Higgs Physics at LHC

Lecture 3 –*Searches and future challenges* TAE 2017

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Overall Contents

Lecture 1: Fundamentals, The beauty and overwhelming success of the Standard Model

Lecture 2: Experimental profile of the Higgs boson, current challenges

Lecture 3: Future challenges (and future machines), implications and searches for new physics beyond the Standard Model

Higgs physics Landscape Redefined

Flurry of new ideas !

Precision
- Mass and width
- Coupling properties
- Quantum numbers (Spin, CP)
- Differential cross sections
- Off Shell couplings and width
- Interferometry

Rare decays
- $Z\gamma$, $\gamma\gamma^*$
- Muons $\mu\mu$
- LFV $\mu\tau$, $e\tau$
- $J/\Psi\gamma$, $Z\Upsilon$, WD etc...

$$H^0$$

Is the SM minimal?
- 2 HDM searches
- MSSM, NMSSM searches
- Doubly charged Higgs bosons

Tool for discovery
- Portal to DM (invisible Higgs)
- Portal to hidden sectors
- Portal to BSM physics with H^0 in the final state (ZH^0, WH^0, H^0H^0)

...and More!
- FCNC top decays
- Di-Higgs production
- Trilinear couplings prospects
- Etc...

Higgs Physics - Lecture 3

Beyond main channels, and future challenges

1.- Searches for rare decays

2.- Searches for rare production modes

3.- Double Higgs production

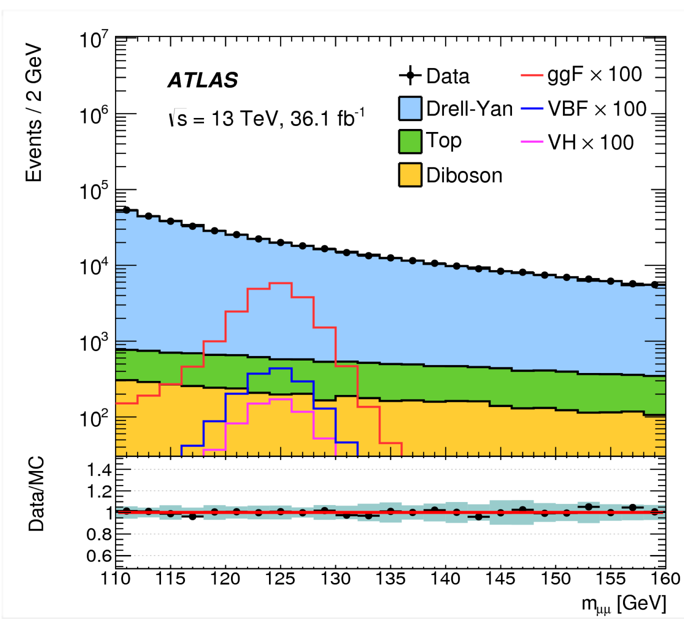
4.- Searches for extended Higgs sectors

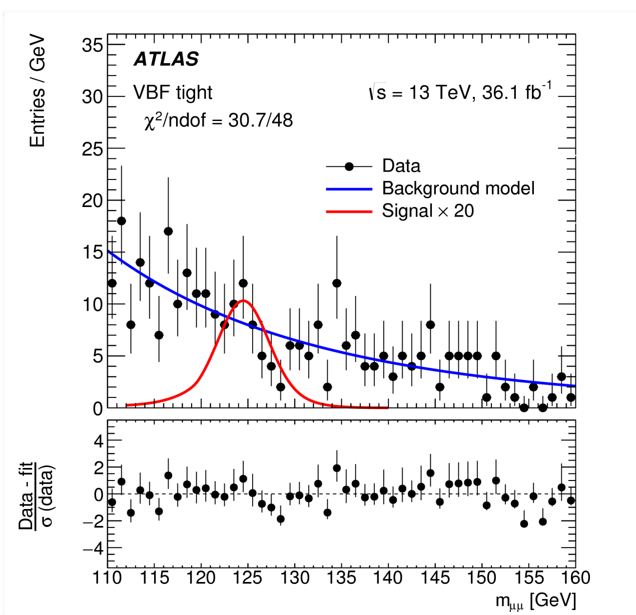
5.- Future projects

Dimuon Channel

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

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



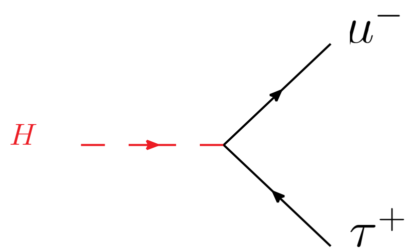


95% CL limits at 2.8 (obs) and 2.9 (exp), no significant signal seen:

$$\mu = -0.1 \pm 1.4$$

Combined sensitivity with Run 3

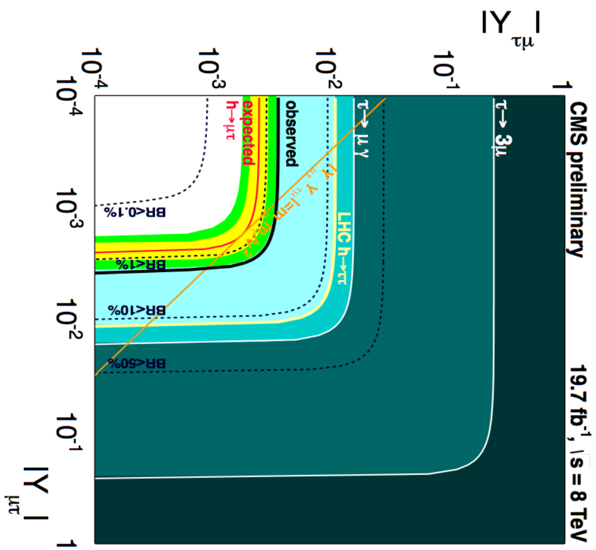
LFV Decays of the Higgs boson



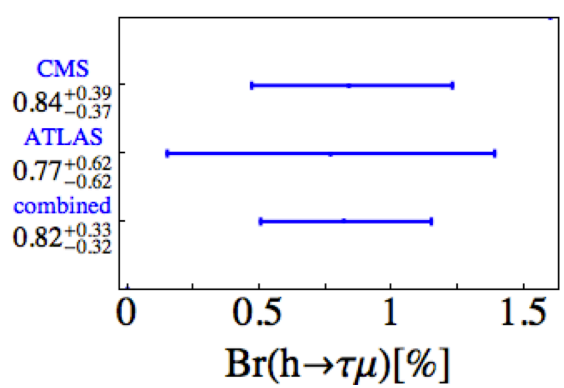
Strong Constraints on $Br(H \to e\mu) < O(10^{-8})$ from $\mu \to e\gamma$

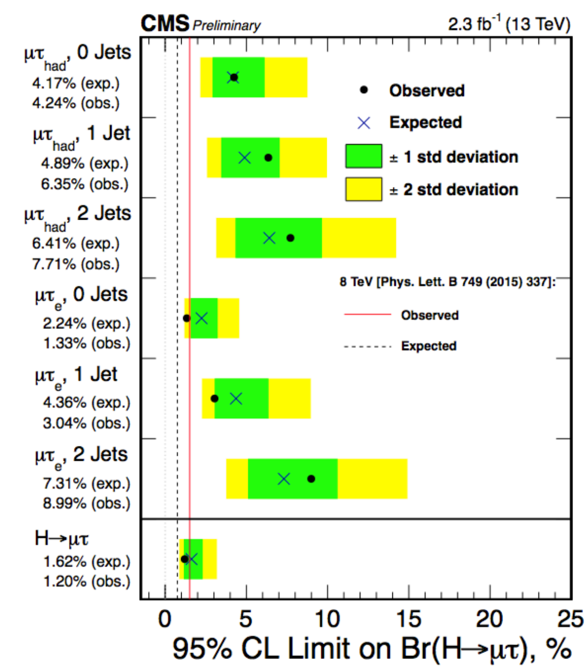
$\tau\mu$ channel studied at Run 1, with analyses in both the hadronic and leptonic decay channels of the tau both in ATLAS and CMS.

- Different background estimation strategy in ATLAS and CMS for the fully leptonic channel.
- Modest excess observed (more significant in CMS) at Run 1.
- Early Run 2 analysis performed by CMS in 2015 data no excess observed.
- Worth keeping an eye on it.

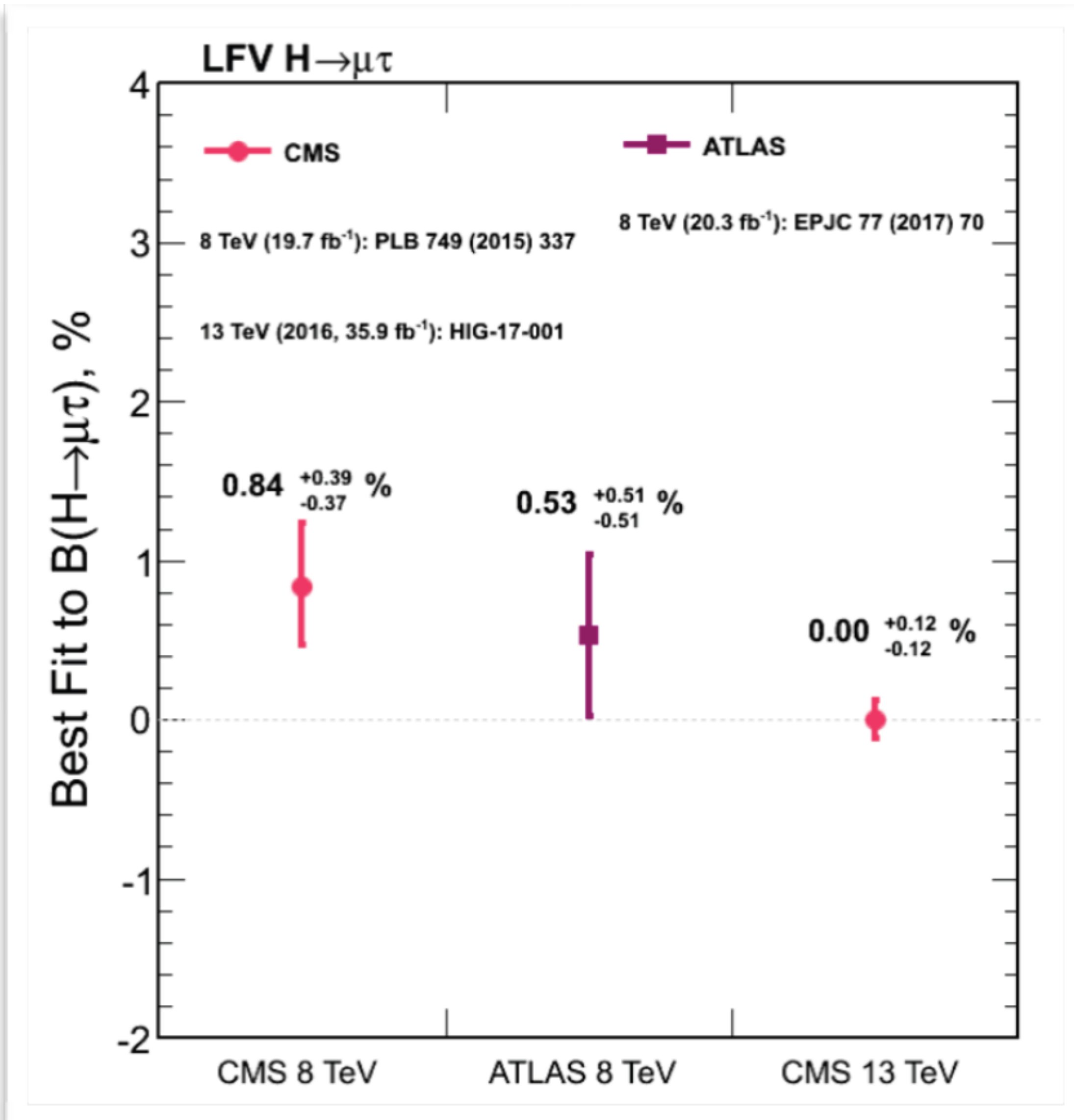


Run 1 results





LFV Decays of the Higgs boson

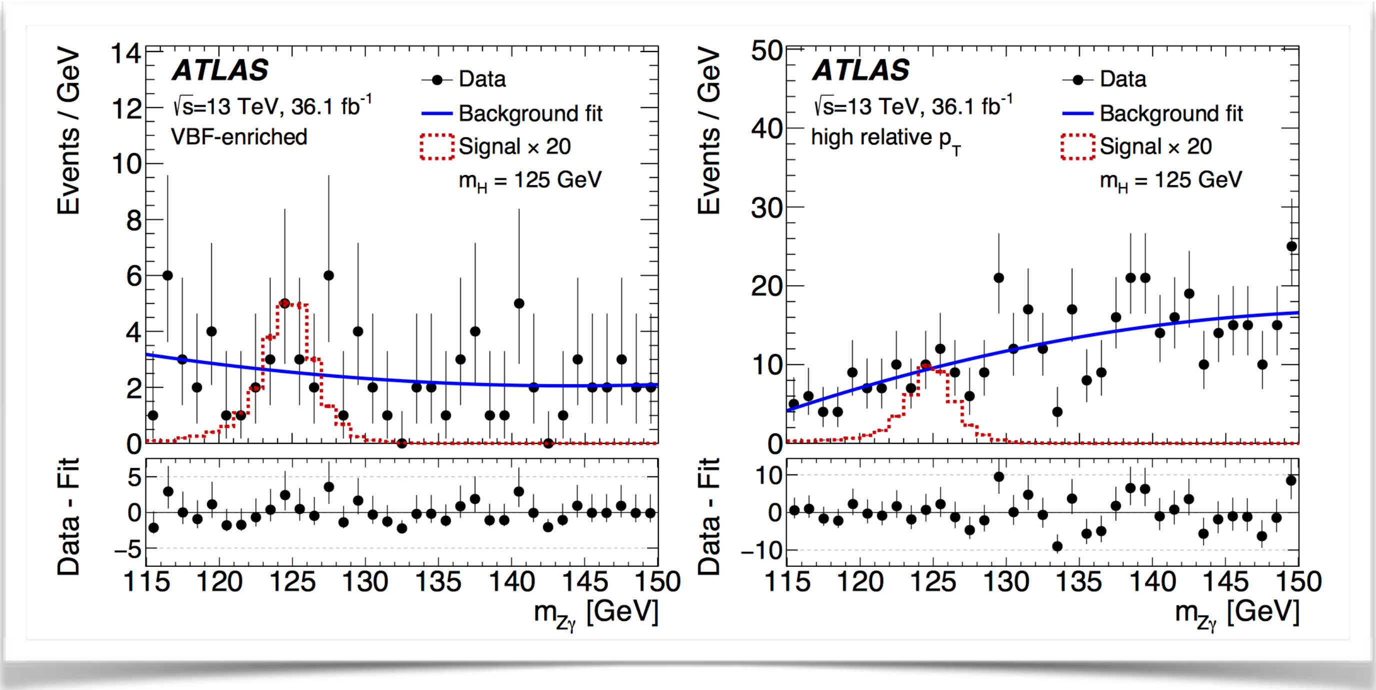


F. Meng Higgs Hunting 2017

$Z\gamma$ 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.

