UNIVERSITÀ DEGLI STUDI
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INFN
Istituto Nazionale
di Fisica Nucleare

Tools to describe BSM Higgs production

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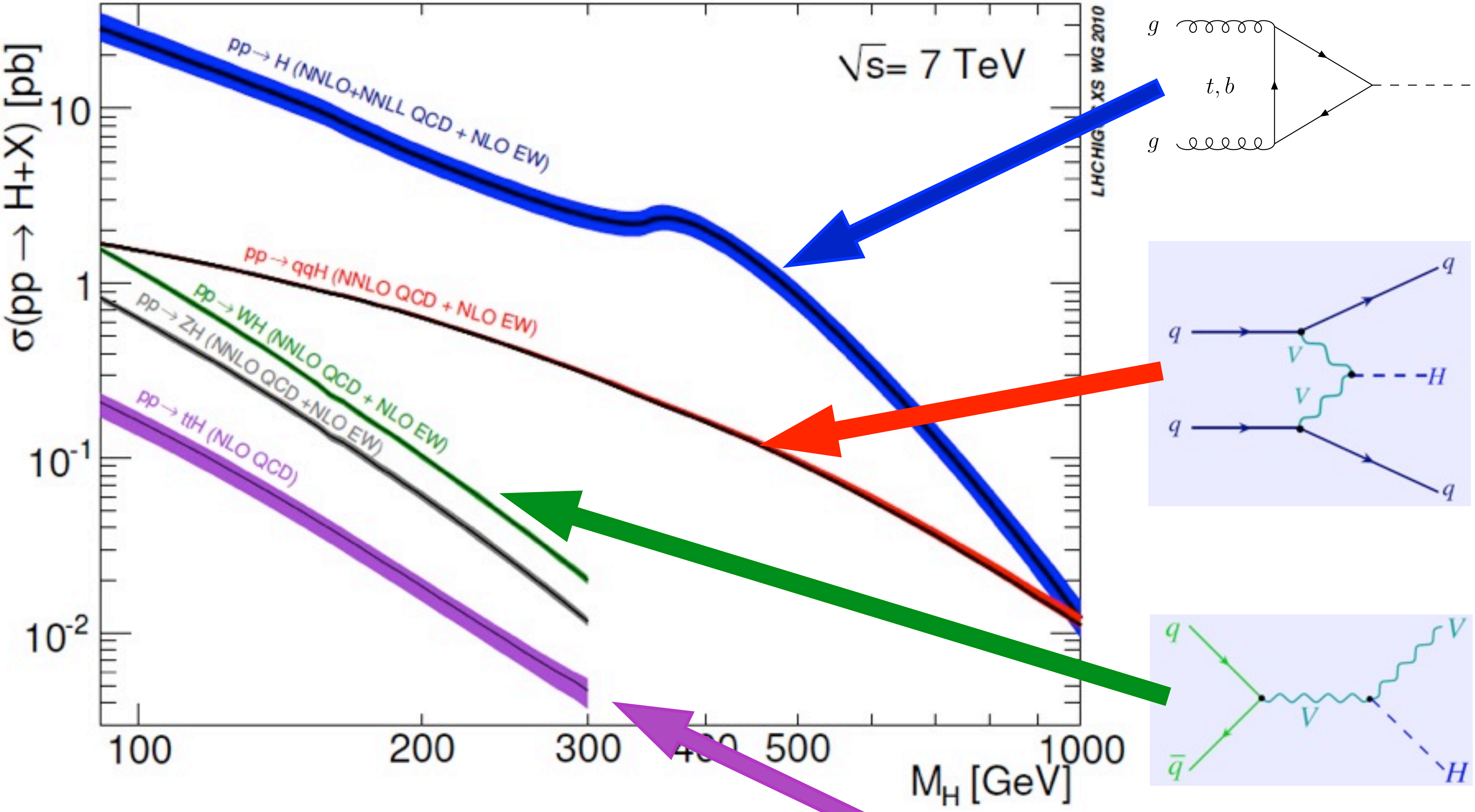
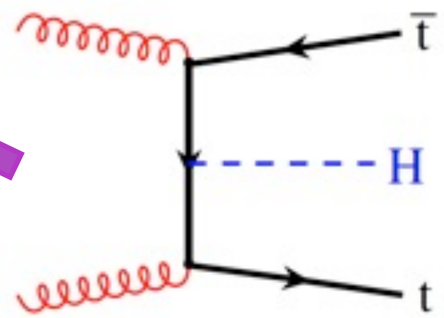
Torino, Higgs Couplings 2014, October 2nd 2014

this talk is not meant to be a systematic and comprehensive review
but it should rather address few question related to BSM simulations

The total production cross section: the SM case

- Yellow Report 1 of the Higgs Cross Section Working Group, arXiv:1101.0593





- the gluon fusion process dominates
  but weak-boson fusion has a very good signal/background ratio
- the uncertainty bands include: PDF+alphas uncertainty, scale uncertainty

The total production cross section: the SM case

- several SM processes available with NNLO-QCD and NLO-EW accuracy for the total xsec
  first examples of matching NNLO results with QCD Parton Shower
  analytical resummation of ptH distributions with NLO+NNLL accuracy of the Higgs ptH

- the theoretical uncertainties still represent a major bottleneck for precision studies
  first important steps towards NNNLO calculations of the gluon fusion process in progress

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Higgs total production cross section: BSM tools

- gluon fusion + bbar annihilation

HIGLU	MSSM, 2HDM
SusHi	MSSM, 2HDM
POWHEG	MSSM, 2HDM
aMC@NLO	MSSM, 2HDM, EFT

- vector boson fusion

VBFNLO	MSSM, anomalous couplings
aMC@NLO	EFT
POWHEG	ZZjj in EFT

- associate production

aMC@NLO	EFT
VBFNLO	anomalous couplings

Outline

- Study of the Higgs properties:

    - within any specific model (SM or BSM), for a given choice of input parameters, we can test its likelihood (we need to evaluate the uncertainties) and set limits

    - using an effective field theory (EFT) approach, we can relax the model-dependent hypotheses
        - parameterize the general features that the new particle might possess
        - following only general symmetry constraints
        - with a systematic approach to account for the radiative corrections
        - fit the additional free parameters

- Basic steps of a BSM calculation
    - choose a lagrangian that describes a model → Feynman rules
    - the couplings and the masses in the lagrangian can be either computed or are external inputs
    - the partonic subprocesses are embedded in the hadron-collider environment with a non trivial interface with "standard" QCD issues (fixed- and all-orders corrections)

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- In this talk:
  - evaluation of Higgs masses in the real MSSM
  - the 2HDM as a playground to study the top/bottom relative strength
  - accurate evaluation of the MSSM total cross section and of its uncertainties
  - the Higgs ptH distribution in presence of multiple scales
  - EFT in shower-MC

Evaluation of the Higgs masses in the MSSM

cfr Higgs Days 2014, talk by P.Slavich, http://indico.ifca.es/indico/contributionDisplay.py?contribId=21&confId=599

- General features
  - supersymmetry sets a relation between the gauge boson masses and the scalar particle masses such that it is possible to compute the Higgs mass
  - the radiative corrections overcome the tree-level limit Mh<MZ
  - the light Higgs should have Mh~125 GeV
    restriction in the allowed region in the MSSM parameter space
    → large stop mixing or
    → very heavy stops are necessary to push the lightest Higgs mass to O(125 GeV)

- Available codes for Real-MSSM spectra share the 1-loop full set of corrections
  - SPheno
  - SuSpect
  - SoftSusy
  - NMSSMTools
  - FeynHiggs

the 2-loop corrections (at zero momentum)

$\mathcal{O}(\alpha_t\alpha_s),\ \mathcal{O}(\alpha_b\alpha_s)$

$\mathcal{O}(\alpha_t^2),\ \mathcal{O}(\alpha_t\alpha_b+\alpha_b^2)$

$\mathcal{O}(\alpha_\tau^2),\ \mathcal{O}(\alpha_\tau\alpha_b)$ RG codes only

Evaluation of the Higgs masses in the MSSM

Simplified benchmark point: *tanβ* = 20, all SUSY masses = 1 TeV, A_t varied to maximize m_h

Code	Mh (GeV)
SPheno 3.3.3	126.2
SuSpect 2.43	125.8
SoftSUSY 3.5.1	124.3
NMSSMTools 4.2.1	124.4
FeynHiggs 2.10.1	129.8

All codes include
full 1-loop + dominant (strong+Yukawa) 2-loop
corrections to Mh

results obtained as the maximum Mh value
upon variation of the stop mixing parameters

- differences between the codes
  - determination of the top Yukawa coupling
  - renormalization scheme choice DRbar *vs* on-shell

- to obtain Mh ~ 125 GeV it is necessary to enter a region of the real MSSM parameter space where large corrections make the perturbative expansion slowly convergent and genuine 3-loop corrections would be needed to stabilize the result

Higgs production

Gluon fusion: total cross section in the SM

LO-QCD

Georgi Glashow Machacek Nanopoulos 1978

NLO-QCD

HQET
exact

Dawson 1991, Djouadi Graudenz Spira Zerwas 1992
Spira Djouadi Graudenz Zerwas 1995
Aglietti Bonciani Degrassi AV 2007
Anastasiou Beerli Bucherer Daleo Kunszt 2007

HIGLU
POWHEG
FeHipro

NNLO-QCD
HQET

Harlander Kilgore 2002
Anastasiou Melnikov 2002
Ravindran Smith van Neerven 2003

iHixs, ggh@nnlo, HNNLO

NNLO-QCD + soft gluon resummation NNLL-QCD
HQET

Catani De Florian Grazzini Nason 2003
Moch Vogt 2005 Ravindran 2006 Idilbi Ji Yuan 2006
Ravindran Smith van Neerven 2007

NNLO-QCD + finite top mass effects

Marzani Ball Del Duca Forte AV 2008
Harlander Ozeren 2009 Pak Rogal Steinhauser 2009
Harlander Mantler Marzani Ozeren 2009

NLO-EW

Djouadi Gambino 1994
Aglietti Bonciani Degrassi AV 2004
Degrassi Maltoni 2004
Actis Passarino Sturm Uccirati 2008

mixed NLO EWxQCD

Anastasiou Boughezal Petriello 2009

iHixs

NNNLO-QCD soft approximation
HQET

Anastasiou Duhr Dulat Furlan Gehrmann Herzog Mistlberger 2014
Bonvini Ball Forte Marzani Ridolfi 2014

ggHiggs

The 2HDM in a nutshell

- 2 complex scalar doublets Φ_1 and Φ_2 with VEVs v_1 and v_2
  3 d.o.f. are the longitudinal polarization of Ws and Z
  5 d.o.f. are in the physical spectrum: 2 charged scalars, 2 neutrals CP-even, 1 neutral CP-odd

- input parameters are: α, $\tan\beta = v_2/v_1$, Mh, MH, MA, M±, M_{12}

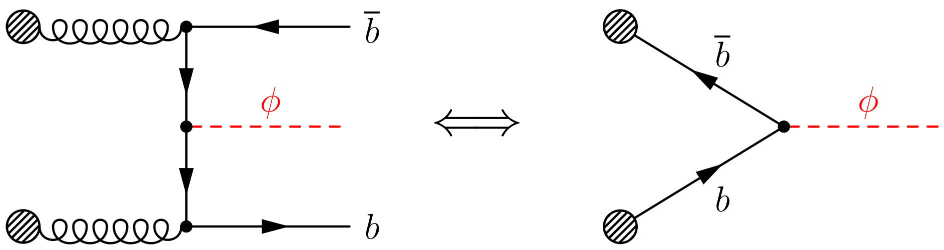
- the presence of additional discrete symmetries forbids the appearance of tree-level FCNC leading to different types of models;
  the couplings of the Higgs scalars to fermions are:

	Type I	Type II	Lepton-specific	Flipped
ξ_h^u	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$
ξ_h^d	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$
ξ_h^ℓ	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$-\sin\alpha/\cos\beta$	$\cos\alpha/\sin\beta$
ξ_H^u	$\sin\alpha/\sin\beta$	$\sin\alpha/\sin\beta$	$\sin\alpha/\sin\beta$	$\sin\alpha/\sin\beta$
ξ_H^d	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$
ξ_H^ℓ	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$	$\cos\alpha/\cos\beta$	$\sin\alpha/\sin\beta$
ξ_A^u	$\cot\beta$	$\cot\beta$	$\cot\beta$	$\cot\beta$
ξ_A^d	$-\cot\beta$	$\tan\beta$	$-\cot\beta$	$\tan\beta$
ξ_A^ℓ	$-\cot\beta$	$\tan\beta$	$\tan\beta$	$-\cot\beta$

