Inclusive Quarkonium Production at the B factories

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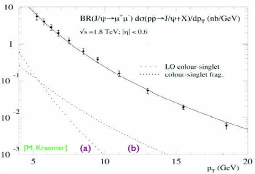
Introduction

- Perturbative and non-perturbative QCD, hadronization, factorization
- Color-singlet and Color-octet mechanism was proposed based on NRQCD since c-quark is heavy.
- Clear signal to detect J/ψ.
- heavy quarkonium production is a good place to testify these theoretical framework.
- But there are still many difficulties.
  - J/ψ photoproduction at HERA
  - J/ψ production at the B factories
  - J/ψ polarization at the Tevatron
- NLO corrections are important.
  - Data on inelastic J/ψ photoproduction are adequately described by the color singlet channel alone at NLO
  - Double charmonium production at the B factories



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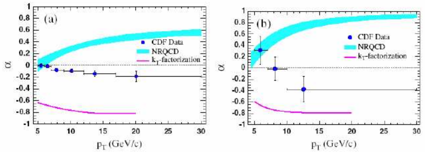
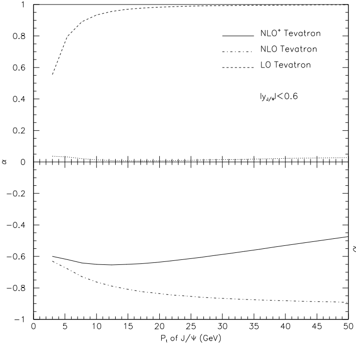
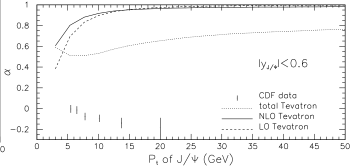


FIG. 4 (color online). Prompt polarizations as functions of p_T: (a) J/ψ and (b) $\psi(2S)$. The band (line) is the prediction from NRQCD [4] (the k_T-factorization model [9]).





$e^+e^- \rightarrow J/\psi + \eta_c$

Experimantal Data

BELLE: $\sigma[J/\psi + \eta_c] \times B^{\eta_c}[\geq 2] = (25.6 \pm 2.8 \pm 3.4)$ fb
BARAR: $\sigma[J/\psi + \eta_c] \times B^{\eta_c}[\geq 2] = (17.6 \pm 2.8^{+1.5}_{-2.1})$ fb
[Abe et al.(2002), Pakhlov(2004), Aubert et al.(2005)]

LO NRQCD Predictions

$2.3 \sim 5.5$ fb
[Braaten and Lee(2003), Liu et al.(2003), Hagiwara et al.(2003)]

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NLO QCD corrections

$K \equiv \sigma^{NLO}/\sigma^{LO} \sim 2$
[Zhang et al.(2006), Gong and Wang(2007)]

Our calculation Confirmed the result given by [Zhang et al.(2006)] analytically.

$e^+e^- \to J/\psi + J/\psi$

Problem

LO NRQCD prediction indicates that the cross section of this process is large than that of $J/\psi + \eta_c$ production by a factor of 1.8, but no evidence for this process was found at the B factories. [Bodwin et al.(2003a), Abe et al.(2004)]

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NLO QCD corrections

- Greatly decreased, with a K factor ranging from $-0.31 \sim 0.25$ depending on the renormalization scale.
- Might explain the situation.

[Gong and Wang(2008b)]

LO NRQCD Predictions:

$$e^+e^- \to J/\psi + c\bar{c} \qquad 0.07 \sim 0.20\text{pb}$$
$$e^+e^- \to J/\psi + gg \qquad 0.15 \sim 0.3\text{pb}$$
$$e^+e^- \to J/\psi^{(8)}({}^3P_J, {}^1S_0) + g \qquad 0.3 \sim 0.8\text{pb}$$

Experimental Data:

$$BARAR \qquad \sigma[e^+e^- \to J/\psi + X] = (2.54 \pm 0.21 \pm 0.21)\ \text{pb}$$
$$\text{CLEO} \qquad \sigma[e^+e^- \to J/\psi + X] = (1.9 \pm 0.20)\ \text{pb}$$
$$\text{BELLE} \qquad \sigma[e^+e^- \to J/\psi + X] = (1.45 \pm 0.10 \pm 0.13)\ \text{pb}$$
$$\sigma[e^+e^- \to J/\psi + c\bar{c} + X] = (0.87^{+0.21}_{-0.19} \pm 0.17)\ \text{pb}$$