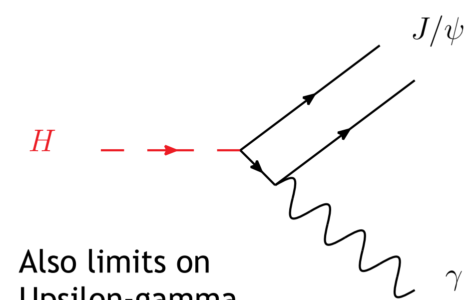


95% CL limits at 6.6 (obs) and 5.2 (exp), no significant signal observed.

Decays with to Quarkonia and a photon

Phys.Rev.Lett. 114 (2015) no.12, 121801

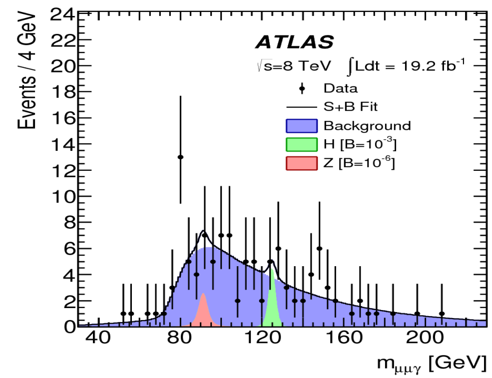
Current limits



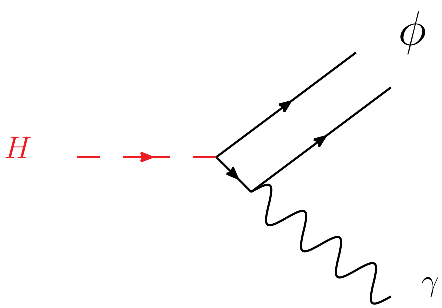
Also limits on Upsilon-gamma

Potentially sensitive to charm Yukawa

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

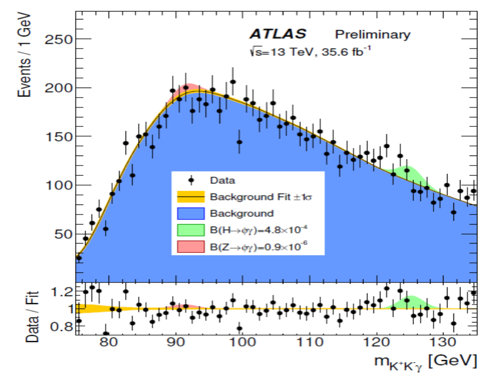


Higgs ~400 x SM

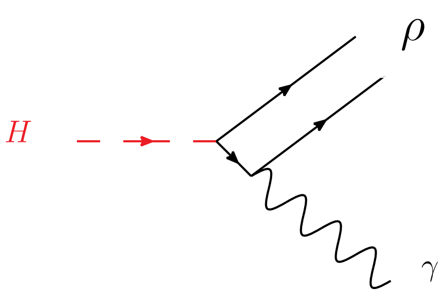


Potentially sensitive to strange Yukawa

$K^+K^-\gamma$

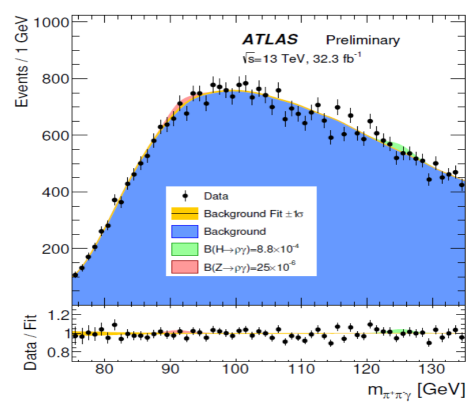


Higgs ~200 x SM



Potentially sensitive to light Yukawa

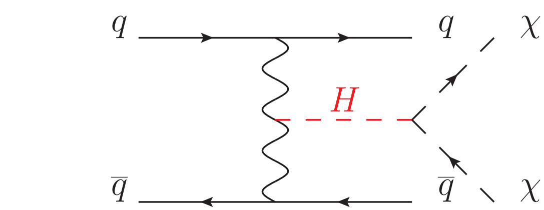
$\pi^+\pi^-\gamma$



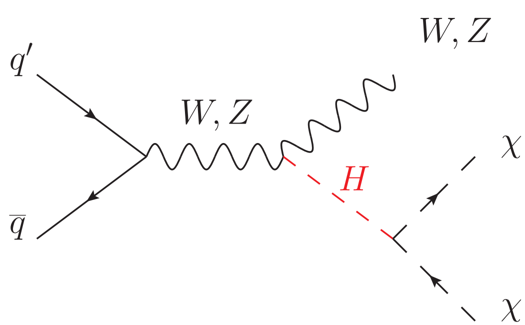
Higgs ~50 x SM

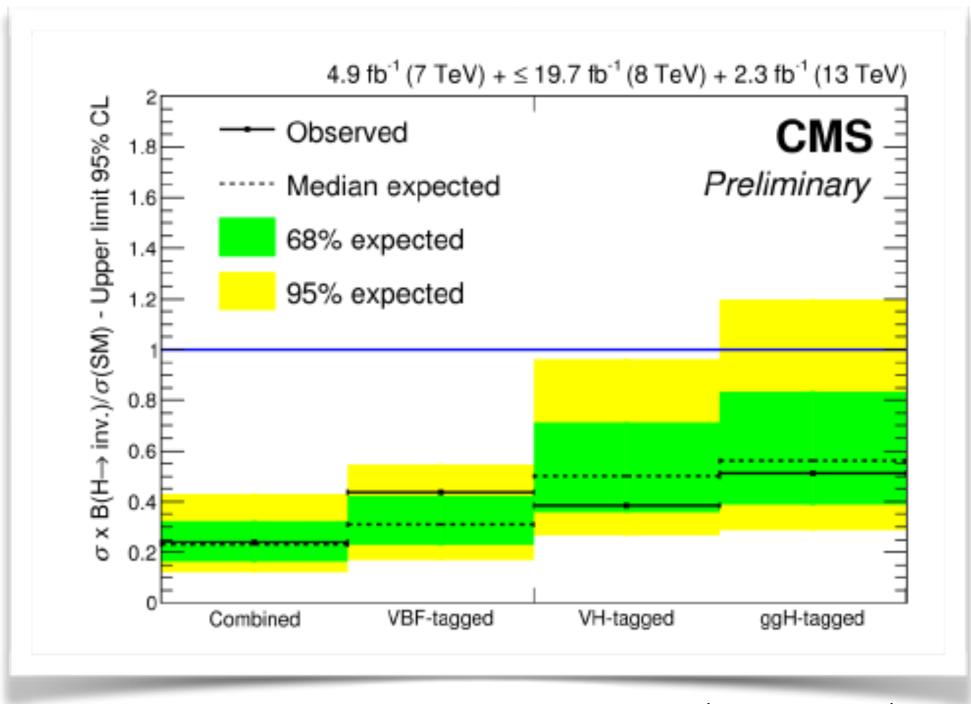
Invisible decays of the Higgs boson

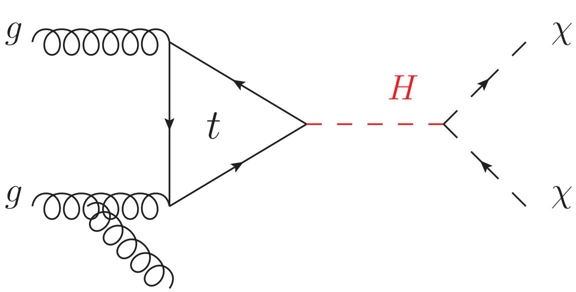
CMS-PAS-HIG-16-016



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







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

Higgs Physics - Lecture 3

Beyond main channels, and future challenges

1.- Searches for rare decays

2.- Searches for rare production modes

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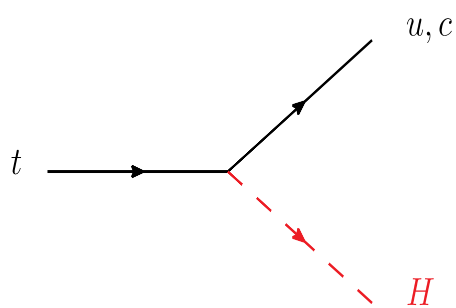
Rare Production Modes

CMS-PAS-HIG-16-019

Run 1 only

Flavor changing neutral curent decays of the top quark



Various decay channels of the Higgs boson (gg, bb)

Limits on $Br(t \rightarrow Hq)$

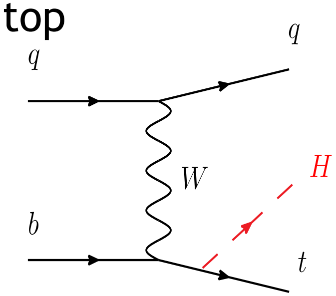
SM Branching ~10^{-15}

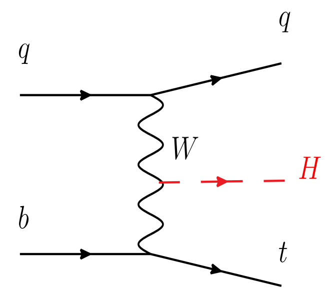
$$Br(t \rightarrow cH) < 0.79\ (0.51)\%$$

JHEP 06 (2014) 08

Single top associated production

Tree level interference between W and top

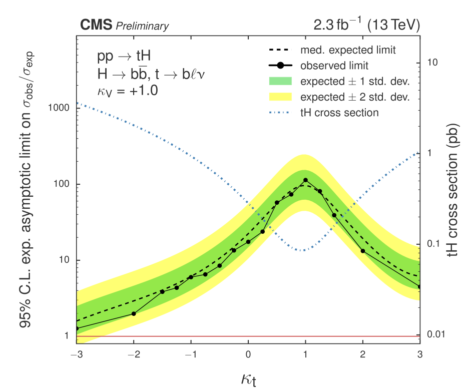




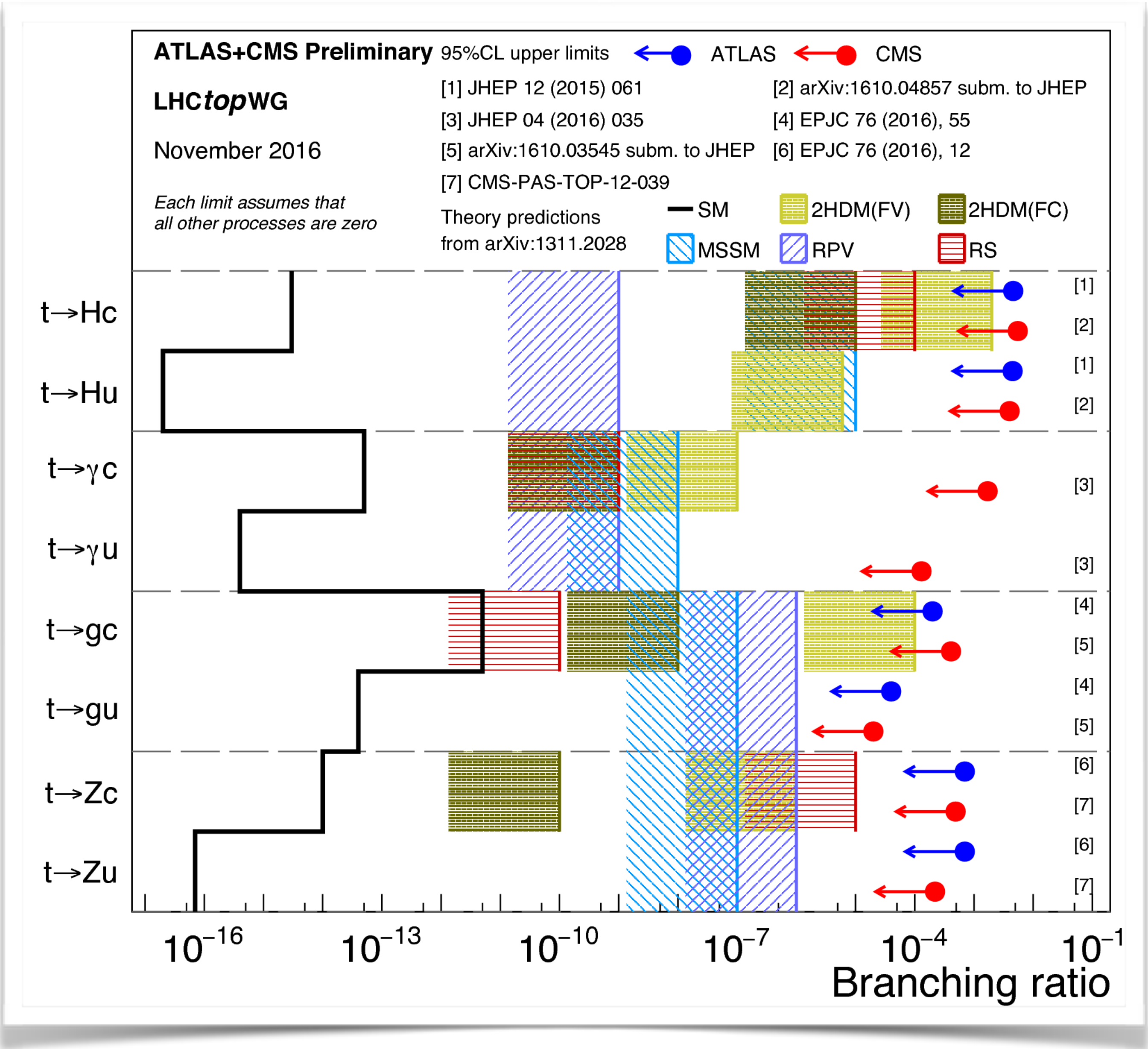
$$\propto 3.3 \times \kappa_W^2 - 5.1 \times \kappa_t \kappa_W + 2.8 \times \kappa_t^2$$

