Physics Program

of the experiments at

Large Hadron Collider

Lecture 5

Physics with

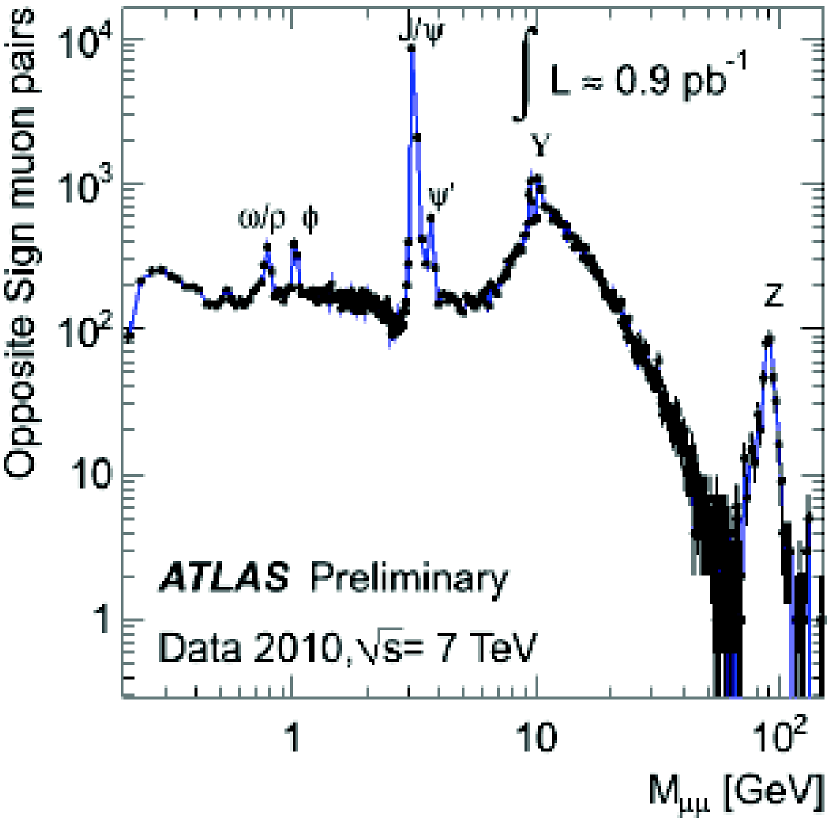
W and Z bosons: part I

Latest news!!!

- 150ns period ended Friday last week,
  - 48.9pb^{-1} delivered (total)
    - 19 pb^{-1} delivered last week
  - Max peak luminosity 2.1 x 10^{32}
- Friday (last week) started commissioning period of 50ns
- Tonight: planned last stable pp beam 2010
- Heavy-ion run starts on Thursday (this week)
- Technical stop (winter) :
  - 11 weeks, starting Xmass break

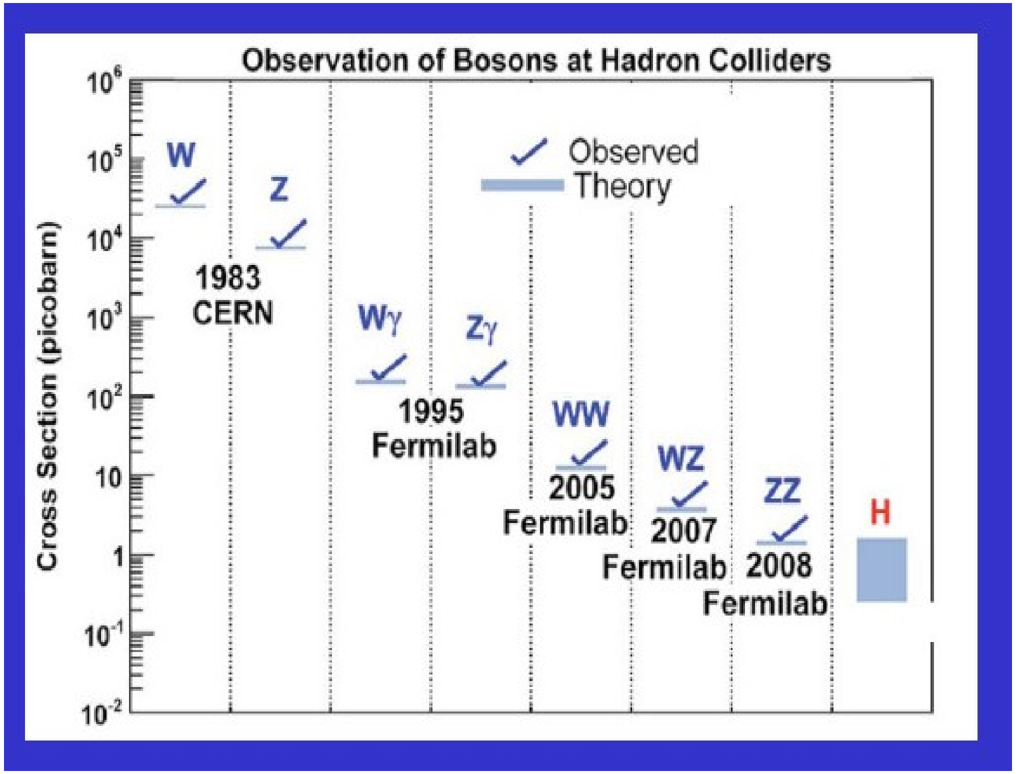
Retracing history of particle physics

- With up to 1pb^{-1} (public results) we made it up to 80's
- Results at sumer conferences 2010
- Onia(J/Psi, Ψ, Y,...) + first hundreds of W,Z in the leptonic channels



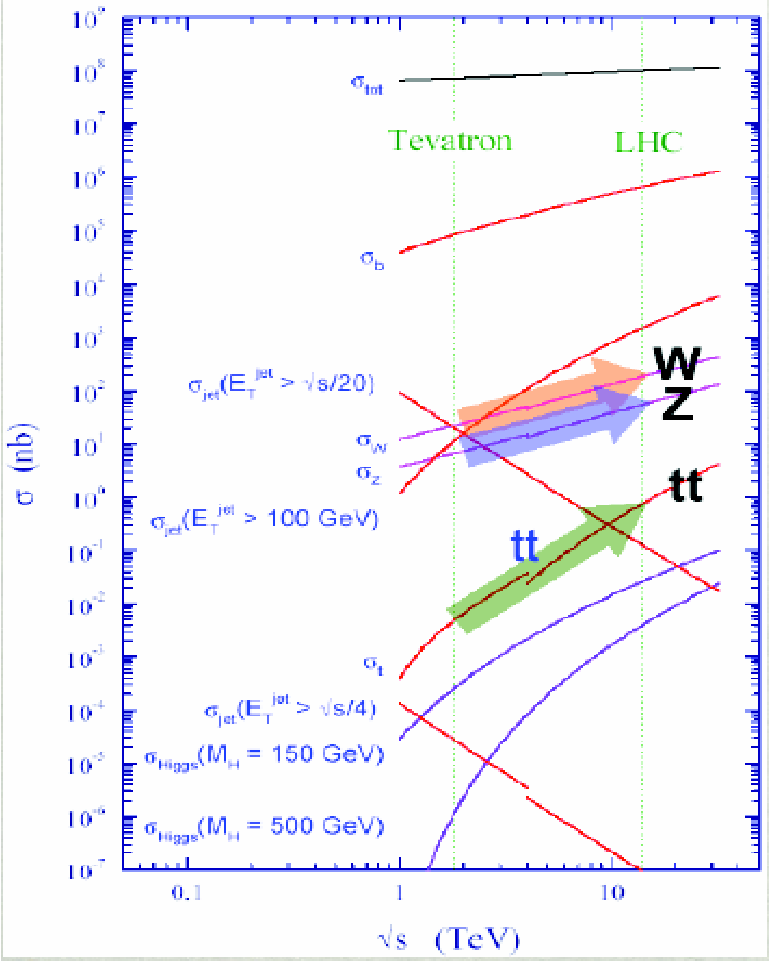
Bosons at hadron colliders

- So far the primary measurement channel is through leptonic decays
  - BR(W→e ν) ~ 10%
  - BR(Z→ ee) ~ 3%
- It means that we are probing σ x BR values orders of magnitude smaller
- At LHC cross-section 5-10 x higher than at Tevatron at Fermilab.



Bosons at LHC

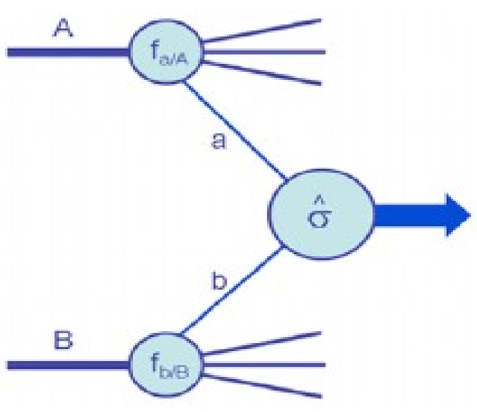
- Well measured by previous experiments
  - Inclusive cross sections, $R(W^+/W^-)$, $R(W/Z)$
  - Differential distributions, associated jet multiplicity, A_{FB}, etc.
- Yet still educational at the LHC
  - Cross sections at $\sqrt{s} = 7 TeV$
  - New pdf constraints possible
- "Standard candles" for high-p_T analyses
  - Calibration, alignment
  - Independent luminosity measurements



Just departure point for high-p_T Beyond Standard Model analyses

Drell-Yan cross-section

- Keywords:
  - factorisation μ_F and renormalisation μ_R scales
  - universal parton distribution functions
  - LO, NLO, NNLO matrix elements and DGLAP kernels



$$\sigma_{AB} = \int dx_a dx_b \; f_{a/A}(x_a, Q^2) f_{b/B}(x_b, Q^2) \; \hat{\sigma}_{ab \to X}$$

$$\sigma_{AB} = \int dx_a dx_b \; f_{a/A}(x_a, \mu_F^2) \; f_{b/B}(x_b, \mu_F^2) \; \times \; [\, \hat{\sigma}_0 + \alpha_S(\mu_R^2) \, \hat{\sigma}_1 + \cdots]_{ab \to X}.$$

also depends on μ_R and μ_F, so as to cancel scale dependence in PDF's and α_s, to this order

- All orders cross section has no dependence on μ_F and μ_R; a residual dependence remains (to order α_s^{n+1}) for a finite order (α_s^n) calculations.