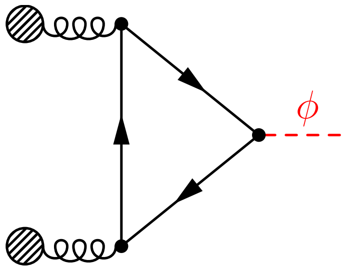
Neutral Higgs production in the 2HDM: gg+bbar

R.Harlander, M.Mühlleitner, J.Rathsmann, M.Spira, O.Stål, arXiv:1312.5571

bottom quark annihilation



gluon fusion



- The gluon fusion is mediated only by quark loops (no additional colored particles)

- LO, NLO-QCD and NNLO-QCD (HQET) corrections are borrowed form the SM, with rescaling of the top and bottom Yukawa couplings

- full NLO-EW corrections are not available in the 2HDM; only the light-fermion subset can be taken from the SM and properly rescaled

- available codes for the production of h, H, A (neutral Higgses)
  - → HIGLU NLO-QCD (exact t, b) + NNLO-QCD (HQET) + NLO-EW (light f)
    M.Spira, hep-ph/9510347
  - → SusHi NLO-QCD (exact t, b) + NNLO-QCD (HQET) + NLO-EW (light f)
    R.Harlander, S.Liebler, H.Mantler, arXiv:1212.3249
  - → POWHEG gg_H_2HDM NLO-QCD (exact t, b) + NLO-EW (light f) in gluon fusion
    E.Bagnaschi, G.Degrassi, P.Slavich, AV, arXiv:1111.2854

good agreement (0.1% level) between the three codes (with same accuracy) for the total cross section predictions

Neutral Higgs production in the 2HDM: gg+bbar

R.Harlander, M.Mühlleitner, J.Rathsmann, M.Spira, O.Stål, arXiv:1312.5571

- caveat

  the couplings have an important impact not only at LO but also at NLO-QCD

  → a global rescaling of 2HDM LO results with a SM K-factor is not possible

$$\sigma_{2HDM}^{approx} = \frac{\sigma_{SM}^{NNLO}}{\sigma_{SM}^{LO}} \left(g_t^2\, \sigma_{tt}^{LO} \; + \; g_t g_b\, \sigma_{tb}^{LO} \; + \; g_b^2\, \sigma_{bb}^{LO} \right) \qquad g_q = \frac{y_q^{(2HDM)}}{y_q^{(SM)}}$$

can differ by 50% from the correct result

the use of dedicated codes is highly recommended

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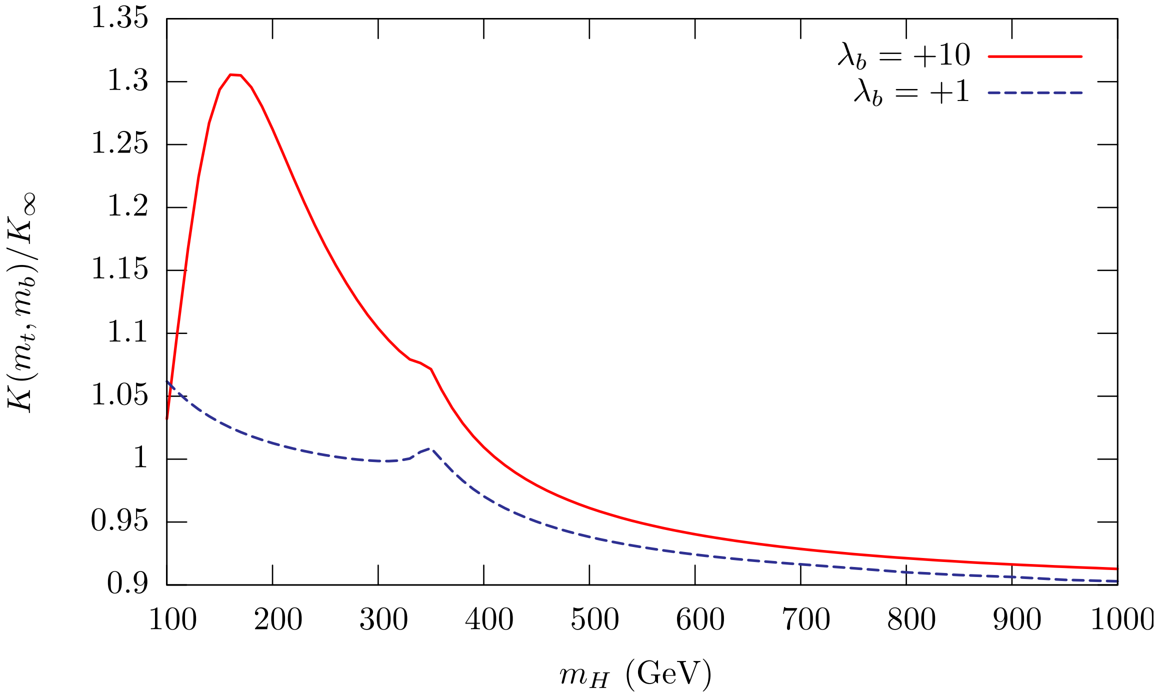
$$K(m_t, m_b) \equiv \frac{\sigma_{NLO}(m_t, m_b)}{\sigma_{LO}(m_t, m_b)}$$

$$K_\infty \equiv \frac{\sigma_{NLO}(HQET)}{\sigma_{LO}(HQET)}$$



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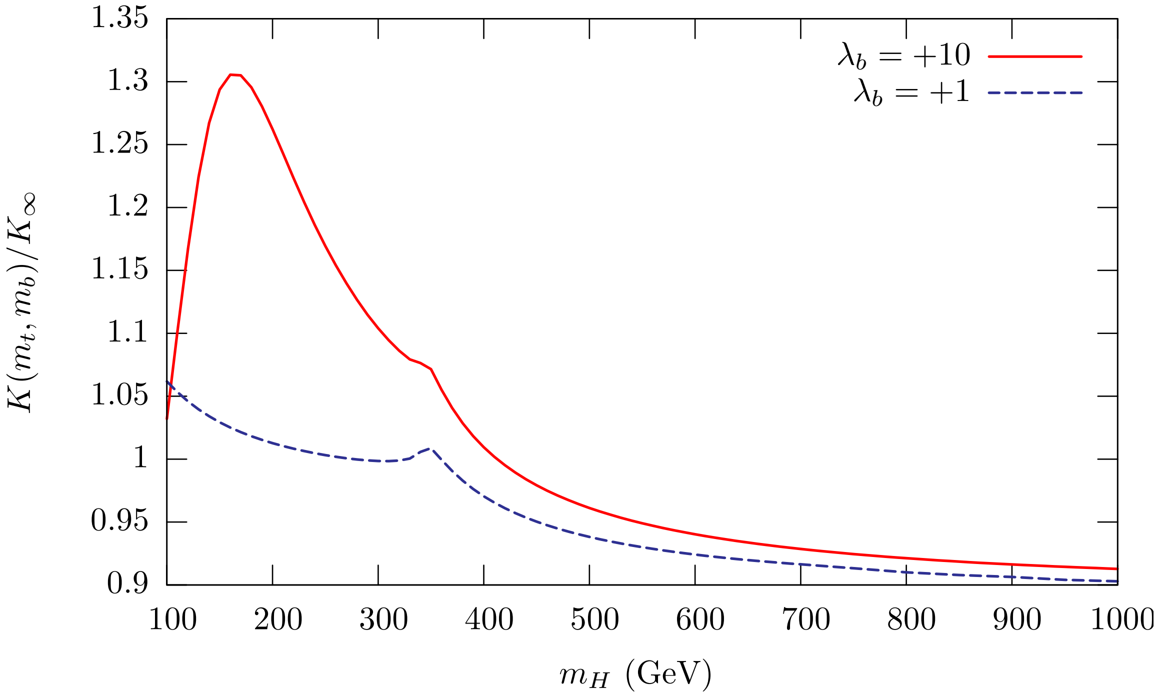


- effective accuracy of the result: it depends on the relative strength of the top and bottom couplings

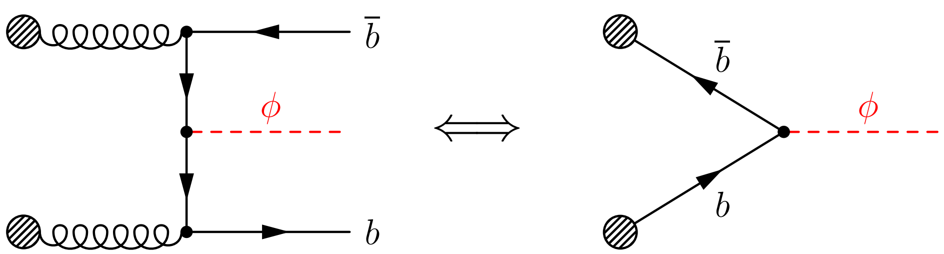
→ NNLO-QCD when the top quark dominates the amplitude,

→ NLO-QCD when the bottom quark gives the leading contribution

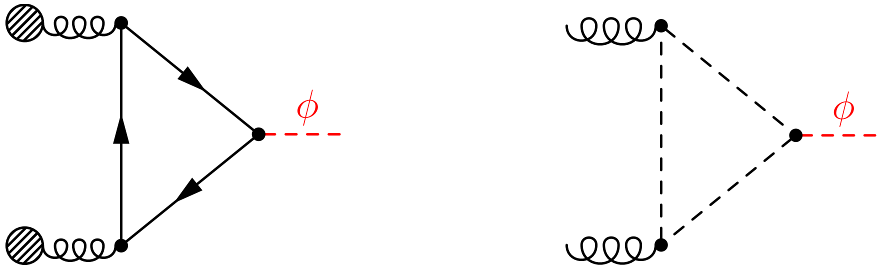
→ the residual uncertainty (e.g. estimated via scale variations) depends on the model parameters (more details along the same lines in the MSSM slides)

Neutral Higgs production in the MSSM, gg+bbar: available corrections

bottom quark annihilation

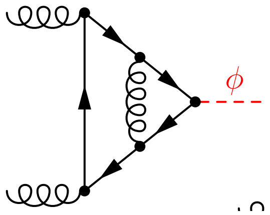


gluon fusion

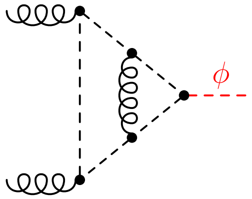


- the MSSM dominant production channel is (gluon fusion + bottom quark annihilation)
- as in the 2HDM, the Higgs top and bottom Yukawa couplings depend on the model parameters

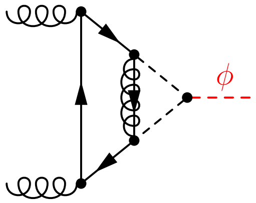
- gluon-quark corrections: NLO analytical results
  Spira Djouadi Graudenz Zerwas 1995, Harlander Kant 2005,
  Aglietti Bonciani Degrassi AV 2006, Bonciani Degrassi AV 2007



- gluon-squark corrections: NLO analytical and numerical
  Anastasiou Beerli Bucherer Daleo Kunszt 2006,
  Aglietti Bonciani Degrassi AV 2006, Mühlleitner Spira 2006, Bonciani Degrassi AV 2007



- gluino-squark-quark interaction:
  semi-analytical results
  Anastasiou Beerli Daleo 2008, Mühlleitner Rzehak Spira 2010
  Taylor expansion in small Higgs mass
  Harlander Steinhauser 2003,2004 Harlander Steinhauser Hoffmann 2005 Degrassi Slavich 2008
  expansion in heavy SUSY masses
  Harlander Hoffmann Mantler 2010, Degrassi Slavich 2010, Degrassi Di Vita Slavich 2011 2012



- complete NLO-EW corrections in the MSSM are not available;
  the SM light-fermion contribution can be included with the proper rescaling of the couplings

