重夸克偶素产生机制：现状及未来

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Outline

I. Introduction of quarkonium

II. NRQCD factorization and difficultities

III. Recent progresses

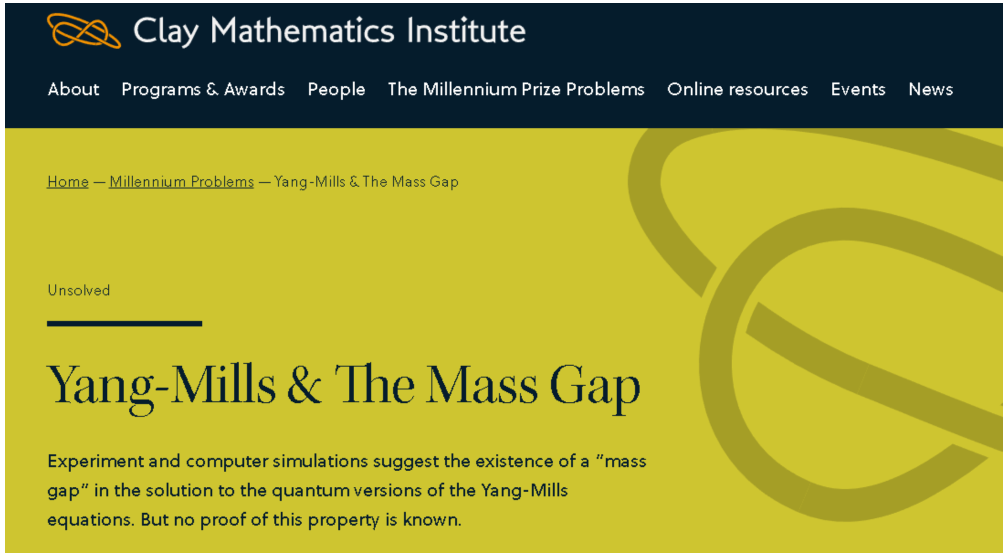
- Negative cross section
- Universality problem
- Question the heavy quark spin symmetry
- Double J/ψ and $X(6900)$
- Quarkonium energy correlator

IV. Summary

Confinement and hadronization

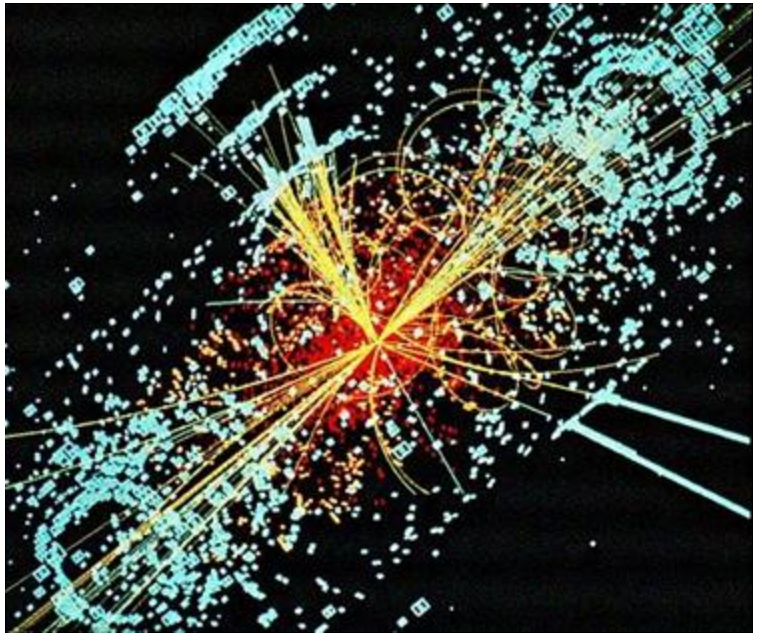
➢ Confinement

- 1/7 millennium prize problems in 21st century
- Not yet understood
- Equivalent: why and how produced quarks and gluons become hadrons?



➢ Hadronization

- Light hadrons: factorization → fragmentations functions, do not know how to compute
- Heavy quarkonium: localized color charge, perturbative QCD can help, the simplest system
- HQ production: near 50 years after the discovery, still not well understood



Velocity of heavy quarks in quarkonium

- Coulomb potential between color singlet heavy quark pair:

$$V(r) = -C_F \frac{\alpha_s(1/r)}{r}$$

- Virial theorem:

$$mv^2 \sim V(r) \sim \frac{\alpha_s(1/r)}{r}$$

- Uncertainty principle:

$$r \sim \frac{1}{mv}$$

- Velocity is determined by quark mass

$$\alpha_s(mv) \sim mv^2\, r \sim v$$

Properties

- **A non-relativistic QCD system:** $v^2 \ll 1$
  - **Charmonium:** $\mathrm{m}\sim 1.3\mathrm{Ge}V,\ v^2 \approx 0.3$
  - **Bottomonium:** $m\sim 4.5GeV,\ v^2 \approx 0.1$

- **Multiple well-separated scales :**
  - **Quark mass:** M
  - **Momentum:** $\mathrm{M}v$
  - **Energy:** Mv^2

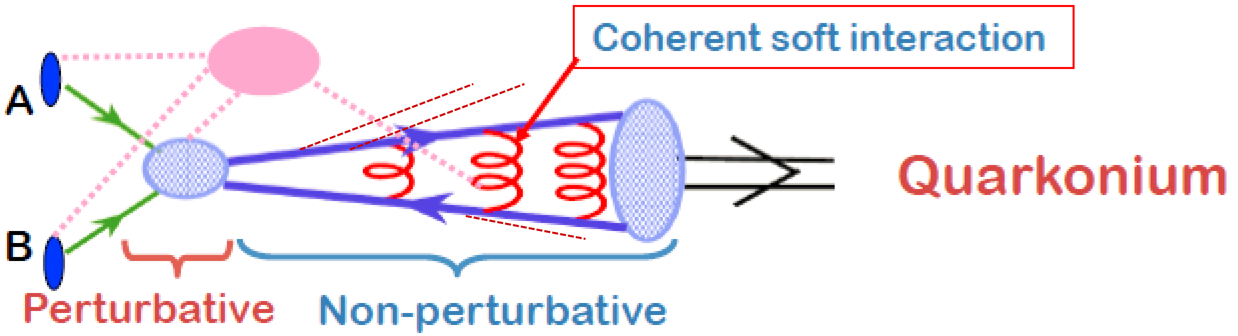
  $\mathrm{M} \gg \mathrm{Mv} \gg \mathrm{Mv}^2 \sim \boldsymbol{\Lambda}_{\mathbf{QCD}}$

- **Involving both perturbative and nonperturbative physics**

- **Production is ideal to understand hadronization: why and how quarks become hadrons?**

Space-time picture for production

- Hadronization followed by production of an off-shell heavy quark pair



$$\Delta r \sim \frac{1}{2m}, \quad \frac{1}{m\,v}, \quad \frac{1}{m\,v^2}$$

- Time scale for producing heavy quark pair: $\frac{1}{2\,m}$
- Time scale for expansion: $\frac{1}{m\,v}$
- Time scale for forming bound state: $\frac{1}{m\,v^2}$

Approximation

➢ On-shell pair + hadronization

$$\sigma_{AB\to H+X} = \sum_n \int_n d\Gamma_{(Q\bar{Q})_n} \left[\frac{d\hat{\sigma}(Q^2)}{d\Gamma_{(Q\bar{Q})_n}}\right] F_{(Q\bar{Q})_n\to H}(p_Q, p_{\bar{Q}}, P_H)$$

- Needs justification
- Corrections are at higher order in v, may need to consider
- Different assumptions/treatments on how the heavy quark pair becomes a heavy quarkonium: different factorization methods

Theories for $p_T \sim m$

1. 1975 – CSM&CEM

- CSM: IR div., ψ' surplus — Einhorn, Ellis (1975), Chang (1980) ...
- CEM: wrong for ratio — Fritzsch (1977), Halzen (1977) ...

  (Improved-CEM: helpful in some problems) — YQM, Vogt, 1609.06042

2. 1994 - NRQCD

Bodwin, Braaten, Lepage, 9407339

- Polarization puzzle; Universality problem; Hierarchy problem;

  Negative cross sections; ...

3. 2017- SGF

YQM, Chao, 1703.08402
Chen, YQM, 2005.08786

- Resum kinematic effects in NRQCD
- May resolve some problems

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NRQCD: factorization

➢ Factorization formula

Bodwin, Braaten, Lepage, 9407339

$$(2\pi)^3 2P_H^0 \frac{d\sigma_H}{d^3P_H} = \sum_n d\hat{\sigma}_n(P_H)\langle \mathcal{O}_n^H \rangle$$

Production of a heavy quark pair
Expansion in: α_s

Hadronization (LDMEs)
Expansion in: v

- n: quantum numbers of the pair: color, spin, orbital angular momentum, total angular momentum, spectroscopic notation ${}^{2S+1}L_J^{[c]}$

➢ A glory history

- Solved IR divergences in P-wave quarkonium decay
- Explained ψ' surplus
- Explained χ_{c2}/χ_{c1} production ratio
- ....

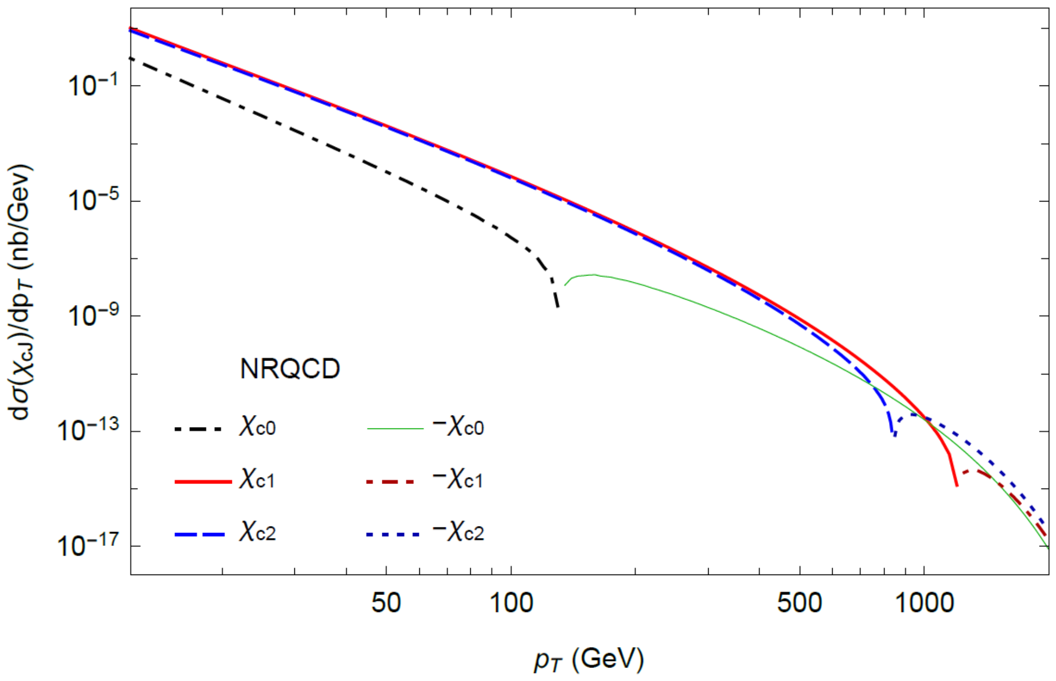
Thanks to color-octet mechanism

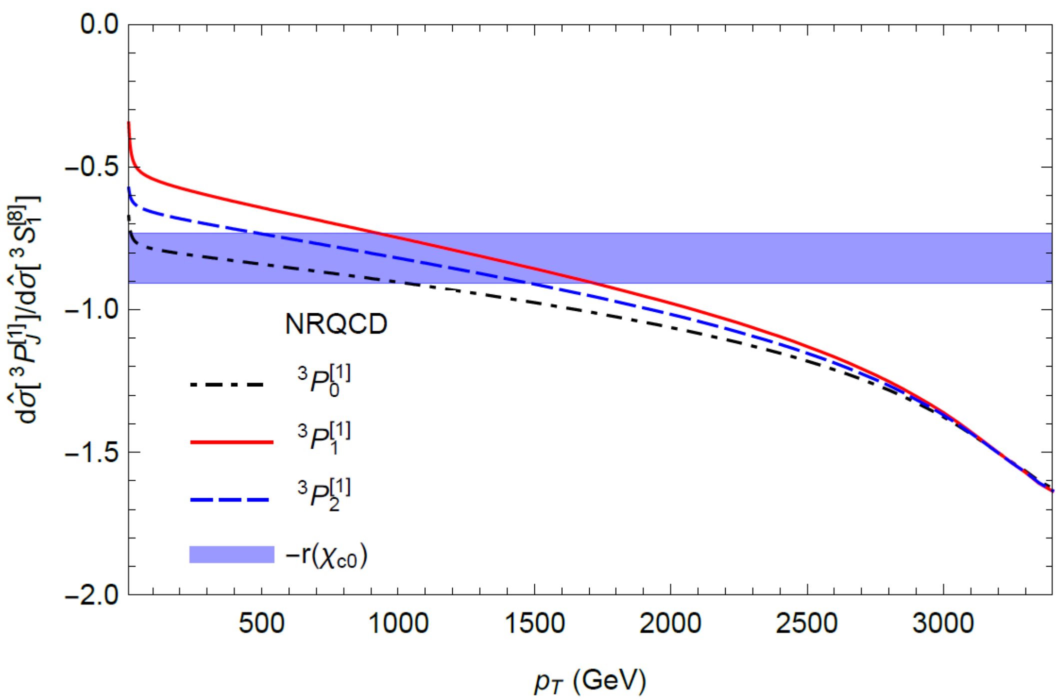
Negative differential cross sections

➢ **Cross sections become negative at exceptionally high p_T**

$$d\sigma(\chi_{cJ}) = (2J+1)\, d\hat{\sigma}[{}^3S_1^{[8]}]\, \frac{\langle \mathcal{O}^{\chi_{c0}}({}^3P_0^{[1]})\rangle}{m_c^2} \times \left[r(\chi_{c0}) + \frac{d\hat{\sigma}[{}^3P_J^{[1]}]}{d\hat{\sigma}[{}^3S_1^{[8]}]} \right].$$

$$r(\chi_{c0}) \equiv \frac{\langle \mathcal{O}^{\chi_{c0}}({}^3S_1^{[8]})\rangle}{\langle \mathcal{O}^{\chi_{c0}}({}^3P_0^{[1]})\rangle / m_c^2},$$





