西南大學

Fully heavy tetraquark production at LHC

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Outline：

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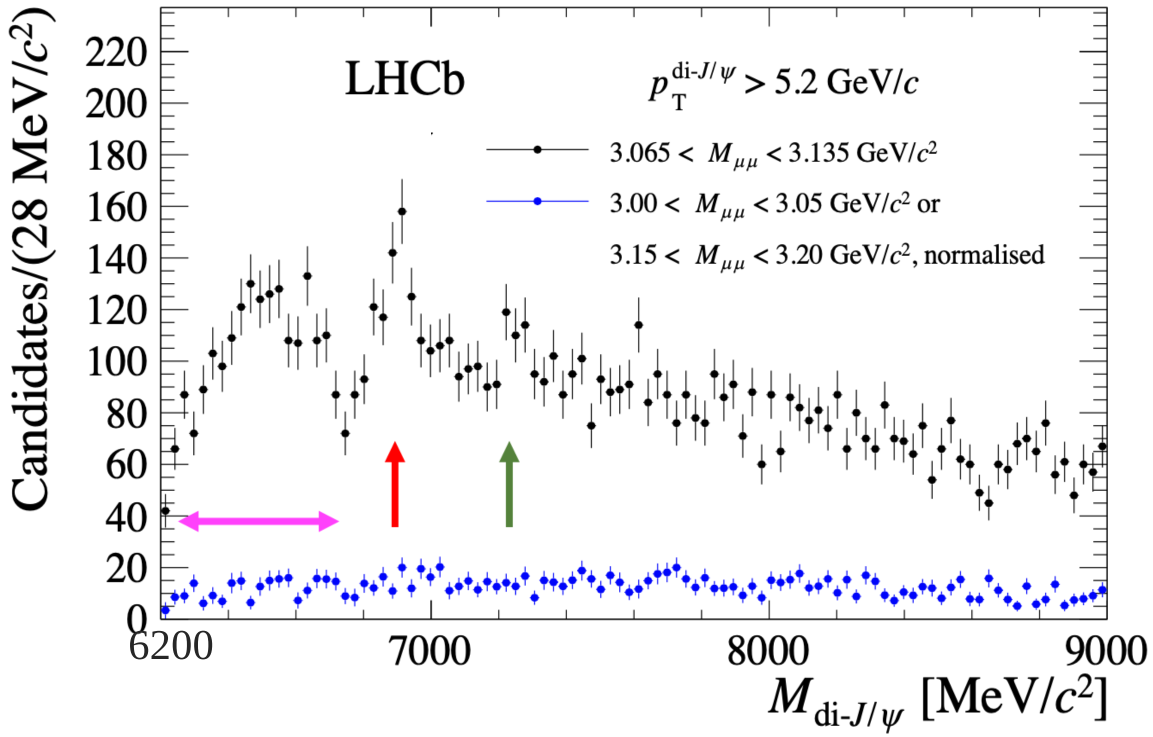
3. T_{4c} production at LHC

4. Summary

1. Introduction

Sci.Bull. 65 (2020) 23, 1983-1993

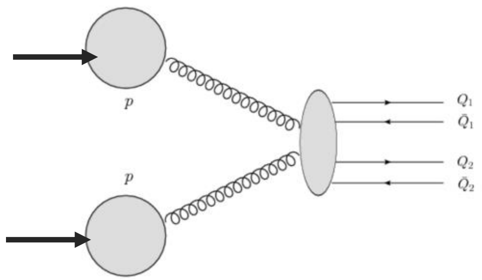
In 2020, LHCb collaboration observed some structures in the di-J/ψ mass spectrum (CM energies of 7, 8, and 13 TeV, with an integrated luminosity of 9 fb^{-1}).



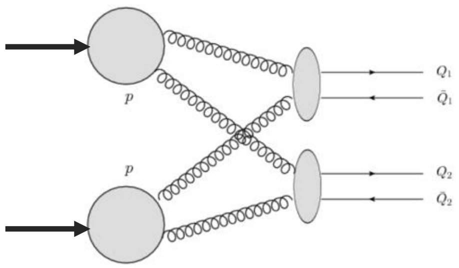
- Broad structure at 6.2 − 6.8 GeV slightly above di-J/ψ mass threshold
- Narrow peak at 6.9 GeV
- **Hint of another structure** at 7.2 GeV
- Structure not present in J/ψ background sample

1. Introduction

Sci.Bull. 65 (2020) 23, 1983-1993



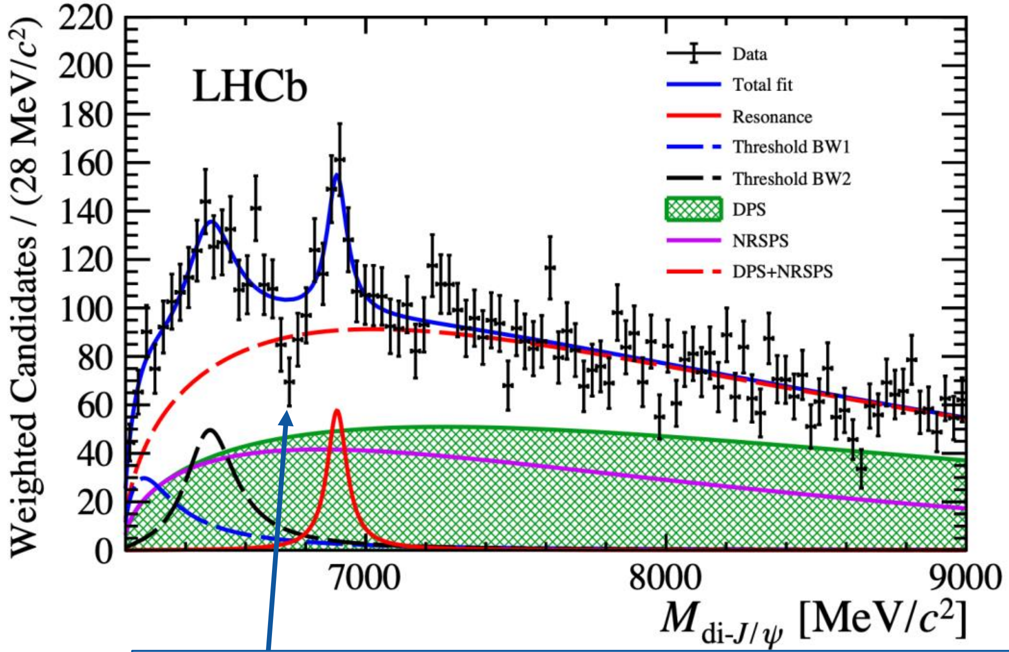
SPS



DPS

LHCb adopt several methods to fit the experimental data.

