Quarkonium Physics at CEPC

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Workshop on CEPC Physics
IHEP, Beijing, Dec. 13th-15th , 2016

Study of QCD

- **Test QCD: perturbation theory**

  Test RGE running of important quantities, α_s, PDFs and FFs

- **Understanding the QCD: nonperturbative**

  Confinement, hadronization

Outline

Quarkonium: test twist-4 effects

Quarkonium: study hadronization mechanism

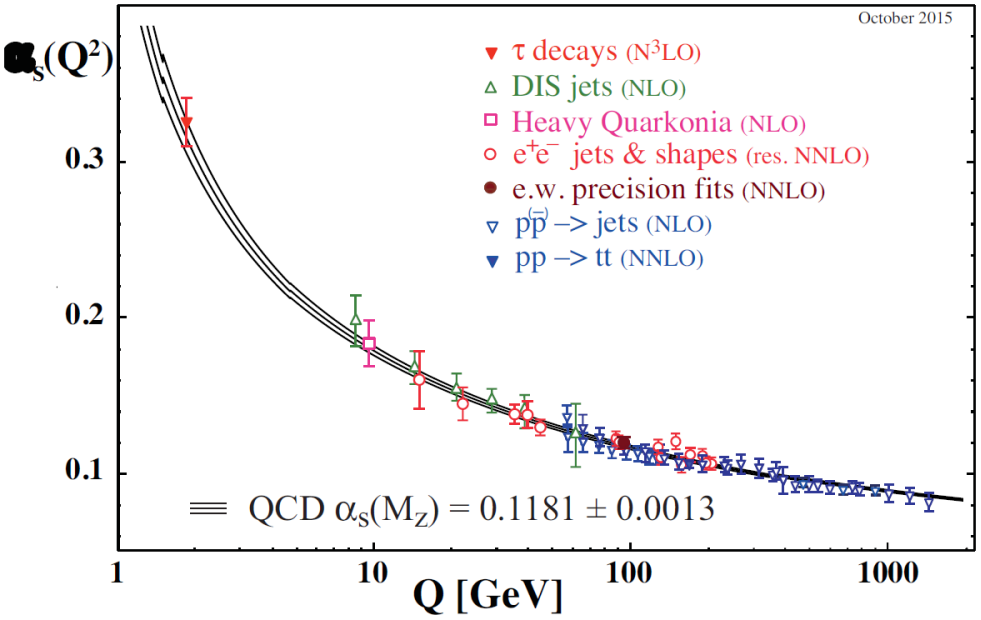
Fundamental parameter of QCD: α_s

- α_s running

$$\mu_R^2 \frac{d\alpha_s}{d\mu_R^2} = \beta(\alpha_s) = -(b_0\alpha_s^2 + b_1\alpha_s^3 + b_2\alpha_s^4 + \cdots)$$

b_i pQCD calculable: e.g.

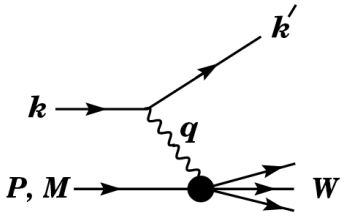
$$b_0 = (11C_A - 4n_f T_R)/(12\pi) = (33 - 2n_f)/(12\pi)$$



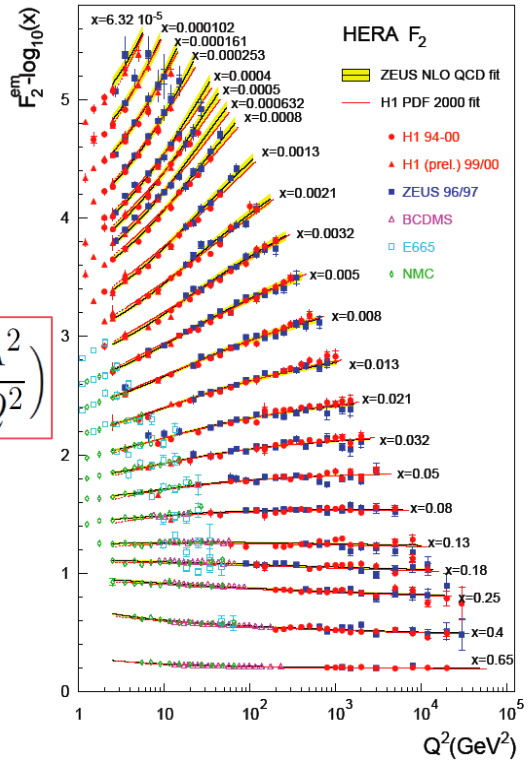
- Data (running) agree well with QCD prediction
- e^+e^- data: big contribution

