Production rates and branching fractions of heavy hadrons & quarkonia at LHC experiments

P. Ronchese - CMS + ATLAS & LHCb collaborations

University and INFN Padova

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Outline

- Introduction
- Production cross-sections:
  - inclusive *b*-hadrons
  - bottom mesons and baryons
  - quarkonia
- Branching fractions:
  - bottom baryon decay
  - baryon production in meson decays
  - look for intermediate states
- Conclusions

Motivations

- Cross-sections measurements:
  - probe the underlying QCD processes,
  - reference or ingredient for searches and measurements of rarer or new processes,
  - baseline for associated production of HF and other objects.
- Decay properties studies and branching fractions measurements:
  - test form-factor models,
  - look for new and exotic states.
- Look for effects of new physics beyond the Standard Model:
  - look for new physics effects in rare decays.

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- Decay properties studies and branching fractions measurements:
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  - look for r
- Look for effe
  - look for r

> - Branching fractions often measured as ratios
> - Cross-section / fragmentation-fractions ratio possibly needed

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Not covered here

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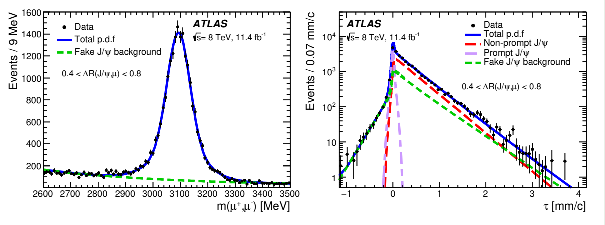
b-hadron pair production (ATLAS, $\sqrt{s} = 8$ TeV)

- First b-hadron decay channel containing $J/\psi \to \mu^+\mu^-$
- Second b-hadron decay channel containing a muon

$$p_{T,\mu} > 6 \text{ GeV}\ ,\ |\eta_{\mu,J/\psi}| < 2.3\ ,\ |\eta_\mu| < 2.5$$

Signal extraction ($\mathcal{L} = 11.4$ fb^{-1})

- J/ψ : 2D fit to dimuon mass and proper decay time
- muon: 2D fit to BDT(sig/bkg) and impact parameter



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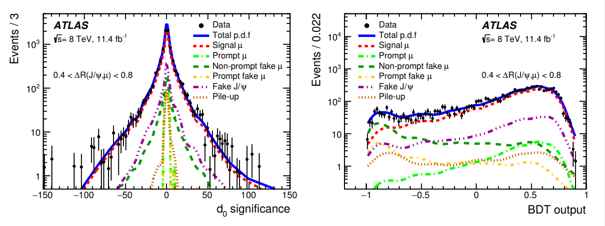

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Total cross section in fiducial region:

JHEP 11 (2017) 062

$$\sigma(B(\to J/\psi[\to \mu^+\mu^-] + X)B(\to \mu + X))) =$$
$$(17.7 \pm 0.1(\text{stat}) \pm 2.0(\text{syst}))\text{ nb}$$

Differential cross section vs. several variables compared with various predictions/simulation

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B^+ production cross-section (CMS, $\sqrt{s} = 13$ TeV)

$\mathcal{L} = 48.1\ \mathrm{pb}^{-1}$, $|y_B| < 2.1$, 10 GeV $< p_{T,B} <$ 100 GeV PLB 771 (2017) 435

Differential cross-section, vs. transverse momentum and rapidity

$$\frac{d\sigma(pp \to B^+ X)}{dz} = \frac{n_{\mathrm{sig}}(z)}{2 \cdot \mathcal{B} \cdot A \cdot \epsilon(z) \cdot \mathcal{L} \cdot \Delta z}$$

$B^\pm$ reconstructed in the channel $B^\pm \to J/\psi K^\pm$, $J/\psi \to \mu^+\mu^-$

z	=	$p_{T,B}$, $\|y_B\|$	$n_{\mathrm{sig}}(z)$	=	signal yield
2	=	account for	A	=	acceptance
		B charge symmetry	$\epsilon(z)$	=	efficiency
$\mathcal{B}$	=	$\mathcal{B}(B^\pm \to J/\psi K^\pm)$	$\mathcal{L}$	=	integrated luminosity
		$\cdot\mathcal{B}(J/\psi \to \mu^+\mu^-)$	Δz	=	bin width

Event selection

- $\left|M(\mu^+\mu^-) - m_{J/\psi}\right| < 150$ MeV
- $L_{xy}/\sigma_{xy} > 3.5$, $\cos(\theta)_{xy} > 0.99$

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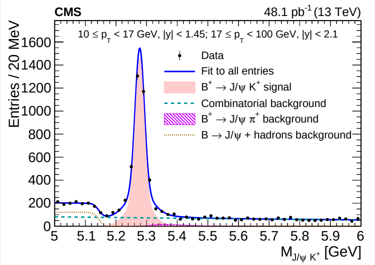
z = $p_{T,B}$, $|y_B|$

$n_{\mathrm{sig}}(z)$ = signal yield

$B^\pm$ Invariant mass distributions

- $p_{T,B}$ and $|y_B|$ bins
- Unbinned max likelihood fit:
  - Sum of 2 gaussians (signal)
  - exponential (background)
  - error function

  (mis-reconstructed $B^\pm \to J/\psi KX$)



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2	=	account for B charge symmetry	A	=	acceptance
			$\epsilon(z)$	=	efficiency
$\mathcal{B}$	=	$\mathcal{B}(B^\pm \to J/\psi K^\pm)$	$\mathcal{L}$	=	integrated luminosity

Acceptance and efficiency

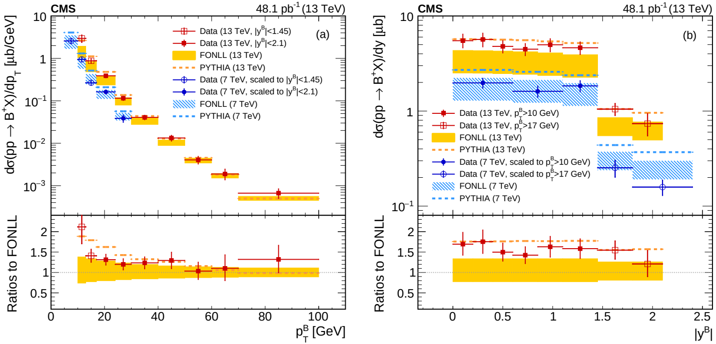
- Overall $A \cdot \epsilon$ estimated from simulation
- Efficiency measured also in data (tag and probe) to estimate systematic error

B^+ production: results (CMS, $\sqrt{s} = 13$ TeV)

Differential cross-section vs. $p_{T,B}$, $|y_B|$

- Left: $d\sigma / dp_{T,B}$ (integrated over [$|y_B| < 1.45$] or [$|y_B| < 2.1$])
- Right: $d\sigma / d\,|y_B|$ (integrated over [10 GeV $< p_{T,B} <$ 100 GeV] or [17 GeV $< p_{T,B} <$ 100 GeV])
- Comparison with FONLL and PYTHIA

M.Cacciari *et al.*, JHEP 05 (1998) 007 , JHEP 03 (2001) 006 , JHEP 10 (2012) 137
T. Sjöstrand *et al.*, CPC 178 (2008) 852

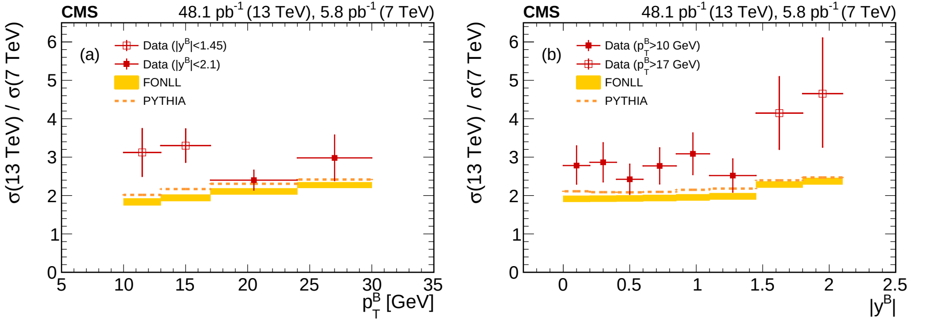


B^+ production: results (CMS, $\sqrt{s} = 13$ TeV)

Differential cross-section ratios (13 TeV/7 TeV) vs. $p_{T,B}$, $|y_B|$

- Left: $R(d\sigma/dp_{T,B})$ (integrated over [$|y_B| < 1.45$] or [$|y_B| < 2.1$])
- Right: $R(d\sigma/d|y_B|)$ (integrated over [10 GeV $< p_{T,B} <$ 100 GeV] or [17 GeV $< p_{T,B} <$ 100 GeV])
- Reduced sensitivity to scale uncertainty, constraint to gluon PDF

M.Cacciari *et al.*, EPJC 75 (2015) 610



$B^{\pm}$ production cross-section (LHCb)

Analogous measurement from LHCb

- Double differential cross-section, vs. transverse momentum and rapidity (all plots and numbers not shown here...)
- Collision energy $\sqrt{s} = (7, 13)$ TeV
- Complementary rapidity range

$\mathcal{L} = (1.0, 0.3)\ \text{pb}^{-1}$, $2.0 < |y_B| < 4.5$, $p_{T,B} < 40$ GeV JHEP 12 (2017) 026

