3D Parton Distributions: path to the LHC

Frascati - 29Nov-2Dec 2016

Quarkonium polarization @LHC

(production)

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Motivation

From the document summarizing physics motivations of this workshop:

- Heavy flavor production. […] All such studies are interesting at top quark scales as well as at lower mass scales with bottom and charm quarks. In particular, despite the complexity of the bound state, the $c\bar{c}$ and $b\bar{b}$ quarkonia production is a useful probe of TMD gluon effects at low mass scales. Measurements of the spectra and especially of the polarization for J/ψ, Υ and all quarkonium states at the LHC Run II will be particularly interesting for studying polarized gluon effects.

…and reading few papers:

- **arXiv:1401.7611v2** [Dunnen, Lansberg, Pisano, Schlegel] : production $\Upsilon \leftrightarrow \gamma$ would probe non-zero gluon polarization in unpolarized protons

- **Phys. Rev. D 86, 094007 (2012)** [Boer, Pisano]
  Phys. Rev. D 88, 014027 (2013) [Ma, Wang, Zhao]
  arXiv:1602.03405v1 [Signori]

  } Production of η_c, η_b, χ_c at low transverse momentum

- …

NAE = Not An Expert disclaimer

Introduction

Understanding quarkonium production

Quarkonium production involves different energy scales: the $q\bar{q}$ formation is a hard process, while the binding of the constituents and the evolution of the bound state occur at softer scales.

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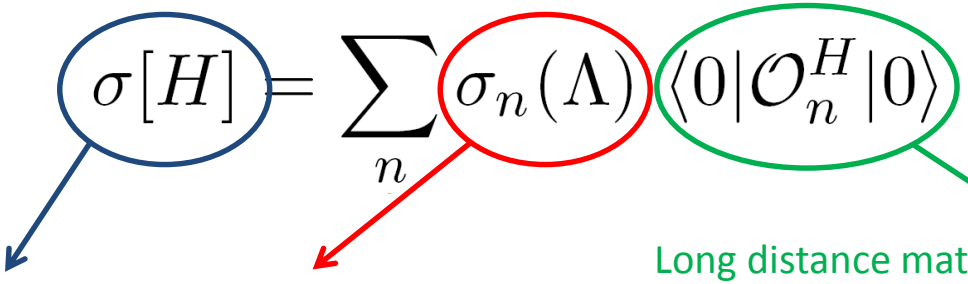

Cross section for the production of the quarkonium H

Short distance coefficients: perturbative cross sections (+PDF) for the production of a $q\bar{q}$ pair in a given quantum state n (Λ: ultraviolet cut-off)

Long distance matrix elements: they embed the non-perturbative part of the calculation. The operator O create a $q\bar{q}$ pair in the vacuum, project it into a heavy quarkonium plus anything, and then annihilate it.
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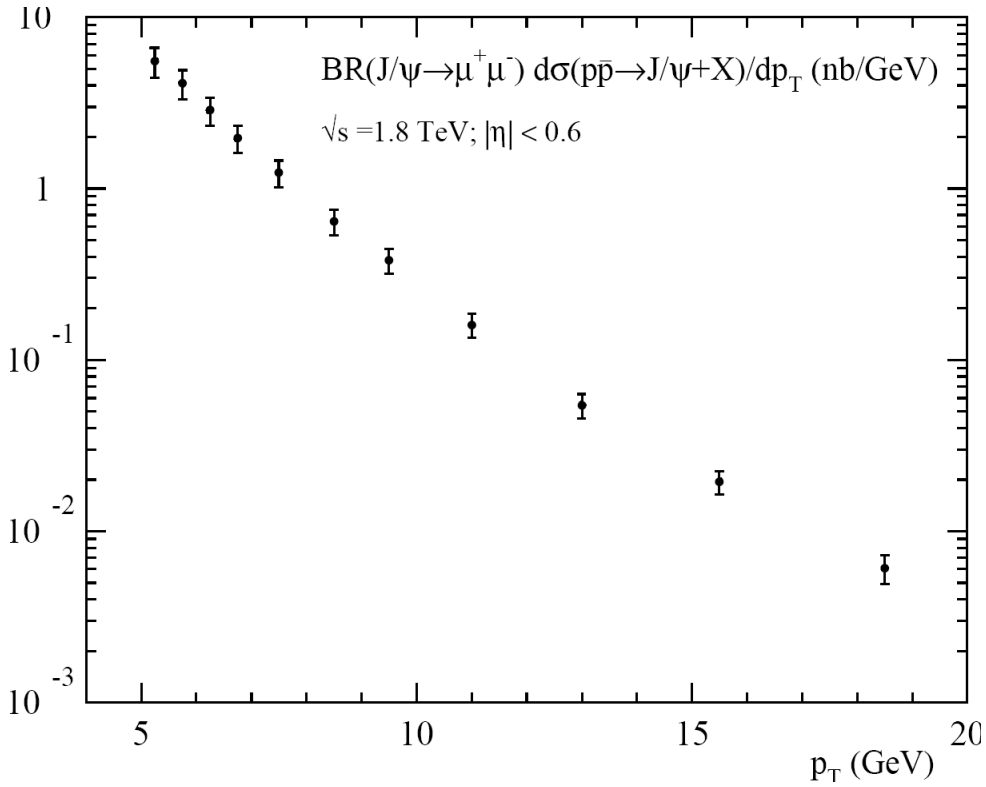
Different implementations of the factorization formula:

- **Color Singlet Model (CSM)**: the color of the $q\bar{q}$ pair neutralizes in the hard process
- **Nonrelativistic QCD (NRQCD)**: the color can be neutralized also in the long distance part → the perturbative cross section can create singlet and octet $q\bar{q}$ systems. The color octet matrix elements are estimated through a fit to the p_t-differential J/ψ cross sections

The CDF test bench



The J/ψ production mechanism in hadronic collisions is still an open issue.

CDF results on p_t-differential cross section for (e.g.) J/ψ: important testing ground.

N. Brambilla *et al.,* arXiv:hep-ph/0412158v2

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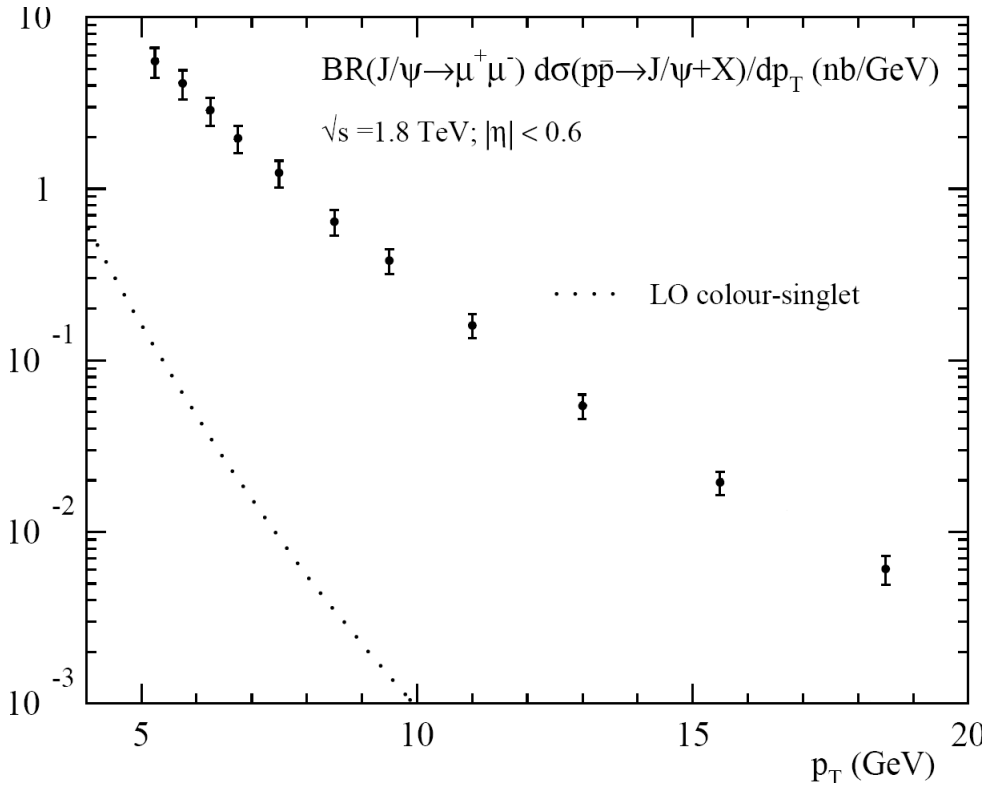

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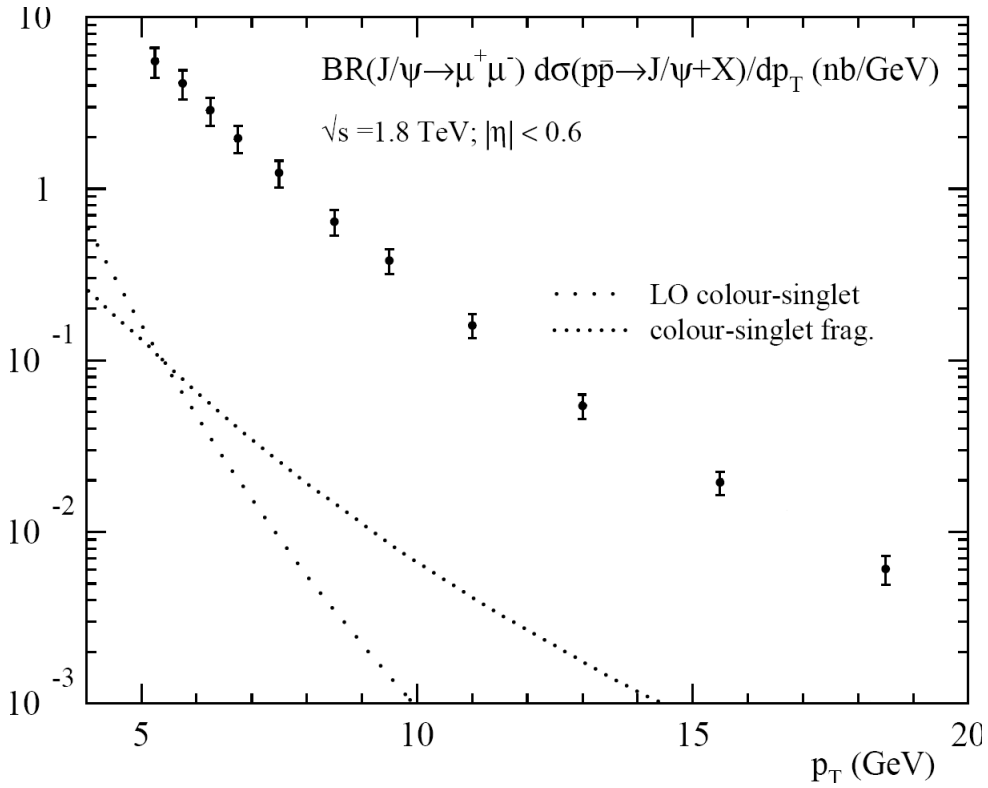

