J/ψ polarization scenarios from the Tevatron to the LHC

- General polarization concepts and ideas
- The past experimental puzzles
- Possible interpretations of CDF results
- Predictions for LHC polarization measurements
- Current Statistical Discrimination power of possible scenarios

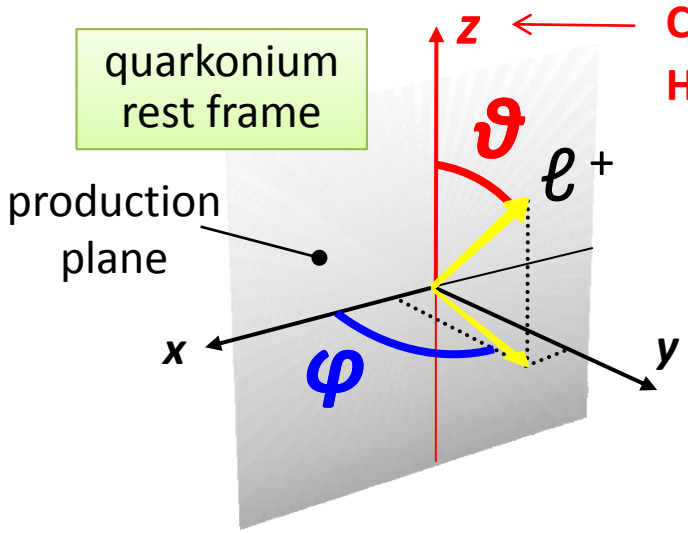
Valentin Knünz – HEPHY, Vienna

in collaboration with
Pietro Faccioli, Carlos Lourenço, João Seixas and Hermine Wöhri

Quarkonium production workshop
April 21st 2011

HEPHY
Institute of High Energy Physics

Reference Frames and polarization parameters



Collins-Soper axis (CS): ≈ dir. of colliding partons

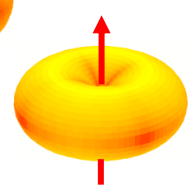
Helicity axis (HX): dir. of quarkonium momentum

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

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

$J_z = \pm 1$ → $\lambda_\vartheta = +1$: **"transverse"** pol.

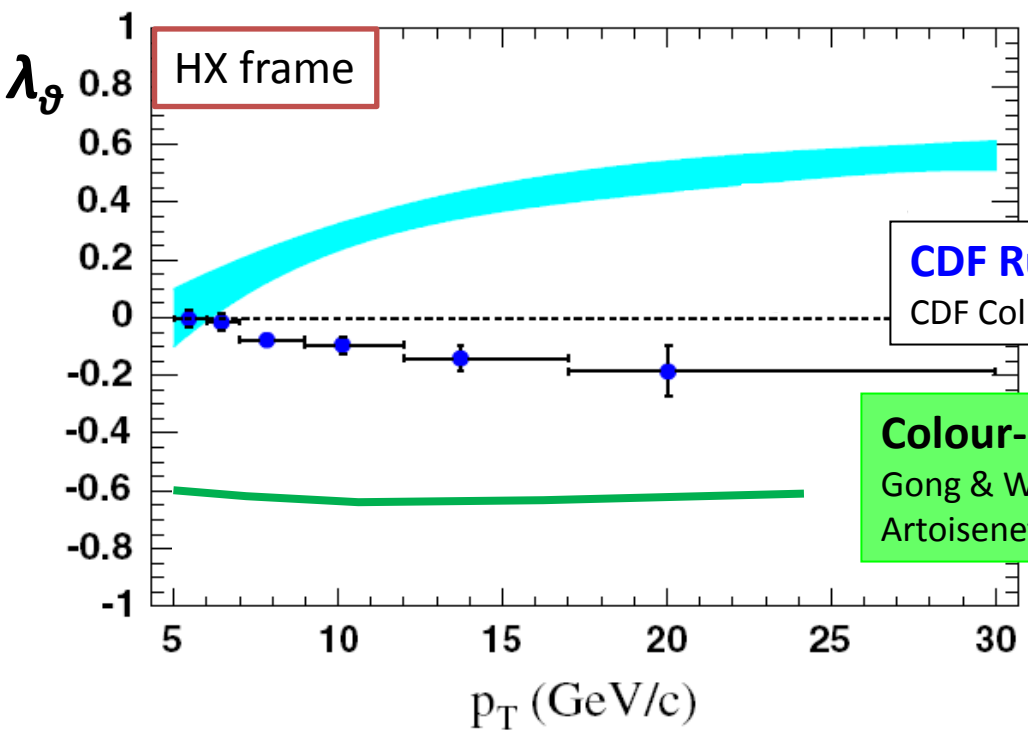
$\lambda_\vartheta = -1$
$\lambda_\varphi = \lambda_{\vartheta\varphi} = 0$



$J_z = 0$ → $\lambda_\vartheta = -1$: **"longitudinal"** pol.

Quarkonium polarization: a "puzzle"

- Quarkonium production mechanisms are not understood
- How important are *long-distance effects* (formation of the q-qbar bound state) in the observed rates and polarizations? Two opposite approaches:
  - **Colour Singlet Model:** pure perturbative calculations, ignoring long-distance effects
  - **NRQCD:** quarkonia are also produced as coloured quark pairs; long distance colour-octet matrix elements are adjusted to the cross-section data dσ/dpT
- Both approaches reproduce the decay-averaged dσ/dpT , but…

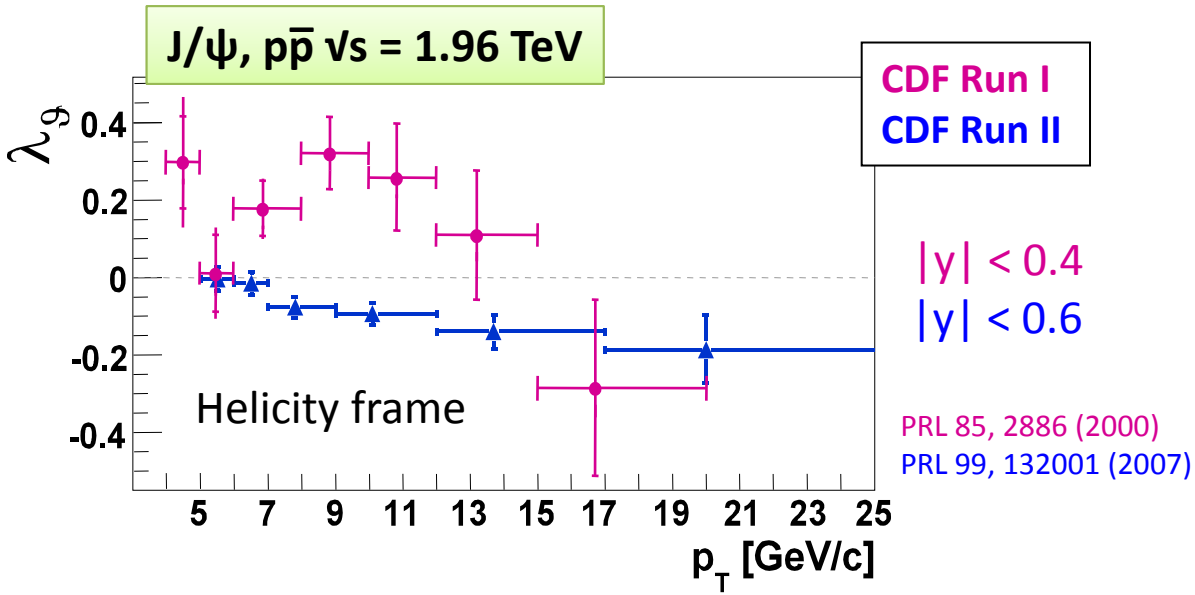


NRQCD factorization: prompt J/ψ
Braaten, Kniehl & Lee, PRD62, 094005 (2000)

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

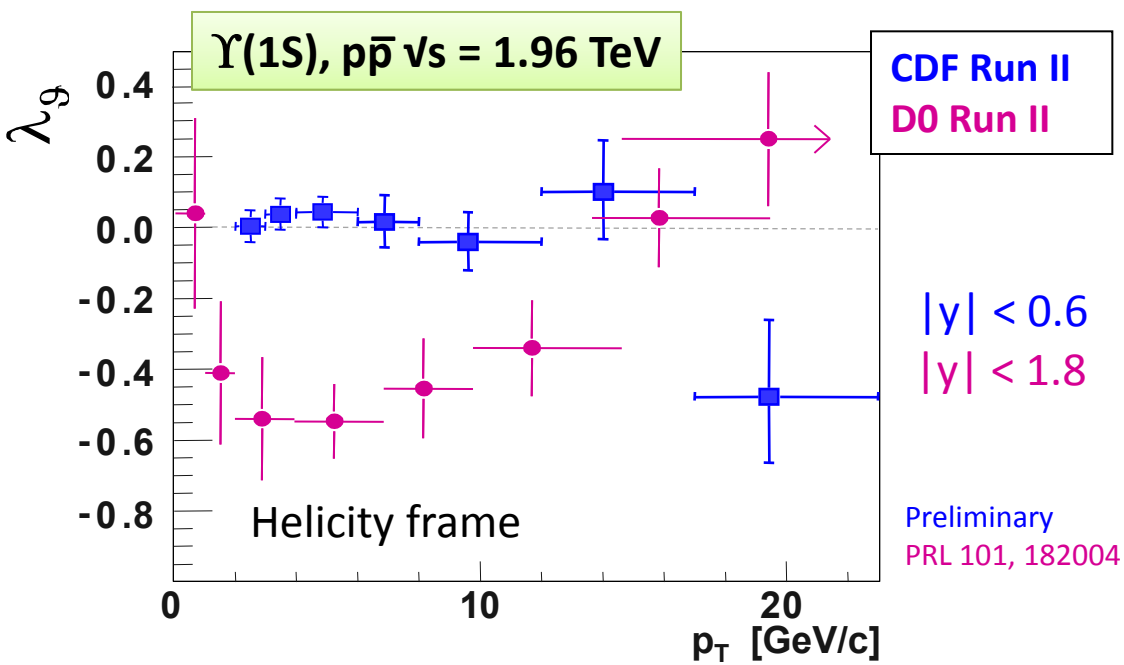
Colour-singlet @NLO: *direct* J/ψ
Gong & Wang, PRL 100, 232001 (2008)
Artoisenet et al., PRL 101, 152001 (2008)

Experimental puzzles: collider data



PRL 85, 2886 (2000)
PRL 99, 132001 (2007)

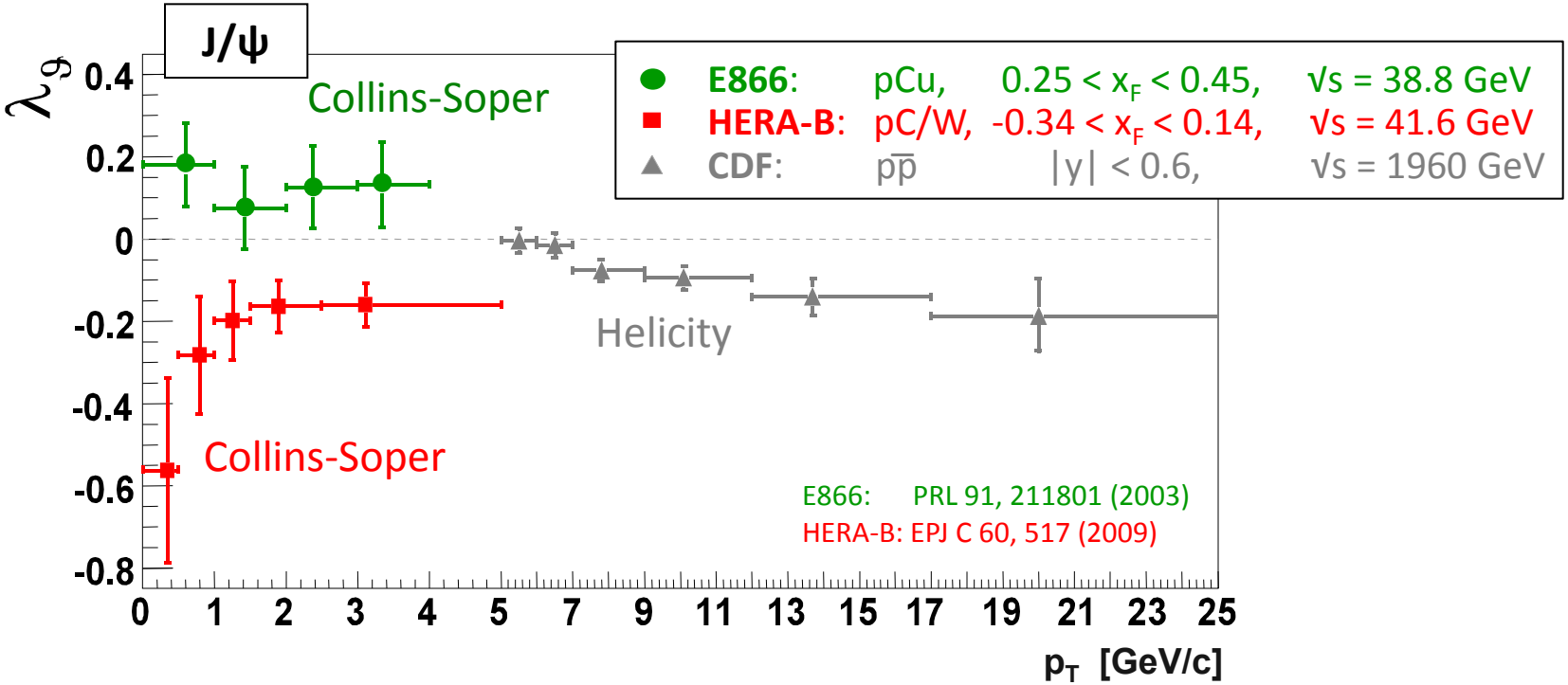
- **CDF II** vs **CDF I**
  → not known what caused the change



Preliminary
PRL 101, 182004 (2008)

- **CDF** vs **D0**
  → can a strong *rapidity dependence* justify the discrepancy?

