Exclusive production of Higgs boson, $b\bar{b}$ and gluonic dijets

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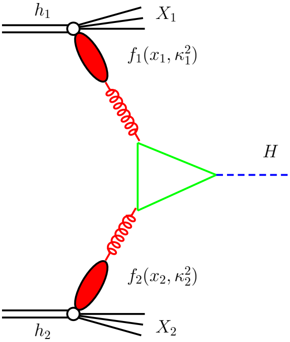
Introduction

- 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

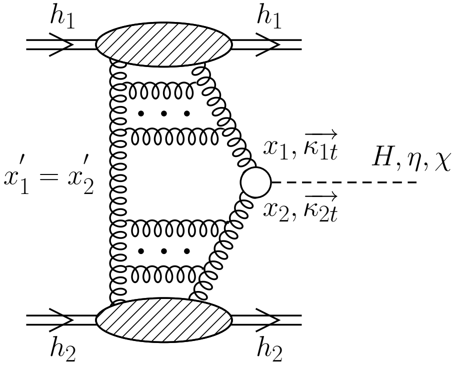
Introduction

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 primary task for LHC.
  Diffractive production of the Higgs boson an alternative 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

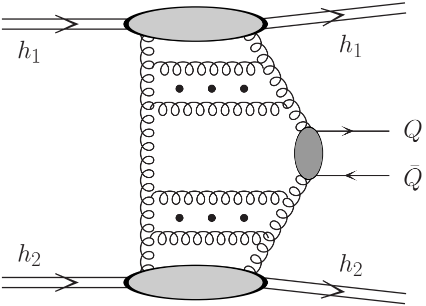


3-body process

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

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

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

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 are shown explicitly in a paper published in Phys. Rev. D

Let us go to massless quarks:
$V_{++} \rightarrow 0$ when $m_q \rightarrow 0$ ($J_z = 0$ 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 $x_2' \ll x_2$)

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

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

based on the Shuvaev method for collinear off-diagonal PDFs.

Sudakov-like form factor

It was proposed (Martin-Ryskin:)

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

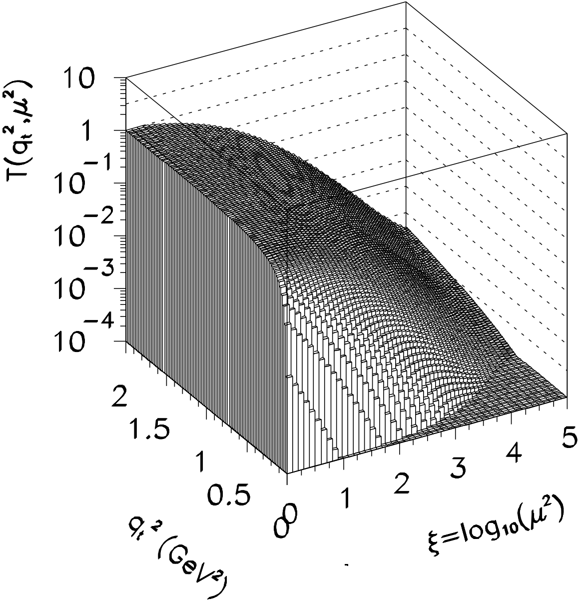
$$T_g(q_\perp^2, \mu^2) = \exp\left(-\int_{q_\perp^2}^{\mu^2} \frac{d\mathbf{k}_\perp^2}{\mathbf{k}_\perp^2} \frac{\alpha_s(k_\perp^2)}{2\pi} \int_0^{1-\Delta} \left[zP_{gg}(z) + \sum_q P_{qg}(z) \right] dz \right), \quad (1)$$

where the upper limit is taken to be

$$\Delta = \frac{k_\perp}{k_\perp + aM_{q\bar{q}}}\ . \quad (2)$$

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

Sudakov form factor



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

Exclusive Higgs production

R. Maciuła, R. Pasechnik and A. Szczurek,
arXiv:1006.3007 [hep-ph], Phys. Rev. **D82** (2010) 114011
Subprocess amplitude for $g^* g^* \to H$

