CHARGED HIGGS PAIRS AT THE LHC : A NLO ANALYSIS

Michael Spira (PSI)

I Introduction

II Charged Higgs Pair Production

III Theoretical Uncertainties

in coll. with M. Ahmed, L. Biermann, H. Ita, I. Rusetski, M. Spira, and Y. Yedelkina

→ see talk by L. Biermann on Friday

I INTRODUCTION

2HDM

- minimal extension: 2 Higgs doublets

ESB $\rightarrow$ 5 Higgs bosons:

h, H	neutral, $\mathcal{CP}$ even
A	neutral, $\mathcal{CP}$ odd
$H^{\pm}$	charged

- modified couplings:
2HDM type I [II]

ϕ	g_u^ϕ	g_d^ϕ	g_V^ϕ
h	c_α/s_β	c_α/s_β $[-s_\alpha/c_\beta]$	$s_{\beta-\alpha}$
H	s_α/s_β	s_α/s_β $[c_\alpha/c_\beta]$	$c_{\beta-\alpha}$
A	ctgβ	$-$ctgβ [tgβ]	0

two scenarios

$M_h = 125$ GeV, $M_{H^\pm} = 300 \ldots 2000$ GeV

scenario 1:

$$\begin{aligned} \tan\beta &= 2, & \lambda_1 &= 6.499, & \lambda_3 &= -1.459, \\ & & \lambda_4 &= 1.106, & \lambda_5 &= -0.3621, \end{aligned} \tag{1}$$

scenario 2:

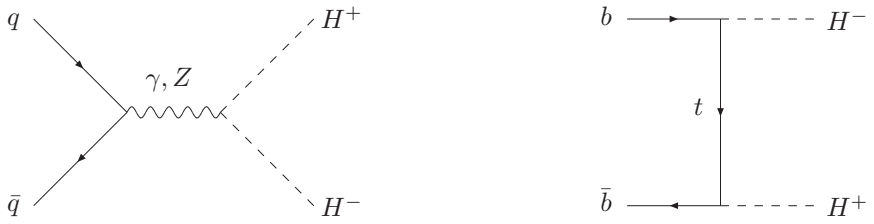
$$\begin{aligned} \tan\beta &= 20, & \lambda_1 &= 2.651, & \lambda_3 &= 0.2799, \\ & & \lambda_4 &= 2.392, & \lambda_5 &= 2.412, \end{aligned} \tag{2}$$

- λ_2 determined iteratively

- checked with `ScannerS` and `HiggsBounds`

II CHARGED HIGGS PAIR PRODUCTION

(i) DY-like charged Higgs pair production [type I]



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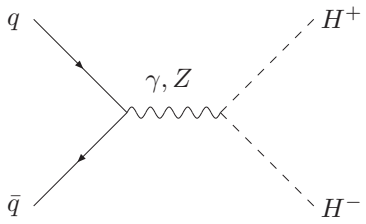

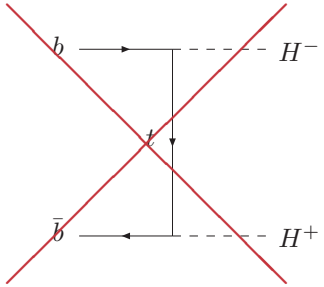

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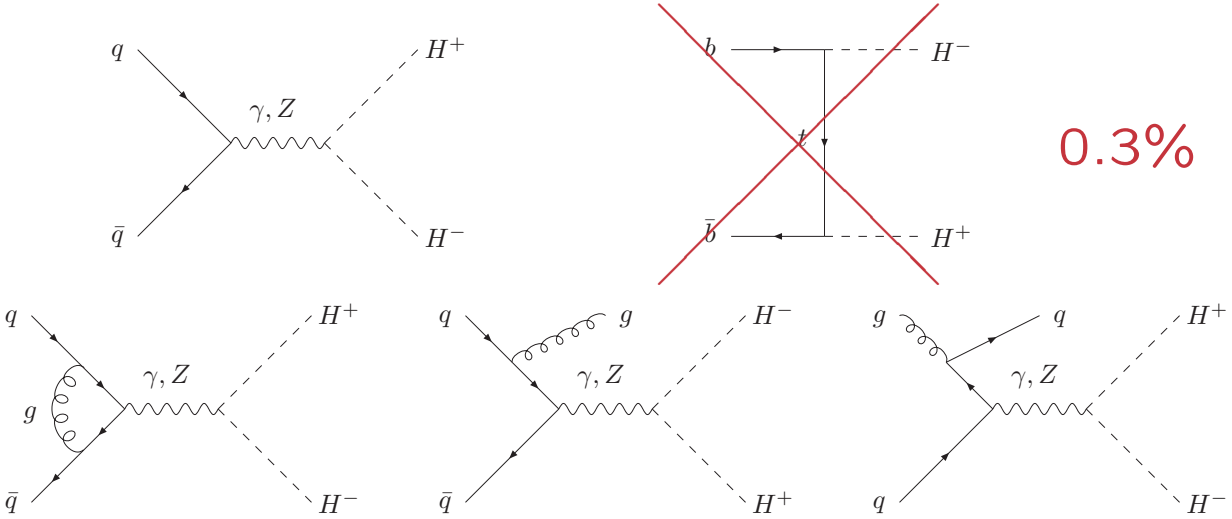


$$\sigma_{\mathrm{NLO}}(pp \to HH + X) = \sigma_{\mathrm{LO}} + \Delta\sigma_{q\bar{q}} + \Delta\sigma_{qg}$$

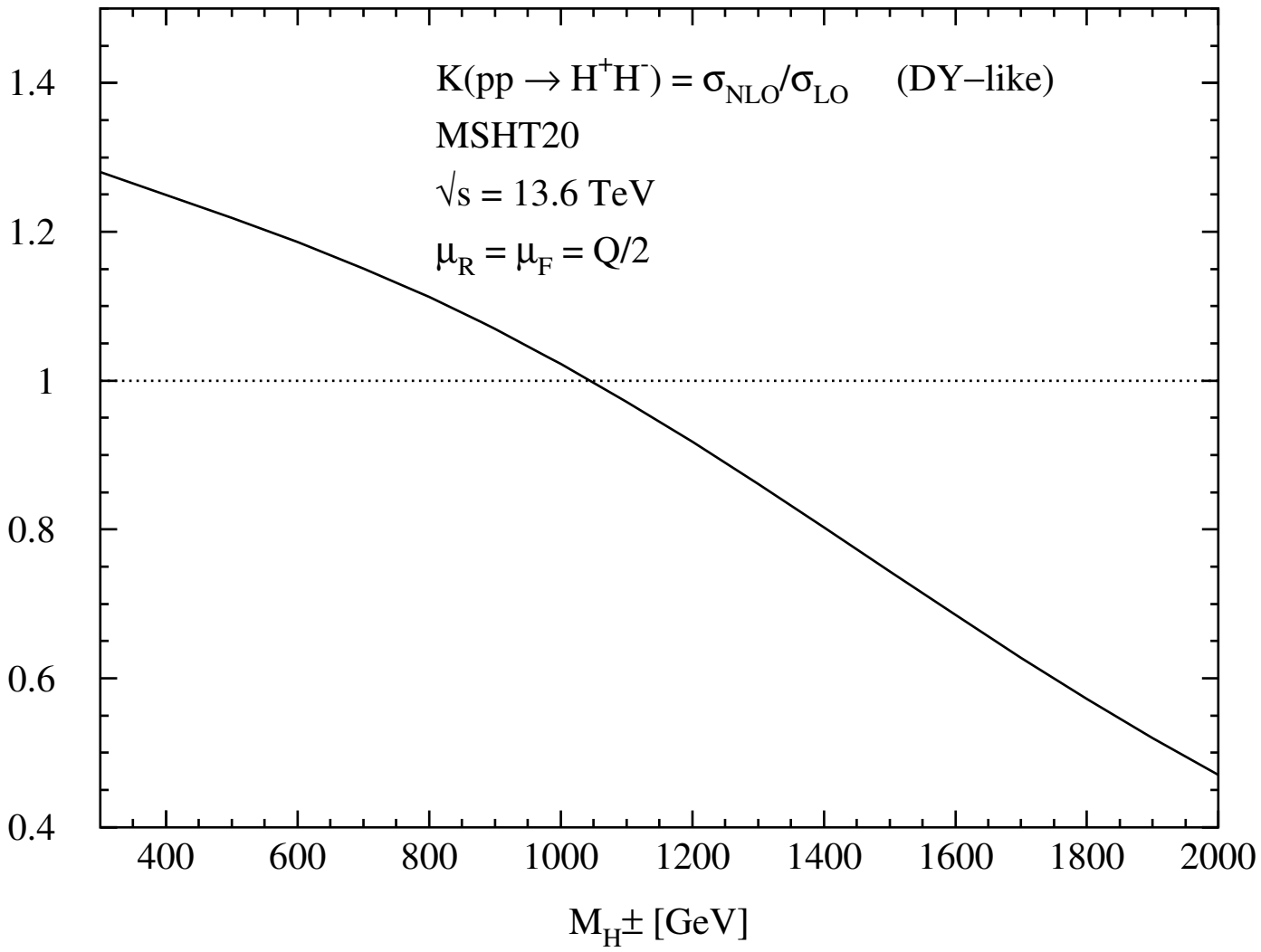
$$\sigma_{\mathrm{LO}} = \int_{\tau_0}^{1} d\tau \, \frac{d\mathcal{L}^{q\bar{q}}}{d\tau} \, \hat{\sigma}_{\mathrm{LO}}(Q^2 = \tau s)$$

