Central exclusive production of Higgs boson and $b\bar{b}$ dijets

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School on diffractive and electromagnetic processes

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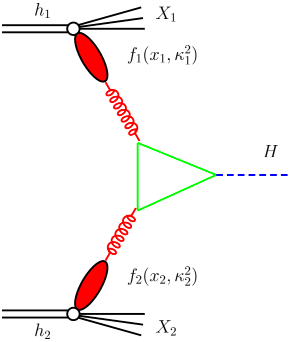
Introduction

- Standard search for Higgs boson in inclusive processes $pp \to HX$. X means a complicated final state with many mesons.
- The dominant mechanism is gluon-gluon fusion.
- Several decay channels of interest: $\gamma\gamma$, $\tau^+\tau^-$, $b\bar{b}$, jet-jet, (W^+W^-, Z^0Z^0, $t\bar{t}$)



Analysis in each of the channel complicated

Introduction

Exclusive reaction: $pp \to pXp$

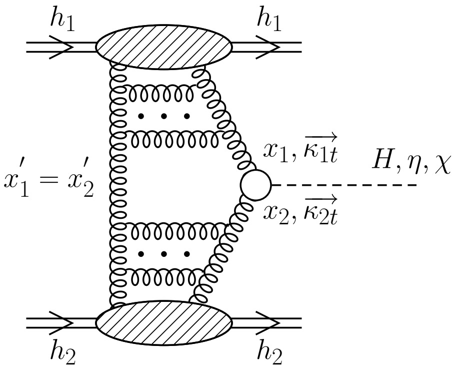
($X = H, Z, \eta', \eta_c, \eta_b, \chi_c, \chi_b$, jj, $c\bar{c}$, $b\bar{b}$).

At high energy - one of many open channels (!)

$\Rightarrow$ rapidity gaps.

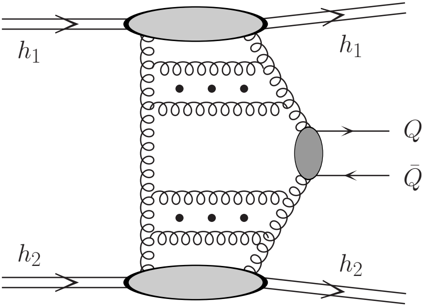
- Search for Higgs was primary task for LHC.
  Diffractive production of the Higgs boson would be a nice supplement to inclusive production.
  proposed by Schäfer-Nachtmann-Schopf and Białas-Landshoff (simplified QCD approach)
  A new QCD look with UGDFs (Khoze-Martin-Ryskin).
- $H \to b\bar{b}$ versus $b\bar{b}$ continuum
- exclusive diffractive production of $Q\bar{Q}$ interesting by itself

The QCD mechanism for exclusive Higgs production



3-body process
KMR: on-shell matrix element
Pasechnik-Szczurek-Teryaev: off-shell matrix element

The QCD mechanism for exclusive $q\bar{q}$



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

4-body process

with exact matrix element (without $J_z = 0$ selection rule)

with exact kinematics in the full phase space

Kinematics, continued

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

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

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 $pp \to ppQ\bar{Q}$

$$\mathcal{M}^{pp\to ppq\bar{q}}_{\lambda_q\lambda_{\bar{q}}}(p_1',p_2',k_1,k_2) = s\,\frac{\pi^2}{2}\,\frac{\delta_{c_1c_2}}{N_c^2-1}\,\Im\int d^2q_{0,t}\; V^{c_1c_2}_{\lambda_q\lambda_{\bar{q}}}(q_1,q_2,k_1,k_2)$$
$$\frac{f^{\rm off}_{g,1}(x_1,x_1',q_{0,t}^2,q_{1,t}^2,t_1)\,f^{\rm off}_{g,2}(x_2,x_2',q_{0,t}^2,q_{2,t}^2,t_2)}{q_{0,t}^2\,q_{1,t}^2\,q_{2,t}^2}\,,$$

where λ_q, $\lambda_{\bar{q}}$ are helicities of heavy q and $\bar{q}$.
$f^{off}_{g,1}(......)$ and $f^{off}_{g,2}(......)$ - off-diagonal unintegrated gluon distributions

$$x_1 = \frac{m_{3,t}}{\sqrt{s}}\exp(+y_3) + \frac{m_{4,t}}{\sqrt{s}}\exp(+y_4)\,,$$
$$x_2 = \frac{m_{3,t}}{\sqrt{s}}\exp(-y_3) + \frac{m_{4,t}}{\sqrt{s}}\exp(-y_4)\,.$$

$gg \longrightarrow Q\bar{Q}$ vertex

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

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

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

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

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

$gg \longrightarrow Q\bar{Q}$ vertex

The tensorial part:

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

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

$gg \longrightarrow Q\bar{Q}$ vertex

The exact form of the vertex depends on the frame of reference (proton-proton c.m.s., $Q\bar{Q}$ c.m.s.).

