PAUL SCHERRER INSTITUT

ASSOCIATED MSSM HIGGS PRODUCTION WITH HEAVY QUARKS : SUSY – QCD CORRECTIONS

Michael Spira (PSI)

I $t\bar{b}H^-$ Production

II $t\bar{t}/b\bar{b}+\phi^0$ Production

III Conclusions

in collaboration with S. Dittmaier, P. Häfliger, M. Krämer and M. Walser

- minimal model: 2 Higgs doubletts $\phi_1, \phi_2 \rightarrow$ 5 Higgs bosons: $h, H, A, H^\pm$

- LO: 2 input parameters: $M_A, \mathrm{tg}\beta = \frac{v_2}{v_1}$

$$M_h^2 = \frac{1}{2}\left\{M_A^2 + M_Z^2 + \epsilon - \sqrt{(M_A^2 + M_Z^2 + \epsilon)^2 - 4M_A^2 M_Z^2 c_{2\beta}^2 - 4\epsilon(M_A^2 s_\beta^2 + M_Z^2 c_\beta^2)}\right\}$$

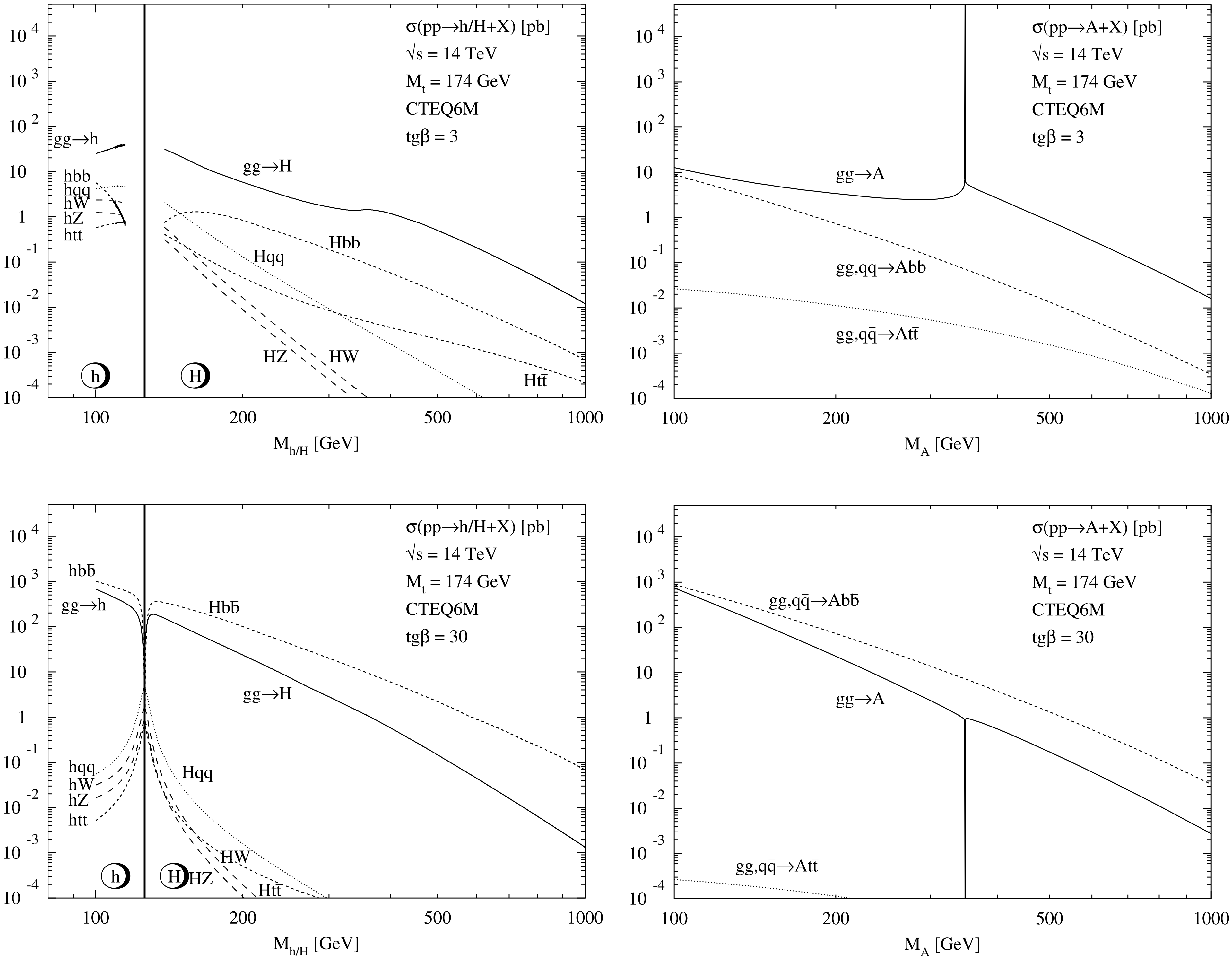
- large radiative corrections:

$$\epsilon = \frac{3G_F}{\sqrt{2}\pi^2}\frac{m_t^4}{s_\beta^2}\left\{\log\frac{m_{\tilde{t}_1} m_{\tilde{t}_2}}{m_t^2} + \frac{X_t^2}{M_{SUSY}^2}\left[1 - \frac{X_t^2}{12 M_{SUSY}^2}\right]\right\}$$

Haber,. . .
Carena,. . .
Heinemeyer,. . .
Zhang
Slavich,. . .
etc.

$$M_h < M_Z \rightarrow \boxed{M_h \lesssim 140 \text{ GeV}}$$

- Yukawa couplings: $\mathrm{tg}\beta\uparrow \quad \Rightarrow \quad g_u^\phi\downarrow \quad g_d^\phi\uparrow \quad g_V^\phi\downarrow$



σ(pp→h/H+X) [pb]
√s = 14 TeV
M_t = 174 GeV
CTEQ6M
tgβ = 3
gg→h
hbb̄
hqq
hW
hZ
htt̄
gg→H
Hbb̄
Hqq
HZ
HW
Htt̄
h
H
M_h/H [GeV]
σ(pp→A+X) [pb]
√s = 14 TeV
M_t = 174 GeV
CTEQ6M
tgβ = 3
gg→A
gg,qq̄→Abb̄
gg,qq̄→Att̄
M_A [GeV]
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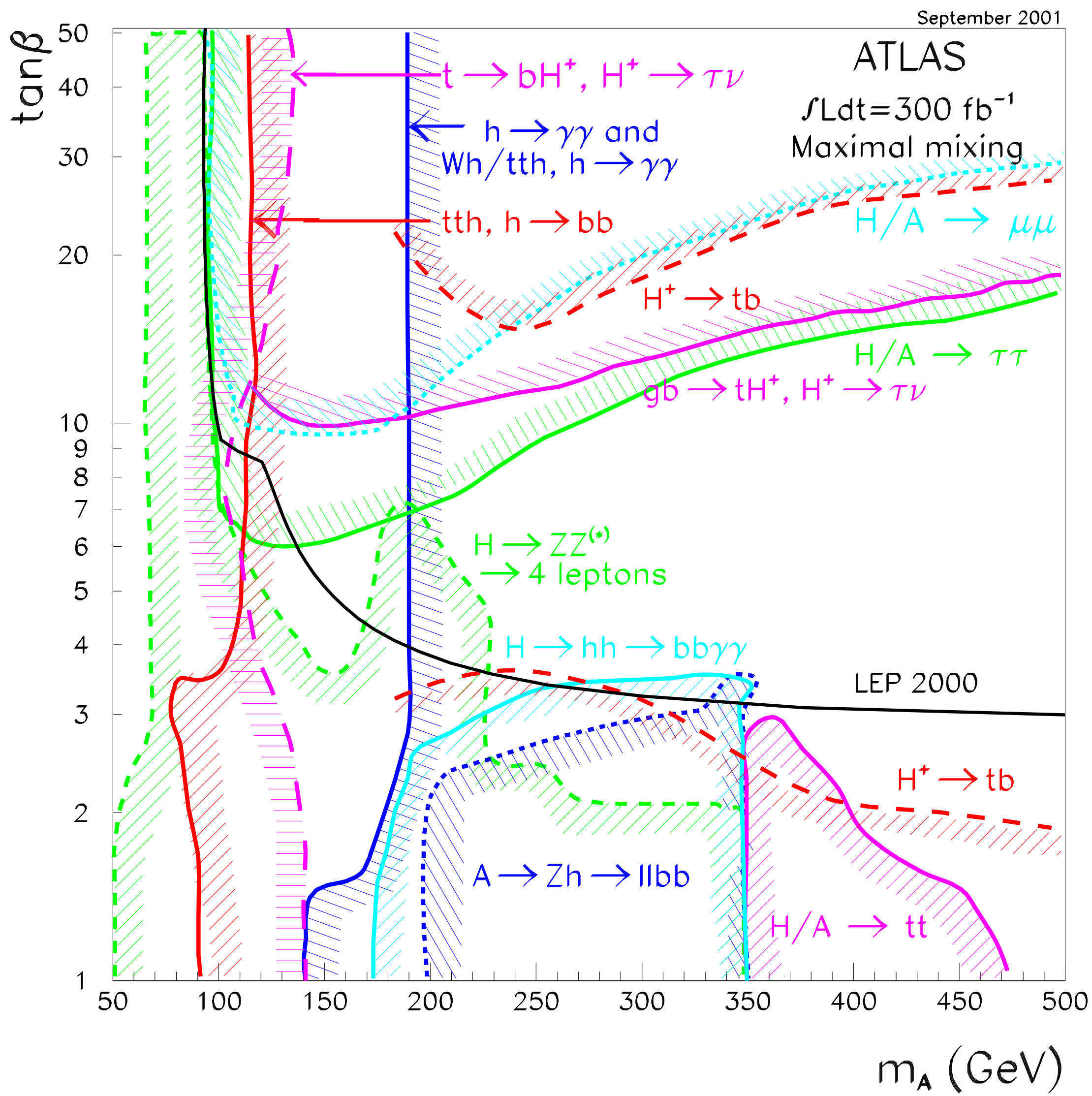
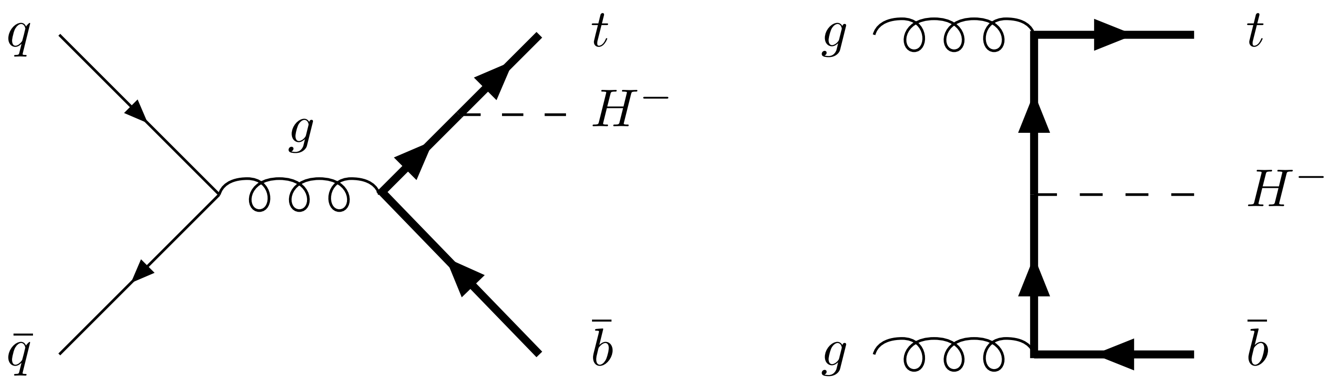
M_A [GeV]



September 2001
ATLAS
∫Ldt=300 fb^-1
Maximal mixing
t → bH+, H+ → τν
h → γγ and
Wh/tth, h → γγ
tth, h → bb
H/A → μμ
H+ → tb
H/A → ττ
gb → tH+, H+ → τν
H → ZZ(*)
→ 4 leptons
H → hh → bbγγ
LEP 2000
H+ → tb
A → Zh → llbb
H/A → tt
tanβ
mA (GeV)

I $t\bar{b}H^-$ PRODUCTION

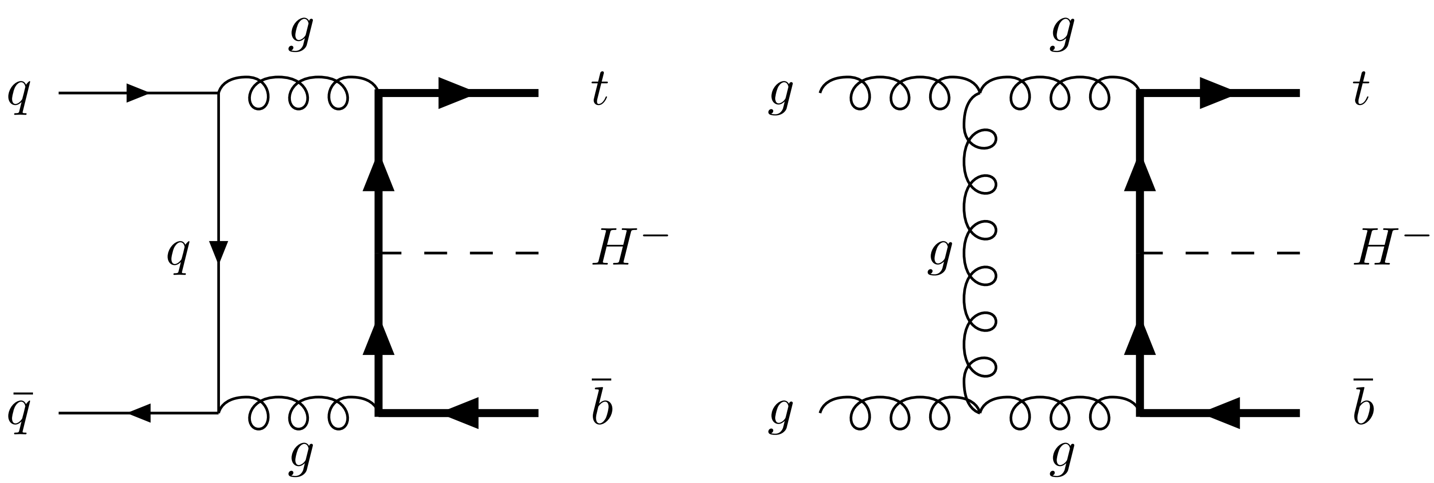


dominant

- dominant charged Higgs production process
- clear signal of extended Higgs sector
- continuum calculation [$M_{H^\pm} > m_t - m_b \quad \Rightarrow \quad t \not\to H^+ b$]
- SUSY-QCD corrections to $bg \to H^- t$ known

