Heavy quarkonia production at CEPC

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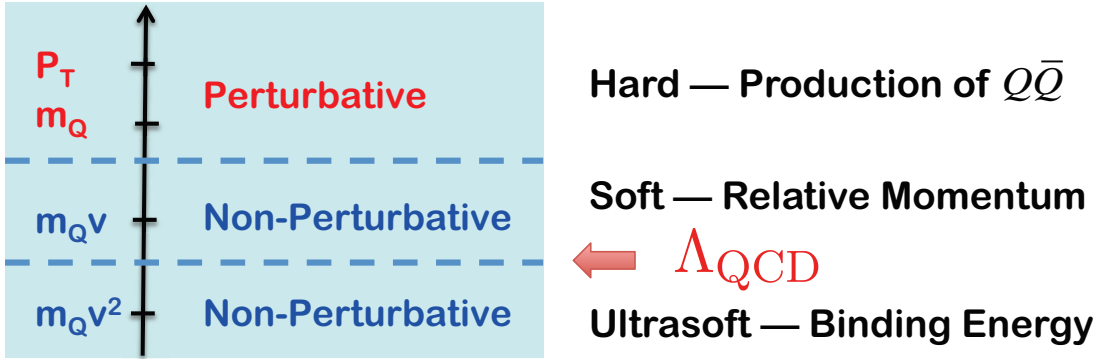
Outline

1. Introduction
2. Heavy quarkonium production through e^+e^- annihilation
3. Heavy quarkonium production in $\gamma\gamma$ collision
4. Summary

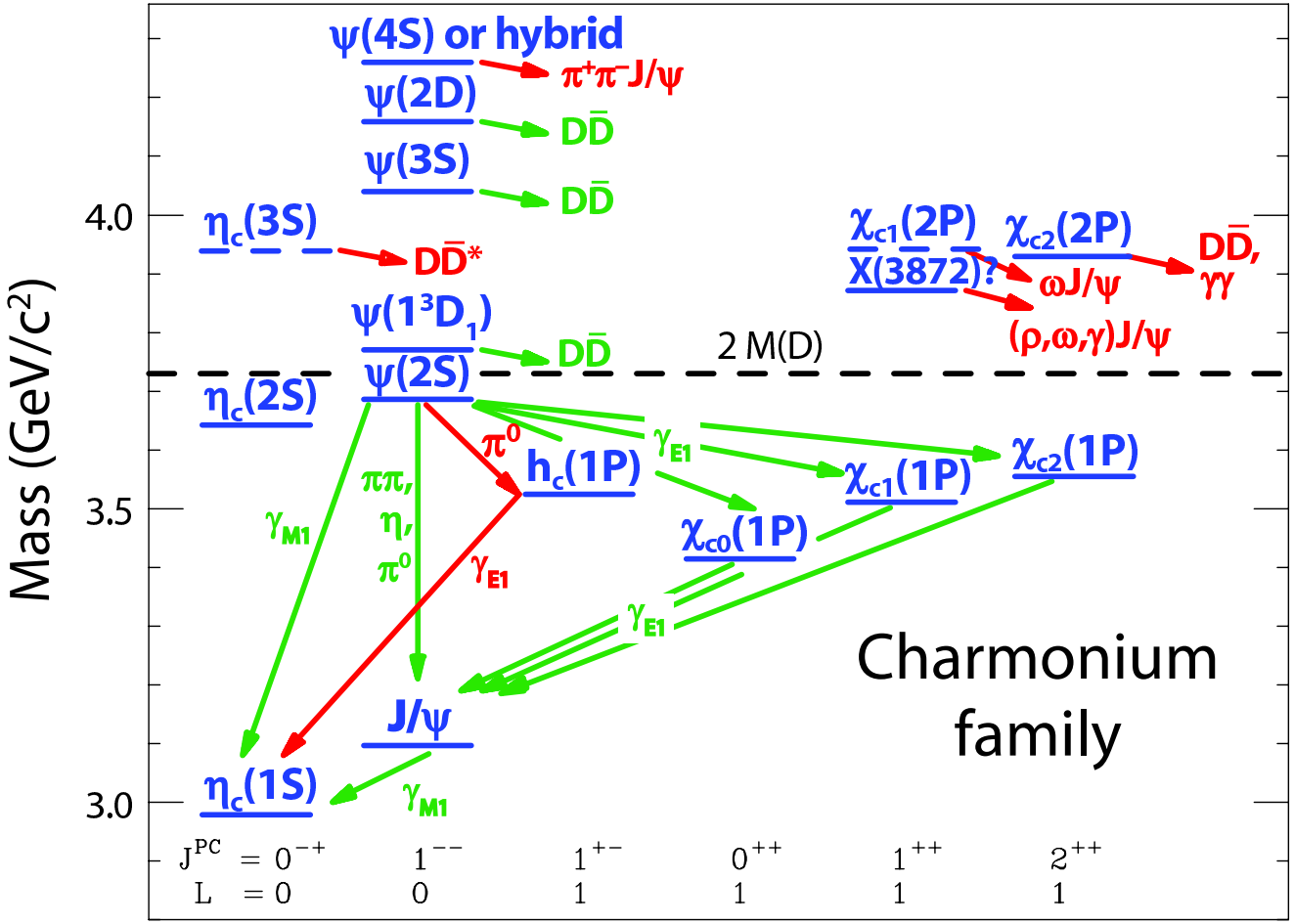
What is heavy quarkonium?

- Heavy quarkonium is one of the simplest QCD bound state constituted by heavy quark pair $Q\bar{Q}$ ($m_Q \gg \Lambda_{QCD}$).
- It is labeled by the spectroscpic notation $n^{2S+1}L_J$.
  - Its parity $P = (-1)^{L+1}$.
  - Its charge conjuagation parity $C = (-1)^{L+S}$.
- There are 3 typical energy scales besides Λ_{QCD}:

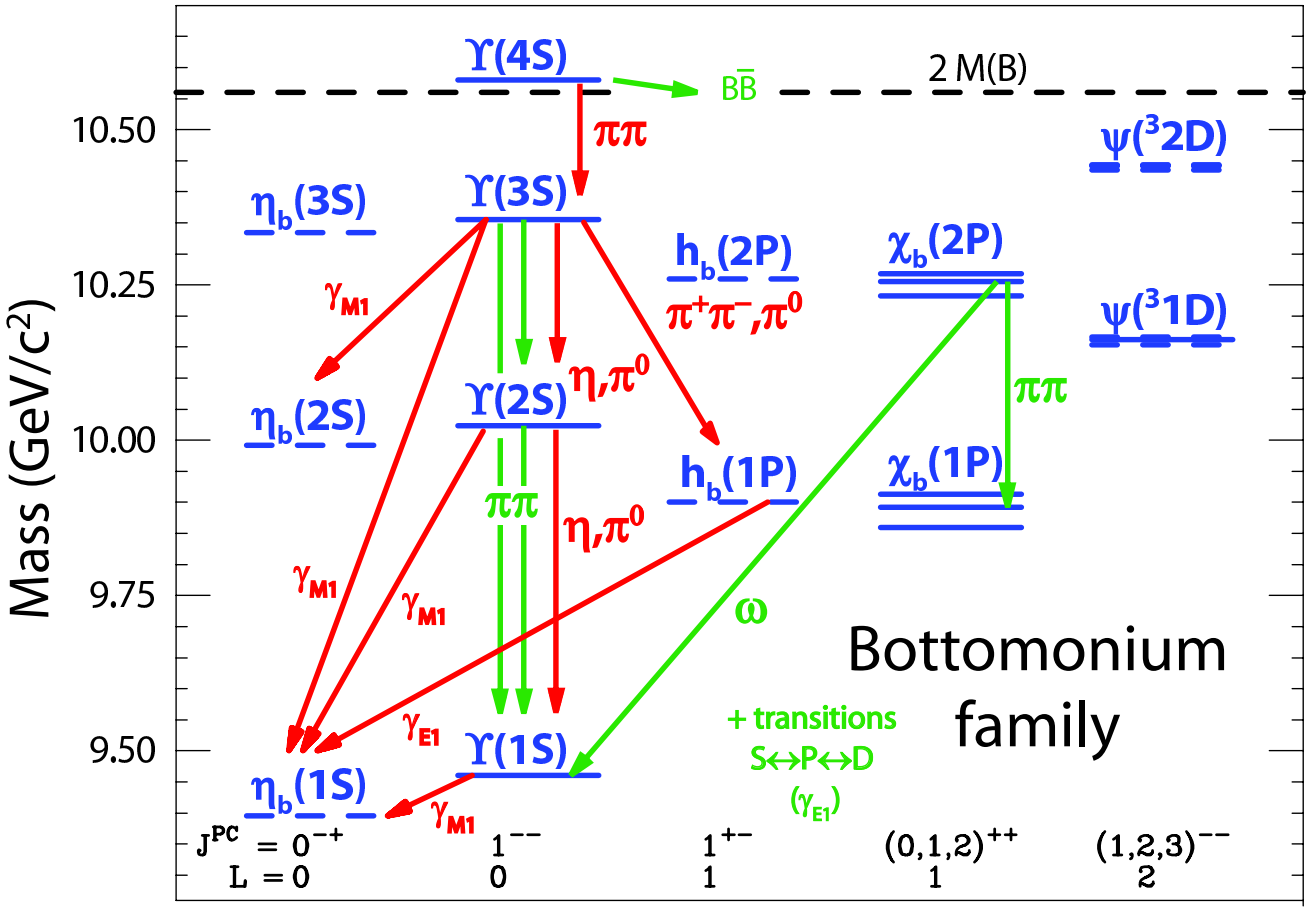


- It is an approximately non-relativistic system:
  - Charmonium: $v^2 \approx 0.23 \ll 1$
  - Bottomonium: $v^2 \approx 0.08 \ll 1$

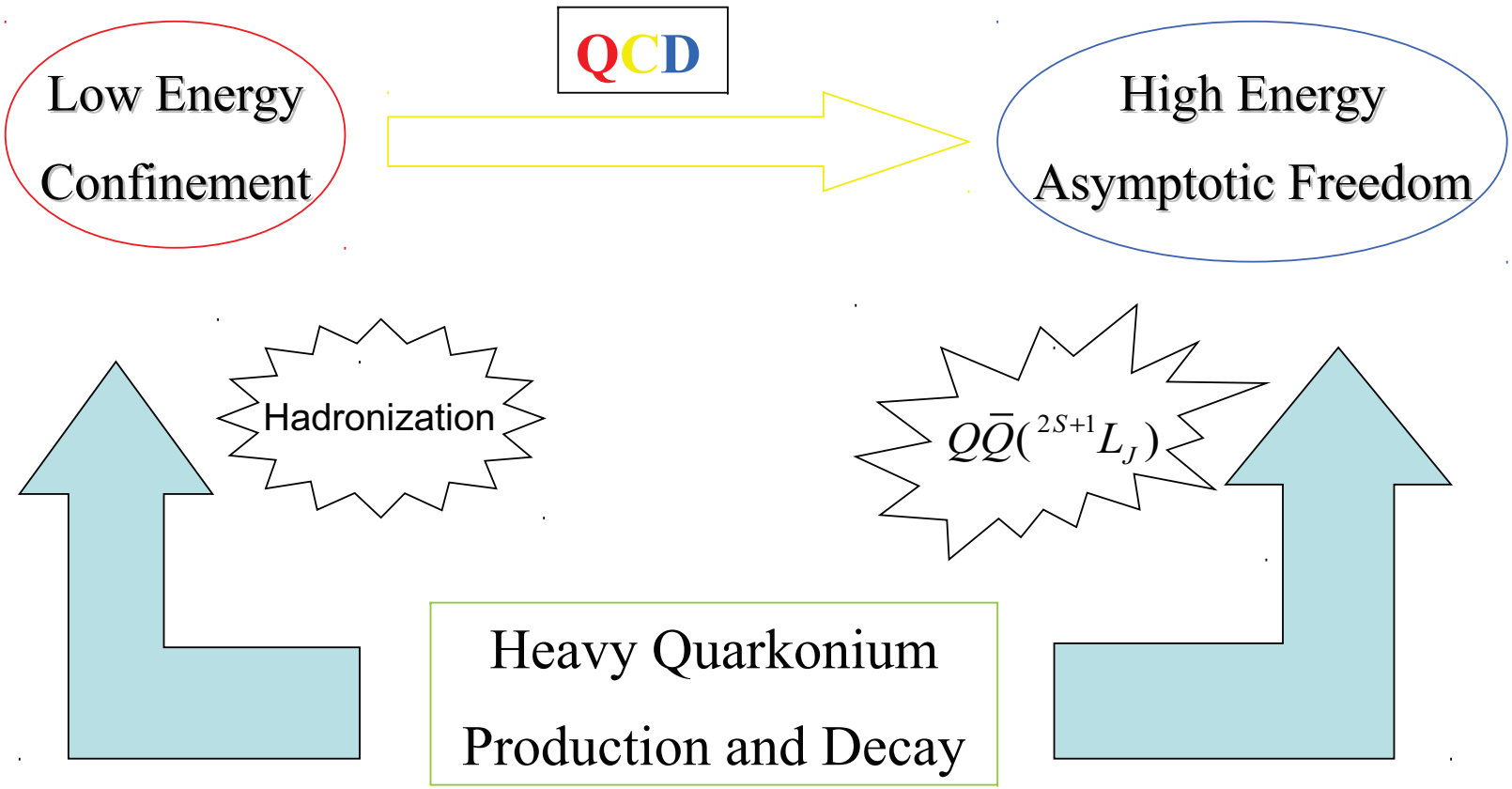
Charmonium family



Bottomonium family



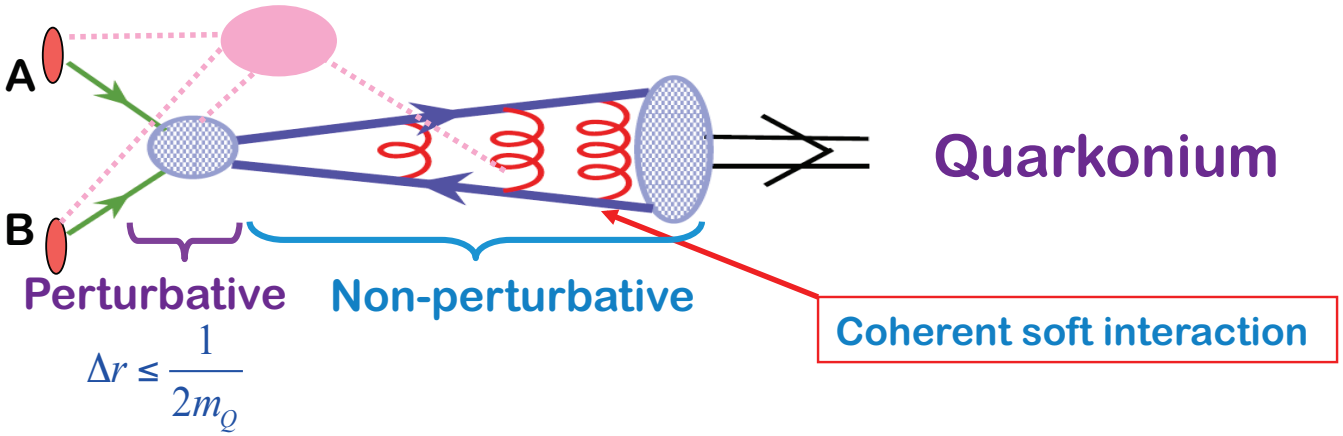
Why heavy quarkonium production?



J/ψ and Υ are ideal candidates for their large leptonic branching functions!