Integrated cross-section

$$\sigma(pp \to B^{\pm}X\ , \sqrt{s} = \ \ 7\ \text{TeV} = (43.0 \pm 0.2(\text{st}) \pm 2.5(\text{sy}) \pm 1.7(\text{br}))\ \mu\text{b}$$
$$\sigma(pp \to B^{\pm}X\ , \sqrt{s} = 13\ \text{TeV} = (86.6 \pm 0.5(\text{st}) \pm 5.4(\text{sy}) \pm 3.4(\text{br}))\ \mu\text{b}$$

$B^{\pm}$ production cross-section (LHCb)

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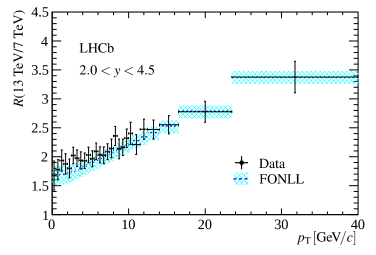
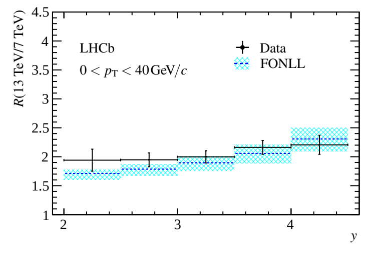
Differential cross-section ratios vs. $p_{T,B}$, $|y_B|$

JHEP 12 (2017) 026





Ξ_b^- baryon production cross-section (LHCb)

Ξ_b^- decay modes

- New decay modes of bottom-strange baryons observed and studied
- Branching ratio measured:
  $(f_{\Xi_b^-}/f_{\Lambda_b^0})\mathcal{B}(\Xi_b^- \to \Lambda_b^0\pi^-) = (5.7 \pm 1.8^{+0.8}_{-0.9}) \times 10^{-4}$ PRL 115 (2015) 241801
- Absolute branching fraction determination requires fragmentation ratio knowledge

$$R = \frac{f_{\Xi_b^-}}{f_{\Lambda_b^0}} \cdot \frac{\mathcal{B}(\Xi_b^- \to J/\psi\Xi^-)}{\mathcal{B}(\Lambda_b^0 \to J/\psi\Lambda^0)} = \frac{f_{\Xi_b^-}}{f_{\Lambda_b^0}} \cdot \frac{\Gamma(\Xi_b^- \to J/\psi\Xi^-)}{\Gamma(\Lambda_b^0 \to J/\psi\Lambda^0)} \cdot \frac{\tau_{\Xi_b^-}}{\tau_{\Lambda_b^0}}$$

Ratio measurement

PRD 99 (2019) 052006

$$R = \frac{N(\Xi_b^- \to J/\psi\Xi^-)}{N(\Lambda_b^0 \to J/\psi\Lambda^0)} \frac{\epsilon_{\Lambda_b^0}}{\epsilon_{\Xi_b^-}}$$

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From SU(3) flavor symmetry

$$\frac{\Gamma(\Xi_b^- \to J/\psi \Xi^-)}{\Gamma(\Lambda_b^0 \to J/\psi \Lambda^0)} = \frac{2}{3}$$

From PDG

$$R = \frac{f_{\Xi_b^-}}{f_{\Lambda_b^0}} \cdot \frac{\mathcal{B}(\Xi_b^- \to J/\psi \Xi^-)}{\mathcal{B}(\Lambda_b^0 \to J/\psi \Lambda^0)} = \frac{f_{\Xi_b^-}}{f_{\Lambda_b^0}} \cdot \frac{\Gamma(\Xi_b^- \to J/\psi \Xi^-)}{\Gamma(\Lambda_b^0 \to J/\psi \Lambda^0)} \cdot \frac{\tau_{\Xi_b^-}}{\tau_{\Lambda_b^0}}$$

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$\Xi_b^- \to J/\psi \Xi^-$ signal extraction (LHCb)

- $J/\psi \to \mu^+\mu^-$: two muons $\left|M(\mu^+\mu^-) - m_{J/\psi}\right| < 40$ MeV
- "long"/"downstream" tracks:
  including/without hits in the vertex detector
  - $\Lambda^0 \to p\pi^-$: two "downstream" tracks, $|M(p\pi^-) - m_{\Lambda^0}| < 8$ MeV
  - $\Xi^- \to \Lambda^0\pi^-$: "long" track as pion candidate,
    $\left|(M(\Lambda^0\pi^-) - M(p\pi^-) + m_{\Lambda^0} - m_{\Xi^-}\right| < 10$ MeV
- good vertex quality, displaced vertices from PV
- Λ_b^0 , Ξ_b^- candidates: $2 < |\eta| < 6$, $p_T < 20$ GeV

$\sqrt{s} = (7, 8, 13)$ GeV , $\mathcal{L} = (1.0, 2.0, 1.6)$ pb^{-1}

- $\Lambda_b^0 \to J/\psi\Lambda^0$, $\Xi_b^- \to J/\psi\Xi^-$ invariant mass distributions
- Unbinned max likelihood fit:
  - Sum of 2 CB function, common peak position and sigma (signal)
  - exponential (background)
- $m_{\Xi_b^-} = (5796.70 \pm 0.39(\text{stat}) \pm 0.15(\text{syst}) \pm 0.17(m_{\Lambda_b^0}))$ MeV

$\Xi_b^- \to J/\psi \Xi^-$ signal extraction (LHCb)

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  - $\Xi^- \to \Lambda^0\pi^-$: "long" track as pio… $|(M(\Lambda^0\pi^-) - M(p\pi^-) + m_{\Lambda^0} - $ …
- good vertex quality, displaced ver…
- Λ_b^0 , Ξ_b^- candidates: $2 < |\eta| < 6$, …

$\sqrt{s} = (7, 8, 13)$ GeV , $\mathcal{L} =$ …

- $\Lambda_b^0 \to J/\psi\Lambda^0$, $\Xi_b^- \to J/\psi\Xi^-$ invari…
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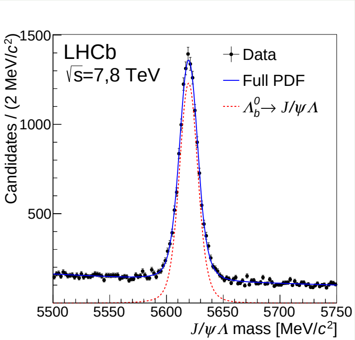
$\Lambda_b^0 \to J/\psi\Lambda^0$, $\sqrt{s} = 7, 8$ TeV



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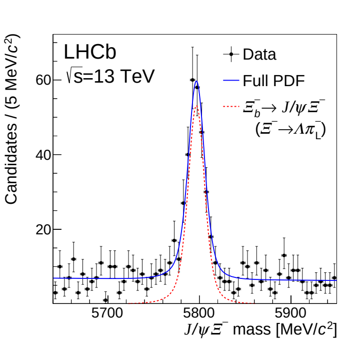
$\Xi_b^- \to J/\psi \Xi^-$, $\sqrt{s} = 13$ TeV



$\sqrt{s} = (7, 8, 13)$ GeV , $\mathcal{L} = ...$

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$f_{\Xi_b^-}/f_{\Lambda_b^0}$ (LHCb)

$$R = \frac{N(\Xi_b^- \to J/\psi\Xi^-)}{N(\Lambda_b^0 \to J/\psi\Lambda^0)} \frac{\epsilon_{\Lambda_b^0}}{\epsilon_{\Xi_b^-}}$$

- $N(\Xi_b^- \to J/\psi\Xi^-)$, $N(\Lambda_b^0 \to J/\psi\Lambda^0)$ from mass distributions fit
- $\epsilon_{\Lambda_b^0}$, $\epsilon_{\Xi_b^-}$ from simulation ($\epsilon_{\Lambda_b^0}/\epsilon_{\Xi_b^-} \sim 14\%$)

Production rate times branching fractions ratio

$$R = (10.8 \pm 0.9(\text{stat}) \pm 0.8(\text{syst})) \times 10^{-2} \quad [\sqrt{s} = 7, 8\ \text{TeV}]$$
$$R = (13.1 \pm 1.1(\text{stat}) \pm 1.0(\text{syst})) \times 10^{-2} \quad [\sqrt{s} = 13\ \text{TeV}]$$

Fragmentation ratio

PRD 99 (2019) 052006

$$\frac{f_{\Xi_b^-}}{f_{\Lambda_b^0}} = (6.7 \pm 0.5(\text{stat}) \pm 0.5(\text{syst}) \pm 2.0(\text{f.s.})) \times 10^{-2}\ [\sqrt{s} = 7, 8\ \text{TeV}]$$
$$\frac{f_{\Xi_b^-}}{f_{\Lambda_b^0}} = (8.2 \pm 0.7(\text{stat}) \pm 0.6(\text{syst}) \pm 2.5(\text{f.s.})) \times 10^{-2}\ [\sqrt{s} = 13\ \text{TeV}]$$

$f_{\Xi_b^-}/f_{\Lambda_b^0}$ (LHCb)

$$R = \frac{N(\Xi_b^- \to J/\psi\Xi^-)}{N(\Lambda_b^0 \to J/\psi\Lambda^0)}\frac{\epsilon_{\Lambda_b^0}}{\epsilon_{\Xi_b^-}}$$

SU(3) flavor symmetry (30%)

- $N(\Xi_b^- \to J/\psi\Xi^-)$, $N(\Lambda_b^0 \to J/\psi\Lambda^0)$ from mass distributions fit
- $\epsilon_{\Lambda_b^0}$, $\epsilon_{\Xi_b^-}$ from simulation ($\epsilon_{\Lambda_b^0}/\epsilon_{\Xi_b^-} \sim 14\%$)

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Quarkonia production cross-section