Zhu
Gao, Lu, Xiong, Yang
Plehn
Berger, Han, Jiang, Plehn
Kidonakis

(i) Virtual Corrections



• most difficult part: Pentagon diagrams [infared and collinear divergent]

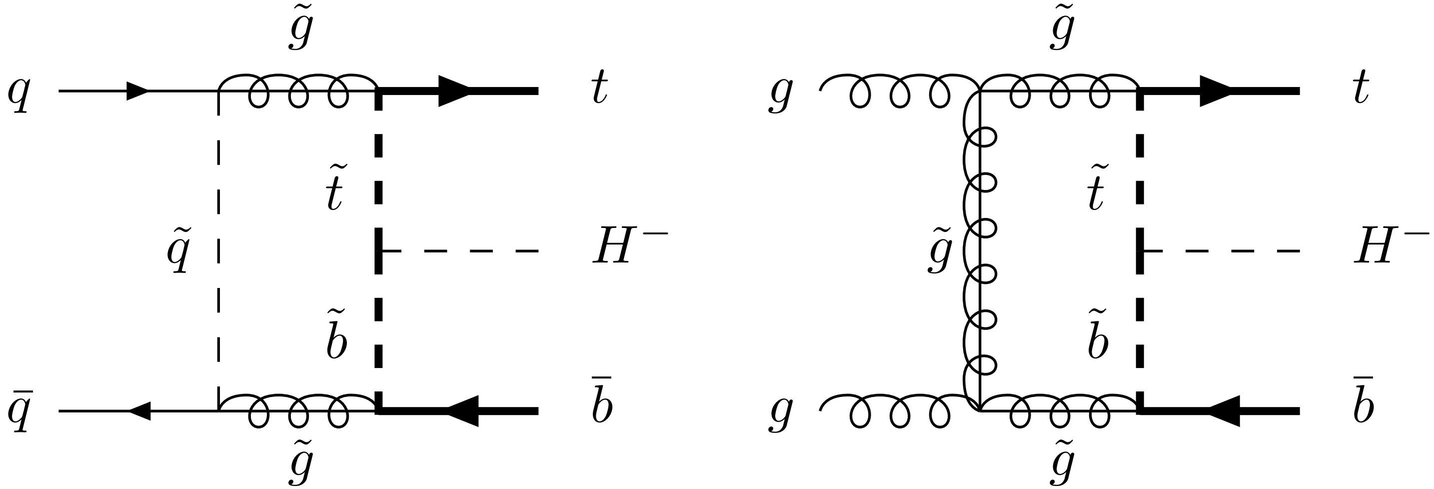
• problematic regions in phase space: avoid inverse Gram determinants

Denner, Dittmaier

• α_s: $\overline{\text{MS}}$ scheme [4 flavours, bottom decoupled], m_Q: on-shell, g_b: $\overline{\text{MS}}$ scheme

• ren./fact. scales: $\mu = (M_{H^-} + m_t + m_b)/3 \to \alpha_s$, PDFs, g_b

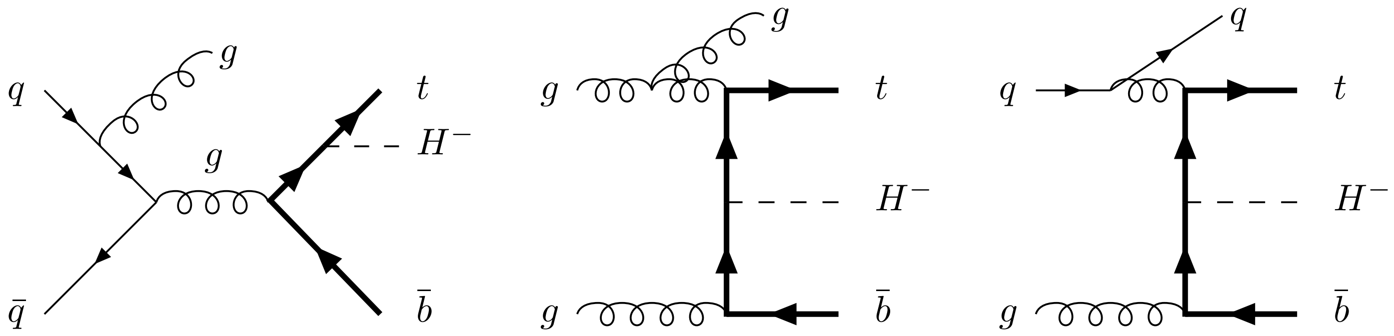
SUSY-QCD Corrections



- no infrared singularities

- massive gluinos and squarks decoupled from $\alpha_s \to$ 4 active flavours

(ii) Real Corrections



- complex matrix elements

- infrared and collinear singularities cancel against virtual corrections and counter terms of PDFs [mass factorization]

- PDF: $\overline{\text{MS}}$ scheme [4 flavours]

- multi-channel integration

SUSY-QCD Corrections to $b\bar{b}\phi^0$

$$\mathcal{L}_{eff} = -\lambda_b \overline{b_R} \left[\phi_1^0 + \frac{\Delta_b}{\text{tg}\beta} \phi_2^{0*} \right] b_L + h.c. \quad \text{valid to all orders in } \Delta m_b, \Delta_1$$

$$= -m_b \bar{b} \left[1 + i\gamma_5 \frac{G^0}{v} \right] b - \frac{m_b/v}{1+\Delta_b} \bar{b} \left[g_b^h \left(1 - \frac{\Delta_b}{\text{tg}\alpha \ \text{tg}\beta} \right) h \right.$$

$$\left. + g_b^H \left(1 + \Delta_b \frac{\text{tg}\alpha}{\text{tg}\beta} \right) H - \underbrace{g_b^A \left(1 - \frac{\Delta_b}{\text{tg}^2\beta} \right)}_{\leftrightarrow H^\pm} i\gamma_5 A \right] b$$

$$\Delta_b = \frac{\Delta m_b}{1+\Delta_1}$$

$$\Delta m_b = \frac{2}{3} \frac{\alpha_s}{\pi} m_{\tilde{g}} \, \mu \, \text{tg}\beta \, I(m^2_{\tilde{b}_1}, m^2_{\tilde{b}_2}, m^2_{\tilde{g}})$$

$$\Delta_1 = -\frac{2}{3} \frac{\alpha_s}{\pi} m_{\tilde{g}} \, A_b \, I(m^2_{\tilde{b}_1}, m^2_{\tilde{b}_2}, m^2_{\tilde{g}})$$

$$I(a,b,c) = -\frac{ab\log\frac{a}{b} + bc\log\frac{b}{c} + ca\log\frac{c}{a}}{(a-b)(b-c)(c-a)}$$

$\Rightarrow$ resummed Yukawa couplings

Carena, Garcia, Nierste, Wagner
Guasch, Häfliger, S.

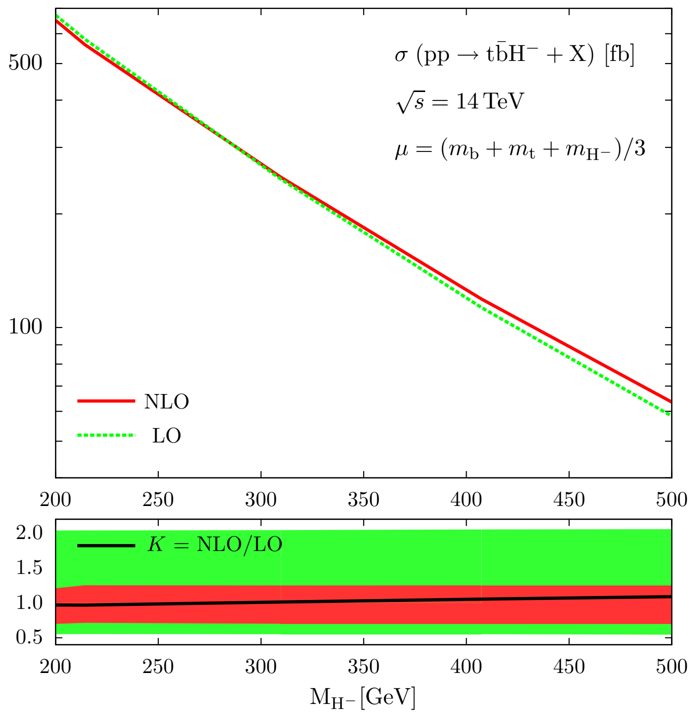
- NNLO: $\mathcal{O}(10\%)$, $\mu = M_{SUSY}$

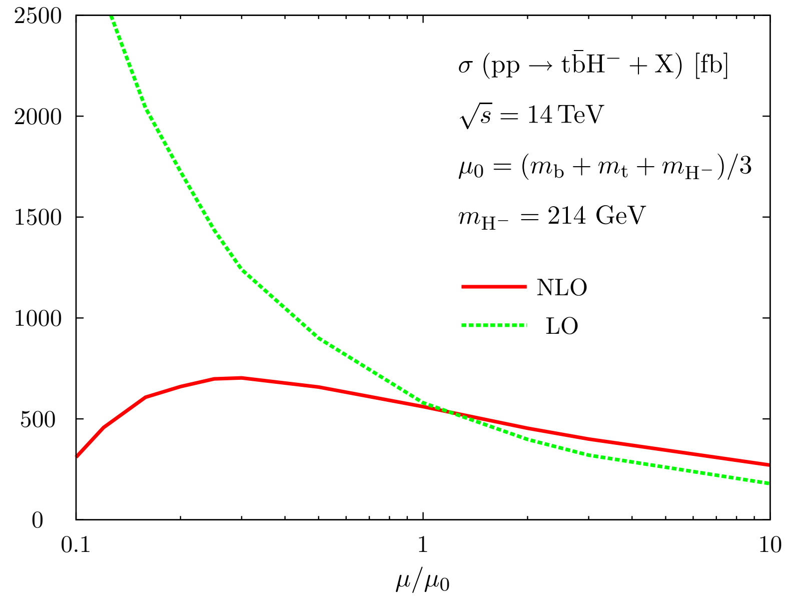
Noth, S.

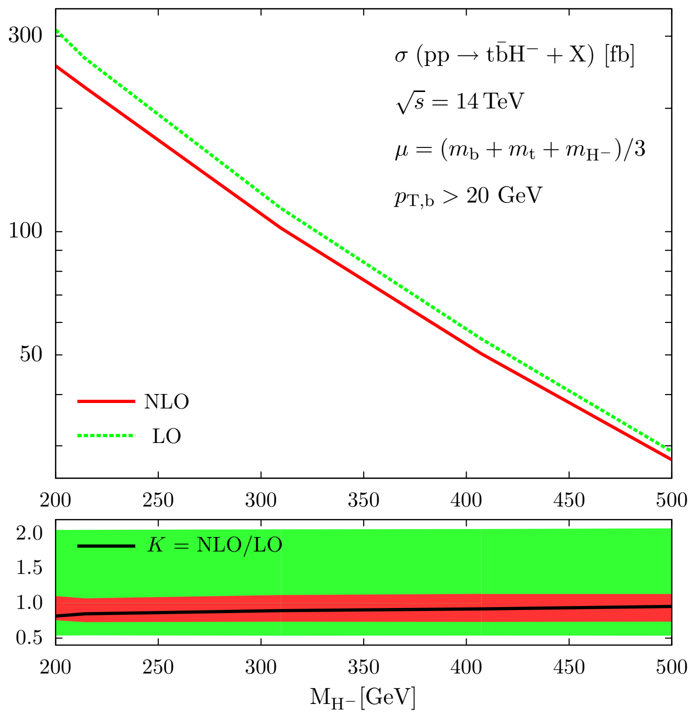
$b\bar{b}\phi^0$: SPS 1b

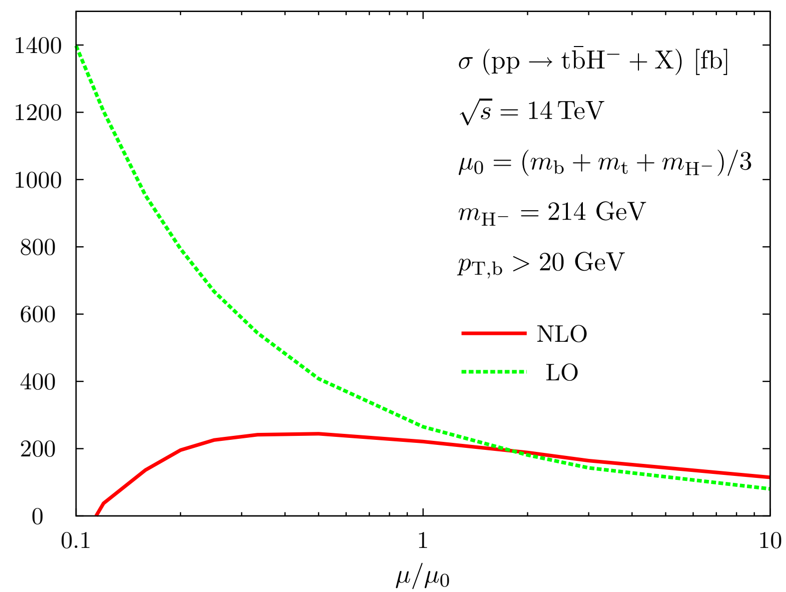
$$
\begin{aligned}
\mathrm{tg}\beta &= 30 \\
\mu &= 495.6\ \mathrm{GeV} \\
A_t &= -729.3\ \mathrm{GeV} \\
A_b &= -987.4\ \mathrm{GeV} \\
m_{\tilde{g}} &= 916.1\ \mathrm{GeV} \\
m_{\tilde{q}_L} &= 762.5\ \mathrm{GeV} \\
m_{\tilde{b}_R} &= 780.3\ \mathrm{GeV} \\
m_{\tilde{t}_R} &= 670.7\ \mathrm{GeV}
\end{aligned}
$$

$$\longrightarrow m_{\tilde{b}_1} = 745.8\ \mathrm{GeV}, m_{\tilde{b}_2} = 798.9\ \mathrm{GeV}$$





