# Prospects for Quarkonium Polarization Measurements at the LHC

8th VIENNA CENTRAL EUROPEAN SEMINAR
ON PARTICLE PHYSICS AND QUANTUM FIELD THEORY

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# Outline

*Introduction to Quarkonium Physics*

*Quarkonium Production Models*

*New Perspectives on Quarkonium Polarization*

*Influences of Feed-Down Contributions*

*Towards the Clarification of Quarkonium Polarization*

# Introduction and motivation

- Quarkonia are bound states of a **heavy quark and a heavy antiquark ($c\bar{c}$ or $b\bar{b}$)** and exist in „families“ of several states (colorless, uncharged mesons)

$c\bar{c}$ $b\bar{b}$

$m_{c\bar{c}} \sim 3 - 4$ GeV $m_{b\bar{b}} \sim 9.5 - 10.5$ GeV

- Quarkonium spectra and decays are well understood – **Quarkonium production** is still an active field of research

- The quarkonium production rates at LHC are very high = **Quarkonium Factory**

- The physics program of all main LHC experiments include several quarkonium production measurements, in different kinematic regions (*see talk by Hermine Wöhri*)

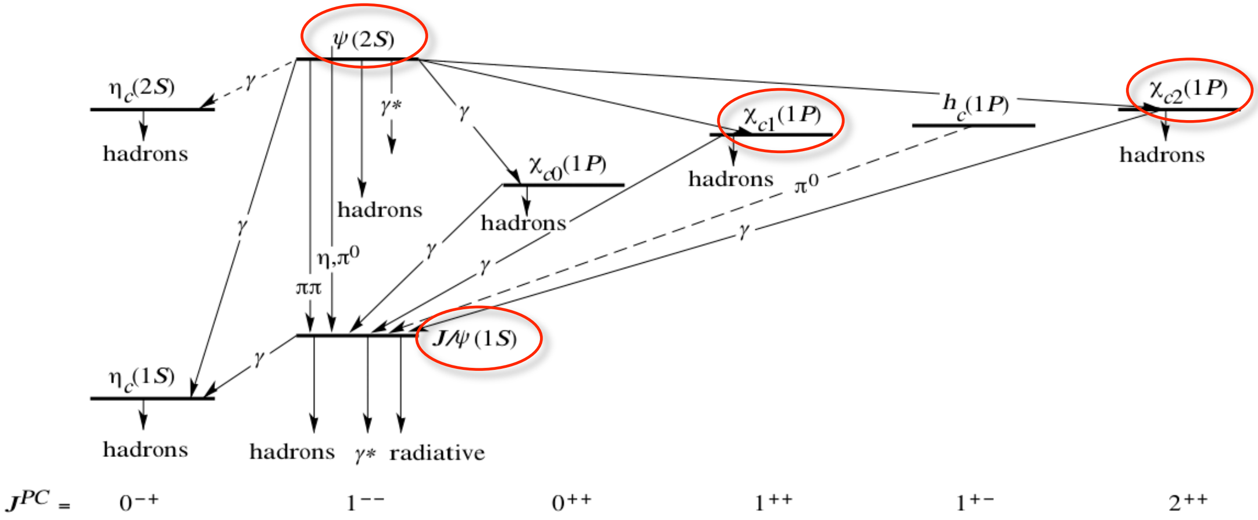
- Properties of QCD can be probed through several quarkonium production measurements, including the **production cross sections** and the **polarizations**, among others

- Hot QCD thermodynamics (quark-gluon plasma, phase transitions) can also be probed through quarkonium suppression in heavy-ion collisions (*see talk by Carlos Lourenço*)

# Quarkonium spectrum

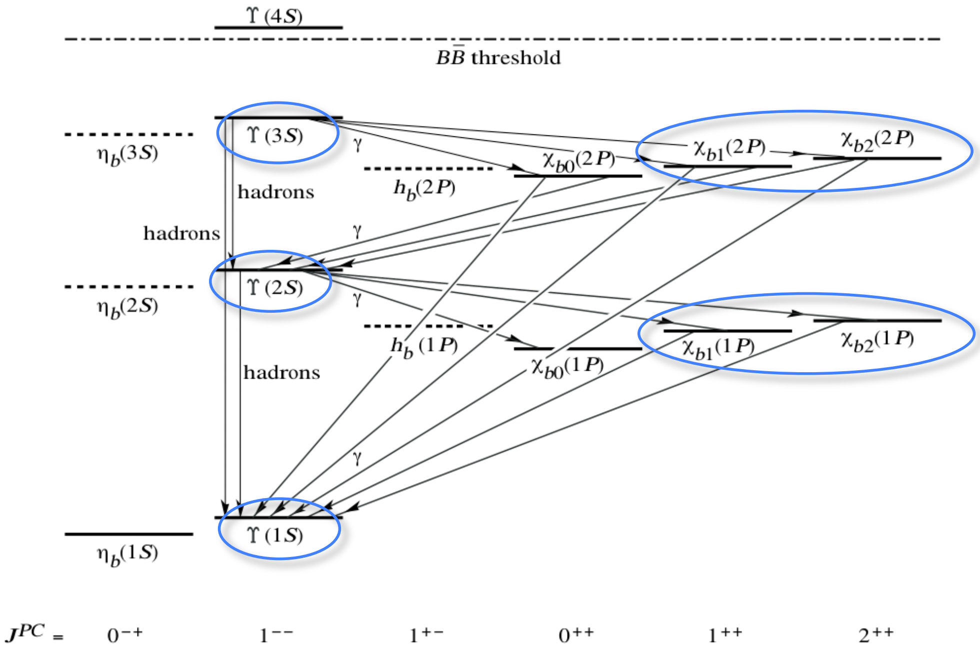
**Charmonium** spectrum

$c\bar{c}$



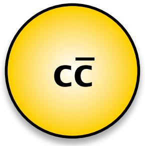
**Bottomonium** spectrum

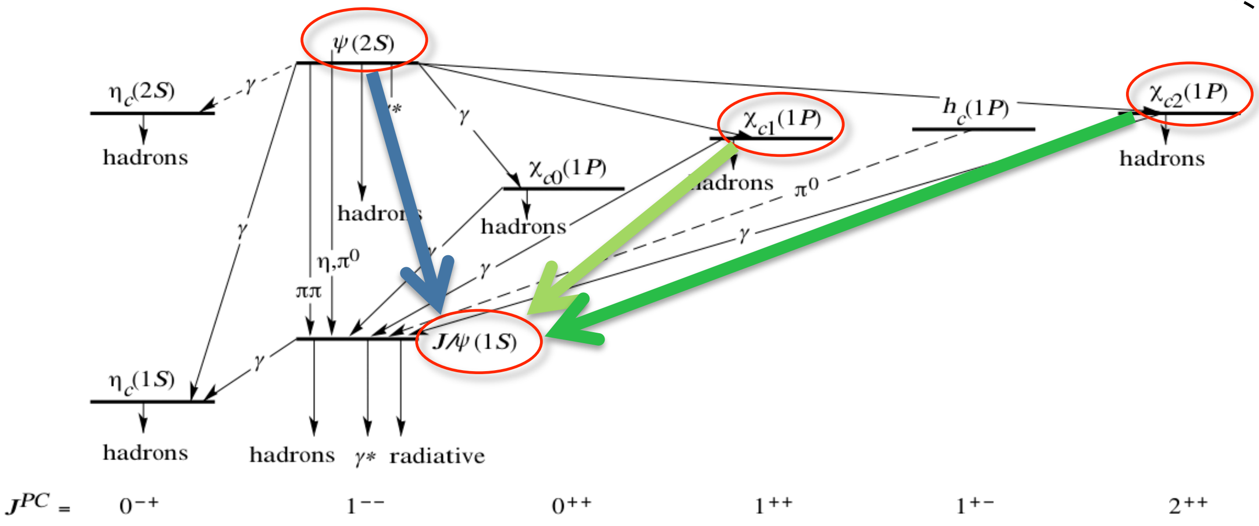
$b\bar{b}$



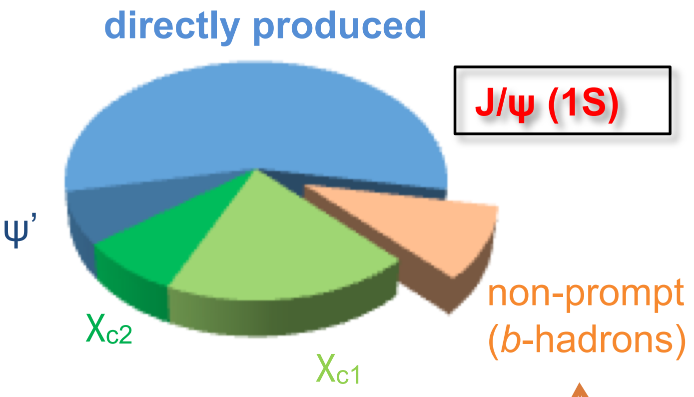
# Quarkonium spectrum

**Charmonium** spectrum





**prompt J/ψ**: direct J/ψ + J/ψ from decay of $c\bar{c}$ states
**non-prompt J/ψ**: J/ψ from decay of b-hadrons



(see talk by Hermine Wöhri)

# Quarkonium production

## Basic concept: The non-relativistic QCD factorization approach

- **NRQCD**: Effective field theory, treats quarkonia as non-relativistic systems

- **NRQCD Factorization Theorem:** Quarkonium production can be factorized in
  1) production of the initial $q\bar{q}$ pair (perturbative QCD)
  2) formation of the bound quarkonium state (non-perturbative QCD)

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

$$n = {}^{2S+1}L_J^{(color\ multiplicity)}$$

**Short-distance coefficients:**
Cross section of partonic processes to form
$q\bar{q}$ in state $n$ $\otimes$ PDF

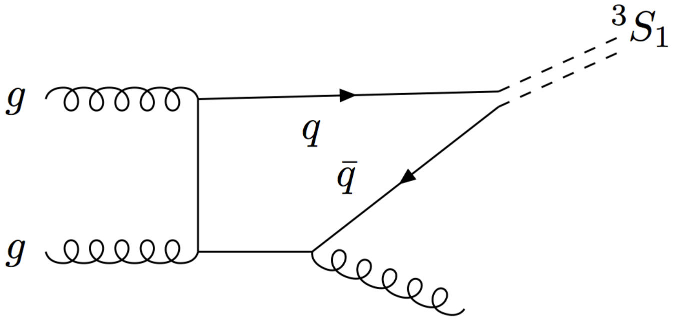
**Long-distance matrix elements:**
Probability of $q\bar{q}$ in state $n$ to form
quarkonium state $\mathcal{Q}$

- Factorization approach is not a model, but a direct consequence of full QCD
(in the limit of $m_q \to \infty$)

# Quarkonium production

## Color singlet model (CSM)

- **Assumption:** Quarkonium and initial q$\bar{q}$ state have same quantum numbers!
-> color singlet state



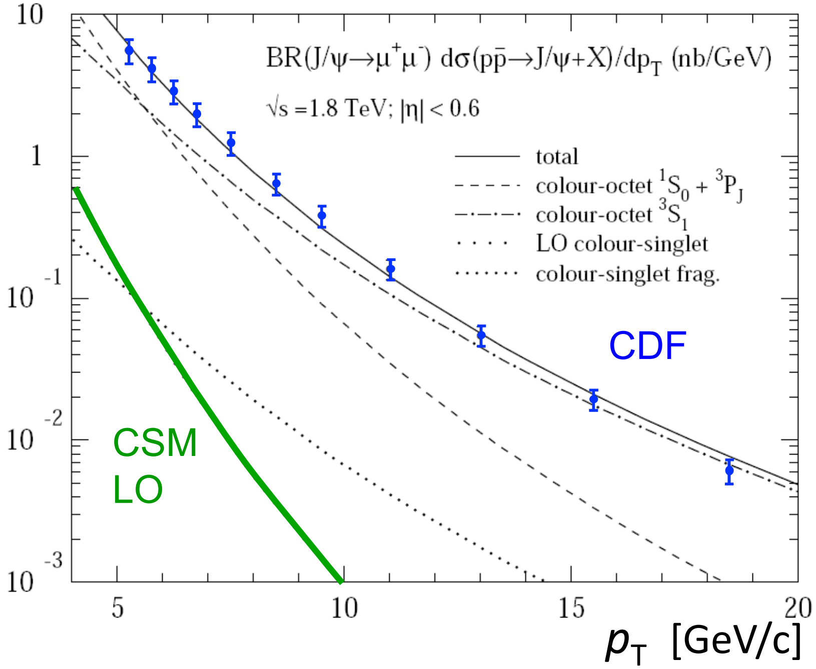
LO diagram for color singlet production of a $^3S_1$ quarkonium

