CEP at LHCb

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on behalf of the LHCb collaboration

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Madrid meeting of WG for Forward Physics at the LHC

Overview

1. Forward physics at LHCb
2. The LHCb detector
3. Central Exclusive Production at LHCb
   - Single charmonium (J Phys G41 055002)
   - Double charmonium (J Phys G41 115002)
   - Single bottomonium (preliminary)
4. LHCb prospects for Run 2

Forward physics at LHCb: studying QCD

Hard QCD:

- Perturbative and predictable
- Abundant experimental tests

Soft QCD:

- Difficult to calculate
- Crucially important: describes bound hadrons and the vacuum!
- Many opportunities for experimental input

Many open questions:

- Study of colourless objects: pomeron, odderon
- Existence of glueballs?
- Gluon PDF rise violates unitarity: new QCD phenomenology at low energy (saturation?)

Forward physics at LHCb

Diffraction:

- processes mediated by colour singlet exchange between colliding hadrons, with large rapidity gaps in the final state
  - Exchange involving pomeron: probe $g(x)$
  - ... in the low-x region where poorly constrained
  - ... but region of great interest: e.g. describe underlying event
  - ... and where saturation effects could contribute
  - Cross sections modified by odderon etc
- Must either tag outgoing protons or detect proton remnants
- ... requires detector coverage at $\eta > 5$!
- LHCb instruments:
  - $2 < \eta < 5$
  - $(-3.5 < \eta < -1.5)$
- Can exploit pp and pA collisions

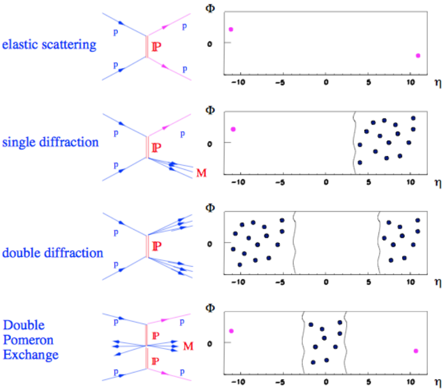
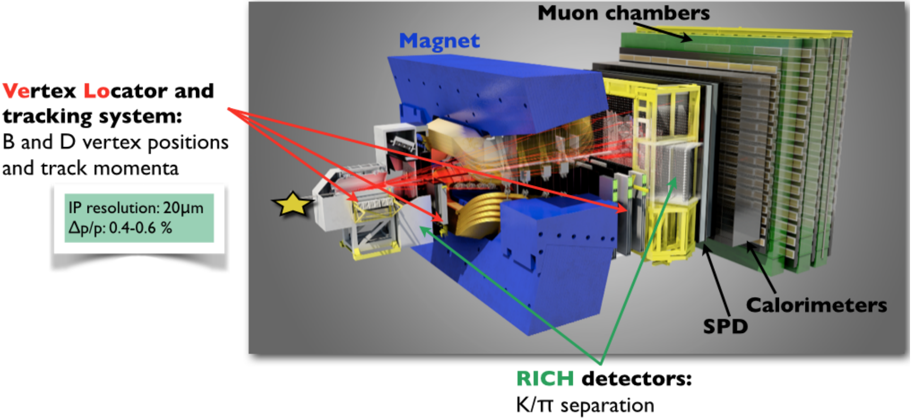


Image credit: Czech. J. Phys. 55 (2005) B757

The LHCb detector

- Downstream: $2 < \eta < 5$
- Upstream: $(-3.5 < \eta < -1.5)$
- Maximum rapidity gap 3.5 units
- Can trigger on very low p_T tracks

