Why July 4th is celebrated (not only in the US):

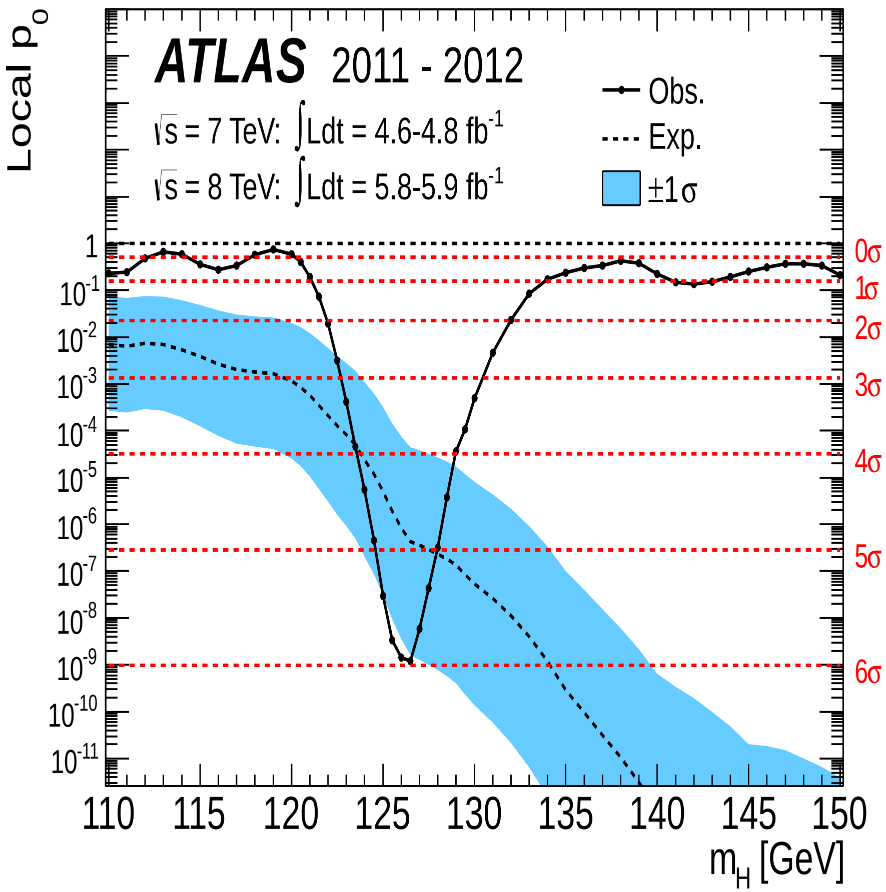
Higgs Physics in the SM and the MSSM

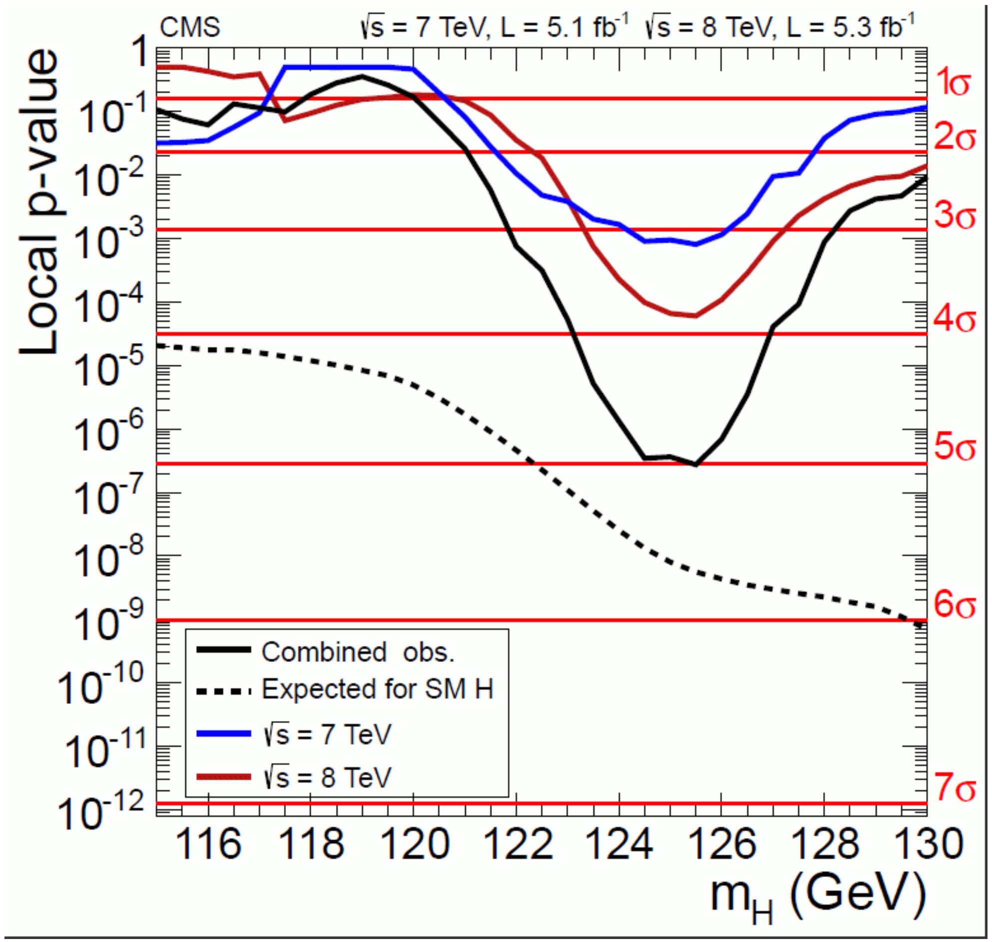
Sven Heinemeyer, IFCA (CSIC, Santander)

Manchester, 07/2014

1. Motivation

We have a discovery!





We have a discovery!

<u>But what is it?</u>

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!

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How can we decide?

A: Measure all its characteristics

A: Compare to the predictions of the various models

We have a discovery!

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How can we decide?

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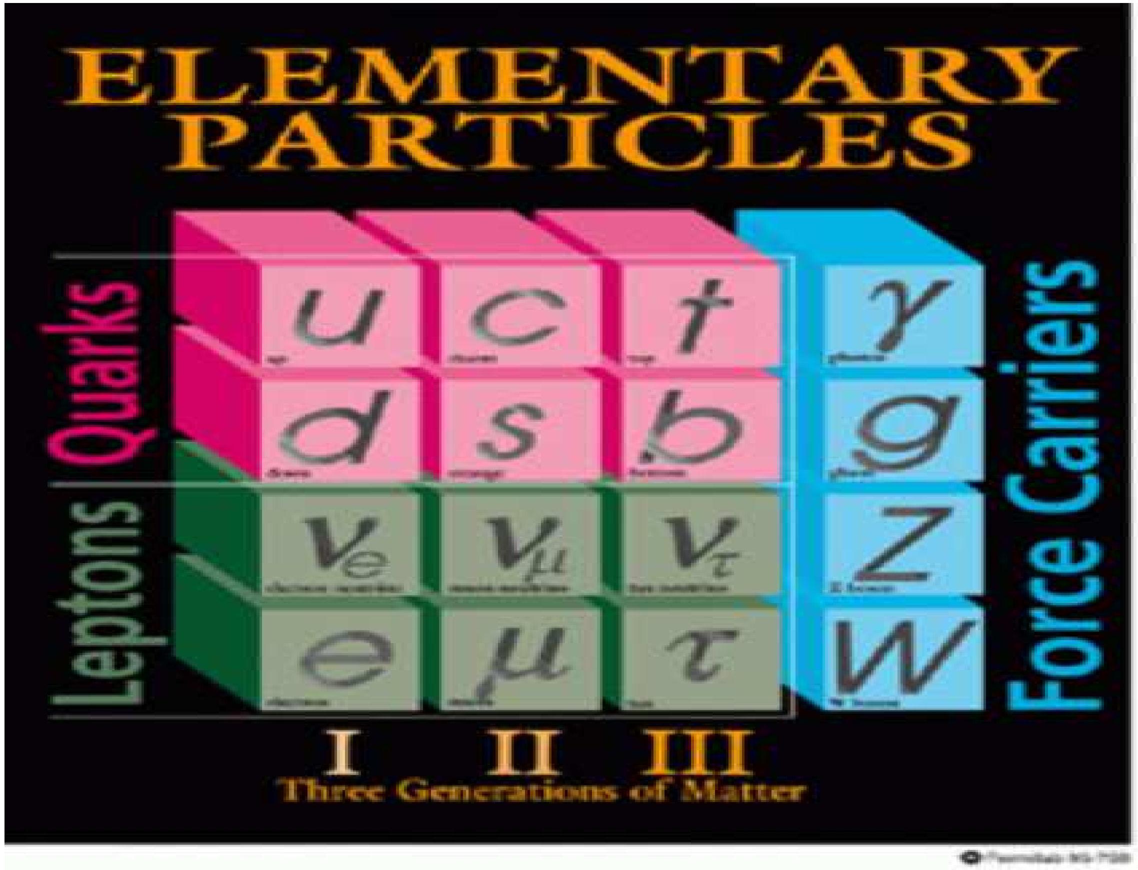
A: Compare to the predictions of the various models

⇒ Overview about implications in the SM and MSSM!

2. Higgs Physics in the SM

Current status of knowledge: the Standard Model (SM)



⇒ all particles experimentally seen

2. Higgs Physics in the SM

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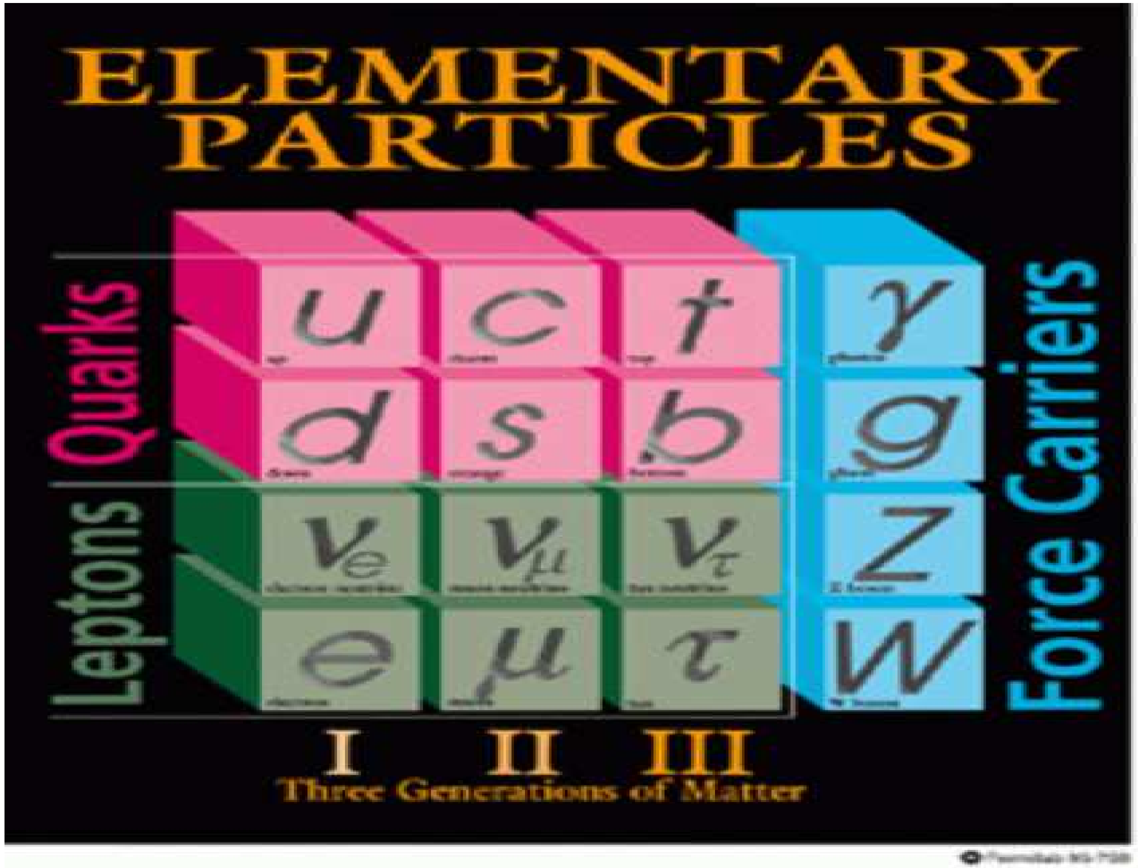


⇒ all particles experimentally seen

⇒ but it predicts massless gauge bosons . . .

Problem:

Gauge fields Z, W^+, W^- are massive

explicite mass terms in the Lagrangian $\Leftrightarrow$ breaking of gauge invariance

Solution: Higgs mechanism

scalar field postulated, mass terms from coupling to Higgs field

Higgs sector in the Standard Model:

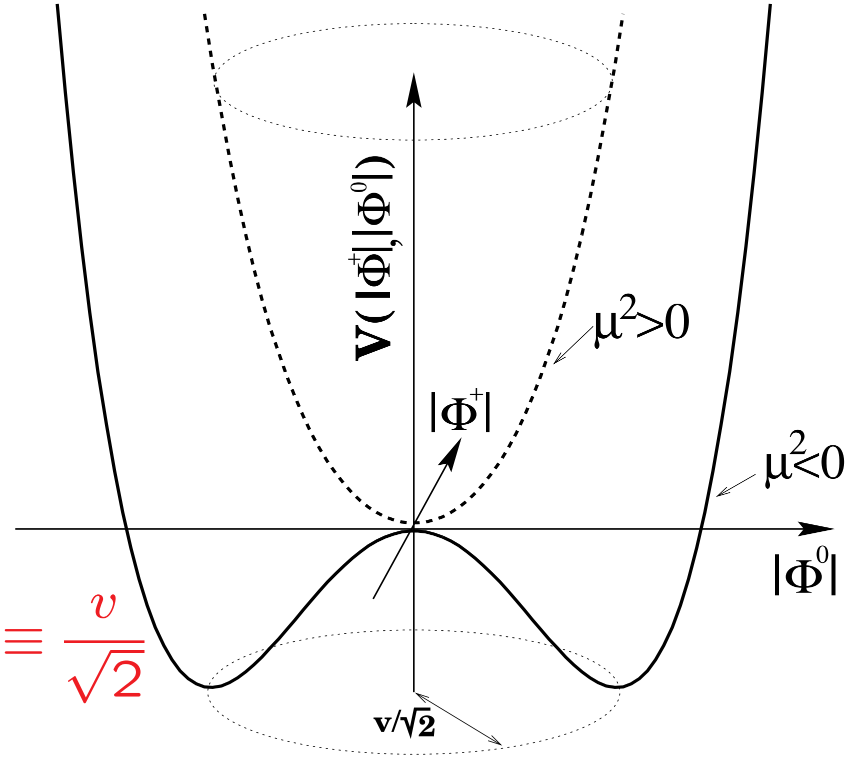
Scalar SU(2) doublet: $\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$

Higgs potential:

$$V(\phi) = \mu^2 \left|\Phi^\dagger \Phi\right| + \lambda \left|\Phi^\dagger \Phi\right|^2, \quad \lambda > 0$$

$\mu^2 < 0$: Spontaneous symmetry breaking

minimum of potential at $|\langle \Phi_0 \rangle| = \sqrt{\frac{-\mu^2}{2\,\lambda}} \equiv \frac{v}{\sqrt{2}}$



$$\Phi = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + H \end{pmatrix} \quad \text{(unitary gauge)}$$