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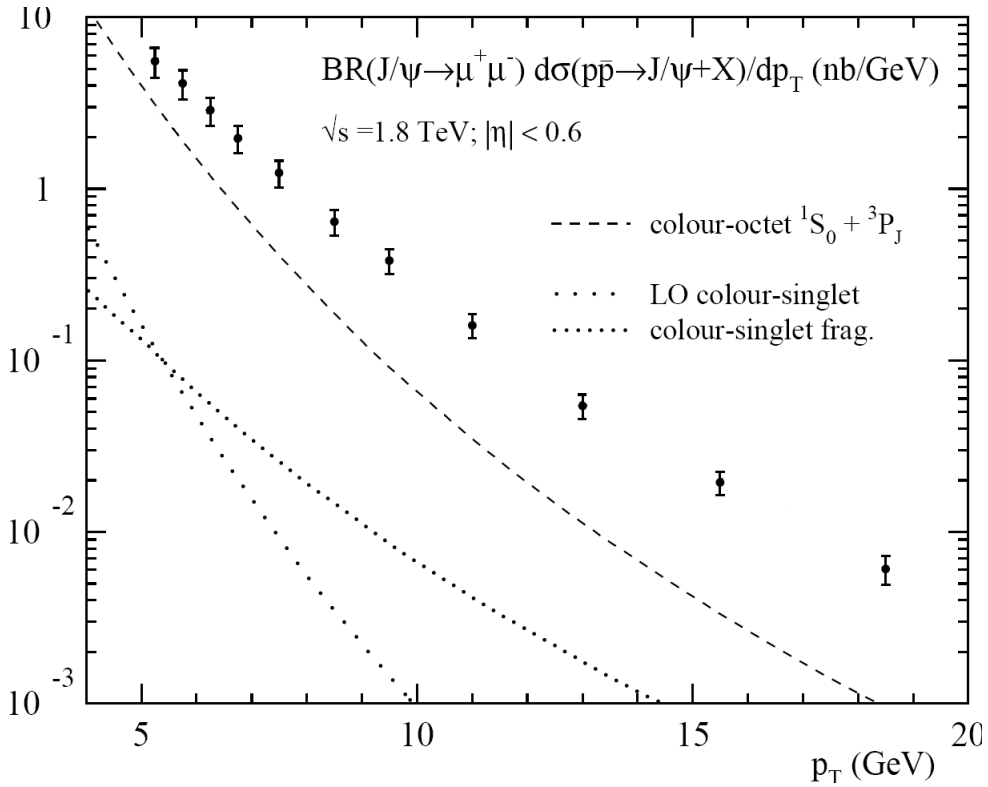

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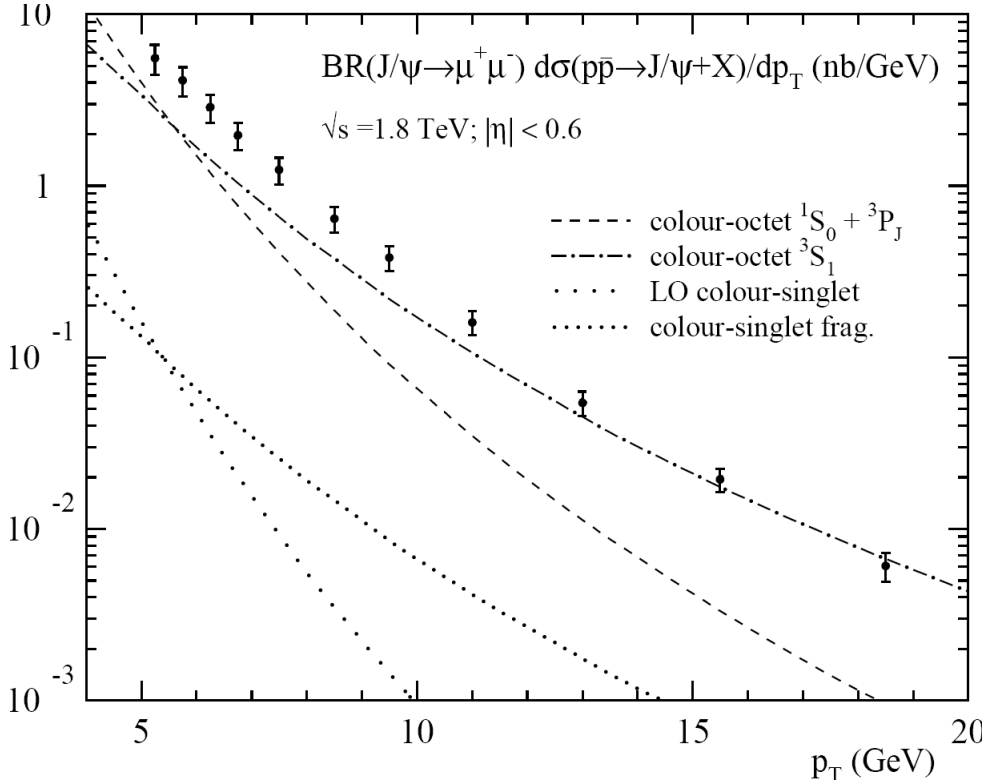

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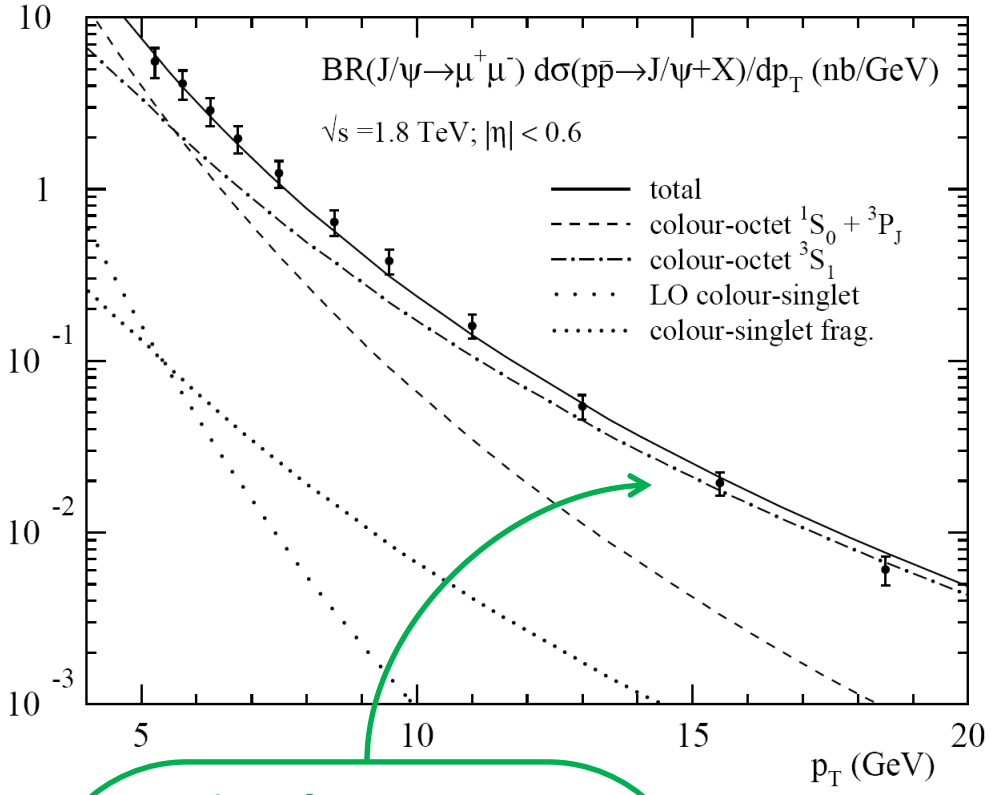

Gluon fragmentation dominant mechanism at high p_t

gluons almost on shell → transversely polarized

The long distance coefficients do not dilute $c\bar{c}$ polarization

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LO NRQCD prediction:
Transverse polarization for high-p_t J/ψ

N. Brambilla *et al.*, arXiv:hep-ph/0412158v2

How to study quarkonium polarization

2-body decay: q-onium polarization measured through anisotropies in daughters' angular distribution:

$$W(\cos\theta,\phi) \propto \frac{1}{3+\lambda_\theta}\cdot(1+\lambda_\theta\cos^2\theta+\lambda_\phi\sin^2\theta\cos 2\phi+\lambda_{\theta\phi}\sin 2\theta\cos\phi)$$

θ and ϕ are the polar and azimuth angles of the μ^+ momentum in a given reference frame.

λ_θ is the fundamental parameter:

λ_θ = +1 → **transverse**
λ_θ = 0 → **no**
λ_θ = -1 → **longitudinal**

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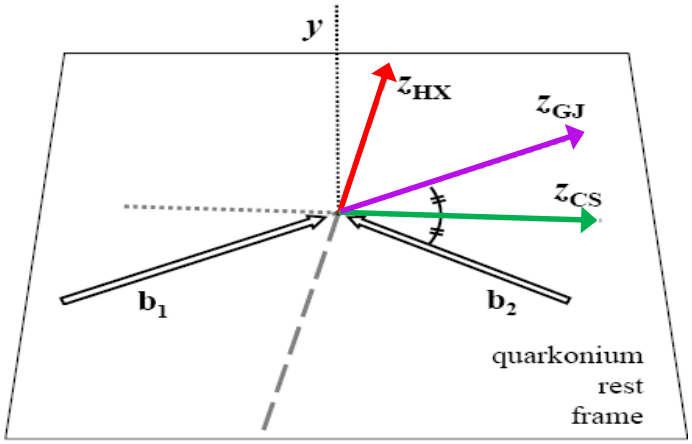
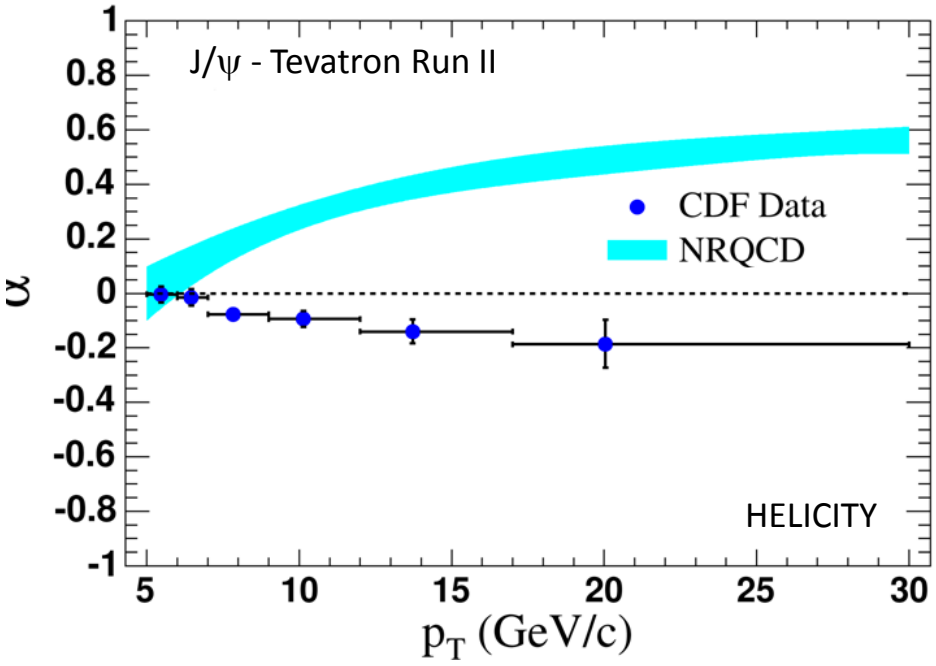


Several definitions of the *z*-axis :

- **helicity**: quarkonium momentum direction in the collision's reference frame;
- **Collins-Soper**: bisector of the angle between one beam and the opposite of the other beam in the quarkonium rest frame;
- **Gottfried-Jackson**: direction of one beam in the quarkonium rest frame (mostly used in fixed target experiments)

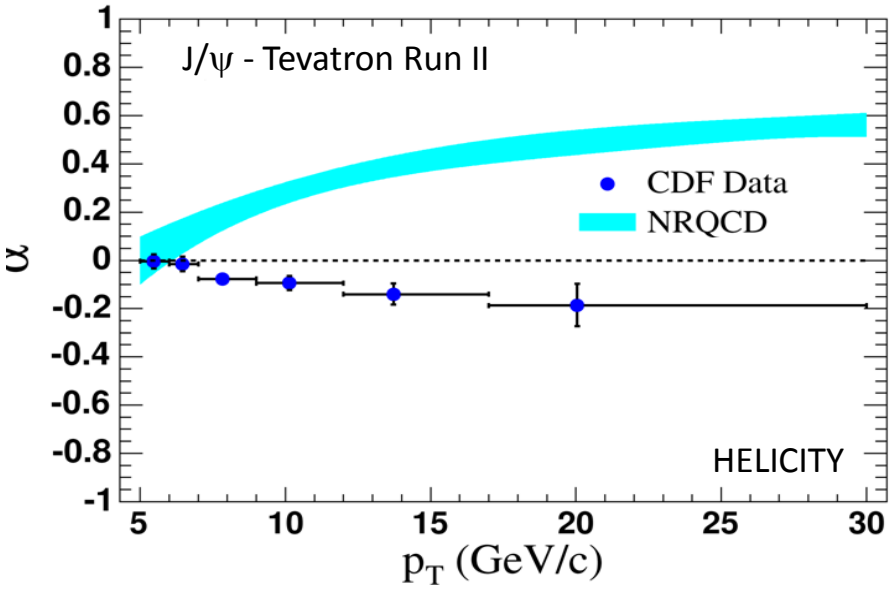
Early measurements tackle-down early predictions...