$$\Delta\sigma_{q\bar{q}} = \frac{\alpha_s(\mu_R)}{\pi} \int_{\tau_0}^{1} d\tau \, \frac{d\mathcal{L}^{q\bar{q}}}{d\tau} \int_{\tau_0/\tau}^{1} \frac{dz}{z} \, \hat{\sigma}_{\mathrm{LO}}(Q^2 = z\tau s)\omega(z)$$

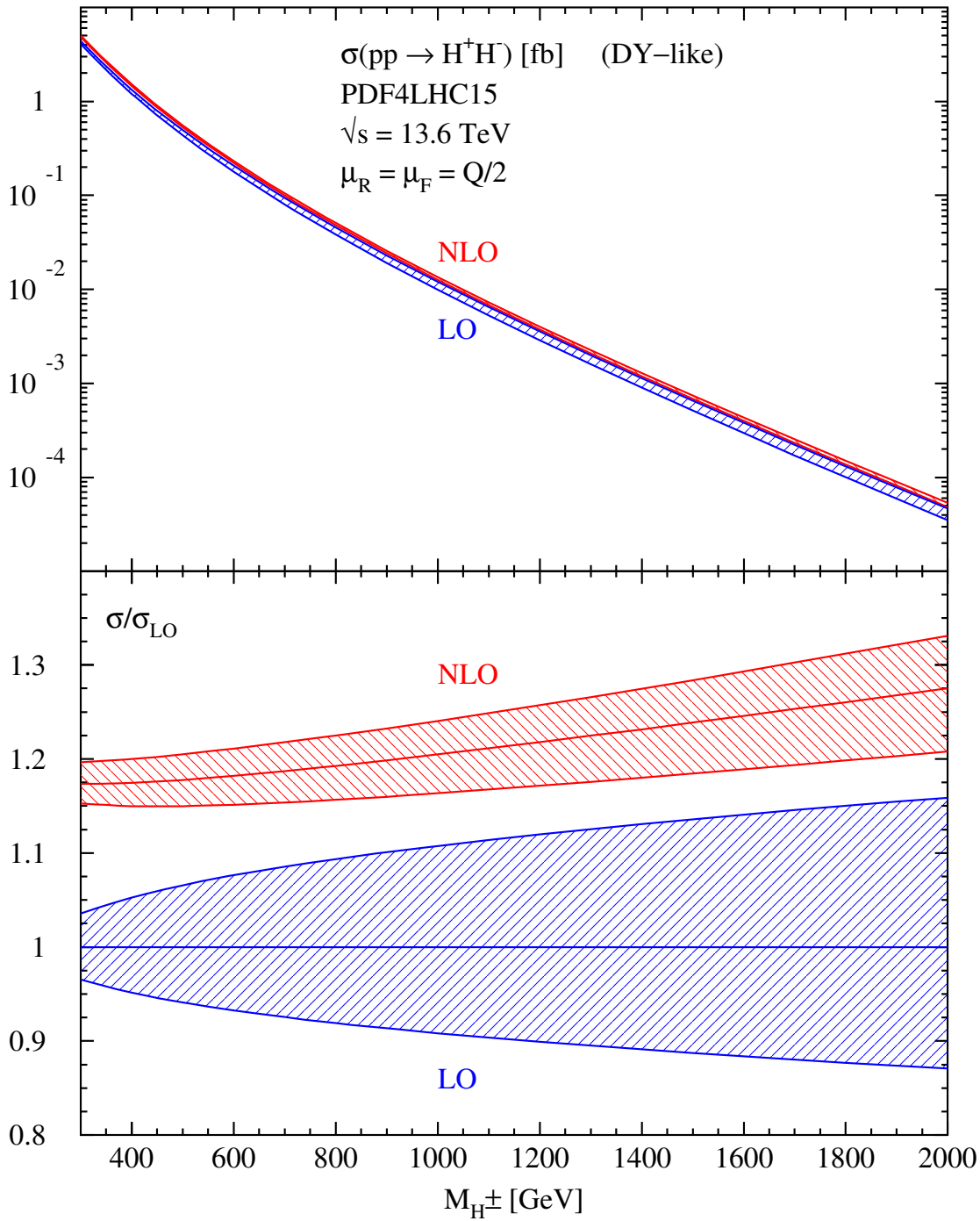
$$\Delta\sigma_{gq} = \frac{\alpha_s(\mu_R)}{\pi} \int_{\tau_0}^{1} d\tau \sum_{q,\bar{q}} \frac{d\mathcal{L}^{gq}}{d\tau} \int_{\tau_0/\tau}^{1} \frac{dz}{z} \, \hat{\sigma}_{\mathrm{LO}}(Q^2 = z\tau s)\omega_{qg}(z)$$

$$\omega_{q\bar{q}}(z) = -P_{qq}(z) \log \frac{\mu_F^2}{\tau s} + \frac{4}{3}\left\{2[\zeta_2 - 2]\delta(1-z) + 4\mathcal{D}_1(z) - 2(1+z)\log(1-z)\right\}$$

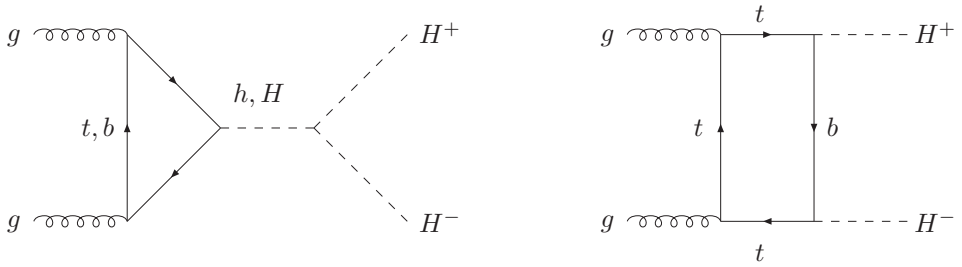
$$\omega_{qg}(z) = -\frac{1}{2}P_{qg}(z) \log\left(\frac{\mu_F^2}{(1-z)^2\tau s}\right) + \frac{1}{8}\left\{1 + 6z - 7z^2\right\}$$



