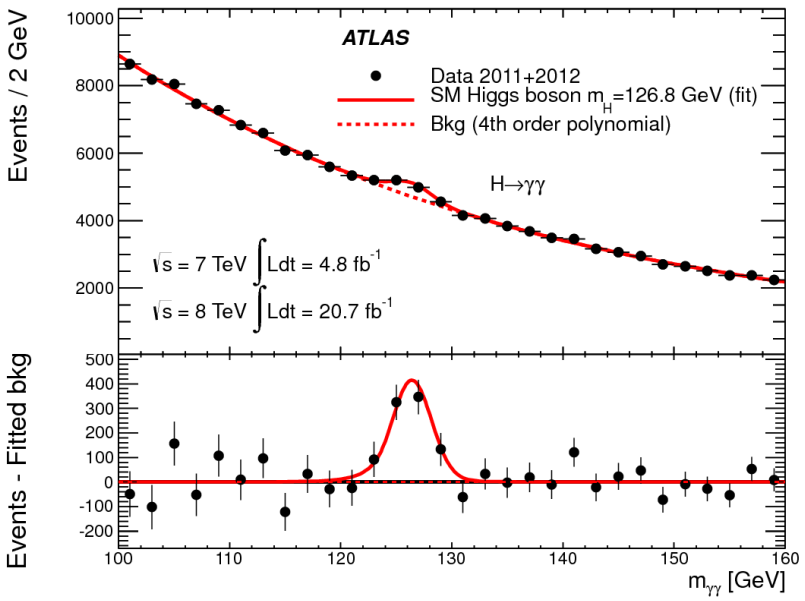
Differential cross section for the Higgs boson production in 4 lepton channel at LHC and k_T factorization approach

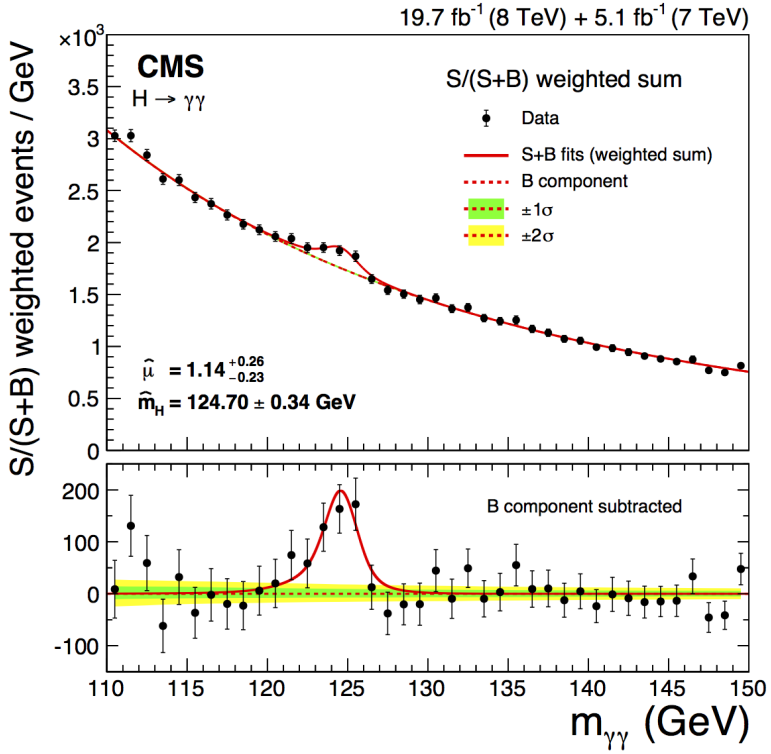
Vaibhav S. Rawoot,
IMSc, Chennai, India

In collaboration with

Rashidul Islam (Calcutta University, Kolkata), Mukesh Kumar (University of Witwatersrand, Johannesburg) and V. Ravindran (IMSc, Chennai)

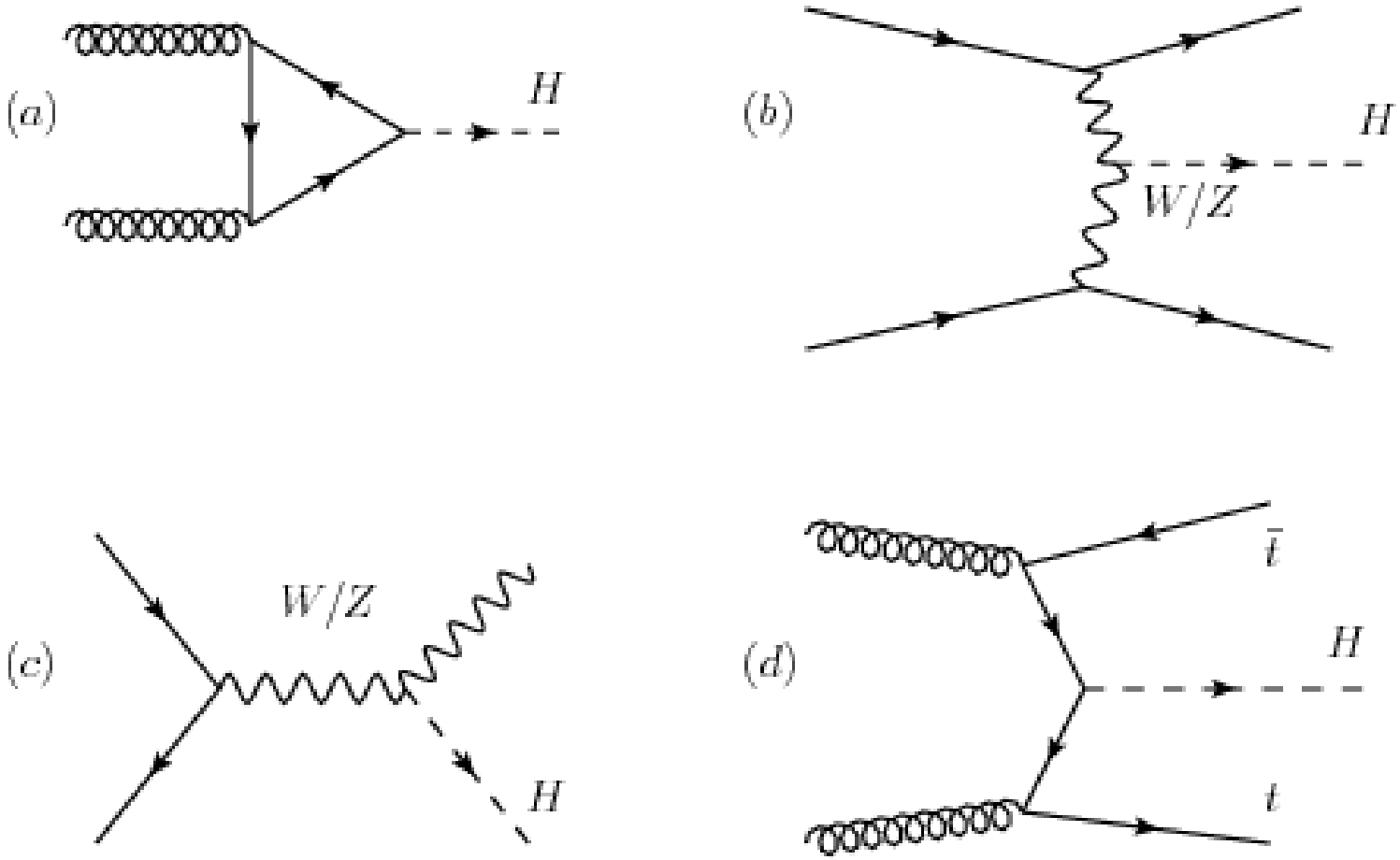
The Higgs Discovery at ATLAS and CMS





Plots from CMS and ATLAS collaboration.

