Associated $\Upsilon + J/\psi$ production
and prospects to observe
a new hypothetical tetraquark

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1. **Motivation for a new interaction mechanism**
2. $\Upsilon + J/\psi$ **production at the LHCb conditions**
3. $\Upsilon + J/\psi$ **production at the D0 conditions**
4. **Conclusions**

Motivation

After a number of discoveries of tetra-quark mesonic states and penta-quark baryonic states, it would not be unreasonable to suggest the existence of a $b\bar{b}c\bar{c}$ state composed of four heavy quarks. Its inner structure can be described as a hadron molecule B_c+$\bar{B}_c$, or a hadro-quarkonium Υ+J/ψ, or, most probably, thequantum superposition of these two.

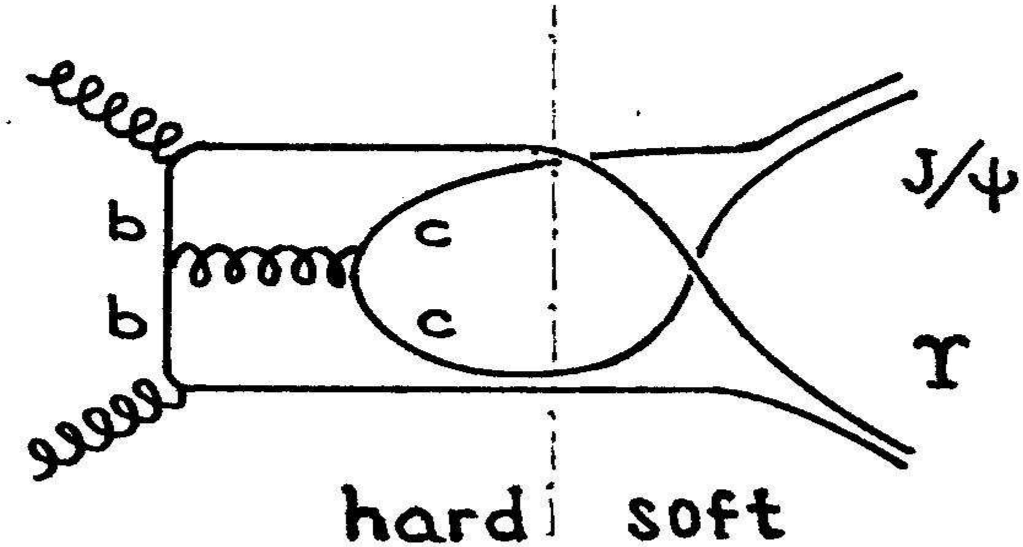
Such a state is then naturally connected to both B_c+$\bar{B}_c$ and Υ+J/ψ channels, so that these quark configurations can transform into one another if the invariant energy of the system is close to the four-quark resonant mass.

This opens a new production mechanism for J/ψ+Υ states.
The issues considered in the present talk:

– **Can we observe the hypothetical tetraquark in J/ψ+Υ channel?**

– **Can this new mechanism take credit for J/ψ+Υ events at D0?**

Production mechanism in more detail



Hard production of two quark pairs, then soft reshuffling;
looks like OZI-violating process with topological suppression $\simeq 1/N_c^2$
Two ways to estimate the cross section:

– **take the color projection of** $(B_c+\bar{B}_c)$ **onto** $(\Upsilon+J/\psi)$, **and then assume quark-hadron duality,** $\sigma(\Upsilon+J/\psi)_{\rm Res} \simeq \sigma(\Upsilon+J/\psi)_{\rm NR} \simeq \sigma(B_c+\bar{B}_c)/N_c^2$

– **or integrate over a restricted phase space**
$\sigma(\Upsilon+J/\psi) \simeq \int_{M_0-\delta M}^{M_0+\delta M} \sigma(B_c+\bar{B}_c)\, dM$ **with** δM **taken as** $\Gamma/2$ **or** $E_{\rm bind}$.

What is new compared to the already known mechanisms?

