TESTING THE STANDARD MODEL IN THE FORWARD REGION AT THE LHC

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Irish Quantum Foundations,
Castletown House, 3,4th May 2013
Outline

- **Theory**: The Standard Model
- **Experiment**: LHCb detector
  1. Electroweak tests using $W \rightarrow \mu \nu$, $Z \rightarrow \mu \mu$; probing the proton structure
  2. Electroweak tests using $Z \rightarrow \tau \tau$; sensitivity to Higgs
  3. Test EM & QCD with exclusive production of dimuons, $J/\psi$ and $\chi_c$.

<table>
<thead>
<tr>
<th>Analysis</th>
<th>Paper</th>
<th>Luminosity</th>
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</thead>
<tbody>
<tr>
<td>$W \rightarrow \mu \nu$</td>
<td>JHEP 06 (2012) 058</td>
<td>37pb$^{-1}$</td>
</tr>
<tr>
<td>$\rightarrow \mu \mu$</td>
<td>CERN-LHCb-CONF-2013-007</td>
<td>1fb$^{-1}$</td>
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<td>$\rightarrow \tau \tau$</td>
<td>JHEP 1301 (2013) 111.</td>
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<td>$J/\psi$</td>
<td>arXiv:1304.2591</td>
<td>1fb$^{-1}$</td>
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<td>Exclusive $J/\psi$</td>
<td>JPG 40 (2013) 045001</td>
<td>37pb$^{-1}$</td>
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<td>Exclusive $\chi_c$</td>
<td>CERN-LHCb-CONF-2011-022</td>
<td>37pb$^{-1}$</td>
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</tbody>
</table>
This is what we want to test....

\[ \mathcal{L} = \sum_f (\bar{\Psi}_f (i \gamma^\mu \partial_\mu - m_f) \Psi_f - eQ_f \bar{\Psi}_f \gamma^\mu \Psi_f A_\mu) + \]

\[ + \frac{g}{\sqrt{2}} \sum_i (\bar{a}_L^i \gamma^\mu b_L^i W^+_\mu + \bar{b}_L^i \gamma^\mu a_L^i W^-_\mu) + \frac{g}{2c_w} \sum_f \bar{\Psi}_f \gamma^\mu (I_f^3 - 2s_w^2 Q_f - I_f^3 \gamma_5) \Psi_f Z_\mu + \]

\[ - \frac{1}{4} |\partial_\mu A_\nu - \partial_\nu A_\mu - i e (W^-_\mu W^+_\nu - W^+_\mu W^-_\nu)|^2 - \frac{1}{2} |\partial_\mu W^+_\nu - \partial_\nu W^+_\mu + \]

\[ - i e (W^+_\mu A_\nu - W^+_\nu A_\mu) + ig' c_w (W^+_\mu Z_\nu - W^+_\nu Z_\mu)|^2 + \]

\[ - \frac{1}{4} |\partial_\mu Z_\nu - \partial_\nu Z_\mu + ig' c_w (W^-_\mu W^+_\nu - W^+_\mu W^-_\nu)|^2 + \]

\[ - \frac{1}{2} M^2 \eta^2 - \frac{g M^2}{8 M_W} \eta^3 - \frac{g'^2 M^2}{32 M_W} \eta^4 + |M_W W^+_\mu + \frac{g}{2} \eta W^+_\mu|^2 + \]

\[ + \frac{1}{2} |\partial_\mu \eta + i M_Z Z_\mu + \frac{ig}{2c_w} \eta Z_\mu|^2 - \sum_f \frac{g}{2 M_W} \bar{\Psi}_f \Psi_f \eta \]