Higgs Production



Higgs Decay Modes

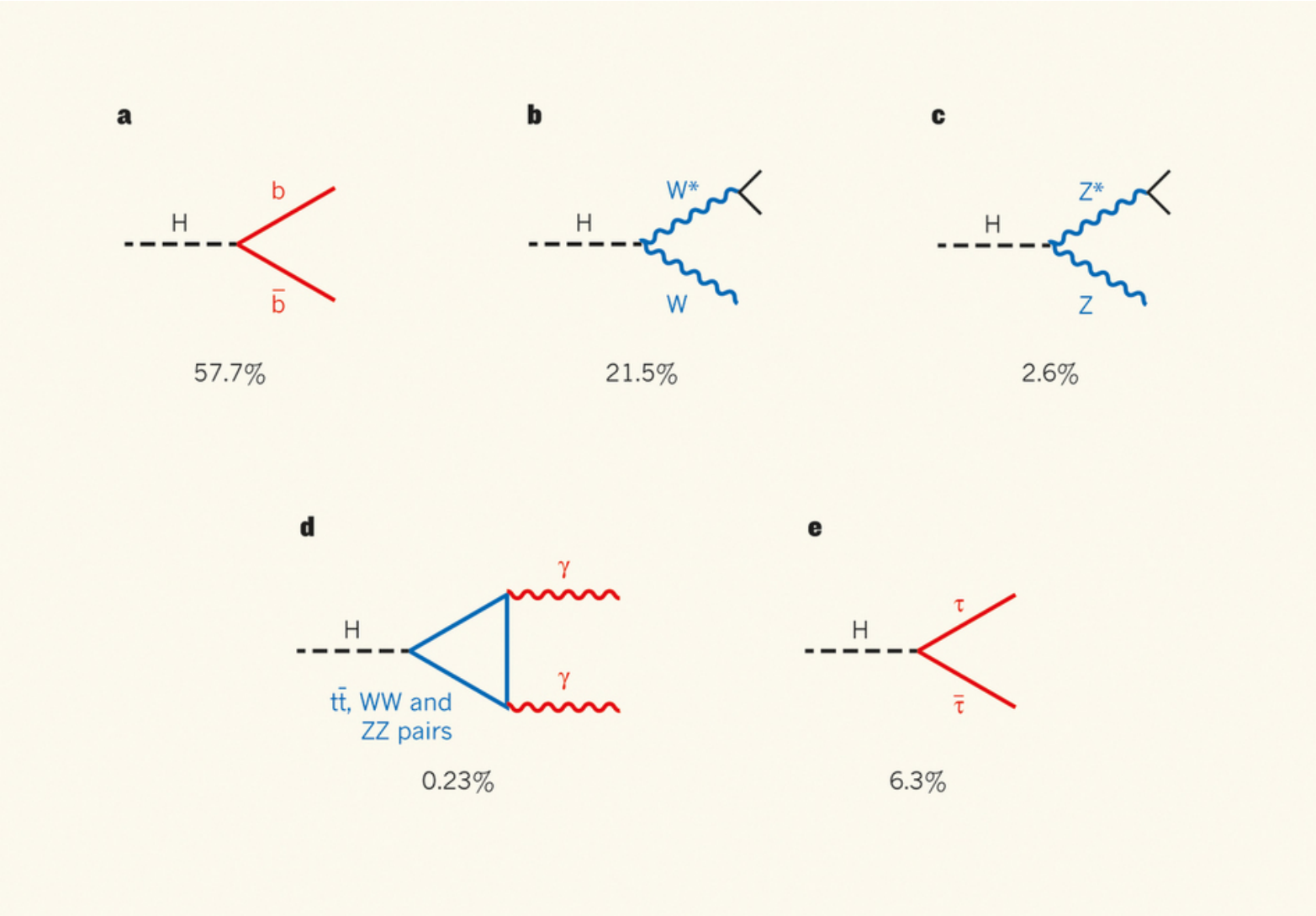
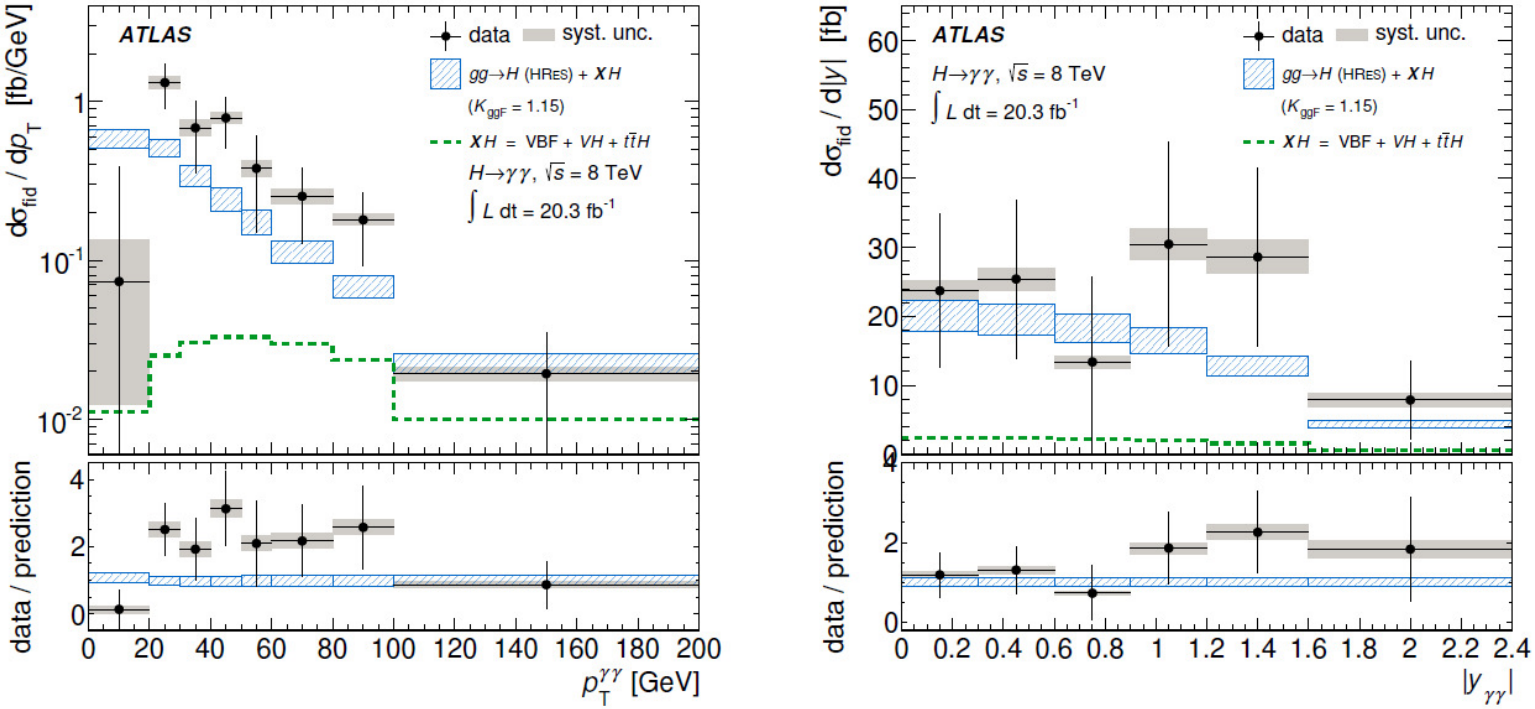


Fig taken from "Frank Wilczek, Nature 496, 439441"

Differential cross section measurement @ATLAS



G. Aad *etal*. [ATLAS Collaboration], JHEP **1409**, 112 (2014)

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- $|\eta| < 2.37$
- $p_T/m_{\gamma\gamma}$ >0.35(0.25)