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

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

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

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

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

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

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

Exclusive Higgs production

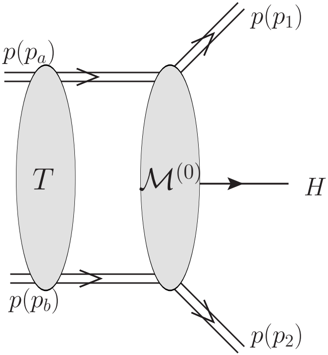
$$\mathcal{M}^{off-shell}_{pp\to ppH} = s\pi^2 \frac{1}{2} i \frac{\delta_{ab}}{N_c^2 - 1} \int d^2 q_{0,t} V^{ab}_{g^* g^* \to H}(q^2_{1\perp}\, q^2_{2\perp}, P^2_\perp)$$
$$\frac{f^{\rm off}_{g,1}(x_1, x', q^2_{0\perp}, q^2_{1\perp}, t_1) f^{\rm off}_{g,2}(x_2, x', q^2_{0\perp}, q^2_{2\perp}, t_2)}{q^2_{0,t}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

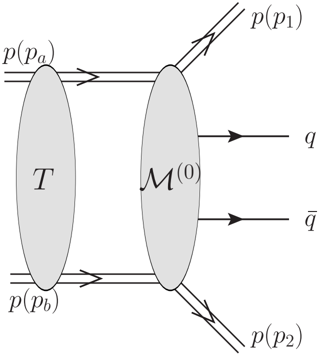
$$V^{ab}_{g^* g^* \to H}(q^2_{1\perp}\, q^2_{2\perp}, P^2_\perp) = n^+_\mu n^-_\nu\, T^{ab}_{\mu\nu}(q_1, q_2) = \frac{4}{s} \frac{q^\mu_{1\perp}}{x_1} \frac{q^\nu_{2\perp}}{x_2} T^{ab}_{\mu\nu}(q_1, q_2),$$
$$q^\mu_1 T^{ab}_{\mu\nu} = q^\nu_2 T^{ab}_{\mu\nu} = 0,$$

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





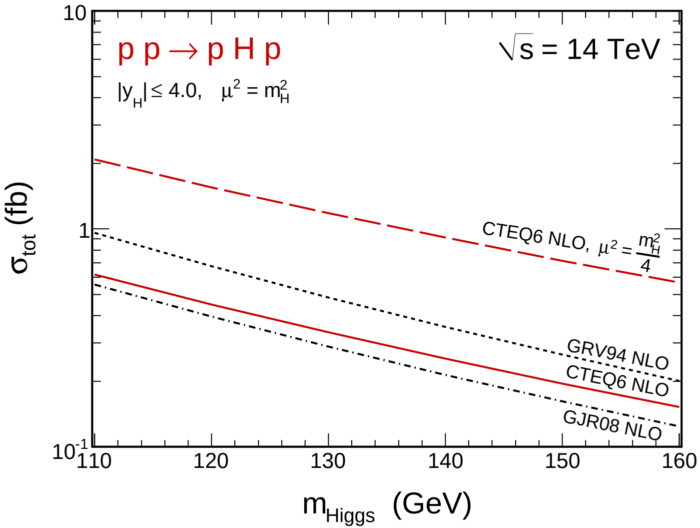
Absorption effects, continued

Absorption effects:

- Elastic rescattering (single channel)
- Inelastic rescattering (multi channel in general)
  In practice two-channel approaches.
- Enhanced diagram corrections (Khoze-Martin-Ryskin)

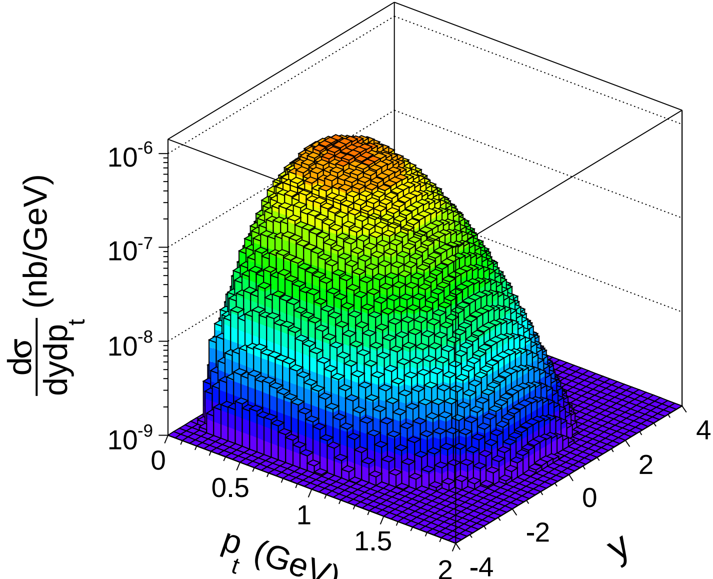
Very often the cross sections and even distributions are multiplied by a soft gap survival probability
Here we follow this approach ($S_g = S_g(s)$)
This is not yet consistent!

