Production Cross-Sections of B_c Mesons in pp, pA, and AA Collision at LHC Energies.

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Charm-Beauty Meson and its States

- It is a bound state of charm and antibottom quarks or vise versa.

$$B_c^+(c\bar{b}), \qquad B_c^-(\bar{c}b)$$

- Internal state of this meson is defined by following quantum numbers

1. Total spin of $Q\bar{Q}$ pair: $S = 0,1$
2. Orbital angular momentum: $L = 0,1,2,3, \ldots$ represented by $(S, P, D, F, \ldots)$
3. Total angular momentum: $J = |L - S|, \ldots, L + S$
4. Principle quantum number $n = 1,2, \ldots$
5. $Q\bar{Q}$ pair can either be in singlet or octet states: $3 \otimes \bar{3} = 8 \oplus 1$

- Internal states: $Q\bar{Q}[n^{2S+1}L_J^{(c)}]$ where $c = 1$ (singlet), 8 (octet state)

S states ($L = 0$):		P states ($L = 1$):	
For $S = 0, J = 0$:	${}^1S_0$	For $S = 0, J = 1$:	${}^1P_1$
For $S = 1, J = 1$:	${}^3S_1$	For $S = 1, J = 0, 1, 2$:	${}^3P_0$, ${}^3P_1$ ${}^3P_2$

Production Cross Section of B_c meson in pp Collisions

- We want to calculate the cross section of inclusive B_c production process in pp collision.

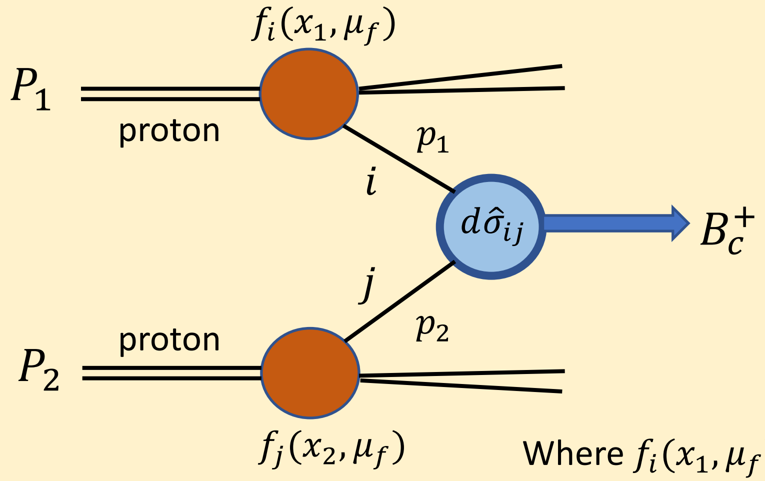
$$p + p \to B_c^+ + X \qquad \text{(Main process)}$$

- Most likely method of B_c^+ production is via a hard process in which above process occur through the interactions of partons (say i and j) of the colliding protons.

$$i + j \to B_c^+ + X \qquad \text{(Subprocess)}$$

- QCD factorization theorem

$$d\sigma(pp \to B_c^+ X) = \sum_{i,j} \int dx_1 dx_2 f_i(x_1, \mu_f) f_j(x_2, \mu_f) d\hat{\sigma}(ij \to B_c^+ X)$$



Where $f_i(x_1, \mu_f)$ and $f_j(x_2, \mu_f)$ are parton distribution functions (PDFs) of i and j partons.

Production Cross Section of B_c meson in pp Collisions

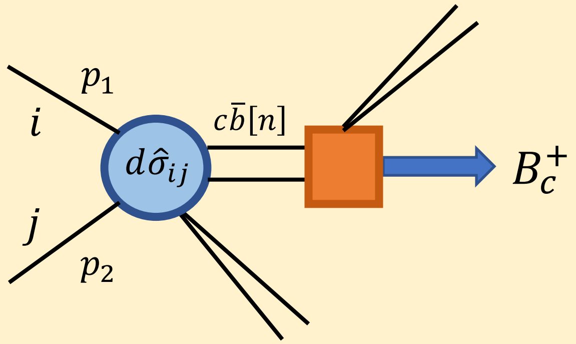
- Two subprocesses contribute.

  1. Gluon fusion subprocess: $g + g \to B_c^+ + X$
  2. $q\bar{q}$ annihilation subprocess: $q + \bar{q} \to B_c^+ + X$ where $q = u, d, s$

- To calculate the cross sections of a subprocess $(ij \to B_c^+ X)$ we use NRQCD factorization approach.

