Quarkonium and charmed baryon production at LHCb

Ronan McNulty (UCD Dublin)
on behalf of the LHCb collaboration

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Overview

• LHCb
  • Charmed baryons
    • Observation of $\Xi^{++}_{cc}$. Measurement of branching fractions and lifetime.
    • Lifetime of $\Omega^0_c$
  • Quarkonium production
    • $J/\psi$ and $Y$ inclusive in $pp$
    • $J/\psi$ and $\psi(2S)$ exclusive in $pp$, PbPb
• Summary
The LHCb detector

Fully instrumented from 2 < η < 5
Trigger on muons p_T > 400 MeV, and on J/ψ p_T > 0 MeV.
Precise vertex reconstruction. Excellent particle identification
Data-taking 2010-2018

typically 1.1 pp interactions per beam-crossing

LHCb Integrated Recorded Luminosity in pp, 2010-2018

Run1 (2010-2012): $\sqrt{s} = 7,8$ TeV (pp)
Run2 (2015-2018) : $\sqrt{s} = 13$ TeV (pp)
Also $pA$, $AA$, and fixed target
Double-charmed Baryons

Weak decay expected for ground states of $\Xi^{+}_{ccd} \Xi^{++}_{ccu} \Omega^{+}_{ccs}$

Predictions
- Mass $\sim 3500$-3700 MeV
- Few MeV mass splitting $\Xi^{+}_{ccd} / \Xi^{++}_{ccu}$
- $\tau(\Xi^{++}) \sim 200$-700 fs
- $\tau(\Xi^{+}) \sim \tau(\Omega^{+}) \sim 50$-250 fs

(To be continued...)

Strong/EM decays for excited $\Xi^{+}_{ccd} \Xi^{++}_{ccu} \Omega^{+}_{ccs}$
Search for $\Xi^{++}_{cc}$

**History**

SELEX (2002) observe (6.3σ) in $\Lambda_c^+ K^- \pi^+$ (4.8σ in $D^+ K^- p^+$): Mass $\sim 3520$ MeV, $\tau < 33$ fs

FOCUS and BaBar: no evidence.

2013 LHCb (0.65 fb$^{-1}$) no evidence

$$R = \frac{\sigma(\Xi^{++}_{cc}) \times BF(\Xi^{++}_{cc} \rightarrow \Lambda_c^+ K^- \pi^+)}{\sigma(\Lambda_c^+)}$$

R < 0.013 for $\tau(\Xi^{++}_{cc}) = 100$ fs

R < $3.3 \times 10^{-4}$ for $\tau(\Xi^{++}_{cc}) = 400$ fs

(not inconsistent with SELEX)
Search for $\Xi^{++}_{cc}$

**History**

SELEX: hep-ex/0702001, Charm 2007

6.3$\sigma$ excess in $\Lambda_c^+K^-\pi^+\pi^-$, Mass~3520 MeV

Candidate in $\Xi_c^+\pi^+\pi^+\pi^-$, Mass~3452 MeV

LHCb $(1.7 fb^{-1}, \sqrt{s} = 13$ TeV$)$

$\Xi^{++}_{cc} \rightarrow \Lambda_c^+ K^-\pi^+\pi^+$ decays with $\Lambda_c^+ \rightarrow pK^-\pi^+$

- Local significance $> 12\sigma$
- Resolution $6.6 \pm 0.8$ MeV (=detector resolution)
- Signal yield $313 \pm 33$
- Mass: $3621.40 \pm 0.72$(stat) $\pm 0.31$(sys) MeV
LHCb (1.7fb$^{-1}$, $\sqrt{s} = 13$ TeV)

Search in $\Xi^{++}_{cc} \rightarrow \Xi^{+}$ ($\rightarrow pK^-\pi^+$)$\pi^+$

- Strategy similar to $\Xi^{++}_{cc} \rightarrow \Lambda^{+}_c K^-\pi^+\pi^+$
  but more efficient due to fewer particles.
- Analysis performed blind, using MC and sidebands to optimise selection.
- Signal yield $91 \pm 20$
- Significance: 5.9 $\sigma$
- Mass: $3620.56 \pm 1.45$ (stat) $\pm 0.61$ (sys) MeV
- Agrees with observation in $\Xi^{++}_{cc} \rightarrow \Lambda^{+}_c K^-\pi^+\pi^+$

$$\mathcal{R}(B) = \frac{B(\Xi^{++}_{cc} \rightarrow \Xi^{+} \pi^+) \times B(\Xi^{+} \rightarrow pK^-\pi^+)}{B(\Xi^{++}_{cc} \rightarrow \Lambda^{+}_c K^-\pi^+\pi^+) \times B(\Lambda^{+}_c \rightarrow pK^-\pi^+)}$$

$$= 0.035 \pm 0.008 \text{ (stat)} \pm 0.003 \text{ (sys)}$$
Lifetime of $\Xi^{++}_{cc}$

Peak remains after requiring inconsistency with primary vertex.

