SUSY Higgs cross sections

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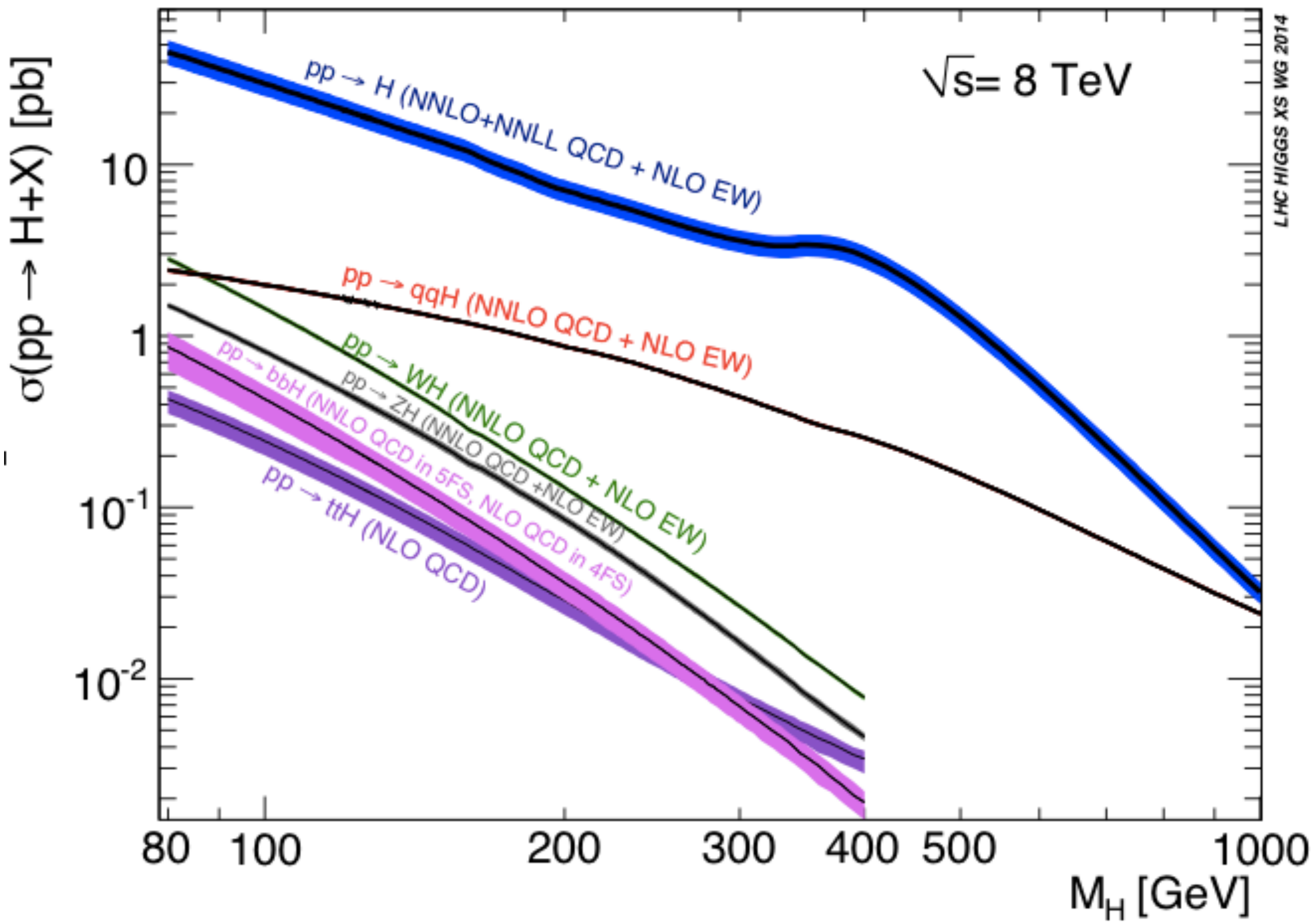
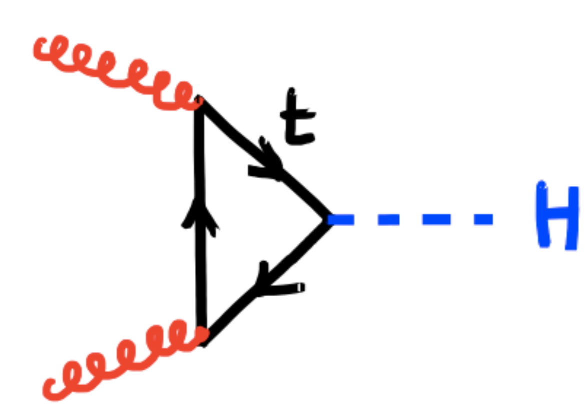
und Forschung

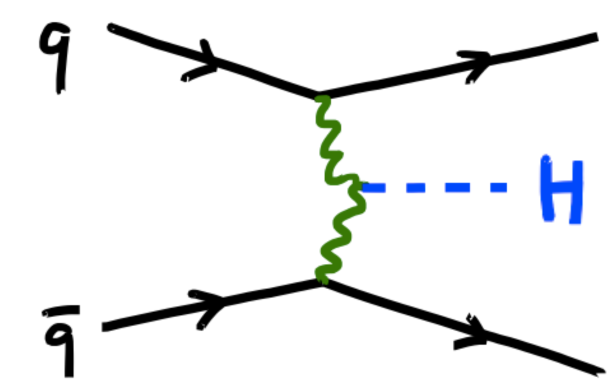
PHYSICS AT THE TERA SCALE
Helmholtz Alliance



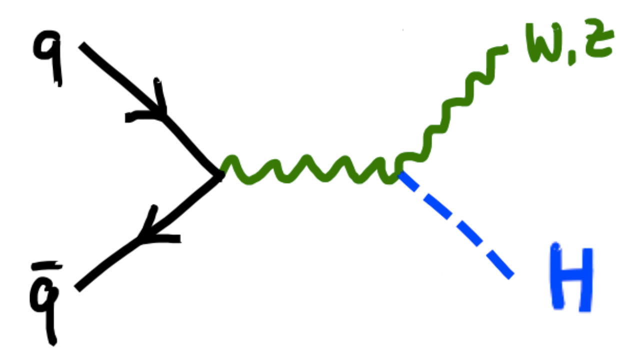
√s= 8 TeV
LHC HIGGS XS WG 2014
σ(pp → H+X) [pb]
10
1
10⁻¹
10⁻²
80 100 200 300 400 500 1000
M_H [GeV]
pp → H (NNLO+NNLL QCD + NLO EW)
pp → qqH (NNLO QCD + NLO EW)
pp → WH (NNLO QCD + NLO EW)
pp → ZH (NNLO QCD +NLO EW)
pp → bbH (NNLO QCD in 5FS, NLO QCD in 4FS)
pp → ttH (NLO QCD)



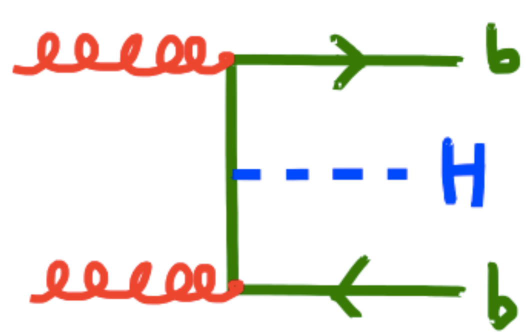
t
H



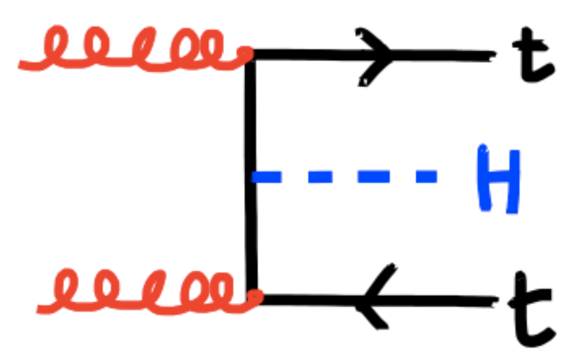
q
H
q̄



q
W,Z
q̄
H



b
H
b

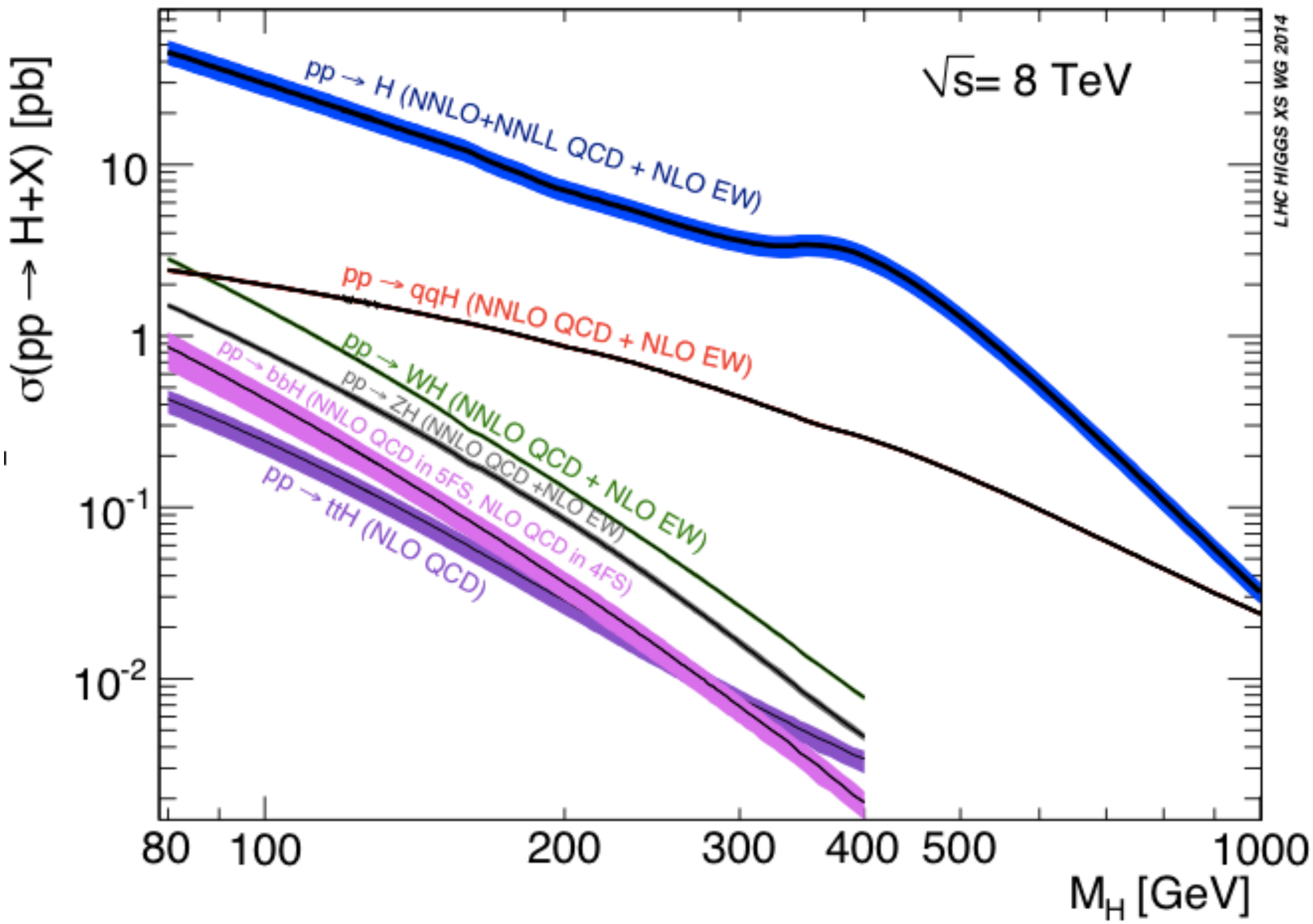


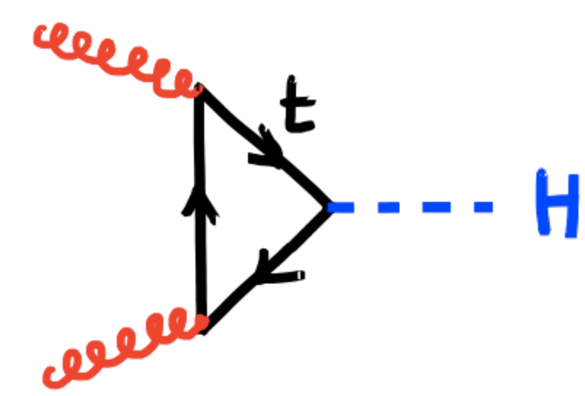
t
H
t

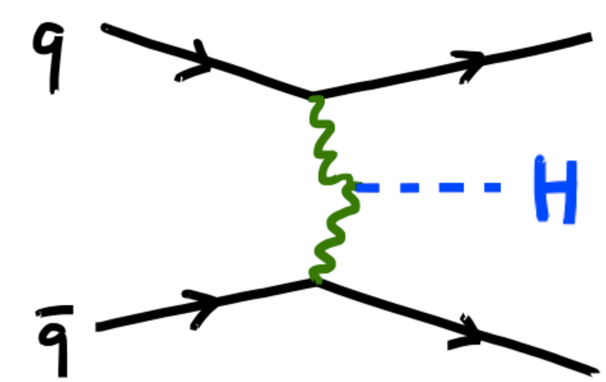
SUSY effects

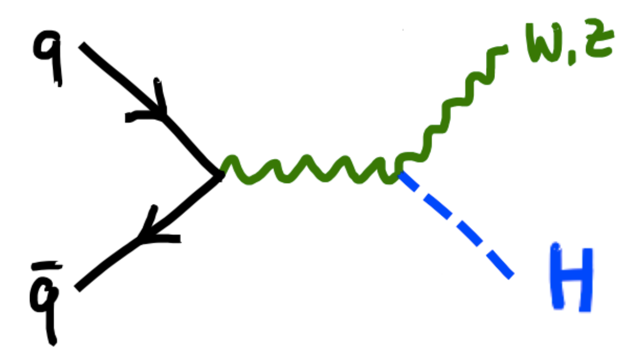
SUSY effects

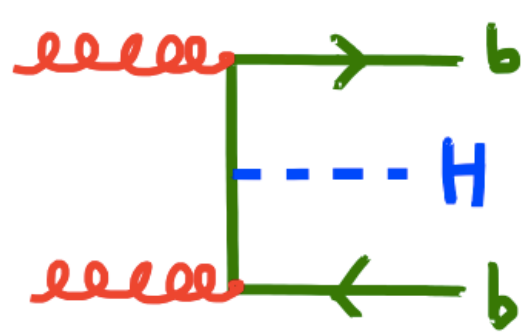
- rescaling of couplings

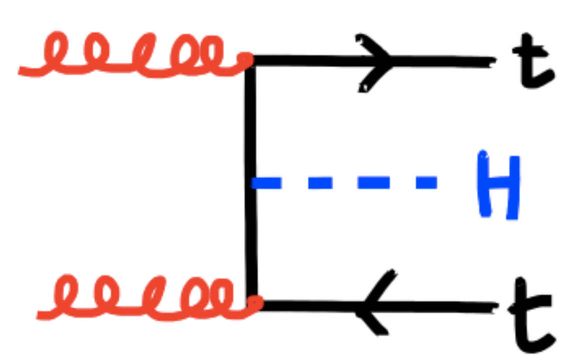

σ(pp → H+X) [pb]
√s= 8 TeV
LHC HIGGS XS WG 2014
pp → H (NNLO+NNLL QCD + NLO EW)
pp → qqH (NNLO QCD + NLO EW)
pp → WH (NNLO QCD + NLO EW)
pp → ZH (NNLO QCD +NLO EW)
pp → bbH (NNLO QCD in 5FS, NLO QCD in 4FS)
pp → ttH (NLO QCD)
10
1
10-1
10-2
80
100
200
300
400
500
1000
M_H [GeV]

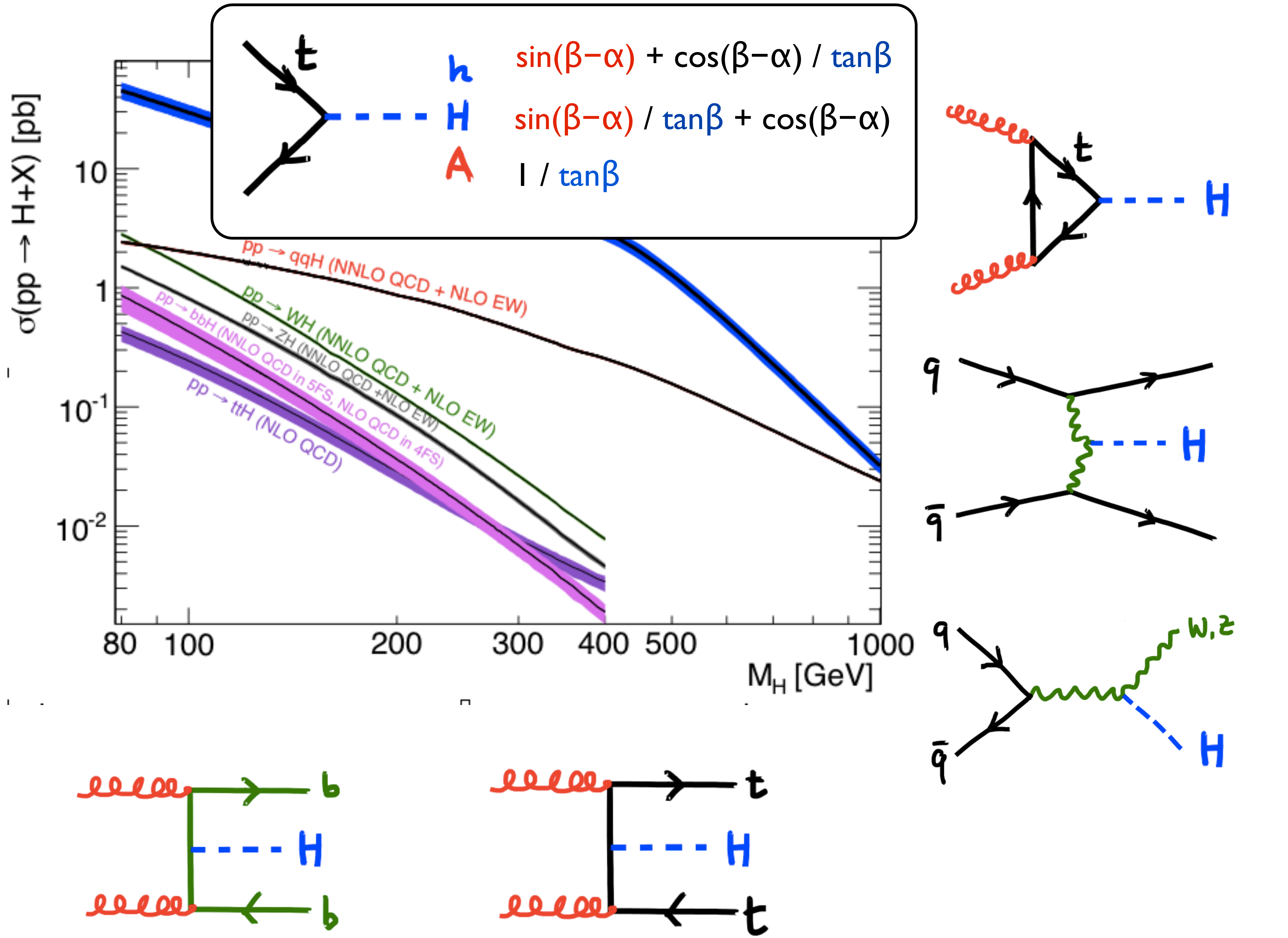

t
H

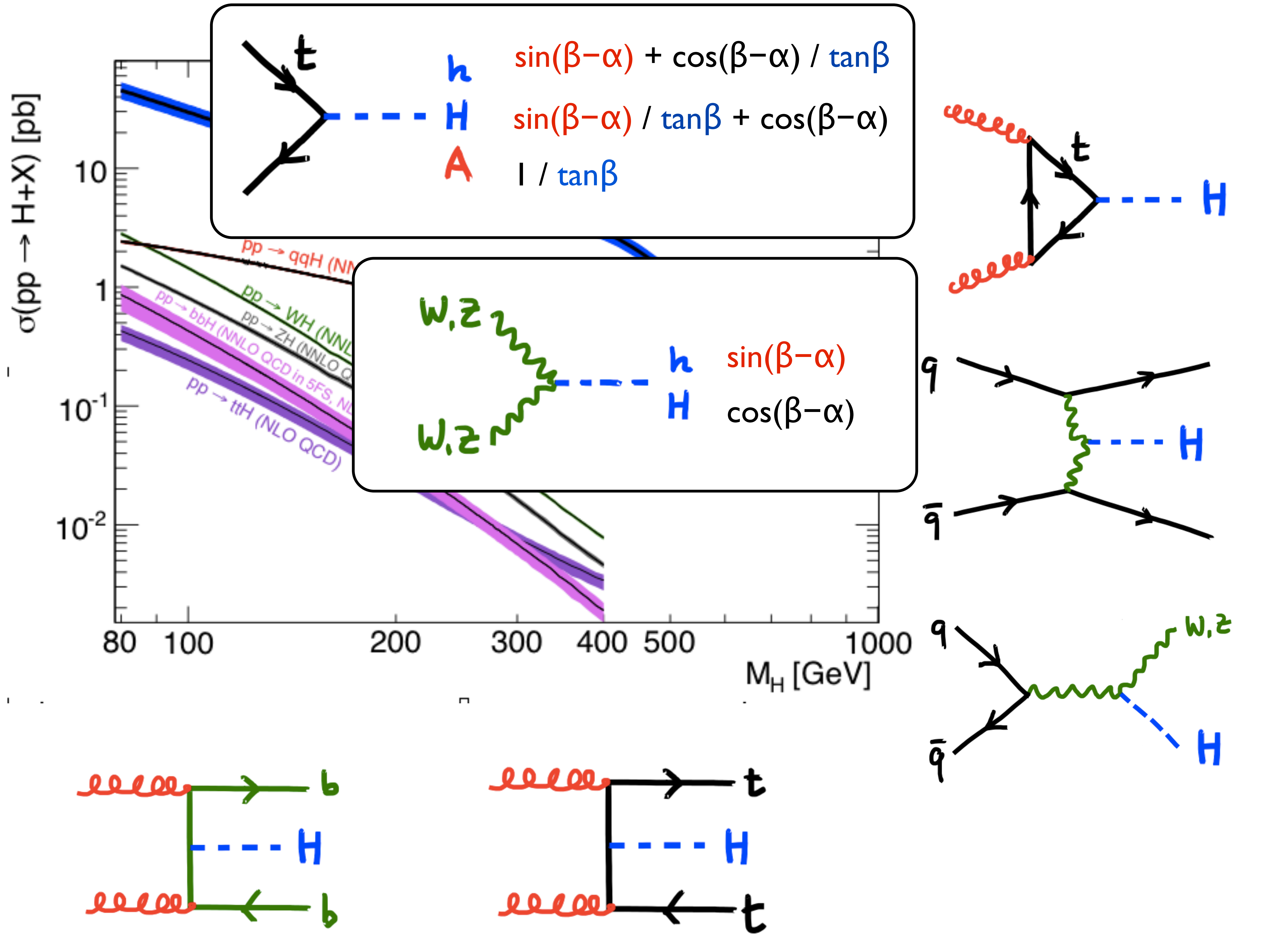

q
q̄
H


q
q̄
W,Z
H

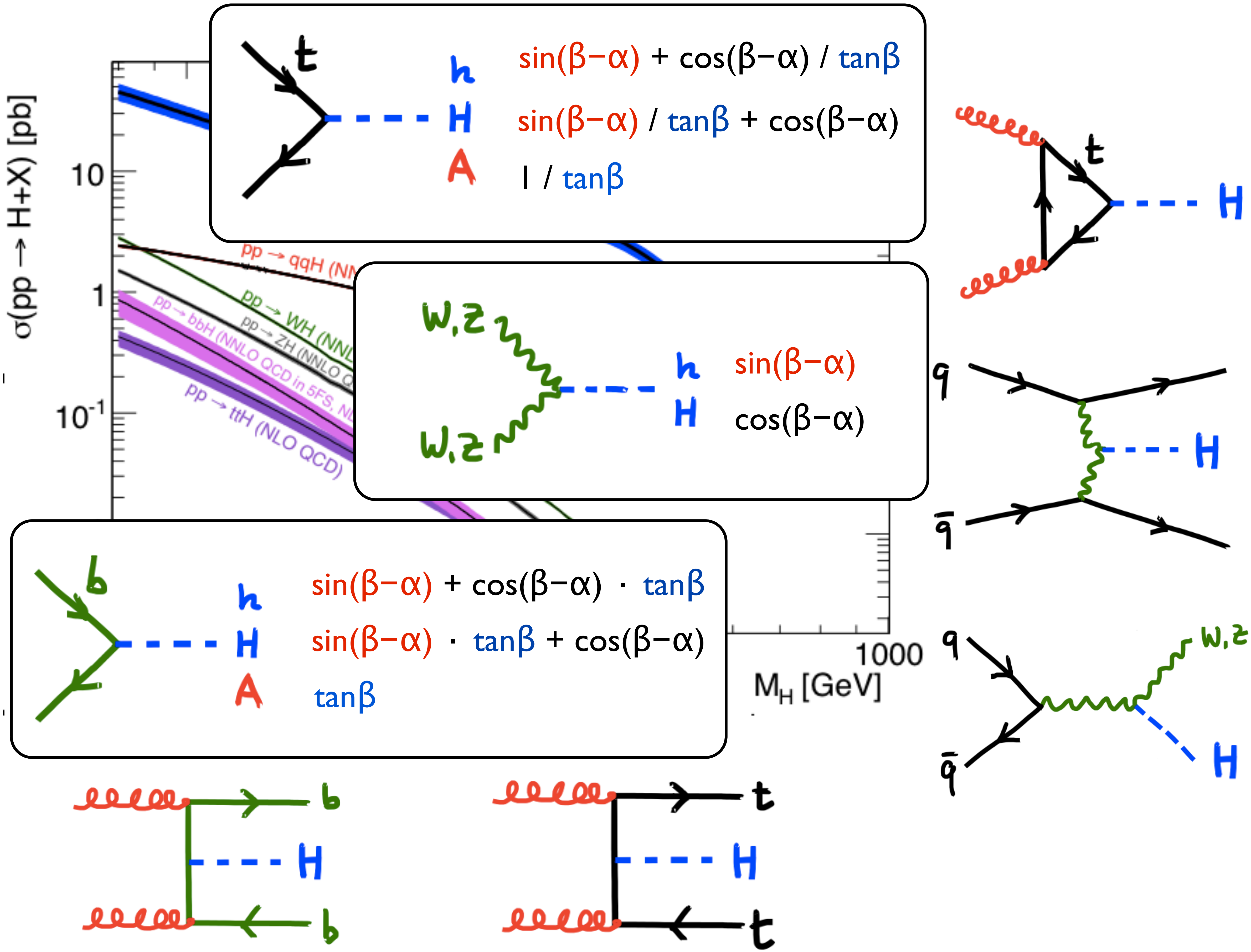

b
H
b


t
H
t


t
h
H
A
sin(β−α) + cos(β−α) / tanβ
sin(β−α) / tanβ + cos(β−α)
1 / tanβ
σ(pp → H+X) [pb]
10
1
10^-1
10^-2
80
100
200
300
400
500
1000
M_H [GeV]
pp → qqH (NNLO QCD + NLO EW)
pp → WH (NNLO QCD + NLO EW)
pp → ZH (NNLO QCD +NLO EW)
pp → bbH (NNLO QCD in 5FS, NLO QCD in 4FS)
pp → ttH (NLO QCD)
t
H
q
H
q̄
q
W,Z
q̄
H
b
H
b
t
H
t



t
h
H
A
sin(β−α) + cos(β−α) / tanβ
sin(β−α) / tanβ + cos(β−α)
1 / tanβ
W,Z
W,Z
h
H
sin(β−α)
cos(β−α)
σ(pp → H+X) [pb]
10
1
10^{-1}
10^{-2}
80
100
200
300
400
500
1000
M_H [GeV]
pp → qqH
pp → WH
pp → ZH
pp → bbH (NNLO QCD in 5FS,
pp → ttH (NLO QCD)
t
H
q
q̄
H
q
q̄
W,Z
H
b
H
b
t
H
t


t
h
H
A
sin(β−α) + cos(β−α) / tanβ
sin(β−α) / tanβ + cos(β−α)
1 / tanβ
σ(pp → H+X) [pb]
10
1
10^-1
pp → qqH (NN
pp → WH (NNL
pp → ZH (NNLO Q
pp → bbH (NNLO QCD in 5FS, NL
pp → ttH (NLO QCD)
1000
M_H [GeV]
W,Z
W,Z
h
H
sin(β−α)
cos(β−α)
b
h
H
A
sin(β−α) + cos(β−α) · tanβ
sin(β−α) · tanβ + cos(β−α)
tanβ
t
H
q
q̄
H
q
q̄
W,Z
H
b
H
b
t
H
t

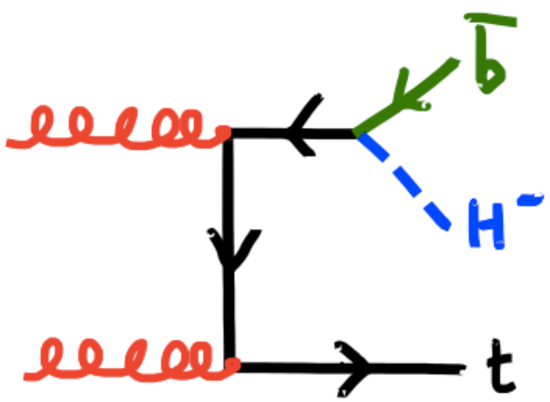
SUSY effects

- rescaling of couplings

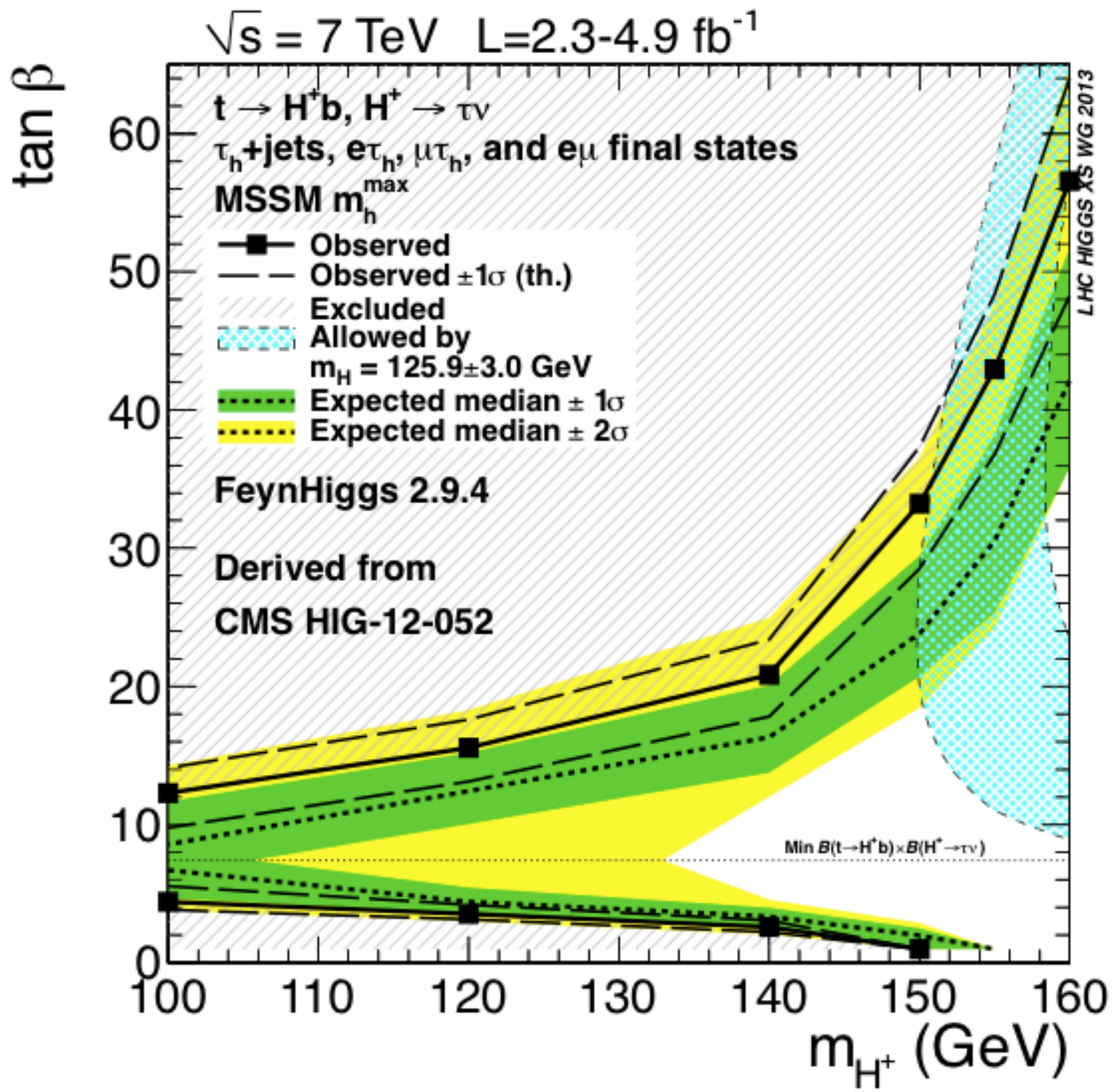
SUSY effects

- rescaling of couplings
- new Higgs bosons

Light H$^{\pm}$

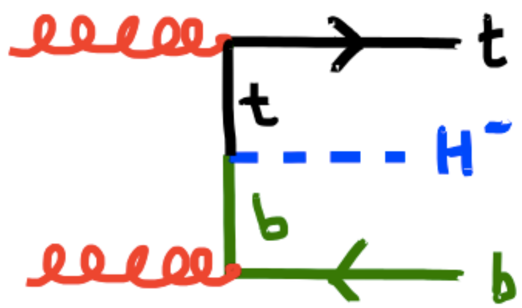


b̄
H⁻
t

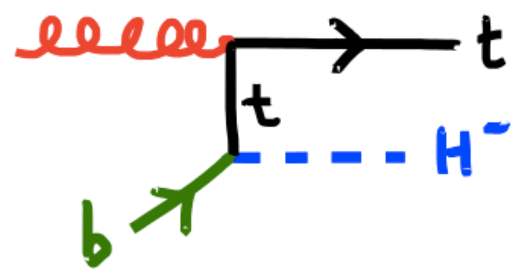


√s = 7 TeV L=2.3-4.9 fb⁻¹
tan β
t → H⁺b, H⁺ → τν
τ_h+jets, eτ_h, μτ_h, and eμ final states
MSSM m_h^max
Observed
Observed ±1σ (th.)
Excluded
Allowed by
m_H = 125.9±3.0 GeV
Expected median ± 1σ
Expected median ± 2σ
FeynHiggs 2.9.4
Derived from
CMS HIG-12-052
Min B(t→H⁺b)×B(H⁺→τν)
LHC HIGGS XS WG 2013
m_H⁺ (GeV)
0
10
20
30
40
50
60
100
110
120
130
140
150
160