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)



Higgs decays in Top Summary of FCNCs



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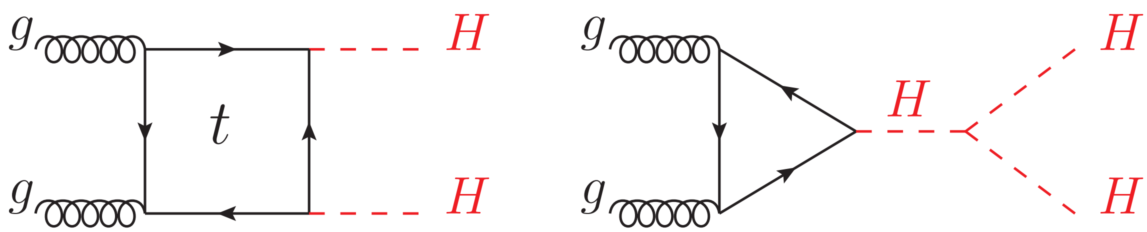
Double Higgs Production



- 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.

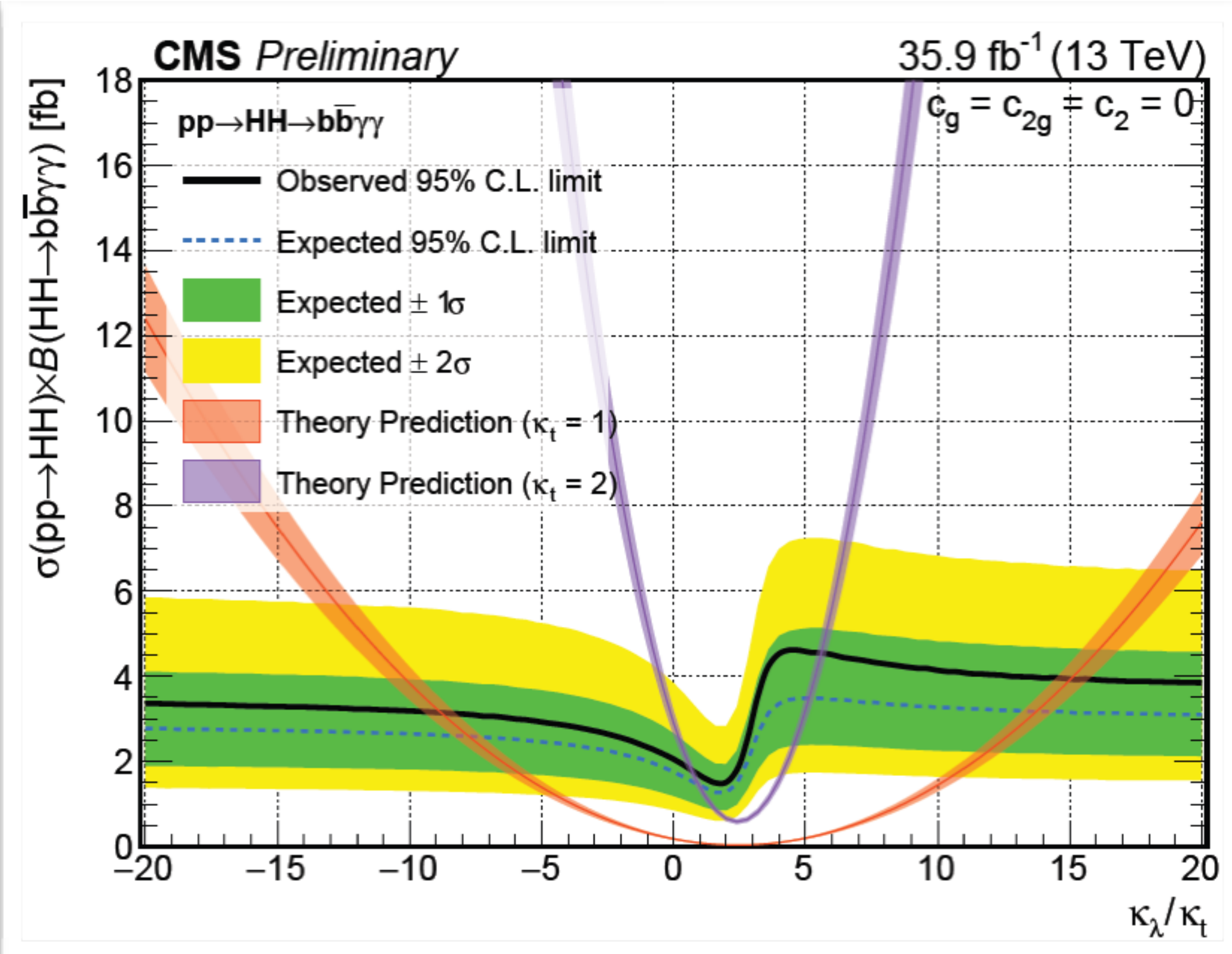
- Similarly to the Off-Shell analysis there is a large destructive interference between the triangle and the box contributions.

- The total production cross section is very small.

- The main channels are:

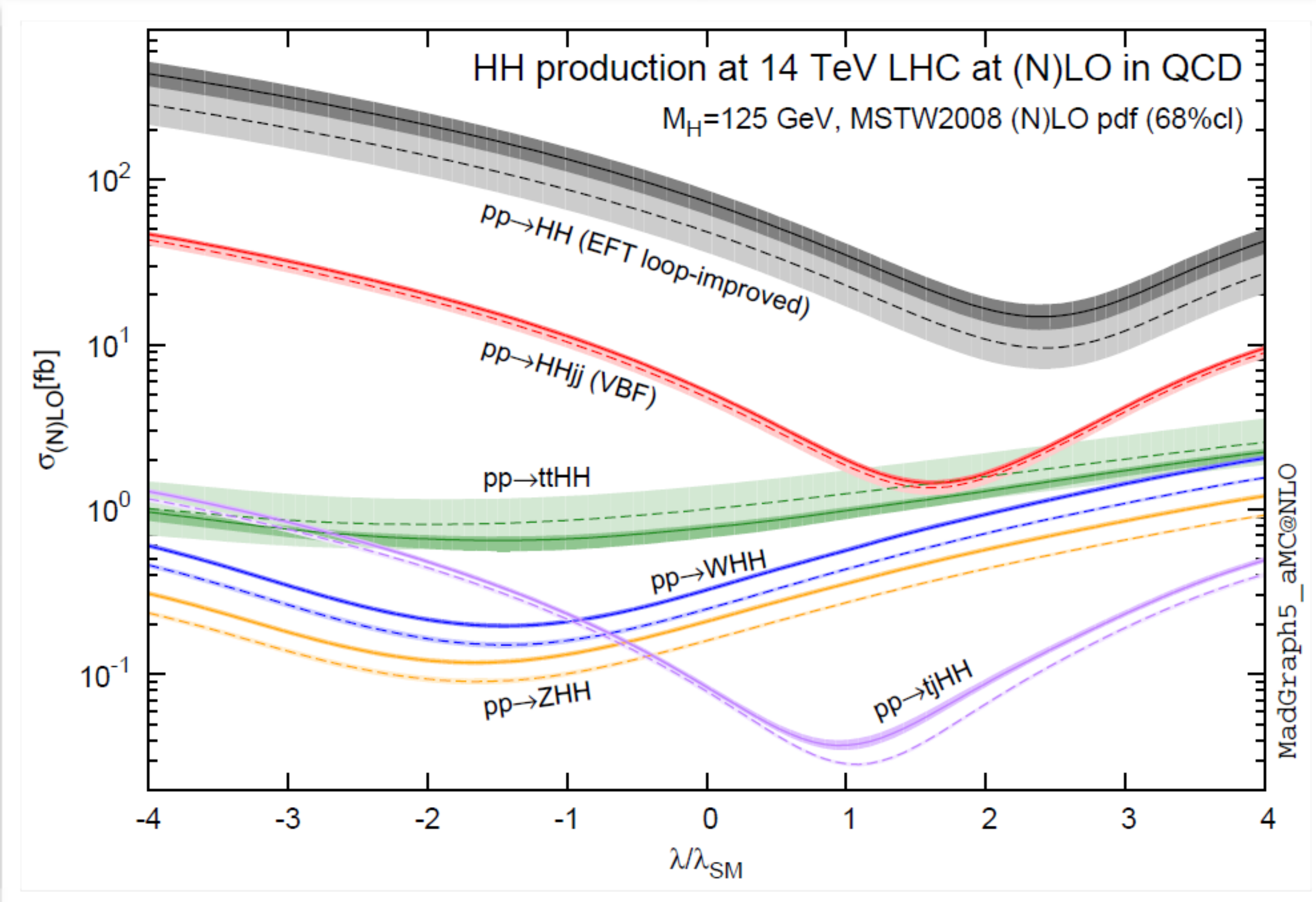
$$b\bar{b}\gamma\gamma \quad b\bar{b}\tau^+\tau^- \quad b\bar{b}b\bar{b} \quad b\bar{b}W^+W^- \quad \gamma\gamma W^+W^-$$

Double Higgs Production



Current 95% CL limit is at 19.2 x SM expectation

Double Higgs Production



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

Double Higgs Production

Summary of Results

	bbgg	bbtt	bbWW	bbbb	WWgg
ATLAS	<117 (161)	-	-	<29 (38)	<747 (386)
CMS	**<19 (17)**	**<30 (25)**	**<79 (89)**	<342 (308)	-

Run 2 data

3 fb-1

12 fb-1

36 fb-1

Higgs Physics - Lecture 3

Beyond main channels, and future challenges

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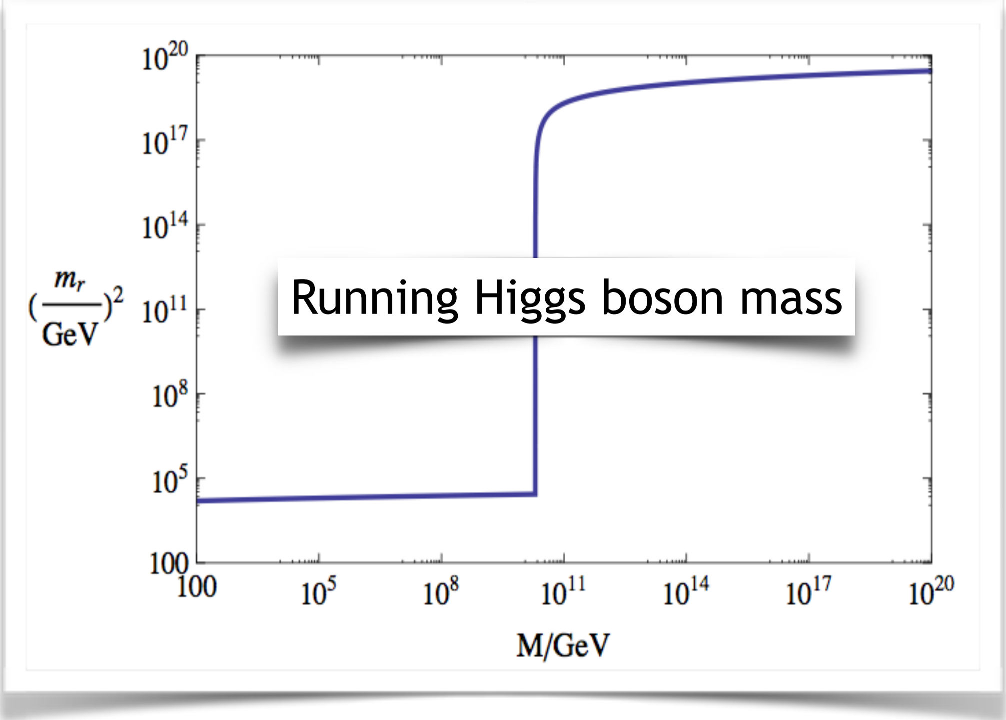
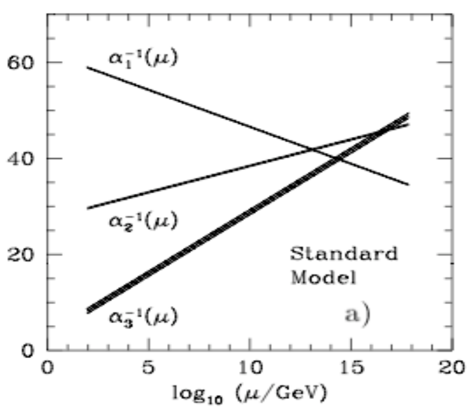
A word on Naturalness and the Higgs boson

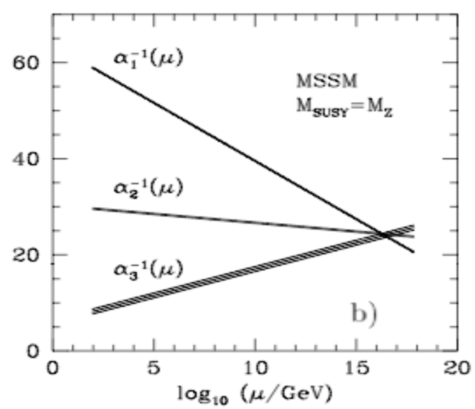


R. Barbieri
Nobel Coloquium

Solutions:

- Weakly coupled (SUSY)
- Strongly coupled (Composite)
- Anthropic principle





SUSY also…

- Allows the unification of couplings
- Local SUSY: spin 3/2 gravitino (essential ingredient in strings)
- Natural candidate for Dark Matter

Extented Higgs Sectors

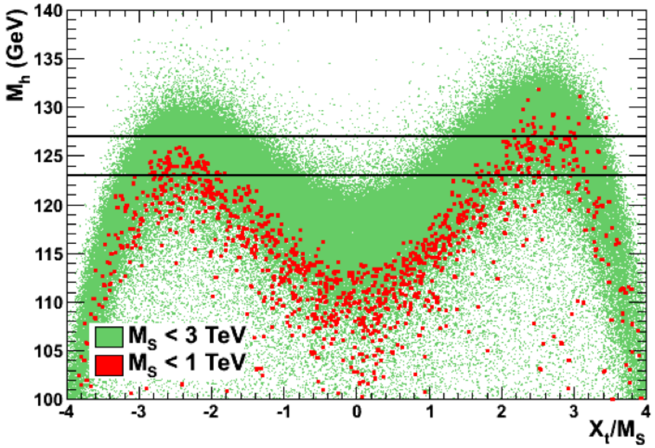
1.- Why should it be minimal?