Heavy quarkonia production models & tests

- Test factorization and NRQCD

  G.T.Bodwin *et al.*, PRD 51 (1995) 1125 , PRD 55 (1997) 5853
  P.Cho and A.K.Leibovich, PRD 53 (1996) 150 , PRD 53 (1996) 6203
- 2 phases:

  B. Gong *et al.*, PRL 112 (2014) 032001 , Z.-B. Kang *et al.*, PRD 91 (2015) 014030
  - perturbative generation of $Q\bar{Q}$ pair (singlet/octet)
  - hadronization producing bound state (LDME)
- Different center of mass energies:
  - perturbative calculations appropriate for energy
  - same LDME

    P.Faccioli *et al.*, PLB 736 (2014) 98
    G.T.Bodwin *et al.*, PRL 113 (2014) 022001
- Higher energy and higher cross-section: extended p_T reach

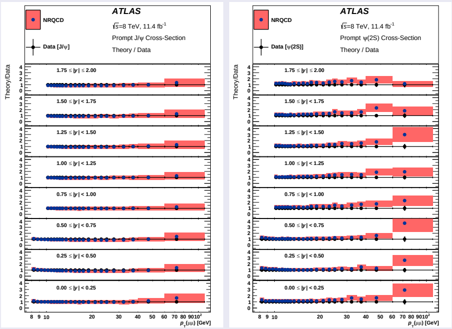
Several $pp \to q\bar{q}$ cross-section measurements at ATLAS, CMS and LHCb

Quarkonia production cross-section (ATLAS)

$\sigma(pp \to (J/\psi\,, \psi(2S))X)$	$\sqrt{s} = 7, 8$ TeV	EPJC 76 (2017) 283
$\sigma(pp \to \Upsilon(nS)X)$	$\sqrt{s} = 7$ TeV	PLB 705 (2011) 9

- Test factoriza... 5) 1125 , PRD 55 (1997) 5853
) 150 , PRD 53 (1996) 6203
- 2 phases: *et al.*, PRD 91 (2015) 014030
  - perturba...
  - hadroniz...
- Different cer...
  - perturba... *t al.*, PLB 736 (2014) 98
  - same LD... *t al.*, PRL 113 (2014) 022001
- Higher energ... p_T reach

J/ψ , $\psi(2S)$: comparison with NRQCD



Several $pp \to q\bar{q}$ cross-section measurements at ATLAS, CMS and LHCb

Quarkonia production cross-section (CMS)

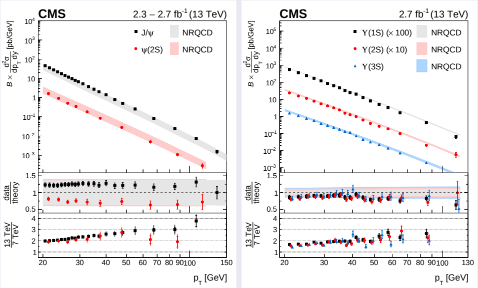
$\sigma(pp \to (J/\psi\,,\psi(2S))X)$	$\sqrt{s} =$ 7 TeV	JHEP 02 (2012) 011, PRL 114 (2015) 191802
$\sigma(pp \to \Upsilon(nS)X)$	$\sqrt{s} =$ 7 TeV	PLB 727 (2013) 101, PLB 749 (2015) 14
$\sigma(\chi_{c2})/\sigma(\chi_{c1})$, $\sigma(\chi_{b2})/\sigma(\chi_{b1})$	$\sqrt{s} =$ 7 TeV	EPJC 72 (2012) 2251, PLB 743 (2015) 383
$\sigma(pp \to (J/\psi\,,\psi(2S),\Upsilon(nS))X)$	$\sqrt{s} =$ 13 TeV	PLB 780 (2018) 251

53
203

- 2 phas...
  - pe...
  - ha...
- Differe...
  - pe...
  - sa...
- Higher... ach

91 (2015) 014030
PLB 736 (2014) 98
13 (2014) 022001

$J/\psi\,,\psi(2S)\,,\Upsilon(1S)\,,\Upsilon(2S)\,,\Upsilon(3S)$: comparison with NRQCD



Several $pp \to q\bar{q}$ cross-section measurements at ATLAS, CMS and LHCb

Quarkonia production cross-section (LHCb)

$\sigma(pp \to (J/\psi\,, \psi(2S))X)$	$\sqrt{s} =$ 7 TeV	EPJC 71 (2011) 1645, EPJC 72 (2012) 2100
$\sigma(pp \to \Upsilon(nS)X)$	$\sqrt{s} =$ 7 TeV	EPJC 72 (2012) 2025
$\sigma(\chi_{c2})/\sigma(\chi_{c1})$	$\sqrt{s} =$ 7 TeV	PLB 714 (2012) 215
$\sigma(J/\psi)/\sigma(\chi_c)$	$\sqrt{s} =$ 7 TeV	PLB 718 (2012) 431
$\sigma(\chi_{c0})/\sigma(\chi_{c2})$, $\sigma(\chi_{c2})/\sigma(\chi_{c1})$	$\sqrt{s} =$ 7 TeV	JHEP 10 (2013) 115
$\sigma(pp \to (J/\psi\,, \Upsilon(nS))X)$	$\sqrt{s} =$ 8 TeV	JHEP 06 (2013) 064
$\sigma(pp \to \Upsilon(nS)X)$	$\sqrt{s} =$ 7, 8 TeV	JHEP 11 (2015) 103
$\sigma(pp \to J/\psi X)$	$\sqrt{s} =$ 13 TeV	JHEP 10 (2015) 172, JHEP 05 (2017) 063
$\sigma(pp \to \Upsilon(nS)X)$	$\sqrt{s} =$ 13 TeV	JHEP 07 (2018) 134

53
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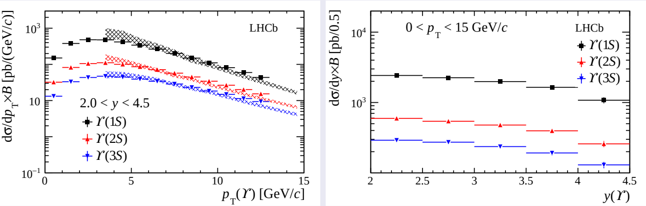
30

$\Upsilon(1S)$, $\Upsilon(2S)$, $\Upsilon(3S)$: comparison with NRQCD



014) 98
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at ATLAS, CMS and LHCb

Quarkonia production cross-section in HI collisions

Quarkonia production	5.02 TeV	ATLAS	EPJC 78 (2018) 171
J/ψ elliptic flow	5.02 TeV	ATLAS	EPJC 78 (2018) 784
J/ψ and ψ(2S) production	5.02 TeV	ATLAS	EPJC 78 (2018) 762
J/ψ production	5.02 TeV	ATLAS	PRC 92 (2015) 034904
Υ production	8.16 TeV	LHCb	JHEP 11 (2018) 194
J/ψ production and nuclear modification	8.16 TeV	LHCb	PLB 774 (2017) 159
ψ(2S) production and cold nuclear matter effects	5 TeV	LHCb	JHEP 03 (2016) 133
Υ production and cold nuclear matter effects	5 TeV	LHCb	JHEP 07 (2014) 094
J/ψ production and cold nuclear matter effects	5 TeV	LHCb	JHEP 02 (2014) 072
J/ψ elliptic flow	8.16 TeV	CMS	PLB 791 (2019) 172
Nuclear modification factors of Υ	5.02 TeV	CMS	PLB 790 (2019) 270
ψ(2S) production	5.02 TeV	CMS	PLB 790 (2019) 509
Charmonium suppression	5.02 TeV	CMS	EPJC 78 (2018) 509
Suppression of excited Υ	5.02 TeV	CMS	PRL 120 (2018) 142301
J/ψ production	5.02 TeV	CMS	EPJC 77 (2017) 269
Relative modification of prompt ψ(2S) and J/ψ yields	5.02 TeV	CMS	PRL 118 (2017) 162301
Suppression of Υ	2.76 TeV	CMS	PLB 770 (2017) 357
Suppression of J/ψ	2.76 TeV	CMS	EPJC 77 (2017) 252
Prompt ψ(2S) to J/ψ yield ratios	2.76 TeV	CMS	PRL 113 (2014) 262301
Suppression of J/ψ and Υ(1S))	2.76 TeV	CMS	JHEP 05 (2012) 063
Suppression of Excited Υ	2.76 TeV	CMS	PRL 107 (2011) 052302
Υ production ratios vs. multiplicity	7 TeV	CMS	CMS-PAS-BPH-14-009

Double quarkonia production

High parton densities in *pp* collisions

- Single parton scattering (SPS):
  - assumed to dominate
  - strongly correlated pairs, small $|\Delta y|$
- Double parton scattering (DPS):
  - multiple heavy-flavour production,
  - large $|\Delta y|$ values

S. Baranov,*et al.*, PLB 705 (2011) 116-119, C.H.Kom *et al.*, PRL 107 (2011) 082002

Quarkonium pair production mechanism

- Color singlet: dominant at low p_T
- Color octet: important at high p_T

P. Ko *et al.*, JHEP 01 (2011) 070, J.Campbell *et al.*, PRL 98 (2007) 252002

Possibly produced in decays of tetra-quarks

A.V.Berezhnoy, *et al.*, PRD 86 (2012) 034004

Double quarkonia production

High parton densities in *pp* collisions

Measurements at LHC experiments

double J/ψ	$\sqrt{s} =$ 7 TeV	LHCb	PLB 707 (2012) 52
double J/ψ	$\sqrt{s} =$ 7 TeV	CMS	JHEP 09 (2014) 094
double J/ψ	$\sqrt{s} =$ 8 TeV	ATLAS	EPJC 77 (2017) 76
double Υ	$\sqrt{s} =$ 8 TeV	CMS	JHEP 05 (2017) 013
double J/ψ	$\sqrt{s} =$ 13 TeV	LHCb	JHEP 06 (2017) 047, JHEP 10 (2017) 068