H: elementary scalar field, Higgs boson

Lagrange density:

$$\begin{aligned} \mathcal{L}_{\text{Higgs}} = \quad & (D_\mu \Phi)^\dagger (D^\mu \Phi) \\ & - g_d \bar{Q}_L \Phi d_R \; - \; g_u \bar{Q}_L \Phi_c u_R \\ & - V(\Phi) \end{aligned}$$

with

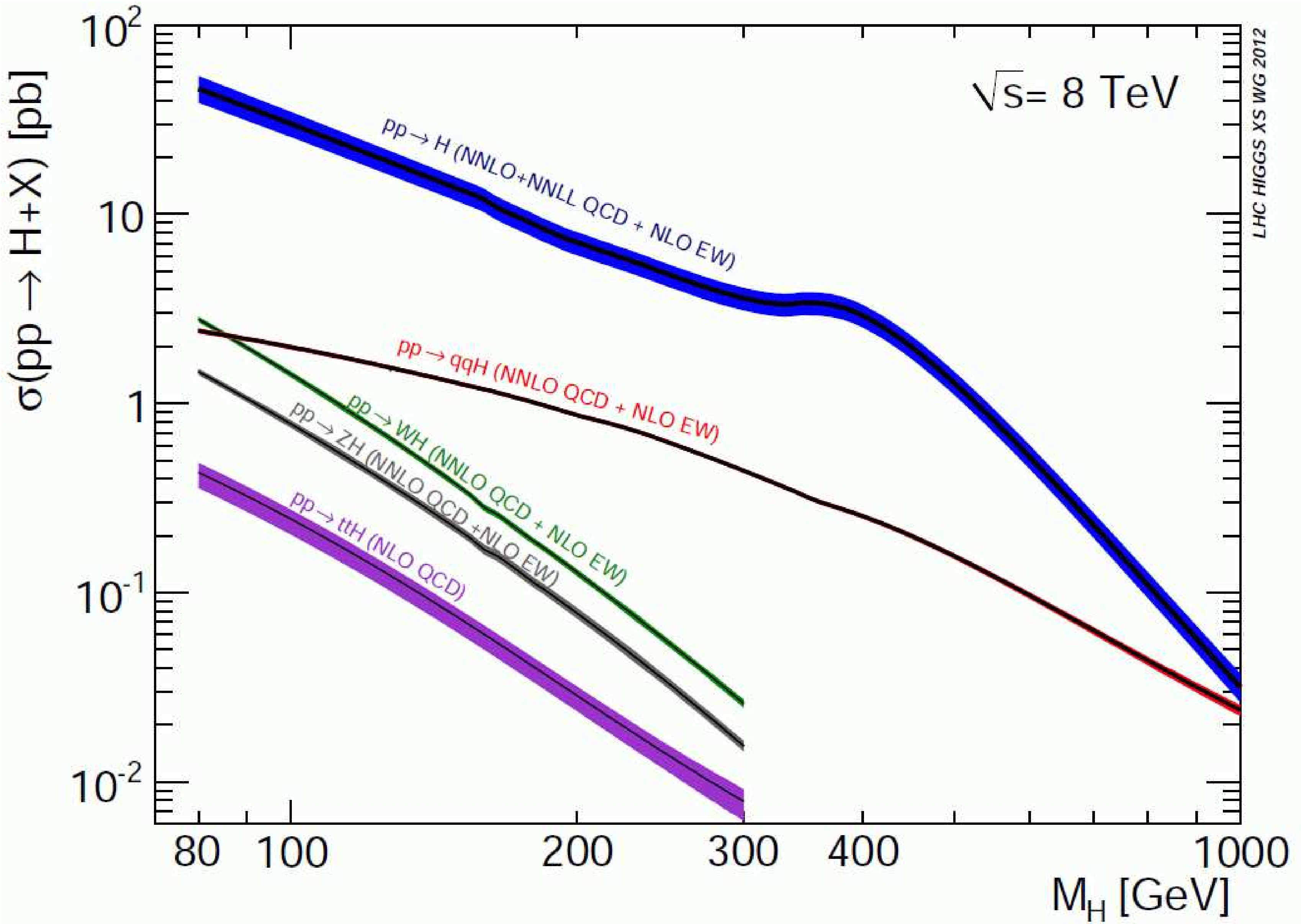
$$\begin{aligned} iD_\mu &= i\partial_\mu - g_2 \vec{I}\vec{W}_\mu - g_1 Y B_\mu \\ \Phi_c &= i\sigma_2 \Phi^* \qquad\qquad Q_L \sim \begin{pmatrix} u_L \\ d_L \end{pmatrix}, \; \Phi \sim \begin{pmatrix} 0 \\ v \end{pmatrix}, \; \Phi_c \sim \begin{pmatrix} v \\ 0 \end{pmatrix} \end{aligned}$$

Gauge invariant coupling to gauge fields

$\Rightarrow$ mass terms for gauge bosons and fermions

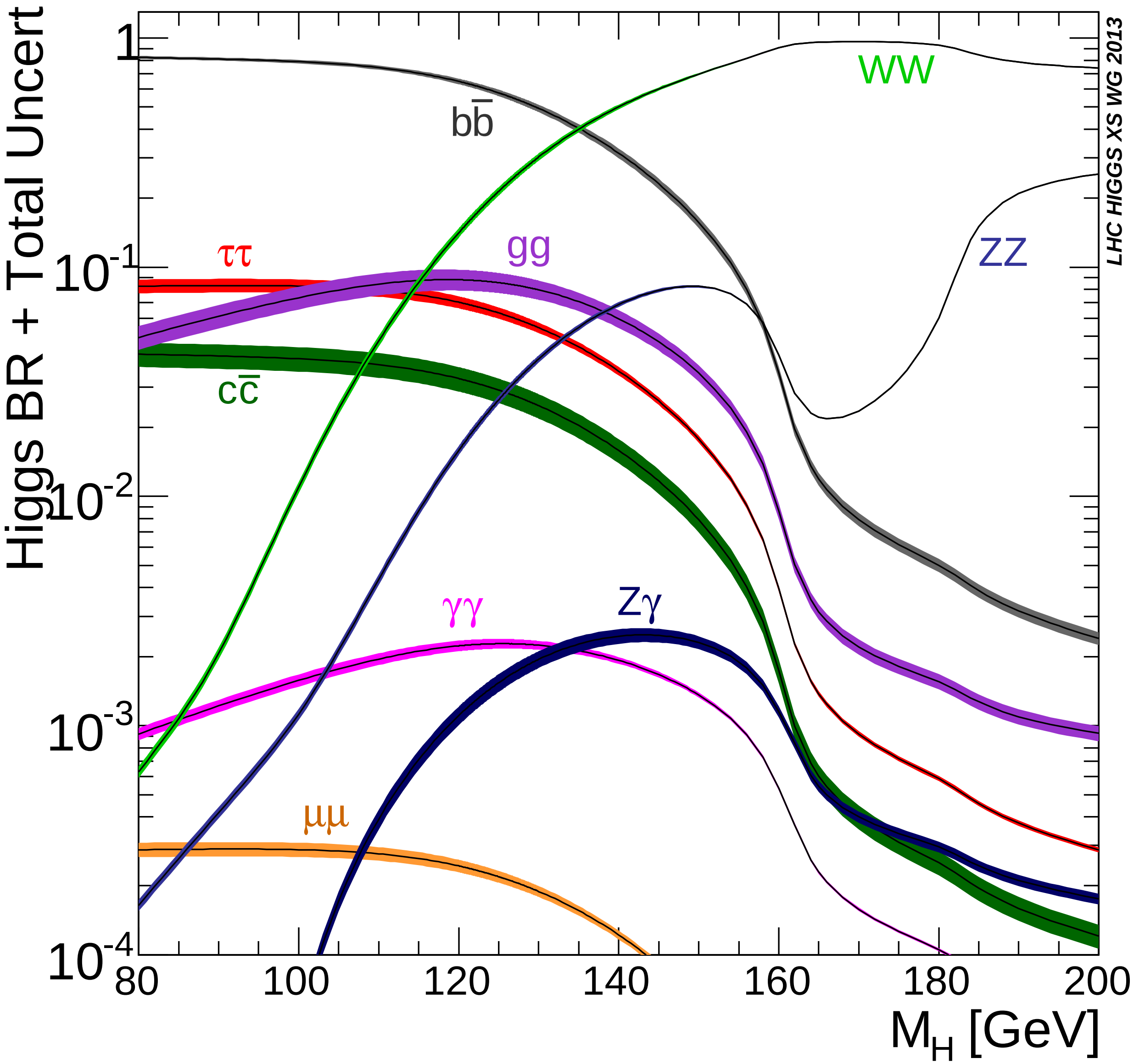
Latest theory predictions for the SM Higgs: LHC production XS

[*LHC Higgs XS WG '10 – '12*]

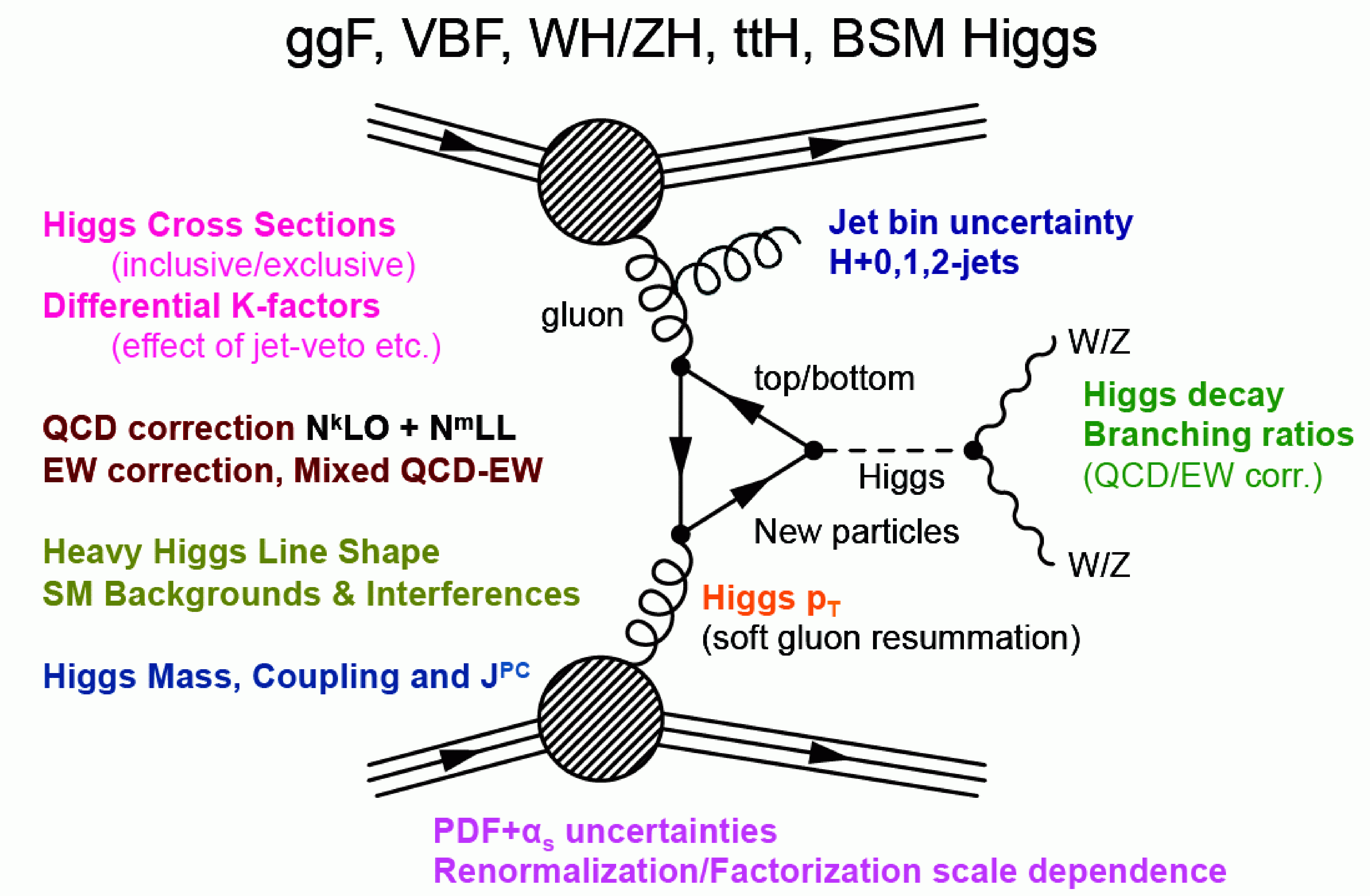


Latest theory predictions for the SM Higgs: branching ratios

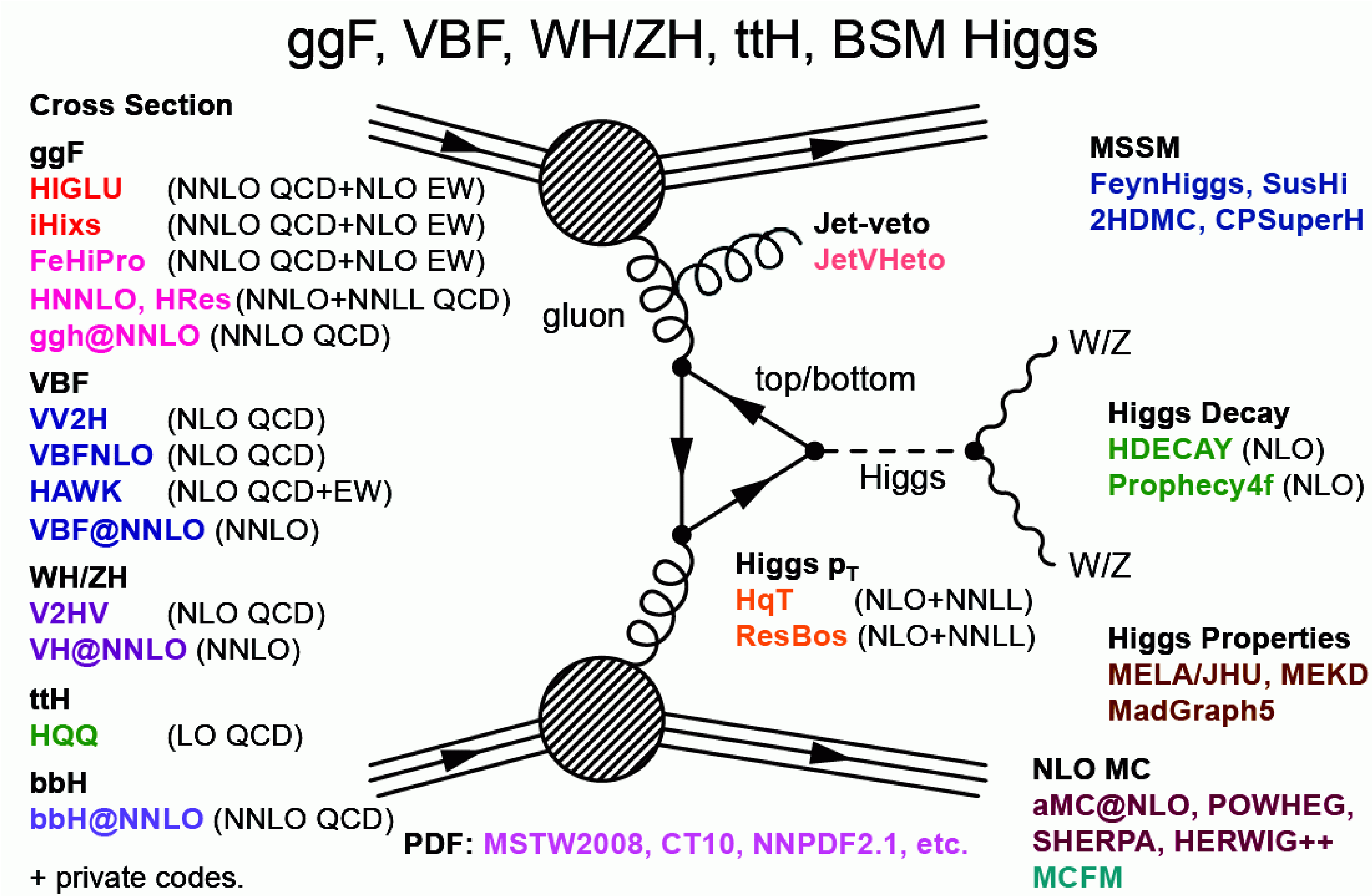
[*LHC Higgs XS WG '13*]



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

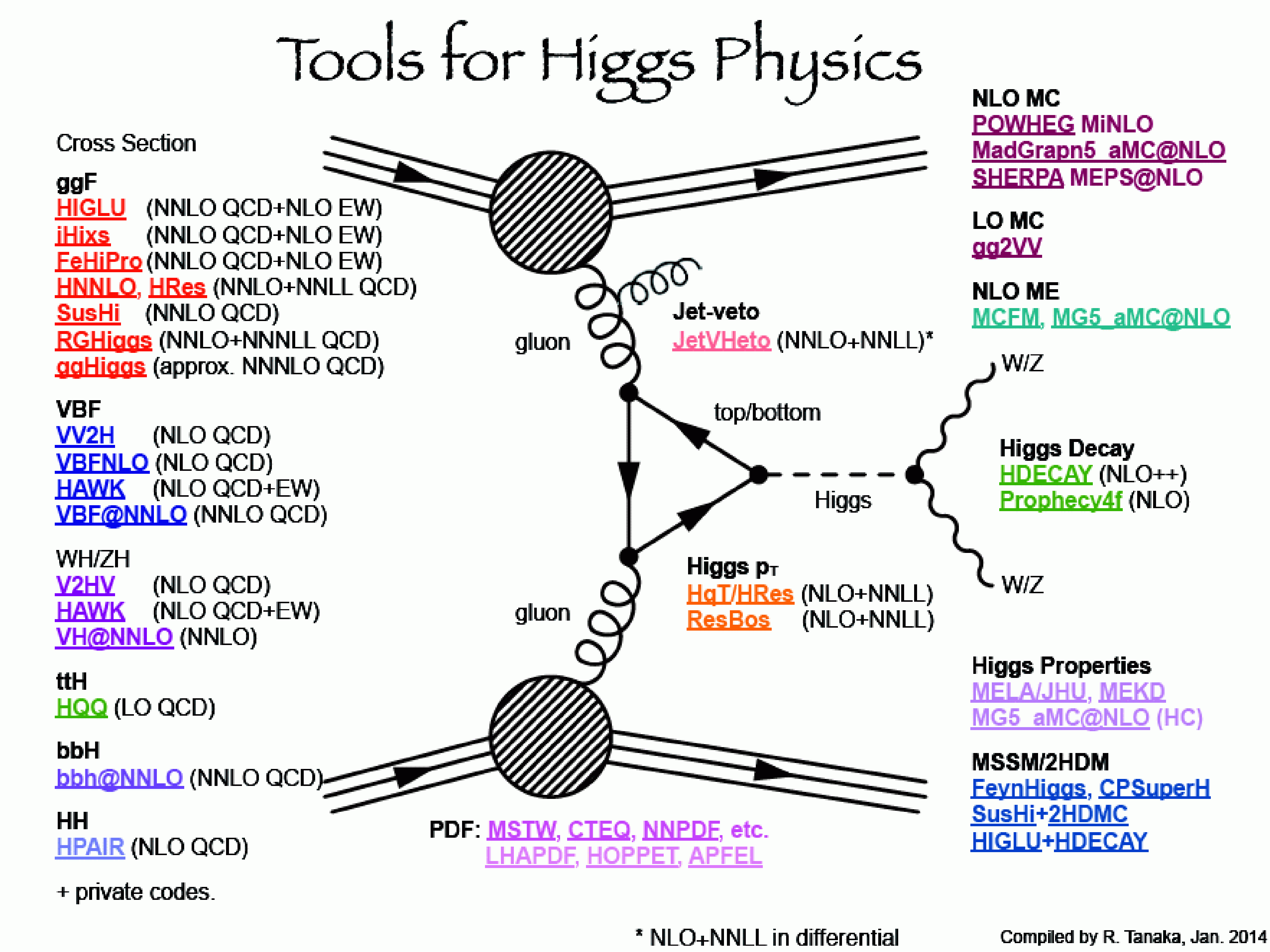


The "solutions": (taken from [R. Tanaka, talk at Aspen Higgs WS 03/13])



