Some estimates of exotic production at STCF

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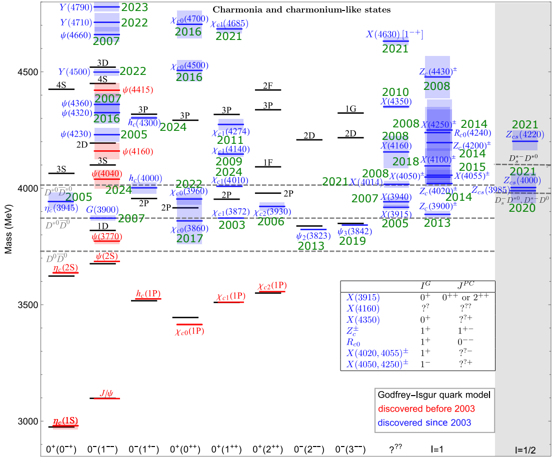
What we expect at STCF: Searching for Exotic States

- C. M. energy range: $2 \sim 7$ GeV
- Integrated luminosity: 1 ab^{-1} per year
- Ideal place to study exotic states containing a $c\bar{c}$
- $\rightarrow$ Two $c\bar{c}$ state $X(6200)$?
  X. K. Dong et al., PRL (2021)
  PhysRevD.111.034038

  Lattice QCD: Geng Li et al.,
  arXiv.2505.24213
- $\rightarrow$ Hidden charm baryons P_c



Overview

1. **Existence of $X(6200)$ from double Jpsi Spectrum**

2. **Estimates of $X(6200)$ Production at STCF**

3. **Production of Jpsi, proton and anti-proton in electron-positron collisions**

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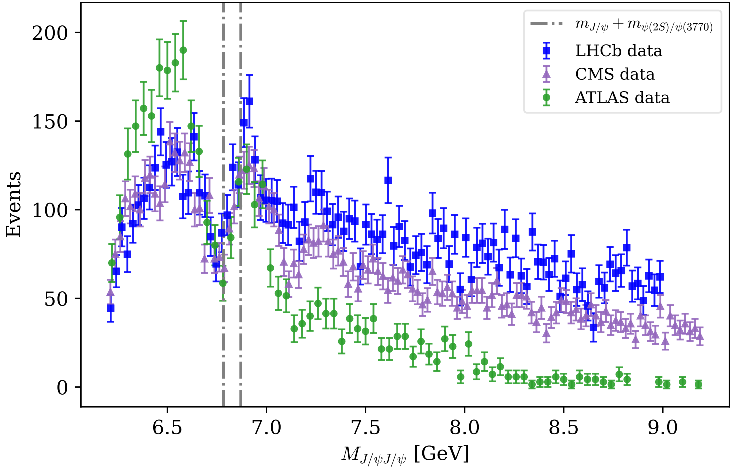


LHCb: Sci. Bull. 65, 1983-1993 (2020)
CMS: Phys. Rev. Lett. 132, 111901 (2024)
ATLAS: Phys. Rev. Lett. 131, 151902 (2023)

Energy range of interest:

6.2-7.1 GeV

Two Coupled-Channel Models:

- $\{J/\psi J/\psi, J/\psi\psi(2S)\}$
- $\{J/\psi J/\psi, J/\psi\psi(2S), J/\psi\psi(3770)\}$

X. K. Dong et al., Phys. Rev. Lett. 126, 132001 (2021)

Channel	$J/\psi J/\psi$	$J/\psi h_c$	$J/\psi\psi(2S)$	$\chi_{c0}\chi_{c0}$	$\chi_{c0}\chi_{c1}$	$J/\psi\psi(3770)$	$\chi_{c1}\chi_{c1}$	$h_c h_c$	$\chi_{c2}\chi_{c2}$
Threshold	6.194	6.622	6.783	6.830	6.925	6.870	7.021	7.051	7.132
Model	2 and 3 ch.	...	2 and 3 ch.	...	...	3 ch.	...	...	...