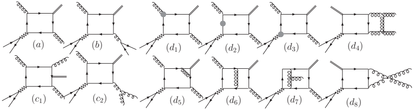
[Aubert et al.(2001), Aubert et al.(2005), Briere et al.(2004), Abe et al.(2002a), Abe et al.(2002)]

New BELLE Data

$$\begin{aligned}\sigma[e^+e^- \to J/\psi + X] &= (1.17 \pm 0.02 \pm 0.07)\ \mathrm{pb} \\ \sigma[e^+e^- \to J/\psi + c\bar{c}] &= (0.74 \pm 0.08^{+0.09}_{-0.08})\ \mathrm{pb} \\ \sigma[e^+e^- \to J/\psi + X_{\mathrm{non}-c\bar{c}}] &= (0.43 \pm 0.09 \pm 0.09)\ \mathrm{pb}\end{aligned}$$

[Pakhlov et al.(2009)]

$e^+e^- \to J/\psi + gg$ with Typical Feynman Diagrams shown

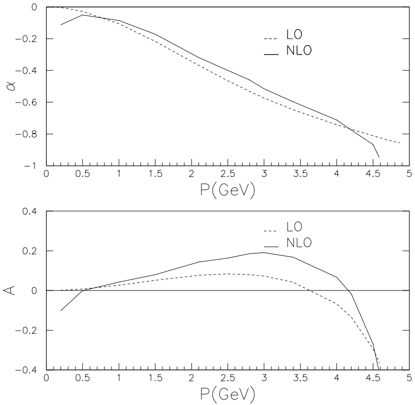


$$\sigma^{(1)} = \sigma^{(0)} \left\{ 1 + \frac{\alpha_s(\mu)}{\pi} \left[a(\hat{s}) + \beta_0 \ln\left(\frac{\mu}{2m_c}\right) \right] \right\}$$

m_c(GeV)	$\alpha_s(\mu)$	$\sigma^{(0)}$(pb)	$a(\hat{s})$	$\sigma^{(1)}$(pb)	$\sigma^{(1)}/\sigma^{(0)}$
1.4	0.267	0.341	2.35	0.409	1.20
1.5	0.259	0.308	2.57	0.373	1.21
1.6	0.252	0.279	2.89	0.344	1.23

Cross sections with different charm quark mass m_c where the renormalization scale $\mu = 2m_c$ and $\sqrt{s} = 10.6$ GeV.

Consistent with the calculation by [Ma et al.(2009)].



Polarization parameter α and angular distribution parameter A

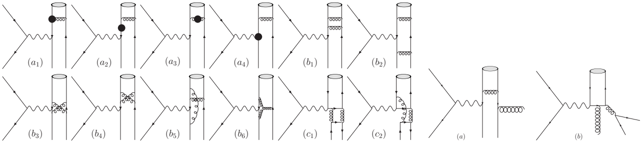
of J/ψ as functions of p with $m_c = 1.5$ GeV and $\mu = 2m_c$.

$$\frac{d^2\sigma}{d\cos\theta\, dp} = S(p)[1 + A(p)\cos\theta]$$

$$\alpha = \frac{\sigma_T - 2\sigma_L}{\sigma_T + 2\sigma_L}$$

Results on the left contain potentially large numerical errors in our calculation for $p < 0.5$ GeV or $p > 4.2$ GeV due to the cancellation of large numbers.

Typical Feynman Didgrams at NLO for $e^+e^- \to J/\psi + c\bar{c}$



$$\sigma^{(1)} = \sigma^{(0)} \left\{ 1 + \frac{\alpha_s(\mu)}{\pi} \left[a(\hat{s}) + \beta_0 \ln\left(\frac{\mu}{2m_c}\right) \right] \right\}$$

m_c(GeV)	$\alpha_s(\mu)$	$\sigma^{(0)}$(pb)	$a(\hat{s})$	$\sigma^{(1)}$(pb)	$\sigma^{(1)}/\sigma^{(0)}$
1.4	0.267	0.224	8.19	0.380	1.70
1.5	0.259	0.171	8.94	0.298	1.74
1.6	0.252	0.129	9.74	0.230	1.78

Cross sections with different charm quark mass m_c with the renormalization scale $\mu = 2m_c$ and $\sqrt{s} = 10.6$ GeV.

