Is Higgs production a low-x phenomenon?

Antoni Szczurek
Institute of Nuclear Physics (PAN), Cracow, Poland
Rzeszów University, Rzeszów, Poland

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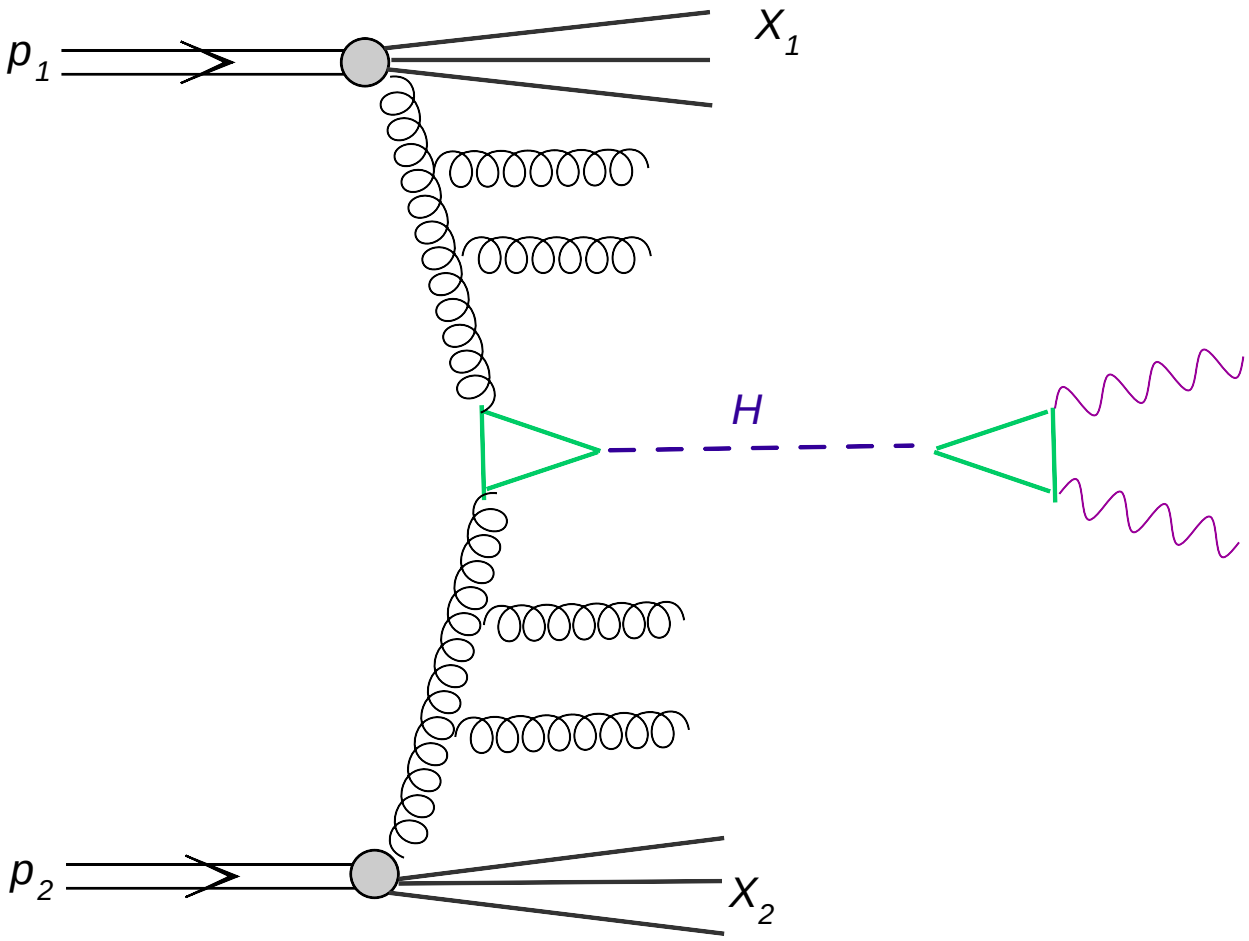
Contents

Introduction

- Higgs boson has been discovered (ATLAS, CMS).
- It has been clearly seen in different channels (e.g. $\gamma\gamma$, $Z^0 Z^{0*}$).
- Now we know its mass ($M_H \approx$ 125-126 GeV).
- We slowly enter era of more detailed studies -- spin, cross section, distributions
- Precise data for Higgs boson production - exploration of unintegrated gluon distributions
  Cipriano, Dooling, Grebenyuk, Gunnellini, Hautmann, Jung, Katsas
- Preliminary ATLAS data with first differential distributions, ATLAS-CONF-2013-072.
- First comparison within k_t-factorization - Lipatov, Malyshev and Zotov, arXiv:1402.6481.

QCD mechanism of Higgs boson production



k_t-factorization - a way of quantitative description

k_t-factorization approach

Hautmann, Jung
Lipatov, Zotov
Łuszczak, Szczurek

$$\sigma_{pp\to H} = \int \frac{dx_1}{x_1}\frac{dx_2}{x_2}\frac{d^2q_{1t}}{\pi}\frac{d^2q_{2t}}{\pi} \quad \delta\left((q_1+q_2)^2 - M_H^2\right)\sigma_{gg\to H}(x_1, x_2, q_1, q_2$$
$$\mathcal{F}_g(x_1, q_{1t}^2, \mu_F^2)\mathcal{F}_g(x_2, q_{2t}^2, \mu_F^2)\ , \qquad (1$$

where $\mathcal{F}_g$ are so-called unintegrated (or TMD) gluon distributions and $\sigma_{gg\to H}$ is $gg \to H$ (off-shell) cross section.
After some manipulation:

$$\sigma_{pp\to H} = \int dy d^2p_t d^2q_t \frac{1}{sx_1x_2}\frac{1}{m_{t,H}^2}\overline{|\mathcal{M}_{gg\to H}|^2}\mathcal{F}_g(x_1, q_{1t}^2, \mu_F^2)\mathcal{F}_g(x_2, q_{2t}^2, \mu_F^2)/4,$$

k_t-factorization approach

$\vec{p}_t = \vec{q}_{1t} + \vec{q}_{2t}$ -- transverse momentum of the Higgs boson
and $\vec{q}_t = \vec{q}_{1t} - \vec{q}_{2t}$ is auxiliary variable which is used in the integration.
$x_1 = \frac{m_{t,H}}{\sqrt{s}} \exp(y)$, $x_2 = \frac{m_{t,H}}{\sqrt{s}} \exp(-y)$
and $m_{t,H}$ is the so-called Higgs boson transverse mass. The factor $\frac{1}{4}$ is the jacobian of transformation from $(\vec{q}_{1t}, \vec{q}_{2t})$ to $(\vec{p}_t, \vec{q}_t)$.
The off-shell matrix element has been used in the approximation of infinitly heavy top in the triangle-coupling of gluons to the Higgs boson.
Then the effective $gg \to H$ coupling is relatively simple:

$$\mathcal{M}^{ab}_{gg\to H} = -i\delta^{ab} \frac{a_s}{4\pi} \frac{1}{v} \left(m_H^2 + p_t^2\right) cos(\phi) \frac{2}{3} \ , \tag{3}$$

where $v^2 = \left(G_F \sqrt{2}\right)^{-1}$.

Off-shell matrix element

The effect of finite-mass corrections was studied by Pasechnik, Teryaev and Szczurek, Eur. Phys. J. **C47** (2006) 429.

$$\mathcal{M}^{ab}_{gg\to H} = -i\delta^{ab}\frac{a_s}{4\pi}\frac{1}{v}\left[\left(m_H^2+p_t^2\right)cos(\phi)G_1(q_1,q_2,q) - \frac{2(m_H^2+p_t^2)^2|q_{1t}||q_{2t}|}{(m_H^2+q_{1t}^2+q_{2t}^2)}G_2(q_1, \tag{4}$$

For not too big virtualities of gluons and Higgs boson the following approximate formula for the G_1 and G_2 form factors can be used:

$$G_1 = \frac{2}{3}\left(1+\frac{7}{30}\chi+\frac{2}{21}\chi^2+\frac{11}{30}(\xi_1+\xi_2)+\ldots\right), \tag{5}$$

$$G_2 = -\frac{1}{45}(\chi-\xi_1-\xi_2)-\frac{4}{315}\chi^2+\ldots., \tag{6}$$

where the expansion variables χ, ξ_1, ξ_2 defined as:

$$\chi = \frac{q^2}{4m_f^2}, \xi_1 = \frac{q_1^2}{4m_f^2} < 0, \xi_2 = \frac{q_2^2}{4m_f^2} < 0. \tag{7}$$

$H \to \gamma\gamma$

The matrix element for the Higgs boson decay into photons with helicity λ_1 and λ_2 can be written as

$$\mathcal{M}_{H\to\gamma\gamma}(\lambda_1, \lambda_2) = T^{\mu\nu}_{H\to\gamma\gamma}\epsilon^*_\mu(\lambda_1)\epsilon^*_\nu(\lambda_2) \ . \tag{8}$$

The leading-order vertex funtion can be decomposed as the sum

$$T^{\mu\nu}_{H\to\gamma\gamma} = T^{\mu\nu,W}_{H\to\gamma\gamma} + T^{\mu\nu,t}_{H\to\gamma\gamma} + \dots \ , \tag{9}$$

where the first term includes loops with intermediate $W^\pm$ and the second term triangle(s) with top quarks. The dots represent contribution of triangles with bottom and charm quarks and with τ leptons, etc.

$$T^{\mu\nu}_{H\to\gamma\gamma}(p_1, p_2) = i\frac{a_{em}}{2\pi}\mathcal{A}\left(G_F\sqrt{2}\right)^{1/2}\left(p_2^\mu p_1^\nu - (p_1\cdot p_2)g^{\mu\nu}\right) \ . \tag{10}$$

$H \to \gamma\gamma$

In the Standard Model:

$$\mathcal{A} = \mathcal{A}_W(\tau_W) + N_c e_f^2 \mathcal{A}_t(\tau_t) + \ldots, \tag{11}$$

where the arguments are:

$$\tau_W = \frac{m_H^2}{4m_W^2} \quad , \quad \tau_t = \frac{m_H^2}{4m_t^2} \ . \tag{12}$$

The functions $\mathcal{A}_W$ and $\mathcal{A}_t$ have the simple form:

$$\mathcal{A}_W(\tau) = -\left(2\tau^2 + 3\tau + 3(2\tau - 1)f(\tau)\right)/\tau^2 \ , \tag{13}$$

$$\mathcal{A}_t(\tau) = 2\left(\tau + (\tau - 1)f(\tau)\right)/\tau^2 \ , \tag{14}$$

where the function f:

$$f(\tau) = arcsin^2(\sqrt{t}) \ . \tag{15}$$

For light fermions the function f is slightly different.

$H \to \gamma\gamma$

The two-photon decay width can be calculated as:

$$\Gamma_{H\to\gamma\gamma} = \frac{1}{32\pi^2}\Sigma_{\lambda_1\lambda_2}|\mathcal{M}_{H\to\gamma\gamma}(\lambda_1,\lambda_2)|^2\frac{p}{m_H^2}\frac{1}{2} \ . \tag{16}$$

$\Gamma_{H\to\gamma\gamma} = 0.91 \times 10^{-5}$ which, when combined with the total decay width $\Gamma_H \approx 4$ MeV, gives branching fraction $BF_{H\to\gamma\gamma} = 2.27 \times 10^{-3}$.