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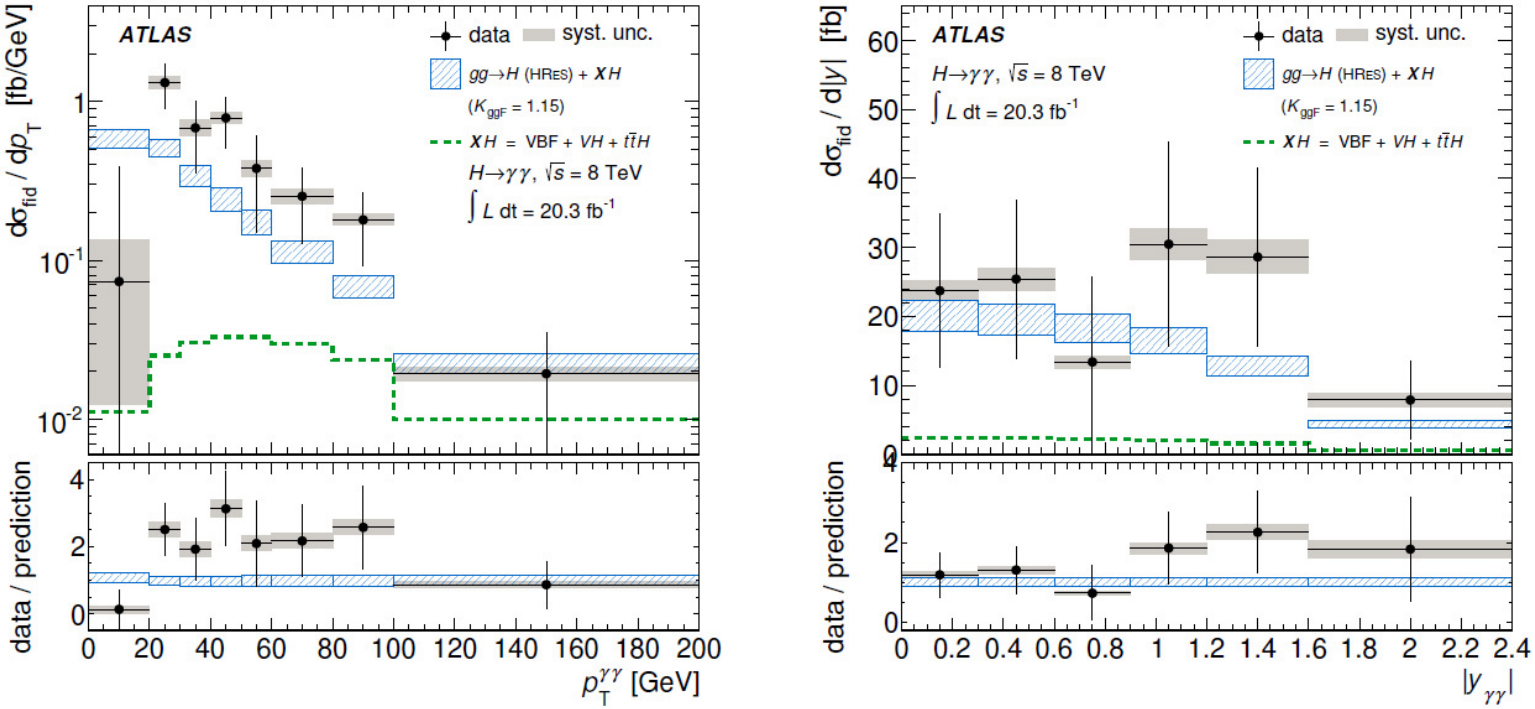

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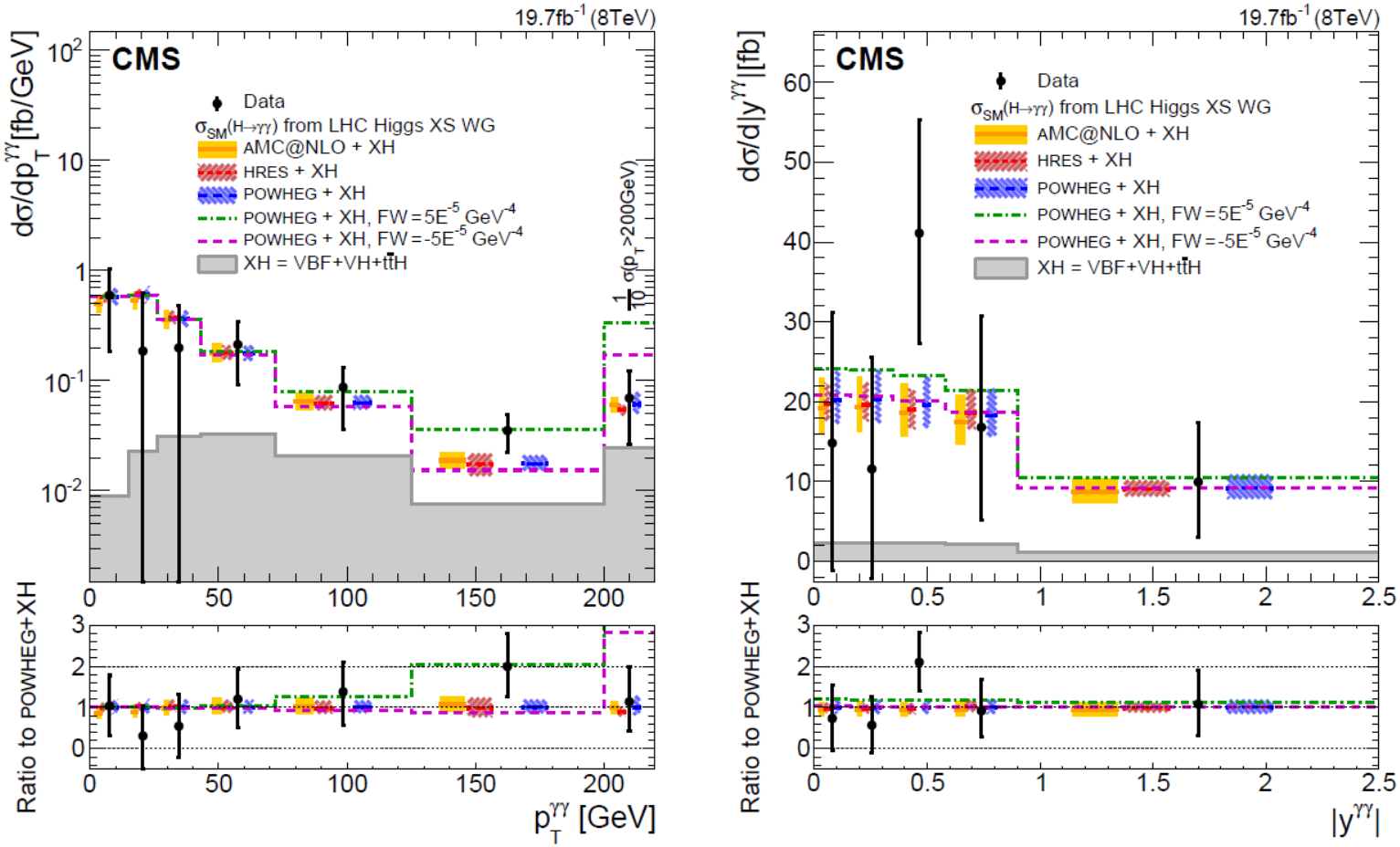

V. Khachatryan *et al.* [CMS Collaboration], arXiv:1508.07819 [hep-ex].

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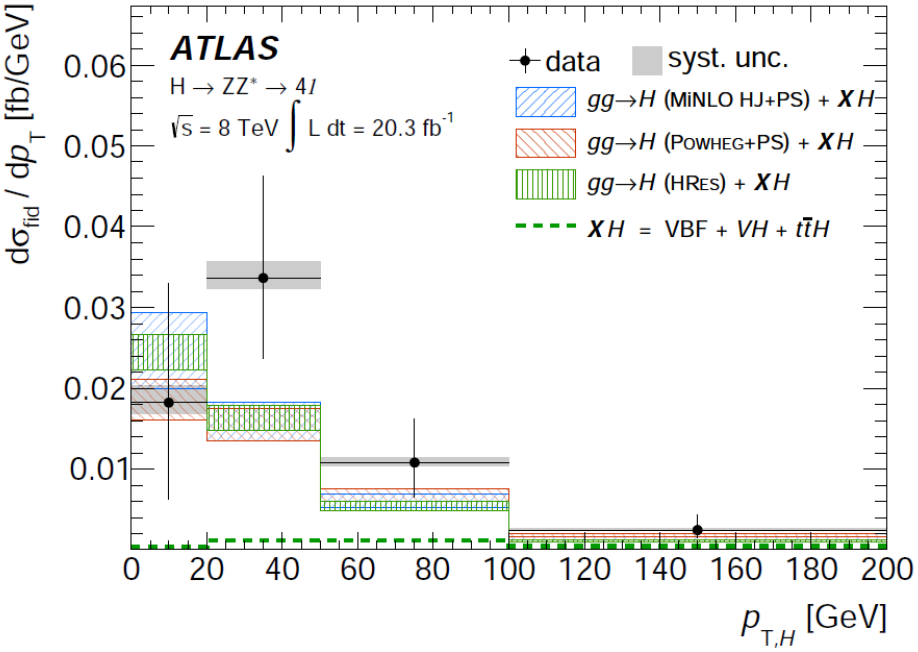

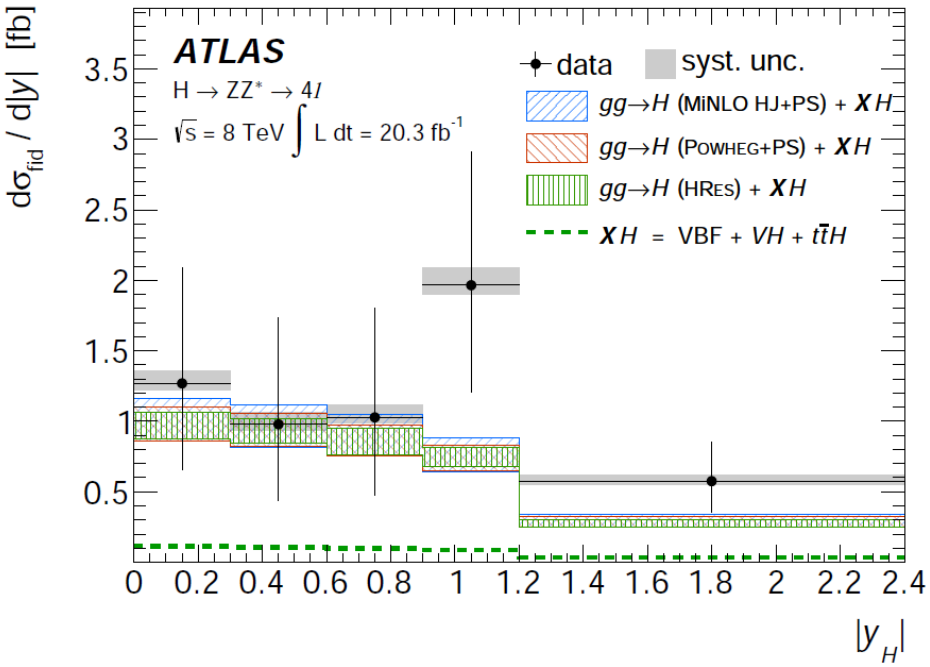

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- $|\eta| < 2.5$
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- 50$< m_{12} <$106 GeV, 12$< m_{34} <$115 GeV.

