Quarkonium production and polarization: a review over relevant experiments

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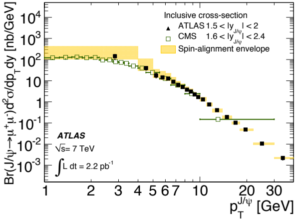
(http://www.coepp.org.au/)

XIth International Conference on Heavy Quarks and Leptons,
Charles University, Prague; 11th June 2012



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Outline

1. **Status: clarification needed from experiment**
2. **Polarization:**
   - Review of principles
   - Developments in experimental practice
3. **Reconstruction performance**
4. **Spectroscopy**
5. **Differential cross-sectons**
   - $\Upsilon(nS)$ states
   - J/ψ and $\psi(2S)$
6. **Production ratios**
7. **Study of richer final states**
8. **Summary**

Status: one thing that's clear is that little is clear

QWG review: Eur. Phys. J. C 71, 1534 (2011) {arXiv:1010.5827v3 [hep-ph]}

> Despite recent theoretical advances, which we shall detail below, we are still lacking a clear picture of the mechanisms at work in quarkonium hadroproduction. These mechanisms would have to explain, in a consistent way, both the cross section measurements and the polarization measurements for charmonium production at the Tevatron [329, 628, 650, 655–658] and at RHIC [659–664]. For example, the observed p_T spectra in prompt ψ production seem to suggest that a dominant contribution at large p_T arises from a color-octet process in which a gluon fragments into a $Q\bar{Q}$ pair, which then evolves nonrelativistically into a quarkonium. Because of the approximate heavy-quark spin symmetry of NRQCD, the dominance of such a process would lead to a substantial transverse component for the polarization of ψ's produced at large p_T [665–667]. This prediction is clearly challenged by the experimental measurements [658].

- no consistent theoretical account
- some serious disagreements: →
  [figure: CDF; PRL **99**, 132001 (2007)]
- ∃ experimental disagreements too

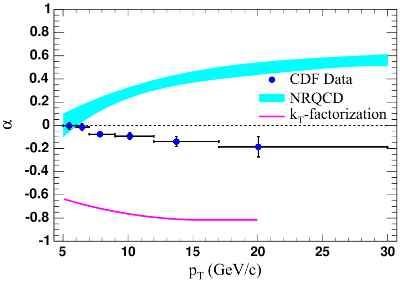

Fig. 55 The polarization parameter α for prompt J/ψ production in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV as a function of p_T. The *points* are the CDF data [658], the *band* is the prediction from LO NRQCD factorization [667], and the *line* is the prediction from k_T factorization [640]. The theoretical uncertainty in the LO NRQCD factorization prediction was obtained by combining the uncertainties from the parton distributions (estimated by comparing the MRST98LO [732] and the CTEQ5L [733] distributions), the uncertainties from the color-octet NRQCD long-distance matrix elements, the uncertainties that are obtained by varying m_c in the range 1.45 GeV < m_c < 1.55 GeV, and the uncertainties that are obtained by varying the factorization and renormalization scales in the range $0.5m_T < \mu_f = \mu_r < 2m_T$.

Polarization (1): general description

Faccioli, Lourenço, Seixas, and Wöhri, EPJC 69, 657–673 (2010)

for $(J^{PC} = 1^{--})$ $|V\rangle = b_{+1}\,|+1\rangle + b_{-1}\,|-1\rangle + b_0\,|0\rangle$ decaying $\rightarrow \ell^+\ell^-$,

- the angular distribution $W(\cos\vartheta, \varphi)$

$$\propto \frac{\mathcal{N}}{(3+\lambda_\vartheta)}\,(1 + \lambda_\vartheta \cos^2\vartheta$$

$$+\ \lambda_\varphi \sin^2\vartheta \cos 2\varphi \ +\ \lambda_{\vartheta\varphi} \sin 2\vartheta \cos\varphi$$

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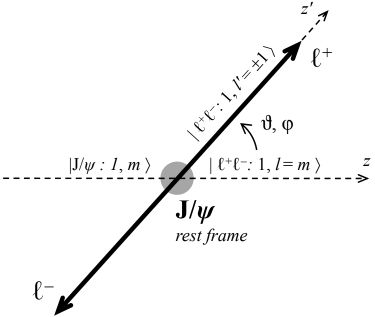

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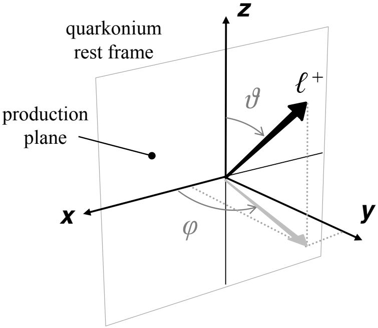

- inclusive production: p_1, p_2, and V only;
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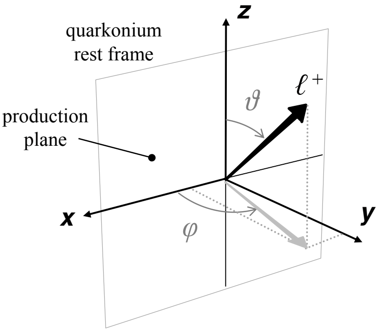

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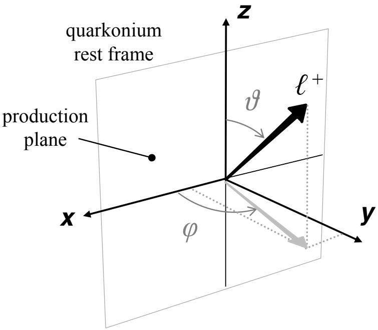

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Polarization (2): choice of frame

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different definitions of the z axis are used, each with motivation:

helicity:
Q direction-of-flight

Gottfried-Jackson:
dir^n of one beam

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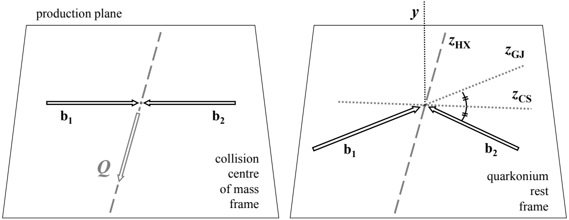

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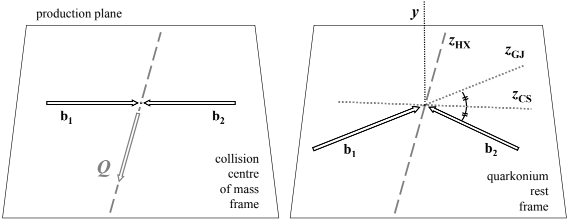

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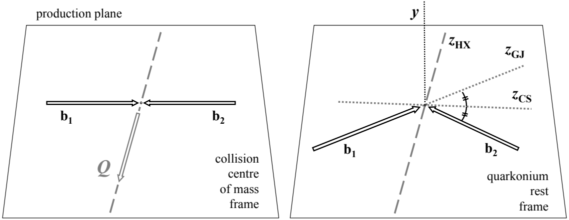

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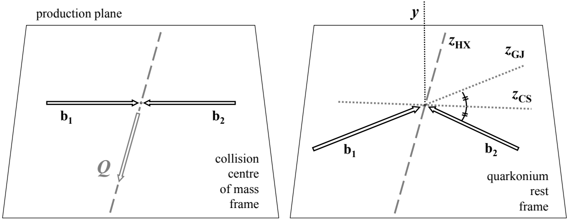

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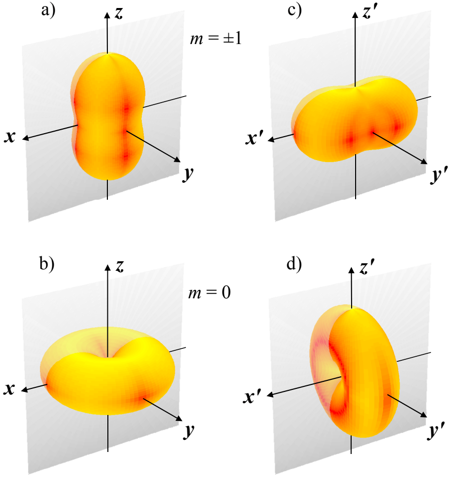
- angles between frames vary event-to-event
  $\longrightarrow$ choice of a more *natural* frame can give greater sensitivity
- full angular distributions (λ_ϑ, λ_φ, $\lambda_{\vartheta\varphi}$) in general needed …

Polarization (3): pitfalls of incomplete treatment

Faccioli, Lourenço, Seixas, and Wöhri, EPJC 69, 657–673 (2010)

- L: polarized { transversely / longitudinally



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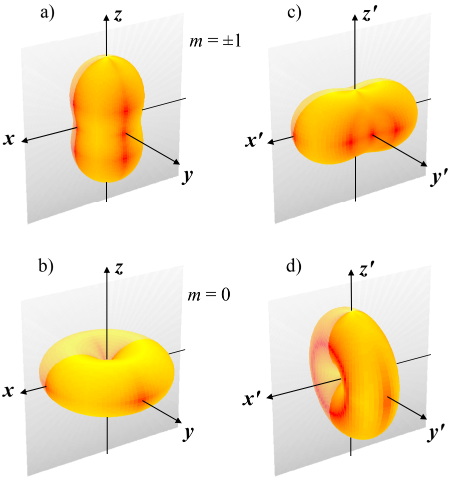

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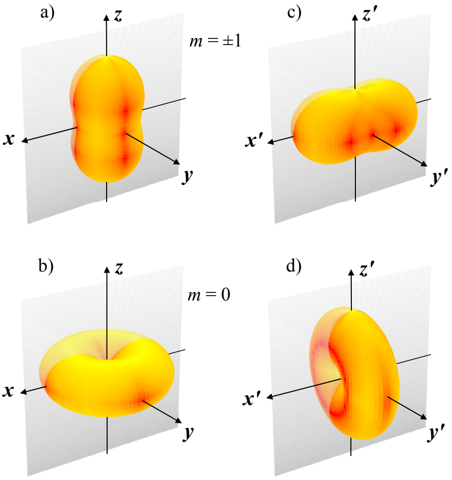

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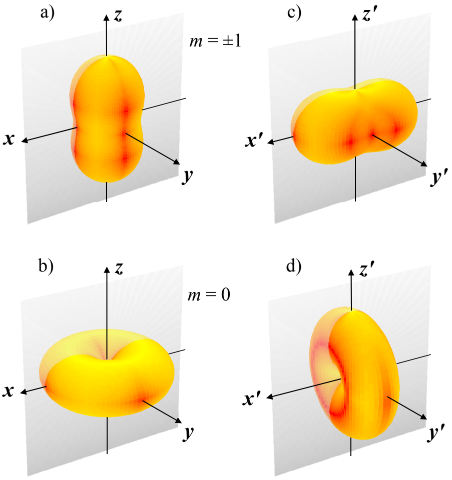

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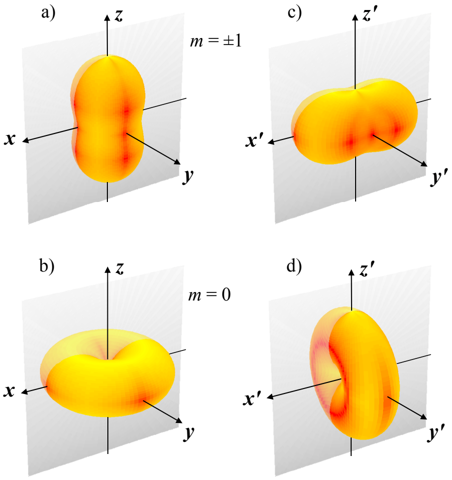

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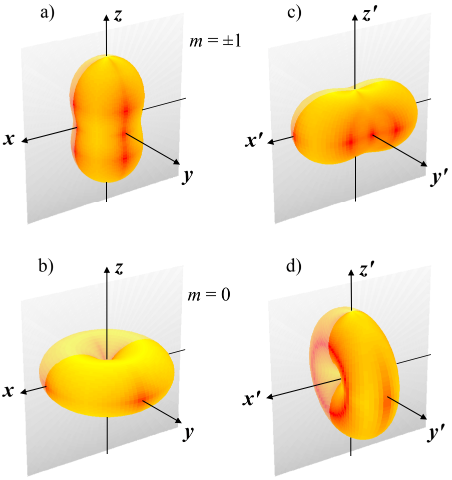
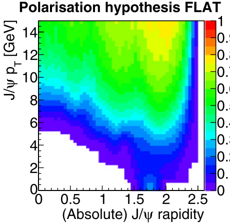
- if frames differ, traditional λ_ϑ-only meas^{ts} can't be compared w/o assumptions
- *experimental acceptance* is also typically a f^n of $(\lambda_\vartheta, \lambda_\varphi, \lambda_{\vartheta\varphi})$

