Quarkonium polarization measurements

Challenges and opportunities

PLB 840 (2023) 137871

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22. May 2024

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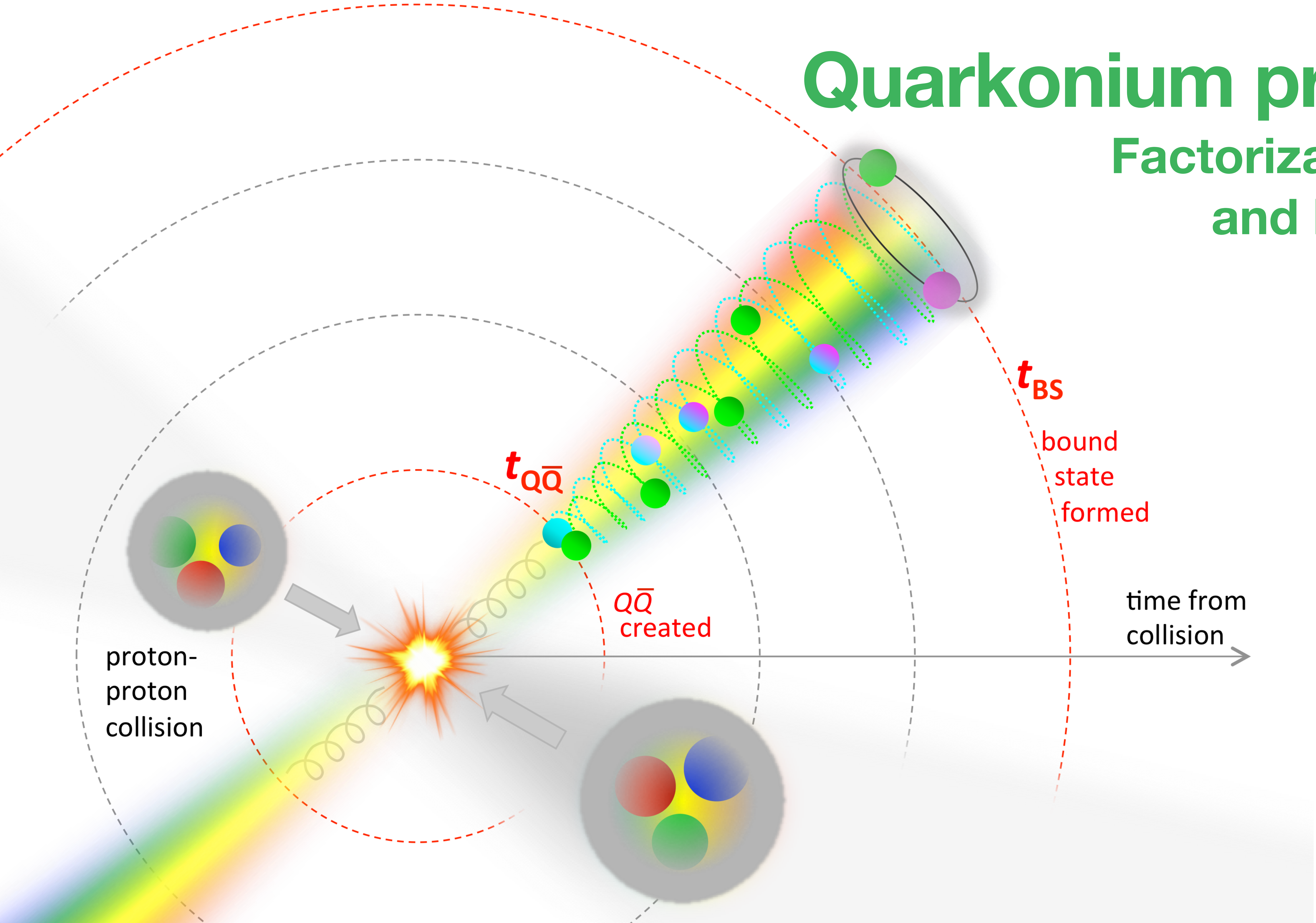
Quarkonium production

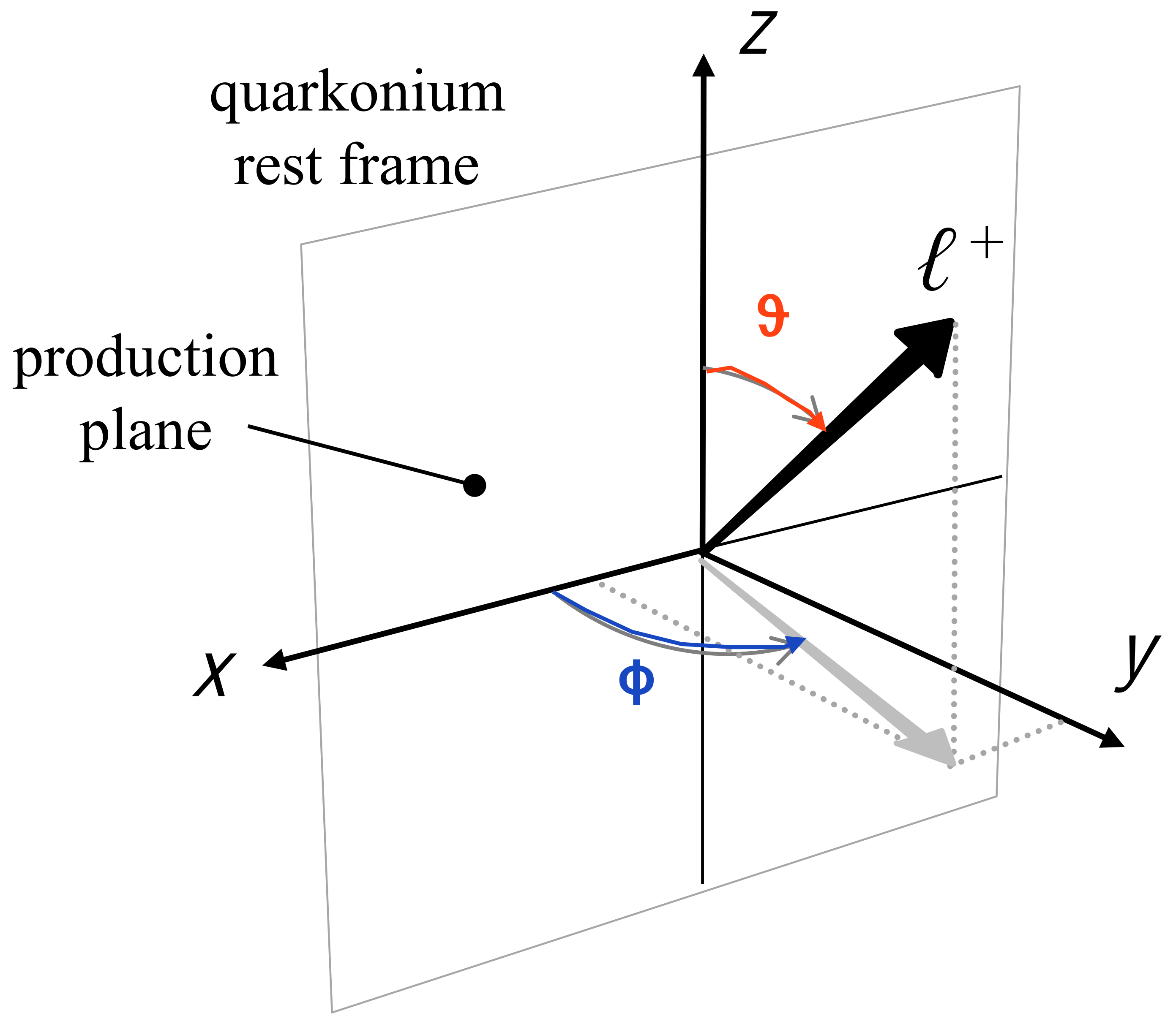
Factorization of short- and long-distance effects



Quarkonium polarization

- Directly reflects mixture of pre-resonance configurations
- Is measured through the angular decay distribution wrt a quantization axis z