Coupled-Channel Formalism

X. K. Dong et al., Phys. Rev. Lett. 126, 132001 (2021)

$$V_{2ch}(E) = \begin{pmatrix} a_1 + b_1 k_1^2 & c \\ c & a_2 + b_2 k_2^2 \end{pmatrix},$$

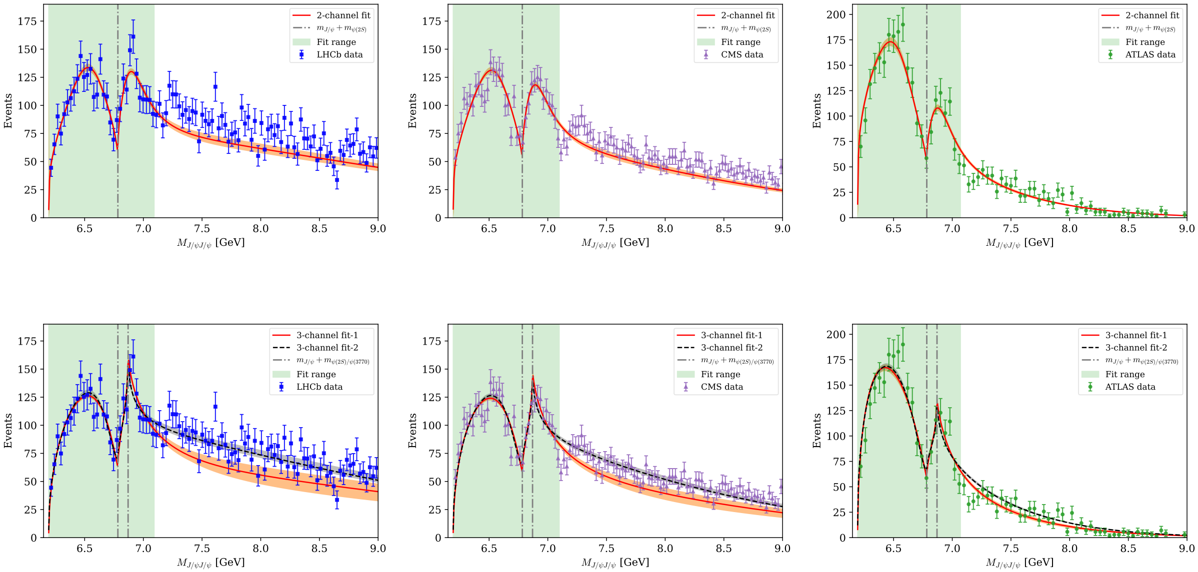
$$V_{3ch}(E) = \begin{pmatrix} a_{11} & a_{12} & a_{13} \\ a_{12} & a_{22} & a_{23} \\ a_{13} & a_{23} & a_{33} \end{pmatrix},$$

$$\mathcal{M}_1 = P(E)(b + G_1 T_{11} + \sum_{i=2,3} r_i G_i T_{1i})$$

$$T(E) = V(E) \cdot [1 - G(E) \cdot V(E)]^{-1},$$

$$G_i(E) = i \int \frac{d^4 q}{(2\pi)^4} \frac{1}{(q^2 - m_{i1}^2 + i\epsilon)[(P-q)^2 - m_{i2}^2 + i\epsilon]}$$

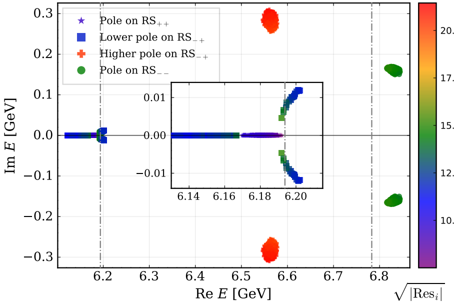
- short-distance source function $P(E) = \alpha e^{-\beta E^2}$
- different background parameters $\{\alpha_i, \beta_i\}$ for different data sets
- $\beta_1 = 0.012, \beta_2 = 0.020, \beta_3 = 0.056$, (in GeV^{-2}) determined from high energy tail
- a possible violation of unitarity in the inclusive production amplitude $b \neq 1$
- Combined fitting $\chi^2 = \sum_j \chi_j^2$

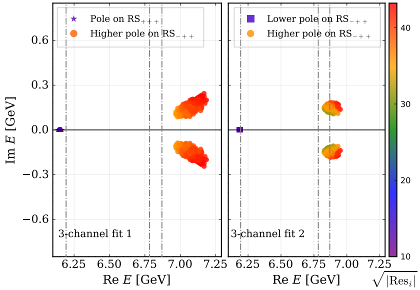

2-channel fit
$m_{J/\psi}+m_{\psi(2S)}$
Fit range
LHCb data
CMS data
ATLAS data
3-channel fit-1
3-channel fit-2
$m_{J/\psi}+m_{\psi(2S)/\psi(3770)}$
Events
$M_{J/\psi J/\psi}$ [GeV]