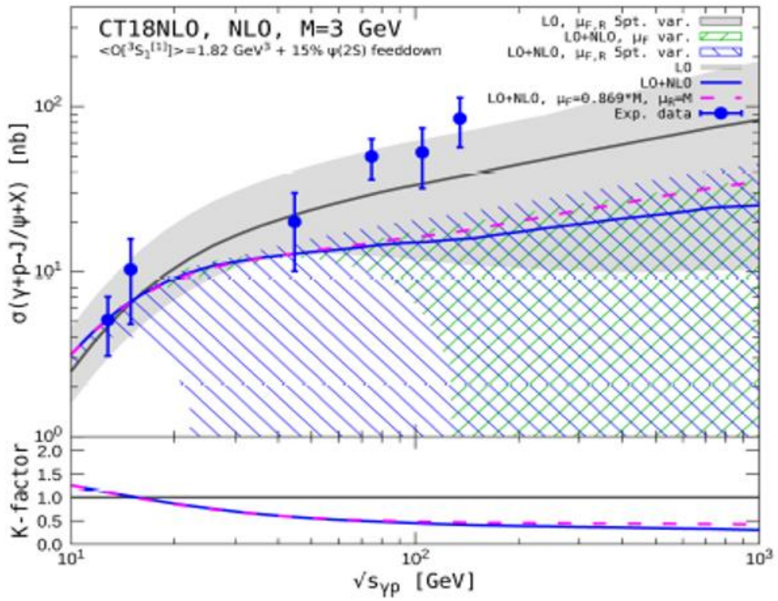
Negative total cross sections

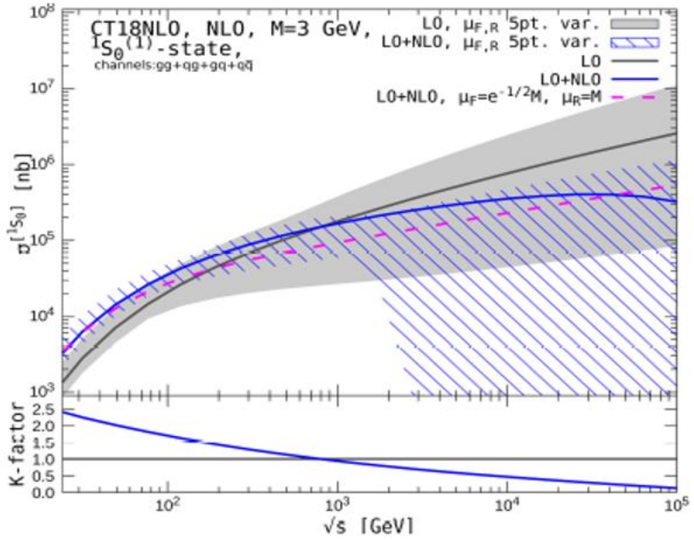
Inclusive J/ψ-photoproduction (CSM):

$$\gamma + p \to c\bar{c}\left[{}^3S_1^{[1]}\right] + X,\ \text{LO: } \gamma(q) + g(p_1) \to c\bar{c}\left[{}^3S_1^{[1]}\right] + g,$$

Inclusive η_c-hadroproduction (CSM):

$$p + p \to c\bar{c}\left[{}^1S_0^{[1]}\right] + X,\ \text{LO: } g(p_1) + g(p_2) \to c\bar{c}\left[{}^1S_0^{[1]}\right]$$





Lansberg, Nefedov, Ozcelik, 2112.06789

Universality problem

- **Fit J/ψ yield data at Tevatron with $p_T > 7$ GeV**

YQM, Wang, Chao, 1009.3655

- Due to p_T^{-4} and p_T^{-6} behaviors, constrain two combinations
- $M_0 = \langle O({}^1S_0^{[8]})\rangle + 3.9\langle O({}^3P_0^{[8]})\rangle/m_c^2 \approx (7.4 \pm 1.9)\times 10^{-2}\mathrm{GeV}^3$
- $M_1 = \langle O({}^3S_1^{[8]})\rangle - 0.56\langle O({}^3P_0^{[8]})\rangle/m_c^2 \approx (0.05 \pm 0.02)\times 10^{-2}\,\mathrm{GeV}^3$

See also:
Butenschoen, Kniehl, 1105.0820
Gong, Wan, Wang, Zhang, 1205.6682

- **Upper bound from Belle total cross section**

$$M_0 < 2\times 10^{-2}\mathrm{GeV}^3$$

Zhang, YQM, Wang, Chao, 0911.2166

- No universality of NRQCD LDMEs!

Polarization puzzle at LO

➢ LO NRQCD

- Dominated by ${}^3S_1^{[8]}$, LO NRQCD predicts transversely polarized $\psi(\mathrm{nS})$, contradicts with CDF data

CDF, 0704.0638

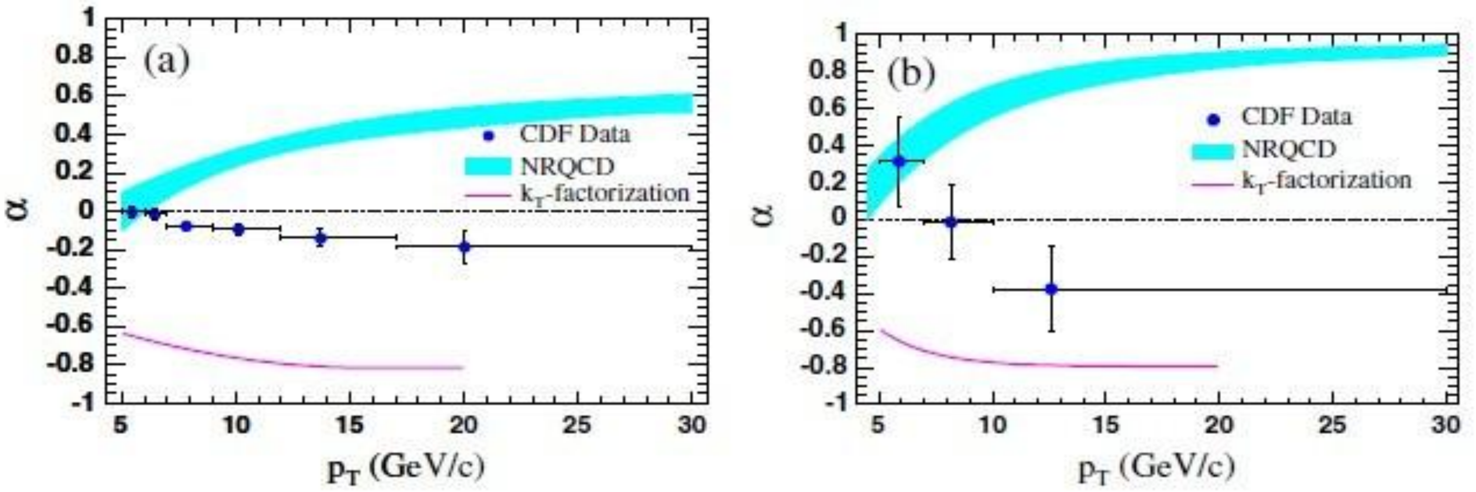
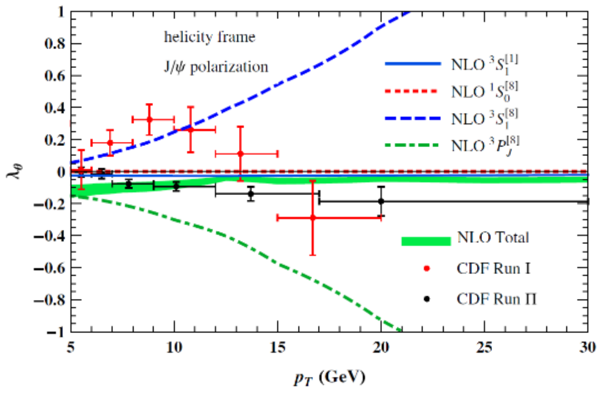


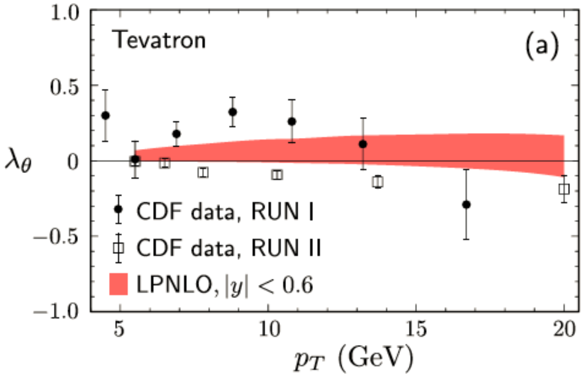
FIG. 4 (color online). Prompt polarizations as functions of p_T: (a) J/ψ and (b) $\psi(2S)$. The band (line) is the prediction from NRQCD [4] (the k_T-factorization model [9]).

Polarization puzzle at NLO

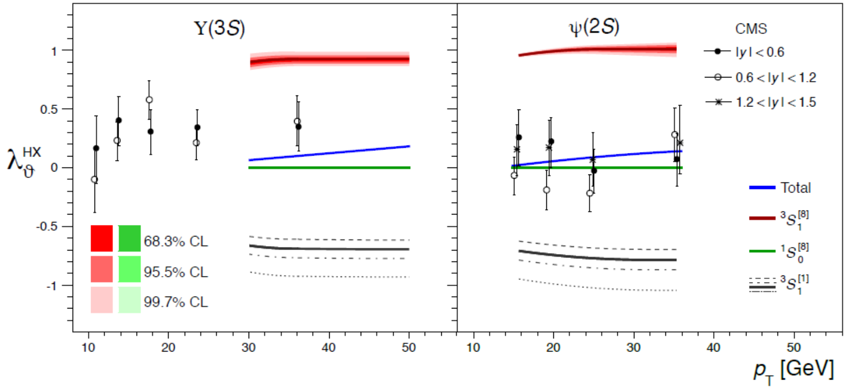
➢ J/ψ: transverse canceled (results in hierarchy) in ${}^3S_1^{[8]}$ and ${}^3P_J^{[8]}$



Chao,YQM,Shao,Wang, Zhang,1201.2675

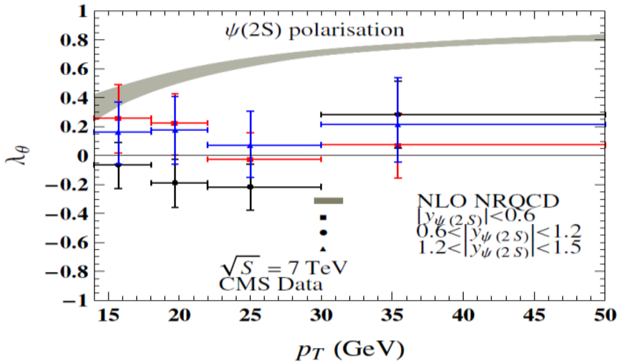


Bodwin, Chung, Kim, Lee, 1403.3612

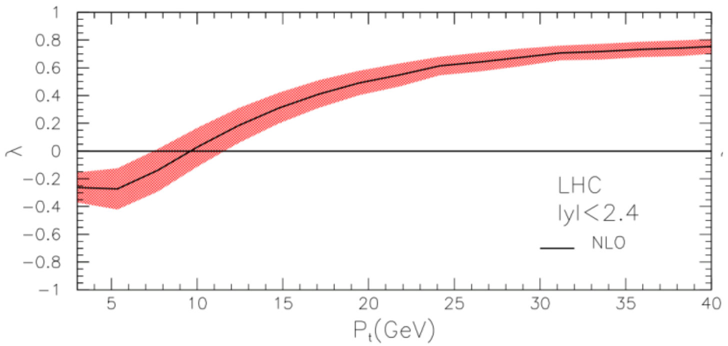


Faccioli,Knunz,Lourenco, Seixas,Wohri,1403.3970

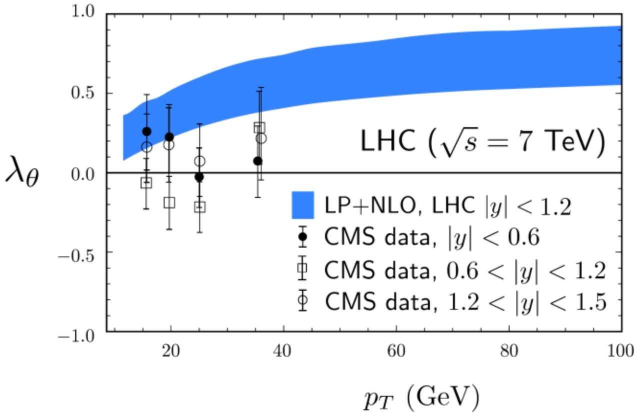
➢ $\psi(2S)$: cancelation weak, **hard to understand data**