- large $|\Delta y|$ values

S. Baranov, *et al.*, PLB 705 (2011) 116-119, C.H.Kom *et al.*, PRL 107 (2011) 082002

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Double J/ψ production cross-section (ATLAS, $\sqrt{s} = 8$ TeV)

$\mathcal{L} = 11.4\ \text{fb}^{-1}$, $|y_{J/\psi}| < 2.1$, $p_{T,J/\psi} > 8.5$ GeV

EPJC 77 (2017) 76

- Different pp interaction removed: $|d_z| < 1.2$ cm
- Data split in 2 rapidity regions: $|y_{J/\psi}| < 1.05$, $1.05 < |y_{J/\psi}| < 2.1$
- Di-J/ψ signal: fit on 2D mass distribution ($p_{T,\mu} \geq 2.5$ GeV , $|\eta_\mu| < 2.3$)
- Prompt-prompt fraction: fit on 2D transverse decay length L_{xy}
- Residual pile-up contamination:
  - estimated with a fit on wide d_z range
  - kinematic variables distributions from sidebands $|d_z| > 1.2$ cm

Double parton scattering contribution:
J/ψ mesons assumed to be produced independently

- DPS template $\Delta y, \Delta\phi$ distribution with J/ψ pairs from different events
- Event weights computed: $w_{\text{DPS}}(\Delta\phi, \Delta y) = \frac{N_{\text{DPS}}(\Delta\phi,\Delta y)}{N_{\text{Data}}(\Delta\phi,\Delta y)}$

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EPJC 77 (2017) 76

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Normalized with data at large Δy

Double parton scattering contribution:
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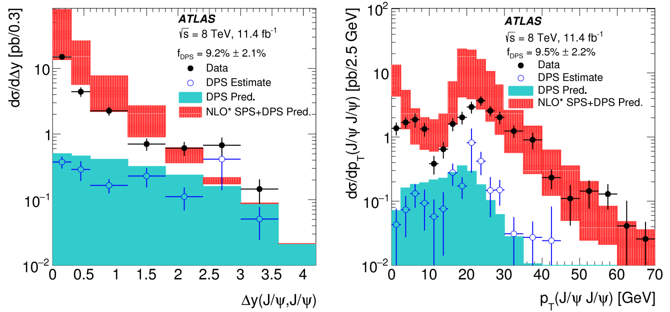
Double J/ψ production: results (ATLAS, $\sqrt{s} = 8$ TeV)

Differential cross-section vs. p_T , Δy

- DPS fraction estimated from event weights
- Predictions from NLO* J.P. Lansberg, H.S. Shao PLB 751 (2015) 479, PRL 111 (2013) 122001



$$\sigma_{\text{Fid}} = (15.6 \pm 1.3(\text{st}) \pm 1.2(\text{sy}) \pm 0.2(\text{br}) \pm 0.3(\text{lum}))\ \text{pb} \qquad |y_{J/\psi}| < 1.05$$

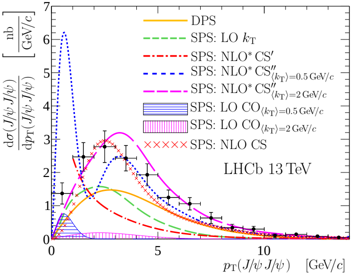
$$\sigma_{\text{Fid}} = (13.5 \pm 1.3(\text{st}) \pm 1.1(\text{sy}) \pm 0.2(\text{br}) \pm 0.3(\text{lum}))\ \text{pb} \qquad 1.05 < |y_{J/\psi}| < 2.1$$

$$f_{\text{DPS}} = (9.2 \pm 2.1(\text{stat}) \pm 0.5(\text{syst}))\%$$

Double J/ψ production cross-section (LHCb, $\sqrt{s} = 13$ TeV)

Analogous measurement from LHCb

- DPS predictions from pseudoexperiments
- SPS predictions from different models (LO-CO, NLO*-CS, $k_{T,\text{gluon}}$)
- Fraction from fits to different variables ($p_{T,\psi\psi}$, $y_{\psi\psi}$, $M_{\psi\psi}$, $|\Delta y|$)



$\mathcal{L} = 279$ pb^{-1} , $2.0 < |y| < 4.5$, $p_T < 10$ GeV JHEP 06 (2017) 047, JHEP 10 (2017) 068

$\sigma = (15.2 \pm 1.0(\text{stat}) \pm 0.9(\text{syst}))$ nb ; $f_{\text{DPS}} = ((42 \pm 25) \div (86 \pm 55))\%$

Outline

- Introduction
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- Conclusions

$\mathcal{B}(\Lambda_b^0 \to \psi(2S)\Lambda^0)/\mathcal{B}(\Lambda_b^0 \to J/\psi\Lambda^0)$ ratio (LHCb)

Bottom hadrons decays with charmonia in final state

- Ratios of branching fractions of b-hadrons into $\psi(2S)X$ and $J/\psi X$: test factorisation of amplitudes.
- Measured by ATLAS:
  $\frac{\mathcal{B}(\Lambda_b^0 \to \psi(2S)\Lambda^0)}{\mathcal{B}(\Lambda_b^0 \to J/\psi\Lambda^0)} = 0.501 \pm 0.033(\text{stat}) \pm 0.019(\text{syst})$ PLB 751 (2015) 63
- Discrepancy from covariant quark model prediction:
  $\frac{\mathcal{B}(\Lambda_b^0 \to \psi(2S)\Lambda^0)}{\mathcal{B}(\Lambda_b^0 \to J/\psi\Lambda^0)} = 0.8 \pm 0.1$ T. Gutsche *et al.* PRD 88 (2013) 114018, PRD 92 (2015) 114008

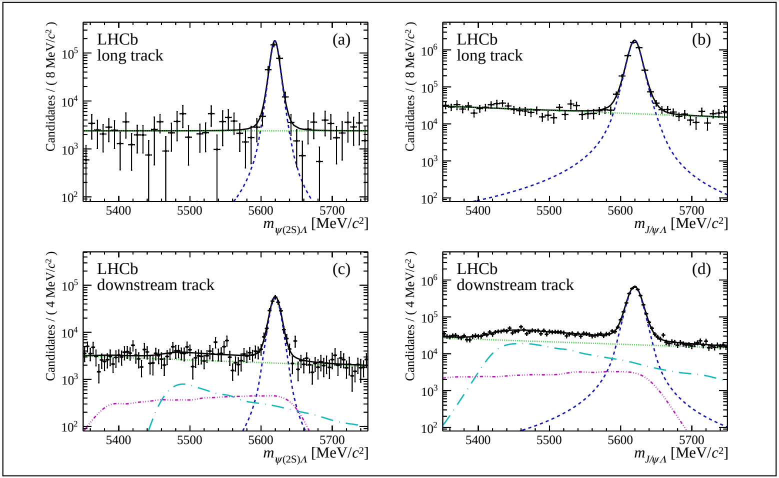
$2.0 < \eta_{\Lambda_b^0} < 4.5$, $p_{T,\Lambda_b^0} < 20$ GeV

JHEP 03 (2019) 126

- J/ψ , $\psi(2S)$: two muons not coming from any PV
- Λ^0 : two tracks, same "type" (long/downstream)
- Common vertex, displaced from PV
- $m_{\Lambda_b^0}$: kinematic fit, constrained m_ψ , m_{Λ^0}

$\mathcal{B}(\Lambda_b^0 \to \psi(2S)\Lambda^0)/\mathcal{B}(\Lambda_b^0 \to J/\psi\Lambda^0)$ ratio (LHCb)

- Efficiency from simulation, weights given by inverse of efficiency
- $B^0 \to \psi(K_S^0 \to \pi^+\pi^-)$, $\Xi_b^- \to \psi(\Xi^- \to \Lambda^0\pi^-)$ bg from simulation



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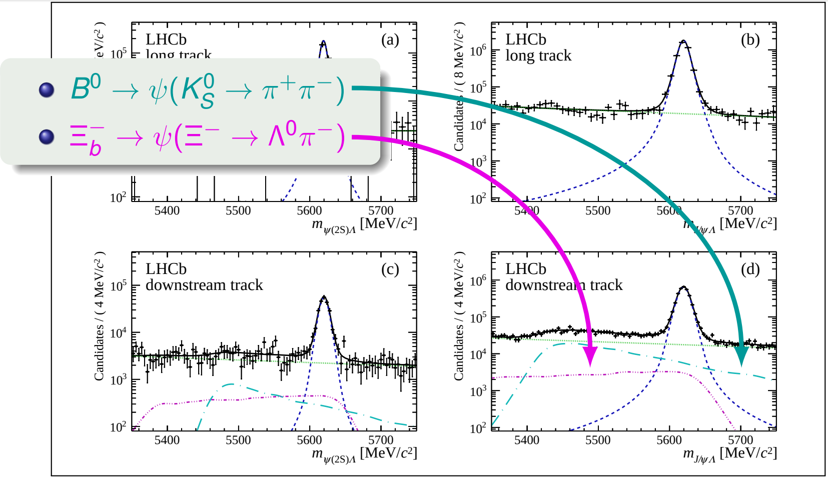

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- $B^0 \to \psi(K_S^0 \to \pi^+\pi^-)$, $\Xi_b^- \to \psi(\Xi^- \to \Lambda^0\pi^-)$ bg from simulation