DGLAP equations

- Parton distributions used in hard scattering calculations are solutions of DGLAP equations

$$\frac{\partial q_i(x,\mu^2)}{\partial \log \mu^2} = \frac{\alpha_S}{2\pi} \int_x^1 \frac{\mathrm{d}z}{z} \left\{ P_{q_i q_j}(z,\alpha_S) q_j(\frac{x}{z},\mu^2) + P_{q_i g}(z,\alpha_S)\; g(\frac{x}{z},\mu^2) \right\},$$

$$\frac{\partial g(x,\mu^2)}{\partial \log \mu^2} = \frac{\alpha_S}{2\pi} \int_x^1 \frac{\mathrm{d}z}{z} \left\{ P_{g q_j}(z,\alpha_S) q_j(\frac{x}{z},\mu^2) + P_{gg}(z,\alpha_S) g(\frac{x}{z},\mu^2) \right\},$$

- Splitting functions have perturbative expansions

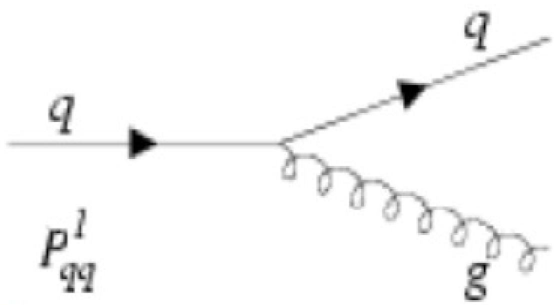
$$P_{ab}(x,\alpha_S) = P_{ab}^{(0)}(x) + \frac{\alpha_S}{2\pi} P_{ab}^{(1)}(x) + \cdots$$

Thus, a full NLO calculation will contain both $\hat{\sigma}_1$ (previous slide) and $P_{ab}^{(1)}$

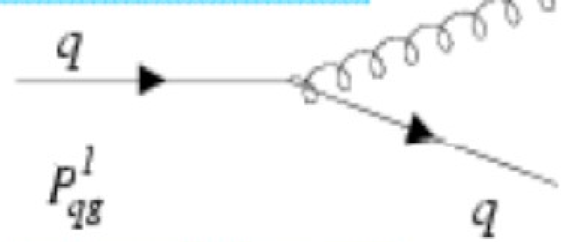
Altarelli-Parisi splitting functions

Altarelli-Parisi splitting functions:

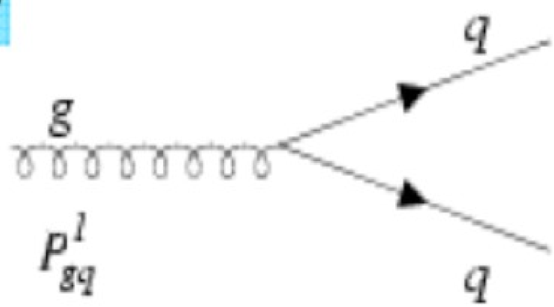
$$P_{q\to qg} = \frac{4}{3}\left(\frac{1+z^2}{1-z}\right)$$



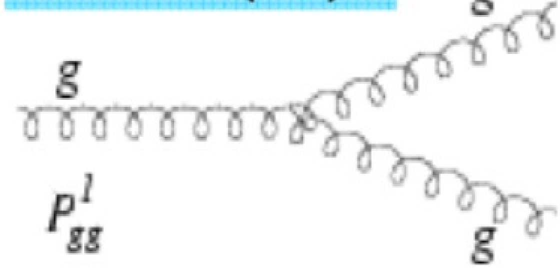
$$P_{q\to gq} = \frac{4}{3}\frac{1+(1-z)^2}{z}$$



$$P_{g\to q\bar{q}} = \frac{n_f^2}{2}\left(z^2+(1-z)^2\right)$$



$$P_{g\to gg} = 3\frac{(1-z(1-z))^2}{z(1-z)}$$



Kinematics

- Double differential cross section for production of Drell-Yan pair of mass M and at rapidity y is given by

$$\frac{d\sigma}{dM^2 dy} = \frac{\hat{\sigma}_0}{Ns}\left[\sum_k Q_k^2\left(q_k(x_1, M^2)\bar{q}_k(x_2, M^2) + [1 \leftrightarrow 2]\right)\right]$$

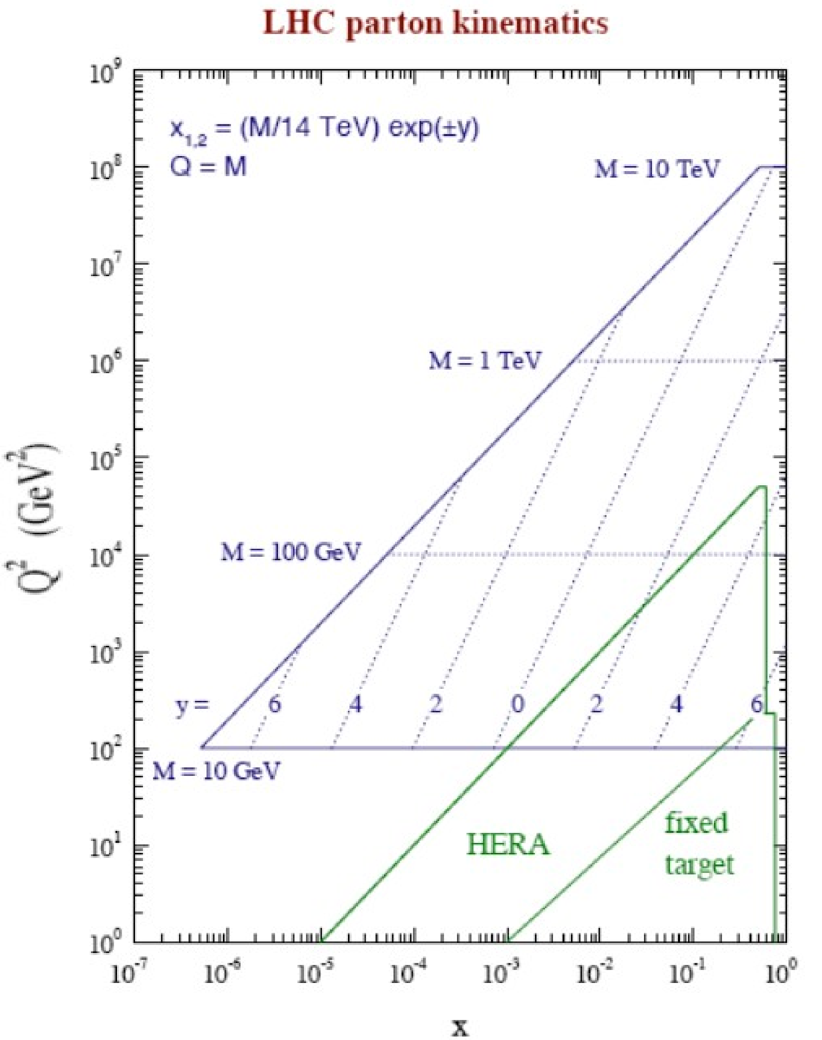
  - where

$$\hat{\sigma}_o = \frac{4\pi\alpha^2}{3M^2}$$

  - and

$$x_1 = \frac{M}{\sqrt{s}}\, e^{y}\,, \qquad x_2 = \frac{M}{\sqrt{s}}\, e^{-y}.$$

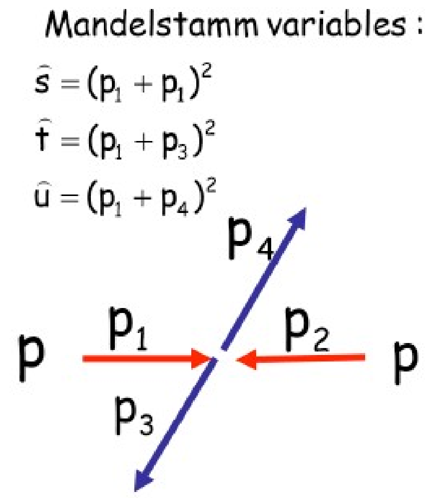
- Different values of M and y probes different values of x and Q^2



W/Z production

- Cross sections for on-shell W and Z production (in narrow width limit) given by

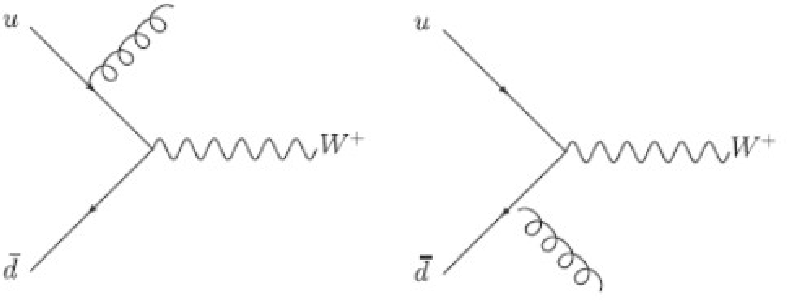
$$\hat{\sigma}^{q\bar{q}'\to W} = \frac{\pi}{3}\sqrt{2}G_F M_W^2 |V_{qq'}|^2 \delta(\hat{s} - M_W^2),$$
$$\hat{\sigma}^{q\bar{q}\to Z} = \frac{\pi}{3}\sqrt{2}G_F M_Z^2 (v_q^2 + a_q^2) \delta(\hat{s} - M_Z^2),$$



- Where $V_{qq'}$ is appropriate CKM matrix element and v_q and a_q are the vector and axial couplings of the Z to quarks
- At LO there is no α_s dependence; EW vertex only
- NLO contribution to the cross section is proportional to α_s; NNLO to α_s^2; ...

W/Z p_T distributions

- Most of W/Z produced at low p_T but can be produced at non-zero p_T due to the diagrams with emitted gluon

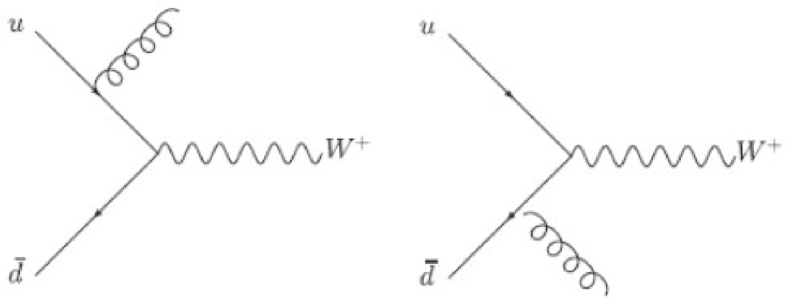


$$\sum |\mathcal{M}^{q\bar{q}' \to Wg}|^2 = \pi \alpha_S \sqrt{2} G_F M_W^2 |V_{qq'}|^2 \, \frac{8}{9} \, \frac{\hat{t}^2 + \hat{u}^2 + 2M_W^2 \hat{s}}{\hat{t}\hat{u}} ,$$

$$\sum |\mathcal{M}^{gq \to Wq'}|^2 = \pi \alpha_S \sqrt{2} G_F M_W^2 |V_{qq'}|^2 \, \frac{1}{3} \, \frac{\hat{s}^2 + \hat{u}^2 + 2\hat{t} M_W^2}{-\hat{s}\hat{u}} ,$$

- Sum over colors and spins in initial states and average over same in final states
- Transverse momentum distribution obtained by convoluting these matrix elements with pdf's in usual way