Experimental puzzles: J/ψ in proton-nucleus



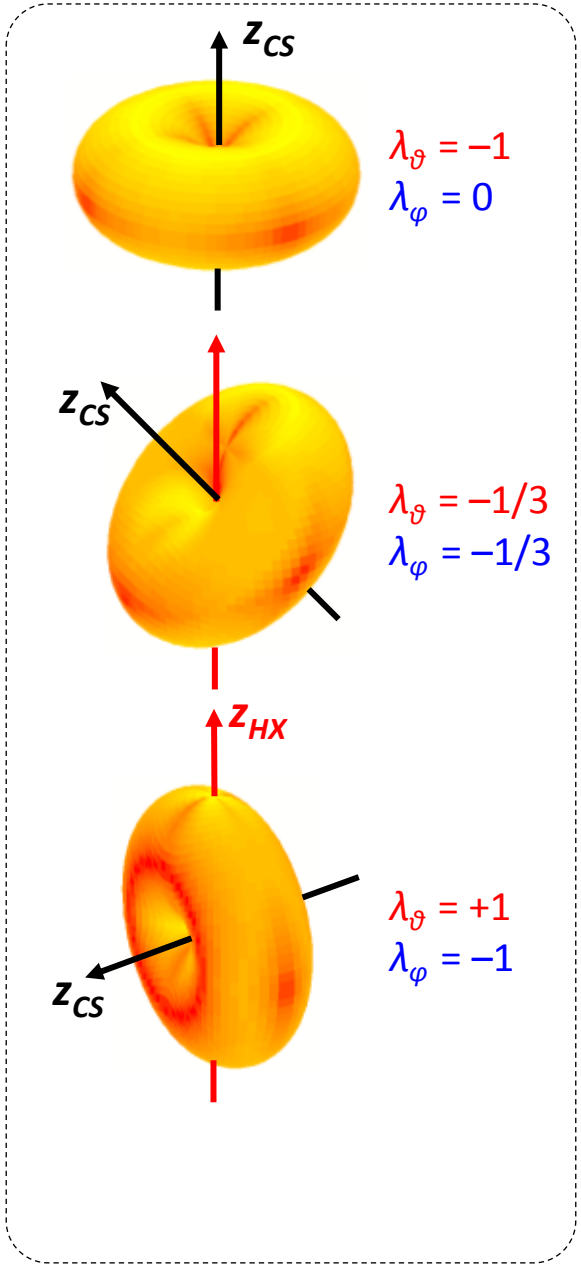
- **E866** vs **HERA-B**

  → *strong p_L dependence?*

- **CDF** vs low-p_T

  → *frame conventions?*

Frame (in)dependence and azimuthal anisotropy



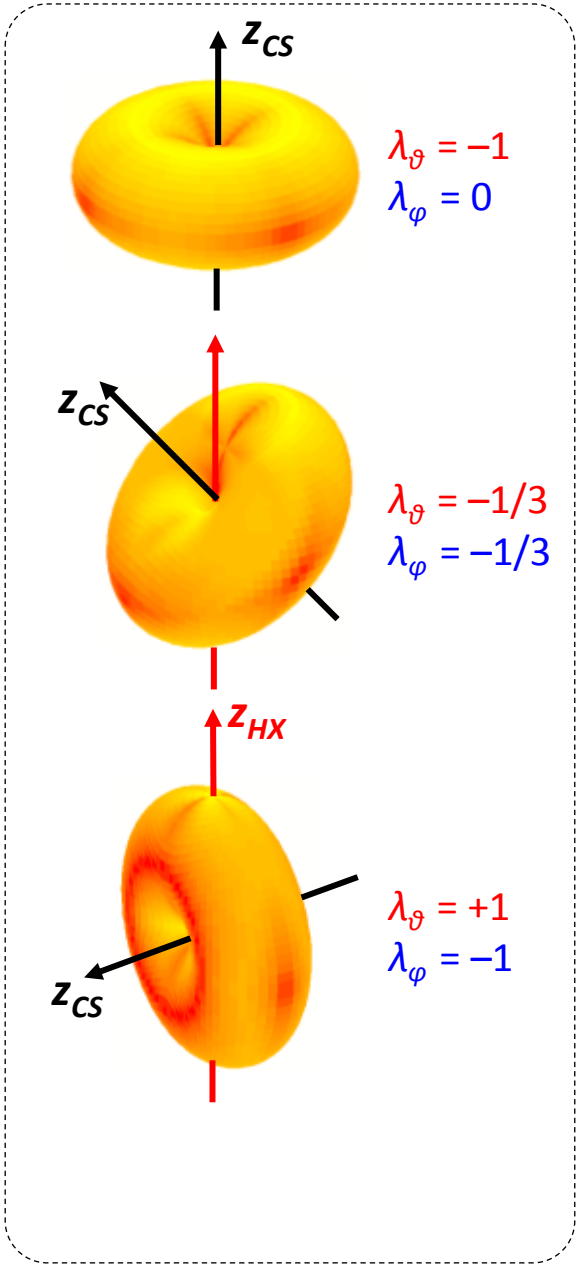
1) The observed polarization depends on the frame

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

for mid rap. / high p_T

i.e. $p_T >> |p_L|$

Frame (in)dependence and azimuthal anisotropy



1) The observed polarization depends on the frame

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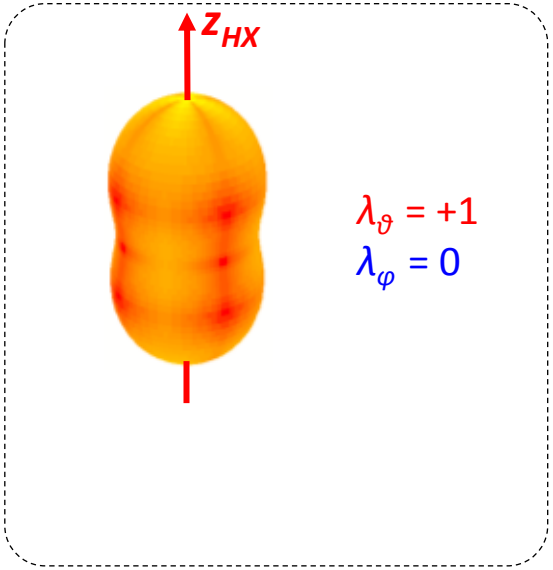
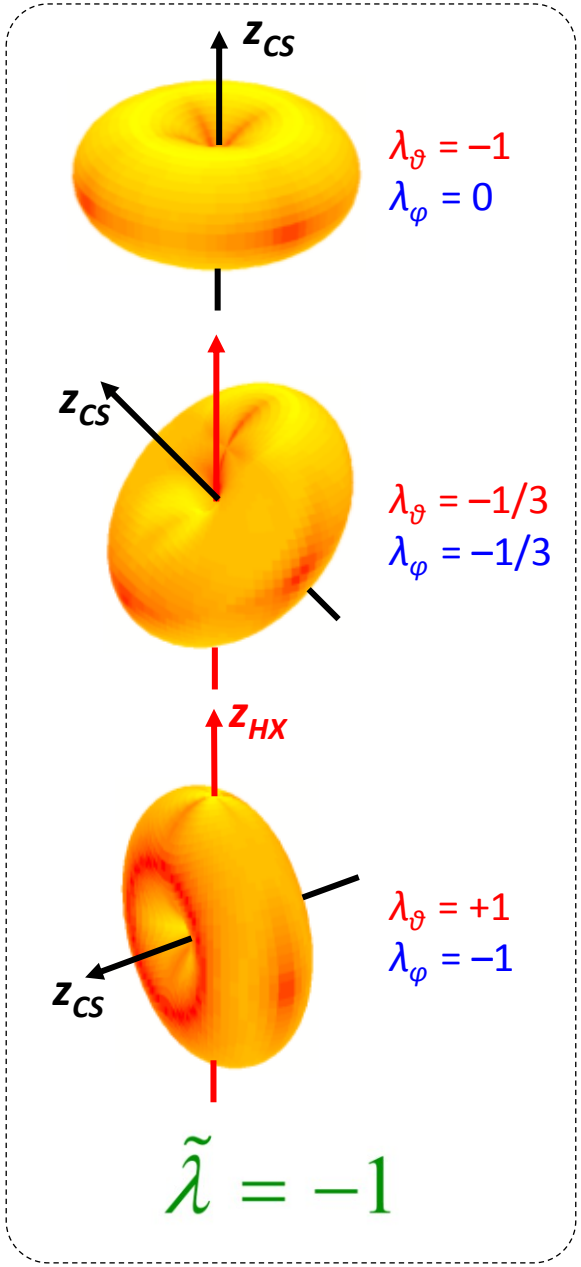
i.e. $p_T >> |p_L|$

2) The azimuthal anisotropy is not a detail

Two very different physical cases,
indistinguishable if $\boldsymbol{\lambda_\varphi}$ is not measured (integration over $\boldsymbol{\varphi}$)



Frame (in)dependence and azimuthal anisotropy



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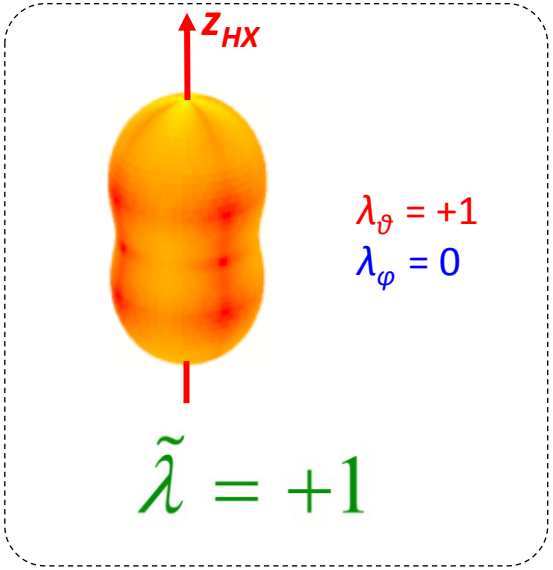


