Standard Model Electroweak Processes at the LHC

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Outline

Snapshot of the electroweak Standard Model

- Electroweak Standard Model:
  - developed by Glashow, Salam and Weinberg in the 1960s
  - unified gauge theory of QED and weak interactions
    $\rightarrow$ gauge group $SU(2)_L \times U(1)_Y$
- Matter particles are fermions
  - leptons and quarks
  - left-handed doublets
  - right-handed singlets

$$\begin{pmatrix} \nu_e \\ e^- \end{pmatrix}_L \quad \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix}_L \quad \begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix}_L$$

$$e_R^- \quad \mu_R^- \quad \tau_R^-$$

$$[\nu_{e,R} \quad \nu_{\mu,R} \quad \nu_{\tau,R}]$$

$$\begin{pmatrix} u \\ d \end{pmatrix}_L \quad \begin{pmatrix} c \\ s \end{pmatrix}_L \quad \begin{pmatrix} t \\ b \end{pmatrix}_L$$

$$u_R \quad c_R \quad t_R$$

$$d_R \quad s_R \quad b_R$$

- Interactions are mediated by gauge bosons
  - $W^\pm$ and Z bosons, photons
  - mixing of neutral fields
  - weak mixing angle θ_W
  - non-abelian theory: gauge bosons can couple to themselves

$$\begin{pmatrix} A \\ Z \end{pmatrix} = \begin{pmatrix} \cos\theta_w & \sin\theta_w \\ -\sin\theta_w & \cos\theta_w \end{pmatrix} \begin{pmatrix} B \\ W_3 \end{pmatrix}$$

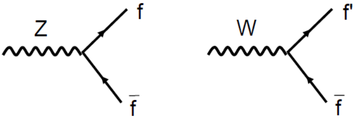
- Higgs mechanism provides masses for fermions and bosons

Electroweak measurements

- Masses of gauge bosons: M_W, M_Z
- Masses of fermions: the most important is the mass of the top quark m_t
- Important prediction of the Standard Model (to lowest order):

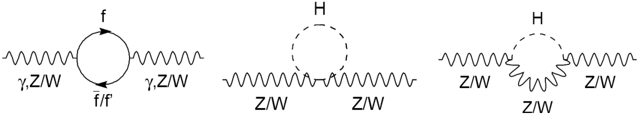
$$\frac{M_W}{M_Z} = \cos\theta_W \quad \text{or} \quad \rho = \frac{M_W}{M_Z \cos\theta_W} = 1$$

- Couplings of fermions to gauge bosons:
  $-ig\frac{1}{2}(c_V\gamma^\mu - c_A\gamma^\mu\gamma^5)$
- Couplings to Z-and W-bosons involve θ_W:
  $c_A^{f,Z} = T_3 = \pm\frac{1}{2}, 0$
  $c_V^{f,Z} = T_3 - 2Q\sin^2\theta_W$



$$g_Z = \frac{e}{\sin\theta_W \cos\theta_W} \qquad g_W = \sqrt{2}\frac{e}{\sin\theta_W}$$

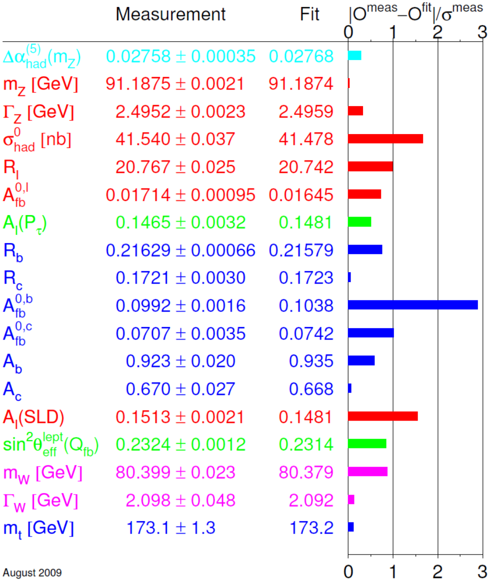
- Consequence: measurement of masses and couplings test Standard Model relations
  $\rightarrow$ $M_Z, M_W, \sin 2\theta_W$ are precisely measured
  $\rightarrow$ radiative corrections need to be included



$\sim m_t^2$

$\sim \log\frac{M_H}{M_W}$

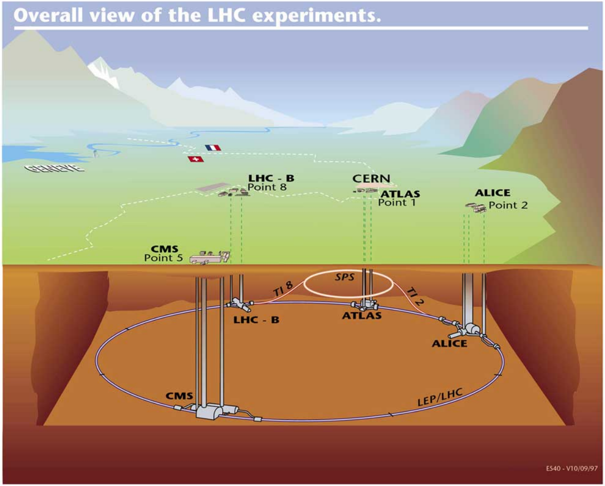
Test of the electroweak Standard Model



- Bars show difference between measurement and theory
- Relatively good agreement of measurements with predictions
- But room for new physics (SUSY, ...)

