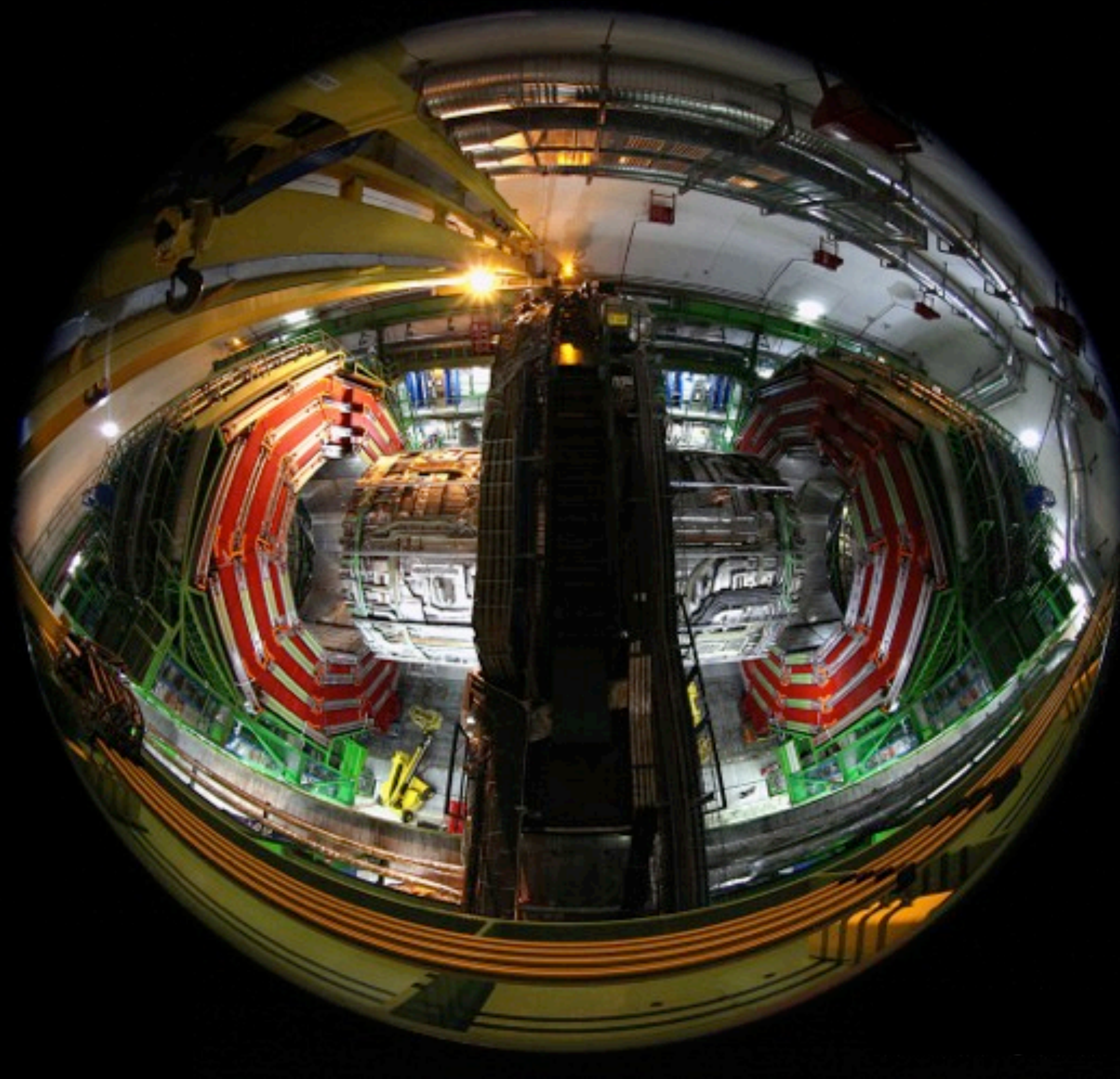
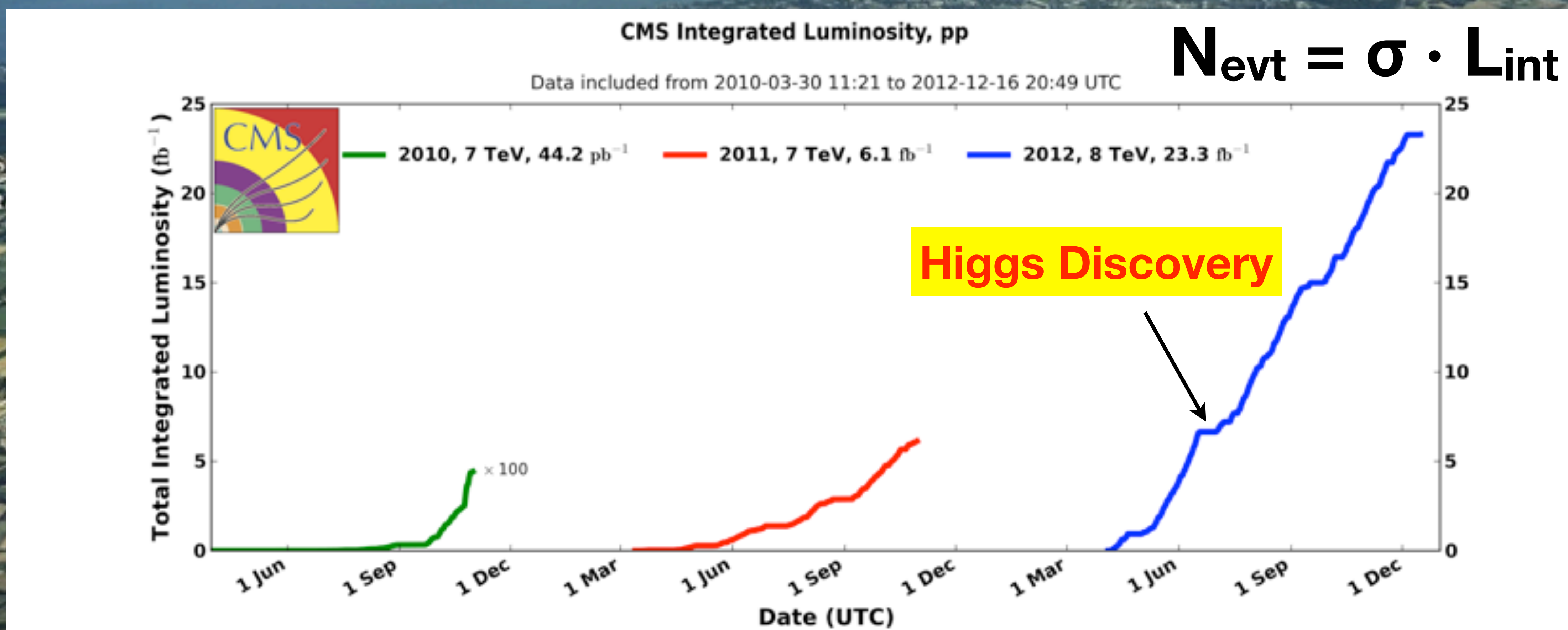


QCD Tools for LHC Physics: From 8 to 14 TeV. What is needed and why?
November 15th, 2013
Markus Klute (MIT)