Model I



Can not explain the dip around 6.75 GeV !

- X(6900) structrure as a resonance
- Threshold enhancement by a superposition of two resonances
- Other Background: **NRSPS**(nonresonant single-parton scattering)+**DPS**(double-parton scattering)
- Without any interferences

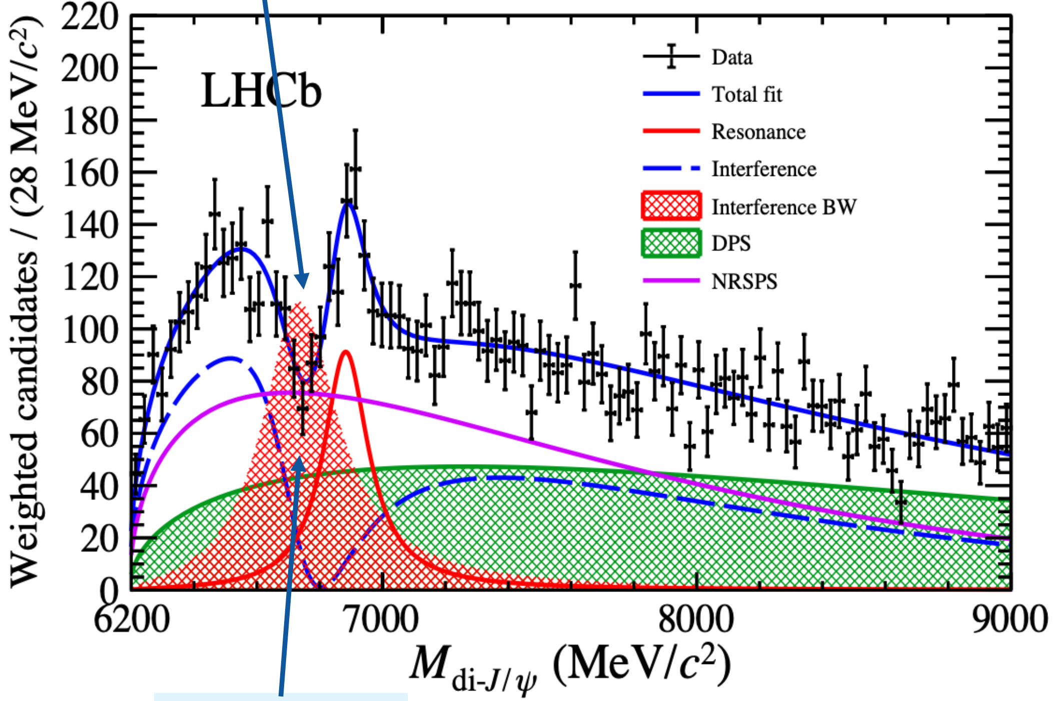
The determined mass and width for the narrow structure:

$$M = 6950 \pm 11 \pm 7\,\text{MeV}$$
$$\Gamma = 80 \pm 19 \pm 33\,\text{MeV}$$

1. Introduction

Well fitted the dip

Model II



Wide BW

$m = 6741\ \mathrm{MeV}/c^2$
$\Gamma = 288\ \mathrm{MeV}/c^2$

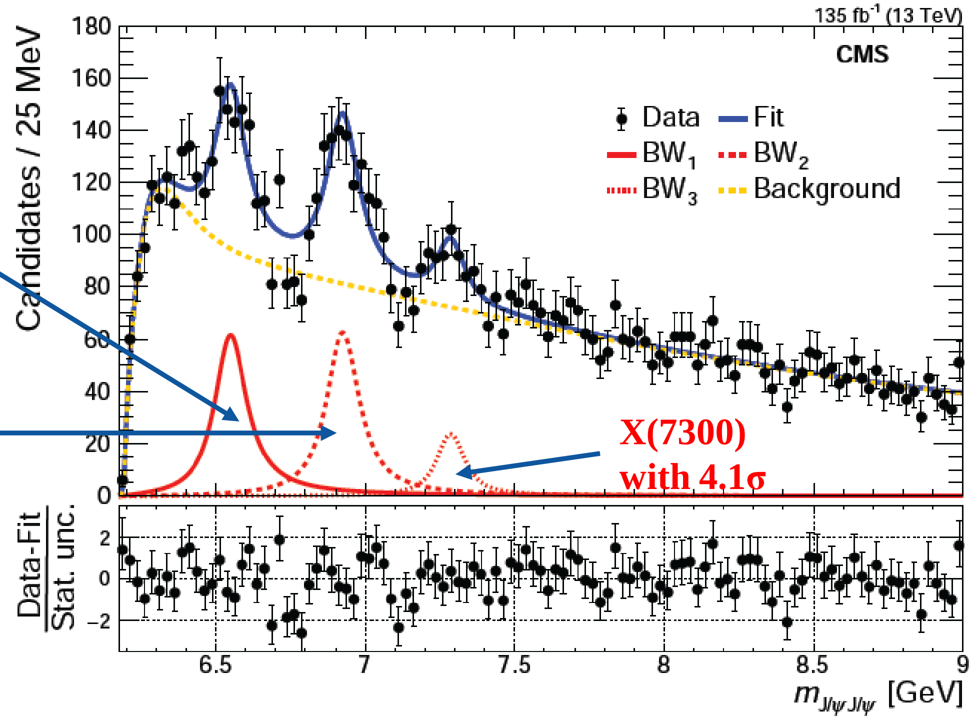
- X(6900) structrure as a resonance
- Threshold enhancement by interference between NRSPS and a wide resonance
- Other background: DPS

