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

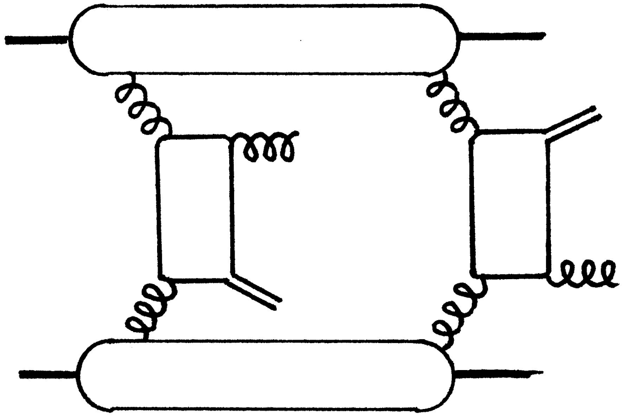
Sergey Baranov
P.N.Lebedev Institute of Physics, Moscow, Russia

PLAN OF THE TALK

1. **Motivation**
2. **$\Upsilon + J/\psi$ production at D0**
3. **$\Upsilon + J/\psi$ production at LHCb**
4. **Conclusions**

Motivation

An introduction to Double Parton Scattering



Two independent interactions $\hat{\sigma}^A$ and $\hat{\sigma}^B$ at a time:

$$\sigma^{\mathrm{AB}}_{\mathrm{DPS}} = \frac{1}{2}\sum_{i,j,k,l}\int \Gamma_{ij}(x_1,x_1';\mathbf{b_1},\mathbf{b_2};Q^2,Q'^2)\hat{\sigma}^A_{ik}(x_1,x_2,Q^2)$$
$$\times\Gamma_{kl}(x_2,x_2';\mathbf{b_1}-\mathbf{b},\mathbf{b_2}-\mathbf{b};Q^2,Q'^2)\hat{\sigma}^B_{jl}(x_1',x_2',Q'^2)$$
$$\times dx_1\,dx_2\,dx_1'\,dx_2'\,d^2b_1\,d^2b_2\,d^2b$$

with $\mathrm{b_i}$ being the impact parameters and Q^2, Q'^2 the probing scales

N. Paver, D. Treleani, Nuovo Cimento A 70, 215 (1982)

Further assumptions:

Decoupling of longitudinal and transversal variables

$$\Gamma_{ij}(x, x'; \mathbf{b_1}, \mathbf{b_2}; Q^2, Q'^2) = \mathcal{D}_{ij}(x, x'; Q^2, Q'^2) f(\mathbf{b_1}) f(\mathbf{b_2})$$

where $f(\mathrm{b})$ is supposed to be an universal function normalized as

$$\int f(\mathbf{b_1}) f(\mathbf{b_1} - \mathbf{b})\, d^2\mathbf{b_1}\, d^2\mathbf{b} = 1$$

Factorization of parton distributions

$$\mathcal{D}_{ij}(x, x'; Q^2, Q'^2) = \mathcal{F}_i(x, Q^2) \mathcal{F}_j(x', Q'^2)$$

Result in the "pocket formula" $\sigma_{\mathrm{DPS}}^{\mathrm{AB}} = \frac{1}{2} \frac{\sigma_{\mathrm{SPS}}^{A} \sigma_{\mathrm{SPS}}^{B}}{\sigma_{\mathrm{eff}}}$

