Quarkonium production at the LHC: A polarized perspective

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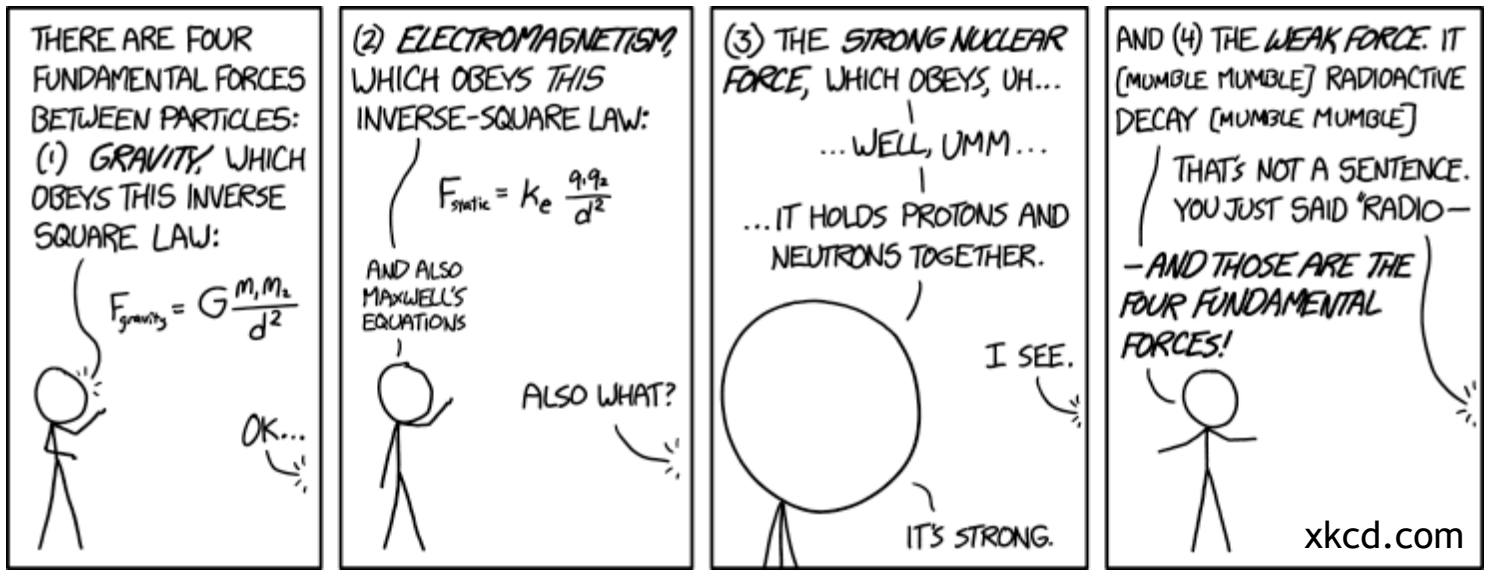
in collaboration with P. Faccioli, V. Knünz, C. Lourenço, J. Seixas, H. Wöhri

Humboldt Kolleg
28 June 2016



* supported by Austrian Science Fund (FWF): P28411-N36

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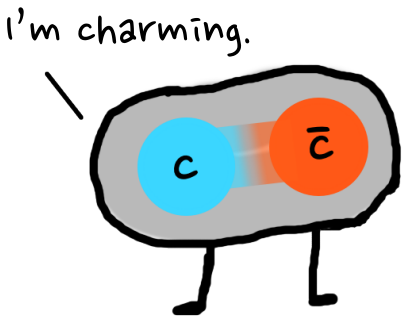
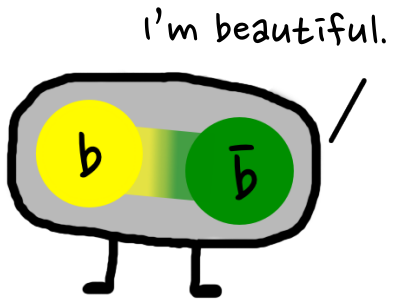
Motivation

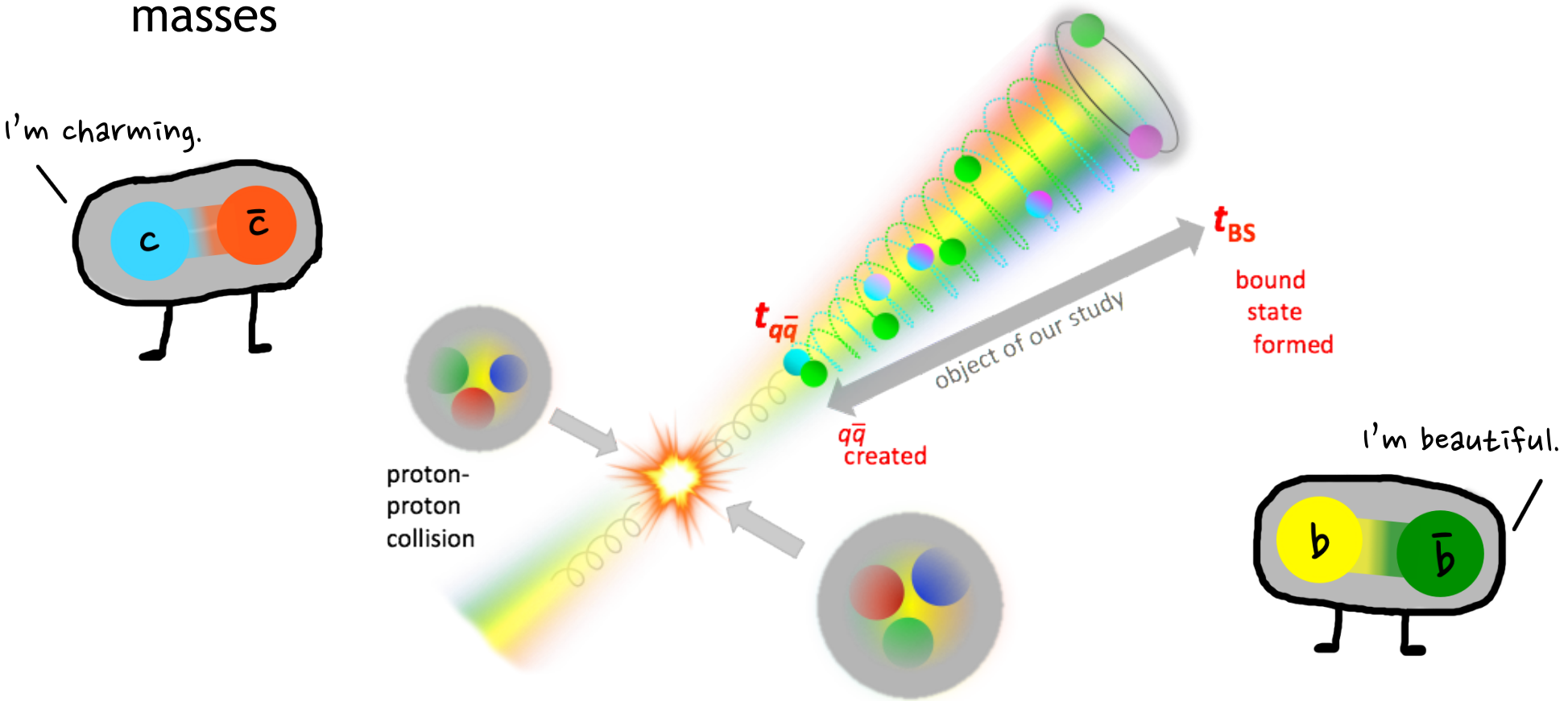
- Our knowledge about the strong force is limited
- Quarkonia ($c\bar{c}$, $b\bar{b}$) are the ideal probe to study hadron formation