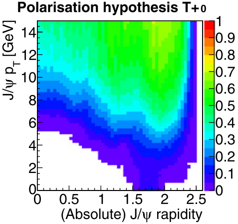


Polarization (4): treatment in new J/ψ x-sections

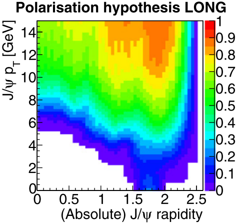
ATLAS: NPB 850, 387; cf. CMS: EPJC 71, 1575; LHCb: EPJC 71, 1645 (2011)



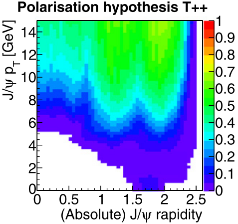
(a) $\lambda_\theta = \lambda_\phi = \lambda_{\theta\phi} = 0$



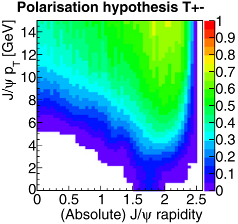
(b) $\lambda_\theta = +1, \lambda_\phi = \lambda_{\theta\phi} = 0$



(c) $\lambda_\theta = -1, \lambda_\phi = \lambda_{\theta\phi} = 0$



(d) $\lambda_\theta = +1, \lambda_\phi = +1, \lambda_{\theta\phi} = 0$



(e) $\lambda_\theta = +1, \lambda_\phi = -1, \lambda_{\theta\phi} = 0$

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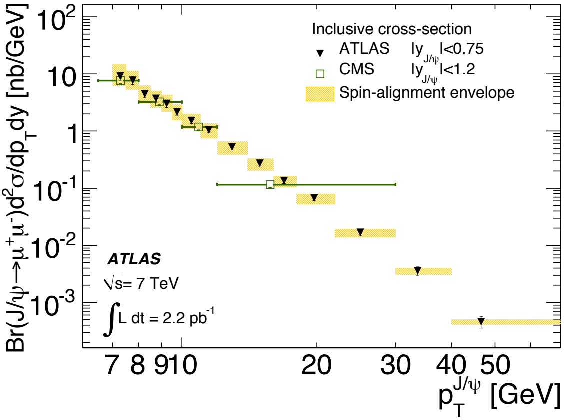

low rapidity $\begin{cases} \text{ATLAS with } 2.3 \text{ pb}^{-1} \\ \text{CMS with } 0.314\,\text{pb}^{-1} \end{cases}$

[large stats increase from CMS later in this talk]

Polarization (4): treatment in new J/ψ x-sections

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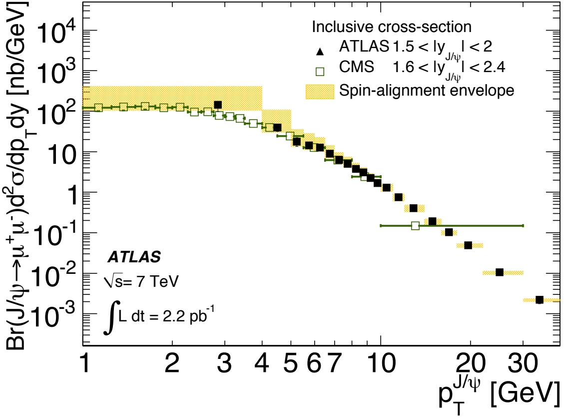

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p_T(GeV/c)	$2.0 < y < 2.5$	$2.5 < y < 3.0$	$3.0 < y < 3.5$	$3.5 < y < 4.0$	$4.0 < y < 4.5$
0–1	$1091 \pm 70 \pm 226 \pm 144$	$844 \pm 13 \pm 133 \pm 111$	$749 \pm 7 \pm 46 \pm 99$	$614 \pm 6 \pm 23 \pm 81$	$447 \pm 5 \pm 28 \pm 59$
1–2	$1495 \pm 38 \pm 282 \pm 197$	$1490 \pm 12 \pm 39 \pm 197$	$1376 \pm 8 \pm 26 \pm 182$	$1101 \pm 7 \pm 23 \pm 145$	$807 \pm 7 \pm 28 \pm 107$
2–3	$1225 \pm 20 \pm 109 \pm 162$	$1214 \pm 9 \pm 24 \pm 160$	$1053 \pm 7 \pm 19 \pm 139$	$839 \pm 6 \pm 19 \pm 111$	$588 \pm 6 \pm 22 \pm 78$
3–4	$777 \pm 11 \pm 44 \pm 103$	$719 \pm 6 \pm 18 \pm 95$	$611 \pm 5 \pm 14 \pm 81$	$471 \pm 4 \pm 13 \pm 62$	$315 \pm 4 \pm 14 \pm 42$
4–5	$424 \pm 6 \pm 22 \pm 56$	$392 \pm 3 \pm 12 \pm 52$	$325 \pm 3 \pm 9 \pm 43$	$244 \pm 3 \pm 7 \pm 32$	$163 \pm 3 \pm 6 \pm 22$
5–6	$230 \pm 4 \pm 12 \pm 30$	$206 \pm 2 \pm 8 \pm 27$	$167 \pm 2 \pm 5 \pm 22$	$119 \pm 2 \pm 5 \pm 16$	$76 \pm 2 \pm 3 \pm 10$
6–7	$116 \pm 2 \pm 6 \pm 15$	$104 \pm 1 \pm 4 \pm 14$	$82 \pm 1 \pm 3 \pm 11$	$59 \pm 1 \pm 2 \pm 8$	$34 \pm 1.1 \pm 1.4 \pm 4.5$
7–8	$64 \pm 1 \pm 3 \pm 8$	$57 \pm 1 \pm 3 \pm 7$	$44 \pm 1 \pm 1 \pm 6$	$29 \pm 1 \pm 1 \pm 4$	$17 \pm 0.7 \pm 0.8 \pm 2.3$
8–9	$37 \pm 1 \pm 1 \pm 5$	$31 \pm 1 \pm 1 \pm 4$	$23 \pm 1 \pm 1 \pm 3$	$15.9 \pm 0.5 \pm 0.1 \pm 2.1$	$8.5 \pm 0.5 \pm 0.4 \pm 1.1$
9–10	$19.3 \pm 0.7 \pm 0.5 \pm 2.6$	$17.4 \pm 0.5 \pm 0.2 \pm 2.3$	$12.6 \pm 0.4 \pm 0.1 \pm 1.7$	$8.2 \pm 0.4 \pm 0.1 \pm 1.1$	$4.1 \pm 0.3 \pm 0.2 \pm 0.5$
10–11	$11.6 \pm 0.5 \pm 0.3 \pm 1.5$	$9.8 \pm 0.4 \pm 0.1 \pm 1.3$	$7.8 \pm 0.3 \pm 0.1 \pm 1.0$	$4.9 \pm 0.3 \pm 0.1 \pm 0.6$	$2.2 \pm 0.2 \pm 0.1 \pm 0.3$
11–12	$6.7 \pm 0.4 \pm 0.2 \pm 0.9$	$5.9 \pm 0.3 \pm 0.1 \pm 0.8$	$4.5 \pm 0.3 \pm 0.1 \pm 0.6$	$2.6 \pm 0.2 \pm 0.1 \pm 0.3$	
12–13	$4.6 \pm 0.3 \pm 0.2 \pm 0.6$	$3.5 \pm 0.2 \pm 0.1 \pm 0.5$	$2.9 \pm 0.2 \pm 0.1 \pm 0.4$	$1.2 \pm 0.1 \pm 0.1 \pm 0.2$	
13–14	$2.9 \pm 0.3 \pm 0.1 \pm 0.4$	$2.6 \pm 0.2 \pm 0.1 \pm 0.3$	$1.3 \pm 0.2 \pm 0.1 \pm 0.2$		

LHCb $\frac{d^2\sigma}{dp_T dy}$, for no polarization

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1–2	$1751 \pm 44 \pm 331 \pm 231$	$1791 \pm 15 \pm 47 \pm 236$	$1603 \pm 10 \pm 31 \pm 212$	$1246 \pm 8 \pm 26 \pm 164$	$902 \pm 7 \pm 31 \pm 119$
2–3	$1438 \pm 24 \pm 129 \pm 190$	$1423 \pm 11 \pm 28 \pm 188$	$1182 \pm 7 \pm 21 \pm 156$	$913 \pm 6 \pm 21 \pm 120$	$631 \pm 6 \pm 24 \pm 83$
3–4	$932 \pm 13 \pm 53 \pm 123$	$839 \pm 7 \pm 21 \pm 111$	$675 \pm 5 \pm 15 \pm 89$	$505 \pm 4 \pm 14 \pm 67$	$334 \pm 4 \pm 15 \pm 44$
4–5	$513 \pm 7 \pm 27 \pm 68$	$455 \pm 4 \pm 14 \pm 60$	$358 \pm 3 \pm 10 \pm 47$	$262 \pm 3 \pm 8 \pm 35$	$172 \pm 3 \pm 7 \pm 23$
5–6	$278 \pm 4 \pm 15 \pm 37$	$238 \pm 3 \pm 9 \pm 32$	$184 \pm 2 \pm 6 \pm 24$	$128 \pm 2 \pm 5 \pm 17$	$79 \pm 2 \pm 3 \pm 11$
6–7	$140 \pm 3 \pm 7 \pm 19$	$120 \pm 2 \pm 5 \pm 16$	$91 \pm 1 \pm 3 \pm 12$	$63 \pm 1 \pm 2 \pm 8$	$36 \pm 1 \pm 2 \pm 5$
7–8	$76 \pm 2 \pm 4 \pm 10$	$64 \pm 1 \pm 3 \pm 8$	$49 \pm 1 \pm 2 \pm 6$	$32 \pm 1 \pm 1 \pm 4$	$18.3 \pm 0.7 \pm 0.8 \pm 2.4$
8–9	$44 \pm 1 \pm 1 \pm 6$	$34 \pm 1 \pm 1 \pm 5$	$25 \pm 1 \pm 1 \pm 3$	$17.1 \pm 0.6 \pm 0.2 \pm 2.3$	$8.9 \pm 0.5 \pm 0.4 \pm 1.2$
9–10	$23 \pm 1 \pm 1 \pm 3$	$19.3 \pm 0.6 \pm 0.2 \pm 2.6$	$13.7 \pm 0.5 \pm 0.1 \pm 1.8$	$8.8 \pm 0.4 \pm 0.1 \pm 1.2$	$4.3 \pm 0.3 \pm 0.2 \pm 0.5$
10–11	$13.5 \pm 0.6 \pm 0.4 \pm 1.8$	$10.9 \pm 0.4 \pm 0.1 \pm 1.4$	$8.5 \pm 0.4 \pm 0.1 \pm 1.1$	$5.2 \pm 0.3 \pm 0.1 \pm 0.7$	$2.4 \pm 0.2 \pm 0.1 \pm 0.3$
11–12	$7.7 \pm 0.4 \pm 0.3 \pm 1.0$	$6.4 \pm 0.3 \pm 0.1 \pm 0.8$	$4.9 \pm 0.3 \pm 0.1 \pm 0.6$	$2.8 \pm 0.2 \pm 0.1 \pm 0.4$	
12–13	$5.2 \pm 0.3 \pm 0.2 \pm 0.7$	$3.8 \pm 0.3 \pm 0.1 \pm 0.5$	$3.1 \pm 0.2 \pm 0.1 \pm 0.4$	$1.3 \pm 0.1 \pm 0.1 \pm 0.2$	
13–14	$3.3 \pm 0.3 \pm 0.1 \pm 0.4$	$2.8 \pm 0.2 \pm 0.1 \pm 0.4$	$1.4 \pm 0.2 \pm 0.1 \pm 0.2$		

