Fitting quarkonium production in NRQCD and LHCb prospects

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Polarisations measurements in pp, ep and heavy ion collisions
virtual Orsay
December 16, 2020

Charmonium production vs QCD

QCD probes : charmonium production processes

Hard processes

- e^+e^- production (B-factories)
- Photoproduction
- **Hadroproduction (hadron colliders)**

Production in decays:

- Higher charmonium states
- b-decays **(~5 GeV)**
  – accessible at B-factories and hadron colliders
- Bottomonium decays **(~10 GeV)**
  – accessible at B-factories and hadron colliders, not many decays observed so far
- Z, W decays **(~80-90 GeV)**
- Higgs decays **(~120 GeV)**
  – not observed so far

Charmonium hadroproduction in the NRQCD

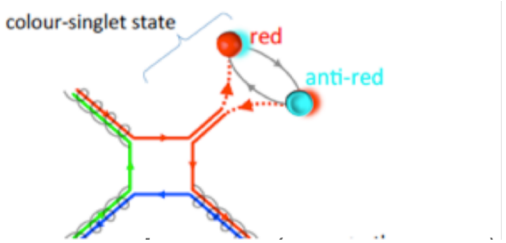
Cross section factorizes:

$$d\sigma_{A+B\to H+X} = \sum_n \boxed{d\sigma_{A+B\to Q\bar{Q}(n)+X}} \times \langle O^H(n)\rangle$$

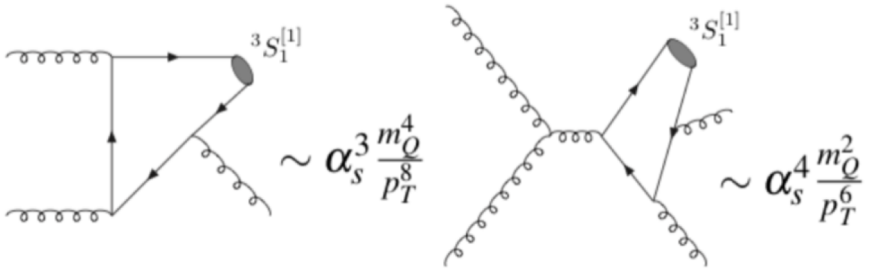
short distance, perturbative

Production mechanisms:

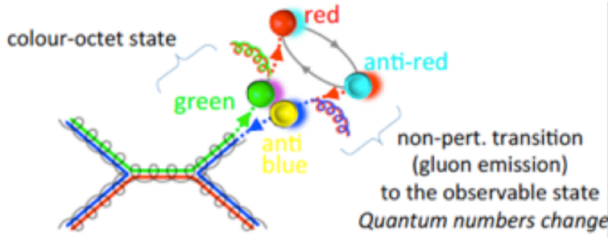
Color Singlet (CS): quantum numbers of $c\bar{c}$ pair and charmonium match



H. Woehri



Color Octet (CO): quantum numbers of $c\bar{c}$ pair are different from charmonium



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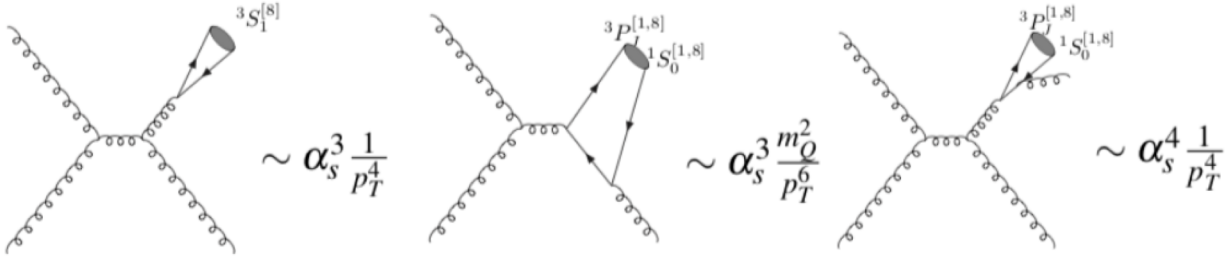

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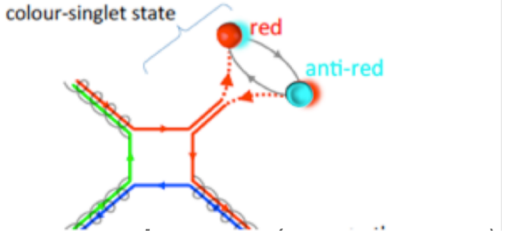

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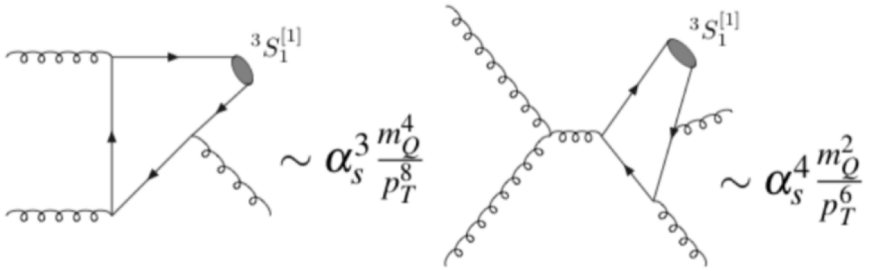

