Introduction, measurement foundations and W/Z physics
Introduction

- Precision measurements at hadron colliders
  - Hadron colliders are ‘messy’, but can still do relevant ‘precision’ measurements
  - Precision can mean a few % (cross-sections), or even <<1% (W mass)
  - Not a complete overview of all precision measurements at hadron colliders, but showcase a few measurements in some detail
    - Also illustrating some of the ‘foundations’ – e.g. object calibration, luminosity and beam energy measurements
  - Examples mainly from ATLAS, and from CMS, a few Tevatron comparisons

- Lecture 1
  - Introduction, W and Z final states, luminosity, parton distribution functions (PDFs)

- Lecture 2
  - Electroweak mixing angle, W mass, jet measurement and jet physics

- Lecture 3
  - Top physics – (differential) cross-sections, top quark mass
Outline of lecture 1

- Introduction
  - Precision measurements and the electroweak fit
- The experimental environment
  - Comparison of LHC, Tevatron and LEP
- W/Z cross-sections
  - Importance of fiducial measurements
  - Calibration of lepton efficiencies and scales – role of $m_Z$
  - LHC luminosity measurement
  - Parton distribution functions
- W/Z cross-section results
  - Results and constraints on PDFs

Thanks to Gautier Hamel de Monchenault for some diagrams …
Why precision measurements?

- LHC is primarily a ‘discovery machine’ – explore a new energy regime
  - Found the/a Higgs boson, what else will we find…?
- Can also perform precision measurements within the Standard Model
  - Improve on measurements of SM parameters
    - E.g. W vs top quark vs Higgs masses
    - E.g. $\alpha_s$ in different processes, electroweak mixing angle $\sin^2\theta_W$
  - Study QCD dynamics at high energy, test QCD calculations
    - Improve knowledge of proton parton distribution functions (PDFs)
    - Test QCD with multiple high scales
    - Understand the physics of the top quark (the heaviest, and strangest quark)
- Study the properties of the Higgs boson
- Test SM predictions for very rare processes
- SM physics also forms the backdrop to any new physics search
  - Essential to fully understand background (particularly W/Z+jets and top) in order to search for new physics
  - SM physics processes (particularly W and Z decays to leptons) provide ‘standard candles’ to understand and calibrate the detector performance
Testing the consistency of the Standard Model

- Electroweak parameters

\[ \rho \equiv \frac{m_W^2}{m_Z^2 \cos^2 \theta_W} \quad \text{(=} 1) \quad s_W^2 \equiv 1 - \frac{m_W^2}{m_Z^2} \quad \text{(=} \sin^2 \theta_W) \]

- Physical observables modified by radiative corrections at the % level

\[ \bar{\rho} = 1 + \Delta \rho \quad M_W^2 = m_W^2 (1 + \Delta r) \quad \sin^2 \theta_W^{\text{eff}} = s_W^2 (1 + \Delta \kappa) \]

\[ \Delta r, \Delta \rho, \Delta \kappa = f(m_t^2, \ln(m_H), ...) \]

- Complementary info. from asymmetries

- \( e^+e^- \rightarrow e^+e^-, \mu^+\mu^-, bb \) etc.

- Major achievement of LEP – what can LHC add?

- Mass measurements, but also asymmetries…

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Global electroweak fit

- Comparison of measured and fitted electroweak parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Input value</th>
<th>Free in fit</th>
<th>Fit Result</th>
<th>w/o exp. input in line</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_H$ [GeV]</td>
<td>125.14 ± 0.24</td>
<td>yes</td>
<td>125.14 ± 0.24</td>
<td>$93^{+25}_{-21}$</td>
</tr>
<tr>
<td>$M_W$ [GeV]</td>
<td>80.385 ± 0.015</td>
<td>–</td>
<td>80.364 ± 0.007</td>
<td>80.358 ± 0.008</td>
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<tr>
<td>$\Gamma_W$ [GeV]</td>
<td>2.085 ± 0.042</td>
<td>–</td>
<td>2.091 ± 0.001</td>
<td>2.091 ± 0.001</td>
</tr>
<tr>
<td>$M_Z$ [GeV]</td>
<td>91.1875 ± 0.0021</td>
<td>yes</td>
<td>91.1880 ± 0.0021</td>
<td>91.200 ± 0.011</td>
</tr>
<tr>
<td>$\Gamma_Z$ [GeV]</td>
<td>2.4952 ± 0.0023</td>
<td>–</td>
<td>2.4950 ± 0.0014</td>
<td>2.4946 ± 0.0016</td>
</tr>
<tr>
<td>$\sigma_{\text{had}}^0$ [nb]</td>
<td>41.540 ± 0.037</td>
<td>–</td>
<td>41.484 ± 0.015</td>
<td>41.475 ± 0.016</td>
</tr>
<tr>
<td>$R^0$</td>
<td>20.767 ± 0.025</td>
<td></td>
<td>20.743 ± 0.017</td>
<td>20.722 ± 0.026</td>
</tr>
<tr>
<td>$A^0_{FB}$</td>
<td>0.0171 ± 0.0010</td>
<td></td>
<td>0.01626 ± 0.0001</td>
<td>0.01625 ± 0.0001</td>
</tr>
<tr>
<td>$A^0_e$</td>
<td>0.1499 ± 0.0018</td>
<td></td>
<td>0.1472 ± 0.0005</td>
<td>0.1472 ± 0.0005</td>
</tr>
<tr>
<td>$\sin^2 \theta_{\text{eff}} (Q_{FB})$</td>
<td>0.2324 ± 0.0012</td>
<td></td>
<td>0.23150 ± 0.00006</td>
<td>0.23149 ± 0.00007</td>
</tr>
<tr>
<td>$A_c$</td>
<td>0.670 ± 0.027</td>
<td></td>
<td>0.6680 ± 0.0022</td>
<td>0.6680 ± 0.0022</td>
</tr>
<tr>
<td>$A_b$</td>
<td>0.923 ± 0.020</td>
<td></td>
<td>0.93463 ± 0.00004</td>
<td>0.93463 ± 0.00004</td>
</tr>
<tr>
<td>$A^0_{c_F}$</td>
<td>0.0707 ± 0.0035</td>
<td></td>
<td>0.0738 ± 0.0003</td>
<td>0.0738 ± 0.0003</td>
</tr>
<tr>
<td>$A^0_{b_F}$</td>
<td>0.0992 ± 0.0016</td>
<td></td>
<td>0.1032 ± 0.0004</td>
<td>0.1034 ± 0.0004</td>
</tr>
<tr>
<td>$R^0_{c_F}$</td>
<td>0.1721 ± 0.0030</td>
<td></td>
<td>0.17226 ± 0.00009</td>
<td>0.17226 ± 0.00008</td>
</tr>
<tr>
<td>$R^0_{b_F}$</td>
<td>0.21629 ± 0.00066</td>
<td></td>
<td>0.21578 ± 0.00011</td>
<td>0.21577 ± 0.00011</td>
</tr>
<tr>
<td>$m_t$ [GeV]</td>
<td>173.34 ± 0.76</td>
<td>yes</td>
<td>173.81 ± 0.85</td>
<td>$177.0^{+2.06}_{-2.04} (\uparrow)$</td>
</tr>
</tbody>
</table>