\[ - g G^a_\mu \bar{\psi}_i \gamma^\mu T^a_{ij} \psi_j - \frac{1}{4} G^a_\mu G_{\mu\nu}^a \]
\[
\mathcal{L} = \sum_f (\bar{\Psi}_f (i \gamma^\mu \partial_\mu - m_f) \Psi_f - e Q_f \bar{\Psi}_f \gamma^\mu \Psi_f A_\mu) + \\
+ \frac{g}{\sqrt{2}} \sum_i (\bar{u}_L^i \gamma^\mu \gamma^\nu \gamma^\rho \gamma^\sigma \bar{d}_L^i + \bar{d}_L^i \gamma^\mu \gamma^\nu \gamma^\rho \gamma^\sigma \bar{u}_L^i) + \frac{g}{2 c_w} \sum_f \bar{\Psi}_f \gamma^\mu (I_f^3 - 2 s_w^2 Q_f - I_f^3 \gamma_5) \Psi_f Z_\mu + \\
- \frac{1}{4} |\partial_\mu A_\nu - \partial_\nu A_\mu - i e (W^-_\mu W^+_\nu - W^+_\mu W^-_\nu)|^2 - \frac{1}{2} |\partial_\mu W^+_\nu - \partial_\nu W^+_\mu + \\
- i e (W^+_\mu A_\nu - W^+_\nu A_\mu) + ig' c_w (W^+_\mu Z_\nu - W^+_\nu Z_\mu)|^2 + \\
- \frac{1}{4} |\partial_\mu Z_\nu - \partial_\nu Z_\mu + i g' c_w (W^-_\mu W^+_\nu - W^+_\mu W^-_\nu)|^2 + \\
\text{Higgs mass:} \quad \frac{1}{2} M^2_{\eta} \eta^2 - \frac{g M^2_\eta}{8 M_W} \eta^3 - \frac{g'^2 M^2_\eta}{32 M_W} \eta^4 + (M_W W^+_\mu) + \frac{g}{2} \eta W^+_\mu |^2 + \\
+ \frac{1}{2} |\partial_\mu \eta - i M_Z \eta Z_\mu| + \frac{ig}{2 c_w} \eta Z_\mu|^2 - \sum_f \frac{g}{2 M_W} \bar{\Psi}_f \Psi_f \eta \\
\text{W mass} \\
\text{Z mass} \quad - g G^a_\mu \bar{\psi}_i \gamma^\mu T^a_{ij} \psi_j - \frac{1}{4} G^a_{\mu \nu} G^{\mu \nu}_a
\]
\[
\mathcal{L} = \sum_f \left( \bar{\psi}_f (i \gamma^\mu \partial_\mu - m_f) \psi_f - e Q_f \bar{\psi}_f \gamma^\mu \psi_f A_\mu \right) + \\
+ \frac{g}{\sqrt{2}} \sum_i \left( \bar{a}^i L \gamma^\mu b^i L W^+ W^- + \bar{b}^i L \gamma^\mu a^i L W^- \right) + \frac{g}{2 c_w} \sum_f \bar{\psi}_f \gamma^\mu (I_f^3 - 2 s^2_w Q_f - I_f^3 \gamma_5) \psi_f Z_\mu + \\
- \frac{1}{4} |\partial_\mu A_\nu - \partial_\nu A_\mu - i e (W^- W^+ - W^+ W^-)|^2 + \frac{1}{2} |\partial_\mu W^+ - \partial_\nu W^+|^2 + \\
- ie(W^+_\mu A_\nu - W^+_\nu A_\mu) + ig' c_w (W^+_\mu Z_\nu - W^+_\nu Z_\mu)^2 + \\
- \frac{1}{4} |\partial_\mu Z_\nu - \partial_\nu Z_\mu + ig' c_w (W^- W^+_\nu - W^+_\mu W^-)|^2 + \\
- \frac{1}{2} M_Z^2 \eta^2 - \frac{g M^2}{8 M_W} \eta^3 - \frac{g'^2 M^2}{32 M_W} \eta^4 + |M_W W^+_\mu|^2 + \frac{g}{2} \eta W^+_\mu|^2 + \\
+ \frac{1}{2} |\partial_\mu \eta + i M_Z \eta| + \frac{g}{2 c_w} \eta Z_\mu |^2 - \sum_f \frac{g}{2 M_W} \bar{\psi}_f \psi_f \eta + \\
- g G^\mu_{\mu'} \psi_i \gamma^\mu T^u_{ij} \psi_j - \frac{g^u}{4} G^\mu_{\mu \nu} G^\nu_{\nu} \\
gluon propagator
\]
The Lagrangian $\mathcal{L}$ for QED and weak interactions is given by:

$$\mathcal{L} = \sum_f \left( \bar{\psi}_f (i \gamma^\mu \partial_\mu - m_f) \psi_f - e Q_f \bar{\psi}_f \gamma^\mu \psi_f A_\mu \right) + \frac{g}{\sqrt{2}} \sum_i \left( \bar{a}_L^i \gamma^\mu b_L^i W^+_\mu + \bar{b}_L^i \gamma^\mu a_L^i W^-_\mu \right) + \frac{g}{2c_w} \sum_f \bar{\psi}_f \gamma^\mu (I_f^3 - 2s_w Q_f - I_f^3) \psi_f Z_\mu +$$

**Fermion propagator**

$$-\frac{1}{4} |\partial_\mu A_\nu - \partial_\nu A_\mu| - ie (W^- W^+ - W^+_W^-)^2 + \frac{1}{2} |\partial_\mu W^+ - \partial_\nu W^-|^2 +$$

**Photonic propagator**

$$-ie (W^+_W^- A_\nu - W^+_W^- A_\mu) + ig' c_w (W^+_W^- Z_\nu - W^+_W^- Z_\mu)^2 +$$

**Z propagator**

$$-\frac{1}{4} |\partial_\mu Z_\nu - \partial_\nu Z_\mu| + ig' c_w (W^- W^+ - W^+_W^-)^2 +$$

**Higgs mass**

$$-\frac{1}{2} M_\eta^2 \eta^2 - \frac{g M_\eta^2}{8M_W} \eta^3 - \frac{g'^2 M_\eta^2}{32M_W} \eta^4 +$$

**Higgs propagator**

$$+ \frac{1}{2} |\partial_\mu \eta|^2 + iM_Z \eta Z_\mu^\dagger - \frac{ig}{2c_w} \eta Z_\mu^\dagger - \sum_f \frac{g m_f}{2 M_W} \bar{\psi}_f \psi_f \eta$$

**Z mass**

$$- g G^a_\mu \bar{\psi}_i \gamma^\mu T^a_{ij} \psi_j - \frac{1}{4} G^a_\mu G^{\mu\nu}_a$$

**QCD vertex**

$$- g G^a_\mu \bar{\psi}_i \gamma^\mu T^a_{ij} \psi_j$$

**Gluon propagator**

$$\frac{1}{4} G^a_\mu G^{\mu\nu}_a$$
\[ \mathcal{L}_G = \sum_f \left( \bar{\psi}_f (i \gamma^\mu \partial \mu - m_f) \psi_f - e Q_f \bar{\psi}_f \gamma^\mu \psi_f A_{\mu} \right) + \frac{g}{\sqrt{2}} \sum_i (\bar{d}_L \gamma^\mu b_L W^+_{\mu} + \bar{b}_L \gamma^\mu a_L W^-_{\mu}) + \frac{g}{2c_w} \sum_f \bar{\psi}_f \gamma^\mu (I_f^3 - 2s^2_w Q_f - I_f^3 \gamma_5) \psi_f Z_{\mu} + \]

\[ - \frac{1}{4} |\partial_\mu A_\nu - \partial_\nu A_\mu|^2 - ie(W^-_\mu W^+_{\nu} - W^+_{\mu} W^-_{\nu})|^2 - \frac{1}{2} |\partial_\mu W^+_{\nu} - \partial_\nu W^+_{\mu}|^2 + \]

\[ - ie(W^+_{\mu} A_\nu - W^+_{\nu} A_\mu) + ig' c_w (W^+_{\mu} Z_\nu - W^+_{\nu} Z_\mu|^2 + \]