The picture of heavy quarkonium production

- $A + B \to \text{Quarkonium} + X$



- General Factorization Formula

$$\sigma_{(A+B\to J/\psi+X)} = \sum_n \int \sigma_{A+B\to(c\bar{c})_n+X} \times f[(c\bar{c})_n \to J/\psi]$$

Factorization models

Color Singlet Model

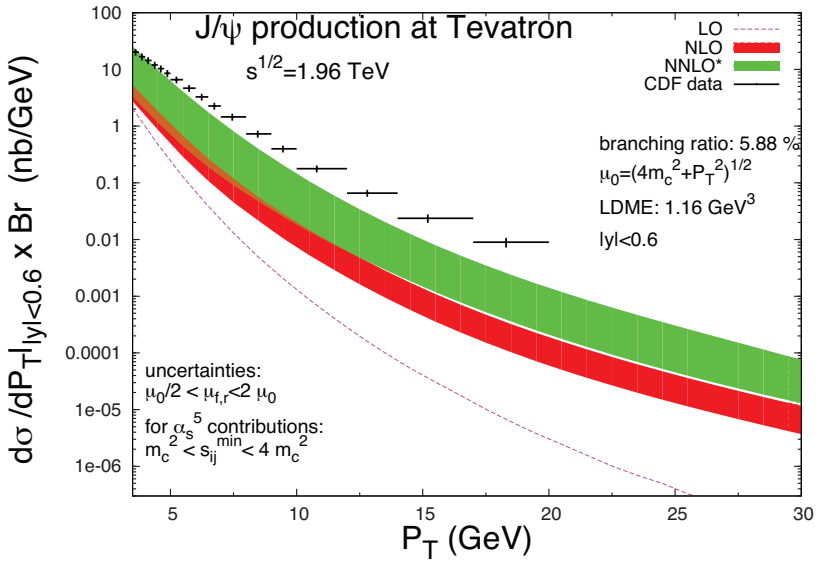
- Short Distance Part: The produced $Q\bar{Q}$ pair shares **the same quantum number** as the heavy meson.
- Long Distance Part: The non-relativistic wave function or its derivatives at origin.
- Non-factorizable in production and decay: S-wave relativistic corrections, P-wave at v^2 LO.

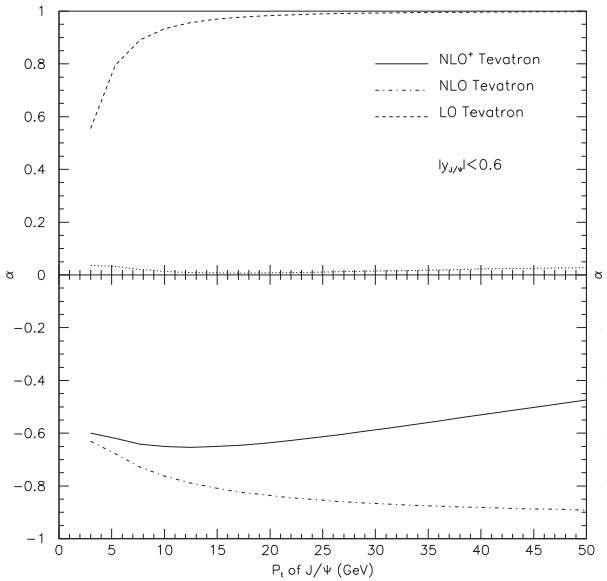
NRQCD Factorization Approach

- Short Distance Part: The produced $Q\bar{Q}$ pair can be **any possible quantum numbers**, even in **color octet**.
- Long Distance Part: The relative size of contribution from each Fock state obeys velocity scaling rules.
- The infrared divergence is absorbed into the QCD corrections to the long distance matrix elements.

CSM @ QCD NLO

- Comparison between CSM predictions at QCD NLO with CDF measurements for yield (left, Artoisenet 2008) and polarization (right,Gong et al .2008) of prompt J/ψ production:





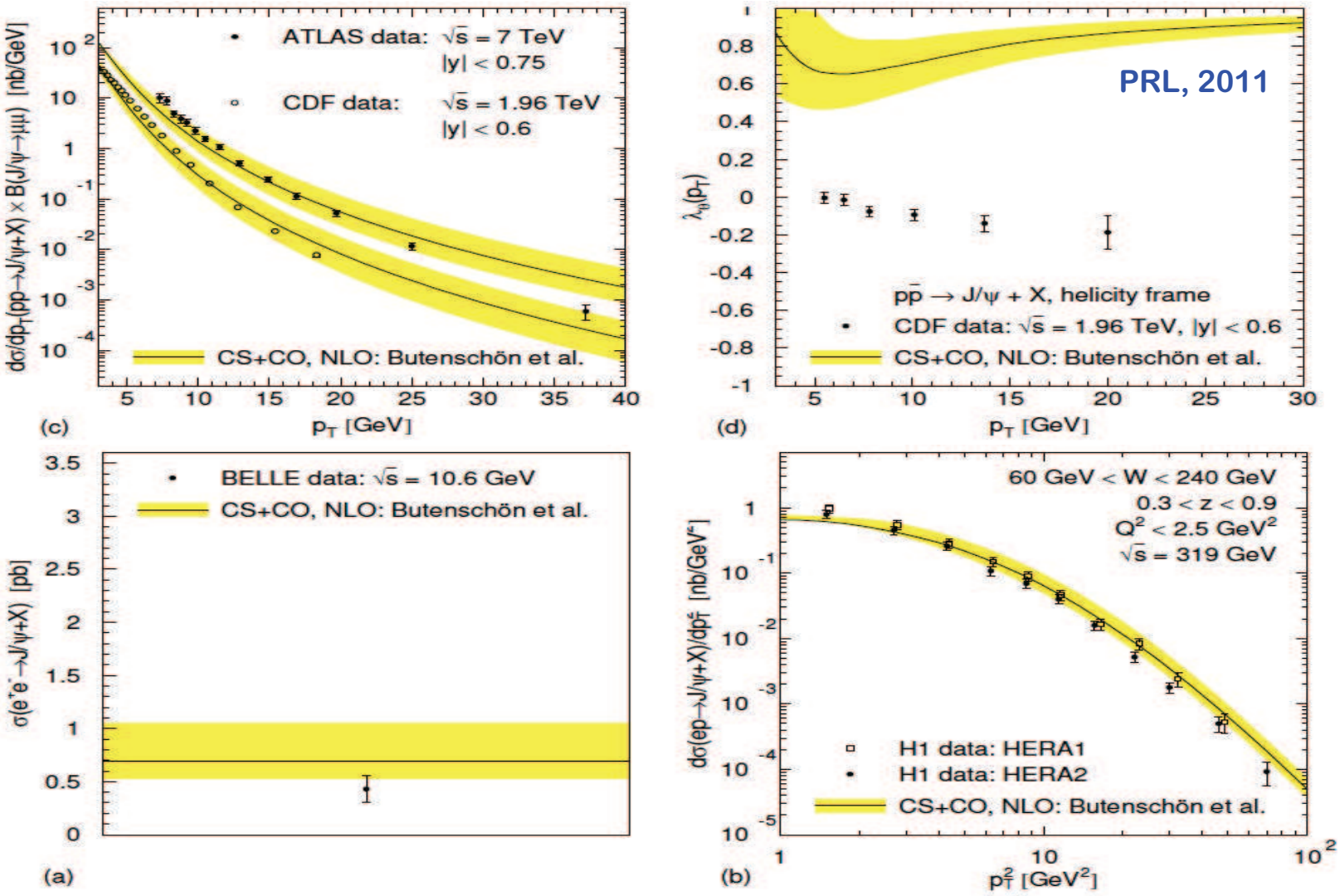
At QCD NLO, the CSM can neither explain J/ψ yield nor polarization distribution!! 😔

