.96 ± 0.04 nb for $[66-116]$ GeV mass window

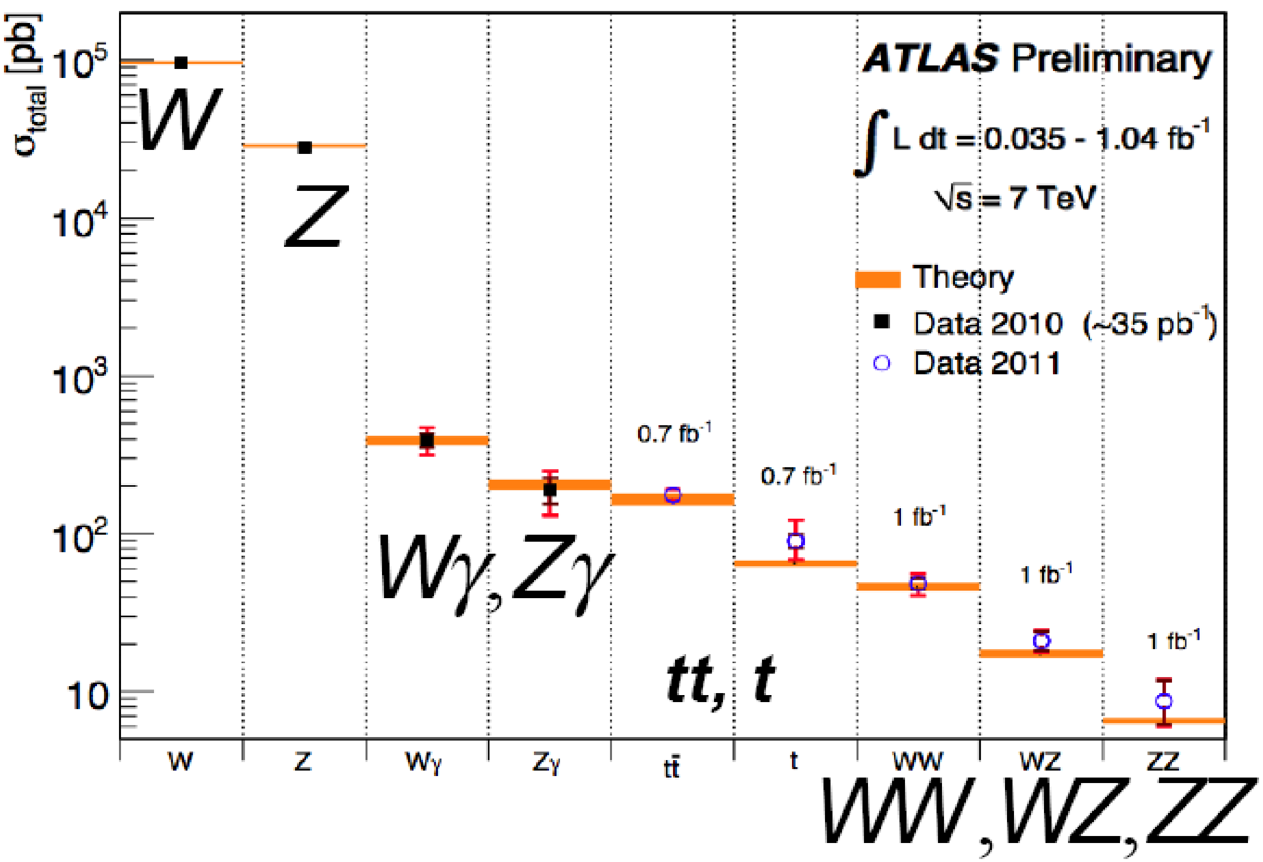
$$\sigma_Z \times BR(Z \rightarrow e^+e^-) = [0.75 \pm 0.09(stat) \pm 0.08(sys) \pm 0.08(lumi)]\, nb$$

$$\sigma_Z \times BR(Z \rightarrow \mu^+\mu^-) = [0.87 \pm 0.08(stat) \pm 0.06(sys) \pm 0.10(lumi)]\, nb$$



