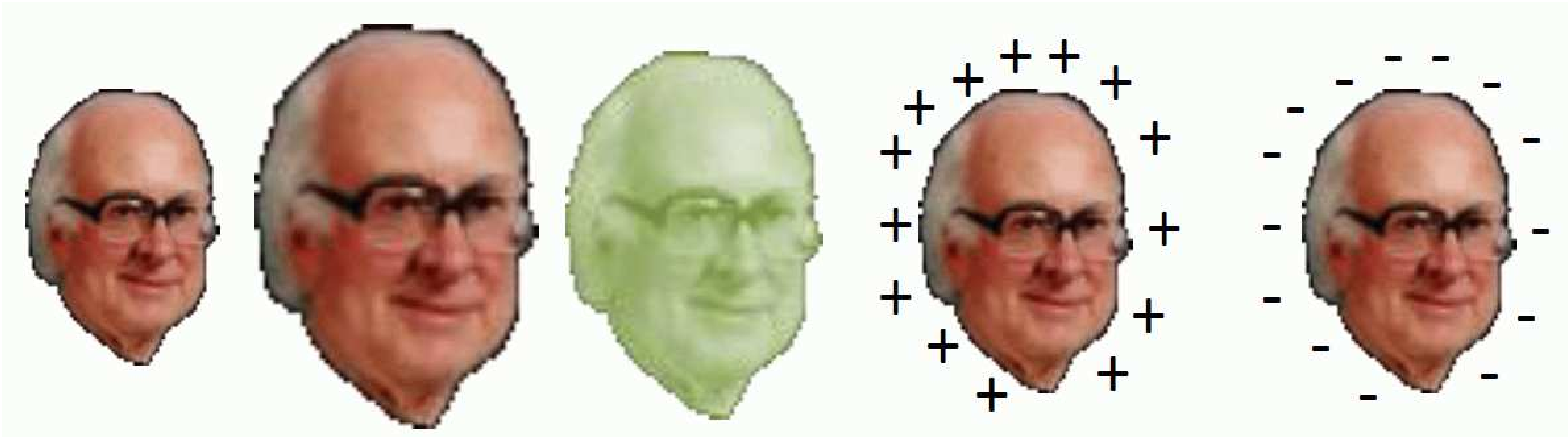


Report from the LHCHXSWG

(LHC Higgs Cross Section Working Group)

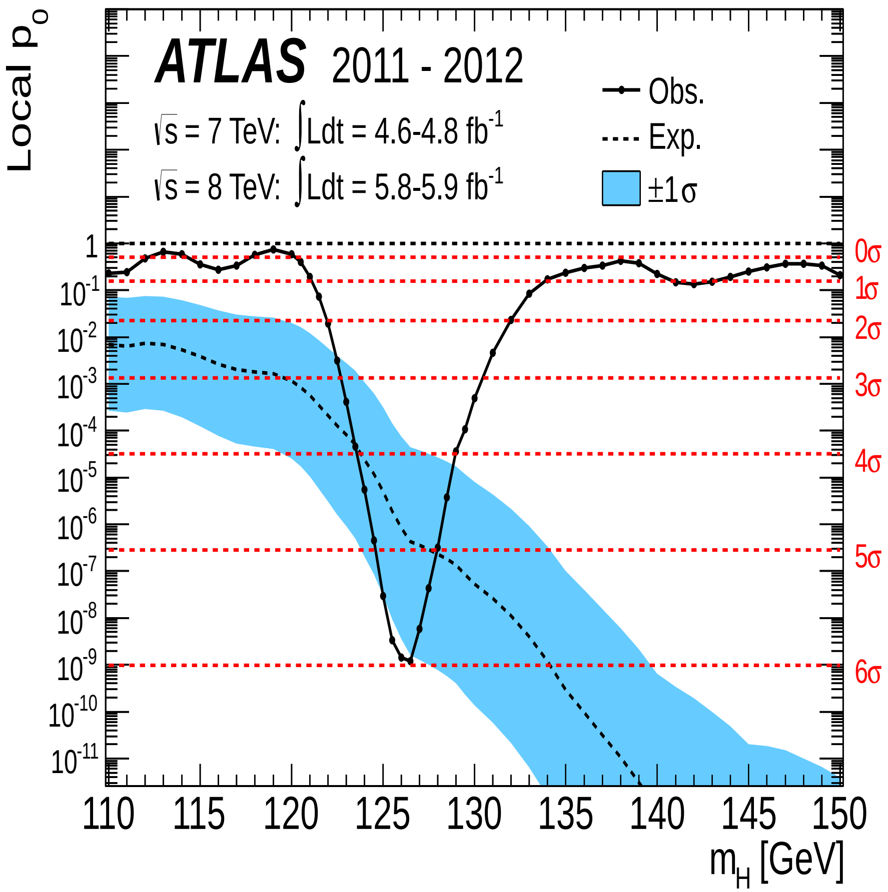
Sven Heinemeyer, IFCA (CSIC, Santander)

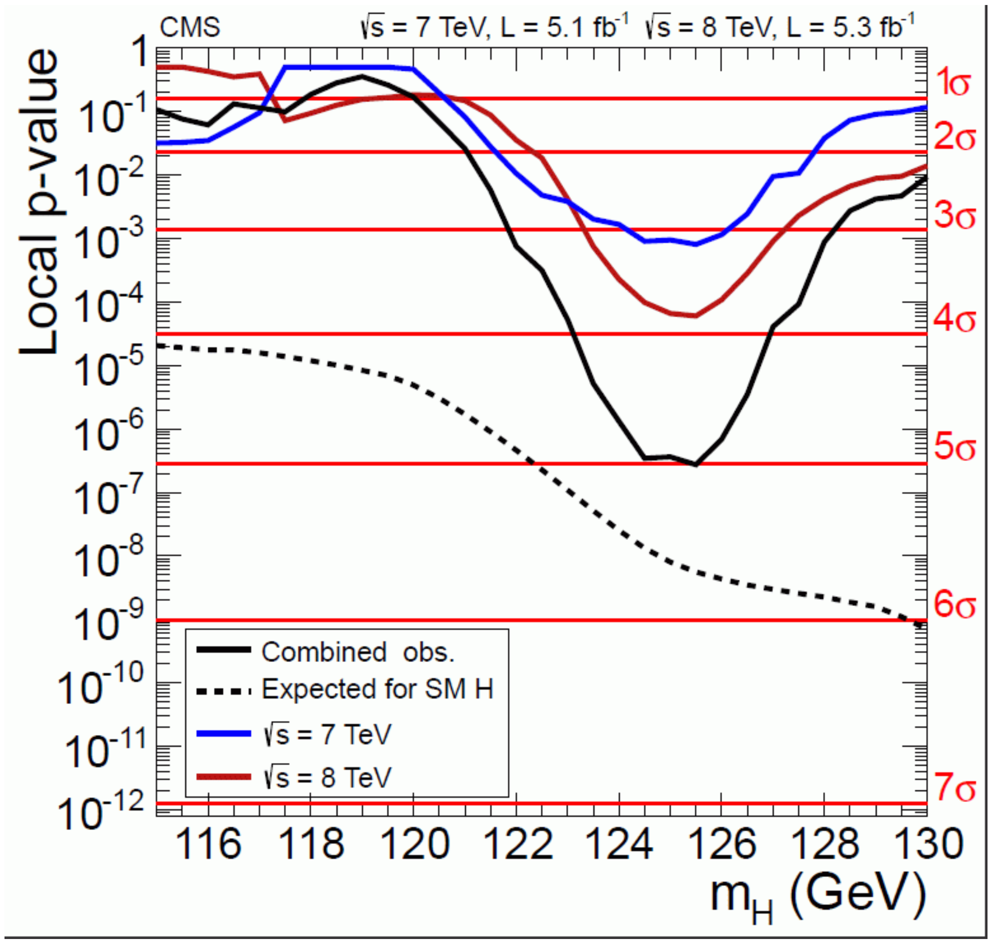
Uppsala, 09/2014

1. Introduction
2. The LHC Higgs Cross Section Working Group
3. Success stories (charged and neutral)
4. Challenges for the future

1. Introduction

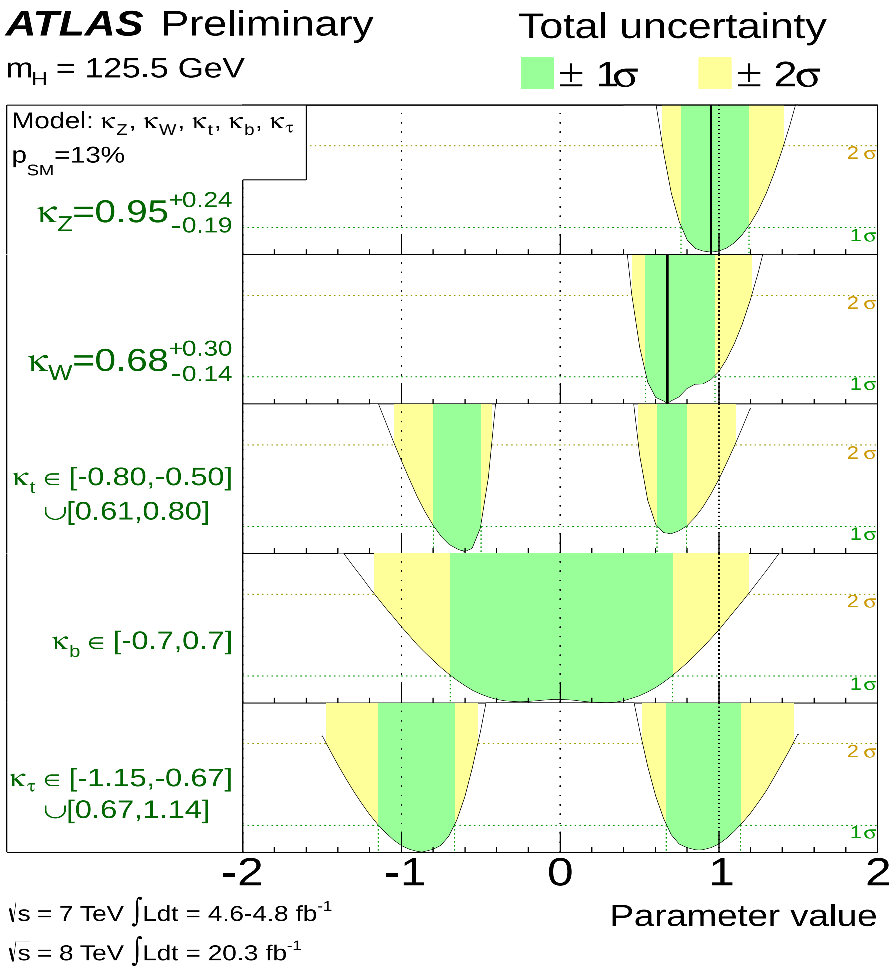
We have a discovery!

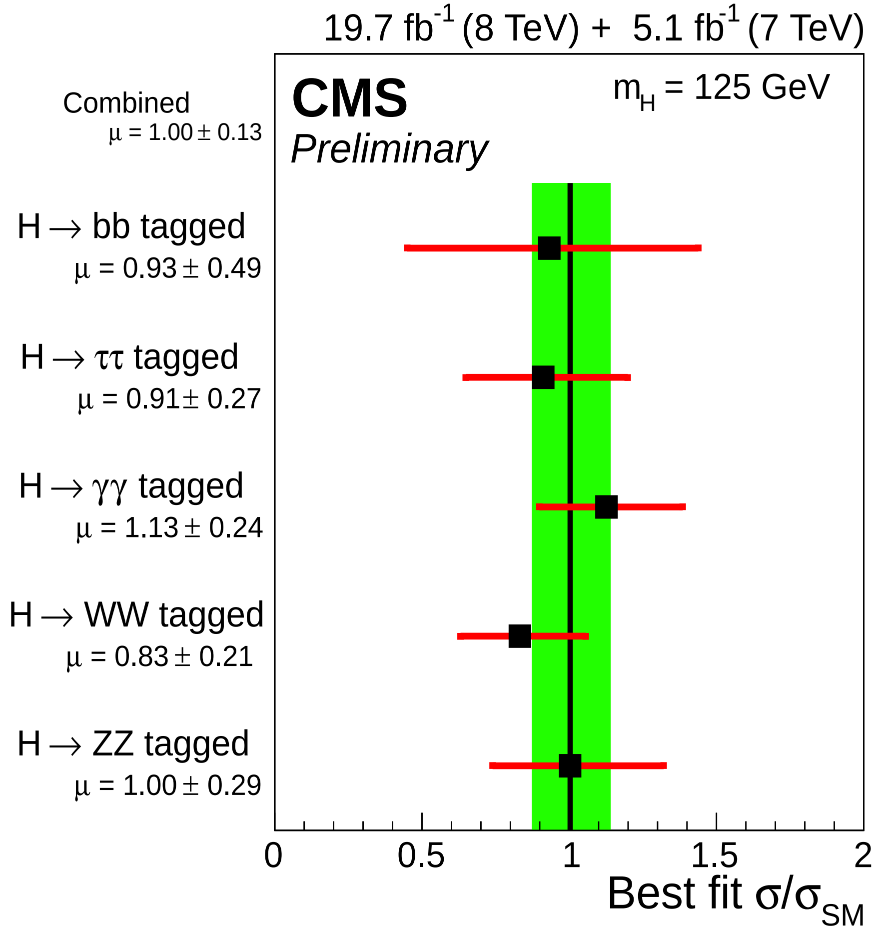




1. Introduction

We have a discovery!





But there is more than meets the eye - more than experimental analyses!

But there is more than meets the eye - more than experimental analyses!

Needed for these plots/analyses:

Precise predictions for

- SM Higgs cross sections (incl. uncertainty evaluation)
- SM Higgs branching ratios (incl. uncertainty evaluation)
- backgrounds
- included in validated Monte Carlos

But there is more than meets the eye - more than experimental analyses!

Needed for these plots/analyses:

Precise predictions for

– SM Higgs cross sections
 (incl. uncertainty evaluation)
– SM Higgs branching ratios
 (incl. uncertainty evaluation)
– backgrounds
– included in validated Monte Carlos

as well as strategies for the extraction of

– coupling strength factors
– coupling structures
– spin, $\mathcal{CP}$, . . .

But there is more than meets the eye - more than experimental analyses!

Needed for these plots/analyses:

Precise predictions for

- SM Higgs cross sections (incl. uncertainty evaluation)
- SM Higgs branching ratios (incl. uncertainty evaluation)
- backgrounds
- included in validated Monte Carlos

as well as strategies for the extraction of

- coupling strength factors
- coupling structures
- spin, $\mathcal{CP}$, . . .

Have to ensure that ATLAS and CMS use the same numbers/strategies to compare and/or combine numbers

We have a discovery!

But what is it?

Q: Is it a Higgs boson?

Q: Is it the Higgs boson of the SM?

Q: Is it an MSSM Higgs boson?

Q: Is it a Higgs boson of a different model?

Q: Is it an impostor?

We have a discovery!

But what is it?

Q: Is it a Higgs boson? $\Rightarrow$ yes according to CERN!

Q: Is it the Higgs boson of the SM?

Q: Is it an MSSM Higgs boson?

Q: Is it a Higgs boson of a different model?

Q: Is it an impostor? $\Rightarrow$ no according to CERN!

We have a discovery!

But what is it?

Q: Is it a Higgs boson? ⇒ yes according to CERN!

Q: Is it the Higgs boson of the SM?

Q: Is it an MSSM Higgs boson?

Q: Is it a Higgs boson of a different model?

Q: Is it an impostor? ⇒ no according to CERN!

How can we decide?

A: Measure all its characteristics

⇒ SM predictions for XS, BR, couplings, . . .

A: Investigate BSM physics:

– predictions for EW singlet, 2HDM, (N)MSSM, Composites Triplets, . . .
– benchmark models needed
– $V_L V_L$ scattering?

2. The LHC Higgs Cross Section Working Group

→ created in 2010 (the year 2 BH) to take care of these issues

→ re-organized in April 2014

New structure not "fully started" (ask me over coffee ;-)

Steering Committee Members

ATLAS		CMS		THEORY			
Markus Schumacher (Freiburg)	Reisaburo Tanaka (LAL)	Chiara Mariotti (Torino)	Alexander Nikitenko (Imperial, London)	Charalampos Anastasiou (ETH, Zurich)	Daniel de Florian (Buenos Aires)	Christophe Grojean (Barcelona)	Fabio Maltoni (Louvain)

Working Group Conveners

- We are organized in 3 working groups.