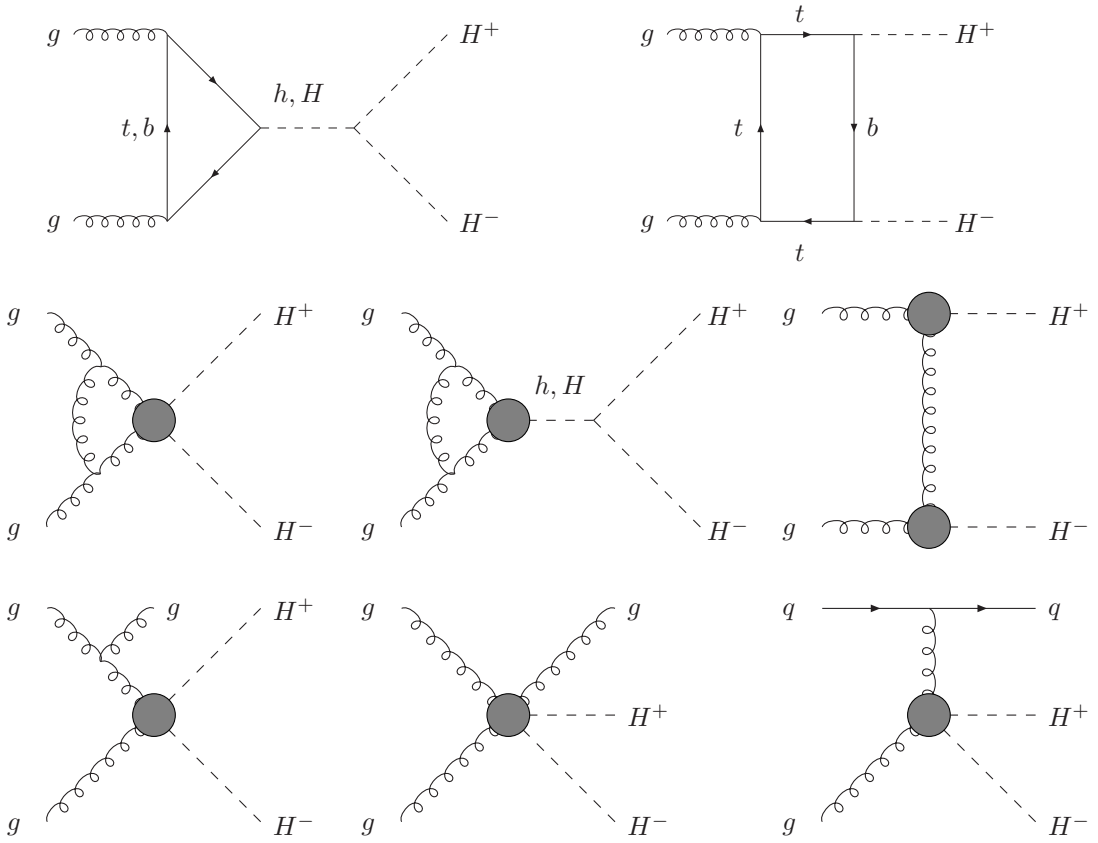
agrees with Alves, Plehn


σ(pp → H+H-) [fb] (DY−like)
PDF4LHC15
√s = 13.6 TeV
μR = μF = Q/2
NLO
LO
σ/σLO
NLO
LO
1
10-1
10-2
10-3
10-4
1.3
1.2
1.1
1
0.9
0.8
400
600
800
1000
1200
1400
1600
1800
2000
MH± [GeV]

(ii) Charged Higgs pair production via ggF



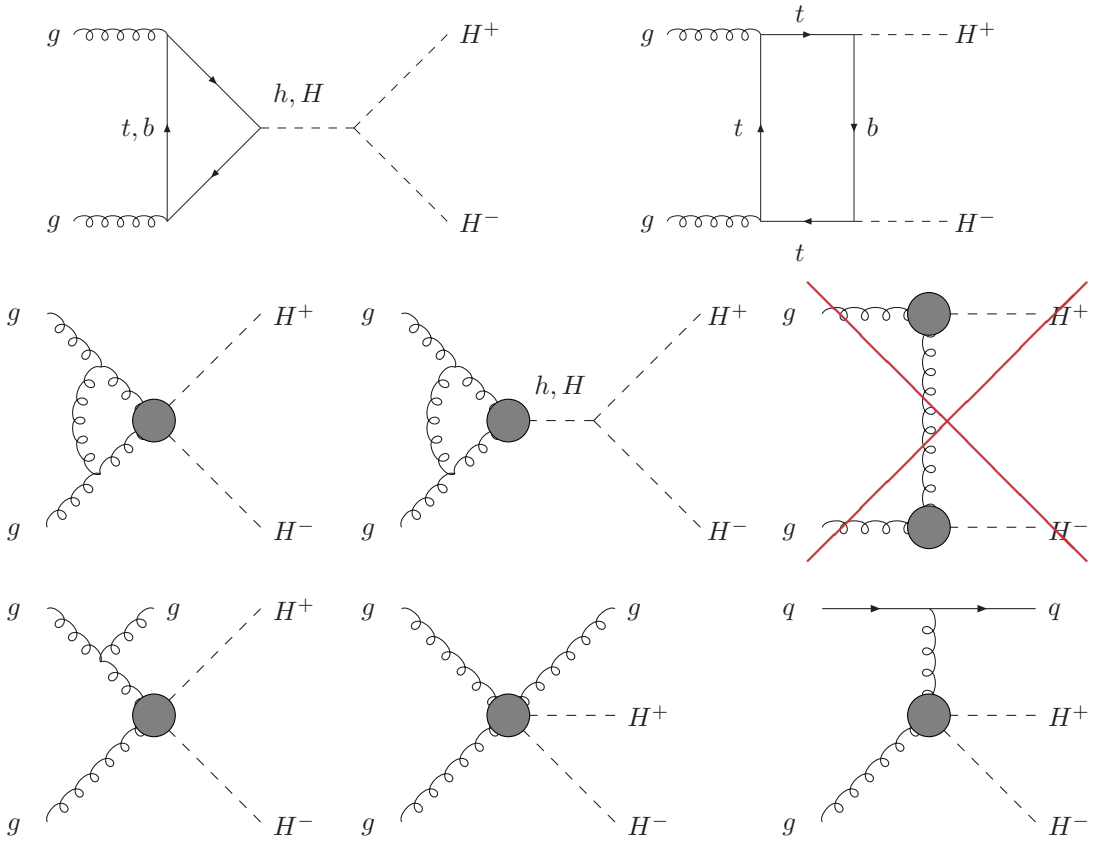
(ii) Charged Higgs pair production via ggF



$$\mathcal{L}_{eff} = \frac{\alpha_s}{24\pi} G^{a\mu\nu} G^a_{\mu\nu} \log\left(\frac{2|\phi_2|^2}{v_2^2}\right) \left(1 + \frac{11}{4}\frac{\alpha_s}{\pi}\right)$$

$$= \frac{\alpha_s}{12\pi v} G^{a\mu\nu} G^a_{\mu\nu} \left\{ h\frac{s_\alpha}{s_\beta} + H\frac{c_\alpha}{s_\beta} + \frac{H^+H^-}{v\tan^2\beta} + \cdots \right\} \left(1 + \frac{11}{4}\frac{\alpha_s}{\pi}\right)$$

