Higgs Physics - Experiment Lecture 2

Combination, beyond the main channels and future challenges

CERN-Fermilab Hadron Collider Physics School

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Marumi Kado
LAL, Orsay and Sapienza Roma

CERN-FERMILAB
HADRON COLLIDER PHYSICS
Summer School

Outline of the Lectures

***Lecture 1**: Main Channels and Precision Higgs physics*

- Preamble
- Introduction
- The discovery of the Higgs boson
- Precision with diboson channels
- The Higgs boson width
- Measurement of 3^{d} generation Yukawas
- Run 2 milestones

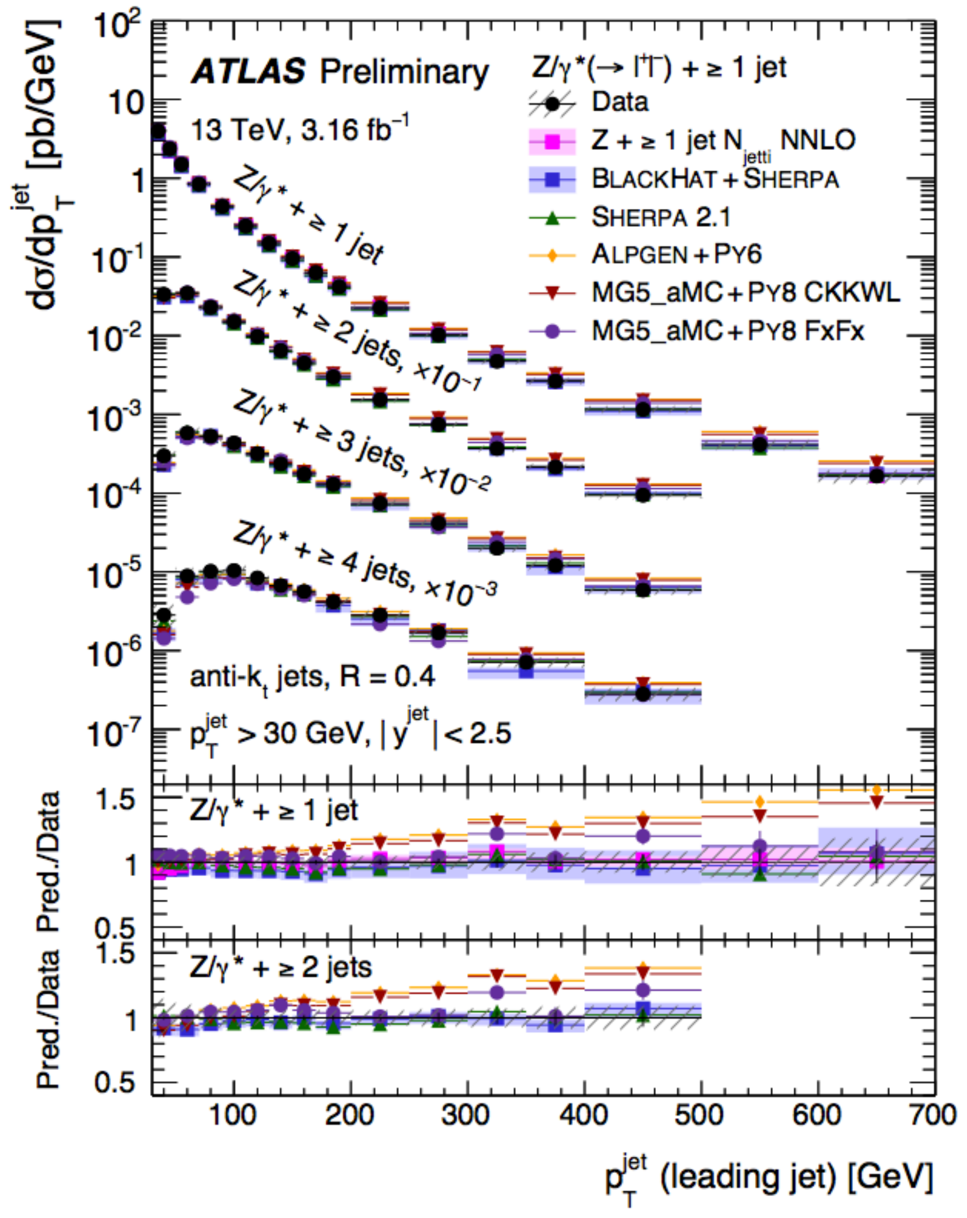
***Lecture 2**: Combination, beyond the main channels and future challenges*

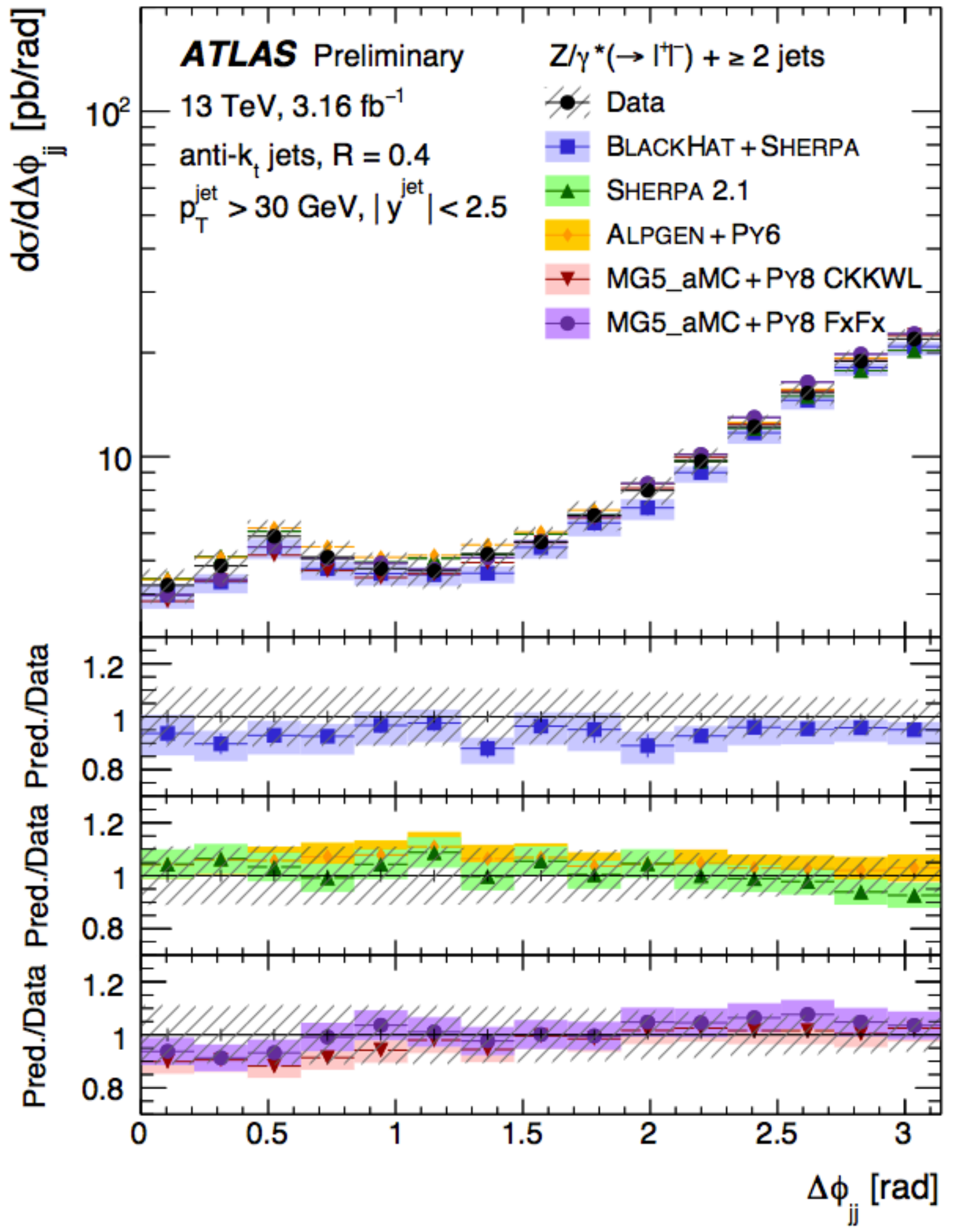
- A word about modelling
- Combined measurements of coupling properties
- Rare decays modes
- Rare production modes
- Di-Higgs production and the Higgs self coupling
- Probing an Extended Higgs sector
- EFTs in a tiny nutshell
- Higgs Physics at HL-LHC and beyond
- What have we learned?
- Conclusions and Outlook

A word about modelling

Modeling, Ancillary Measurements and HEP Data

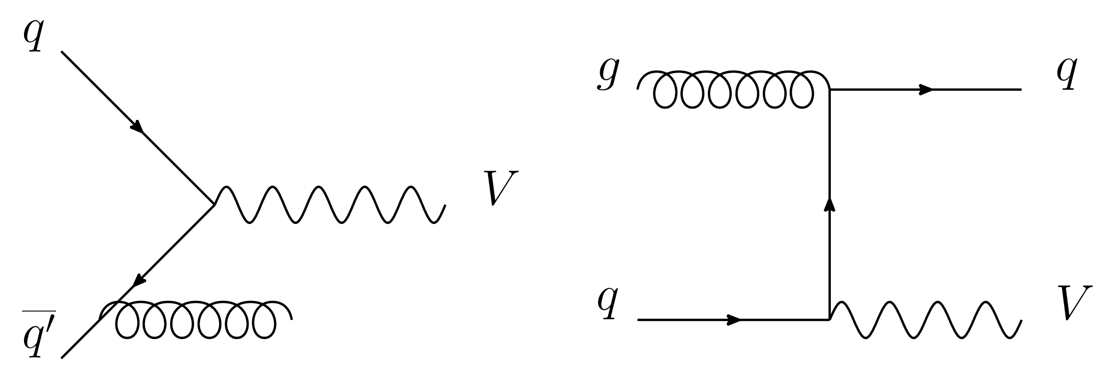
Huge effort to move to State-of-the-Art MC and Importance of differential fiducial results





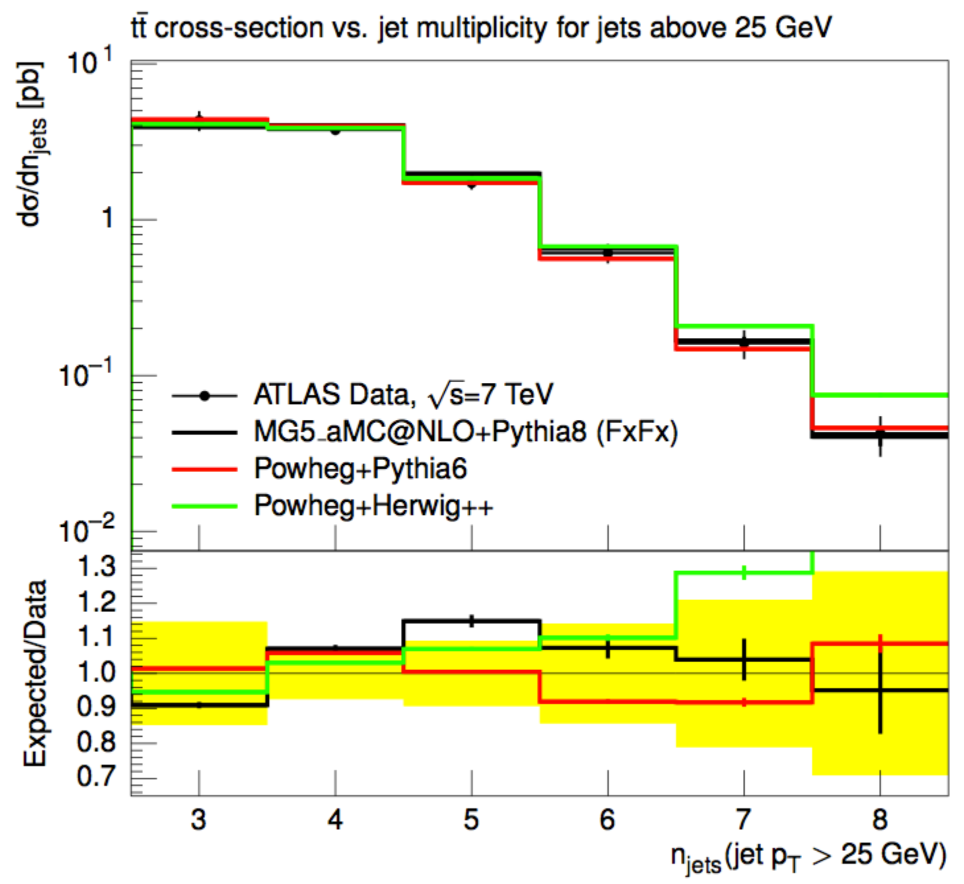
V+jets production

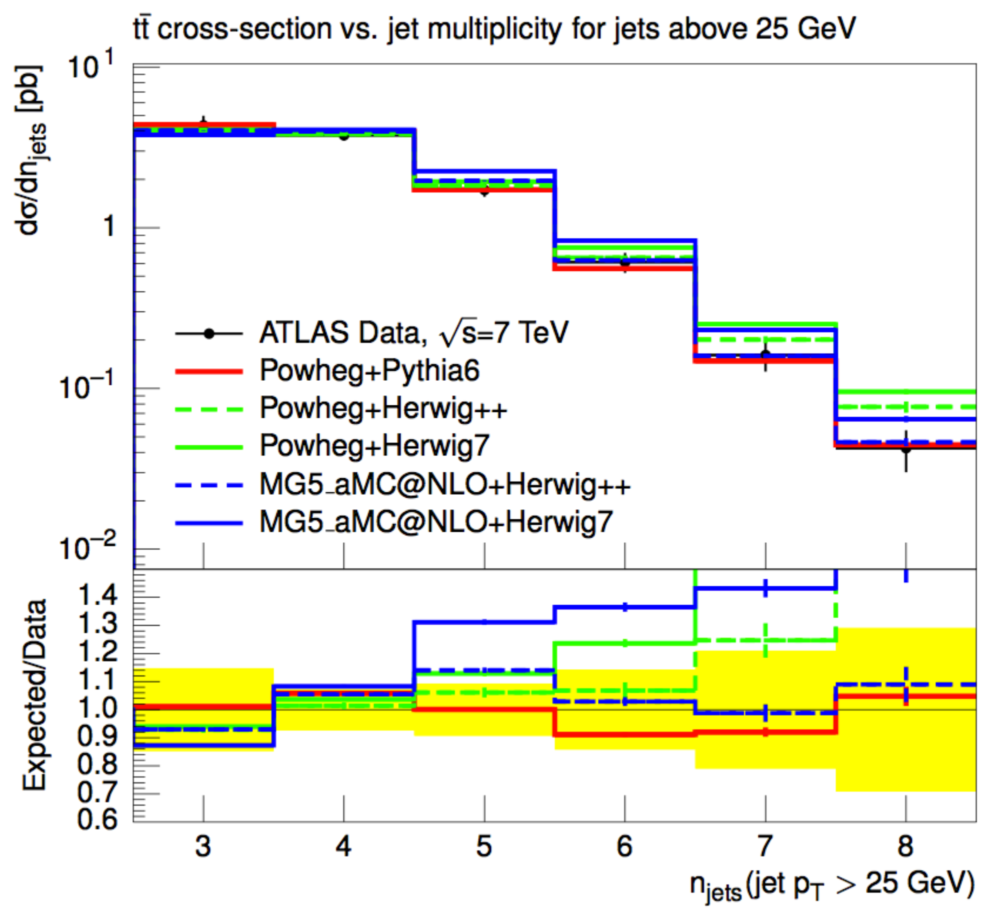
Crucial in the VH(bb) analysis and many more



Already improvements w.r.t. to Run 1 and for the full dataset considering Sherpa 2.2.

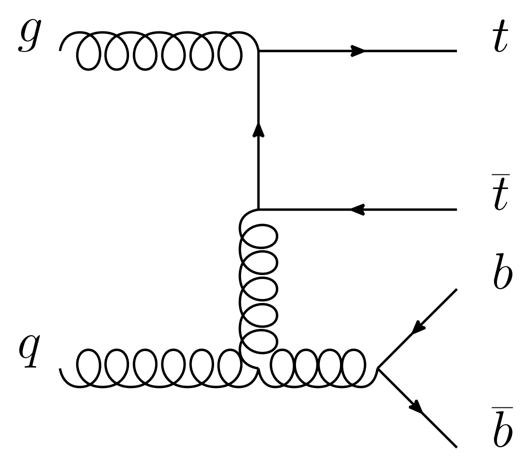
This illustrates the very fast turn around to include latest MC developments.





Top(+jets) production

Crucial in the ttH(bb) analysis and many more



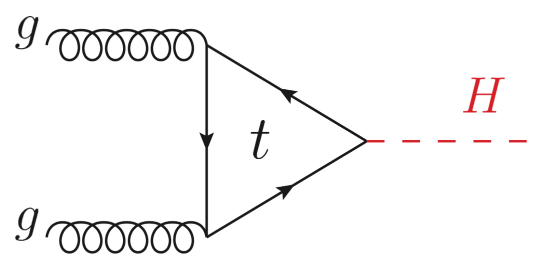
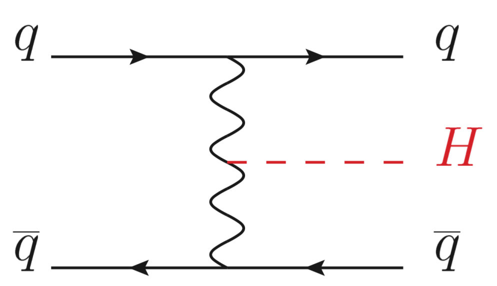
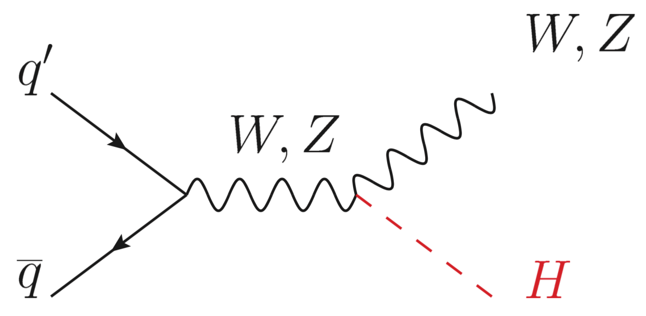
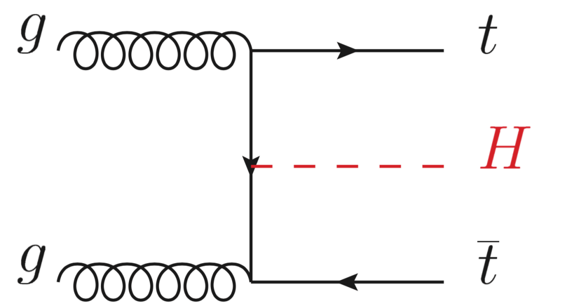
Crucial role played by HEPData and Rivet !

Combined Measurements of Coupling Properties

Panorama of Main Higgs Analyses

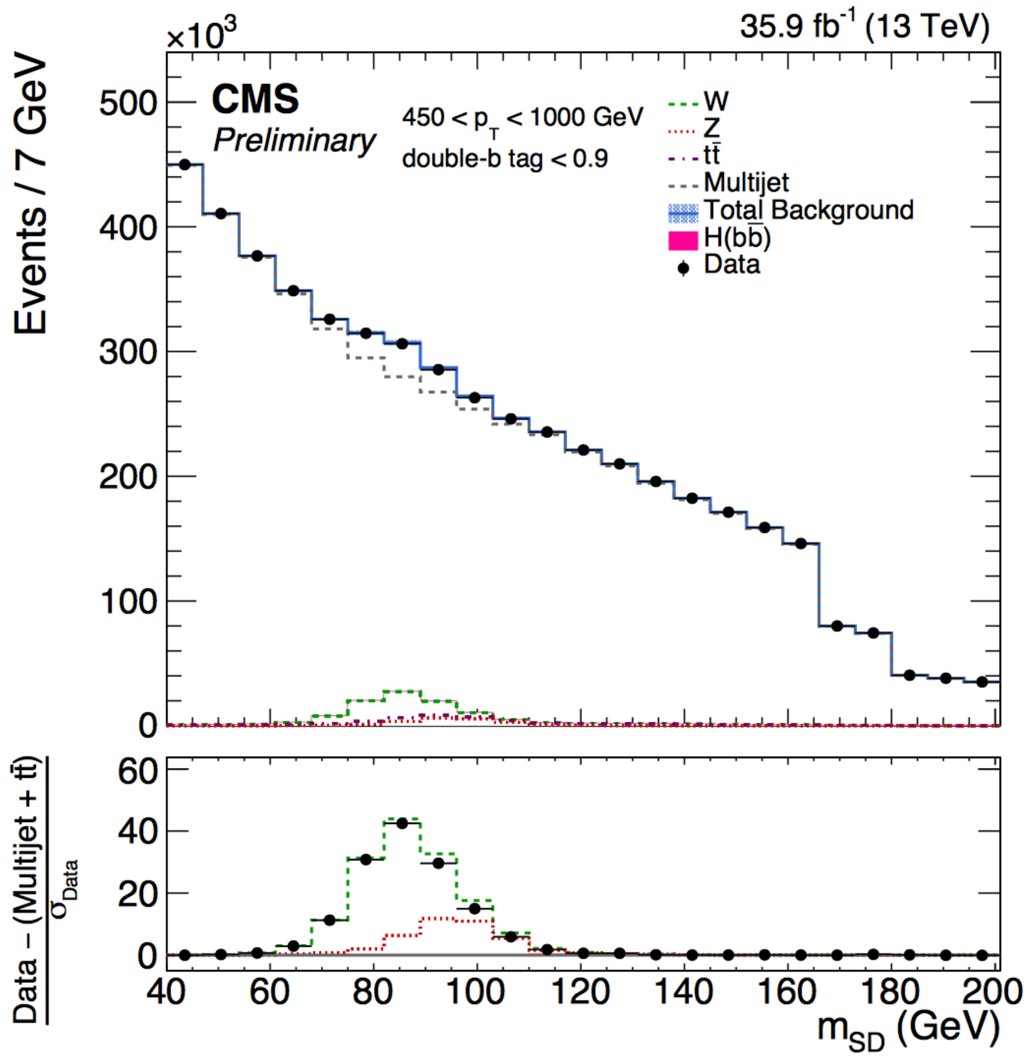
Already impressive harvest of results

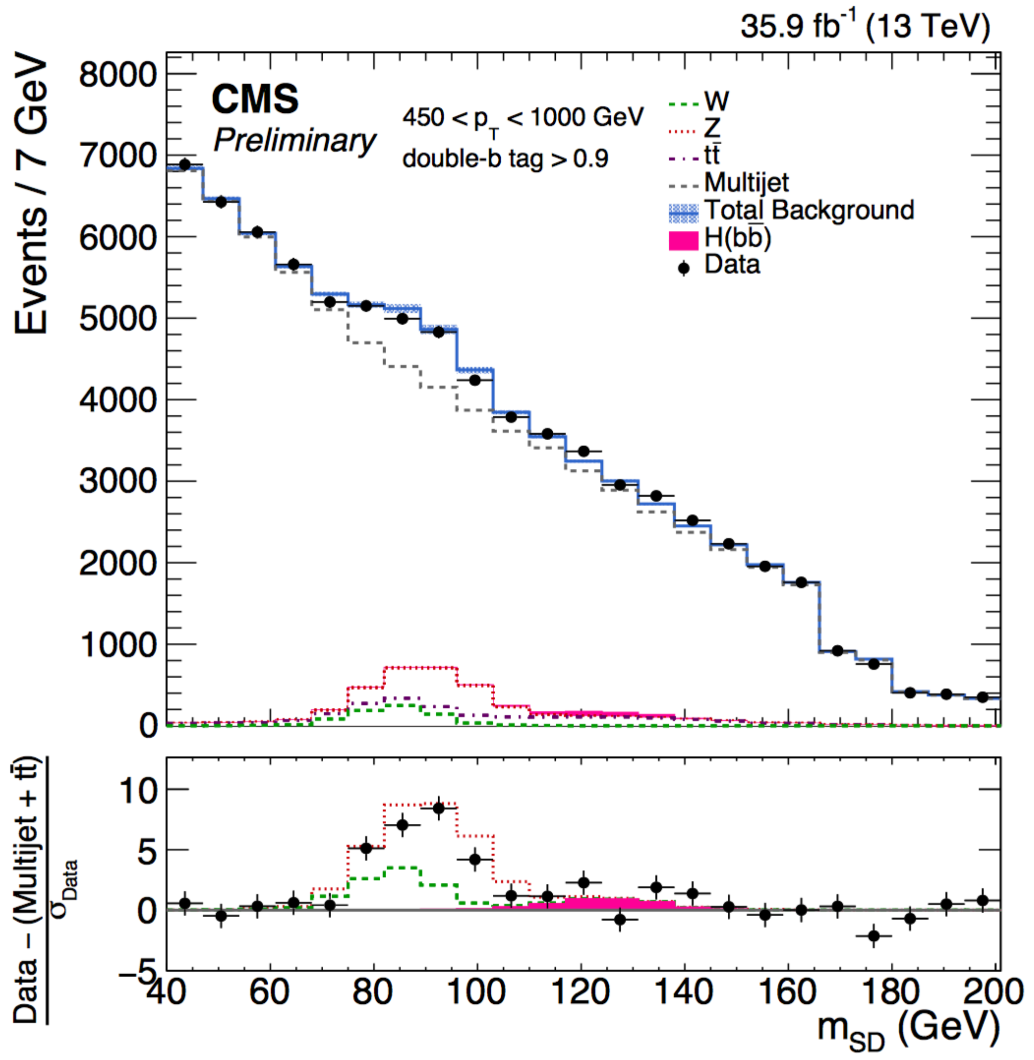
All production processes have been observed

	Channel categories	ggF 	VBF 	VH 	ttH 
Observed decay modes	γγ	✓	✓	✓	✓
	ZZ (llll)	✓	✓	✓	✓
	WW (lνlν)	✓	✓	✓	✓
	ττ	✓	✓	✓	✓
	bb	✓	✓	✓	✓
Remaining to be observed	Zγ and γγ*	✓	✓		
	μμ	✓	✓		
Strong limits will be sufficient	Invisible	✓ (monojet)	✓	✓	

Two Interesting Additions to the H(bb) Picture

H(bb) Inclusive (and boosted)



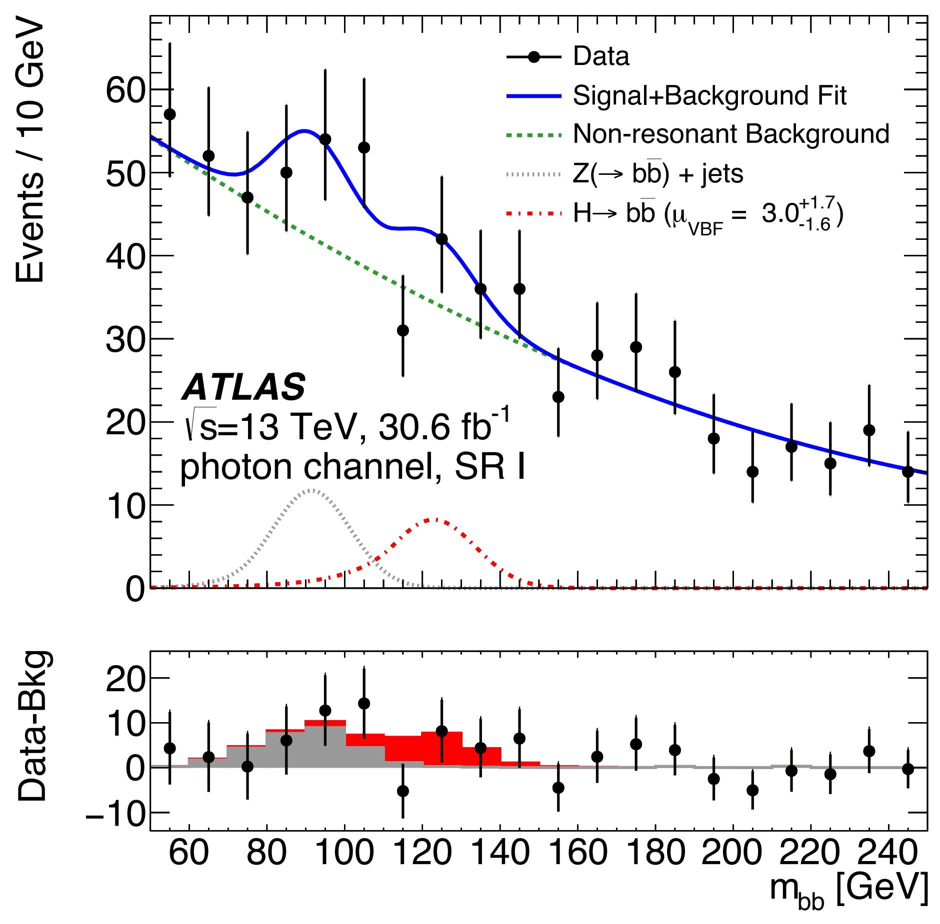


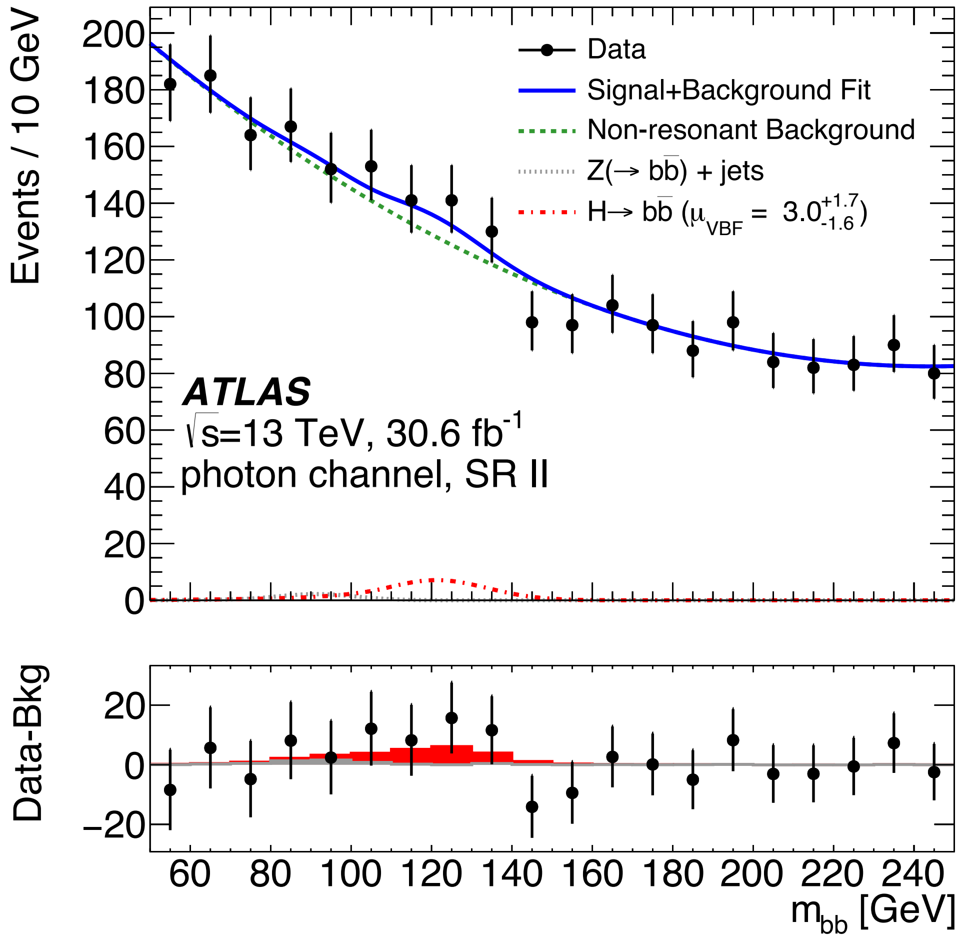
- At least one AK8 jet of 450 GeV
- One or two b-tags (double b-tagging efficiency pT dependent)

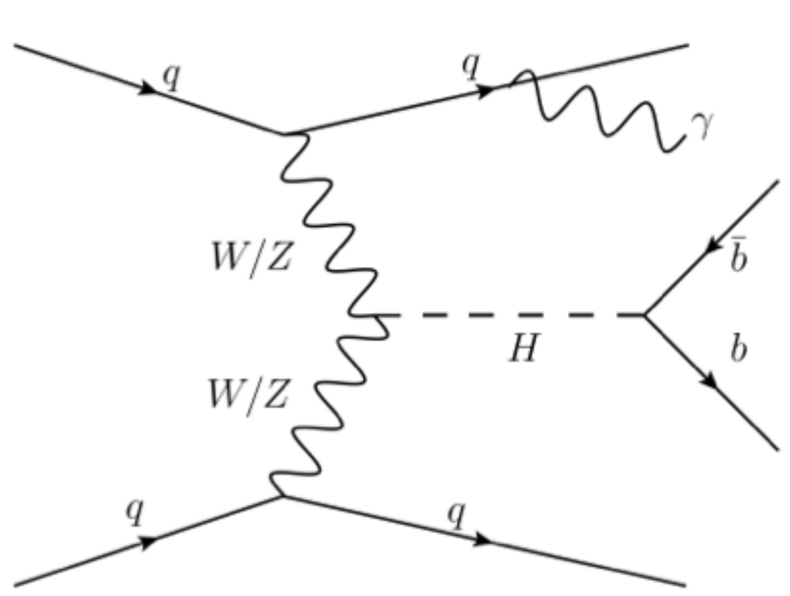
Result: $1.5\sigma \ (obs)$

$0.7\sigma \ (exp)$

VBF H(bb) with a photon







Analysis strategy:

- Photon useful for triggering.
- Useful for distinguishing from gluon induced background processes.
- Most importantly: reduces QCD background greatly due to negative interference.

$$\mu = 2.5 \pm 1.4$$

Combination Procedure and Master Formula

What is done in Higgs boson couplings analyses is to count number of signal events in specific production and decay channels.

$$n_s^c = \mu \sum_{i \subset \{\mathrm{prod}\}} \sum_{f \subset \{\mathrm{decay}\}} \mu^i \sigma^i_{SM} \times \mu^f Br^f \times \mathcal{A}^{ifc} \times \varepsilon^{ifs} \times \mathcal{L}$$

Same formula as the total cross section measurement formula

These « mu » or signal strength factors cannot be fitted simultaneously, typical fit models include:

μ	$\mu_{if} = \mu_i \mu_f$	$\mu_i \; (\mu_f = 1)$	$\mu_f \; (\mu_i = 1)$
Extrapolated total cross section	Cross section times branching	Cross sections	Branching fractions

Manifest in this formula why absolute couplings cannot be measured with this procedure: μ_i, μ_f cannot be fitted simultaneously.

