LHCb measurements on soft particle productions including heavy flavour

heavy quark hadroproduction - from collider to astroparticle physics

Albert Frithjof Bursche[1], on behalf of the LHCb collaboration.

1st October 2019

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1. *precision from pQCD*
   - inclusive vector bosons
2. *QCD resummation needed*
   - vector bosons with jets
3. *multi parton interactions*
4. *diffractive production*
   - 2015 preliminary ultraperipheral J/ψ
5. *charmonium puzzle*
6. *hadronisation*
7. *open heavy flavour*
8. *open double heavy flavour*

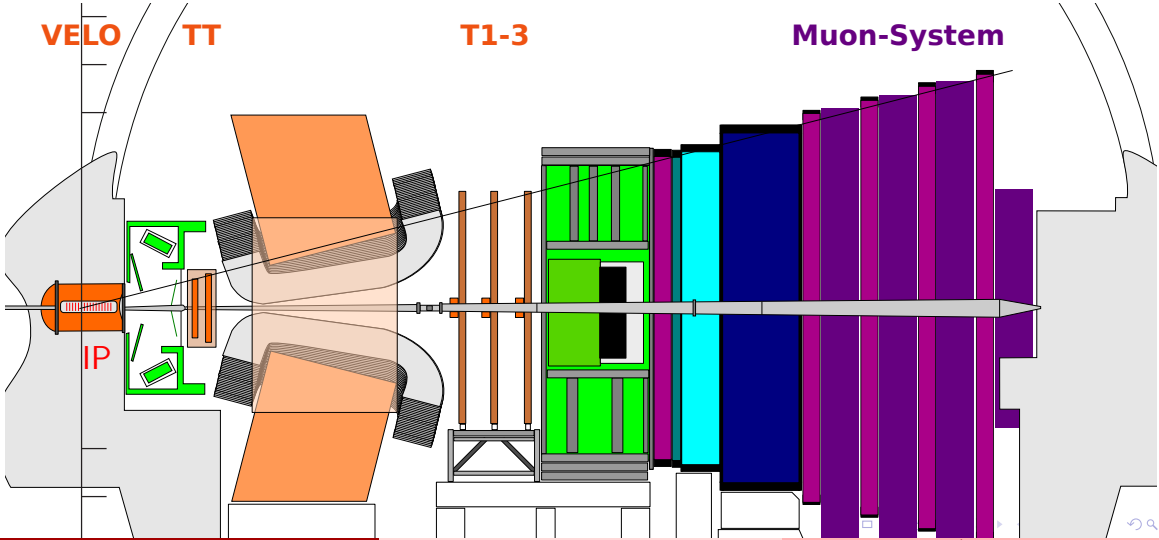
This talk is intended to show as many LHCb results as possible. Some are well modelled others not so much. I have to make a selection since there are currently 493 papers published by the LHCb collaboration. The full list is here. I recommend to have a look at this list. My selection is strongly biased by my personal interest.

What is needed to describe LHCb data?

- Some data are well described by collinear factorisation together with hadron fragmentation.
- Other data also need parton showers and resummation of the logarithms.
- The general picture it that the theory description is difficult for the processes that have more than two partons in the initial state or more than one parton fragmenting.

I try to briefly touch a variety of our results to highlight these.

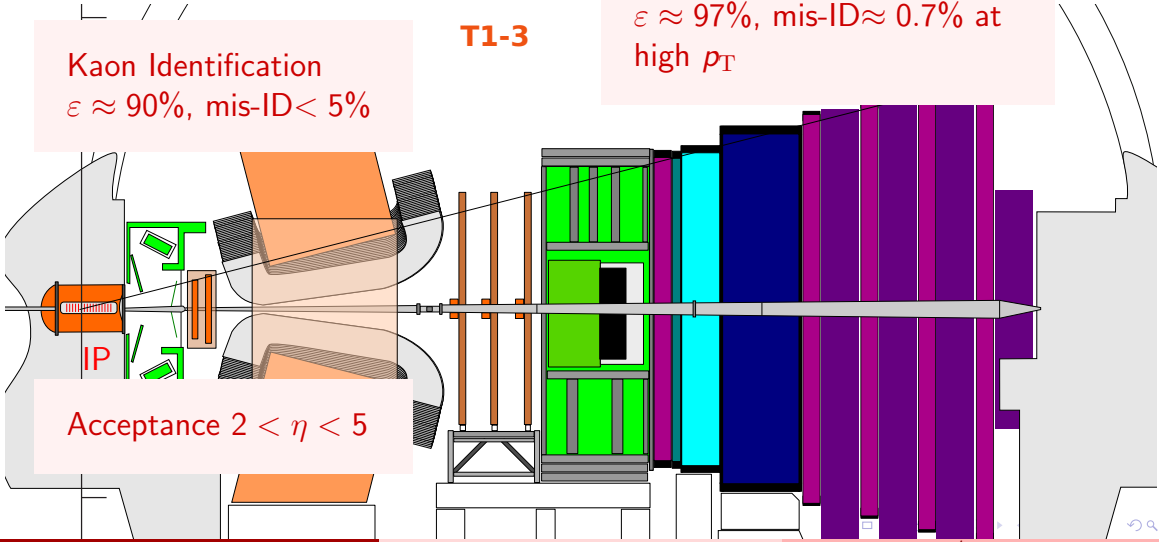
LHCb experiment



LHCb experiment

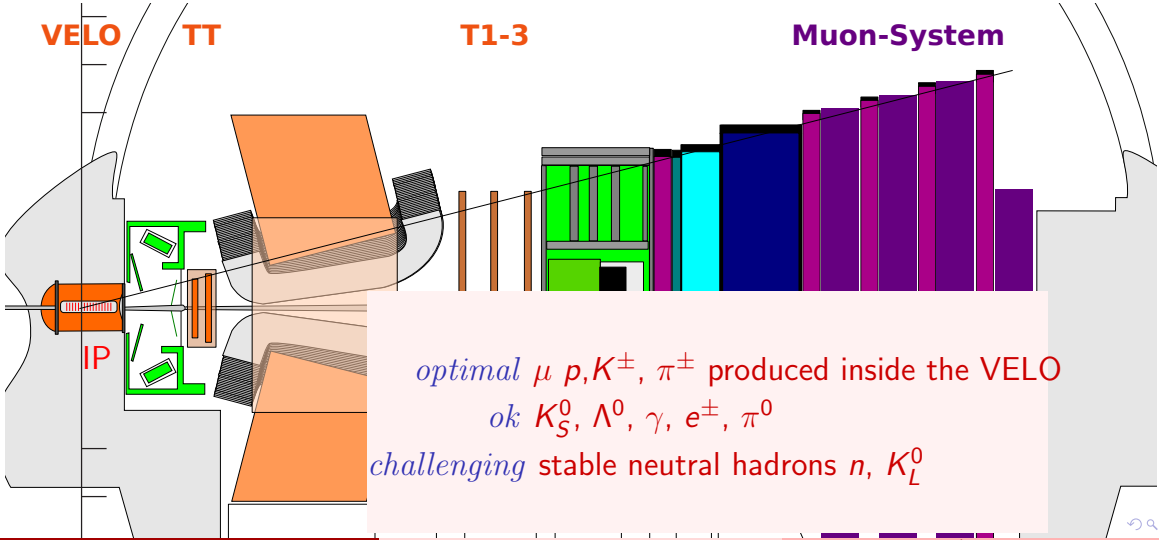
Kaon Identification
$\varepsilon \approx 90\%$, mis-ID$< 5\%$

Muon Identification
$\varepsilon \approx 97\%$, mis-ID$\approx 0.7\%$ at high p_{T}



Acceptance $2 < \eta < 5$

LHCb experiment



optimal μ p,$K^{\pm}$, $\pi^{\pm}$ produced inside the VELO

ok K^0_S, Λ^0, γ, $e^{\pm}$, π^0

challenging stable neutral hadrons n, K^0_L

available data

proton collisions

Large samples at 7,8 and 13 TeV,
smaller samples at 0.9, 2.76 and 5 TeV

protons on lead ions

$1\,\mathrm{nb}^{-1}$ at 5 TeV and $10\,\mathrm{nb}^{-1}$ at 8.1 TeV

lead ions

Two samples from 2015 and 2018 of about $200\,\mu\mathrm{b}^{-1}$

xenon ions

Few hours of data taking with a low intensity beam.

