Precision QCD Physics at CEPC

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Including contribution from **Hua-Xing Zhu** *(MIT)*

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Beihang University, Beijing, Sep 2nd, 2016

Outline

I. Over view

II. Jet: pQCD and extract α_s (by HXZ)

III. Quarkonium: twist-4 effects

IV. Quarkonium: hadronization mechanism

Study of QCD

- **Test QCD: perturbation theory**

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

- **Understanding the QCD**

  Confinement, hadronization

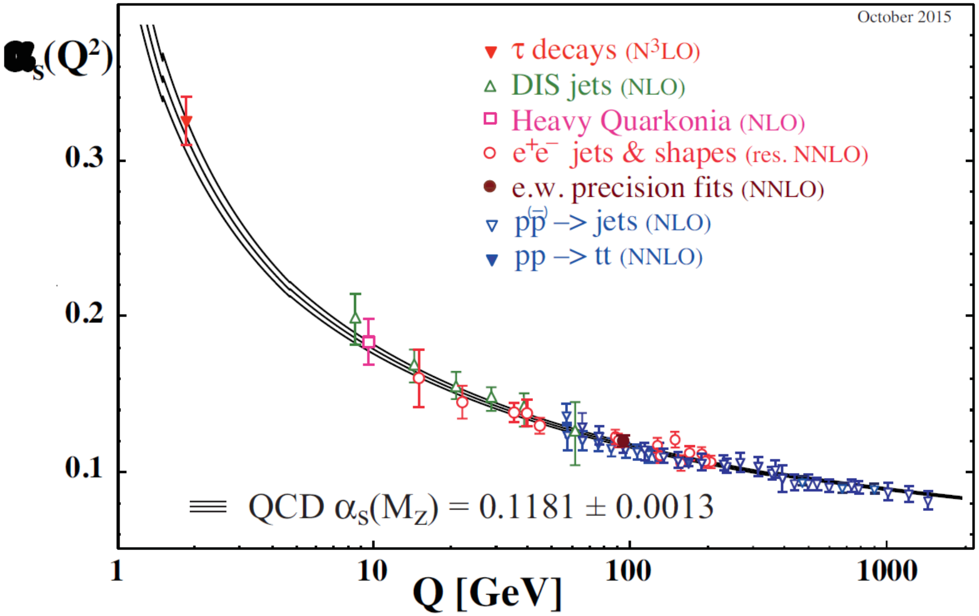
Fundamental parameter of QCD: α_s

- **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.**

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

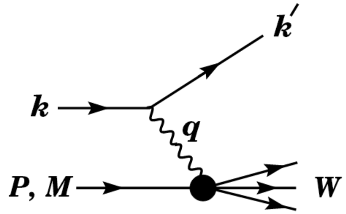


- **Data (running) agree well with QCD prediction**

- **e^+e^- data: big contribution**

Twist expansion for QCD

➢ **DIS structure function**

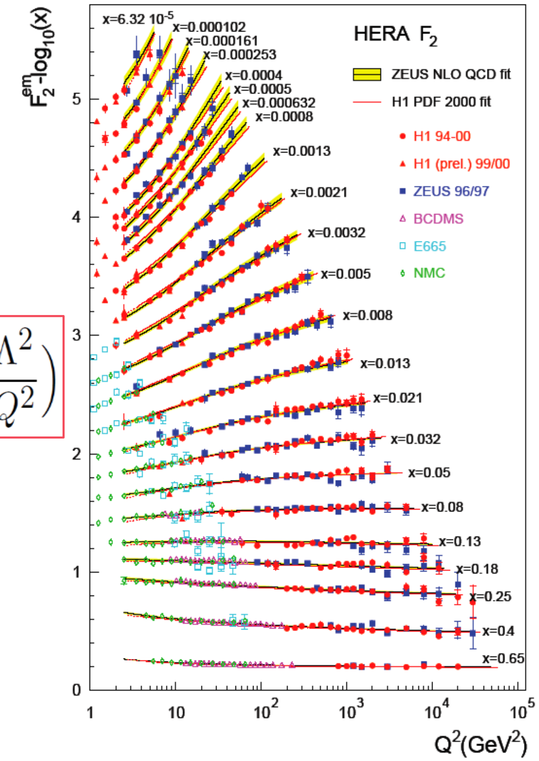


$$F_2(x,Q^2) = x\sum_{n=0}^{\infty}\frac{\alpha_s^n(\mu_R^2)}{(2\pi)^n}\sum_{i=q,g}\int_x^1\frac{dz}{z}C_{2,i}^{(n)}(z,Q^2,\mu_R^2,\mu_F^2)\,f_{i/p}\Big(\frac{x}{z},\mu_F^2\Big)\boxed{+\mathcal{O}\Big(\frac{\Lambda^2}{Q^2}\Big)}$$