The factorisation explicit in the formula is based on the narrow width approximation, it is an assumption (corroborated in part by the current measurements).

Overview of the Run 1 Higgs Couplings Measurements

These measurement correspond to cross sections times branching fractions

$$\mu \;(\text{fit}) \quad \mu_i = 1 \quad \mu_f = 1$$

$$\begin{aligned}\mu = 1.09 \quad & \pm 0.11 \\ & (\pm 0.07\,(Stat) \\ & \pm 0.04\,(Exp) \\ & \pm 0.03\,(Th.\,bkg) \\ & \pm 0.07\,(Th.\,sig)\,)\end{aligned}$$

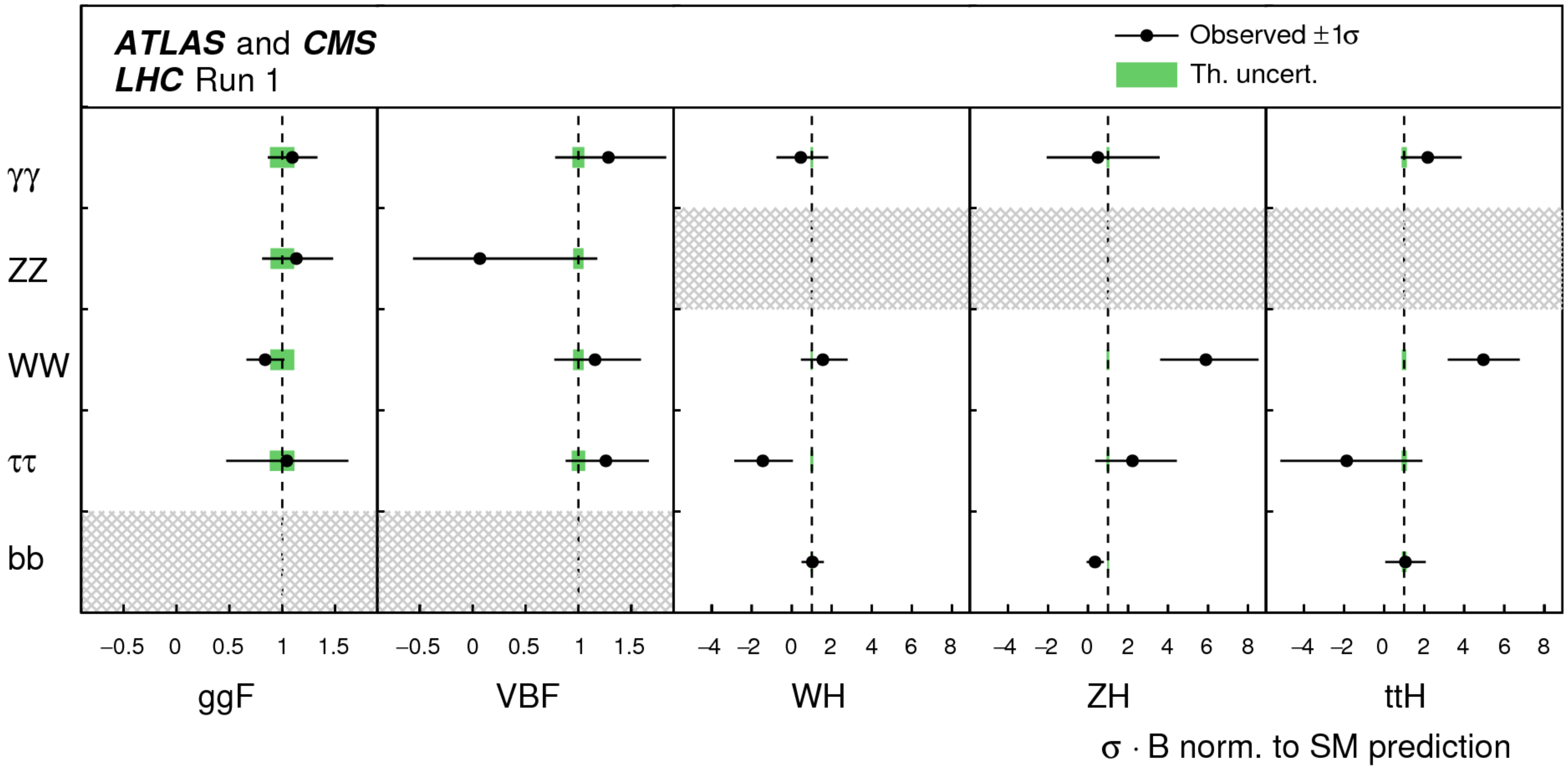
Signal strength illustrates the agreement of measurements with the SM and the importance of the TH input.

TH uncertainties have evolved already and improved significantly.

Overview of the Run 1 Higgs Couplings Measurements

These measurement correspond to cross sections times branching fractions

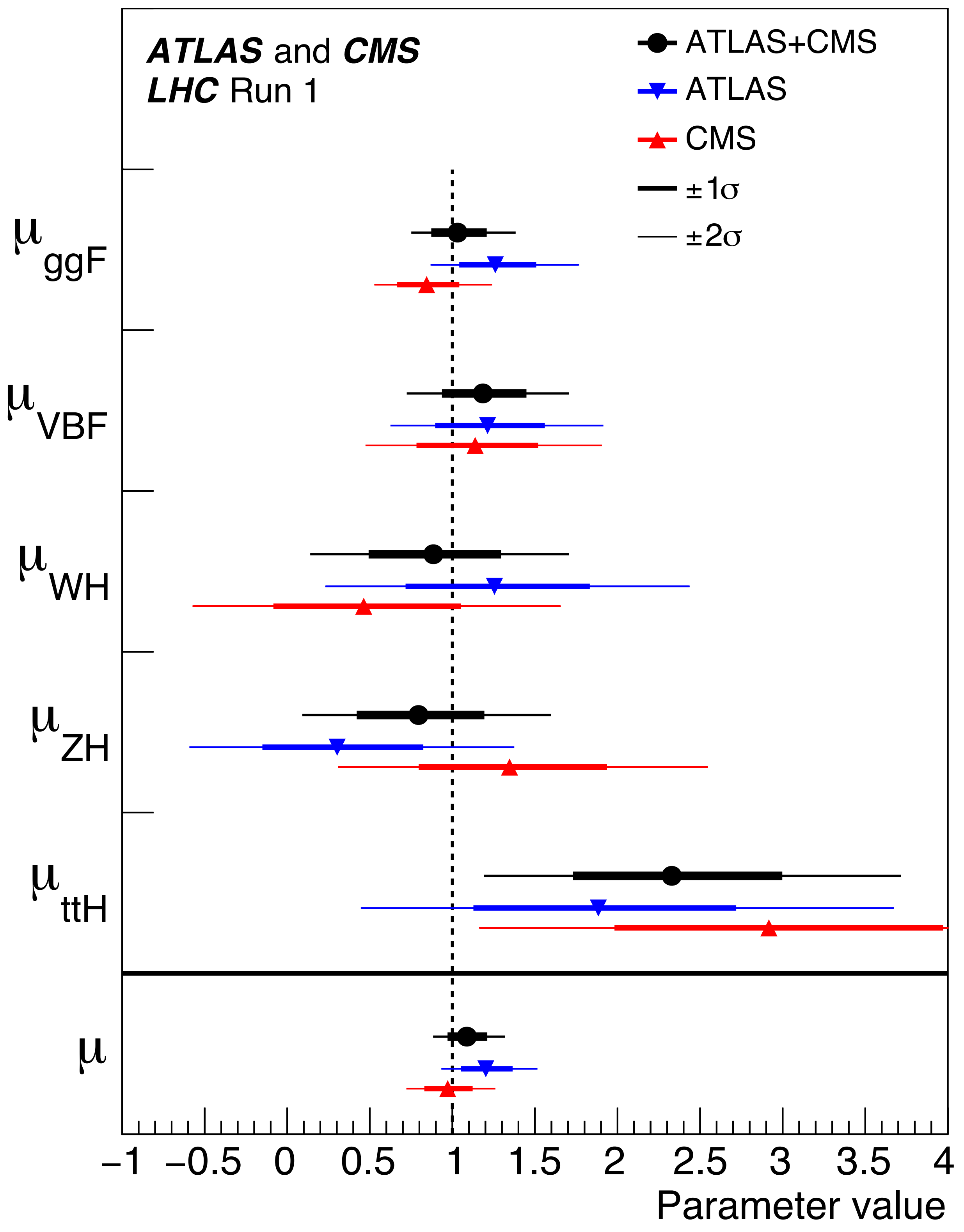
$$\mu_{if} = \mu_i \mu_f$$



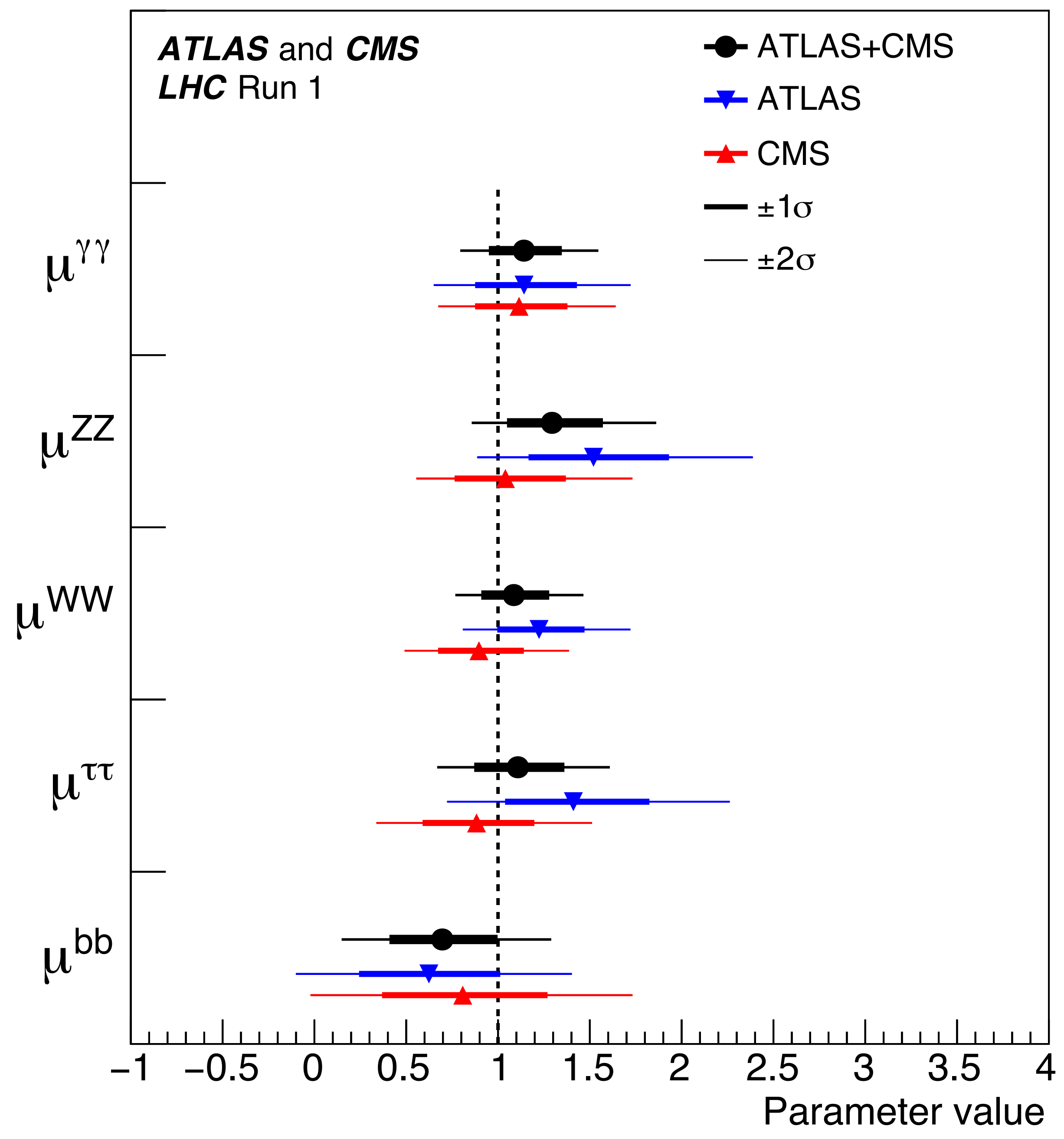
Overview of the Run 1 Higgs Couplings Measurements

These measurement correspond to cross sections times branching fractions

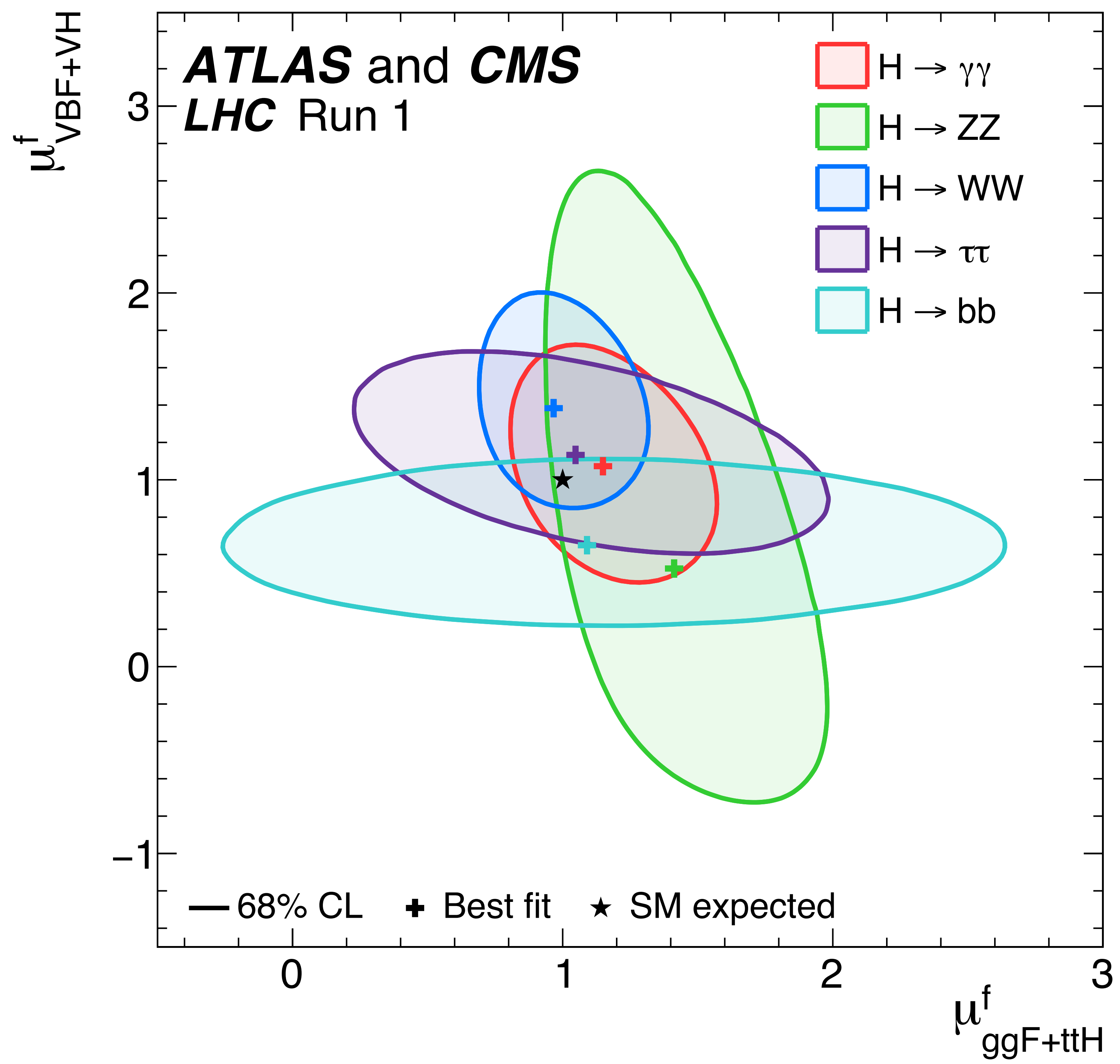
μ_i (fit) $\mu = 1$ $\mu_f = 1$



μ_f (fit) $\mu = 1$ $\mu_i = 1$



μ_i (fit) $\mu = 1$ $\mu_f = 1$

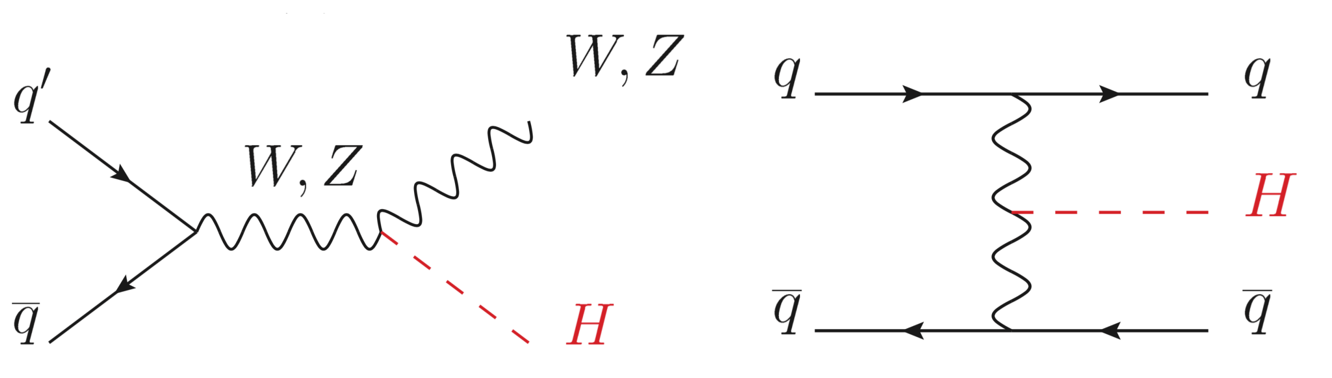


The Kappa Formalism

Introducing simple scale factors of the Standard Model couplings in a « naive » effective Lagrangian (assumes that the tensor structure of is that of the SM).

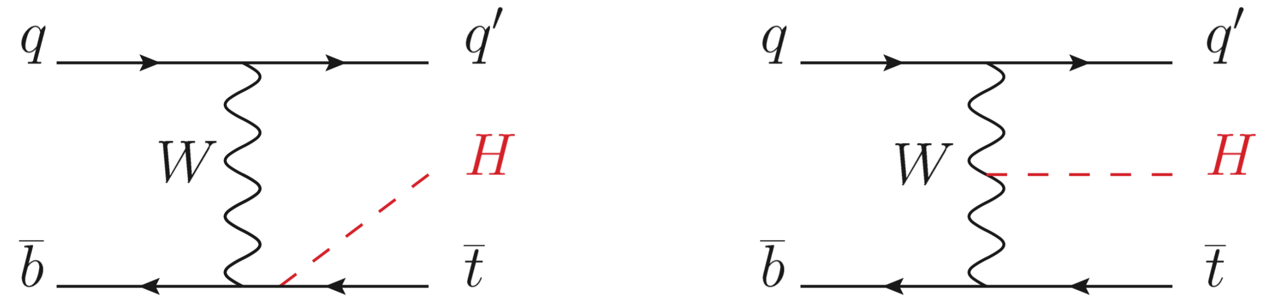
$$\mathcal{L} \supset \kappa_Z \frac{\mathrm{m}_\mathrm{Z}^2}{v} Z_\mu Z^\mu + \kappa_W \frac{\mathrm{m}_\mathrm{W}^2}{v} W_\mu W^\mu + \kappa_\gamma \frac{\alpha}{2\pi v} A_{\mu\nu} A^{\mu\nu} + \sum_f \kappa_f \frac{\mathrm{m}_f}{v} f \overline{f}$$

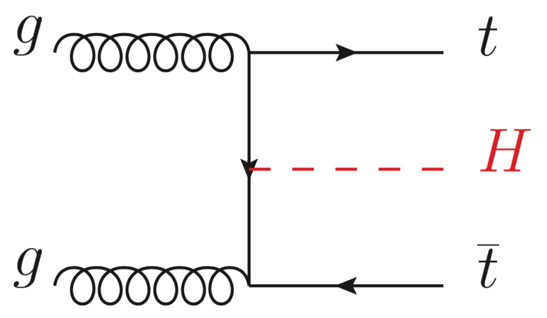
Then parametrise the production and decays at tree level



$\propto \kappa_V^2$

$\propto 3.3 \times \kappa_W^2 - 5.1 \kappa_W \kappa_t + 2.8 \kappa_t^2$

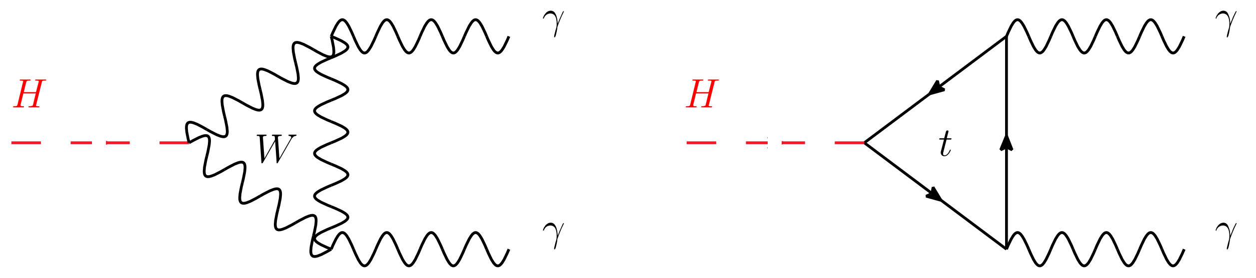




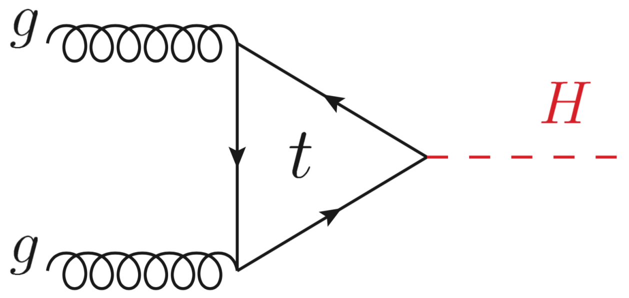
$\propto \kappa_t^2$

… and in loops (as a function of the know SM field content)

$\propto 1.6 \times \kappa_W^2 - 0.7 \kappa_W \kappa_t + 0.1 \kappa_t^2$



$\propto 1.06 \times \kappa_t^2 - 0.07 \kappa_t \kappa_b + 0.01 \kappa_b^2$



The Couplings Fit

In order to measure the coupling modifiers (kappas) the signal strengths are re-parametrised as follows:

$$\mu_i = \frac{\sigma_i}{\sigma_i^{SM}} \qquad \mu_f = \frac{\Gamma_f}{\Gamma_H} \quad \text{where} \quad \Gamma_H = \sum_f \Gamma_f \qquad \mu_f = \frac{\kappa_f^2}{\kappa_H^2}$$

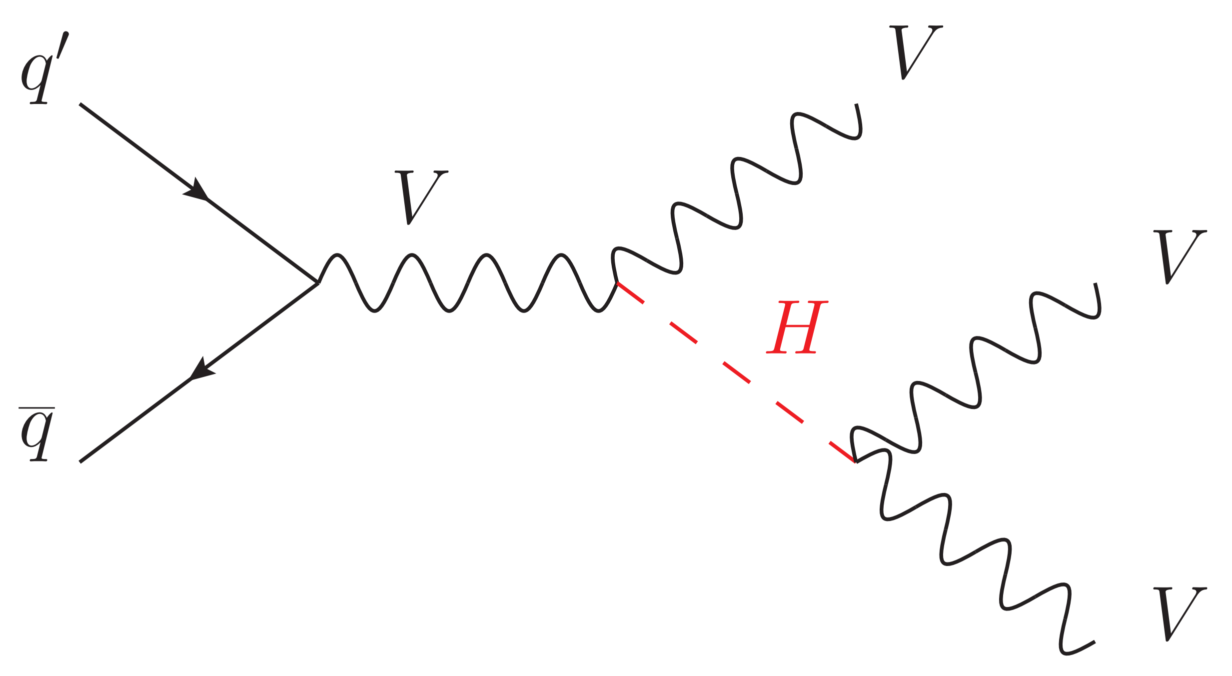
Then introducing: $\kappa_H^2 = \frac{\sum_f \Gamma_f}{\Gamma_H^{SM}}$

$$\begin{aligned}\kappa_H^2 \quad \sim \quad & 0.57\kappa_b^2 + 0.22\kappa_W^2 + 0.09\kappa_g^2 \\ & +0.06\kappa_\tau^2 + 0.03\kappa_Z^2 + 0.03\kappa_c^2 \\ & +0.0023\kappa_\gamma^2 + 0.0016\kappa_{Z\gamma}^2 + 0.00022\kappa_\mu^2\end{aligned}$$

Fits can then be done under different assumptions:

- No new physics in the loops (resolved loops with SM field content)
- No new physics in the Higgs decay (resolved Higgs width with SM field content)
- Re-parametrise the signal strengths in terms of ratios of coupling modifiers (lambdas)
- Assume different couplings to vary in same way (e.g. Vector bosons and Fermions)