Shao, Han, YQM, Meng, Zhang, Chao, 1411.3300



Gong, Wan, Wang, Zhang, 1205.6682

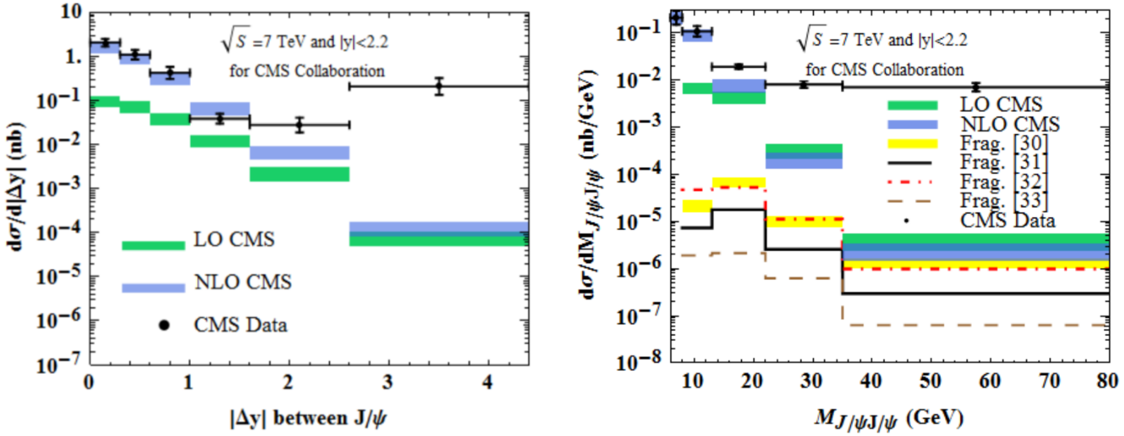


Bodwin et al., 1509.07904

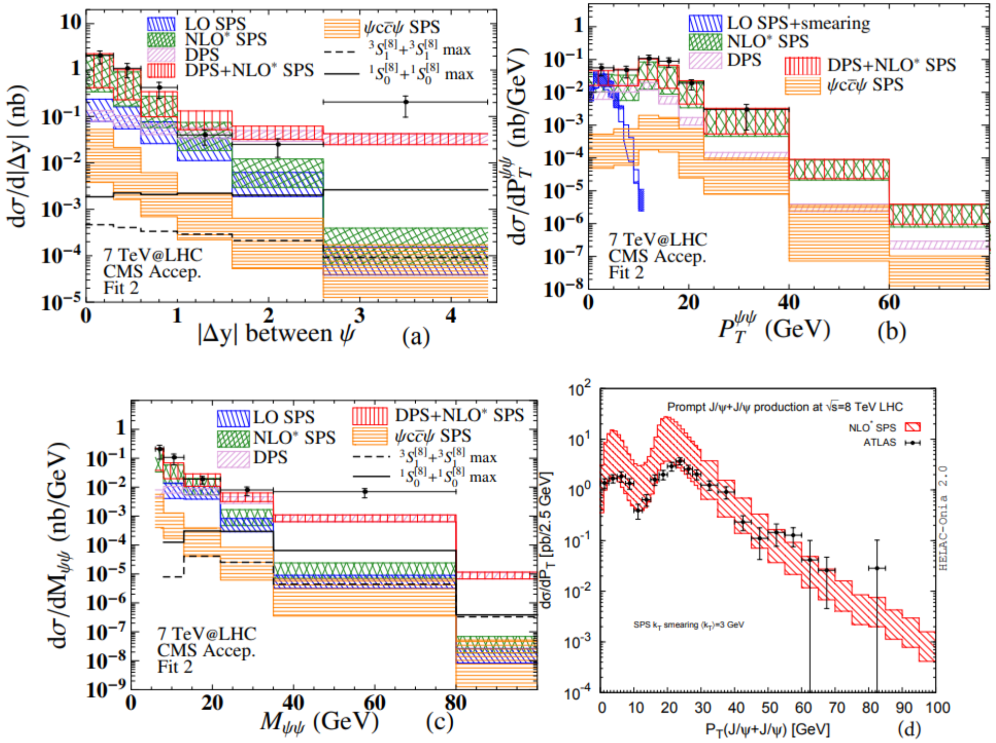
Double J/ψ production

➢ **Cannot explain data**

- 3 orders of discrepancy between data and single-parton scattering
- 1 order discrepancy still exist after including double-parton scattering
- What is missing?



Sun, Han, Chao, 1404.4042

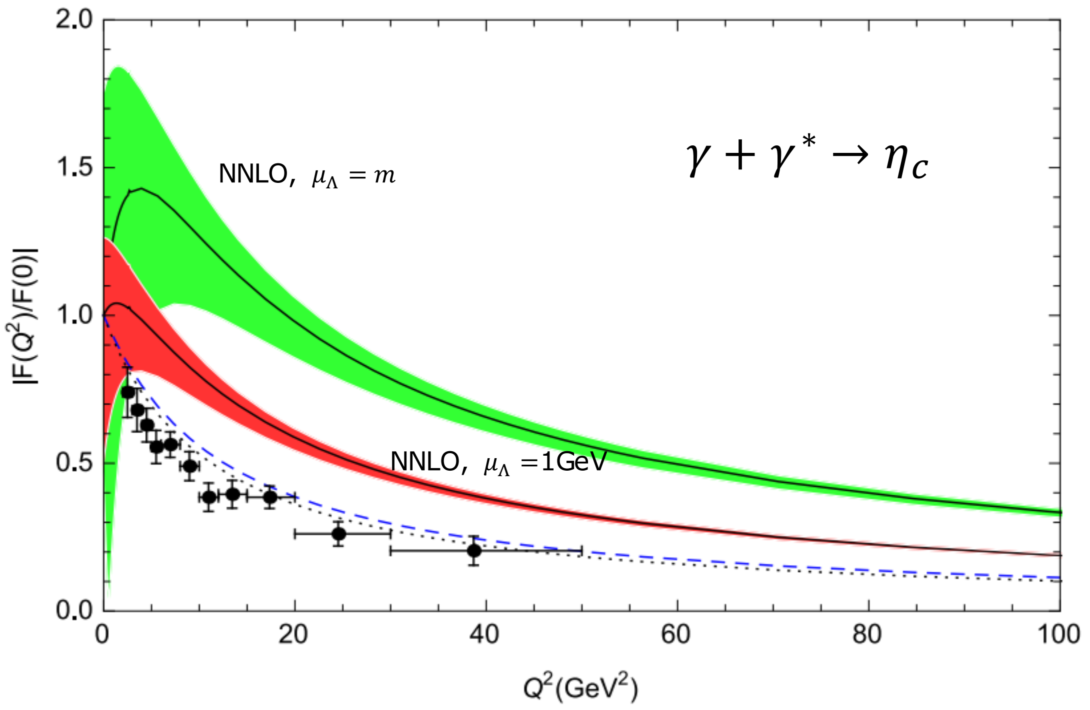


Lansberg, Shao, 1410.8822

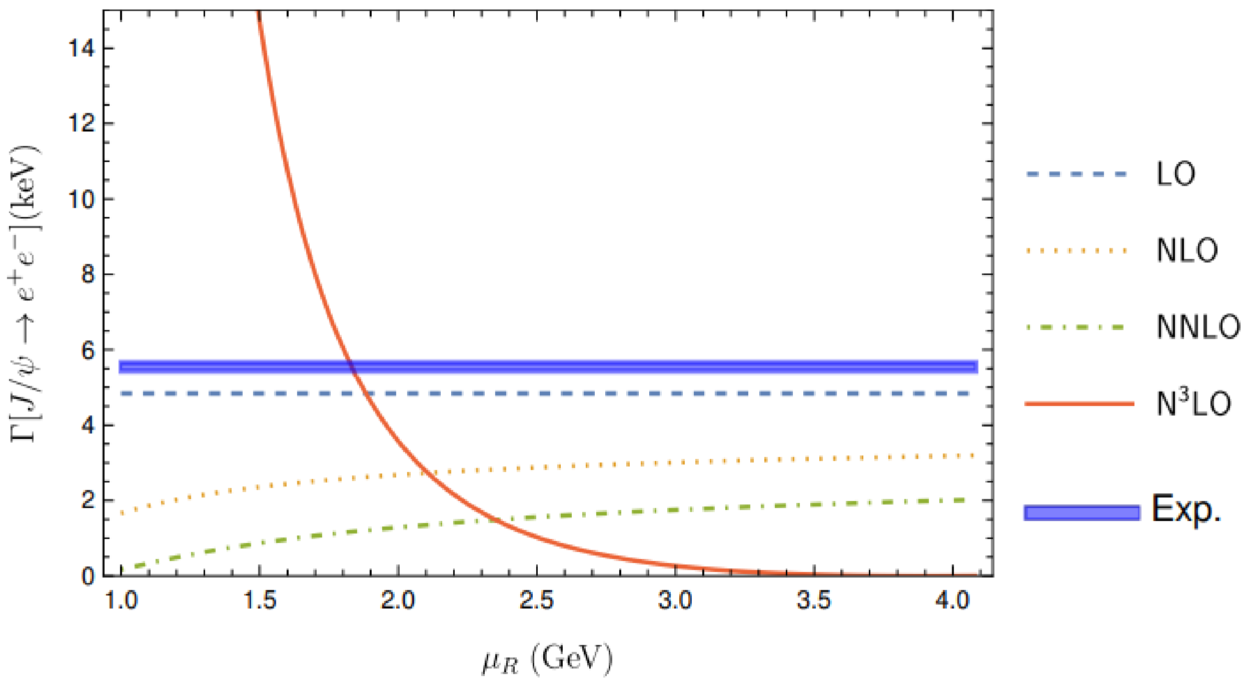
Beyond NLO

- **Very big high order correction!**
  - Higher orders fail to describe data
  - Strange: breaking down of perturbation theory? Or other mechanism?

Feng, Jia, Sang, 1505.02665



Feng, Jia, Mo, Pan, Sang, Zhang, 2207.14259



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Negative cross section

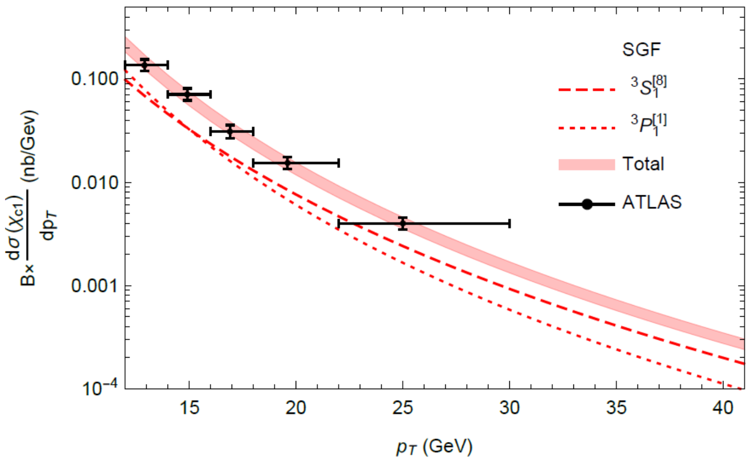
Resolve negative cross section at high p_T

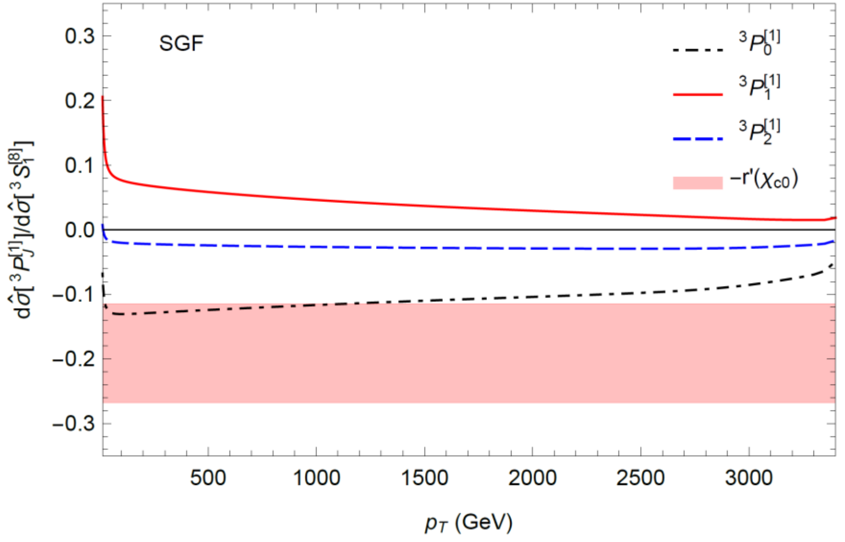
➢ **SGF framework**

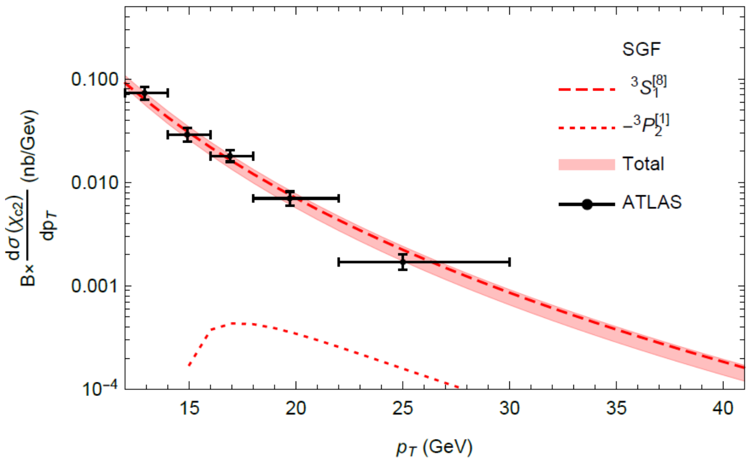
Chen, YQM, Meng, 2304.04552

□ χ_{cJ} production

- $\chi^2/d.o.f = 0.63/8$, as good as NRQCD
- No substantial cancellations
- Cross sections are positive at high p_T







Resolve negative cross section at high p_T

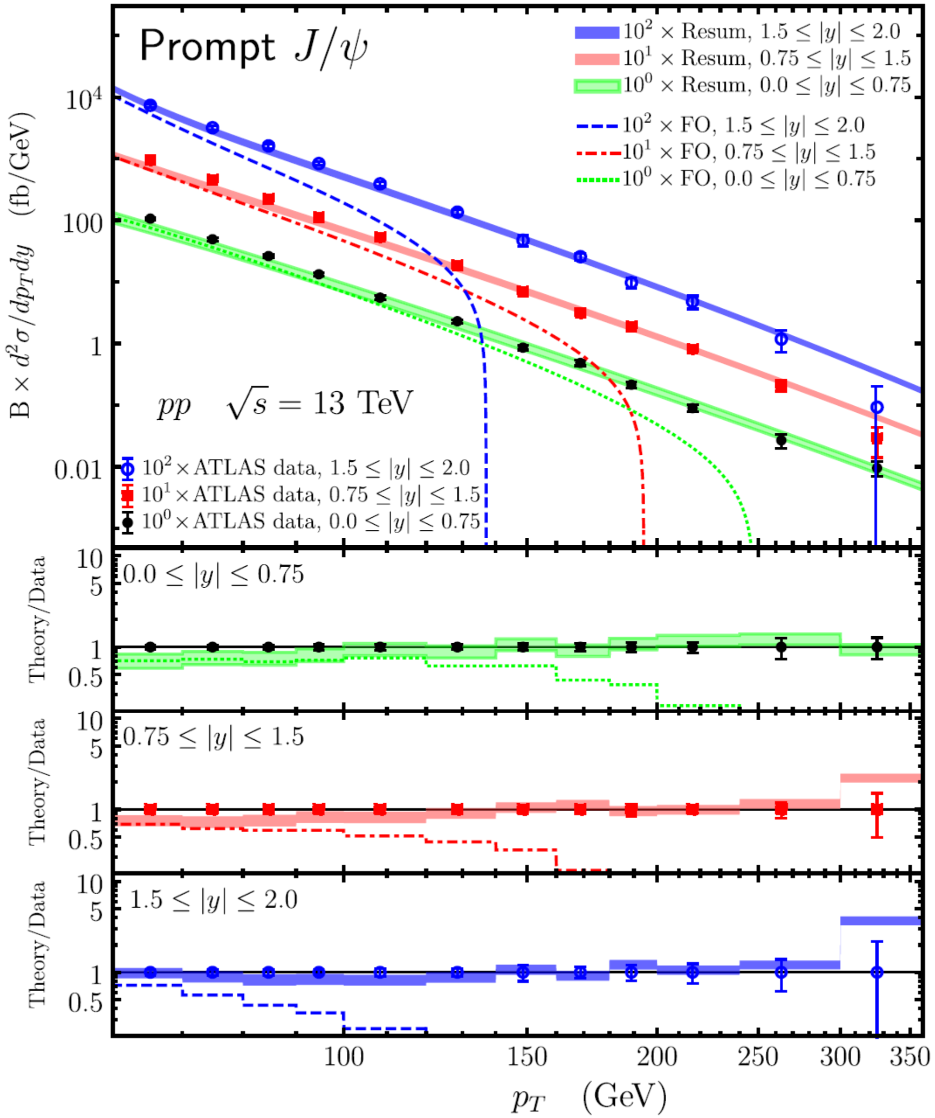
- NRQCD framework
  - Resummation within NRQCD framework Chung, Kim, Lee, 2408.04255
    - Resummed FFs in Mellin space