- LHC/Tevatron: $m_W$ (and $m_H$, $m_{\text{top}}$), asymmetries also interesting

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W, top and Higgs masses

- Impressive consistency of the direct and indirect determination of masses

- Important in particular to measure $m_W$ better (but already $\Delta m_W/m_W=0.02\%$)

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The physics landscape at LHC

- LHC is a W/Z/H/top factory
  - But it is also a jet / b / soft interaction factory
  - Rates for nominal LHC, 13 TeV, L=10^{34} cm^{-2}s^{-1}

<table>
<thead>
<tr>
<th>Process</th>
<th>Rate @13TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inelastic pp collision</td>
<td>10^9 Hz</td>
</tr>
<tr>
<td>b-quark pair production</td>
<td>10^6 Hz</td>
</tr>
<tr>
<td>Jet production, E_T&gt;250 GeV</td>
<td>10^3 Hz</td>
</tr>
<tr>
<td>W→l_ν</td>
<td>10^2 Hz</td>
</tr>
<tr>
<td>Top-quark pair production</td>
<td>10 Hz</td>
</tr>
<tr>
<td>Higgs (m_H=125 GeV)</td>
<td>0.1 Hz</td>
</tr>
</tbody>
</table>

- Interesting processes – a needle in a haystack
  - Limited to recording 10^2 - 10^3 Hz of events
  - Trigger selections based on high-p_T electrons, photons, muons, taus, jets, E_T^{miss}
  - Cannot record all W→l_ν events
    - Control of trigger biases is crucial

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The LHC experimental environment

- High pileup complicates precision physics measurements
  - Additional pp interactions in same bunch crossing, and in nearby bunch crossings for slow detectors
  - $\langle \mu \rangle \approx 20$ in run-1, higher in run-2

- Effects of pileup
  - Deterioration of jet and $E_T^{\text{miss}}$ resolution, additional pileup jets
    - Higher trigger thresholds
  - Additional jets from pileup
  - Misidentification of primary vertex
  - Pileup-dependent efficiencies, even for leptons

- Pileup mitigation techniques
  - Particle flow (jets, $E_T^{\text{miss}}$, isolation)
  - Jet-area based pileup corrections

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Z$\rightarrow$\(\mu\mu\) event with ~25 reconstructed vertices

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Comparison of LHC with LEP and Tevatron

Samples of W, Z and top-pair events at the different colliders

<table>
<thead>
<tr>
<th></th>
<th>LEP</th>
<th>Tevatron</th>
<th>LHC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Particles</td>
<td>e+e−</td>
<td>p-pbar</td>
<td>pp</td>
</tr>
<tr>
<td>√s (GeV)</td>
<td>88-209 GeV</td>
<td>1.8-1.96 TeV</td>
<td>7-13 TeV</td>
</tr>
<tr>
<td>Int. L/ expt</td>
<td>200-700 pb⁻¹</td>
<td>2-10 fb⁻¹</td>
<td>5-300 fb⁻¹</td>
</tr>
<tr>
<td>Typical &lt;µ&gt;</td>
<td>&lt;&lt;1</td>
<td>~1-10</td>
<td>20-40</td>
</tr>
<tr>
<td># W→lv / expt</td>
<td>10k</td>
<td>~1-2M</td>
<td>10M (in 5 fb⁻¹)</td>
</tr>
<tr>
<td># Z→ll / expt</td>
<td>0.5M</td>
<td>~100k</td>
<td>1M (in 5 fb⁻¹)</td>
</tr>
<tr>
<td># ttbar / expt</td>
<td>-</td>
<td>10⁵</td>
<td>10⁷</td>
</tr>
</tbody>
</table>

LEP e+e- collider

- Very clean e+e− events, Ws only produced in pairs, full event reconstruction, limited data samples, no top quarks

Tevatron/LHC

- Larger samples, pileup and underlying event, no complete reconstruction, tops

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Z→μμ at LEP and LHC

- OPAL e⁺e⁻→Z→μ⁺μ⁻ from 1993, ATLAS 13 TeV pp→Z→μ⁺μ⁻ from 2015
Z and W cross-section measurements