It can be shown:
$q_1^\nu V_{\lambda_q \lambda_{\bar{q}},\mu\nu} = 0$ for each λ_q, $\lambda_{\bar{q}}$
$q_2^\mu V_{\lambda_q \lambda_{\bar{q}},\mu\nu} = 0$ for each λ_q, $\lambda_{\bar{q}}$
gauge invariance

Define:
$V_{\lambda_q \lambda_{\bar{q}}} = n_\mu^+ n_\nu^- V_{\lambda_q \lambda_{\bar{q}},\mu\nu}$
Then:
$V_{\lambda_q \lambda_{\bar{q}}} \rightarrow 0$ when $q_{1t} \rightarrow 0$ or $q_{2t} \rightarrow 0$

$gg \longrightarrow Q\bar{Q}$ vertex

Let us take $Q\bar{Q}$ c.m.s. frame
In general the vertex is a function of many variables:
$V^{c_1 c_2}_{\lambda_q \lambda_{\bar{q}}}(q_1, q_2, k_1, k_2; m_Q)$

Two matrix elements are independent: $V_{+-}(...)$ and $V_{++}(...)$
formulas will be shown explicitly in a paper in preparation

Let us go to massless quarks:
$V_{++} \to 0$ when $m_q \to 0$ ($J_z = 0$ only)
$\frac{|V_{++}|}{|V_{+-}|} \ll 1$ for large $M_{q\bar{q}}$

Off-diagonal unintegrated gluon distributions

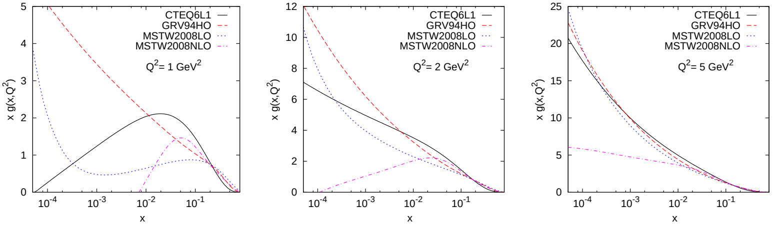
KMR method ($x_1' \ll x_1$ and $x_2' \ll x_2$)

$$
\begin{aligned}
f_1^{\rm KMR}(x_1, Q_{1,t}^2, \mu^2, t_1) &= R_g \frac{d[g(x_1, k_t^2) S_{1/2}(k_t^2, \mu^2)]}{d \log k_t^2}\Big|_{k_t^2 = Q_{1t}^2} F(t_1) \\
&\approx R_g \frac{d g(x_1, k_t^2)}{d \log k_t^2}\Big|_{k_t^2 = Q_{1,t}^2} S_{1/2}(Q_{1,t}^2, \mu^2)\, F(t_1) \,,
\end{aligned}
$$

$$
\begin{aligned}
f_2^{\rm KMR}(x_2, Q_{2,t}^2, \mu^2, t_2) &= R_g \frac{d[g(x_2, k_t^2) S_{1/2}(k_t^2, \mu^2)]}{d \log k_t^2}\Big|_{k_t^2 = Q_{2t}^2} F(t_2) \\
&\approx R_g \frac{d g(x_2, k_t^2)}{d \log k_t^2}\Big|_{k_t^2 = Q_{2,t}^2} S_{1/2}(Q_{2,t}^2, \mu^2)\, F(t_2) \,,
\end{aligned}
$$

Collinear gluon distributions

Scales of collinear GDFs: $\mu_1^2 = q_{1t}^2$ or $\mu_2^2 = q_{2t}^2$
(scales $=$ transverse momenta squared of active gluons)
$xg(x,\mu^2)$ for characteristic $\mu^2 = q_t^2$:



Large differences at the small scales

Sudakov-like form factor

It was proposed (Martin-Ryskin:)

$$S_{1/2}(q_t^2, \mu^2) = \sqrt{T_g(q_t^2, \mu^2)} \, .$$

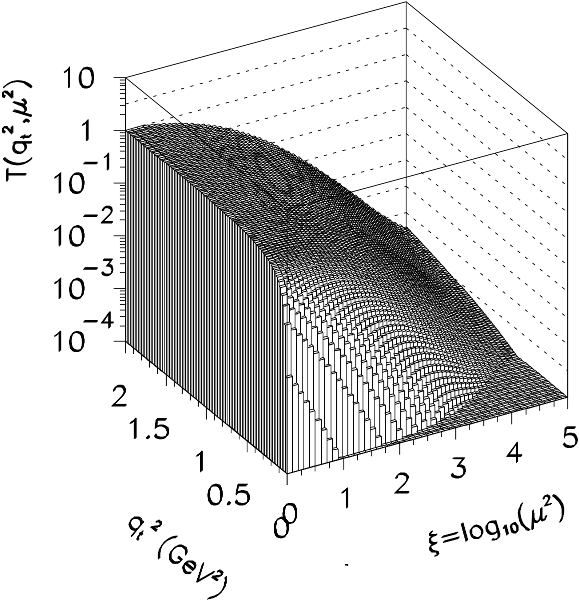
$$T_g(q_\perp^2, \mu^2) = \exp\left(-\int_{q_\perp^2}^{\mu^2} \frac{d\mathbf{k}_\perp^2}{\mathbf{k}_\perp^2} \frac{\alpha_s(k_\perp^2)}{2\pi} \int_0^{1-\Delta} \left[zP_{gg}(z) + \sum_q P_{qg}(z) \right] dz \right), \tag{1}$$

where the upper limit is taken to be

$$\Delta = \frac{k_\perp}{k_\perp + aM_{q\bar{q}}} \, . \tag{2}$$

KMR: a = 0.62, Coughlin-Forshaw: a=1

Sudakov form factor



The $pp \longrightarrow pp Q\bar{Q}$ 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) $2 \longrightarrow 4$ amplitude.

Exclusive Higgs production

R. Maciuła, R. Pasechnik and A. Szczurek,
arXiv:1006.3007 [hep-ph], in print in PRD
Subprocess amplitude for $g^* g^* \to H$

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

$$+ \quad \left[q_{1,\mu}q_{2,\nu} - \frac{q_1^2}{(q_1q_2)}q_{2,\mu}q_{2,\nu} - \frac{q_2^2}{(q_1q_2)}q_{1,\mu}q_{1,\nu} + \frac{q_1^2q_2^2}{(q_1q_2)^2}q_{1,\nu}q_{2,\mu}\right] G_2\Bigg),$$

$v = (G_F\sqrt{2})^{-1/2}$ is the electroweak parameter. Let us introduce:

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

Since $m_H^2 \gg |q_1^2|, |q_2^2|$

$$G_1(\chi,\chi_1,\chi_2) = \frac{2}{3}\left[1 + \frac{7}{30}\chi + \frac{2}{21}\chi^2 + \frac{11}{30}(\chi_1+\chi_2) + \ldots\right],$$

$$G_2(\chi,\chi_1,\chi_2) = -\frac{1}{45}(\chi - \chi_1 - \chi_2) - \frac{4}{315}\chi^2 + \ldots .$$

Exclusive Higgs production

$$\mathcal{M}^{off-shell}_{pp\to ppH} = s\pi^2 \frac{1}{2} i \frac{\delta_{ab}}{N_c^2-1} \int d^2 q_{0,t} V^{ab}_{g^* g^* \to H}(q^2_{1\perp}\, q^2_{2\perp}, P^2_\perp) \frac{f^{\rm off}_{g,1}(x_1, x', q^2_{0\perp}, q^2_{1\perp}, t_1) f^{\rm off}_{g,2}(x_2, x', q^2_{0\perp}, q^2_{2\perp}, t_2)}{q^2_{0,t} q^2_{1,t} q^2_{2,t}},$$

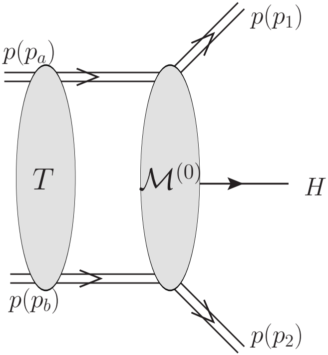
$$V^{ab}_{g^* g^* \to H}(q^2_{1\perp}\, q^2_{2\perp}, P^2_\perp) = n^+_\mu n^-_\nu\, T^{ab}_{\mu\nu}(q_1, q_2) = \frac{4}{s} \frac{q^\mu_{1\perp}}{x_1} \frac{q^\nu_{2\perp}}{x_2} T^{ab}_{\mu\nu}(q_1, q_2),$$

$$q_1^\mu T^{ab}_{\mu\nu} = q_2^\nu T^{ab}_{\mu\nu} = 0,$$

The cross section

$$d\sigma_{pp\to pHp} = \frac{1}{2s} |\mathcal{M}|^2 \cdot d^3 PS, \quad d^3 PS = \frac{1}{2^8 \pi^4 s} dt_1 dt_2 dy_H d\Phi\,.$$