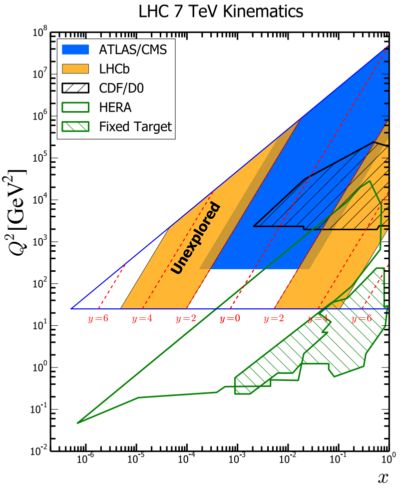
- For diffractive physics need to detect outgoing proton or fragmentation **or**
- at least detect central system including presence of rapidity gap
  - All diffractive events will have a large rapidity gap
  - Most pp interactions distribute particles throughout 4π



- LHCb trigger reduces 40MHz →(hardware) 1MHz →(software trigger) 3 kHz

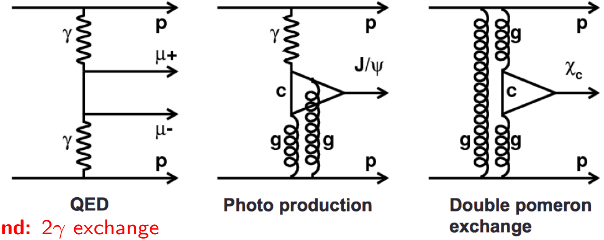
The LHCb detector

- LHCb explores an unusual portion of $x - Q^2$ down to $x = 10^{-6}$
- Complementary to LHC GPDs
- Effectively one colliding parton in a well-understood region, one unknown
- LHCb run 1 data set: 3 fb^{-1} pp collisions: 1.2% precision(!) [JINST 9 12005]
  - LHCb average number of interactions per bunch crossing ~ 1.5: ideal
  - Low multiplicity required (to establish rapidity gap) so single-interaction events only



LHCb diffractive measurements

Interactions of the form $pp \rightarrow pEp$



QED background: 2γ exchange

- QED process with small proton form-factor corrections

Pomeron exchange:

- Pomeron is, at leading order, a pair of gluons in $++$ state

\- **Photoproduction:** Photon-pomeron fusion

- Probes gluon density at small values of proton's momentum fraction, x
- Perturbative calculations accessible for higher mass of E

\- **Double pomeron exchange:** Pomeron-pomeron fusion

- E must be neutral $PC = ++$, no net flavour: $f_{0,2}, \chi_{c,b}, \gamma\gamma, JJ, H$

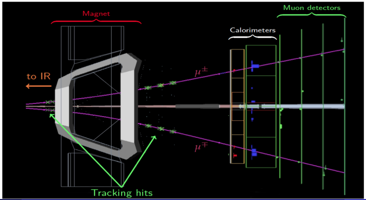
1) Exclusive J/ψ and $\psi(2S)$ production

(J Phys G41 055002)

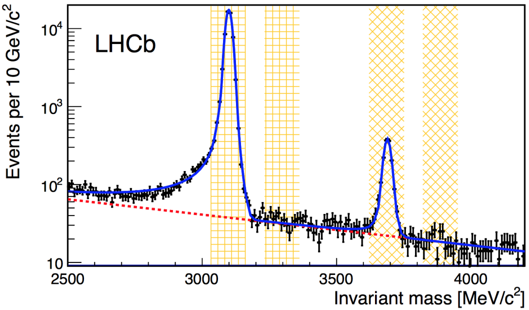
Differential production cross-section $\frac{d\sigma}{dy}$

Selection: J/ψ **or** $\psi(2S) \to \mu^+\mu^-$ in 930 pb^{-1} 7TeV data

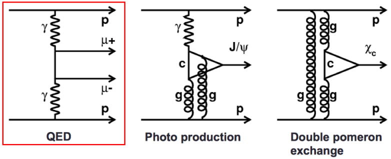
- Hardware trigger:
  - 1 muon with $p_T > 400$ MeV, or dimuon with each $p_T > 80$ MeV
  - Number of SPD hits < 10
- Software trigger:
  - Dimuon with mass > 2.9 GeV, or with mass < 1 GeV and $p_T < 900$ MeV and distance of closest approach < 150 mm
- Offline:
  - Two identified muons in $2 < \eta(\mu) < 4.5$
  - No photons, no other forward tracks: $\Delta y = 3.5$
  - No backward tracks: $\Delta y = 1.7$
  - Dimuon mass in 65 MeV mass window of the J/ψ and $\psi(2S)$ masses.