Higgs Coupling Measurements at 8 and 14 TeV

First three year of the LHC

$N_{evt} = \sigma \cdot L_{int}$

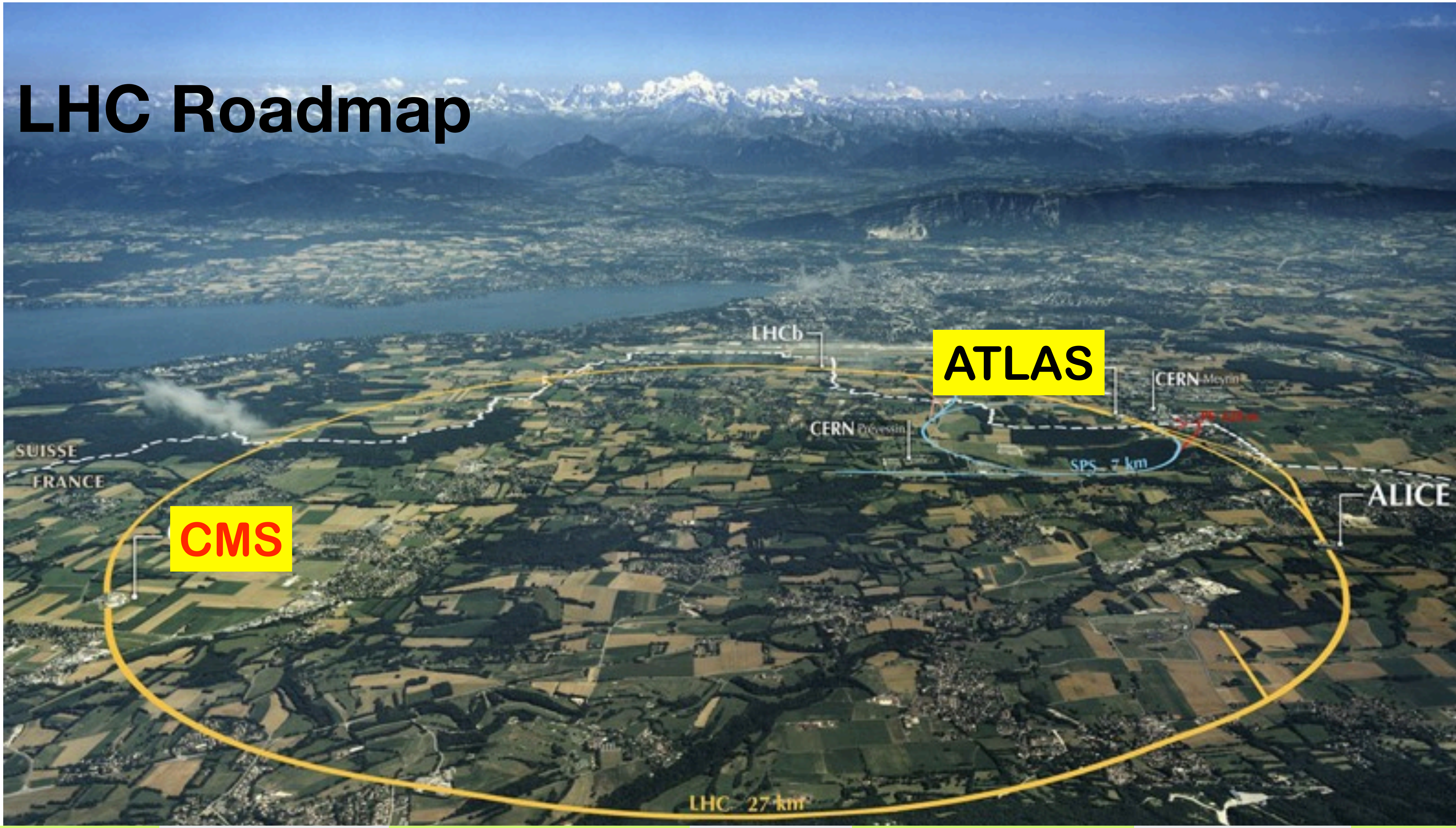


2010
7 TeV

2011
7 TeV

2012
8 TeV

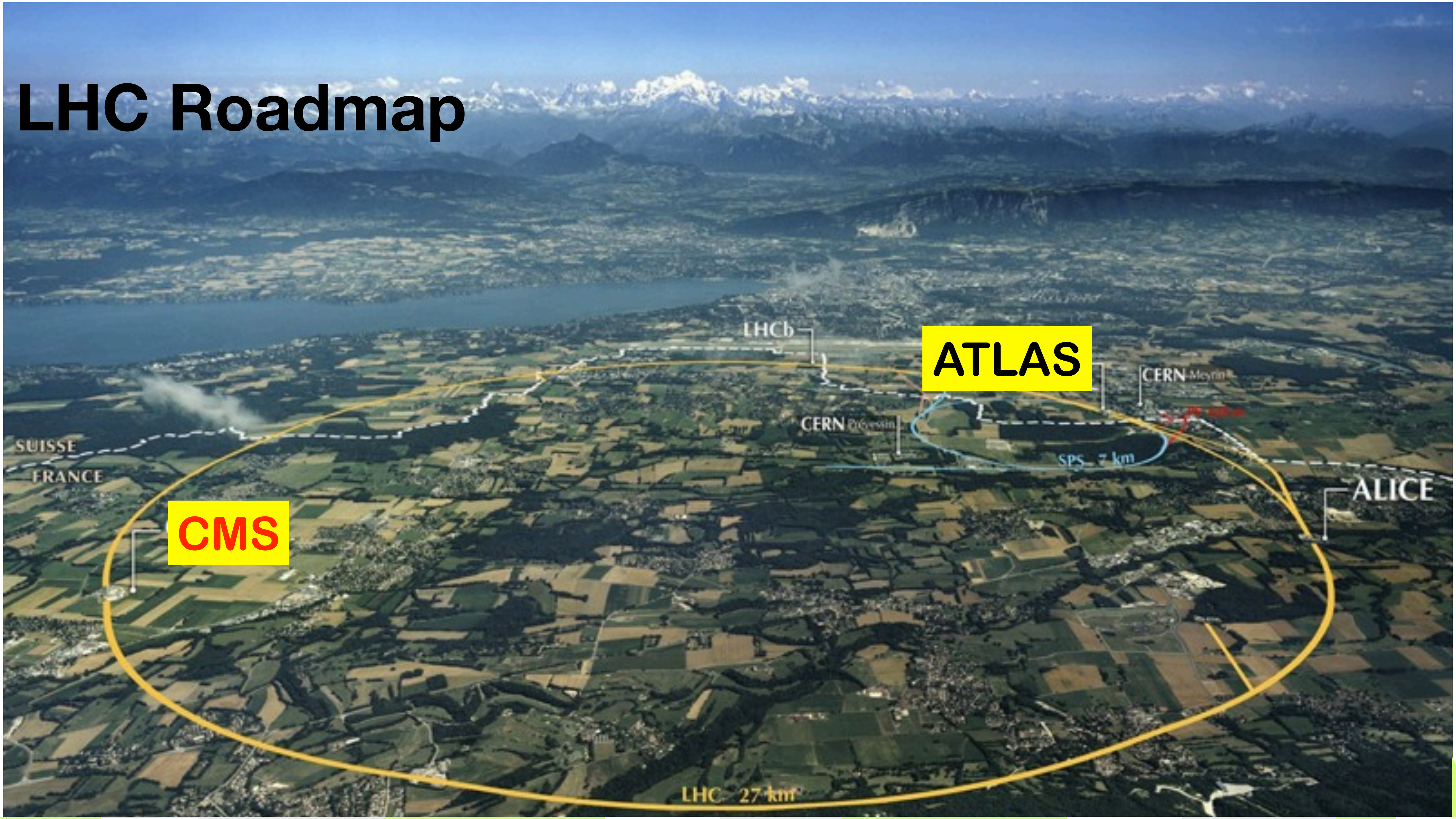
LHC Roadmap



8 TeV	LS1	13-14 TeV →	LS2		LS3	HL-LHC
2012	2013 | 2014	2015 | 2016 | 2017	2018	2019 | 2020 | 2021	2022 | 2023	2024
$0.7\times10^{34} cm^{-2}s^{-1}$		$1\times10^{34} cm^{-2}s^{-1}$		$2\times10^{34} cm^{-2}s^{-1}$		$5\times10^{34} cm^{-2}s^{-1}$

The Large Hadron Collider (LHC) at CERN, Switzerland

LHC Roadmap



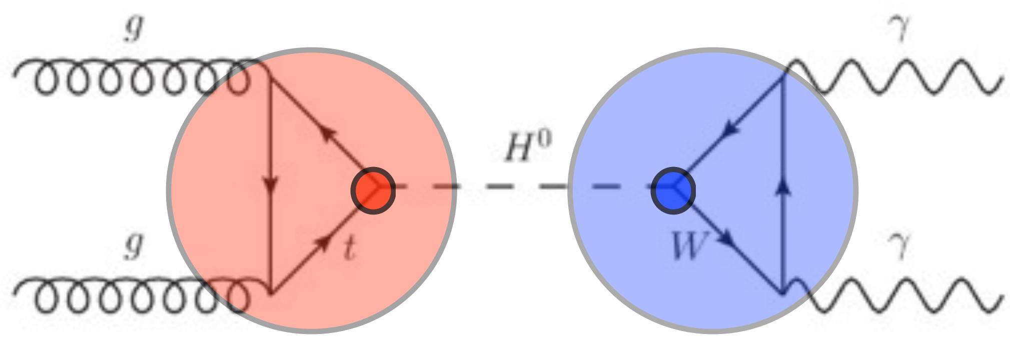
8 TeV | $30fb^{-1}$ | LS1 | 13-14 TeV → | $120fb^{-1}$ | LS2 | $300fb^{-1}$ | LS3 | HL | $3000fb^{-1}$

2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 | 2022 | 2023 | 2024

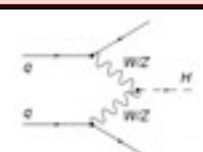
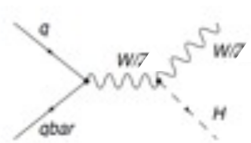
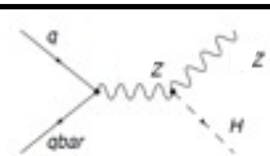
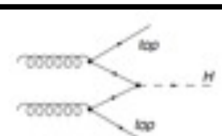
$0.7 \times 10^{34} cm^{-2}s^{-1}$ | $1 \times 10^{34} cm^{-2}s^{-1}$ | $2 \times 10^{34} cm^{-2}s^{-1}$ | $5 \times 10^{34} cm^{-2}s^{-1}$

The Large Hadron Collider (LHC) at CERN, Switzerland

Higgs production and decay



m_H = 125 GeV, 8 TeV

Process	Diagram	Cross section [fb]	Unc. [%]
gluon-gluon fusion		19520	15
vector boson fusion		1578	3
WH		697	4
ZH		394	5
ttH		130	15

m_H = 125 GeV

Decay	BR [%]	Unc. [%]
bb	57.7	3.3
ττ	6.32	5.7
cc	2.91	12.2
μμ	0.022	6.0
WW	21.5	4.3
gg	8.57	10.2
ZZ	2.64	4.3
γγ	0.23	5.0
Zγ	0.15	9.0
ΓH [MeV]	4.07	4.0

* uncertainties need improvements for future precision measurements

Status of Higgs physics program

Channel	ATLAS Lumi [1/fb]	CMS Lumi [1/fb]	Specialty	Inclusive signature	σ Obs. (Exp.)	mass [GeV]	Signal Strength μ	Spin/ Parity
H ➜ ZZ ➜ 4l	4.6+20.7	5.1+19.6	mass, discovery, spin/parity	4 leptons	6.6 (4.4)	124.3 ±0.6 (stat) ±0.5 (sys)	1.5 ± 0.4	√
					6.7 (7.2)	125.8 ±0.5 (stat) ±0.2 (sys)	0.91+0.30-0.24	√
H ➜ WW ➜ 2l2ν	4.6+20.7	4.9+19.5	cross section, coupling	2 leptons, MET	3.8 (3.7)	consistent	0.99+0.31-0.32	√
					4.0 (5.1)	consistent	0.76 ± 0.21	√
H ➜ γγ	4.8+20.7	5.1+19.6	mass, discovery, couplings	two photons	7.4 (4.3)	126.8 ±0.2 (stat) ±0.7 (sys)	1.55+0.33-0.28	√
					3.2 (4.2)	125.4 ±0.5 (stat) ±0.6 (sys)	0.78+0.28-0.26	-
H ➜ bb	4.7+20.3	5.0+19.0	coupling to fermions	two b-jets	-	consistent	0.2+0.7-0.6	-
					2.1 (2.1)	consistent	1.0 ± 0.4	-
H ➜ ττ	4.6+13.0	4.9+19.4	couplings to leptons	hadronic taus, leptons, MET	1.1 (1.7)	consistent	0.8 ± 0.7	-
					3 (2.6)	120+9-7	1.1 ± 0.4	-

Status of Higgs studies at CMS

Fantastic progress since discovery July 2012

- Observation in three bosonic channels
- Evidence for fermion couplings
- Precision mass measurement
- Spin determined
- **Looks more and more like the SM Higgs boson**
- No evidence for non-SM decays
- No evidence for additional Higgs boson

Discovery opened a new era of Higgs precision measurements

Summary of the Higgs boson properties

- Mass
  - $M = 125.7 \pm 0.3 \pm 0.3$ GeV
  - 0.5% precision
- Signal strength
  - $\mu = 0.80 \pm 0.14$
- Spin/CP
  - $J^{CP} = 0^{++}$ (SM-like Higgs boson) preferred
  - 0^{+-} (2^{++}) disfavored

Status of Higgs studies at ATLAS

Fantastic progress since discovery July 2012

- Observation in three bosonic channels

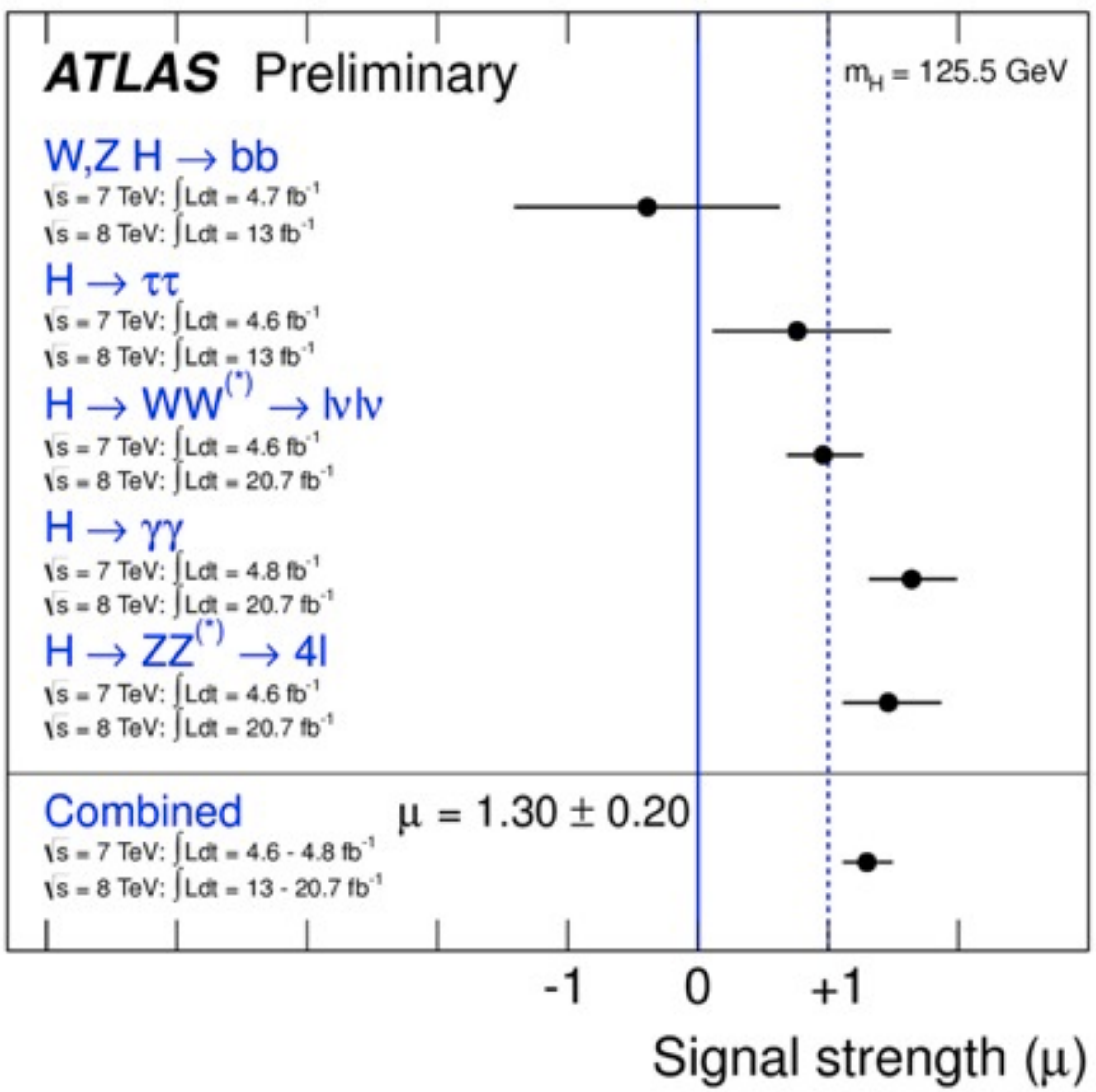
- Precision mass measurement
- Spin determined
- **Looks more and more like the SM Higgs boson**
- No evidence for non-SM decays
- No evidence for additional Higgs boson