NRQCD@ QCD NLO

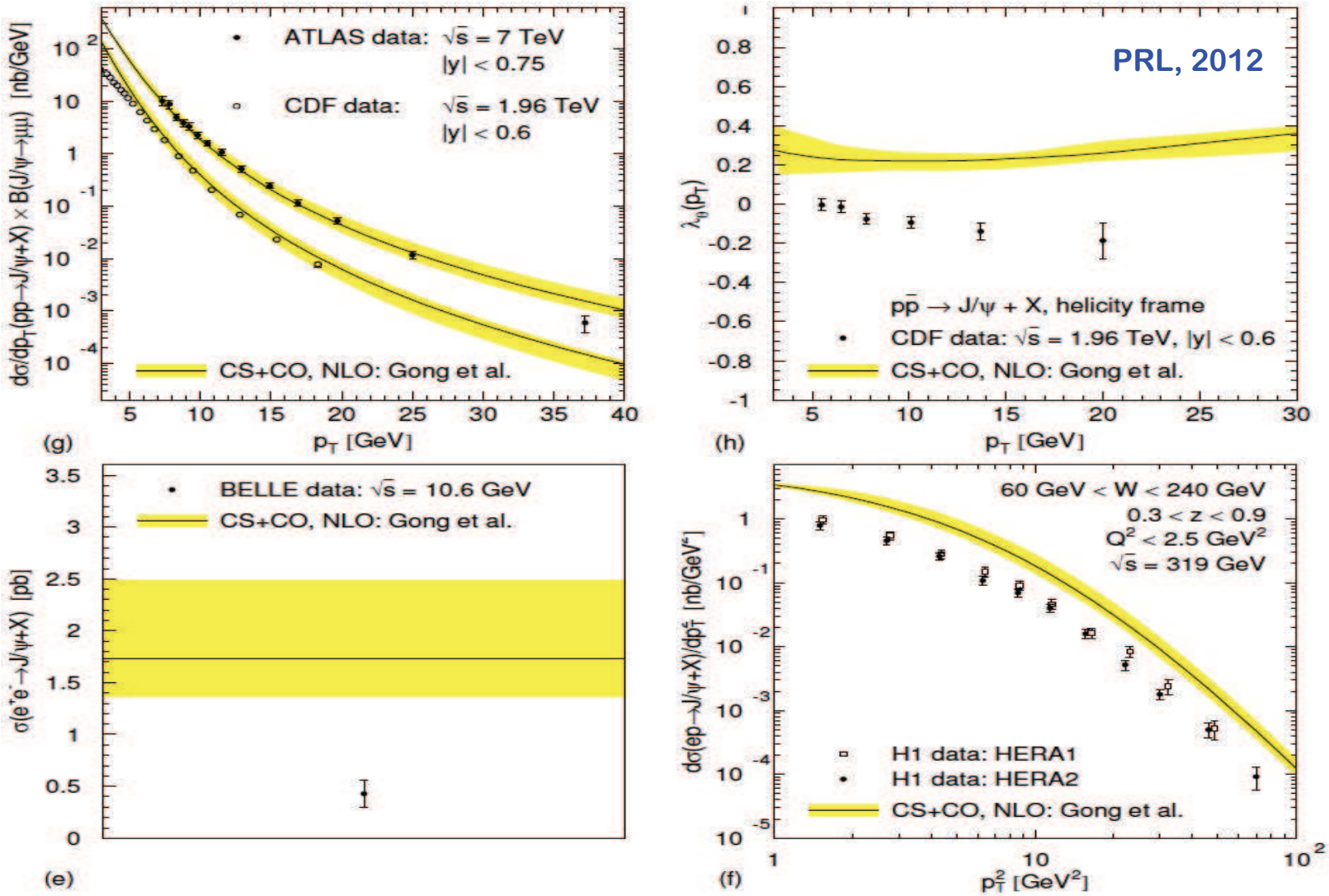
- SDCs: The SDCs for both yield and polarization including χ_c feed-down contribution were calculated by 3 groups independently. They are all in agreement with each other.
- Different sets of long-distance matrix elements (LDMEs) are obtained by fitting the SDCs @ QCD NLO to experimental data under different considerations leading to different predictions.

	Butenschön, Kniehl [4]	Chao, Ma, Shao, Wang, Zhang [6]	Gong, Wan, Wang, Zhang [7]
$\langle \mathcal{O}^{J/\psi}(^3S_1^{[1]})\rangle/\mathrm{GeV}^3$	1.32	1.16	1.16
$\langle \mathcal{O}^{J/\psi}(^1S_0^{[8]})\rangle/\mathrm{GeV}^3$	0.0304 ± 0.0035	0.089 ± 0.0098	0.097 ± 0.009
$\langle \mathcal{O}^{J/\psi}(^3S_1^{[8]})\rangle/\mathrm{GeV}^3$	0.0016 ± 0.0005	0.0030 ± 0.012	-0.0046 ± 0.0013
$\langle \mathcal{O}^{J/\psi}(^3P_0^{[8]})\rangle/\mathrm{GeV}^5$	-0.0091 ± 0.0016	0.0126 ± 0.0047	-0.0214 ± 0.0056
$\langle \mathcal{O}^{\chi_0}(^3P_0^{[1]})\rangle/\mathrm{GeV}^5$			0.107
$\langle \mathcal{O}^{\chi_0}(^3S_1^{[8]})\rangle/\mathrm{GeV}^3$			0.0022 ± 0.0005