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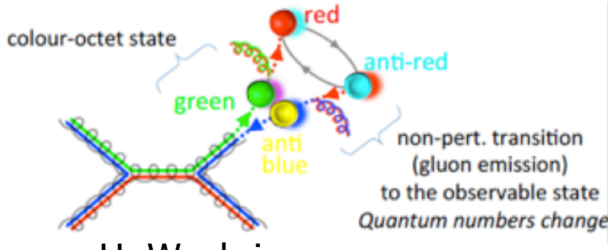

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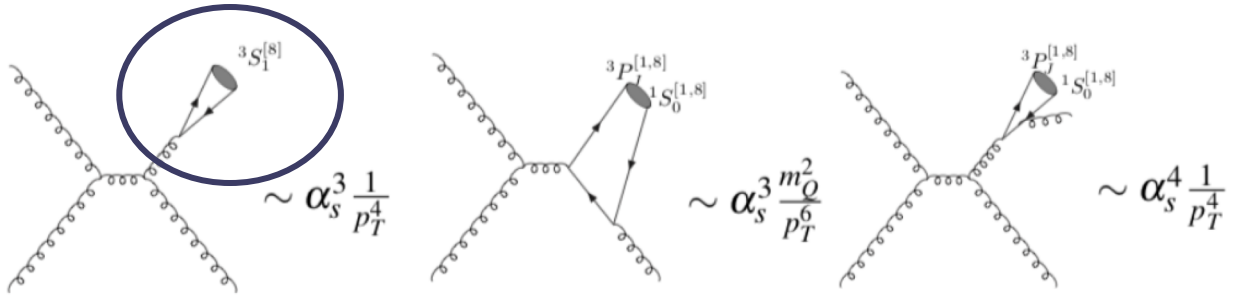


strong J/ψ polarization at large p_T

Charmonium hadroproduction in the NRQCD

Cross section factorizes:

$$d\sigma_{A+B\to H+X} = \sum_n d\sigma_{A+B\to Q\bar{Q}(n)+X} \times \langle O^H(n)\rangle$$

long distance matrix elements (LDMEs), non-perturbative
can be obtained from fits to data

- **Universality:** same LDMEs for different production processes (e.g. hadroproduction and b-decays)

- **Heavy quark spin-symmetry (HQSS) for LDMEs**: Links between the CS and CO LDMEs of **different charmonia states**

Simultaneous study of J/ψ and η_c →

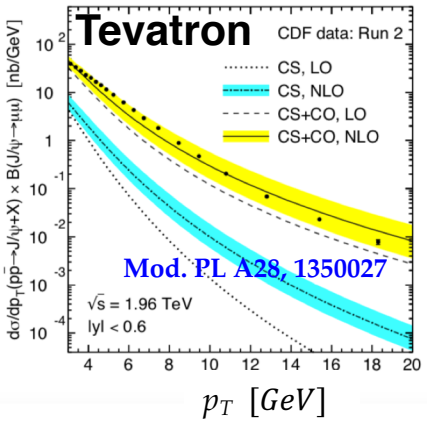
$$\langle O_1^{\eta_c}(^1S_0)\rangle = \tfrac{1}{3}\langle O_1^{J/\psi}(^3S_1)\rangle$$
$$\langle O_8^{\eta_c}(^1S_0)\rangle = \tfrac{1}{3}\langle O_8^{J/\psi}(^3S_1)\rangle$$
$$\langle O_8^{\eta_c}(^3S_1)\rangle = \langle O_8^{J/\psi}(^1S_0)\rangle$$
$$\langle O_8^{\eta_c}(^1P_1)\rangle = 3\langle O_8^{J/\psi}(^3P_0)\rangle$$

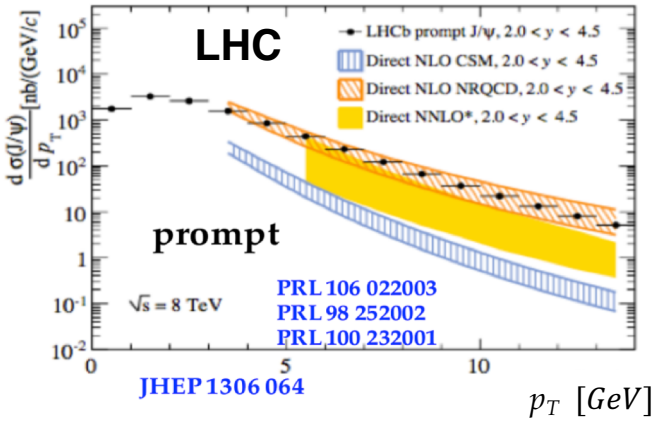
*other contributions are small according to the **expansion on *v***