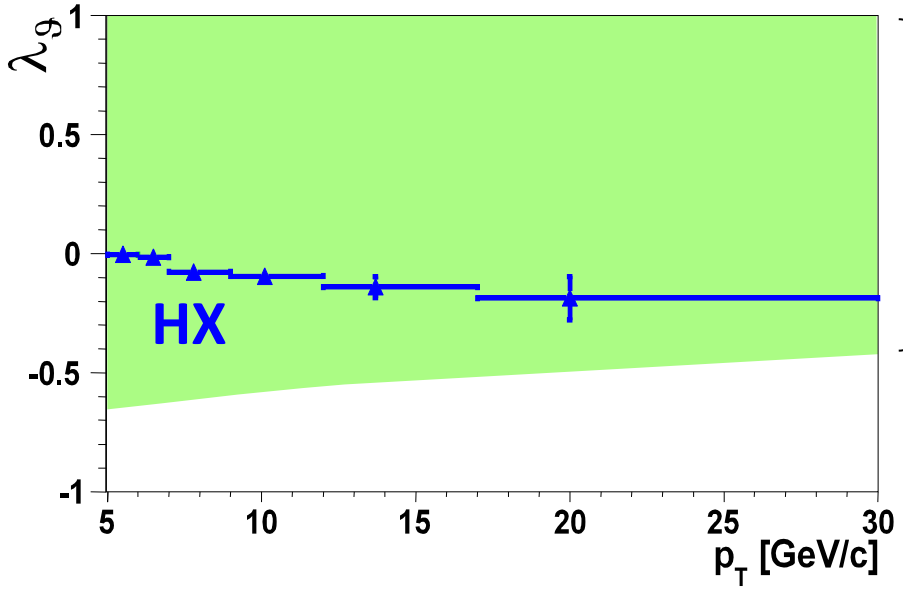
3) The shape of the distribution is frame-invariant

→ it can be characterized by a frame-independent parameter, e.g

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

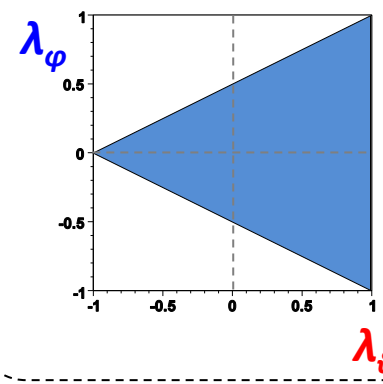
Ambiguous measurements

Has CDF measured a “natural” J/ψ polarization?
The reported weakly “longitudinal” polarization in the HX frame is perfectly compatible with a fully “transverse” polarization in the CS frame !



CS, for all **possible** hypotheses on λ_φ^{HX}

$|\lambda_\varphi| \leq ½(1 + \lambda_\vartheta)$



CDF has not measured λ_φ
Without this information, the polarization state in which the J/ψ is produced is undefined

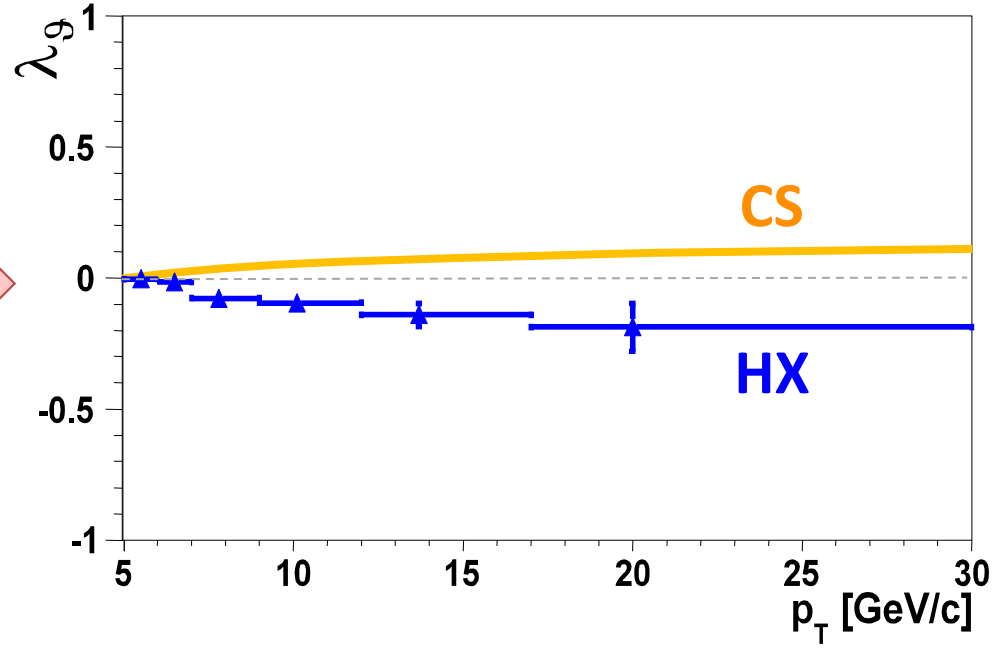
Several very different polarization scenarios can reproduce the CDF measurement but would be distinguishable in the φ dimension and/or in the CS frame

Scenario 1

λ_φ = 0 in the HX frame

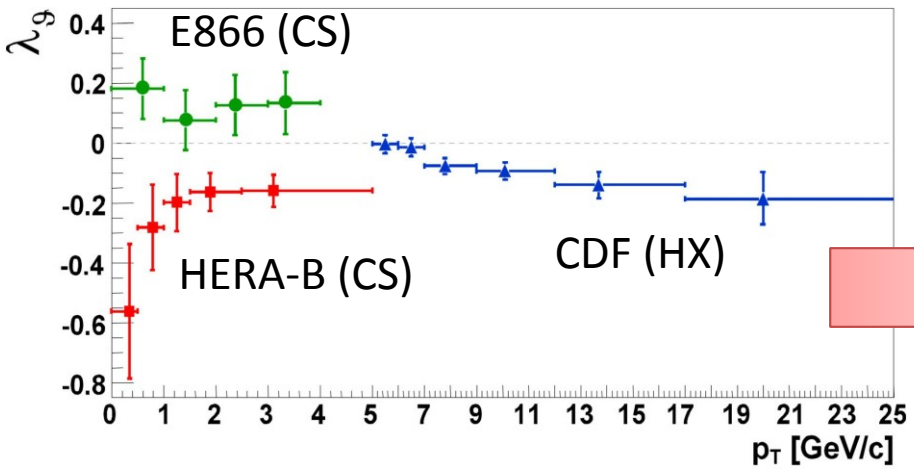
'Natural polarization in HX frame'

$\lambda_\varphi^{HX} = 0$



-> almost unobservable λ_ϑ (and λ_φ) in the CS frame

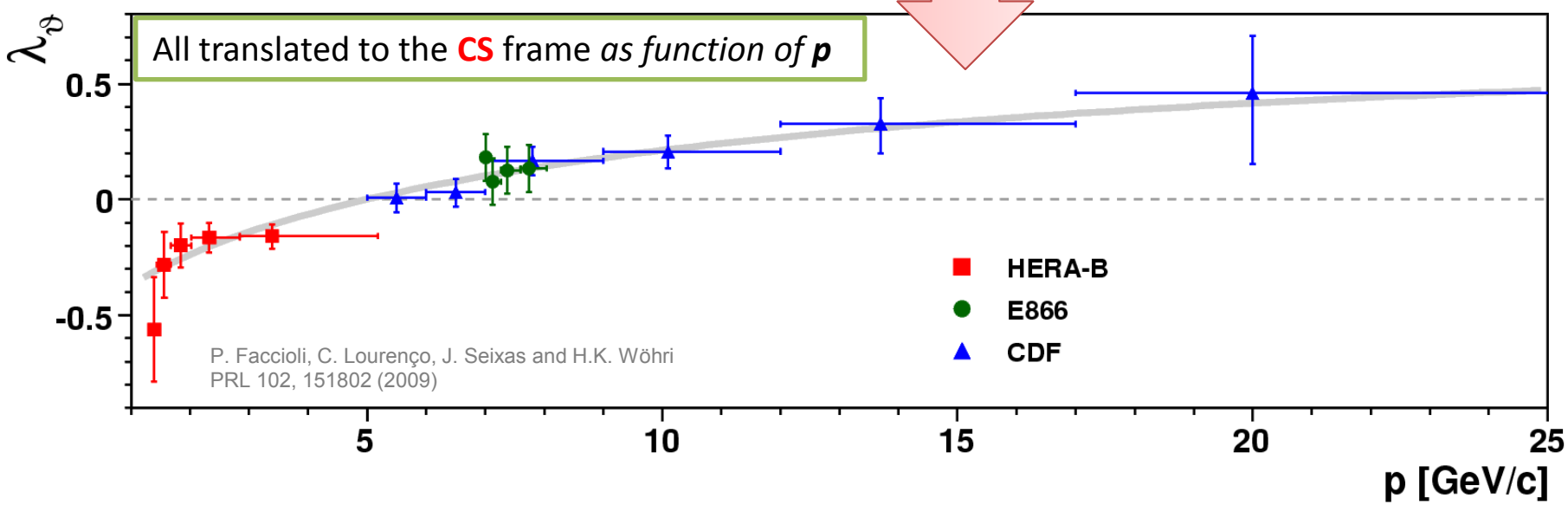
Scenario 2



λ_φ = 0 in the CS frame

'Natural polarization in CS frame'

$\lambda_\varphi^{CS} = 0$



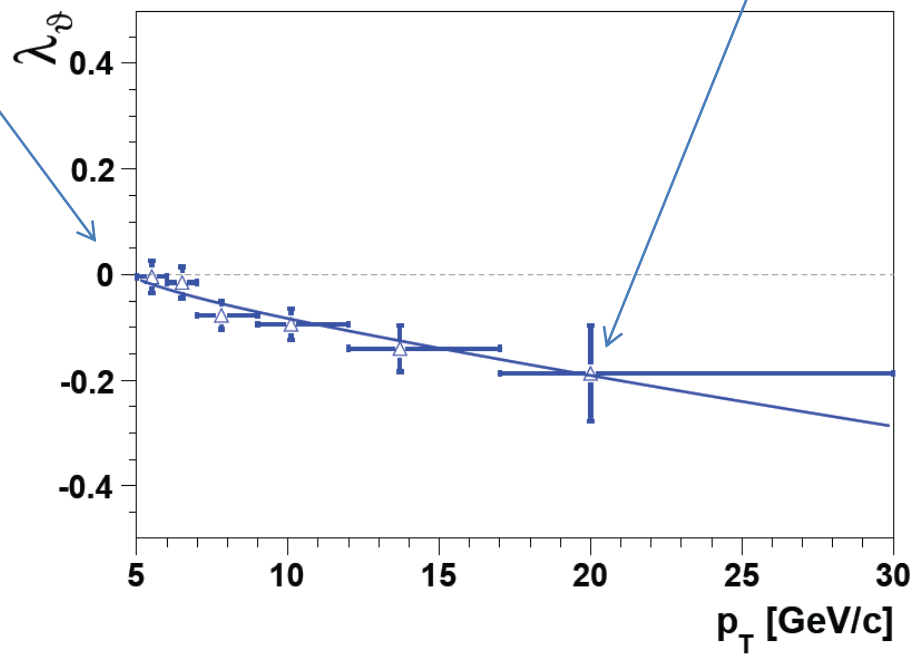
-> a significant λ_φ should be measured in the HX frame

Scenario 3

J/ψ's have always **fully *transverse* polarization**, either in the CS or in the HX frame, with suitable proportions between the two samples

