SUSY Higgs cross sections

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Bergische Universität Wuppertal

SUSY 2014 (Manchester, UK)

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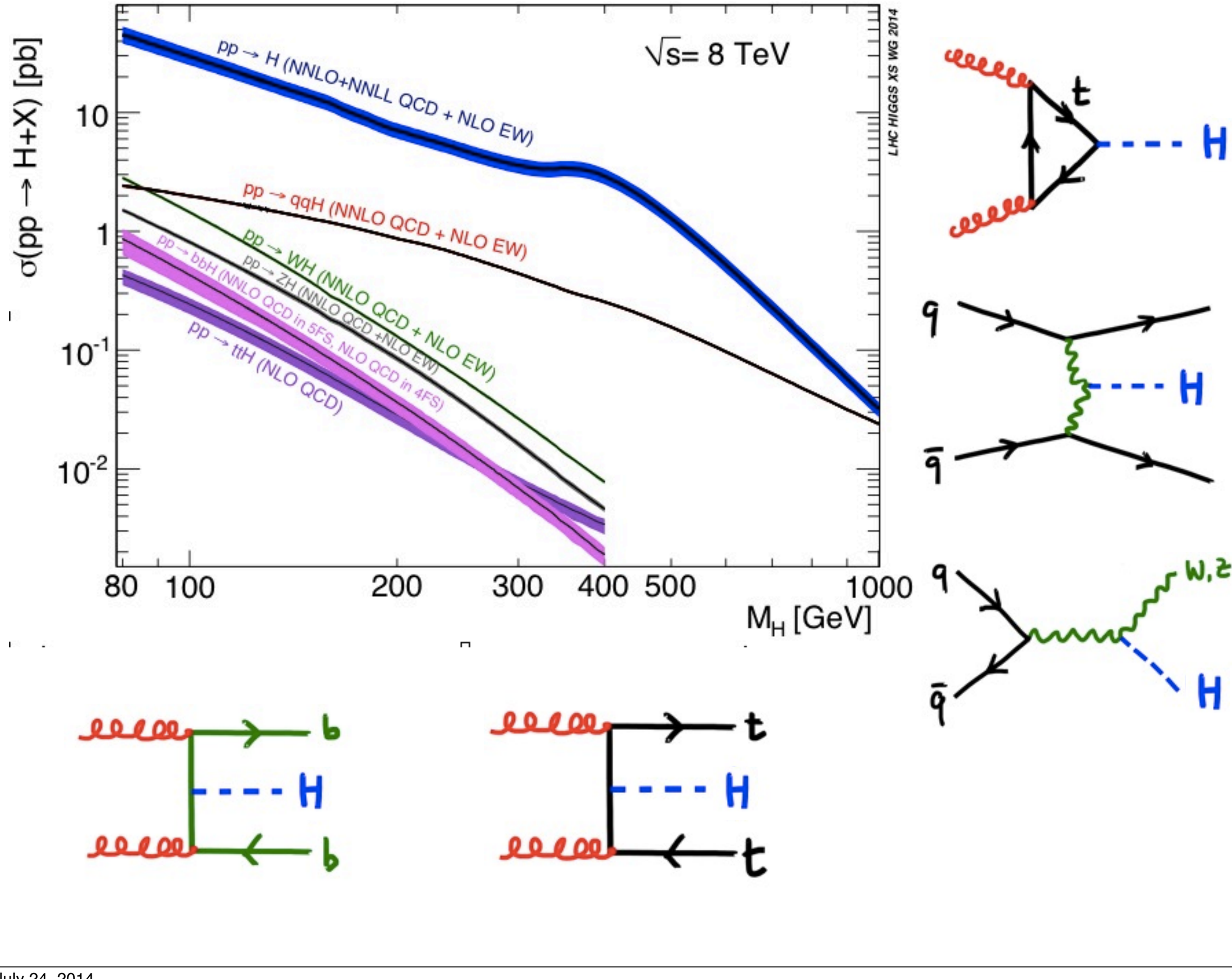
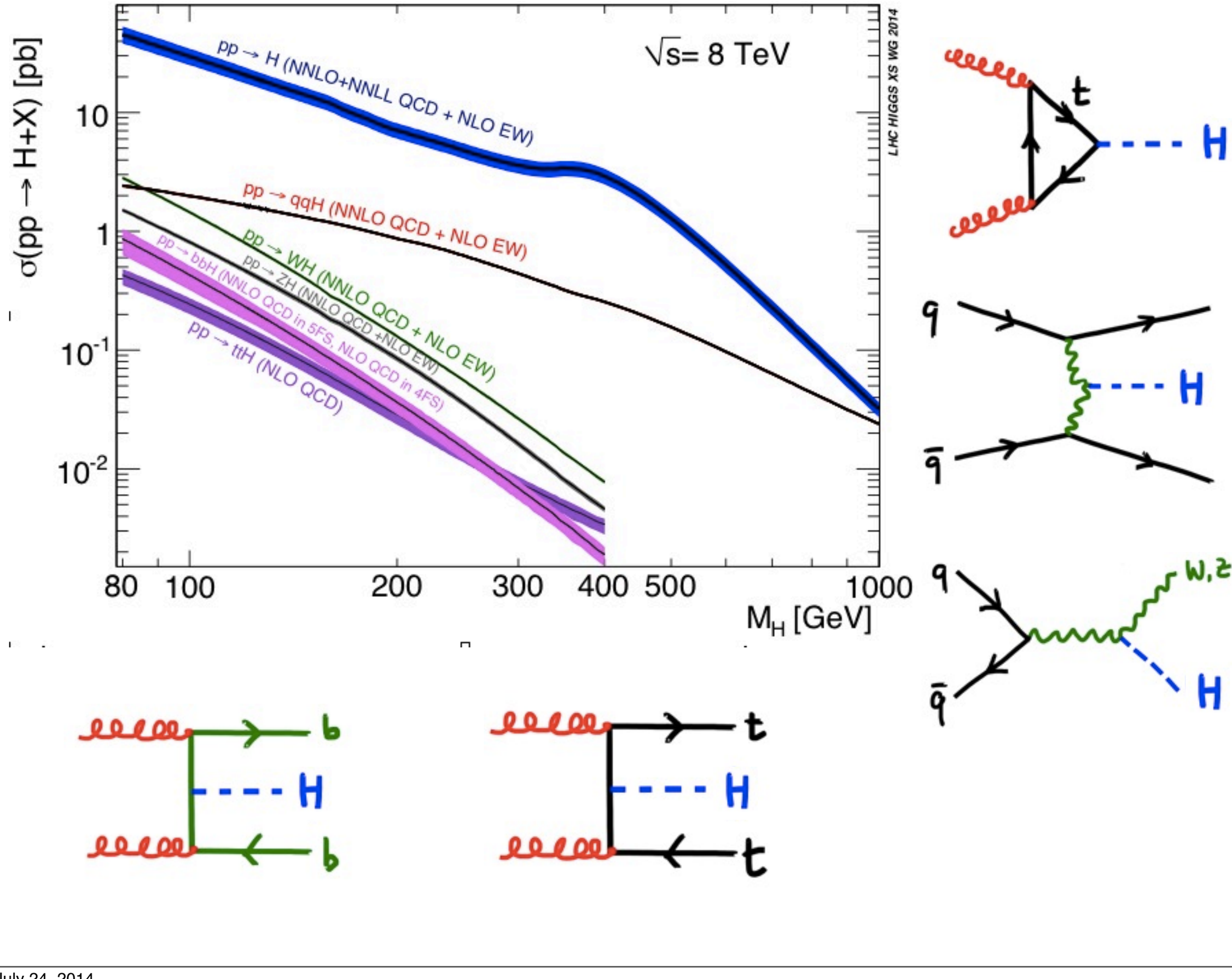
PHYSICS AT THE TERA SCALE Helmholtz Alliance


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

SUSY effects

SUSY effects

- rescaling of couplings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H
b
H
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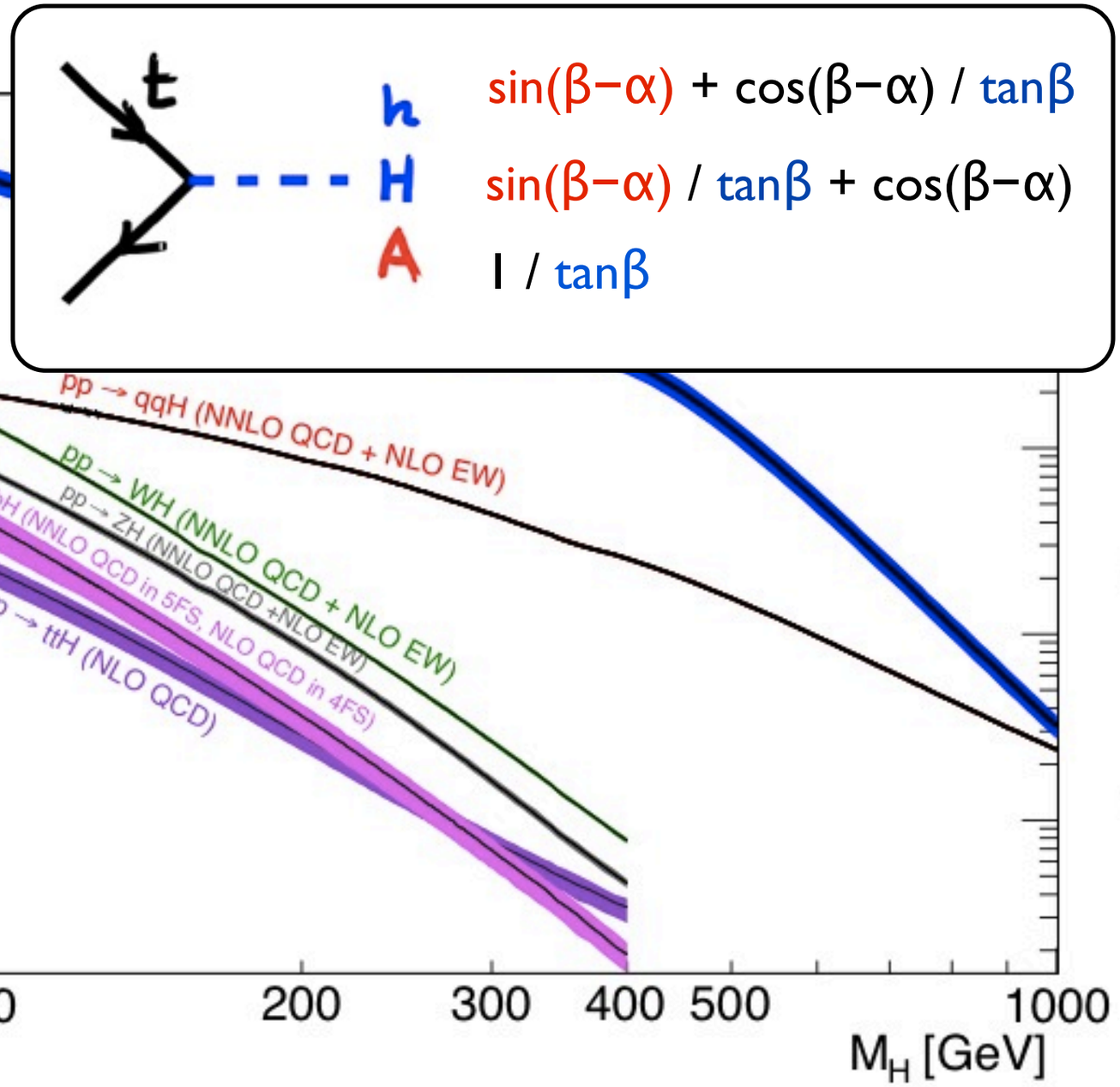
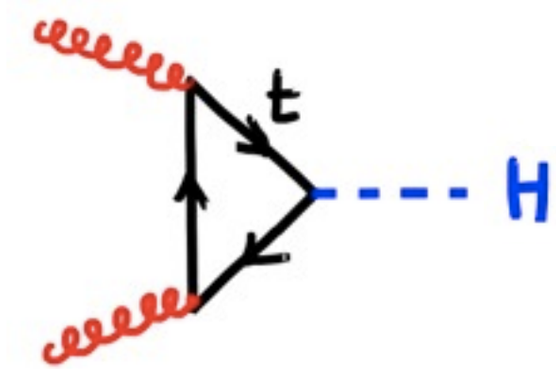
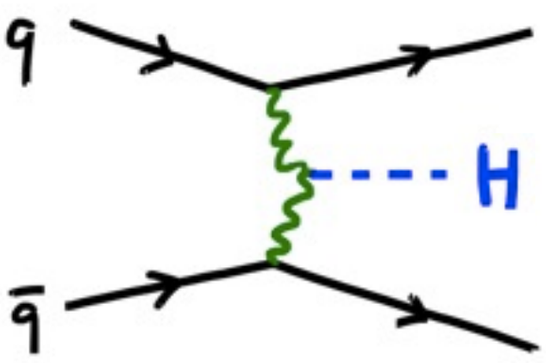
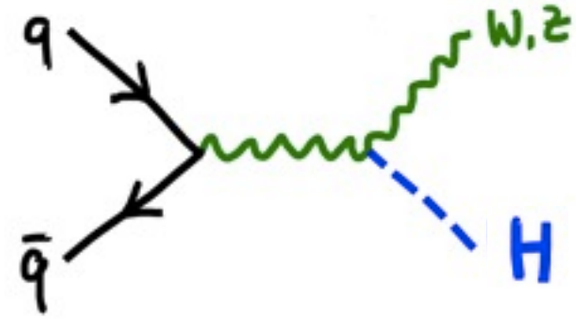
t
H
t

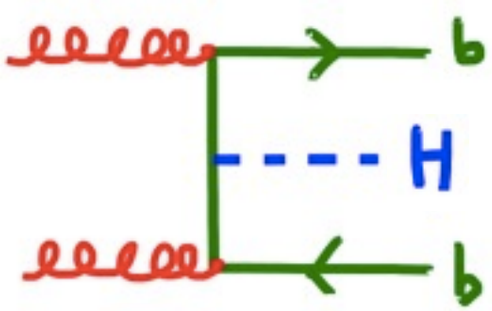

t
h
H
A
sin(β−α) + cos(β−α) / tanβ
sin(β−α) / tanβ + cos(β−α)
1 / tanβ

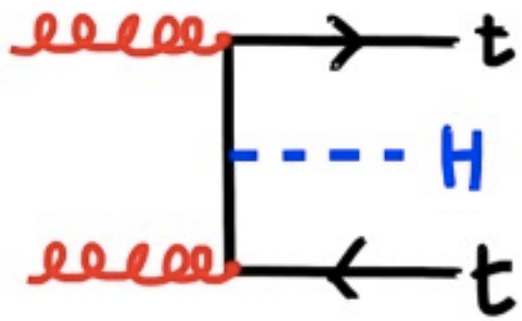
σ(pp → H+X) [pb]
10
1
10⁻¹
10⁻²
pp → qqH (NNLO QCD + NLO EW)
pp → WH (NNLO QCD + NLO EW)
pp → ZH (NNLO QCD +NLO EW)
pp → bbH (NNLO QCD in 5FS, NLO QCD in 4FS)
pp → ttH (NLO QCD)
80
100
200
300
400
500
1000
M_H [GeV]

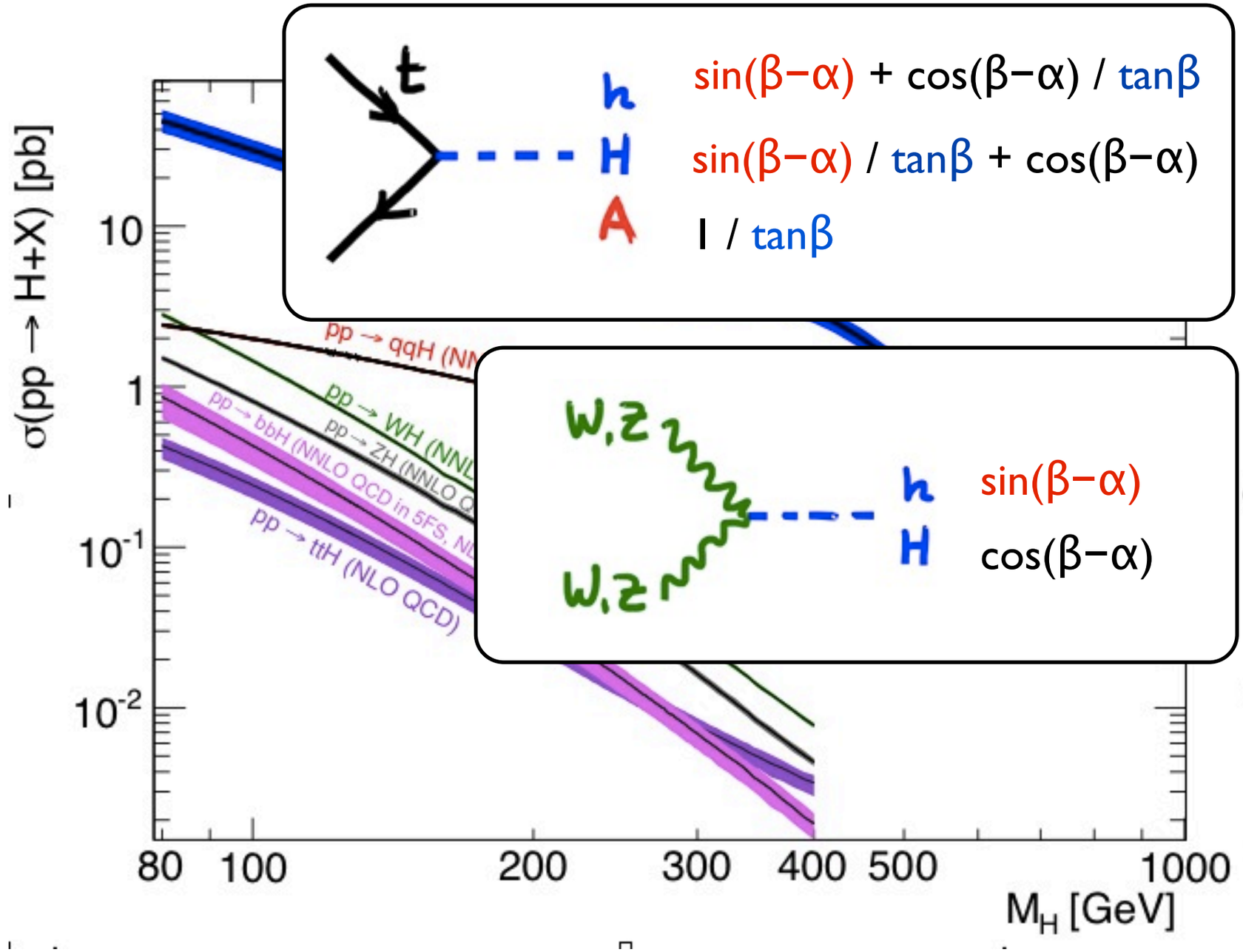

t
H


q
q̄
H


q
q̄
W,Z
H


b
H
b


t
H
t


σ(pp → H+X) [pb]
10
1
10⁻¹
10⁻²
pp → qqH (NN
pp → WH (NNL
pp → ZH (NNLO Q
pp → bbH (NNLO QCD in 5FS, NL
pp → ttH (NLO QCD)
80
100
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M_H [GeV]

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h
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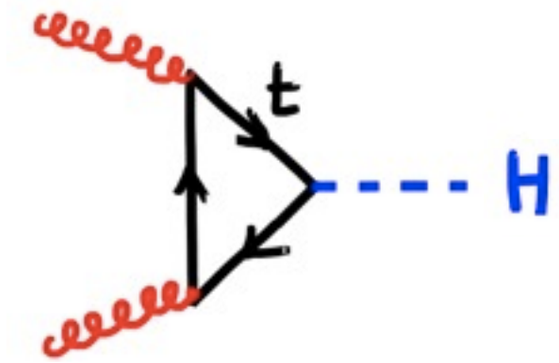
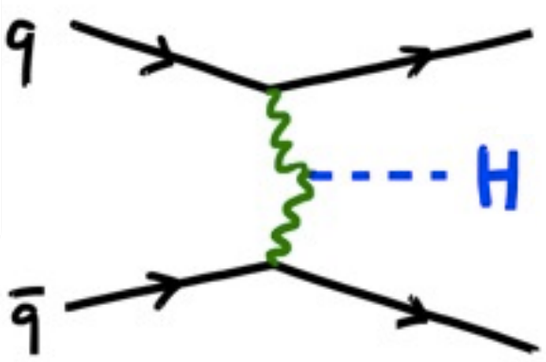
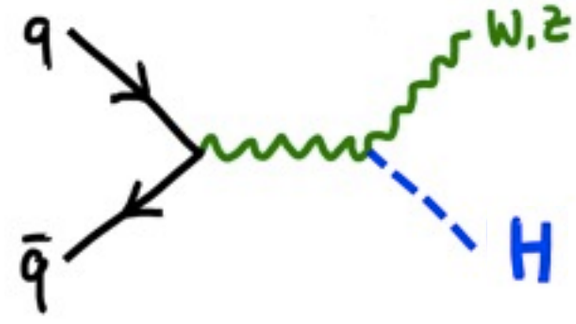
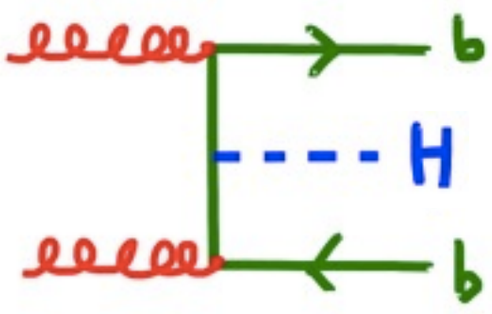
A
sin(β−α) + cos(β−α) / tanβ
sin(β−α) / tanβ + cos(β−α)
1 / tanβ

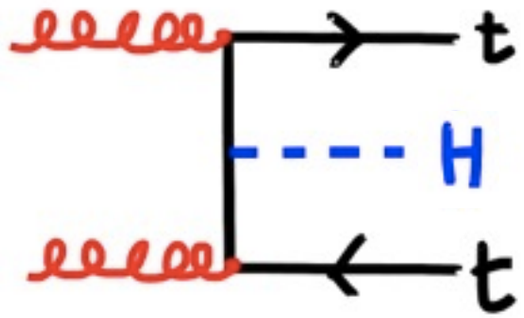
W,Z
W,Z
h
H
sin(β−α)
cos(β−α)

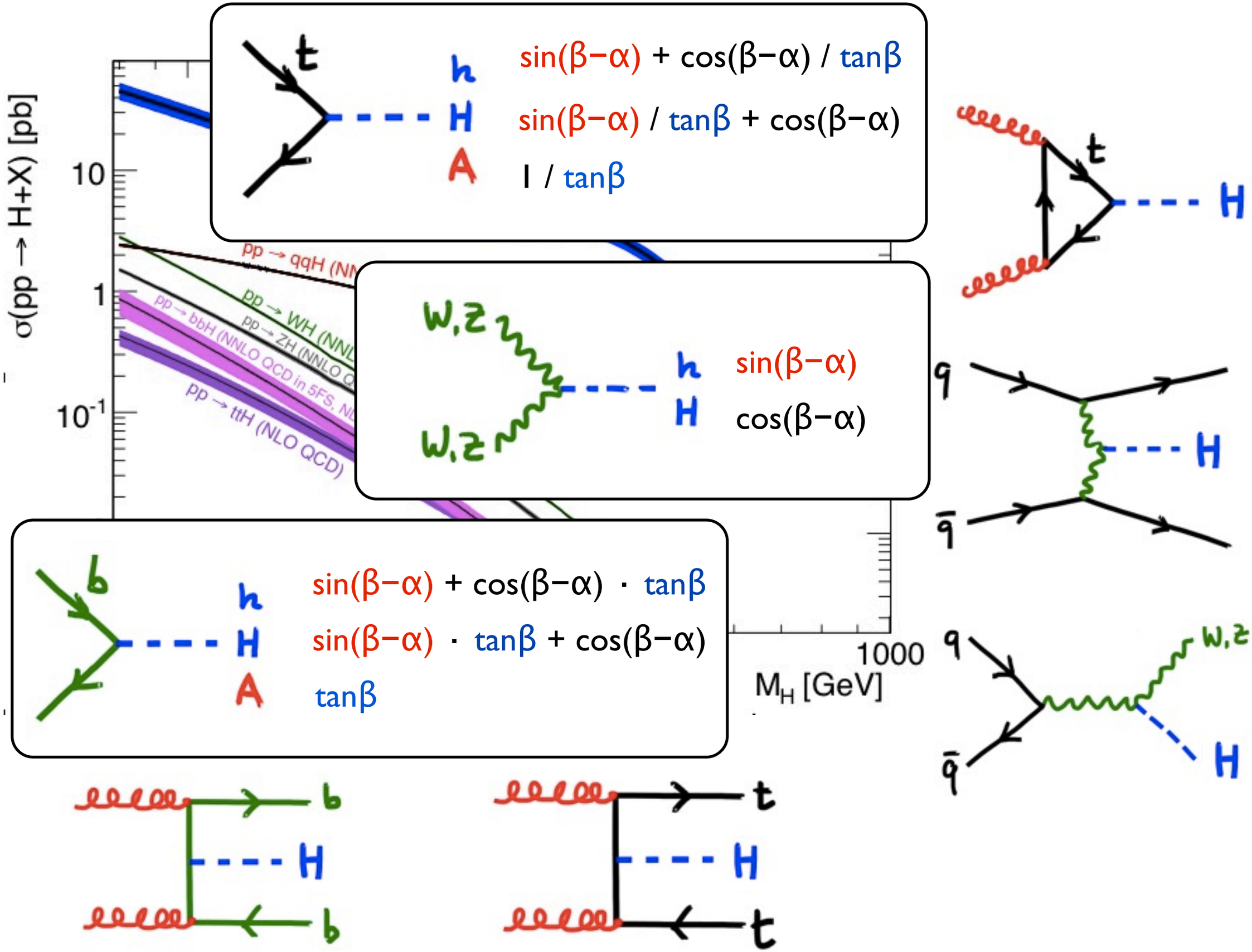

t
H


q
q̄
H


q
q̄
W,Z
H


b
H
b


t
H
t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1 / tanβ
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