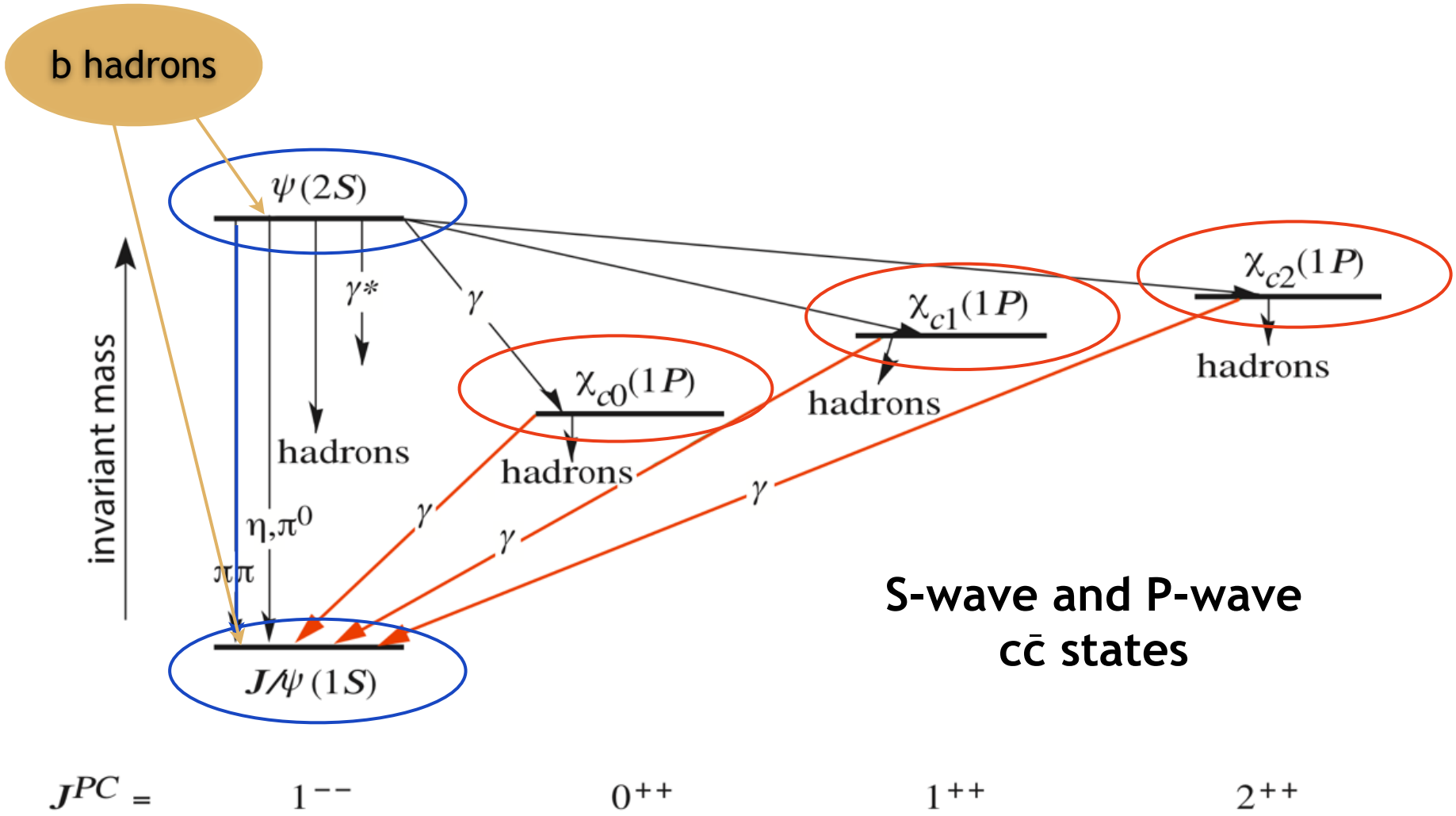


Motivation

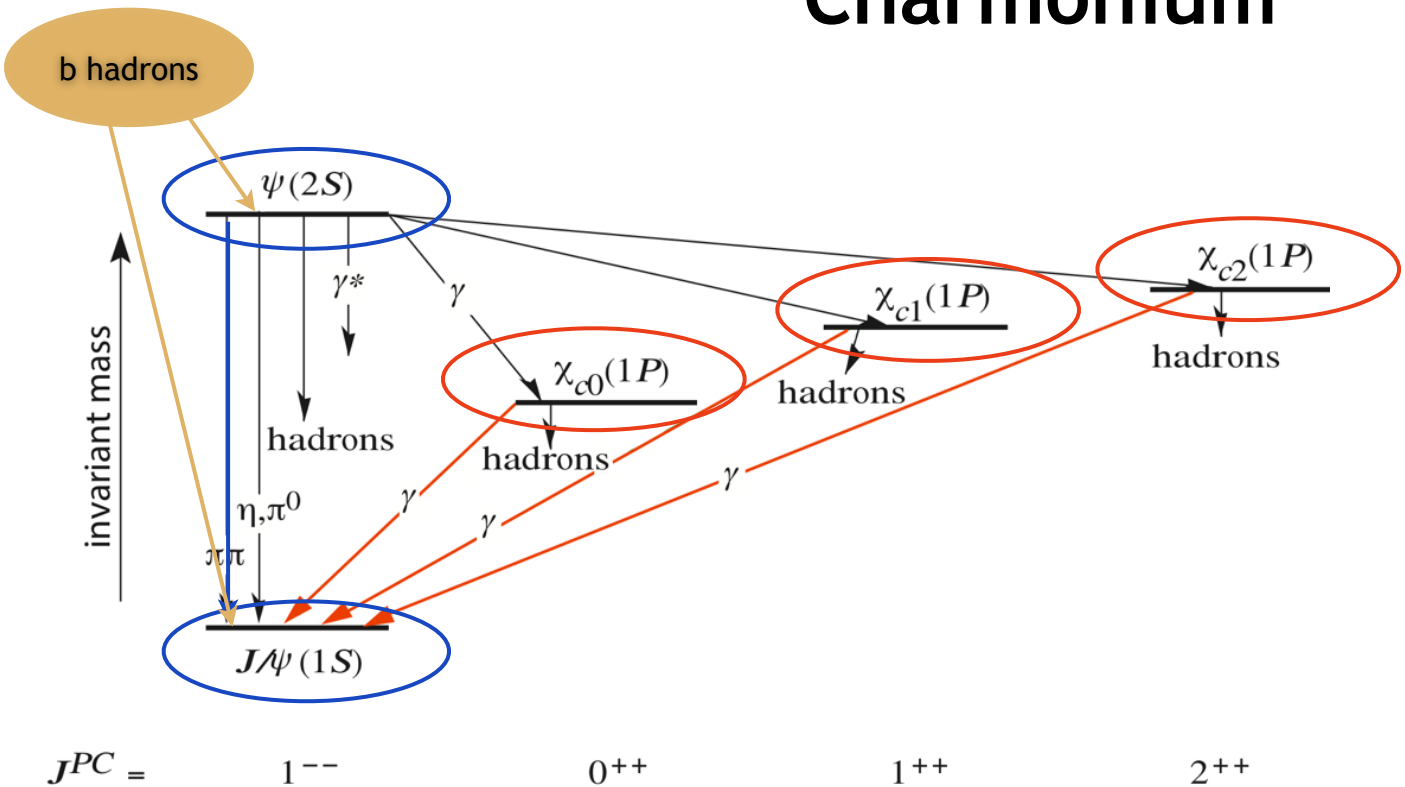
- Our knowledge about the strong force is limited
- Quarkonia ($c\bar{c}$, $b\bar{b}$) are the ideal probe to study hadron formation
- Quark-antiquark production and quarkonium formation are well separated processes at distinct timescales due to heavy quark masses



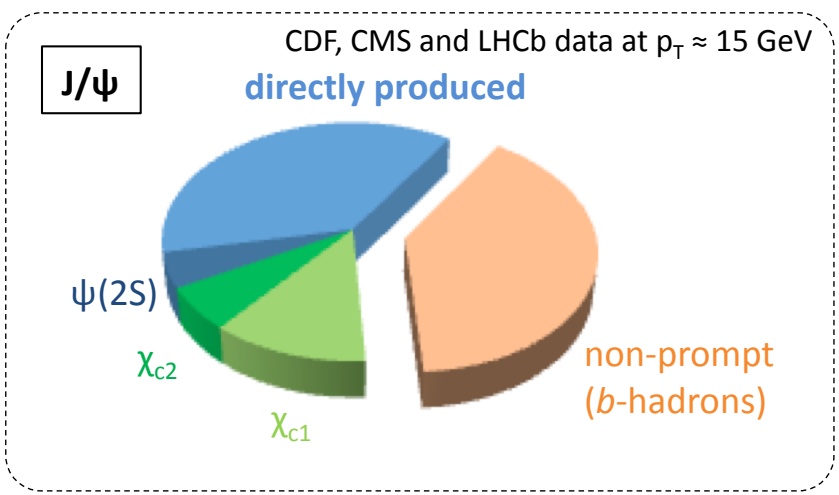
Charmonium

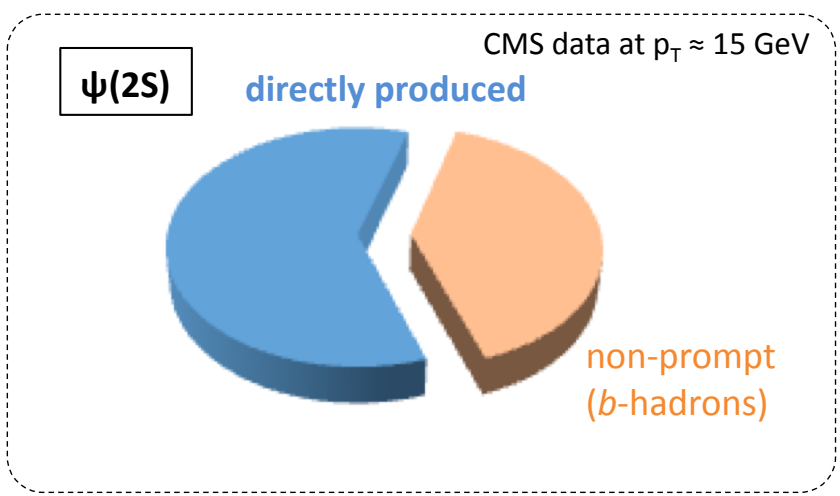

b hadrons
$\psi(2S)$
γ^*
γ
hadrons
$\chi_{c0}(1P)$
hadrons
$\chi_{c1}(1P)$
hadrons
$\chi_{c2}(1P)$
hadrons
invariant mass
η,π^0
$\pi\pi$
γ
γ
γ
$J/\psi\,(1S)$
S-wave and P-wave
$c\bar{c}$ states
J^{PC} = 1^{--} 0^{++} 1^{++} 2^{++}

Charmonium

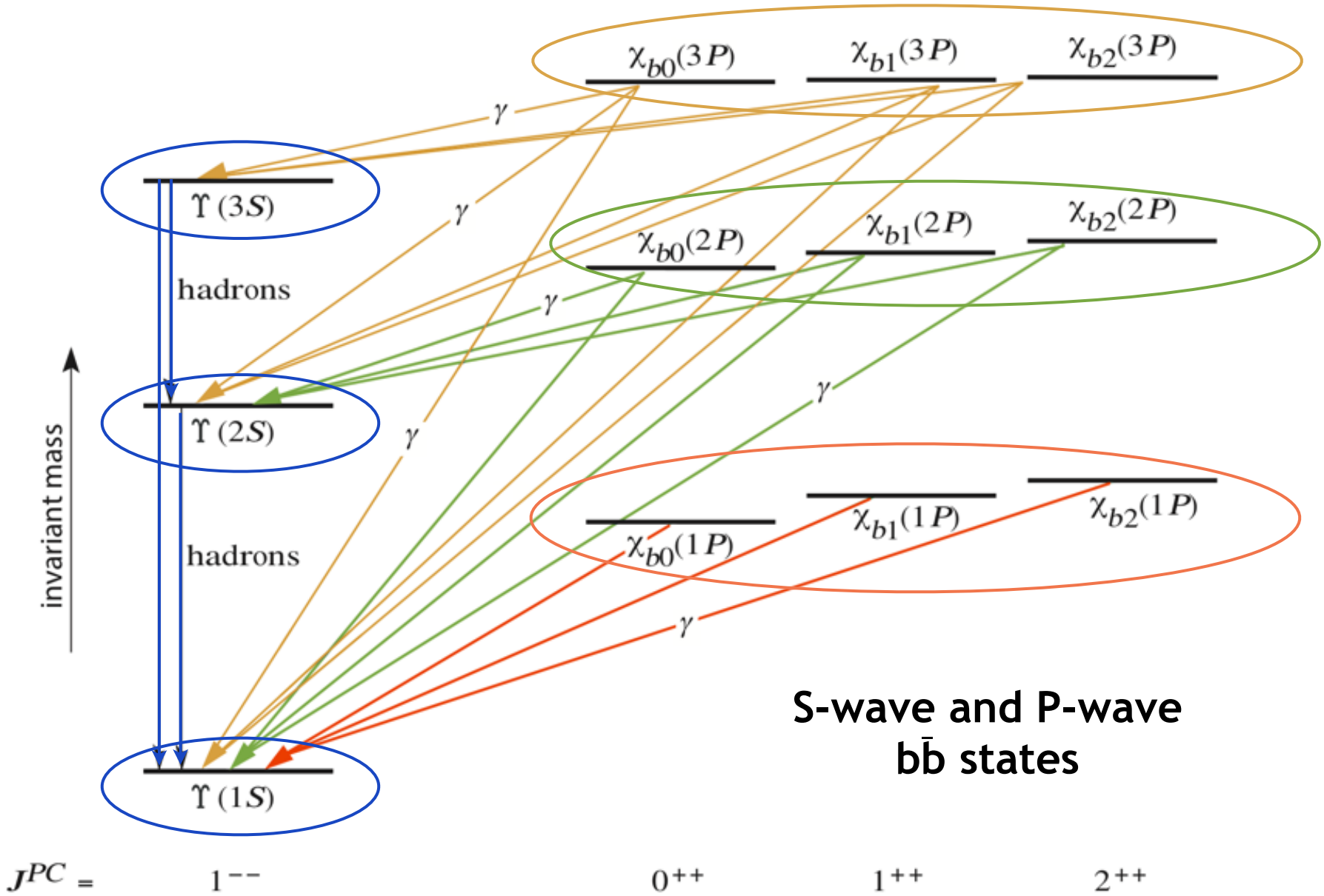


- Non prompt contribution from B-decays separated experimentally
- Prompt J/ψ production = direct production + feed-down from χ_c and ψ(2S)
- No feed-down contribution to ψ(2S)