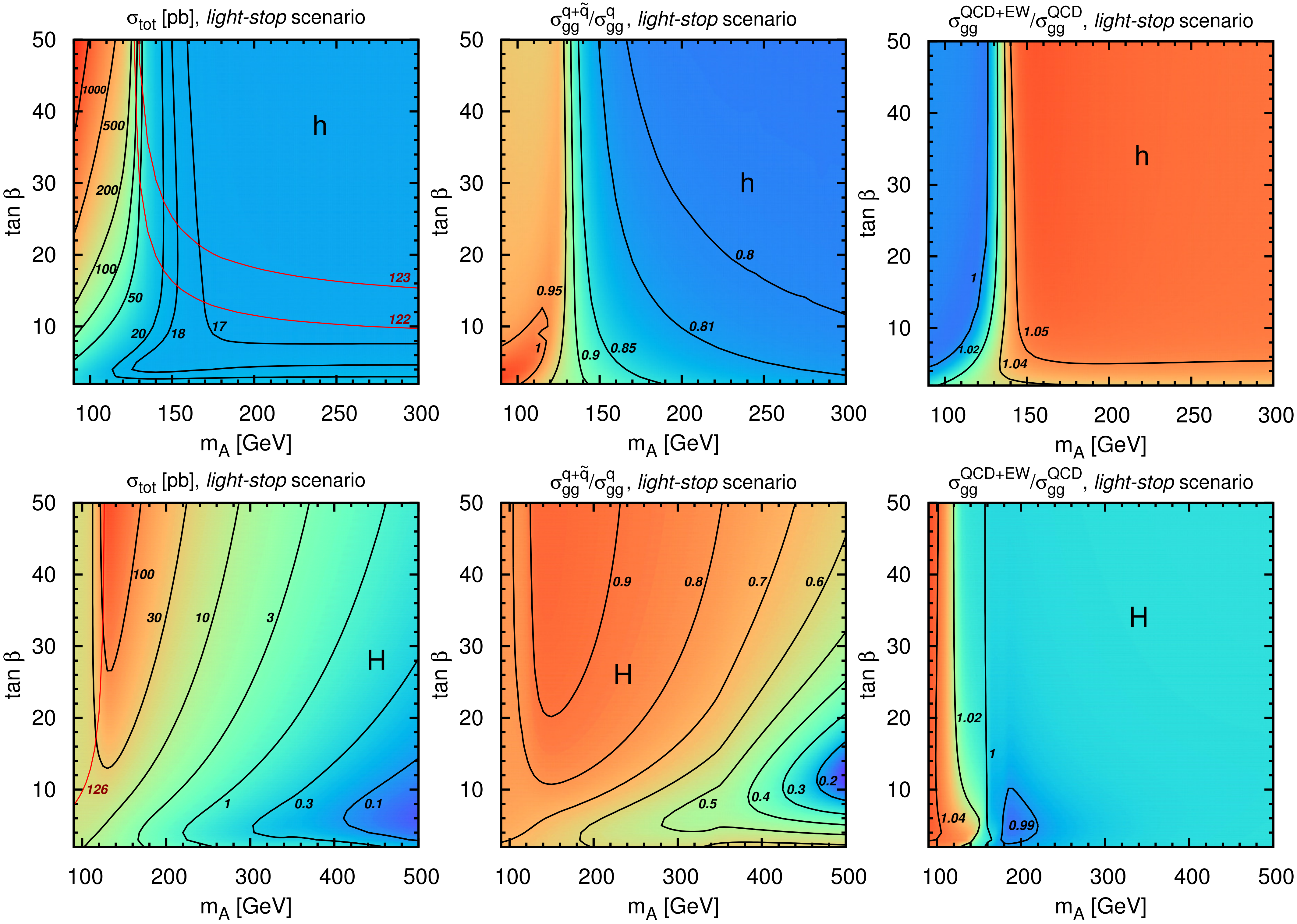
Neutral Higgs production in the MSSM: gg+bbar

- available codes for the production of h, H, A via gluon fusion / bbar annihilation
  - SusHi R.Harlander, S.Liebler, H.Mantler, arXiv:1212.3249 includes
    the complete set of NLO-QCD corrections in the MSSM (either analytical or via mass expansions)
    the NLO-EW light fermion contributions
    the NNLO-QCD corrections to the quark loops (HQET) and
    to the stop loop diagrams (mass expansion)
  - POWHEG gg_H_MSSM E.Bagnaschi, G.Degrassi, P.Slavich, AV, arXiv:1111.2854
    shows very good agreement (with same accuracy) with SusHi
    for the total cross section prediction of the gluon fusion process;
    both codes share the same NLO matrix elements
  - aMC@NLO https://cp3.irmp.ucl.ac.be/projects/madgraph/wiki/HSushi
    includes the porting of the SusHi results in this matching/showering framework

Neutral Higgs production in the MSSM: neutral CP-even scalars

E.Bagnaschi, R.Harlander, S.Liebler, H.Mantler, P.Slavich, AV, arXiv:1404.0327

total cross section | squark contribution | electroweak corrections



- not negligible squark contribution (light stop scenario) to the total cross section

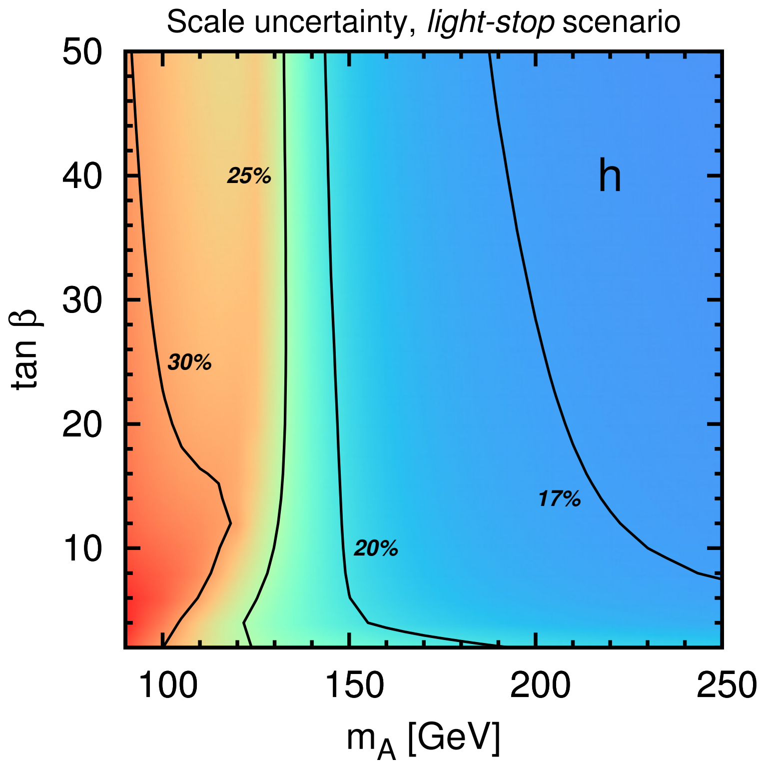
Neutral Higgs production in the MSSM: uncertainties of the total cross section

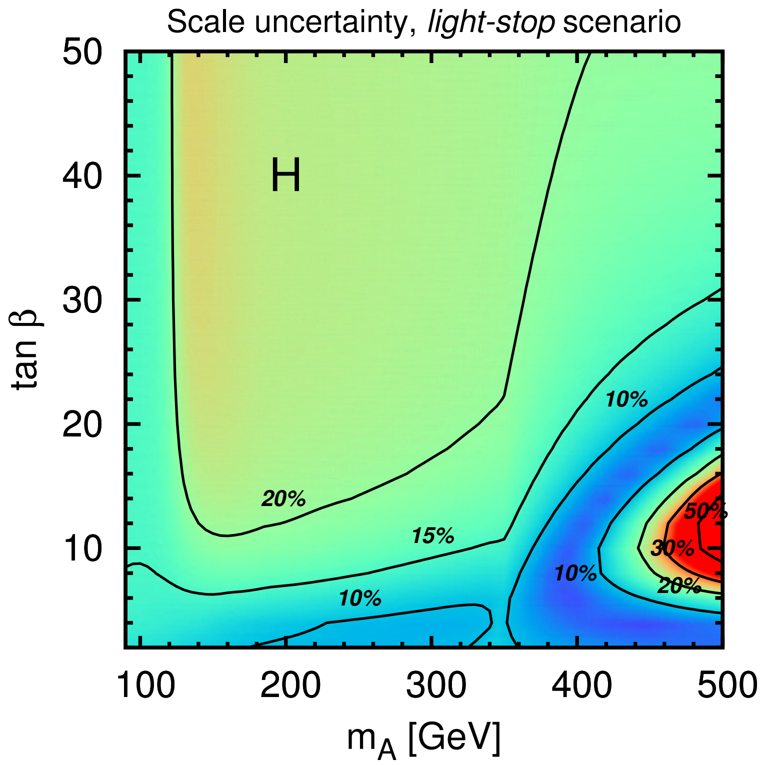
E.Bagnaschi, R.Harlander, S.Liebler, H.Mantler, P.Slavich, AV, arXiv:1404.0327

- sources of uncertainty under discussion
  - scale variations
  - PDF + α_s
  - inclusion of NNLO stop contributions
  - determination of the bottom Yukawa coupling

$$\mu_R = \{m_\phi/4,\, m_\phi/2,\, m_\phi\}$$
$$\mu_F = \{m_\phi/4,\, m_\phi/2,\, m_\phi\}$$

C_μ are all the scale combinations with the constraint $1/2 \le \bar\mu_R/\bar\mu_F \le 2$





$$\sigma^+ \equiv \max_{(\mu_R,\,\mu_F)\,\in\, C_\mu}\{\sigma(\mu_R,\mu_F)\}$$
$$\sigma^- \equiv \min_{(\mu_R,\,\mu_F)\,\in\, C_\mu}\{\sigma(\mu_R,\mu_F)\}$$

$$\Delta^\pm_\mu \equiv \frac{\sigma^\pm - \sigma(\mu_R^0,\mu_F^0)}{\sigma(\mu_R^0,\mu_F^0)}$$
$$\Delta_\mu \equiv \Delta^+ - \Delta^-$$

- light h
  - → in the decoupling limit, the uncertainty reaches the SM level
  - → when the bottom dominates, the accuracy is effectively NLO
- heavy H
  - → additional structures appear at large MA, where top,bottom and stop contributions tend to cancel increasing the sensitivity to higher orders
- the renormalization scale variation yields the largest contribution to the uncertainty

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- PDF + α_s uncertainty read from the SM results, for any given Higgs mass:
  the probed range of *x* and the associated PDF uncertainty is dictated by kinematics (i.e. by Mh)

- inclusion of NNLO stop contributions
  - good quality of the mass expansion, uncertainty of O(5%),
    with the exception of the region where accidental cancelations occur at NLO
  - missing 3-loop corrections in the stop sector are estimated to be at the 1% level

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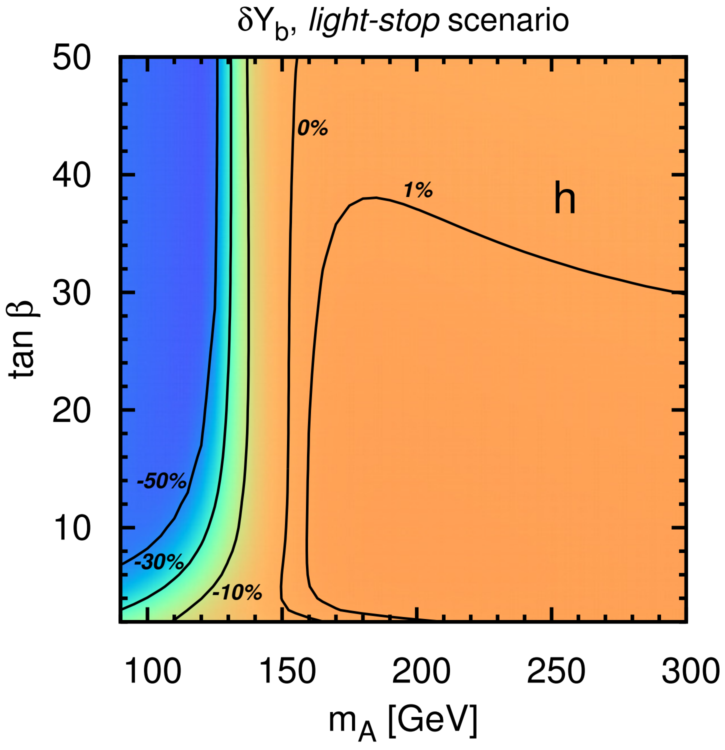
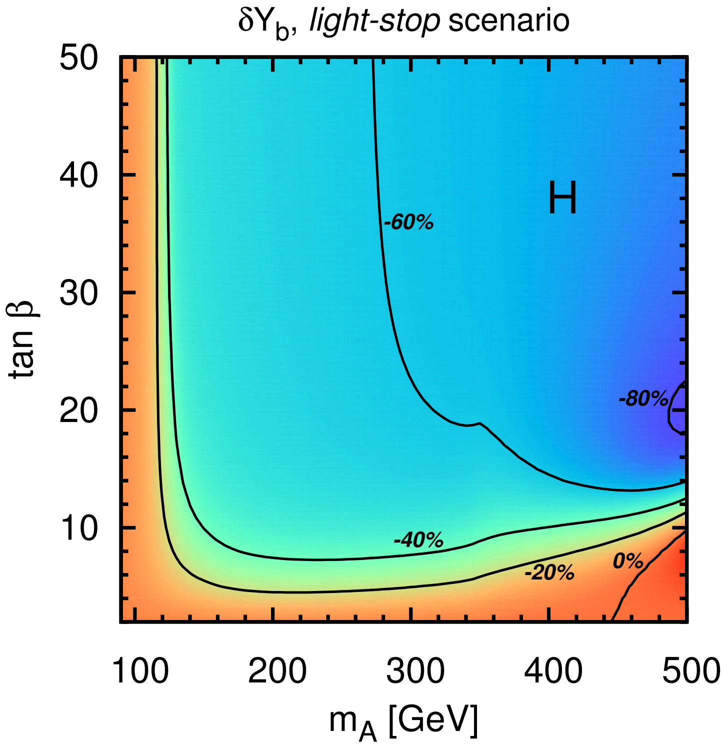
- determination of the bottom Yukawa coupling
  - choice of renormalization scheme and scale that define the bottom mass of the Yukawa coupling
  - higher-order tanβ-enhanced Δ_b terms that can be resummed in the effective Higgs-bottom coupling