- Drell-Yan production: lepton pairs from quark-antiquark annihilation

- Boson rapidity is correlated with parton $x_1$, $x_2$ – gives information on proton PDFs
- Studying both $Z/\gamma^*/Z \rightarrow l^+l^-$ and $W \rightarrow l\nu$ allows disentangling quark flavours
- Experimentally, very attractive process:
  - High $p_T (>20 \text{ GeV})$ leptons easy to trigger, identify offline and measure precisely
  - Low backgrounds (dominant process giving high $p_T$ leptons at LHC)
  - ‘Standard candle’ for calibration measurements
    - Z has two leptons and the Z mass is precisely known from LEP
Z→ee and Z→μμ event samples

- Large cross-section: \( \sigma(pp\rightarrow Z) \times \text{BR}(Z\rightarrow ll) = 0.9 \text{ nb at 7 TeV, } \times 2 \text{ at 13 TeV} \)
  - Final ATLAS 7 TeV analysis (4.6 fb\(^{-1}\)) has 1M Z→ee and 1.6M Z→μμ
  - Pure samples – <1% backgrounds from Z→ττ, dibosons, top and QCD multijet

- Define total Z/γ\(^*\) cross-section in a mass window, e.g. 46<m\(_{ll}\)<150 GeV

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More $Z\rightarrow ee$ and $Z\rightarrow \mu\mu$ event samples

- Even small samples ($<100 \text{ pb}^{-1}$) lead to $10^4$-$10^5$ $Z\rightarrow ll$ event samples
  - Inclusive cross-section analyses do not need the full data statistics
  - Early analyses done with both Run-1 and Run-2 data

Early analyses done with both Run-1 and Run-2 data.
Total and fiducial cross-section definitions

- Measurement of total cross-section from event counting in mass window
  \[ \sigma^{\text{tot}} = \frac{(N - B)}{(\varepsilon \cdot L)} \]
  - Efficiency \( \varepsilon \) includes both the lepton identification efficiencies ...
  - ...and probability of event to satisfy kinematic requirements for detector acceptance
    - E.g. \( p_T > 20 \) GeV (trigger, reconstruction) and \( |\eta| < 2.5 \) (coverage of detector)
    - Acceptance calculation needs a MC simulation model – uncertainties can be large

- Alternative of fiducial cross-section – ‘measure what you detect’
  - Split efficiency \( \varepsilon \) into an acceptance \( A \) and recon effiency \( C \); \( \varepsilon = A \times C \)
  - Define a fiducial phase space at particle level: \( p_T^{\text{fid}} > 20 \) GeV, \( |\eta^{\text{fid}}| < 2.5 \)

\[
\sigma^{\text{fid}, e(\mu) \rightarrow e(\mu)v}[Z \rightarrow ee(\mu)] = \frac{N_{W[Z]} - B_{W[Z]}}{C_{W[Z]} \cdot L_{\text{int}}} \quad C_{W[Z]} = \frac{N_{MC,\text{gen, fid}}}{N_{W[Z]}^{MC, \text{rec}}} \]

- Advantages – avoid extrapolations into unmeasured phase space
  - Can make use of updated acceptance predictions once they become available
- Disadvantage – acceptance calculation moved to theory (prediction)
  - Need to calculate \( pp \rightarrow Z \rightarrow ll \) with decay kinematics (at NLO, NNLO), not just \( pp \rightarrow Z \)
    - Becomes challenging for more complex final states, e.g. top-pair production

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Lepton efficiency measurements

- $Z \rightarrow ll$ (and $J/\psi, \Upsilon \rightarrow ll$) used for **tag and probe** efficiency measurements
  - One tightly-identified lepton (tag), other with just a subset of requirements
    - E.g. loose track+calo match for electron, ID track only for muon
  - $Z$-mass requirement ensures probe sample is still dominated by real leptons
  - Efficiency of requirement under test can then be calibrated on this pure sample
    - Need careful background subtraction in the sample failing the requirement
  - Compare data and simulation results to derive correction factors for simulation
Lepton efficiency measurements – continued

- Typically achieve sub-percent precision
  - For lepton $p_T$ close to those in Z decays
  - $J/\psi, \Upsilon \rightarrow ll$ harder to trigger on, poorer S/B
- More difficult at high $p_T$
  - Run out of statistics beyond Z-peak region
  - And relatively more background at high $p_T$
  - Extrapolation with MC-based inputs
- Becomes important in top-quark analyses

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Lepton energy/momentum calibration

- $Z \rightarrow ll$ samples (+J/ψ, $γ \rightarrow ll$) also used for electron and muon energy calibration
  - For electrons, typically ‘bottom up’ cluster calibration+detailed material model
    - Final in-situ corrections using template fits to $Z \rightarrow ee$ data in bins of electron $|\eta|$
  - For muons, scale and resolution depend on ID alignment, muon chamber alignment and drift time calibration, magnetic field map, material, …
    - In-situ corrections using $Z \rightarrow μμ$ template fits in bins of $\eta$ and $φ$
  - Typical scale uncertainties are below $10^{-3}$ in relevant $p_T$ and $\eta$ ranges

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How do we know $m_Z$?