\[ - \frac{1}{4} |\partial_\mu Z_\nu - \partial_\nu Z_\mu|^2 + ig' c_w (W^-_\mu W^+_{\nu} - W^+_{\mu} W^-_{\nu})|^2 + \]

\[ \frac{1}{2} \left( \frac{g M^2}{8 M_W} \right) \eta^2 - \frac{g^2 M^2}{32 M_W} \eta^4 + |M_W W^+_{\mu} + \frac{g}{2} \eta W^+ |^2 + \]

\[ + \frac{1}{2} |\partial_\mu \eta|^2 + \frac{i g}{2 c_w} \eta Z_{\mu}^2 - \sum_f \frac{g m_f}{2 M_W} \bar{\psi}_f \psi_f \eta \]

\[ - g G^\mu_a \bar{\psi}_i \gamma^\mu T^a_{ij} \psi_j - \frac{1}{4} G^\mu \nu_a G^\nu_a \]

fermion propagator  
fermion mass  
QED vertex  
W,Z vertex  

photon prop.  
W propagator  
Z propagator  
W,Z,photon interactions  

Higgs mass  
Higgs prop.  
Z mass  
QCD vertex  
gluon propagator  

W mass  
Higgs interactions with fermions and bosons
ATLAS and CMS surround the interaction region

Fully instrumented in region: \(-2 < \eta < 2\)
Partial instrumentation: \(-5 < \eta < 5\)
The LHCb detector

Interaction point

Beam

Vertex detector

Tracking

Calo

Muon

Fully instrumented within $1.9 \leq \eta \leq 4.9$
Complementarity of LHC detectors
1. Electroweak tests using $W \rightarrow \mu \nu$, $Z \rightarrow \mu \mu$; probing the proton structure
Parton Density Function (PDF): $f_q(x, Q^2)$

Probability that the proton contains this parton with this momentum fraction

$$Q = \text{Invariant mass of parton interaction}$$

$$x = Q e^{\pm y} / \sqrt{s}$$

[y is rapidity, $\sqrt{s}$ c.o.m]
Theory v Experiment at the LHC

\[
\sigma_x(Q^2) = \sum_{a,b \geq 0} \int dx_1 dx_2 f_a(x_1, Q^2) f_2(x_2, Q^2) \hat{\sigma}_{ab \to x}(x_1, x_2, Q^2)
\]

- Test the Standard Model at the highest energies. W/Z theory known to 1%
- Constrain parton distribution functions.
- Test QCD – of particular interest in regions with very soft gluons
Production of object of mass $Q$ at rapidity

$$y = \ln\left( x \frac{\sqrt{s}}{Q} \right)$$
ATLAS & CMS:

Collision between two partons having similar momentum fractions.

PDFs either already measured by HERA or Tevatron, or requiring modest extrapolation through DGLAP.
Collision between one well understood parton and one unknown or large DGLAP evolved parton.
ATLAS & CMS:
Collision between two partons having similar momentum fractions.

PDFs either already measured by HERA or Tevatron, or requiring modest extrapolation through DGLAP.
LHCb:
Collision between one well understood parton and one unknown or large DGLAP evolved parton.

Potential to go to very low x, where PDFs essentially unknown.
Pre-LHC precision on $W,Z$ cross-sections

\[ W^+ + W^- = u d \approx u d \]

e.g. very roughly

\[ \frac{W^+}{W^-} = \frac{u d}{\bar{u} \bar{d}} \approx \frac{u}{d} \]
W and Z production in the forward region

Experimentally: \( \sigma = \frac{N}{L} \)
Count number of events: \( Z \rightarrow \mu \mu, \ W \rightarrow \mu \nu \)