Results

- Riemann sheet $R_{\dots}$ is defined by signs of Imk_is

Model	Two-channel fit	Three-channel fit 1	Three-channel fit 2
$X(6200)$	$[6171, 6194]$ (RS$_{++}$) or $[6124, 6202] - i[0, 12]$ (RS$_{-+}$)	6151^{+12}_{-16} (RS$_{+++}$)	6189^{+3}_{-6} (RS$_{-++}$)
$X(6900)$	$6831^{+15}_{-17} - i162^{+8}_{-12}$ (RS$_{--}$)	$7071^{+107}_{-101} - i147^{+81}_{-55}$ (RS$_{-++}$)	$6872^{+77}_{-45} - i148^{+37}_{-43}$ (RS$_{-++}$)
Other poles	$6564^{+13}_{-14} - i282^{+27}_{-27}$ (RS$_{-+}$)	...	...





PDG:

$T_{cc\bar{c}\bar{c}}(6900)$

$M = 6899 \pm 12$ MeV

$\Gamma = 153 \pm 29$ MeV

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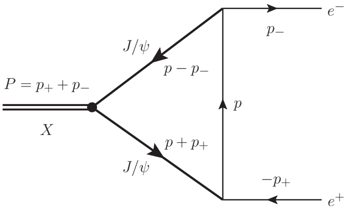
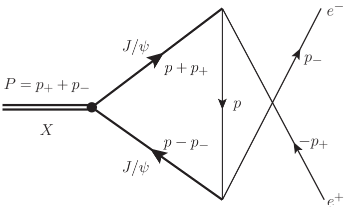
$X(6200) \to e^+e^-$ width and its production in e^+e^- annihilation





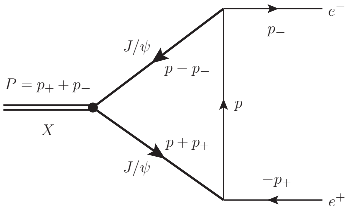
For $J^{PC} = 2^{++}$, $\mathcal{A} = 2(2eg_{J/\psi})^2 g_X \epsilon_{jk} \bar{u}(p_-)\gamma_j \not{l} \gamma_k u(-p_+)$

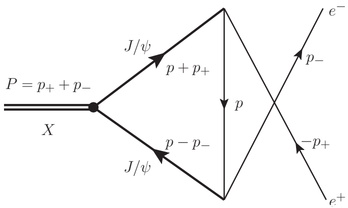
$$T(s \simeq m_X^2) \approx \frac{g_X^2}{s - m_X^2} \qquad \Gamma^{ee}_{\chi_{c2}(1P)} = 0.014 \text{ eV (VMD)},\ 0.07 \text{ eV (NRQCD)}$$

Nucl. Phys. B 157, 125-144 (1979) JHEP 02, 032 (2016)

	Two-channel bound state	Two-channel virtual state or resonance	Three-channel fit 1	Three-channel fit 2
$\lvert g_X \rvert$ [GeV]	[7.04,9.87]	[10.64,15.25]	[19.05,21.92]	[10.36,14.79]
$\Gamma^{ee}_{X_2(6200)}$ [eV]	[0.002,0.004]	[0.005,0.010]	[0.016,0.022]	[0.005,0.010]

$X(6200) \to e^+e^-$ width and its production in e^+e^- annihilation





$J^{PC} = 2^{++}$,

P. P. Shi et al.(2024) $\sigma_C = \dfrac{20\pi\Gamma^{ee}_{X_2}}{\Gamma_X m_X^2} \sim 10^0\text{-}10^2$ pb, For $\Gamma_X = 0.1\text{-}10$ MeV

Super τ-Charm Facility: Front. Phys. (Beijing) 19, 14701 (2024)

- expected 1-yr integrated luminosity around 1 ab^{-1}

$\to$ Events: $10^6\text{-}10^8$ per year

- For $J^{PC} = 0^{++}$,

$$\Gamma^{ee}_{X_0} \sim \left(\frac{m_e}{m_{J/\psi}}\right)^2 \Gamma^{ee}_{X_2}$$