- In this approach we assume that the subproccess occur in two steps

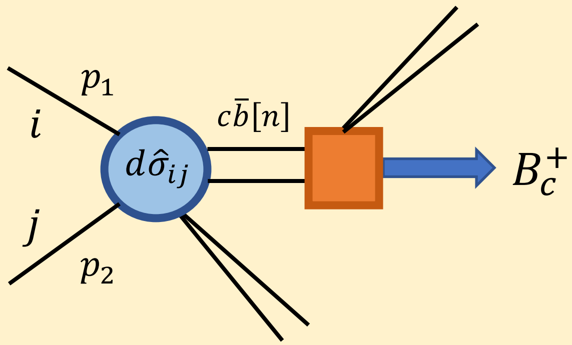
  Step 1: From the interaction of i and j partons $c\bar{b}$ pair is produced in state $n \equiv {}^{2S+1}L_J^{(c)}$.
  Step 2: The pair $c\bar{b}[n]$ tranforms into a physical quarkonium state of B_c^+.



Production Cross Section of B_c meson in pp Collisions

- NRQCD factorization formula

$$d\hat{\sigma}(ij \to B_c^+ X) = \sum_n d\hat{\sigma}(ij \to c\bar{b}[n]X) \left\langle \mathcal{O}_n^{B_c^+} \right\rangle$$



Where,

- $d\hat{\sigma}(ij \to c\bar{b}[n]X)$ is cross section of producing $c\bar{b}$ pair in state n.
  It can be calculated using Feynman Rules and called short distance coefficient (SDC).

- $\left\langle \mathcal{O}_n^{B_c^+} \right\rangle$ is called long-distance matrix element (LDME) descrbing non-perturbative transition of $c\bar{b}[n]$ into physical quarkonium state of B_c^+.

- Intermediate state of $c\bar{b}$ pair is defined by $n \equiv {}^{2S+1}L_J^{(c)}$

Production Cross Section of B_c meson in pp Collisions

- At leading order in v, we get following results.

For ${}^1S_0^{(1)}$ B_c^+: $d\hat{\sigma}(ij \to B_c^+ X) = d\hat{\sigma}(ij \to c\bar{b}[{}^1S_0^{(1)}]X) \left\langle \mathcal{O}^{B_c^+}[{}^1S_0^{(1)}] \right\rangle$

For ${}^3S_1^{(1)}$ B_c^+: $d\hat{\sigma}(ij \to B_c^+ X) = d\hat{\sigma}(ij \to c\bar{b}[{}^3S_1^{(1)}]X) \left\langle \mathcal{O}^{B_c^+}[{}^3S_1^{(1)}] \right\rangle$

For ${}^1P_1^{(1)}$ B_c^+: $d\hat{\sigma}(ij \to B_c^+ X) = d\hat{\sigma}(ij \to c\bar{b}[{}^1P_1^{(1)}]X) \left\langle \mathcal{O}^{B_c^+}[{}^1P_1^{(1)}] \right\rangle + d\hat{\sigma}(ij \to c\bar{b}[{}^1S_0^{(8)}]X) \left\langle \mathcal{O}^{B_c^+}[{}^1S_0^{(8)}] \right\rangle$

For ${}^3P_J^{(1)}$ B_c^+: $d\hat{\sigma}(ij \to B_c^+ X) = d\hat{\sigma}(ij \to c\bar{b}[{}^3P_J^{(1)}]X) \left\langle \mathcal{O}^{B_c^+}[{}^3P_J^{(1)}] \right\rangle + d\hat{\sigma}(ij \to c\bar{b}[{}^3S_1^{(8)}]X) \left\langle \mathcal{O}^{B_c^+}[{}^3S_1^{(8)}] \right\rangle$
(where $J = 0,1,2$)