beam on gas (fixed target)

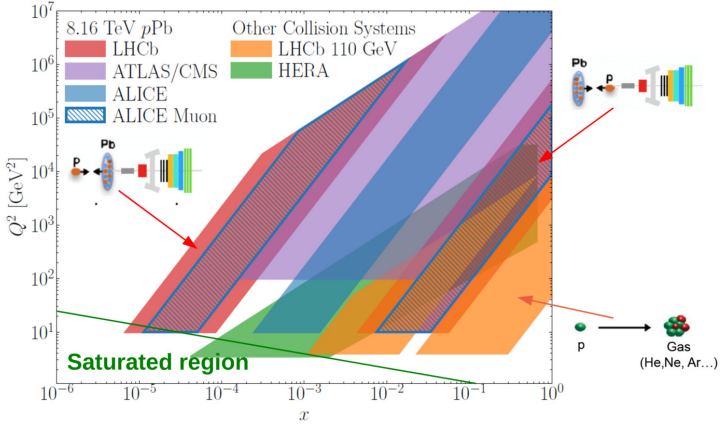
beam	gas	$\sqrt{s}$
p	Ne	110 GeV
p	He	110 GeV
p	Ar	110 GeV
Pb	Ar	69 GeV
p	He	110 GeV
p	He	86.6 GeV
p	Ne	110 GeV
Pb	Ne	69 GeV

Upgraded gas cell scheduled for installation this fall.

Increase gas pressure by two orders of magnitude.

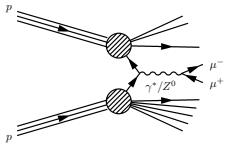
perturbative QCD

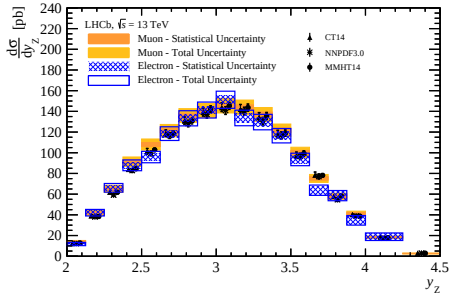
J.Phys.Conf.Ser. 1271 (2019) no.1, 012008



Z boson production

JHEP 09 (2016) 136





- Results at 7, 8 and 13 TeV and in p lead at 8.1 TeV
- PDFs already include the previous LHCb results
- Collinear factorisation is working perfectly for the fully inclusive quantities
- For a description of ϕ^* and boson p_{T} resummation of parton showers are needed

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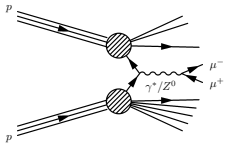

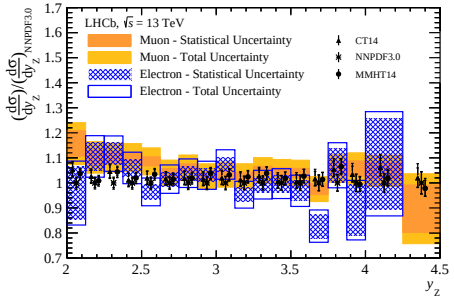

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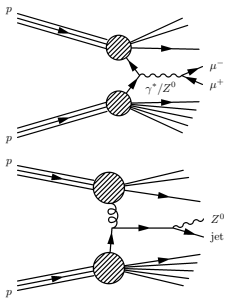

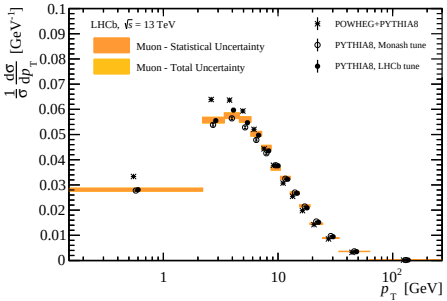

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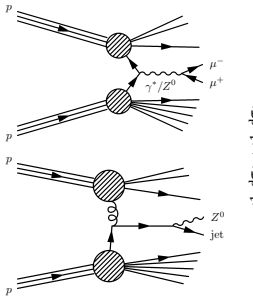

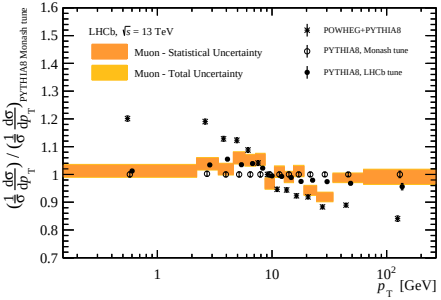

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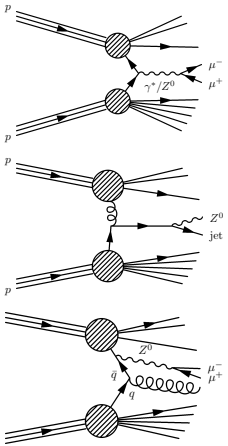
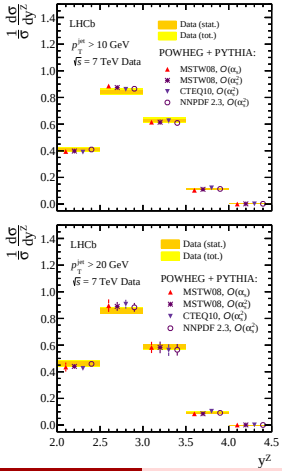
Z plus jet

JHEP 01 (2014) 33

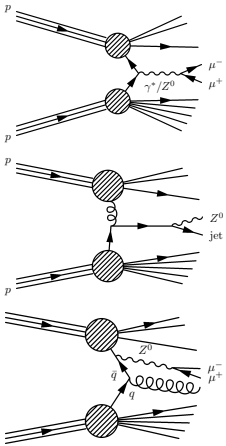


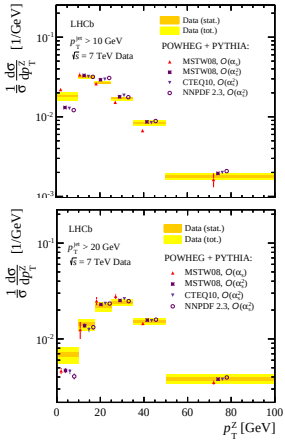


- Jets are $R = 0.5$ anti-k_T jets
- p_{T} thresholds are $10\,\mathrm{GeV}$ and $20\,\mathrm{GeV}$
- Description decent of the y distribution
- The low boson p_{T} distribution is poorly described

Z plus jet

JHEP 01 (2014) 33





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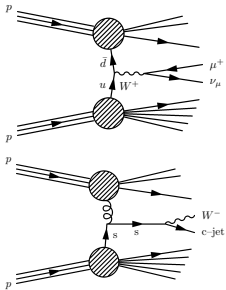
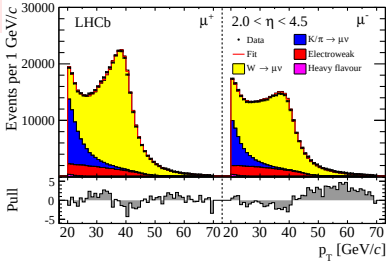
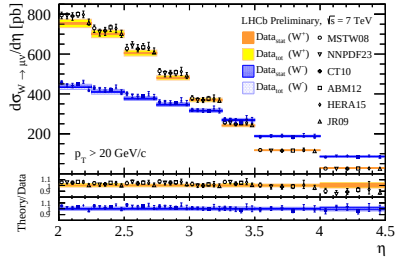
W boson production