**NRQCD factorization**

$$\sigma(\mathrm{J}/\psi) = \sigma[q\bar{q}(n_{\mathrm{J}/\psi})] \left\langle \mathcal{O}^{\mathrm{J}/\psi}(n_{\mathrm{J}/\psi}) \right\rangle$$

- **Predictions for cross section:** Absolute Values

- CDF cross sections showed that the CSM LO predictions were far too low (***J/ψ anomaly).***
A new approach was developed:
**Can color octet contributions explain the large yield at high $p_T$?**



# Quarkonium production

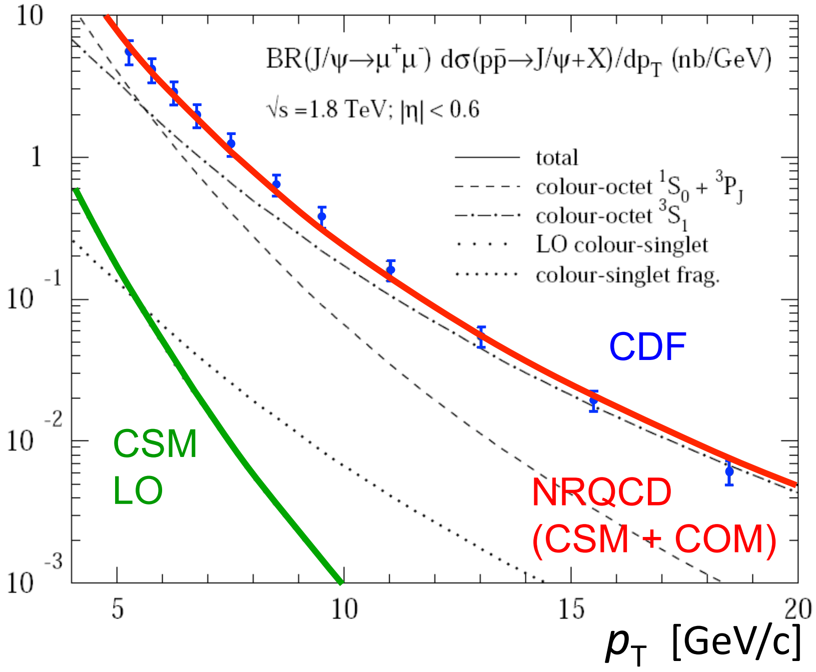
## Color octet model (COM)

- The matrix elements can be estimated through **velocity scaling rules**
- The color octet model chooses to include four terms in the sum

$$\underbrace{\left\langle \mathcal{O}^{J/\psi}({}^3S_1^{(1)}) \right\rangle}_{\textit{1 color singlet term}}, \underbrace{\left\langle \mathcal{O}^{J/\psi}({}^1S_0^{(8)}) \right\rangle, \left\langle \mathcal{O}^{J/\psi}({}^3S_1^{(8)}) \right\rangle, \left\langle \mathcal{O}^{J/\psi}({}^3P_0^{(8)}) \right\rangle}_{\textit{3 color octet terms}}$$

- Possible transition **color octet $q\bar{q}$ state** to **color singlet quarkonium state** (emission of soft gluons)

- **Predictions for cross section:** Matrix elements cannot be calculated → fit to data (no absolute predictions)

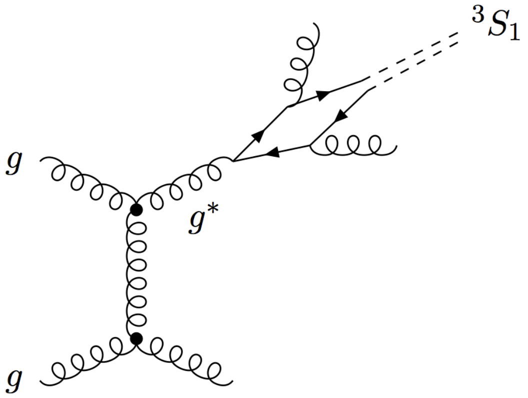


# Quarkonium production - progress

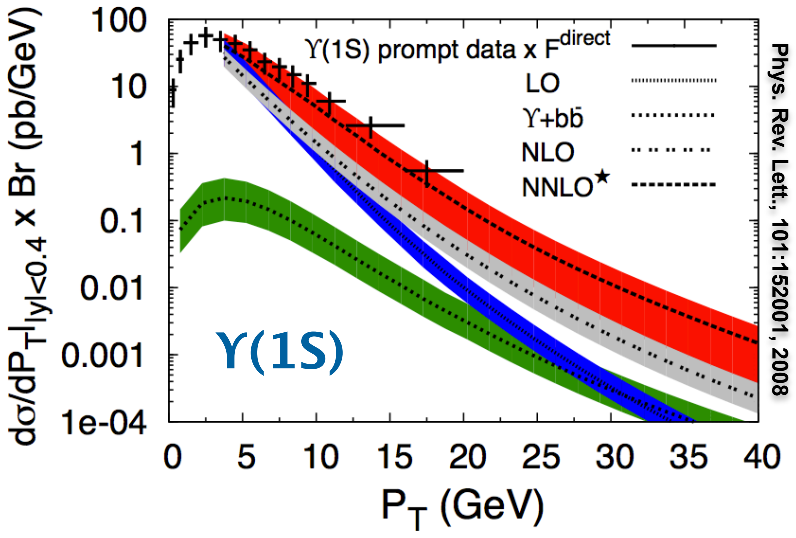
## CSM: Higher order corrections

Recent calculations of **higher order corrections of CSM**
The comeback of the CSM!

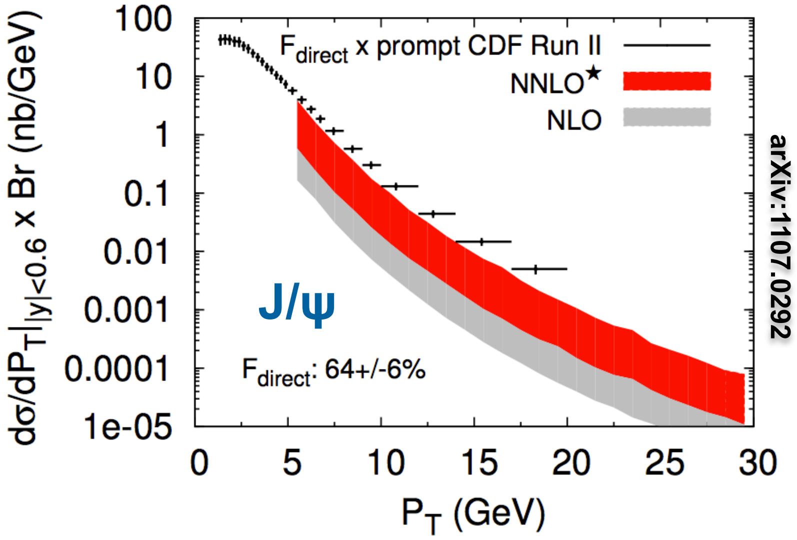
**NLO** and **NNLO*** enhance the predictions of CSM LO (especially at high $p_T$) and approach the CDF data



Gluon fragmentation
to a $^3S_1$ quarkonium



Phys. Rev. Lett., 101:152001, 2008



arXiv:1107.0292

# Quarkonium production - progress

## COM: Higher order corrections

Applying **CSM NLO** to the fits of the color octet matrix elements:

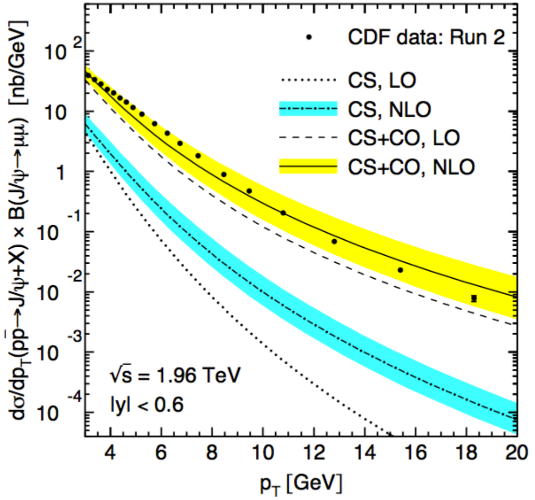
Good consistency of the shape of the differential cross section vs. $p_T$ for several measurements over a broad range in rapidity

Both models seem to describe well the differential cross section → no discrimination

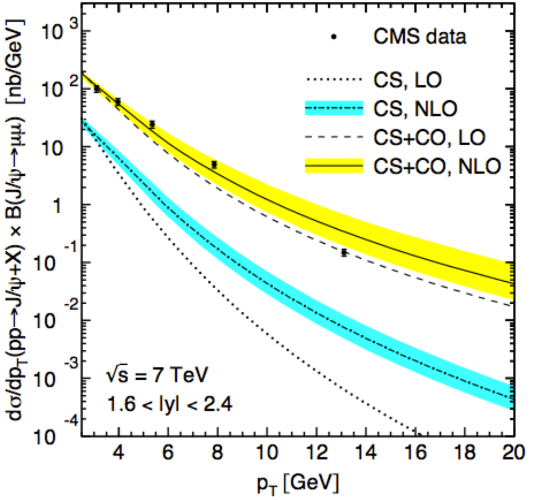
**We need an observable which differentiates the models:**

**→ Quarkonium Polarization!**

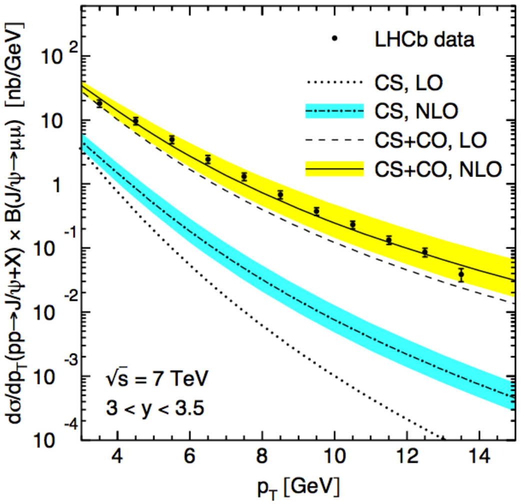
J/ψ: CDF, |y| < 0.9



J/ψ: CMS, 1.6 < |y| < 2.4



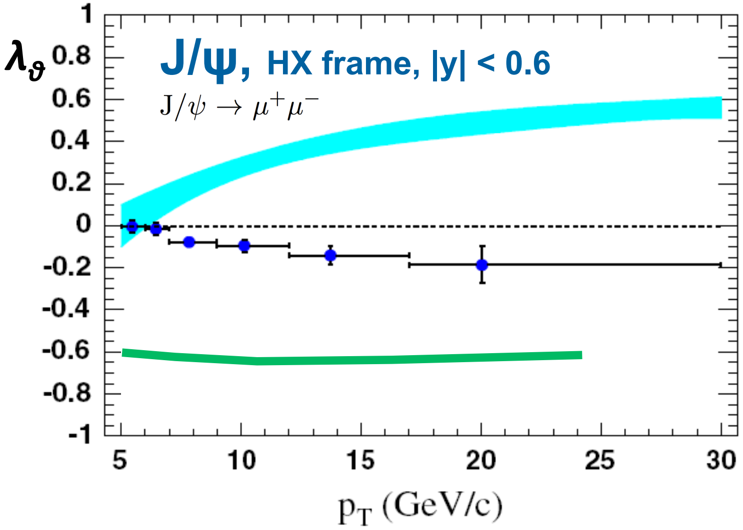
J/ψ: LHCb, 3 < y < 3.5



arXiv:1105.0820

# Quarkonium polarization – progress?

## The CDF J/ψ polarization measurement



**NRQCD factorization: *prompt* J/ψ**
Braaten, Kniehl & Lee, PRD62, 094005 (2000)

**CDF Run II data: *prompt* J/ψ @1.96 TeV**
CDF Coll., PRL 99, 132001 (2007)

**Colour-singlet @NLO: *direct* J/ψ**
Gong & Wang, PRL 100, 232001 (2008)
Artoisenet et al., PRL 101, 152001 (2008)

*„There is no better way to test a theory than to apply it to a scenario different from the one that initially prompted its development“*