The "solutions" (final update):

(compiled by [R. Tanaka '14])



Solutions provided by: **LHC Higgs Cross Section Working Group**

LHCHXSWG work is documented in:

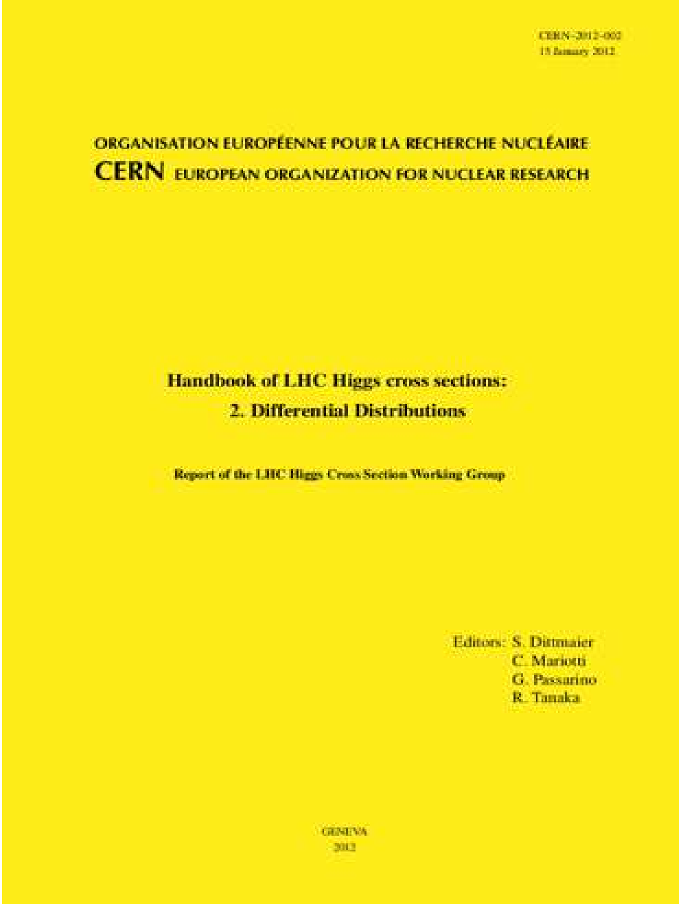
ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUCLÉAIRE
CERN EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

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



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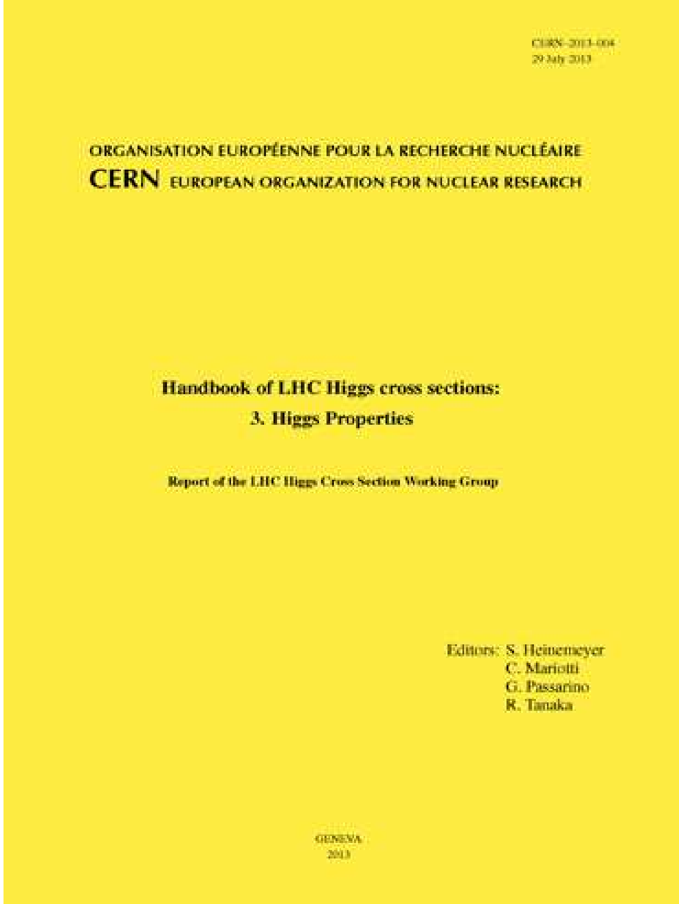
Handbook of LHC Higgs cross sections:
2. Differential Distributions

Report of the LHC Higgs Cross Section Working Group

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

GENEVA
2012



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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: 730+, 360+, 160+

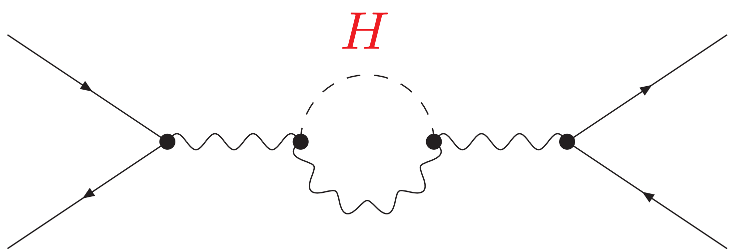
How did we make predictions for the SM Higgs mass before observation?

How did we make predictions for the SM Higgs mass before observation? Comparison of electro-weak precision observables with theory:

EW Precision data:		Theory:
$M_W, \sin^2\theta_{\rm eff}, a_\mu, \ldots$	$\leftrightarrow$	SM, MSSM , . . .

$\Downarrow$

Test of theory at quantum level: Sensitivity to loop corrections, e.g. H



$\Downarrow$

SM: limits on M_H

Very high accuracy of measurements and theoretical predictions needed

Example: prediction of M_W

Theoretical prediction for M_W in terms of $M_Z, \alpha, G_\mu, \Delta r$:

$$M_W^2 \left(1 - \frac{M_W^2}{M_Z^2}\right) = \frac{\pi\,\alpha}{\sqrt{2}\,G_\mu}(1 + \Delta r)$$

$\Updownarrow$

loop corrections

Evaluate Δr from μ decay $\Rightarrow M_W$

One-loop result for M_W in the SM:

[*A. Sirlin '80*] , [*W. Marciano, A. Sirlin '80*]

$$\Delta r_{1-\text{loop}} = \Delta\alpha - \frac{c_W^2}{s_W^2}\Delta\rho + \Delta r_{\text{rem}}(M_H)$$

$$\sim \log\frac{M_Z}{m_f} \qquad \sim m_t^2 \qquad \log(M_H/M_W)$$

$$\sim 6\% \qquad \sim 3.3\% \qquad \sim 1\%$$

Comparison of SM prediction of M_W with direct measurements:

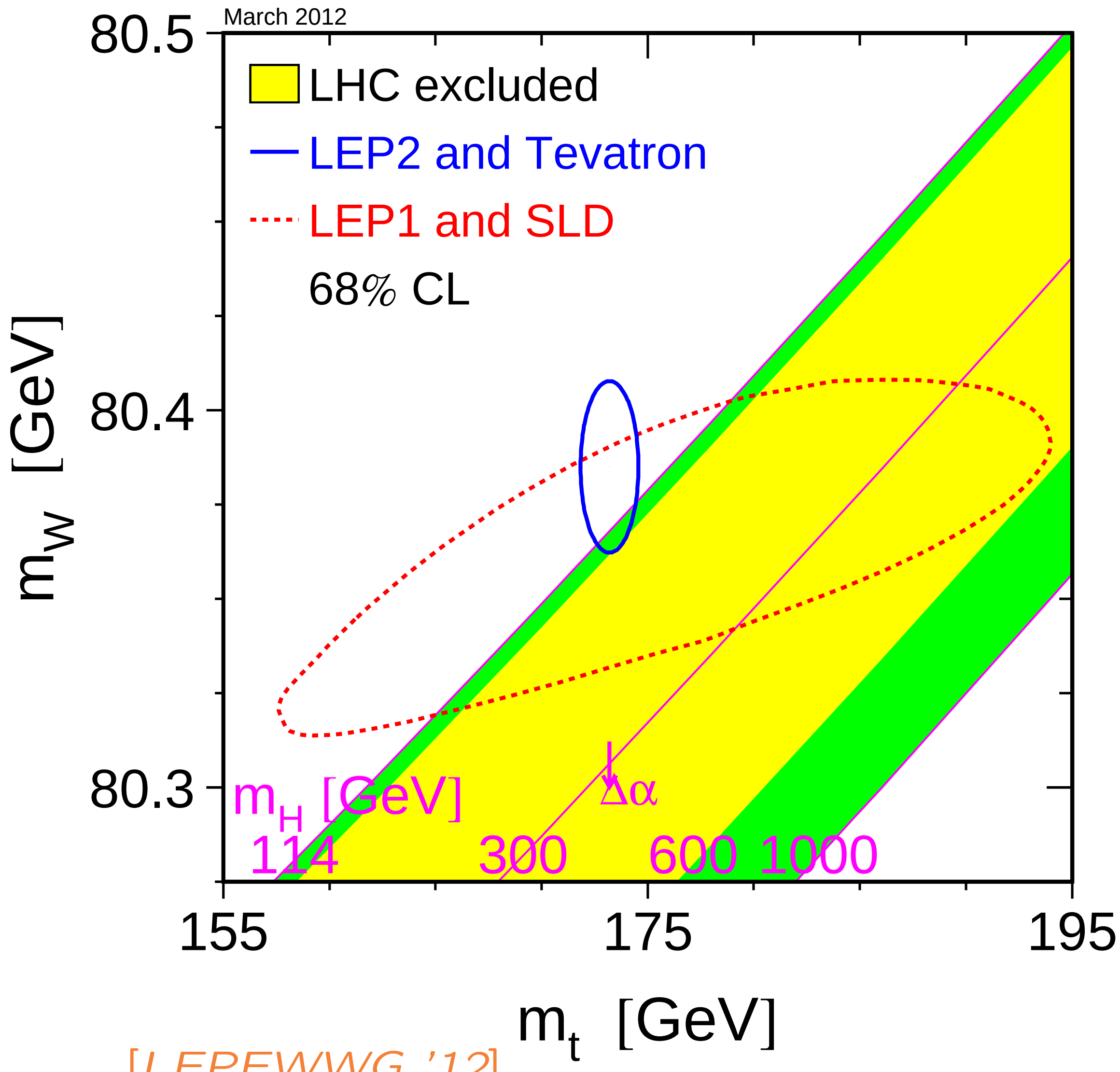
$$\Delta r = -\frac{11 g_2^2}{96\,\pi^2}\frac{s_W^2}{c_W^2} \log\left(\frac{M_H}{M_W}\right)$$

general for EWPO:

$$\Delta \sim g_2^2 \left[\log\left(\frac{M_H}{M_W}\right) + g_2^2 \frac{M_H^2}{M_W^2}\right]$$

leading term: $\log(M_H)$

first term $\sim M_H^2$ with g_2^4



[LEPEWWG '12]

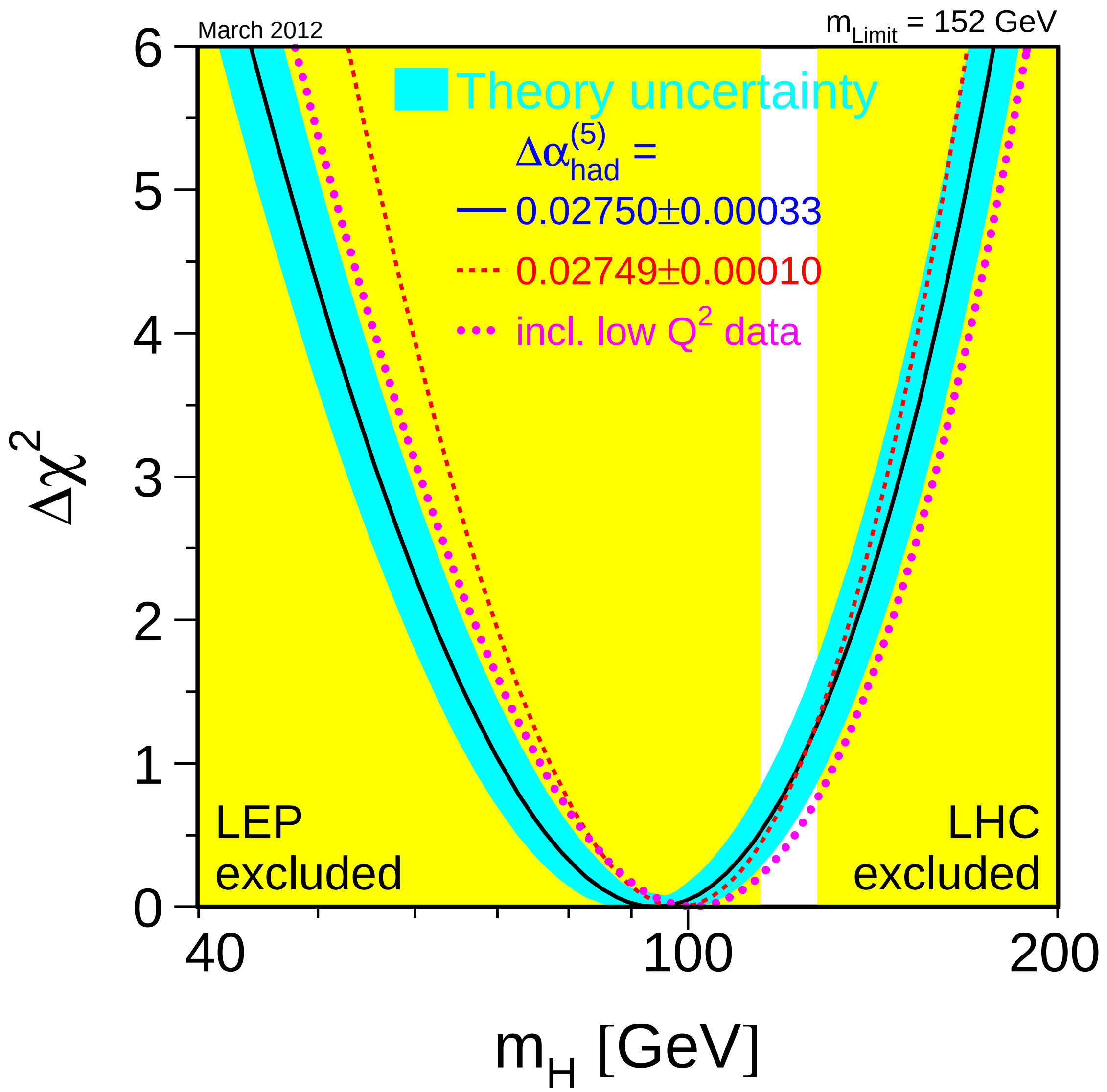
⇒ light Higgs boson preferred

Indirect prediction vs. "the discovery":

[*LEPEWWG '12*]

$\Rightarrow M_H = 94^{+29}_{-24}$ GeV

$M_H < 152$ GeV, 95% C.L.