'Empty-detector' signal

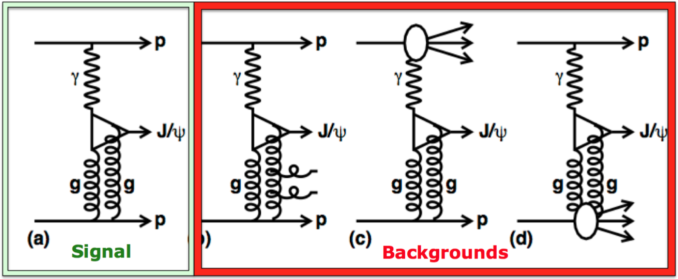


- Fit invariant mass: isolate QED background
  - **Signal:** Crystal ball function: 56,000 J/ψ, 1,600 $\psi(2S)$
  - **QED background:** Exponential (1% J/ψ and 17% $\psi(2S)$ contamination)



A number of peaking backgrounds remain:

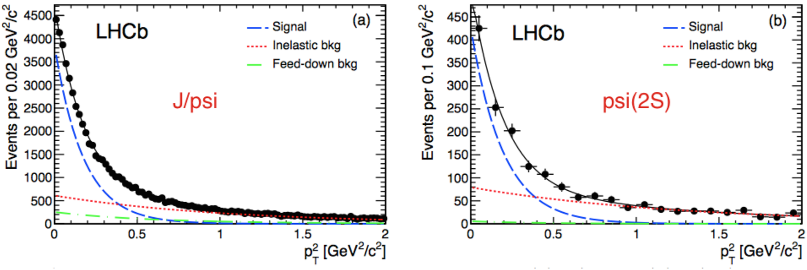
- 'Feed-down' decays: contamination can be estimated
  - $\psi(2S) \to J\psi\pi\pi$: $2.5 \pm 0.2\%$
  - $\chi_c \to J\psi\gamma$ $7.6 \pm 0.9\%$
  - $X(3872) \to \psi(2S)\gamma$ $2.0 \pm 2.0\%$
- Inelastic CEP background



- These backgrounds tend to produce a J/ψ or $\psi(2S)$ spectrum with harder p_T distribution than the exclusive signal

Determining exclusive contribution

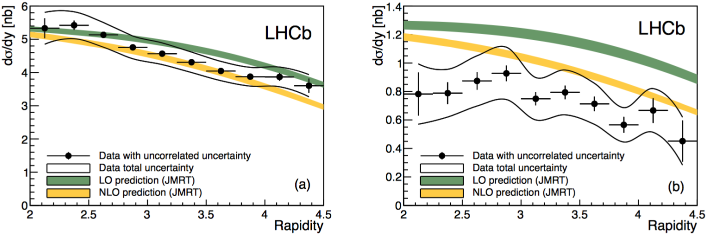
- Fit the p_T^2 distribution of the $J/\psi/\psi(2S)$ candidates



- **Feed-down background:** Yield and shape determined using data
- **Inelastic background:** Yield and shape vary
  - J/ψ slope $.97 \pm .04$ and $\psi(2S)$ slope $.8 \pm .2$ consistent with HERA
- **Exclusive signal:** Yield and shape vary
  - Signal slope $5.7 \pm .1$ and $5.1 \pm .7$ consistent with Regge theory extrapolation of HERA data
  - Signal purity: $59 \pm 1\%$ (J/ψ) and $52 \pm 7\%$ ($\psi(2S)$)
- Largest systematic uncertainties arise through the description of the p_T^2 fit

Interpretation

- LO and NLO[1] extrapolations from HERA data have been performed
- J/ψ (left) and $\psi(2S)$ (right) data are superimposed: good agreement with NLO