2.- Additional doublets (2 HDMs) ?

SUSY: Two doublets with opposite hypercharges are needed to cancel anomalies (and to give masses independently to different isospin fermions)

2 HDMs in general : 5 Higgs bosons

- Two CP even h and H
- One CP odd A
- Two charged Higgs bosons



Parameter space in MSSM growing thin

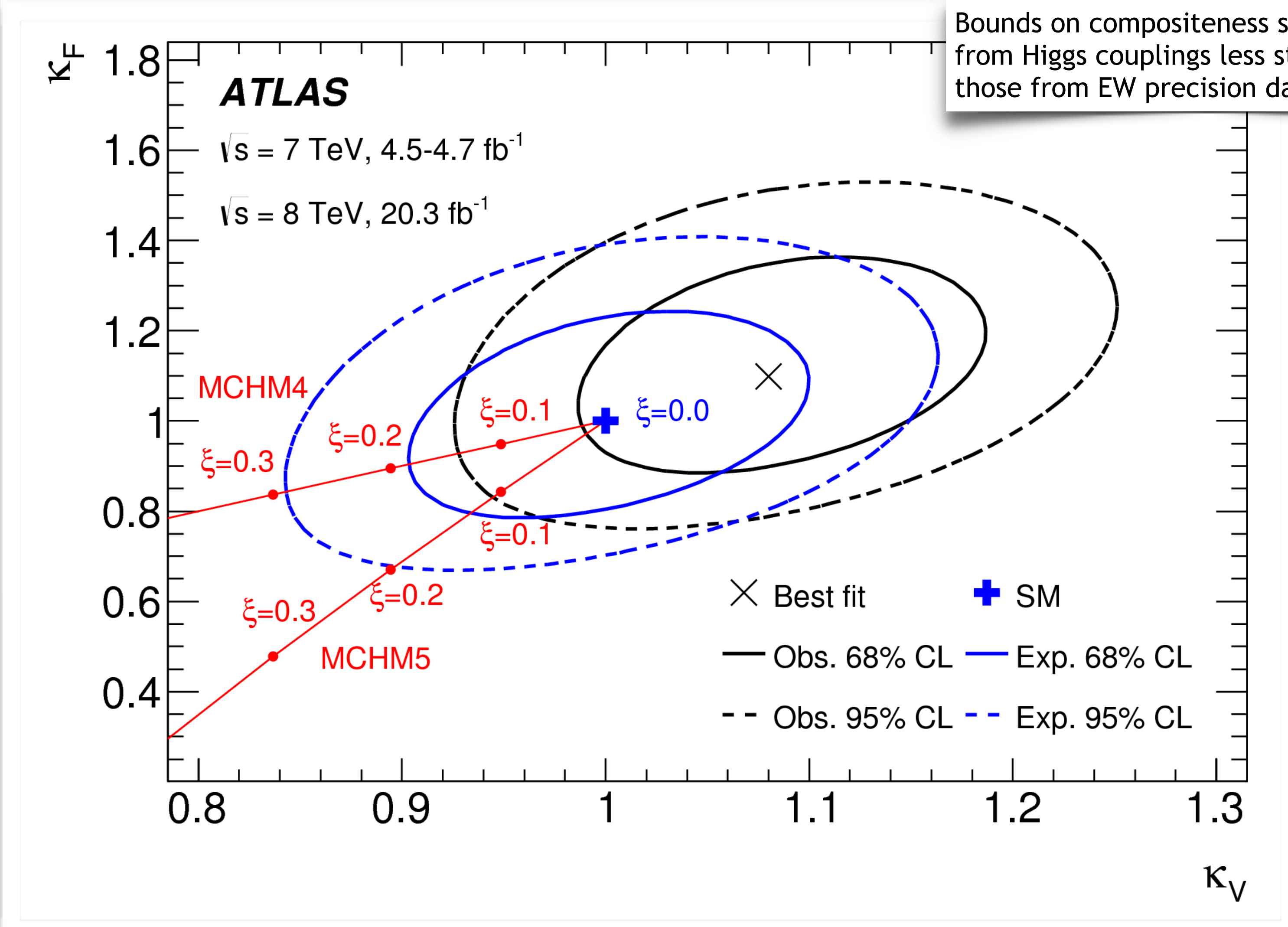
3.- Additional singlets ?

μ parameter (of the superpotential) problem in SUSY, can be solved by the introduction of a singlet field in the NMSSM

4.- Additional triplet(s) ?

In order to generate Majorana mass terms for neutrinos

Minimal Composite Higgs Scenarios



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

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

Summary of Searches

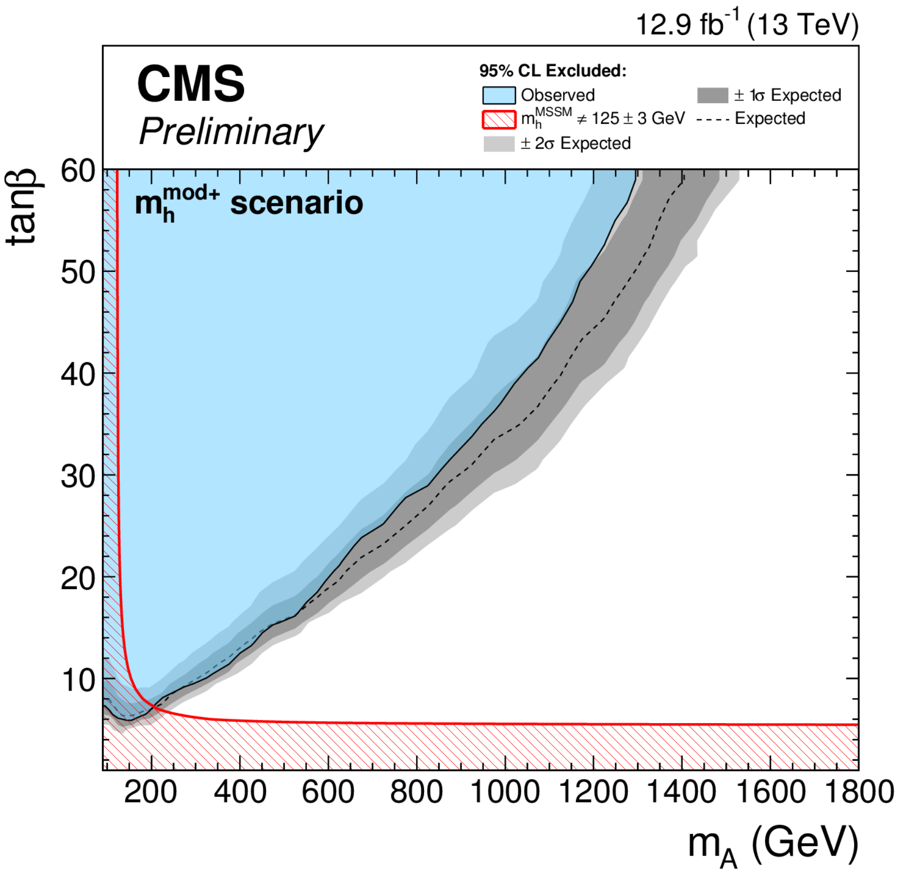
	ATLAS	CMS	Other experiments
CP-even H			
$H \to \gamma\gamma$	*	*	
$H \to Z\gamma$	*	*	
$H \to ZZ \to 4\ell$	*	*	
$H \to ZZ \to \ell\ell\nu\nu$	*	*	
$H \to ZZ \to \ell\ell q\bar{q}$	*	*	
$H \to ZZ \to \nu\nu q\bar{q}$	*	*	
$H \to WW \to \ell\nu\ell\nu$	*	*	
$H \to WW \to \ell\nu\ell\nu$ (2HDM)	*	*	
$H \to WW \to \ell\nu q\overline{q'}$	*	*	
$H \to VV \to q\overline{q'}q\overline{q'}(JJ)$	*	*	
$H \to hh \to b\bar{b}\tau\tau, b\bar{b}\gamma\gamma, 4b, \gamma\gamma WW^*$	*	*	

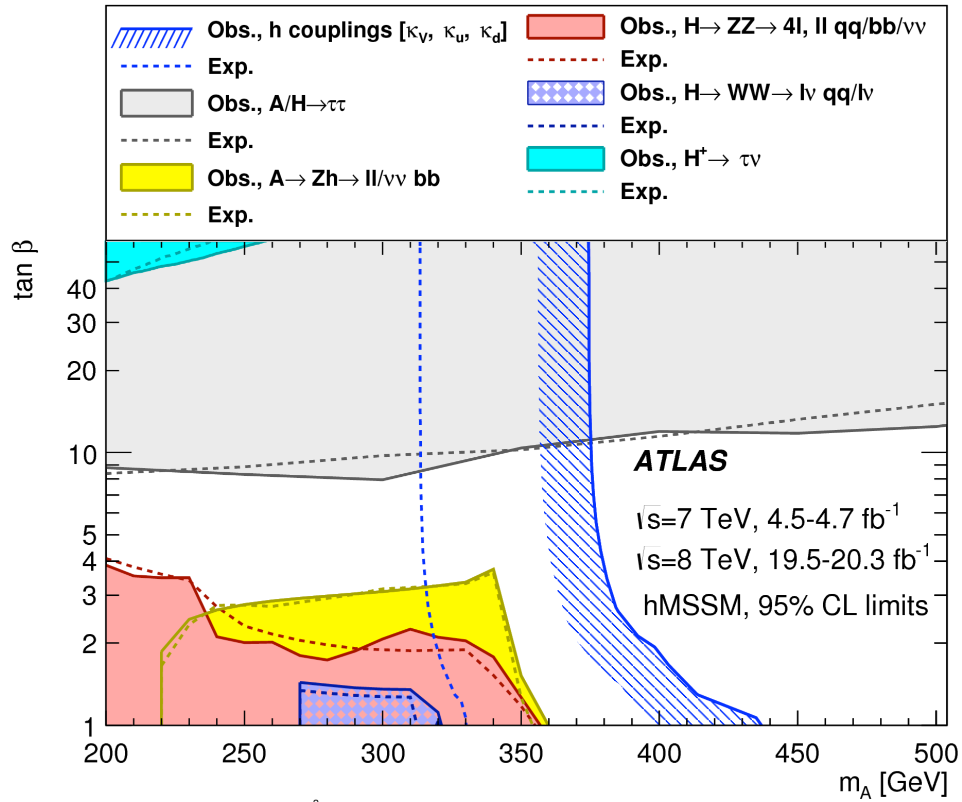
* Run 1 or other experiments   * Run 2

Summary of Searches

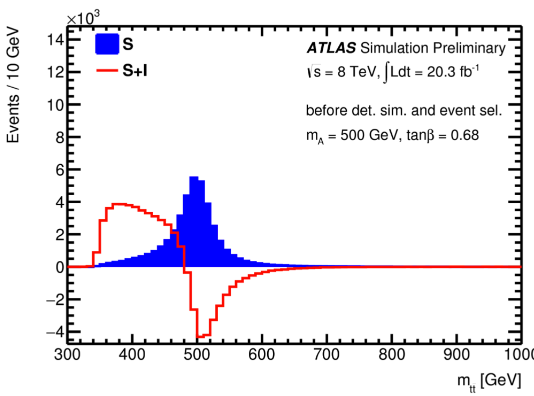
	ATLAS	CMS	Other experiments
CP-odd A (and/or CP-even H)			
$H, A \to \tau^+\tau^-$	*	*	*
$H, A \to \mu^+\mu^-$	*	*	
$H, A \to t\bar{t}$	*	*	
$H, A \to b\bar{b}$		*	*
$A \to hV \to b\bar{b}q\overline{q'}, b\bar{b}\ell\nu, b\bar{b}\ell\ell, \ell\ell\tau\tau, \nu\bar{\nu}b\bar{b}$	*	*	
Charged $H^\pm$			
$H^\pm \to \tau^\pm\nu$	*	*	
$H^\pm \to cs$	*	*	
$H^\pm \to tb$	*	*	
$H^\pm \to W^\pm Z$	*	*	
CP-odd NMSSM a			
$a \to \mu^+\mu^-$	*	*	
$h \to aa \to 4\mu, 4\tau, 2\mu2\tau, 4\gamma$	*	*	
$\Upsilon_{1s,3s} \to a\gamma$			*
Doubly Charged $H^\pm$	*	*	