Master formula: \( \sigma = \frac{pN}{\epsilon L} \)
The LHCb detector

Interaction point

Vertex detector

Magnet

Bending plane

RICH 1

RICH 2

ECAL HCAL

Muon detector

Beam

300 mrad

Fully instrumented within $1.9 \leq \eta \leq 4.9$
Z cross-section measurement

\[ \sigma = \frac{pN}{\varepsilon L} \]
Efficiencies for W and Z analysis found from tag-and-probe
First W candidate
Purity of W selection

\[ \sigma = \frac{pN}{\varepsilon L} \]
W charge asymmetry

$W^+ / W^-$ Charge Asymmetry

LHCb preliminary, 37.1 pb$^{-1}$

NNLO predictions (DYNNOLO)

- MSTW08
- ABKM09
- JR09
- 2010 Data

Lepton Pseudorapidity
Comparison to CMS

$p_T^l > 25 \text{ GeV/c}$

Lepton charge asymmetry

- LHCb 2010, $W \rightarrow \mu \nu$
- CMS 2010, $W \rightarrow \mu \nu$
- CMS 2010, $W \rightarrow e \nu$
Testing the theory

LHCb, $\sqrt{s} = 7$ TeV

- MSTW08
- NNPDF21
- p_T^\mu > 20 GeV/c
- 2.0 < $\eta^\mu$ < 4.5
- 60 < $m_{\mu\mu}$ < 120 GeV/c²

$\sigma_{Z \rightarrow \mu\mu}$ [pb]

$\sigma_{W^- \rightarrow \mu^- \nu}$ [pb]

$\sigma_{W^- \rightarrow \mu^- \bar{\nu}}$ [pb]

$\sigma_{W^- \rightarrow \mu^- \nu} + \sigma_{W^- \rightarrow \mu^- \bar{\nu}}$

$\sigma_{Z \rightarrow \mu\mu}$

$\sigma_{W^- \rightarrow \mu^- \nu} \quad \sigma_{Z \rightarrow \mu\mu}$

$\sigma_{W^- \rightarrow \mu^- \bar{\nu}} \quad \sigma_{Z \rightarrow \mu\mu}$
Z differential cross-section as fn of rapidity and transverse momentum compared to various PDF sets and different generators.
1. Summary

- Electroweak data from LHC is in good agreement with Standard Model Predictions.

- PDFs constrained and thus predict other processes (e.g. Higgs) with greater precision.
2. Electroweak tests using $Z \rightarrow \tau\tau$; sensitivity to Higgs

Are these couplings the same?

Could something else produce $\tau\tau$?
Z→ττ signal and background

- Leptonic:
  - $\Phi^0 \rightarrow \tau^+ \tau^-$
  - $\nu_\tau$ and lepton (e or $\ell$)
- Semi-leptonic:
  - $\Phi^0 \rightarrow \tau^+ \tau^-$
  - $\nu_\tau$ and jet

QCD:
- $\tau_\mu \tau_\mu$, $\tau_e \tau_\mu$
- Jet

EWK:
- $\tau_\mu \tau_\mu$, $\tau_e \tau_\mu$
- $W^+$

WW:
- $\tau_\mu \tau_\mu$, $\tau_e \tau_\mu$
- $W^-$
Trigger and selection

- triggers
  - muon \( (p_T > 15 \text{ GeV}) \)
  - electron \( (p_T > 10 \text{ GeV}) \)
- muon
  - muon track
- electron
  - large \( E_{\text{ECAL}}/p \)
  - small \( E_{\text{HCAL}}/p \)
- hadron (single-pronged)
  - small \( E_{\text{ECAL}}/p \)
  - large \( E_{\text{HCAL}}/p \)
Estimated signal contributions

$\mu\mu$

$LHCb\ \sqrt{s} = 7\text{ TeV}$

$e\mu$

$LHCb\ \sqrt{s} = 7\text{ TeV}$

$\mu\mu$

$LHCb\ \sqrt{s} = 7\text{ TeV}$

$e\mu$

$LHCb\ \sqrt{s} = 7\text{ TeV}$

$\mu\mu$

$LHCb\ \sqrt{s} = 7\text{ TeV}$

$e\mu$
Comparison of $Z \rightarrow \mu \mu$ and $Z \rightarrow \tau \tau$ results

LHCb preliminary

$\sigma(Z \rightarrow ll)$ [pb]

$Z \rightarrow \mu \mu$

$Z \rightarrow ee$

$Z \rightarrow \tau \tau$
Reinterpretation in terms of Higgs
Higgs boson in the forward region

Model independent limits

SUSY limits (mhmax scenarios)
2. Summary

- Lepton universality holds

- SUSY parameter space severely constrained.