$$\tilde{D}^{\text{resum}}_{g\to Q\bar{Q}(\mathcal{N})}(N) = \exp[J^N_{\mathcal{N}}]\left(\tilde{D}^{\text{FO}}_{g\to Q\bar{Q}(\mathcal{N})}(N) - J^N_{\mathcal{N}}\tilde{D}^{\text{LO}}_{g\to Q\bar{Q}(\mathcal{N})}(N)\right),$$

$$J^N_{^3S_1^{[8]}} = \frac{\alpha_s C_A}{\pi}\int_0^1 dz\, z^{N-1}\left[\frac{-2\log(1-z)}{1-z}\right]_+,$$

$$J^N_{^3P^{[8]}} = J^N_{^3P^{[1]}} = \frac{4}{3}J^N_{^3S_1^{[8]}}.$$

Leading Double Logarithm



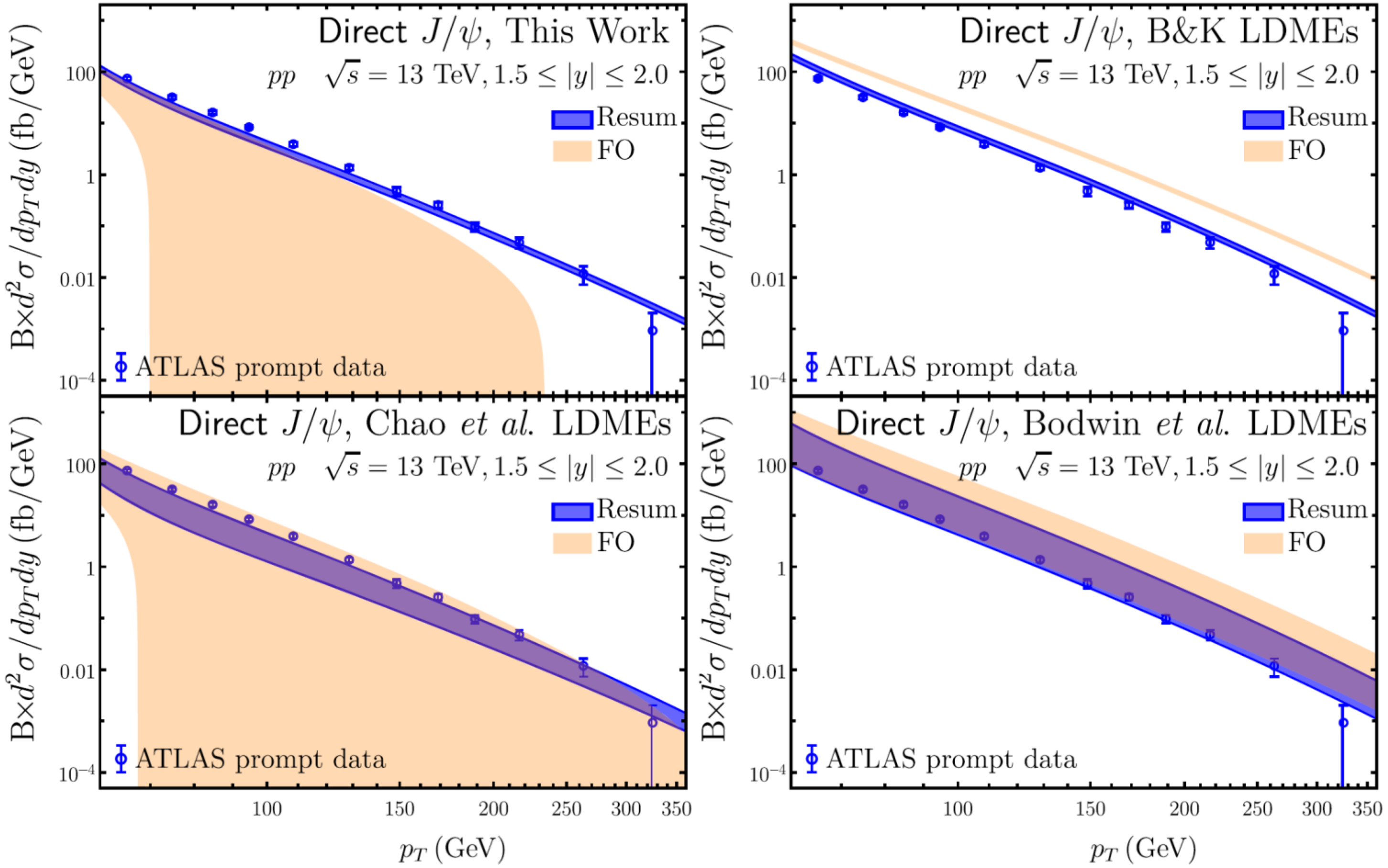
- J/ψ production rates are positive at high p_T

Resolve negative cross section at high p_T

- **NRQCD framework**

  - **Resummation within NRQCD framework** Chung, Kim, Lee, 2408.04255

    - J/ψ production rates are positive at high p_T for different LDMEs

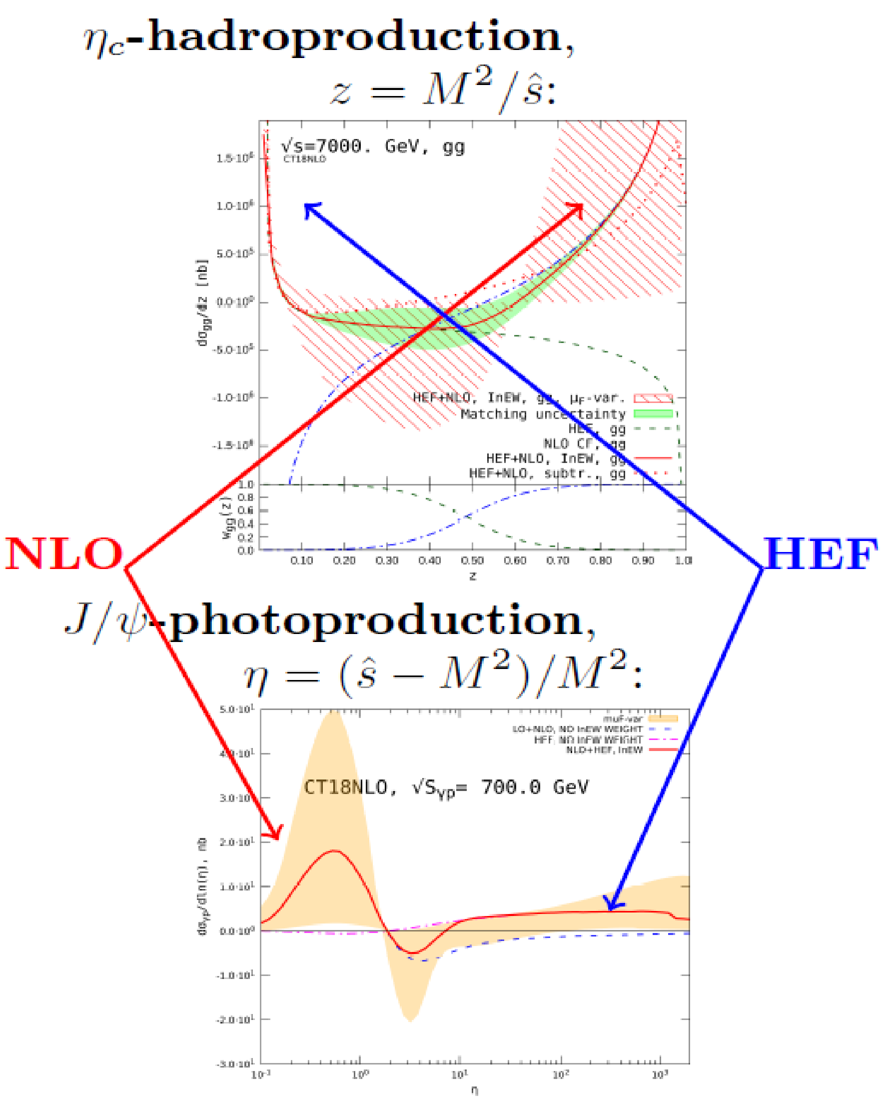


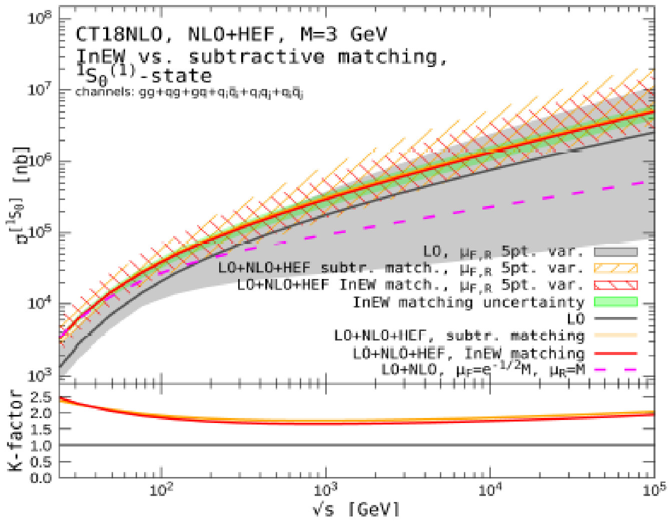
Resolve negative total cross section

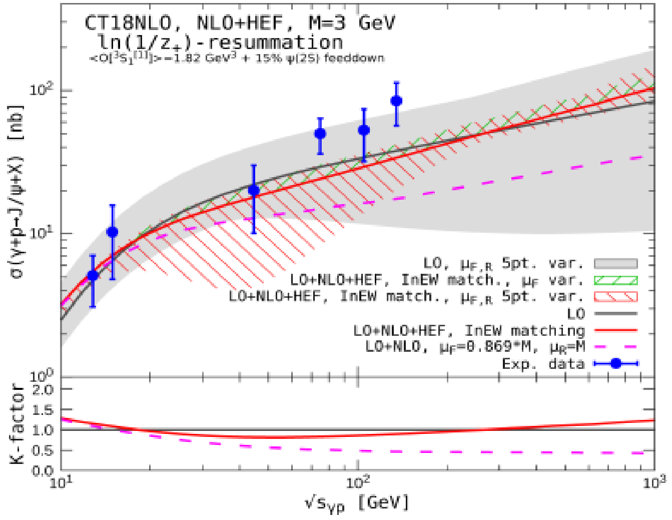
- Resum large log $\ln(S/m^2)$ using high energy factorization

Lansberg, Nefedov, Ozcelik, 2112.06789

See also: YQM, Venugopalan, 1408.4075







Universality problem

More recent fit

➢ NLO NRQCD factorization

◻ NLO fit of J/ψ CO LDMEs to J/ψ and η_c production data

Brambilla, Butenschoen, Wang, 2411.16384

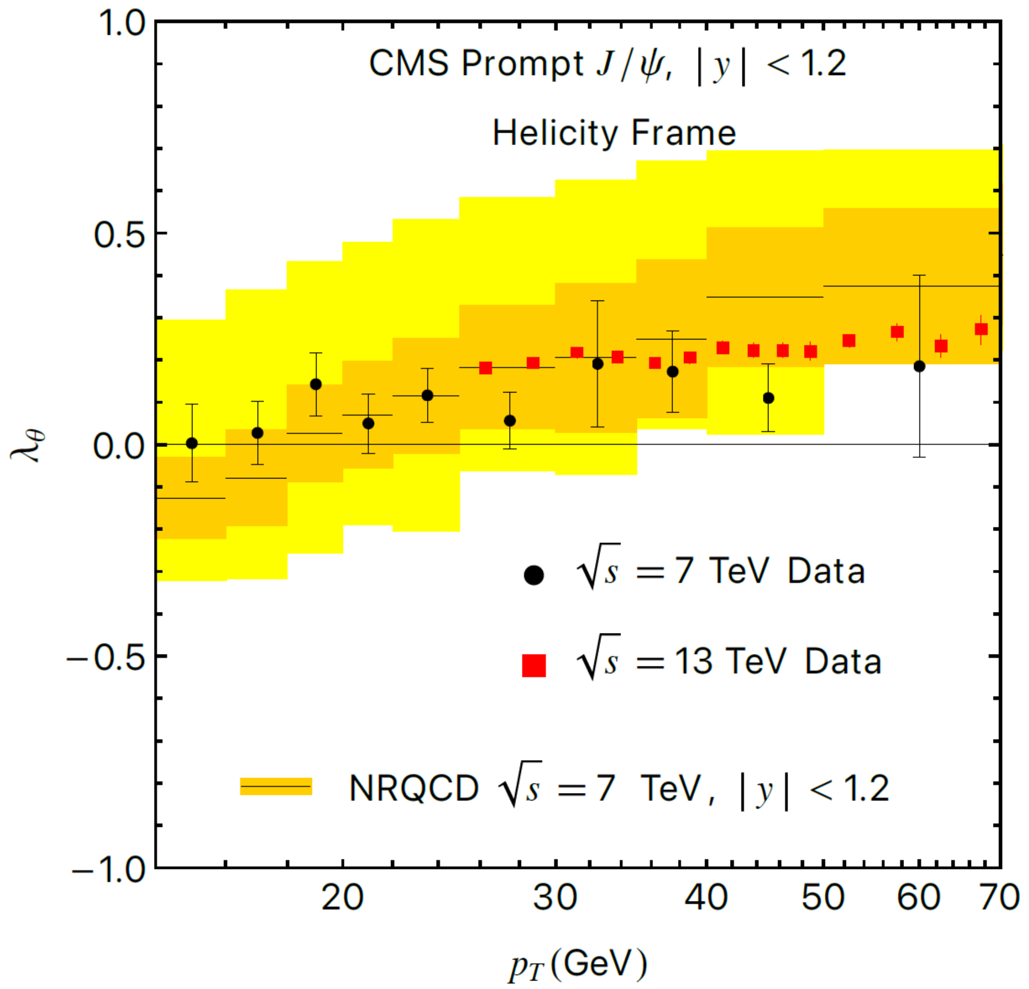
- Fit results in units of 10^{-2}GeV^3

	$\langle\mathcal{O}^{J/\psi}(^3S_1^{[8]})\rangle$	$\langle\mathcal{O}^{J/\psi}(^1S_0^{[8]})\rangle$	$\langle\mathcal{O}^{J/\psi}(^3P_0^{[8]})\rangle/m_c^2$	$\chi^2_{\text{min}}/\text{d.o.f}$
$\mu_r=\mu_f=m_T/2$	0.604 ± 0.106	-0.501 ± 0.171	0.716 ± 0.169	0.26
$\mu_r=\mu_f=m_T$	1.062 ± 0.195	-0.204 ± 0.229	1.905 ± 0.422	0.18
$\mu_r=\mu_f=2m_T$	1.367 ± 0.261	0.094 ± 0.288	3.232 ± 0.732	0.15