Absorption effects



Absorption effects, continued

$$S^2_{\rm eik}(\mathbf{p}_{1,t},\mathbf{p}_{2,t}) = \frac{|\mathcal{M}^{bare}(\mathbf{p}_{1,t},\mathbf{p}_{2,t}) + \mathcal{M}^{res}(\mathbf{p}_{1,t},\mathbf{p}_{2,t})|^2}{|\mathcal{M}^{bare}(\mathbf{p}_{1,t},\mathbf{p}_{2,t})|^2} \qquad (3)$$

where $\mathbf{p}_{1/2,t}$ are the transverse momenta of the final protons
The elastic rescattering amplitude at high energy:

$$\mathcal{M}_{res} = i\int \frac{d^2k_t}{8\pi^2}\frac{1}{s}\beta(t_1)\beta(t_2)\mathcal{M}_{bare}M_0 e^{B(s)k_t^2/2}\;, \qquad (4)$$

where $t_1 \approx -(\vec{k}_t - \vec{p}_{1t})^2$ and $t_2 \approx -(\vec{k}_t - \vec{p}_{2t})^2$
If $\beta(t) = e^{bt/2}$ the amplitude can be written as:

$$\mathcal{M}^{res}(\mathbf{p}_{1,t},\mathbf{p}_{2,t}) \simeq \frac{iM_0(s)}{4\pi s(B+2b)}\exp\left(\frac{b^2|\mathbf{p}_{1,t}-\mathbf{p}_{2,t}|^2}{2(B+2b)}\right)\cdot\mathcal{M}^{bare}(\mathbf{p}_{1,t},\mathbf{p}_{2,t})$$

where $\mathrm{Im}M_0(s) = s\sigma^{\rm tot}_{pp}(s)$
(the real part is small in at high energies)
B is the t-slope of the elastic pp differential cross section,
$b \simeq 4\; GeV^{-2}$ is the t-slope of the proton form factor.

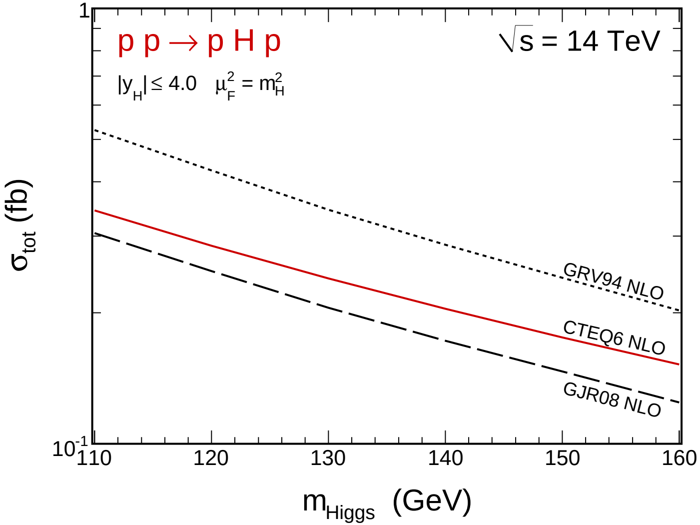
Absorption effects, continued

Absorption effects:

- Elastic rescattering (single channel)
- Inelastic rescattering (multi channel in general)
  In practice two-channel approaches.
- Enhanced diagram corrections (not clear how important)

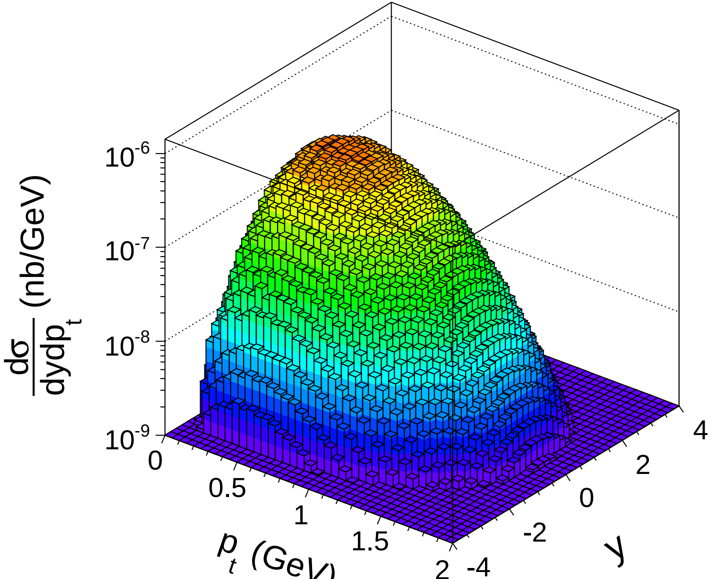
Very often the cross sections and even distributions are multiplied by a soft gap survival probability
Here we follow this approach ($S_g = S_g(s)$)
This is not yet consistent!