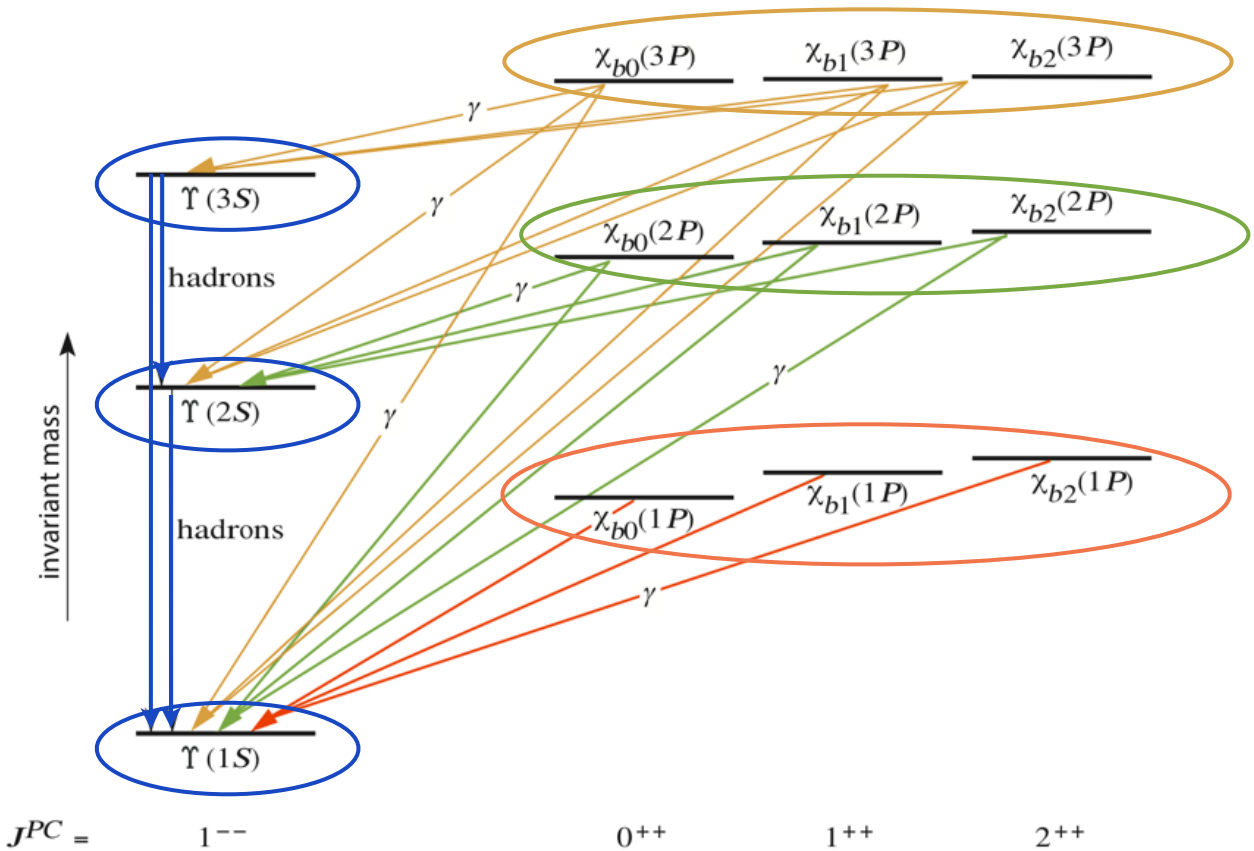


Bottomonium

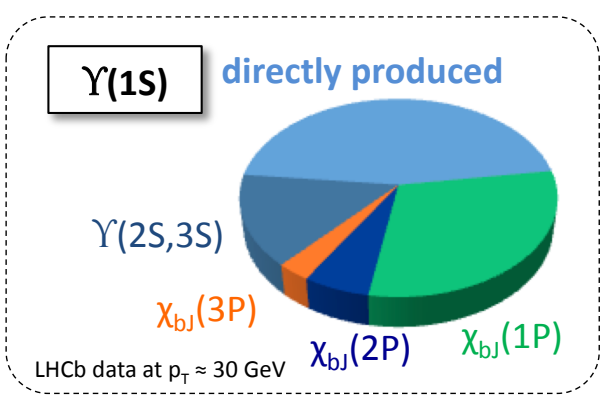


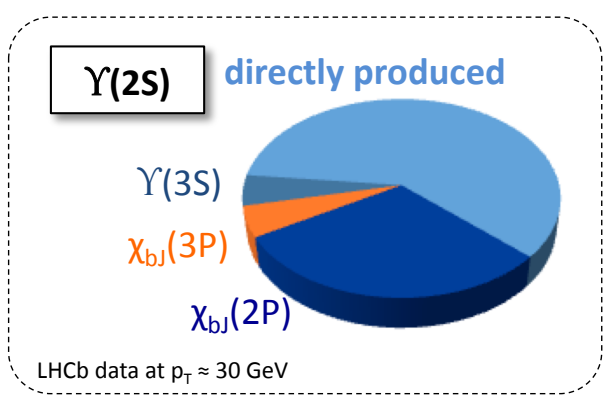
S-wave and P-wave $b\bar{b}$ states

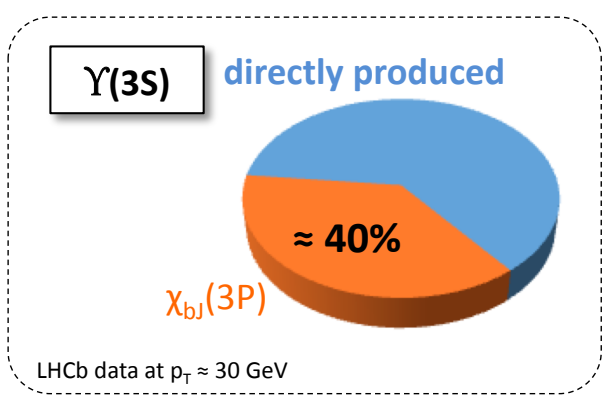
Bottomonium



- All S-wave states affected by feed-down
- No non prompt decays







NRQCD factorization approach

Non Relativistic Quantum ChromoDynamics (NRQCD) is an effective theory that factorizes quarkonium production into 2 steps

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1. Production of the initial quark-antiquark pair

possibly *colored* $Q\bar{Q}$ pair
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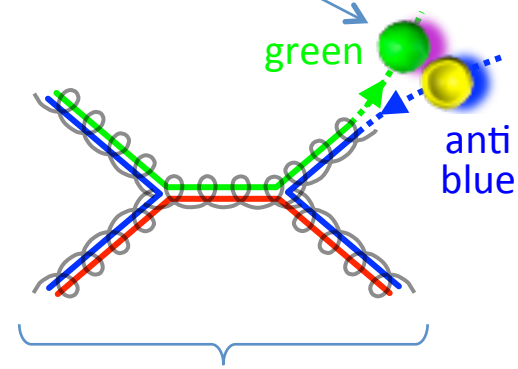
quantum numbers



1) perturbative phase

$$\sigma(\mathcal{Q}) = \sum_n \mathcal{S}[Q\bar{Q}(n)]$$

$n = {}^{2S+1}L_J^{[C]}$ with C = 1,8 and S, L, J = spin, orbital and total angular momentum

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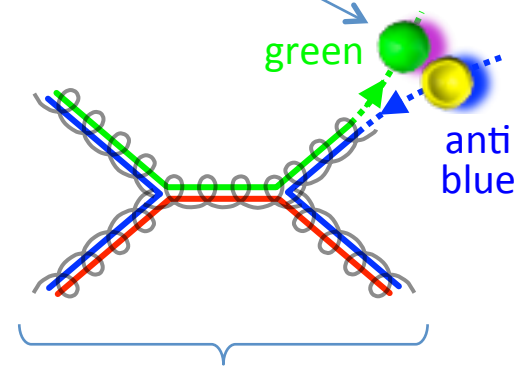

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1. Production of the initial quark-antiquark pair
2. Hadronization of the initial pair into a bound state

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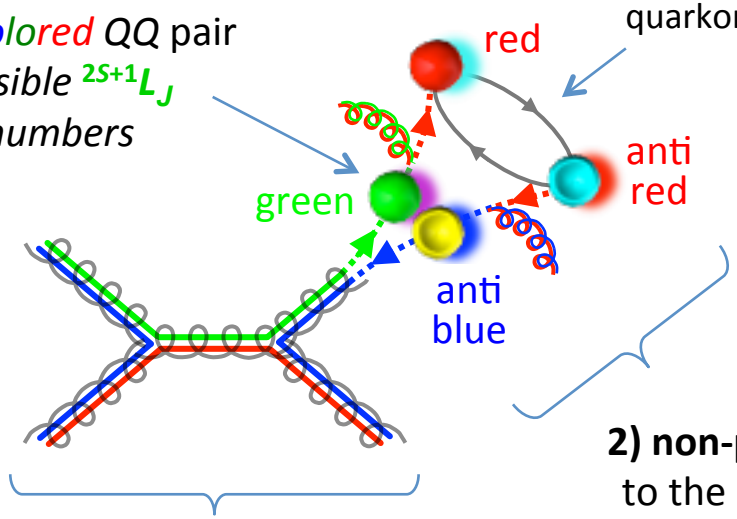
quarkonium ($\mathcal{Q}$)



1) perturbative phase

2) non-perturbative evolution to the observed bound state
Quantum numbers change!

$$\sigma(\mathcal{Q}) = \sum_n \mathcal{S}[Q\bar{Q}(n)] \qquad \langle \mathcal{O}^{\mathcal{Q}}(n) \rangle$$

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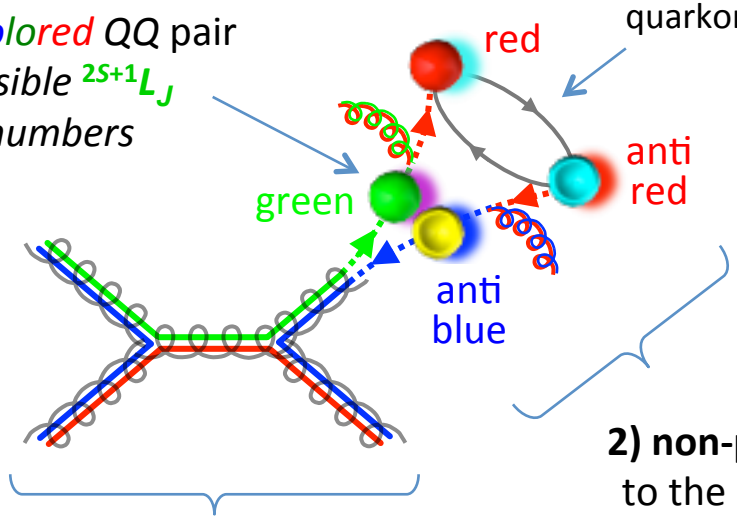

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Short Distance Coefficients

Long Distance Matrix Elements

$n = {}^{2S+1} L_J^{[C]}$ with C = 1,8 and S, L, J = spin, orbital and total angular momentum

Long distance matrix elements

- Proportional to relative quark velocity squared v^2

S-wave quarkonia: $J^{PC} = 1^{--}$

$^{3S+1}L_J$ =	$^1S_0$	$^3S_1$	$^1P_1$	^3P_J	^3D_J	$^1D_2$	...
color singlet		1					
color octet	v^4	v^4	v^8	v^4	v^8	v^{12}	...

