Prospects for Higgs Coupling Measurements at the High-Luminosity LHC with CMS

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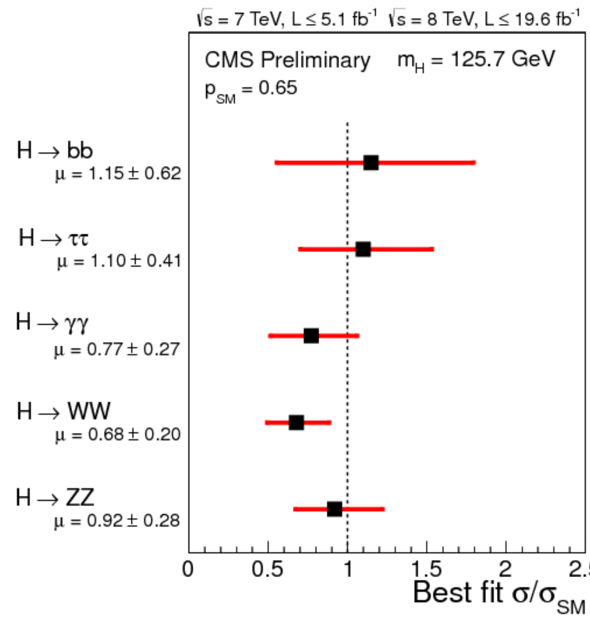
Last year discovery of a new boson at the LHC opened the new horizons at the Energy Frontiers

☞ The boson that we found looks rather **"standard"** scalar at first sight

☞ Unraveling its nature is the major effort

A Higgs Boson→
The Higgs Boson→
The SM Higgs Boson



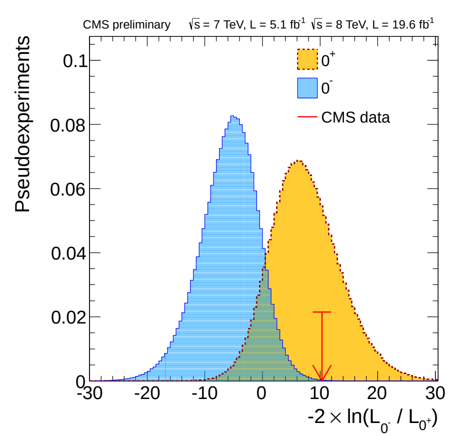
☞ The SM begins to unravel when probed beyond the range of current accelerators

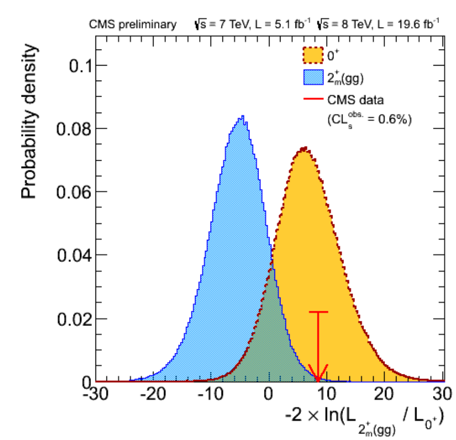
☞ **No hint of New Physics so far:** **indirect searches become pivotal!**

➠ precision coupling measurement

$$\Delta k/k \propto 1/M_\Lambda^2$$

$\Delta k/k$ ~10(1)%⇒ M_Λ ~1-1.5(3-4) TeV

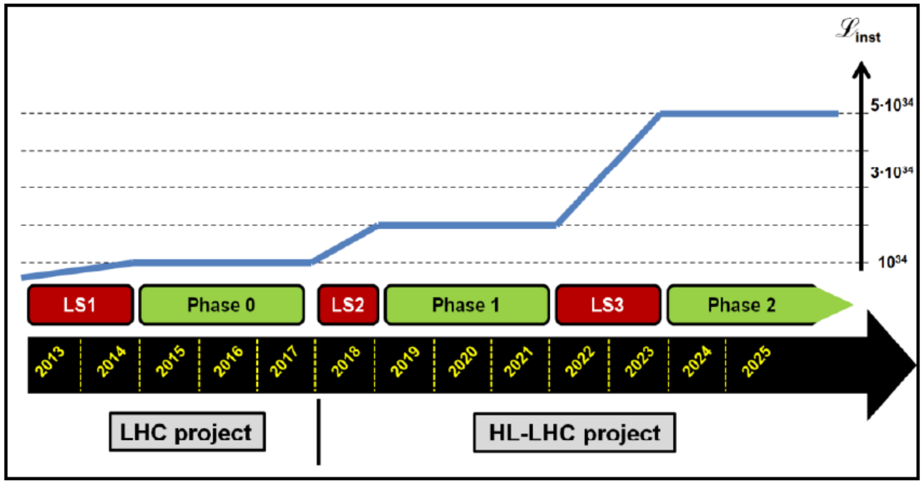




LHC approved running to deliver 300 fb^{-1} by 2021 with 20x Higgs boson production so far

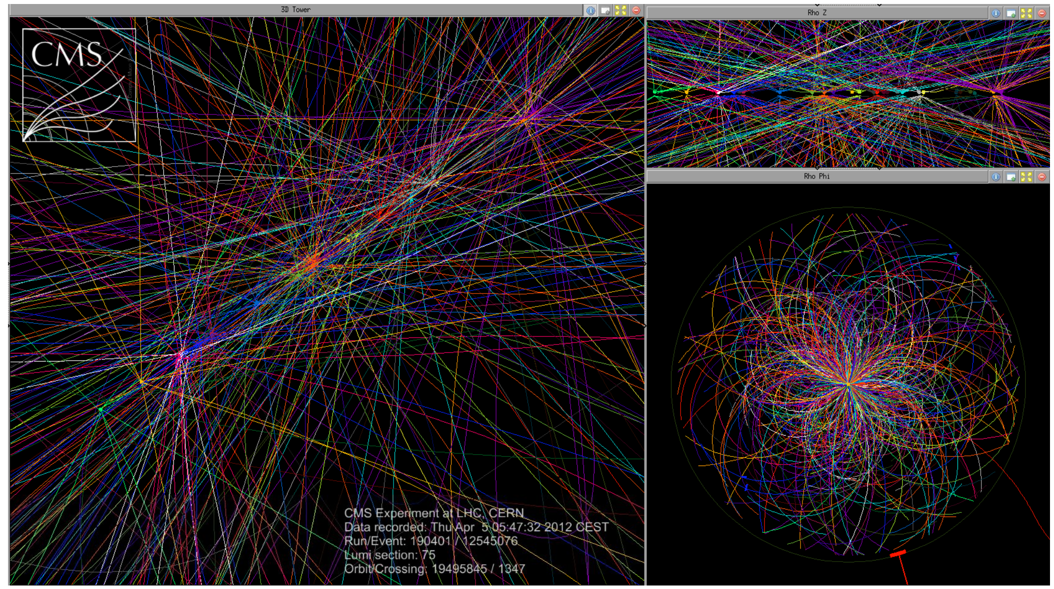
- Post LS3 operation at 5×10^{34} $cm^{-2}s^{-1}$
  - 25 ns bunch spacing
  - **3000 fb^{-1} over 10 years**
  - 140 events per bunch crossing
- Major upgrades required on the LHC **(replace more than 1.2 km):**
  - new IR-quads Nb_3Sn (inner triplets)
  - new 11 T Nb_3Sn (short) dipoles
  - collimation upgrade
  - cryogenics upgrade
  - crab cavities

LHC revamp is resuming in 2015, with $\sqrt{s}$ unlikely exceeding 13 TeV



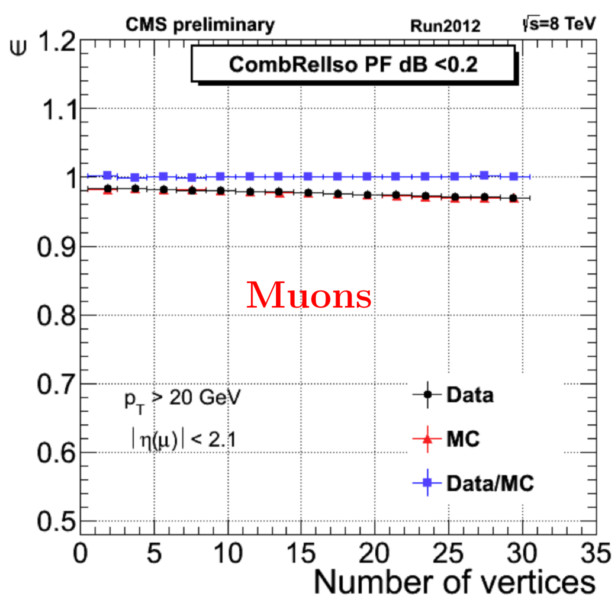
Projections done assuming 14 TeV, little difference for analysis performance

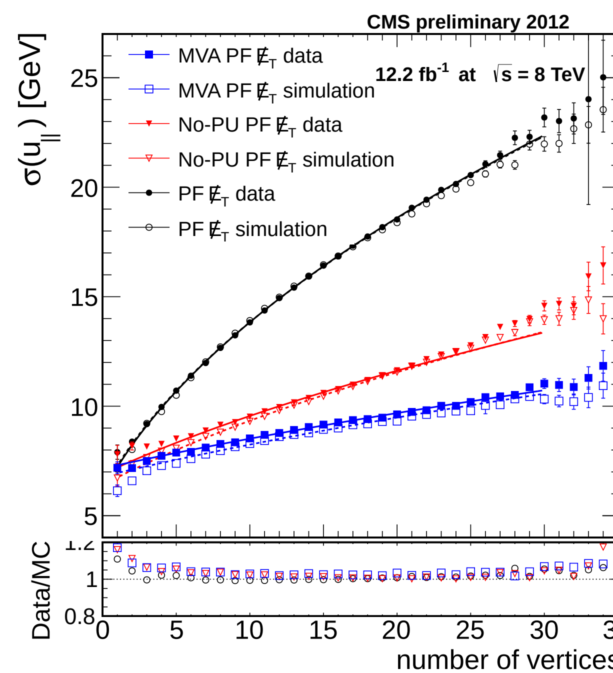
29 distinct vertices have been reconstructed corresponding to 29 distinct collisions within a single crossing of the LHC beam



Leptons and MET are almost insensitive to pileup at current lumi

- ☞ Experiment was designed for mean 20 events per bunch-crossing
- ☞ continue to do an excellent job with 30 events
- ☞ handle 70 events of pileup

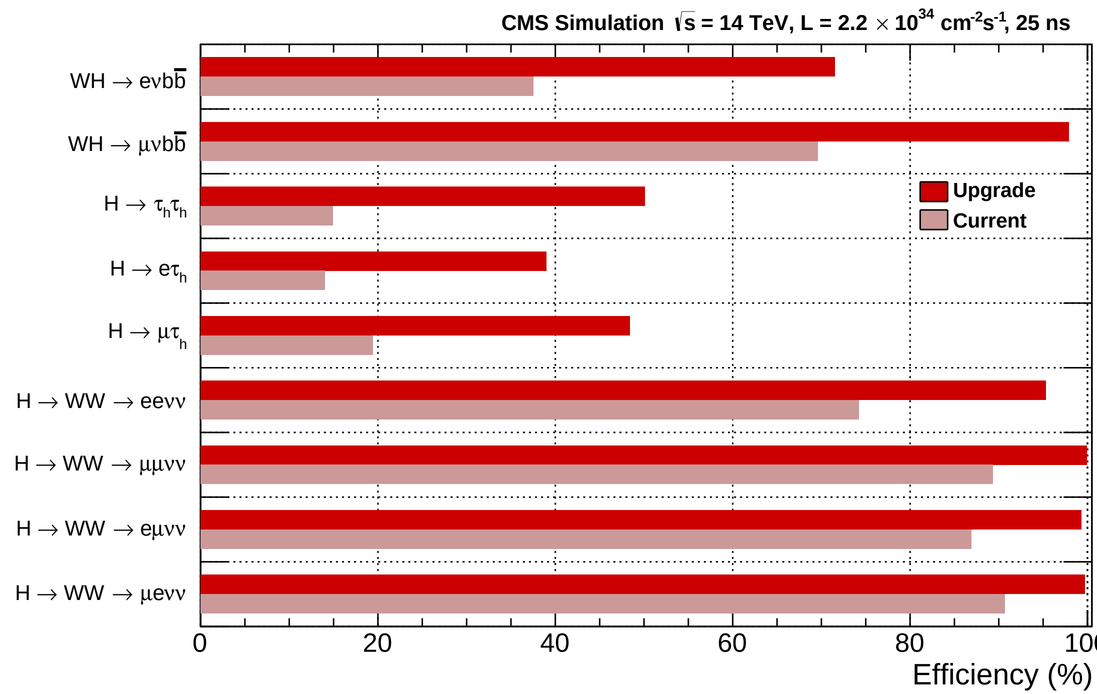




But 140 events of pileup will be a challenge

- Detector upgrade needed
  - to withstand radiation damage and pileup
  - to maintain or enhance the current physics performance
- CMS will undergo a series of detector and trigger upgrades
  - several subdetectors will be improved or replaced
  - trigger is a key component
    - mandated by need to study the Higgs boson
    - thresholds not too dissimilar to today

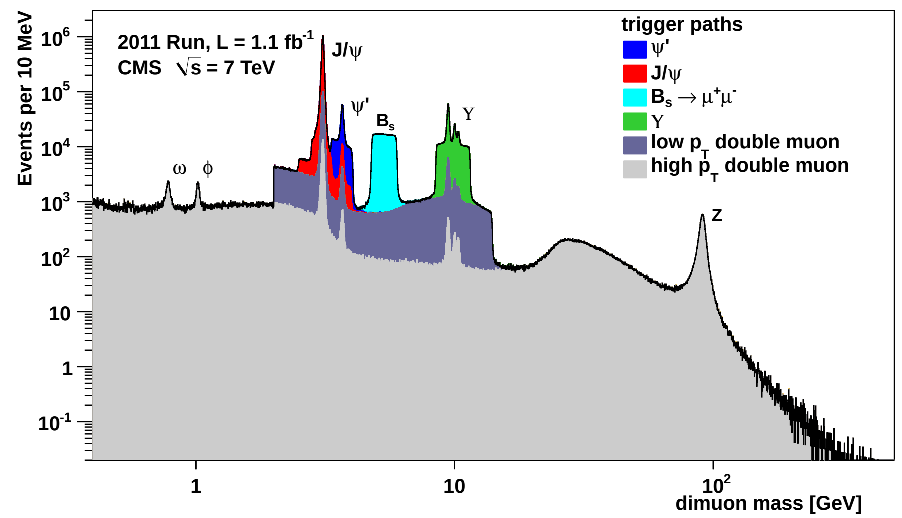
[CMS-NOTE-13-002, arXiv:1307.7135]



Current and Phase 1 trigger efficiency: upgraded trigger system available for data taking in 2016

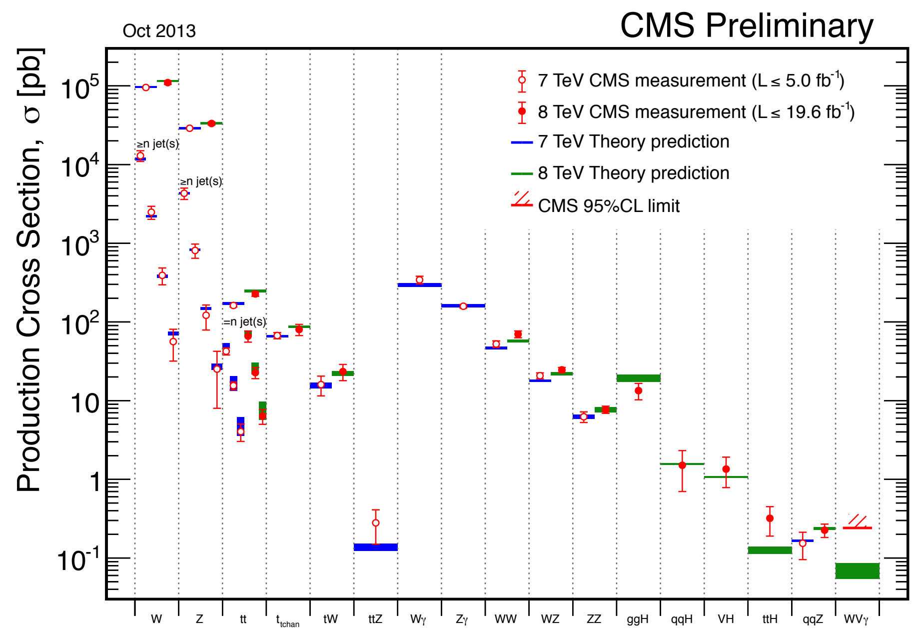
What have we learned?