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

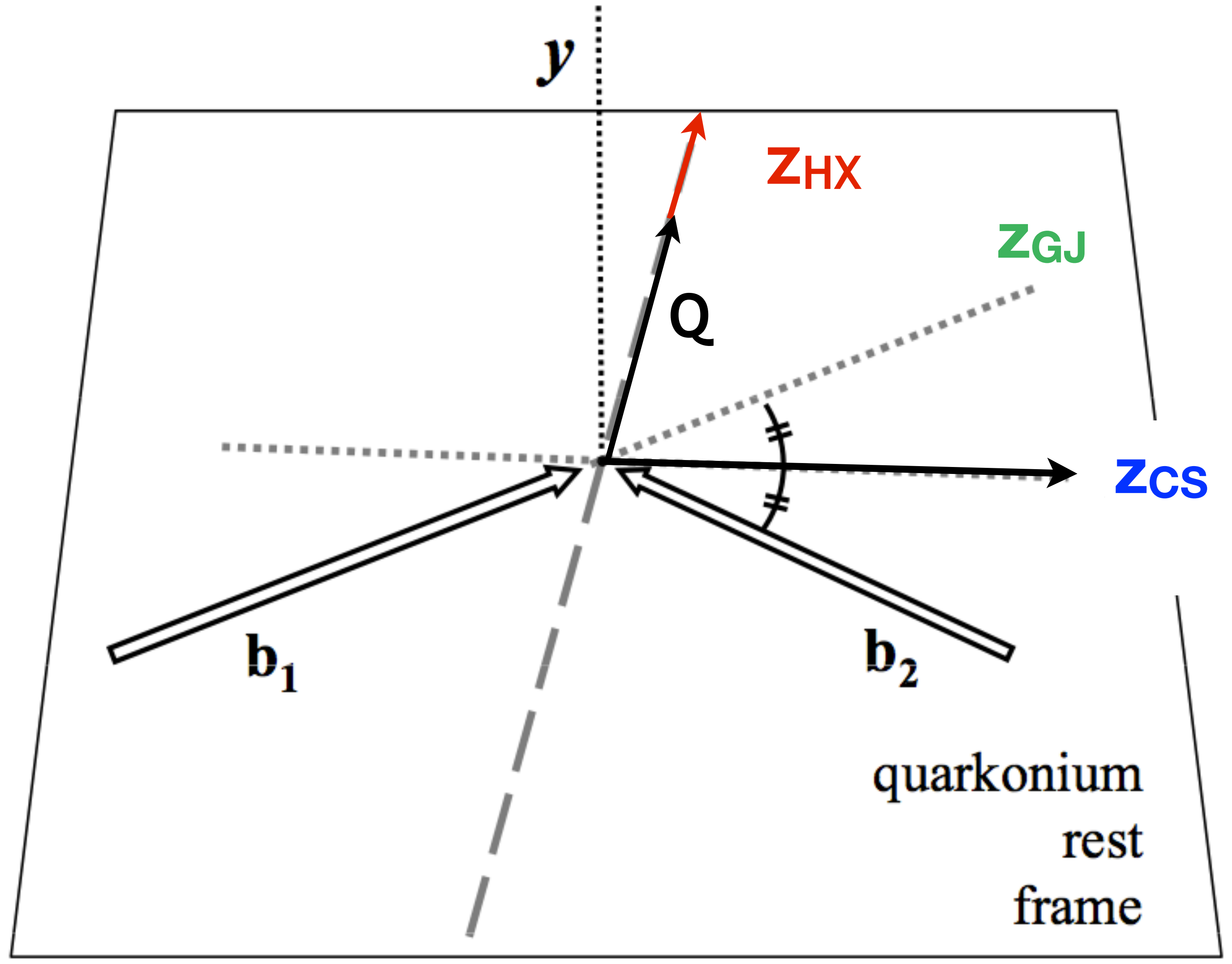


Reference frames:

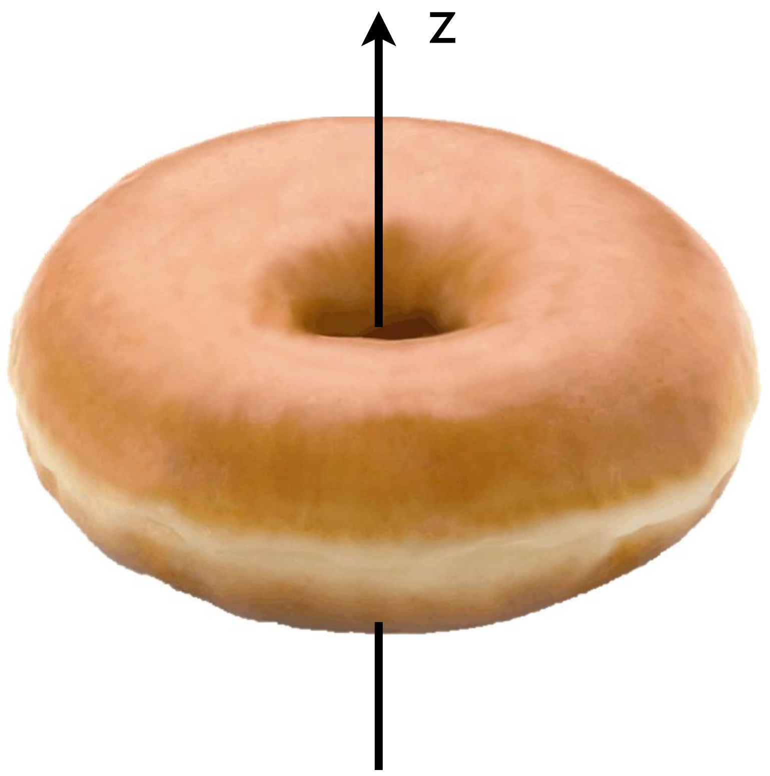
Center-of-mass helicity HX: z_{HX} ≈ direction of quarkonium momentum