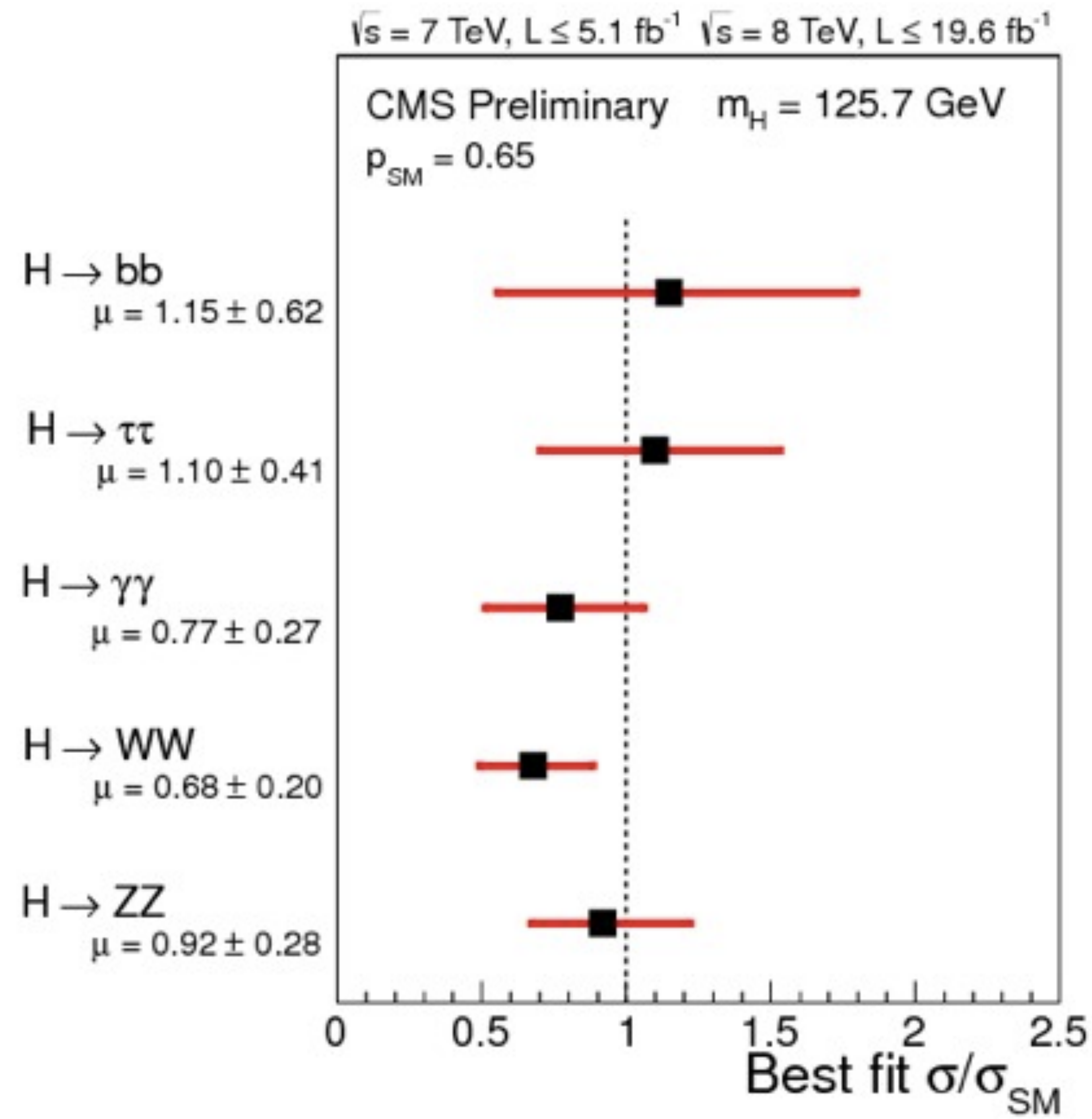
Discovery opened a new era of Higgs precision measurements

Summary of the Higgs boson properties

- Mass
  - M = 125.5 ± 0.2 ± 0.6 GeV
  - 0.5% precision
- Signal strength
  - $\mu = 1.30 \pm 0.20$
- Spin/CP
  - $J^{CP} = 0^{++}$ (SM-like Higgs boson) preferred
  - 0^{+-} (2^{++}) disfavored

Higgs signal strength





combined: **μ** = 0.80 ± 0.14

Sensitive Higgs channels

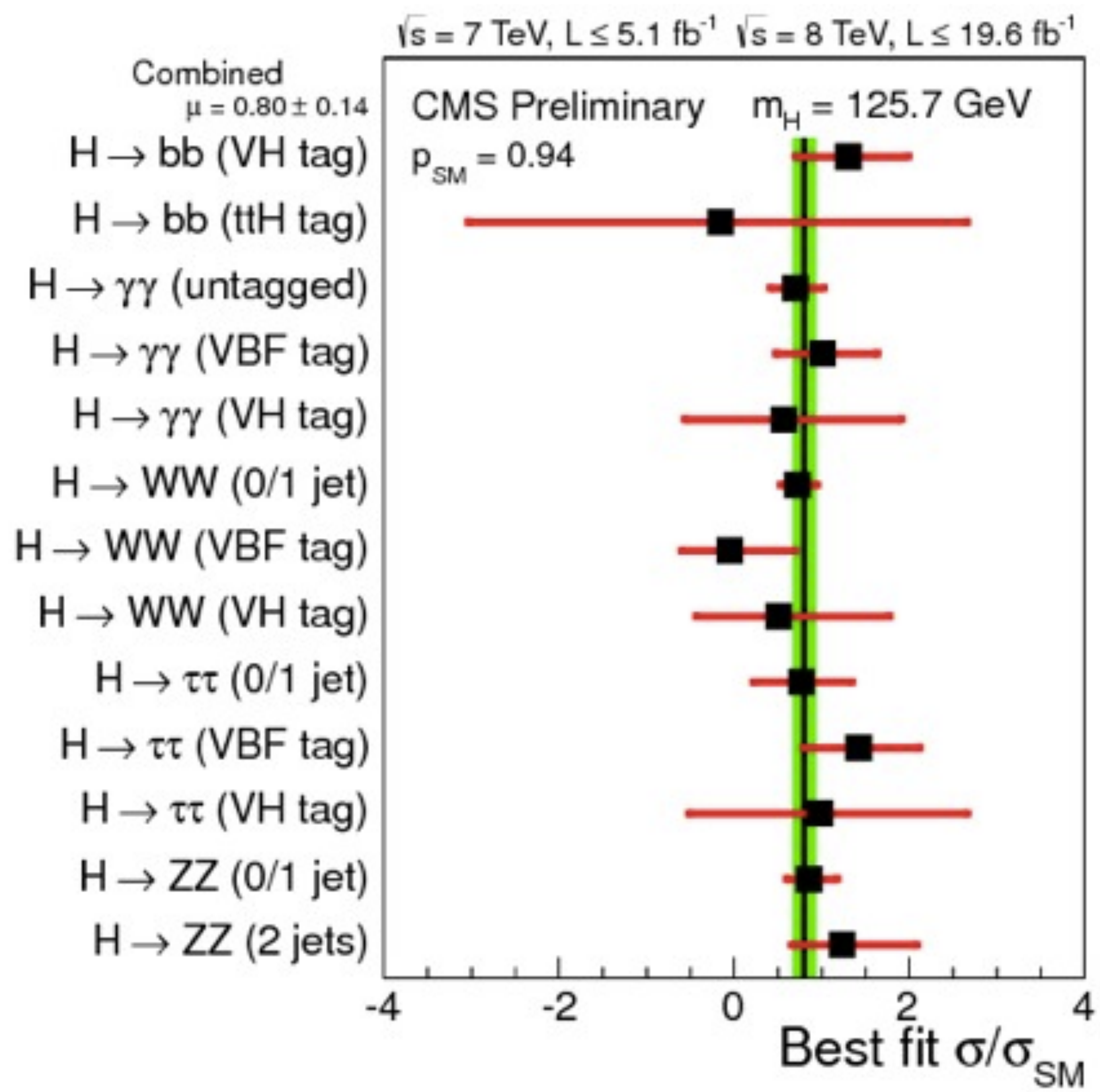
	untagged	jet-tag	VBF	VH	ttH
$H \rightarrow \gamma\gamma$	used				
$H \rightarrow WW \rightarrow 2l2\nu$					
$H \rightarrow ZZ \rightarrow 4l$		possible			
$H \rightarrow bb$					
$H \rightarrow \tau\tau$					
$H \rightarrow Z\gamma$					
$H \rightarrow \mu\mu$					
$H \rightarrow$ invisible					

Measure rate of Higgs events with different production and decay combinations.

Cross-contamination of production and decay channels in categories.

Sensitive Higgs channels

	untagged	jet-tag
H ➜ γγ	used	
H ➜ WW ➜ 2l2v		
H ➜ ZZ ➜ 4l		possible
H ➜ bb		
H ➜ ττ		
H ➜ Zγ		
H ➜ μμ		
H ➜ invisible		



Measure rate of Higgs events with different production and decay combinations.

Cross-contamination of production and decay channels in categories.