W/Z p_T distributions



- Back to 2->2 subprocess, where Q2 is virtuality of the W

$$|\mathcal{M}^{u\bar{d}\to W+g}|^2 \sim \left(\frac{\hat{t}^2+\hat{u}^2+2Q^2\,\hat{s}}{\hat{t}\,\hat{u}}\right)$$

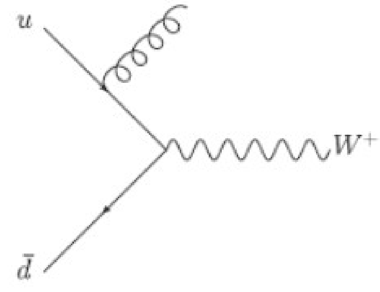
- Convolute with pdf's

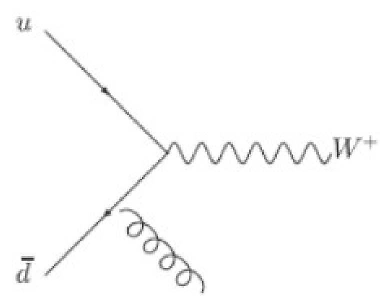
$$\sigma = \int \mathrm{d}x_1\mathrm{d}x_2\, f_u(x_1, Q^2)\, f_{\bar{d}}(x_2, Q^2)\, \frac{|\mathcal{M}|^2}{32\pi^2\hat{s}}\, \frac{\mathrm{d}^3 p_W}{E_W}\, \frac{\mathrm{d}^3 p_g}{E_g}\, \delta(p_u + p_{\bar{\mathrm{d}}} - p_g - p_W)$$

- Transform into differential cross-section

$$\frac{\mathrm{d}\sigma}{\mathrm{d}Q^2\mathrm{d}y\mathrm{d}p_T^2} \sim \frac{1}{s}\int \mathrm{d}y_g\, f_u(x_1, Q^2)\, f_{\bar{\mathrm{d}}}(x_2, Q^2)\frac{|\mathcal{M}|^2}{\hat{s}}$$

W/Z p_T distributions





- In the limit of leading divergence we can write

$$\frac{d\sigma}{dQ^2 dy dp_T^2} \sim \frac{2}{s}\frac{1}{p_T^2}\int dy_g\, f_u(x_1, Q^2) f_{\bar{d}}(x_2, Q^2) + (\text{sub-leading in } p_T^2)$$

- As pT of W becomes small, limits on y_g integration are given by +- $\log(s^{1/2}/p_T)$
- The results is then

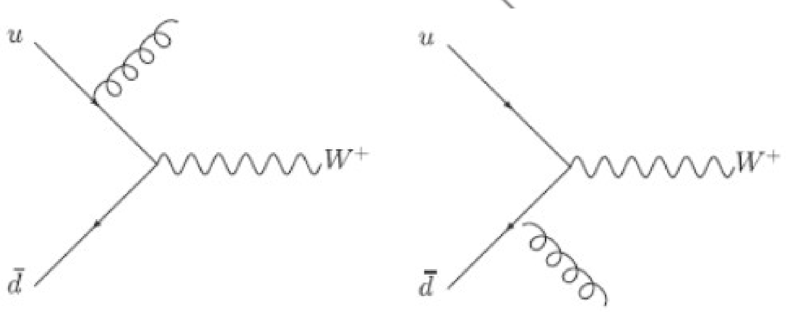
$$\frac{d\sigma}{dQ^2 dy dp_T^2} \sim \frac{\log(s/p_T^2)}{p_T^2}$$

- It diverges unless we apply a p_T^{min} cut; final distribution depends on α_s times log

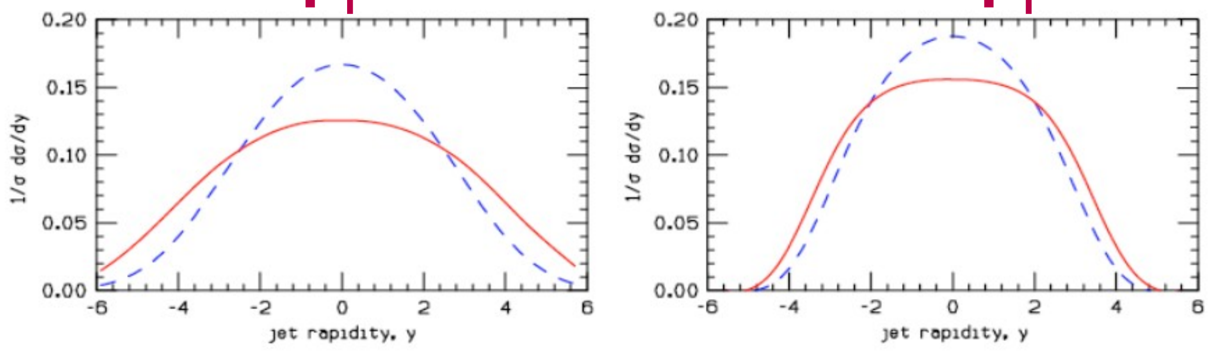
W/Z rapidity distributions

- Rapidity distribution for 2 different choices of p_T^{min}
- Final state parton is not in the forward region, but central due to the requirement on p_T^{min}

the p_T requirement of the gluon serves as the cutoff



2GeV p_T^{min} **50GeV p_T^{min}**

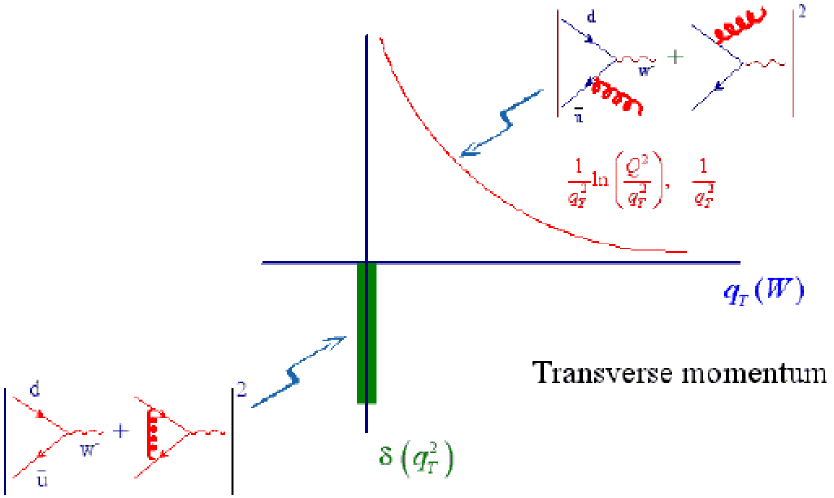


Blue: qg process
Red: qqbar process

Figure 9. The rapidity distribution of the final-state parton found in a lowest-order calculation of the $W+1$ jet cross section at the LHC. The parton is required to have a p_T larger than 2 GeV (left) or 50 GeV(right). Contributions from $q\bar{q}$ annihilation (solid red line) and the qg process (dashed blue line) are shown separately.

Shortcomings of fixed order calculations

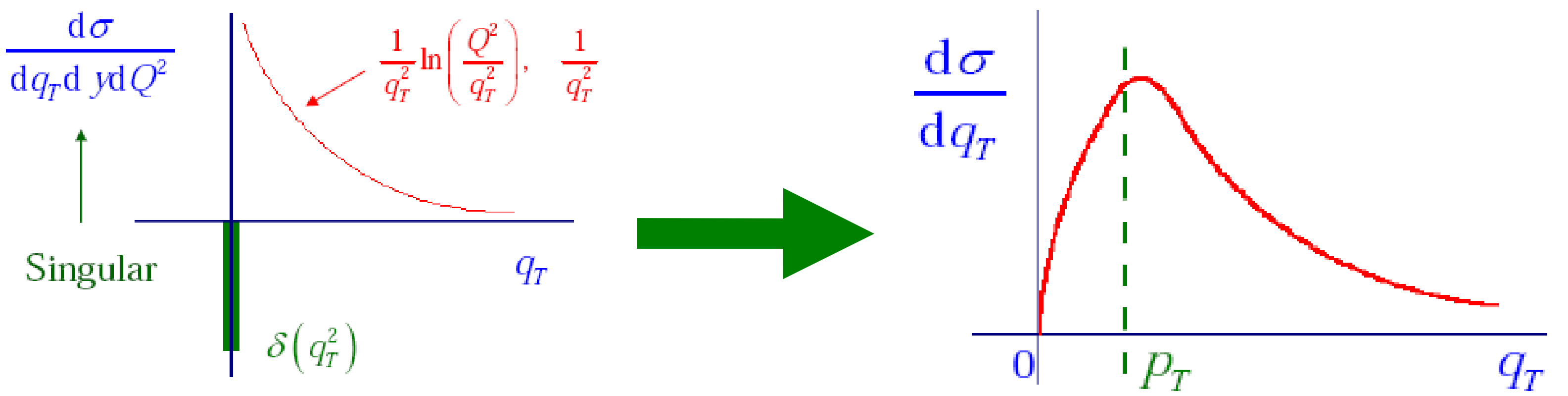
- Divergent, without cut on p_T^{min}, cannot describe the data



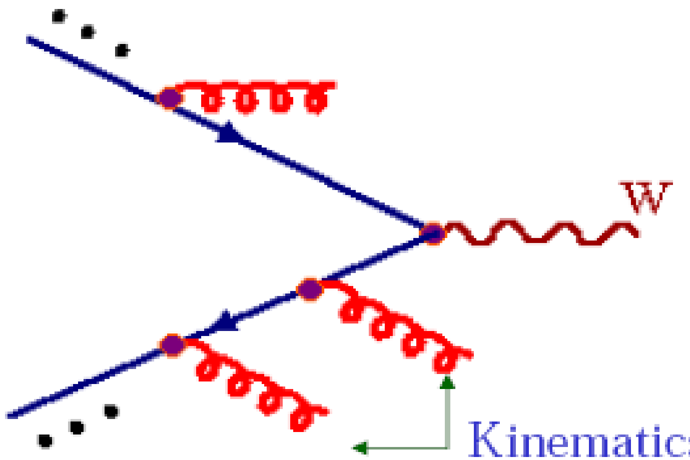
(at NLO)

QCD resummation

- Resummation: reorganise calculations in terms of large Logs $L(Q^2/p_T^2)$; regularised at low p_T range;
- Different schemes: CSS which includes also non-perturbative effects; Sudakov form factors; exponentation;



Monte Carlo approach example: Parton Shower



Backward Radiation
(Initial State Radiation)

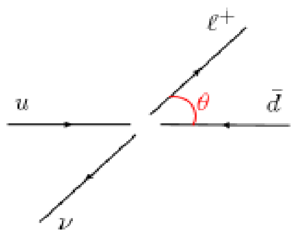
Kinematics of the radiated gluon, controlled by Sudakov form factor with some arbitrary cut-off. (In contrast to perform integration in impact parameter space, i.e., b space.)