Exclusive Higgs production

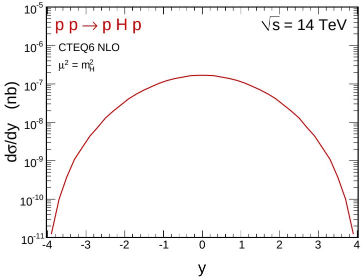


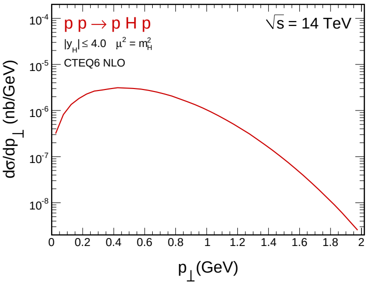
very small cross sections !

Exclusive Higgs production

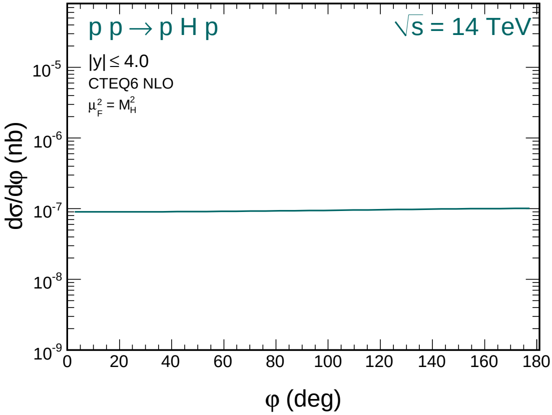


Exclusive Higgs production



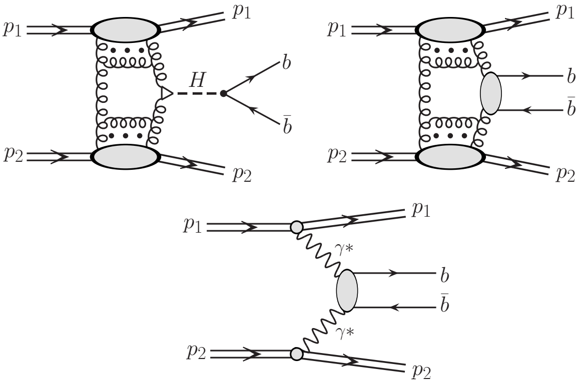


Exclusive Higgs production



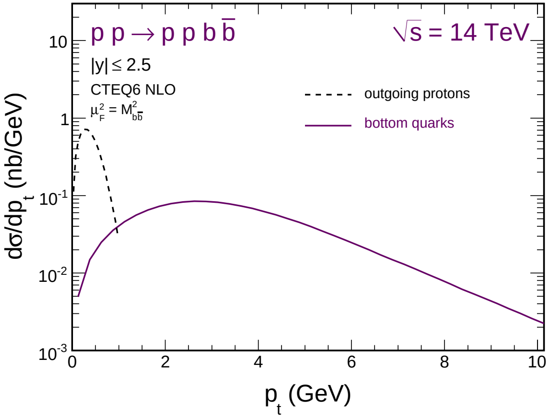
ϕ is azimuthal angle between outgoing protons

Exclusive $b\bar{b}$ production



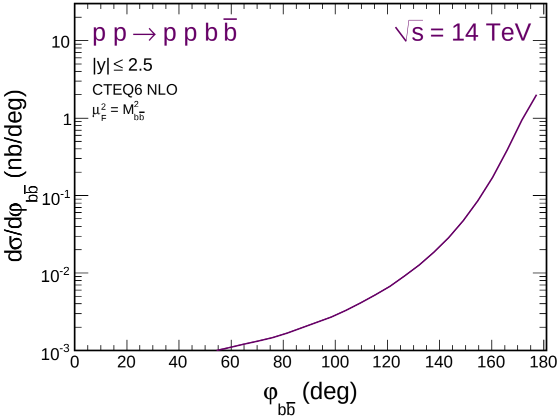
Maciula, Pasechnik, Szczurek, arXiv:1011.5842,
Phys. Rev. **D83** (2011) 114034.