(ii) Charged Higgs pair production via ggF



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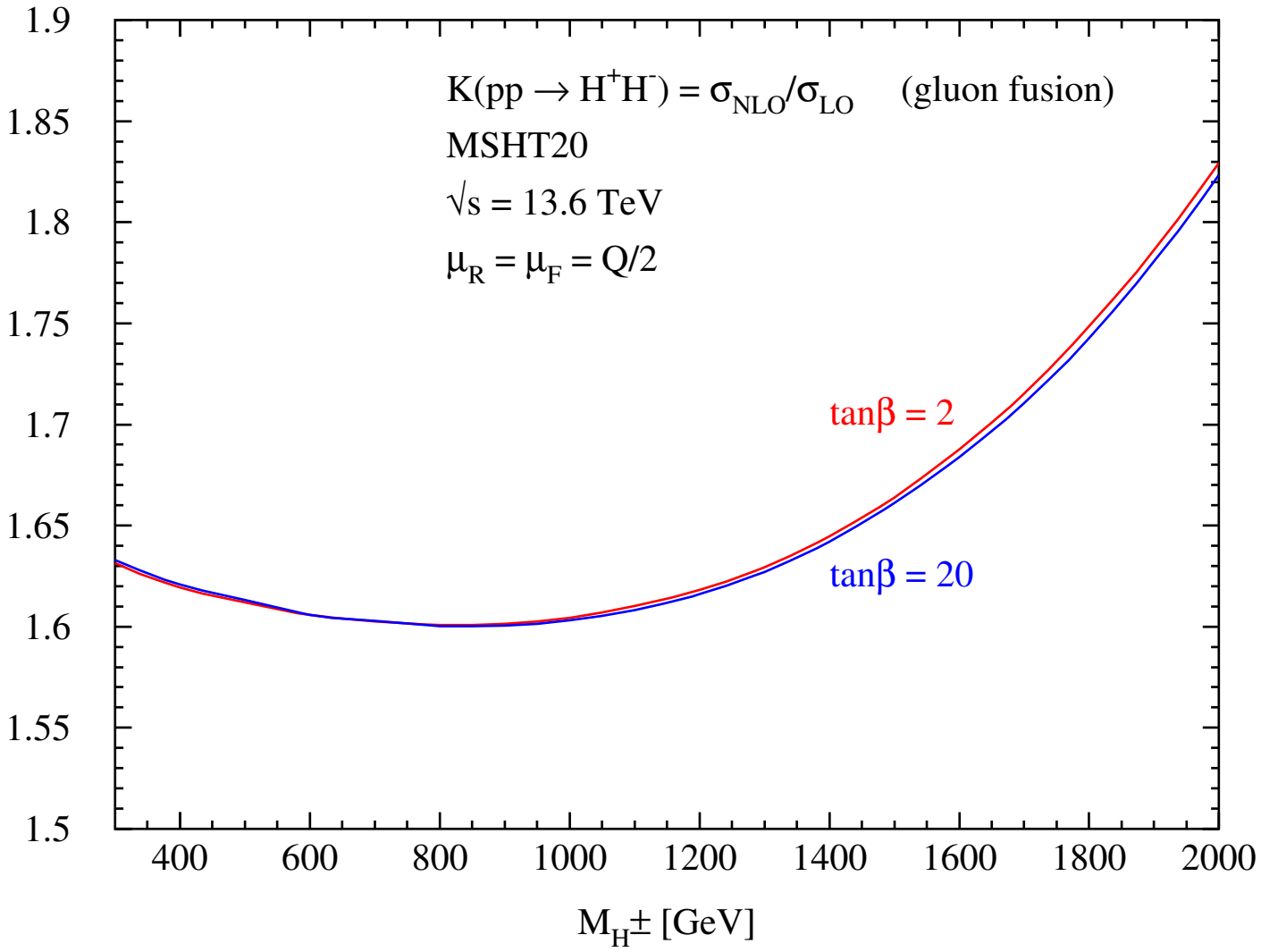
$$= \frac{\alpha_s}{12\pi v} G^{a\mu\nu} G^a_{\mu\nu} \left\{ h\frac{s_\alpha}{s_\beta} + H\frac{c_\alpha}{s_\beta} + \frac{H^+H^-}{v\tan^2\beta} + \cdots \right\} \left(1 + \frac{11}{4}\frac{\alpha_s}{\pi}\right)$$

$$\sigma_{\mathrm{NLO}}(pp \to HH + X) = \sigma_{\mathrm{LO}} + \Delta\sigma_{\mathrm{virt}} + \Delta\sigma_{gg} + \Delta\sigma_{gq} + \Delta\sigma_{q\bar{q}}$$

$$\begin{aligned}
\sigma_{\mathrm{LO}} &= \int_{\tau_0}^{1} d\tau \, \frac{d\mathcal{L}^{gg}}{d\tau} \, \hat{\sigma}_{\mathrm{LO}}(Q^2 = \tau s) \\
\Delta\sigma_{\mathrm{virt}} &= \frac{\alpha_s(\mu)}{\pi} \int_{\tau_0}^{1} d\tau \, \frac{d\mathcal{L}^{gg}}{d\tau} \, \hat{\sigma}_{\mathrm{LO}}(Q^2 = \tau s) \left\{ \pi^2 + \frac{11}{2} + \frac{33 - 2N_F}{6} \log \frac{\mu_R^2}{Q^2} \right\} \\
\Delta\sigma_{gg} &= \frac{\alpha_s(\mu)}{\pi} \int_{\tau_0}^{1} d\tau \, \frac{d\mathcal{L}^{gg}}{d\tau} \int_{\tau_0/\tau}^{1} \frac{dz}{z} \, \hat{\sigma}_{\mathrm{LO}}(Q^2 = z\tau s) \left\{ -z P_{gg}(z) \log \frac{M^2}{\tau s} \right. \\
&\qquad \left. - \frac{11}{2}(1-z)^3 + 6[1 + z^4 + (1-z)^4] \left(\frac{\log(1-z)}{1-z} \right)_+ \right\} \\
\Delta\sigma_{gq} &= \frac{\alpha_s(\mu)}{\pi} \int_{\tau_0}^{1} d\tau \sum_{q,\bar{q}} \frac{d\mathcal{L}^{gq}}{d\tau} \int_{\tau_0/\tau}^{1} \frac{dz}{z} \, \hat{\sigma}_{\mathrm{LO}}(Q^2 = z\tau s) \left\{ -\frac{z}{2} P_{gq}(z) \log \frac{M^2}{\tau s (1-z)^2} + \frac{2}{3} z^2 - (1-z)^2 \right\} \\
\Delta\sigma_{q\bar{q}} &= \frac{\alpha_s(\mu)}{\pi} \int_{\tau_0}^{1} d\tau \sum_{q} \frac{d\mathcal{L}^{q\bar{q}}}{d\tau} \int_{\tau_0/\tau}^{1} \frac{dz}{z} \, \hat{\sigma}_{\mathrm{LO}}(Q^2 = z\tau s) \, \frac{32}{27}(1-z)^3
\end{aligned}$$