- So we have 8 LDMEs

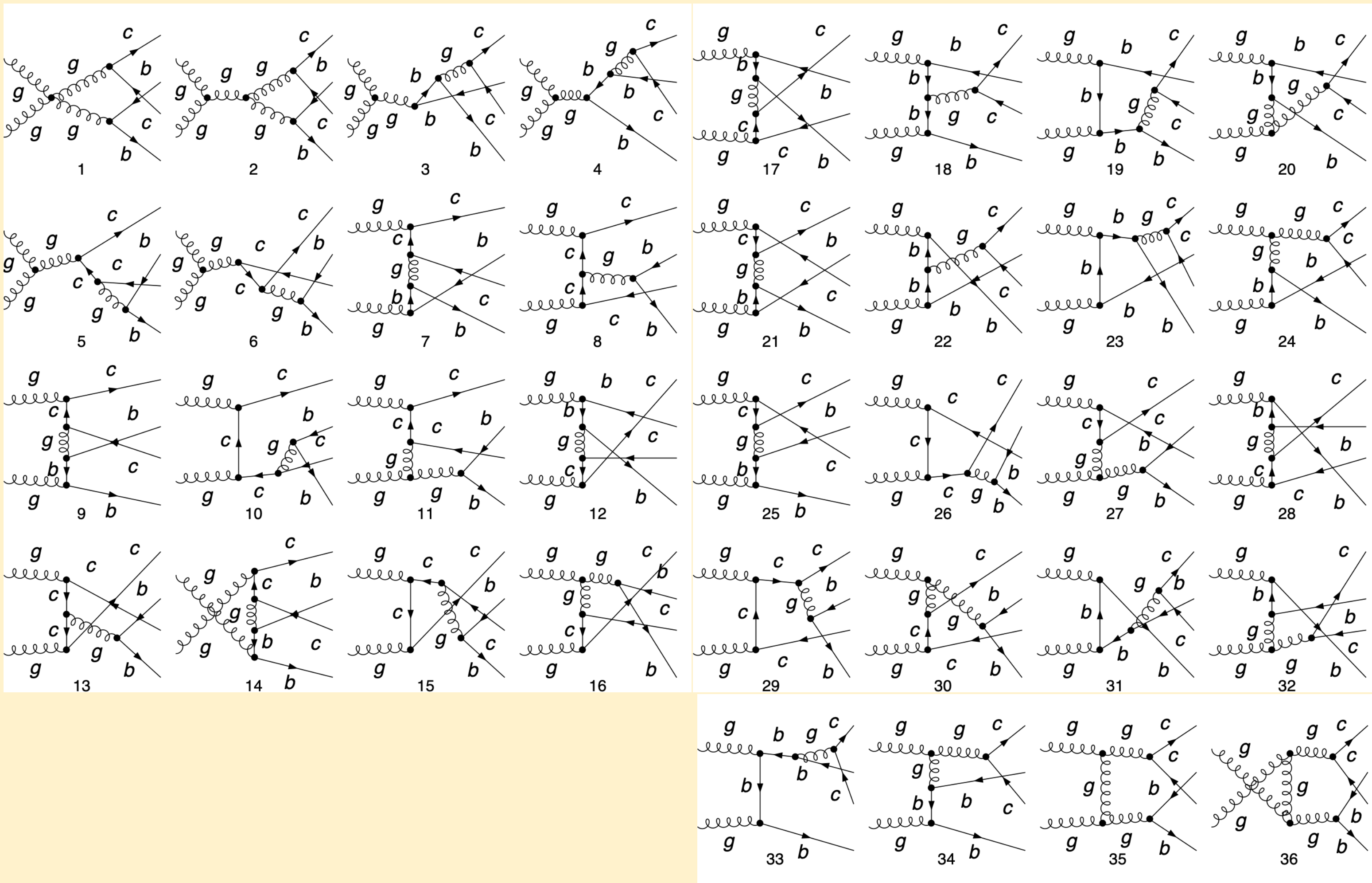
$$\left\langle \mathcal{O}^{B_c^+}[{}^1S_0^{(1)}] \right\rangle, \left\langle \mathcal{O}^{B_c^+}[{}^3S_1^{(1)}] \right\rangle \sim v^0$$

$$\left\langle \mathcal{O}^{B_c^+}[{}^1P_1^{(1)}] \right\rangle, \left\langle \mathcal{O}^{B_c^+}[{}^3P_0^{(1)}] \right\rangle, \left\langle \mathcal{O}^{B_c^+}[{}^3P_1^{(1)}] \right\rangle, \left\langle \mathcal{O}^{B_c^+}[{}^3P_2^{(1)}] \right\rangle; \left\langle \mathcal{O}^{B_c^+}[{}^1S_0^{(8)}] \right\rangle, \left\langle \mathcal{O}^{B_c^+}[{}^3S_1^{(8)}] \right\rangle \sim v^2$$

- And 8 corresponding SDC are required to calculate production cross sections of B_c^+ states.

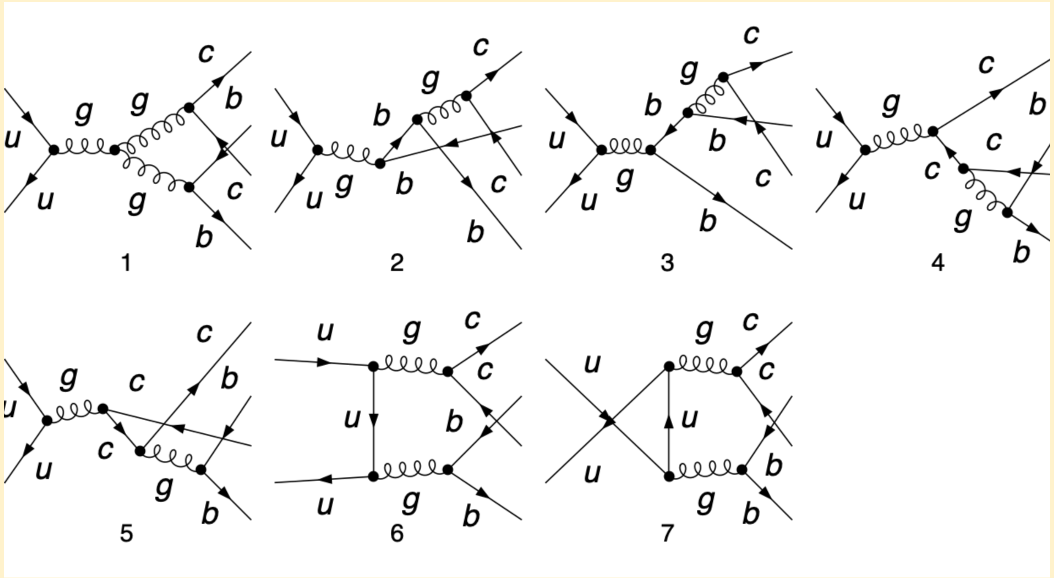
Production Cross Section of B_c meson in pp Collisions