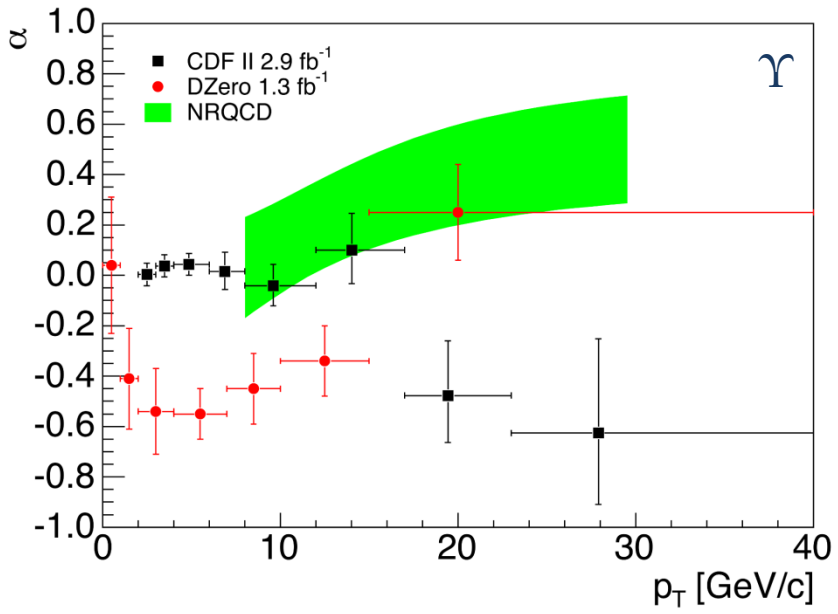


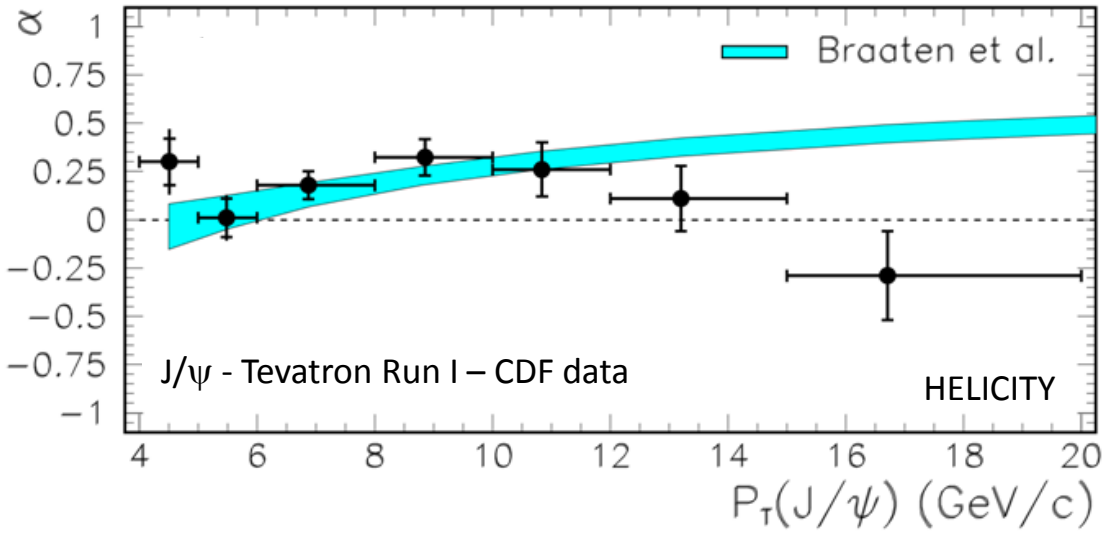
The CDF experiment measured the λ_θ (=α) parameter for direct J/ψ hadroproduction

Strong disagreement with LO NRQCD prediction

...but data were not 100% clear anyway!







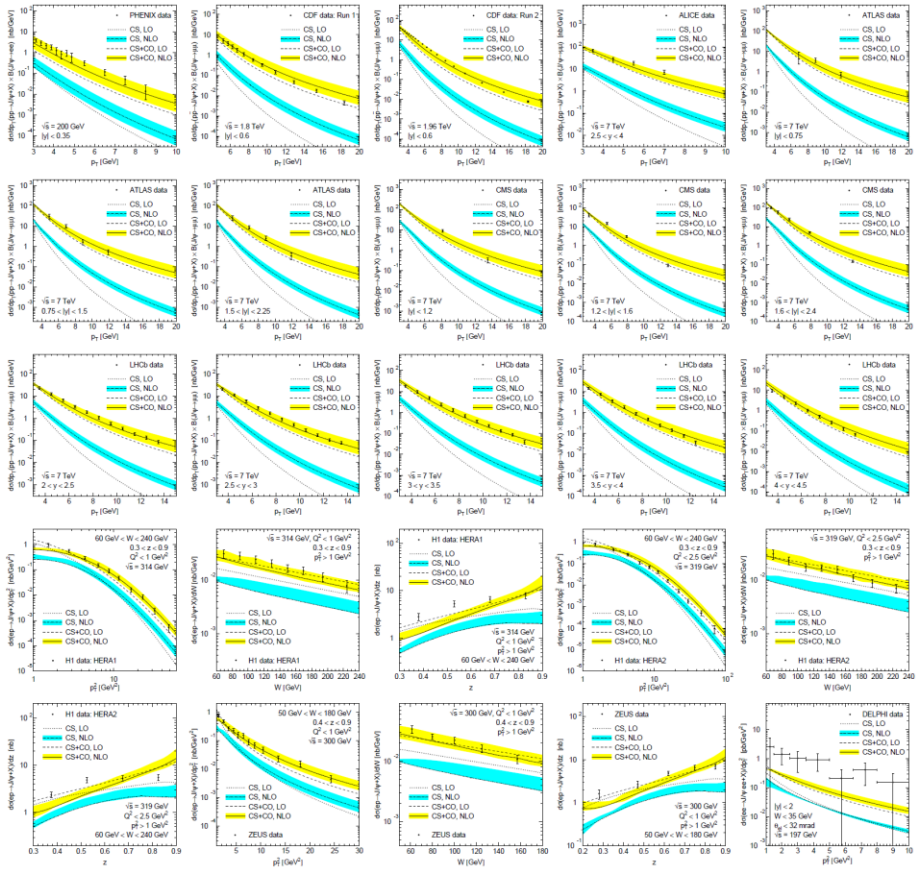
Results from Run I and Run II of the Tevatron:

- no consistency between the two sets in CDF
- No consistency between CDF and D0 concerning Υ

Theoretical developments at LHC start

NLO full calculations of NRQCD and CSM

Long-distance octet elements: global fit to x-sections from all experiments of hadro and photo-production, up to LHC



M. Butenschön B.A. Kniehl, PRL 106 (2011) 022003

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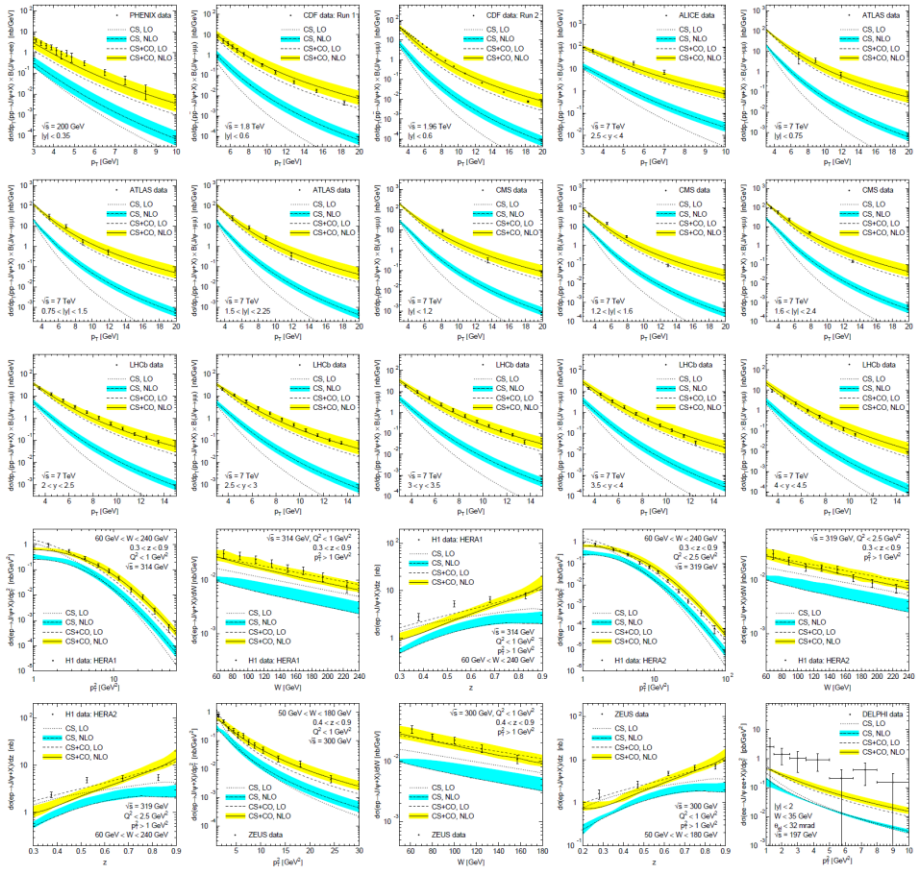

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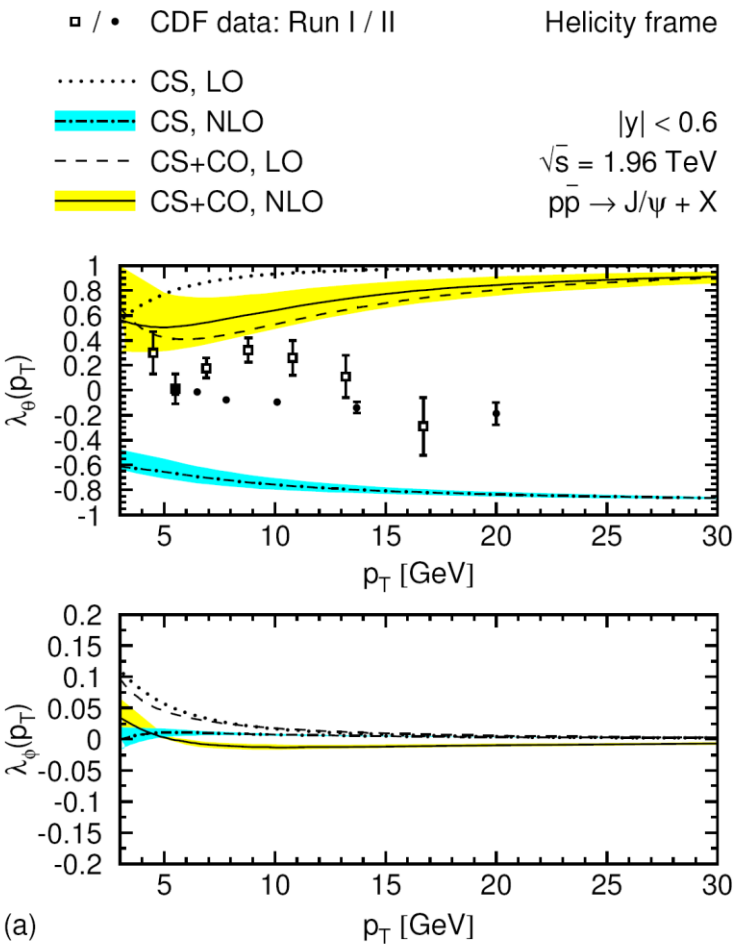
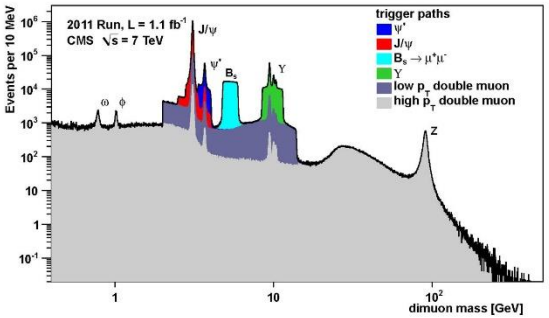
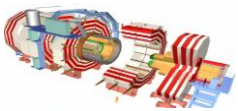
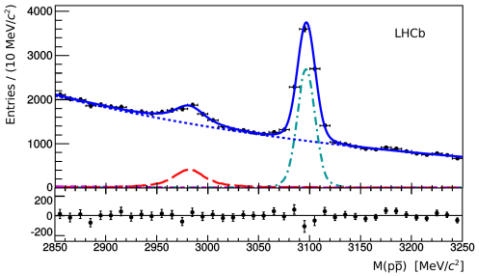
…but still not good news on the polarization side!