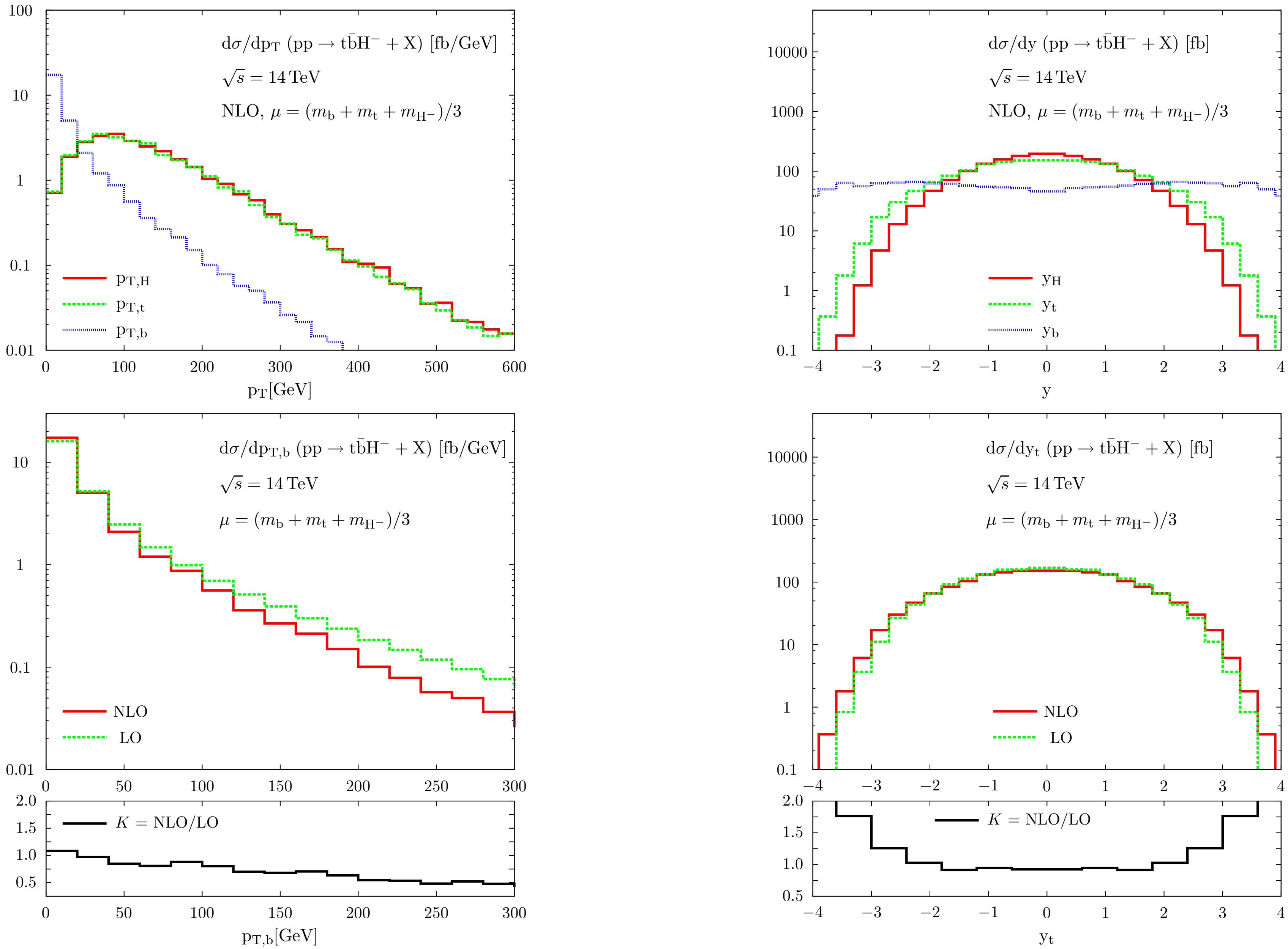




Dittmaier, Krämer, S., Walser

M_{A} [GeV]	$M_{\mathrm{H}^{\pm}}$ [GeV]	$\overline{m}_b^{\mathrm{NLO}}(\mu)$ [GeV]	$\sigma(\mathrm{pp} \to \bar{\mathrm{t}}\mathrm{bH}^- + X)$ [fb]		$\mathrm{K} = \sigma_{\mathrm{NLO}}/\sigma_{\mathrm{LO}}$
			LO	NLO	
200	214.28	2.80	583	562(2)	0.96
300	309.70	2.76	248	251(1)	1.01
400	407.33	2.72	114	119(1)	1.04
500	505.88	2.68	56.5	61.0(2)	1.09

$M_{\mathrm{H}^{\pm}}$ [GeV]	$\sigma_{\mathrm{NLO}} = \sigma_0 \times (1+\delta_{\mathrm{SUSY}}^{\tan\beta-\mathrm{resum.}}) \times (1+\delta_{\mathrm{QCD}}+\delta_{\mathrm{SUSY}}^{\mathrm{remainder}})$				$\sigma_{\mathrm{NLO}}^{\mathrm{fixed-order}}$ [fb]
	σ_0 [fb]	δ_{QCD}	$\delta_{\mathrm{SUSY}}^{\tan\beta-\mathrm{resum.}}$	$\delta_{\mathrm{SUSY}}^{\mathrm{remainder}}$	
214.28	512	0.55	-0.30	-0.0008	563(2)
309.70	224	0.61	-0.30	-0.0012	258(1)
407.33	106	0.61	-0.30	-0.0009	125(1)
505.88	53.3	0.62	-0.30	-0.0003	64.1(2)



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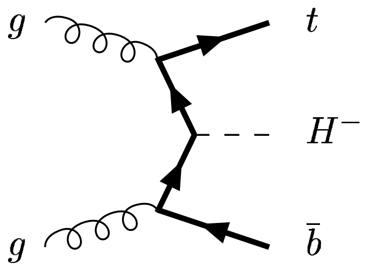
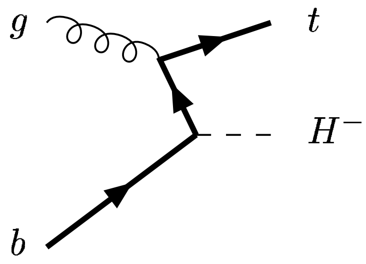


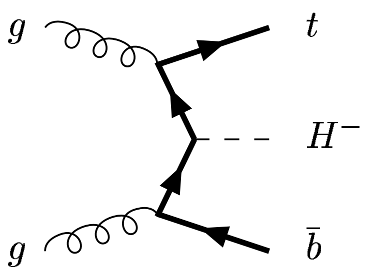


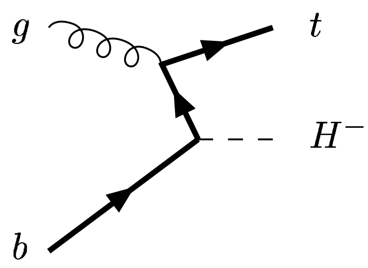
exact $g \to b\bar{b}$ splitting & mass/off-shell effects

no resummation of $\log M_H^2/m_b^2$ terms

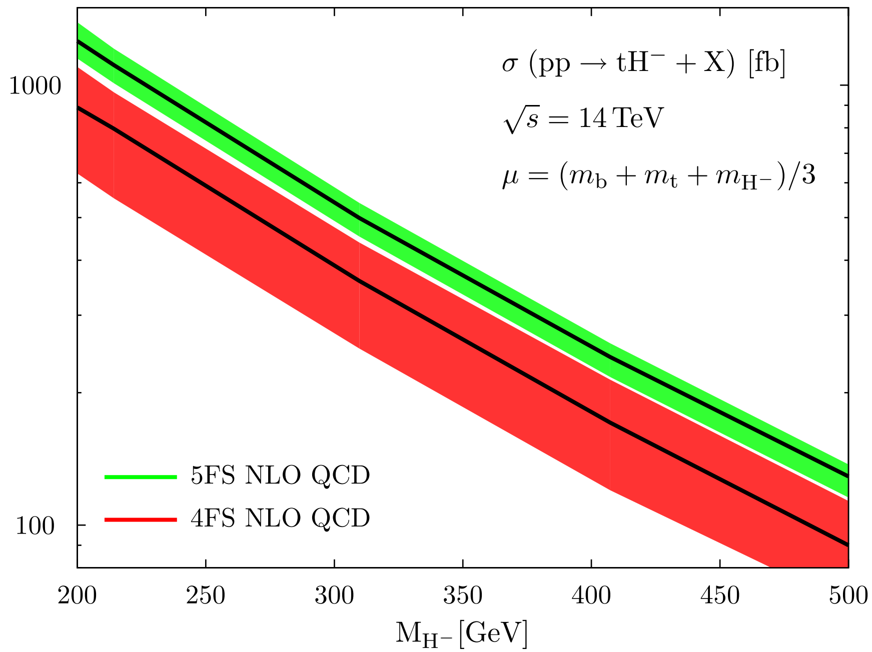
massless/on-shell b's, no p_{Tb}

resummation of $\log M_H^2/m_b^2$ terms





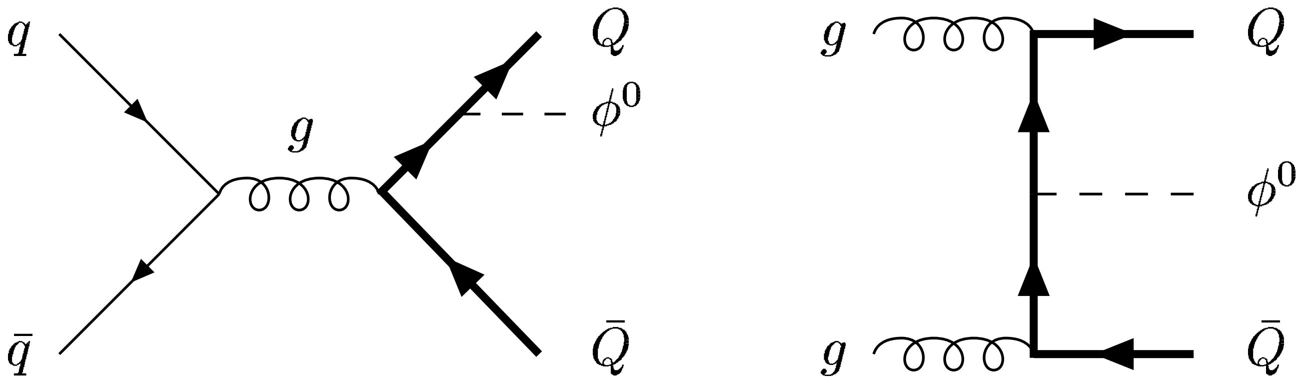
exact $g \to b\bar{b}$ splitting & mass/off-shell effects	massless/on-shell b's, no p_{Tb}
no resummation of $\log M_H^2/m_b^2$ terms	resummation of $\log M_H^2/m_b^2$ terms



Dittmaier, Krämer, S., Walser

Plehn

II $t\bar{t}/b\bar{b} + \phi^0$ PRODUCTION

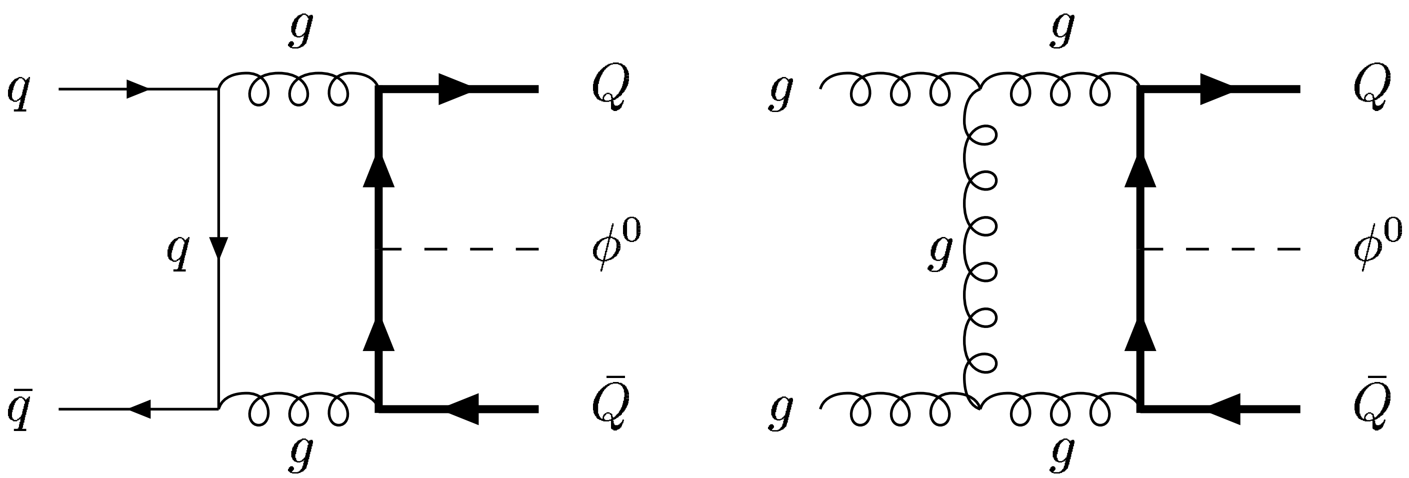


dominant

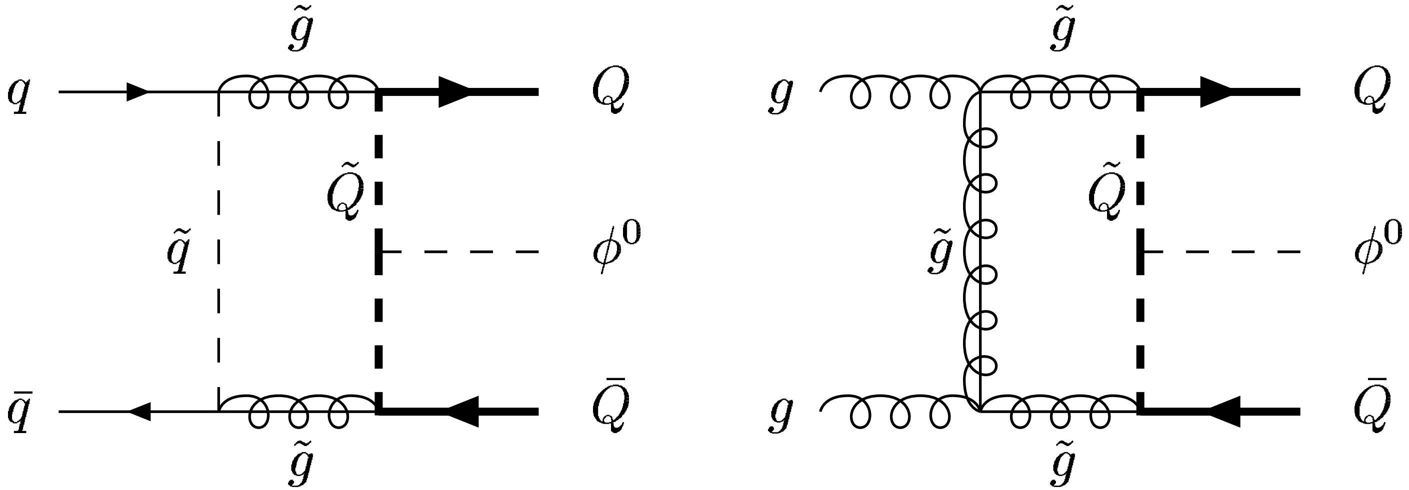
- $gg, q\bar{q} \to t\bar{t}\phi^0$ important for $M_\phi \lesssim$ 130 GeV
- crucial for determination of top Yukawa coupling
- $b\bar{b} + H/A$ dominant for large tgβ
- measurement of tgβ
- $t\bar{t}h$: SUSY-QCD corrections computed