Twist expansion for QCD

➢ DIS structure function



$$F_2(x,Q^2) = x\sum_{n=0}^{\infty}\frac{\alpha_s^n(\mu_R^2)}{(2\pi)^n}\sum_{i=q,g}\int_x^1\frac{dz}{z}C_{2,i}^{(n)}(z,Q^2,\mu_R^2,\mu_F^2)\,f_{i/p}\left(\frac{x}{z},\mu_F^2\right) + \mathcal{O}\left(\frac{\Lambda^2}{Q^2}\right)$$



➢ DGLAP evolution

$$\mu_F^2\frac{\partial f_{i/p}(x,\mu_F^2)}{\partial\mu_F^2} = \sum_j\frac{\alpha_s(\mu_F^2)}{2\pi}\int_x^1\frac{dz}{z}P_{i\leftarrow j}^{(1)}(z)f_{j/p}\left(\frac{x}{z},\mu_F^2\right)$$

Similar for fragmentation function

➢ Twist-2: evolution well tested

➢ How about higher twist effects?

Higher twist effects

- **Twist-4 contribution: studied long times ago**

  Hard to observe, $O(\frac{\Lambda_{\mathrm{QCD}}^2}{Q^2})$ contribution is highly suppressed

- **Current hot topic: double parton scattering**

  Modeling: $\sigma_{A+B} \approx \frac{\sigma_A \sigma_B}{\sigma_{eff}}$, σ_{eff} cannot be process independent, more theoretic studies needed.
  If confirmed, twist-4 effects, but QCD evolution is hard

- **Quarkonium production at CEPC: twist-4 effects**

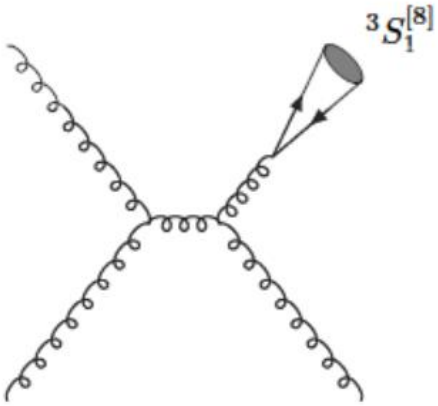
  Significant signal, well established theory, test QCD rigorous

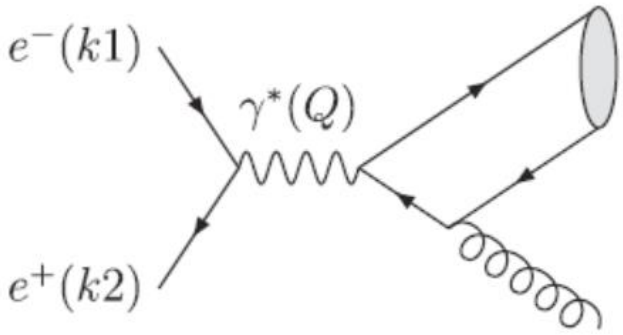
Quarkonium: test twist 4

- **twist-4 contributions for quarkonium:**

$O(\frac{m_Q^2}{Q^2})$ **suppression instead of** $O(\frac{\Lambda_{QCD}^2}{Q^2})$

- pp **collision: dominated by gluon fragmentation, twist-4 contributions suppressed**





- e^+e^- **collision: gluon fragmentation suppressed by** α_s**, twist-4 contributions important**

Factorization theory for quarkonium

➢ Pictrue:

$$E\frac{d\sigma_{J/\psi}}{d^3P}: \left| \quad + \quad + \ldots \right|^2 \approx \log^n\left(\frac{P_T^2}{\mu_0^2}\right) + \mu_0^2 \log^n\left(\frac{P_T^2}{\mu_0^2}\right) + \ldots$$

$$+ \mathcal{O}\left(\frac{1}{P_T^4}\right) \qquad + \mathcal{O}\left(\frac{1}{P_T^6}\right)$$