$gg \to H^* \to \gamma\gamma$

Let us combine now all elements defined above and write matrix element for the $gg \to H \to \gamma\gamma$ process.

$$\mathcal{M}_{gg\to H\to\gamma\gamma}(\lambda_1, \lambda_2) = \mathcal{M}_{gg\to H}(\vec{q}_{1t}, \vec{q}_{2t}; \hat{s}) \frac{1}{\hat{s} - M_H^2 + i\Gamma_H M_H} \mathcal{M}_{H\to\gamma\gamma}(\lambda_1, \lambda_2) \ . \tag{17}$$

In the infinitly heavy quark approximation the matrix element squared for $gg \to H^* \to \gamma\gamma$ averaged over colors can be written in the quite compact way:

$$\overline{|\mathcal{M}|^2} = \frac{1}{1152\pi^4} a_{em}^2 a_s^2 G_F^2 |\mathcal{A}|^2 \frac{\hat{s}(\hat{s} + p_t^2)^2}{(\hat{s} - m_H^2)^2 + m_H^2 \Gamma_H^2} \cos^2(\phi) \ . \tag{18}$$

$gg \to H^* \to \gamma\gamma$

The differential (in photon rapidities y_1, y_2 and transverse momenta p_{1t}, p_{2t}) cross section for the production of a pair of photons from the $gg \to H^* \to \gamma\gamma$ subprocess with intermediate virtual Higgs boson:

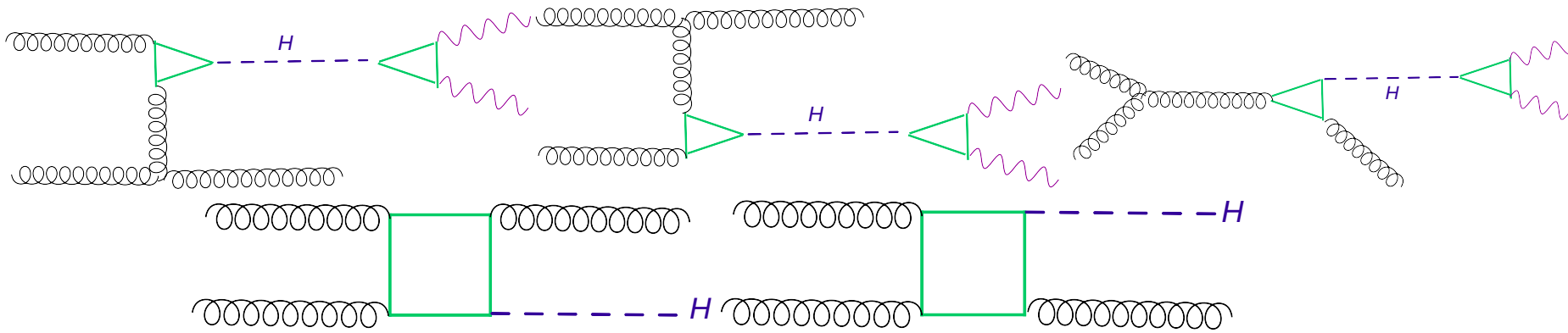
$$\frac{d\sigma(pp \to HX \to \gamma\gamma X)}{dy_1 dy_2 d^2p_{1t} d^2p_{2t}} = \frac{1}{16\pi^2\hat{s}^2} \int \frac{d^2k_{1t}}{\pi} \frac{d^2k_{2t}}{\pi} \overline{|\mathcal{M}^{off}_{g^*g^* \to H \to \gamma\gamma}|^2} \frac{1}{2}$$
$$\times \ \delta^2\left(\vec{k}_{1t} + \vec{k}_{2t} - \vec{p}_{1t} - \vec{p}_{2t}\right) \mathcal{F}_g(x_1, k_{1t}^2, \mu^2) \mathcal{F}_g(x_2, k_{2t}^2, \mu^2) \ . \qquad (19)$$

(20)

Please note that in this case the $m_H^2 + p_t^2$ term in (3) for on shell Higgs boson is replaced by $\hat{s} + p_t^2$ for virtual Higgs boson. In principle also M_H^2 in definition of the $\mathcal{A}$ functions should be replaced by $\hat{s}$ here.
Since we integrate over full phase space in y_1, y_2, p_{1t} and p_{2t} we have to include in addition identity factor $\frac{1}{2}$, in full analogy to the calculation of the decay width into two photons.

NLO contributions

Typical diagrams for QCD NLO contributions to Higgs boson production:



The boxes dominate at high energy.

We shall calculate them also in k_t-factorization approach.

$gg \to Hg$ in k_t-factorization approach

$$\frac{d\sigma(pp \to HgX)}{dy_H dy_g d^2p_{H,t} d^2p_{g,t}} = \frac{1}{16\pi^2\hat{s}^2} \int \frac{d^2q_{1t}}{\pi} \frac{d^2q_{2t}}{\pi} \overline{|\mathcal{M}_{g_1^* g_2^* \to Hg}|^2}$$
$$\times \ \delta^2\left(\vec{q}_{1t} + \vec{q}_{2t} - \vec{p}_{H,t} - \vec{p}_{g,t}\right) \mathcal{F}(x_1, q_{1t}^2, \mu^2) \mathcal{F}(x_2, q_{2t}^2, \mu^2) \ , \quad (21)$$

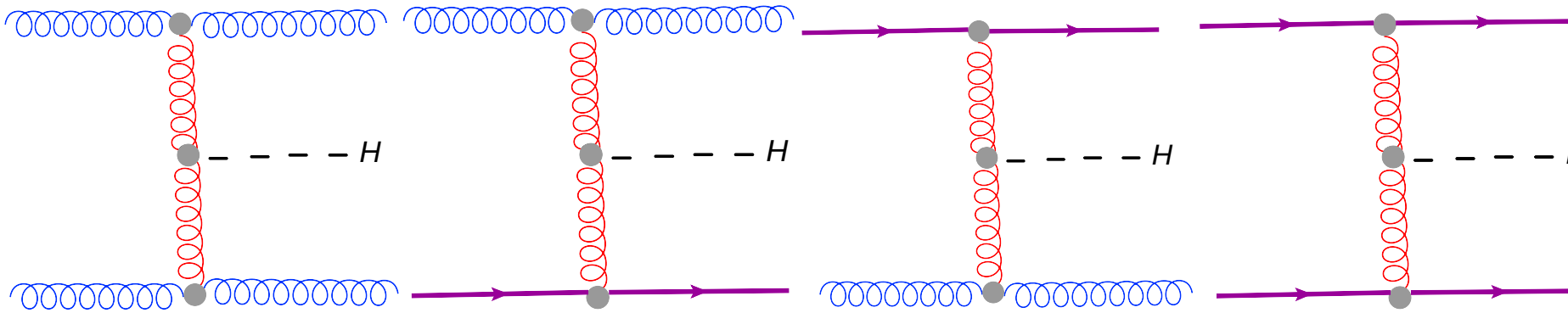
Calculation of the off-shell matrix element is rather complicated in general case as it involves loops (triangles and boxes).

$$\overline{|\mathcal{M}_{gg\to Hg}^{off-shell}|^2} \to \overline{|\mathcal{M}_{gg\to Hg}^{on-shell}(s,t,u)|^2} \ , \quad (22)$$

analytical continuation

Higgs boson and dijets in the context of k_t-factorization approach

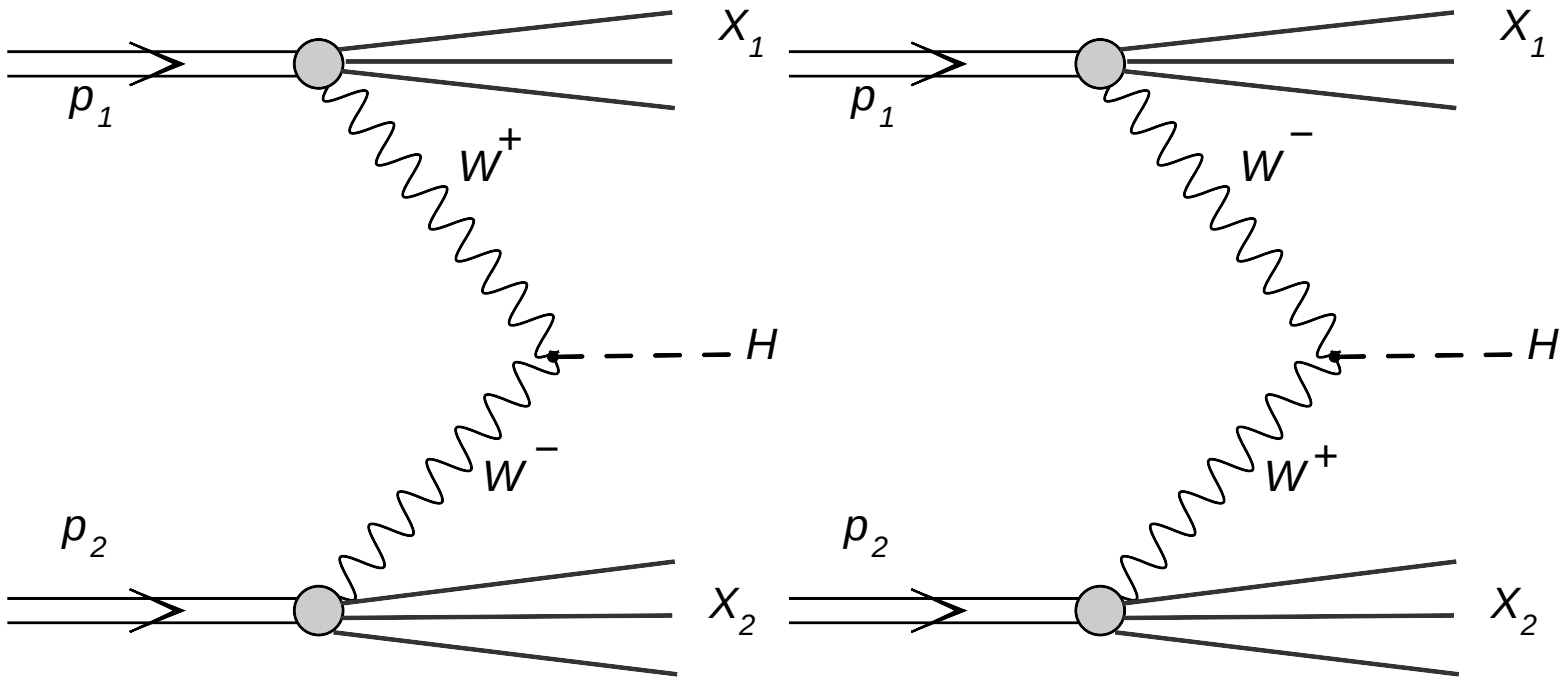
The leading-order diagrams:



The $gg \to gHg$ diagram has relevance for the $2 \to 1$ k_t-factorization calculation.

The other processes not included in the k_t-factorization approach.

WW fusion



The dominant electroweak correction.

WW fusion

The corresponding proton-proton cross section can be written as

$$d\sigma = \mathcal{F}_{12}^{VV}(x_1, x_2)\ \frac{1}{2\hat{s}}\ \overline{|\mathcal{M}_{qq\to qqH}|^2}\ \frac{d^3p_3}{(2\pi)^3 2E_3}\frac{d^3p_4}{(2\pi)^3 2E_4}\frac{d^3p_H}{(2\pi)^3 2E_H}$$
$$(2\pi)^4\delta^4(p_1 + p_2 - p_3 - p_4 - p_H)\ dx_1 dx_2\ . \quad (23)$$

Matrix element

$$\overline{|\mathcal{M}|^2} = 128\sqrt{2}G_F^3 \frac{M_W^8(p_1\cdot p_2)(p_3\cdot p_4)}{(2p_3\cdot p_1 + M_W^2)^2(2p_4\cdot p_2 + M_W^2)^2}\ . \quad (24)$$

WW fusion

For the WW fusion, limiting to light flavours, the partonic function is

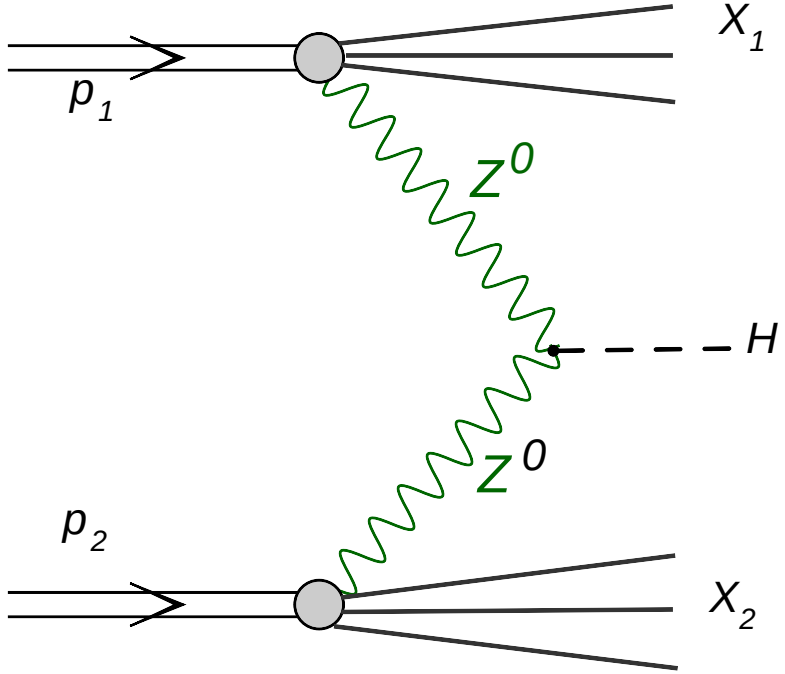
$$\mathcal{F}_{12}^{WW}(x_1, x_2) =$$
$$\left(u_1(x_1, \mu_1^2) + \bar{d}_1(x_1, \mu_1^2) + \bar{s}_1(x_1, \mu_1^2)\right)\left(\bar{u}_2(x_2, \mu_2^2) + d_2(x_2, \mu_2^2) + s_2(x_2, \mu_2^2)\right)$$
$$\left(\bar{u}_1(x_1, \mu_1^2) + d_1(x_1, \mu_1^2) + s_1(x_1, \mu_1^2)\right)\left(u_2(x_2, \mu_2^2) + \bar{d}_2(x_2, \mu_2^2) + \bar{s}_2(x_2, \mu_2^2)\right)$$

In the following we take $\mu_1^2 = \mu_2^2 = M_H^2$. It is convenient to introduce the following new variables:

$$\begin{aligned} \vec{p}_+ &= \vec{p}_3 + \vec{p}_4 \ , \\ \vec{p}_- &= \vec{p}_3 - \vec{p}_4 \ , \end{aligned} \tag{26}$$

$$\frac{d\sigma}{dy d^2 p_t} = \int dy_1 dy_2 \ x_1 x_2 \mathcal{F}(x_1, x_2, \mu_1^2, \mu_2^2) \ \frac{1}{2\hat{s}} \frac{d^3 p_-}{16} \ \overline{|\mathcal{M}_{qq\to qqH}|^2} \ \frac{1}{2E_3} \ \frac{1}{2E_4}$$
$$\frac{1}{(2\pi)^5} \ \delta(E_1 + E_2 - E_3 - E_4 - E_H) \ . \tag{27}$$

ZZ fusion



Much smaller.