Exclusive Higgs production

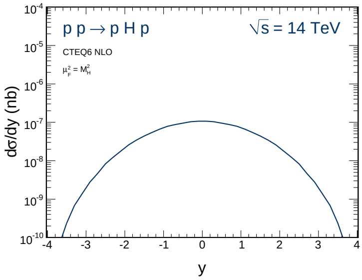


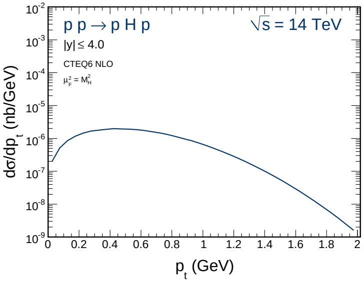
very small cross sections !

Exclusive Higgs production

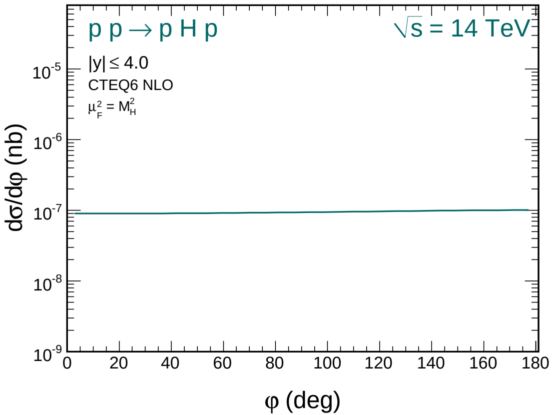


Exclusive Higgs production

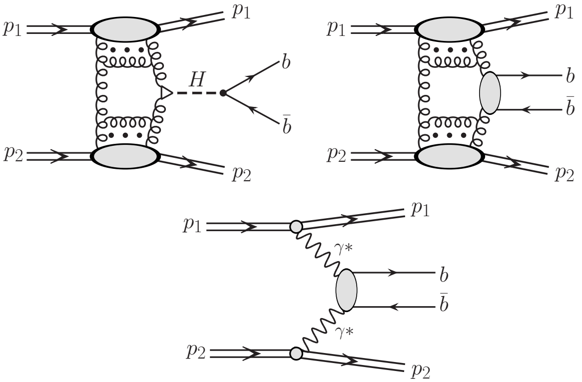




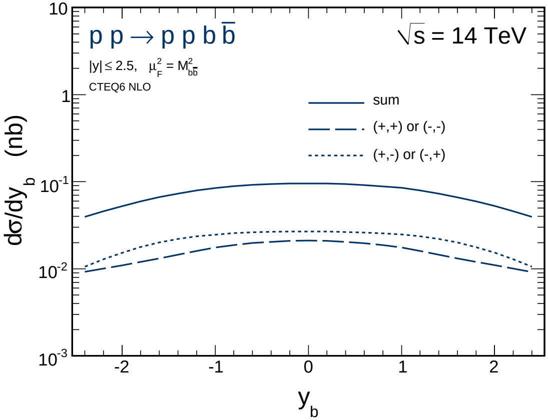
Exclusive Higgs production



Exclusive $b\bar{b}$ production

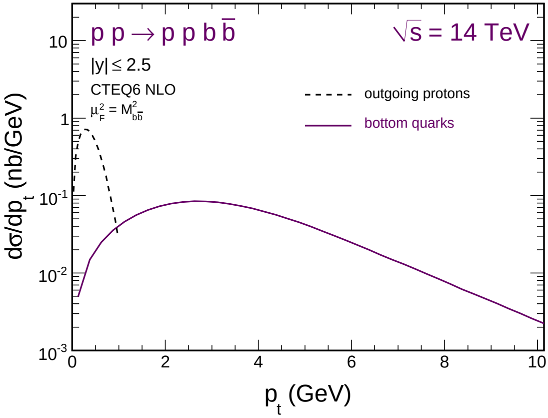


Exclusive $b\bar{b}$ production



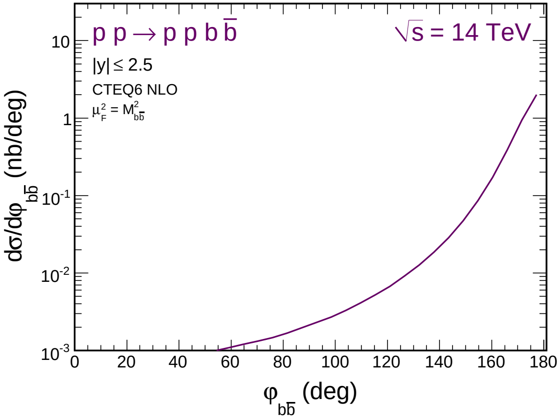