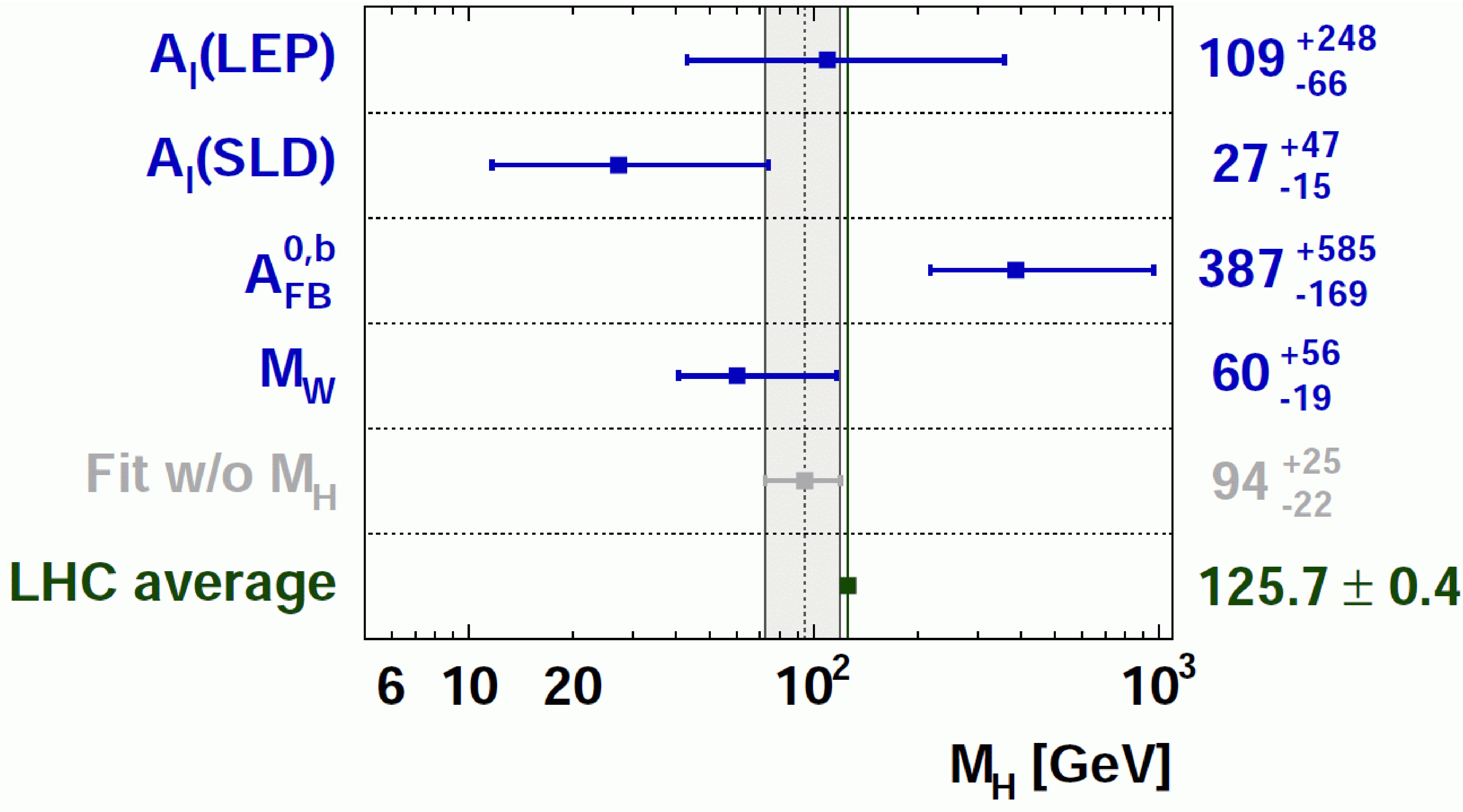
Assumption for the fit:
SM incl. Higgs boson

$\Rightarrow$ no confirmation of Higgs mechanism

$\Rightarrow$ Observed excess well compatible with SM prediction

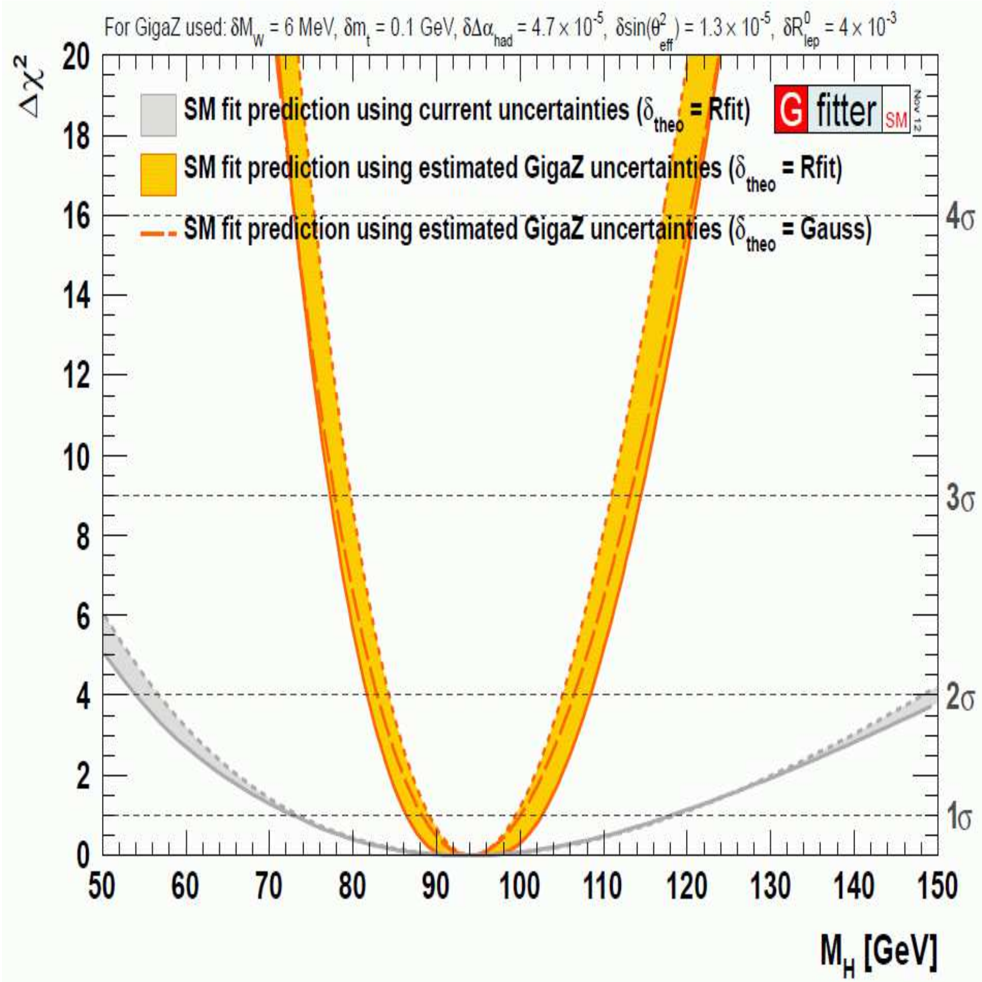
Comparison for single observables:

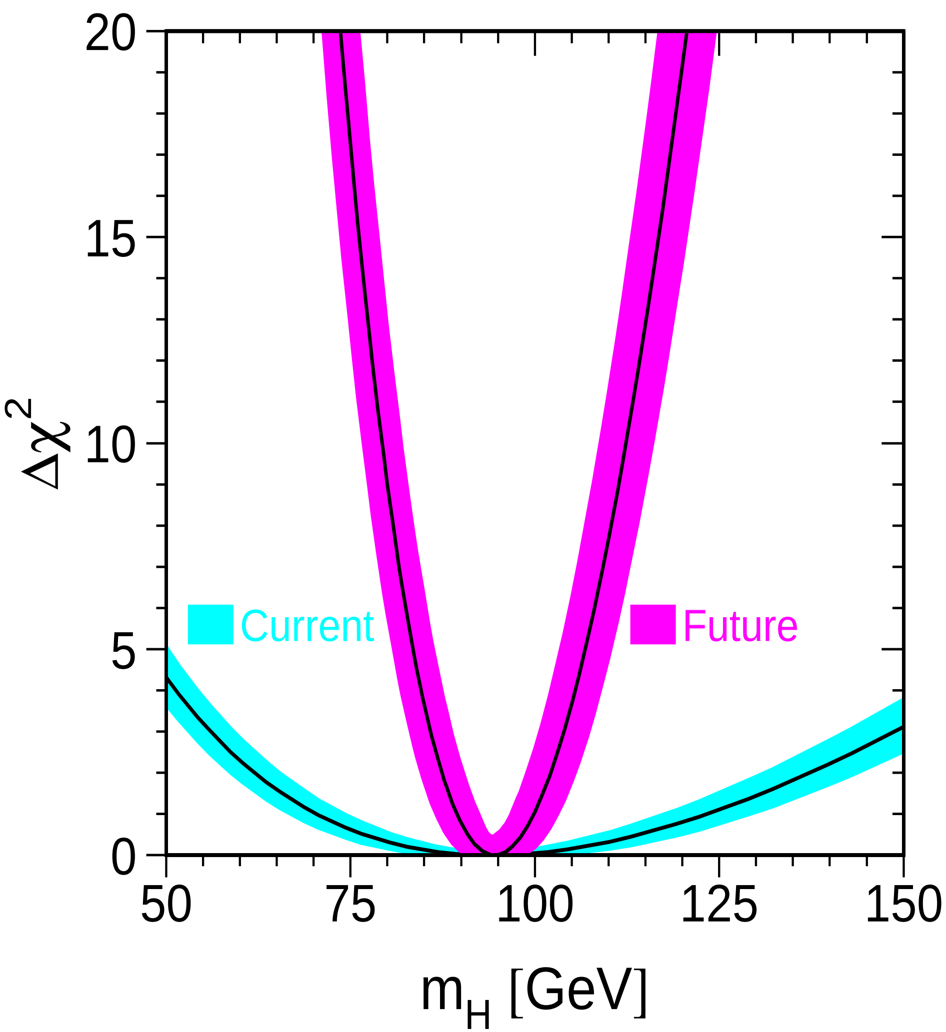
[*GFitter '12*]



Future “M_H test” with ILC accuracy:

[*GFitter '13*] [*LEPEWWG '13*]





$\Rightarrow \delta M_H^{\text{ind}} \approx \pm 6$ GeV

$\Rightarrow$ extremely sensitive test of SM (and BSM) possible

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)

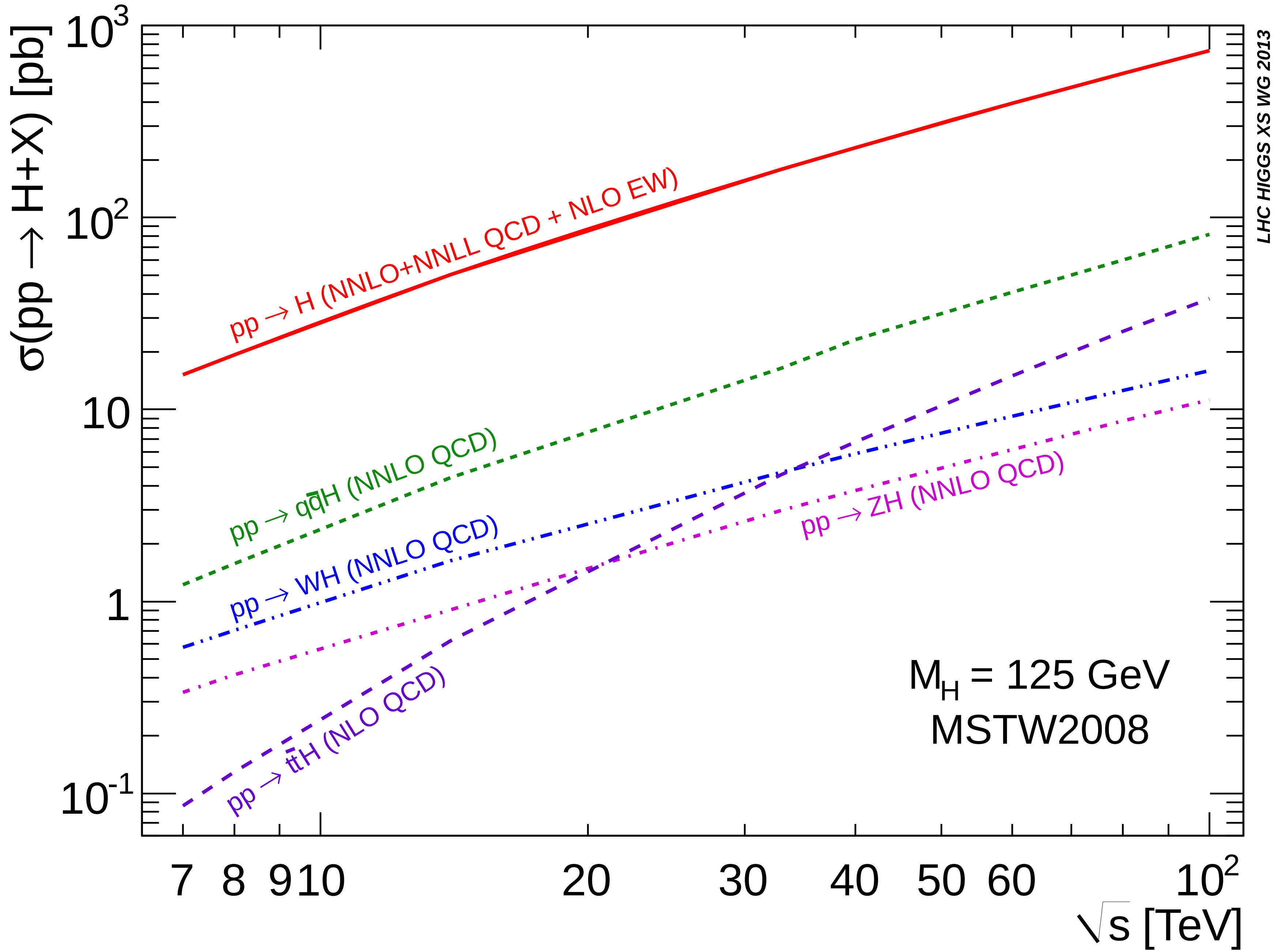
2. Precision coupling determination from future data:
   Higher precision than for 2012 data (i.e. κ prescription) needed
   $\Rightarrow$ Higgs Effective Field Theory

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):

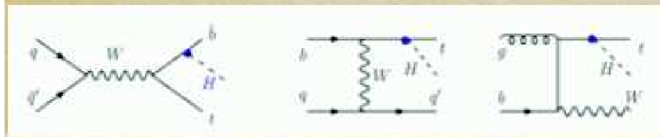
– MadGraph5
– Hawk
– eHdecay

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

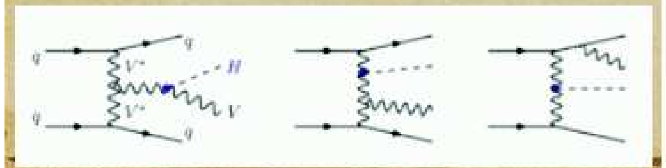
Additional Higgs production modes?

(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 (VVH)		
	qq→WWH	~8-9 fb	A. Djouadi, Phys. Rep. 457 (2008), Fig. 3.42
	qq→ZZH	~2 fb	pT_γ>10GeV, |y_γ|<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

