Diffractive exclusive production of heavy quark pairs at high energy proton-proton collisions

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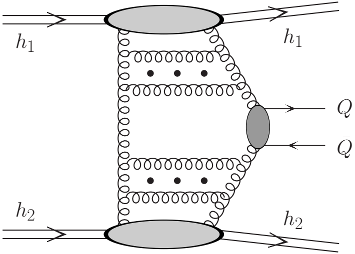
Introduction

Exclusive reaction: $pp \to pXp$
($X = H, Z, \eta', \eta_c, \eta_b, \chi_c, \chi_b$, jj, $J/\Psi, \Upsilon$, ...).

At high energy - one of many open channels (!)
$\Rightarrow$ rapidity gaps.

- Search for Higgs primary task for LHC.
- Diffractive production of the Higgs an alternative to inclusive production (Białas-Landshoff).
- QCD mechanism for the central exclusive production (Khoze-Martin-Ryskin).
- $H \to b\bar{b}$ versus $b\bar{b}$ continuum
- exclusive diffractive production of $Q\bar{Q}$ interesting by itself

The QCD mechanism for exclusive $Q\bar{Q}$ production



$c\bar{c}$: central exclusive open charm production

R. Maciula, R. Pasechnik and A. Szczurek, Phys. Lett. B **685**, 165 (2010) arXiv:0912.4345.

$b\bar{b}$: background to exclusive Higgs production

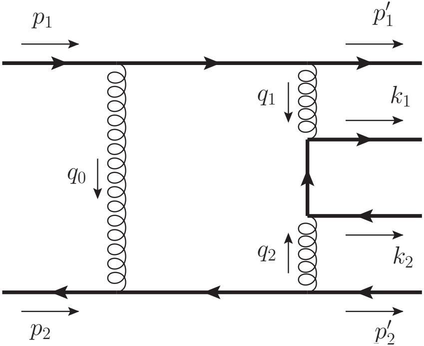
R. Maciula, R. Pasechnik and A. Szczurek, arXiv:1006.3007.

4-body process

with exact matrix element

with exact kinematics in the full phase space

Kinematics



Kinematics (continued)

Decomposition of gluon momenta into longitudinal and transverse parts in the high-energy limit:

$$q_1 = x_1 p_1 + q_{1,t}, \qquad q_2 = x_2 p_2 + q_{2,t}, \qquad 0 < x_{1,2} < 1,$$
$$q_0 = x_1' p_1 + x_2' p_2 + q_{0,t}, \quad x_1' \sim x_2' \ll x_{1,2}, \quad q^2_{0,1,2} \simeq q^2_{0/1/2,t}.$$

Making use of energy-momentum conservation laws

$$q_1 = p_1 - p_1' - q_0, \qquad q_2 = p_2 - p_2' + q_0, \qquad q_1 + q_2 = k_1 + k_2$$

we write

$$s\, x_1 x_2 = M^2_{q\bar{q}} + |\mathbf{P}_t|^2 \equiv M^2_{q\bar{q},\perp}, \qquad M^2_{q\bar{q}} = (k_1 + k_2)^2 \ ,$$

$M_{q\bar{q}}$ – invariant mass of the $q\bar{q}$ pair, and $\mathbf{P}_t$ its transverse 3-momentum.

The amplitude for $pp \to pp Q\bar{Q}$

$$
\mathcal{M}^{pp \to pp q\bar{q}}_{\lambda_q \lambda_{\bar{q}}}(p_1', p_2', k_1, k_2) = s \, \frac{\pi^2}{2} \frac{\delta_{c_1 c_2}}{N_c^2 - 1} \Im \int d^2 q_{0,t} \; V^{c_1 c_2}_{\lambda_q \lambda_{\bar{q}}}(q_1, q_2, k_1, k_2)
$$

$$
\frac{f^{\mathrm{off}}_{g,1}(x_1, x_1', q_{0,t}^2, q_{1,t}^2, t_1) f^{\mathrm{off}}_{g,2}(x_2, x_2', q_{0,t}^2, q_{2,t}^2, t_2)}{q_{0,t}^2 \, q_{1,t}^2 \, q_{2,t}^2} \; ,
$$

where λ_q, $\lambda_{\bar{q}}$ are helicities of heavy q and $\bar{q}$.

