Charmonia production at LHC

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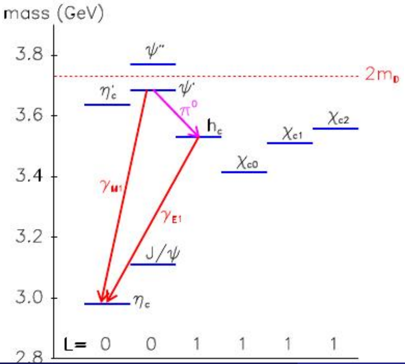
Contents

Charmonium mesons

$(c\bar{c})$ $\qquad P = (-1)^{L+1}, C = (-1)^{L+S}$

$\alpha_s(m_c) \ll 1 \Rightarrow$ Perturbation theory check



Observed via radiative decays into J/ψ

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

Hadronic Production

- At high energies produced mainly in gg interaction

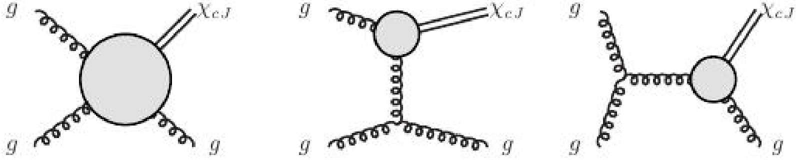
$$\sigma = \int dx_1 dx_2 f_g(x_1) f_g(x_2) \hat{\sigma}$$

- At LO ($gg \to (c\bar{c})$):
  1. Only $C = +1$ states (χ_{cJ}, η_c) states can be produced, J/ψ cannot be produced
  2. Production of χ_{c1} meson is forbidden (Landau-Yang theorem),
  3. p_T distributions cannot be described.

  All these problems can be solved at NLO ($gg \to (c\bar{c})g$)

NLO

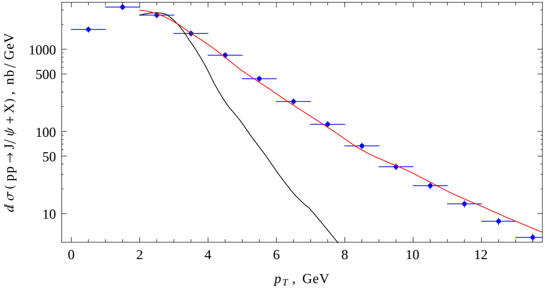
CSM



[V.G. Kartvelishvili, A.K. Likhoded, A.K. and S.R. Slabospitsky, Sov.J.Nucl.Phys. 28 (1978) 678]

1. direct J/ψ production is possible,
2. χ_{c1} meson can be produced,
3. Transverse momentum of final charmonium appears.

Experimental data cannot be described using such approach.
J/ψ production:



Some other mechanisms are required

$$|J/\psi\rangle = |(c\bar{c})_{CS}\rangle + |(c\bar{c})_{CO} + g\rangle + \ldots$$

Additional color octet states are suppressed by v, coupling constants should be determined from experiment

Expansion in v:

$$|\chi_{cJ}\rangle = \sqrt{|R'(0)|^2}\left|c\bar{c}\left[{}^3P_J^{[1]}\right]\right\rangle + \sqrt{\langle\mathcal{O}_S\rangle}\left|c\bar{c}\left[{}^3S_1^{[8]}\right]g\right\rangle + \sqrt{\langle\mathcal{O}_P\rangle}\left|c\bar{c}\left[{}^1P_1^{[8]}\right]g\right\rangle + \ldots .$$

$\mathcal{Q}$	$c\bar{c}[{}^3P_1^{[1]}]$	$c\bar{c}[{}^3P_{0,2}^{[1]}]$	$c\bar{c}[{}^1P_1^{[8]}]g$	$c\bar{c}[{}^3S_0^{[8]}]g$
$p_T \ll M_\chi$	$\sim p_T$	$\sim 1/p_T$	$\sim 1/p_T$	$\sim p_T$
$p_T \gg M_\chi$	$\sim 1/p_T^5$	$\sim 1/p_T^5$	$\sim 1/p_T^5$	$\sim 1/p_T^3$

So in high p_T region

- It is hard to separate CS and *P*-wave CO contributions,
- One should use e.g. χ_{c2}/χ_{c1} ratio to separate different contributions
- *S*-wave CO should dominate.