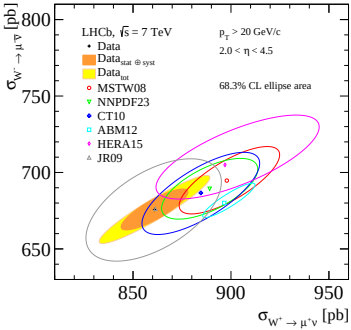
JHEP 12 (2014) 079





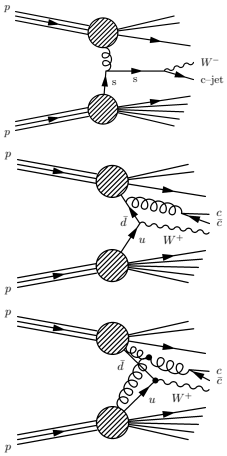


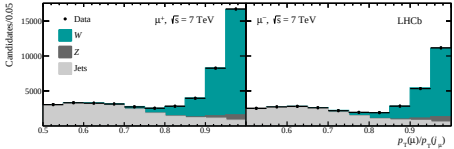
- Pythia reweighted to RESBOS
- Measurement based on muon properties



associated production of $W^{\pm}$ bosons with heavy jets

Phys. Rev. D92 (2015) 052001





- Use muon isolation to identify $W^{\pm}$ boson
- Two BDTs to separate light/heavy and beauty/charm jets
- 20 GeV jets, anti-k_T, $R = 0.5$

	Results		MCFM (CT10) prediction	
	7 TeV	8 TeV	7 TeV	8 TeV
$\frac{\sigma(Wb)}{\sigma(Wj)} \times 10^2$	$0.66 \pm 0.13 \pm 0.13$	$0.78 \pm 0.08 \pm 0.16$	$0.74^{+0.17}_{-0.13}$	$0.77^{+0.18}_{-0.13}$
$\frac{\sigma(Wc)}{\sigma(Wj)} \times 10^2$	$5.80 \pm 0.44 \pm 0.75$	$5.62 \pm 0.28 \pm 0.73$	$5.02^{+0.80}_{-0.69}$	$5.31^{+0.87}_{-0.52}$
$\mathcal{A}(Wb)$	$0.51 \pm 0.20 \pm 0.09$	$0.27 \pm 0.13 \pm 0.09$	$0.27^{+0.03}_{-0.03}$	$0.28^{+0.03}_{-0.03}$
$\mathcal{A}(Wc)$	$-0.09 \pm 0.08 \pm 0.04$	$-0.01 \pm 0.05 \pm 0.04$	$-0.15^{+0.02}_{-0.04}$	$-0.14^{+0.02}_{-0.03}$
$\frac{\sigma(W^+j)}{\sigma(Zj)}$	$10.49 \pm 0.28 \pm 0.53$	$9.44 \pm 0.19 \pm 0.47$	$9.90^{+0.28}_{-0.24}$	$9.48^{+0.16}_{-0.33}$
$\frac{\sigma(W^-j)}{\sigma(Zj)}$	$6.61 \pm 0.19 \pm 0.33$	$6.02 \pm 0.13 \pm 0.30$	$5.79^{+0.21}_{-0.18}$	$5.52^{+0.13}_{-0.25}$

forward top production

Phys. Rev. Lett. 115 (2015) 112001, JHEP 08 (2018) 174

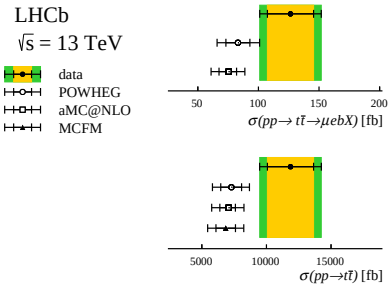
total cross section measurement (7 and 8 TeV)

$$\sigma_{t\bar{t}} = 239 \pm 53(stat) \pm 33(sys) \pm 24(theory)\text{fb}$$
$$\sigma_{t\bar{t}} = 289 \pm 43(stat) \pm 40(sys) \pm 29(theory)\text{fb}$$

beμ final state (13 TeV)

$$\sigma_{t\bar{t}} = 126 \pm 19(stat) \pm 16(sys) \pm 5(lumi)\text{fb}$$

All measurements are between 2 and 4.5 in rapidity.



multi parton interactions

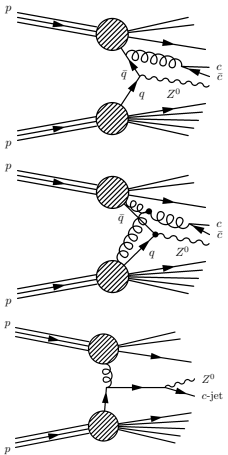
- Golden channel: same sign W production
- In LHCb: Same sign open charm, Double Quarkonia
- Often described as two independent scatterings

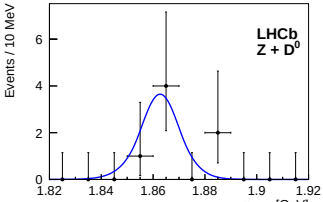
$$\sigma^{\mathrm{DPS}}_{C_1,C_2} = \alpha \frac{\sigma_{C_1}\sigma_{C_2}}{\sigma^{\mathrm{DPS}}_{\mathrm{eff}}}$$

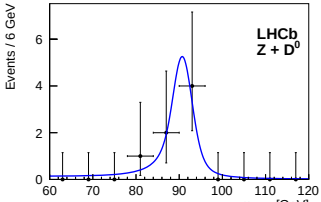
- Violates energy momentum conservation
- Not applicable in the presence of initial state correlations

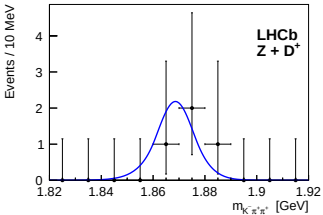
associated production of Z bosons with D mesons

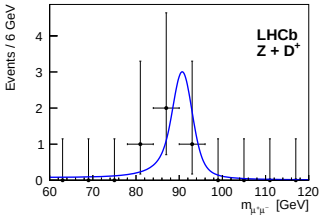
JHEP 04 (2014) 91



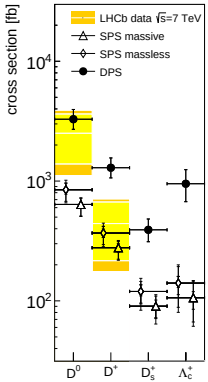






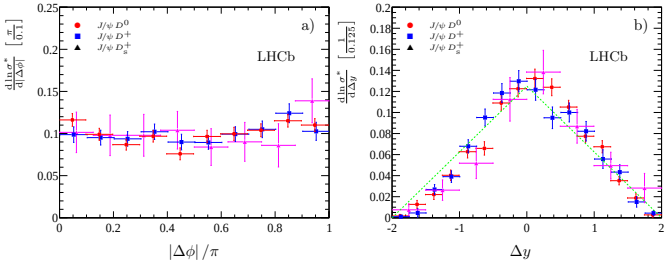


MCFM predictions

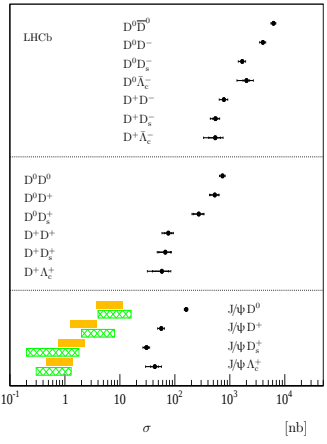


double charm

JHEP 06 (2012) 141, Addendum JHEP 03 (2014) 108



$$\sigma^{\mathrm{DPS}}_{C_1,C_2} = \alpha \frac{\sigma_{C_1}\sigma_{C_2}}{\sigma^{\mathrm{DPS}}_{\mathrm{eff}}} \qquad \mathcal{R}_{C_1,C_2} = \alpha' \frac{\sigma_{C_1,C_2}}{\sigma_{C_1}\sigma_{C_2}}$$



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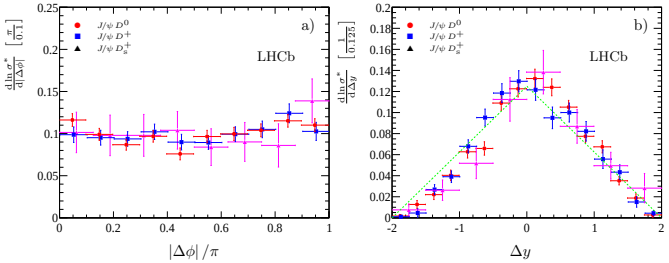

