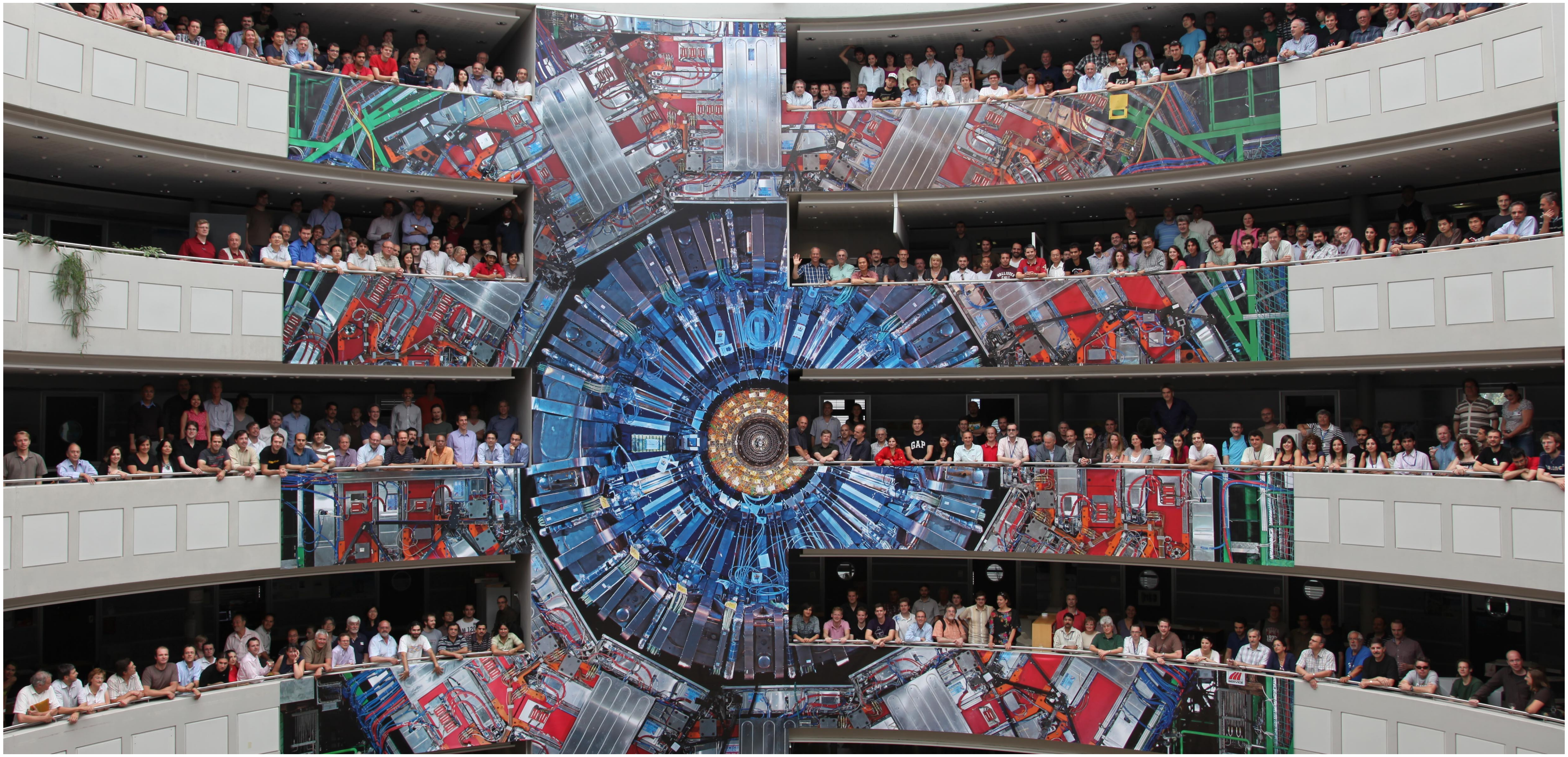


Higgs boson studies in the CMS experiment

Guenakh Mitselmakher
University of Florida
Becici, Montenrgro, October 5, 2016

Outline

- **Introduction:**
  - **- LHC performance in Run I and Run II. CMS detector**
  - **- SM Higgs production and decays at LHC**
  - **- Higgs as a tool for finding new physics**

- **Higgs profile @ LHC Run I (7Tev + 8 Tev)**

- **Some Higgs results from CMS @ 13 TeV (Run II)**
  – Boson channels: $H \to \gamma\gamma$, $H \to ZZ4l$
  – Higgs production associated with top quarks
  – Searches for BSM Higgses

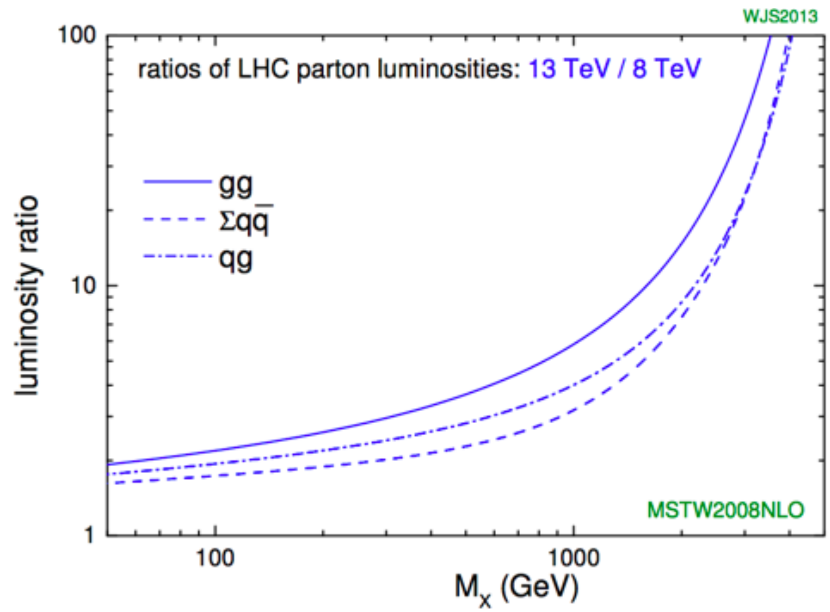
LHC Run II (2015 -2018)

