Gauge Boson Physics in the Forward Region at LHCb

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Outline

- The LHCb Detector and the Forward Region

- $W^\pm/Z$ Production in pp Collisions at 7, 8, 13 TeV
  
  Inputs for proton PDF tuning. Katharina Müller's talk in plenary session tomorrow morning.

- $Z$ Production Asymmetry and the Weinberg Angle

Electroweak boson production with jets and top measurements
  
  Wouter Hulsbergen's talk tomorrow
The LHCb detector and the Forward Region


Full coverage for $2 < \eta < 5$ – complementary to ATLAS and CMS phase space

Excellent luminosity determination: %-level uncertainty
Van der Meer scan & Beam-Gas Imaging – SMOG system [JINST 9 (2014) 12005]

High precision tracking & vertexing
Impact Parameter (IP) resolution: 15-20 μm at high $p_T$

Good momentum resolution
$\Delta p/p$: 0.5 % (<20 GeV/c)
1.0 % (200 GeV/c)

Good PID efficiency
e, $\gamma$, $\mu$ – (E/H)CAL; M1-M5
- $e$: ~ 90%; ~ 5% $e \rightarrow h$ mis-id prob.
- $\mu$: ~ 97%; 1-3% $\pi \rightarrow \mu$ mis-id prob.

QCD@LHC: August 22nd, 2016

Parallel: Hard QCD+EW, A. Grecu

More numbers in back-up slides...
The LHCb detector and the Forward Region

Probing Parton Density Functions (PDFs) in the Forward Region

- probe two distinct regions in (x-Björken, Q^2) space
- access previously unexplored region of low-x, high-Q^2
- at W^±/Z scale: x ~ 10^{-4} and 10^{-1}

Integrated Luminosity

- 7 TeV (2011): 1.0/fb ± 1.7%
- 8 TeV (2012): 2.0/fb ± 1.2%
- 13 TeV (2015): 0.3/fb ± 3.9% (improve in 2016)
\[ Z \rightarrow \mu^+ \mu^- \]

- Selection: 2 muons,\( 2 < \eta_\mu < 4.5, p_T > 20 \text{ GeV/c}, \]
  \( 60 < M_{\mu\mu} < 120 \text{ GeV/c}^2 \)
- **Signal purity** \( \sim 99\% \)
- Differential cross-sections in \( y(Z), p_T(Z); \phi^*(Z) \)
  \[
  \phi^* = \tan \left( \frac{\pi - |\Delta \phi|}{2} \right) \cosh \left( \frac{\Delta \eta}{2} \right) \approx \frac{p_T^{(\mu\mu)}}{M_{\mu\mu}}
  \]
- Total uncertainty on cross-section:
  - 7 TeV: 2.3 % (main: lumi + beam energy)
  - 8 TeV: 1.8 % (main: lumi + beam energy)

- Good overall agreement to NLO (POWHEG) and NNLO (FEWZ) predictions w/ different PDFs

* Superseeds JHEP 06 (2012) 058

QCD@LHC: August 22nd, 2016  Parallel: Hard QCD+EW, A. Grecu
\( Z \rightarrow e^+ e^- \)

- Selection: 2 electrons, \( 2 < \eta_e < 4.5 \), \( p_T > 20 \text{ GeV/c}, M_{ee} > 40 \text{ GeV/c}^2 \)
- Bremsstrahlung recovery limited by ECAL saturation at \( p_T > 10 \text{ GeV/c} \) \( p_T \) not well known
- Results corrected to Born level using simulation

- **Signal purity** \( \sim 95\% \) (electron mis-ID – main bkg)

- Diff. cross-section in \( y(Z), \phi^*(Z) \)
  - Good agreement to NNLO estimation w/ PDFs in \( y_Z \) distribution
  - (N)LO models overestimate low \( \phi^* \) and underestimate at high values. RESBOS seems to agree better.

*Older measurements w/ higher uncertainties: JHEP 06 (2012) 058, JHEP 01 (2013) 011

Parallel: Hard QCD+EW, A. Grecu
• Limited data set (2015): 0.3 fb\(^{-1}\) (sizable stat. error)
• Probe lower x-Björken values than Run I
• Systematic error: 2.4/2.5\%(\mu\mu/ee) + lumi: 3.9%
• Good agreement:
  ✓ \(\sigma(Z \rightarrow \text{ee})\) vs. \(\sigma(Z \rightarrow \mu\mu)\) – back-up slides
  ✓ \(y_Z\) distribution vs. NNLO pQCD + PDFs
  ✓ \(P_T, \phi^*\) distributions vs. higher order pQCD + matching schemes

arXiv: 1607.06495
$W \rightarrow \mu \nu_{\mu}$

- Similar selection as $Z \rightarrow \mu\mu$ papers; additionally: prompt, isolated muons w/ small E(CALO)/pc; veto on second lepton
- **Signal purity:** $\sim 77 - 79\%$
- Signal estimated from fit to $p_T(\mu)$ spectrum in $\eta(\mu)$ bins
- Backgrounds: decay of heavy hadron, hadron mis-ID (from data); EW sources (from MC)
- Errors (2 – 4%) dominated by uncertainties on luminosity and beam energy
- Data agrees w/ NNLO predictions (FEWZ) using a set of PDFs