- the experiment is working remarkably
  - ➔ operations, detector performance and simulation
- the SM is in great shape
  - ➔ N(N)LO calculations match data very well



HL-LHC Physics Goal in Higgs Sector

- rare decays & couplings
- spin and CP studies
- BSM Higgs boson searches
- Higgs boson pair production



☞ HL-LHC is a real Higgs factory

- a couple of Higgs events produced per sec
- compare to e^+e^- colliders:
  - ➔ less than 10 events per hour at $L = 10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$

☞ Most of the exclusive final states are accessible, including in particular very rare ones

- **20K** $\mathrm{H} \rightarrow \mathrm{ZZ} \rightarrow 4\mathrm{l}$
- **30K** $\mathrm{H} \rightarrow \mu\mu$
- **50** $\mathrm{H} \rightarrow \mathrm{J}/\psi\gamma$

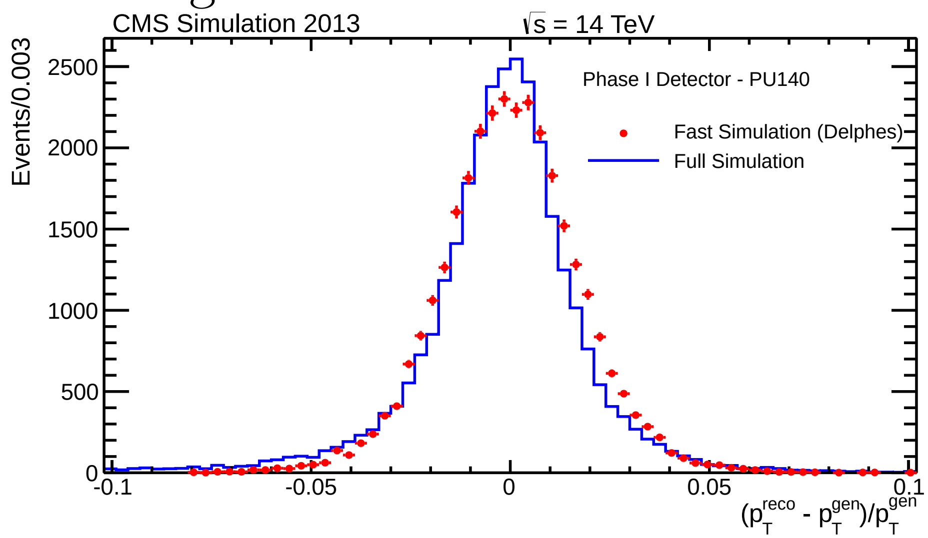
Channel	σ, pb (14 TeV)	Rate, Hz L=50 pb^{-1} s^{-1} (14TeV)	Events, L=3ab^{-1} (14TeV)	Events , L=30 fb^{-1} (8TeV)
ggH	50.4	2.52	150M	600K
VBF	4.2	0.21	13M	48K
WH	1.5	0.08	4.5M	21K
ZH	0.9	0.04	2.6M	12K
ttH	0.6	0.03	1.8M	4K

Enable to probe redundantly most of the coupling factors

Projection Approach:

- ☞ Scale results of current analyses
- ☞ **Two scenarios considered:**
  - ➠ **Scenario 1 (conservative):** same experimental and theory systematic uncertainties as today
  - ➠ **Scenario 2 (ambitious):** experimental syst. scaled by $1/\sqrt{L}$, theory syst. halved
- ☞ Assume detector upgrade keeps current performance
- ☞ Supported by full simulation studies

Fast simulation (DELPHES) validated against full G4 simulation

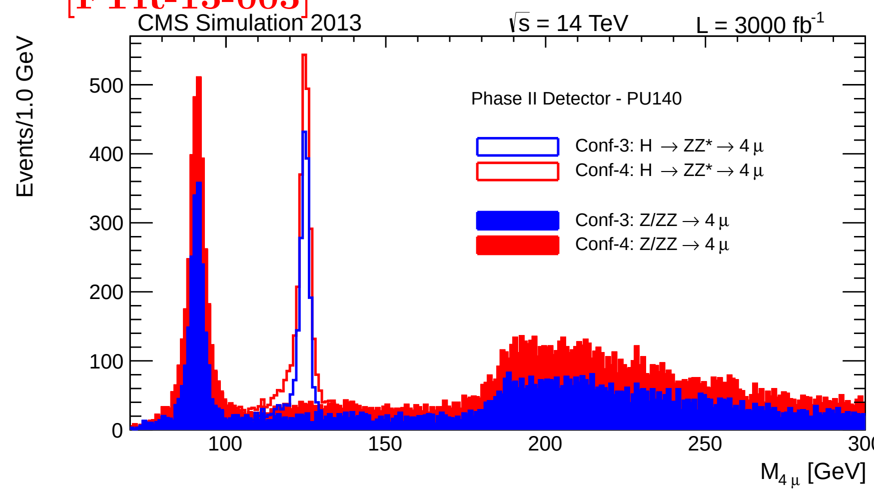


use more pessimistic performance for current studies

$H \to ZZ \to 4\mu$

- Worth **full** study with DELPHES
- Considered coverage extension from $|\eta| < 2.4$ to $|\eta| < 4 \to$ in **Phase II** detector upgrades
  - sizable acceptance increases 45%

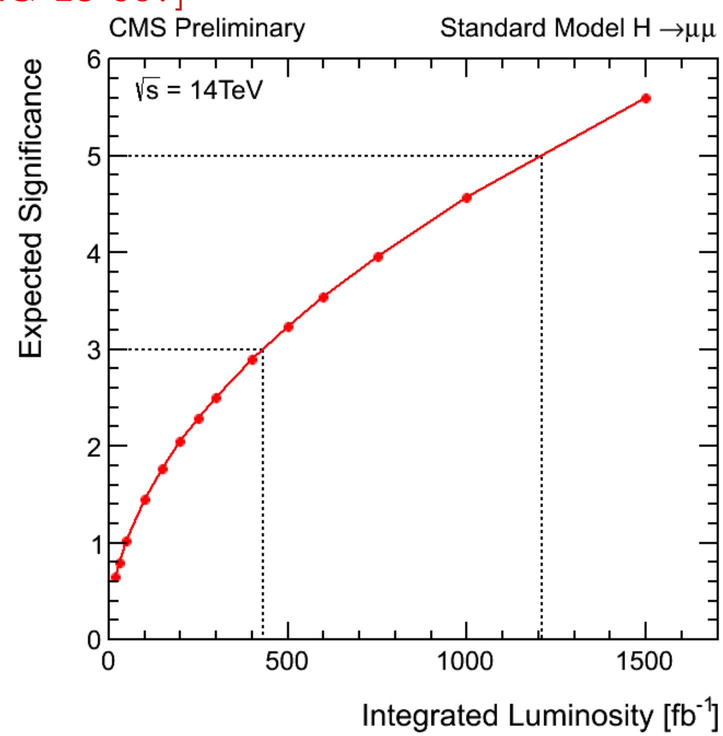
[FTR-13-003]



$H \to 2\mu$

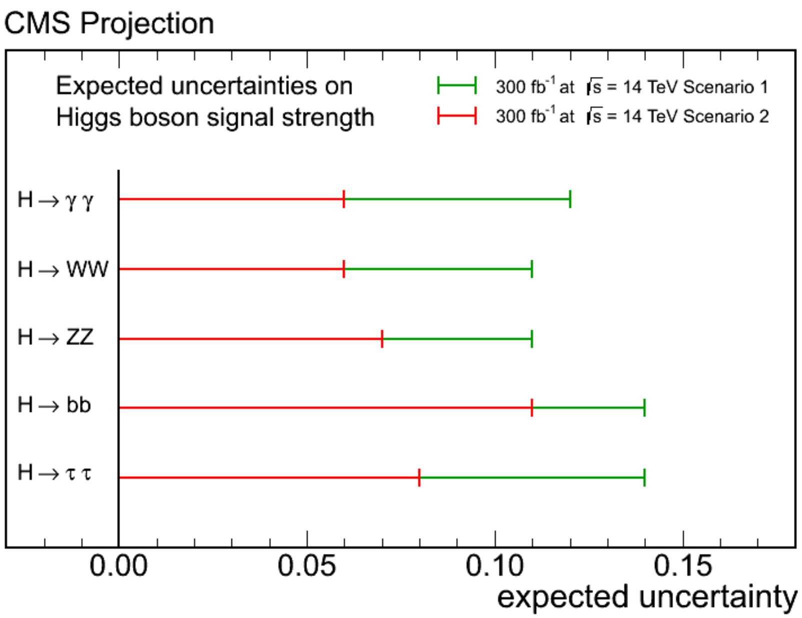
- **Rescale** of current analysis
- Allows direct study of coupling to two different leptons
  - tests lepton flavor violation
- **$3000\,\mathrm{fb}^{-1}$ at 14TeV offers new possibilities**
  - signal to background marginal
  - but a measurement is possible

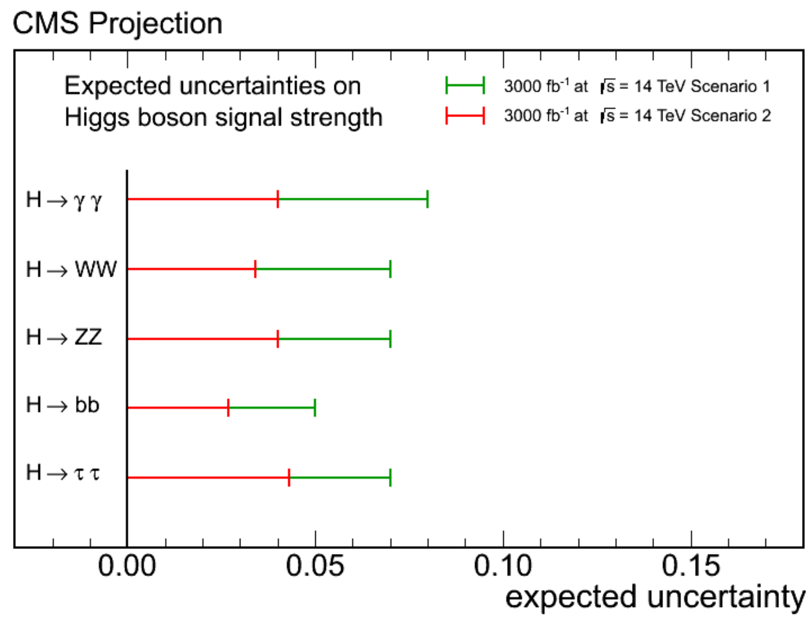
[HIG-13-007]



☞ First step to assess **compatibility to SM**

- perform single parameter fit, signal strength $\mu = \sigma/\sigma_{SM}$
- group decay channels together and express results as σ_μ/μ





[Scenario 2, Scenario 1]

L (fb^{-1})	$\gamma\gamma$	WW	ZZ	bb	$\tau\tau$	Zγ	$\mu\mu$	inv.
300	[6, 12]	[6, 11]	[7, 11]	[11, 14]	[8, 14]	[62, 62]	[40,42]	[17, 28]
3000	[4, 8]	[4, 7]	[4, 7]	[5, 7]	[5, 8]	[20, 24]	[14,20]	[6, 17]

Not always straightforward to interpret: worth separation of production modes

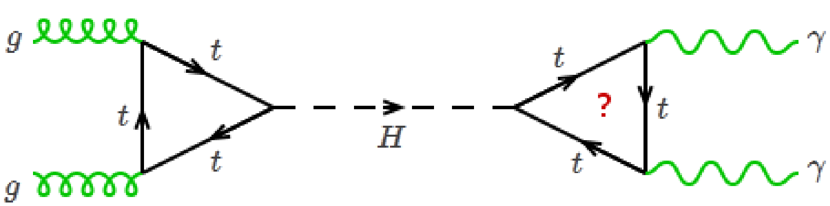
☞ Attach a modifier to the SM prediction

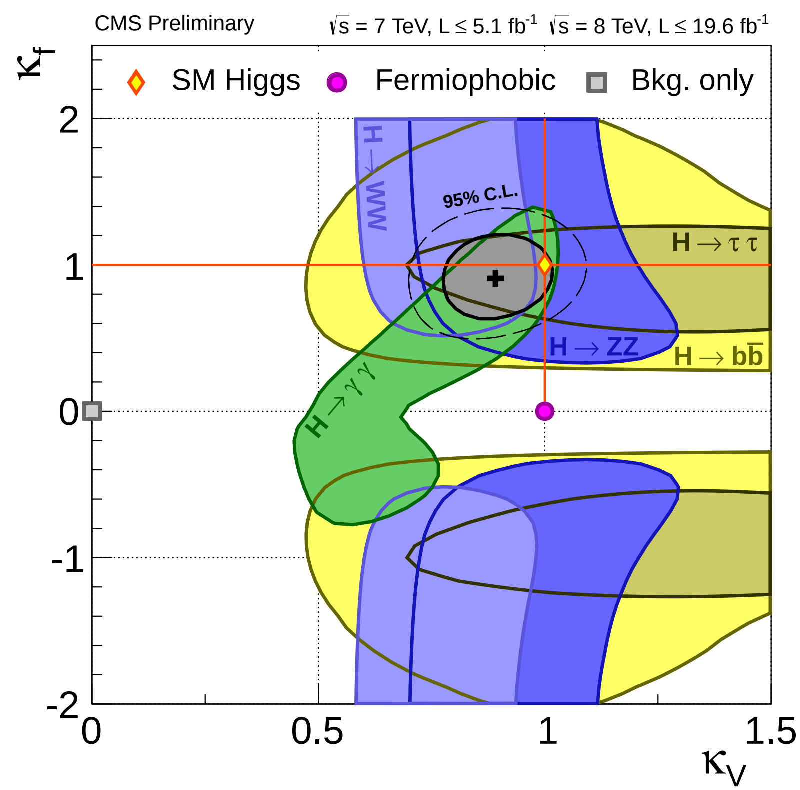
$$\sigma\mathcal{B}(ii \to H \to ff) \sim \frac{\Gamma_{ii}\Gamma_{ff}}{\Gamma_{tot}} = \sigma_{SM} \cdot \mathcal{B}_{SM}\frac{k_i^2 \cdot k_f^2}{k_H^2}$$