Consistent with the former result given by [Zhang and Chao(2007)].

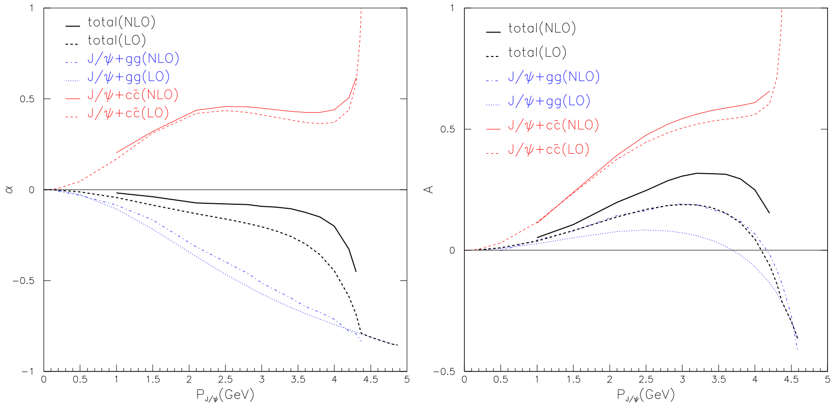
More about the scale and comparision with data

Use Brodsky, Lepage and Mackenzie (BLM) scale setting [Brodsky et al.(1983)]

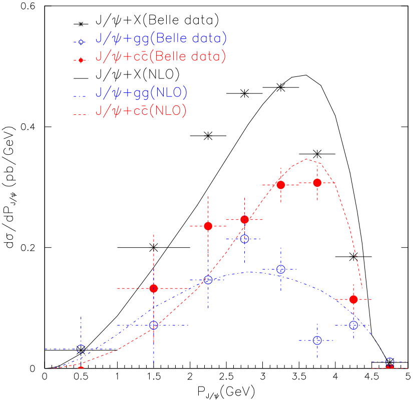
$$\sigma^{(1)} = \sigma^{(0)}(\mu^*)[1 + \frac{\alpha_s(\mu^*)}{\pi} b(\hat{s})].$$

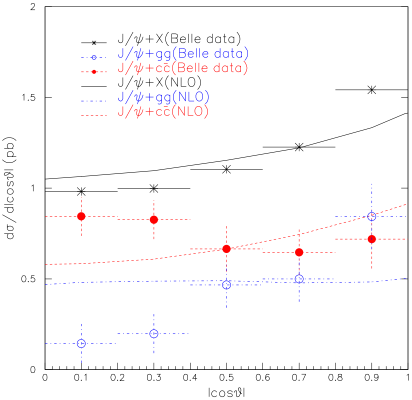
m_c(GeV)	$\alpha_s(\mu^*)$	$\sigma^{(0)}$(pb)	$b(\hat{s})$	$\sigma^{(1)}$(pb)	$\sigma^{(1)}/\sigma^{(0)}$	μ^*(GeV)
1.4	0.348	0.381	3.77	0.540	1.42	1.65
1.5	0.339	0.293	4.31	0.429	1.47	1.72
1.6	0.332	0.222	4.90	0.337	1.52	1.79

Cross sections with different charm quark mass m_c. The renormalization scale $\mu = \mu^* \sim m_c$.

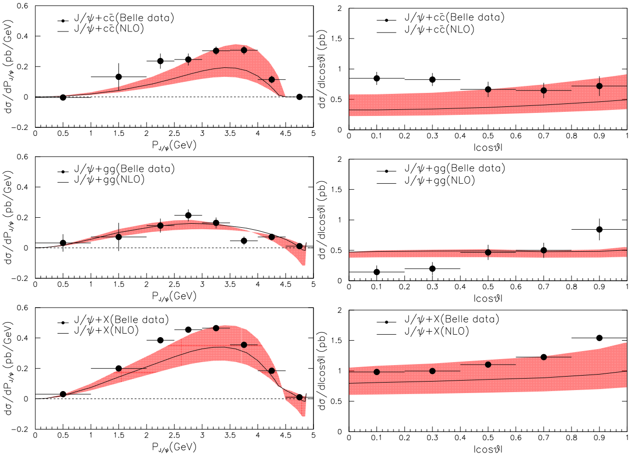


Polarization parameter α and angular distribution parameter A of J/ψ as functions of p.