The Standard Model

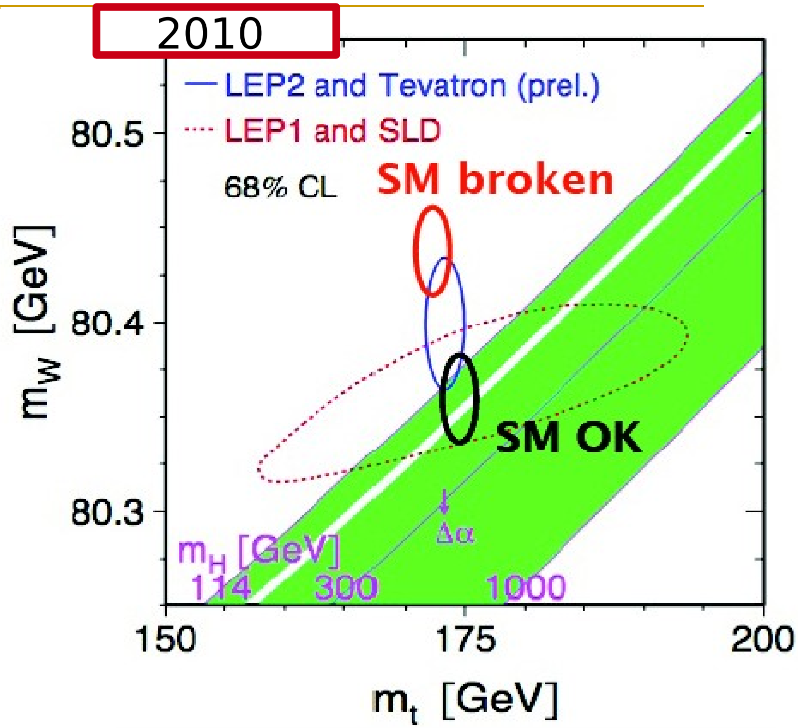
- SM measurements are the foundations of all searches



W mass:

SM consistency check

- Derive W boson mass from precisely measured electroweak quantities
- Measuring the W boson mass and to quark mass precisely allows for predictions of the mass of the Higgs boson
- **Δr – large** radiative corrections
  - Dominated by tb and Higgs loops
  - Sensitive to new physics



m_{top}=(173.3 ± 1.1) GeV (0.6%)

m_W=(80.399±0.023) GeV (0.028%)

$\Delta m_W \sim 0.006 \times \delta m_{top} \sim 7$ MeV for equal weights in Higgs limits

known to 0.015%

$$M_W^2 = \frac{\pi\alpha(M_Z^2)}{\sqrt{2}G_F}\frac{1}{1-M_W^2/M_Z^2}\frac{1}{1-\Delta r}$$