The shape of q_T (w) is generated. But, the integrated rate remains the same as at Born level (finite virtual correction is not included).

Recently, there are efforts to include part of higher order effect in the event generator.

Transverse momenta of charged lepton

- In (ud) c.m. system,

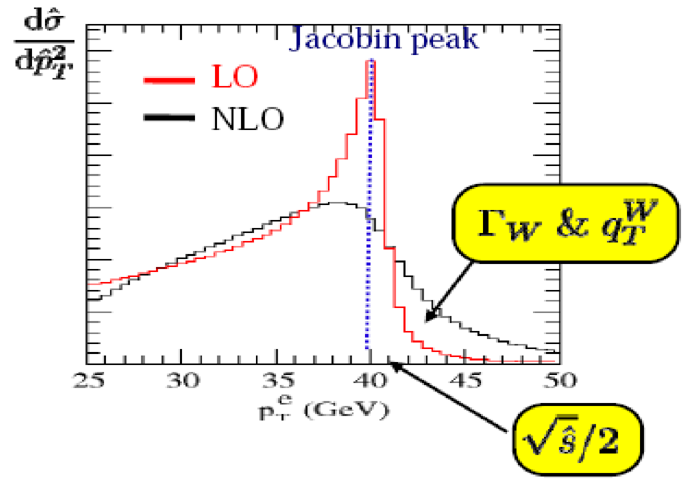


$$\hat{p}_T^2 = \frac{1}{4}\hat{s}\sin^2\theta$$

Jacobin factor

$$\frac{d\cos\theta}{d\hat{p}_T^2} = -\frac{2}{\hat{s}}\frac{1}{\sqrt{1-\frac{4\hat{p}_T^2}{\hat{s}}}}$$

$$\Longrightarrow \frac{d\hat{\sigma}}{d\hat{p}_T^2} \sim \frac{d\hat{\sigma}}{d\cos\theta} \times \frac{1}{\sqrt{1-4\hat{p}_T^2/\hat{s}}}$$

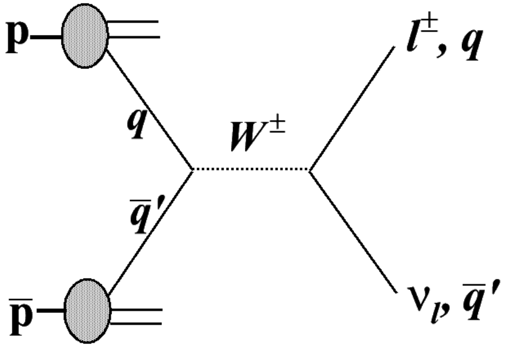


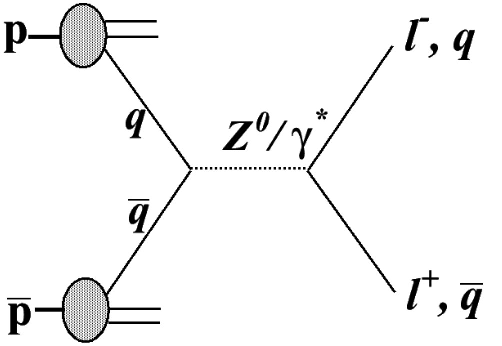
sensitive region for measuring

M_W : $p_T^e \sim 30 - 45$ GeV

Γ_W : not a good observable

Cross-section at LHC (7TeV)





$$\sigma^{NNLO}_{W^+\to\ell\nu} = 6.15\,\mathrm{nb}$$

$$\sigma^{NNLO}_{W^-\to\ell\nu} = 4.3\,\mathrm{nb}$$

$$\sigma^{NNLO}_{W\to\ell\nu} = 10.45\,\mathrm{nb}$$

$$\sigma^{NNLO}_{Z/\gamma*\to\ell\ell} = 0.989\,\mathrm{nb}$$

$$\sigma(W^+) \neq \sigma(W^-)$$

W^+ production: $u\bar{d} + c\bar{s}$

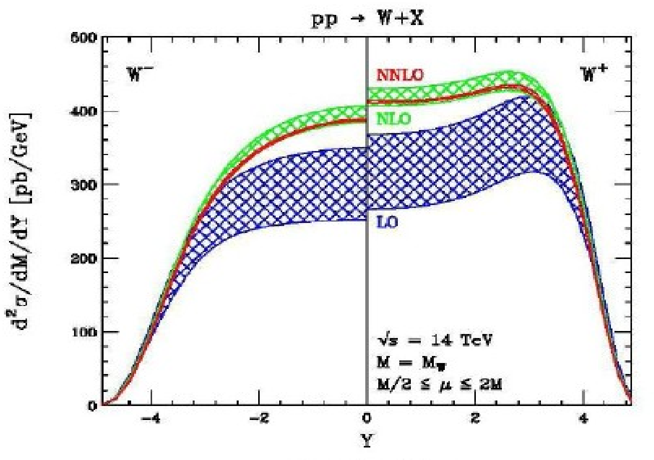
W^- production: $d\bar{u} + s\bar{c}$

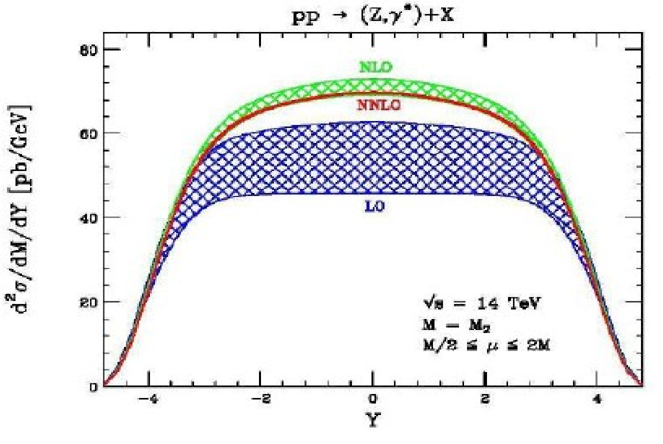
Z production: $u\bar{u} + d\bar{d} + s\bar{s} + c\bar{c} + b\bar{b}$

- Test QCD (up to NNLO) in production
  - Hard and soft gluon emission
- Sensitive to parton distribution functions
- Extract electroweak parameters
  - $\sin\Theta_W$, m_W, quark-boson couplings

Monte Carlo simulations

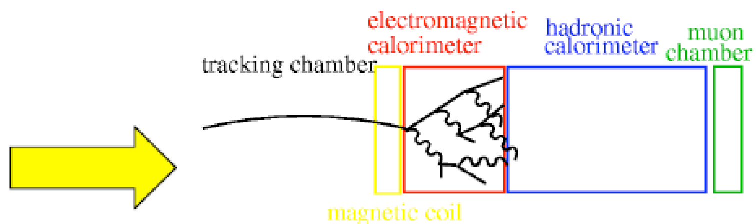
- Base-line generators:
  - Pythia, Herwig (LO),
  - MCatNLO (NLO)
  - POWHEG (NLO)
- Used as components of for cross-checks
  - FEWZ: complete NLO, NNLL
  - ResBos: NNLL resumation
  - Horace: full 1-loop electroweak
  - PHOTOS:final state QED (exponentiated)



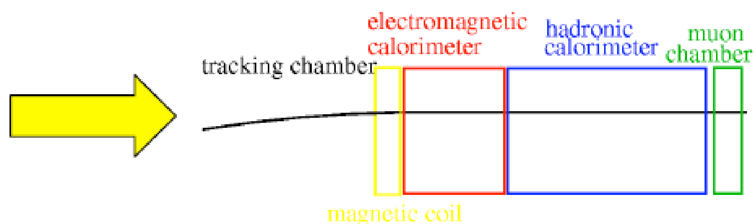


Lepton identification

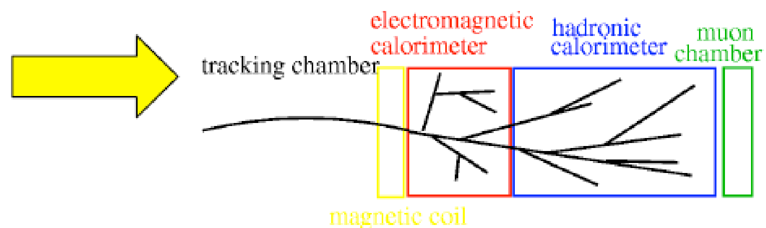
- Electron:
  - Compact electromagnetic cluster in calorimeter
  - Matched to track



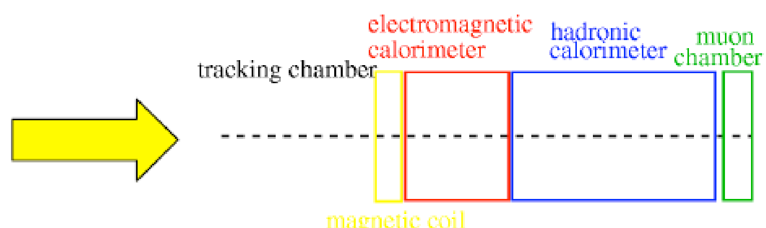
- Muons:
  - Track in the muon chambers
  - Matched to track



- Taus:
  - Narrow jet
  - Matched to one or three tracks

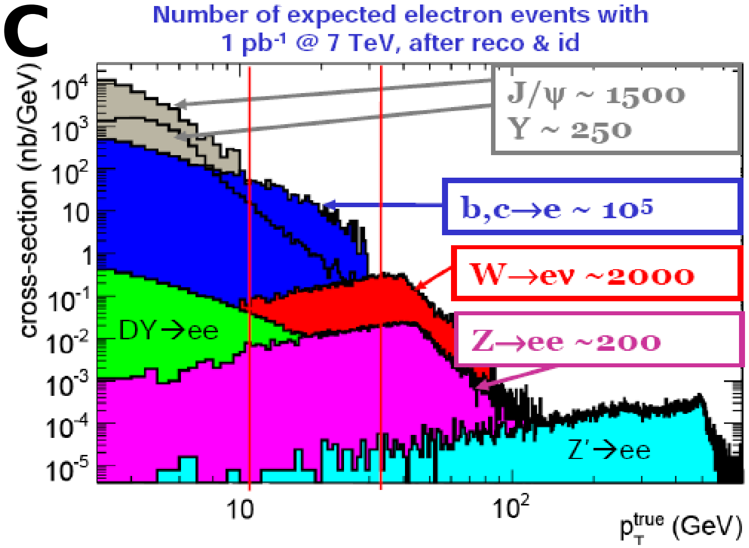


- Neutrinos
  - Imbalanse in transverse momentum
  - Inferred from total transverse energy in detector