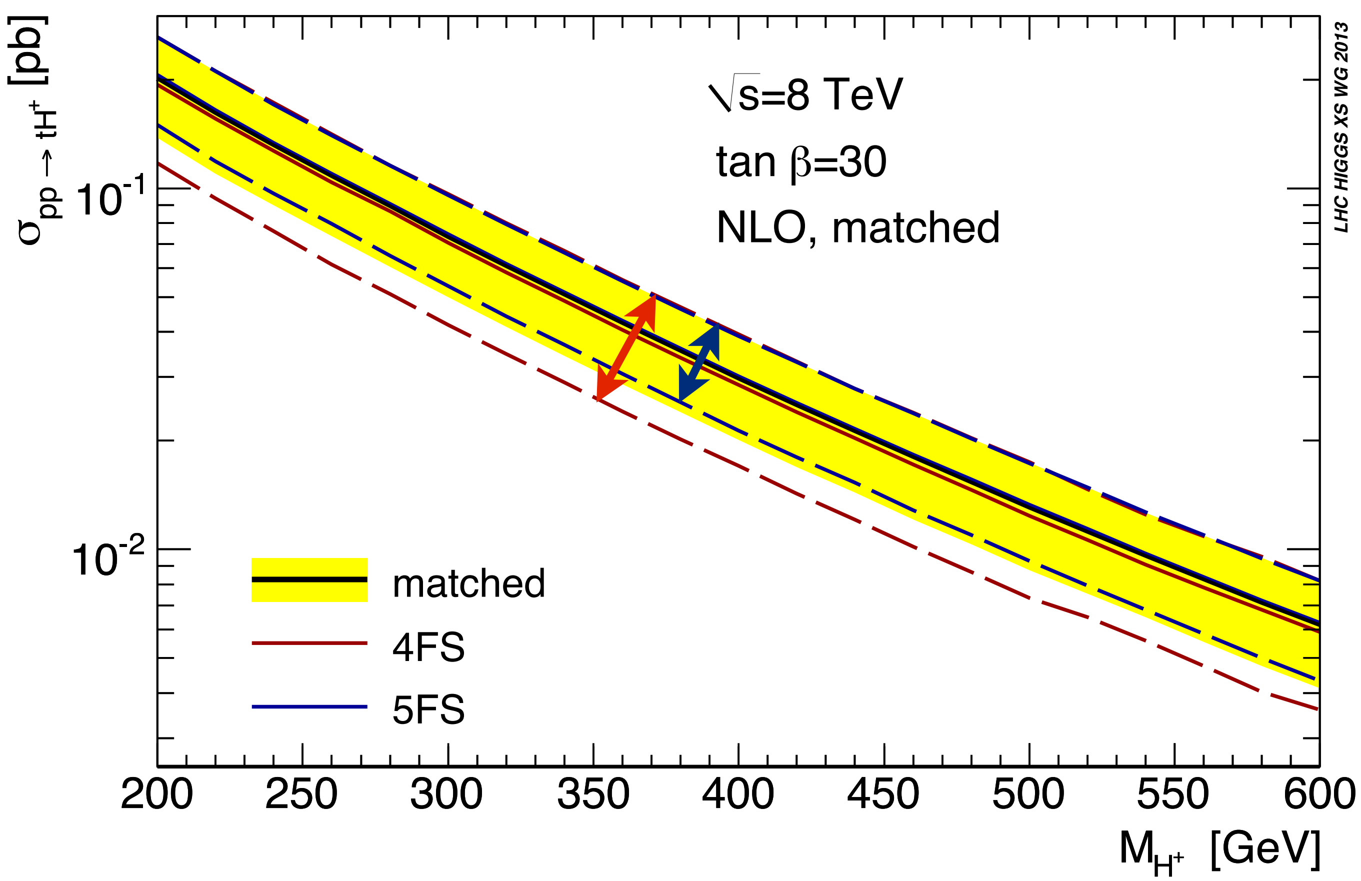
Heavy $H^{\pm}$



4-flavor scheme
(4FS)



5-flavor scheme
(5FS)



Heavy H±

S. h. Zhu, Phys. Rev. D **67** (2003) 075006 [arXiv:hep-ph/0112109].

G. P. Gao, G. R. Lu, Z. H. Xiong and J. M. Yang, Phys. Rev. D **66** (2002) 015007 [arXiv:hep-ph/0202016].

T. Plehn, Phys. Rev. D **67** (2003) 014018 [arXiv:hep-ph/0206121].

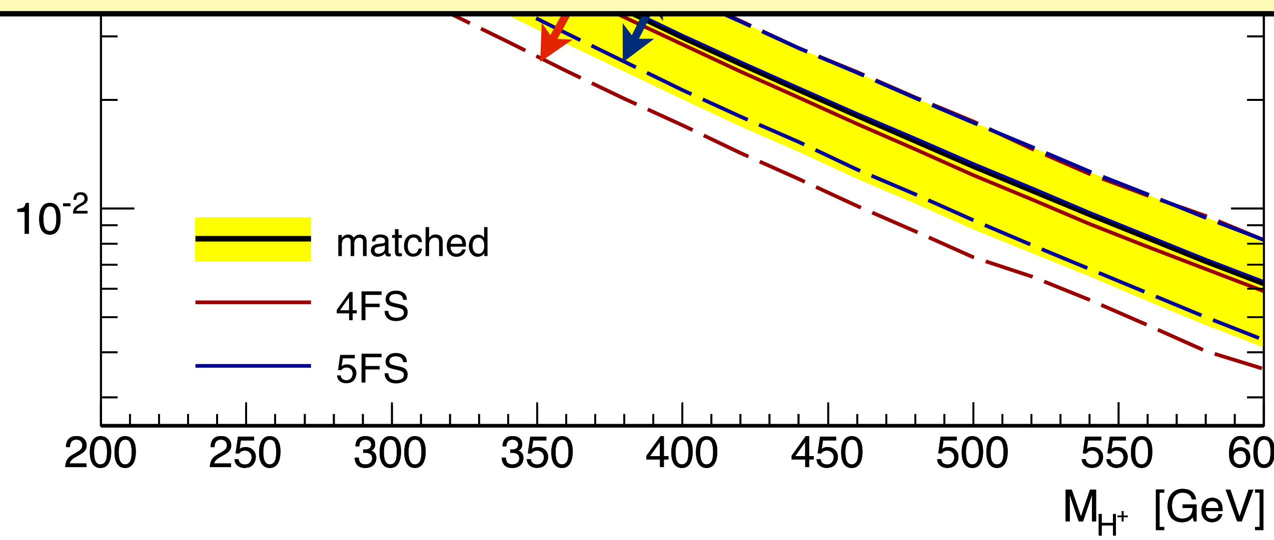
E. L. Berger, T. Han, J. Jiang and T. Plehn, Phys. Rev. D **71** (2005) 115012 [arXiv:hep-ph/0312286].

N. Kidonakis, PoS HEP2005 (2006) 336 [arXiv:hep-ph/0511235].

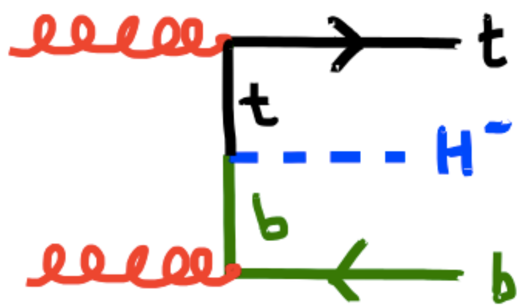
W. Peng, M. Wen-Gan, Z. Ren-You, J. Yi, H. Liang and G. Lei, Phys. Rev. D **73** (2006) 015012 [arXiv:hep-ph/0601069].

S. Dittmaier, M. Kramer, M. Spira, and M. Walser, Phys.Rev. **D83**, 055005 (2011), arXiv:0906.2648.

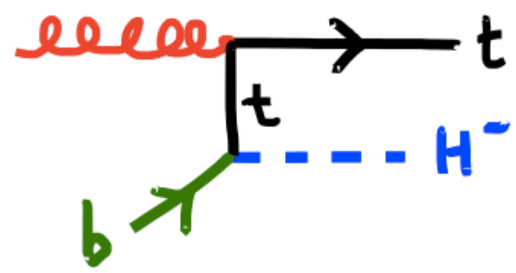
Nhung, Hollik, Ninh, Phys. Rev. D87 (2013) 113006



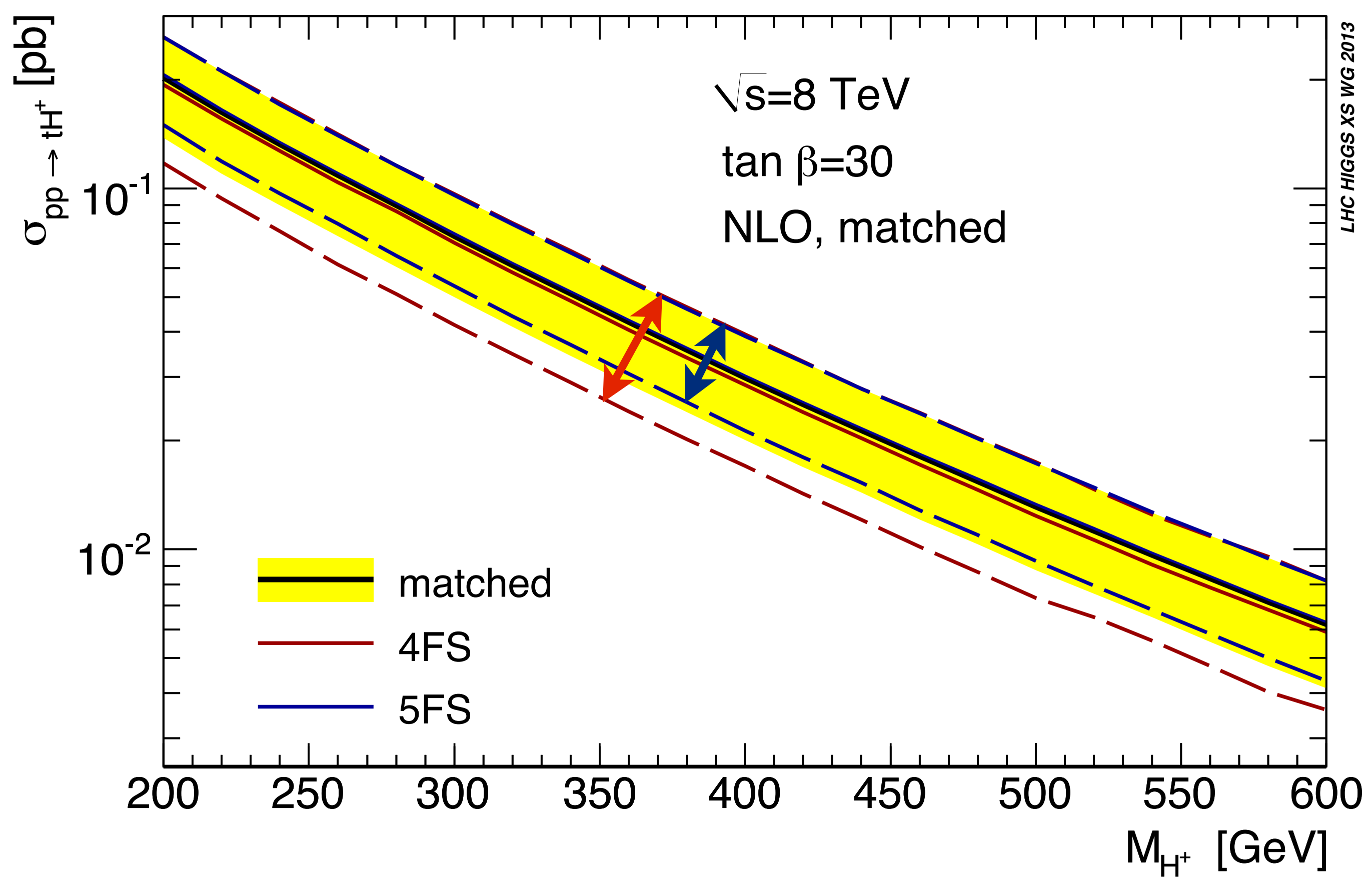
Heavy H±



4-flavor scheme
(4FS)



5-flavor scheme
(5FS)



SUSY effects

- rescaling of couplings
- new Higgs bosons

SUSY effects

- rescaling of couplings
- new Higgs bosons
- SUSY particle effects

SUSY effects

- rescaling of couplings
- new Higgs bosons
- SUSY particle effects
    - ⋆ in radiative corrections

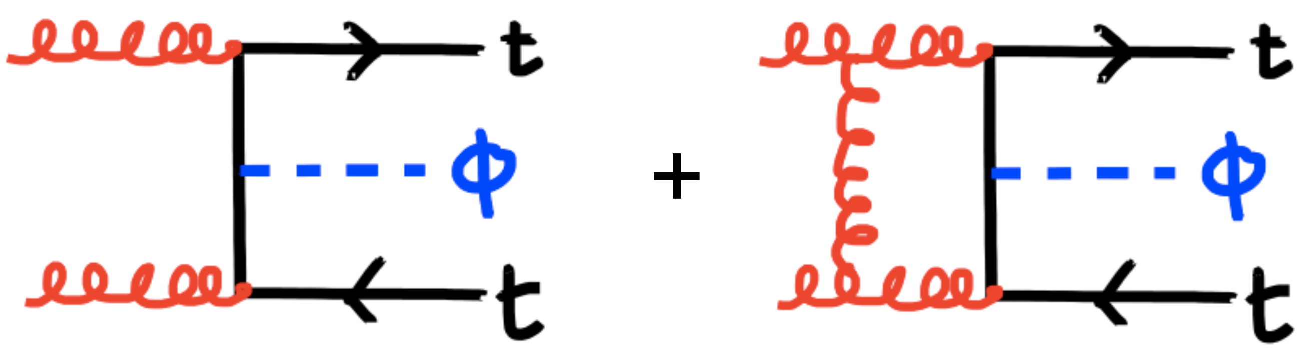
SUSY particle effects:

in radiative corrections:

SUSY particle effects:

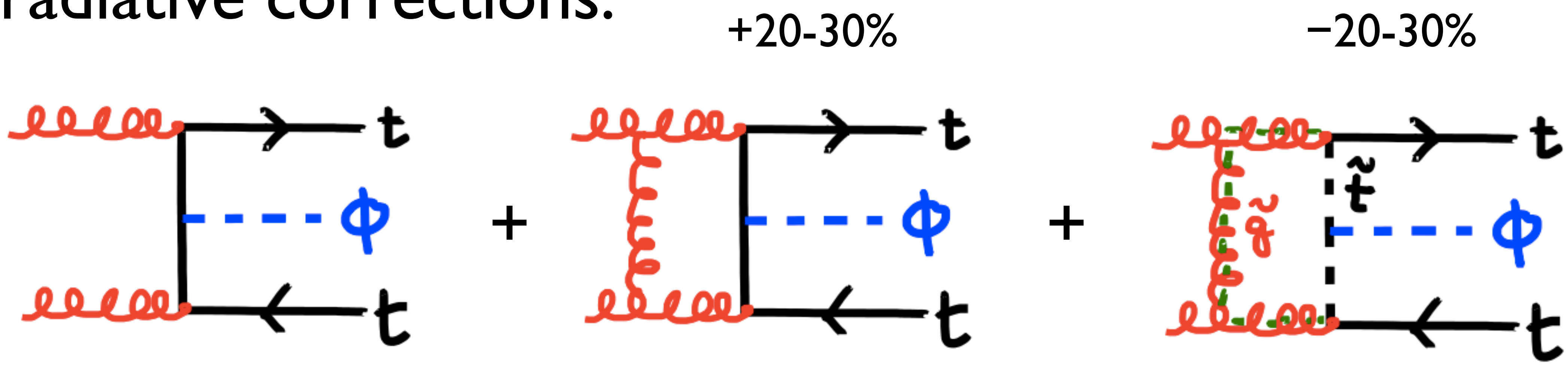
in radiative corrections:

+20-30%



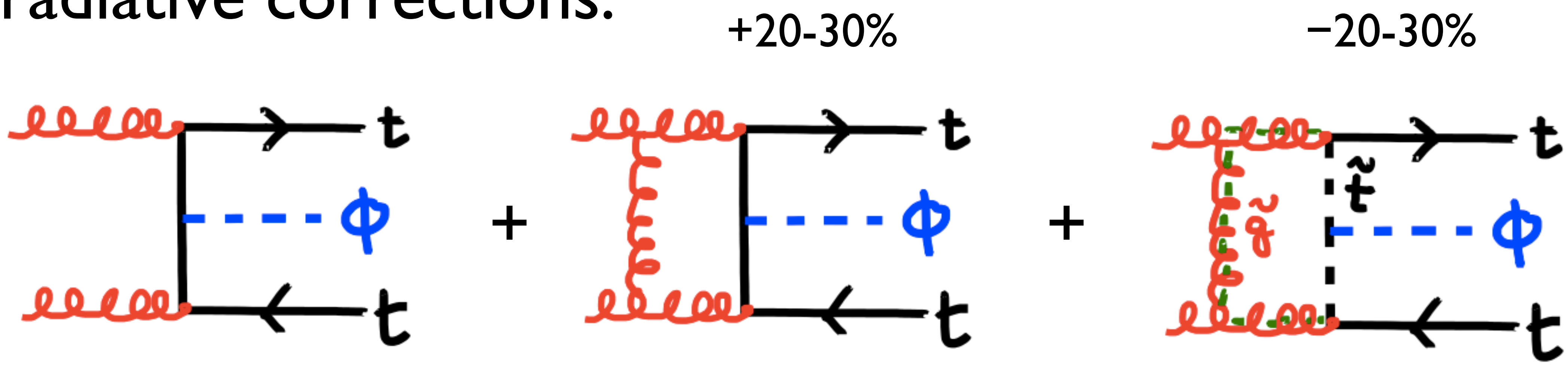
SUSY particle effects:

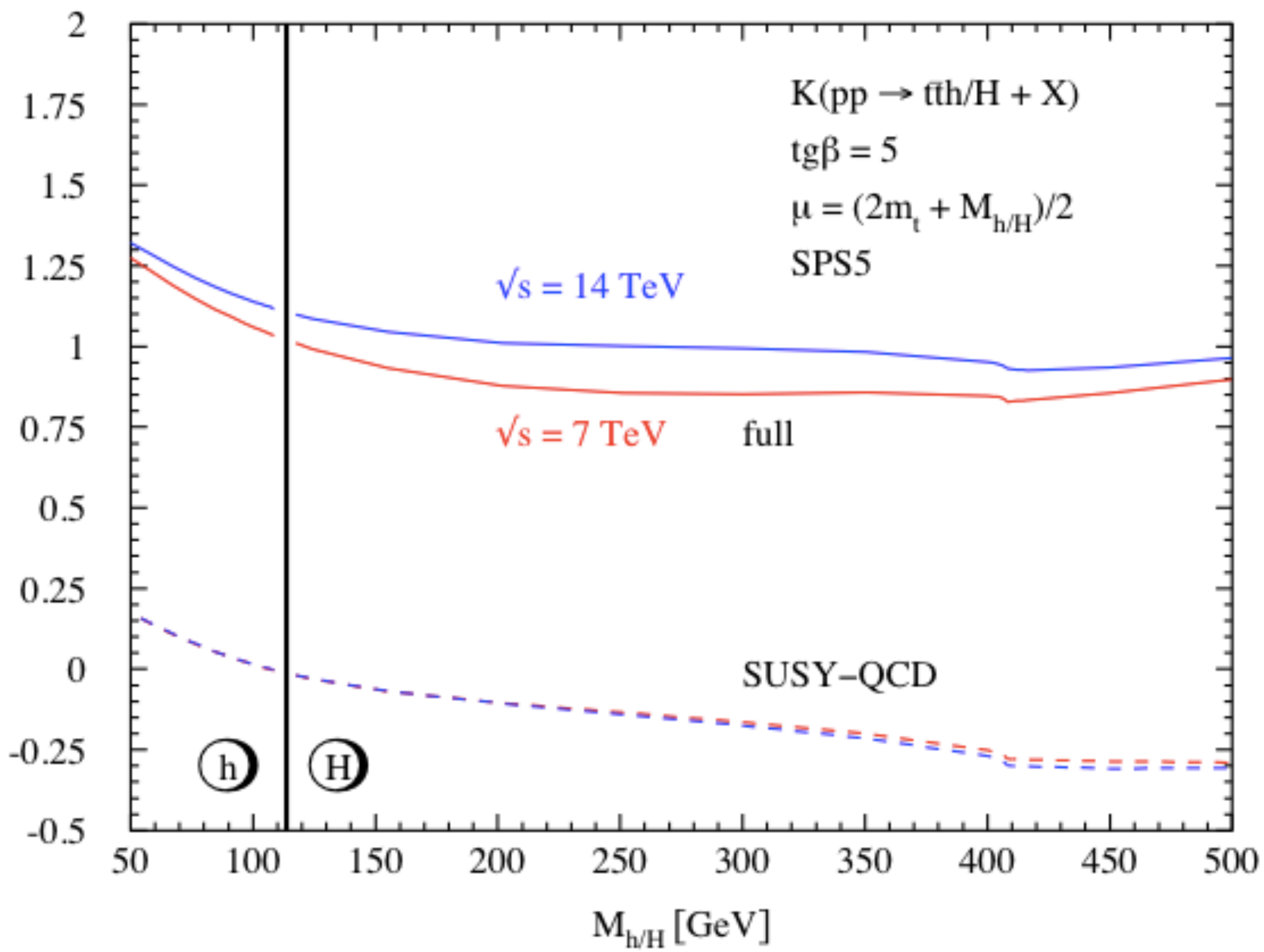
in radiative corrections:



SUSY particle effects:

in radiative corrections:





Peng *et al.* '05
Hollik, Rauch '06
Dittmaier, Häfliger, Krämer, Spira, Walser '14

SUSY effects

- rescaling of couplings
- new Higgs bosons
- SUSY particle effects
    - ⋆ in radiative corrections

SUSY effects

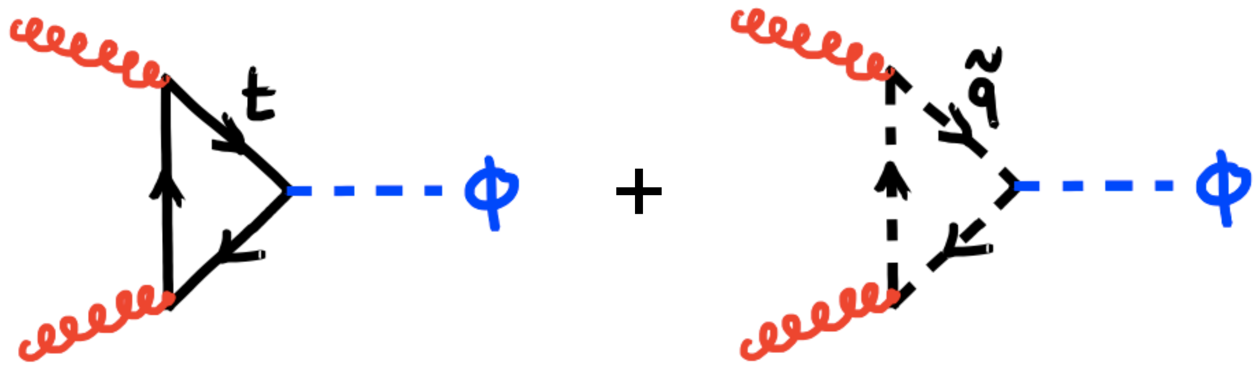
- rescaling of couplings
- new Higgs bosons
- SUSY particle effects
    - ⋆ in radiative corrections
    - ⋆ at leading order

SUSY particle effects:

at leading order:

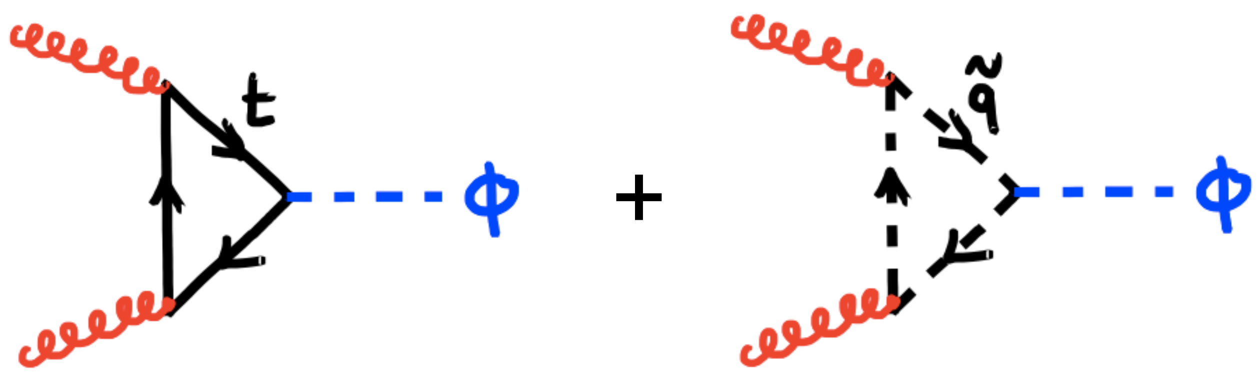
SUSY particle effects:

at leading order:



SUSY particle effects:

at leading order:



can interfere distructively (gluophobic Higgs)

(see later)

Djouadi '98

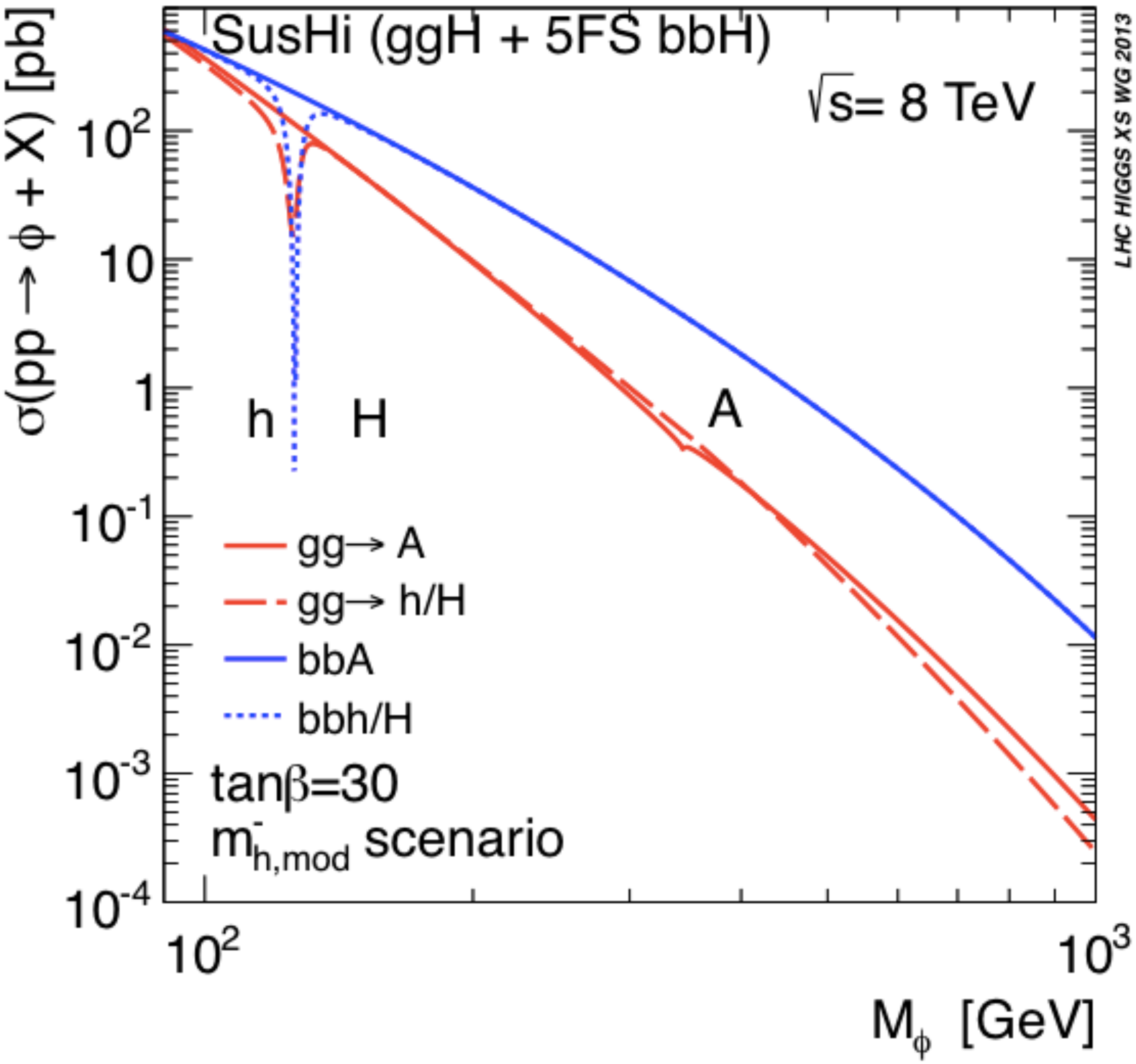
SUSY effects

- rescaling of couplings
- new Higgs bosons
- SUSY particle effects
  - ⋆ in radiative corrections
  - ⋆ at leading order