Simultaneous study of P-wave charmonia

NRQCD vs experiment: J/ψ hadroproduction and polarization

a) production

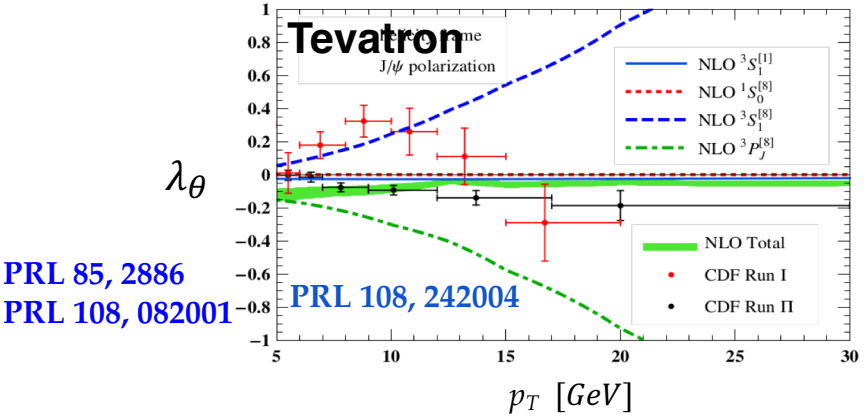




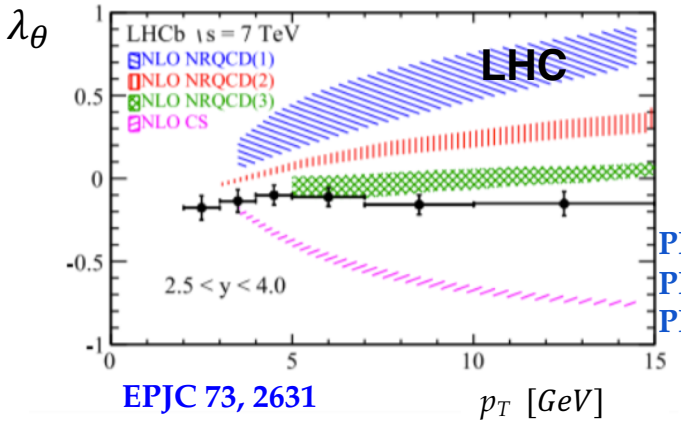
- ***CS*** NLO and NNLO* cannot describe prompt production at both LHC and Tevatron
- ***NRQCD*** description with dominating ***CO*** contribution

→ **great success by NRQCD**

b) polarization



PRL 85, 2886
PRL 108, 082001



PRL 108, 172002
PRL 110, 042002
PRL 108, 242004

- ***CO*** predicts strong polarization
- ***CS*** contribution / feed-down effect from χ_c to describe small observed polarization ?

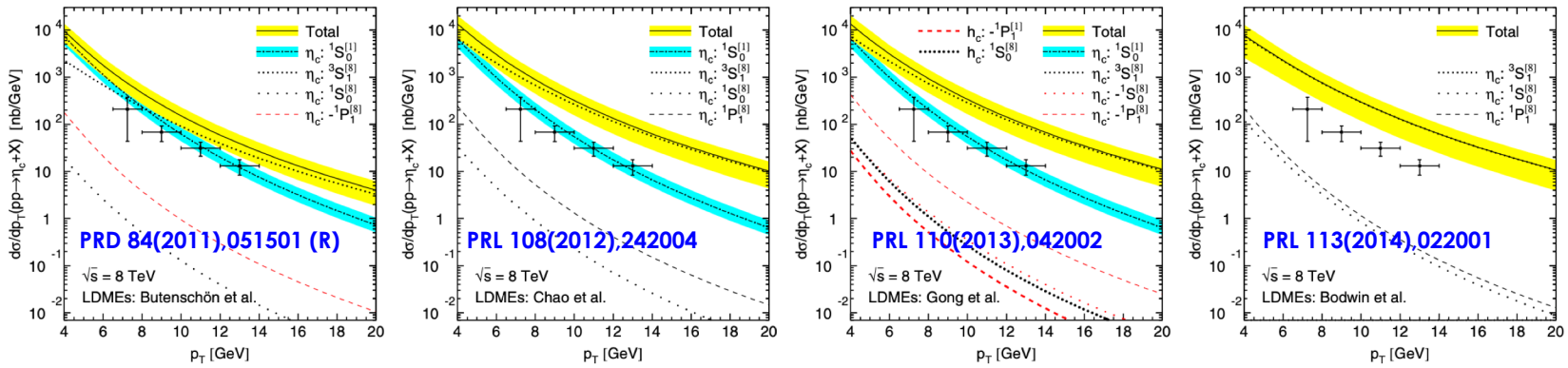
η_c hadroproduction challenges NRQCD

First measurement by LHCb **EPJC 75 (2015) 311** triggered important theory progress