Summary of Searches

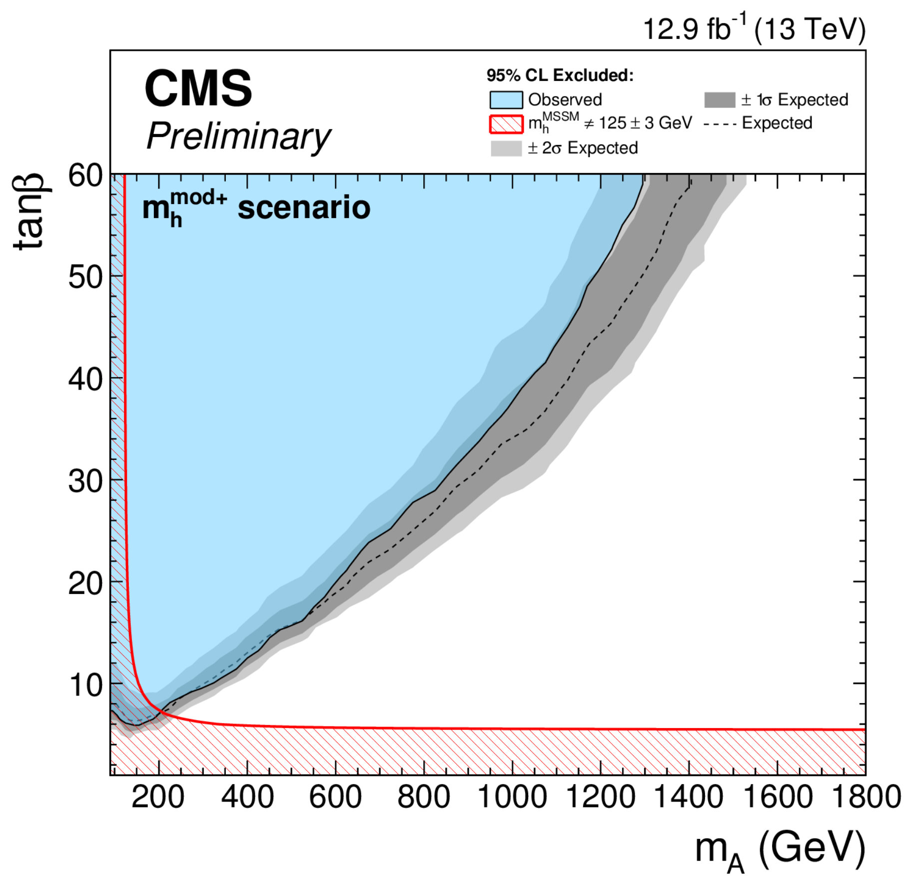


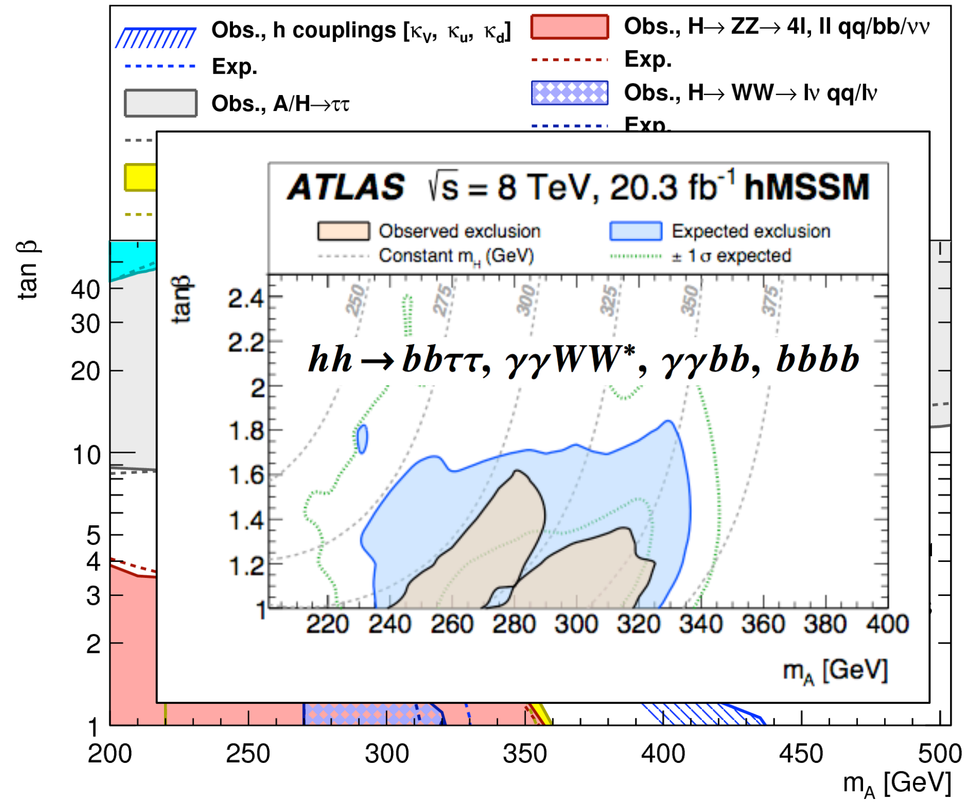


Searches for tt resonances are important to cover higher masses (above tt threshold), taking correctly interference effects into account is crucial – first attempt (8 TeV):

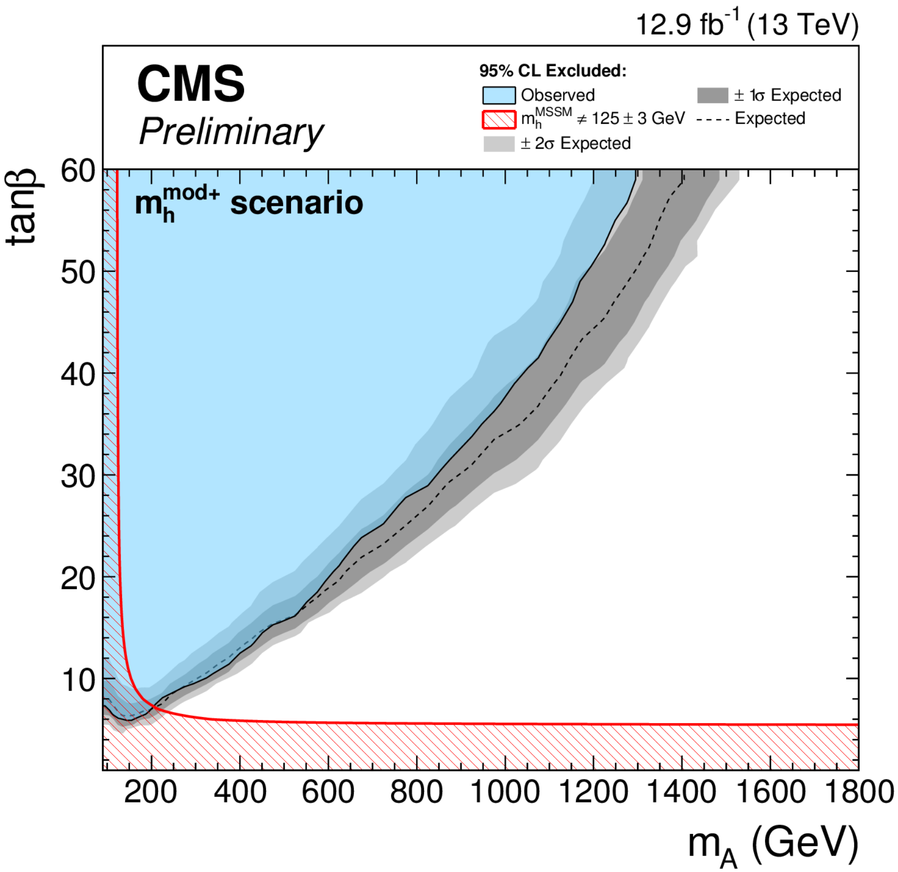


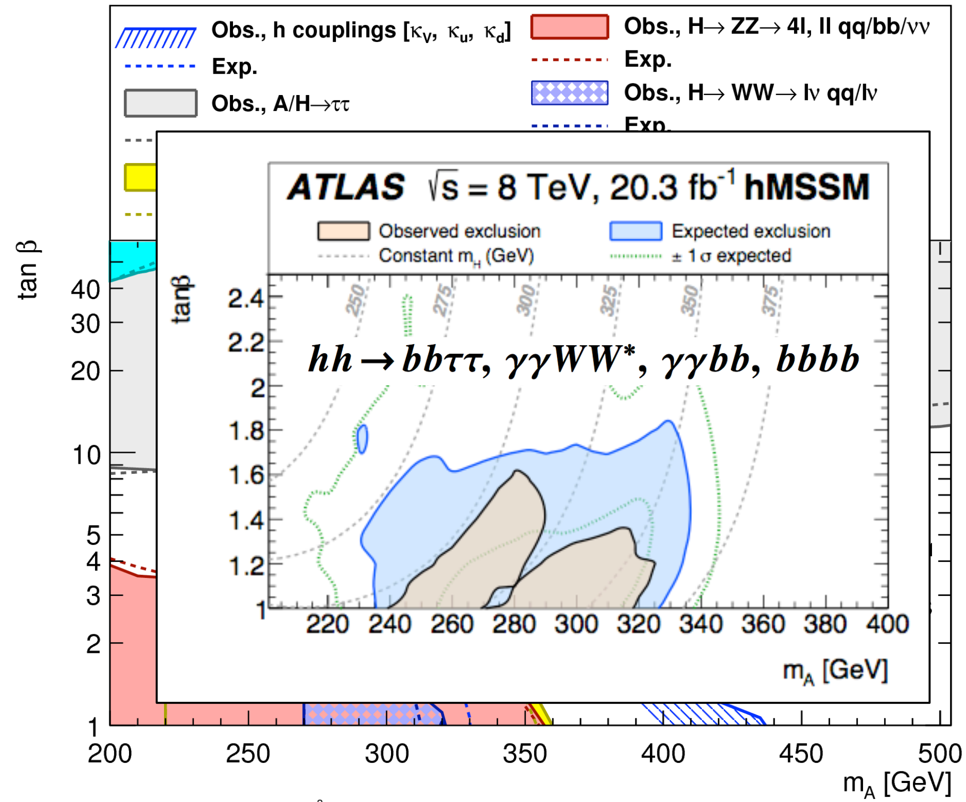
Summary of Searches





Summary of Searches





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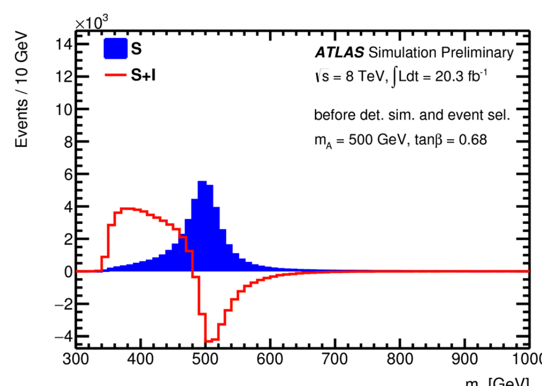

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European Strategy Update

Europe's top priority should be the exploitation of the full potential of the LHC, including the high-luminosity upgrade of the machine and detectors with a view to collecting ten times more data than in the initial design, by around 2030.

Pushing LHC Limits

HL-LHC

$$\mathcal{L} = \frac{N_p^2 k_b f_{rev} \gamma}{4\pi\beta^* \varepsilon_N} F$$

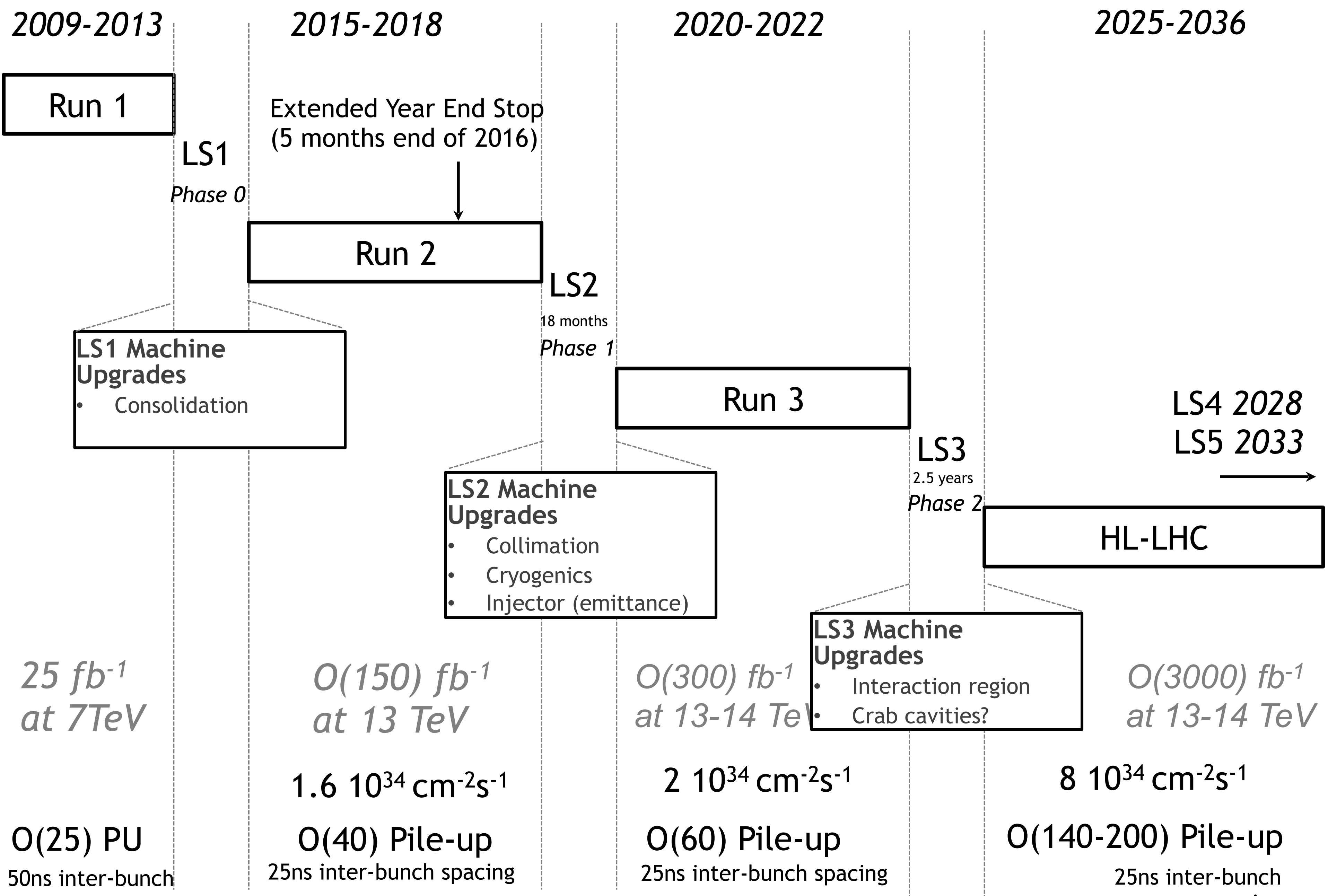
- **Filling at the beam-beam effects limit** Increasing the number of protons per bunch by a factor of 2 to 3.
- **Going to smaller β*** Going to 15cm - will require larger quadrupole aperture.
- **Luminosity leveling** To mitigate the highest peak instantaneous luminosity level luminosity to minimize loss in integrated luminosity.
- **Crossing angle** To mitigate the long range beam-beam effect 285 μrad to 590 μrad.