$$
x_1 = \frac{m_{3,t}}{\sqrt{s}} \exp(+y_3) + \frac{m_{4,t}}{\sqrt{s}} \exp(+y_4) \; ,
$$

$$
x_2 = \frac{m_{3,t}}{\sqrt{s}} \exp(-y_3) + \frac{m_{4,t}}{\sqrt{s}} \exp(-y_4) \; .
$$

$g^* g^* \to Q\bar{Q}$ vertex

$k_\perp$-factorization approach
reggeized gluons + UGDFs + gluon $q_\perp$ (virtualities) are important:
prominently successful in inclusive heavy quark production!
P. Hagler et al, Phys. Rev. D **62**, 071502 (2000);
Phys. Rev. Lett. **86**, 1446 (2001).

$$V^{c_1 c_2}_{\lambda_q \lambda_{\bar{q}}}(q_1, q_2, k_1, k_2) \equiv n^+_\mu n^-_\nu \, V^{c_1 c_2, \mu\nu}_{\lambda_q \lambda_{\bar{q}}}(q_1, q_2, k_1, k_2),$$

$$V^{c_1 c_2, \mu\nu}_{\lambda_q \lambda_{\bar{q}}}(q_1, q_2, k_1, k_2) = -g^2 \sum_{i,k} \langle 3i, \bar{3}k | 1 \rangle \times$$

$$\bar{u}_{\lambda_q}(k_1) (t^{c_1}_{ij} t^{c_2}_{jk} \, b^{\mu\nu}(q_1, q_2, k_1, k_2) - t^{c_2}_{kj} t^{c_1}_{ji} \, \bar{b}^{\mu\nu}(q_1, q_2, k_1, k_2)) v_{\lambda_{\bar{q}}}(k_2),$$

$$b^{\mu\nu}(q_1, q_2, k_1, k_2) = \gamma^\nu \frac{\hat{q}_1 - \hat{k}_1 - m}{(q_1 - k_1)^2 - m^2} \gamma^\mu \ ,$$

$$\bar{b}^{\mu\nu}(q_1, q_2, k_1, k_2) = \gamma^\mu \frac{\hat{q}_1 - \hat{k}_2 + m}{(q_1 - k_2)^2 - m^2} \gamma^\nu \ .$$

$g^* g^* \to Q\bar{Q}$ vertex

The tensorial part:

$$V^{\mu\nu}_{\lambda_q \lambda_{\bar{q}}}(q_1, q_2, k_1, k_2) \sim g_s^2 \, \bar{u}_{\lambda_q}(k_1) \left(\gamma^\nu \frac{\hat{q}_1 - \hat{k}_1 - m}{(q_1 - k_1)^2 - m^2} \gamma^\mu - \gamma^\mu \frac{\hat{q}_1 - \hat{k}_2 + m}{(q_1 - k_2)^2 - m^2} \gamma^\nu \right) v_{\lambda_{\bar{q}}}(k_2).$$

Matrix element calculated numerically for different helicities of Q and $\bar{Q}$

Unintegrated gluon distributions

Different models on the market:

scale independent: BFKL, Kharzeev-Levin

scale dependent: Kwieciński, KMR

In the present analysis we use Kimber-Martin-Ryskin UGDF:

$$f_g(x, k_t^2, \mu^2) = \frac{d}{d\log Q^2}\left[xg(x, Q^2)\, T_g(Q^2, \mu^2)\right]_{Q^2=k_t^2}$$

(Diakonov-Dokshitzer-Troyan)

Sudakov form factor

Probability of no emission (rapidity gaps)

$$T_g(q_t^2, \mu^2) = exp\left(-\int_{q_t^2}^{\mu^2} \frac{dk_t^2}{k_t^2}\frac{\alpha_s(k_t^2)}{2\pi}\int_0^{1-\Delta}[zP_{gg}(z) + \sum_f P_{qg}(z)]\, dz\right)$$

$\Delta = \frac{k_t}{k_t+\mu}$

For large μ strong suppression.