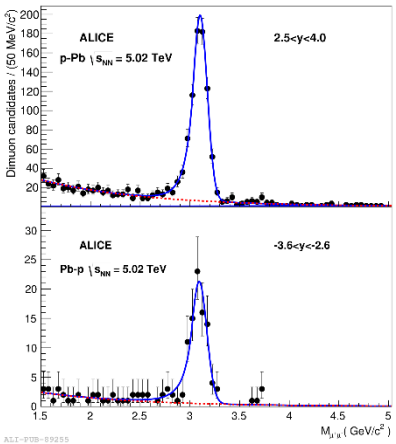


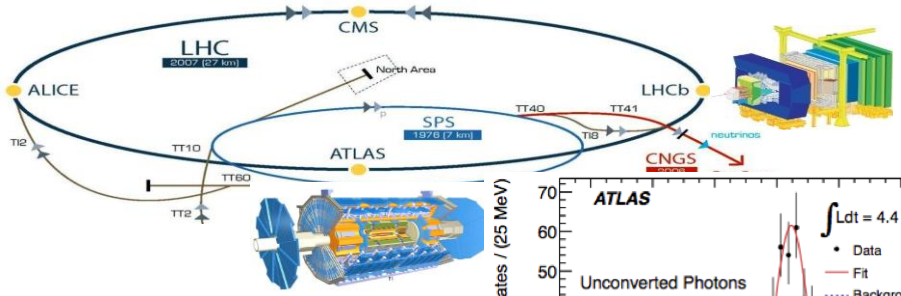
Polarization measurements @LHC

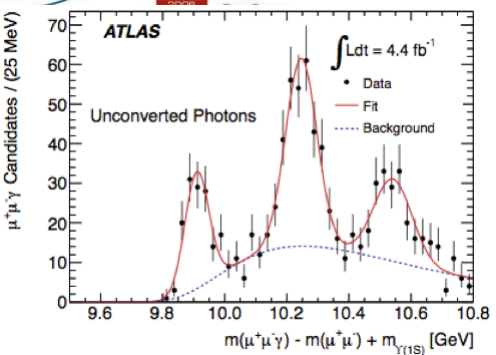










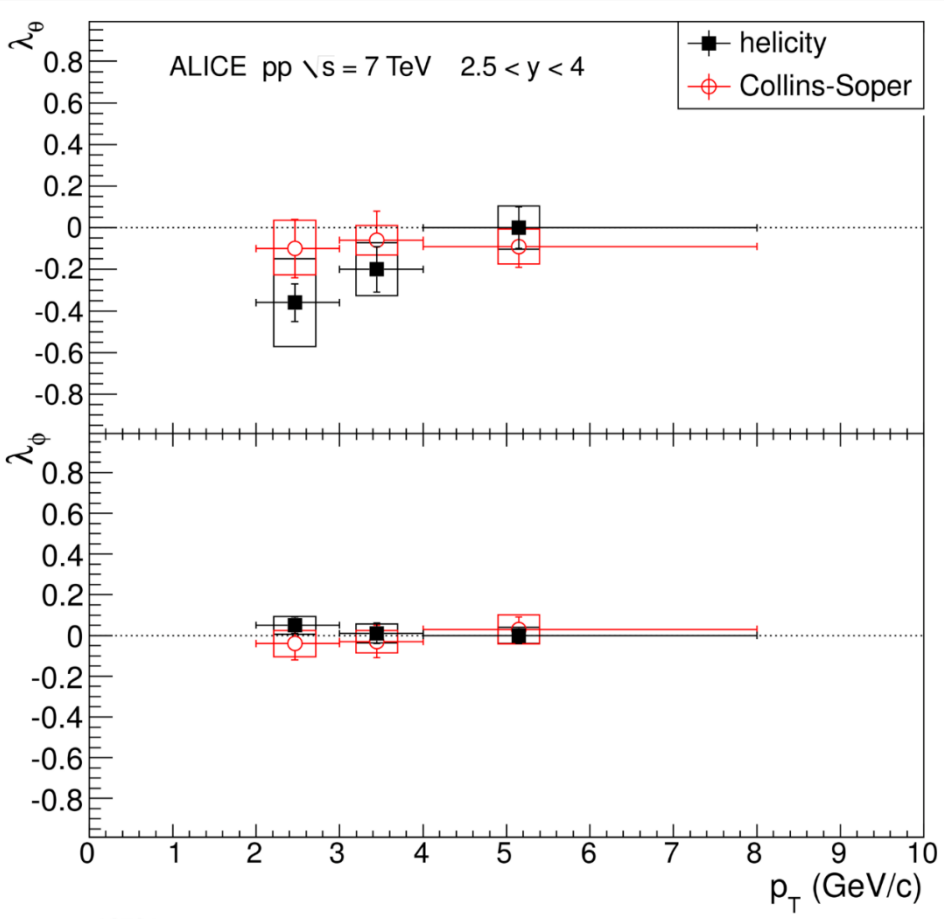


ALICE: first J/ψ measurement

Statistics-limited, covering low-p_T.

No strong evidence for $\lambda_\theta \neq 0$

(only a hint for HE at low-p_T)



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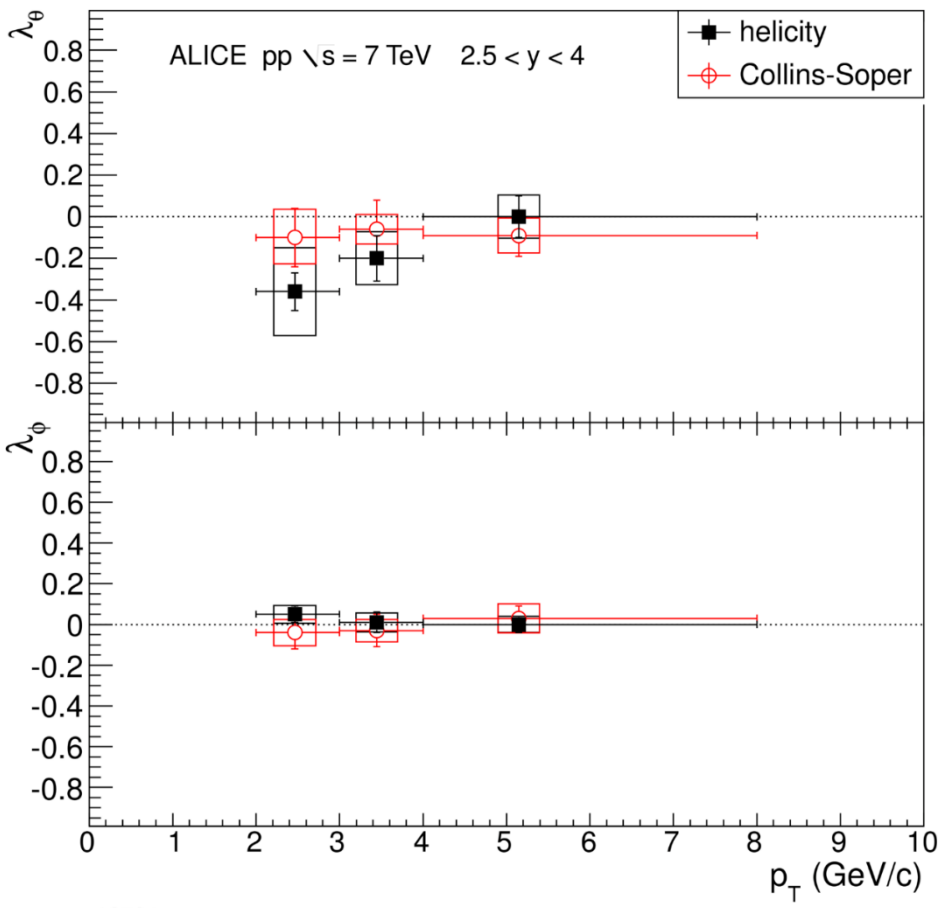
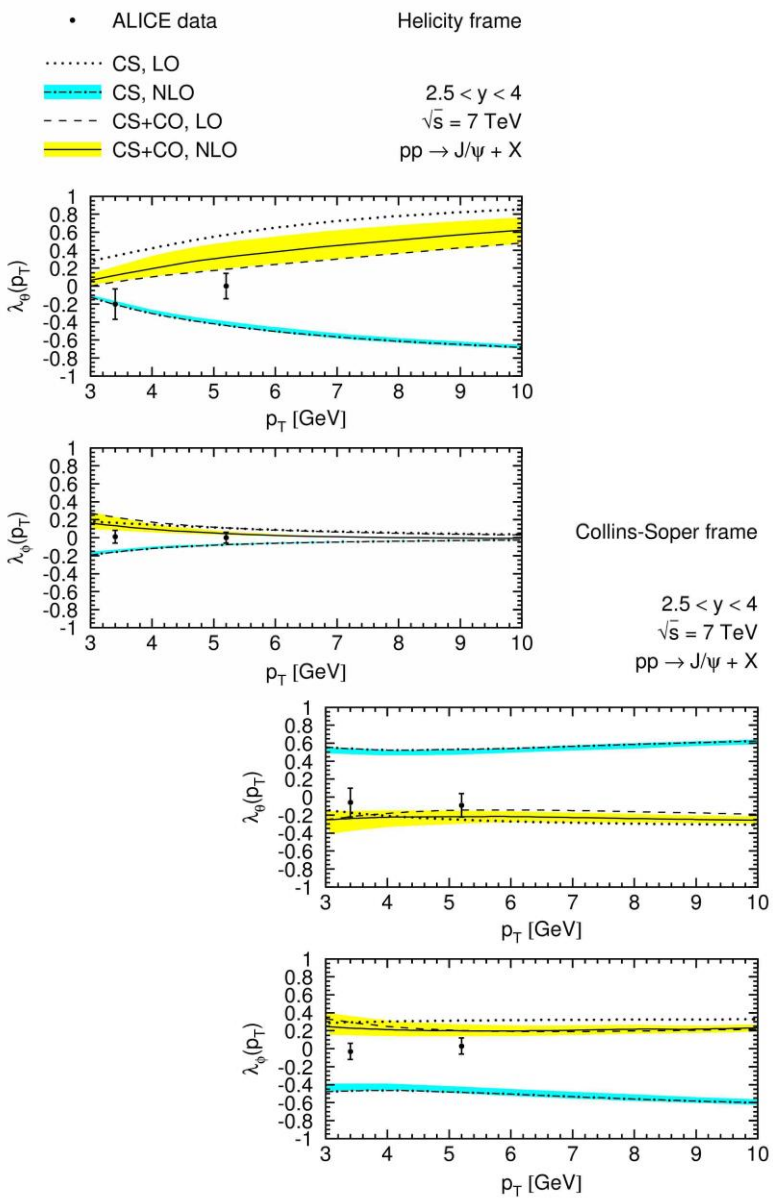
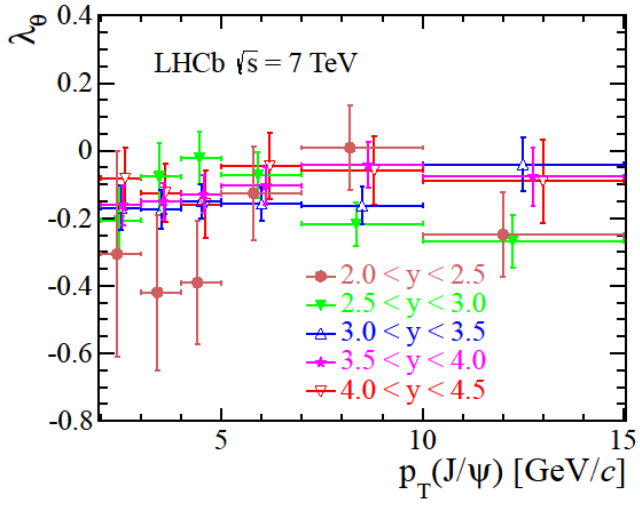
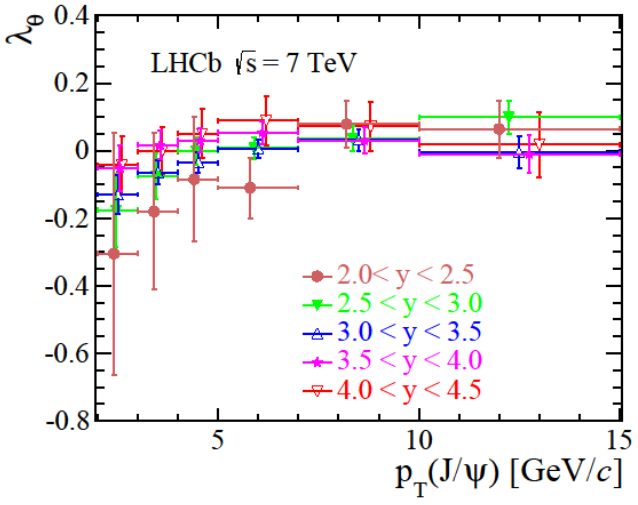