Peng, Wen-Gan, Hong-Shen,
Ren-You, Liang
Rauch, Hollik

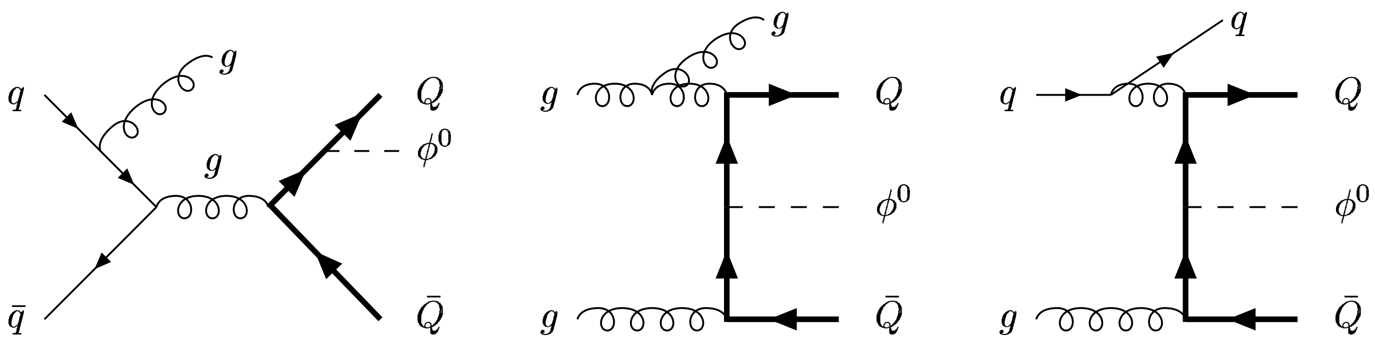
SUSY-QCD Corrections



QCD



SUSY-QCD



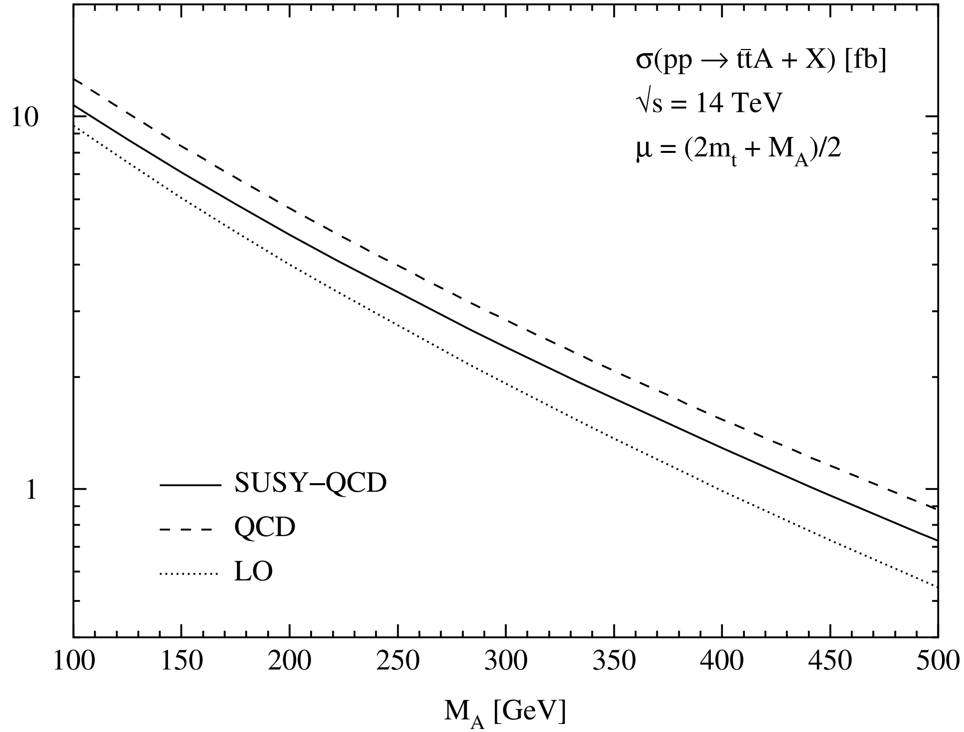
real

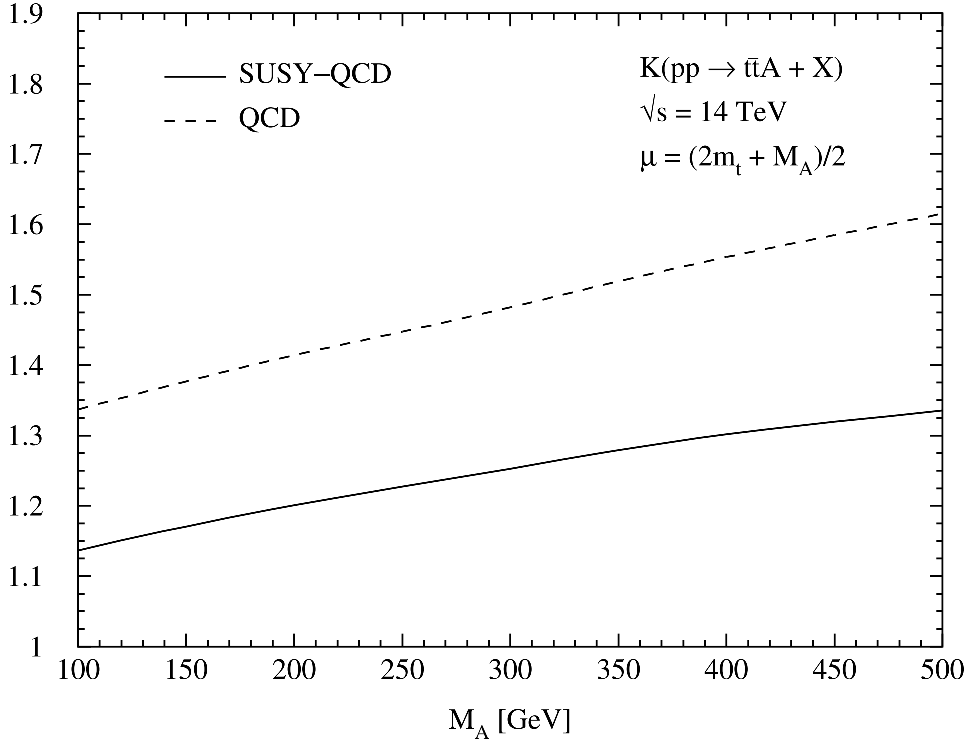
$t\bar{t}\phi^0$: SPS 5

$$
\begin{aligned}
\mathrm{tg}\beta &= 5 \\
\mu &= 639.8 \text{ GeV} \\
A_t &= -1671.4 \text{ GeV} \\
A_b &= -905.6 \text{ GeV} \\
m_{\tilde{g}} &= 710.3 \text{ GeV} \\
m_{\tilde{q}_L} &= 535.2 \text{ GeV} \\
m_{\tilde{b}_R} &= 620.5 \text{ GeV} \\
m_{\tilde{t}_R} &= 360.5 \text{ GeV}
\end{aligned}
$$

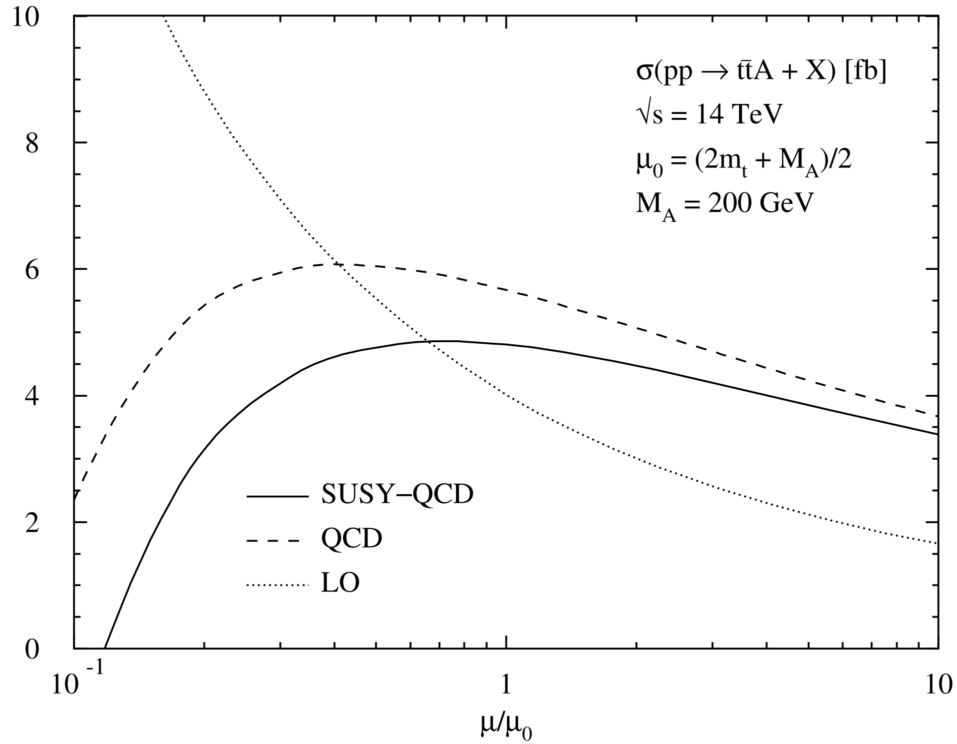
$$\longrightarrow m_{\tilde{t}_1} = 230.4 \text{ GeV}, m_{\tilde{t}_2} = 637.8 \text{ GeV}$$