$\gamma^*\gamma^* \to Q\bar{Q}$ subprocess

Matrix element at high-energies and small t_1 and t_2:

$$\mathcal{M} \approx eF_1(t_1)\frac{(p_1+p_1')^\mu}{t_1} V_{\mu\nu}^{\gamma^*\gamma^*\to Q\bar{Q}}(q_1,q_2)\frac{(p_2+p_2')^\nu}{t_2} eF_1(t_2)$$

where F_1 is Dirac proton EM ff

$$V_{\lambda_Q\lambda_{\bar{Q}},\mu\nu}^{\gamma^*\gamma^*\to Q\bar{Q}} = (ee_f)^2\, \bar{u}_{\lambda_Q}(k_1)\Big(\gamma^\nu \frac{\hat{q}_1-\hat{k}_1-m_Q}{(q_1-k_1)^2-m_Q^2}\gamma^\mu - \gamma^\mu \frac{\hat{q}_1-\hat{k}_2+m_Q}{(q_1-k_2)^2-m_Q^2}\gamma^\nu\, v_{\lambda_{\bar{Q}}}(k_2)\Big)\,.$$

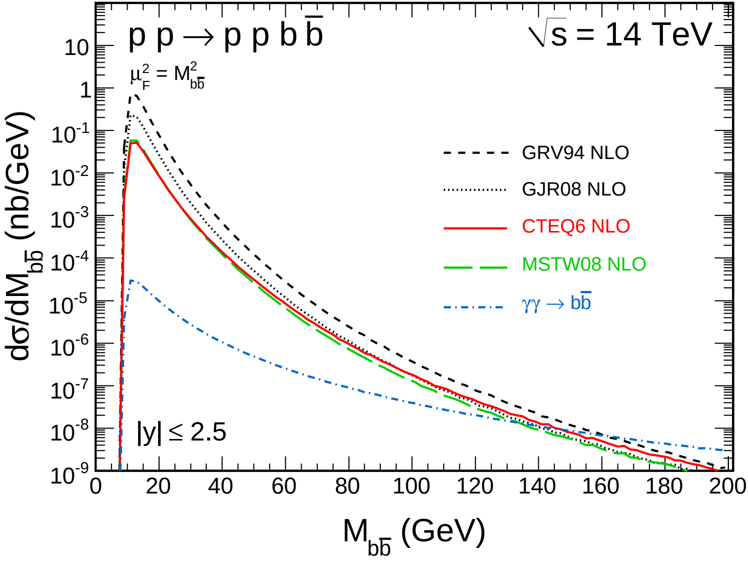
The $pp \to ppQ\bar{Q}$ cross section

Exact four-body kinematics

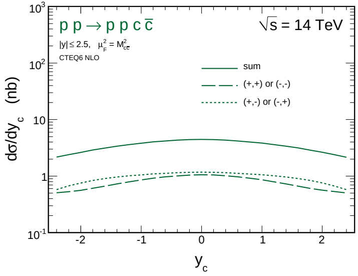
$$d\sigma = \frac{1}{2s} |\mathcal{M}_{2\to 4}|^2 (2\pi)^4 \delta^4(p_a + p_b - p_1 - p_2 - p_3 - p_4) \times \frac{d^3p_1}{(2\pi)^3 2E_1} \frac{d^3p_2}{(2\pi)^3 2E_2} \frac{d^3p_3}{(2\pi)^3 2E_3} \frac{d^3p_4}{(2\pi)^3 2E_4}$$

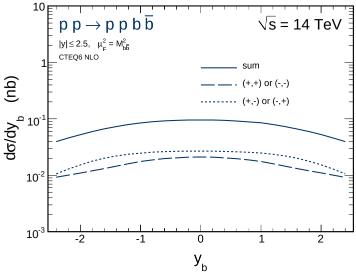
with exact (including quark mass and gluon virtualities!) $2 \to 4$ amplitude.