- $\frac{\mathcal{B}(\Lambda_b^0 \to \psi(2S)\Lambda^0)}{\mathcal{B}(\Lambda_b^0 \to J/\psi\Lambda^0)} = \frac{N_{\Lambda_b^0 \to \psi(2S)\Lambda^0}}{N_{\Lambda_b^0 \to J/\psi\Lambda^0}} \cdot \frac{\mathcal{B}(J/\psi \to \mu^+\mu^-)}{\mathcal{B}(\psi(2S) \to \mu^+\mu^-)}$
- $N_{\Lambda_b^0 \to \psi(2S)\Lambda^0}$, $N_{\Lambda_b^0 \to J/\psi\Lambda^0}$ from extended UML fit
- $\mathcal{B}(J/\psi \to \mu^+\mu^-)$, $\mathcal{B}(\psi(2S) \to \mu^+\mu^-)$ from PDG

Branching fraction ratio

JHEP 03 (2019) 126

$$\frac{\mathcal{B}(\Lambda_b^0 \to \psi(2S)\Lambda^0)}{\mathcal{B}(\Lambda_b^0 \to J/\psi\Lambda^0)} = 0.513 \pm 0.023(\text{stat}) \pm 0.016(\text{syst}) \pm 0.011(\text{br})$$

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$\mathcal{B}(B^0_{d,s} \to J/\psi p\bar{p})$ (LHCb)

Bottom hadrons decays with baryons & charmonia in final state

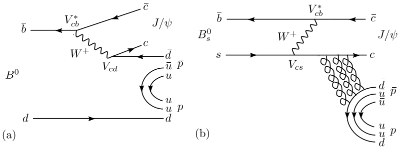
- Possible pentaquark intermediate states
- Previous evidence from LHCb in $\Lambda^0_b \to J/\psi p K^-$ decay

PRL 115 (2015) 072001, PRL 117 (2016) 082002

- Baryon-antibaryon system: possible glueball states

PRD 60 (1999) 034509, PRD 73 (2006) 014516

- $B^0_d \to J/\psi p\bar{p}$ Cabibbo suppressed
- $B^0_s \to J/\psi p\bar{p}$ OZI suppressed



- Branching ratio expected at 10^{-9} level, possible enhancement via resonant contribution $f_J(2220) \to p\bar{p}$

EPJC 75 (2015) 101

$\mathcal{B}(B^0_{d,s} \to J/\psi p\bar{p})$: strategy & signal extraction (LHCb)

Branching ratio extracted by comparison with a normalization channel

$$\mathcal{B}(B^0_{d,s} \to J/\psi p\bar{p}) = \frac{N_{B^0_{d,s} \to J/\psi p\bar{p}}}{N_{B^0_s \to J/\psi \phi}} \cdot \mathcal{B}(B^0_s \to J/\psi \phi) \cdot \mathcal{B}(\phi \to K^+K^-)[\cdot \frac{f_s}{f_d}]$$

- $J/\psi \to \mu^+\mu^-$ candidates paired with two tracks:
    - identified as protons
    - identified as kaons, $|M_{K^+K^-} - M_\phi| < 5$ MeV
- BDT used to discriminate signal and background
- Acceptance and efficiency from simulation, applied event by event
- Signal yield from extended UML fit

$\mathcal{B}(B^0_{d,s} \to J/\psi p\bar{p})$: strategy & signal extraction (LHCb)

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- Signal yield from extended UML fit

From previous measurements

$$\mathcal{B}(B^0_s \to J/\psi \phi) \cdot \mathcal{B}(\phi \to K^+K^-) \cdot \frac{f_s}{f_d} = (1.314 \pm 0.016 \pm 0.079) \times 10^{-4}$$

PRD 87 (2013) 072004

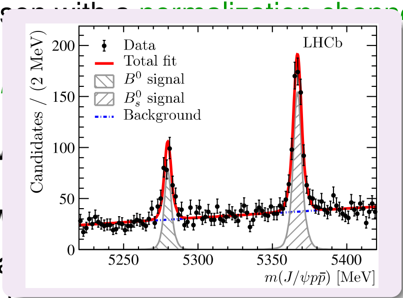
$$\frac{f_s}{f_d} = 0.259 \pm 0.015[\cdot(1.068 \pm 0.046)]$$

JHEP 04 (2013) 001, PRL 118 (2017) 191801
LHCb-CONF-2013-011

$\mathcal{B}(B^0_{d,s} \to J/\psi p\bar{p})$: strategy & signal extraction (LHCb)

Branching ratio extracted by comparis… normalization channel

$$\mathcal{B}(B^0_{d,s} \to J/\psi p\bar{p}) = \frac{N_{B^0_{d,s}\to J/\psi p\bar{p}}}{N_{B^0_s \to J/\psi\phi}} \cdot \mathcal{B}(\ldots]$$



- $J/\psi \to \mu^+\mu^-$ candidates paired w…
  - identified as protons
  - identified as kaons, $|M_{K^+K^-} - M$…
- BDT used to discriminate signal a…
- Acceptance and efficiency from simulation, applied event by event
- Signal yield from extended UML fit

$B^0_{d,s}$ mass determination

arXiv:1902.05588

$$m_{B^0_d} = (5279.74 \pm 0.30(\text{stat}) \pm 0.10(\text{syst}))\ \text{MeV}$$
$$m_{B^0_s} = (5366.85 \pm 0.19(\text{stat}) \pm 0.13(\text{syst}))\ \text{MeV}$$

$\mathcal{B}(B^0_{d,s} \to J/\psi p\bar{p})$: result (LHCb)

Branching ratio extracted by comparison with a normalization channel

$$\mathcal{B}(B^0_{d,s} \to J/\psi p\bar{p}) = \frac{N_{B^0_{d,s} \to J/\psi p\bar{p}}}{N_{B^0_s \to J/\psi \phi}} \cdot \mathcal{B}(B^0_s \to J/\psi \phi) \cdot \mathcal{B}(\phi \to K^+K^-)[\cdot \frac{f_s}{f_d}]$$

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Absolute branching fractions

arXiv:1902.05588

$$\mathcal{B}(B^0_d \to J/\psi p\bar{p}) = (4.51 \pm 0.40(\text{stat}) \pm 0.44(\text{syst})) \times 10^{-7}$$
$$\mathcal{B}(B^0_s \to J/\psi p\bar{p}) = (3.58 \pm 0.19(\text{stat}) \pm 0.33(\text{syst})) \times 10^{-6}$$

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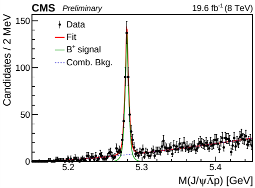
$\mathcal{B}(B^+ \to J/\psi\bar{\Lambda}^0 p)$ (CMS)

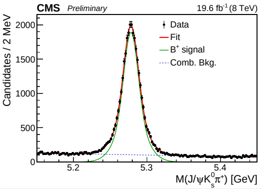
- First seen at B-factories PRL 90 (2003) 231801, PRD 72 (2005) 051105
- Search for new exotic states in $J/\psi\bar{\Lambda}^0$ and $J/\psi p$ systems
- Branching fraction ratio with normalization channel $B^+ \to J/\psi K^{*+}$ ($K^{*+} \to K^0_S\pi^+$, $K^0_S \to \pi^+\pi^-$)

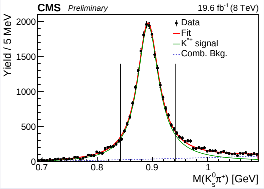
Signal extraction

CMS-PAS-BPH-18-005

- $J/\psi \to \mu^+\mu^-$ candidates paired with:
  - a $\bar{\Lambda}^0 \to \bar{p}\pi^+$ ($K^0_{S(\Lambda^0)} \to \pi^+\pi^-_{(\bar{p})}$ reflection veto) for signal
  - a $K^{*+} \to K^0_S\pi^+$ ($\bar{\Lambda}^0_{(K^0)} \to \bar{p}_{(\pi^-)}\pi^+$ reflection veto) for normalization
- Events weighted with inverse of efficiency







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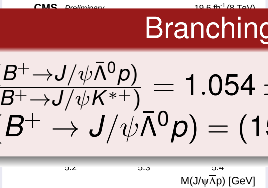
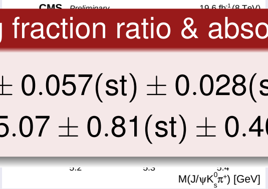
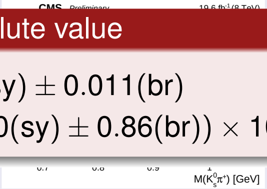






Branching fraction ratio & absolute value

$$\frac{\mathcal{B}(B^+ \to J/\psi\bar{\Lambda}^0 p)}{\mathcal{B}(B^+ \to J/\psi K^{*+})} = 1.054 \pm 0.057(\text{st}) \pm 0.028(\text{sy}) \pm 0.011(\text{br})$$

$$\mathcal{B}(B^+ \to J/\psi\bar{\Lambda}^0 p) = (15.07 \pm 0.81(\text{st}) \pm 0.40(\text{sy}) \pm 0.86(\text{br})) \times 10^{-6}$$

$\mathcal{B}(B^+ \to J/\psi\bar{\Lambda}^0 p)$: mass spectra (CMS)

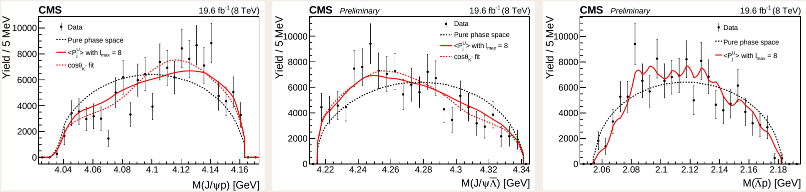
Invariant mass distributions for $J/\psi\bar{\Lambda}^0$, $J/\psi p$, $\bar{\Lambda}^0 p$

