B_c-meson wave function from the CDF and LHCb data

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PLAN OF THE TALK

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Motivation

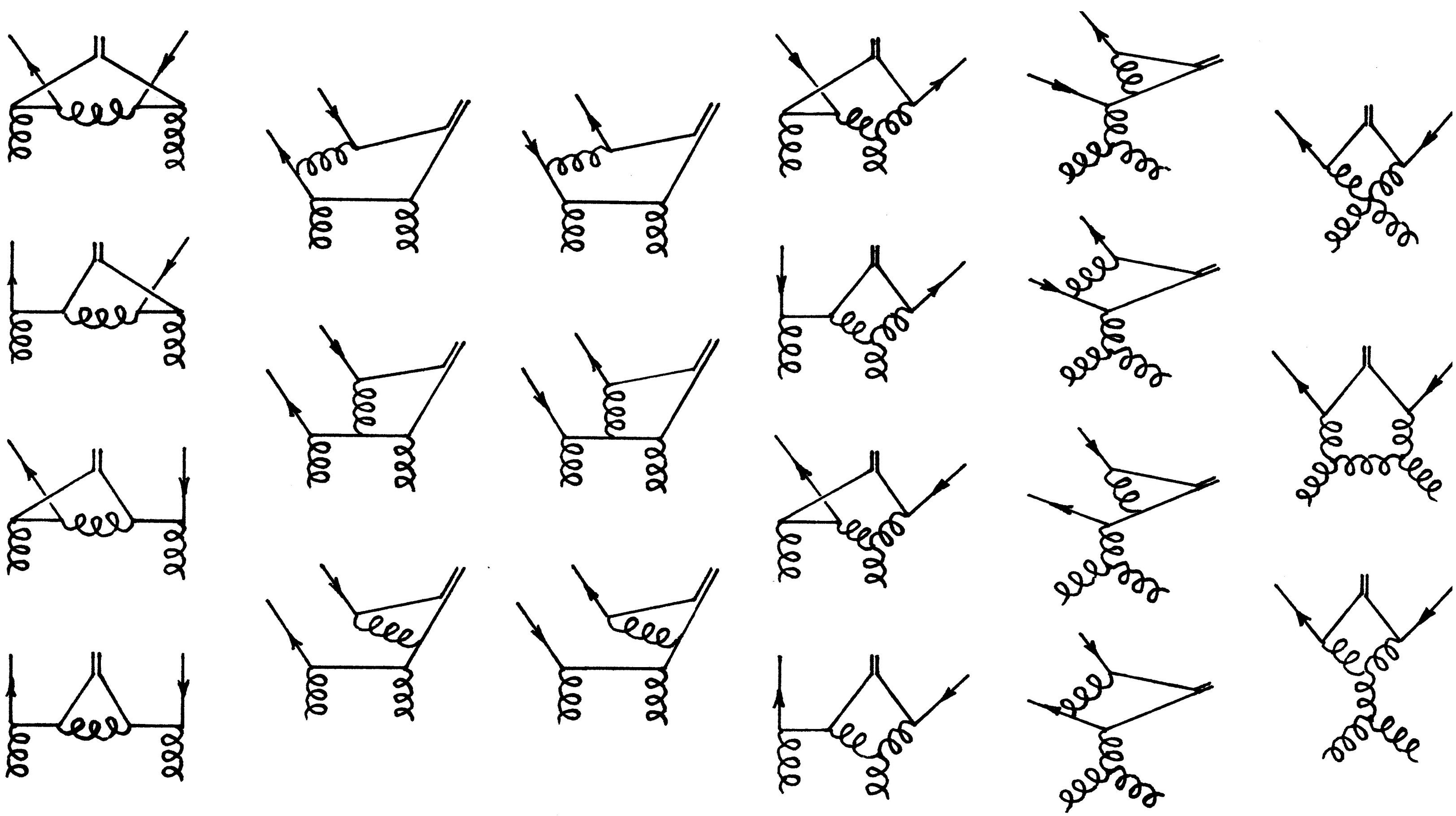
$B_c^{(*)}$ mesons family is an interesting though poorly explored part of quarkonium world. Although some properties of these mesons may look apparently different from the ones of the hidden-flavor onium states, their inner structure is similar and is driven by the same physics. Studying the $B_c^{(*)}$ properties is important on its own and can provide an additional cross check of the exploited theoretical models.