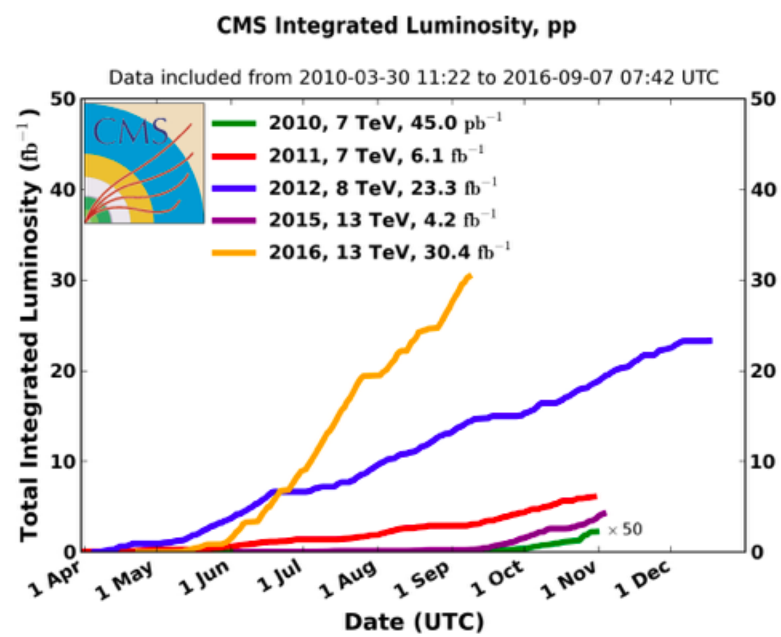
- LHC energy in Run II increased to 13 TeV- → Increased parton luminosity: Higgs (125) production rate Increased ≥2 compared to 8 teV (larger for high masses)

- CMS released the first 2016 Higgs analyses using ~1/3 of data accumulated in 2016.

- These results are the beginning of what is expected in Run II , but they already double the statistics in similar Higgs analyses from Run I

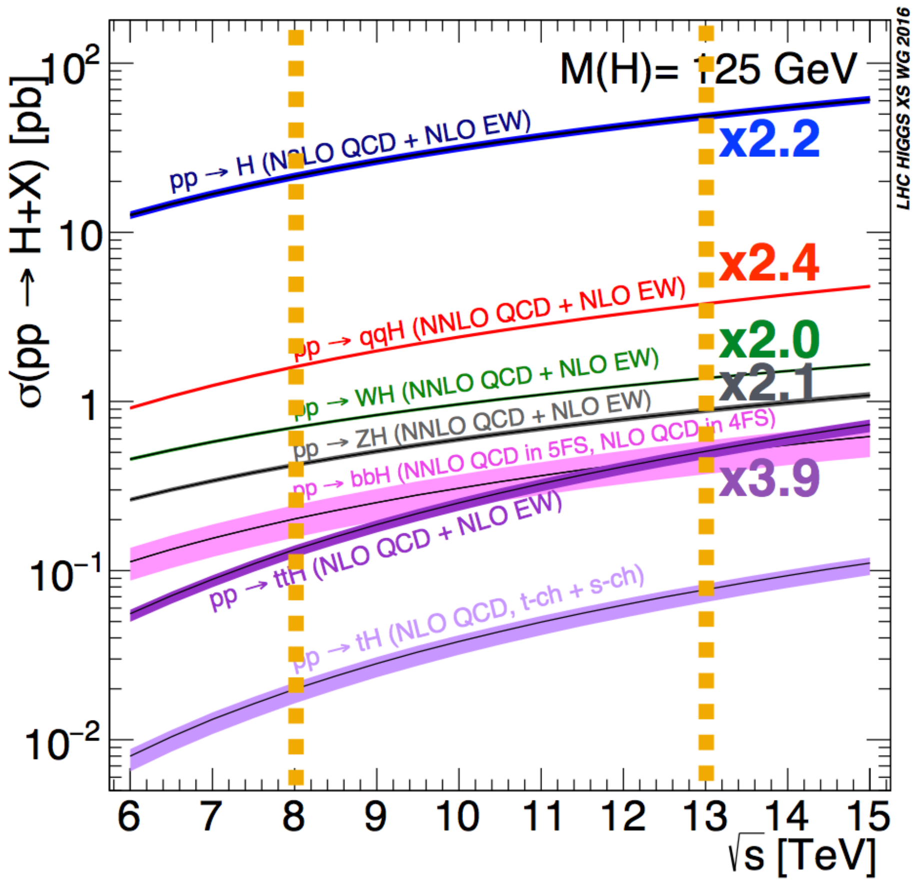
	peak lumi E34 $cm^{-2}s^{-1}$	day of proton physics	approx. int lumi [fb^{-1}]
2015	~0.5	65	3
2016	1.2	160	30
2017	1.5	160	36
2018	1.5	160	36