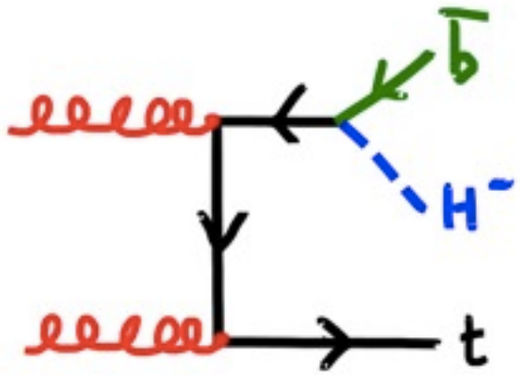
SUSY effects

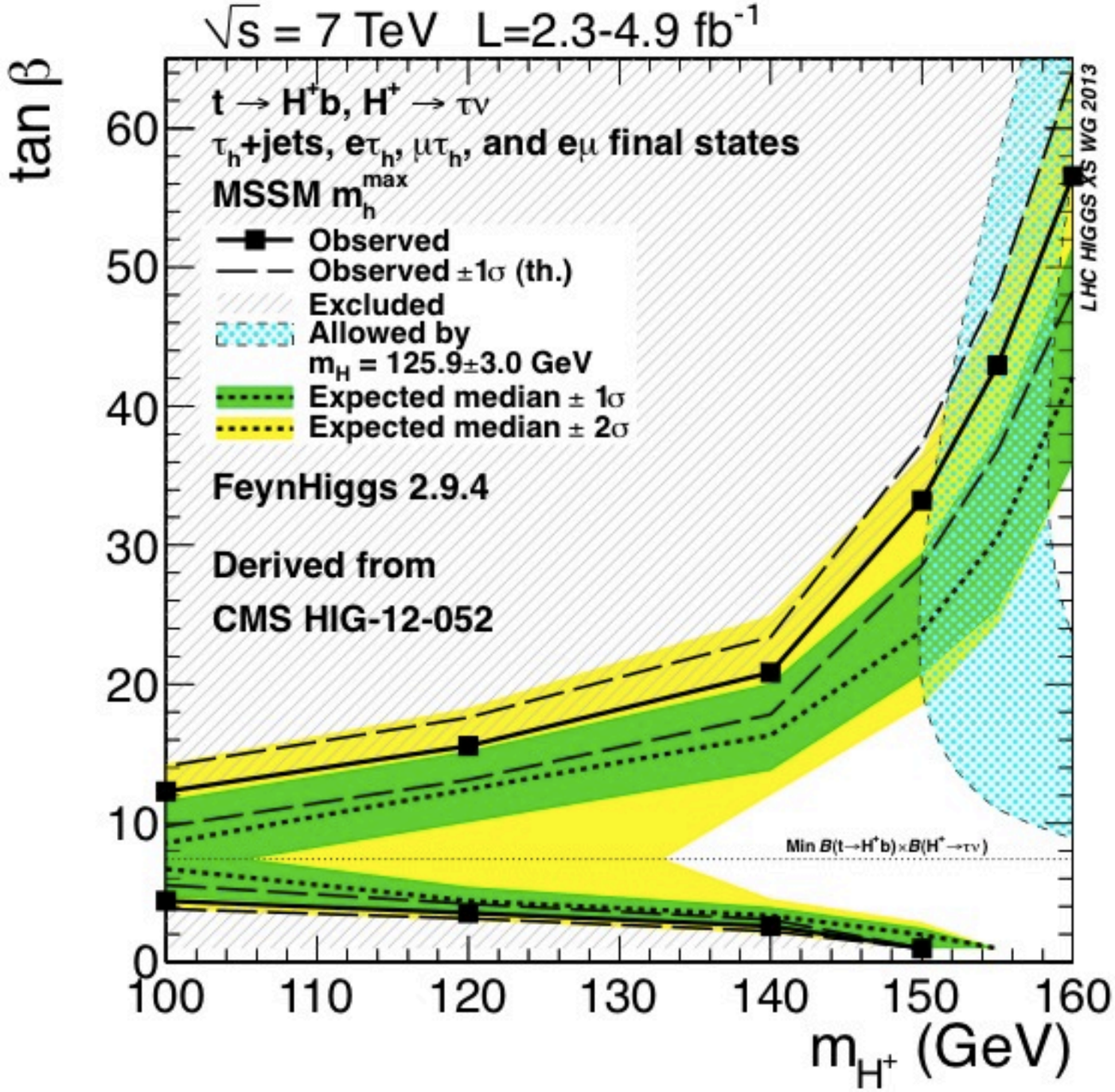
- rescaling of couplings

SUSY effects

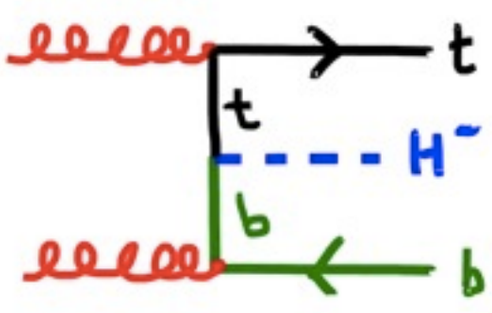
- rescaling of couplings
- new Higgs bosons

Light $H^{\pm}$

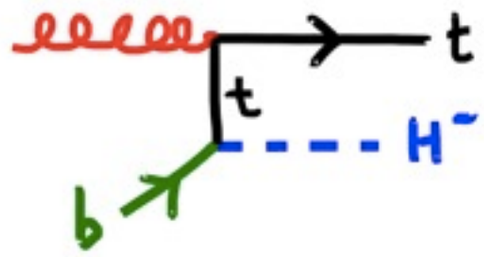

b
H⁻
t


√s = 7 TeV L=2.3-4.9 fb⁻¹
tan β
t → H⁺b, H⁺ → τν
τh+jets, eτh, μτh, 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)

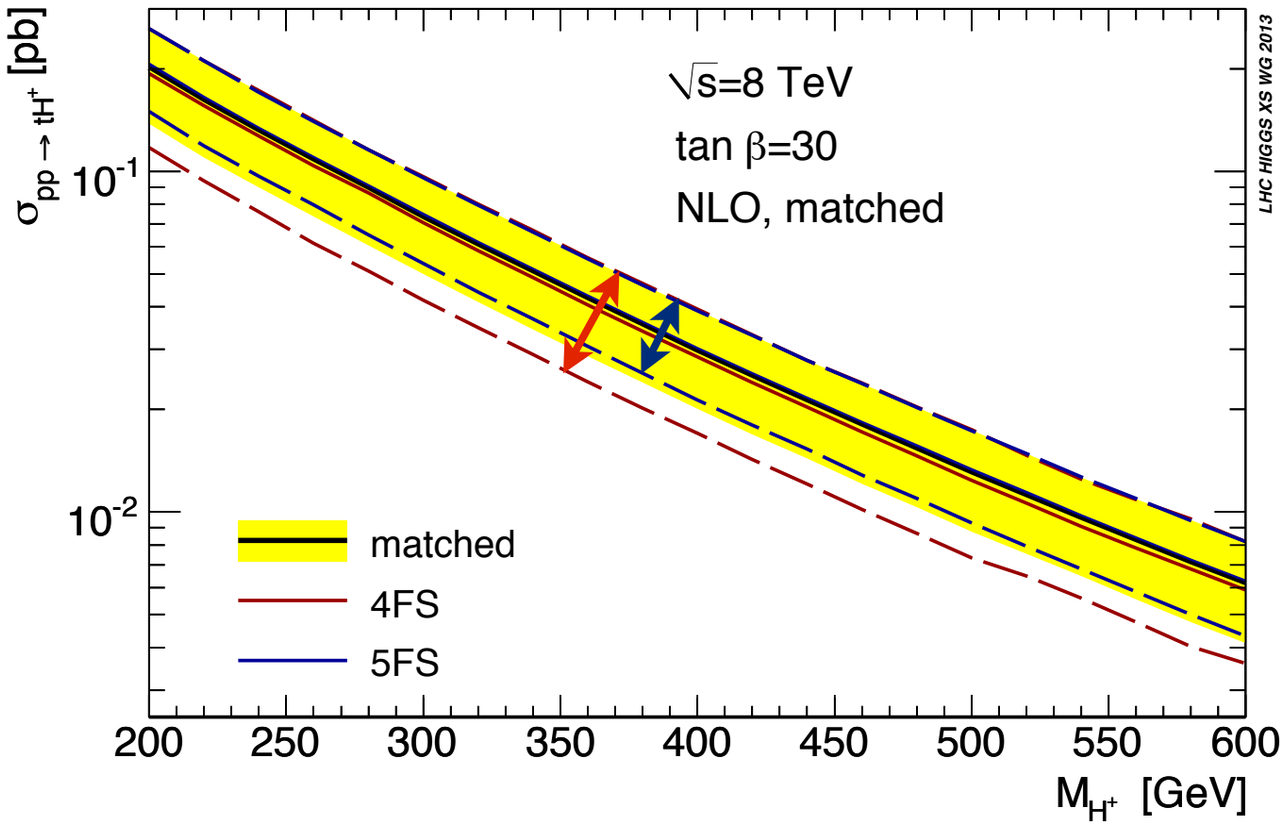
Heavy $H^{\pm}$



4-flavor scheme
(4FS)



5-flavor scheme
(5FS)



Heavy $H^{\pm}$

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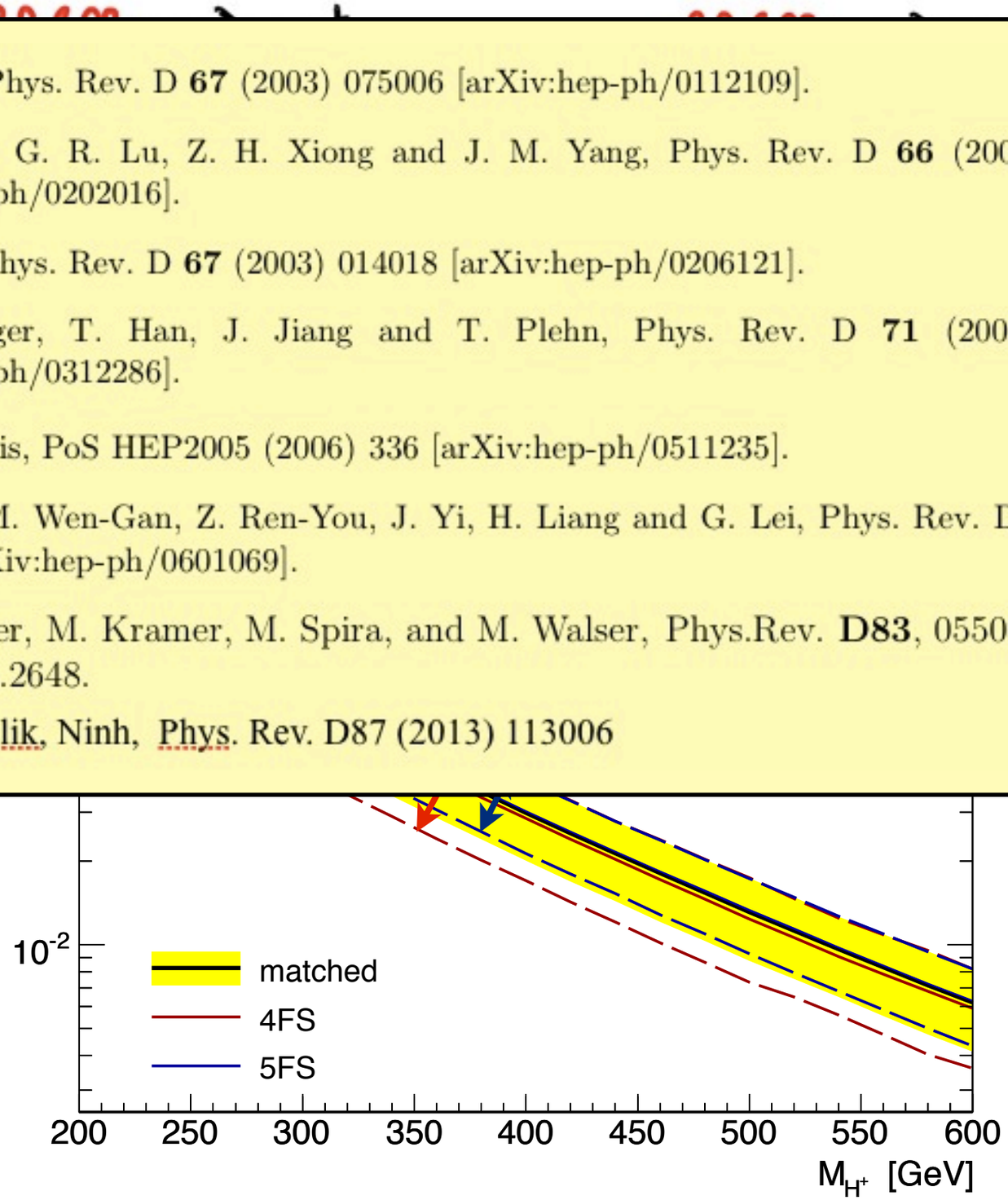
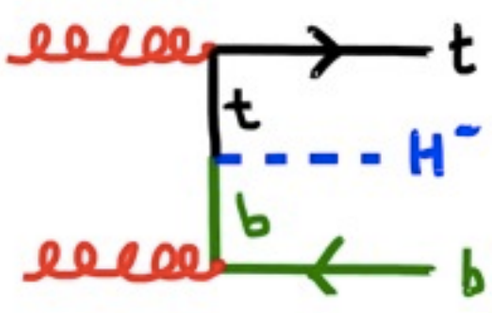
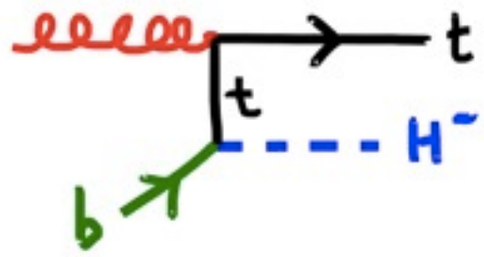


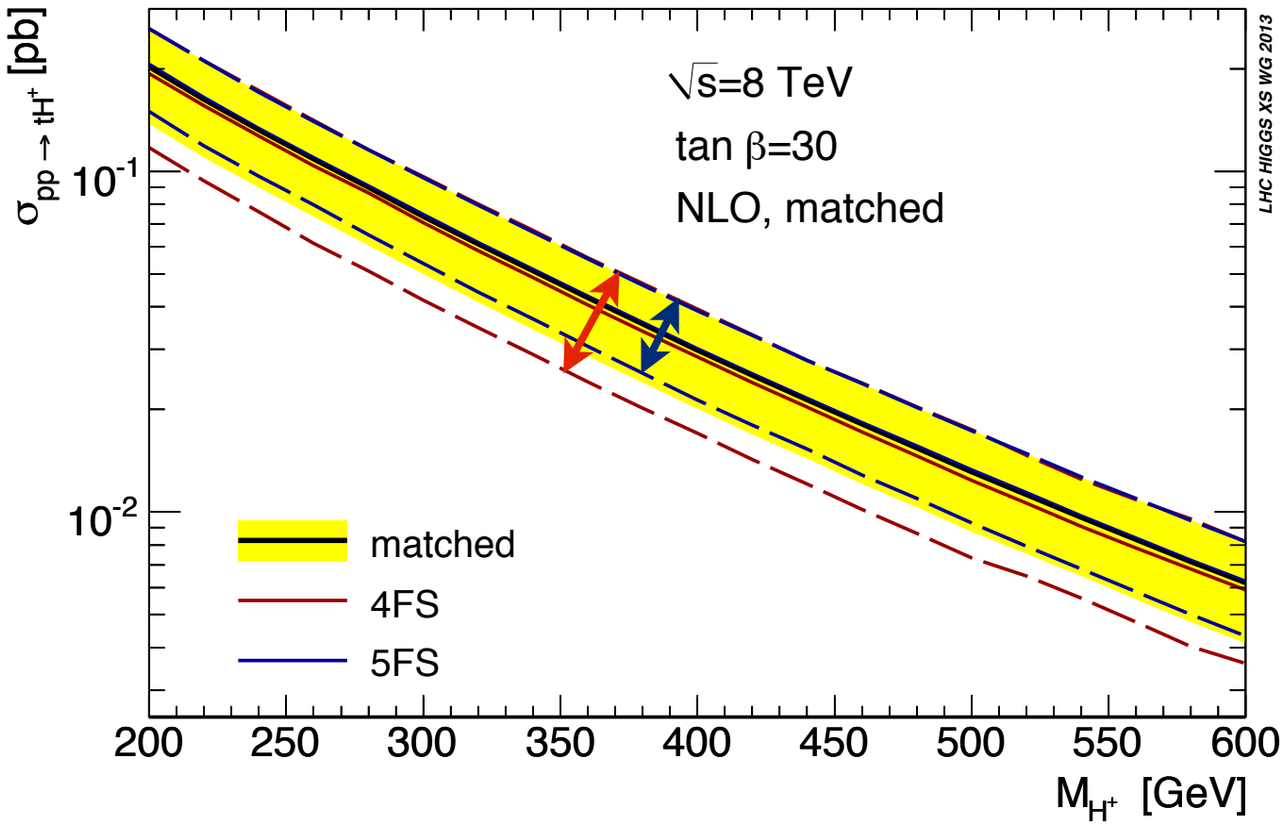
Heavy $H^{\pm}$



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

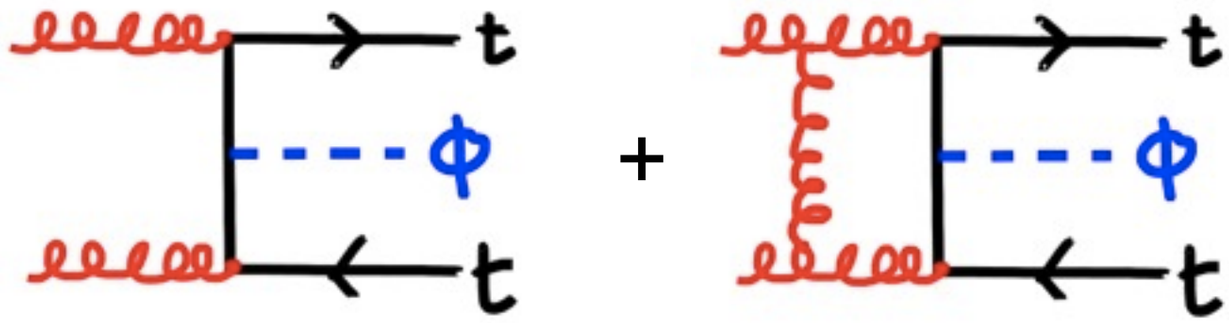
SUSY particle effects:

in radiative corrections:

SUSY particle effects:

in radiative corrections:

+20-30%

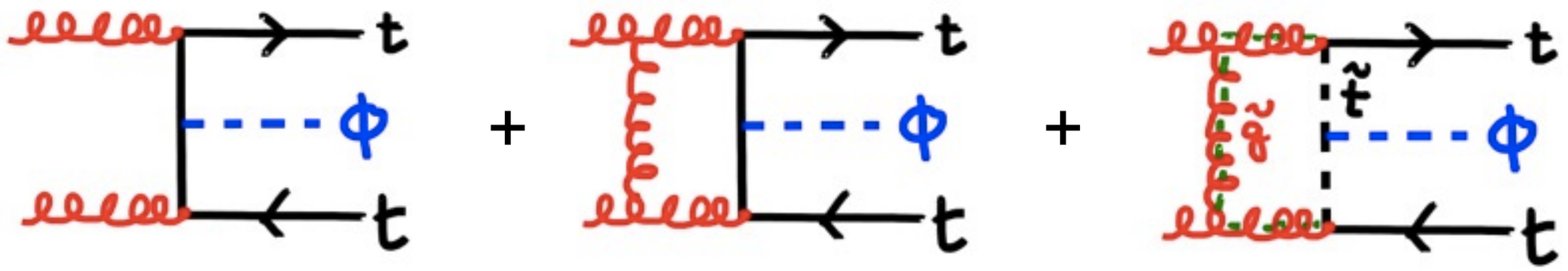


SUSY particle effects:

in radiative corrections:

+20-30%

−20-30%

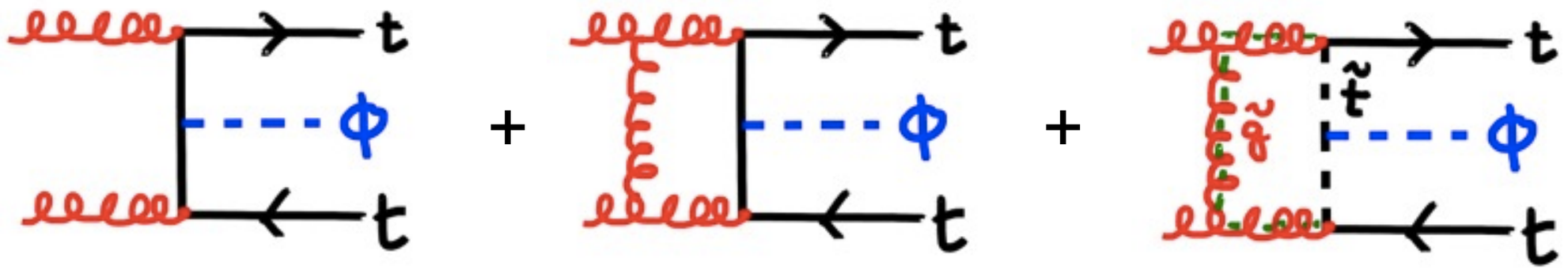


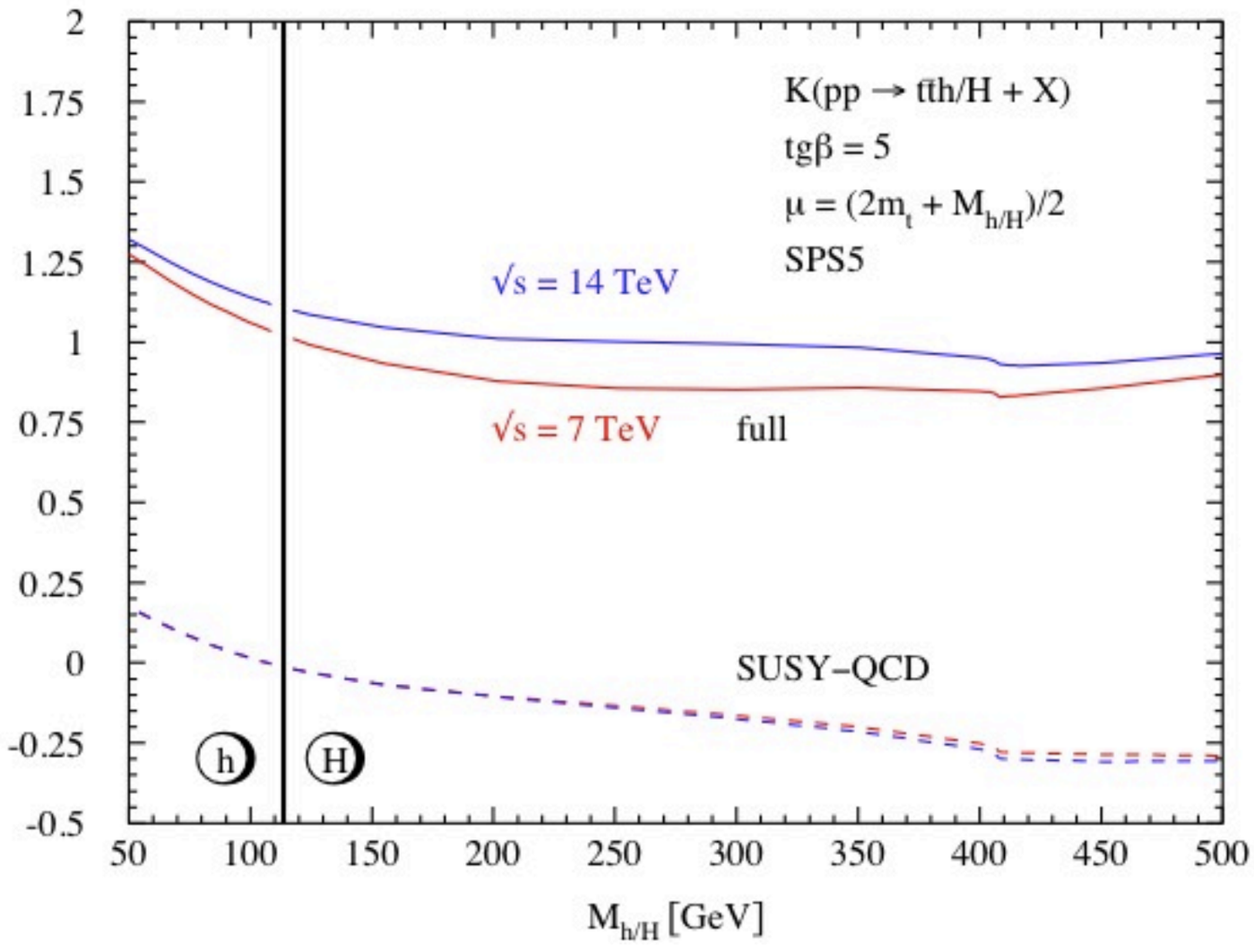
SUSY particle effects:

in radiative corrections:

+20-30%

−20-30%





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

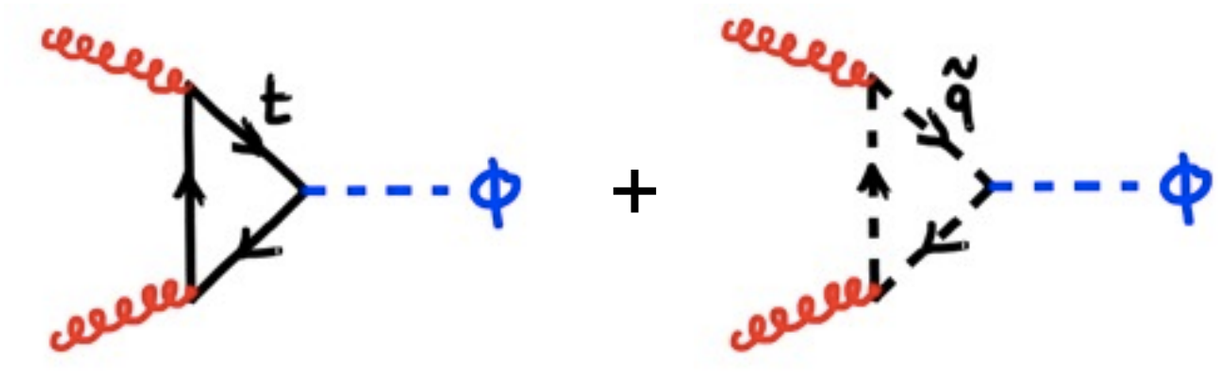
- rescaling of couplings
- new Higgs bosons
- SUSY particle effects
  - ★ in radiative corrections
  - ★ at leading order

SUSY particle effects:

at leading order:

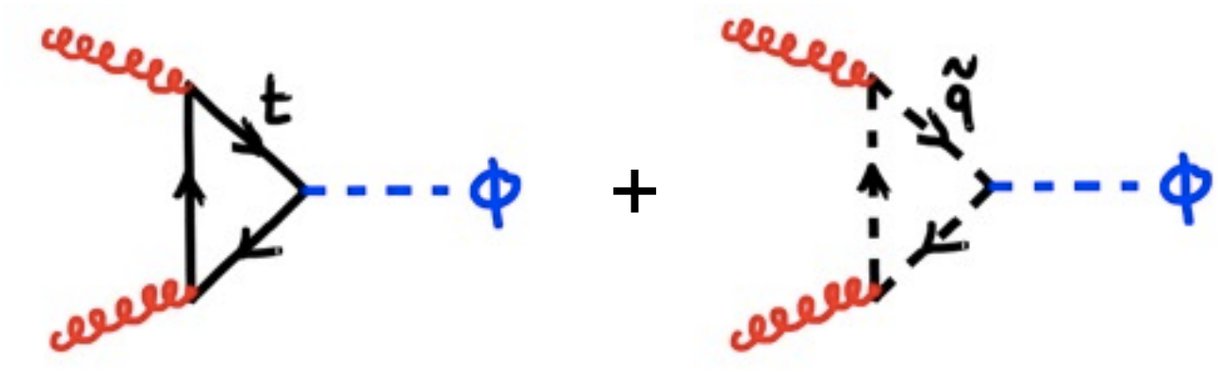
SUSY particle effects:

at leading order:



SUSY particle effects:

at leading order:



can interfere distructively (gluophobic Higgs)

(see later)

