Forward physics and diffraction at LHCb

J. Blouw, on behalf of the LHCb collaboration

Max-Planck-Institut für Kernphysik, Heidelberg

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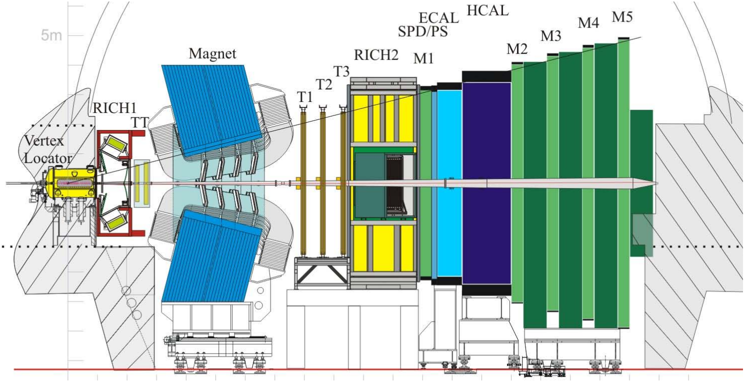
Outline

- The LHCb spectrometer
- Forward energy flow: compare diffractive enriched events to models
- Exclusive di-muon production
- Exclusive production of di-muon pairs
- Conclusions & Outlook



- Acceptance from $2 < \eta < 5$
- Probes down to $x \approx 5 \times 10^{-6}$
- Maximum rapidity coverage: 3.5 units
- μ ID efficiency: ~ 97 % for < 3 % $\pi \to \mu$ mis-id probability from $p = 2 - 100$ GeV

JoI 3 (2008) S08005

Measure energy flow

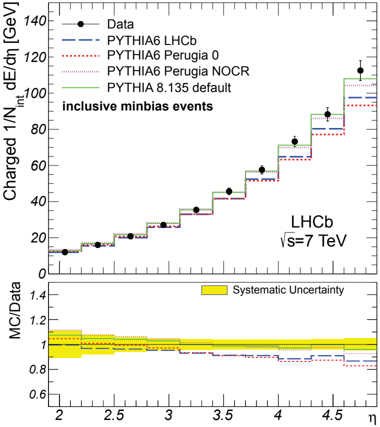
$$\frac{1}{N_{\text{int}}}\frac{dE_{\text{total}}}{d\eta} = \frac{1}{\Delta\eta}\left(\frac{1}{N_{\text{int}}}\sum_{i=1}^{N_{\text{part},\eta}} E_{i,\eta}\right)$$

- Sensitive to parton radiation and multi-parton interaction
- Study diffractive effects in various simulation models
- Minimum bias (MB) data used
- Only use data with 1 interaction per bunch crossing
- Employ 2 event classes to test different aspects of models

- minimum bias events $\rightarrow$ At least one track from primary vertex
- diffractive enriched events $\rightarrow$ No tracks in rapidity range $-3.5 < \eta < -1.5$

Forward energy flow: diffraction in simulation

Comparison to Pythia tunes

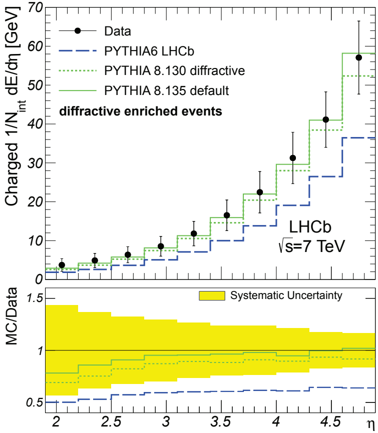


- MB data underestimated by all Pythia tunes

EPJ C73 (2013) 2421

Forward energy flow: diffraction in simulation

Comparison to Pythia tunes



- MB data underestimated by all Pythia tunes
- Pythia6 fails to describe diffractive enriched events
- Diffractive. events well described by Pythia8

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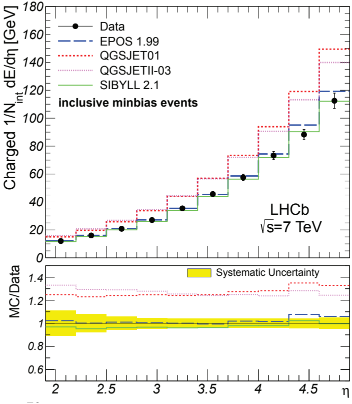
Forward energy flow: diffraction in simulation
Comparison to air shower models



