Prompt Double J/ψ Hadroproduction in Parton Reggeization Approach

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Based on work in Collaboration with Bernd.A.Kniehl, M.A.Nefedov(SNRU, Russia), and V.A.Saleev(SNRU, Russia) (In preparation)

The 12th International Workshop on Heavy Quarkonium
November 06-10,2017, Peking University, Beijing

Outline

Double J/ψ production from theoretical point of view

- In double J/ψ production, the hadronization of charm quark pair takes twice. Therefore, it provides an particularly sensitive test on NRQCD hypothesis.
- The double J/ψ production also provides an additional crucial constrain on the J/ψ LDMEs.
- It is believed that double J/ψ can be produced also through double parton scattering (DPS) mechanism, which can help to extract the parameters in DPS (Kom, et al. 2011, Baranov, et al. 2013).

- Studying the double J/ψ production was first proposed by Barger, et al. in 1996, in which the $2(c\bar{c}(^3S_1^{[8]}))$ CO contribution (CO*) was studied.
- Later, it is found that the CS $2(c\bar{c}(^3S_1^{[1]}))$ channel contributes (CS*)predominately to the total hadroproduction rate (Qiao 2002).
- In 2013, Li, et al. cacluated the relativistic corrections to both the CS* and CO* channels.
- Further work shows that in large invariant mass region of the 2 J/ψ, the $^1S_0^{[8]}$, $^3P_J^{[8]}$ contribution including χ_{cJ} feed-down should also be considered (He, et al. 2015).
- Recently the next-to leading QCD corrections to the CS* channel is obtained by Sun et al.

- Production of double heavy quarkonia other than double J/ψ are also studied, such as, double η_c (Li, ea al. 2009), $J/\psi + \Upsilon$ (Ko, et al. 2011), $J/\psi + \eta_c + X$ (Lansberg, et al. 2013)
- Investigation of SPS+DPS contribution to double quarkonium production @LHC and after@LHC has also been performed (Lansberg et al. 2015).
- The double quarkonium production also is studied in the framework of k_t factorization (Baranov 2015).
- And more ...

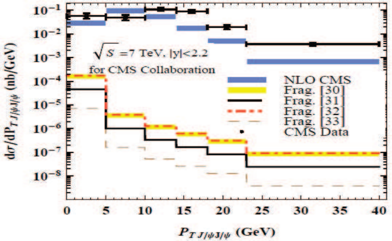
Experimental measurements for double J/ψ hadroproduction

- Double J/ψ is first measured by LHCb Collaboration at 7 TeV in the rapidity range of $2.0 < y^{J/\psi} < 4.5$ and $p_T^{J/\psi} < 10$GeV (PLB 707,52), and recently updated at 13 TeV LHC. (See talk of Liupan An)
- It is also measured by D0 Collaboration at 1.96 TeV with $p_T^{J/\psi} > 4$GeV and $|\eta^{J/\psi}| < 2.0$, where the single parton scatting (SPS) and DPS contributions are discriminated (PRD90, 111101).
- The CMS Collaboration measure double J/ψ production in details with cut condition shown in page 19 of this talk (JHEP 09 (2014) 094).
- The double J/ψ production in central rapidity range $|y^{J/\psi}| < 2.1$ with higher cut on J/ψ p_t ($p_T^{J/\psi} > 8.5$GeV) is measured by ATLAS Collaboration at 8 TeV LHC (EPJC 77,76).

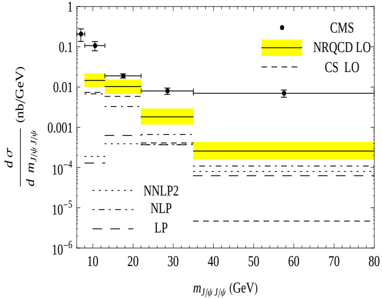
- Total cross section:

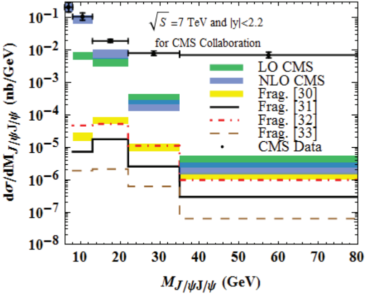
$$\sigma^{\rm CMS} = (1.49 \pm 0.07 \pm 0.13)\ {\rm nb},\ \sigma^{\rm LO}_{\rm CS+CO} = 0.15^{+0.08}_{-0.05}\ \text{nb}$$
$$\sigma^{\rm NLO}_{\rm CS} = 0.98 \pm 0.16\ \text{nb}.$$