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*Superseeds JHEP 12 (2014) 079*
\[ W \rightarrow e \nu_e \]

- Slightly different (from \( Z \rightarrow ee \)) kinematic region: \( 2 < \eta^e < 4.25 \) (CALO acc.), \( p_T^e > 20 \text{ GeV/c} \)
- Additional selection: energy deposition in CALO sub-systems consistent with electron; isolation criteria keeping bremsstrahlung photons
- Similar fit to \( p_T^e \) spectrum to determine signal yield. Backgrounds: EW processes (simulation); fake electrons, heavy flavour hadron decays (data)
- **Signal purity**: 64% (\( W^+ \)); 56% (\( W^- \))
- Systematic uncertainty dominated by purity, efficiency, beam energy and lumi evaluation.
- Satisfactory agreement with NNLO predictions with different parametrisations of PDFs. Small tension in \( W^+ \) distribution at high \( \eta^e \) (large PDF uncertainty region)

\[ 8 \text{ TeV: arXiv: 1608.01484} \]
Test of Lepton Universality

- Measurements coincide in kinematic region: $p_T^\ell > 20$ GeV/c; $2.00 < \eta^\ell < 3.50$

- Overall good agreement (also in charge asymmetries and cross-section ratios). Almost 3 $\sigma$ tension in bin $3.00 < \eta^\ell < 3.25$ for $W^+$.  

- Ratios of branching fractions exceed each previous determinations; comparable to combined LEP result.

$W \to \mu\nu$: JHEP 01 (2016) 155
$W \to e\nu_e$: arXiv: 1608.01484
**W and Z Cross-sections**

Correlation between cross-sections → systematic uncertainties cancel/reduce for asymmetries/ratios.

\[
A_\ell = \frac{\sigma(W^+ \rightarrow \ell^+\nu_\ell) - \sigma(W^- \rightarrow \ell^-\bar{\nu}_\ell)}{\sigma(W^+ \rightarrow \ell^+\nu_\ell) + \sigma(W^- \rightarrow \ell^-\bar{\nu}_\ell)}
\]

\[
R_{W\pm} = \frac{\sigma(W^+)\sigma(W^-)}{\sigma(Z)}
\]

\[
R_{W^+Z} = \frac{\sigma(W^+)}{\sigma(Z)}
\]

\[
R_{W^-Z} = \frac{\sigma(W^-)}{\sigma(Z)}
\]

- Experimental uncertainties:  
  - Luminosity  
  - Efficiencies  
  - Purity evaluation  

- Theoretical uncertainties:  
  - PDF uncertainties  
  - scale uncertainties
Charge Asymmetries in W Leptonic Decays

- Charge asymmetries for W and $R_{W^\pm}$ probe differences between distributions of $u$ and $d$ valence quarks in protons

- Good agreement with NNLO theory predictions configured with a series of PDFs
  For electron decay channels, difference at high $\eta$ due to observed tension in $W^+$ cross-section

Electron channel – arXiv: 1608.01484

Muon channel – JHEP 01 (2016) 155

QCD@LHC: August 22nd, 2016
Parallel: Hard QCD+EW, A. Grecu
Cross-section Ratios

- $R_{W^\pm}$ smaller uncertainties (mainly statistical) than theoretical predictions
- Probing strange content of proton $R_{W^\pm Z}(\eta)$
- PDF uncertainties very much reduced in cross-section ratios at different $\sqrt{s}$

- Smaller experimental errors recommend ratios for strict testing of pQCD models and improvement of PDFs* at high/low-x where their uncertainties are largest

*Talks by Katharina Müller and Voica Rădescu in plenary session tomorrow morning.
Weinberg (weak mixing) angle $\theta_W$ free MSM parameter of electroweak (EW) Lagrangian:

$$\mathcal{L}_{EW} = \sum_{\psi} \bar{\psi} \gamma^{\mu} \left( i \partial_{\mu} - \frac{g'}{2} Y_{VW} B_{\mu} - \frac{g}{2} A_{\mu} \right) \psi,$$

$$\cos \theta_W = \frac{g}{\sqrt{g'^2 + g^2}} = \frac{M_W}{M_Z}$$

- Z couplings differ for left- and right-handed fermions $\rightarrow$ asymmetry in angular distribution of negative and positive daughter leptons

- $\sin^2 \theta_W$ defined as function of the ratio of vector(V) and axial-vector(A) effective (including higher order EW corrections) couplings of the Z boson to daughter leptons $\sim \sin^2 \theta_W$.