– **Simultaneous $J/\psi$and Υ production in the color-singlet mode is not possible at $\mathcal{O}(\alpha_s^4)$**

– **The leading production mechanism refers to a mixed singlet-octet scheme, where Υ is formed in the color-singlet mode $g+g \to \Upsilon+g^*$ and J/ψ comes from the virtual gluon fragmentation $g^* \to c\bar{c}[^3S_1^8] \to J/\psi$.**

– **The fully octet modes are suppressed because of typically small values of the color-octet matrix elements (only important at high p_T).**

– **Color-singlet production of P-wave states $g+g \to \chi_b+\chi_c$ is possible at $\mathcal{O}(\alpha_s^4)$, but is suppressed by P-state wave functions and by the decay branching fractions $\chi_c \to J/\psi+\gamma$, $\chi_b \to \Upsilon+\gamma$.**

– **Simultaneous production of S-wave color-singlets is possible at $\mathcal{O}(\alpha_s^6)$ but is suppressed by extra α_s^2 and, especially, by the color algebra.**

– **Non-prompt production via $\Upsilon + b + \bar{b}$ states followed by the decays $b, \bar{b} \to J/\psi + X$ is suppressed by small decay branchings $Br \simeq 3\,10^{-3}$**

– **Color-singlet $B_c^{(*)}\bar{B}_c^{(*)}$ production is possible at $\mathcal{O}(\alpha_s^4)$**

Computational technique and parameter setting

Standard QCD Feynman rules to calculate $g + g \to B_c^{(*)} + \bar{B}_c^{(*)}$
(basically, a repetition of S.P.Baranov, Phys. Rev. D 55, 2756 (1997))
but 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 (** $\to$ **important modifications in the event kinematics). 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: $m_c = m_{\psi}/2 = 1.55$ **GeV and** $m_b = m_{\Upsilon}/2 = 4.8$ **GeV (also** $m_{B_c} = m_b + m_c$**);**

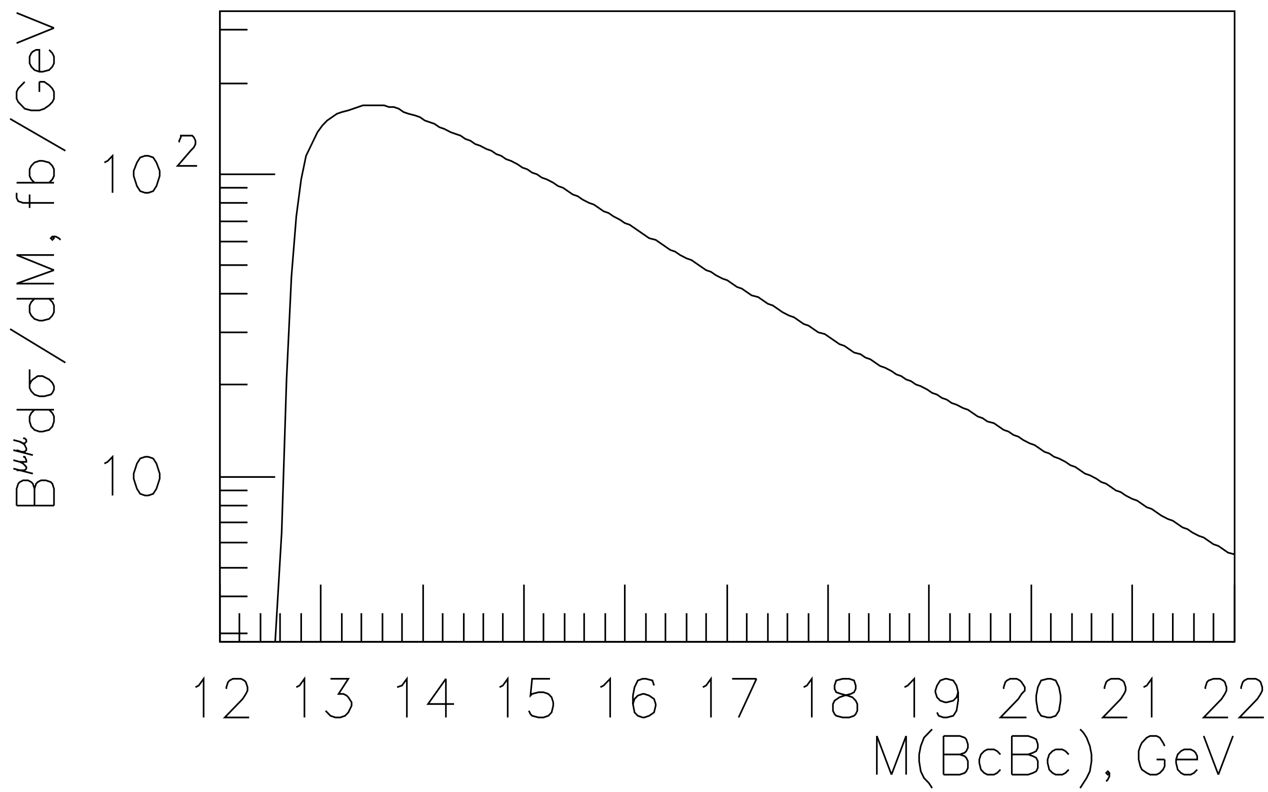
Factorization and renormalization scales: $\mu_F^2 = \mu_R^2 = \hat{s}/4$ **(Lorentz-invariant choice symmetric w.r.t. the final particles)**