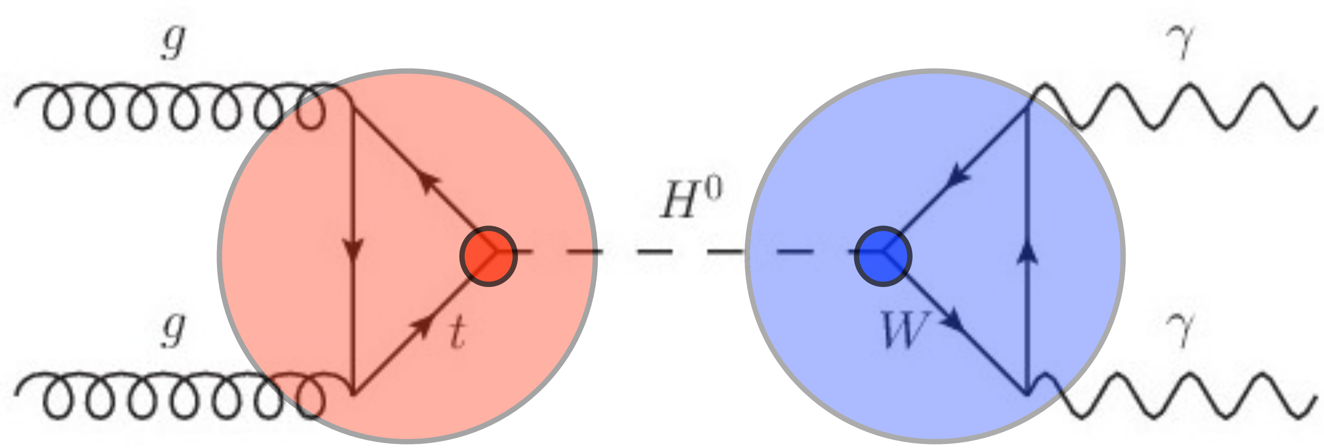
Coupling "Measurements"

Investigate the consistency of the "new scalar boson" with the SM Higgs boson.

Assume the observed signal stems from one narrow resonance.

$$(\sigma \cdot \mathrm{BR})\,(ii \to \mathrm{H} \to ff\,) = \frac{\sigma_{ii} \cdot \Gamma_{ff}}{\Gamma_{\mathrm{H}}}$$

Parametrize deviations w.r.t. the SM in production and decay. This implies precise knowledge of the SM Higgs. Not considered are BSM acceptance effects.

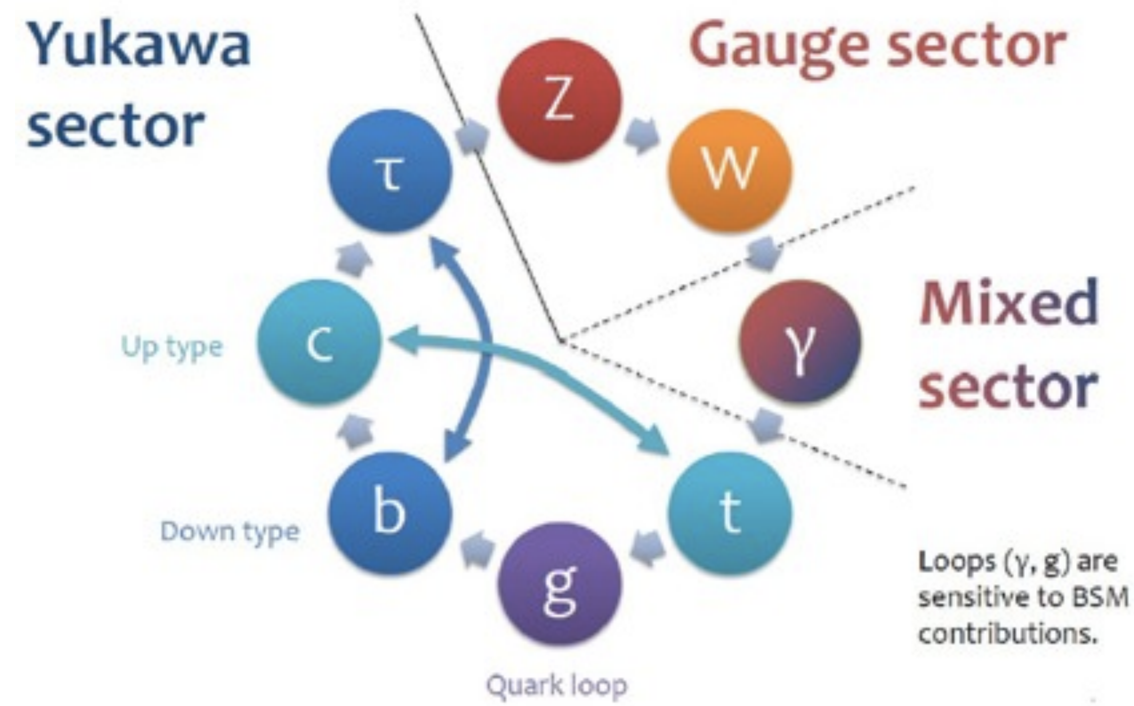


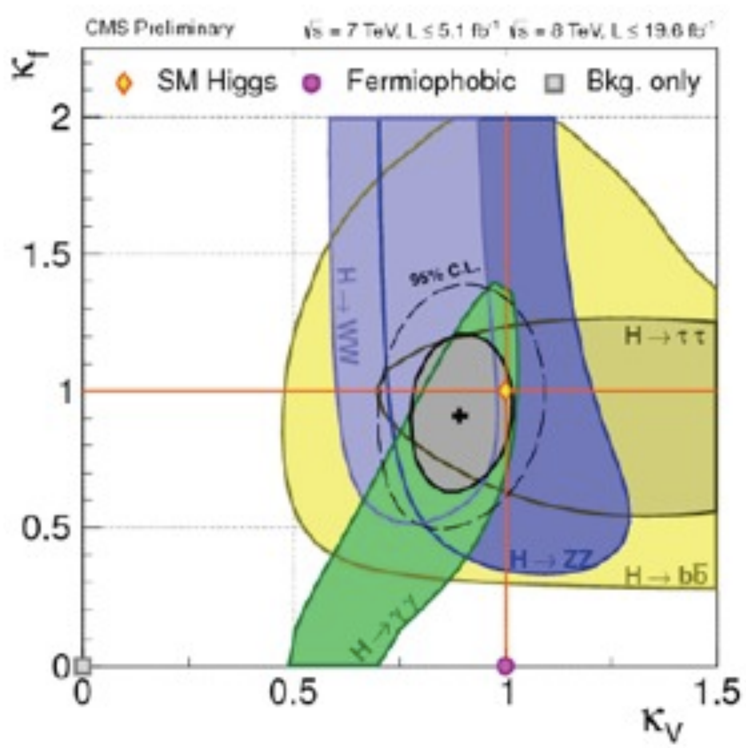
$$(\sigma \cdot \mathrm{BR})\,(\mathrm{gg} \to \mathrm{H} \to \gamma\gamma) = \sigma_{\mathrm{SM}}(\mathrm{gg} \to \mathrm{H}) \cdot \mathrm{BR}_{\mathrm{SM}}(\mathrm{H} \to \gamma\gamma) \cdot \frac{\kappa_{\mathrm{g}}^2 \cdot \kappa_{\gamma}^2}{\kappa_{\mathrm{H}}^2} \qquad \kappa_H^2 = \sum_X \kappa_X^2 \frac{\mathrm{BR}_{\mathrm{SM}}(H \to X)}{1 - \mathrm{BR}_{\mathrm{BSM}}}$$