IJMPA 12 (1997) 3951

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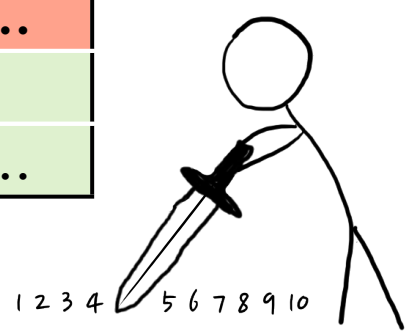
Sum of LDMEs is truncated at order v^4



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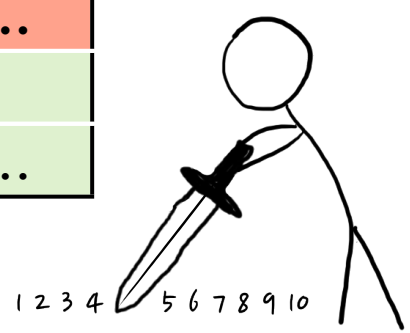

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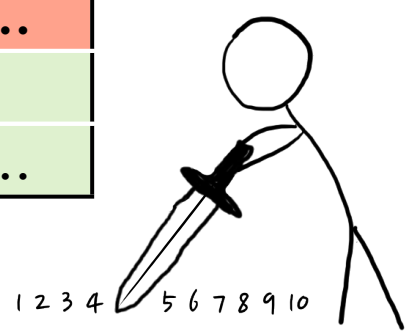

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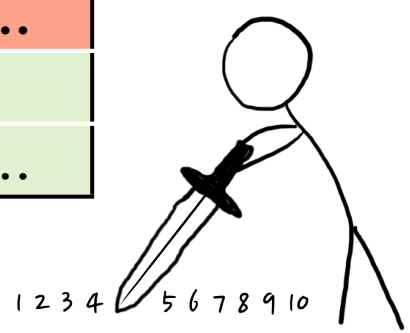

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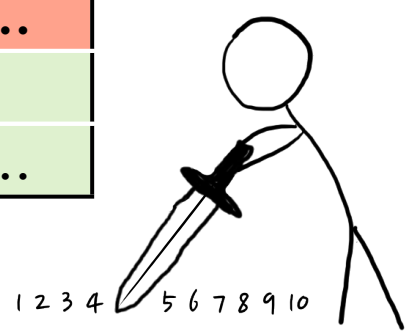

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Haunted by anomalies and puzzles

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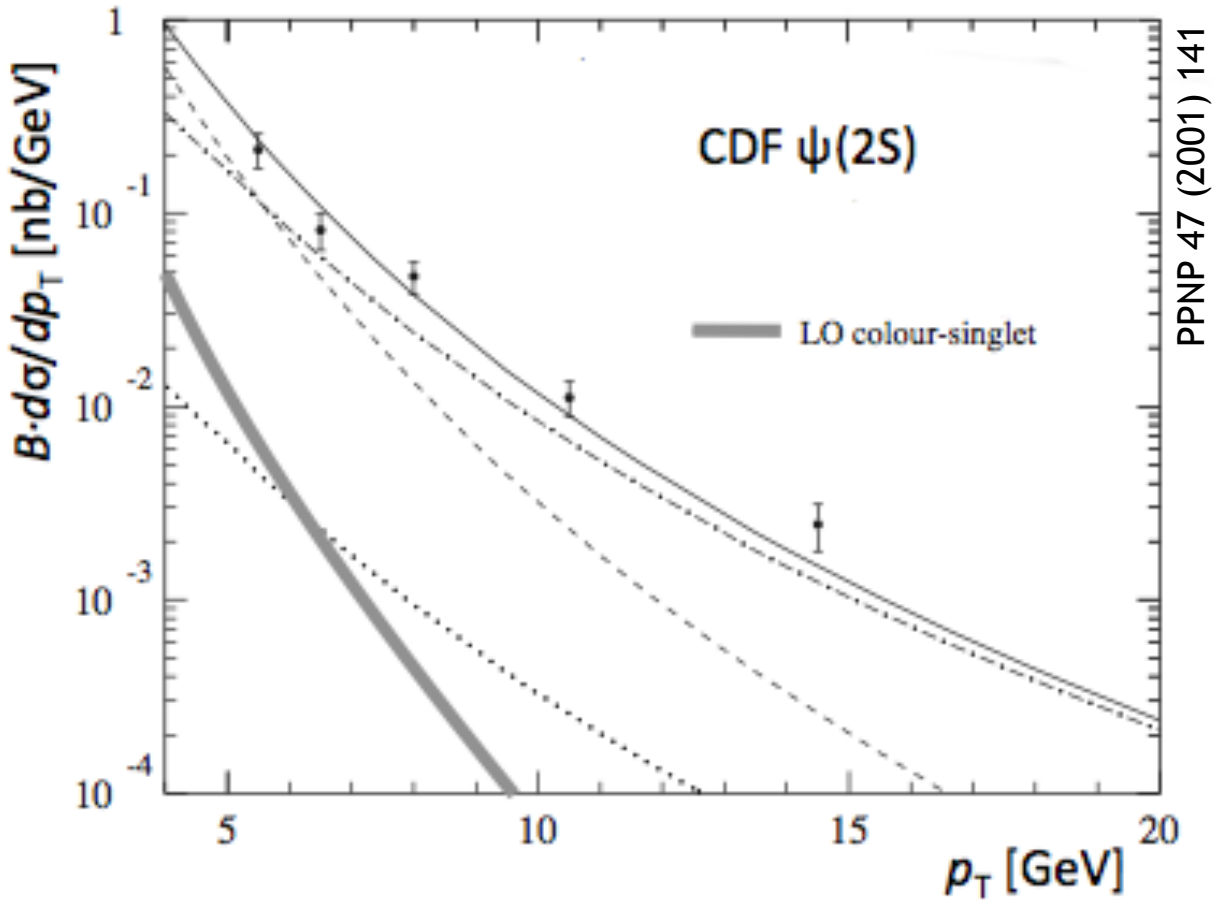

PPNP 47 (2001) 141

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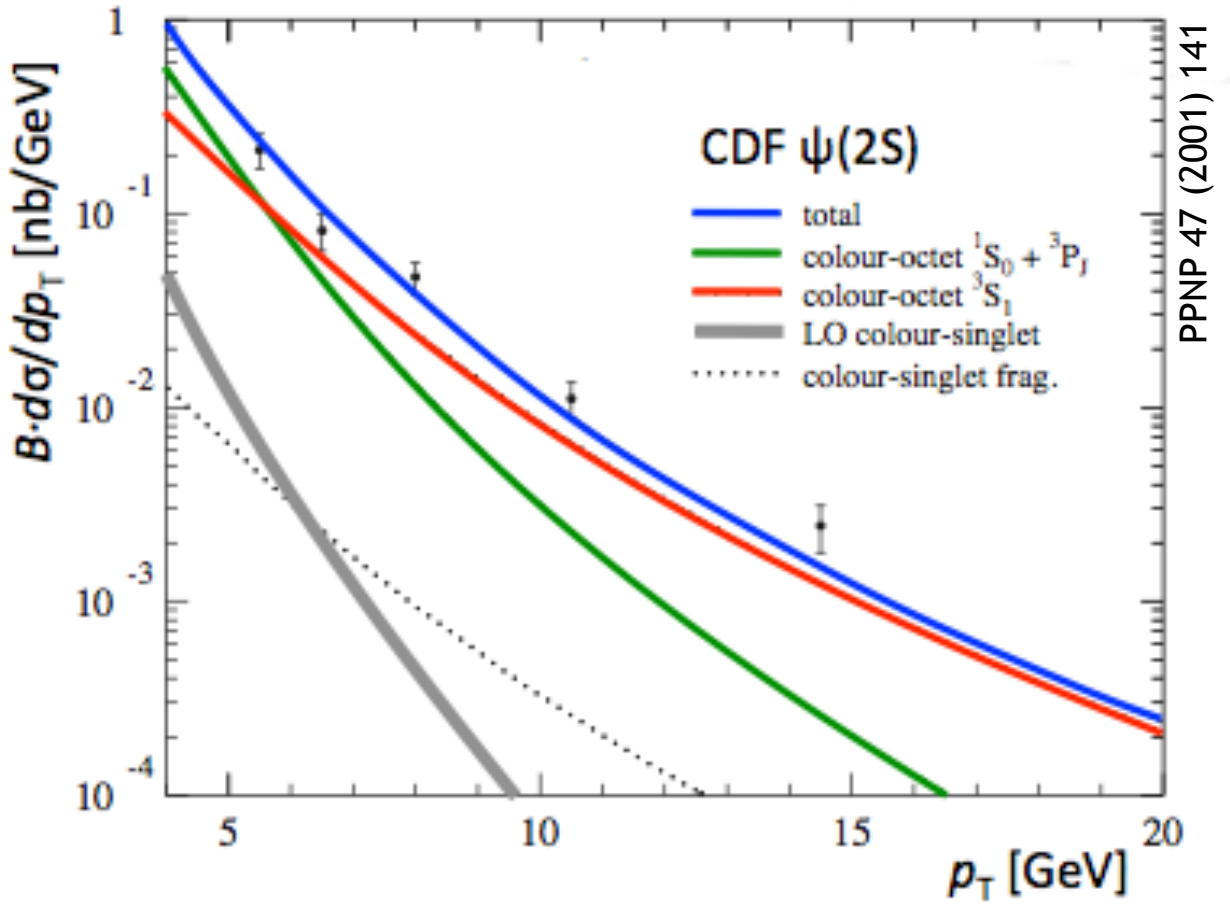

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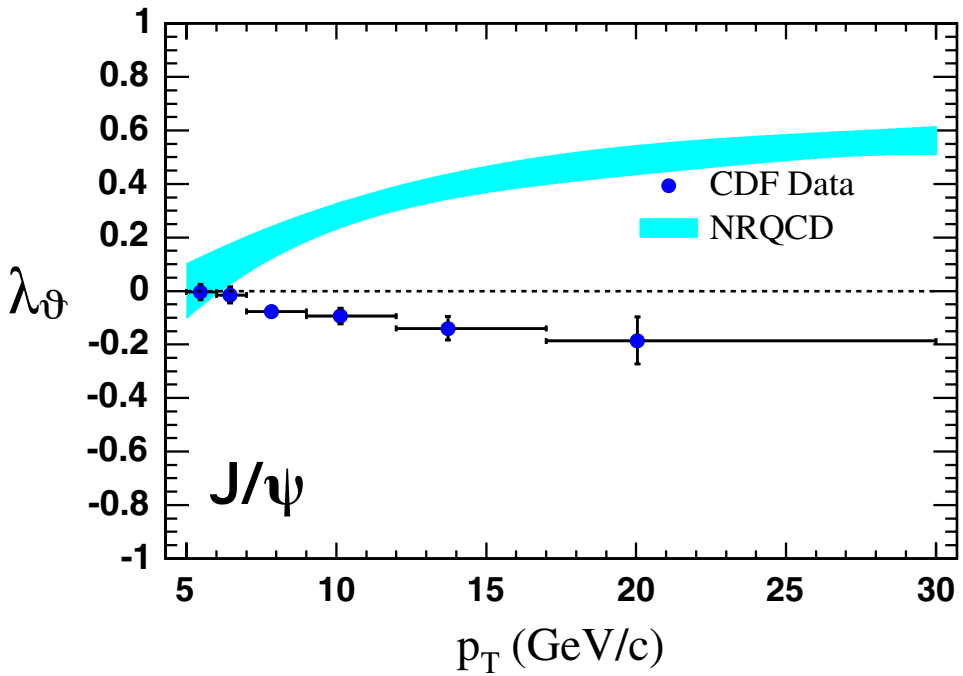