- $m_Z$ determined from Z-lineline at LEP
  - Total cross-section for $e^+e^-\rightarrow$ hadrons vs $\sqrt{s}$
  - Measurements at peak and 6 off-peak energies
  - Fit to model to determine $m_Z$, $\Gamma_Z$ and $\sigma^0_{\text{had}}$
    - 6 years of data-taking, 10 years of analysis...
    
    $$m_Z = 91.1875 \pm 0.0021 \text{ GeV}$$
    (0.002%)

- Uncertainty dominated by energy calibration
  - Based on technique of resonant depolarisation
  - Spin precession frequency of electrons

  $$\nu = \frac{E[\text{MeV}]}{440.6486(1)[\text{MeV}]}$$

  - Wait for polarisation to build up due to synchrotron radiation, find frequency of a depolarising magnetic field

  - Many corrections to translate to physics data, e.g.
    - Lunar tides change the radius of LEP/LHC tunnel
    - Return current from electric trains (TGV)

- Only at LEP1 – polarisation too weak above 100 GeV

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W→eν and W→μν samples

- W selections also require the use of $E_T^{\text{miss}}$ to measure the neutrino $p_T$
  - Cannot fully reconstruct the W boson mass as the neutrino $p_Z$ is not measured
  - Use the transverse mass $m_T$: \[ m_T = \sqrt{2p_T^\nu p_T^{\text{miss}}(1 - \cos \Delta \phi)}, \]
  - Extract signal from $E_T^{\text{miss}}$ or $m_T$ distributions, cut and count or shape fit
  - Significant background from QCD multijet events; ~10% in W→eν, ~5% in W→μν

![Graphs showing data and distributions for W and μν samples](image-url)
$W \rightarrow \mu \nu$ and $W \rightarrow e \nu$ event displays

- Events from early 2010
  - Very little pileup, but still see tracks from underlying event accompanying the W boson production
Backgrounds in W (and Z)

- Backgrounds with **prompt** leptons (mainly top) evaluated from simulation
  - Reliable simulation of physics and selection efi.
- Backgrounds from QCD multi-jet more difficult
  - Jet misidentified as electron or muon due to
    - $b/c$ hadron decay ($b,c \rightarrow e, \mu$)
    - Hadron mis-ID as lepton (EM-like shower, $K, \pi \rightarrow \mu$)
    - Electron from photon conversion
  - Hard to model in simulation, uncertain jet x-sec
  - Rejection factors of $\sim 10^5$ from lepton ID and isolation cuts – cannot simulate enough events
- Measure backgrounds from data control samples
  - E.g. invert lepton isolation or ID cuts and fit background in a control region close to signal
  - Shapes in signal region are distorted by relaxed cuts
    - Fit in different slices of isolation or kinematic variables and extrapolate to signal region
Systematic uncertainties on ATLAS 7 TeV precision W/Z fiducial x-sec

<table>
<thead>
<tr>
<th>Source</th>
<th>$\delta\sigma_{W^+}$</th>
<th>$\delta\sigma_{W^-}$</th>
<th>$\delta\sigma_Z$</th>
<th>$\delta\sigma_{\text{forward } Z}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trigger efficiency</td>
<td>0.03</td>
<td>0.03</td>
<td>0.05</td>
<td>0.05</td>
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<tr>
<td>Reconstruction efficiency</td>
<td>0.12</td>
<td>0.12</td>
<td>0.20</td>
<td>0.13</td>
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<tr>
<td>Identification efficiency</td>
<td>0.09</td>
<td>0.09</td>
<td>0.16</td>
<td>0.12</td>
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<tr>
<td>Forward identification efficiency</td>
<td>−</td>
<td>−</td>
<td>−</td>
<td>1.51</td>
</tr>
<tr>
<td>Isolation efficiency</td>
<td>0.03</td>
<td>0.03</td>
<td>−</td>
<td>0.04</td>
</tr>
<tr>
<td>Charge misidentification</td>
<td>0.04</td>
<td>0.06</td>
<td>−</td>
<td>−</td>
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<tr>
<td>Electron $p_T$ resolution</td>
<td>0.02</td>
<td>0.03</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td>Electron $p_T$ scale</td>
<td>0.22</td>
<td>0.18</td>
<td>0.08</td>
<td>0.12</td>
</tr>
<tr>
<td>Forward electron $p_T$ scale + resolution</td>
<td>−</td>
<td>−</td>
<td>−</td>
<td>0.18</td>
</tr>
<tr>
<td>$E_T^{\text{miss}}$ soft term scale</td>
<td>0.14</td>
<td>0.13</td>
<td>−</td>
<td>−</td>
</tr>
<tr>
<td>$E_T^{\text{miss}}$ soft term resolution</td>
<td>0.06</td>
<td>0.04</td>
<td>−</td>
<td>−</td>
</tr>
<tr>
<td>Jet energy scale</td>
<td>0.04</td>
<td>0.02</td>
<td>−</td>
<td>−</td>
</tr>
<tr>
<td>Jet energy resolution</td>
<td>0.11</td>
<td>0.15</td>
<td>−</td>
<td>−</td>
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<tr>
<td>Signal modelling (matrix-element generator)</td>
<td>0.57</td>
<td>0.64</td>
<td>0.03</td>
<td>1.12</td>
</tr>
<tr>
<td>Signal modelling (parton shower and hadronization)</td>
<td>0.24</td>
<td>0.25</td>
<td>0.18</td>
<td>1.25</td>
</tr>
<tr>
<td>PDF</td>
<td>0.10</td>
<td>0.12</td>
<td>0.09</td>
<td>0.06</td>
</tr>
<tr>
<td>Boson $p_T$</td>
<td>0.22</td>
<td>0.19</td>
<td>0.01</td>
<td>0.04</td>
</tr>
<tr>
<td>Multijet background</td>
<td>0.55</td>
<td>0.72</td>
<td>0.03</td>
<td>0.05</td>
</tr>
<tr>
<td>Electroweak+top background</td>
<td>0.17</td>
<td>0.19</td>
<td>0.02</td>
<td>0.14</td>
</tr>
<tr>
<td>Background statistical uncertainty</td>
<td>0.02</td>
<td>0.03</td>
<td>&lt;0.01</td>
<td>0.04</td>
</tr>
<tr>
<td>Unfolding statistical uncertainty</td>
<td>0.03</td>
<td>0.04</td>
<td>0.04</td>
<td>0.13</td>
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<tr>
<td>Data statistical uncertainty</td>
<td>0.04</td>
<td>0.05</td>
<td>0.10</td>
<td>0.18</td>
</tr>
<tr>
<td>Total experimental uncertainty</td>
<td>0.94</td>
<td>1.08</td>
<td>0.35</td>
<td>2.29</td>
</tr>
<tr>
<td>Luminosity</td>
<td>−</td>
<td>−</td>
<td>−</td>
<td>1.8</td>
</tr>
</tbody>
</table>
Luminosity measurement – principles