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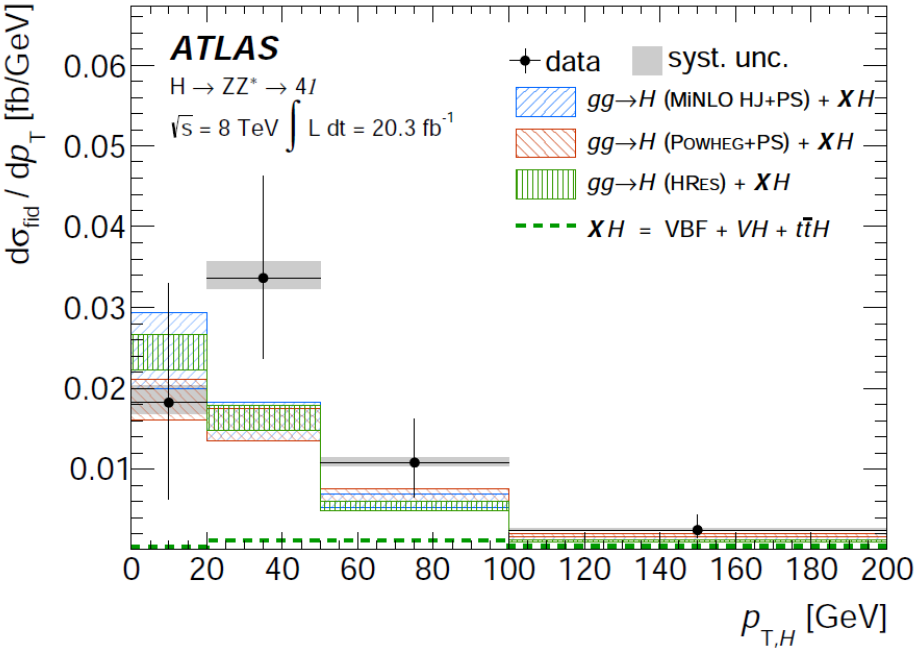

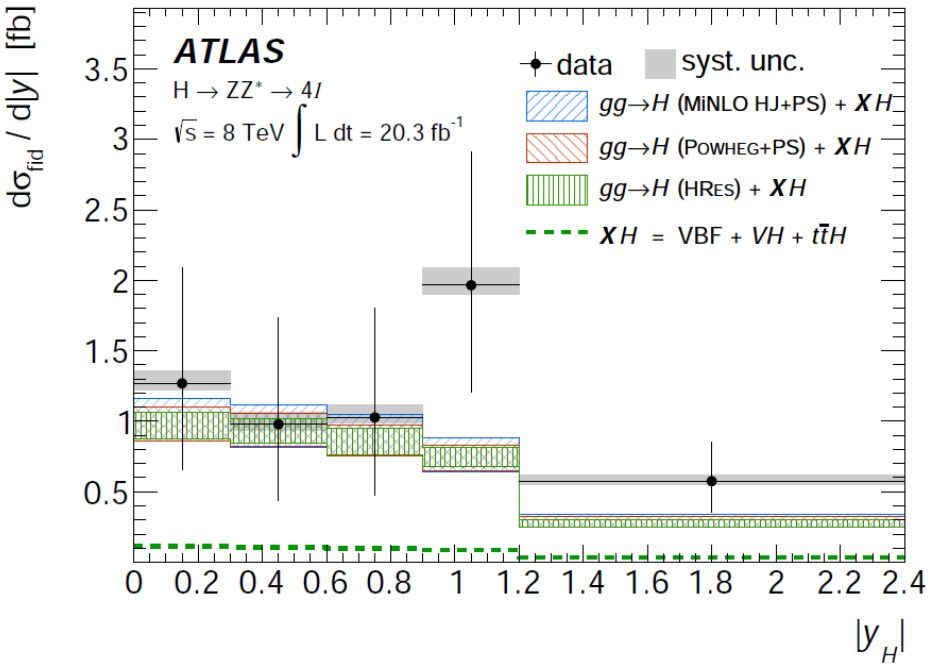

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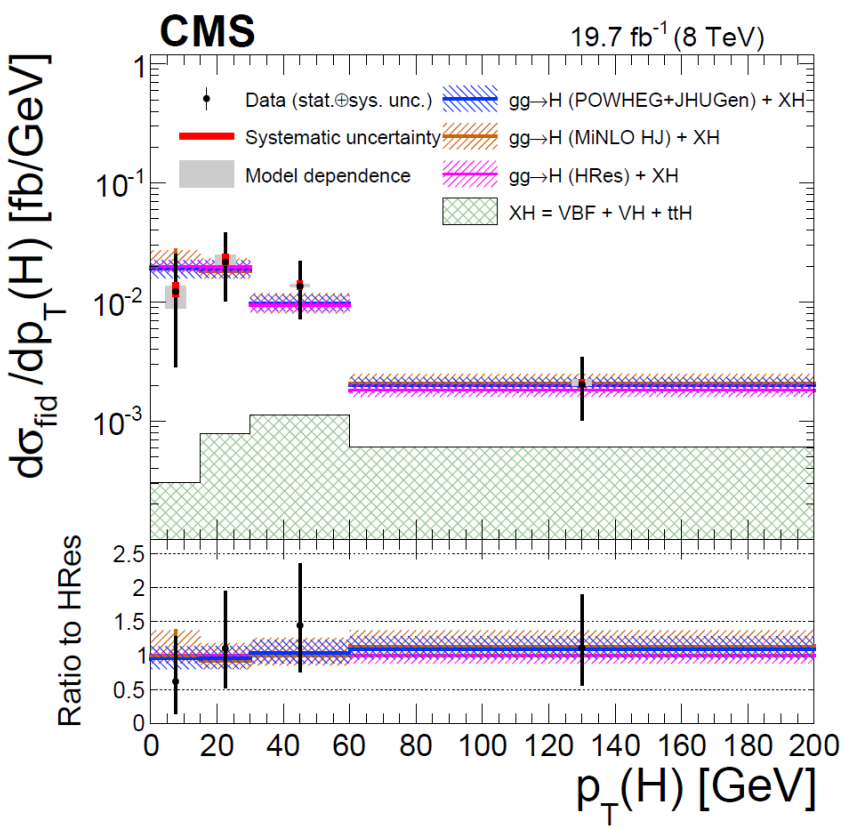