Djouadi ’98

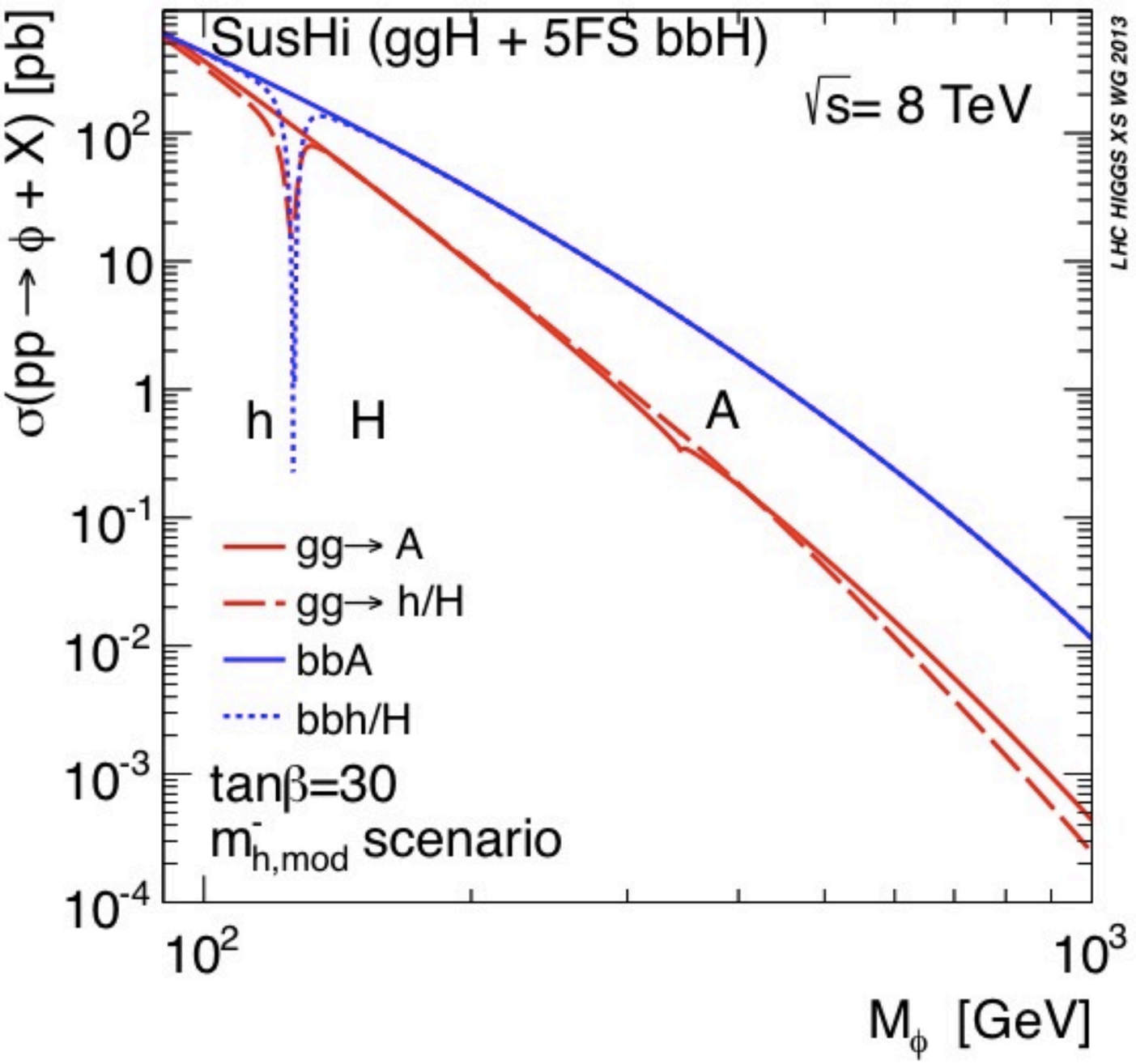
SUSY effects

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

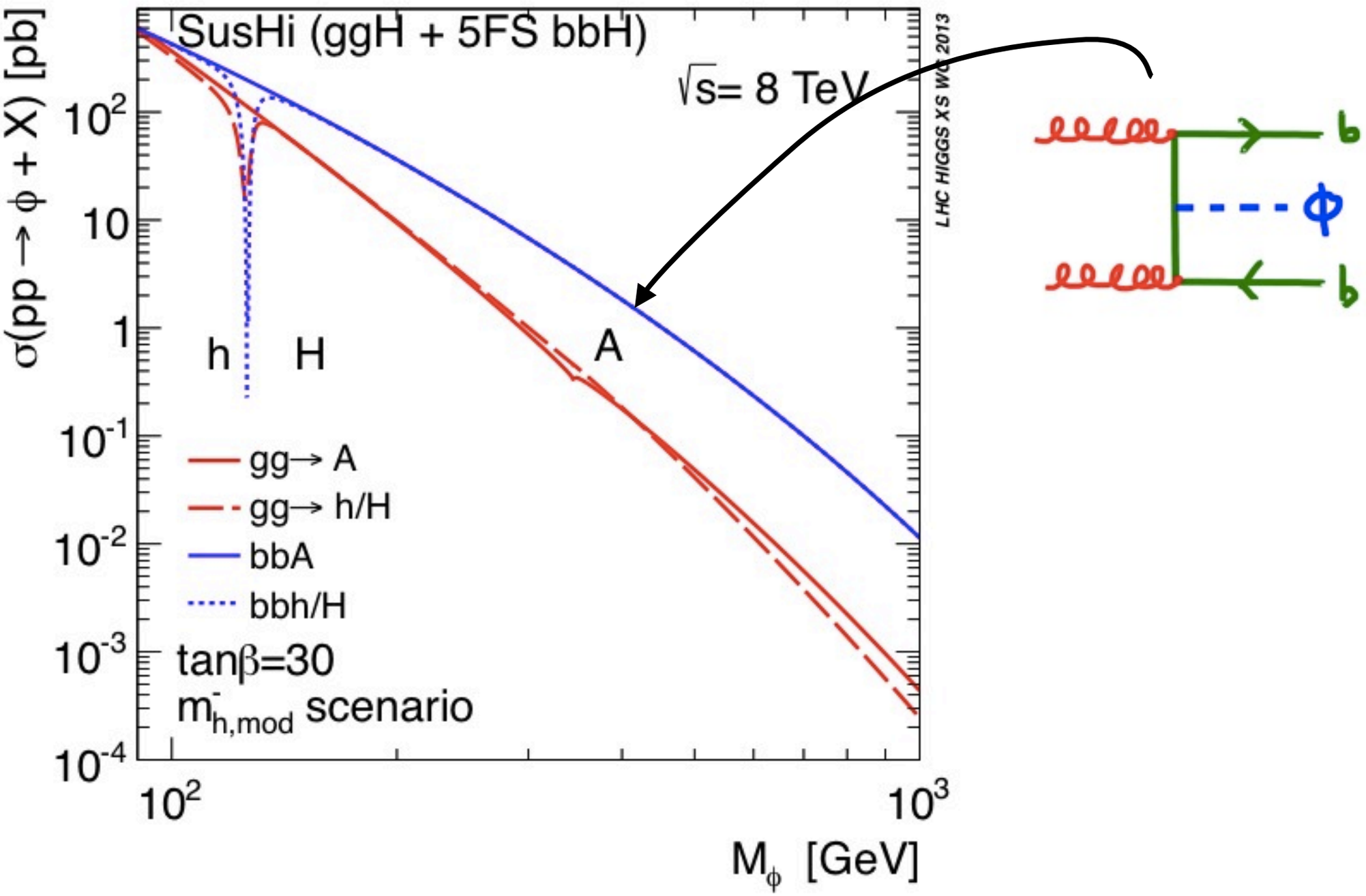
SUSY effects

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

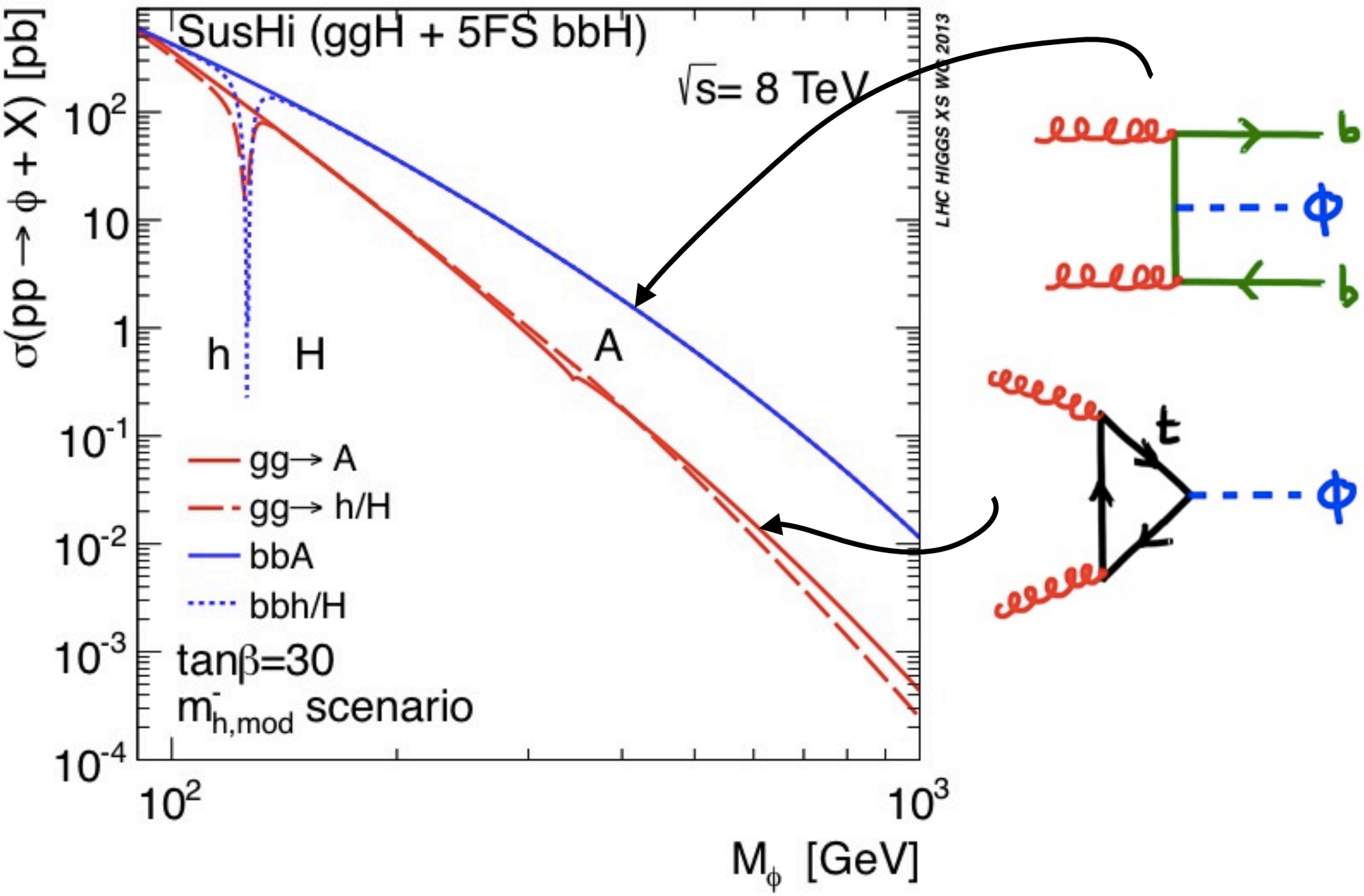
“New” production modes:

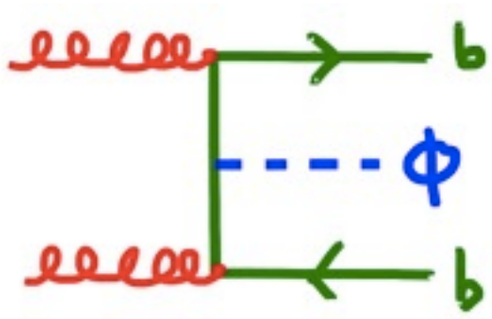


“New” production modes:

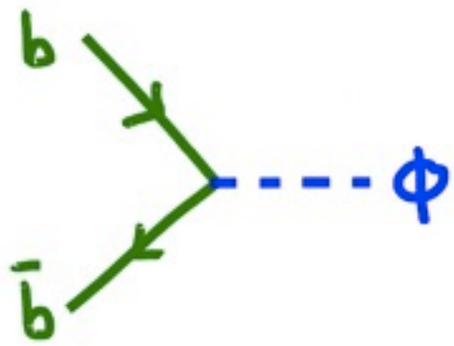


“New” production modes:

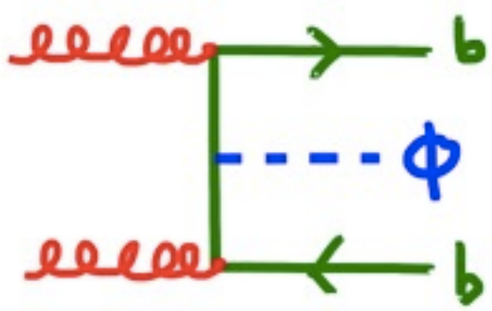




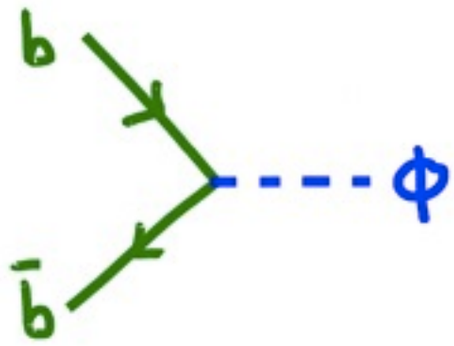
4FS: through NLO



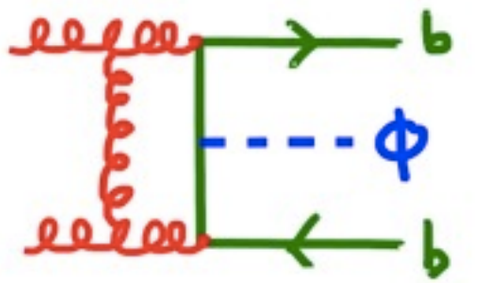
5FS: through NNLO



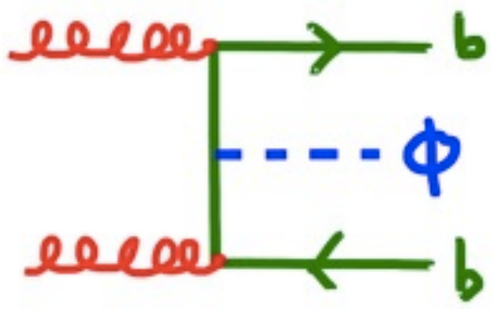
4FS: through NLO



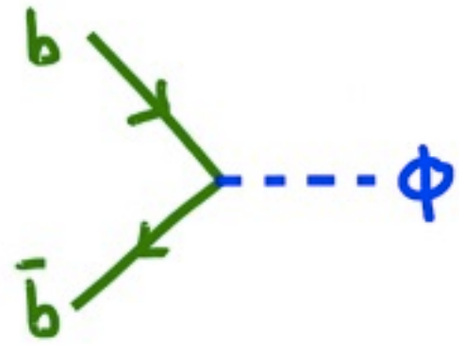
5FS: through NNLO



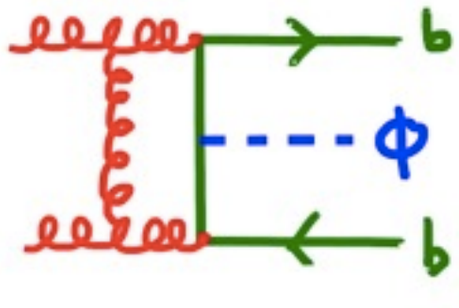
not in 5FS NNLO!



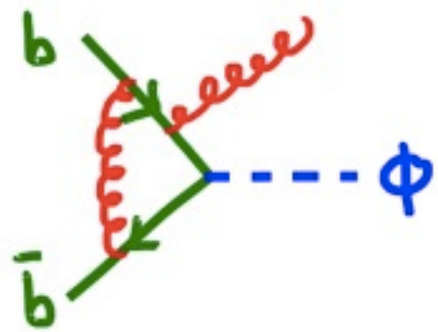
4FS: through NLO



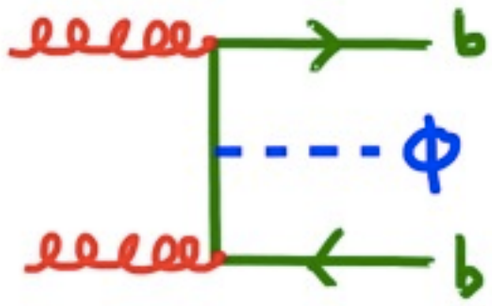
5FS: through NNLO



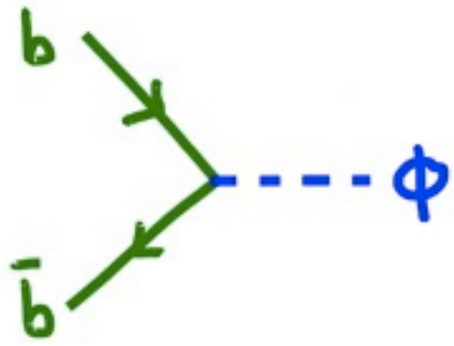
not in 5FS NNLO!



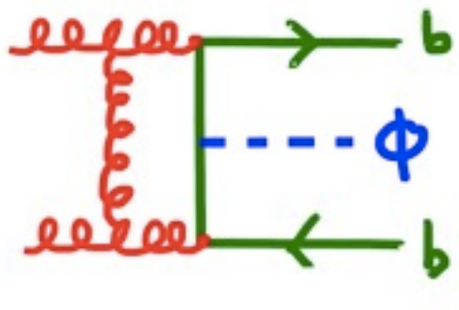
not in 4FS NLO!



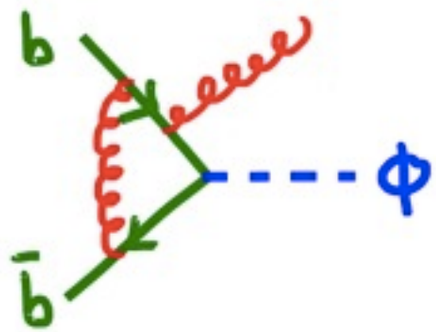
4FS: through NLO



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

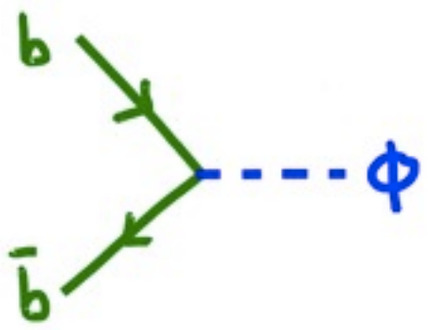
RH, Krämer, Schumacher '11

see also: Maltoni, Ridolfi, Ubiali '12

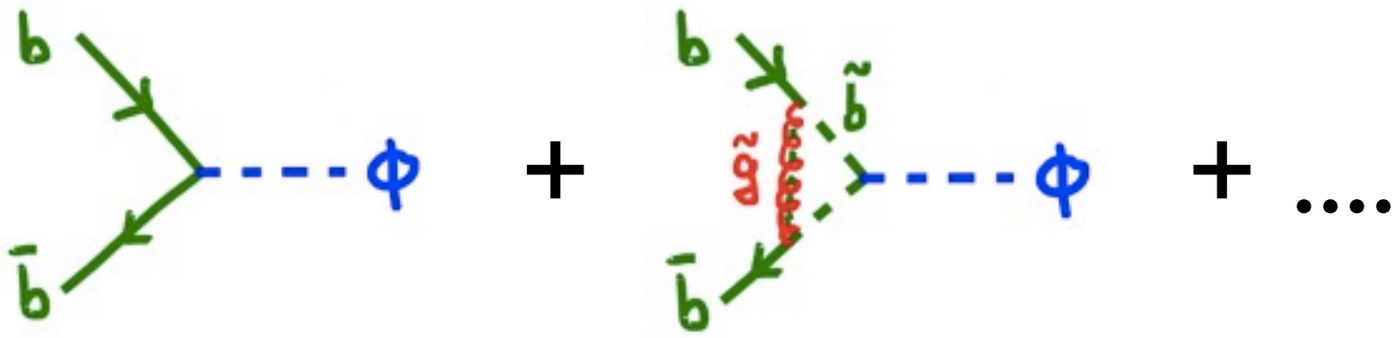
SUSY effects

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

SUSY particle effects:



SUSY particle effects:



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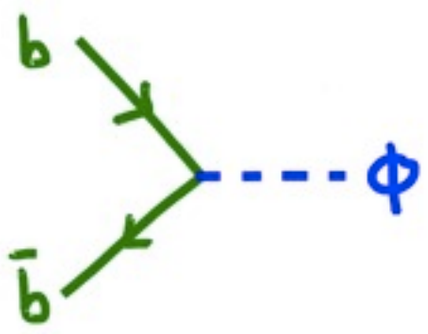

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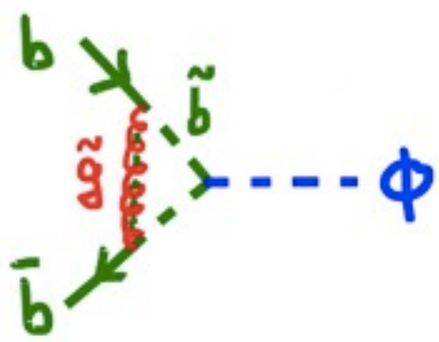


+ ....

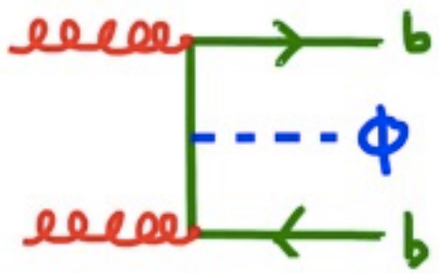
$$\rightarrow \left(\alpha_s \frac{\mu}{M_{SUSY}} \tan\beta\right)^n$$

resummation:

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

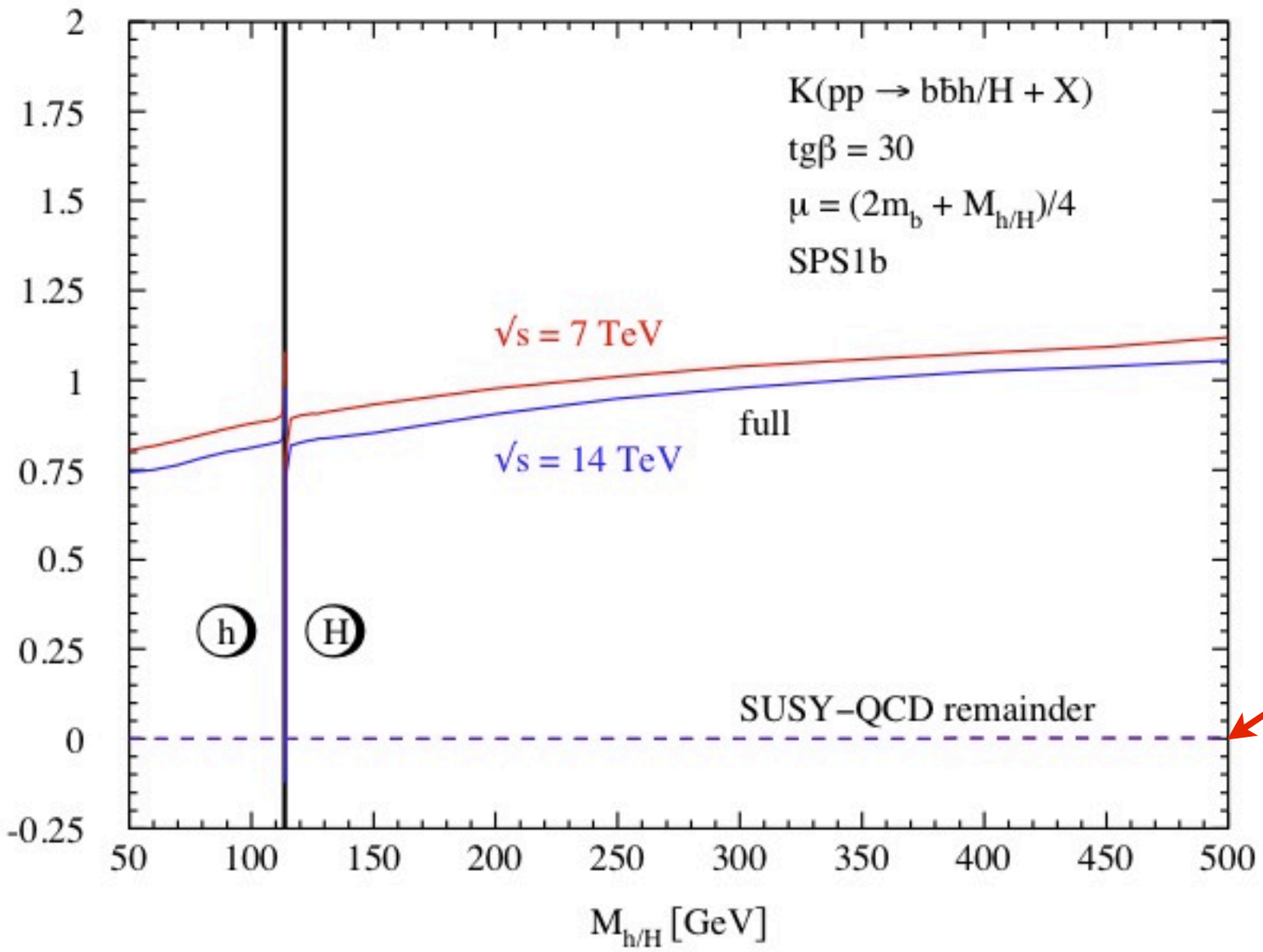
Carena, Garcia, Nierste, Wagner '99

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



4FS

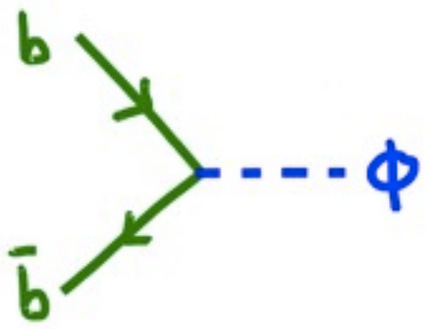
$$\sigma^{\phi}_{\rm NLO} = \sigma^{\phi}_{0} \times (1 + \delta^{\phi}_{\rm SUSY}) \times (1 + \delta^{\phi}_{\rm QCD} + \delta^{\phi}_{\rm SUSY-rem})$$



not covered by

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

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
$+\Delta_b^{weak}$	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

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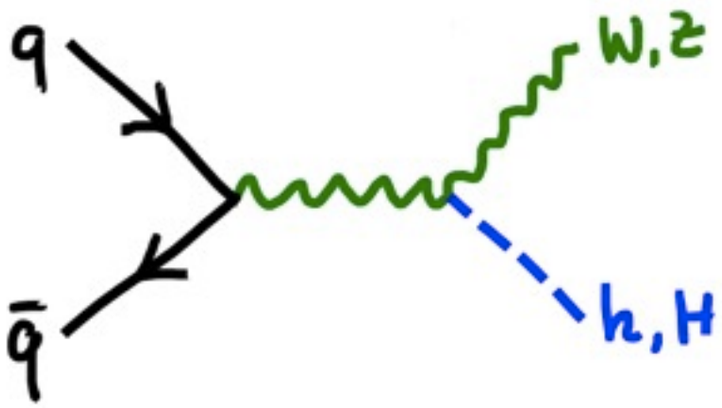
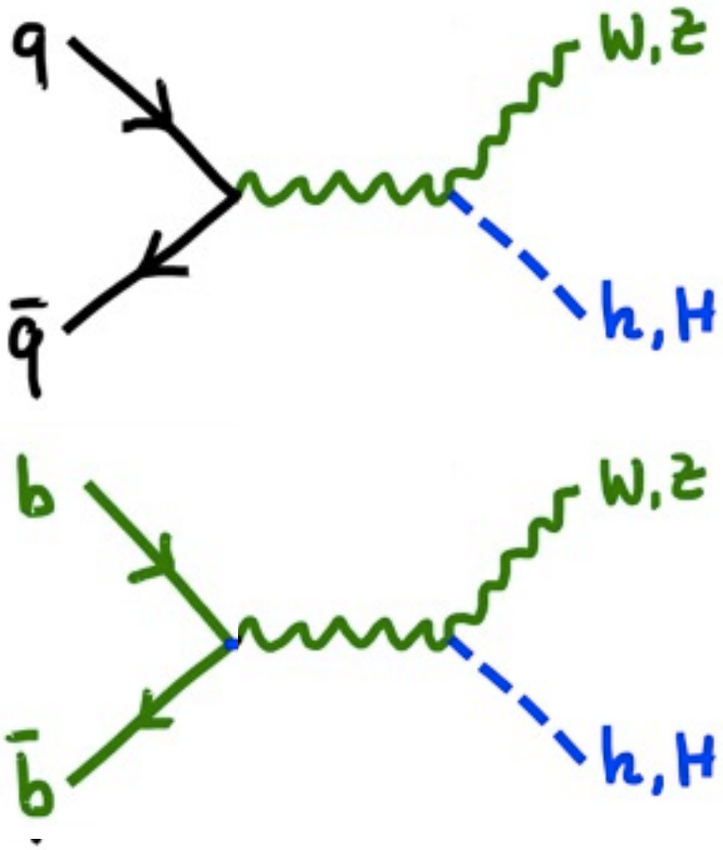


QCD effects under very good control

Effects due to new Higgs bosons:



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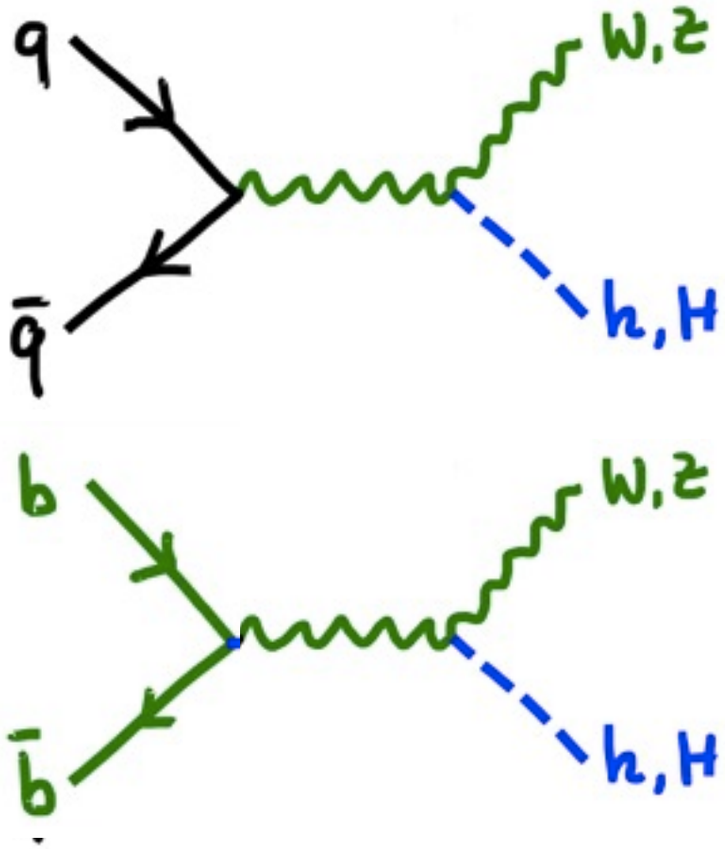
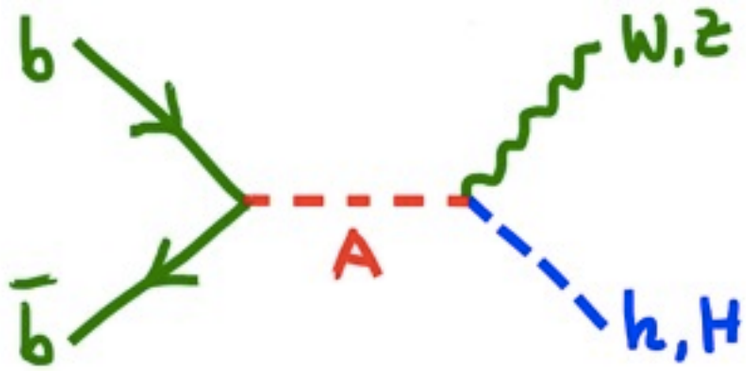


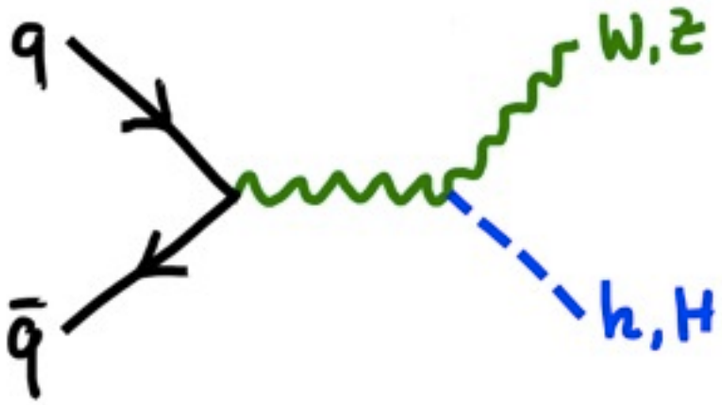
QCD effects under very good control

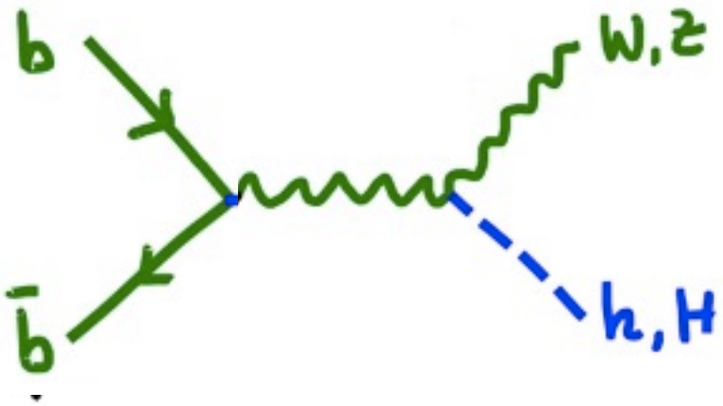
small, but:



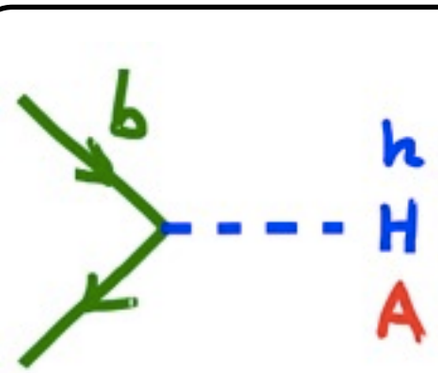
new s-channel contribution!

Effects due to new Higgs bosons:





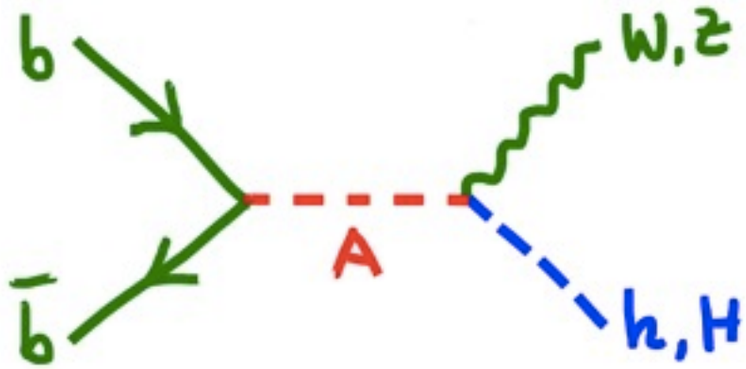
small, but:



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

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

$\tan\beta$



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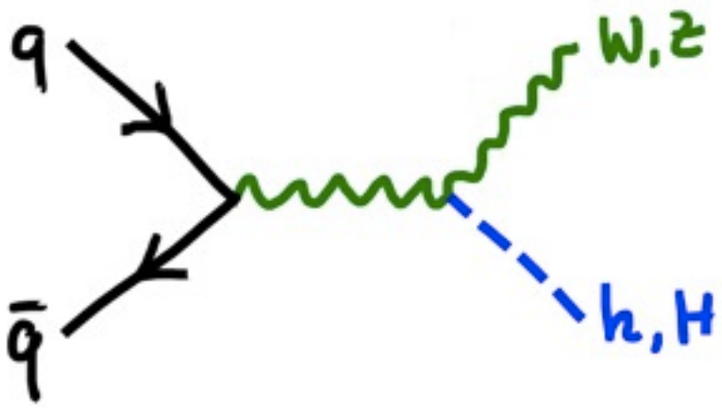
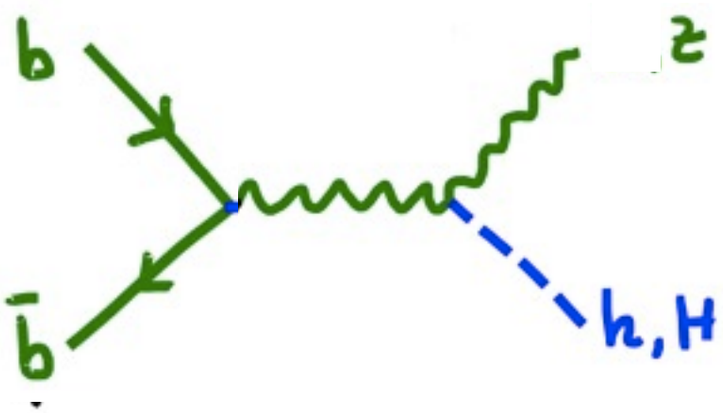
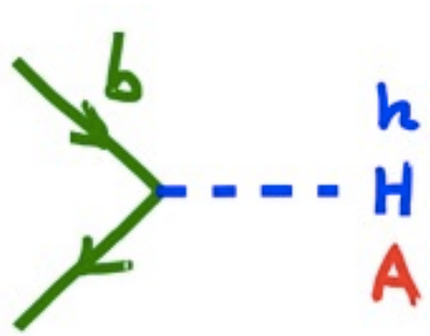




small, but:



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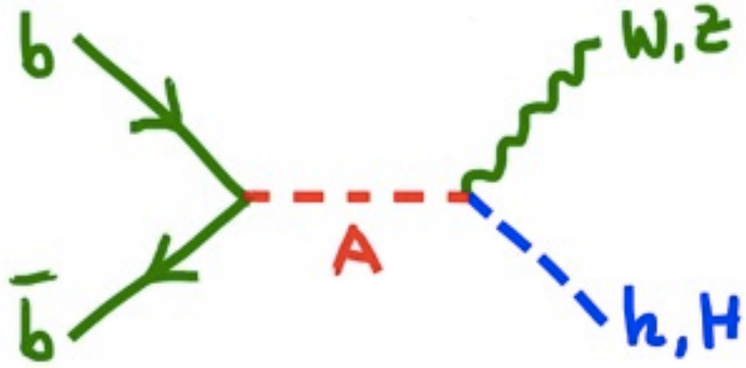
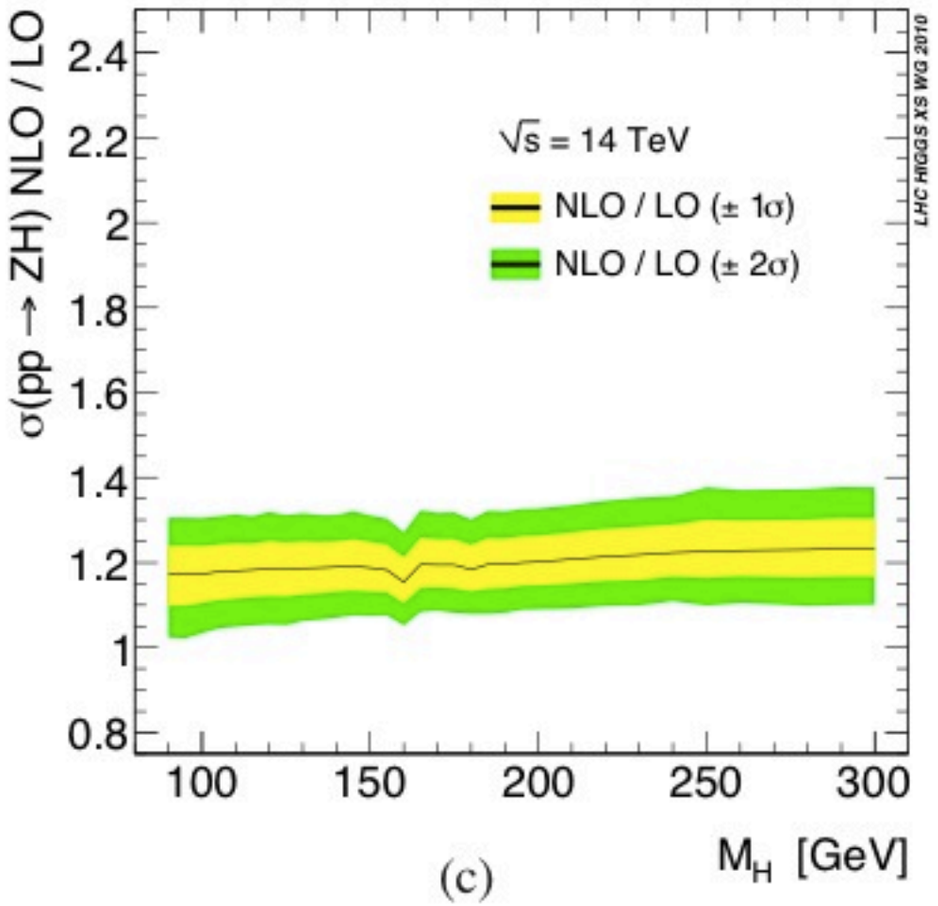


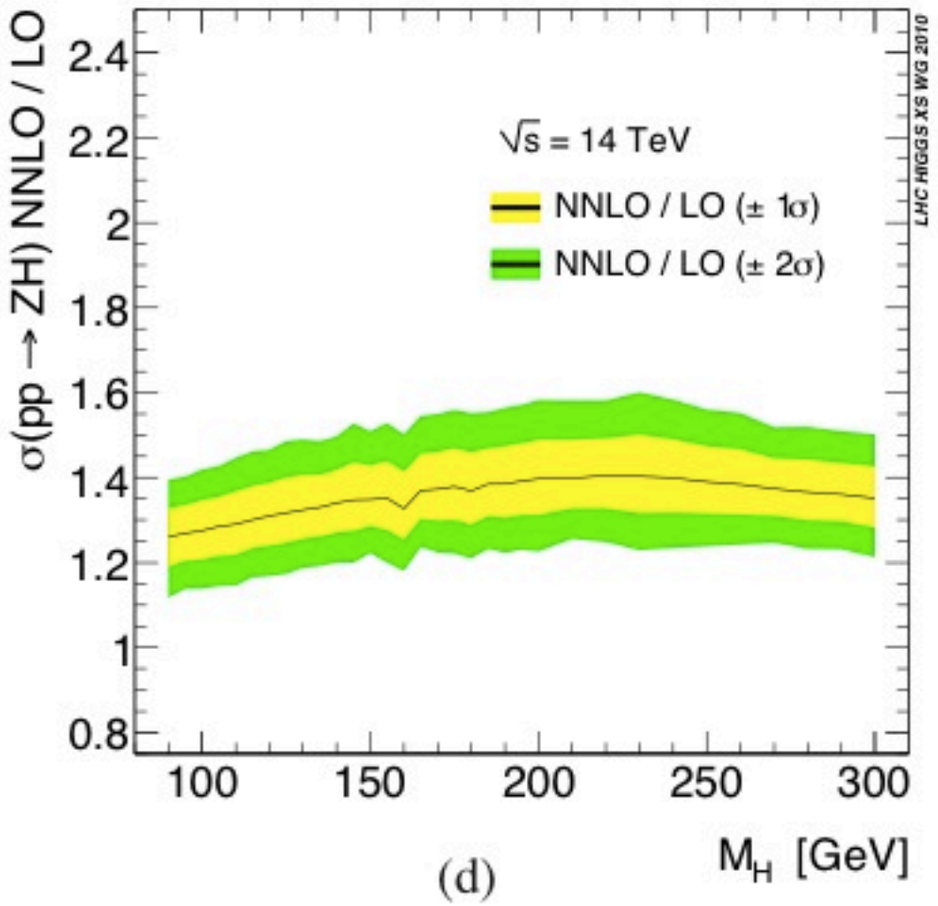
new s-channel contribution!

only for ZH, not WH!

... while talking of Higgs Strahlung:

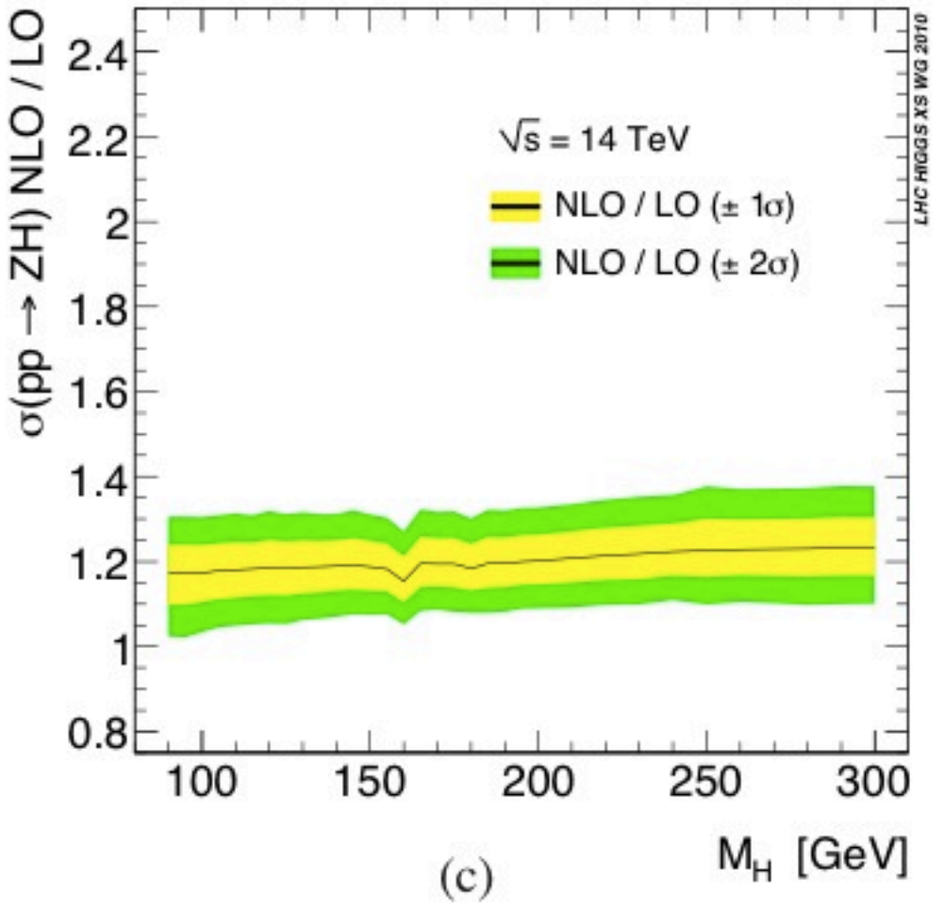


(c)



(d)

... while talking of Higgs Strahlung:



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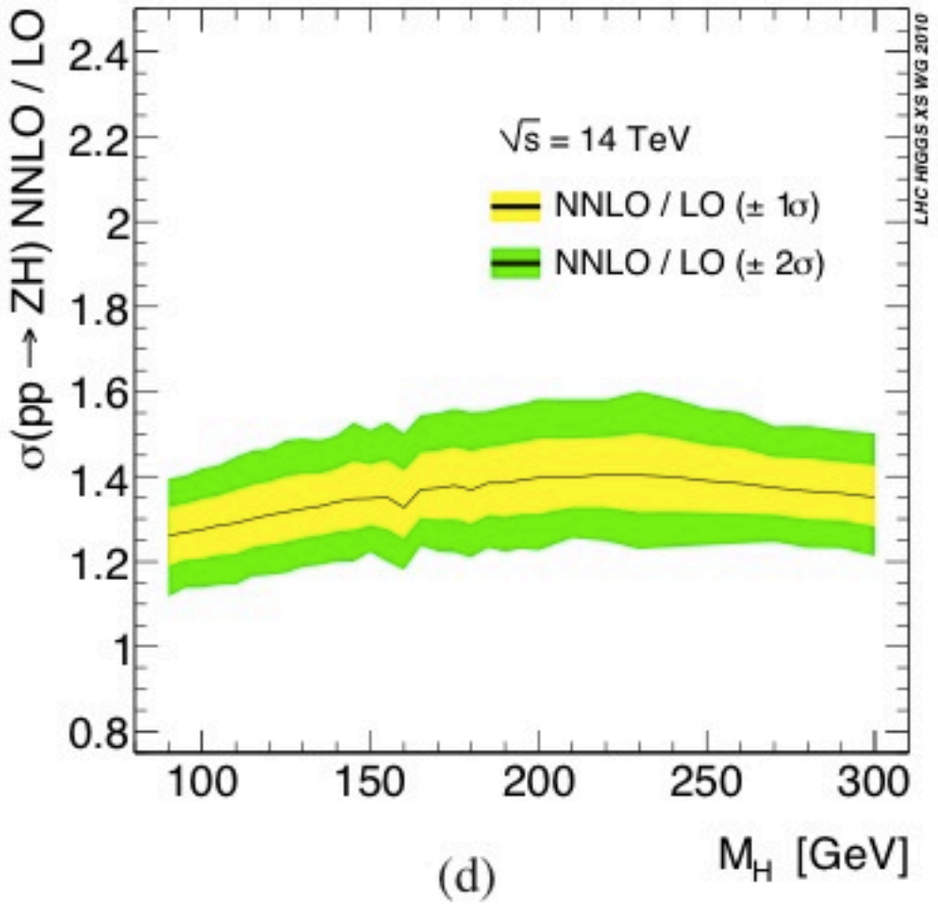
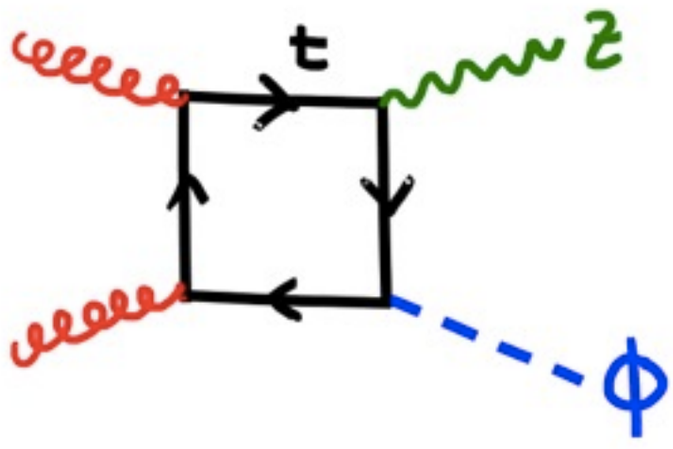
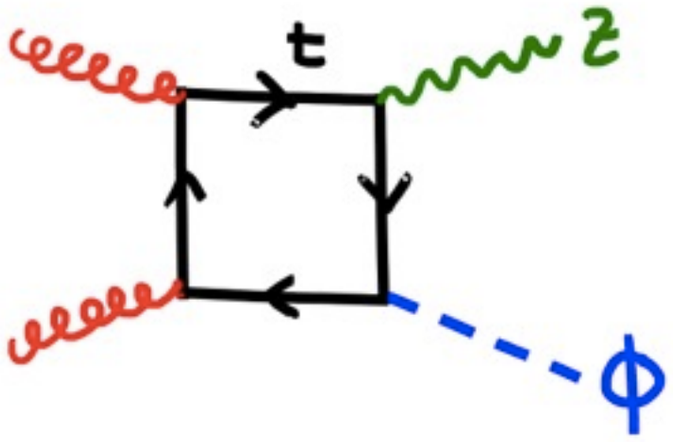
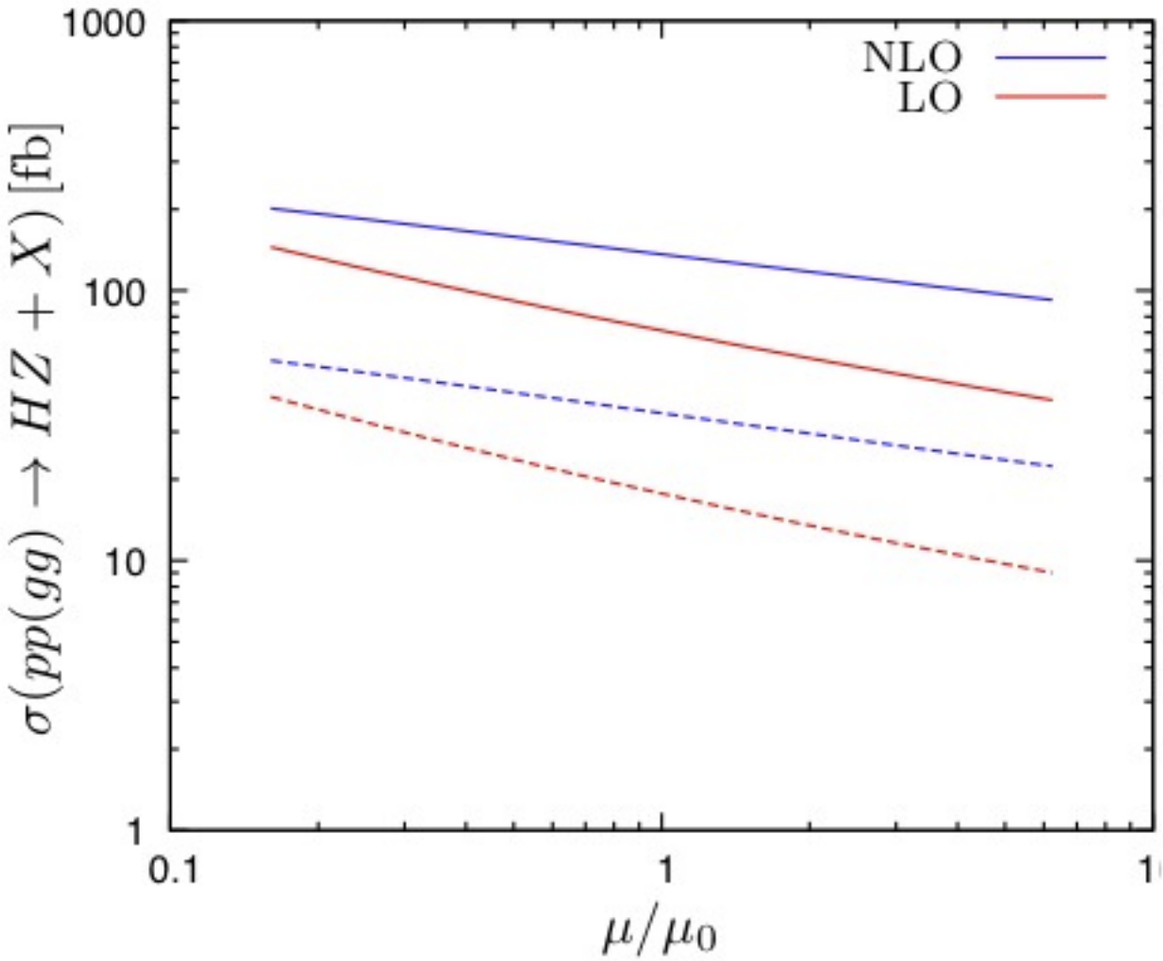


(d)

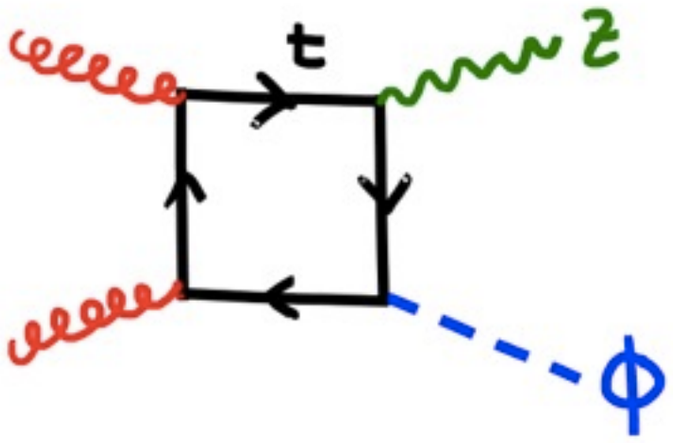




at NLO:



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



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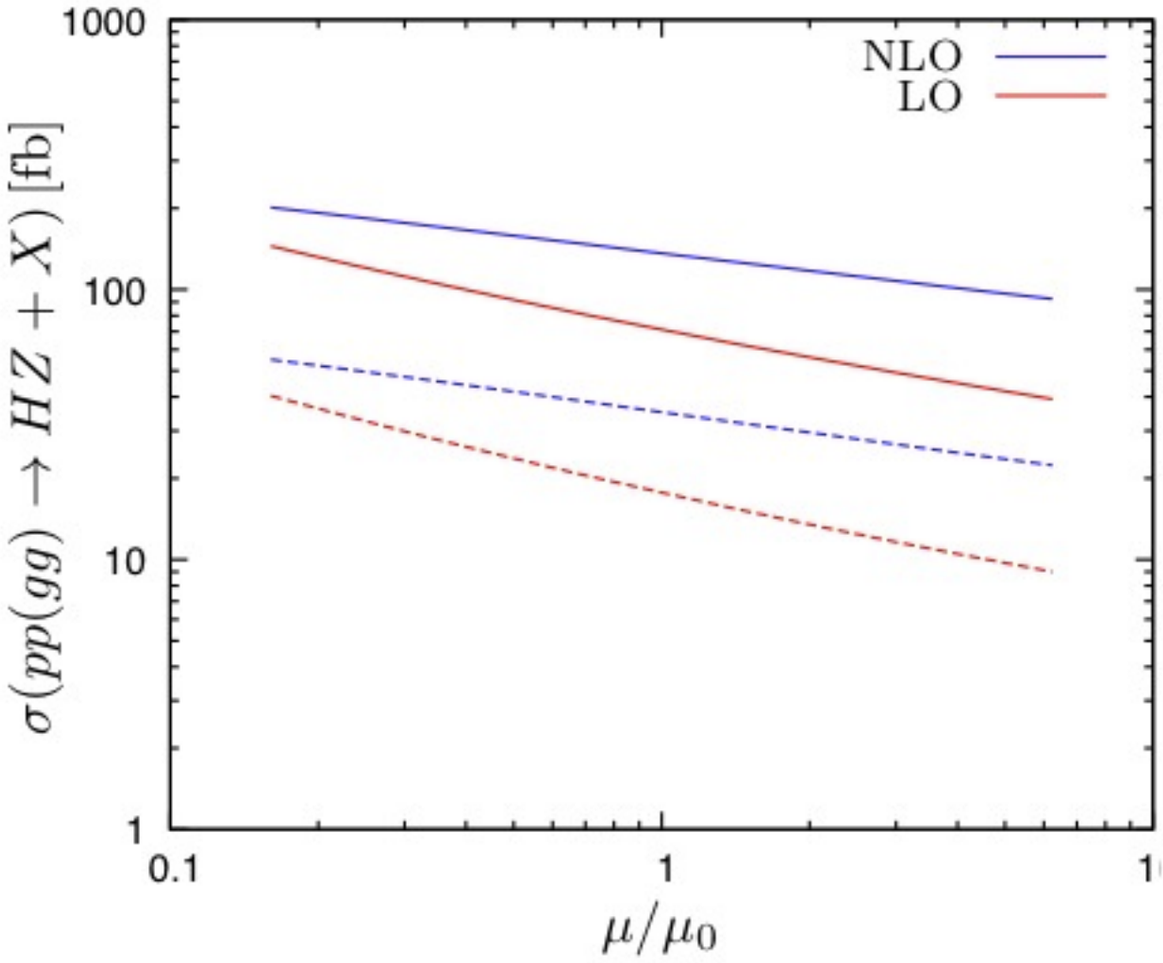