K(pp → H+H-) = σNLO/σLO (gluon fusion)
MSHT20
√s = 13.6 TeV
μR = μF = Q/2
tanβ = 2
tanβ = 20
1.9
1.85
1.8
1.75
1.7
1.65
1.6
1.55
1.5
400
600
800
1000
1200
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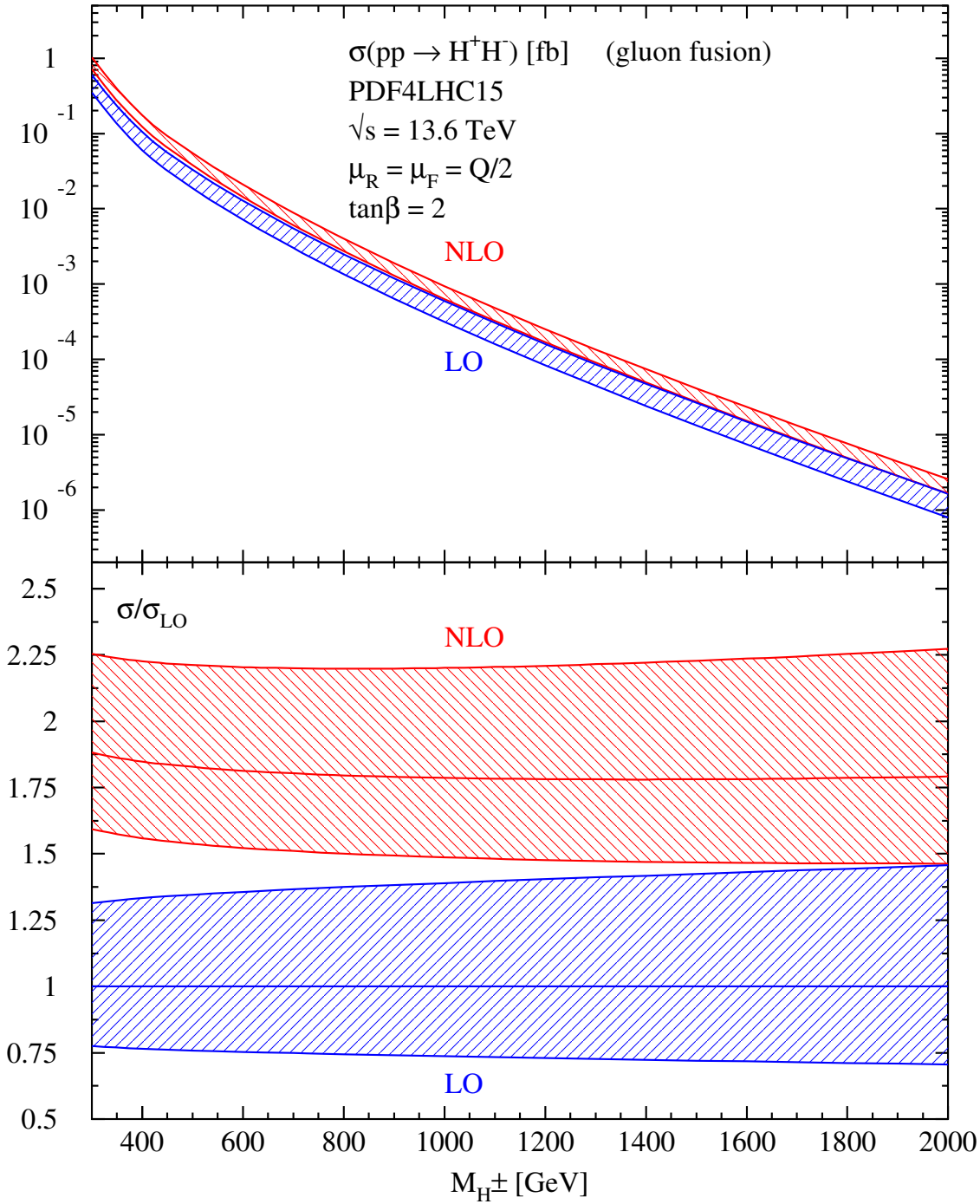
1800
2000
MH± [GeV]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NLO
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NLO
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1
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10-3
10-4
10-5
10-6
2.5
2.25
2
1.75
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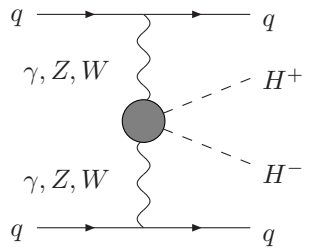
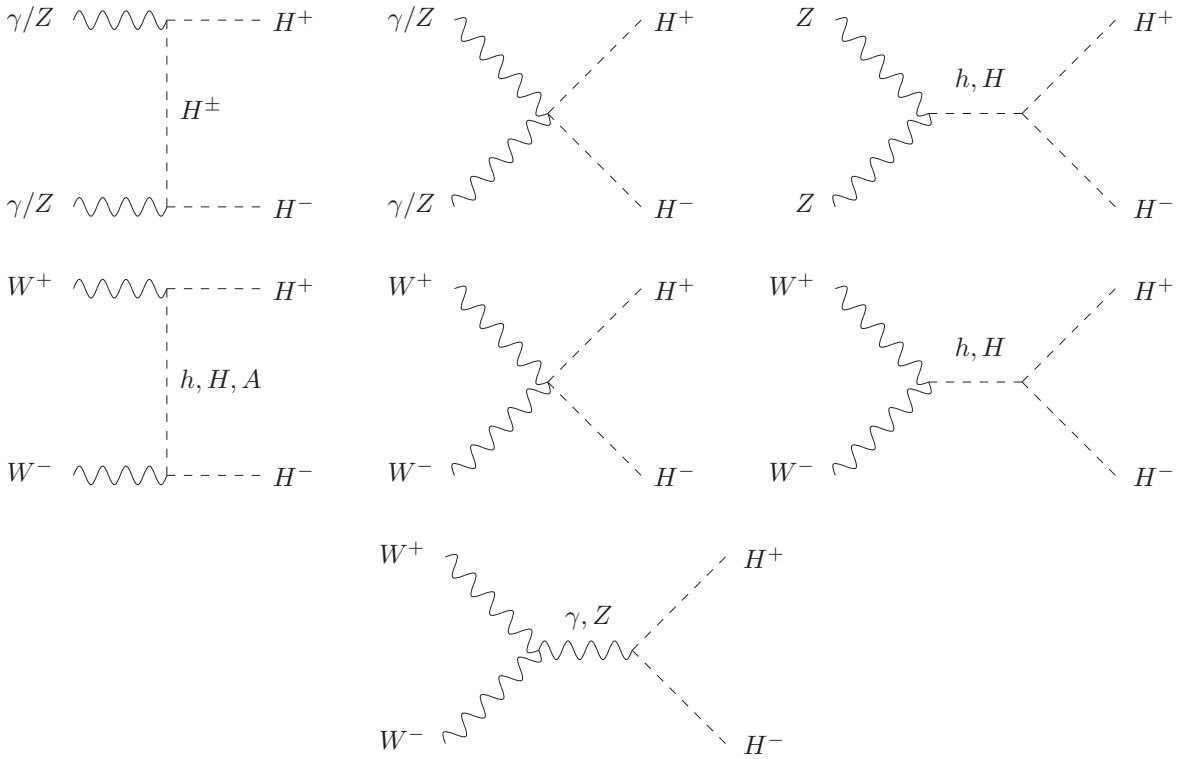
MH± [GeV]

(iii) Charged Higgs pair production via VBF

structure-function approach (SFA)

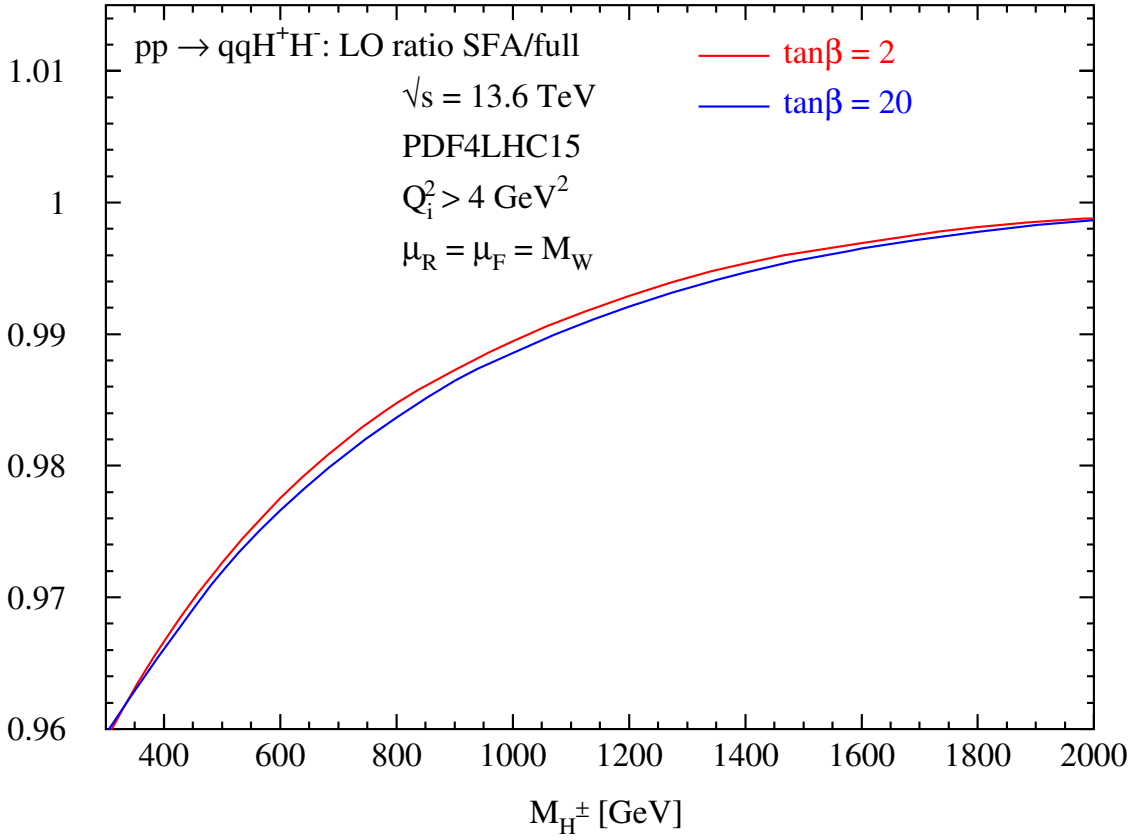




$$|\mathcal{M}|^2 = 4q_1^2q_2^2 \sum_{V_{1,\ldots,4}=\gamma,Z} \frac{g_{V_1}g_{V_2}g_{V_3}g_{V_4}}{(q_1^2-M_{V_1}^2)(q_2^2-M_{V_2}^2)(q_1^2-M_{V_3}^2)(q_2^2-M_{V_4}^2)} W_{V_1V_3}^{\mu\rho} W_{V_2V_4}^{\nu\sigma} \mathcal{M}_{V_1V_2}^{\mu\nu} \mathcal{M}_{V_3V_4}^{*\rho\sigma}$$