ZZ fusion

$$\overline{|\mathcal{M}|^2_{f_1 f_2}} = 128\sqrt{2}G_F^3 M_Z^8 \frac{C_1^Z(f_1 f_2)(p_1\cdot p_2)(p_3\cdot p_4) + C_2^Z(f_1 f_2)(p_1\cdot p_4)(p_2\cdot p_3)}{(2p_3\cdot p_1 + M_Z^2)^2(2p_4\cdot p_2 + M_Z^2)^2} \,. \tag{28}$$

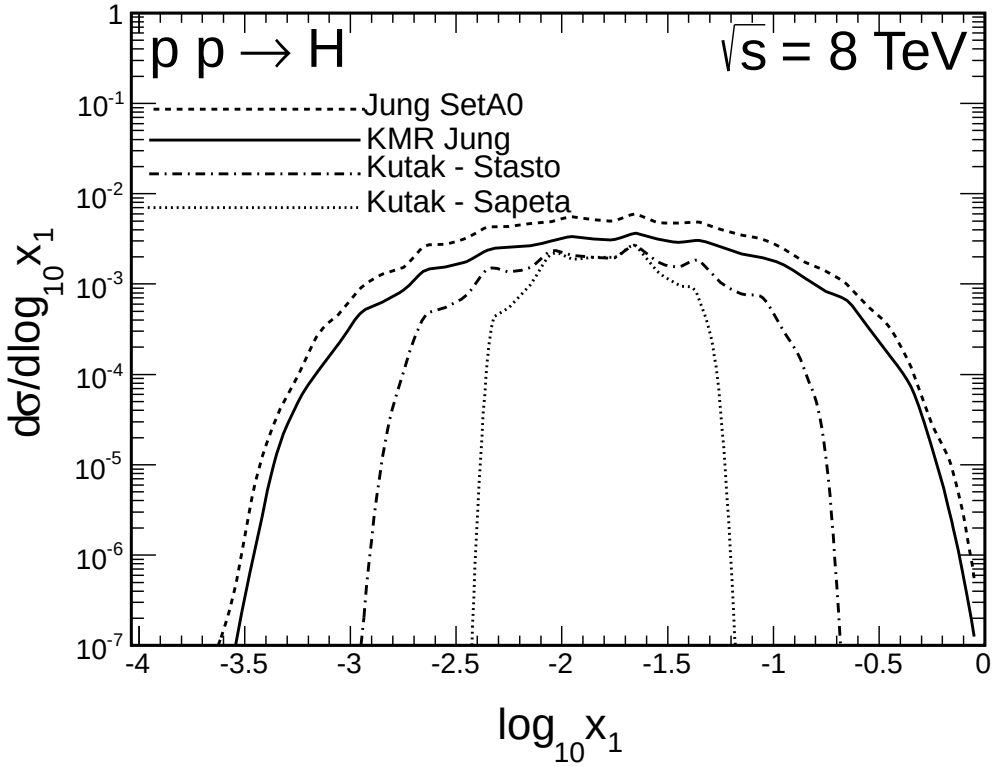
$$\begin{aligned} C_1^Z(f_1 f_2) &= \frac{1}{4}\left((V_{f_1} - A_{f_1})^2(V_{f_2} - A_{f_2})^2 + (V_{f_1} + A_{f_1})^2(V_{f_2} + A_{f_2})^2\right) \,, \\ C_2^Z(f_1 f_2) &= \frac{1}{4}\left((V_{f_1} - A_{f_1})^2(V_{f_2} + A_{f_2})^2 + (V_{f_1} + A_{f_2})^2(V_{f_2} - A_{f_2})^2\right) \,. \end{aligned} \tag{29}$$

Results, summary of numbers

Table: The cross section for Higgs production $p_t < 400$ GeV in pb for W = 8 TeV.

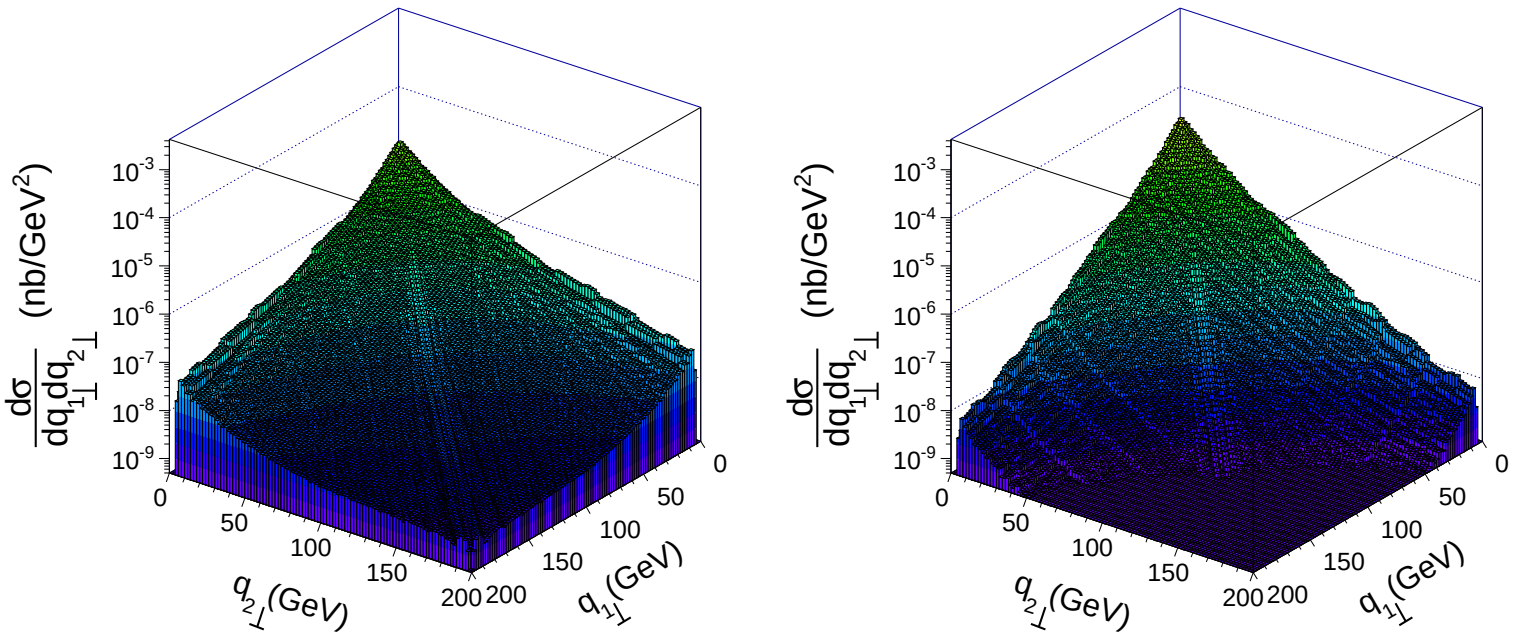
contribution	$\mu_r^2 = \mu_f^2 = m_H^2$
KMR	5.2349
Jung CCFM (A0)	8.2705
Jung CCFM (A0+)	12.3791
Jung CCFM (A0-)	5.7335
Kutak-Staśto	2.6074
Kutak-Sapeta	1.5465
KMR, $q_{1t}, q_{2t} > 10$ GeV	2.4585
$gg \to gHg$, $q_{1t}, q_{2t} > 10$ GeV	0.24
$ij \to iHj$, $q_{1t}, q_{2t} > 10$ GeV	0.57
WW fusion	0.9332
ZZ fusion	0.02641

Inspection of UGDFs



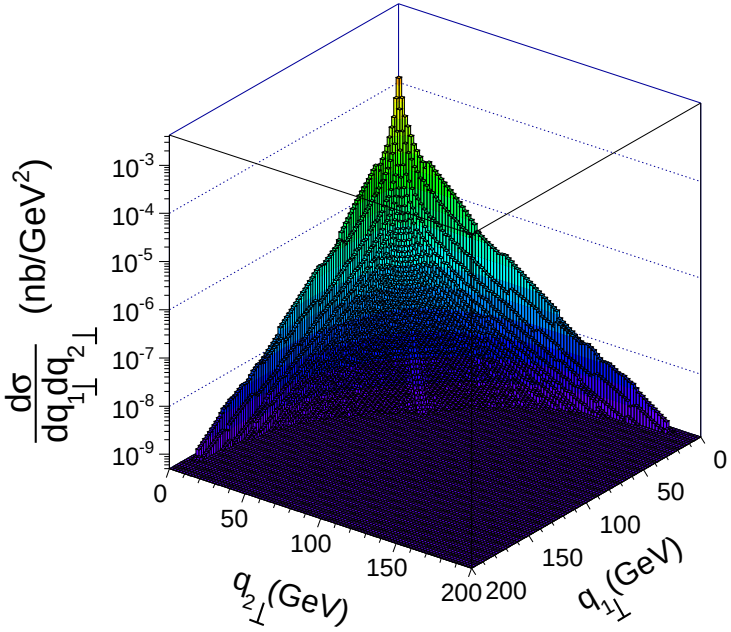
Low-x UGDFs limited to low x.