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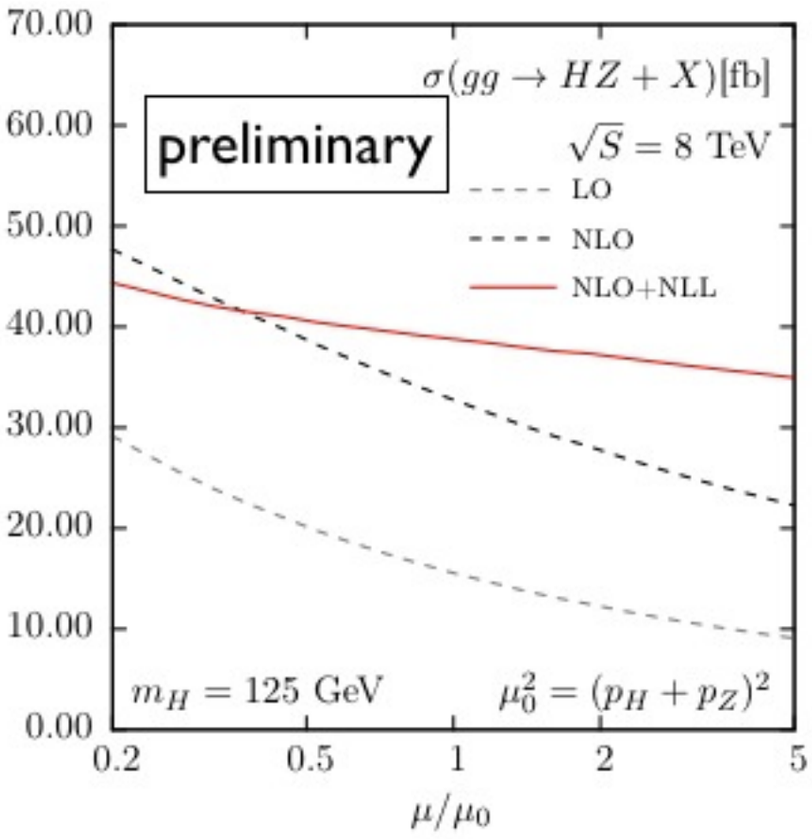
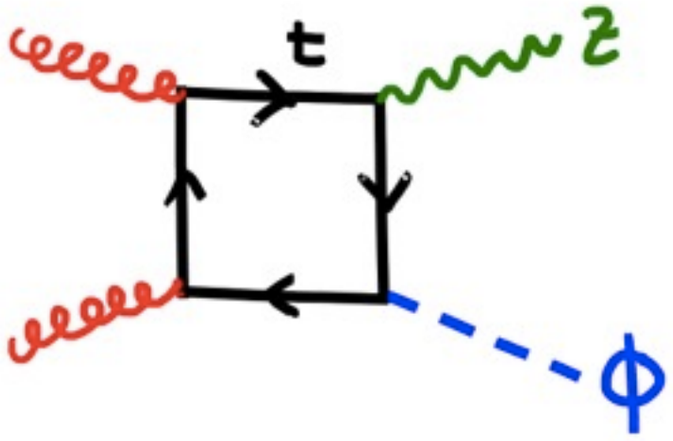
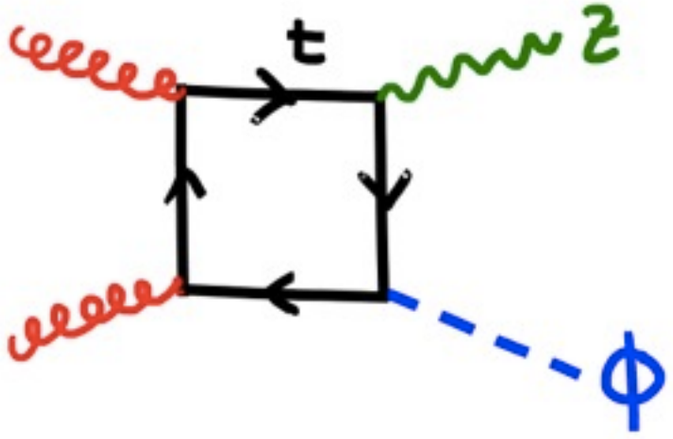


NLO+NLL:
RH, Kulesza, Theeuwes, Zirke



in SUSY?



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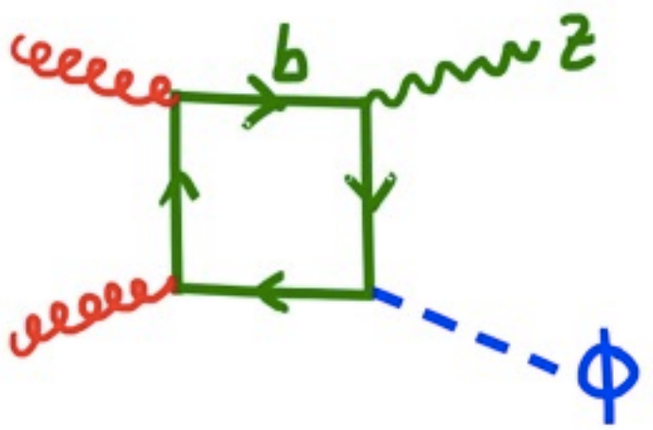
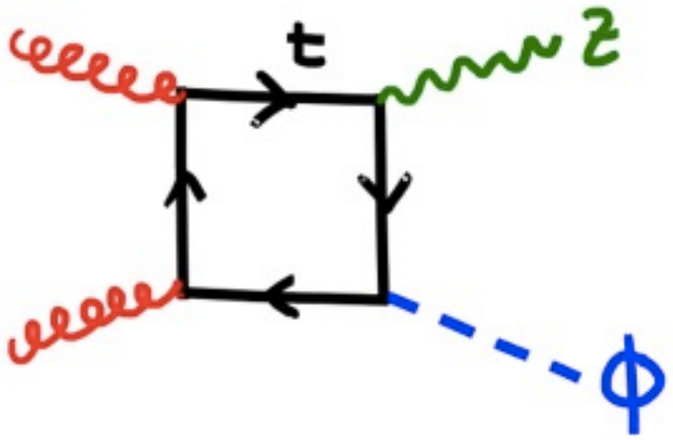


enhancement
by tanβ



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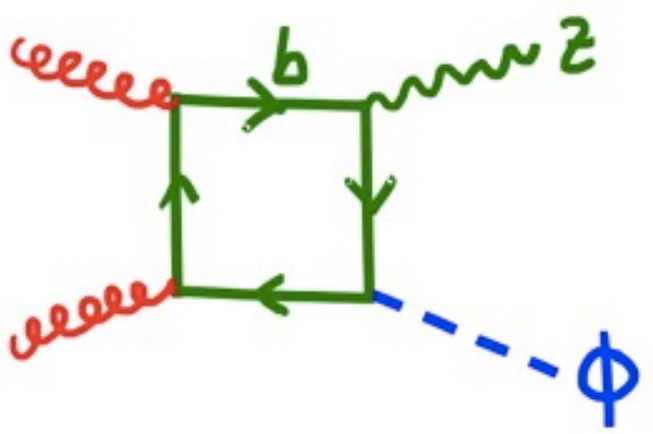

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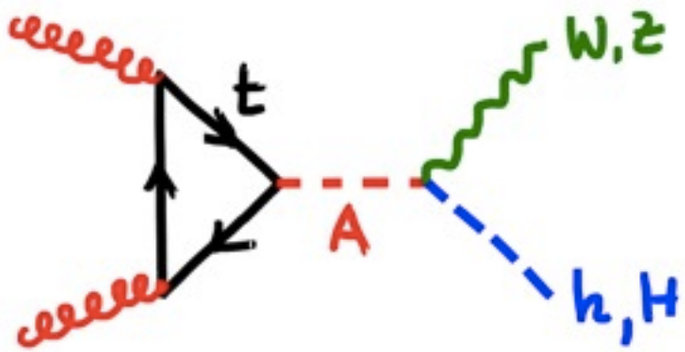

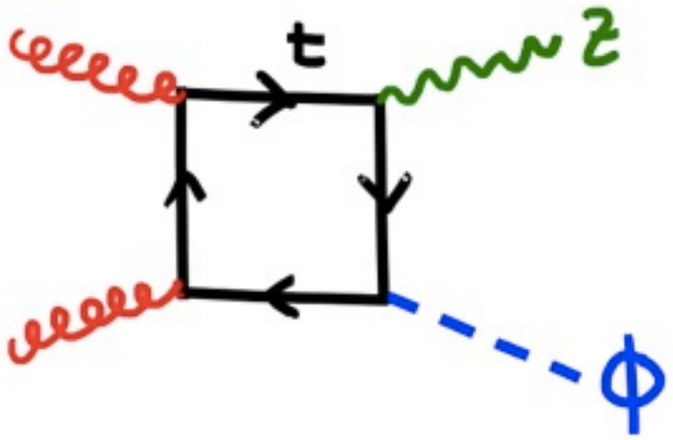

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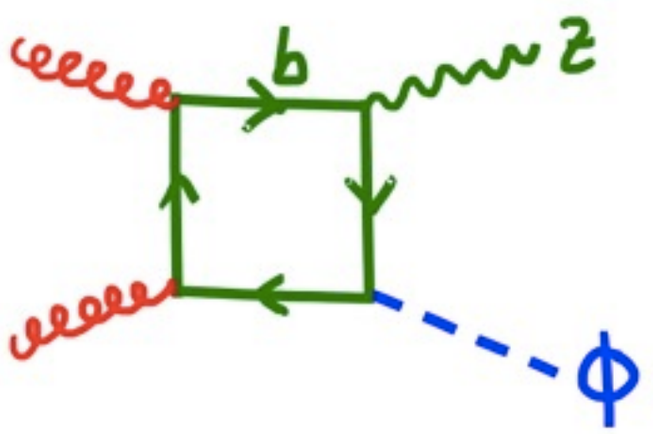

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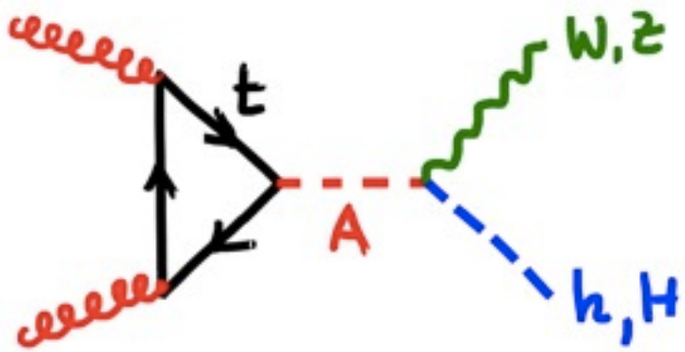
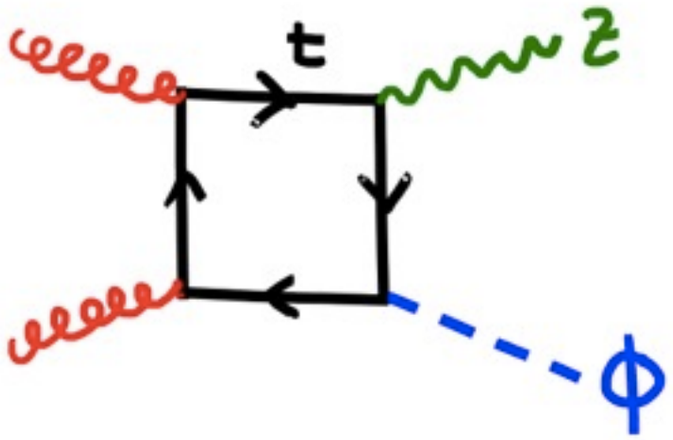


Squarks?



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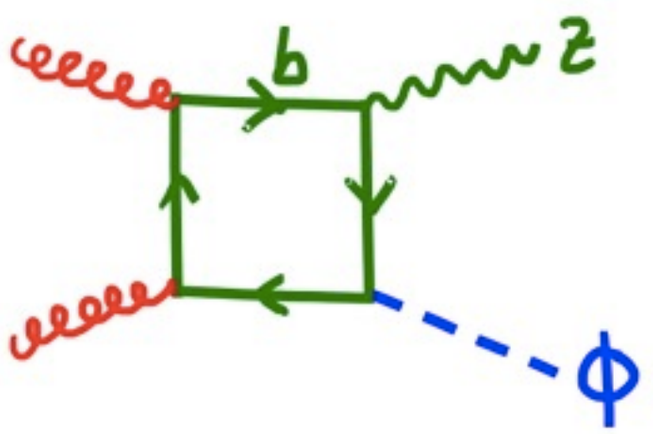
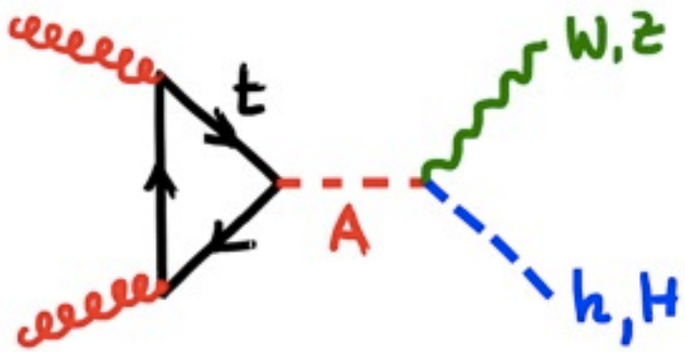
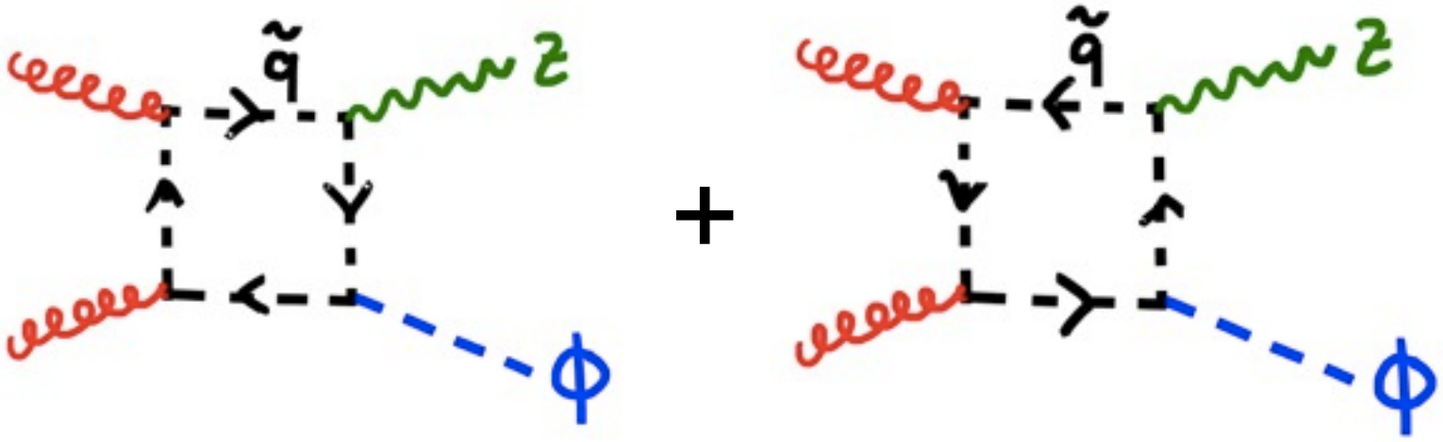


enhancement by tanβ



Squarks?



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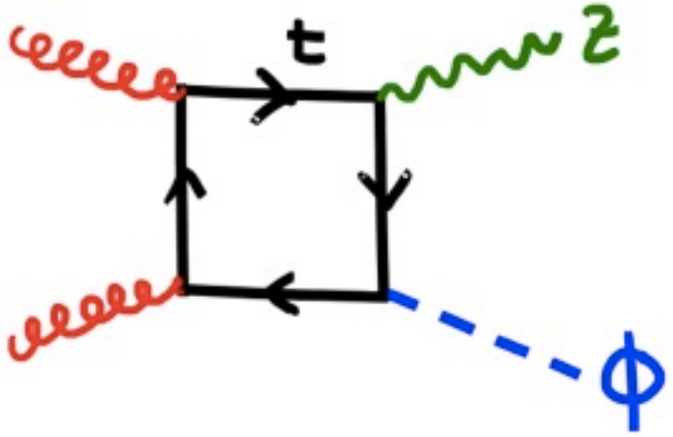
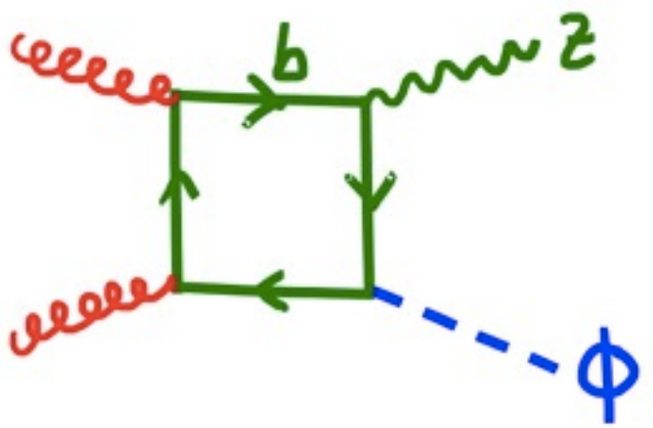
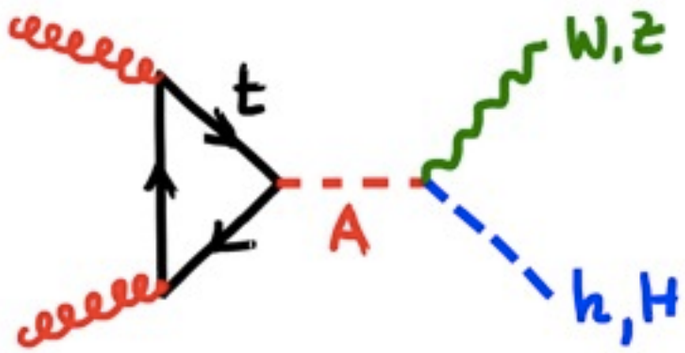
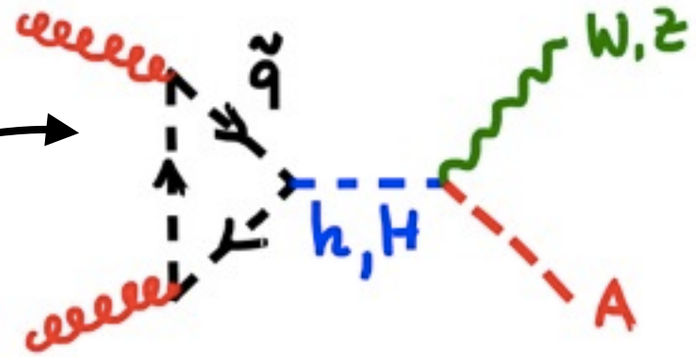


in SUSY?



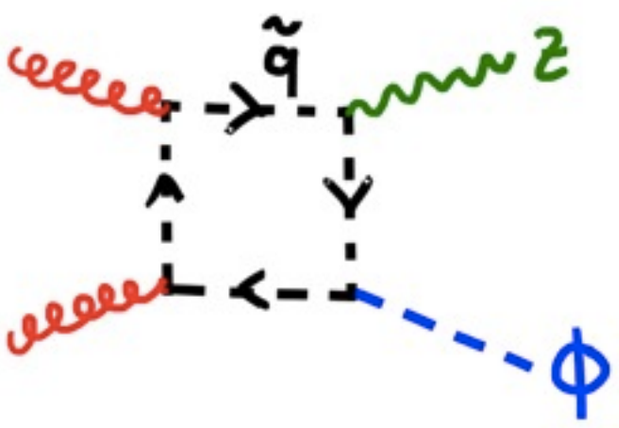
enhancement by tanβ





only

Squarks?



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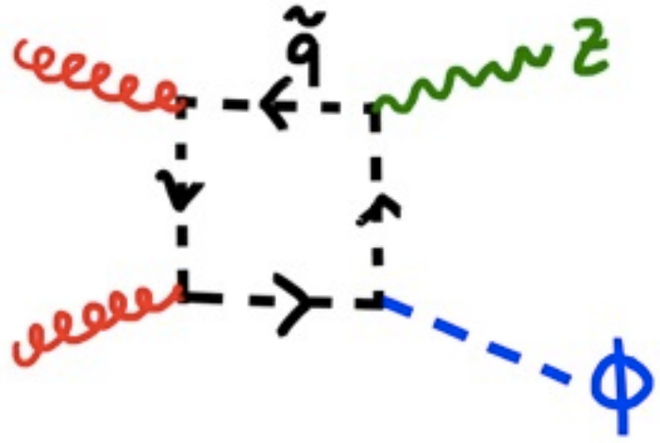

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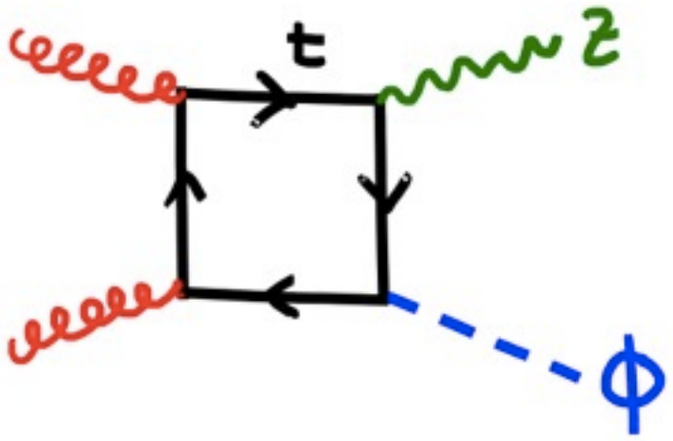
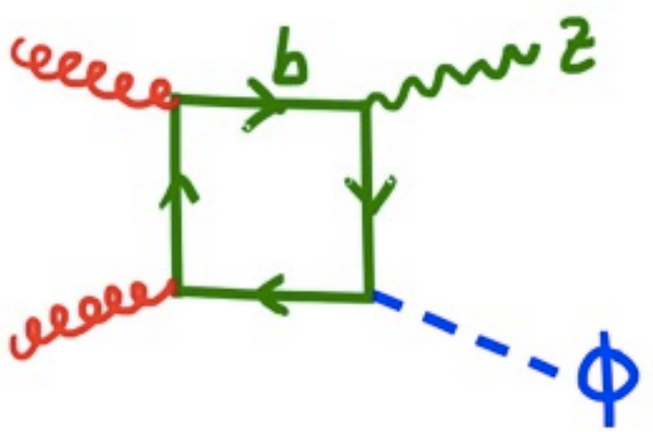


in SUSY?



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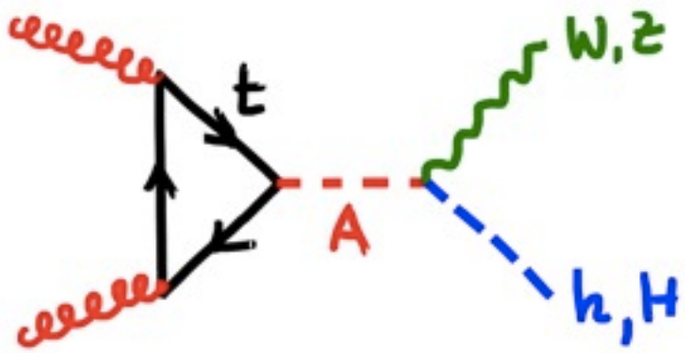

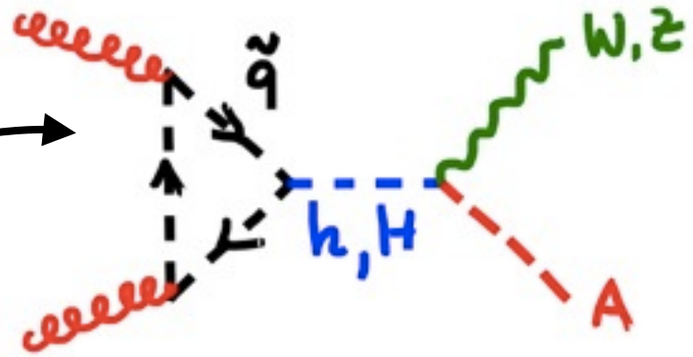

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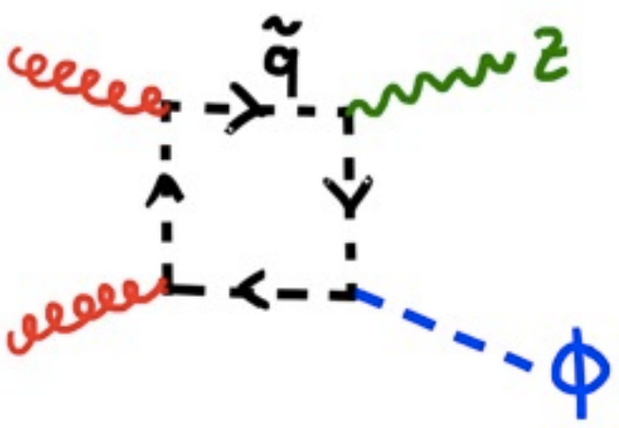
Squarks?