☞ Estimate Higgs boson couplings into "**Vectorial**" and "**Fermionic**" sets:

- $H \to \gamma\gamma$ is the only channel that is sensitive to k_V or k_F relative sign
  - ➔ possible to sort out degeneracy

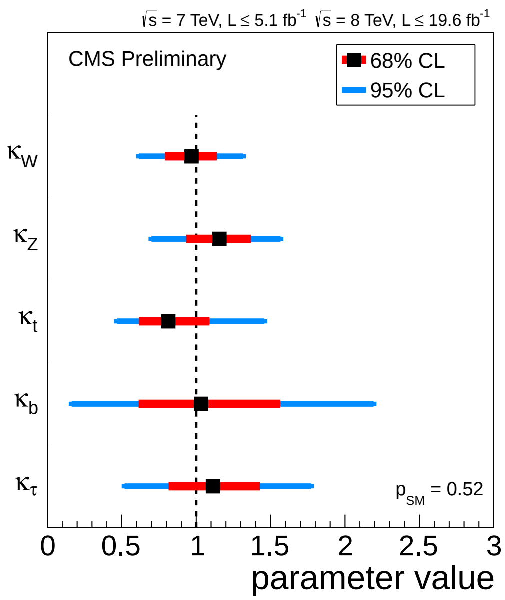
$\Gamma_{gg} \sim k_F^2$ $\Gamma_{\gamma\gamma} \sim |\alpha k_V + \beta k_F|^2$

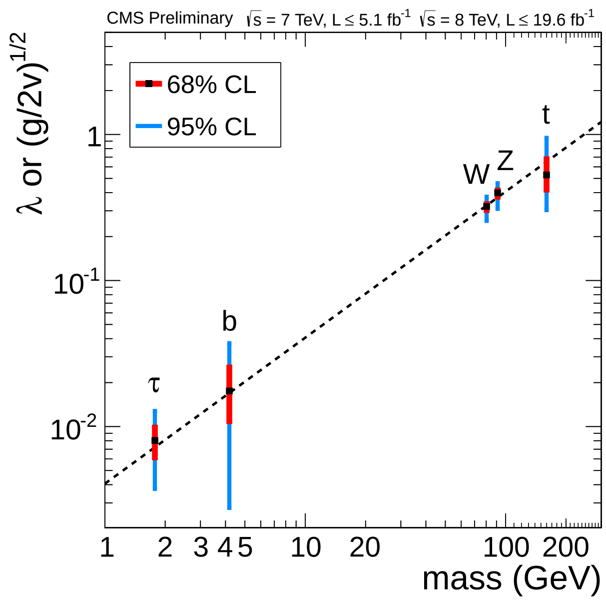


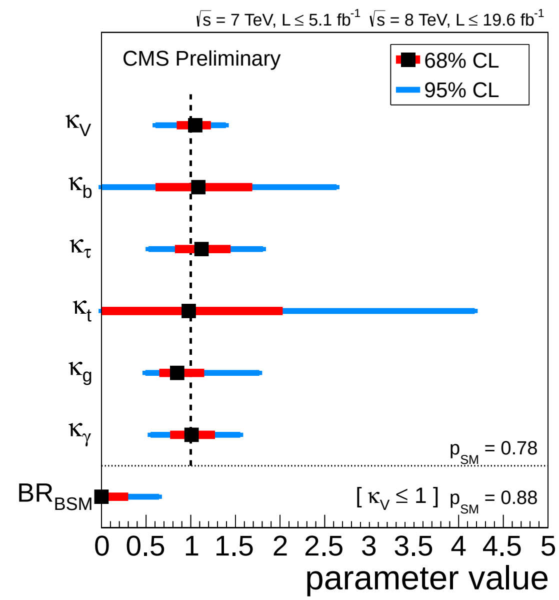


In agreement with the SM within uncertainties

Compatibility with the SM Higgs Boson Couplings







The generic five-parameter model not effective loop couplings
(the SM structure is assumed for loop-induced couplings)

Not effective loop couplings as function of the mass

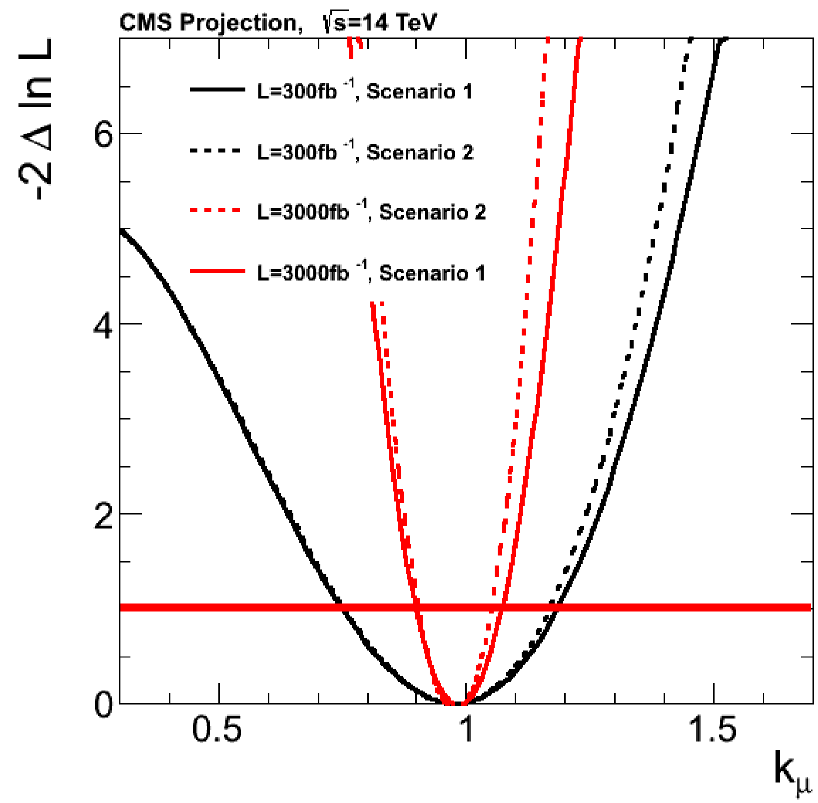
New particles can modify the loop-mediated couplings and contribute to the total width

$$\Gamma_{tot} = \sum \Gamma_{i(SM)} + \Gamma_{BSM}$$

No significant deviations from the SM Higgs boson are found so far

Extracting Higgs couplings requires assumptions at LHC

- Total width $\Gamma_{\rm H} \sim k_H^2$ is not measurable
  - not possible to measure directly a production cross section as at a e^+e^- **collider**
- Follow recommendations and fit models described in Yellow Report 3 [arXiv:1307.1347]
  - assumed $k_H = \Sigma\, k_i BR_i$, only for i in SM
    - ➔ total width controlled by $\rm H \to bb$
    - ➔ $\rm H \to cc$ is a 5% unaccessible contribution (assumed to scale with bb)
    - ➔ no contributions from BSM
- **Global fits targeting the k factors**
  - do not resolve loops, effective coupling instead (k_γ, k_g and $k_{Z\gamma}$)



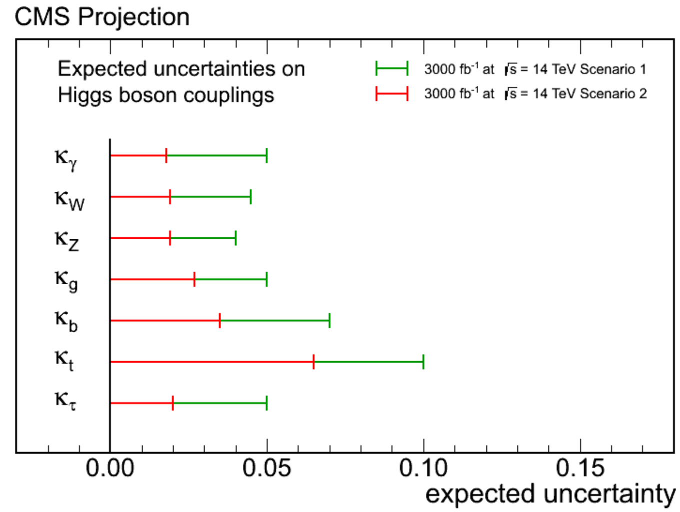
Results reported in terms of 68% uncertainties (-2$\Delta \ln L$=1) on k

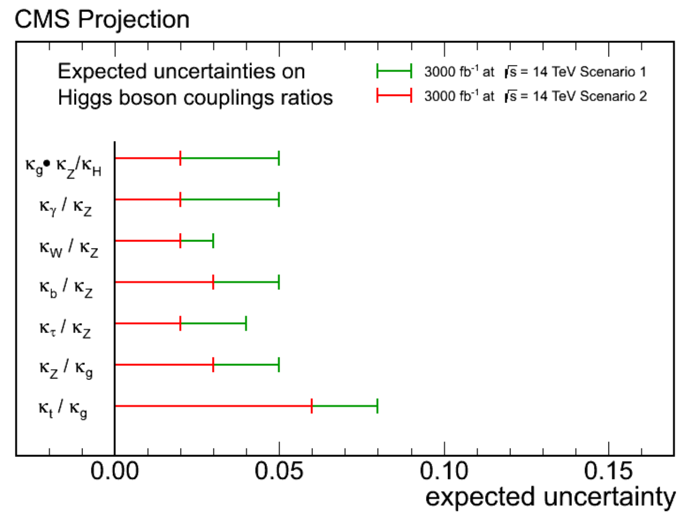
☞ **Assume no new undetectable modes**

➠ in an ambitious scenario, ultimate precision is about 2% for couplings involved in the main decay modes

☞ Results are more "stable" if total width absorbed by a reference scale factor

➠ look at **ratios of couplings** for direct comparison





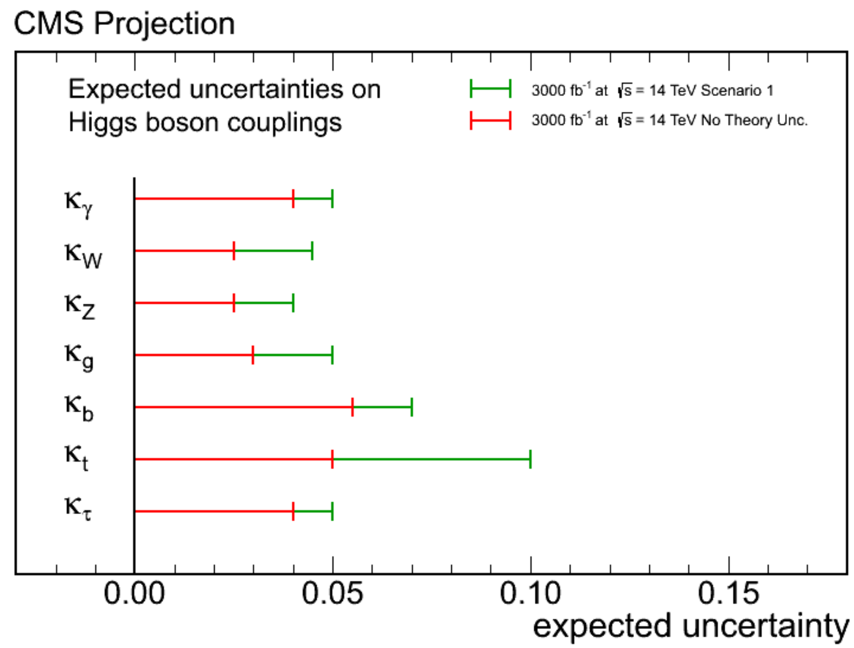
HL-LHC can lead to an accuracy of about 5-8% for many coupling constants in scenario conservatively covering the range of future performances

[Scenario 2, Scenario 1]

L (fb^{-1})	k_γ	k_W	k_Z	k_g	k_b	k_t	k_τ	$k_{Z\gamma}$	$k_{\mu\mu}$	BR_{SM}
300	[5, 7]	[4, 6]	[4, 6]	[6, 8]	[10, 13]	[14, 15]	[6, 8]	[41, 41]	[23, 23]	[14, 18]
3000	[2, 5]	[2, 5]	[2, 4]	[3, 5]	[4, 7]	[7, 10]	[2, 5]	[10, 12]	[8, 8]	[7, 11]

Current results are still limited by statistical uncertainty

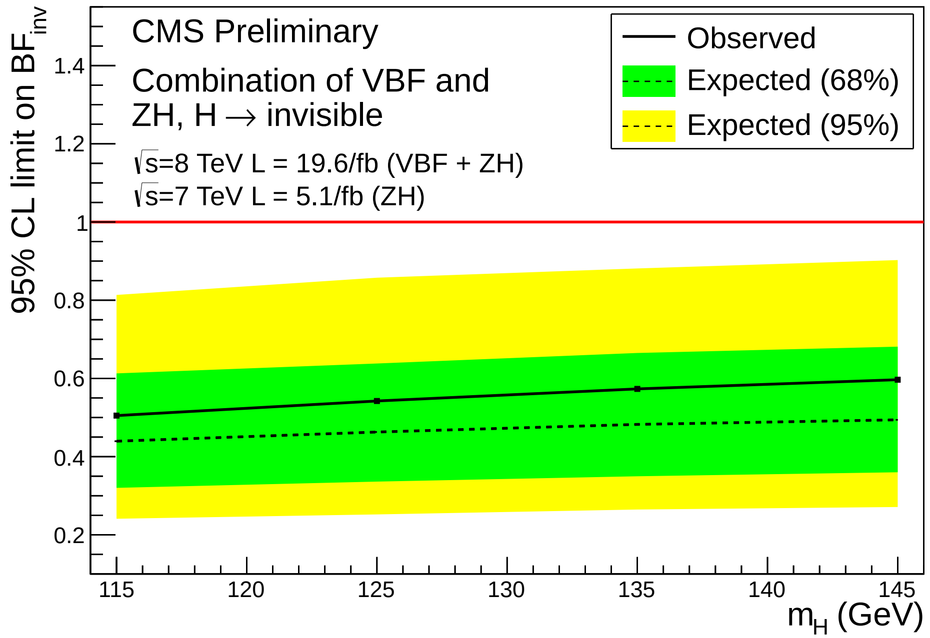
- Two major questions arise for the future prospectives:
  - what are the most relevant **systematic uncertainties**?
  - what role do the **theoretical uncertainties** play?
- Theoretical uncertainties affects the ultimate precision achievable by experiment
- Reducing them it is worth the effort!