Measure:

$$\Xi^{++}_{cc} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^-$$
$$\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^- \pi^+ \pi^-$$

$$\tau(\Xi^{++}_{cc}) = 256^{+22}_{-20} (\text{stat}) \pm 14 (\text{sys}) \text{fs}$$

weakly decaying!
Comparison of theory and experiment

Tricky but possible to reconcile both signals e.g. \texttt{arXiv:1709.09903}

Future for LHCb: Measure other decay modes of $\Xi^{++}$ and observe $\Xi^+$
Omega Baryon Lifetime

arXiv: 1807.02024

Test of HQE but note spin of spectators and c→Ws interference

Compare

\[ \Omega_c^0 \rightarrow pK^-K^+\pi^- \]

in b meson/baryon decays

Much larger (and cleaner) signal than previous experiments
Omega Baryon Lifetime

Summary of Omega lifetime measurements

Dominant systematic is MC stats

... something to understand theoretically in determining hierarchy of lifetimes.
Inclusive quarkonia production

J/ψ hadroproduction is not completely understood - cross-section, pT dependence, polarisation

Prompt: direct and charmonia feed-down

J/ψ from-b
(better theoretical agreement)

Y hadroproduction: heavier mass should give better agreement with NRQCD predictions

\[ d\sigma[pp \rightarrow H + X] = \sum_{i,j,n} dx_1 dx_2 G_p^i G_p^j \times d\hat{\sigma}[ij \rightarrow (Q\bar{Q})_n X] \langle \vartheta^H_n \rangle \]

intermediary states
long-distance matrix elements

LHCb: more data at new energies and forward rapidities.
Compare ratios to remove experimental and theoretical uncertainties
Examine in different productions modes: pPb PbPb and compare to other quarkonia e.g. \( \chi_c, \eta_c, J/\psi J/\psi \) etc (not covered in this talk)
J/Ψ in pp at 13 TeV with 3pb⁻¹

\[ \sigma(\text{prompt } J/\psi, p_T < 14 \text{ GeV}, 2.0 < y < 4.5) = 15.03 \pm 0.03 \pm 0.94 \mu b \]

\[ \sigma(\text{J/ψ-from-}b, p_T < 14 \text{ GeV}, 2.0 < y < 4.5) = 2.25 \pm 0.01 \pm 0.14 \mu b \]

\[ \sigma(pp \rightarrow b\bar{b}X) = 495 \pm 2 \pm 52 \mu b \]
J/Ψ in pp at 13 TeV with 3pb⁻¹

full double differential distributions as fn of $p_T$ and rapidity in paper
Y in pp at 13 TeV with 277 pb$^{-1}$

JHEP 07(2018)134

Full double differential distributions in paper
J/Ψ and Υ in pp: ratio of 13/8 TeV

Quarkonium and double charged baryon production at LHCb
Motivation: Photo-production of vector mesons (at HERA)

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

Here QCD works nicely!

Note:
- soft/hard transition
- \( \sigma \sim x^\lambda \)
- \( g(x, Q^2) \)
  (down to \( x=2E-6 \))

Quarkonium and double charged baryon production at LHCb

JHEP 11 (2013) 085
Central Exclusive Production (CEP)

Laboratory to study
- physics of the vacuum
- soft/hard QCD
- saturation
- exotics (tetraquarks, glueballs, hybrids)

Experimentally: Reconstruct central system and identify rapidity gaps
Elastic Scattering
Single Diffraction
Double Diffraction
Central Exclusive Production (elastic)
Central Exclusive Production (inelastic)

Veto (Run 2)

Rough LHCb coverage 13 TeV
High Rapidity Shower Counters at LHCb (HeRSCheL)

JINST 13 (2018) P04017

arXiv:1806.04079

“Activity in HeRSCheL”
J/ψ and ψ(2S) candidate

Tag with Herschel

Anti-Tag with Herschel

\[ \frac{d\sigma}{dt} \sim \exp(b_{sig} t) \]

\[ b_{sig} \sim 6 \text{ GeV}^{-2} \]

\[ \frac{d\sigma}{dt} \sim \exp(b_{sig} t) \]

\[ b_{sig} \sim 1 \text{ GeV}^{-2} \]

LHCb \ (\sqrt{s}=13 \text{ TeV})

Proton dissociation

Feed-down

Nonresonant

Candidates per 0.04 GeV²

J/ψ \ p_T² [GeV²]

Candidates per 10 MeV

Mass(\mu^+\mu^-) [MeV]
Quarkonium and double charged baryon production at LHCb
**Pb-Pb collisions**

The photon comes from the (coherent) Pb nucleus

The pomeron comes from the nucleus -> Nuclear PDFs
Pb-Pb collisions

LHCb Preliminary
Pb-Pb $\sqrt{s_{NN}} = 5$ TeV

HeRSCheL suppresses incoherent events

Quarkonium and double charged baryon production at LHCb
Pb-Pb collisions

LHCb

$\Xi^{++}_{cc}$

$\Omega^0_c$

Inclusive $J/\psi$, $\Upsilon$

Exclusive $J/\psi$

Guzey et al.

LTA_W

LTA_S

EPS09

Goncalves et al

IP-SAT

IIM

Cepila et al.

GG-hs

GS-hs

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Quarkonium and double charged baryon production at LHCb
Summary

• A small selection of recent results
  • Charmed baryons
    • Observation of $\Xi^{++}_{cc}$. Measurement of branching fractions and lifetime.
    • Lifetime of $\Omega^0_c$
  • Quarkonium production
    • $J/\psi$ and $Y$ inclusive in $pp$
    • $J/\psi$ exclusive in $pp$, $PbPb$

• More information at http://lhcbproject.web.cern.ch/lhcbproject/Publications/LHCbProjectPublic/Summary_all.html
Sample 1: Response to CEP events

First bin is > 95% pure CEP QED di-muons.
Sample 2: Non-CEP events ($J/\psi$ dissociation)

Quarkonium and double charged baryon production at LHCb