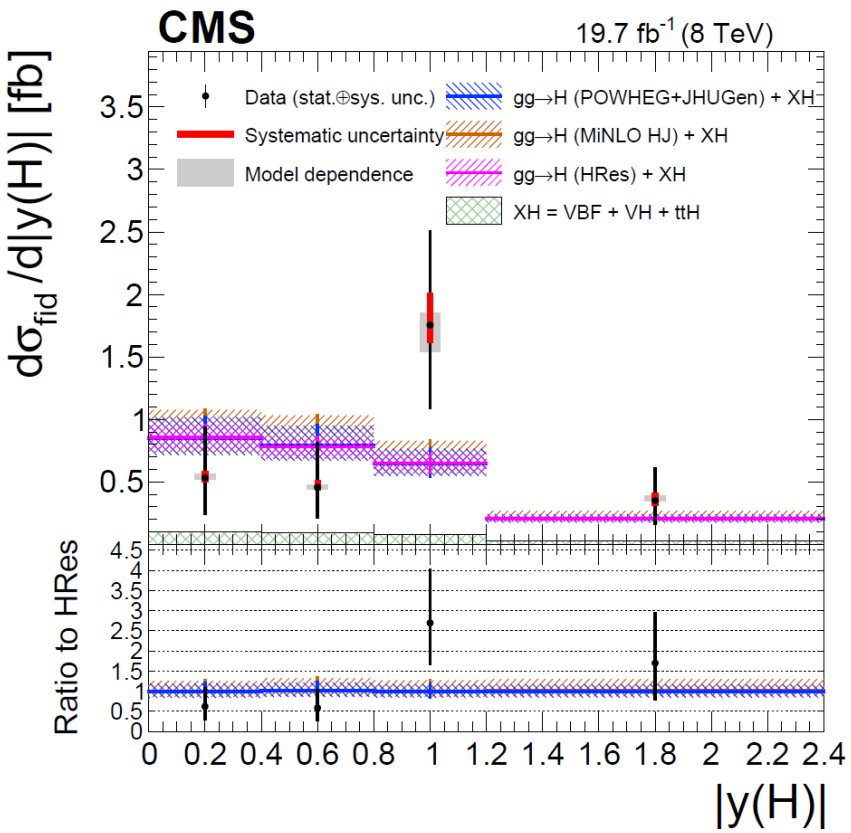

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HNNLO and HRes

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- $H \to \gamma\gamma, H \to ZZ \to l'\bar{l}'l\bar{l}, H \to WW \to lvl'v'$
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- Collinear factorization

$$\sigma(h_1 h_2 \to F) = f_{a/h_1}(x_1, Q^2) \otimes f_{b/h_2}(x_2, Q^2) \otimes \hat{\sigma}_{(ab\to F)}(Q^2) + \mathcal{O}(\Lambda/Q)$$

- Process dependent partonic cross section

$$\begin{aligned} \hat{\sigma}(Q^2) &= \underset{LO}{\hat{\sigma}^{(0)}} + \underset{NLO}{\alpha_s(Q^2)\hat{\sigma}^{(1)}} + \underset{NNLO}{\alpha_s^2(Q^2)\hat{\sigma}^{(2)}} + \ldots\ldots \end{aligned}$$

- Collinear approximation in parton model and evolution of parton densities discribed by Dokshitzer-Gribov-Lipatov-Altarelli-Parisi (DGLAP) evolution equation.
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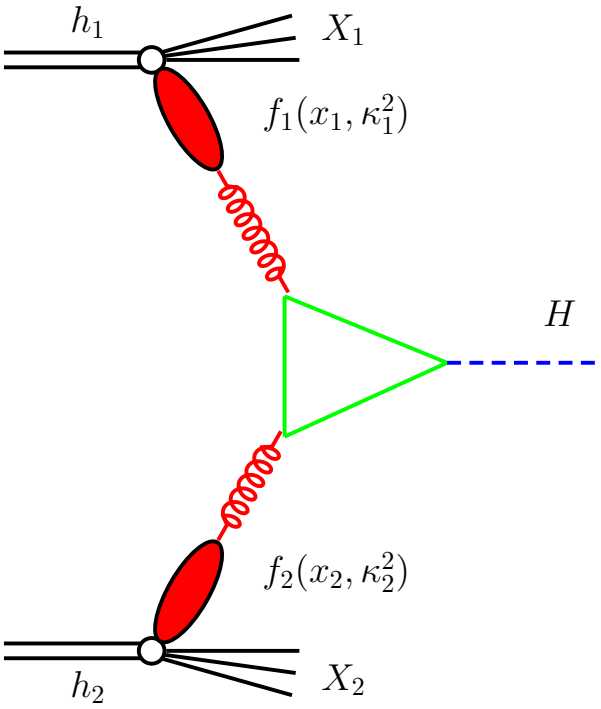
k_T factorisation for the inclusive Higgs production

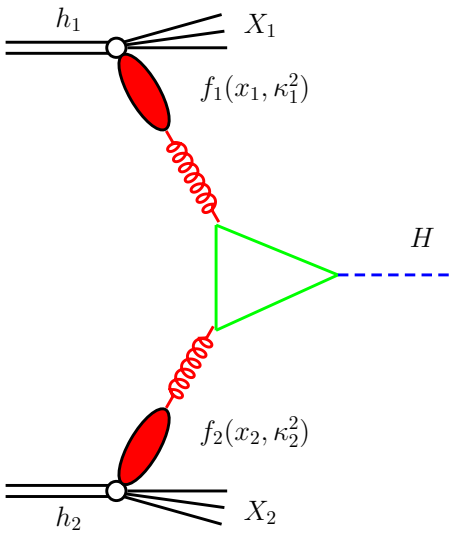


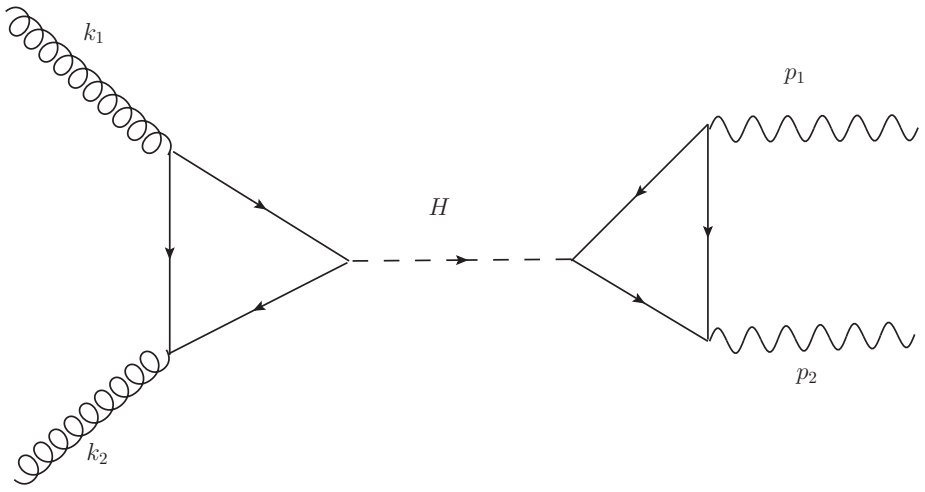
$$\sigma_{pp\to H} = \int \frac{dx_1}{x_1}\frac{dx_2}{x_2}\frac{d^2k_{1T}}{\pi}\frac{d^2k_{2T}}{\pi} \quad \delta\left((k_1+k_2)^2 - M_H^2\right)\sigma_{g^*g^*\to H}(x_1, x_2, k_1, k_2)$$

$$\times\, f_g(x_1, k_{1T}^2, \mu_F^2) f_g(x_2, k_{2T}^2, \mu_F^2)$$

k_T factorisation for $pp \to H \to \gamma\gamma$

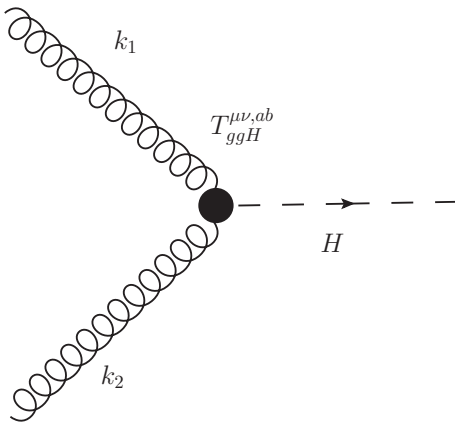
A. V. Lipatov, M. A. Malyshev and N. P. Zotov, Phys. Lett. B **735**, 79 (2014)





$$\frac{d\sigma(pp \to H \to \gamma\gamma)}{dy_1 dy_2 d^2p_{1T} d^2p_{2T}} = \frac{1}{16\pi^2 (x_1 x_2 s)^2} \frac{1}{2} \int \frac{d^2k_{1T}}{\pi} \frac{d^2k_{2T}}{\pi} |\bar{\mathcal{M}}|^2$$
$$\times \quad \delta^2(\boldsymbol{k}_{1T} + \boldsymbol{k}_{2T} - \boldsymbol{p}_{1T} - \boldsymbol{p}_{2T})$$
$$\times \quad f_g(x_1, \boldsymbol{k}_{1T}^2, \mu^2) f_g(x_2, \boldsymbol{k}_{2T}^2, \mu^2)$$