Exclusive diffractive $b\bar{b}$ production



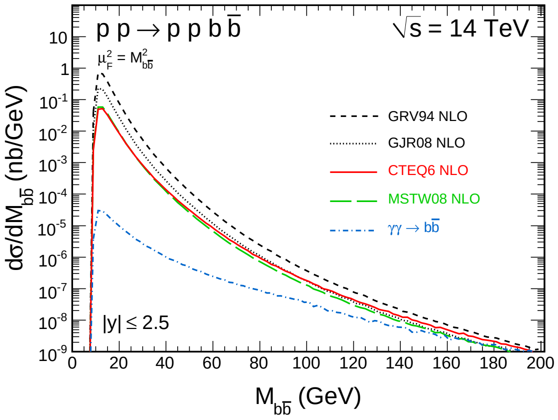
CTEQ6

Exclusice diffractive $b\bar{b}$ production



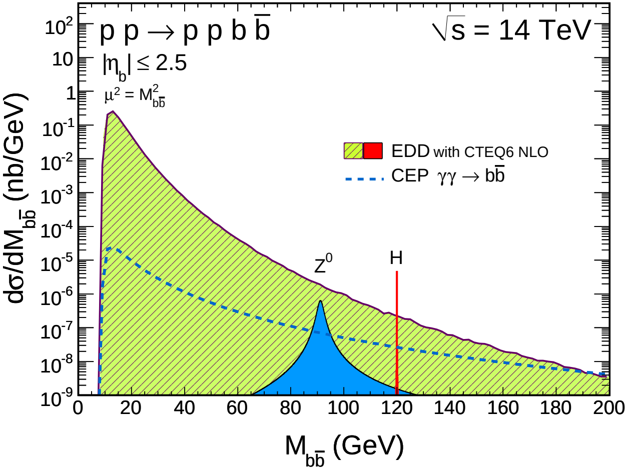
CTEQ6

Exclusive diffractive $b\bar{b}$ production

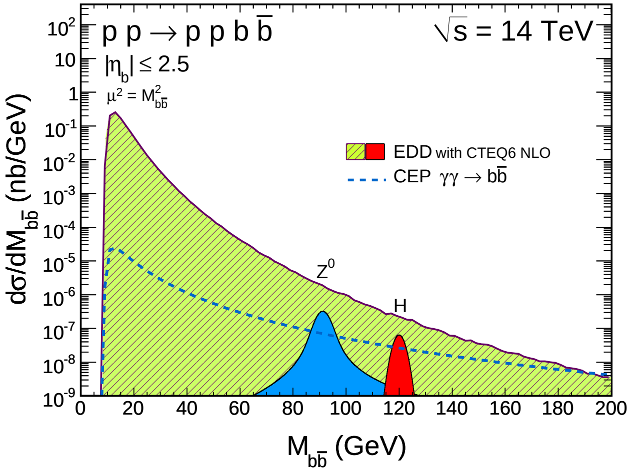


different UPDFs

M_{bb} spectrum, theory

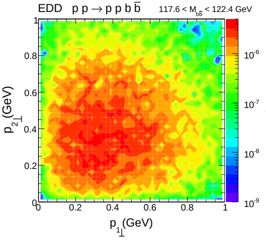


M_{bb} spectrum, experiment

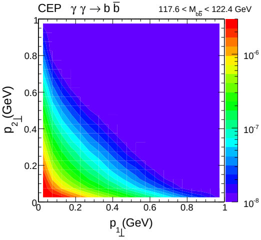


- Looks rather difficult
- How to improve the signal-to-background ratio ?

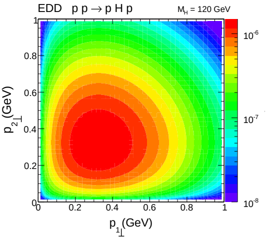
(p_{1t}, p_{2t}) distributions for different mechanisms



diffractive background

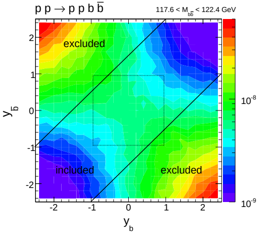


QED background

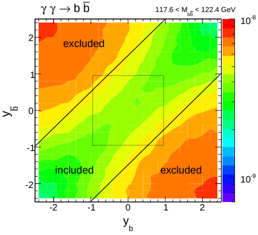


diffractive Higgs

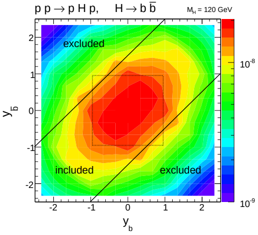
$(y_b, y_{\bar{b}})$ distributions for different mechanisms