$$\begin{aligned} m_b(m_b) &= 4.16\,\mathrm{GeV} \\ m_b(m_\phi/2) &= 2.93\,\mathrm{GeV} \\ M_b &= 4.92\,\mathrm{GeV} \end{aligned}$$



δY_b, *light-stop* scenario



δY_b, *light-stop* scenario

- the choice of different values for the mass of the bottom Yukawa yields sizeable differences for the ggH xsec when bottom diagrams dominate

- the largest differences occur where Higgs production is dominated by bbar annihilation

- the resummation of the large logs of the renormalization scale would stabilize the ggH results (cfr H→γγ)

- the tanβ-enhanced terms induce O(10-25%) uncertainties

Neutral Higgs production in the MSSM: uncertainties of the total cross section

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  - choice of renormalization scheme and scale that define the bottom mass of the Yukawa coupling
  - higher-order tanβ-enhanced Δ_b terms that can be resummed in the effective Higgs-bottom coupling

$$\widetilde{Y_b}^h = \frac{Y_b^h}{1+\Delta_b}\left(1-\Delta_b\,\frac{\cot\alpha}{\tan\beta}\right),$$

$$\widetilde{Y_b}^H = \frac{Y_b^H}{1+\Delta_b}\left(1+\Delta_b\,\frac{\tan\alpha}{\tan\beta}\right),$$

$$\widetilde{Y_b}^A = \frac{Y_b^A}{1+\Delta_b}(1-\Delta_b\,\cot^2\beta)\,,$$

- these effective couplings can be computed in the limit of heavy superparticles
- depending on the parameter point the perturbative regime becomes questionable

- the precise evaluation of the factor Δ_b and its matching with the fixed order results can help to stabilize the predictions

- the choice of different values for the mass of the bottom Yukawa yields sizeable differences for the ggH xsec when bottom diagrams dominate

- the largest differences occur where Higgs production is dominated by bbar annihilation

- the resummation of the large logs of the renormalization scale would stabilize the ggH results (cfr H→γγ)

- the tanβ-enhanced terms induce O(10%) uncertainties

Neutral Higgs production in the MSSM: uncertainties of the total cross section

E.Bagnaschi, R.Harlander, S.Liebler, H.Mantler, P.Slavich, AV, arXiv:1404.0327

- sources of uncertainty under discussion

scale variations		± (8-30) %
PDF + α_s		± (7-10) %
inclusion of NNLO stop contributions		± (5-20) %
bottom Yukawa coupling:	missing terms in Δ_b	± 10 %
	Y_b renormalization	- (0-80) %

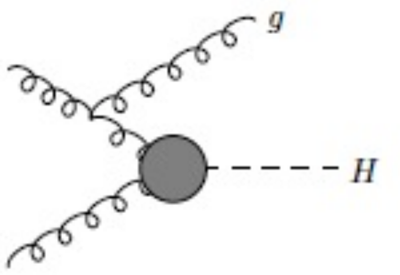
- the qualitative features of the total cross section depend crucially
  - on the top-bottom interplay
  - on the point chosen in parameter space

- the largest uncertainty comes from the definition of the bottom Yukawa coupling and could be stabilized with the resummation of the large log(Mh/mb)
  - this problem occurs in a region where the gluon fusion is subleading compared to bbar annihilation

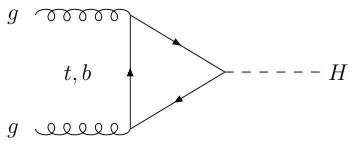
Differential cross sections

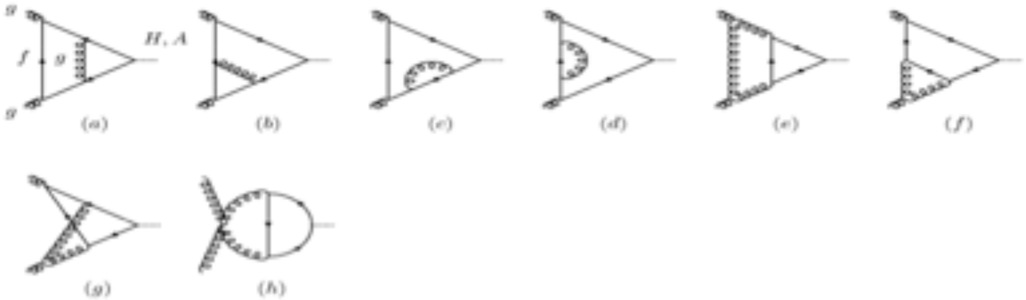
Higgs ptH distribution: a tool to discriminate models

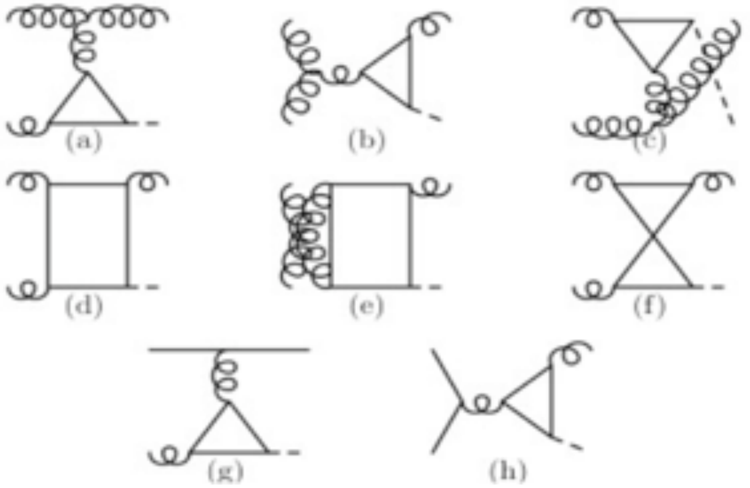
- the Higgs transverse momentum is due to its recoil against QCD radiation



- in the full theory (SM or BSM) gluon emissions occur also from internal lines of the loop







⇒ the shape of the distribution is sensitive to the BSM content running in the ggH loop

E.Bagnaschi, G.Degrassi, P.Slavich, AV, arXiv:1111.2854

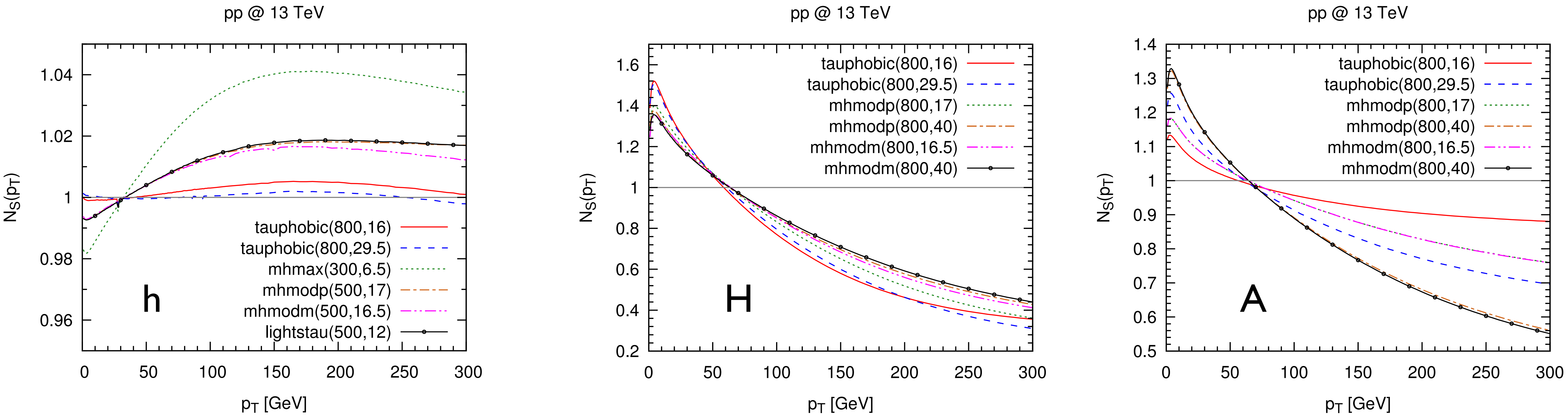
- the interplay between an enhanced bottom and other heavy particles might be non trivial

- the HQEFT is a good approximation of the full theory, for heavy particles in the loop, only for a light Higgs;
  in the case of heavy Higgs searches, the mass effects in the full theory are important over the whole ptH range

Higgs ptH distribution: relevance of an exact description

E.Bagnaschi, G.Degrassi, P.Slavich, AV, arXiv:1111.2854
R.Harlander, A.Tripathi, M.Wiesemann, arXiv:1403.7196
R.Harlander, H.Mantler, M.Wiesemann, arXiv:1409.0531

- MSSM study in different still allowed scenarios



(a) (b)

- the shape of the ptH distributions is compared to the SM prediction (same Higgs mass)

- for heavy scalars, distortions of O(30-40%) are possible
  impact on the determination of the acceptances
  identification of the BSM signal

- the HQET approximation can not be applied to heavy scalar production

The Higgs transverse momentum distribution: general issues

- a sensible description of the Higgs ptH distribution requires
  the matching between fixed-order result and all-order resummation of multiple gluon emissions

- the resummation is based on the factorization of the amplitude in the collinear limit

- in the analytical formulation there is a resummation scale Q
  necessary to factorize the universal terms describing multiple partons emissions
  from the process dependent part of the xsec

- in the Shower MC language there are different parameters that play an analogous role
  the scale *h* of the damping factor in POWHEG
  the scale at which the shower starts in MC@NLO

- the total cross section is independent of all these scale (unitarity constraint)

- the unitarity constraint implies an anti-correlation between low-ptH and high-ptH regions

The Higgs transverse momentum distribution in gluon fusion

- in presence of exact quark loops, the description of the Higgs ptH distribution is a multiscale problem
  MH, ptH, mq M. Grazzini, H.Sargsyan, arXiv:1306.4581
  which can be treated by introducing more than one resummation scale

- when does the radiation 1) resolve the loop and 2) break the factorization hypothesis ?
  which is the appropriate resummation scale for every heavy quark ?