Cross sections' ratios are very sensitive to CS and CO matrix elements

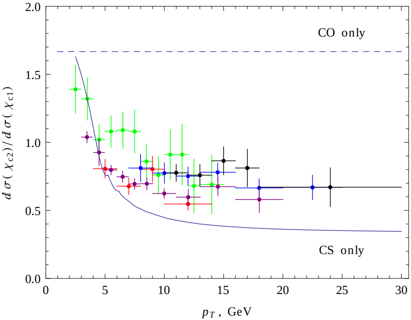
- Nonzero $\langle\mathcal{O}_S\rangle$:

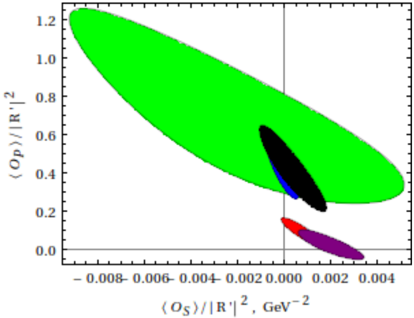
$$\frac{d\sigma(\chi_{cJ_1})/dp_T}{d\sigma(\chi_{cJ_2})dp_T} = r_{J_1 J_2}(p_T \gg M_\chi) \approx \frac{2J_1+1}{2J_2+1}.$$

- Without $\langle\mathcal{O}_S\rangle$

$$r_{2,1}(p_T \gg M_\chi) \approx \frac{1}{3} + \frac{\langle\mathcal{O}_P\rangle}{0.75|R'(0)|^2 + 0.64\,\langle\mathcal{O}_P\rangle},$$
$$r_{0,1}(p_T \gg M_\chi) \approx \frac{1}{6} + \frac{\langle\mathcal{O}_P\rangle}{6|R'(0)|^2 + 5.11\,\langle\mathcal{O}_P\rangle},$$
$$r_{0,2}(p_T \gg M_\chi) \approx \frac{1}{2} - \frac{\langle\mathcal{O}_P\rangle}{3.3|R'(0)|^2 + 0.56\,\langle\mathcal{O}_P\rangle}.$$

χ_{c2}/χ_{c1}





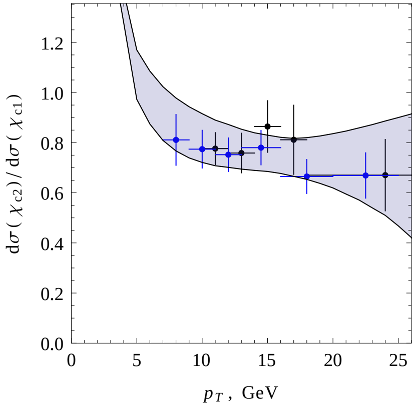
Experimental data can be diveded into two groups

- LHCbOld, CMS, ATLAS
- LHCbNew, CDF

$$\chi^2/DOF = 0.41$$

$$\frac{\langle \mathcal{O}_S \rangle}{|R'(0)|^2} = (-0.1 \pm 1)\frac{10^{-3}}{\text{GeV}^2}$$

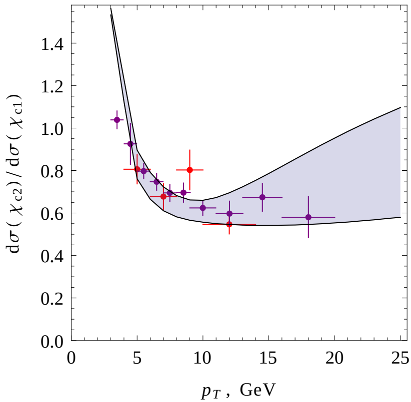
$$\frac{\langle \mathcal{O}_P \rangle}{|R'(0)|^2} = 0.44 \pm 0.23$$