diffractive background

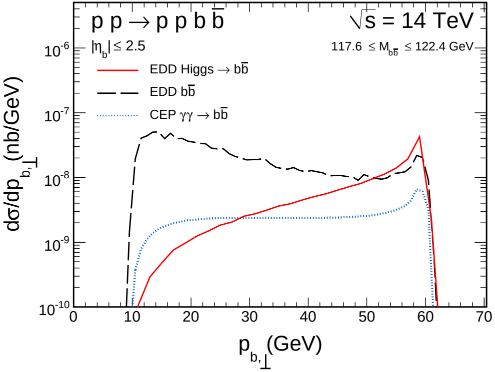


QED background

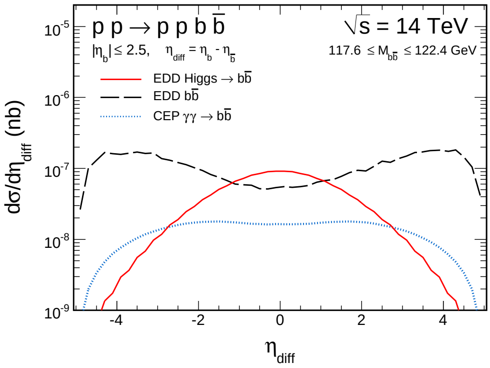


diffractive Higgs

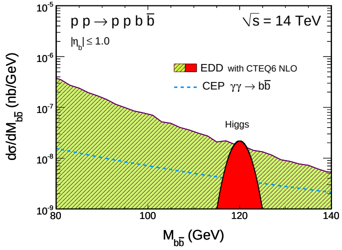
Jet transverse momenta

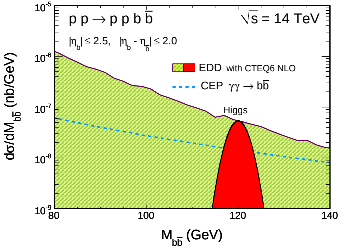


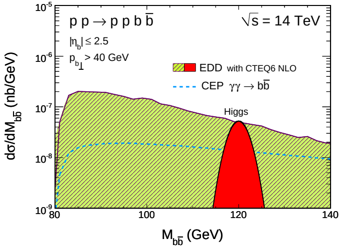
Rapidity difference

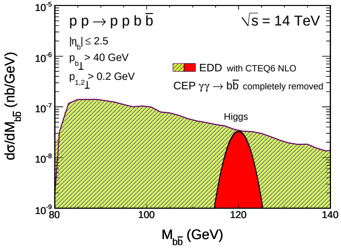


M_{bb} spectrum, cuts

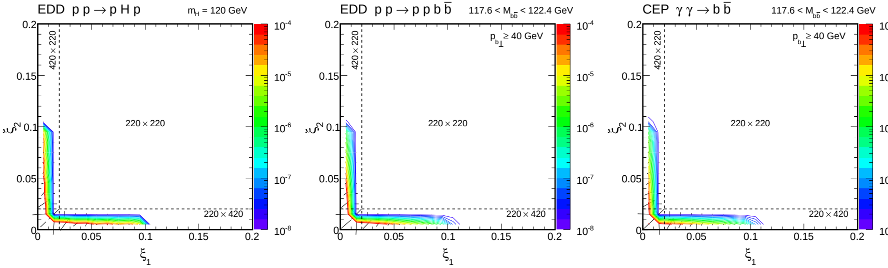






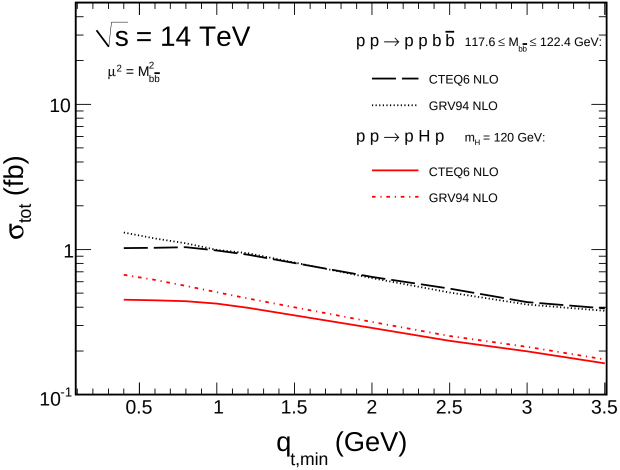


Longitudinal momentum fraction loss



$\xi_1 = (p_{1f} - p_{1i})/p_{1i}$
$\xi_2 = (p_{2f} - p_{2i})/p_{2i}$
RP220, FP420 detectors were planned