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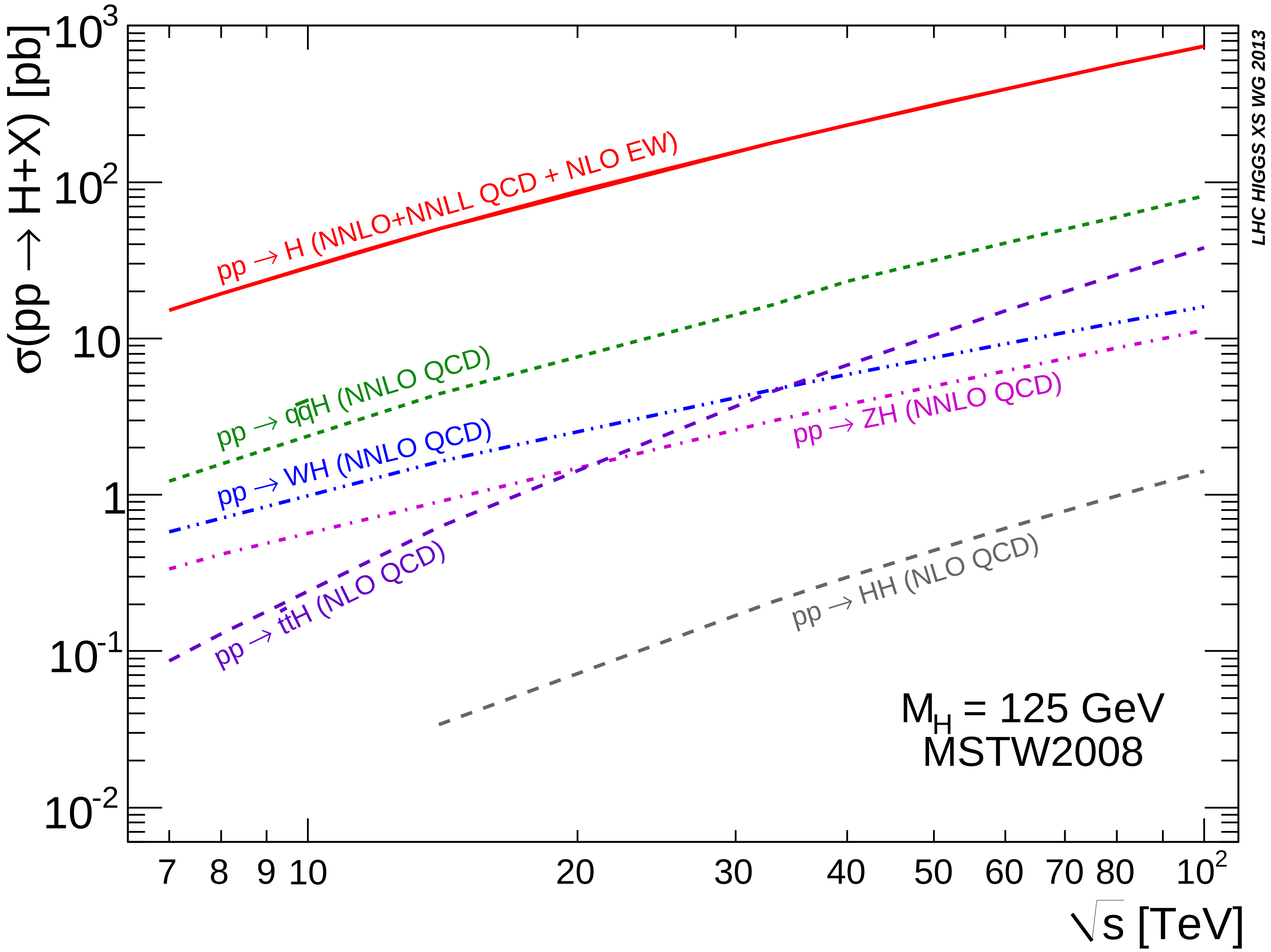
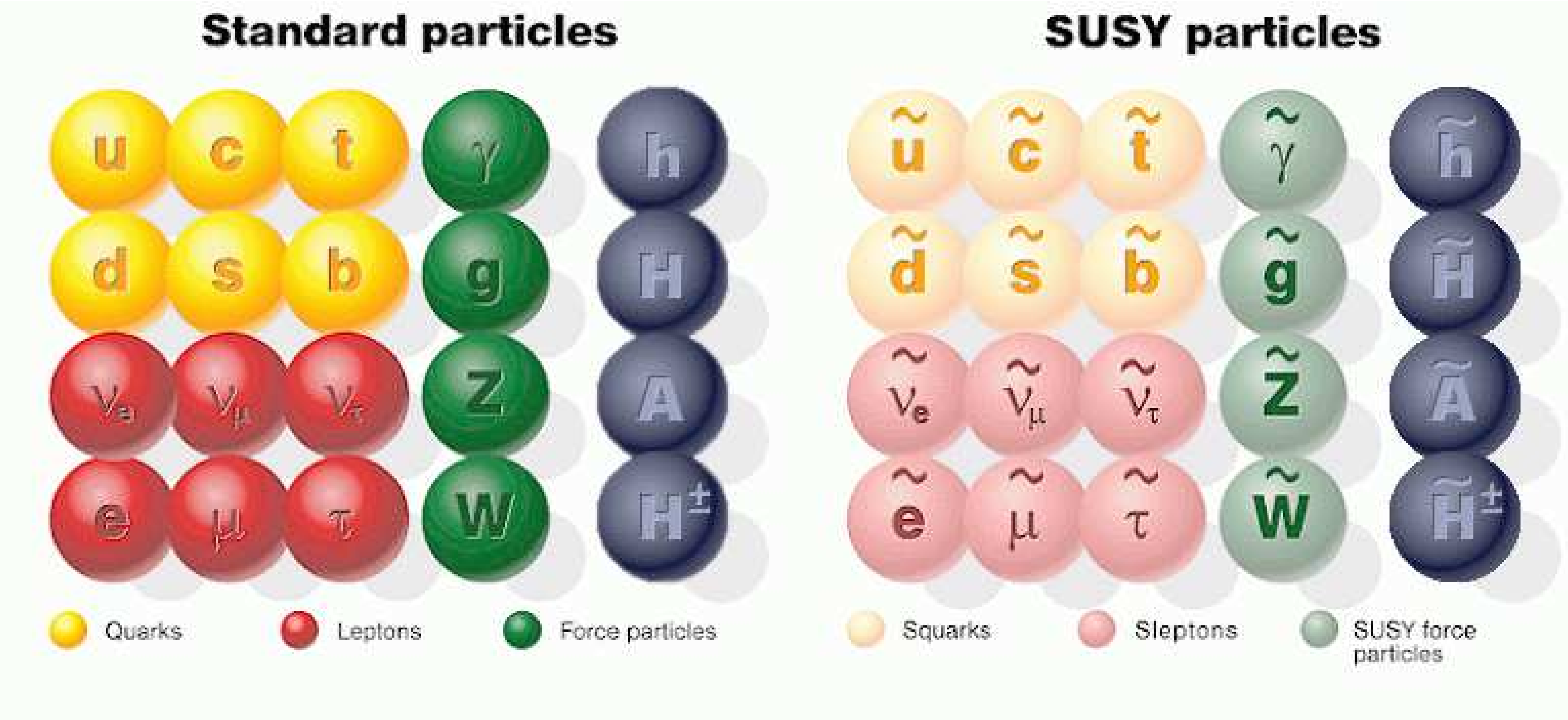
Triple Higgs coupling:

[*LHCHXSWG '13*]



⇒ LHC perspectives unclear . . .

3. Higgs Physics in the MSSM:



→ MSSM always predicted $M_h \lesssim 135$ GeV

→ MSSM predicts (over large parts of the parameter space) that the lightest Higgs is SM-like

⇒ discovery can be identified with the lightest MSSM Higgs boson!

The simplest case: **MSSM with real paremeters**

Enlarged Higgs sector: Two Higgs doublets

$$H_1 = \begin{pmatrix} H_1^1 \\ H_1^2 \end{pmatrix} = \begin{pmatrix} v_1 + (\phi_1 + i\chi_1)/\sqrt{2} \\ \phi_1^- \end{pmatrix}$$

$$H_2 = \begin{pmatrix} H_2^1 \\ H_2^2 \end{pmatrix} = \begin{pmatrix} \phi_2^+ \\ v_2 + (\phi_2 + i\chi_2)/\sqrt{2} \end{pmatrix}$$

$$V = m_1^2 H_1 \bar{H}_1 + m_2^2 H_2 \bar{H}_2 - m_{12}^2(\epsilon_{ab} H_1^a H_2^b + \text{h.c.})$$

$$+ \underbrace{\frac{g'^2 + g^2}{8}} (H_1 \bar{H}_1 - H_2 \bar{H}_2)^2 + \underbrace{\frac{g^2}{2}} |H_1 \bar{H}_2|^2$$

gauge couplings, in contrast to SM $\Rightarrow m_h \leq M_Z$

physical states: $h^0, H^0, A^0, H^\pm$

Goldstone bosons: $G^0, G^\pm$

Input parameters: (to be determined experimentally)

$$\tan\beta = \frac{v_2}{v_1}, \qquad M_A^2 = -m_{12}^2(\tan\beta + \cot\beta)$$

$\tilde{t}$ sector of the MSSM:

Stop mass matrices

$$\mathbf{M}^2_{\tilde{t}} = \begin{pmatrix} M^2_{\tilde{t}_L} + m_t^2 + DT_{t_1} & m_t X_t \\ m_t X_t & M^2_{\tilde{t}_R} + m_t^2 + DT_{t_2} \end{pmatrix} \xrightarrow{\theta_{\tilde{t}}} \begin{pmatrix} m^2_{\tilde{t}_1} & 0 \\ 0 & m^2_{\tilde{t}_2} \end{pmatrix}$$

with

$$X_t = A_t - \mu / \tan\beta$$

$\Rightarrow$ mixing important in stop sector!

Simplifying abbreviation:

$$M_{\text{SUSY}} := M_{\tilde{t}_L} = M_{\tilde{t}_R}$$

Most relevant issues about the MSSM Higgs(es):

1. Prediction of M_h

2. Prediction of SUSY Higgs cross sections and branching ratios

3. Search for deviations in XS, BR induced by SUSY

4. Search for additional Higgs bosons

3 A) Prediction of M_h

The embarrasing situation:

Experiment:

ATLAS:	$M_H^{\text{exp}} = 125.5 \pm 0.4 \pm 0.2$ GeV
CMS:	$M_H^{\text{exp}} = 125.7 \pm 0.3 \pm 0.3$ GeV

3 A) Prediction of M_h

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Theory:

$$\delta M_h^{\text{theo}} \sim 3 \text{ GeV}$$

3 A) Prediction of M_h

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Theory:

$$\delta M_h^{\text{theo}} \sim 3 \text{ GeV}$$

$\Rightarrow$ Theory prediction must be improved to match the experimental accuracy!

Method I:

Higher-order corrections in the Feynman diagrammatic method:

Propagator/Mass matrix at tree-level:

$$\begin{pmatrix} q^2 - m_H^2 & 0 \\ 0 & q^2 - m_h^2 \end{pmatrix}$$

Propagator / mass matrix with higher-order corrections
($\to$ Feynman-diagrammatic approach):

$$M_{hH}^2(q^2) = \begin{pmatrix} q^2 - m_H^2 + \hat{\Sigma}_{HH}(q^2) & \hat{\Sigma}_{Hh}(q^2) \\ \hat{\Sigma}_{hH}(q^2) & q^2 - m_h^2 + \hat{\Sigma}_{hh}(q^2) \end{pmatrix}$$

$\hat{\Sigma}_{ij}(q^2)$ $(i, j = h, H)$: renormalized Higgs self-energies

$\mathcal{CP}$-even fields can mix

$\Rightarrow$ complex roots of $\det(M_{hH}^2(q^2))$: $\mathcal{M}_{h_i}^2 (i = 1, 2)$: $\mathcal{M}^2 = M^2 - iM\Gamma$

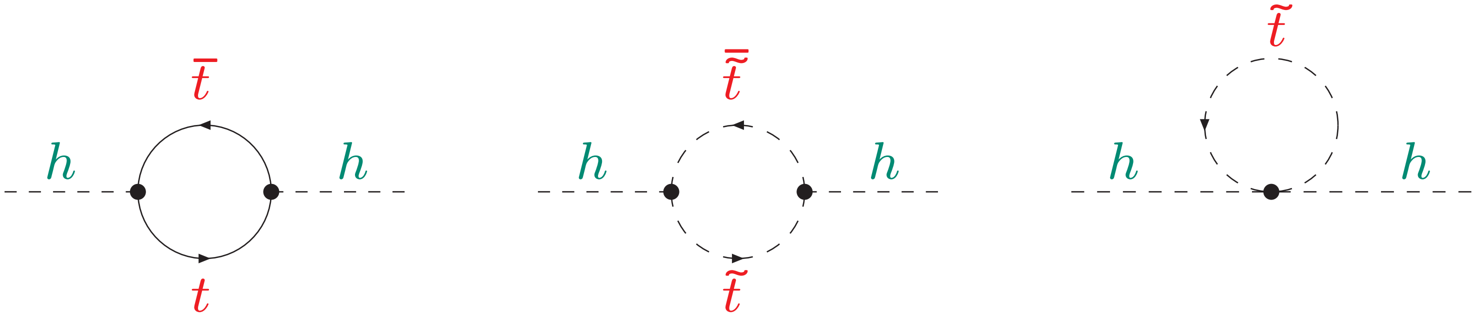
Calculation of renormalized Higgs boson self-energies:

$$\hat{\Sigma}(q^2) = \hat{\Sigma}^{(1)}(q^2) + \hat{\Sigma}^{(2)}(q^2) + \ldots$$

all MSSM particles contribute

main contribution: $t/\tilde{t}$ sector ($\tilde{t}$: scalar top, SUSY partner of the t)

Very leading 1-Loop:



Recent updates:

– $\mathcal{O}(\alpha_t \alpha_s)$ p^2-dependent corrections ⇒ talk by Sophia Borowka

– $\mathcal{O}\left(\alpha_t^2\right)$ corrections in cMSSM [*W. Hollik, S. Paßehr '13*]

⇒ effects larger than current experimental accuracy

Advantages of Feynman-diagrammatic method:

– all contributions at fixed order are captured

– trivial to include many SUSY scales

– full control over Higgs boson self-energies
$\rightarrow$ needed for other quantities (production and decay)

Problems of Feynman-diagrammatic method:

– always only fixed order

– large logs not captured beyond the calculated order

Method II: Log resummation via RGE's:

Excellent recent overview paper: [*P. Draper, G. Lee, C. Wagner, arXiv:1312.5743*]

Simple example for log resummation:

SUSY mass scale: $M_{\rm SUSY} = M_{\rm S} \sim m_{\tilde{t}}$

Above $M_{\rm SUSY}$: MSSM
Below $M_{\rm SUSY}$: SM

Relevant SM parameters:
– quartic coupling λ
– top Yukawa coupling h_t ($\alpha_t = h_t^2/(4\,\pi)$)
– strong coupling constant g_s ($\alpha_s = g_s^2/(4\,\pi)$)

Procedure:

1. Take: $h_t(m_t), g_s(m_t)$

   SM RGEs for h_t, g_s: $h_t, g_s(m_t) \to h_t, g_s(M_{\rm S})$

2. Take $\lambda(M_{\rm S}), h_t(M_{\rm S}), g_s(M_{\rm S})$

   SM RGEs for λ, h_t, g_s: $\lambda, h_t, g_s(M_{\rm S}) \to \lambda, h_t, g_s(m_t)$

3. Evaluate M_h^2

$$M_h^2 \sim 2\lambda(m_t)v^2$$

Advantages of RGE log resummation:

– large logs taken into account to all orders

– calculation can easily be extended to very large scales

Problems of RGE log resummation:

– not all contributions at fixed order are captured

$\rightarrow$ sub-leading logs more difficult

$\rightarrow$ momentum dependence

– difficult (impossible?): include many different SUSY scales

– difficult (impossible?): control over Higgs boson self-energies

$\rightarrow$ needed for other quantities (production and decay)

The best of both worlds:

to get the most precise prediction of M_h:

Combination of FD and RGE result!

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Problem:

Some terms exist in both calculations!

One-loop:

$$\Delta M_h^2 \sim m_t^2 \alpha_t \left[L + L^0 \right] \quad , \qquad L := \log \left(\frac{m_{\tilde{t}}}{m_t} \right)$$

Two-loop:

$$\Delta M_h^2 \sim m_t^2 \left\{ \alpha_t \alpha_s \left[L^2 + L \right] + \alpha_t^2 \left[L^2 + L \right] \right\}$$

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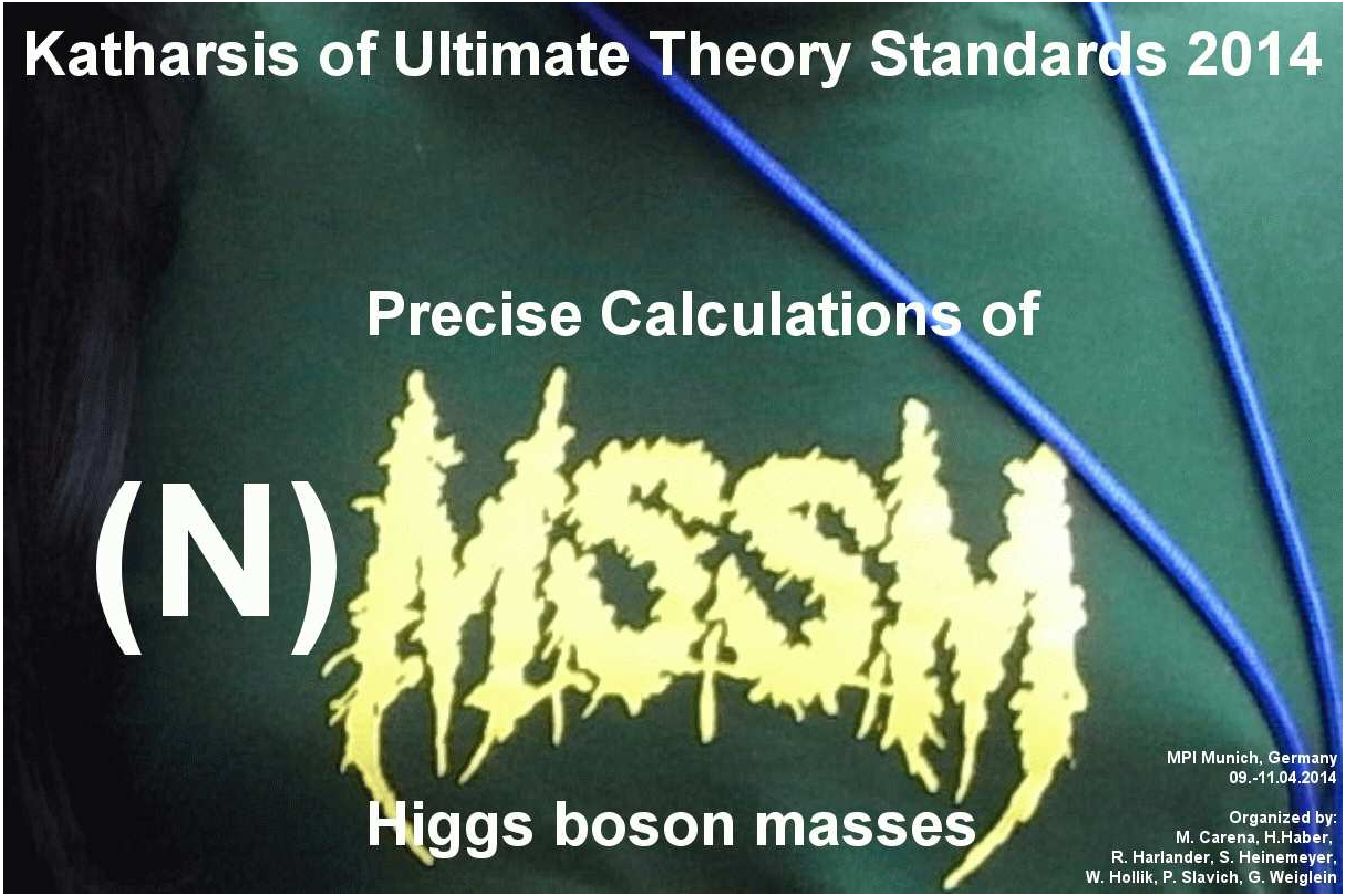
$\Rightarrow$ subtract to avoid double counting $\Rightarrow$ included in FeynHiggs 2.10.0