- $p_t^{J/\psi J/\psi}$ distribution:

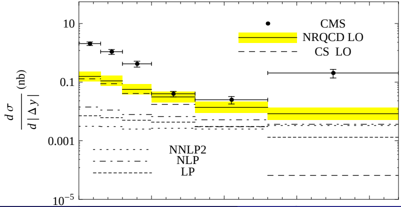


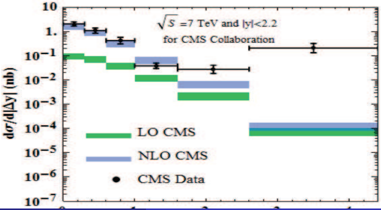
- The invariant mass spectrum:





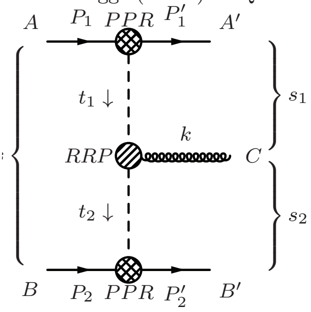
- The $|\Delta y| = |y_1 - y_2|$ distribution:





- In contrast to CPM, in k_t factorization motivated by BFKL resummation of $\log(\frac{1}{x})$ the initial partons carry $\mathbf{k}_t$, so the LO calculation in k_t factorization can effectively take into account the effects of gluon radiation by initial partons and small x, which typically is in the range of $10^{-3} - 10^{-2}$ for double J/ψ production.
- In the old-k_t factorization approach the polarization, $\epsilon^\mu(q)$, of the initial gluon with 4-momentum $q = (q_0, \mathbf{q}_T, q_z)$ is described by $\epsilon^\mu(q) = \frac{q_T^\mu}{|\mathbf{q}_T|}$, but it is not a gauge invariant approach.
- This problem is solved by Reggeization of the amplitudes in QCD.
- In single quarkonium production case, the PRA predictions agree well with the experimental data (See Maxim talk)

PRA is based on the Reggeization of amplitudes in gauge theories (QED, QCD, Gravity). The *high energy asymptotics* of the $2 \to 2+n$ amplitude is dominated by the diagram with t-channel exchange of the effective (Reggeized) particle and Multi-Regge (MRK) or Quasi-Multi-Regge Kinematics (QMRK) of final state.



In the limit $s \to \infty$, $s_{1,2} \to \infty$, $-t_1 \ll s_1$, $-t_2 \ll s_2$ (Regge limit), $2 \to 3$ amplitude has the form:

$$\mathcal{A}_{AB}^{A'B'C} = 2s\gamma_{A'A}^{R_1} \left(\frac{s_1}{s_0}\right)^{\omega(t_1)} \frac{1}{t_1} \times$$
$$\times \Gamma_{R_1 R_2}^{C}(q_1, q_2) \times \frac{1}{t_2} \left(\frac{s_2}{s_0}\right)^{\omega(t_2)} \gamma_{B'B}^{R_2}$$

$\Gamma_{R_1 R_2}^{C}(q_1, q_2)$ - RRP effective production vertex,

$\gamma_{A'A}^{R}$ - PPR effective scattering vertex,

$\omega(t)$ - Regge trajectory.

Two approaches to obtain this asymptotics:

- BFKL-approach (Unitarity, renormalizability and gauge invariance), see e. g. [Ioffe, Fadin, Lipatov, 2010].
- Effective action approach [Lipatov, 1995].

The effective Lagrangain for PRA I

To produce the amplitudes for the arbitrary QMRK processes, the effective-action approach is very useful. Light-cone coordinates and derivatives:

$$n^{+} = \frac{2P_2}{\sqrt{S}},\ n^{-} = \frac{2P_1}{\sqrt{S}},\ n^{+}n^{-} = 2$$

$$x^{\pm} = n^{\pm}x = x^0 \pm x^3,\ \partial_{\pm} = 2\frac{\partial}{\partial x^{\mp}}$$

Lagrangian of the effective theory $L = L_{kin} + \sum_y \left(L_{QCD} + L_{ind}\right),\ v_\mu = v_\mu^a t^a,$