Lower cut on gluon transverse momenta

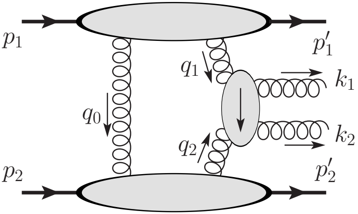


Slow dependence on the cut

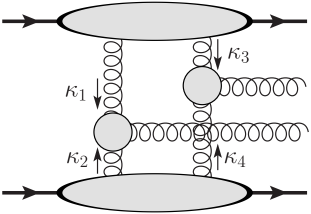
Summary of the EDD Higgs and $b\bar{b}$ production

- 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 less than 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.

Mechanism of gluonic dijet production



A



B

Maciula,Pasechnik,AS
Ivanov,Cudell

Amplitudes

$$\mathcal{M}^A_{ab}(\lambda_1,\lambda_2) = is\,\mathcal{A}\,\frac{\delta_{ab}}{N_c^2-1}\int d^2\mathbf{q}_0\,\frac{f_g^{\rm off}(q_0,q_1)f_g^{\rm off}(q_0,q_2)\cdot\epsilon^*_\mu(\lambda_1)\epsilon^*_\nu(\lambda}{\mathbf{q}_0^2\mathbf{q}_1^2\mathbf{q}_2^2}$$

$$\left[\frac{C_1^\mu(q_1,r_1)C_2^\nu(r_1,-q_2)}{\mathbf{r}_1^2}+\frac{C_1^\mu(q_1,r_2)C_2^\nu(r_2,-q_2)}{\mathbf{r}_2^2}\right],$$

$$\mathcal{M}^B_{ab}(\lambda_1,\lambda_2) = -is\,\mathcal{A}\,\frac{\delta_{ab}}{N_c^2-1}\int d^2\boldsymbol{\kappa}_1\,\frac{f_g^{\rm off}(\kappa_1,\kappa_3)f_g^{\rm off}(\kappa_2,\kappa_4)\cdot\epsilon^*_\mu(\lambda_1)\epsilon^*_\nu}{\boldsymbol{\kappa}_1^2\boldsymbol{\kappa}_2^2\boldsymbol{\kappa}_3^2\boldsymbol{\kappa}_4^2}$$

$$C_1^\mu(\kappa_1,-\kappa_2)C_2^\nu(\kappa_3,-\kappa_4),$$

where $C^\mu(\kappa,\kappa')$ – Lipatov vertices.

Diagram B

$$x_1 \simeq \frac{p_{3\perp}}{\sqrt{s}} \exp(+y_3)\,, \qquad x_2 \simeq \frac{p_{4\perp}}{\sqrt{s}} \exp(-y_3)\,,$$
$$x_3 \simeq \frac{p_{3\perp}}{\sqrt{s}} \exp(+y_4)\,, \qquad x_4 \simeq \frac{p_{4\perp}}{\sqrt{s}} \exp(-y_4)\,.$$

$$f_g^{\mathrm{off}}(x_1, x_3, \boldsymbol{\kappa}_1^2, \boldsymbol{\kappa}_3^2, \mu_1^2, \mu_2^2; t) = \sqrt{f_g(x_1, \boldsymbol{\kappa}_1^2, \mu_1^2) f_g(x_3, \boldsymbol{\kappa}_3^2, \mu_2^2)} \cdot F(t_1)\,,$$
$$f_g^{\mathrm{off}}(x_2, x_4, \boldsymbol{\kappa}_2^2, \boldsymbol{\kappa}_4^2, \mu_1^2, \mu_2^2; t) = \sqrt{f_g(x_2, \boldsymbol{\kappa}_2^2, \mu_1^2) f_g(x_4, \boldsymbol{\kappa}_4^2, \mu_2^2)} \cdot F(t_2)\,.$$

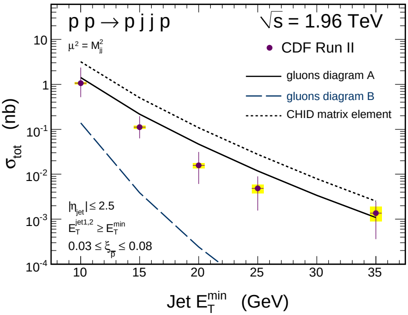
Smooth interpolation between on-diagonal UGDFs