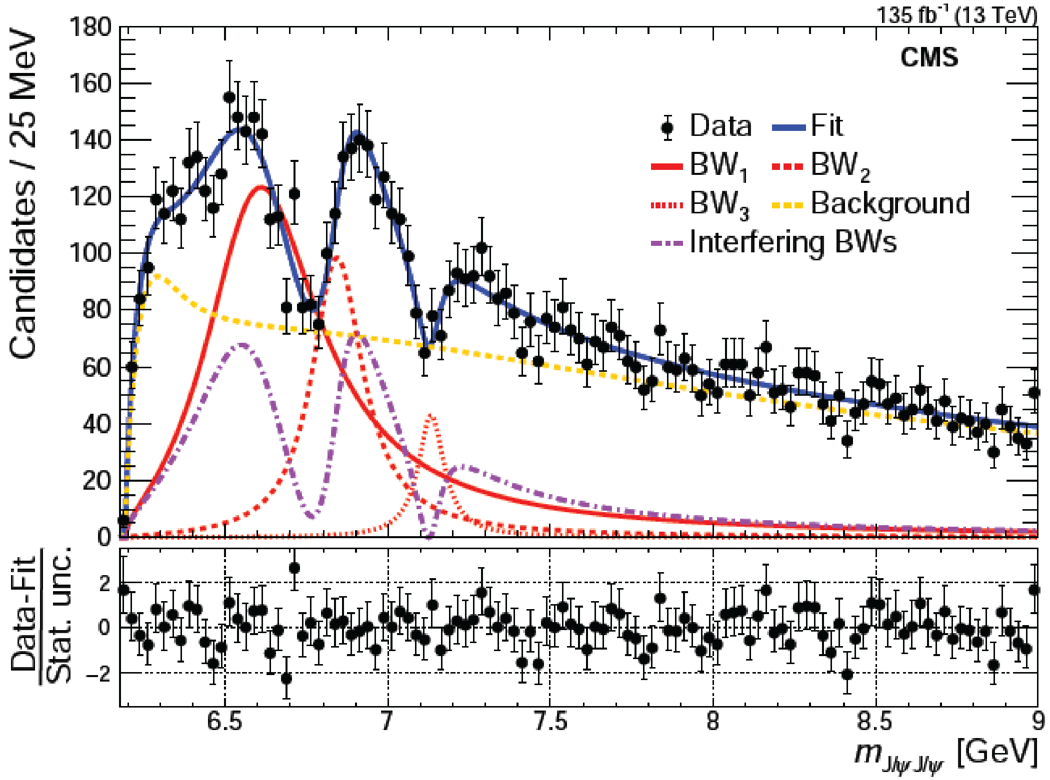
The determined mass and width for the narrow structure:

$$M = 6886 \pm 11 \pm 11\,\mathrm{MeV}$$
$$\Gamma = 168 \pm 33 \pm 69\,\mathrm{MeV}$$

1. Introduction

CMS collaboration **2306.07164**





- Signals: 3 resonances
- Background: NRSPS+DPS+BW$_0$(model a threshold enhancement)
- Without interference

$$M = 6927 \pm 9 \pm 5\,\mathrm{MeV}$$
$$\Gamma = 122 \pm 22 \pm 19\,\mathrm{MeV}$$

$$M = 6552 \pm 10 \pm 12\,\mathrm{MeV}$$
$$\Gamma = 124 \pm 29 \pm 34\,\mathrm{MeV}$$

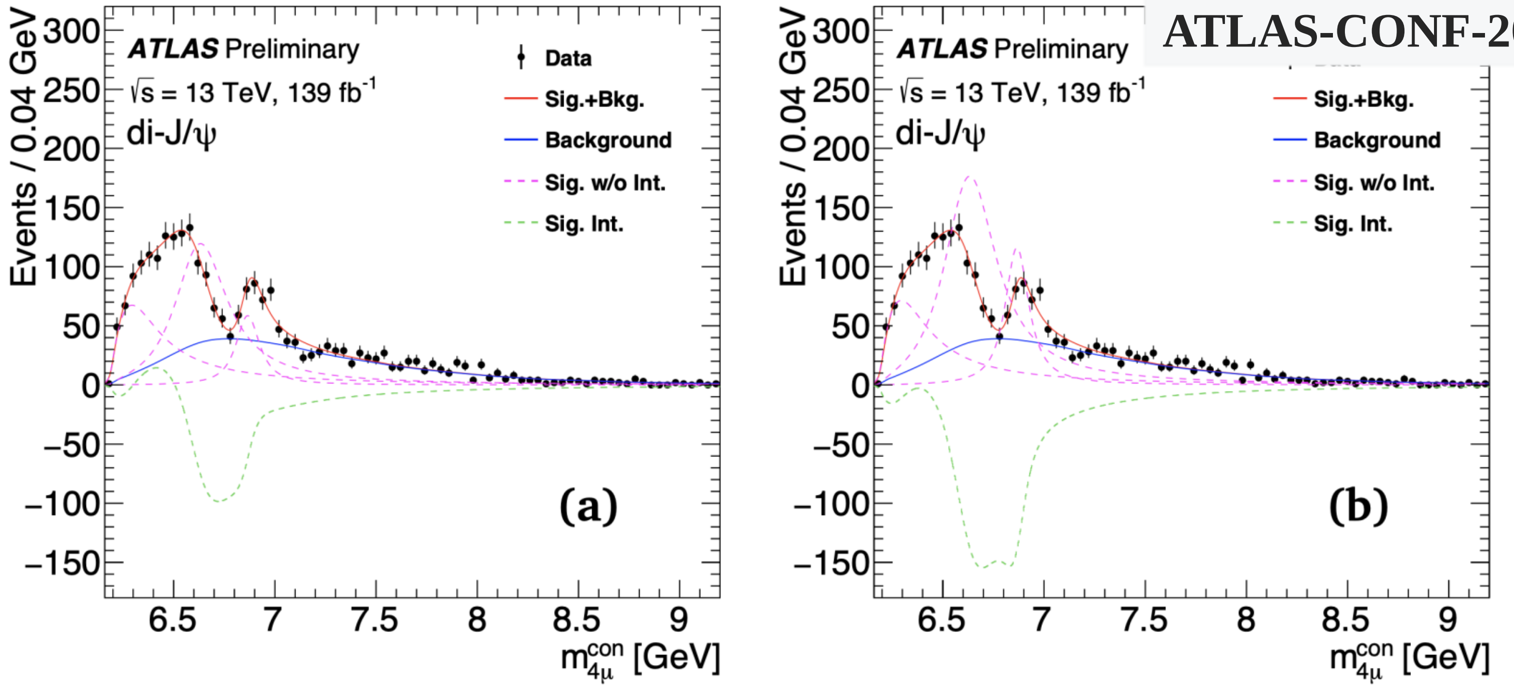
$$M = 7287 \pm 19 \pm 5\,\mathrm{MeV}$$
$$\Gamma = 95 \pm 46 \pm 20\,\mathrm{MeV}$$

- Signals: 3 resonances
- Background: NRSPS+DPS+BW$_0$
- Interference between the 3 BWs (By assuming all the signals have the same J^{PC})

1. Introduction

ATLAS collaboration

ATLAS-CONF-2022- 040



Statistically significant excesses are seen in the di-J/ψ channel consistent with a narrow resonance at **6.9 GeV** and a broader structure at lower mass

In the bottom sector, the searches by LHCb (2018) and CMS (2020) are inconclusive.