More recent fit

☐ Predictions

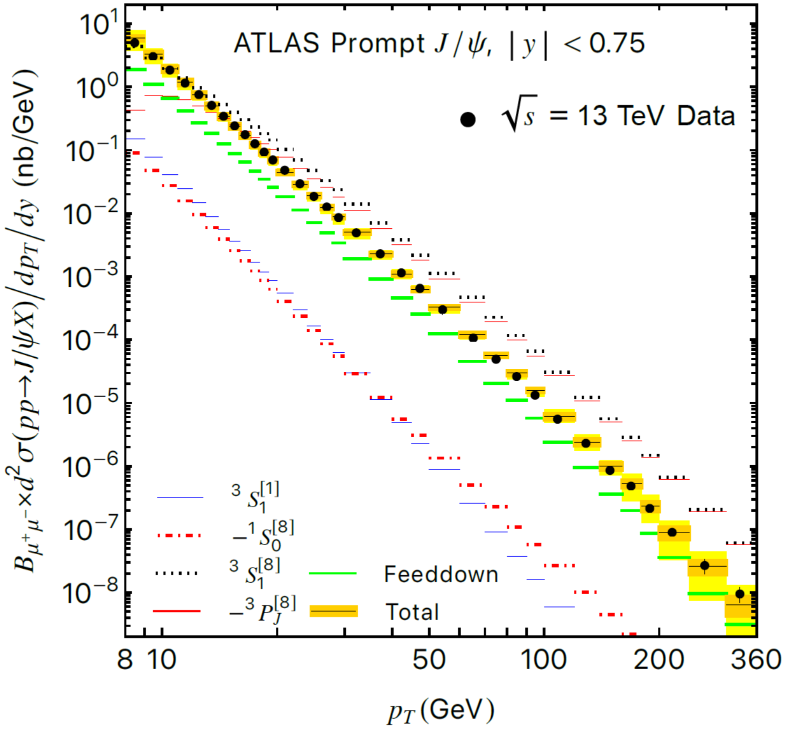
- J/ψ polarization: good agreement with the measurements

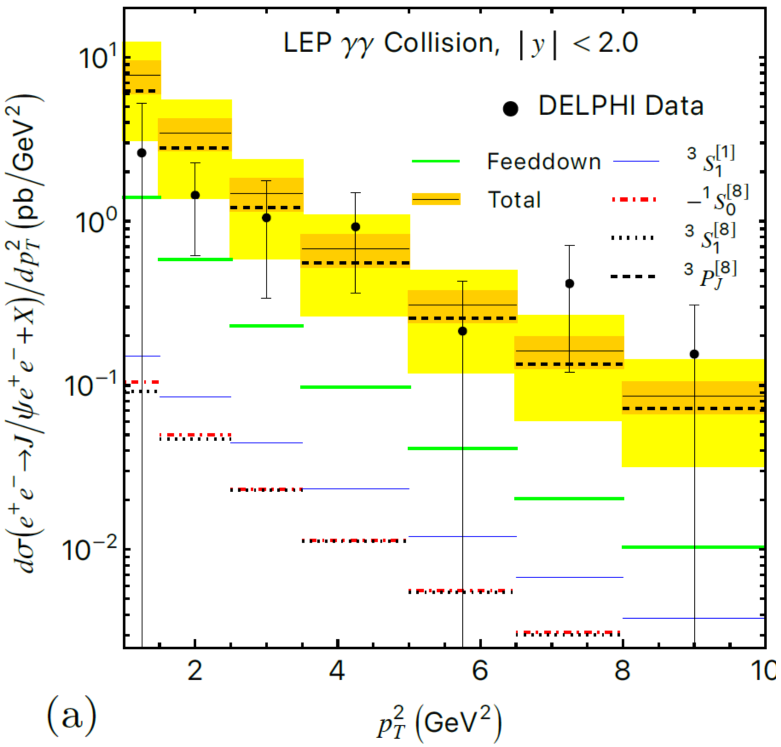


More recent fit

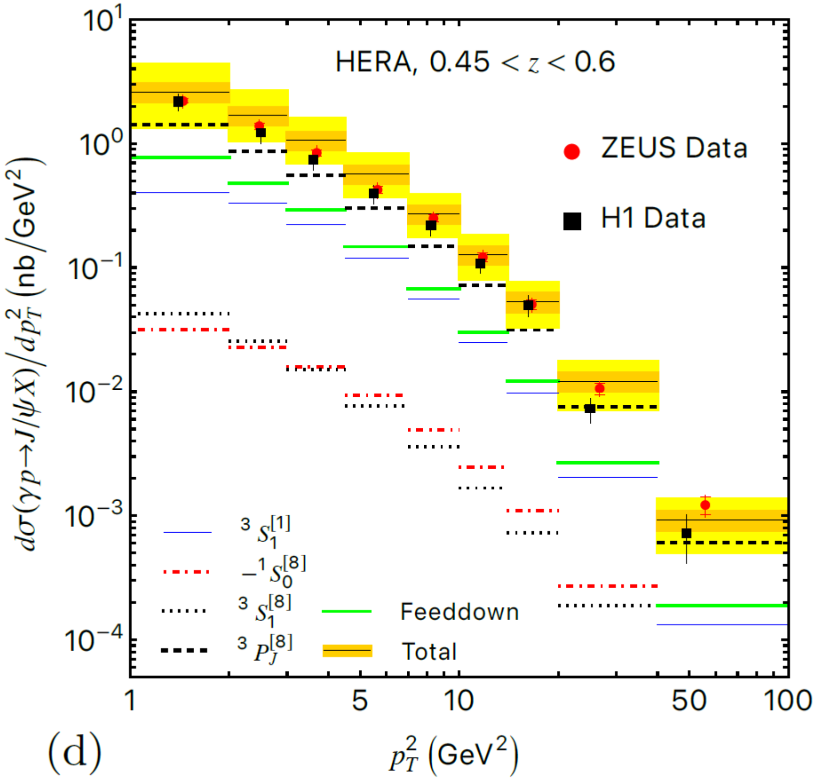
☐ Predictions

- **J/ψ production : well describe J/ψ hadroproduction, production in γγ scattering and production in HERA photoproduction**





(a)



(d)

☐ Problem

- No universality

$$\text{pp}: M_0 = \langle O\left({}^1S_0^{[8]}\right)\rangle + 3.9\langle O\left({}^3P_0^{[8]}\right)\rangle / m_c^2 \approx (7.23 \pm 1.87)\times 10^{-2}\,\text{GeV}^3; \quad e^+e^-: M_0 < 0.02\,\text{GeV}^3$$

Universality after resummation

- **Application to $e^+e^- \to J/\psi({}^3P_J^{[8]}, {}^1S_0^{[8]}) + X$**

  - **Partonic differential cross sections**

Chen, Jin, Ma, Meng, 2201.04492

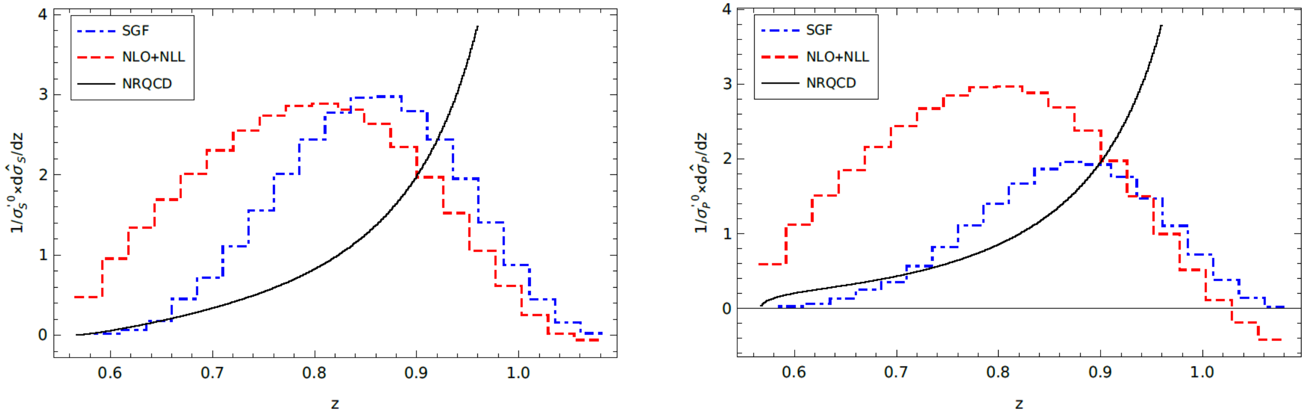


Figure 4. The differential cross sections in SGF and NRQCD factorization approaches.

  - **Smaller partonic cross section, larger LDMEs allowed**

$$M_k^X = \langle \mathcal{O}^{J/\psi}({}^1S_0^{[8]})\rangle + k\frac{\langle \mathcal{O}^{J/\psi}({}^3P_0^{[8]})\rangle}{m_c^2}$$

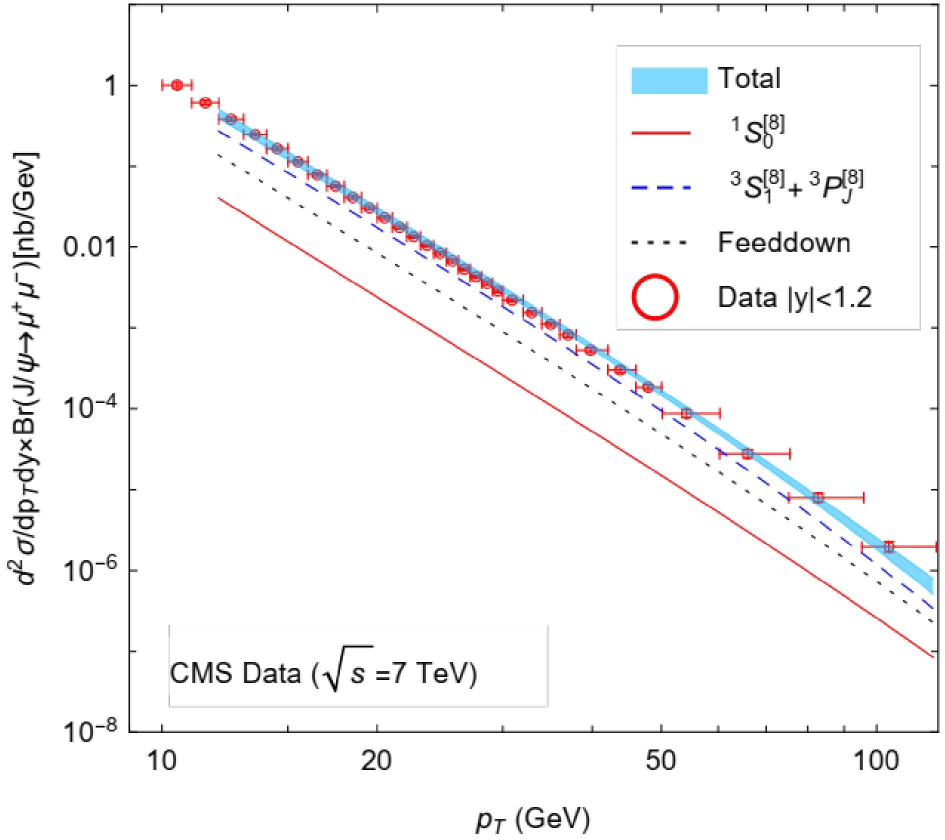
$$M_{3.9}^{\text{NRQCD}} < (2.4 \pm 0.7) \times 10^{-2}\,\text{GeV}^3,$$
$$M_{3.9}^{\text{NLO+NLL}} < (5.8 \pm 1.8) \times 10^{-2}\,\text{GeV}^3,$$

Universality after resummation

➢ LDMEs extracted from pp after resummation

Chen, YQM, Meng, In preparation

$$3.198\times10^{-2} < M_0' = \mathcal{O}^{J/\psi}({}^1S_0^{[8]}) + 3.9\frac{\mathcal{O}^{J/\psi}({}^3P_0^{[8]})}{m_c^2} < 1.662\times10^{-1}\ \mathrm{GeV}^3$$



- LDMEs in e^+e^- can be consistent with that extracted in pp

$$M_{3.9}^{\mathrm{NRQCD}} < (2.4\pm0.7)\times10^{-2}\ \mathrm{GeV}^3,$$
$$M_{3.9}^{\mathrm{NLO+NLL}} < (5.8\pm1.8)\times10^{-2}\ \mathrm{GeV}^3,$$

Universality problem solved by resummation!