Above on-diagonal UGDfs include Sudakov form factors in the same way as in the KMR UGDF

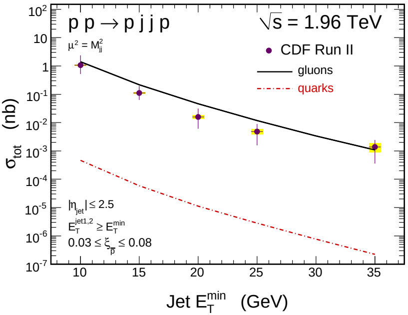
Very simplistic(!)

$\mu_1 = p_{3\perp}$ and $\mu_2 = p_{4\perp}$ or $\mu_1 = \mu_2 = M_{gg}$.

CDF data

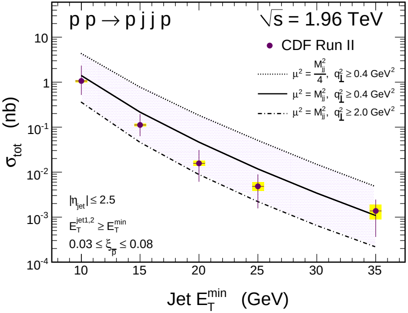


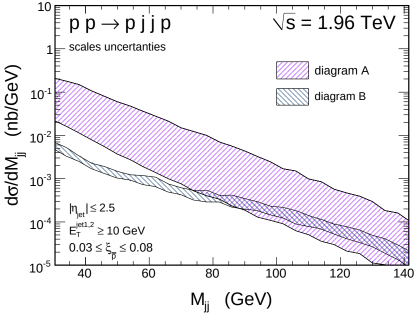
p p → p j j p
√s = 1.96 TeV
μ² = M²jj
CDF Run II
gluons diagram A
gluons diagram B
CHID matrix element
|ηjet| ≤ 2.5
E_T^jet1,2 ≥ E_T^min
0.03 ≤ ξp̄ ≤ 0.08
σtot (nb)
Jet E_T^min (GeV)



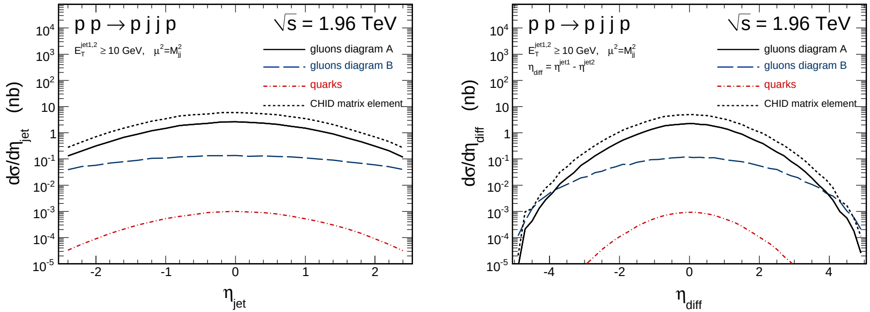
p p → p j j p
√s = 1.96 TeV
μ² = M²jj
CDF Run II
gluons
quarks
|ηjet| ≤ 2.5
E_T^jet1,2 ≥ E_T^min
0.03 ≤ ξp̄ ≤ 0.08
σtot (nb)
Jet E_T^min (GeV)