LHCb $\frac{d^2\sigma}{dp_T dy}$, for transverse polarization

Polarization (4): treatment in new J/ψ x-sections

ATLAS: NPB 850, 387; cf. CMS: EPJC 71, 1575; LHCb: EPJC 71, 1645 (2011)

p_T(GeV/c)	$2.0 < y < 2.5$	$2.5 < y < 3.0$	$3.0 < y < 3.5$	$3.5 < y < 4.0$	$4.0 < y < 4.5$
0–1	$839 \pm 54 \pm 174 \pm 111$	$601 \pm 9 \pm 94 \pm 79$	$543 \pm 5 \pm 33 \pm 72$	$468 \pm 4 \pm 21 \pm 62$	$341 \pm 4 \pm 21 \pm 45$
1–2	$1157 \pm 29 \pm 219 \pm 153$	$1114 \pm 9 \pm 29 \pm 147$	$1073 \pm 7 \pm 21 \pm 142$	$892 \pm 5 \pm 18 \pm 118$	$667 \pm 6 \pm 23 \pm 88$
2–3	$945 \pm 16 \pm 84 \pm 125$	$938 \pm 7 \pm 19 \pm 124$	$865 \pm 5 \pm 16 \pm 114$	$721 \pm 5 \pm 16 \pm 95$	$517 \pm 5 \pm 20 \pm 68$
3–4	$583 \pm 8 \pm 33 \pm 77$	$559 \pm 4 \pm 14 \pm 74$	$514 \pm 4 \pm 11 \pm 68$	$415 \pm 3 \pm 12 \pm 55$	$282 \pm 4 \pm 13 \pm 37$
4–5	$315 \pm 4 \pm 16 \pm 42$	$307 \pm 3 \pm 9 \pm 41$	$274 \pm 2 \pm 8 \pm 36$	$215 \pm 2 \pm 7 \pm 28$	$148 \pm 2 \pm 6 \pm 20$
5–6	$171 \pm 3 \pm 9 \pm 23$	$163 \pm 2 \pm 6 \pm 22$	$140 \pm 2 \pm 4 \pm 19$	$104 \pm 1 \pm 4 \pm 14$	$69 \pm 2 \pm 3 \pm 9$
6–7	$87 \pm 2 \pm 5 \pm 12$	$83 \pm 1 \pm 3 \pm 11$	$70 \pm 1 \pm 3 \pm 9$	$51 \pm 1 \pm 2 \pm 7$	$31 \pm 1 \pm 1 \pm 4$
7–8	$48 \pm 1 \pm 2 \pm 6$	$46 \pm 1 \pm 2 \pm 6$	$38 \pm 1 \pm 1 \pm 5$	$26 \pm 1 \pm 1 \pm 3$	$15.8 \pm 0.6 \pm 0.7 \pm 2.1$
8–9	$29 \pm 1 \pm 1 \pm 4$	$25 \pm 1 \pm 1 \pm 3$	$19.8 \pm 0.5 \pm 0.1 \pm 2.6$	$13.9 \pm 0.5 \pm 0.1 \pm 1.8$	$7.6 \pm 0.4 \pm 0.3 \pm 1.0$
9–10	$14.9 \pm 0.5 \pm 0.4 \pm 2.0$	$14.5 \pm 0.4 \pm 0.2 \pm 1.9$	$10.8 \pm 0.4 \pm 0.1 \pm 1.4$	$7.1 \pm 0.3 \pm 0.1 \pm 0.9$	$3.6 \pm 0.3 \pm 0.2 \pm 0.5$
10–11	$9.1 \pm 0.4 \pm 0.3 \pm 1.2$	$8.3 \pm 0.3 \pm 0.1 \pm 1.1$	$6.7 \pm 0.3 \pm 0.1 \pm 0.9$ 10–11	$4.3 \pm 0.2 \pm 0.1 \pm 0.6$	$2.0 \pm 0.2 \pm 0.1 \pm 0.3$
11–12	$5.3 \pm 0.3 \pm 0.2 \pm 0.7$	$5.0 \pm 0.3 \pm 0.1 \pm 0.7$	$4.0 \pm 0.2 \pm 0.1 \pm 0.5$	$2.3 \pm 0.2 \pm 0.1 \pm 0.3$	
12–13	$3.7 \pm 0.2 \pm 0.1 \pm 0.5$	$3.0 \pm 0.2 \pm 0.1 \pm 0.4$	$2.5 \pm 0.2 \pm 0.1 \pm 0.4$	$1.0 \pm 0.1 \pm 0.1 \pm 0.1$	
13–14	$2.3 \pm 0.2 \pm 0.1 \pm 0.3$	$2.3 \pm 0.2 \pm 0.1 \pm 0.3$	$1.2 \pm 0.1 \pm 0.1 \pm 0.2$		

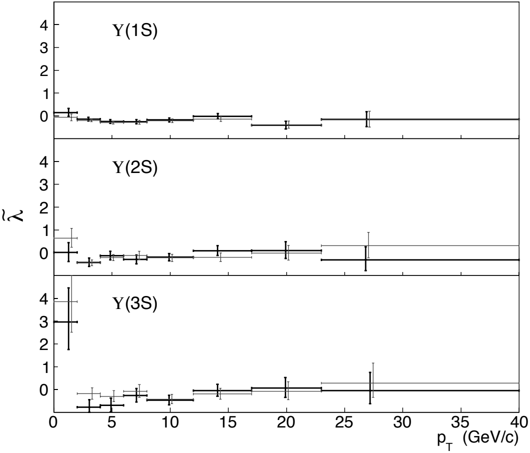
LHCb $\frac{d^2\sigma}{dp_T dy}$, for longitudinal polarization

Polarization (5): measurement for Υ(nS) at CDF

CDF: Physical Review Letters 108, 151802 (2012)

from 6.7 fb^{-1} in Run II: {550k, 150k, 76k} $\Upsilon(1S, 2S, 3S)$ events

- invariant $\tilde{\lambda} = \frac{\lambda_\vartheta + 3\lambda_\varphi}{1-\lambda_\varphi}$ determined in both helicity & CS frames
  — consistent save first few 3S bins



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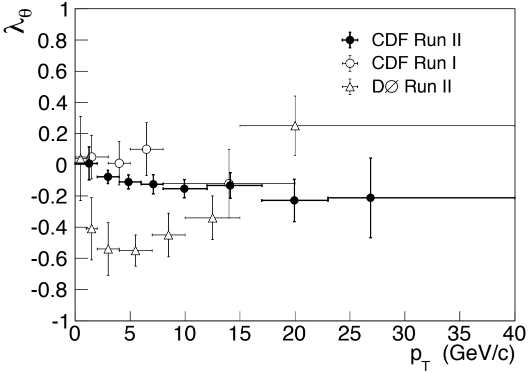

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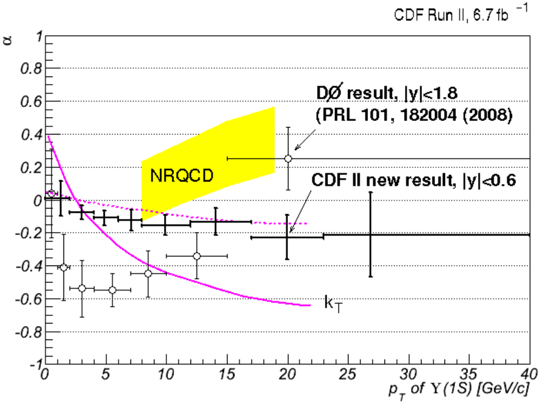
- confirms tension with older NRQCD calculations . . .



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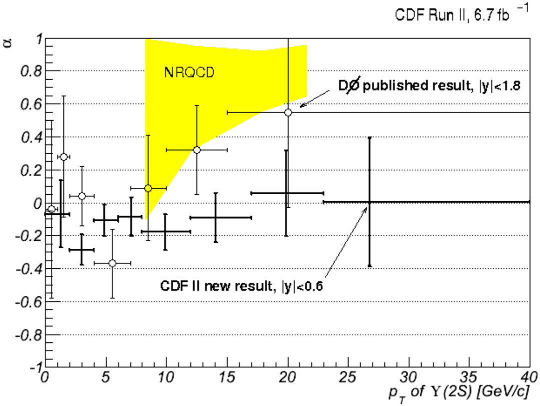

- $\Upsilon(2S)$: qualitatively similar conclusions; less power

Polarization (5): measurement for $\Upsilon(nS)$ at CDF

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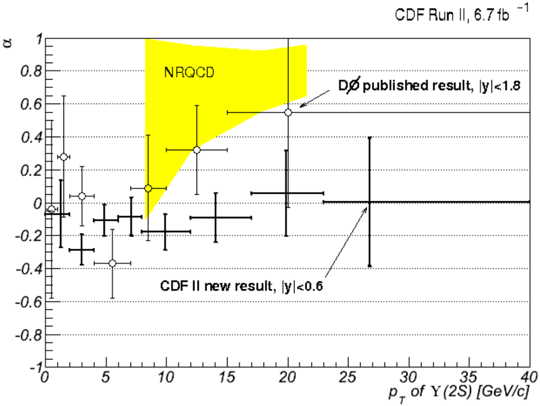
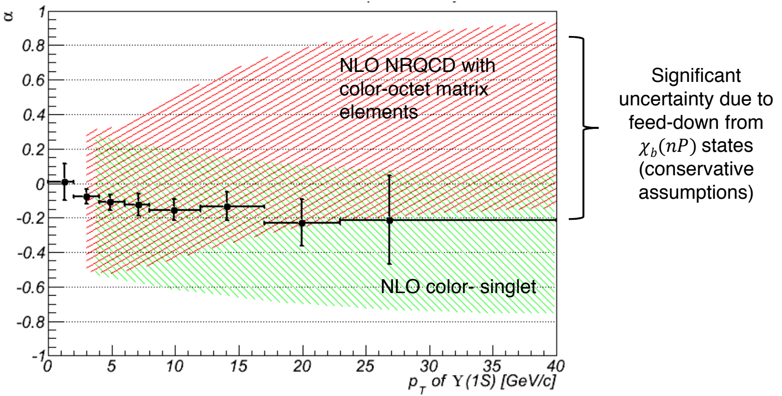


- $\Upsilon(2S)$: qualitatively similar conclusions; less power
- thorough polarization meas^{ts} in (p_T, η) underway at the LHC exp^{ts} . . .

Polarization (5): measurement for $\Upsilon(nS)$ at CDF

CDF: from Matthew Jones' presentation 2012/03/02 @ Fermilab

calculations have since moved on . . .



Nucl. Phys. B 214, 3 (2011) summary:

- NLO NRQCD – Gong, Wang & Zhang, Phys. Rev. D83, 114021 (2011)
- Color-singlet NLO and NNLO* - Artoisenet, *et al.* Phys. Rev. Lett. 101, 152001 (2008)

Performance: reconstruction of basic samples

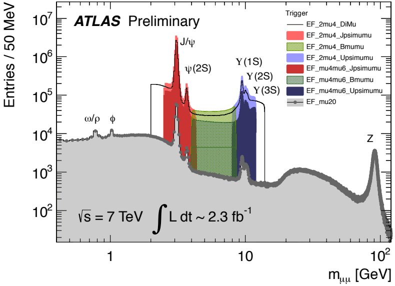
CENTRAL experiments: →

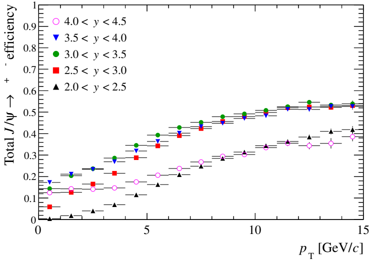
triggers on $\mu(\mu)$ with high-p_T, low-p_T threshold, & $M(\mu\mu)$-restricted-samples

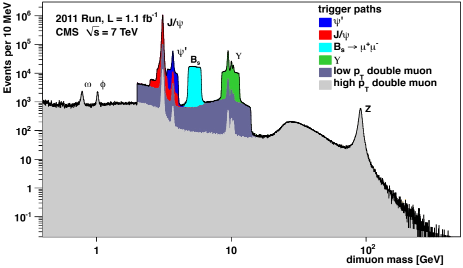
- increasing $\mathcal{L}$ → higher-p_T triggers
- p_T^{μ}-dependence → acceptance $\mathcal{A}^{\psi,\Upsilon}(p_T, y)$ *polarization*-dependent