Physics at the LHC

The proton-proton collider LHC and the 4 experiments:



LHC luminosities and centre-of-mass energies:

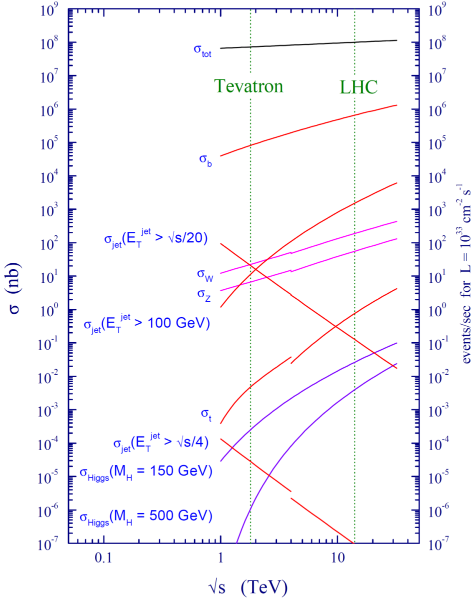
- 2010/2011:

  7 TeV max. energy, up to 1 fb^{-1}
- 2012:

  ~ 8 TeV and 5 fb^{-1}?
- Later:

  $13 - 14$ TeV ultimate energy,
  $50 - 70$ fb^{-1} until 2016,
  3000 fb^{-1} until 2030

Overview of production rates at the LHC



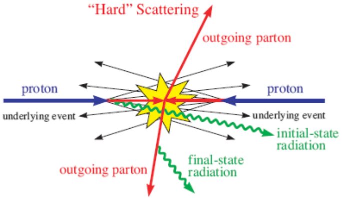
Typical production cross-sections at Tevatron and the LHC:

- Inelastic pp scattering dominates $\rightarrow$ “minimum bias”
- QCD processes have large cross-sections $\rightarrow$ 2-jet & 3-jet events
- Many events with W and Z bosons
- Top-pair production
- New particles: Higgs, SUSY, ...
- 13 orders of magnitude
- Number of physics events:

$$N = L \cdot \sigma$$

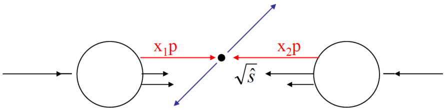
L = luminosity
σ = cross-section

Properties of pp-collision events



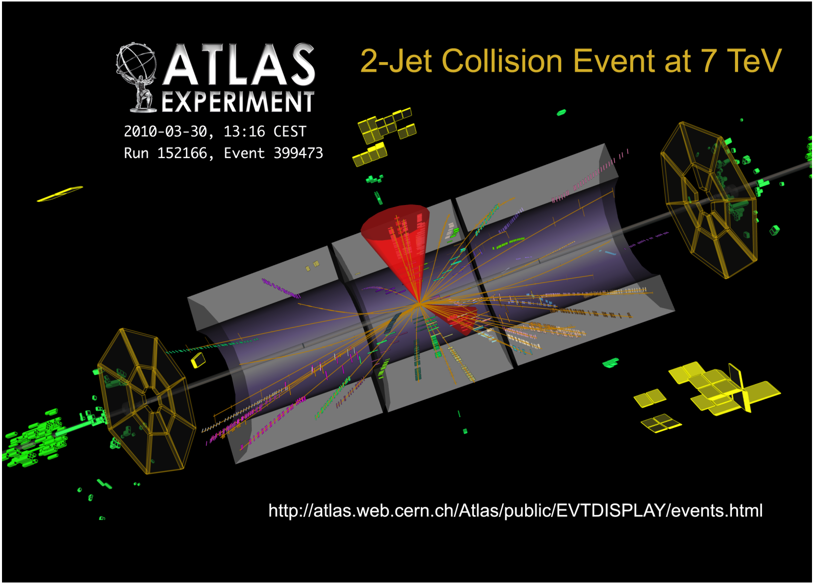
- pp collisions at the LHC mostly result in peripheral events with small momentum transfer: inelastic pp scattering
  $\rightarrow$ "minimum-bias" events $\rightarrow$ pile-up
- Many hadrons produced from proton remnants: "underlying event"

- In rare cases: hard scattering of the protons constituents (quarks and gluons) with large (transverse) momentum transfer (scattering at large angle)
  $qq \rightarrow qq, \quad gg \rightarrow gg, \quad gq \rightarrow gq$
- Quarks and gluons carry fractions x_1, x_2 of the proton momentum
  $\rightarrow$ centre-of-mass energy of quark/gluon collisions is < 7 TeV



Strategy:
identify interesting physics with high-p_T leptons, photons and jets or missing transverse energy (MET)

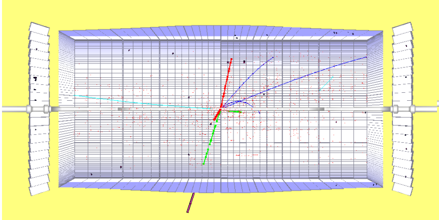
Properties of pp-collision events



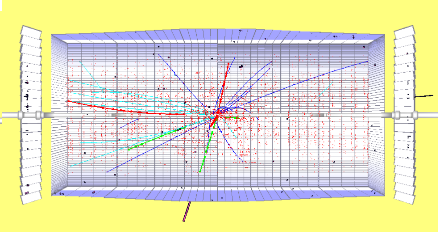
Effect of event pile-up

Number of simultaneous pp reactions increase with luminosity:

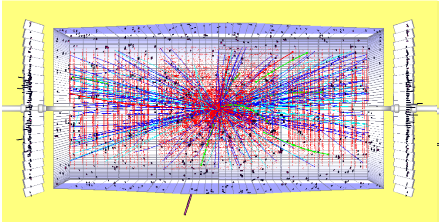
$10^{32} cm^{-2} s^{-1}$



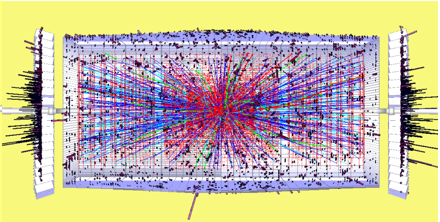
$10^{33} cm^{-2} s^{-1}$



$10^{34} cm^{-2} s^{-1}$



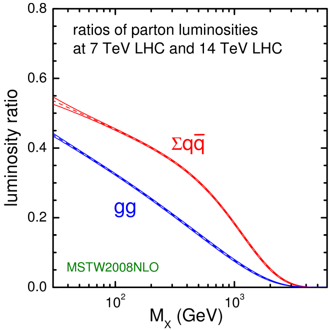
$10^{35} cm^{-2} s^{-1}$



At nominal LHC luminosity of $10^{34} cm^{-2} s^{-1}$: about 25 events per bunch crossing