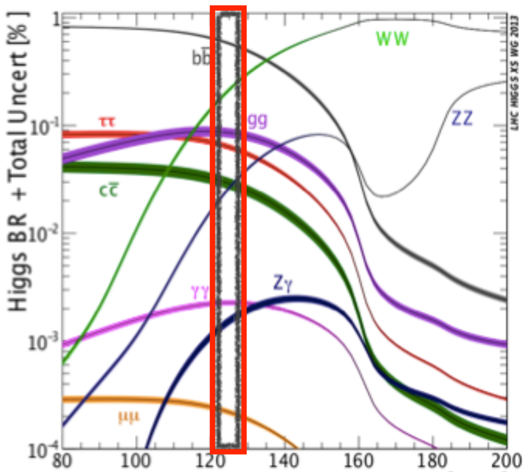
Increased Higgs production cross sections

Run I, 8 Tev **Run II 13 Tev**

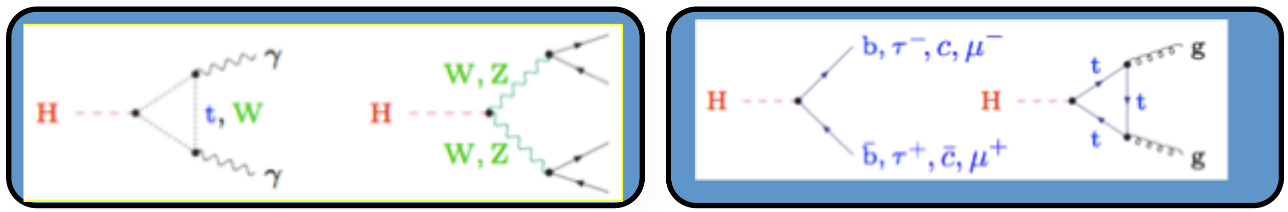


Higgs decays in Standard Model

At Higgs mass ~125 Gev we have access to several decay modes.
Allows for detailed studies of couplings. We are lucky!

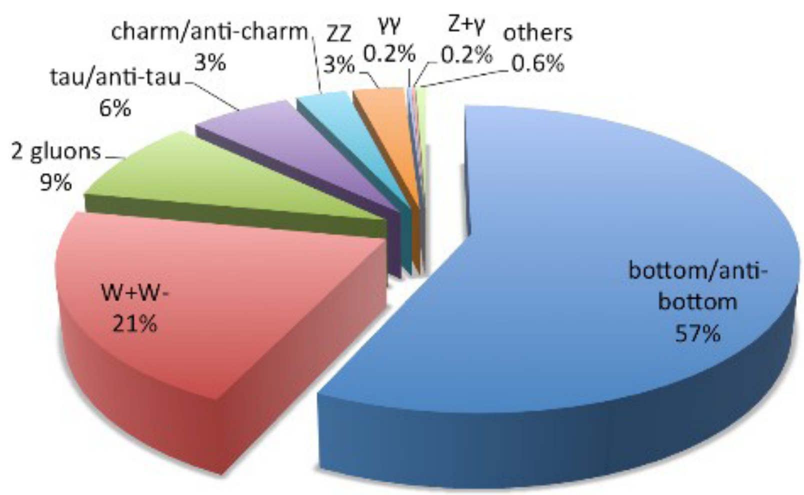


Decays



$\mathrm{BR}(h \to b\bar{b}) = 58\%$, $\mathrm{BR}(h \to WW^*) = 21.6\%$, $\mathrm{BR}(h \to \tau^+\tau^-) = 6.4\%$,
$\mathrm{BR}(h \to ZZ^*) = 2.7\%$, $\mathrm{BR}(h \to gg) = 8.5\%$, $\mathrm{BR}(h \to \gamma\gamma) = 0.22\%$,
$\mathrm{BR}(h \to c\bar{c}) = 2.7\%$

Decays of a 125 GeV Standard-Model Higgs boson



Higgs trivia (2016)

- **About 4 million Higgs (125) particles already produced at LHC (most in 2016)**

- **Studies of most production and decay processes have large backgrounds, detection efficiencies sometimes low. It all makes analyses very difficult**

- **Only a fraction of data analyses using ~ 1/3 of data collected in 2016 completed in CMS. Statistical errors generally dominate**