FORWARD (LHCb): ↓

- ϵ reduced at low- & high-y
- polarization → 3–30% changes



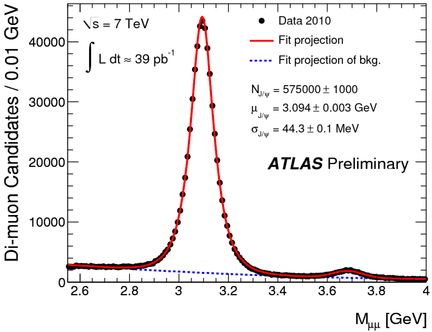


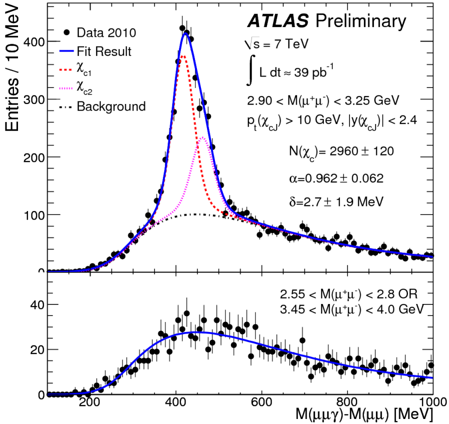


Performance: reconstruction of higher states

ATLAS χ_{cJ}(1P) observation: ATLAS-CONF-2011-136

from the 2010 data: $p_t^{\chi} > 10\,\mathrm{GeV}$, $|y^{\chi}| < 2.4$; $\cos(\Phi^{lab}_{(\psi,\gamma)}) > 0.99$





sim. fit to signal and sideband regions in $J/\psi \to \mu^+\mu^-$; bkgd modelling (2.3%) dominates yield systematics (3.0%)

Performance: reconstruction of higher states

CMS X(3872) & ψ(2S) production ratio: BPH-10-018-PAS

from the 2010 data:

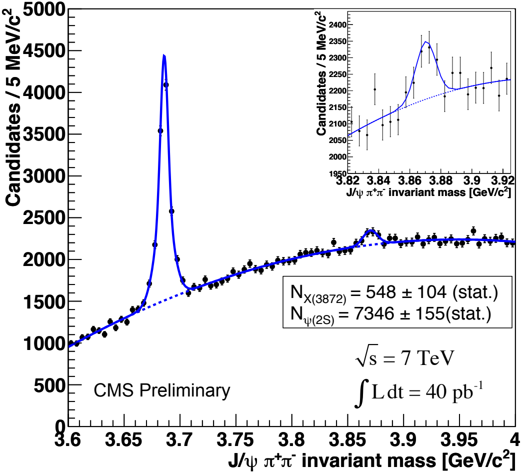
$p_t^X > 8\,\mathrm{GeV}$, $|y^X| < 2.2$,

$$R = \frac{\sigma(\mathrm{pp} \to X + \text{any}) \times \mathcal{B}_{X\to\pi\pi\psi}}{\sigma(\mathrm{pp} \to \psi' + \text{any}) \times \mathcal{B}_{\psi'\to\pi\pi\psi}}$$
$$= 0.087 \pm 0.017 \pm 0.009$$

non-prompt fraction:

30% assumed ($\approx$ TeVatron),
consistent with studies;
$[20\%, 40\%] \to 6\%$ variat^n in R

cf. 2011 data ...



Performance: reconstruction of higher states

CMS X(3872) observation, & ψ(2S): DPS-2011/009

Fit:
Unbinned maximum likelihood fit.
J/ψ mass fixed to the PDG value.

Fit results:

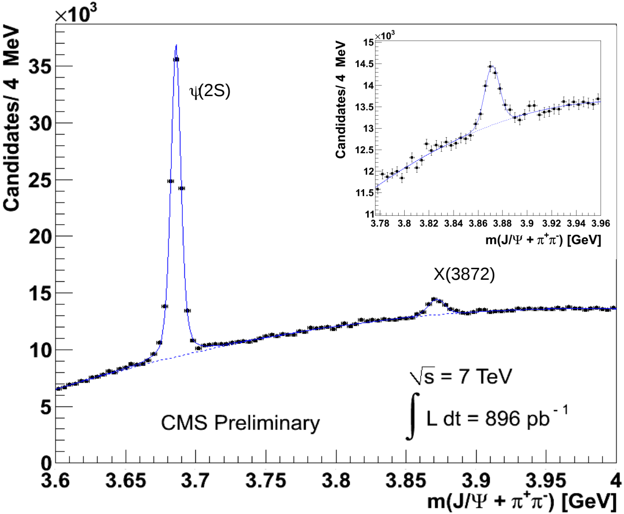
ψ(2S) Voigtian:
μ = 3685.90 ± 0.02 MeV
σ = 3.2 ± 0.1 MeV
γ = 0.00283 ± 0.00005
N = 72594 ± 518

X(3872) Gaussian:
μ = 3871.5 ± 0.5 MeV
σ = 6.1 ± 0.4 MeV
N = 5303 ± 341

Chebychev Polynomial:
c1 = 0.321 ± 0.002
c2 = -0.091 ± 0.002

χ^2/ndf = 0.99

PDG mass values:
ψ(2S) = 3686.09 ± 0.04 MeV
X(3872) = 3871.57 ± 0.25 MeV



Performance: reconstruction of higher states

LHCb X(3872) production: EPJC 72, 1972 (2012) {arXiv:1112.5310v1 [hep-ex]}

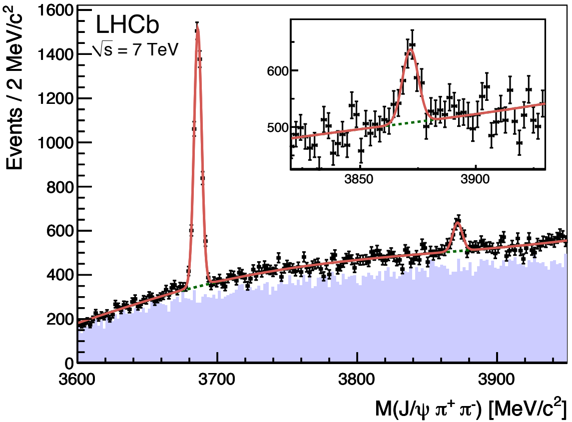
<ins>from the 2010 data:</ins>

$p_t^X \in [5, 20]\,\mathrm{GeV}$,
$y^X \in [2.5, 4.5]$;

$\sigma(\mathrm{pp} \to X + \text{any}) \times \mathcal{B}_{X\to\pi\pi\psi}$
$= 5.4 \pm 1.3 \pm 0.8\,\mathrm{nb}$;

2.4σ below $13.0 \pm 2.7\,\mathrm{nb}$ (Artoisenet & Braaten, PRD **81**, 114018 (2010))

mass measurement is already 2nd-most precise (after Belle 2011)



$$m_X = 3871.95 \pm 0.48\,(\text{stat.}) \pm 0.12\,(\text{syst.})\,\mathrm{MeV}/c^2$$

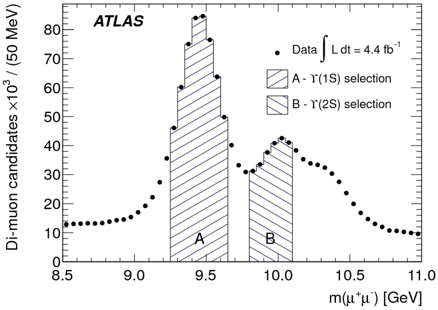
cf. WA $= 3871.71 \pm 0.19\,\mathrm{MeV}/c^2$ (private, from QWG2011/Darmstadt)

Spectroscopy: observation of the $\chi_b(nP)$ states

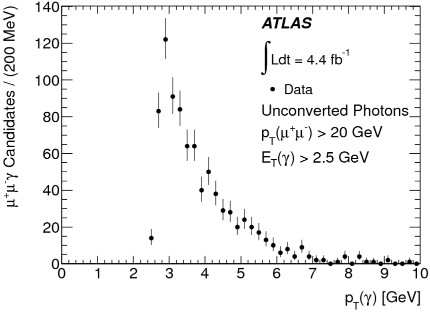
ATLAS: PRL 108, 152001 (2012) {1112.5154}; DØ conf^n: 1203.6034 → PRD(RC)

from 2011 data: "combined" muon tracks, $p_T > 4\,\text{GeV}$, $|\eta| < 2.3$;
well-vertexed $\mu^+\mu^-$: $p_T > 12\,\text{GeV}$, $|y| < 2.0$

$\Upsilon(1S)$ and $(2S) \to \mu^+\mu^-$ sel^n



unconverted photon selection

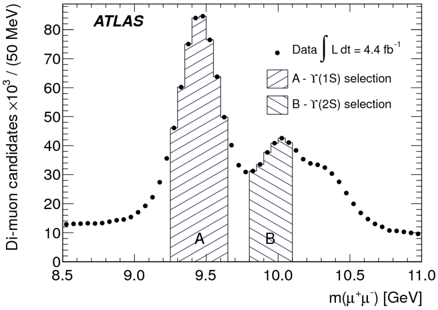


Spectroscopy: observation of the χ_b(nP) states

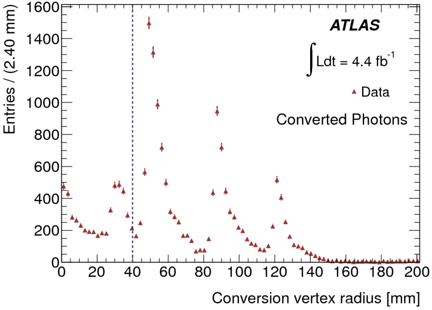
ATLAS: PRL 108, 152001 (2012) {1112.5154}; **DØ conf^n:** 1203.6034 → **PRD(RC)**

from 2011 data: "combined" muon tracks, $p_T > 4\,\mathrm{GeV}$, $|\eta| < 2.3$;
well-vertexed $\mu^+\mu^-$: $p_T > 12\,\mathrm{GeV}$, $|y| < 2.0$

$\Upsilon(1S)$ and $(2S) \to \mu^+\mu^-$ sel^n



converted photon vertices (xy)

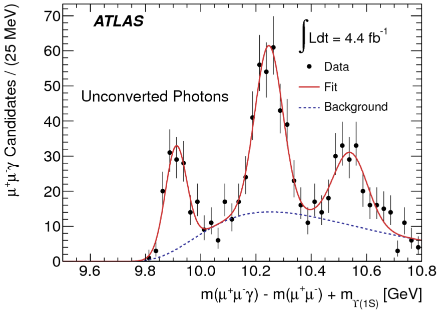


Spectroscopy: observation of the χ_b(nP) states

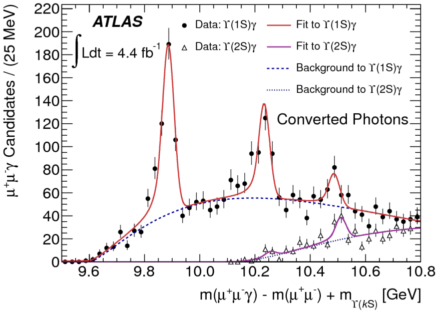
ATLAS: PRL 108, 152001 (2012) {1112.5154}; **DØ conf^n:** 1203.6034 → **PRD(RC)**

from 2011 data: "combined" muon tracks, $p_T > 4\,\mathrm{GeV}$, $|\eta| < 2.3$;
well-vertexed $\mu^+\mu^-$: $p_T > 12\,\mathrm{GeV}$, $|y| < 2.0$

$\chi_b \to \gamma_{\text{uncon}}\Upsilon(1S)$ fit



$\chi_b \to \gamma_{\text{convert}}\Upsilon(nS)$ fit



Spectroscopy: observation of the $\chi_b(nP)$ states

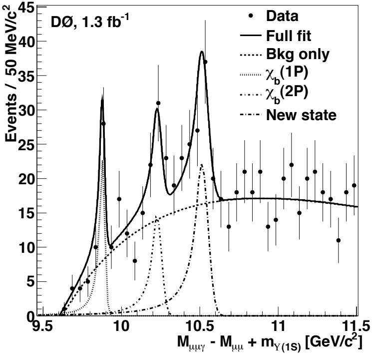
ATLAS: PRL 108, 152001 (2012) {1112.5154}; **DØ conf^n:** 1203.6034 → **PRD(RC)**

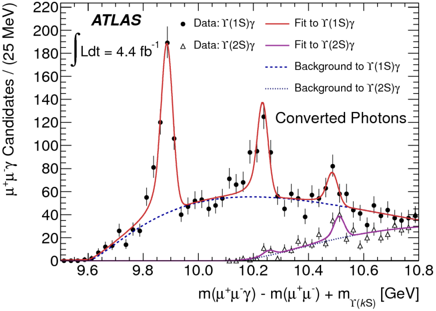
from 2011 data: "combined" muon tracks, $p_T > 4\,\mathrm{GeV}$, $|\eta| < 2.3$;

well-vertexed $\mu^+\mu^-$: $p_T > 12\,\mathrm{GeV}$, $|y| < 2.0$

DØ confirmation (also conversions)

$\chi_b \to \gamma_{\text{convert}} \Upsilon(nS)$ fit





Spectroscopy: first observation of the $\chi_{bJ}(3P)$

ATLAS: PRL 108, 152001 (2012) {1112.5154}; **DØ conf^n:** 1203.6034 → **PRD(RC)**

$\chi_b(3P)$ significance $> 6\sigma$ in each sample;

for the photon conversions:

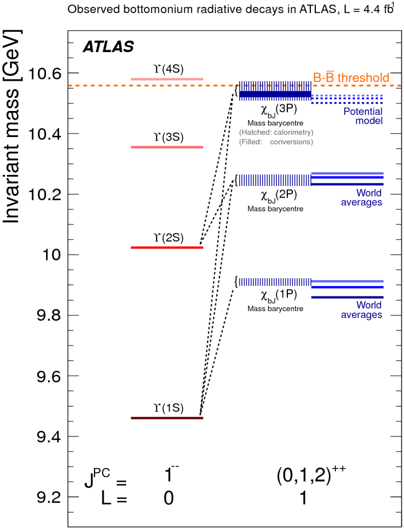
- $\chi_{b0} \to \gamma\Upsilon$ suppressed: omitted
- $\chi_{b1,b2}(1P, 2P)$ fixed to WA
- $\chi_{b1,b2}(3P)$ splitting $= 12\,\mathrm{MeV}$ assumed

$\chi_b(3P)$ barycenter $\tilde{m}_3$ determination:

calo.	$10.541 \pm 0.011 \pm 0.030\,\mathrm{GeV}$
conv^{ns}	$10.530 \pm 0.005 \pm 0.009\,\mathrm{GeV}$
predicted	10.525

(PRD 36, 3401 (1987); 38, 279 (1988); EPJC 4, 107 (1998))

there will be indirect $\Upsilon(3S)$ production !