ALI-PUB-12784

LHCb: increasing precision on J/ψ...

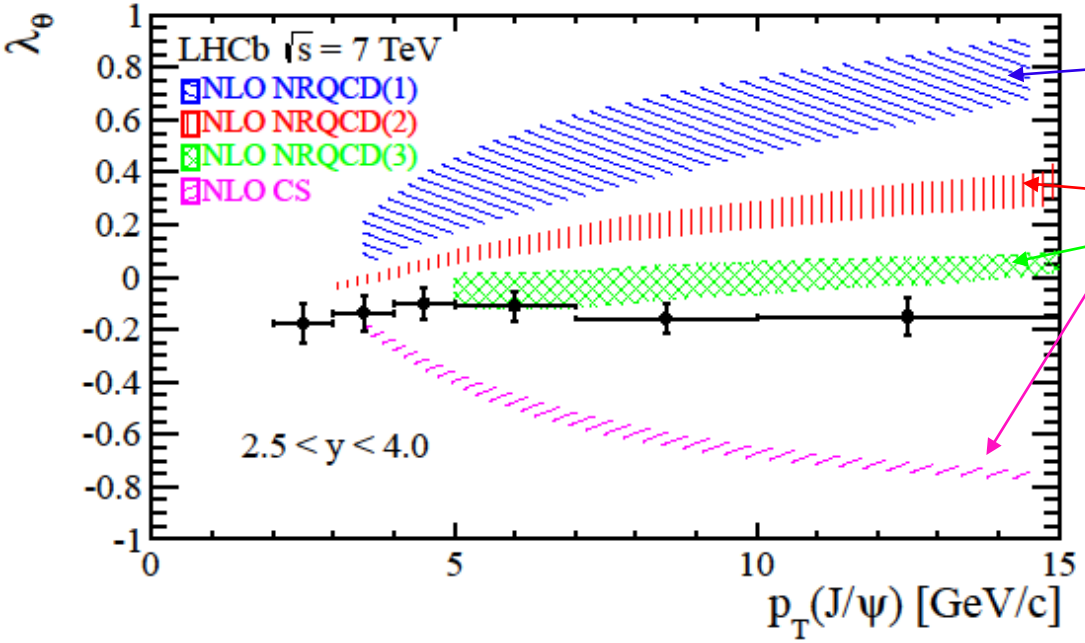




No strong dependence on rapidity

Mildly longitudinal polarization in Helicity frame

Perfect agreement with ALICE



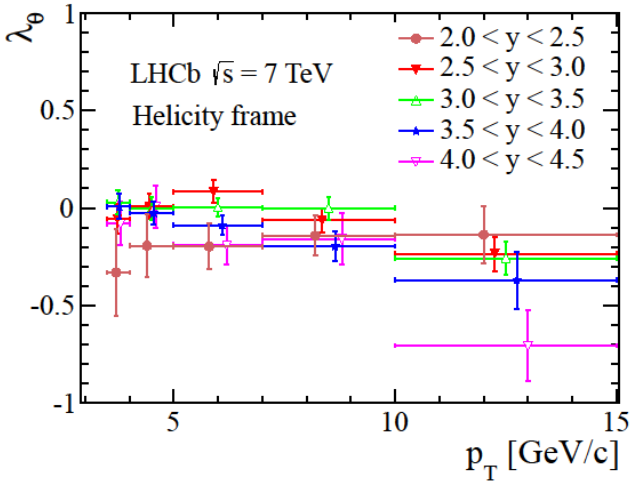
Direct J/ψ

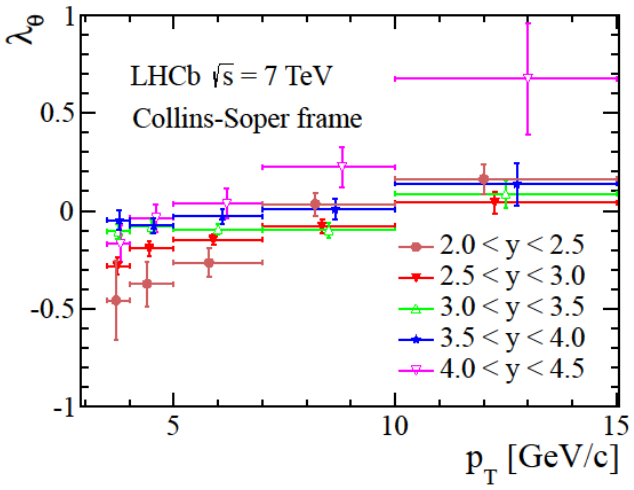
Prompt J/ψ

Data are for prompt J/ψ

Including feeddown from χ_c states **NRQCD** predictions tend towards a much more **diluted polarization** scenario

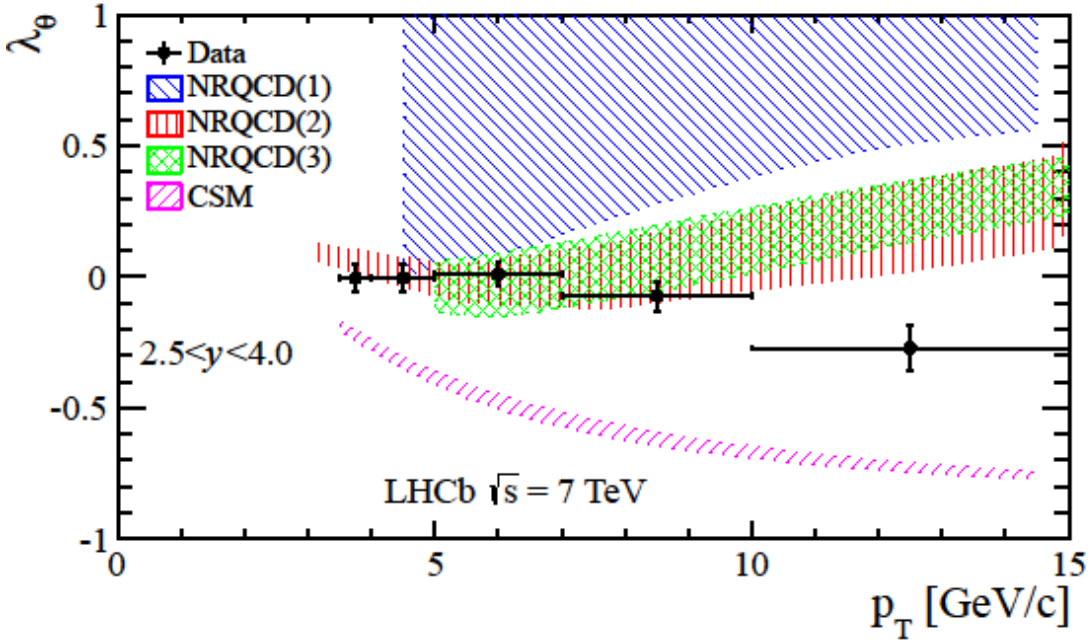
LHCb: ...and exploring ψ(2S)





Almost not affected by feeddown…

…but larger statistical errors and not really different conclusion

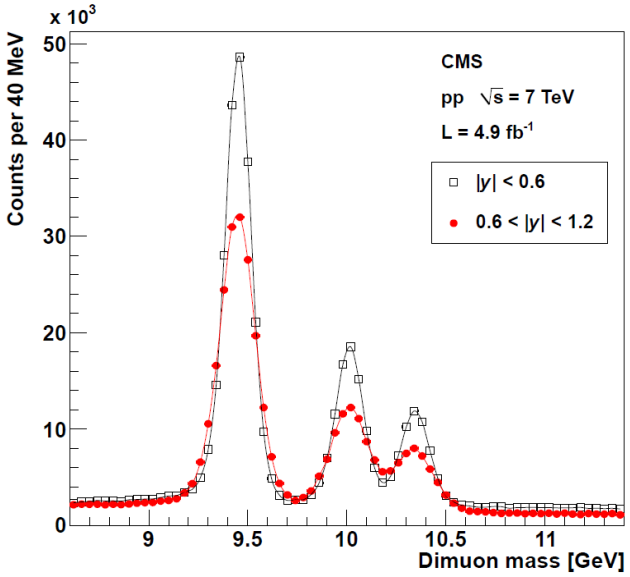


In order to avoid feeddown, better to concentrate on ϒ…

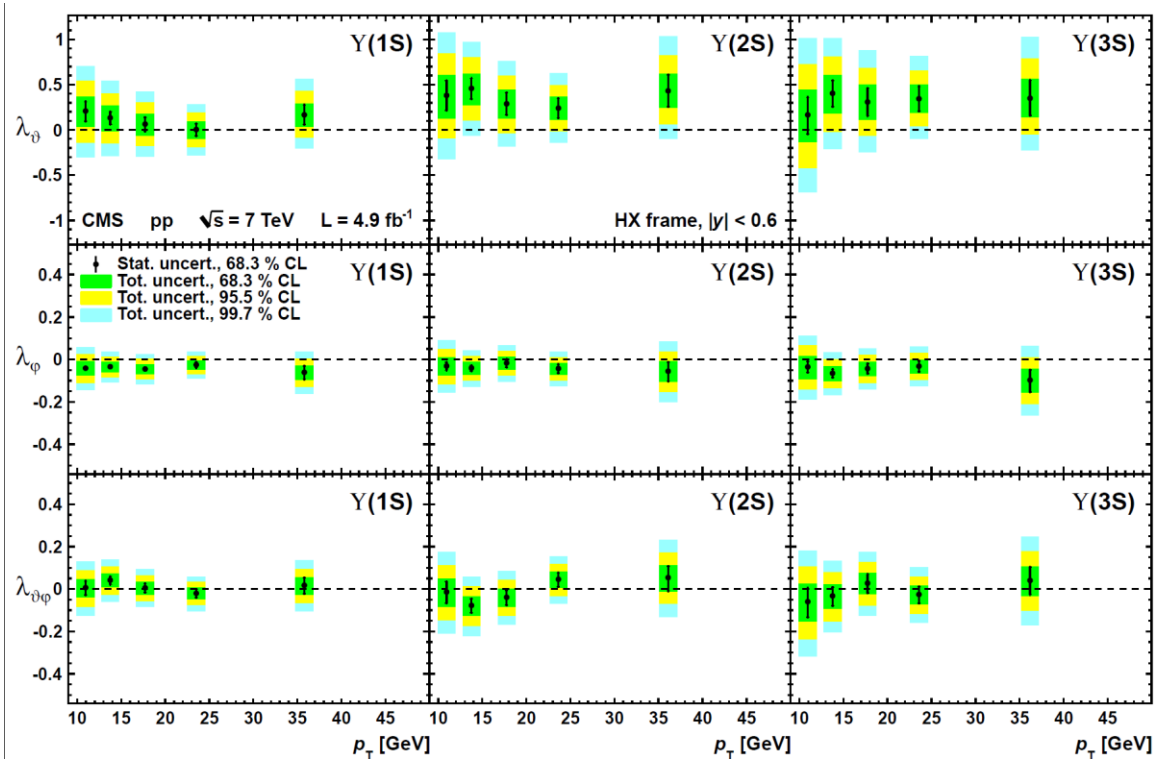
↓

CMS: concentrating on ϒ...