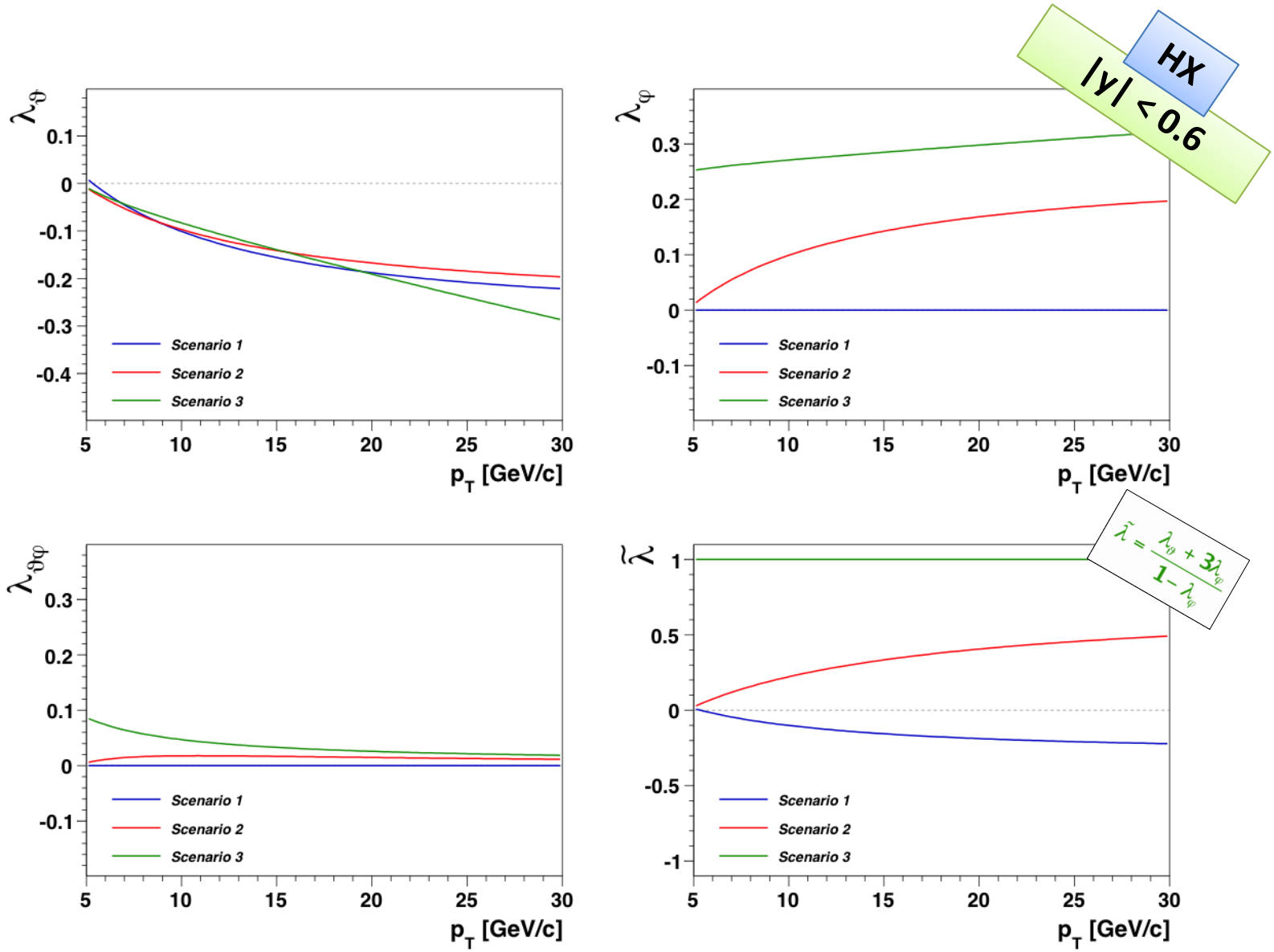
30% transverse in HX frame
70% transverse in CS frame

15% transverse in HX frame
85% transverse in CS frame



-> a large λ_φ should be measured in the HX frame

Summary CDF-Scenarios



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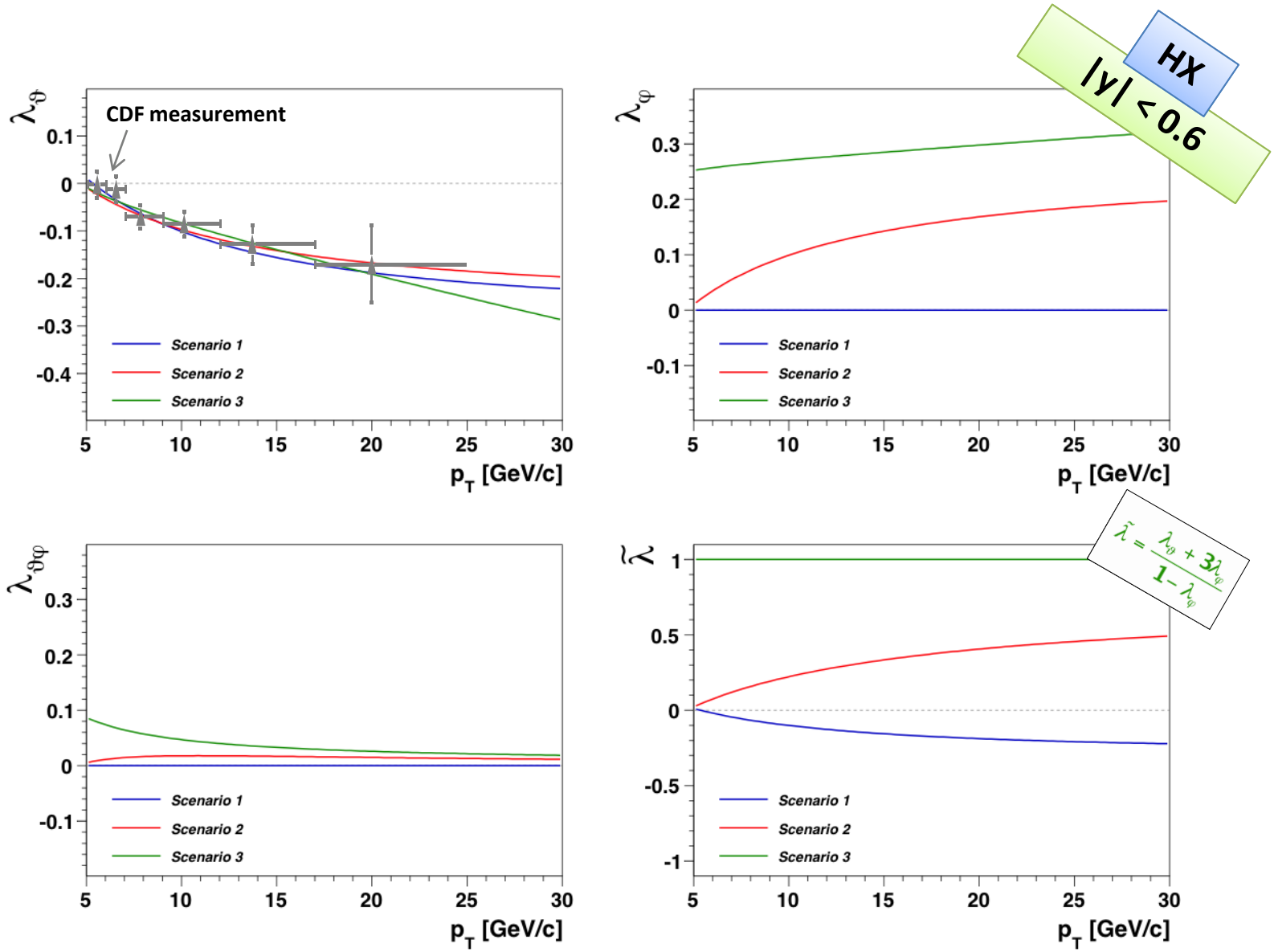

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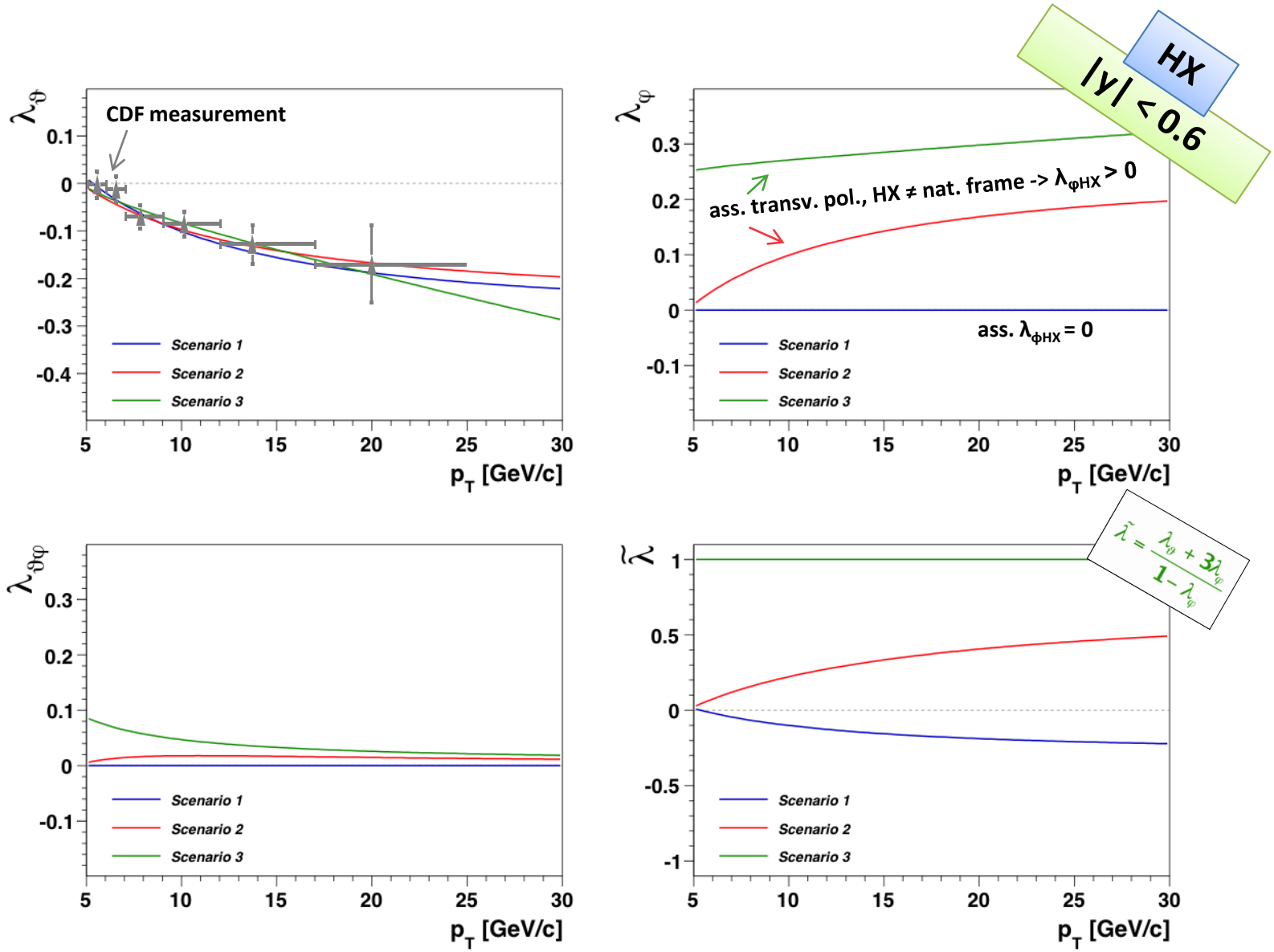