The $pp \to ppQ\bar{Q}$ cross sections



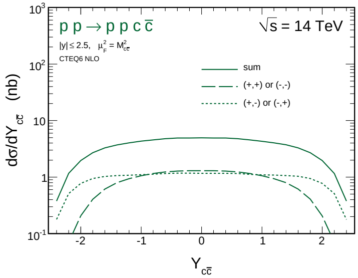
The $pp \to ppQ\bar{Q}$ cross sections

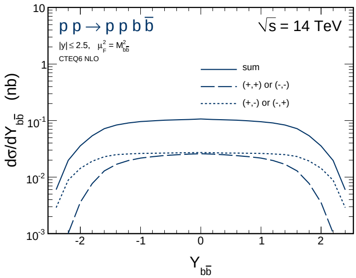




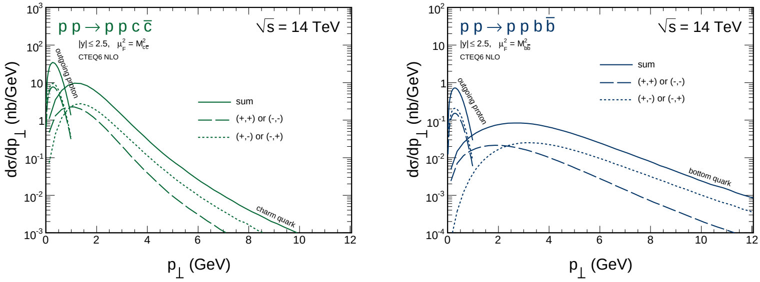
integrated over total invariant $Q\bar{Q}$ mass range
$2m_Q < M_{Q\bar{Q}} < 200$ GeV!

The $pp \to pp Q\bar{Q}$ cross sections

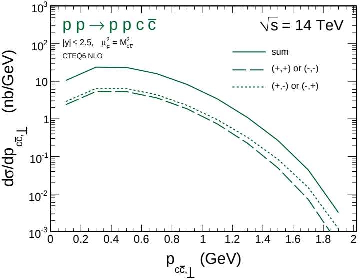


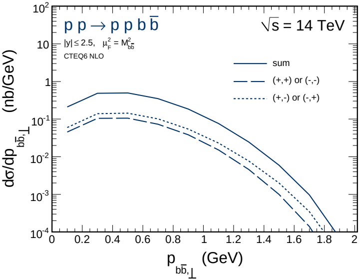


The $pp \to pp Q\bar{Q}$ cross sections



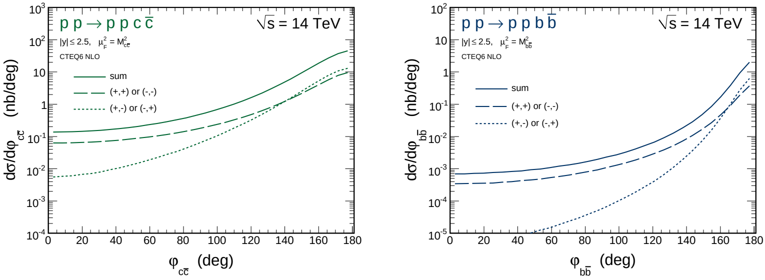
The $pp \to ppQ\bar{Q}$ cross sections



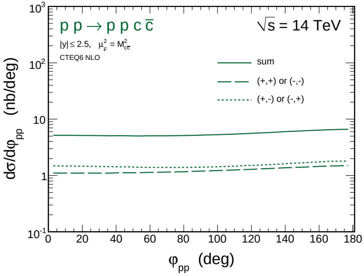


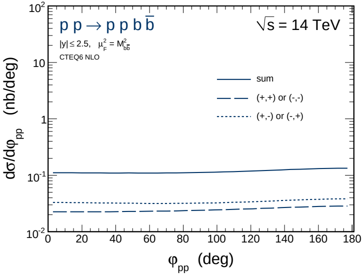
$\vec{p}_{t,sum} = \vec{p}_{3,t} + \vec{p}_{4,t}$