WG	ATLAS	CMS	THEORY		
Higgs XS&BR	Bruce Mellado (Witwatersrand)	Pasquale Musella (CERN)	Massimiliano Grazzini (Zurich)	Robert Harlander (Wuppertal)	
Higgs Properties	Michael Dührssen (CERN)	Andre David (CERN)	Adam Falkowski (Orsay-LPT)	Gino Isidori (Zurich)	
BSM Higgs	Nikolaos Rompotis (Washington)	Mario Pelliccioni (Torino)	Ian Low (Argonne and Northwestern)	Margarete Mühlleitner (Karlsruhe)	Andreas Weiler (CERN and DESY)

The group structure (I): SWG1: Higgs XS & BR

[taken from talk by M. Grazzini 08/14]

Task forces

- ggH
- VH+VBF
- ttH
- bbH (bottom-initiated processes)
- HH
- off-shell production
- BR (continued from "old" HXSWG)

Thursday, August 28, 2014

$\Rightarrow$ best available predictions (common for ATLAS and CMS!)

The group structure (II): SWG2: Higgs properties

Main focus:

⇒ just started . . .

The group structure (III): SWG3: BSM

→ take care of BSM physics

→ first meeting: 07.10.2014

⇒ not more details possible . . .

→ charged Higgs ?!

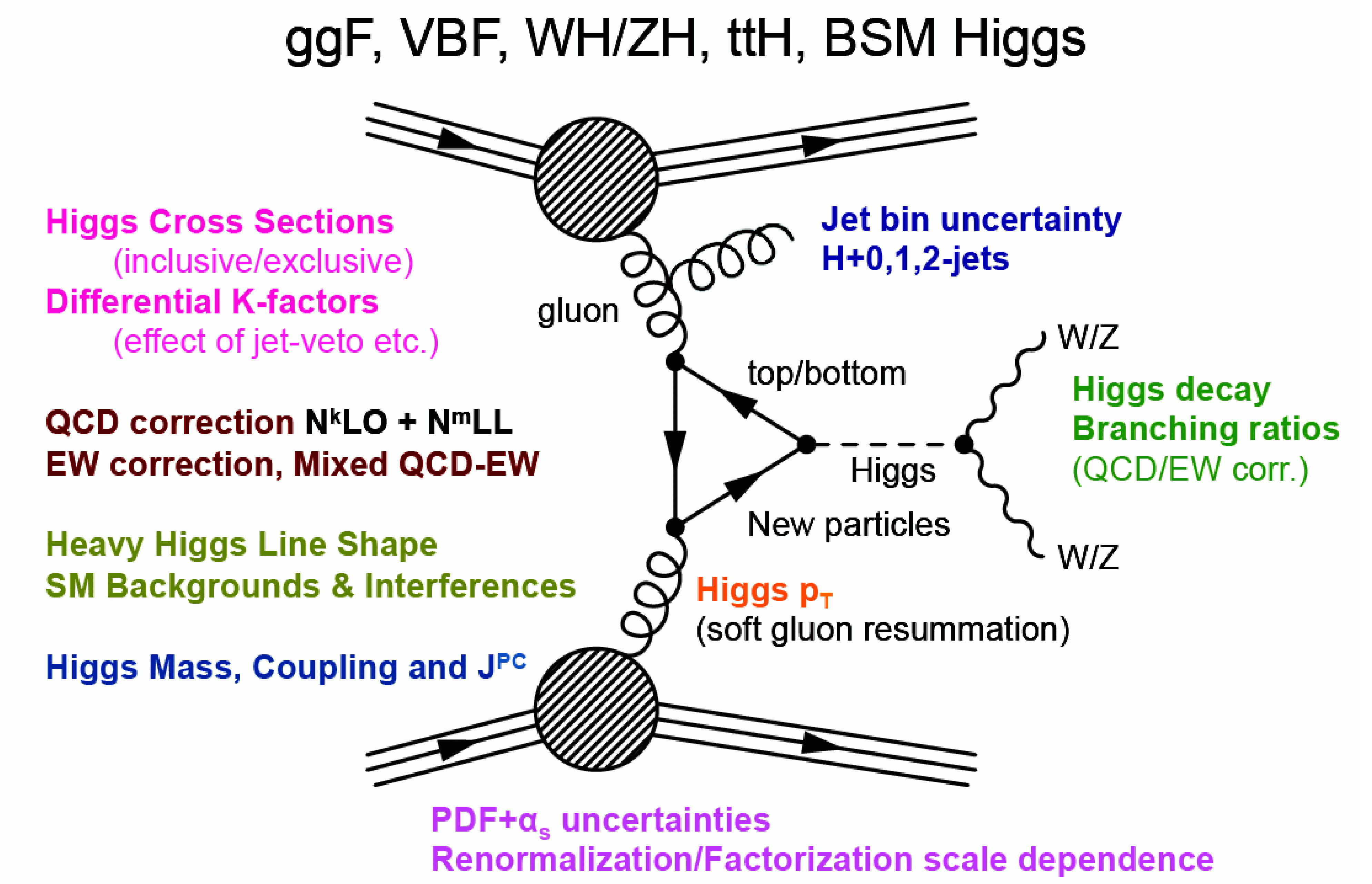
– 2HDM's ?!

– MSSM ?!

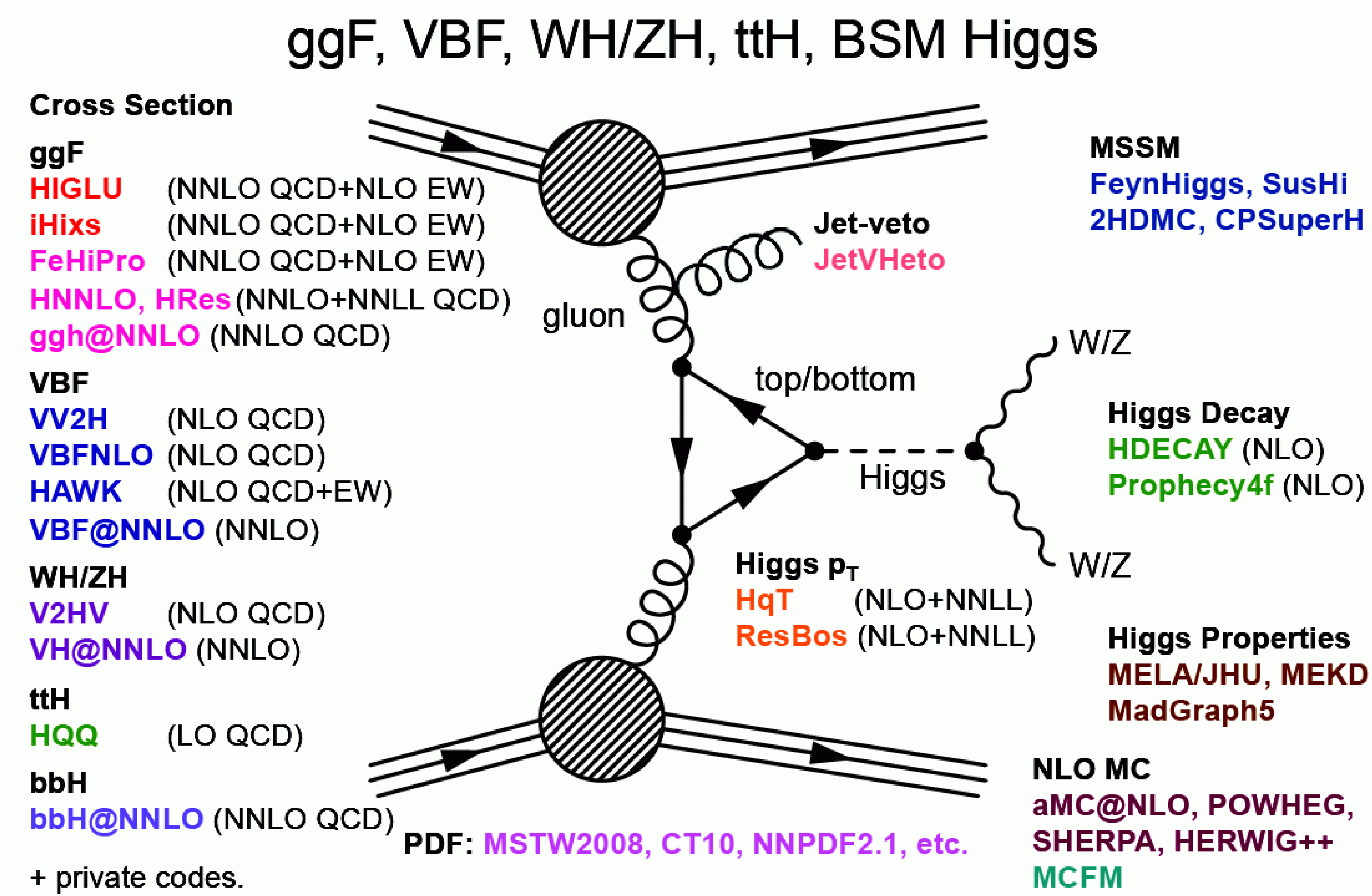
– NMSSM ?!

– . . .

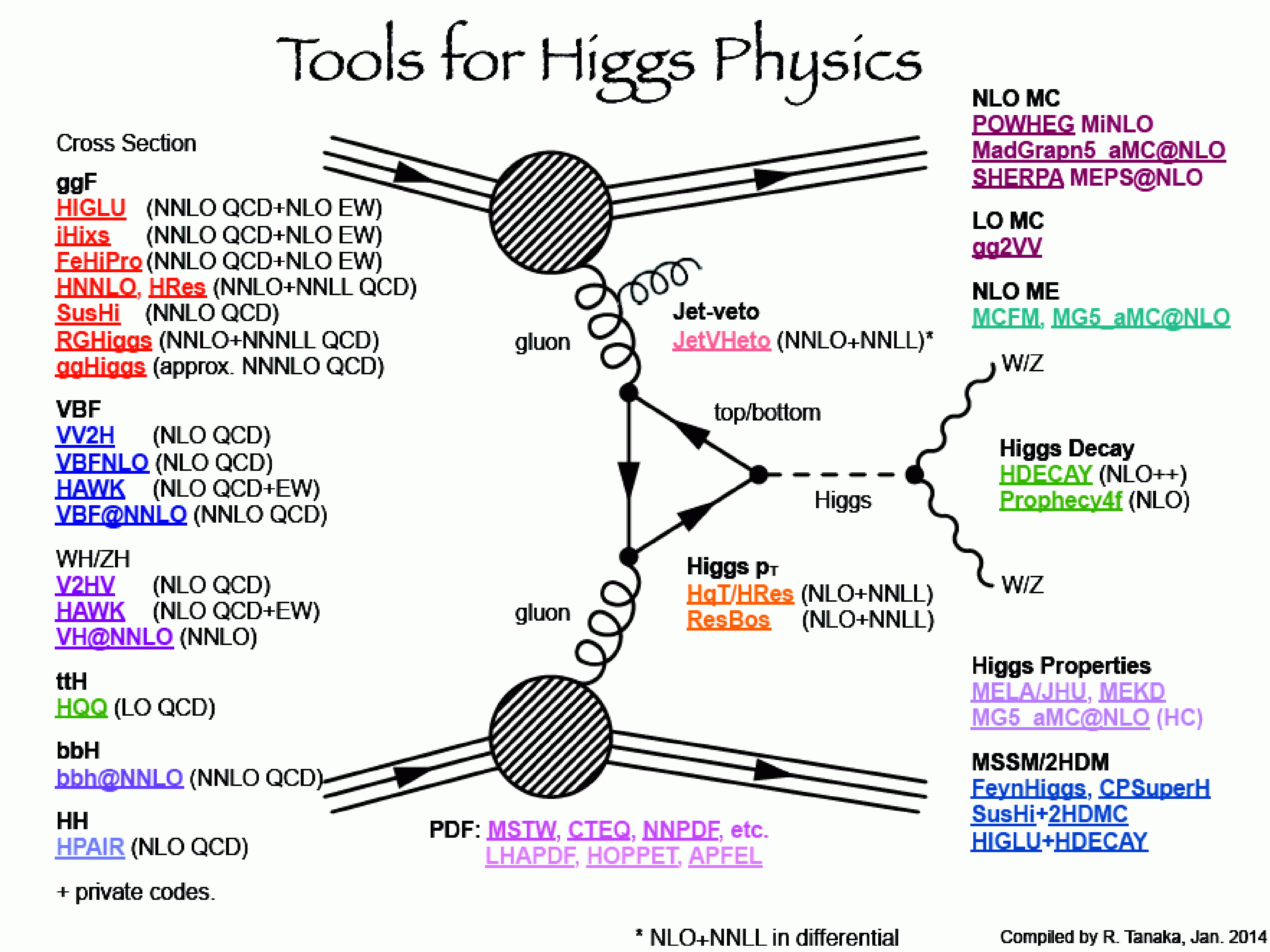
The challenges: (taken from [R. Tanaka, talk at Aspen Higgs WS 03/13])



The “solutions”: (taken from [R. Tanaka, talk at Aspen Higgs WS 03/13])



The "solutions" (final update): (compiled by [R. Tanaka '14])



3. Success stories

LHCHXSWG work is documented in:

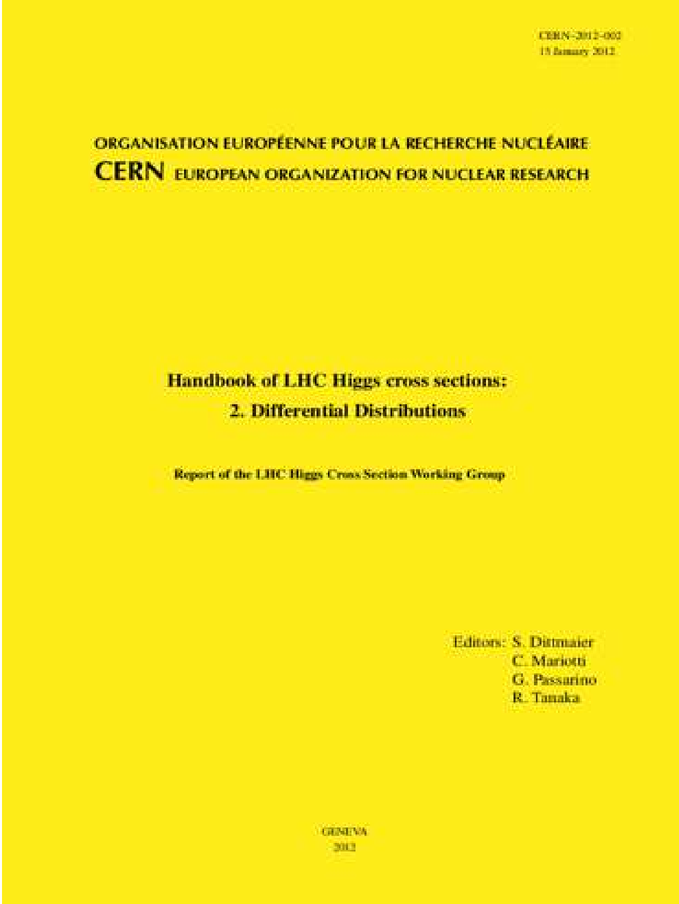

ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUCLÉAIRE
CERN EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Handbook of LHC Higgs cross sections:
1. Inclusive observables