➢ **DGLAP evolution**

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

Similar for fragmentation function



➢ **Twist-2: evolution well tested**

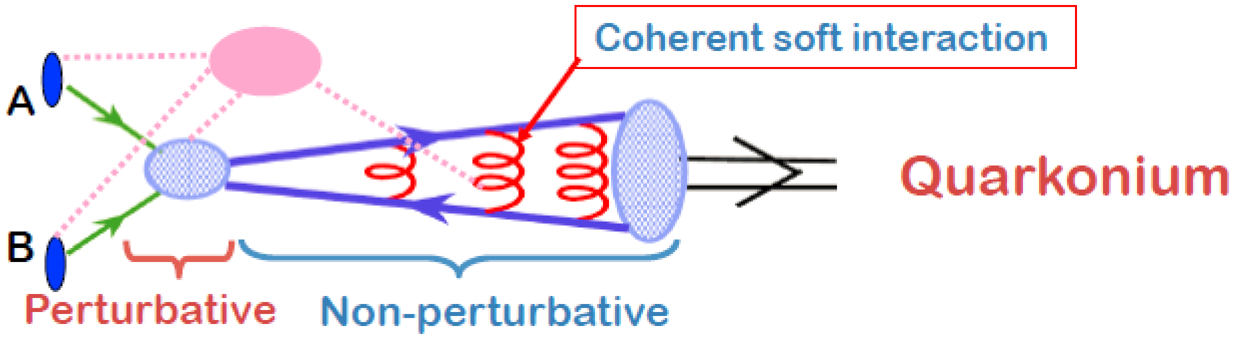
➢ **How about higher twist effects?**

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**



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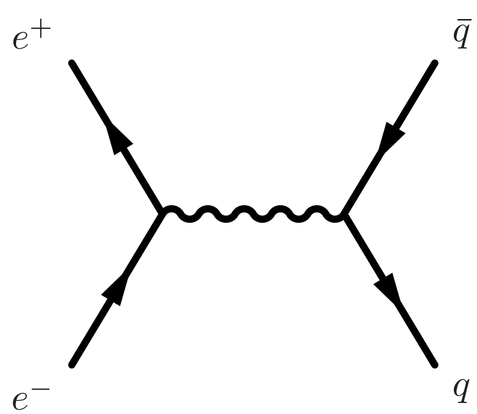
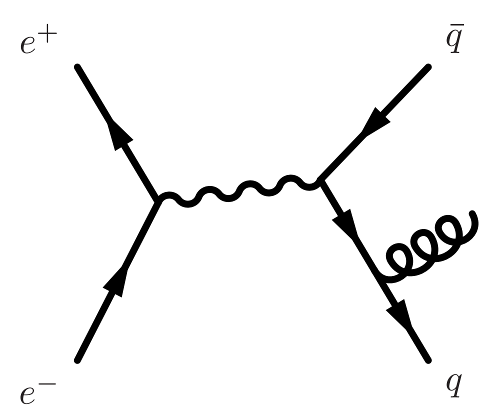
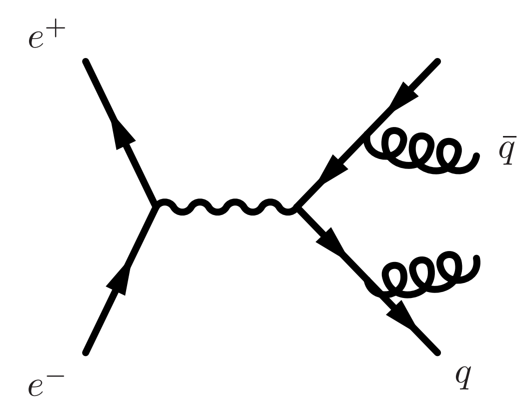
Jet production at e+e- Collider

- High energy e+e- Collider is an ideal environment for studying precision QCD physics
  - Colorless initial state: Doesn't require non-perturbative input like PDFs, significantly reduce theoretical uncertainty
  - No multiple interaction or underlying event, factorization theorem for jet cross section and event shape expected to exist







$+ \ldots$

Precision calculation of R_μ

Event shape observables:
Thrust
Heavy Jet Mass
Jet broaden
C parameter
……

Four jet rates
Transition parameter distribution
…….

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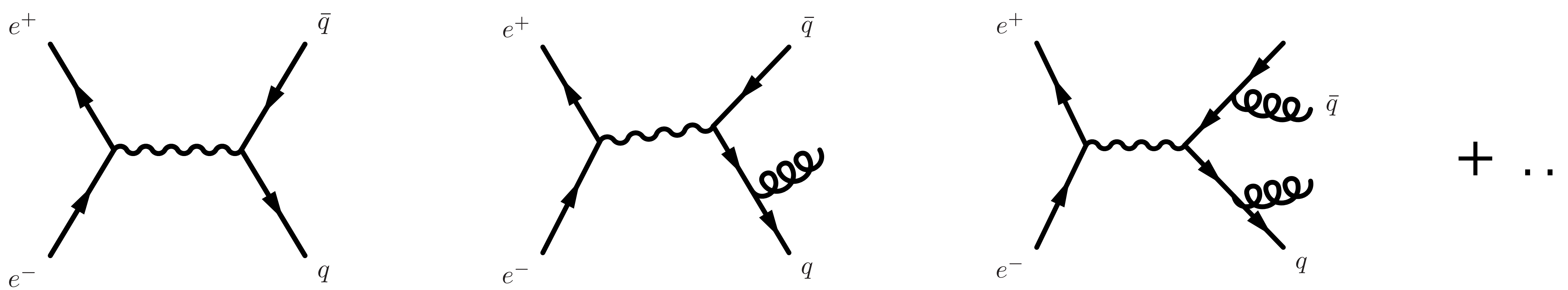