Typical event rates of SM processes at the LHC

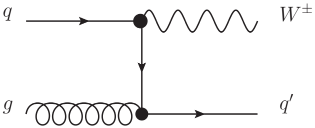
Process	σLO @ 7 TeV [pb]	σLO @ 14 TeV [pb]	Evts (7 TeV) in 200 pb^{-1}	7 TeV/ 14 TeV
QCD $P_T > 100$ GeV	$3.2 \cdot 10^5$	$1.4 \cdot 10^6$	$64 \cdot 10^7$	0.2
Z inclusive	$2.4 \cdot 10^4$	$5.7 \cdot 10^4$	$5 \cdot 10^6$ (3% $Z \to \ell\ell$)	0.4
W inclusive	$9.5 \cdot 10^4$	$2.1 \cdot 10^5$	$1.9 \cdot 10^7$ (11% $W \to \ell\nu$)	0.5
Top pairs	84	470	17000	0.2
H(m = 150 GeV)	4	16	800	0.3

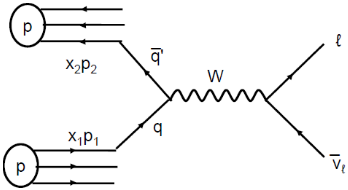


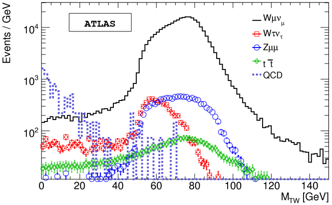
W boson production at the LHC

Physics measurements:

- Cross-section measurement in $W \to e\nu, \mu\nu, \tau\nu$ channels (hadronic final states difficult to select at the LHC)
- Measurement of the W boson mass and width
- PDF constraints
- MET calibration from $W \to \mu\nu$
- Background to search channels (W + jets)



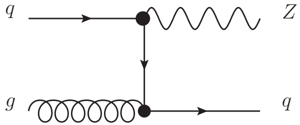


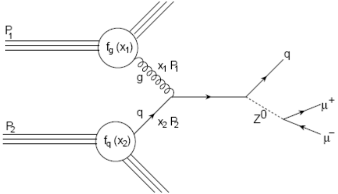


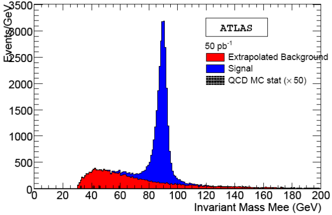
Z boson production at the LHC

Physics measurements:

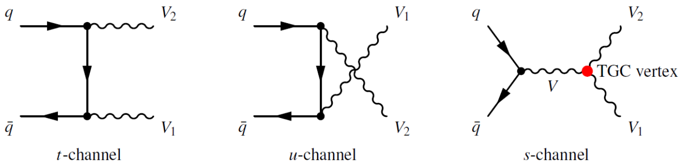
- Cross-section measurement in $Z \to ee, \mu\mu, \tau\tau$ channels
- Detector calibration: reconstruction, trigger and isolation efficiencies, resolution, alignment
- PDF constraints
- $\sin 2\theta_W$ from forward-backward asymmetry in $Z \to ee$ events
- Measurement of systematic uncertainties for other processes
- Background to search channels (Z + jets)







Di-boson production at the LHC

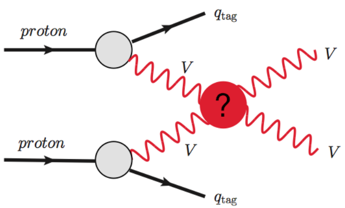


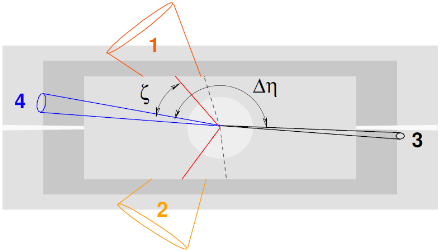
- Measurement of $WW, ZZ, W\gamma, Z\gamma$ final states
- Determination of production cross-sections
- Measurement of the couplings between gauge bosons $\rightarrow$ prediction of the SM
- Triple-gauge boson vertex
- Examples of cross-sections:

Diboson mode	Conditions	$\sqrt{s} = 14$ TeV $\sigma[pb]$
W^+W^- [15]	W-boson width included	111.6
$W^\pm Z$ [15]	Z and W on mass shell	47.8
ZZ [15]	Z's on mass shell	14.8
$W^\pm\gamma$ [16]	$E_T^\gamma > 7$ GeV, $\Delta R(\ell,\gamma) > 0.7$	451
$Z\gamma$ [17]	$E_T^\gamma > 7$ GeV, $\Delta R(\ell,\gamma) > 0.7$	219

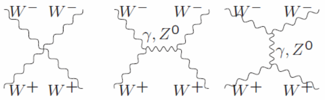
Factor 100-1000 smaller than for W, Z production

Vector Boson Scattering (VBS) at the LHC





e.g. in the pure gauge sector:



Feature of VBS: tagging jets
→ analysis of the process:

$$qq \rightarrow q_{\text{tag}} q_{\text{tag}} VV$$

rapidity gap between jets (no color flow)

→ Measurement of WW, WZ, ZZ final states:

$$WW \rightarrow l\nu l\nu$$
$$WW \rightarrow ql l\nu$$

$$WZ \rightarrow l\nu ll$$
$$WZ \rightarrow l\nu qq$$
$$WZ \rightarrow qqll$$

$$ZZ \rightarrow llll$$
$$ZZ \rightarrow ll\nu\nu$$
$$ZZ \rightarrow llqq$$

LHC Detectors: ATLAS and CMS

Challenges for LHC detectors:

- High collision rate: 25 ns proton bunch-crossing
- Up to 25 minimum-bias events/crossing $\rightarrow$ pile-up
- Radiation hardness $\rightarrow$ detectors and electronics tolerate 10^{15} particles/cm^2
- High granularity $\rightarrow$ isolate interesting leptons/photons/jets from pile-up
- Very good angular coverage $\rightarrow$ measure missing energy (neutrinos, SUSY)
- Fast trigger with high background suppression rate (~ 1 accepted event/10^6)

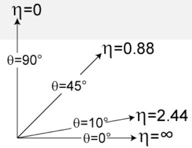
Performance goals:

- Get high efficiency for particle detection
- Suppress background from QCD jets

Object	Efficiency	BG suppr.	Motivation
electrons	>70%	100000	Z,W,top,H→4ℓ,...
photons	80%	1000	H→γγ
muons	>97% for p_T>1GeV		H→4ℓ,...
tau leptons	50%	100	H/A→ττ, SUSY,...
b-jets	50%	100	top, H→bb,SUSY,...