- in the SM the bottom effects are a correction (of O(5%)) to the leading top-quark contribution

- in BSM scenarios the bottom role might be enhanced
  the description of its contribution requires a discussion

- the choice of the resummation scale has been discussed with different approaches
  for the top, the bottom and the top-bottom interference contributions
  - at parton level with a study of the collinear behavior of top and of bottom diagrams
    E.Bagnaschi, G.Degrassi,AV
  - at hadron level, imposing the positivity at large ptH and the recovery of fixed order
    R.Harlander, H.Mantler, M.Wiesemann, arXiv:1409.0531

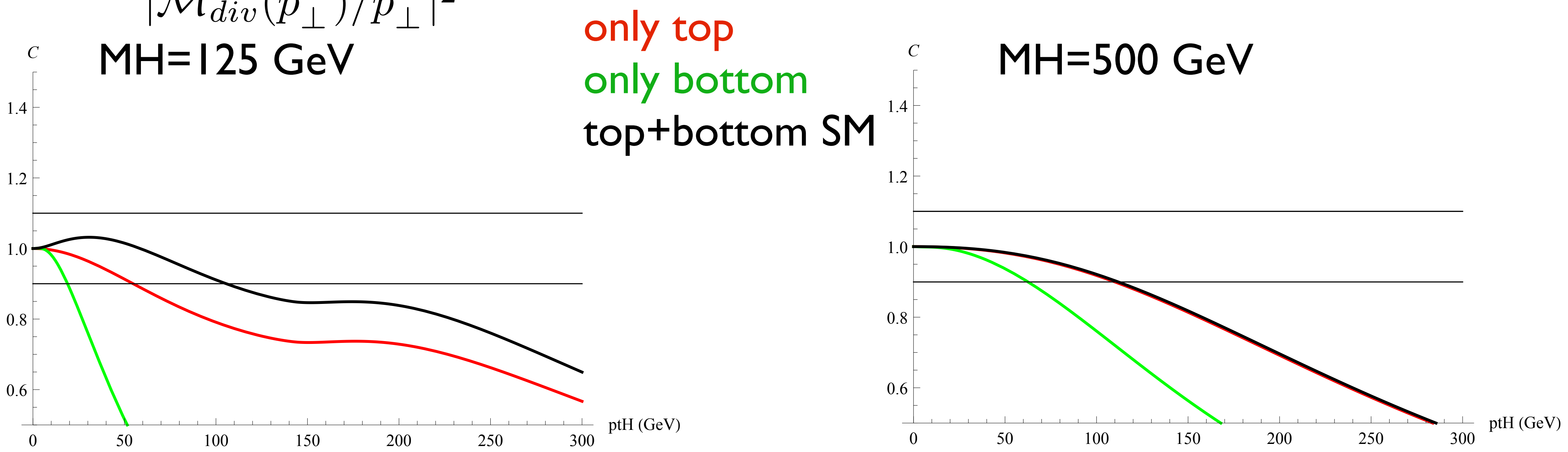
  with a general quantitative agreement

- the scale choice may have an important impact
  - on the acceptance estimates
  - to disentangle a new physics signal from the QCD uncertainty band

Choice of the resummation scale: analysis of the partonic matrix elements

$$C(p_\perp^H) = \frac{|\mathcal{M}_{exact}(p_\perp^H)|^2}{|\mathcal{M}_{div}(p_\perp^H)/p_\perp^H|^2}$$

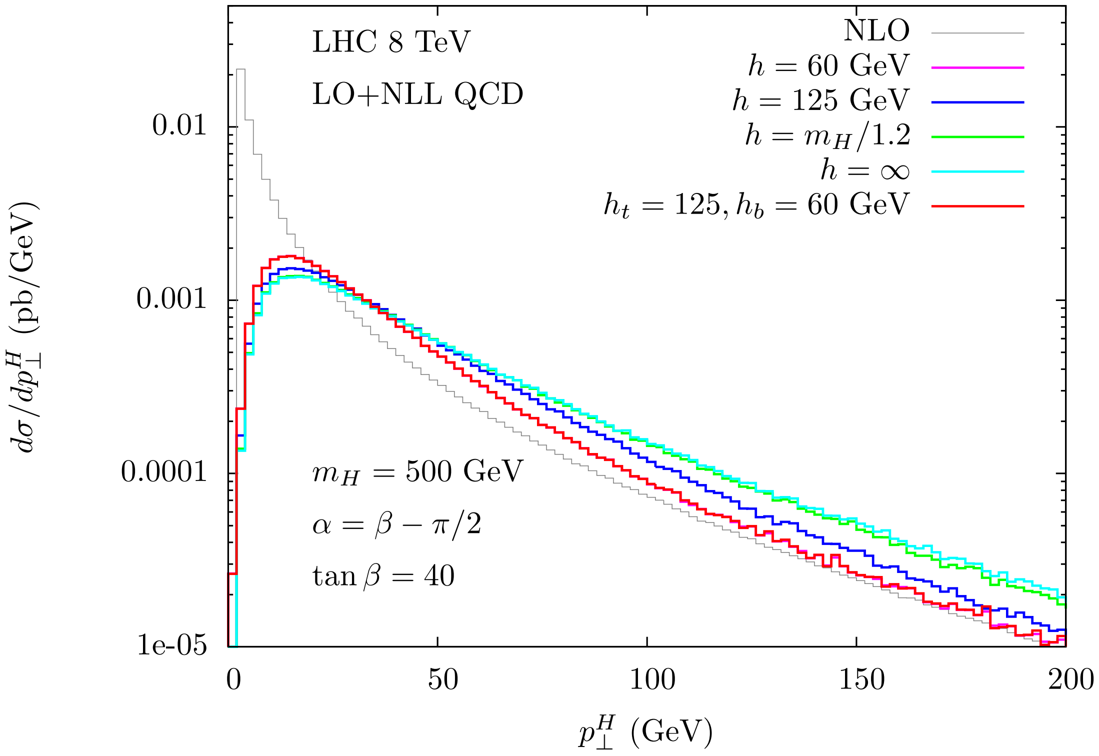
unpolarized squared matrix element

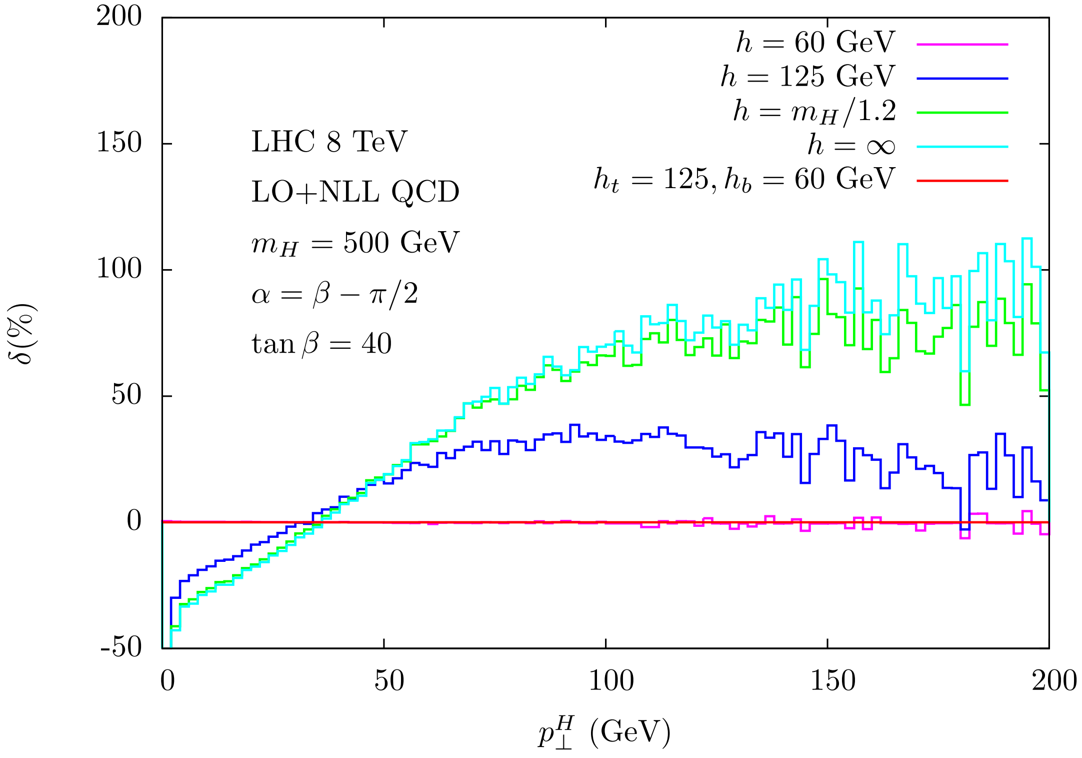


- the deviation of 0.1 ~ α_s represents the typical size of a subleading term in the log expansion
- when C(ptH) deviates from 1 by more than 0.1, we question the validity of factorization
- for MH=125 GeV, Q(t)= 55 GeV, Q(b)=20 GeV, Q(t+b, SM)=105 GeV
  for MH=500 GeV, Q(t)=110 GeV, Q(b)=65 GeV, Q(t+b, SM)=110 GeV
- the analysis for the only-top and only-bottom cases is model independent
  in the top+bottom case the relative strength of the couplings plays a crucial role

	MH=125	MH=200	MH=250	MH=300	MH=400	MH=500	MH=600	MH=700	MH=900
only top	Q=55	Q=85	Q=130	Q=135	Q=95	Q=110	Q=135	Q=155	Q=210
only bottom	Q=20	Q=30	Q=35	Q=40	Q=50	Q=65	Q=70	Q=85	Q=100

Resummation scale choices in gluon fusion : 2HDM, heavy CP-even production





- in a type II 2HDM, the choice α=β-π/2 is called a decoupling limit because it makes the light CP-even scalar *h* SM-like, i.e. the couplings to the fermions are like in the SM

  the coupling to the bottom of the heavy CP-even scalar H are enhanced by tanβ

- partonic analysis → ht(MH=500)=125 GeV, hb(MH=500)=60 GeV for the two *h* scales (red)
  in the large ptH tail the NLO result is recovered

- setting ht=hb= 60 GeV still ok (the bottom dominates)
  ht=hb=125 GeV deviations (-25 , +30 %) w.r.t. "best" choice
  ht=hb=MH/2 the large ptH tail deviates from the "best" by O(50%)

- the resummation scale uncertainty represents an important source of ambiguity

The Higgs effective field theory lagrangian

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_{i=1}^{N_6} \frac{a_i^{(6)}}{\Lambda^2} \mathcal{O}_i^{d=6} + \sum_{k>6} \sum_{i=1}^{N_k} \frac{a_i^{(k)}}{\Lambda^{k-4}} \mathcal{O}_i^{d=k}$$

valid up to a scale Λ

renormalizable order by order in the ($\sqrt{s} / \Lambda$) expansion

it makes explicit the actual d.o.f. : e.g. SM + one scalar field

heavier states are integrated out and appear in the Wilson coefficients

it allows the systematic inclusion in the Wilson coefficients of QCD/EW radiative corrections

it can be extended by adding higher-dimension operators

it does not include, by definition, new heavy states → good framework for characterization of the light h

- general classification of SU(2)xU(1) gauge invariant dimension 6 operators
  C. J. C. Burges and H. J. Schnitzer, Nucl. Phys. B 228 (1983) 464;
  C. N. Leung, S.T. Love and S. Rao, Z. Phys. C 31 (1986) 433;
  W. Buchmuller and D.Wyler, Nucl. Phys. B 268 (1986) 621;
  B. Grzadkowski, M. Iskrzynski, M. Misiak and J. Rosiek, arXiv:1008.4884

- specialization to the Higgs effective lagrangian, also in presence of radiative corrections
  G. F. Giudice, C. Grojean, A. Pomarol and R. Rattazzi, hep- ph/0703164
  G.Passarino, arXiv:1209.5538
  R.Contino, M.Ghezzi, C.Grojean, M.Mühlleitner, M.Spira, arXiv:1303.3876
  P.Artoisenet, P. de Aquino, F. Demartin, R. Frederix, S. Frixione, F. Maltoni, M. K. Mandal, P. Mathews, K. Mawatari, V. Ravindran, S. Seth, P. Torrielli, M. Zaro, arXiv:1306.6464
  ...