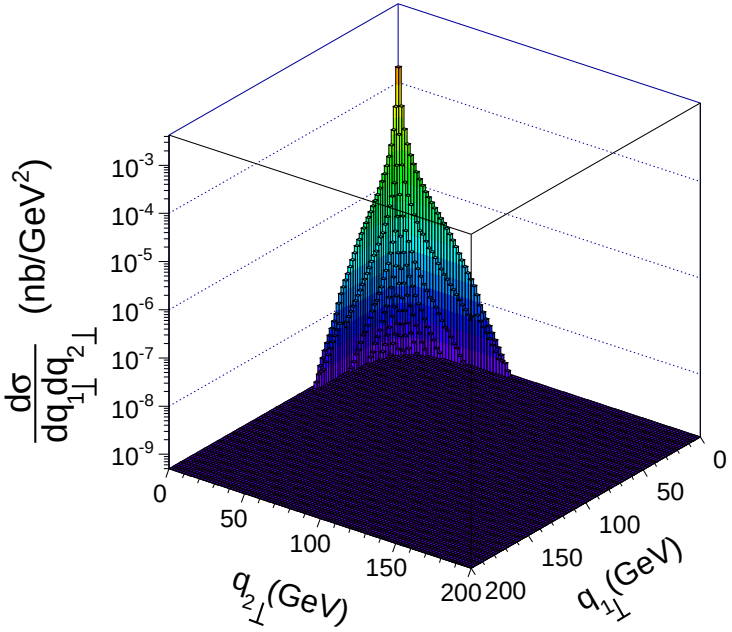
Results



KMR, Jung CCFM A0

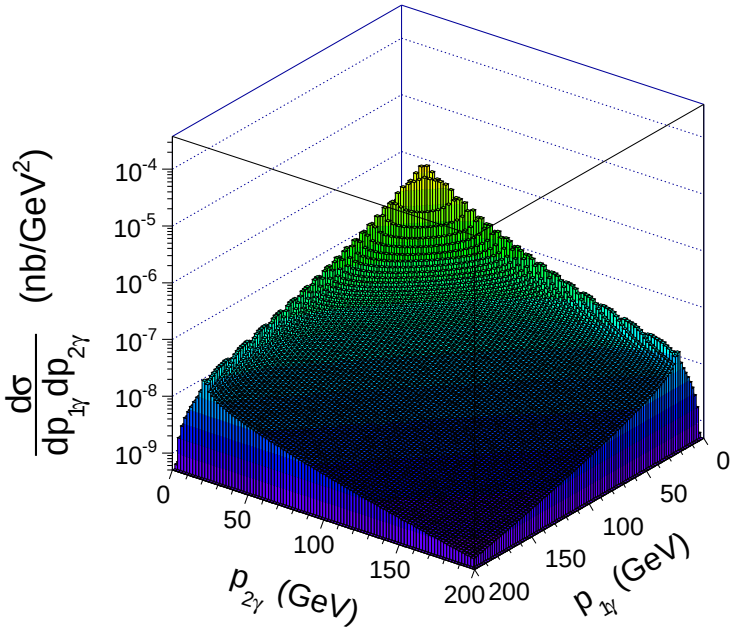
Results

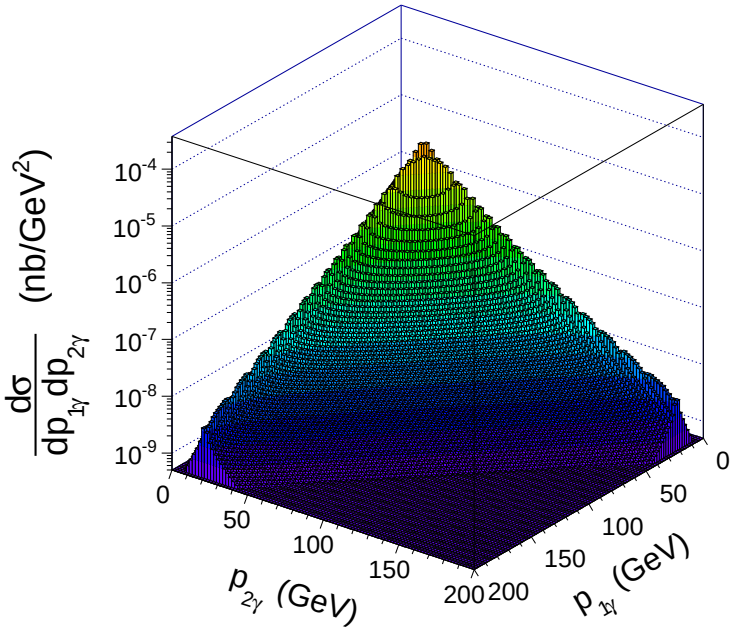




Kutak-Stasto, Kutak-Sapeta

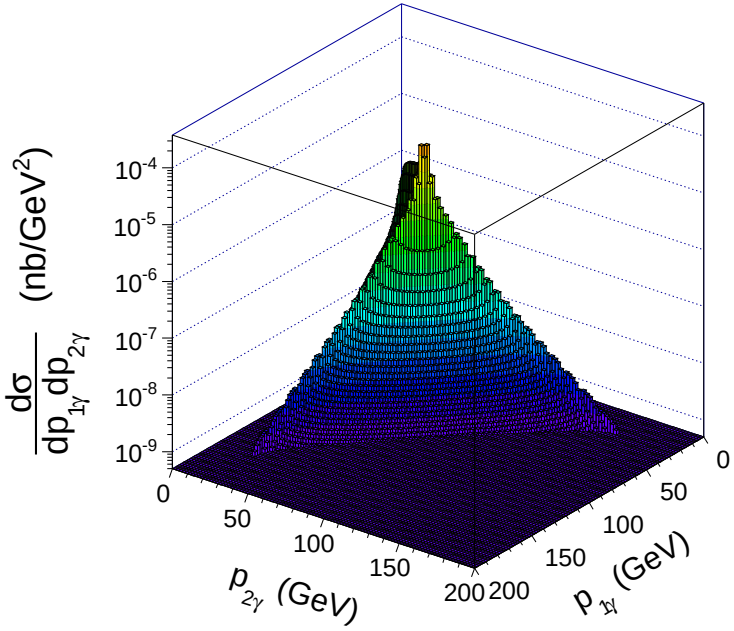
Results

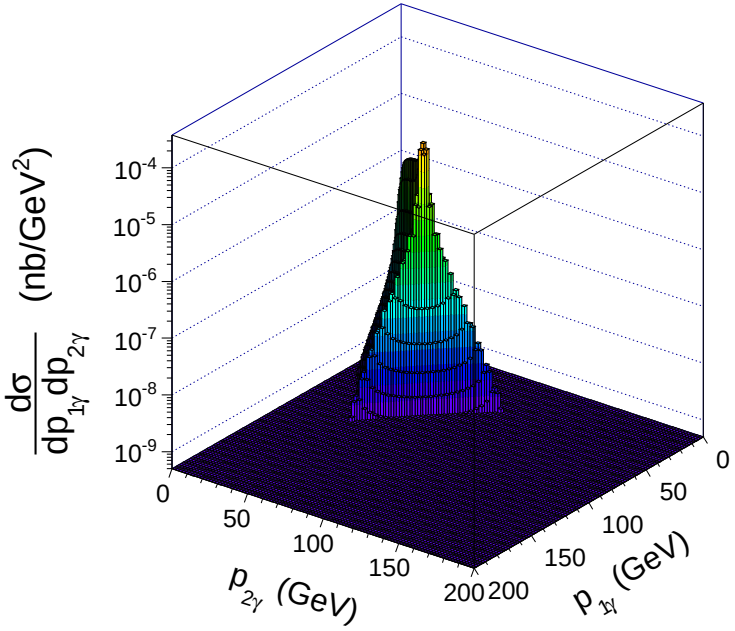




KMR, Jung CCFM A0

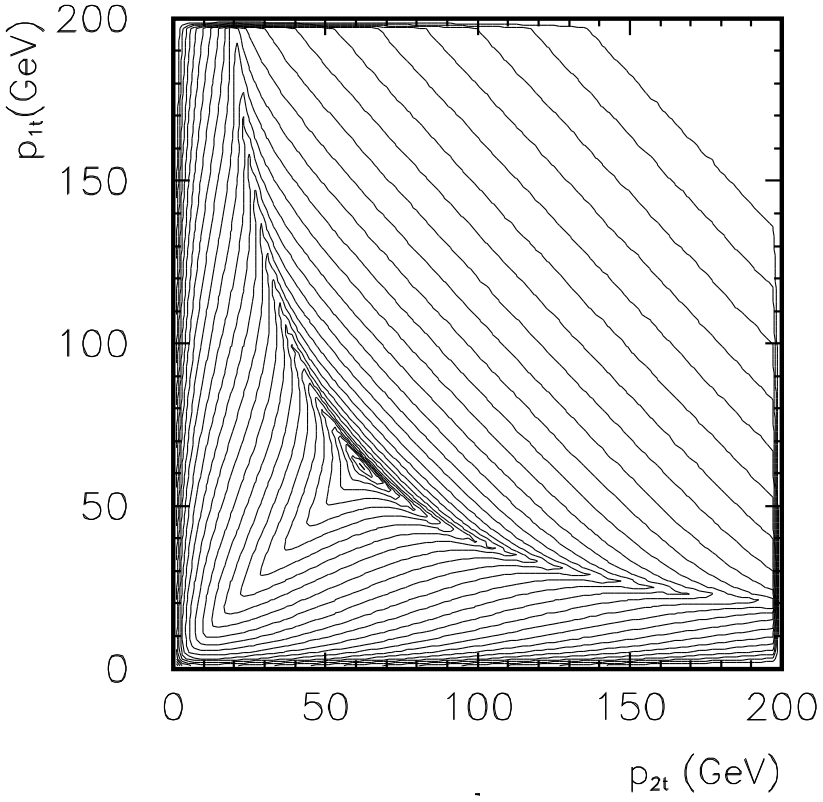
Results

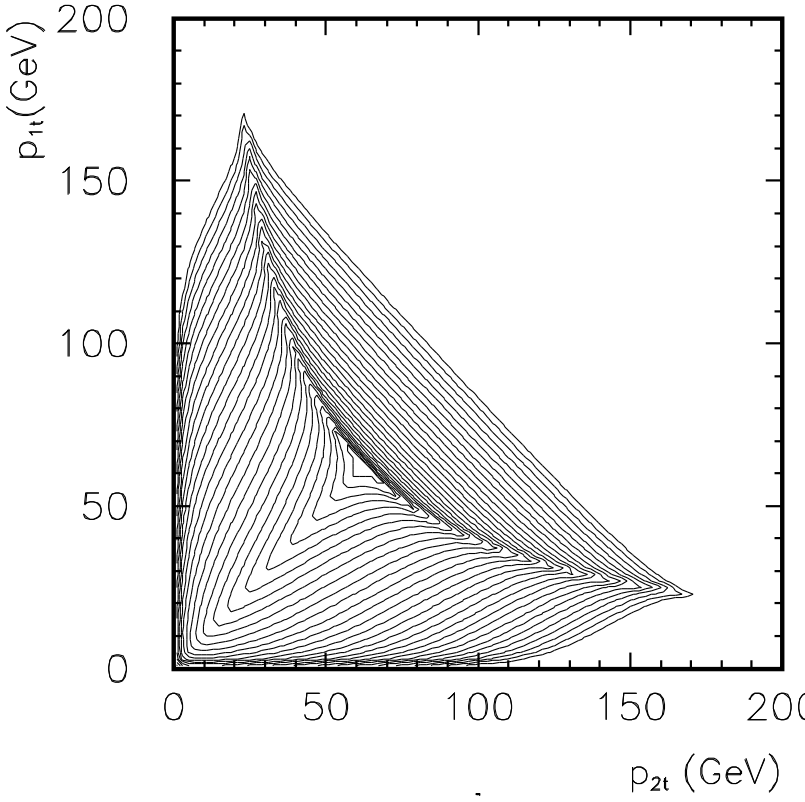




Kutak-Stasto, Kutak-Sapeta

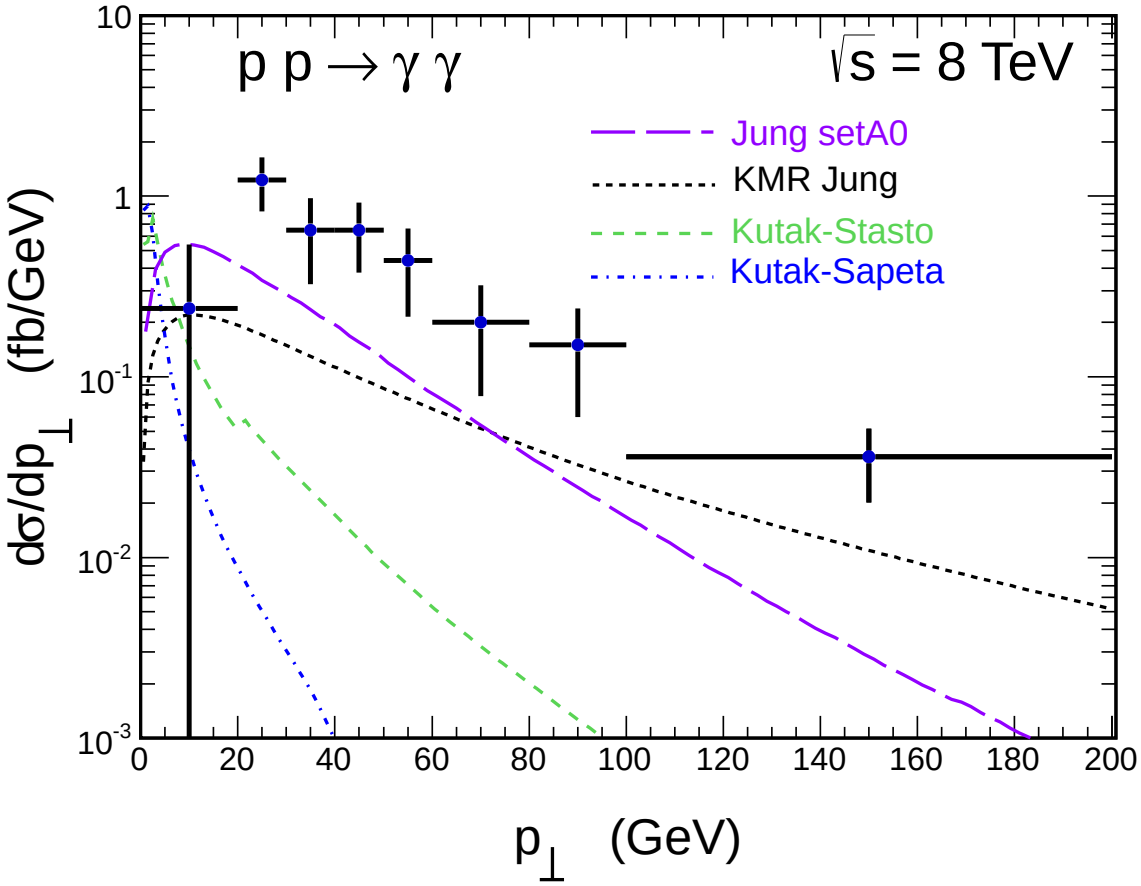
Distribution in transverse momenta of photons





KMR, Jung CCFM A0

Transverse momentum distribution of Higgs boson



All distributions much below experimental data.

leading-order k_t-factorization is not sufficient.