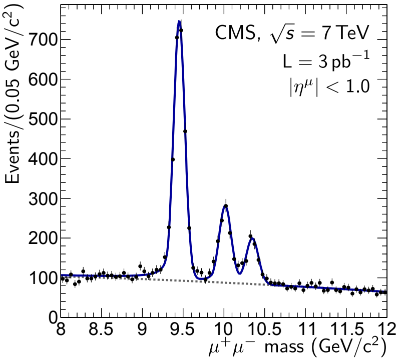


Differential cross-sections: Υ(nS)

ATLAS: PLB 705, 9-27; CMS: PRD 83, 112004; LHCb: acc. EPJC {1202.6579v1}

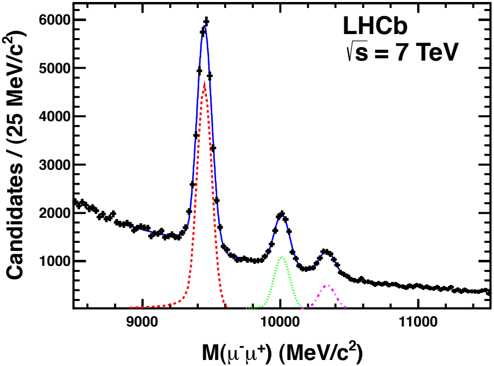
$3.1\,\mathrm{pb}^{-1}$ (2010 data), $\mu\mu$ trigger;

$$\begin{cases} p_T^\mu > 3.5\,\mathrm{GeV} & |\eta| < 1.6 \\ p_T^\mu > 2.5\,\mathrm{GeV} & |\eta| \in [1.6, 2.4] \end{cases}$$



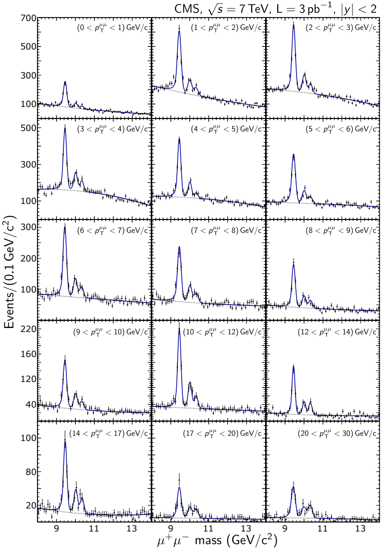
$25\,\mathrm{pb}^{-1}$ (2010 data),

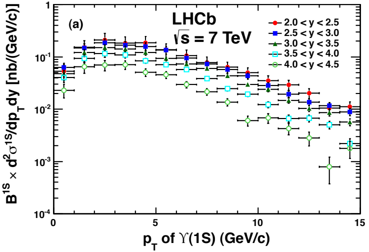
$$\begin{cases} \mu \text{ trigger}: & p_T > 1.4\,\mathrm{GeV} \\ \mu\mu \text{ trigger}: & p_T > 0.56,\ 0.48\,\mathrm{GeV} \end{cases}$$

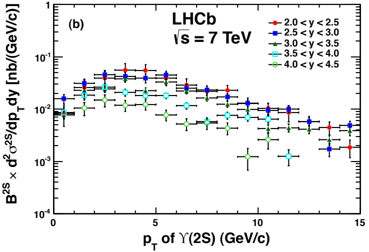


Differential cross-sections: Υ(nS)

ATLAS: PLB 705, 9-27; CMS: PRD 83, 112004; LHCb: acc. EPJC {1202.6579v1}

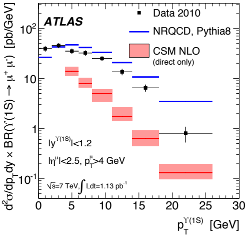


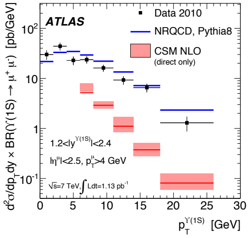


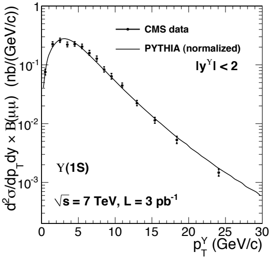


Differential cross-sections: Υ(nS)

ATLAS: PLB 705, 9-27; CMS: PRD 83, 112004; LHCb: acc. EPJC {1202.6579v1}



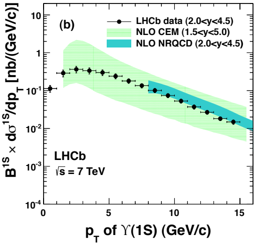


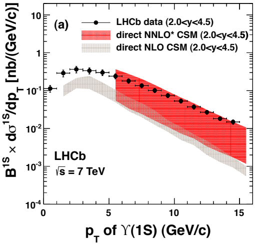


PYTHIA: with NRQCD m.e.'s, tuned to the TeVatron data

CEM: $\longrightarrow$

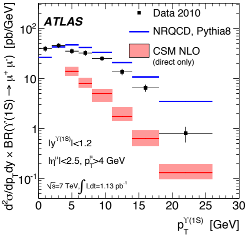
CSM: various orders

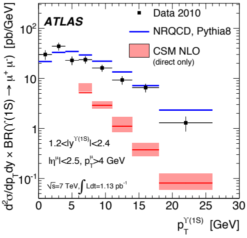


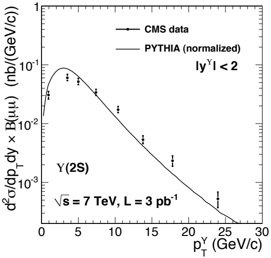


Differential cross-sections: Υ(nS)

ATLAS: PLB 705, 9-27; CMS: PRD 83, 112004; LHCb: acc. EPJC {1202.6579v1}



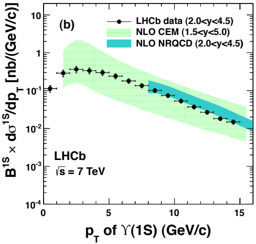


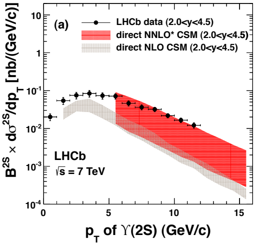


PYTHIA: with NRQCD m.e.'s, tuned to the TeVatron data

CEM: $\longrightarrow$

CSM: various orders





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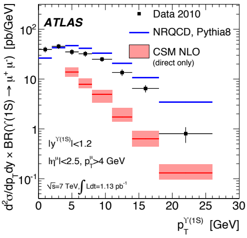

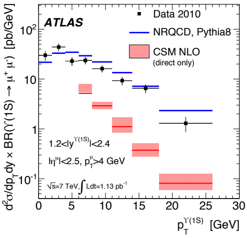

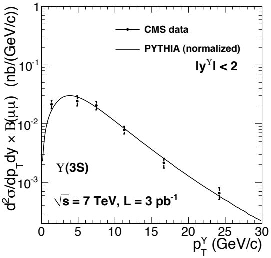

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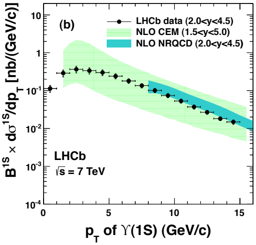
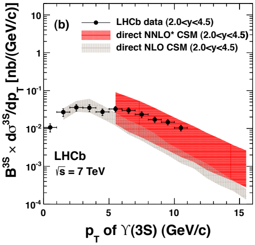
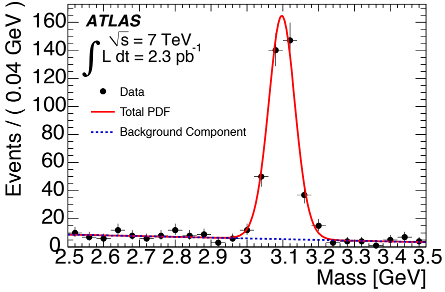


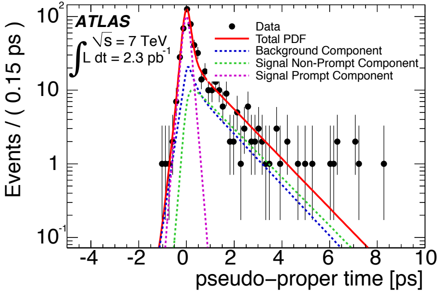


Differential cross-sections: J/ψ

ATLAS: PLB 705, 9-27; CMS: PRD 83, 112004; LHCb: acc. EPJC {1202.6579v1}

- complication: non-prompt fraction, $\{B^{\pm}, B^0_{(s)}, \Lambda_b\} \to J/\psi\, X$
- use J/ψ as a proxy for the b-hadron:
  2D UML fit to $M(\mu\mu)$ and *pseudo-proper time* $\tau = L_{xy}.m^{\psi}/p_T^{\psi}$





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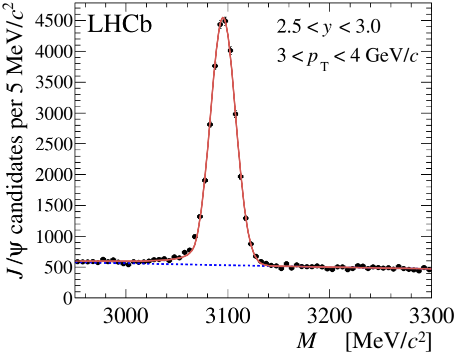
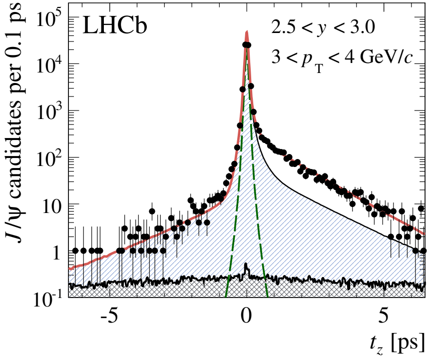
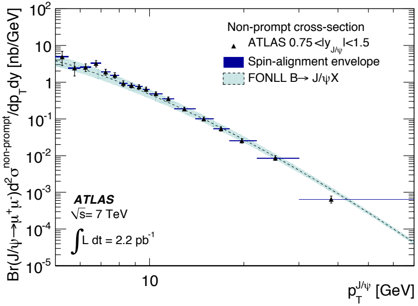