Gottfried-Jackson GJ: z_{GJ} = direction of one beam or the target

Collins-Soper CS: z_{CS} ≈ direction of relative velocity of colliding particles



Angular decay distributions



Longitudinal polarization
$J_z = 0$

$\lambda_\vartheta = -1$

$\lambda_\varphi = 0$

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

No polarization/
isotropic decay

$\lambda_\vartheta = 0$

$\lambda_\varphi = 0$

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

Transverse
polarization
$J_z = \pm 1$

$\lambda_\vartheta = +1$

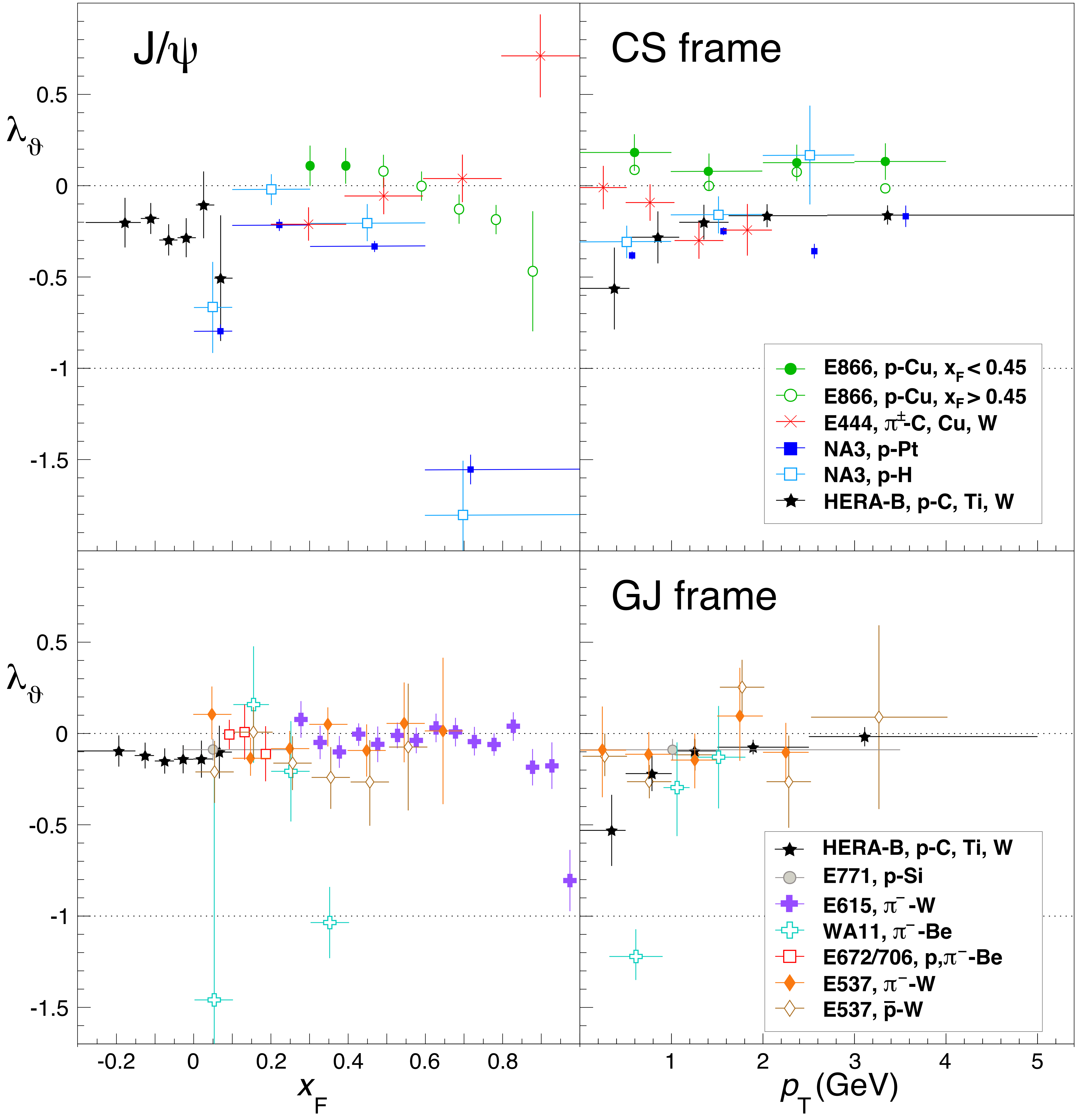
$\lambda_\varphi = 0$

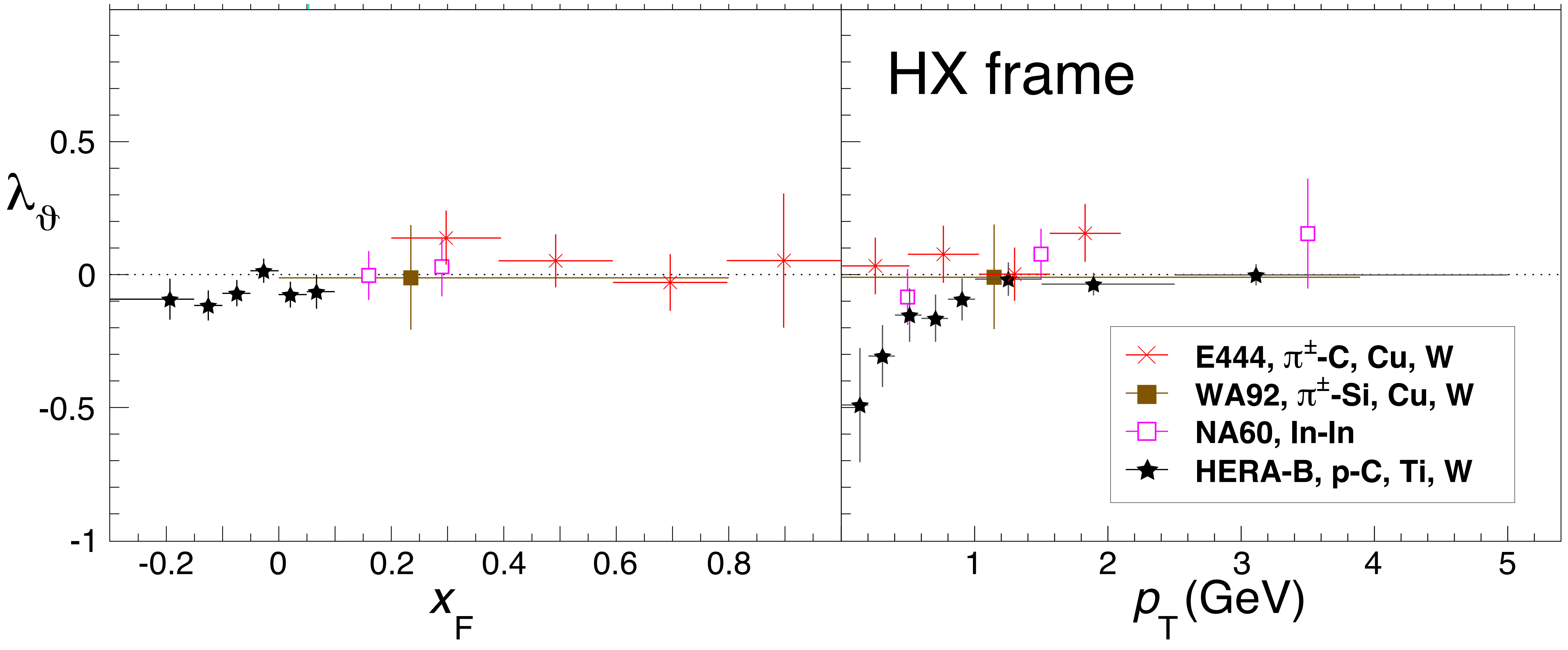
$\lambda_{\vartheta\varphi} = 0$

The shape of the distribution is invariant and can be characterized by the frame-independent quantity $\tilde{\lambda} = (\lambda_\vartheta + 3\lambda_\varphi)/(1 - \lambda_\varphi)$

Measurements

in fixed-target experiments with several beam particles, target nuclei and collision energies





Indications from existing measurements

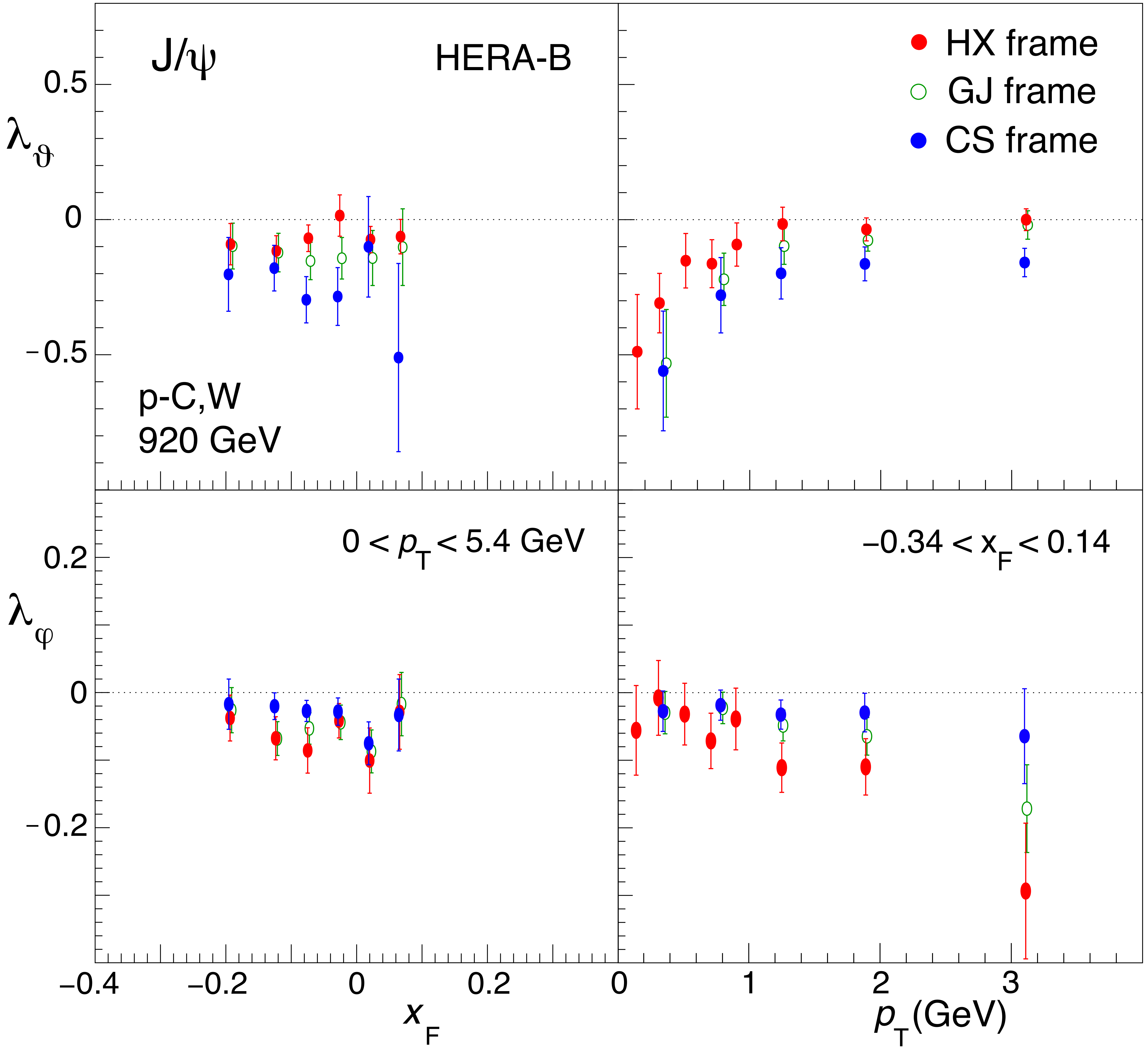
1. Hierarchy in λ_θ and λ_ϕ parameters:
   CS - GJ - HX