- 5 active flavours → top, squarks, gluinos decoupled
- PDF: CTEQ6L1/M



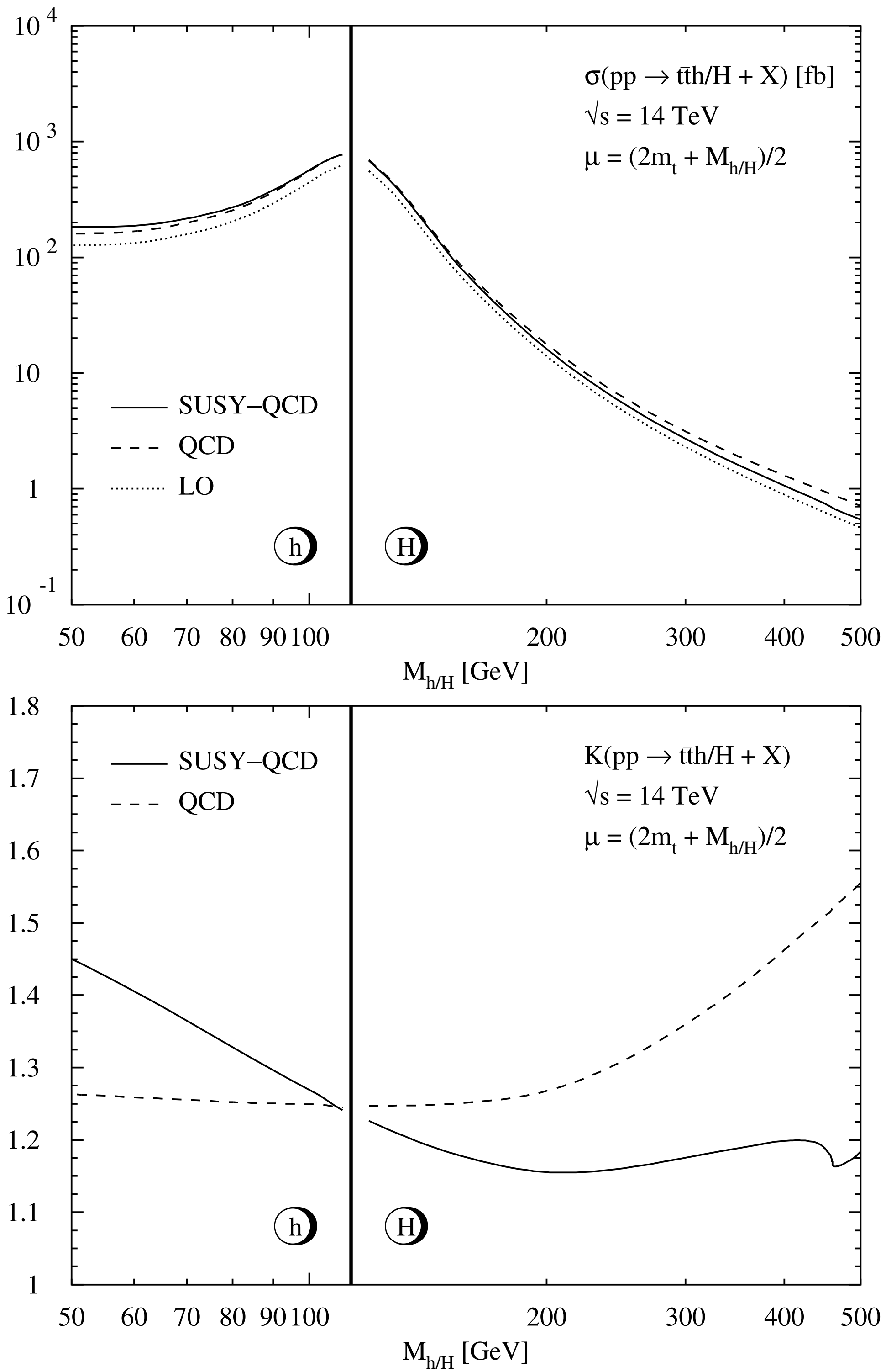


PRELIMINARY

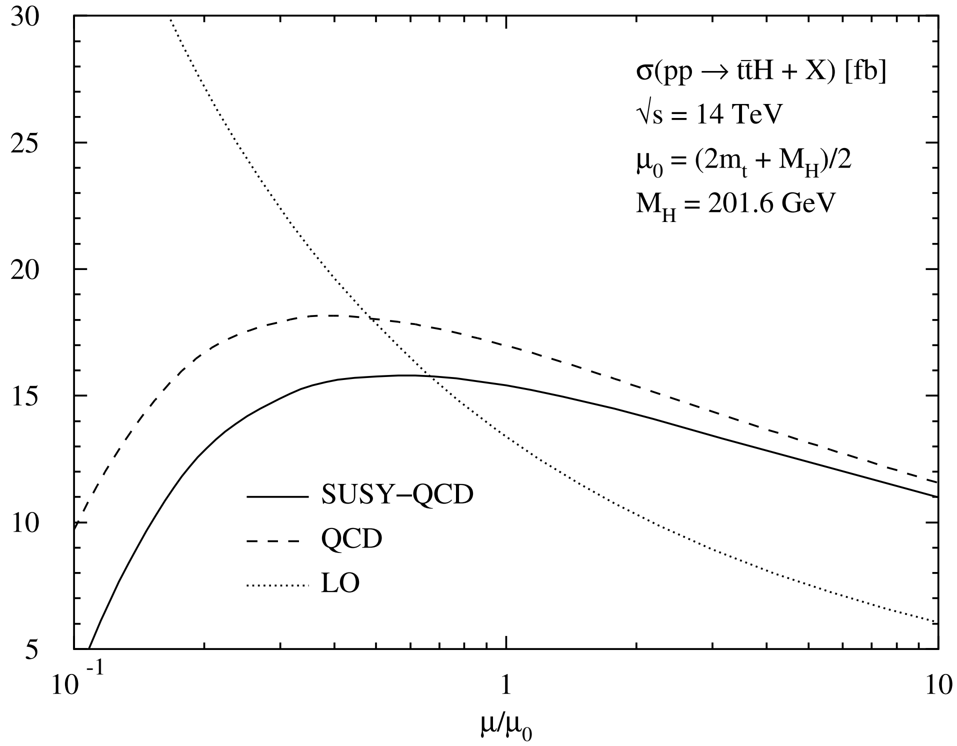


$\Rightarrow \Delta \lesssim 10\%$

Dittmaier, Häfliger,
Krämer, S., Walser



PRELIMINARY



$\Rightarrow \Delta \lesssim 10\%$

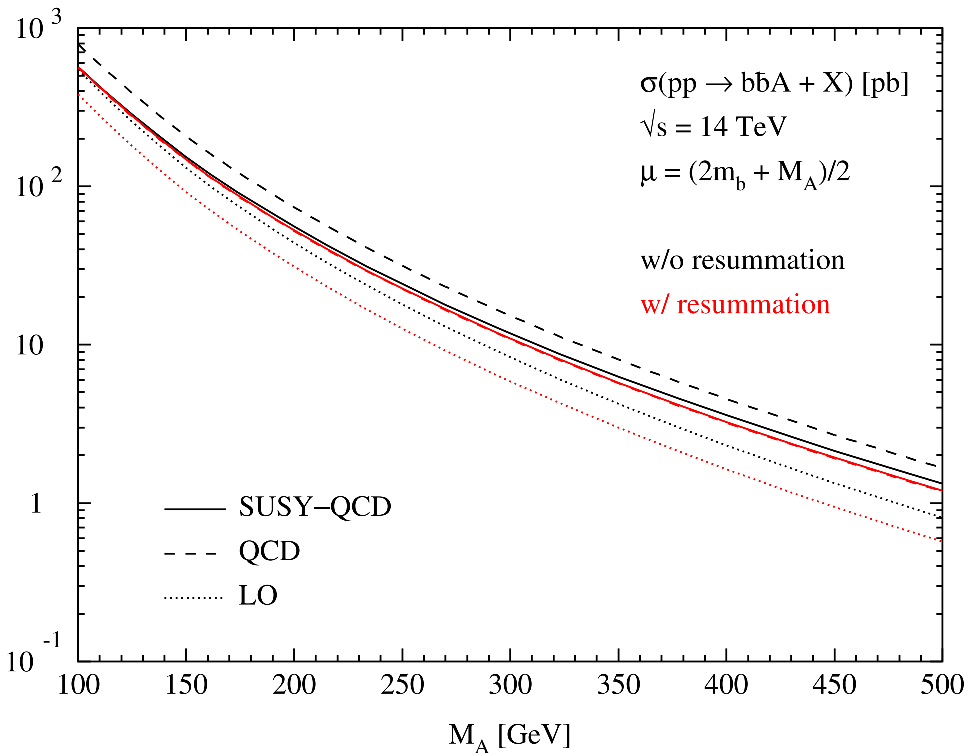
Dittmaier, Häfliger, Krämer, S., Walser

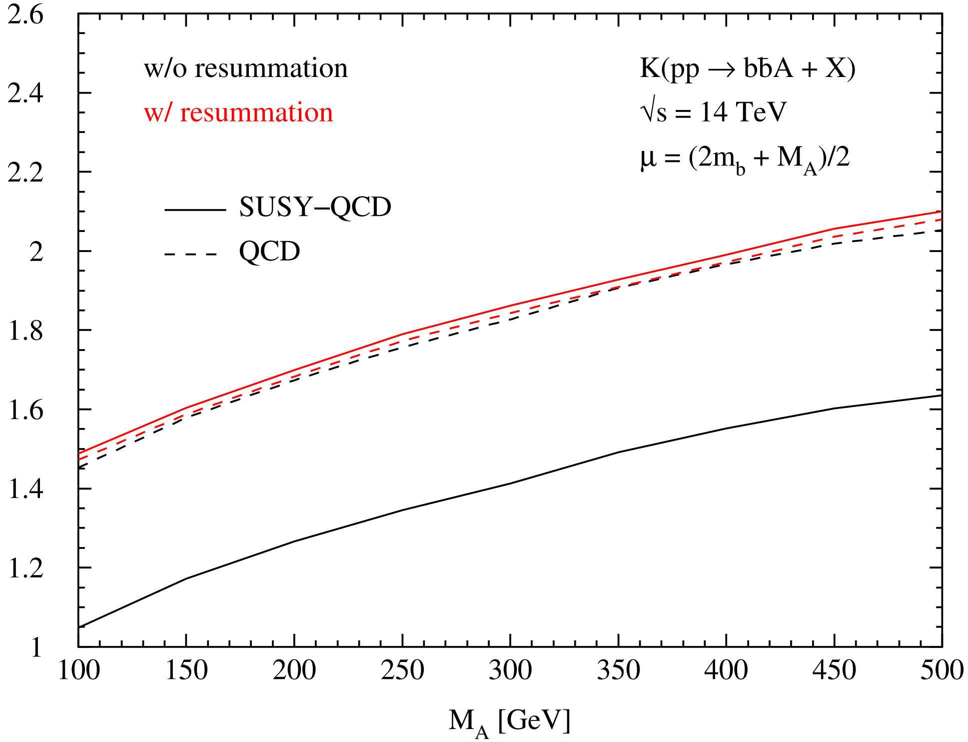
$b\bar{b}\phi^0$: SPS 1b

$$
\begin{aligned}
\mathrm{tg}\beta &= 30 \\
\mu &= 495.6 \text{ GeV} \\
A_t &= -729.3 \text{ GeV} \\
A_b &= -987.4 \text{ GeV} \\
m_{\tilde{g}} &= 916.1 \text{ GeV} \\
m_{\tilde{q}_L} &= 762.5 \text{ GeV} \\
m_{\tilde{b}_R} &= 780.3 \text{ GeV} \\
m_{\tilde{t}_R} &= 670.7 \text{ GeV}
\end{aligned}
$$

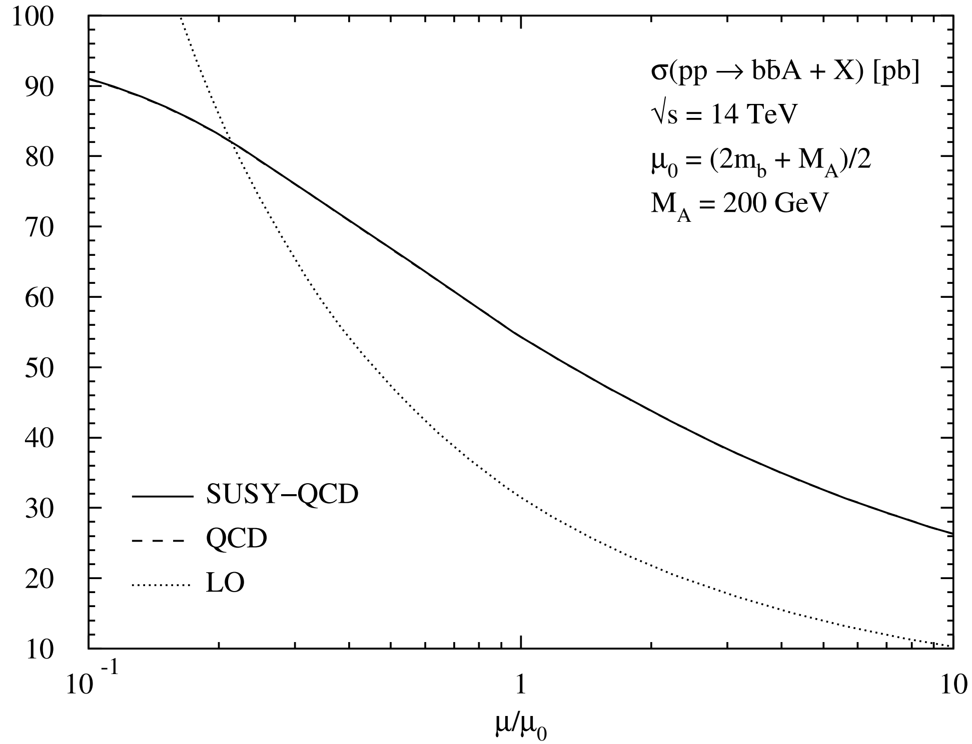
$$
\longrightarrow m_{\tilde{b}_1} = 745.8 \text{ GeV}, m_{\tilde{b}_2} = 798.9 \text{ GeV}
$$

- 4 active flavours $\rightarrow$ bottom, top, squarks, gluinos decoupled
- PDF: CTEQ6L1/M [$\leftarrow$ to be changed]