$$\lambda_{kl} = \frac{\kappa_k}{\kappa_l}$$

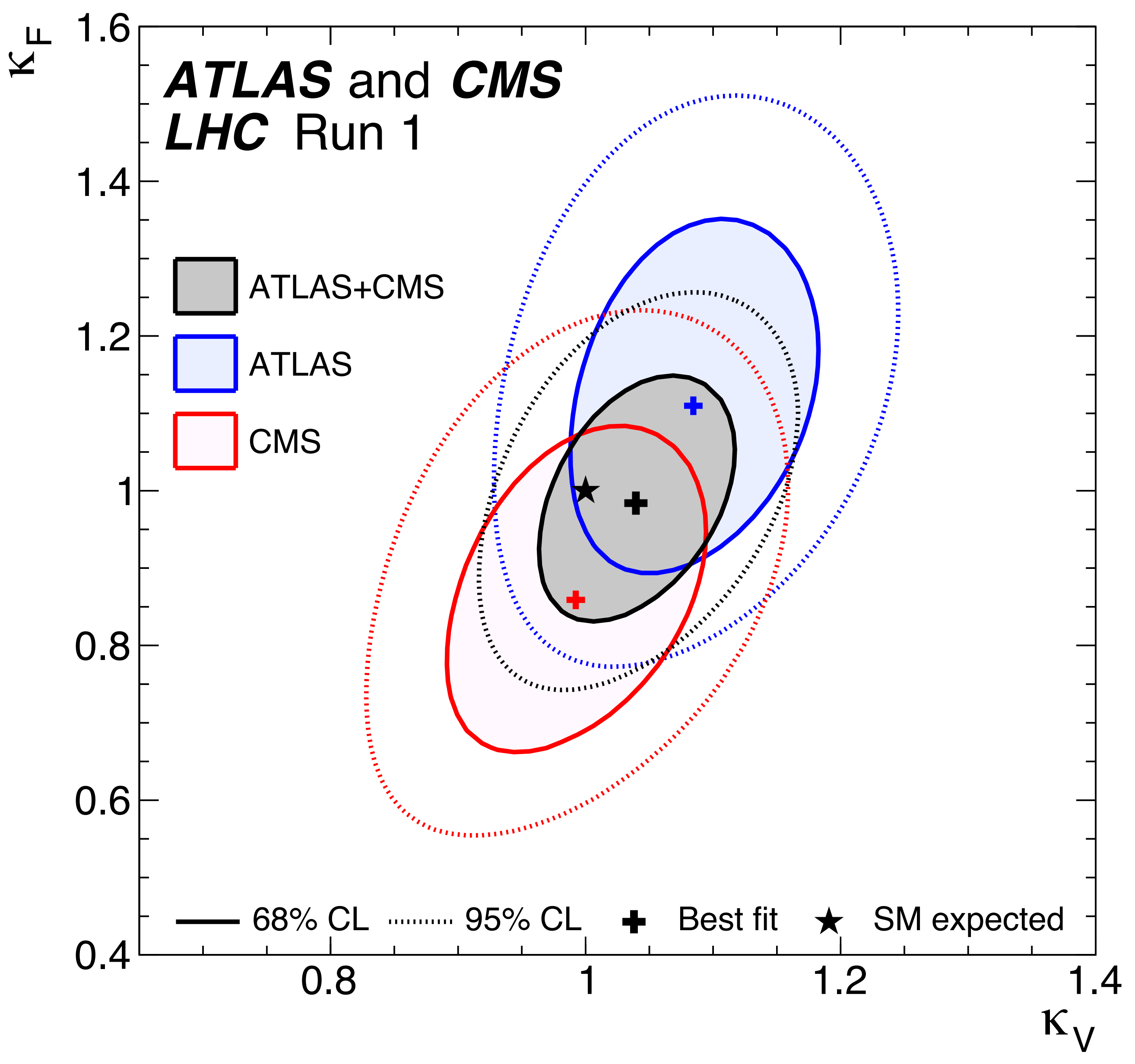


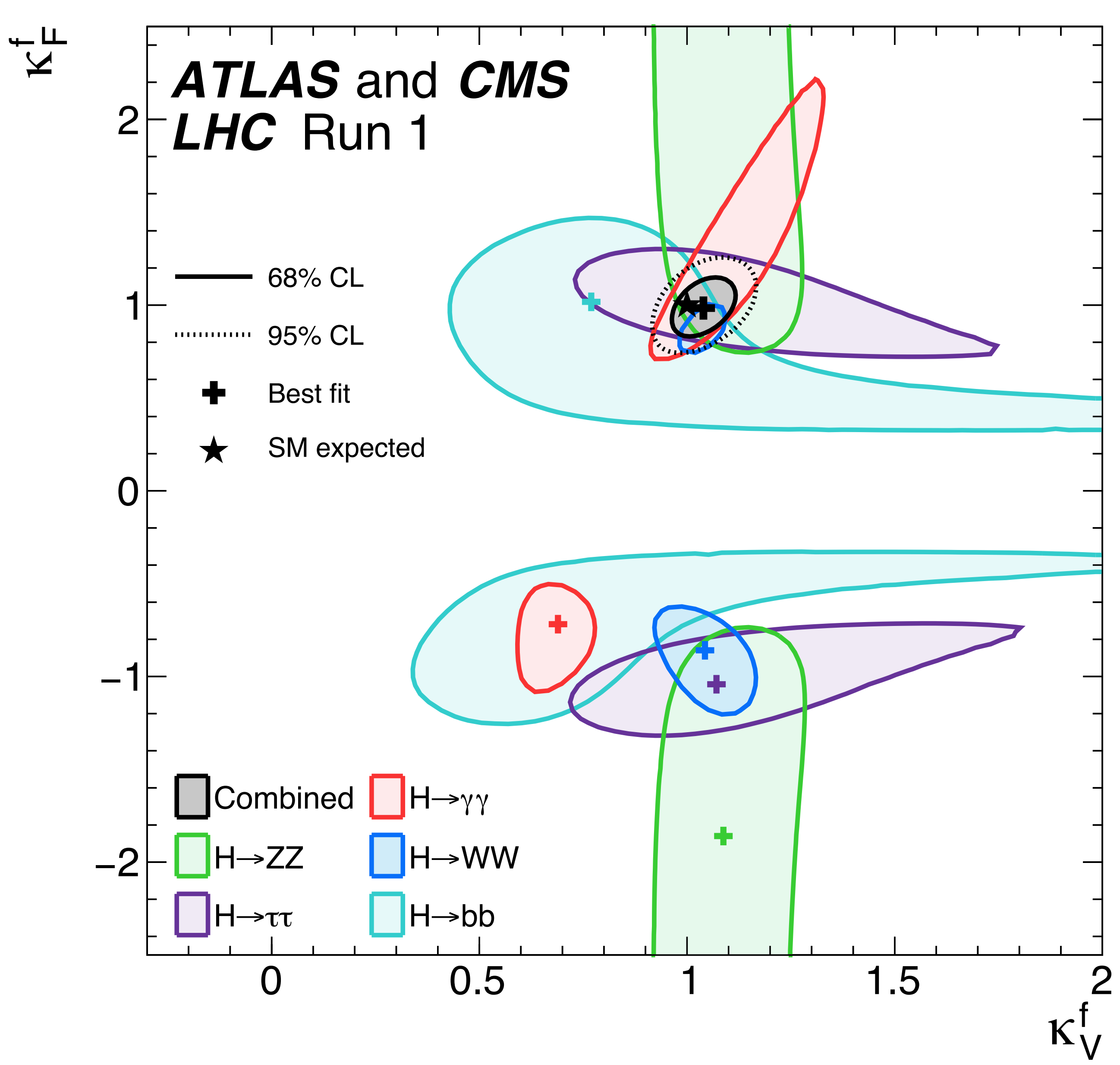
$$\mu_i = \kappa_V^2$$

$$\mu_f = \frac{\kappa_V^2}{0.75\kappa_F^2 + 0.25\kappa_V^2}$$

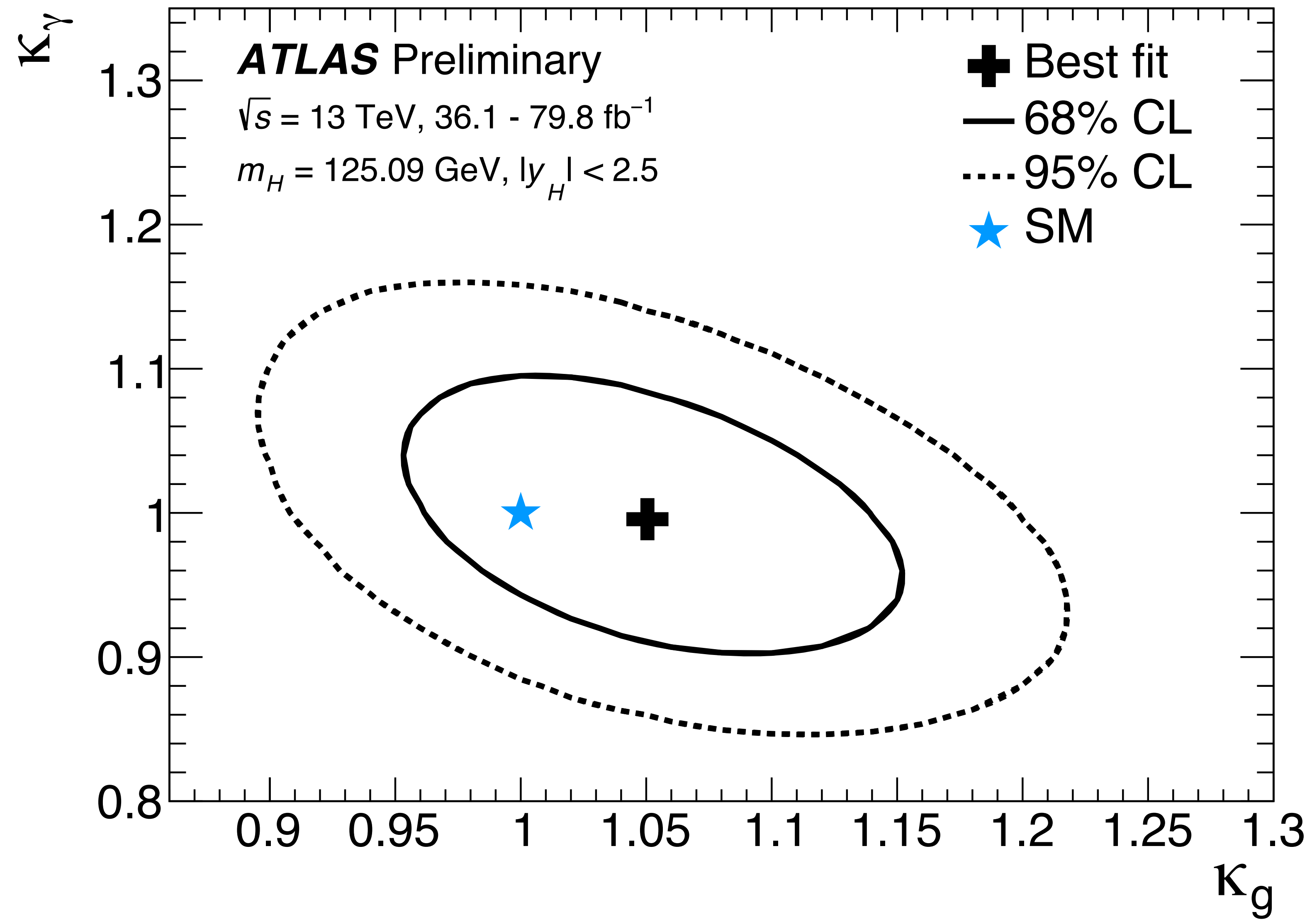
Beyond Run 1 Higgs Couplings Measurements

Fit assuming one coupling modifier for all fermions and one coupling modifier for all fermions with **resolved loops** and **no new particles in the decay**





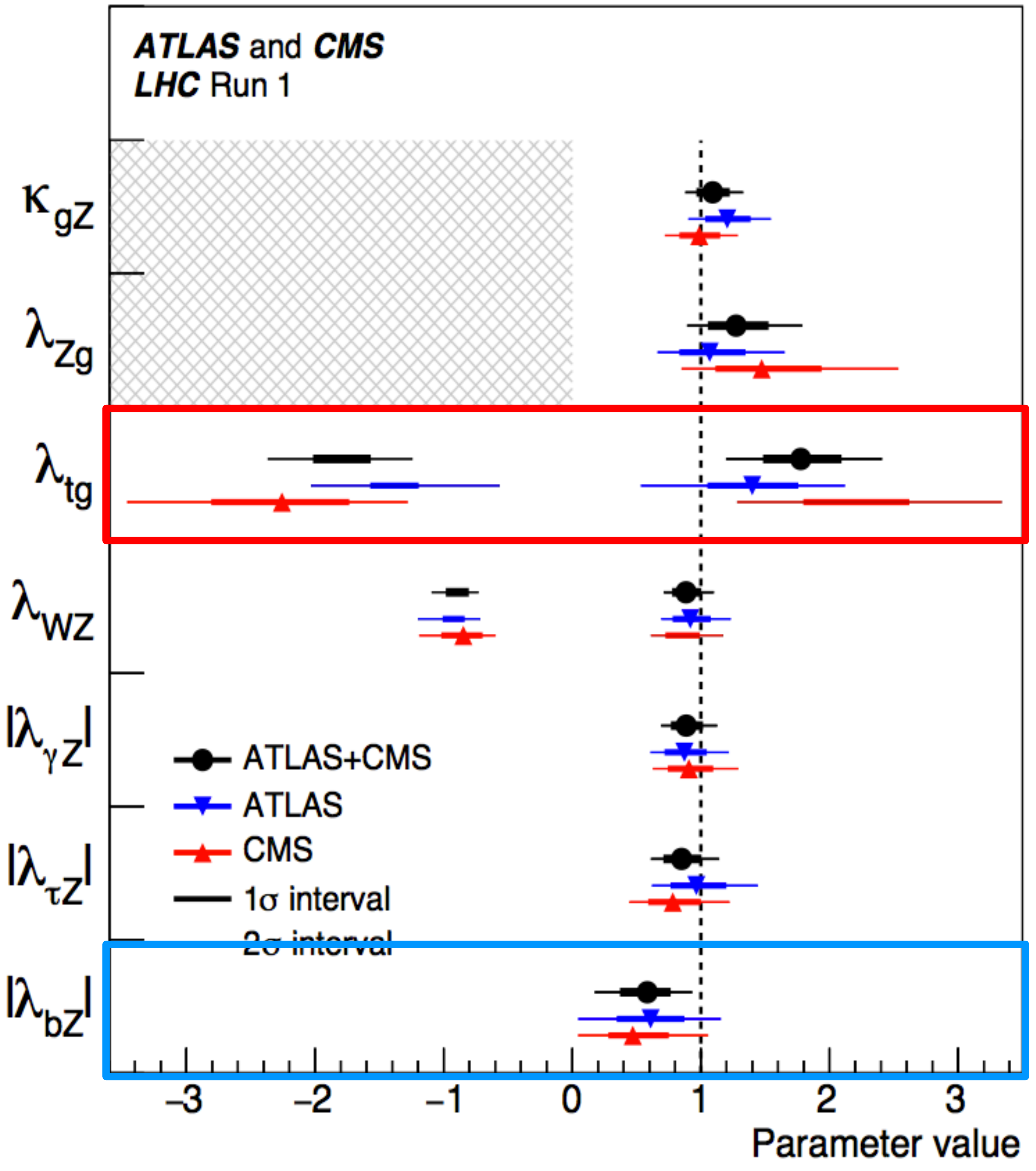
Fit assuming that the Higgs couples **to all SM according to the SM**, but **no assumptions made on the loops nor on the decay**

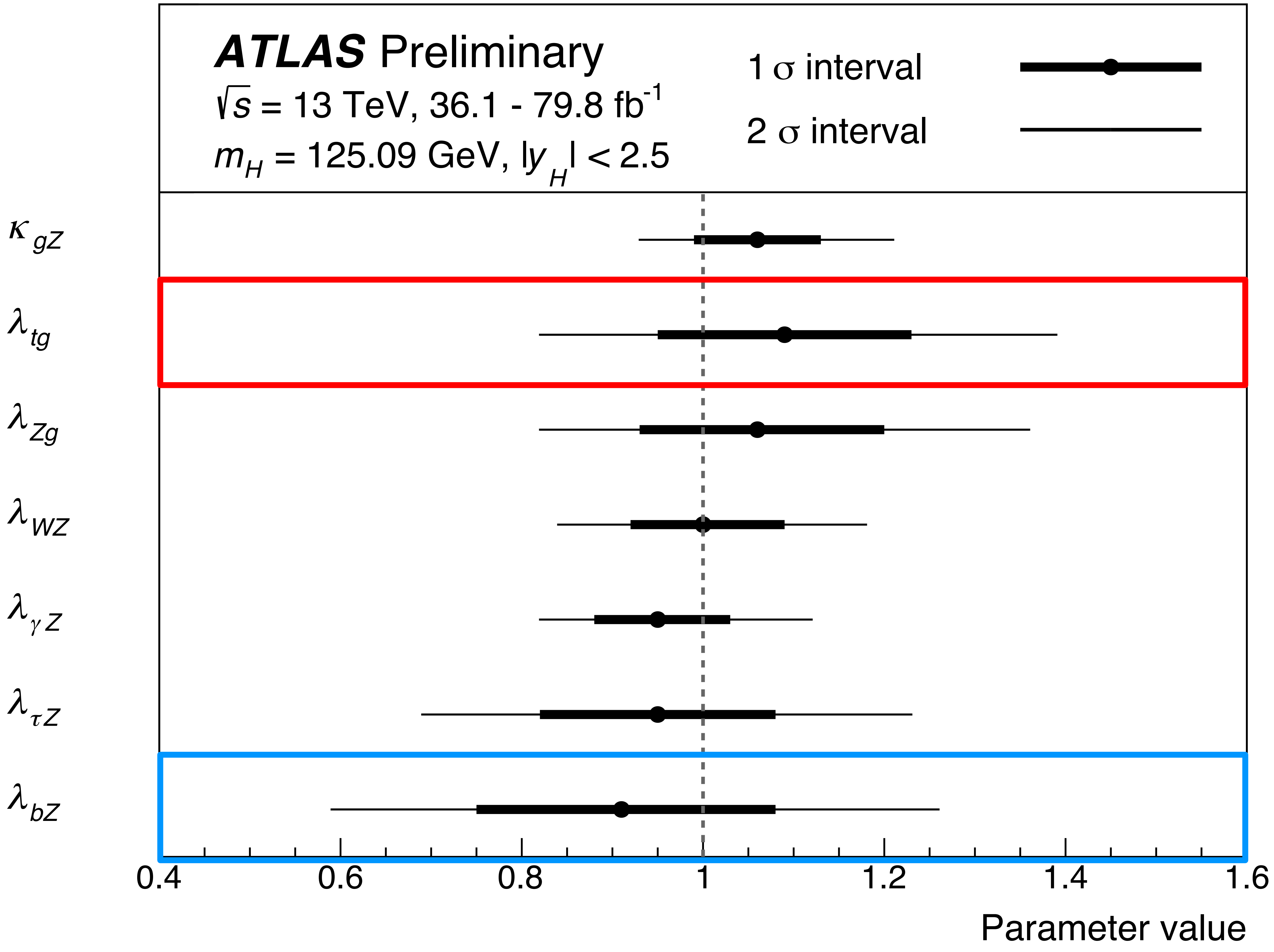


$$B_{BSM} < 0.13 \text{ at } 95\% \text{ CL}$$

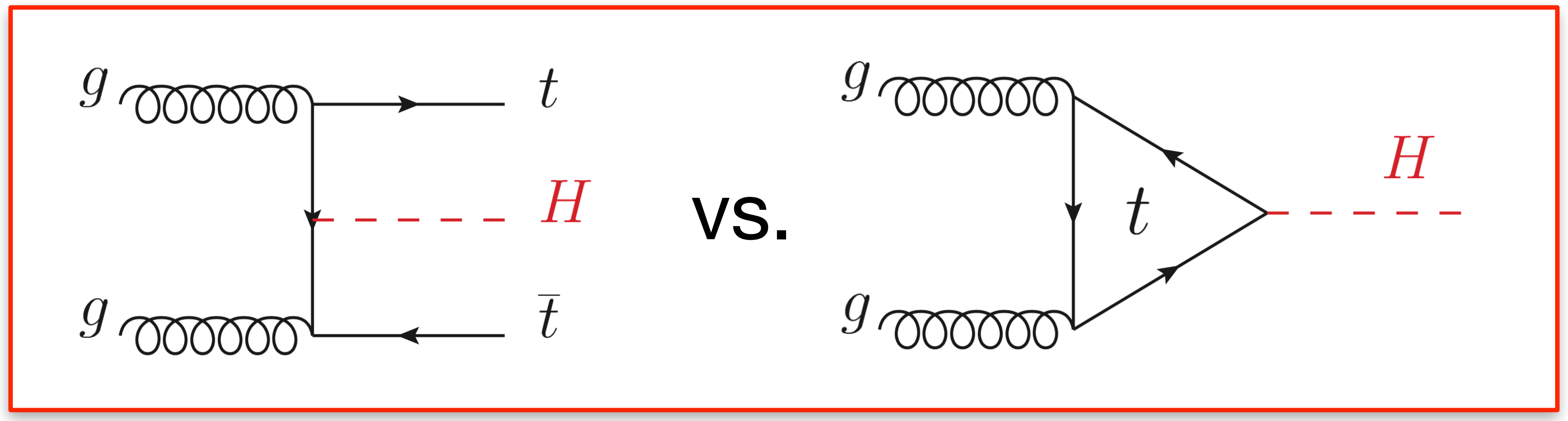
Run 1 versus (partial) Run 2

$\Delta\kappa/\kappa$ ~ 11%
$\Delta\lambda/\lambda$ ~ 23%
$\Delta\lambda/\lambda$ ~ 30%
$\Delta\lambda/\lambda$ ~ 11%
$\Delta\lambda/\lambda$ ~ 12%
$\Delta\lambda/\lambda$ ~ 16%
$\Delta\lambda/\lambda$ ~ 34%

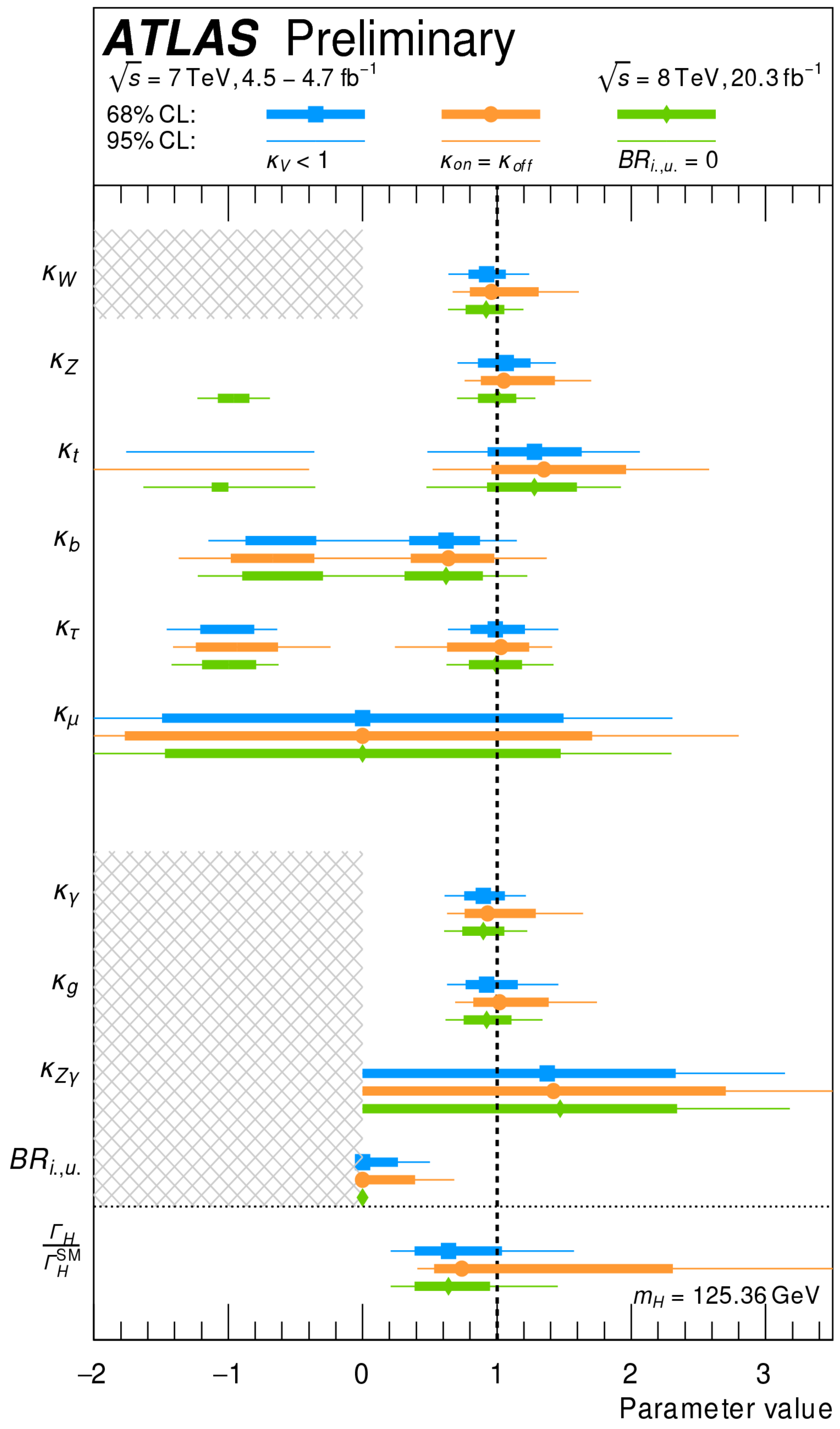




$\Delta\kappa/\kappa$ ~ 7%
$\Delta\lambda/\lambda$ ~ 15%
$\Delta\lambda/\lambda$ ~ 15%
$\Delta\lambda/\lambda$ ~ 9%
$\Delta\lambda/\lambda$ ~ 8%
$\Delta\lambda/\lambda$ ~ 13%
$\Delta\lambda/\lambda$ ~ 18%



Absolute Measurement of Couplings?



Absolute couplings measurements under specific conditions:

- **Green**: Constrain the width to SM field content only.
- **Blue**: Unitarity inspired constraint $k_V < 1$
- **Orange**: Use Run 1 constraints from Off-Shell coupling

$$\Gamma_{tot} < 22.7\ \mathrm{MeV}$$

Limit using three channels ZZ(4l and llvv) and WW(lvlv).

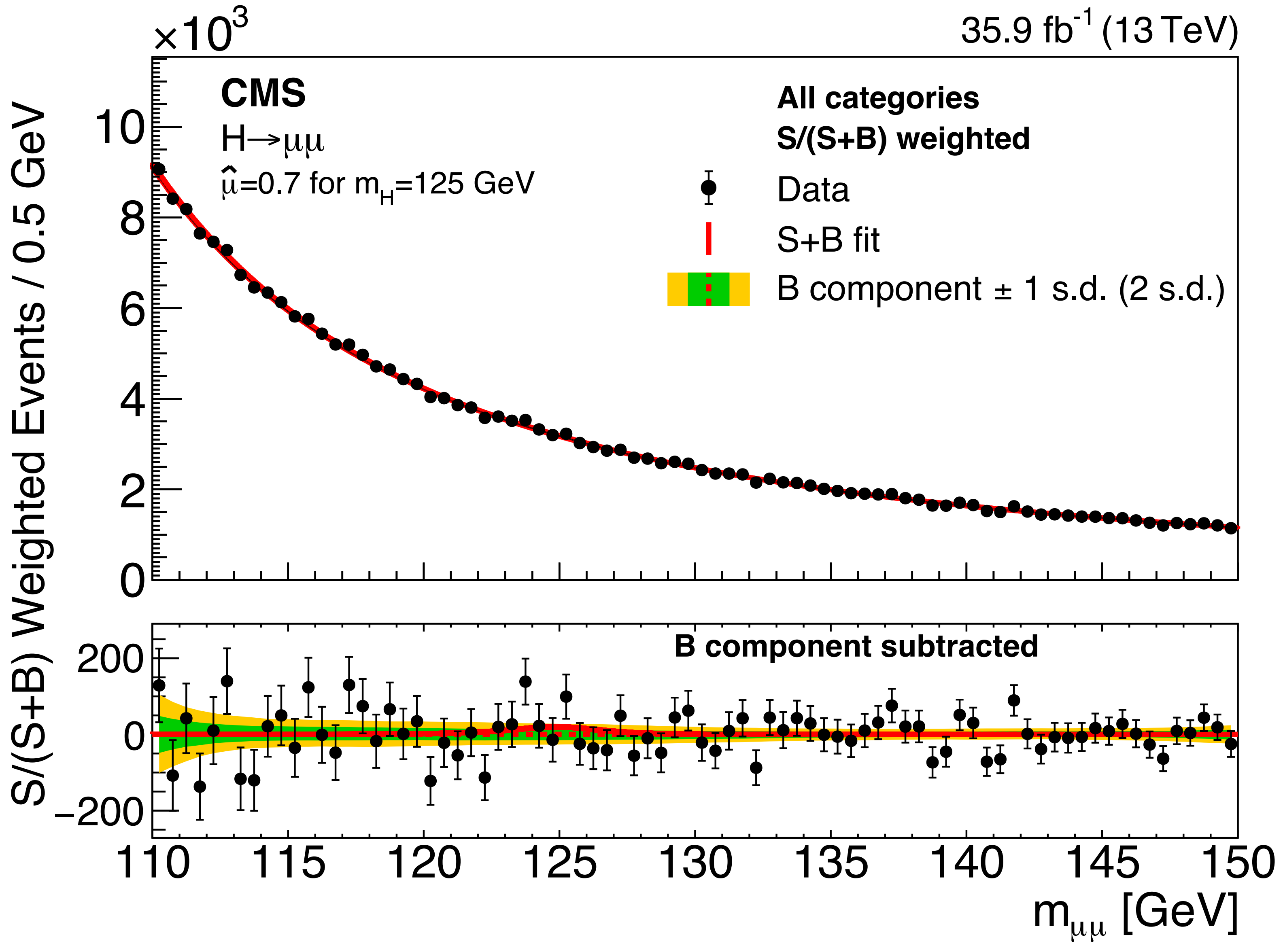
Rare Decays and Production Modes

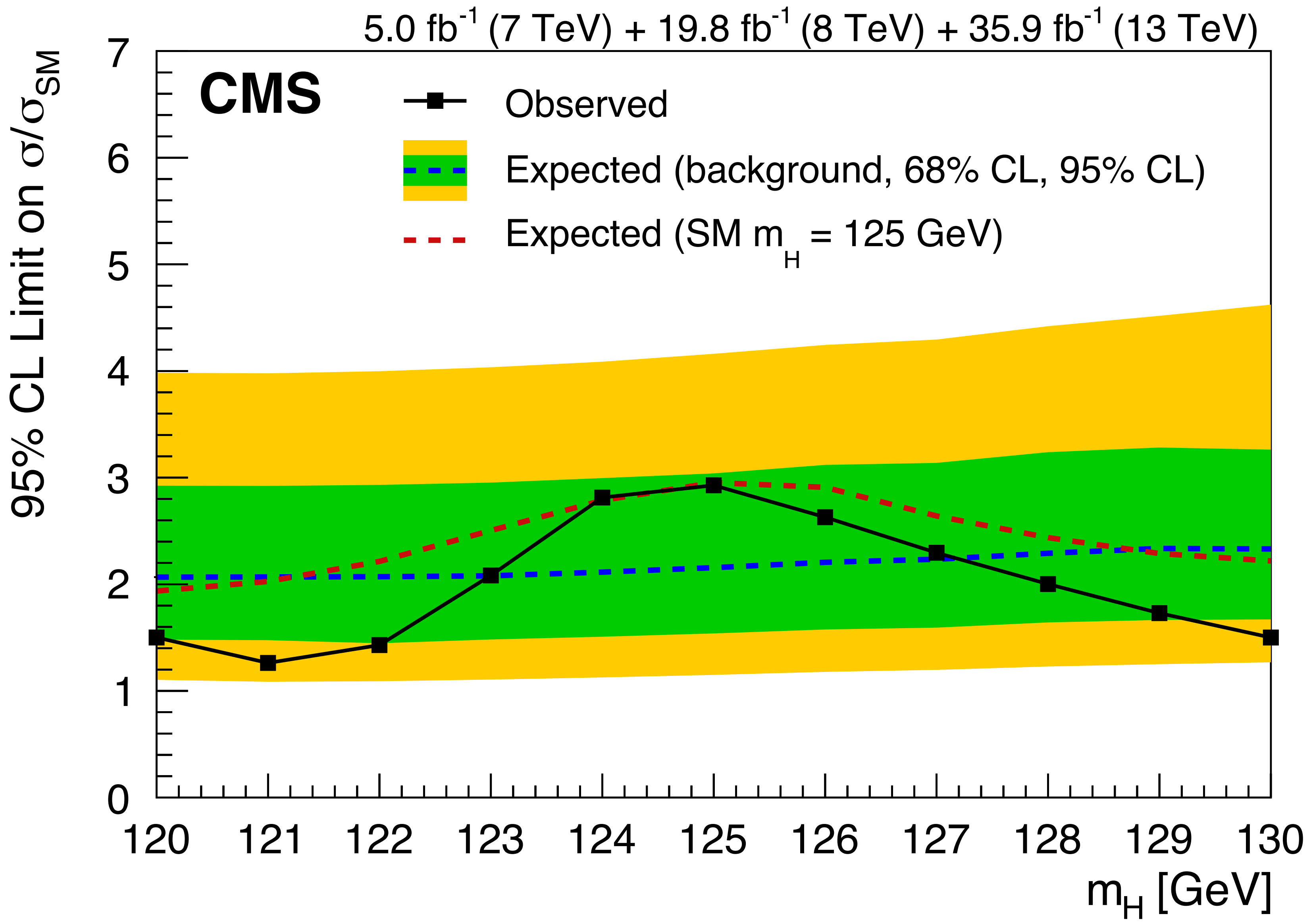
Measuring 2d Generation Yukawa Couplings

The Next Challenge for Run 3

Analysis strategy: Very low s/b, search for peak in $m_{\mu\mu}$ spectrum over smooth background (categorize events according to a BDT which also separates ggF, VBF and VH signatures). Very low s/b require excellent background description.

Excellent data/MC agreement, but s/b very low, background systematic uncertainties are a delicate point.





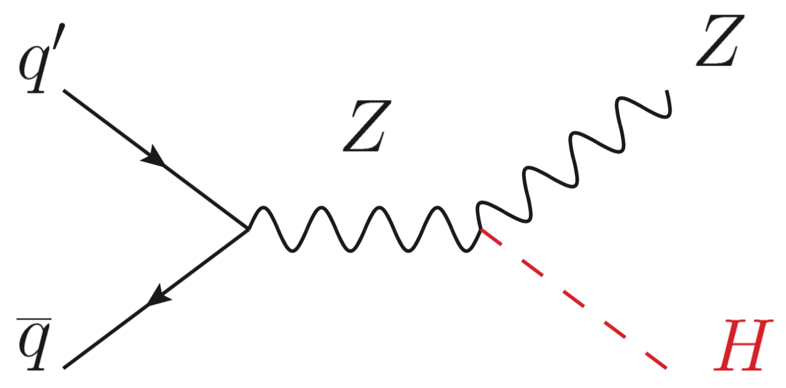
Limits at

$$\mu < 2.92\ (2.16\ \text{exp.})\ \text{at}\ 95\%\ \text{CL}$$

slight non significant excess (within 1 standard deviation at around 125 GeV.