Theoretical uncertainties

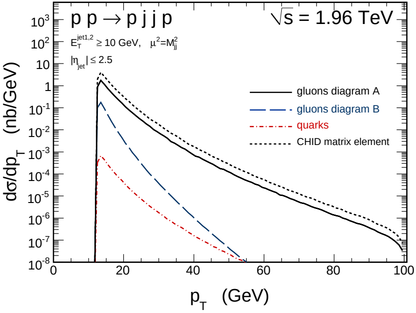


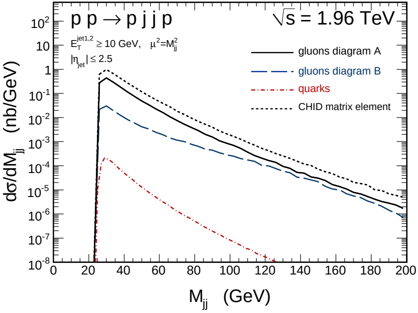


Rapidity distributions, Tevatron

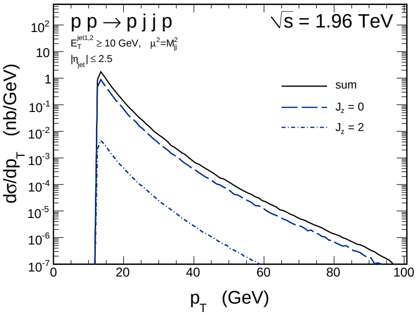


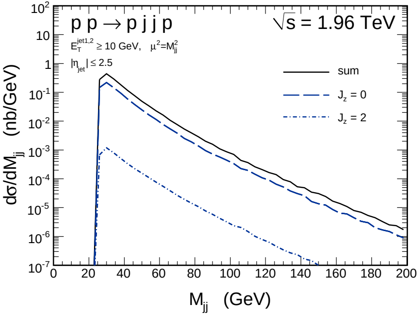
Other distributions, Tevatron



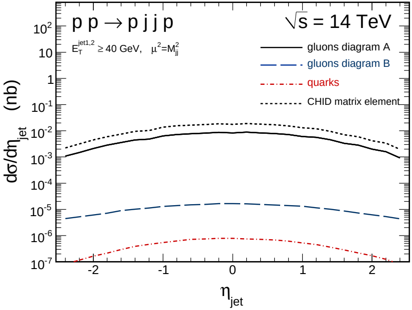


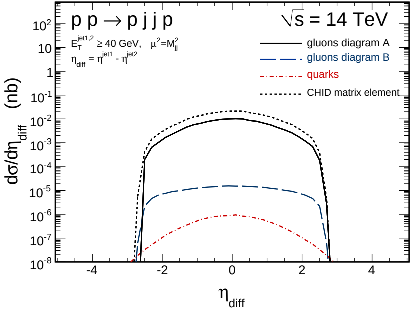
Helicity contributions



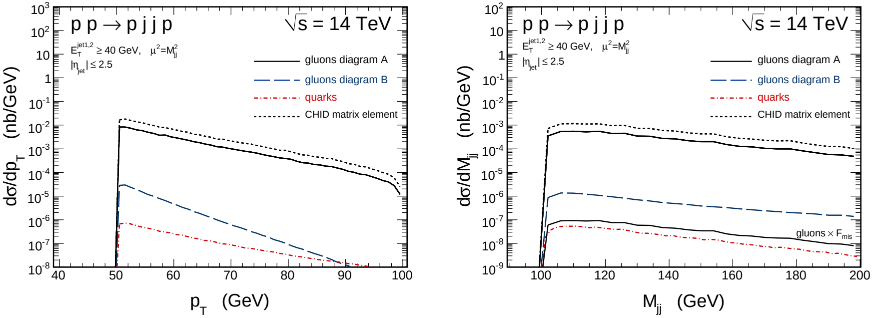


Rapidity distributions, LHC



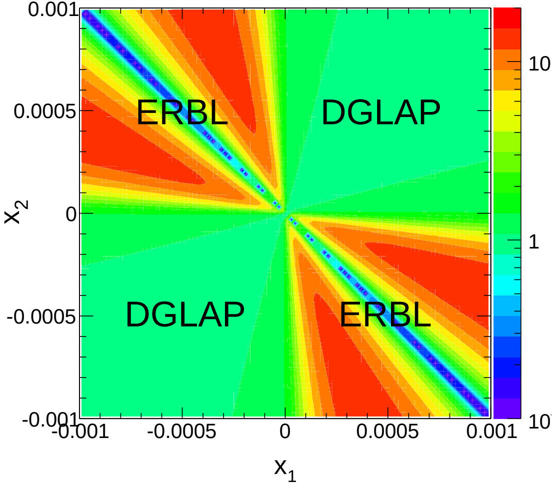


Other distributions, LHC



Off-diagonal GPDs

$$R(x_1, x_2, ; \mu^2, t = 0) = H_g(x, \xi; \mu^2, t = 0)/H_g(x, 0; \mu^2, t = 0)$$



Summary of the EDD gluonic-dijet production

- Exclusive central diffractive gg was calculated using UGDFs.
- Matrix elements calculated using Lipatov vertices.
- Rough agreement with CDF data.
- Diagram B – a simple estimate
  Important at small jet transverse momenta and big (pseudo)rapidity differences.
  Important as background for Higgs.
- Quark-antiquark contribution negligible.
- Possible to separate diagram-B contribution?