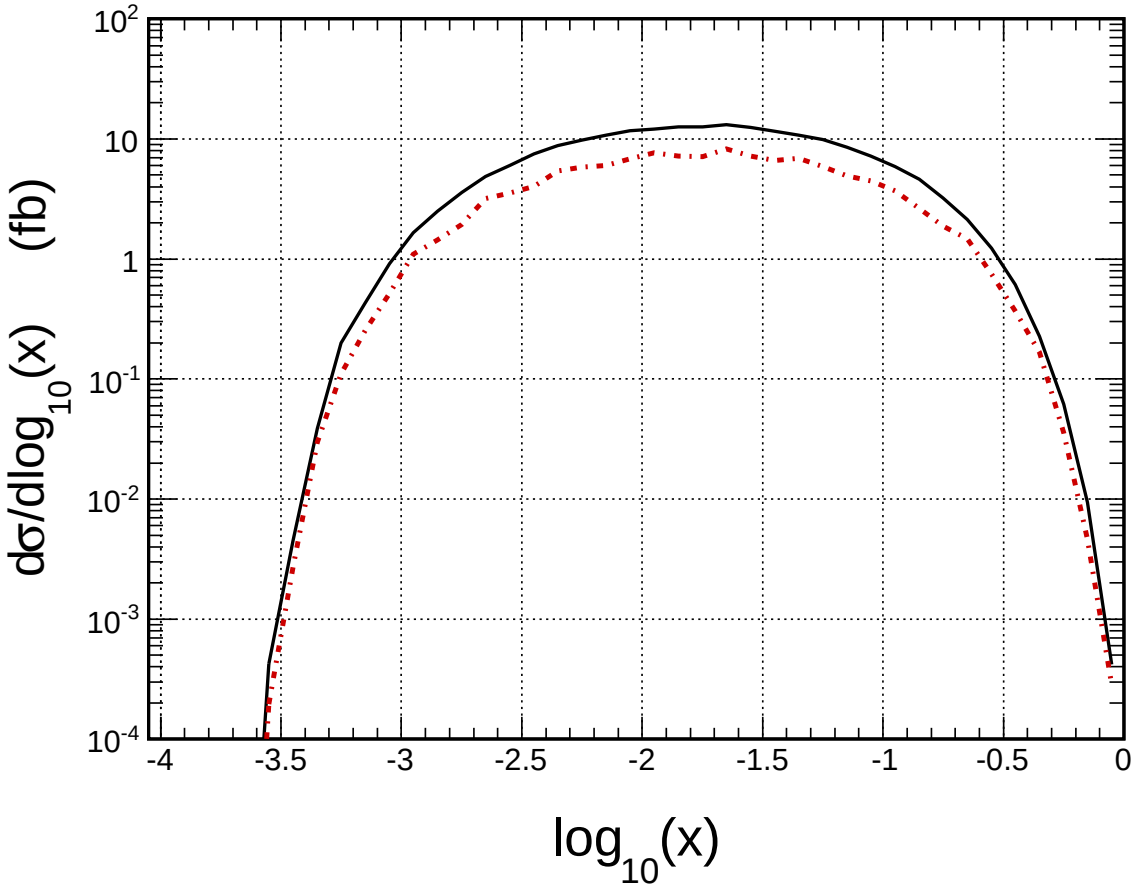
Two methods

We have made calculation with two methods:

- Calculate $\frac{d\sigma}{dydp_t}$ distribution of on-shell Higgs boson.
  Perform relativistic decays of moving Higgs boson into $\gamma\gamma$ channel.
- Make the direct calculation for two photon production with off-shell Higgs boson.

Let us compare the two methods.