CTEQ6

Exclusive $b\bar{b}$ production



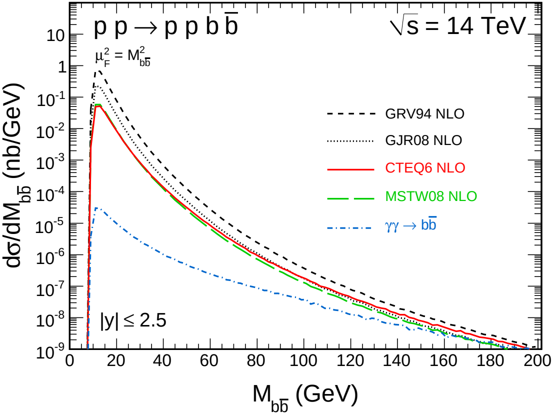
CTEQ6

Exclusive $b\bar{b}$ production



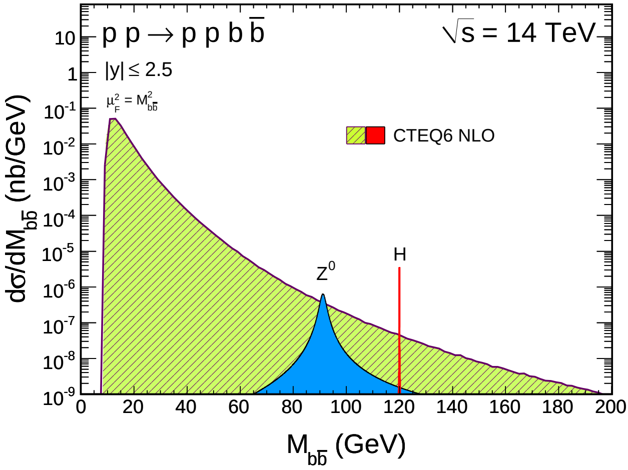
CTEQ6

Exclusive $b\bar{b}$ production

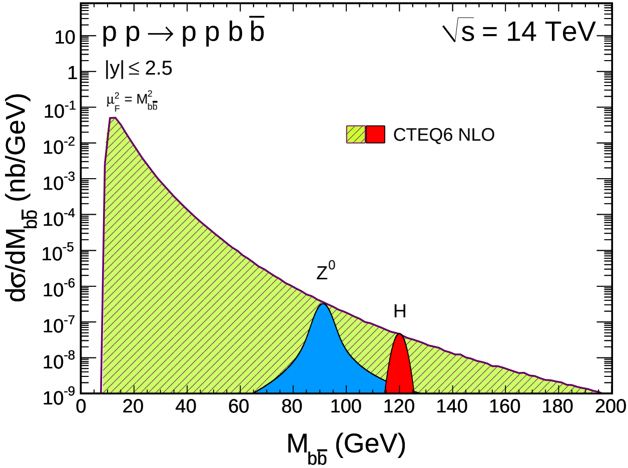


different UPDFs

M_{bb} spectrum, theory

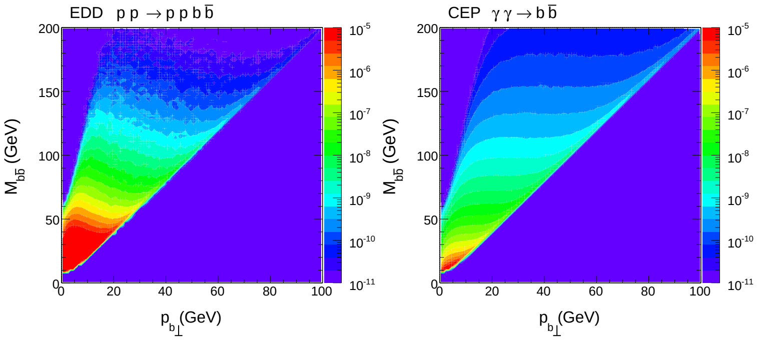


M_{bb} spectrum, experiment



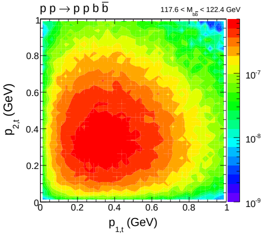
- Looks rather difficult
- How to improve the signal-to-background ratio ?