Experiments mostly agree about $\sigma_{\mathrm{eff}} = 14.5\ mb$

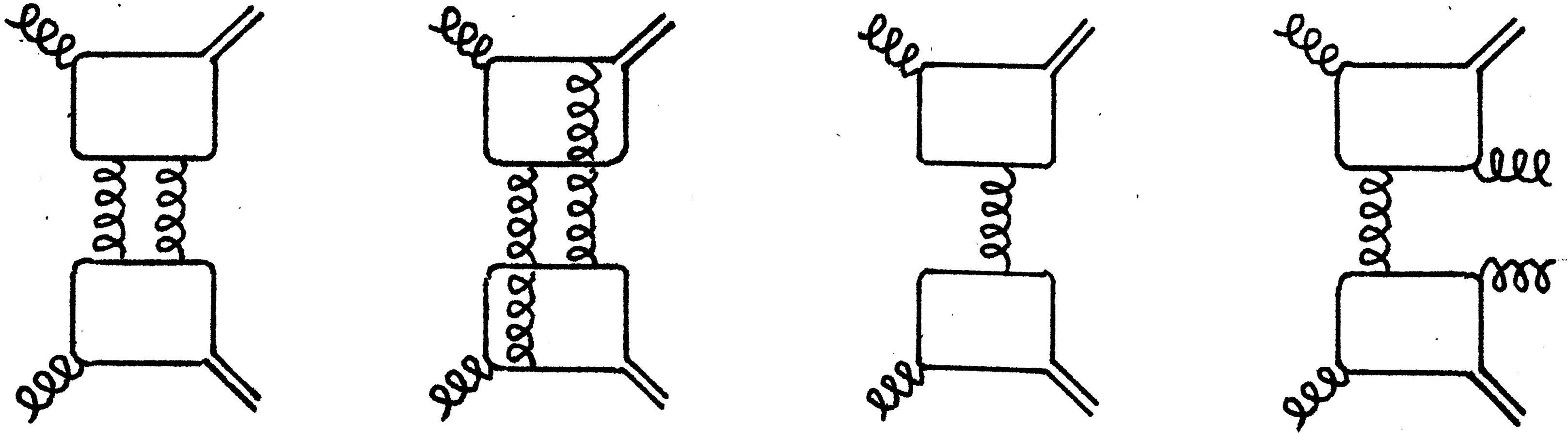
An exception is $\Upsilon + J/\psi$ at D0, with $\sigma_{\mathrm{eff}} = 2.5\ mb$

Can it be explained with someting missed in Single Parton Scattering? Have a clodser look. (Maybe).

Single Parton Scattering contributions

Onium-onium scattering at $\mathcal{O}(\alpha_s^6)$

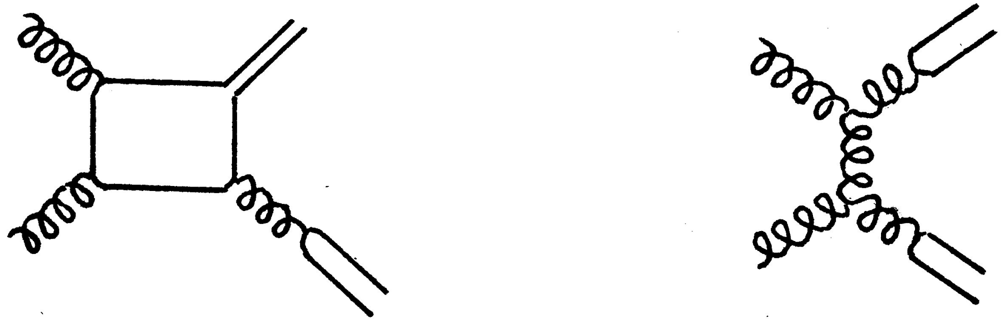
close to DPS in kinematical properties, can mimic the latter



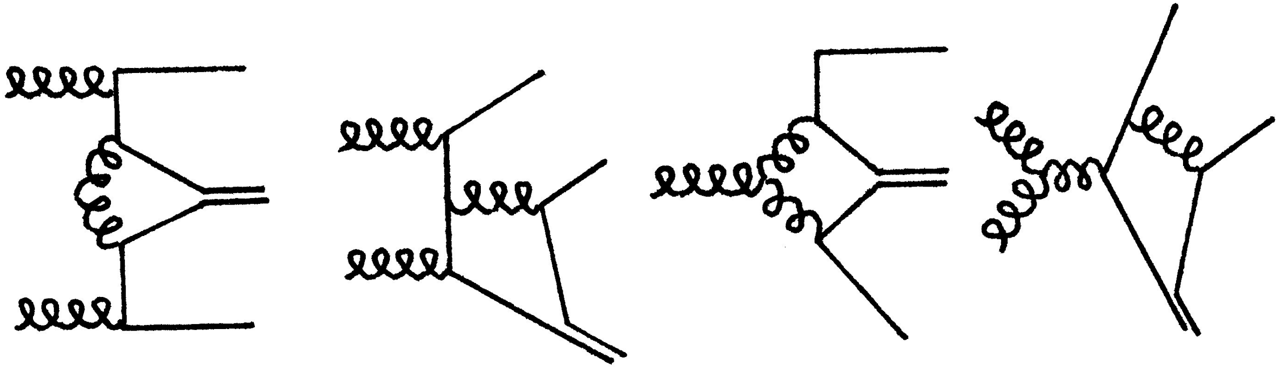
Two-gluon exchange, pseudodiffractive, may produce Υ and J/ψ
One-gluon exchange, pseudodiffractive, may produce χ_b and χ_c
or color-octet states further evolving into Υ and J/ψ
One-gluon exchange, with extra gluons, may produce Υ and J/ψ