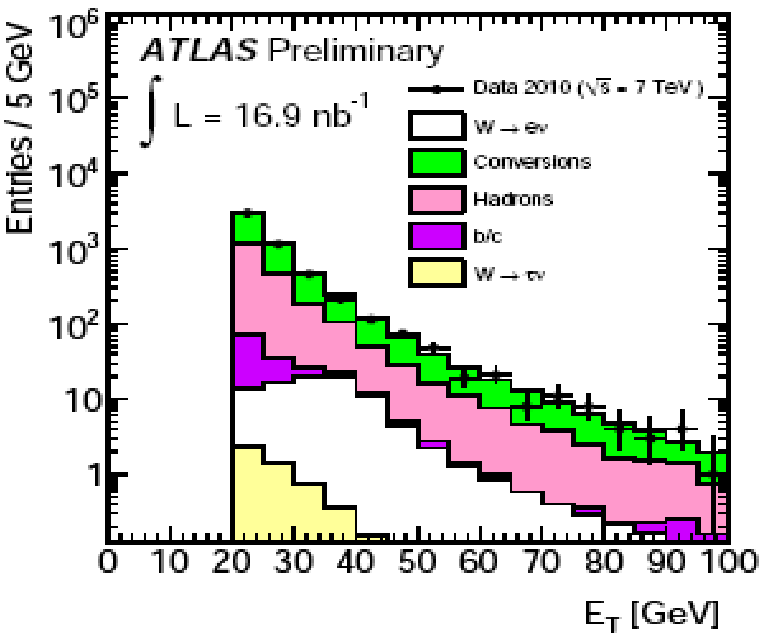
Electrons and jets

MC



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

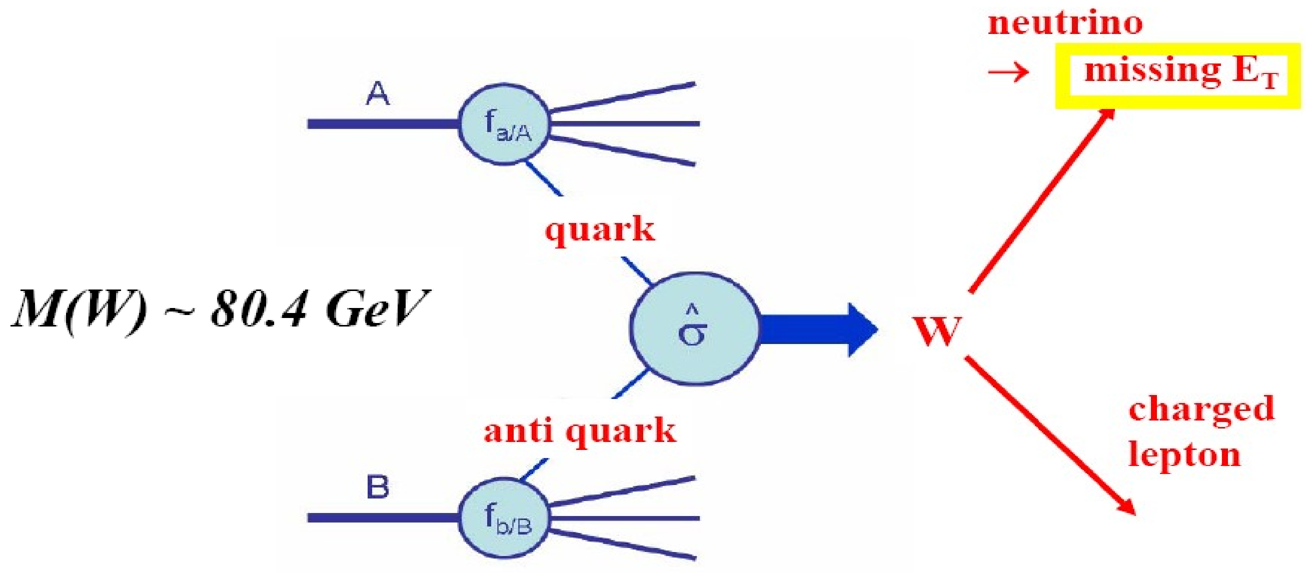
DATA: loose electron ID



- 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

Measurement: $W \rightarrow l\,\nu$

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



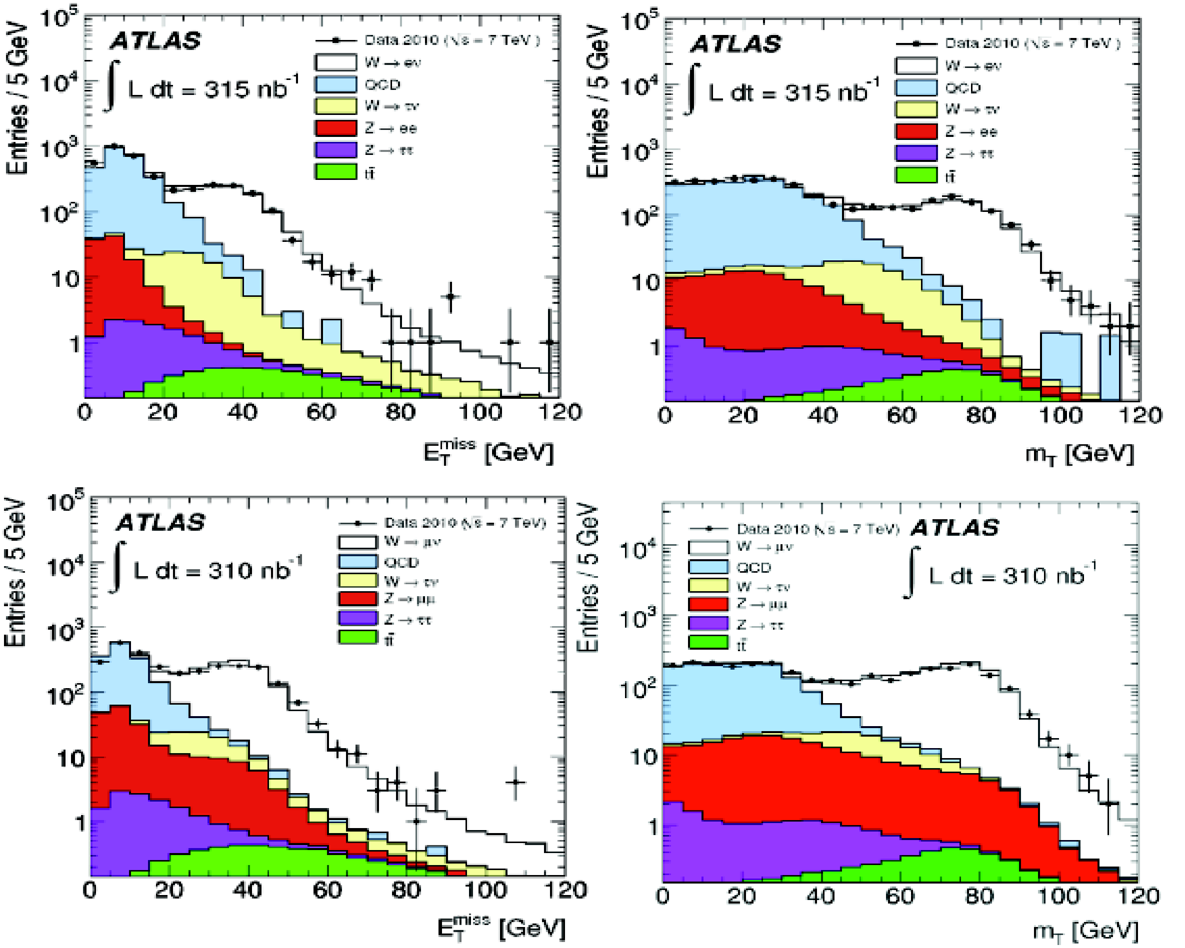
W selection

Electrons:

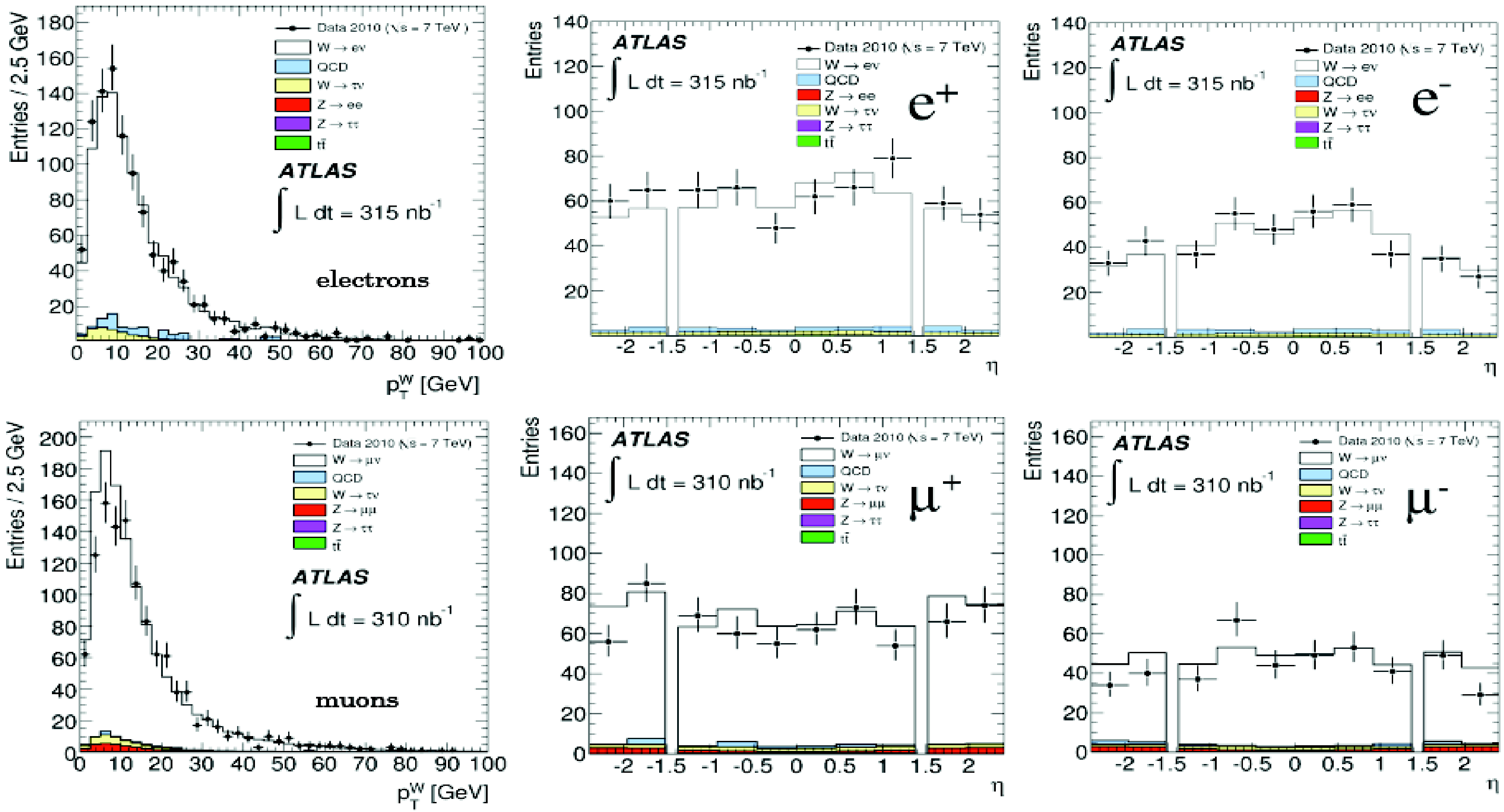
- $E_T > 20\ GeV$
- *Tight ID*
- $Missing\ E_T > 25\ GeV$
- $m_T > 40\ GeV$
- ➢ *1069 Candidates*