➡ CS axis more naturally reflects the alignment of the J/ψ angular momentum

➡ Quarkonium production is dominated by 2-to-1 processes, where the produced state is strongly polarized:

- gg → Q fully longitudinally polarized
- $q\bar{q}$ → Q fully transversely polarized

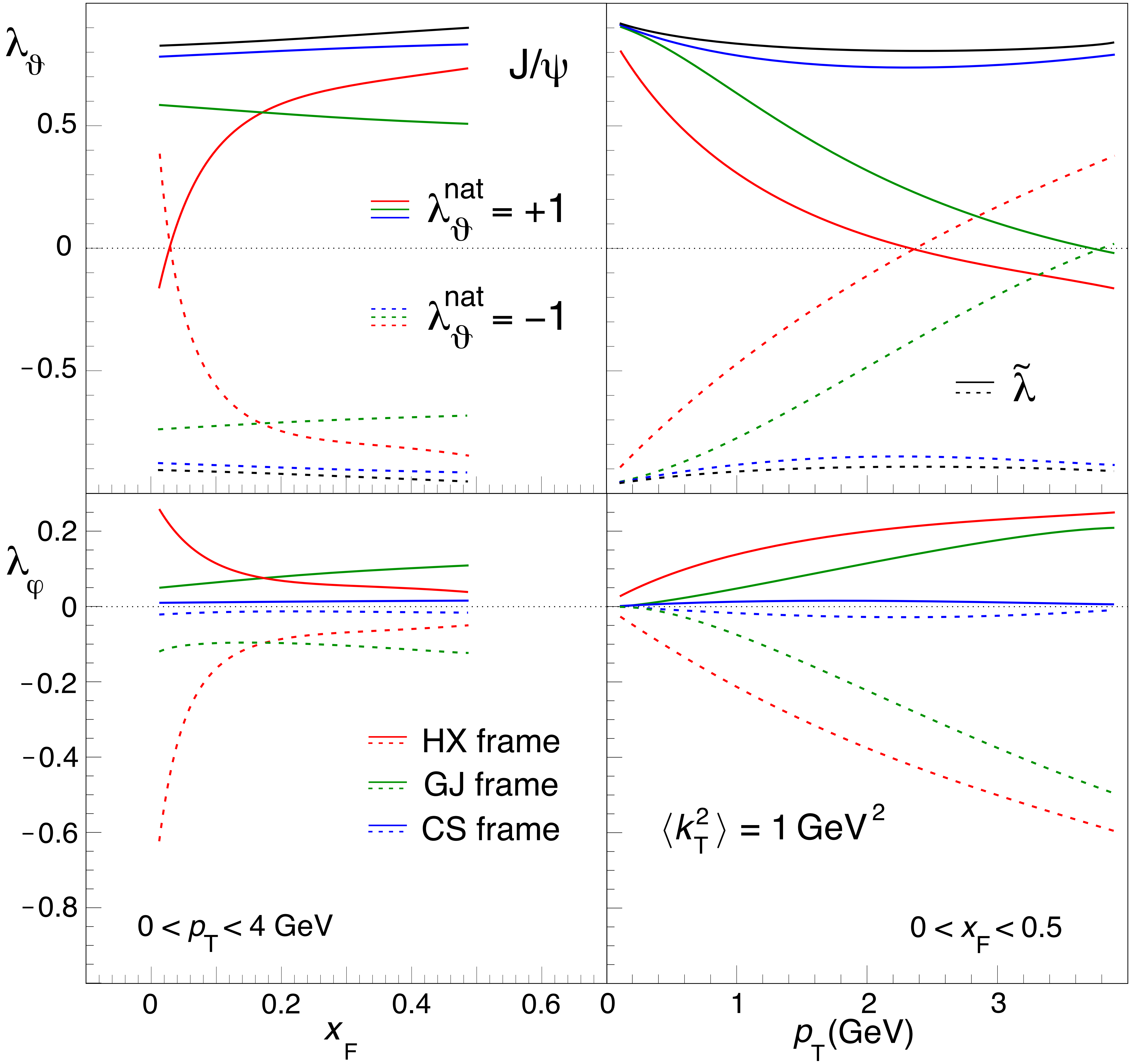
for directly produced quarkonia along the natural polarization axis
(PRD 83 (2011) 056008)



Indications from existing measurements

2. Decreasing magnitude of polarization with increasing p_T

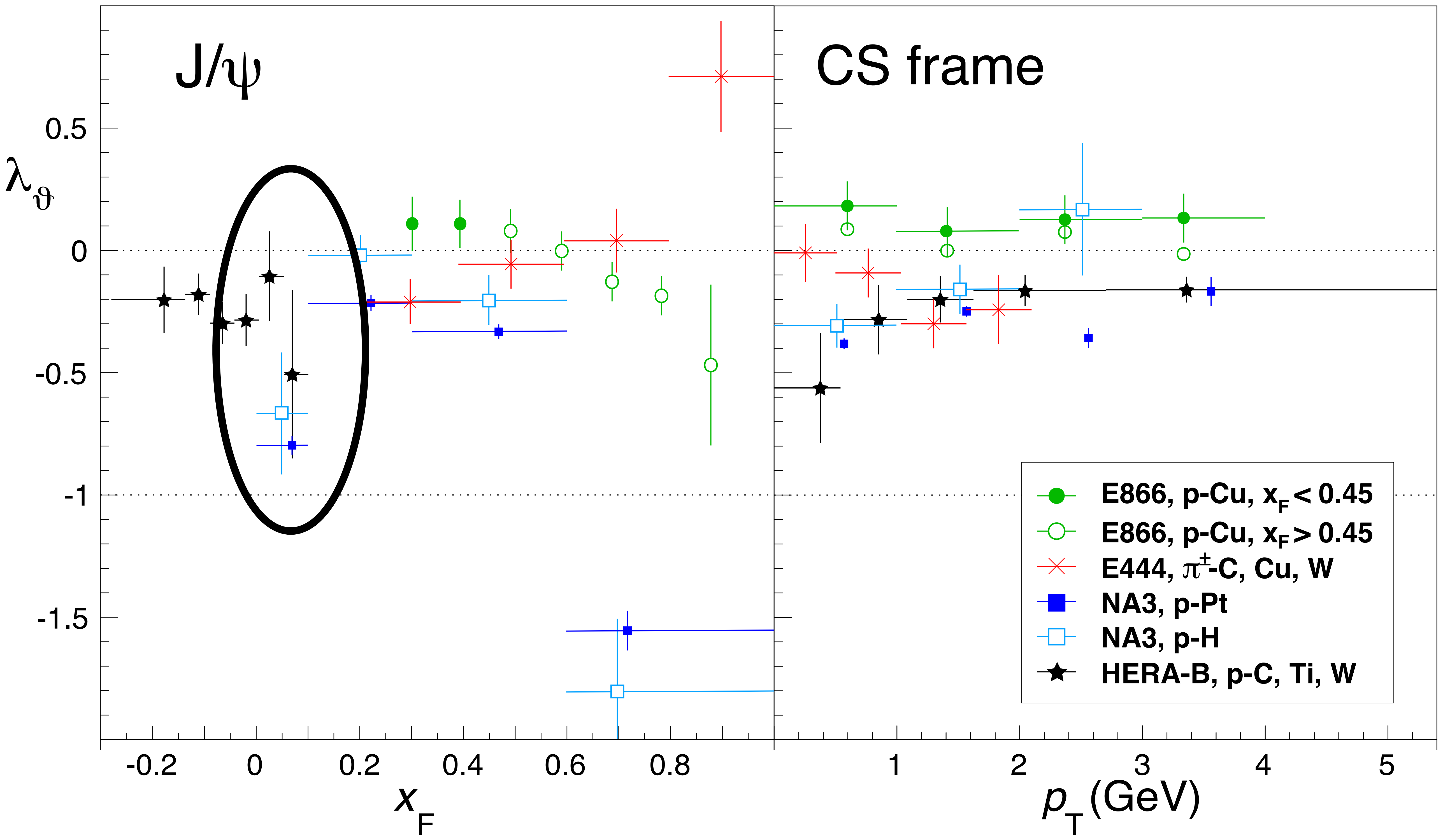
➡ Nonzero transverse momentum distribution of colliding partons has an effect for light quarkonia at low p_T and small x_F