- $\sin^2 \theta_W$ measurements at $e^- e^+$ colliders differ by 3 standard deviations. Measured also at hadron colliders by D0, CDF, ATLAS, CMS.

- LHCb measured Z asymmetry in the process $q\bar{q} \rightarrow Z/\gamma^* \rightarrow \mu^- \mu^+$
**Z Production Asymmetry. Weinberg Angle**

- **Collins-Soper** (dimuon rest) frame
  - minimize influence of incoming quark $p_T$

- Z angular distribution:
  \[
  \frac{d\sigma}{d \cos \theta^*} = A (1 + \cos^2 \theta^*) + B \cos \theta^*
  \]
  A, B \sim dimuon mass, color charge of quarks, V-A couplings; B \sim \sin^2 \theta_W \sim A_{FB}

- forward-backward asymmetry:
  \[
  A_{FB} = \frac{N(\cos \theta^* > 0) - N(\cos \theta^* < 0)}{N(\cos \theta^* > 0) + N \cos \theta^* < 0}
  \]

- Symmetric pp collisions @ LHC
  - high-x valence quark + sea anti-quark \rightarrow Z boson
  - initial quark direction inferred from Z momentum
  - “dilution” of $A_{FB}$ sensitivity to $\sin^2 \theta_W$

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Symmetric pp collisions @ LHC
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Z Production Asymmetry. Weinberg Angle

- Same selection as inclusive $Z \rightarrow \mu\mu$ measurement

- $\sin^2\theta^\text{eff}_W$ estimated from comparison to simulation (POWHEG+PYTHIA, NNPDF2.3) considering the min. of a $\chi^2$ w/ respect to measured $A_{FB}$

- Statistically limited – more data expected in Run II → double differential $A_{FB}(m_{\mu\mu}, \eta_\mu)$

- Main systematic error: momentum scale uncertainty

- $A_{FB}$ distributions in good agreement with SM predictions
Z Production Asymmetry. Weinberg Angle

![Graph showing data points for different experiments and their measurements of sin^2θ_{\text{eff}}.](image)

Measurement for combined 7 and 8 TeV data sets (~3 fb^{-1}):

\[ \sin^2 \theta_{\text{eff}} = 0.23142 \pm 0.00073(\text{stat.}) \pm 0.00052(\text{sys.}) \pm 0.00056(\text{th.}) \]

LHCb result consistent with world average; most precise from hadron colliders!
Conclusions & Outlook

➔ LHCb acceptance complementary to ATLAS and CMS
  – sensitivity to high and low Björken-x
  – very low experimental uncertainties

➔ Many precision measurements involving EW boson production
  – constraints on PDFs
  – more stringent tests on SM pQCD models
  – testing the lepton universality at precisions comparable to LEP
  – most precise determination at hadron colliders of weak mixing angle empiric SM parameter

➔ More to follow:
  – increased precision with more data ~ 2/fb/year in LHC Run II
  – measurements of cross-sections and ratios at higher energies to infer the existence of physics beyond Standard Model
Thank you!
BACKUPS
The LHCb detector and the Forward Region

LHCb Detector Performance

- Impact Parameter (IP) resolution: $(15 + 29/p_T[GeV/c]) \mu m$, i.e., $\sim 20 \mu m$ at high $p_T$
- Momentum resolution: $\Delta p/p \sim 0.5 \%$ ($p < 20$ GeV/c) $\rightarrow 1.0 \%$ ($p \sim 200$ GeV/c)
- ECAL resolution (nominal): $1 \% + 10 \%/ \sqrt{E[GeV]}$
- Invariant mass resolution:
  - $\sim 8$ MeV/c$^2$ for $B \rightarrow J/\psi X$ decays with constraint on $J/\psi$ mass
  - $\sim 22$ MeV/c$^2$ for two-body $B$ decays
  - $\sim 100$ MeV/c$^2$ for $B_s \rightarrow \phi \gamma$, dominated by photon contribution
- Trigger efficiencies:
  - $\sim 90 \%$ for dimuon channels
  - $\sim 30 \%$ for multi-body hadronic final states
- Track reconstruction efficiency: $\sim 96\%$ for Long Tracks
- Particle ID efficiency:
  - Electron ID $\sim 90 \%$ for $\sim 5 \%$ $e \rightarrow h$ mis-id probability
  - Kaon ID $\sim 95 \%$ for $\sim 5 \%$ $\pi \rightarrow K$ mis-id probability
  - Muon ID $\sim 97 \%$ for $1-3 \%$ $\pi \rightarrow \mu$ mis-id probability
- Integrated luminosity for datasets:
  - 7 TeV (2011): $1.0/fb \pm 1.7\%$
  - 8 TeV (2012): $2.0/fb \pm 1.2\%$
  - 13 TeV (2015): $0.3/fb \pm 3.9\%$ (to improve in 2016)
- Data taking efficiency: 90% (99% good for physics analyses)
Total cross-sections (at Born level):