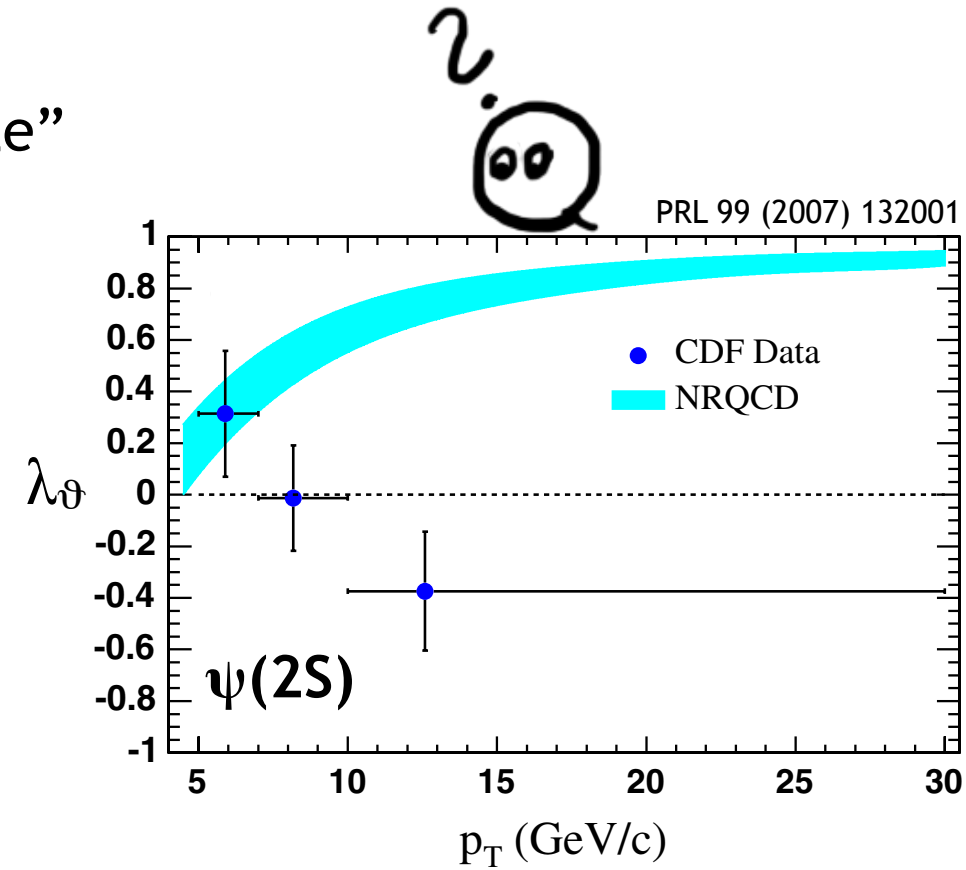

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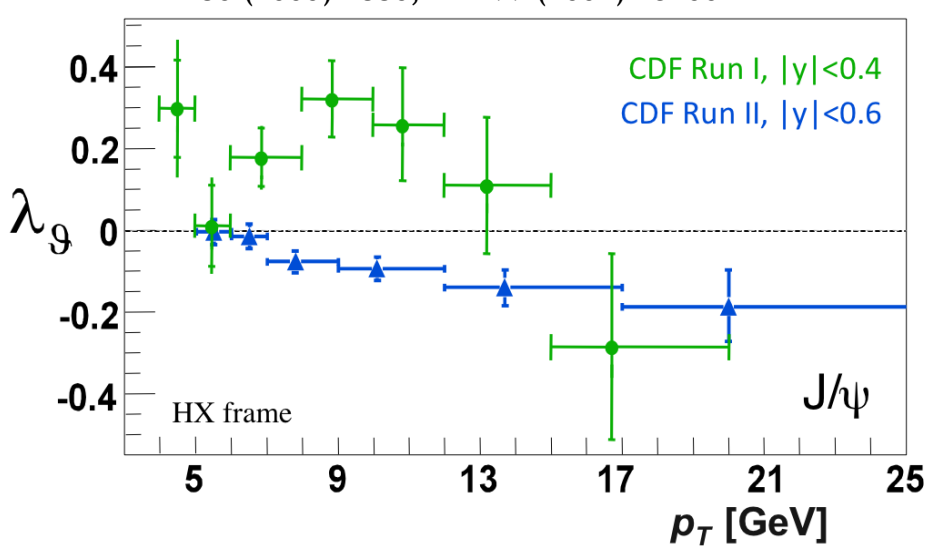
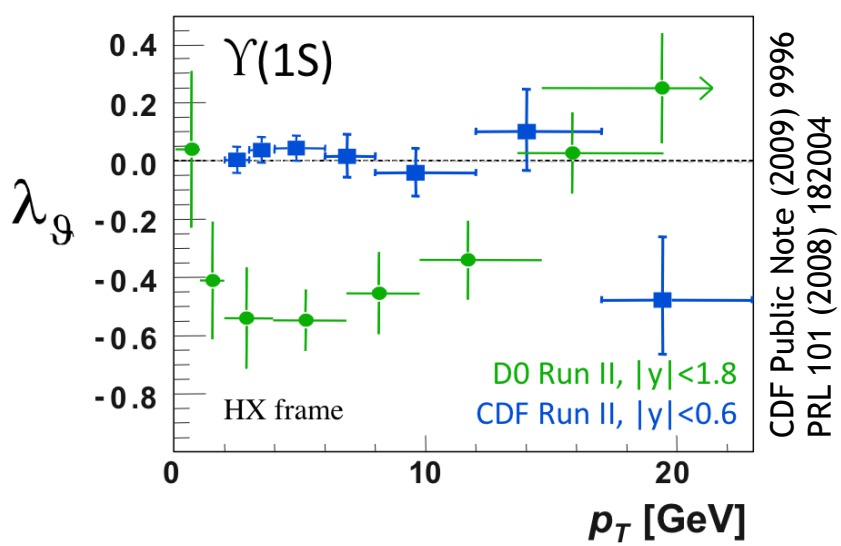
PRL 86 (2000) 2886; PRL 99 (2007) 132001





CDF Public Note (2009) 9996
PRL 101 (2008) 182004

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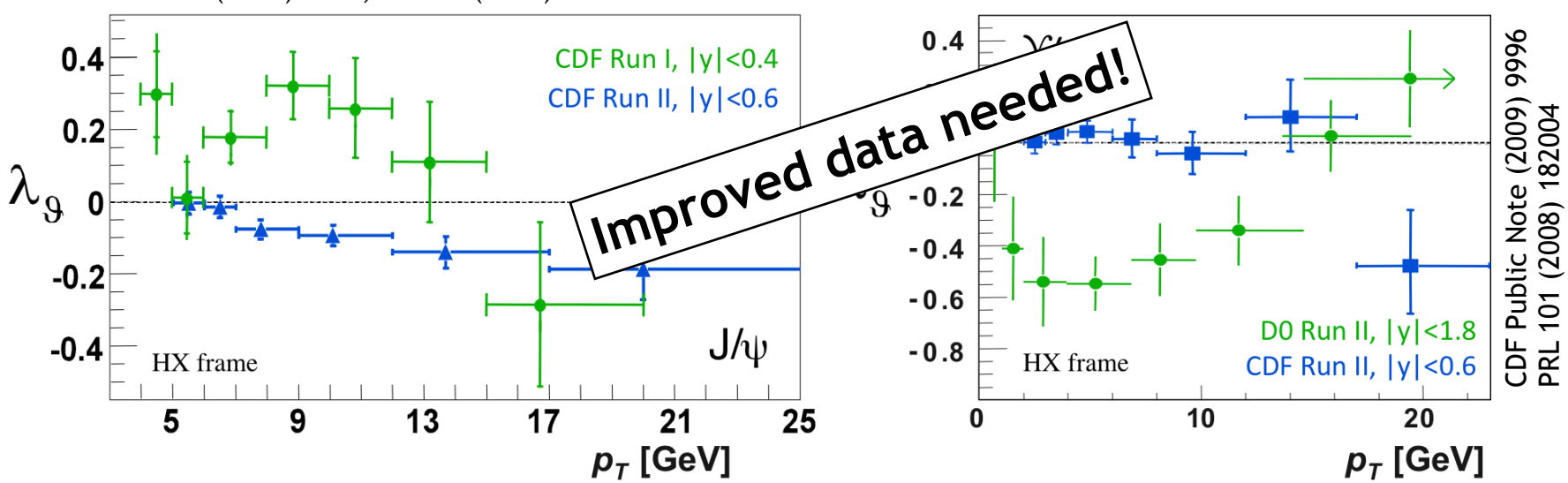
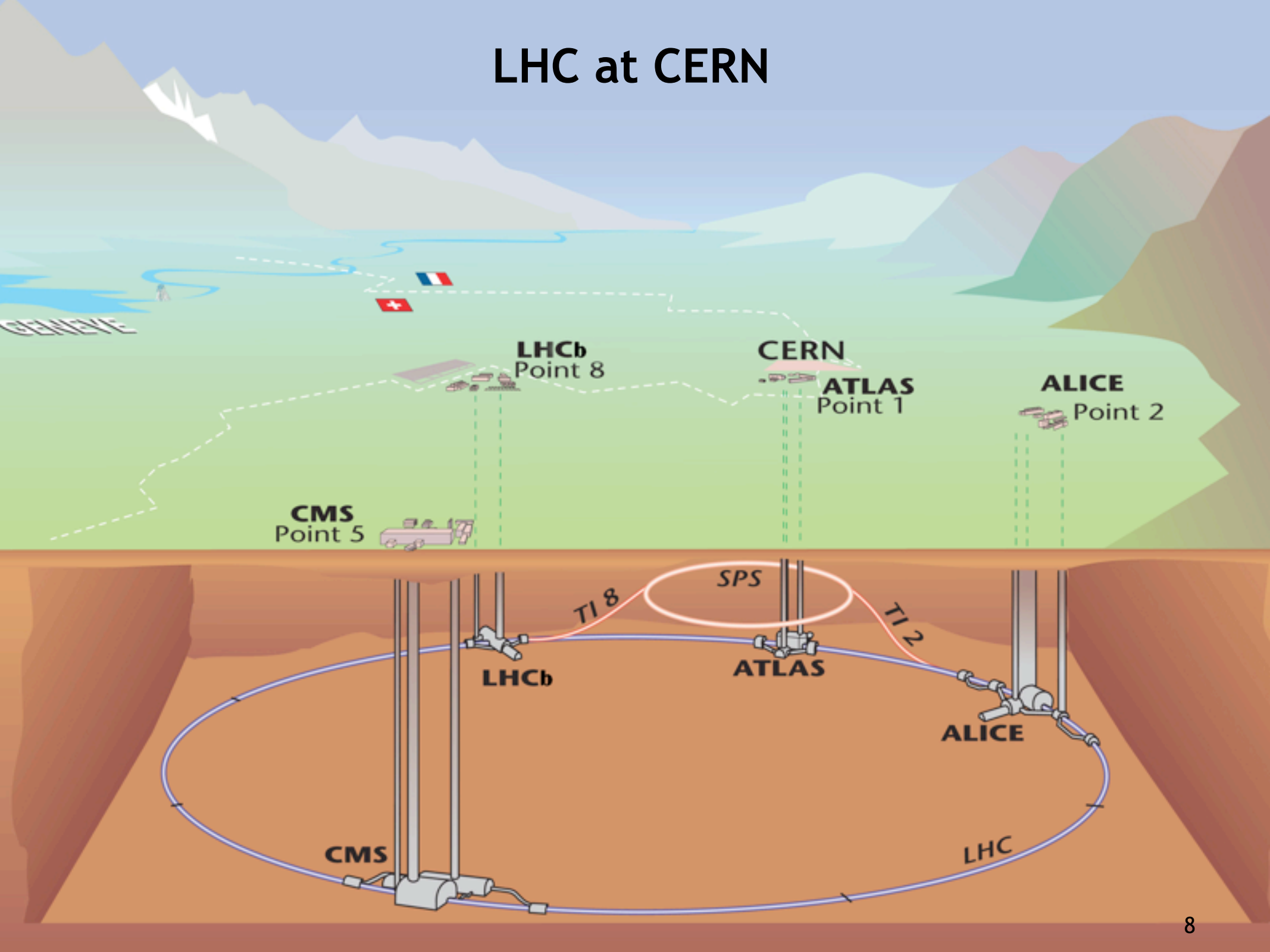