Indications from existing measurements

3. More longitudinal J/ψ polarization at small x_F

➡ Relative dominance of gg fusion compared to $q\bar{q}$ annihilation at x_F close to 0



$q\bar{q}$ / gg ratios

pp and p-nucleus collisions

- $q\bar{q}$ and gg parton densities computed as the product of the corresponding PDFs using CT14NLO from LHAPDF and EPPS16
- Minimum of ratio around $x_F = 0$
- Nuclear effects are negligible
- $q\bar{q}$ annihilation is more important for heavier quarkonia

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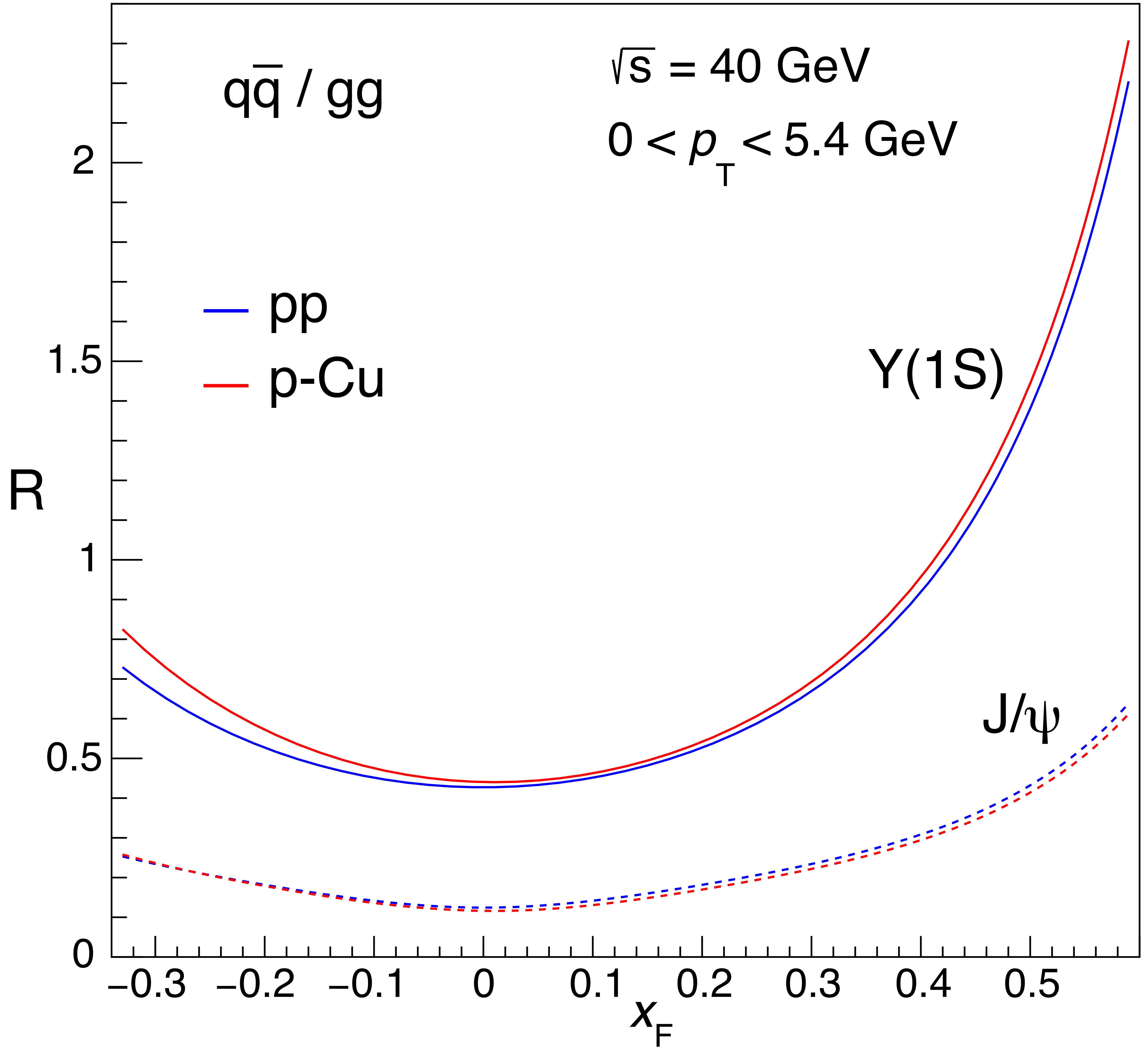


Empirical model

Assumptions

- Observed polarization of directly produced quarkonia results from the interplay between $q\bar{q}$ annihilation and gg fusion processes.
- Observable mixture of longitudinal (from gg) and transverse (from $q\bar{q}$) polarizations is fully determined by the product of two ratios:
  1. ratio between $q\bar{q}$ and gg parton densities, R
  2. ratio between $q\bar{q}$ and gg partonic cross sections, r
- Natural polarization parameter in parton-parton CS frame

$$\lambda = \frac{f_{q\bar{q}}\,\lambda^{q\bar{q}}/(3+\lambda_\vartheta^{q\bar{q}}) + f_{gg}\,\lambda^{gg}/(3+\lambda_\vartheta^{gg})}{f_{q\bar{q}}\,/(3+\lambda_\vartheta^{q\bar{q}}) + f_{gg}\,/(3+\lambda_\vartheta^{gg})}$$

according to sum rule in EPJC 69 (2010) 657

$$f_{q\bar{q}} = R \times r/(1+R\times r) \qquad f_{gg} = 1/(1+R\times r)$$

Feed-down from heavier quarkonium states

- S-wave states have the same polarization: $\psi(2S) \to J/\psi\pi\pi$ (PRD 62 (2000) 032002)

- P-wave states have different production mechanism due to emission of a transversely polarized gluon (PRD 83 (2011) 096001)

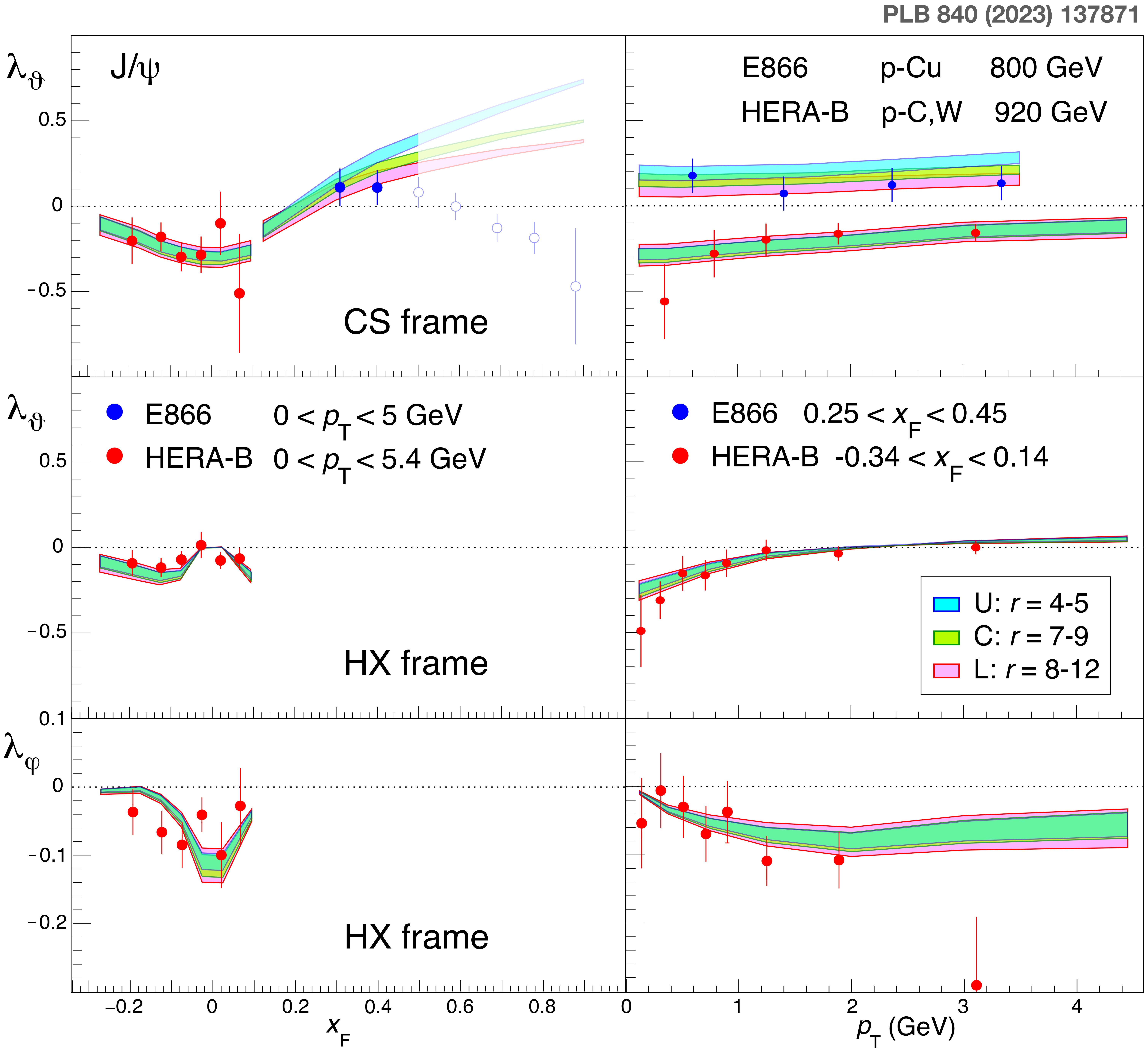
➡ Weaker polarization due to mixture from feed-down