At LO in α_s gluons fusion process $g + g \rightarrow \underbrace{c + \bar{b}}_{c\bar{b}[n]} + \underbrace{b + \bar{c}}_{X}$



Production Cross Sections of B_c mesons in pp Collisions

At LO in α_s $q\bar{q}$ annihilation process $q + \bar{q} \to \underbrace{c + \bar{b}}_{c\bar{b}[n]} + \underbrace{b + \bar{c}}_{X}$



Production Cross Section of B_c meson in pp Collisions

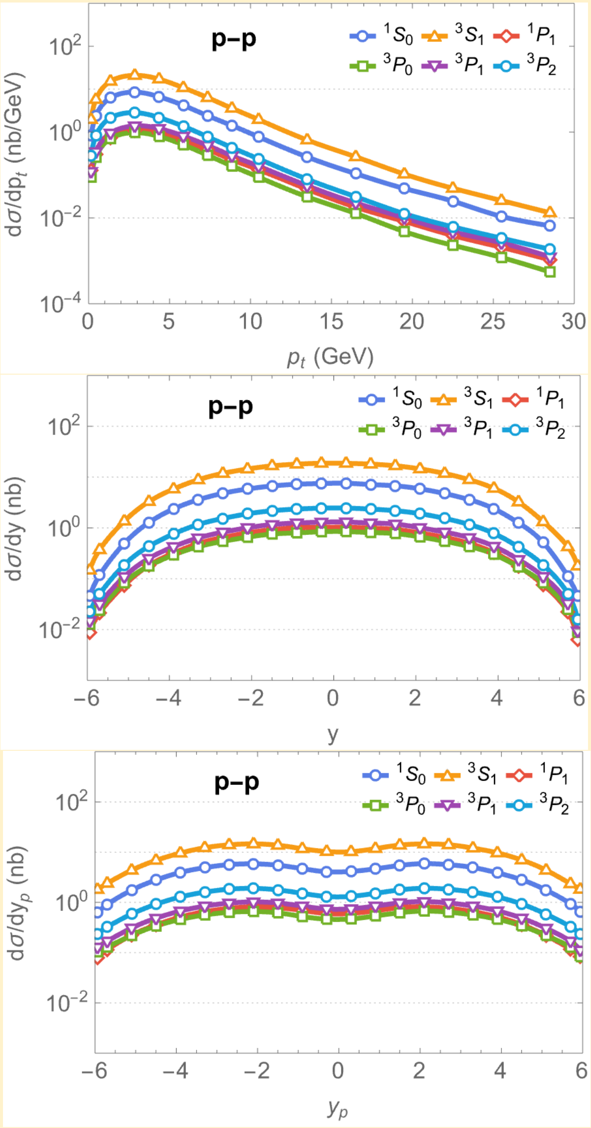
Input parameters:

$E_{\text{cm}} = 13$ TeV

$m_c = 1.5$ GeV, $m_b = 4.5$ GeV

$\mu_F = M_T \equiv \sqrt{p_T^2 + M_{B_c}}, \;\; M_{B_c} \approx m_c + m_b$

α_s is taken running. CTEQ6L1 PDF set is used.



Results:

State	$\sigma(pp \to B_c^+ X)$ (nb) (via gluon fusion) Our results	$\sigma(pp \to B_c^+ X)$(nb) (via gluon fusion) Results of Ref[1,2]	$\sigma(pp \to B_c^+ X)$(nb) (via $q\bar{q}$ annihilation) Our results
$^1S_0^{(1)}$	47.9	42.4	0.13
$^3S_1^{(1)}$	119.5	105	0.83
$^1P_1^{(1)}$	5.79	4.74	0.03
$^3P_0^{(1)}$	2.03	1.9	0.01
$^3P_1^{(1)}$	4.90	4.1	0.03
$^3P_2^{(1)}$	12.10	10.2	0.07

[1] Gu. Chen, Chao-His Chang, and Xing-Gang Wu, Phys. Rev. D 97, 114022 (2018).
[2] Chao-Hsi Chang, Jian-Xiong Wang, and Xing-Gang Wu, Phys. Rev. D **70,** 114019 (2004)