Question the HQSS for production

Long-standing polarization puzzle

- LO

CDF, 0704.0638

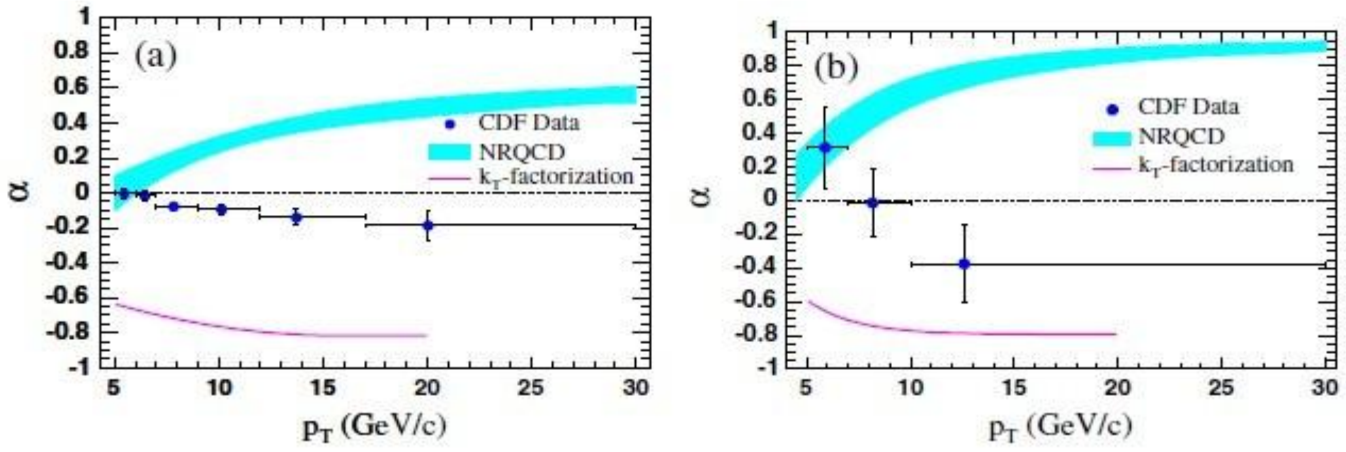
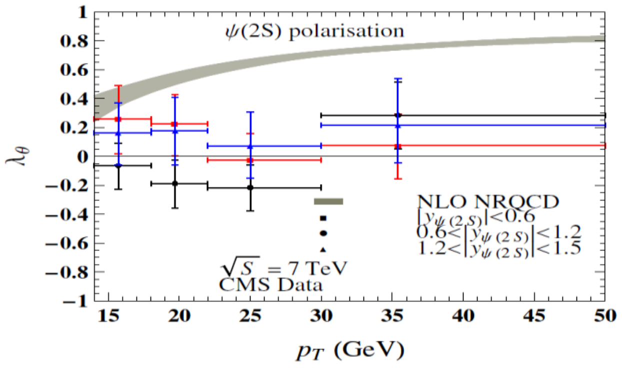
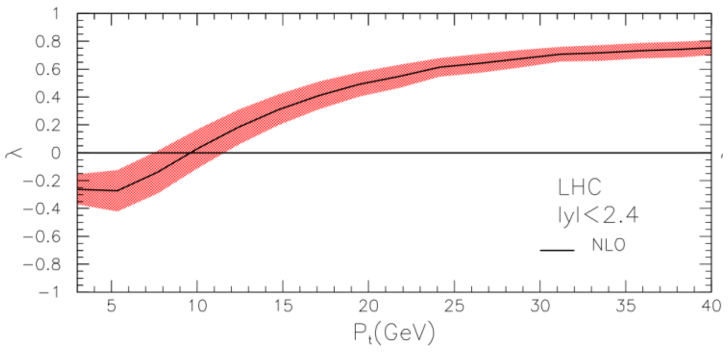


FIG. 4 (color online). Prompt polarizations as functions of p_T: (a) J/ψ and (b) $\psi(2S)$. The band (line) is the prediction from NRQCD [4] (the k_T-factorization model [9]).

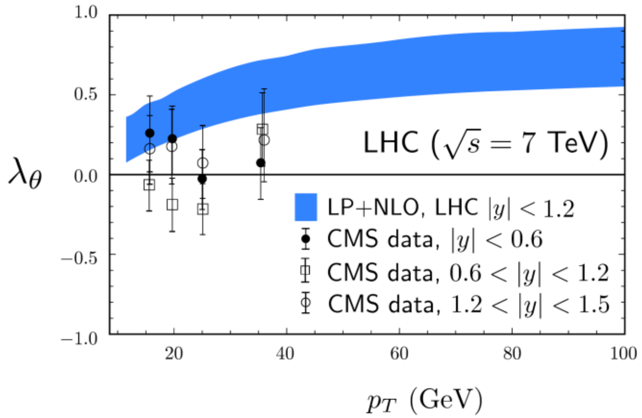
- $\psi(2S)$ at NLO



Shao, Han, YQM, Meng, Zhang, Chao, 1411.3300



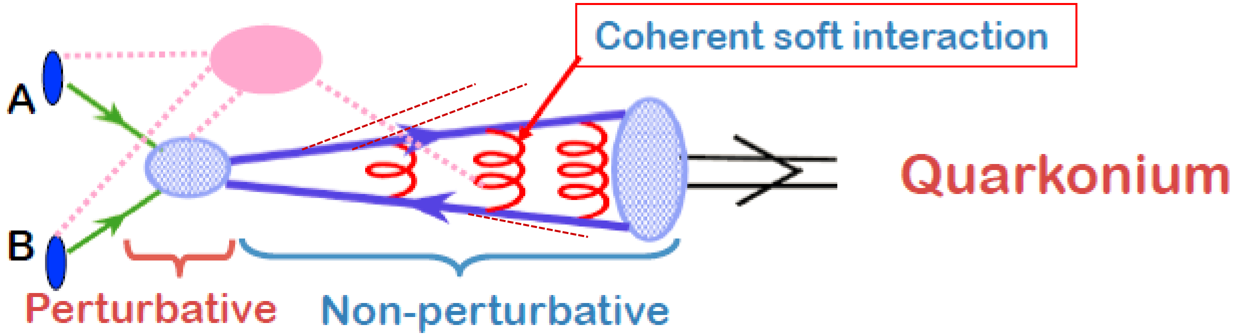
Gong, Wan, Wang, Zhang, 1205.6682



Bodwin et al., 1509.07904

Spin symmetry broken?

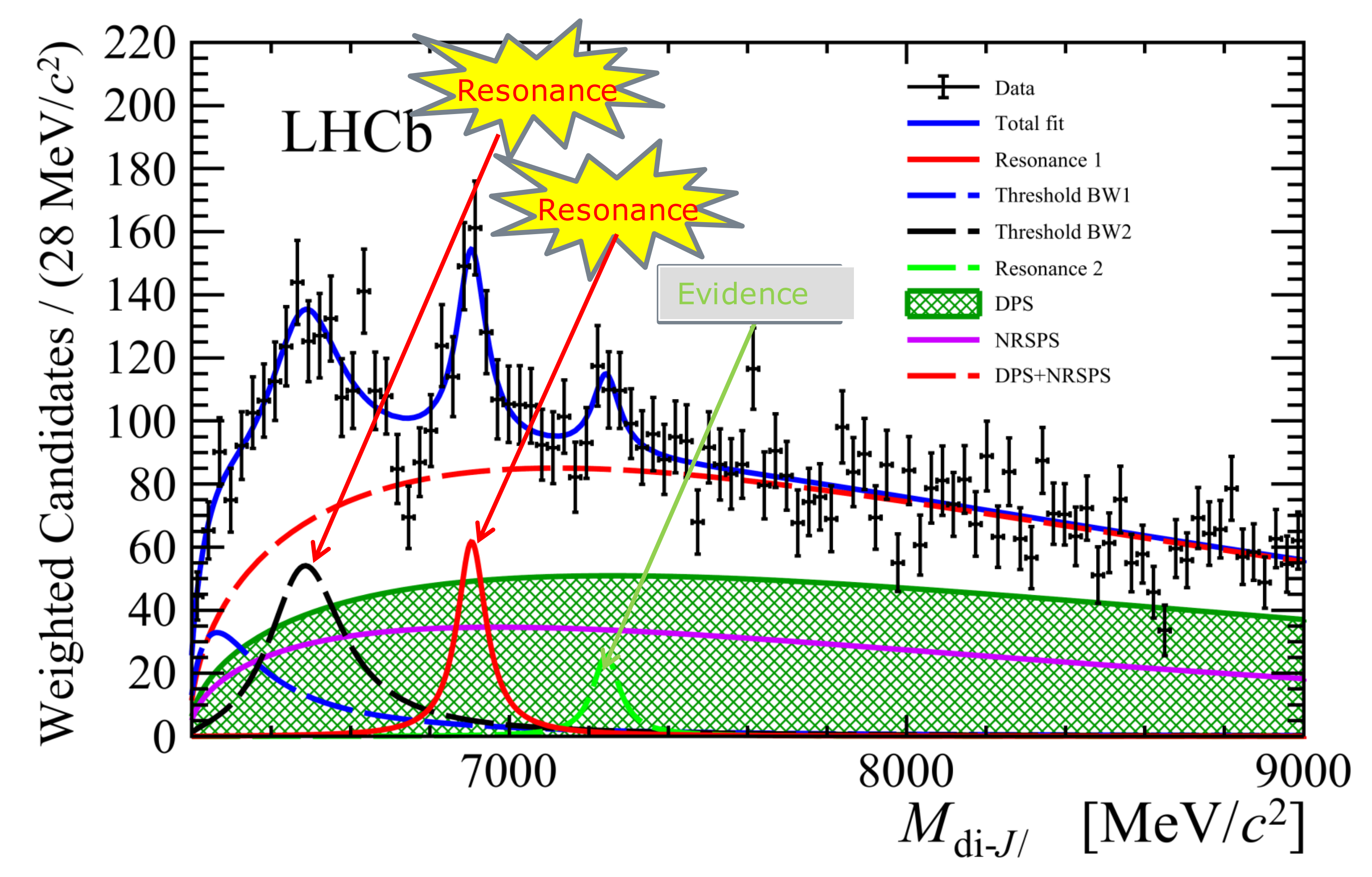
- Heavy quark spin symmetry (HQSS): spin of ${}^3S_1^{[8]}$ is the same as $\psi(nS)$
  - HQSS tested for quarkonium decay
  - Never tested for quarkonium production
- Why broken for production: off-shell heavy quark pair



- TEST IT!
  - Eg. Via B-decay to J/ψ v.s. η_c (χ_{cJ} v.s. h_c)

Double J/ψ and $X(6900)$

Di-J/ψ Resonance(s) at LHC



Possible candidates (S-wave)

- **Different configurations**

$T_{cc\bar{c}\bar{c}}$	${}^1S_0({}^1S_0, {}^1S_0)$	${}^1S_0({}^3S_1, {}^3S_1)$	${}^5S_2({}^3S_1, {}^3S_1)$
$M_{J/\psi J/\psi}$	${}^1S_0$	${}^5S_2$	

- **Ratio of cross sections for spin-2 to spin-0**

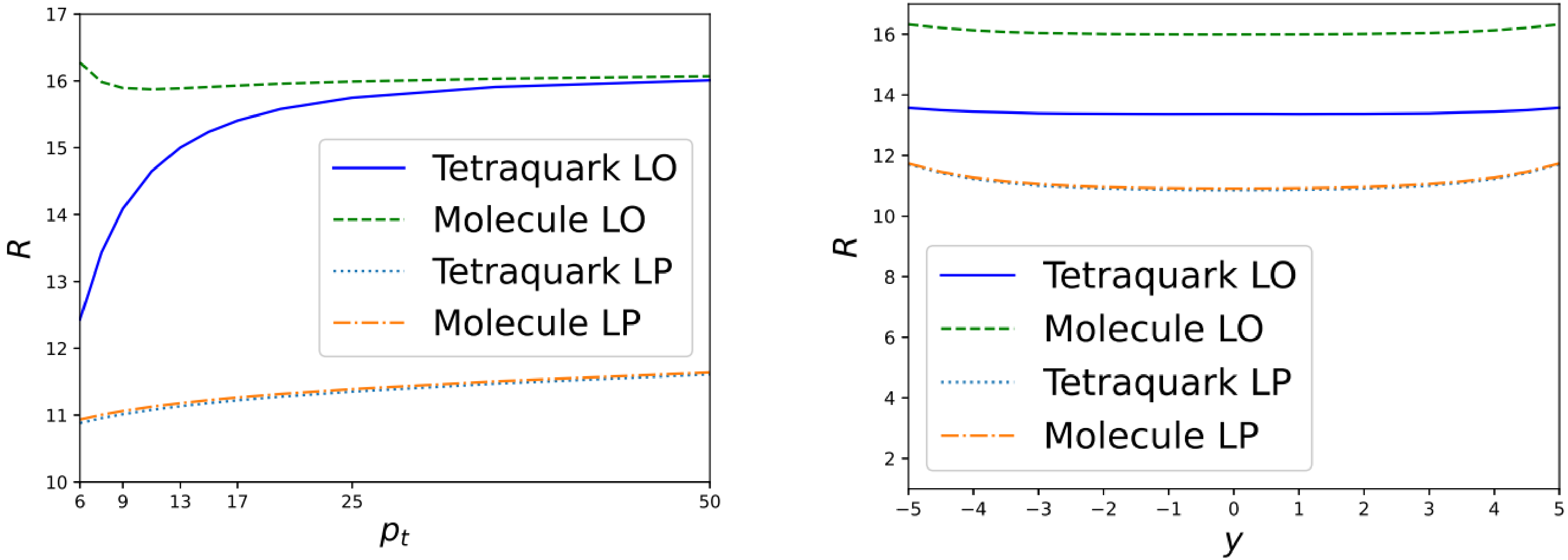
$$R(T) \equiv \frac{\mathrm{d}\sigma(T_{cc\bar{c}\bar{c}}[2^{++}])}{\mathrm{d}\sigma(T_{cc\bar{c}\bar{c}}[0^{++}])} = \frac{5\mathrm{d}\hat{\sigma}(cc\bar{c}\bar{c}[2^{++}])}{\mathrm{d}\hat{\sigma}(cc\bar{c}\bar{c}[0^{++}])}$$

$$R(M) \equiv \frac{\mathrm{d}\sigma(M_{\psi\psi}[2^{++}])}{\mathrm{d}\sigma(M_{\psi\psi}[0^{++}])} = \frac{5\mathrm{d}\hat{\sigma}(\psi\psi[2^{++}])}{\mathrm{d}\hat{\sigma}(\psi\psi[0^{++}])}$$

Results from perturbative QCD

Zhang, YQM, Sang, 2009.08376 [Sci. Bull. 70, 1915 (2025)]

- Much larger production rate for spin-2 particles (either tetraquark or molecule), indicating the measured resonances are spin-2



CMS measurement

Confirmed by the CMS measurement!