Report of the LHC Higgs Cross Section Working Group

S. Dittmaier
C. Mariotti
G. Passarino
R. Tanaka

GENEVA
2011

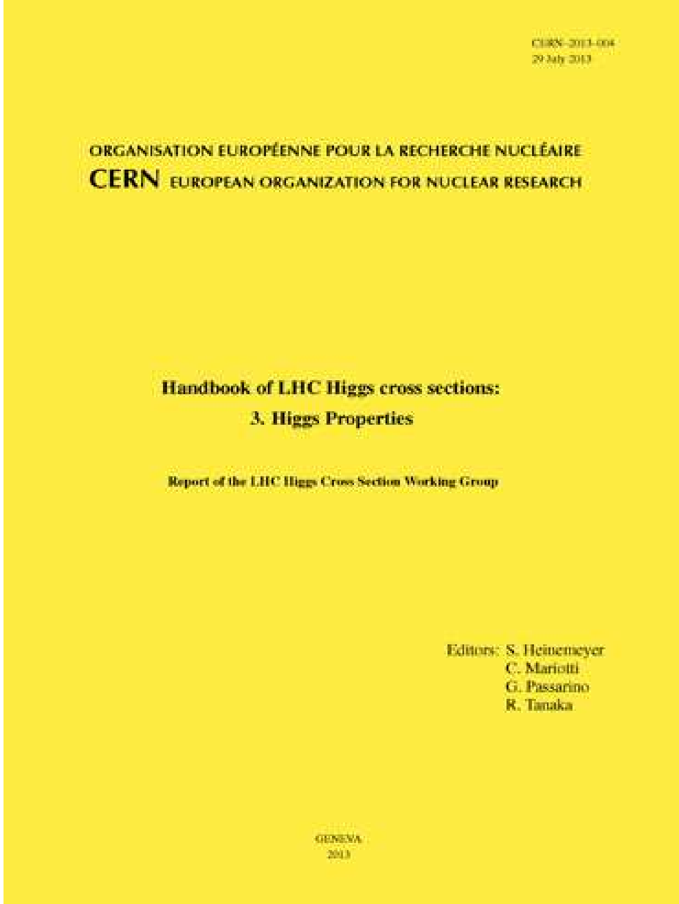

ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUCLÉAIRE
CERN EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Handbook of LHC Higgs cross sections:
2. Differential Distributions

Report of the LHC Higgs Cross Section Working Group

Editors: S. Dittmaier
C. Mariotti
G. Passarino
R. Tanaka

GENEVA
2012


ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUCLÉAIRE
CERN EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Handbook of LHC Higgs cross sections:
3. Higgs Properties

Report of the LHC Higgs Cross Section Working Group

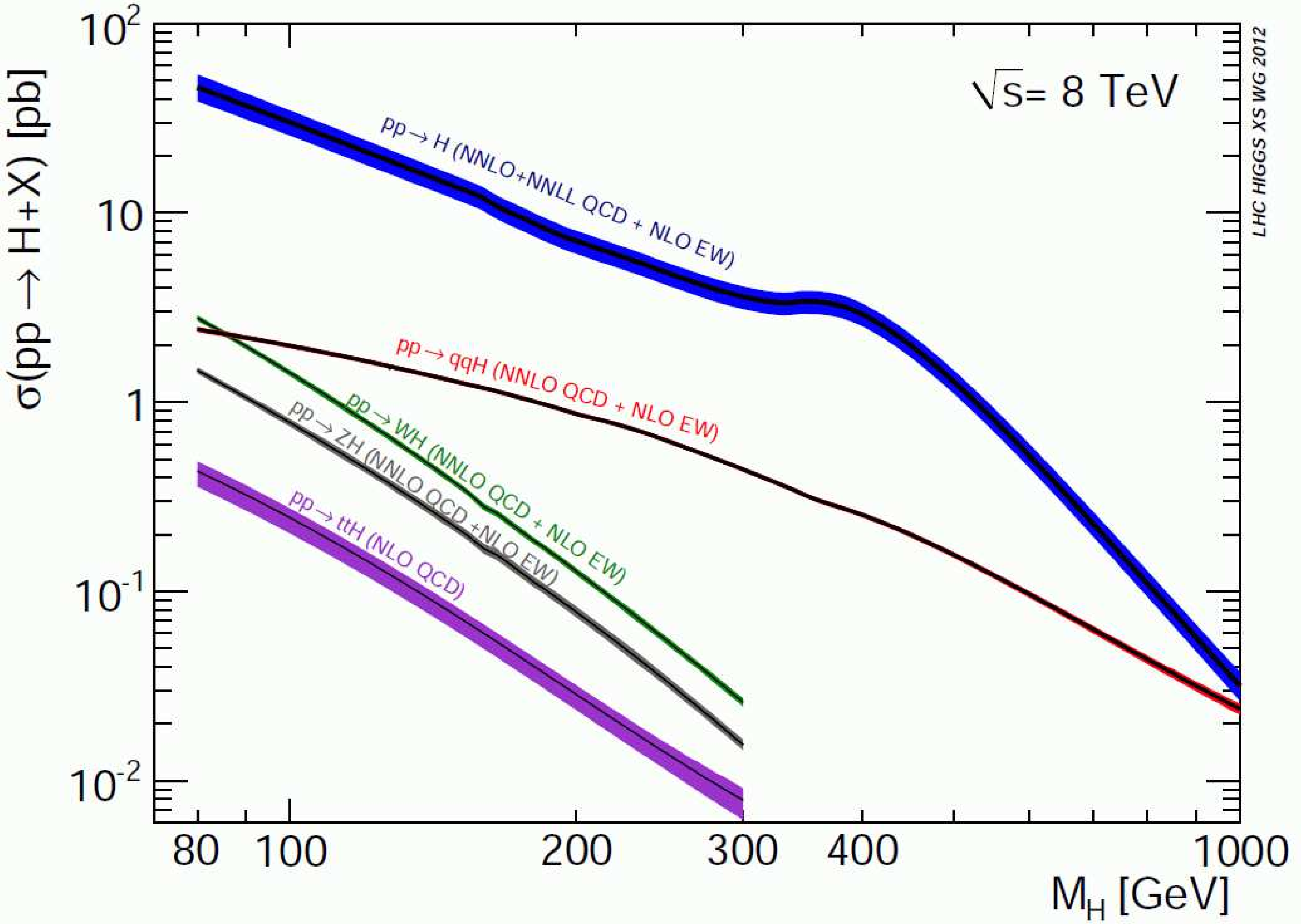
Editors: S. Heinemeyer
C. Mariotti
G. Passarino
R. Tanaka

GENEVA
2013

Appeared: 01/11, 01/12, 07/13
Authors: 64, 120, 157
Pages: 151, 275, 404
Citations: 764, 375, 191

"Official" theory predictions for the SM Higgs: LHC production XS

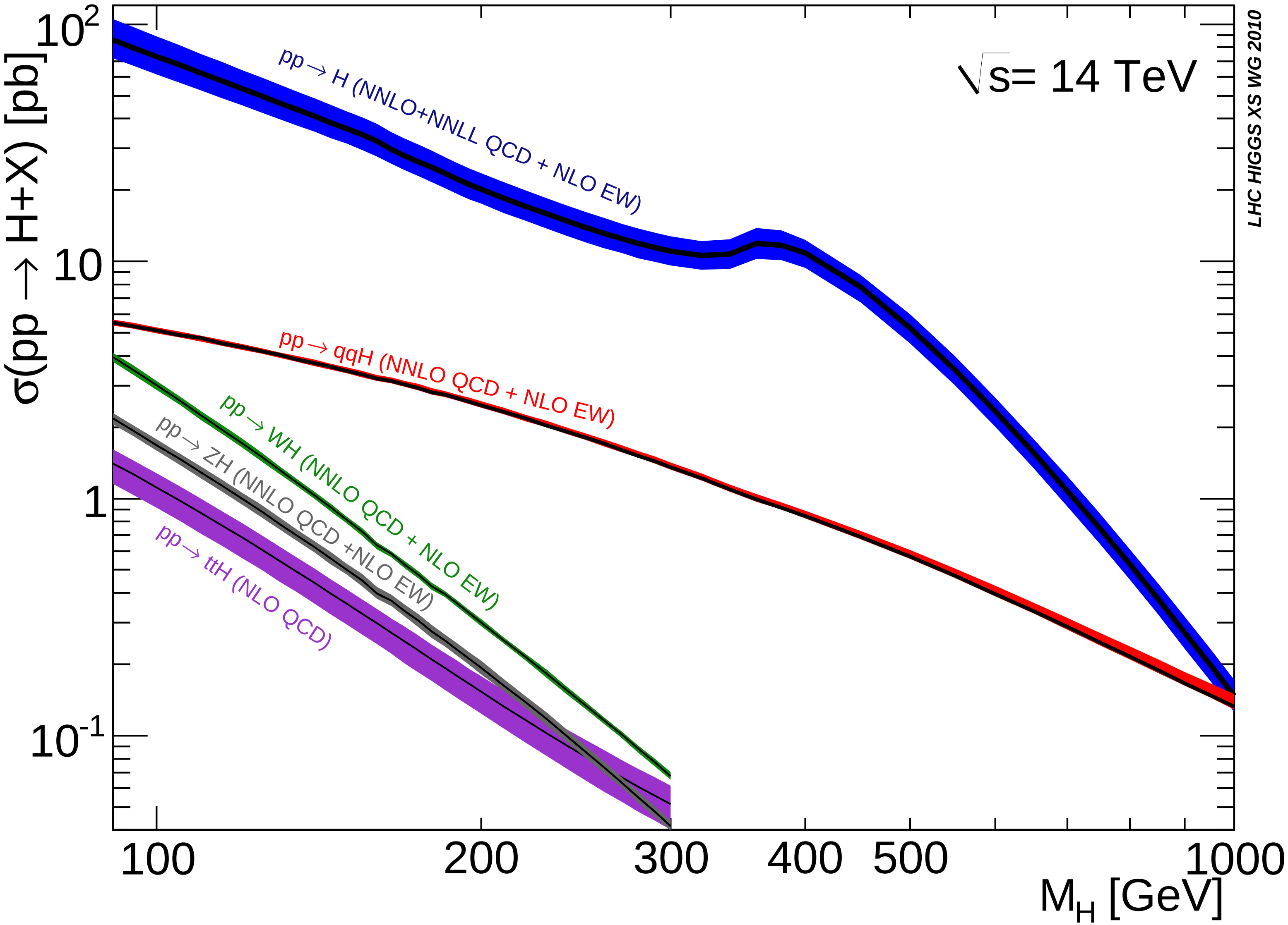
[*LHC Higgs XS WG '12*]



⇒ best available prediction

“Official” theory predictions for the SM Higgs: LHC production XS

[*LHC Higgs XS WG ’10*]

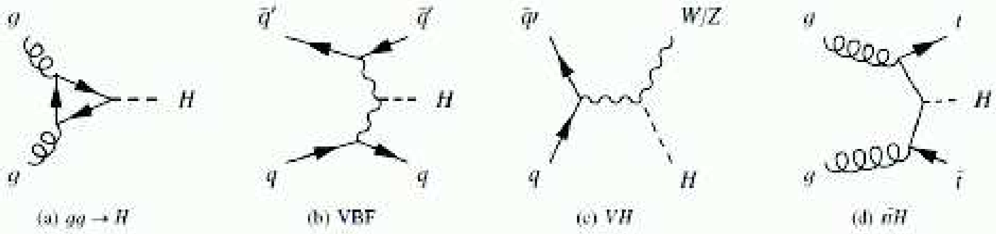


⇒ best available prediction

Higgs cross section uncertainty: [LHCHXSWG '13]

M_H=125 GeV

K-factor, QCD scale and PDF uncertainties



	7 TeV				8 TeV		
	$K_{NNLO/NLO}$ ($K_{NLO/LO}$)	Scale	PDF+α_s	Scale +PDF	Scale	PDF+α_s	Scale +PDF
ggF	+25% (+100%)	+7-8%	±8%	**±15%**	+7-8%	±8%	**±15%**
VBF	<1% (+5-10%)	±1%	±4%	**±5%**	±1%	±4%	**±5%**
WH/ ZH	+2-6% (+30%)	±1%	±4%	**±5%**	±1%	±4%	**±5%**
ttH	- (+5-20%)	+3 -9%	±8%	**+12 -18%**	+4 -9%	±8%	**+12 -17%**

- Renormalization and factorization scale uncertainty study by M. Cacciari et al. work in progress.
- Higher-order calculations, ex. ggF QCD scale: ±8%@NNLO → ±5%@NNNLO in few years ?
- PDF+α_s (PDF4LHC prescription): ±8% → <5% with improvements with LHC data ?
  - jets, top, prompt photons and Z p_T distributions contribute gluon PDF determination.

  (but paradoxically, ggF is the best measure to determine gg parton luminosity around M_H=125GeV!)

(taken from [R. Tanaka, talk at Aspen Higgs WS 03/13])

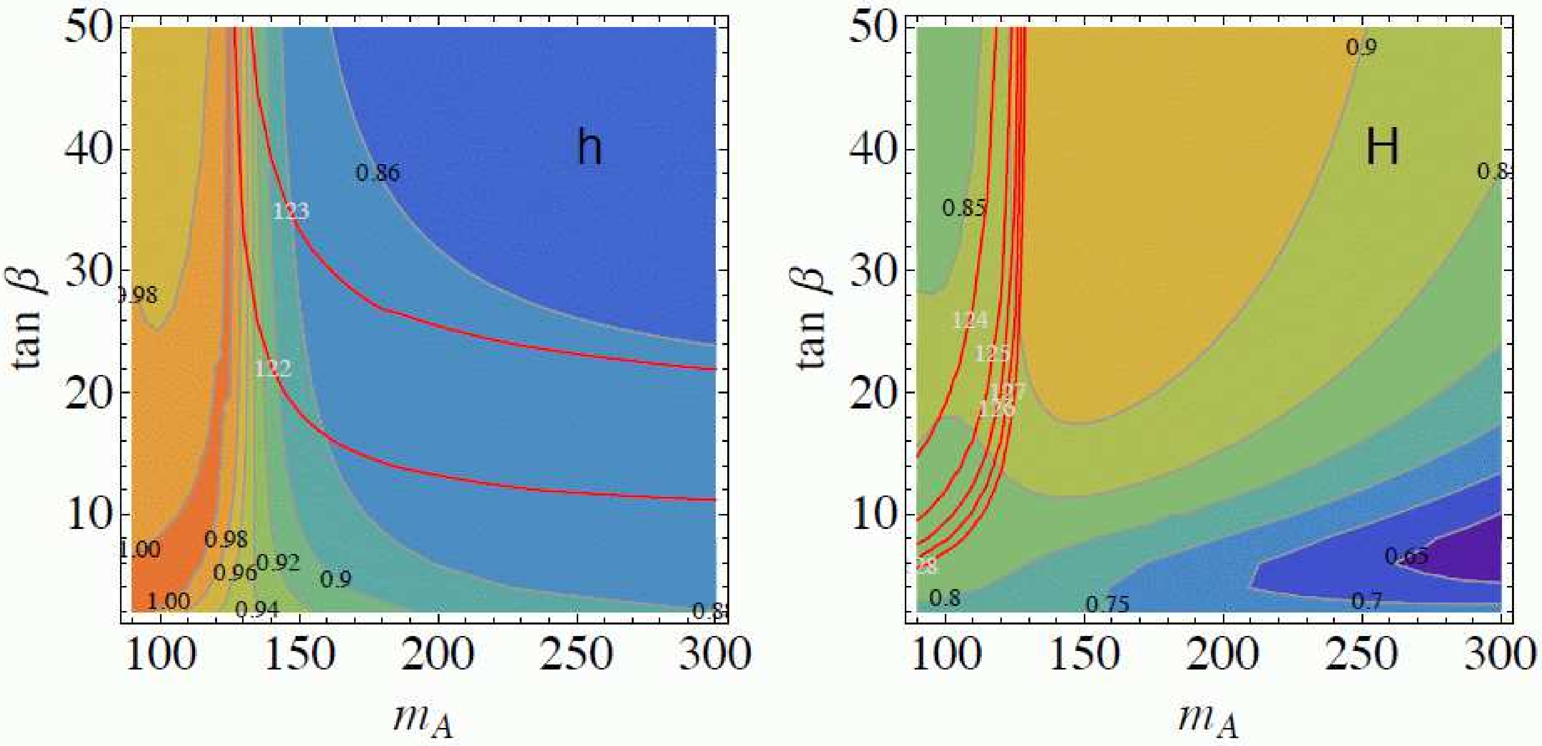
“Official” theory predictions for the MSSM neutral Higgs XS:

[*LHCHXSWG - MSSM ’13*] [*E. Bagnaschi et al. ’14*] [*SusHi*]

A benchmark scenario with light stops and large mixing:

$M_S = 0.5$ TeV, $X_t = 1$ TeV, $\mu = M_2 = 350$ GeV, $m_{\tilde{g}} = 1.5$ TeV

[parameters from Carena *et al.*, arXiv:1302.7033]



$\sigma_{gg}^{q+\tilde{q}} \,/\, \sigma_{gg}^{q}$ [*P. Slavich, talk given at HDays13*]

“Official” theory predictions for light charged Higgs

Sources of theory uncertainties:

1. PDF and α_s uncertainties on $\sigma(pp \to t\bar{t})$

2. experimental uncertainties on m_t, affecting $\sigma(pp \to t\bar{t})$

3. Uncertainties of Δ_b

4. Experimental uncertainties in SUSY masses entering Δ_b

5. Further missing higher order corrections in BR$(t \to H^+ b)$

– How large are the uncertainties?