– All are suppressed by unfavorable color factor (see backup slide)

Gluon-gluon fusion at $\mathcal{O}(\alpha_s^4)$ Not possible for color-singlets.
Only possible in mixed singlet-octet or fully octet modes.

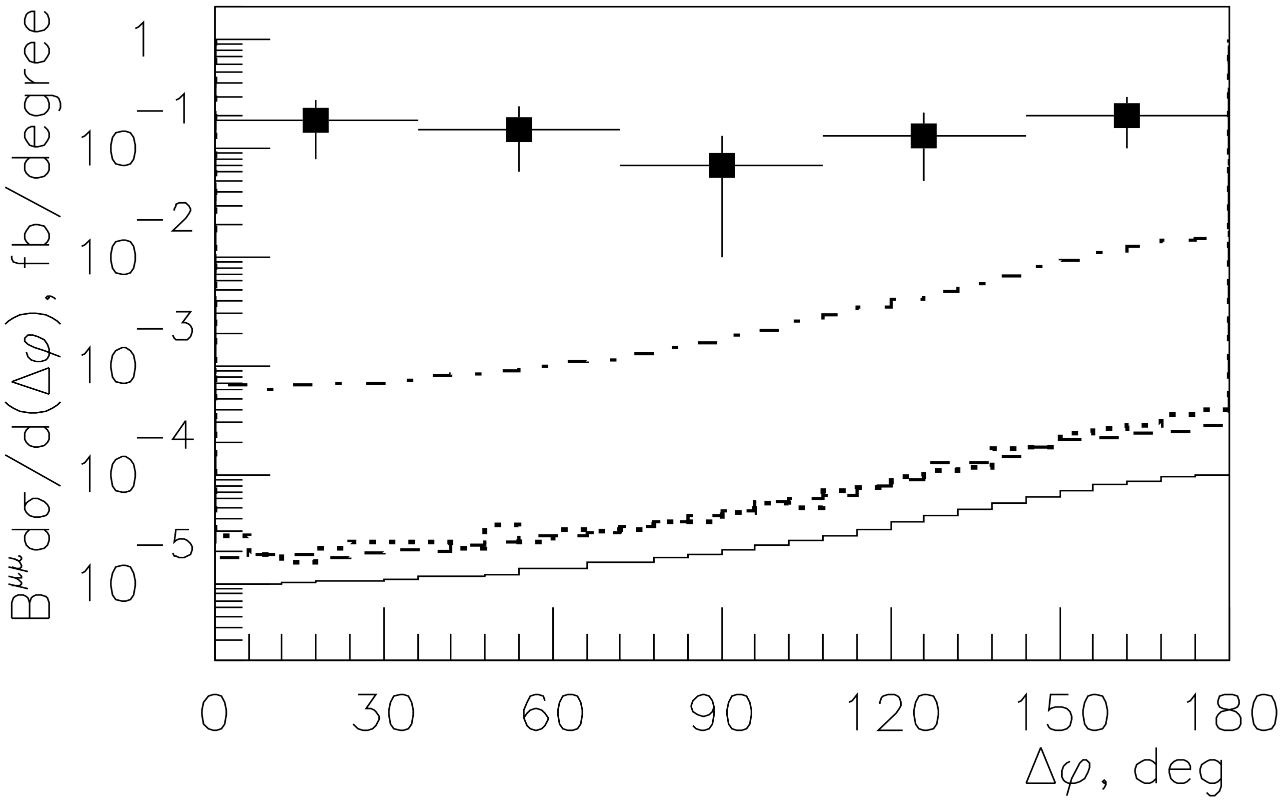


Non-prompt: $\Upsilon + b + \bar{b}$ followed by decays $b \to J/\psi$
Suppressed by small decay branching $Br(b \to J/\psi) \sim 8{\cdot}10^{-3}$