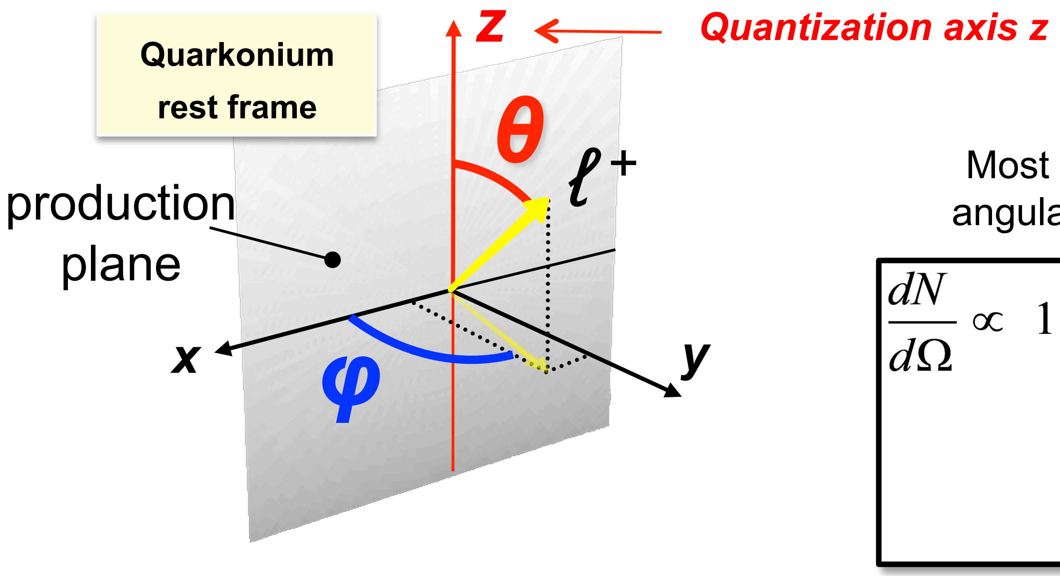
- The **CDF J/ψ** polarization measurement seems to exclude both CSM NLO and NRQCD predictions

- **Note:** CDF measured prompt **J/ψ** (including feed-down from **ψ‘** and $\chi_c$), while the CSM NLO calculation is for the directly produced **J/ψ** (the NRQCD curve includes feed-down)

- A **recent series of papers** provides a deeper insight into quarkonium polarization
→ See CDF results from a critical perspective and
propose new measurements to reach unambiguous interpretations

# Quarkonium polarization

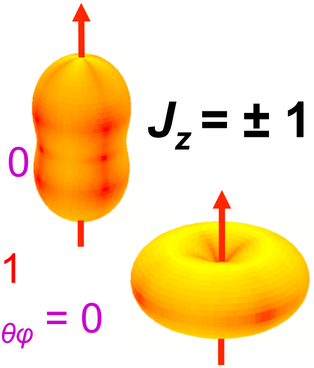
## General concepts of the polarization of vector quarkonia



Most general observable angular decay distribution:

$$\frac{dN}{d\Omega} \propto 1 + \lambda_\theta \cos^2\theta + \lambda_\varphi \sin^2\theta \cos 2\varphi + \lambda_{\theta\varphi} \sin 2\theta \cos\varphi$$

$\lambda_\theta = +1$
$\lambda_\varphi = \lambda_{\theta\varphi} = 0$



**$J_z = \pm 1$** → **$\lambda_\theta$ = +1** : **“transverse”** polarization

$\lambda_\theta = -1$
$\lambda_\varphi = \lambda_{\theta\varphi} = 0$

**$J_z = 0$** → **$\lambda_\theta$ = -1** : **“longitudinal”** pol.

**arXiv:1006.2738**

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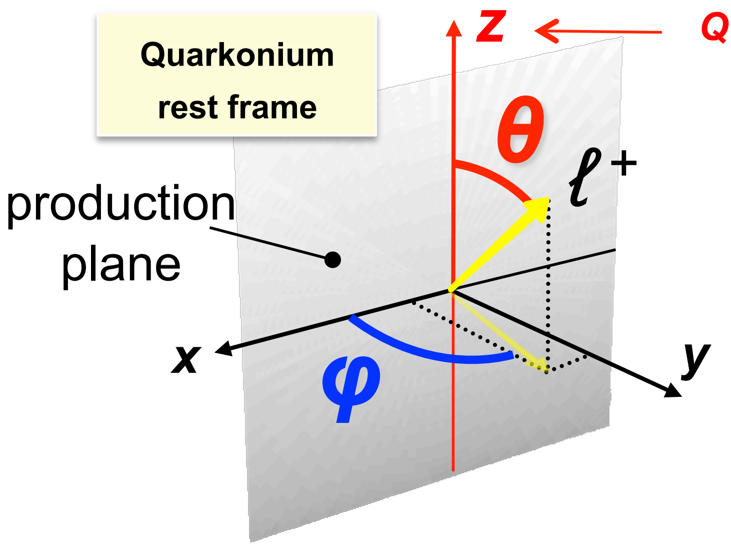
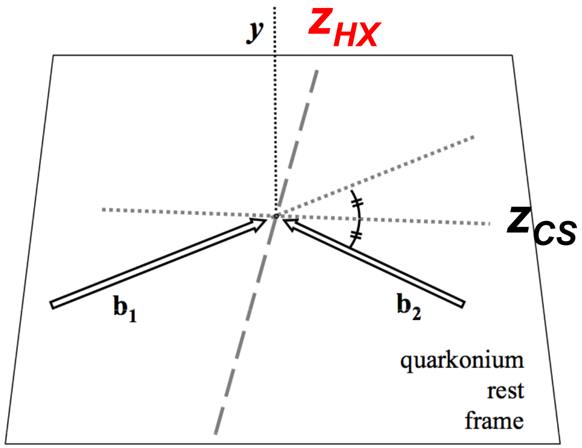
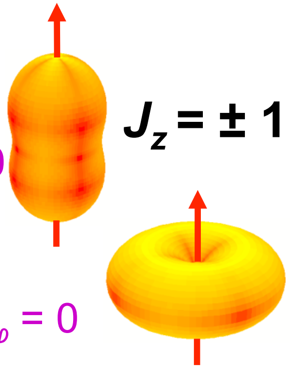




$z_{CS}$ ≈ direction of colliding partons

$z_{HX}$ = direction of quarkonium momentum



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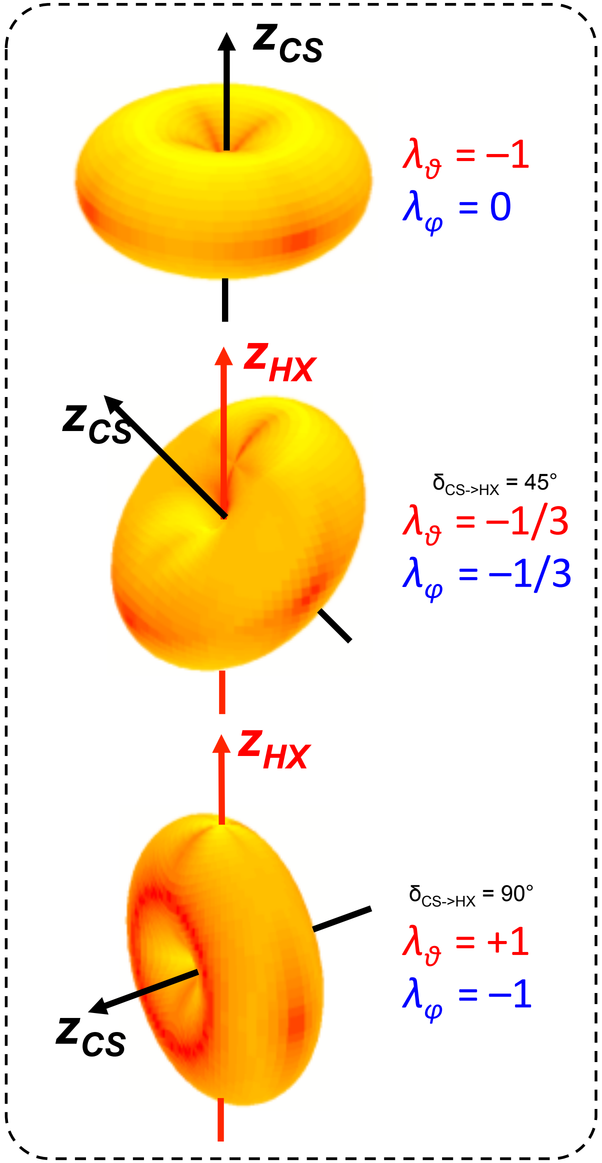
# Quarkonium polarization

## Frame (in)dependence and azimuthal anisotropy

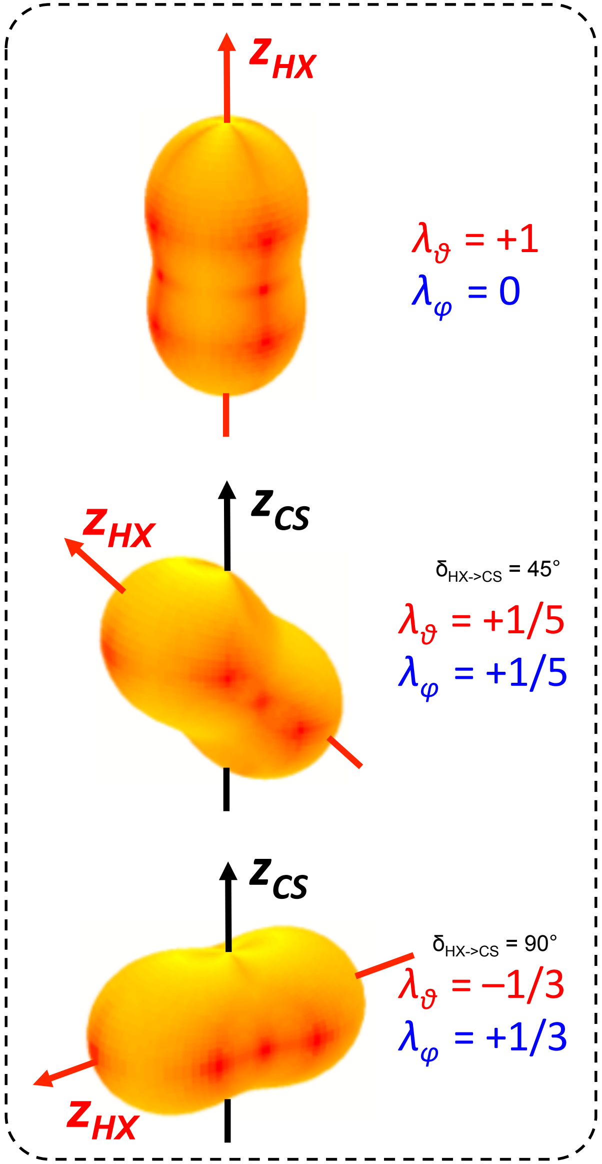


**The observed polarization depends on the frame**

The anlge $\delta_{CS\text{->}HX}$ depends on $p_T$ and rapidity:

$z_{CS} \perp z_{HX}$

for mid rapidity & high $p_T$



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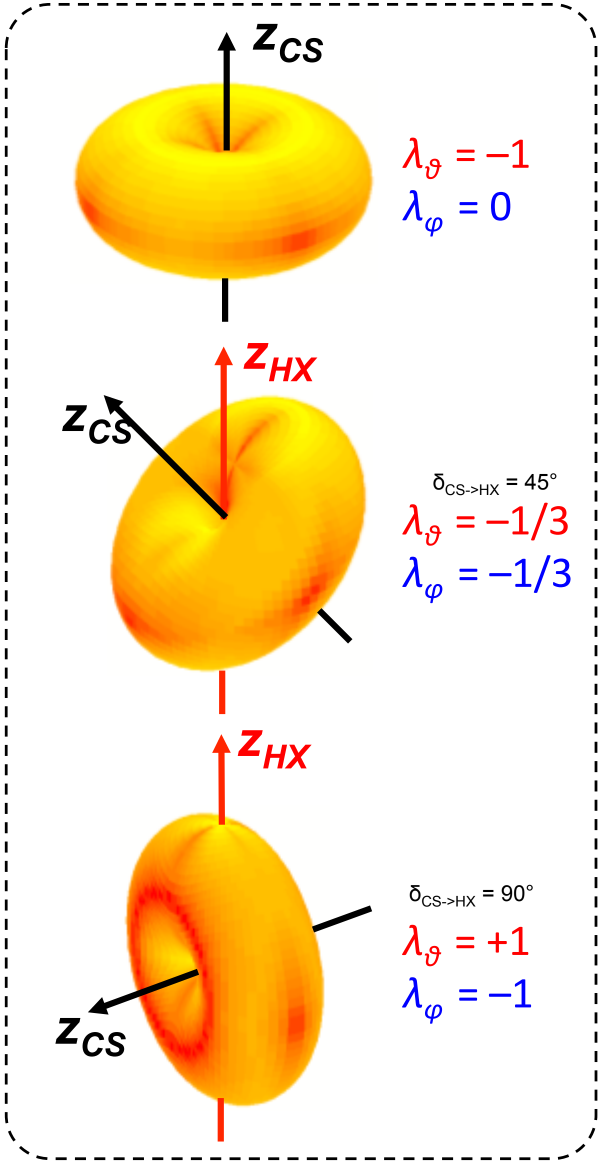

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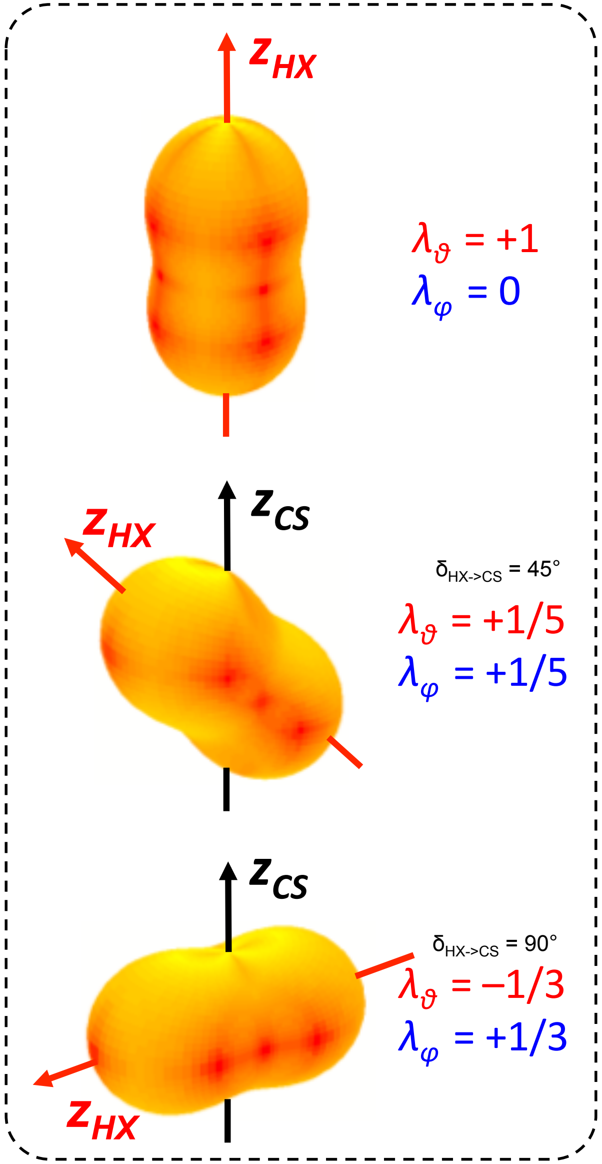
**The azimuthal anisotropy is not a detail**

Several very different physical cases are indistinguishable if $\lambda_\varphi$ is not measured (integration over $\varphi$)



arXiv:1006.2738

# Quarkonium polarization

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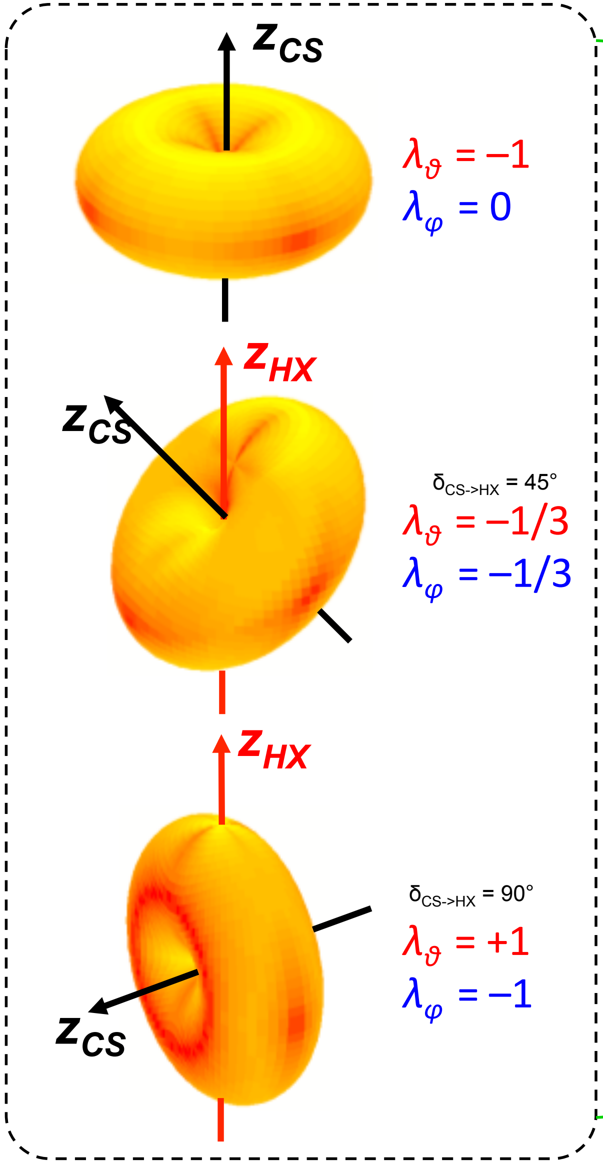


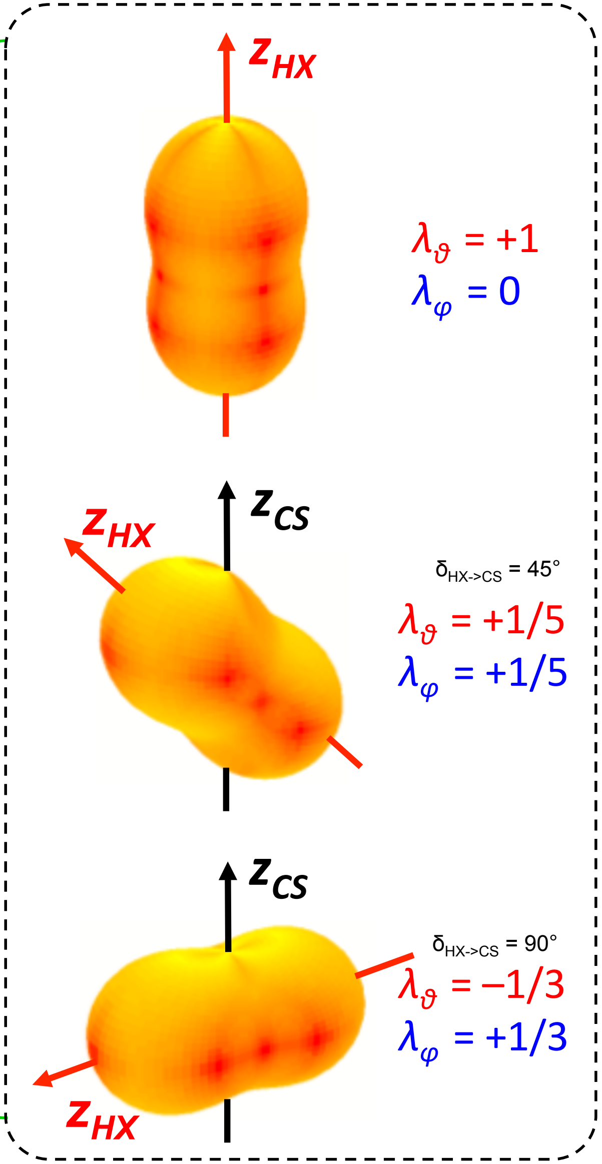
$$\tilde{\lambda} = +1$$

**The shape of the distribution is frame-invariant**

→ it can be characterized by frame-independent parameters such as

$$\boxed{\tilde{\lambda} = \frac{\lambda_\vartheta + 3\lambda_\varphi}{1 - \lambda_\varphi}}$$

$$\tilde{\lambda} = -1$$



arXiv:1006.2738

# Quarkonium polarization

## Possible interpretations of the ambiguous CDF result

- CDF has not measured the azimuthal anisotropy $\lambda_\varphi$
- CDF has only measured the polar anisotropy in one frame (HX)

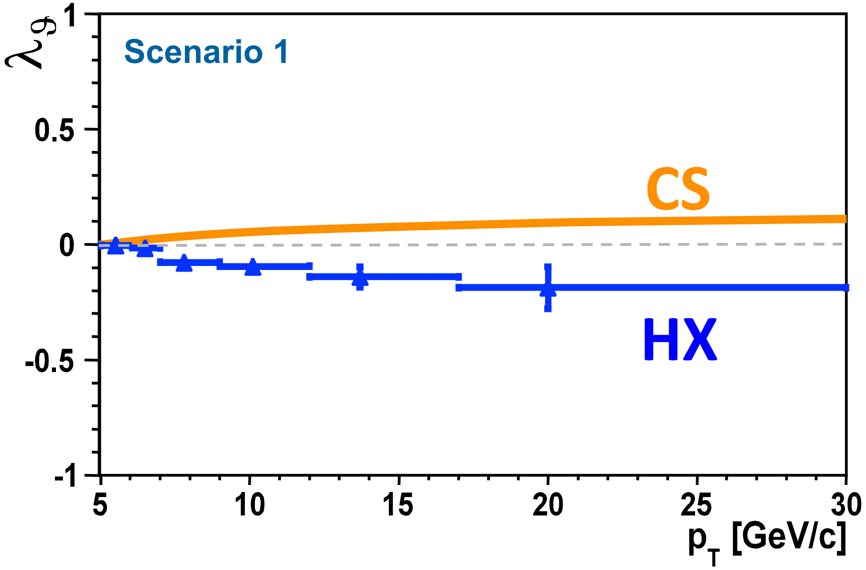
**With this limited information, the J/ψ polarization state remains ambiguous**

Several very different polarization scenarios can reproduce the CDF measurement but would be distinguishable in the $\varphi$ dimension and/or in the Collins-Soper frame