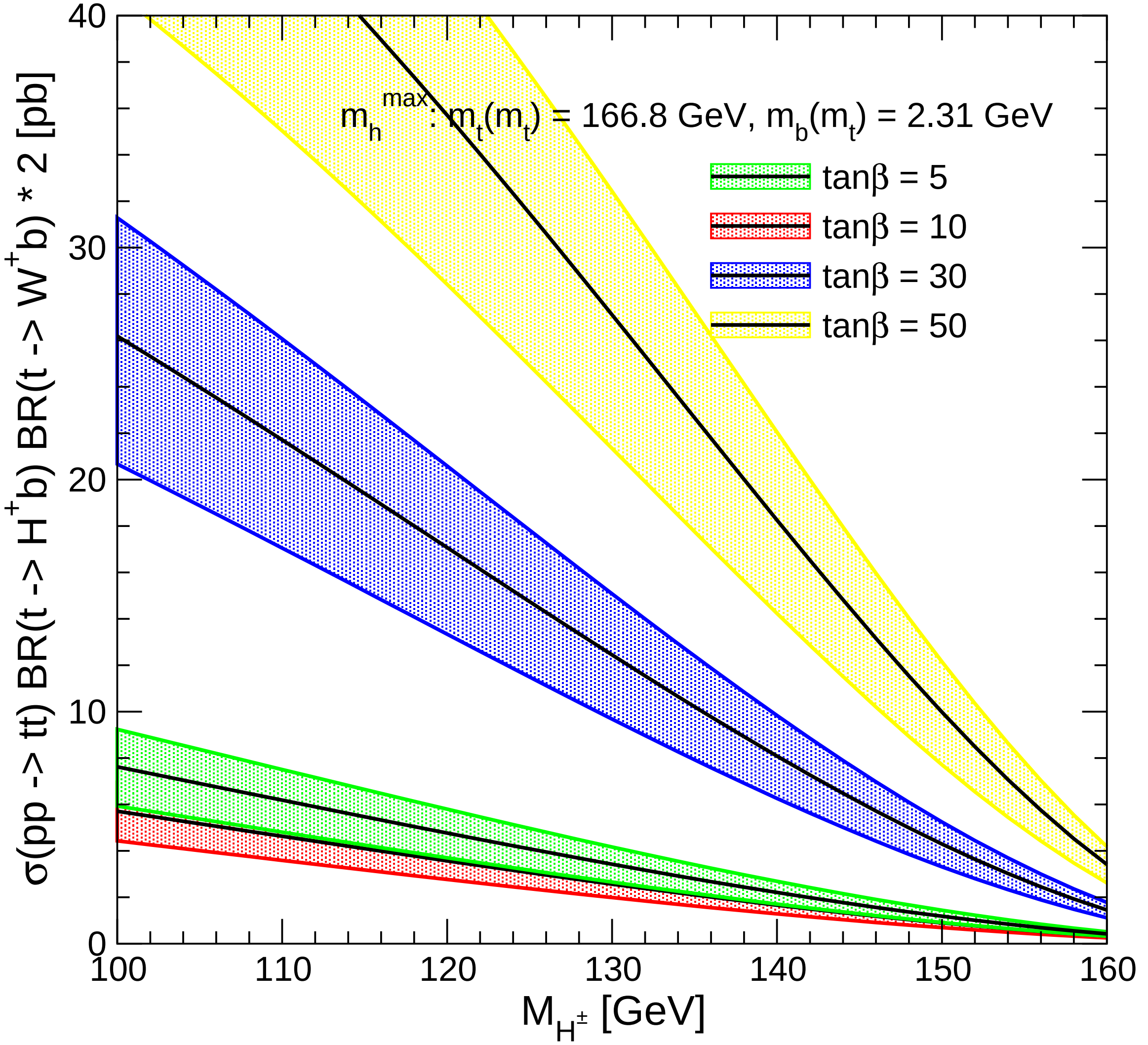
– How large are the corresponding effects?

⇒ details: *[S.H., talk at “Charged Higgs 2012”]*

Combination of everything:

[*LHCHXSWG '12*]

$$\sigma(pp \to t\bar{t}) \times \mathrm{BR}(t \to H^{\pm}b) \times \mathrm{BR}(t \to W^{\pm}b) \times 2$$



⇒ non-negligible . . .

“Official” theory predictions for heavy charged Higgs

Heavy charged Higgs NLO cross sections without SUSYQCD corrections, Update September 2014

Contact: Martin Flechl, Michael Krämer, Michael Spira, Maria Ubiali

A **preliminary** version (pending final discussion in a WG3 meeting) of a grid of Santander-matched cross sections in tan beta (1-60) and mH+ (200-600 GeV) is available here for 8TeV and here for 14 TeV. Also given are total uncertainties (PDF, alphas, scale, mb). Numbers are for 2HDM type-II (a la MSSM), but without SQCD corrections. For how to transform this into MSSM cross sections, see below. Contact Martin Flechl for questions of format etc, and Maria Ubiali, Michael Krämer, Michael Spira, Martin Flechl for physics-related questions.

A paper documenting these numbers will be submitted to arXiv within a few days, and the reference added here.

– 2HDM type II
– no SUSY corrections (Δ_b)

“Private” extension:

⇒ included into FeynHiggs to produce MSSM XS
– SUSY corrections (Δ_b) consistently added
– external Z-factor for on-shell charged Higgs added

"Official" theory predictions for MSSM heavy charged Higgs

Heavy charged Higgs cross sections for MSSM scenarios

Contact: Martin Flechl

SUSY-QCD NLO corrections can be added to the NLO cross sections at very good approximation by including the so-called delta_b corrections. The delta_b values for the scenarios lightstau, lightstop, lowMH, mhmaxup, mhmodm, mhmodp and tauphobic are provided here.

Recipe to add delta_b corrections, for a point with charged Higgs mass mhp and tan beta tb (recipe from Sven Heinemeyer):

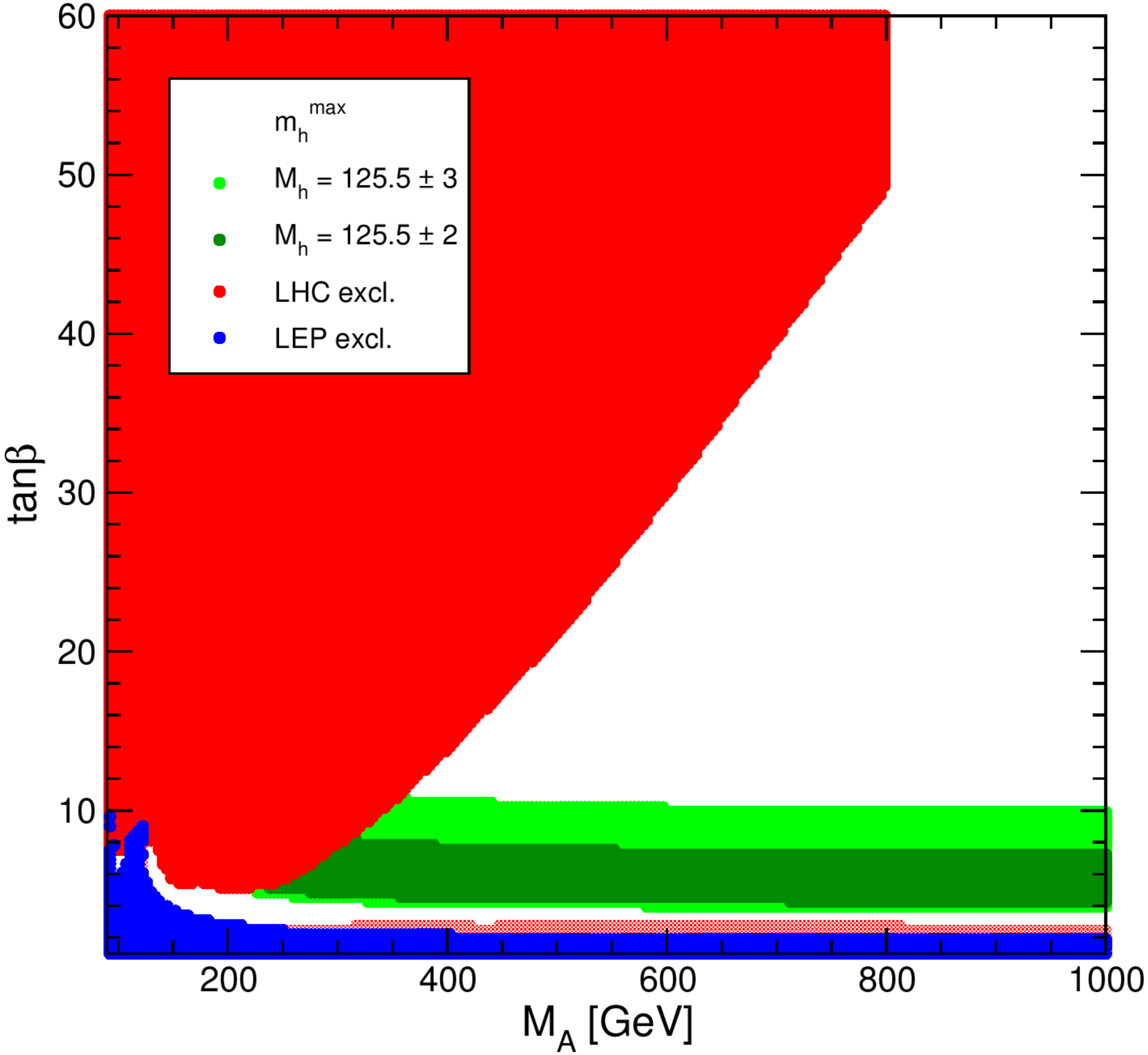
- Find the delta_b value corresponding to tb
- Calculate tbeff = tb/sqrt{1 + delta_b}
- Using the cross sections without SUSY-QCD NLO corrections, get the cross section which corresponds to tbeff (!)
- Multiply the result from the previous bullet with 1/(1 + delta_b) => this is your cross section [Note: corrected on 2014-01-27 thanks to Alexandre Nikitenko]

Note that this typically is not sufficient at low tan beta, where other SQCD-related corrections on top of delta_b corrections are not negligible. There is no official recipe on how to deal with this, but a conservative way would be to assign an extra relative uncertainty of 10% for tan beta<10 -- but of course these additional contributions depend heavily on the scenario.

scenarios_feynhiggs.tar: FeynHiggs input files for MSSM scenarios, as used in CERN Report v3

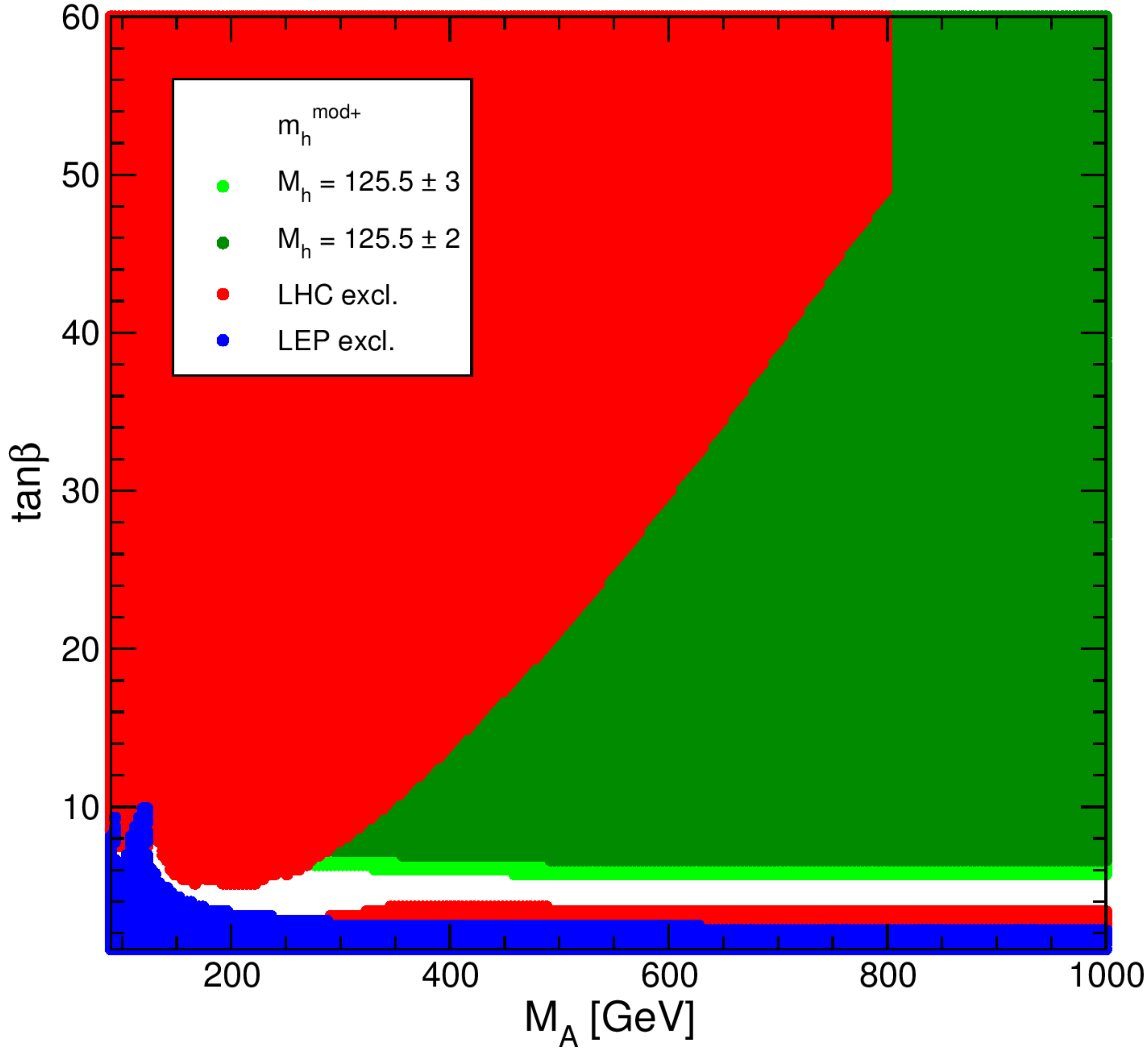
– SUSY corrections (Δ_b) consistently added (taken from FeynHiggs)
– evaluated for MSSM benchmark scenarios