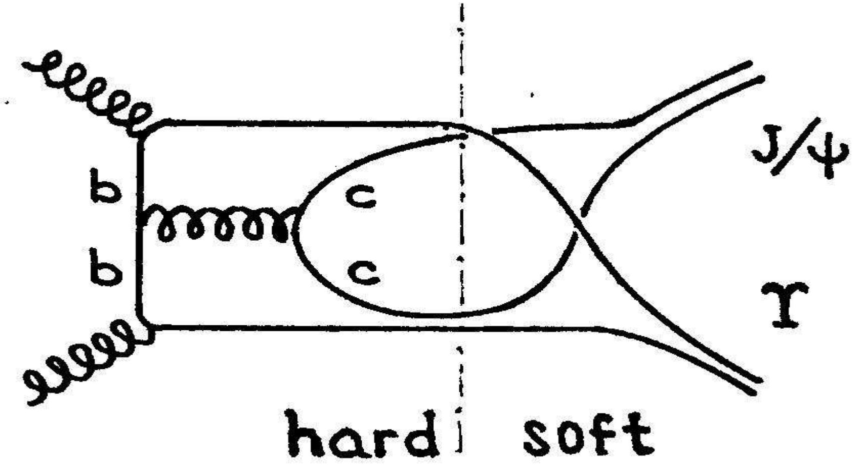
Numerical results at D0

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 $\Upsilon b\bar{b}$

A new production mechanism



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,** $\sigma(\Upsilon{+}J/\psi)_{\rm Res} \simeq \sigma(\Upsilon{+}J/\psi)_{\rm NR} \simeq \sigma(B_c{+}\bar{B}_c)/N_c^2$

– **there may be a resonant state: 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** $E_{\rm binding}$.

What is new compared to the already known mechanisms?

– **Simultaneous J/ψ 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 $Br \simeq 8\,10^{-3}$**

– **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 (→ 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 $m_{B_c} = m_b + m_c$);

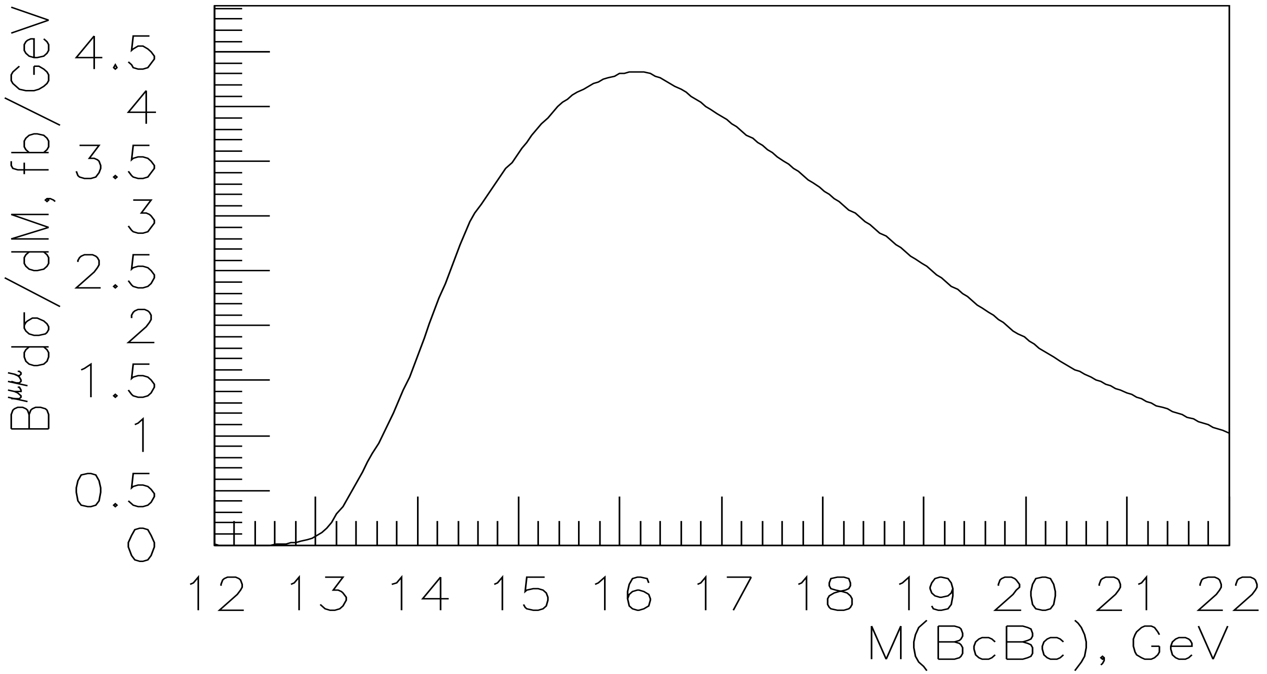
Factorization and renormalization scales: $\mu_F^2 = \mu_R^2 = \hat{s}/4$ (Lorentz-invariant choice symmetric w.r.t. the final particles)