LHC at CERN


GENEVE
LHCb
Point 8
CERN
ATLAS
Point 1
ALICE
Point 2
CMS
Point 5
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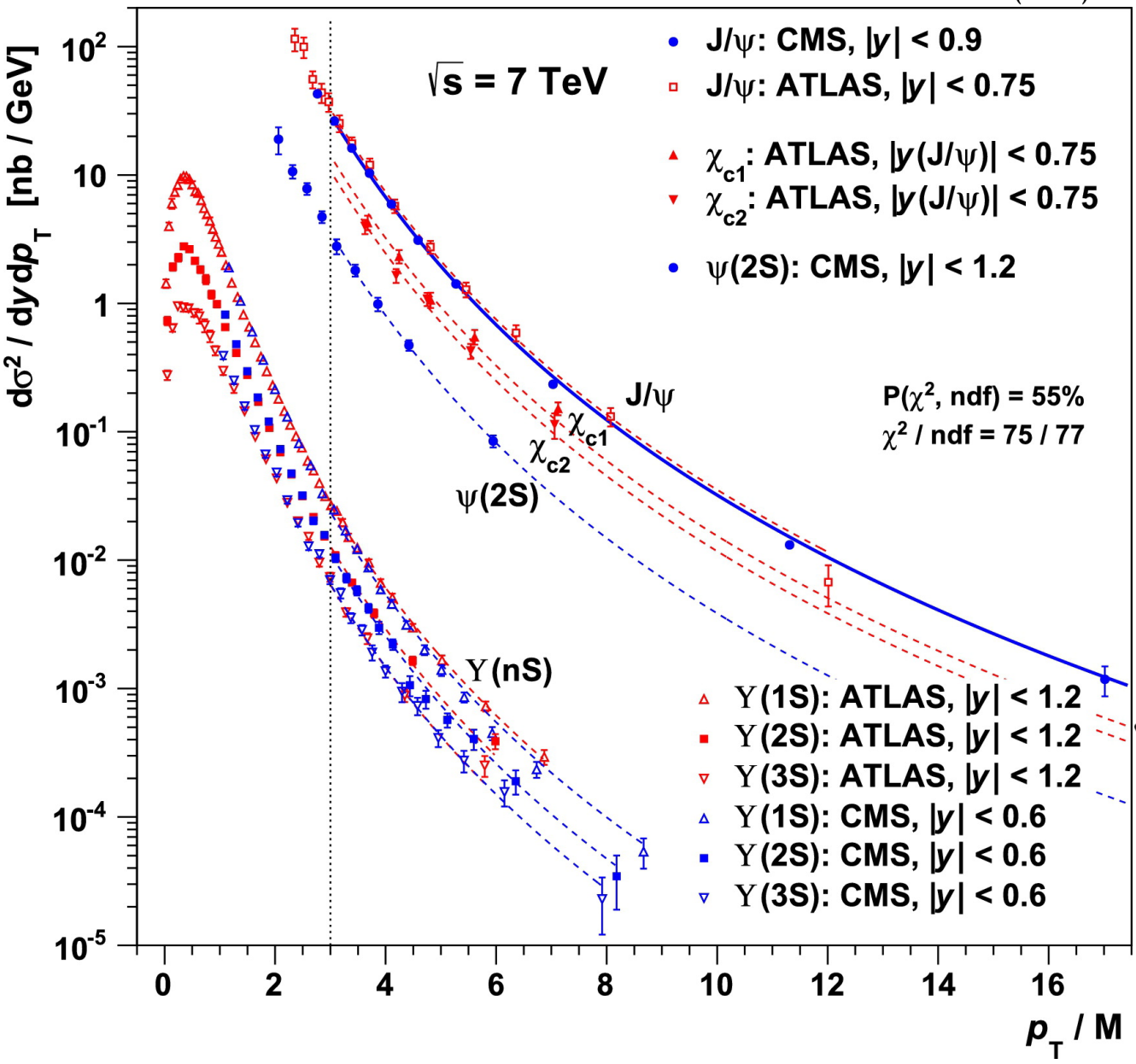
Quarkonium cross sections at the LHC

PLB 736 (2014) 98

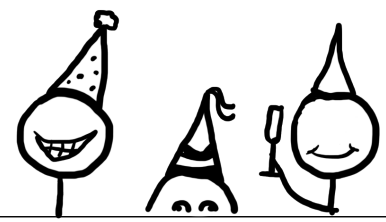


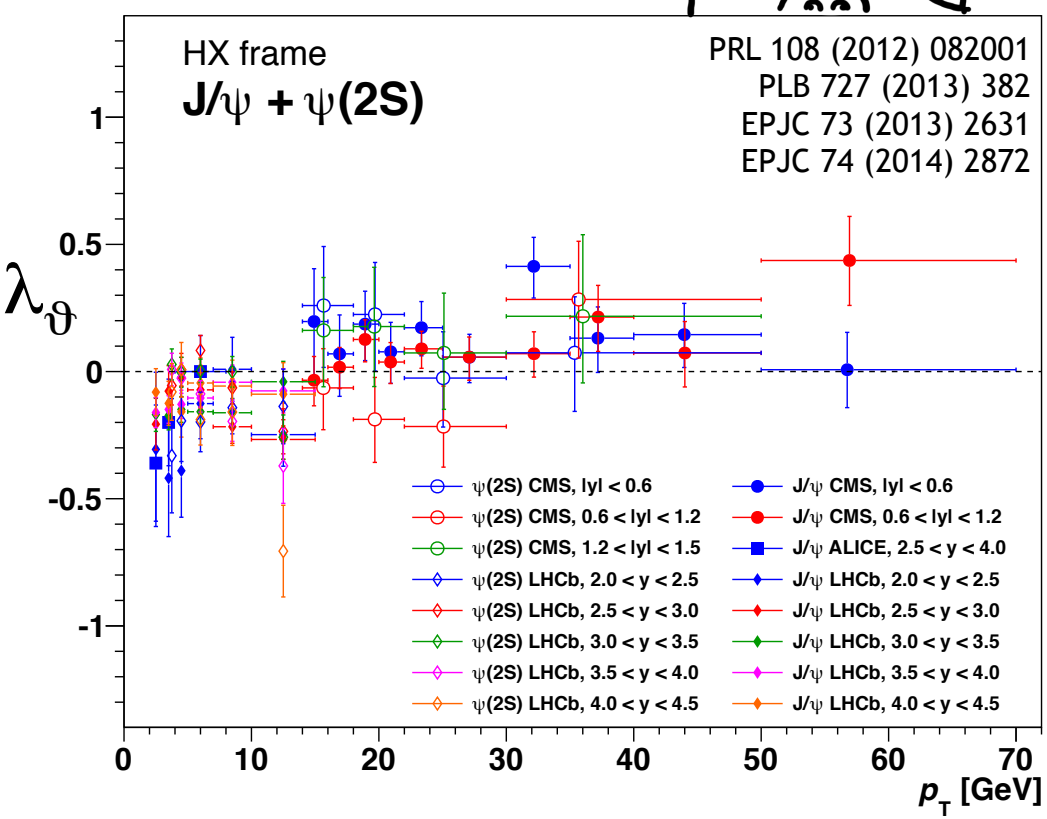
- Differential cross sections of all measured quarkonium states show identical p_T/M shapes for $p_T/M > 3$

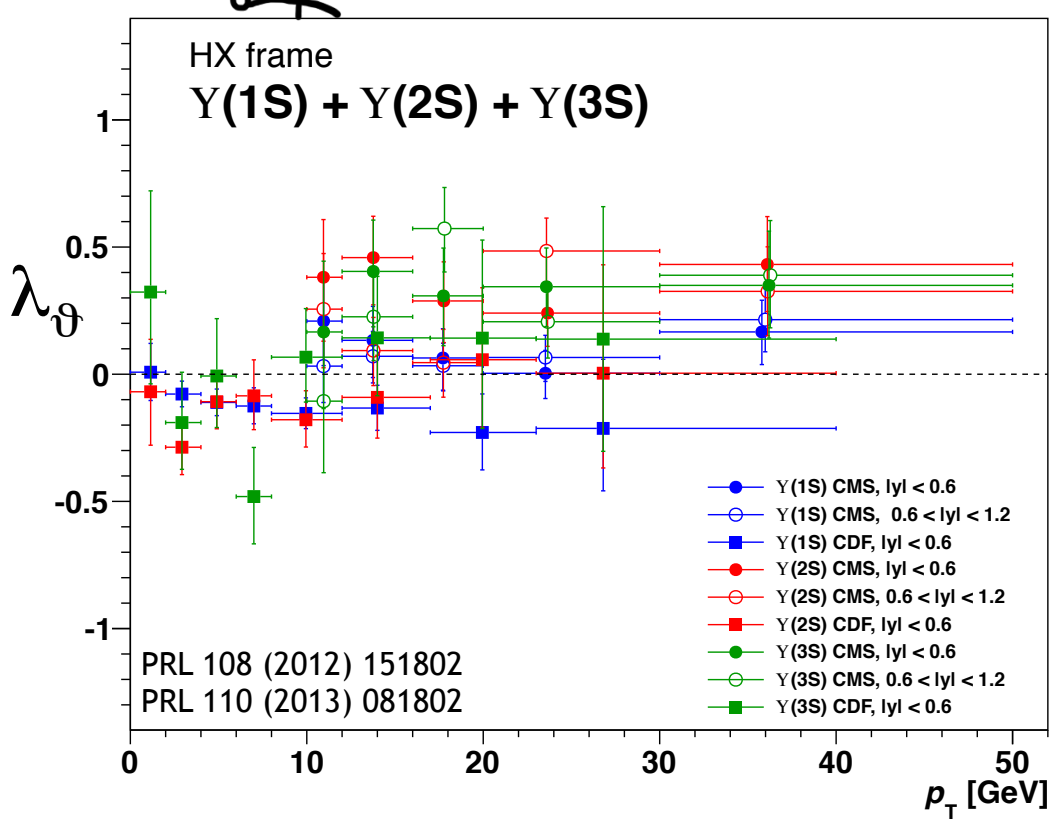
➡ All quarkonia are dominantly produced by a single process

Quarkonium polarizations at the LHC

- Good consistency between results from CMS, LHCb, ALICE and CDF
- No evidence for significant deviations from the unpolarized limit