The $pp \to pp Q\bar{Q}$ cross sections

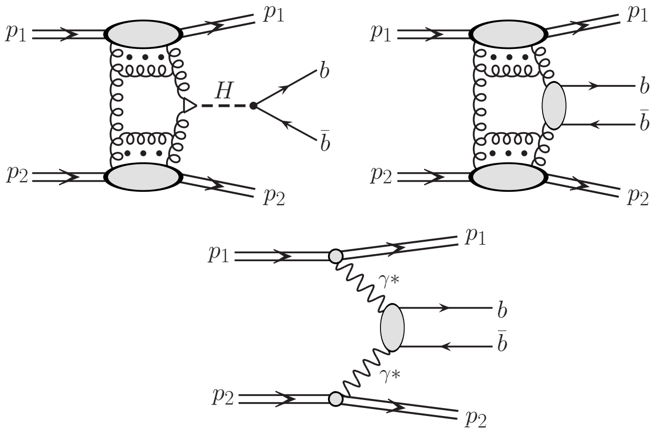


The $pp \to pp Q\bar{Q}$ cross sections

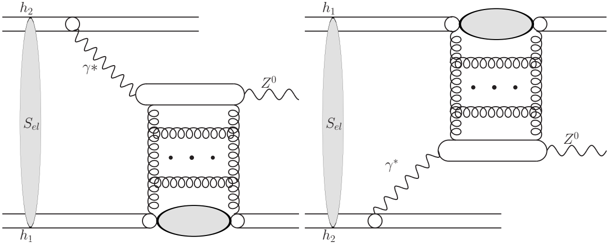




Irreducible $b\bar{b}$ background for Higgs CEP



Exclusive Z^0 production



Cisek, Schäfer, Szczurek,
Phys. Rev. **D80** (2009) 074013.

Exclusive Higgs production revisited

Subprocess amplitude for $g^*g^* \to H$

$$T^{ab}_{\mu\nu}(q_1,q_2) = i\delta^{ab}\frac{\alpha_s}{2\pi}\frac{1}{v}\Big\{\left[(q_1q_2)g_{\mu\nu} - q_{1\mu}q_{2\nu}\right]G_1(q_1,q_2) + \left[q_{1\mu}q_{2\nu} - \frac{q_1^2}{(q_1q_2)}q_{1\mu}q_{1\nu} - \frac{q_2^2}{(q_1q_2)}q_{2\mu}q_{2\nu}\right]G_2(q_1,q_2)\Big\}$$

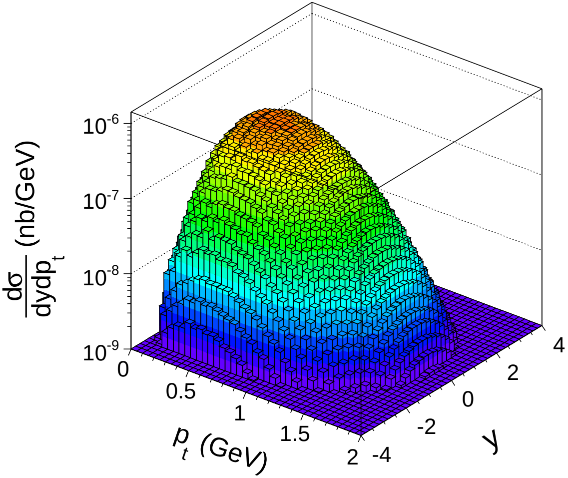
$v = (G_F\sqrt{2})^{-1/2}$ (Pasechnik-Teryaev-Szczurek)
Eur. Phys. J. **C47** (2006) 429.

$$\chi = \frac{m_H^2}{4m_f^2} > 0, \qquad \chi_1 = \frac{q_1^2}{4m_f^2} < 0, \quad \chi_2 = \frac{q_2^2}{4m_f^2} < 0, \tag{1}$$

$$\begin{aligned} G_1(\chi,\chi_1,\chi_2) &= \frac{2}{3}\left[1 + \frac{7}{30}\chi + \frac{2}{21}\chi^2 + \frac{11}{30}(\chi_1+\chi_2) + ...\right] \\ G_2(\chi,\chi_1,\chi_2) &= -\frac{1}{45}(\chi - \chi_1 - \chi_2) - \frac{4}{315}\chi^2 + \ldots . \end{aligned}$$

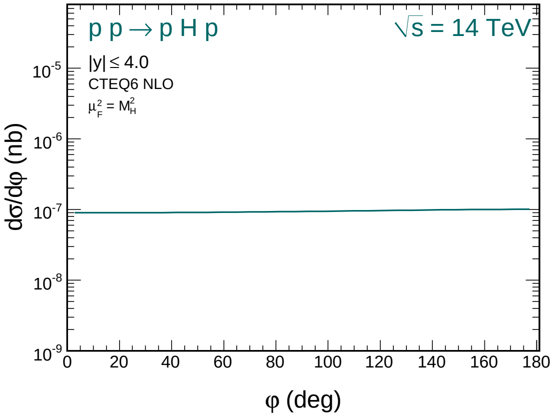
virtualities contributes only 6 % in the total cross section! small!