**Scenario 1:** $\lambda_\varphi = 0$ in the HX frame
→ HX frame is natural polarization frame

**Scenario 2:** $\lambda_\varphi = 0$ in the CS frame
→ CS frame is natural polarization frame

**Scenario 3:** Superposition of two fully transverse processes, induced in different frames



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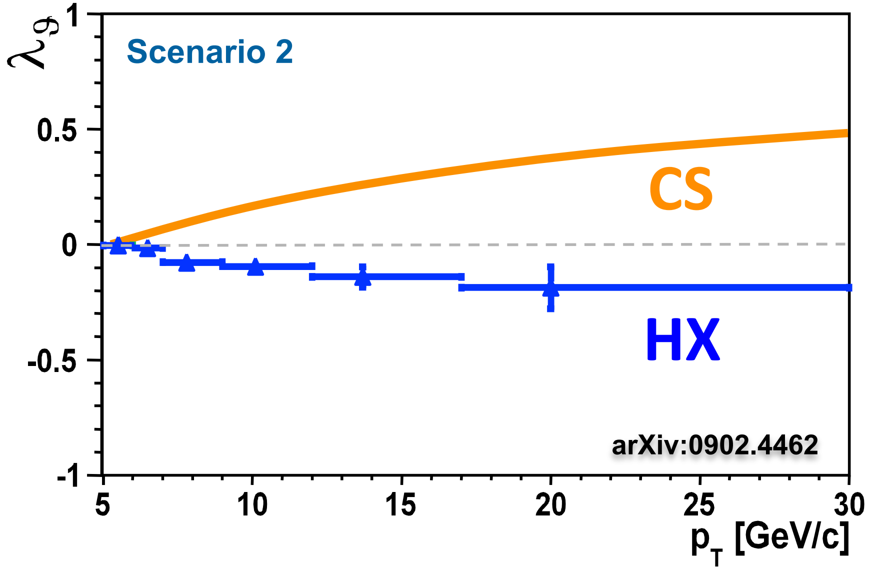

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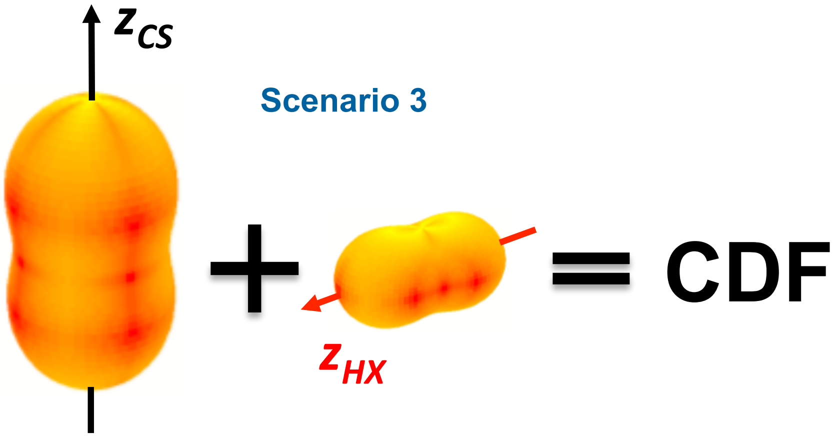
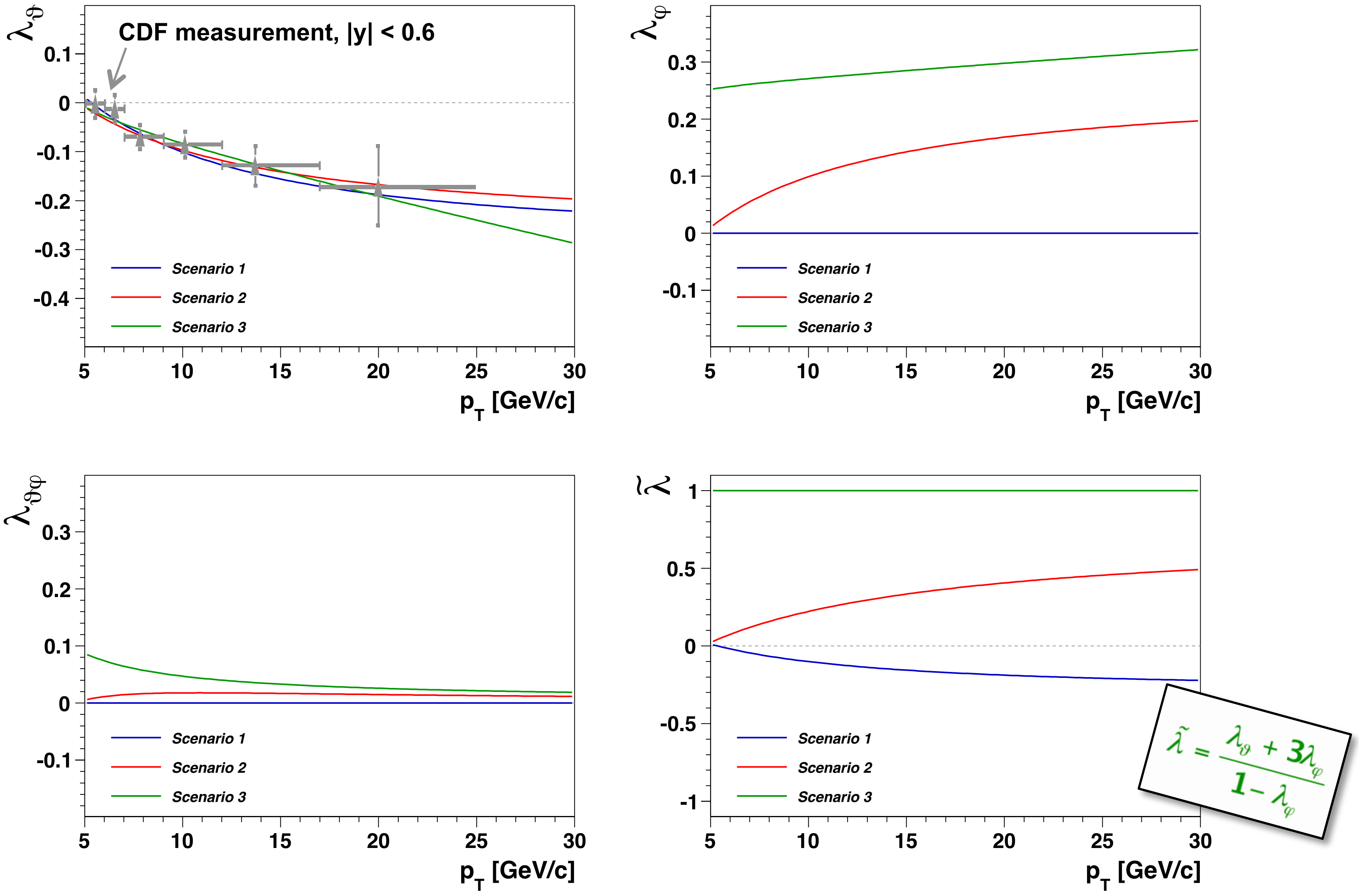


These scenarios can be ’confirmed’ or falsified by improved analyses, applying the new formalism

# Quarkonium polarization

## Summary of scenarios in the HX frame



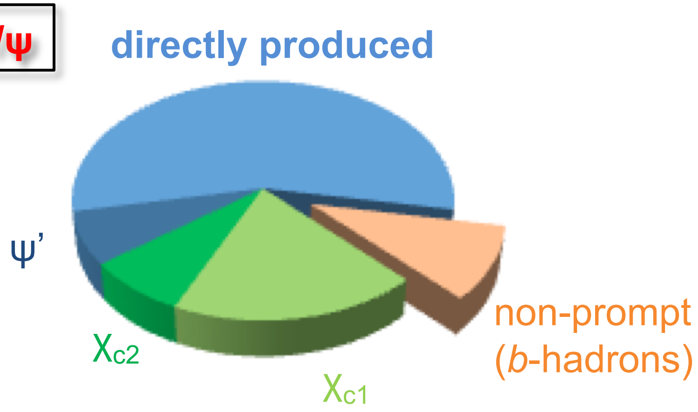
$$\tilde{\lambda} = \frac{\lambda_\vartheta + 3\lambda_\varphi}{1 - \lambda_\varphi}$$

# Feed-down considerations

## Overview of feed-down contributions into S states

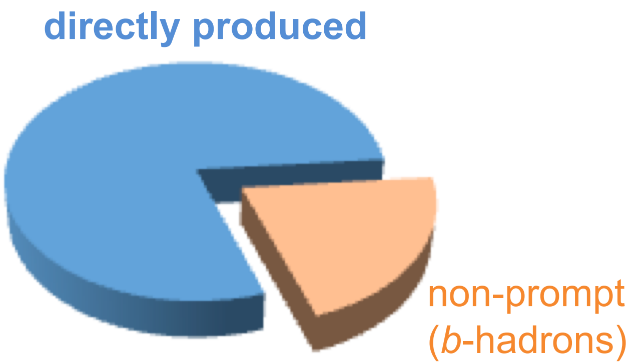
**Charmonium**

**J/ψ**

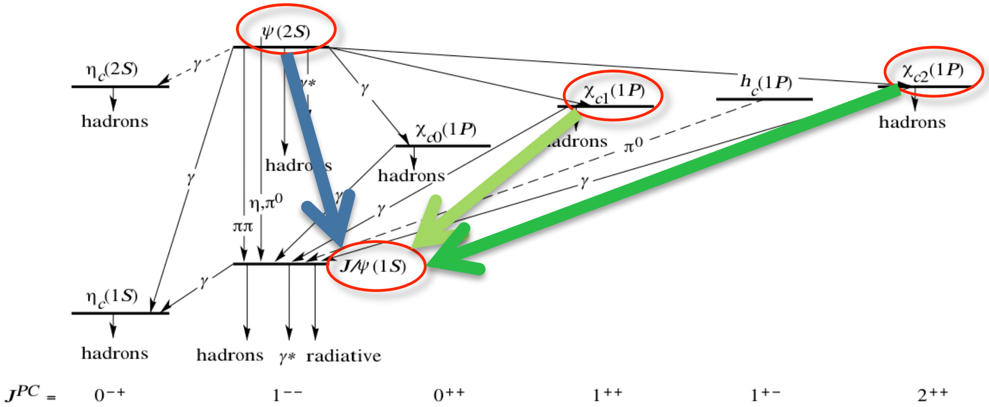


CDF data

**ψ‘**



CDF data (rough estimation)



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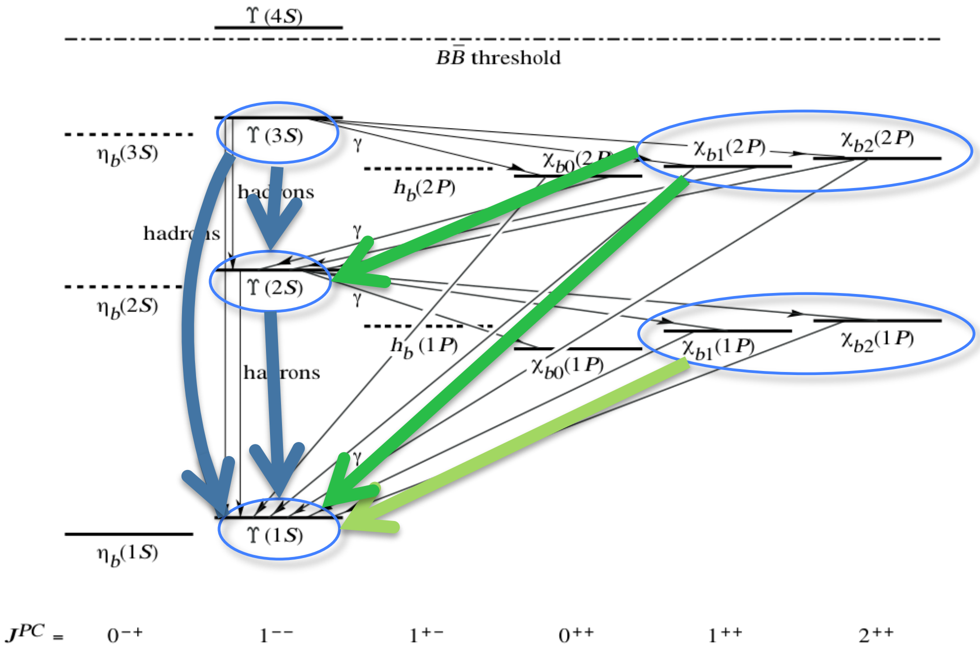
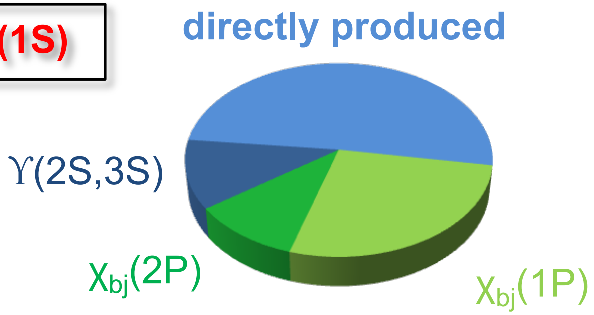
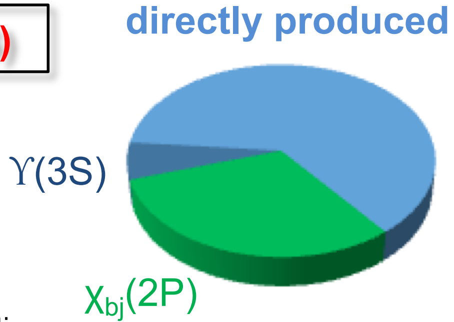