- Search for intermediate states
- Comparison with expectations:
  - pure phase space
  - phase space corrected for $K^{*+} \to \bar{\Lambda}^0 p$ resonances reflection

- Sample divided in $M(\bar{\Lambda}^0 p)$ bins
- In each bin Legendre polynomials and moments computed, using $K^{*+}(\bar{\Lambda}^0 p)$ helicity angle
- Simulated events reweighted:
  - $M(\bar{\Lambda}^0 p)$ data/MC distributions ratio
  - weight given by Legendre polynomials and moments
- Obtained distributions fitted to data

$\mathcal{B}(B^+ \to J/\psi\bar{\Lambda}^0 p)$: mass spectra (CMS)

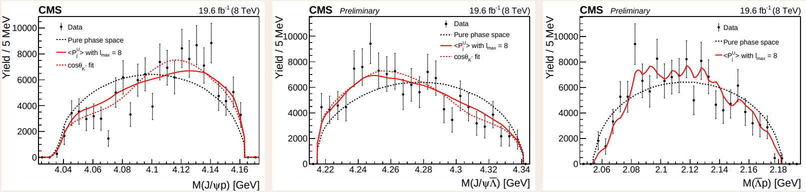
Invariant mass distributions & comparison



- 2000 pseudoexperiments generated according to the PDF for
  - pure phase space
  - reweighted angular distributions
- Log-likelihood ratio computed for invariant mass distributions
- (In)compatibility significance from difference between log-likelihood ratio in data and mean value in pseudoexperiments

$\mathcal{B}(B^+ \to J/\psi\bar{\Lambda}^0 p)$: mass spectra (CMS)

Invariant mass distributions & comparison



- 2000 pseudoexperiments generated according to the PDF for

Discrepancy significance

CMS-PAS-BPH-18-005

	$J/\psi p$	$J/\psi\bar{\Lambda}^0$	$\bar{\Lambda}^0 p$
pure phase-space	$5.5 \div 7.4$	$6.1 \div 8.0$	$3.4 \div 4.6$
reweighted phase-space	$1.3 \div 2.8$	$1.3 \div 2.7$	–

log-likelihood ratio in data and mean value in pseudoexperiments

Conclusions

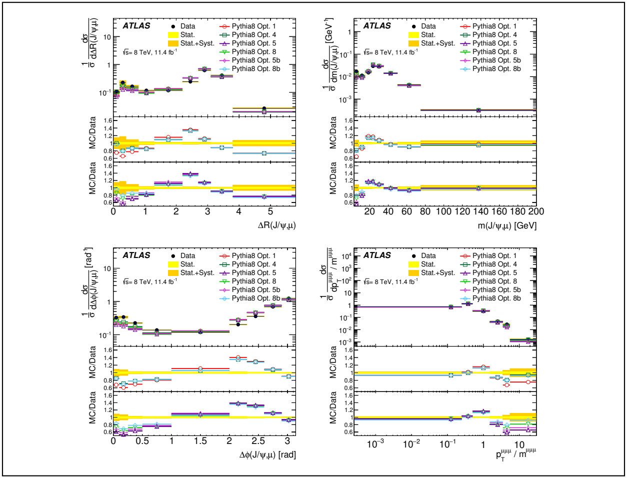
- ATLAS, CMS and LHCb have produced many measurements of heavy hadrons production cross-section and decay branching fractions:
  - cross-sections have been compared to predictions and simulations and are input for other measurements,
  - branching fractions allow test model predictions,
  - in the study of decays the possible presence of intermediate exotic states has been investigated.
- All those measurements allow important tests of QCD.

Extra informations

BACKUP

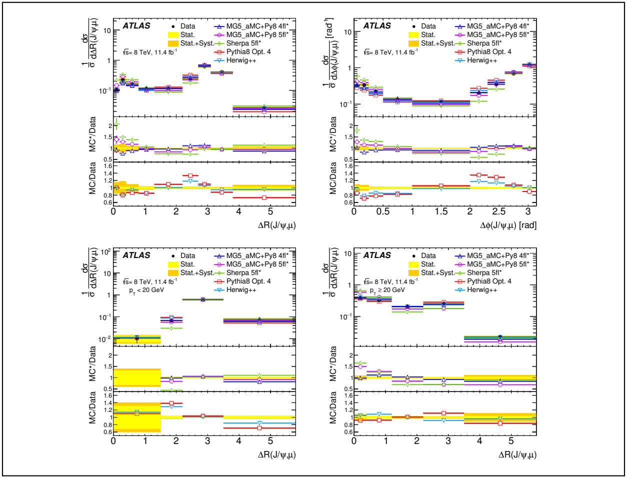
b-hadron pair production (ATLAS, $\sqrt{s} = 8$ TeV)

Comparison of differential cross section with several PYTHIA options



b-hadron pair production (ATLAS, $\sqrt{s} = 8$ TeV)

Comparison of differential cross section with PYTHIA, MADGRAPH, SHERPA & HERWIG



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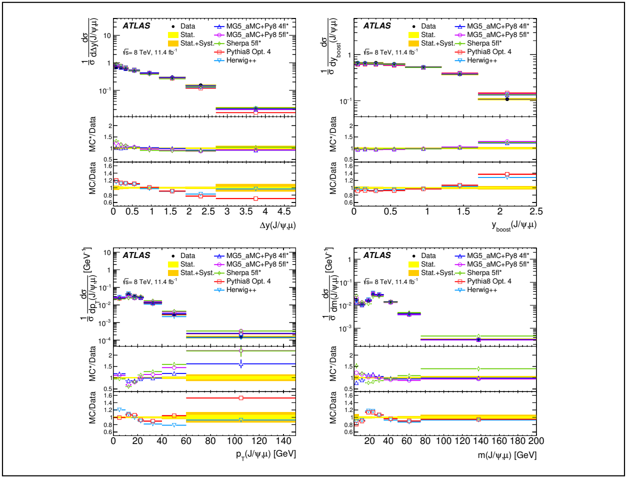

b-hadron pair production (ATLAS, $\sqrt{s} = 8$ TeV)

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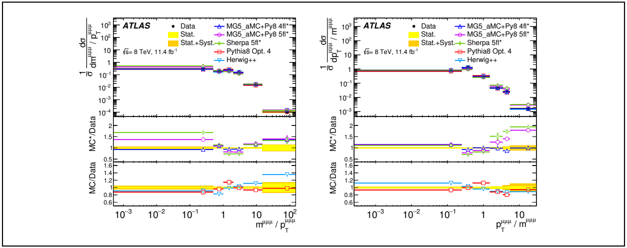
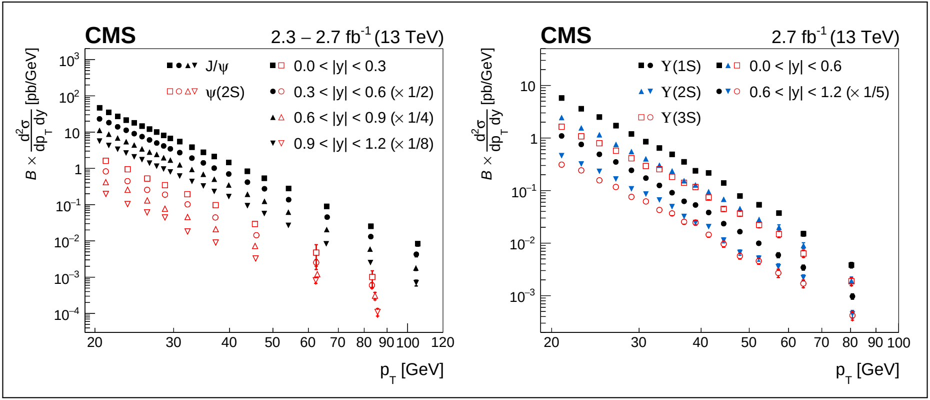
with PYTHIA, MADGRAPH, SHERPA & HERWIG



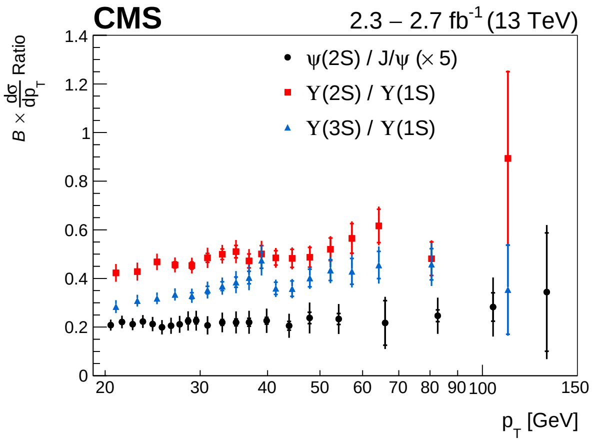
Quarkonia production cross-section (CMS)