Momentum distribution of inclusive J/ψ production with $\mu = \mu^*$ and $m_c = 1.4$ GeV is taken for the $J/\psi cc$ channel. The contribution from the feed-down of ψ' has been added to all curves by multiplying a factor of 1.29.



Momentum and angular distributions of inclusive J/ψ production.

The contribution from the feed-down of ψ' has been added to all curves by multiplying a factor of 1.29.

The fragmentation function of charm into J/ψ

According to the fragmentation mechanism, we have

$$\frac{d\sigma[e^+e^- \to J/\psi c\bar{c}]}{dE_J/\psi}$$

$$= \int \frac{dE_c}{E_c} \frac{d\sigma[e^+e^- \to c\bar{c}]}{dE_c} \times D_{c\to J/\psi}\left(\frac{E_J/\psi}{E_c}\right) + (c \leftrightarrow \bar{c})$$

$$= 2\int \frac{dE_c}{E_c} \frac{d\sigma[e^+e^- \to c\bar{c}]}{dE_c} \times D_{c\to J/\psi}\left(\frac{E_J/\psi}{E_c}\right) \quad (1)$$

where $D_{c\to J/\psi}(z) = D_{\bar{c}\to J/\psi}(z)$ has been used.

LO Result

$$\frac{d\sigma^{LO}[e^+e^- \to J/\psi c\bar{c}]}{dE_J/\psi} = \frac{4}{\sqrt{s}}\sigma^{LO}[e^+e^- \to c\bar{c}] \times D_{c\to J/\psi}(z)$$

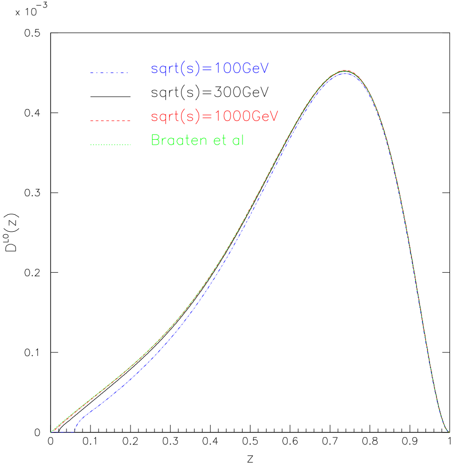
with $z = 2E_J/\psi/\sqrt{s}$.

Thus it's easy to exact the fragmentation function at LO in α_s:

$$D_{c\to J/\psi}(z) = \frac{1}{\sigma^*_{c\bar{c}}}\frac{d\sigma^{LO}[e^+e^- \to J/\psi c\bar{c}]}{dE_J/\psi} \quad (2)$$

where $\sigma^*_{c\bar{c}}$ is defined as

$$\sigma^*_{c\bar{c}} \equiv 4\sigma^{LO}[e^+e^- \to c\bar{c}]/\sqrt{s}$$



LO Fragmentation function of charm into J/ψ with $\mu_r = 2m_c$.
As shown in the figure, the result has little difference with the one given by Braaten *et al* [?] as $\sqrt{s}$ goes larger.