- Sibyll & EPOS describe MB data well
- QGSJET overestimates MB data

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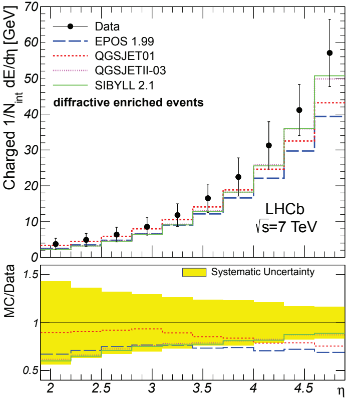

- Sibyll & EPOS describe MB data well
- QGSJET overestimates MB data
- Diffractive events syst. underestimated by all models

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Central Exclusive Production at LHCb:

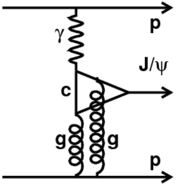
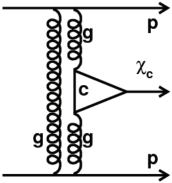


Photo production

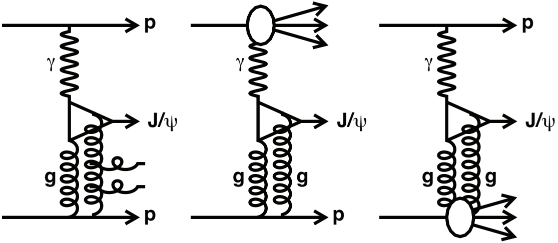


Double pomeron exchange

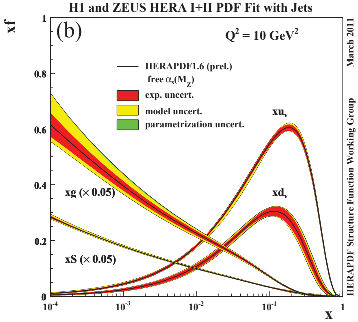
- Exchange of colorless object
- Protons do not break-up

Exclusive production of di-muon states at LHCb

Inelastic contributions:



- Exchange of colorless object
- Protons do not break-up
- At LHCb: contributions from inelastic scattering



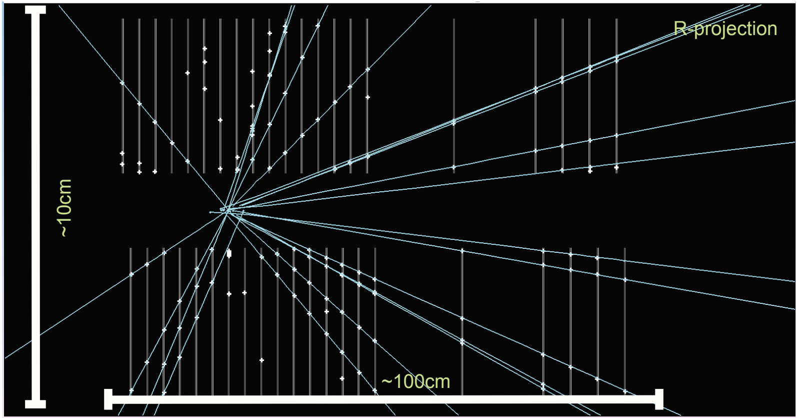
Photoproduction of J/Ψ and $\Psi(2S)$, parameterization by H1/ZEUS
(AIP Conf.Proc. 1441 (2012) 225-228 (arXiv:1112.0224))

$$\sigma(\gamma p \rightarrow J/\Psi p) \propto (xg(x, Q^2))^2$$

- At LHCb: contributions from inelastic scattering
- Probe non-perturbative, soft QCD
- Study quarkonia production
- Exclusive production: sensitive to pomeron/odderon
- Probes gluon pdf down to $x \approx 5 \cdot 10^{-6}$
- Sensitive to gluon-saturation effects

Exclusive production of di-muon states

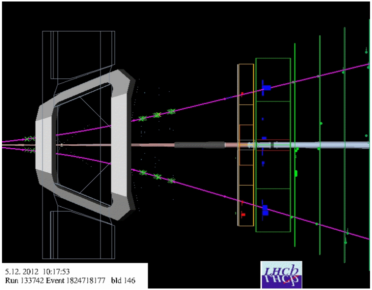
- Primary vertex displaced from beginning of VeLo