HL-LHC can ultimately reach an accuracy of below 5% for many coupling constants

- Current direct observation using **VBF and VH channels:**
  - $\boldsymbol{BR_{inv} < 0.54}$ **at 95% CL**
  - consistent with global fit: $BR_{inv} < 0.52$ at 95% CL
- Estimate sensitivity to BR_{inv} by E_T^{miss} control in **ZH, Z $\rightarrow$ ll**
  - about 10% with 3ab^{-1}
- Sensitivity can be remarkably improved if VBF channel is considered
  - strongly dependent on experimental conditions
  - not reliably projectable so far

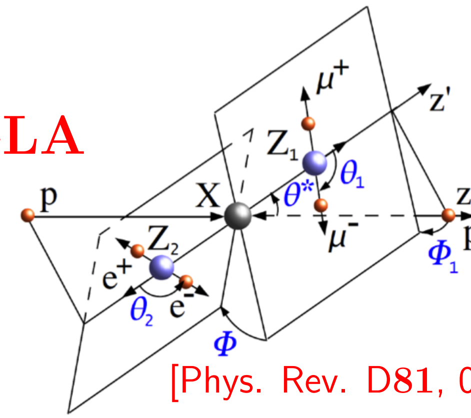
[HIG-13-018]



If direct searches are combined with the other SM channels, precision could be pinned down to 5% level

Tensor structure of the Higgs sector (J^{CP} numbers) can be best probed by angular analysis

MELA

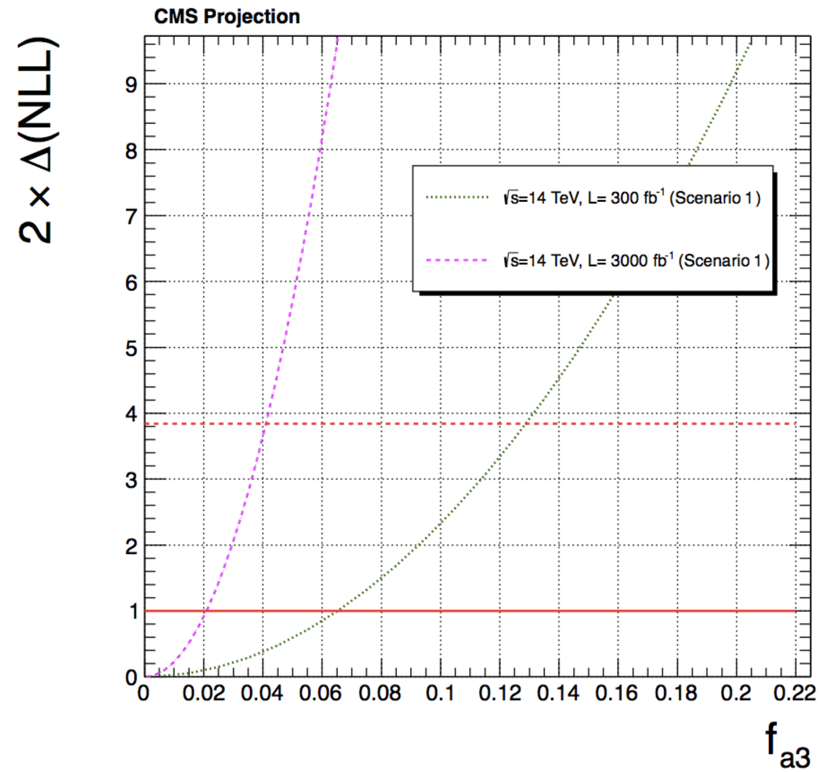


[Phys. Rev. D81, 075022(2010)]

- HL-LHC will allow assessing the individual terms in a generic parameterization of the Lagrangian
- Mixing between CP-even and CP-odd state can in particular being studied
- The decay amplitude for a **spin-0** boson

$$A = v^{-1}\epsilon_1^{*\mu}\epsilon_2^{*\nu}(\mathbf{a_1} g_{\mu\nu}M_X^2 + \mathbf{a_2} q_{1\mu}q_{2\nu} + \mathbf{a_3}\epsilon_{\mu\nu\alpha\beta}q_1^\alpha q_2^\beta)$$

  - SM-Higgs → ZZ,WW:
    ➔ $\mathbf{a_1} \neq 0$, $\mathbf{a_2} \sim O(10^{-2})$, $\mathbf{a_3} \sim O(10^{-11})$
  - BSM pseudo-scalar Higgs: $\mathbf{a_3} \neq 0$
- Fraction of CP-odd $\mathbf{f_{a_3}}$ is defined under the assumption $\mathbf{a_2} = \mathbf{0}$



Big sensitivity gain from HL-LHC

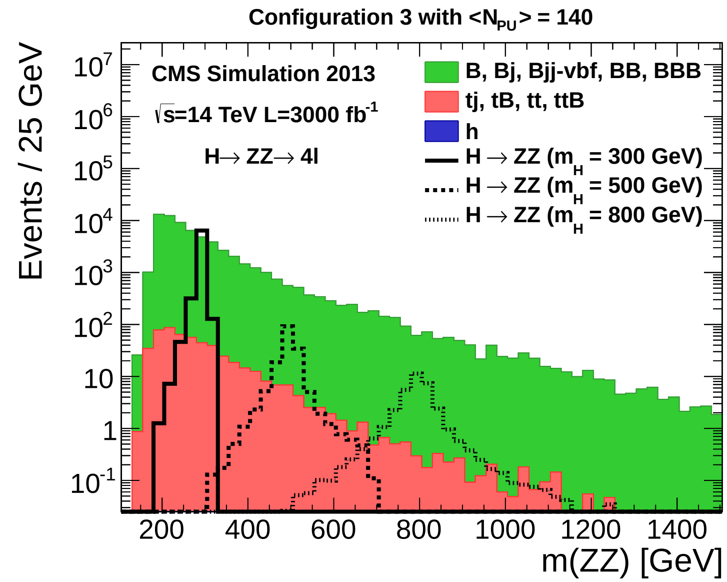
BSM (2HDM)

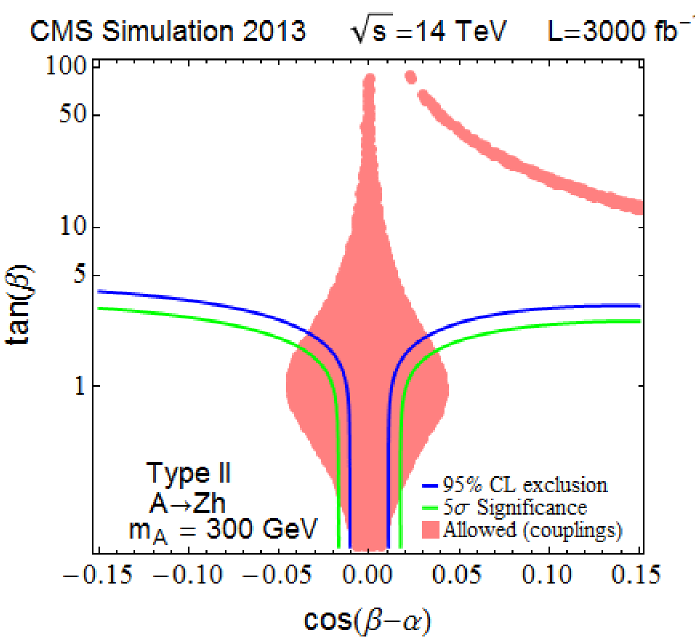
[FTR-13-024]

Many BSM models have extra doublet $(\mathrm{H}, \mathrm{A}, \mathrm{H}^+, \mathrm{H}^-)$

- Search additional Higgs fields at high masses
- Performed full MC analysis of $\mathrm{H} \to \mathrm{ZZ}$ and $\mathrm{A} \to \mathrm{Zh}$ resonances in Type I and II 2HDM's
  - **type II includes MSSM**
  - constrained 2HDM parameter space of $\tan\beta$ and $\cos(\beta - \alpha)$
  - indirect constrain from coupling fits favor $\cos(\beta - \alpha) \to 0$ (the SM Higgs boson)
  - H/A decays have tt threshold effect
    - ➔ discovery potential $\mathrm{m_{H/A}} < 2\mathrm{m_t}$ (type II)

Direct search can probe region close to the alignment limit, that may still be allowed by coupling fits





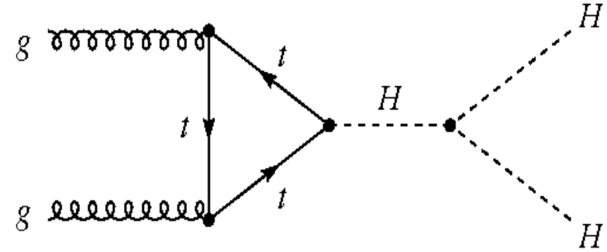
Higgs Self Coupling

Double Higgs production among the main objectives of HL-LHC, but this process is very challenging

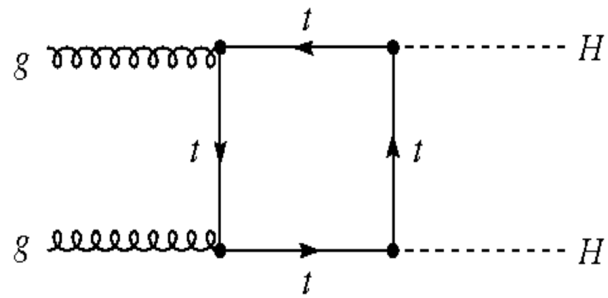
- Low rate makes high demands on detectors and integrated luminosity
  - tiny cross section $\sigma(\mathrm{HH}) = 40 \pm 3\,\mathrm{fb}$ (120K)
  - finding one requires at least 500K events
  - theoretical studies suggest possible: [arXiv:1309.6318]
  - problematic also at high energy e^+e^- machines
- Self coupling diagrams **interferes destructively** with double Higgs processes
  - look for a deficiency in a small signal

Ongoing studies suggest some sensitivity

Higgs self coupling process



SM Double Higgs production



Produced Events at 3000 fb^{-1}

Mode	Yield
bbWW	30000
bb$\tau\tau$	9000
WWWW	6000
$\gamma\gamma$bb	320

Summary

☞ 30 fb^{-1} of LHC data has allowed the Higgs discovery

➠ **overall we see so far is very well compatible with the SM**

☞ The approved LHC plan is to deliver 300 fb^{-1} by 2021

➠ the upgrade of the machine is designed to integrate up to 3ab^{-1} in about 10 years

➠ experiment will have to cope harsh conditions

➠ major detector and trigger upgrades are planned to maintain or improve current physics performances

☞ Vast Higgs physics program ahead that will profit from a HL-LHC

➠ precision Higgs couplings to 8 particles

➠ coupling structure

➠ Higgs invisible BR

➠ discovery potential for heavier Higgs bosons

➠ some sensitivity to self coupling

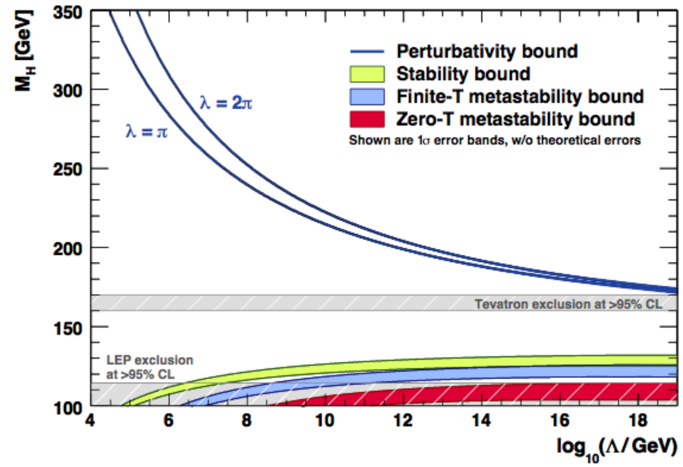
Higgs properties are expected to be pinned down to the level of a few percent

Backup

The boson that we found looks rather "standard" scalar at first sight:

(Check the vacuum stability up to the Plank scale $M_{Pl} \sim 10^{19}$ GeV)

[J.Ellis, et al., Phys. Lett. **B679**:369-375 (2009)]

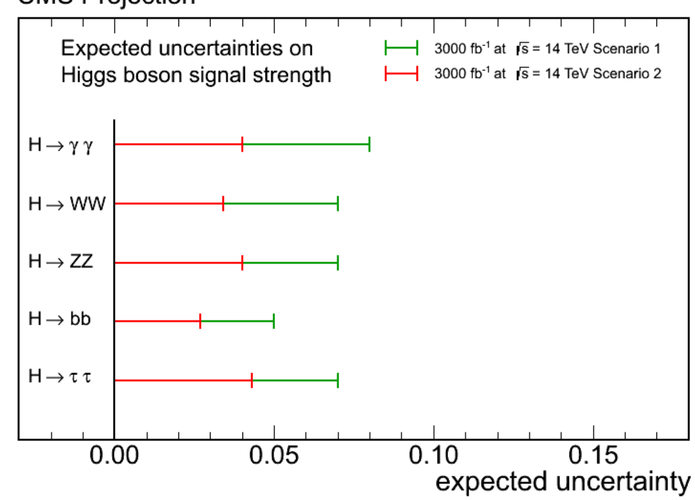


- Experimental clues of the BSM physics
  - Dark Matter (DM) points to WIMPs
  - Baryogenesis requires $\not{B}$ processes
  - neutrino mass

- **Indirect Searches**
  - precision coupling measurement

$$\Delta k/k \propto 1/M_{\Lambda}^2$$

  - extended Higgs sector in SUSY
  - $B_{s,d} \to \mu^+\mu^-$, TGC, etc



$\Delta k/k \sim$10(1)%$\Rightarrow M_{\Lambda} \sim$1-1.5(3-4) TeV

- **Direct Searches of BSM**
  - SUSY, DM, heavy resonances

☞ Allow for free cross sections in three channels and fit for the common mass

[HIG-13-005]