Pre

The study of these processes require deep knowledge of perturbative QCD; in return, we gain better understanding of QCD and precise measurement of SM parameter

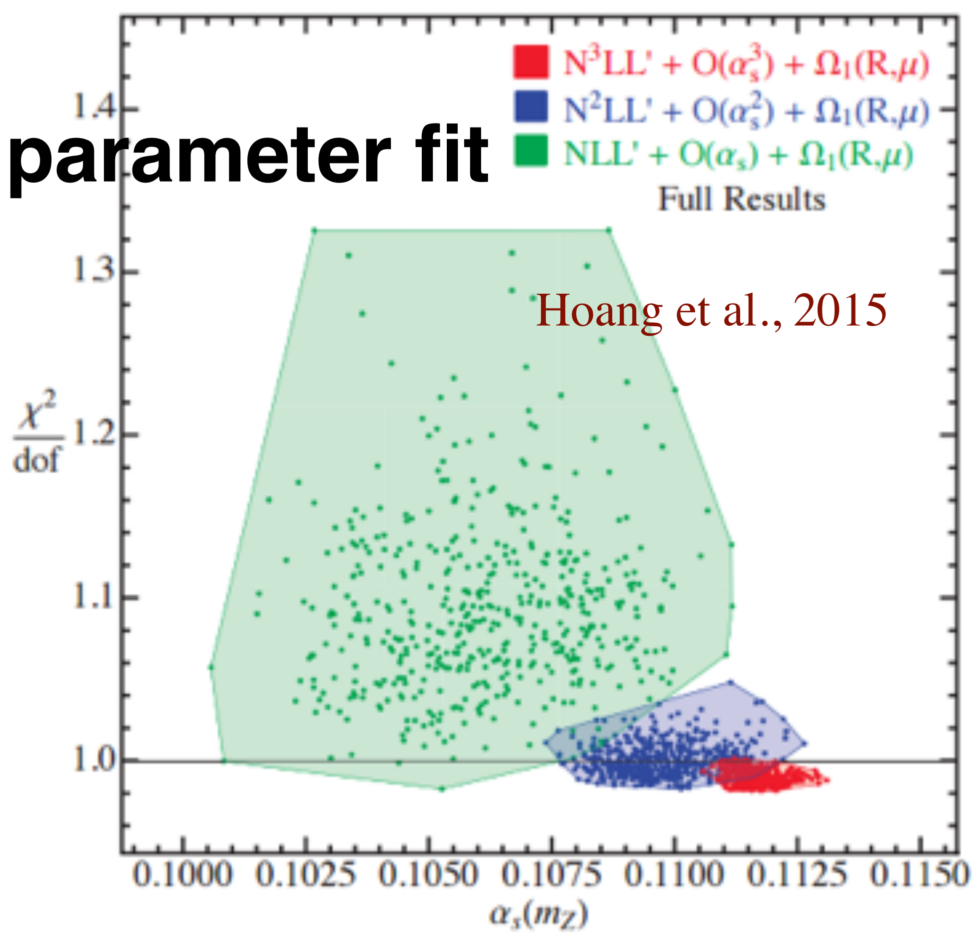
C parameter

……

Precision α_s extraction at e+e- collider

- Event shape and jet rates are two important observables for precision α_s extraction (others include total e+e- Xsec, Z pole fit, etc.)

C parameter fit



$$\alpha_S(m_Z) = 0.1134 \pm 0.0002(\mathrm{exp}) \pm 0.0005(\mathrm{hadr}) \pm 0.0011(\mathrm{pert})$$

five jet production fit

	LEP2, no hadr. $\sigma_{\rm tot}^{-1}{\rm d}\sigma/{\rm d}y_{45}$	LEP2, no hadr. R_5	LEP2, no hadr. $\sigma_{\rm tot}^{-1}{\rm d}\sigma/{\rm d}y_{45}$, R_5
stat.	$+0.0020$ -0.0022	$+0.0022$ -0.0025	$+0.0015$ -0.0016
syst.	$+0.0008$ -0.0009	$+0.0012$ -0.0012	$+0.0008$ -0.0008
pert.	$+0.0049$ -0.0034	$+0.0029$ -0.0020	$+0.0029$ -0.0020
fit range	$+0.0038$ -0.0038	$+0.0030$ -0.0030	$+0.0028$ -0.0028
$\alpha_s(M_Z)$	$0.1189^{+0.0066}_{-0.0057}$	$0.1120^{+0.0050}_{-0.0047}$	$0.1155^{+0.0044}_{-0.0039}$