Production Cross Sections of B_c mesons in pA and AA Collisions

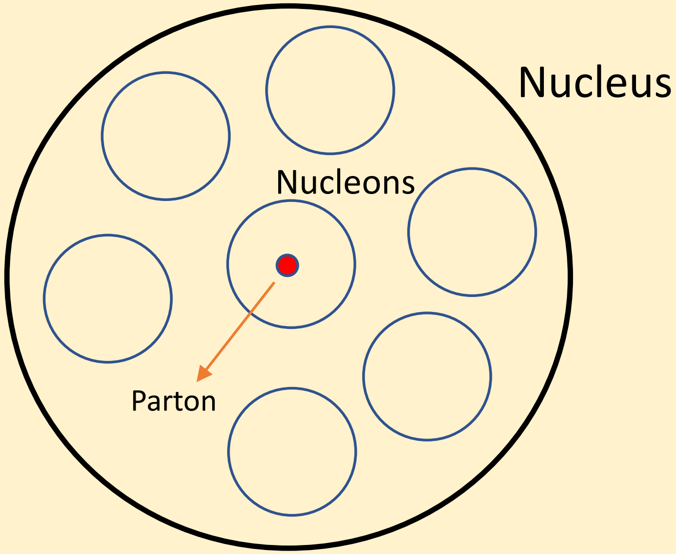
$$d\sigma(pA \to B_c^+ X) = N_A \sum_{i,j} \int dx_1 dx_2 f_i(x_1, \mu_f) f_j^A(x_2, \mu_f) d\hat{\sigma}(ij \to B_c^+ X)$$

$$d\sigma(AA \to B_c^+ X) = N_A^2 \sum_{i,j} \int dx_1 dx_2 f_i^A(x_1, \mu_f) f_j^A(x_2, \mu_f) d\hat{\sigma}(ij \to B_c^+ X)$$

Where $f_i^A(x_1, \mu_f)$ and $f_j^A(x_2, \mu_f)$ are nuclear PDFs, modified due to nuclear shadowing effect.

A parton of a proton/neturon in a nucleus is surrounded by other nucleons, which change the parton distribution functions.

This effect is called nuclear shadowing



Production Cross Section of B_c meson in pA and AA Collisions

Our Results:

State	$\sigma(p\text{Pb} \to B_c^+ X)$ (nb)	$\sigma(p\text{Xi} \to B_c^+ X)$ (nb)	$\sigma(\text{XiXi} \to B_c^+ X)$ (nb)	$\sigma(\text{PbPb} \to B_c^+ X)$ (nb)
${}^1S_0^{(1)}$	41.9×10^2	3.39×10^2	15.2×10^4	23.2×10^4
${}^3S_1^{(1)}$	104.8×10^2	84.4×10^2	38.1×10^4	78.2×10^4
${}^1P_1^{(1)}$	5.1×10^2	4.1×10^2	1.8×10^4	2.8×10^4
${}^3P_0^{(1)}$	1.7×10^2	1.4×10^2	0.64×10^4	0.97×10^4
${}^3P_1^{(1)}$	4.3×10^2	3.5×10^2	1.6×10^4	2.4×10^4
${}^3P_2^{(1)}$	10.6×10^2	8.6×10^2	3.9×10^4	5.9×10^4

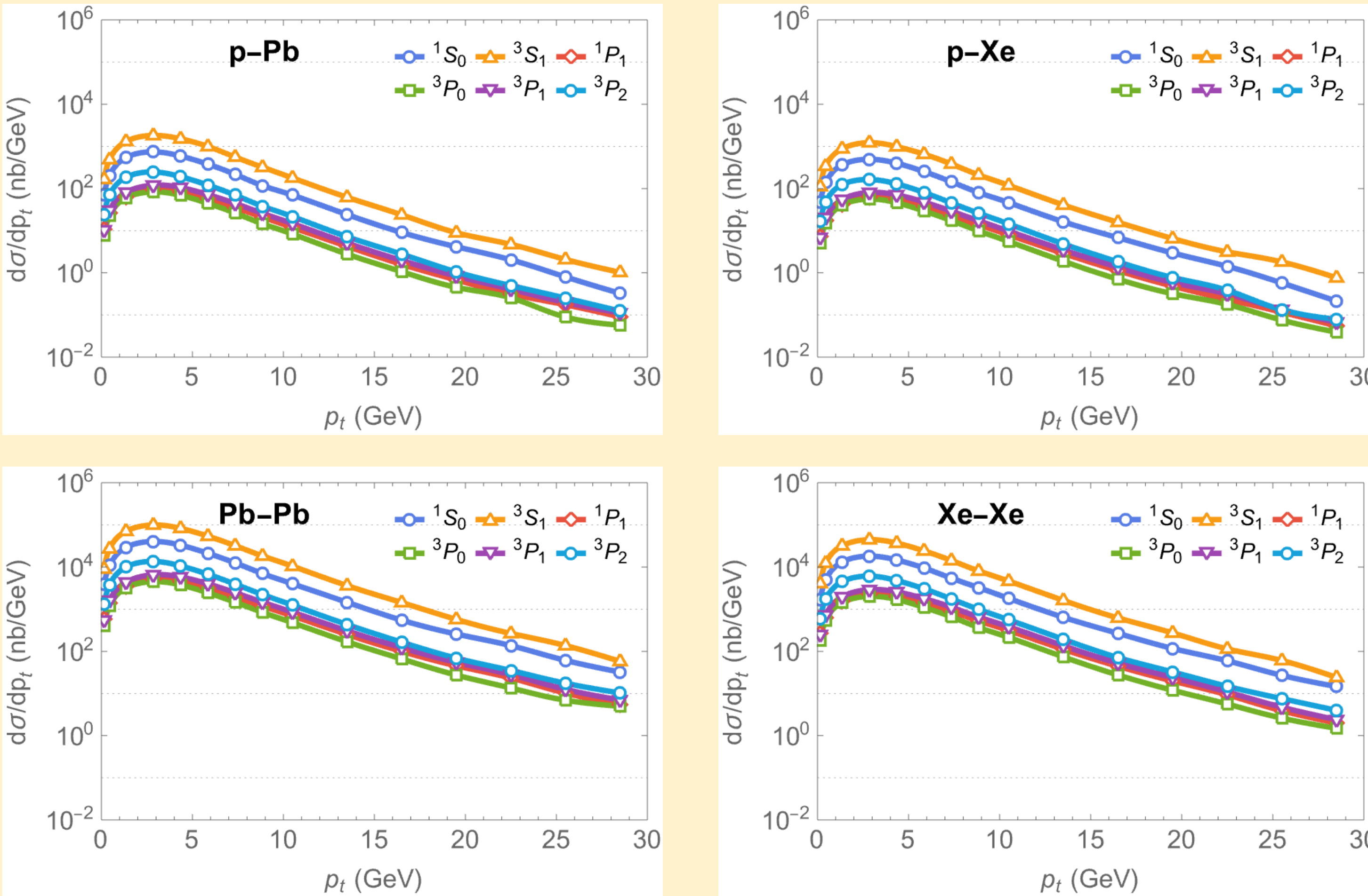
(via gluon fussion process)