1. Introduction

On the theoretical side

- The explorations on fully heavy tetraquark date back to 1970s
  Iwasaki, PRL(1976); Chao, ZPC(1981); Ader et al. PRD(1982)

- Extensive studies are performed after the discovery of X(6900) (e.g., **>280 works** by inspire-hep)
  e.g., the excellent works by Y.B. Dong, S.L. Zhu, X. Liu, F.K, Guo, Q.Zhao, Z.G.Wang, J.L.Ping…… 's groups.

- Theoretical studies are based on various approaches: constituent quark models, QCD sum rules, Lattice, color evaporation model …

1. Introduction

On the theoretical side

- Interpretations on the nature of the fully-heavy charm quark state are still **controversial**

- ✓ **P-wave tetraquark** (M.-S. Liu et al., 2020; H.-X. Chen et al., 2020, R. Zhu 2020).

- ✓ **Radial excitation of 0^{++}** (Z.-G. Wang, 2020; Lü et al., 2020; Giron, Lebed, 2020; Karliner& Rosner, 2020; J. Zhao et al., 2020; R. Zhu, 2020; B.-C. Yang et al., 2020; Z. Zhao, 2020; H.-W. Keet al., 2020),

- ✓ **Ground state S-wave tetraquark** (Gordillo et al., 2020).

- ✓ **$\chi_{c0}\chi_{c0}$ molecular state** (Albuquerque et al., 2020)

- ✓ **0^{++} hybrid** (B.-D. Wan, C.-F. Qiao, 2020),

- ✓ **Resonance formed in charmonium-charmonium scattering** (G. Yang et al., 2020; X. Jinet al., 2020), or the **kinematic cusp arising from final-state interaction** (J.-Z.Wang et al., 2020; X.-K. Dong et al., 2020; Z.-H. Guo2021; C. Gong et al. 2020).

1. Introduction

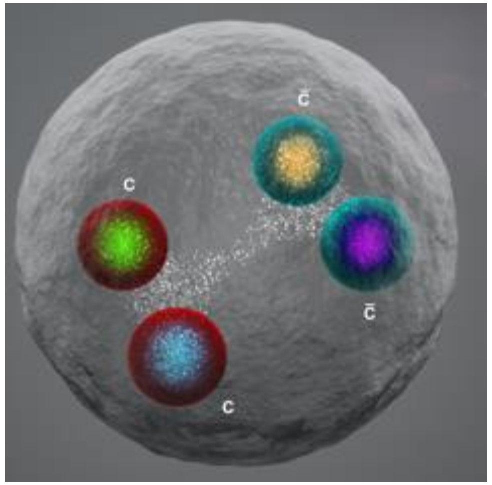
On the theoretical side

While the spectra and decay properties have been widely studied, the production mechanism of fully-heavy tetraquarks was relatively rare.

It is worthwhile to study the fully-heavy tetraquarks production in various colliders, particularly based on factorization.

Similar ideas can be found in the papers of Y.-Q. Ma, H. F. Zhang, 2020;
R.-L. Zhu, 2020

2. NRQCD factorization on T_{4c} production



$T_{4c}: cc\bar{c}\bar{c}$

For simplification, X(6900) is dubbed $\boldsymbol{T_{4c}}$

- Since the charm quark is too heavy, T_{4c} is free from the light constitutes contamination. **Thus T_{4c} is widely believed to be a fully-heavy compact tetraquark state** (Other possibilities exist)

- Analogous to the fact that heavy quarkonia are the simpliest hadrons, the fully-charmed tetraquark may be the simpliest exotic hadrons from theoretical perspective

- Whether is it possible to understand the T_{4c} production in the framework of NRQCD? Like the case of quarkonium production

2. NRQCD factorization on T_{4c} production

A key observation is that, prior to hadronization, two charms and two anticharms have to be created at a rather large energy > m_c, thus one can invoke asymptotic freedom to factorize the production rate as the product of the perturbatively calculable short-distance part and the nonperturbative long-distance part

Scale as > m_c ,
perturbative calculable

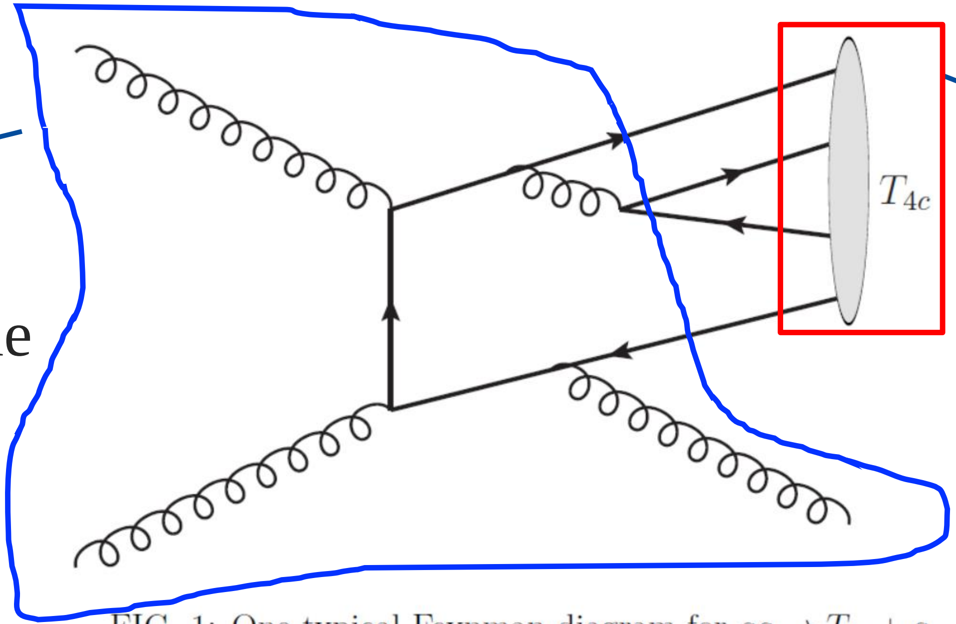


FIG. 1: One typical Feynman diagram for $gg \to T_{4c} + g$.