Tremendous capabilities in reconstructing bottomonia states!



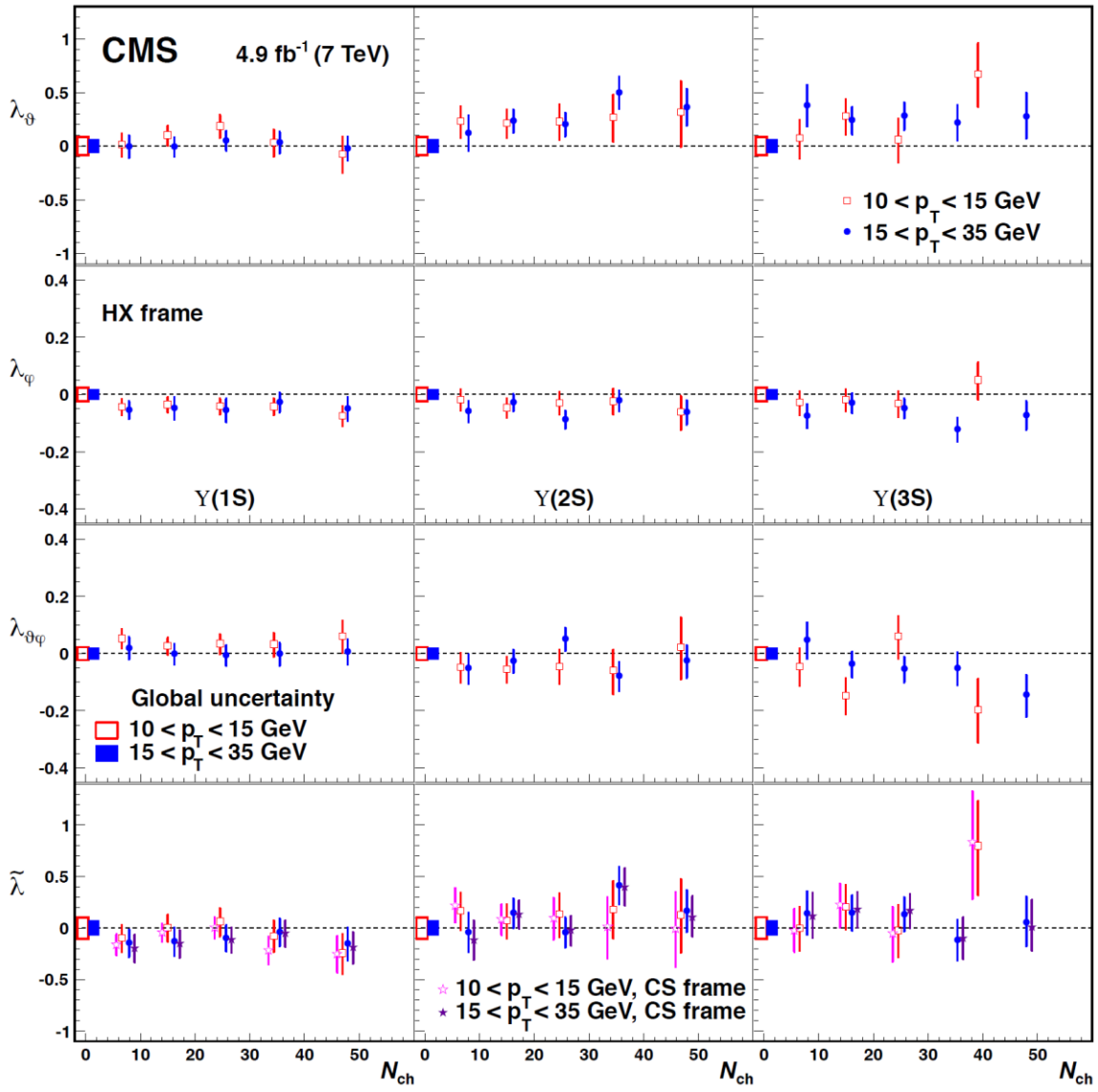
No evidence for a significant $\lambda_\theta \neq 0$ up to very high p_T!



Does this result threaten NRQCD as a whole?

It depends on the perspective...

CMS: an eye on multiplicity...

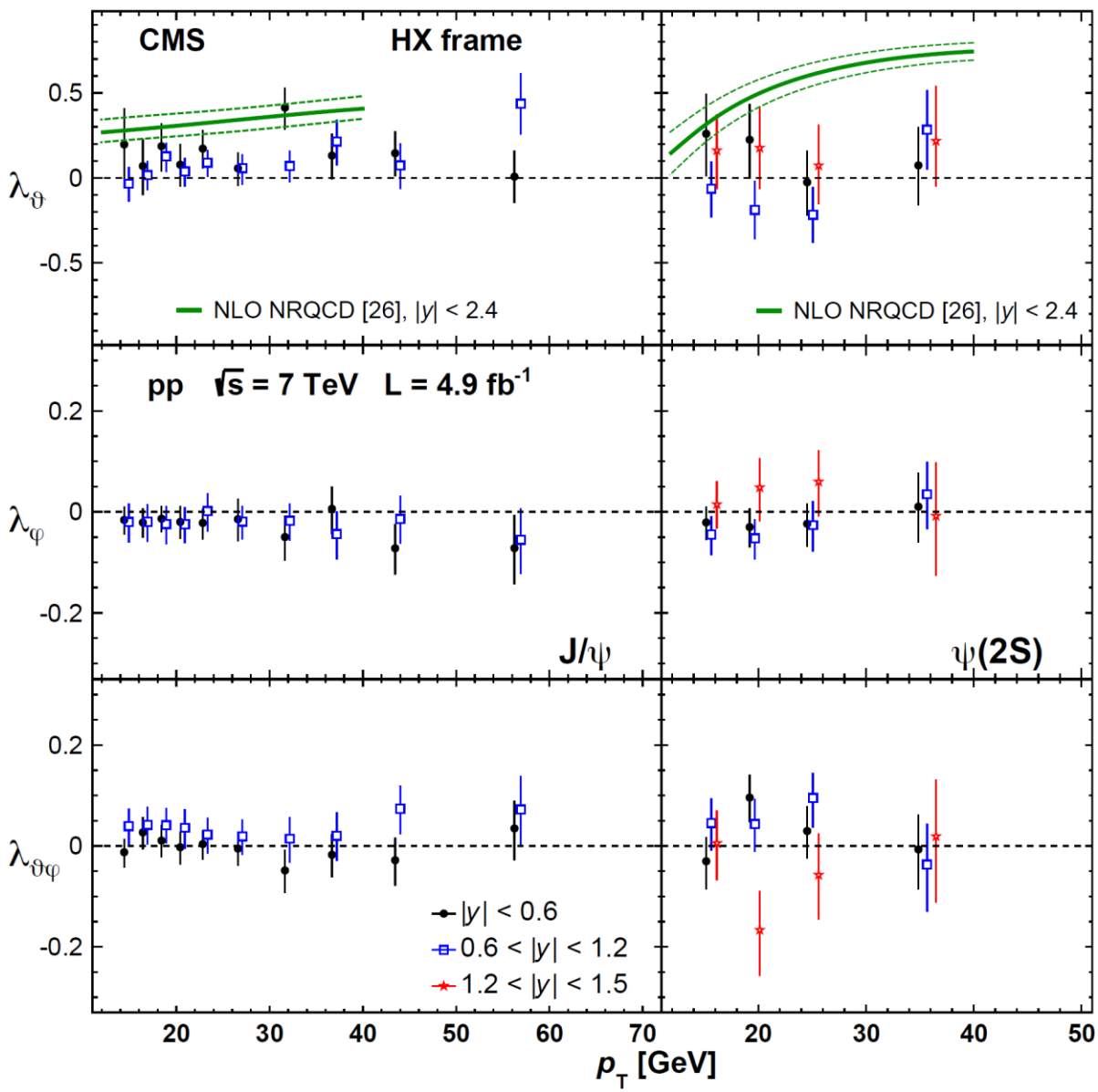


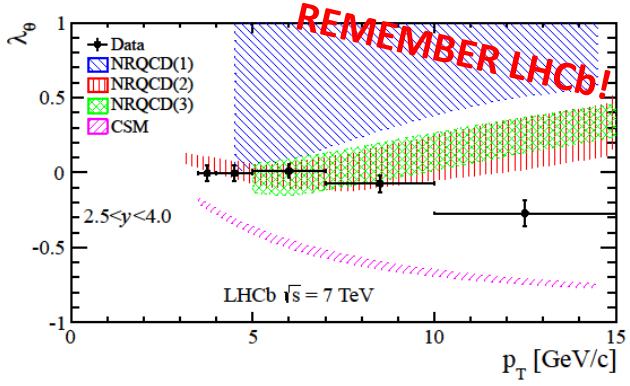
Multiplicity study is motivated by two main reasons:

- bridging to HI
- checking regions where activity is lower should enhance singlet terms' importance.

NO dependence on multiplicity!

CMS: ...but not forgetting J/ψ and ψ(2S)





CMS extends to much higher p_T the measurement performed by LHCb (but in a different rapidity domain)

Still no polarization observed.

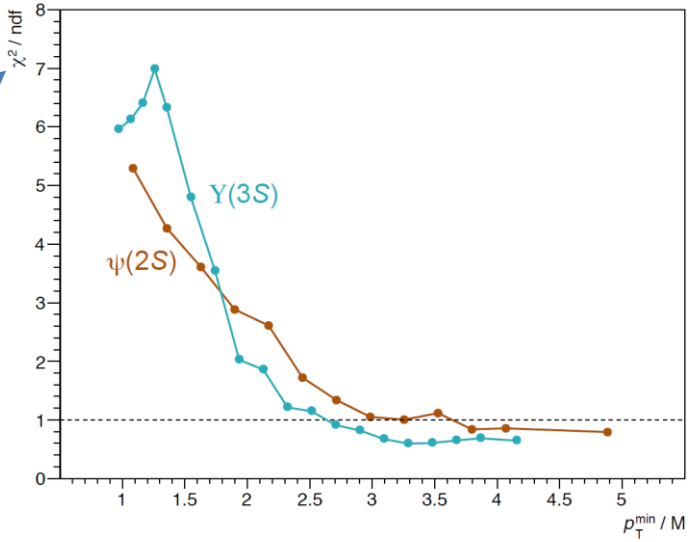
Are we allowed to change perspective?