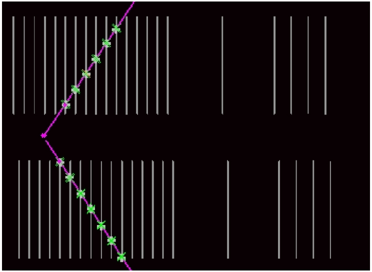


Typical event in LHCb VeLo

Exclusive production of di-muon states

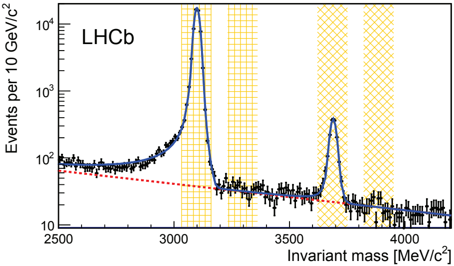
- Primary vertex displaced from beginning of VeLo
- Require only two tracks in forward acceptance
- No tracks in backward region





- Velo acceptance larger than LHCb spectrometer: rapidity coverage of 3.5 units in VeLo
- Rapidity coverage of 1.7 ± 0.5 in backward region

Exclusive production of di-muon states



Selection:

- $p_{\mu^+,\mu^-} > 6$ GeV for each μ
- $p_T > 0.4$ GeV for each μ
- Only two tracks in VeLo (3.5 rapidity units)
- No backward tracks (in 1.7 ± 0.5 units)

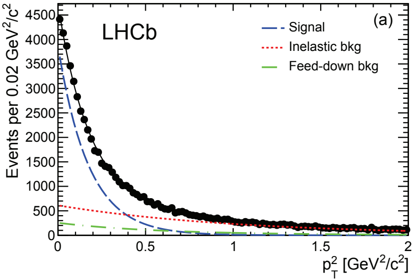
Results:

- Background not subtracted
- 55985 J/Ψ and 1565 $\Psi(2S)$
- Signal fitted with Crystal Ball function
- Sideband used for background (exponential)

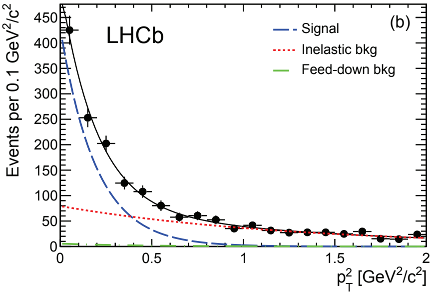
LHCb: JPG: Nucl. Part. Phys. 41 (2014) 055002 (arXiv:1401.3288)

Inelastic background for J/Ψ and $\Psi(2S)$:

For J/Ψ:



For $\Psi(2S)$:

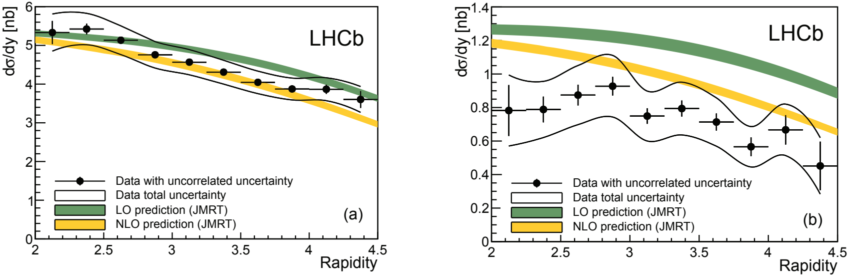


- Use Regge theory ($\frac{d\sigma}{dt} \propto e^{bt}$) to model signal and background
- Use fit to determine fractions of background (inelastic and feed-down)
- Expectations for LHCb well matched by results from fit

LHCb: JPG: Nucl. Part. Phys. 41 (2014) 055002 (`arXiv:1401.3288`)

Comparison to theory:

- Predictions by JMRT at LO and NLO (extrapolation to LHC energies)
- LO: power-law photoproduction from HERA with photon flux function and gap-survival factor



- NLO predictions compare well with J/Ψ data
- Not so good comparison to $\Upsilon(2S)$ data

Jones, Martin, Ryskin & Teubner, JHEP 1311 (2013) 085 (arXiv:1307.7099)
LHCb: JPG: Nucl. Part. Phys. 41 (2014) 055002 (arXiv:1401.3288)