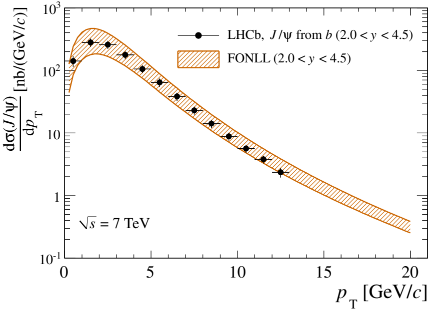


Differential cross-sections: J/ψ

ATLAS: NPB 850, 387; CMS: Eur. Phys. J. C 71, 1575; LHCb: 71, 1645 (2011)

non-prompt: agreement with Fixed Order Next-to-Leading Logarithm





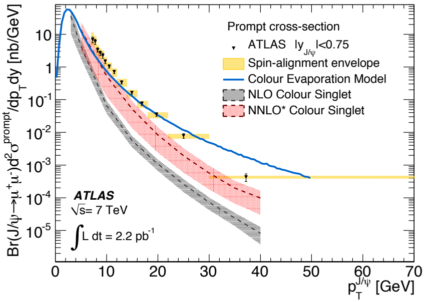
Differential cross-sections: J/ψ

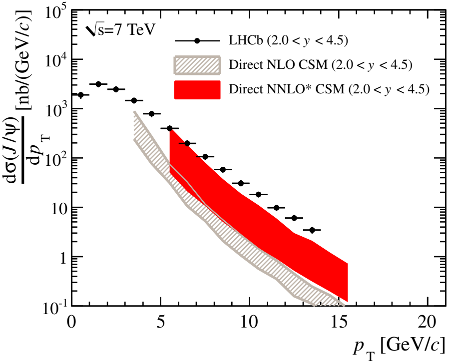
ATLAS: NPB 850, 387; CMS: Eur. Phys. J. C 71, 1575; LHCb: 71, 1645 (2011)

non-prompt: agreement with Fixed Order Next-to-Leading Logarithm

prompt:

CSM: NNLO* an improvement; comparison still uncertain (feed-down)





Differential cross-sections: J/ψ

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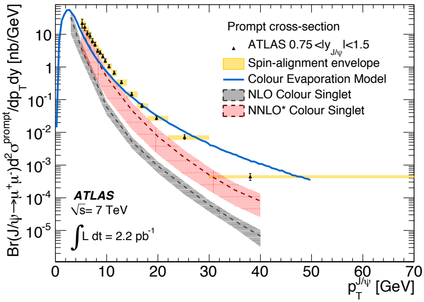
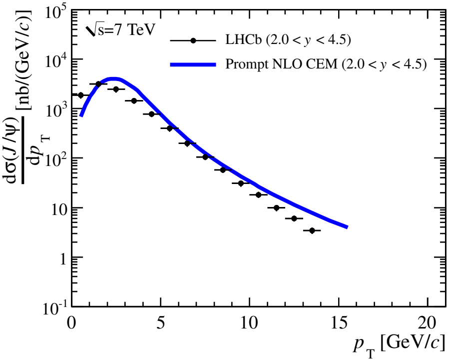
prompt:

- CSM: NNLO* an improvement; comparison still uncertain (feed-down)
- CEM: feed-down included; disagreements in shape and normalisation

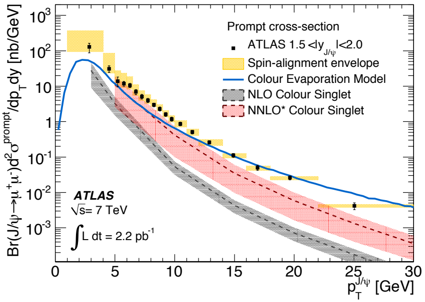


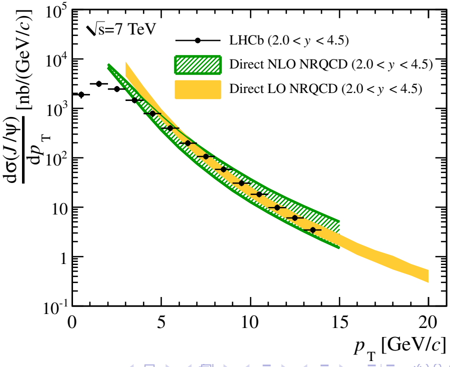


Differential cross-sections: J/ψ

ATLAS: NPB 850, 387; CMS: Eur. Phys. J. C 71, 1575; LHCb: 71, 1645 (2011)

non-prompt:	agreement with Fixed Order Next-to-Leading Logarithm
prompt:	
CSM:	NNLO* an improvement; comparison still uncertain (feed-down)
CEM:	feed-down included; disagreements in shape and normalisation
NRQCD:	reasonable agreement at $y > 2.0$ without feed-down





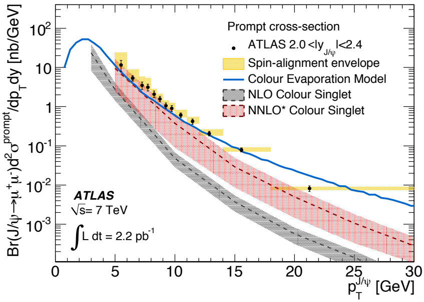
Differential cross-sections: J/ψ

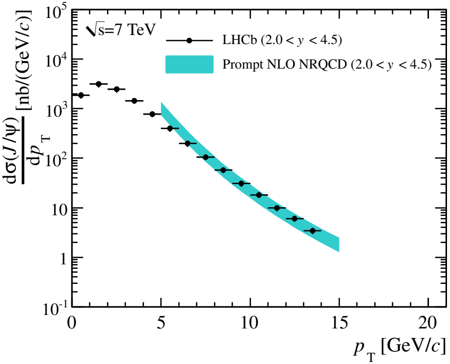
ATLAS: NPB 850, 387; CMS: Eur. Phys. J. C 71, 1575; LHCb: 71, 1645 (2011)

non-prompt: agreement with Fixed Order Next-to-Leading Logarithm

prompt:

- CSM: NNLO* an improvement; comparison still uncertain (feed-down)
- CEM: feed-down included; disagreements in shape and normalisation
- NRQCD: reasonable agreement at $y > 2.0$ without or with feed-down





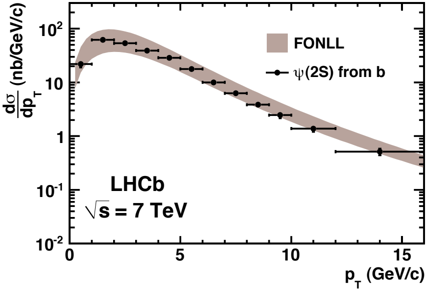
Differential cross-sections: $\psi(2S)$ — feed-down free

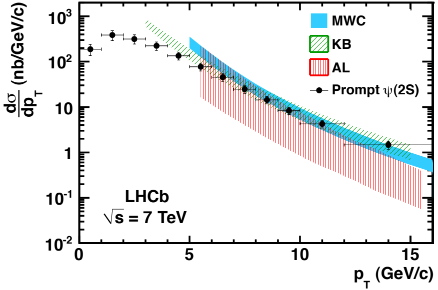
LHCb: to be published in Eur. Phys. J. C {arXiv:1204.1258v1 [hep-ex]}; see ref's

non-prompt: described well by Fixed Order NLL

prompt: color-singlet reasonable at partial NNLO, save high p_T

singlet+octet at NLO agrees; less well at low p_T





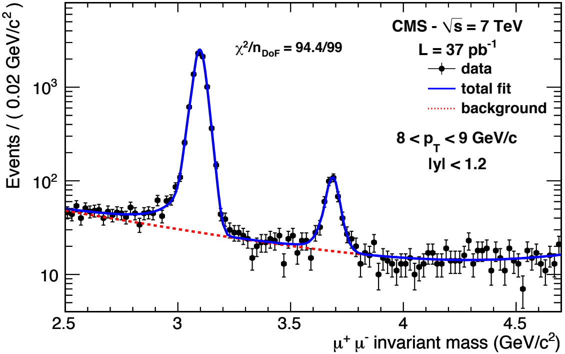
$\mathcal{B}(b \to \psi(2S)\,X) =$ [used as input for FONLL above]

PDG	$(4.8 \pm 2.4) \times 10^{-3}$
LHCb	$(2.73 \pm 0.06\,(\text{stat.}) \pm 0.16\,(\text{syst.}) \quad \pm 0.24\,(\mathcal{B}_{\text{PDG}})) \times 10^{-3}$
CMS (next slide)	$(3.08 \pm 0.12\,(\text{stat.,syst.}) \pm 0.13\,(\text{theor.}) \pm 0.42\,(\mathcal{B}_{\text{PDG}})) \times 10^{-3}$

Differential cross-sections: J/ψ and $\psi(2S)$

CMS: JHEP 02, 011 (2012) {arXiv:1111.1557v1 [hep-ex]}

- simultaneous fits, with constraints on relationship of parameters; partial cancellation of experimental and theoretical uncertainties



Differential cross-sections: J/ψ and $\psi(2S)$

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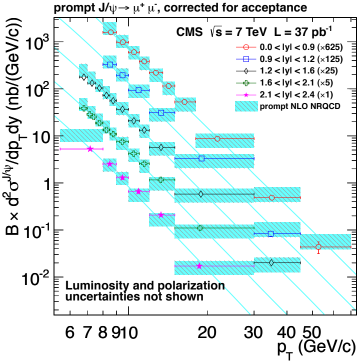
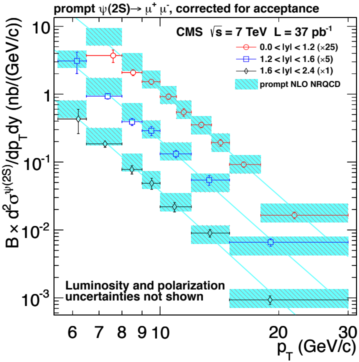
- prompt *cf.* NLO NRQCD: large uncert^s $\ni$ feed-down; TeVatron CO m.e.'s





Differential cross-sections: J/ψ and $\psi(2S)$

CMS: JHEP 02, 011 (2012) {arXiv:1111.1557v1 [hep-ex]}

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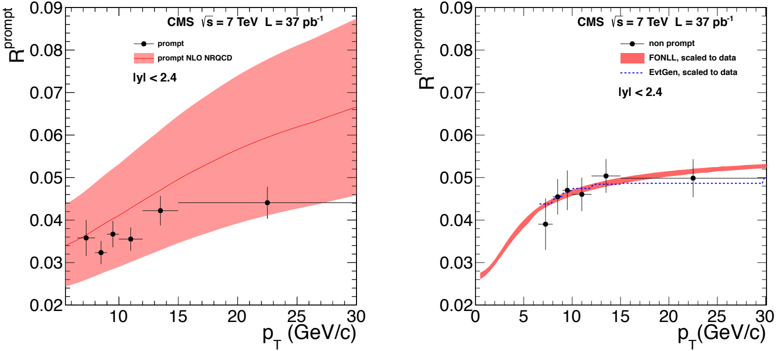
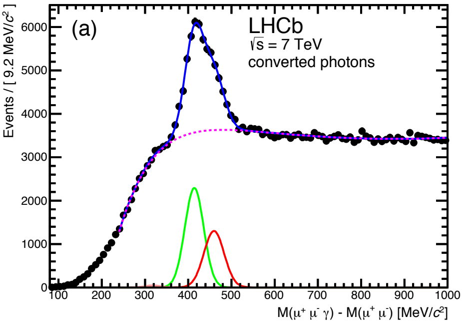
- prompt *cf.* NLO NRQCD: large uncert^s $\ni$ feed-down; TeVatron CO m.e.'s
- extra $\Delta R_{\text{prompt}} = 12$–$20\%$, uncert^y in χ_{cJ} polariz^n; non-prompt *cf.* FONLL

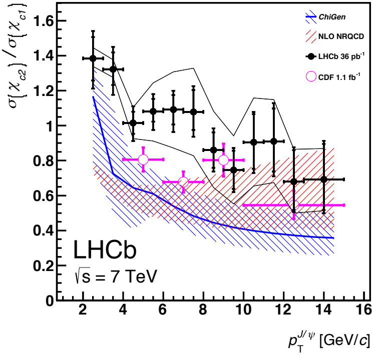


LHCb prompt χ_{c2} to χ_{c1} cross-section ratio

to be published in Physics Letters B {arXiv:1202.1080v1 [hep-ex]}

- ratio is sensitive to color singlet / octet mechanisms





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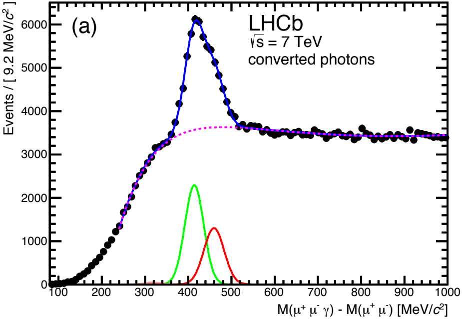