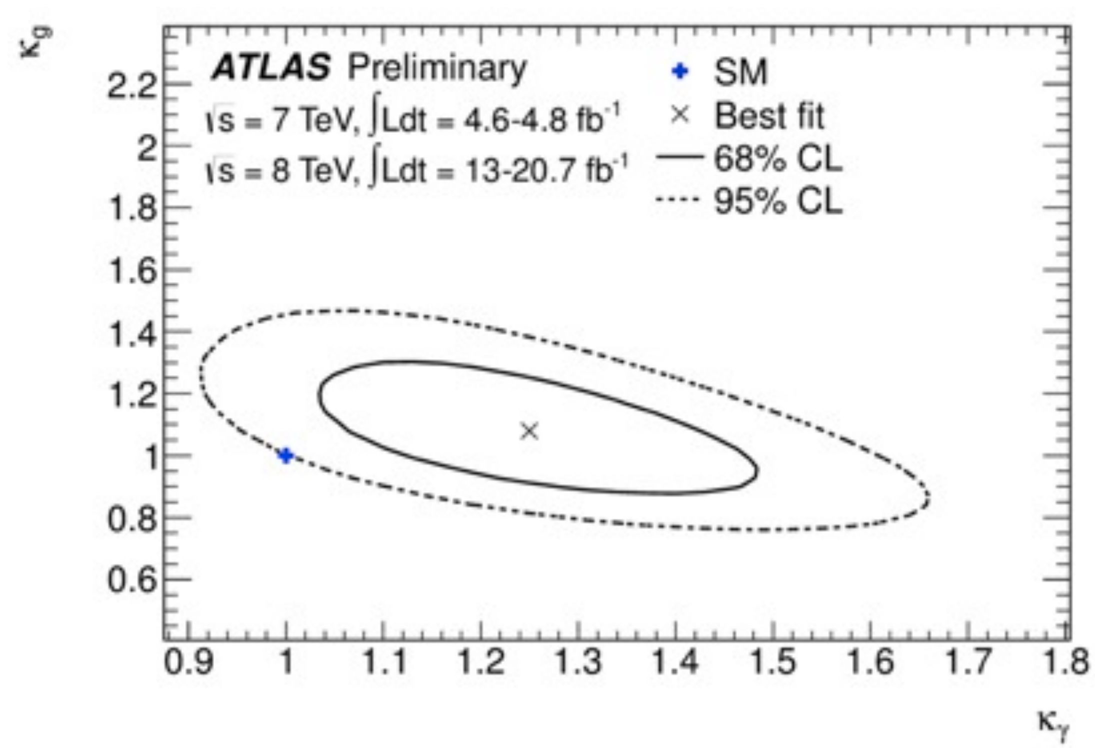
Benchmarks fits and parameter choices

Probe interesting BSM physics scenarios directly in limited dataset

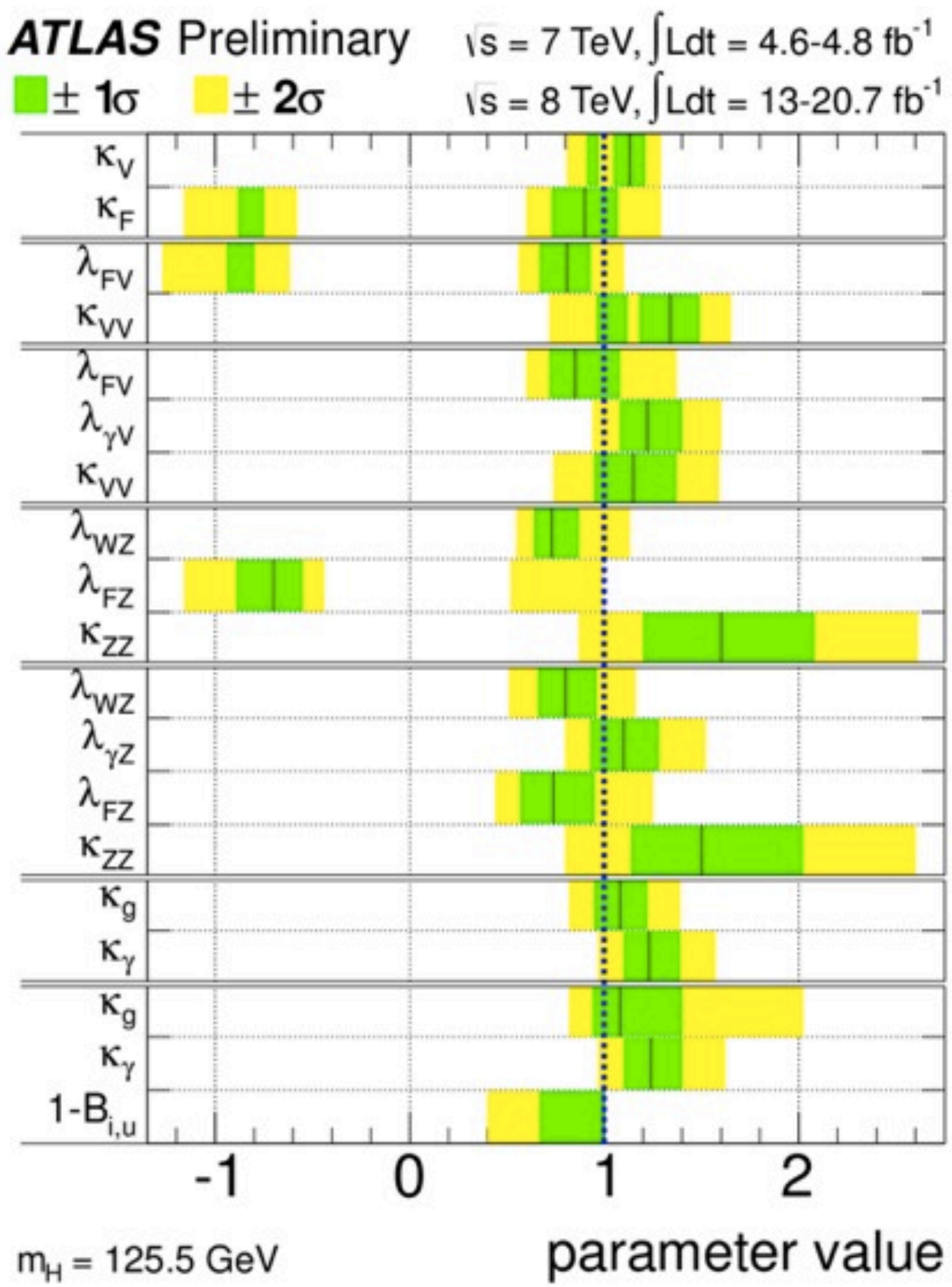
- one common scale factor
- scale vector and fermion coupling
- custodial symmetry
- new physics in loops
- BSM Higgs decays
- ...

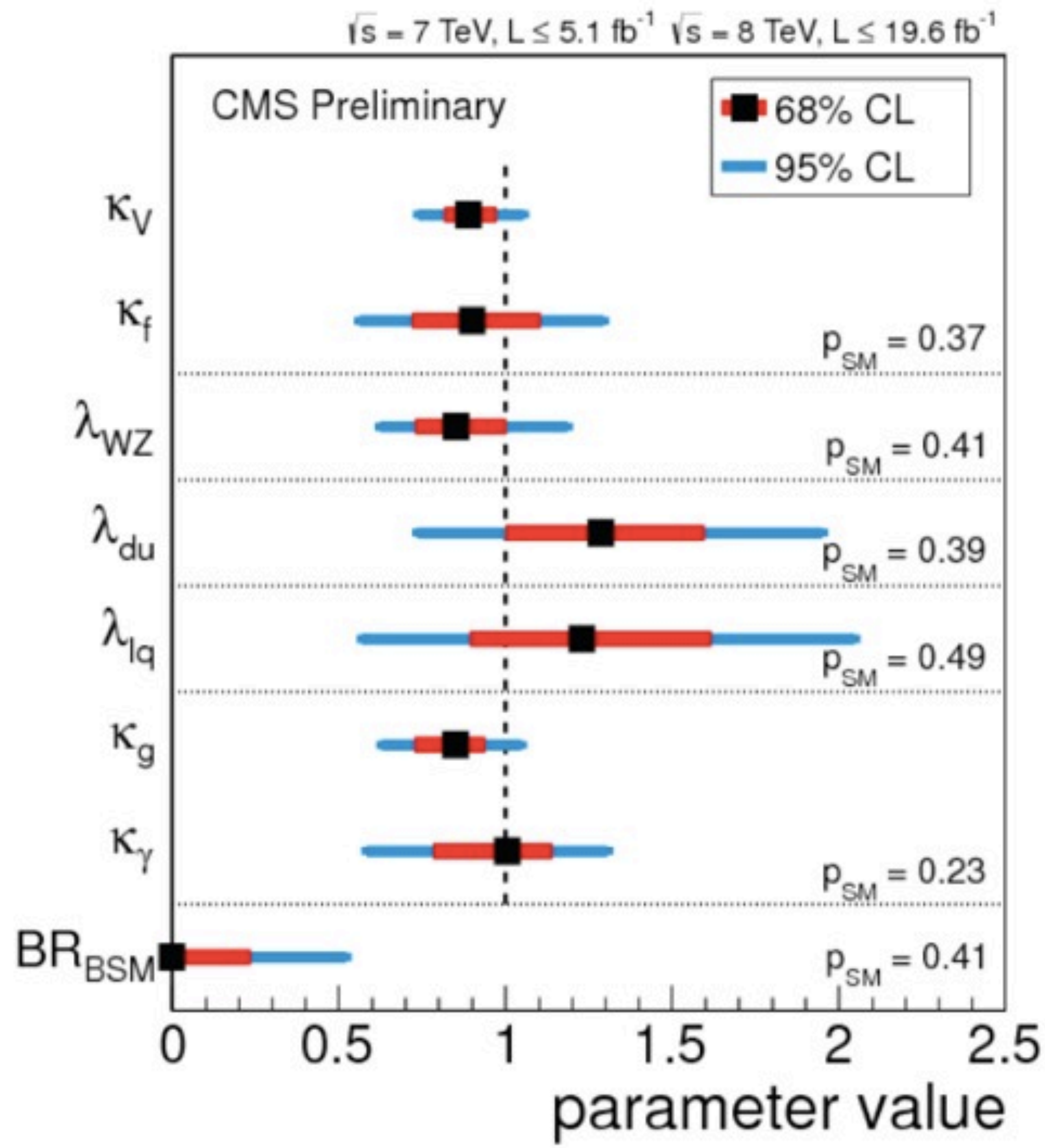






Benchmarks fits and parameter choices





General coupling fit

κ_g, κ_γ: loop diagrams ➜ allow potential new physics

κ_V: assume custodial symmetry

κ_t, κ_b: up- and down-type quarks

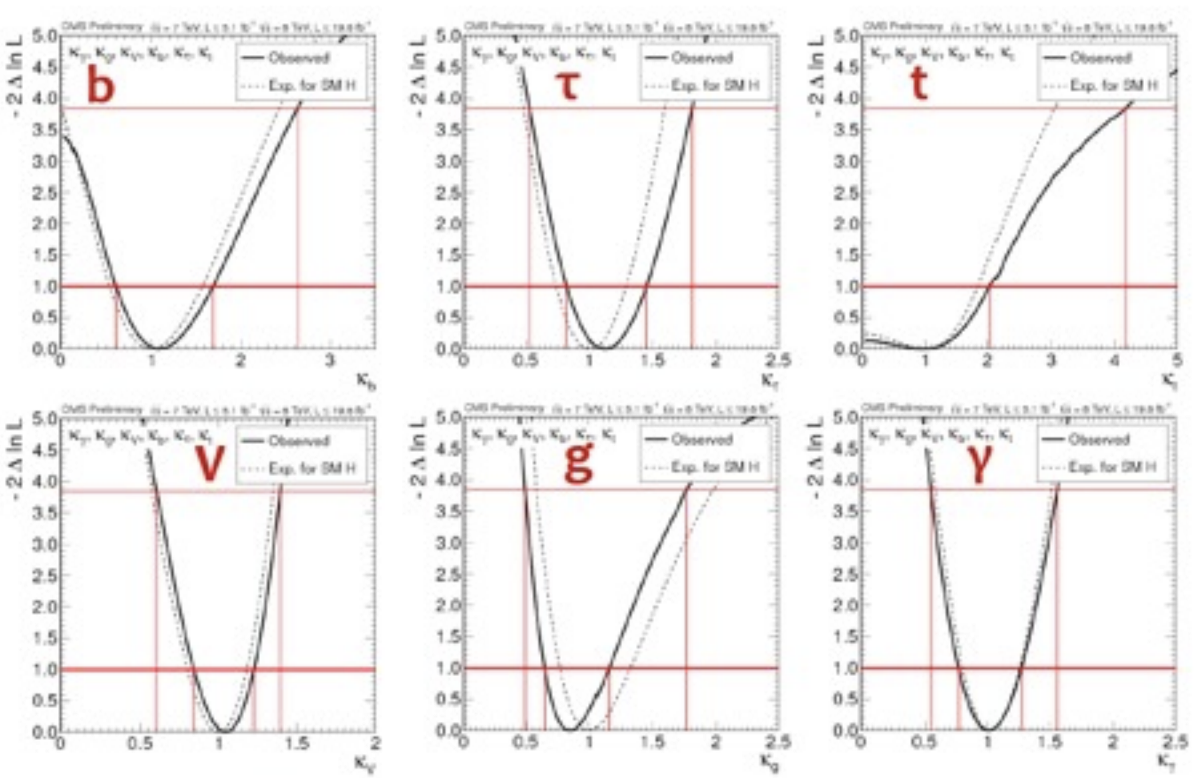
κ_τ: charged leptons

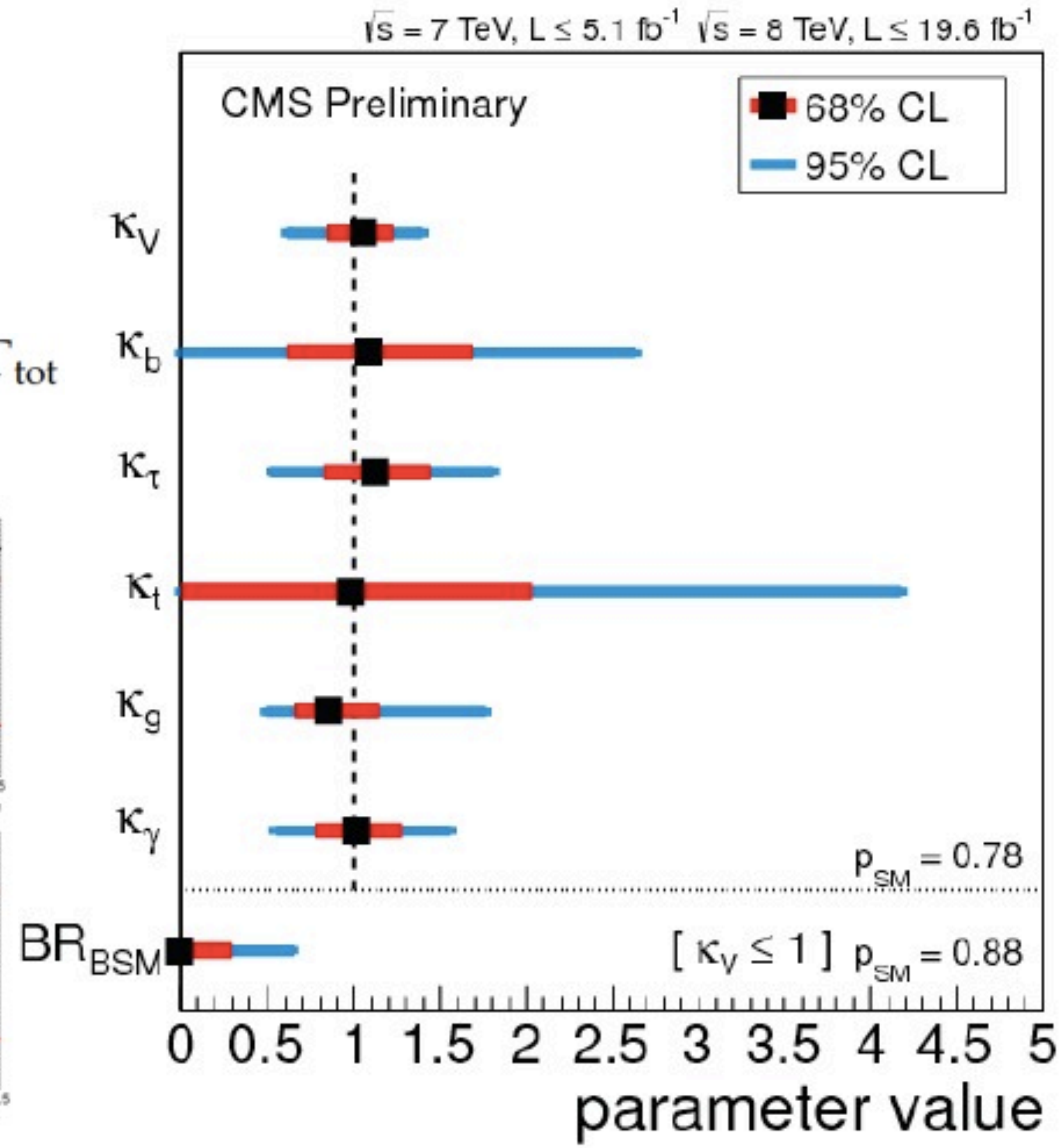
total width from sum of partial widths

alternatively:

$$\Gamma_{tot} = \sum \Gamma_{ii} + \Gamma_{BSM} \qquad BR_{BSM} = \Gamma_{BSM}/\Gamma_{tot}$$

assumption here κ_W, $\kappa_Z < 1$

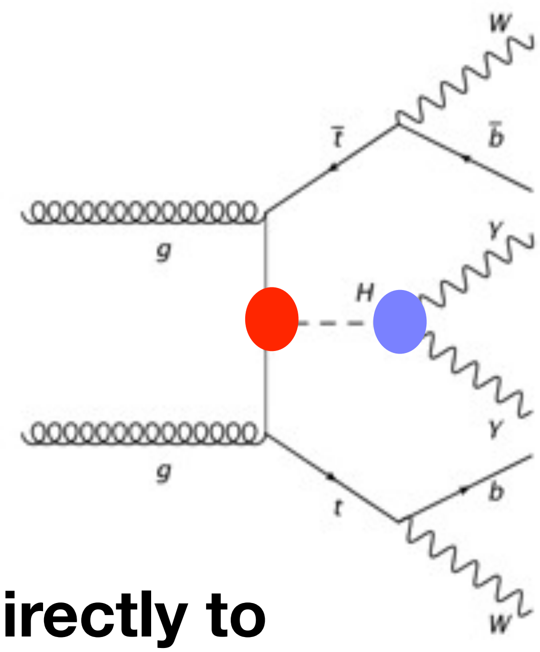




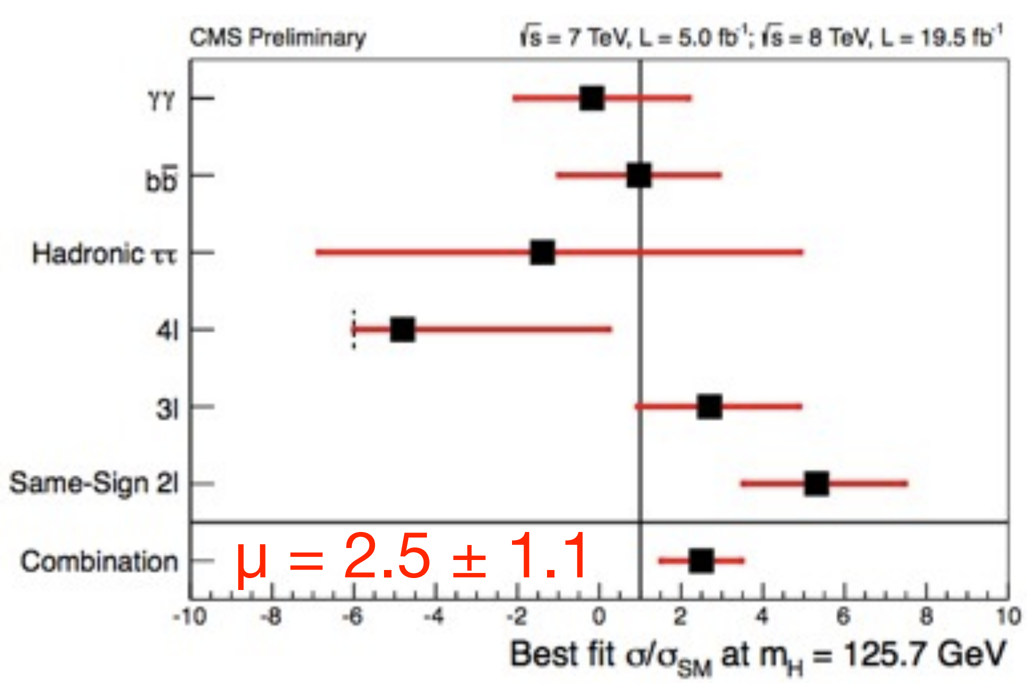
Significant progress in ttH channel in CMS

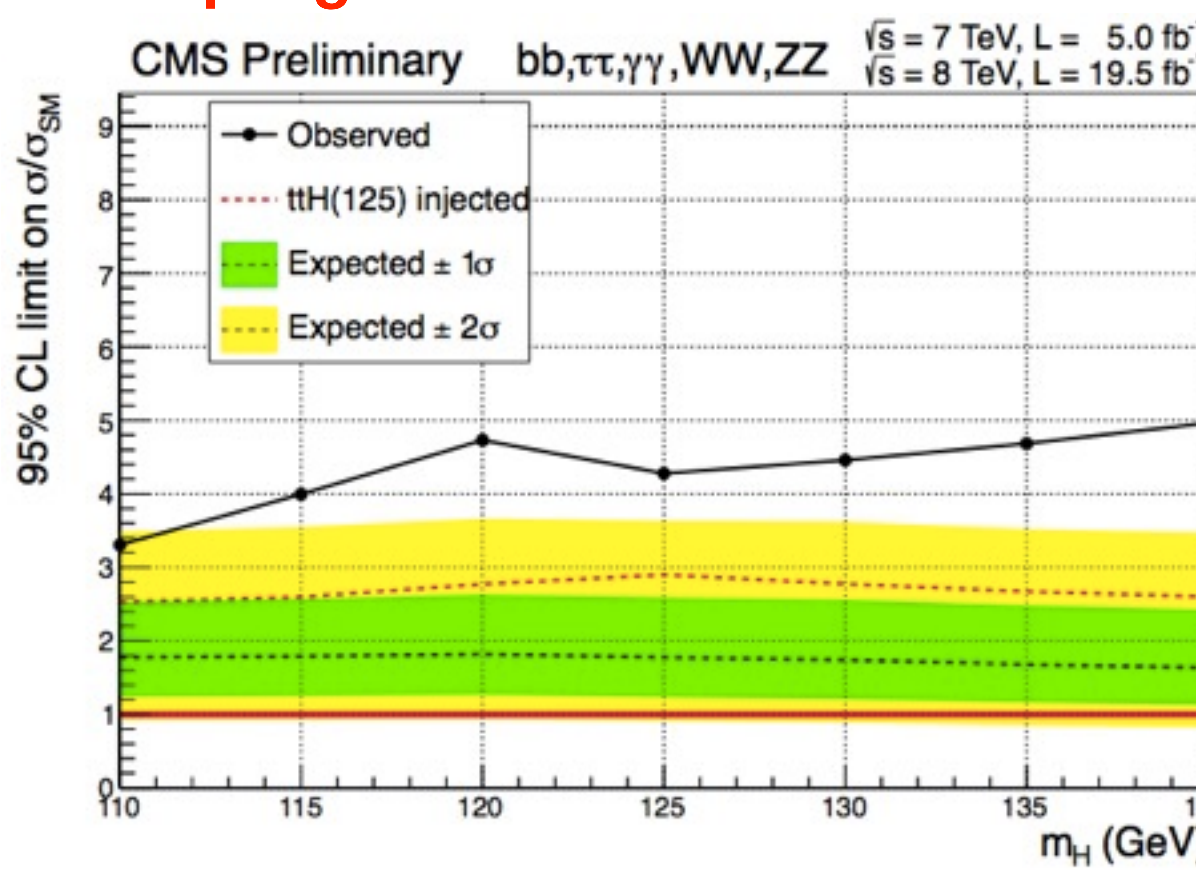
- H ➞ γγ
- H ➞ bb
- H ➞ ττ
- H ➞ ZZ
- H ➞ WW

→ HIG-13-015 (H ➞ γγ); HIG-13-019 (H ➞ bb, H ➞ ττ); HIG-13-020 (H ➞ ττ, H ➞ ZZ, H ➞ WW)