☞ **H→ZZ→4l:**

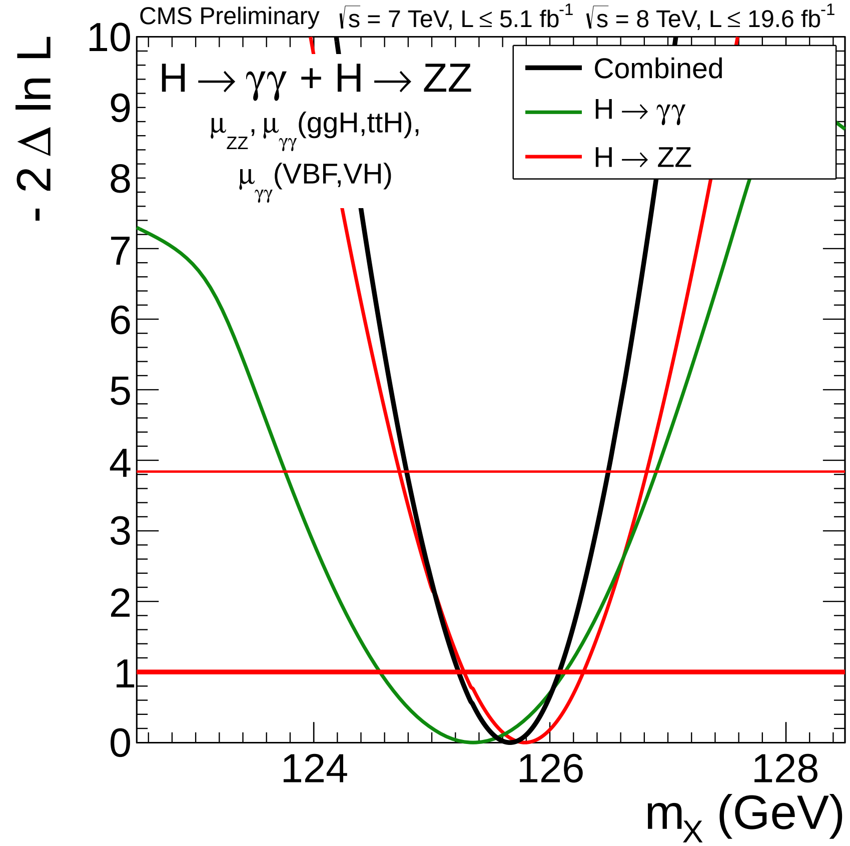
➠ limited by statistics

➠ exploit m(4l) and k_D

➠ very good control of lepton energy scale and resolution

$m_X = 125.8 \pm 0.5(\text{stat}) \pm 0.2(\text{syst})$ GeV

Combine two best mass resolution decays $\gamma\gamma$ and ZZ



☞ **H→ $\gamma\gamma$:**

➠ limited by systematics

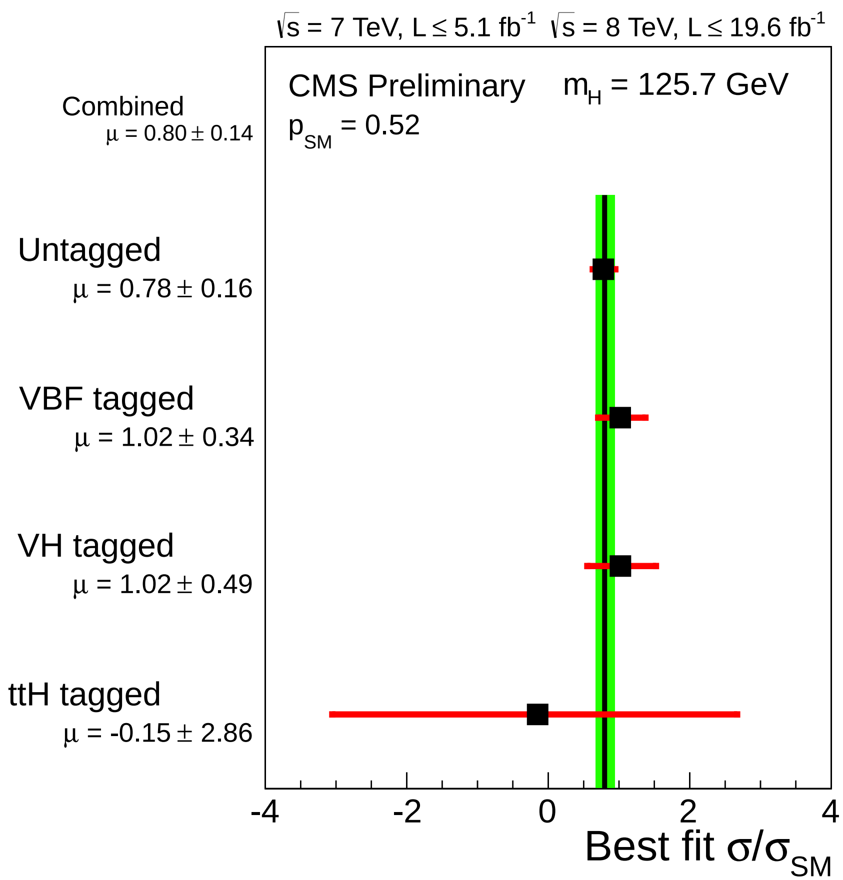
➠ 0.2% due to $e \to \gamma$ uncertainty

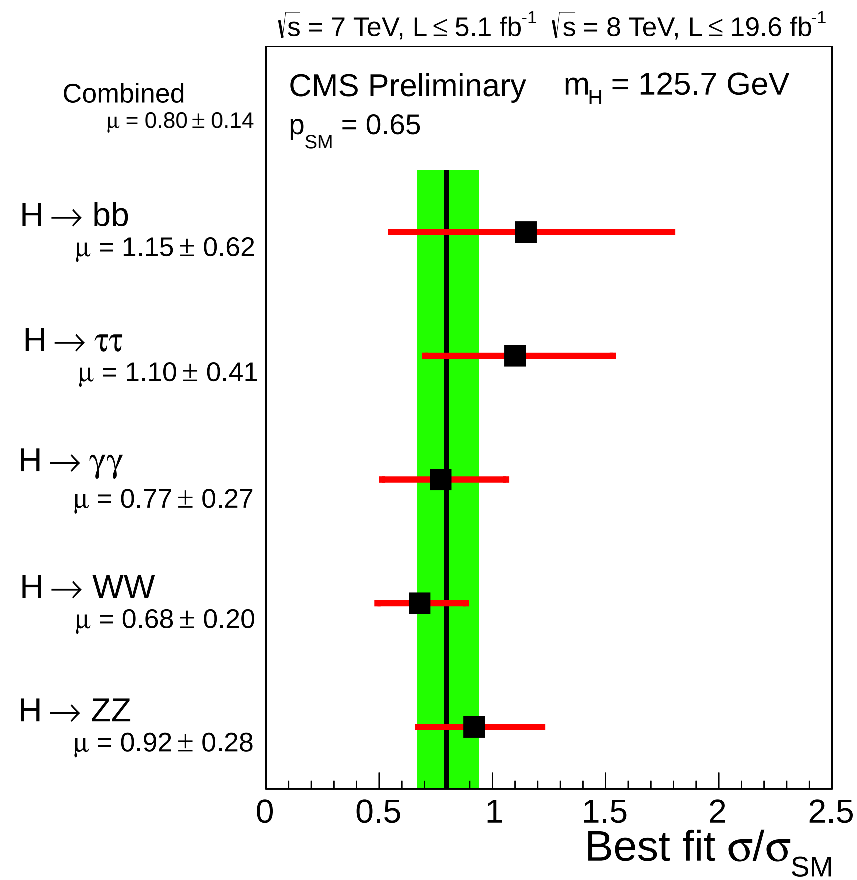
➠ 0.4% extrapolation Z→ee to H→ $\gamma\gamma$

$m_X = 125.4 \pm 0.5(\text{stat}) \pm 0.6(\text{syst})$ GeV

$m_X = 125.7 \pm 0.3(\text{stat}) \pm 0.3(\text{syst})$ GeV

[HIG-13-005]





☞ Overall best-fit signal strength in the combination: $\boldsymbol{\sigma/\sigma_{SM} = 0.80 \pm 0.14}$

Event yields in different production and decay modes are self-consistent

☞ Combination of "inclusive" WW (0/1jet) and ZZ yields gives the ratio of the Higgs couplings to WW and ZZ, g_W/g_Z, which is protected by **custodial symmetry**

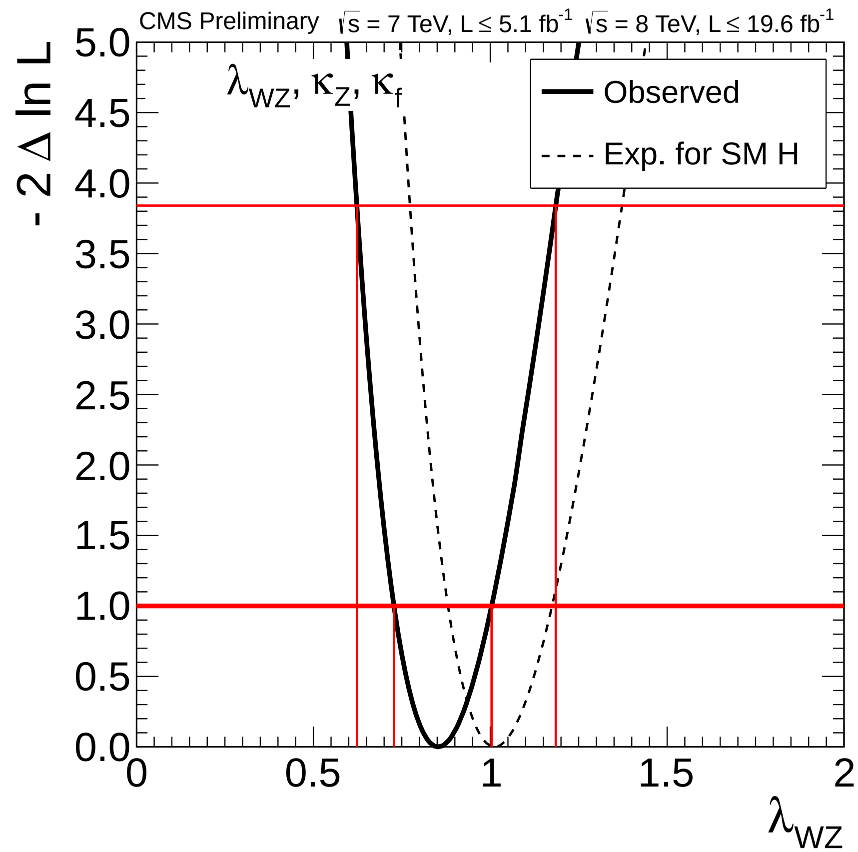
$$\rho = \frac{M_W}{M_Z \cos\theta_W} = \frac{g_W}{g_Z \cos\theta_W} = 1$$

➠ $\rho \neq 1$ **is possible in new physics models**

☞ Perform combination of all channels to assess $\lambda_{WZ} = k_W/k_Z$

➠ likelihood scan versus 3 n.d.f.: λ_{WZ}, k_Z, and k_F gives

$\boldsymbol{\lambda_{WZ} = [0.62 - 1.19]}$ at 95% CL



Consistent with the SM expectation

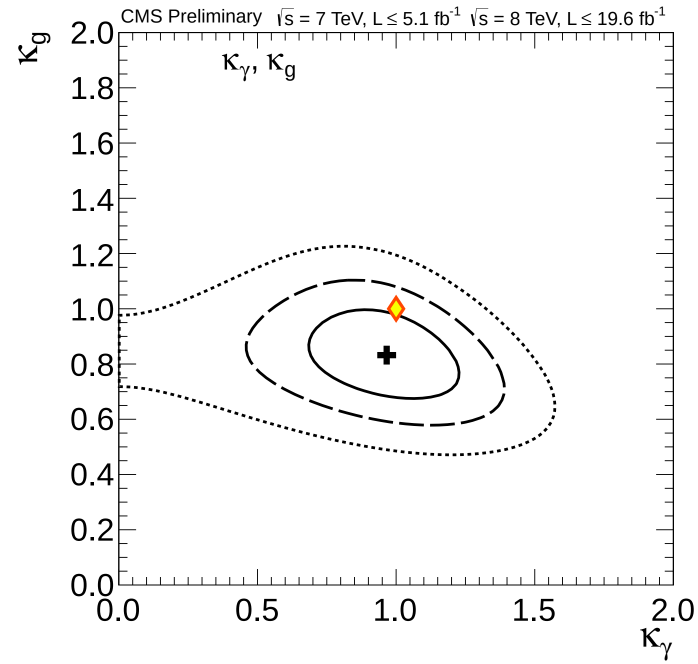
☞ New particles can modify the loop-mediated couplings and contribute to the total width

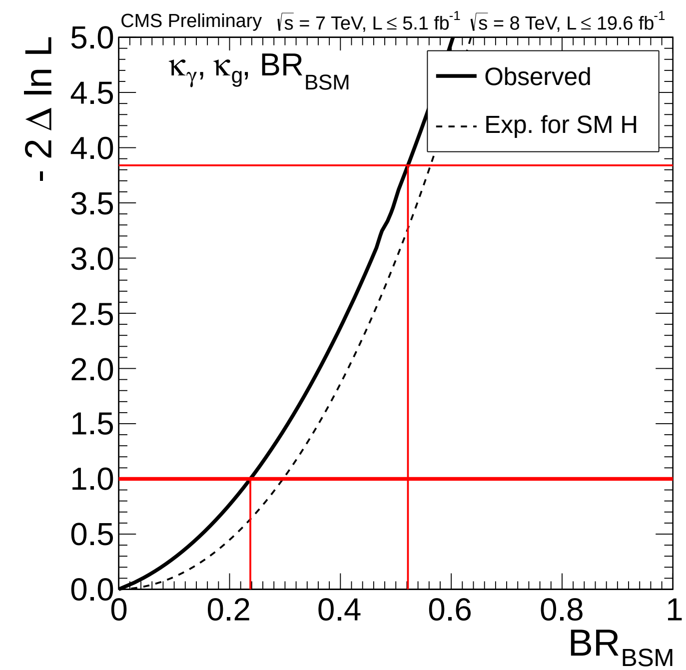
$$\Gamma_{tot} = \sum \Gamma_{i(SM)} + \Gamma_{BSM}$$

☞ Parameterize the photon and the gluon loops with effective scale factors (k_g,k_γ)

☞ Allow total width to scale as $1/(1\text{-}\mathcal{B}_{\rm inv})$

No large invisible branching fraction





☞ Spin-0 and 2 are only allowed by $H \to \gamma\gamma$ channel

- spin-0 is required if it is a Higgs
- spin-2 induced by KK-graviton couplings

☞ Parity

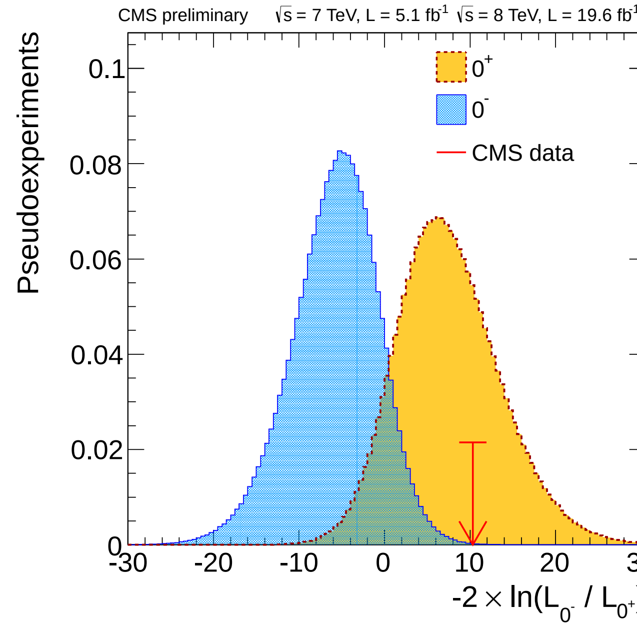
- SM Higgs - CP-even
- BSM Higgs - CP-odd