k_T**-dependent gluon densities A0 (default), A+, A- taken from H.Jung *et al.*, Eur. Phys. J. C 70, 1237 (2010)**

Radial wave functions of $B_c^{(*)}$**mesons** $|\mathcal{R}_{B_c}(0)|^2 = \mathbf{1.2}$ **GeV**^{3} **from potential model E.Bagan *et al.*, Z. Phys. C 64, 57 (1994)**

Numerical results at LHCb

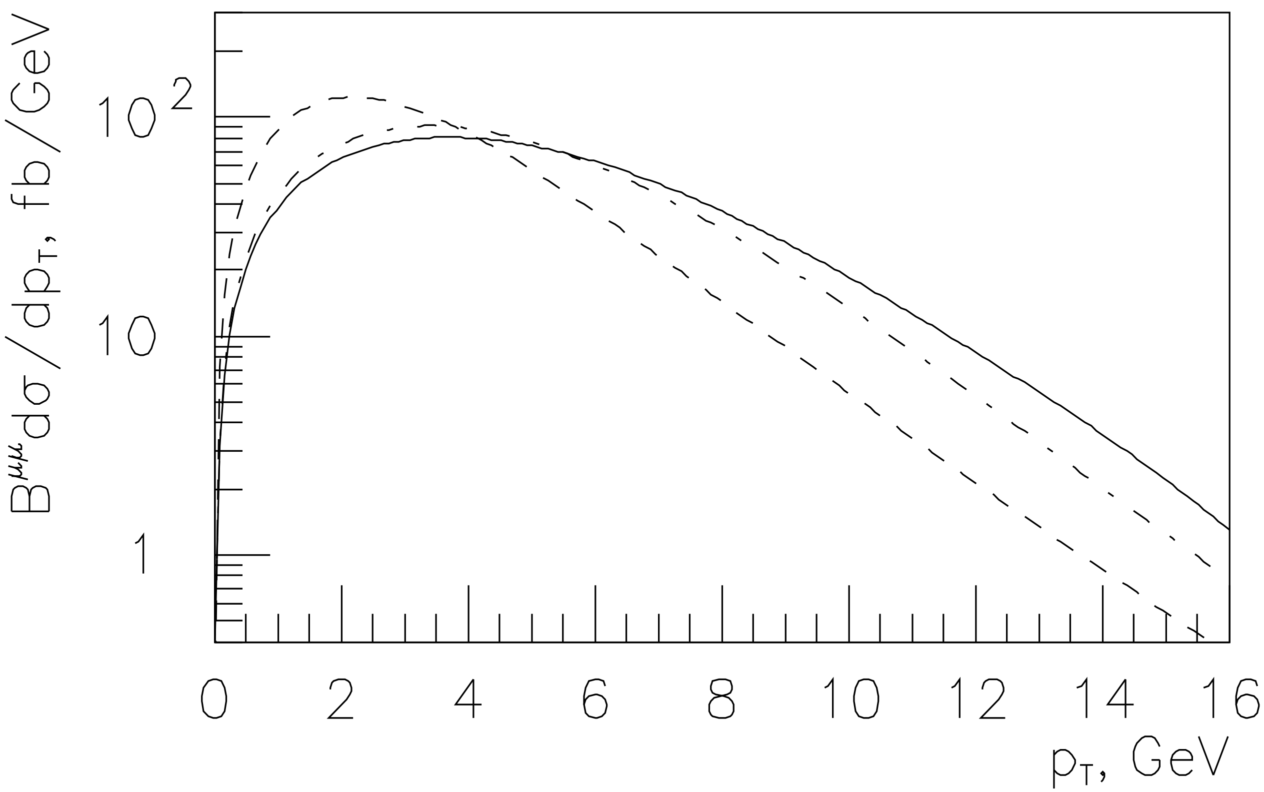
Four-quark invariant mass spectrum at $\sqrt{s} = 13$ TeV