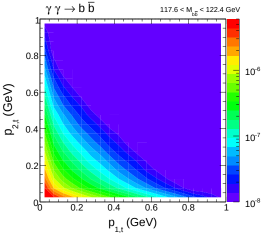
How to get $M_{b\bar{b}} = M_H$?

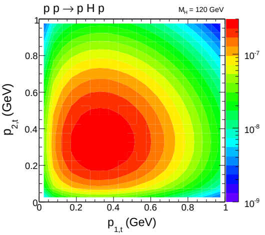


large transverse momenta or large rapidity difference

(p_{1t}, p_{2t}) distributions for different mechanisms





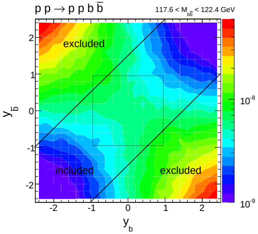


diffractive background

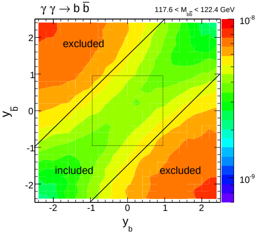
QED background

diffractive Higgs

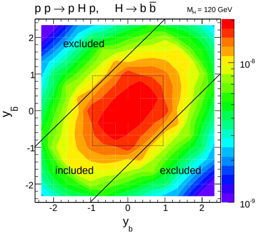
$(y_b, y_{\bar{b}})$ distributions for different mechanisms