Frederix et al., 2010

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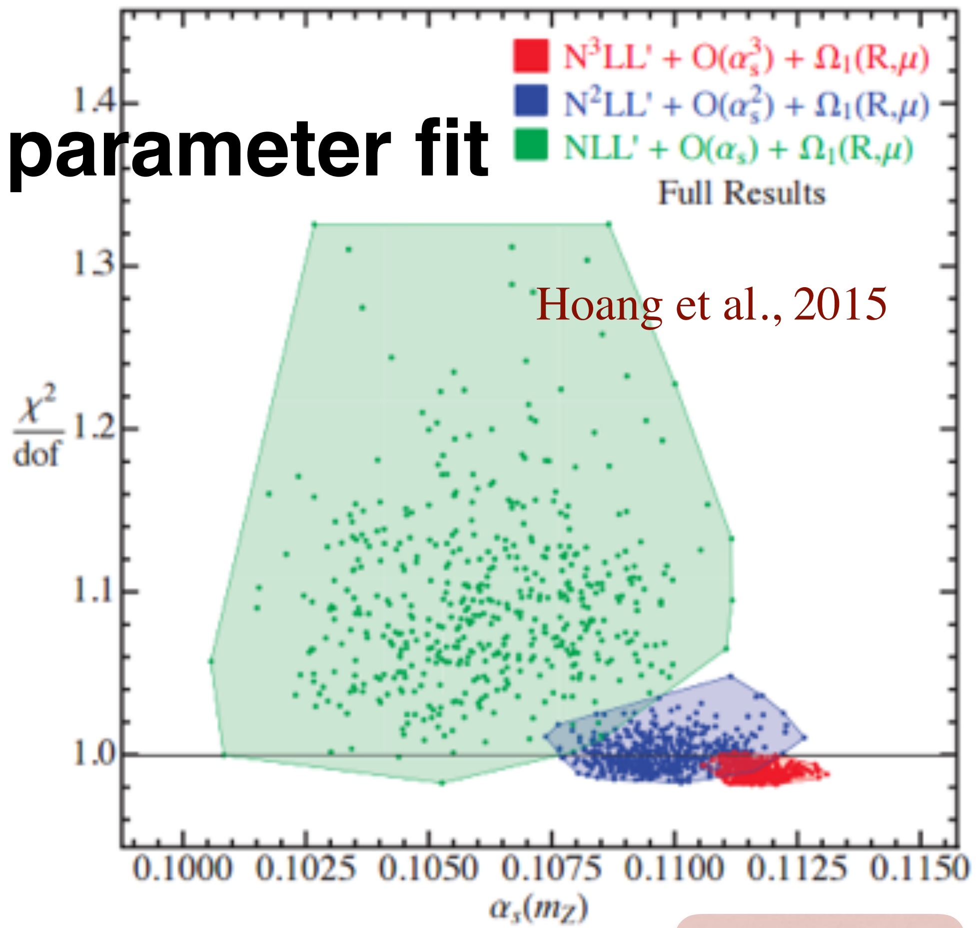

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Frederix et al., 2010

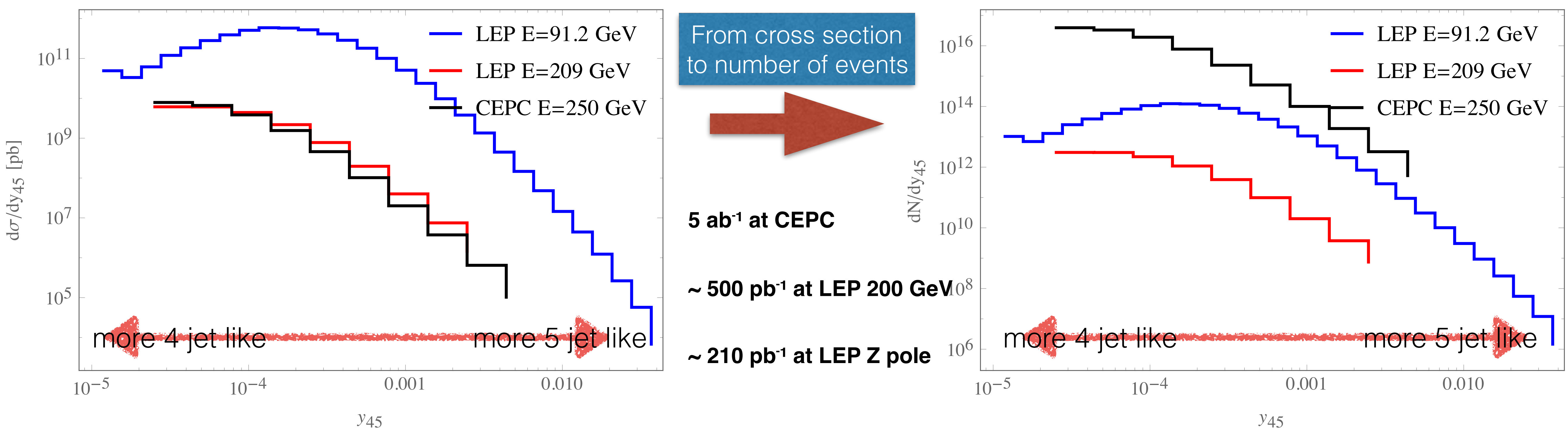
- **Non-negligible hadronization uncertainty for event shape. Can be significantly reduced by going to higher energy at CEPC**
- **Sizable statistical and systematic uncertainty for five jet production. High luminosity at CEPC will be very helpful!**
- **Expected to see continuous progress on the theoretical side to reduce perturbative uncertainties**