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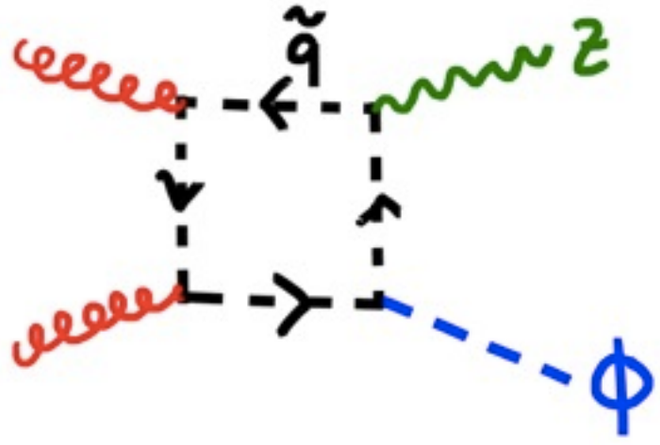

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⇒ MSSM is like 2HDM Type II for h,H

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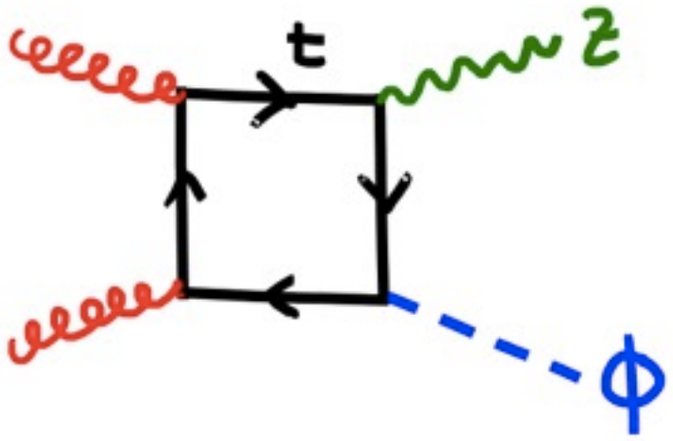

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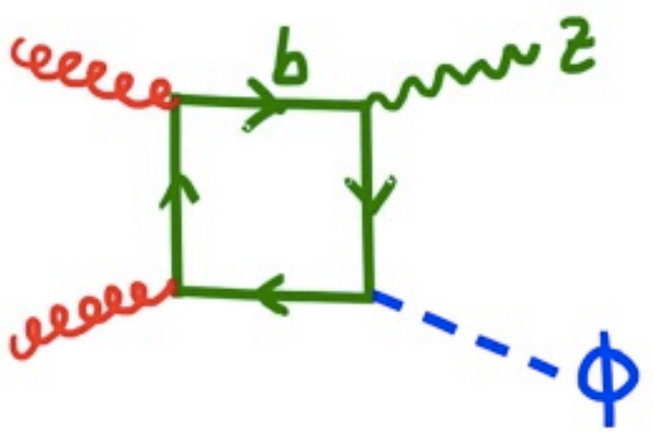
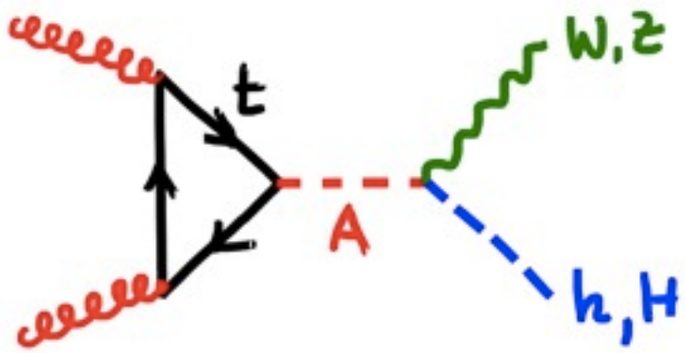
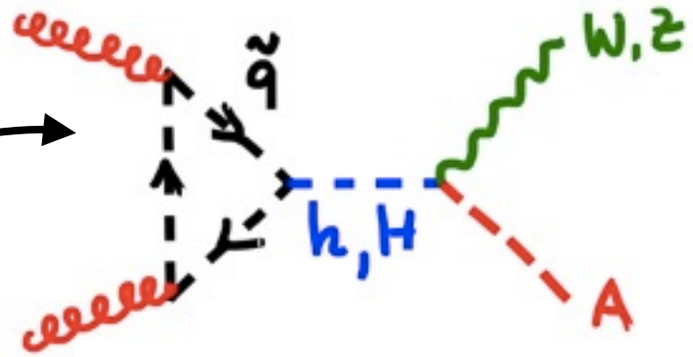


enhancement by tanβ





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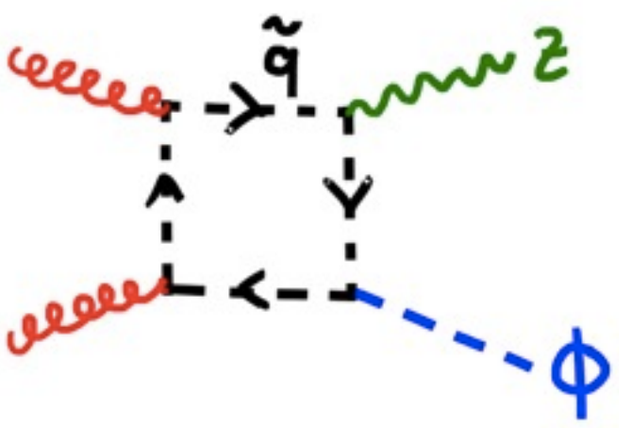
Squarks?



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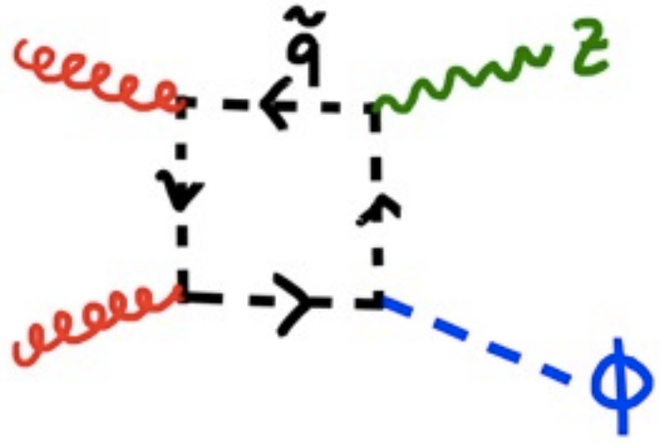

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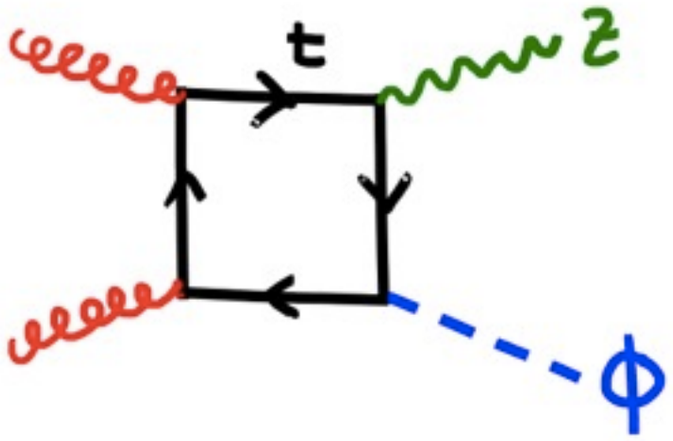

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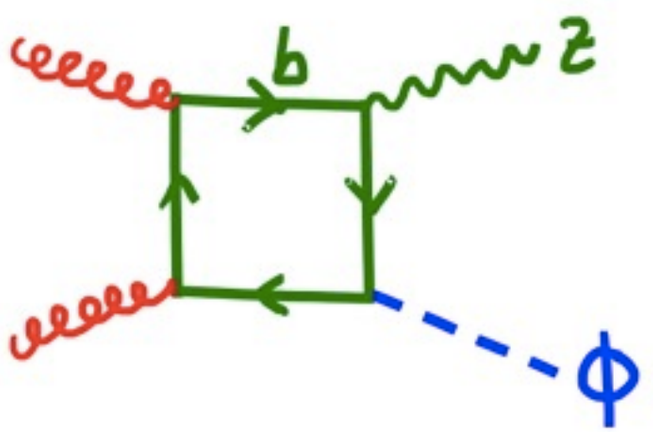
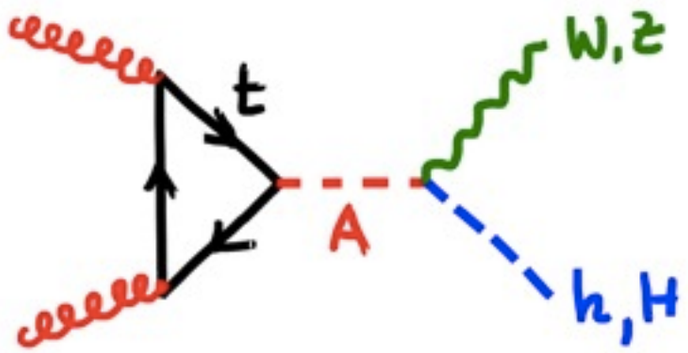
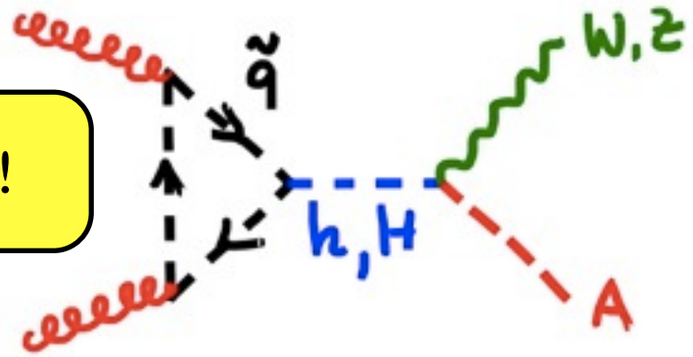


enhancement by tanβ



only for ZH, not WH!



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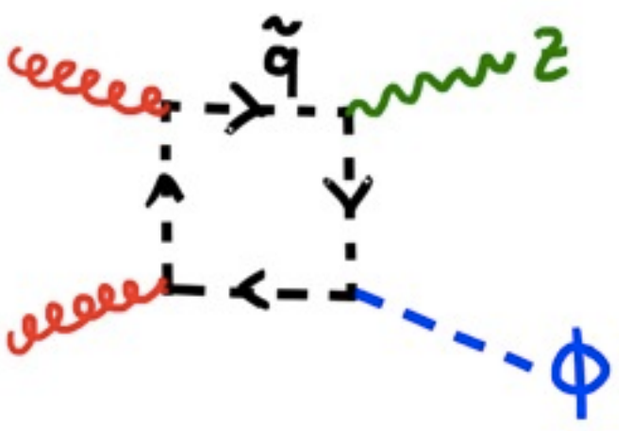
Squarks?



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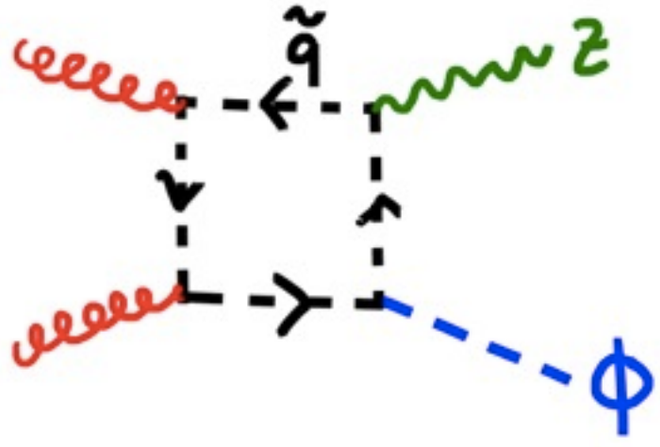

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⇒ MSSM is like 2HDM Type II for h,H

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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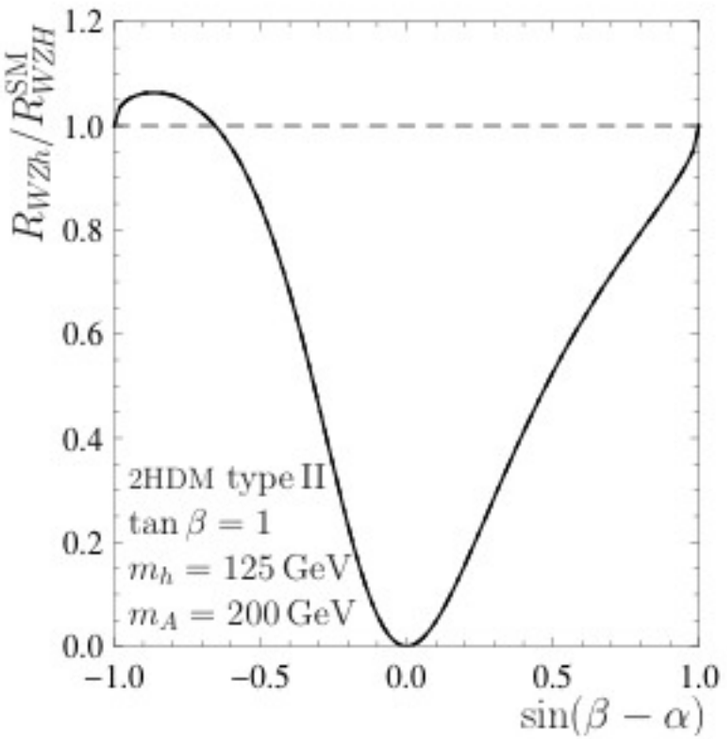
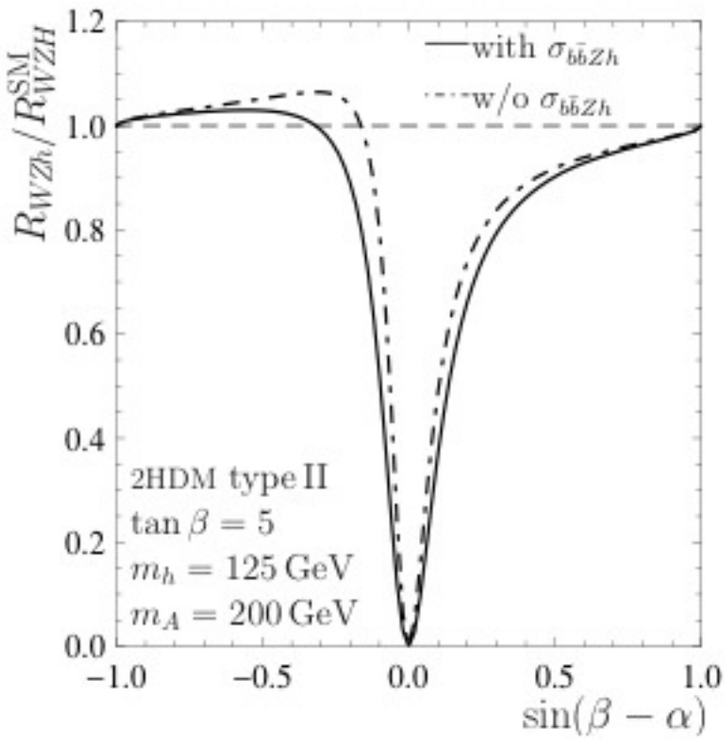




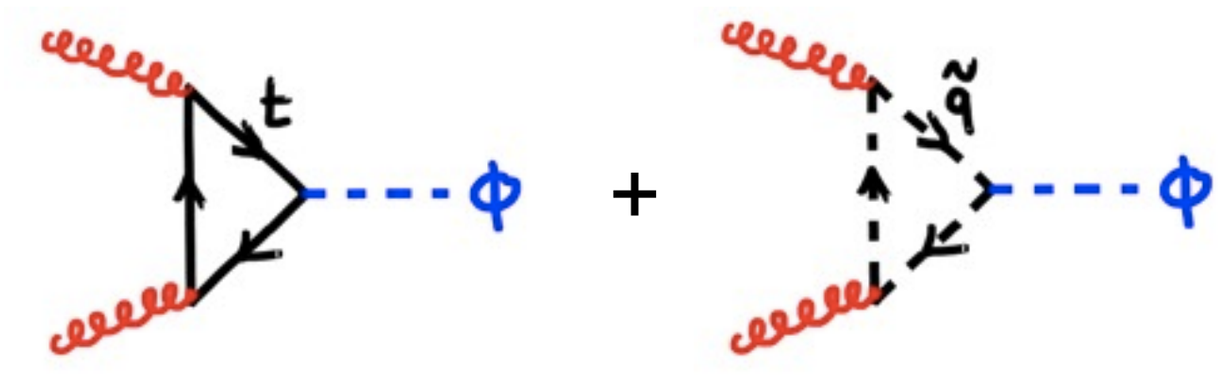
2HDM

RH, Liebler, Zirke '13

see also: Englert, McCullough, Spannowsky '13

SUSY particle effects:

at leading order:



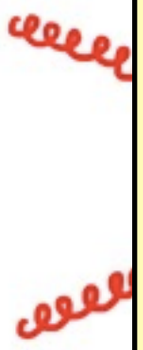
can interfere distructively (gluophobic Higgs)

Djouadi ’98

Gluon fusion

exact through NLO

Gluon fusion



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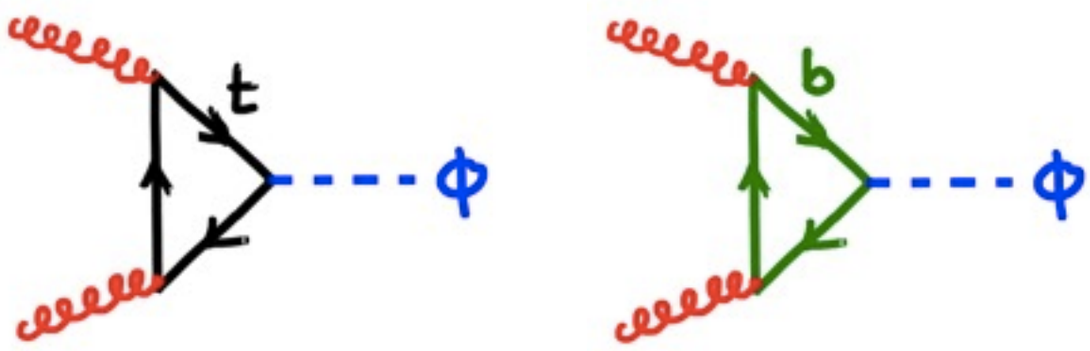
LHC Higgs XS WG, YR2 (2012):

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

no SUSY particles in loops!

Gluon fusion



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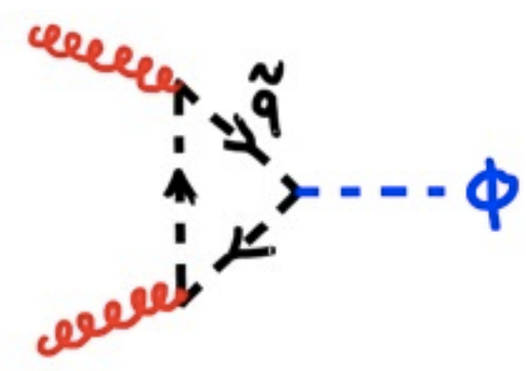
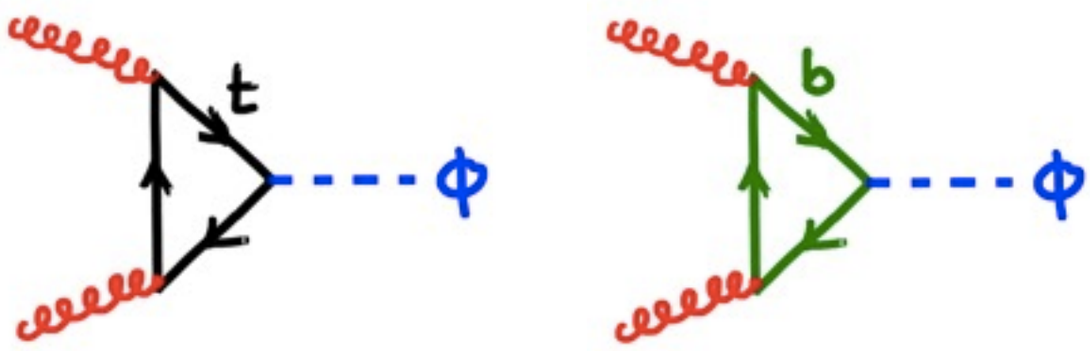


Gluon fusion



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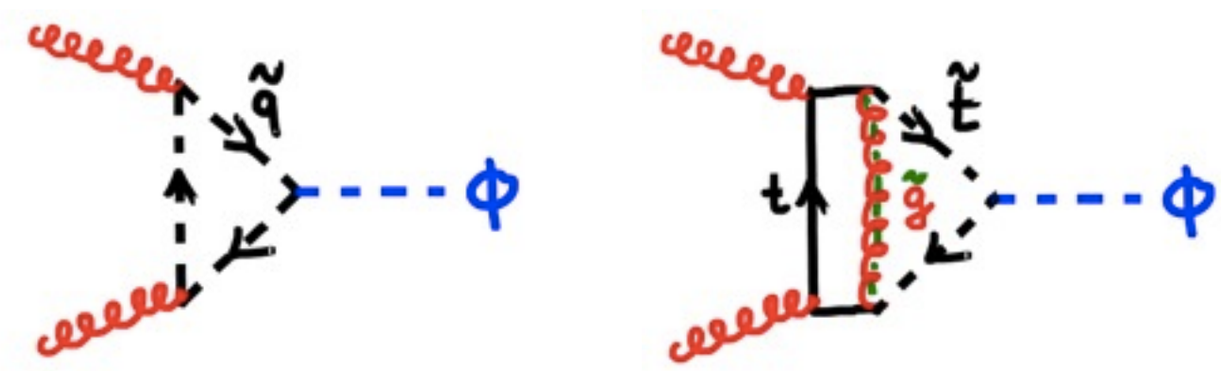

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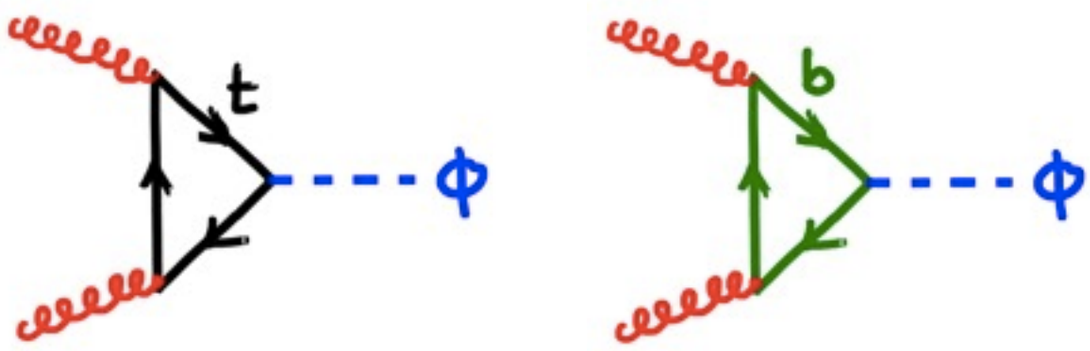

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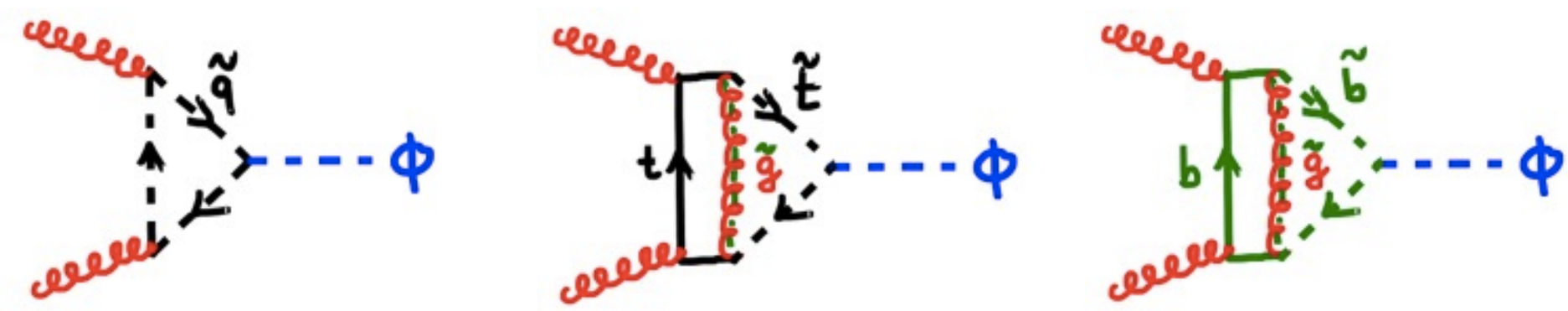
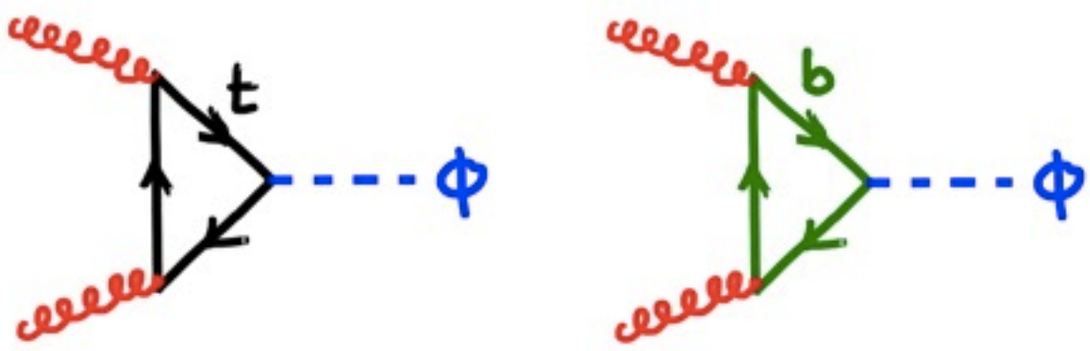


Gluon fusion



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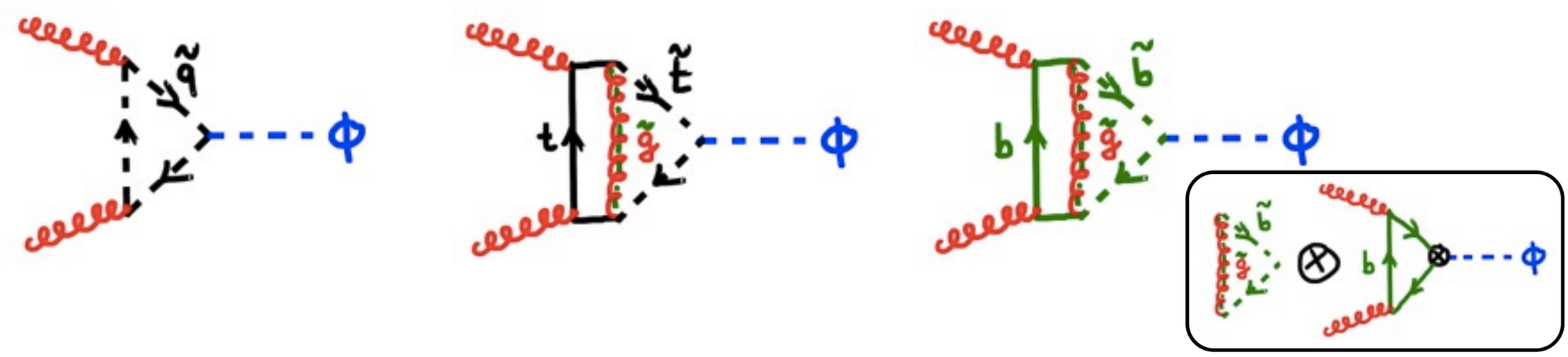

Gluo

LHC Higg

$\sigma^{\rm MSSM}(gg \to$ $_b(gg \to \phi)$,

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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].