Goal is a leveled luminosity of ~5 10^{34} $cm^{-2}s^{-1}$

HE-LHC

Doubling the energy will require new magnets e.g. Nb3Sn to reach ~15 T

The LHC: *Only ~1% of the total so far*

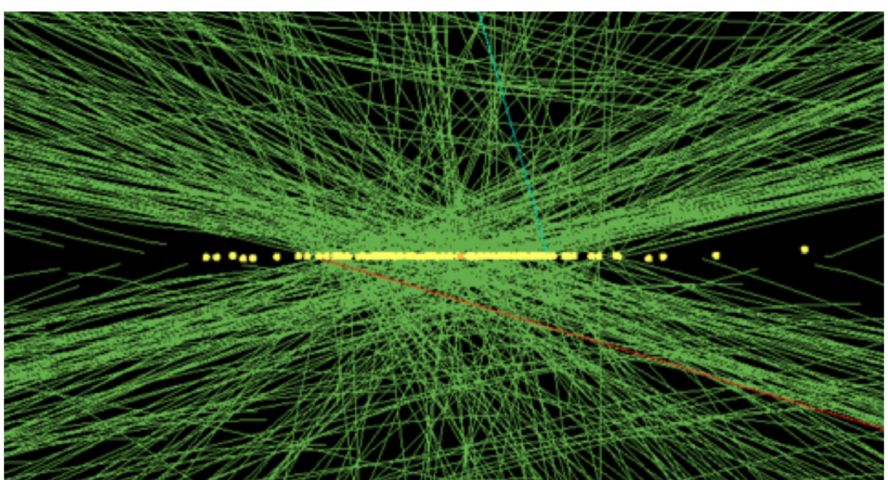


HL-LHC Beam Parameters

Two HL-LHC scenarii

$$\mathcal{L} = \frac{N_p^2 k_b f_{rev} \gamma}{4\pi \beta^* \epsilon_n} F$$

Parameter	2016	Nominal	HL-LHC (25 ns)	HL-LHC (50 ns)
C.O.M Energy	13 TeV	13-14 TeV	14 TeV	14 TeV
N_p	1.2 10^{11}	1.15 10^{11}	2.0 10^{11}	3.3 10^{11}
Bunch spacing / k	25ns /2300	25 ns /2808	25 ns /2808	50ns /1404
ε (mm rad)	2.6	3.75	2.5	3.0
β* (m)	0.4	0.55	0.15	0.15
L ($cm^{-2}s^{-1}$)	1.5x10^{34}	10^{34}	7.4 10^{34}	8.4 10^{34}
Pile up	~30	~20	~140	~260

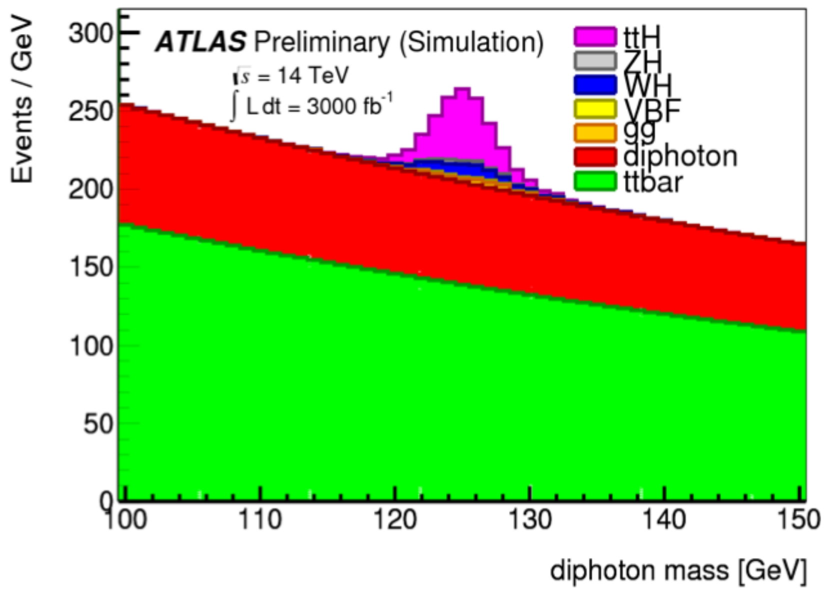


How non-linear are the PU effects?

CMS event with 78 reconstructed vertices

Reaching ttH Production in (robust) rare modes

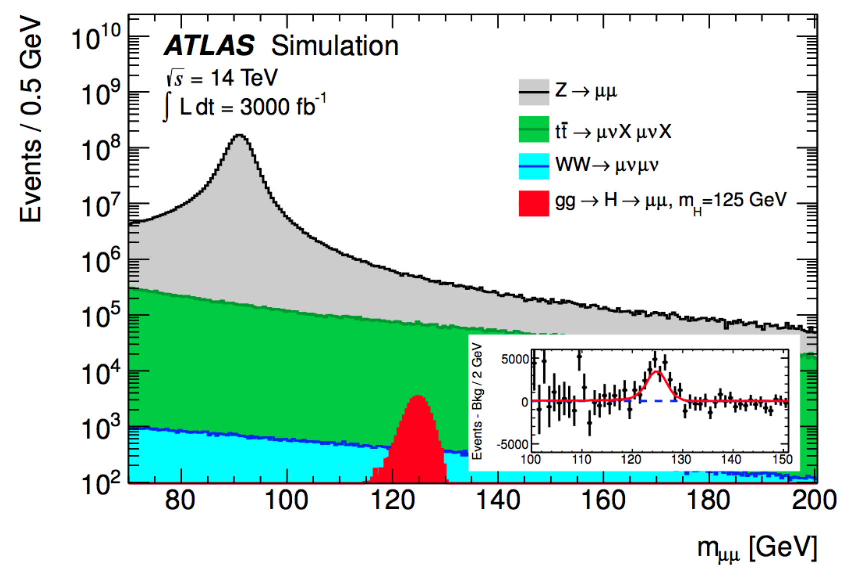
Analyses not relying on more intricate decay channels (bb, tt and WW)



- $\gamma\gamma$ channel: more than 100 Events expected with s/b~1/5
- $\mu\mu$ channel: approximately 30 Events expected with s/b~1

Analyses (rather) robust to PU

$\mu\mu$ decay mode should reach more than 5 standard deviation

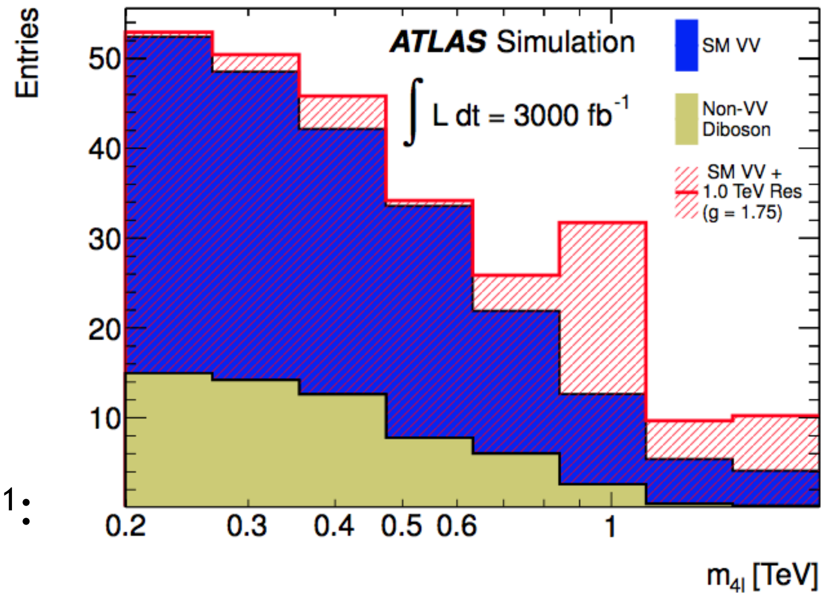


Completing the Picture WBS
Weak Boson Scattering

Of course with a Higgs boson the case is thinner!

Only taking into account the cleanest signals : ZZjj in the 4 leptons final state

Very clean signature for a TeV resonance (in anomalous WBS models)

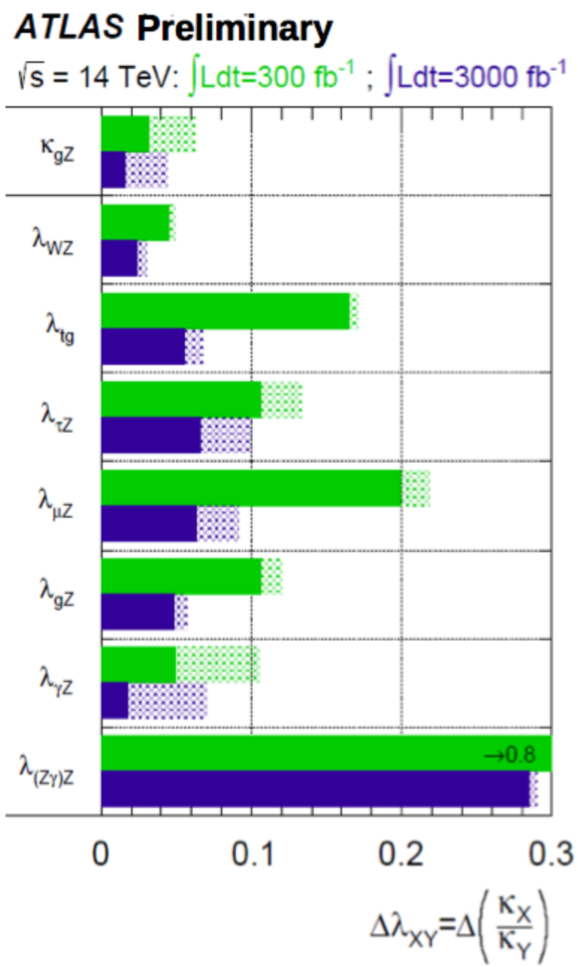


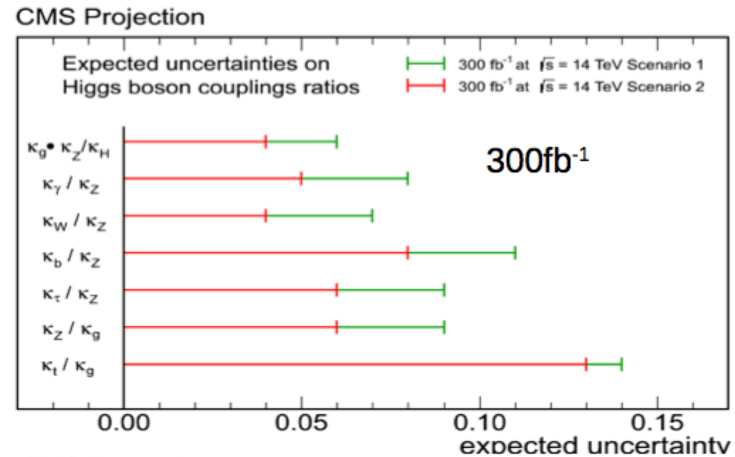
Sensitivities for 300 fb^{-1} and 3 ab^{-1}:

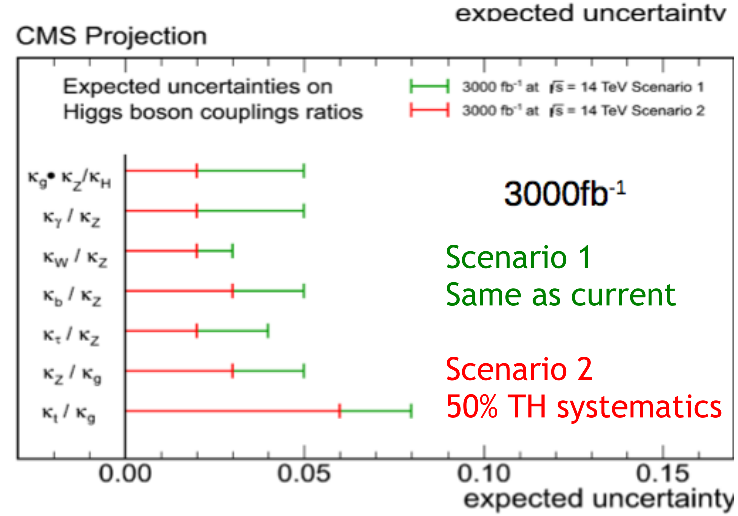
Model (anomalous WBS)	300 fb^{-1}	3 ab^{-1}
500 GeV and g=1	2.4 σ	7.5 σ
1 TeV and g=1.75	1.7 σ	5.5 σ
1 TeV and g=2.5	3.0 σ	9.4 σ