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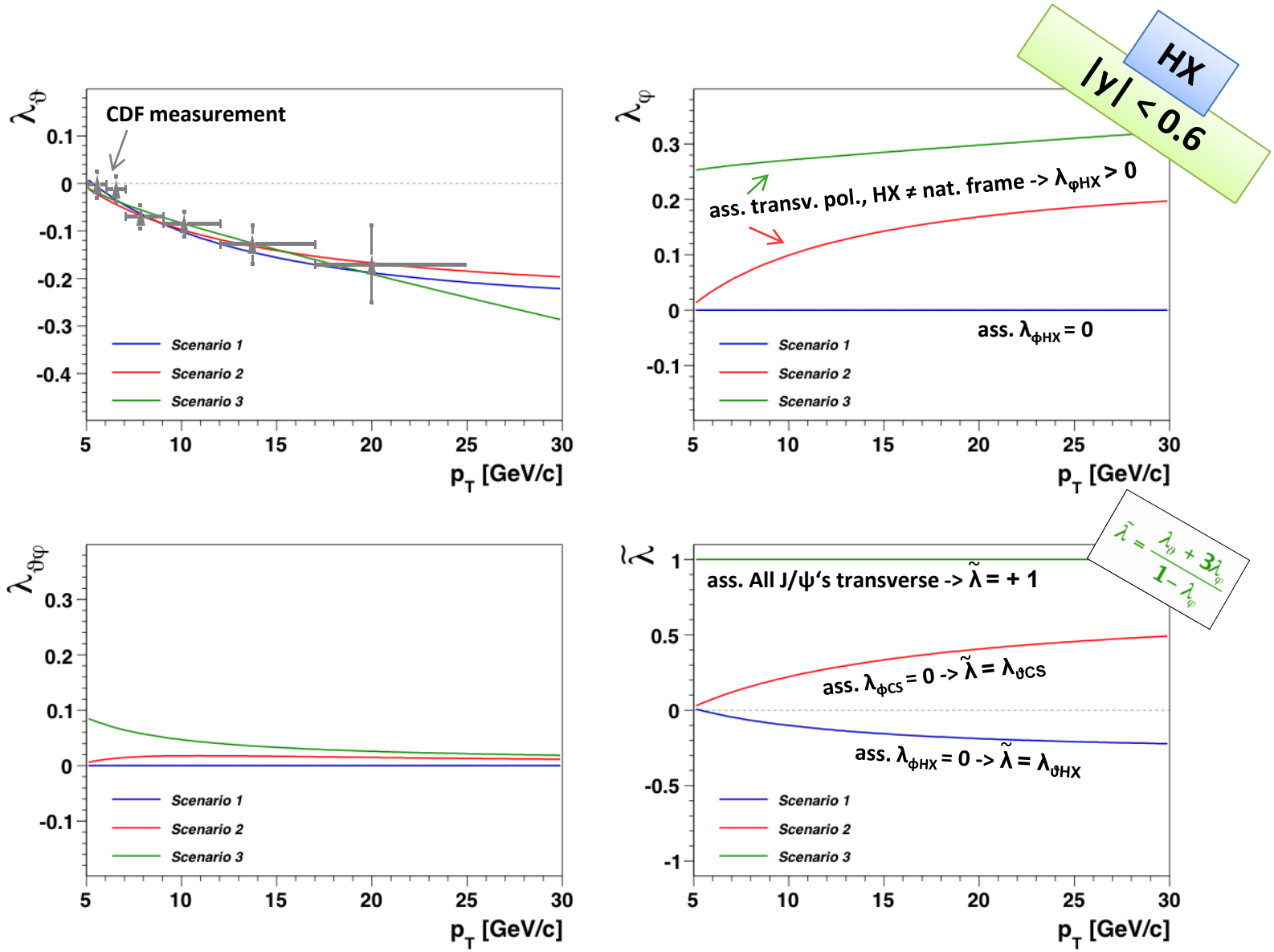
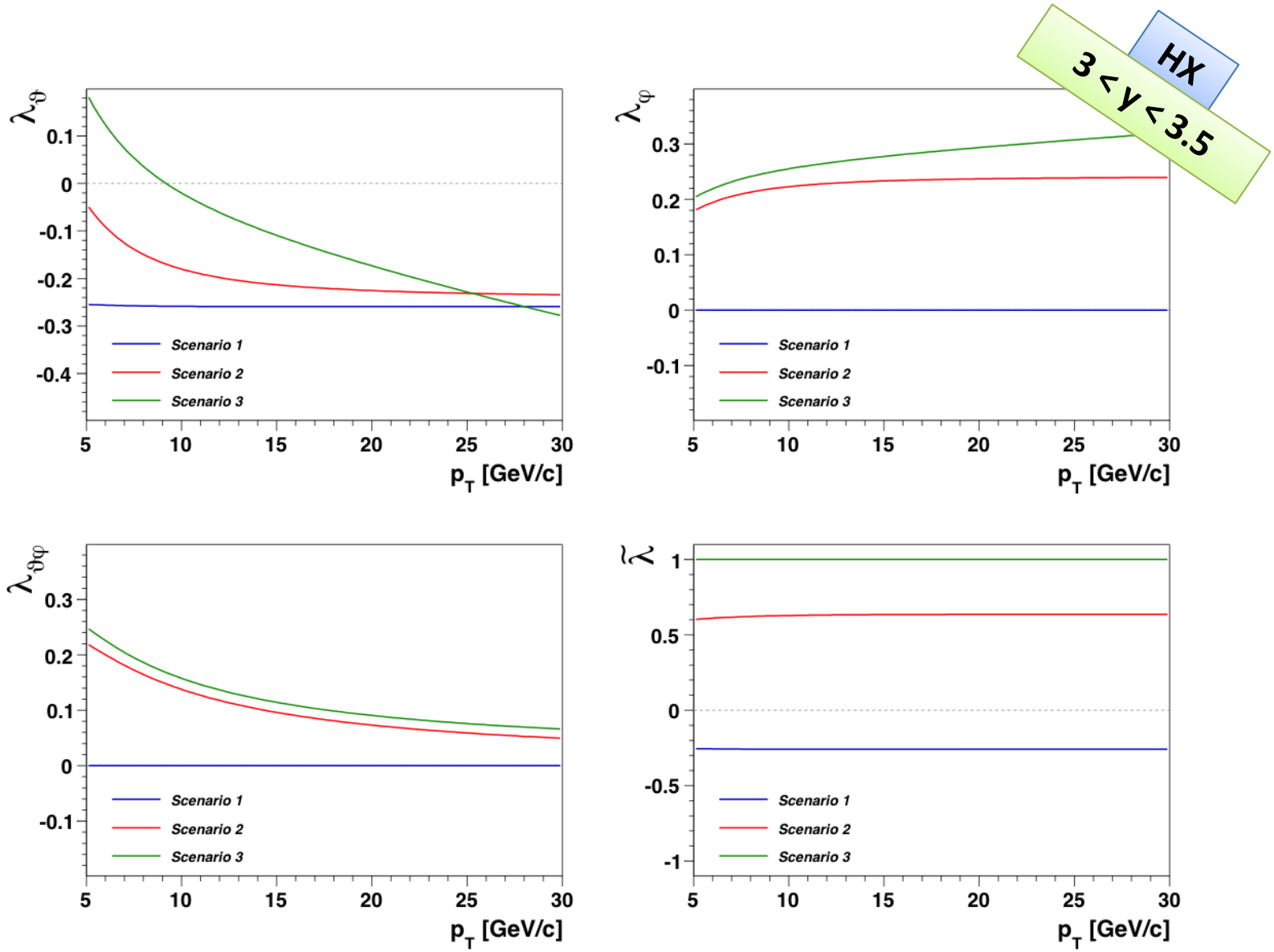
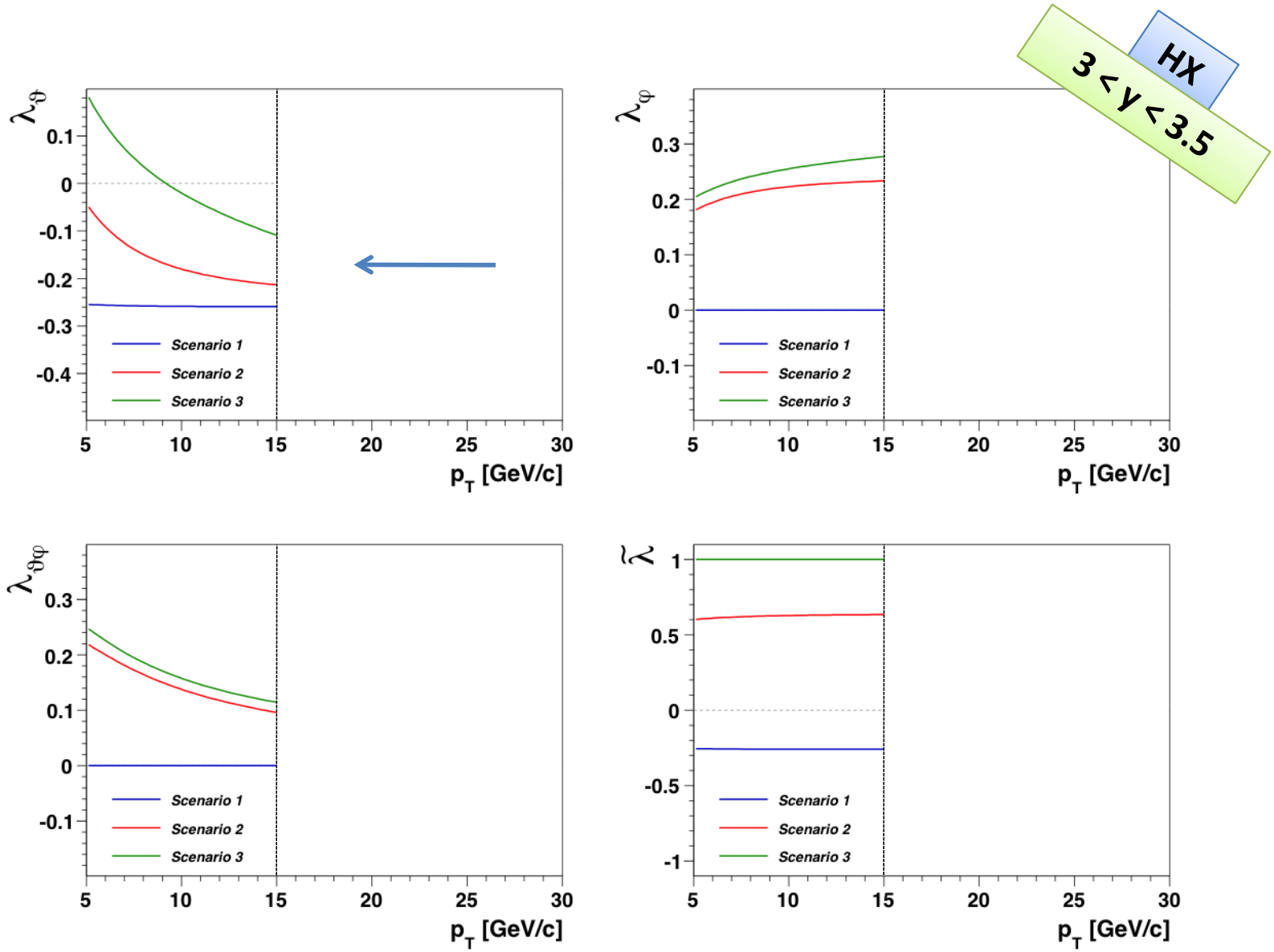


Predictions for LHCb



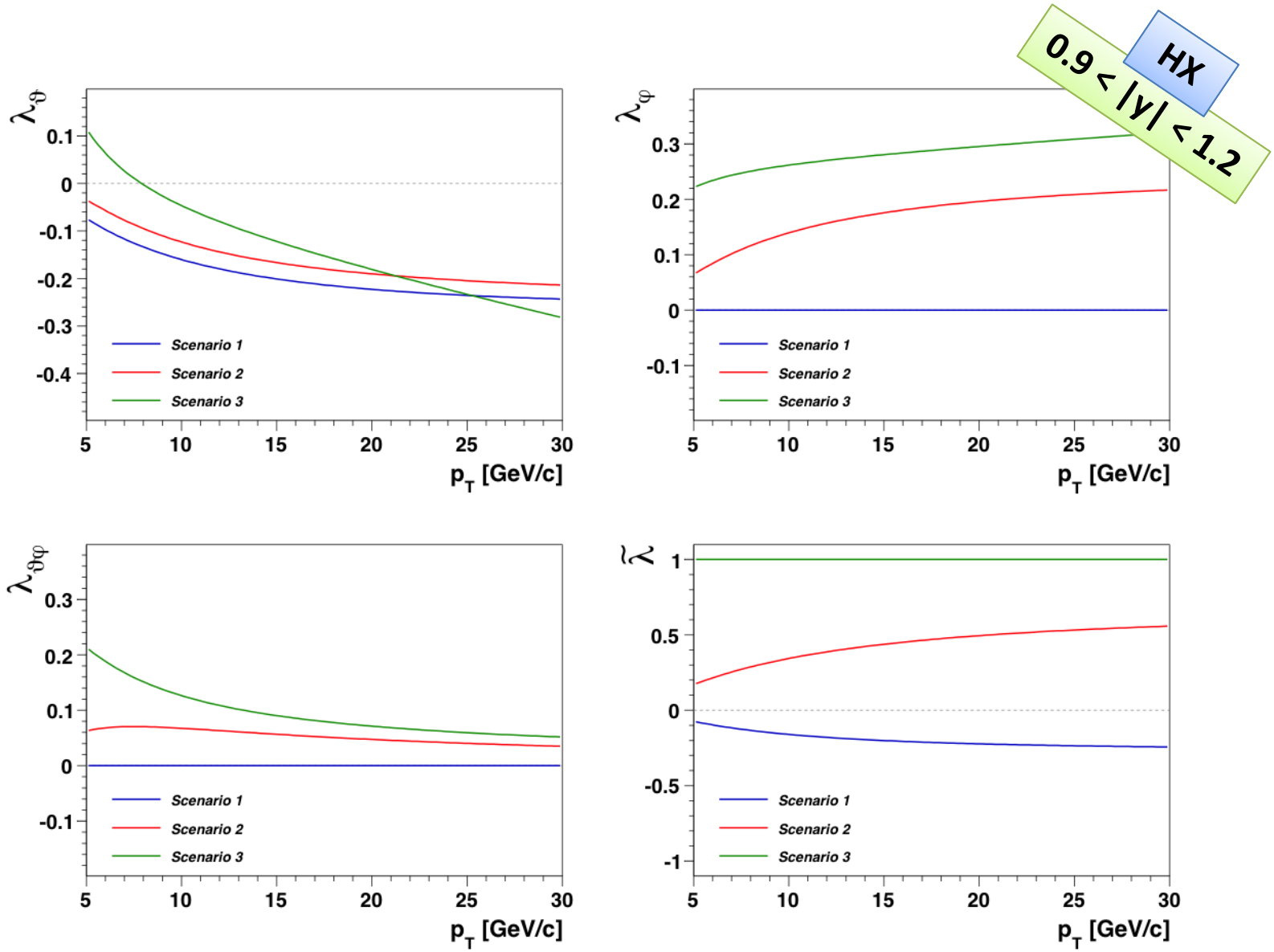
LHCb Predictions for Scen. 2 and Scen. 3 are very close in λ_ϕ and $\lambda_{\vartheta\phi}$ -> **Discrimination via $\tilde{\lambda}$?**