$$\chi^2/DOF = 8.2$$

$$\frac{\langle \mathcal{O}_S \rangle}{|R'(0)|^2} = (1.56 \pm 1.5) \frac{10^{-3}}{\text{GeV}^2}$$

$$\frac{\langle \mathcal{O}_P \rangle}{|R'(0)|^2} = 0.04 \pm 0.09$$



To obtain overall normalization one should use some cross section distributions

F. Abe *et al.* [CDF Collaboration], Phys. Rev. Lett. **79**, 578 (1997).

CMS, ATLAS

$$\chi^2/DOF = 1.16$$

$$|R'(0)|^2 = (0.31 \pm 0.17)\text{GeV}^5$$

$$\langle \mathcal{O}_S \rangle = (0.7 \pm 9) \times 10^{-4}\text{GeV}^3$$

$$\langle \mathcal{O}_P \rangle = (0.12 \pm 0.09)\text{GeV}^5$$

CDF, LHCbNew

$$\chi^2/DOF = 4.5$$

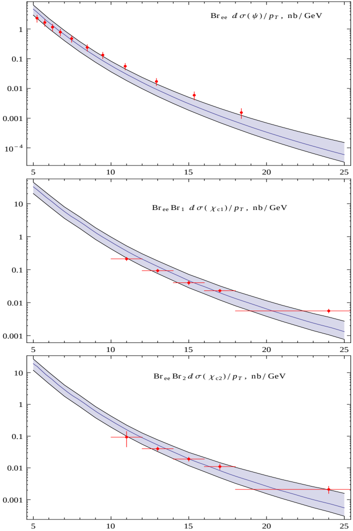
$$|R'(0)|^2 = (0.43 \pm 0.18)\text{GeV}^5$$

$$\langle \mathcal{O}_S \rangle = (8.2 \pm 8.1) \times 10^{-4}\text{GeV}^3$$

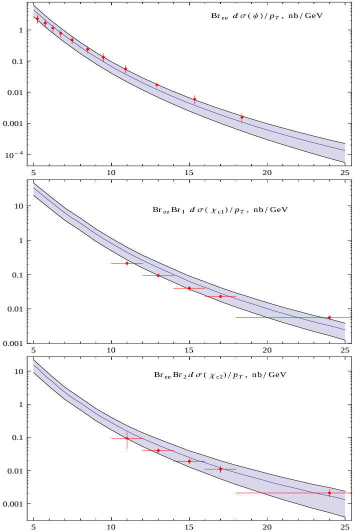
$$\langle \mathcal{O}_P \rangle = (0.1 \pm 0.5)\text{GeV}^5$$

χ_c, comparison with experiments

CMS, ATLAS



CDF, LHCbNew



χ_c, Discussion

- CS gives main contributions,
- $|R'(0)|^2$ is about 4 times larger than phenomenological value $|R'(0)|^2 = 0.075\text{GeV}^5$
- S wave CO are neglible

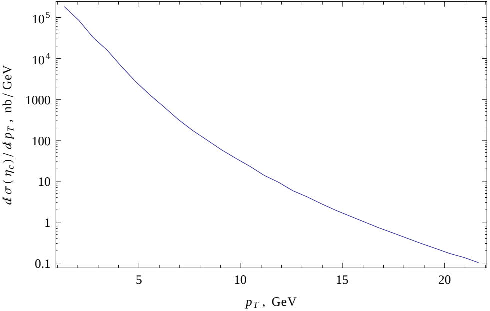
$|R'(0)|^2$ is a result of Bohr-Oppenheimer apprixímation

$$\int A_{hard}(q)\psi(q)d^3q \approx A_{hard}(0)\int \psi(q)d^3q + \nabla A_{hard}(0)\int \mathbf{q}\psi(q)d^3q = $$
$$= A_{hard}(0)\psi(0) + A'_{hard}(0)\psi'(0)$$