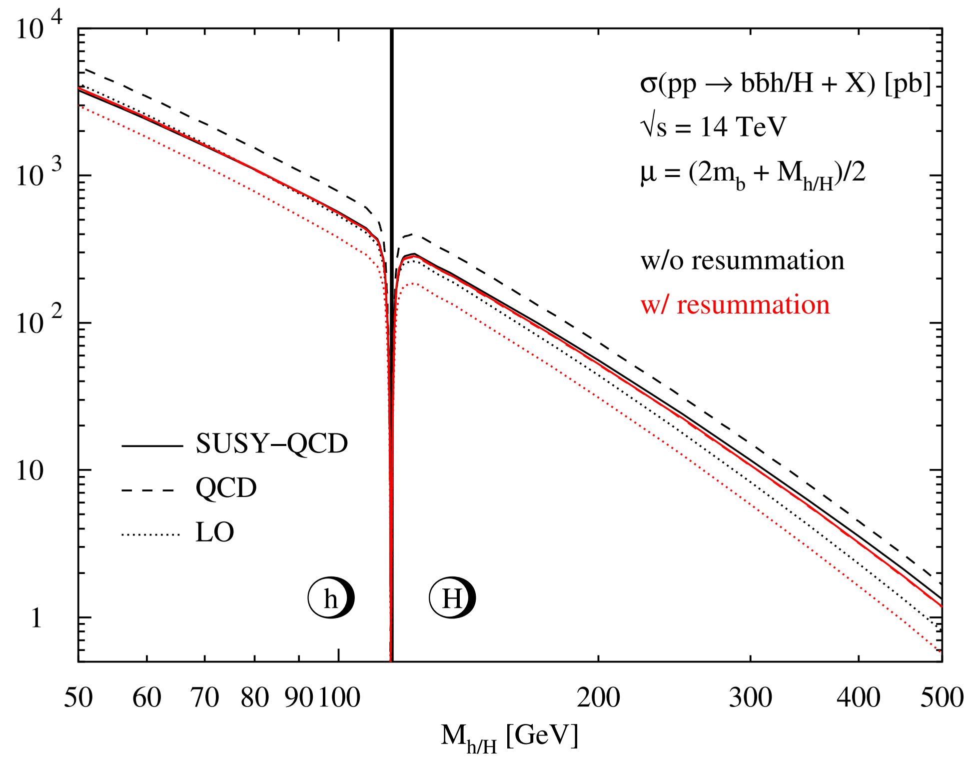


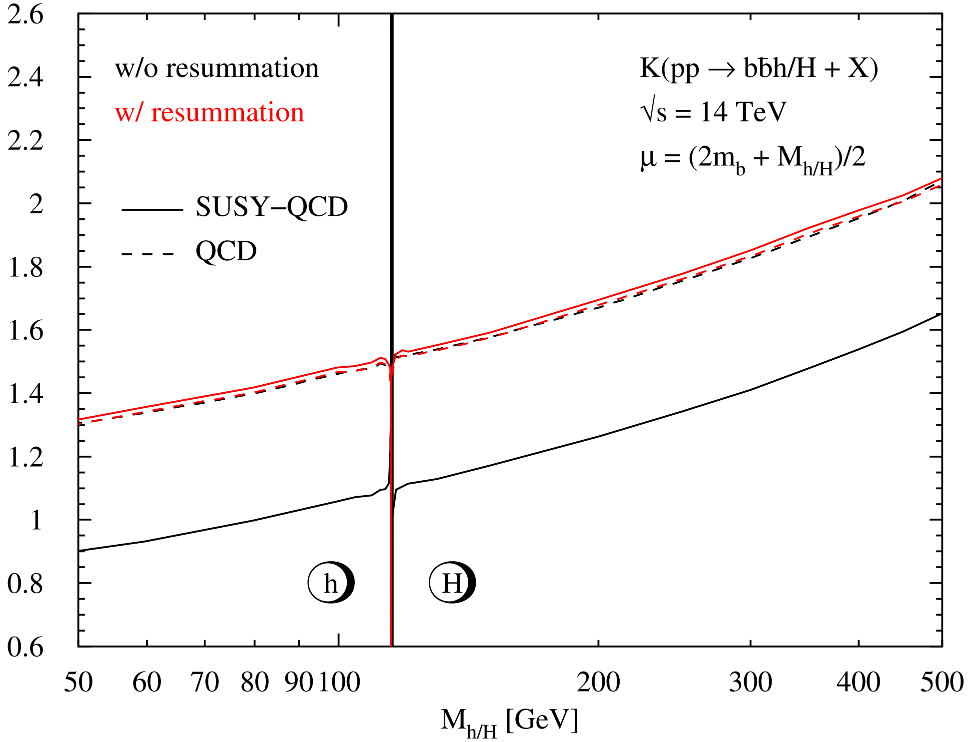
PRELIMINARY



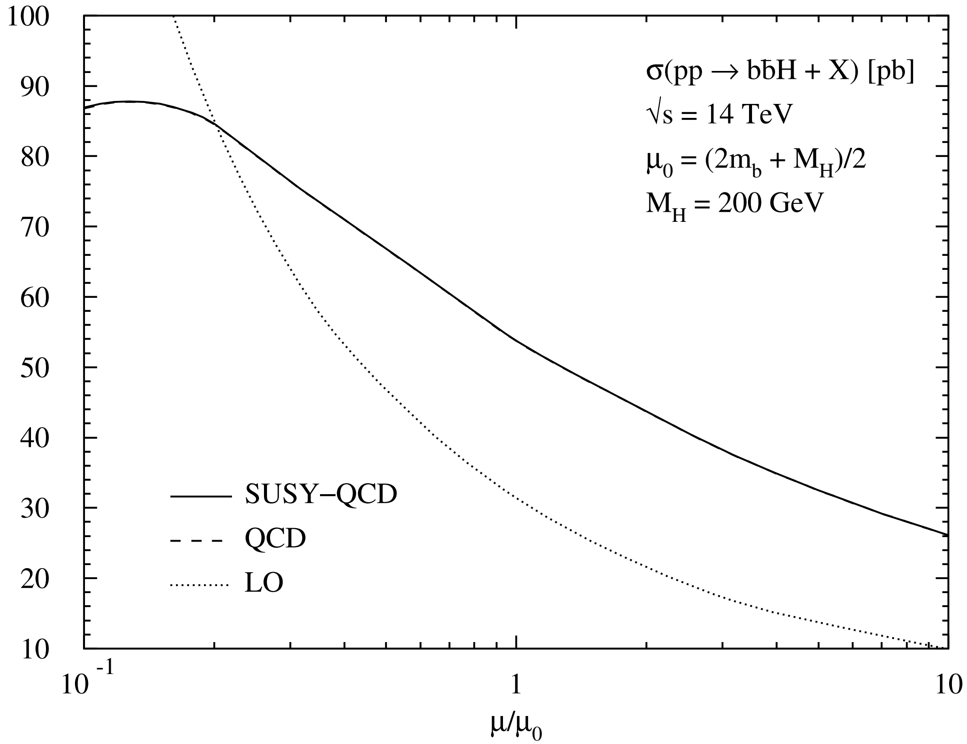
$\Rightarrow \Delta \lesssim 25\%$

Dittmaier, Häfliger,
Krämer, S., Walser





PRELIMINARY



$\Rightarrow \Delta \lesssim 25\%$

Dittmaier, Häfliger,
Krämer, S., Walser

III *CONCLUSIONS*

(i) $t\bar{b}H^-$

- QCD corrections: (50–60)% $\Rightarrow \Delta \lesssim 25\%$
  finite p_{Tb}: moderate $\Rightarrow \Delta \lesssim 10-15\%$
- SUSY-QCD corrections: small after resummation $[\Delta_b]$ for large tgβ
- 4FS and 5FS barely consistent: 40% discrepancy

(ii) $t\bar{t}\phi^0$

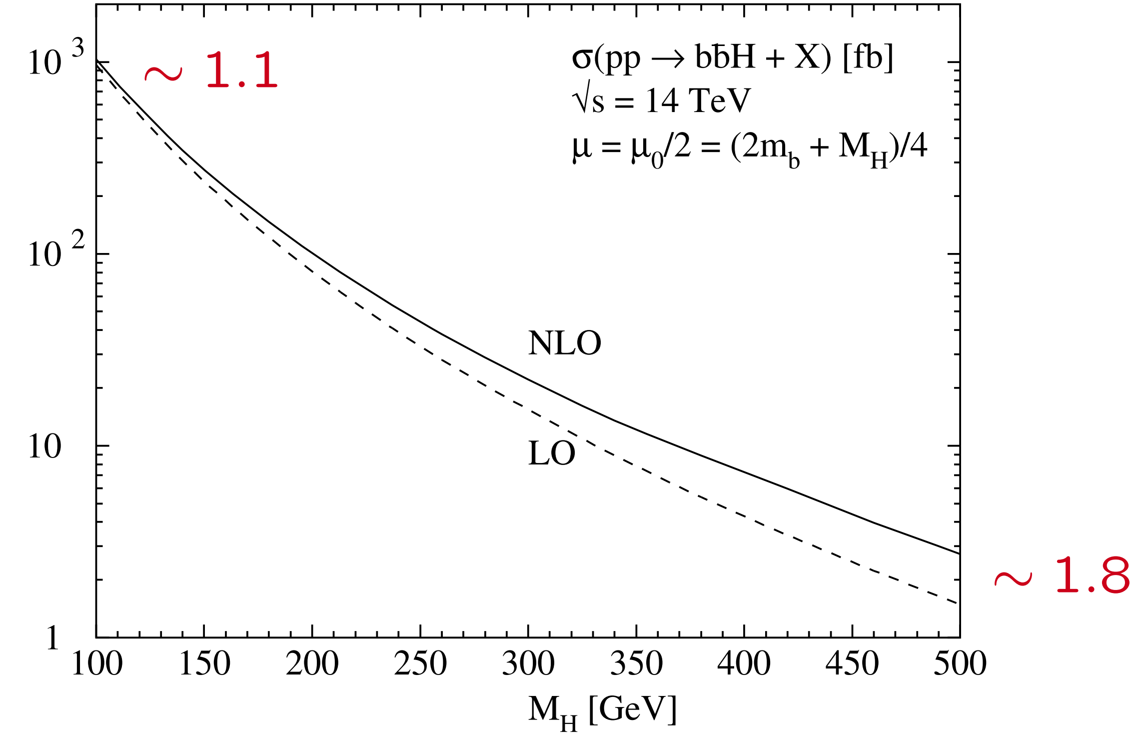
- QCD corrections: $\sim (20-60)\%$ @ LHC $\Rightarrow \Delta \lesssim 10-15\%$
- SUSY-QCD corrections: $\sim \pm(20-30)\%$ @ LHC

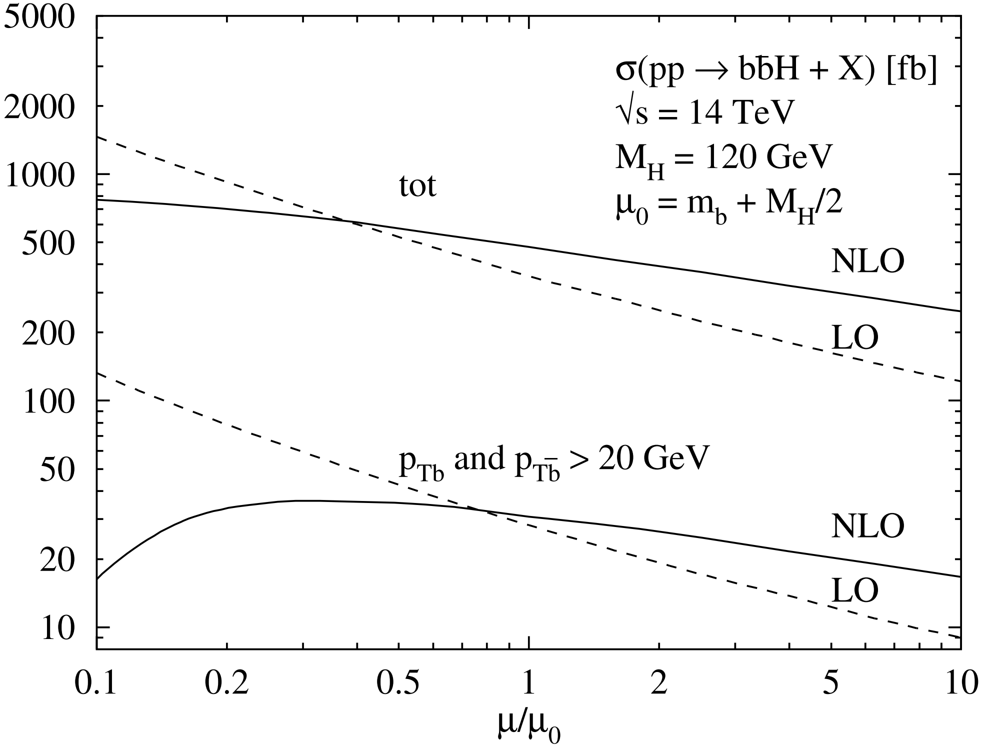
(iii) $b\bar{b}\phi^0$

- QCD corrections: $\lesssim 100\%$ for total cxn $\Rightarrow \Delta \lesssim 25\%$
  [moderate for larger p_{Tb}]
- SUSY-QCD corrections: small after resummation $[\Delta_b]$ for large tgβ
- 4FS $\leftrightarrow$ 5FS: soon...

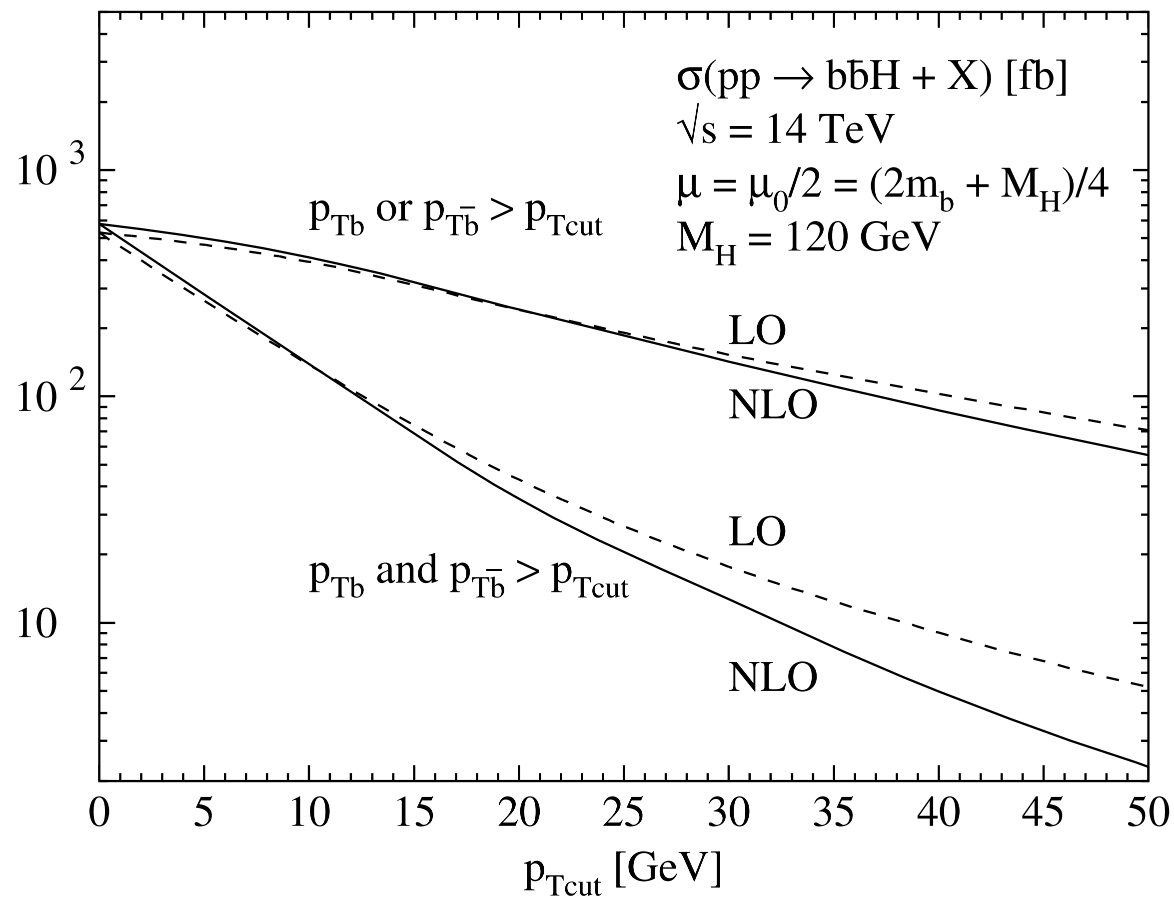
BACKUP SLIDES

Standard Model



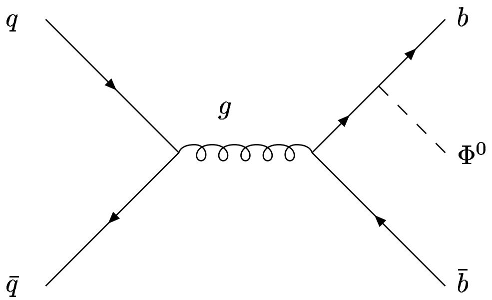


Dittmaier, Krämer, S.