diffractive background

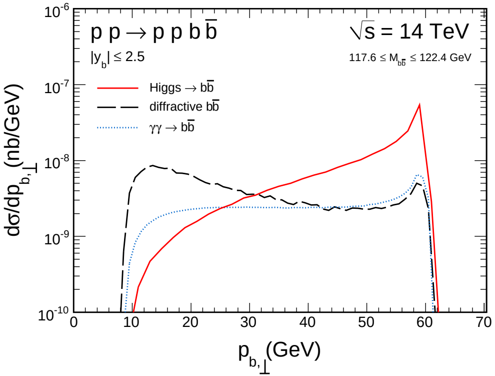


QED background

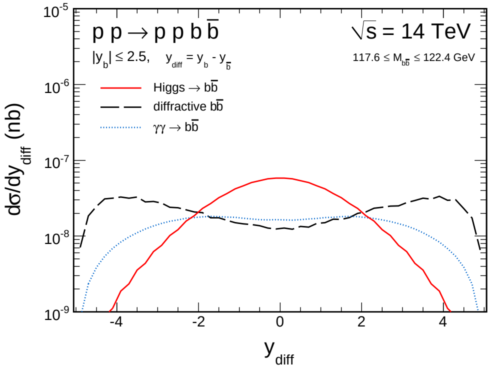


diffractive Higgs

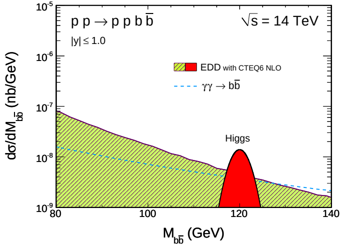
Jet transverse momenta

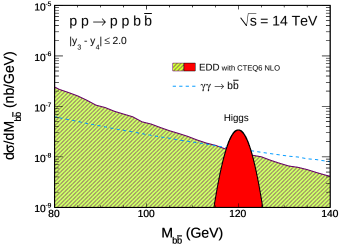


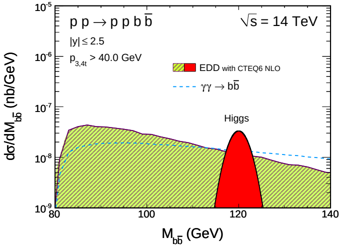
Rapidity difference

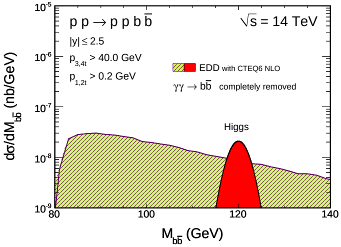


M_{bb} spectrum, cuts

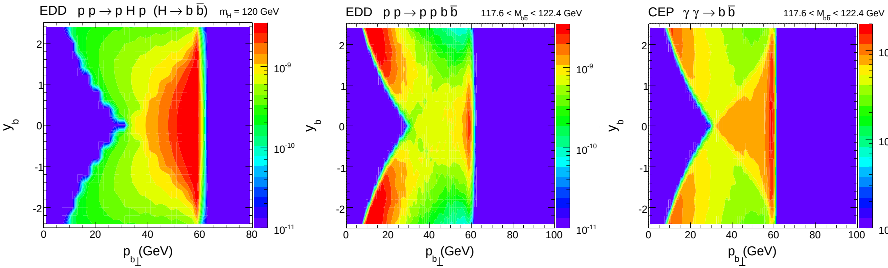






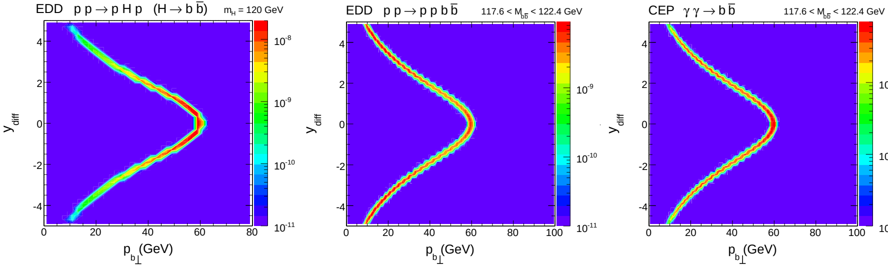


How to cut?



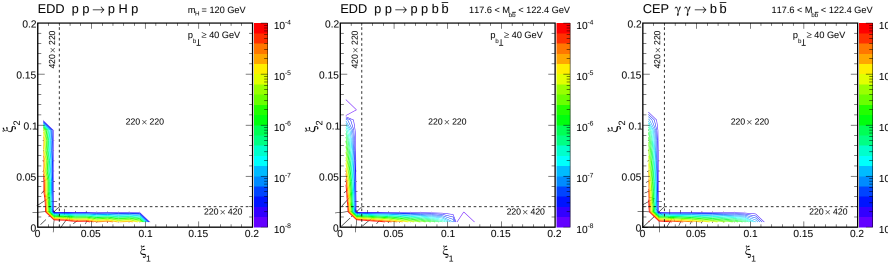
both cut in rapidity and transverse momentum is possible

Correlation of variables



For narrow bin in $M_{b\bar{b}}$ $y_{diff} = y_b - y_{\bar{b}}$ and jet transverse momentum are strongly correlated.

Longitudinal momentum fraction loss

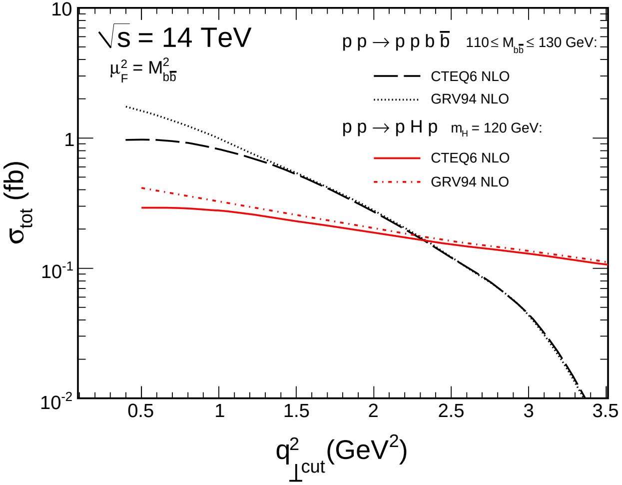


$\xi_1 = (p_{1f} - p_{1i})/p_{1i}$

$\xi_2 = (p_{2f} - p_{2i})/p_{2i}$

RP220, FP420 detectors were planned

Lower cut on gluon transverse momenta



Higgs - fast dependence, $b\bar{b}$ background slow dependence

Summary of the EDD Higgs and $b\bar{b}$ production

- Exclusive double diffractive $b\bar{b}$ was calculated using UGDFs obtained with different integrated gluon distributions.
- Exact matrix elements for the Higgs and continuum have been calculated (analytically and numerically), including explicit quark masses for $b\bar{b}$
- $\sigma < 1$ fb (Cudell-Dechambre-Hernandez)
- Sizeable cross sections for $c\bar{c}$ and $b\bar{b}$ have been obtained, i.e. the processes 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 and transverse momenta of b quarks/antiquarks and/or on transverse momenta of protons are imposed.