For J/ψ, η_c: $v^2 \approx 0.21$
For χ_c: $v^2 \approx 0.3$

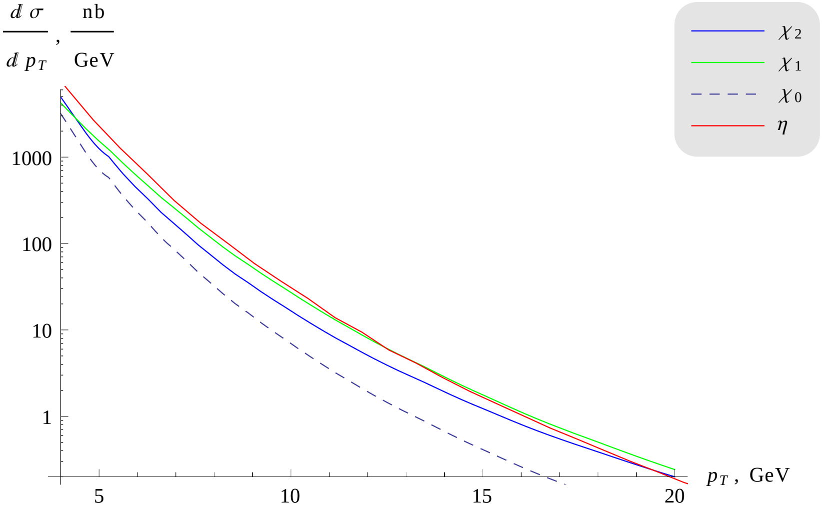
$q \sim m_c/2 \Rightarrow$ BO approximation ?
(e^+e^- annihilation at Belle)

It is interesting to check if such enhancement is present in η_c production



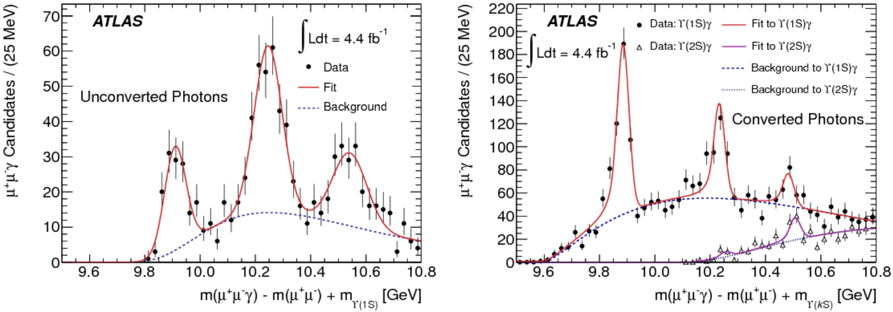
Waiting for the experiment

η_c vs χ_{cJ}



χ_b

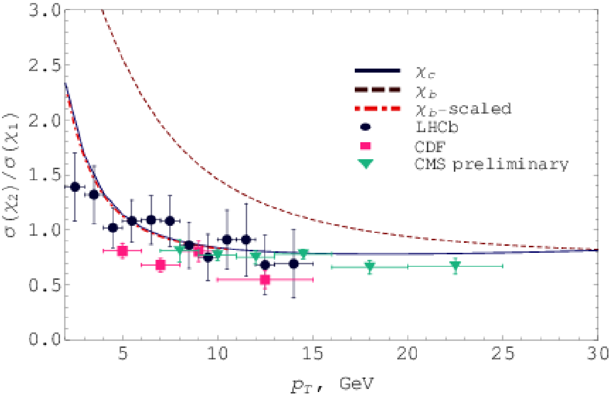
$$|\chi_{bJ}\rangle = \sqrt{|R'(0)|^2}\left|b\bar{b}\left[{}^3P_J^{[1]}\right]\right\rangle + \sqrt{\langle\mathcal{O}_S\rangle}\left|b\bar{b}\left[{}^3S_1^{[8]}\right]g\right\rangle + \sqrt{\langle\mathcal{O}_P\rangle}\left|b\bar{b}\left[{}^1P_1^{[8]}\right]g\right\rangle + \ldots$$