Measuring 2d Generation Yukawa Couplings

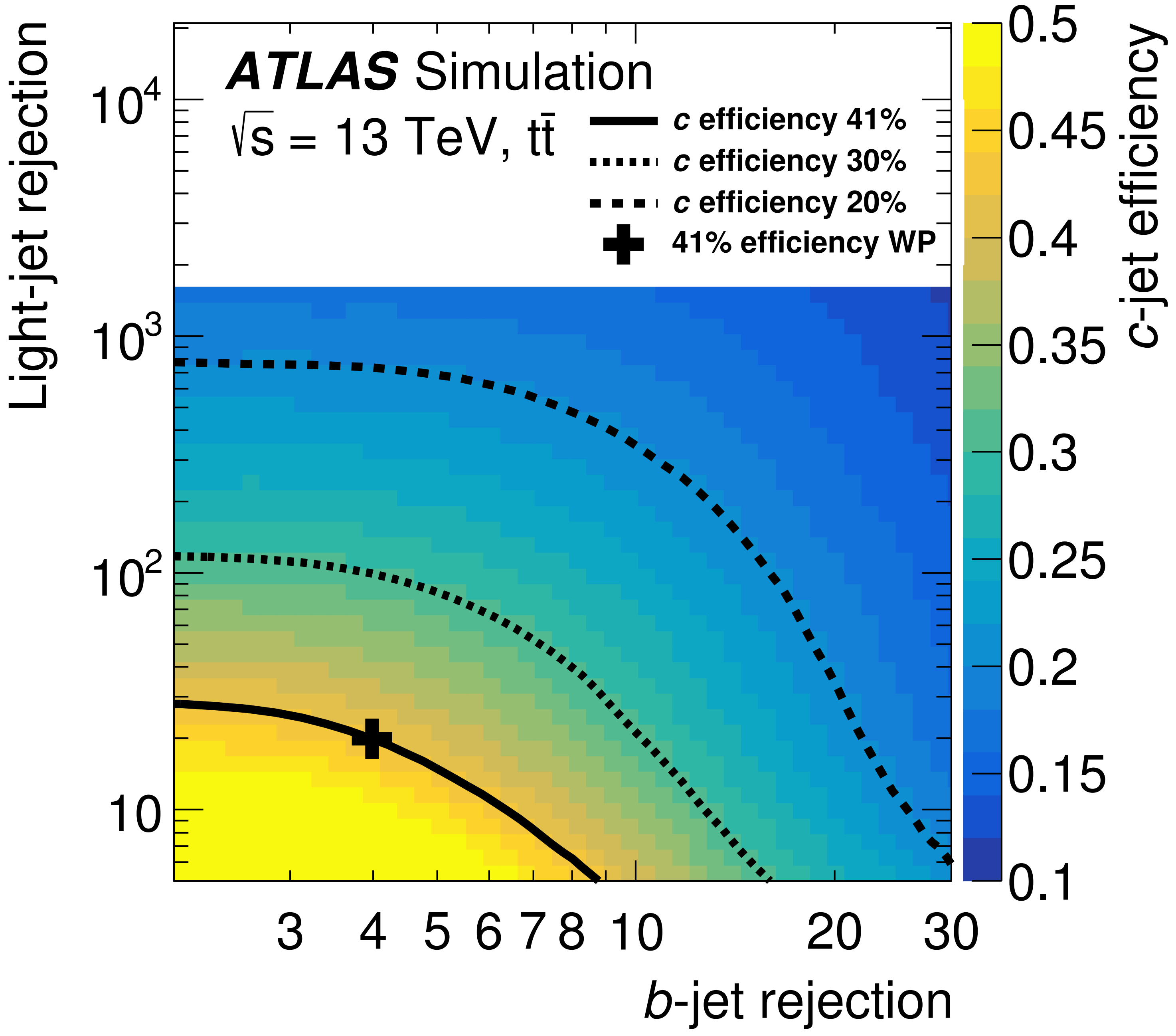
More challenging channel Charm-Yukawa (inclusive)

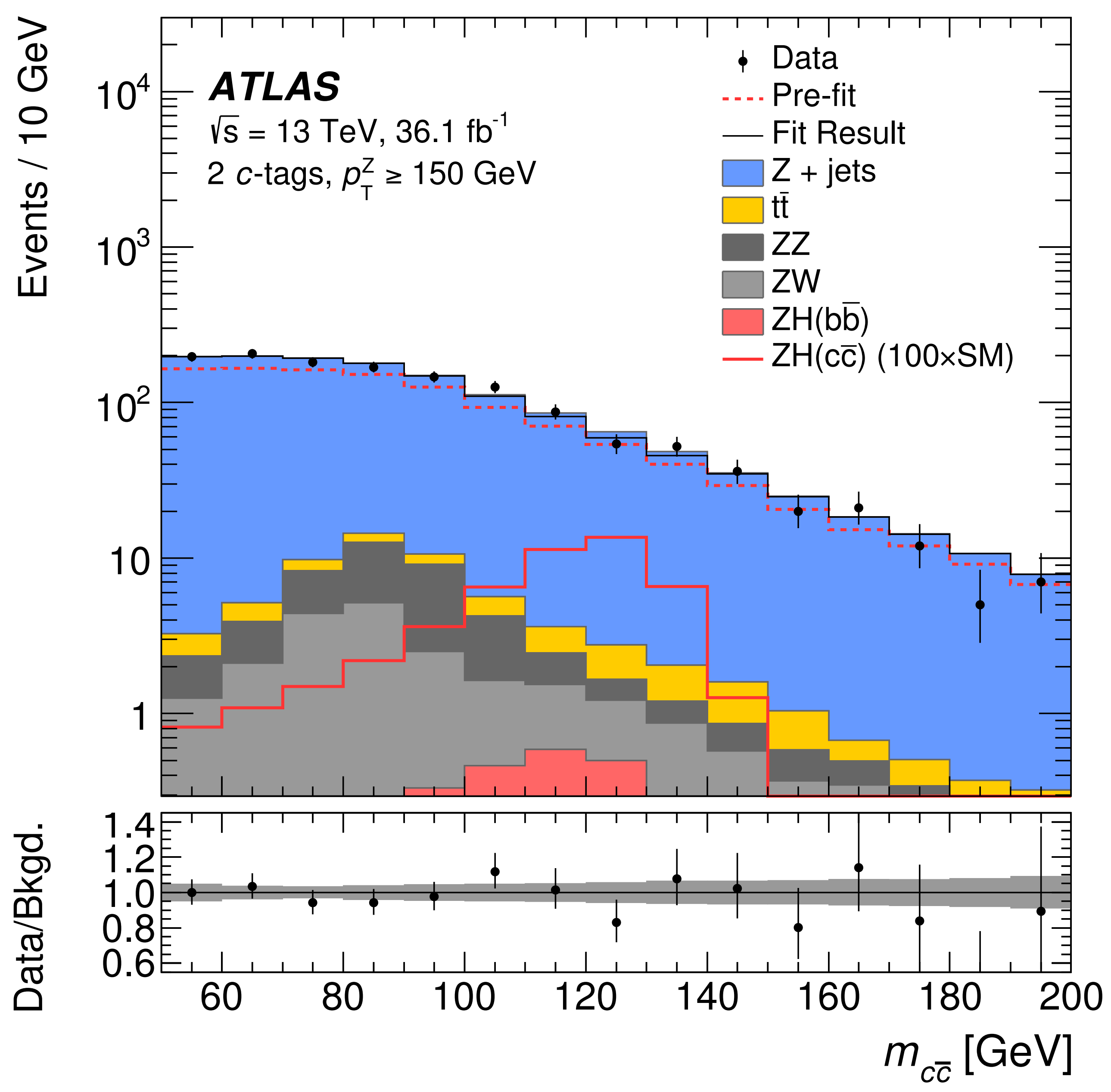


ZH(cc) search in ATLAS: Using charm tagging (essentially same algorithm as b-tagging but trained to tag charm specifically.

Analysis strategy: Same as the VH(bb) analysis going towards high pT with the cleaner Z channel only with subsequent decay of the Z to two leptons.

Still very limited sensitivity, more methods will be needed!

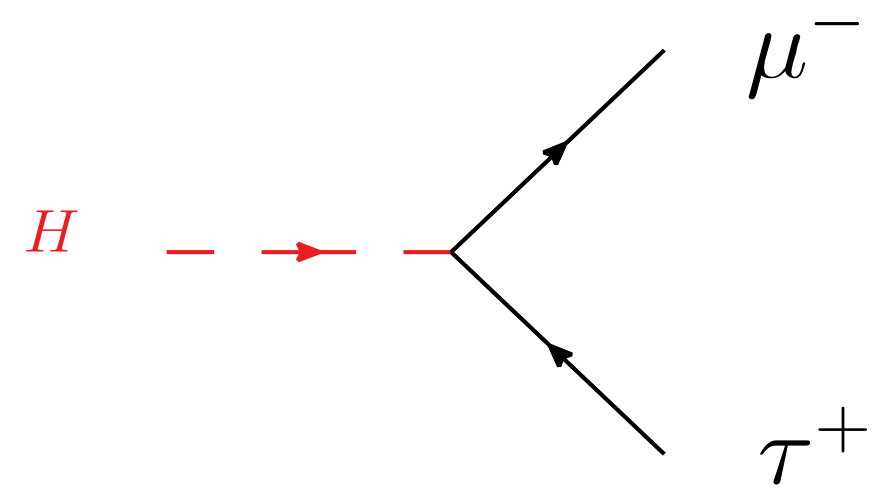




Limits at

$$\mu <\sim 100\ (150\ \text{exp.})\ \text{at}\ 95\%\ \text{CL}$$

LFV Decays of the Higgs boson

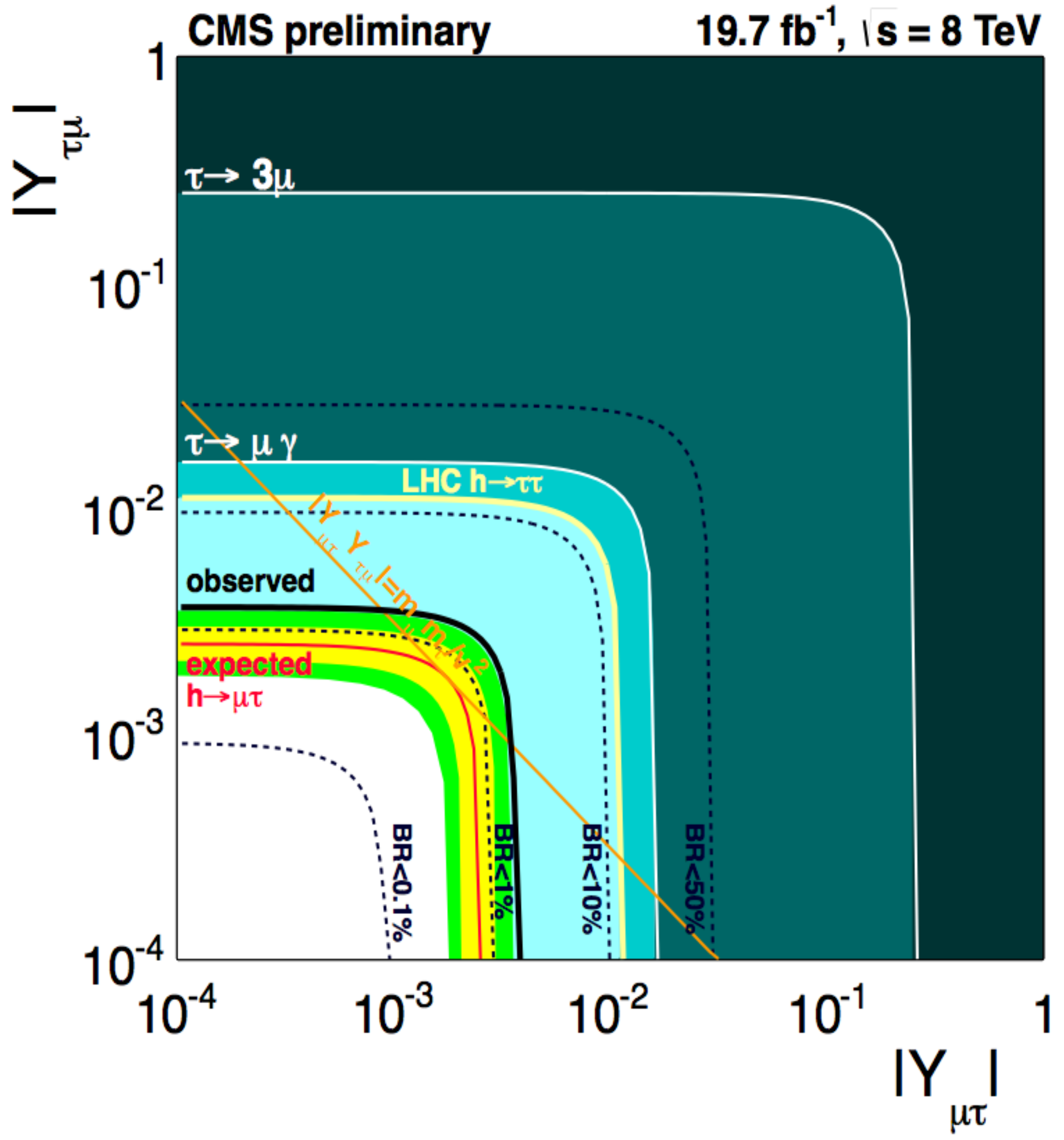


Strong Constraints on $Br(H \to e\mu) < O(10^{-8})$

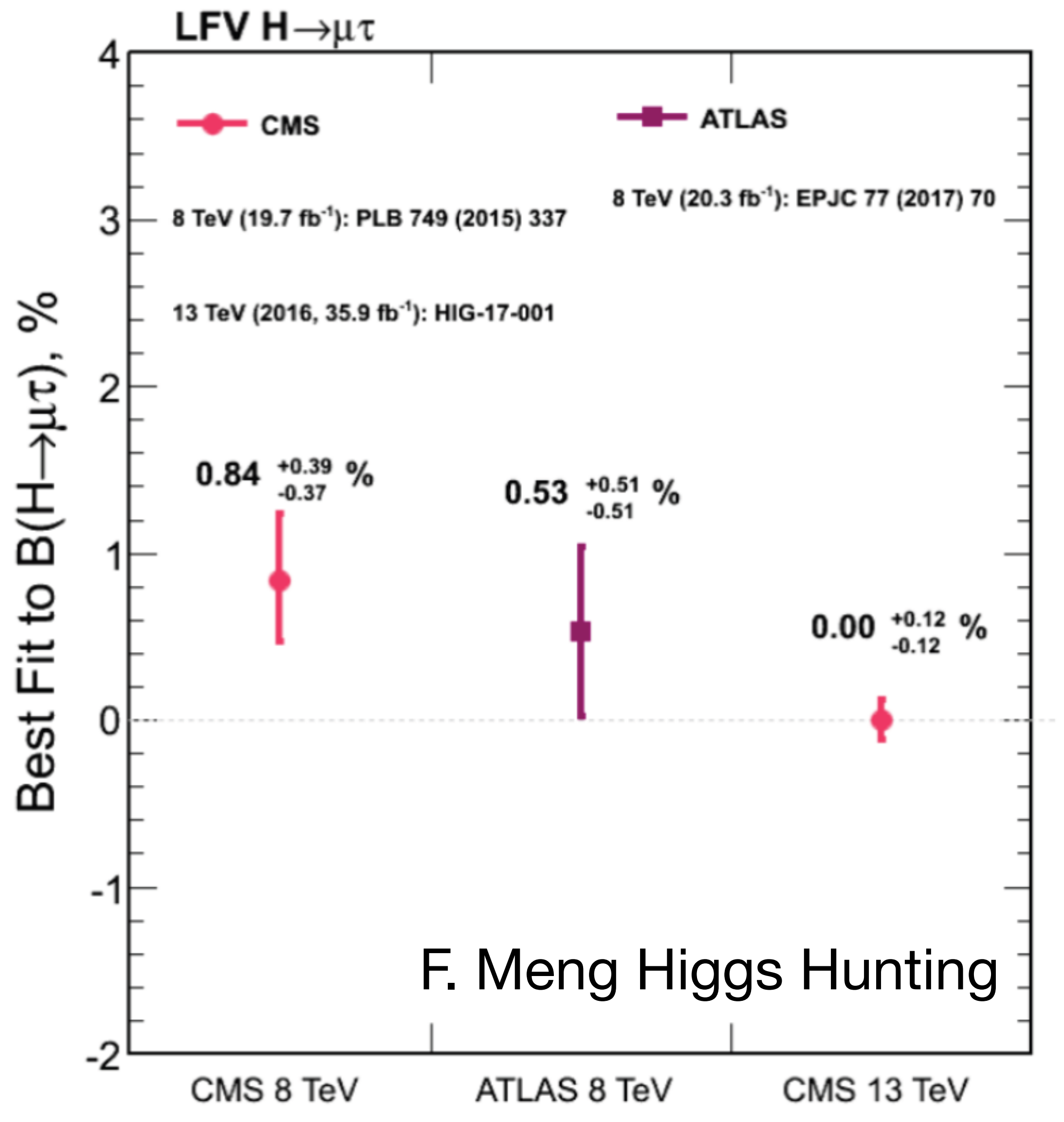
From $\mu \to e\gamma$

τμ channel studied at Run 1, with analyses in both the hadronic and leptonic decay channels of the tau both in ATLAS and CMS.

τμ channel studied at Run 1, with analyses in both the hadronic and leptonic decay channels of the tau both in ATLAS and CMS.



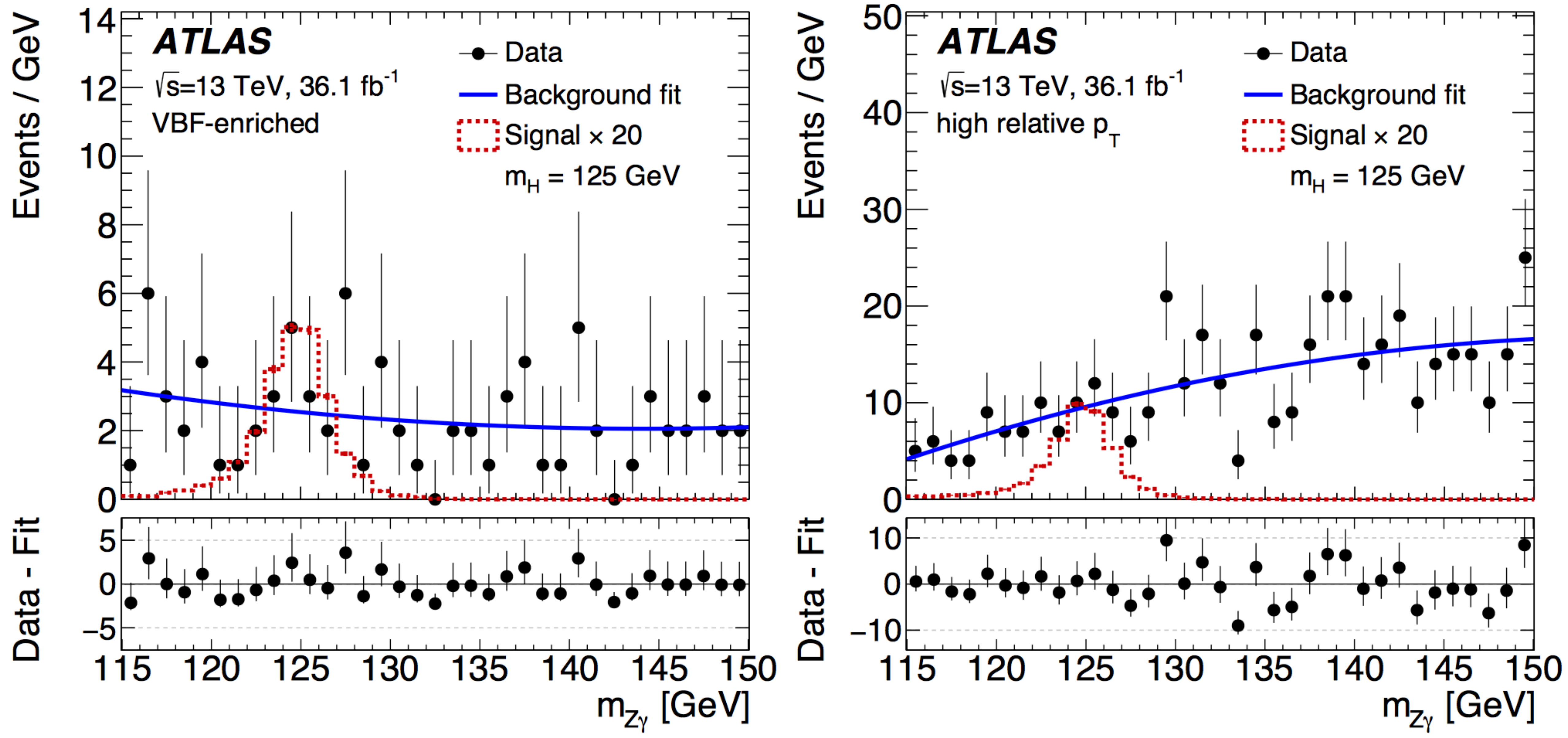
- Modest excess observed (more significant in CMS) at Run 1.
- Early Run 2 analysis performed by CMS in 2015 data no excess observed.



$Z\gamma$ Channel

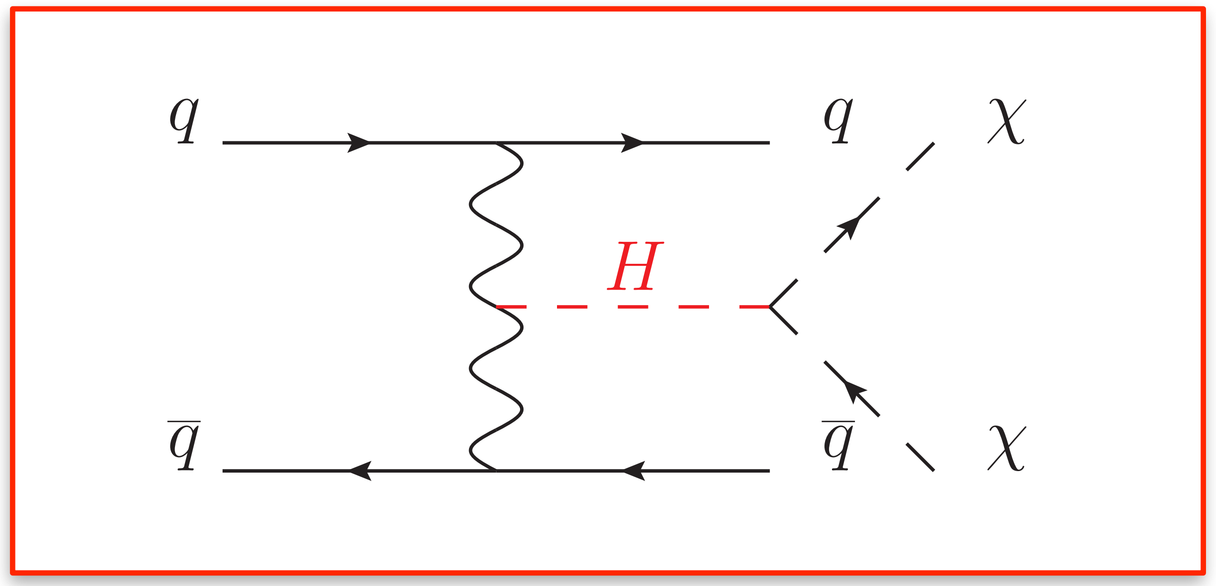
Not so small branching fraction of 1.5 10-3 however search for leptonic decays of the Z boson.

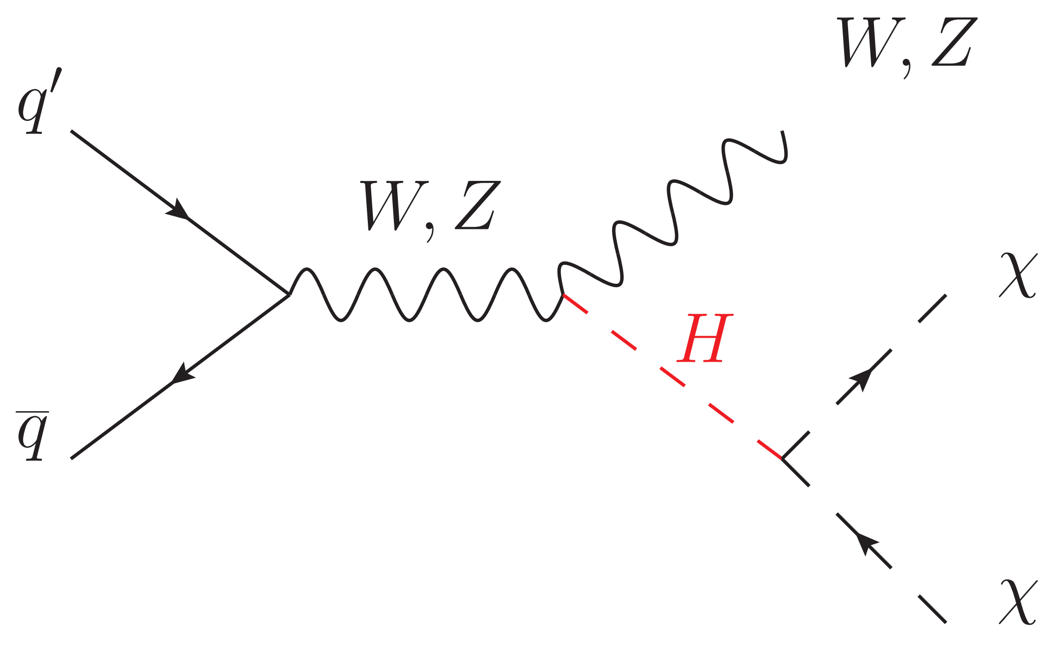
Analysis strategy: Categorised in main production modes gluon fusion (at high pT) and VBF (with the typical VBF topology). Improved mass reconstruction with FS correction for muons.

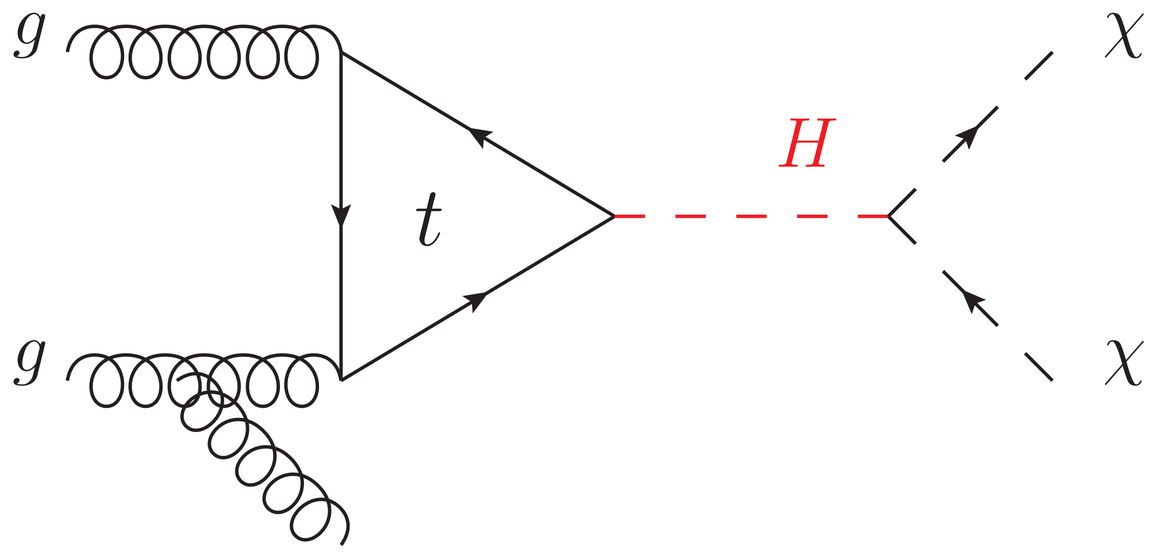


95% CL limits at **6.6** (obs) and **5.2** (exp), no significant signal observed.

Invisible decays of the Higgs boson

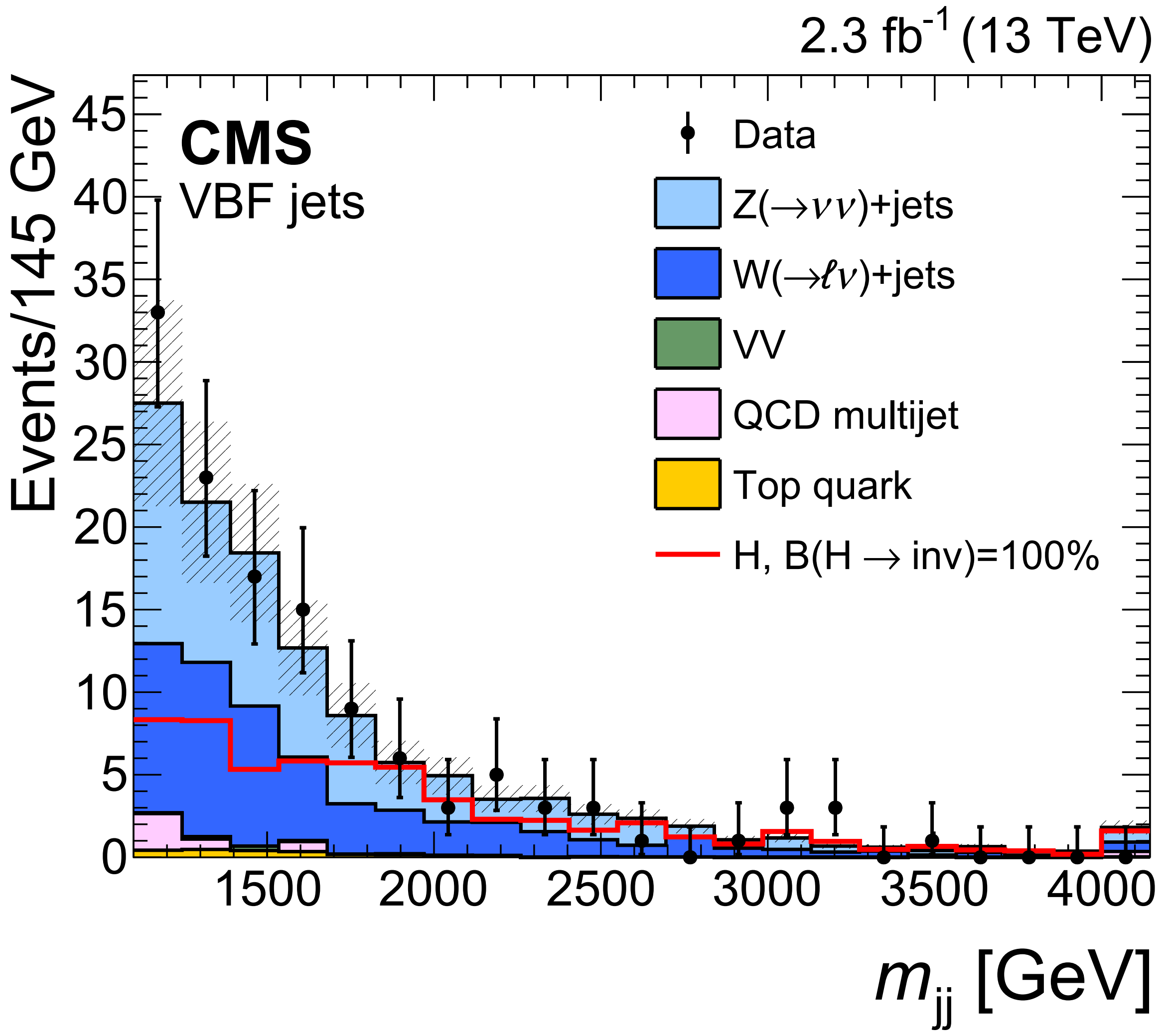


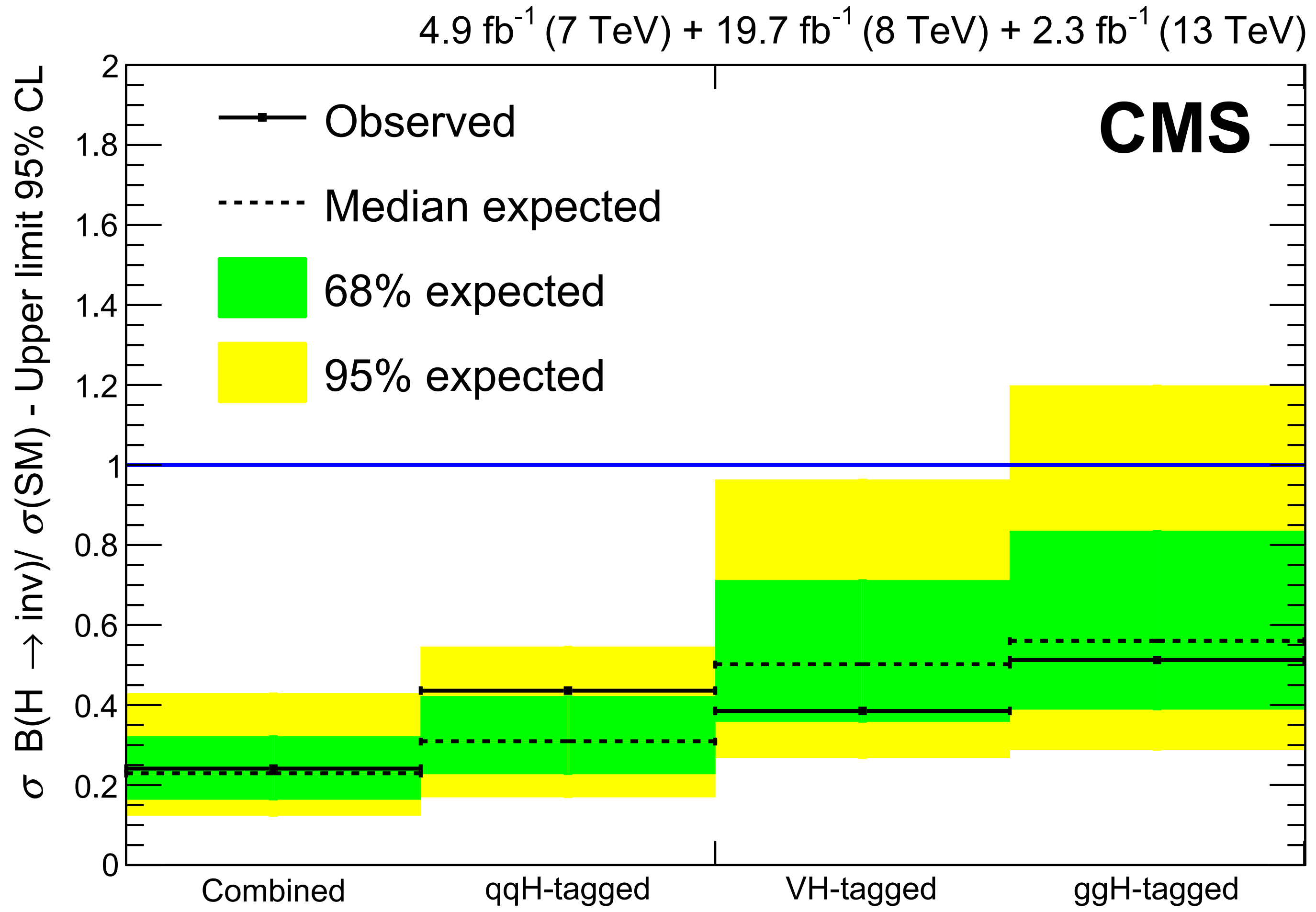




Comprehensive analysis of several channels and several datasets by CMS, to give current level of sensitivity on invisible branching fraction.