Scale as < m_c ,
nonperturbative

long-distance matrix elements (LDME)

$$\sigma(T_{4c}) = \sum_i c_i \times \langle O \rangle_i$$

short-distance coefficients (SDC)

2. NRQCD factorization on T_{4c} production

We construct the operators in diquark-antidiquark basis

The diquark (cc) in **spin-singlet**

$$[\psi_a^T(i\sigma^2)\psi_b]$$

The diquark in **spin-triplet**

$$[\psi_a^T(i\sigma^2)\sigma^i\psi_b]$$

Color indices

Due to the identities,

$$\left[\psi_a^T(i\sigma^2)\psi_b\right] = \left[\psi_b^T(i\sigma^2)\psi_a\right]$$

$$\left[\psi_a^T(i\sigma^2)\sigma^i\psi_b\right] = -\left[\psi_b^T(i\sigma^2)\sigma^i\psi_a\right]$$

⇒

The color indices in **spin-singlet** are symmetric

The color indices in **spin-triplet** are antisymmetic

So the spin configuration and color configuration of the diquark are correlated

2. NRQCD factorization on T_{4c} production

Assuming $\boldsymbol{T_{4c}}$ to be a **S-wave tetraquark** (the J^{PC} quantum number can be 0^{++}, 1^{+-} and 2^{++}).

The complement annihilation operators for $\boldsymbol{T_{4c}}$ are

$$\mathcal{O}^{(0)}_{\bar{\mathbf{3}}\otimes\mathbf{3}} = -\frac{1}{\sqrt{3}}[\psi_a^T(i\sigma^2)\sigma^i\psi_b][\chi_c^\dagger\sigma^i(i\sigma^2)\chi_d^*]\,\mathcal{C}^{ab;cd}_{\bar{\mathbf{3}}\otimes\mathbf{3}},$$

$$\mathcal{O}^{i;(1)}_{\bar{\mathbf{3}}\otimes\mathbf{3}} = -\frac{i}{\sqrt{2}}[\psi_a^T(i\sigma^2)\sigma^j\psi_b][\chi_c^\dagger\sigma^k(i\sigma^2)\chi_d^*]\,\epsilon^{ijk}\,\mathcal{C}^{ab;cd}_{\bar{\mathbf{3}}\otimes\mathbf{3}},$$

$$\mathcal{O}^{ij;(2)}_{\bar{\mathbf{3}}\otimes\mathbf{3}} = [\psi_a^T(i\sigma^2)\sigma^k\psi_b][\chi_c^\dagger\sigma^l(i\sigma^2)\chi_d^*]\,\Gamma^{ij;kl}\,\mathcal{C}^{ab;cd}_{\bar{\mathbf{3}}\otimes\mathbf{3}},$$

$$\mathcal{O}^{(0)}_{\mathbf{6}\otimes\bar{\mathbf{6}}} = [\psi_a^T(i\sigma^2)\psi_b][\chi_c^\dagger(i\sigma^2)\chi_d^*]\,\mathcal{C}^{ab;cd}_{\mathbf{6}\otimes\bar{\mathbf{6}}}$$

where

$$\mathcal{C}^{ab;cd}_{\bar{\mathbf{3}}\otimes\mathbf{3}} \equiv \frac{1}{(\sqrt{2})^2}\epsilon^{abm}\epsilon^{cdn}\frac{\delta^{mn}}{\sqrt{3}} = \frac{1}{2\sqrt{N_c}}(\delta^{ac}\delta^{bd} - \delta^{ad}\delta^{bc})$$

Anti-symmetric color tensor

$$\mathcal{C}^{ab;cd}_{\mathbf{6}\otimes\bar{\mathbf{6}}} \equiv \frac{1}{2\sqrt{6}}(\delta^{ac}\delta^{bd} + \delta^{ad}\delta^{bc})$$

Symmetric color tensor

2. NRQCD factorization on T_{4c} production

The corresponding **J^{PC}** quantum number for each operator

$$\mathcal{O}^{(0)}_{\bar{\mathbf{3}}\otimes\mathbf{3}} = -\frac{1}{\sqrt{3}}[\psi_a^T(i\sigma^2)\sigma^i\psi_b][\chi_c^\dagger\sigma^i(i\sigma^2)\chi_d^*]\,\mathcal{C}^{ab;cd}_{\bar{\mathbf{3}}\otimes\mathbf{3}}, \quad \Rightarrow \quad J^{PC} = 0^{++}$$

$$\mathcal{O}^{i;(1)}_{\bar{\mathbf{3}}\otimes\mathbf{3}} = -\frac{i}{\sqrt{2}}[\psi_a^T(i\sigma^2)\sigma^j\psi_b][\chi_c^\dagger\sigma^k(i\sigma^2)\chi_d^*]\,\epsilon^{ijk}\,\mathcal{C}^{ab;cd}_{\bar{\mathbf{3}}\otimes\mathbf{3}}, \quad \Rightarrow \quad J^{PC} = 1^{+-}$$

$$\mathcal{O}^{ij;(2)}_{\bar{\mathbf{3}}\otimes\mathbf{3}} = [\psi_a^T(i\sigma^2)\sigma^k\psi_b][\chi_c^\dagger\sigma^l(i\sigma^2)\chi_d^*]\,\Gamma^{ij;kl}\,\mathcal{C}^{ab;cd}_{\bar{\mathbf{3}}\otimes\mathbf{3}}, \quad \Rightarrow \quad J^{PC} = 2^{++}$$

$$\mathcal{O}^{(0)}_{\mathbf{6}\otimes\bar{\mathbf{6}}} = [\psi_a^T(i\sigma^2)\psi_b][\chi_c^\dagger(i\sigma^2)\chi_d^*]\,\mathcal{C}^{ab;cd}_{\mathbf{6}\otimes\bar{\mathbf{6}}} \quad \Rightarrow \quad J^{PC} = 0^{++}$$

$$\psi_a(t,x) \overset{P}{\leftrightarrow} \psi_a(t,-x)$$

$$\psi_a(t,x) \overset{C}{\leftrightarrow} -i\sigma^2\chi_a^*(t,x)$$

$$\chi_a(t,x) \overset{P}{\leftrightarrow} -\chi_a(t,-x)$$

$$\chi_a(t,x) \overset{C}{\leftrightarrow} i\sigma^2\psi_a^*(t,x)$$

3. T_{4c} production at LHC

Applying the NRQCD factorization, we compute the $\boldsymbol{T_{4c}}$ (**S-wave**) production at LHC

We compute the T_{4c} production through **two different ways**.