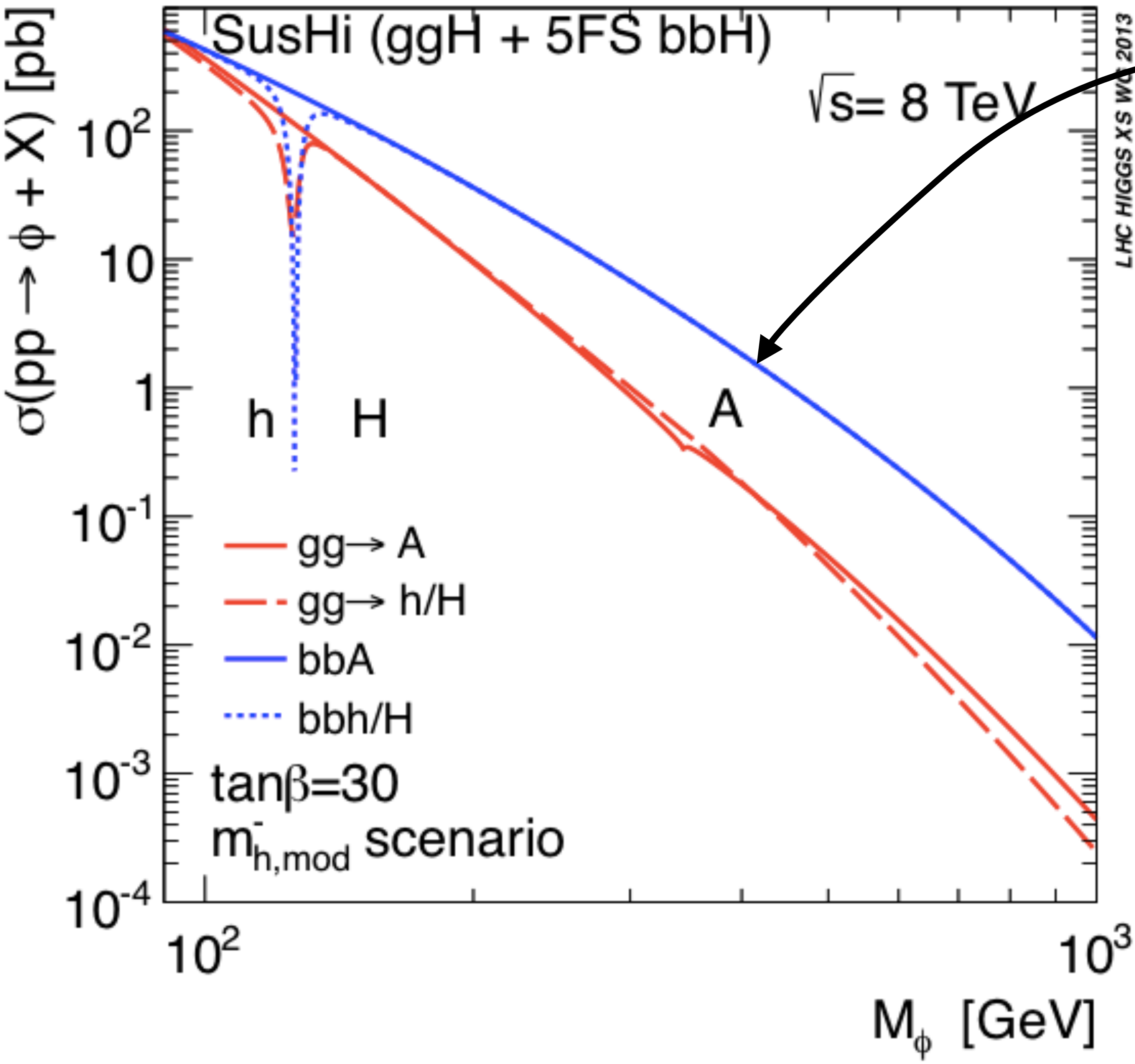
SUSY effects

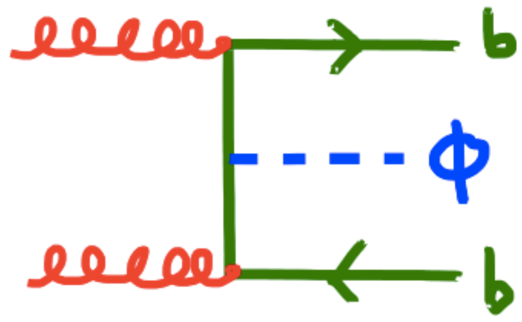
- rescaling of couplings
- new Higgs bosons
- SUSY particle effects
  - ⋆ in radiative corrections
  - ⋆ at leading order
- New production modes

“New” production modes:

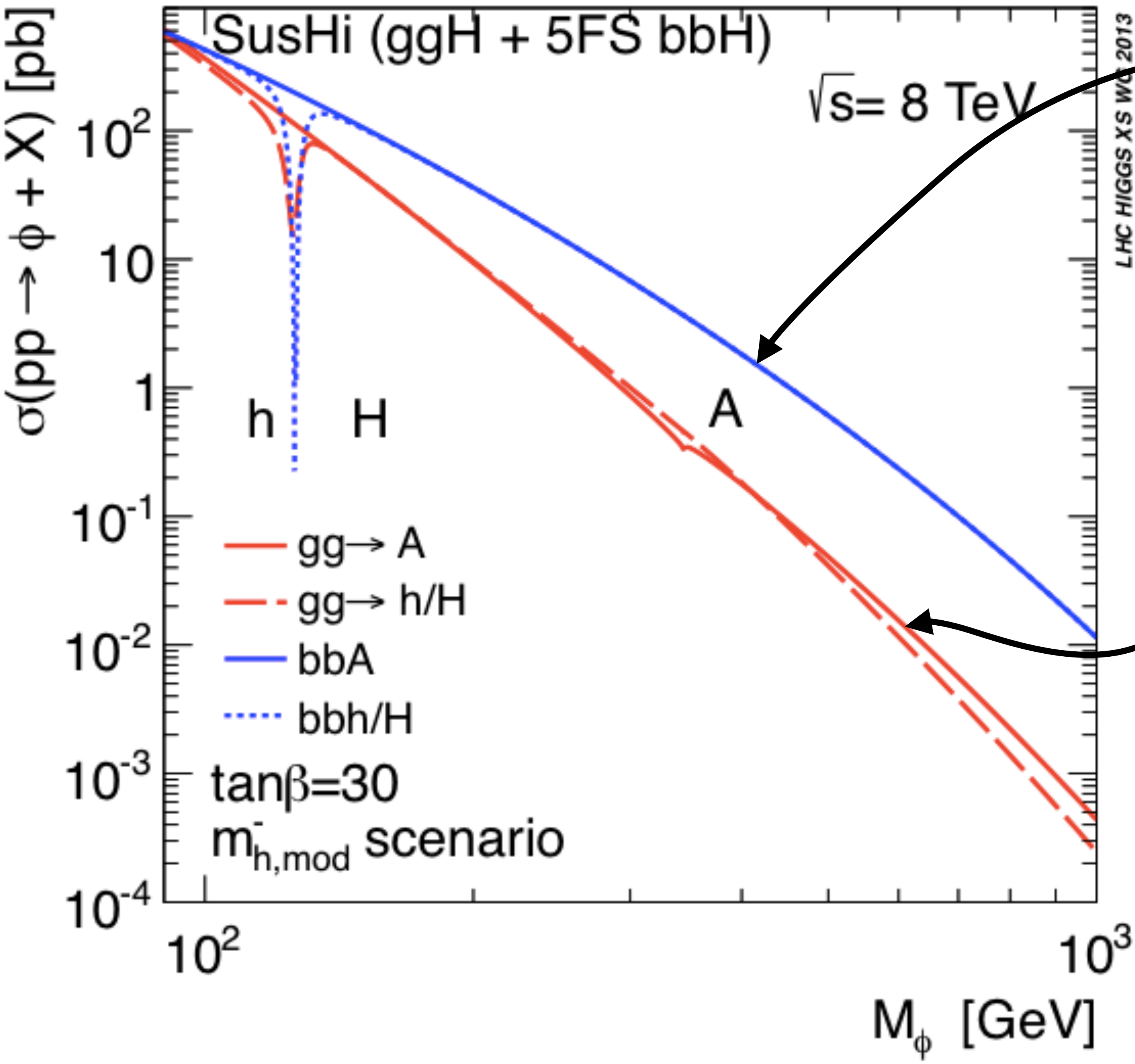


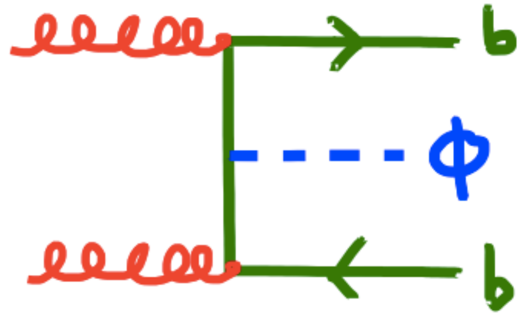
“New” production modes:

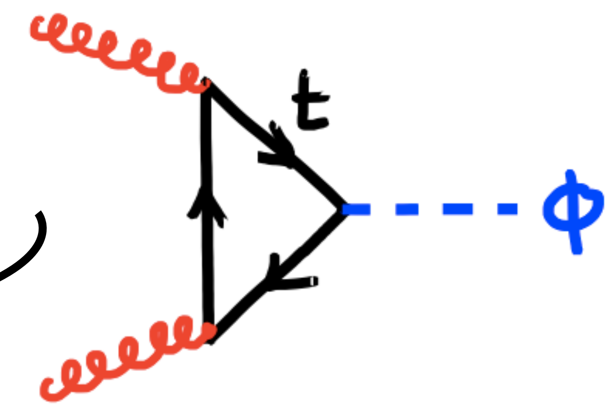


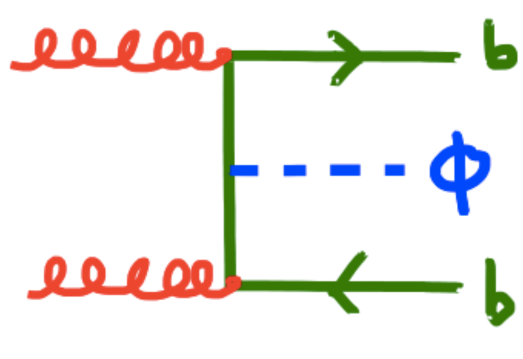


“New” production modes:

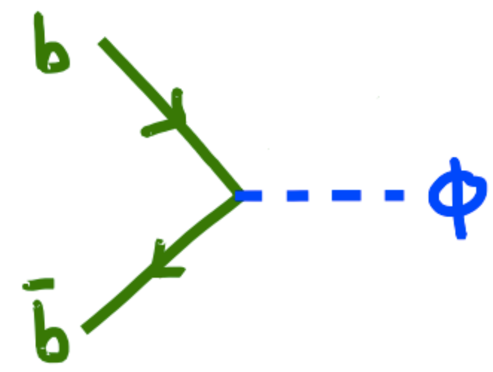




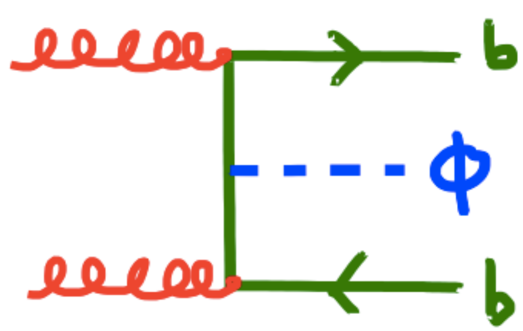




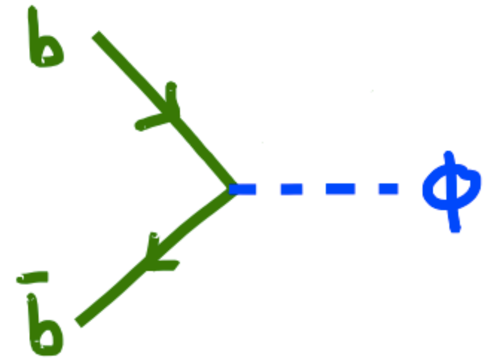
4FS: through NLO



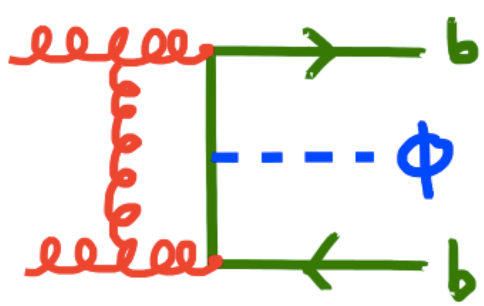
5FS: through NNLO



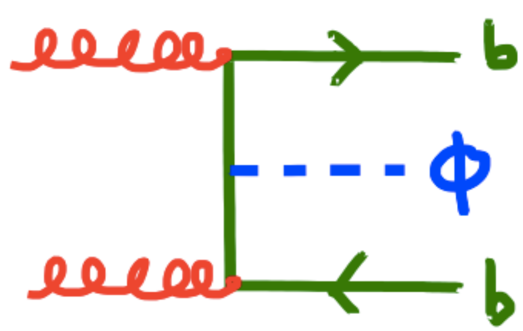
4FS: through NLO



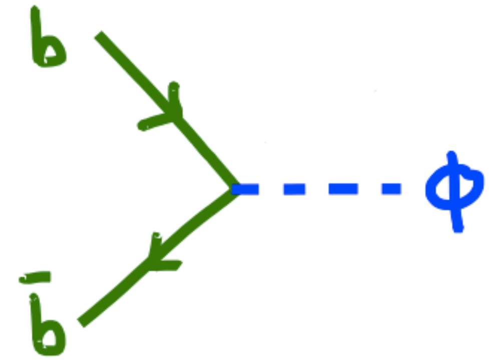
5FS: through NNLO



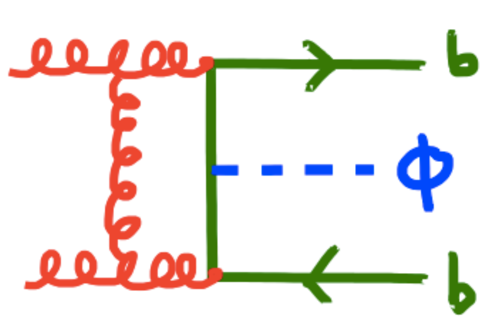
not in 5FS NNLO!



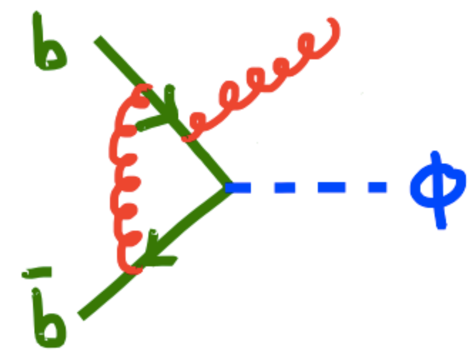
4FS: through NLO



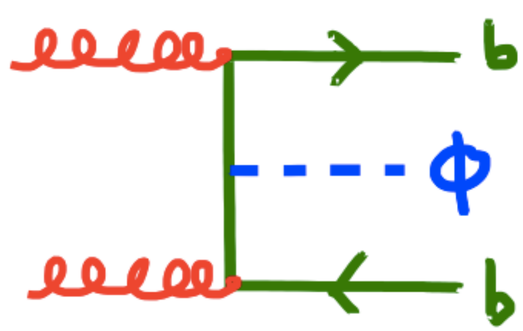
5FS: through NNLO



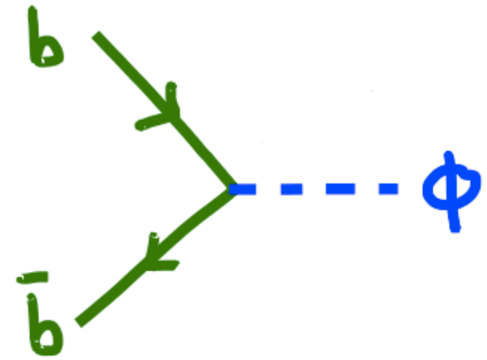
not in 5FS NNLO!



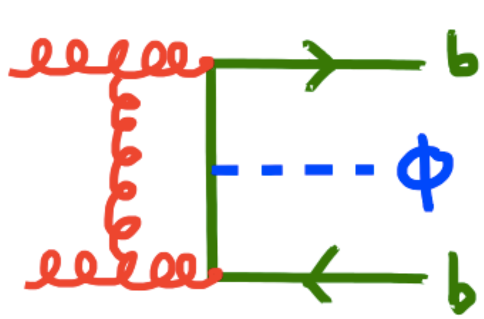
not in 4FS NLO!



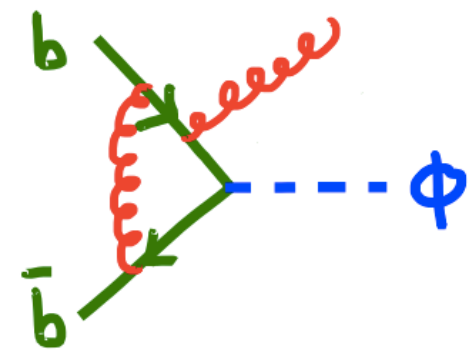
4FS: through NLO



5FS: through NNLO



not in 5FS NNLO!



not in 4FS NLO!

$$\sigma^{\text{matched}} = \frac{\sigma^{\text{4FS}} + w\,\sigma^{\text{5FS}}}{1+w}$$

$$w = \ln\frac{m_{\text{H}}}{m_{\text{b}}} - 2$$

Santander matching

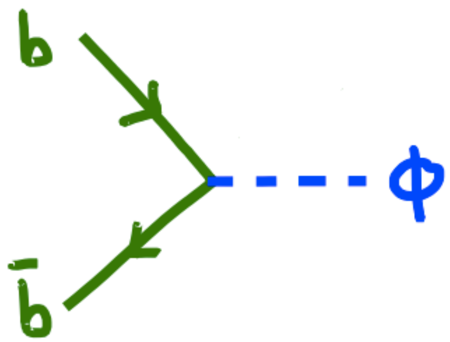
RH, Krämer, Schumacher '11

see also: Maltoni, Ridolfi, Ubiali '12

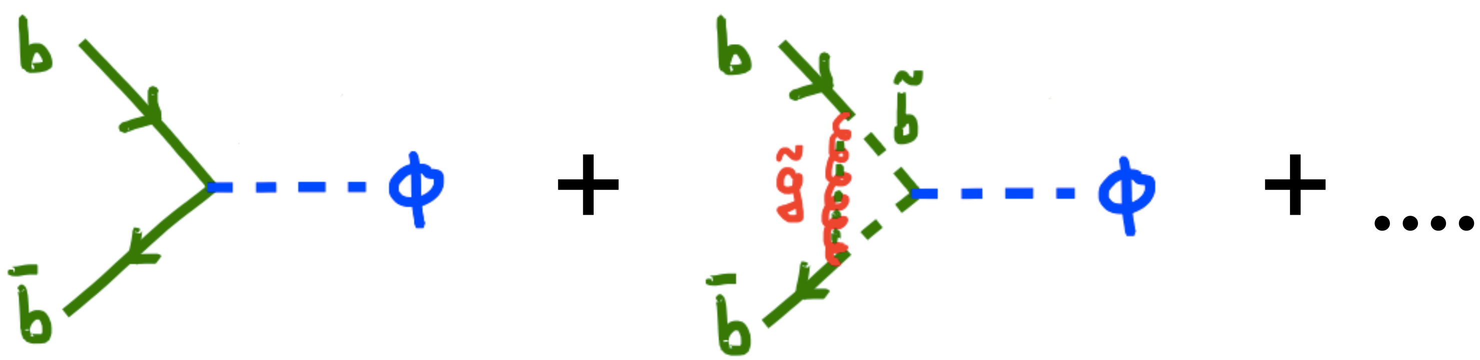
SUSY effects

- rescaling of couplings
- new Higgs bosons
- SUSY particle effects
  - ⋆ in radiative corrections
  - ⋆ at leading order
- New production modes

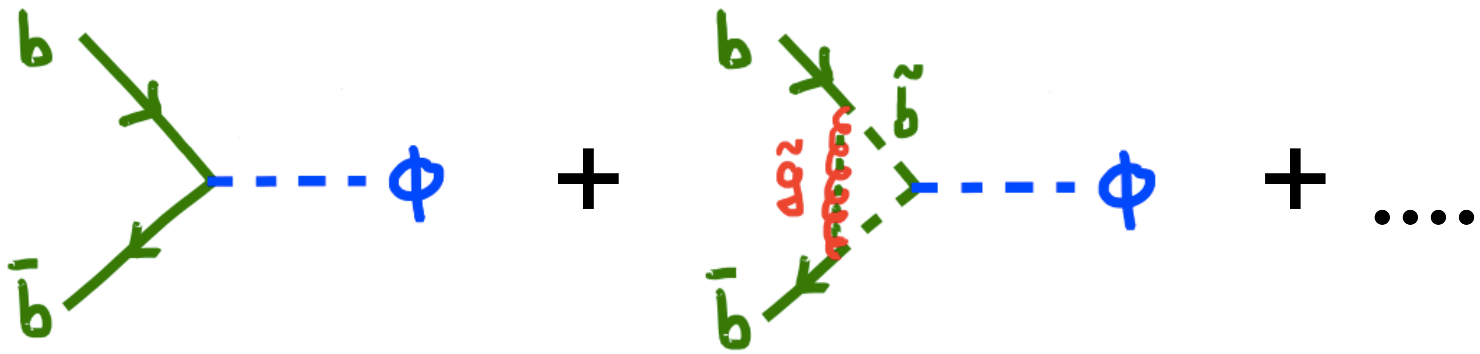
SUSY particle effects:



SUSY particle effects:

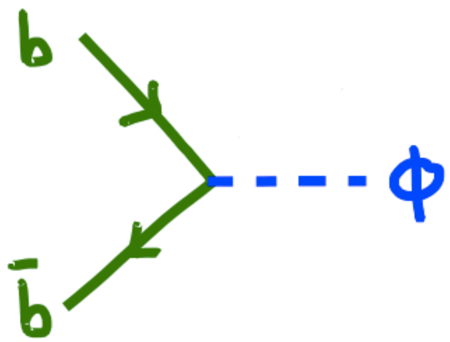


SUSY particle effects:



$$\rightarrow \left(\alpha_s \frac{\mu}{M_{SUSY}} \tan\beta\right)^n$$

SUSY particle effects:



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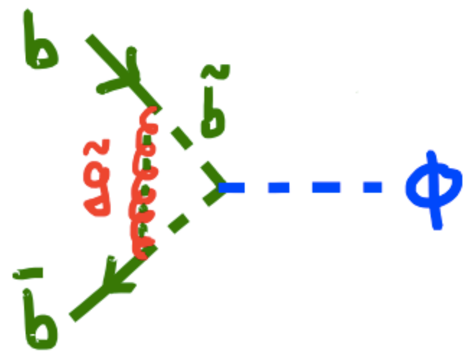


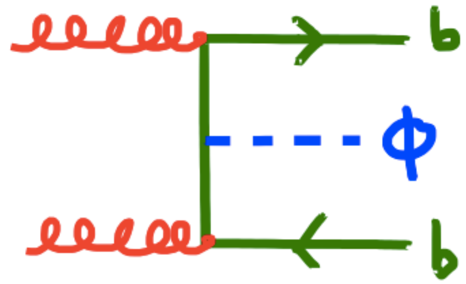
+ ....

$$\to \left(\alpha_s \frac{\mu}{M_{SUSY}} \tan\beta\right)^n$$

resummation: $\to \dfrac{1}{1+\Delta_b}$

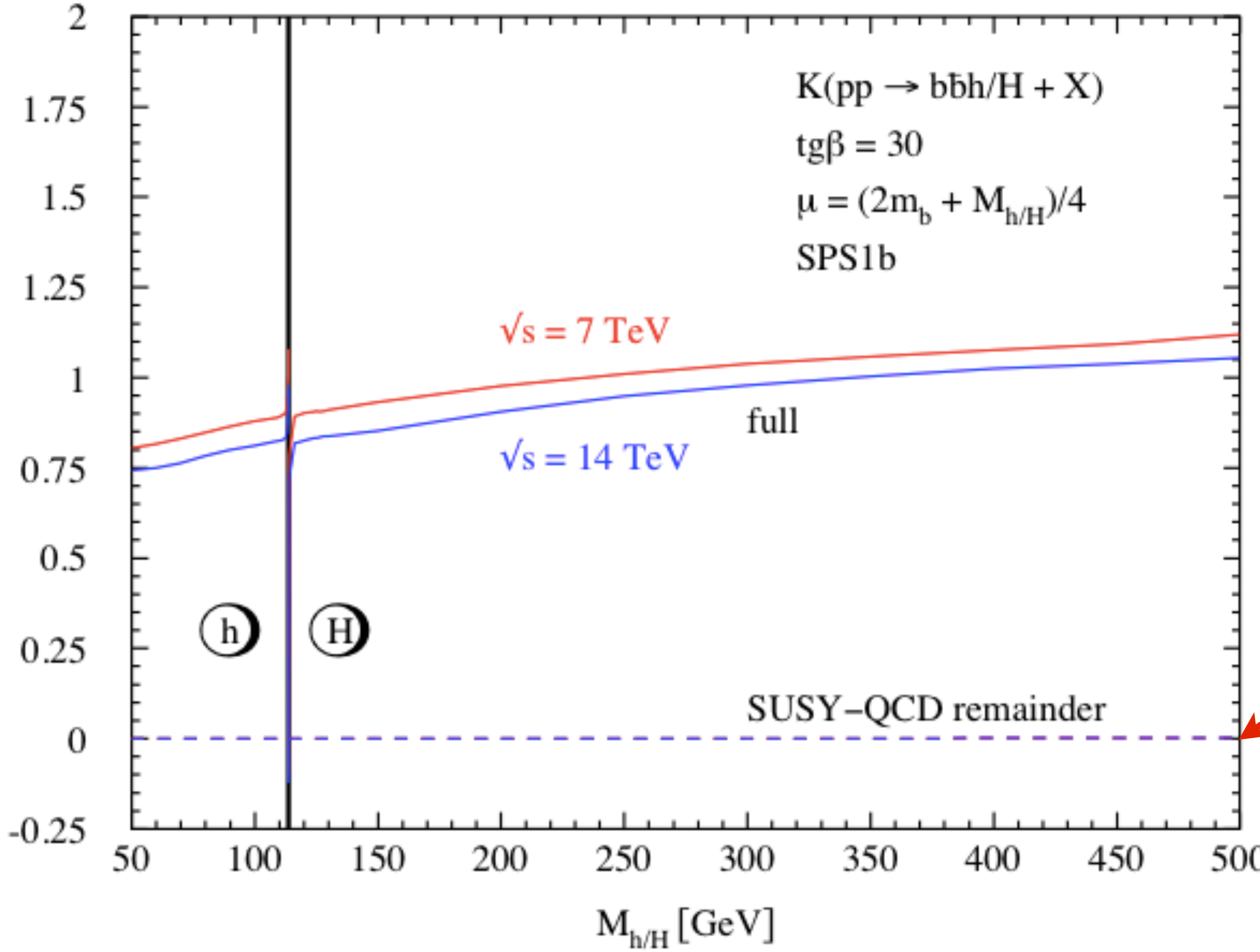
Carena, Garcia, Nierste, Wagner '99

$$\Delta_b = \frac{2\,\alpha_s}{3\,\pi}\,\frac{m_{\tilde{g}}\,\mu\,\tan\beta}{m_{\tilde{b}_1}^2 - m_{\tilde{b}_2}^2}\left(\frac{m_{\tilde{b}_1}^2}{m_{\tilde{b}_1}^2 - m_{\tilde{g}}^2}\ln\frac{m_{\tilde{b}_1}^2}{m_{\tilde{g}}^2} - \frac{m_{\tilde{b}_2}^2}{m_{\tilde{b}_2}^2 - m_{\tilde{g}}^2}\ln\frac{m_{\tilde{b}_2}^2}{m_{\tilde{g}}^2}\right)$$



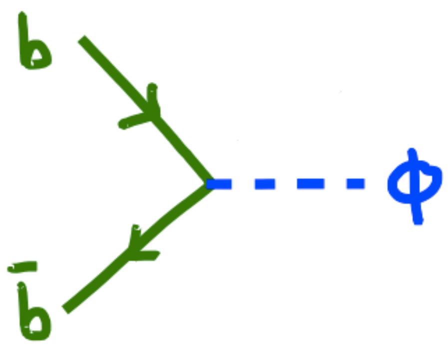
4FS

$$\sigma^{\phi}_{\rm NLO} = \sigma^{\phi}_{0} \times (1 + \delta^{\phi}_{\rm SUSY}) \times (1 + \delta^{\phi}_{\rm QCD} + \delta^{\phi}_{\rm SUSY-rem})$$



not covered by $\dfrac{1}{1+\Delta_b}$

Dittmaier, Häfliger, Krämer, Spira, Walser '14



5FS

	h^0		H^0		A^0	
	m_b[GeV]	σ[pb]	m_b[GeV]	σ[pb]	m_b[GeV]	σ[pb]
QCD	2.80	0.97	2.55	24.12	2.55	24.13
+QED	2.80	0.97	2.55	24.07	2.55	24.09
$+\Delta_b^{\tilde{g}}$	2.72	0.92	1.95	14.14	1.95	14.15
$+\Delta_b^{\mathrm{weak}}$	2.75	0.94	2.24	18.66	2.24	18.67
$+\sin(\alpha_{eff})$	2.75	0.88	2.24	18.66	2.24	18.67
full calculation	2.75	0.87	2.24	18.43	2.24	18.44

1%
not covered by

$$\frac{1}{1+\Delta_b}$$

Dittmaier, Krämer, Mück, Schlüter ’06

SUSY effects

- rescaling of couplings
- new Higgs bosons
- SUSY particle effects
  - ⋆ in radiative corrections
  - ⋆ at leading order
- New production modes

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- Effects due to new Higgs bosons

Effects due to new Higgs bosons:

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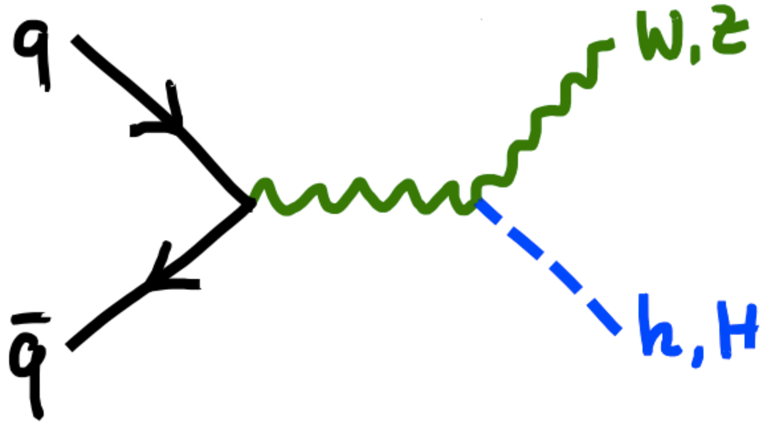
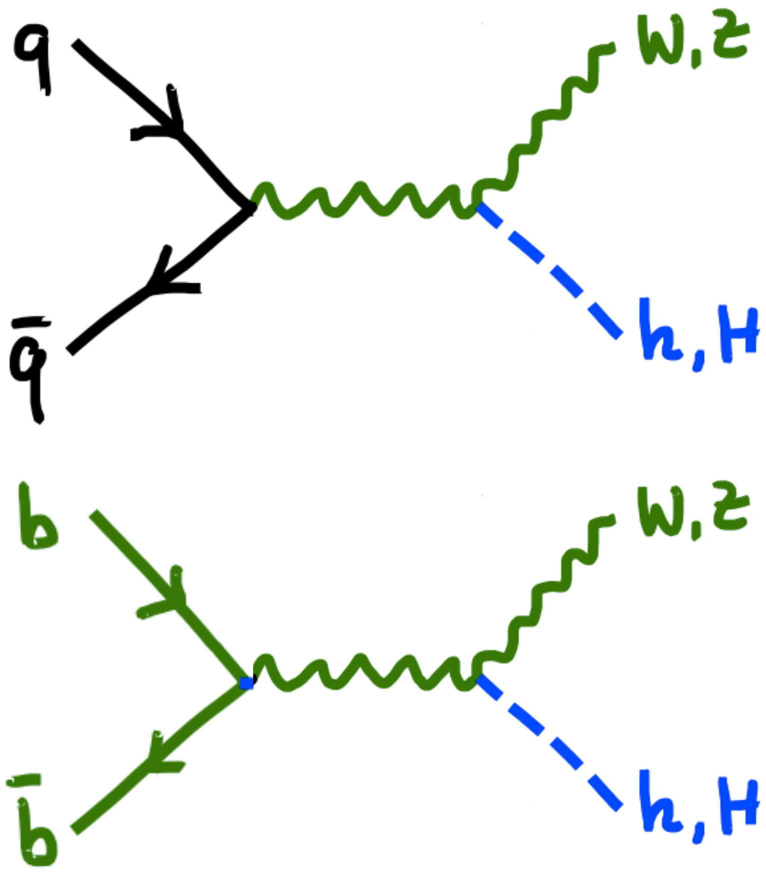


QCD effects under very good control

Effects due to new Higgs bosons:



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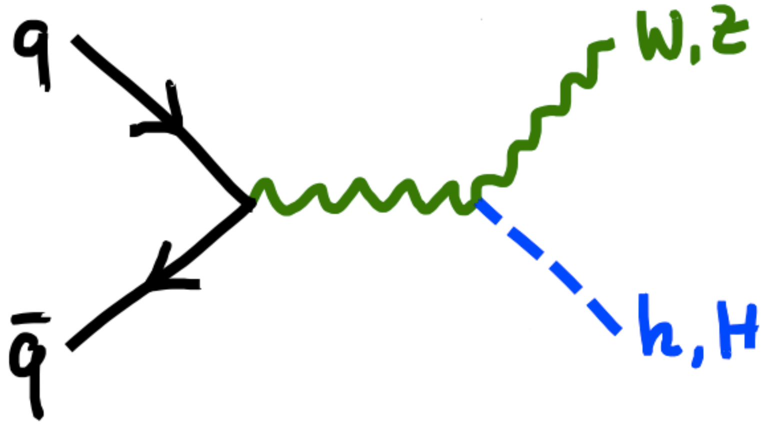

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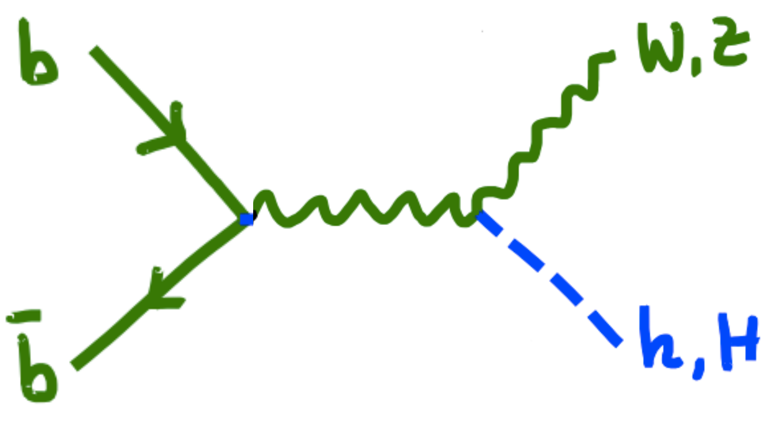
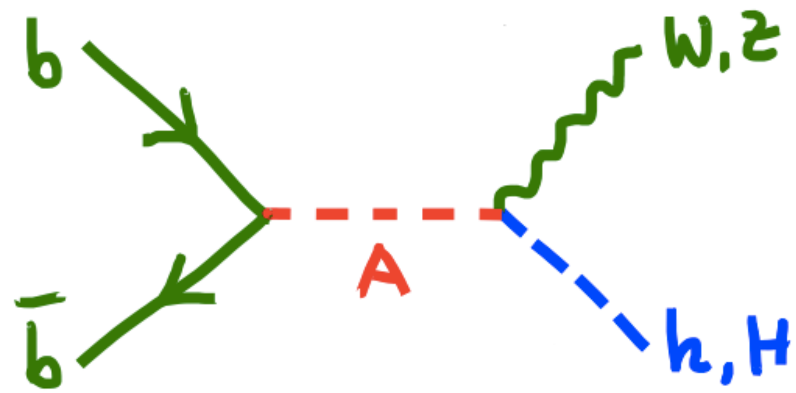
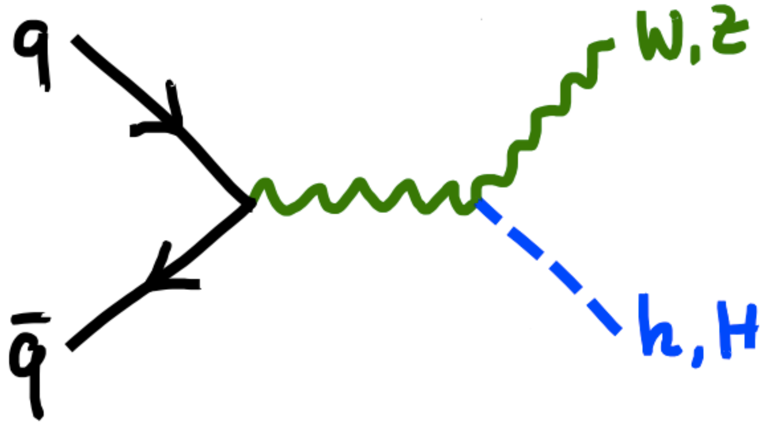


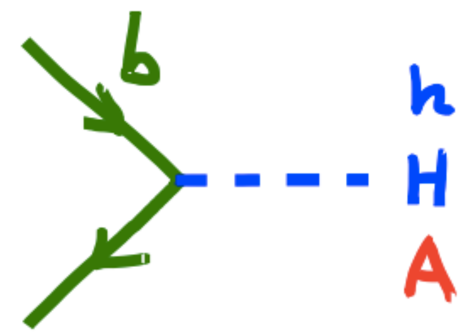
small, but:



new s-channel contribution!