- Includes a mono-V hadronic boosted mode
- VBF is the most sensitive channel
- Challenge is the estimate of the V-jets backgrounds: estimated from control regions using W, Z and photon-jet events.



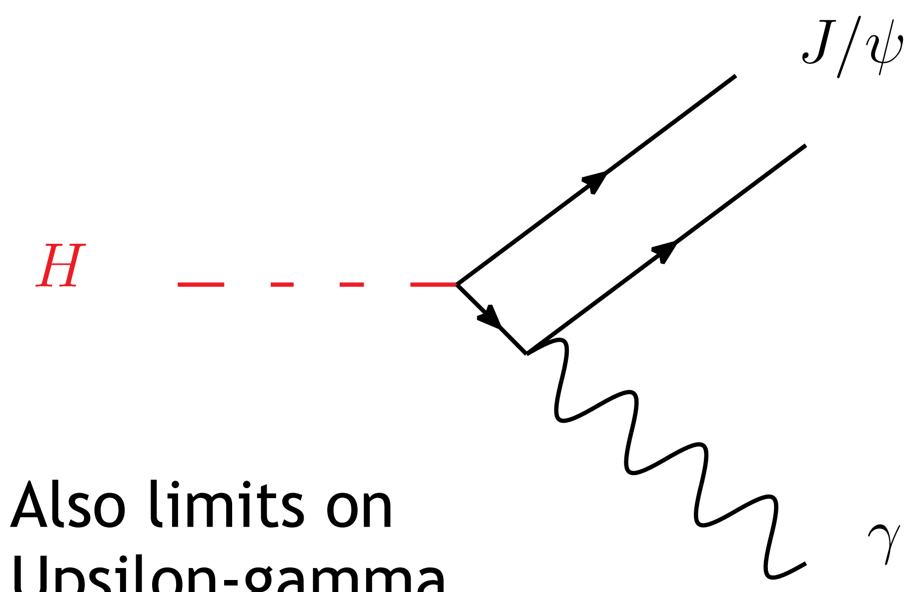


These results are still with a very small run 2 dataset!

$$Br_{inv} < 0.24\ (0.23)$$

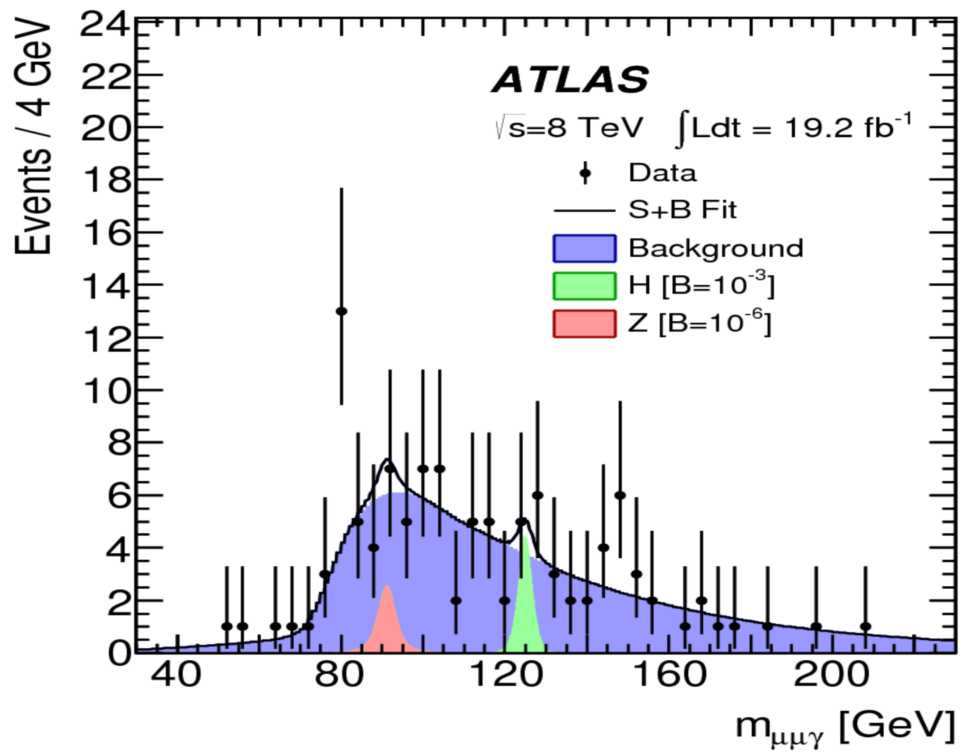
ATLAS has performed the ZH (Z dilepton) analysis with 36 fb-1, substantially less sensitive (limit at 67%)

Decays with to Quarkonia and a photon



Potentially sensitive to charm Yukawa

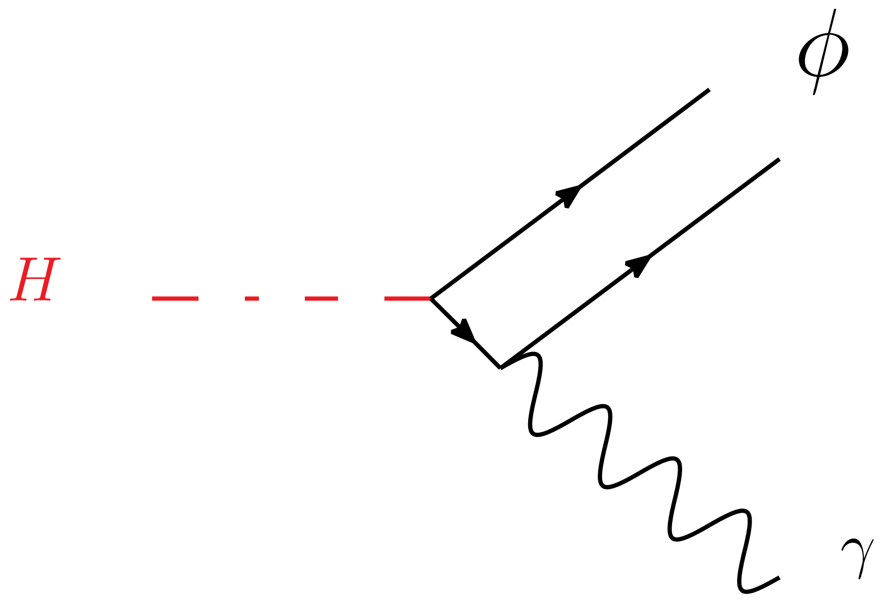
$$\mu^+\mu^-\gamma$$



Also limits on Upsilon-gamma

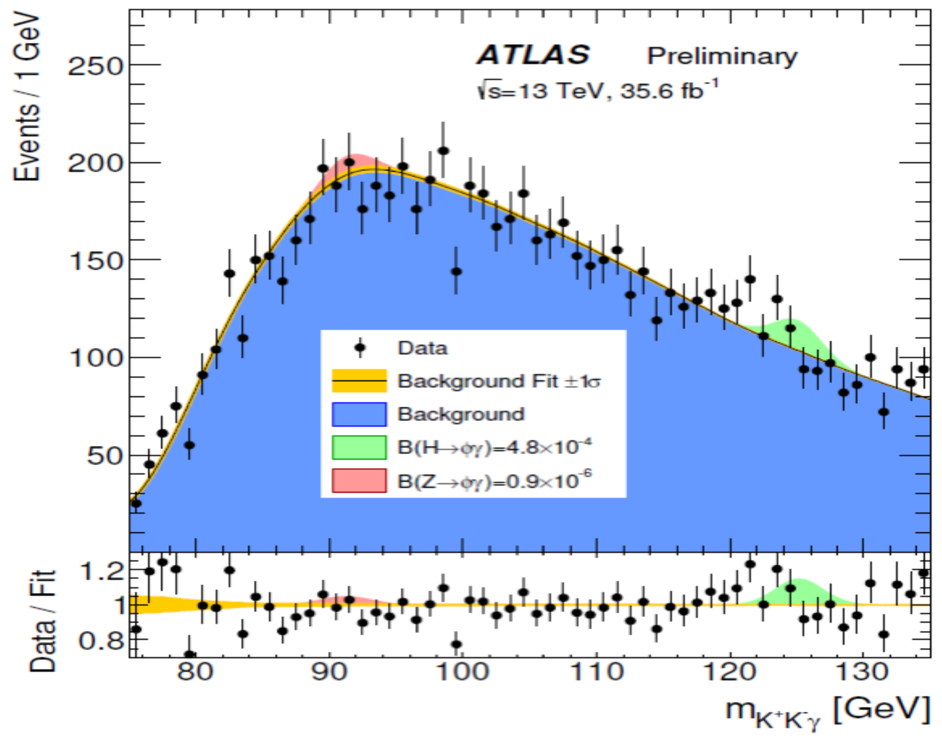
Current limits

~400 x SM

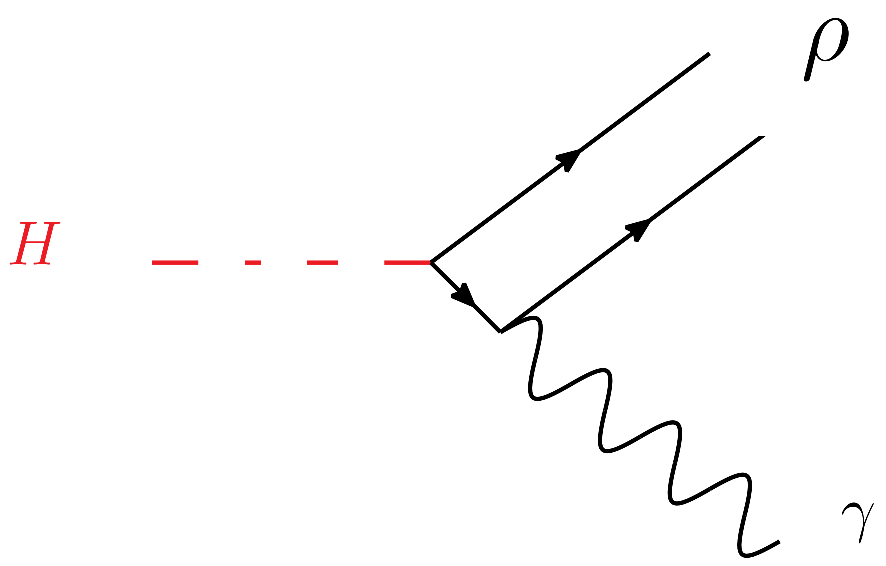


Potentially sensitive to strange Yukawa

$$K^+K^-\gamma$$

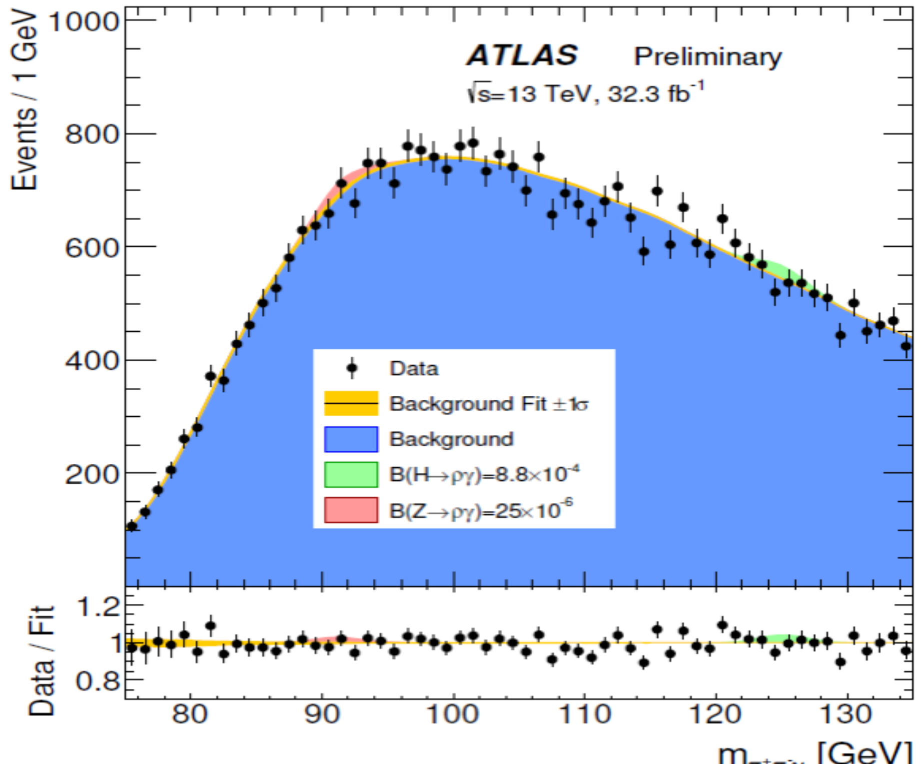


~200 x SM



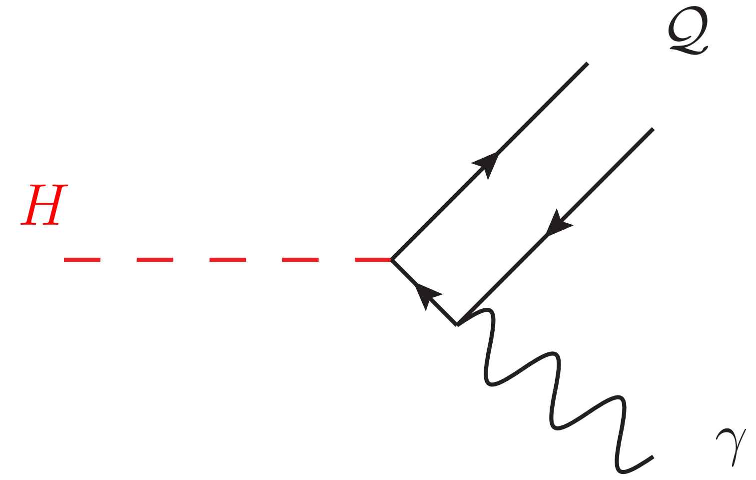
Potentially sensitive to light Yukawa

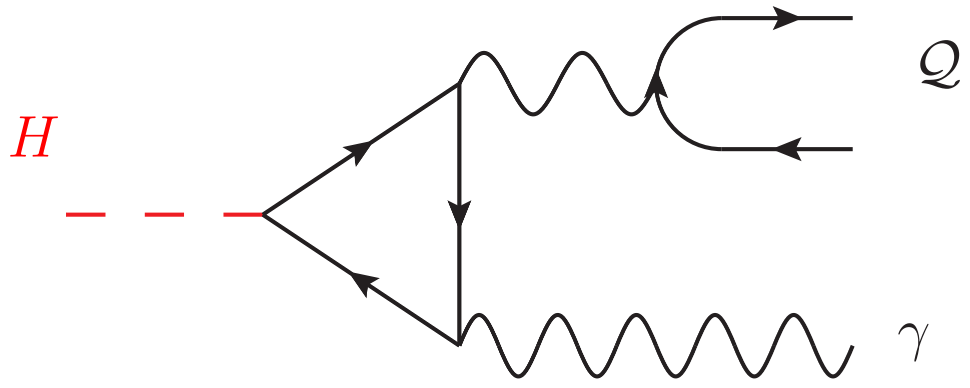
$$\pi^+\pi^-\gamma$$



~50 x SM

Measuring the Higgs decays to quarkonia and a photon do not give sole access to the Yukawa

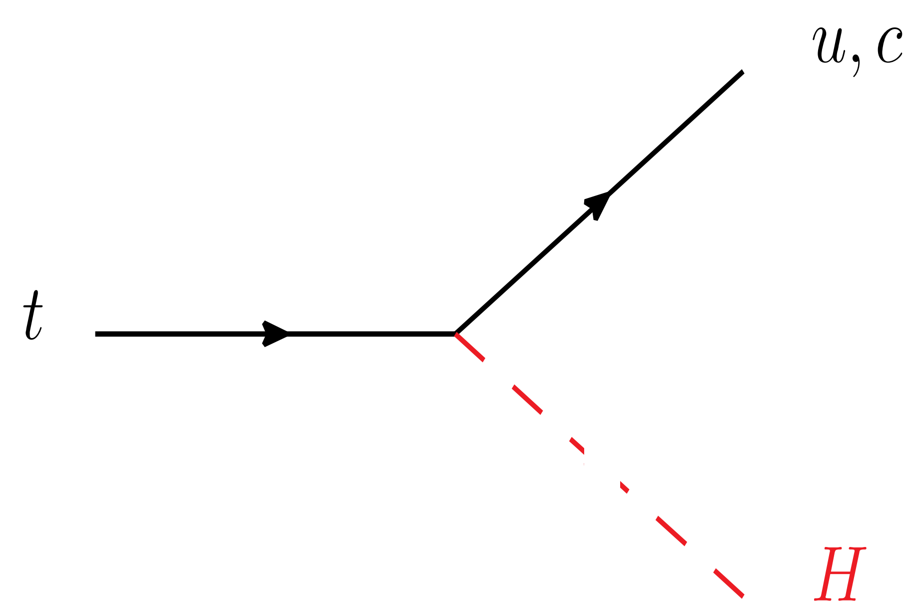




Di-Higgs and Higgs Self Coupling

Rare Production Modes

Flavor changing neutral current decays of the top quark



Various decay channels of the Higgs boson (yy, bb, WW)

$$B(t \to Hq)$$

SM Branching ~10^{-15}

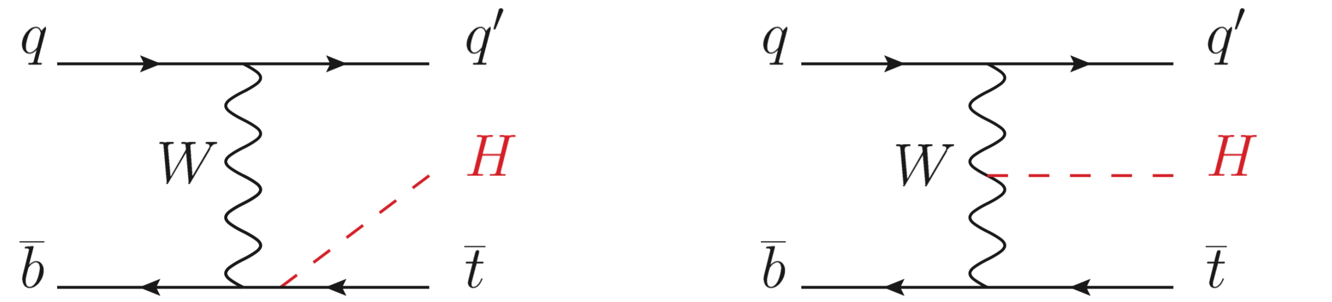
Limits on

$$B(t \to Hc) < 0.79\% \; (0.51\% \text{ exp.})$$

Single top associated production

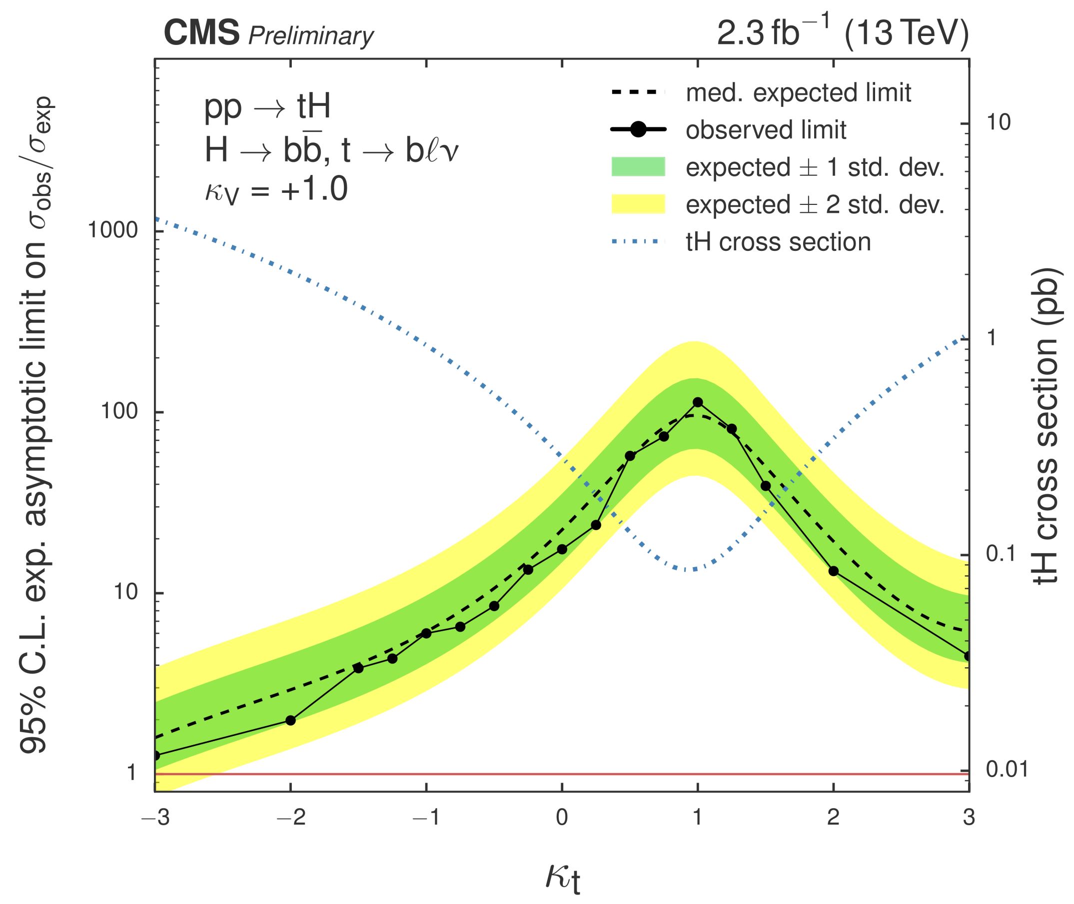
Tree level interference between W and top

$$\propto 3.3 \times \kappa_W^2 - 5.1\kappa_W\kappa_t + 2.8\kappa_t^2$$

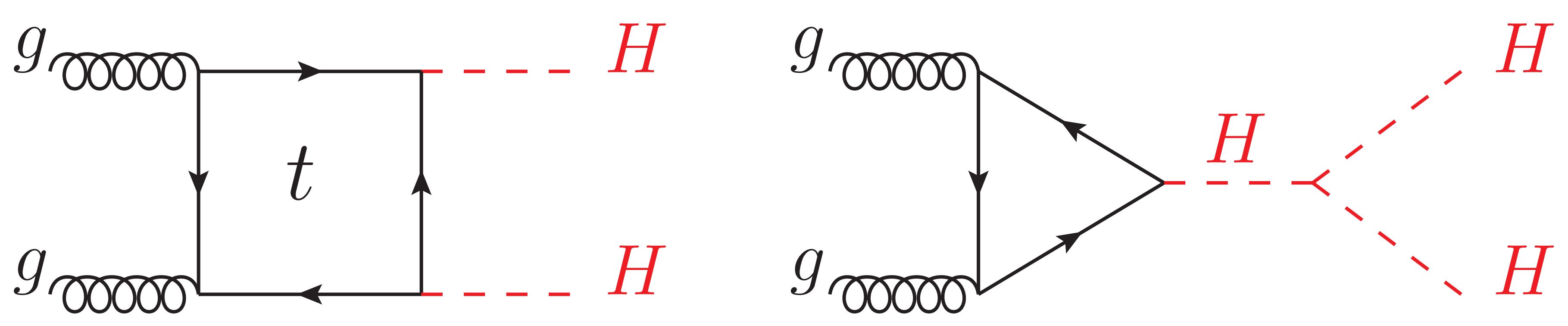


Allows to further constrain the top Yukawa coupling, in particular to exclude a negative relative sign

CMS	Upper limit x SM (expected)
SM	113.7 (98.6)
ITC	6.0 (6.4)



Double Higgs Production



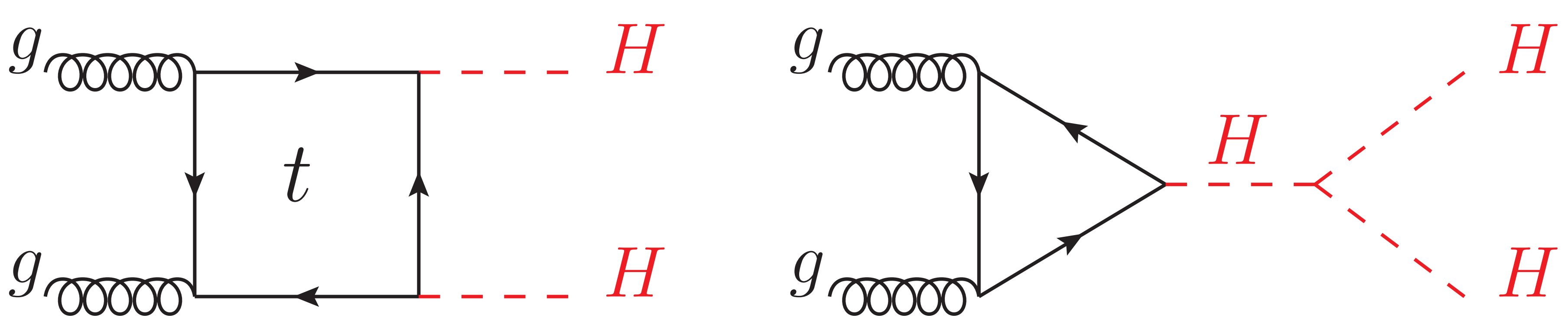
- **Off Shell Higgs analysis**: Search very similar to the Off Shell couplings of the Higgs boson in the two vector bosons channels. It is also done far Off shell in mass.
- Similarly to the Off-Shell analysis there is a large destructive interference between the triangle and the box contributions.
- The total production cross section is very small. First step is a limit on HH production (**inclusively**).
- **Multiple channels investigated:** depending on the both Higgs decays considering (bb, yy, tautau, WW)
- It has been very important to investigate as many channels as possible. Studies invaluable for extrapolations at higher luminosities (and centre-of-mass energies).
- Evolution of sensitivities has brought interesting surprises.

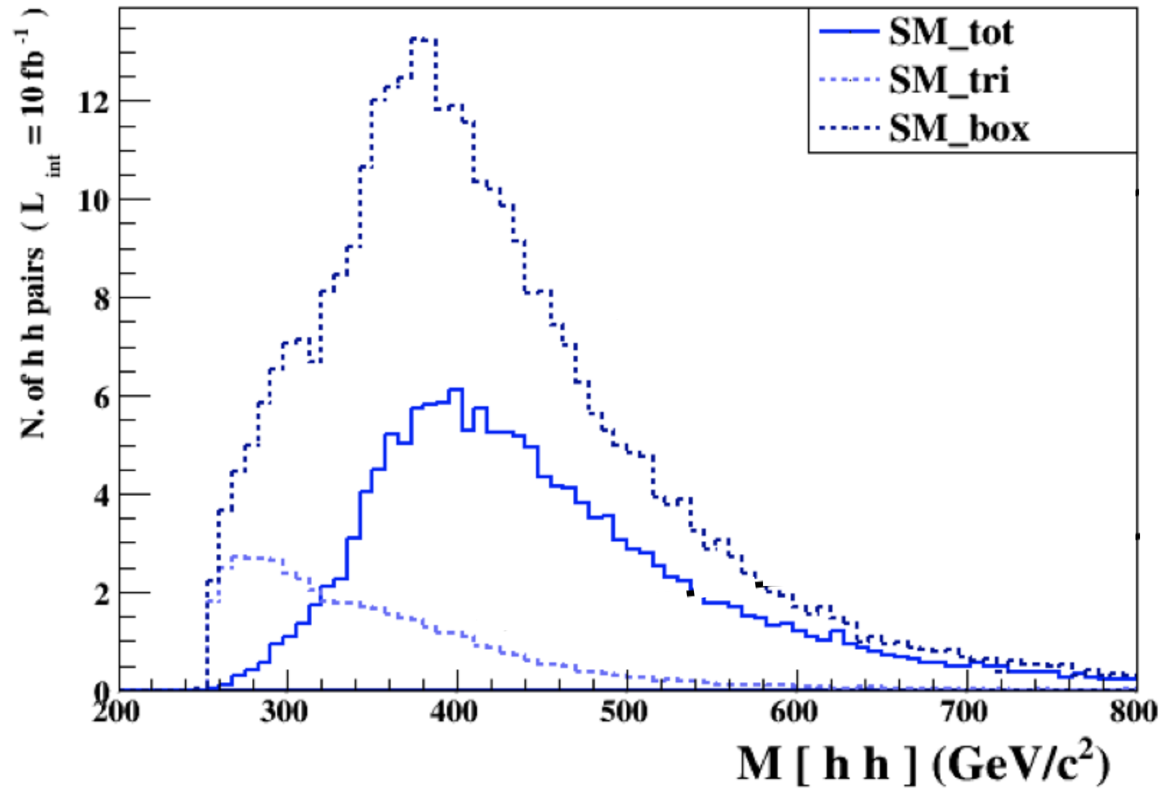
exp.	WW$\gamma\gamma$	bb $\gamma\gamma$	bb $\tau\tau$	bbWW	bbbb
$\sigma \times B$	0.1 %	0.26 %	7 %	25 %	34 %
ATLAS	<747 (386)	<22 (28)	**<13 (15)**	-	<29 (38)
CMS	-	<24 (19)	<30 (25)	<79 (89)	<75 (37)

12 fb-1 (yellow)

36 fb-1 (orange)

Double Higgs Production



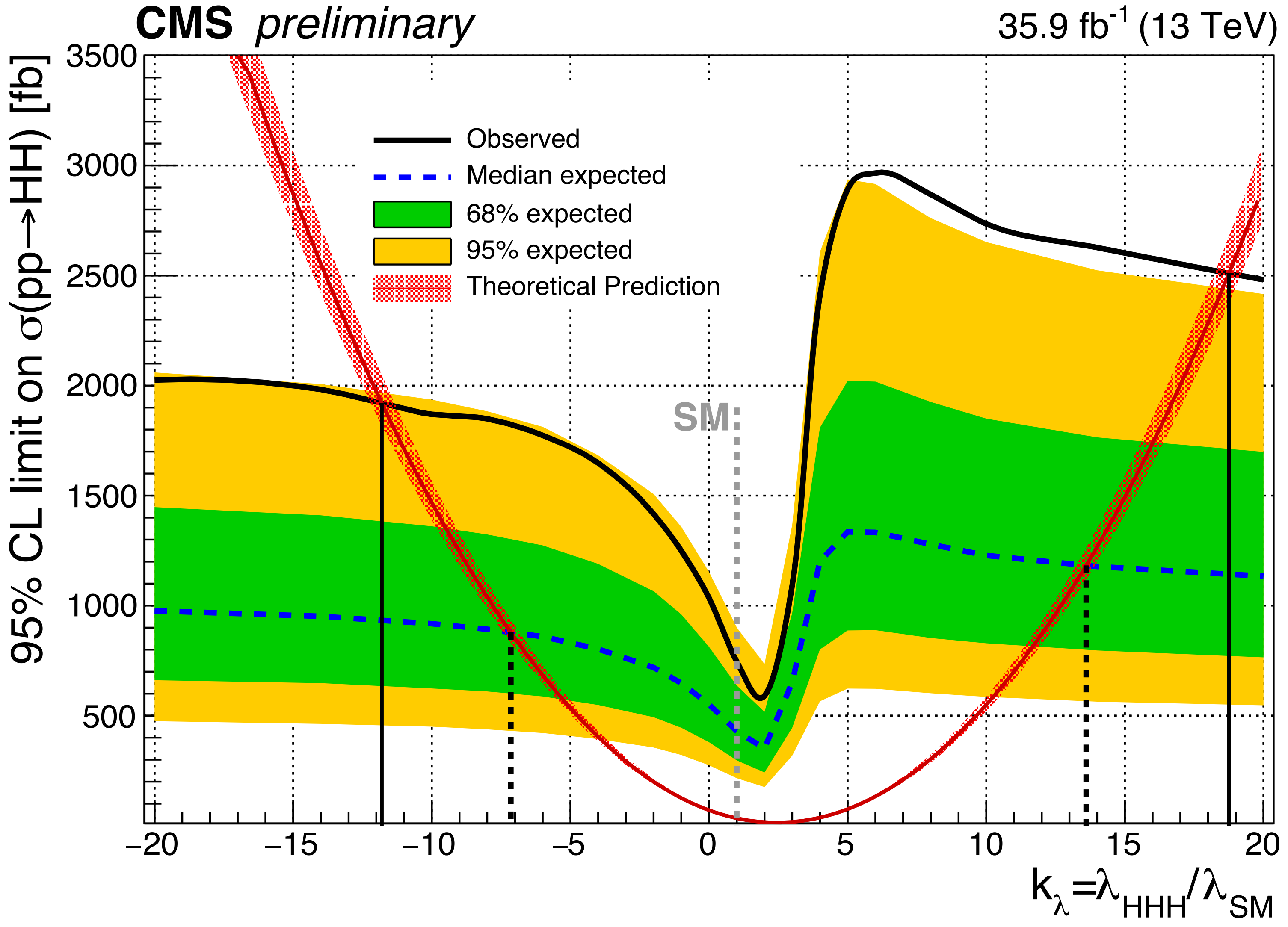


Limits on the HH production do not translate immediately into constraints on the Higgs self coupling due to the non Higgs background and the signal-background interference!