$\Rightarrow$ talk tomorrow in the "SUSY Precision" track

Working group dedicated to SUSY Higgs mass calculations:



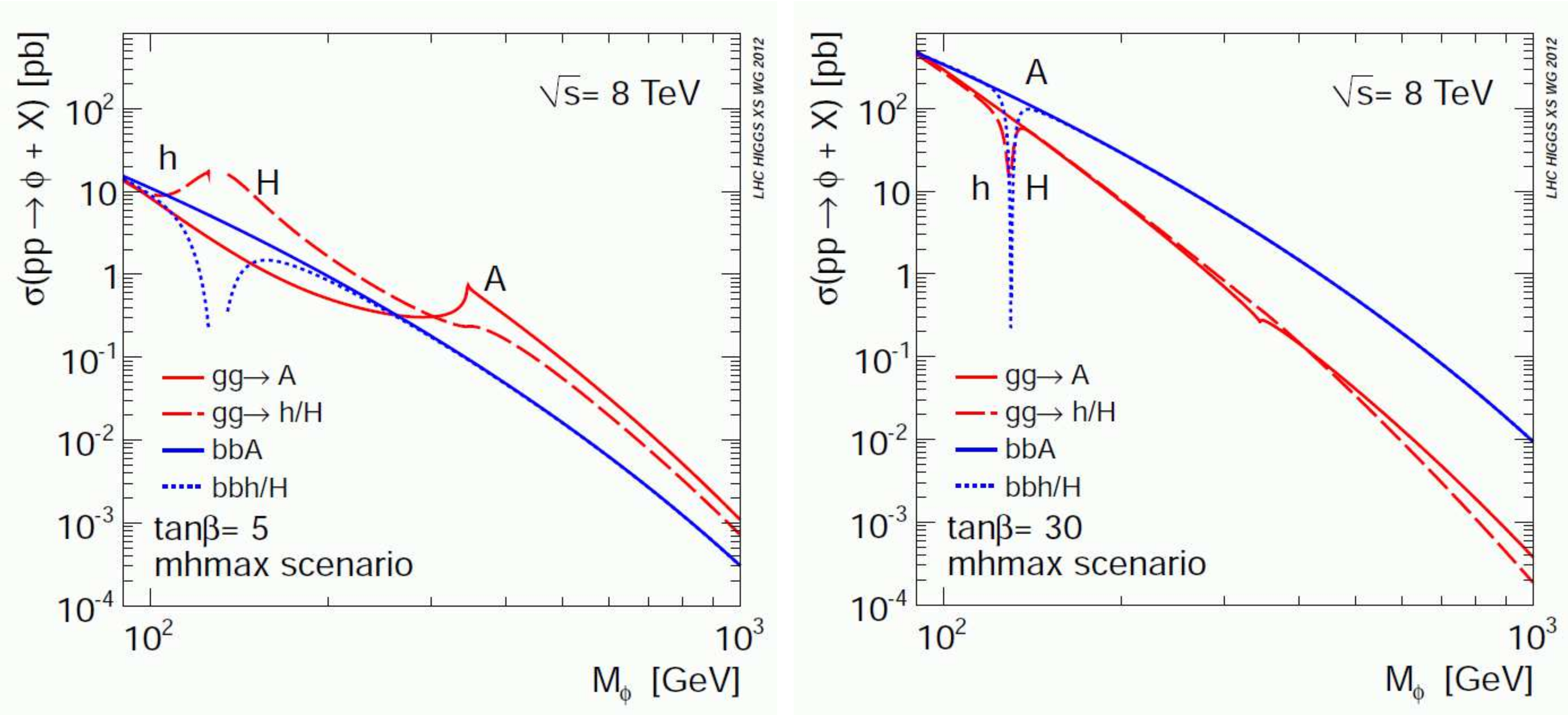
Next meeting: 20.-22.10.2014, DESY, Hamburg, Germany

3 B) Prediction of SUSY Higgs Cross Sections (and BRs):

"Official" theory predictions for the MSSM Higgs XS: [*LHC Higgs XS WG '12*]

Masses, couplings: FeynHiggs

Cross sections: combination of Higlu, bbh@nnlo, FeynHiggs, . . .



⇒ most relevant cross sections ($bb\Phi$: Santander matching)

⇒ update for $gg \to \Phi$ . . .

Update for $gg \to \Phi$: [LHCHXSWG - MSSM '13] [E. Bagnaschi et al. '14]

The old LHC-HXSWG numbers for gluon fusion

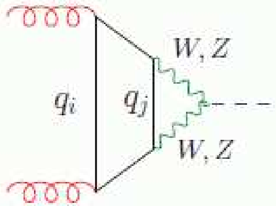
NLO top/bottom contributions from HIGLU + NNLO top bit from ggH@NNLO, rescaled by MSSM Higgs-quark couplings from FeynHiggs:

$$\sigma(gg \to \phi) \;=\; (g_t^\phi)^2 \left(\sigma_{\rm NLO}^{\rm tt} + \Delta\sigma_{\rm NNLO}^{\rm tt}\right) \;+\; (g_b^\phi)^2\, \sigma_{\rm NLO}^{\rm bb} \;+\; g_t^\phi\, g_b^\phi\, \sigma_{\rm NLO}^{\rm tb}$$

e.g., for h :
$$g_t^h \;=\; \frac{\cos\alpha}{\sin\beta}\,, \qquad g_b^h \;=\; -\frac{\sin\alpha}{\cos\beta}\,\frac{1}{1+\Delta_b}\left(1 - \frac{\Delta_b}{\tan\alpha\tan\beta}\right)$$

$$\Delta_b \;=\; \frac{2\,\alpha_s}{3\pi}\, m_{\tilde g}\, \mu\, \tan\beta\, I(m^2_{\tilde b_1}, m^2_{\tilde b_2}, m^2_{\tilde g}) \;+\; \ldots$$

- No stop/sbottom contributions (apart from those implicit in Δ_b)
- No electroweak contributions (not even the known SM ones)



From the first "Yellow report": (1101.0593)

"In further steps we will have to include the full SUSY QCD and SUSY electroweak corrections where available..."

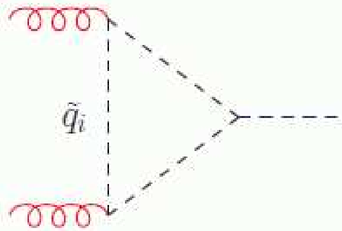
[P. Slavich, talk given at HDays13]

Update for $gg \to \Phi$:

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

In the MSSM, additional contributions to Higgs production
from loops involving superparticles:

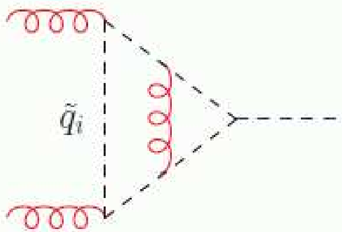
At LO, 1-loop
squark contribution:



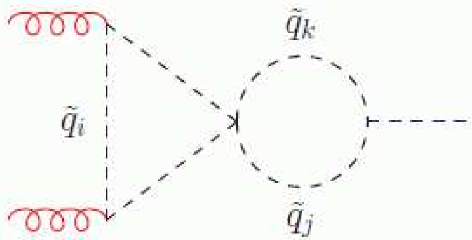
$(\tilde{q} = \tilde{t}, \tilde{b})$

At NLO, different classes of 2-loop SUSY contributions:

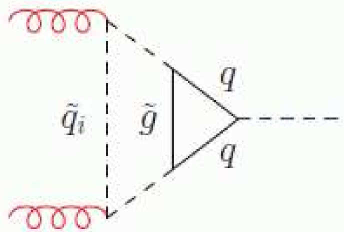
gluon-squark:



quartic squark coupling:



gluino-quark-squark:



Also, squark contributions from 1-loop diagrams with real parton emission

[*P. Slavich, talk given at HDays13*]

Update for $gg \to \Phi$: [LHCHXSWG - MSSM '13] [E. Bagnaschi et al. '14]

Towards a state-of-the-art NLO calculation in the MSSM

A joint effort:

- ➡ Bagnaschi, Degrassi, Slavich, Vicini
- ➡ Harlander, Mantler, Liebler (SusHi)

Full NLO top/bottom + expanded NLO stop/sbottom + NNLO top + SM-EW

The road map (HDays'13)

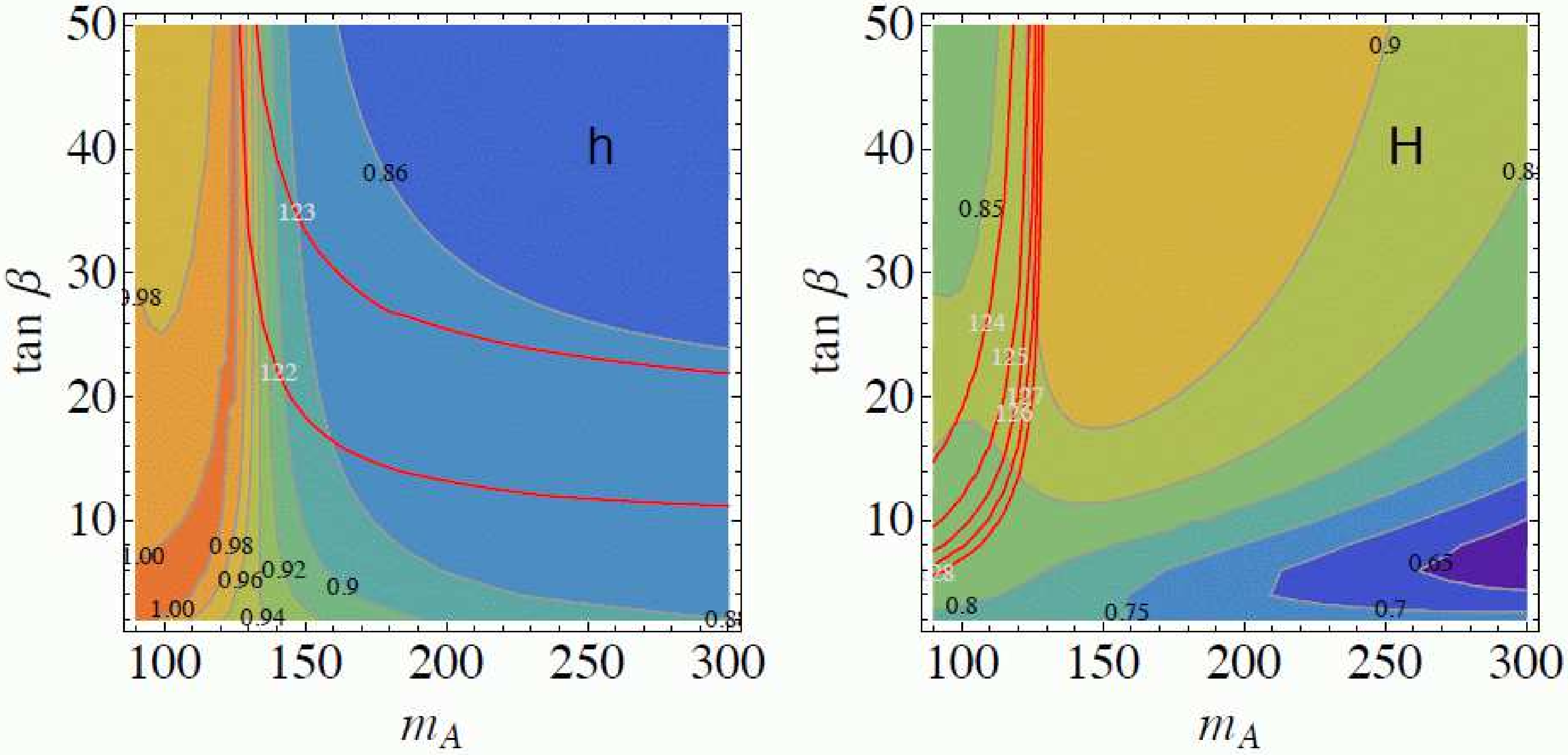
- ✓ Compare the two codes at pure NLO and understand any discrepancies
- ✓ Explore different options for renormalization schemes (esp. large $\tan\beta$)
- ✓ Determine best way to include known NNLO and EW effects
- ✓ Produce new numbers and compare with the "official" LHCHXSWG ones

[P. Slavich, talk given at HDays13]

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]

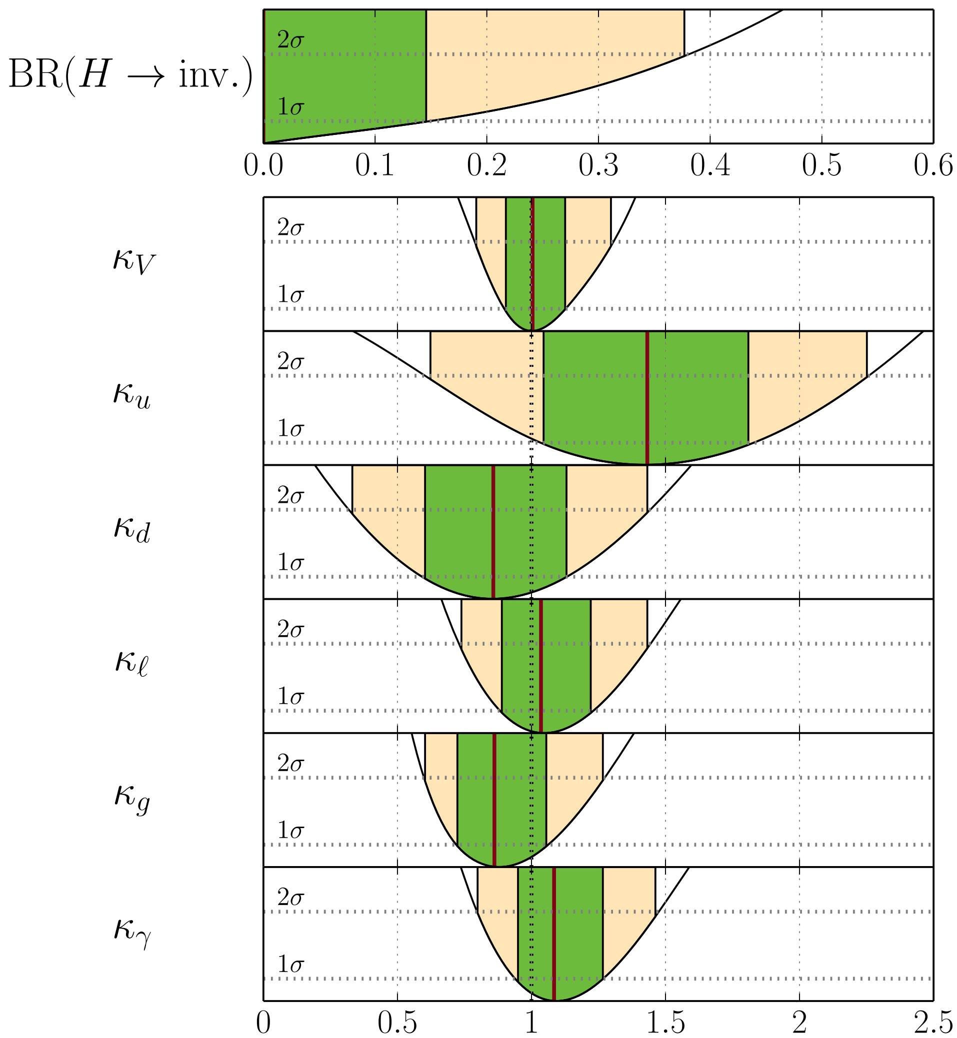


$\sigma_{gg}^{q+\tilde{q}} \,/\, \sigma_{gg}^{q}$ [*P. Slavich, talk given at HDays13*]

3 C) Search for deviations in XS, BR induced by SUSY

Lastet coupling measurement (κ framework) including all data:

[*P. Bechtle, S.H., O. Stål, T. Stefaniak, G. Weiglein '14*]



Very general model:

$\kappa_V, \kappa_u, \kappa_d, \kappa_l, \kappa_g, \kappa_\gamma$, BR($H \to$ inv.)