Exclusive Higgs production



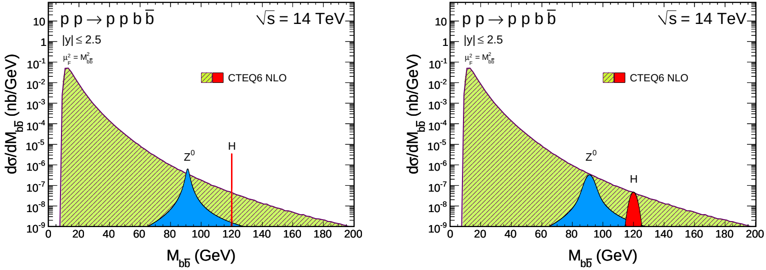
This distribution is used to produce distributions of b and $\bar{b}$

Exclusive Higgs production



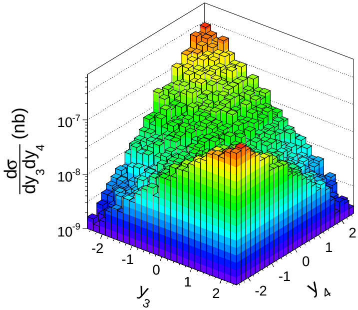
CTEQ6

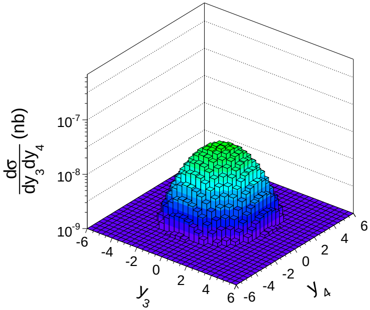
Higgs CEP backgrounds



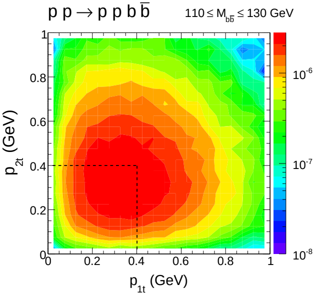
The same gap survival factor is taken: $\langle S^2 \rangle = 0.03$

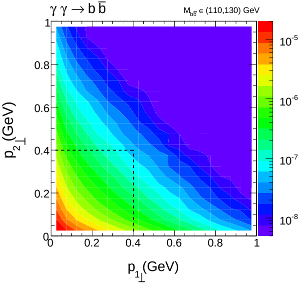
Where the background comes from?

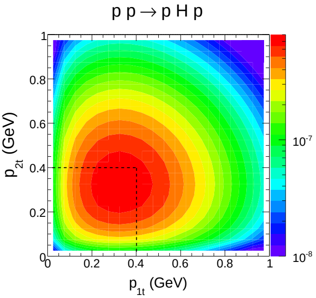




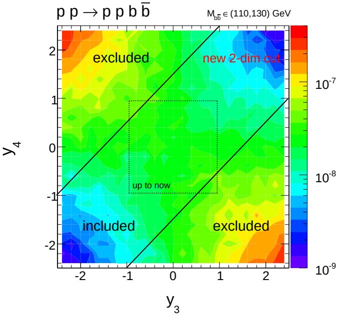
Where the background comes from?

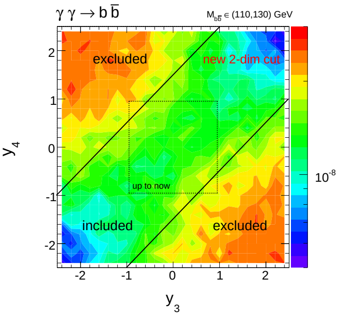


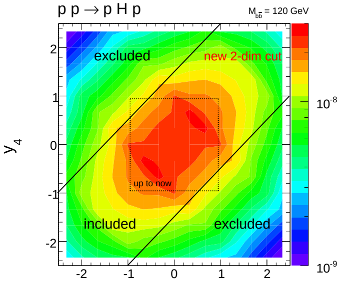




Optimal cuts







Summary

- Exclusive double diffractive $b\bar{b}$ was calculated using UGDFs obtained with different integrated gluon distributions.
- Exact matrix element was calculated numerically, including explicitly quark masses.
- Sizeable cross sections have been obtained which can be measured.
- The continuum constitutes irreducible background to exclusive Higgs production.
- If the experimental resolution is included the signal to background ratio is about 1.
- This can be further improved if cuts on rapidities of b quarks/antiquarks and/or on transverse momenta of protons are imposed.
- Further studies are necessary.