- Total feed-down fraction from χ_c: 19% from HERAb (PRD 79 (2009) 012001)

		$\lambda_\vartheta^{\chi_1}$	$\lambda_\vartheta^{\chi_2}$
central, C	gg	$+1$	$-3/5$
	$q\bar{q}$	$-1/3$	$-1/3$
lower, L	gg, $q\bar{q}$	$-1/3$	$-3/5$
upper, U	gg, $q\bar{q}$	$+1$	$+1$

Results

p-nucleus collisions



r = ratio between qq̄ and gg partonic cross section

$q\bar{q}$ / gg ratio
pion-nucleus collisions

- Significant differences for various pion PDFs because of poorly known gluon densities
- Negligible differences between positive and negative pions
- Nuclear effects have minor impact on x_F dependence

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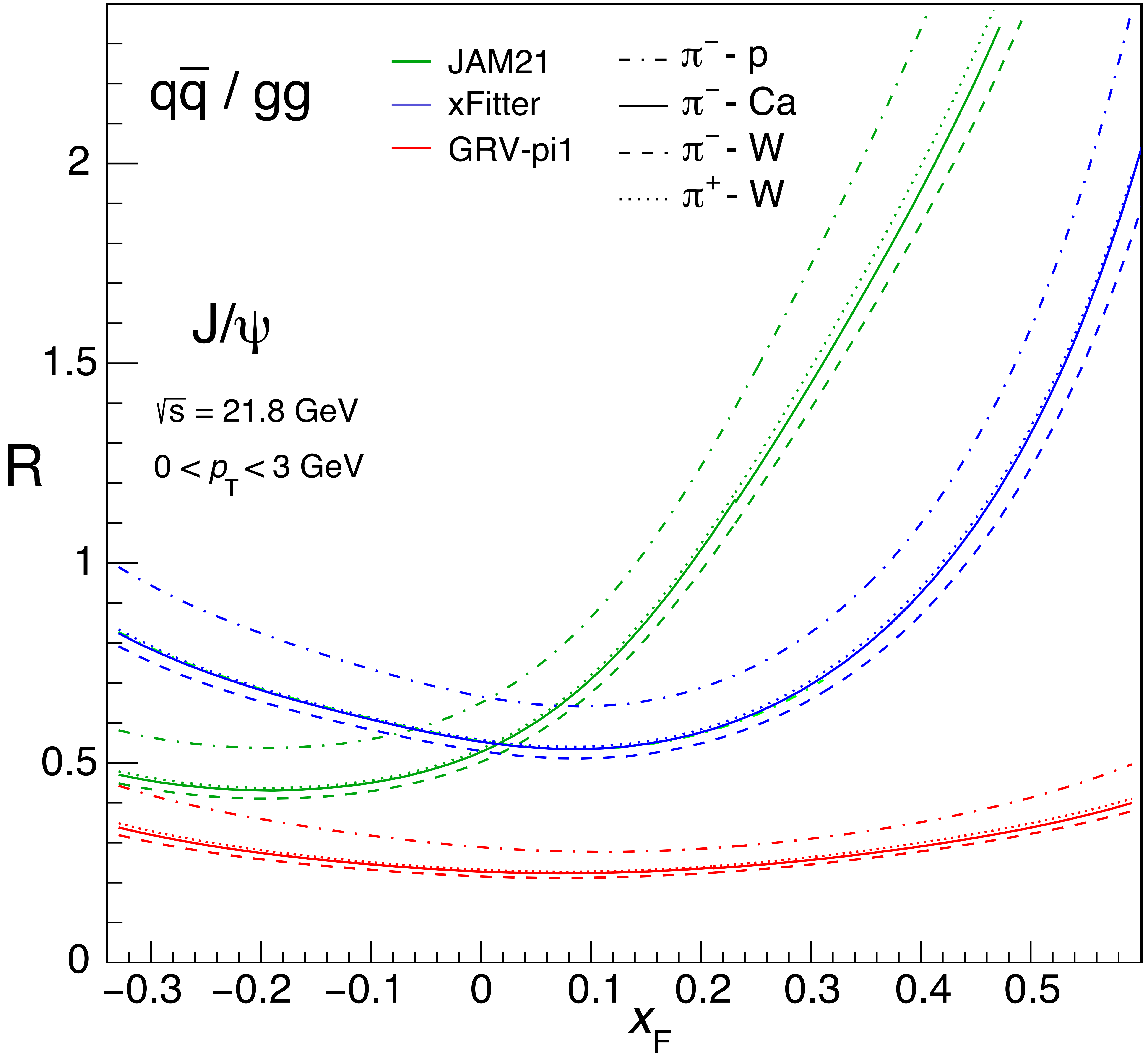
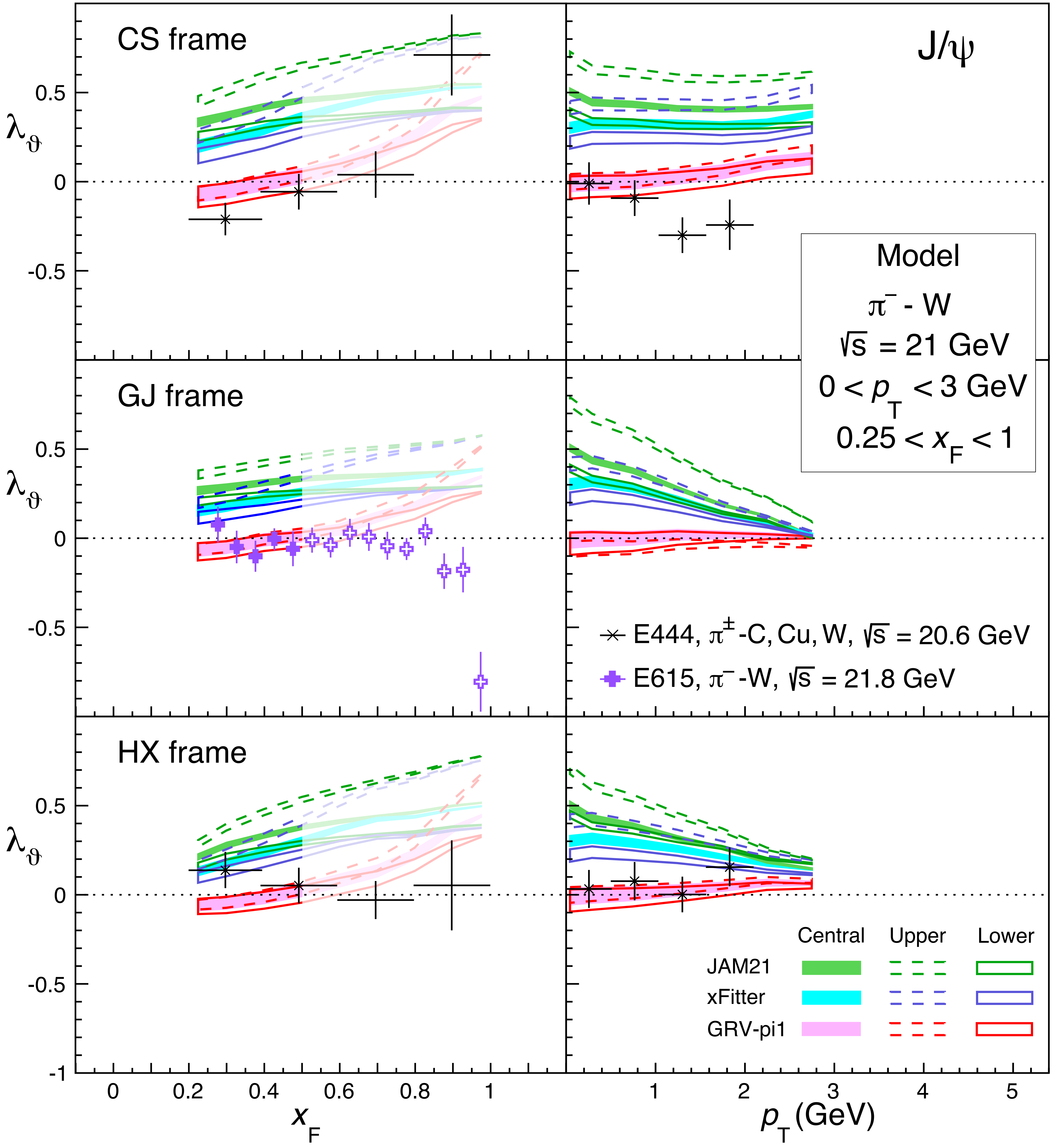