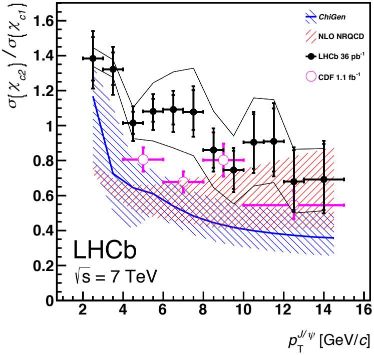

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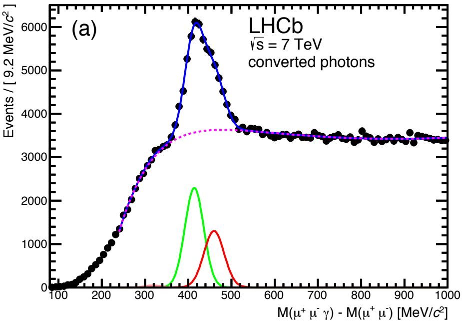
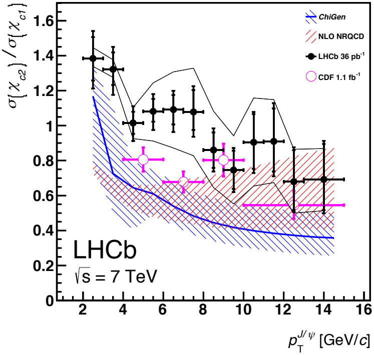
- photons: $p_T^{\gamma} > 650\,\mathrm{MeV}$, $p^{\gamma} > 5\,\mathrm{GeV}$, $\mathcal{L}$ cuts; converted





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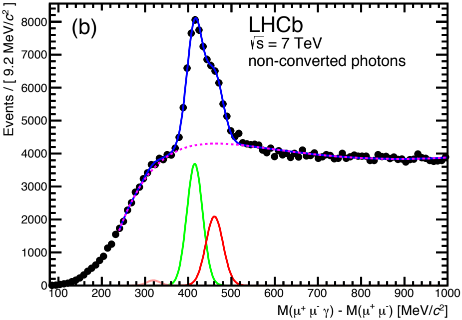

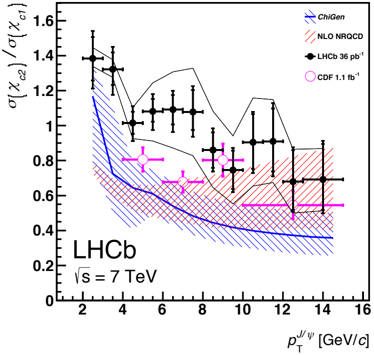

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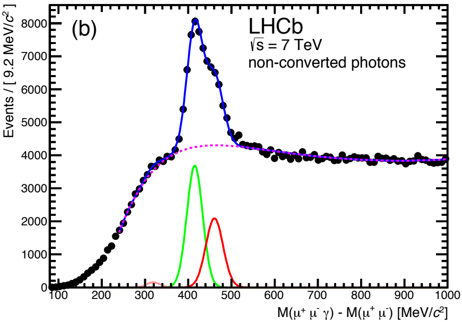
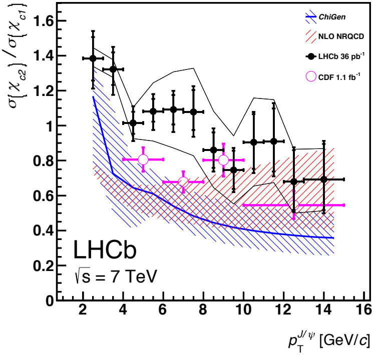
- disagreement with LO CSM and NLO NRQCD > pol^n uncertainty

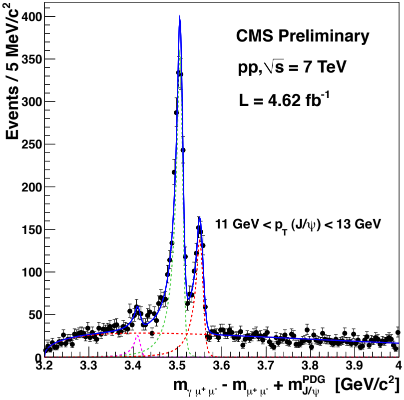


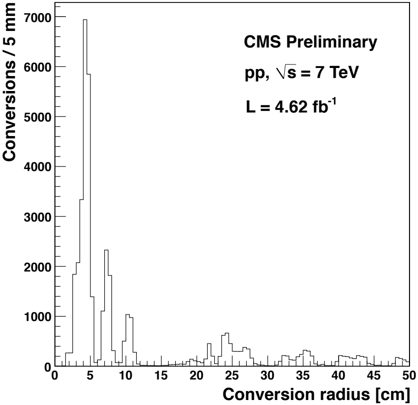


CMS prompt χ_{c2}/χ_{c1} cross-section ratio

CMS-PAS-BPH-11-010, $4.6\,\mathrm{fb}^{-1}$; presented by S. Argirò at Blois 2012

- $\chi_{c1,c2} \to \gamma_{\text{convert}} J/\psi$; $|y^{\psi}| < 1.0$, $p_T^{\gamma} > 0.5\,\mathrm{GeV}/c$; $l_{J/\psi} < 30\,\mu\mathrm{m}$





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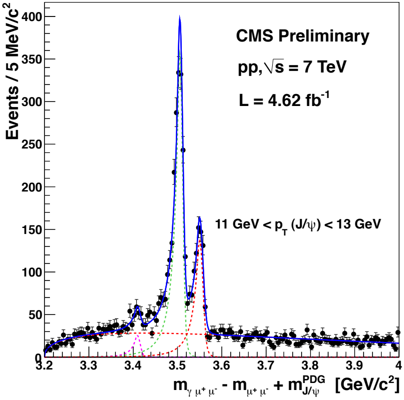
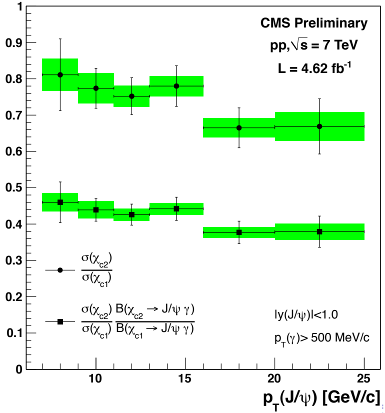
- ratio meas^{ts}





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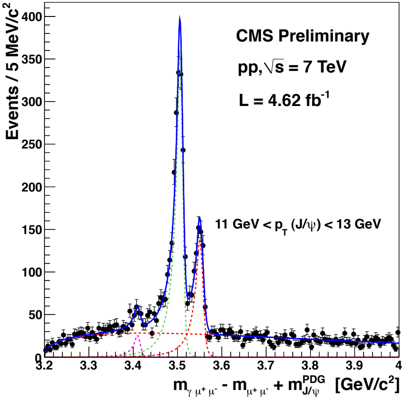
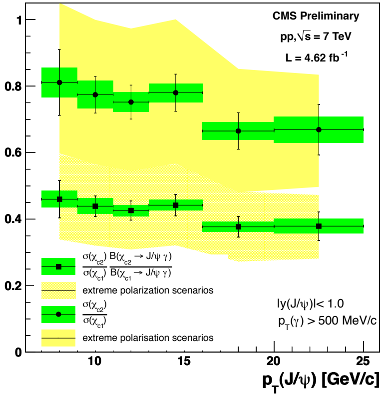
- ratio meas^{ts} subject to pol^{n} uncertainties: $+$ $(h = +1, +2)$ and $-$ $(h = 0, 0)$





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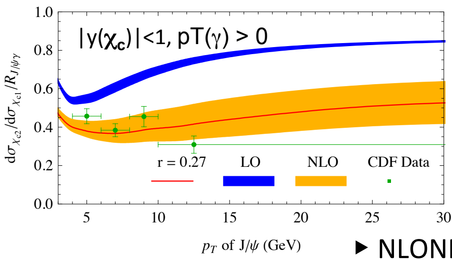
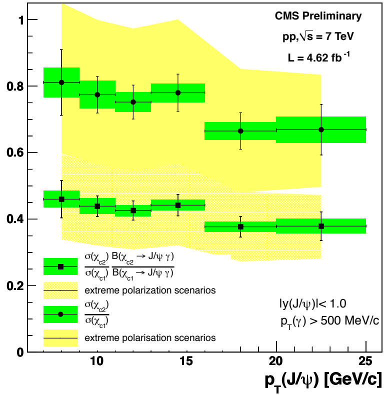
- ratio meas^{ts} subject to pol^n uncertainties: $+$ $(h = +1, +2)$ and $-$ $(h = 0, 0)$
- *cf.* theory comparisons from Argirò presentation: NRQCD

Predictions for Tevatron



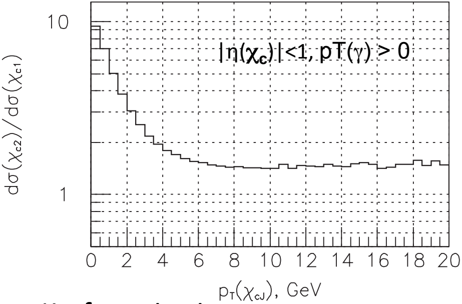
▶ NLONRQCD
Phys. Rev. D 83, 111503(R) (2011)



CMS prompt χ_{c2}/χ_{c1} cross-section ratio

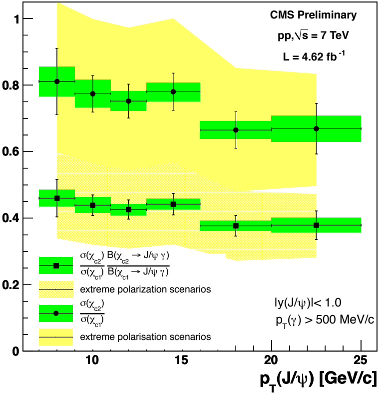
CMS-PAS-BPH-11-010, $4.6\,\mathrm{fb}^{-1}$; presented by S. Argirò at Blois 2012

- $\chi_{c1,c2} \to \gamma_{\mathrm{convert}} J/\psi$; $|y^{\psi}| < 1.0$, $p_T^{\gamma} > 0.5\,\mathrm{GeV}/c$; $l_{J/\psi} < 30\,\mu\mathrm{m}$
- ratio meas^{ts} subject to pol^n uncertainties: $+$ $(h = +1, +2)$ and $-$ $(h = 0, 0)$
- *cf.* theory comparisons from Argirò presentation: NRQCD and k_T factoris^n



▸ K-t factorization

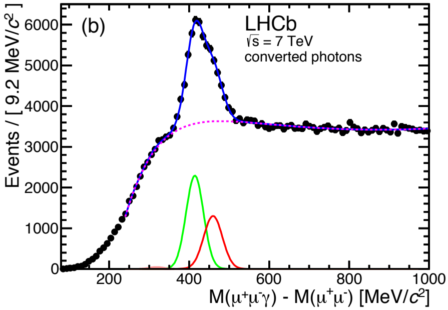
Phys. Rev. D 83, 034035 (2011)

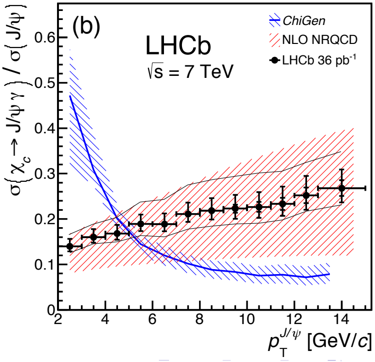


LHCb prompt χ_c to J/ψ cross-section ratio

submitted to Physics Letters B {arXiv:1204.1462v1 [hep-ex]}

- ratio is another test of color singlet / octet mechanisms





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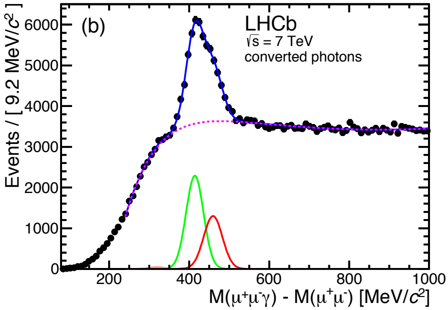