The flavor composition of $B_c^{(*)}$ mesons excludes the convenient strong and electromagnetic decays channels that could be used as a prompt measure of the nonrelativistic wave function. Instead, we try to obtain an estimate of this essential parameter via considering the production process. We rely on the data collected by CDF at 1.8 TeV [1] and 1.96 TeV [2] and by LHCb at 7 TeV [3] and 8 TeV [4].

[1] CDF Collab., Phys. Rev. D **58**, 112004 (1998)
[2] CDF Collab., Phys. Rev. D **93**, 052001 (2016)
[3] LHCb Collab., Phys. Rev. Lett. **109**, 132001 (2012)
[4] LHCb Collab., Phys. Rev. Lett. **114**, 132001 (2015)

Production mechanism

Full set of $\mathcal{O}(\alpha_s^4)$ Feynman diagrams



Computational technique and parameter setting

Standard QCD Feynman rules to calculate $g + g \to B_c^{(*)} + b + \bar{c}$
Basically, a repetition of S.P.Baranov, Phys. Rev. D **54**, 3228 (1996), now within the k_t-factorization approach. Advantages are in the ease of including higher-order corrections, which can be taken into account in the form of k_T-dependent parton densities.

Technically, use the gluon polarization matrix in the form

$\overline{\epsilon_g^{\mu}\epsilon_g^{*\nu}} = k_T^{\mu}k_T^{\nu}/|k_T|^2$ [Phys. Rep. **100**, 1 (1983)].

Quark masses: $m_c = 1.55$ GeV and $m_b = 4.8$ GeV, $m_{B_c} = m_b + m_c$;

Factorization and renormalization scales: $\mu_F^2 = \hat{s} + q_T^2 \quad \mu_R^2 = m_{B_c T}^2$

k_T-dependent gluon densities HJ2013 (default) taken from
F.Hautmann and H.Jung, Nucl. Phys. B **883**, 1 (2014)

Color-singlet model for heavy quark bound states
C.-H. Chang, Nucl. Phys. B **172**, 425 (1980)
E.L.Berger, D.Jones, Phys. Rev. D **23**, 1521 (1981)
R.Baier, R.Rückl, Phys. Lett. B **102**, 364 (1981)

Comparison with the data

CDF at $\sqrt{s} = 1.8$ TeV

$$p_T^{B_c} > 6 \text{ GeV}, \quad p_T^{B^+} > 6 \text{ GeV}, \quad |y^{B_c}| < 1, \quad |y^{B^+}| < 1$$

$$\frac{\sigma(B_c)\, Br(B_c \to J/\psi\, l\nu)}{\sigma(B^+)\, Br(B^+ \to J/\psi\, K)} = 0.132 \pm {}^{0.061}_{0.052}.$$

Within the specified kinematic cuts, we calculate:

$$\begin{aligned}
\sigma^{theor}(B_c^+) &= |\mathcal{R}(0)|^2 \cdot 0.248 \text{ nb/GeV}^3, \\
\sigma^{theor}(B_c^{*+}) &= |\mathcal{R}(0)|^2 \cdot 0.515 \text{ nb/GeV}^3, \\
\sigma^{theor}(B_c^+ + B_c^{*+}) &= |\mathcal{R}(0)|^2 \cdot 0.763 \text{ nb/GeV}^3,
\end{aligned}$$

and for the production of B^+ mesons

$$\sigma^{theor}(B^+)\, Br(B^+ \to J/\psi\, K^+) = 3.56 \text{ nb}$$

with the branching fraction $Br(B^+ \to J/\psi\, K^+) = 1.026 \cdot 10^{-3}$

CDF at $\sqrt{s} = 1.96$ TeV

$$p_T^{B_c} > 6 \text{ GeV}, \quad p_T^{B^+} > 6 \text{ GeV}, \quad |y^{B_c}| < 0.6, \quad |y^{B^+}| < 0.6$$

$$\frac{\sigma(B_c)\, Br(B_c \to J/\psi\, l\nu)}{\sigma(B^+)\, Br(B^+ \to J/\psi\, K)} = 0.211 \pm {}^{0.024}_{0.023}.$$