Results

Pion-nucleus collisions



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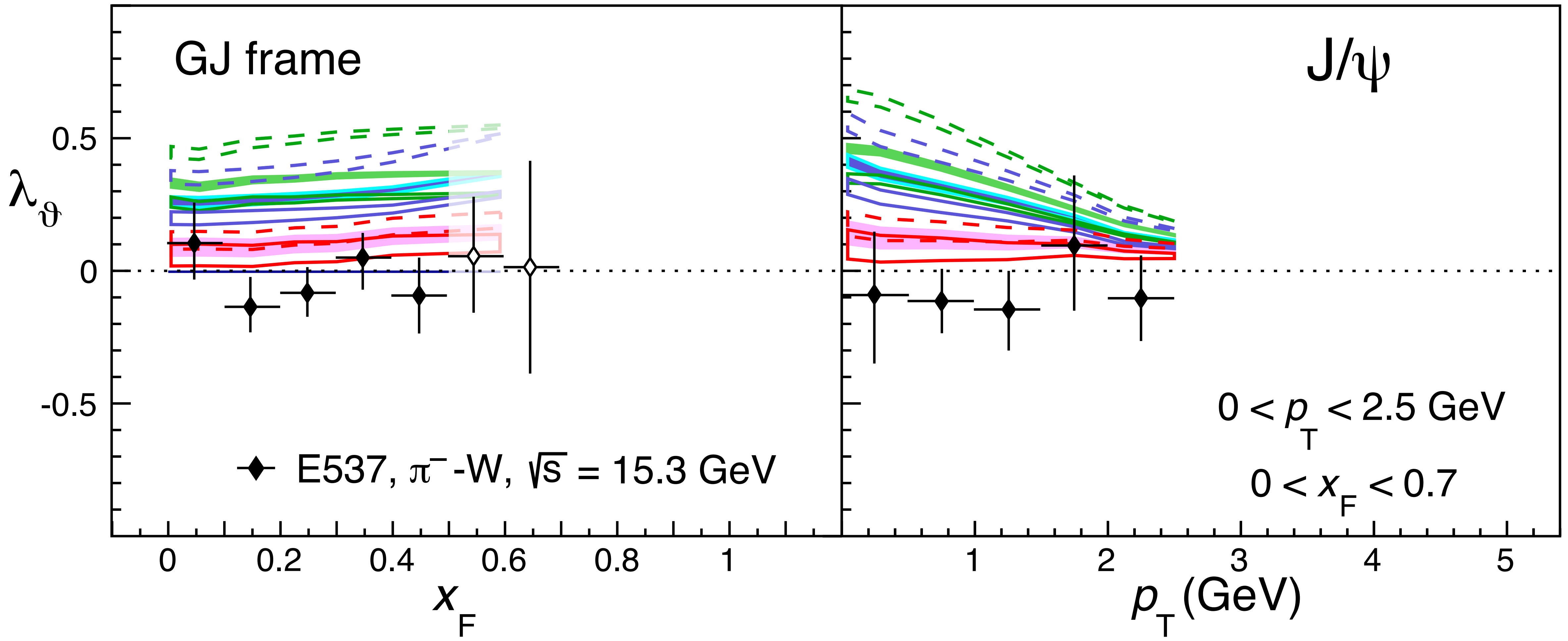

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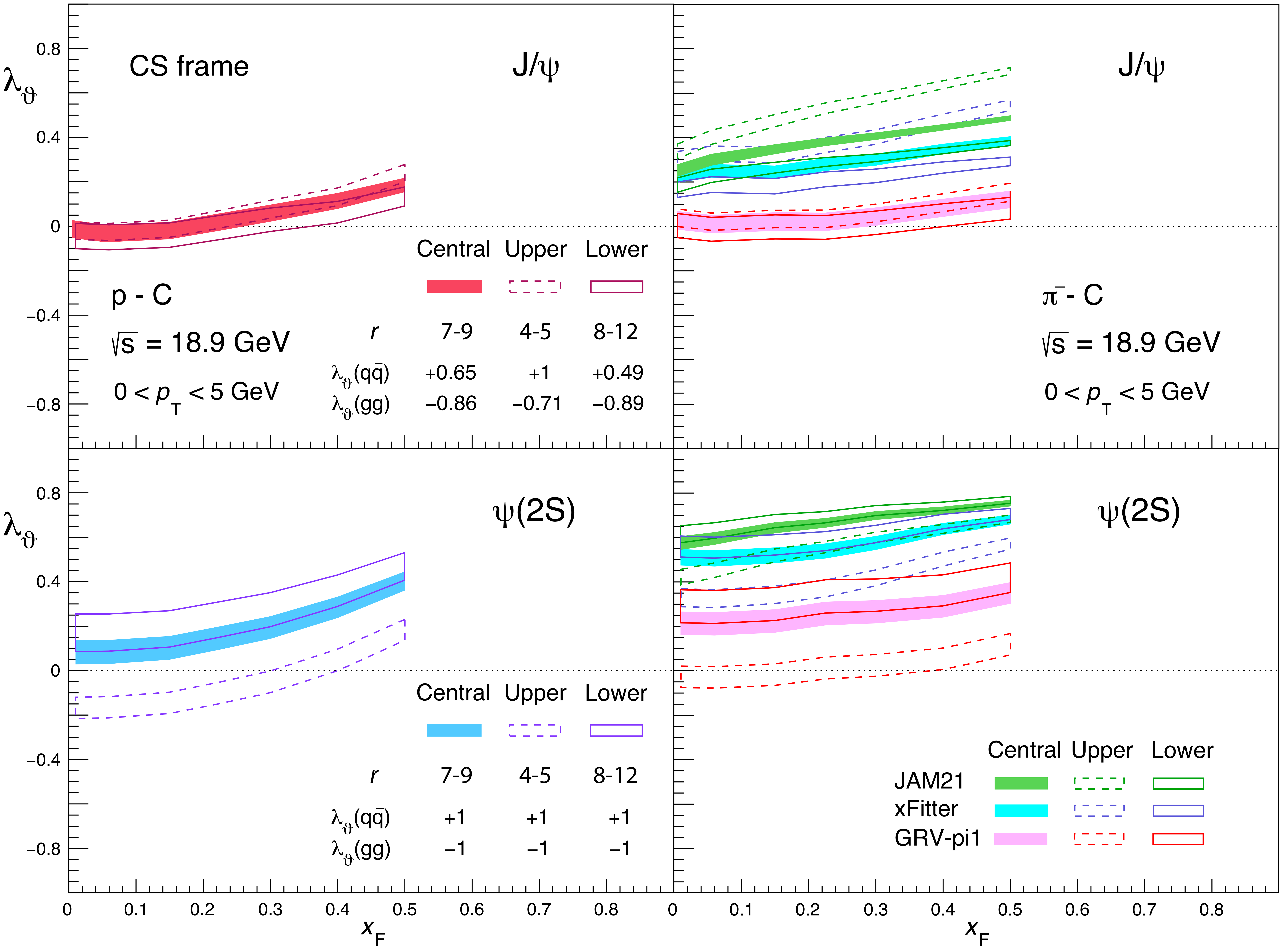
Predictions

AMBER
Apparatus for Meson and Baryon Experimental Research



Conclusions and summary

- Our simple model assumes that observed polarization results from the interplay between $q\bar{q}$ annihilation and gg fusion.
- Future polarization measurements in proton-nucleus collisions can test our model.
- The polarization observable has the potential to provide a strong constraint on the pion PDFs.
- $\psi(2S)$ polarization measurements are particularly interesting since there is no feed-down.