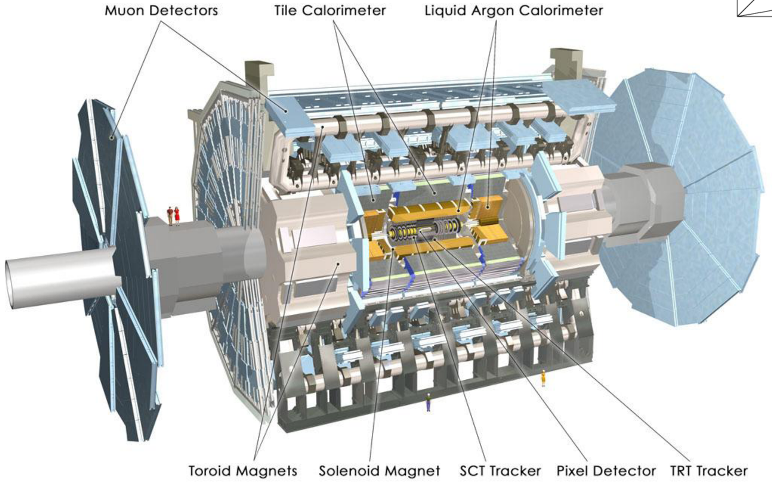
The ATLAS detector

Pseudo-rapidity: $\eta = -\ln \tan \frac{\theta}{2}$



Dimensions: $46m \times 22m \times 22m$, weight: 7000 tons

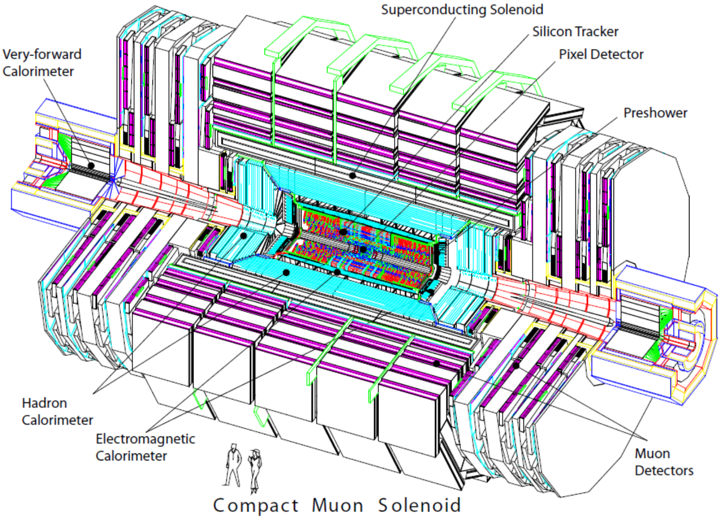
$\eta < 3.0$ $\eta < 4.9$



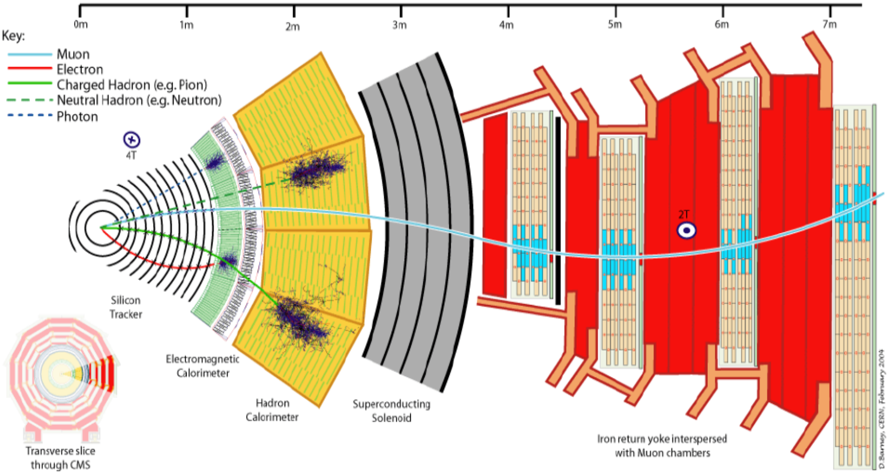
4 Tesla 2 Tesla $\eta < 2.5$

The CMS detector

Dimensions: $22m \times 15m \times 15m$, weight: 12500 tons

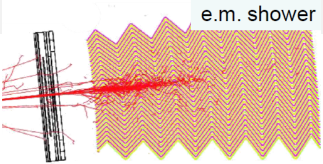


Particle identification



Charged Particles | Electrons Photons | Hadrons | 3.8 Tesla Solenoid | Iron yoke (return flux) Muons

Particle identification

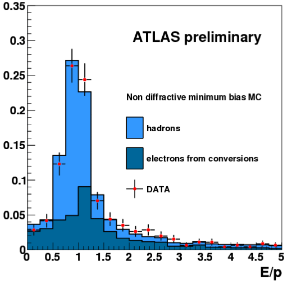


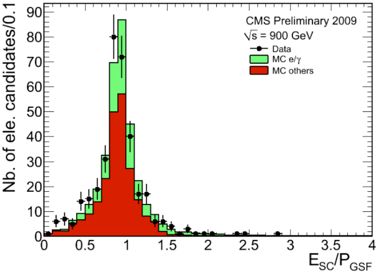
E.g. electron:

- Energy and shower shape measured in calorimeter
- Track matched to energy cluster using angles

$$\Delta R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2}$$

- Compare calorimetric energy and momentum measurement in tracker: $E/p \approx 1$
- No leakage of energy into hadronic calorimeter





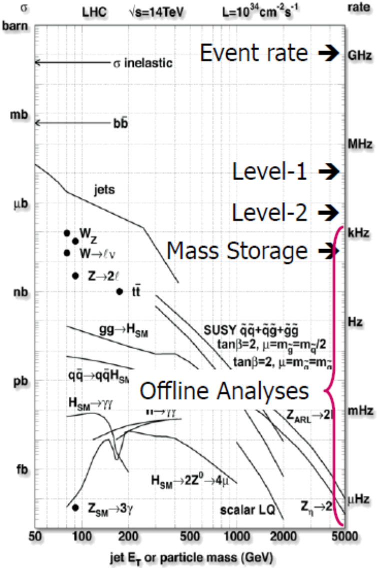
→ Combined performance is important!