η_c LDMEs determined from J/ψ production using HQSS relations:

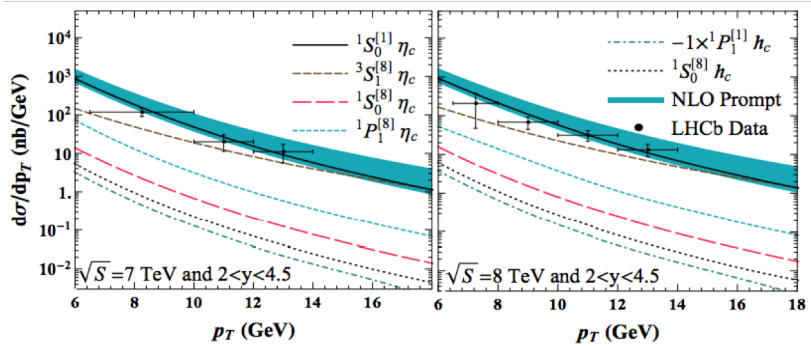
$$\langle O_1^{\eta_c}(^1S_0)\rangle = \tfrac{1}{3}\langle O_1^{J/\psi}(^3S_1)\rangle$$
$$\langle O_8^{\eta_c}(^1S_0)\rangle = \tfrac{1}{3}\langle O_8^{J/\psi}(^3S_1)\rangle$$
$$\langle O_8^{\eta_c}(^3S_1)\rangle = \langle O_8^{J/\psi}(^1S_0)\rangle$$
$$\langle O_8^{\eta_c}(^1P_1)\rangle = 3\langle O_8^{J/\psi}(^3P_0)\rangle$$

**mind the log scale*



LHCb data entirely described by CS contribution, no room for predicted CO contribution

Progress in theoretical description: **Han, Ma, Chao, Shao, Meng PRL 114 (2015) 092005**



Using constraints from **J/ψ and η_c production measurements**, upper limit on CO LDME extracted:

$$0 < O_8^{\eta_c}(^3S_1) < 1.46\times10^{-3}\,\mathrm{GeV}^3$$

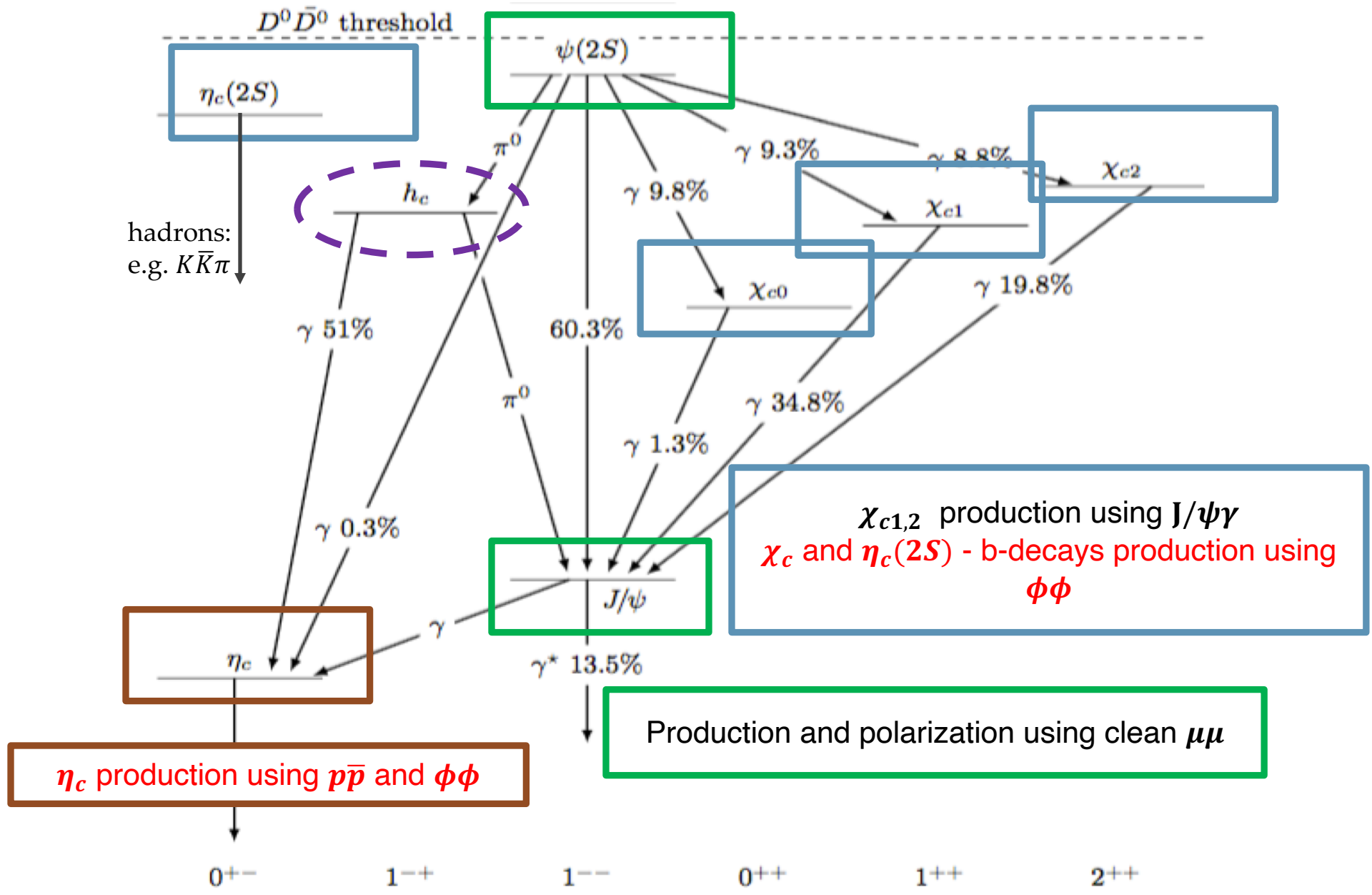
η_c **hadroproduction** challenges NRQCD