- JHU (framework to test spin and parity hypothesis of the new resonance)
  S.Bolognesi, Y.Gao, A.Gritsan, K.Melnikov, M.Schulze, N.V.Tran, A.Whitbeck, arXiv:1208.4018

- eHDECAY (evaluation of decay width and BRs in an EFT approach)
  R.Contino, M.Ghezzi, C.Grojean, M.Mühlleitner, M.Spira, arXiv:1303.3876

- FeynRules + Madgraph_aMC@NLO
  P.Artoisenet, P. de Aquino, F. Demartin, R. Frederix, S. Frixione, F. Maltoni, M. K. Mandal, P. Mathews, K. Mawatari, V. Ravindran, S. Seth, P. Torrielli, M. Zaro, arXiv:1306.6464

The Higgs EFT lagrangian: the FeynRules + Madgraph_aMC@NLO chain

- FeynRules: A.Alloul, B.Fuks, V.Sanz, arXiv:1310.1921, arXiv:1310.5150
  in input takes the Lagrangian provided by the user
  in output provides the Feynman rules of all the interaction vertices
  in a standard format (UFO)

- Madgraph_aMC@NLO: they use the Feynman rules to generate any tree-level process
  compute the NLO-QCD corrections and all the counterterms
  match the results with a QCD PS
  caveat: loop-induced processes (in LO) require a dedicated handling
  of the counterterm generation

- any additional set of higher-dimension operators can be added to define an extended model
  e.g. the HiggsCharacterization model includes only operators that modify the Higgs 3-point coupling
  the development of the Lagrangian with the full set of d=6 operators is in progress

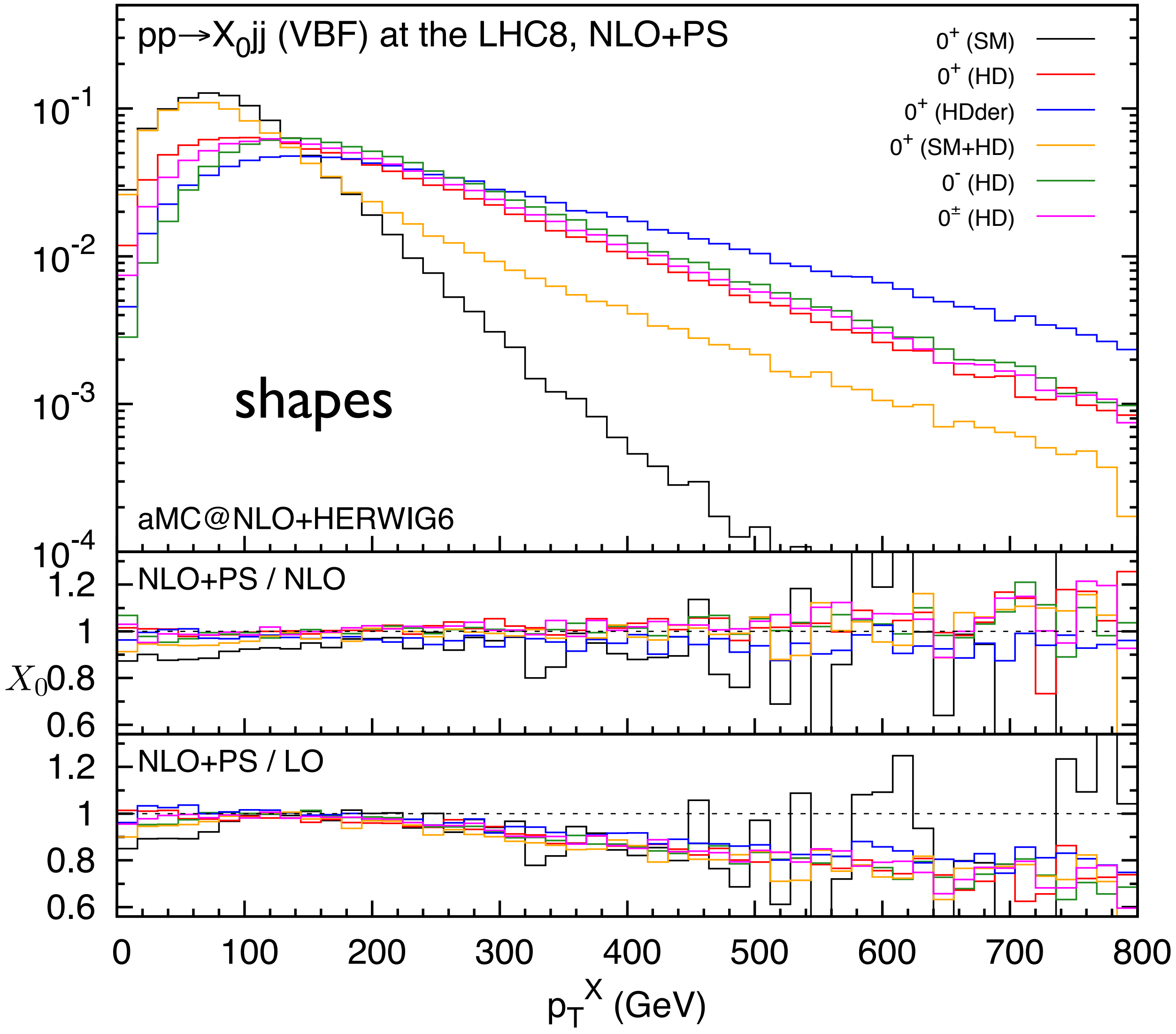
- the inclusion of the NLO-QCD corrections is the critical point in the implementation
  because specific model dependent couterterms can not (yet) be automatically computed
  and have to be provided by hand by the user

- the "standard" QCD ambiguities set a limit on the sensitivity that EFT can reach

The Higgs EFT lagrangian:VBF in aMC@NLO

F.Maltoni, K,Mawatari, M.Zaro, arXiv:1311.1829

$$
\begin{aligned}
\mathcal{L}_0^V = \Big\{ & c_\alpha \kappa_{\rm SM} \big[\tfrac{1}{2} g_{HZZ}\, Z_\mu Z^\mu + g_{HWW}\, W^+_\mu W^{-\mu}\big] \\
& - \frac{1}{4}\big[c_\alpha \kappa_{H\gamma\gamma} g_{H\gamma\gamma}\, A_{\mu\nu} A^{\mu\nu} + s_\alpha \kappa_{A\gamma\gamma} g_{A\gamma\gamma}\, A_{\mu\nu} \widetilde{A}^{\mu\nu}\big] \\
& - \frac{1}{2}\big[c_\alpha \kappa_{HZ\gamma} g_{HZ\gamma}\, Z_{\mu\nu} A^{\mu\nu} + s_\alpha \kappa_{AZ\gamma} g_{AZ\gamma}\, Z_{\mu\nu} \widetilde{A}^{\mu\nu}\big] \\
& - \frac{1}{4}\big[c_\alpha \kappa_{Hgg} g_{Hgg}\, G^a_{\mu\nu} G^{a,\mu\nu} + s_\alpha \kappa_{Agg} g_{Agg}\, G^a_{\mu\nu} \widetilde{G}^{a,\mu\nu}\big] \\
& - \frac{1}{4}\frac{1}{\Lambda}\big[c_\alpha \kappa_{HZZ}\, Z_{\mu\nu} Z^{\mu\nu} + s_\alpha \kappa_{AZZ}\, Z_{\mu\nu} \widetilde{Z}^{\mu\nu}\big] \\
& - \frac{1}{2}\frac{1}{\Lambda}\big[c_\alpha \kappa_{HWW}\, W^+_{\mu\nu} W^{-\mu\nu} + s_\alpha \kappa_{AWW}\, W^+_{\mu\nu} \widetilde{W}^{-\mu\nu}\big] \\
& - \frac{1}{\Lambda} c_\alpha \big[\kappa_{H\partial\gamma}\, Z_\nu \partial_\mu A^{\mu\nu} + \kappa_{H\partial Z}\, Z_\nu \partial_\mu Z^{\mu\nu} + \big(\kappa_{H\partial W}\, W^+_\nu \partial_\mu W^{-\mu\nu} + h.c.\big)\big] \Big\} X_0
\end{aligned}
$$



scenario	HC parameter choice
0^+(SM)	$\kappa_{\rm SM}=1\ (c_\alpha=1)$
0^+(HD)	$\kappa_{HZZ,HWW}=1\ (c_\alpha=1)$
0^+(HDder)	$\kappa_{H\partial Z,H\partial W}=1\ (c_\alpha=1)$
0^+(SM+HD)	$\kappa_{SM,HZZ,HWW}=1\ (c_\alpha=1,\ \Lambda=v)$
0^-(HD)	$\kappa_{AZZ,AWW}=1\ (c_\alpha=0)$
$0^\pm$(HD)	$\kappa_{HZZ,AZZ,HWW,AWW}=1\ (c_\alpha=1/\sqrt{2})$

scenario	$\sigma_{\rm LO}$ (fb)	$\sigma_{\rm NLO}$ (fb)	K
0^+(SM)	$1509(1)\ ^{+4.7\%}_{-4.4\%}$	$1633(2)\ ^{+2.0\%}_{-1.5\%}$	1.08
0^+(HD)	$69.66(6)\ ^{+7.5\%}_{-6.6\%}$	$67.08(13)\ ^{+2.2\%}_{-2.3\%}$	0.96
0^+(HDder)	$721.9(6)\ ^{+11.0\%}_{-9.0\%}$	$684.9(1.5)\ ^{+2.3\%}_{-2.8\%}$	0.95
0^+(SM+HD)	$3065(2)\ ^{+5.6\%}_{-5.1\%}$	$3144(5)\ ^{+1.6\%}_{-1.1\%}$	1.03
0^-(HD)	$57.10(4)\ ^{+7.7\%}_{-6.7\%}$	$55.24(11)\ ^{+2.1\%}_{-2.5\%}$	0.97
$0^\pm$(HD)	$63.46(5)\ ^{+7.6\%}_{-6.7\%}$	$61.07(13)\ ^{+2.3\%}_{-2.0\%}$	0.96

the k_i coefficients will be fit to the data,

different operators can contribute simultaneously (weighted by the corresponding xsecs)

a full set of observables is needed to (possibly) disentangle the different contributions