From detector to physics: the trigger

Bunch crossing	40 MHz
σ_{total}	70 mb
Event rate	$\sim$ 1 GHz
Number of events/BC	$\sim$ 25
Number of particles/event	$\sim$ 1500
Event size	$\sim$ 1.5 MB
Mass storage rate	$\sim$ 200 Hz

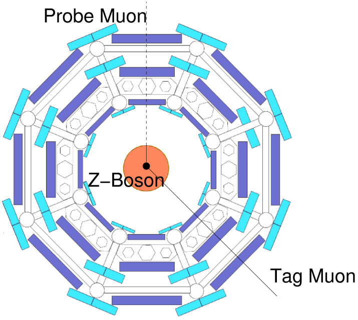
- Need to have trigger of high performance
  $\rightarrow$ 6 orders of rate reduction
  $\rightarrow$ complex events and 140 M channels

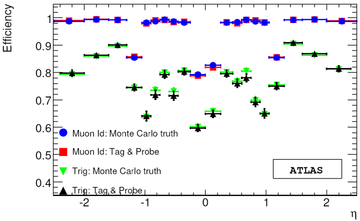
- Level-1: hardware based at 40 MHz
- Level-2: software based at 100 kHz
- Level-3: event filter at 3 kHz
- Storage at 200 Hz



Detector performance with Z bosons

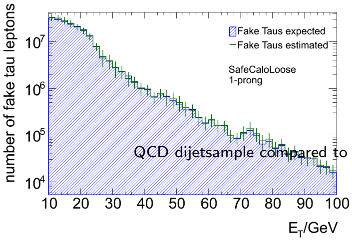
- Commonly applied method to measure performance in data:
  → "tag & probe" method
- Example: Measurement of muon identification efficiency with $Z \to \mu\mu$ events
  - Identify triggered and well measured muon: → tag
  - Use of Z decay kinematics to find the 2nd reconstructed muon:
    → probe
  - If 2nd (probe) muon passed selection
    → muon identification efficiency
  - similar for muon trigger and muon reconstruction efficiency
- Many more examples: $Z \to ee, J/\Psi \to ee, \ldots$



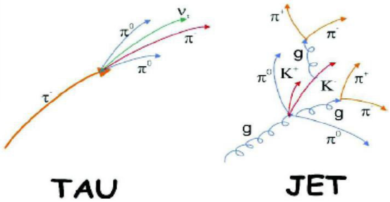


Detector performance with Z bosons

- Identification of hadronically decaying τ leptons
  - Collimated hadronic jet
  - 1 or 3 particle tracks
- Large QCD background: τ may look like hadronic jets from quarks and gluons
- Estimation of jets misidentified as a τ with $Z(\rightarrow ll)$ + jet events



QCD dijetsample compared to Z+jet estimate



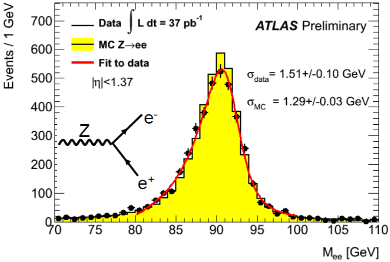
τ^- decay mode	BR %		
$e^- \bar{\nu}_e \bar{\nu}_\tau$	17.85	leptonic	
$\mu^- \bar{\nu}_\mu \bar{\nu}_\tau$	17.36		
$\pi^- \bar{\nu}_\tau$	10.91	hadronic	72%
$\pi^- \pi^0 \bar{\nu}_\tau$	25.52	1-prong	
$\pi^- 2\pi^0 \bar{\nu}_\tau$	9.27		
$\pi^- 3\pi^0 \bar{\nu}_\tau$	1.04		
$K^- \bar{\nu}_\tau$ + Neutrals	1.57		
$\pi^- \pi^+ \pi^- \bar{\nu}_\tau$	9.32	hadronic	23%
$\pi^- \pi^+ \pi^- \pi^0 \bar{\nu}_\tau$	4.61	3-prong	
$K^- \pi^+ \pi^- \bar{\nu}_\tau$ + Neutrals	0.48		

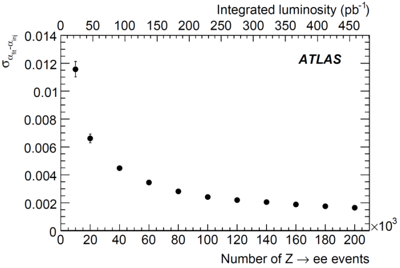
Detector performance with Z bosons

- Reconstruct pairs of electrons and positrons in the detector
- Measure the invariant mass of electron and positron M_{ee}
- The mass spectrum should peak at the Z boson mass M_Z
- Line-shape modelled with Breit-Wigner distribution:

$$BW(M) \sim \frac{M^2}{(M^2 - M_Z^2)^2 + \Gamma_Z^2 M^4 / M_Z^2}$$

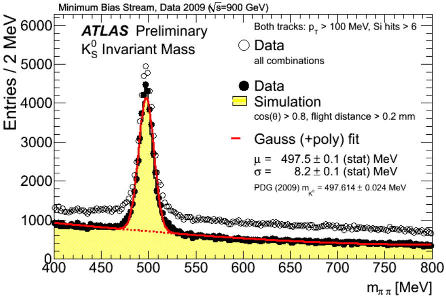
- Use the Z mass constraint from LEP $M_Z = 91.1875$ GeV to calibrate the energy scale of the calorimeter
- E.g. constant term of the energy resolution: 140 k $Z \to ee$ events needed to reach 0.2%





Detector performance with first physics data

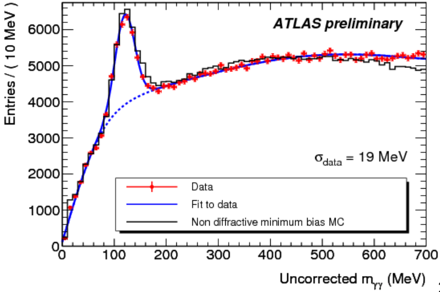
- Tracking performance using K_S mesons:



- Calorimeter performance with $\pi^0 \to \gamma\gamma$

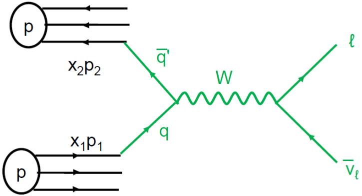
  Peak value agrees with pion mass to $1\% (1.5\ \mathrm{MeV})$