Within the above cuts, we obtain

$$\begin{aligned}
\sigma^{theor}(B_c^+) &= |\mathcal{R}(0)|^2 \cdot 0.175 \text{ nb/GeV}^3, \\
\sigma^{theor}(B_c^{*+}) &= |\mathcal{R}(0)|^2 \cdot 0.363 \text{ nb/GeV}^3, \\
\sigma^{theor}(B_c^+ + B_c^{*+}) &= |\mathcal{R}(0)|^2 \cdot 0.538 \text{ nb/GeV}^3,
\end{aligned}$$

and for B^+ mesons

$$\sigma^{theor}(B^+)\, Br(B^+ \to J/\psi\, K^+) = 2.43 \text{ nb}.$$

LHCb at $\sqrt{s} = 7$ TeV

$$p_T^{B_c} > 4 \text{ GeV}, \quad p_T^{B^+} > 4 \text{ GeV}, \quad 2.0 < y^{B_c} < 4.5, \quad 2.0 < y^{B^+} < 4.5$$

$$\frac{\sigma(B_c)\, Br(B_c \to J/\psi\, \pi^+)}{\sigma(B^+)\, Br(B^+ \to J/\psi\, K)} = 0.0061 \pm 0.0012.$$

Our predictions are:

$$\begin{aligned} \sigma^{theor}(B_c^+) &= |\mathcal{R}(0)|^2 \cdot 1.23 \text{ nb/GeV}^3, \\ \sigma^{theor}(B_c^{*+}) &= |\mathcal{R}(0)|^2 \cdot 1.80 \text{ nb/GeV}^3, \\ \sigma^{theor}(B_c^+ + B_c^{*+}) &= |\mathcal{R}(0)|^2 \cdot 3.03 \text{ nb/GeV}^3, \end{aligned}$$

and

$$\sigma^{theor}(B^+)\, Br(B^+ \to J/\psi\, K^+) = 9.04 \text{ nb}.$$

LHCb at $\sqrt{s} = 8$ TeV

$$p_T^{B_c} < 20 \text{ GeV}, \quad p_T^{B^+} < 20 \text{ GeV}, \quad 2.0 < y^{B_c} < 4.5, \quad 2.0 < y^{B^+} < 4.5$$

$$\frac{\sigma(B_c)\, Br(B_c \to J/\psi\, \pi^+)}{\sigma(B^+)\, Br(B^+ \to J/\psi\, K)} = 0.0068 \pm 0.0002;$$

Our predictions are:

$$\begin{aligned} \sigma^{theor}(B_c^+) &= |\mathcal{R}(0)|^2 \cdot 4.92 \text{ nb/GeV}^3, \\ \sigma^{theor}(B_c^{*+}) &= |\mathcal{R}(0)|^2 \cdot 5.63 \text{ nb/GeV}^3, \\ \sigma^{theor}(B_c^+ + B_c^{*+}) &= |\mathcal{R}(0)|^2 \cdot 10.55 \text{ nb/GeV}^3, \\ \sigma^{theor}(B^+)\, Br(B^+ \to J/\psi\, K^+) &= 32.66 \text{ nb} \end{aligned}$$

The above numbers have to be combined with

$$Br(B_c \to J/\psi\, \pi^+)/Br(B_c \to J/\psi\, \mu\nu) = 0.047$$

LHCb Collab., Phys. Rev. D **90**, 032009 (2014)

$$Br(B_c \to J/\psi\, \pi^+) = 0.0033.$$

C.-F.Qiao, P.Sun, D.Yang, R.-L.Zhu, Phys. Rev. D **89**, 034008 (2014)