Results of Ref [1]: [1] Gu. Chen, Chao-His Chang, and Xing-Gang Wu, Phys. Rev. D 97, 114022 (2018).

State	$\sigma(p\text{Pb} \to B_c^+ X)$ (nb)	$\sigma(\text{PbPb} \to B_c^+ X)$ (nb)
${}^1S_0^{(1)}$	33×10^2	36×10^4
${}^3S_1^{(1)}$	82.6×10^2	92×10^4

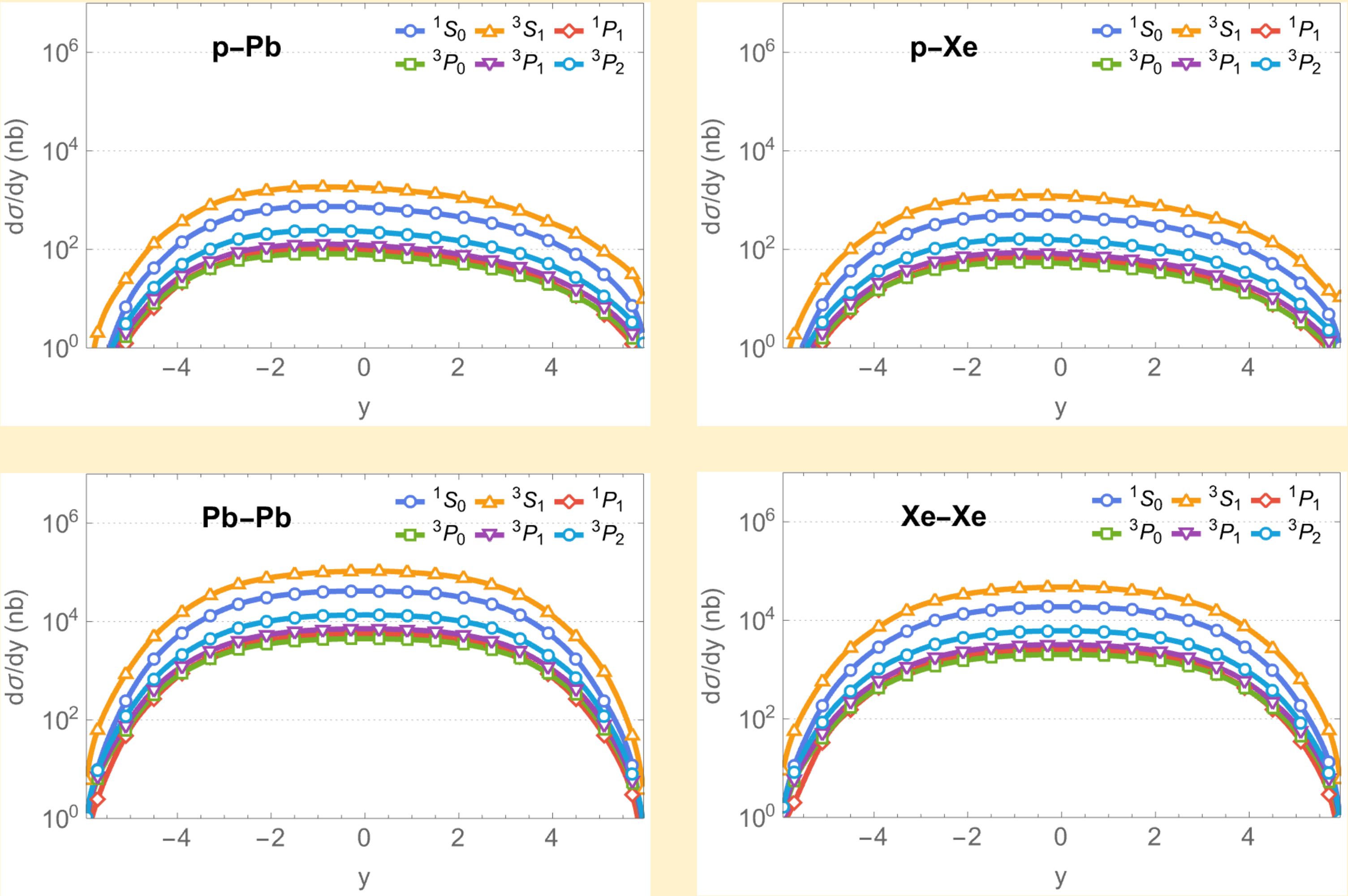
Production Cross Section of B_c meson in pA and AA Collisions