Double differential cross sections



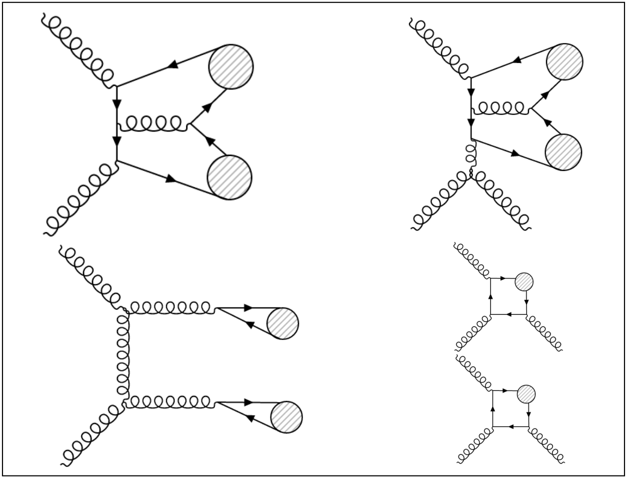
Quarkonia production cross-section (CMS)

Ratios of differential cross sections vs. p_T



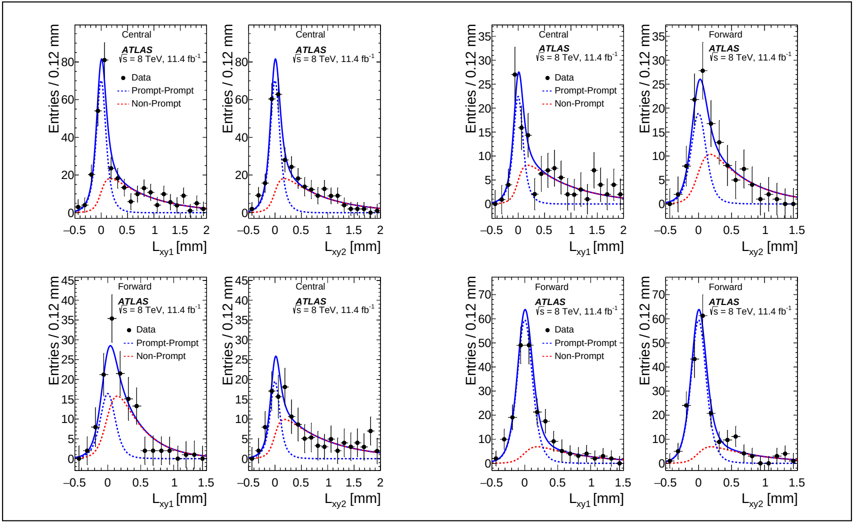
Double J/ψ production: results (ATLAS, $\sqrt{s} = 8$ TeV)

Comparison of differential cross section with predictions



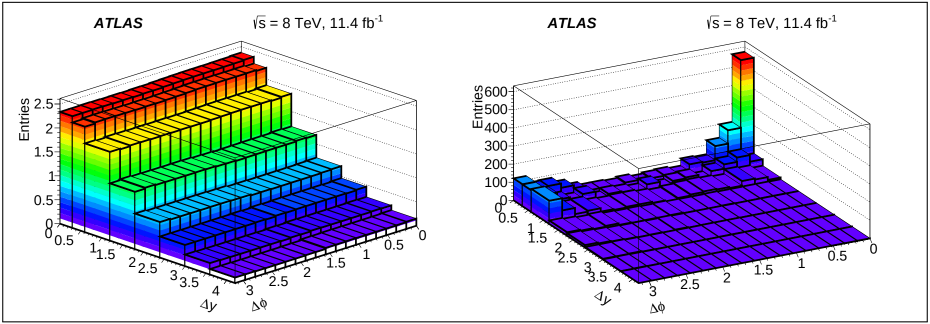
Double J/ψ production: results (ATLAS, $\sqrt{s} = 8$ TeV)

Transverse dacay spectra for leading and subleading J/ψ



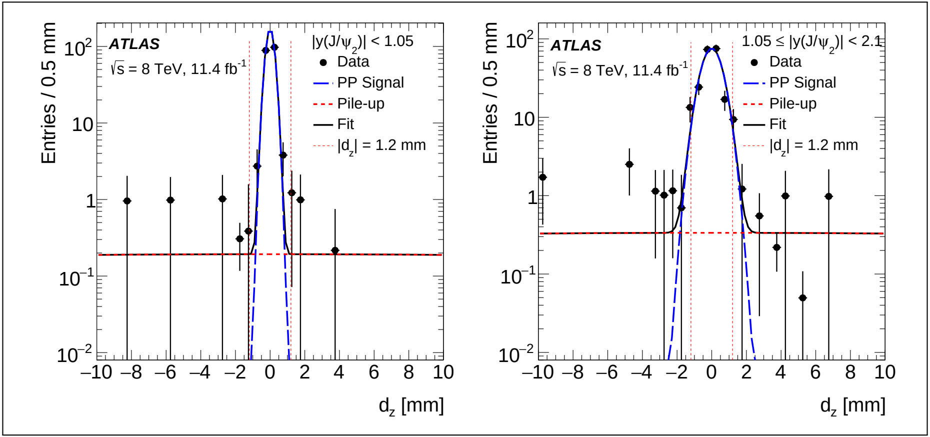
Double J/ψ production: results (ATLAS, $\sqrt{s} = 8$ TeV)

Double and Single Parton Scattering templates



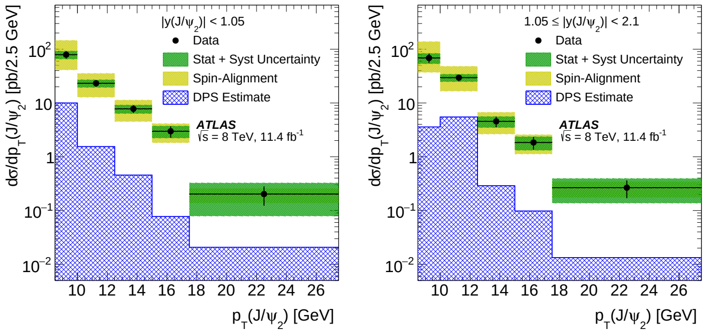
Double J/ψ production: results (ATLAS, $\sqrt{s} = 8$ TeV)

Distance distribution for signal and pile-up



Double J/ψ production: results (ATLAS, $\sqrt{s} = 8$ TeV)

J/ψ polarization effect

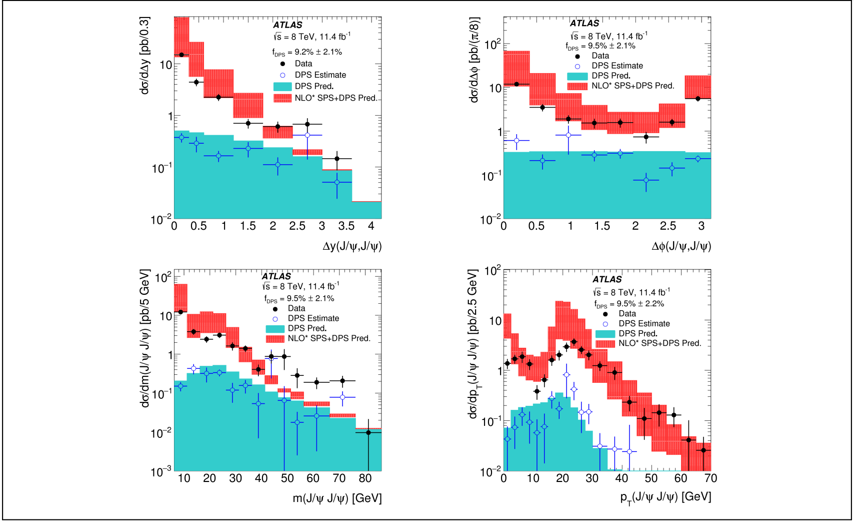


Maximum spin-alignment scenarios: di-J/ψ cross-section		
Scenario	$\lvert y(J/\psi_2)\rvert \leq 1.05$	$1.05 \leq \lvert y(J/\psi_2)\rvert < 2.1$
Longitudinal	-47%	-45%
Transverse positive	+68%	+82%
Transverse negative	+39%	+28%
Transverse zero	+51%	+47%

Maximum spin-alignment scenarios: di-J/ψ DPS cross-section		
Scenario	$\lvert y(J/\psi_2)\rvert \leq 1.05$	$1.05 \leq \lvert y(J/\psi_2)\rvert < 2.1$
Longitudinal	-47%	-45%
Transverse positive	+79%	+65%
Transverse negative	+35%	+35%
Transverse zero	+54%	+48%

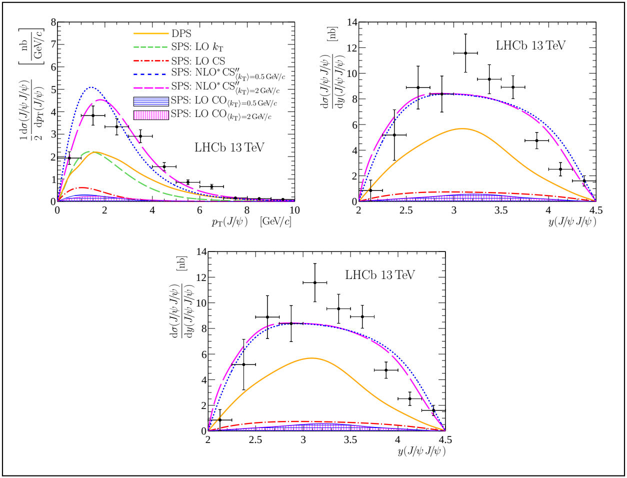
Double J/ψ production: results (ATLAS, $\sqrt{s} = 8$ TeV)

Differential cross-section vs. Δy , $\Delta\phi$, $M_{J/\psi J/\psi}$, $p_{T,J/\psi J/\psi}$