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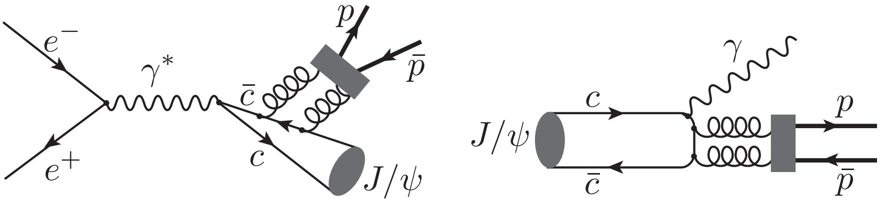
Production of $J/\psi p\bar{p}$ in electron-positron collisions

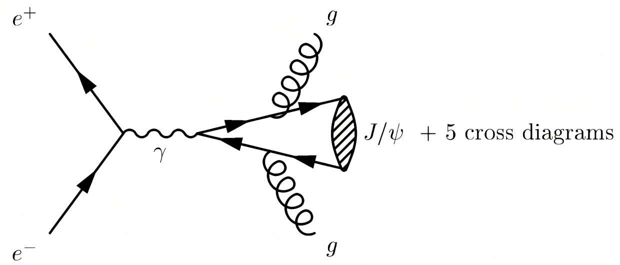


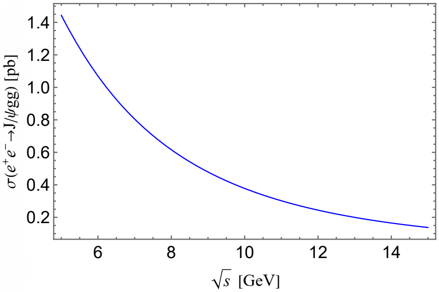
$$\mathcal{A}(e^+e^- \to J/\psi p\bar{p}) \sim \mathcal{A}(e^+e^- \to J/\psi gg) \otimes \mathcal{A}(gg \to p\bar{p})\,, \tag{1}$$

$$\mathcal{A}(J/\psi \to \gamma p\bar{p}) \sim \mathcal{A}(J/\psi \to \gamma gg) \otimes \mathcal{A}(gg \to p\bar{p})\,, \tag{2}$$

$$\frac{\sigma(e^+e^- \to J/\psi p\bar{p})}{\Gamma(J/\psi \to \gamma p\bar{p})} \approx \frac{\sigma(e^+e^- \to J/\psi gg)}{\Gamma(J/\psi \to \gamma gg)}, \tag{3}$$

$e^+e^- \to J/\psi gg$ in NRQCD Framework





- For c.m. Energy 6-7 GeV and to LO:

$$\sigma(e^+e^- \to J/\psi gg) = \mathcal{O}(1\ \text{pb}) \tag{4}$$

$$\mathcal{B}(J/\psi \to \gamma gg) = (8.8 \pm 1.1)\% \,,$$
$$\mathcal{B}(J/\psi \to \gamma p\bar{p}) = (3.8 \pm 1.0) \times 10^{-4} \,, \tag{5}$$

we get

$$\sigma(e^+e^- \to J/\psi p\bar{p}) \approx \sigma(e^+e^- \to J/\psi gg) \times 4 \times 10^{-3}. \tag{6}$$

$$\sigma(e^+e^- \to J/\psi p\bar{p}) = \mathcal{O}(4 \text{ fb}). \tag{7}$$

- at STCF: annually integrated luminosity of 1 ab^{-1} $\to \mathcal{O}(4 \times 10^3)$ $J/\psi p\bar{p}$ events
- Hidden charm Pentaquarks: Assuming $\mathcal{B}(P_c \to J/\psi p) \sim 0.01$

$$\sigma(e^+e^- \to P_c\bar{p}) \lesssim \frac{\sigma(e^+e^- \to J/\psi p\bar{p})}{\mathcal{B}(P_c \to J/\psi p)} = \mathcal{O}(0.1 \text{ pb}), \tag{8}$$

- $\lesssim \mathcal{O}(10^5)$ $P_c\bar{p}$ events

P_c production in open-charm channels

$P_c \to \Lambda_c \bar{D}^{(*)}$, $P_c \to \Sigma_c^{(*)} \bar{D}^{(*)}$

- $P_c \to$ open-charm more easily than $J/\psi nn$
  Nucl. Phys. A 954, 393 (2016)
  Phys. Rev. D 100, 056005 (2019)
  JHEP 08 (8), 157
- P_c couples strongly to its molecular components