using HiggsSignals with
80 channels from
ATLAS, CMS, CDF, DØ

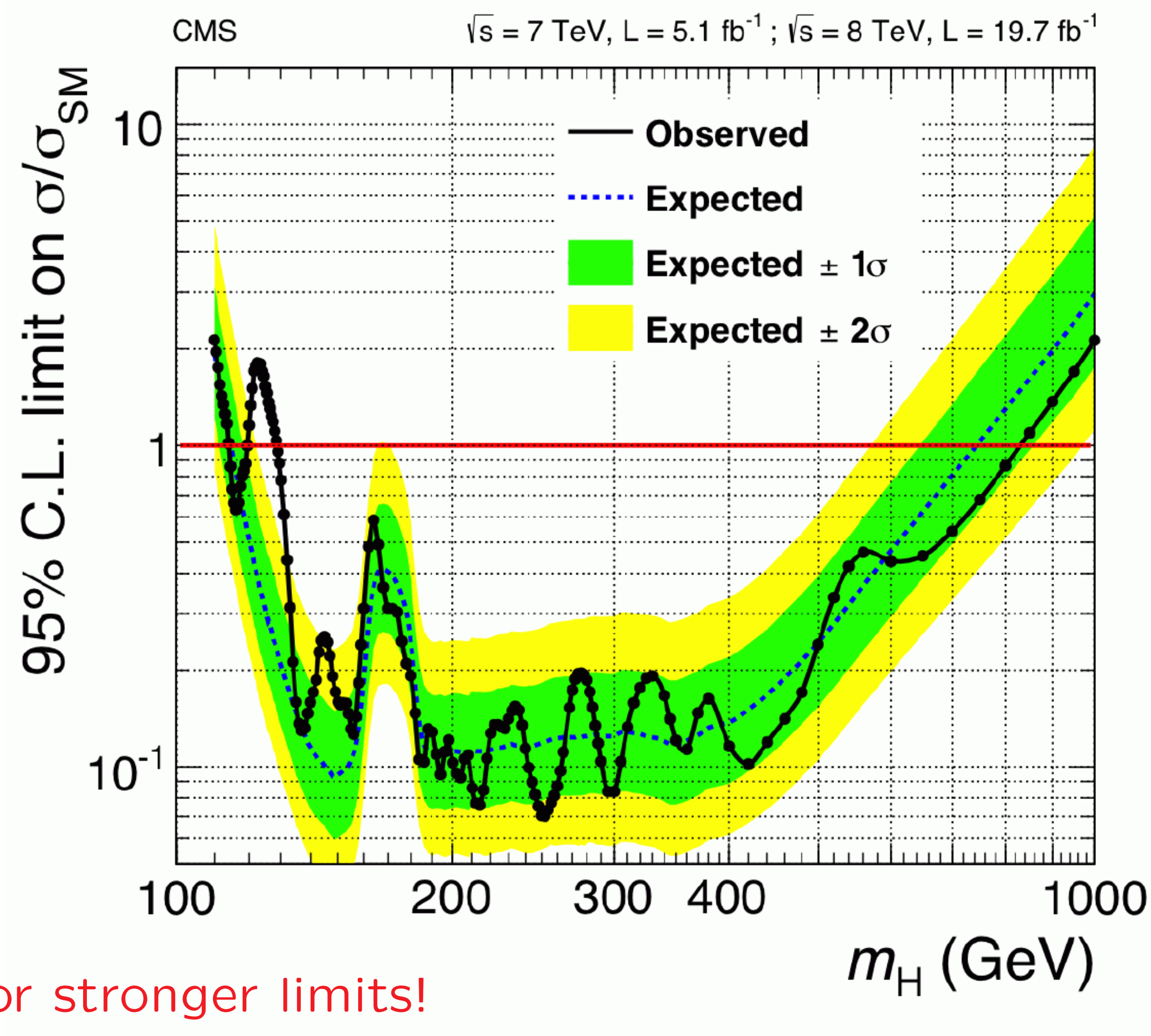
$\Rightarrow$ no deviations so far!

$\Rightarrow$ Overview talk by
Margarete Mühlleitner

Re-interpretation of SM Higgs search results:

$g^2_{hVV} = \sin^2(\beta - \alpha)\, g^2_{HVV,\text{SM}}$, $\quad g^2_{HVV} = \cos^2(\beta - \alpha)\, g^2_{HVV,\text{SM}}$

$\Rightarrow$ some coupling strength could remain for the heavy Higgs



$\Rightarrow$ go ahead for stronger limits!

3 D) Search for additional Higgs bosons

Search (interpretation) in new benchmark scenarios: [*arXiv:1302:7033*]

⇒ designed to have $M_h \sim 125.5 \pm 3$ GeV
and to reproduce rate measurements

⇒ designed to exhibit certain features of Higgs phenomenology

– light Higgs phenomenlogy
– heavy Higgs phenomenology

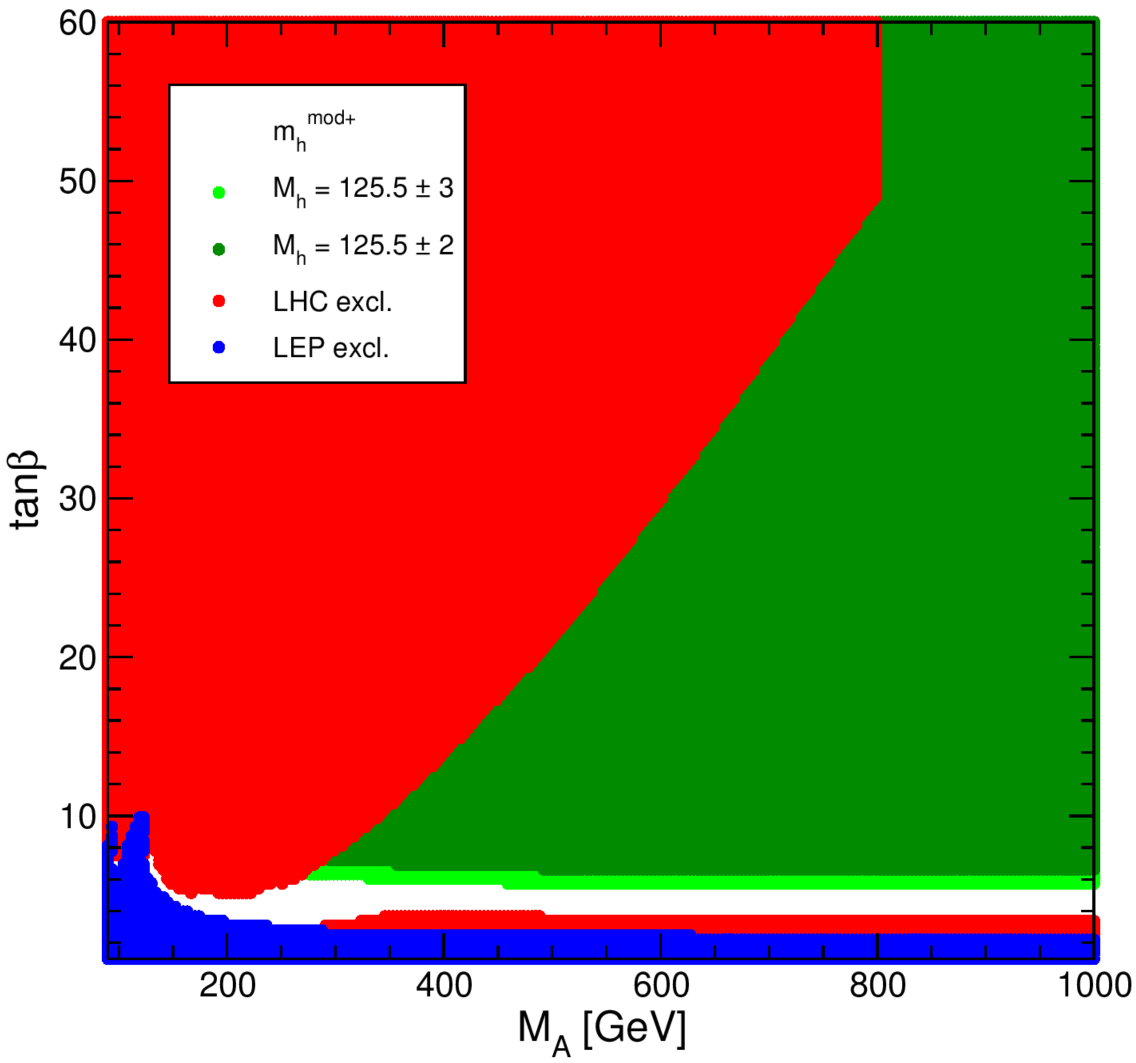
Not taken into account on purpose:

– Flavor contraints
– Precision observables
– Dark Matter
– . . .

⇒ can all be avoided easily by small model modification
that do not change the Higgs phenomenology

⇒ do not overconstrain yourself!

$m_h^{\text{mod}+}$ scenario:

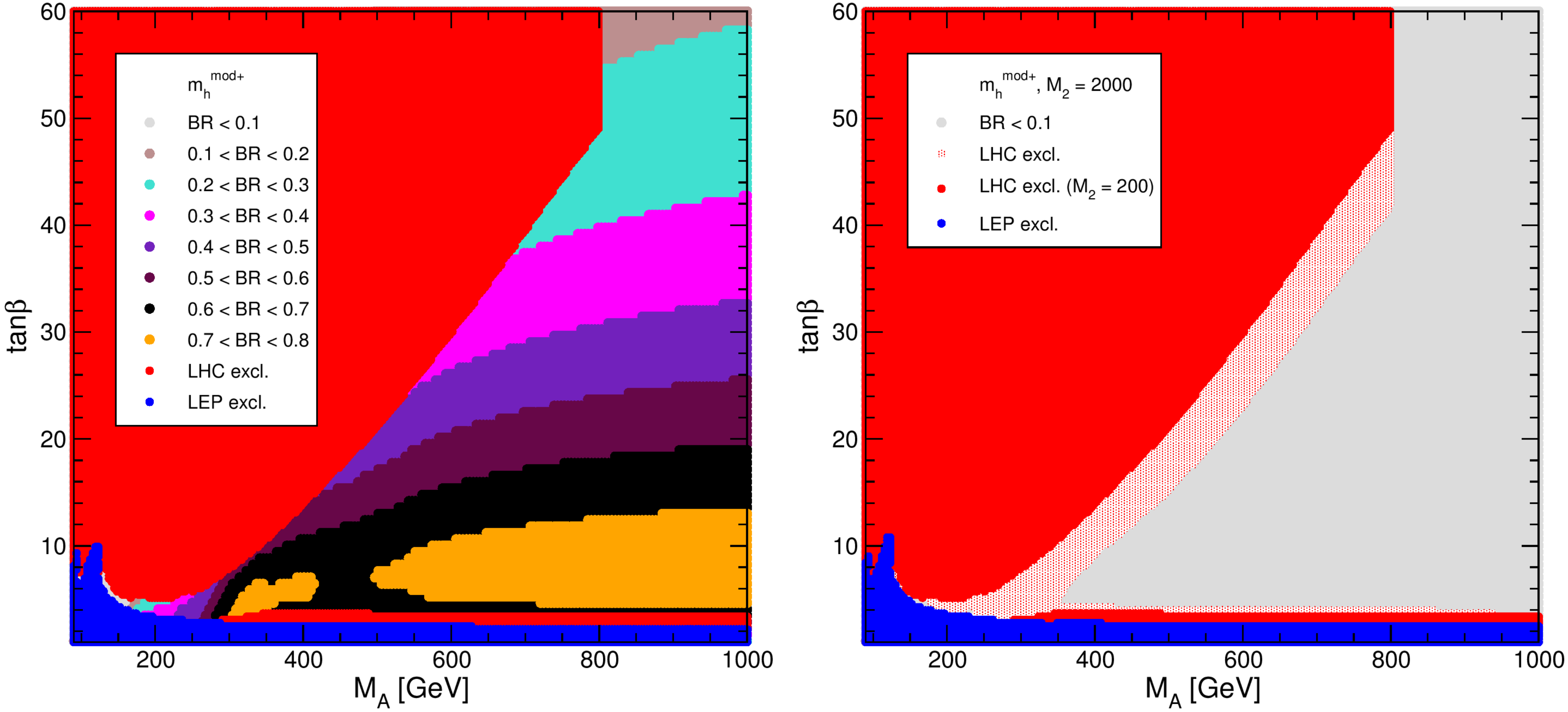


$$
\begin{aligned}
m_t &= 173.2 \text{ GeV}, \\
M_{\text{SUSY}} &= 1000 \text{ GeV}, \\
\mu &= 200 \text{ GeV}, \\
M_2 &= 200 \text{ GeV}, \\
X_t^{\text{OS}} &= 1.5\, M_{\text{SUSY}} \\
A_b &= A_\tau = A_t, \\
m_{\tilde{g}} &= 1500 \text{ GeV}, \\
M_{\tilde{l}_3} &= 1000 \text{ GeV} \;.
\end{aligned}
$$

$\Rightarrow M_h \approx 125.5$ GeV nearly "everywhere"

$m_h^{\text{mod}+}$ scenario:

⇒ effect of non-SM Higgs decays:

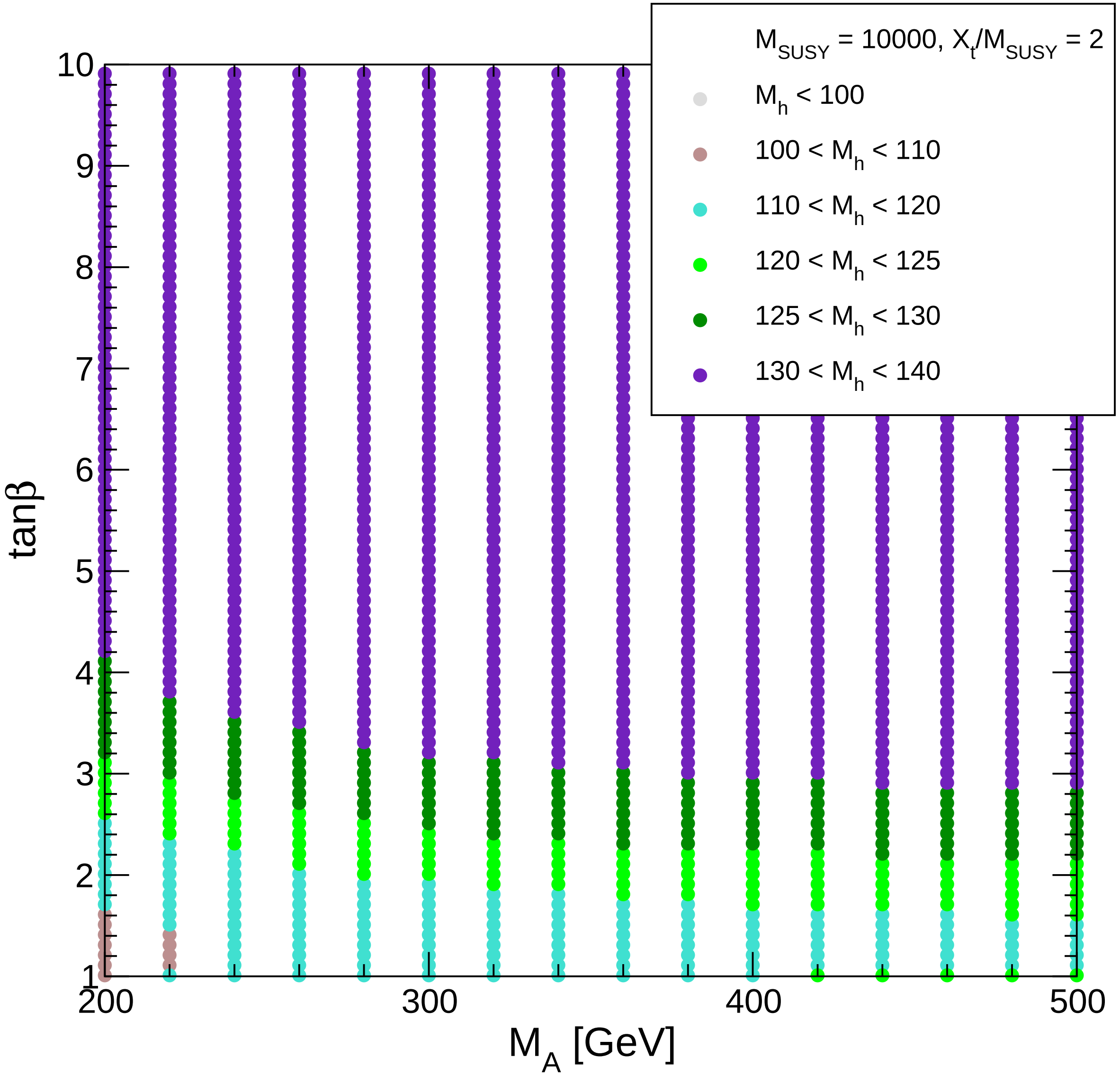


⇒ strong impact from $H/A \to \tilde{\chi}_i^0 \tilde{\chi}_j^0, \tilde{\chi}_k^\pm \tilde{\chi}_l^\mp$

⇒ disover heavy Higgses and SUSY at the same time!