- Luminosity from a single pair of colliding bunches, rotation freq. $f_r$:
  \[
  L_b = \frac{\mu f_r}{\sigma_{\text{inel}}} \quad \text{and} \quad L_b = \frac{\mu_{\text{vis}} f_r}{\sigma_{\text{vis}}}
  \]

- Measure counting rate per bunch-crossing $\mu_{\text{vis}}$ for any lumi-dependent signal
  - Hit rate in a detector, current in a calorimeter, number of tracks/clusters …
    - Poisson fluctuations in $\mu_{\text{vis}}$, becomes saturated if $\mu_{\text{vis}} \gg 1$
  - Calibrate $\sigma_{\text{vis}}$ from accelerator/beam parameters in dedicated low-lumi fills
    \[
    L_b = \frac{f_r n_1 n_2}{2\pi \Sigma_x \Sigma_y} \quad \sigma_{\text{vis}} = \mu_{\text{vis}} \frac{\Sigma_x \Sigma_y}{n_1 n_2}
    \]
  - Absolute luminosity calculated from number of protons per beam $(n_1,n_2)$ – bunch currents, and size of the overlap of the beams $\Sigma_x, \Sigma_y$ in x and y planes
    - Dedicated ‘van der Meer’ fills with larger beam sizes and well-controlled conditions

- Many luminosity-dependent signals employed
  - Forward Cerenkov counters, diamond beam conditions monitors
    - Need to have deadtime-less readout, independent of high-level trigger
  - Calorimeter photomultiplier and HV gap currents – integrate over all bunches
  - Pixel cluster counting and track counting
Luminosity measurement – vdM scan

- **Scan beam separation in x or y plane**
  - Determine beam widths $\Sigma_x$, $\Sigma_y$
  - Determine maximum count rate $\mu_{\text{vis}}^{\text{MAX}}$
  - Measure bunch currents $n_1$ and $n_2$ from precise LHC instrumentation (DCCT)
    - $O(1 \text{ min})$ per scan point, many scan points, $(x,y)$, repeat scans…
    - Several days dedicated beam time

- **Many complications**
  - Absolute x/y displacement calibration
    - Use beamspot movement in tracker
  - Beam size (emittance) growth within fill
  - Satellite bunches, ghost charge
  - Non-Gaussian beam shapes, tails
  - Non-factorisation: overlap $\neq \Sigma_x \Sigma_y$
    - Check with ‘off-axis’ scans
  - Beam-beam kicks, bunch-bunch variations

29th August 2017
Richard Hawkings
Luminosity measurement – transfer and stability

- vdM scans done 1-3 times/year, \( \mu \approx 1 \)
  - Calibrate each detector/algorithm \( \sigma_{\text{vis}} \)
- Extrapolate to physics environment
  - \( \mu = 20—50 \), even higher soon
  - Higher counting rates, non-linear effects, bunch trains, detector ageing
- Check consistency of different methods
  - Typically agreeing at ~% level after lots of effort, corrections several %
  - Differences evolve with time, can be pileup dependent
  - Which algorithms do you trust most?
    - E.g. two track-counting selections with the same detector diverge at 2% level
  - ATLAS mainly used BCM and Lucid, CMS pixel counting and FCal for final run-1 results
  - Additional approaches being explored at run-2
Final uncertainties on integrated luminosity $\mathcal{O}(2\text{-}3\%)$

- Tend to be dominated by calibration transfer to high-$L$, rather than vdM scans

### ATLAS 8 TeV pp – $\Delta L/L=1.9\%$

<table>
<thead>
<tr>
<th>Source</th>
<th>Uncertainty [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference specific luminosity</td>
<td>0.50</td>
</tr>
<tr>
<td>Noise and background subtraction</td>
<td>0.30</td>
</tr>
<tr>
<td>Length-scale calibration</td>
<td>0.40</td>
</tr>
<tr>
<td>Absolute ID length scale</td>
<td>0.30</td>
</tr>
<tr>
<td>Subtotal, instrumental effects</td>
<td>0.77</td>
</tr>
<tr>
<td>Orbit drifts</td>
<td>0.10</td>
</tr>
<tr>
<td>Beam-position jitter</td>
<td>0.20</td>
</tr>
<tr>
<td>Beam–beam corrections</td>
<td>0.28</td>
</tr>
<tr>
<td>Fit model</td>
<td>0.50</td>
</tr>
<tr>
<td>Non-factorization correction</td>
<td>0.50</td>
</tr>
<tr>
<td>Emittance-growth correction</td>
<td>0.10</td>
</tr>
<tr>
<td>Bunch-by-bunch consistency</td>
<td>0.23</td>
</tr>
<tr>
<td>Scan-to-scan consistency</td>
<td>0.31</td>
</tr>
<tr>
<td>Subtotal, beam conditions</td>
<td>0.89</td>
</tr>
<tr>
<td>Bunch-population product</td>
<td>0.24</td>
</tr>
<tr>
<td>Total</td>
<td>1.20</td>
</tr>
</tbody>
</table>