$\left[t^a, t^b\right] = f^{abc}t^c$. The rapidity space is sliced into the subintervals, corresponding to the groups of final-state particles, close in rapidity. Each subinterval in rapidity $(1 \ll \eta \ll Y)$ has it's own set of QCD fields:

$$L_{QCD} = -\frac{1}{2}tr\left[G_{\mu\nu}^2\right],\ G_{\mu\nu} = \partial_\mu v_\nu - \partial_\nu v_\mu + g\left[v_\mu, v_\nu\right].$$

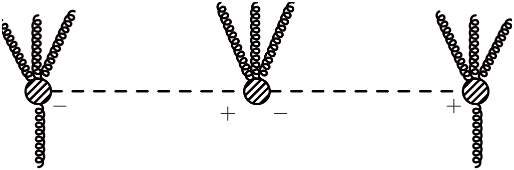
Different rapidity intervals communicate via the gauge-invariant fields of Reggeized gluons $(A_\pm = A_\pm^a t^a)$ with the kinetic term:

$$L_{kin} = -\partial_\mu A_+^a \partial^\mu A_-^a,$$

and the kinematical constraint:

$$\partial_- A_+ = \partial_+ A_- = 0 \Rightarrow$$

$$A_+ \text{ has } k_- = 0 \text{ and } A_- \text{ has } k_+ = 0.$$



Particles and Reggeons interact via *induced interactions*:

$$L_{ind} = -tr\left\{\left(\frac{1}{g}\partial_+ U\left[v^+\right]\right)\cdot\partial_\sigma\partial^\sigma A_-(x) + \left(\frac{1}{g}\partial_- U\left[v^-\right]\right)\cdot\partial_\sigma\partial^\sigma A_+(x)\right\}$$

$$U\left[v^\pm\right] = P\exp\left(-\frac{g}{2}\int_{-\infty}^{x^\mp} dx'^\mp v_\pm(x')\right)$$

Wilson lines generate the infinite chain of the induced vertices:

$$\begin{aligned} L_{ind} &= tr\left\{\left[v_+ - gv_+\partial_+^{-1}v_+ + g^2 v_+\partial_+^{-1}v_+\partial_+^{-1}v_+ - ...\right]\partial_\sigma\partial^\sigma A_- + \right. \\ &+ \left.\left[v_- - gv_-\partial_-^{-1}v_- + g^2 v_-\partial_-^{-1}v_-\partial_-^{-1}v_- - ...\right]\partial_\sigma\partial^\sigma A_+\right\} \end{aligned}$$

- $R^{+,a} \to Q + \bar{Q}$

$$i\, g_s T^a \gamma^+$$

- $R^+(k_1, a) + R^-(k_2, b) \to g(k1 + k2, \mu, c)$

$$-2\, g_s f_{abc}((\frac{k_2^2}{k_1^+} + k_2^-)n_+^\mu - (\frac{k_1^2}{k_2^-} + k_1^+)n_-^\mu + (k_1 - k_2)^\mu)$$

- $R^+(k_1, a) \to g(p_1, \mu_1, c) + g(k_1 - p_1, \mu_2, c)$

$$
\begin{aligned}
&- g_s f_{abc}(n_-^{\mu_2}(p_1 - 2k_1)^{\mu_1} + n_-^{\mu_1}(k_1 + p_1)^{\mu_2} \\
&+ \frac{k_1^2 n_-^{\mu_1} n_-^{\mu_2}}{p_1^-} - 2g^{\mu_1\mu_2} p_1^-)
\end{aligned}
$$

- $R^+(k_1, a) + R^-(k_2, b) \to g(p_1, \mu_1, c) + g(p_2, \mu_2, d)$

$$
\begin{aligned}
&-i\, g_s^2(n_+^{\mu_1} n_-^{\mu_2}(f_{abe}f_{cde} + f_{ace}f_{bde}) - n_-^{\mu_1} n_+^{\mu_2}(f_{abe}f_{cde} - f_{ade}f_{bce}) \\
&- \frac{2k_1^2 n_-^{\mu_1} n_-^{\mu_2}(p_1^- f_{abe}f_{cde} - k_2^- f_{ace}f_{bde})}{k_2^- p_1^- p_2^-} - 2g^{\mu_1\mu_2}(f_{ade}f_{bce} + f_{ace}f_{bde}) \\
&+ \frac{2k_2^2 n_+^{\mu_1} n_+^{\mu_2}(p_1^+ f_{ace}f_{bde} + p_2^+ f_{ade}f_{bce})}{k_1^+ p_1^+ p_2^+})
\end{aligned}
$$

Factorization formula in PRA

Similar to the CPM, we ignore the contribution of $q\bar{q}$ channel.