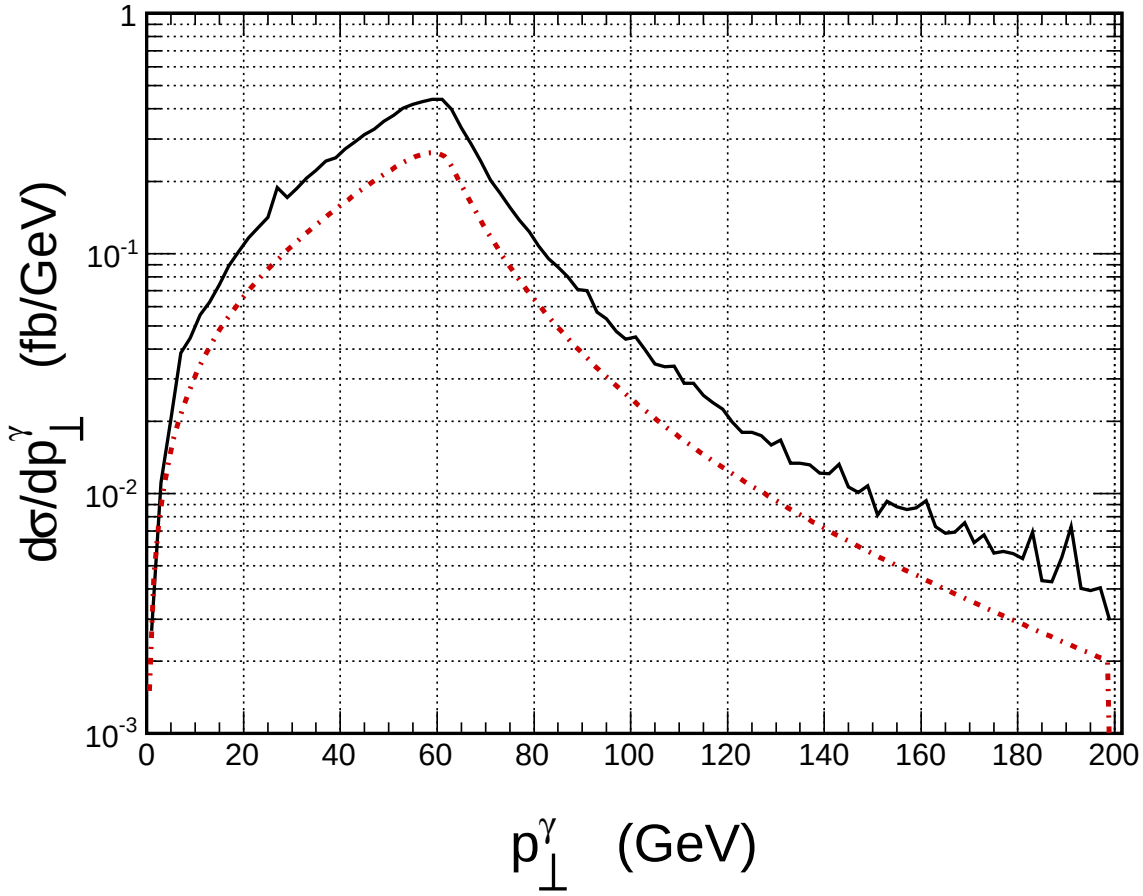
Two methods



KMR, $\mu_F^2 = m_{t,H}^2$

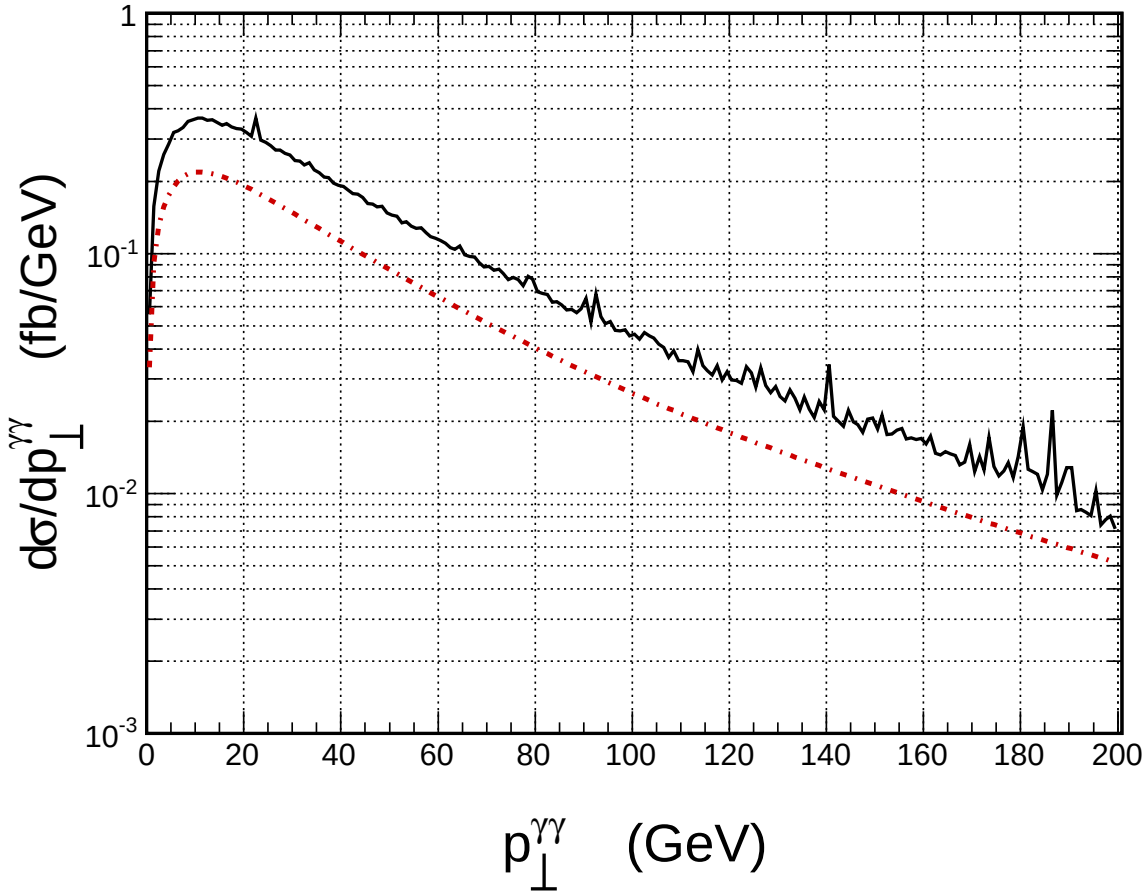
small and large x physics

Two methods



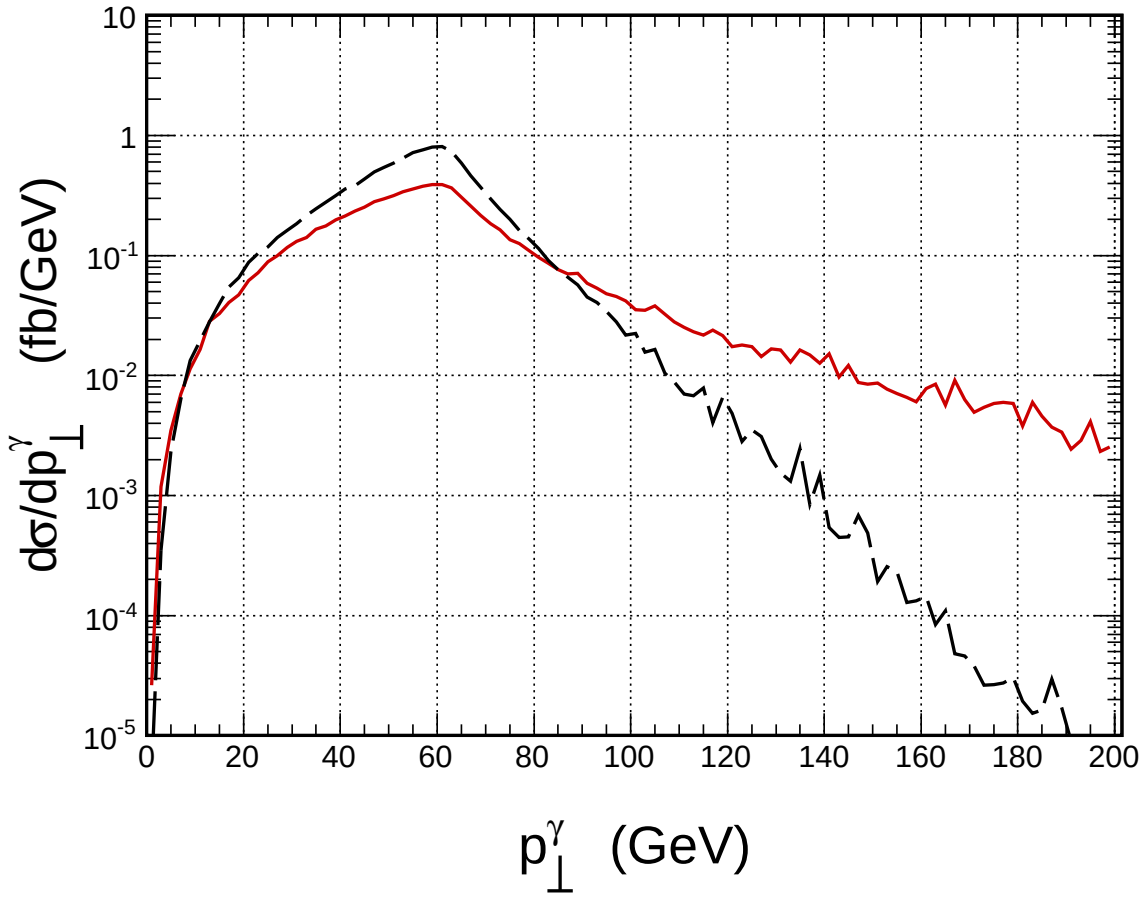
KMR, $\mu_F^2 = m_{t,H}^2$

Two methods



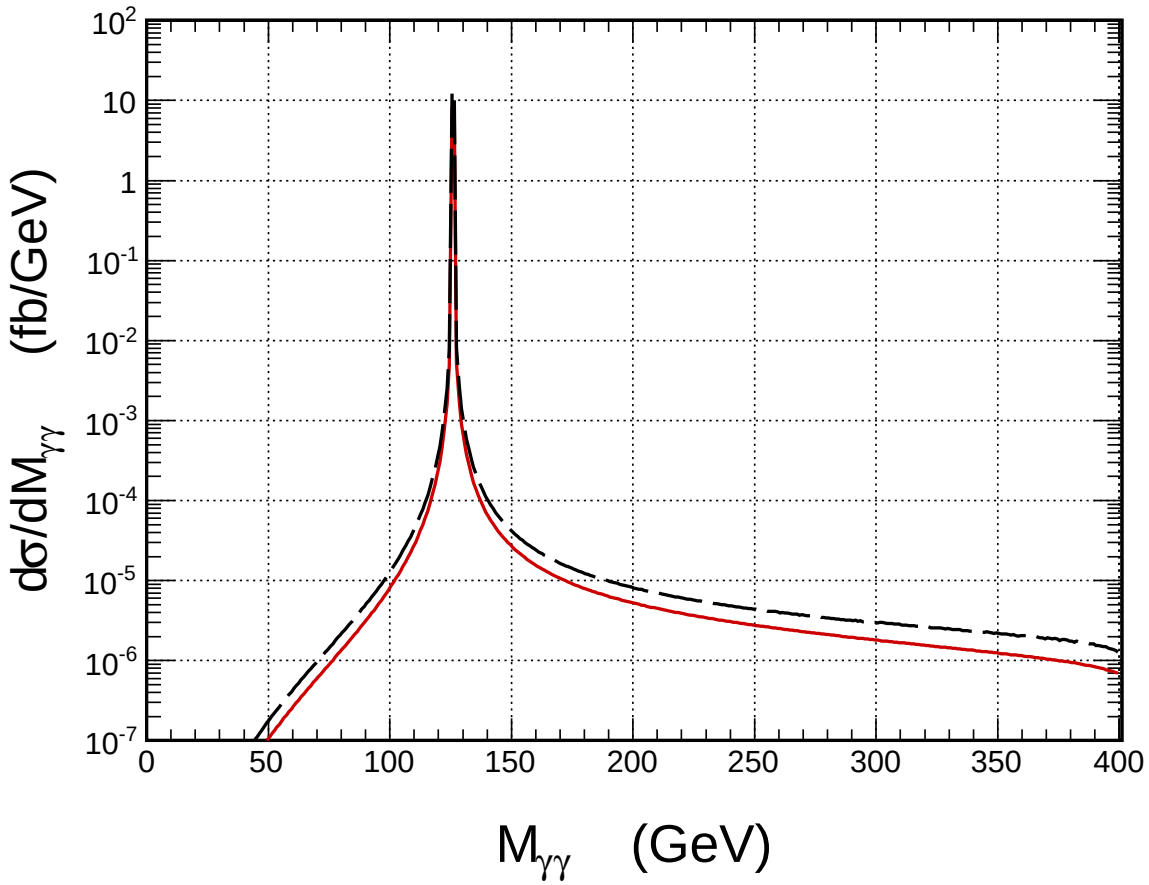
KMR, $\mu_F^2 = m_{t,H}^2$

Second method