### CMS 8 TeV pp – $\Delta L/L=2.5\%$

<table>
<thead>
<tr>
<th>Source</th>
<th>correction (%)</th>
<th>uncertainty (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stability</td>
<td>-</td>
<td>1</td>
</tr>
<tr>
<td>Dynamic inefficiencies</td>
<td>-</td>
<td>0.5</td>
</tr>
<tr>
<td>Afterglow</td>
<td>$\sim 2$</td>
<td>0.5</td>
</tr>
<tr>
<td>Fit model</td>
<td>-</td>
<td>2</td>
</tr>
<tr>
<td>Beam current calibration</td>
<td>-</td>
<td>0.3</td>
</tr>
<tr>
<td>Ghosts and satellites</td>
<td>-0.4</td>
<td>0.2</td>
</tr>
<tr>
<td>Length scale</td>
<td>-0.9</td>
<td>0.5</td>
</tr>
<tr>
<td>Emittance growth</td>
<td>-0.1</td>
<td>0.2</td>
</tr>
<tr>
<td>Orbit Drift</td>
<td>0.2</td>
<td>0.1</td>
</tr>
<tr>
<td>Beam-beam</td>
<td>1.5</td>
<td>0.5</td>
</tr>
<tr>
<td>Dynamic-β</td>
<td>-</td>
<td>0.5</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>2.5</td>
</tr>
</tbody>
</table>

- C.f. Tevatron $\Delta L/L=6\%$, from counting rates wrt total inelastic cross-section
  - Latter inferred from inelastic/elastic rates, not vdM scans
  - Some measurements normalised to assumed $Z$ cross-section
W and Z cross-section results

- Results from 7 TeV ATLAS analysis

### Electrons

<table>
<thead>
<tr>
<th>Process</th>
<th>Cross Section $\sigma_{W\rightarrow e\nu}^{\text{fid},e}$ [pb]</th>
<th>$\sigma_{Z/\gamma\rightarrow e\nu}^{\text{fid},e}$ [pb]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$W^+ \rightarrow e^+\nu$</td>
<td>$2726 \pm 1$ (stat) $\pm 28$ (syst) $\pm 49$ (lumi)</td>
<td>$439.5 \pm 0.4$ (stat) $\pm 1.5$ (syst) $\pm 7.9$ (lumi)</td>
</tr>
<tr>
<td>$W^- \rightarrow e^-\bar{\nu}$</td>
<td>$1823 \pm 1$ (stat) $\pm 21$ (syst) $\pm 33$ (lumi)</td>
<td></td>
</tr>
</tbody>
</table>

### Muons

<table>
<thead>
<tr>
<th>Process</th>
<th>Cross Section $\sigma_{W\rightarrow \mu\nu}^{\text{fid},\mu}$ [pb]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$W^+ \rightarrow \mu^+\nu$</td>
<td>$2839 \pm 1$ (stat) $\pm 17$ (syst) $\pm 51$ (lumi)</td>
</tr>
<tr>
<td>$W^- \rightarrow \mu^-\bar{\nu}$</td>
<td>$1901 \pm 1$ (stat) $\pm 11$ (syst) $\pm 34$ (lumi)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Process</th>
<th>Cross Section $\sigma_{Z/\gamma\rightarrow \mu\mu}^{\text{fid},\mu}$ [pb]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z/\gamma^* \rightarrow \mu^+\mu^-$</td>
<td>$477.8 \pm 0.4$ (stat) $\pm 2.0$ (syst) $\pm 8.6$ (lumi)</td>
</tr>
</tbody>
</table>

- Statistical uncertainties negligible
- Systematics $\sim 1.8/0.6\%$ (e/$\mu$) for W and $0.2/0.3\%$ (ee/$\mu\mu$) for Z fiducial x-sec
  - Plus 1.5-3% on acceptance for total x-sec
- 1.8% luminosity uncertainty dominates absolute fiducial cross-sections
- Use normalised distributions or ratios

29th August 2017

Richard Hawkings

arXiv:1612.0301
Electron-muon universality

- BR for $W \rightarrow e$ and $W \rightarrow \mu$ should be equal
  - $E_{eW}$ and $E_{\mu W}$ correct to same fiducial definition
    \[ R_W = \frac{\sigma_{W \rightarrow e\bar{e}}/E_{eW}}{\sigma_{W \rightarrow \mu\bar{\mu}}/E_{\mu W}} = \frac{BR(W \rightarrow e\bar{e})}{BR(W \rightarrow \mu\bar{\mu})} = 0.9967 \pm 0.0004 \text{ (stat)} \pm 0.0101 \text{ (syst)} \]
    \[ = 0.997 \pm 0.010. \]

- Compare with other measurements

<table>
<thead>
<tr>
<th>Measurement</th>
<th>$R_W$</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATLAS pp 7TeV</td>
<td>0.997±0.010</td>
</tr>
<tr>
<td>CDF pbar-p 1.96 TeV</td>
<td>1.018±0.025</td>
</tr>
<tr>
<td>LHCb pp</td>
<td>1.020±0.019</td>
</tr>
<tr>
<td>LEP2 $W^+W^-$</td>
<td>1.007±0.019</td>
</tr>
<tr>
<td>$\tau$ decays average</td>
<td>0.9964±0.0028</td>
</tr>
<tr>
<td>K decays NA62</td>
<td>1.0044±0.0040</td>
</tr>
<tr>
<td>$\pi$ decays</td>
<td>0.9992±0.0024</td>
</tr>
</tbody>
</table>

- Electron-muon universality confirmed at <1%

29th August 2017

Richard Hawkings
Theoretical predictions and PDFs

- Calculations available at NNLO in QCD
  - DYNNLO and FEWZ codes, with additional NLO EW corrections (several % for Z)
- Large uncertainties from the proton PDFs
  - Region $10^{-3} < x < 10^{-1}$ relevant for central W and Z production with $|y| < 2$
  - Use ‘global’ PDF sets CT10/14, MSTW/MMHT, NNPDF2-3 from fits to DIS and collider data (Tevatron +LHC)
- LHC W/Z data adds to PDF knowledge
  - W$: ud, us, (cd, cs)$, opp. for for W$^-$
  - Z$: uu, dd, ss (cc, bb)$