Outcome:

- *Progress in data* description
- Upper limit on $O^{\eta c}(^3S_1^{[8]})$ ⇒ new powerful constraint on J/ψ polarization
- **Two large CO contributions cancel each other ⇒ hierarchy problem**
  - **Recent global fit with kt-factorization**
    S. P. Baranov, A. V. Lipatov arXiv:1906.07182

what LHCb can measure?

Charmonium family



$\chi_{c1,2}$ production using $J/\psi\gamma$

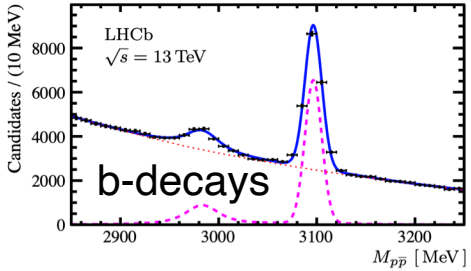
χ_c and $\eta_c(2S)$ - b-decays production using $\phi\phi$

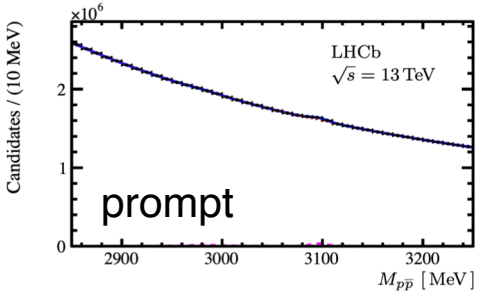
Production and polarization using clean $\mu\mu$

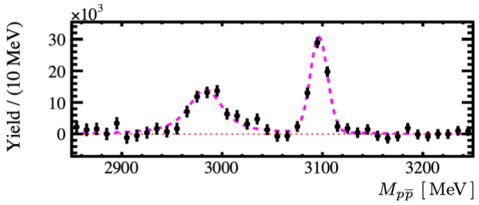
η_c production using $p\bar{p}$ and $\phi\phi$

LHCb so far: charmonium production without muons

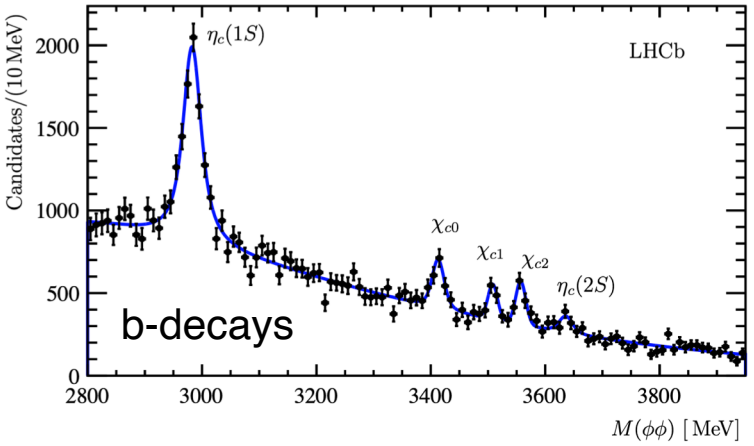
- **$\eta_c(1S)$ production at 7 and 8 TeV EPJC 75 (2015) 31**
  - *Decay mode*: $p\bar{p}$
  - *Measurements*:
    - Cross-section, total + p_T-differential
    - Both prompt and b-decays
    - $\eta_c(1S)$ mass measurement
- **$\eta_c(1S)$ production at 13 TeV EPJC 80 (2020) 191**
  - *Decay mode* and *measurements* – same as above
  - Improved stat. uncertainty
  - Two analysis techniques cross-validate each other
  - Most precise mass measurement