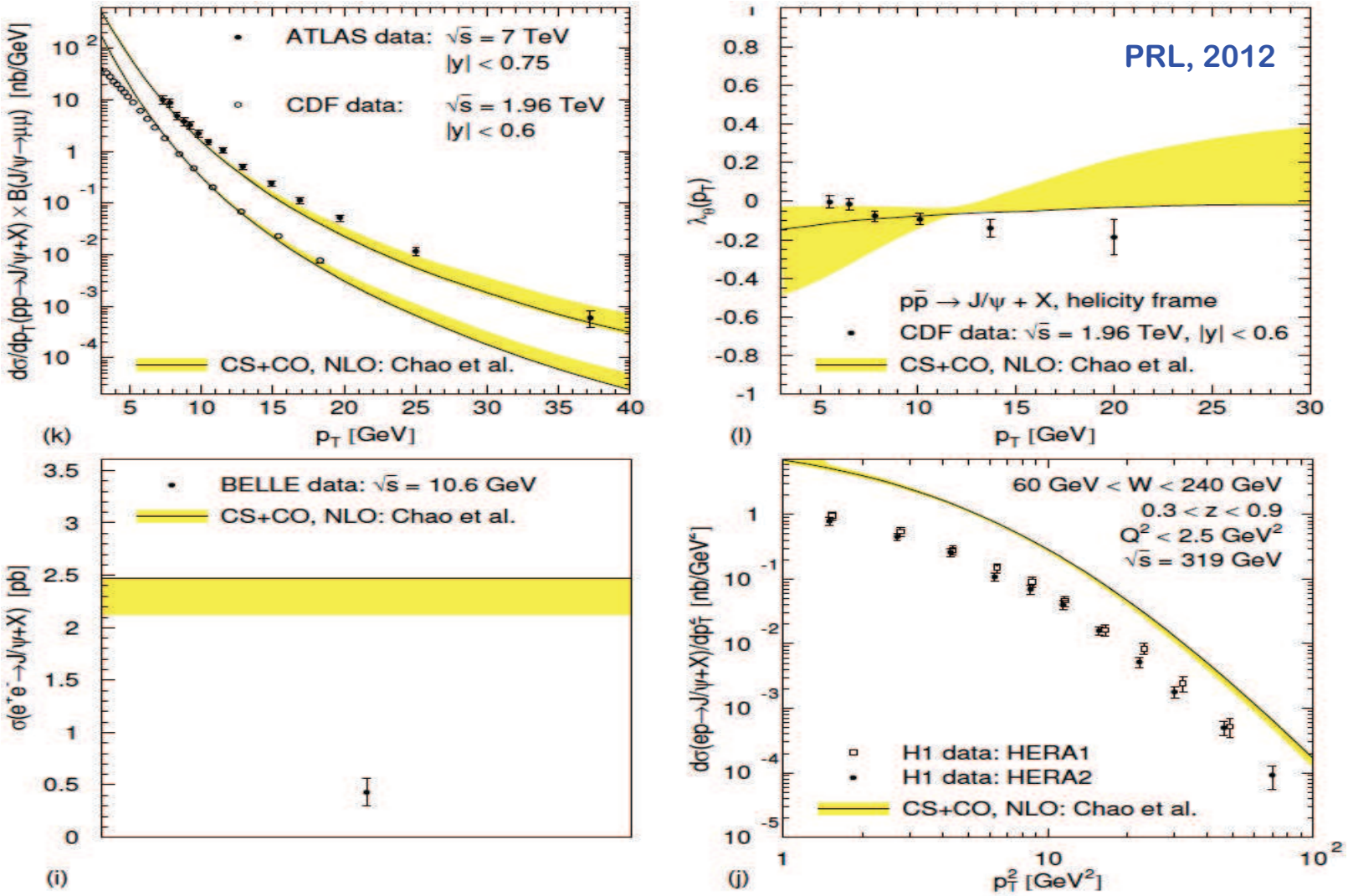
The results of Kniehl group



The results of Wang's group

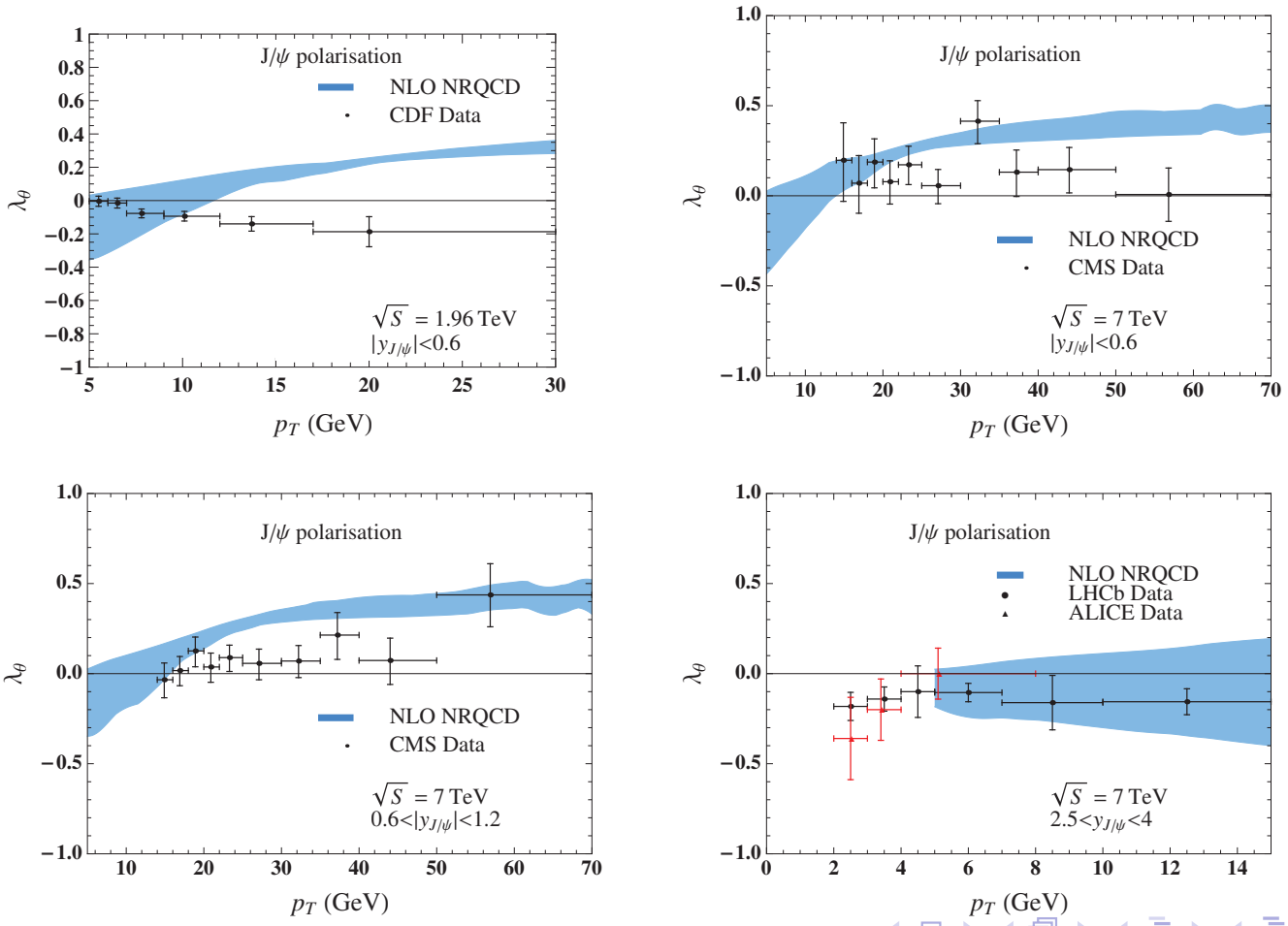


The results of Chao's group



The updated results of Chao's group

- Only the 2 combinations of three LDMEs, $M_{0,3.9} = (7.4 \pm 1.9) \times 10^{-2}$, $M_{0,0.56} = (0.05 \pm 0.02) \times 10^{-2}$ were obtained by fitting Tevatron yield data (Shao et al. 2015).



Prompt η_c hadroproduction

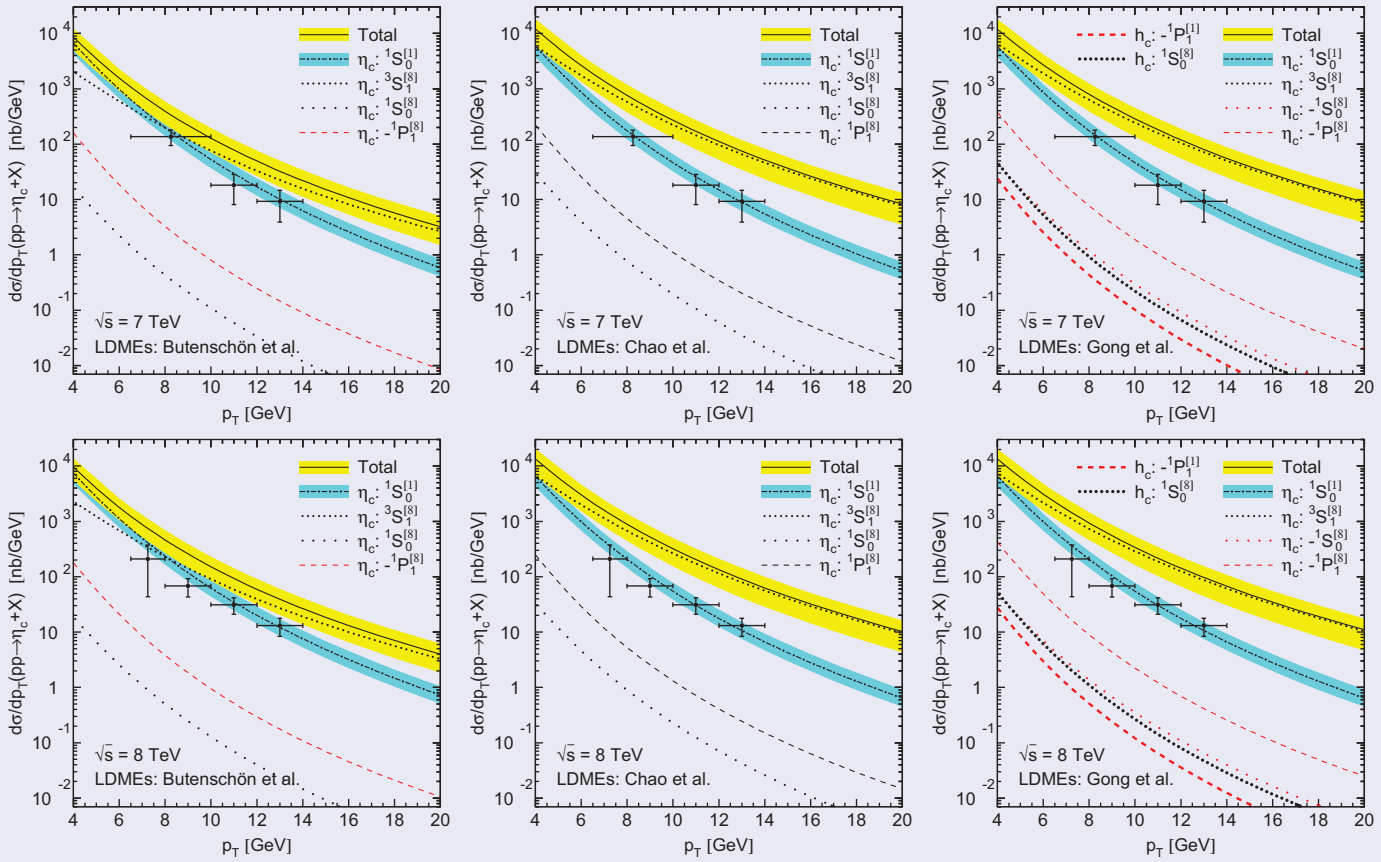
- η_c is another quarkonium state with $J^{PC} = 0^{-+}$ other than J/ψ with $J^{PC} = 1^{--}$, which can provide a new test on NRQCD factorization.
- In NRQCD, η_c is related to J/ψ through the heavy quark spin symmetry(HQSS), so do the corresponding LDMEs in their production. For example,

$$\langle \mathcal{O}^{\eta_c}(^1S_0^{[1,8]})\rangle = \frac{1}{3}\langle \mathcal{O}^{J/\psi}(^3S_1^{[1,8]})\rangle$$
$$\langle \mathcal{O}^{\eta_c}(^3S_1^{[8]})\rangle = \langle \mathcal{O}^{J/\psi}(^1S_0^{[8]})\rangle$$
$$\langle \mathcal{O}^{\eta_c}(^1P_1^{[8]})\rangle = 3\langle \mathcal{O}^{J/\psi}(^3P_0^{[8]})\rangle$$
$$\langle \mathcal{O}^{h_c}(^1P_1^{[1]}/^1S_0^{[8]})\rangle = \langle \mathcal{O}^{\chi_{c0}}(^3P_0^{[1]}/^3S_1^{[8]})\rangle$$

Its production provides an additional constrain on the LDMEs for J/ψ production.