- **LHC and upgraded HL-LHC will produce ~100 times more data**

CMS Higgs analyses released in 2016

Higgs (125) "rediscovered" at 13 TeV

The main goal is now to look for BSM physics

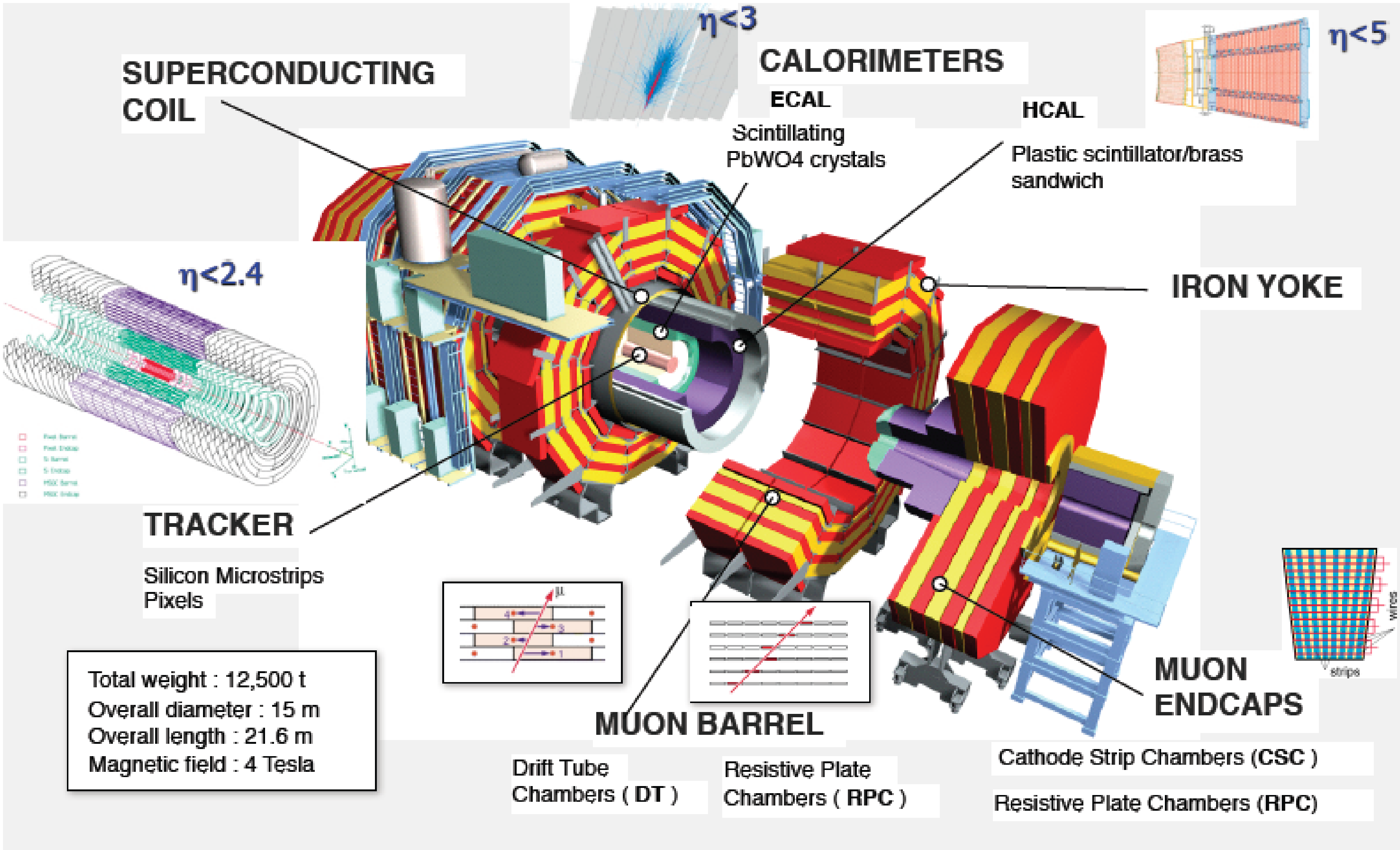
There are several ways to look for BSM physics with Higgs bosons:
- precision studies of H (125): looking for deviations from the SM predictions
- searching for new H(125) modes, not predicted by the SM
- searching for Higgs (125) in SUSY dnd BSM decay chains
- searching for "anomalous" di-Higgs (125) production
- searching for additional Higgs bosons

Recent CMS Higgs results can be found here:

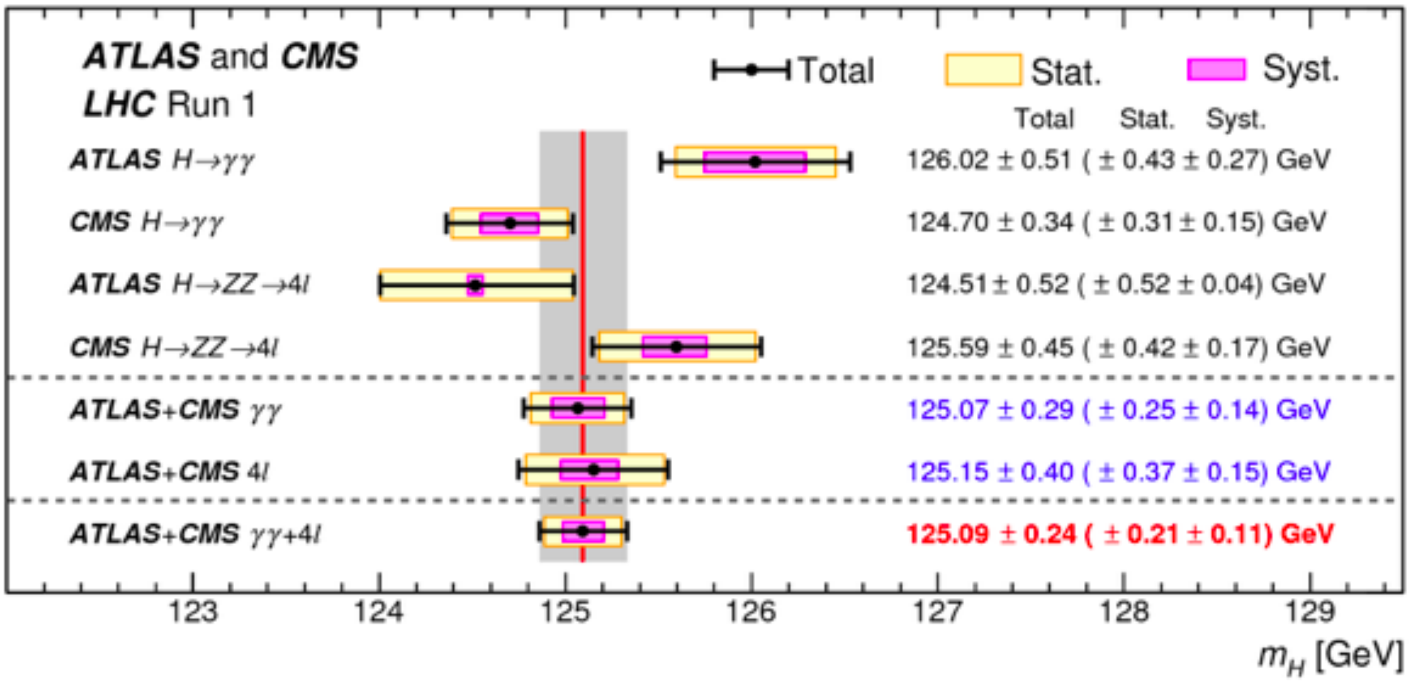
HIG-16-020: H → $\gamma\gamma$ (2016)
HIG-16-033: H → ZZ → 4l (2016)
HIG-16-022: ttH (2016)
HIG-16-029: X → HH → bb$\tau\tau$ (2016)
HIG-16-028: non-resonant HH → bb$\tau\tau$ (2016)
HIG-16-024: non-resonant HH → bbWW (2016)
HIG-16-026: non-resonant HH → bbbb (2015)
HIG-16-023: high mass H → WW (2015)
HIG-16-025: high mass H → bb (2015)
HIG-16-027: VBF $H^{\pm}$ → WZ (2015+2016)
HIG-16-030: $H^{\pm}$ → cb (2012)
HIG-16-019: t → $H^{\pm}$ q (2015)
HIG-16-016: H → invisible (2011+2012+2015)