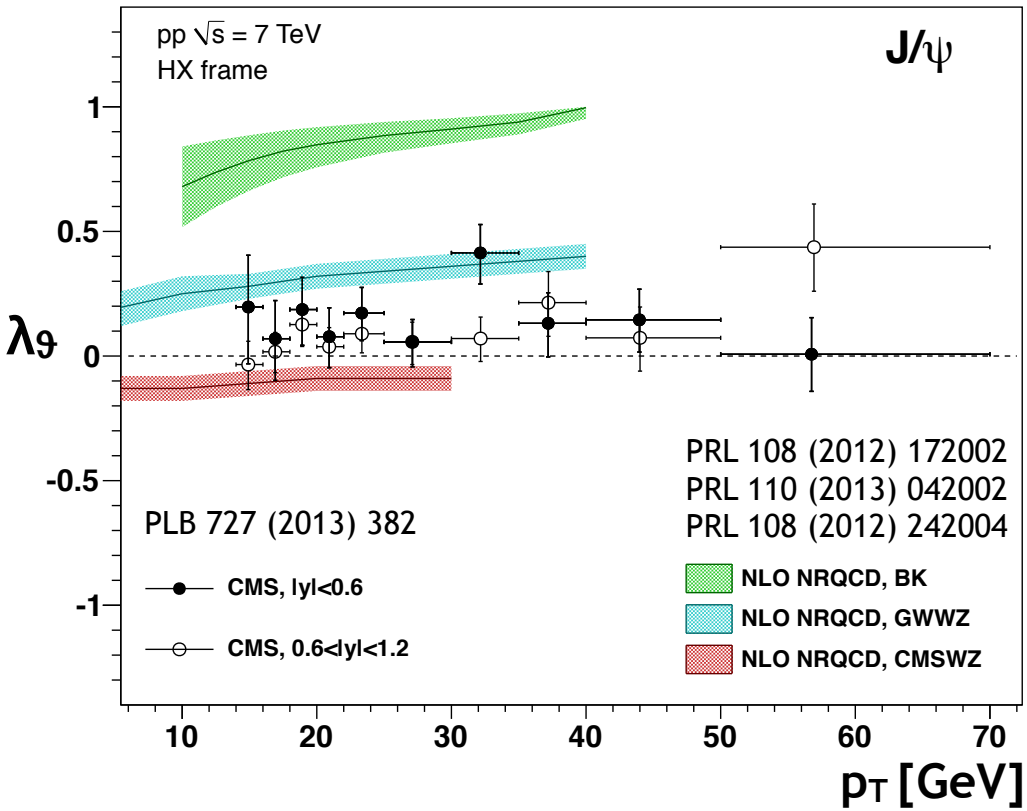


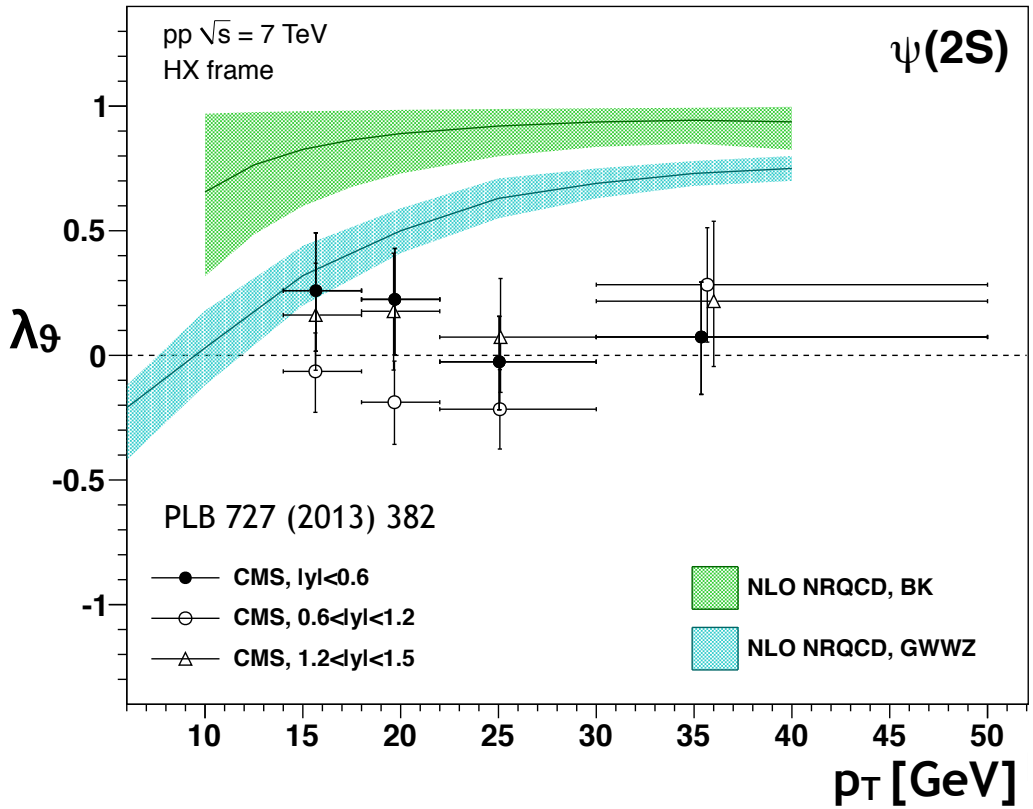


NLO NRQCD calculations

- NRQCD calculations start from compatible SDCs
- Different datasets used in LDME fits

➡ Contradictory theoretical results

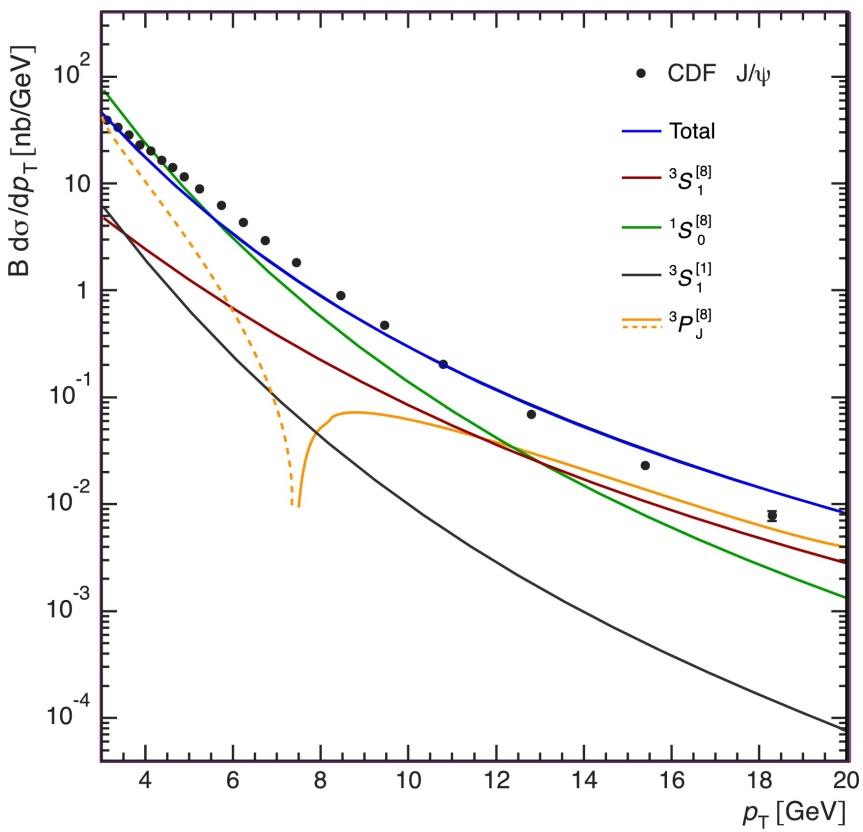


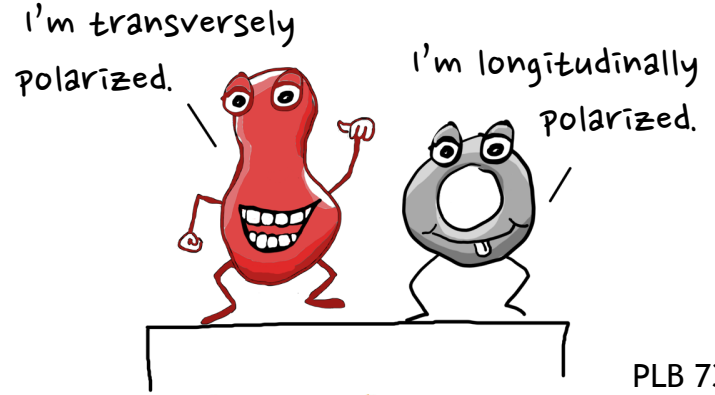


Data-driven global fit analysis

- Starting from SDCs calculated by Butenschön, Kniehl (PRL 108 (2012) 172002)
- Each color singlet and octet has a specific polarization

➡ Polarization is moved to the center of the study





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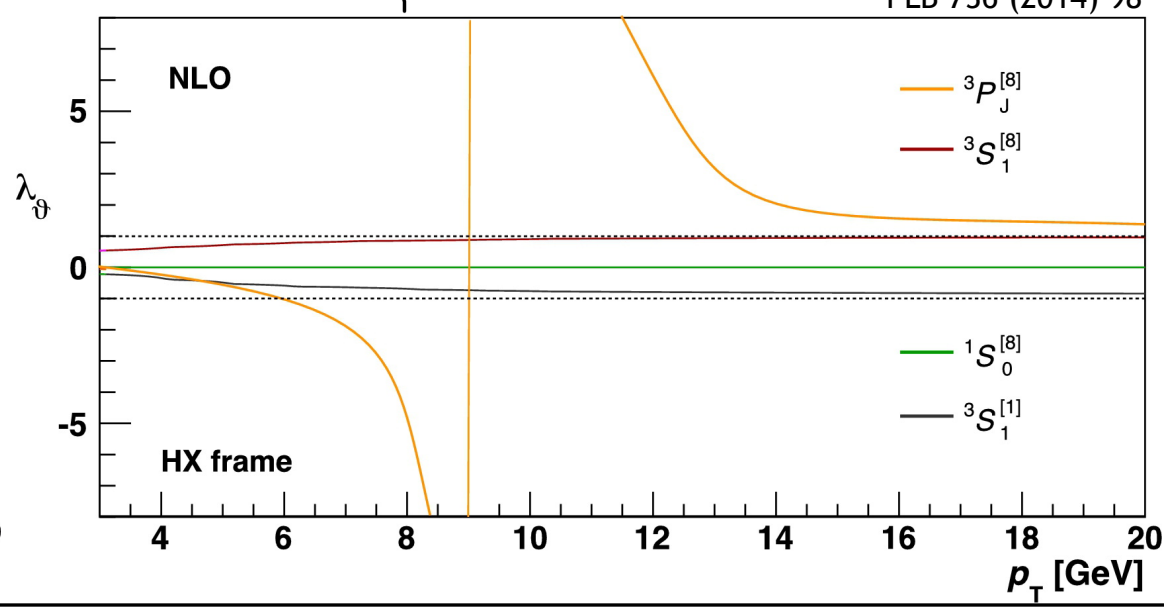

Data-driven global fit analysis

- Starting from SDCs calculated by Butenschön, Kniehl (PRL 108 (2012) 172002)
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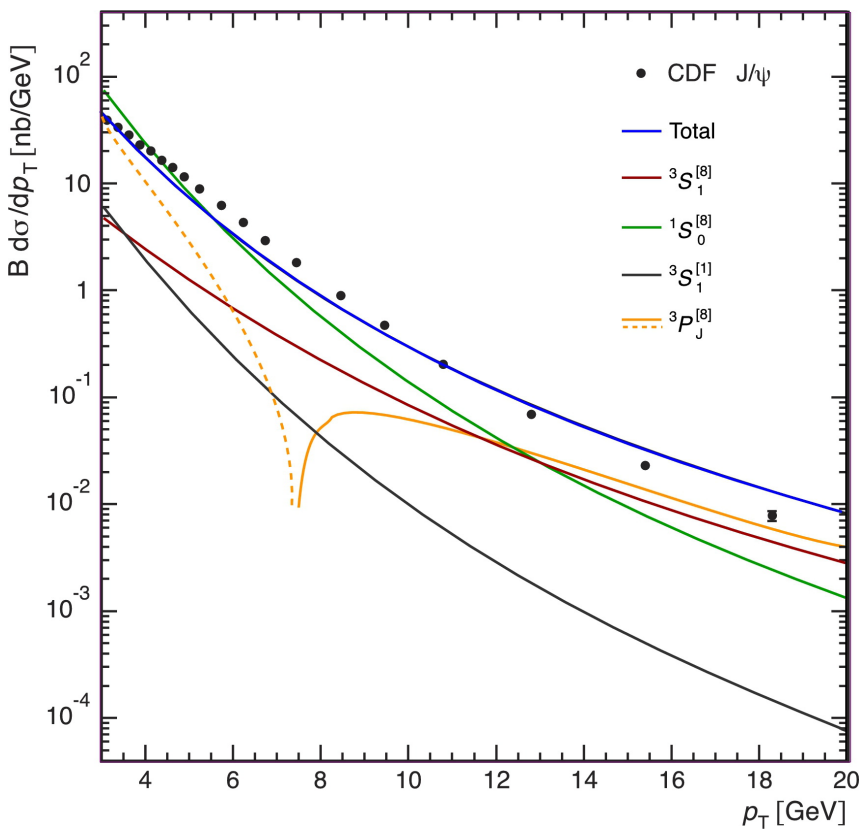
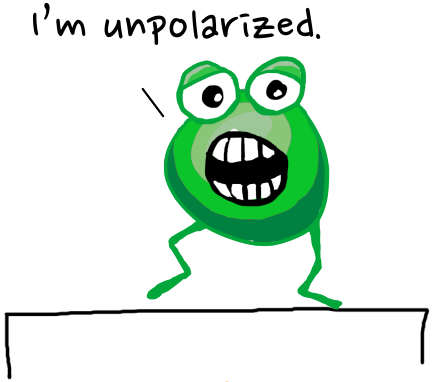
- "Hyper-polarized" $^3P_J^{[8]}$ component is neglected