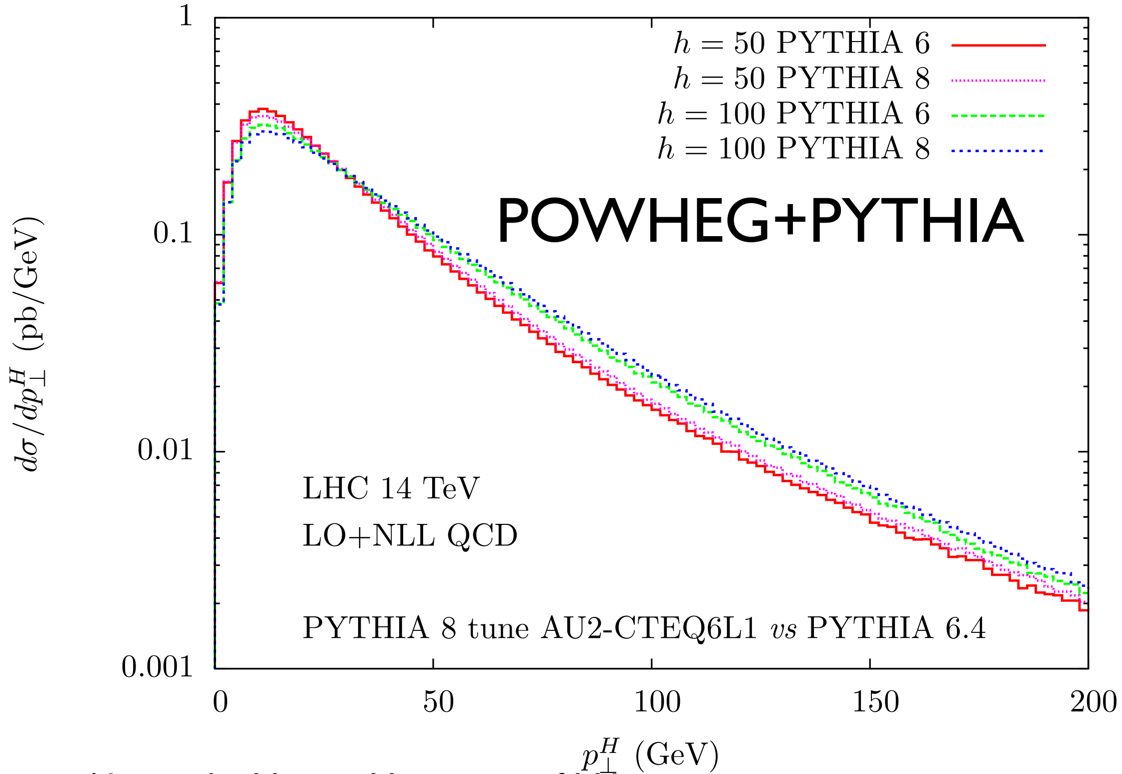
A naïve question

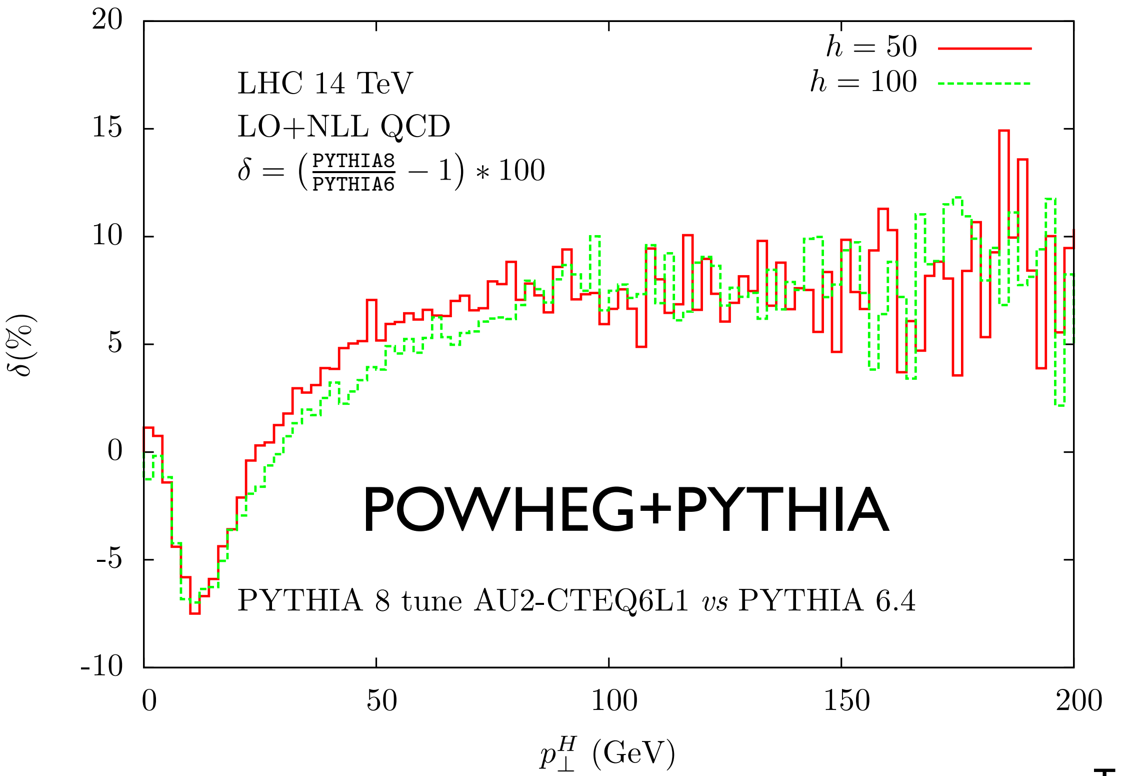
- the embedding of the EFT partonic subprocesses in the hadron collider environment introduces a "competition" between
  the effects of higher-dimension operators and the ambiguities of the QCD predictions

- the precise shape of many observables depends on the details of the QCD PS:
  ggH+bbar observables are more sensitive, VBF is less sensitive to these details

- the QCD PS (PYTHIA, HERWIG,SHERPA) are tuned on the data in the SM assumption,
  i.e. they reabsorbs whatever is not described by the SM matrix elements,
  potentially also BSM effects

- the QCD PS affects the description of the low-pt regions
  but
  observables like the Higgs ptH have a correlation between low-ptH and high-ptH (unitarity constraint)
  so that the QCD PS might affect also the "signal region", where a BSM deviation is expected





Conclusions

- Higgs masses: their accurate evaluation of in the Real MSSM is still a challenging task in the allowed region of the MSSM parameter space

- total cross sections (2HDM, MSSM):
  - it is crucial to account exactly for the relative strength of the top- and bottom-quark contributions
  - the uncertainties of the MSSM total cross section for gluon fusion + bbar annihilation have a strong element of uncertainty in the definition of the bottom Yukawa coupling (other sources are better understood or under control)

- differential distributions
  - available in various production channels (gg, bbar, VBF) with (NLO+PS)-QCD accuracy in the MSSM and more recently in EFT approaches
  - the sensitivity of the Higgs ptH distribution to new physics via the gluon fusion channel requires the use of appropriate resummation scales for the top and for the bottom contributions

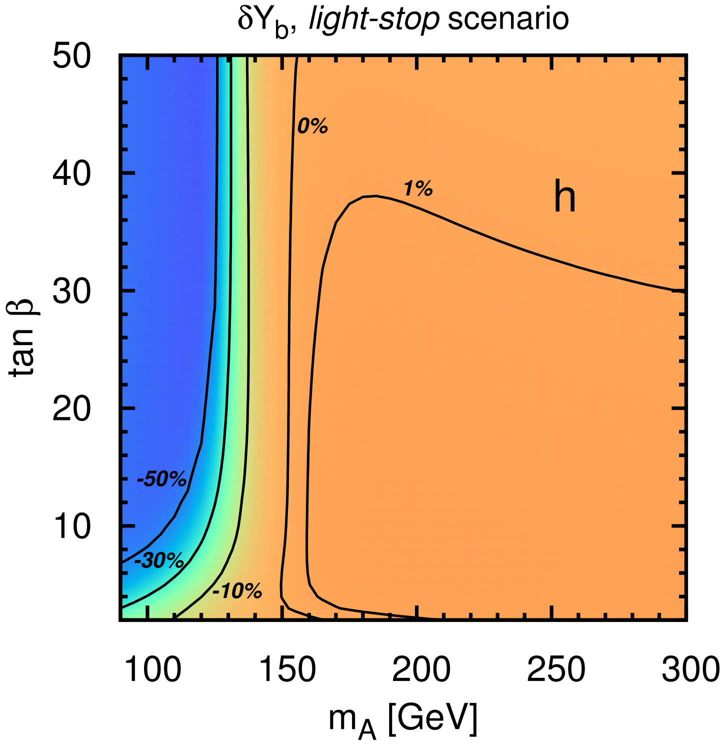
- EFT
  - promising approach for the Higgs characterization and for a less biased parameterization of new physics effects
  - major step is the systematic inclusion of NLO-QCD/EW corrections (in progress in public codes)
  - limiting factors are standard QCD issues, which will benefit from the progress of the SM calculations

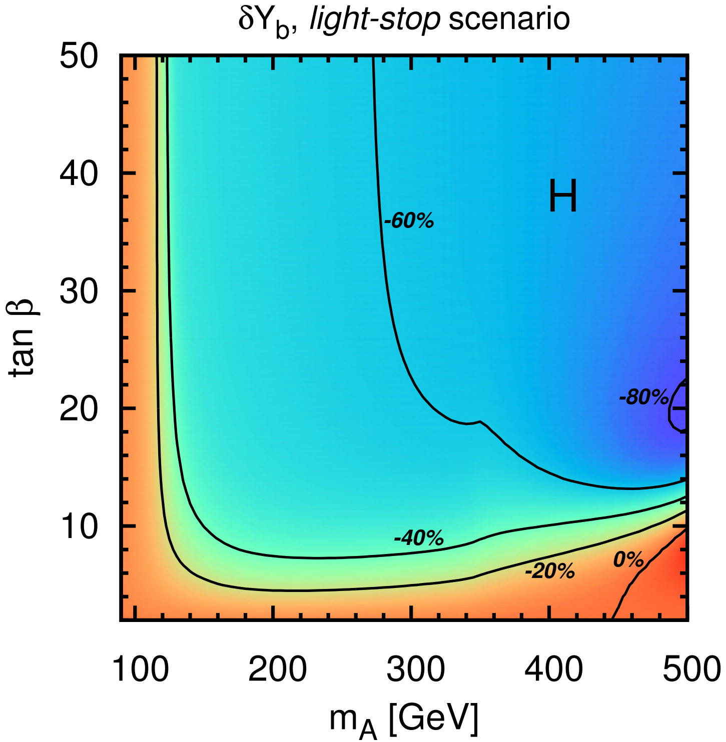
back-up slides

Neutral Higgs production in the MSSM: uncertainties of the total cross section

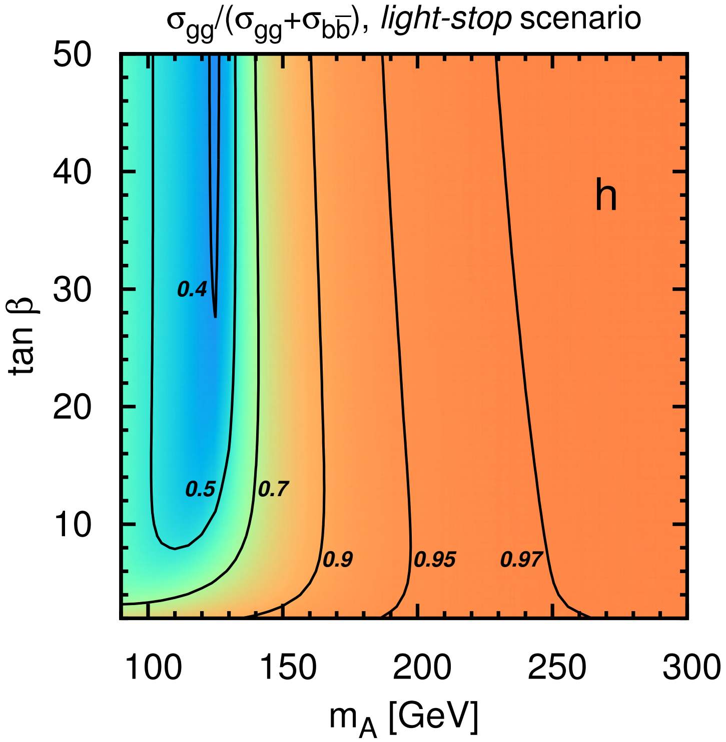
- the choice of renormalization scheme and scale can have a huge impact on the gluon fusion xsec

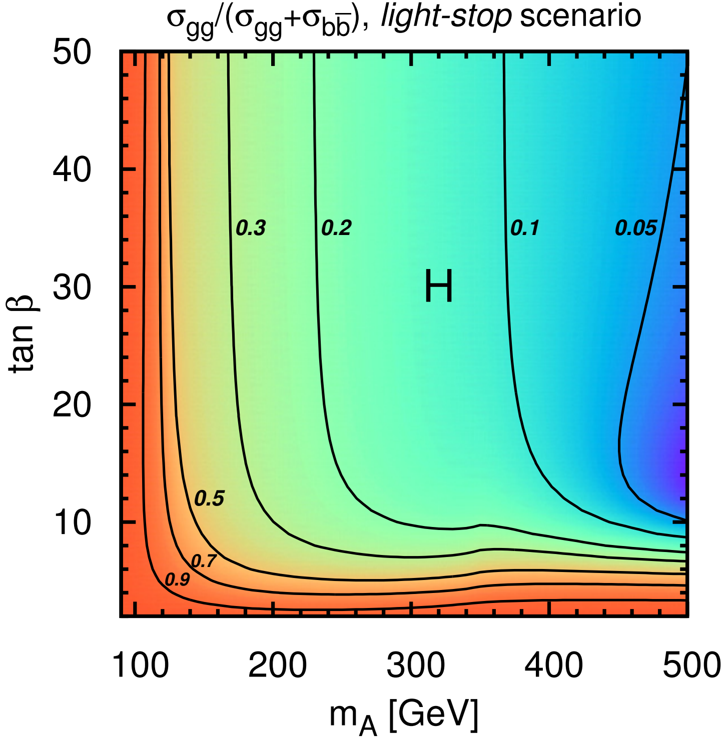
- the largest effects are where the total Higgs production xsec is dominated by bbar annihilation





impact of the Y_b renormalization
on the gluon fusion cross section



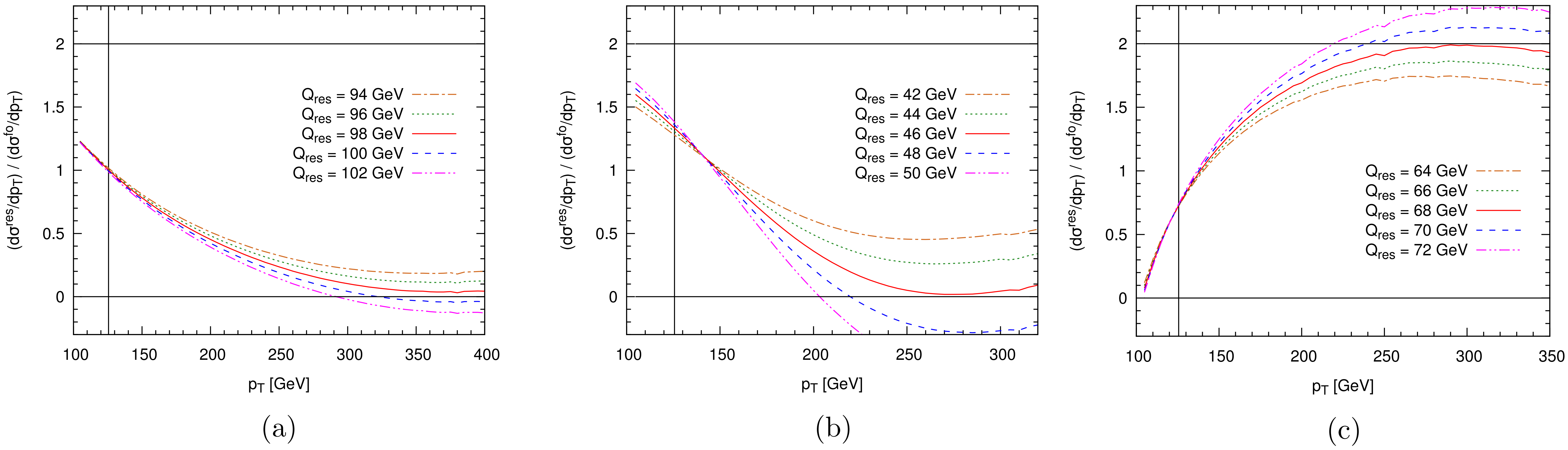


relative contribution
of the gluon fusion cross section
with respect to the total