LHC Higgs Physics Program: Main Couplings

Couplings Projections recently reappraised with a sample of analyses







Only indirect (however not negligible) constraint on the total width

Necessary to use assumptions or measure ratios: Precision down to ~5% level

LHC Higgs Physics Program: Main Couplings

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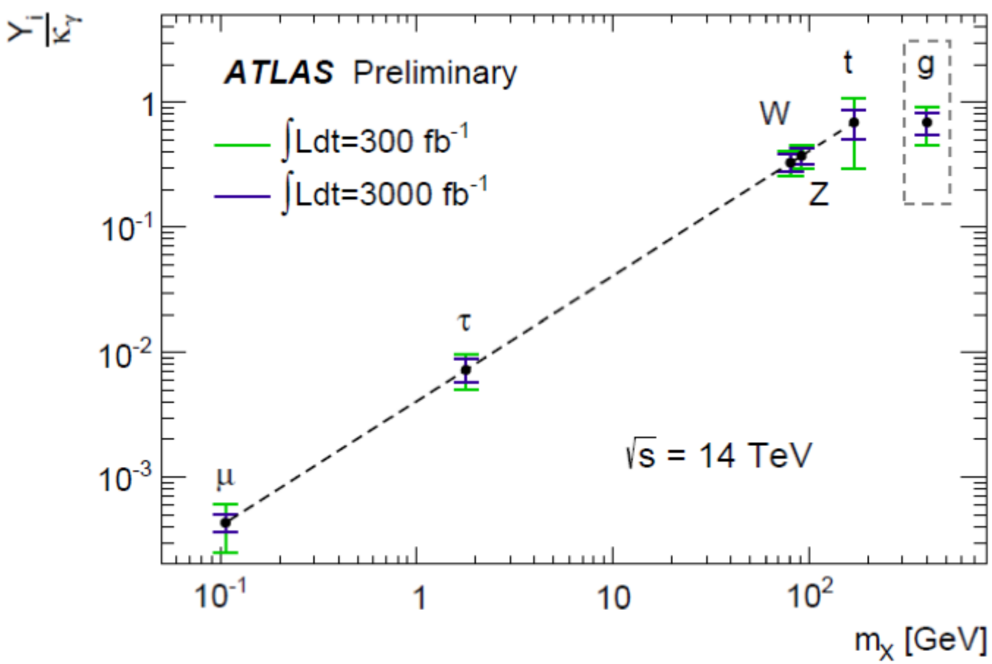
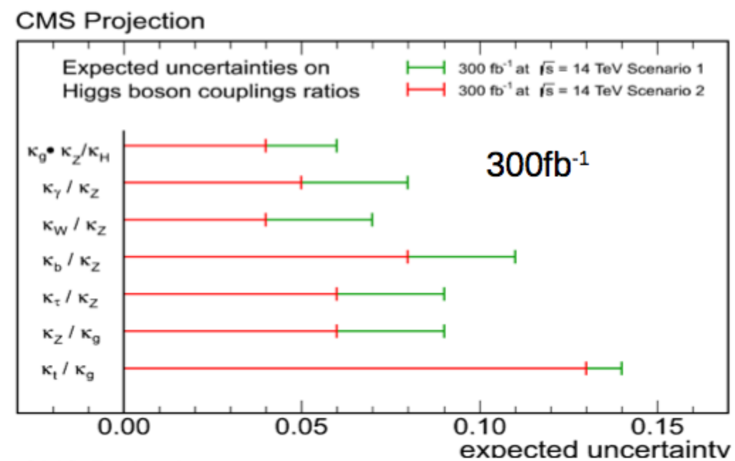
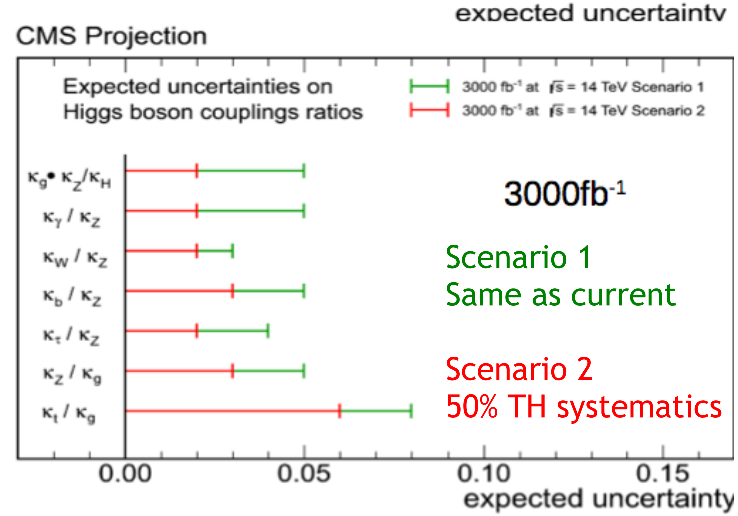






Only indirect (however not negligible) constraint on the total width

Necessary to use assumptions or measure ratios: Precision down to ~5% level

Di-Higgs Production Self Couplings

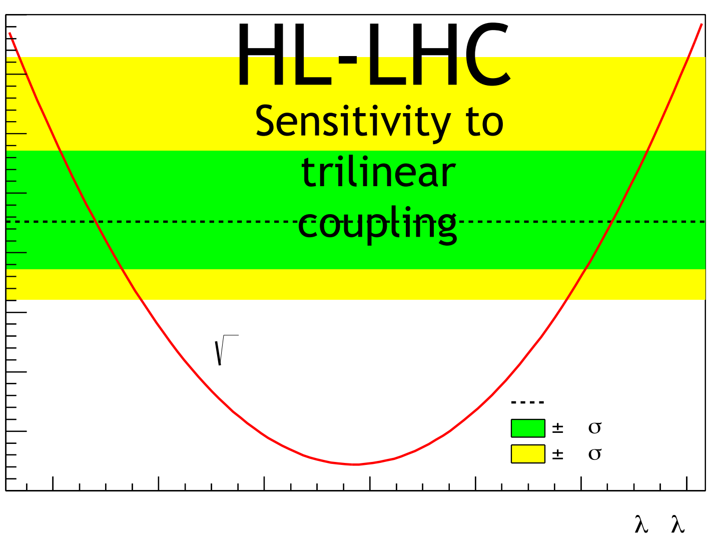
ATL-PHYS-PUB-2014-019

At HL-LHC sensitivity to SM HH

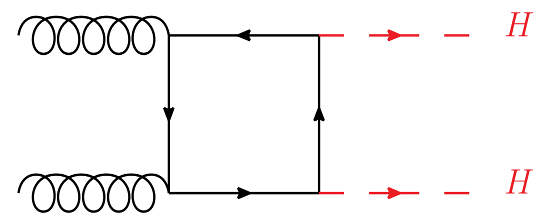
1.3 σ

Extremely challenging!

Similarities with Off-Shell Couplings measurements



Associated production of two Higgs bosons



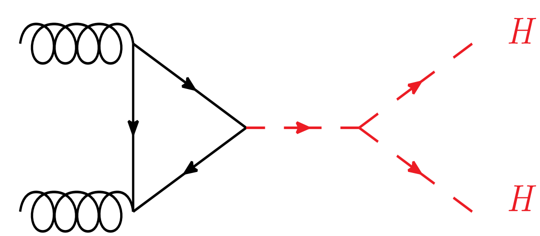
Various channels searched for (bbγγ)

Limit on non resonant cross section times branching:

$\sigma_{HH}\, Br_{bb,\, \gamma\gamma} < O(2)$ pb

Background to …

Tri-linear coupling production



λ_3 : Extremely difficult on of the main challenges for the HL-LHC

λ_4 : Incredibly difficult

Beyond LHC Programs

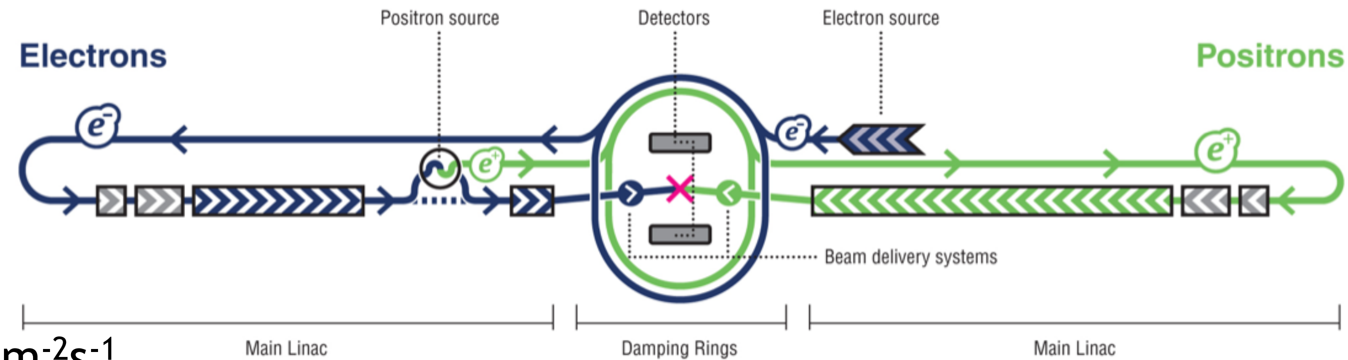
e^+e^- colliders

ILC

Three scenarios

- 250 GeV
- 500 GeV
- 1000 GeV

Lumi 0.7 to 5 10^{34} $cm^{-2}s^{-1}$

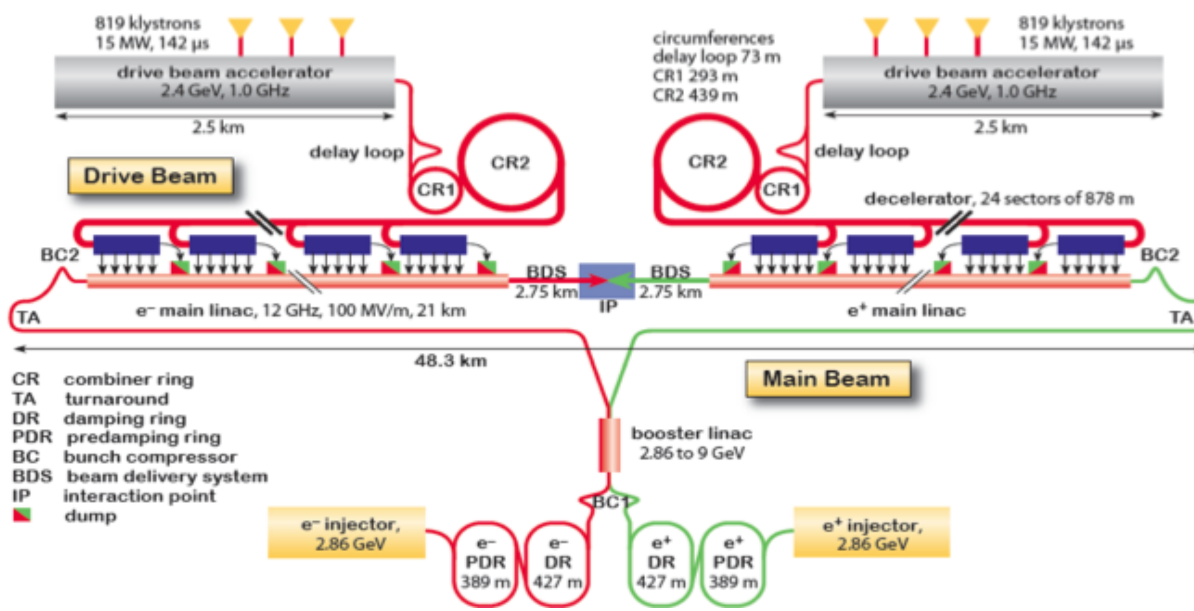


CLIC

Three scenarios

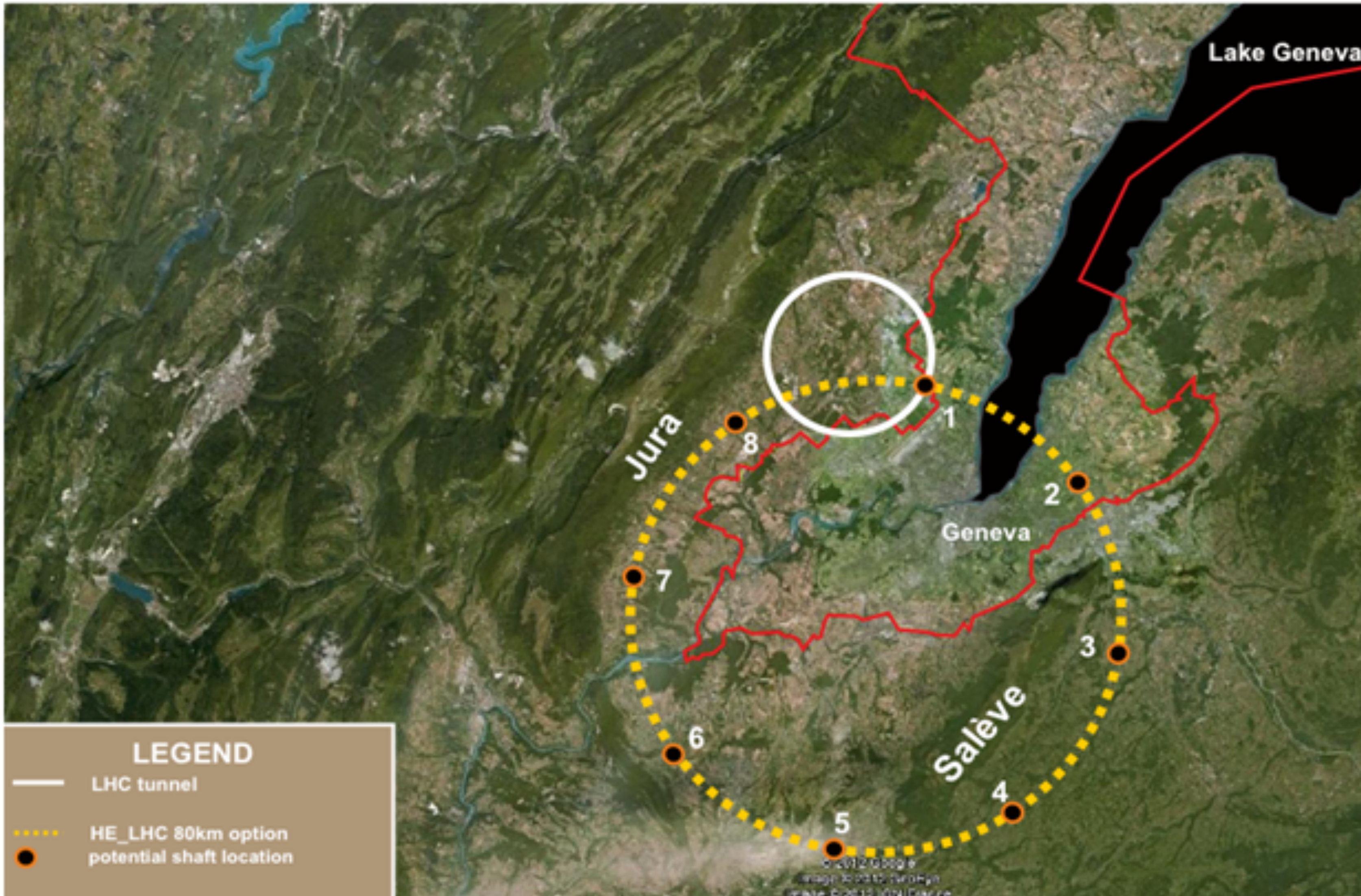
- 500 GeV
- 1500 GeV
- 3000 GeV

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



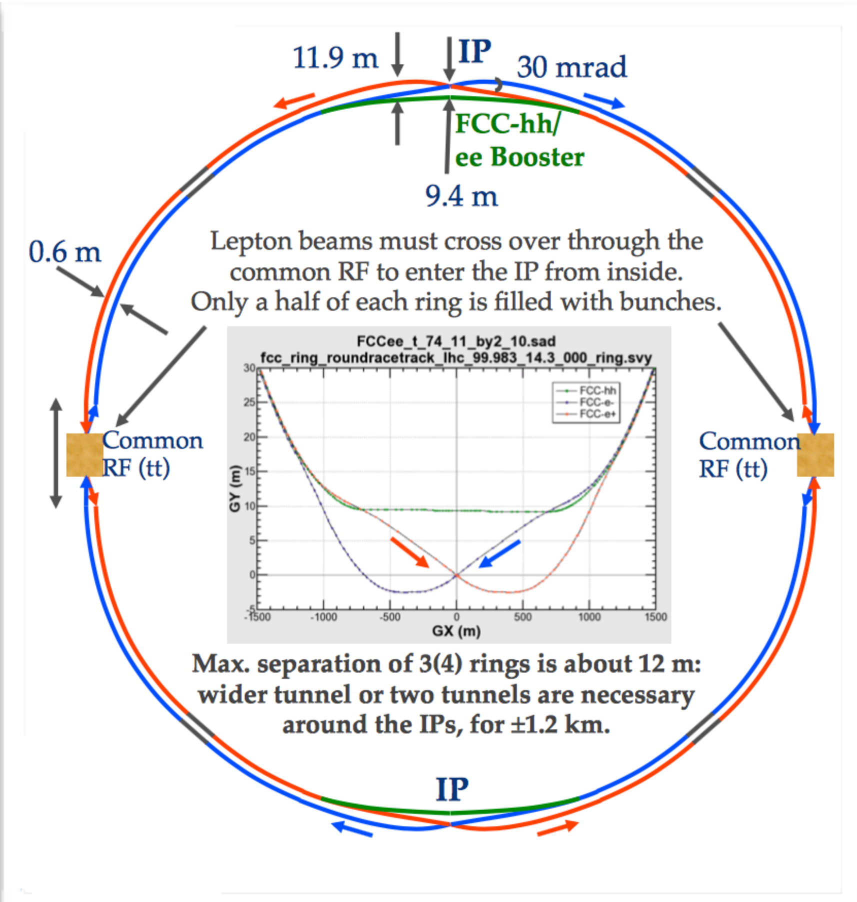
Beyond LHC Programs

Future circular collider, the FCC project



Beyond LHC Programs

Future circular collider, the FCC-ee, -eh, and -hh project



From M. Benedikt

Precision physics at FCC-ee:

- **>mH+mZ for precise Higgs measurements**
- mZ for Tera Z and extreme precision EW measurements
- 2xmW for precision W measurements
- 2xmt for precise top measurements

Options: 240 GeV and 350 GeV (with respectively 10 and 2.6 ab-1) and 2 or 4 IPs.

Other important options: ILC, CepC

Beyond LHC Programs

Higgs physics at e^+e^- colliders

Facility	ILC			ILC(LumiUp)	TLEP (4 IP)		CLIC		
$\sqrt{s}$ (GeV)	250	500	1000	250/500/1000	240	350	350	1400	3000
$\int \mathcal{L}dt$ (fb^{-1})	250	+500	+1000	1150+1600+2500[‡]	10000	+2600	500	+1500	+2000
Γ_H	12%	5.0%	4.6%	2.5%	1.9%	1.0%	9.2%	8.5%	8.4%
κ_γ	18%	8.4%	4.0%	2.4%	1.7%	1.5%	–	5.9%	<5.9%
κ_g	6.4%	2.3%	1.6%	0.9%	1.1%	0.8%	4.1%	2.3%	2.2%
κ_W	4.9%	1.2%	1.2%	0.6%	0.85%	0.19%	2.6%	2.1%	2.1%
κ_Z	1.3%	1.0%	1.0%	0.5%	0.16%	0.15%	2.1%	2.1%	2.1%
κ_μ	91%	91%	16%	10%	6.4%	6.2%	–	11%	5.6%
κ_τ	5.8%	2.4%	1.8%	1.0%	0.94%	0.54%	4.0%	2.5%	<2.5%
κ_c	6.8%	2.8%	1.8%	1.1%	1.0%	0.71%	3.8%	2.4%	2.2%
κ_b	5.3%	1.7%	1.3%	0.8%	0.88%	0.42%	2.8%	2.2%	2.1%
κ_t	–	14%	3.2%	2.0%	–	13%	–	4.5%	<4.5%
BR_{inv}	0.9%	< 0.9%	< 0.9%	0.4%	0.19%	< 0.19%			

- Reaching few permil to percent level precision on the couplings
- Direct measurement of branching fractions

Beyond LHC Programs

Future circular collider, the FCC project

parameter	FCC-hh		HE-LHC* (*tentative)	(HL) LHC
collision energy cms [TeV]	100		>25	14
dipole field [T]	16		16	8.3
circumference [km]	100		27	27
# IP	2 main & 2		2 & 2	2 & 2
beam current [A]	0.5		1.12	(1.12) 0.58
bunch intensity [10^{11}]	1	1 (0.2)	2.2	(2.2) 1.15
bunch spacing [ns]	25	25 (5)	25	25
beta* [m]	1.1	0.3	0.25	(0.15) 0.55
luminosity/IP [10^{34} $cm^{-2}s^{-1}$]	5	20 - 30	>25	(5) 1
events/bunch crossing	170	<1020 (204)	850	(135) 27
stored energy/beam [GJ]	8.4		1.2	(0.7) 0.36
synchrotr. rad. [W/m/beam]	30		3.6	(0.35) 0.18

From M. Benedikt

Beyond LHC Programs

Higgs Couplings at FCC

g_{HXY}	ee [240+350 (4IP)]	pp [100 TeV] 20ab^{-1}	ep [60GeV/50TeV], 1ab^{-1}
ZZ	0.15%		
WW	0.19%		
bb	0.42%		0.2%
cc	0.71%		1.8%
gg	0.80%		
ττ	0.54%		
μμ	6.2%	<1%	
γγ	1.5%	<0.5%	
Zγ		<1%	
tt	~13%	1%	
HH	~30%	3.5%	
uu,dd	H->ργ, under study		
ss	H->ϕγ, under study		
BR_{inv}	< 0.45%	< 0.1%	
Γ_{tot}	1%		

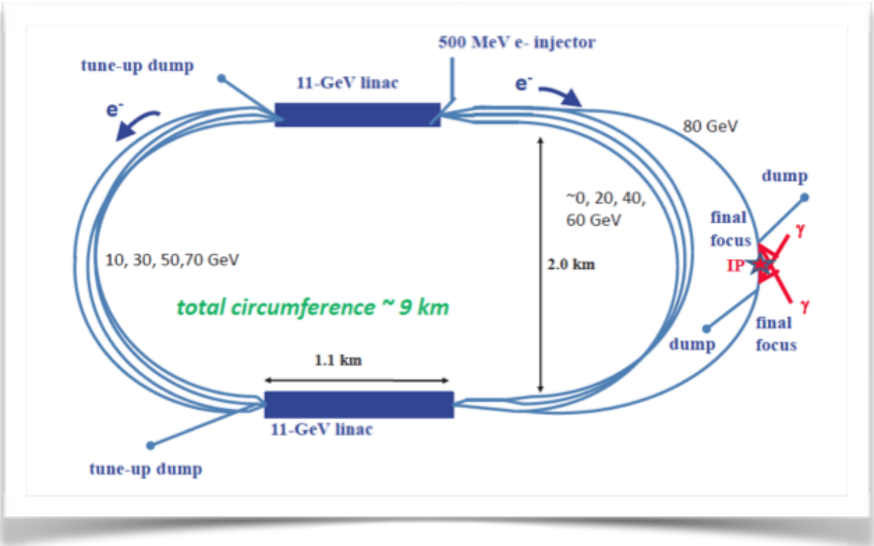
FCC-ep based on LHeC type design with ERL (Energy Recovery Linacs)

From M. Mangano

Beyond LHC Programs

Further Programs

γγ Collider

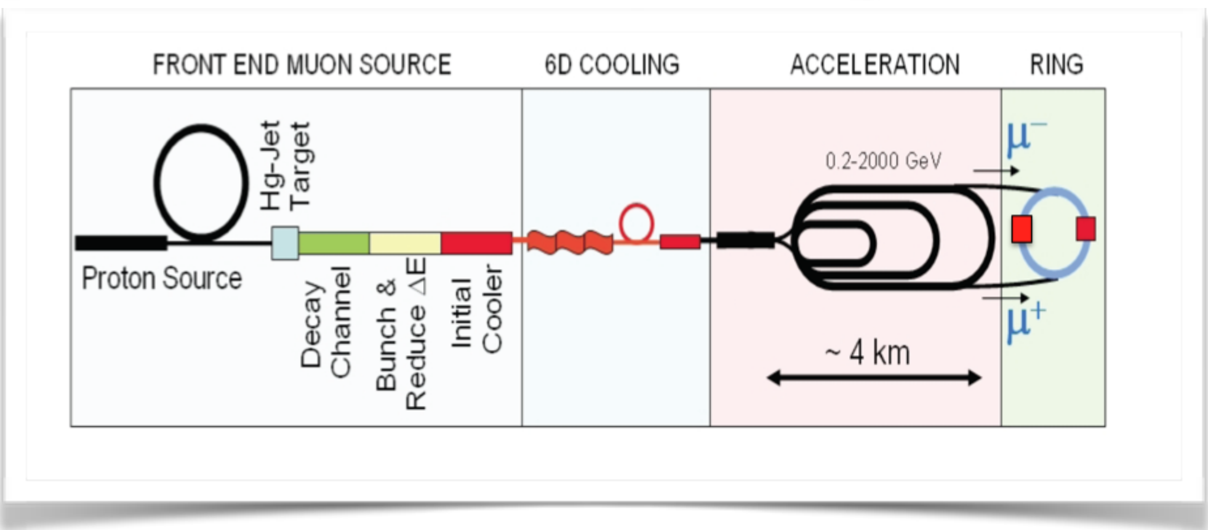


Higgs factory

μμ Collider

With a new exciting idea of muon production at threshold through

$$\sqrt{(s)} = \sqrt{2m_e E_{e^+}}$$



Requires intense source of positrons at an energy of approximately 45 GeV on target

Disclaimer

Important points that could not be covered in this lecture:

- Searches for exotic decays of the Higgs boson

- Searches for new phenomena using the Higgs boson

- Constraining parameters of the Higgs sector difficult to access such as charm Yukawa or the trilinear coupling using the differential cross sections.

- Status of a general EFT approach to parametrise possible BSM effects

Summary and 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 (1 permit level).
- The Higgs physics program has blossomed and the boundaries of what is possible in Higgs properties measurements have been impressively expanded.
- The existence of the Higgs boson poses the key question of naturality of the Standard Model.
- Measuring the trilinear coupling to further understand the scalar potential with implication on EW phase transition and cosmology.
- Key developments in Higgs physics to address main fundamental questions:
    - Precise measurement of its properties.
    - Investigate how minimal the Higgs sector really is (extended EWSB sector, additional Higgs bosons).
    - Use the Higgs boson as a tool for discovery.