Muons:

- $p_T > 20\ GeV$
- *Track isolation*
- $Missing\ E_T > 25\ GeV$
- $m_T > 40\ GeV$
- ➢ *1181 Candidates*



W candidate kinematic distribution



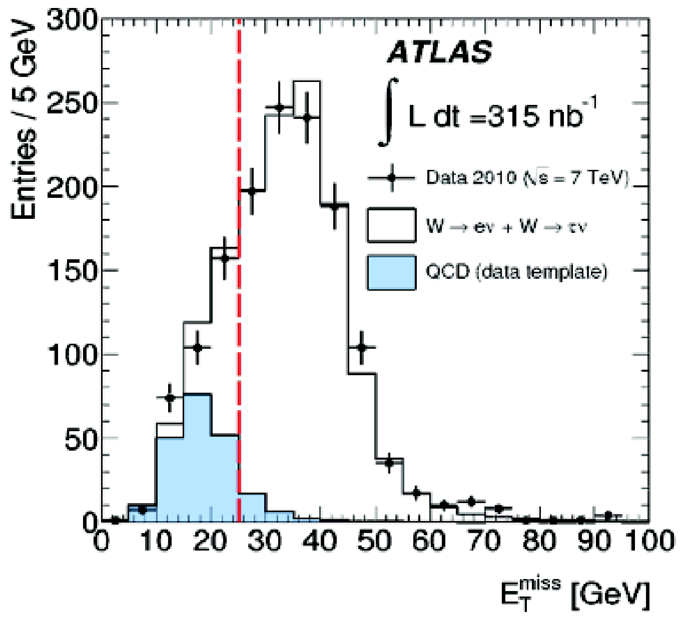
W backgrounds

Electrons:

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

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

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

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

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

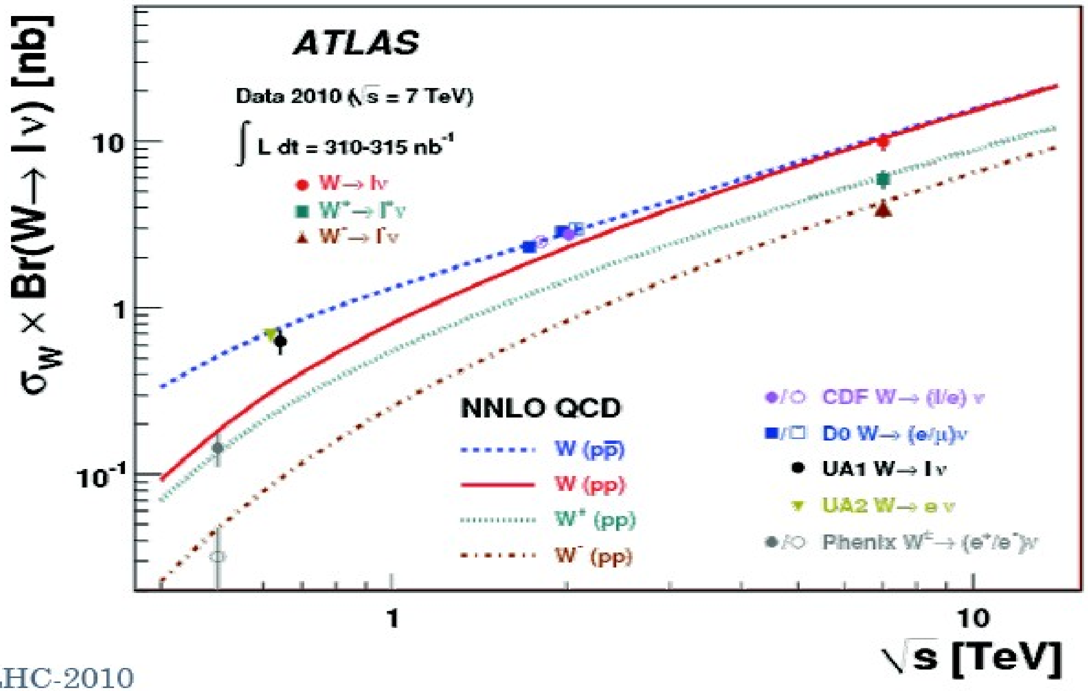
W cross-section results

L ≈ 310 - 315 nb^{-1}

Theory prediction : 10.46 ± 0.42 nb

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

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



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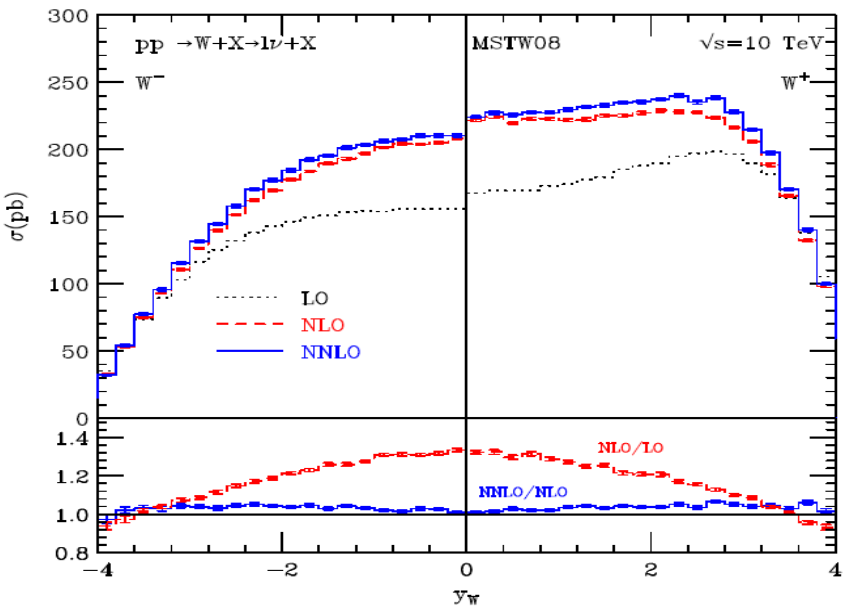
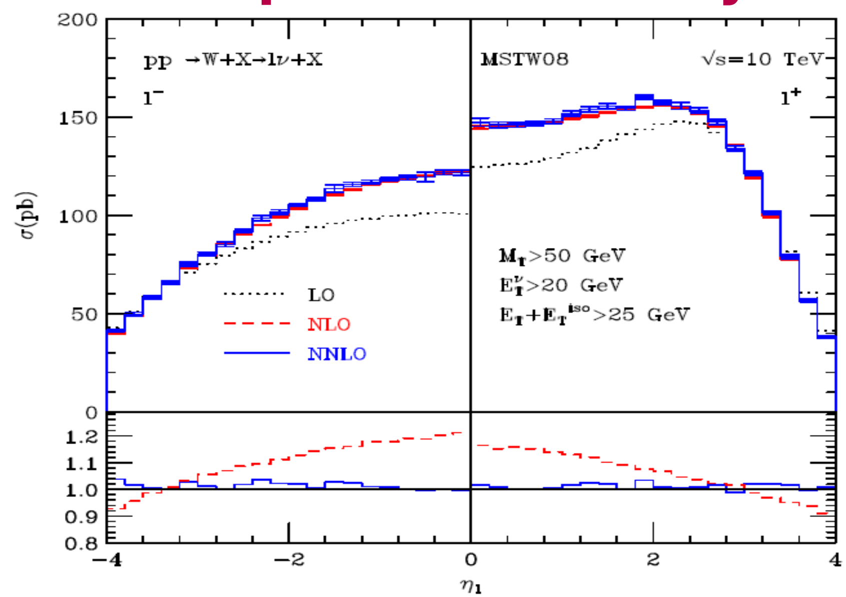
W rapidity distribution in pp collision (7TeV LHC)

- In pp collision production asymmetry between positive and negative charge; effective asymmetry in rapidity distribution follow

W boson



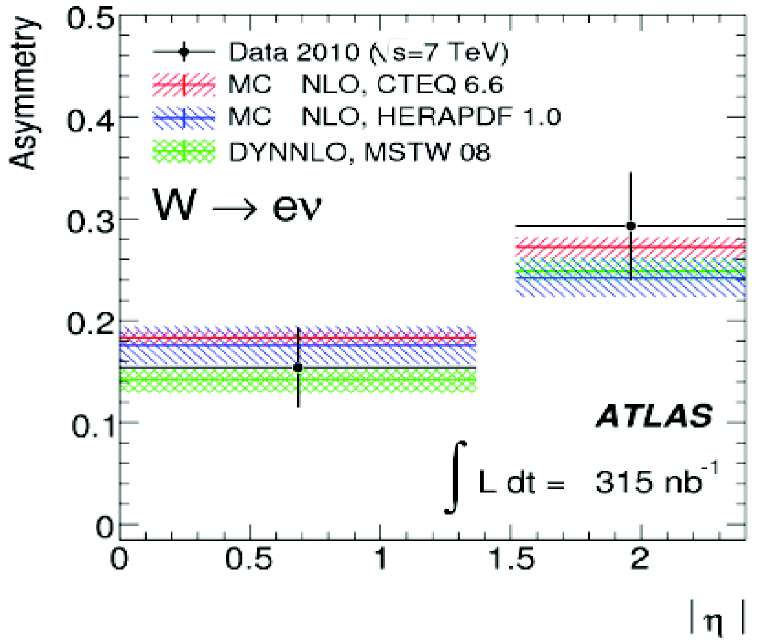
Lepton from decay

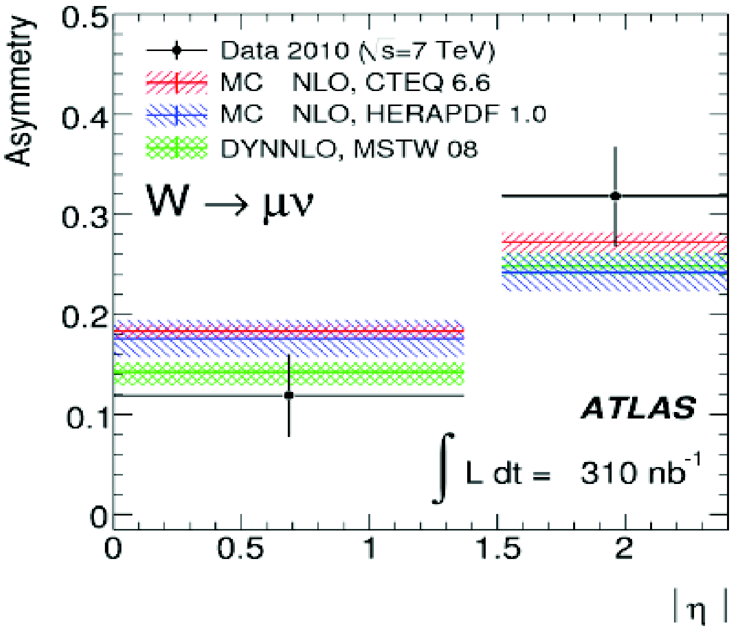


W charge asymmetry

- W+ and W- are produced at different rates, which can be measured via the lepton charge asymmetry. This measurement is important to constraint PDFs.
- Many uncertainties cancel fully or partially
- Asymmetry is expected to increase with rapidity