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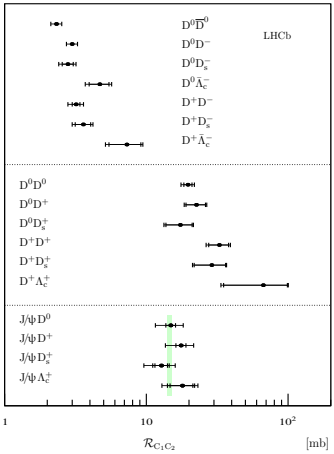
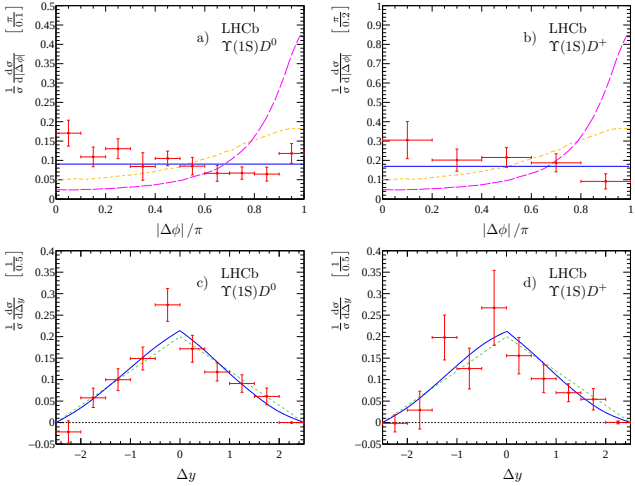
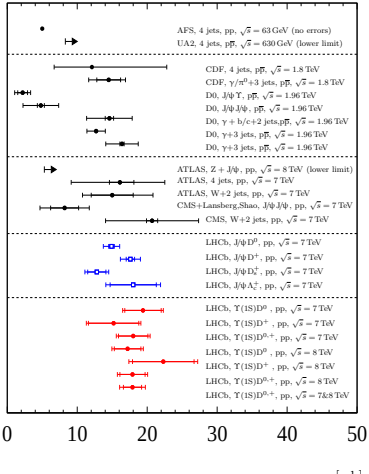


open charm and bottomonium

JHEP 07 (2016) 052

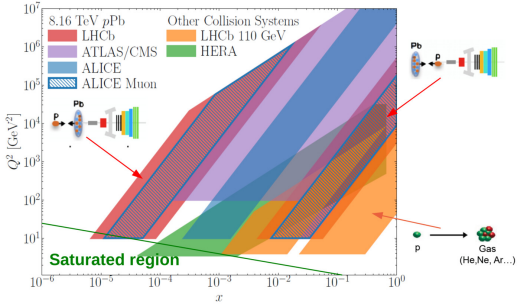
double J/ψ at 7 TeV and 13 TeV

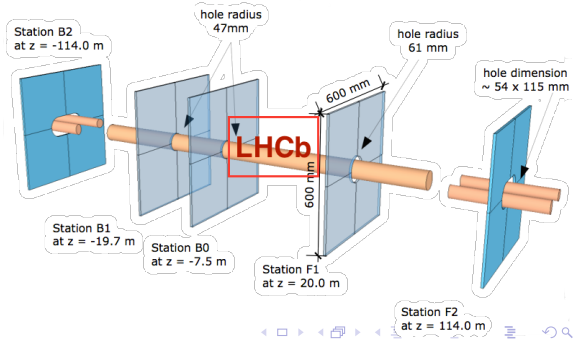




exclusive production

- Projectiles stay intact
- There can be no net colour exchange
- In LHCb mainly measurements of exclusive vector meson production and production of two exclusive pairs

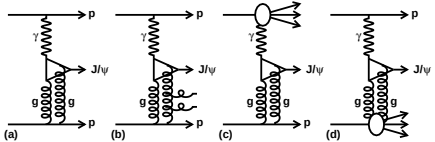




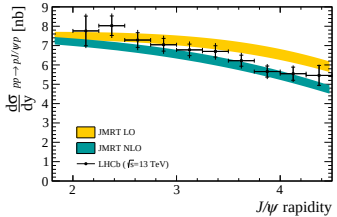
central exclusive production

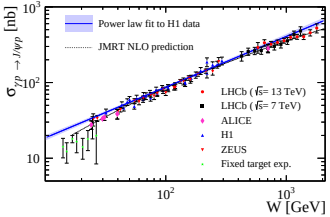
JHEP 10 (2018) 167

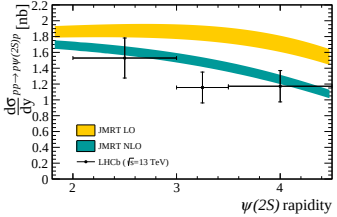
- 13 TeV data ($204 \pm 8\,\mathrm{pb}^{-1}$)
- also measured in 7 TeV data
- exclusive Υ also available

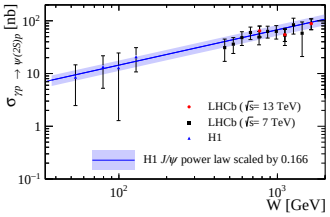


$$\sigma_{J/\psi} = 307 \quad \pm 21 \quad \pm 36 \quad \mathrm{pb}$$
$$\sigma_{\psi(2S)} = \quad 7.8 \pm \quad 1.3 \pm \quad 1.0\,\mathrm{pb}$$







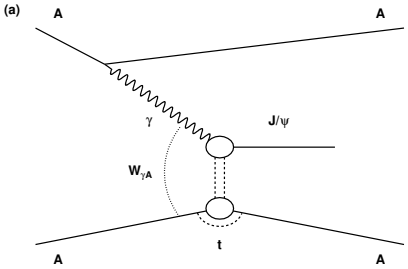


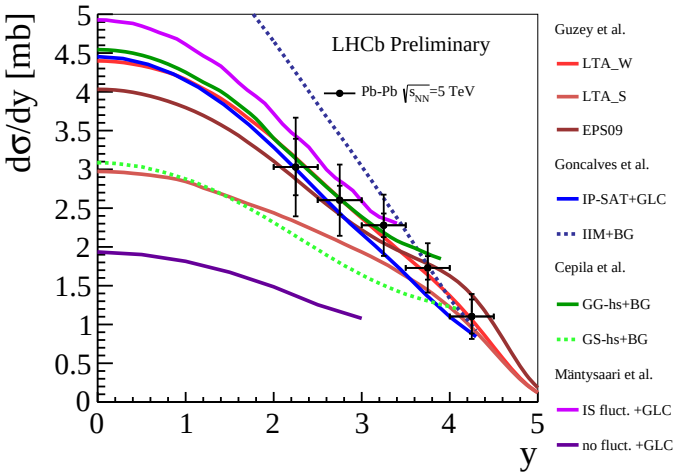
differential coherent cross section

LHCb-CONF-2018-003

LHCb preliminary

$$\sigma = 5.27 \pm 0.21_{stat} \pm 0.49_{sys} \pm 0.68_{lumi}\ \text{mb}$$





differential coherent cross section

LHCb-CONF-2018-003

LHCb preliminary

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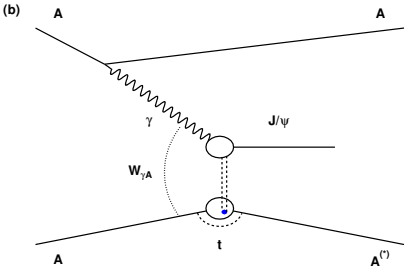