⇒ maximize all contributions and assume $M_h = 125.5 \pm 3$ GeV



⇒ new bounds: $M_A > 200$ GeV, $\tan\beta > 4$

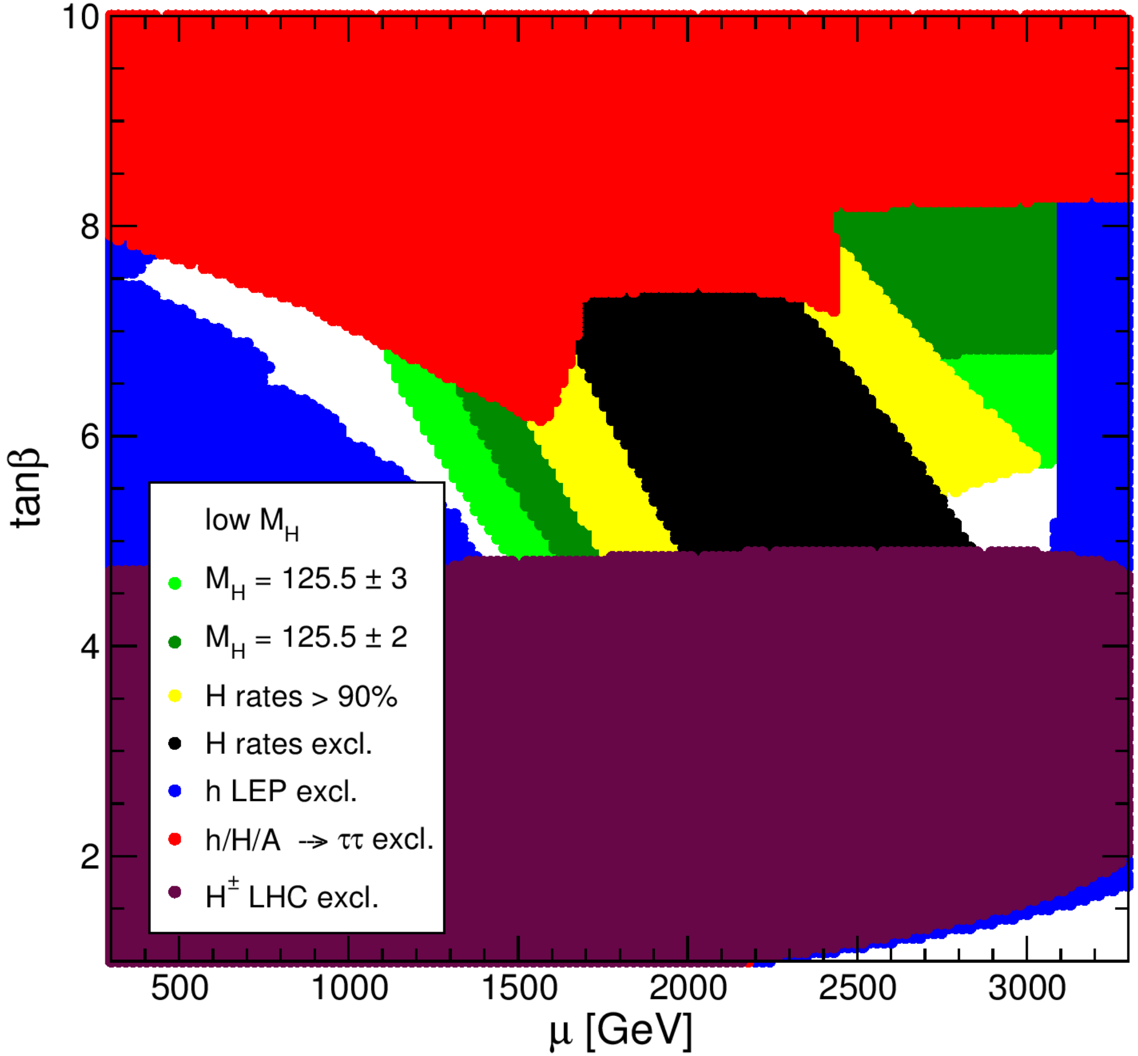
⇒ new scenario: $m_h^{\text{mod}+}$



⇒ light Higgs mass "correct" over the whole parameter space!

A "heavy" SUSY Higgs at 125.5 GeV?

[*LHCHXSWG '13*]



$m_t = 173.2$ GeV,

$M_A = 110$ GeV,

$M_{\mathrm{SUSY}} = 1500$ GeV,

$M_2 = 200$ GeV,

$X_t^{\mathrm{OS}} 2.45 M_{\mathrm{SUSY}}$

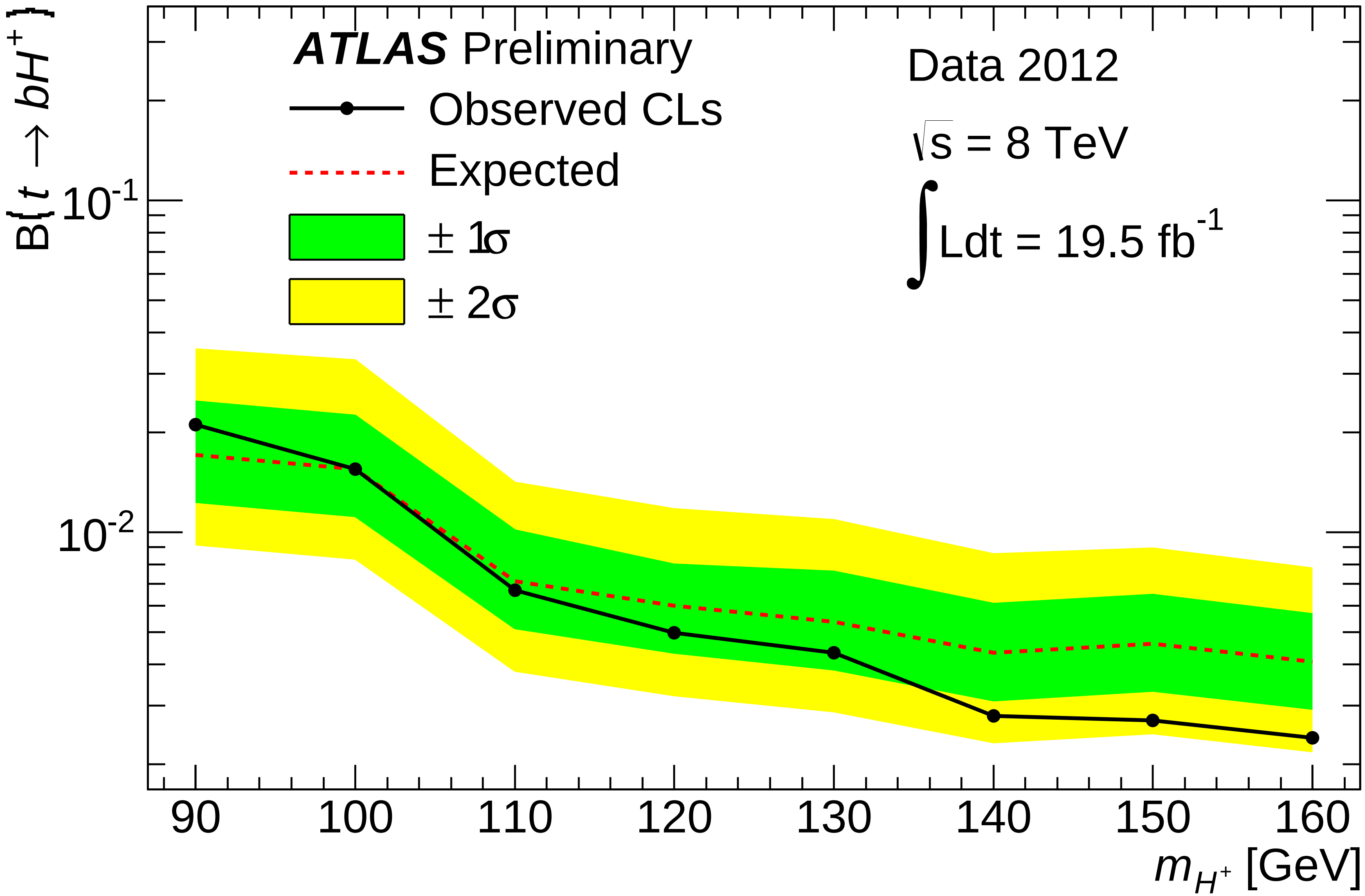
$A_b = A_\tau = A_t$,

$m_{\tilde{g}} = 1500$ GeV,

$M_{\tilde{l}_3} = 1000$ GeV .

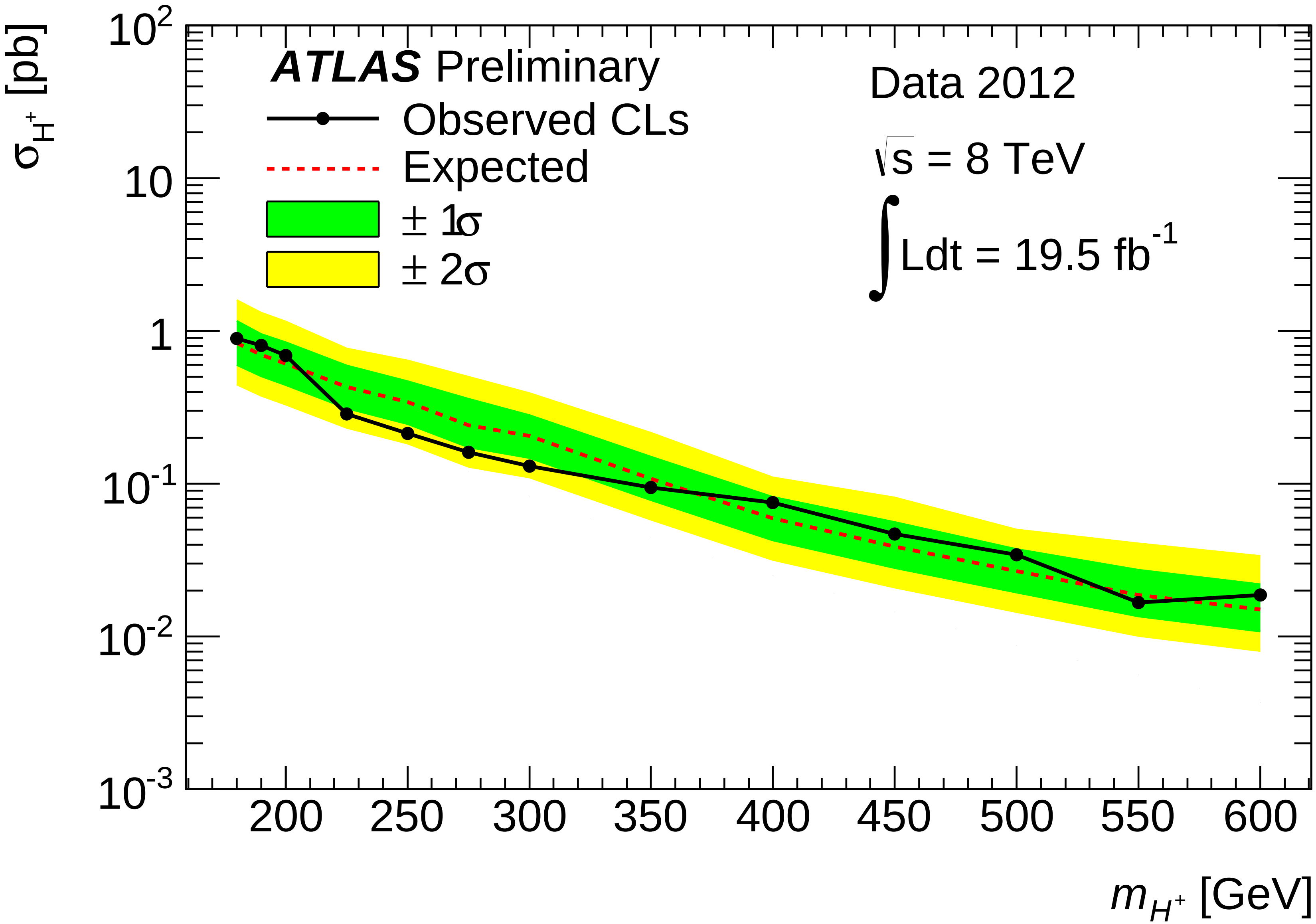
⇒ $M_H \approx 125.5$ GeV can in principle be realized

⇒ now challenged by search for light charged Higgs . . .



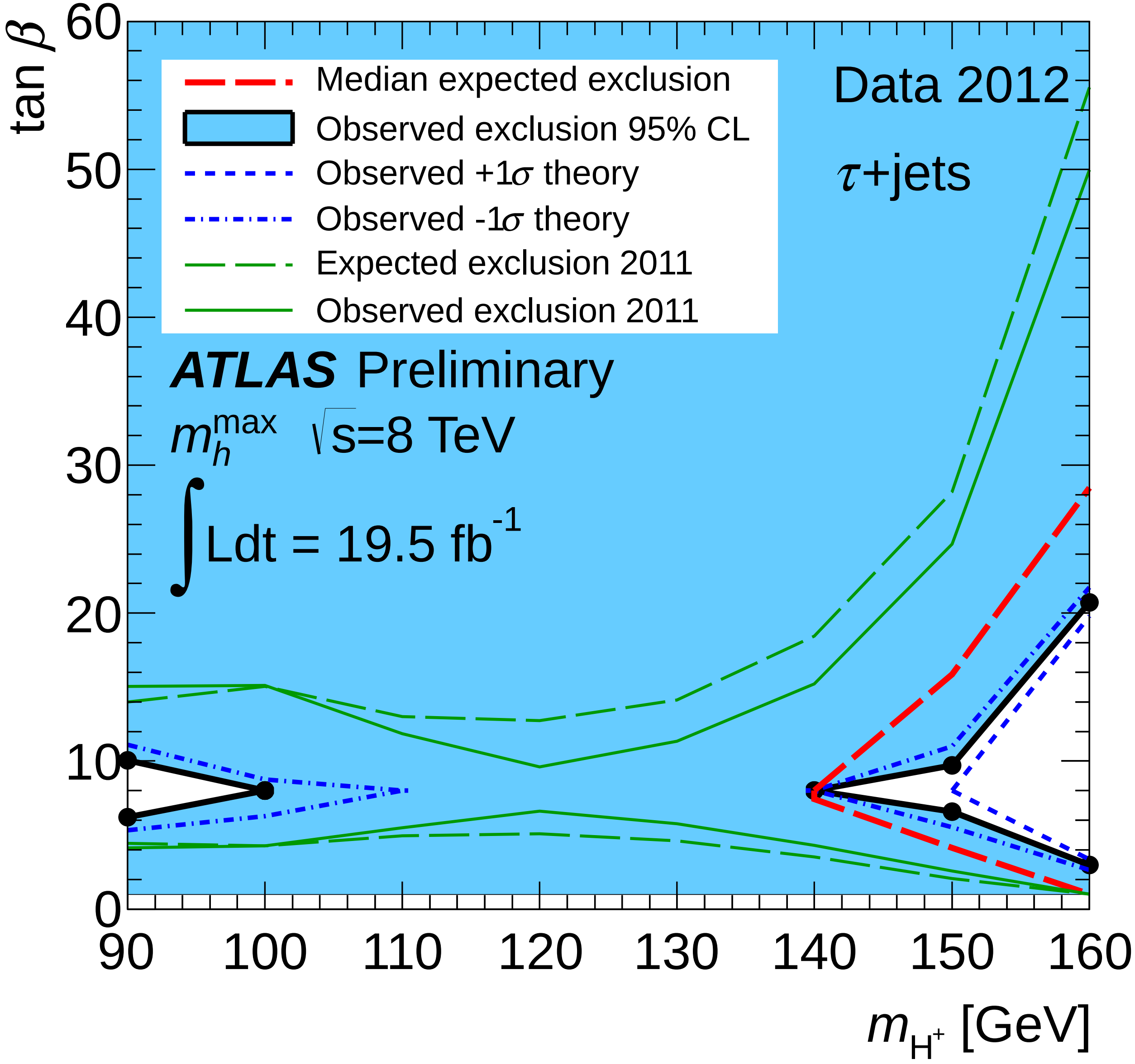
⇒ model independent limits!

Latest ATLAS results for charged Higgs searches: [ATLAS '13]



⇒ model independent limits!