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

New SPS production mechanism at D0

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



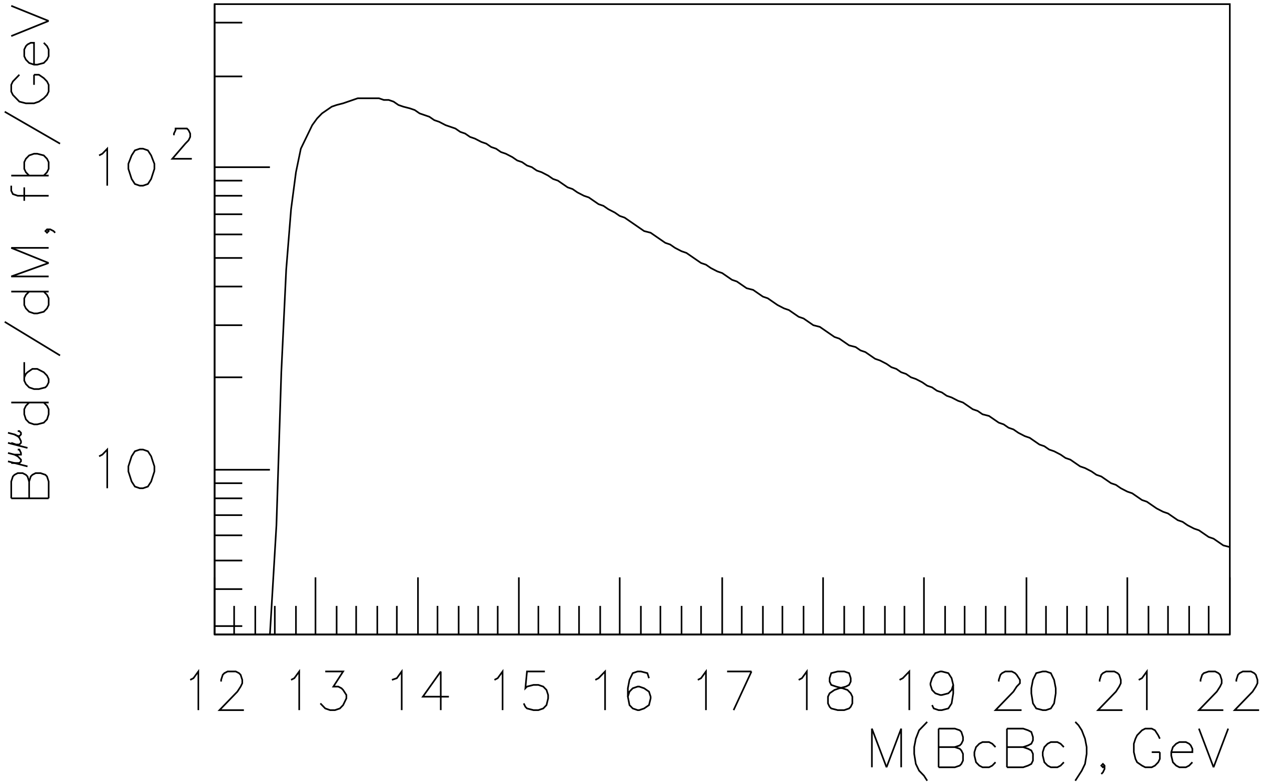
Cross section times muon branching fraction

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

After ‘resuffling’ to Υ+J/ψ reduces to $\simeq 2$ fb, too low to explain the data. But, maybe, not too low to detect a resonsnce?