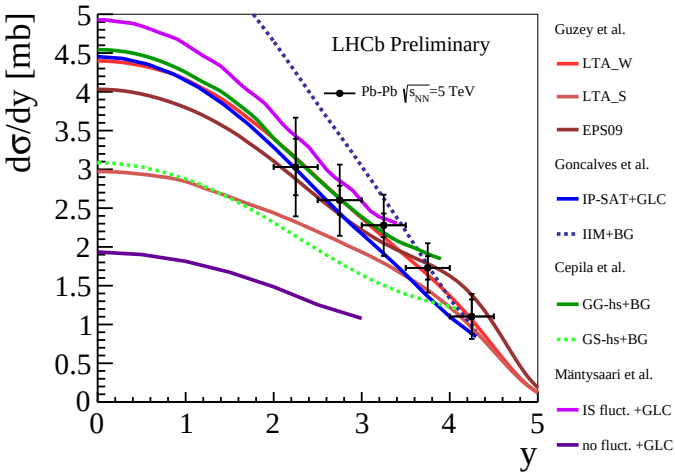

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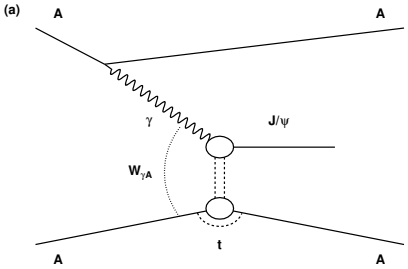
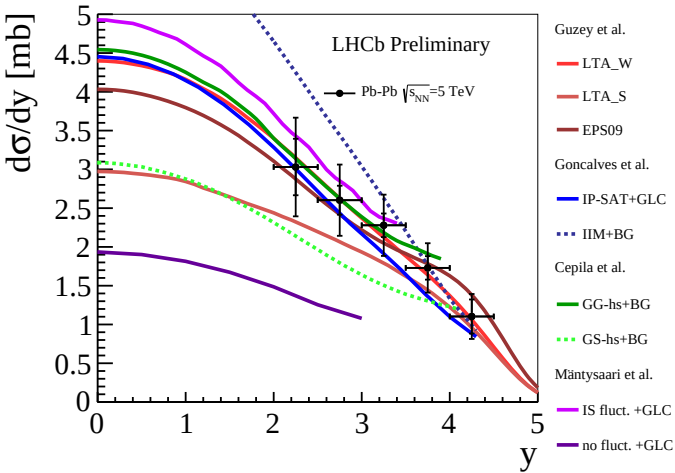


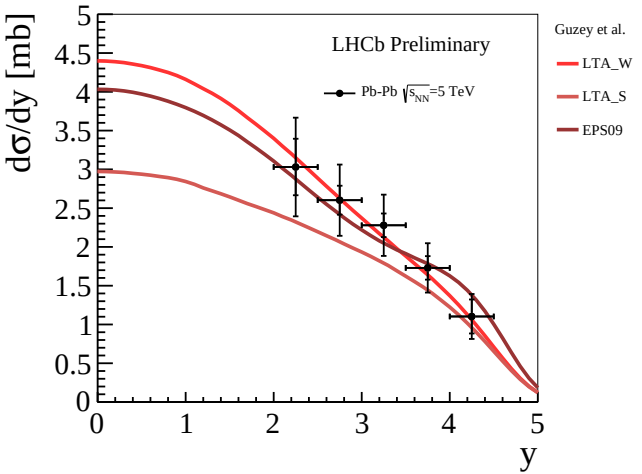


non relativistic QCD

LHCb-CONF-2018-003

- pQCD calculation
- leading order
- leading twist
  - EPS09 PDF
  - LTA_S strong nuclear shadowing
  - LTA_W weak nuclear shadowing

V. Guzey et. al.
Phys. Rev. C93 (2016) 055206

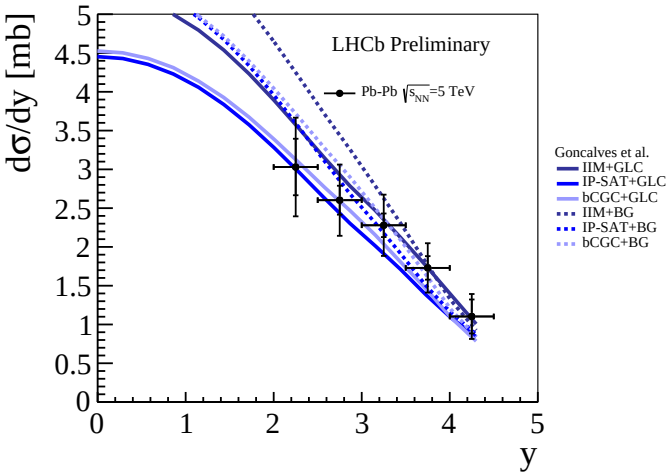


colour dipole model

LHCb-CONF-2018-003

- Three parametrisations for the dipole nucleon cross section
  - IIM
  - IP-Sat
  - CGC
- Two wavefunctions
  - Boosted Gaussian
  - Gauss LC

Gonçalves et. al.
Phys. Rev. D 96, 094027 (2017)



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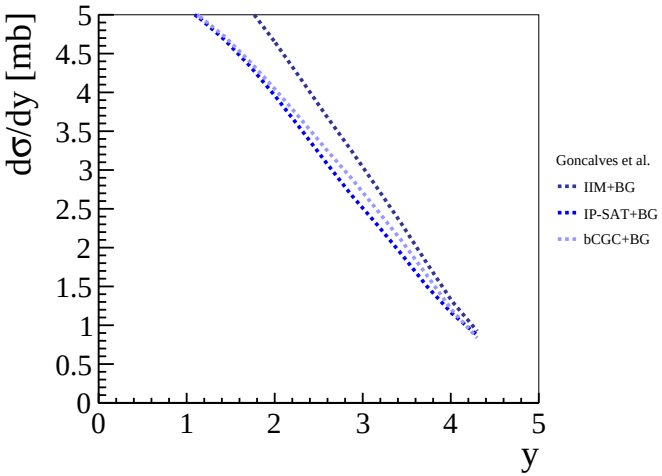

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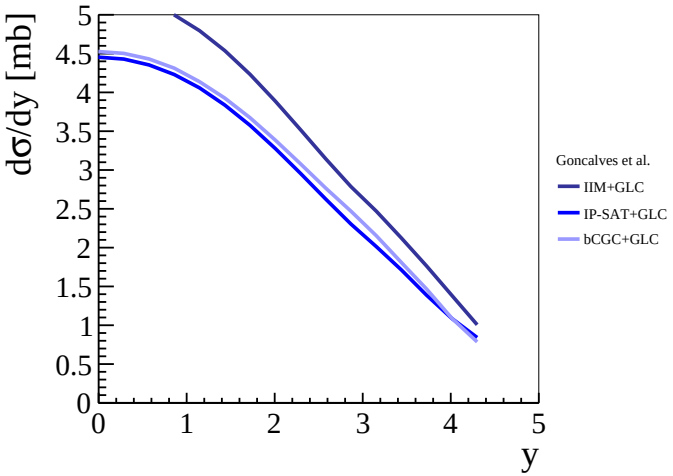

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LHCb-CONF-2018-003

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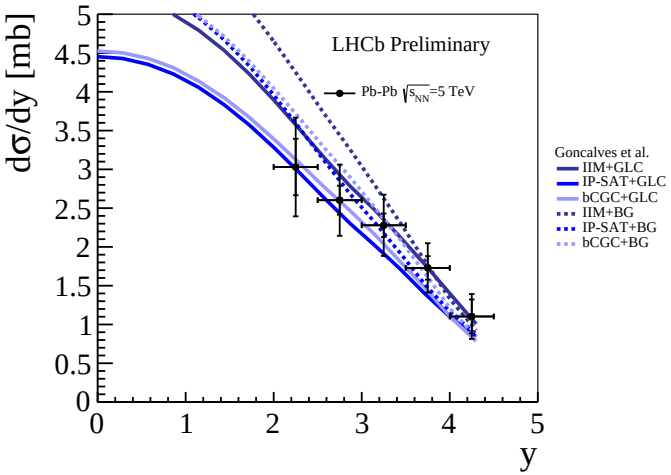
Gonçalves et. al.
Phys. Rev. D 96, 094027 (2017)