$D^{\pm}$	$K_S^0\,\pi^+$	$(1.562 \pm 0.031)\%$	D^0	$K^-\pi^+$	$(3.950 \pm 0.031)\%$	Λ_c^+	pK_S^0	$(1.59 \pm 0.08)\%$
	$K_L^0\,\pi^+$	$(1.46 \pm 0.05)\%$		$K_S^0\,\pi^0$	$(1.240 \pm 0.022)\%$		$pK^-\pi^+$	$(6.28 \pm 0.32)\%$
	$K^- 2\,\pi^+$	$(9.38 \pm 0.16)\%$		$K_S^0\,\pi^+\pi^-$	$(2.80 \pm 0.18)\%$		$\Lambda\pi^+$	$(1.30 \pm 0.07)\%$
	$K_S^0\,\pi^+\pi^0$	$(7.36 \pm 0.21)\%$		$K^-\pi^+\pi^0$	$(14.4 \pm 0.5)\%$		$\Lambda\pi^+\pi^0$	$(7.1 \pm 0.4)\%$

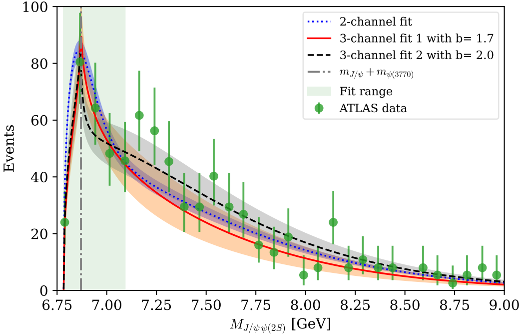
Summary

- $X(6200)$ from combined double J/ψ spectra analysis
- tensor $X(6200)$ 10^6-10^8 events per year but the scalar ones can not be observed at STCF
- $\mathcal{O}(4 \times 10^3)$ $J/\psi p\bar{p}$ events and $\lesssim \mathcal{O}(10^5)$ $P_c\bar{p}$ events
- P_c should also be searched in open-charm final states

Thanks for your attention

Back Up

$J/\psi\psi(2S)$ **Line Shape**



three-channel fit	α_3	b	χ^2/dof
fit 1	2441^{+657}_{-720}	$1.71^{+0.30}_{-0.16}$	0.08
fit 2	2072^{+597}_{-646}	$2.04^{+0.38}_{-0.19}$	0.29

Compositeness of the $X(6200)$

ERE in $J/\psi J/\psi$ channel:

$$T(k) = -8\pi\sqrt{s}\left[\frac{1}{a_0} + \frac{1}{2}r_0 k^2 - i\,k + \mathcal{O}(k^4)\right]^{-1}$$

Compositeness:

$$\bar{X}_A = (1 + 2|r_0/a_0|)^{-1/2}$$

Matuschek et al.'2021

	Two-channel fit	Three-channel fit 1	Three-channel fit 2
a_0(fm)	≤ -0.31 or ≥ 0.78	$-0.52^{+0.07}_{-0.08}$	$1.63^{+0.75}_{-0.38}$
r_0(fm)	$-1.75^{+0.16}_{-0.48}$	$-0.05^{+0.01}_{-0.01}$	$-0.08^{+0.02}_{-0.02}$
$\bar{X}_A$	$0.37^{+0.62}_{-0.09}$	$0.92^{+0.02}_{-0.02}$	$0.95^{+0.02}_{-0.02}$

NRQCD

G. T. Bodwin Phys. Rev. D 51, 1125 (1995)

- An effective field theory involving heavy quarks
- Energy seperation: M from Mv, Mv^2, Λ_{QCD}

$$\mathcal{L}_{\text{NRQCD}} = \mathcal{L}_{\text{light}} + \mathcal{L}_{\text{heavy}} + \delta\mathcal{L} \tag{9}$$

$$\mathcal{L}_{\text{light}} = -\frac{1}{2}Tr(G_{\mu\nu}G^{\mu\nu}) + \sum \bar{q}i\not{D}q \tag{10}$$

$$\mathcal{L}_{\text{heavy}} = \psi^{\dagger}\left(iD_t + \frac{\mathbf{D}^2}{2M}\right)\psi + \chi^{\dagger}\left(iD_t - \frac{\mathbf{D}^2}{2M}\right)\chi \tag{11}$$