KMR ($\mu_F^2 = m_H^2$) - red, versus Jung CCFM A0 - black

Second method



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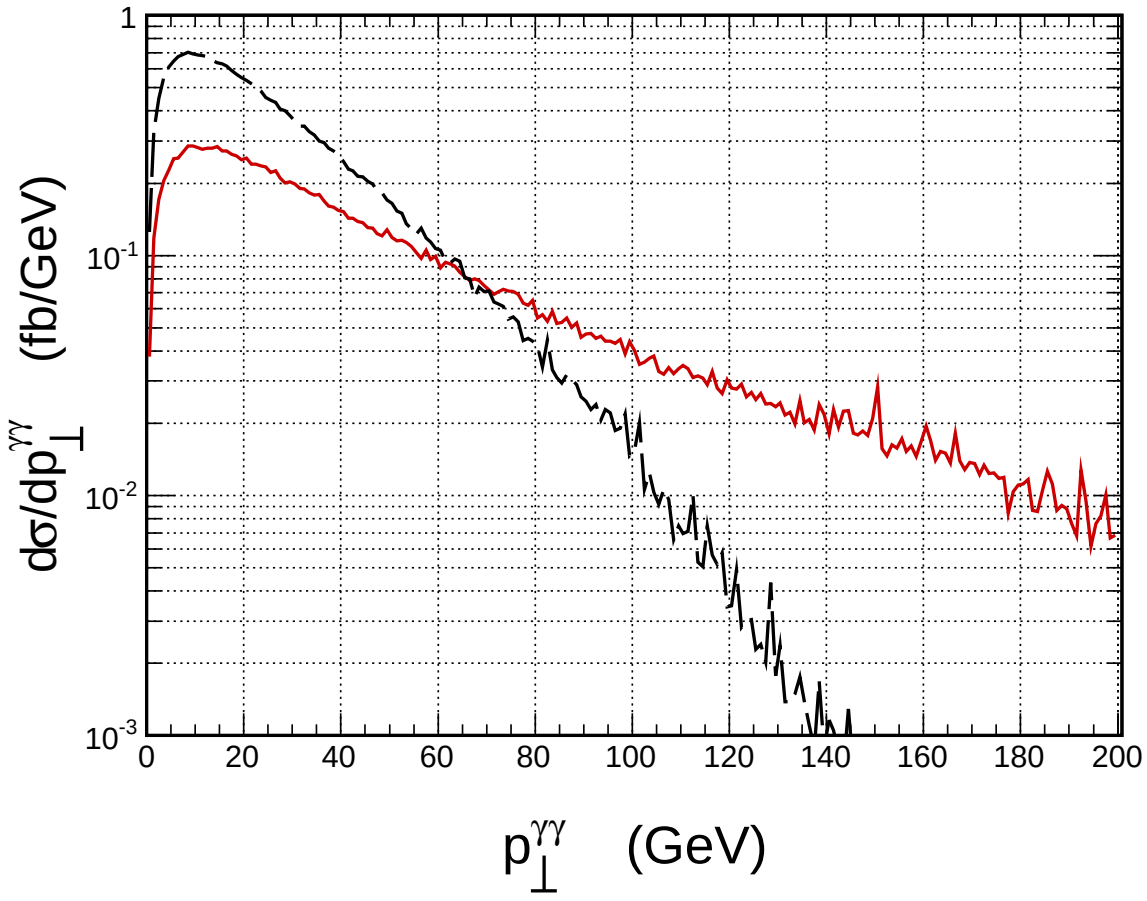

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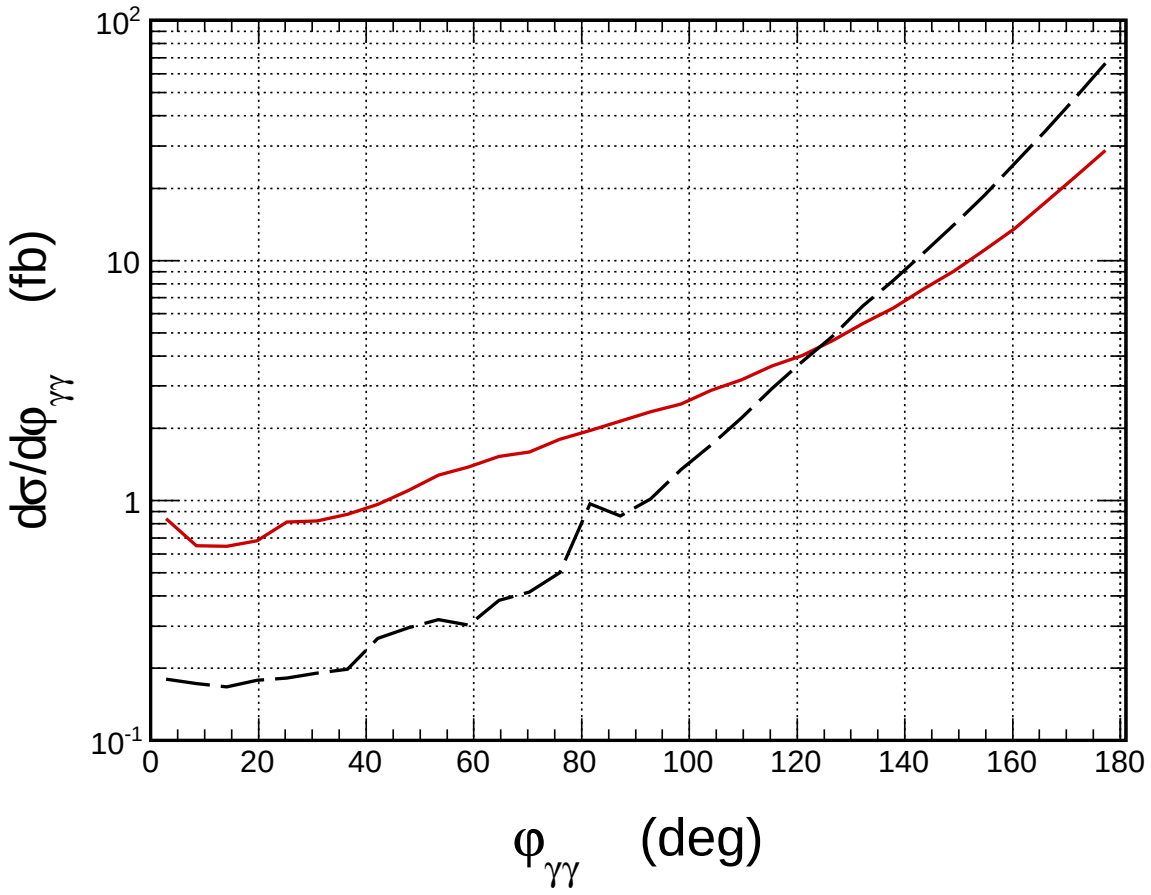
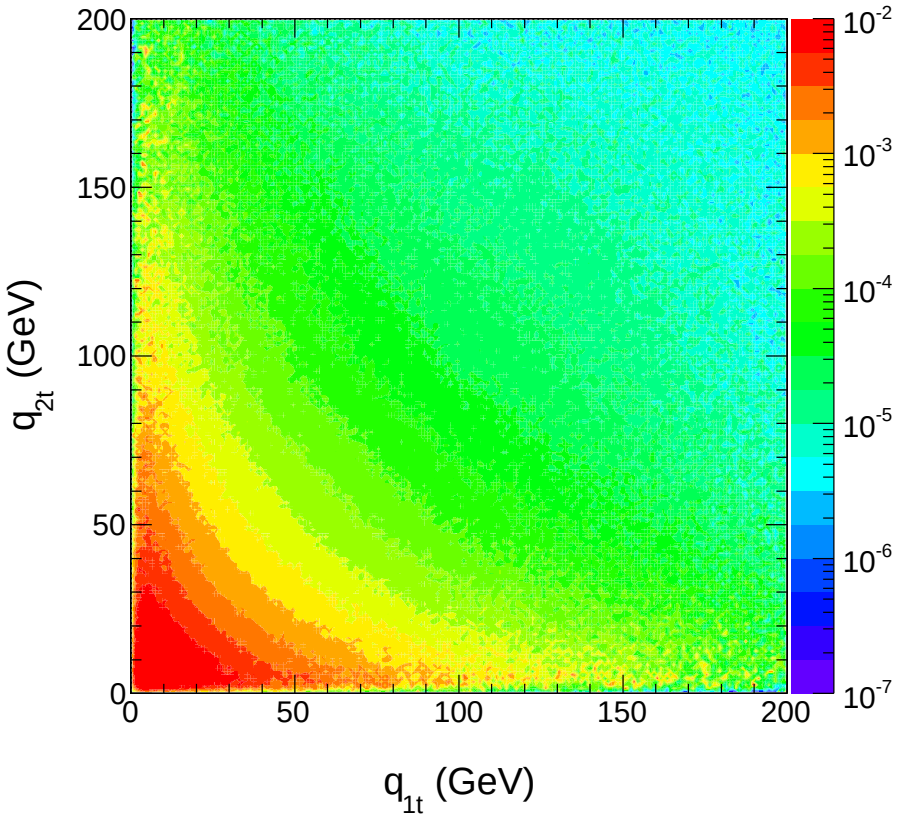
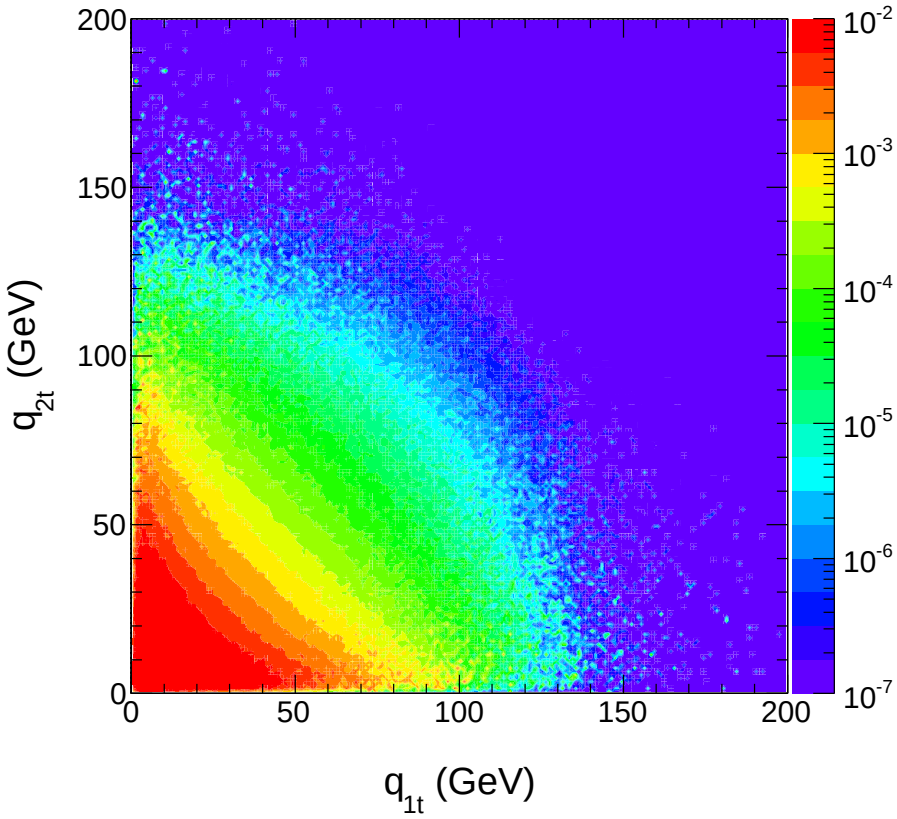