$$d\sigma(AB \to 2J/\psi + X) = \sum_{m,n,H_1,H_2} \int \frac{dx_1}{x_1} \int \frac{d^2\mathbf{q}_{T_1}}{\pi} \int \frac{dx_2}{x_2} \int \frac{d^2\mathbf{q}_{T_2}}{\pi}$$
$$\times \Phi_{R^+/A}(x_1, |\mathbf{q}_{T_1}|^2, \mu^2) \Phi_{R^-/B}(x_2, |\mathbf{q}_{T_2}|^2, \mu^2) d\hat{\sigma}(R^+R^- \to c\bar{c}(m) + c\bar{c}(n$$
$$\times \langle \mathcal{O}^{H_1}(m) \rangle \mathrm{Br}(H_1 \to J/\psi + X) \times \langle \mathcal{O}^{H_2}(n) \rangle \mathrm{Br}(H_2 \to J/\psi + X),$$

where

$$d\hat{\sigma}(R^+R^- \to c\bar{c}(m) + c\bar{c}(n)) = \frac{\overline{|\mathcal{M}|^2}_{PRA}}{2Sx_1x_2} \, d \, \mathrm{LIPS}$$

with

$$\overline{|\mathcal{M}|^2}_{PRA} = \frac{1}{8^2} \left(\frac{q_1^+ q_2^-}{4|\mathbf{q}_{T_1}||\mathbf{q}_{T_2}|} \right)^2 \sum_{color,spin} |\mathcal{M}|^2_{PRA}$$

Connection to CPM

- Relation between pdfs.

$$\int dt\Phi_{R/A}(x,t,\mu^2) = xf_{g/A}(x,\mu^2)$$

- Relation between matrix elements,

$$\int_0^{2\pi} \frac{d\phi_1 d\phi_2}{(2\pi)^2} \lim_{|\mathbf{q}_{T_{1,2}}|\to 0} = \overline{|\mathcal{M}|^2}_{PRA} = \frac{1}{2^2 8^2} \sum_{color,spin} |\mathcal{M}|_{CPM}$$

- he collinear limit is checked both analytically and numerically with the test pdf

$$\Phi_{test}(x,t,\mu) = xf_g(x,\mu)\frac{2}{\mu^2\sigma\sqrt{\pi}}\exp(-\frac{t^2}{\mu^4\sigma^2})$$

Some features in PRA computation

- The number of the sub-processes we need to calculate is also $7 \times 8/2 - 3 = 25$, which is identical to the CPM at LO.
- For each sub-process, the # of Feynman diagrams is also the same as the corresponding sub-process in LO CPM.
- The diagrams for the sub-process in the PRA can be viewed as changing the initial gluons gg of the corresponding sub-process in CPM by by R^+R^-.
- However, the p_t scaling for the sub-process in the PRA can become different, due to that the initial partons carry $|\mathbf{q}_T|$.

The Numerical inputs

LDMEs in units of GeV^3 (PRD,62,114027) and Branch functions from higher states to J/ψ (PDG 2012)

$\mathcal{O}^{J/\psi}(^3S_1^{[1]}) = 1.3$, $\mathcal{O}^{J/\psi}(^3S_1^{[8]}) = 2.23 \times 10^{-3}$, $\mathcal{O}^{J/\psi}(^1S_0^{[8]}) = 1.84 \times 10^{-2}$, $\mathcal{O}^{J/\psi}(^3P_0^{[8]}) = 0$, $\mathcal{O}^{\psi'}(^3S_1^{[1]}) = 0.65$, $\mathcal{O}^{\psi'}(^3S_1^{[8]}) = 9.33 \times 10^{-4}$, $\mathcal{O}^{\psi'}(^1S_0^{[8]}) = 3.27 \times 10^{-3}$, $\mathcal{O}^{\psi'}(^3P_0^{[8]}) = 0$, $\mathcal{O}^{\chi_{c0}}(^3P_0^{[1]})/m_c^2 = 3.96 \times 10^{-2}$, $\mathcal{O}^{\chi_{c0}}(^3S_1^{[8]}) = 1.69 \times 10^{-4}$, $\mathrm{Br}(\chi_{c1} \to J/\psi\gamma) = 33.9\%$, $\mathrm{Br}(\chi_{c2} \to J/\psi\gamma) = 19.2\%$, and $\mathrm{Br}(\psi' \to J/\psi + X) = 60.9\%$.