- With more statistics we are sensitive to Higgs production in the forward region.
3. Exclusive J/ψ and ψ(2S), χ_c and μμ

Exclusive J/ψ and ψ(2S) production in pp collisions at \( \sqrt{s} = 7 \) TeV

Results based on 37pb\(^{-1}\) of data taken in 2010
Physics of the Vacuum

Elastic

\[ \sigma_{\text{elastic}} \approx 40 \text{mb} \]

\[ \sigma_{\text{diffractive}} \approx 10 \text{mb} \]

\[ \sigma_{\text{inelastic}} \approx 60 \text{mb} \]

It’s QCD – but not as we normally see it. It’s colour-free.
Physics of the Vacuum

Elastic

It’s QCD – but not as we normally see it. It’s colour-free

\[ \sigma_{\text{elastic}} \approx 40\text{mb} \]
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Physics of the Vacuum

It’s QCD – but not as we normally see it. It’s colour-free

\[
\begin{align*}
\sigma_{\text{elastic}} &\approx 40\text{mb} \\
\sigma_{\text{diffractive}} &\approx 10\text{mb} \\
\sigma_{\text{inelastic}} &\approx 60\text{mb}
\end{align*}
\]
Physics of the Vacuum

Diffractive

It’s QCD – but not as we normally see it. It’s colour-free

\[
\begin{align*}
\sigma_{\text{elastic}} & \approx 40\text{mb} \\
\sigma_{\text{diffractive}} & \approx 10\text{mb} \\
\sigma_{\text{inelastic}} & \approx 60\text{mb}
\end{align*}
\]
Physics of the Vacuum

Central Exclusive

Elastic diffractive: clean environment to study vacuum, and in particular, transition between soft and hard pomeron.

\[ \sigma_{\text{elastic}} \approx 40 \text{mb} \]
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\[
\sigma_{\text{elastic}} \approx 40\text{mb} \\
\sigma_{\text{diffractive}} \approx 10\text{mb} \\
\sigma_{\text{inelastic}} \approx 60\text{mb}
\]
Sensitivity to gluon PDF

Leading order cross-section

\[
\frac{d\sigma}{dt} (\gamma^* p \to J/\psi p) \bigg|_{t=0} = \frac{\Gamma_{ee} M_{J/\psi}^3 \pi^3}{48\alpha} \left[ \frac{\alpha_s(Q^2)}{Q^4} xg(x, Q^2) \right]^2 \left(1 + \frac{Q^2}{M_{J/\psi}^2}\right)
\]

Gluon PDF enters squared

Examples of dependence of Jpsi cross-section on PDF (left) and extraction of gluon PDF (right) from Martin, Nockles, Ryskin, Teubner, arXiv:0709.4406v1

\[xg \propto x^{-\lambda}\]
The LHCb detector

interaction point

vertex detector
(some sensitivity $-3.5 < \eta < -1.5$)

tracking

fully instrumented within $1.9 \leq \eta \leq 4.9$

trigger: $p_\mu > 3$ GeV, $p_{t\mu} > 0.4$ GeV, $m_{\mu\mu} > 2.5$ GeV

low multiplicity required. restricts to single-interaction collisions
VELO sub-detector measures particle positions to 5um

UCD helped build, commission and operate the VELO
Graphical Representation

- Elastic Scattering
- Single Diffraction
- Double Diffraction
- Central Exclusive Production (elastic)
- Central Exclusive Production (inelastic)
Effect of rapidity gap requirement on muon triggered events