Fixed-order production

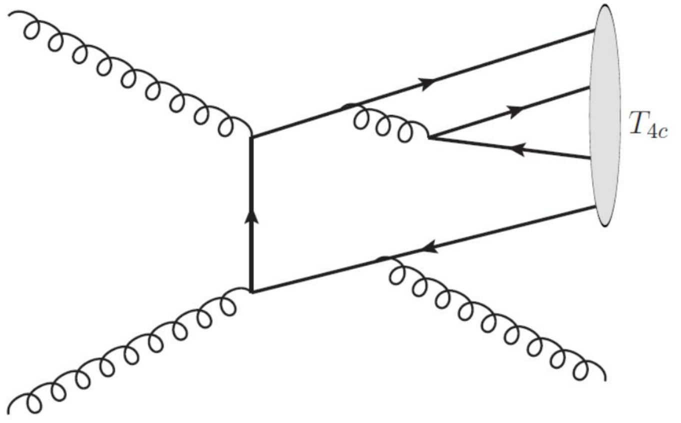


FIG. 1: One typical Feynman diagram for $gg \to T_{4c} + g$.

$$\alpha_s \sim 0.1$$
$$m_{T_{4c}} \sim 7\,\mathrm{GeV}$$

By naive estimation,

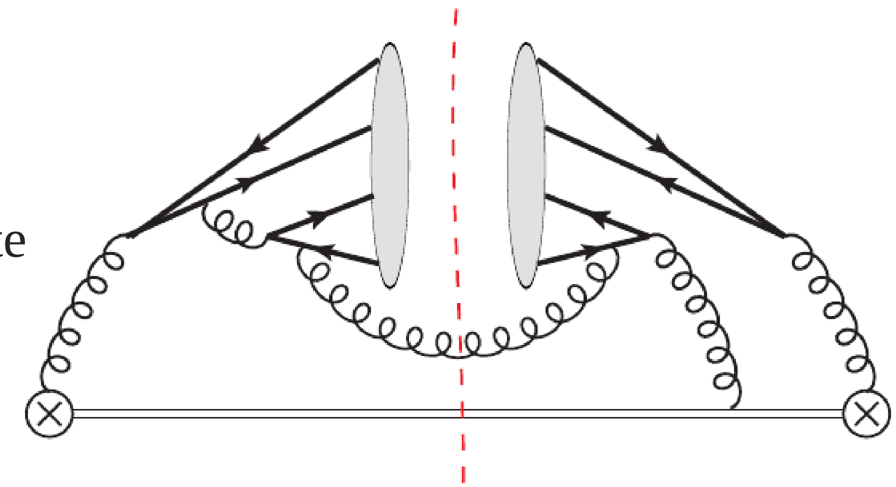
at $p_T > 20\,\mathrm{GeV}$,

fragmentation dominate

at $p_T < 20\,\mathrm{GeV}$,

fixed-order dominate

Fragmentation production



Relative to the fixed-order production, the differential cross section of the fragmentation production suffers $\mathcal{O}(\alpha_s)$ suppression, however is enhanced by $p_T^2/m_{T_{4c}}^2$ at large p_T.

3. T_{4c} production at LHC

The NRQCD factorization for the **fixed-order T_{4c} production** at LHC

$$\frac{d\hat{\sigma}(T_{4c}^{(J)}+X)}{d\hat{t}} = \frac{2m_{T_{4c}}}{m_c^{14}}\left[F_{3,3}^{(J)}\left\langle O_{3,3}^{(J)}\right\rangle + 2F_{3,6}^{(J)}\left\langle O_{3,6}^{(J)}\right\rangle + F_{6,6}^{(J)}\left\langle O_{6,6}^{(J)}\right\rangle\right]$$

where

The SDCs can be perturbatively matched

$$O_{3,3}^{(J)} = \mathcal{O}_{\bar{\mathbf{3}}\otimes\mathbf{3}}^{(J)}\sum_X |T_{4c}^J + X\rangle\langle T_{4c}^J + X|\mathcal{O}_{\bar{\mathbf{3}}\otimes\mathbf{3}}^{(J)\dagger}$$

$$O_{6,6}^{(0)} = \mathcal{O}_{\mathbf{6}\otimes\bar{\mathbf{6}}}^{(0)}\sum_X |T_{4c}^0 + X\rangle\langle T_{4c}^0 + X|\mathcal{O}_{\mathbf{6}\otimes\bar{\mathbf{6}}}^{(0)\dagger}$$

$$O_{3,6}^{(0)} = \mathcal{O}_{\bar{\mathbf{3}}\otimes\mathbf{3}}^{(0)}\sum_X |T_{4c}^0 + X\rangle\langle T_{4c}^0 + X|\mathcal{O}_{\mathbf{6}\otimes\bar{\mathbf{6}}}^{(0)\dagger}$$

Have been constructed previously

642 Feynman diagrams

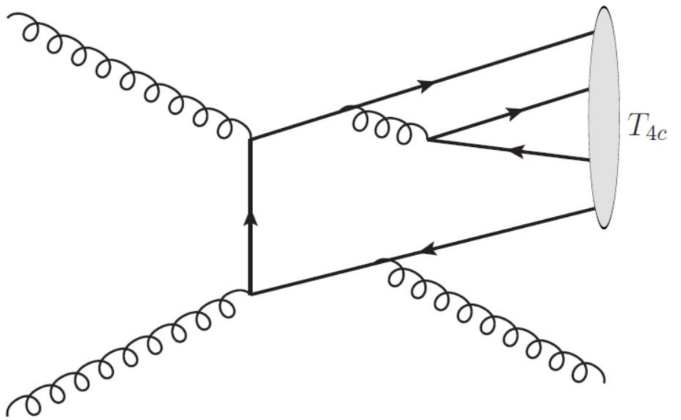


FIG. 1: One typical Feynman diagram for $gg \to T_{4c} + g$.