➢ Factorization correct to all order

Qiu, Sterman (1991)
Kang, YQM, Qiu, Sterman, 1401.0923

➢ Factorization formalism:

produce pair at $1/m_Q$

$$d\sigma_{A+B\to H+X}(p_T) = \sum_f d\hat{\sigma}_{A+B\to f+X}(p_f = p/z) \otimes D_{H/f}(z, m_Q)$$

$$+ \sum_{[Q\bar{Q}(\kappa)]} d\hat{\sigma}_{A+B\to[Q\bar{Q}(\kappa)]+X}(p(1\pm\zeta)/2z, p(1\pm\zeta')/2z) \otimes \mathcal{D}_{H/[Q\bar{Q}(\kappa)]}(z, \zeta, \zeta', m_Q)$$

$$+ \mathcal{O}(m_Q^4/p_T^4)$$

produce pair at $1/p_T$

Twist-4 evolution equation

- **Independence of the factorization scale:**

$$\frac{d}{d\ln(\mu)}\sigma_{A+B\to HX}(P_T)=0$$

- **Evolution equations at NLP:** Kang, YQM, Qiu, Sterman, 1401.0923

produce pair between $[1/p_T,\ 1/m_Q]$

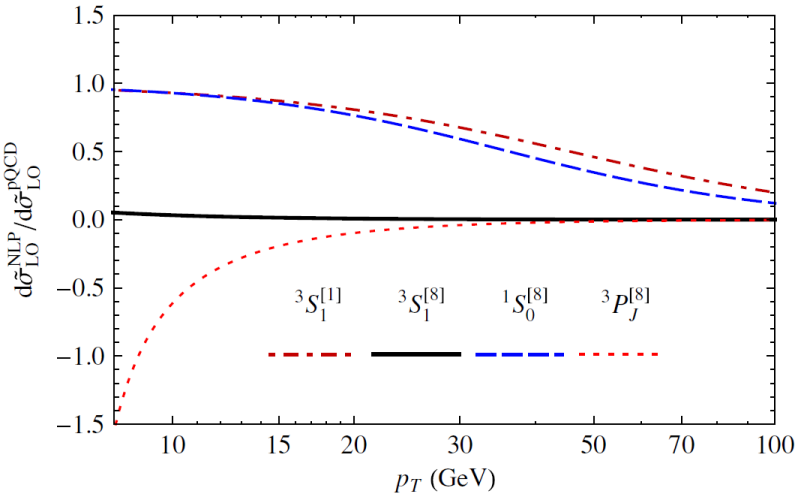
$$\frac{d}{d\ln\mu^2}D_{H/f}(z,m_Q,\mu)=\sum_j\frac{\alpha_s}{2\pi}\gamma_{f\to j}(z)\otimes D_{H/j}(z,m_Q,\mu)$$
$$+\frac{1}{\mu^2}\sum_{[Q\bar{Q}(\kappa)]}\frac{\alpha_s^2}{(2\pi)^2}\Gamma_{f\to[Q\bar{Q}(\kappa)]}(z,\zeta,\zeta')\otimes\mathcal{D}_{H/[Q\bar{Q}(\kappa)]}(z,\zeta,\zeta',m_Q,\mu)$$

$$\frac{d}{d\ln\mu^2}\mathcal{D}_{H/[Q\bar{Q}(c)]}(z,\zeta,\zeta',m_Q,\mu)=\sum_{[Q\bar{Q}(\kappa)]}\frac{\alpha_s}{2\pi}K_{[Q\bar{Q}(c)]\to[Q\bar{Q}(\kappa)]}(z,\zeta,\zeta')$$
$$\otimes\mathcal{D}_{H/[Q\bar{Q}(\kappa)]}(z,\zeta,\zeta',m_Q,\mu)$$