Phenomenology at very low $\tan\beta$: Just one first example:

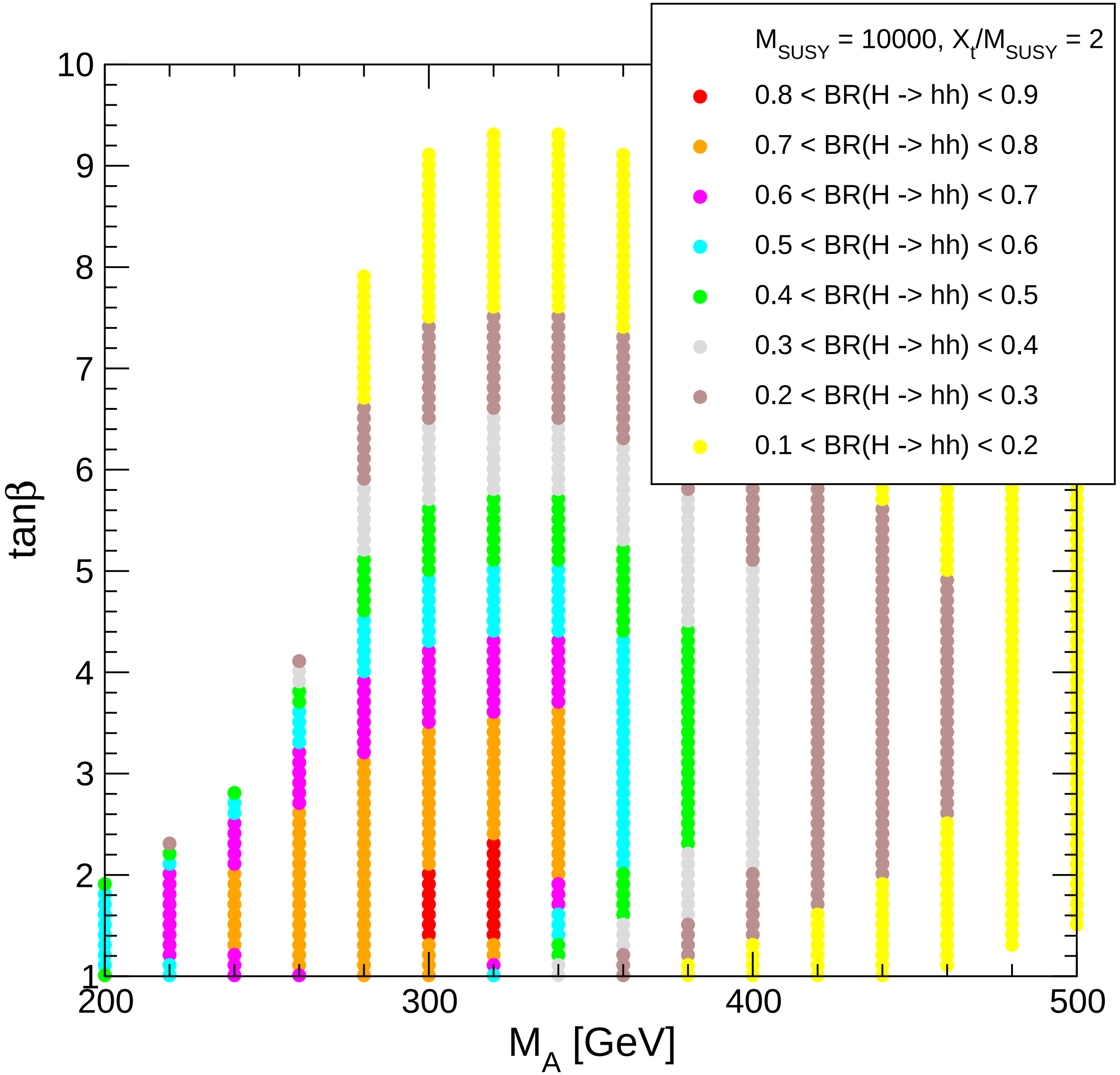
$M_{\text{SUSY}} = m_{\tilde{g}} = 10$ TeV, $X_t/M_{\text{SUSY}} = 2$, $M_2 = \mu = 1$ TeV



⇒ lower $\tan\beta$ values possible! Relevant? ⇒ "new" relevant decay channels!

$H \to hh$:

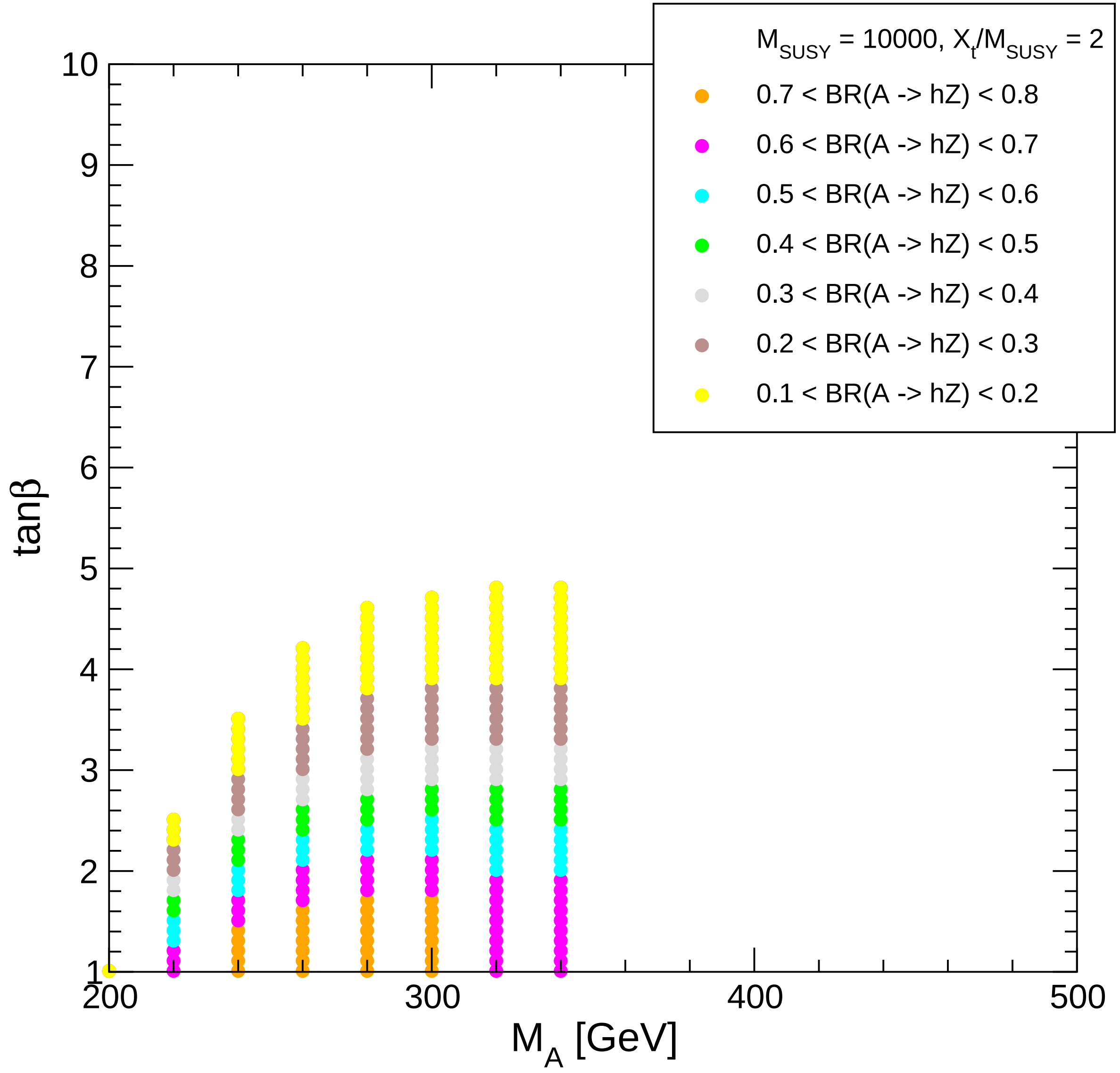
$M_{\text{SUSY}} = m_{\tilde{g}} = 10$ TeV, $X_t/M_{\text{SUSY}} = 2$, $M_2 = \mu = 1$ TeV



$\Rightarrow$ important at low $\tan\beta$ $\Rightarrow$ new benchmarks necessary . . .

$A \to hZ$:

$M_{\mathrm{SUSY}} = m_{\tilde{g}} = 10$ TeV, $X_t/M_{\mathrm{SUSY}} = 2$, $M_2 = \mu = 1$ TeV



⇒ important at low $\tan\beta$ ⇒ new benchmarks necessary . . .

The "exotic" solution:
the discovery is interpreted as the heavy $\mathcal{CP}$-even Higgs

In principle also possilbe:

$$M_h < 125.5 \text{ GeV}$$
$$M_H \approx 125.5 \text{ GeV}$$

Consequences:
– all Higgs bosons very light
– easy(?) discovery of additional Higgs bosons at the LHC

Constraints:
– direct searches for the lightest $\mathcal{CP}$-even Higgs
– direct searches for the heavy neutral Higgses
– direct searches for charged Higgses
– flavor constraints (BR($B_s \to \mu^+\mu^-$) etc.)

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Constraints:
- direct searches for the lightest $\mathcal{CP}$-even Higgs
- direct searches for the heavy neutral Higgses
- direct searches for charged Higgses $\Leftarrow$ strong constraint in the MSSM!
- flavor constraints (BR($B_s \to \mu^+\mu^-$) etc.)

The general possibility:
the discovered Higgs is the second-lightest one

– more contrived in the MSSM with real parameters

– "easier" (?) possible in the MSSM with complex parameters

– "easier" (!) possible in the NMSSM $\to$ 8 talks, but ...
$\Rightarrow$ light Higgs can be singlet like
can more easily escape detection

Is such a light Higgs detectable at the LHC?

– $h_2 \to h_1 h_1$ possible, but strongly suppressed for $M_{h_1} \gtrsim 63$ GeV
– so far no LHC searches for a Higgs with $M_{h_1} \lesssim 100$ GeV
– Possible: SUSY $\to$ SUSY h_1 , e.g. $\tilde{\chi}^0_2 \to \tilde{\chi}^0_1 h_1$

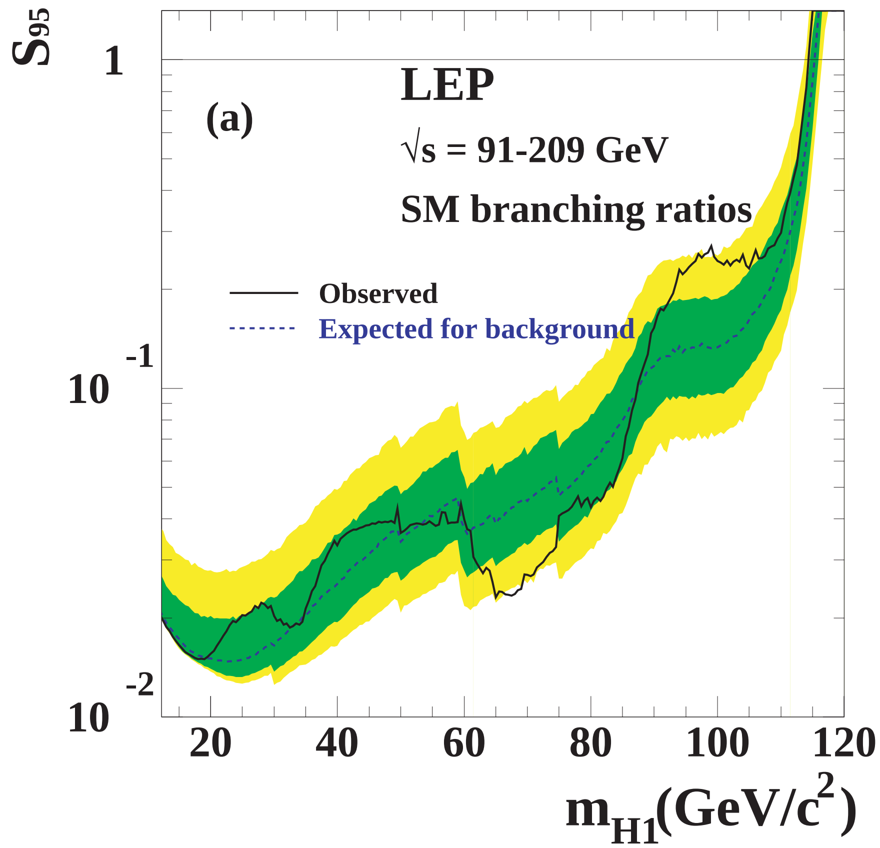
LHC Higgs searches below 100 GeV:

– crucial to cover extended Higgs sectors

– needed to re-check LEP exclusions ($\sim 2.x\,\sigma$ "excess" around 98 GeV)

Best channel? $h_1 \to \gamma\gamma$??

You tell me!



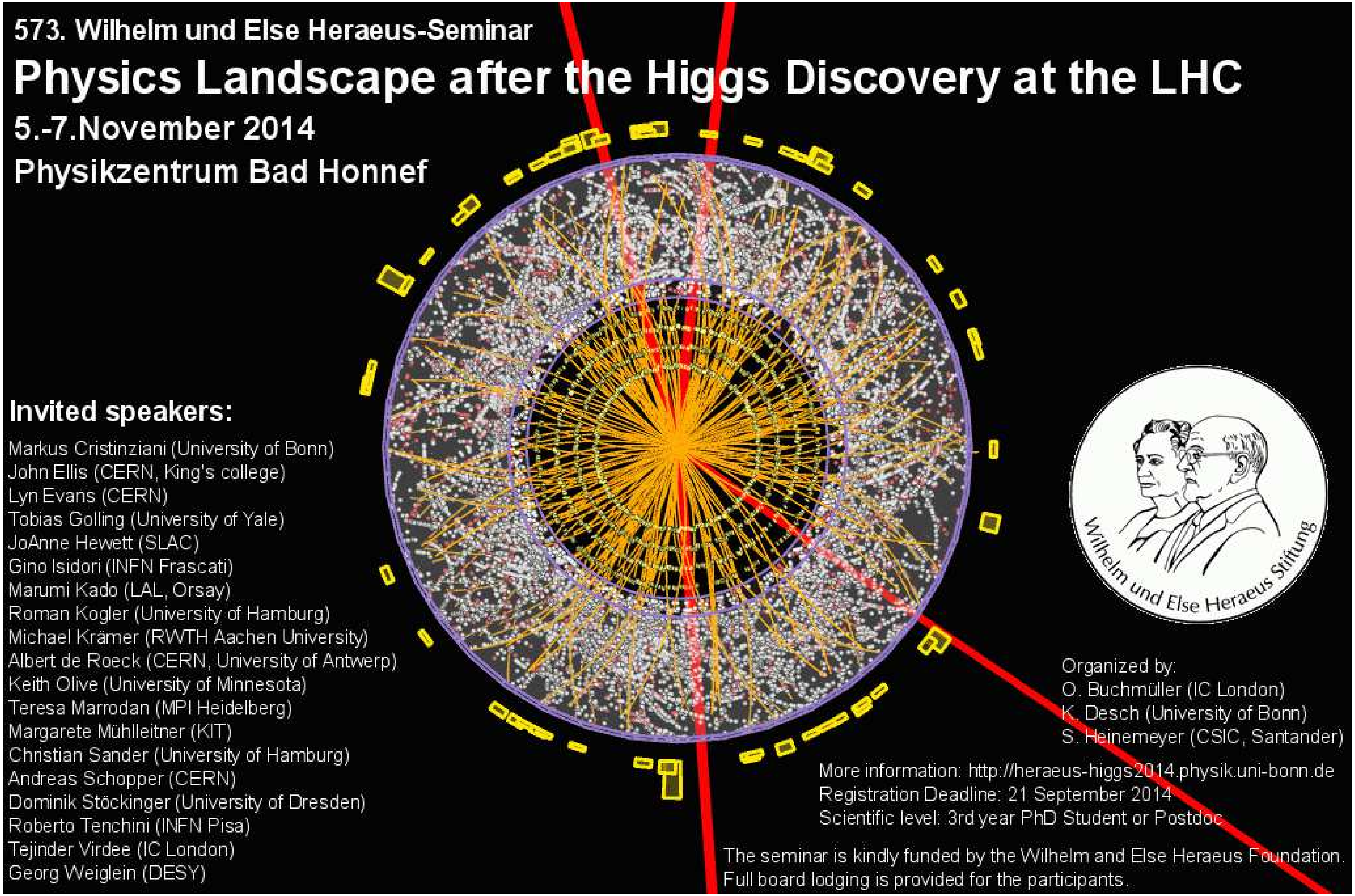
⇒ we cannot encourage you enough to perform this search!

4. Conclusinos

- Higgs discovery fits well with SM predictions
  - M_H prediction via EWPO
  - prediction of cross sections $\times$ branching ratios
- Calculation challenges: LHC Higgs Cross Section WG provides
  - higher-order total and differential cross sections, BRs, ...
  - property analysis strategies
  - preparation for future challenges: higher energies, exotic modes, ...
- Higgs discovery fits well with lightest MSSM Higgs boson
  - direct prediction of M_h
  - prediction of cross sections $\times$ branching ratios
- Unsolved calculation challenge: $\delta M_h^{\text{exp}} \ll \delta M_h^{\text{theo}}$
  - combination of Feynman-diagrammatic and RGE calculations
  - recent progress (see parallel sessions)
  - dedicated working group formed ...
- Search for additional Higgs bosons:
  - new benchmarks are in place: Higgs $\to$ SUSY, SUSY $\to$ Higgs
  - even newer benchmarks needed for very low $\tan\beta$: $H \to hh$, ...
  - do not forget about (SUSY) Higgses lighter than 125 GeV!


Higgs Days at Santander 2014
Theory meets Experiment
08.-12.September
Instituto de Física de Cantabria
CSIC
UC
UNIVERSIDAD DE CANTABRIA
CPAN
Ingenio 2010
MultiDark
Multimessenger Approach for Dark Matter Detection
contact:Sven.Heinemeyer@cern.ch
www.ifca.es/HDays14

(PBIO)



Please apply - it's worth it! :-)