χ_b, Scaling

$$\frac{d\sigma(\chi_{b2})/dp_T}{d\sigma(\chi_{b1})/dp_T}(zp_T;s) \approx \frac{d\sigma(\chi_{c2})/dp_T}{d\sigma(\chi_{c1})/dp_T}(p_T;s)$$

where $z = M_b/M_c$



$$|J/\psi\rangle = |c\bar{c}[^3S_1]_{CS}\ \rangle + |c\bar{c}[^3S_1]_{CO}\ g\rangle + \ldots$$

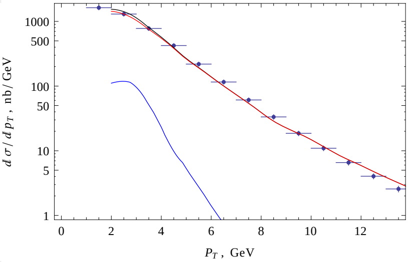
Fit results

$$\frac{\chi^2}{DOF} = 2.4$$

$$|R(0)|^2 = 0.43 \pm 0.46\text{GeV}^3$$

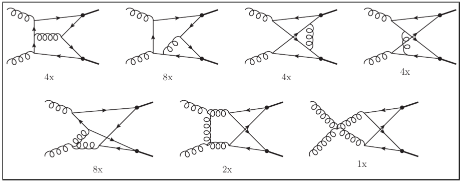
$$(\text{ vs } R|(0)|^2_{ph} \approx 0.8\text{GeV}^3)$$

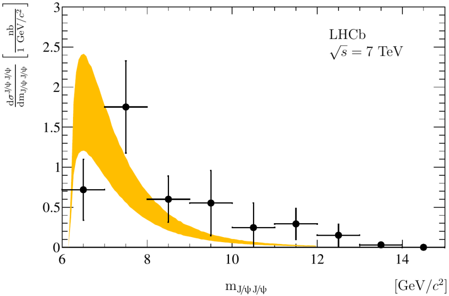
$$\langle \mathcal{O}_P \rangle = (7.7 \pm 0.3) \times 10^{-3}\text{GeV}^3$$



In CS only C=+1 final state can be produced

- $2J/\psi$, $2\chi_c$, etc
- $J/\psi\eta_c$, $J/\psi\chi_c$ production is forbidden





$$\sigma(2J/\psi) : \sigma(J/\psi + \psi') : \sigma(2\psi') \approx$$

$$\left|\Psi_{J/\psi}(0)\right|^4 : \left|\Psi_{J/\psi}(0)\Psi_{\psi'}(0)\right|^2 : \left|\Psi_{\psi'}(0)\right|^4 = 1 : 1/2 : 1/16$$

In CO situation is different.

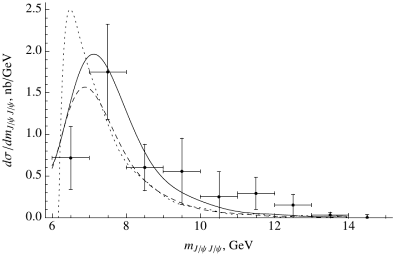


Figure 2: Distribution over the invariant mass of the J/ψ-meson pairs in the "duality" approach compared with the LHCb measurement. Solid curve was obtained with $\Delta = 0.5$ GeV, dashed — with $\Delta = 0.3$ GeV and dotted — in the δ-approximation.

$$\hat{\sigma}^{\rm dual}(gg \to J/\psi(\psi')J/\psi(\psi')) \approx$$
$$\approx \iint_{2m_c}^{2m_D+\Delta} \frac{d^2\sigma\left(gg \to (c\bar{c})^{S=1}_{1_{\rm C}} + (c\bar{c})^{S=1}_{1_{\rm C}}\right)}{dm_{c\bar{c}_1} dm_{c\bar{c}_2}} dm_{c\bar{c}_1} dm_{c\bar{c}_2}, \quad (1)$$

$$T_{4c} = [cc][\bar{c}\bar{c}]$$

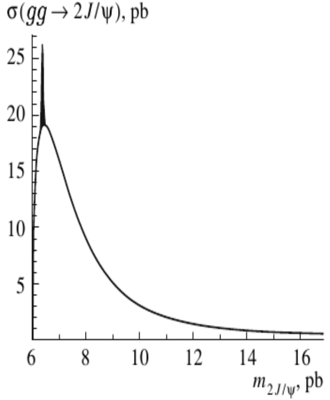


Fig. 9. Invariant-mass distribution of a J/ψ-meson pair from gluon–gluon interaction with allowance for the tetraquark contribution.