3. T_{4c} production at LHC

The LDMEs are **universal**, however **nonperturbative**. We resort to the quark models.
One can relate the LDMEs to the phenomenological wave functions at the origin

$$\langle O_{3,3}^{(J)}\rangle = \langle 0|\mathcal{O}_{\bar{\mathbf{3}}\otimes\mathbf{3}}^{(J)}|T_{4c}\rangle\langle T_{4c}|\mathcal{O}_{\bar{\mathbf{3}}\otimes\mathbf{3}}^{(J)+}|0\rangle \approx 16(2J+1)\psi_3(0)\psi_3^*(0)$$

$$\langle O_{6,6}^{(0)}\rangle = \langle 0|\mathcal{O}_{\mathbf{6}\otimes\bar{\mathbf{6}}}^{(0)}|T_{4c}\rangle\langle T_{4c}|\mathcal{O}_{\mathbf{6}\otimes\bar{\mathbf{6}}}^{(0)+}|0\rangle \approx 16\psi_6(0)\psi_6^*(0),$$

$$\langle O_{3,6}^{(0)}\rangle = \mathrm{Re}[\langle 0|\mathcal{O}_{\bar{\mathbf{3}}\otimes\mathbf{3}}^{(0)}|T_{4c}\rangle\langle T_{4c}|\mathcal{O}_{\mathbf{6}\otimes\bar{\mathbf{6}}}^{(0)+}|0\rangle] \approx 16\psi_3(0)\psi_6^*(0),$$

where $\psi(0)$ denotes the four-body Schrödinger wave function at the origin.

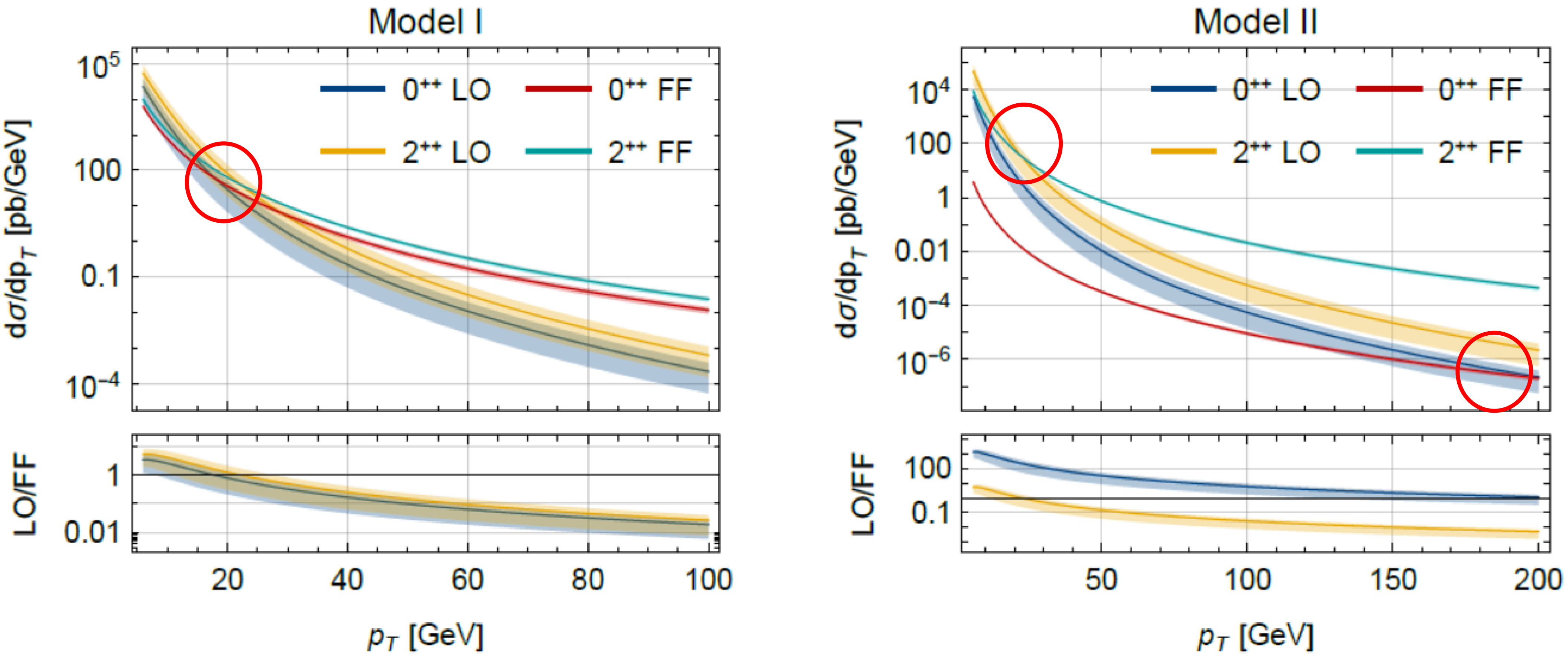
	LDME	Model I	Model II
0^{++}	$\left\langle O_{3,3}^{(0)}\right\rangle$ [GeV^9]	0.0347	0.0187
	$\left\langle O_{3,6}^{(0)}\right\rangle$ [GeV^9]	0.0211	-0.0161
	$\left\langle O_{6,6}^{(0)}\right\rangle$ [GeV^9]	0.0128	0.0139
1^{+-}	$\left\langle O_{3,3}^{(1)}\right\rangle$ [GeV^9]	0.0780	0.0480
2^{++}	$\left\langle O_{3,3}^{(2)}\right\rangle$ [GeV^9]	0.072	0.0628

Model I: EPJC80,871 (2020);
by Q. F. Lü, D. Y. Chen and Y. B. Dong

Model II: arXiv: 2006.11952;
by M. S. liu, F. X. Liu, X. H. Zhong and Q. Zhao

3. T_{4c} production at LHC

Comparison of the p_T distributions of the T_{4c} between **fixed-order** and **fragmentation predictions**



3. T_{4c} production at LHC

By assuming the integrated luminosity of **3000 fb^{-1}** .

	Model I		Model II	
	σ [nb]	$N_{\text{events}}/10^9$	σ [nb]	$N_{\text{events}}/10^9$
0^{++}	37 ± 26	110 ± 80	9 ± 6	27 ± 19
1^{+-}	0.28 ± 0.16	0.8 ± 0.5	0.17 ± 0.10	0.52 ± 0.29
2^{++}	93 ± 65	280 ± 200	81 ± 57	240 ± 170

Table 1: The integrated production rates for various S-wave T_{4c} states ($6\,\text{GeV} \leq p_T \leq 100\,\text{GeV}$) and the estimated event yields.