29th August 2017

Richard Hawkings
More on PDFs

- Industry of PDF fitting groups, with different input datasets and assumptions

<table>
<thead>
<tr>
<th></th>
<th>CT14</th>
<th>MMHT14</th>
<th>NNPDF3.0</th>
<th>HERAPDF2.0</th>
<th>ABM12(ABMP)</th>
<th>CJ12(15)</th>
<th>JR14</th>
</tr>
</thead>
<tbody>
<tr>
<td>HERA data</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HERA I+ charm</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>HERA I charm jets</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>HERA I+ H1 and ZEUS II charm</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>

- HERA ep DIS data is the ‘backbone’ of all modern PDF sets, supplemented by various choices of fixed target DIS, Drell-Yan and jet data from Tevatron and LHC
- Groups also differ in data treatment (e.g. tensions between datasets), theory calculations used, parameterisation of PDFs vs x,Q², treatment of heavy quarks
- Important to consider uncertainties from a particular PDF set AND predictions of different PDF sets

References:
- arXiv:1506.07443
- arXiv:1412.3989
- arXiv:1410.8849
- arXiv:1506.06042
- arXiv:1310.3059
- arXiv:1212.1702
- arXiv:1403.1852
Differences between PDF sets

- $u$, $d$, and $g$: differences of 5-10% in range $10^{-3} < x < 10^{-1}$, non-overlapping bands
  - Strange quark contribution less well-determined
W and Z cross-section comparisons

- 2D plots of $W^+$ vs $W^-$ and $W$ vs $Z$ make expt. and pred. correlations clear
  - Most PDFs (in particular global sets) a little below the data for $\sigma(Z)$

---

29th August 2017

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**W⁺/W⁻ and W/Z cross-section ratios**

- Significant uncertainty cancellations in ratios of cross-sections
  - W⁺/W⁻ measured to 0.25%, W/Z to 0.5%, much smaller than PDF uncertainties
  - W/Z smaller than all predictions
  - Considerable spread in predictions and their uncertainties with different PDFs

---

**ATLAS**

$\sqrt{s} = 7$ TeV, 4.6 fb⁻¹

1.42 1.44 1.46 1.48 1.5 1.52 1.54

$\frac{\sigma_{W^+ \rightarrow l^+\nu}}{\sigma_{W^- \rightarrow l^-\bar{\nu}}}^\text{fid}$

- Data
- stat. uncertainty
- total uncertainty
- ABM12
- CT14
- HERAPDF2.0
- JR14
- MMHT2014
- NNPDF3.0

9.2 9.4 9.6 9.8 10 10.2

$\sigma_{W^± \rightarrow l^±\nu}^\text{fid}$ / $\sigma_{Z/\gamma^* \rightarrow l^±l^±}^\text{fid}$

- Data
- stat. uncertainty
- total uncertainty
- ABM12
- CT14
- HERAPDF2.0
- JR14
- MMHT2014
- NNPDF3.0
Lepton rapidity distributions

- More information in the rapidity distributions – sampling different x-values
  - Big difference in cross-section and shape between $W^+$ and $W^-$
    - More up than down quarks in the proton, with larger momentum fractions
  - Most ‘global’ PDF sets below the data for both $W^+$ and $W^-$ ($\pm 1.8\%$ lumi not shown)

ATLAS

$\sqrt{s} = 7$ TeV, 4.6 fb$^{-1}$

$W^+ \rightarrow l^+ \nu$

$W^- \rightarrow l^- \bar{\nu}$

- $p_{T,l} > 25$ GeV
- $p_{T,\nu} > 25$ GeV
- $m_\tau > 40$ GeV

29th August 2017

Richard Hawkings
W charge asymmetry

- Another ratio measurement:
  \[ A_\ell = \frac{d\sigma_{W^+}/d|\eta_\ell| - d\sigma_{W^-}/d|\eta_\ell|}{d\sigma_{W^+}/d|\eta_\ell| + d\sigma_{W^-}/d|\eta_\ell|} \]

  - Expt. uncertainties 0.5-1%/bin
  - NNPDF 3.0 agrees particularly well
    - Already includes W data from CMS

---

**Graphical Content**

- **Legend**:
  - Data
  - ABM12
  - CT14
  - HERAPDF2.0
  - JR14
  - MMHT2014
  - NNPDF3.0

- **Legend Descriptions**:
  - Uncorr. uncertainty
  - Total uncertainty

- **Axes**:
  - Vertical axis: Charge asymmetry
  - Horizontal axis: Muon $|\eta|$ for $p_T > 25$ GeV

- **Graph Title**: ATLAS

- **Graph Details**:
  - $\sqrt{s} = 7$ TeV, 4.6 fb$^{-1}$
  - $W^+ - W^-$
  - Lepton Asymmetry

---

Richard Hawkings
PDF profiling using $W$ and $Z$ distributions

- Form a data vs. $\chi^2$ across all bins of all rapidity-differential cross-sections

\[
\chi^2(b_{\text{exp}}, b_{\text{th}}) = \sum_{i=1}^{N_{\text{data}}} \left[ \frac{\sigma_i^{\exp} - \sigma_i^{\text{th}}(1 - \sum_j \gamma_{ij}^{\exp} b_{j,\exp} - \sum_k \gamma_{ik}^{\text{th}} b_{k,\text{th}})}{\Delta_i^2} \right]^2 + \sum_{j=1}^{N_{\exp,sys}} b_{j,\exp}^2 + \sum_{k=1}^{N_{\text{th,sys}}} b_{k,\text{th}}^2
\]

- $\gamma_{ij}^{\exp}$ express experimental uncertainties $j$ via nuisance parameters $\beta_{j,\exp}$
- $\gamma_{ik}^{\text{th}}$ express theoretical (PDF and other) uncertainties $k$ via nuisance parameters $\beta_{k,\text{th}}$
- $\beta = \pm 1$ represents changes in results/predictions corresponding to $\pm 1\sigma$ uncertainties
- ‘Profiled’ values of $\beta_{k,\text{th}}$ after $\chi^2$ minimisation represent ‘improved’ PDF
  - But only if the original distributions are reasonably close to data
- $\chi^2$ results for fit to all ATLAS 7 TeV $W/Z$ data (including | excluding PDF unc.)