- **7 TeV**: JHEP 02 (2013) 106; JHEP 08 (2015) 039
  \[ \sigma(Z \to ee) = 76.0 \pm 0.8 \text{ (stat)} \pm 2.0 \text{ (sys)} \pm 2.6 \text{ (lumi)} \pm 0.4 \text{ (FSR)} \text{ pb} \]
  \[ \sigma(Z \to \mu\mu) = 76.0 \pm 0.3 \text{ (stat)} \pm 0.5 \text{ (sys)} \pm 1.0 \text{ (beam)} \pm 1.3 \text{ (lumi)} \text{ pb} \]

- **8 TeV**: JHEP 05 (2015) 109
  \[ \sigma(Z \to \mu\mu) = 95.0 \pm 0.3 \text{ (stat)} \pm 0.7 \text{ (sys)} \pm 1.1 \text{ (beam)} \pm 1.1 \text{ (lumi)} \text{ pb} \]
  \[ \sigma(Z \to \ell\ell) = 94.9 \pm 0.2 \text{ (stat)} \pm 0.6 \text{ (sys)} \pm 1.1 \text{ (beam)} \pm 1.1 \text{ (lumi)} \text{ pb} ; \ell=e \text{ & } \mu \]

- **13 TeV**: arXiv: 1607.06495
  \[ \sigma(Z \to ee) = 190.2 \pm 0.9 \text{ (stat)} \pm 4.7 \text{ (sys)} \pm 7.7 \text{ (lumi)} \text{ pb} \]
  \[ \sigma(Z \to \mu\mu) = 198.0 \pm 1.7 \text{ (stat)} \pm 4.7 \text{ (sys)} \pm 7.4 \text{ (lumi)} \text{ pb} \]
  \[ \sigma(Z \to \ell\ell) = 194.3 \pm 0.9 \text{ (stat)} \pm 3.3 \text{ (sys)} \pm 7.6 \text{ (lumi)} \text{ pb} \]
Total cross-sections (at Born level):


\[ \sigma(W^+ \rightarrow \mu^+ \nu) = 878.0 \pm 2.1 \text{ (stat)} \pm 6.7 \text{ (sys)} \pm 9.3 \text{ (beam)} \pm 15.0 \text{ (lumi)} \text{ pb} \]

\[ \sigma(W^- \rightarrow \mu^- \bar{\nu}) = 689.5 \pm 2.0 \text{ (stat)} \pm 5.3 \text{ (sys)} \pm 6.3 \text{ (beam)} \pm 11.8 \text{ (lumi)} \text{ pb} \]

8 TeV: JHEP 01 (2016) 155

\[ \sigma(W^+ \rightarrow \mu^+ \nu) = 1093.6 \pm 2.1 \text{ (stat)} \pm 7.2 \text{ (sys)} \pm 10.9 \text{ (beam)} \pm 12.7 \text{ (lumi)} \text{ pb} \]

\[ \sigma(W^- \rightarrow \mu^- \bar{\nu}) = 818.4 \pm 1.9 \text{ (stat)} \pm 5.0 \text{ (sys)} \pm 7.0 \text{ (beam)} \pm 9.5 \text{ (lumi)} \text{ pb} \]

\[ \sigma(W^+ \rightarrow e^+ \nu_e) = 1124.4 \pm 2.1 \text{ (stat)} \pm 21.5 \text{ (sys)} \pm 11.2 \text{ (beam)} \pm 13.0 \text{ (lumi)} \text{ pb} \]

\[ \sigma(W^- \rightarrow e^- \bar{\nu}_e) = 809.0 \pm 1.9 \text{ (stat)} \pm 18.1 \text{ (sys)} \pm 7.0 \text{ (beam)} \pm 9.4 \text{ (lumi)} \text{ pb} \]

\[ \sigma(W \rightarrow e \nu) = 1933.3 \pm 2.9 \text{ (stat)} \pm 38.2 \text{ (sys)} \pm 18.2 \text{ (beam)} \pm 22.4 \text{ (lumi)} \text{ pb} \]
• Good agreement:
  ✓ Measurements slightly larger than NNLO pQCD (+ different PDF sets) at low $y_Z$
  ✓ Lower systematic effects in $p_T$, $\phi^*$ distributions (statistically dominated)
  ✓ PYTHIA 8 predictions better than (POWHEG + PYTHIA8 – NLO)
  ✓ No significant difference between LHCb and Monash 2013 tunes

arXiv: 1607.06495