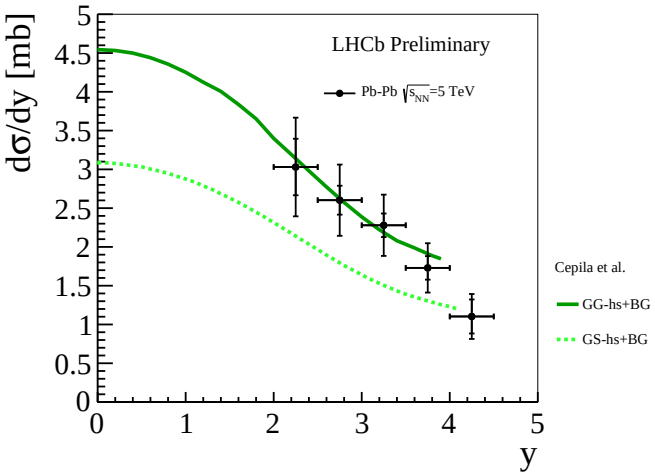


colour dipole model

LHCb-CONF-2018-003

- Similar Model
- Boosted Gaussian wavefunction
- Glauber Gribov methodology
- Geometric Scaling

J. Cepila et. al.
Phys. Rev. C97 (2018) 024901

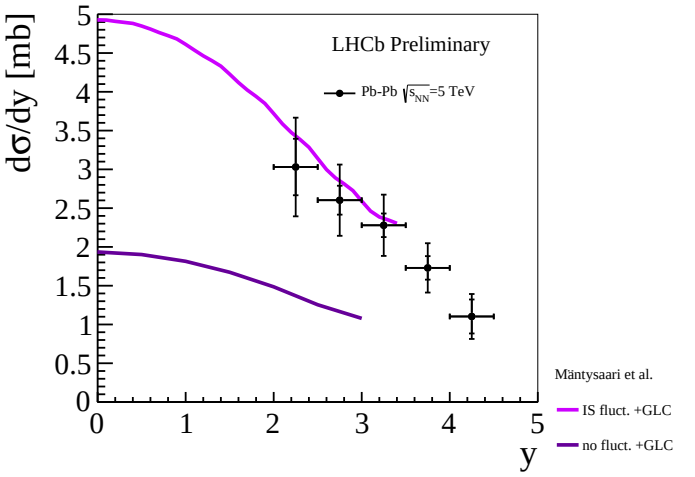


colour dipole model

LHCb-CONF-2018-003

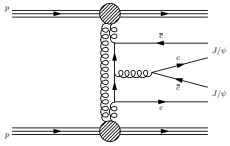
- IP-Sat with
- Gauss LC wavefunction
- Calculations with and without nuclear fluctuations

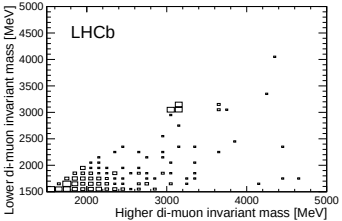
H. Mäntysaari, B. Schenke
Phys. Lett. B772 (2017) 832

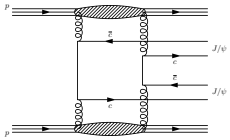


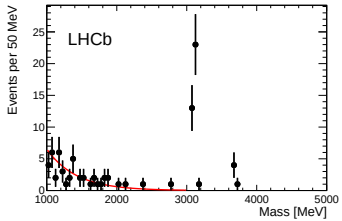
double central exclusive production

J. Phys. G41 (2014) 115002









exclusive DPS?

$$\sigma_{J/\psi\,J/\psi} = 58 \quad \pm 10(stat) \pm \ 6(sys)\,\text{pb}$$

$$\sigma_{J/\psi\,\psi(2S)} = 63 \quad {}^{+27}_{-18}(stat) \pm 10(sys)\,\text{pb}$$

- 7 TeV, 8 TeV data merged

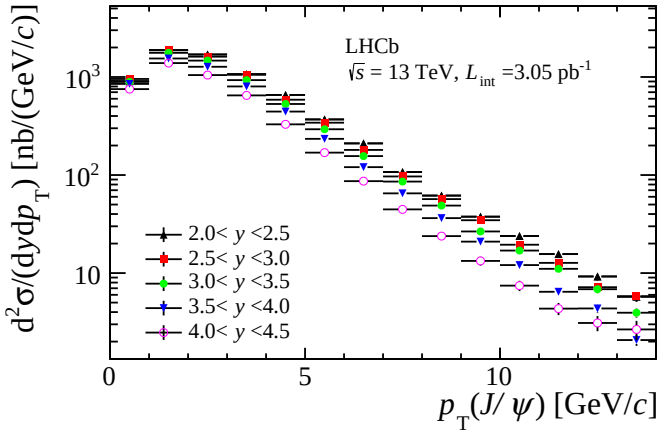
quarkonia

J/ψ is the main workhorse
but many other states are studied, $\psi(2S)$, η_c, χ_{c1}, χ_{c2}, $\chi_{c1}(3872)$, Υ, χ_b...

prompt inclusive J/ψ production cross section

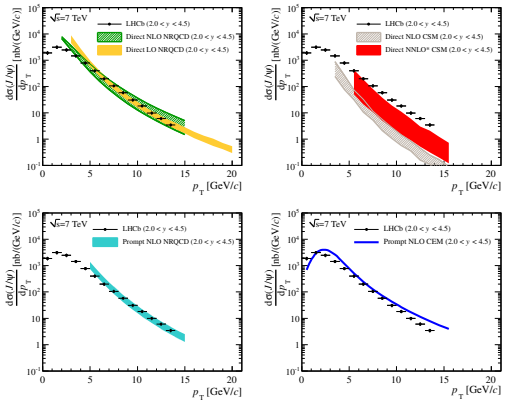
JHEP 10 (2015) 172

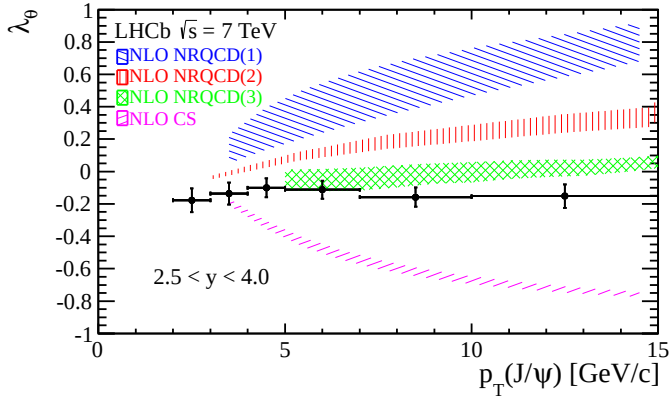
- protons
  - 2.76 TeV
  - 7 TeV
  - 8 TeV
  - 13 TeV
- proton lead
  - 5 TeV
  - 8.1 TeV
- fixed target
  - 86.6 GeV pHe
  - 110.4 GeV pAr