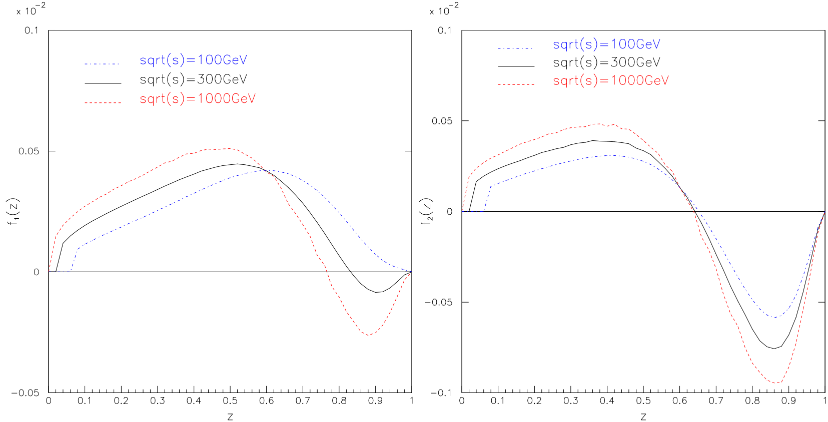
NLO Result

$$\begin{aligned}
&\frac{d\sigma^{NLO}[e^+e^- \to J/\psi c\bar{c}]}{dE_{J/\psi}} \\
= \quad & 2\int \frac{dE_c}{E_c}\frac{d\sigma^{NLO}[e^+e^- \to c\bar{c}]}{dE_c} \times D^{NLO}_{c\to J/\psi}\left(\frac{E_J/\psi}{E_c}\right) \\
= \quad & 2\int \frac{dE_c}{E_c}\frac{d\sigma^{LO}[e^+e^- \to c\bar{c}]}{dE_c} \times D^{NLO}_{c\to J/\psi}\left(\frac{E_J/\psi}{E_c}\right) \\
+ \quad & 2\int \frac{dE_c}{E_c}\frac{d\sigma^{NLO}[e^+e^- \to c\bar{c}] - \sigma^{LO}[e^+e^- \to c\bar{c}]}{dE_c} \times D^{LO}_{c\to J/\psi}\left(\frac{E_J/\psi}{E_c}\right) + \mathcal{O}(\alpha_s^4).
\end{aligned}$$

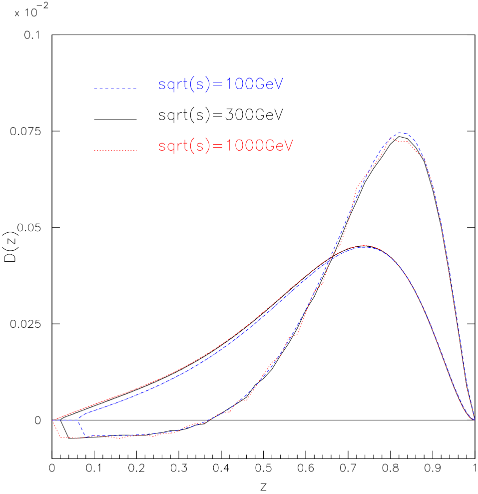
$$D^{NLO}_{c\to J/\psi}(z) \quad = \quad f_1(z) - f_2(z) \qquad (3)$$

$$f_1(z) \quad \equiv \quad \frac{1}{\sigma^*_{c\bar{c}}}\frac{d\sigma^{NLO}[e^+e^- \to J/\psi c\bar{c}]}{dE_{J/\psi}}, \quad \sigma^{NLO*} \equiv \sigma^{NLO} - \sigma^{LO}$$

$$f_2(z) \quad \equiv \quad \frac{2}{\sigma^*_{c\bar{c}}}\int \frac{dE_c}{E_c}\frac{d\sigma^{NLO*}[e^+e^- \to c\bar{c}]}{dE_c} \times D^{LO}_{c\to J/\psi}\left(\frac{E_J/\psi}{E_c}\right) \qquad (4)$$



Behavior of $f_1(z)$ and $f_2(z)$ with different $\sqrt{s}$.



NLO Fragmentation function of charm into J/ψ with $\mu_r = 2m_c$ (The curves with lower peaks are LO ones). The limit without $\sqrt{s}$ dependence is seen. The one with $\sqrt{s} = 1000$ GeV is a bit unstable because of large number cancelation between $f_1(z)$ and $f_2(z)$.