<table>
<thead>
<tr>
<th>Number of events</th>
<th>Number of forward tracks</th>
<th>LHCb</th>
</tr>
</thead>
<tbody>
<tr>
<td>12000</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>11000</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>10000</td>
<td>20</td>
<td></td>
</tr>
<tr>
<td>9000</td>
<td>30</td>
<td></td>
</tr>
</tbody>
</table>

All triggered events

<table>
<thead>
<tr>
<th>Number of events</th>
<th>Number of forward tracks</th>
<th>LHCb</th>
</tr>
</thead>
<tbody>
<tr>
<td>5000</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>4000</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>3000</td>
<td>20</td>
<td></td>
</tr>
<tr>
<td>2000</td>
<td>30</td>
<td></td>
</tr>
</tbody>
</table>

With veto on backward tracks
Central exclusive di-muon signals

Before and after requiring precisely two tracks

Tracks have $p_T > 400\text{MeV}$
$2 < \eta < 5$
Non-resonant background very small

Distributions are not background-subtracted.
37pb-1 of data: 1492 J/ψ and 40 ψ(2s)
Cross-section measurement

Purity:
1. non-resonant bkg (1%)
2. Chi_c feeddown (9%)
3. Psi’ feeddown (2%)
4. Inelastic Jpsi production (30%)

\[ \sigma = \frac{pN}{\varepsilon L} \]

Efficiency:
1. Trigger
2. Tracking & muon id.
3. Single interaction beam-crossing

Number of events observed

Luminosity

\[ P(n) = \frac{\mu^n e^{-\mu}}{n!} \]
Feed-down backgrounds
Inelastic background

Characterise $p_T$ spectrum of background using shapes with 3-8 tracks and extrapolate to 2 track case.
Inelastic background

Signal shape
Estimated from Superchic using $\exp(-b p_T^2)$ (arXiv: 0909.4748)
Take $b$ from HERA data. Extrapolate to LHCb energies to get $b = 6.1 \pm 0.3 \text{ GeV}^{-2}$
Crosscheck: Fit to spectrum below with $b$ free gives $b = 5.8 \pm 1 \text{ GeV}^{-2}$

Purity of exclusive signal below 900 MeV/c $p_T$ = $(70 \pm 4 \pm 6)\%$

Inelastic background shape
Estimated from data.
Characterise shape for 3-8 tracks and extrapolate to 2 tracks.

This approach works for QED production of dimuons, tested using LPAIR simulation.
Also checked with PYTHIA simulation of diffractive events.
LHCb compared to theory & experiment

<table>
<thead>
<tr>
<th>Predictions</th>
<th>$\sigma_{pp \rightarrow J/\psi} (\rightarrow \mu^+ \mu^-)$</th>
<th>$\sigma_{pp \rightarrow \psi(2S)} (\rightarrow \mu^+ \mu^-)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gonçalves and Machado</td>
<td>275</td>
<td></td>
</tr>
<tr>
<td>Starlight</td>
<td>292</td>
<td>6.1</td>
</tr>
<tr>
<td>Motyka and Watt</td>
<td>334</td>
<td></td>
</tr>
<tr>
<td><strong>SUPERChIC</strong>(^a)</td>
<td>396</td>
<td></td>
</tr>
<tr>
<td>Schäfer and Szczurek</td>
<td>710</td>
<td>17</td>
</tr>
<tr>
<td>LHCb measured value</td>
<td>$307 \pm 21 \pm 36$</td>
<td>$7.8 \pm 1.3 \pm 1.0$</td>
</tr>
</tbody>
</table>

\(^a\) **SUPERChIC** simulation does not include a gap survival factor.