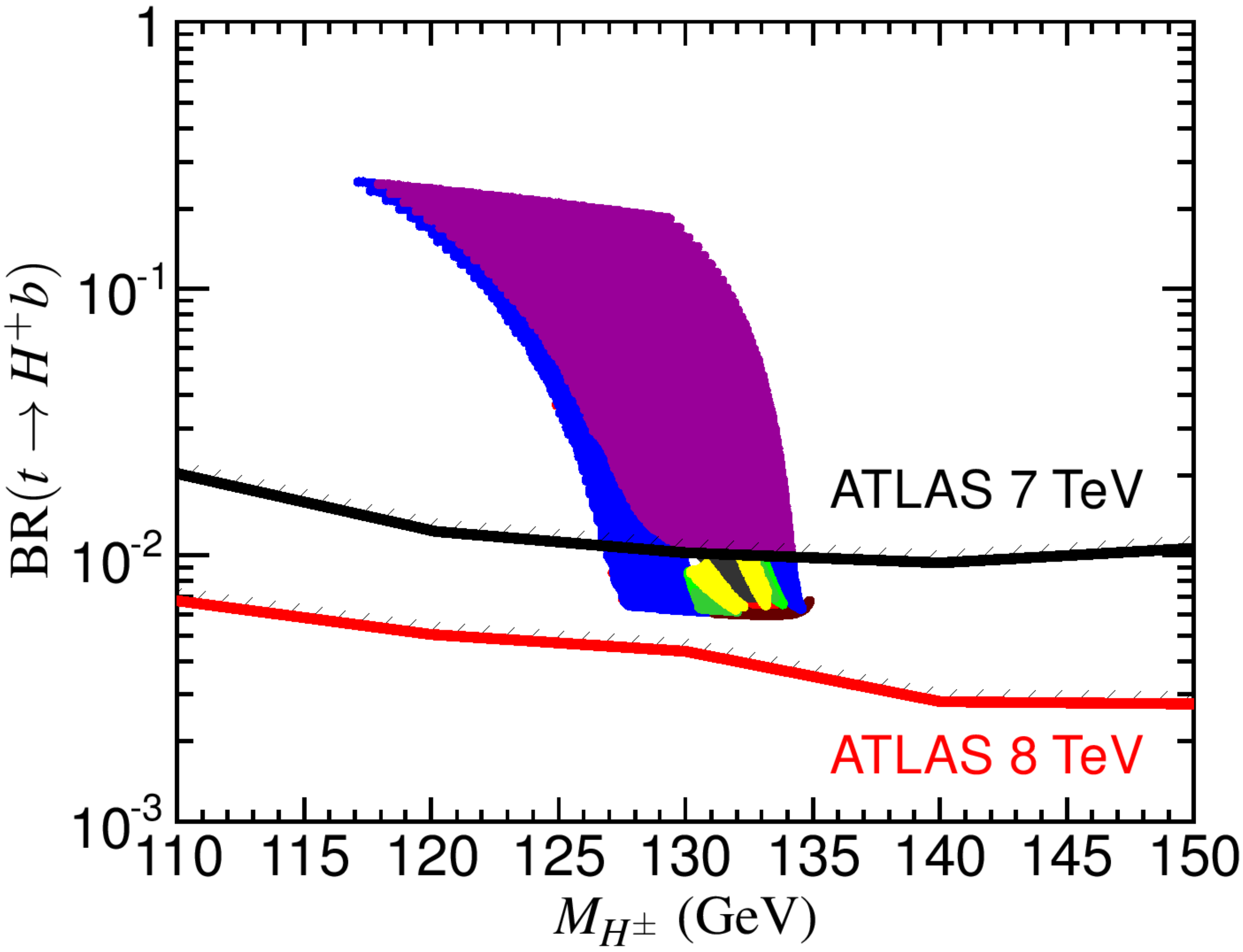
Latest ATLAS results for charged Higgs searches: [*ATLAS '13*]



⇒ exclusion of light $M_{H^\pm}$ in the m_h^{max} scenario! . . . low-M_H?

Application of charged Higgs limits on low-M_H scenario:

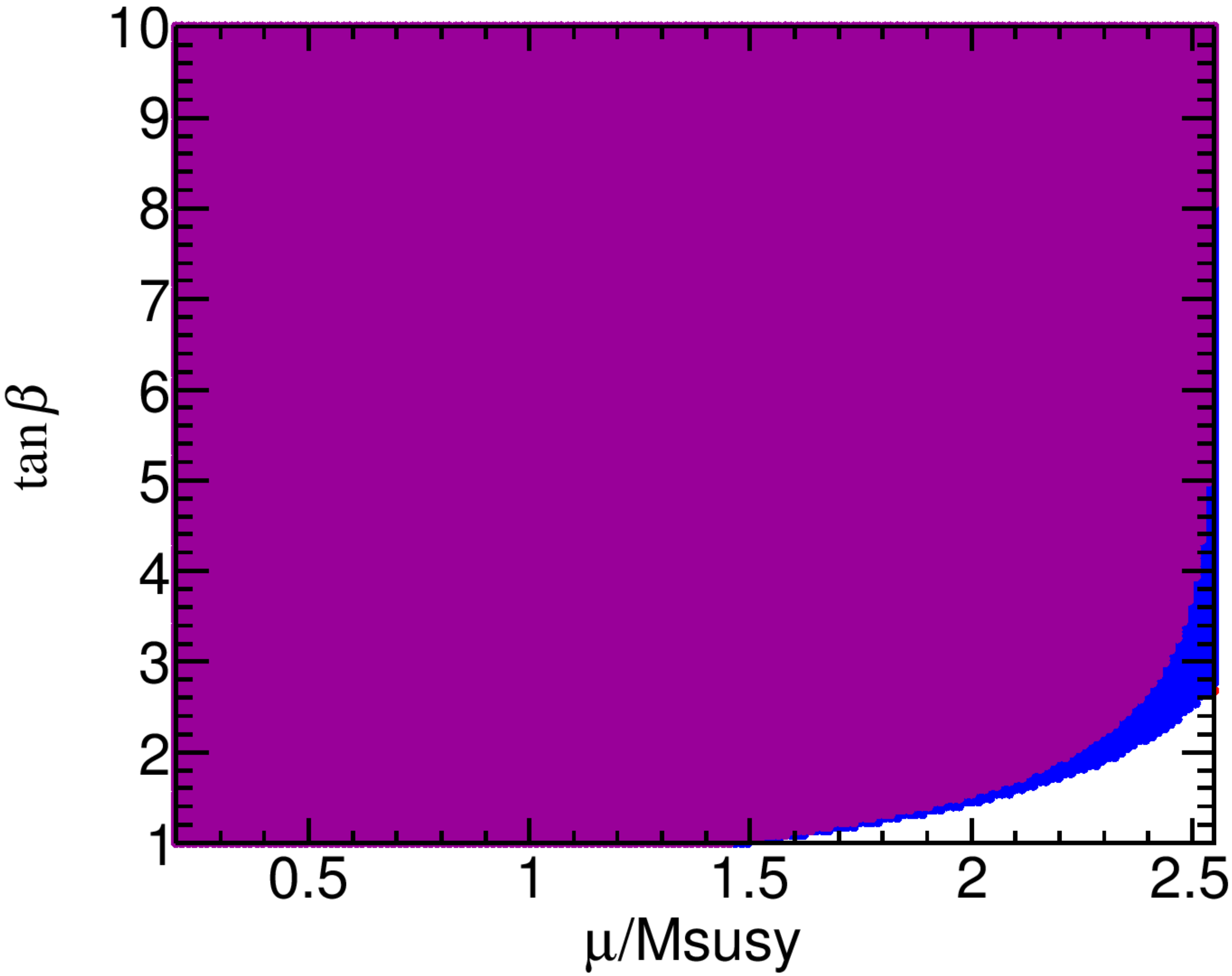
[*HiggsBounds 4.1*]



$\Rightarrow$ that (particular incarnation of the) low-M_H scenario is excluded?

Application of charged Higgs limits on low-M_H scenario:

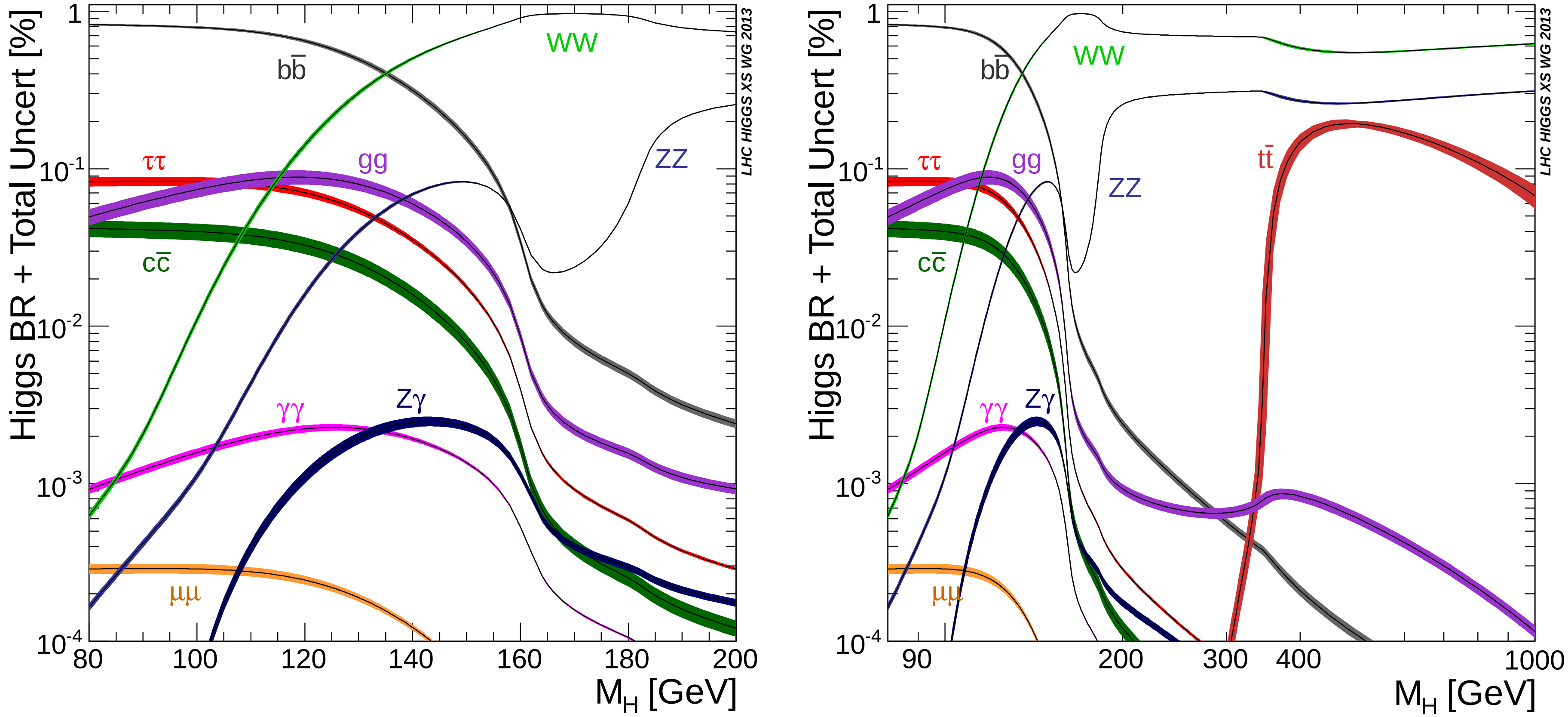
[*HiggsBounds 4.1*]



⇒ that (particular incarnation of the) low-M_H scenario is excluded?

"Official" theory predictions for the SM Higgs: branching ratios

[*LHC Higgs XS WG '13*]



Based on HDECAY and Prophecy4f:

$$\Gamma_H = \Gamma^{\rm HD} - \Gamma^{\rm HD}_{ZZ} - \Gamma^{\rm HD}_{WW} + \Gamma^{\rm P4f}_{4f}$$

⇒ best available prediction based on code combination

"Official" calculation of MSSM BR's: [LHCHXSWG '11-'14]

1. Input parameters to FeynHiggs (native format or SLHA)

2. FeynHiggs $\Rightarrow$ Higgs masses, couplings, decay widths/BRs

   Output via SLHA file (total width and BRs)

3. SLHA file is stored and fed to HDECAY

4. HDECAY $\Rightarrow$ decay widths

   Output via SLHA file (total width and BRs)

5. "Script" reads both SLHA files, extracts total and branching ratios
   $\Rightarrow$ calculation of partial widths

6. "Script" calculates total width:

$$\Gamma_\phi = \Gamma^{\rm FH}_{\phi\to\tau\tau} + \Gamma^{\rm FH}_{\phi\to\mu\mu} + \Gamma^{\rm FH/P4f}_{\phi\to W^{(*)}W^{(*)}} + \Gamma^{\rm FH/P4f}_{\phi\to Z^{(*)}Z^{(*)}} + \Gamma^{\rm HD}_{\phi\to b\bar b} + \Gamma^{\rm HD}_{\phi\to t\bar t} + \Gamma^{\rm HD}_{\phi\to c\bar c} + \Gamma^{\rm HD}_{\phi\to gg} + \Gamma^{\rm HD}_{\phi\to\gamma\gamma} + \Gamma^{\rm HD}_{\phi\to Z\gamma}$$

7. "Script" calculates BRs

"Official" calculation of MSSM BR's: [LHCHXSWG '11-'14]

1. Input parameters to FeynHiggs (native format or SLHA)

2. FeynHiggs $\Rightarrow$ Higgs masses, couplings, decay widths/BRs

   Output via SLHA file (total width and BRs)

3. SLHA file is stored and fed to HDECAY

4. HDECAY $\Rightarrow$ decay widths

   Output via SLHA file (total width and BRs)

5. "Script" reads both SLHA files, extracts total and branching ratios
   $\Rightarrow$ calculation of partial widths

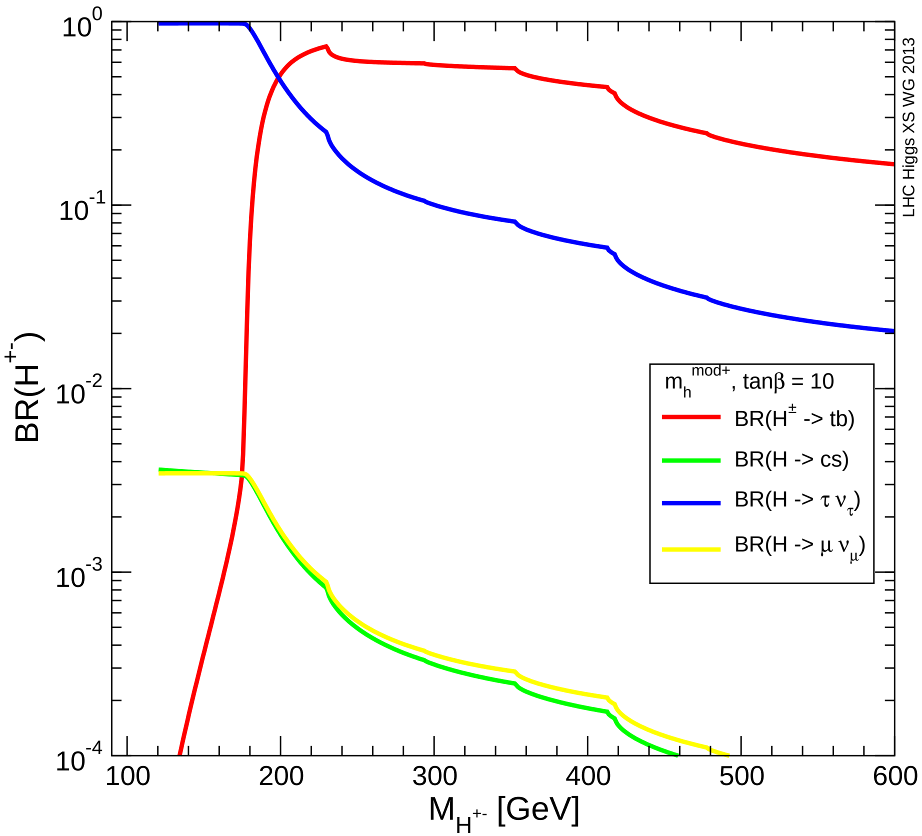
6. "Script" calculates total width:

$$\Gamma_{H^\pm} = \Gamma^{\mathsf{HD}}(H^\pm \to tb) + \Gamma^{\mathsf{FH}}(H^\pm \to \tau\nu_\tau) + \Gamma^{\mathsf{FH}}(H^\pm \to \mu\nu_\mu) + \Gamma^{\mathsf{HD}}(H^\pm \to cs) + \Gamma^{\cdots}(H^\pm \to AW) + \Gamma^{\cdots}(H^\pm \to HW) + \ldots$$