**$\Upsilon(1S)$**



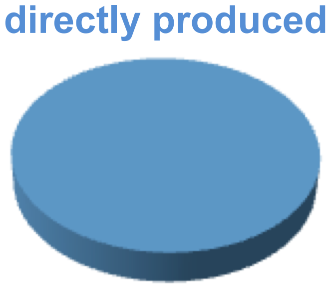
CDF data

**$\Upsilon(2S)$**



Arbitrary fractions

**$\Upsilon(3S)$**



**Bottomonium**

# Feed-down considerations

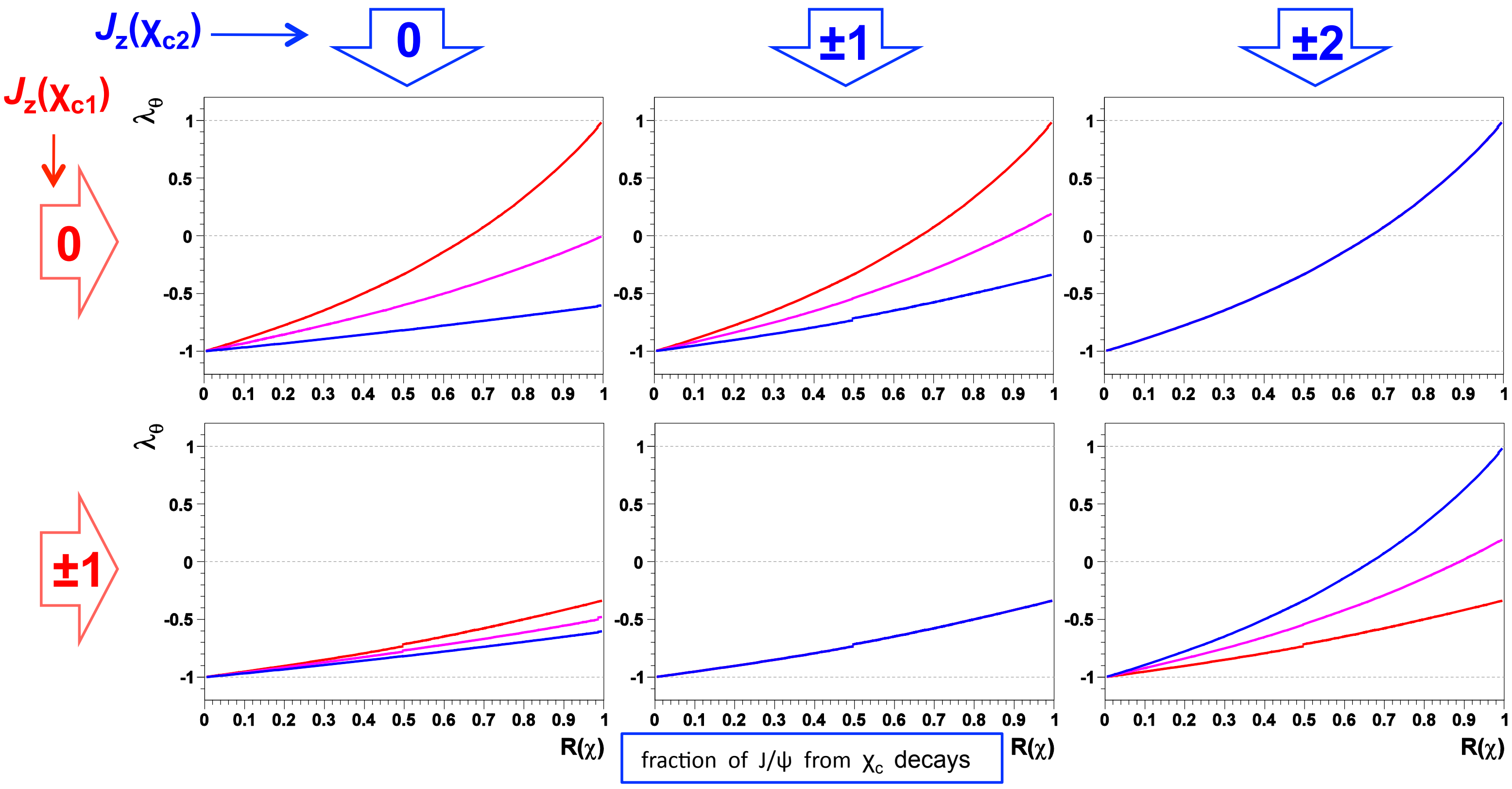
## Influence of $\chi_c$ polarization on a prompt J/ψ measurement

- **$\chi_c$** have different angular momentum and parity properties, and are produced in different partonic processes → **J/ψ's from $\chi_c$'s** should have different polarization properties!
- The $\chi_c$ feed-down contribution can significantly affect the observed *prompt* J/ψ polarization.

**Hypothetical polarization scenario:**

Directly produced **J/ψ** are fully longitudinal: $\lambda_\vartheta = -1$

**What would one measure as prompt J/ψ polarization? -> 'less longitudinal' in any case!**



fraction of J/ψ from $\chi_c$ decays

— **$FD(\chi_{c1}) > FD(\chi_{c2})$**

— **$FD(\chi_{c1}) \approx FD(\chi_{c2})$**

— **$FD(\chi_{c1}) < FD(\chi_{c2})$**

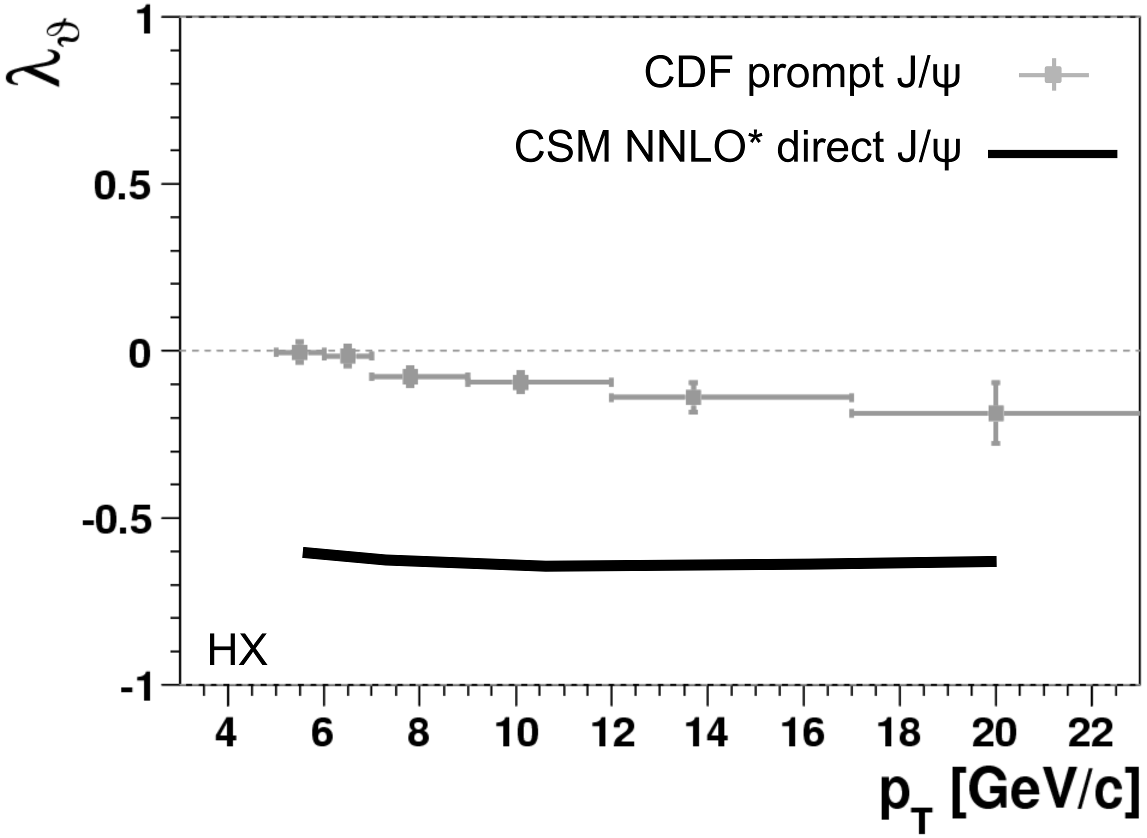
FD = feed-down fraction

# Feed-down considerations

## Extrapolation of direct J/ψ polarization

The **direct J/ψ** polarization (cleanest theory prediction) can be derived from the **prompt J/ψ** polarization measurement of CDF assuming

- **$\chi_c$ to J/ψ feed-down fractions**
- **$\chi_c$ polarizations**



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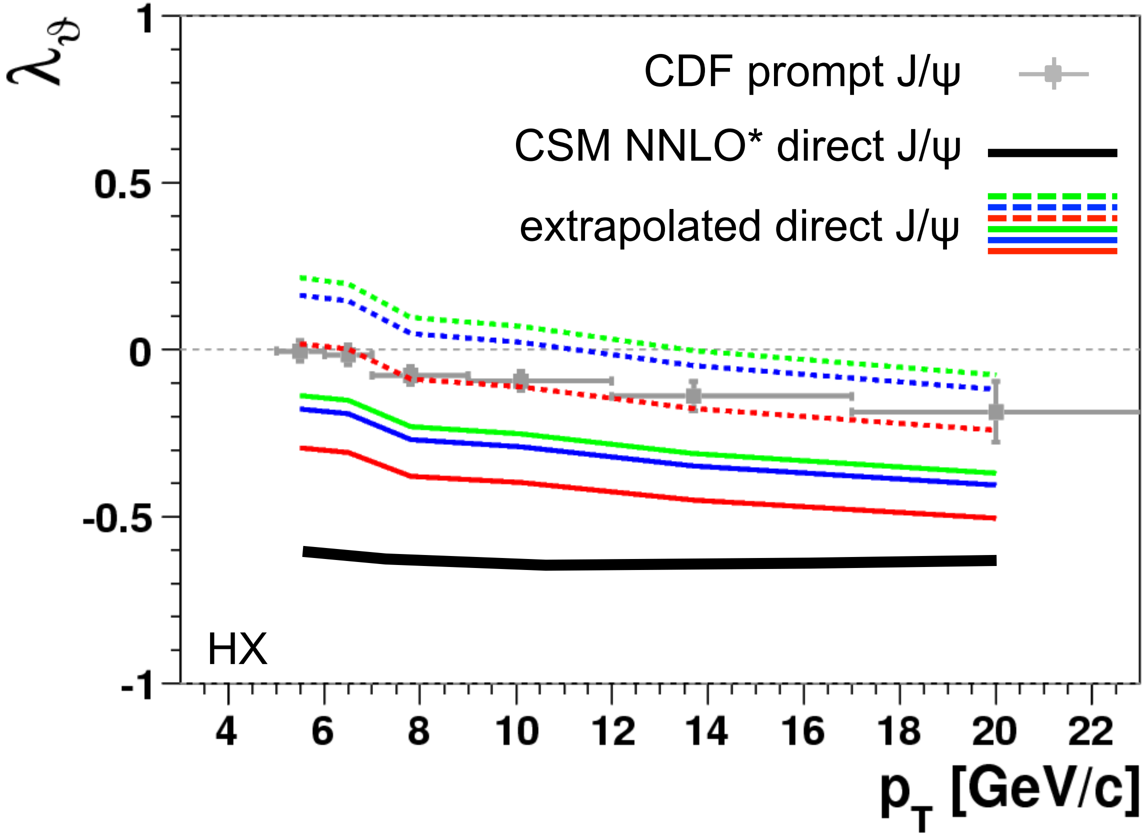
CDF data