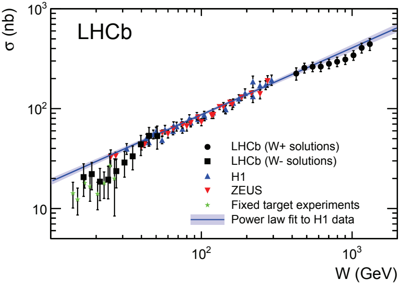
Exclusive production of di-muon states

Relation between exclusive J/Ψ production and photoproduction:

$$\frac{d\sigma}{dy}_{pp\to pJ/\Psi p} = r_+ k_+ \frac{dn}{dk_+}\sigma_{\gamma p\to J/\Psi p}(W_+) + r_- k_- \frac{dn}{dk_-}\sigma_{\gamma p\to J/\Psi p}(W_-)$$

- $W_\pm$ and $r_\pm$ absorptive corrections
- $\frac{dn}{dk}$ photon flux factor for photon with energy $k_\pm$
- Derive $W_\pm$ from data using power-law results for $W_\mp$ by H1(Eur.Phys.J. C73 (2013) 2466 (arXiv:1304.5162))

$$\sigma_{\gamma p\to J/\Psi p}(W) = 81(W/90\ \text{GeV})^{0.67}\ \text{nb}$$



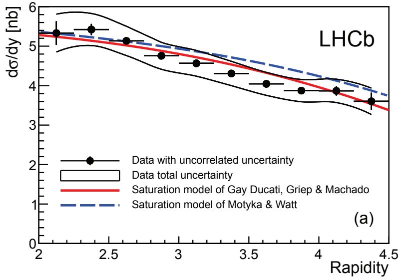
Only marginal agreement of H1 power-law fit with LHCb data

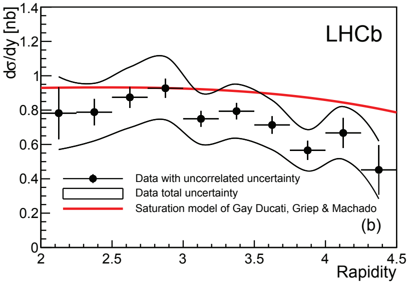
LHCb: JPG: Nucl. Part. Phys. 41 (2014) 055002 (arXiv:1401.3288)

Exclusive production of di-muon states

Comparison of LHCb data with saturation models by Gay, Ducati Griep & Machado, and Motyka & Watt:

J/Ψ: *idem dito* for $\Psi(2S)$:





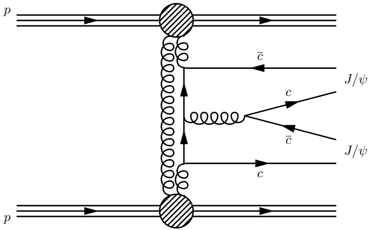
Good agreement found with both saturation models.

GDG & M: PRD 88, 017504 (2013) (arXiv:1305.4611)
M & W: PRD 78:014023, 2008 (arXiv:0805.2113)
LHCb: JPG: Nucl. Part. Phys. 41 (2014) 055002 (arXiv:1401.3288)

- Central exclusive production: both protons remain intact
- Only possible by exchange of two photons or colorless objects
- Study J/Ψ-pair production
- Study pomeron

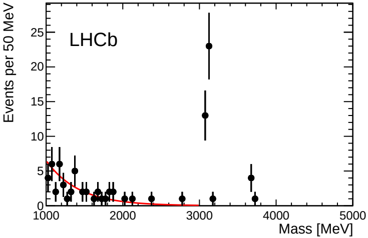
Some experimental facts:

- maximum rapidity coverage: 5.2 units
- data comprise also inclusive J/Ψ-pairs
- employ full data set of $\mathcal{L} = 3\ \mathrm{fb}^{-1}$ at $\sqrt{s_{\mathrm{av}}} = 7.6\ \mathrm{TeV}$
- still, expect only few events...

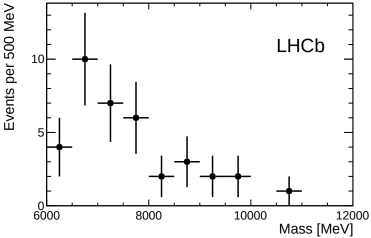


Double Pomeron exchange

- in 3 fb^{-1} found 37 $J/\Psi\ J/\Psi$ candidates
- 5 $J/\Psi\ \psi(2S)$
- no $\psi(2S)\ \psi(2S)$ candidates



Di-muon invariant mass.