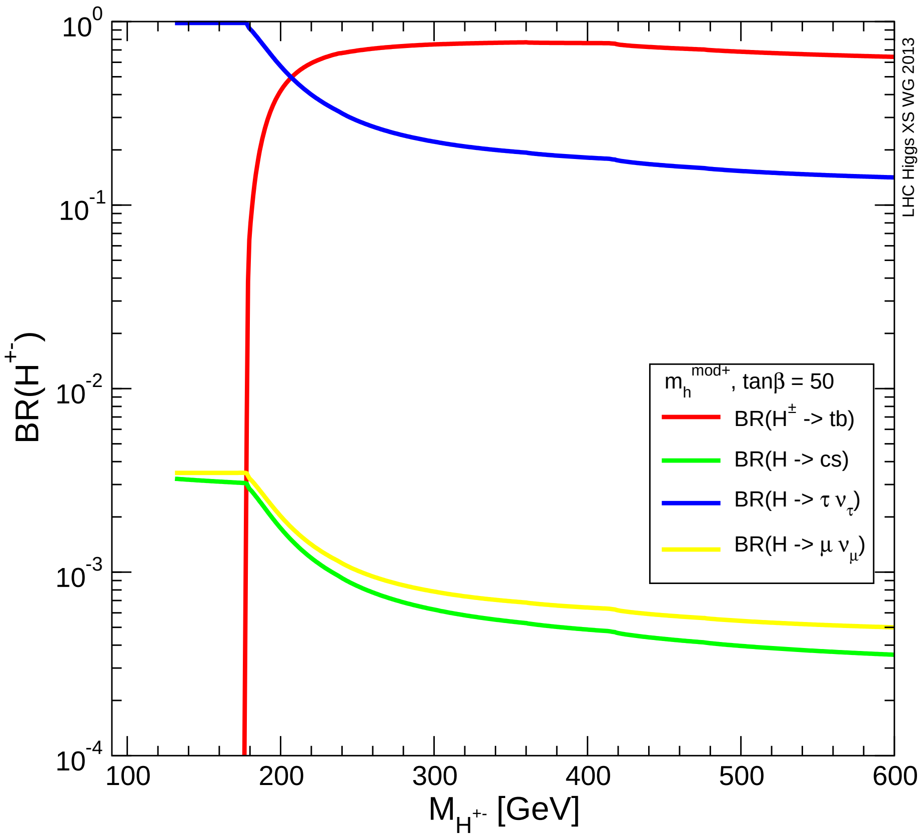
7. "Script" calculates BRs

Example results: charged Higgs BRs in $m_h^{\rm mod+}$ scenario: [*LHCHXSWG '13*]

$\tan\beta = 10$

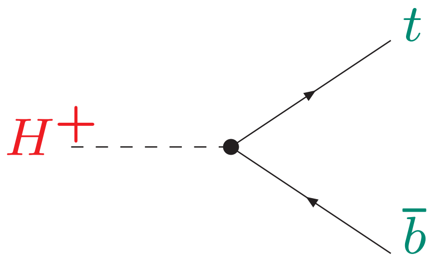


$\tan\beta = 50$



$\Rightarrow$ kinks from chargino/neutralino thresholds

Effects of Δ_b on production $\times$ decay:



$$y_b \, \frac{\tan\beta}{1+\Delta_b}$$

$$\Delta_b = \frac{2\alpha_s}{3\,\pi} m_{\tilde{g}}\, \mu \, \tan\beta \times I(m_{\tilde{b}_1}, m_{\tilde{b}_2}, m_{\tilde{g}}) + \frac{\alpha_t}{4\,\pi} A_t\, \mu \, \tan\beta \times I(m_{\tilde{t}_1}, m_{\tilde{t}_2}, \mu) + \ldots$$

$\Rightarrow$ other parameters enter $\Rightarrow$ strong μ dependence

$$H^\pm : \frac{\tan^2\beta}{(1+\Delta_b)^2} \times \mathrm{BR}(H^\pm \to \tau\nu_\tau)$$

$$: \frac{\tan^2\beta}{(1+\Delta_b)^2} \times \frac{\Gamma(H^\pm \to \tau\nu_\tau)}{\Gamma^{\mathrm{THDM}}(H^\pm \to tb)/(1+\Delta_b)^2 + \Gamma(H^\pm \to \tau\nu_\tau) + \ldots}$$

$\Rightarrow$ no compensation of Δ_b effects for light charged Higgs
$\Rightarrow$ partial compensation for heavy charged Higgs
$\Rightarrow$ crucial: consistent treatment of Δ_b

Latest (interim) recommendation: XS, BR in the 2HDM: [*LHCHXSWG '13*]

LHCHXSWG-2013-001

KA–TP–41–2013
LU TP 13–44
PSI–PR–13–17
WUB/13-19

LHC Higgs Cross Section Working Group

Interim recommendations for the evaluation of Higgs production cross sections and branching ratios at the LHC in the Two-Higgs-Doublet Model

R. Harlander[1], M. Mühlleitner[2], J. Rathsman[3], M. Spira[4], O. Stål[5]

– SusHi & 2HDMC ⇒ talk by Oscar this afternoon
– Higlu & Hdecay
– updates/improvements expected (Powheg, MadGraph5, . . .)

- **2HDM cross sections ($gg \to \phi$, $b\bar{b} \to \phi$):** HIGLU [Spira] and SUSHI [Harlander,Liebler,Mantler]

$$\sigma^{\text{2HDM}}(gg \to \phi) = \left(\frac{g_t^{\text{2HDM}}}{g_t^{\text{SM}}}\right)^2 \sigma_{tt}(gg \to \phi) + \left(\frac{g_b^{\text{2HDM}}}{g_b^{\text{SM}}}\right)^2 \sigma_{bb}(gg \to \phi) + \frac{g_t^{\text{2HDM}}}{g_t^{\text{SM}}}\frac{g_b^{\text{2HDM}}}{g_b^{\text{SM}}}\sigma_{tb}(gg \to \phi)$$

$$\Delta\sigma_{tt}^{NNLO}(gg \to \phi) = \Delta K_{NNLO}\, \sigma_{tt}^{LO}(gg \to \phi), \qquad \Delta K_{NNLO} = \frac{\sigma_{NNLO} - \sigma_{NLO}}{\sigma_{LO}}$$

$\sqrt{s}$ /TeV	$\sigma(gg \to h)$/pb SusHi	HIGLU	%	$\sigma(gg \to H)$/pb SusHi	HIGLU	%	$\sigma(gg \to A)$/pb SusHi	HIGLU	%
7	21.99	21.25	3.4	0.07199	0.06996	2.9	4.061	4.063	0.06
8	28.02	27.07	3.5	0.09895	0.09617	2.9	5.639	5.642	0.06
13	63.94	61.79	3.4	0.2845	0.2766	2.8	16.69	16.70	0.06
14	72.03	69.60	3.4	0.3303	0.3212	2.8	19.45	19.46	0.06

- **2HDM branching ratios:** type I-IV:
  2HDMC [Eriksson,Rathsman,Støal] and
  HDECAY [Djouadi,Kalinowski,MMM,Spira]
  both include higher-order (QCD) corrections

- **Recommendation: Use**
  2HDMC, HDECAY for BRs, Sushi, HIGLU for cxn;
  links Sushi/2HDMC and HIGLU/HDECAY

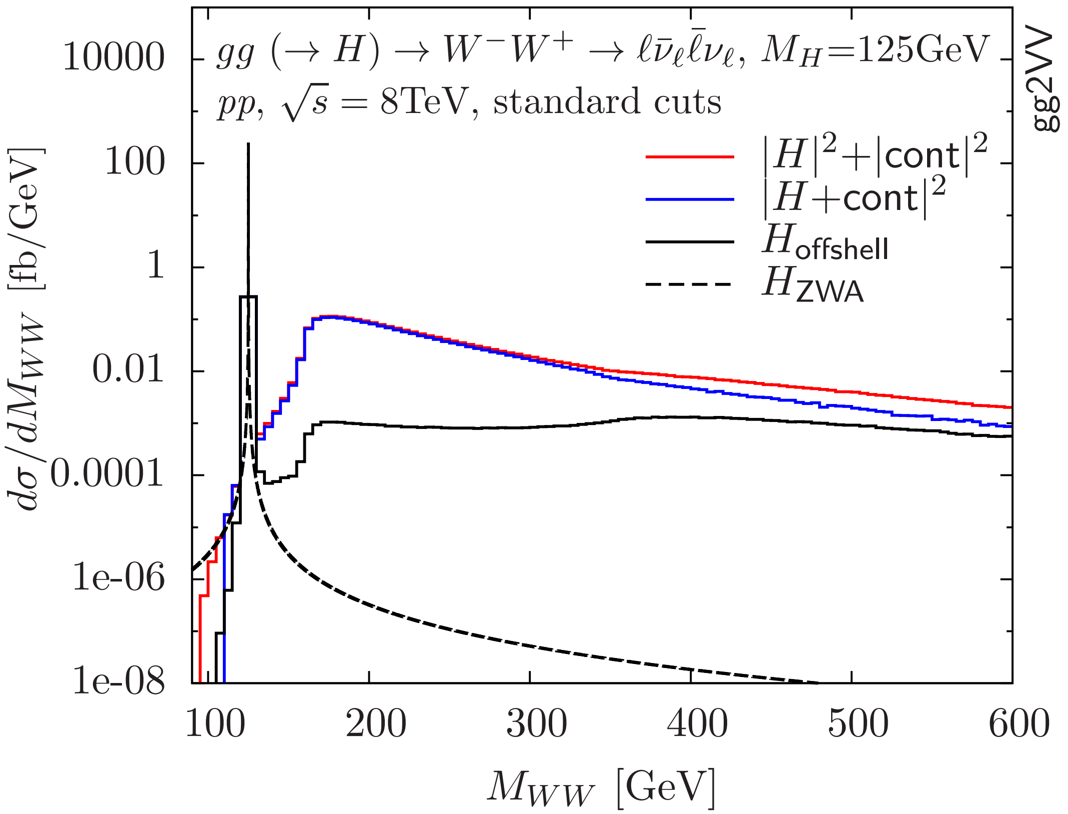
taken from
[M. Mühlleitner '13]

Many further success stories:

Many further success stories:

Analysis of interference effects for $gg \to H \to VV$:

[*N. Kauer, G. Passarino '12*] [*LHCHXSWG '13*]



$gg \to H \to WW$:
-10% negative interference for light Higgs and large positive for heavy Higgs

→MCFM, gg2WW

$gg \to H \to ZZ$:
similar, but smaller effects

strongly cut dependent

Assumptions (for 2012 data):

1. Signal corresponds to only one state, no overlapping signal etc.
2. Zero-width approximation
3. Only modification of coupling strength (absolute values of couplings) but not of tensor structure wrt. to SM

Recommendations (for 2012 data):

1. Use state-of-the-art predictions in the SM and rescale the predictions with "leading order inspired" scale factors κ_i ($\kappa_i = 1$ corresponds to the SM case)
2. Most general case: κ_W, κ_Z, κ_t, κ_b, κ_τ, $\ldots$ $\oplus$ extra loop contributions to $\sigma(gg \to H)$, $\Gamma(H \to gg)$, $\Gamma(H \to \gamma\gamma)$, $\Gamma_{H,\text{tot}}$
3. benchmarks:
   - one parameter: overall signal strength $\kappa^2 \equiv \mu$
   - two parameters: $\kappa_V := \kappa_W = \kappa_Z$, $\kappa_F := \kappa_t = \kappa_b = \kappa_\tau = \ldots$
   - ...

Recommendations continued:

Total width $\Gamma_{H,\text{tot}}$ cannot be measured without further theory assumptions.
(This is not a recommendation, but a fact!)

For each benchmark (except overall coupling strength) two versions are proposed:
with and without taking into account the possibility of additional contributions to the total width

– additional contributions to $\Gamma_{H,\text{tot}}$ are allowed:

⇒ Determination of ratios of scaling factors, e.g. $\kappa_i \kappa_j / \kappa_H$

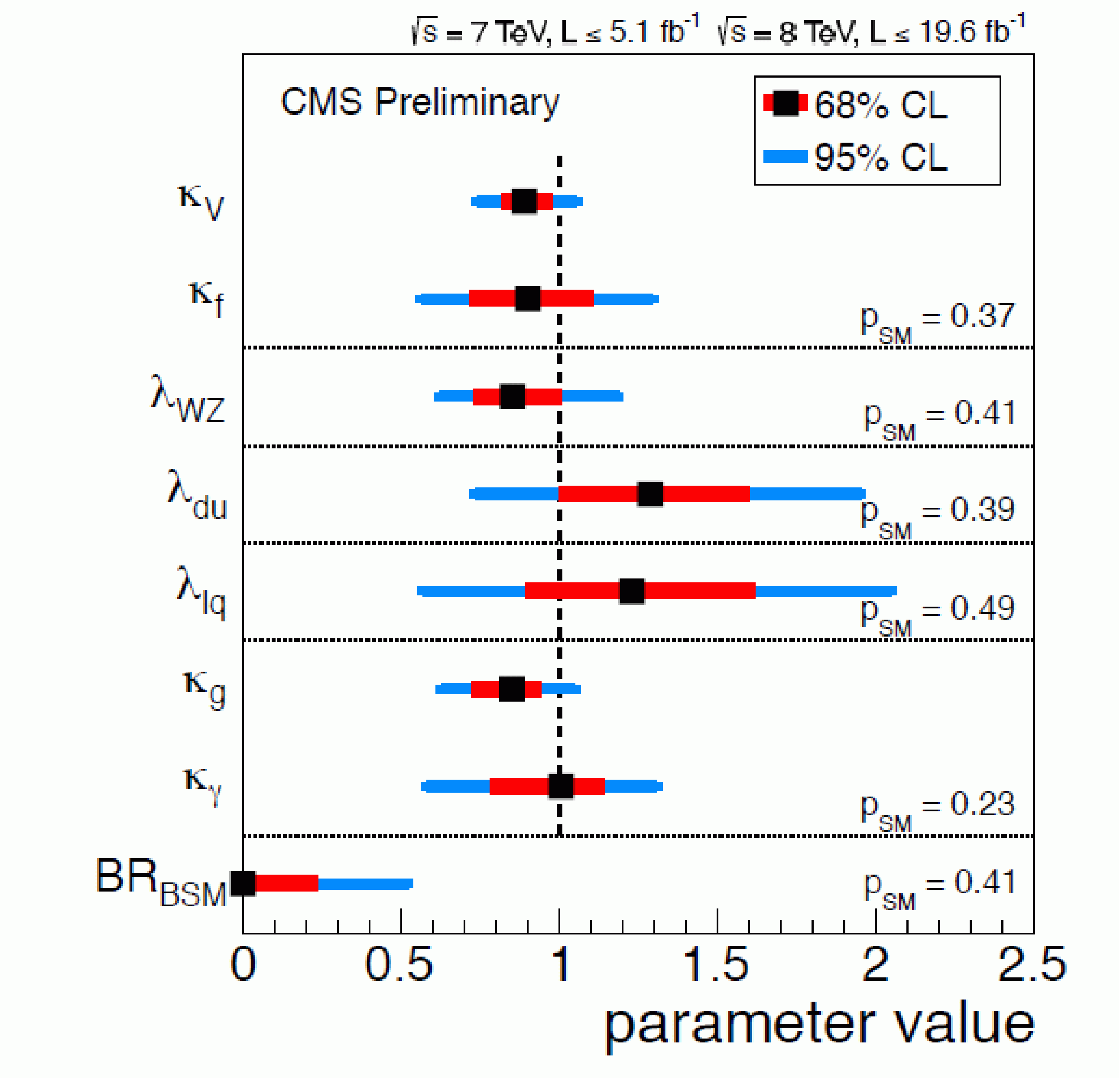
– no additional contributions to $\Gamma_{H,\text{tot}}$ are allowed:

⇒ Determination of κ_i (evaluated to NLO QCD accuracy)

⇒ all "official" coupling strength factor determinations based on this

Example of application:

[CMS '13]



More important topics:

- Jet-bin uncertainty
  - reduction in jet-bin uncertainty for 1-jet exclusive in particular
  - ggF+2jets contamination in VBF category;

  how to reduce contamination and assoc. uncertainty?
  - developments of other categorization methods

- Higgs p_T uncertainty
  - Higgs p_T in ggF important discriminant against VBF and SM bg
  - mass effects important at large p_T
  - NLO corrections: $M_H^2 \ll m_t^2, p_T^2$
  - NLO top mass effects small up to $p_T \sim 300$ GeV
  - finite b-quark mass effects in p_T at NLO?;

    soft gluon resummation for small p_T

- progresses in (N)NLO Monte Carlos
  - Higgs signal: replace POWHEG H + PYTHIA with MINLO HJ

    (multi-scale improved NLO)

    $\Rightarrow$ NLO in H inclusive and H+jet distributions

4. Challenges for the future

1. Calculations for $\sqrt{s} = 13$ TeV, 33 TeV, 100 TeV, . . .

   (plus "normal" updates once better calculations become available, holds equally for decay widths)

2. Precision coupling determination from future data:
   Higher precision than for 2012 data (i.e. κ prescription) needed
   $\Rightarrow$ Higgs Effective Field Theory