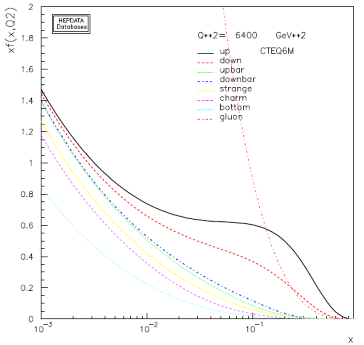
  Resolution is $19\ \mathrm{MeV} (\sim 2\%)$



Detailed example: W production

- W boson production to lowest order:



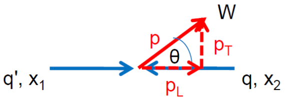


- Quarks carry fractions x_1, x_2 of the proton momentum
- The probability to find a parton i with a given energy fraction x in a proton is given by the parton distribution function $f_i(x, Q^2)$
- It is easy to calculate that the mass of the object produced (e.g. a W) is given by $\sqrt{\hat{s}} = \sqrt{x_1 x_2 s}$ with $s =$ centre-of-mass energy squared
- The production cross-section can then be written as

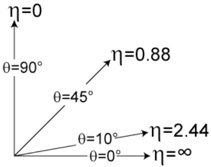
$$\sigma = \sum_{i,j} \int \hat{\sigma}_{ij}(\hat{s}) \int_0^1 \int_0^1 f_i(x_1) f_j(x_2) \delta(\hat{s} - x_1 x_2 s) dx_1 dx_2 d\hat{s}$$

W production kinematics

- At hadron machines the scattering angle θ relative to the beam axis is usually given in terms of pseudo-rapidity:



$$\eta = \frac{1}{2} \ln \frac{|\vec{p}| + p_L}{|\vec{p}| - p_L} = -\ln \tan \frac{\theta}{2}$$



- In a simplified picture, x_1 and x_2 are related to the pseudorapidity of the boson with mass M:

$$x_{1,2} = \frac{M}{\sqrt{s}} e^{\pm\eta}$$

- Examples for $M = 80.4$ GeV and $\sqrt{s} = 7$ TeV:

$$\begin{aligned} \eta = 0 \quad &\rightarrow \quad x_1 = x_2 \approx 0.01 \\ \eta = 0.88 \quad &\rightarrow \quad x_1 \approx 0.03 \quad \text{and} \quad x_2 \approx 0.005 \\ \eta = 3.0 \quad &\rightarrow \quad x_1 \approx 0.23 \quad \text{and} \quad x_2 \approx 0.0006 \end{aligned}$$

- At different scattering directions, different regions of the parton distribution functions are probed

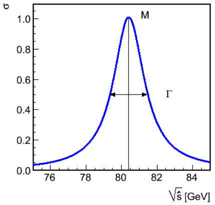
W differential cross-section

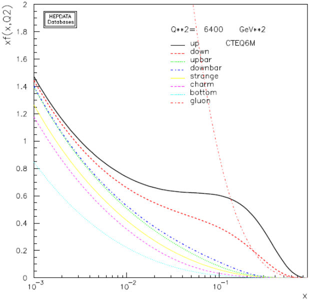
- If one assumes that the W boson resonance has zero width ($\Gamma_W \approx 0$)
  $\hat{\sigma}_{ij}(\hat{s}) = \sigma_{ij}\delta(\hat{s} - M^2)M^2$ with $\sigma_{ij} = \sigma(ij \to W)$
  one can perform the integrals easily and one obtains:

$$\frac{d\sigma}{d\eta}(pp \to X) \approx \sum_{i,j} \sigma_{ij} \frac{M^2}{s} f_i\left(\frac{M}{\sqrt{s}}e^{\eta}\right) f_j\left(\frac{M}{\sqrt{s}}e^{-\eta}\right)$$

  with the parton density functions $f_i(Q^2, x)$
- Consequence: one can calculate the differential cross-section by simply multiplying the PDFs (and by summing over the possible intermediate states ij)

  Plots and numerical tables:
  http://durpdg.dur.ac.uk/HEPDATA/PDF
  Try it yourself! (works also for Higgs at LO, ...)





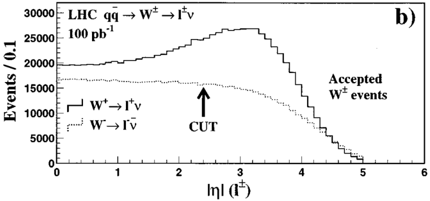
W differential cross-section

$$\frac{d\sigma}{d\eta}(pp \to X) \approx \sum_{i,j} \sigma_{ij} \frac{M^2}{s} f_i\left(\frac{M}{\sqrt{s}}e^{\eta}\right) f_j\left(\frac{M}{\sqrt{s}}e^{-\eta}\right)$$

- Example: $u + \bar{d} \to W^+$ and $\bar{u} + d \to W^-$:

$$\sigma(u + \bar{d} \to W^+) = \sigma(\bar{u} + d \to W^-) = \sigma_W$$

- anti-u and anti-d PDFs are about the same (sea-quarks)
- at $\eta = 3.0$ $(x_1 \approx 0.23, x_2 \approx 0.0006)$ the u- and d-PDF differ by a factor of 2 (valence quarks) $\to$ W^+ production is enhanced with respect to W^-

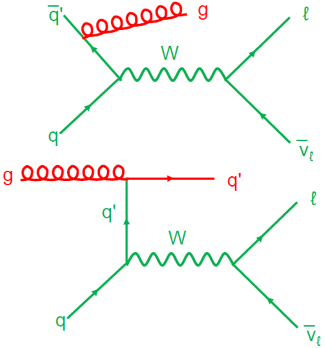


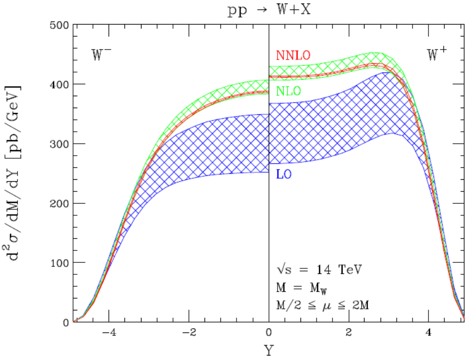
M. Dittmar et al., Phys. Rev. D 56 (1997) 7284