Some of the recent Higgs analyses results are presented in this talk

The Compact Muon Solenoid



Higgs mass from Run I (ATLAS + CMS)



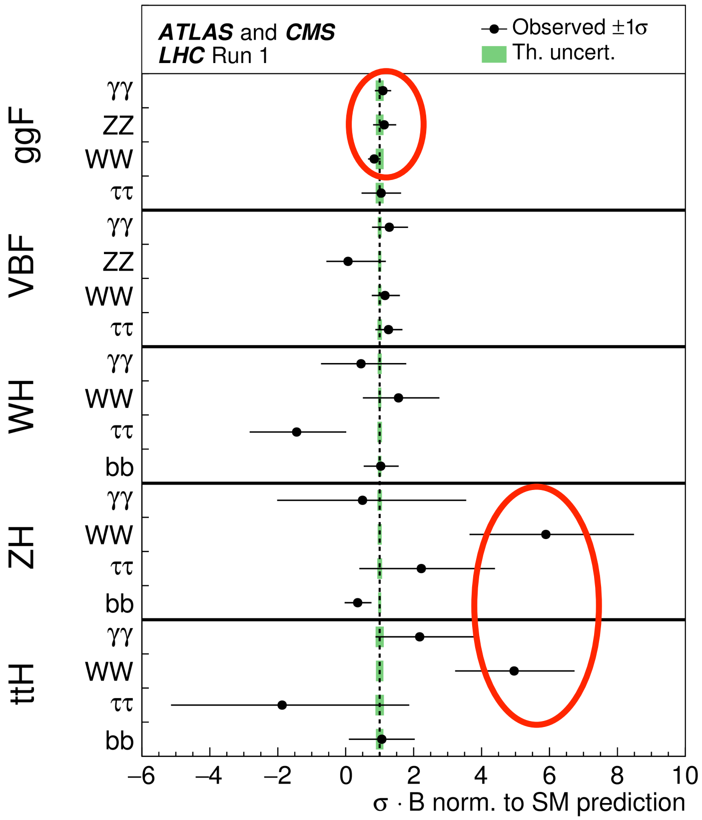
Combined CMS+ATLAS measurement in Run I

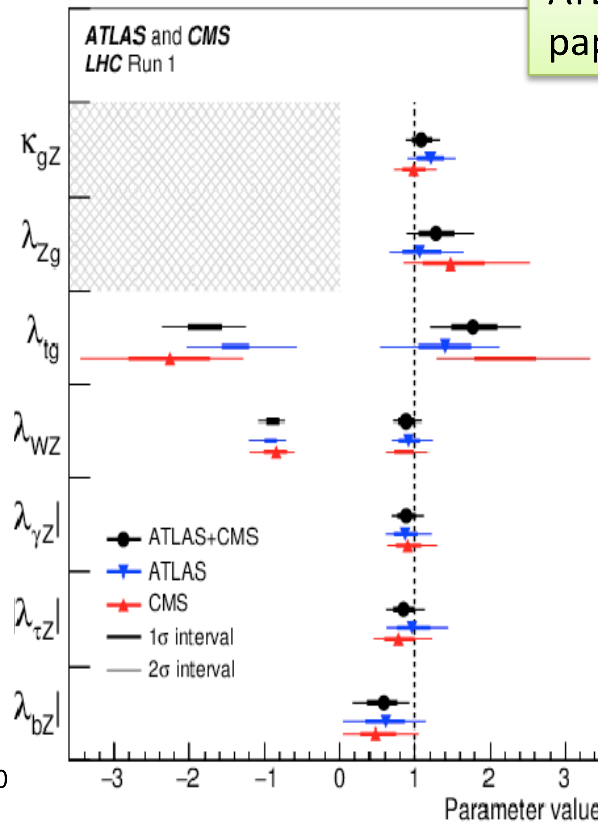
M_H = 125.09 ± 0.21 (stat) ± 0.11 (syst) GeV

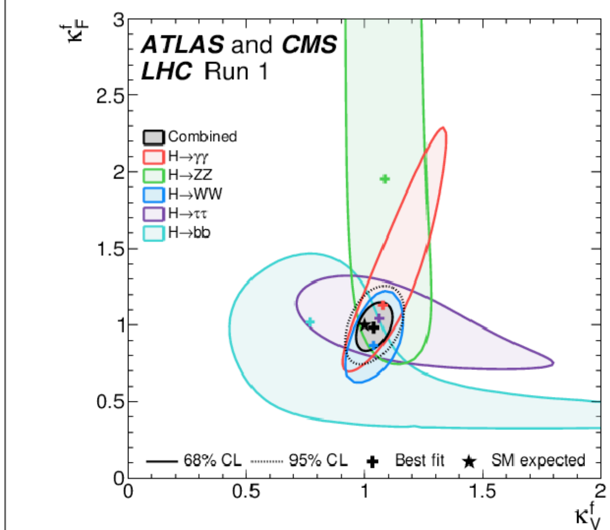
Precision in mass ~0.2% dominated by statistics: need more data