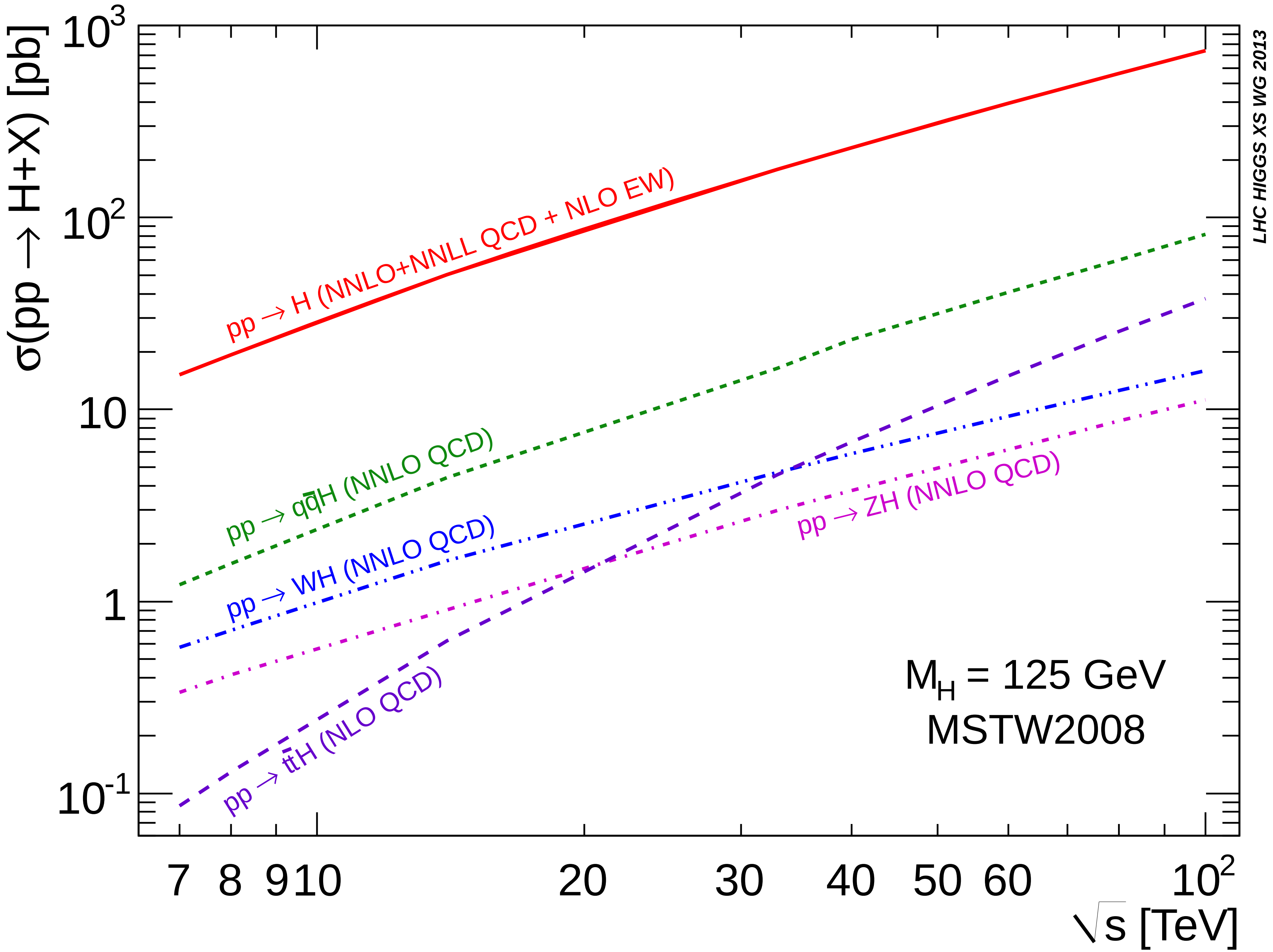
3. Additional Higgs production modes?

4. Triple Higgs coupling?

5. . . .

Calculations for higher energies:

[LHCHXSWG '13]



Precision coupling/spin/parity determination from future data:

Problem:

– κ prescription only accurate up to the 5-10% level

– only valid if data centers around SM values

Solution: Higgs Effective Field Theory [*LHCHXSWG '13*]

– effective Lagrangian: SM + dim 6 operators ($\# \leq 59$)
– linear vs. non-linear parameterization . . .

Existing tools (already):

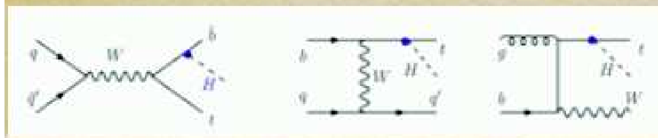
– MadGraph5
– Hawk
– eHdecay

$\Rightarrow$ NLO calculations? Will take time . . .

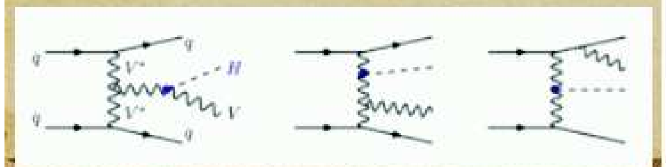
Additional Higgs production modes?

(taken from *[R. Tanaka, talk at ATLAS HSG1 meeting]*)

- Surveyed [H, qqH, VH], [ttH/bbH/ccH], [tH+V/q], [HH, qqHH, VHH, HHH], [VVH], [qqHV].
- Perhaps we are not missing important process.
- bq→tHq' (14% of ttH) generated in HSG8 for k_F=±1.



- qq→HWqq (2% of VBF, 5% of WH) interest for HL-LHC to measure Y_b.



A. Djouadi, Physics Reports 457 (2008) 1

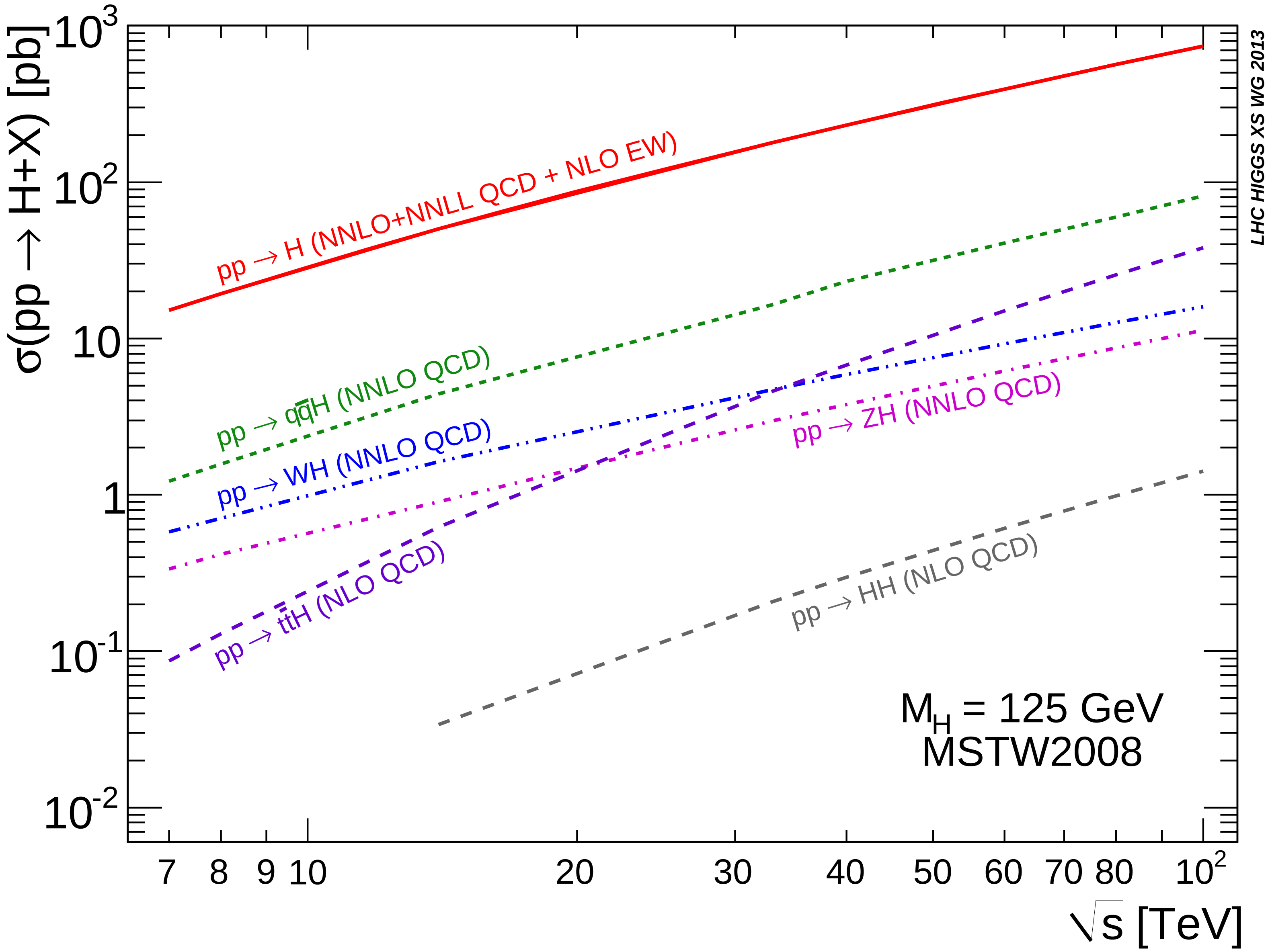
Class	14 TeV	MH=125GeV	
I	Major production processes at LHC (H, qqH, VH)		
	gg→ggF	60.35 pb *	
	qq→VBF	4.172 pb *	
	qq→WH	1.504 pb *	
	qq→ZH	0.883 pb *	
II	Associated Higgs production with heavy quarks (ffH)		
	gg/qq→bbH	0.8-0.9 pb	A. Djouadi, Phys. Rep. 457 (2008), Fig. 3.30
	gg/qq→ttH	0.611 pb *	
	gg/qq→ccH	O(100fb)	ccH should be about 1/9 of bbH due to Yukawa and PDF
III	Associated Higgs production with a single top quark (TH+V/HF)		
	bq→tHq'	88.2 fb	M. Farina et al. JHEP 05 (2013) 022, Table 2
	bg→WtH	~20 fb	F. Maltoni et al., Phys. Rev. D 64 (2001) 094023, Fig. 4
	qq→btH	~2-3 fb	idem.
IV	Higgs boson pair/triple production (HH, qqHH, VHH, HHH)		
	gg→HH	33.86 fb *	
	qq→HH	<0.1 fb	D. Dicus, Z. Phys. C 39 (1988) 583, Fig. 2 @17TeV
	gg/qq→ttHH	~1 fb	F. Gianotti et al., Eur. Phys. J. C 39 (2005) 293, Table 7 by C. G. Papadopoulos
	qq→qqHH	1.807 fb *	
	qq→WHH	0.43 fb *	
	qq→ZHH	0.27 fb *	
	gg→HHH	0.044 fb *	
V	Higgs production in association with gauge bosons (VVHH)		
	qq→WWH	~8-9 fb	A. Djouadi, Phys. Rep. 457 (2008), Fig. 3.42
	qq→ZZH	~2 fb	pT_γ>10GeV, Iy_γI<2.5
	qq→WZH	~3-4 fb	
	qq→γZH	~3-4 fb	
	qq→γWH	~5 fb	
VI	Higgs production in association with a gauge boson and two jets (HVqq)		
	qq→HWqq	78 fb	D. Rainwater, Phys. Lett. B 503 (2001) 320, Table 1 → 5% of WH !?
	qq→HZqq	-	
	qq→Hγqq	-	
VII	Rare processes		
	qq→Hγ	O(1fb)	A. Djouadi, Phys. Rep. 457 (2008), Section 3.6.3.1 (gg→Hγ forbidden by Furry's theorem)
	t→cH	BR~4E-14	B. Mele, S. Petrarca, A. Soddu, Phys. Lett. B 435 (1998) 401, Table 1
	Diffractive	?	

* https://twiki.cern.ch/twiki/bin/view/LHCPhysics/HiggsEuropeanStrategy

14

Triple Higgs coupling:

[*LHCHXSWG '13*]



⇒ new subgroup to be formed

HXSWG

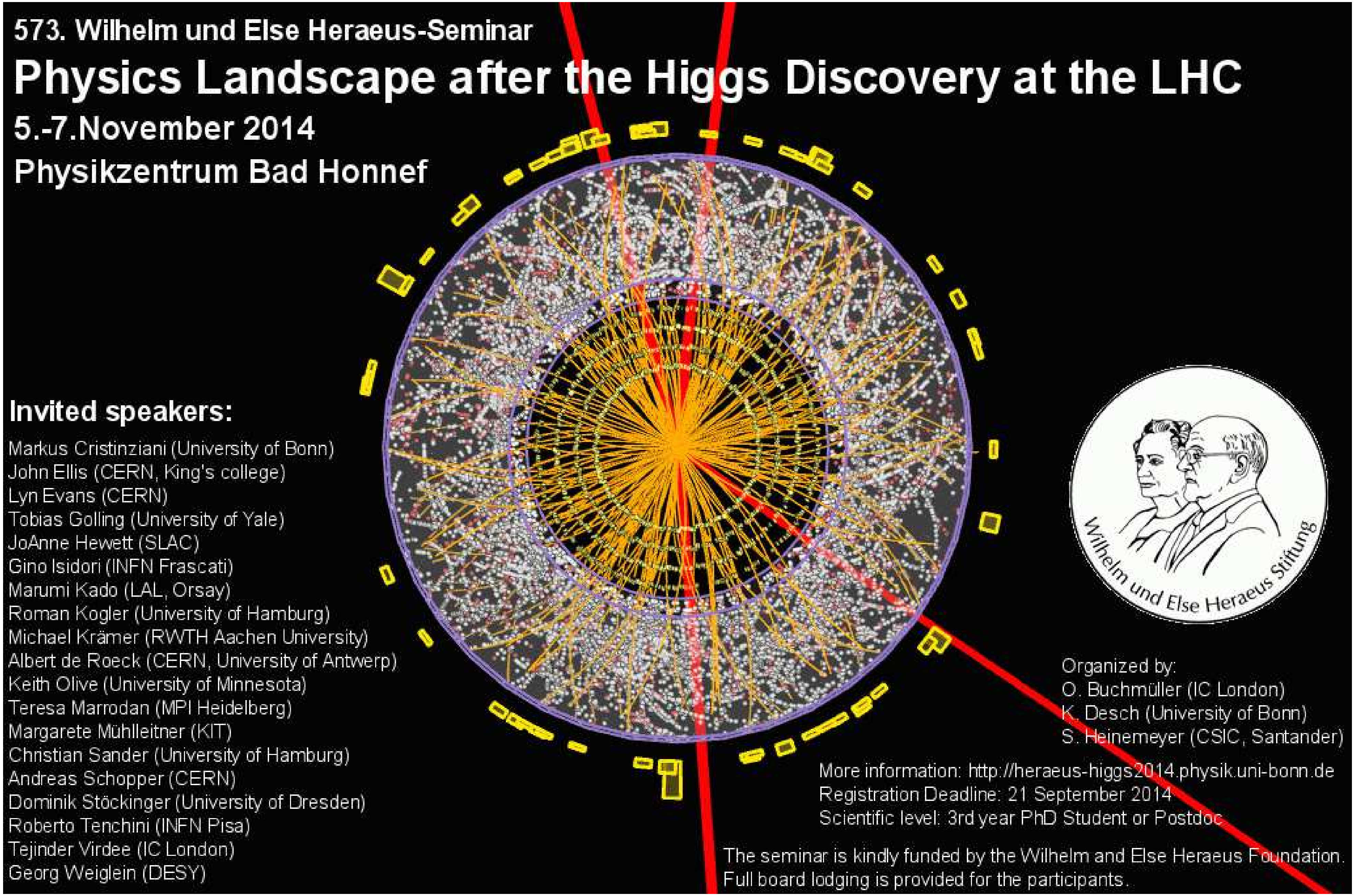
- Important for Higgs discovery

- Important for Higgs property extraction

- Important for BSM Higgs phenomenology

- Important for charged Higgs phenomenology

- Ongoing and crucial effort also for 2015+ data!



Apply - it's worth it! :-)