Predictions for LHCb



LHCb Predictions for Scen. 2 and Scen. 3 are very close in λ_ϕ and $\lambda_{\vartheta\phi}$ -> **Discrimination via $\tilde{\lambda}$?**

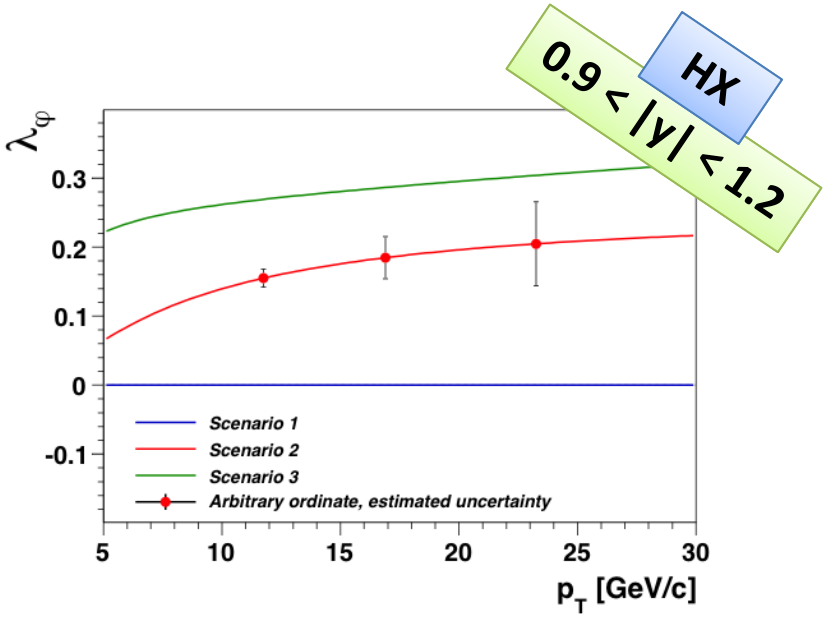
Predictions for CMS

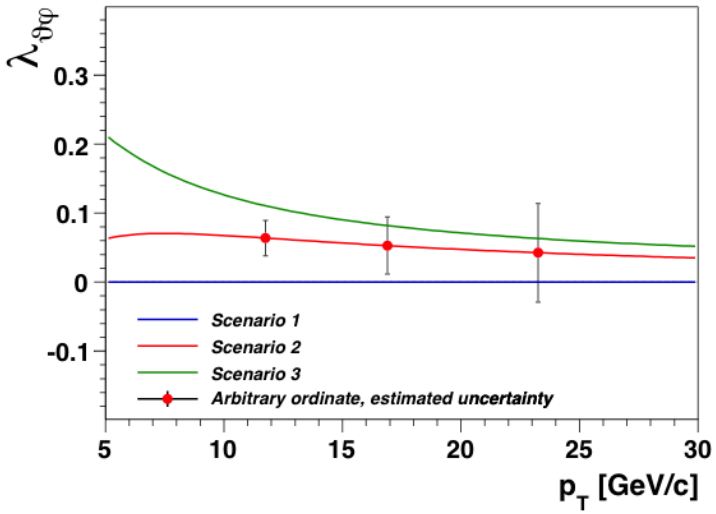


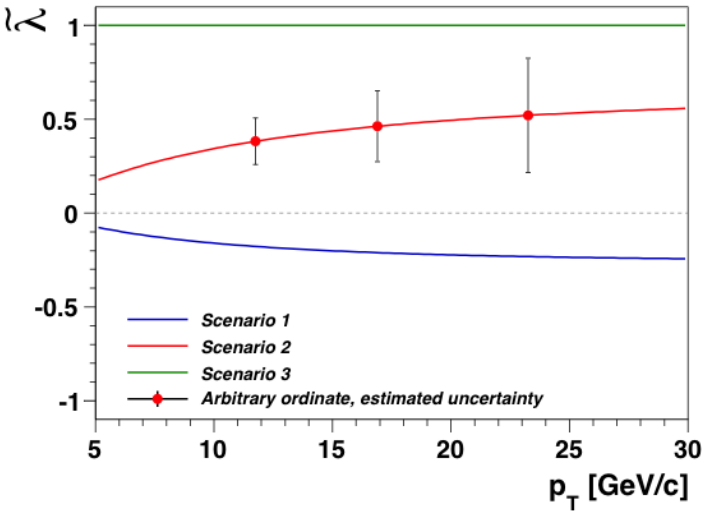
Easier discrimination of all 3 Sen. **-> Discrimination also via $\lambda_{\vartheta\phi}$?**

Discrimination power of CMS

- Statistical uncertainties are estimated by *ToyMC studies*
- Based on *40 pb^{-1}*
- *Number of events* according to data (app. 25000, 6000, 2500)
- Obtained with *same analysis method* as real data analysis
- *B-fraction* simulated according to data (app. 35%, 50%, 60%)