Off-shell $g^* g^* \to H \to \gamma\gamma$ production amplitude

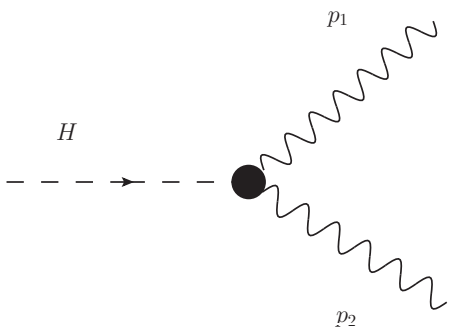


- Effective Trangle Vertex

$$T^{\mu\nu,\,ab}_{ggH}(k_1, k_2) = i\delta^{ab}\frac{\alpha_s}{3\pi}\left(G_F\sqrt{2}\right)^{1/2}\left[k_2^\mu k_1^\nu - (k_1 \cdot k_2)g^{\mu\nu}\right]$$

- Large top mass limit $m_H < 2m_t \to$ Higgs boson mass $m_H \sim 125$ GeV

Off-shell $g^* g^* \to H \to \gamma\gamma$ production amplitude



- Effective vertex $T^{\mu\nu}_{H\gamma\gamma}(p_1, p_2)$

$$T^{\mu\nu}_{H\gamma\gamma}(p_1, p_2) = i\frac{\alpha}{2\pi}\mathcal{A}\left(G_F\sqrt{2}\right)^{1/2}\left[p_2^\mu p_1^\nu - (p_1 \cdot p_2)g^{\mu\nu}\right]$$

Off-shell $g^* g^* \to H \to \gamma\gamma$ production amplitude

Using $k_1^2 = -\boldsymbol{k}_{1T}^2 \neq 0$ and $k_1^2 = -\boldsymbol{k}_{1T}^2 \neq 0$

$$T_{H\gamma\gamma}^{\mu\nu}(p_1, p_2) = i\frac{\alpha}{2\pi}\mathcal{A}\left(G_F\sqrt{2}\right)^{1/2}\left[p_2^\mu p_1^\nu - (p_1 \cdot p_2)g^{\mu\nu}\right]$$

$$T_{ggH}^{\mu\nu,\,ab}(k_1, k_2) = i\delta^{ab}\frac{\alpha_s}{3\pi}\left(G_F\sqrt{2}\right)^{1/2}\left[k_2^\mu k_1^\nu - (k_1 \cdot k_2)g^{\mu\nu}\right]$$

$$\sum \epsilon^\mu \epsilon^{*\nu} = \frac{\boldsymbol{k}_T^\mu \boldsymbol{k}_T^\nu}{\boldsymbol{k}_T^2}$$

- Differential cross section for di-photon production from the $g^* g^* \to H \to \gamma\gamma$

$$\begin{aligned}\frac{d\sigma(pp \to H \to \gamma\gamma)}{dy_1 dy_2 d^2p_{1T} d^2p_{2T}} &= \frac{1}{16\pi^2 (x_1 x_2 s)^2} \frac{1}{2} \int \frac{d^2k_{1T}}{\pi} \frac{d^2k_{2T}}{\pi} |\bar{\mathcal{M}}|^2 \\ &\times \delta^2(\boldsymbol{k}_{1T} + \boldsymbol{k}_{2T} - \boldsymbol{p}_{1T} - \boldsymbol{p}_{2T}) \\ &\times f_g(x_1, \boldsymbol{k}_{1T}^2, \mu^2) f_g(x_2, \boldsymbol{k}_{2T}^2, \mu^2)\end{aligned}$$

- $$x_1\sqrt{s} = |\mathbf{p}_{1T}| e^{y_1} + |\mathbf{p}_{2T}| e^{y_2}$$
$$x_2\sqrt{s} = |\mathbf{p}_{1T}| e^{-y_1} + |\mathbf{p}_{2T}| e^{-y_2}$$

- Study for $pp \to H \to 4\,leptons$ will be an interesting analysis.

- Differential cross section for di-photon production from the $g^* g^* \to H \to \gamma\gamma$

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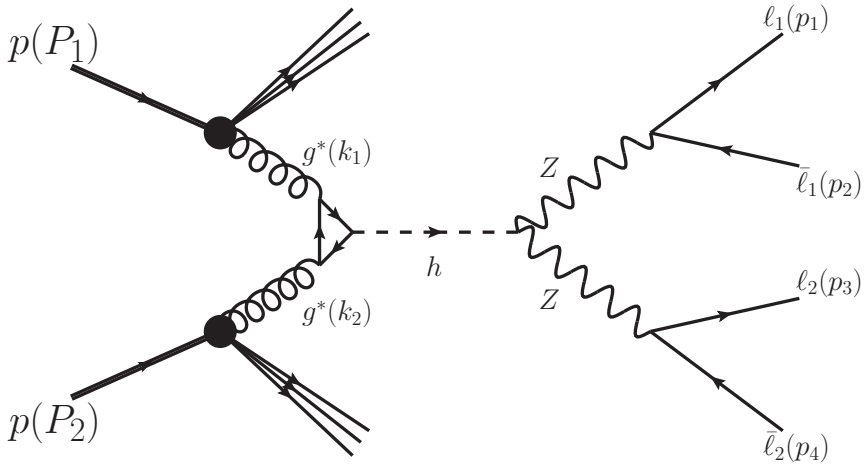
- Study for $pp \to H \to 4\,leptons$ will be an interesting analysis.

$pp \to H \to ZZ \to l_1\bar{l}_1 l_2\bar{l}_2$



$$\sigma = \int dy_1 dy_2 dy_3 dy_4 d^2\boldsymbol{p}_{1T} d^2\boldsymbol{p}_{2T} d^2\boldsymbol{p}_{3T} d^2\boldsymbol{p}_{4T} \frac{d^2\boldsymbol{k}_{1T}}{\pi} \frac{d^2\boldsymbol{k}_{2T}}{\pi} \frac{1}{(2^{12})\pi^8 (x_1 x_2 s)^2} |\bar{\mathcal{M}}|^2 \quad ($$

$$\delta^2(\boldsymbol{k}_{1T} + \boldsymbol{k}_{2T} - \boldsymbol{p}_{1T} - \boldsymbol{p}_{2T} - \boldsymbol{p}_{3T} - \boldsymbol{p}_{4T}) f_g(x_1, \boldsymbol{k}_{1T}^2) f_g(x_2, \boldsymbol{k}_{2T}^2)$$

with

$$x_1 = \frac{|\boldsymbol{p}_{1T}|}{\sqrt{s}} e^{y_1} + \frac{|\boldsymbol{p}_{2T}|}{\sqrt{s}} e^{y_2} + \frac{|\boldsymbol{p}_{3T}|}{\sqrt{s}} e^{y_3} + \frac{|\boldsymbol{p}_{4T}|}{\sqrt{s}} e^{y_4}$$

and

$$x_2 = \frac{|\boldsymbol{p}_{1T}|}{\sqrt{s}} e^{-y_1} + \frac{|\boldsymbol{p}_{2T}|}{\sqrt{s}} e^{-y_2} + \frac{|\boldsymbol{p}_{3T}|}{\sqrt{s}} e^{-y_3} + \frac{|\boldsymbol{p}_{4T}|}{\sqrt{s}} e^{-y_4}$$

$pp \to H \to ZZ \to l_1\bar{l}_2 l_2\bar{l}_2$

$$\frac{d\sigma}{dy_1 dy_2 dy_3 dy_4 d\boldsymbol{p}_{1T}^2 d\boldsymbol{p}_{2T}^2 d\boldsymbol{p}_{3T}^2} = \int d\boldsymbol{k}_{1T}^2 d\boldsymbol{k}_{2T}^2 \frac{d\phi_1}{2\pi}\frac{d\phi_2}{2\pi}\frac{1}{(2^{12})\pi^5(x_1x_2s)^2}$$
$$|\bar{\mathcal{M}}|^2 f_g(x_1, \boldsymbol{k}_{1T}^2) f_g(x_2, \boldsymbol{k}_{2T}^2)$$

$$\boldsymbol{k}_{1T} + \boldsymbol{k}_{2T} = \boldsymbol{p}_{1T} + \boldsymbol{p}_{2T} + \boldsymbol{p}_{3T} + \boldsymbol{p}_{4T}$$