NQCD prediction at QCD NLO

BREAKING OF NRQCD FACTORIZATION OR HQSS!



None of the three sets LDMEs can describe LHCb measurements. All the predictions are above the data (Butenschoen, **He**, and Kniehl 2015).

Advantage of heavy quarkonium production at e^+e^- collider?

- On theoretical aspect:
  - The production mechanism is relative simple. For example, in case of associated production, there is no double parton scattering mechanism.
  - Due to PDF choice and scale setting, the theoretical uncertainties for processes in e^+e^- collision is smaller than those in hadroproduction.
  - Normally, the convergence of theoretical calculation in α_s expansion is faster than that in hadroproduction.
- On experimental aspect:
  - The background of experimental measurements is relative clean, so he results can be very precise.
  - More channels can be investigated, such as quarkonium production plus photon or heavy quark pair, etc.
  - Heavy quarkonium, like η_c, χ_c, can also be detected, which can be used to study heavy quark spin symmetry among them.

Production modes of heavy quarkoium in e^+e^- collider

According to the properties of the intermediate state in the interaction, we can classify the production modes of heavy quarkonium into 2 types:

1. Direct production:
   The heavy quarkonium is produced not through the decay of other heavier quark, gauge boson (W,Z) or Higgs.
2. Indirect Production:
   The heavy quarkonium is produced through the decay of other heavy particles.

Mathematically, in the later case, the production rate of heavy quarkonium can be factorized into the production rate of other heavier particle times the corresponding branching function of the heavier particle decay.

Heavy quarkoium direct production in e^+e^- collision

- There are mainly 2 inclusive processes:
  (a) $e^+e^- \to \mathrm{quarkonium} + \mathrm{Q\bar{Q}} + \mathrm{X}$,
  (b) $e^+e^- \to \mathrm{quarkonium} + \mathrm{X}_{\mathrm{non-Q\bar{Q}}}$.
- Measurment @ $\sqrt{s} = 10.6\ \mathrm{GeV}$ by Belle Collaboration: (Belle 2009):

$$\sigma(e^+e^- \to J/\psi + c\bar{c}) = 0.74 \pm 0.08^{+0.09}_{-0.08}\ \mathrm{pb}$$
$$\sigma(e^+e^- \to J/\psi + X_{\mathrm{non-c\bar{c}}}) = 0.43 \pm 0.09 \pm 0.09\ \mathrm{pb}$$

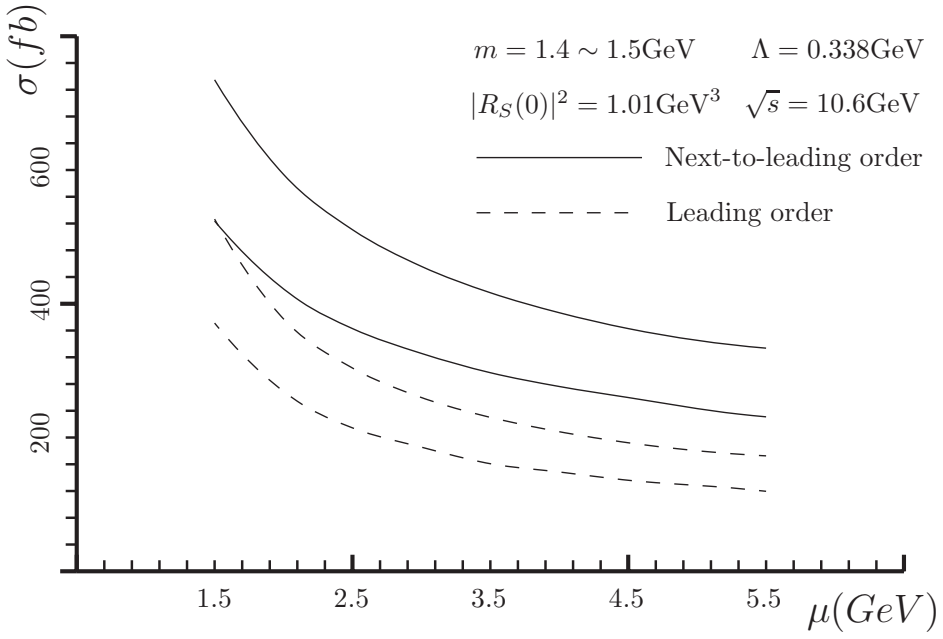
- NRQCD prediction at QCD and v^2 LO are (Yuan et al. 1997):

$$\sigma(e^+e^- \to J/\psi + c\bar{c}) = 0.15\ \mathrm{pb}$$
$$\sigma(e^+e^- \to J/\psi + X_{\mathrm{non-c\bar{c}}}) \approx 1\ \mathrm{pb},$$

where the CS contribution to the $\mathrm{non-c\bar{c}}$ process is about 0.2 pb.

$J/\psi + c\bar{c}$ production I

- Both NLO QCD and relativistic corrections were calculated. The relativistic correction is so tiny that can be ignored (**He** et al. 2007), however the NLO QCD correction is large and the theoretical prediction is $0.53^{+0.59}_{-0.23}$ pb (Zhang et al. 2007).
- The μ and m_c dependence(Zhang et al. 2007):

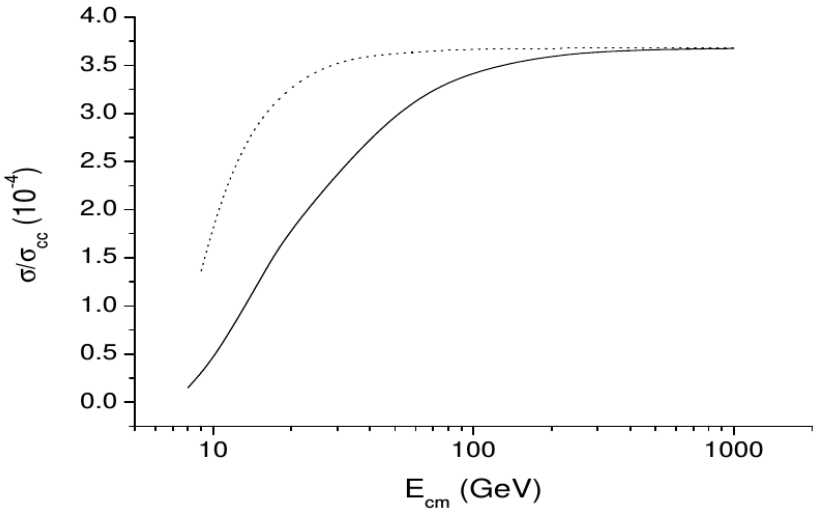


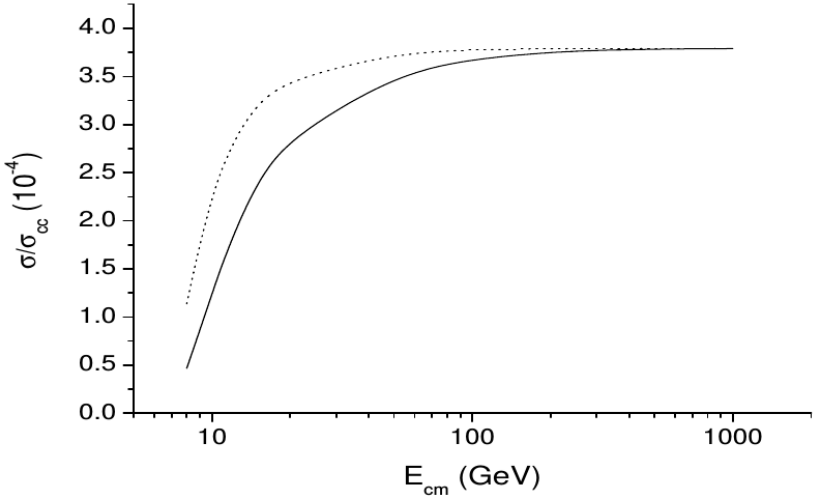
$J/\psi + c\bar{c}$ production II

- To confirm the compatible between NRQCD/CSM prediction at QCD NLO and Belle measurement, and understanding the scale and heavy quark mass setting theoretically, it is necessary to perform the measurement at some other higher energy point.
- Belle can only measure charmonium+$c\bar{c}$ production. At CEPC the bottomonium+$b\bar{b}$ process can also be studied.
- For such processes the CO contribution can be ignored, and v^2 correction is tiny. Comparison between perturbative calculation and experimental measurements can help to extract the CS LDME in NRQCD, which is related to the wave function of quarkonium.