$R(\chi_{c1}) + R(\chi_{c2}) = 30 \pm 6$ %

$R(\chi_{c2}) / R(\chi_{c1}) = 40 \pm 2$ %



possible combinations of $\chi_c$ helicity states

| | $J_z(\chi_{c1})$ | $J_z(\chi_{c2})$ |
|---|---|---|
| 🟩 ╌╌╌ | ±1 | 0 |
| 🟦 ╌╌╌ | ±1 | ±1 |
| 🟥 ╌╌╌ | ±1 | ±2 |
| 🟩 ─── | 0 | 0 |
| 🟦 ─── | 0 | ±1 |
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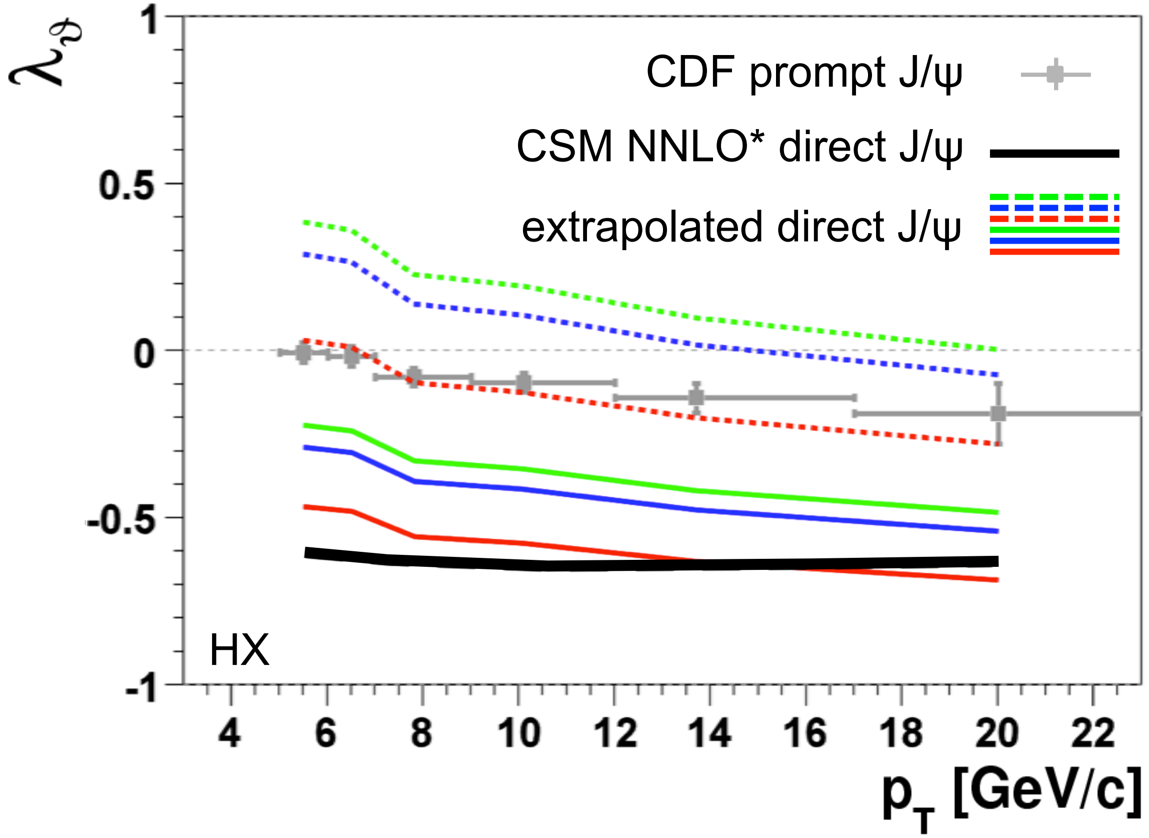
## Extrapolation of direct J/ψ polarization

The **direct J/ψ** polarization (cleanest theory prediction) can be derived from the **prompt J/ψ** polarization measurement of CDF assuming

- **$\chi_c$ to J/ψ feed-down fractions**
- **$\chi_c$ polarizations**

using the values
$R(\chi_{c1}) + R(\chi_{c2}) = 42\ \%$ **(+2σ)**
$R(\chi_{c2}) / R(\chi_{c1}) = 40\ \%$

The CSM prediction of direct J/ψ polarization agrees well with the CDF data *in the scenario*
**$J_z(\chi_{c1}) = 0$ and $J_z(\chi_{c2}) = \pm 2$**



| | $J_z(\chi_{c1})$ | $J_z(\chi_{c2})$ |
|---|---|---|
| 🟩 ╌╌╌ | ±1 | 0 |
| 🟦 ╌╌╌ | ±1 | ±1 |
| 🟥 ╌╌╌ | ±1 | ±2 |
| 🟩 ━━━ | 0 | 0 |
| 🟦 ━━━ | 0 | ±1 |
| 🟥 ━━━ | 0 | ±2 |

# Summary and outlook

## ‚Recipe' for an unambiguous polarization measurement

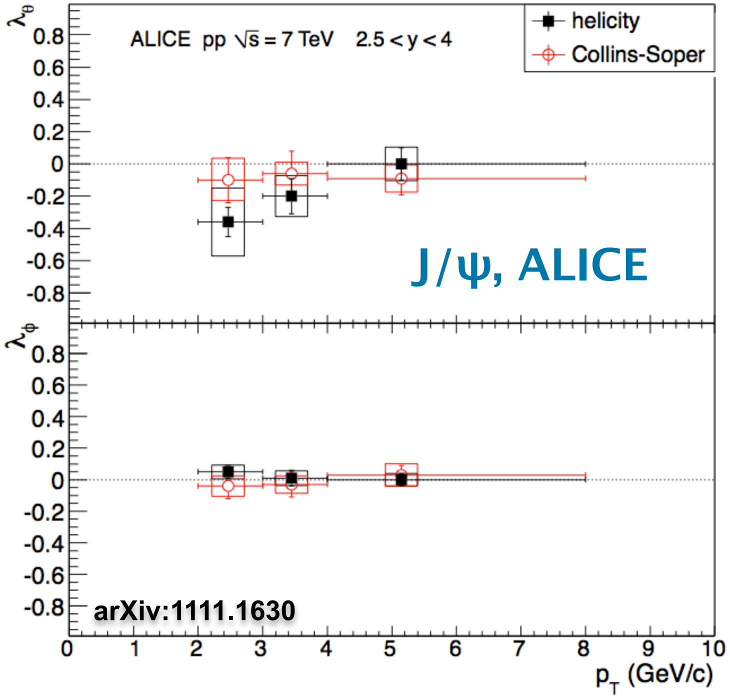
- Polarization measurements are very complex and sensitive analyses
  → crucial to use an extremely careful approach
- Measure polar and azimuthal anisotropies ( $\lambda_\vartheta$, $\lambda_\varphi$, $\lambda_{\vartheta\varphi}$ )
- Measure the polarization in at least two frames (preferably orthogonal)
- Consider a frame invariant parameter (e.g $\tilde{\lambda}$ ), to identify artificial kinematic dependencies, to be able to compare results, and as a powerful experimental cross check
- If feed-down is involved, one has to be very careful when interpreting the results

**arXiv:1006.2738**

## What measurements are necessary in order to understand QP?

1. In order to understand the **J/ψ and ϒ(1S)** polarization one needs to understand the polarizations (and feed-down fractions) of **the P-wave states** (not for today...)
2. A cleaner probe of S-wave polarization is provided by the **ϒ(2S), ϒ(3S) and ψ'** states

# Quarkonium polarization - recent results



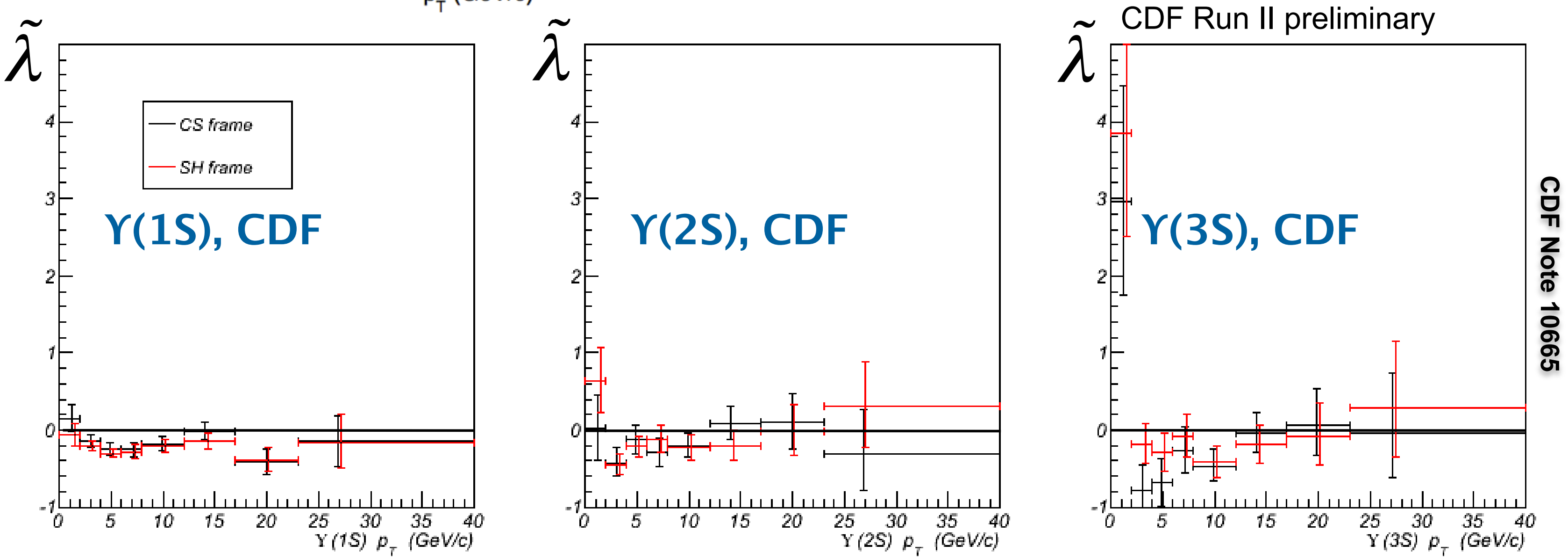
**ALICE J/ψ polarization:**

- Slightly longitudinal polarization in the HX frame at low $p_T$
- Results in CS frame compatible with no polarization

**CDF Υ(nS) polarization:**

- First separate measurement of all Υ(nS) states
- Background events show very large $\tilde{\lambda}$
- No significant polarization for the Υ(2S) and Υ(3S) states but the results suffer from large statistical uncertainties