[1] JHEP 1311 (2013) 085

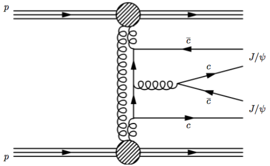
2) Double charmonium production

(J Phys G41 115002)

Production cross-section: $pp \to p(X)p$, $X = \{J/\psi J/\psi, J/\psi\psi(2S), \psi(2S)\psi(2S), \chi_{ci}\chi_{ci}\}$

Motivation

- Exchange of two pomerons
- Cross-section and mass spectrum sensitive to exotics: e.g. glueballs or tetraquarks
- Relate cross section to calculated $\sigma(gg \to J/\psi J/\psi)$ using Durham model[2]

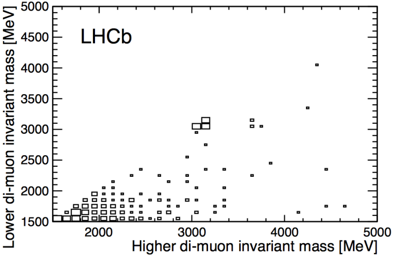


Selection: in 3 fb^{-1} pp collisions

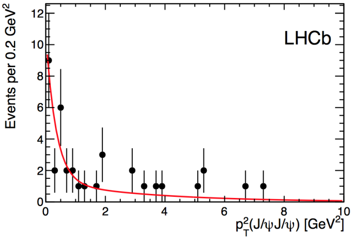
- Very similar to exclusive J/ψ / $\psi(2S)$ analysis
- No additional tracks reconstructed in the VELO
- No additional photon activity
- Reconstruct $\chi_c \to J/\psi\gamma$

[2] Int.J.Mod.Phys. A29 (2014) 1430031

'Empty-detector' signal



(b) Dimuon mass fit



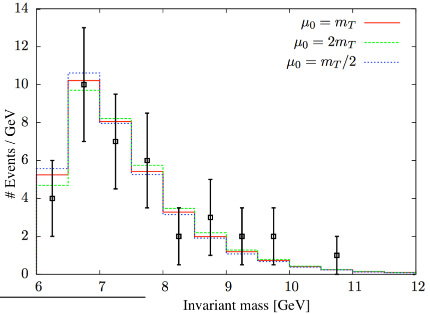
(c) Example: $J/\psi J\psi$ p_T^2 fit

- Cross section calculated for a range of double-charmonium states
- Largest systematic uncertainty relates to the final state geometrical acceptance (estimated for a range of values of dimeson mass, p_T and rapidity)

$$\begin{aligned}
\sigma^{J/\psi\, J/\psi} &= 65 \pm 11\ (\mathrm{stat})^{+6}_{-13}(\mathrm{syst})\ \mathrm{pb}, \\
\sigma^{J/\psi\, \psi(2S)} &= 72^{+30}_{-20}(\mathrm{stat})^{+10}_{-16}(\mathrm{syst})\ \mathrm{pb}, \\
\sigma^{\psi(2S)\psi(2S)} &< 255\ \mathrm{pb}\ \text{ at } 90\%\ \text{c.l.}, \\
\sigma^{\chi_{c0}\chi_{c0}} &< 75\ \mathrm{nb}\ \text{ at } 90\%\ \text{c.l.}, \\
\sigma^{\chi_{c1}\chi_{c1}} &< 49\ \mathrm{pb}\ \text{ at } 90\%\ \text{c.l.}, \\
\sigma^{\chi_{c2}\chi_{c2}} &< 150\ \mathrm{pb}\ \text{ at } 90\%\ \text{c.l.}.
\end{aligned}$$

Interpretation

- First observation of CEP for pairs of charmonium mesons
- Estimate of exclusive component in 'empty-detector' signal is $42 \pm 13\%$
- Measurement of $\sigma(J/\psi J/\psi) = 24 \pm 9pb$ and $\frac{\sigma(J/\psi\psi(2S))}{\sigma(J/\psi J/\psi)} = 1.1^{+0.5}_{-0.4}$ in reasonably good agreement with subsequent theoretical calculation[3]
- Observed $J/\psi J/\psi$ mass spectrum in good agreement with shape (independent of renormalisation/factorisation scales) from MSTW08LO