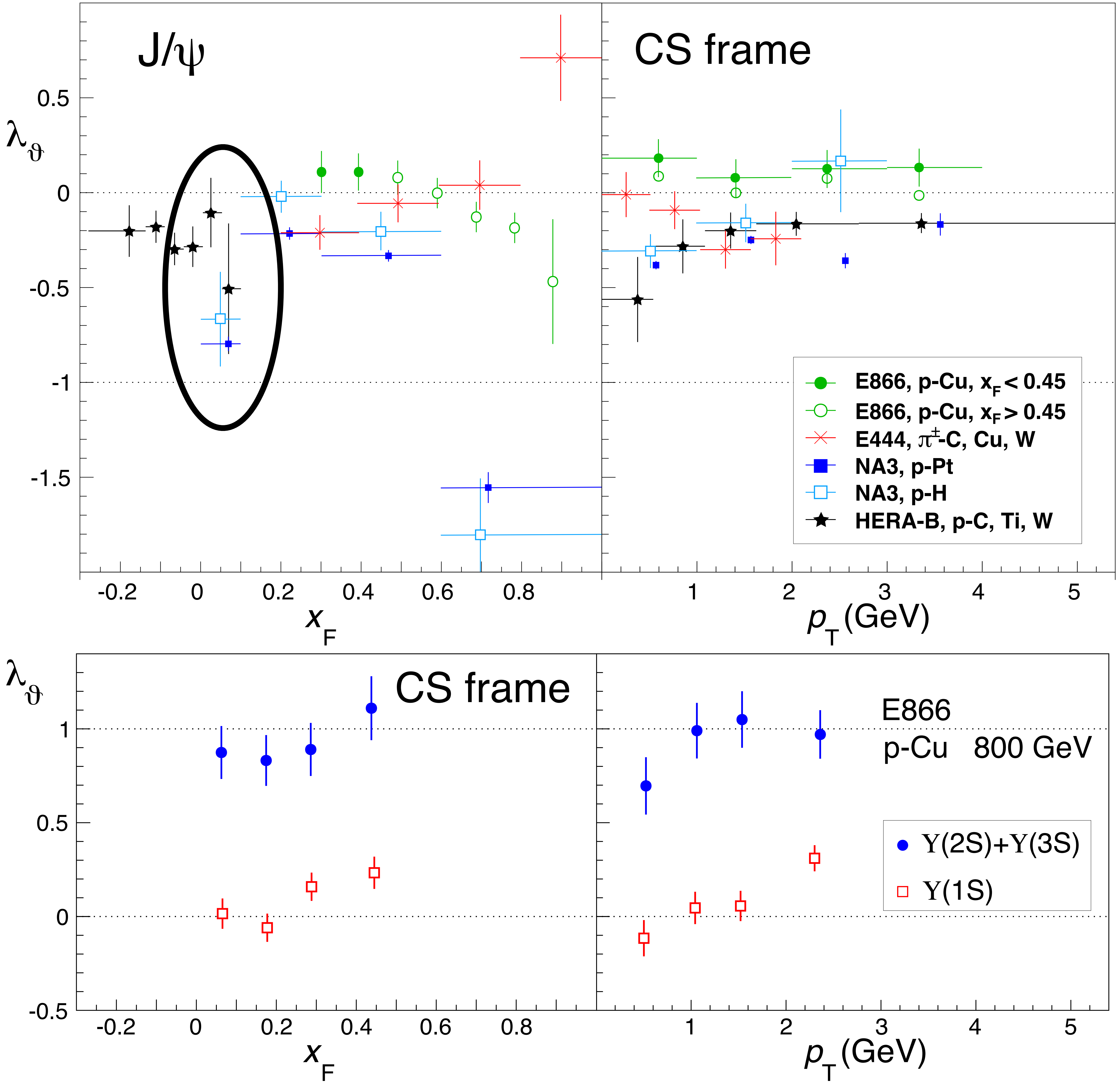
Further reading: “Particle Polarization in High Energy Physics”
https://link.springer.com/book/10.1007/978-3-031-08876-6

BACKUP

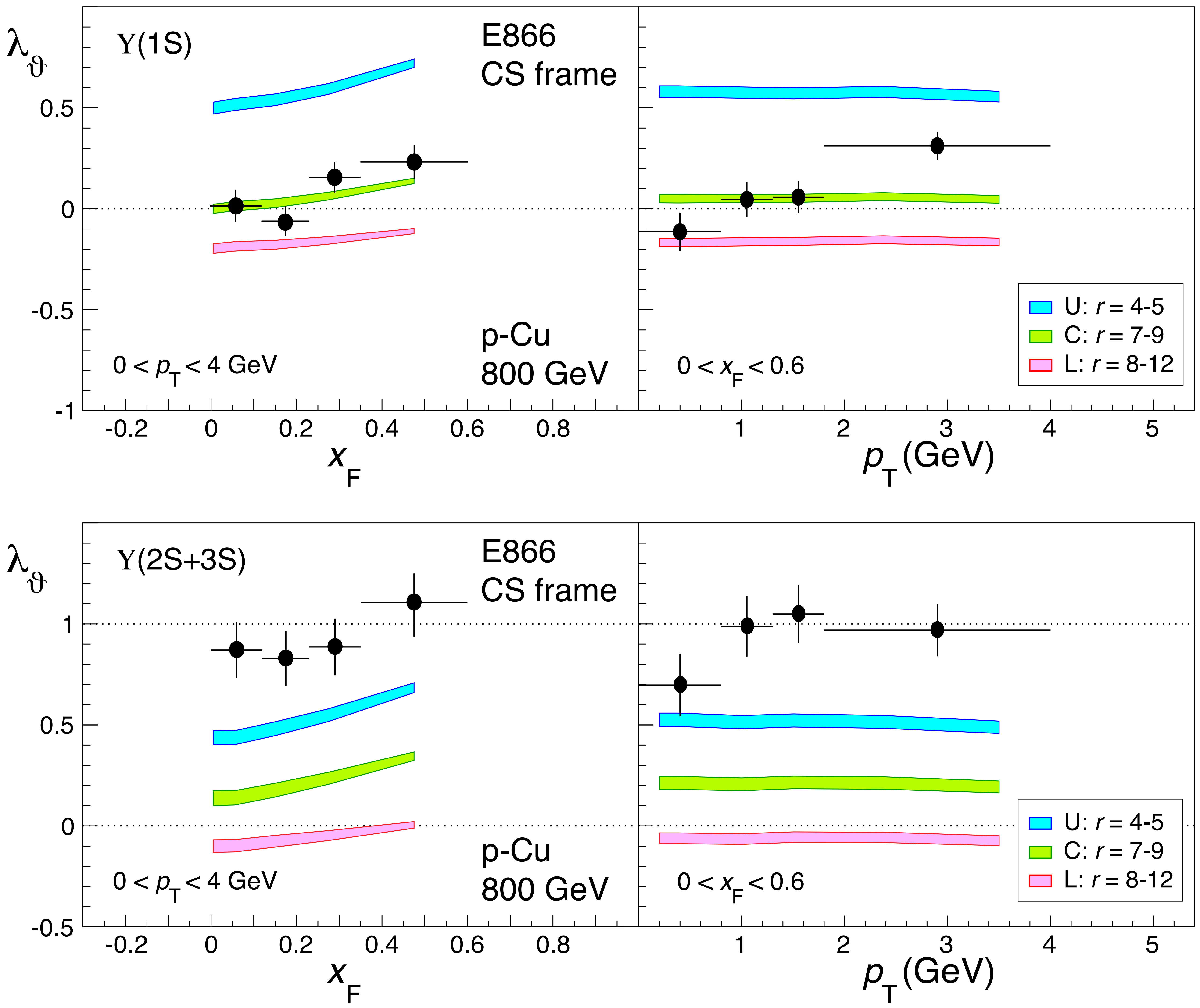
Indications from existing measurements

2. More longitudinal J/ψ polarization at small x_F

➡ Relative dominance of gluon-gluon fusion at mid-rapidity, qq annihilation is more relevant in more forward region



Results



λϑ
Υ(1S)
E866
CS frame
p-Cu
800 GeV
0 < pT < 4 GeV
0 < xF < 0.6
U: r = 4-5
C: r = 7-9
L: r = 8-12
xF
pT (GeV)
Υ(2S+3S)
E866
CS frame
p-Cu
800 GeV
0 < pT < 4 GeV
0 < xF < 0.6
U: r = 4-5
C: r = 7-9
L: r = 8-12
xF
pT (GeV)

Constraints