Effects due to new Higgs bosons:

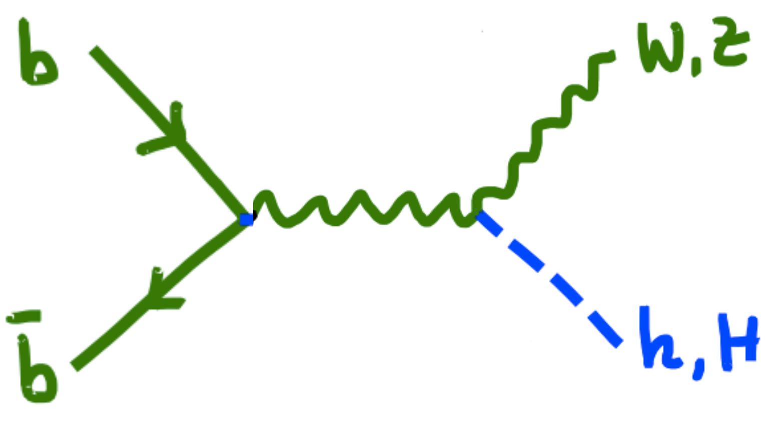




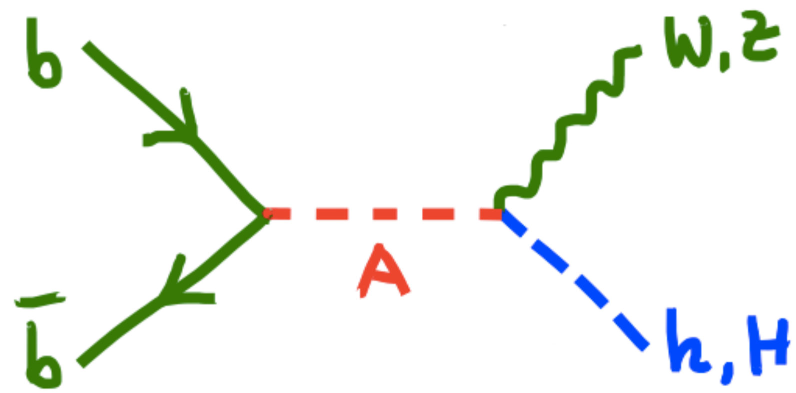
$\sin(\beta-\alpha) + \cos(\beta-\alpha) \cdot \tan\beta$

$\sin(\beta-\alpha) \cdot \tan\beta + \cos(\beta-\alpha)$

$\tan\beta$



small, but:



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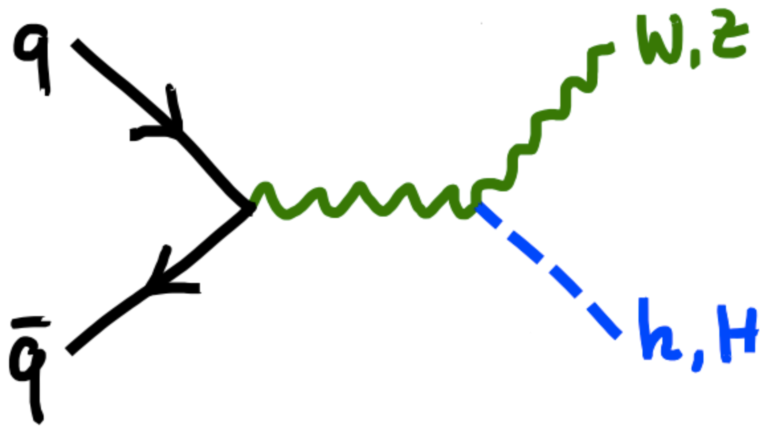
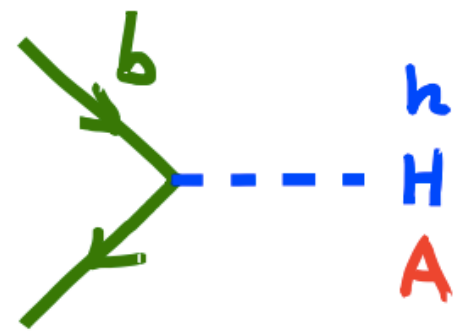
Effects due to new Higgs bosons:

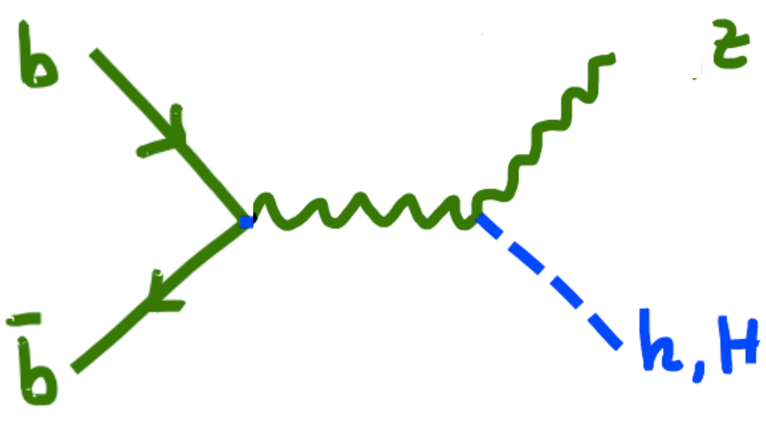




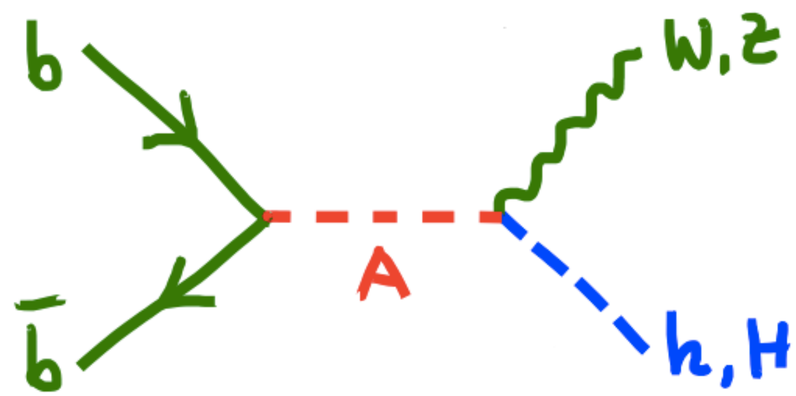
h: $\sin(\beta-\alpha) + \cos(\beta-\alpha) \cdot \tan\beta$

H: $\sin(\beta-\alpha) \cdot \tan\beta + \cos(\beta-\alpha)$

A: $\tan\beta$



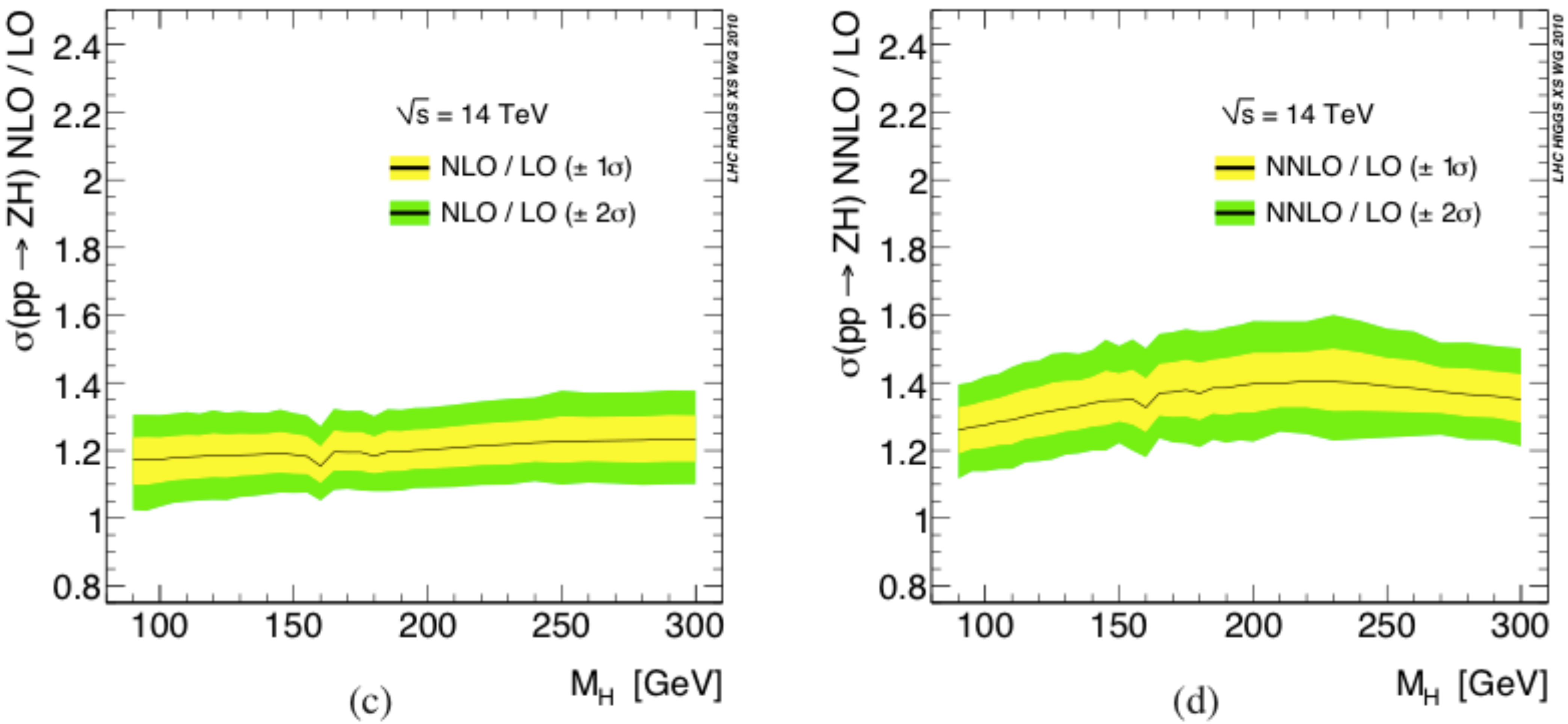
small, but:



new s-channel contribution!

only for ZH, not WH!

... while talking of Higgs Strahlung:



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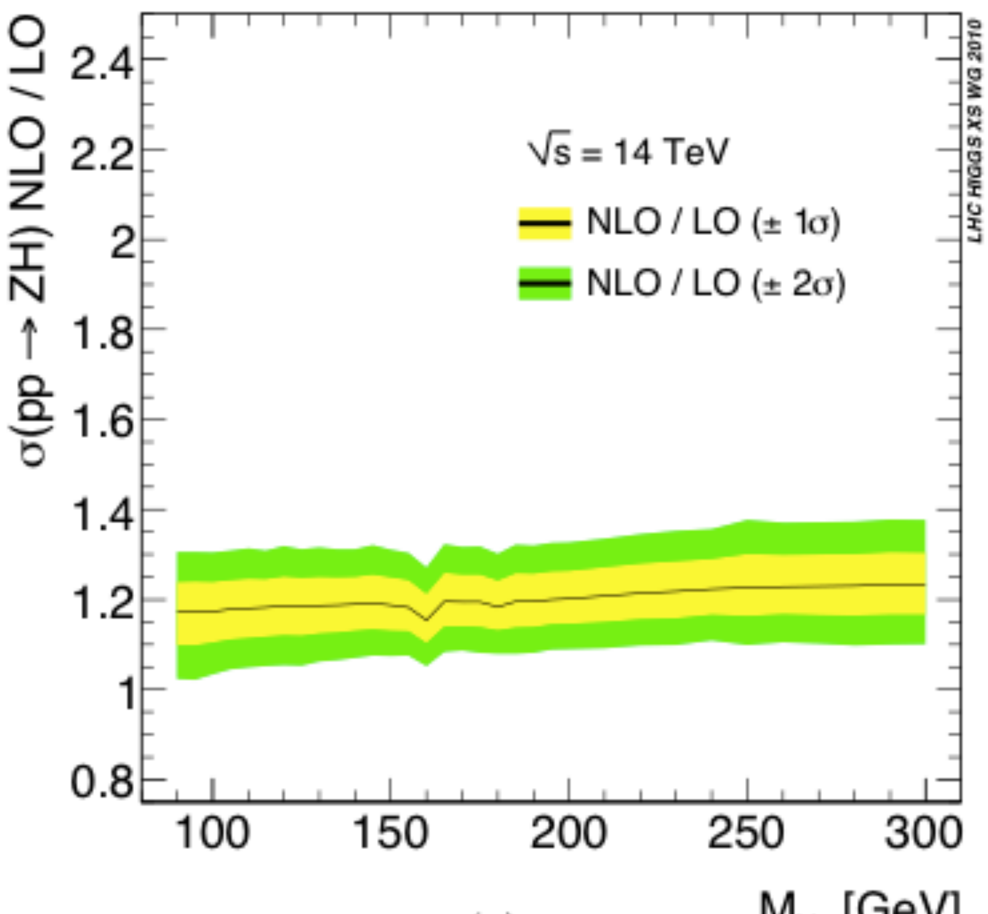
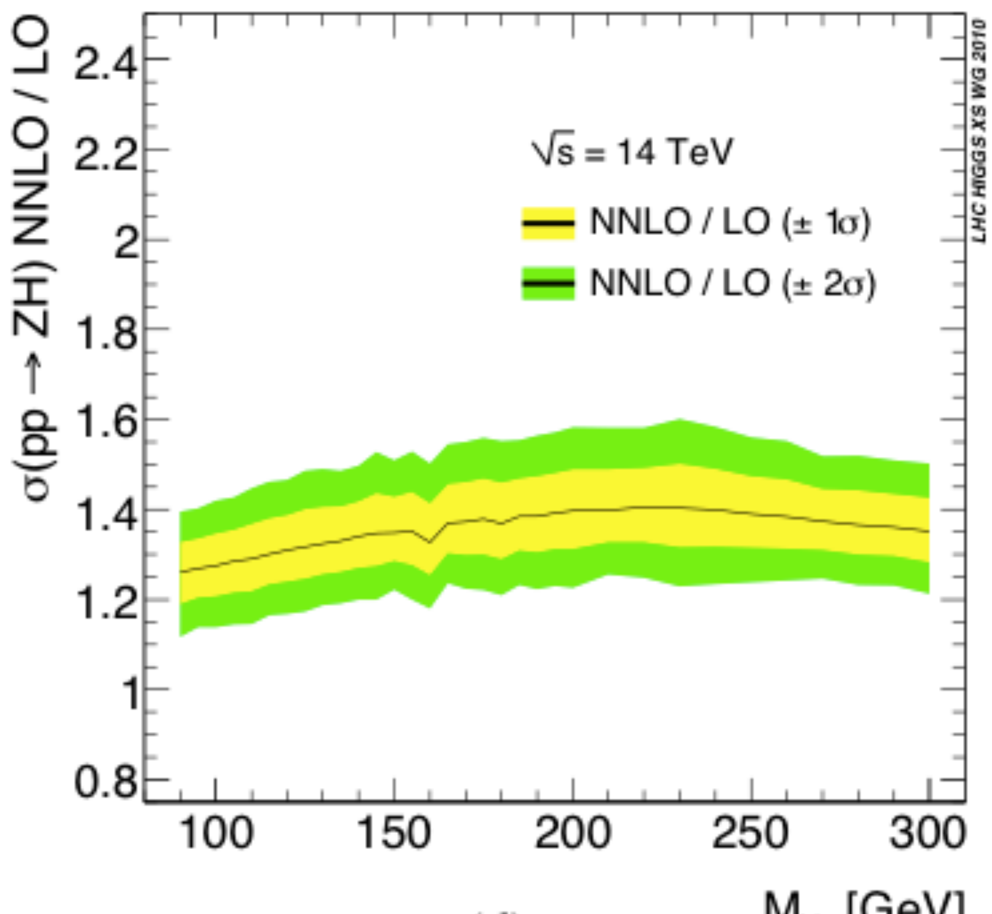
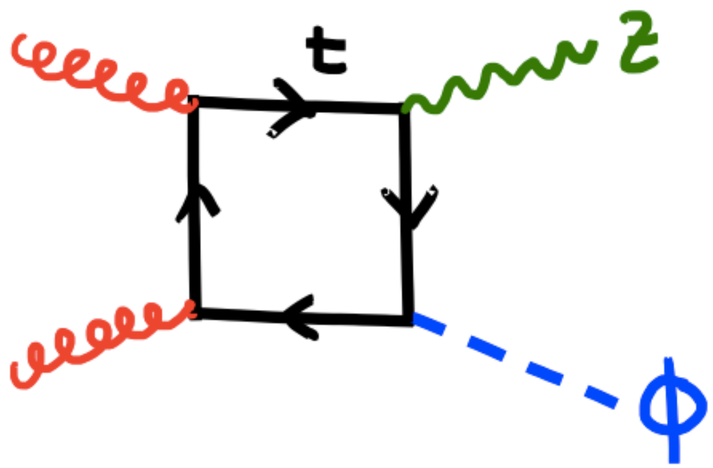
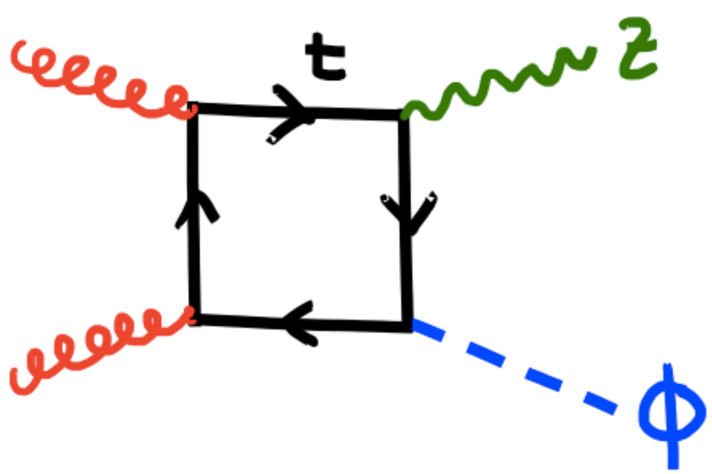


(c)

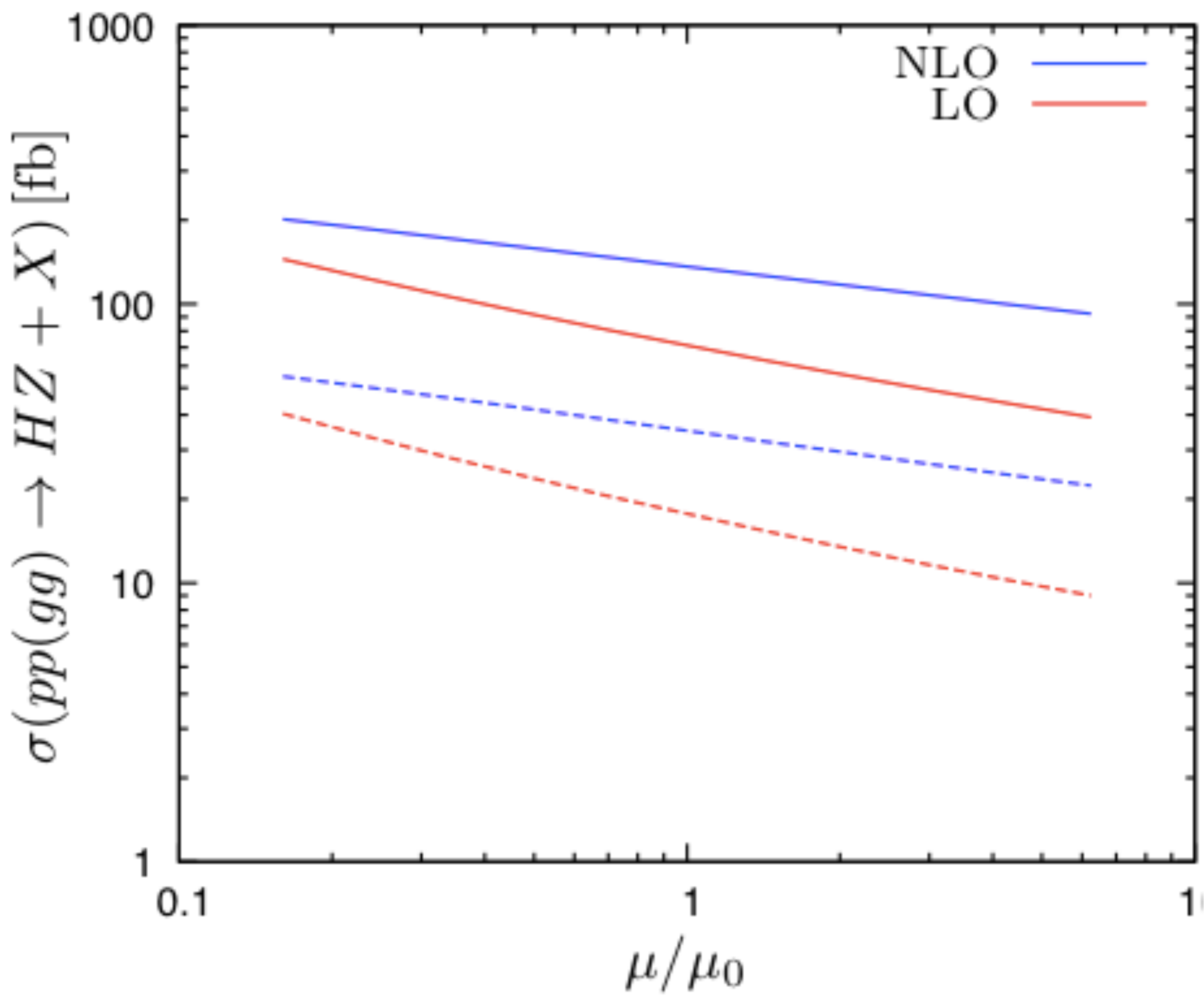


(d)

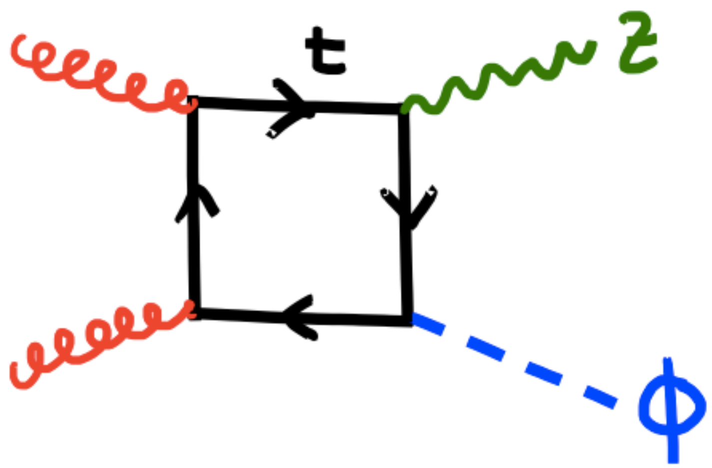




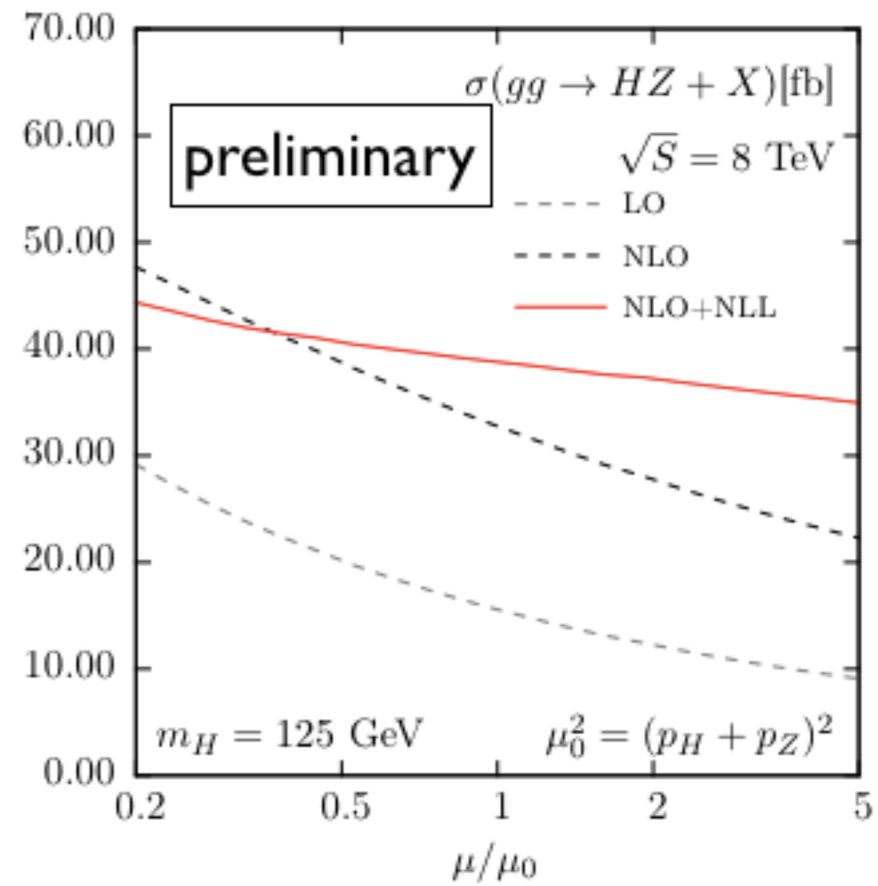
at NLO:

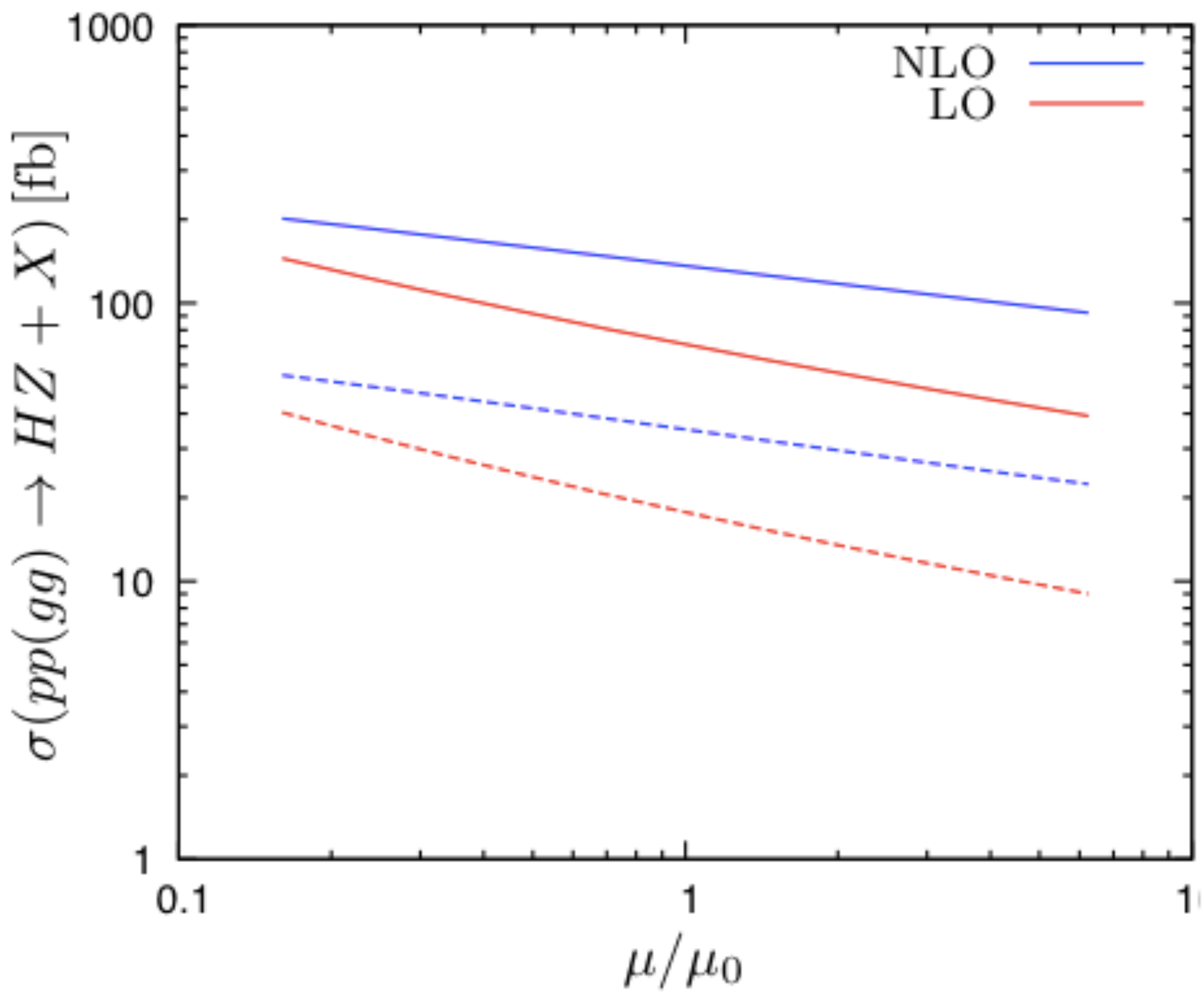


NLO: Altenkamp, Dittmaier, RH, Rzehak, Zirke '12



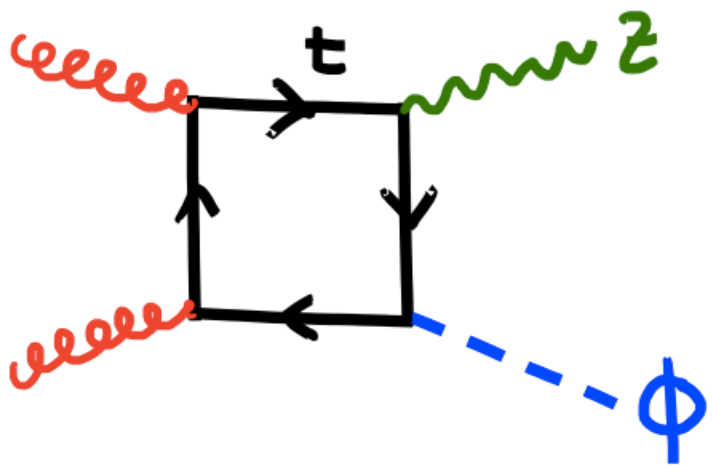
at NLO:



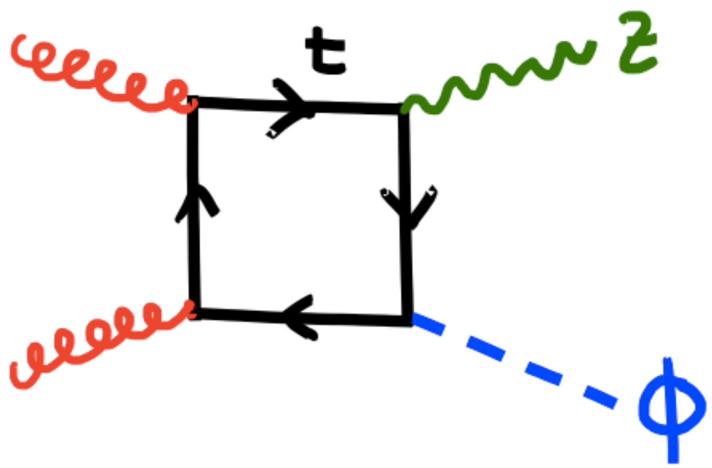


NLO+NLL:
RH, Kulesza, Theeuwes, Zirke

NLO: Altenkamp, Dittmaier, RH, Rzehak, Zirke '12



in SUSY?