(p_T distribution p-Pb, Pb-Pb, p-Xe, Xe-Xe collisions)



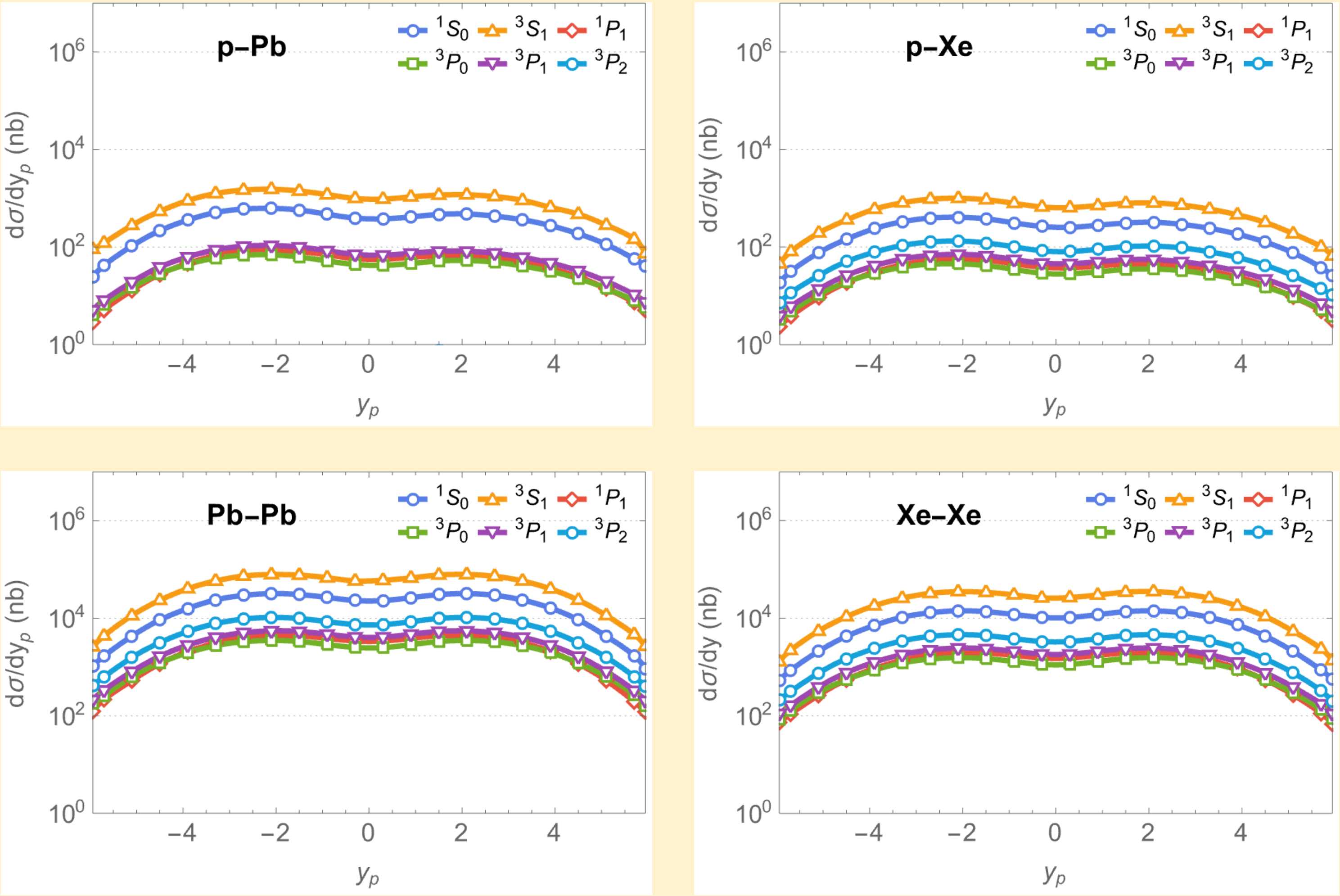
Production Cross Section of B_c meson in pA and AA Collisions