$$F\left(r^2\right) = \exp\left\{-\frac{r^2}{\left\langle r_{[cc]}\right\rangle^2}\right\}.$$

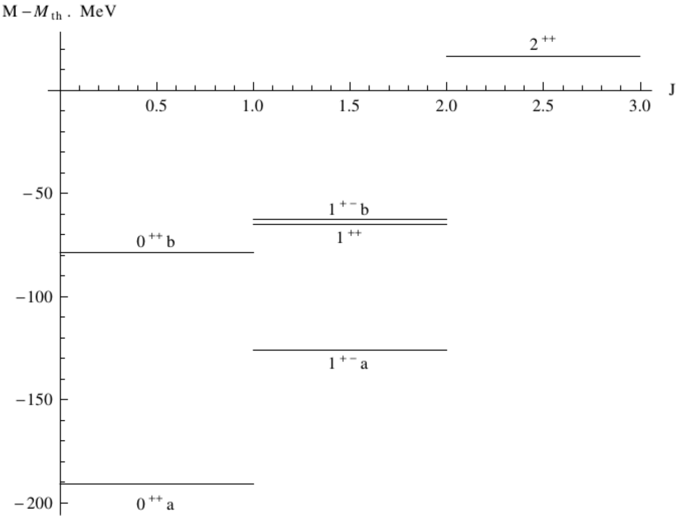
$$V_{SS}(r) = \frac{32\pi}{9}\frac{\alpha_s}{m^2_{[cc]}}(\mathbf{S_1 S_2})\delta(\mathbf{r}).$$

$$J = 0: \quad M_{T_{4c}(0^{++})} = 5.97\ \text{GeV},$$
$$J = 1: \quad M_{T_{4c}(1^{+-})} = 6.05\ \text{GeV},$$
$$J = 2: \quad M_{T_{4c}(2^{++})} = 6.22\ \text{GeV}.$$

Only 2^{++} is above $2J/\psi$ threshold

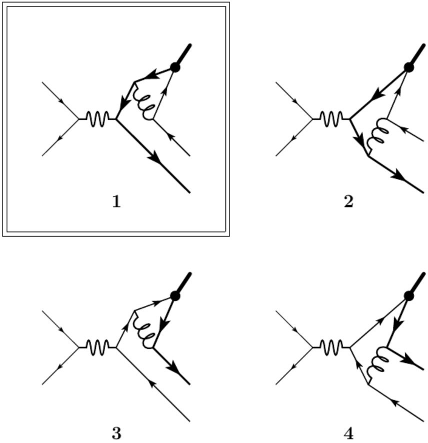
Tetraquarks

$$T_{2bc} = [bc][\bar{b}\bar{c}]$$

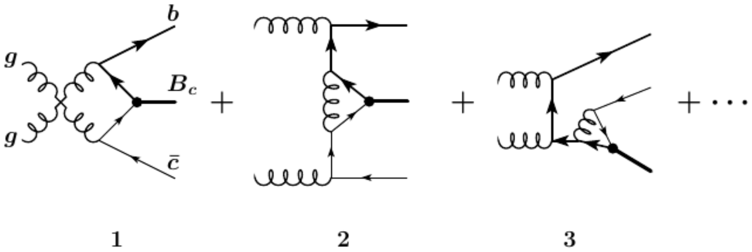


In $s \gg M_{B_c}^2$ the fragmentation picture holds:

$$\frac{d\sigma_{B_c}}{dz} = \sigma D(z)$$



$gg \to B_c g$



The leading order diagrams for the process $gg \to B_c + b + \bar{c}$.