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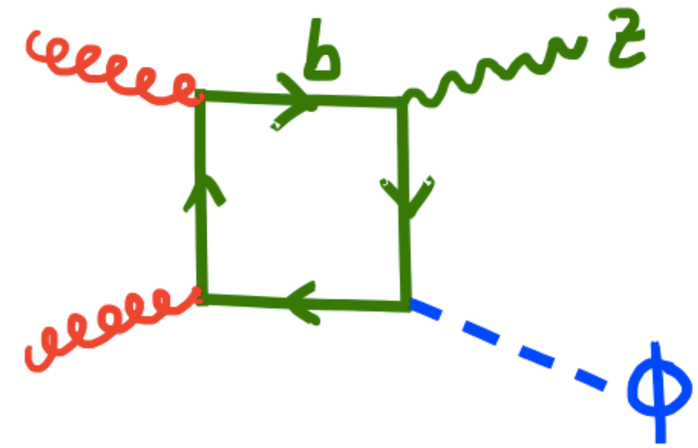
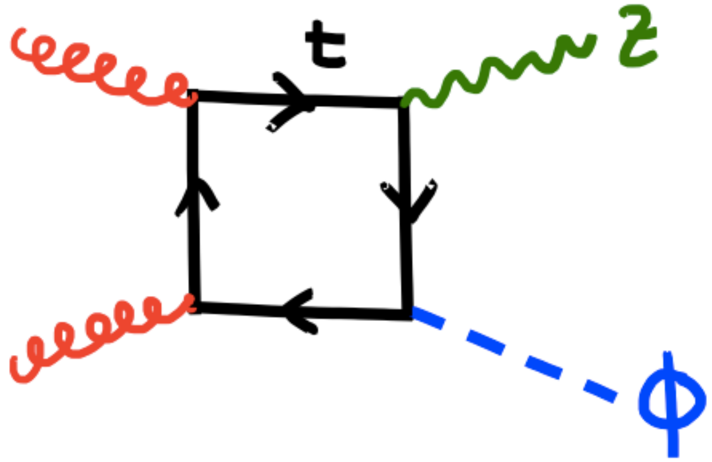


enhancement
by tanβ



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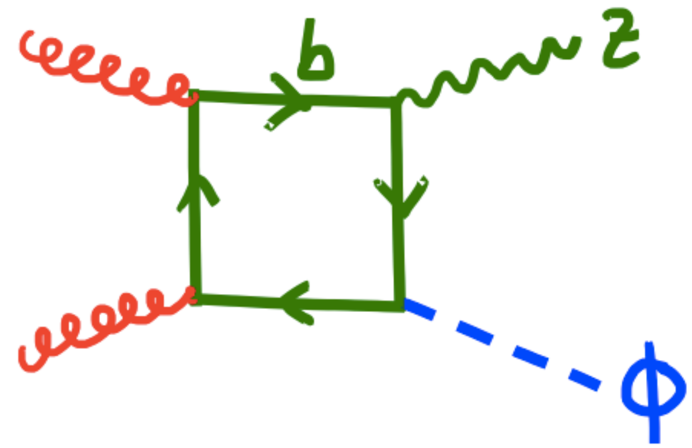

enhancement
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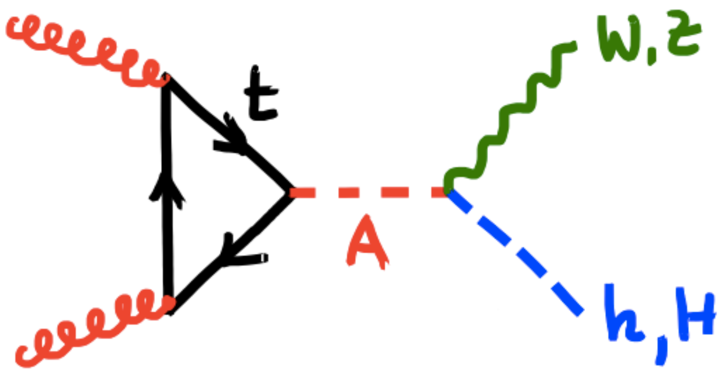

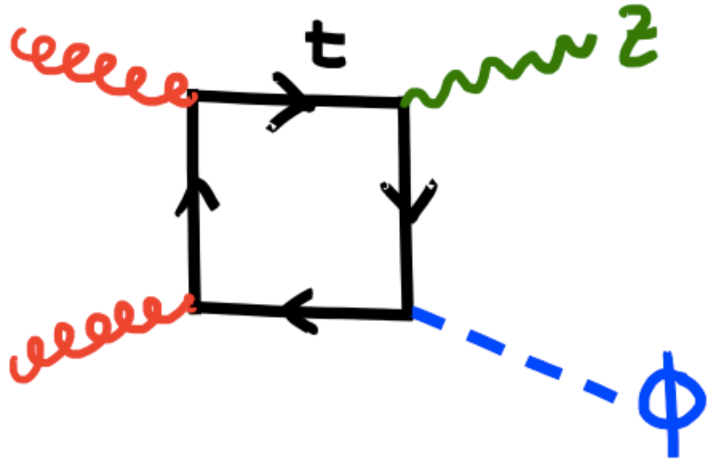

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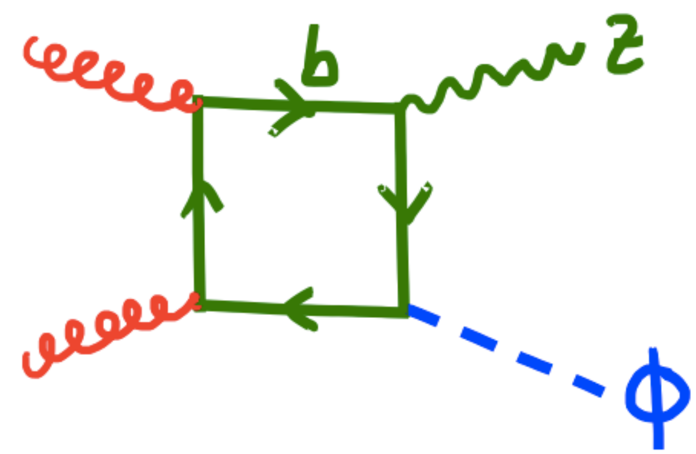

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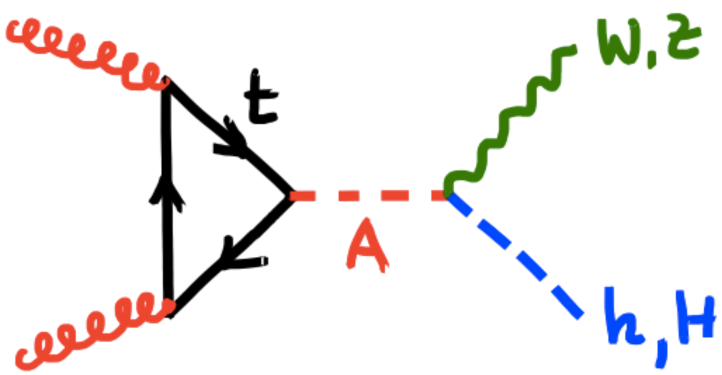
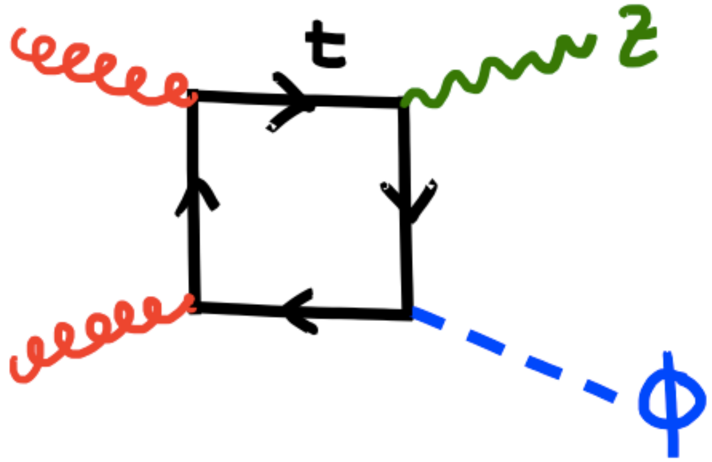


Squarks?



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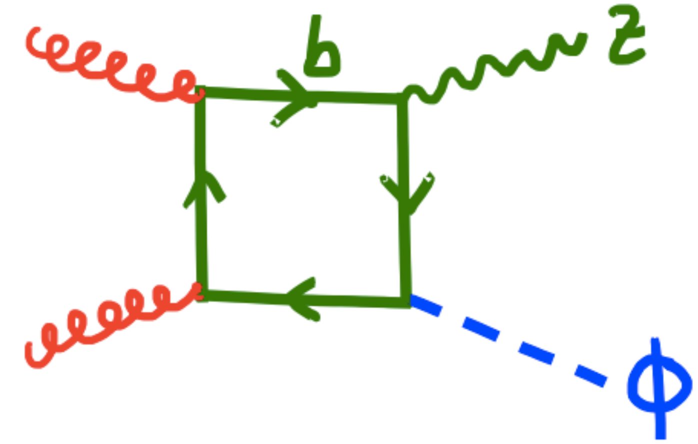
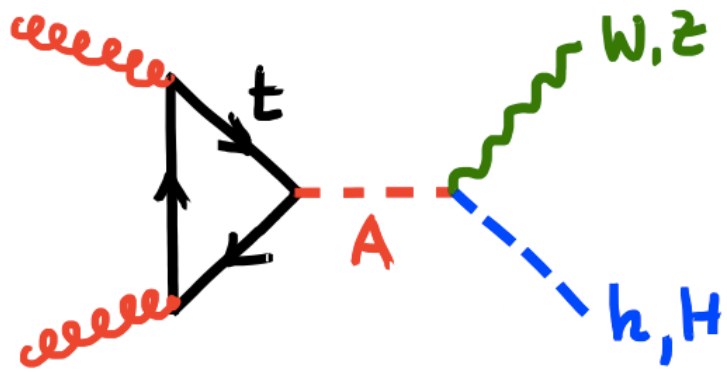


enhancement
by tanβ



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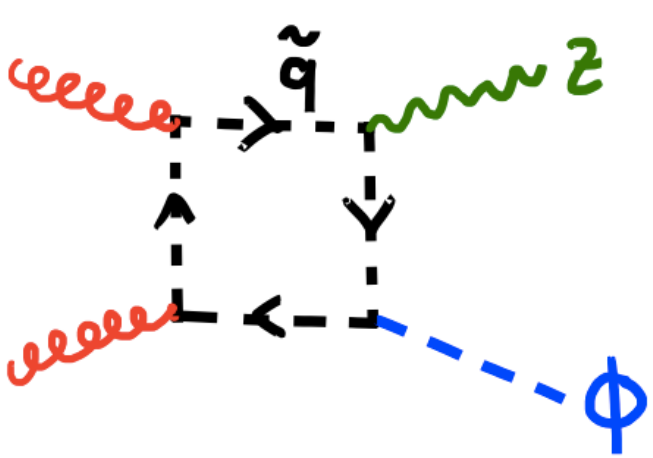

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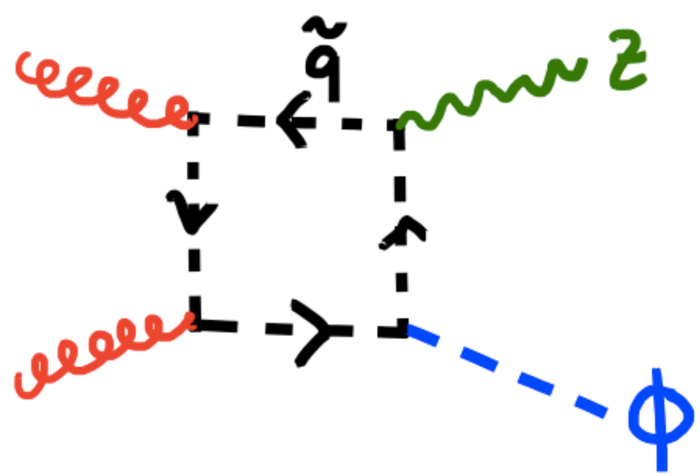

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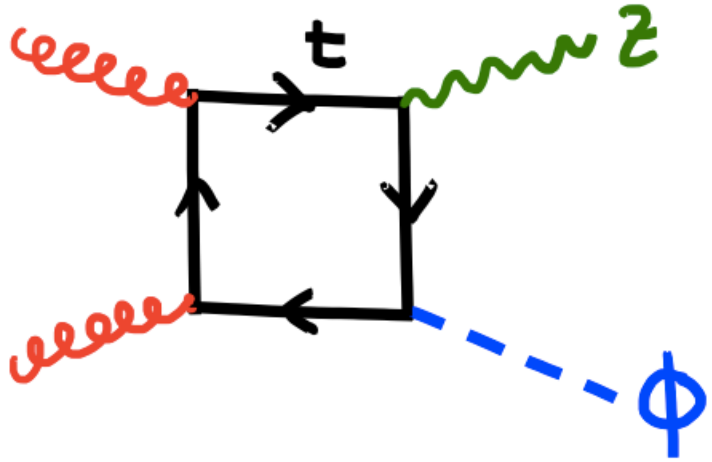

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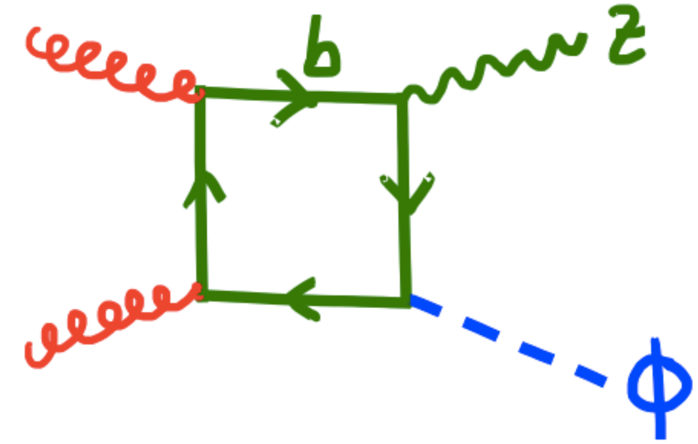
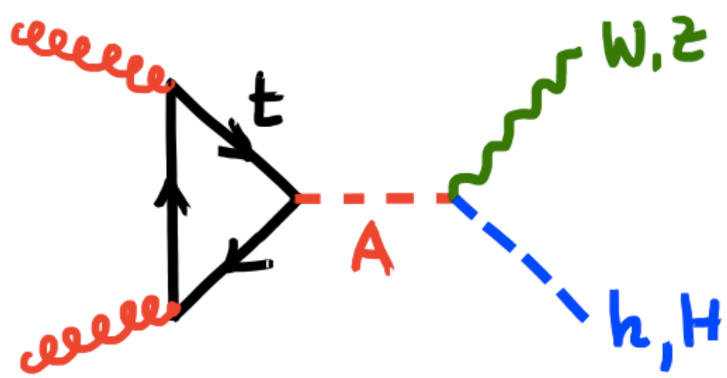
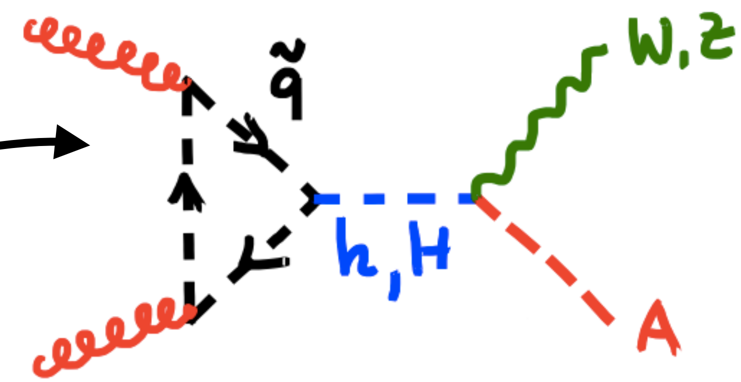


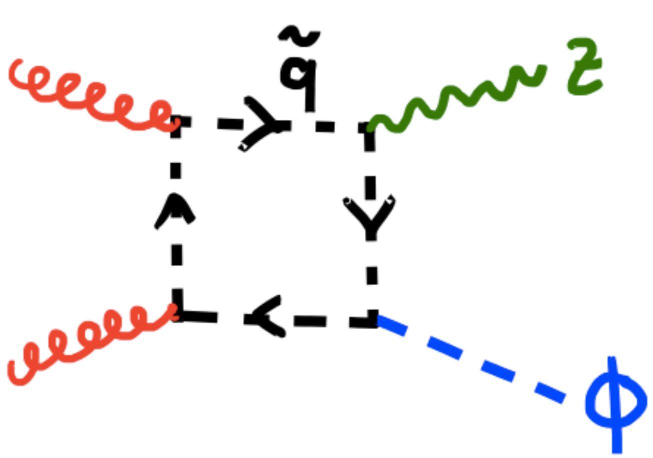
enhancement
by tanβ





only

Squarks?



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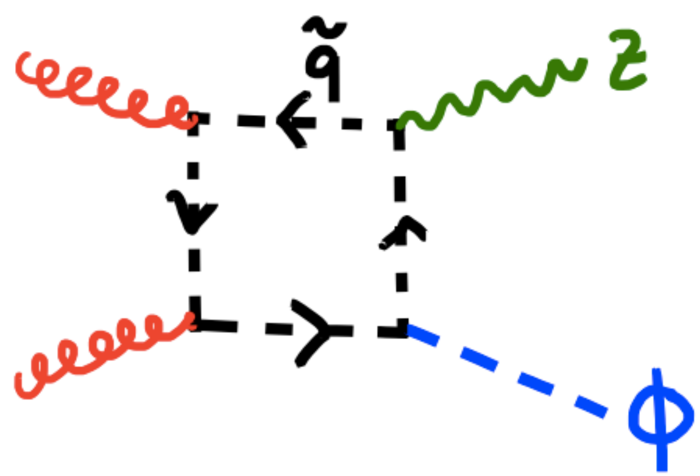

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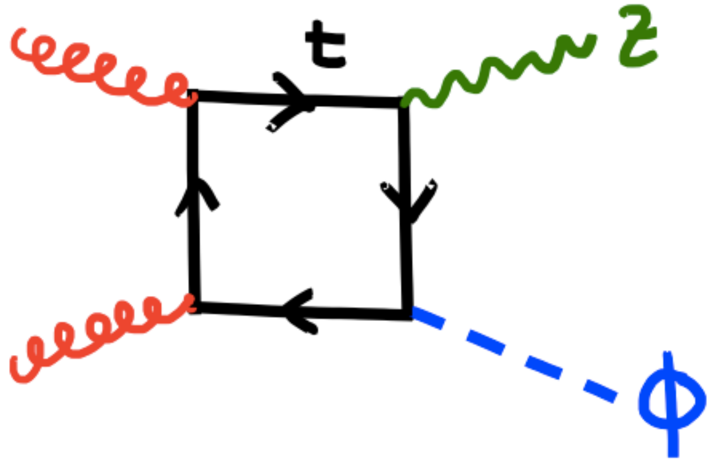
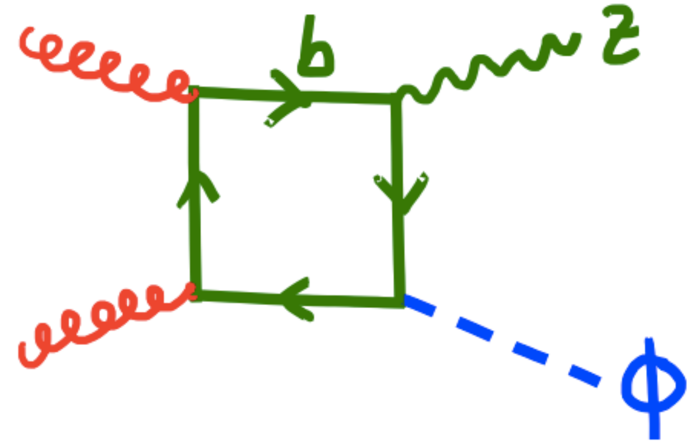
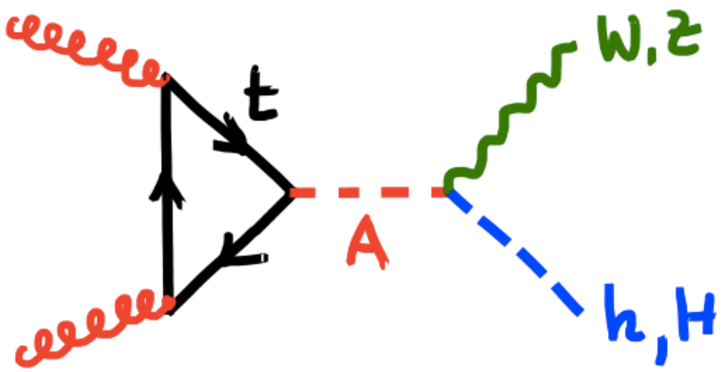
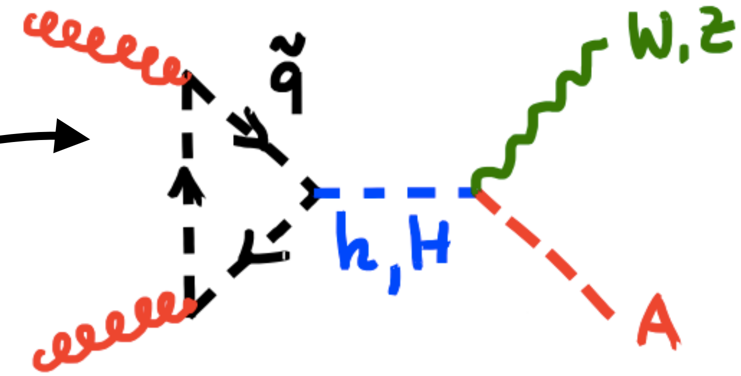


in SUSY?



enhancement by tanβ





only

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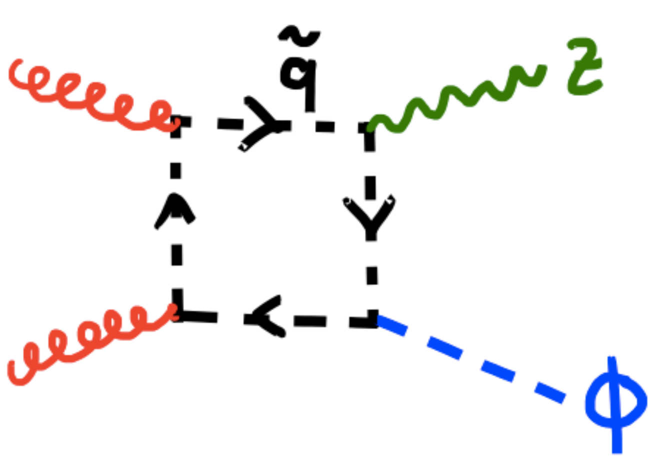

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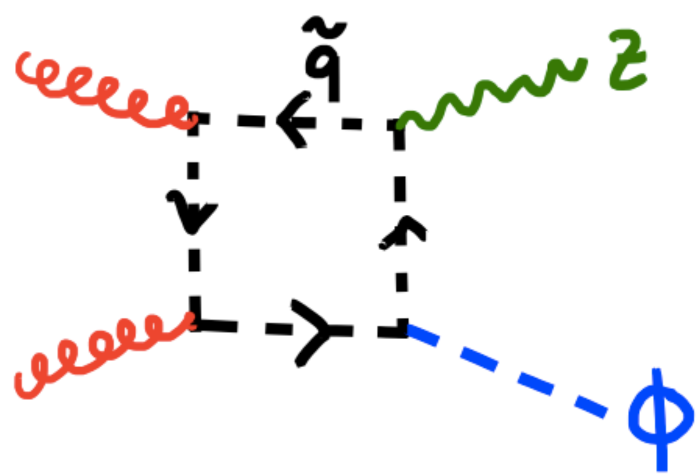


= 0

⇒ MSSM is like 2HDM Type II for h,H

C. Kao, “Production of a pseudoscalar Higgs with a Z boson from gluon fusion”, *Phys. Rev.* **D 46**, 4907 (1992).

J. Yin, W.-G. Ma, R.-Y. Zhang, H.-S. Hou, “A0Z0 associated production at the CERN large hadron collider in the minimal supersymmetric standard model”, *Phys. Rev.* **D 66**, 095008 (2002) [hep-ph/0209279].

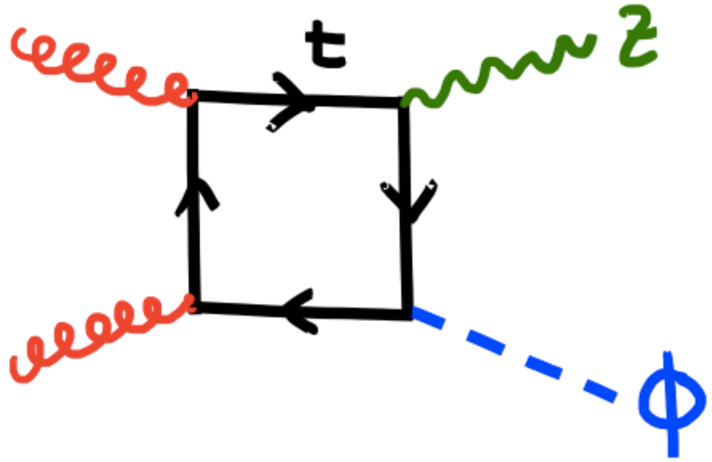
C. Kao, G. Lovelace, L.H. Orr, “Detecting a Higgs pseudoscalar with a Z boson at the LHC”, *Phys. Lett.* **B 567**, 259 (2003) [hep-ph/0305028].

C. Kao and S. Sachithanandam, “Detecting a Higgs pseudoscalar with a Z boson produced in bottom quark fusion”, *Phys. Lett.* **B 620**, 80 (2005) [hep-ph/0411331].

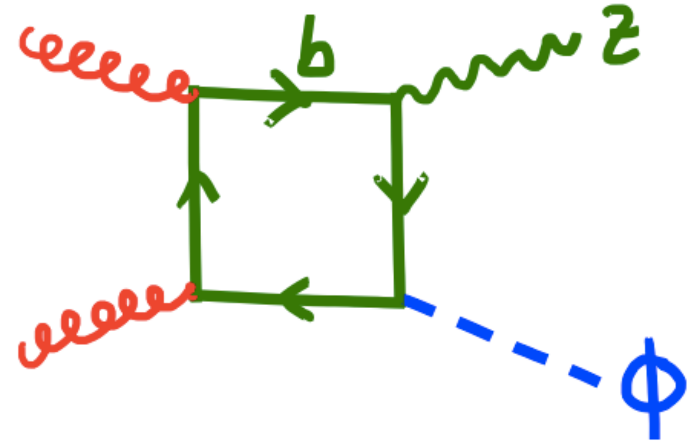
L.L. Yang, C.S. Li, J.J. Liu, L.G. Jin, “Production of scalar Higgs bosons associated with Z^0 boson at the CERN LHC in the MSSM”, *J. Phys. G* **30**, 1821 (2004) [hep-ph/0312179].

Q. Li, C.S. Li, J.J. Liu, L.G. Jin, C.-P. Yuan, “Next-to-leading order QCD predictions for $A^0 Z^0$ associated production at the CERN large hadron collider”, *Phys. Rev.* **D 72**, 034032 (2005) [hep-ph/0501070].

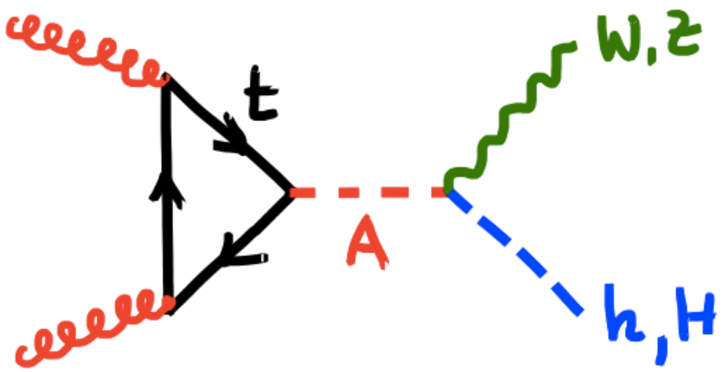
B. A. Kniehl and C. P. Palisoc, “Associated production of Z and neutral Higgs bosons at the CERN Large Hadron Collider”, *Phys. Rev.* **D 85**, 075027 (2012) [arXiv:1112.1575].

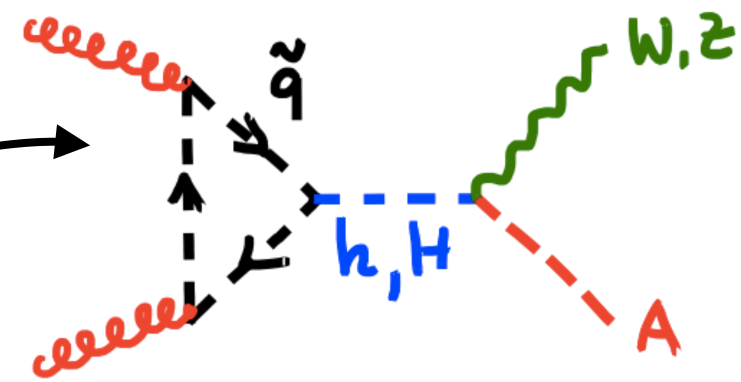


in SUSY?



enhancement
by $\tan\beta$





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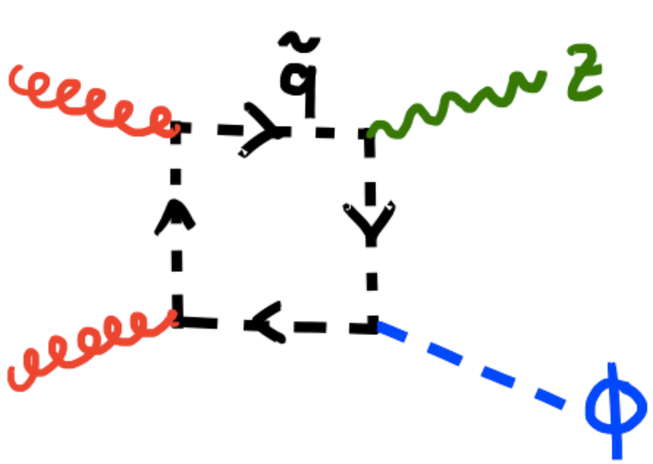
Squarks?