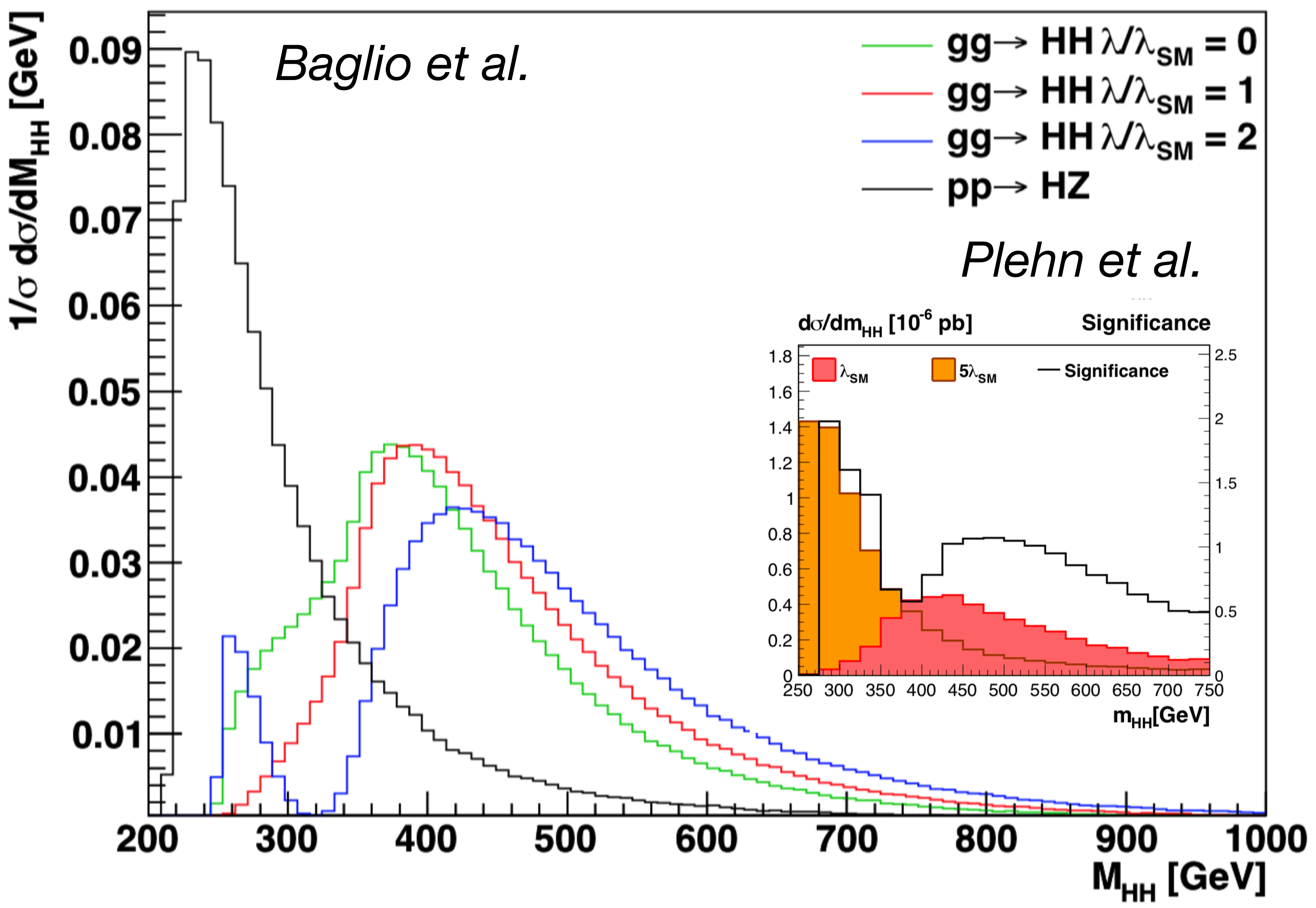
Full combination made by CMS with trilinear limits interpretation.

$$\sigma_{HH} < 13 \times \sigma_{SM} \quad (15 \text{ exp.})$$

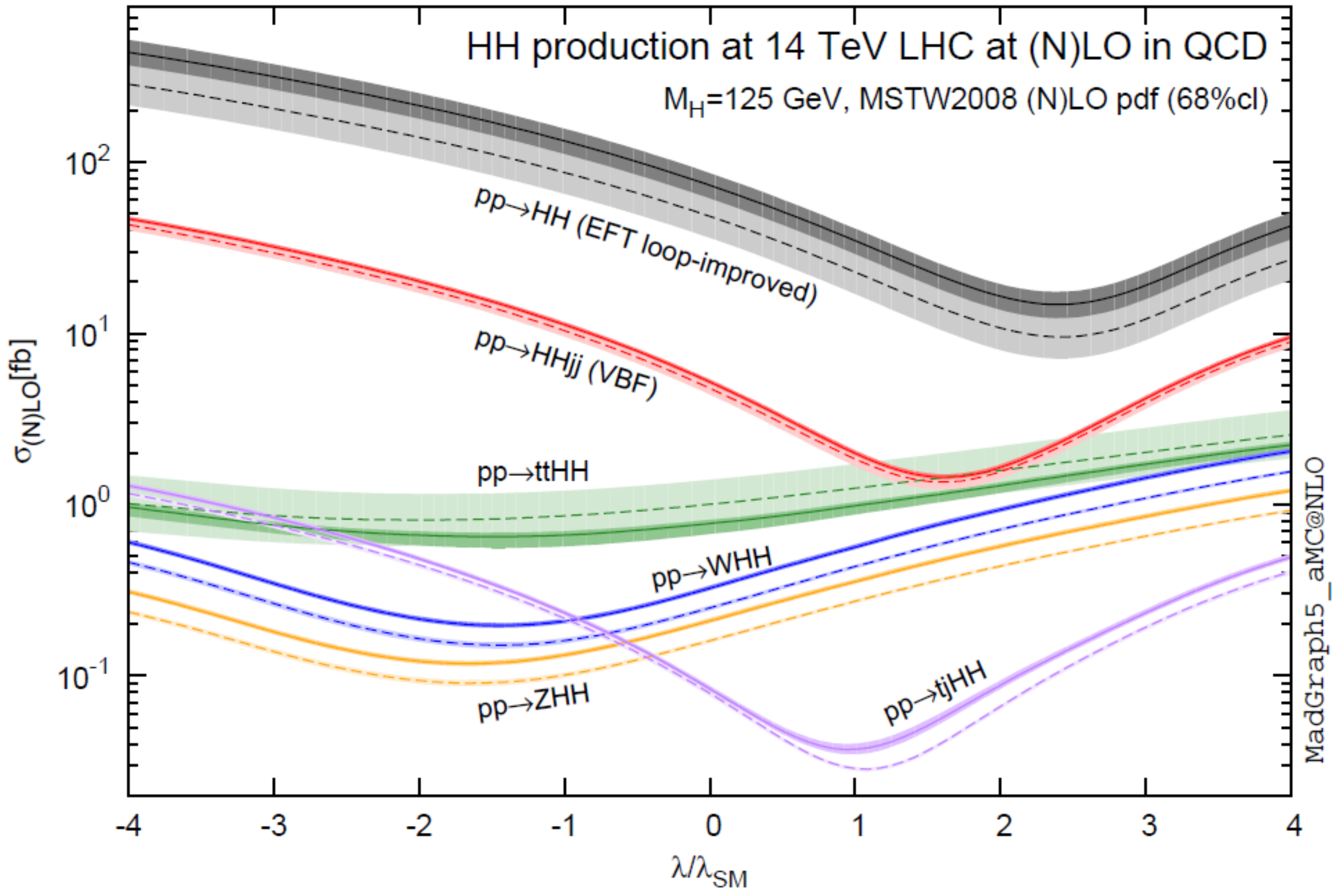
$$12 < \lambda < 19 \text{ at } 95\% \text{ CL}$$



Non trivial dependence of the trilinear (s-channel) contribution on the HH mass, provides discrimination (not fully taken into account in our analyses - **yet**)



Careful analysis of as many decay channels as possible and as many production channels as possible will be important.



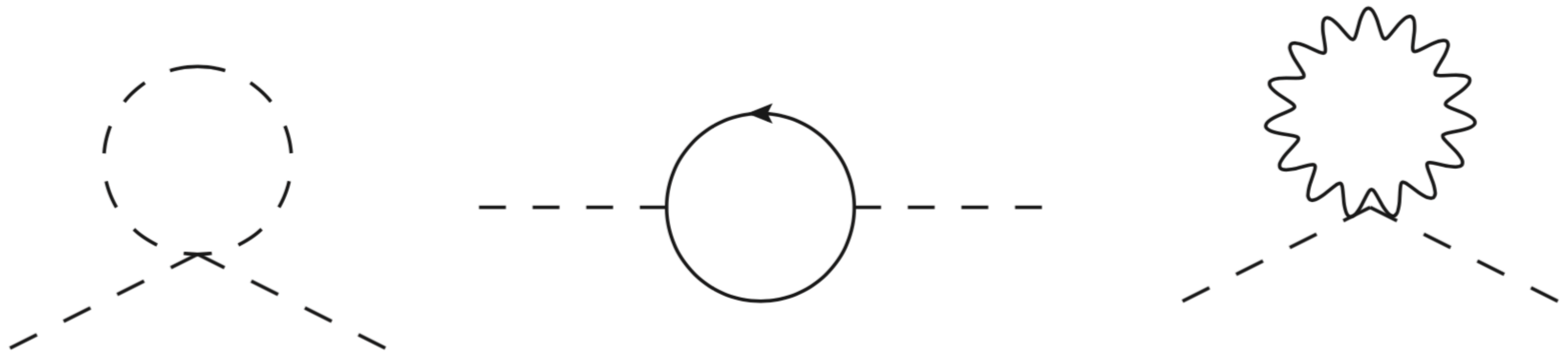
Probing a non Standard Higgs

Through direct and indirect searches

Why is the Hierarchy an Issue?

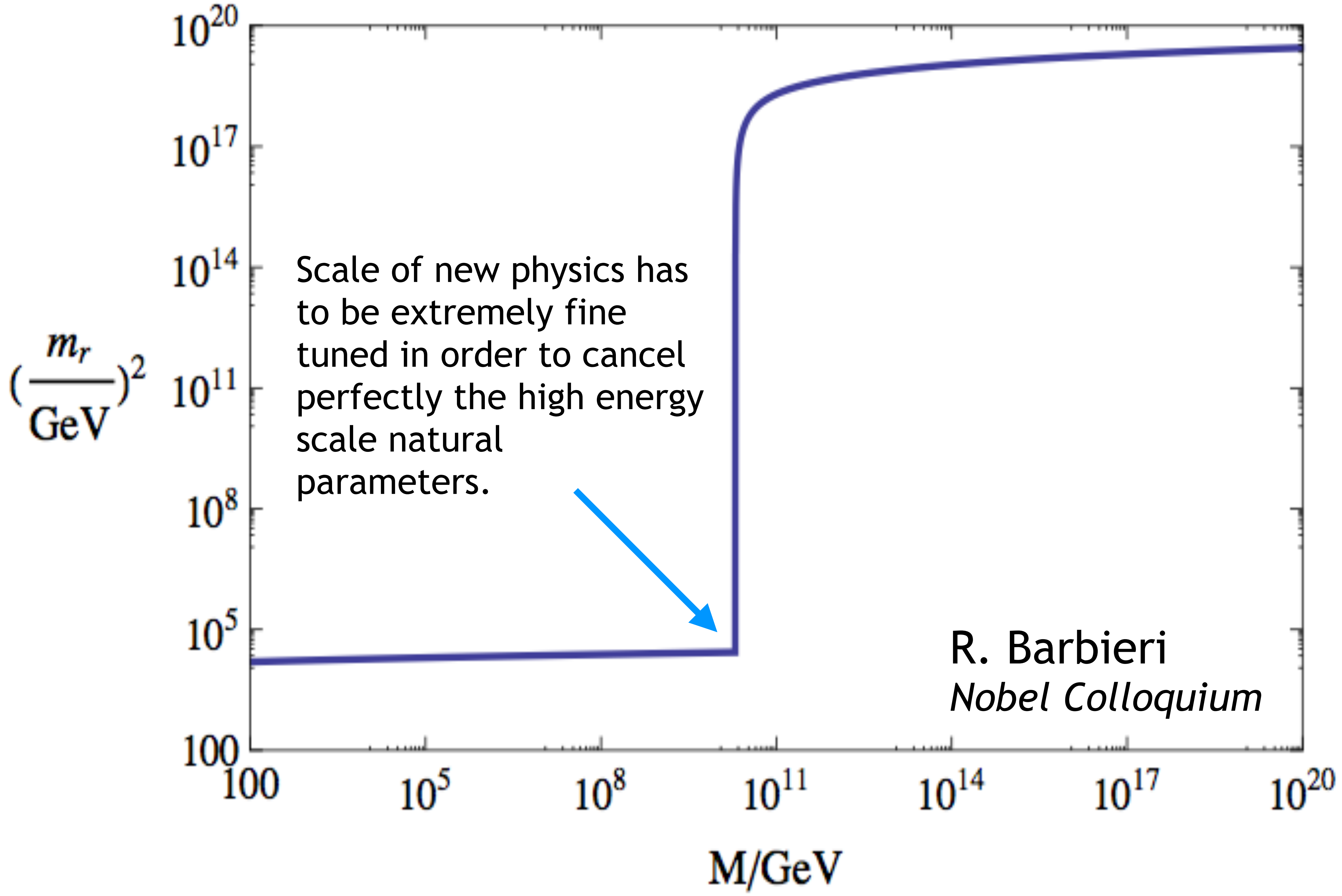
Naturalness

If the Higgs boson is an elementary scalar, loop corrections to its mass are quadratically divergent:



$$\Delta m^2 \propto \int^{\Lambda} \frac{d^4k}{(2\pi)^4}\frac{1}{k^2} \sim \frac{\Lambda^2}{16\pi}$$

The Standard Model is a renormalisable theory quadratic divergences are not a problem per se, but if we look at the running of the Higgs boson mass:



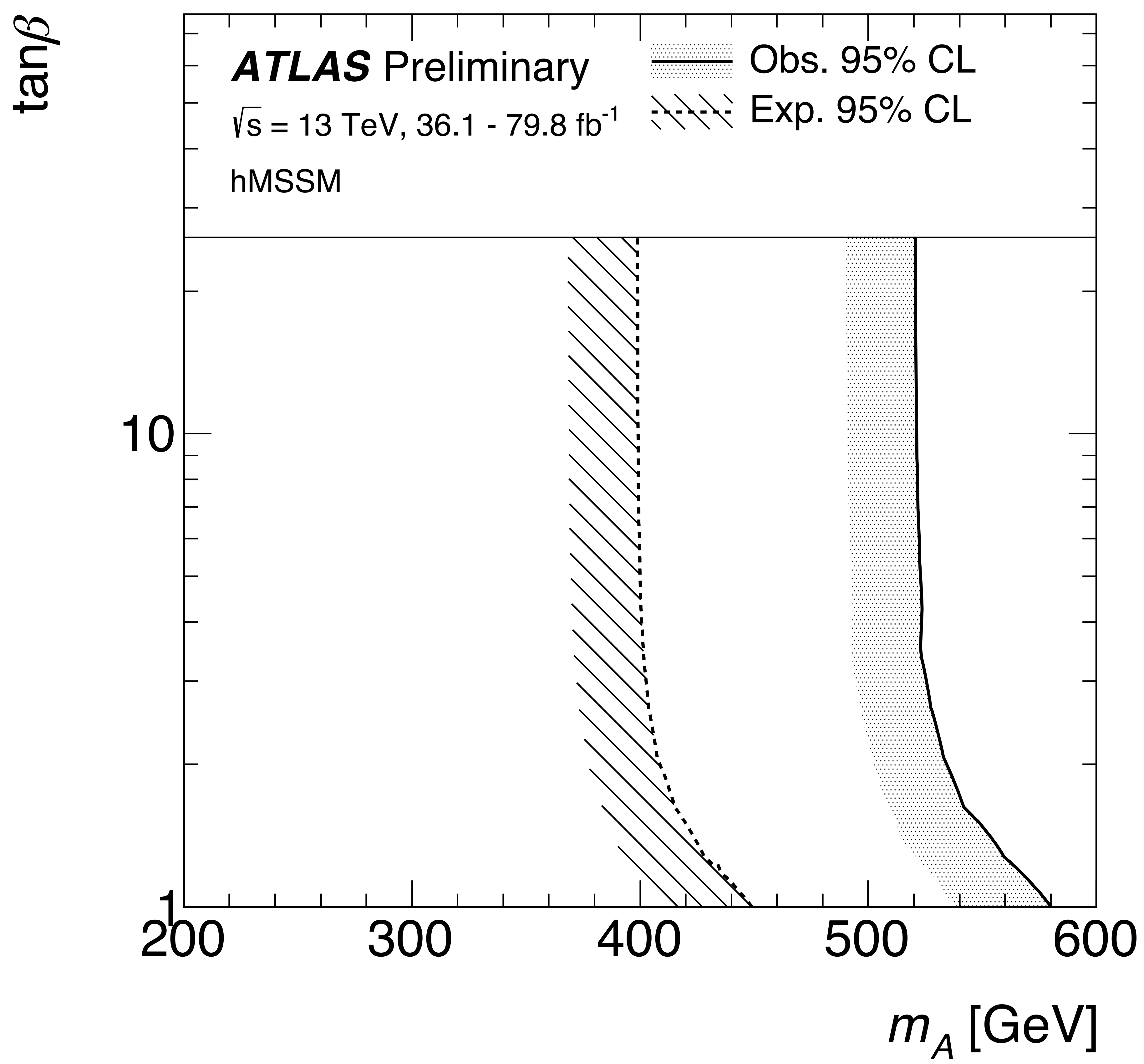
Solutions:

- **Weakly coupled:** introduce fields in the theory that can cancel the quadratic divergence and alleviate the fine tuning (e.g. SUSY)
- **Strongly coupled** (Composite): in this case the above does not apply. The Higgs could be either a generic bound state or a pseudo goldstone boson (similarly to the pion in Chiral perturbation theory).
- **Warped extra dimensions:** Difference between scales generated by warping.
- **Anthropic principle:** fine tuning is acceptable since it is a condition for existence of the universe as it is.

or accepting it as it is

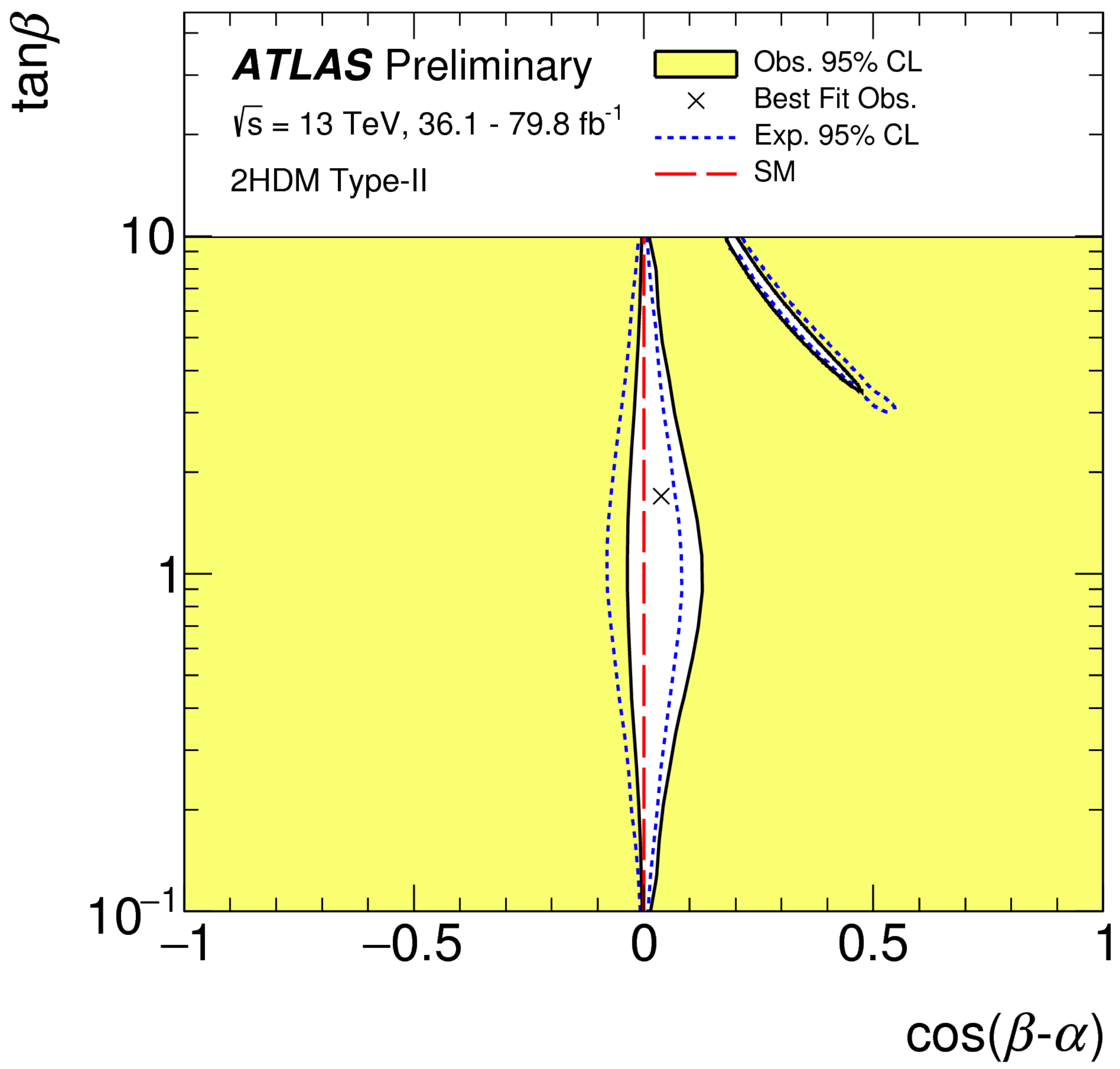
Reaching SUSY from an extended Higgs sector

The MSSM Higgs sector at tree level is governed by only two parameters (mA and tanβ).



SUSY could modify the couplings of the Higgs

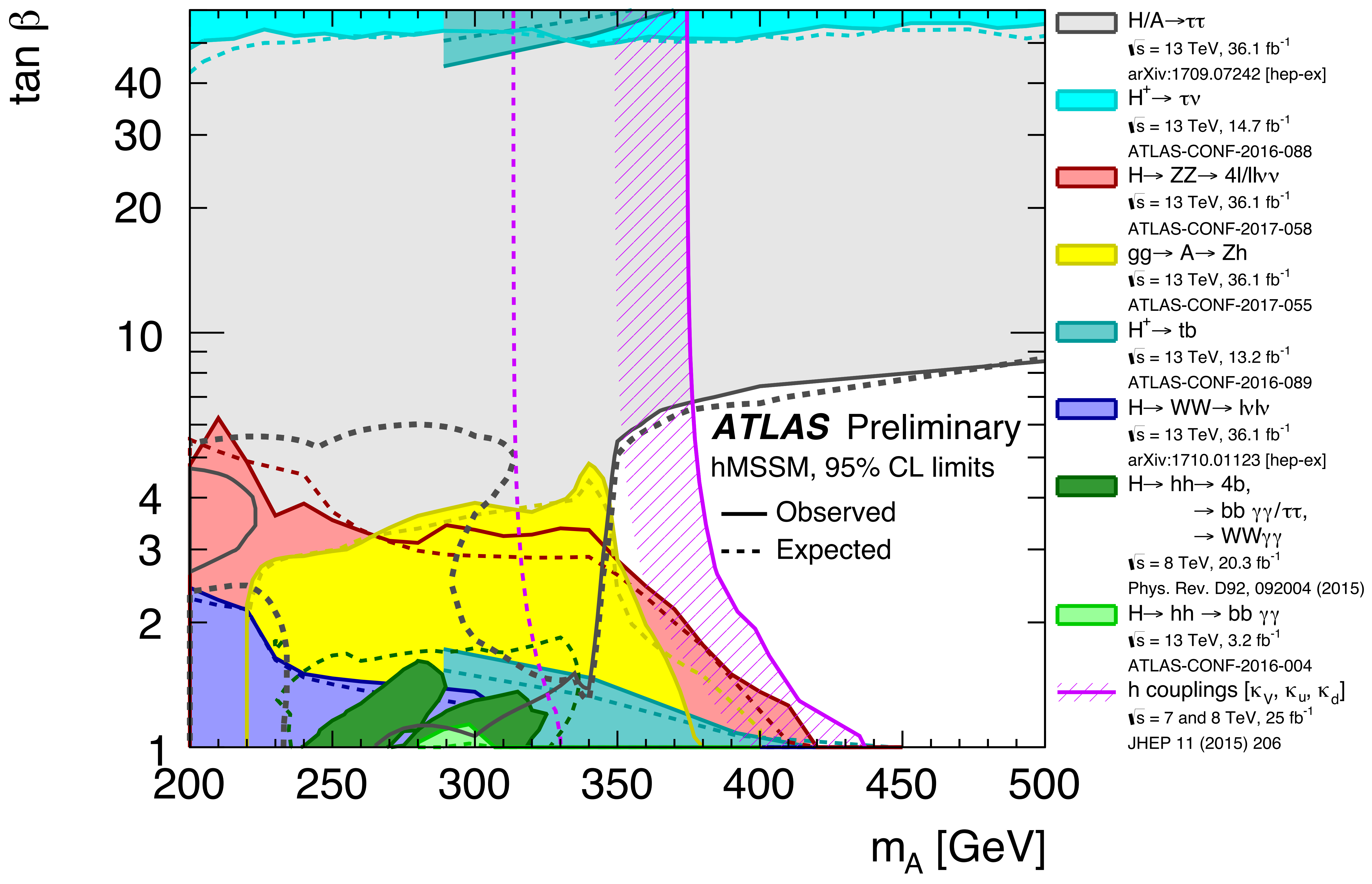
From the combination of all channels, from constraints on **up** versus **down** Yukawa and to a lesser extent coupling to **vector bosons**, limits in the MSSM parameter space can be set.



General 2HDM also considered (though less compelling from a TH point of view).

Reaching SUSY from an extended Higgs sector

The MSSM Higgs sector at tree level is governed by only two parameters (mA and tan β).



SUSY could modify the couplings of the Higgs

From the combination of all channels presented in Lecture 3, from constraints on up versus down Yukawa and coupling to vector bosons, limits in the MSSM parameter space can be set.

Direct searches for additional Higgs bosons (neutral and charged) have been performed:

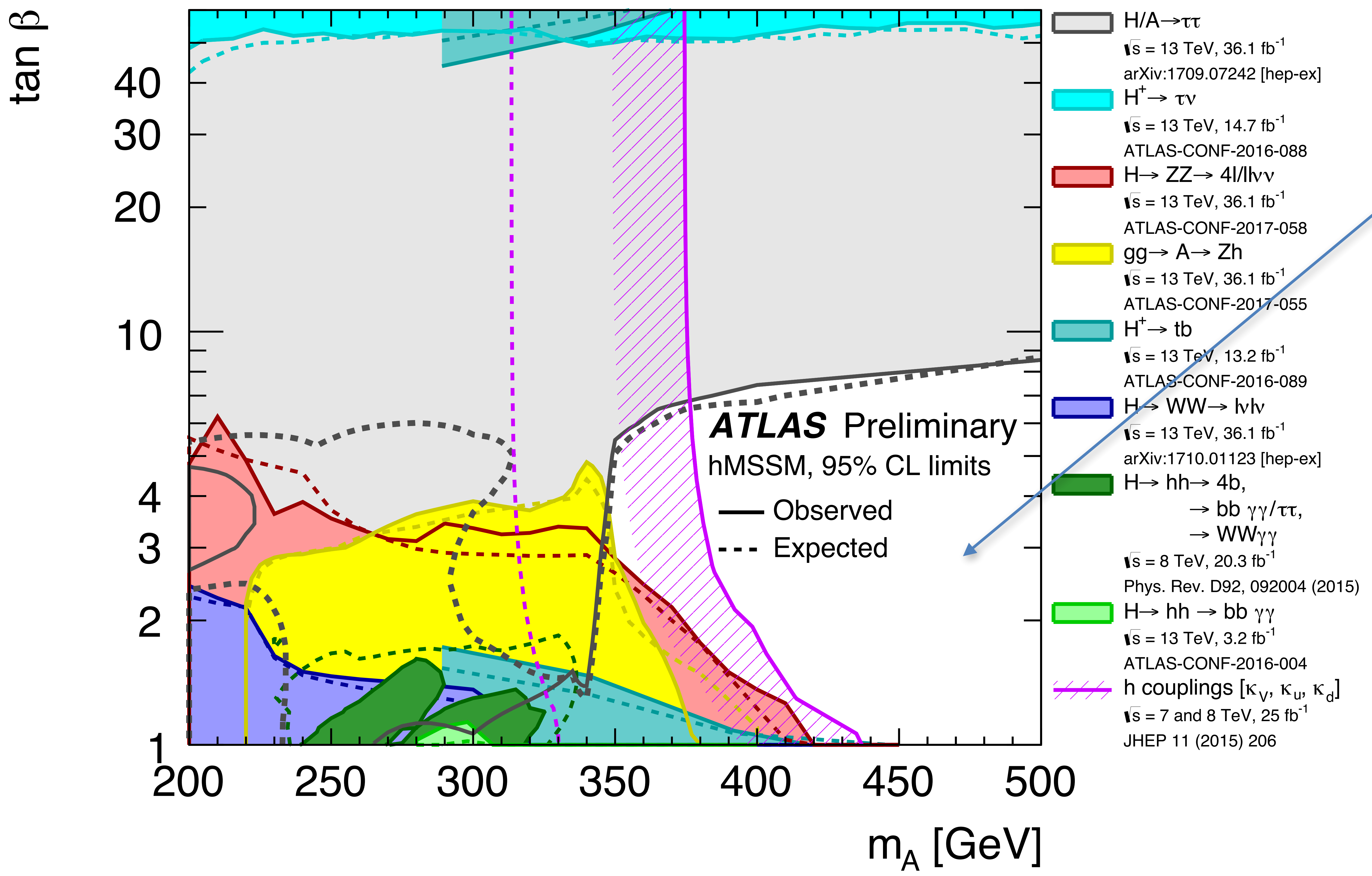
- Neutral heavy Higgs to tau tau
- Charged Higgs to tau neutrino
- Heavy neutral Higgs to ZZ
- Charged Higgs to tb

Using the Higgs boson as a tool for discovery:

- Heavy neutral Higgs to ZH
- Heavy Higgs boson to HH

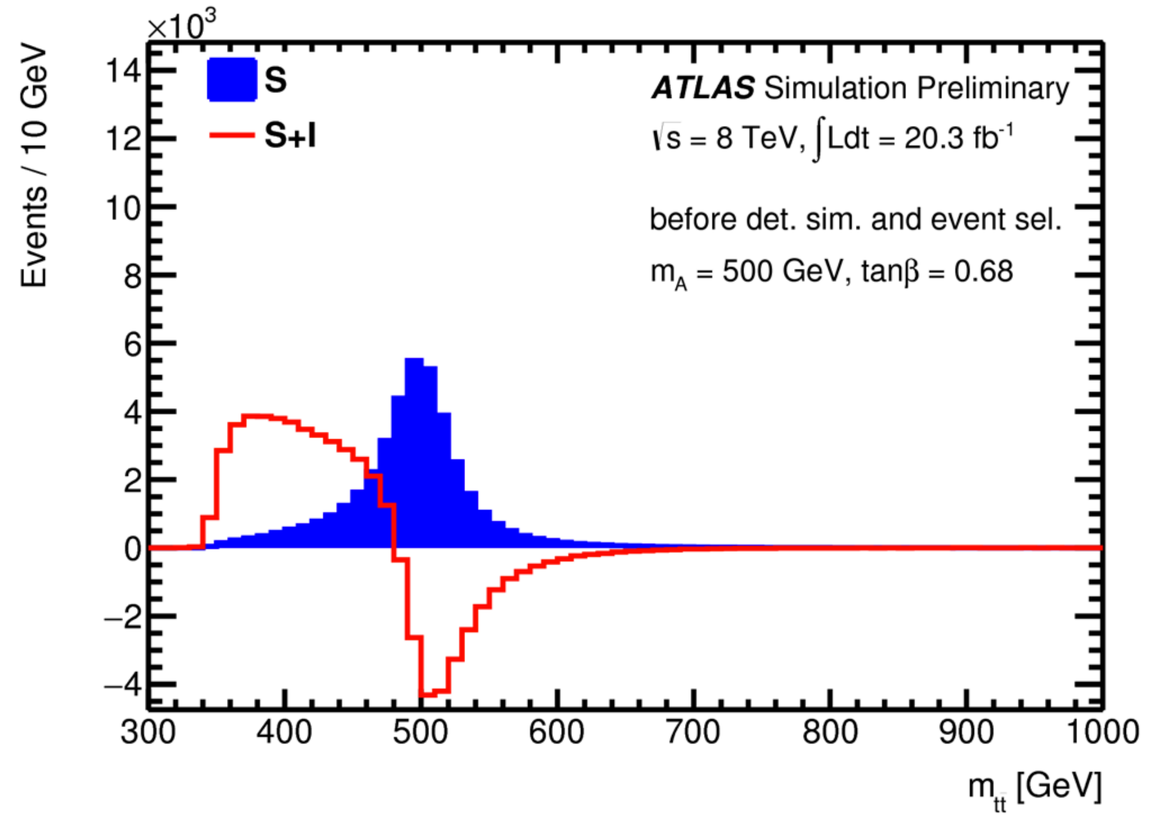
Reaching SUSY from an extended Higgs sector

The MSSM Higgs sector at tree level is governed by only two parameters (mA and tan β).