All predictions (bar Schaefer&Szcaurek) have similar approach and give similar results and are consistent with our data.
LHCb compared to HERA

\[ W^2 \equiv (q + p_2)^2 = x \gamma s - Q^2, \]

Twofold ambiguity

\[ x \gamma = \frac{M_{\psi\perp}}{\sqrt{s}} e^{y_{\psi}}, \]

\[ x = \frac{M_{\psi\perp}}{\sqrt{s}} e^{-y_{\psi}}, \]

LHCb c/s is HERA c/s weighted by photon spectrum + gap survival factor (r)

\[ \frac{d\sigma}{dy_{pp\to p\nu p}} = r(y) \left[ k_+ \frac{dn}{dk_+} \sigma_{\gamma p\to V_p(W_+)} + k_- \frac{dn}{dk_-} \sigma_{\gamma p\to V_p(W_-)} \right]. \]

\[ k_{\pm} \approx (m_{\nu}/2) \exp(\pm |y|), \]

LHCb differential data fitted assuming power law dependence \( \sigma(W) = aW^\delta \)

\[ a = 0.8^{+1.2}_{-0.5} nb \]

\[ \delta = 0.92 \pm 0.15 \]

Power law results

\[ a = 3nb \]

\[ \delta = 0.72 \]
LHCB compared to theory & experiment

\[ \frac{d\sigma}{dy}_{pp \rightarrow p\nu p} = r(y) \left[ k_+ \frac{dn}{dk_+} \sigma_{\gamma p \rightarrow \nu p(W_+)} + k_- \frac{dn}{dk_-} \sigma_{\gamma p \rightarrow \nu p(W_-)} \right] \]

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**Measured**

**From fit**

**Plotted**
Deviations from power law

Saturation model (Motyka&Watt PRD 78 2008 014023) has deviation from pure power law.
LHCb compared to theory & experiment

looks very like

\[
\begin{align*}
\sigma_{\text{tot}}(\gamma p) & \quad W^{0.16} \\
\sigma(\gamma p \to \rho p) & \quad W^{0.22} \\
\sigma(\gamma p \to \omega p) & \quad W^{0.22} \\
\sigma(\gamma p \to \phi p) & \quad W^{0.22} \\
\sigma(\gamma p \to J/\psi p) & \quad W^{0.8} \\
\sigma(\gamma p \to \psi(2S)p) & \quad W^{1.1} \\
\sigma(\gamma p \to Y(1S)p) & \quad W^{1.2}
\end{align*}
\]
Other ways to fill the vacuum with muons

$\chi_c$ 0,1,2 decay to $J/\psi$+photon
Vacuum state should be 0

LHCb Preliminary

$\sqrt{s} = 7$ TeV Data
3. Summary

- Nature of the pomeron investigated
- Sensitive to gluon PDF
- Prospect for new phenomena in QCD
  - saturation
  - odderon (3-bound gluons)
Conclusions

• Rich variety of physics available from LHC

• Standard Model has so far resisted all our attempts to break it!

• Precision physics and new energy regimes are key to improved understanding

• Irish physics very much involved at the energy frontier.
Backup
Determination of non-resonant background

$p_T$ for 3-track events

$p_T$ for 8-track events
Exclusive pseudo-vector production

\[ \sigma_{\chi_{c0} \rightarrow \mu^+ \mu^- \gamma} = 9.3 \pm 2.2 \pm 3.5 \pm 1.8 \text{ pb} \]
\[ \sigma_{\chi_{c1} \rightarrow \mu^+ \mu^- \gamma} = 16.4 \pm 5.3 \pm 5.8 \pm 3.2 \text{ pb} \]
\[ \sigma_{\chi_{c2} \rightarrow \mu^+ \mu^- \gamma} = 28.0 \pm 5.4 \pm 9.7 \pm 5.4 \text{ pb} \]

LHCb preliminary results with 2010 data

\[ \text{BR}(\chi_{c0} \rightarrow J/\psi \gamma) = 1.2\% \]
\[ \text{BR}(\chi_{c1} \rightarrow J/\psi \gamma) = 34.4\% \]
\[ \text{BR}(\chi_{c2} \rightarrow J/\psi \gamma) = 19.5\% \]

Dominance of \( \chi_{c0} \) is confirmed.

Experimentally difficult to separate three resonances and determine non-resonant background for each.