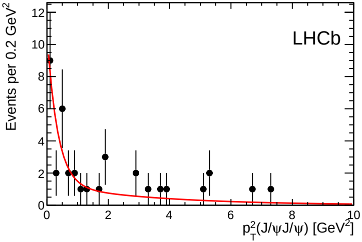
Four-muon invariant mass

$$\begin{aligned}\sigma_{J/\Psi J/\Psi} &= 58 \pm 10(\text{stat}) \pm 6(\text{sys})\ \text{pb}\\ \sigma_{J/\Psi\psi(2S)} &= 63^{+27}_{-18}(\text{stat}) \pm 10(\text{sys})\ \text{pb}\\ \sigma_{\psi(2S)\psi(2S)} &< 237\ \text{pb}\end{aligned}$$

Submitted to JoP G, `arXiv:1407.5973`

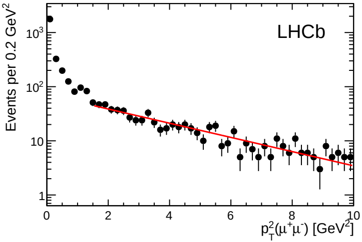
$$\frac{d\sigma}{dp_T^2} = f_{\text{elastic}} b_s e^{-b_s p_T^2} + (1 - f_{\text{elastic}}) b_b e^{-b_b p_T^2}$$

- elastic (b_s) & inelastic (b_b) components
- perform fit to determine b_s, b_b and f_{elastic}
- take b_b from fit to background sample



- $b_s = 2.9 \pm 1.3\ \text{GeV}^{-2}$
- $b_b = 0.29 \pm 0.02\ \text{GeV}^{-2}$
- $f_{\text{elastic}} = 0.42 \pm 0.13$

background sample obtained from di-muon events with $6 < M_{\mu\mu}^{\text{inv}} < 9$ GeV:

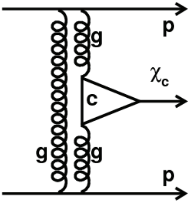


- CEP: $\sigma(J/\Psi J/\Psi) = 24 \pm 9$ pb
- Theory: $\sigma(J/\Psi J/\Psi) \approx 8$ to 36 pb

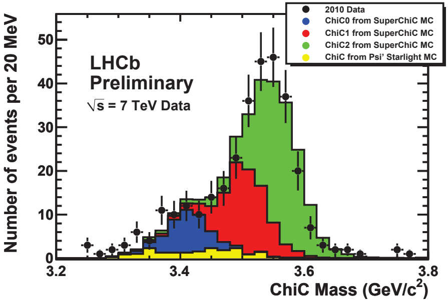
Submitted to JoP G, arXiv:1407.5973

Conclusions & Outlook

- Pythia8 provides better description of MB data $\&$ diffractive enriched events
- Cosmic ray shower models (EPOS, Sibyll) describe MB quite well
- Some discrepancy with diffractive enriched events...
- Unique kinematic regime accessed by LHCb $(x > 5 \cdot 10^{-6})$
- Exclusive J/Ψ and $\Psi(2S)$ well described by theoretical models:
  - from phenomenology (NLO using power-law fits)
  - from saturation models by Gay *et al.*, $\&$ Motyka and Watt
- 40% double J/Ψ production signal in LHCb CEP-events
- Observed 24 events likely agree with theory
- Near future:
  - LHCb upgrade with Herschel (High rapidity shower counters for LHCb)
  - Improves rapidity coverage: $5 < |\eta| < 8$
  - Useful as veto for charged $\&$ neutral particles



Double pomeron exchange



- CEP of χ_cs only possible through double-pomeron exchange
- Select J/Ψs with: $M(J/\Psi) - M_{J/\Psi}(\mathrm{PDG}) < 65\ \mathrm{MeV}/c$
- Only two muon tracks and one photon
- No tracks in backward region
- Use SuperChic generator for χ_c simulations (Comput.Phys.Commun.144:104-110,2002 (arXiv:hep-ph/0010303))
- Result: $(39 \pm 13)\%$ estimated to originate from exclusive production

LHCb: LHCb-CONF-2011-022