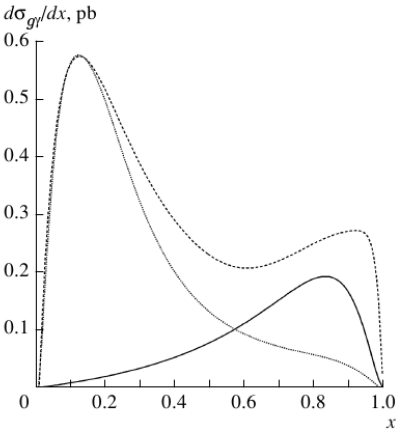


Fig. 11. Distribution of the cross section for B_c-meson production in photon–gluon interaction at $\sqrt{s_{g\gamma}} =$ 100 GeV with respect to the energy fraction carried away, x, in the case of production into the primary-gluon cone (dashed curve) and in the case of production into the primary-photon cone (dotted curve) along with the predictions of the fragmentation model (solid curve).

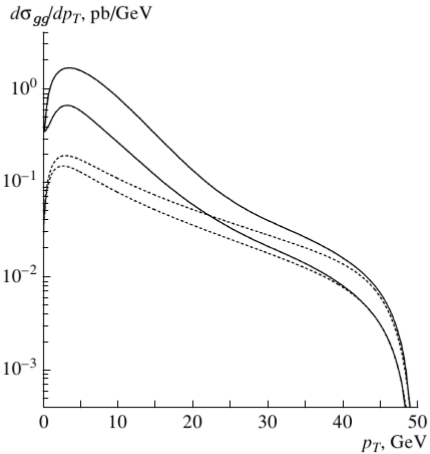


Fig. 8. Distribution of the cross sections for the production of (upper solid curve) B_c^* and (lower solid curve) B_c mesons in gluon–gluon interaction with respect to the transverse momentum at the interaction energy of 100 GeV along with the predictions based on the fragmentation mechanism (dashed curves).

f_{B_c}/f_B

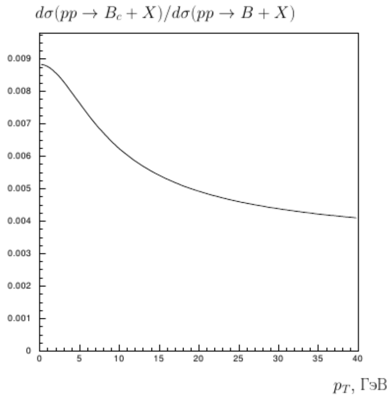
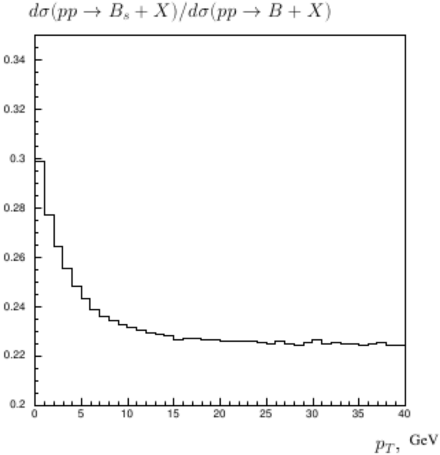
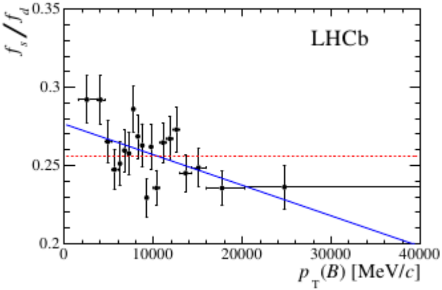


Figure : f_{B_c}/f_B ratio as function of p_T.

f_s/f_d ratio as function of p_T





Important for $\mathrm{Br}(B_s \to \mu^+\mu^-)$

Conclusion

- Heavy quarkoina production can give information on strong interaction at different scales,
- QGP
- Inclusuve χ_c production can be explained using NLO partonic reactions
- CS components give main conribations
- $\chi_{c2}/\chi_{c1} \Rightarrow$ CO components are necessary

References, Experiment

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