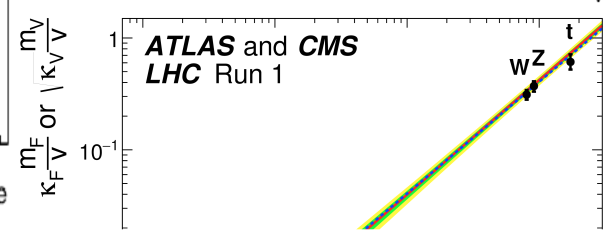
Higgs Profile @ LHC Run I

ATLAS+CMS Run 1 Higgs combination paper : JHEP 1608 (2016) 045



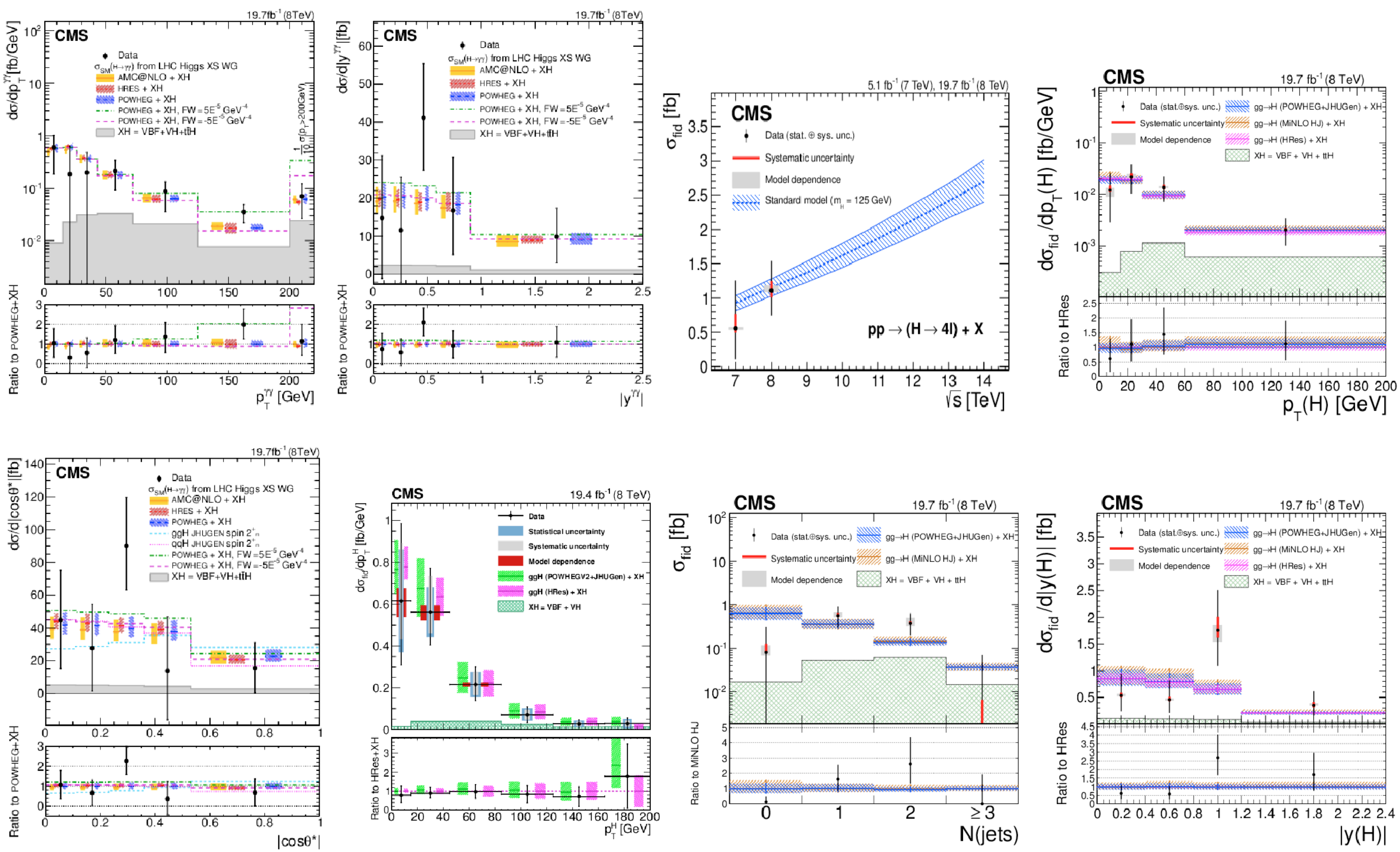






Production process	Measured significance (σ)	Expected significance (σ)
VBF	5.4	4.6
WH	2.4	2.7
ZH	2.3	2.9
VH	3.5	4.2
ttH	4.4	2.0
Decay channel		
$H \to \tau\tau$	5.5	5.0
$H \to bb$	2.6	3.7

Higgs Profile in CMS @ LHC Run I



Higgs boson in Run II (13 TeV)