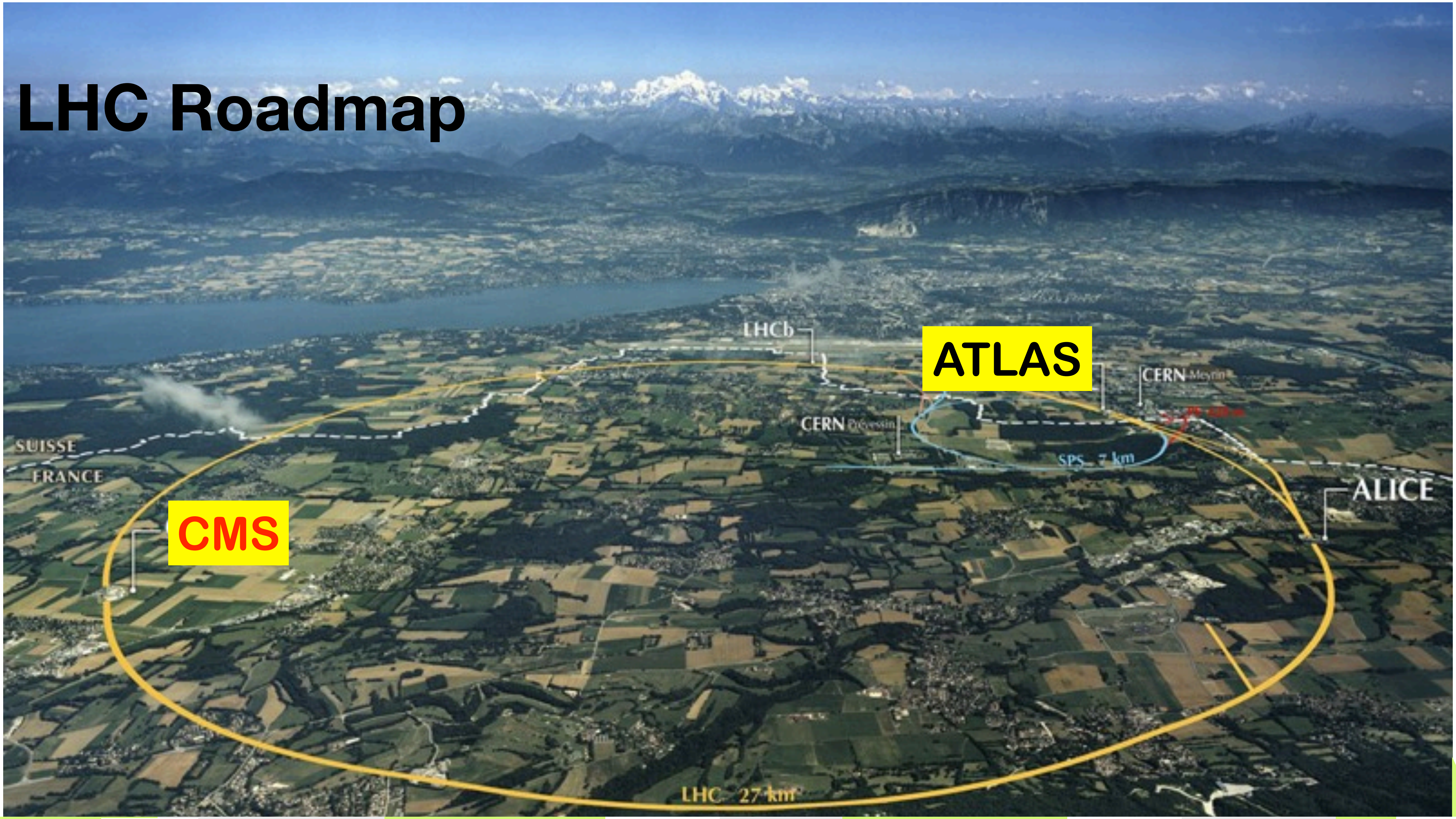


Sensitivity approaching SM Higgs, directly to
top Yukawa coupling





LHC Roadmap



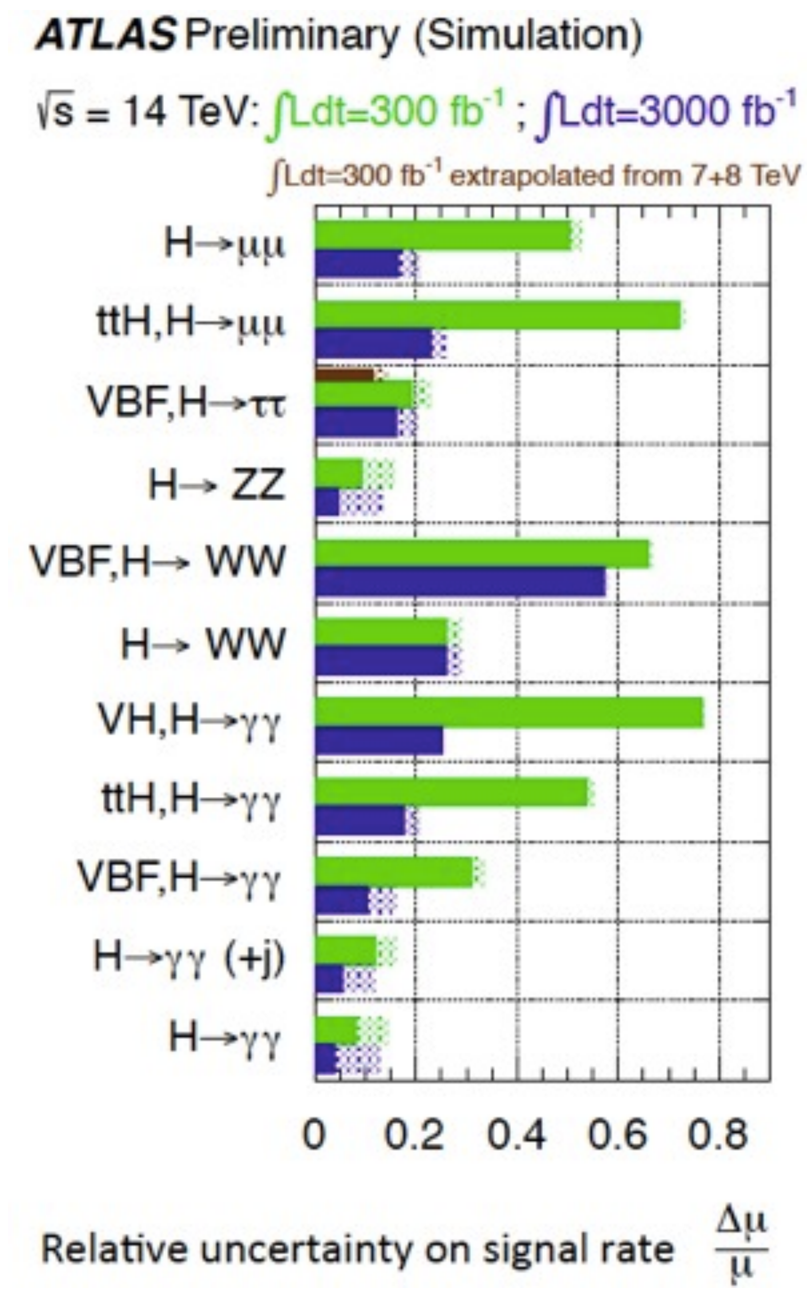
8 TeV | $30fb^{-1}$ | LS1 | 13-14 TeV → | $120fb^{-1}$ | LS2 | $300fb^{-1}$ | LS3 | HL | $3000fb^{-1}$

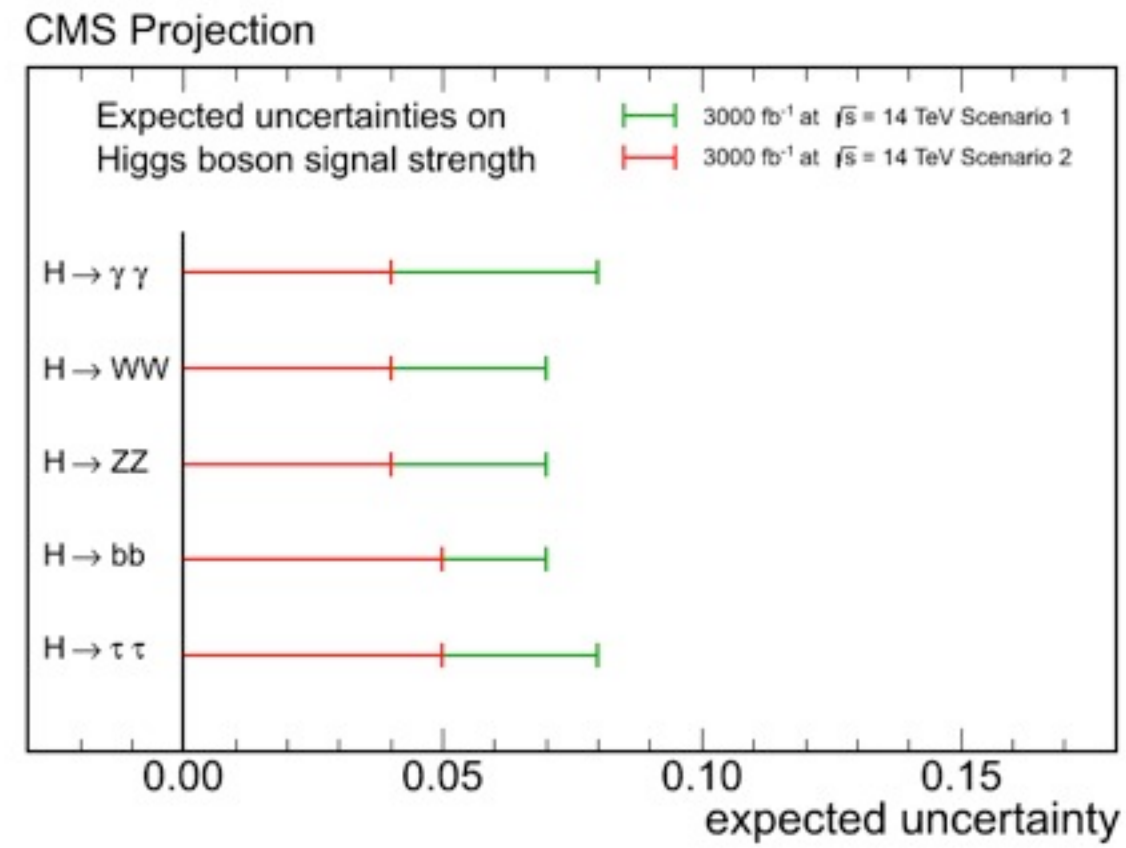
2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 | 2022 | 2023 | 2024

$0.7x10^{34}cm^{-2}s^{-1}$ | $1x10^{34}cm^{-2}s^{-1}$ | $2x10^{34}cm^{-2}s^{-1}$ | $5x10^{34}cm^{-2}s^{-1}$

The Large Hadron Collider (LHC) at CERN, Switzerland

Potential for future LHC couplings fits





L (fb^{-1})	$H \to \gamma\gamma$	$H \to WW$	$H \to ZZ$	$H \to bb$	$H \to \tau\tau$	$H \to Z\gamma$	$H \to inv.$
300	[6, 12]	[6, 11]	[7, 11]	[11, 14]	[8, 14]	[62, 62]	[17, 28]
3000	[4, 8]	[4, 7]	[4, 7]	[5, 7]	[5, 8]	[20, 24]	[6, 17]

Assumptions on systematic uncertainties
Scenario 1: no change
Scenario 2: Δ theory / 2, rest ∝ $1/\sqrt{L}$

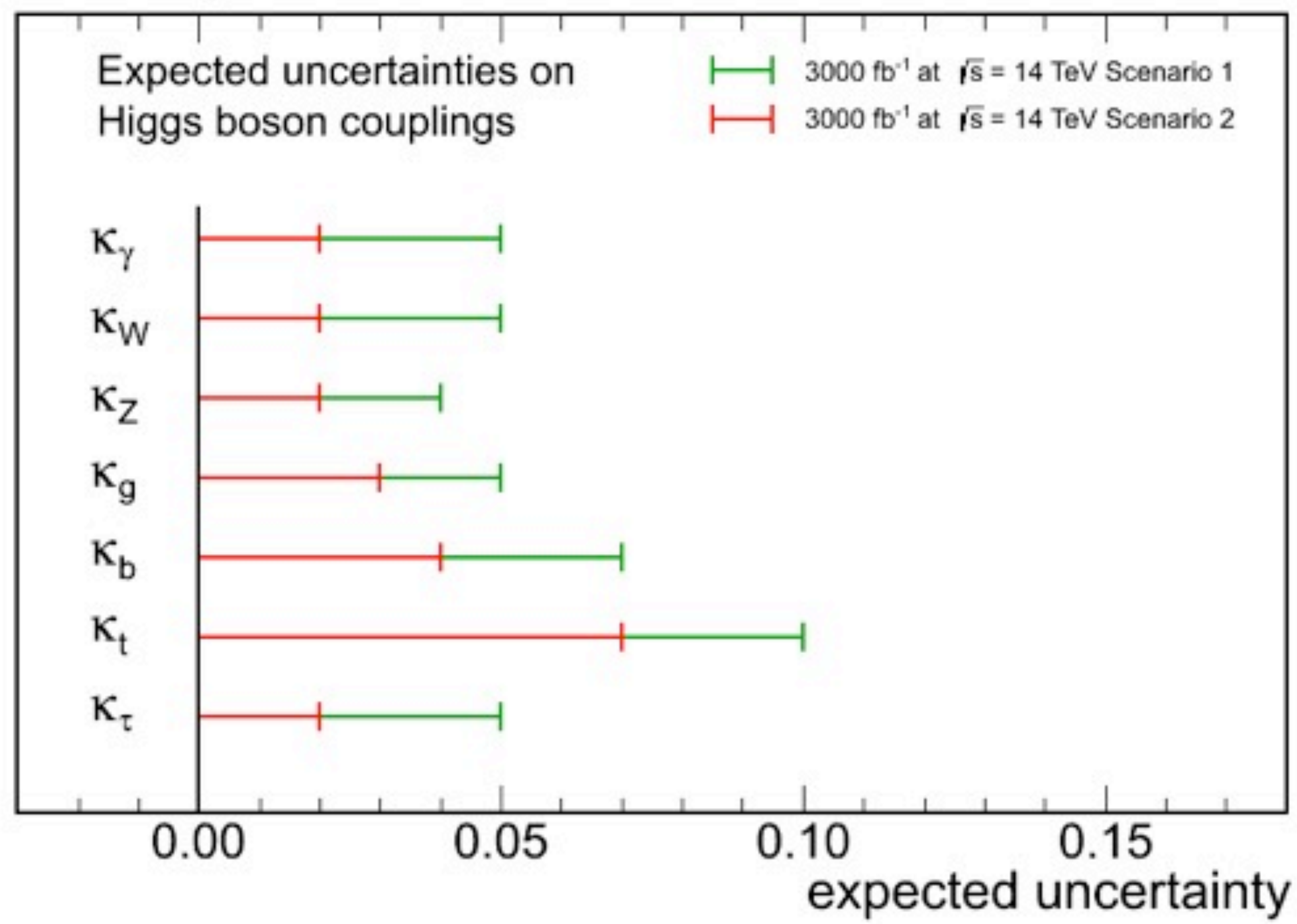
Based on parametric simulation

Extrapolated from 2011/12 results

Higgs Boson coupling fits

κ_g, κ_γ, $\kappa_{Z\gamma}$: loop diagrams ➜ allow potential new physics
κ_W, κ_Z: vector bosons
κ_t, κ_b: up- and down-type quarks
κ_τ, κ_μ: charged leptons
total width from sum of partial widths