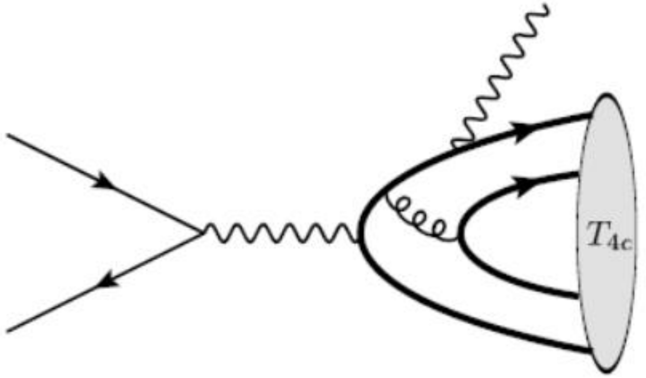
Remarks:

1. The cross section for 1^{+-} is two order-of-magnitude smaller than the other two channels.

2. The cross sections and event numbers for 1^{+-} and 2^{++} are insensitive to the Model. The condition for 0^{++} is different.

3. T_{4c} production at LHC

2011.03039 Feng, Huang, Jia, SWL, Zhang
2104.03887 Huang, Feng, Jia, SWL, Yang, Zhang



Only for **0^{++}** **2^{++}**

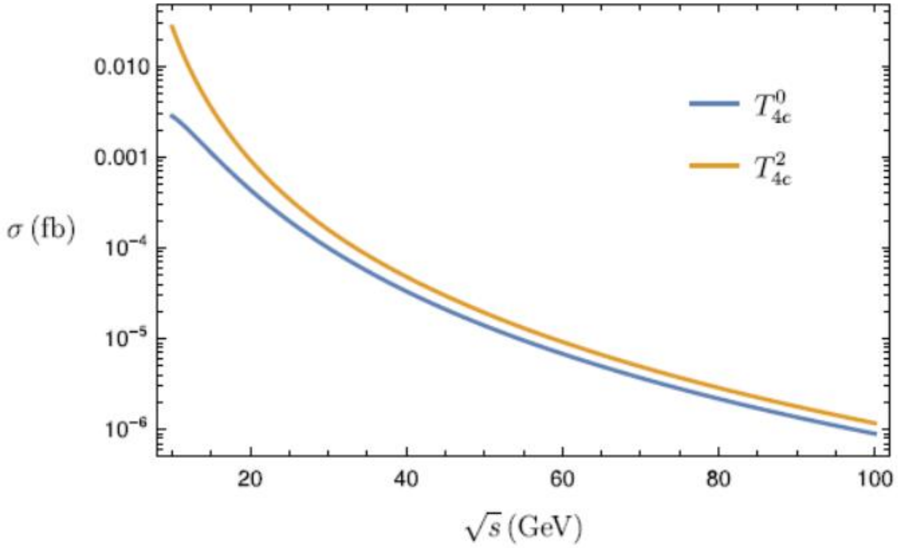
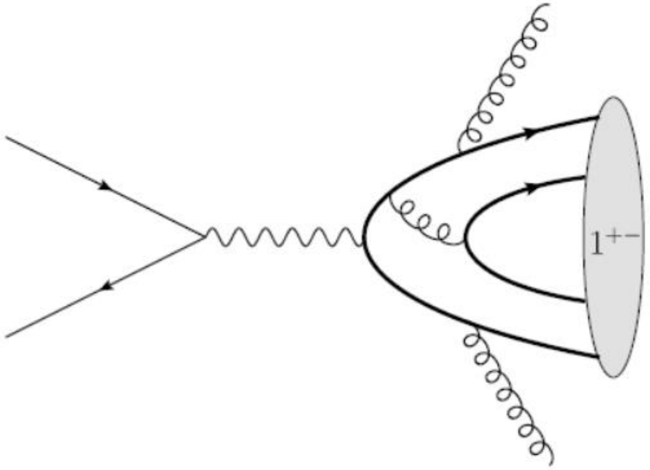
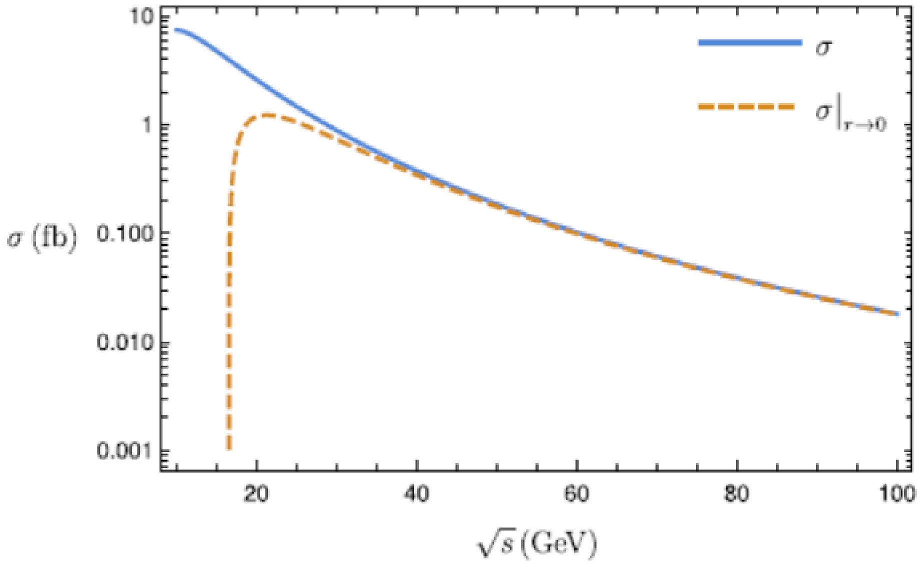


Fig. 2. The total cross sections of $e^+e^- \to \gamma + T^J_{4c}$ $(J = 0, 2)$ as a function of the center-of-mass energy.



Only for **1^{+-}**



4. Summary

1. We **propose a NRQCD factorization formula** for T_{4c} production.

2. We compute the T_{4c} production at LHC in two different ways: fixed-order computation and fragmentation function computation. We find the fragmentation production may be dominant at high p_T >20 GeV.

3. The cross sections can reach **dozens nano-bar** for $J^{PC} = 0^{++}$ and 2^{++}, while less than 1 nb for 1^{+-} .

4. The cross sections at B factories are very small.

Thanks for your attention！