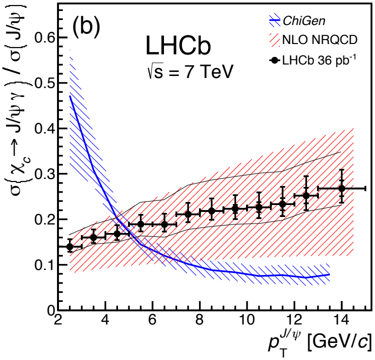

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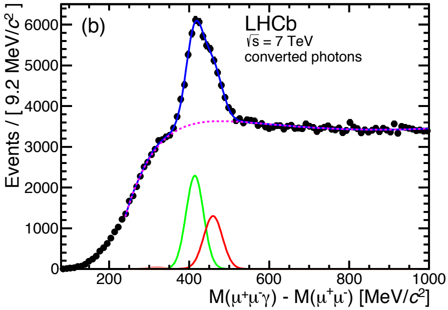

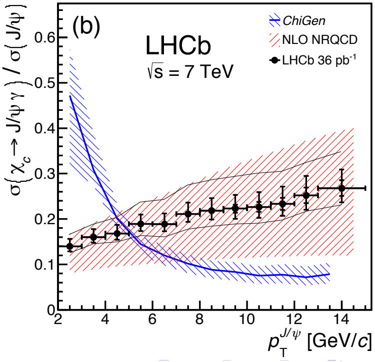

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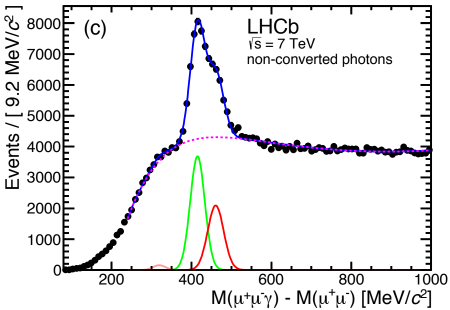

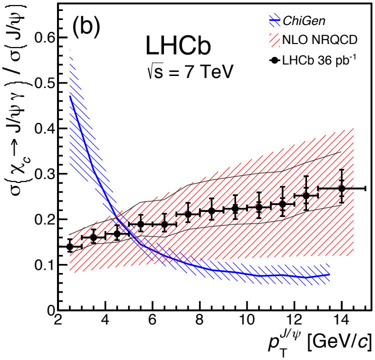

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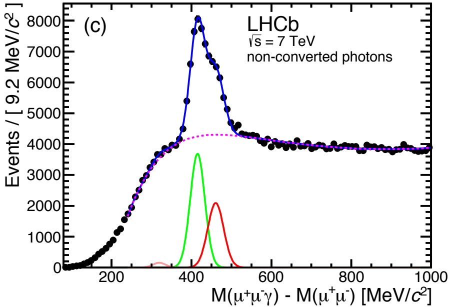
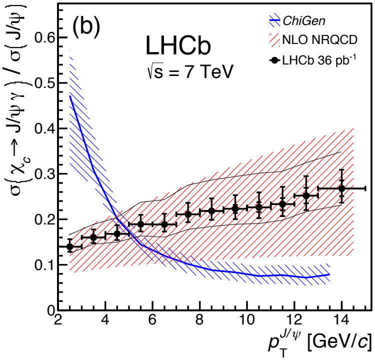
- data $\boxed{\pm\sigma_{\text{pol}}^{\pm}}$ within NLO NRQCD uncert^y; disagrees with LO CSM





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Physics Letters B 707, 52 (2012) {arXiv:1109.0963v2 [hep-ex]}

- almost unknown (NA3 result only); depends strongly on prod^n process
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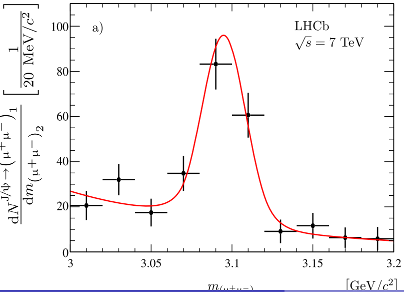
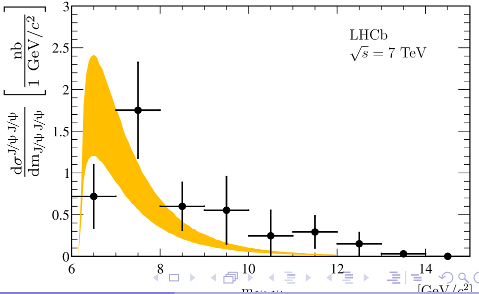
- yield of low-p_T pair fit in bins of high-p_T pair mass,





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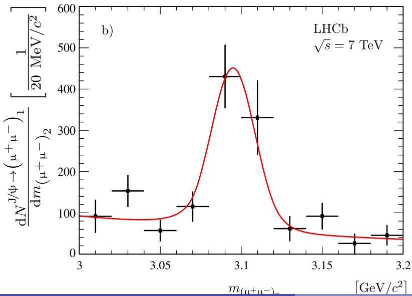
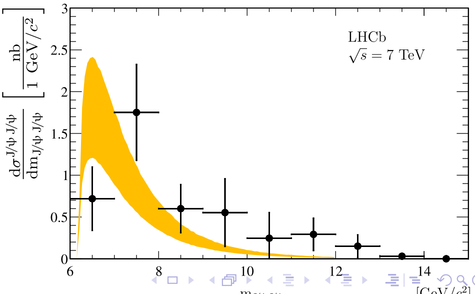
- fit of $\mu^+\mu^-\mu^+\mu^-$ to good common vtx, consistent with a pp collision vtx
- yield of low-p_T pair fit in bins of high-p_T pair mass, then ϵ-corrected
- $\sigma_{\psi\psi}/\sigma_\psi = (5.1 \pm 1.0_{(\text{stat.})} \pm 0.6_{(\text{syst.})}{}^{+1.2}_{-1.0}\,(\text{pol}^n)) \times 10^{-4}$, $\sim$ LO color singlet
- further tests with more data; sensitive to *double parton scattering* (DPS)

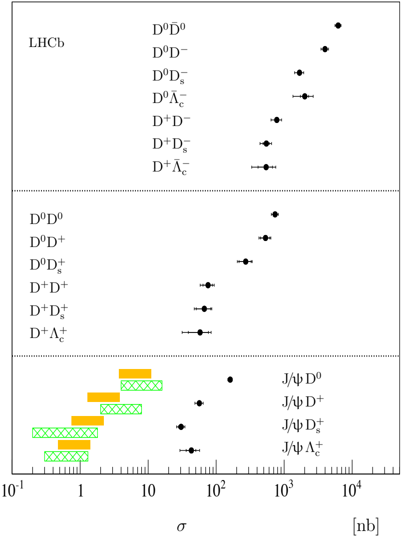




LHCb double charm production

to be published in JHEP {arXiv:1205.0975v1 [hep-ex]}

- $\sigma_{DPS}(C_1 C_2) \sim \sigma(C_1)\sigma(C_2)/\sigma^{eff}_{DPS}$; $\exists$ TeVatron fit for σ^{eff}_{DPS}
- can also arise from *intrinsic charm*
- LO calculations available for $gg \to J/\psi\, J/\psi$, $J/\psi\, c\bar{c}$, $c\bar{c}\, c\bar{c}$
- $355\,\mathrm{pb}^{-1}$ of 2011 data: greatly exceed two LO models



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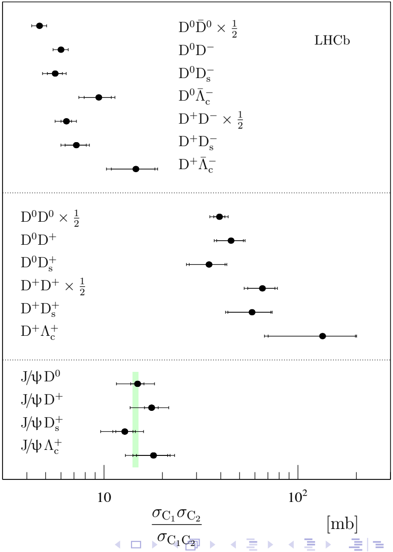

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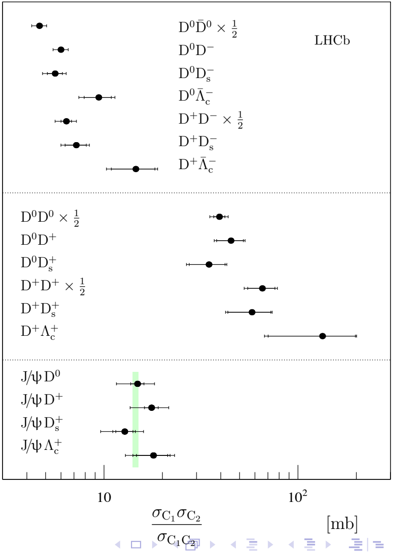
- rate consistent with DPS
- support from: lack of y and ϕ correlations
- complication: $C\overline{C}$ results
- rich set of observables



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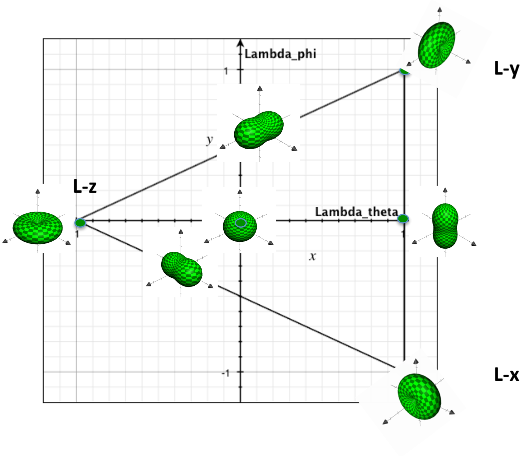
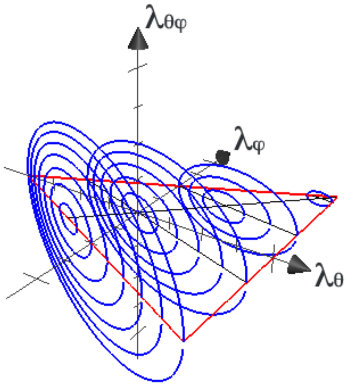
- higher-order calculations raised the CSM to new life; data is challenging it, and color octet . . . nowhere to hide!

BACKUP SLIDES

Relation between $(\lambda_\vartheta, \lambda_\varphi, \lambda_{\vartheta\varphi})$ in different frames

Sandro Palestini, Physical Review D 83, 031503(R) (2011)





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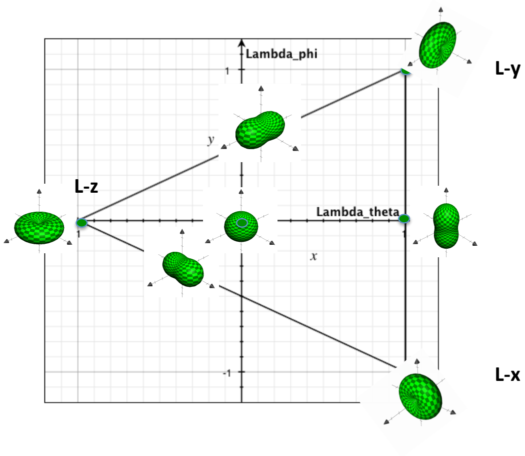

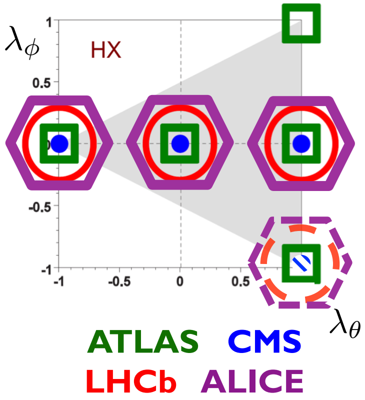

Differential cross-sections: $\Upsilon(nS)$

ATLAS: PLB 705, 9-27; CMS: PRD 83, 112004 (2011); LHCb: 1202.6579v1

"Upsilon events are simulated using PYTHIA 6.412, which generates events based on the leading-order color-singlet and octet mechanisms, with nonrelativistic QCD matrix elements tuned by comparing calculations with the CDF data and applying the normalization and wave-functions as recommended in [M. Krämer, Prog. Part. Nucl. Phys. **47**, 141 (2001)] The simulation includes the generation of χ_b states. Final-state radiation (FSR) is implemented using PHOTOS. The response of the CMS detector is simulated with a GEANT4-based [15] Monte Carlo (MC) program. Simulated events are processed with the same reconstruction algorithms as used for data . . . The normalized p_T-spectrum prediction from PYTHIA is consistent with the measurements, while the integrated cross section is overestimated by about a factor of 2."