(Rapdity (y) distribution p-Pb, Pb-Pb, p-Xe, Xe-Xe collisions)



Production Cross Section of B_c meson in pA and AA Collisions

(Pseudo rapidity (y_p) distribution p-Pb, Pb-Pb, p-Xe, Xe-Xe collisions)



Concluding Remarks

1. We have calculated production cross sections of B_c meson in pPb, pXe, Pb-Pb, and and Xe-Xe modes at LHC energies.

2. We have also calculated the p_T, rapidity (y), and pseudo rapidity (y_p) distributions.

3. Our calculated results indicate that a signinficant number of B_c mesons can be produced at LHC energies.

4. These cross section and related distributions shall be meaured in RUN-3 of LHC and could provide a useful test of the standard model and the factorization approach that has been used.

Backup Slides

Production Cross Sections of B_c mesons in pp Collisions

Applying Projection Method:

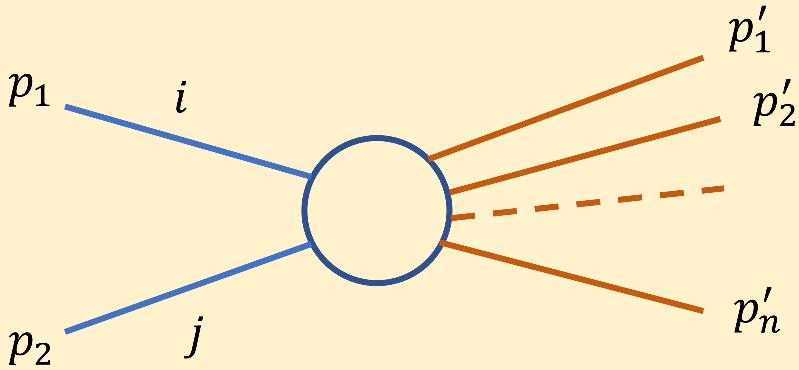
$$n = {}^1S_0^{[1]}: \qquad \mathcal{A}_{S=0,L=0} = \mathrm{Tr}[C_1 \Pi_0 \boldsymbol{\mathcal{A}}]_{q=0}$$
$$n = {}^3S_1^{[1]}: \qquad \mathcal{A}_{S=1,L=0} = \epsilon_\alpha \mathrm{Tr}[C_1 \Pi_1^\alpha \boldsymbol{\mathcal{A}}]_{q=0}$$
$$n = {}^1P_1^{[1]}: \qquad \mathcal{A}_{S=0,L=1} = \epsilon_\alpha \frac{\mathrm{d}}{dq_\alpha} \mathrm{Tr}[C_1 \Pi_0 \boldsymbol{\mathcal{A}}]_{q=0}$$
$$n = {}^3P_J^{[1]}: \qquad \mathcal{A}_{S=1,L=1} = \varepsilon_{\alpha\beta}^{(J)} \frac{\mathrm{d}}{dq_\beta} \mathrm{Tr}[C_1 \Pi_1^\alpha \boldsymbol{\mathcal{A}}]_{q=0}$$

Where, ϵ_α is polarization vector used when $J = 1$.
and $\epsilon_{\alpha\beta}^{(J)}$ is polarization tensor used when $J = 0,1,2$.

- For octet states ${}^1S_0^{[8]}$, ${}^3S_1^{[8]}$, we use color projector C_8 instead of C_1.

How to calculate the cross sections $(d\sigma_{ij})$ of sub processes?

Consider an n body subprocess: $i + j \rightarrow 1 + 2 + \cdots + n$



$$d\sigma_{ij} = \frac{1}{4\sqrt{(p_1.p_2)^2 - (m_1 m_2)^2}} |\mathcal{M}|^2 \mathrm{d}\Phi_n$$

- Where, $|\mathcal{M}|^2$ = Spin average squared modulus of total amplitude of all the Feynman diagrams for given subprocess.

- $\mathrm{d}\Phi_n = \frac{d^3 p_1'}{(2\pi)^3 2E_1'} \frac{d^3 p_2'}{(2\pi)^3 2E_1'} \cdots \frac{d^3 p_1'}{(2\pi)^3 2E_1'} (2\pi)^4 \delta(p_1 + p_2 - p_1' - p_2' - \cdots - p_n')$

- Perturbative calculation are generally very complex as they may involve 100's of diagrams even at leading order (LO).

- So, we mostly use automatic application tools like MadGraph.

Procedure of Calculation:

Step 1: We use **FeynArt** to generate Feynman diagrams and corresponding amplitudes.

Step 2: These amplitudes are used in FeynCalc to apply project method.

Step 3: The results generated from the FeycCalc are used in VEGAS to complete phase space integeration including nuclear PDF's.

Step 4: The results of cross sections and distributions of pp collision are counter checked with HELAC-Onia.