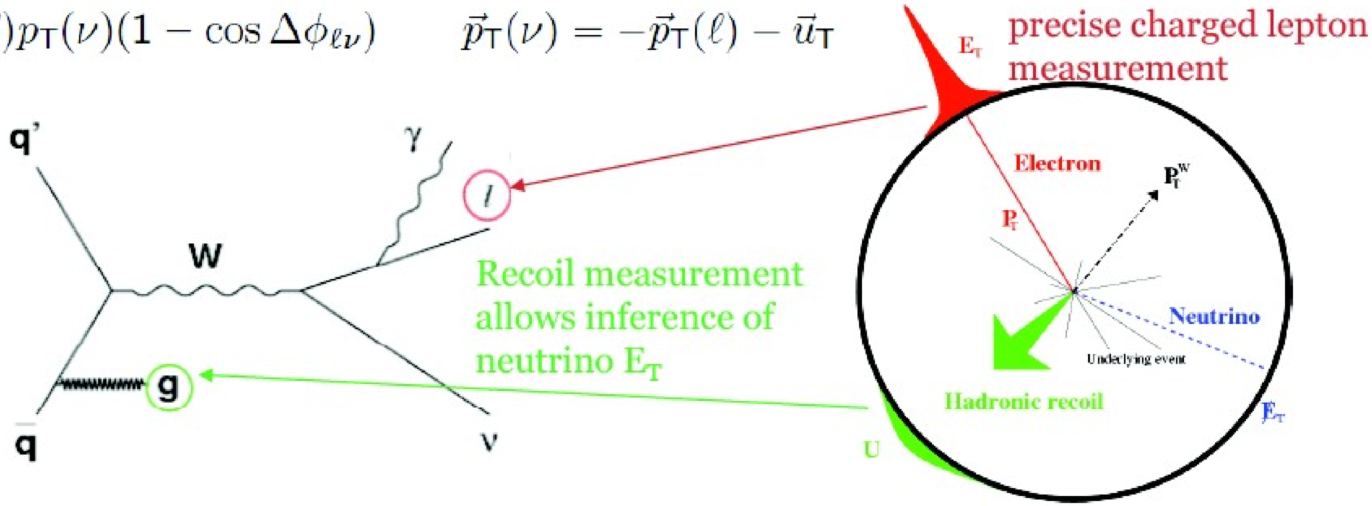
known to 0.0009% M_Z known to 0.002%

$\Delta r \propto m_{top}^2$ $\Delta r \propto \log m_H$

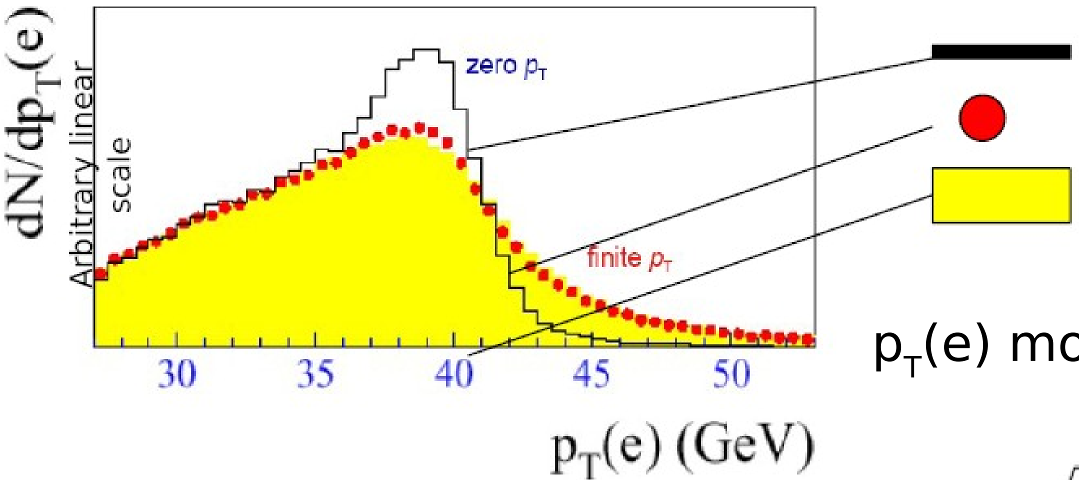
W mass measurement strategy

- At hadrons colliders, rely on transverse variables: m_T, p_T^l , MET (inferred neutrino p_T)
  - Requires precise measure of charged lepton p_T and hadronic recoil
  - Requires detailed knowledge of the detectors

$$m_T^2 = 2p_T(\ell)p_T(\nu)(1 - \cos\Delta\phi_{\ell\nu}) \qquad \vec{p}_T(\nu) = -\vec{p}_T(\ell) - \vec{u}_T$$