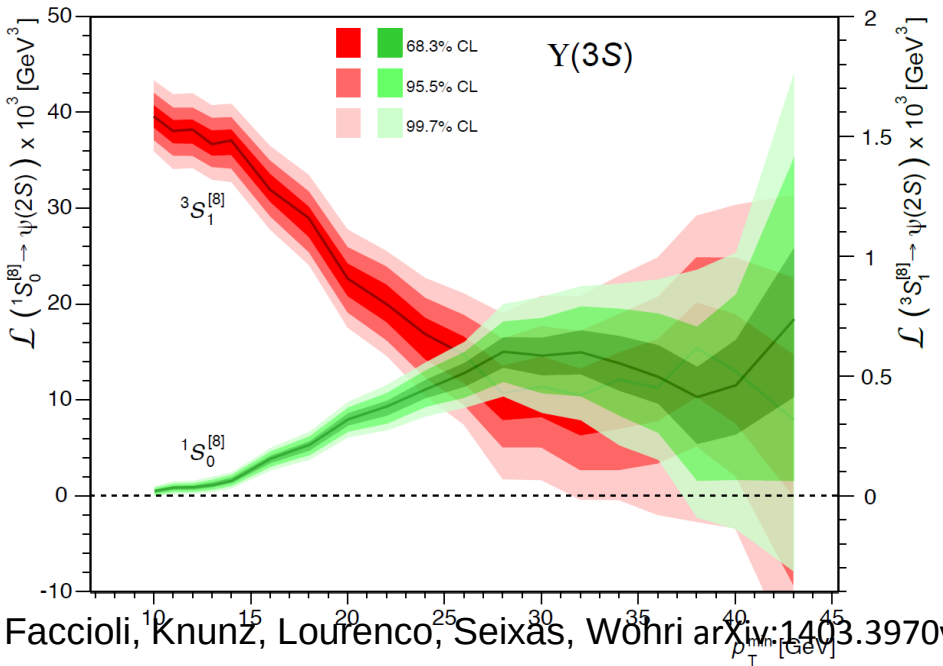
Recently, a change of perspective has been proposed.

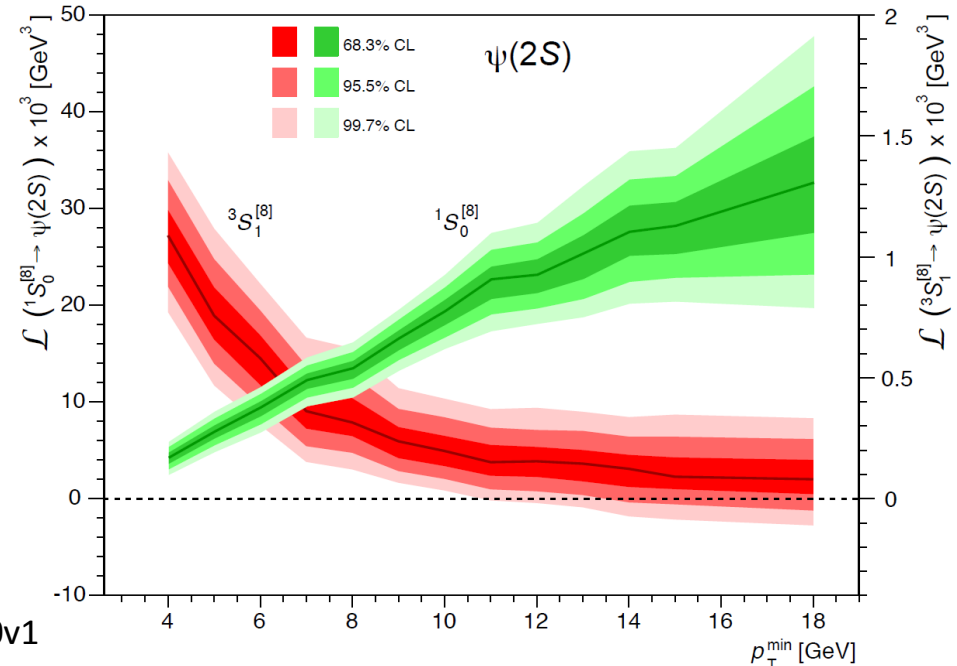
Is there a p_T scale above which NRQCD works?

The fit to the spectra is reliable only at high p_T!

There, LDME start to be constant over p_T(as should be!) So, let's make a combined fit of spectra and polarization at high p_T…





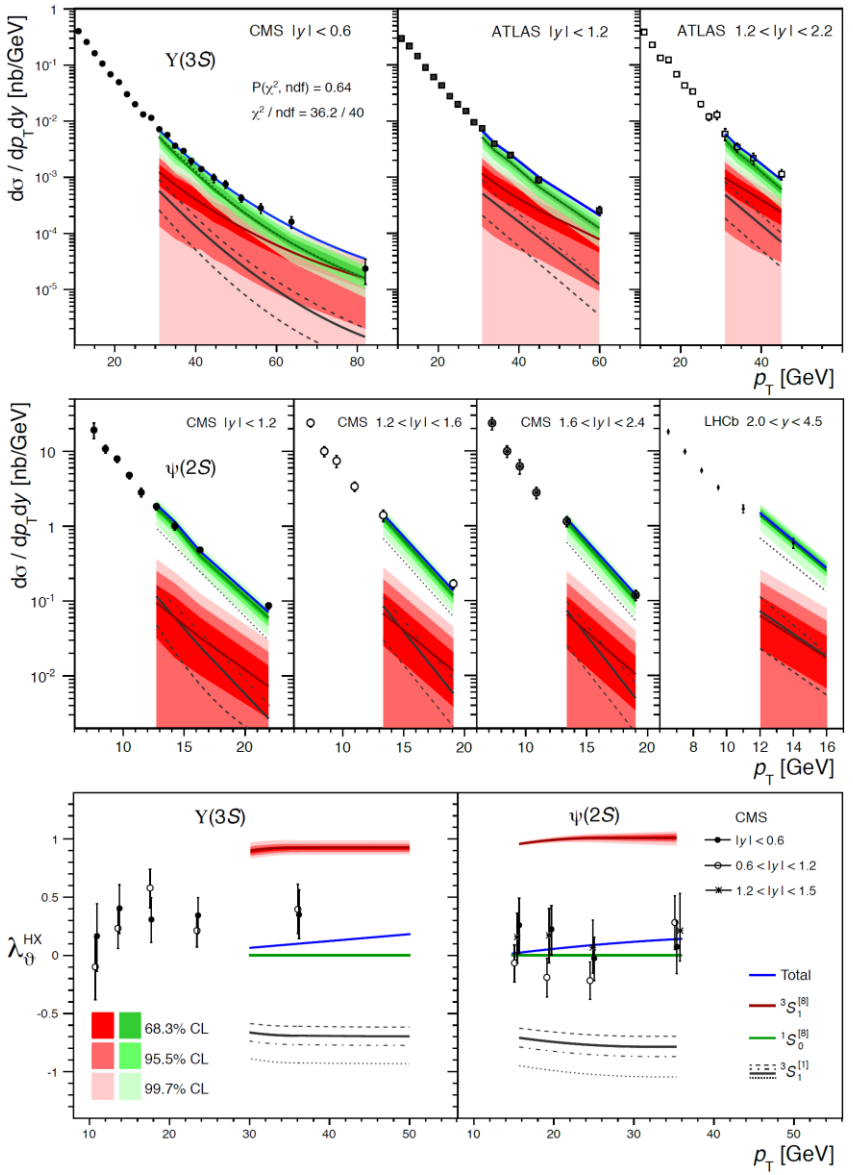


Faccioli, Knunz, Lourenco, Seixas, Wöhri arXiv:1403.3970v1

If yes, we end-up with something… encouraging?

The fit is reasonably well constrained

cross section and polarization are in agreement



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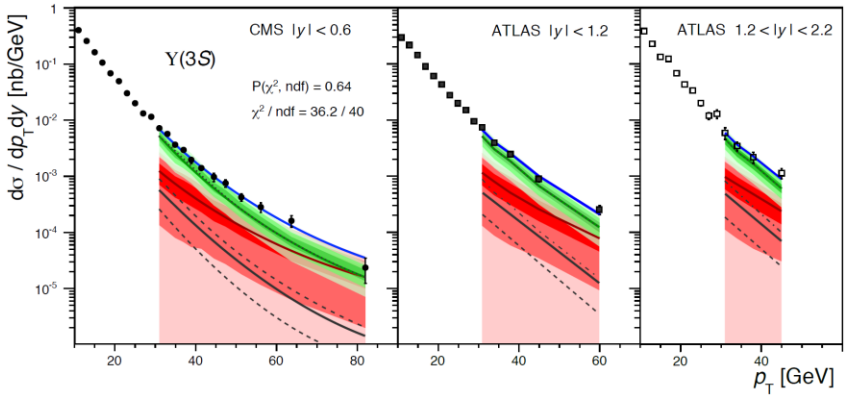
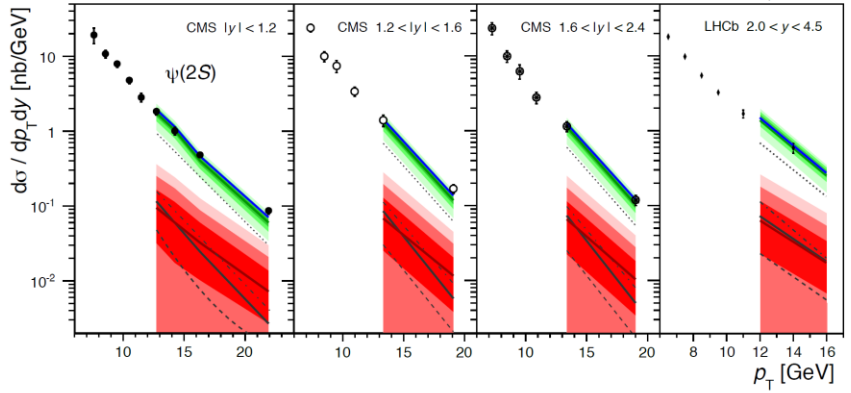
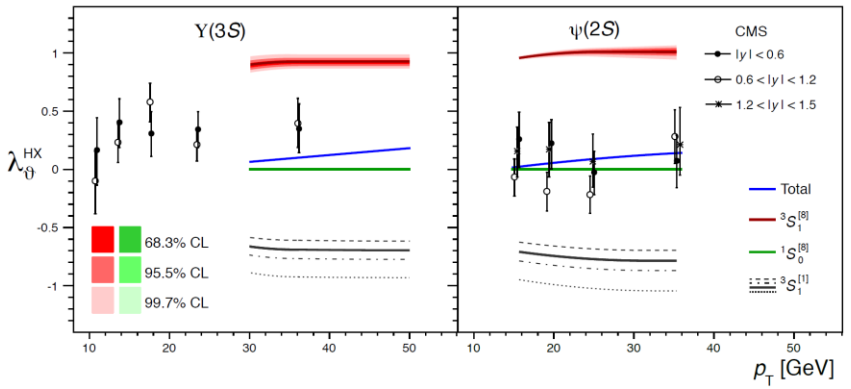
cross section and polarization are in agreement

Is this a SOLUTION?