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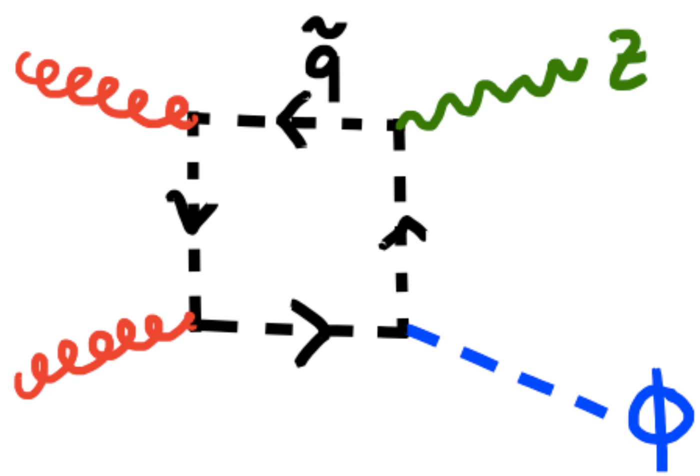
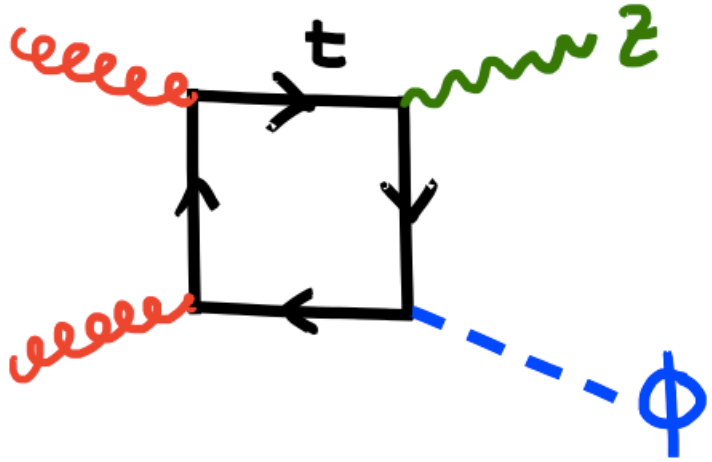
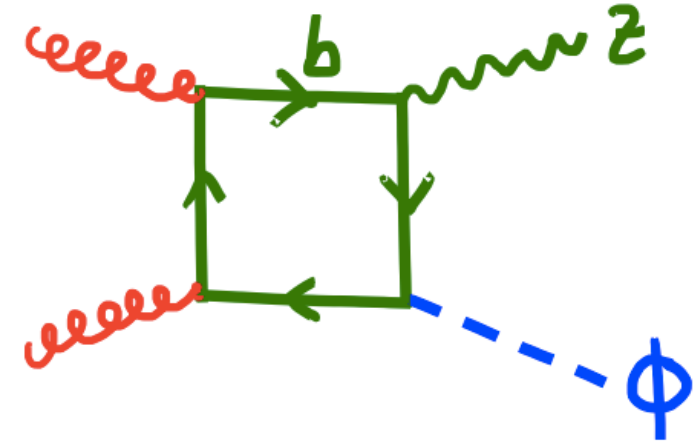


= 0

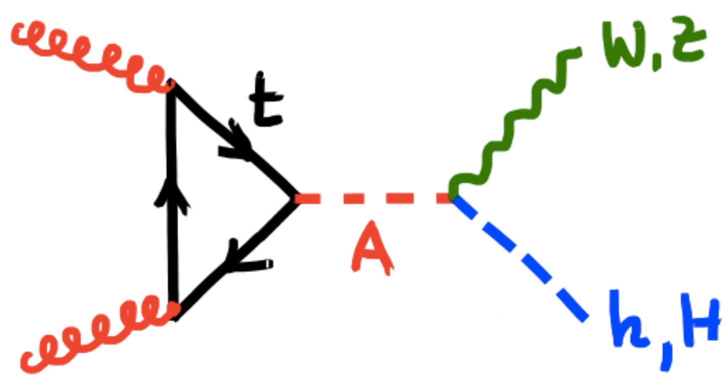
⇒ MSSM is like 2HDM Type II for h,H



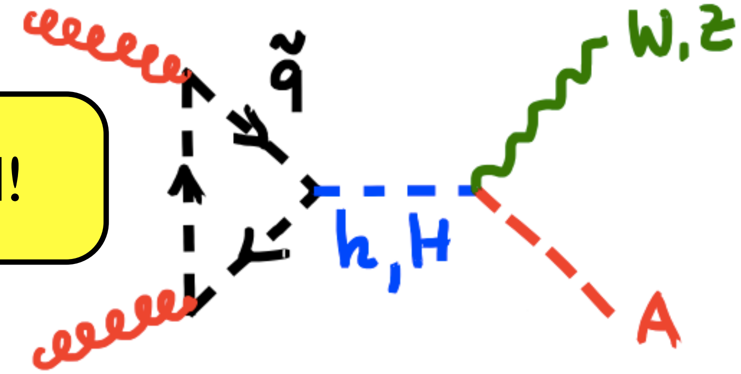
in SUSY?



enhancement
by $\tan\beta$

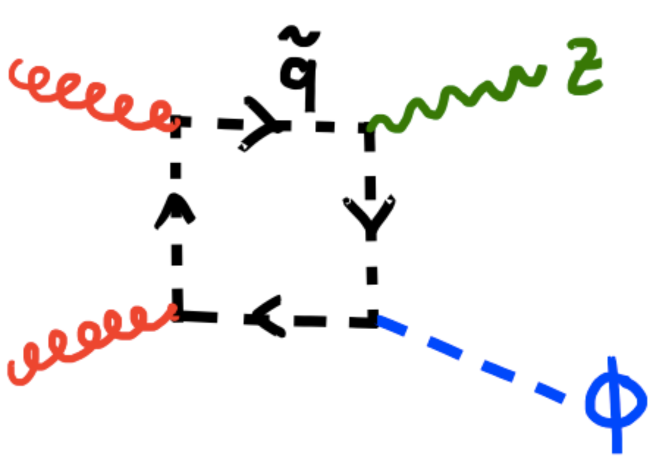


only for ZH, not WH!

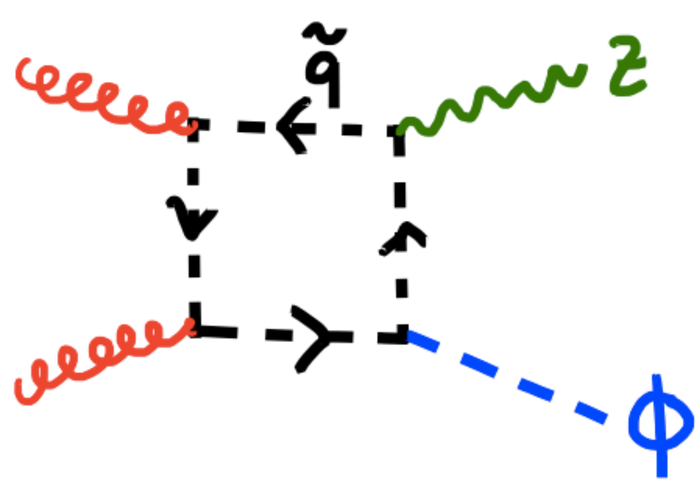


only

Squarks?



+



= 0

$\Rightarrow$ MSSM is like 2HDM Type II for h,H consider ratio: σ_{WH}/σ_{ZH}

consider ratio: σ_{WH}/σ_{ZH}

- very weak dependence on PDFs
- very weak dependence on α_S
- reduced experimental uncertainties

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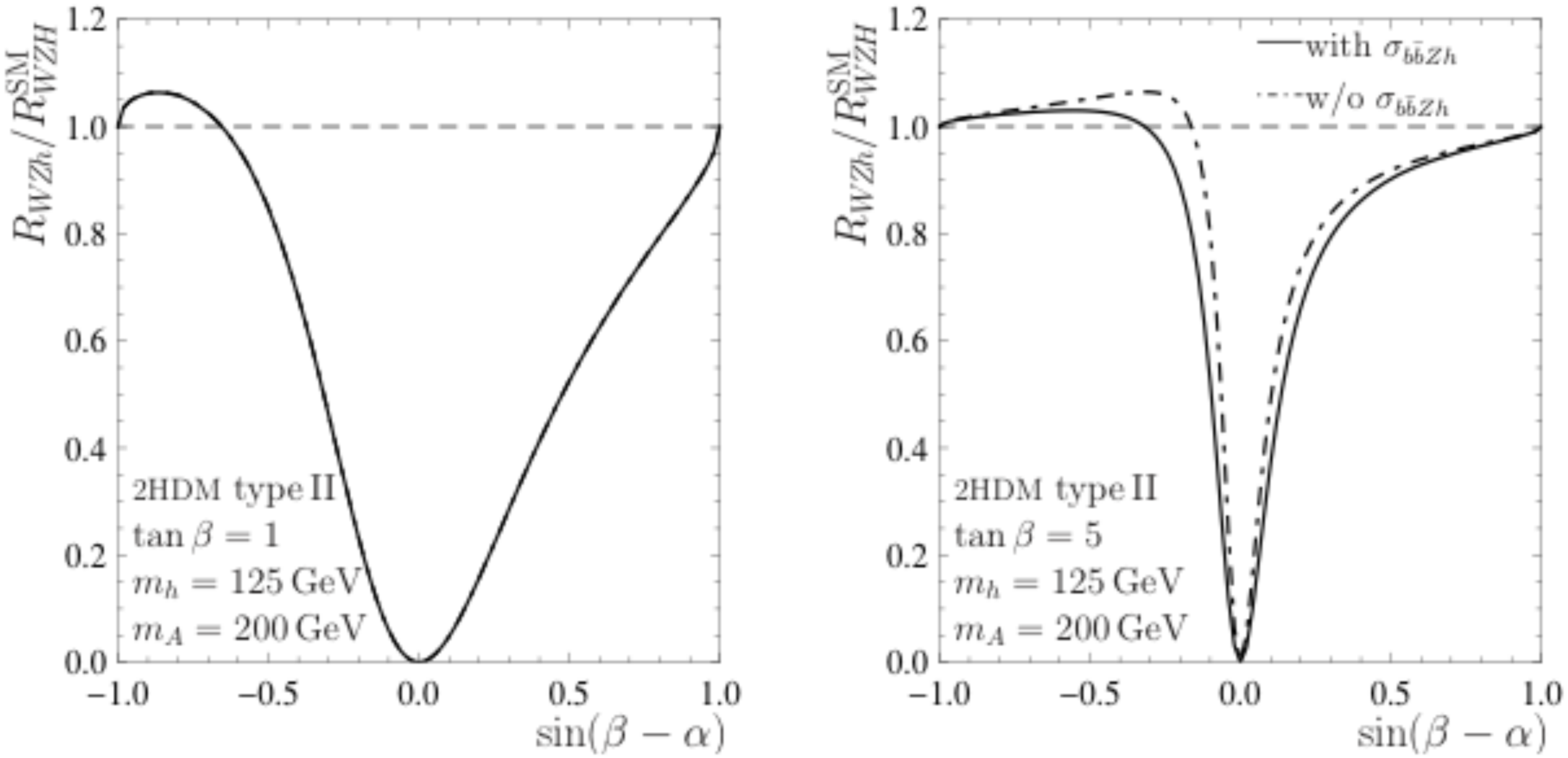


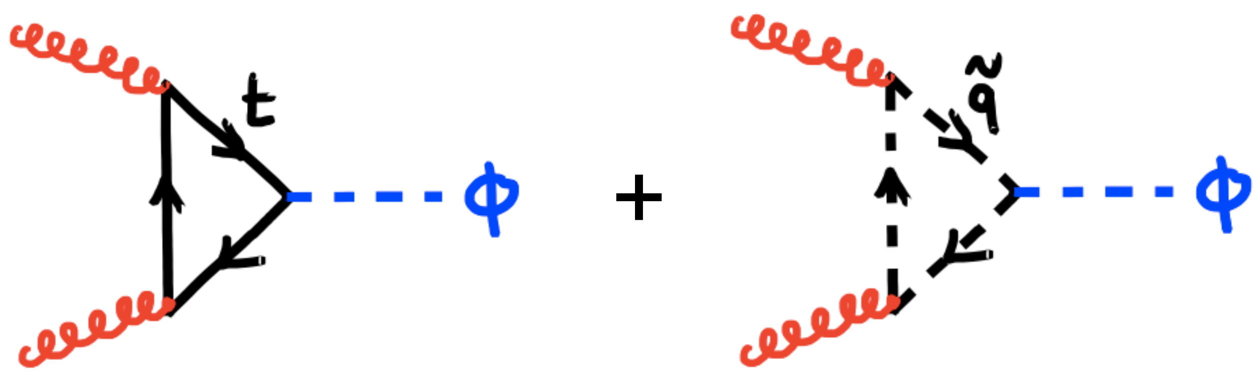
2HDM

RH, Liebler, Zirke '13

see also: Englert, McCullough, Spannowsky '13

SUSY particle effects:

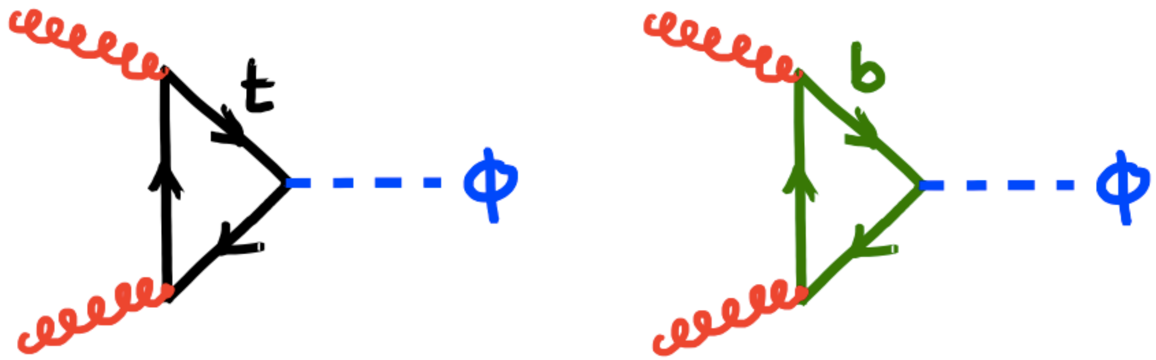
at leading order:



can interfere distructively (gluophobic Higgs)

Djouadi '98

Gluon fusion



exact through NLO

Gluon f

M. Spira, A. Djouadi, D. Graudenz and P.M. Zerwas, *Higgs boson production at the LHC*, *Nucl. Phys.* **B 453** (1995) 17 [hep-ph/9504378] [INSPIRE].

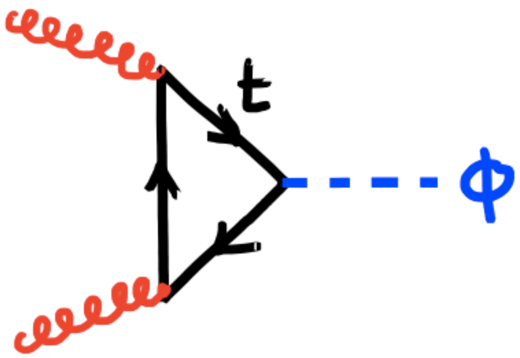
R. Harlander and P. Kant, *Higgs production and decay: analytic results at next-to-leading order QCD*, *JHEP* **12** (2005) 015 [hep-ph/0509189] [INSPIRE].

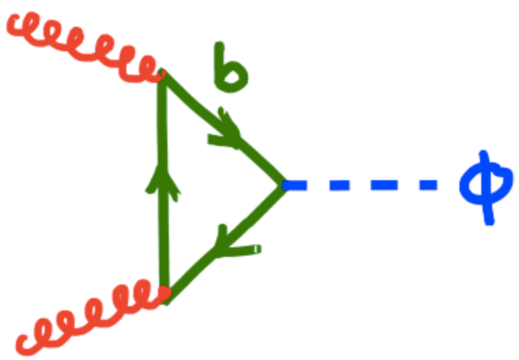
C. Anastasiou, S. Beerli, S. Bucherer, A. Daleo and Z. Kunszt, *Two-loop amplitudes and master integrals for the production of a Higgs boson via a massive quark and a scalar-quark loop*, *JHEP* **01** (2007) 082 [hep-ph/0611236] [INSPIRE].

U. Aglietti, R. Bonciani, G. Degrassi and A. Vicini, *Analytic results for virtual QCD corrections to Higgs production and decay*, *JHEP* **01** (2007) 021 [hep-ph/0611266] [INSPIRE].

R. Bonciani, G. Degrassi and A. Vicini, *Scalar particle contribution to Higgs production via gluon fusion at NLO*, *JHEP* **11** (2007) 095 [arXiv:0709.4227] [INSPIRE].

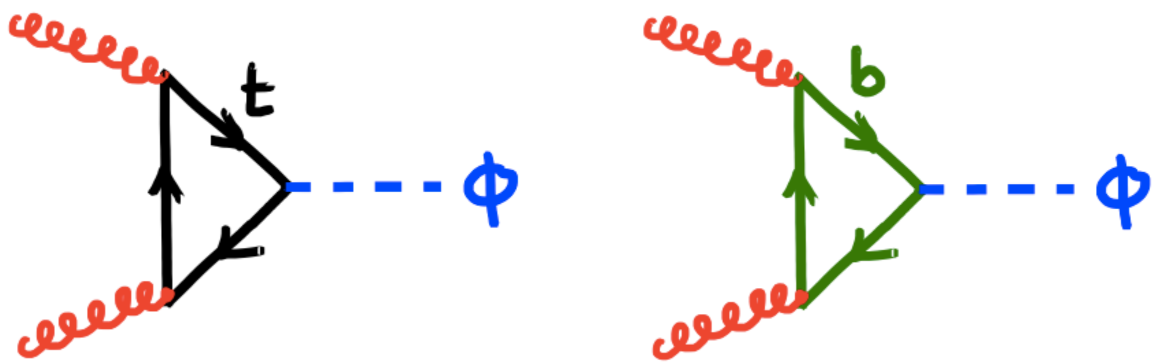
Gluon fusion





exact through NLO

Gluon fusion



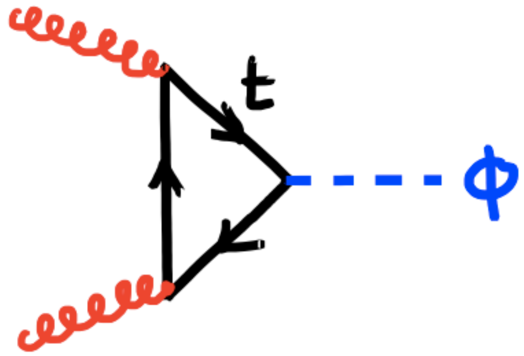
exact through NLO

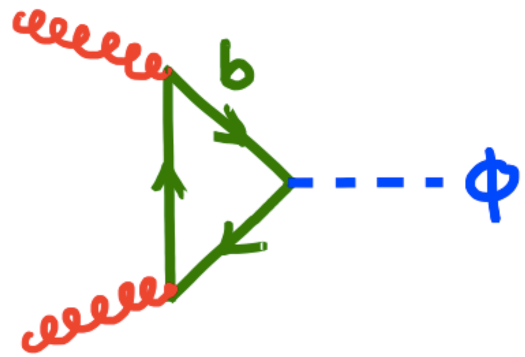
LHC Higgs XS WG, YR2 (2012):

$$\sigma^{\mathrm{MSSM}}(\mathrm{gg} \to \phi) = \left(\frac{g_{\mathrm{t}}^{\mathrm{MSSM}}}{g_{\mathrm{t}}^{\mathrm{SM}}}\right)^2 \sigma_{\mathrm{tt}}(\mathrm{gg} \to \phi) + \left(\frac{g_{\mathrm{b}}^{\mathrm{MSSM}}}{g_{\mathrm{b}}^{\mathrm{SM}}}\right)^2 \sigma_{\mathrm{bb}}(\mathrm{gg} \to \phi) + \frac{g_{\mathrm{t}}^{\mathrm{MSSM}}}{g_{\mathrm{t}}^{\mathrm{SM}}} \frac{g_{\mathrm{b}}^{\mathrm{MSSM}}}{g_{\mathrm{b}}^{\mathrm{SM}}} \sigma_{\mathrm{tb}}(\mathrm{gg} \to \phi),$$

no SUSY particles in loops!

Gluon fusion





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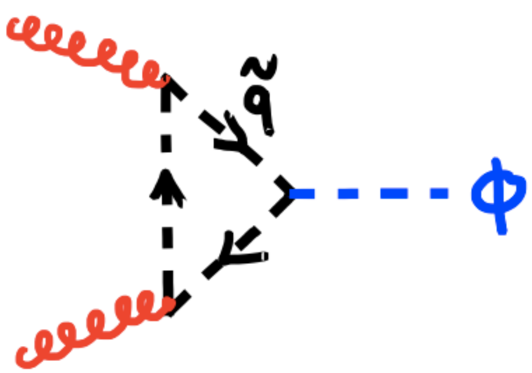
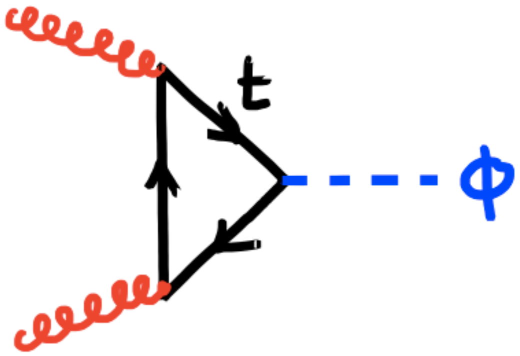
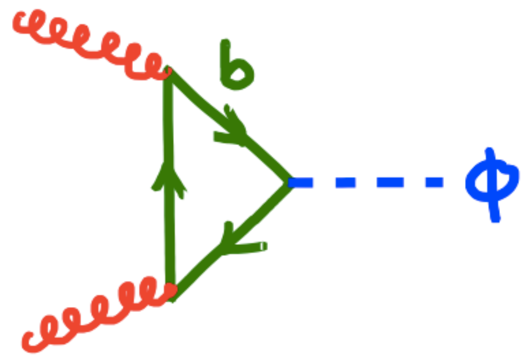


Gluon fusion





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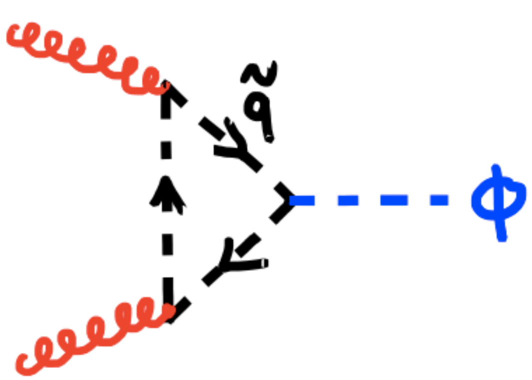
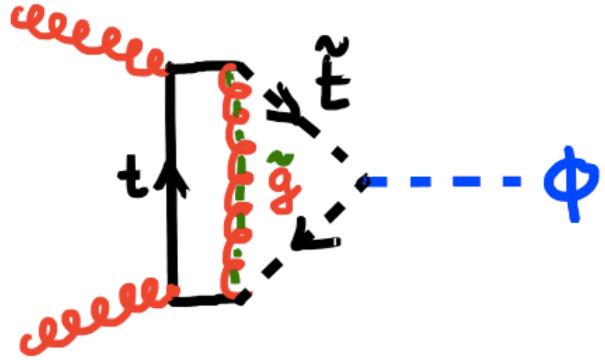
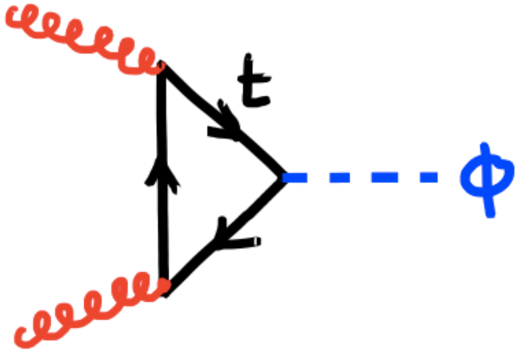
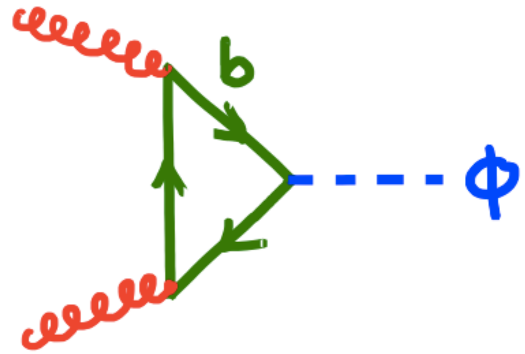




Gluon fusion





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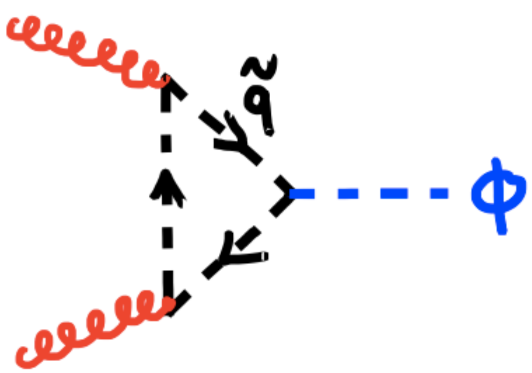
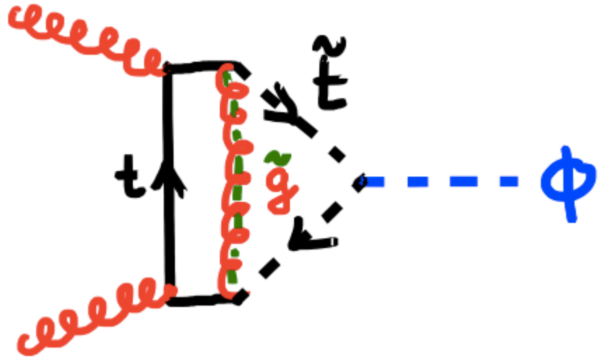
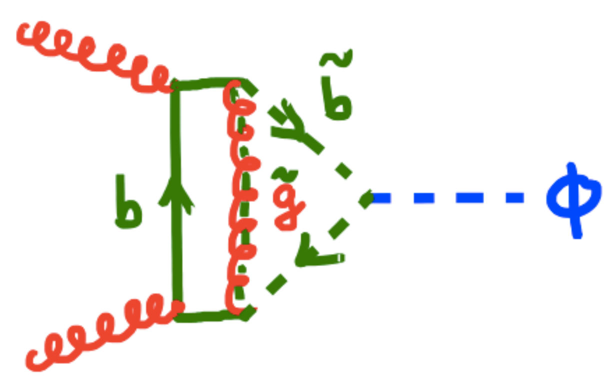
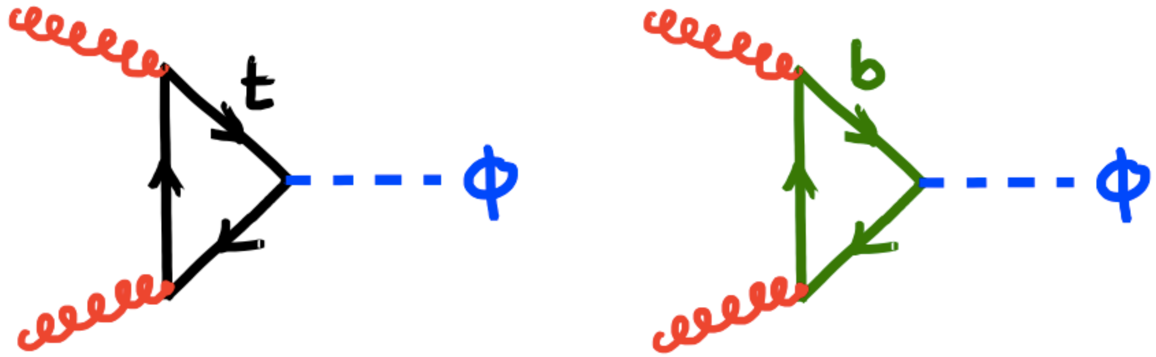






Gluon fusion



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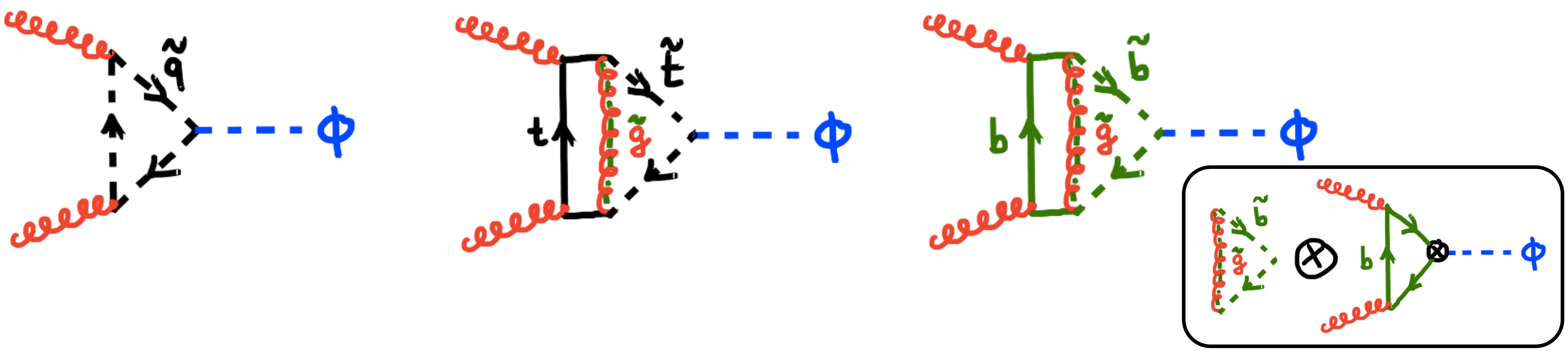


Gluc

LHC Higg

$\sigma^{\mathrm{MSSM}}(\mathrm{gg}$ … $(\mathrm{gg} \to \phi),$

n

R.V. Harlander and M. Steinhauser, *Hadronic Higgs production and decay in supersymmetry at next-to-leading order*, *Phys. Lett.* **B 574** (2003) 258 [hep-ph/0307346] [INSPIRE].

R.V. Harlander and M. Steinhauser, *Supersymmetric Higgs production in gluon fusion at next-to-leading order*, *JHEP* **09** (2004) 066 [hep-ph/0409010] [INSPIRE].

G. Degrassi and P. Slavich, *On the NLO QCD corrections to Higgs production and decay in the MSSM*, *Nucl. Phys.* **B 805** (2008) 267 [arXiv:0806.1495] [INSPIRE].

R.V. Harlander and F. Hofmann, *Pseudo-scalar Higgs production at next-to-leading order SUSY-QCD*, *JHEP* **03** (2006) 050 [hep-ph/0507041] [INSPIRE].

G. Degrassi, S. Di Vita and P. Slavich, *NLO QCD corrections to pseudoscalar Higgs production in the MSSM*, *JHEP* **08** (2011) 128 [arXiv:1107.0914] [INSPIRE].

G. Degrassi and P. Slavich, *NLO QCD bottom corrections to Higgs boson production in the MSSM*, *JHEP* **11** (2010) 044 [arXiv:1007.3465] [INSPIRE].

R.V. Harlander, F. Hofmann and H. Mantler, *Supersymmetric Higgs production in gluon fusion*, *JHEP* **02** (2011) 055 [arXiv:1012.3361] [INSPIRE].

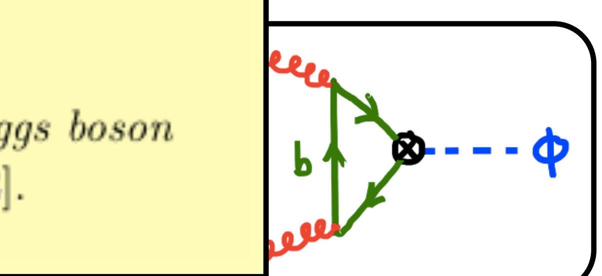
G. Degrassi, S. Di Vita and P. Slavich, *On the NLO QCD corrections to the production of the heaviest neutral Higgs scalar in the MSSM*, *Eur. Phys. J.* **C 72** (2012) 2032 [arXiv:1204.1016] [INSPIRE].

S. Dawson, A. Djouadi and M. Spira, *QCD corrections to SUSY Higgs production: the role of squark loops*, *Phys. Rev. Lett.* **77** (1996) 16 [hep-ph/9603423] [INSPIRE].

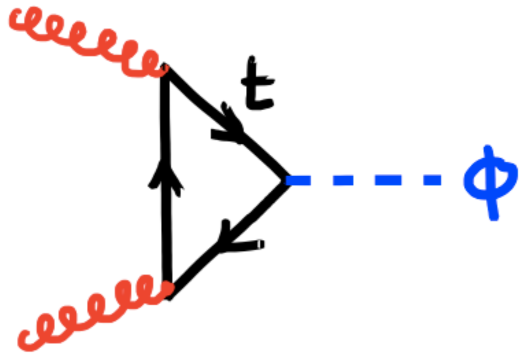
M. Mühlleitner and M. Spira, *Higgs boson production via gluon fusion: squark loops at NLO QCD*, *Nucl. Phys.* **B 790** (2008) 1 [hep-ph/0612254] [INSPIRE].

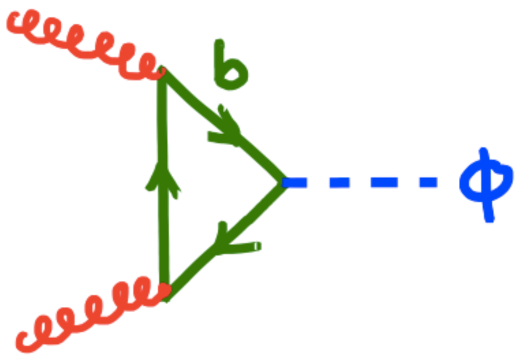
C. Anastasiou, S. Beerli and A. Daleo, *The two-loop QCD amplitude $gg \to h, H$ in the minimal supersymmetric standard model*, *Phys. Rev. Lett.* **100** (2008) 241806 [arXiv:0803.3065] [INSPIRE].

M. Mühlleitner, H. Rzehak and M. Spira, *SUSY-QCD corrections to MSSM Higgs boson production via gluon fusion*, PoS(RADCOR2009)043 [arXiv:1001.3214] [INSPIRE].