KMR ($\mu_F^2 = m_H^2$) - red, versus Jung CCFM A0 - black

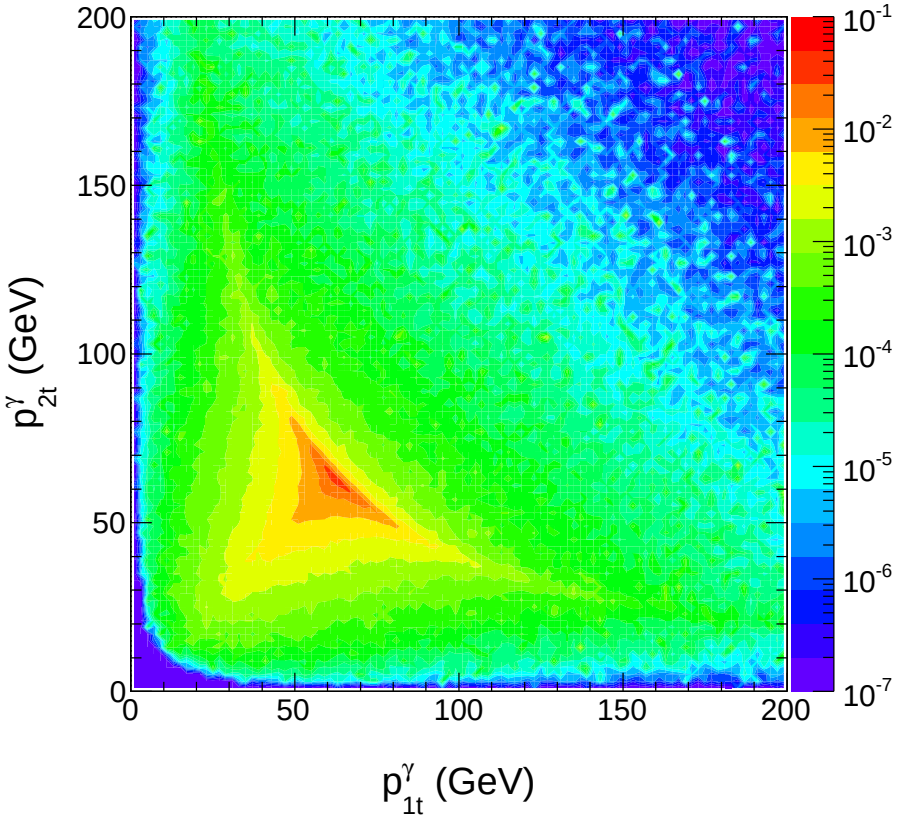
Second method

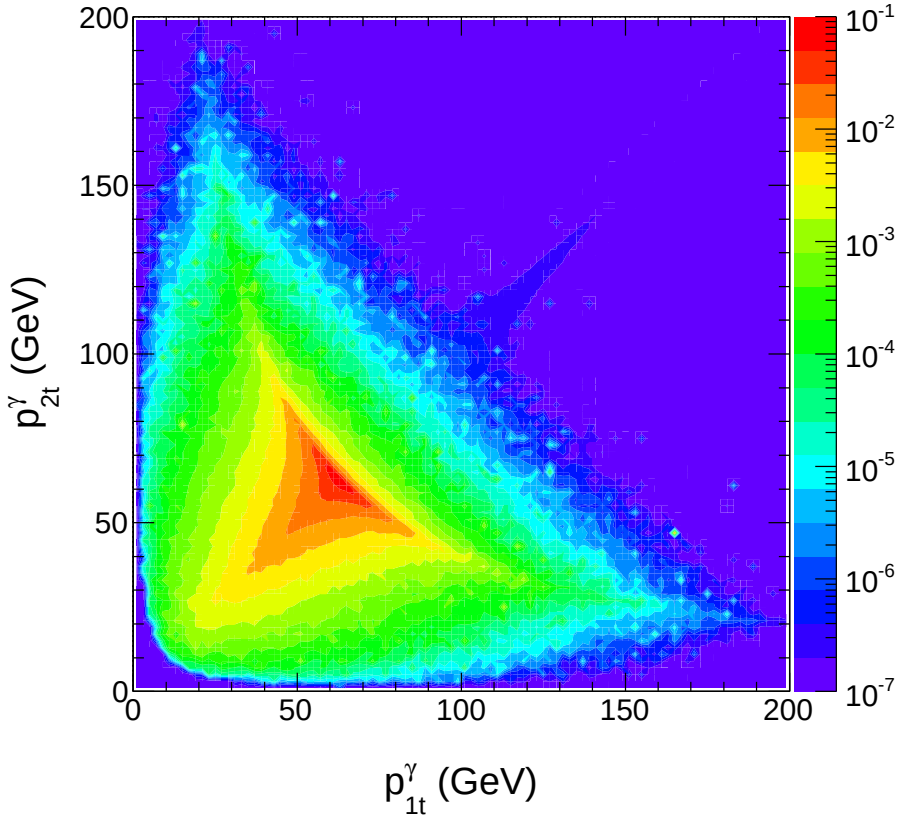




KMR ($\mu_F^2 = m_H^2$) - red, versus Jung CCFM A0 - black

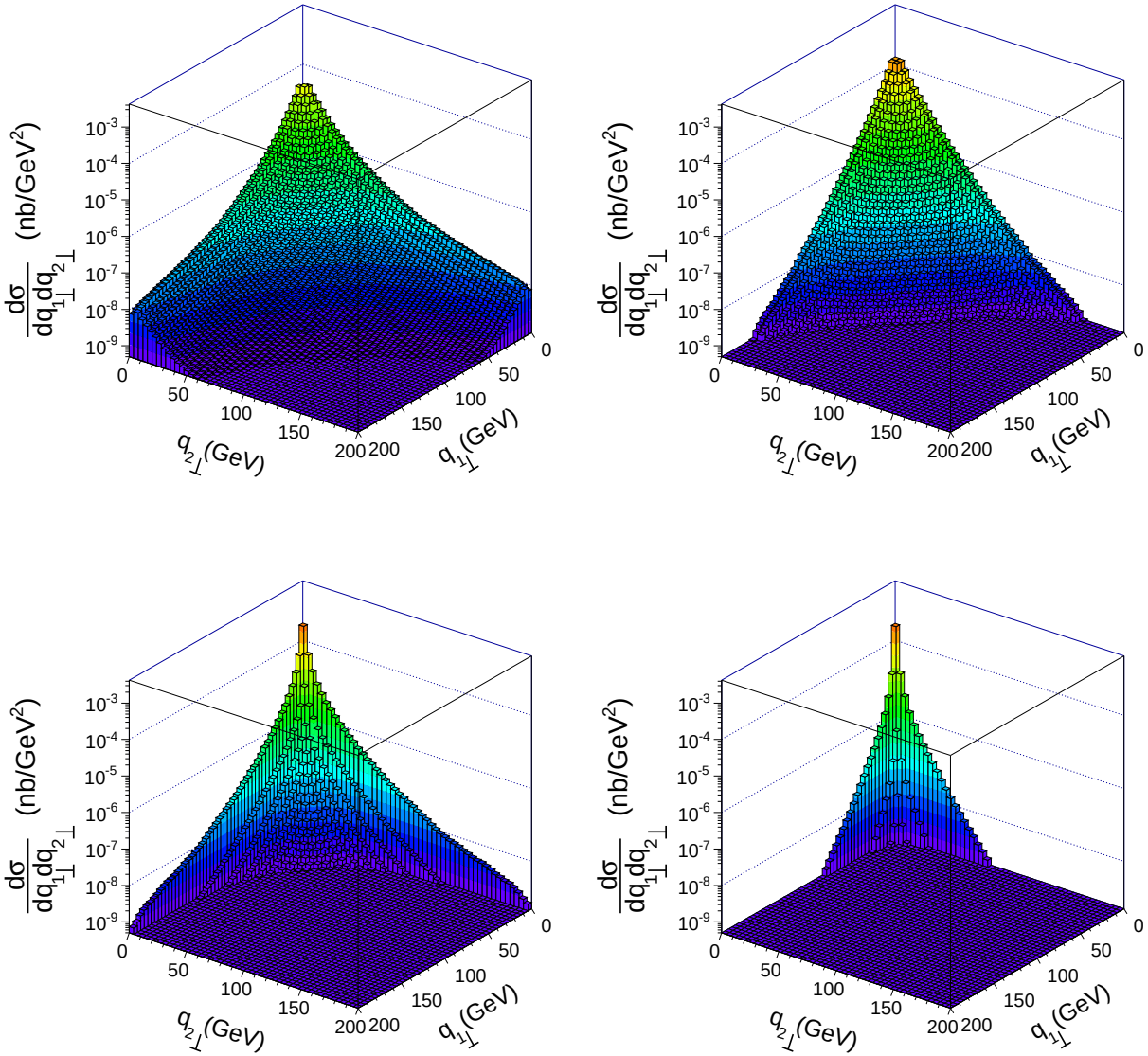
Second method



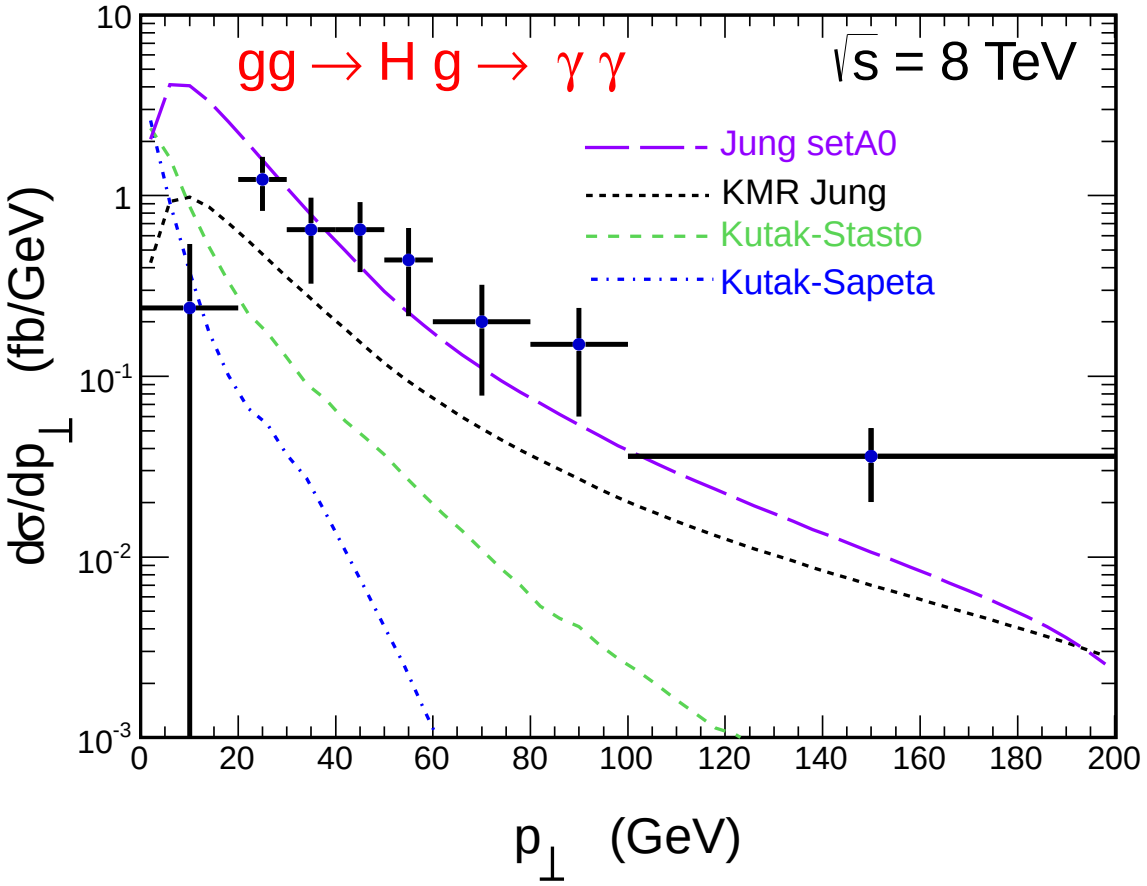


KMR ($\mu_F^2 = m_H^2$) - red, versus Jung CCFM A0 - black

Higgs and one jet

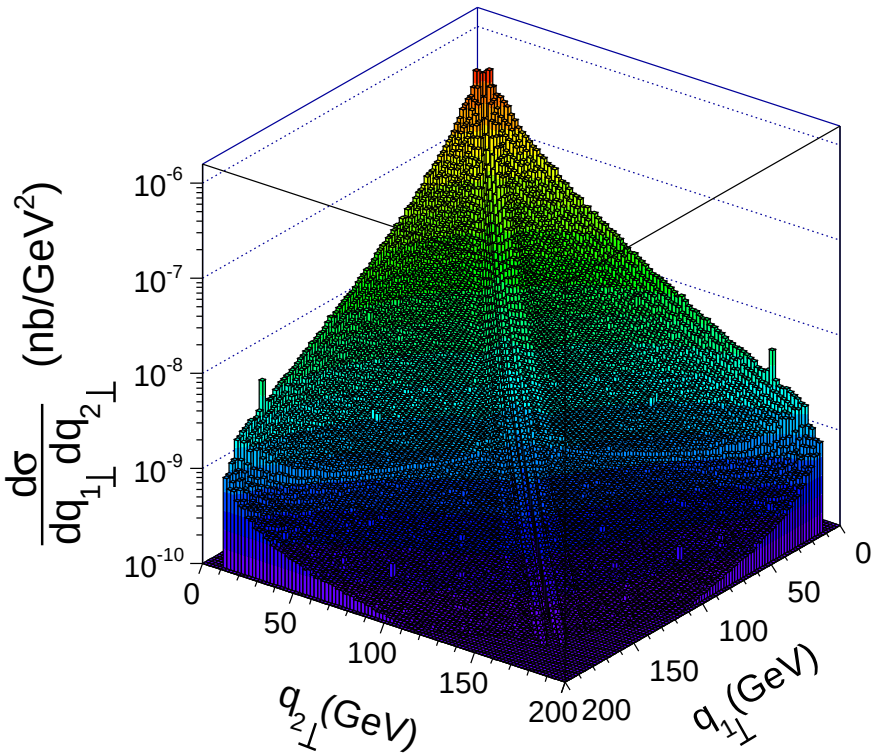


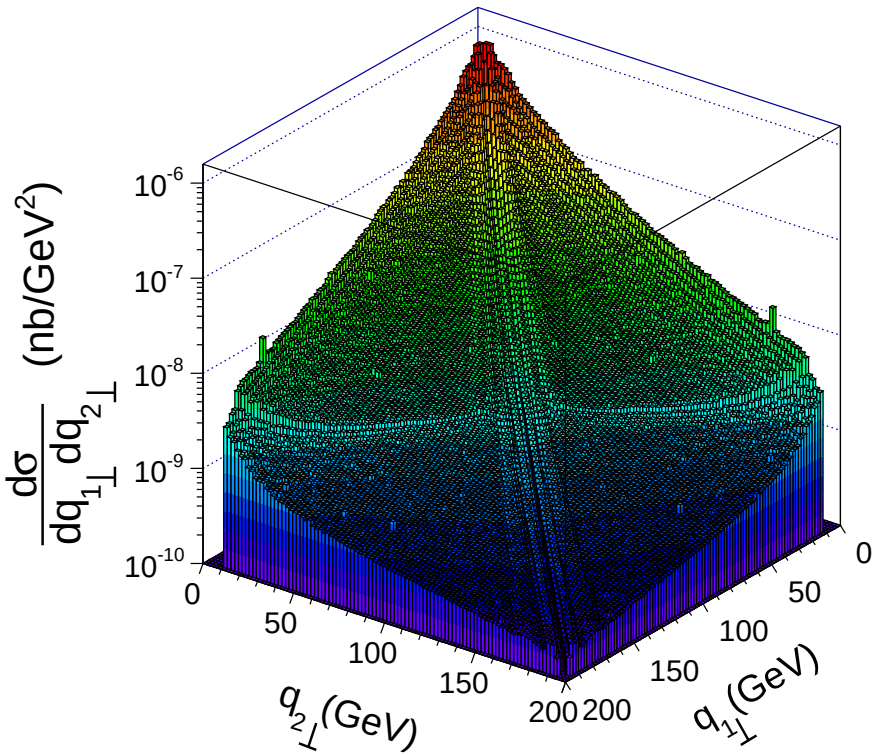
Higgs and one jet



$gg \to Hg$

Higgs and two jets



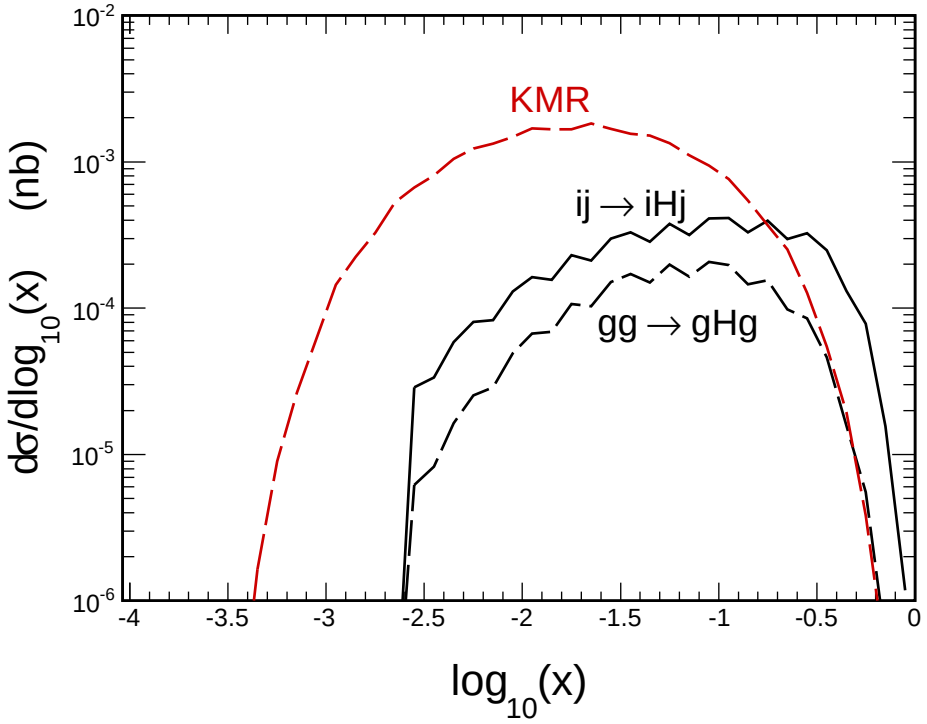


$gg \to gHg$ vs $ij \to iHj$

Del Duca et al. matrix elements

(high-energy approximation, large jet rapidity separation)

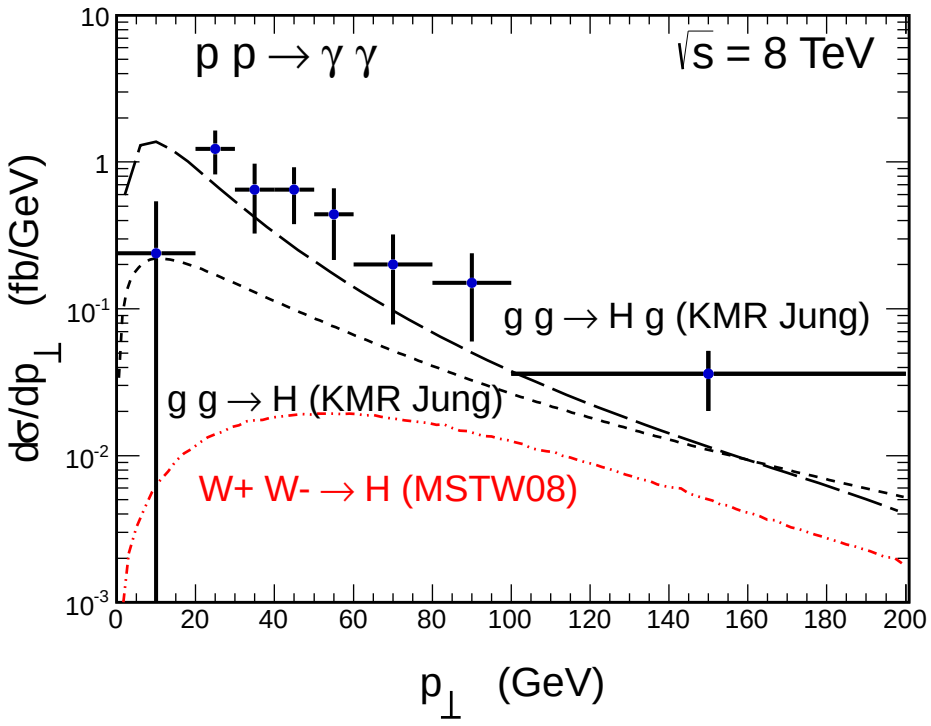
NLO vs KMR UGDF



x_1 and x_2 for k_t-factorization with KMR UGDF much smaller than for NNLO collinear approximation.

k_t-factorization does not include explicitly (di)jets in calculation of x_1 and/or x_2.

Other contributions



some contributions still missing.

Conclusions

- We have analysed production of Higgs boson in the two-photon channel within k_t-factorization.
- Off-shell matrix element and UGDF are ingredients of the approach.
- Two methods has been considered.
  Not completely equivalent.
- Different UGDFs give quite different results.
- LO k_t-factorization underpredicts two-photon data in contrast to recent claims.
- NLO corrections have to be taken into account.
  $gg \to Hg$ especially important. Also Higgs associated with quark/antiquark dijets is nonnegligible.
- Electroweak corrections are large.
- Only combined analysis including all ingredients can provide a possibility to test UGDFs.