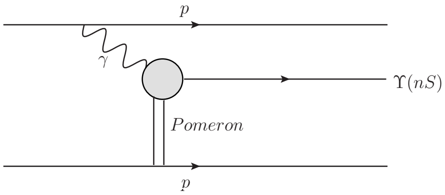


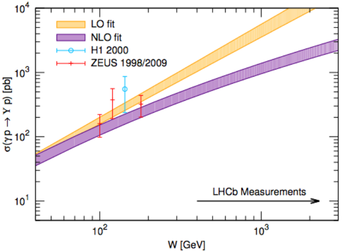
[3] arXiv:1409.4785

Production cross-section: $pp \to p(X)p$, $X = \{\Upsilon(1S), \Upsilon(2S), \Upsilon(3S)\}$; $(d\sigma(\Upsilon(1S)/dy)$

Motivation

- Occurs by photoproduction
- Perturbatively calculable; sensitive to $g(x)^2$ down to $x = 1.5 \times 10^{-5}$
- Compare to predictions at LO and NLO (diverge greatly in this kinematic regime)
- Compare to different models for Υ wavefunction and t-channel exchange (PLB 742 172)
- LHCb probes a new kinematic region ($W_\pm = \sqrt{M_\Upsilon \sqrt{s} e^{\pm y}}$: photon-proton c.m. energy)



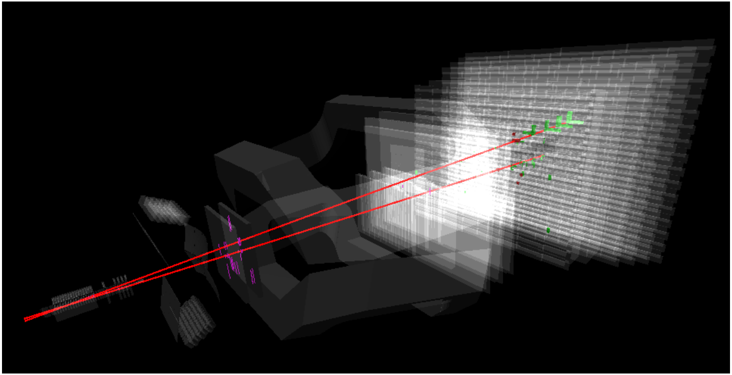


Data set: 2.9 fb^{-1} pp collisions, at 7 and 8 TeV

3) Exclusive $\Upsilon(nS)$ $(n = 1, 2, 3)$ production

Selection very similar to that for J/ψ analysis

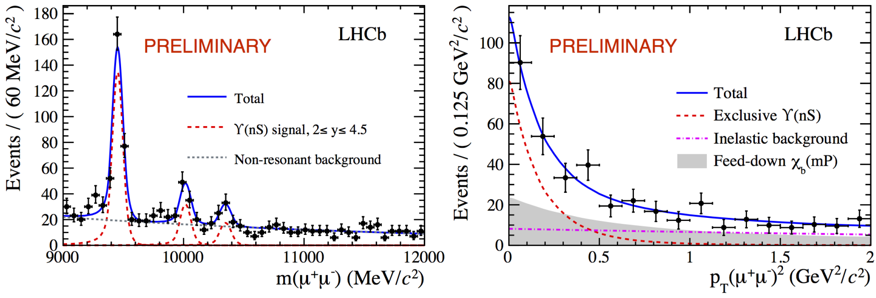
- Two well-reconstructed muons, with invariant mass between 9 and 20 GeV
- No other forward or backward tracks



Candidate: 06:57, July 29th 2011. Mass 9457 MeV$/c^2$ and $p_T^2 = 0.2$ GeV$^2/c^2$