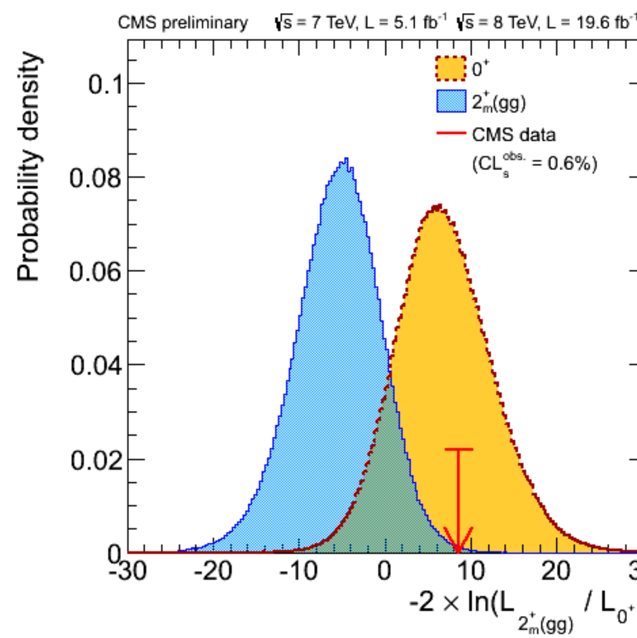
$H \to ZZ \to 4l$ is most straightforward

J^P	production	comment	expect (μ=1)	obs. 0^+	obs. J^P	CL_s
0^-	$gg \to X$	pseudoscalar	2.6σ (2.8σ)	0.5σ	3.3σ	0.16%
0_h^+	$gg \to X$	higher dim operators	1.7σ (1.8σ)	0.0σ	1.7σ	8.1%
2^+_{mgg}	$gg \to X$	minimal couplings	1.8σ (1.9σ)	0.8σ	2.7σ	1.5%
$2^+_{mq\bar{q}}$	$q\bar{q} \to X$	minimal couplings	1.7σ (1.9σ)	1.8σ	4.0σ	<0.1%
1^-	$q\bar{q} \to X$	exotic vector	2.8σ (3.1σ)	1.4σ	>4.0σ	<0.1%
1^+	$q\bar{q} \to X$	exotic pseudovector	2.3σ (2.6σ)	1.7σ	>4.0σ	<0.1%

The data disfavors the 0^- (2_m^+) hypothesis with 99.8% (99.4%) CL

The observation is well compatible with SM Higgs expectations (0^+)



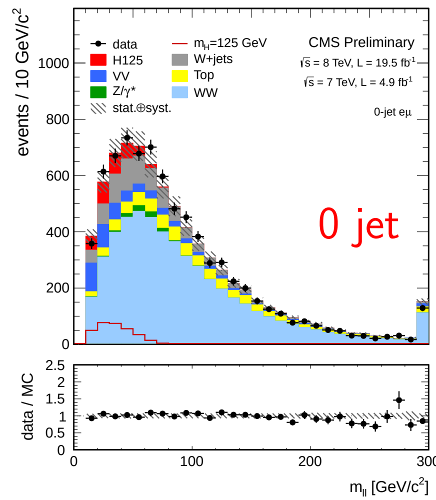


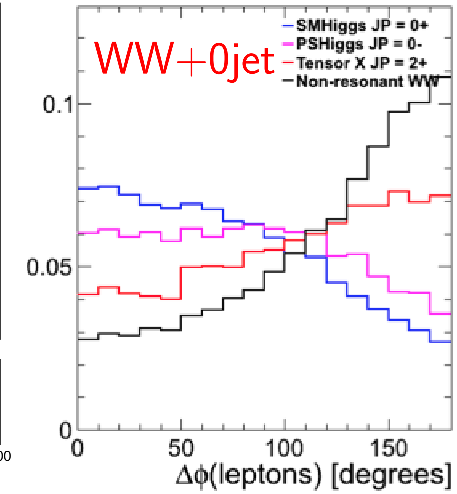
Spin-0 and 2 are only allowed by $H\to\gamma\gamma$ channel

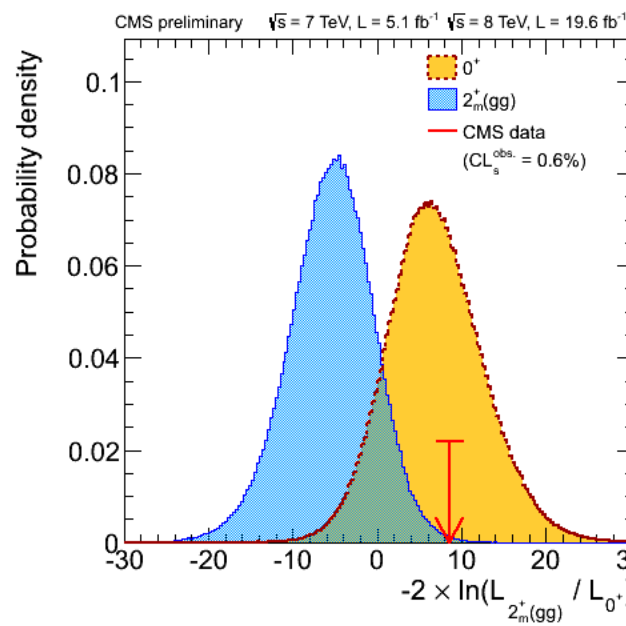
- Discrimination between spin-0 and spin-2 is straightforward with WW and ZZ:
  - WW is most significant (0-jet only)
  - modify selections to extend spin-2 enriched phase space

	ZZ	WW	Comb
exp.	6.8%	1.4%	0.2%
obs.	1.4%	14.0%	0.6%

- Observed results weaker than expected especially for WW due to best fit μ <1 (like having less luminosity)
- Observed better than expected for ZZ due to a fluctuation

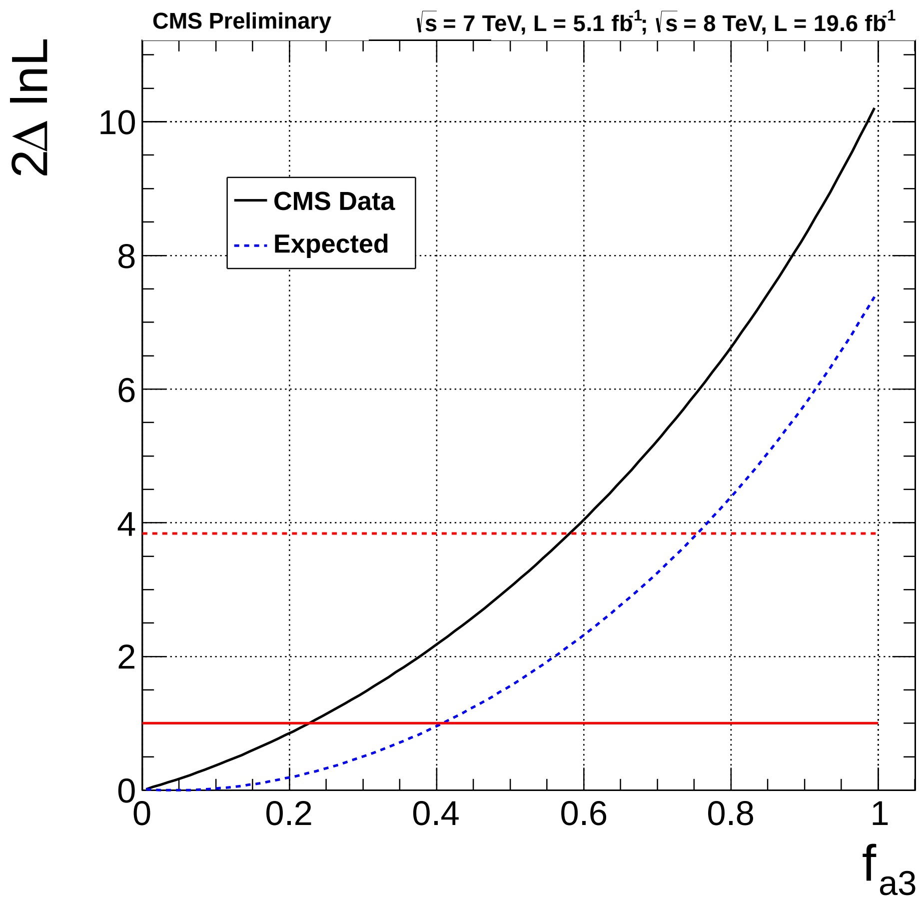


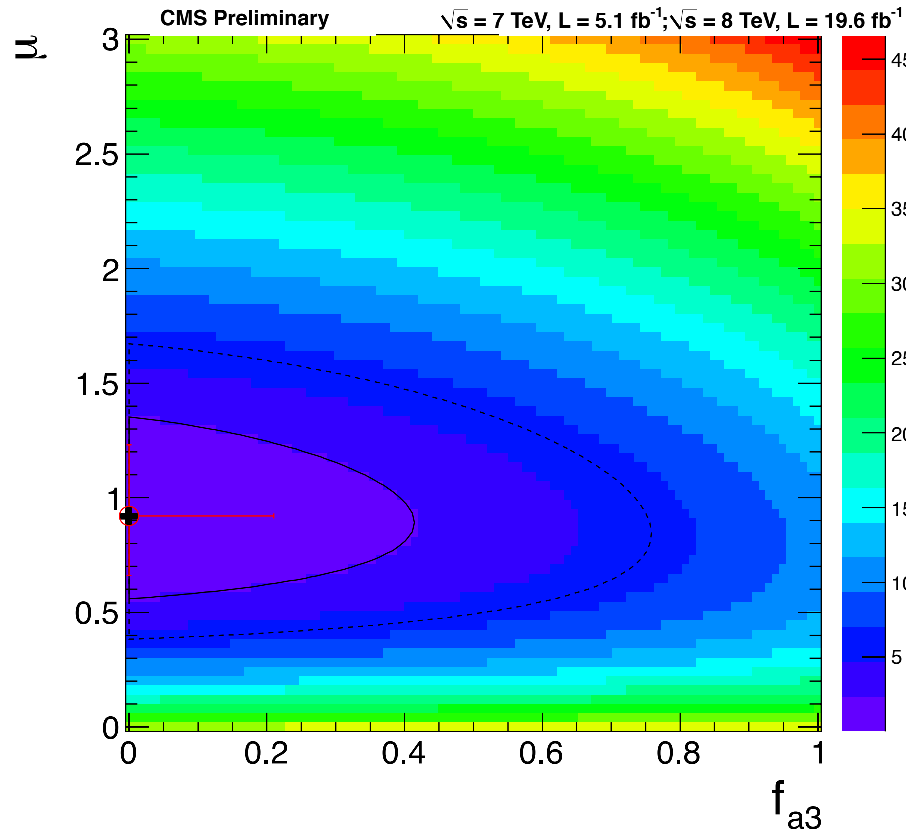




The data disfavors the 2^+_m hypothesis with 99.4% CL

The observation is well compatible with SM Higgs expectations (0^+)





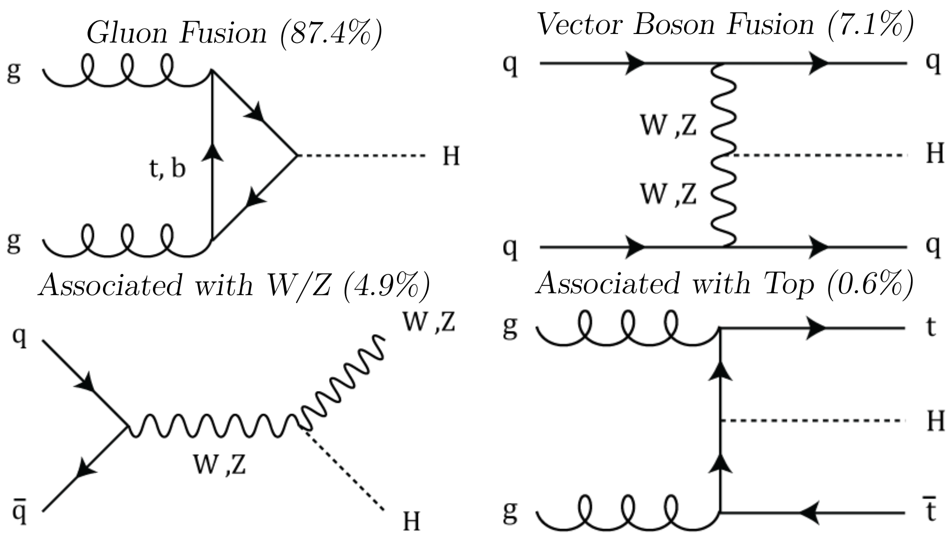
Expected separation between SM 0^+ and 0^- is 2σ

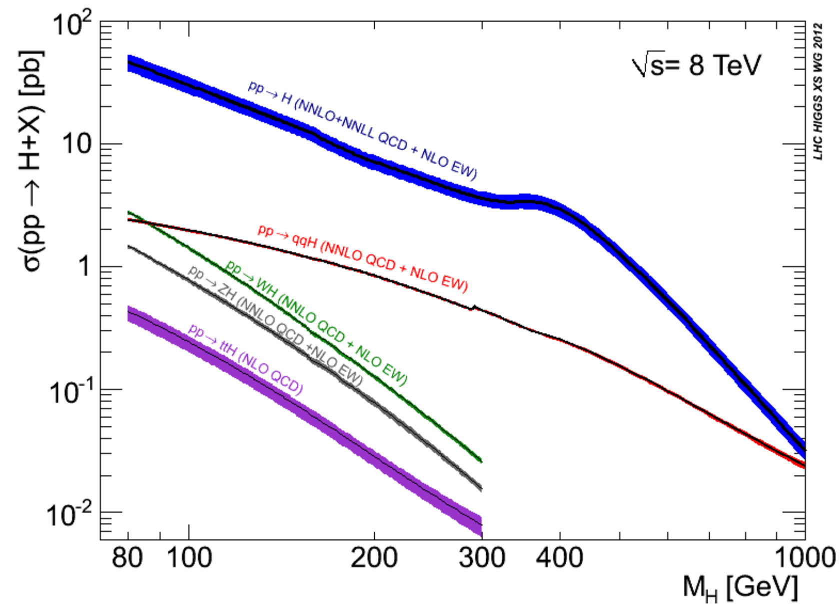
Fraction of CP-violating combination to the decay amplitude: $f_{a3} = 0^{+0.2}_{-0.0}$

Data disfavor $J^P = 0^-$ at 2.5σ ($< 3\%$ CL)

$J^P = 0^+$ is consistent with observation (0.6σ)

Gluon fusion (GF) and Vector Boson Fusion (VBF) are the two most copious Higgs production processes at LHC