Wave function estimations

$$|\mathcal{R}(0)|^2 = 4.39 \pm 2.00 \text{ GeV}^3 \qquad \text{CDF-1998}$$
$$|\mathcal{R}(0)|^2 = 6.79 \pm 0.08 \text{ GeV}^3 \qquad \text{CDF-2016}$$
$$|\mathcal{R}(0)|^2 = 5.52 \pm 0.11 \text{ GeV}^3 \qquad \text{LHCb-2012}$$
$$|\mathcal{R}(0)|^2 = 6.32 \pm 0.18 \text{ GeV}^3 \qquad \text{LHCb-2015}$$

Can be summarised in a mean-square average value

$$|\mathcal{R}(0)|^2 = 5.78 \text{ GeV}^3$$

with an error of ± 0.64 GeV^3 and ± 1.07 GeV^3 at the 60% and 80% confidence levels, respectively.

Discussion

Goog agreement in shape shows that the hard scattering partonic subprocesses are calculated correctly. The choice of the TMD gluon density is unimportant since the gluon distributions cancel out in the ratio. The sensitivity to the renormalization scale is high, because of the fourth power of $\alpha_S(\mu_R^2)$ in the key subprocess.

Our extracted values are of $|\mathcal{R}(0)|^2$ are systematically higher than the predictions of potential models and lattice QCD:

$1.508\ \mathrm{GeV}^3$	C.Quigg, J.L.Rosner, Phys. Lett. B **71**, 153 (1977)
$1.642\ \mathrm{GeV}^3$	W.Buchmüller, S.-H.Tye, Phys. Rev. D **24**, 132 (1981)
$1.710\ \mathrm{GeV}^3$	A.Martin, Phys. Lett. B **93**, 338 (1980)
$3.102\ \mathrm{GeV}^3$	E.Eichten et al., Phys. Rev. D **17**, 3090 (1978)
$1.2\ \mathrm{GeV}^3$	C.McNeile et al., Phys. Rev. D **86**, 074503 (2012)

Discussion

The systematic discrepancy may be taken as an evidence of large radiative corrections (such as $1 - 16\alpha_s/3\pi$ from R.Van Royen, V.F.Weisskopf, Nuovo Cimento **51**, 583 (1967)), obtained by transcription from QED).

Another possible interpretation may guess that the conventional choice of μ_R overestimates the momentum transfer in the hard process. For a gluon splitting into c-quarks (which further assemble with b-quarks to form B_c) it looks reasonable to use $\mu_R^2 = m_{cT}^2$ rather than $m_{B_cT}^2$.