Gluon fusion





exact through NLO

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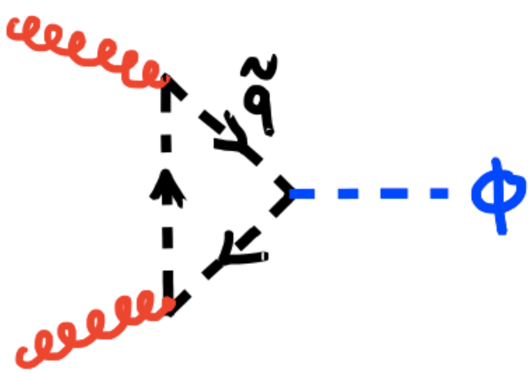

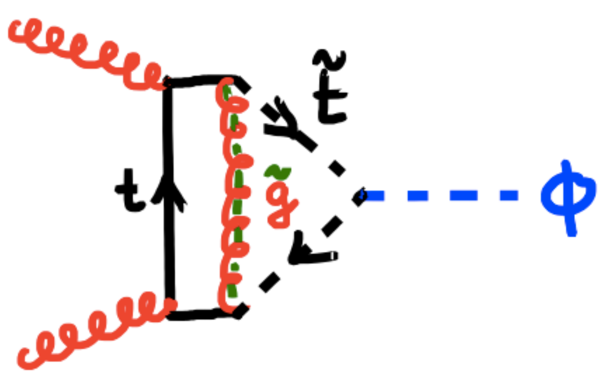

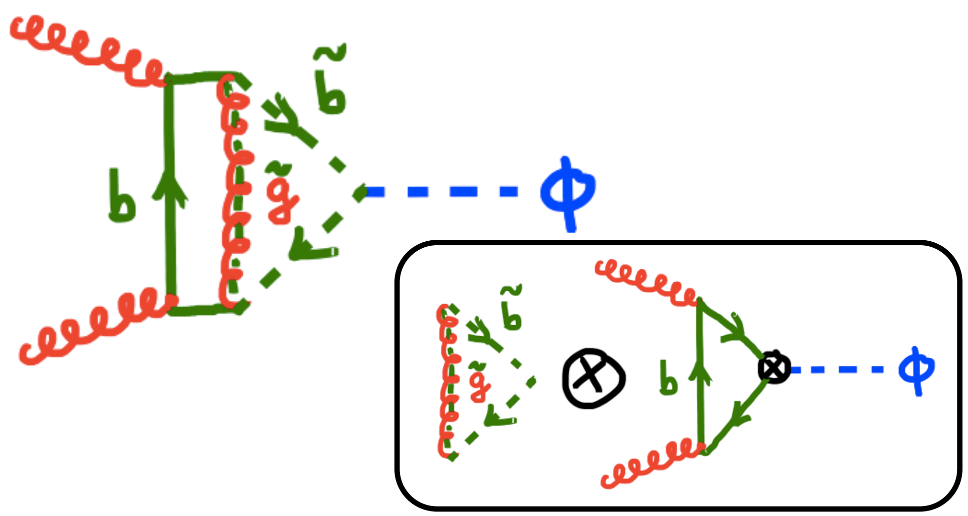

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- Changelog
- Manual
- Examples
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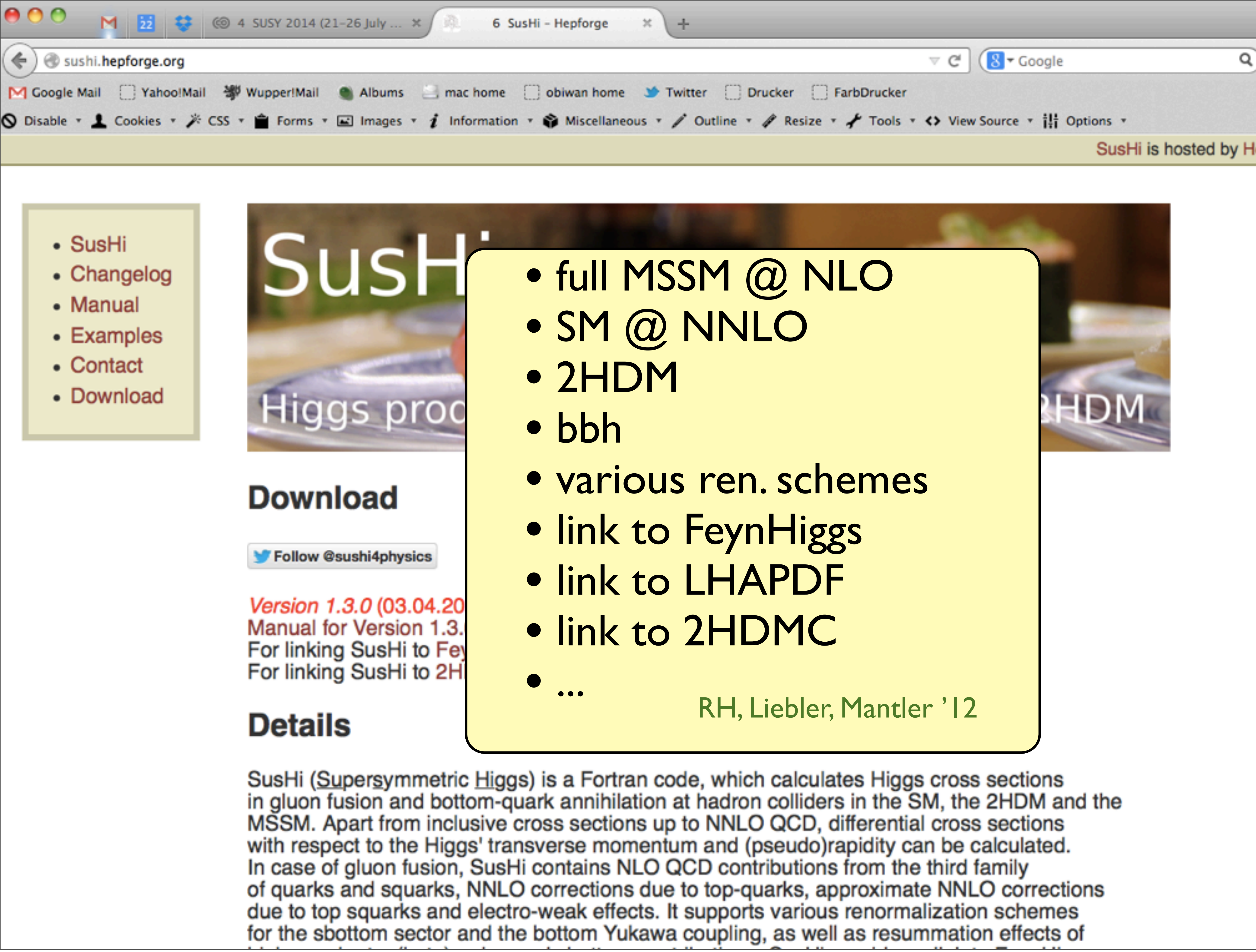
Version 1.3.0 (03.04.2014) is available here: Download
Manual for Version 1.3.0
For linking SusHi to FeynHiggs type "./configure; make predef=FH"!
For linking SusHi to 2HDMC type "./configure; make predef=2HDMC"!

Details

SusHi (Supersymmetric Higgs) is a Fortran code, which calculates Higgs cross sections in gluon fusion and bottom-quark annihilation at hadron colliders in the SM, the 2HDM and the MSSM. Apart from inclusive cross sections up to NNLO QCD, differential cross sections with respect to the Higgs' transverse momentum and (pseudo)rapidity can be calculated. In case of gluon fusion, SusHi contains NLO QCD contributions from the third family of quarks and squarks, NNLO corrections due to top-quarks, approximate NNLO corrections due to top squarks and electro-weak effects. It supports various renormalization schemes for the sbottom sector and the bottom Yukawa coupling, as well as resummation effects of



- full MSSM @ NLO
- SM @ NNLO
- 2HDM
- bbh
- various ren. schemes
- link to FeynHiggs
- link to LHAPDF
- link to 2HDMC
- ...

RH, Liebler, Mantler '12

Neutral MSSM Higgs production — comprehensive study

Bagnaschi, RH, Liebler, Mantler, Slavich, Vicini '14

based on SusHi

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- gluon fusion, including
  - ★ NLO SQCD
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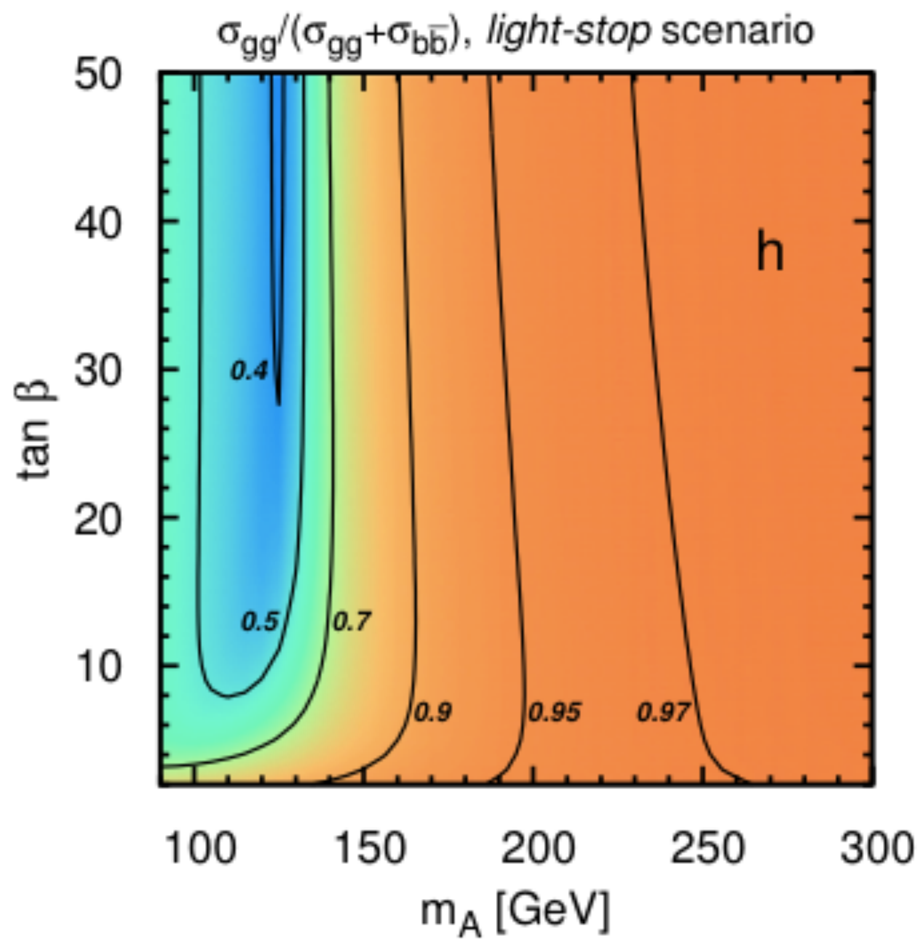
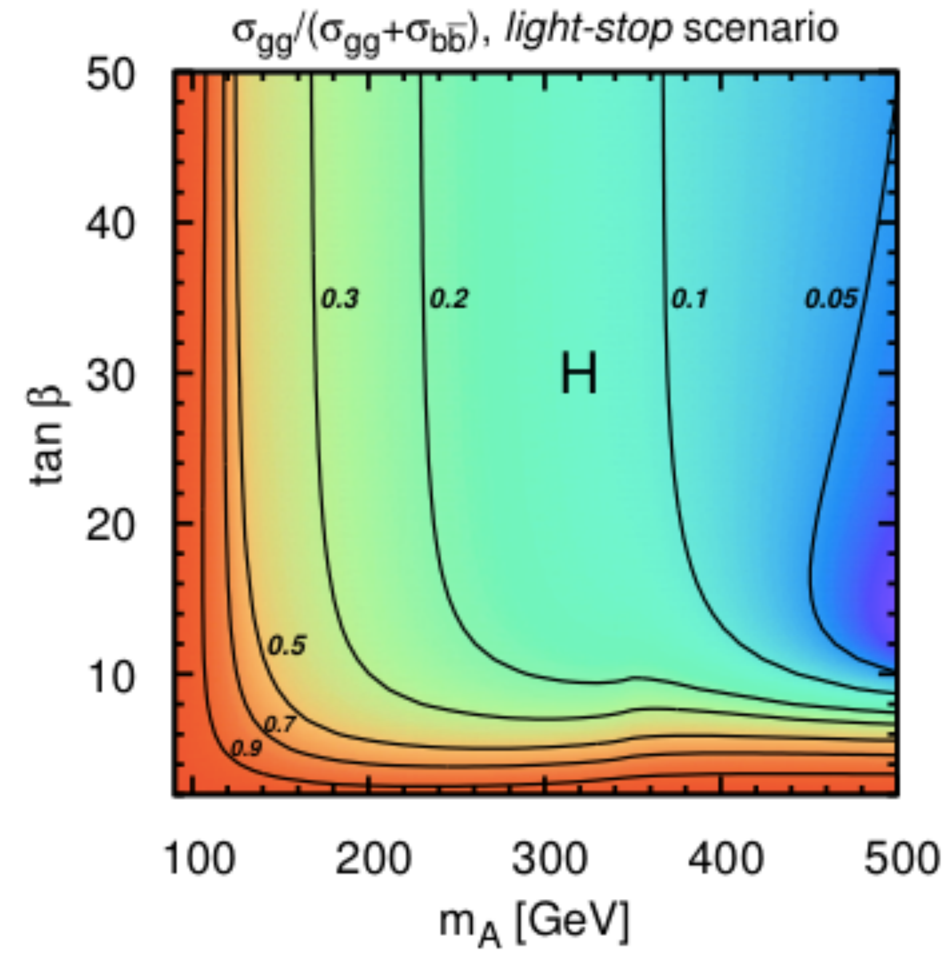
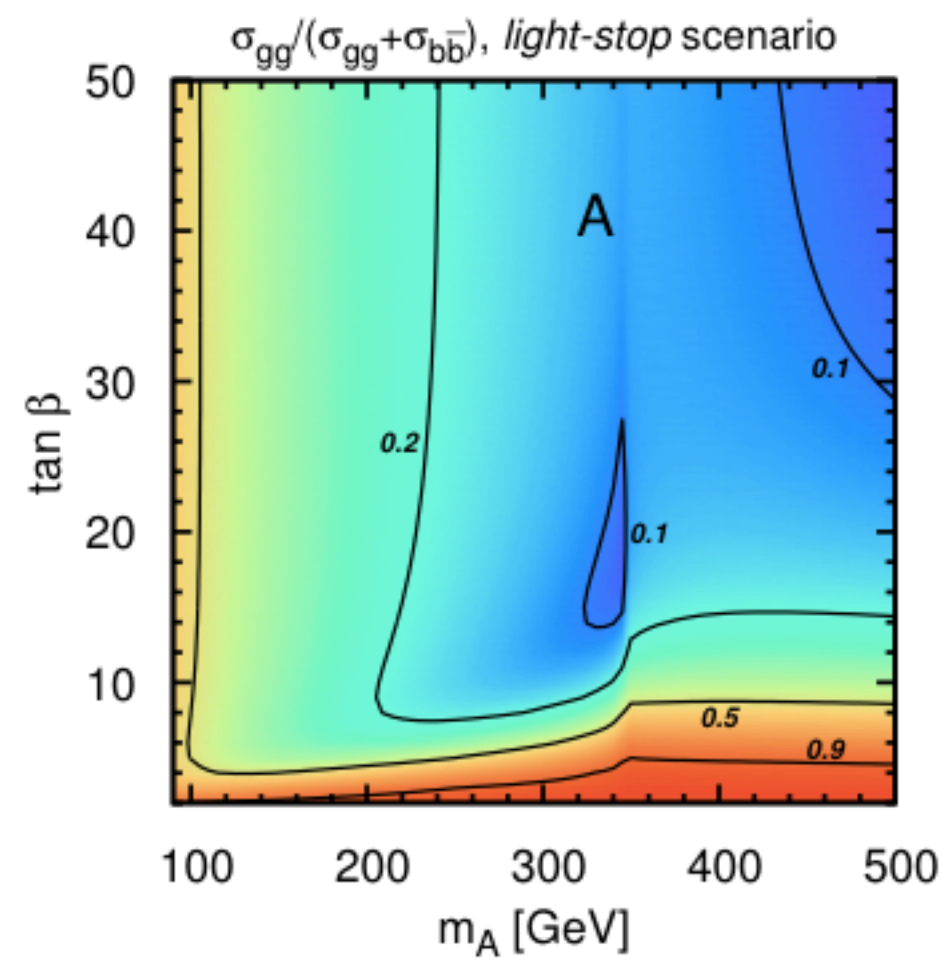
- cross sections for viable MSSM scenarios

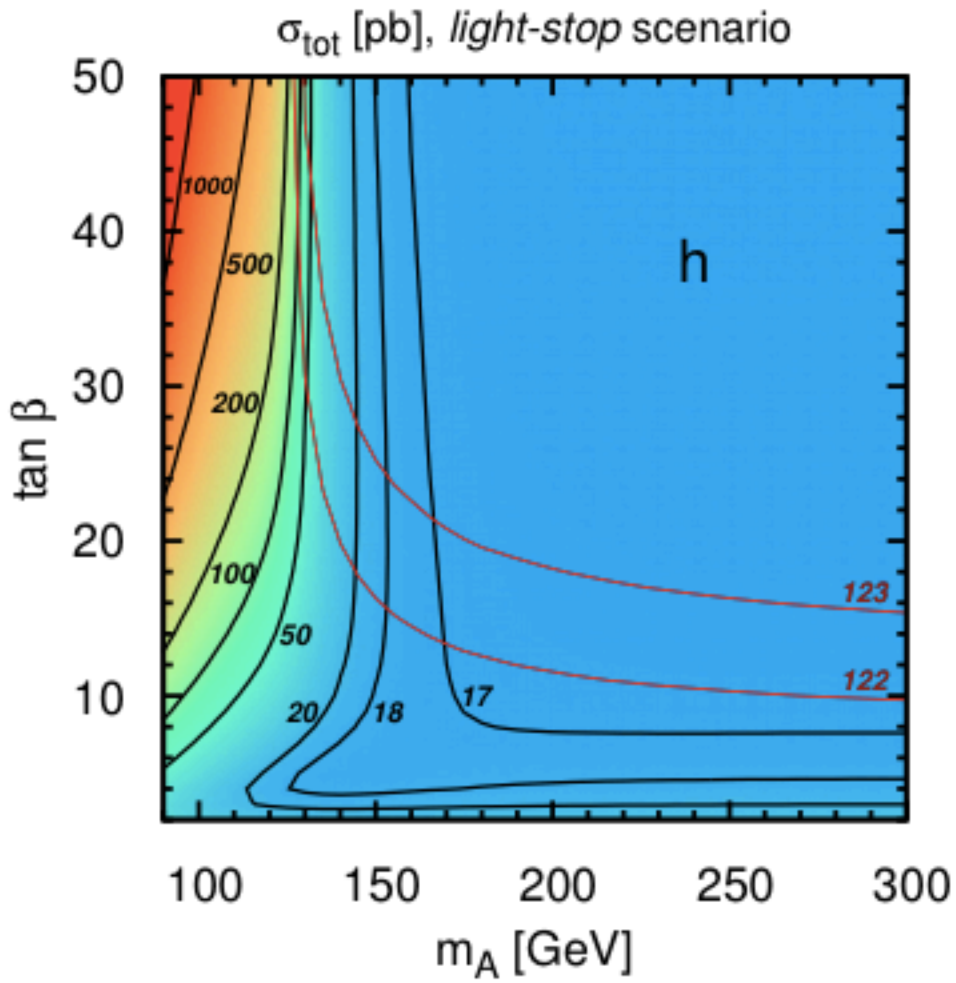
Carena, Heinemeyer, Stål, Wagner, Weiglein '13

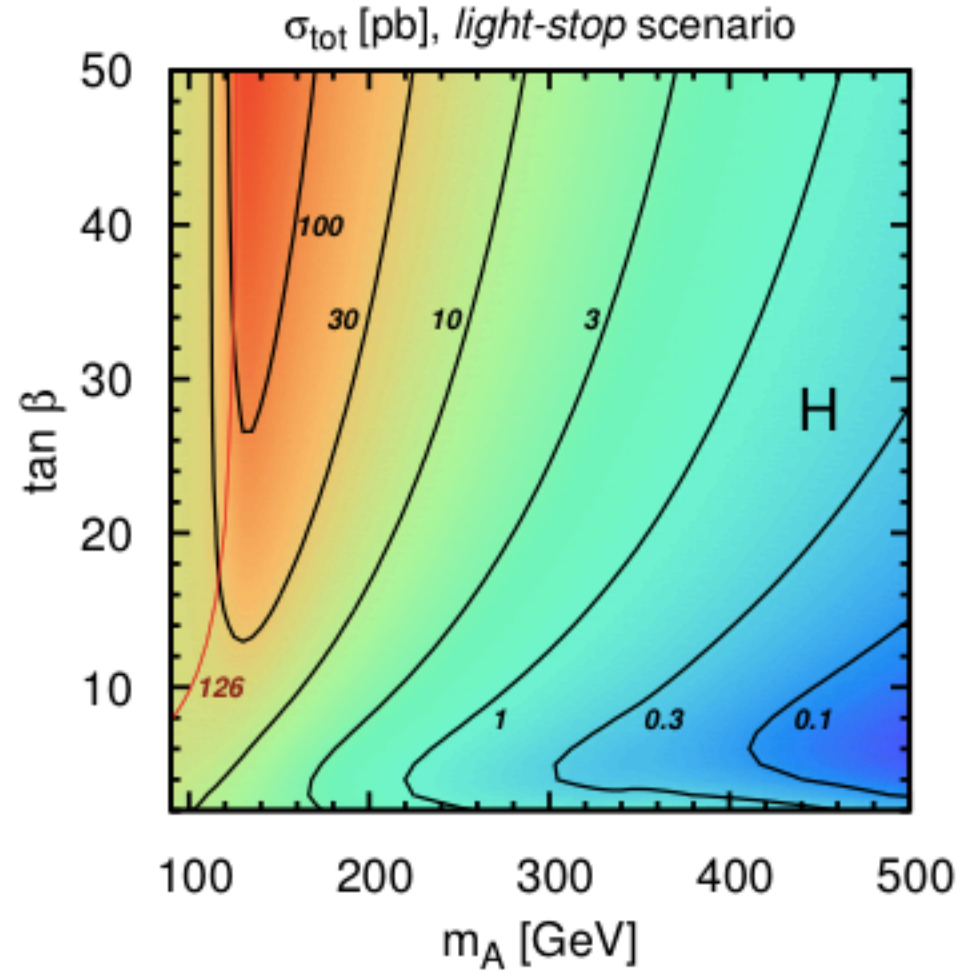




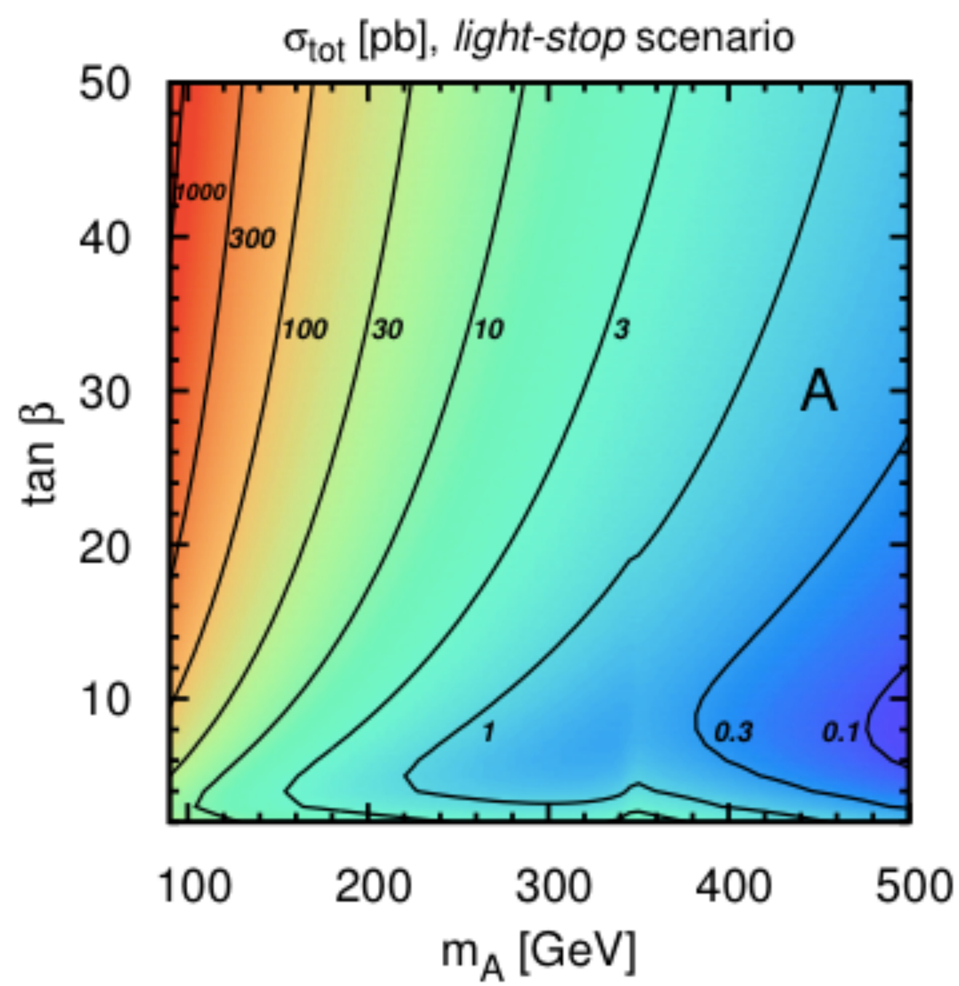
$\sigma_{gg}/(\sigma_{gg}+\sigma_{b\bar{b}})$



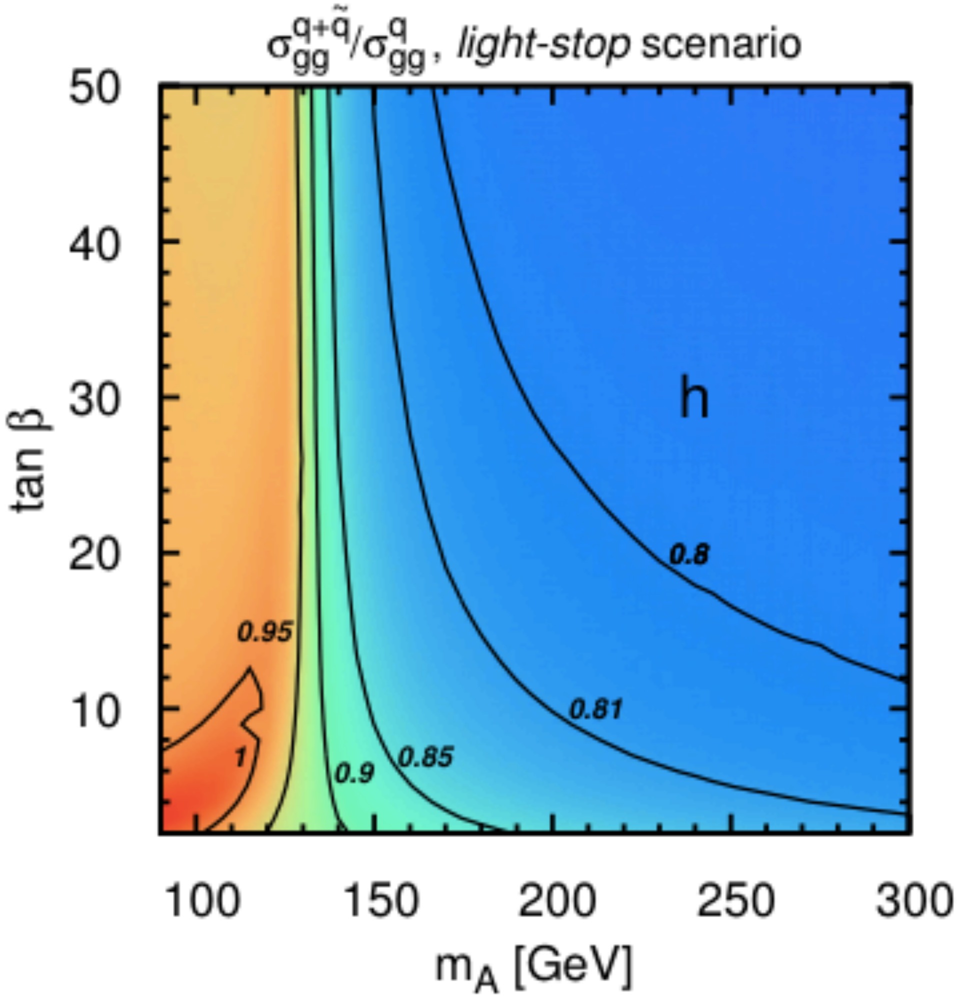


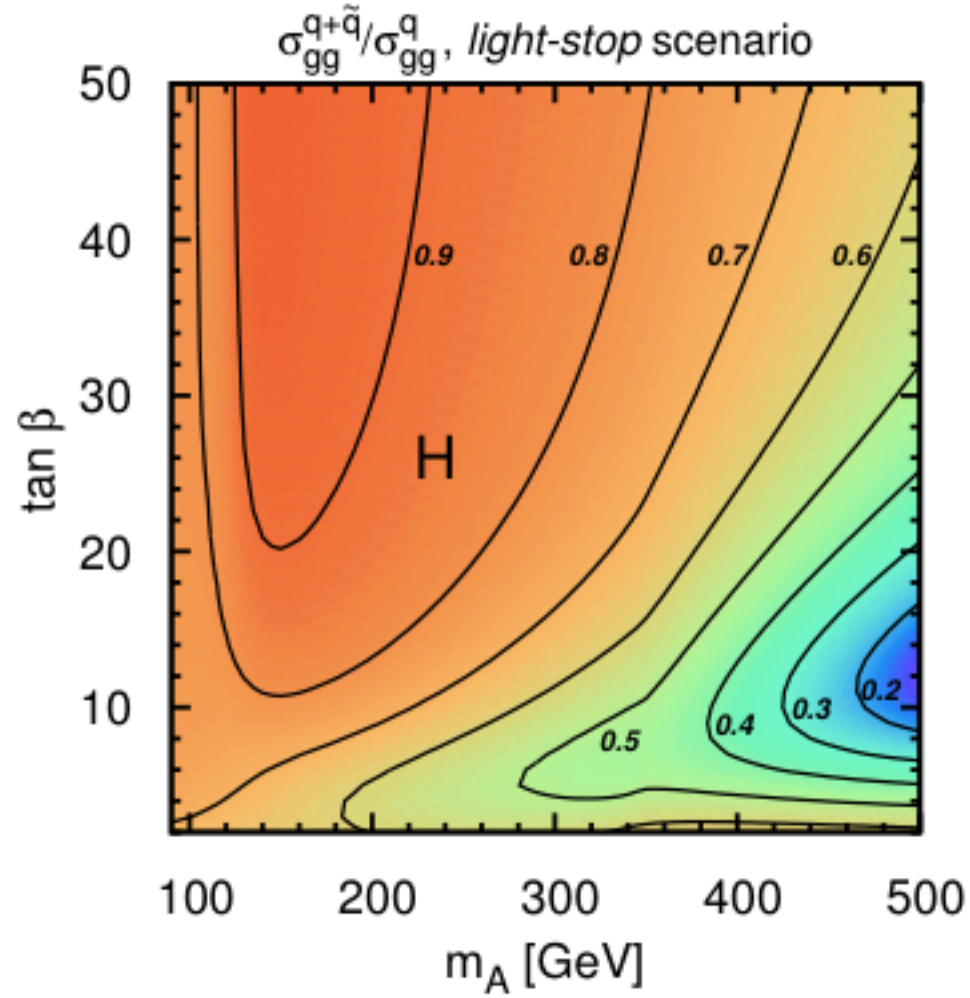


σ_{tot} [pb]