<table>
<thead>
<tr>
<th>Data set</th>
<th>n.d.f.</th>
<th>ABM12</th>
<th>CT14</th>
<th>MMHT14</th>
<th>NNPDF3.0</th>
<th>ATLAS-epWZ12</th>
</tr>
</thead>
<tbody>
<tr>
<td>$W^+ \rightarrow \ell^+ \nu$</td>
<td>11</td>
<td>1121</td>
<td>1026</td>
<td>1137</td>
<td>1118</td>
<td>1215</td>
</tr>
<tr>
<td>$W^- \rightarrow \ell^- \bar{\nu}$</td>
<td>11</td>
<td>1220</td>
<td>8927</td>
<td>8131</td>
<td>1219</td>
<td>7817</td>
</tr>
<tr>
<td>$Z/\gamma^* \rightarrow \ell\ell$ ($m_{\ell\ell} = 46 - 66$ GeV)</td>
<td>6</td>
<td>1721</td>
<td>1130</td>
<td>1824</td>
<td>2122</td>
<td>2836</td>
</tr>
<tr>
<td>$Z/\gamma^* \rightarrow \ell\ell$ ($m_{\ell\ell} = 66 - 116$ GeV)</td>
<td>12</td>
<td>2451</td>
<td>1666</td>
<td>20116</td>
<td>14109</td>
<td>1826</td>
</tr>
<tr>
<td>Forward $Z/\gamma^* \rightarrow \ell\ell$ ($m_{\ell\ell} = 66 - 116$ GeV)</td>
<td>9</td>
<td>7393</td>
<td>1012</td>
<td>1213</td>
<td>1418</td>
<td>6875</td>
</tr>
<tr>
<td>$Z/\gamma^* \rightarrow \ell\ell$ ($m_{\ell\ell} = 116 - 150$ GeV)</td>
<td>6</td>
<td>6166</td>
<td>6361</td>
<td>5966</td>
<td>6188</td>
<td>6766</td>
</tr>
<tr>
<td>Forward $Z/\gamma^* \rightarrow \ell\ell$ ($m_{\ell\ell} = 116 - 150$ GeV)</td>
<td>6</td>
<td>4239</td>
<td>5143</td>
<td>5646</td>
<td>5150</td>
<td>3635</td>
</tr>
<tr>
<td>Correlated $\chi^2$</td>
<td>5790</td>
<td>39123</td>
<td>43167</td>
<td>69157</td>
<td>69157</td>
<td>3148</td>
</tr>
<tr>
<td>Total $\chi^2$</td>
<td>61</td>
<td>136222</td>
<td>103290</td>
<td>118396</td>
<td>147351</td>
<td>113159</td>
</tr>
</tbody>
</table>

- CT14 best, MMHT and ATLAS epWZ OK, ABM12 and NNPDF3.0 less good

29th August 2017

Richard Hawkings
PDF profiling results

- Fitted $\beta_{k,\text{th}}$ can be used to generate new profiled PDF, reduced uncertainties

$$f'_0 = f_0 + \sum_k \left[ b_{k,\text{th}}^{\min} \left( \frac{f^+_k - f^-_k}{2} \right) + (b_{k,\text{th}}^{\min})^2 \left( \frac{f^+_k + f^-_k - 2f_0}{2} \right) \right]$$

- $f_0 (f'_0)$ original (new) central PDF, $f^+_k$ and $f^-_k$ the ± variations for PDF eigenvector $k$
- Effect of profiling on MMHT14 sea quarks – increased s-quark contribution

- Indicative, but not a substitute for full PDF fit with new data…
Flavour composition of light-quark sea

- Full QCD analysis of W/Z data + HERA DIS data to fit a PDF from scratch
  - Computationally challenging – MCFM NLO predictions + APPLGRID tools to convolve PDF, fixed NLO→NNLO corrections
- Neutrino-nucleon scattering ($\nu N \rightarrow c\mu$) suggested strange sea < u/d sea
  - Included in most global PDF sets
- Ratio of W/Z production at LHC is sensitive to strange sea vs u/d sea

$$r_s = \frac{s + \bar{s}}{2\bar{d}}$$

$$r_s = 1.19 \pm 0.07 (\text{exp})^{+0.13}_{-0.14} (\text{mod + par + thy})$$

- Result limited by modelling/theory
- Suggests no strange suppression
Summary of lecture 1

- Precision physics is possible at LHC
  - Can contribute to electroweak fit and other important SM parameters
- W/Z cross-section fiducial and differential cross-section measurements
  - Clean experimental signatures, Z provides ‘in-situ’ calibration for leptons
  - Absolute uncertainties (excluding luminosity) of ~1% for W, <0.5% for Z
  - Luminosity measurement reaches 2% precision at LHC
    - Benefitting from dedicated vdM scan campaigns (few days beamtime per year)
- W/Z measurements provide important constraints on PDFs
  - Previously mainly determined using DIS and jet data
  - Leading source of uncertainty in predicting the W/Z cross-sections
  - Constrain the u/d PDFs in $10^{-3} < x < 10^{-1}$, unique information on strange quarks
- Next … using W and Z to constrain electroweak parameters, physics with jets