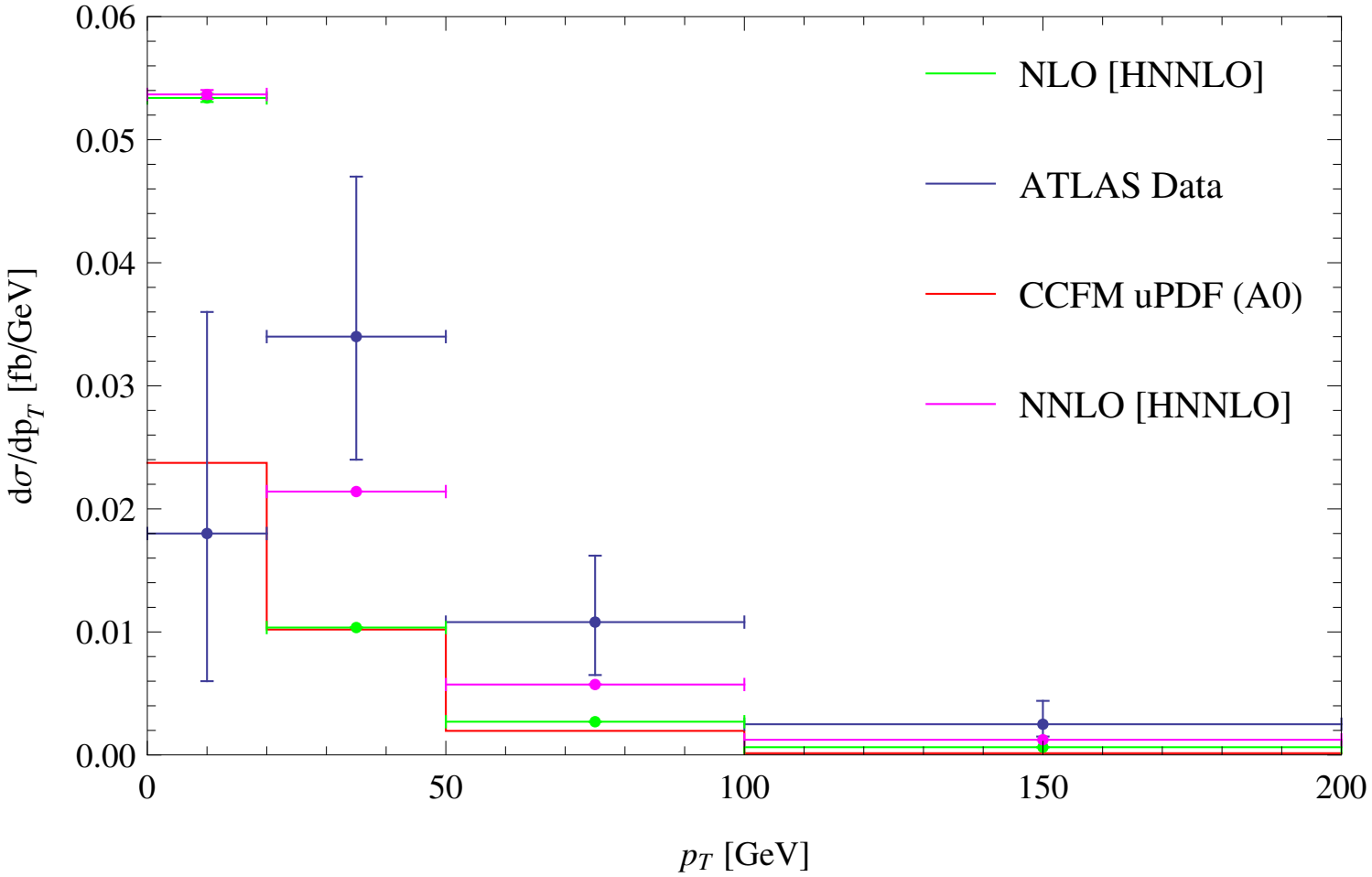
$\mathcal{M}(g*g* \to H \to ZZ \to 4l)$

$$\mathcal{M}(g*g* \to H \to ZZ \to 4l) = \mathcal{M}(g*g* \to H)\frac{1}{\hat{s} - m_H^2 + i\Gamma_H m_H}\mathcal{M}(H \to ZZ \to l_1\,\bar{l_1}\,l_2\,\bar{l_2}$$

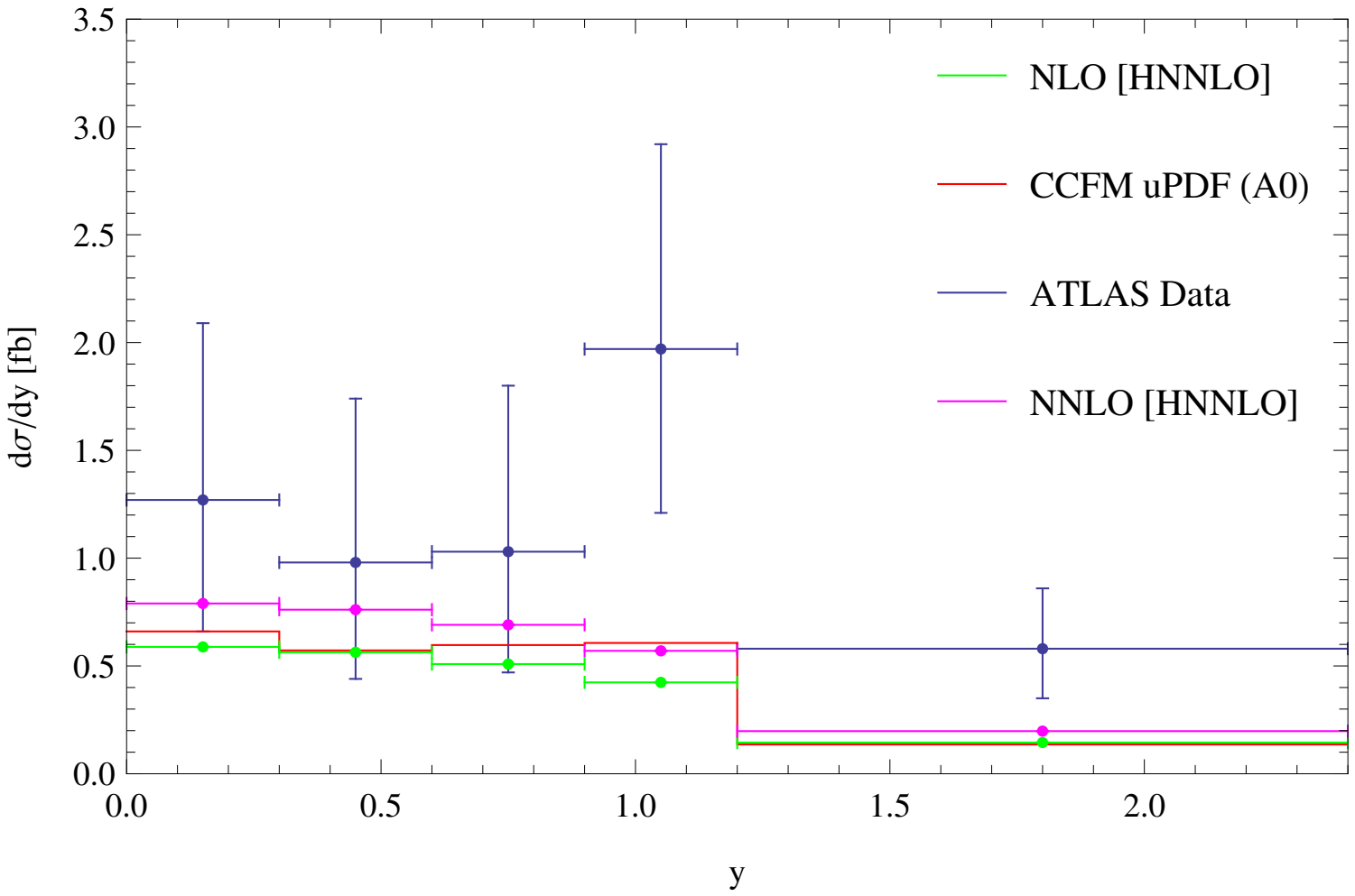
$$\begin{aligned} |\mathcal{M}|^2 \quad = \quad & \frac{2}{9}\frac{\alpha_s^2}{\pi^2}\frac{m_Z^4}{v^4}\frac{\left[(\boldsymbol{k}_{\perp 1} + \boldsymbol{k}_{\perp 2})^2 + \hat{s}\right]^2 \cos^2\phi}{(\hat{s} - m_H^2)^2 + \Gamma_H^2 m_H^2} \\ & \frac{[(p_1 \cdot p_4)(p_2 \cdot p_3)\{2g_L^2 g_R^2\} + (p_1 \cdot p_3)(p_2 \cdot p_4)\{g_L^4 + g_R^4\}]}{[(2p_1 \cdot p_2 - m_Z^2)^2 + \Gamma_Z^2 m_Z^2][(2p_3 \cdot p_4 - m_Z^2)^2 + \Gamma_Z^2 m_Z^2]} \end{aligned}$$

$$g_L = \frac{g_W}{\cos\theta_W}\Big(-\frac{1}{2} + \sin^2\theta_W\Big), \quad g_R = \frac{g_W}{\cos\theta_W}\sin^2\theta_W, \quad \text{and} \quad v = (\sqrt{2}G_F)^{-1/2}$$