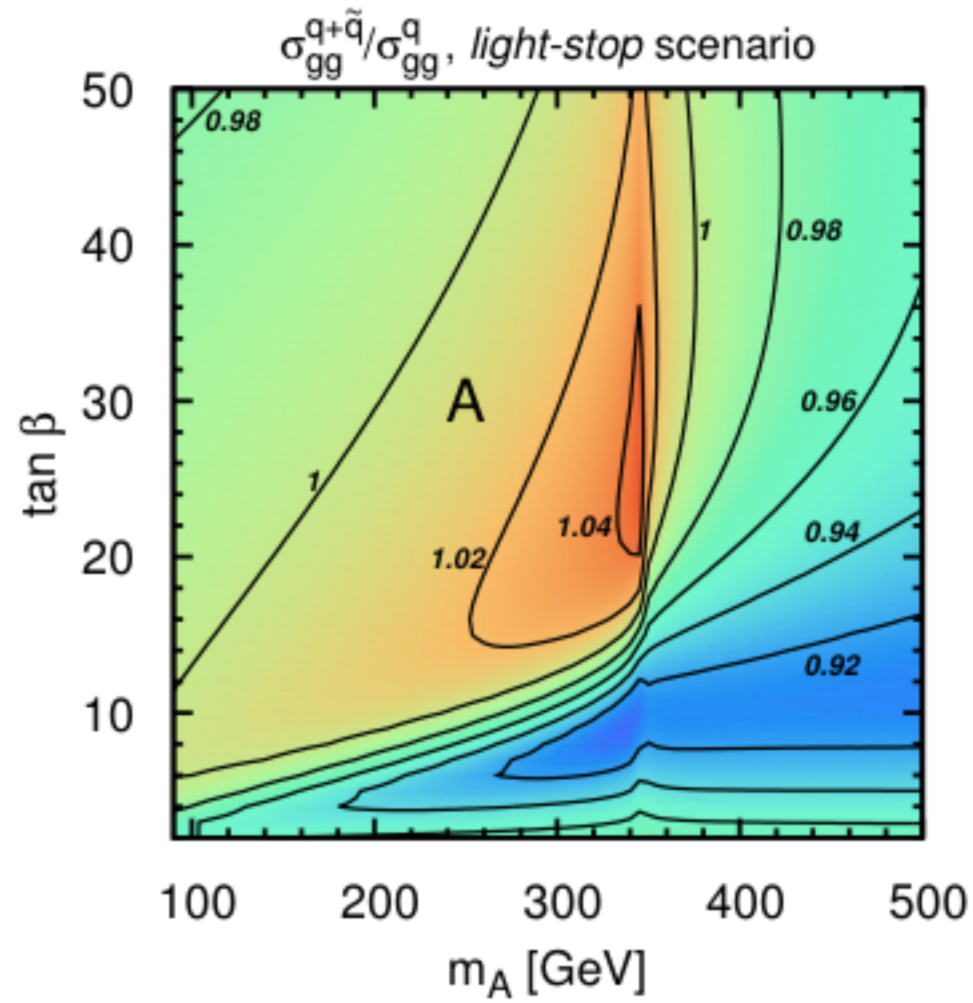
(see also new grids from LHXSWG; thanks for M. Acosta and T. Vickey)





squark effects:

$$\sigma_{gg}^{q+\tilde{q}}/\sigma_{gg}^{q}$$



Uncertainties:

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$\rightarrow$ SM-like

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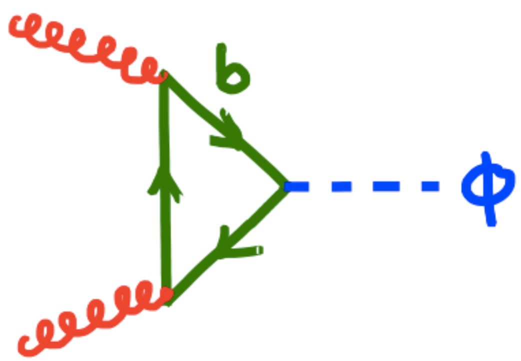

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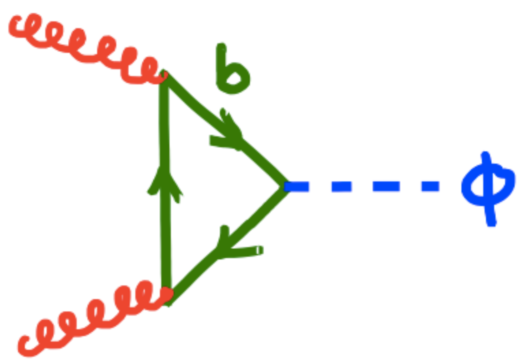

- "usual" scale choice: $\mu = M_H$
- amplitude contains logarithms $\ln(m_b/m_H)$
- partly cancelled by $\mu = m_b$ or $m_b = m_b(\text{pole})$ in Yukawa coupling

Spira, Djouadi, Graudenz, Zerwas '95

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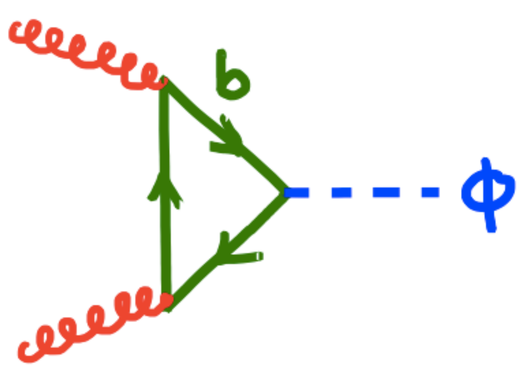

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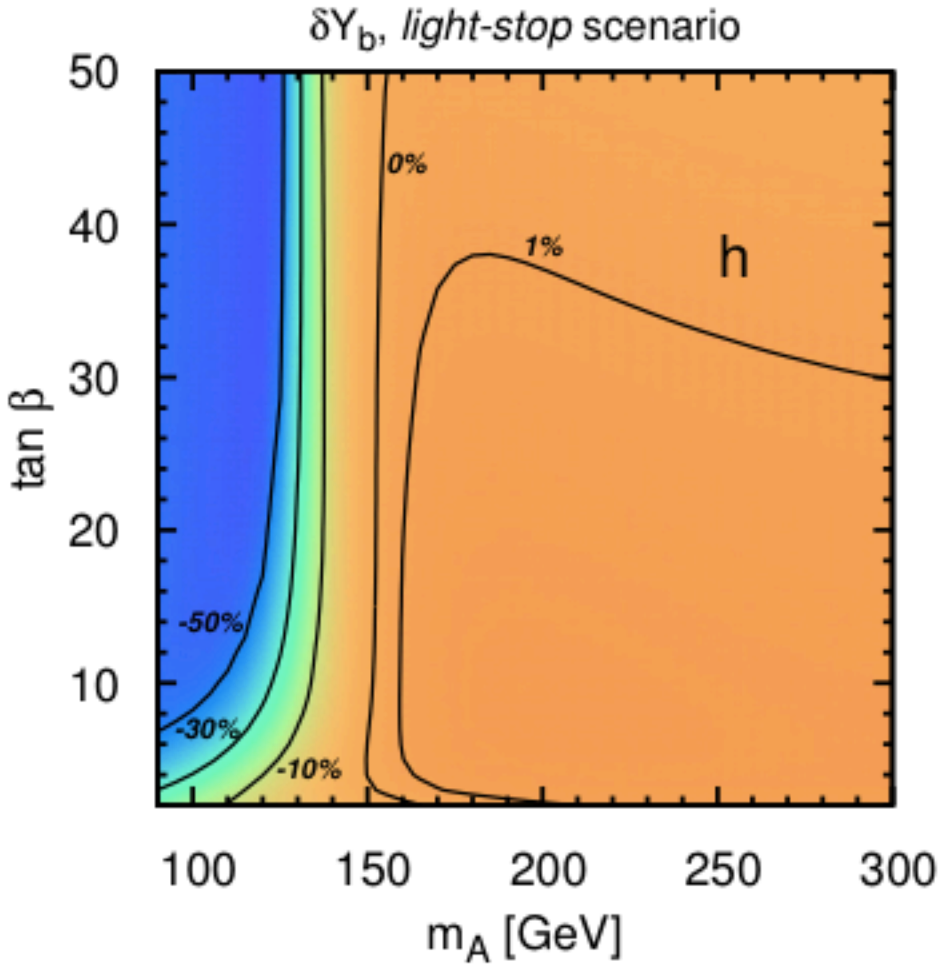
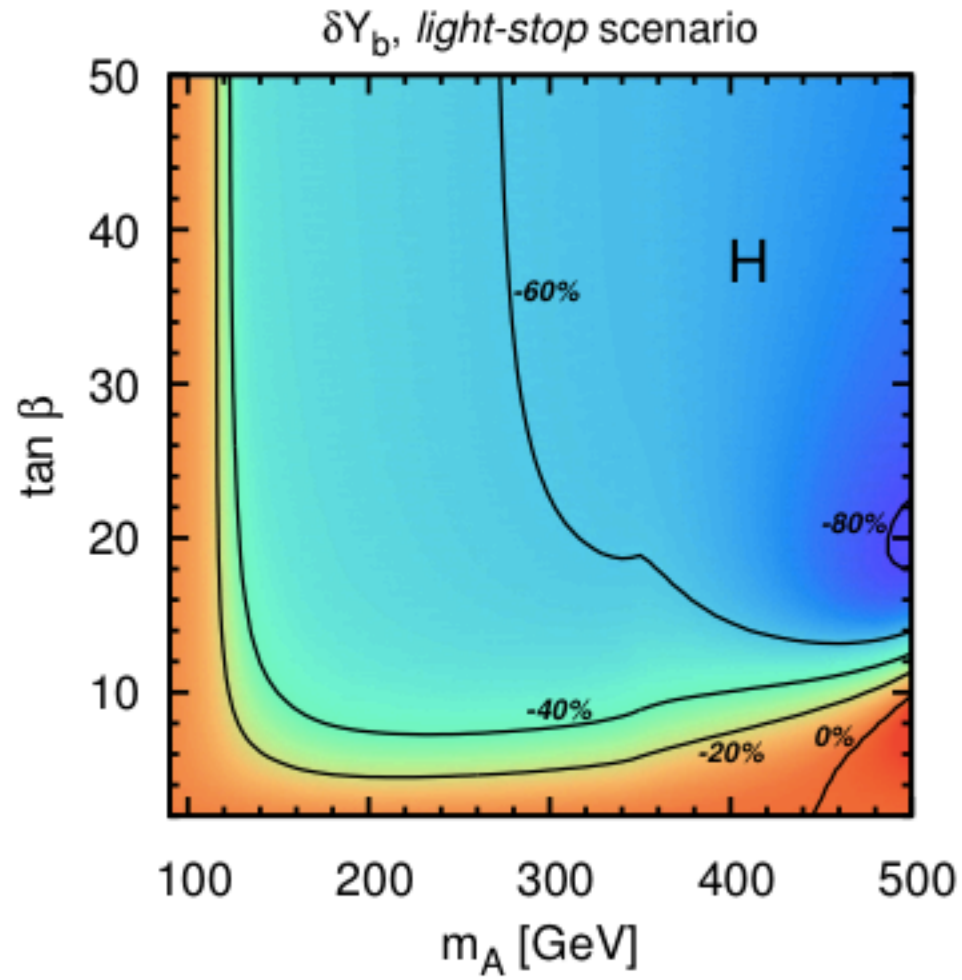
Spira, Djouadi, Graudenz, Zerwas '95

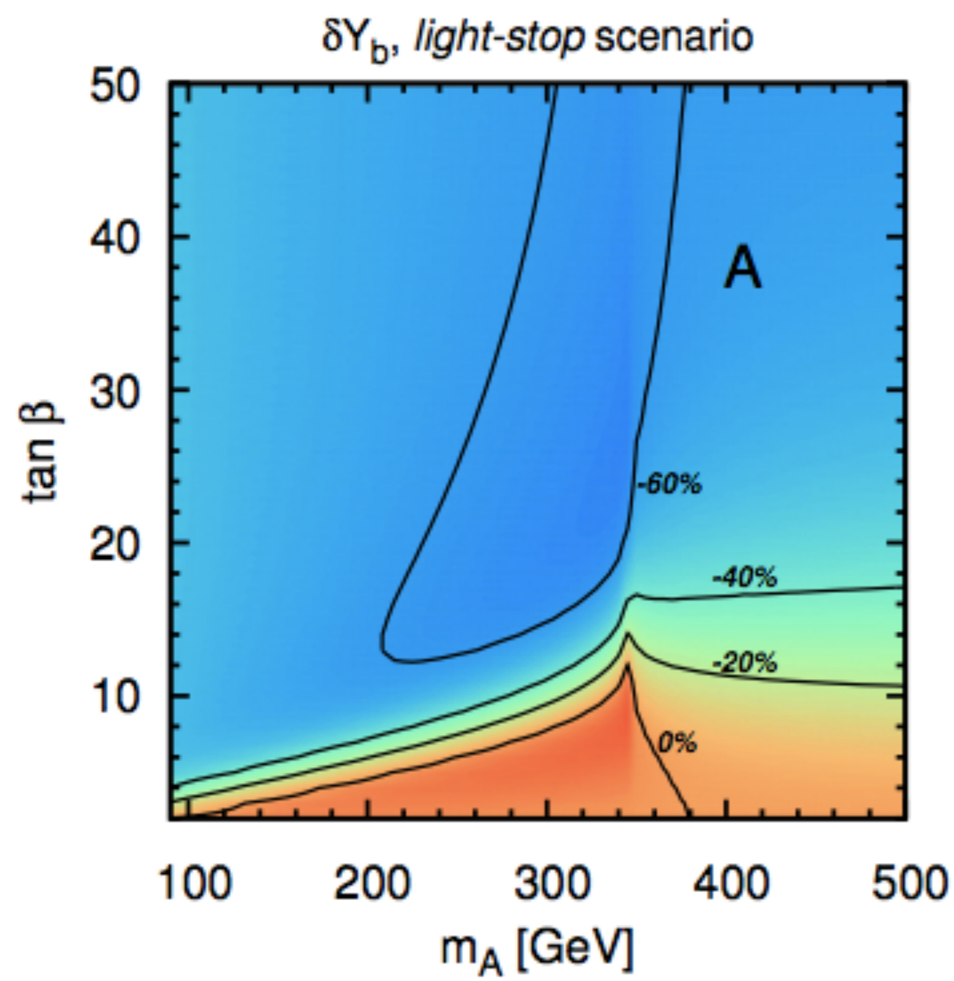
numerical effect $m_b(M_H)$ vs. $m_b(\text{pole})$ huge!





$m_b(M_H/2)$ vs. m_b(pole)

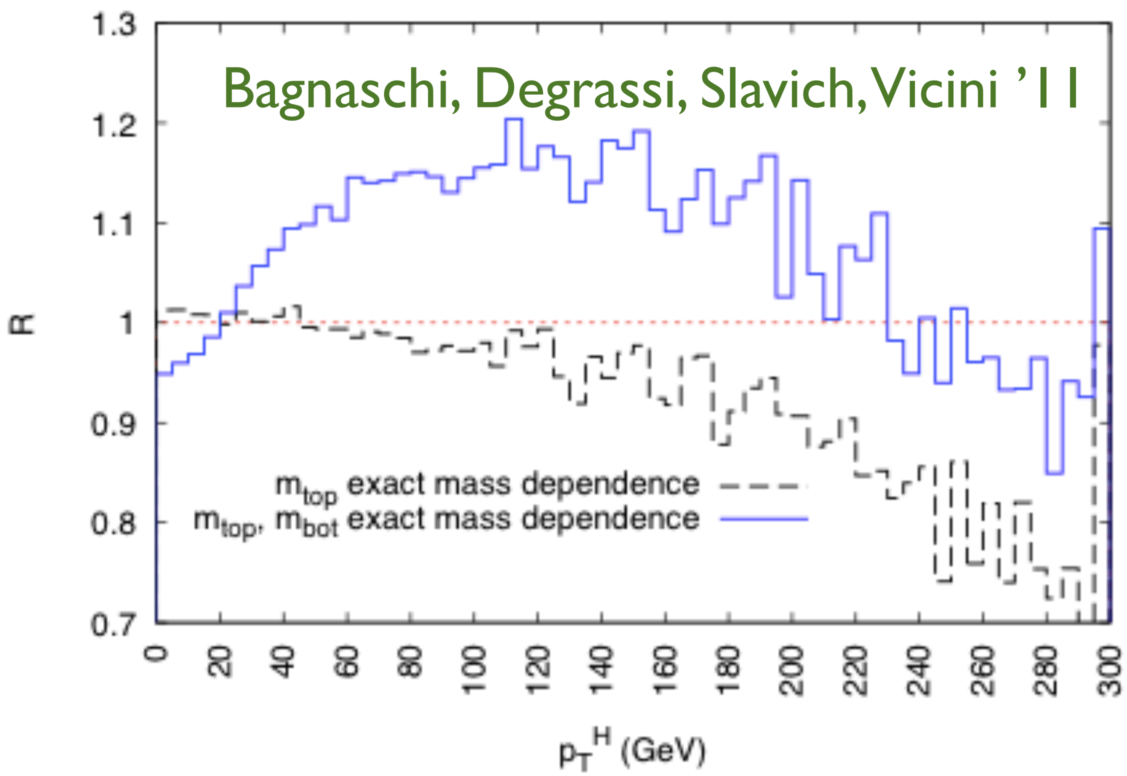
in Yukawa coupling

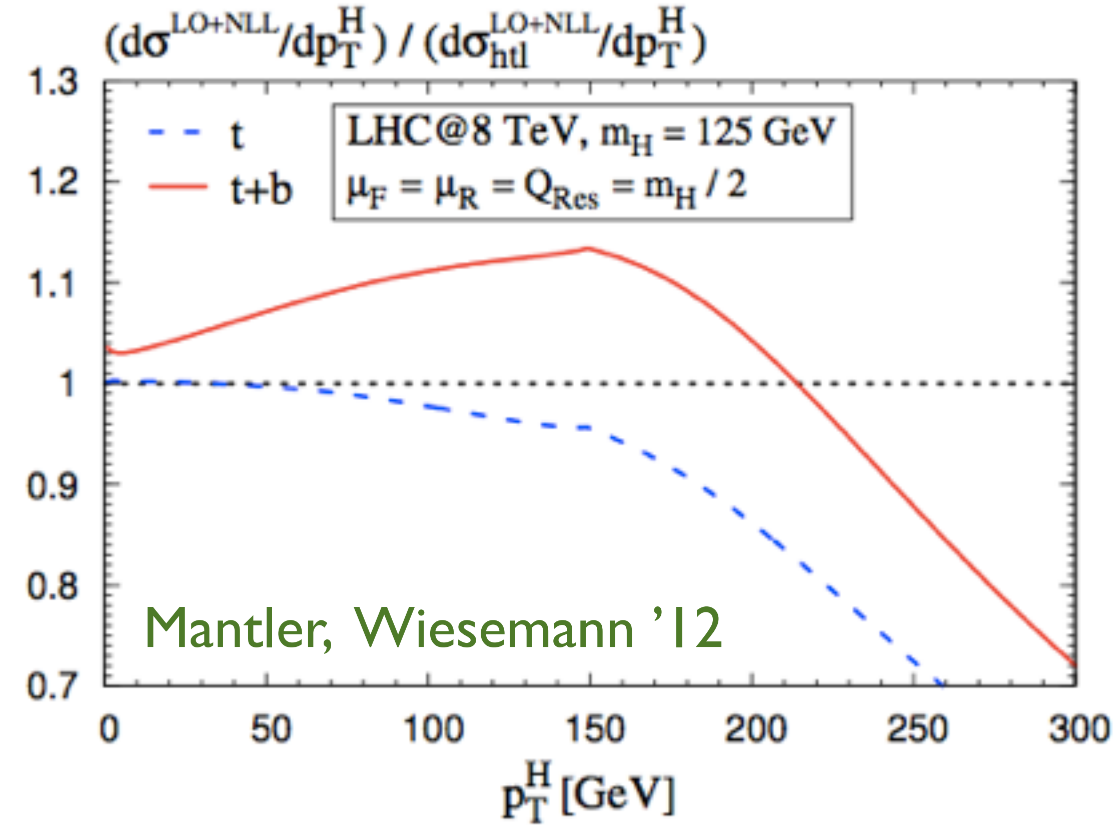


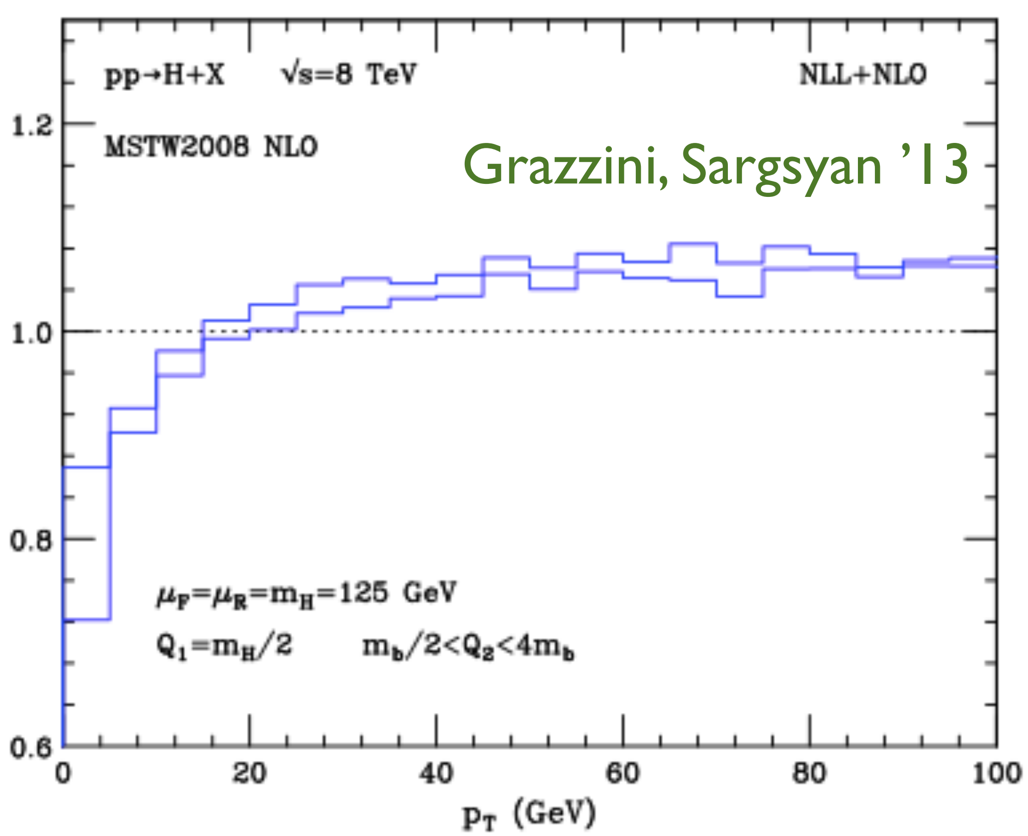
Open issues in gluon fusion:

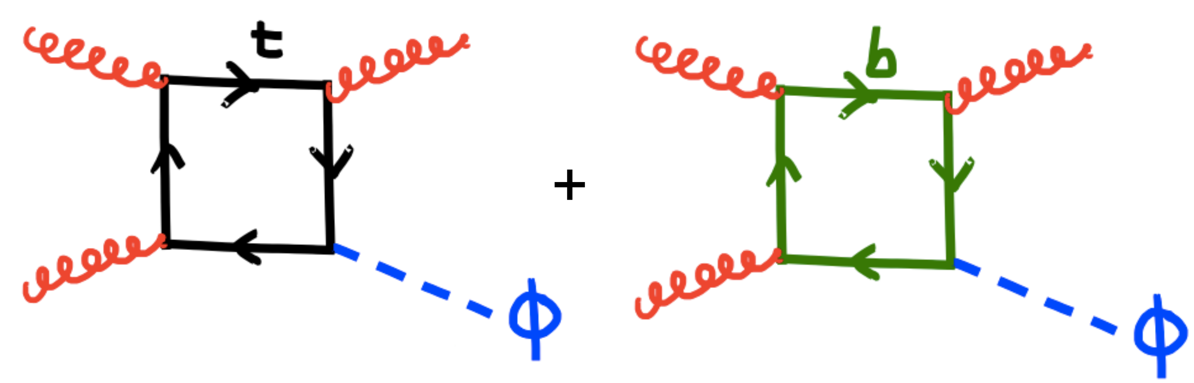
- NNLO (S)QCD only valid for heavy-top limit:
  what about M_H>350 GeV?
- SUSY EW corrections only approximately known
- proper treatment of bottom Yukawa coupling
- bottom effects in p_T distribution

Transverse momentum:









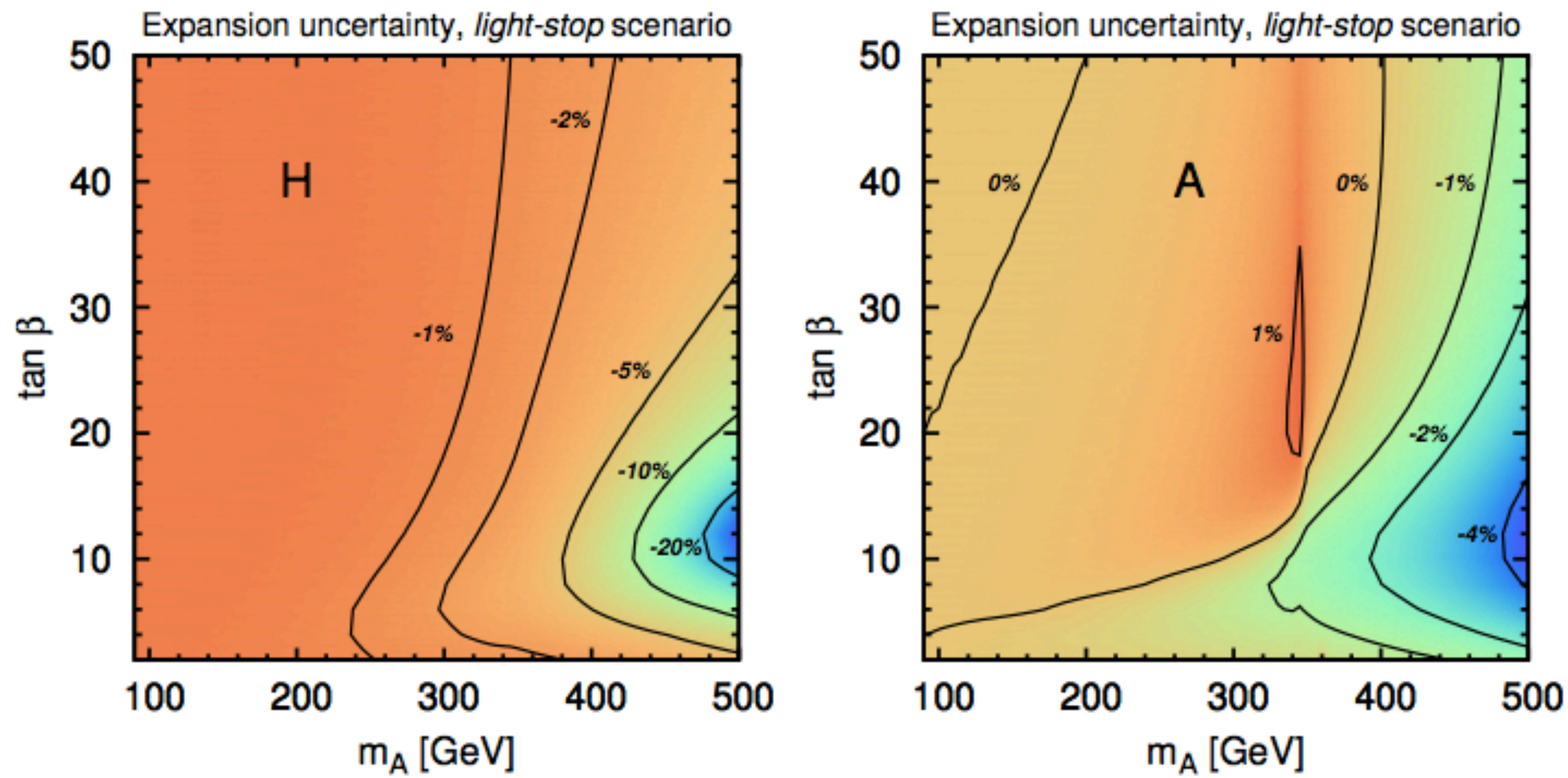
see also: Banfi, Monni, Zanderighi '14

What I could not talk about:

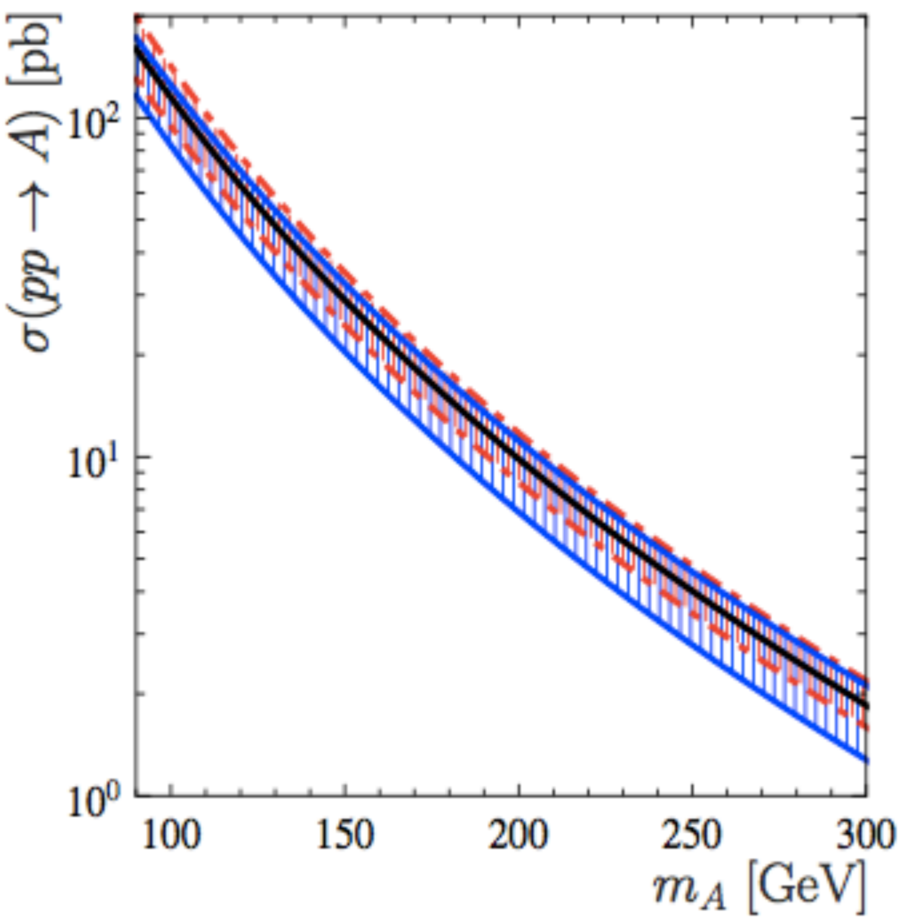
- pure SM calculations
- double Higgs production
- transverse momentum in bbh
- SUSY effects in ggh p_T
- ....

Conclusions

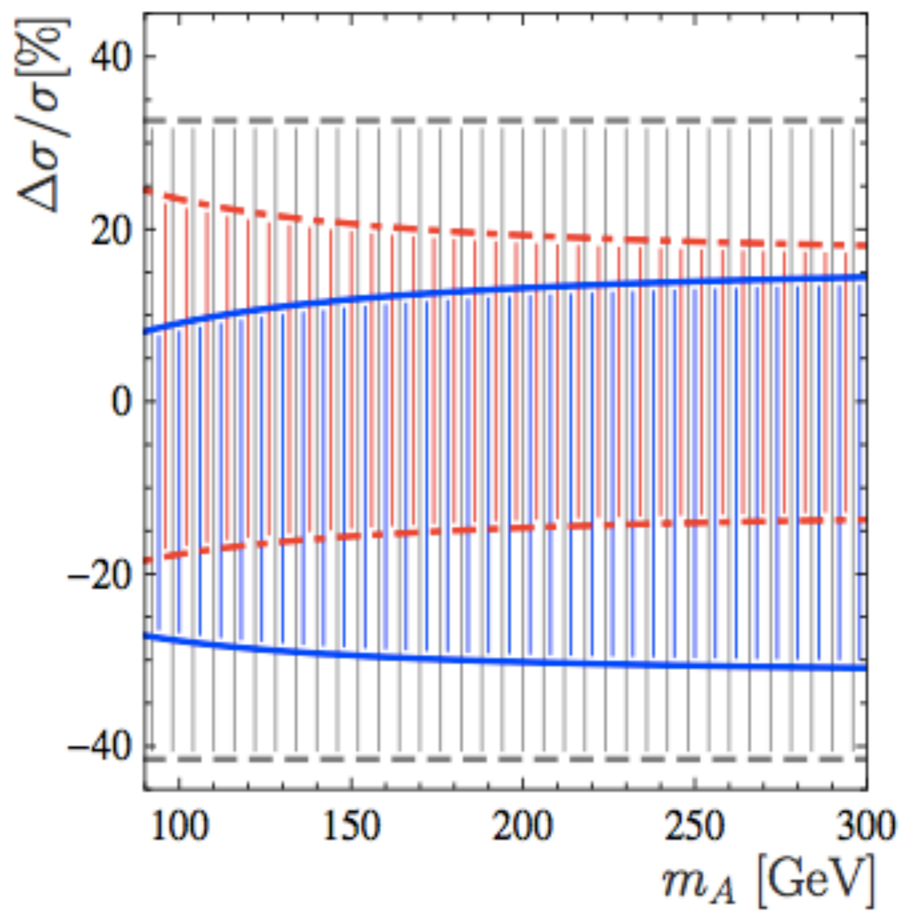
- many SM results trivially applicable
- dedicated SUSY cross section predictions require fast and flexible tools
  ➜ SusHi for gluon fusion
- 4FS vs. 5FS (6FS??) may become very relevant
- next steps: differential quantities



Expansion uncertainty, light-stop scenario
H
-1%
-2%
-5%
-10%
-20%
tan β
m_A [GeV]
Expansion uncertainty, light-stop scenario
A
0%
0%
-1%
1%
-2%
-4%
tan β
m_A [GeV]



$\sigma(pp \to A)$ [pb]
10^2
10^1
10^0
100
150
200
250
300
m_A [GeV]



$\Delta\sigma/\sigma[\%]$
40
20
0
−20
−40
100
150
200
250
300
m_A [GeV]