- **$\chi_{c0,1,2}$ and $\eta_c(2S)$ production in b-decays EPJC 77 (2017) 609**
  - *Decay mode*: $\phi\phi$
  - BRs of $b \to (c\bar{c})X$ and ratios
  - p_T-dependence, mass measurements
  - *Bonus*: evidence of $B_s^0 \to \phi\phi\phi$



Phenomenological fits to J/ψ and η_c production: **prompt + b-decays**

- Compare determination of LDMEs **from hadroproduction and from b-decays**
- **Fit three LDMEs to four measurements**

- Short distance coefficients for prompt production provided by H.-S. Shao

$$d\sigma_{A+B\to H+X} = \sum_n d\sigma_{A+B\to Q\bar{Q}(n)+X} \times \langle O^H(n)\rangle$$

- b-decays prediction: **Beneke, Maltoni, Rothstein, PRD 59 (1999) 054003**
  - *understanding of theoretical uncertainties crucial to make a comparison*

- LDMEs compared to

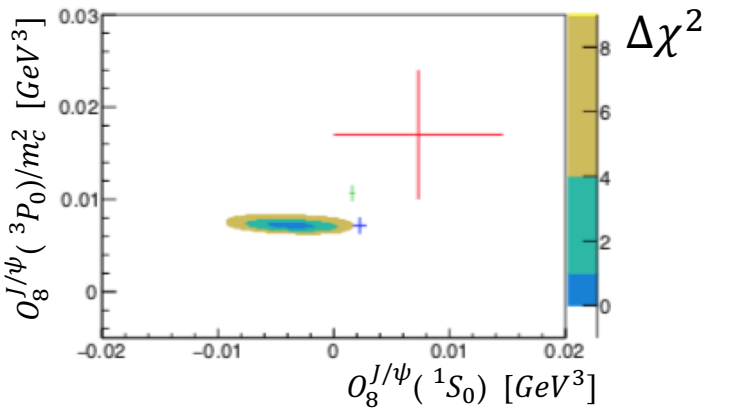
  Shao, Ma, Chao et al PRL 114 092005

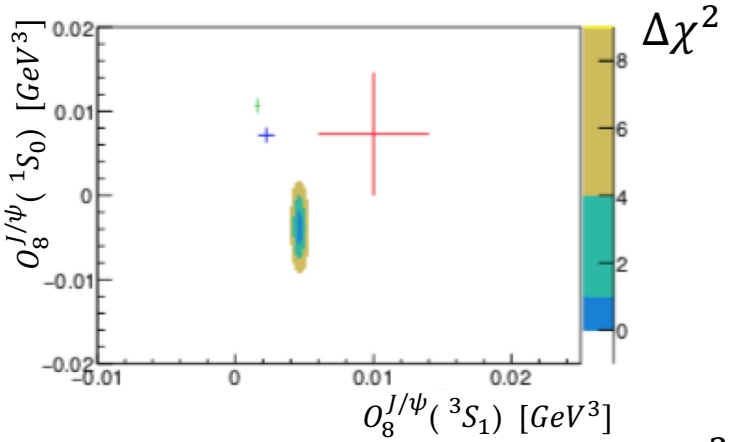
  Baranov. Lipatov arXiv:1904.00400

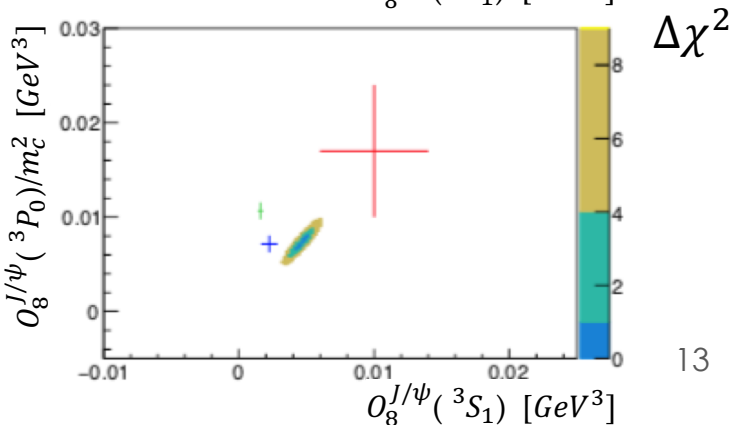
  Butenschoen, Kniehl PRD84 051501

- **First simultaneous study of b-decays and prompt production**
- *Factorization, universality and HQSS can be tested quantitatively?*

Theory errors included







Phenomenological fits to $\chi_{c0,1,2}$ production: b-decays

- From **EPJC 77 (2017) 609** and **PDG**:

Usachov, Kou, Barsuk, LAL-17-051

$$\mathcal{B}(b \to \chi_{c0}{}^{direct} X) = (2.74 \pm 0.47 \pm 0.23 \pm 0.94_{\mathcal{B}}) \times 10^{-3}$$
$$\mathcal{B}(b \to \chi_{c1}{}^{direct} X) = (2.49 \pm 0.59 \pm 0.23 \pm 0.89_{\mathcal{B}}) \times 10^{-3}$$
$$\mathcal{B}(b \to \chi_{c2}{}^{direct} X) = (0.89 \pm 0.20 \pm 0.07 \pm 0.36_{\mathcal{B}}) \times 10^{-3}$$