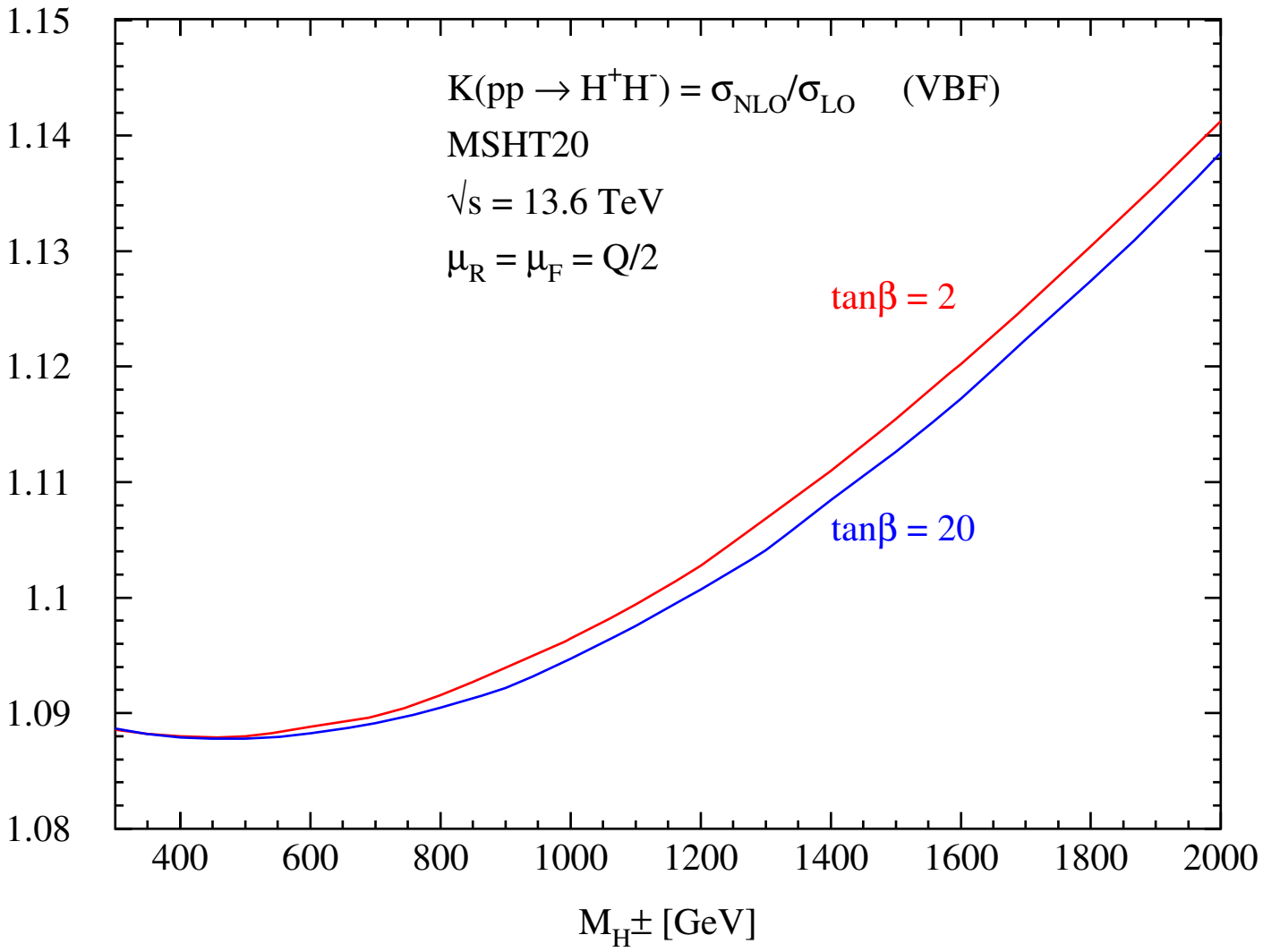
$$+ \frac{4q_1^2q_2^2}{(q_1^2-M_W^2)^2(q_2^2-M_W^2)^2} \sum_{WW'=W^+W^-,W^-W^+} W_{WW}^{\mu\rho} W_{W'W'}^{\nu\sigma} \mathcal{M}_{WW'}^{\mu\nu} \mathcal{M}_{WW'}^{*\rho\sigma}$$

$$W_{V_1V_2}^{\mu\nu} = F_{1,V_1V_2}\left(-g^{\mu\nu}+\frac{q^\mu q^\nu}{q^2}\right) - \frac{F_{2,V_1V_2}}{xpq}\left(p^\mu-\frac{pq}{q^2}q^\mu\right)\left(p^\nu-\frac{pq}{q^2}q^\nu\right) - i\frac{F_{3,V_1V_2}}{2pq}\epsilon^{\mu\nu\rho\sigma}p_\rho q_\sigma$$



LO disagrees with Moretti ($\leftarrow$ understood)

- QCD corrections: $F_i \to F_i + \Delta F_i$ (DIS)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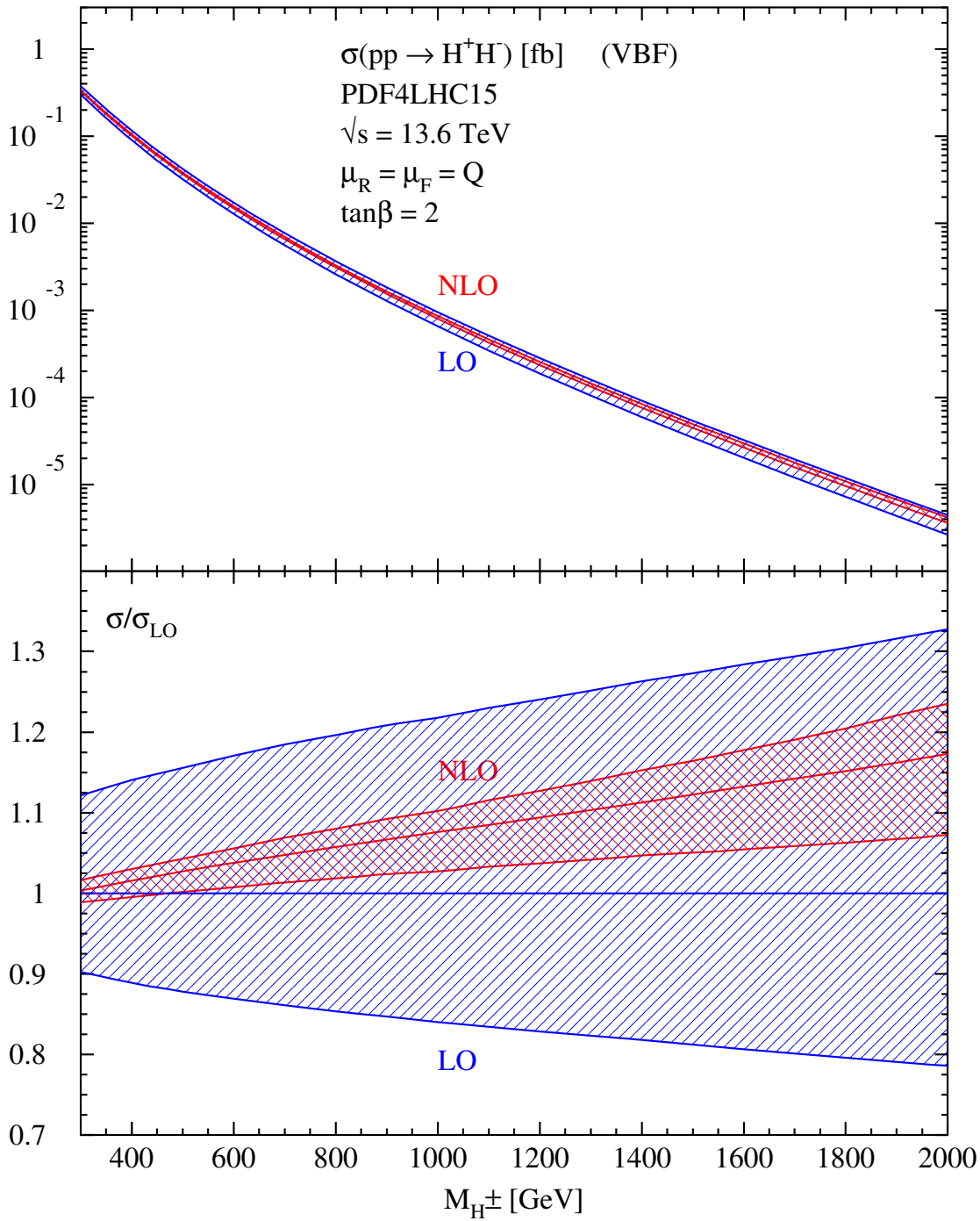
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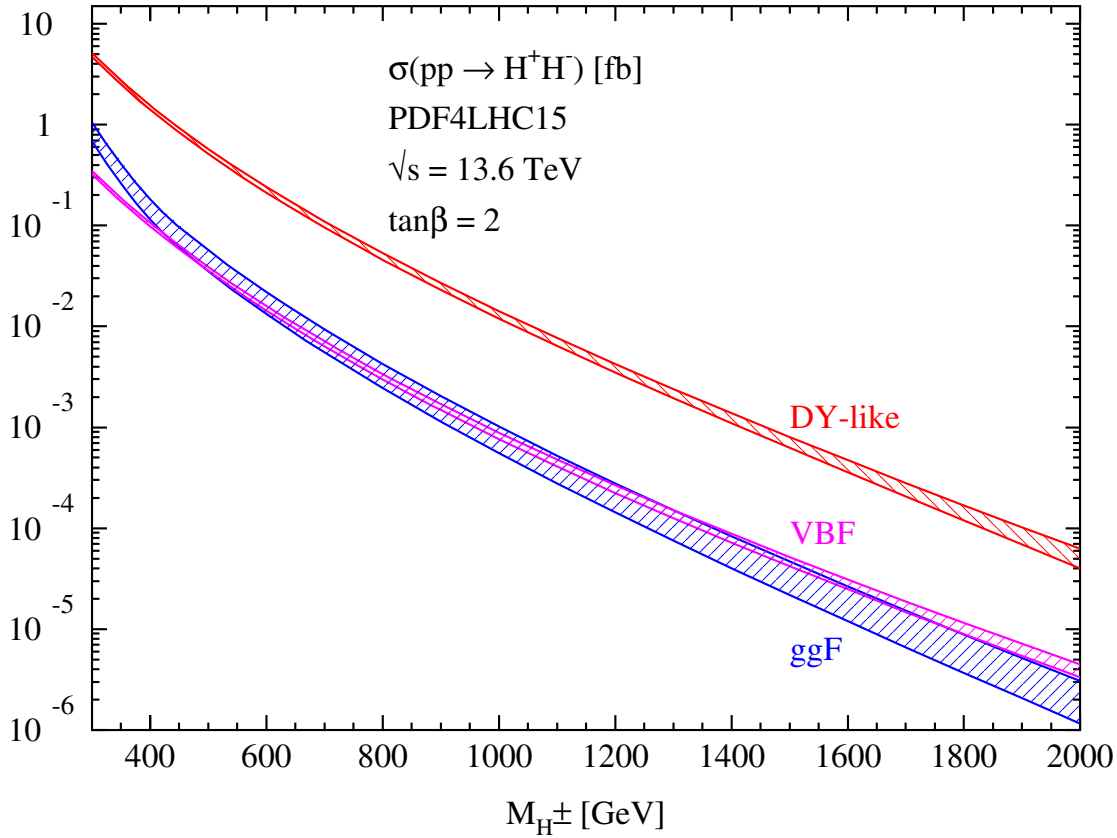
III *THEORETICAL UNCERTAINTIES*