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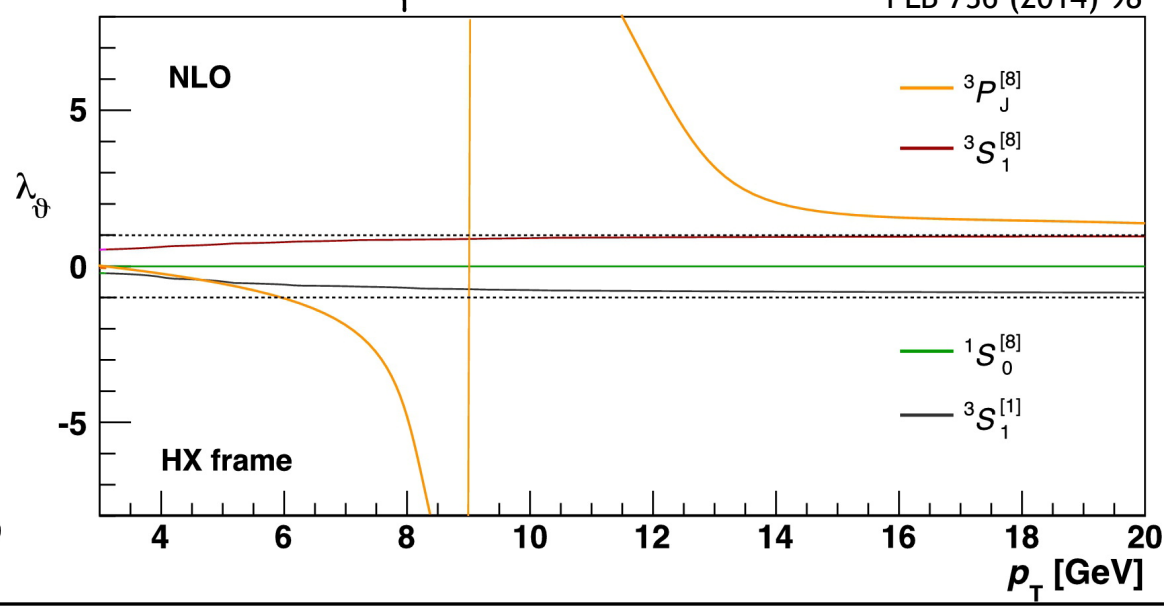

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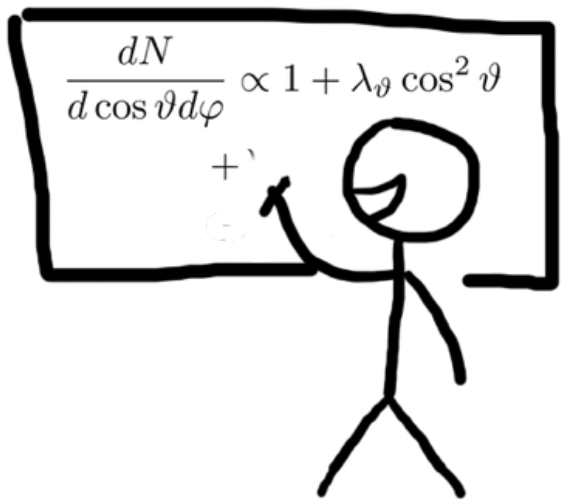
  - Careful treatment of experimental and theoretical uncertainties
  - Acceptance of cross sections recalculated according to the corresponding polarization data



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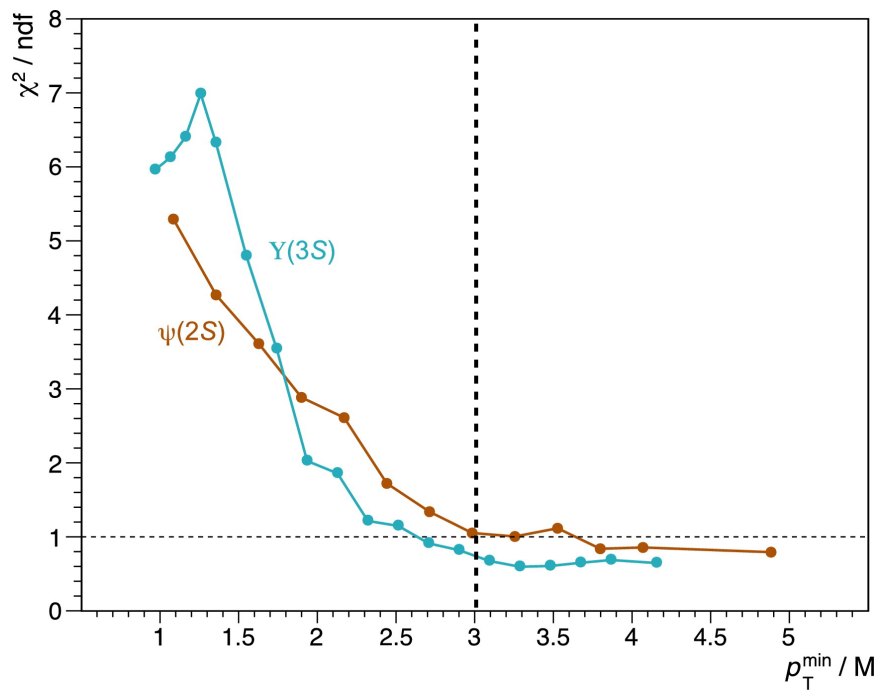
- LHC cross section and polarization data are fit simultaneously
  - Careful treatment of experimental and theoretical uncertainties
  - Acceptance of cross sections recalculated according to the corresponding polarization data
- Perturbative calculation of SDCs not valid at too low p_T

➡ Search for kinematic region where calculations are valid

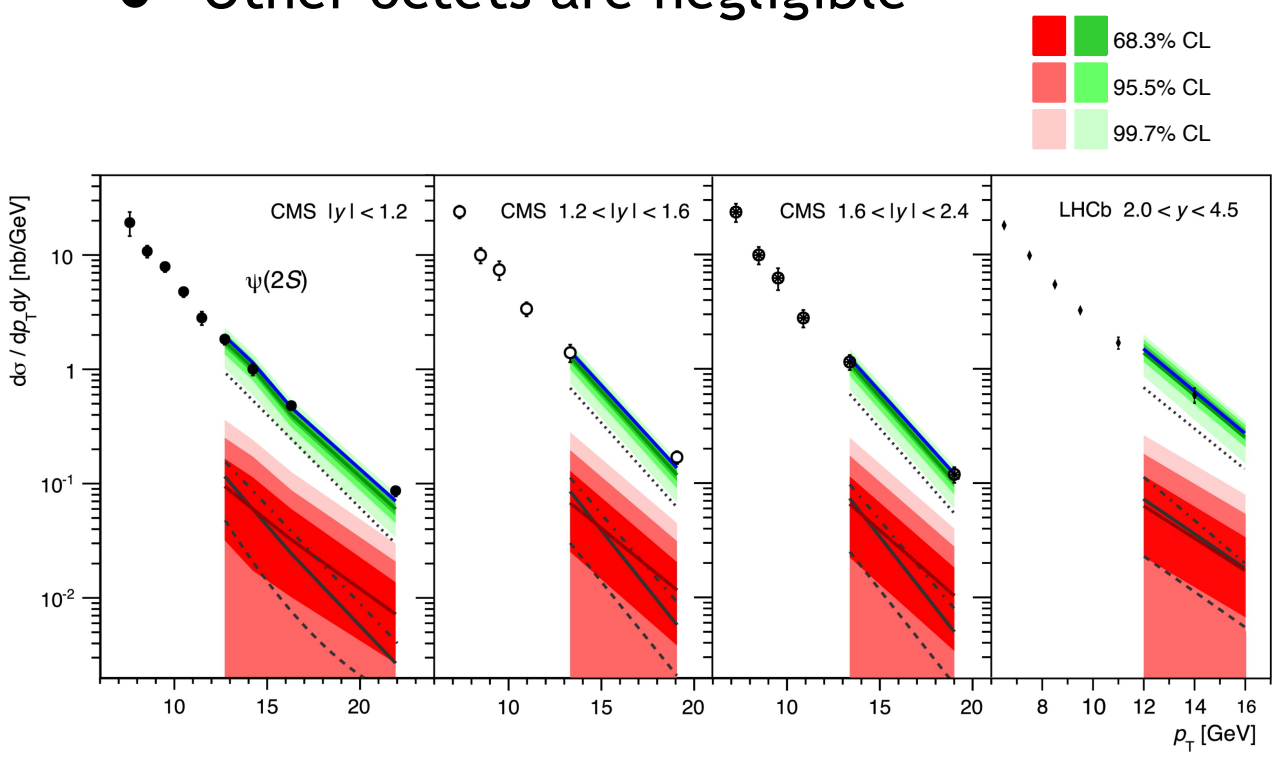
➡ Fit quality improves drastically when removing low p_T/M data

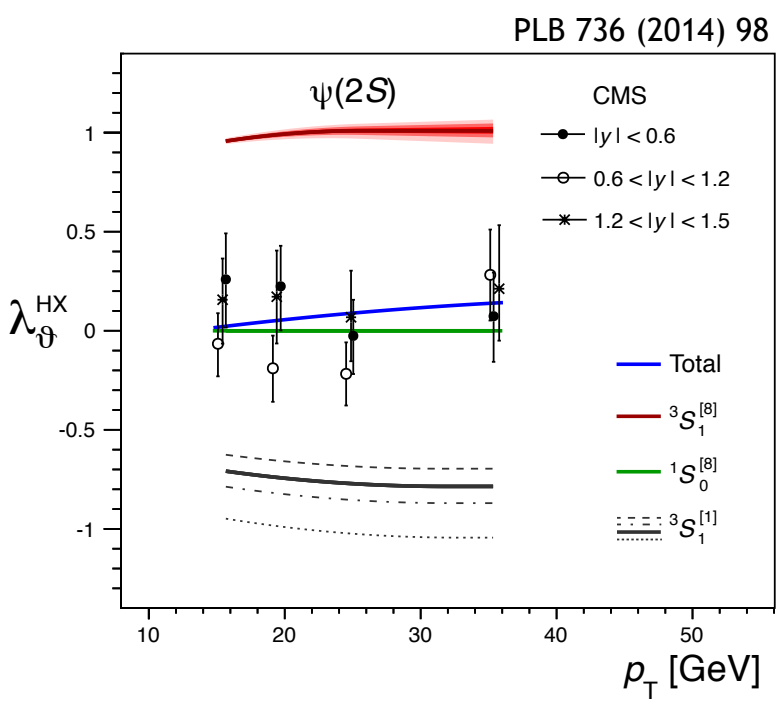
➡ Stable fits for $p_T/M > 3$



Results

- Results obtained for $\psi(2S)$ and $\Upsilon(3S)$ states
  - $\psi(2S)$ is unaffected by feed-down decays
  - $\Upsilon(3S)$ is only affected by $\chi_b(3P)$ decays
- Unpolarized $^1S_0^{[8]}$ octet dominates $\psi(2S)$ and $\Upsilon(3S)$ production
- Other octets are negligible





Extension to full charmonium family

Work in progress!

- Not only $\psi(2S)$, but also J/ψ, $\chi_{c1}(1P)$ and $\chi_{c2}(1P)$
- Taking into account feed-downs and related polarization transfers
- Using newest more precise cross section and polarization data from the LHC extending to higher p_T

Significant improvement

Work in progress!

- J/ψ data are by far the most precise
- NRQCD seems to give very strong predictions for P-wave production
  - Octet LDMEs should be in 5:3 proportions for $\chi_{c2}(1P)$ wrt $\chi_{c1}(1P)$ (heavy quark symmetry)
  - But the measured $\chi_{c2}(1P)$ / $\chi_{c1}(1P)$ ratio is much smaller than 5/3
  - ➡ Color singlet production should dominate χ_c production!
  - Color singlet polarizations are strong and opposite for χ_{c1} and χ_{c2}
- Are these predictions compatible with the simple "universal" quarkonium production scenario favored by data?
- The global charmonium analysis including P-waves has the potential to challenge the foundation of NRQCD more than any previous data-theory comparison
- Future χ_c polarization measurements will be crucial!

Summary and conclusions

- Cross section data at LHC show a common behavior for all measured quarkonium states, indicating production through one single process
- Polarization data at the LHC cluster around the unpolarized limit
- New data-driven approach with a polarized perspective

➡ Quarkonium production is dominated by the unpolarized $^1S_0^{[8]}$ intermediate state for $\psi(2S)$ and $\Upsilon(3S)$

➡ Work ongoing to describe the full charmonium family, including P-wave states, taking into account feed-downs and polarization transfer

➡ Future χ_c polarization measurements are crucial