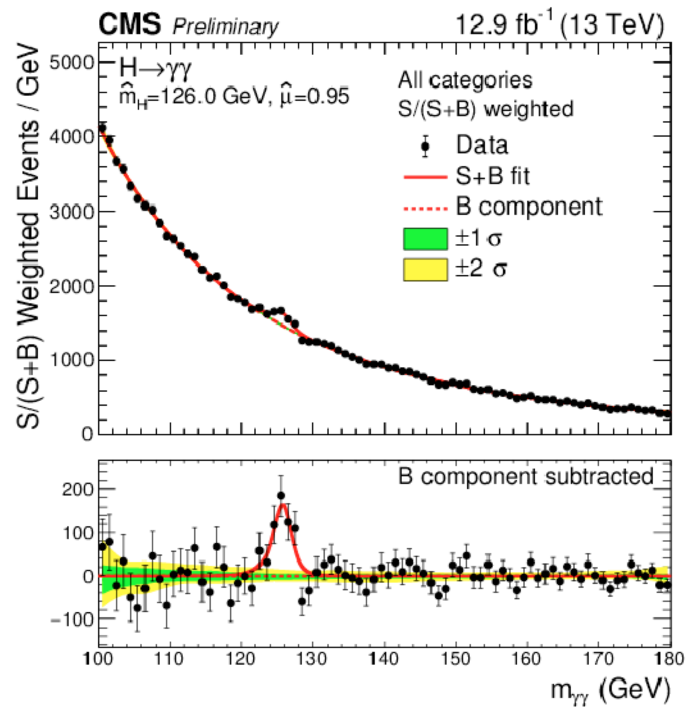
- LHC restarted in 2015 with a collision energy of **13 TeV** and 25 ns bunch spacing
  - Increased sensitivity to tails of differential distributions and to many BSM processes
  - Increased sensitivity to large masses (e.g. ttH production)

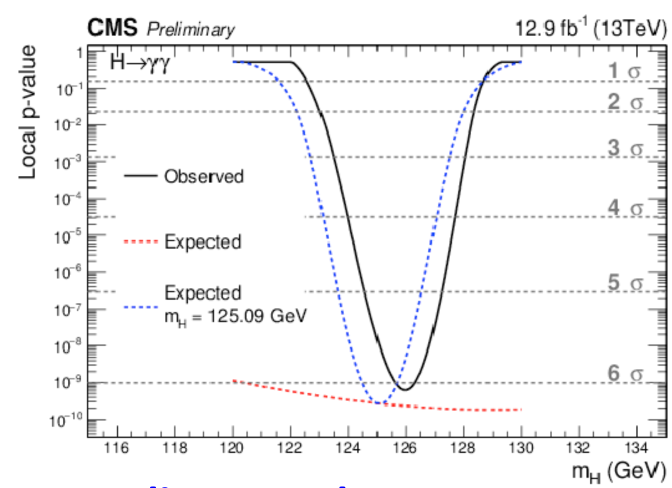
- Most analyses in Run II largely follow methods and strategies developed during Run I

- Few analyses completed, used ~1/3 of data accumulated in 2016
  - The number of Higgses used in Run II at 13 TeV analyses already comparable to available in Run I (at 7 and 8 TeV)
  - Higgs particle "rediscovered" at 13 TeV in Run II

H→γγ, Run II

- Very small branching fraction (~0.2%)
- Clean final state with two isolated high p_T photons and good resolution
- Narrow peak over falling background
  - Main backgrounds γγ and γ-jet
- Production modes probed
  - ggF, VBF, ttH
- Analysis strategy:
  - Events categorized into classes (S/B, mass resolution, additional particles) to improve the analysis sensitivity
  - Extraction of signal through fit of di-photon invariant mass spectrum in each category





The Higgs boson rediscovered: > 5 σ

H→γγ, Run II

Fiducial cross section

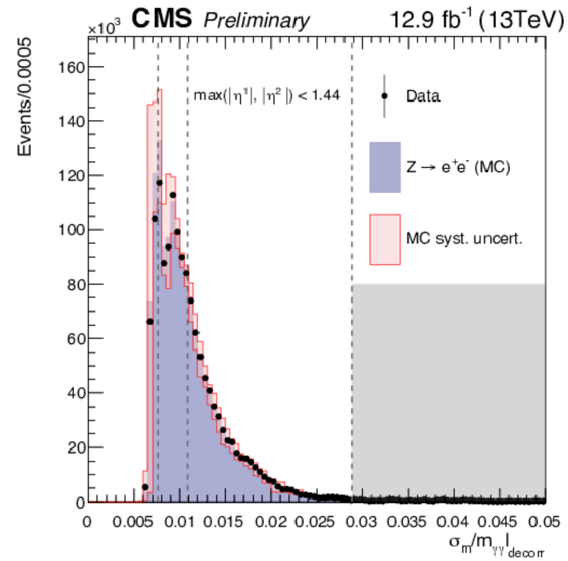
- Different event categorization: 3 mass resolution categories
- Event yields corrected for detector inefficiency and resolution
- Minimal dependence on theoretical modeling

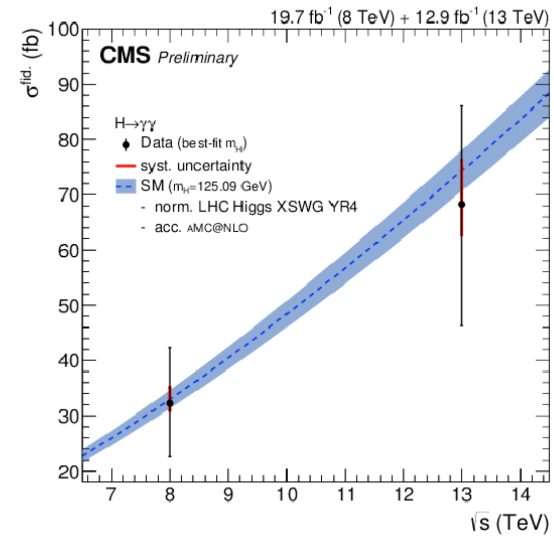
$$\hat{\sigma}_{fid} = 69^{+16}_{-22}(\text{stat.})^{+8}_{-6}(\text{syst.})\text{fb}$$