- scale uncertainties and PDF+α_s added linearly



- DY: 4–22%, ggF: 25–45% (+m_t), VBF: 3–15% (+SFA)

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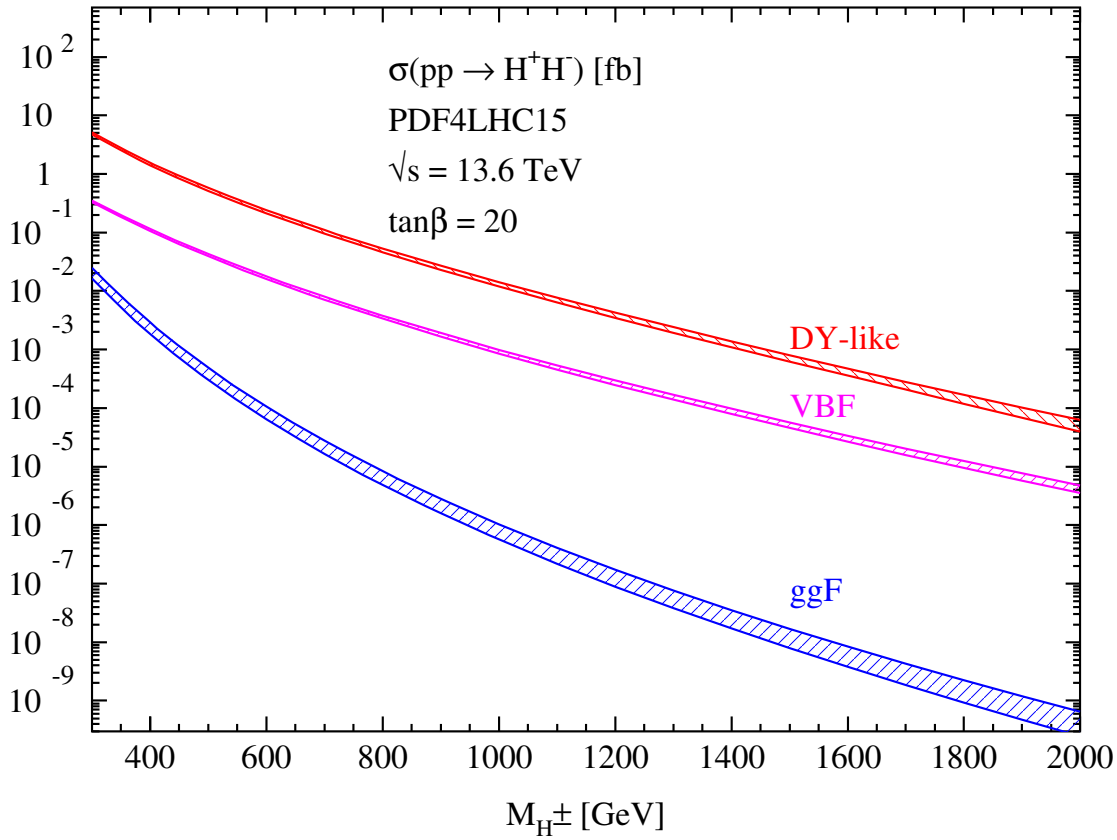