CEPC as a “clean” jet factory

- Jet cross section scale as $1/Q^2$. Going to higher energy reduce the jet cross section

- Compensated by huge increase in luminosity at CEPC (5 ab^{-1} expected)

y_{45}: four jets to five jets transition parameter



- **More five jets event at CEPC than at LEP Z pole !**
- **Hadronization and experimental uncertainty will be negligible at CEPC. If the theory uncertainty can be reduced to the same level might enable α_s extraction at the precision comparable to Lattice!**

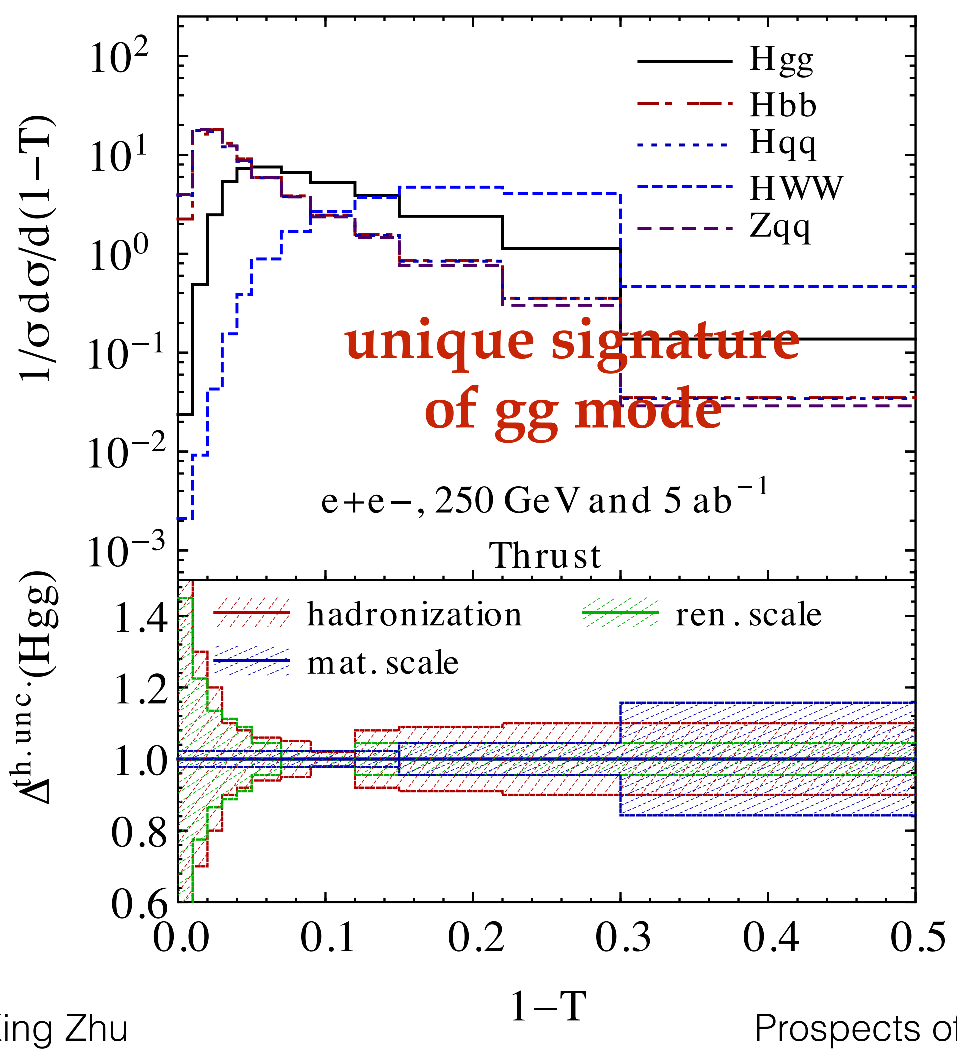
QCD and Higgs physics at CEPC

- CEPC provides an unique opportunity of testing QCD via decay of the Higgs boson