Numerical results at LHCb

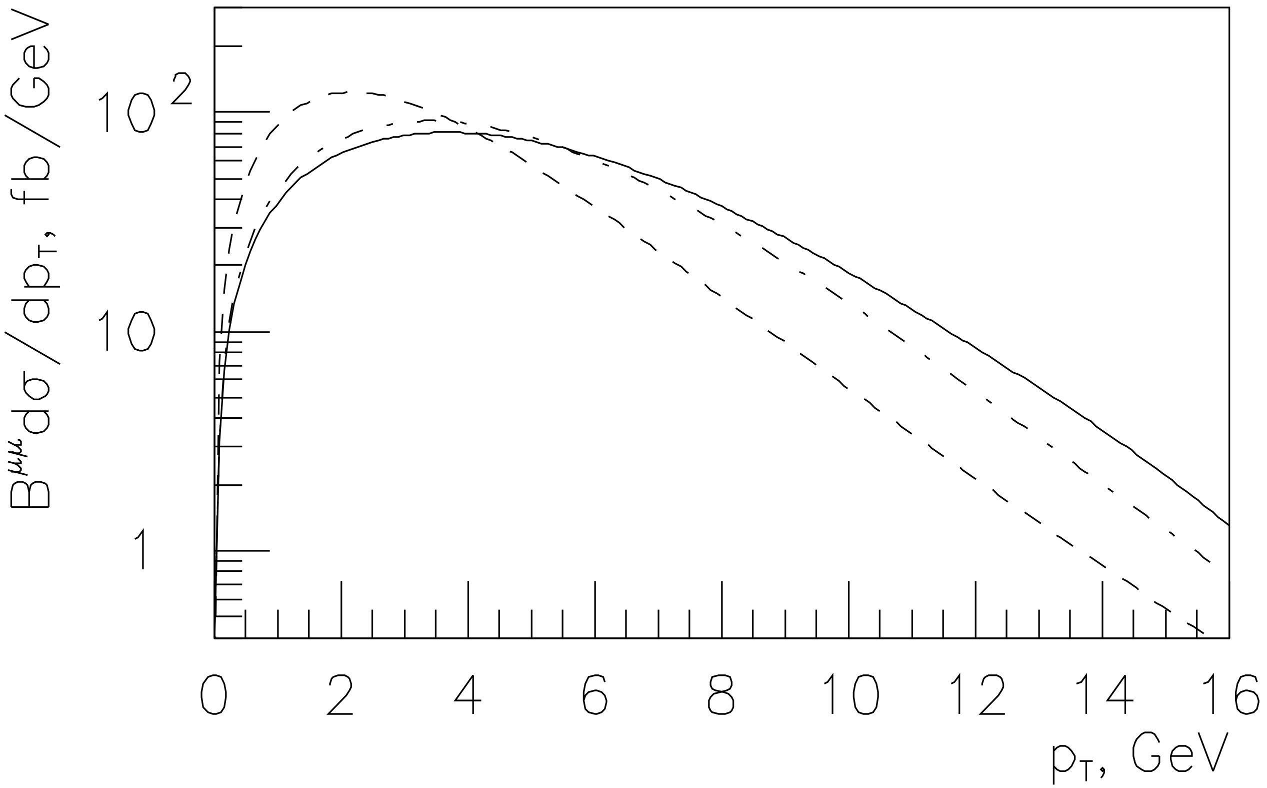
Four-quark invariant mass spectrum at $\sqrt{s} = 13$ TeV