CMS Projection



alternatively:

$$\Gamma_{\text{tot}} = \sum \Gamma_{ii} + \Gamma_{\text{BSM}}$$

$$\text{BR}_{\text{BSM}} = \Gamma_{\text{BSM}} / \Gamma_{\text{tot}}$$

assumption here κ_W, κ_Z < 1

CMS Projection

L (fb^{-1})	κ_γ	κ_W	κ_Z	κ_g	κ_b	κ_t	κ_τ	$\kappa_{Z\gamma}$	κ_μ
300	[5,7]	[4,6]	[4,6]	[6,8]	[10,13]	[14,15]	[6,8]	[41,41]	[23,23]
3000	[2,5]	[2,5]	[2,4]	[3,5]	[4,7]	[7,10]	[2,5]	[10,12]	[8,8]

Snowmass Whitepaper for CMS - http://arxiv.org/abs/1307.7135

coupling precision 2-10 %
factor of ~2 improvement from HL-LHC

Theoretical uncertainties

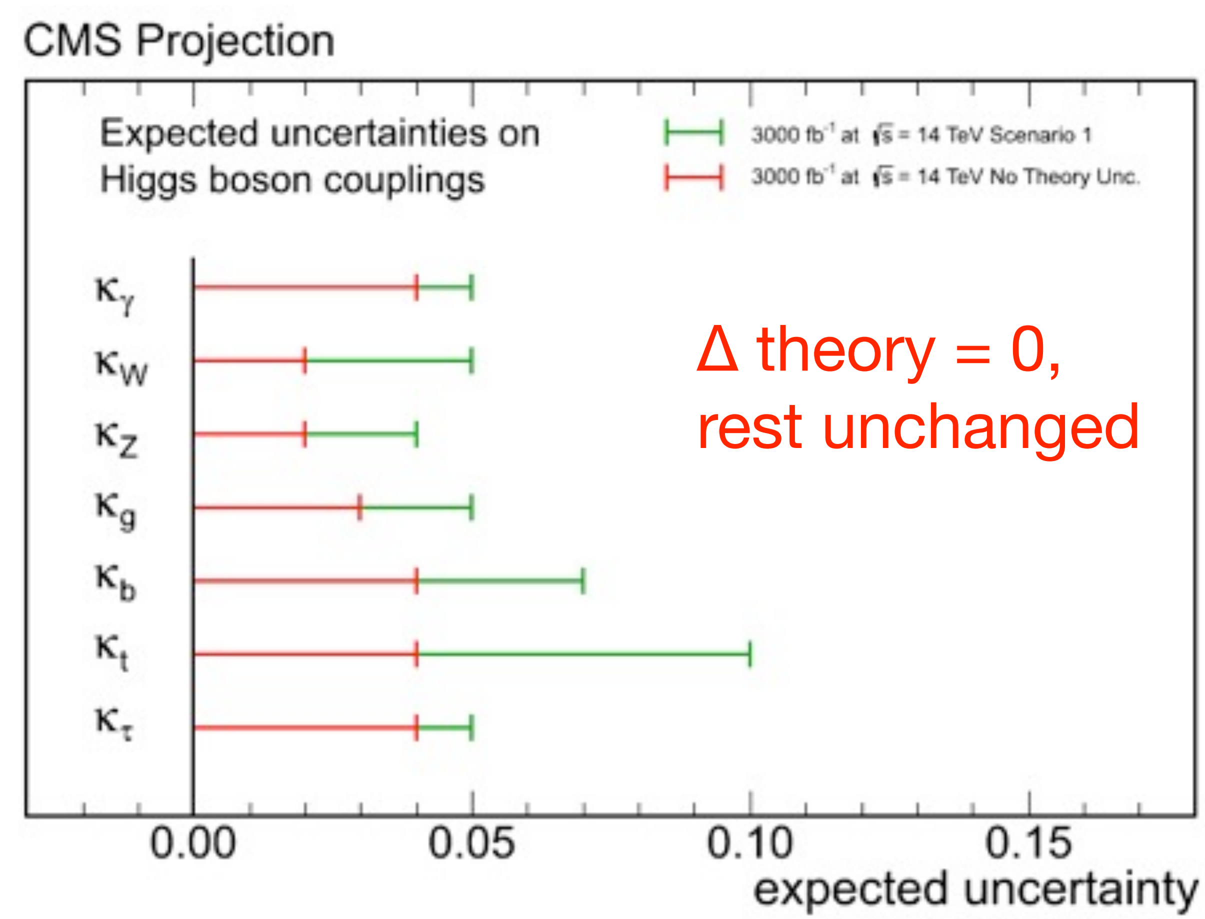
To test the importance of theoretical uncertainties we show the effect of removing them.

Theoretical uncertainties dominated by QCD scale and PDF uncertainties. Uncertainty on BR and acceptance uncertainties become relevant at few % precision.

Process	Cross section (pb)	Relative uncertainty in percent		
		Total	Scale	PDF
Gluon fusion	49.3	$^{+19.6}_{-14.6}$	$^{+12.2}_{-8.4}$	$^{+7.4}_{-6.2}$
VBF	4.15	$^{+2.8}_{-3.0}$	$^{+0.7}_{-0.4}$	$^{+2.1}_{-2.6}$
WH	1.474	$^{+4.1}_{-4.4}$	$^{+0.3}_{-0.6}$	$^{+3.8}_{-3.8}$
ZH	0.863	$^{+6.4}_{-5.5}$	$^{+2.7}_{-1.8}$	$^{+3.7}_{-3.7}$

Channel	$\Delta\alpha_s$	Δm_b	Δm_c	Theory Uncertainty	Total Uncertainty
$H \to \gamma\gamma$	0%	0%	0%	±1%	±1%
$H \to b\bar{b}$	∓2.3%	$^{+3.3\%}_{-3.2\%}$	0%	±2%	±6%
$H \to c\bar{c}$	$^{-7.1\%}_{+7.0\%}$	∓0.1%	$^{+6.2\%}_{-6.1\%}$	±2%	±11%
$H \to gg$	$^{+4.2\%}_{-4.1\%}$	∓0.1%	0%	±3%	±7%
$H \to \tau^+\tau^-$	0%	0%	0%	±2%	±2%
$H \to WW^*$	0%	0%	0%	±0.5%	±0.5%
$H \to ZZ^*$	0%	0%	0%	±0.5%	±0.5%

Handbook of LHC Higgs Cross Sections: 3. Higgs Properties - http://arxiv.org/abs/1307.1347



Comparison of ATLAS and CMS

$L(fb^{-1})$	Exp.	$\gamma\gamma$	WW	ZZ	bb	$\tau\tau$	$Z\gamma$	$\mu\mu$
300	ATLAS	[9, 14]	[8, 13]	[6, 12]	N/a	[16, 22]	[145, 147]	[40,42]
	CMS	[6, 12]	[6, 11]	[7, 11]	[11, 14]	[8, 14]	[62, 62]	[40,42]
3000	ATLAS	[4, 10]	[5, 9]	[4, 10]	N/a	[12, 19]	[54, 57]	[12,15]
	CMS	[4, 8]	[4, 7]	[4, 7]	[5, 7]	[5, 8]	[20, 24]	[14,20]

Uncertainty on signal strength

- Ranges [x,y] are not directly comparable
- ATLAS
    - [no theory uncertainty, Scenario 1]
- CMS
    - [Scenario 2, Scenario 1]

Overall reasonable agreement, but

- ATLAS does not include H ➜ bb mode
- CMS outperforms ATLAS H ➜ ττ mode
- Large differences in H ➜ Zγ mode due to photon id

Comparison with ATLAS and CMS

L(fb^{-1})	Exp.	κ_γ	κ_W	κ_Z	κ_g	κ_b	κ_t	κ_τ	$\kappa_{Z\gamma}$	$\kappa_{\mu\mu}$
300	ATLAS	[8,13]	[6, 8]	[7, 8]	[8, 11]	N/a	[20, 22]	[13, 18]	[78, 79]	[21, 23]
	CMS	[5, 7]	[4, 6]	[4, 6]	[6, 8]	[10, 13]	[14, 15]	[6, 8]	[41, 41]	[23, 23]
3000	ATLAS	[5, 9]	[4, 6]	[4, 6]	[5, 7]	N/a	[8, 10]	[10, 15]	[29, 30]	[8, 11]
	CMS	[2, 5]	[2, 5]	[2, 4]	[3, 5]	[4, 7]	[7, 10]	[2, 5]	[10, 12]	[8, 8]

Large differences in fits for coupling strength

- ATLAS connects Kτ with Kb to overcome H ➜ bb mode, but H ➜ ττ then becomes overall limitation in constraining total width.

$$\kappa_H^2 = \sum_X \kappa_X^2 \mathrm{BR}_{\mathrm{SM}}(H \to X)$$

L(fb^{-1})	Exp.	$\kappa_g \cdot \kappa_Z / \kappa_H$	κ_γ/κ_Z	κ_W/κ_Z	κ_b/κ_Z	κ_τ/κ_Z	κ_Z/κ_g	κ_t/κ_g	κ_μ/κ_Z	$\kappa_{Z\gamma}/\kappa_Z$
300	ATLAS	[3,6]	[5,11]	[4,5]	N/a	[11,13]	[11,12]	[17,18]	[20,22]	[78,78]
	CMS	[4,6]	[5,8]	[4,7]	[8,11]	[6,9]	[6,9]	[13,14]	[22,23]	[40,42]
3000	ATLAS	[2,5]	[2,7]	[2,3]	N/a	[7,10]	[5,6]	[6,7]	[6,9]	[29,30]
	CMS	[2,5]	[2,5]	[2,3]	[3,5]	[2,4]	[3,5]	[6,8]	[7,8]	[12,12]

Conclusion

- Comprehensive set of Higgs coupling fits performed on Run I (7 & 8 TeV) dataset by ATLAS and CMS
    - No significant deviation observed
    - Measurements mostly limited by statistical uncertainties
- Large program for Higgs coupling measurements in Run II (13-14 TeV) to stay ahead of systematical uncertainties
    - Models need to be advanced
    - Theoretical (scale, α_s, and PDF) uncertainties will become dominant
    - Experimental challenges due to large pileup and detector longevity effects