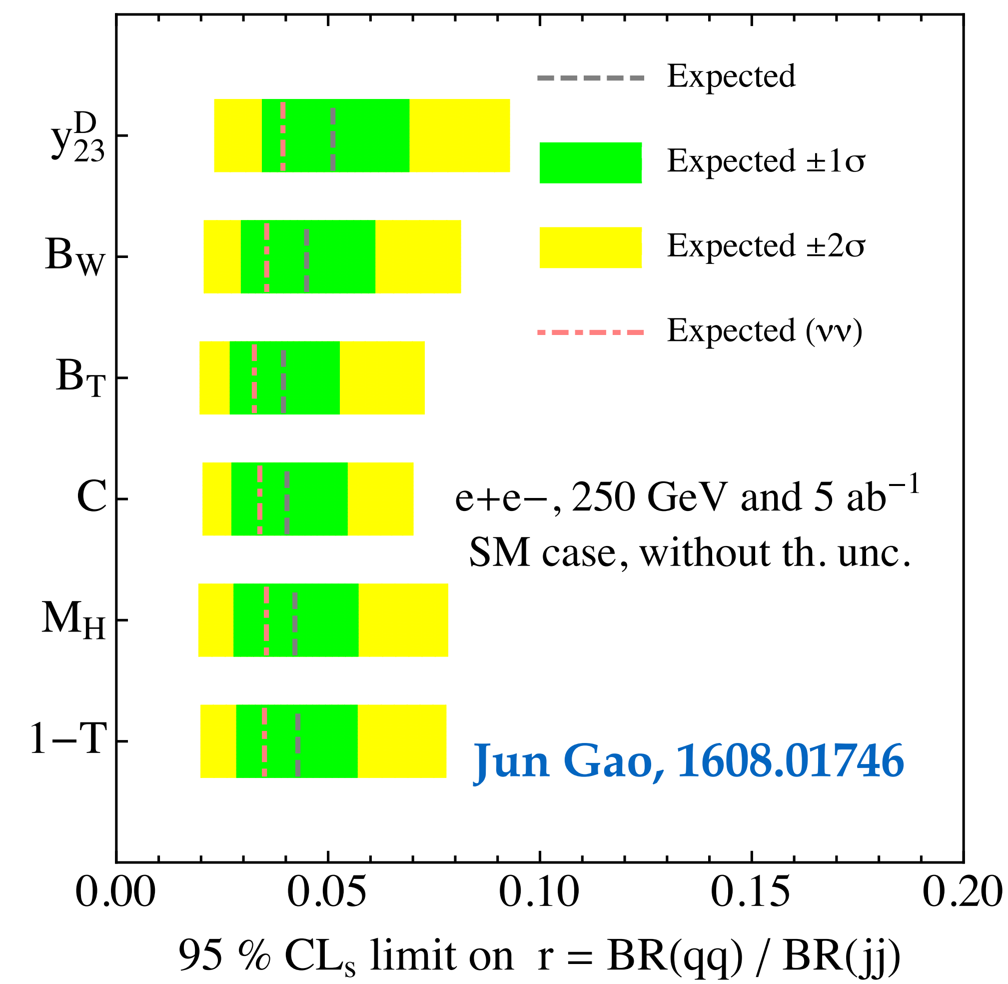
Expected event numbers for different hadronic decay modes of the SM Higgs boson at 250 GeV and with 5 ab^{-1}

$Z(l^+l^-)H(X)$	gg	$b\bar{b}$	$c\bar{c}$	$WW^*(4h)$	$ZZ^*(4h)$	$q\bar{q}$
BR [%]	8.6	57.7	2.9	9.5	1.3	~ 0.02
N_{event}	6140	41170	2070	6780	930	14

QCD event shape distributions



in another way, using QCD observables to test Higgs couplings, e.g., light-quark



Many on going efforts on e+e- QCD study

- Recent progress on Non-global logarithms: H.X. Zhu, Schwartz 14’; Larkoski, Moult, Neill, 15’, 16’; Neill, 15’; Becher, Lorena, Neubert, D.Y. Shao 15’, 16’; …
- Numerical resummation for jet rate, Banfi et al, 16’
- New ability to construct integrand and calculating integrals for e+e- to multi jet: Mastrolia, et al., 11-16’; Badger, Frellsvig, Y. Zhang, 13’; Ita 15’; Gehrmann, Henn, Lo Presti, 15’; …
- Resummation of three-jet event shape (J. Gao, H.X. Zhu, work in progress)
- NNLO QCD corrections to massive b-quark jet production at e+e- collider (J. Gao, H.X. Zhu, work in progress)

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Higher twist effects

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

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

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

  See Qing-Hong Cao's talk

  If confirmed, twist-4 effects

  Modeling: $\sigma_{A+B} \approx \frac{\sigma_A \sigma_B}{\sigma_{eff}}$, σ_{eff} cannot be process independent, more theoretic studies needed.

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

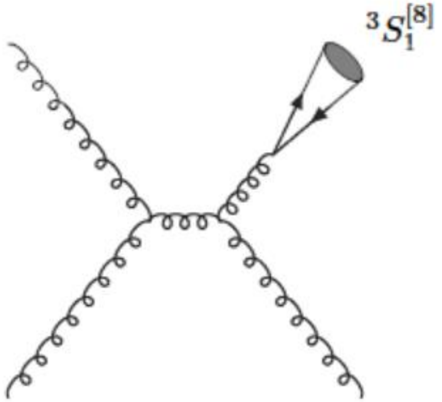
  Significant signal, well established theory, test QCD rigorous