Differential cross section times muon branching fraction

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

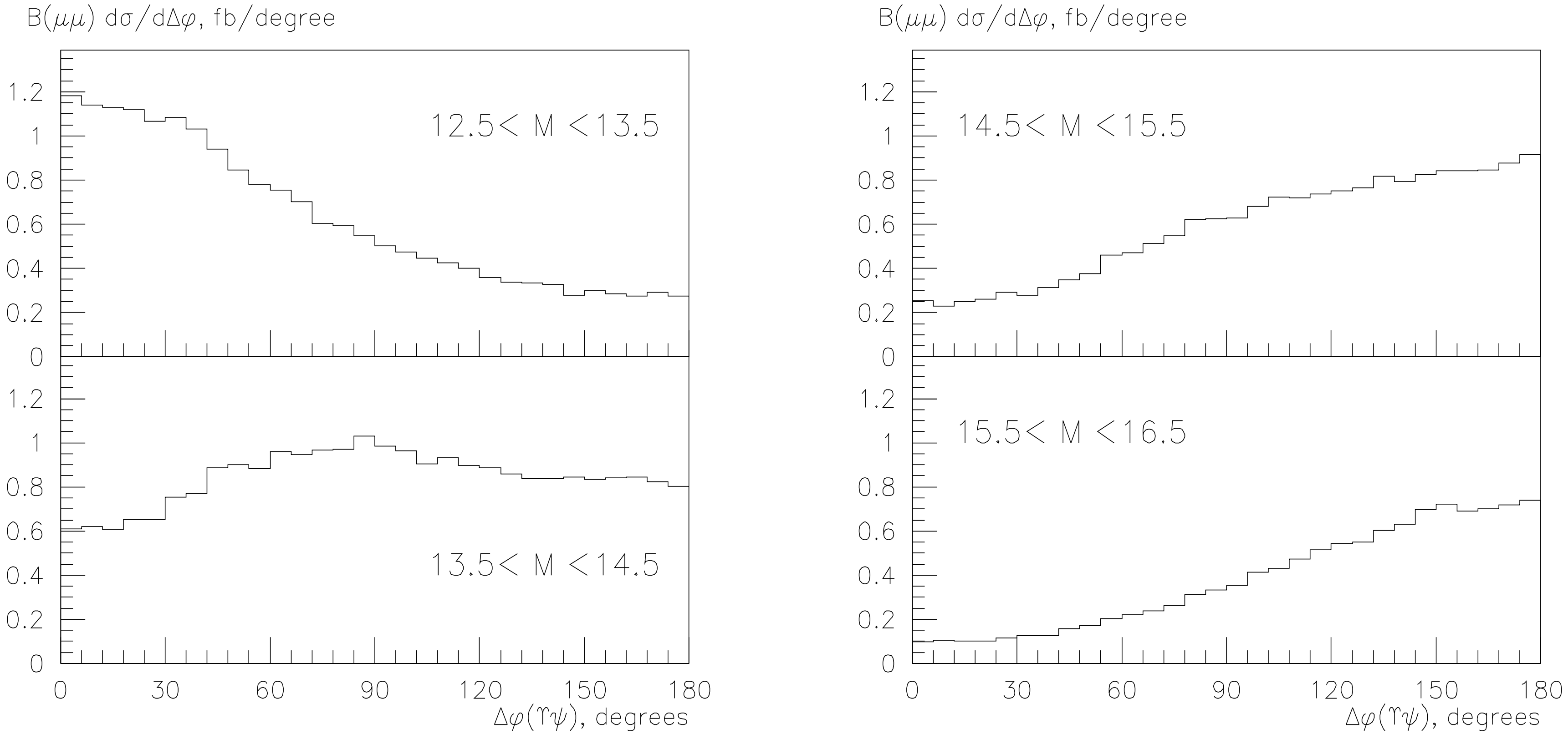
Transverse momentum distributions



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** = $\Upsilon + J/\psi$ **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

CONCLUSIONS

At the 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.

At the 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.

Thank you!

Reasons for pseudo-diffractive processes to be small

- **Two extra powers of** α_s

- **Larger average invariant mass** $M(\psi\psi)$ ⇒ **larger** x ⇒ **smaller PDFs**

- **Color: Direct** $g+g\to B_c+\bar{B}_c$

$$|tr\{T^aT^cT^cT^b\}|^2 = |[(N_c^2-1)/(4N_c)]\delta^{ab}|^2 = [\tfrac{2}{3}\delta^{ab}]^2 = 32/9$$

compared to Pseudodiffractive one- and two-gluon exchange

$$[\tfrac{1}{4}d^{ace}\tfrac{1}{4}d^{bde}]^2 = \frac{(N_c^2-1)(N_c^2-4)^2}{256\ N_c^2} = \frac{1}{256}\frac{200}{9} \simeq 0.1$$

- **Not compensated by** t**-channel gluon propagators:**
  Specific properties of the gluon exchange amplitudes
  to vanish when any of the gluons becomes soft.