**The search for answers continues...**



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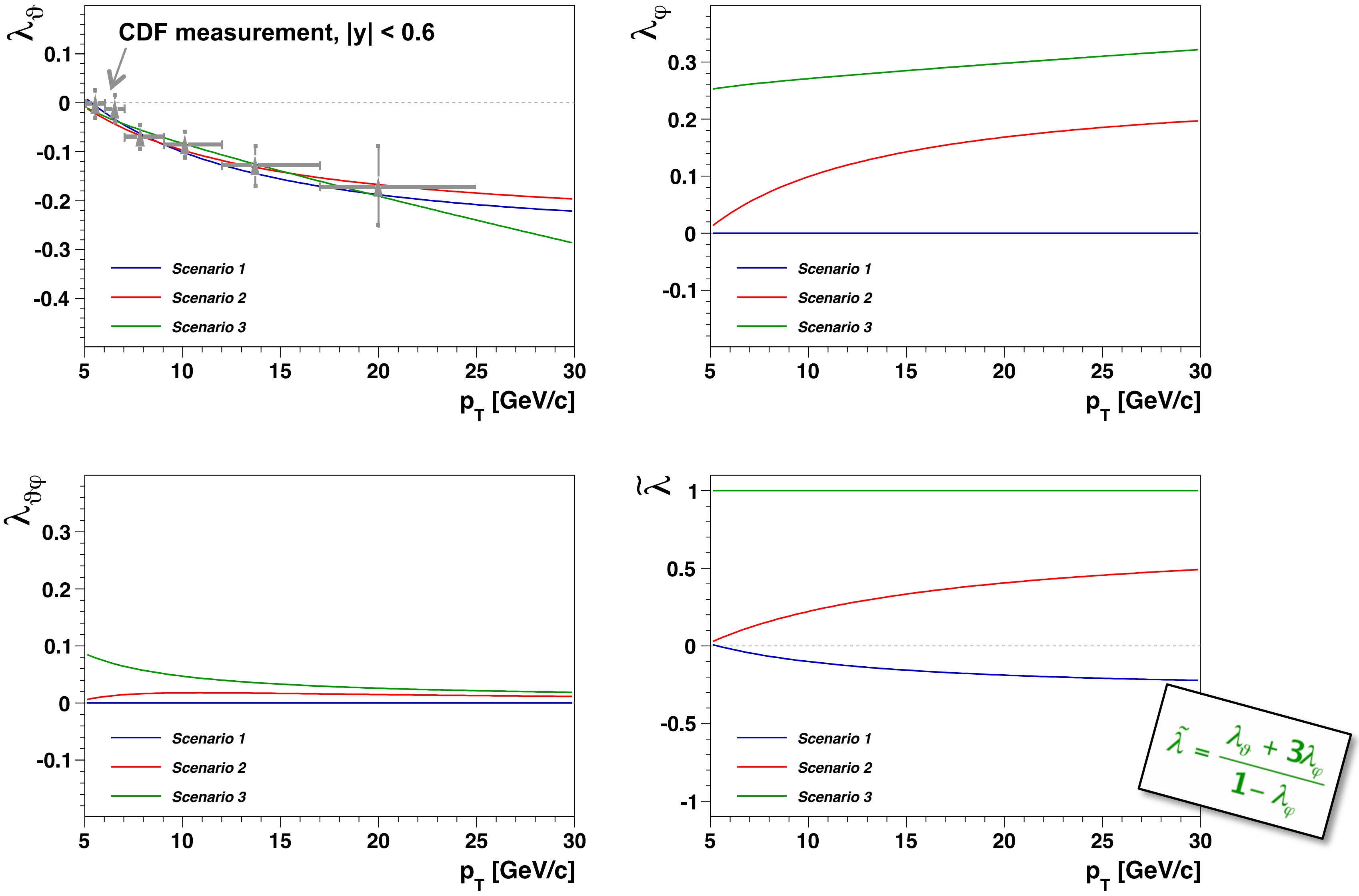
# Quarkonium polarization

## Summary of scenarios in the HX frame



$$\tilde{\lambda} = \frac{\lambda_\vartheta + 3\lambda_\varphi}{1 - \lambda_\varphi}$$

# Quarkonium polarization

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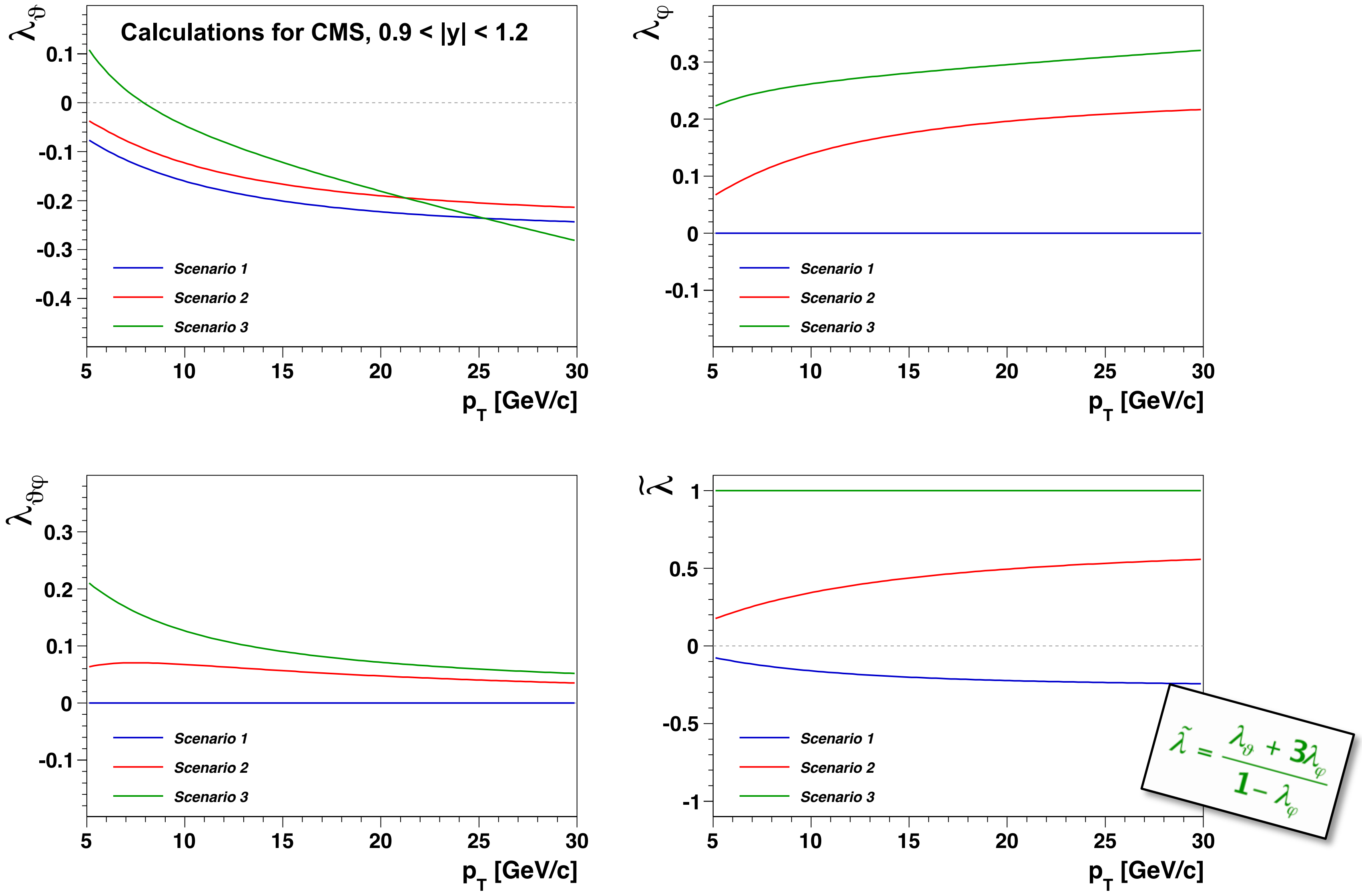

$$\tilde{\lambda} = \frac{\lambda_\vartheta + 3\lambda_\varphi}{1-\lambda_\varphi}$$

# Quarkonium polarization

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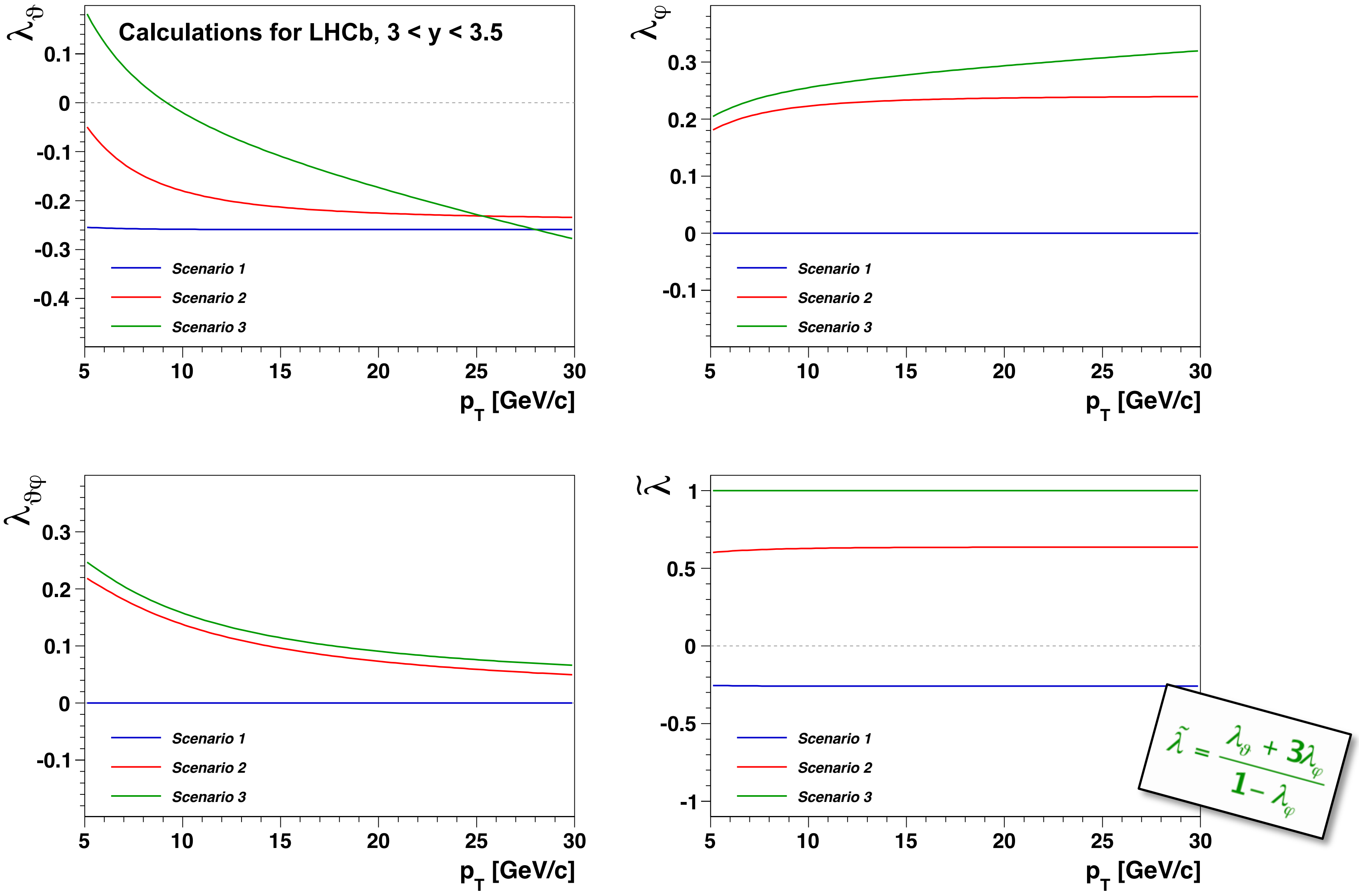

$$\tilde{\lambda} = \frac{\lambda_\vartheta + 3\lambda_\varphi}{1 - \lambda_\varphi}$$