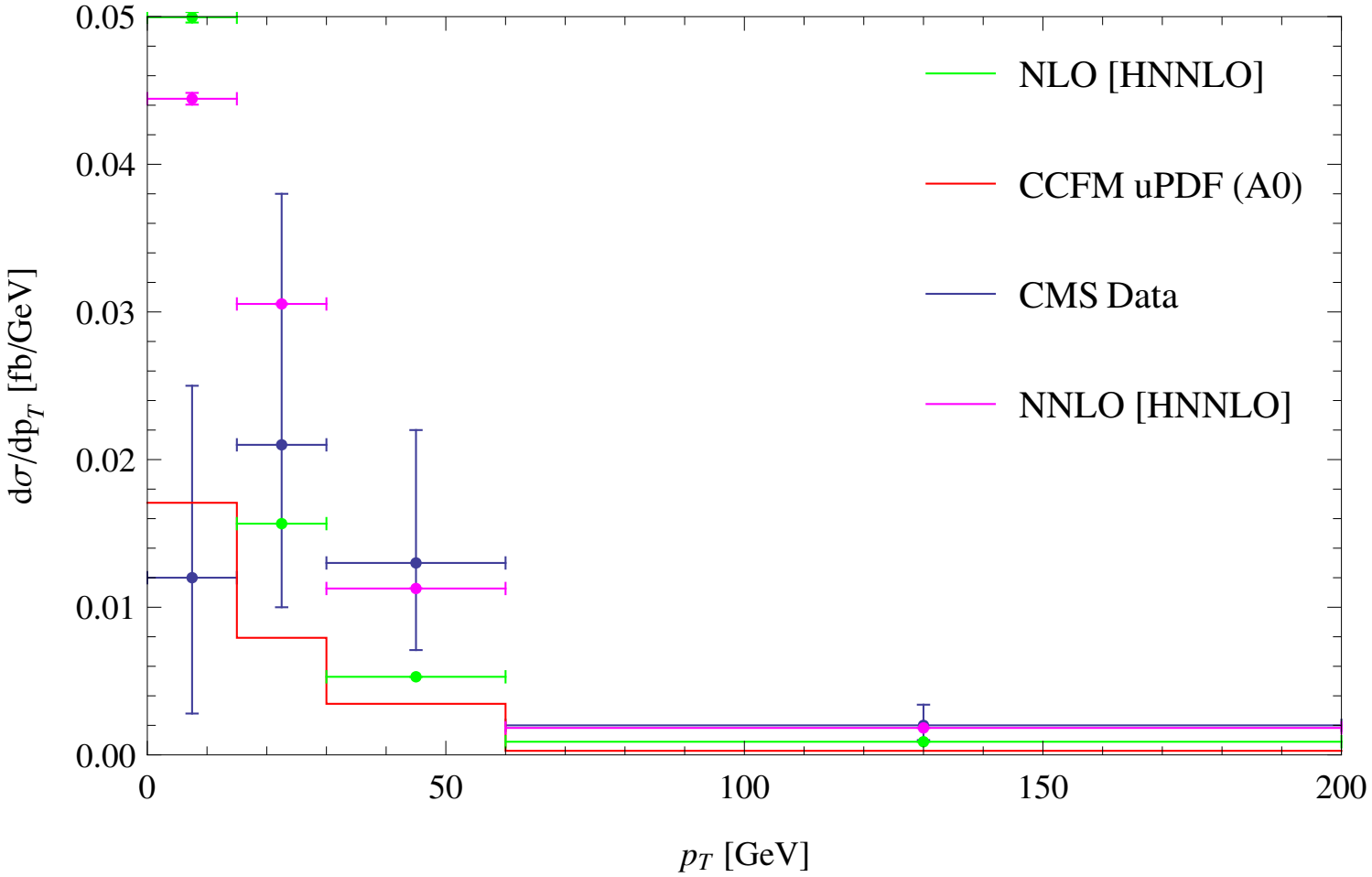
ATLAS data for $pp \to H \to 4\,leptons$ and k_T factorization approach



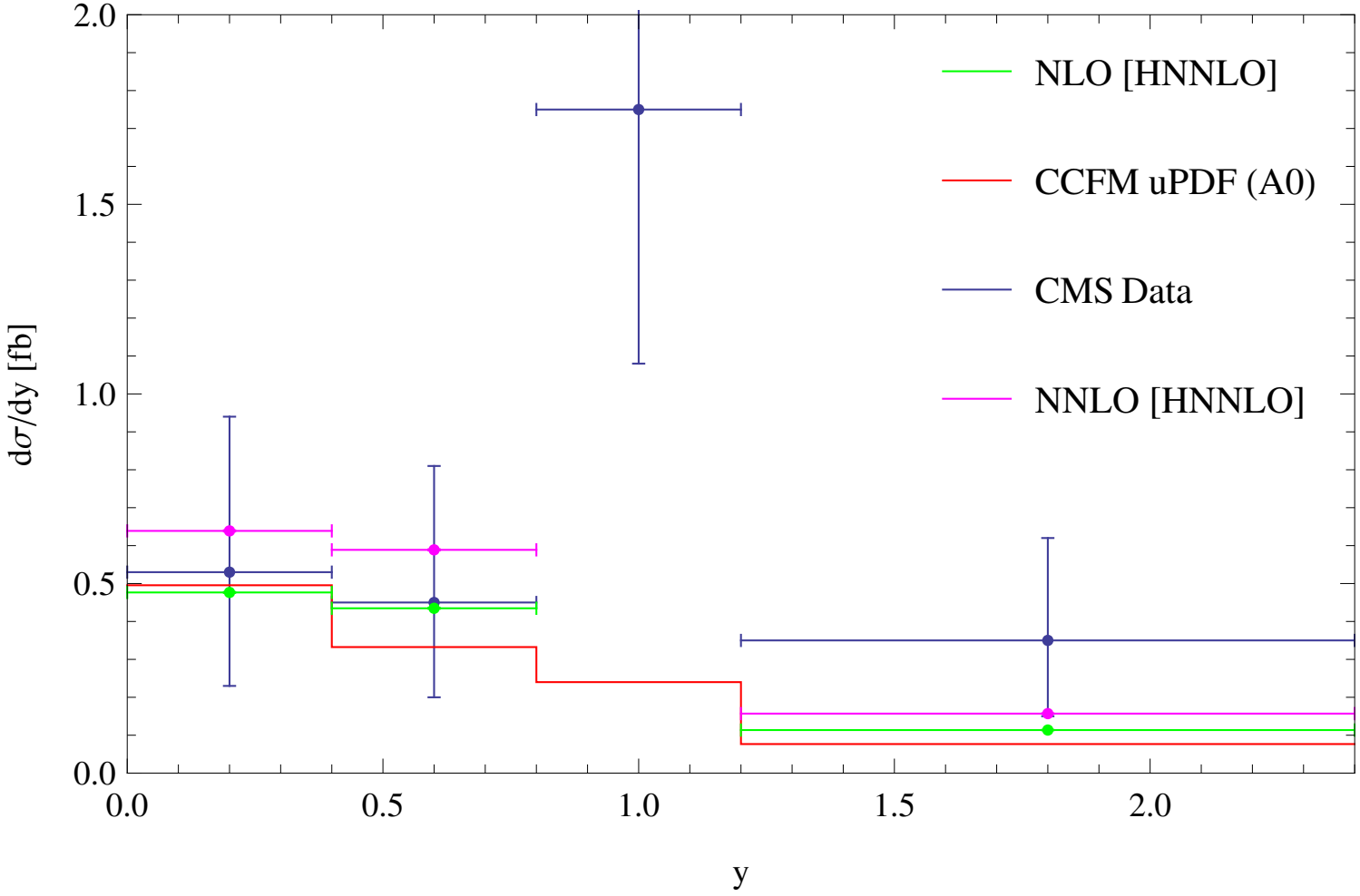
ATLAS data for $pp \to H \to 4\,leptons$ and k_T factorization approach



CMS data for $pp \to H \to 4\,leptons$ and k_T factorization approach



CMS data for $pp \to H \to 4\,leptons$ and k_T factorization approach



Conclusions

- We have estimated differential cross section for higgs production in four lepton channel.
- Recent data from ATLAS and CMS collaboration for differential cross section in fiducial region are important in this study.
- The results obtained using CCFM evolution equations are close to NLO results obtained using collinear factorization.
- Calculating higher order corrections withing k_T factorization is a challenge and it would be an interesting analysis for Phenomenological study.

Thank You