Difficult intermediate $\tan\beta$ and high mass region, above the $t\bar{t}$ threshold

Searches for a high mass Higgs boson in a $t\bar{t}$ resonance is particularly difficult due to the interference between the signal searched and the background.

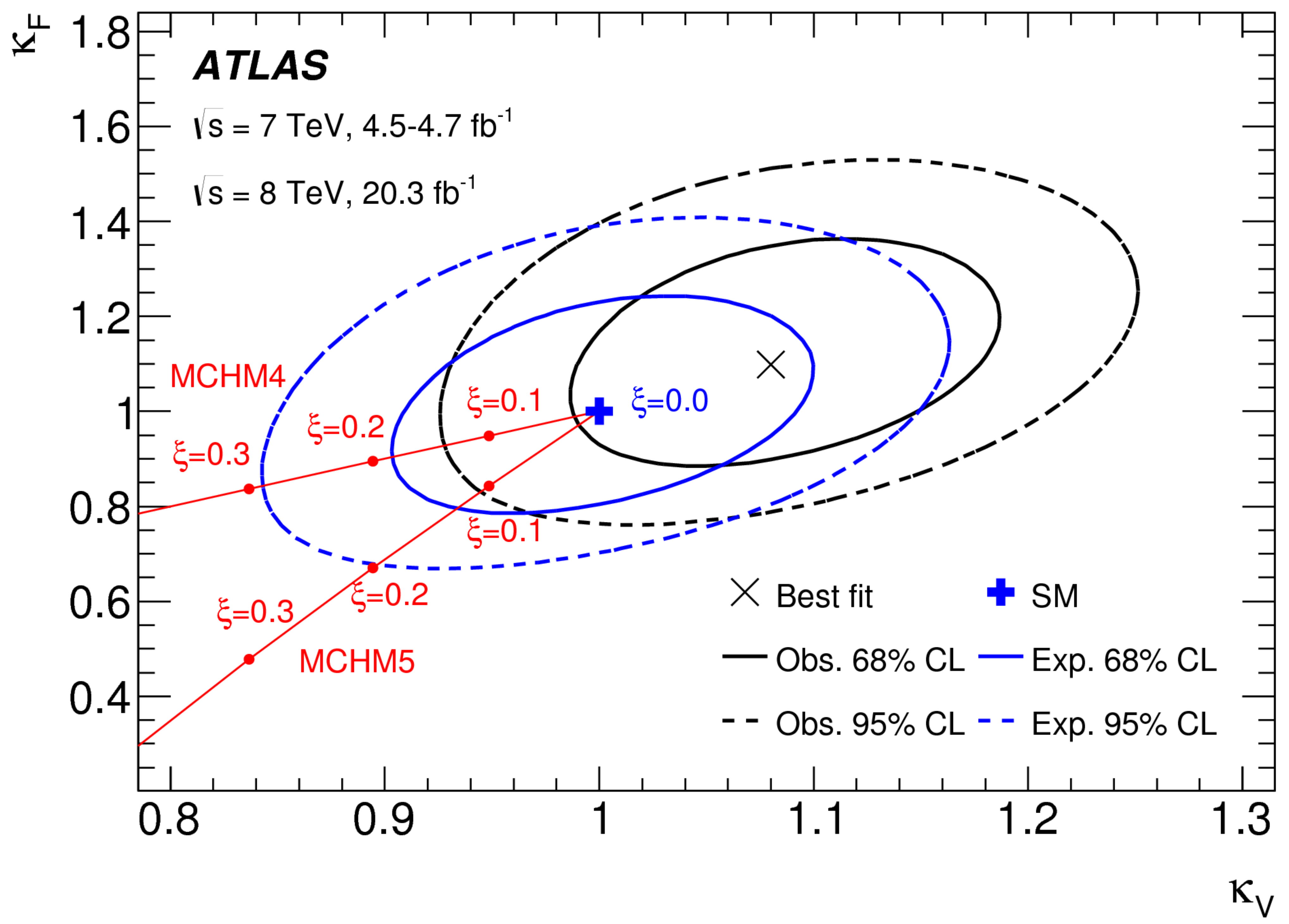


Analysis done at 8 TeV, not yet performed at 13 TeV

Many more searches for additional Higgs bosons:

- low mass range
- In scenarios with additional singlets (e.g. NMSSM) with direct searches of light states or Higgs decays to these light states.
- Searches for doubly charged Higgs bosons

Probing Minimal Composite Higgs Scenarios



MCHM: Indirect constraints from the up vs down type fermions and vector bosons

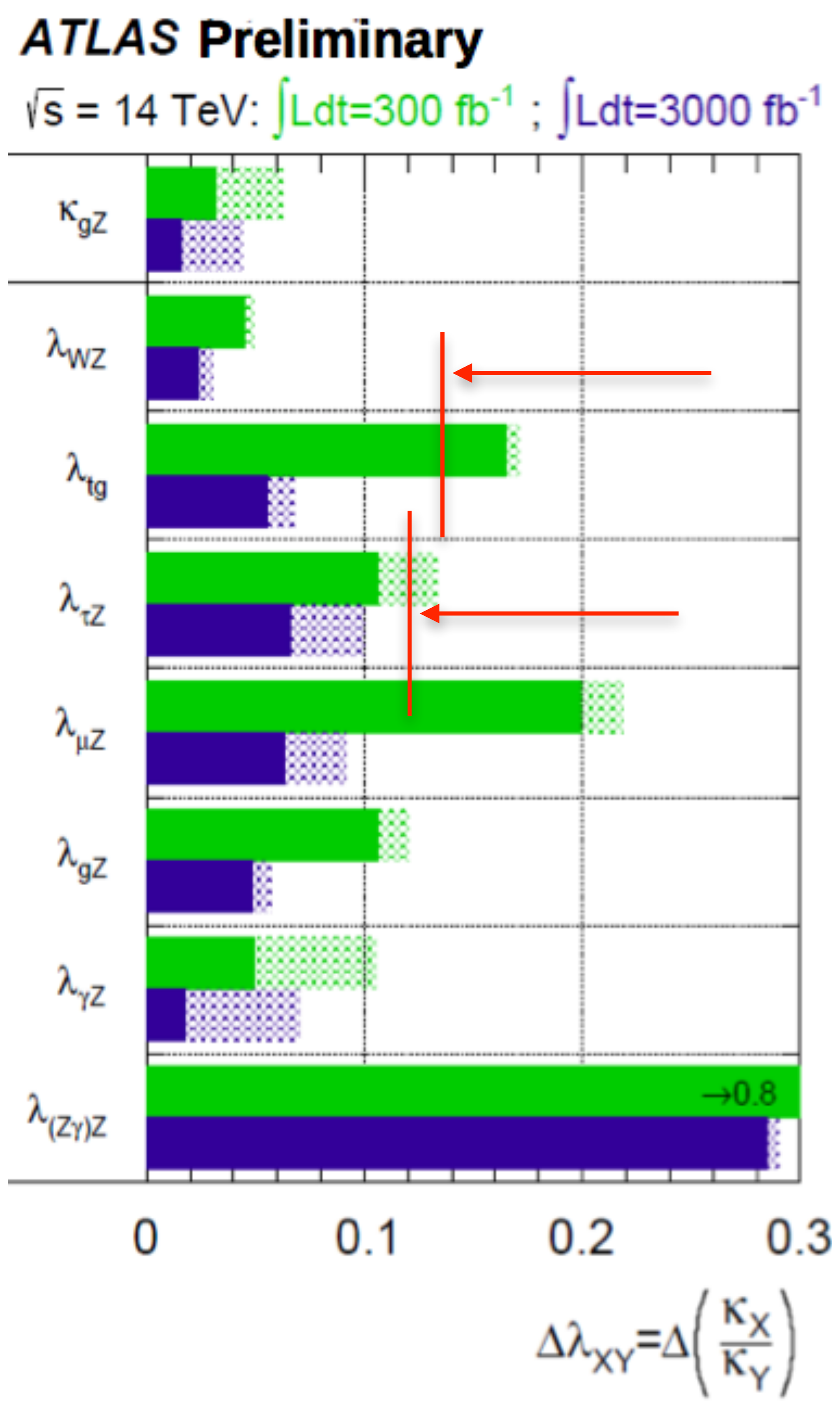
Bounds on compositeness scale ~9 TeV from Higgs couplings less stringent than those from EW precision data ~15 TeV

Based on Run 1 results which are outperformed by Run 2 results (which still need to be interpreted).

Outlook at HL-LHC and Beyond

HL-LHC Physics Program

Currently being completely reappraised in view of the European Strategy update

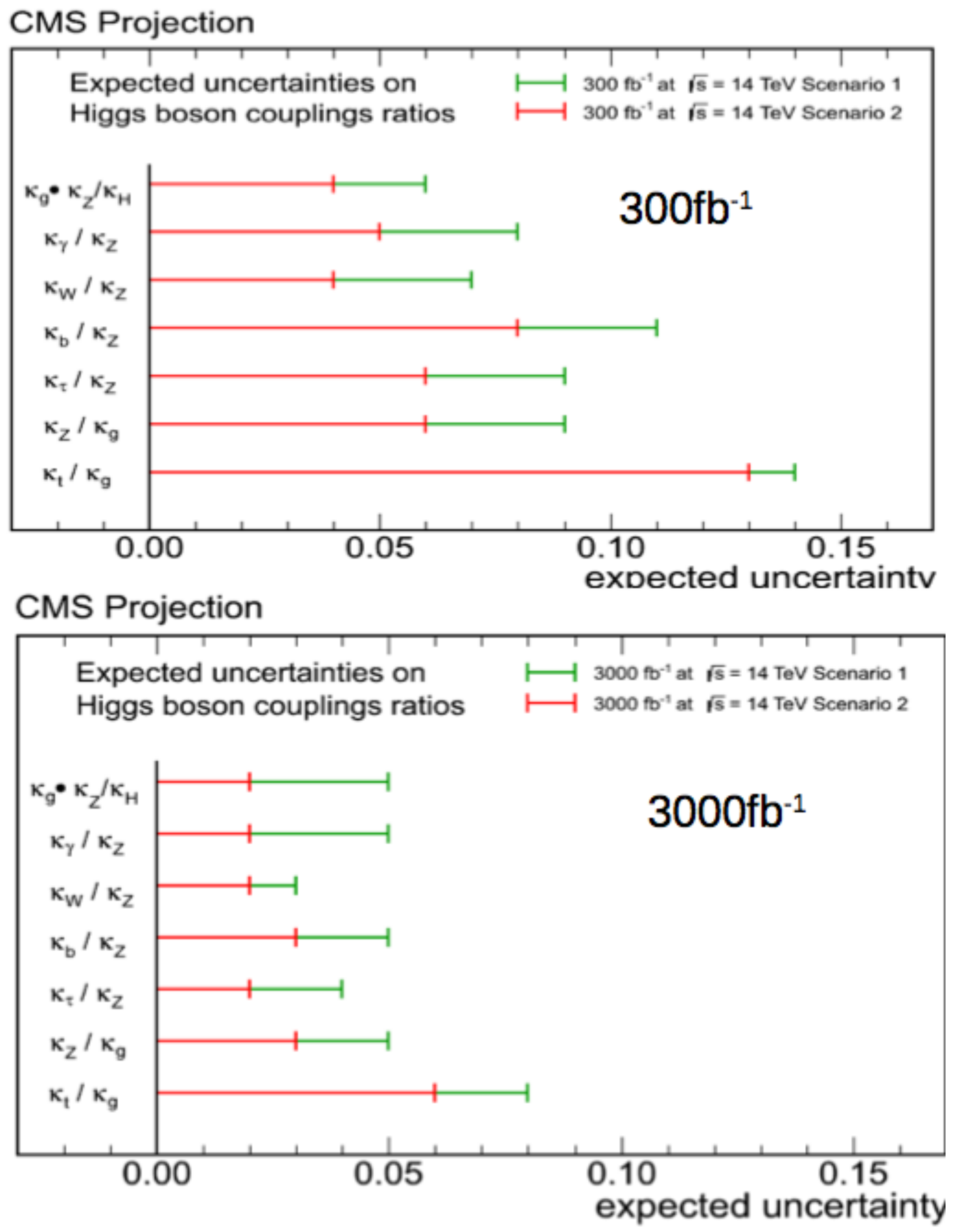


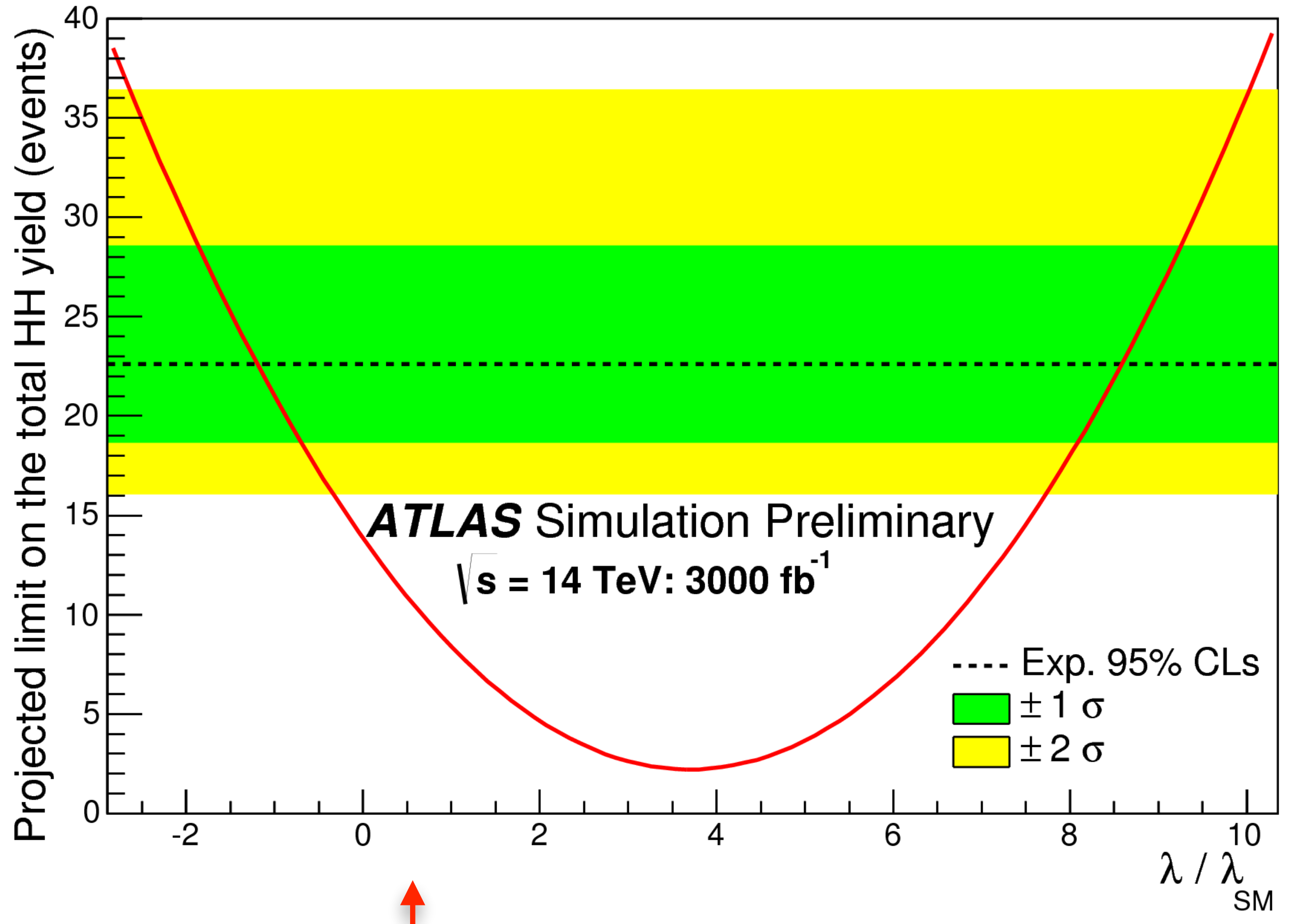
current limit on lambda(tg) with partial Run 2 dataset.

current limit on lambda(tauZ) with partial Run 2 dataset.

Scenario 1
Current (run 1)

Scenario 2
50% TH systematics



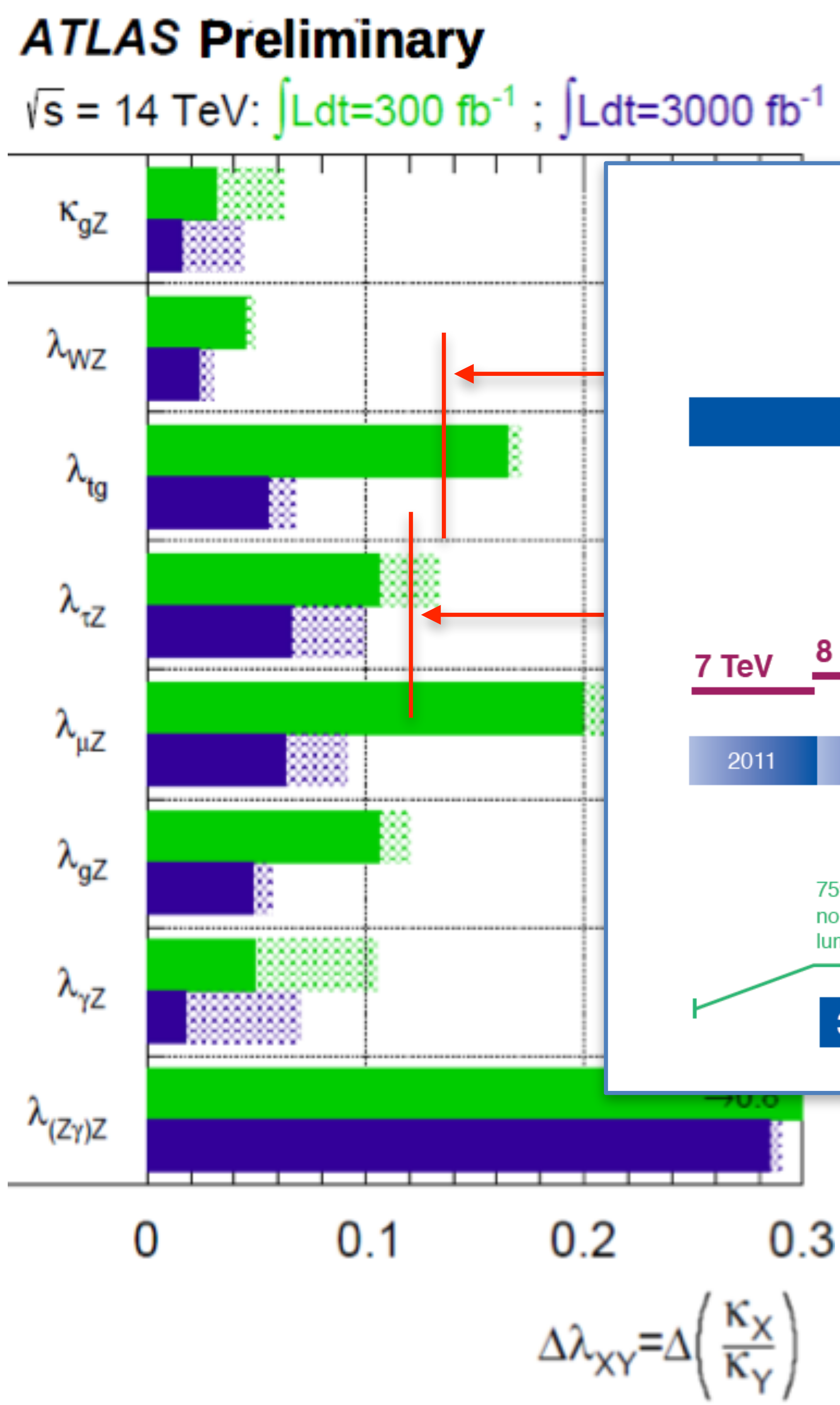


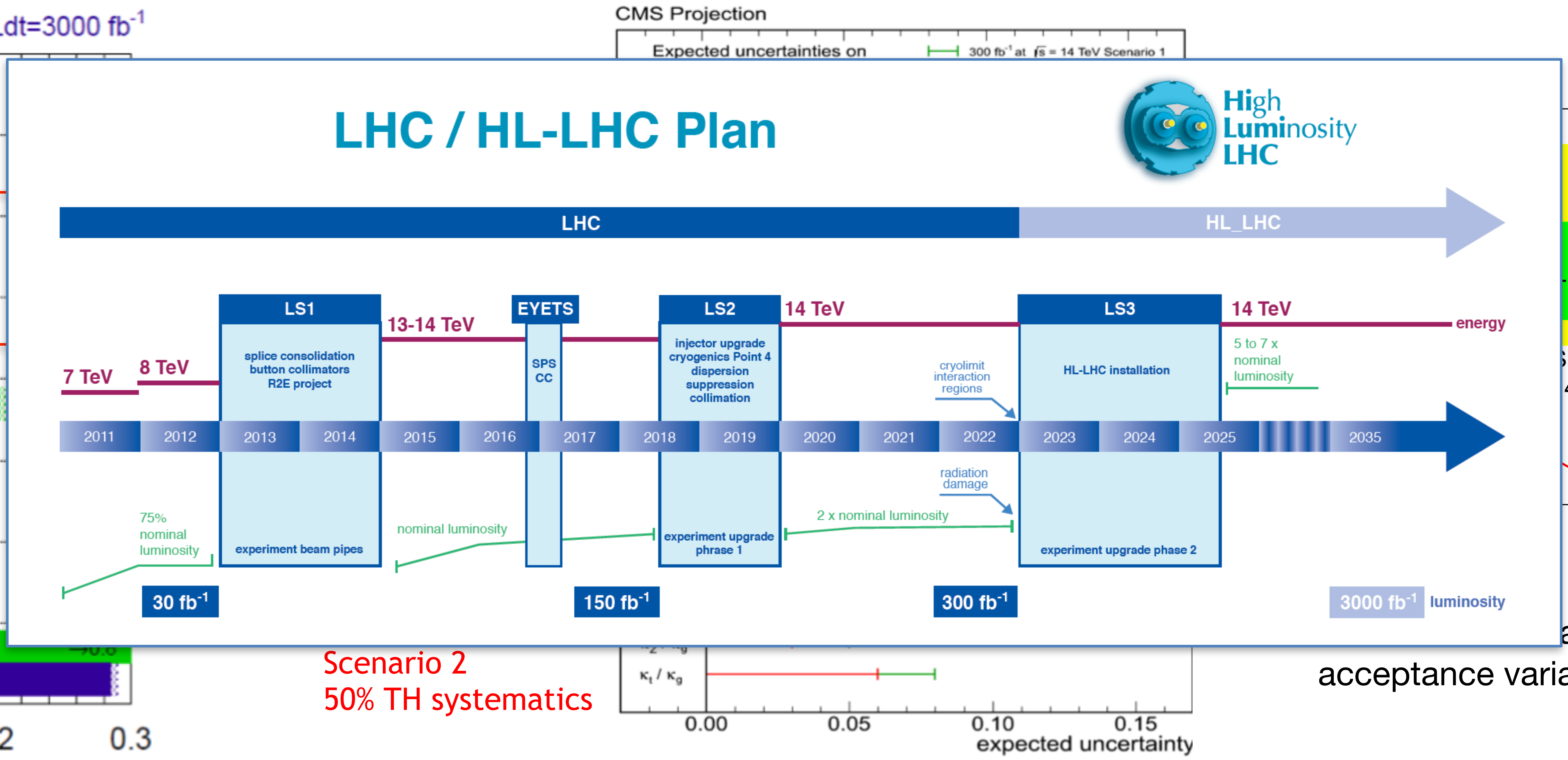
Limits on lambda do not take into account acceptance variations.

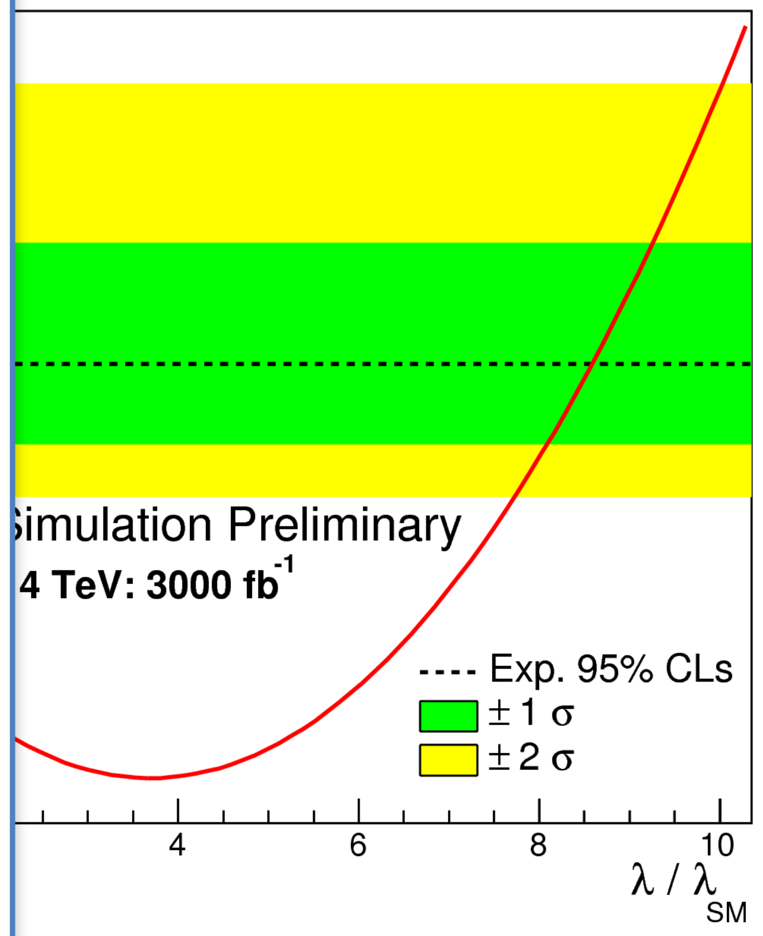
Full reappraisal (of couplings and HH-trilinear analyses) imperative in order to provide a more accurate estimate of the impact on

HL-LHC Physics Program

Currently being completely reappraised in view of the European Strategy update







Scenario 2
50% TH systematics

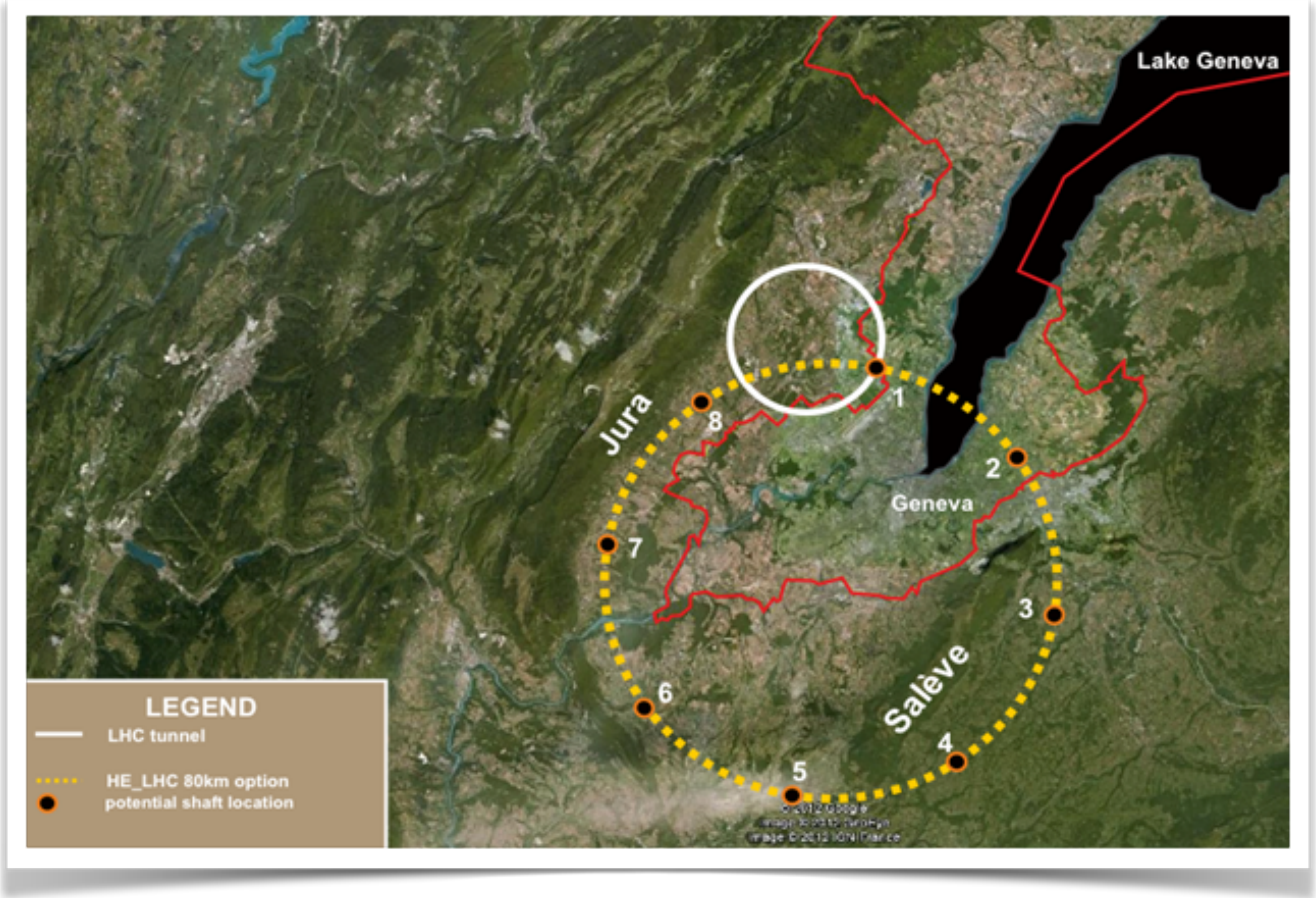
a do not take into account acceptance variations.