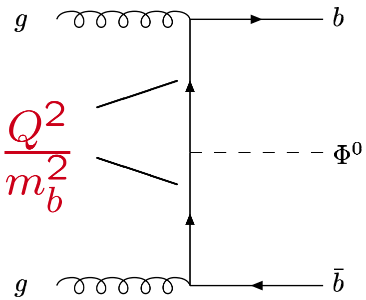


Dittmaier, Krämer, S.

b densities



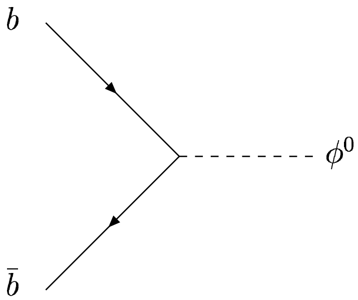
$\log \frac{Q^2}{m_b^2}$



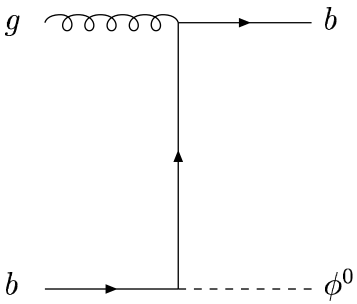
dominant

large logs from phase space integration $\longrightarrow$ bottom PDF
resummation $\equiv$ DGLAP evolution

- new processes:



NNLO



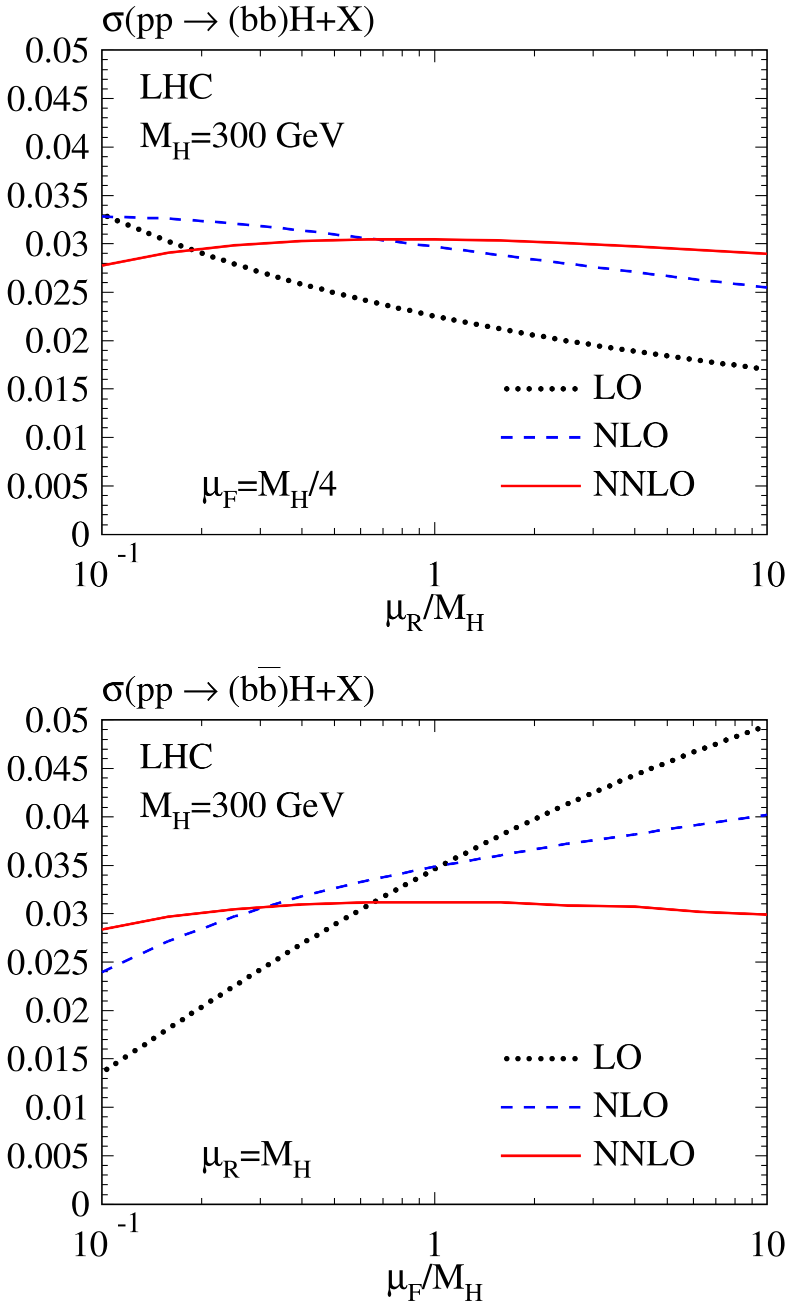
NLO

Dicus,Willenbrock
Stelzer, . . .
Balazs,. . .
Campbell,. . .

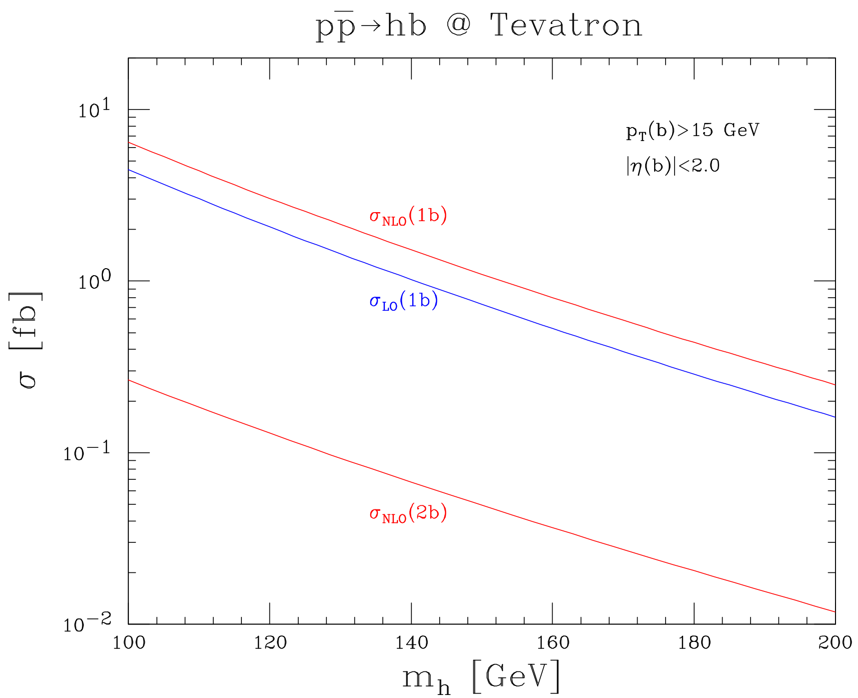
Harlander, Kilgore

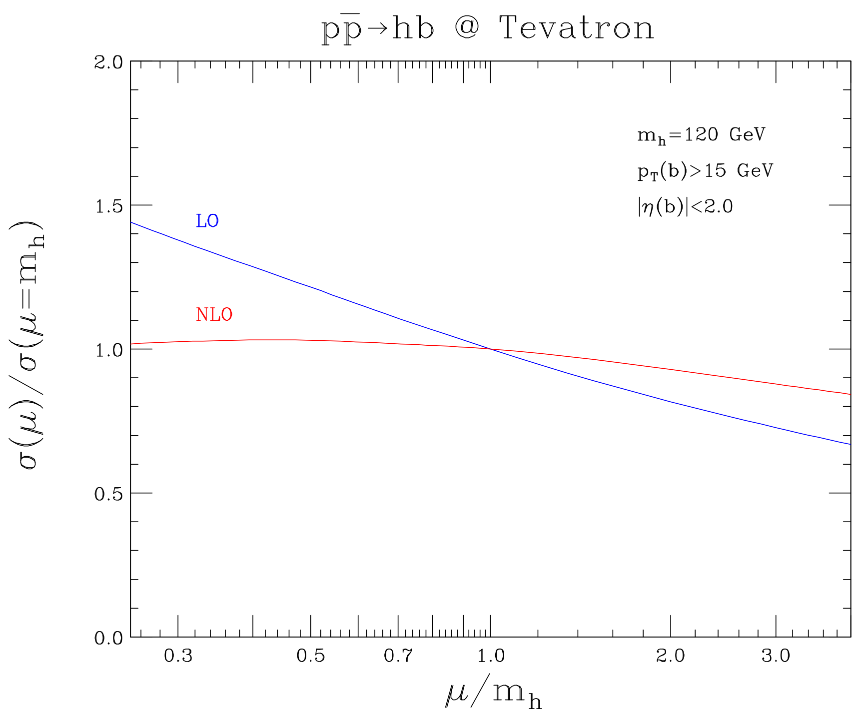
$$b(x,\mu^2) \longrightarrow b(x,\mu^2) - \frac{\alpha_s}{2\pi} P_{qg} \otimes g(x,\mu^2) \log \frac{\mu^2}{m_b^2}$$

$$\mu \sim Q \sim M_\phi/4 \Rightarrow \sigma_{tot}$$

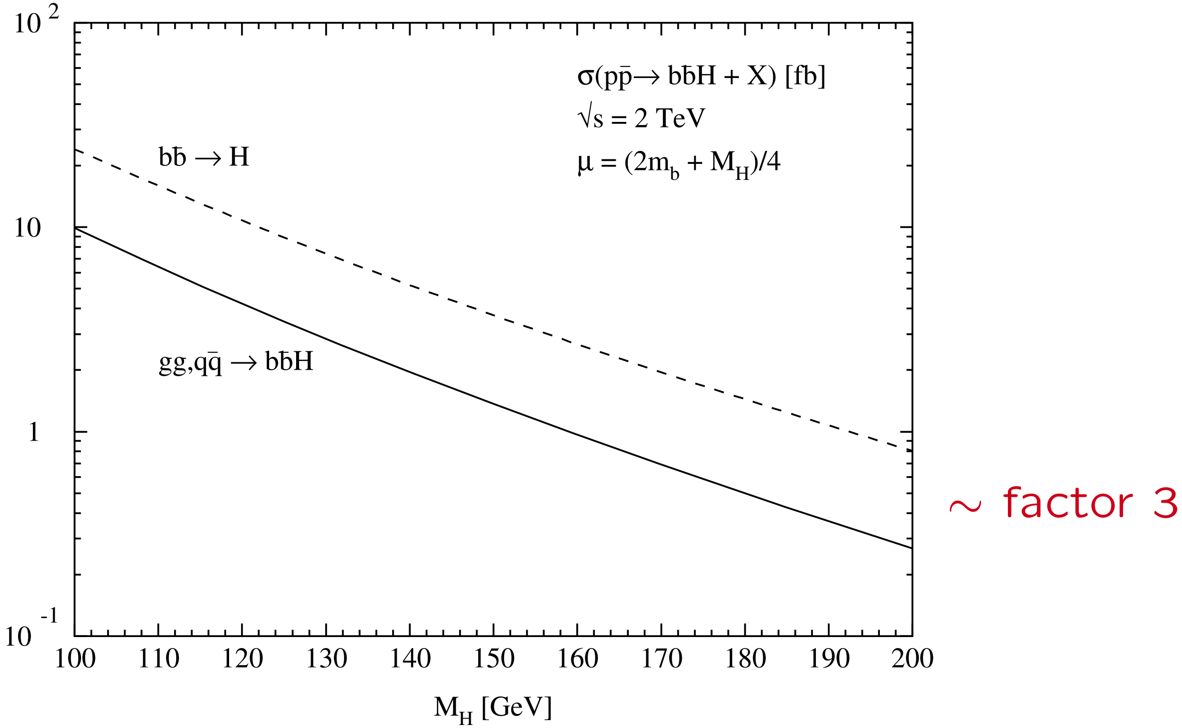


Harlander, Kilgore

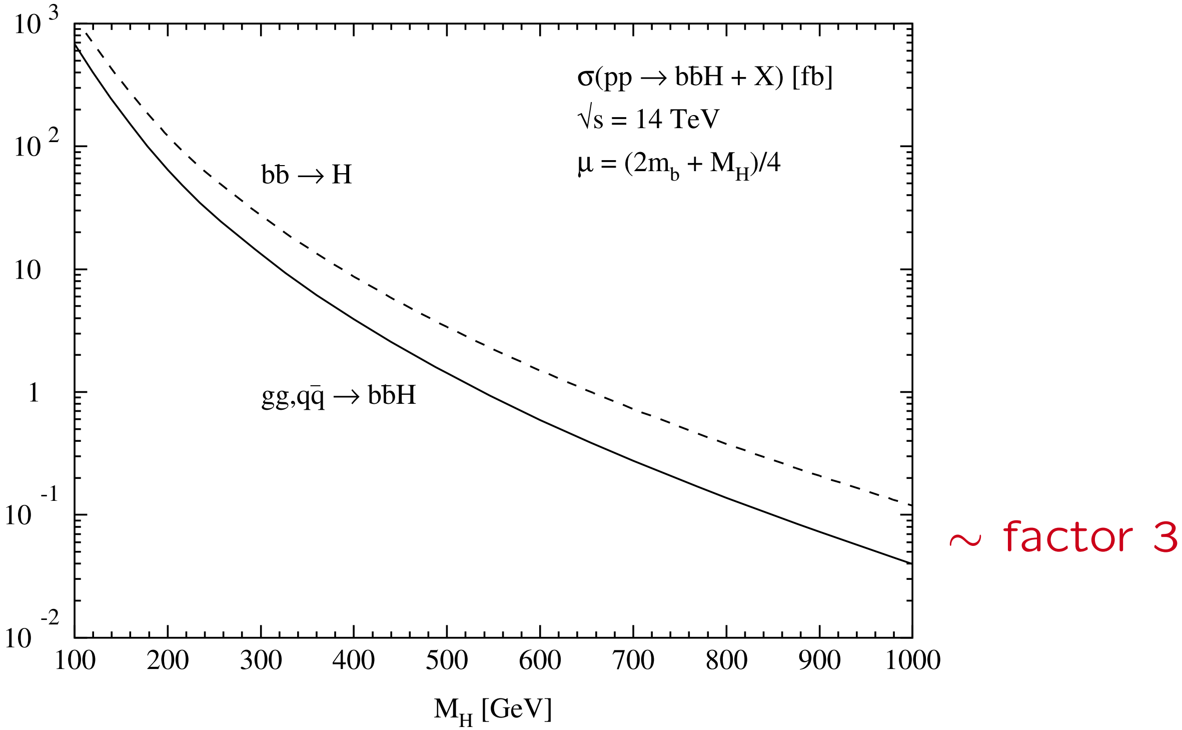




Campbell, Ellis, Maltoni, Willenbrock



σ(pp̄→ bb̄H + X) [fb]
√s = 2 TeV
μ = (2m_b + M_H)/4
bb̄ → H
gg,qq̄ → bb̄H
M_H [GeV]
~ factor 3