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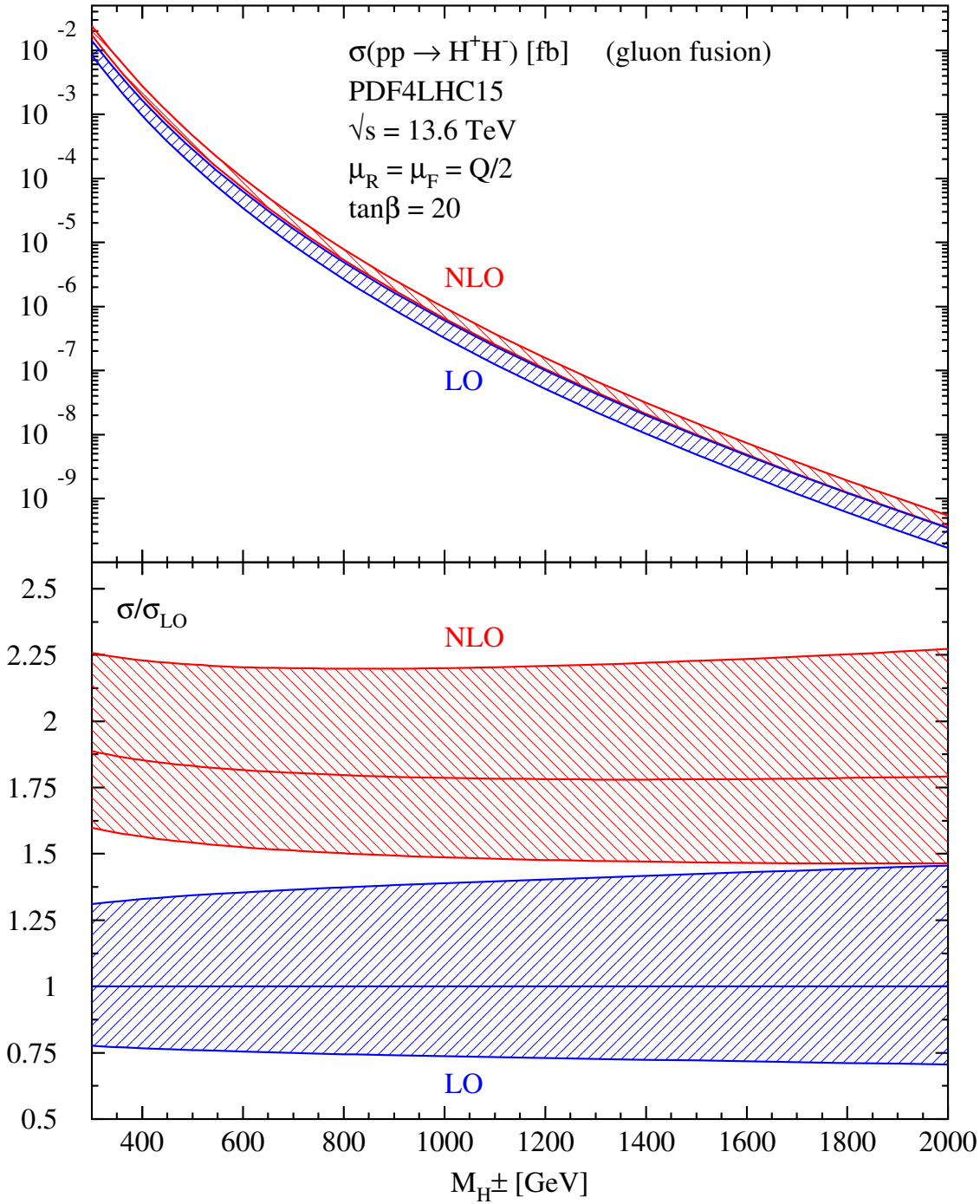
BACKUP SLIDES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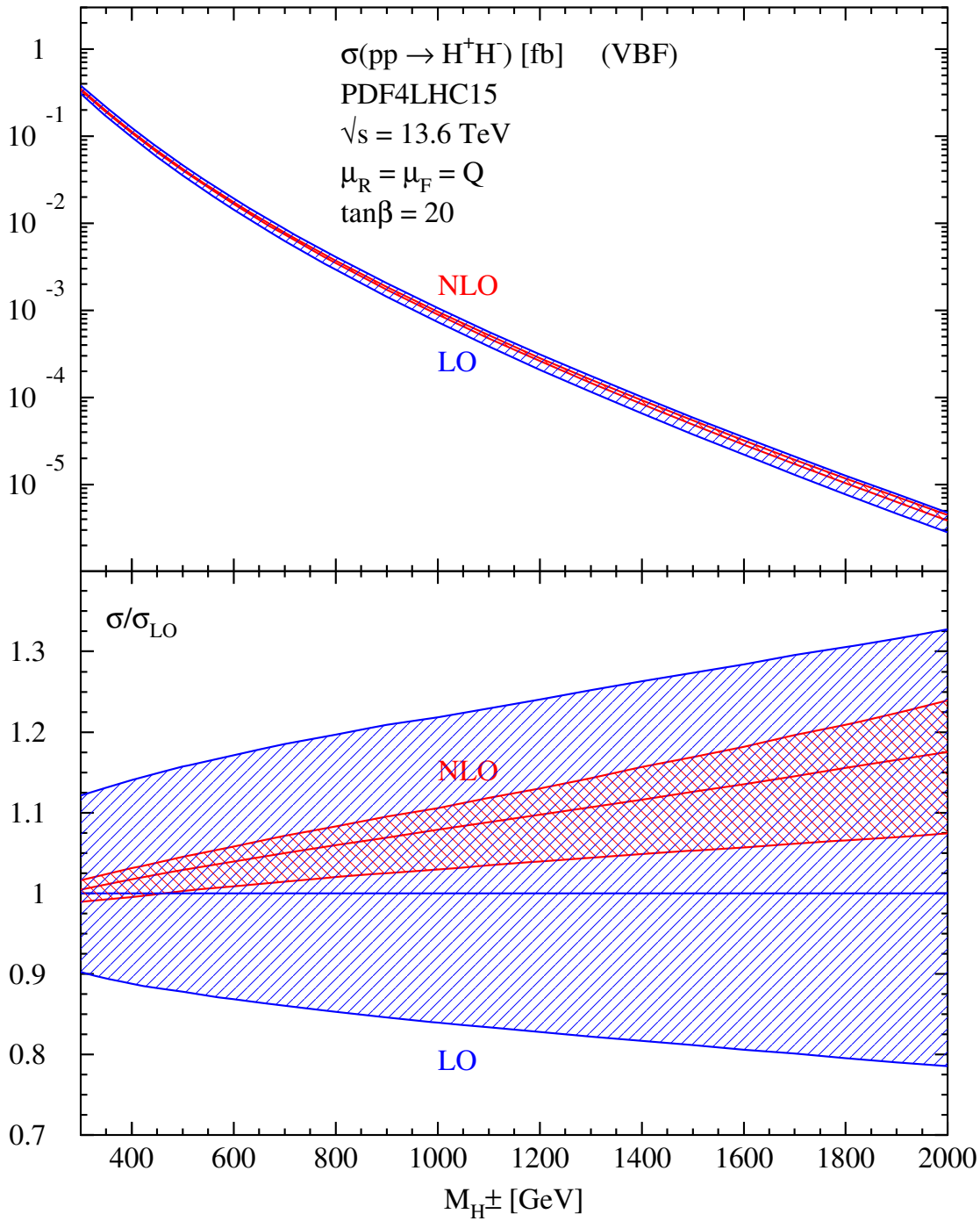
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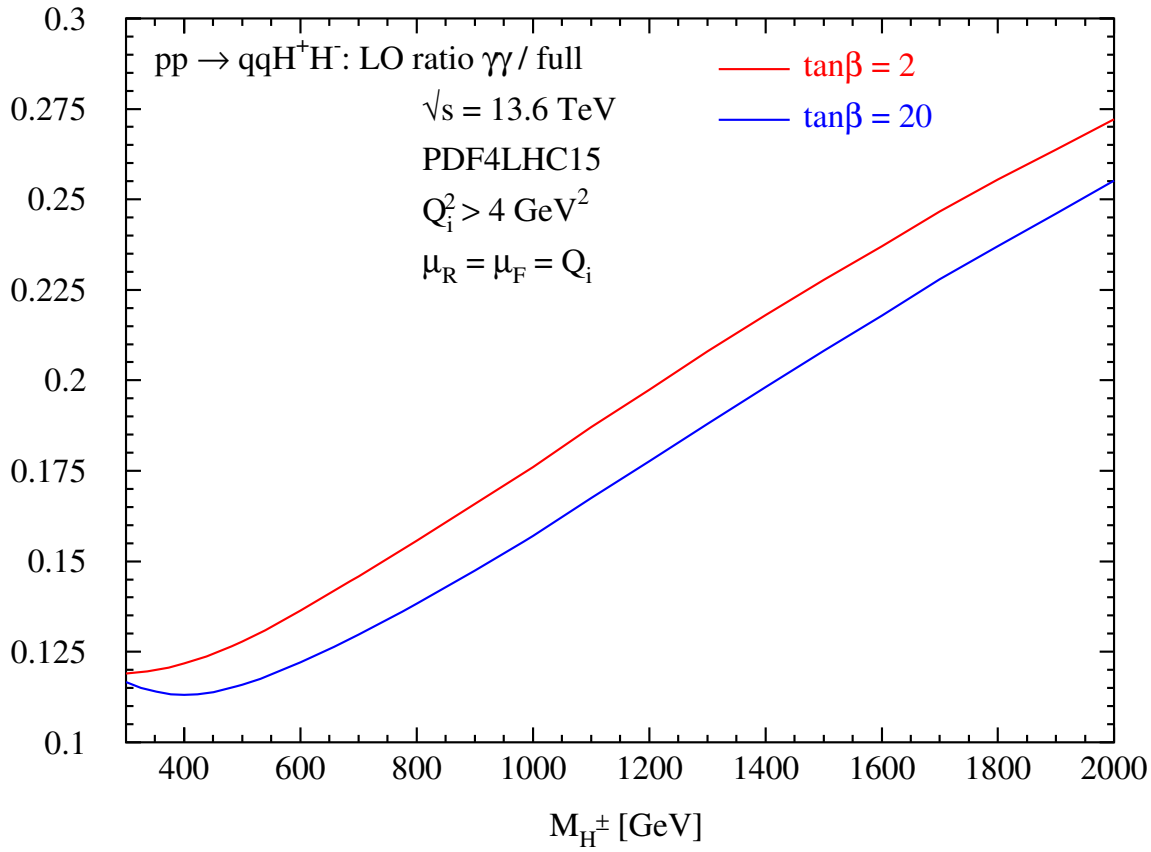

→ Arroyo-Ureña, Félix-Beltrán, Hernández-Sánchez, Honorato, Valencia-Pérez