Differential cross section times muon branching fraction

$$Br^{\psi\to\mu\mu} Br^{\Upsilon\to\mu\mu}\, d\sigma(pp\to B_c\bar{B}_c)/dM$$

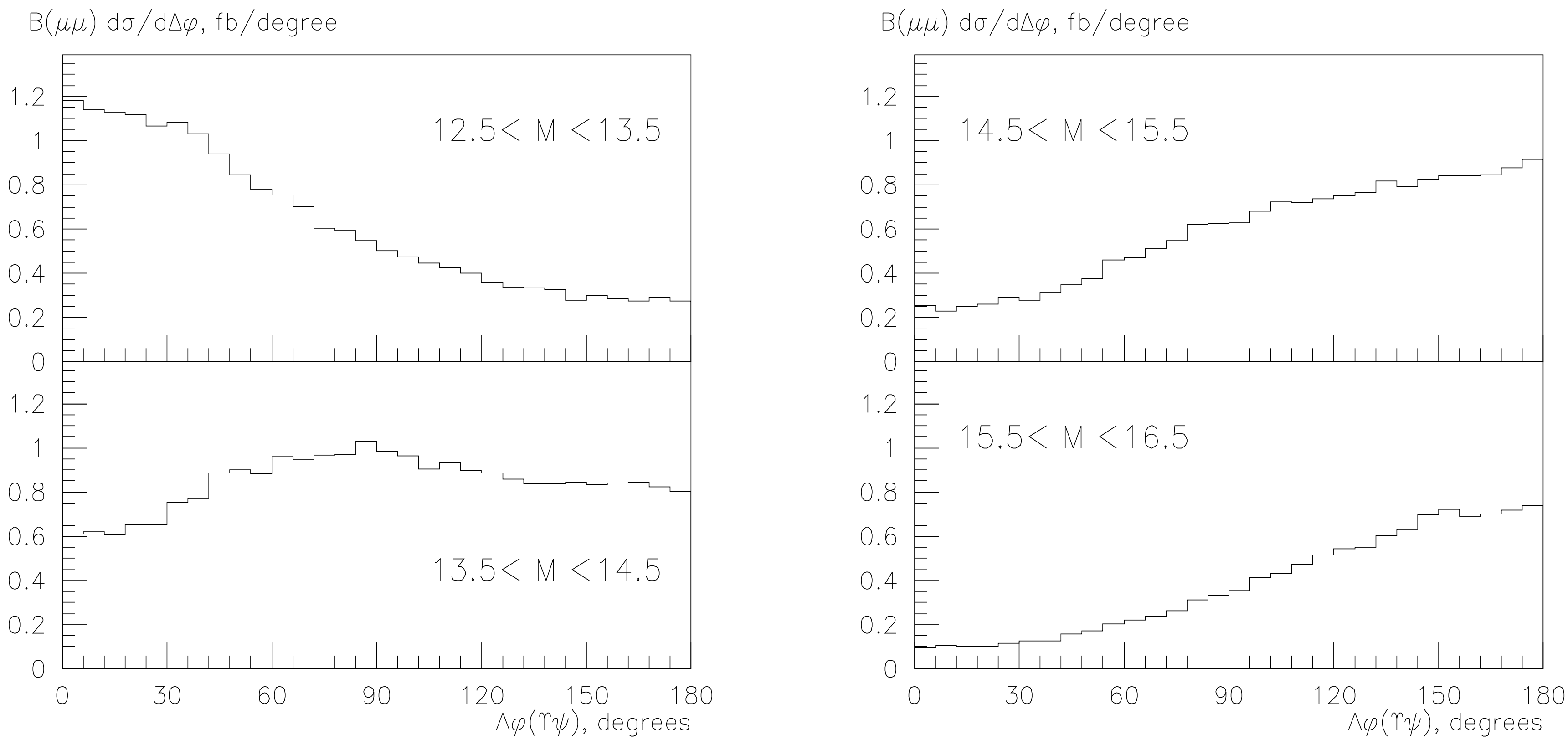
Transverse momentum distributions



Differential cross sections times muon branching fraction $Br^{\psi\to\mu\mu} Br^{\Upsilon\to\mu\mu}\, d\sigma(pp\to B_c\bar{B}_c)/dp_T$ integrated over all masses.

Dash-dotted = Υ; Dashed = J/ψ; Solid = Υ+J/ψ system.

Azimuthal correlations between J/ψ and Υ mesons



Differential cross section times muon branching fraction integrated over several different mass intervals.

Summary of the LHCb perspectives

Integral $B_c\bar{B}_c$ **rate:** $\sigma(pp \to B_c\bar{B}_c)\, Br^{\Upsilon\to\mu\mu} Br^{\psi\to\mu\mu} \simeq 550$ fb

after assuming $\Gamma \simeq 200$ MeV **or applying color suppression factor**

$$\sigma(\Upsilon + J/\psi)\, Br^{\Upsilon\to\mu\mu} Br^{\psi\to\mu\mu} \simeq 20 - 60 \text{ fb}$$

Background from double parton scattering (dominant):

$$\sigma_{\rm DPS}(\Upsilon + J/\psi) = \sigma_{\rm incl}(\Upsilon)\, \sigma_{\rm incl}(J/\psi) \,/\, \sigma_{\rm eff}$$

where $\sigma_{\rm incl}(J/\psi) Br^{\psi\to\mu\mu} \simeq 380$ nb, $\sigma_{\rm incl}(\Upsilon) Br^{\Upsilon\to\mu\mu} \simeq 6$ nb, $\sigma_{\rm eff} = 15$ mb
known from [**LHCb Collab., JHEP 1510, 172 (2015), JHEP 1511, 103 (2015)**]