- Possibility to test/measure PDFs

W + jet production

- There are corrections to the lowest order description, e.g. due to gluon radiation
- Corrections are next-to-leading order (NLO) in α_s or even NNLO, N^{3}LO, ...
  $\rightarrow W$ + jet production





- Theoretical uncertainties are typically reduced when going to higher order calculations

W and Z production cross-section

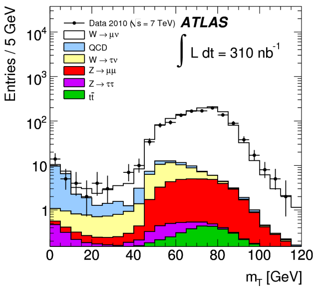
- W selection:
  - lepton with $p_T > 20$ GeV
  - $MET > 25$ GeV $\rightarrow$ neutrino
  - W mass would be

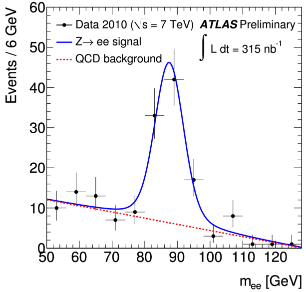
$$M_W \approx \sqrt{E^l E^\nu (1 - \cos\alpha(l,\nu))}$$

  but E^ν and angle cannot be measured
  $\rightarrow$ transverse mass: $M_T > 40$ GeV

$$M_T \approx \sqrt{p_T^l p_T^{\text{miss}} (1 - \cos\Delta\phi(p_T^l, p_T^{\text{miss}}))}$$

- Z selection:
  - isolated leptons with $p_T > 20$ GeV
  - $66 < M_{ll} < 116$ GeV
- Background at 10% level (QCD)
- Stat. uncertainty $\sim 1/\sqrt{N}$ will be very small
- Systematics will dominate: background uncertainties, luminosity and theory (PDF, gluon radiation, underlying event,...)





W and Z production cross-section

Production cross-sections for W and Z bosons times the branching ratios for decays into leptons:

$$\sigma^{\text{tot}}_{W(Z)} \cdot BR(W(Z) \to l\nu(ll)) = \frac{N^{\text{sig}}_{W(Z)}}{A_{W(Z)} \cdot C_{W(Z)} \cdot L_{W(Z)}}$$

- N^{sig}_W and N^{sig}_Z: numbers of background-subtracted signal events
- A_W and A_Z: fiducial acceptances $\to$ fraction of decays satisfying the geometrical and kinematical constraints at the generator level (defined before QED FSR)
- C_W and C_Z:

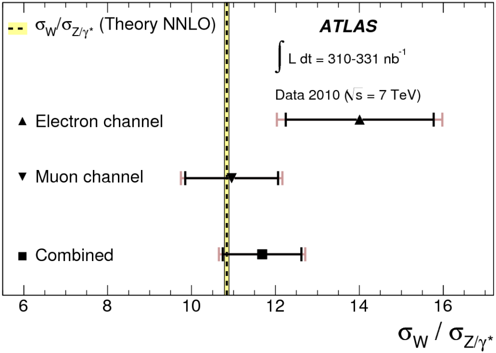
  $$\frac{\#\text{ generated events which pass the final selection requirements after reconstruction}}{\#\text{ generated events within the fiducial acceptance}}$$

  $\to$ include the efficiencies for triggering, reconstructing, and identifying the W and Z boson decays falling within the acceptance
- L_W and L_Z: integrated luminosities for the channels of interest

W and Z production cross-section

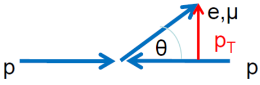
Production cross-sections for W and Z bosons times the branching ratios for decays into leptons:

$$\sigma^{tot}_{W(Z)} \cdot BR(W(Z) \to l\nu(ll)) = \frac{N^{sig}_{W(Z)}}{A_{W(Z)} \cdot C_{W(Z)} \cdot L_{W(Z)}}$$

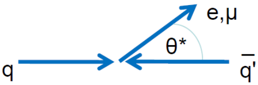


M_W measurement

- Kinematics of the $W \to l\nu_l$ decay $\to$ only the lepton is measured in the detector:



lab frame

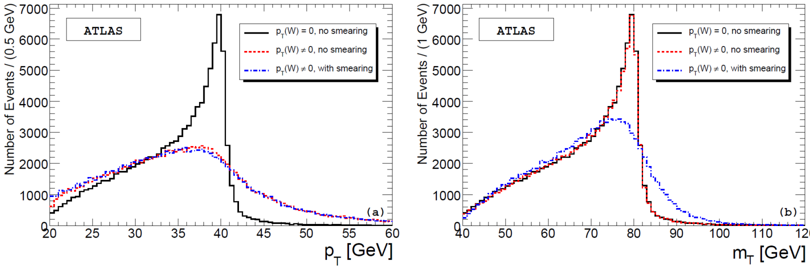


W rest frame

- Differential decay rate in the lab frame can be traced back to decay rate in rest frame:

$$\frac{dN}{dp_T} = \frac{2p_T}{M_W}\frac{1}{\sqrt{\left(\frac{M_W}{2}\right)^2 - p_T^2}}\frac{dn}{d\cos\theta^*}$$

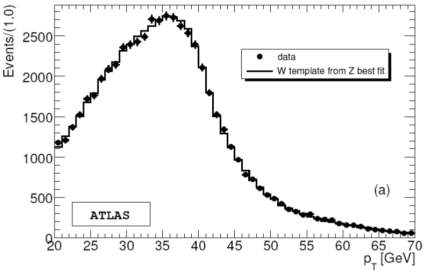
Jacobian factor is singular at $p_T = \frac{M_W}{2}$ $\to$ Mass peak in p_T spectrum



- p_T of W is non-zero $\to$ changes spectrum $M_T \approx \sqrt{p_T^l p_T^{\text{miss}}(1 - \cos\Delta\phi(p_T^l, p_T^{\text{miss}}))}$

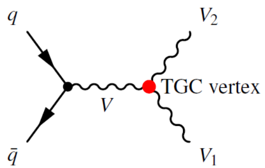
M_W measurement

- Fit spectra of lepton p_T and $M_T \approx \sqrt{p_T^l p_T^{\text{miss}}(1-\cos\Delta\phi(p_T^l, p_T^{\text{miss}}))}$
- Lepton energy scale from Z events
- Adjust Monte-Carlo samples with different M_W to fit best to data spectrum
- Most sensitive region is upper edge of the Jacobian peak (~ 40 GeV)