Experimental observables

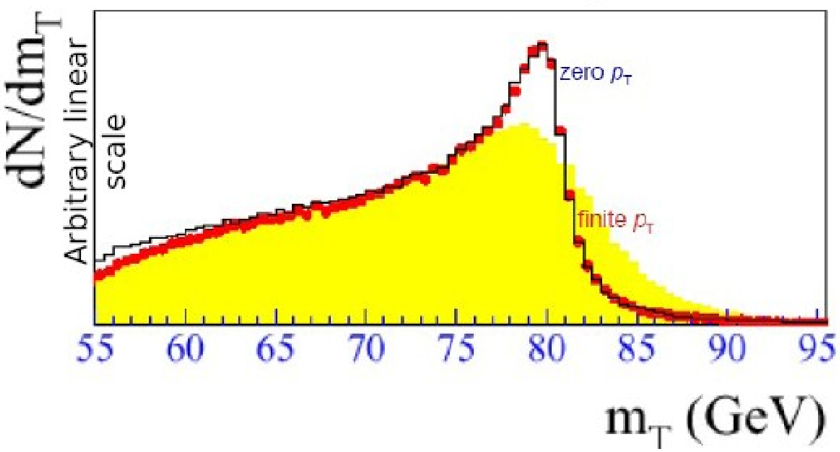


No $P_T(W)$

$P_T(W)$ included

Detector Effects added

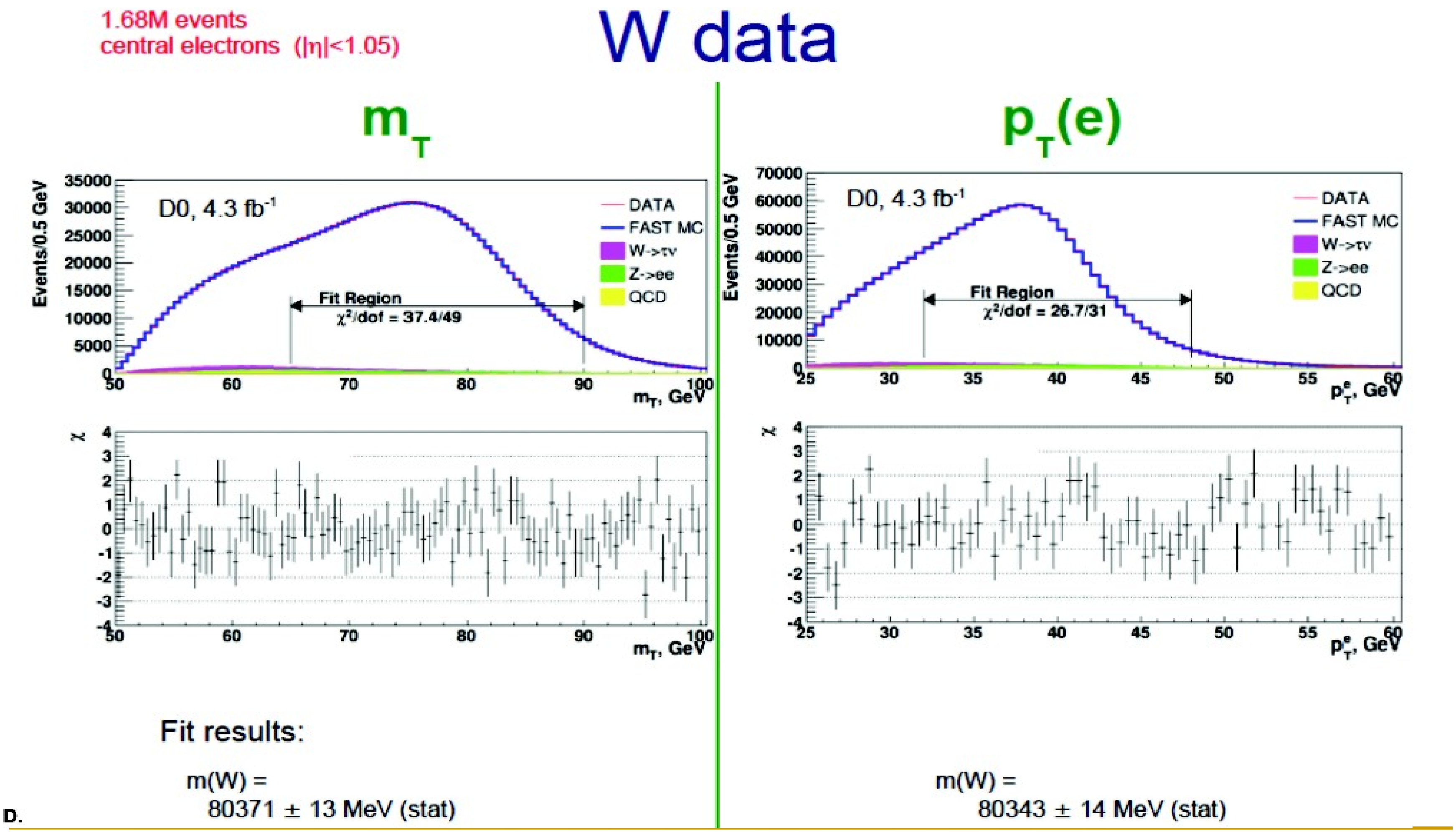
$p_T(e)$ most affected by $p_T(W)$



$$m_T = \sqrt{2 p_T^l p_T^\nu (1 - \cos \Delta\phi)}$$

m_T most affected by measurement of MET

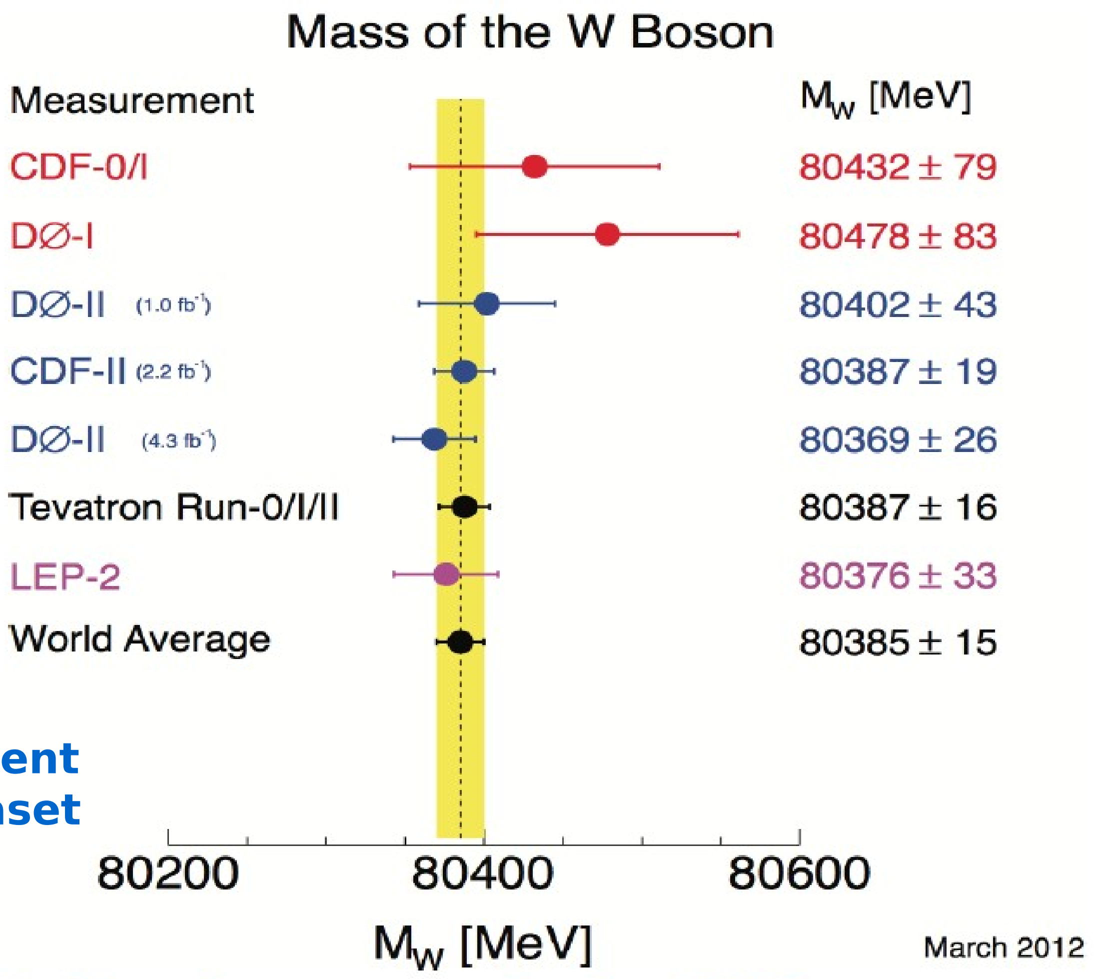
W mass measurement: D0



W mass combination

World average
computed by TeVEWWG
ArXiv:0908.1374
FERMILAB-TM-2439-E

Previous world average:
80399 ± 23 MeV



Not yet final word!
Further precision improvement possible with complete dataset

New Tevatron result is significantly more precise than LEP average