- $Q\bar{Q} \rightarrow Q\bar{Q}$:

$$\delta\mathcal{L}_{4-fermion} = \sum_n \frac{f_n(\Lambda)}{M^{d_n-4}}\mathcal{O}_n \tag{12}$$

NRQCD

- For dimension-6:

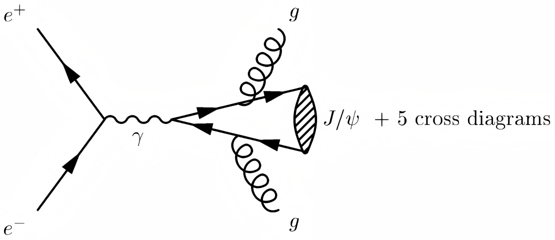
$$(\delta\mathcal{L}_{4-\text{fermion}})_{d=6} = \frac{f_1(^1S_0)}{M^2}\mathcal{O}_1(^1S_0) + \frac{f_1(^3S_1)}{M^2}\mathcal{O}_1(^3S_1) + \frac{f_8(^1S_0)}{M^2}\mathcal{O}_8(^1S_0) + \frac{f_8(^3S_1)}{M^2}\mathcal{O}_8(^3S_1), \tag{13}$$

$$\mathcal{O}_1(^3S_1) = \psi^\dagger \boldsymbol{\sigma}\chi \cdot \chi^\dagger \boldsymbol{\sigma}\psi \tag{14}$$

- Matching coefficients to QCD:

$$A(Q\overline{Q} \to Q\overline{Q})\Big|_{\text{pert. QCD}} = \sum_n \frac{f_n(\Lambda)}{M^{d_n-4}} \langle Q\overline{Q}|\mathcal{O}_n(\Lambda)|Q\overline{Q}\rangle\Big|_{\text{pert. NRQCD}} . \tag{15}$$

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



F. Yuan, C.-F. Qiao, and K.-T. Chao, Phys. Rev. D 56, 1663 (1997)

$$\frac{d\sigma(e^+e^- \to J/\psi gg)}{\sigma_{\mu\mu} dz dx_1} = \frac{64 e_c^2 \alpha_s^2}{27} \frac{\langle \mathcal{O}_1^{\psi}(^3S_1) \rangle}{m^3} r^2 f(z, x_1; r), \tag{16}$$

- Vacuum-saturation approximation: G. T. Bodwin Phys. Rev. D 51, 1125 (1995)

$$\langle \psi | \mathcal{O}_1(^3S_1) | \psi \rangle = \left| \langle 0 | \chi^\dagger \boldsymbol{\sigma} \psi | \psi \rangle \right|^2 (1 + O(v^4)) \tag{17}$$

$$f(z,x_1;r) = \frac{(2+x_2)x_2}{(2-z)^2(1-x_1-r)^2} + \frac{(2+x_1)x_1}{(2-z)^2(1-x_2-r)^2} + \frac{(z-r)^2-1}{(1-x_2-r)^2(1-x_1-r)^2} + \frac{1}{(2-z)^2}\left(\frac{6(1+r-z)^2}{(1-x_2-r)^2(1-x_1-r)^2} + \frac{2(1-z)(1-r)}{(1-x_2-r)(1-x_1-r)r} + \frac{1}{r}\right), \tag{18}$$

$$z = \frac{2p\cdot k}{s}, \quad x_i = \frac{2p_i\cdot k}{s}, \quad r = \frac{m^2}{s}. \tag{19}$$

k, p, p_i are the four-momenta of the virtual photon, J/ψ, and the gluons, respectively.

- Integration region: $2\sqrt{r} \leqslant z \leqslant 1+r$,
  $(2-z-\sqrt{z^2-4r})/2 \leqslant x_1 \leqslant (2-z+\sqrt{z^2-4r})/2$
- $m_c = 1.5$ GeV, $\alpha_s(2m) = 0.26$, $\langle \mathcal{O}_1^{\psi}(^3S_1)\rangle = \frac{9}{2\pi}|R_{J/\psi}(0)|^2 = 1.45$ GeV^3

  Y.-Q. Ma, Y.-J. Zhang, and K.-T. Chao, Phys. Rev. Lett. 102, 162002 (2009)
- In ultra-relativistic limit:

$$\sigma_{\mu\mu} = \frac{4\pi\alpha_{EM}}{3s} \tag{20}$$