Determination of the spin and parity of all-charm tetraquarks

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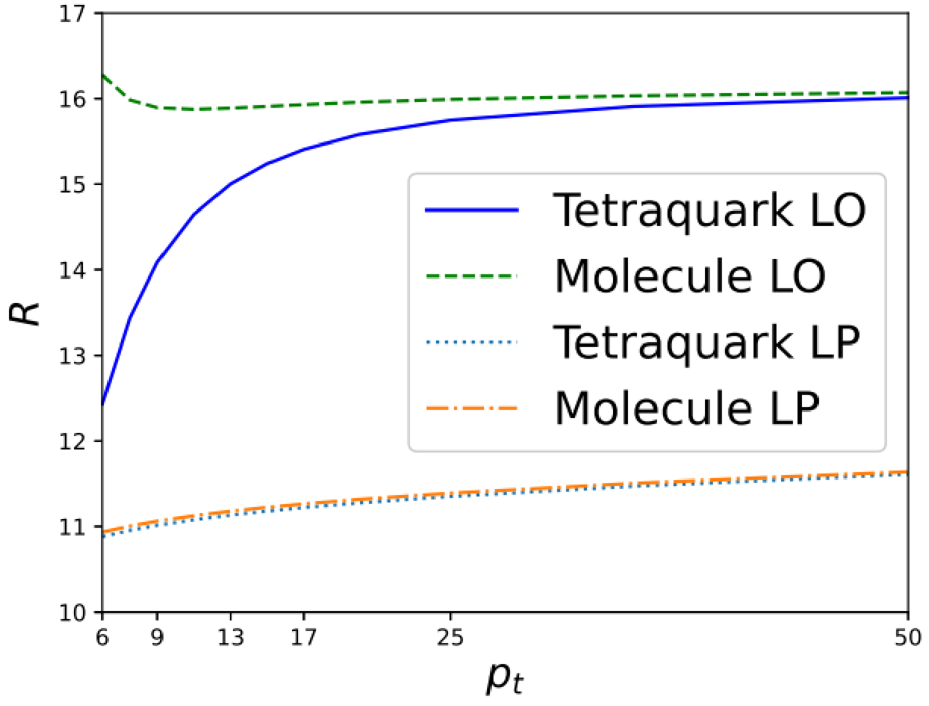
The CMS Collaboration*

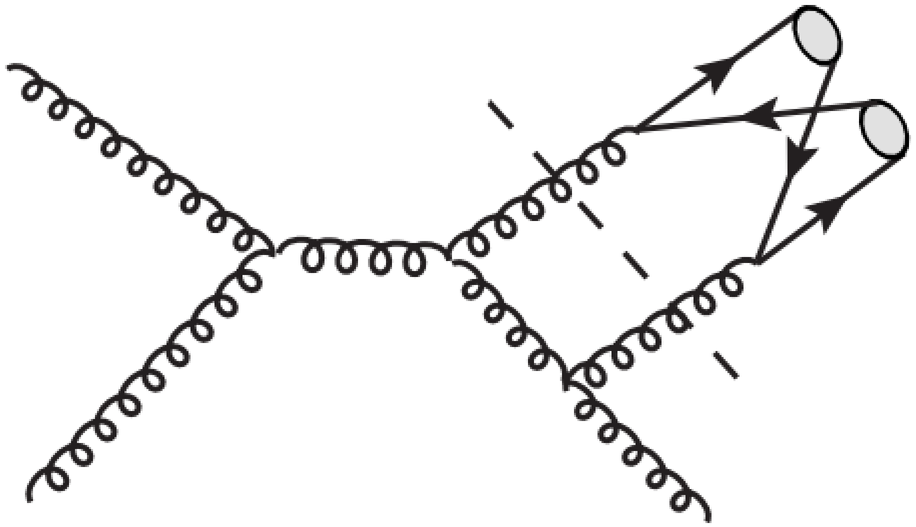
The traditional quark model[1,2] accounts for the existence of baryons, such as protons and neutrons, which consist of three quarks, as well as mesons, composed of a quark–antiquark pair. Only recently has substantial evidence started to accumulate for exotic states composed of four or five quarks and antiquarks[3]. The exact nature of their internal structure remains uncertain[4–29]. Here we report the first measurement of quantum numbers of the recently discovered family of three all-charm tetraquarks[30–32], using data collected by the CMS experiment at the Large Hadron Collider from 2016 to 2018 (refs. 33,34). The angular analysis techniques developed for the discovery and characterization of the Higgs boson[35–37] have been applied to the new exotic states. Here we show that the quantum numbers for parity P and charge conjugation C symmetries are found to be +1. The spin J of these exotic states is determined to be consistent with $2\hbar$, while $0\hbar$ and $1\hbar$ are excluded at 95% and 99% confidence levels, respectively. The $J^{PC} = 2^{++}$ assignment implies particular configurations of constituent spins and orbital angular momenta, which constrain the possible internal structure of these tetraquarks.

Further investigation

In preparation

- Why large ratio?
- Double parton fragmentation, resulting interesting polarization predictions





Quarkonium energy correlator

J/ψ production within jets

- **Definition: A J/ψ, produced within a jet of energy E and cone size R, in which the J/ψ carries a fraction of the jet energy, z.**

Baumgart, Leibovich, Mehen, Rothstein, 1406.2295; Kang, Qiu, Ringer, Xing, Zhang, 1702.03287.

- Factorization

$$\frac{d\sigma^{J/\psi}}{dp_T d\eta dz_h} = \sum_{a,b,c} f_a \otimes f_b \otimes H_{ab}^c \otimes \mathcal{G}_c^{J/\psi}.$$

- Fragmenting jet function (FJF): describe the fragmentation of a J/ψ inside a jet.

$$\mathcal{G}_i^{J/\psi}(z, z_h, p_{\rm jet}^+ R, \mu) = \sum_j \int_{z_h}^1 \frac{dz_h'}{z_h'} \mathcal{J}_{ij}(z, z_h/z_h', p_{\rm jet}^+ R, \mu) \times D_j^{J/\psi}(z_h', \mu) + \mathcal{O}(m_{J/\psi}^2/(p_{\rm jet}^+ R)^2). \qquad (3)$$

J/ψ production within jets

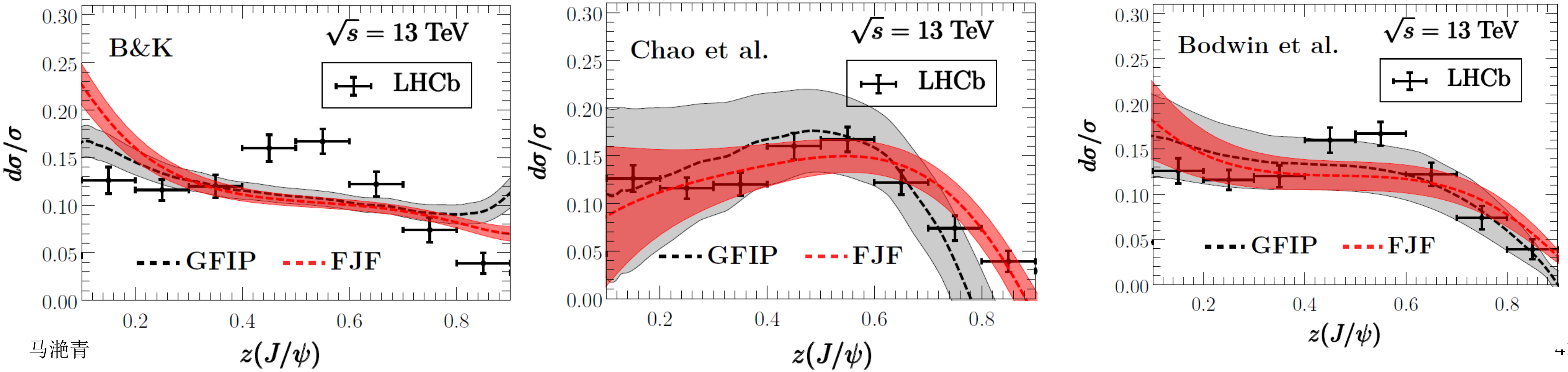
➢ **A useful observable to help explore the J/ψ production mechanism**

- Discriminate between different NRQCD fits

Kang, Qiu, Ringer, Xing, Zhang, 1702.03287.
Bain, Makris, Mehen, Dai, Leibovich, 1702.05525.

	$\langle\mathcal{O}^{J/\psi}(^3S_1^{[1]})\rangle$ $\times$ GeV^3	$\langle\mathcal{O}^{J/\psi}(^3S_1^{[8]})\rangle$ $\times10^{-2}$ GeV^3	$\langle\mathcal{O}^{J/\psi}(^1S_0^{[8]})\rangle$ $\times10^{-2}$GeV^3	$\langle\mathcal{O}^{J/\psi}(^3P_0^{[8]})\rangle/m_c^2$ $\times10^{-2}$GeV^3
B & K [5, 6]	1.32 ± 0.20	0.224 ± 0.59	4.97 ± 0.44	-0.72 ± 0.88
Chao, et al. [12]	1.16 ± 0.20	0.30 ± 0.12	8.9 ± 0.98	0.56 ± 0.21
Bodwin et al. [13]	1.32 ± 0.20	1.1 ± 1.0	9.9 ± 2.2	0.49 ± 0.44

- **Predicted z(J/ψ) distribution using PYTHIA (gray) and FJF (red) for the different choices of LDMEs**



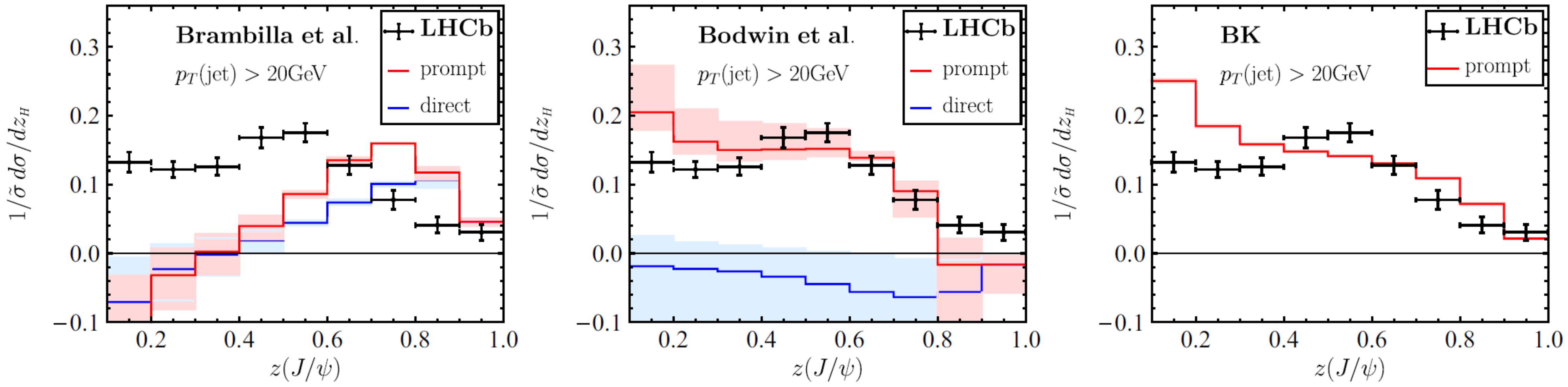
J/ψ production within jets

➢ **Improve theoretical prediction by resuming the threshold double logarithms**   Wang, Kang, Chung, 2507.19022.

- The divergence as $z \to 1$ cured by the threshold resummation

		$\langle\mathcal{O}(^3S_1^{[1]})\rangle$	$\langle\mathcal{O}(^3S_1^{[8]})\rangle$	$\langle\mathcal{O}(^1S_0^{[8]})\rangle$	$\langle\mathcal{O}(^3P_0^{[8]})\rangle/m_c^2$
		$\times$GeV^3	$\times10^{-2}$ GeV^3	$\times10^{-2}$ GeV^3	$\times10^{-2}$ GeV^3
J/ψ	Brambilla *et al.* [13]	1.18 ± 0.35	1.40 ± 0.42	-0.63 ± 3.22	2.33 ± 0.83
	Bodwin *et al.* [14]	1.32 ± 0.20	-0.71 ± 0.36	11.0 ± 1.4	-0.31 ± 0.15
	BK [15]	1.32 ± 0.20	0.22 ± 0.06	4.97 ± 0.44	-0.72 ± 0.09

- **Predicted z(J/ψ) distribution for different choices of LDMEs**



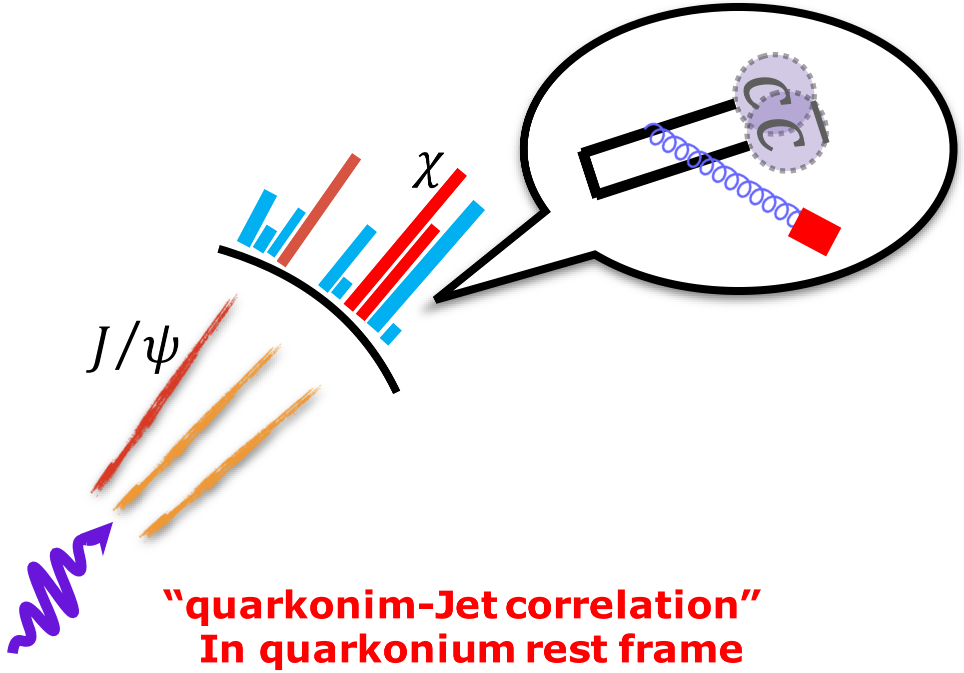
Quarkonium Energy Correlator and hadronization

➢ **Quarkonium Energy Correlator** Chen et al., 2405.10056

$$\Sigma_{\text{QEC}}(\chi) = \frac{1}{\sigma_{J/\psi}} \int d\sigma_{J/\psi} \frac{E_i}{M} \delta(\chi - \chi_i)$$

~ average energy at the angle χ

- IRC safe, can be calculated perturbatively
- $\Sigma_{QEC} = \Sigma_{QEC,P.T.} + \Sigma_{QEC,had.}$
  - Hadronization enters as an additive correction, not in the form of convolution
  - $\Sigma_{QEC,had.}$ can be extracted from "Measured - pQCD", If $\Sigma_{QEC,had.}$ is not too small