Large $\log(p_T/m)$: can be resumed by solving evolution equation

Significance of twist-4 effects

➢ NLP (twist-4) can be very important

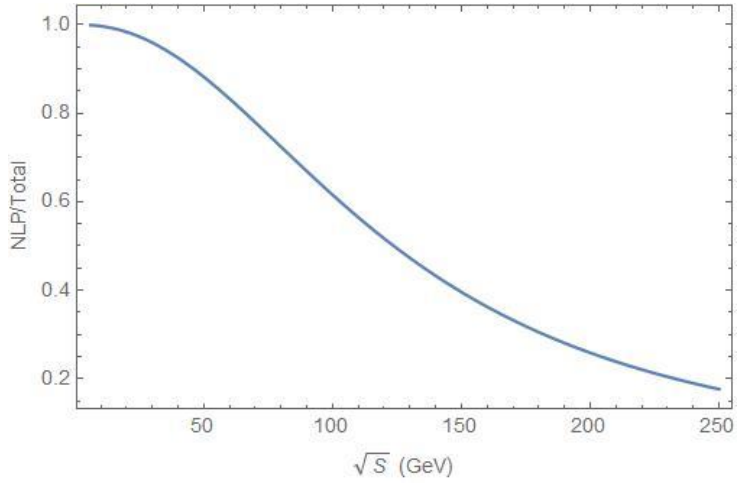


YQM, Qiu, Sterman, Zhang, 1407.0383

- LP dominates: $^3S_1^{[8]}$ and $^3P_J^{[8]}$ channels
- NLP dominates: $^1S_0^{[8]}$ and $^3S_1^{[1]}$ channels

Significance of twist-4 effects

➢ Relative importance of twist-4: J/ψ



- Twist 4 contributes 20% when $\sqrt{S} = 250$GeV
- Even relatively larger for J/ψ with smaller momentum
- Energy scan: can test QCD evolution equation at twist-4 using CEPC data
- Similar to test DGLAP evolution equation using HERA data
- More studies are needed

Outline

Quarkonium: test twist-4 effects

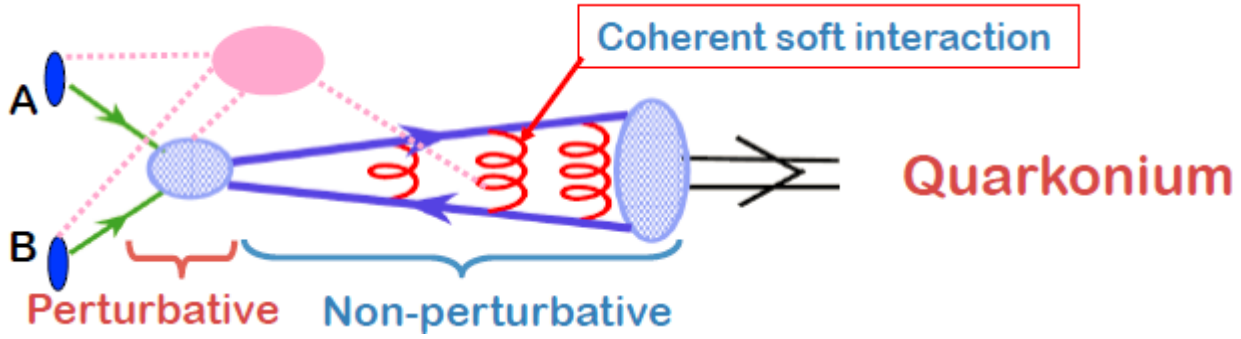
Quarkonium: study hadronization mechanism

Hadronization of QCD

- **Currently well established method: single parton fragmentation**

  Black box, had to really understand how hadronization happens even though FFs are precisely determined.

- **Heavy quarkonium production: localized color source, deeper understanding of hadronization**



NRQCD

Bodwin, Braaten, Lepage, 9407339

➢ NRQCD factorization

$$d\sigma_H = \sum_\kappa d\hat{\sigma}^\kappa \langle \mathcal{O}_\kappa^H \rangle$$

- $\langle O_\kappa^H \rangle$: LDME, number, nonperturbative, determined by data
- If NRQCD is correct, $\langle O_\kappa^H \rangle$ can tell us a lot about hadronization