Full reappraisal (of couplings and HH-trilinear analyses) imperative in order to provide a more accurate estimate of the impact on

Glimpse at Future Hadron Colliders

The candidate machines in a tiny nutshell

Project	HL-LHC	HE-LHC	FCC-hh	SppC
Location	CERN	CERN	CERN	China TBD
Circ.	27 km	27 km	100 km	55 - 100 km
COM energy	14 (15?) TeV	27 TeV	100 TeV	70 -140 TeV
Luminosity	3 ab-1	15 ab-1	20-30 ab-1	TBD
PU	up to 200	up to 800	up to 1000	TBS
Bunch sp.	25 ns	25 ns	25 ns	25 ns
Field	8T	16T	16T	20T
When?	Until 2037	After 2037?	After 2037	TBS



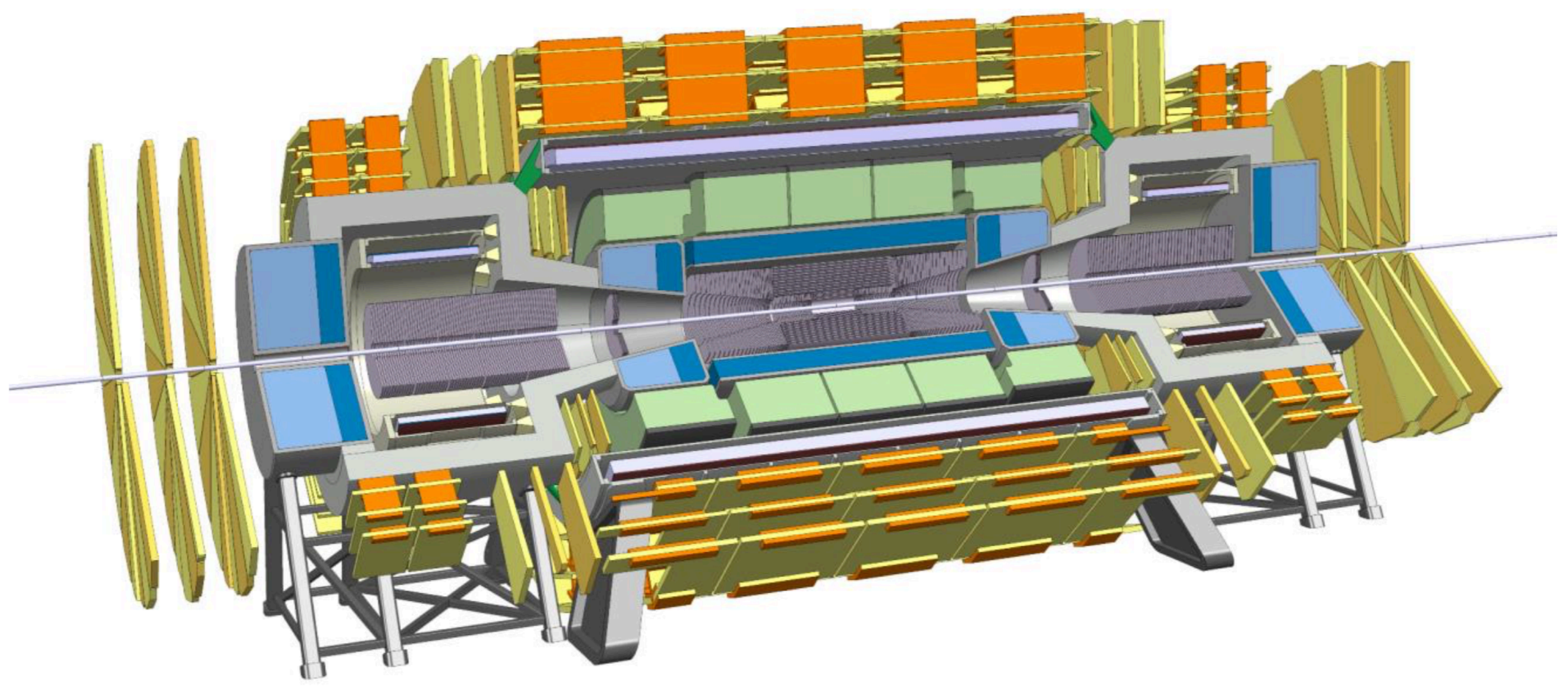
Detector, Trigger DAQ, Reconstruction challenges

Two challenges: higher PU (1000) higher pT

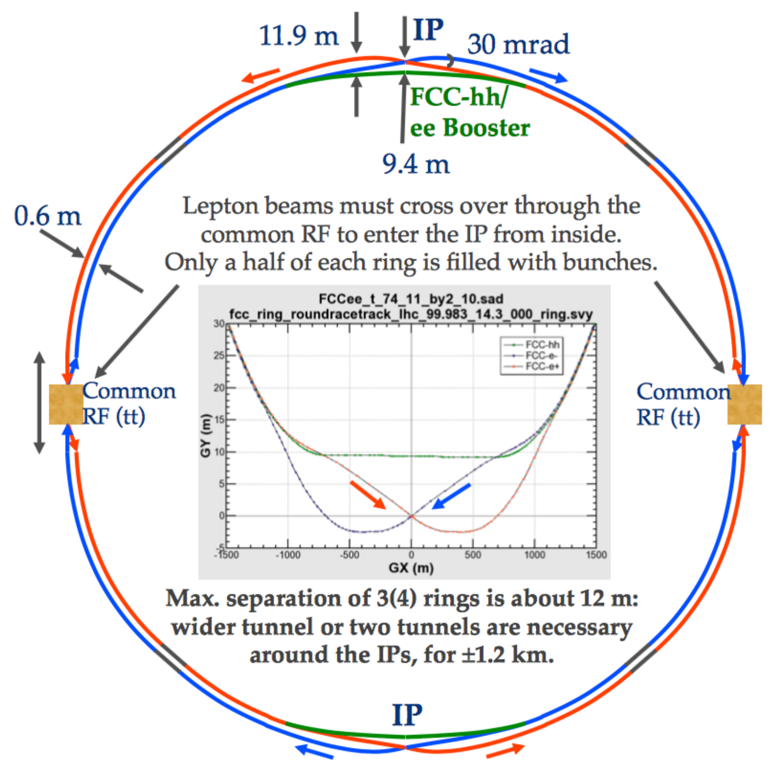
Answer: granularity and resolution

Decay products of a Z at 10 TeV are separated by $\Delta R = 0.01$

A b at 5 TeV can travel 50cm and a tau 10 cm

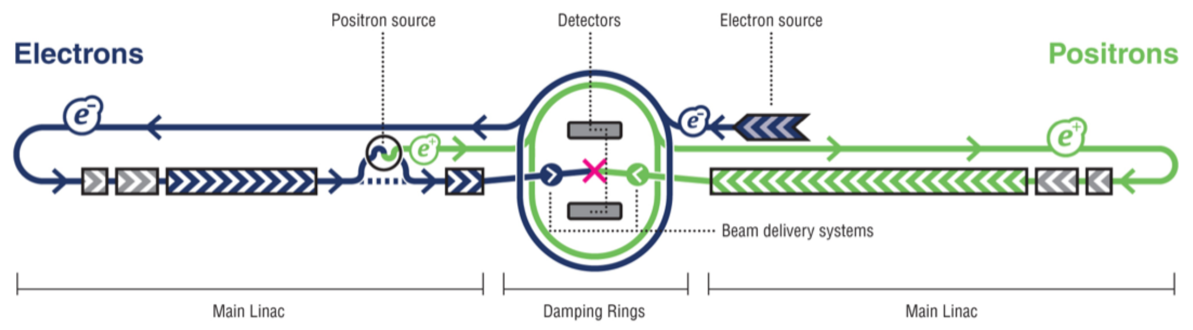


Electron-Positron Projects

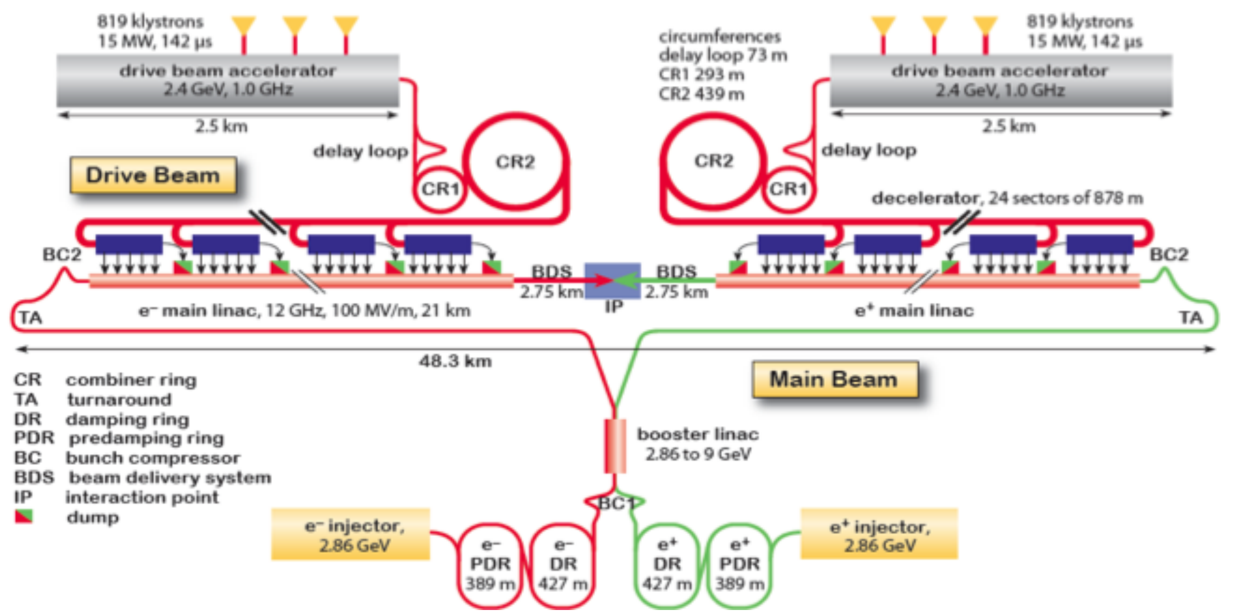


Precision physics at FCC-ee:

- >mH+mZ Higgs precision
- mZ for Tera Z extreme EW precision
- 2xmW precision W physics
- 2xmt for precision top physics



ILC
One baseline scenario
scenario 250 GeV
Lumi 0.7 to 5 10^{34} $cm^{-2}s^{-1}$



CLIC
Three scenarios
- 500 GeV
- 1500 GeV
- 3000 GeV

Lumi 1.3 to 6 10^{34} $cm^{-2}s^{-1}$

Coupling	FCC-ee	FCC-hh	FCC-ep
ZZ	0.15 %		
WW	0.19 %		
bb	0.42 %		0.2 %
cc	0.71 %		1.8 %
gg	0.8 %		
$\tau\tau$	0.54 %		
$\mu\mu$	6.2 %	<1%	
$\gamma\gamma$	1.5 %	<0.5%	
$Z\gamma$		<1%	
tt	~13%	1 %	
HH	~30 %	4 %	
uu, dd			
Binv	<0.45%	<0.1%	
Γ_{tot}	1 %		

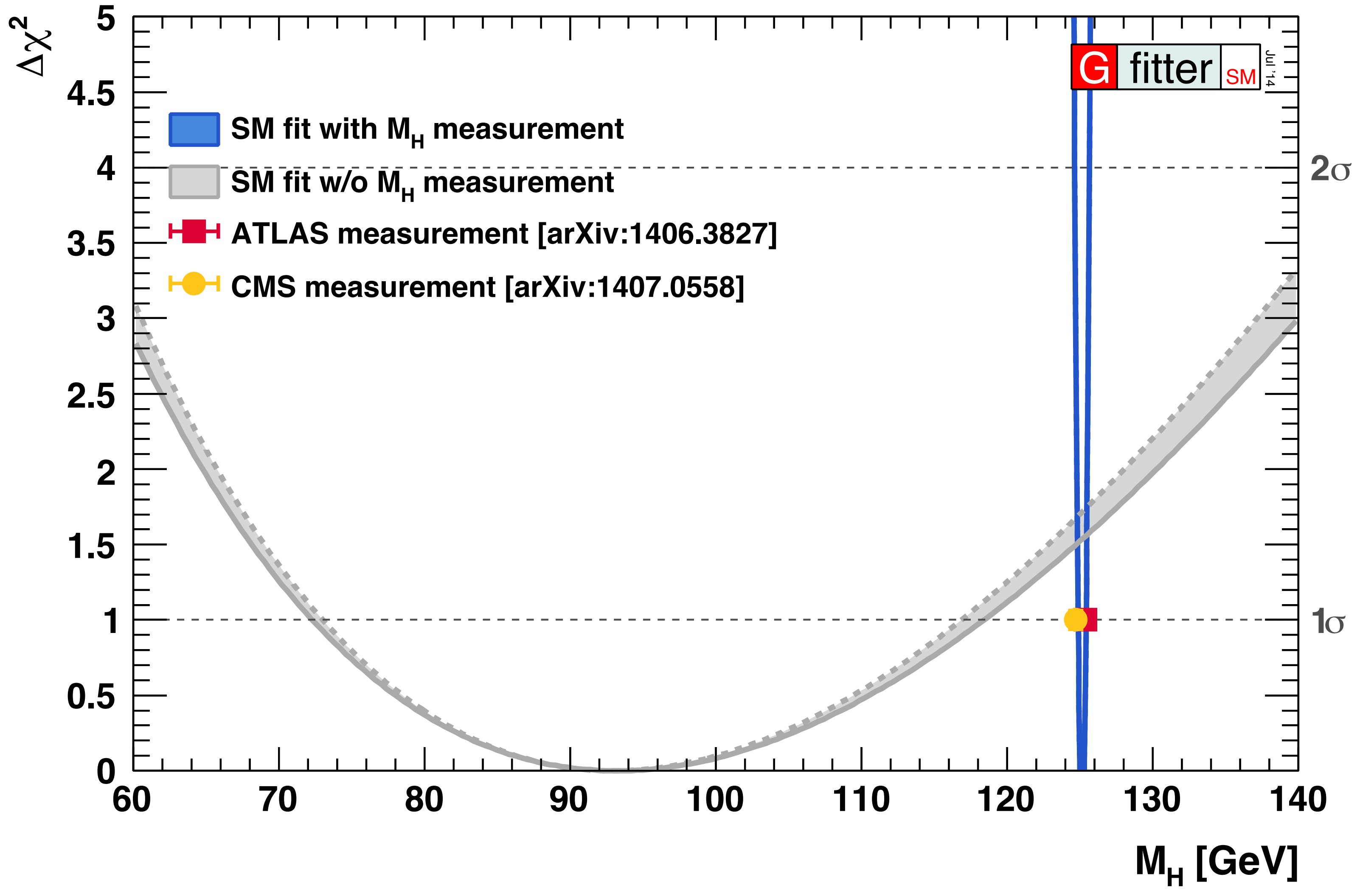
From M. Mangano

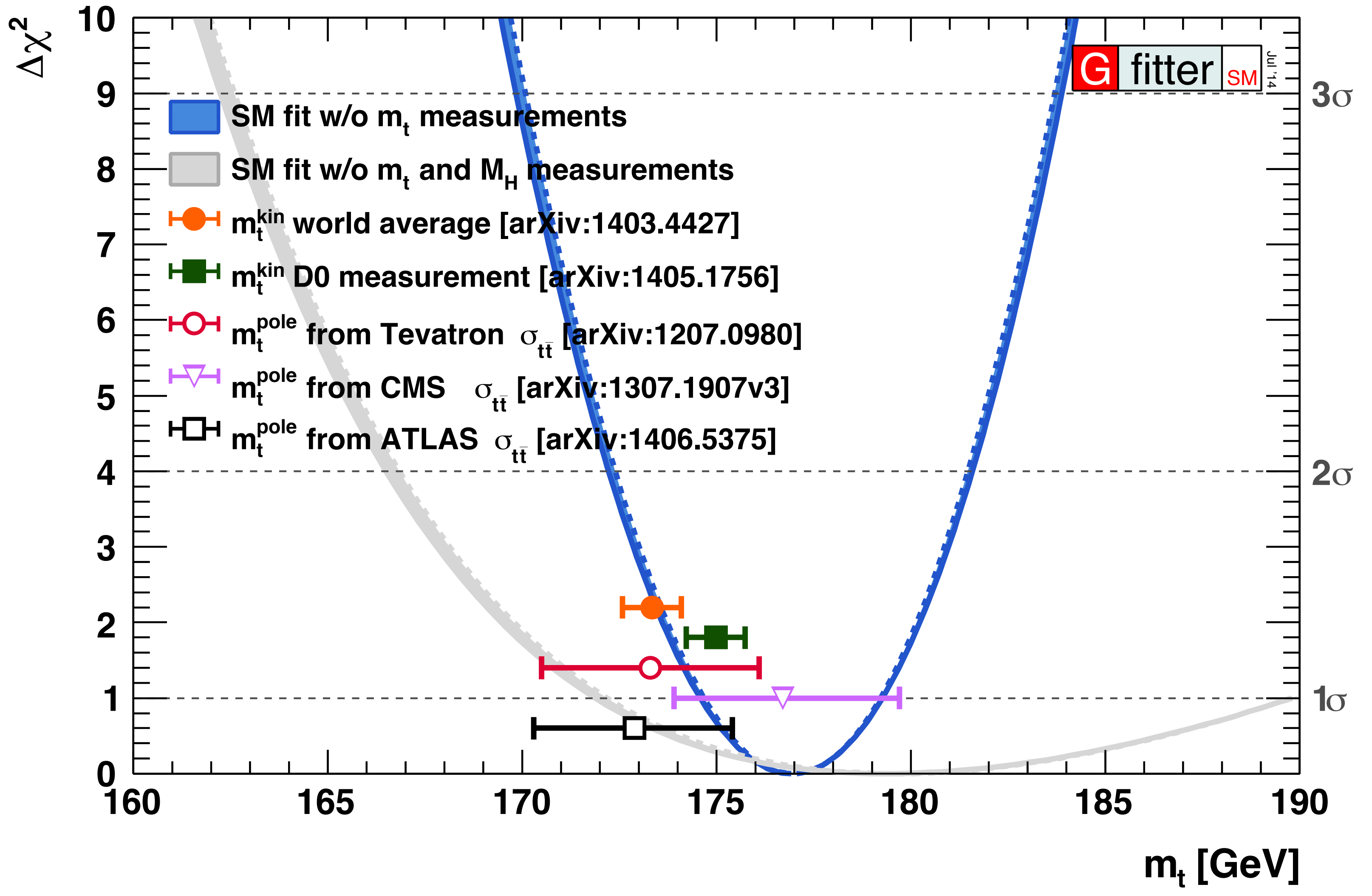
FCC-ep based on LHeC type design with ERL (Energy Recovery Linacs)

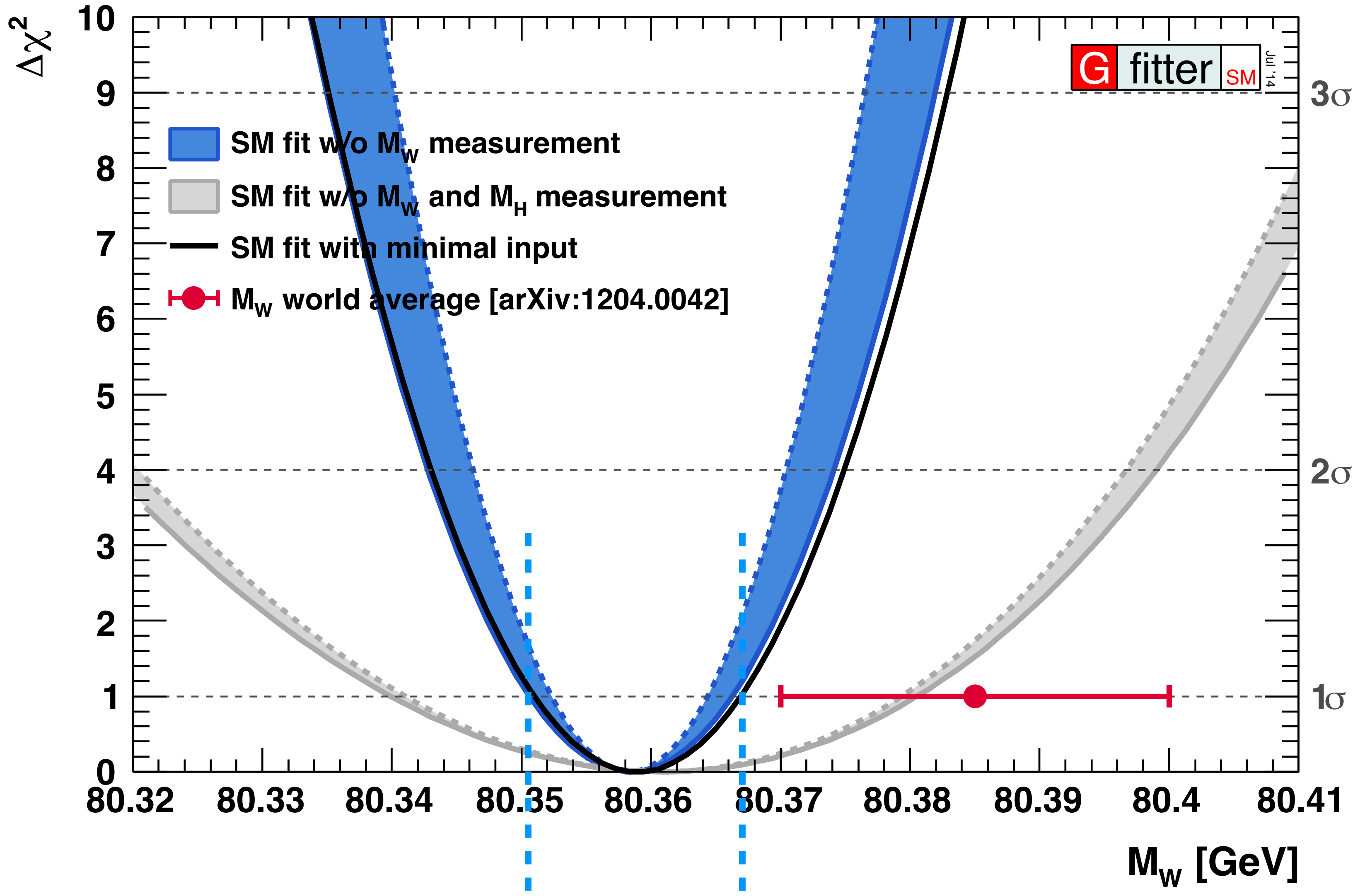
More possible projects…
- Muon collider
- Photon collider

What Have we Learned?

Implications (I) - Global fit of the Standard Model

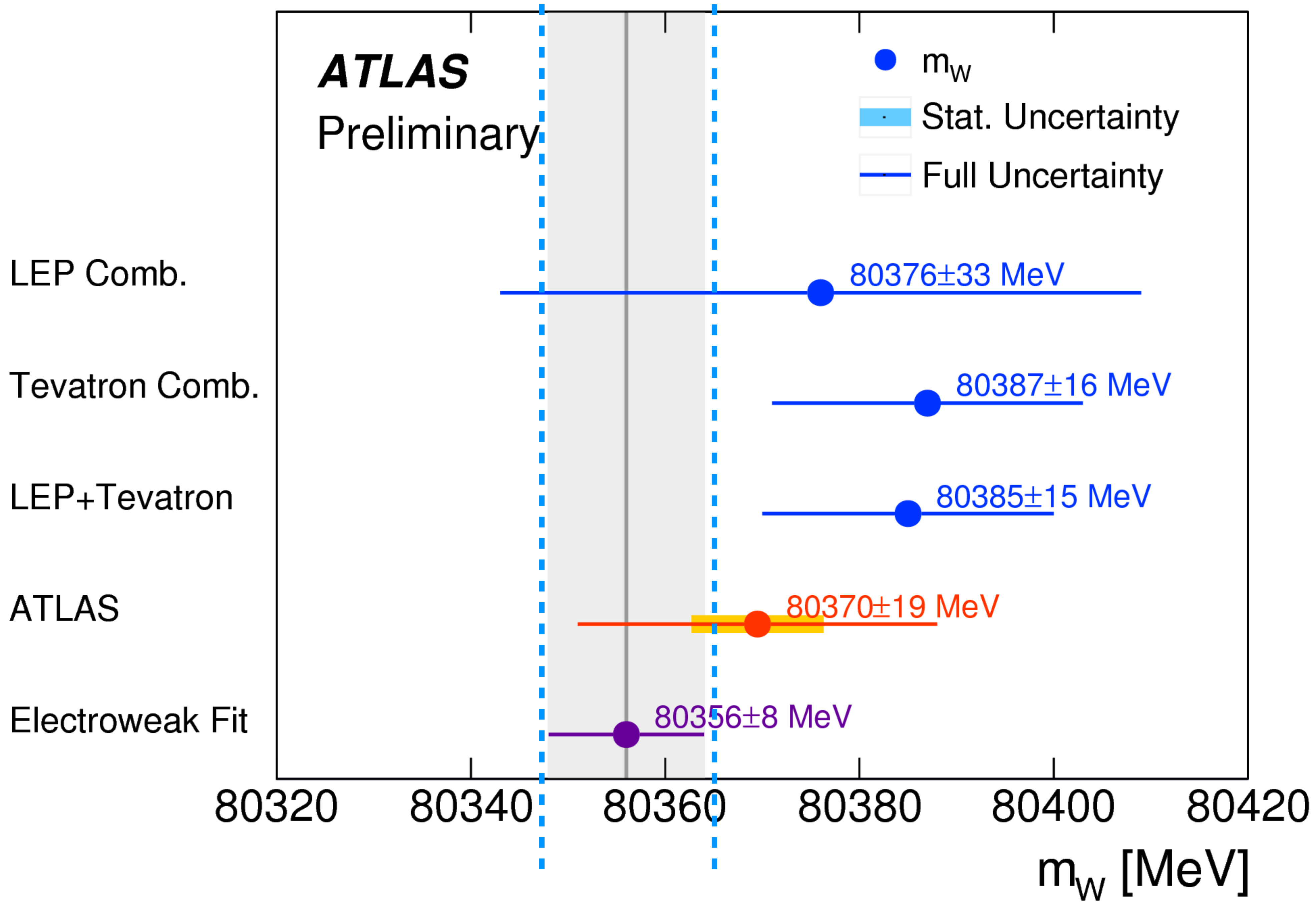






Direct measurement of the Higgs boson mass is much more precise than the indirect one.

Knowing the Higgs boson mass has a important effect on global analysis



The Standard Model is consistent between direct and indirect measurements!!

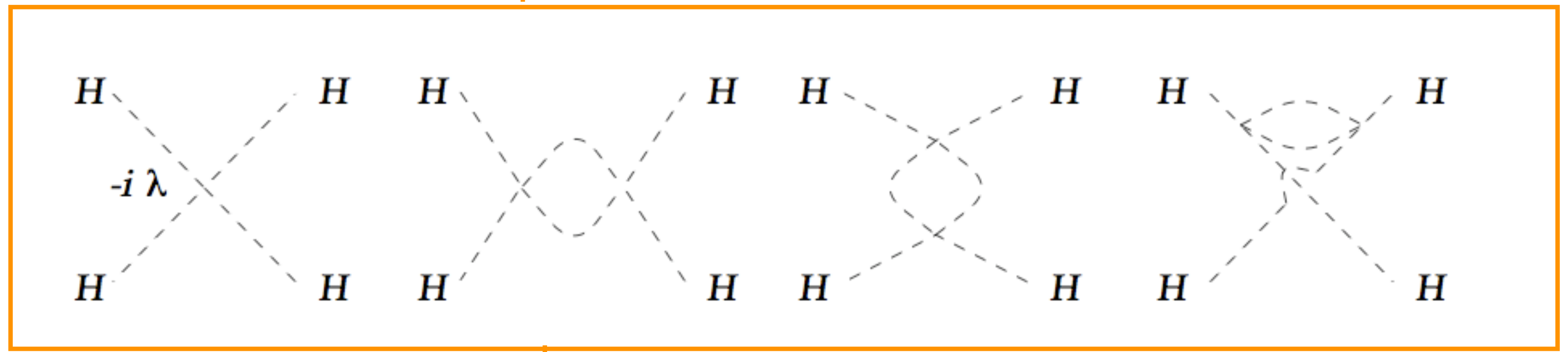
If there is new physics, it does not seem to be affecting the Standard Model through quantum corrections.

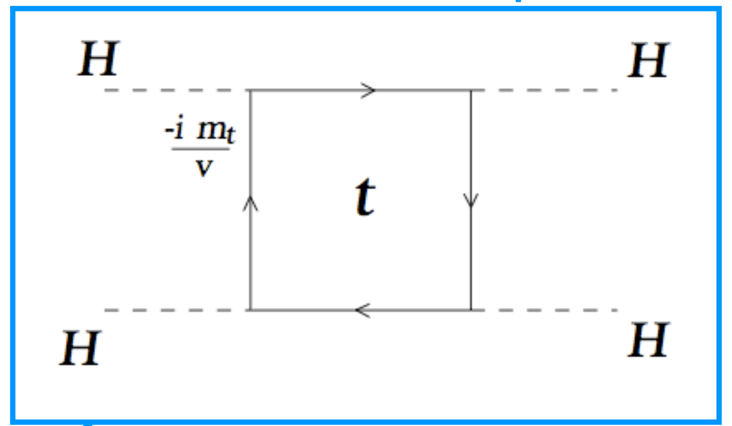
With the recent W mass measurement, the Standard Model is even more consistent!

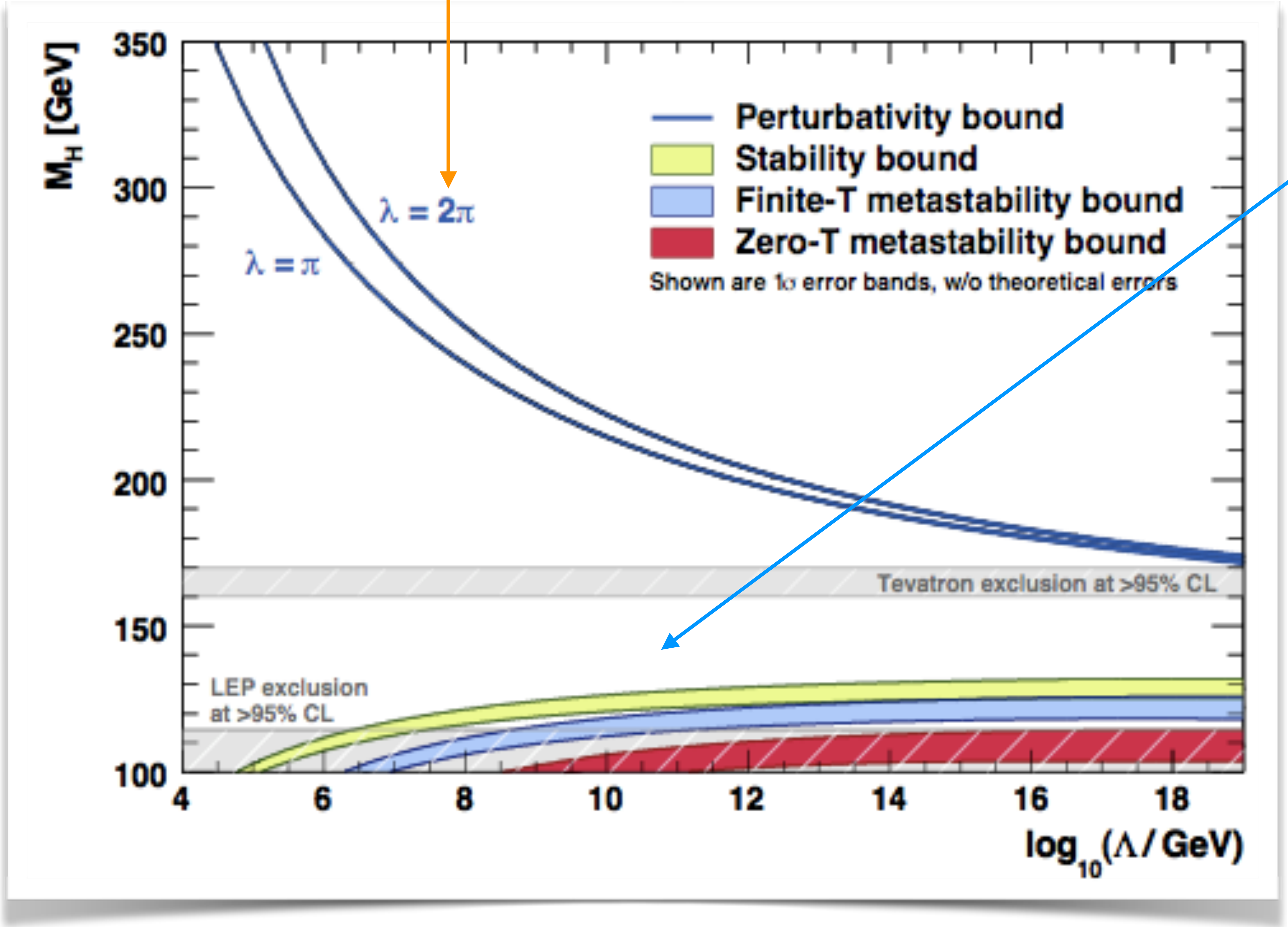
Implications II - TH consistency

Running of the Higgs self coupling:

$$32\pi^2 \frac{d\lambda}{dt} = 24\lambda^2 - (3g'^2 + 9g^2 - 24y_t^2)\lambda + \frac{3}{8}g'^4 + \frac{3}{4}g'^2 g^2 + \frac{9}{8}g^4 - 24y_t^4 + \cdots$$







With the discovery of the Higgs, for the first time in our history, we have a self-consistent theory that can be extrapolated to exponentially higher energies.

Nima Arkani Hamed

Triumph of the SM ?

Conclusions

Conclusions

- The discovery of the Higgs boson compatible with the SM Higgs boson has sealed the immense success of the Standard Model.

- The until then unknown parameter (Higgs boson mass) is now one of the most precisely measured parameters at the LHC (0.1% level).

- The Higgs physics program has blossomed and the boundaries of what is possible in Higgs properties measurements have been impressively expanded.

- The Higgs boson also raises many fundamental questions

- Key developments in Higgs physics to address these questions:
    - Precise measurement of its properties.
    - Search for rare production and decay process.
    - Particular attention to the diHiggs final state.
    - Searches for additional states.
    - Use the Higgs boson as a tool for discovery.