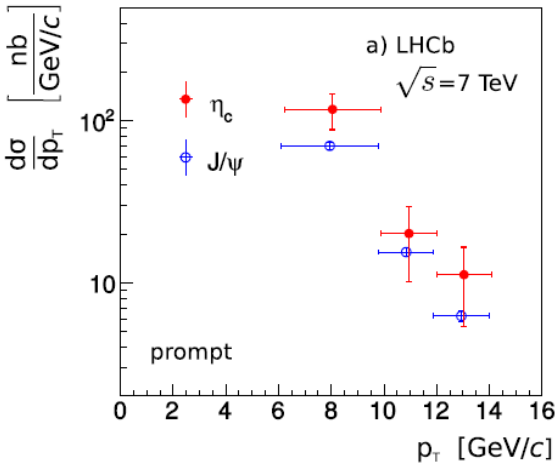


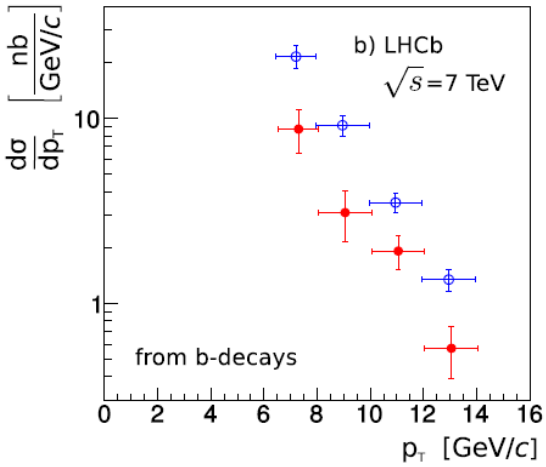


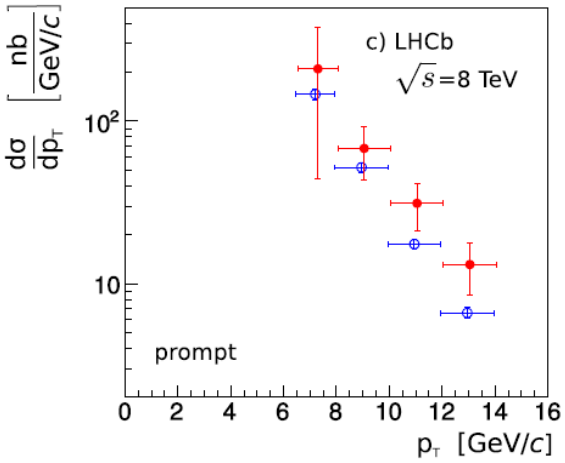
Faccioli, Knunz, Lourenco, Seixas, Wohri arXiv:1403.3970v1

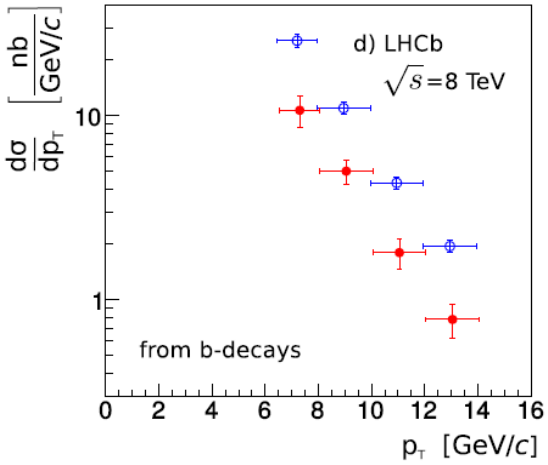
Evolution and perspectives (1 example)

η_c cross section in LHCb









First measurement of η_c from the LHCb experiment.

Limited statistics and restricting to rather high p_T

But still…

Very interesting for the quarkonium production saga!

↓

η_c cross section in LHCb

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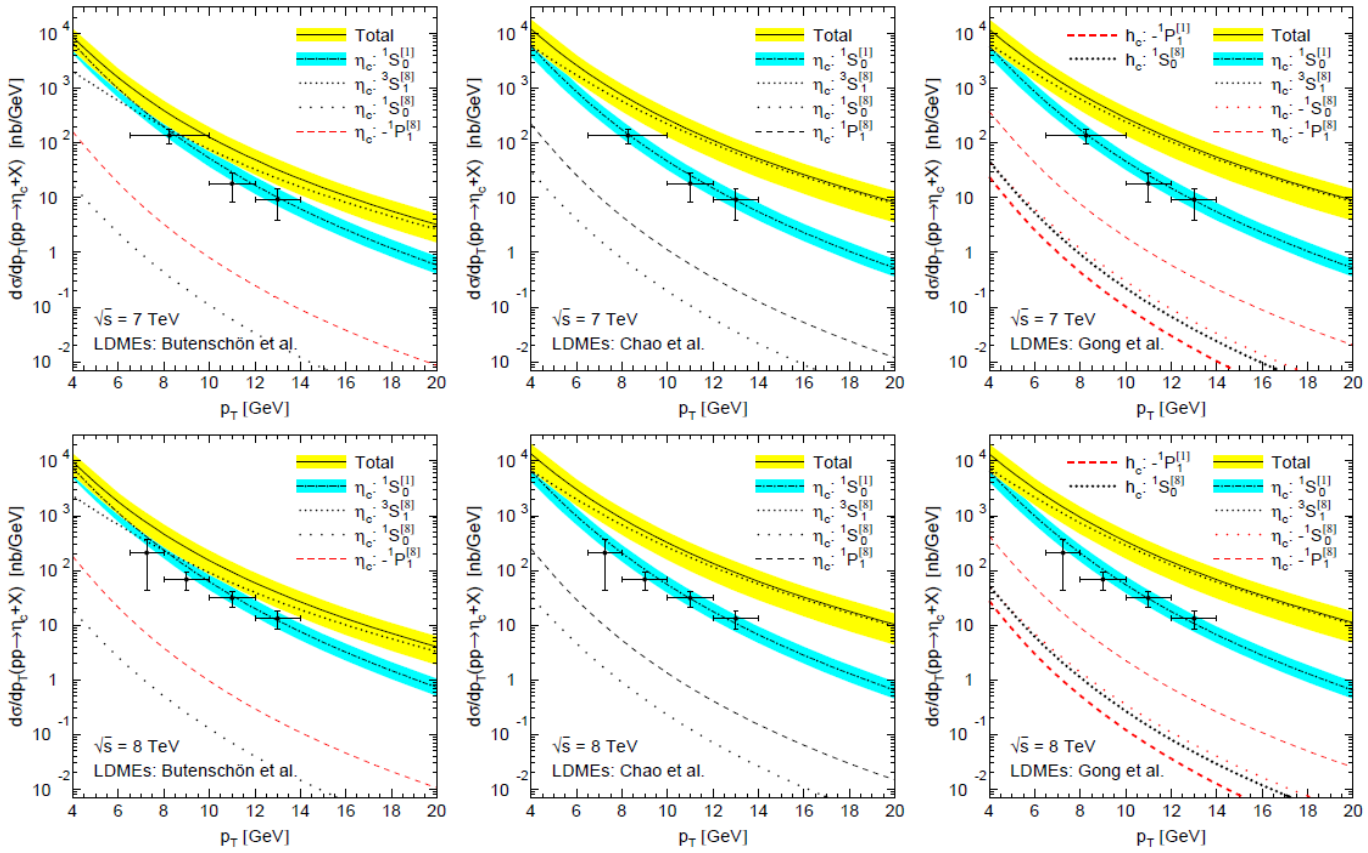
η_c production at the LHC challenges nonrelativistic-QCD factorization

Mathias Butenschoen, Zhi-Guo He, and Bernd A. Kniehl
II. Institut für Theoretische Physik, Universität Hamburg,
Luruper Chaussee 149, 22761 Hamburg, Germany
(Dated: January 20, 2015)



Being η_c the spin-singlet partner of the J/ψ, LDMEs are related to those of the J/ψ by HQSS

So one can use η_c as a bench test

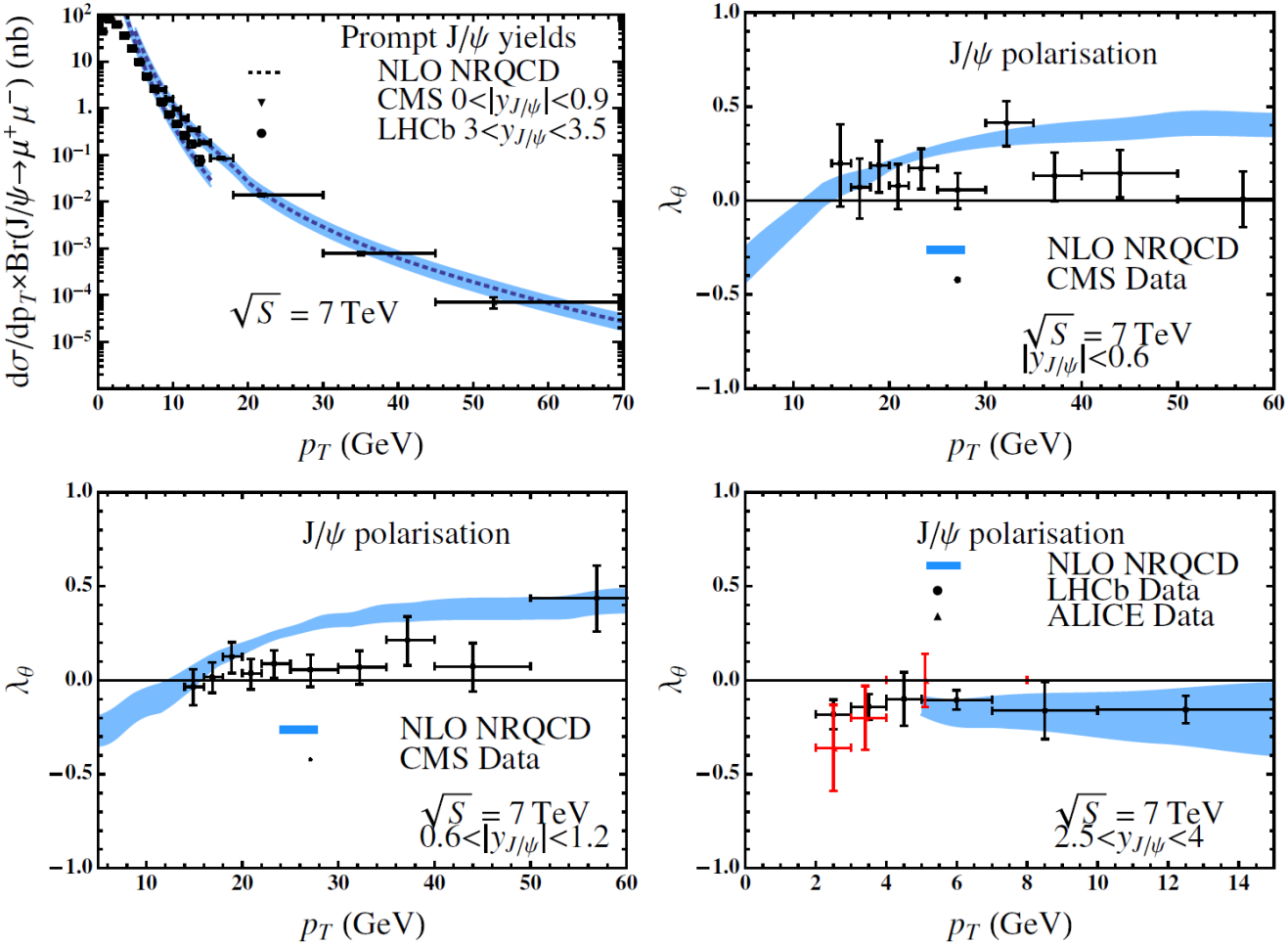
(as polarization is)

Color Singlet nicely reproduces data, while color octet terms lead to much higher cross-section

Butenschön, He, Kniehl, arXiv:1411.5287v2

η_c cross section in LHCb

…Or one can constrain J/ψ polarization prediction using η_c measurement!



Han, Ma, Meng, Shao, Chao, PRL 114, 092005 (2015)

Conclusions (or at least some thoughts)

Still a long way, but exciting journey!

- The 4 LHC experiments are delivering very precise measurements on cross-section, and polarization for most of the known quarkonium states

- These data, more than allowing a fine-tuning of the theory parameters, are uncovering issues in the LDME estimation (non-perturbative is non-hard stuff!)

- NAE In order to use quarkonium production as a probe for gluon TMD-related studies, we probably have to fully solve these issues, in order to be able to isolate effects coming from the short-distance perturbative calculations

THIS SAID…

- **LHC experiments** have collected a **huge amount of pp events** which can be exploited much deeper (and they will)

- More precise and refined measurement will come out sooner or later (we have big collaborations, but we search for people! ☺)

- Please, propose new interesting measurements!