$$A_\ell = \frac{\sigma_{W^+} - \sigma_{W^-}}{\sigma_{W^+} + \sigma_{W^-}}$$

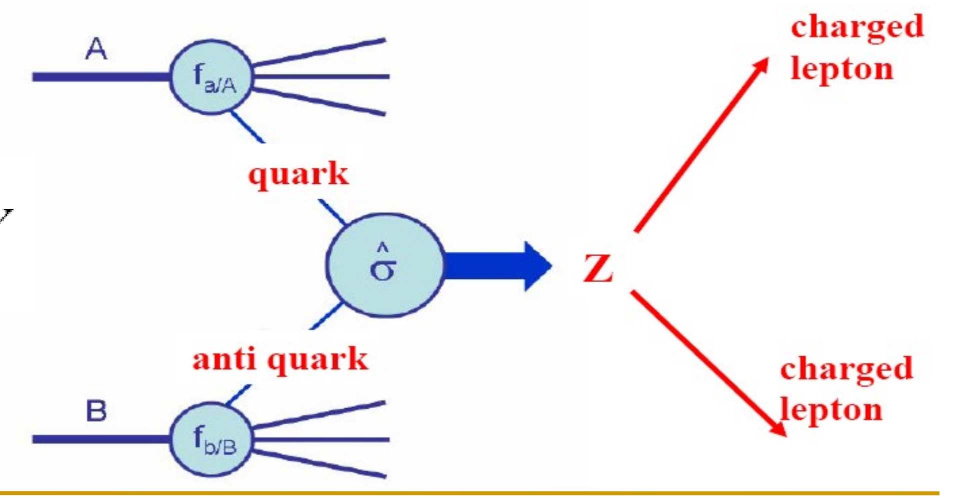




Z cross-section measurement

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

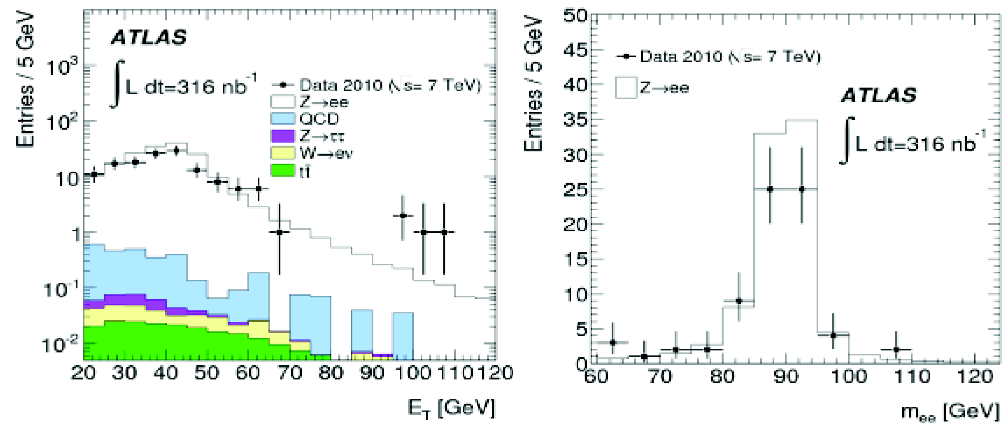
M(Z) ~ 91.2 GeV



Z events selection

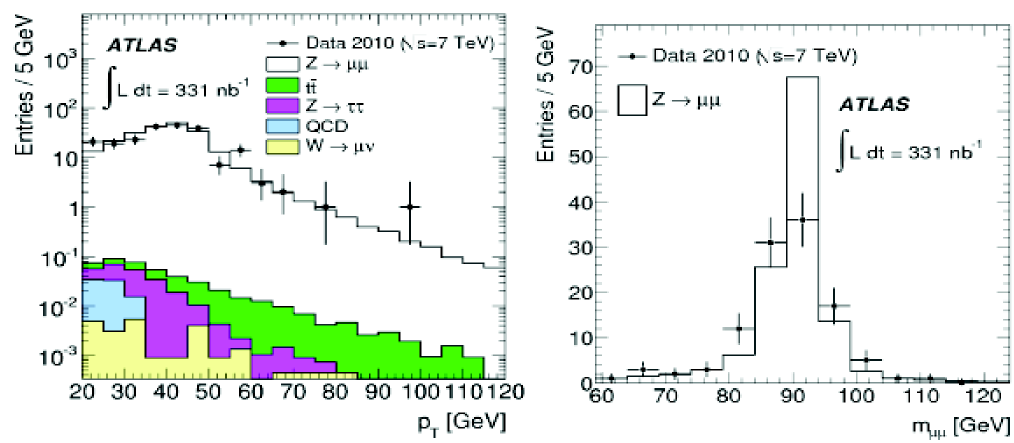
2 Electrons :

- $E_T > 20$ 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: $65.1\% \pm 6.1\%$
  - Muon: $77.3\% \pm 4.3\%$
  - 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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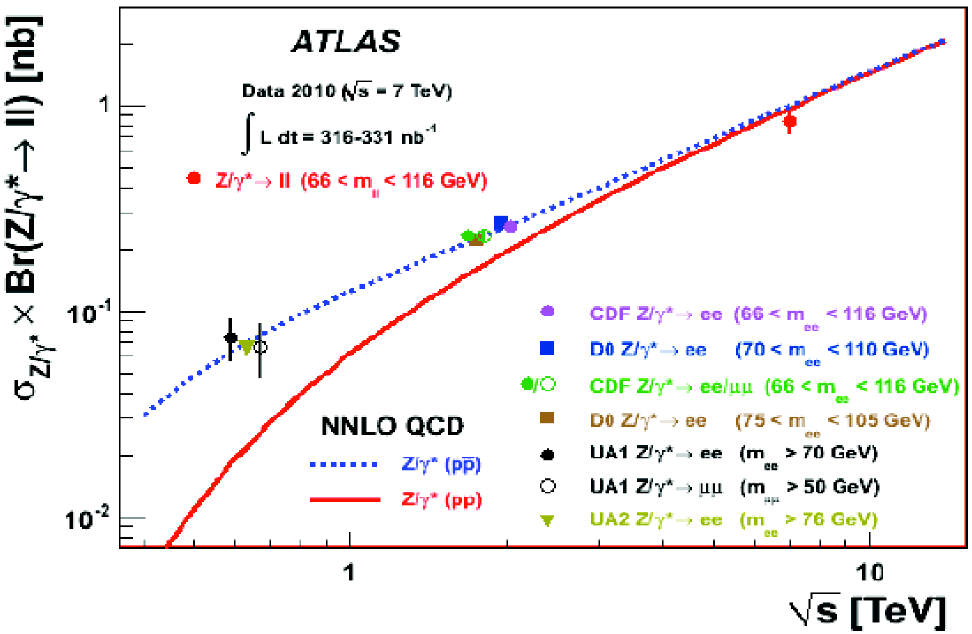
Z/γ* cross-section results

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

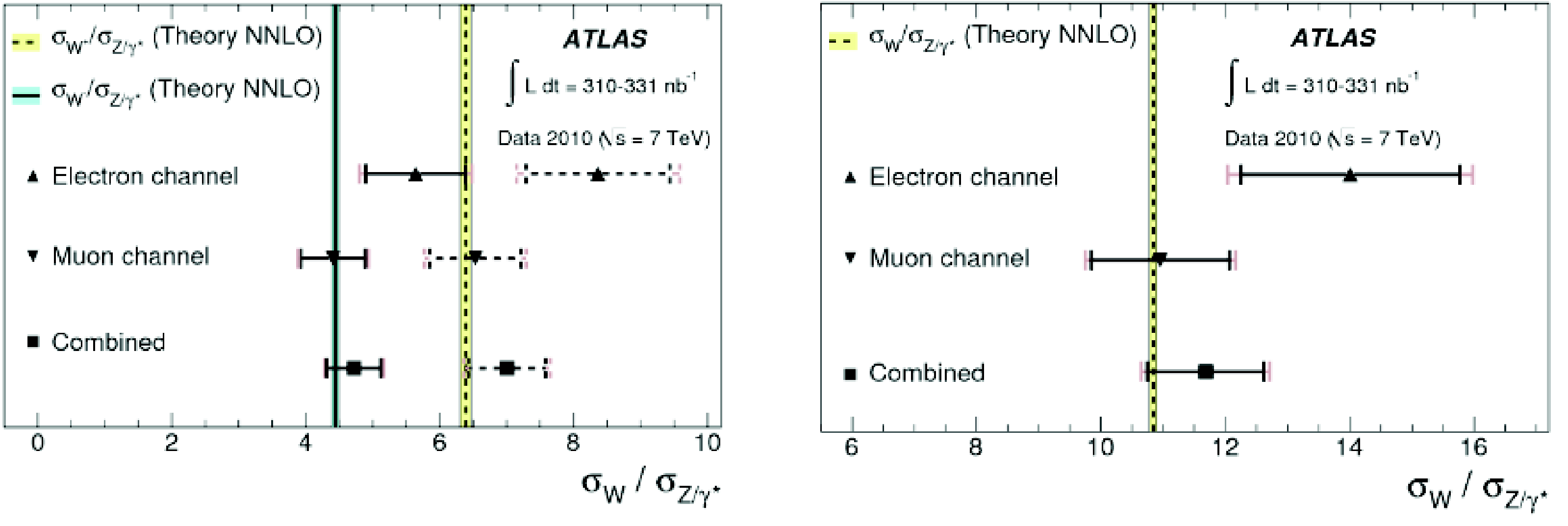
$$\sigma_Z \times BR(Z \to e^+e^-) = [0.75 \pm 0.09(stat) \pm 0.08(sys) \pm 0.08(lumi)]\, nb$$

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



W/Z ratio measurement

- The measured ratios between the W+ and W− and the Z cross section in the electron and muon decay channels compared to the theoretical predictions based on NNLO QCD calculations.