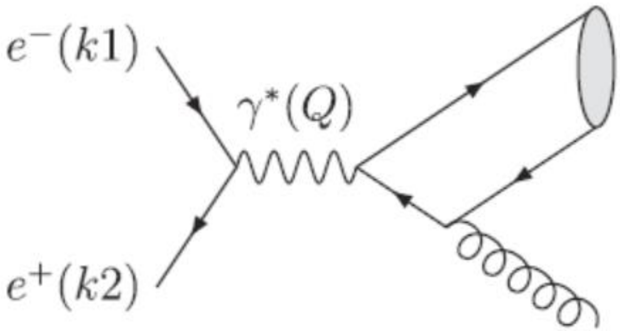
Quarkonium production

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

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

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

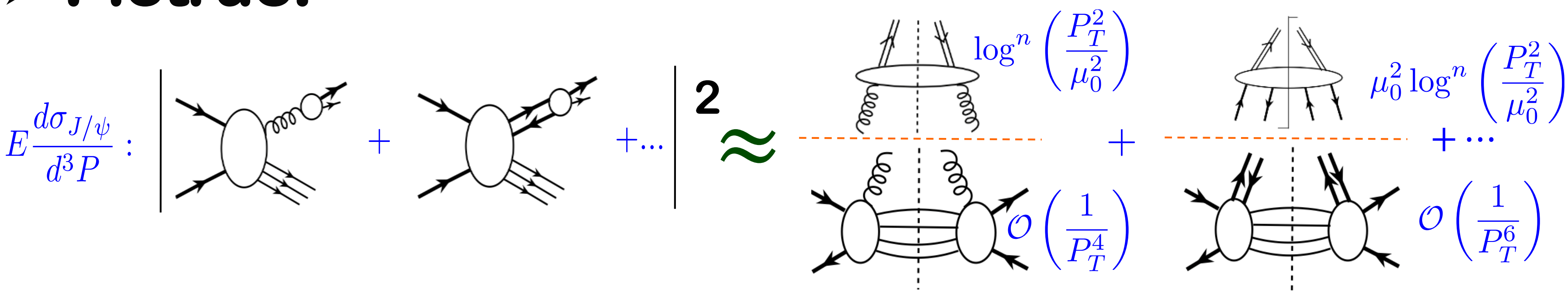




- **e^+e^- collision: gluon fragmentation suppressed by α_s, twist-4 contributions important**

Collinear factorization approach

- **Pictrue:**



- **Factorization correct to all order** Qiu, Sterman (1991)
  Kang, YQM, Qiu, Sterman, 1401.0923

- **Factorization formalism:**

produce pair at $1/m_Q$

$$
\begin{aligned}
d\sigma_{A+B\to H+X}(p_T) = &\sum_f d\hat{\sigma}_{A+B\to f+X}(p_f=p/z)\otimes D_{H/f}(z,m_Q)\\
&+\sum_{[Q\bar{Q}(\kappa)]} d\hat{\sigma}_{A+B\to[Q\bar{Q}(\kappa)]+X}(p(1\pm\zeta)/2z,p(1\pm\zeta')/2z)\\
&\qquad\otimes\mathcal{D}_{H/[Q\bar{Q}(\kappa)]}(z,\zeta,\zeta',m_Q)\\
&+\mathcal{O}(m_Q^4/p_T^4)
\end{aligned}
$$

produce pair at $1/p_T$

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 $[1/p_T,\ 1/m_Q]$

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

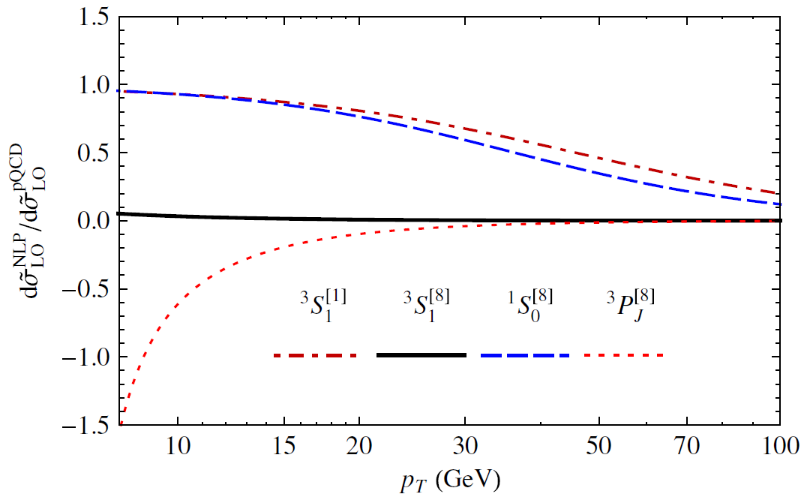
$$\frac{d}{d\ln\mu^2}\mathcal{D}_{H/[Q\bar{Q}(c)]}(z,\zeta,\zeta',m_Q,\mu)=\sum_{[Q\bar{Q}(\kappa)]}\frac{\alpha_s}{2\pi}K_{[Q\bar{Q}(c)]\to[Q\bar{Q}(\kappa)]}(z,\zeta,\zeta')$$
$$\otimes\mathcal{D}_{H/[Q\bar{Q}(\kappa)]}(z,\zeta,\zeta',m_Q,\mu)$$