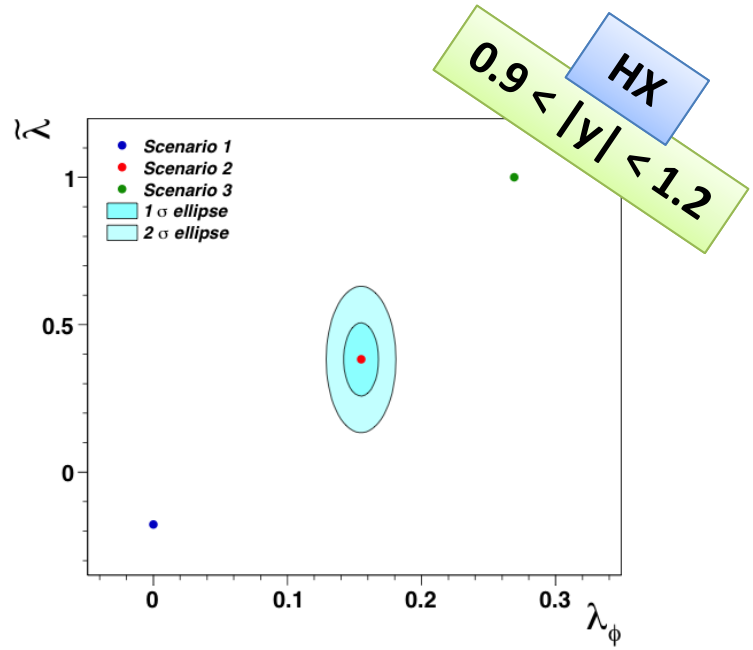


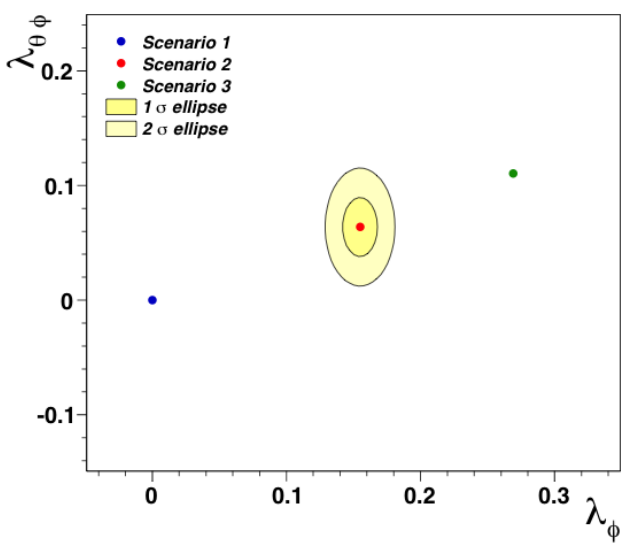


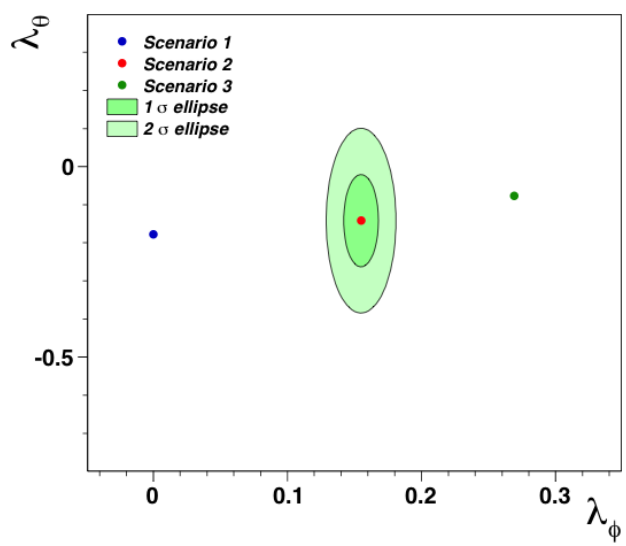
Discrimination power of CMS

Best Bin:
$10 < p_T < 15$ GeV/c

λ_ϕ and $\tilde{\lambda}$ have individual discrimination power at C.L. >> 95%



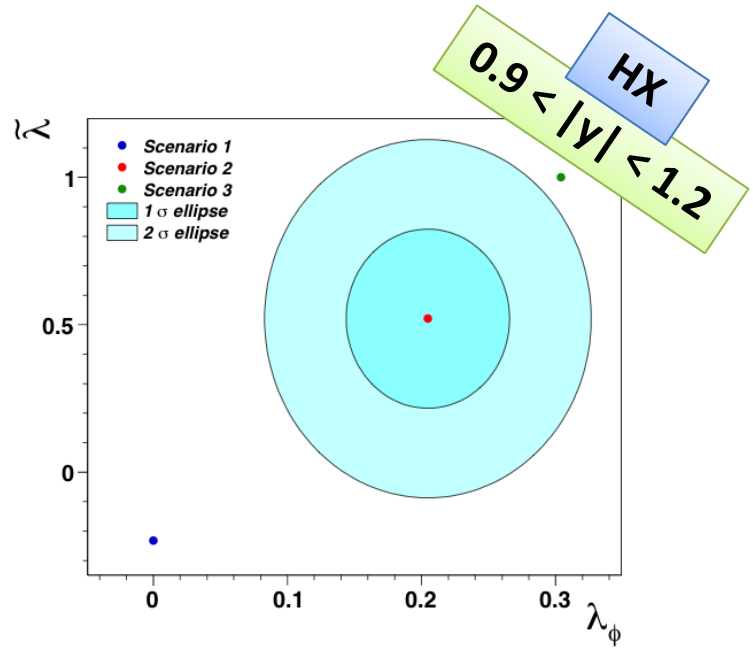


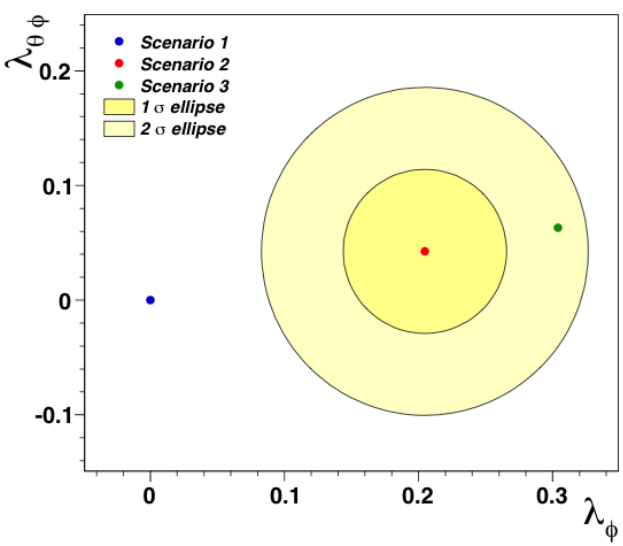


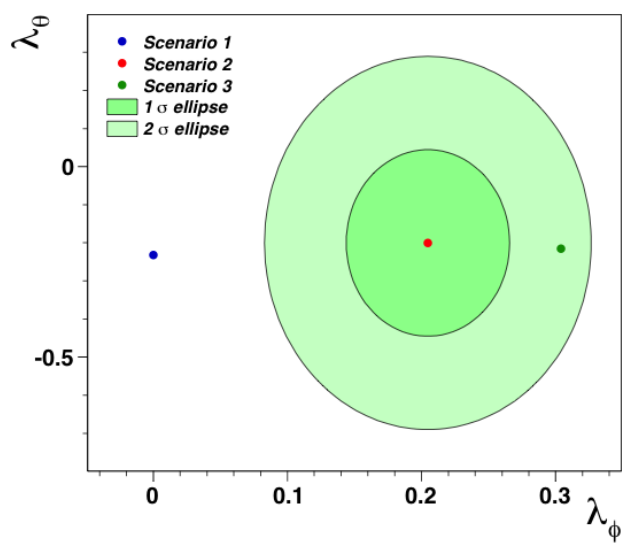
Discrimination power of CMS

Worst Bin:
$20 < p_T < 30$ GeV/c

λ_ϕ and $\tilde{\lambda}$ have combined discrimination power at C.L. > 95%







Summary

• The LHC experiments will be able to rule out several of the scenarios that can explain the CDF pattern...

... even with a relatively small event sample

• The LHC experiments can **not yet** determine λ_ϑ with the precision of CDF. But by also measuring the azimuthal anisotropy, by making use of **the invariant approach** and by measuring both in the **CS and HX frames**, these measurements can still **gain more information** about the physical polarization state of the J/ψ than known today.

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Backup slides

Effect of production kinematics on the observed decay kinematics

Rotation about y-axis (perpendicular to production plane)

$$R_y(\delta) = \begin{pmatrix} \cos\delta & 0 & -\sin\delta \\ 0 & 1 & 0 \\ \sin\delta & 0 & \cos\delta \end{pmatrix}$$

Resulting Decay angular distribution

$$\begin{aligned} W'(\cos\vartheta', \varphi') \quad &\propto \quad \frac{1}{3+\lambda'_\vartheta}\,(1 + \lambda'_\vartheta \cos^2\vartheta' \\ &+ \quad \lambda'_\varphi \sin^2\vartheta' \cos 2\varphi' + \lambda'_{\vartheta\varphi} \sin 2\vartheta' \cos\varphi')\,, \end{aligned}$$

where

$$\lambda'_\vartheta = \frac{\lambda_\vartheta - 3\Lambda}{1+\Lambda}\,, \quad \lambda'_\varphi = \frac{\lambda_\varphi + \Lambda}{1+\Lambda}\,,$$

$$\lambda'_{\vartheta\varphi} = \frac{\lambda_{\vartheta\varphi}\cos 2\delta - \frac{1}{2}\,(\lambda_\vartheta - \lambda_\varphi)\sin 2\delta}{1+\Lambda}\,,$$

$$\text{with} \quad \Lambda = \frac{1}{2}\,(\lambda_\vartheta - \lambda_\varphi)\sin^2\delta - \frac{1}{2}\,\lambda_{\vartheta\varphi}\sin 2\delta\,.$$

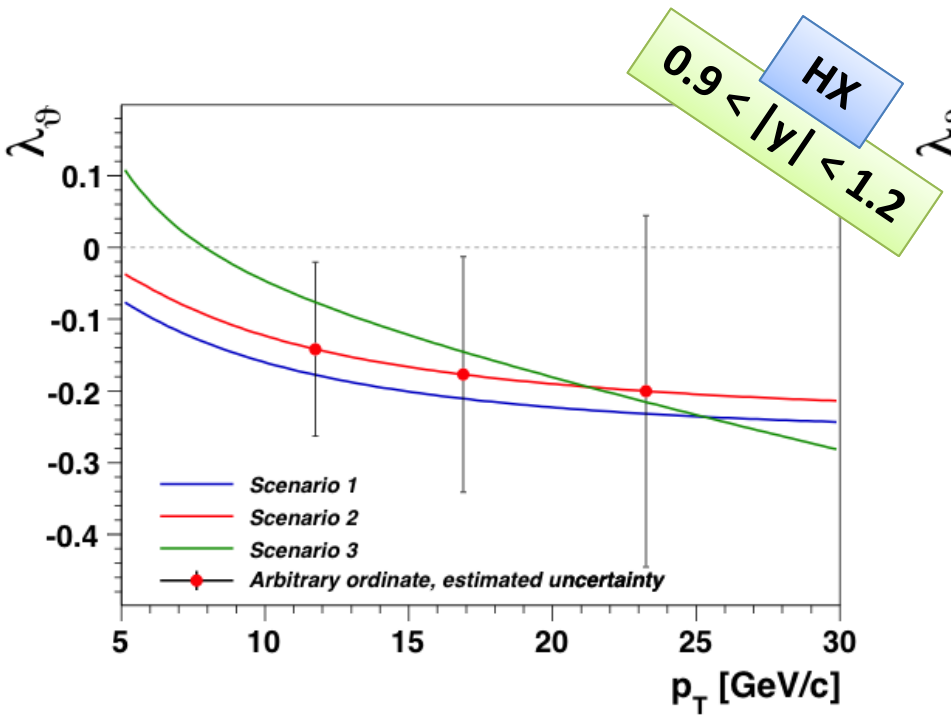
With this production kinematic dependence

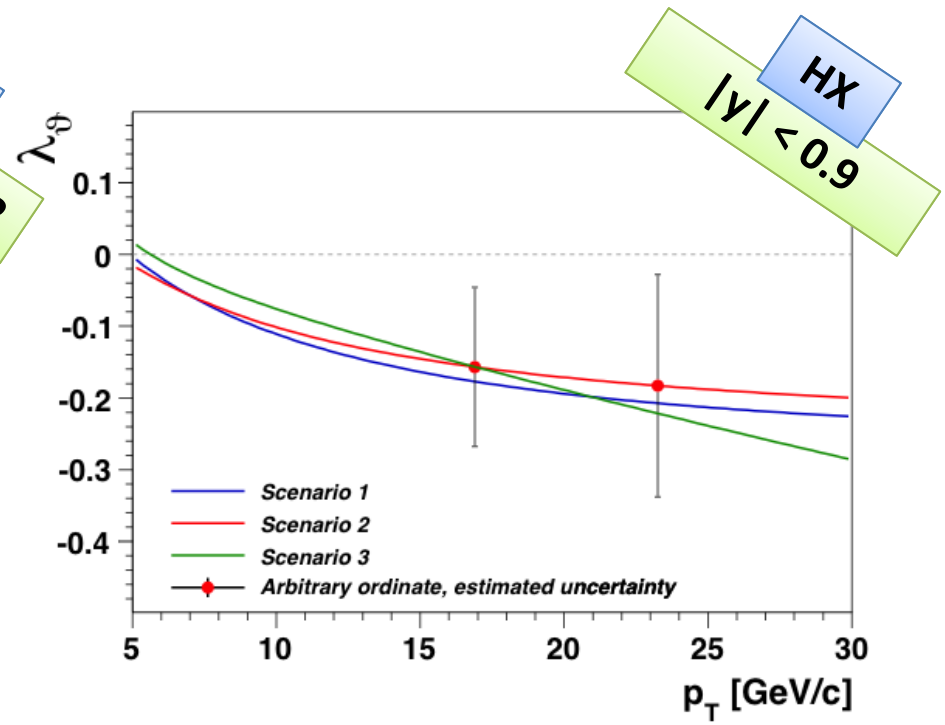
$$\begin{aligned} \sin^2\delta_{\mathrm{HX}\to\mathrm{CS}} \;&=\; \sin^2\delta_{\mathrm{CS}\to\mathrm{HX}} \;=\; \frac{p_{\mathrm{T}}^2\,E^2}{p^2\,m_{\mathrm{T}}^2}\,, \\ \sin 2\delta_{\mathrm{HX}\to\mathrm{CS}} \;&=\; -\sin 2\delta_{\mathrm{CS}\to\mathrm{HX}} \;=\; \frac{2\,m\,p_{\mathrm{T}}\,p_{\mathrm{L}}\,E}{p^2\,m_{\mathrm{T}}^2}\,, \end{aligned}$$

Angle Between frames constrained by

$$\begin{aligned} \cos\tau \;&=\; \frac{\frac{1}{\gamma}\cos\Theta}{\sqrt{\frac{1}{\gamma^2}\cos^2\Theta + \sin^2\Theta}} \;=\; \frac{m\,p_{\mathrm{L}}}{m_{\mathrm{T}}\,p}\,, \\ \sin\tau \;&=\; \frac{\sin\Theta}{\sqrt{\frac{1}{\gamma^2}\cos^2\Theta + \sin^2\Theta}} \;=\; \frac{E\,p_{\mathrm{T}}}{m_{\mathrm{T}}\,p}\,. \end{aligned}$$

λ_ϑ uncertainties



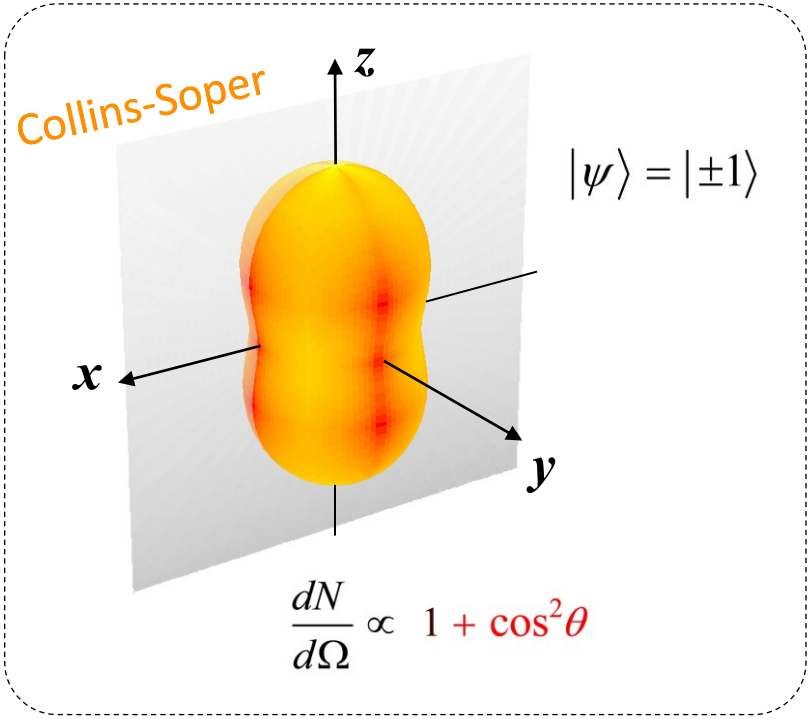


The observed polarization depends on the frame

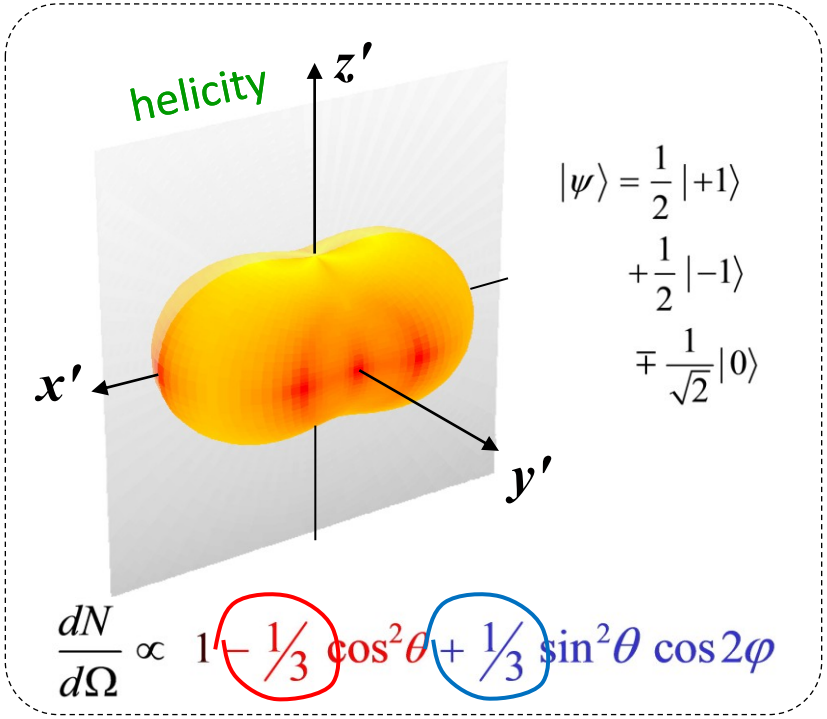
CS ⊥ HX

for mid rap. / high p_T

($p_T >> |p_L|$)