Fragmentation function from e^+e^- collision

- At high energy the predominant contribution is from heavy quark fragmentation. However, $\sqrt{s} = 10.6\mathrm{GeV}$ is too small to extract the information of fragmentation function $Q \to \mathrm{Quarkonium}$.
- The fragmentaion calculation(dotted line) v.s. exact calculation (solid line) for η_c(left) and J/ψ(right) cases(Liu, **He**, and Chao 2003):





The fragmentation function can only be extracted at $\sqrt{s} > 100\mathrm{GeV}$, which is covered by CEPC.

$J/\psi + X_{\mathrm{non-c\bar{c}}}$ production

- For the CS channel $e^+e^- \to J/\psi + gg$, after including the NLO QCD and relativistic corrections, the K-factors of which are both about 1.2, the total cross section is (**He** et al. 2010):

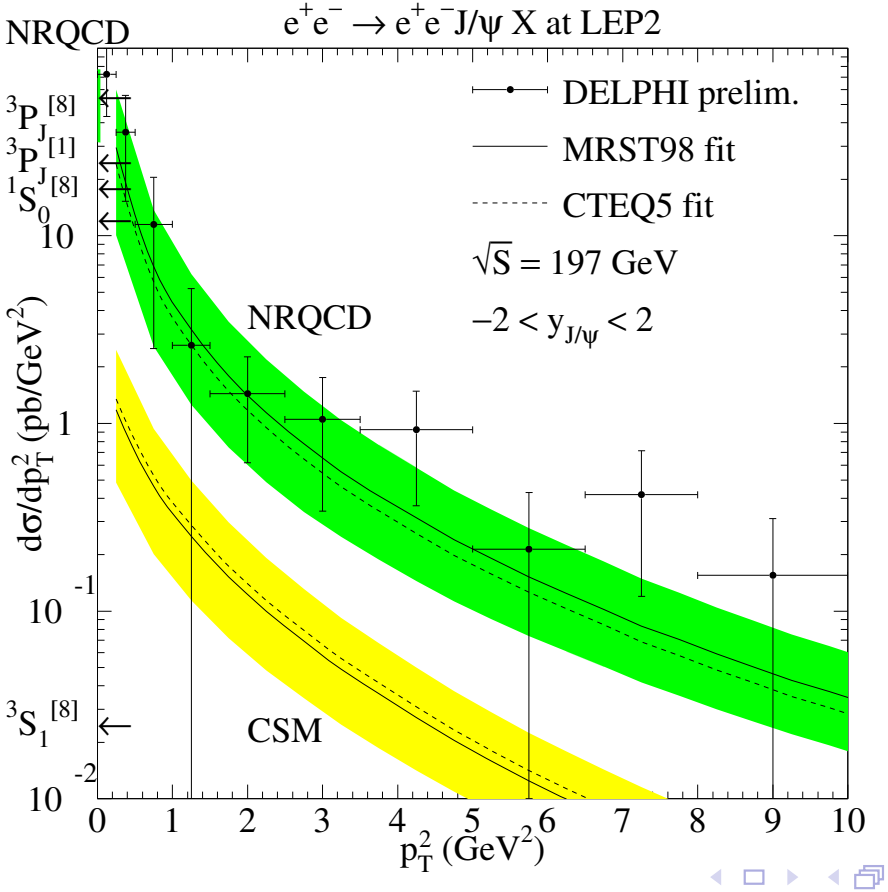
$$\sigma_{\mathrm{NLO}(\mathrm{v_c^2},\alpha_\mathrm{s})}(e^+e^- \to J/\psi + gg) \simeq 437\ \mathrm{fb}$$

  for $\mu = \sqrt{s}/2$ and $m_c = 1.5\mathrm{GeV}$.
- The NLO QCD corrections to $e^+e^- \to c\bar{c}(^1S_0^{[8]}, ^3P_J^{[8]}) + g$ CO channels were also calculated and the lowest value predicted by using LDME set from Kniehl group is around 0.3pb (Zhang et al. 2010).

The e^+e^- data collected by Belle disfavor CO mechanism! However, the results from Babar still leave room for CO contribution! Measurement at higher energy is needed!

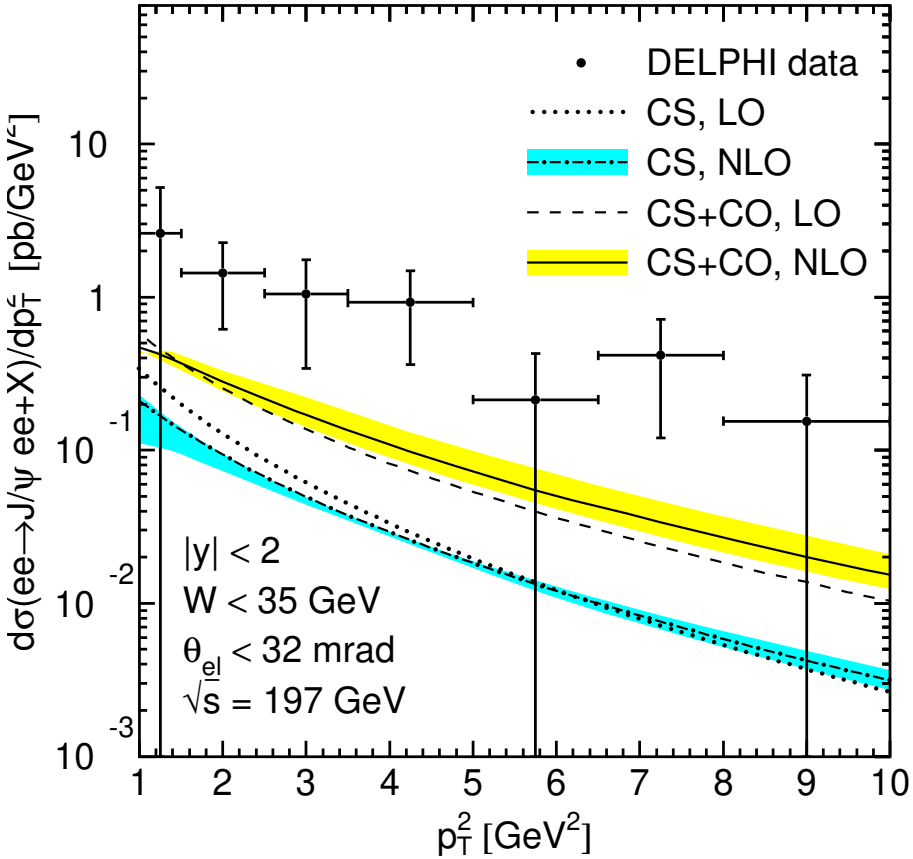
J/ψ production in $\gamma\gamma$ collision I

- The J/ψ production in $\gamma\gamma$ collision was first measured at LEP, which is one of the earliest evidences on CO mechanism.
- Comparison between NRQCD prediction at LO with LEP2 data (Klasen et al. 2001):



J/ψ production in $\gamma\gamma$ collision II

- The NLO QCD corrections to CS channel is small.
- After including the NLO QCD corrections to CO channel and refitting the LDMEs, even the CO contribution can not explain the data (Butenschoen and Kniehl 2011):