Two-stage fitting procedure

- Invariant mass distribution: isolate continuum dimuon production
- Determine background contamination from $\chi_b \to \Upsilon\gamma$ feed-down in data
- p_T^2 distribution: inelastic background has a harder spectrum
  - Exclusive signal and χ_b background shapes modelled using SuperChiC



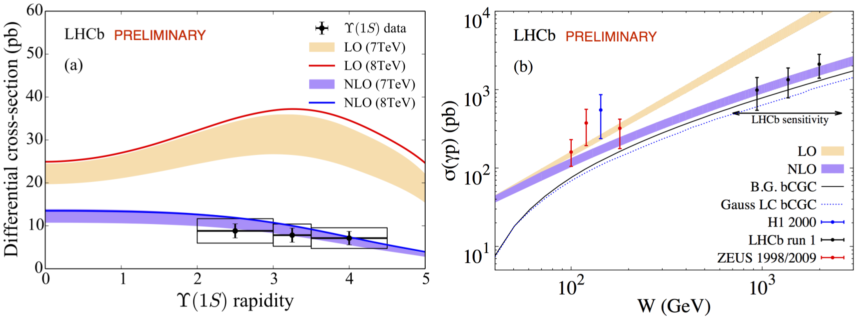
Efficiencies

- Correct using simulated samples: trigger and reconstruction ~80% efficient
- Event-level requirements imply single-interaction events only: 20% of Run-I data

3) Exclusive $\Upsilon(nS)$ $(n = 1, 2, 3)$ production (LHCb-PAPER-2015-011)

Systematic uncertainties

- Largest uncertainties due to description of χ_b background p_T^2 behaviour
- Subdominant contribution from description of exclusive signal
- Installation of forward shower counters for Run-II will have a great impact!

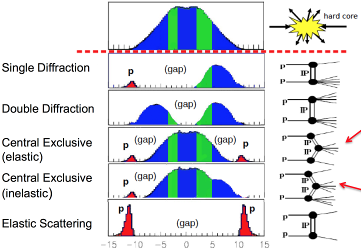


Results

- Compare rapidity distribution with predictions at LO and NLO (JHEP 1311 085)
- Extract underlying photon-proton cross-section and compare to different models
- NLO predictions agree well; slight preference for B.G. model of Υ w.f. (PLB 742 172)

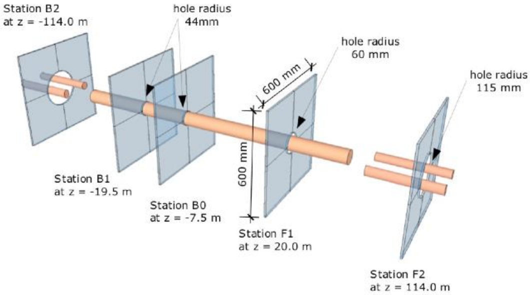
Extending LHCb rapidity coverage

- Biggest challenge currently is to establish the rapidity gap
- High proportion (50% for $J\psi J\psi$ CEP) of 'empty-detector' signal where proton dissociation escapes down the beampipe
- Expecting large run 2 data set at low pile-up



Install scintillators either side of LHCb

- Detect showers from high rapidity particles interacting with the beam-pipe elements



Summary

Exciting opportunities for CEP studies at LHCb

- **Forward acceptance** provides unique window on CEP and other diffractive physics
- **Spectroscopy** in a very clean environment
- **QCD studies**
  - very low-x gluon PDF
    - increased $\sqrt{s}$ allows probing of even lower x (CEP $J/\psi \rightarrow x = 2 \times 10^{-6}$)
  - behaviour of QCD in transition from non-perturbative to perturbative regime
  - search for glueballs, odderons, tetraquarks
- **Run 1**:
  - completed analyses: $J\psi/\psi(2S)$, double-charmonium CEP, $\Upsilon(nS)$
  - many more analyses would be interesting in future: $X(3872)$, light resonances, double open-charm, χ_c, χ_b...
  - exploit pA data
- **Introduction of FSCs** will greatly enhance LHCb's CEP programme