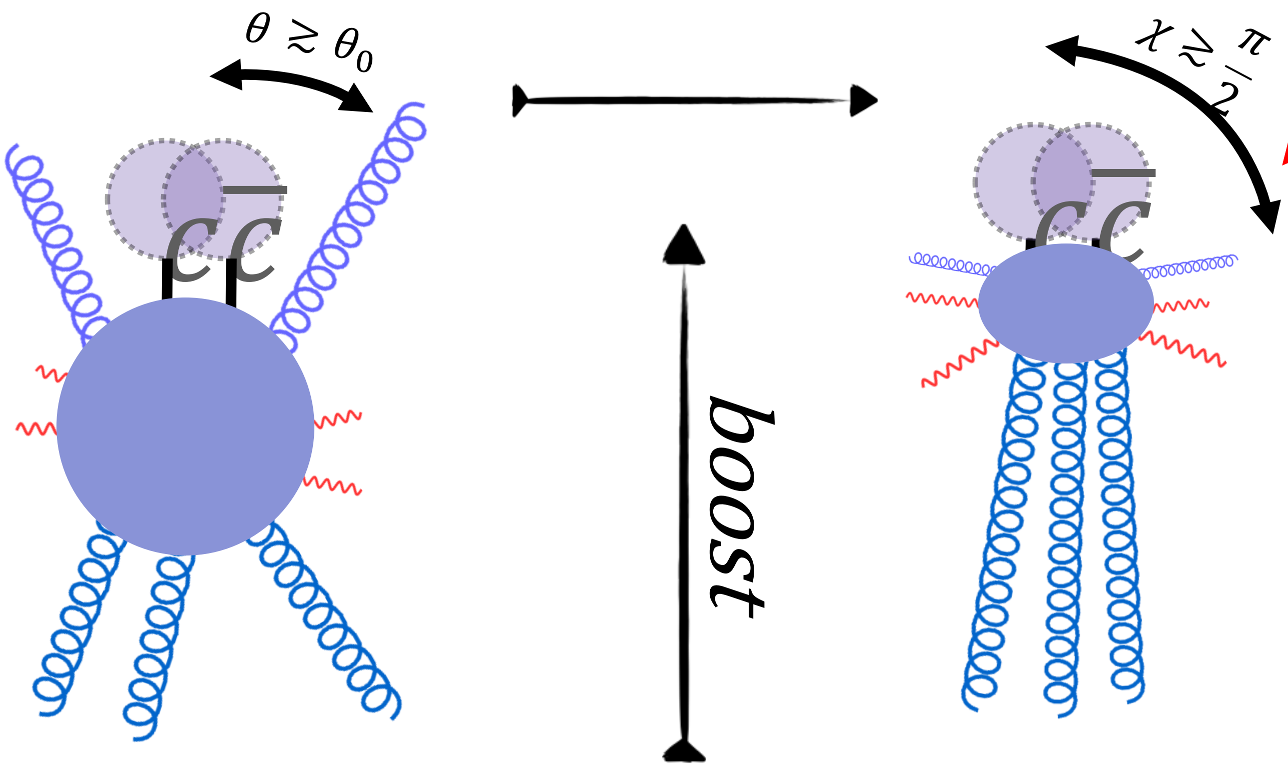


"quarkonim-Jet correlation"
In quarkonium rest frame

Quarkonium Energy Correlator and hadronization

- Generic configuration of boost J/ψ production in pQCD

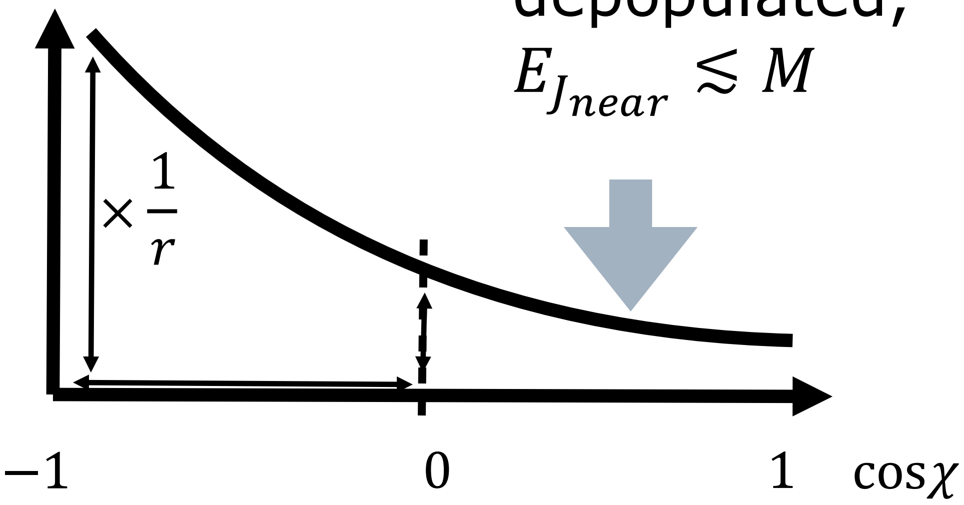
COM frame $\qquad\qquad$ J/ψ rest frame



Near side radiation will be depleted.

- dead-cone effects
- boost factor

pQCD: hard radiation depopulated, $E_{J_{near}} \lesssim M$



$E_s \sim \mathcal{O}(M)$,

$E_{J_{near}} \sim E_{J_{away}} \sim \mathcal{O}\left(\frac{\sqrt{\hat{s}}}{2}\right)$

$E_{J_{near}} \sim E_s \sim \mathcal{O}(M)$,

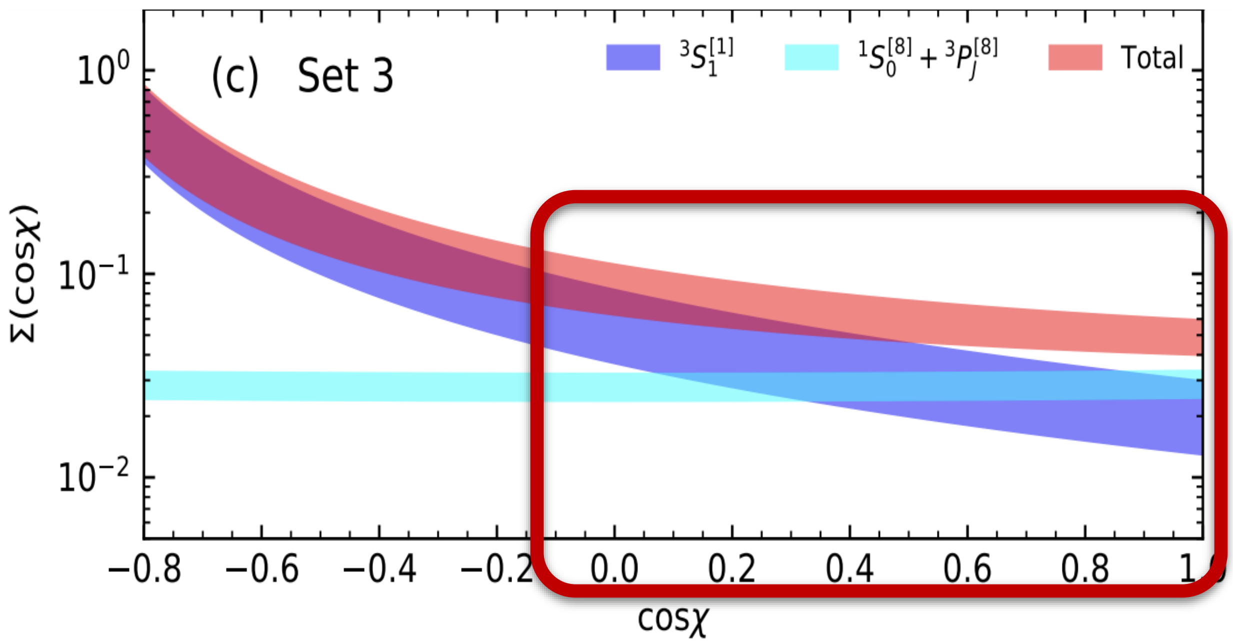
$E_{J_{away}} \sim \mathcal{O}\left(\frac{\hat{s}}{M}\right)$

Quarkonium Energy Correlator and hadronization

➢ **NRQCD Predictions:**

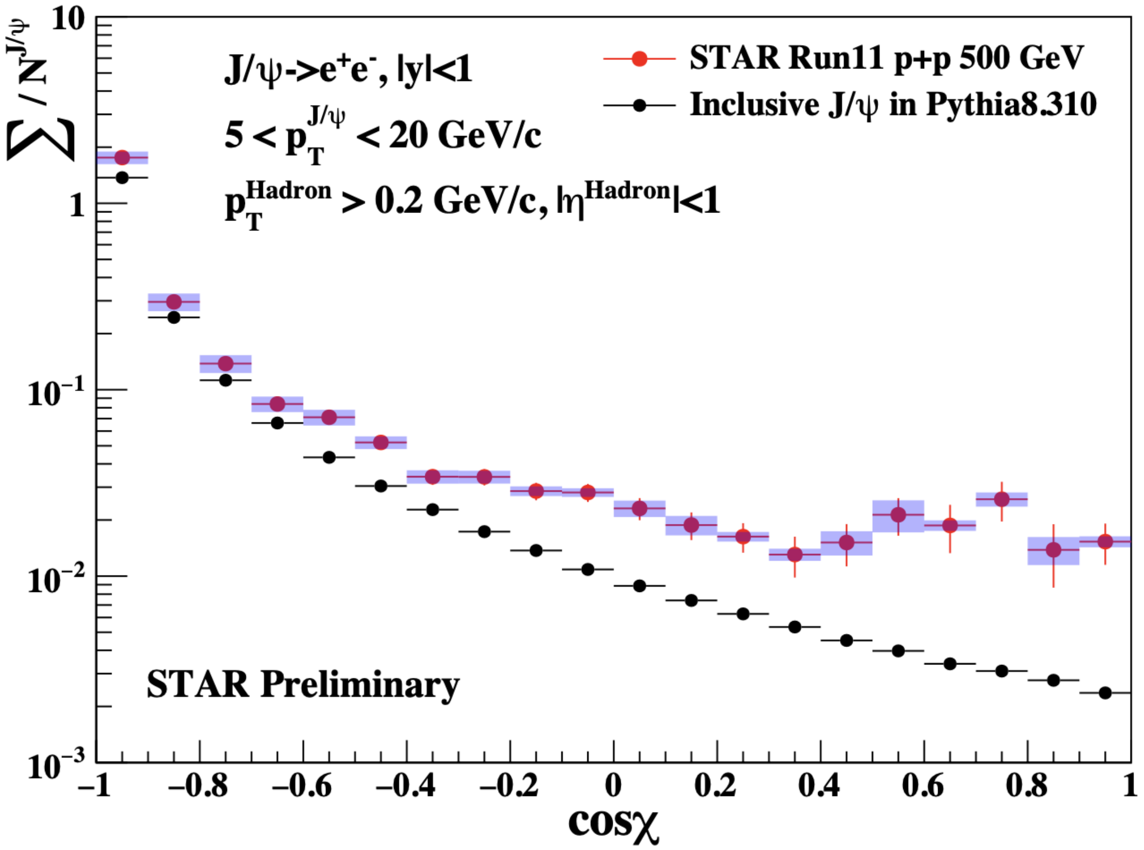
- NP model
  - $c\bar{c} \to J/\psi + g_s$
  - NRQCD matrix element scaling
  - HF spin (rotational co-variance) symmetry

$J/\psi@e^+e^- \quad \sqrt{s} = 10.6GeV$

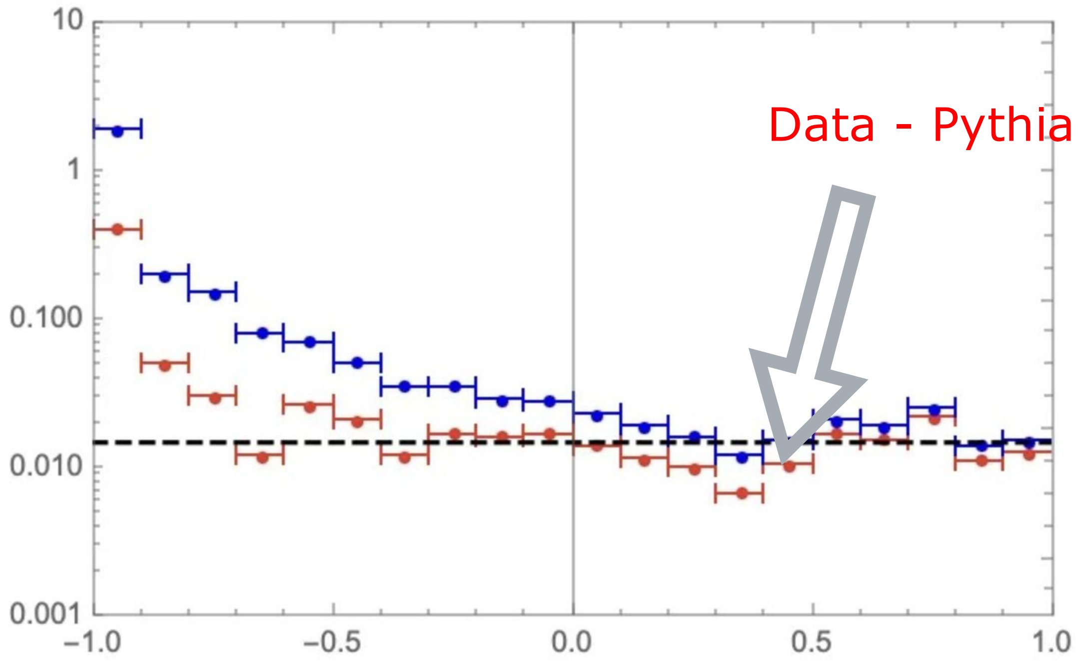


- Sizable hadronization effect
- "See" the hadronization energy distribution

Quarkonium Energy Correlator and hadronization



Dandan Shen's Poster @ QM 2025



- Data - Pythia consistent with the NRQCD NP model
- Have we seen the energy from hadronization? NEED precise INPUT!

Summary

- Difficulties: polarization puzzle, hierarchy problem, universality problem, negative cross sections, J/ψ-pair puzzle, high-order puzzle,…
  - Some of them have been resolved
  - Others still need to be investigated
- Quarkonium production mechanism: a very important topic
  - New theoretical ideas needed
  - New data needed: confirm previous data; test the spin symmetry; test the energy emitted during hadronization; …

Thank you!