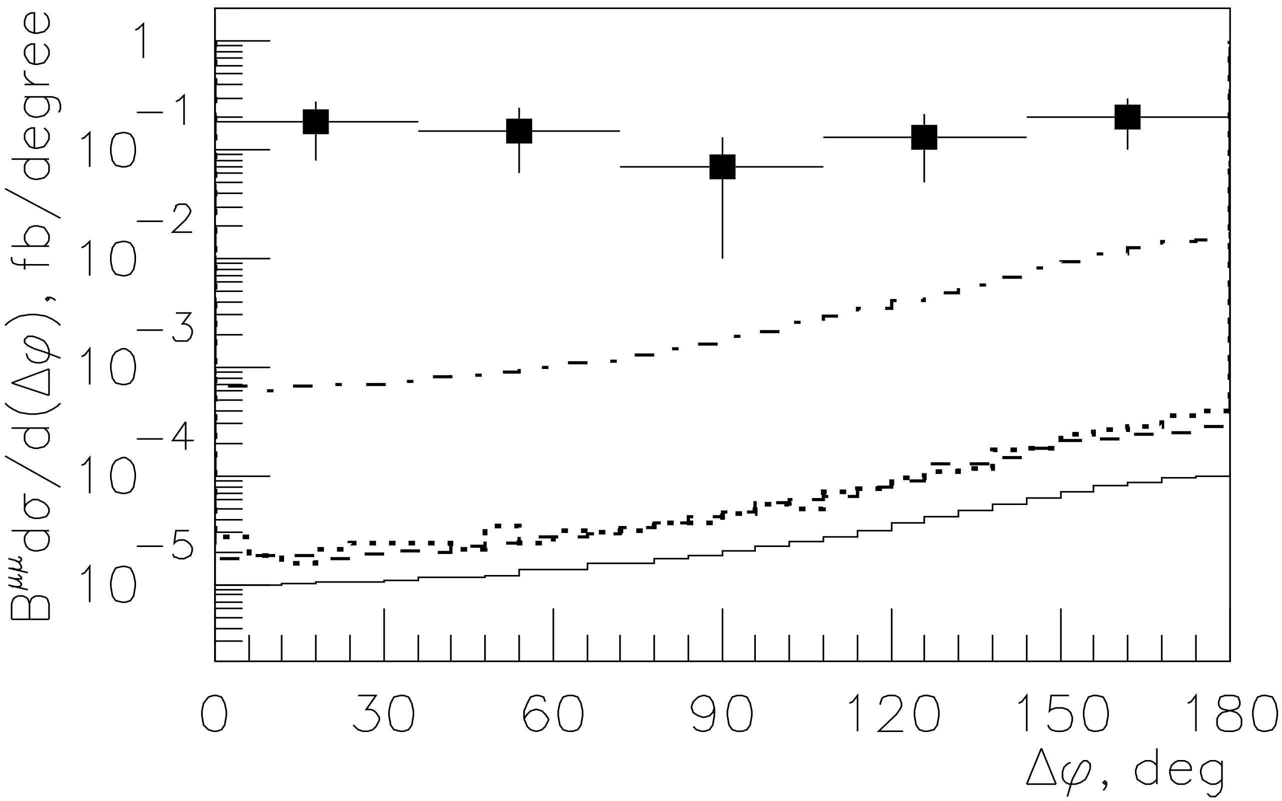
$$\sigma_{DPS}(\Upsilon + J/\psi)\, Br^{\Upsilon\to\mu\mu} Br^{\psi\to\mu\mu} \simeq 150 \text{ fb}$$

– The signal is not small compared to what was already measured;

– The signal is not small compared to the background, clearly distinguishable due to resonant behavior → perspective looks optimistic