➢ Universality of LDMEs

- LDME be process independent

Quarkonium production puzzles

➢ **However**

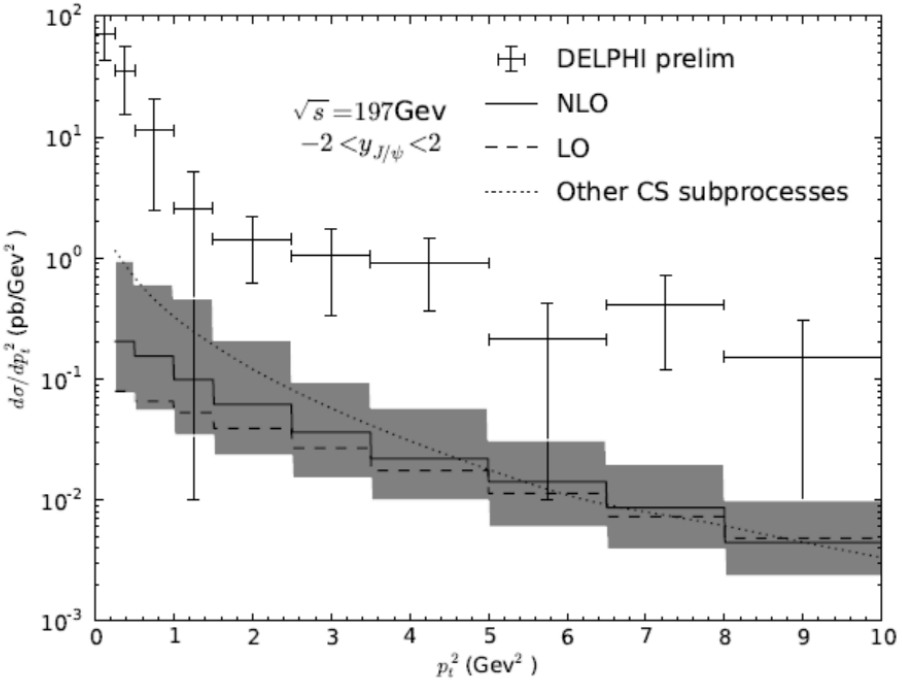
$$\mathrm{M}_0 = \langle O\left({}^1\mathrm{S}_0^{[8]}\right)\rangle + 3.9\,\langle O\left({}^3\boldsymbol{P}_0^{[8]}\right)\rangle/m_c^2$$

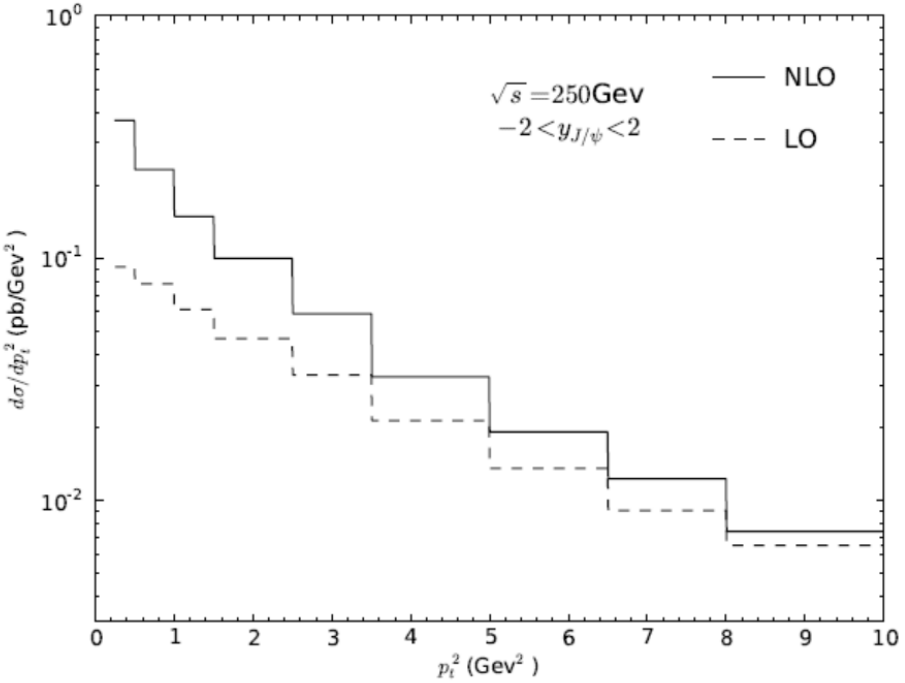
- **To resolve J/ψ polarization puzzle at pp collision: $M_0 > 0.07\ \mathrm{GeV}^3$**
- **To explain B factory data: $M_0 < 0.02\ \mathrm{GeV}^3$**
- **To explain LEP $\gamma\gamma$ data: $M_0 > 0.1\ \mathrm{GeV}^3$?**