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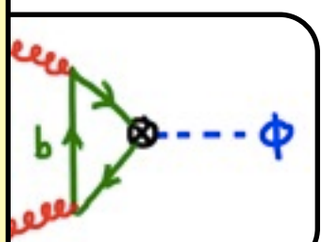
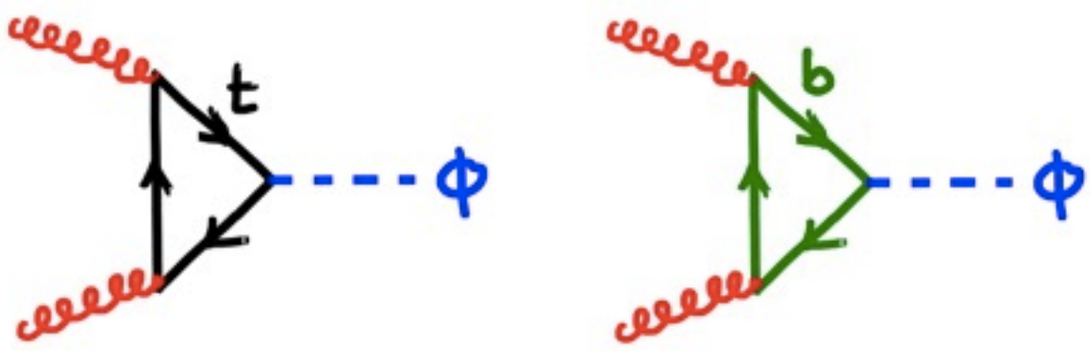


Gluon fusion



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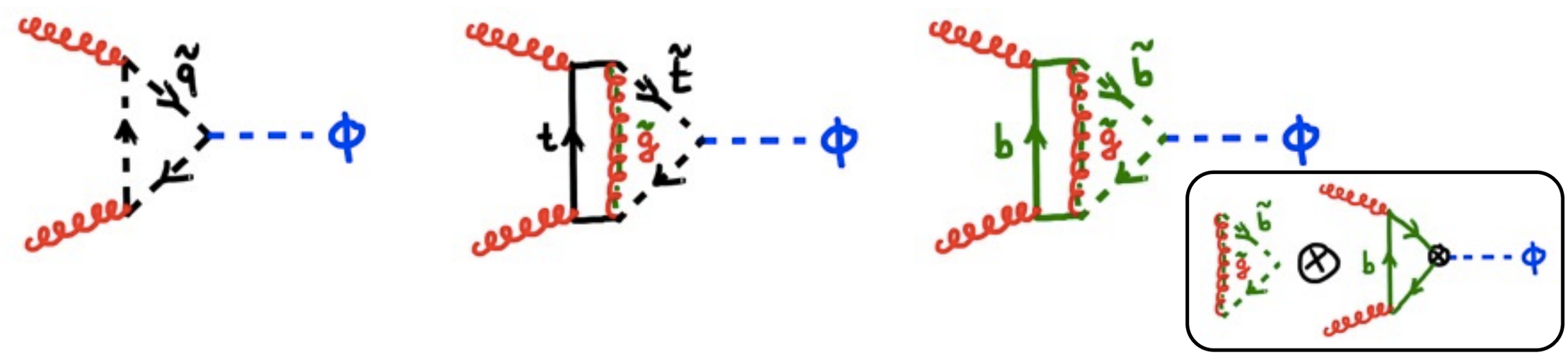

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- Changelog
- Manual
- Examples
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Version 1.3.0 (03.04.2014) is available here: Download
Manual for Version 1.3.0
For linking SusHi to FeynHiggs type "./configure; make predef=FH"!
For linking SusHi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

- SusHi
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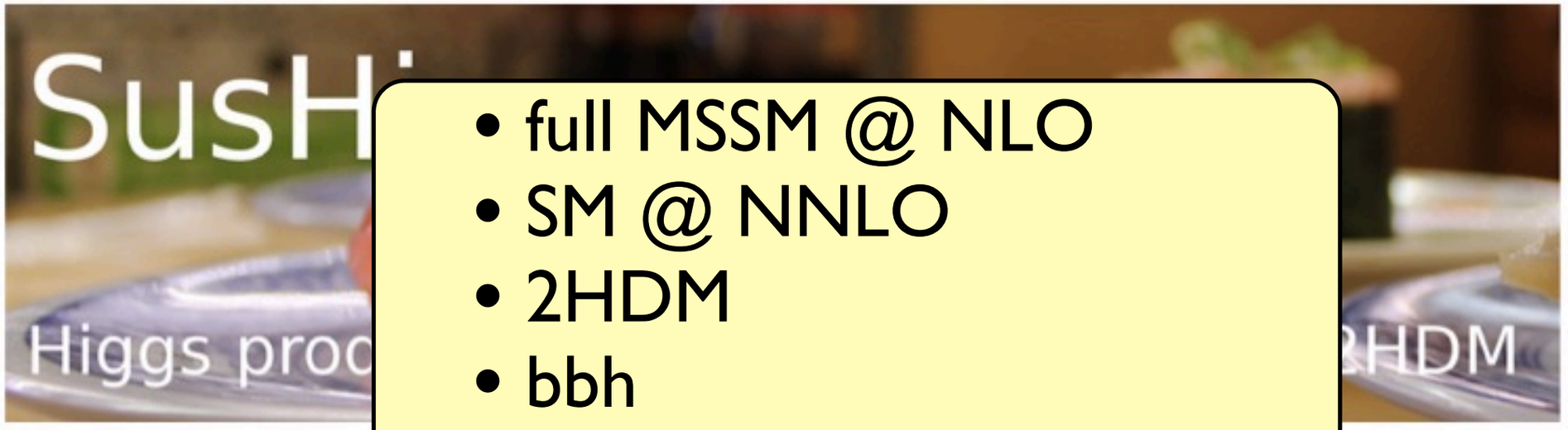

- full MSSM @ NLO
- SM @ NNLO
- 2HDM
- bbh
- various ren. schemes
- link to FeynHiggs
- link to LHAPDF
- link to 2HDMC
- ...

RH, Liebler, Mantler '12

Download

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Version 1.3.0 (03.04.20
Manual for Version 1.3.
For linking SusHi to Fey
For linking SusHi to 2H

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

Neutral MSSM Higgs production — comprehensive study

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

based on SusHi

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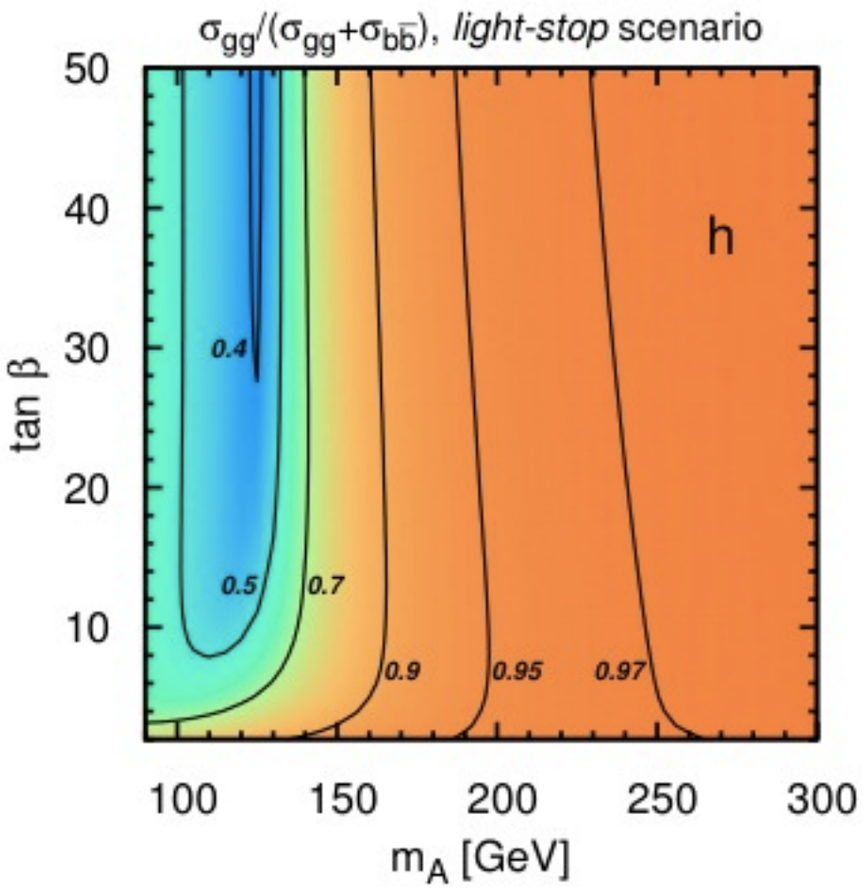
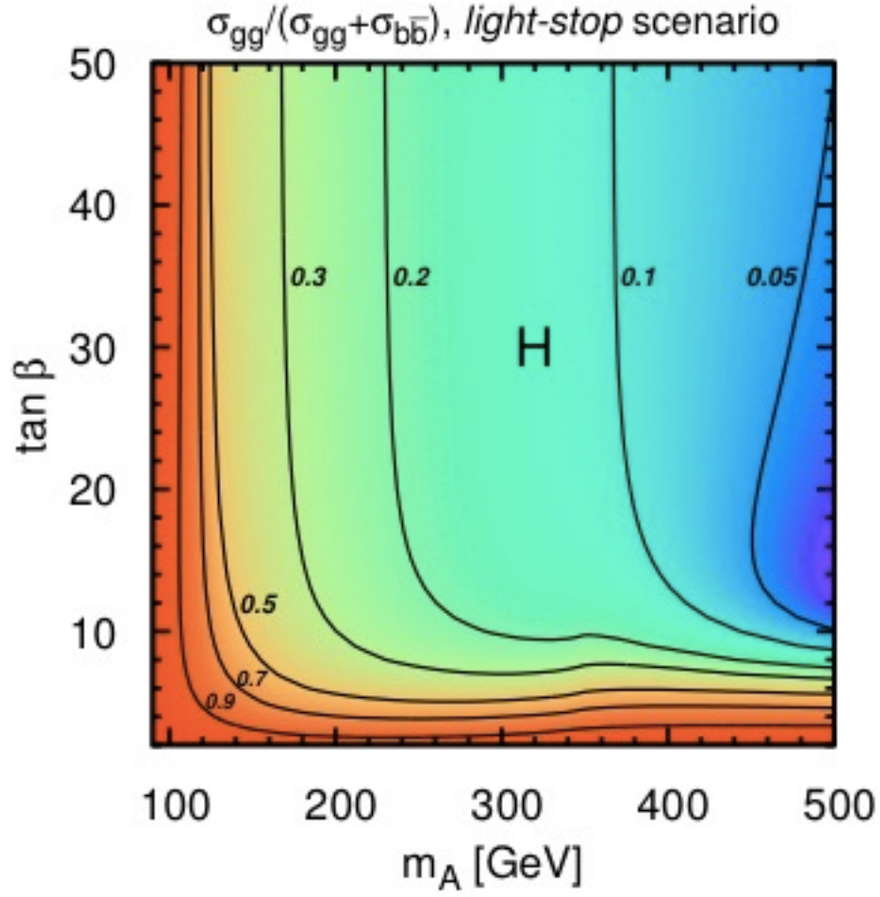
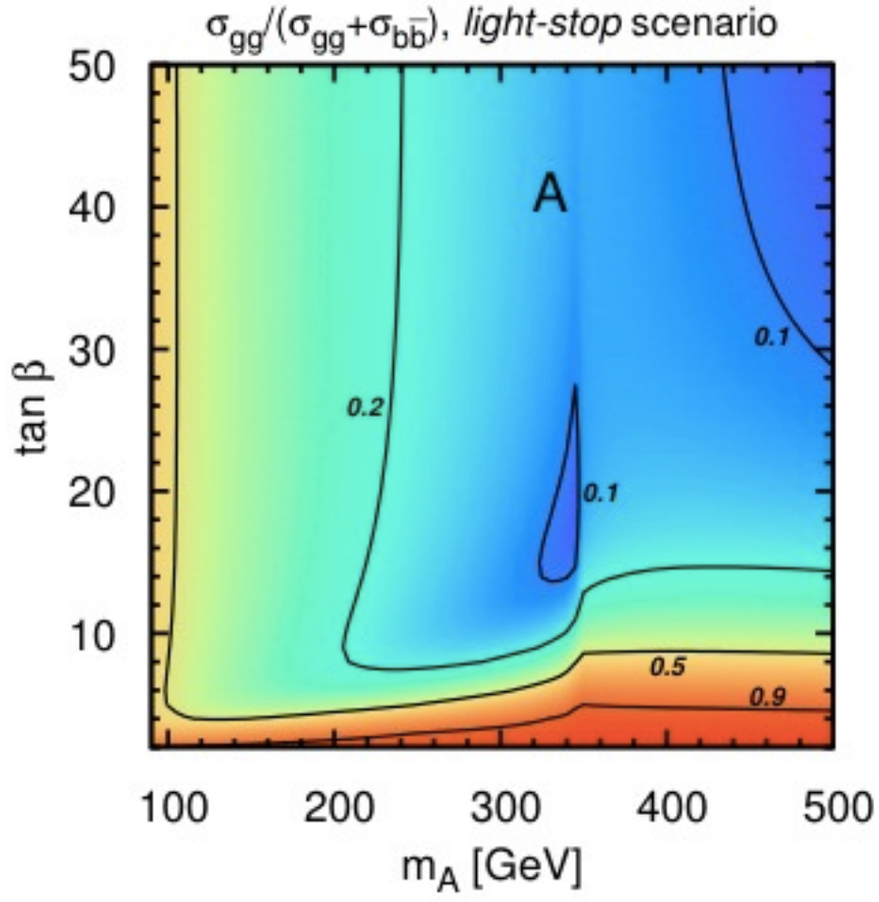
- cross sections for viable MSSM scenarios

Carena, Heinemeyer, Stål, Wagner, Weiglein '13



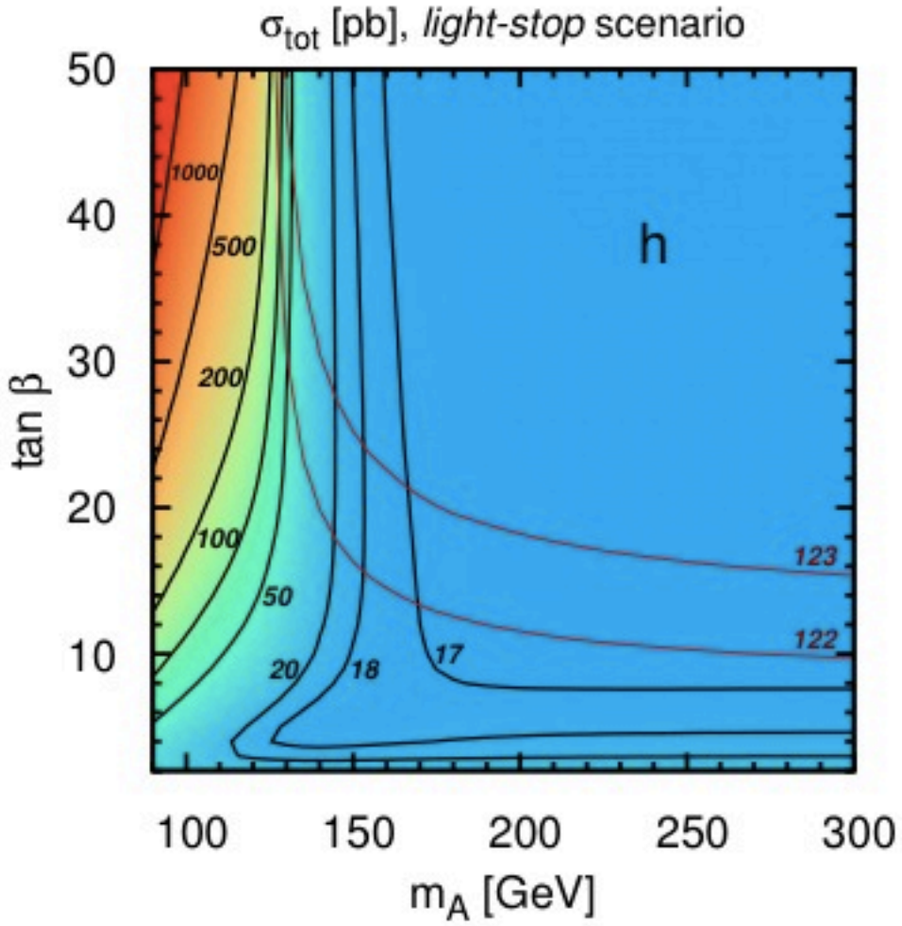


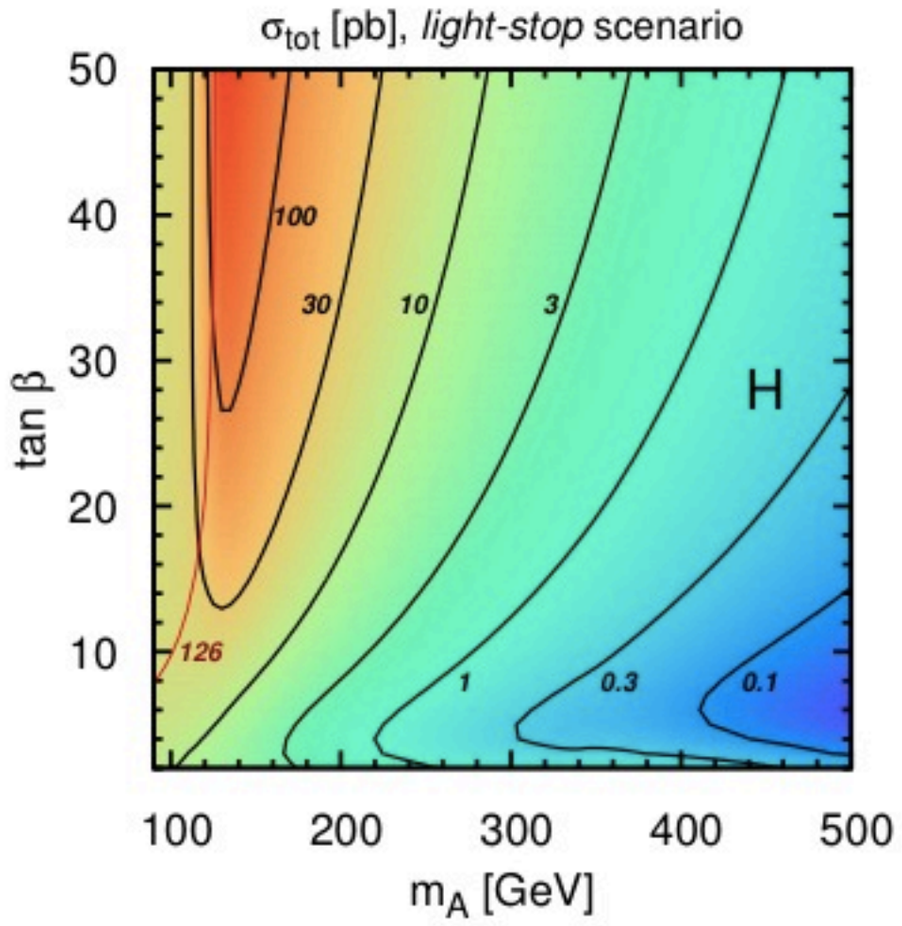
$\sigma_{gg}/(\sigma_{gg}+\sigma_{b\bar{b}})$

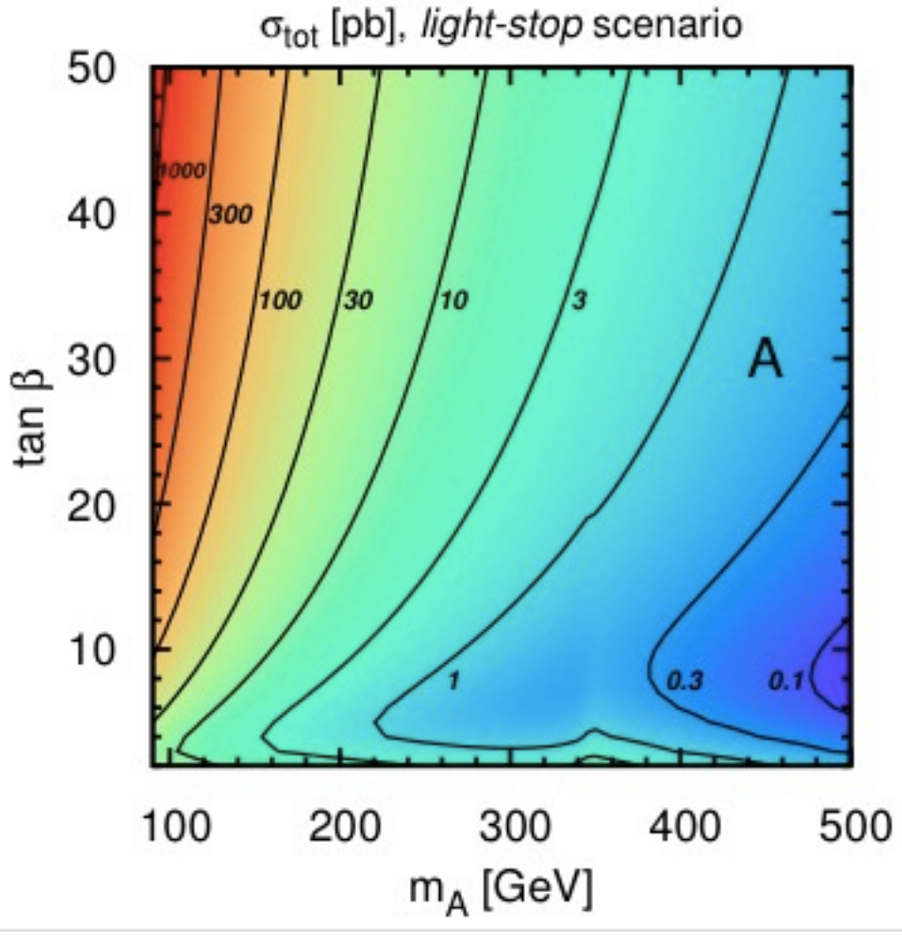


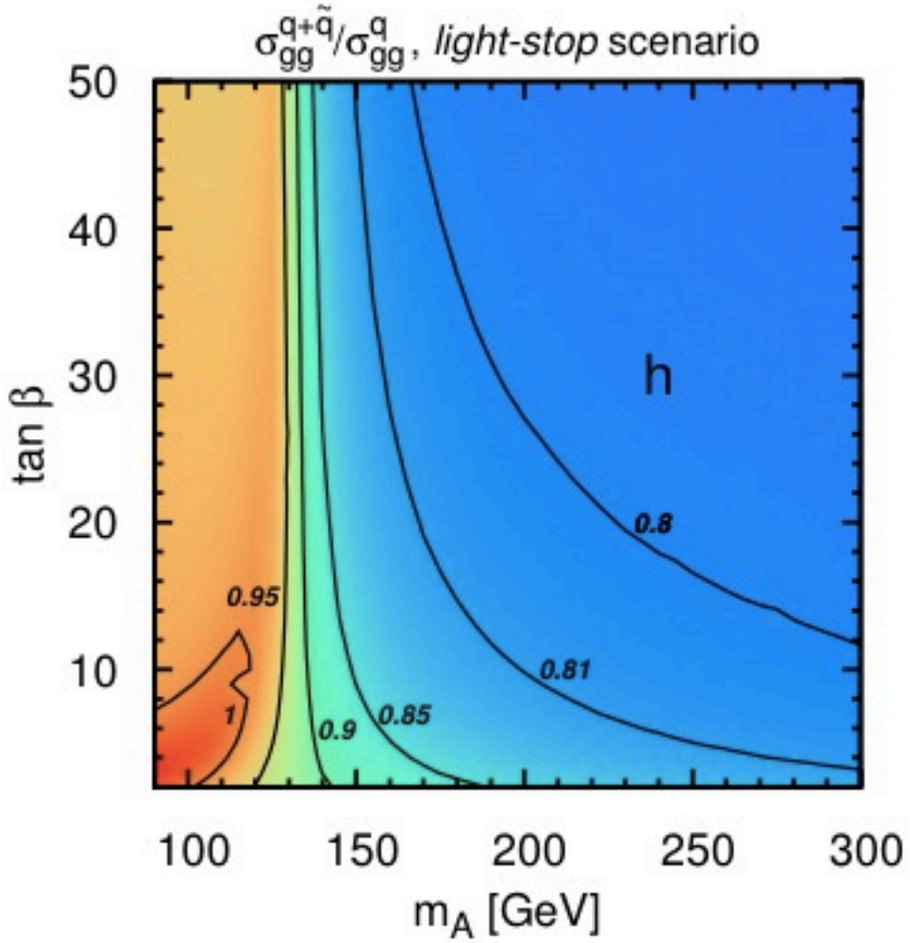
σ_{tot} [pb]

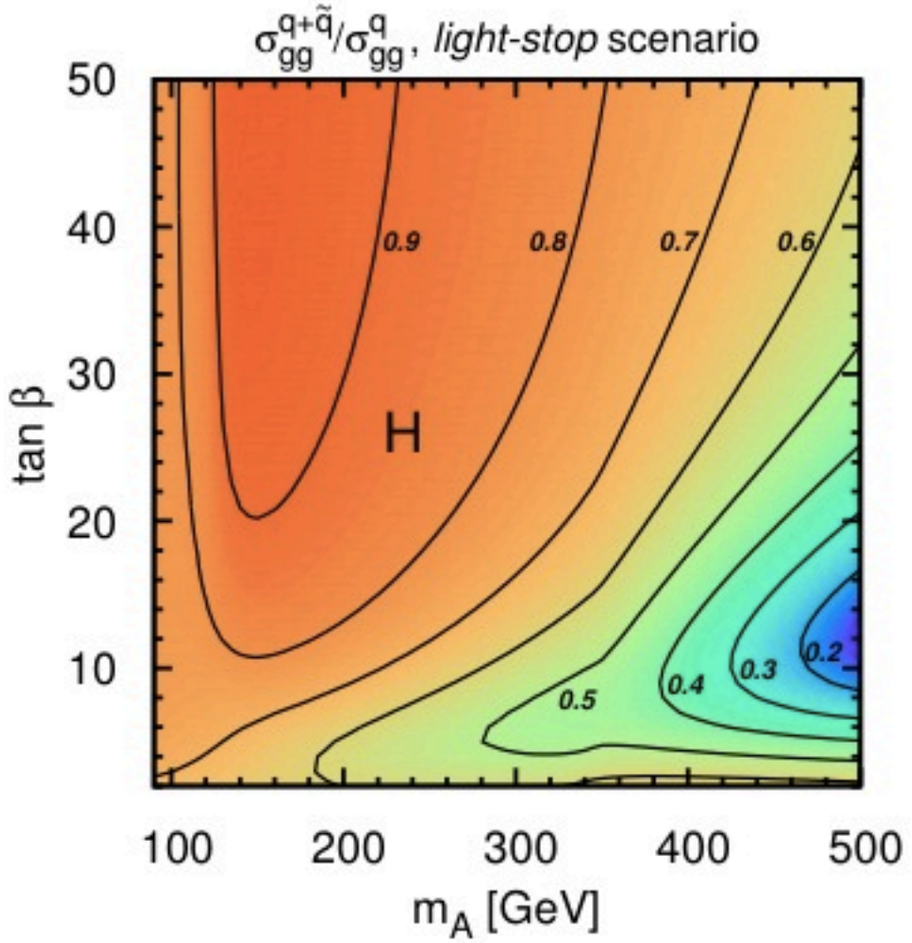
(see also new grids from LHXSWG;
thanks for M. Acosta and T. Vickey)





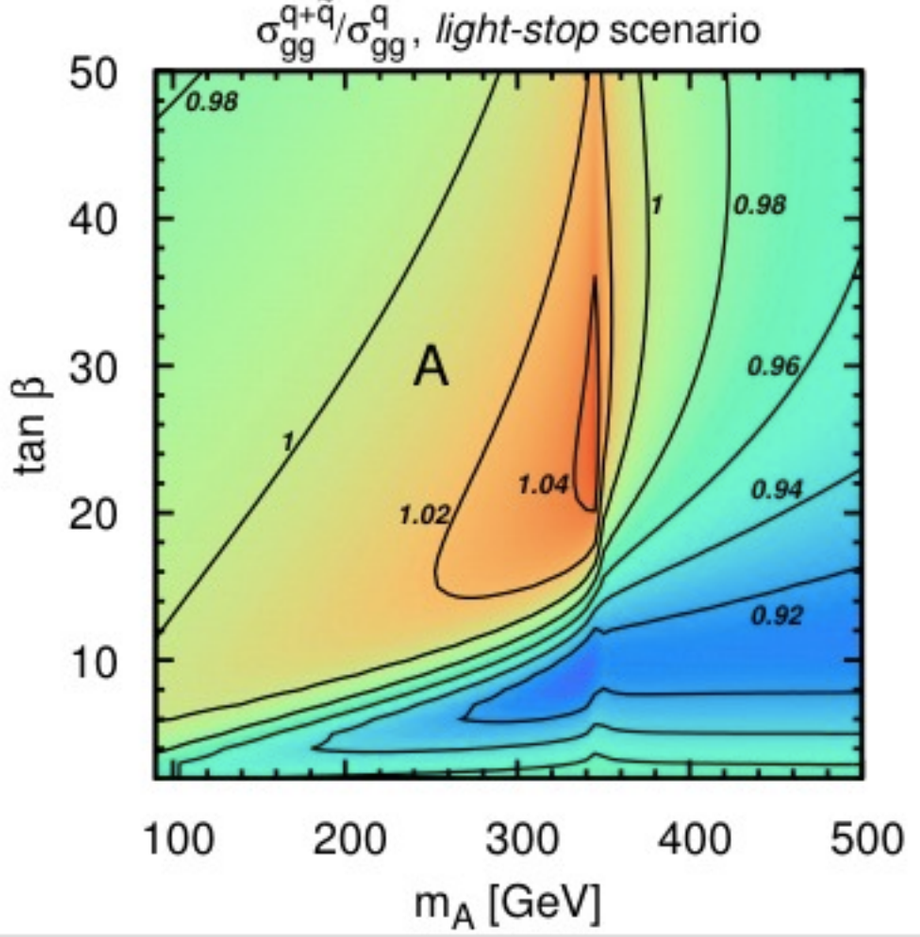






squark effects:

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



Uncertainties:

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- renormalization/factorization scale
- PDF, α_S

→ SM-like

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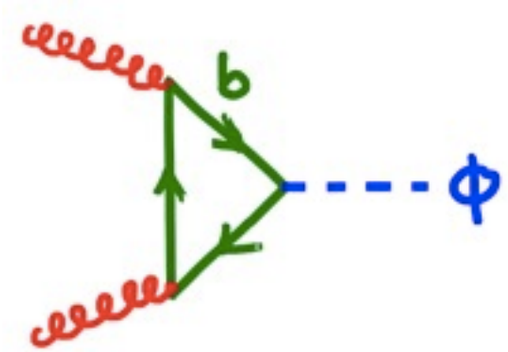
additionally:



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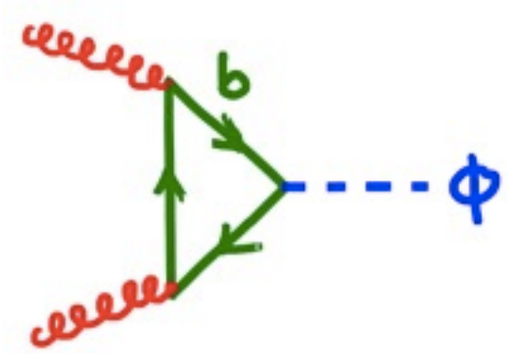

- "usual" scale choice: $\mu=M_H$
- amplitude contains logarithms $\ln(m_b/m_H)$
- partly cancelled by $\mu=m_b$ or $m_b=m_b(\text{pole})$ in Yukawa coupling

Spira, Djouadi, Graudenz, Zerwas '95

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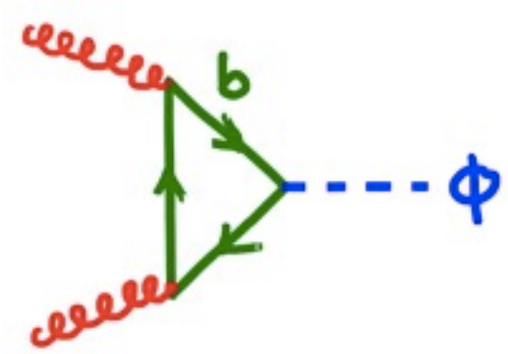

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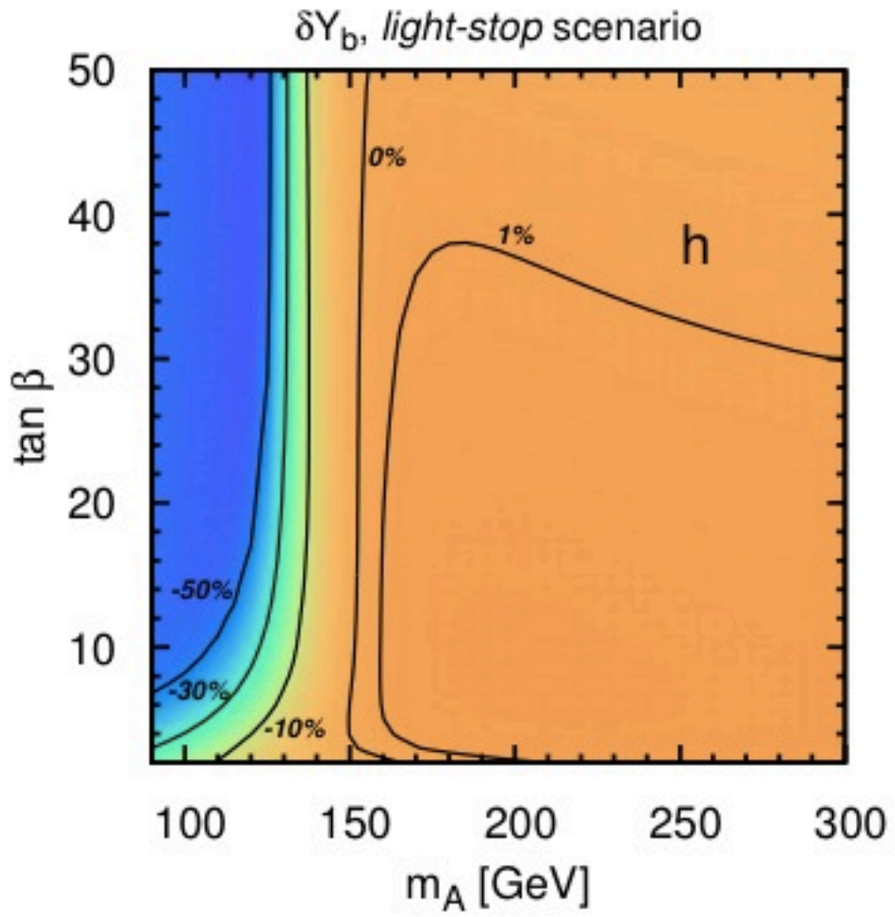
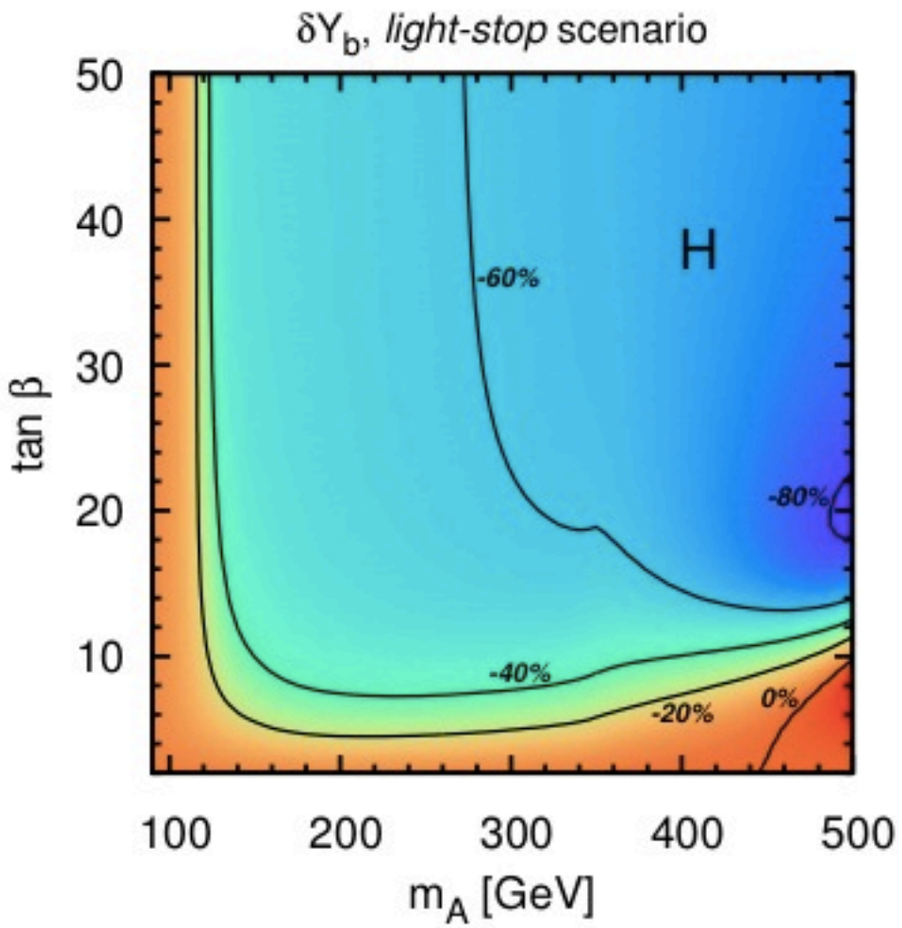
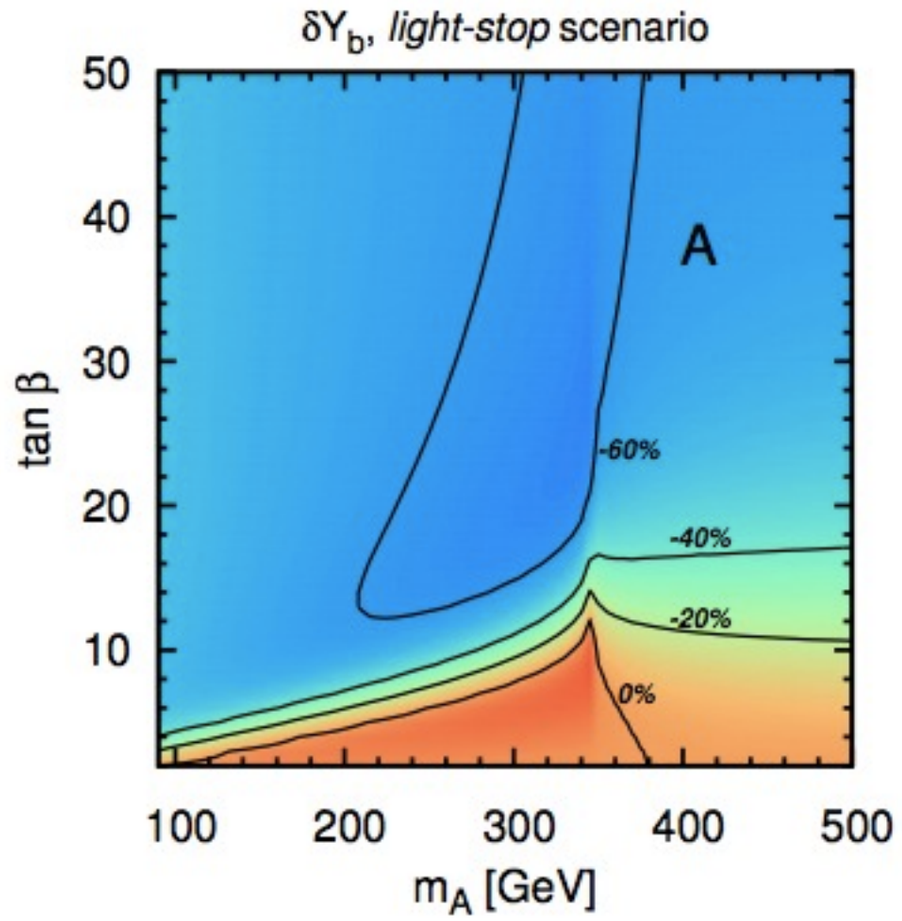
Spira, Djouadi, Graudenz, Zerwas '95

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





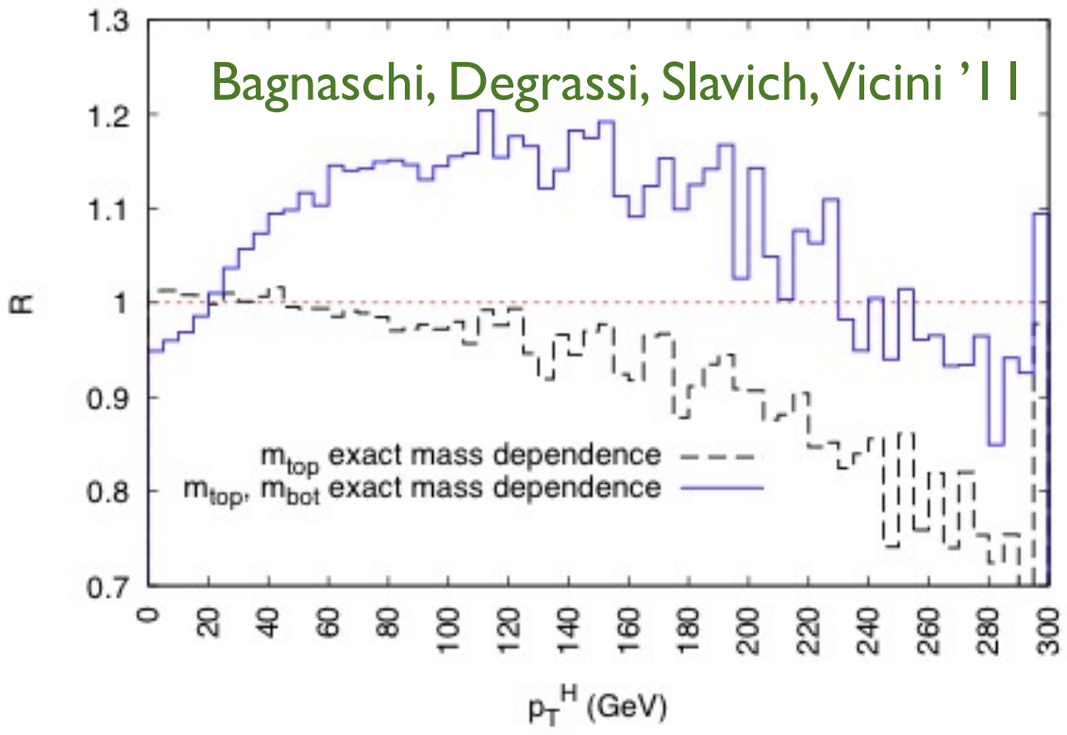
$m_b(M_H/2)$ vs. m_b(pole) in Yukawa coupling

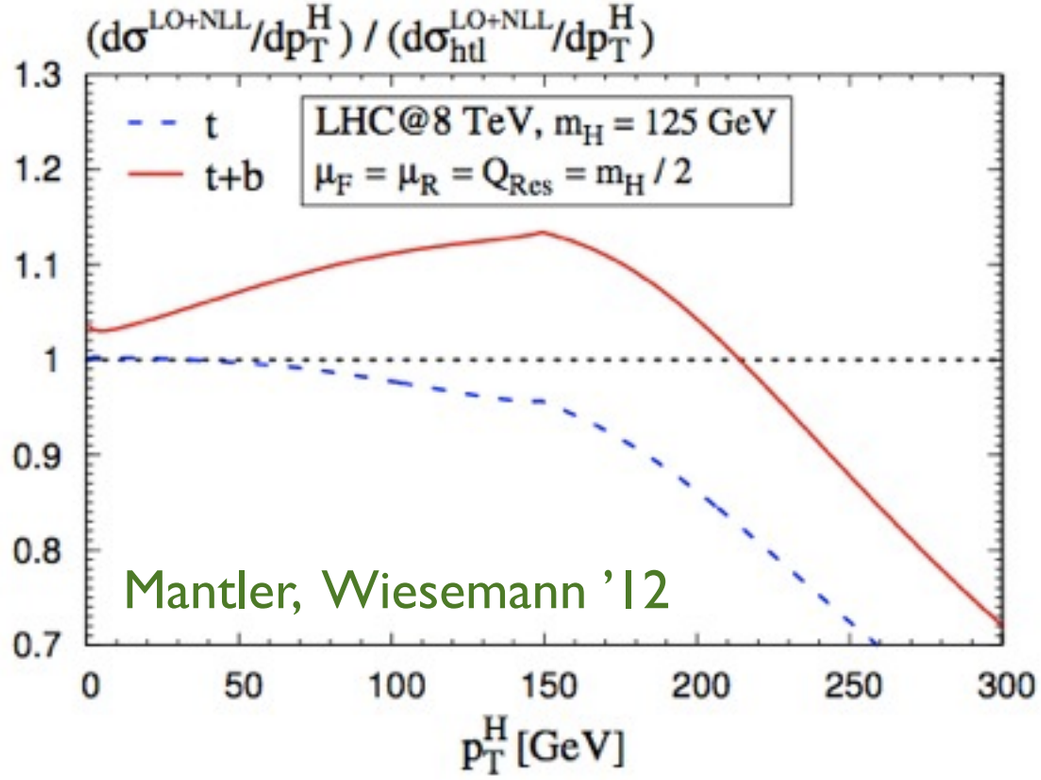


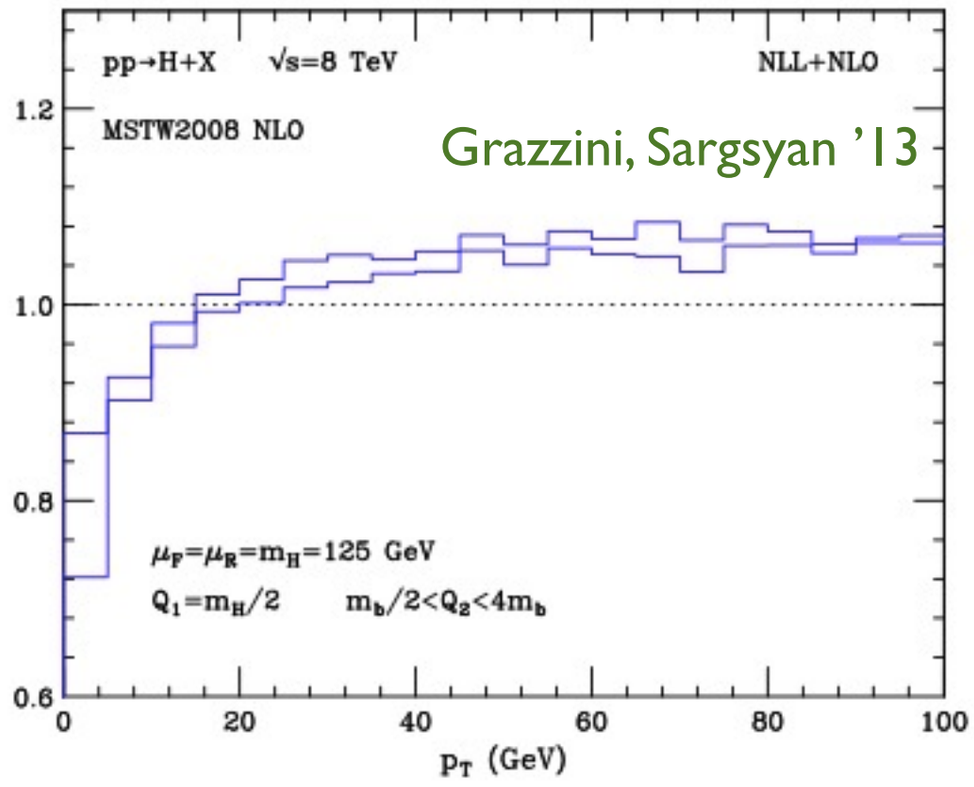
Open issues in gluon fusion:

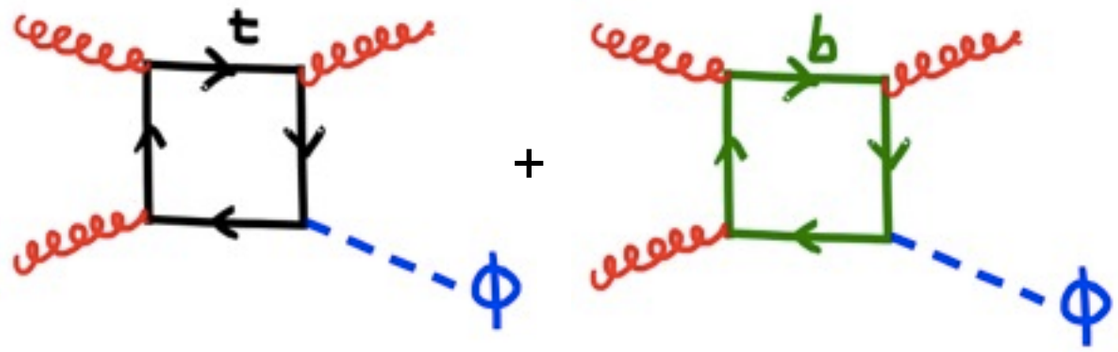
- NNLO (S)QCD only valid for heavy-top limit:
  what about M_H>350 GeV?
- SUSY EW corrections only approximately known
- proper treatment of bottom Yukawa coupling
- bottom effects in p_T distribution

Transverse momentum:









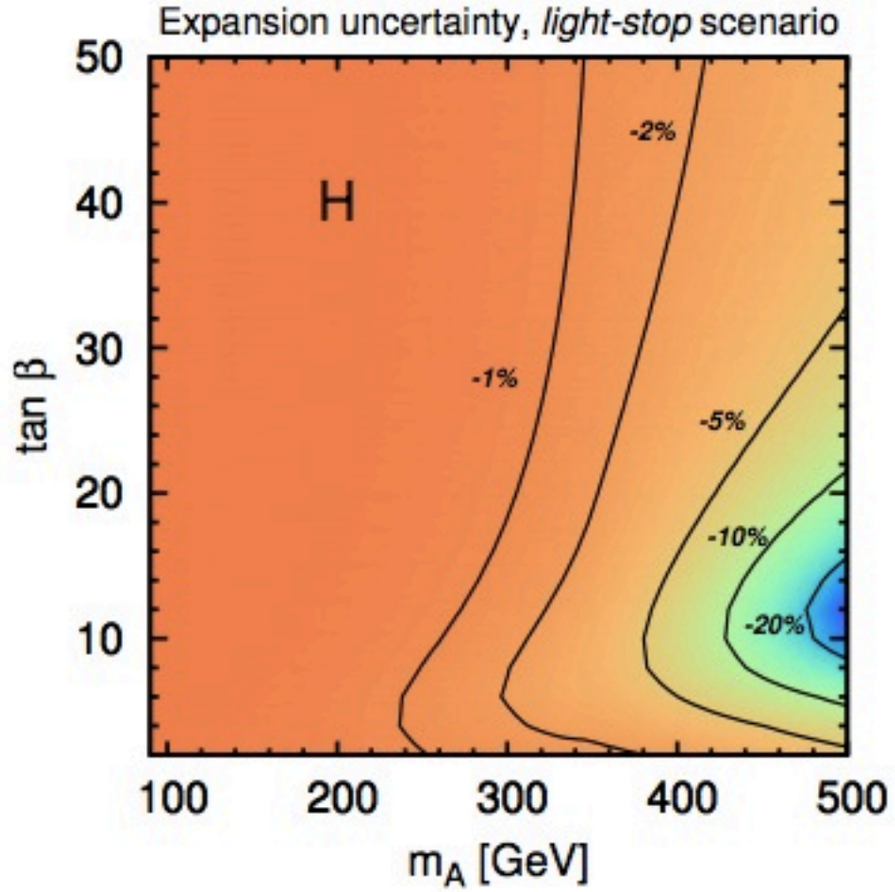
see also: Banfi, Monni, Zanderighi '14

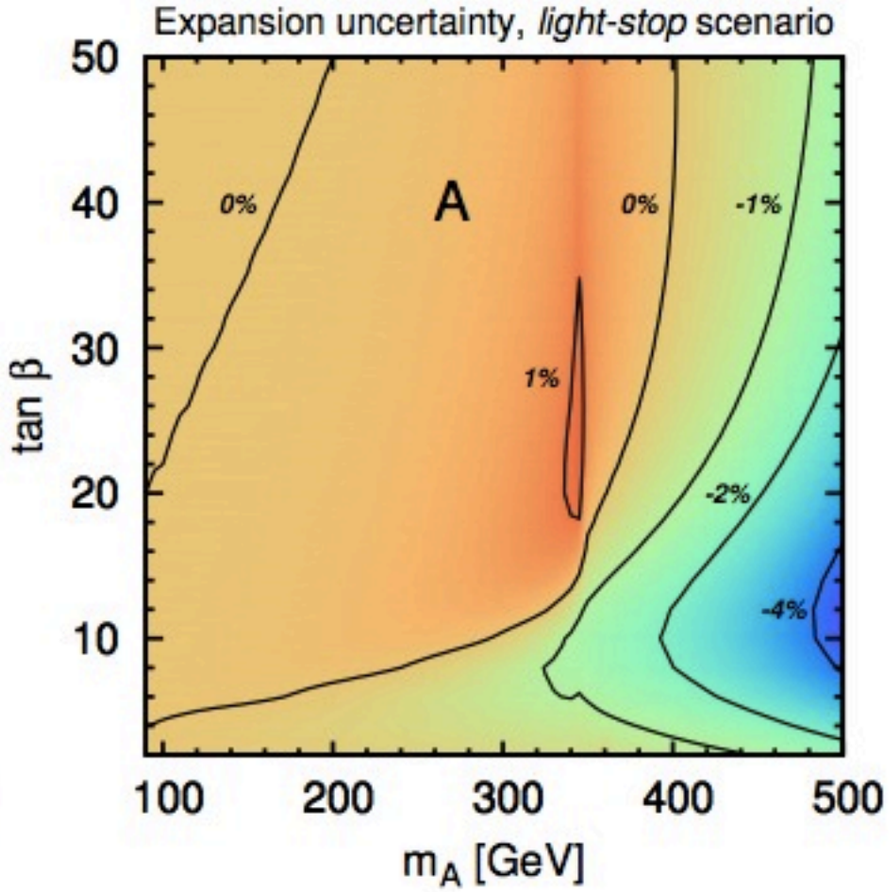
What I could not talk about:

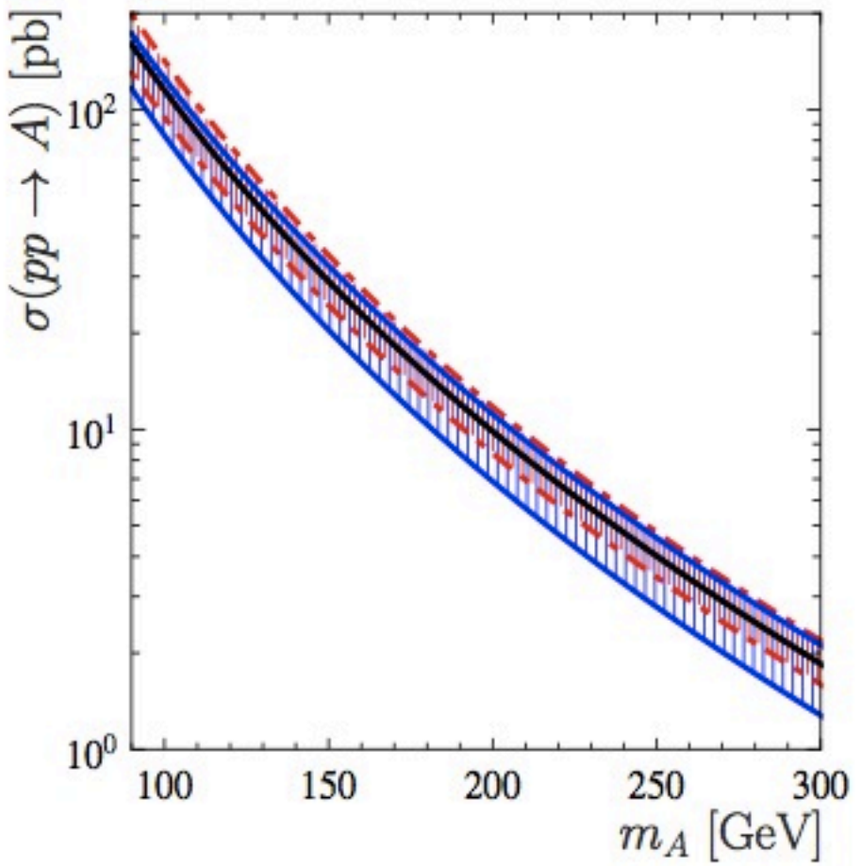
- pure SM calculations
- double Higgs production
- transverse momentum in bbh
- SUSY effects in ggh p_T
- ....

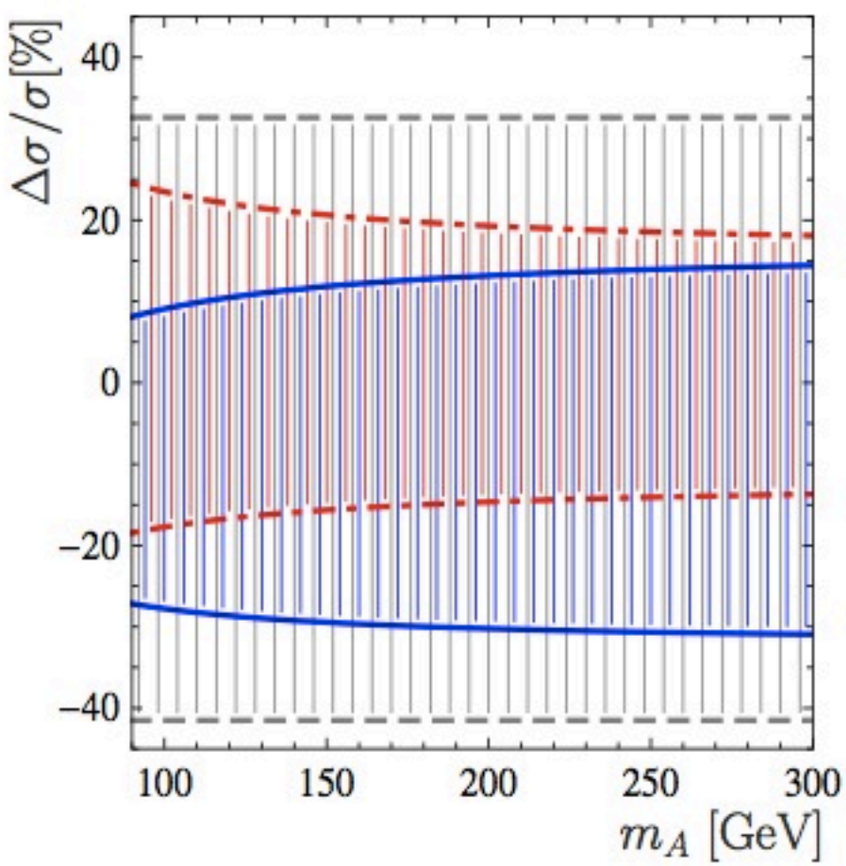
Conclusions

- 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]
50
40
30
20
10
100
200
300
400
500


Expansion uncertainty, *light-stop* scenario
A
0%
1%
-1%
-2%
-4%
tan β
m_A [GeV]
50
40
30
20
10
100
200
300
400
500


$\sigma(pp \to A)$ [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]