J/ψ production polarisation

Eur. Phys. J. C73 (2013) 2631, Eur. Phys. J. C71 (2011) 1645

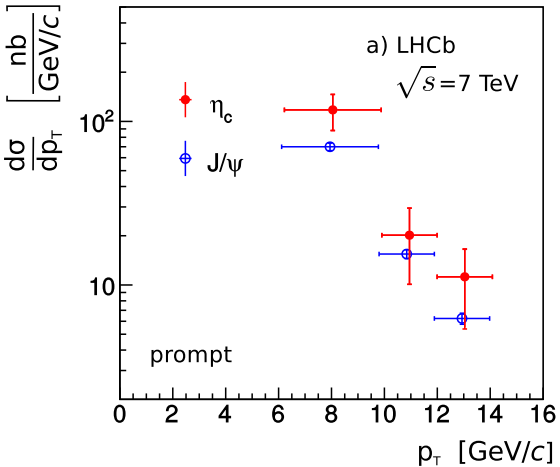


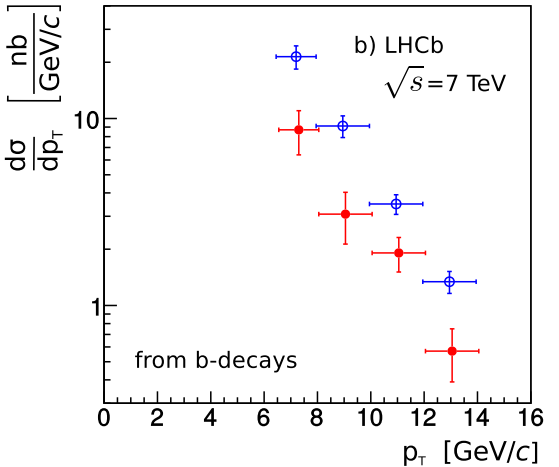


→ Υ (1S,2S,3S) polarisation at 7 and 8 TeV

prompt η_c production

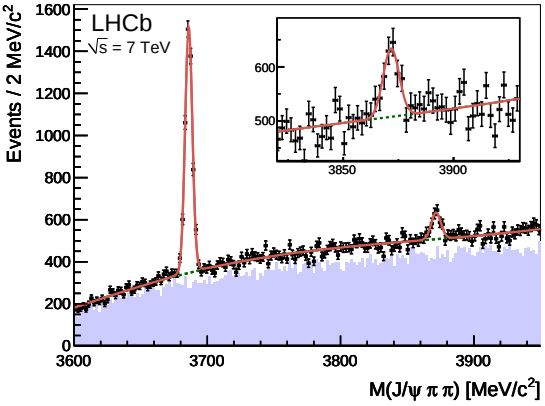
Eur. Phys. J. C75 (2015) 311





prompt production of $\chi_{1c}(3872)$

Eur. Phys. J. C72 (2012) 1972



other quarkonia measurements

- Υ xsec (2.76 TeV, 5 TeV (pPb), 7, TeV, 8 TeV) polarisation (7 TeV, 8 TeV)
- $\psi(2S)$ xsec (7 TeV, 13 TeV) polarisation (7 TeV)
- χ_{c0},χ_{c1},χ_{c2} relative prompt rate and production fraction with respect to J/ψ (7 TeV)
- fraction of Υ from $\chi_b(1P)$

$$\sigma_{\chi_{c1}(3872)}\mathcal{B}_{\chi_{c1}(3872)\to J/\psi\,\pi^+\pi^-} = 5.4 \pm 1.3(stat) \pm 0.8(sys)\,\mathrm{nb}$$

soft particle production

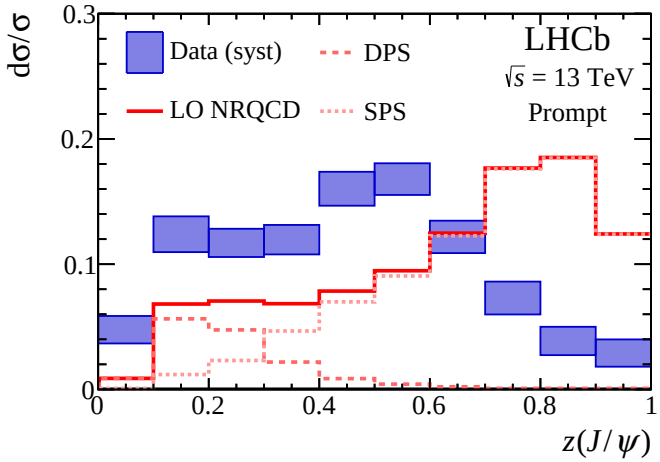
- Collinear factorisation only tells about fully inclusive results
- A full description of an event has to include all particles produced

J/ψ production in jets

Phys. Rev. Lett.118.192001

- prompt production not described by Pythia 8.1
- J/ψ from b are well described

$$z = \frac{p_{\mathrm{T}\,J/\psi}}{p_{\mathrm{T}\,\mathrm{jet}}}$$



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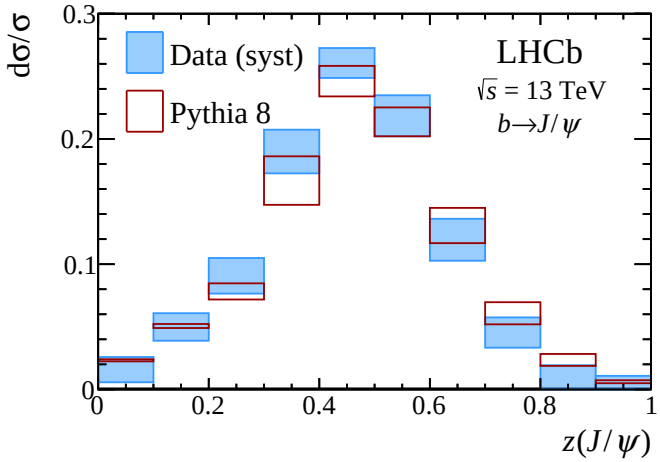
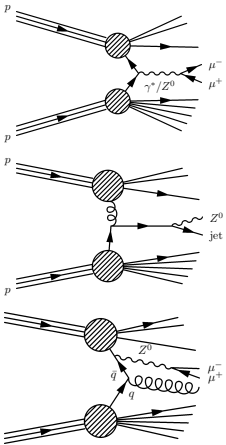
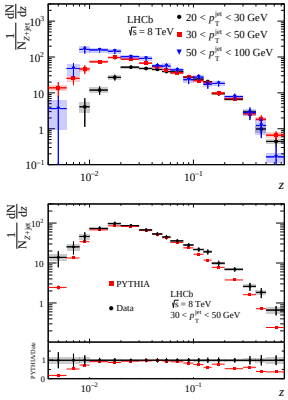


charged hadron production in Z-tagged jets

arxiv:1904.08878 submitted to PRL





- Measurement at 8 TeV
- Fair description from Pythia
- Three jet momentum bins

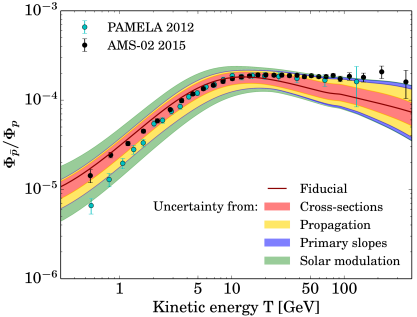
$$z = \frac{p_{\mathrm{T\,hadron}}}{p_{\mathrm{T\,jet}}}$$

anti protons in proton Helium collisions

Phys. Rev. Lett. 121 (2018) 222001

- Some excitement in 2015 about AMS/Pamela data
- This measurement improved the description of the anti-protons during the propagation or CR
- New analysis shows the data are consistent with anti-protons from propagation only

2015



JCAP 1509 (2015) 023

see also

anti protons in proton Helium collisions

Phys. Rev. Lett. 121 (2018) 222001

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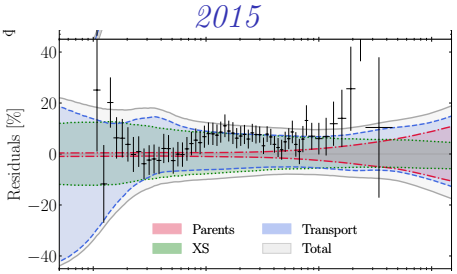


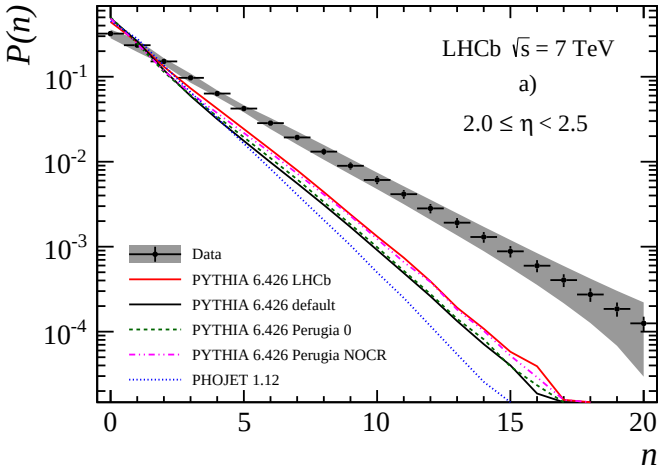
JCAP 1509 (2015) 023
arXiv:1906.07119 (2019)

see also

charged particle multiplicity

Eur. Phys. J. C74 (2014) 2888

- Double differential measurement of charged particle multiplicity
- General picture is that most generators underestimate the particle multiplicity
- $p > 2\,\mathrm{GeV}$, $p_\mathrm{T} > 200\,\mathrm{MeV}$