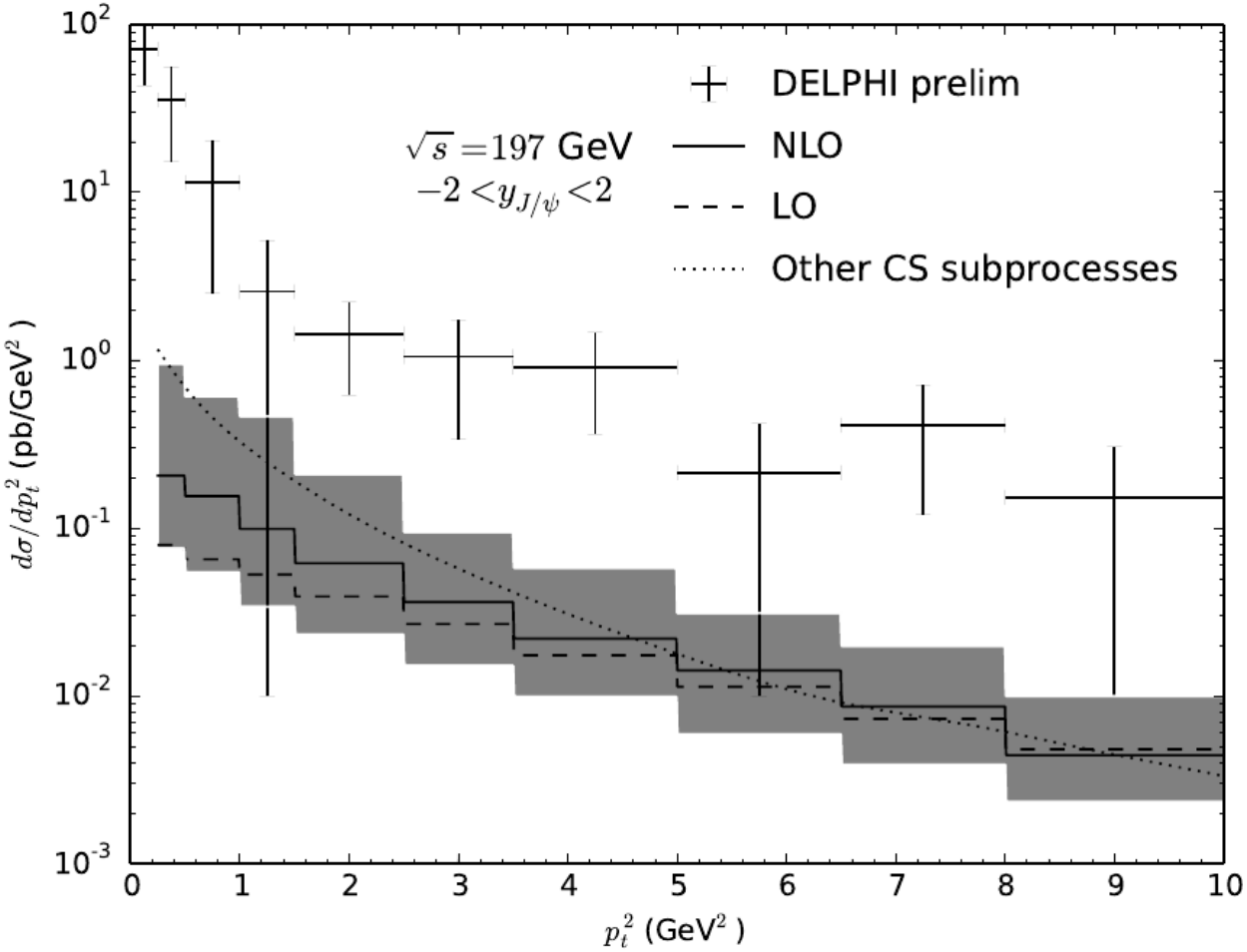


J/ψ production in $\gamma\gamma$ collision III

- However the uncertainties of experimental measurement is large. Only 36 ± 7 events of $J/\psi \to \mu^+\mu^-$ are collected with integrated luminosity $617\mathrm{pb}^{-1}$.
- The expected integrated luminosity of CEPC is of ab^{-1} order, which is about 3 orders of magnitude larger than LEP2 case.
- The much more precise measurements will be surely helpful to investigate J/ψ production mechanism in $\gamma\gamma$ collision.
- Such large amount of data sample even make it possible to study $J/\psi + c\bar{c}$ production in $\gamma\gamma$ collision.

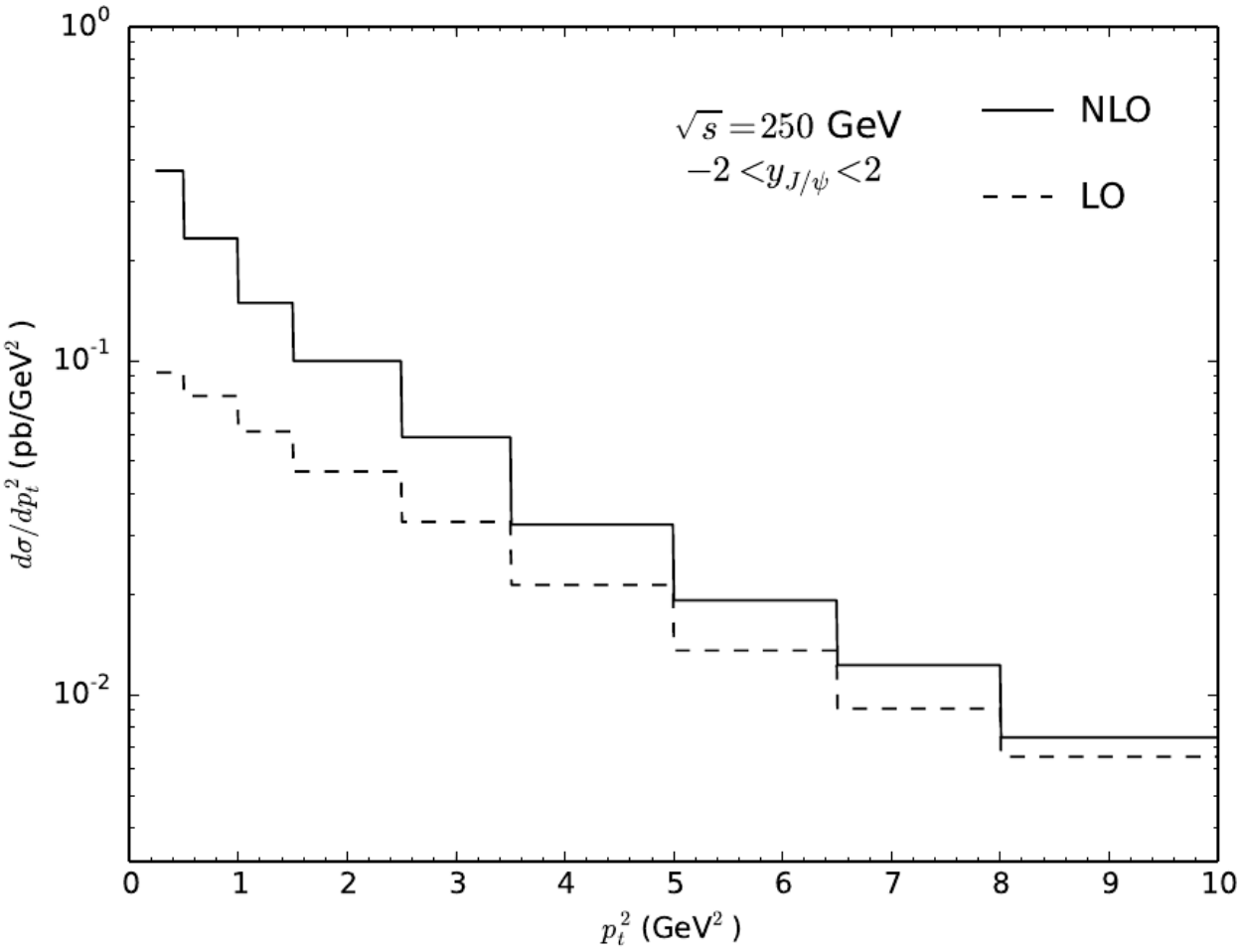
$J/\psi + c\bar{c}$ production in $\gamma\gamma$ collision I

- Recently, the NLO QCD correction to $J/\psi + c\bar{c}$ production was obtained, and compared with LEP2 measurement of J/ψ production (Chen et al. 2017).



$J/\psi + c\bar{c}$ production in $\gamma\gamma$ collision II

- At $\sqrt{s} = 250$ GeV, the differential cross sections becomes around 2 times larger (Chen et al. 2017).



In summary

- The e^+e^- collider like CEPC is a very good complement of hadron collider to study heavy quarkonium production mechanism.
- CEPC will enrich studying heavy quarkonium at different energy and will provide an independent check of the conclusion about NRQCD predictions and Belle measurements.
- The higher integrated luminosity and higher collision energy make it possible to study bottomonium production.
- The fragmentation information of $Q \to \mathrm{quarkonium}$ may be extracted as well.
- CEPC is also helpful to clarify the J/ψ production puzzle in $\gamma\gamma$ collision.

Thank you!