90º

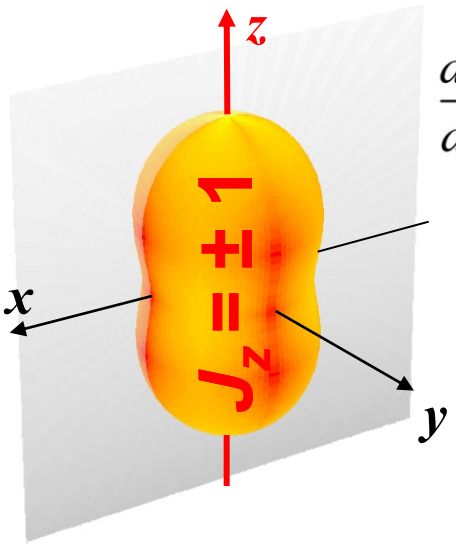


$$\lambda_\vartheta = +1 \qquad \lambda_\varphi = 0$$

$$\lambda_\vartheta = -1/3 \qquad \lambda_\varphi = +1/3$$

The azimuthal anisotropy is not a detail

Case 1: natural transverse polarization

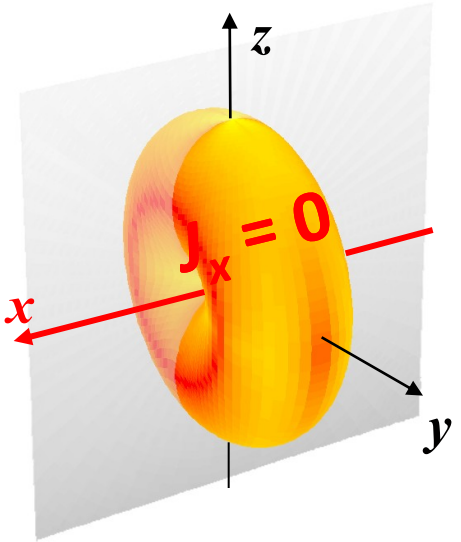


$$\frac{dN}{d\Omega} \propto 1 + \cos^2\theta$$

$\lambda_\vartheta = +1$

$\lambda_\varphi = 0$

Case 2: natural longitudinal polarization, observation frame ⊥ to the natural one



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

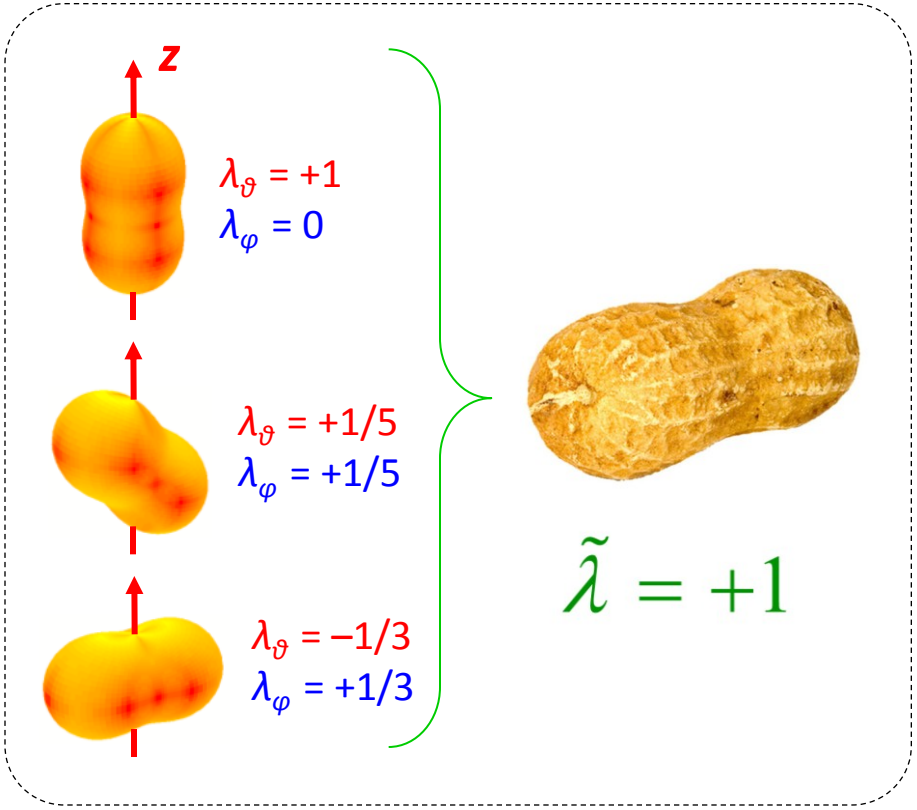
$\lambda_\vartheta = +1$

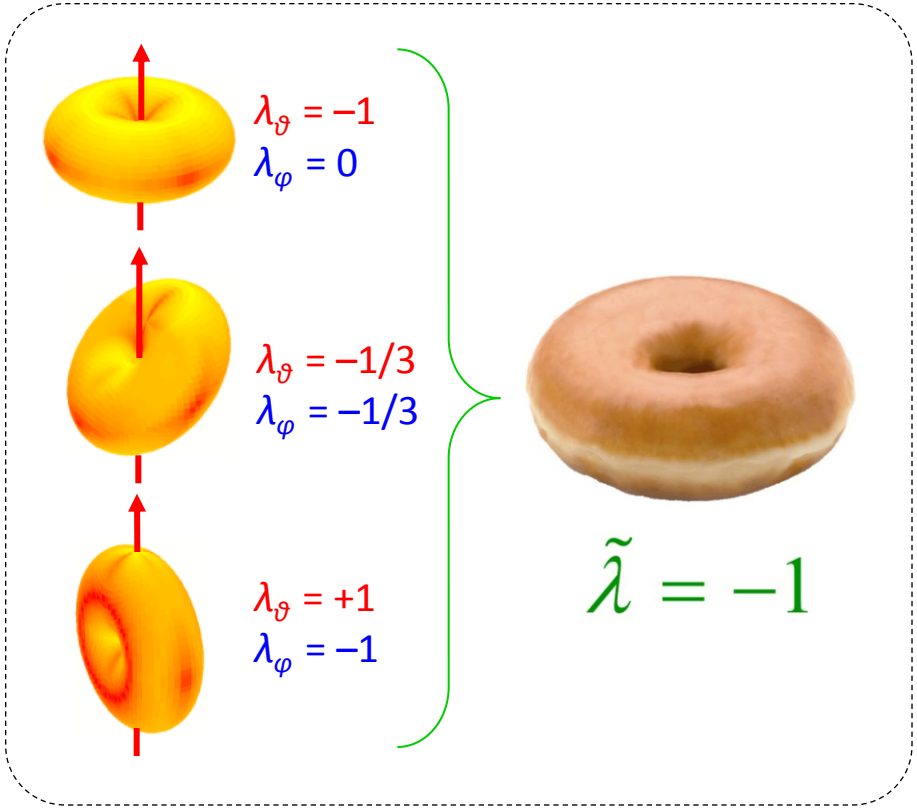
$\lambda_\varphi = -1$

- Two very different physical cases
- Indistinguishable if λ_φ is not measured (integration over φ)

Frame-independent polarization

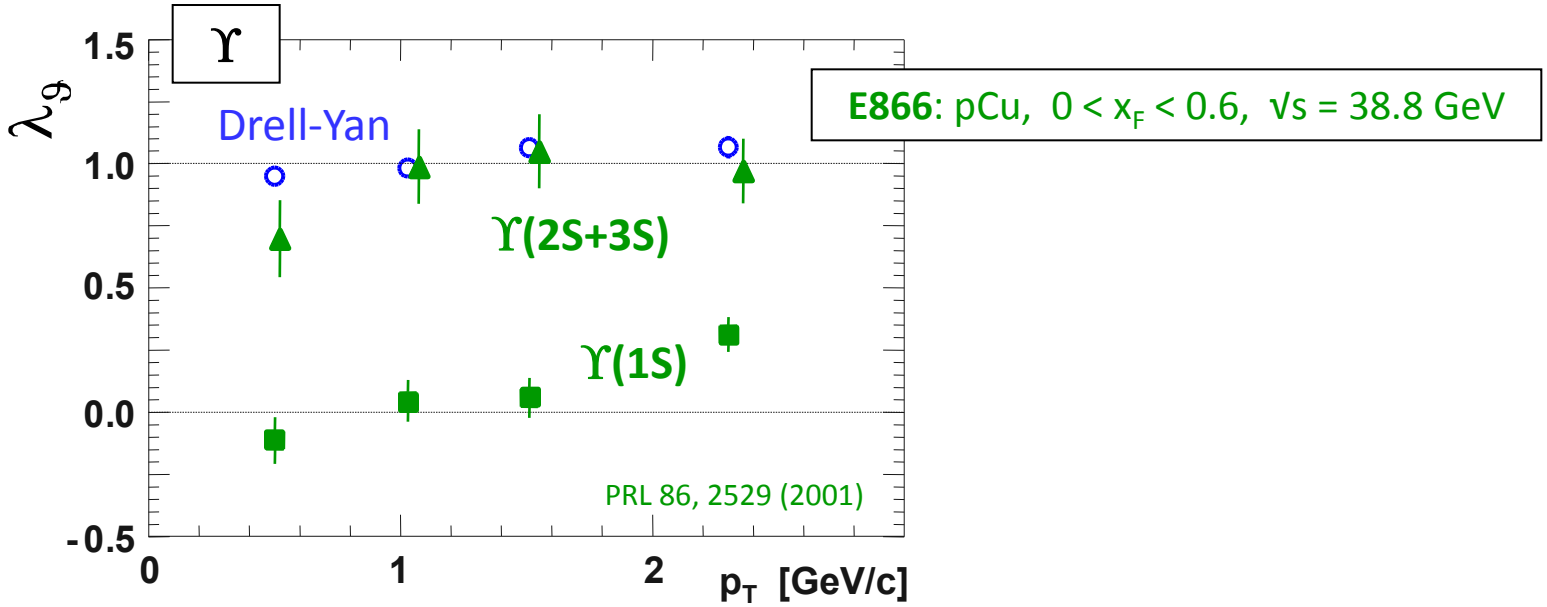
The ***shape*** of the distribution is obviously frame-invariant.
→ it can be characterized by a frame-independent parameter, e.g. $\tilde{\lambda} = \dfrac{\lambda_\vartheta + 3\lambda_\varphi}{1 - \lambda_\varphi}$





FLSW, PRL 105, 061601; PRD 82, 096002; PRD 83, 056008

Experimental puzzles: ϒ in proton-nucleus



- **E866** → (≈ directly produced) ϒ(2S+3S) have same polarization as Drell-Yan (***Collins-Soper*** *frame*!)
- E866 **ϒ(1S)** vs **ϒ(2S+3S)**
  → dominant *feed-down* effects for ϒ(1S)?

Clearest experimental signature !
What indications on ϒ production?