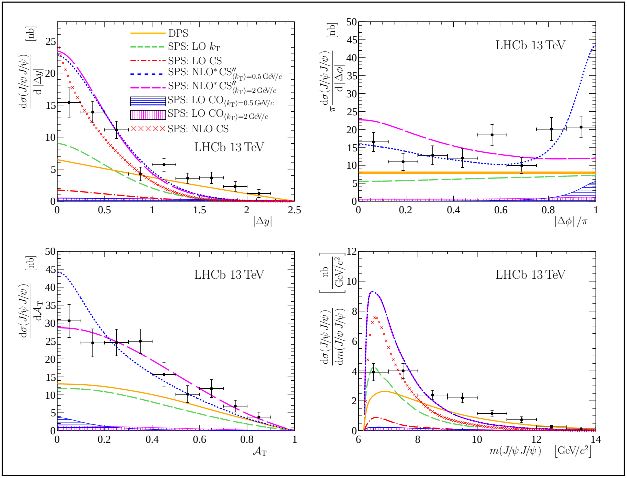
Double J/ψ production cross-section (LHCb, $\sqrt{s} = 13$ TeV)

Comparison of differential cross section with predictions



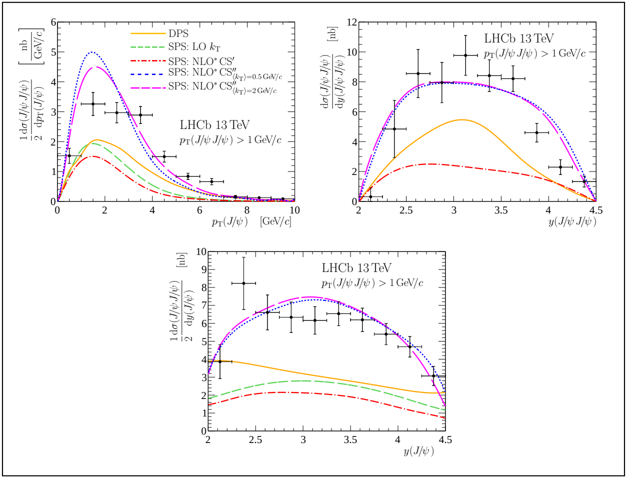
Double J/ψ production cross-section (LHCb, $\sqrt{s} = 13$ TeV)

Comparison of differential cross section with predictions



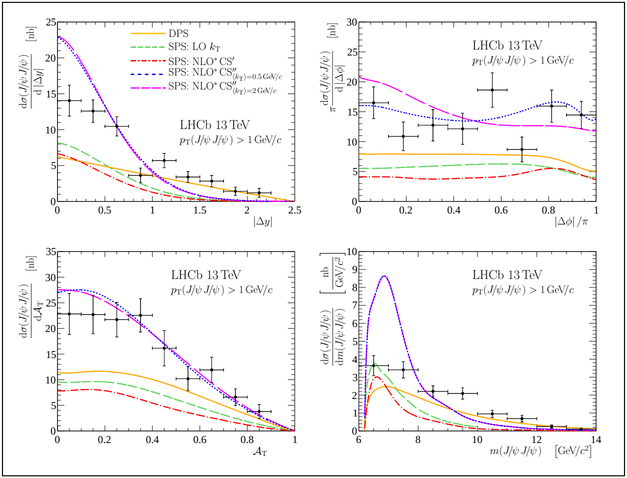
Double J/ψ production cross-section (LHCb, $\sqrt{s} = 13$ TeV)

Comparison of differential cross section with predictions ($p_{T,J/\psi J/\psi} > 1$ GeV)



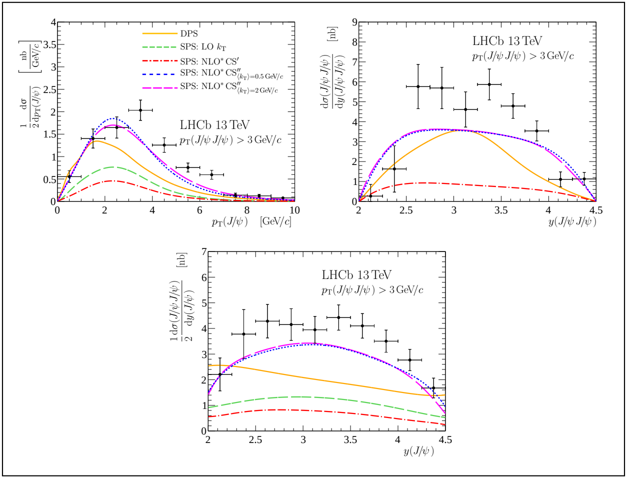
Double J/ψ production cross-section (LHCb, $\sqrt{s} = 13$ TeV)

Comparison of differential cross section with predictions ($p_{T,J/\psi J/\psi} > 1$ GeV)



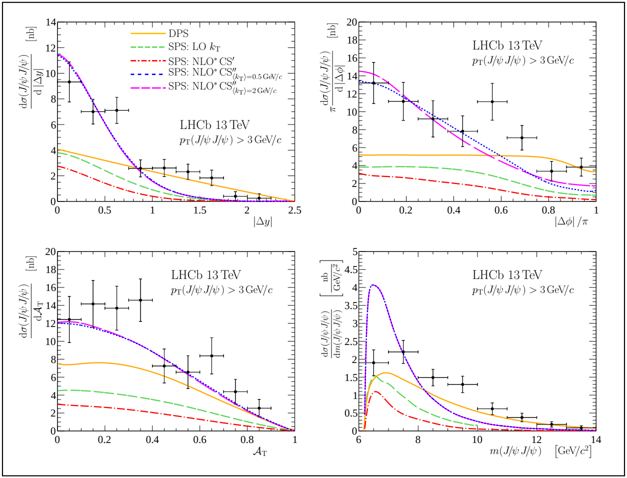
Double J/ψ production cross-section (LHCb, $\sqrt{s} = 13$ TeV)

Comparison of differential cross section with predictions ($p_{T,J/\psi J/\psi} > 3$ GeV)



Double J/ψ production cross-section (LHCb, $\sqrt{s} = 13$ TeV)

Comparison of differential cross section with predictions ($p_{T,J/\psi J/\psi} > 3$ GeV)



Double J/ψ production cross-section (LHCb, $\sqrt{s} = 13$ TeV)

DPS fraction from fits

Variable	LO CS	LO k_T	NLO* CS′	NLO* CS″ $\langle k_T \rangle = 2\,\text{GeV}/c$	NLO* CS″ $\langle k_T \rangle = 0.5\,\text{GeV}/c$
no $p_T(J/\psi\, J/\psi)$ cut					
$p_T(J/\psi\, J/\psi)$	—	78 ± 2	—	86 ± 55	81 ± 7
$y(J/\psi\, J/\psi)$	83 ± 39	—	—	75 ± 37	68 ± 34
$m(J/\psi\, J/\psi)$	76 ± 7	74 ± 7	—	78 ± 7	
$\lvert\Delta y\rvert$	59 ± 21	61 ± 18	—	63 ± 18	61 ± 18
$p_T(J/\psi\, J/\psi) > 1\,\text{GeV}/c$					
$y(J/\psi\, J/\psi)$	—	—	75 ± 24	71 ± 38	68 ± 34
$m(J/\psi\, J/\psi)$	—	73 ± 8	76 ± 7	88 ± 1	
$\lvert\Delta y\rvert$	—	57 ± 20	59 ± 19	60 ± 18	60 ± 19
$p_T(J/\psi\, J/\psi) > 3\,\text{GeV}/c$					
$y(J/\psi\, J/\psi)$	—	—	77 ± 18	64 ± 38	64 ± 35
$m(J/\psi\, J/\psi)$	—	76 ± 10	84 ± 7	87 ± 2	
$\lvert\Delta y\rvert$	—	42 ± 25	53 ± 21	53 ± 21	53 ± 21

$\mathcal{B}(B^0_{d,s} \to J/\psi p\bar{p})$: strategy & signal extraction (LHCb)

$$\frac{\mathcal{B}(B^0_d \to J/\psi p\bar{p})}{\mathcal{B}(B^0_s \to J/\psi \phi) \cdot \mathcal{B}(\phi \to K^+K^-) \cdot \frac{f_s}{f_d}} = (0.329 \pm 0.029 \pm 0.022) \times 10^{-2}$$

$$\frac{\mathcal{B}(B^0_s \to J/\psi p\bar{p})}{\mathcal{B}(B^0_s \to J/\psi \phi) \cdot \mathcal{B}(\phi \to K^+K^-)} = (0.706 \pm 0.037 \pm 0.048) \times 10^{-2}$$

$\mathcal{B}(B^+ \to J/\psi \bar{\Lambda}^0 p)$: mass spectra (CMS)

Phase space correction for $K^{*+} \to \bar{\Lambda}^0 p$ resonances reflection

Resonance	Mass [MeV]	Natural width [MeV]	J^P
$K_4^*(2045)^+$	2045 ± 9	198 ± 30	4^+
$K_2^*(2250)^+$	2247 ± 17	180 ± 30	2^-
$K_3^*(2320)^+$	2324 ± 24	150 ± 30	3^+

$$\frac{dN}{d\cos\theta_{K^*}} = \sum_{j=0}^{l_{\max}} \left\langle P_j^U \right\rangle P_j(\cos\theta_{K^*}) \quad ; \quad \left\langle P_j^U \right\rangle = \sum_{i=1}^{N_{\text{reco}}} \frac{1}{\epsilon_i} P_j(\cos\theta_{K^*})$$

$$w_i = 1 + \sum_{j=0}^{l_{\max}} \left\langle P_j^N \right\rangle P_j(\cos\theta_{K^*}) \quad ; \quad \left\langle P_j^N \right\rangle = \frac{2\left\langle P_j^U \right\rangle}{N_{\text{reco}}^{\text{corr}}}$$