σ(pp → bb̄H + X) [fb]
√s = 14 TeV
μ = (2m_b + M_H)/4
bb̄ → H
gg,qq̄ → bb̄H
M_H [GeV]
~ factor 3

- factorization in high-energy limit: $[M_{Tb} = \sqrt{p_{Tb}^2 + m_b^2}]$

$$\frac{d\sigma^{(2\to3)}}{dM_{Tb}^2} = \frac{1}{M_{Tb}^2} \left\{ \frac{\alpha_s}{2\pi} \Delta_{qg} \otimes g \otimes g \otimes \hat{\sigma}_{\bar{b}g} \right\}_{M_{Tb}=m_b\to 0} + \cdots$$

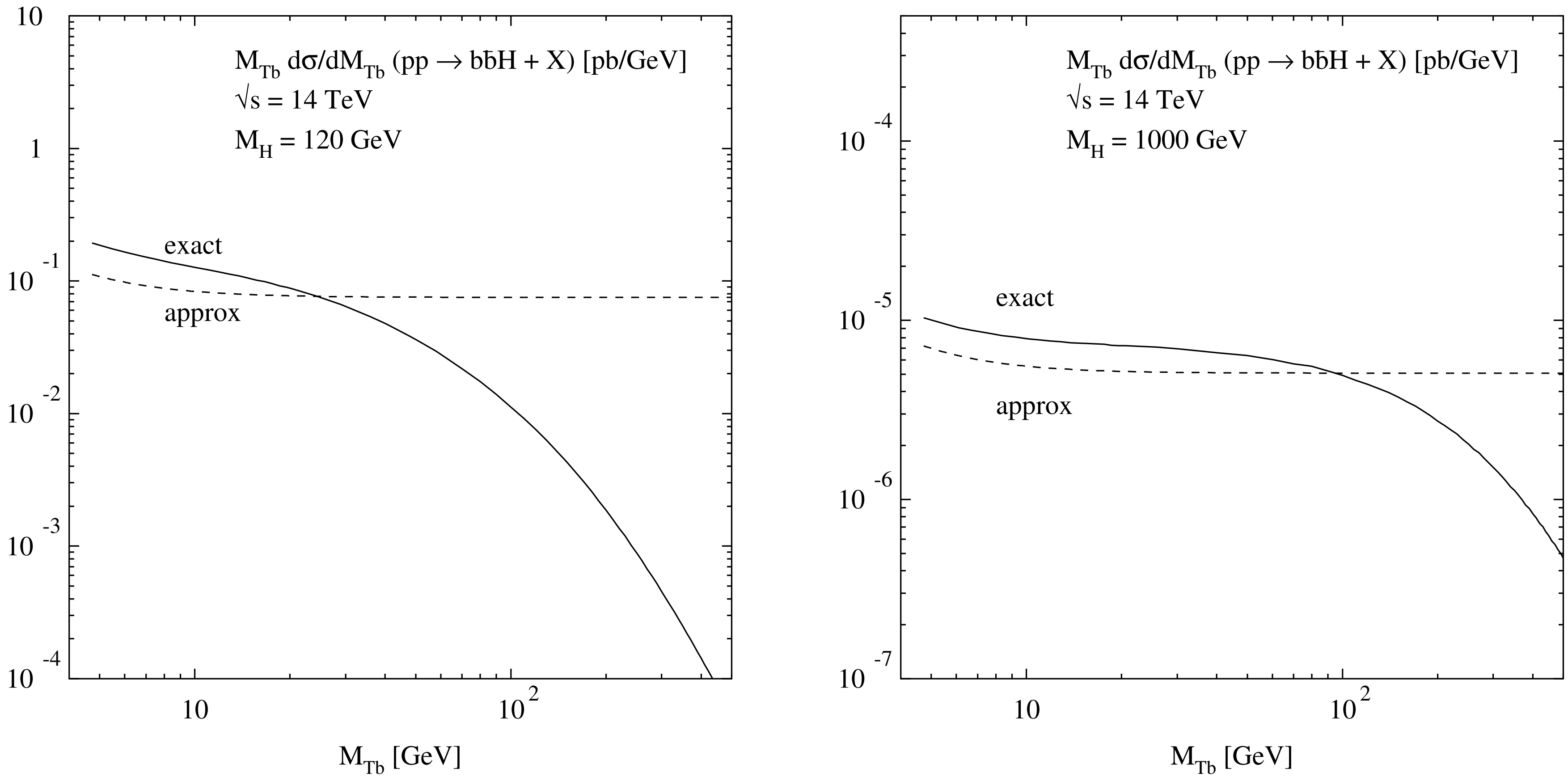
$$\Delta_{qg}(x) = P_{qg}(x) + \frac{m_b^2}{M_{Tb}^2} x(1-x)$$

- total cross section:

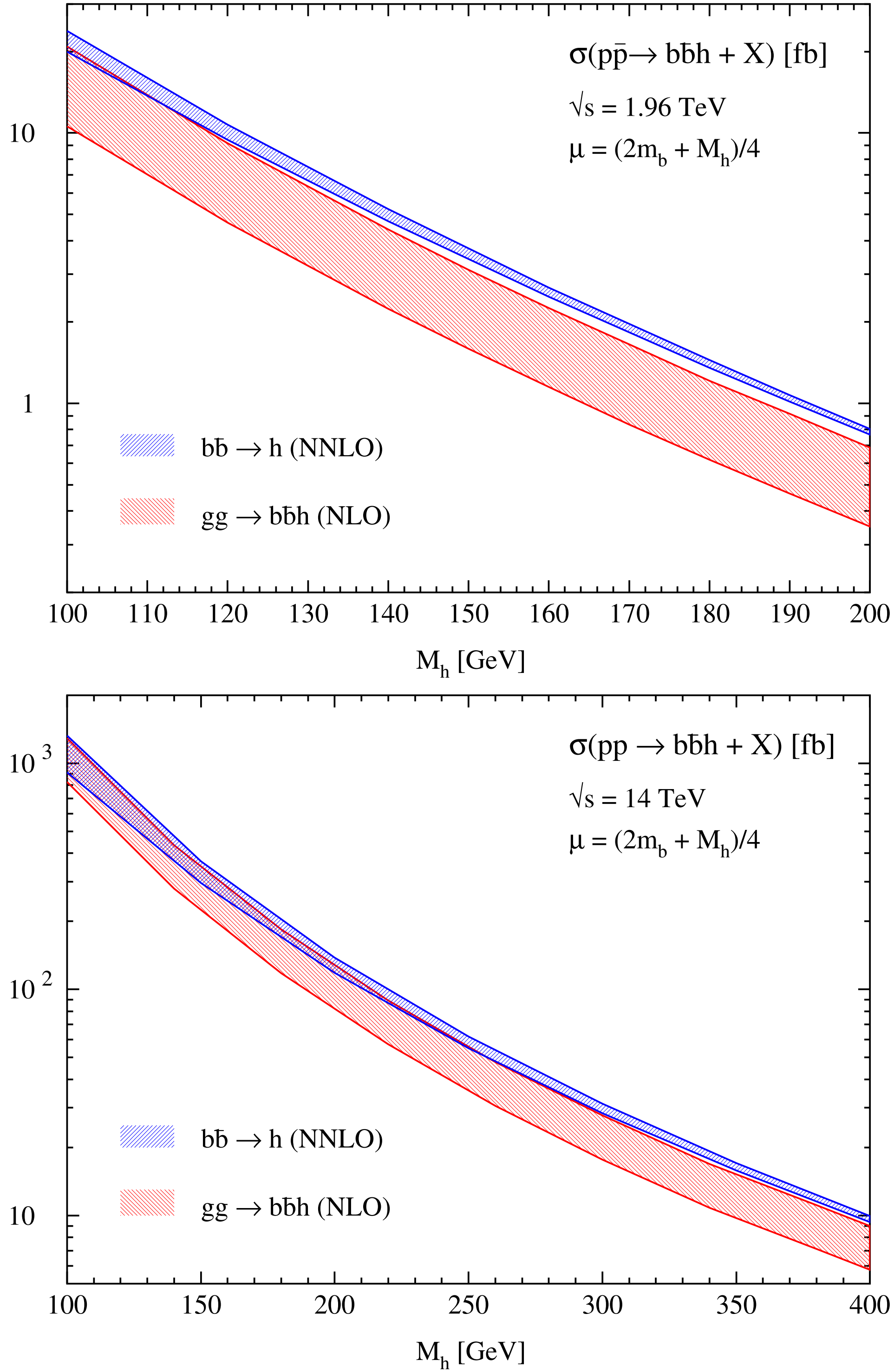
$$\sigma = \underbrace{\int_{m_b^2}^{\mu_F^2} \frac{dM_{Tb}^2}{M_{Tb}^2}}_{\log \frac{\mu_F^2}{m_b^2}} \left\{ \frac{\alpha_s}{2\pi} P_{qg} \otimes g \otimes g \otimes \hat{\sigma}_{\bar{b}g} \right\}_{M_{Tb}=m_b\to 0} + \cdots$$

$\Rightarrow$ crucial condition:

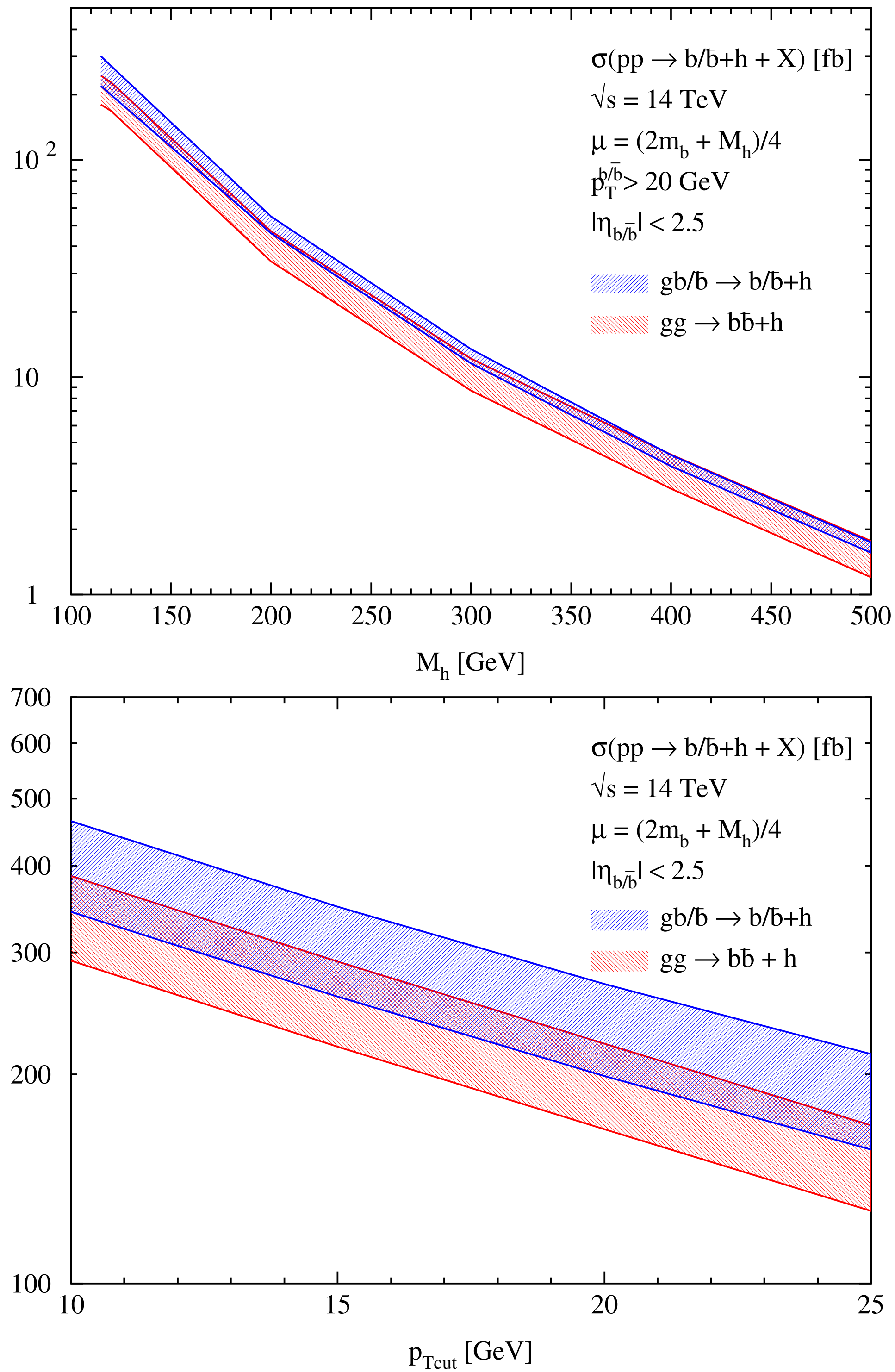
$$\frac{d\sigma^{(2\to3)}}{dM_{Tb}} \propto \frac{1}{M_{Tb}} \quad \text{up to } M_{Tb} \sim \mu_F$$



Rainwater, S., Zeppenfeld



Dittmaier, Krämer, S.
Harlander, Kilgore



Campbell, Dawson, Dittmaier, Jackson, Krämer, Maltoni, Reina, S., Wackeroth, Willenbrock