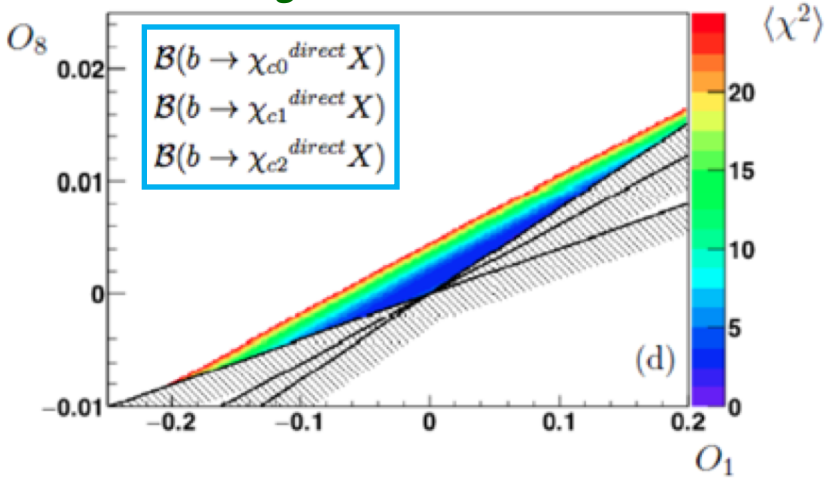
expectation: $\chi_{c2}:\chi_{c1}:\chi_{c0} = 5:3:1$

- Relation between LDMEs from HQSS:

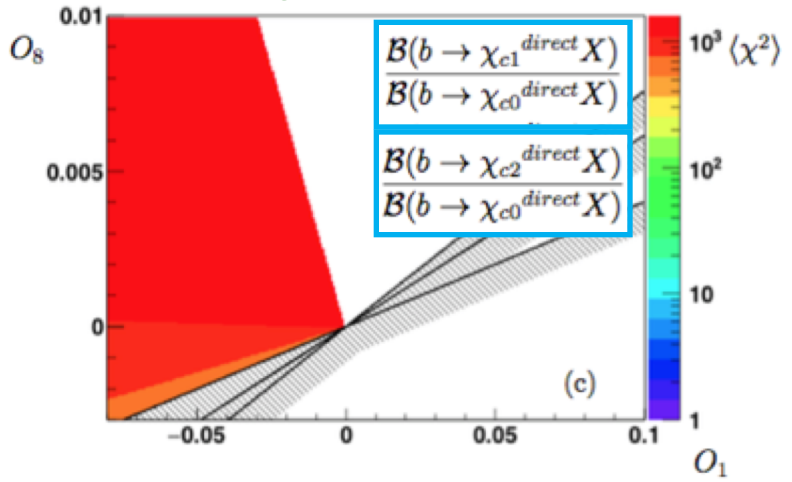
$$O_1 \equiv \langle O_1^{\chi_{c0}}({}^3P_0)\rangle / m_c^2,$$
$$O_8 \equiv \langle O_8^{\chi_{c0}}({}^3S_1)\rangle,$$
$$\langle O_1^{\chi_{cJ}}({}^3P_J)\rangle / m_c^2 = (2J+1)O_1,$$
$$\langle O_8^{\chi_{cJ}}({}^3S_1)\rangle = (2J+1)O_8.$$

- Branching fractions calculated in **Beneke, Maltoni, Rothstein, PRD 59 054003**

Fit to three measurements of branching fractions



Fit to two measurements of branching fraction ratios



- Relative production is not described by theory
- Higher order calculations needed?