PDF, α_s and scale set

The unintegrated PDF is generated from MRST-2008 set of collinear PDFs using Kimber-Martin-Ryskin(KMR) scheme, and the coresponding running of α_s . The default choice of factorization and renormalization scale is $\mu_r = \mu_f = m_T = \sqrt{(4m_c)^2 + p_{T_1}^2}$

- Recall the CMS kinematic cut conditions:

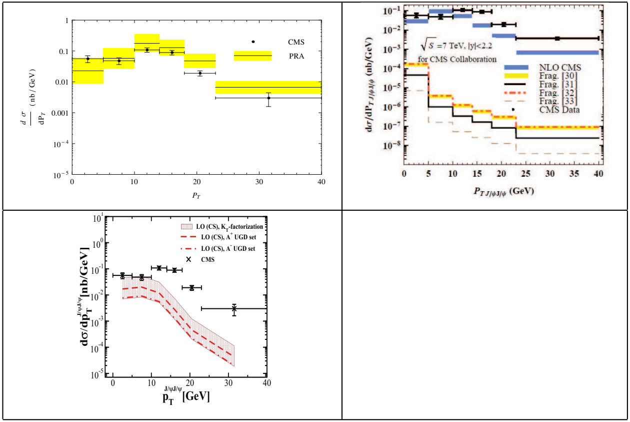
$$
\begin{aligned}
p_T^{J/\psi} &> 4.5\ \mathrm{GeV} && \text{if} \quad 1.43 < |y^{J/\psi}| < 2.2, \\
4.5\ \mathrm{GeV} < p_T^{J/\psi} &< 6.5\ \mathrm{GeV} && \text{if} \quad 1.2 < |y^{J/\psi}| < 1.43, \\
p_T^{J/\psi} &> 6.5\ \mathrm{GeV} && \text{if} \quad |y^{J/\psi}| < 1.2.
\end{aligned}
$$

- Total cross section:

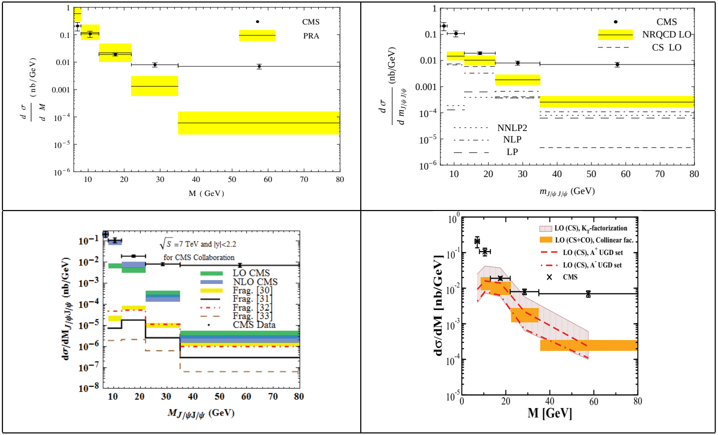
$$
\sigma^{CMS} = (1.49 \pm 0.07 \pm 0.13)\ \mathrm{nb},
$$
$$
\sigma^{PRA} = 1.97^{+1.84}_{-0.92}\ \mathrm{nb},\ \sigma^{\mathrm{CPM}} = 0.15\ \mathrm{nb}.
$$

Comparison with CMS data II

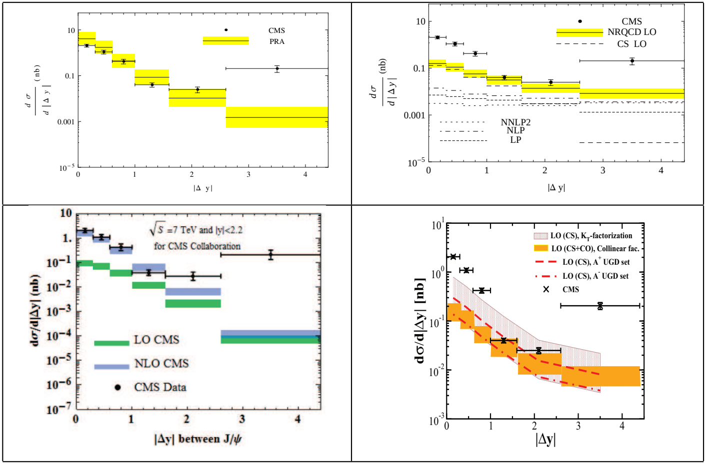
- Compare PRA+NRQCD@LO (up-left),CPM+CSM@NLO (up-right), and k_t+NRQCD@LO (down-left) predictions with CMS data for the spectrum of J/ψ pair transverse momentum:



- Compare PRA+NRQCD@LO (up-left),CPM+NRQCD@LO (up-right), CPM+CSM@NLO (down-left), k_t+NRQCD@LO (down-right) predictions with CMS data for the invariant mass spetrum:



- Compare PRA+NRQCD@LO (up-left),CPM+NRQCD@LO (up-right), CSM@NLO (down-left), and k_t+NRQCD@LO (down-right) preditions with CMS data for the $|\Delta y|$ distribution:



Comparison with ATLAS data I

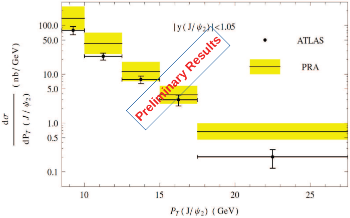
- Recall the ATLAS kinematic cut conditions $p_T^{J/\psi} > 8.5\ \mathrm{GeV}$ and $|y^{J/\psi}| < 2.1$, and they split the total cross section and differential cross section into the central rapdidity region $|y(J/\psi_2)| < 1.05$ and non-central rapidity region $1.05 < |y(J/\psi_2)| < 2.1$ of the sub-leading J/ψ.
- Total cross section:

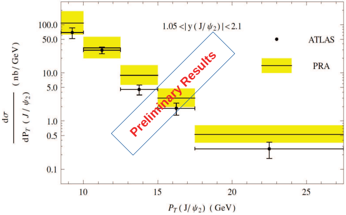
$$\sigma(pp \to J/\psi J/\psi + X) = \begin{cases} 82.2 \pm 8.3\,(\mathrm{stat}) \pm 6.3\,(\mathrm{syst}) \pm 0.9\,(\mathrm{BF}) \pm 1.6\,(\mathrm{lumi})\ \mathrm{pb}, & \text{for } |y| < 1.05, \\ 78.3 \pm 9.2\,(\mathrm{stat}) \pm 6.6\,(\mathrm{syst}) \pm 0.9\,(\mathrm{BF}) \pm 1.5\,(\mathrm{lumi})\ \mathrm{pb}, & \text{for } 1.05 \le |y| < 2.1. \end{cases}$$

$$\sigma^{PRA} = \begin{cases} 143^{+99}_{-57}\ \mathrm{pb}, & |y(J/\psi_2)| < 1.05 \\ 112^{+81}_{-45}\ \mathrm{pb}, & 1.05 < |y(J/\psi_2)| < 2.1, \end{cases}$$

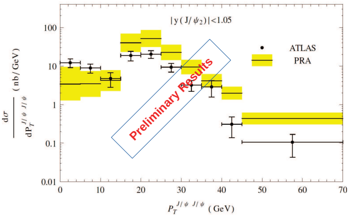
Preliminary Results

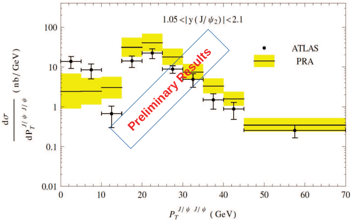
- The $p_T(J/\psi_2)$ distribution:





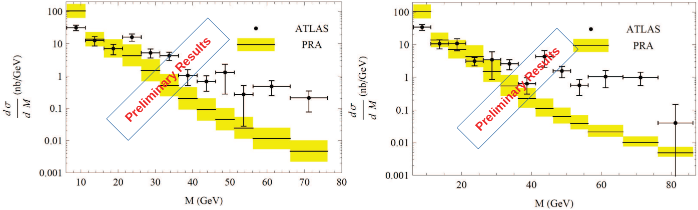
- The $p_T^{J/\psi J/\psi}$ distribution:





Comparison with ATLAS data III

- The invariant mass M distribution:



Summary

- The prompt double J/ψ hadroproduction is studied in Parton Reggeization Approach by including feed-down contribution from the higher excited states χ_{cJ} and ψ'.
- The PRA predictions of the total cross sections agree with both CMS and ATLAS measurements.
- The PRA calculation can also well explain the $P_T^{J/\psi J/\psi}$ distribution for both CMS and ATLAS set up and $P_T(J/\psi_2)$ distribution measured by ATLAS Collaboration.
- However, there are still large discrepancies between PRA predictions and CMS and ATLAS data of the invariant mass $M_{J/\psi J/\psi}$ distribution in large $M_{J/\psi J/\psi}$ region.

Thank you !