The calculations are based on the FEWZ program with the MSTW2008 NNLO PDFs

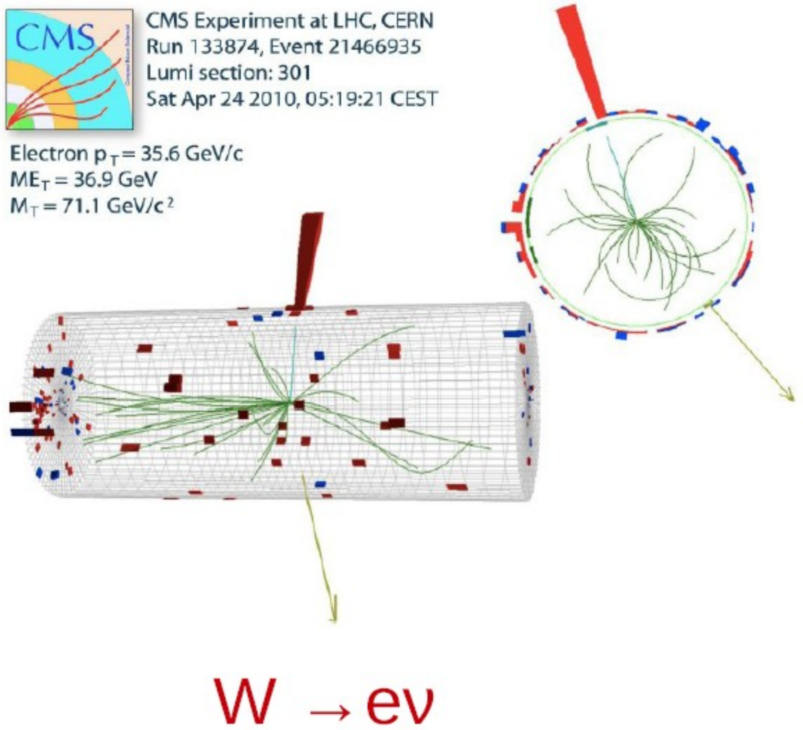
ATLAS results

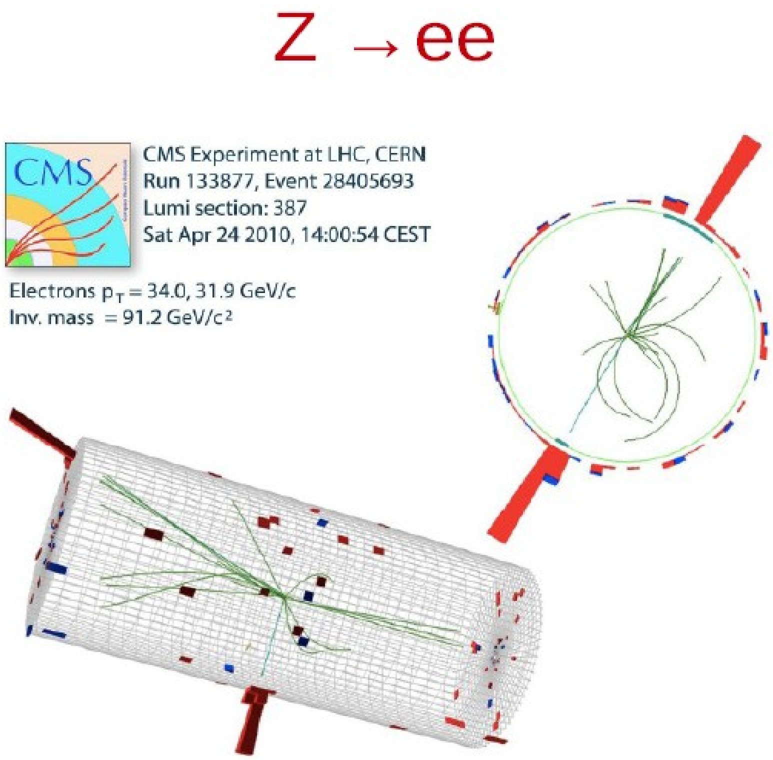
- W and Z cross sections have been extracted with 310 – 315 nb^{-1} with the ATLAS Detector
- W cross-sectuon measurement included observed 1069 $W\rightarrow e\nu$ and 1081 $W\rightarrow \mu\nu$
- Z cross-section measurement included observed 70 $Z\rightarrow e\nu$ and 109 $Z\rightarrow \mu\mu$
- The W asymmetry and Z/W ratio have been extracted
- Results agree well with Standard Model predictions

Paper with results has been submitted for publication to JHEP

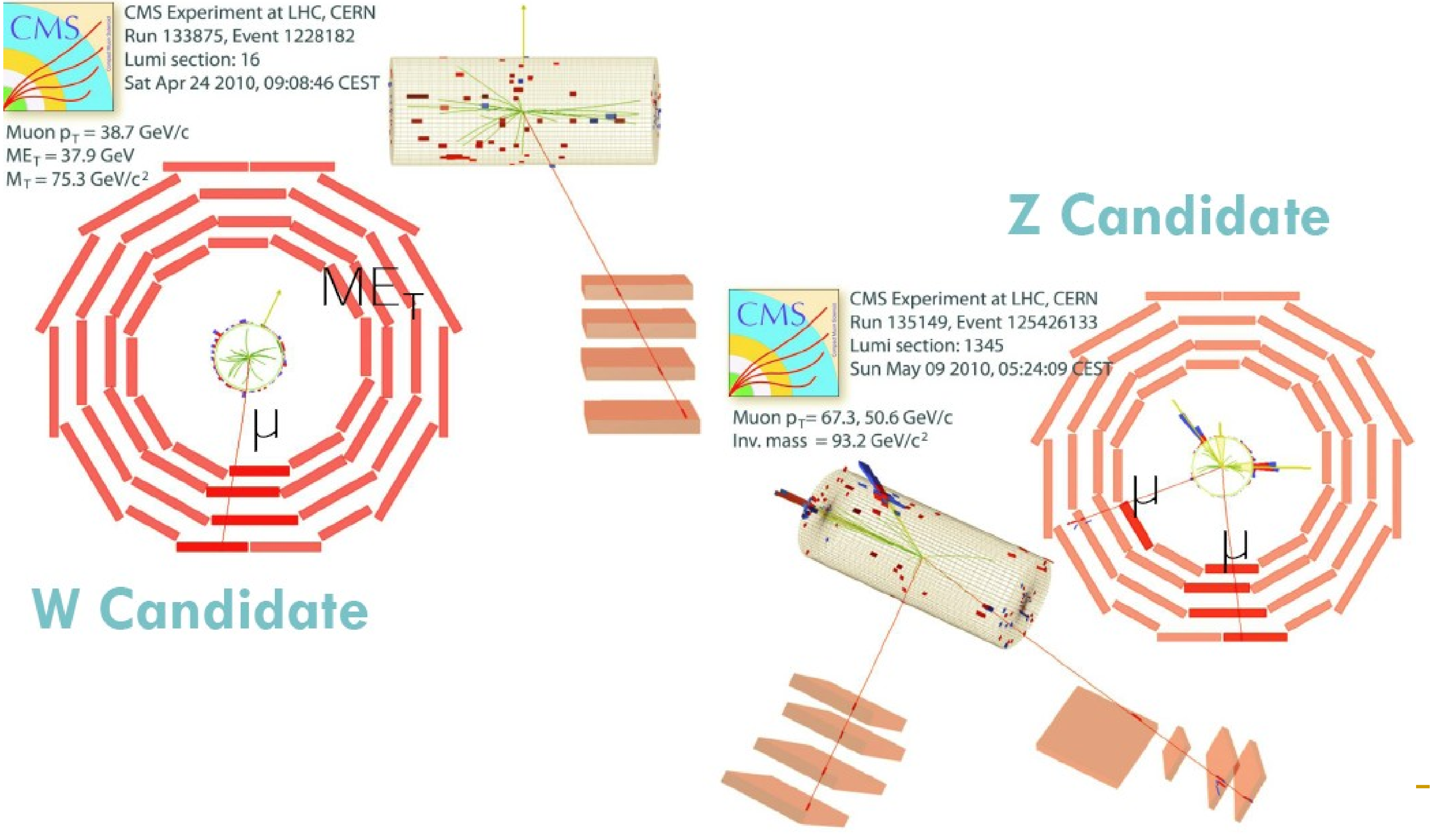
http://arxiv.org/abs/1010.2130

Electron channel W and Z events





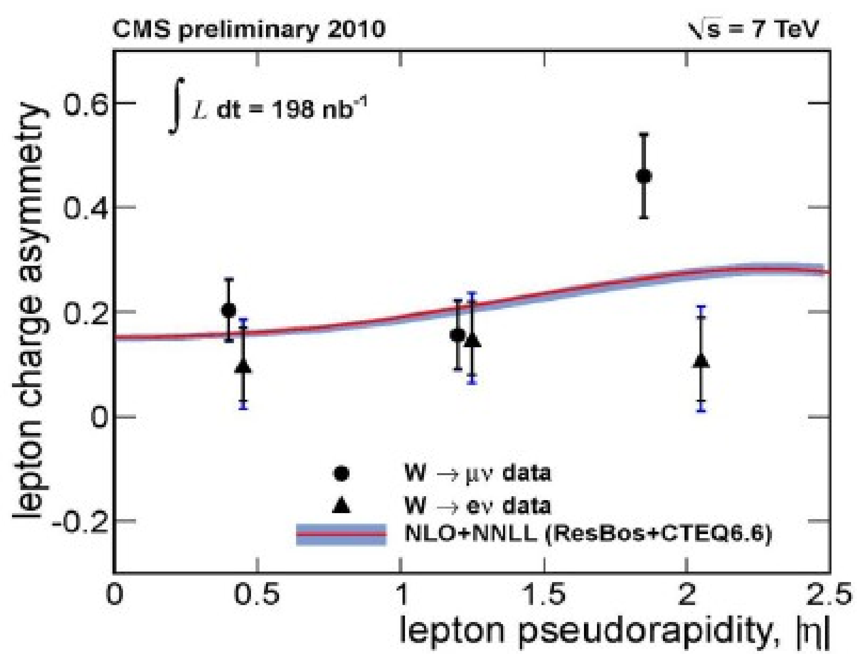
Muon channel W and Z events



CMS results

- Presented at conferences with 198 pb^{-1}
- Here shown asymmetry only

$$A(\eta) = \frac{d\sigma^{(+)}/d\eta_\ell - d\sigma^{(-)}/d\eta_\ell}{d\sigma^{(+)}/d\eta_\ell + d\sigma^{(-)}/d\eta_\ell}$$



- First measurement in three rapidity bins
In agreement with SM predictions

Next topics

- 10.11 - W,Z bosons
  - Precise measurements at Tevatron
  - Phenix, Hera
  - LHC prospects
- 17.11 –
  - W + jets
  - Tops: xsection, mass
- 24.11 – Hot topics: new exclusion limits
- 1.12, 8.12, 15.12 – Higgs