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

➢ **Numerical study at CEPC: work in progress**

Similar to test DGLAP evolution equation using HERA data, can test QCD evolution equation at twist-4 using CEPC data

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Quarkonium production puzzle

Bodwin, Braaten, Lepage, 9407339

➢ NRQCD factorization

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

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

➢ However

- To resolve J/ψ polarization puzzle, needs a large

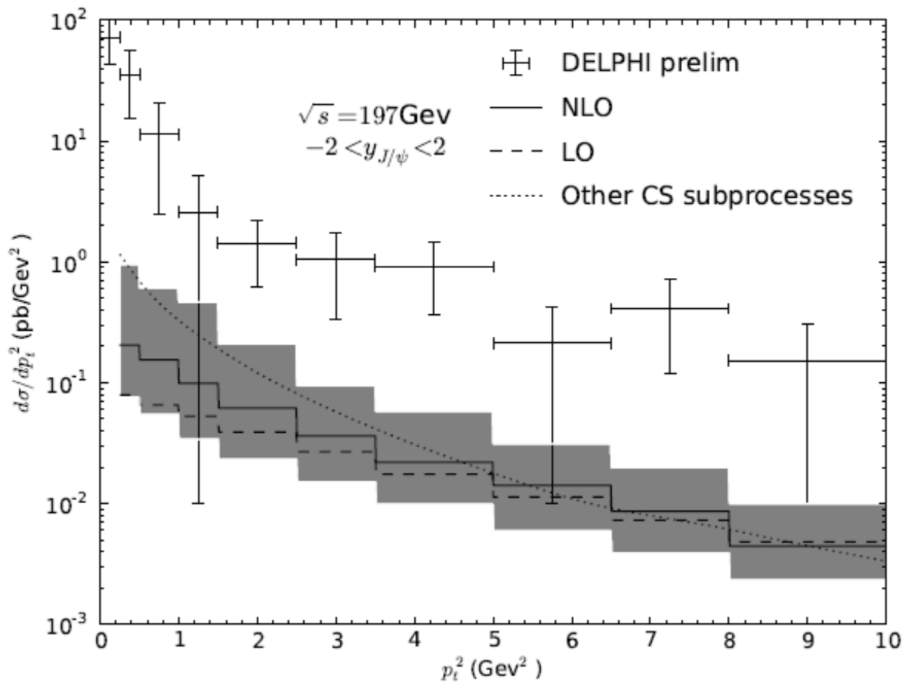
$$\mathrm{M}_0 = \langle O\left({}^1\mathrm{S}_0^{[8]}\right)\rangle + 3.9\,\langle O\left({}^3\boldsymbol{P}_0^{[8]}\right)\rangle\,/m_c^2$$

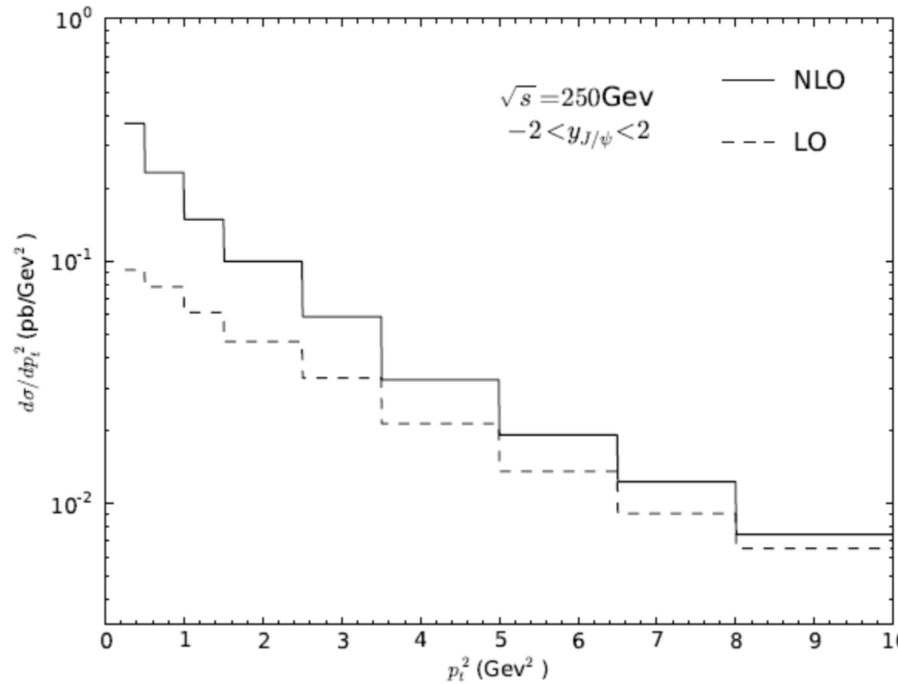
- Conflict with e^+e^- collision data

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

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

Chen, Chen, Qiao, 1608.06231





- **Large experimental error**

Understanding the production mechanism

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

Work in progress

- **Experimentally: data at CEPC is very helpful to reduce statistic error**

Thank you!