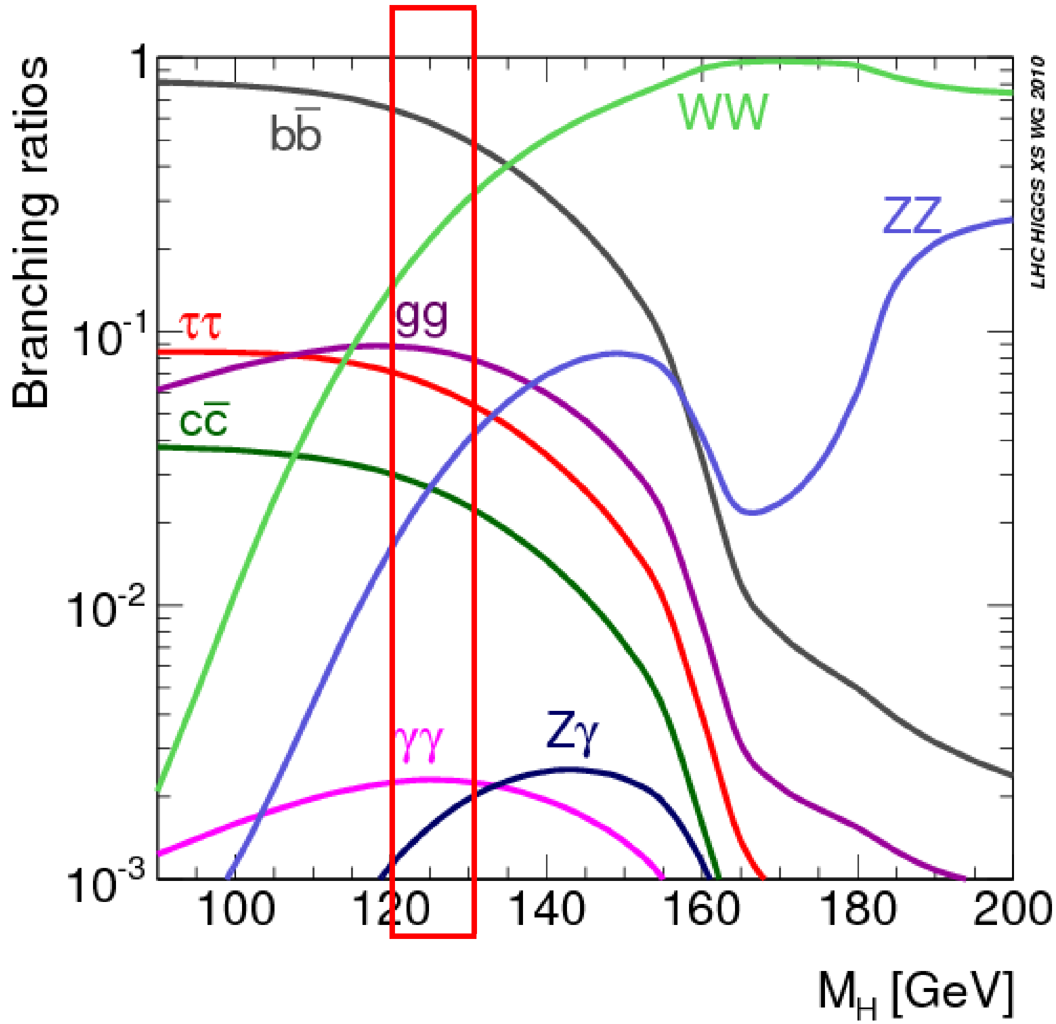


- **GF production is dominant**
  - large k-factor (∼2)
  - associated jets are emerged due to soft gluon radiation at NLO
  - large theory (systematic) uncertainty
- **VBF has clean signature but low rate**
  - low k-factor (∼1.1)
  - associated with LO jets primarily
  - low theory (systematic) uncertainty

Very rich mass region but also very challenging...

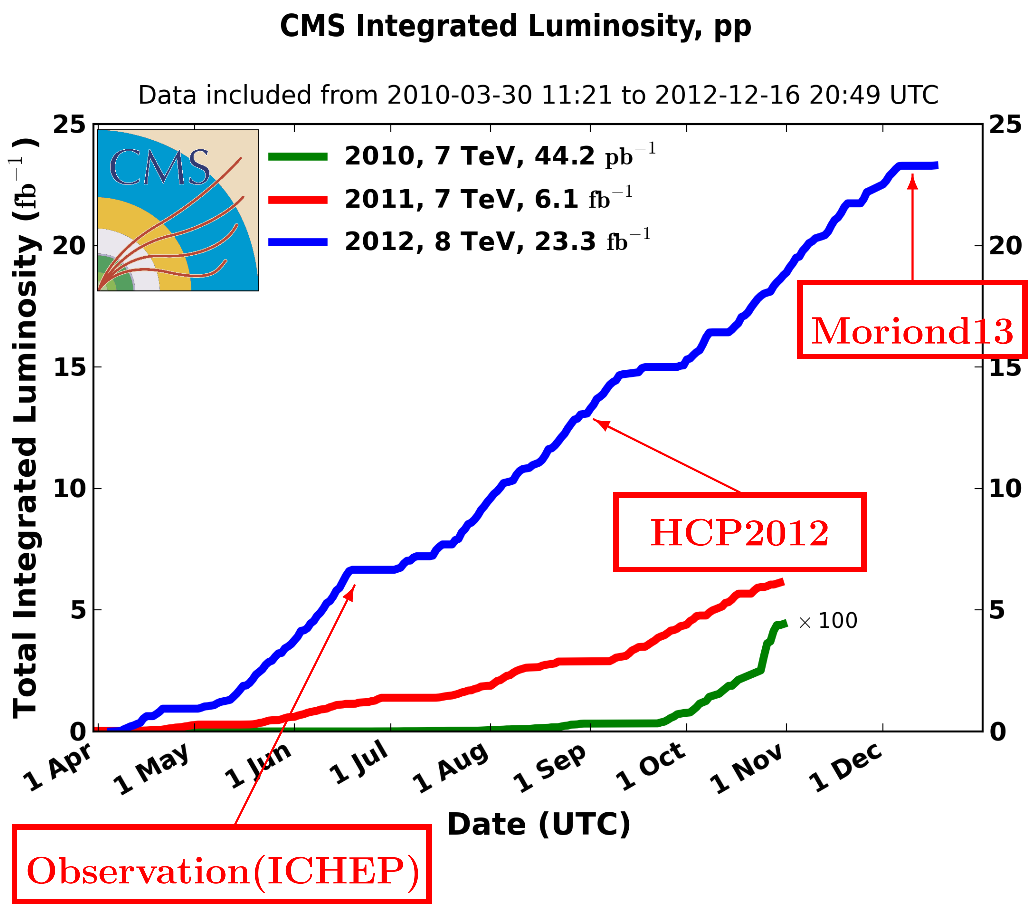
- 5 decay modes exploited: $\gamma\gamma, ZZ, WW, \tau\tau, bb$
- 2 best mass resolution decay modes (~1%): $\gamma\gamma, ZZ$
- Also includes searches in $\mathrm{H} \to \mathrm{Z}\gamma$ decays

Decay	Exp. Sign. at 125.7 GeV	σ_M/M
H→ $\gamma\gamma$	3.9	1-2%
H→ZZ→4l	7.1	1-2%
H→WW→2l2ν	5.3	20%
H→bb	2.2	10%
H→$\tau\tau$	2.6	10%

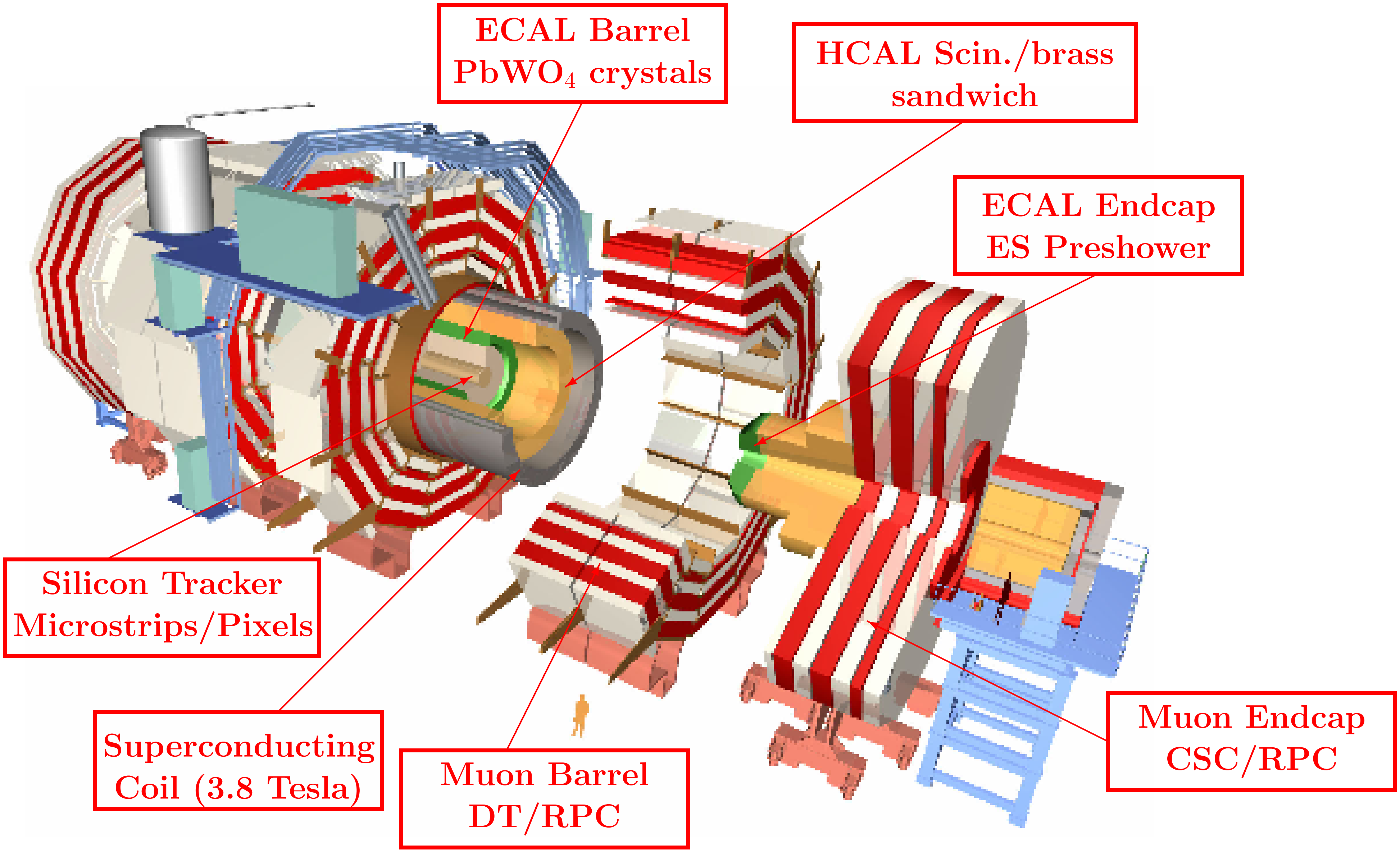


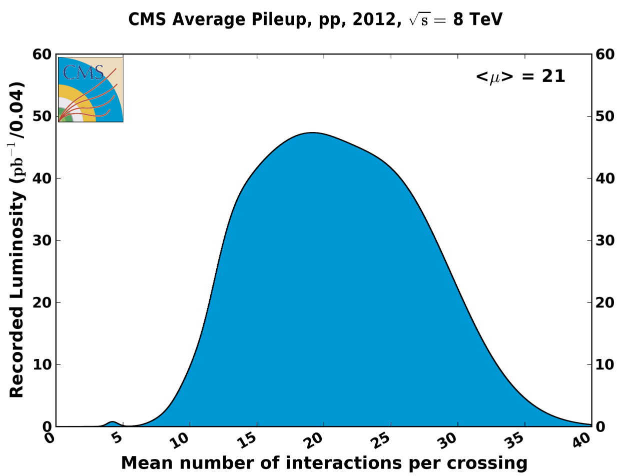
- Stellar performance of the LHC
  - extremely successful operation for these 3 years
  - 7 TeV collisions are started in March 2010
  - upgraded center-of-mass energy to 8 TeV in 2012
- Available dataset for the analyses with all subdetectors on
  - **7 TeV:** $\leq$5.1 fb^{-1}
  - **8 TeV:** $\leq$19.6 fb^{-1}
  - high detector efficiency

LHC restart in 2015 with a collision energy of $\simeq$13 TeV and increased beam intensity



$\sqrt{s}$=8 TeV: 25-30% higher cross section than $\sqrt{s}$=7 TeV at low Higgs boson mass


ECAL Barrel
$PbWO_4$ crystals
HCAL Scin./brass
sandwich
ECAL Endcap
ES Preshower
Silicon Tracker
Microstrips/Pixels
Superconducting
Coil (3.8 Tesla)
Muon Barrel
DT/RPC
Muon Endcap
CSC/RPC



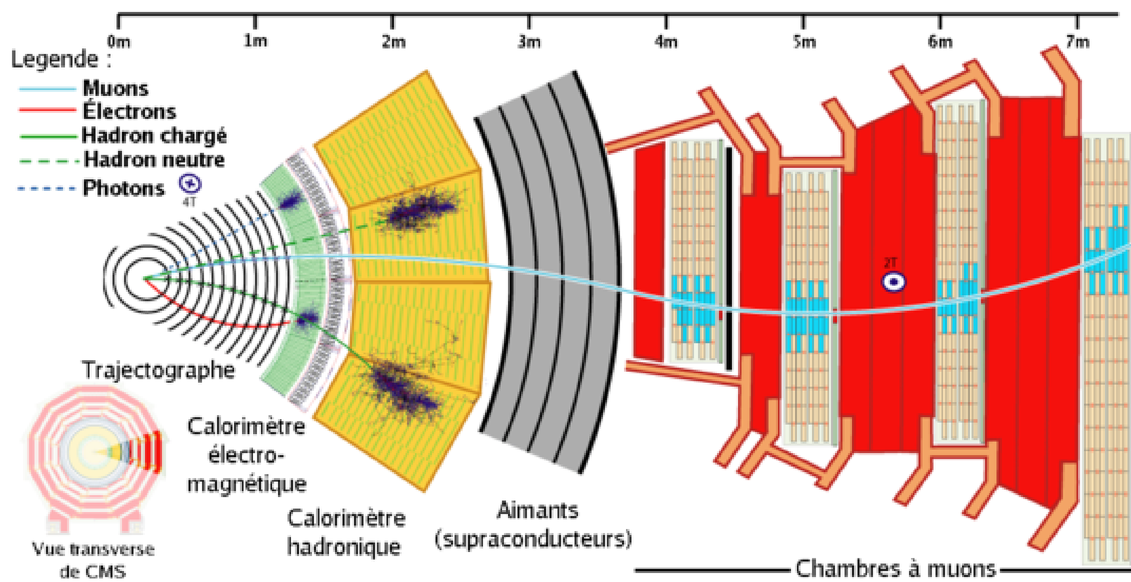
☞ Excellent performance of the CMS experiment in 2012

- 90% of recorded data with all subdetectors on
- peak luminosity $7 \times 10^{33}\text{cm}^{-2}\text{s}^{-1}$ at 8 TeV CM energy
- **mean pile-up (PU) 21 events**

☞ Particle Flow (PF) algorithm:

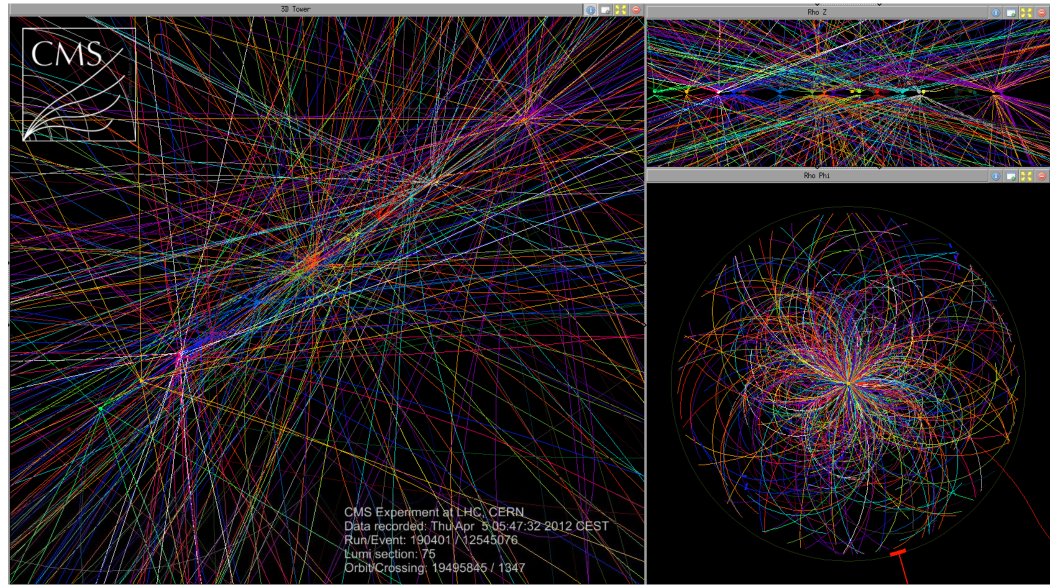
- provides a global event description in form of list of particles
- improvements in jet, tau and E_T^{miss} measurement

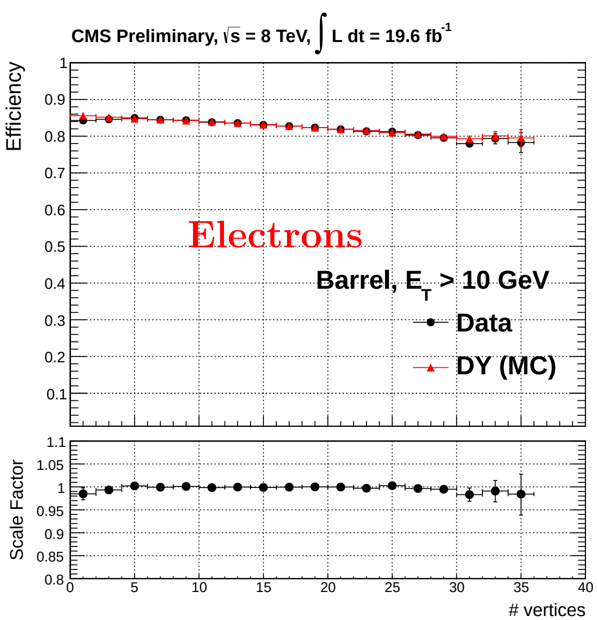
Improves reconstruction performance at high PU

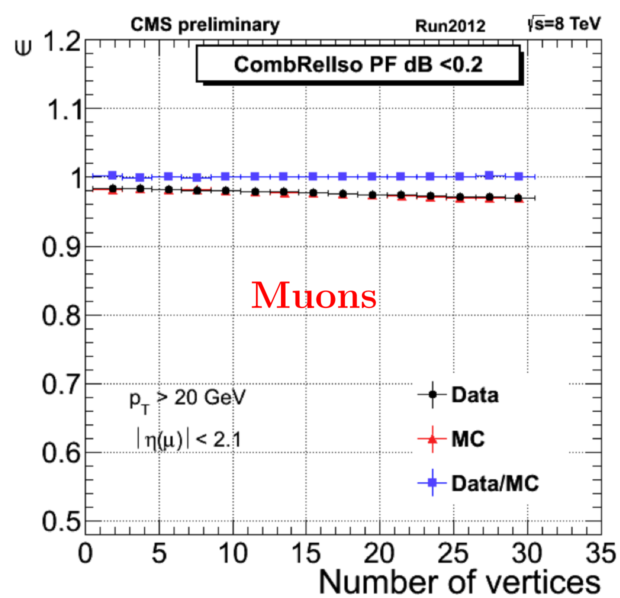


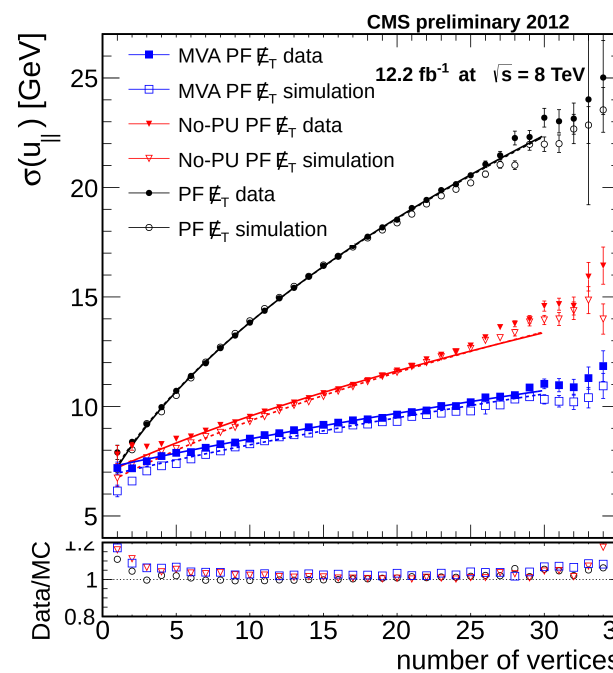
29 distinct vertices have been reconstructed corresponding to 29 distinct collisions within a single crossing of the LHC beam

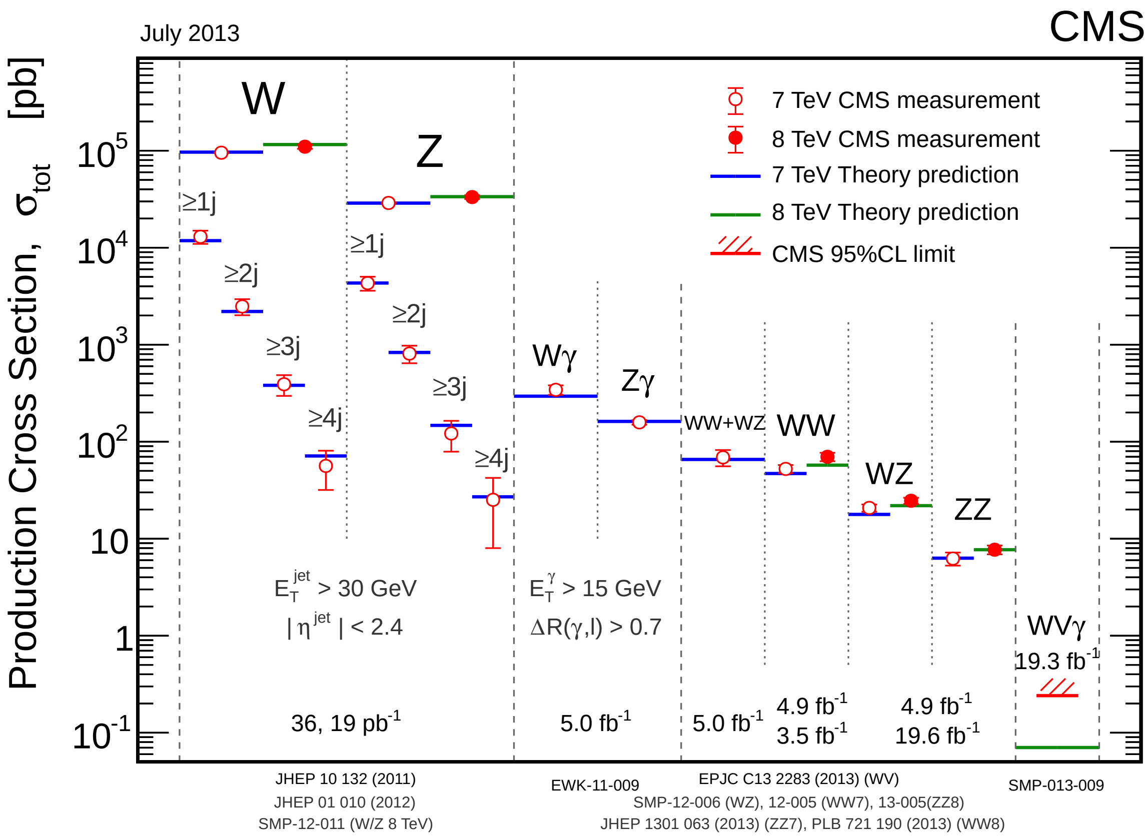
Leptons and MET are almost insensitive to pileup

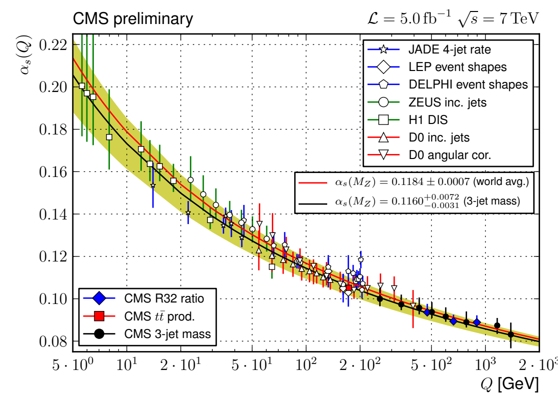


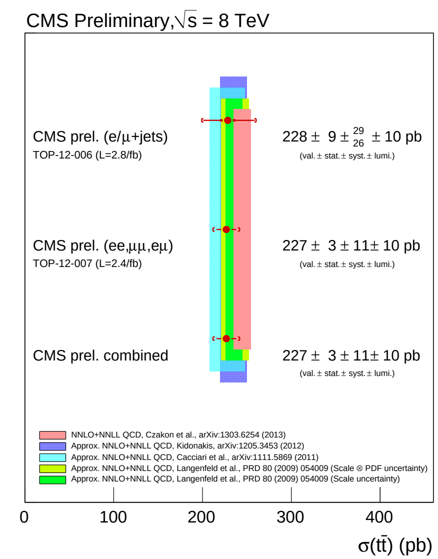












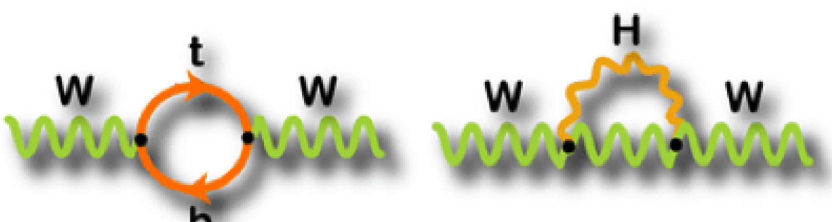
☞ Good understanding of the detector and accurate theory predictions

- ➠ **precise measurements** of the SM processes over many orders of magnitude
- ➠ good knowledge of **the background to Higgs analyses and BSM searches**

- Standard Model (SM) is confirmed to better than 1% uncertainty by 100's of precision measurements
  - **Higgs boson was the only missing piece of the SM**
- Mass of W boson is a fundamental parameter of the SM (WA $m_W = 80385 \pm 15$ MeV)

$$\mathbf{m}_W = \sqrt{\frac{\pi\alpha}{G_F\sqrt{2}}}\frac{1}{\sin\theta_W\sqrt{1-\Delta R}}$$

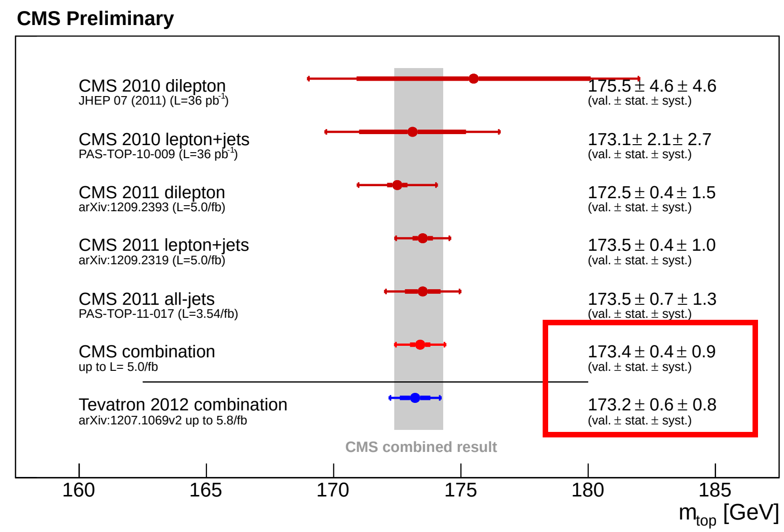
Radiative corrections $\Delta R \sim 4\%$:

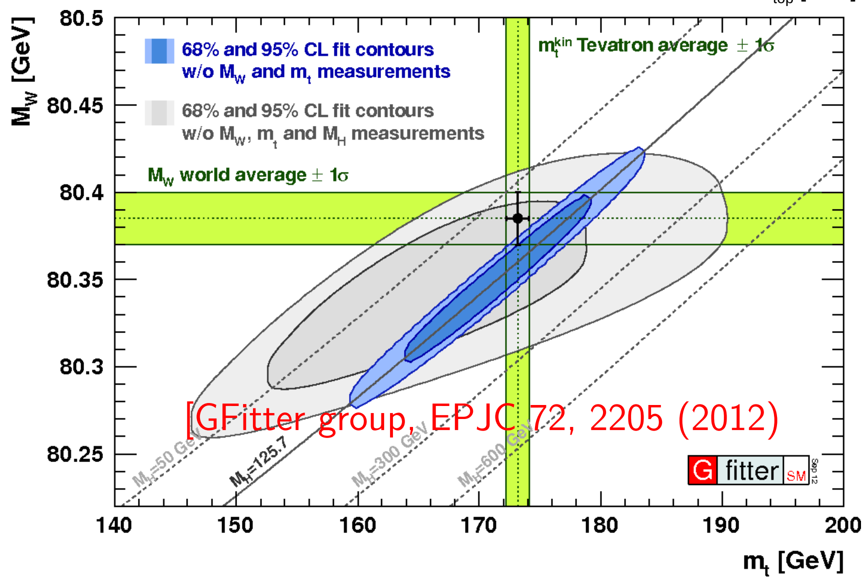


$\Delta R \sim m_t^2$ $\Delta R \sim \log m_H$

CMS: $m_t = 173.4 \pm 1.0$ GeV

Tevatron: $m_t = 173.2 \pm 0.9$ GeV





[GFitter group, EPJC 72, 2205 (2012)]

Observed agreement demonstrates impressive consistency of the SM