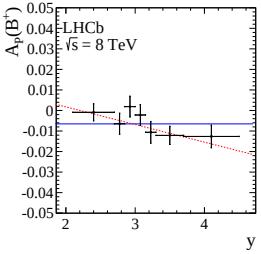
open heavy flavour production

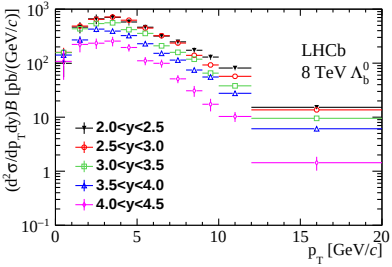
- In principle described by pQCD
- Can probe very low-x
- In LHCb: Measurements of open heavy flavour mesons, baryons and jets

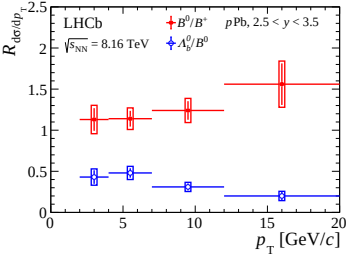
B^0, $B^\pm$, B_s^0 and Λ_b^0 production

Phys. Lett. B774 (2017) 139, Chin. Phys. C 40 (2016) 011001, Phys. Rev. D99 052011 (2019)

- production asymmetry: B^0, $B^\pm$, B_s^0 and Λ_b^0 (7 TeV, 8 TeV)
- production cross section: B^0, Λ_b^0 (7 TeV, 8 TeV) B^+, B^0, Λ_b^0 (8.1 TeV pPb), B^+ 7 TeV, 13 TeV



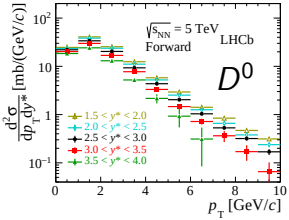


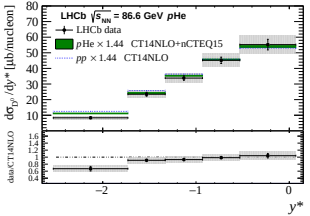


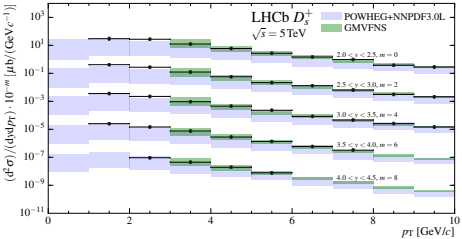
D^0, $D^{\pm}$, D^*, D_s^+ and Λ_c^+ production

JHEP 10 (2017) 090 , Phys. Rev. Lett. 122 (2019) 132002, JHEP 06 (2017) 147

- production cross section: D^0 5 TeV pPp; D^0, D^+, D_s^+, D^* 5 TeV pp; D^0, D^+, D^*, D_s^+, Λ_c^+ 7 TeV; D^0, D^+, D_s^+, D^* 13 TeV; D^0 86.6 GeV pHe and 110.4 GeV pAr
- production asymmetry: $D^{\pm}$ 7 TeV $D_s^{\pm}$ 7 TeV, 8 TeV



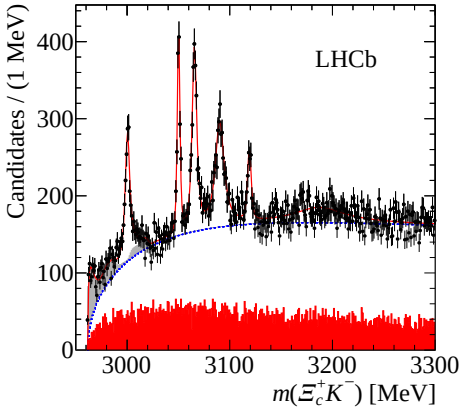




more open heavy flavour

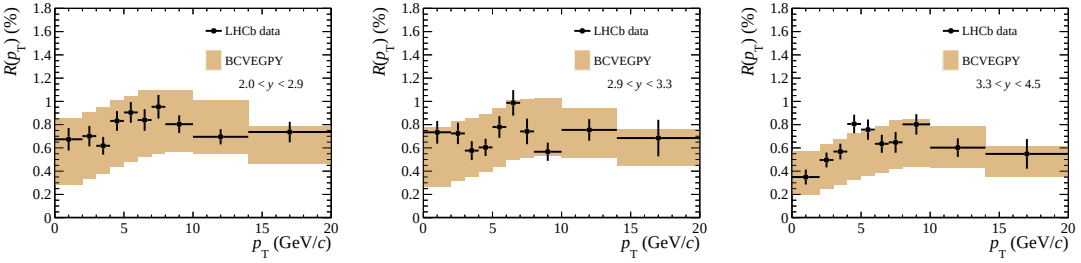
Phys. Rev. Lett. 118 (2017) 182001, Phys. Rev. Lett. 114 (2015) 062004, Phys. Lett. B736 (2014) 154

- production fractions PAPER-2018-047 (Ξ_b^-)
- observation in prompt production ($\Omega_c(3000)^0$, $\Omega_c(3050)^0$, $\Omega_c(3066)^0$, $\Omega_c(3090)^0$, $\Omega_c(3119)^0$)
- observation in prompt production ($\Xi_b^{\prime -}$ and Ξ_b^{*-})
- observation in prompt production (Ω_b^-)



B_c^+ production

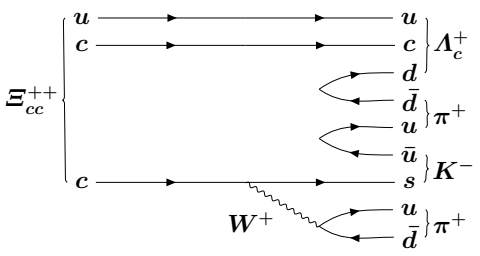
Phys. Rev. Lett. 109 (2012) 232001, Phys. Rev. Lett. 114 (2015) 132001



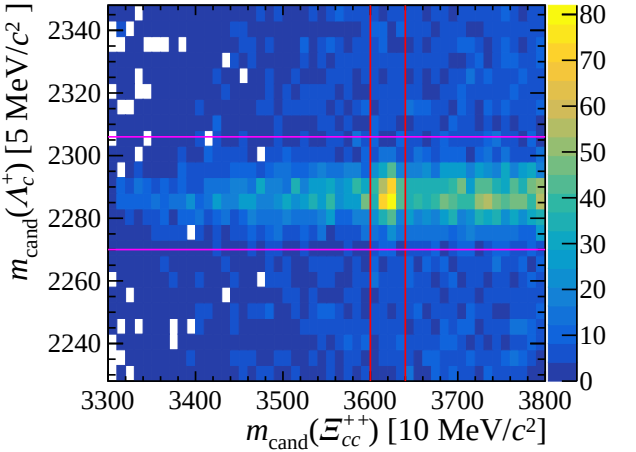
$$R(p_{\mathrm{T}}, y) = \frac{\mathrm{d}\,\sigma_{B_c^+}\mathcal{B}_{B_c^+ \to J/\psi\,\pi^+}}{\mathrm{d}\,\sigma_{B^+}\mathcal{B}_{B^+ \to J/\psi\,K^+}}$$

Ξ_{cc}^{++} production

Phys. Rev. Lett. 119 (2017) 112001



- Observation in prompt production $\Xi_{cc}^{++} \to \Lambda_c^+ \pi^+ K^- \pi^+$
- lifetime and mass measured



conclusion

- There are plenty of LHCb results available to improve our understanding of heavy flavour hadrons
- Description of Charmonium still unclear
- Improvements on the theory are needed to describe doubly heavy final states
- Very low$-x$ is probed in exclusive production but not utilised in PDF fitting