$\gamma\gamma \to J/\psi + X$ at e^+e^- collision

- **CS contribution can not explain $\gamma\gamma$ data**

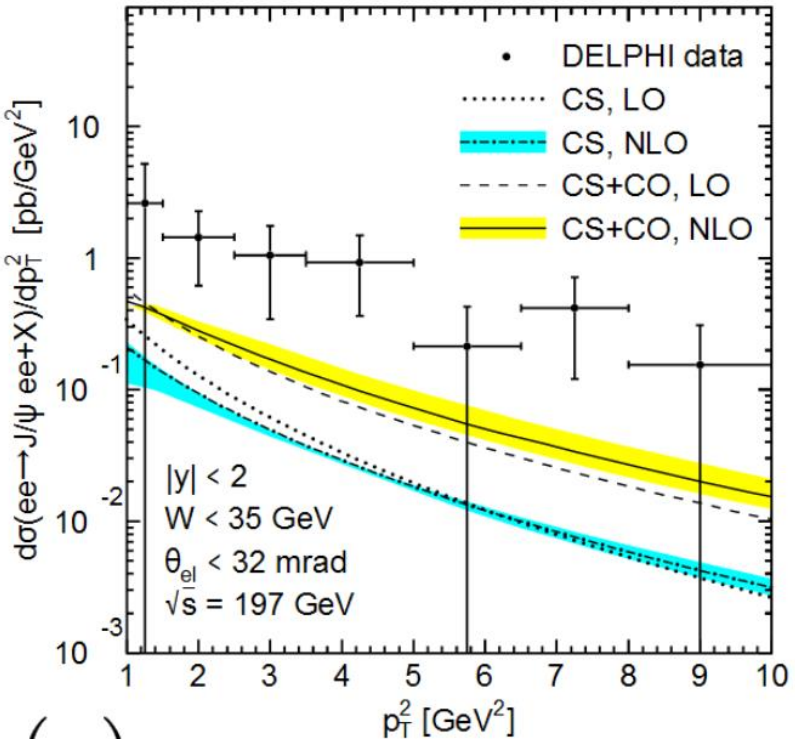
Chen, Chen, Qiao, 1608.06231





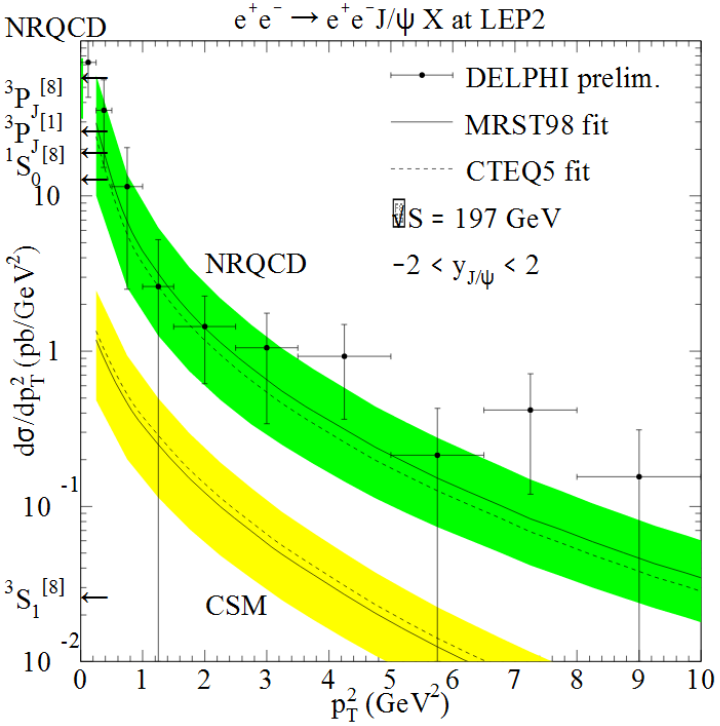
$\gamma\gamma \to J/\psi + X$ at e^+e^- collision

➢ CO: depends on LDMEs



Butenschon, Kniehl, 1105.0820

$M_0 = 0.02\ \mathrm{GeV}^3$



Klasen, Kniehl, Mihaila, Steinhauser, 0112259

$M_0 = ?$

$\gamma\gamma \to J/\psi + X$ at e^+e^- collision

- **Large experimental error at LEP**
- **CEPC is able to reduce the error and thus to test the hadronization theory**

Summary

- **Theoretically: considering evolution effects at twist 4**

  Work in progress

- **Experimentally: CEPC is crucial both for studying twist 4 effects and to testing quarkonium hadronization theory**

Thank you!