Numerical results at D0

Standard production mechanisms at $\sqrt{s} = 1.96$ TeV

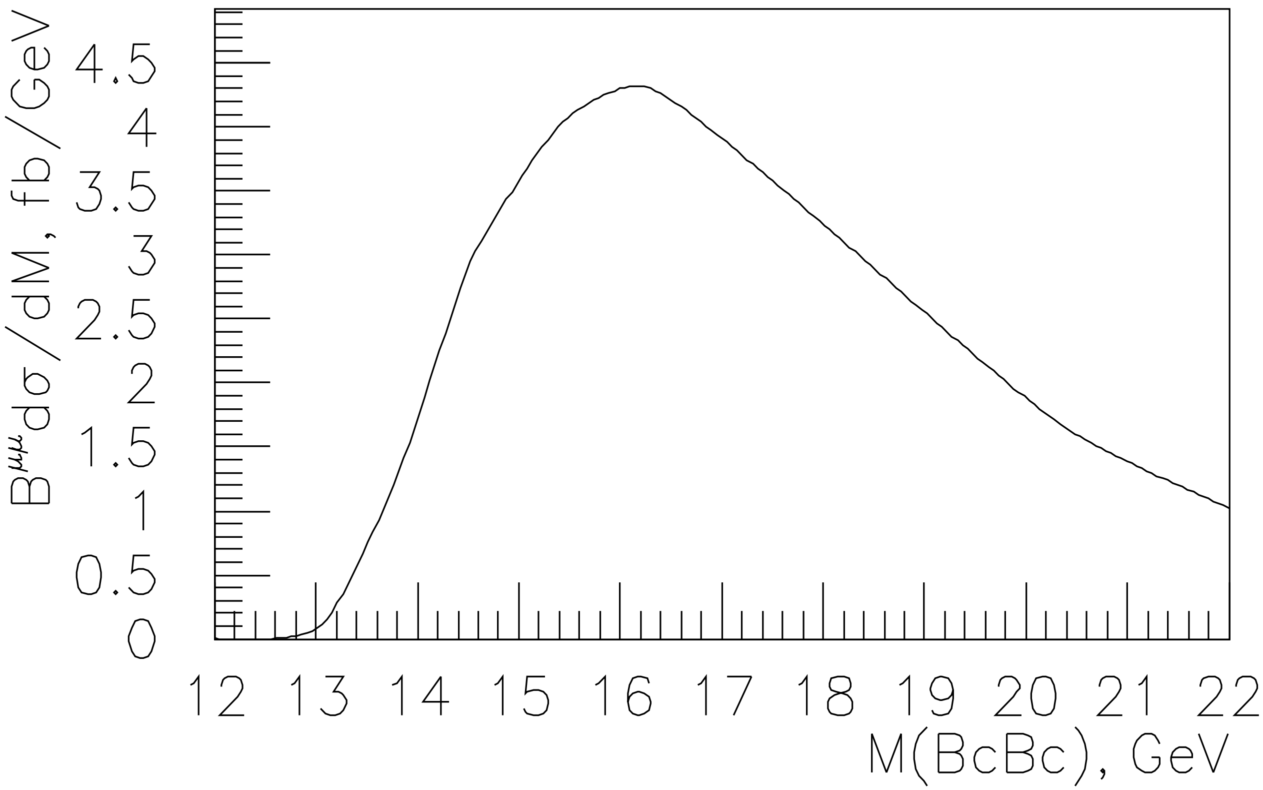


Experiment: $Br^{\psi\to\mu\mu} Br^{\Upsilon\to\mu\mu} \sigma_{fid}(pp\to J/\psi+\Upsilon) \simeq 27$ **fb**

dash-dotted, singlet+octet at $\mathcal{O}(\alpha_s^4)$; dotted, color-octets at $\mathcal{O}(\alpha_s^4)$; dashed, color-singlets at $\mathcal{O}(\alpha_s^6)$; solid, non-prompt production via $\Upsilon b\bar{b}$

Resonant production mechanism at D0

Four-quark invariant mass spectrum at $\sqrt{s} = 1.96$ TeV



Cross section times muon branching fraction

$Br^{\psi\to\mu\mu} Br^{\Upsilon\to\mu\mu}\ \sigma_{tot}(pp\to B_c\bar{B}_c) \simeq 20$ **fb**

(too low to explain the data)

CONCLUSIONS

At LHCb,

– the expected production cross section amounts to approx. 20 fb; this is comparable with that has been measured successfully by other collaborations. The peaking signal is well recognizable over flat background. The measurements (and the detection of a tetraquark) look feasible.

At D0,

– the estimated cross section is about one order of magnitude below the data. The proposed mechanism can hardly explain the $J/\psi + \Upsilon$ events at D0, although the uncertainties are large. Detection of the tetraquark at the LHC (if takes place) could reduce theoretical uncertainties.

Thank you!