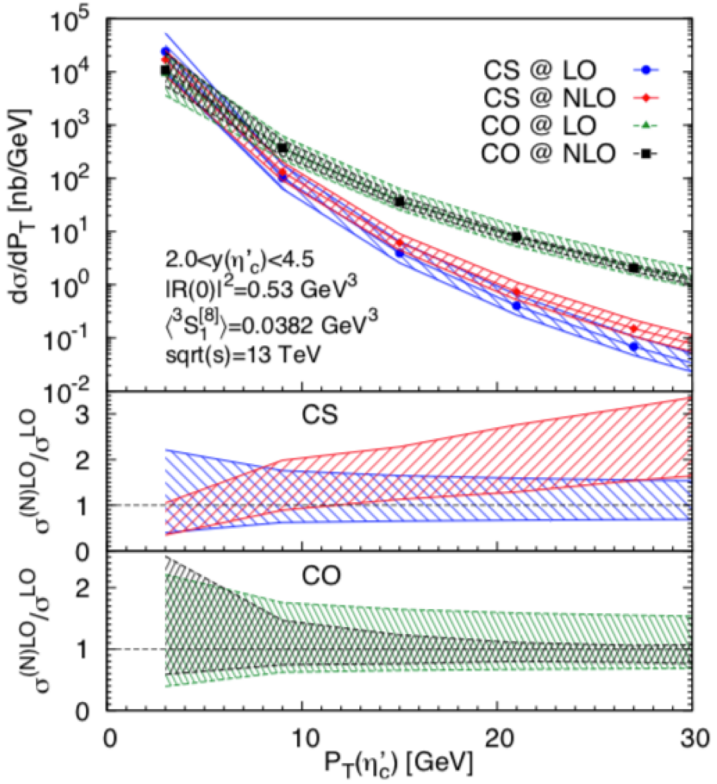
LHCb prospects

Search for prompt $\eta_c(2S)$

- Strongly requested by theorists, powerful separation between theory predictions
  Lansberg, Shao, Zhang PLB 786 342

- To be described **simultaneously** with ψ(2S) production (and polarization)

- Advantage: no feed-downs



- Part of PhD thesis of V. Zhovkovska
- Final states considered: $p\bar{p}$ and $\phi\phi$
- Trigger lines were active during **2018 data taking**
- **VERY promising upper limit (at least)**

bonus: very interesting and unique data (prompt protons) for PID performance study

Prompt charmonium to hadrons in Run 3 and beyond

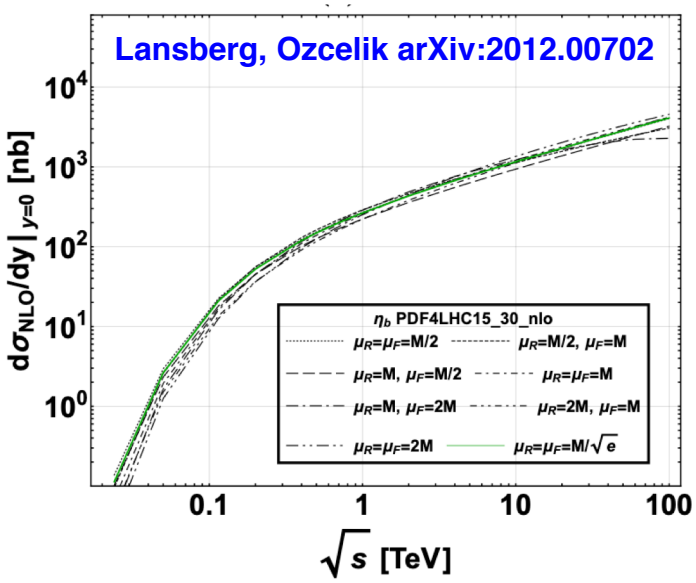
- Prompt trigger lines are expensive
  - Becomes even more complicated at high intensities

- LHCb is converging with reconstruction algorithms for upgrade
- GPUs will be used for online trigger at Run 3
- Trigger lines to be ported in 2021
  - Available bandwidth is not clear yet
  - Decays considered
    - $p\bar{p}$, $\phi\phi$
    - Others? $K_S K\pi$?

- RICH reconstruction online (on GPUs) is a key for future

η_b at LHCb?

- Theoretically more clear than η_c (η_b is less relativistic)
- Links between η_b and Υ production observables
- **First prediction on production cross-section available! Lansberg, Ozcelik arXiv:2012.00702**
- Trigger is much cheaper than for η_c



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but

- Small production cross-section
- No exclusive BR measured
- Decays considered:

mode	BR
$\gamma\gamma$	$O(10^{-4})$
(many) charged hadrons	$O(10^{-6})$
jets?	$O(1)$

$\eta_b(1S)$ $I^G(J^{PC}) = 0^+(0^{-+})$

Mass $m = 9398.7 \pm 2.0$ MeV (S = 1.5)
Full width $\Gamma = 10^{+5}_{-4}$ MeV

$\eta_b(1S)$ DECAY MODES	Fraction (Γ_i/Γ)	Confidence level	p (MeV/c)
hadrons	seen		–
$3h^+3h^-$	not seen		4672
$2h^+2h^-$	not seen		4689
$4h^+4h^-$	not seen		4648
$\gamma\gamma$	not seen		4699
$\mu^+\mu^-$	$<9\times10^{-3}$	90%	4698
$\tau^+\tau^-$	<8 %	90%	4350

Summary

- Important measurements on charmonium production come from using charmonium decays to hadrons at LHCb
  - Access to $\eta_c(1S, 2S)$ and $\chi_{c0,1,2}$; others in future?
  - $\eta_c(1S)$ is measured, $\chi_{c0,1,2}$ measured only for b-decays
  - $\eta_c(2S)$ is on the way

- The NRQCD description is still puzzling when considering LDME universality
  - First simultaneous fit of prompt + b-decays production of J/ψ and η_c
  - Prediction on b-decays has to be revisited

- Studies are limited by trigger bandwidth
  - Way out: RICH reconstruction online

- η_b at LHCb – must have