Choice of the resummation scale: positivity requirement

R.Harlander, H.Mantler, M.Wiesemann, arXiv:1409.0531

- constraint derived from the hadron level cross section
- separately, fixed order (for ptH>0) and resummed expression (for ptH≥0) are positive definite after the matching, the expression might become negative, as a consequence of the unitarity constraint



- a maximal value for the resummation scale is thus allowed,
  in order to preserve the positivity of the distribution in the whole ptH range
  in order to remain close to the fixed order prediction up to a factor 2

- analysis done separately for top squared, bottom squared and top-bottom interference

Test of different spin hypotheses for the Higgs in Madgraph_aMC@NLO

$$\mathcal{L}_0^f = -\sum_{f=t,b,\tau} \bar\psi_f \big(c_\alpha \kappa_{Hff} g_{Hff} + i s_\alpha \kappa_{Aff} g_{Aff}\,\gamma_5\big)\psi_f X_0$$

$$\begin{aligned}\mathcal{L}_0^V = \bigg\{ & c_\alpha \kappa_{\rm SM}\big[\tfrac{1}{2} g_{HZZ}\, Z_\mu Z^\mu + g_{HWW}\, W_\mu^+ W^{-\mu}\big] \\ & - \frac{1}{4}\big[c_\alpha \kappa_{H\gamma\gamma} g_{H\gamma\gamma}\, A_{\mu\nu}A^{\mu\nu} + s_\alpha \kappa_{A\gamma\gamma} g_{A\gamma\gamma}\, A_{\mu\nu}\widetilde{A}^{\mu\nu}\big] \\ & - \frac{1}{2}\big[c_\alpha \kappa_{HZ\gamma} g_{HZ\gamma}\, Z_{\mu\nu}A^{\mu\nu} + s_\alpha \kappa_{AZ\gamma} g_{AZ\gamma}\, Z_{\mu\nu}\widetilde{A}^{\mu\nu}\big] \\ & - \frac{1}{4}\big[c_\alpha \kappa_{Hgg} g_{Hgg}\, G^a_{\mu\nu}G^{a,\mu\nu} + s_\alpha \kappa_{Agg} g_{Agg}\, G^a_{\mu\nu}\widetilde{G}^{a,\mu\nu}\big] \\ & - \frac{1}{4}\frac{1}{\Lambda}\big[c_\alpha \kappa_{HZZ}\, Z_{\mu\nu}Z^{\mu\nu} + s_\alpha \kappa_{AZZ}\, Z_{\mu\nu}\widetilde{Z}^{\mu\nu}\big] \\ & - \frac{1}{2}\frac{1}{\Lambda}\big[c_\alpha \kappa_{HWW}\, W^+_{\mu\nu}W^{-\mu\nu} + s_\alpha \kappa_{AWW}\, W^+_{\mu\nu}\widetilde{W}^{-\mu\nu}\big] \\ & - \frac{1}{\Lambda} c_\alpha \big[\kappa_{H\partial\gamma}\, Z_\nu \partial_\mu A^{\mu\nu} + \kappa_{H\partial Z}\, Z_\nu \partial_\mu Z^{\mu\nu} + \big(\kappa_{H\partial W}\, W_\nu^+ \partial_\mu W^{-\mu\nu} + h.c.\big)\big]\bigg\} X_0\end{aligned}$$

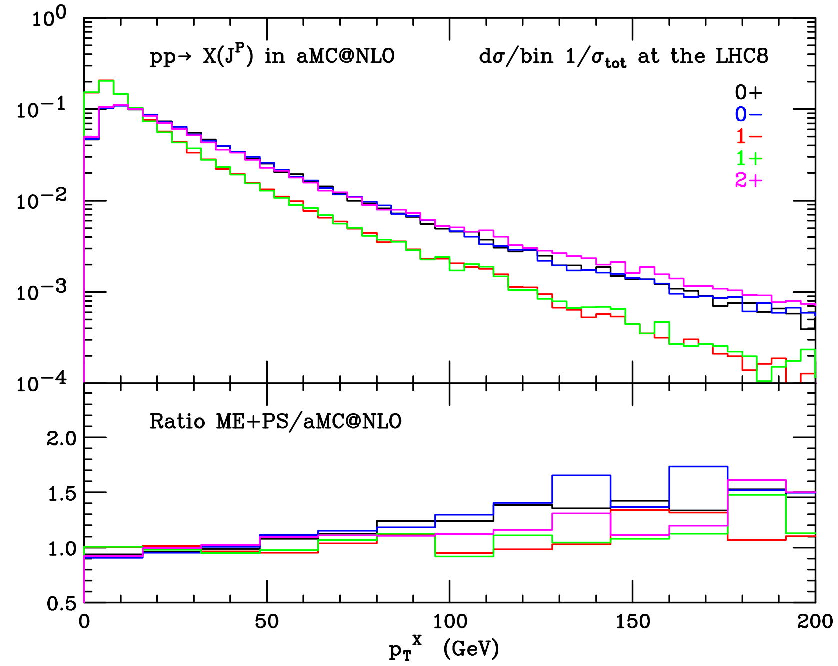
$$\mathcal{L}_1^f = \sum_{f=q,\ell} \bar\psi_f \gamma_\mu (\kappa_{f_a} a_f - \kappa_{f_b} b_f \gamma_5)\psi_f X_1^\mu\,.$$

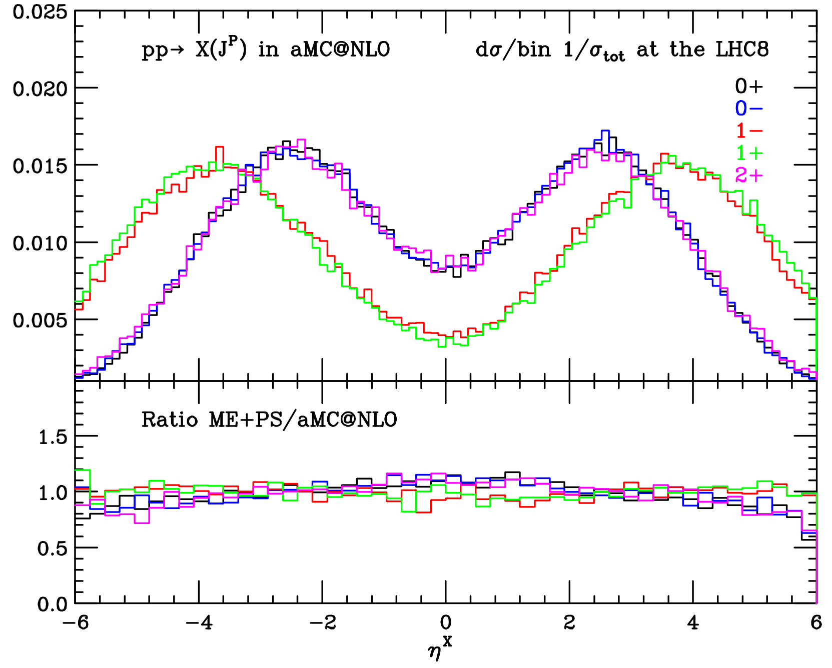
$$\begin{aligned}\mathcal{L}_1^W = & \,i\kappa_{W_1} g_{WWZ}(W^+_{\mu\nu}W^{-\mu} - W^-_{\mu\nu}W^{+\mu})X_1^\nu + i\kappa_{W_2} g_{WWZ} W^+_\mu W^-_\nu X_1^{\mu\nu} \\ & - \kappa_{W_3} W^+_\mu W^-_\nu (\partial^\mu X_1^\nu + \partial^\nu X_1^\mu) \\ & + i\kappa_{W_4} W^+_\mu W^-_\nu \widetilde{X}_1^{\mu\nu} - \kappa_{W_5}\epsilon_{\mu\nu\rho\sigma}[W^{+\mu}(\partial^\rho W^{-\nu}) - (\partial^\rho W^{+\mu})W^{-\nu}]X_1^\sigma\,,\end{aligned}$$

$$\mathcal{L}_1^Z = -\kappa_{Z_1} Z_{\mu\nu} Z^\mu X_1^\nu - \kappa_{Z_3} X_1^\mu (\partial^\nu Z_\mu) Z_\nu - \kappa_{Z_5}\epsilon_{\mu\nu\rho\sigma} X_1^\mu Z^\nu (\partial^\rho Z^\sigma)\,.$$

$$\mathcal{L}_2^f = -\frac{1}{\Lambda}\sum_{f=q,\ell} \kappa_f\, T^f_{\mu\nu} X_2^{\mu\nu}\,, \qquad \mathcal{L}_2^V = -\frac{1}{\Lambda}\sum_{V=Z,W,\gamma,g} \kappa_V\, T^V_{\mu\nu} X_2^{\mu\nu}\,.$$

$$\begin{aligned}T^f_{\mu\nu} = & - g_{\mu\nu}\Big[\bar\psi_f (i\gamma^\rho D_\rho - m_f)\psi_f - \frac{1}{2}\partial^\rho(\bar\psi_f i\gamma_\rho \psi_f)\Big] \\ & + \Big[\frac{1}{2}\bar\psi_f i\gamma_\mu D_\nu \psi_f - \frac{1}{4}\partial_\mu(\bar\psi_f i\gamma_\nu\psi_f) + (\mu \leftrightarrow \nu)\Big]\,, \\ T^\gamma_{\mu\nu} = & - g_{\mu\nu}\Big[-\frac{1}{4}A^{\rho\sigma}A_{\rho\sigma} + \partial^\rho\partial^\sigma A_\sigma A_\rho + \frac{1}{2}(\partial^\rho A_\rho)^2\Big] \\ & - A_\mu{}^\rho A_{\nu\rho} + \partial_\mu\partial^\rho A_\rho A_\nu + \partial_\nu\partial^\rho A_\rho A_\mu\,,\end{aligned}$$





Parameters of the study on the uncertainties of the total xsec in the MSSM

- inclusion of NLO-EW corrections

$$\sigma_{gg\phi}^{\text{MSSM}} = \sigma_{gg\phi,\text{NLO}}^{\text{MSSM}}(1+\delta_{\text{EW}}^{\text{lf}}) + \sigma_{gg\phi,\text{NNLO}}^{t} - \sigma_{gg\phi,\text{NLO}}^{t}.$$

Scenario	M_S [GeV]	X_t [GeV]	μ [GeV]	M_2 [GeV]
m_h^{max}	1000	2000	200	200
$m_h^{\text{mod}+}$	1000	1500	200	200
$m_h^{\text{mod}-}$	1000	-1900	200	200
light stop	500	1000	400	400
light stau	1000	1600	500	200
tau-phobic	1500	3675	2000	200

Table 1. Choices of MSSM parameters for the benchmark scenarios proposed in ref. [90].

- in the light stop scenario $m_{\tilde{t}_1} = 324\text{GeV}$ $m_{\tilde{t}_2} = 672\text{GeV}$