- Statistical uncertainty:
  in ~ 30 pb^{-1} is ~ 60 MeV in $W \to \mu\nu$ and $W \to e\nu$ channel
- Systematics:
  lepton energy scale 110 MeV and 200 MeV due to W recoil, p_T^W
- "warm-up" for the ultimate 15 MeV precision $\to 10-20$ fb^{-1}
- W mass precision today: 23 MeV (LEP+Tevatron)

Couplings between gauge bosons



- Non-abelian nature of SM predicts triple gauge boson couplings (TGC)
- Coupling strength in the SM: $g_{WW\gamma} = e, \quad g_{WWZ} = e \cot\theta_W$
- Measure these couplings and test for anomalous contributions
- Effective Lagrangian is used to model these ($V = \gamma$ or Z):

$$L/g_{WWV} = i g_1^V (W^*_{\mu\nu} W^\mu V^\nu - W_{\mu\nu} W^{*\mu} V^\nu) + i\kappa^V W^*_\mu W_\nu V^{\mu\nu} + \frac{\lambda^V}{M_W^2} W^*_{\rho\mu} W^\mu_\nu V^{\nu\rho}$$

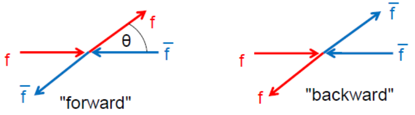
  in the SM: $g_1^\gamma = g_1^Z = 1 \qquad \kappa^\gamma = \kappa^Z = 1 \qquad \lambda^\gamma = \lambda^Z = 0$
- At LHC the di-boson decays to electrons and muons will be measured:

$$\begin{aligned} pp &\to ZW \to lll\nu \\ pp &\to WW \to l\nu l\nu \\ pp &\to ZZ \to llll, ll\nu\nu \\ pp &\to Z\gamma \to ll\gamma \\ pp &\to W\gamma \to l\nu\gamma \end{aligned}$$

  $\to$ high p_T leptons and photons, Z mass and transverse mass constraints
- Anomalous couplings between ZZZ and $ZZ\gamma$ are studied, too (do not exist in SM)

Weak mixing angle measurement at the LHC

- Z boson production at LHC is the "inverse" of the LEP process
  LHC: $q\bar{q} \to Z/\gamma^* \to e^+e^-$ LEP: $e^+e^- \to Z/\gamma^* \to q\bar{q}$
- In the Z rest frame: measurement of forward-backward asymmetry $A_{FB} = \frac{N_F - N_B}{N_F + N_B}$



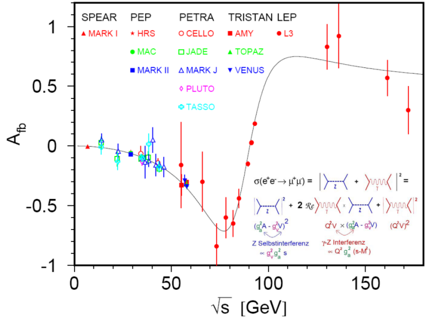
- A_{FB} depends on Z-to-fermion couplings:
  $A_{FB} = A_{FB}(c_V^f, c_A^f) = A_{FB}(\sin^2\theta_W)$

  $\rightarrow$ precise measurement of $\sin^2\theta_W$

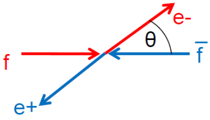
$$\delta \sin^2\theta_W = 1.6 \cdot 10^{-4}$$
$$\delta M_W / M_W = 2.8 \cdot 10^{-4}$$
$$\delta M_Z / M_Z = 0.2 \cdot 10^{-4}$$

$\rightarrow$ test the Standard Model:

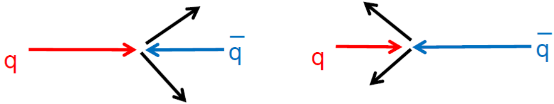
$$\rho = \frac{M_W}{M_Z \cos\theta_W} = 1 + \Delta\rho(\text{rad.corr.})$$

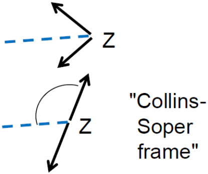


Weak mixing angle measurement at the LHC



- LEP was a e^+e^- collider with symmetric beam energies automatically in Z rest frame
- Quark-quark system at LHC has varying longitudinal momentum $\rightarrow$ depends on share between x_1 and x_2



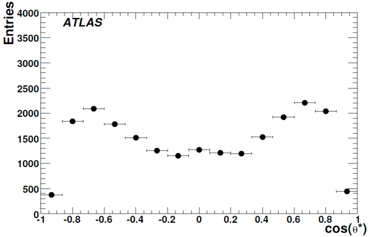


- A trick has to be done: we know the Z decays to e^+e^-
  $\rightarrow$ the reference direction is the bi-section between e^+ and e^-
  $\rightarrow$ go into the e^+e^-rest frame $=$ Z boson rest frame

- Good enough approximation to measure the asymmetry

$$A_{FB} = b(a - \sin^2 \theta^l_{\text{eff}})$$

- LHC expects a precision of $\delta \sin^2 \theta_W = 3 \cdot 10^{-4}$ at 100 fb^{-1} and includes forward detectors
- Compare to LEP: $\delta \sin^2 \theta_W = 1.6 \cdot 10^{-4}$



Summary

- Known Standard Model electroweak processes are a main reference for a good understanding of the ATLAS and CMS detectors

- We know that the Standard Model is just an effective theory which will need extensions at very high energies
  But: good understanding of expected SM signatures needed since it is the background for searches for new physics, subsequently precision measurements:
- Production cross-sections of W and Z boson
  $\rightarrow W$ mass with $15\ \mathrm{MeV}$ ultimate precision
- Di-boson production WW, WZ, ZZ, ...
  $\rightarrow$ Triple gauge boson couplings to precision beyond $\Delta\kappa/\Delta\lambda/\Delta g_1 = 0.01$
- New measurement of the weak mixing angle
  $\rightarrow \delta \sin^2\theta_W = 3 \cdot 10^{-4}$ and maybe better