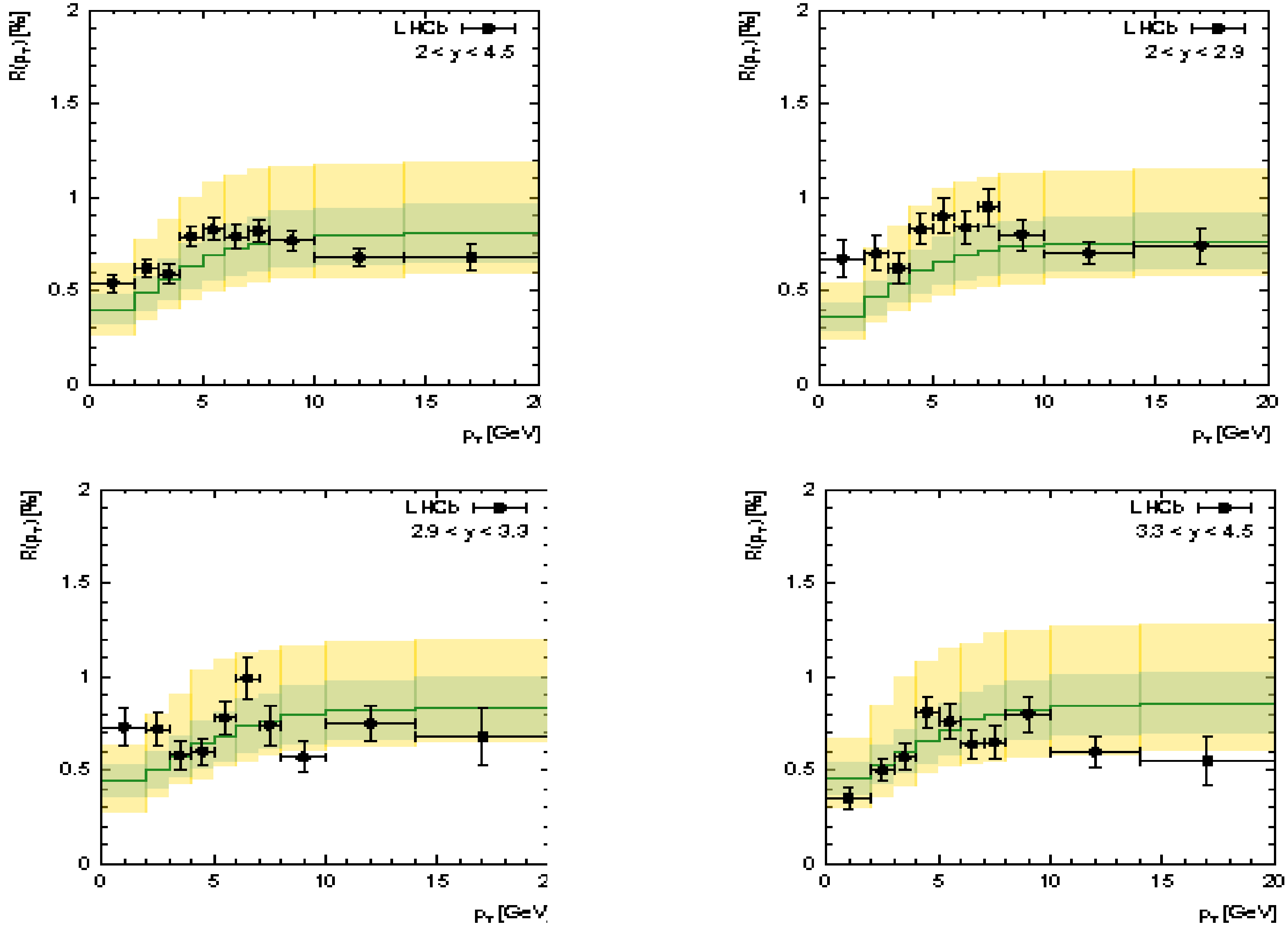
So, replace $\alpha_S^4 \to \alpha_S^2(m_{B_cT}^2) \cdot \alpha_S^2(m_{cT}^2)$ and obtain

$$|\mathcal{R}(0)|^2 = 3.02\ \mathrm{GeV}^3 \quad (1)$$

with an error of $\pm 0.25\ \mathrm{GeV}^3$ and $\pm 0.50\ \mathrm{GeV}^3$ at 60% and 80% c.l.

Much closer agreement with potential models,
though still some tension with the lattice result.

Double differential distributions, $R = \sigma(B_c)/\sigma(B^+)$



Uncertainty bands: grey = statistical; yellow = $\alpha_s^4(\mu^2)$ scale

Conclusion

We present the first attempt to evaluate the $B_c^{(*)}$ wave function by considering the $B_c^{(*)}$ production data. We find that the ambiguity in the choice of the renormalization scale causes numerical uncertainties that are too large to declare a 'real measurement'. We only can judge on the consistency or inconsistency of the fitted values with model prdictions.

We argue for a choice of renormalization scale μ_R^2 different from its conventional definition. We show that the estimates obtained from the $B_c^{(*)}$ production cross sections under our assumption $\alpha_S^4 \to \alpha_S^2(m_{B_cT}^2) \cdot \alpha_S^2(m_{cT}^2)$ are good in shape and are nearly consistent with the predictions of potential models (though, probably, not with the lattice calculation).

Thank you!