- Experimental and Leading-order Theoretical Results.[Acciarri:1998]

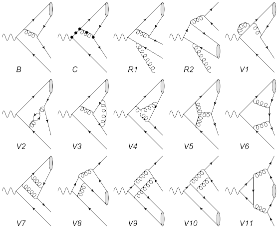
$$Br(Z \to J/\psi_{prompt} + X) = (2.1^{+1.4}_{-1.2}) \times 10^{-4}$$

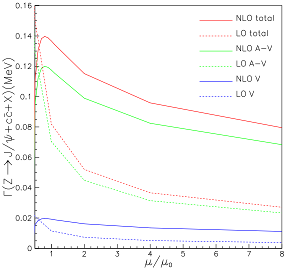
Dominant process: $Z \to J/\psi + c\bar{c} + X$, and the total decay width is presented as

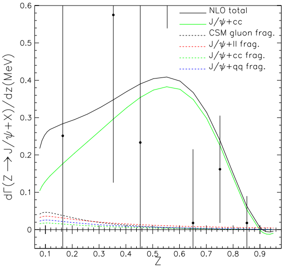
$$\Gamma^{NLO}(\mu) = \Gamma^{LO}(\mu)[1 + \frac{\alpha_s(\mu)}{\pi}(A + \beta_0 ln\frac{\mu}{2m_Q} + Bn_f)]. \qquad (5)$$

$m_c = 1.4$ GeV, $\mu = \mu_{BLM}$ for $J/\psi + c\bar{c}$ and $\mu = 2m_c$ for other processes including ψ' transition.

$\sigma^{BLM}_{J/\psi+c\bar{c}}$(keV)	σ^{gluon}_{QCD}(keV)	$\sigma^{e,\mu,\tau}_{QED}$(keV)	$\sigma^{u,d,s}_{QED}$(keV)	σ^{c}_{QED}(keV)	$\sigma_{tot}(keV)$	$Br.$
209	11.9	13.5	8.08	5.62	248	9.92×10^{-5}







$\mu_0 = 2m_c$. The J/ψ energy distribution in $Z \to J/\psi + X$. Data points from PRD 59, 054016 1999.

The situation for J/ψ production in Υ decay

LO NRQCD Predictions:

$Br(\Upsilon \to J/\psi(^3S_1^8) + gg) = 6.2 \times 10^{-4}$,M. Napsuciale, Phys. Rev. D **57**, 5711 (1998)

$Br(\Upsilon \to J/\psi + c\bar{c}g) = 5.9 \times 10^{-4}$,S. Y. Li, Q. B. Xie and Q. Wang, Phys. Lett. B **482**, 65 (2000)

$Br(\Upsilon \to J/\psi + gg) = orderat \times 10^{-4}$,????

Experimental Data for $Br(\Upsilon \to J/\psi + X)$:

CLEO	$(11 \pm 4 \pm 2) \times 10^{-4}$	*Phys. Lett. B* **224**, 445
ARGUS	$< 6.8 \times 10^{-4}$	*Z. Phys. C***55**, 25(1992)
CLEO	$(6.4 \pm 0.4 \pm 0.6) \times 10^{-4}$	*Phys. Rev. D***70**, 072001(2004)

The situation is quite strange ????

1. The leading order prediction is

$$\mathcal{B}_{\rm Direct}(\Upsilon \to J/\psi + c\bar{c}g) = 3.9 \times 10^{-5}.$$

Phys.Rev.D81:054030,2010.e-Print: arXiv:0911.0139 [hep-ph]

2. Part of NLO prediction from $\Upsilon \to J/\psi + gg$ is

$$\mathcal{B}_{\rm Direct}(\Upsilon \to J/\psi + X) = 3.1 \times 10^{-5}.$$

3. The full QCD correction for the inclusive J/ψ production in Υ decay would be a very interesting and challenge work for explaining the experimental data.
4. Further experiment measurement on the problem is expected.

- Very good convergence behaviour is found in the $J/\psi gg$ channel, with a K factor of about 1.20 and significantly improved scale dependence. And the prediction for the total cross section fits the data well.
- A large K factor (about 1.70) is obtained in the $J/\psi c\bar{c}$ channel, but the QCD perturbative expansion can be improved if the BLM scale setting is adopted. And the results can account for the new data.
- The momentum distribution of both channels are consistent with data.
- The angular distribution of neither channel can fit the data, unless they are added together.
- Further experiment measurement on the J/ψ polarization is expected.

- For J/ψ production in Υ decay, the leading-order theoretical prediction is one order in magnitude smaller than experimental measurement. The full NLO QCD correction would be a very challenge work to explain the experimental data.
- The NLO results for J/ψ production in z^0 decay is just half of experimental measurement.
- $c \to J/\psi$ fragmentation function is obtained at NLO level for then first time.

Thank you!

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