SM exp. @125.09 GeV:

$$\sigma^{th.}_{fid} = 73.8 \pm 3.8\text{fb}$$

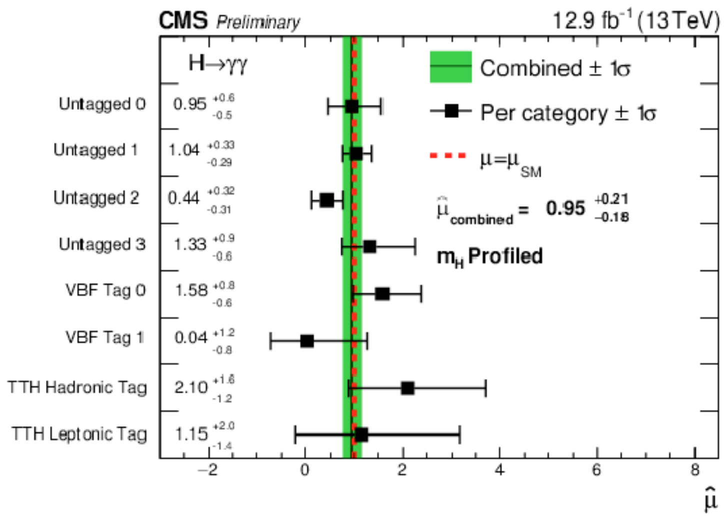
- **Good agreement between data and theory**

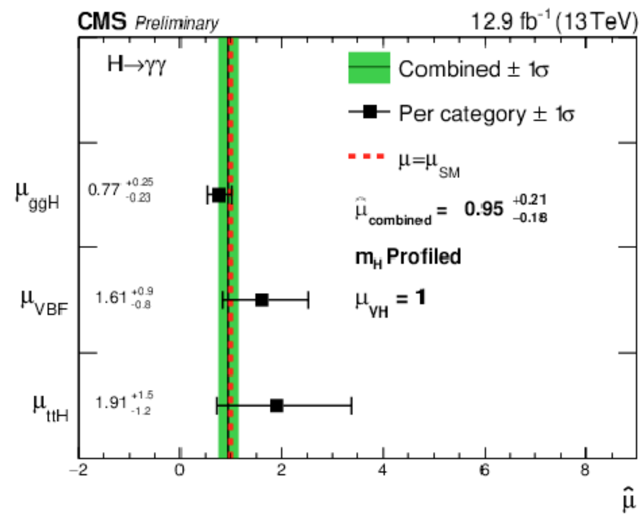


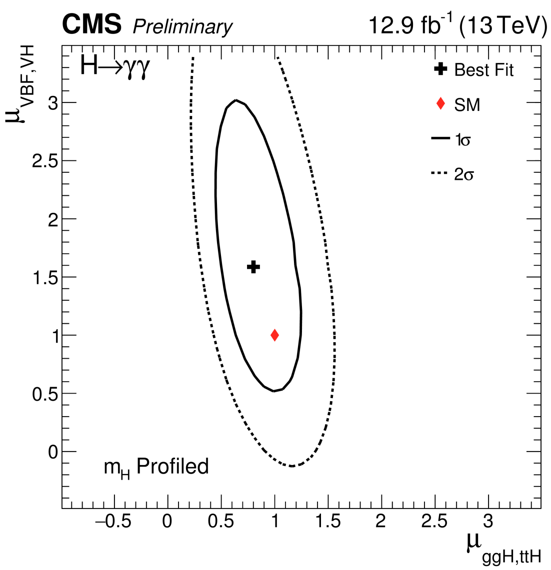


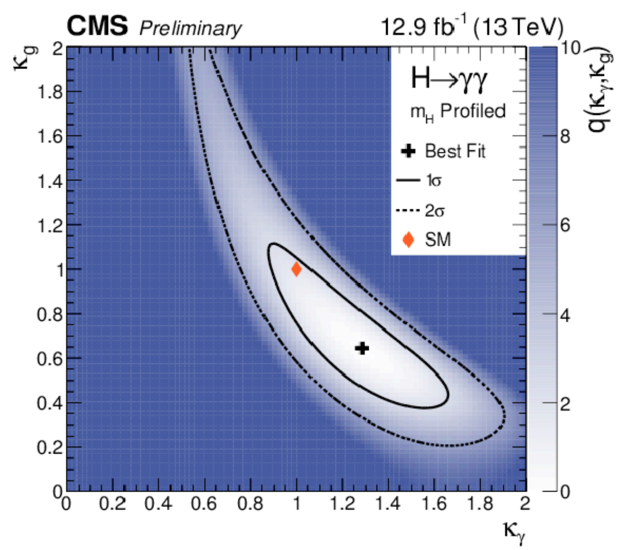
H→γγ, Run II

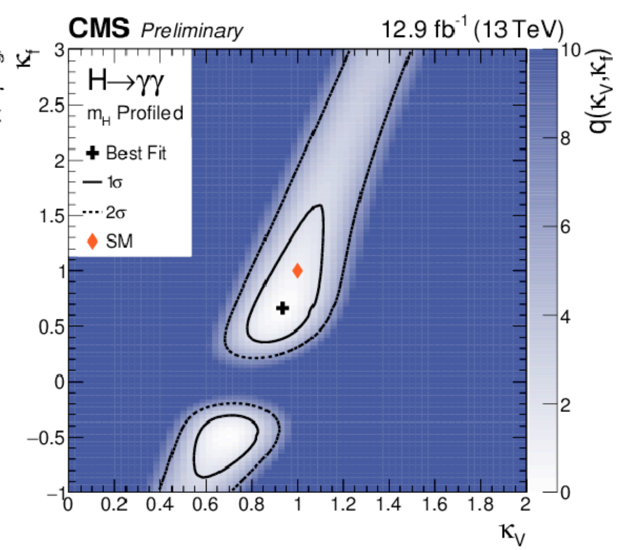
- Consistency tests: signal strengths and couplings





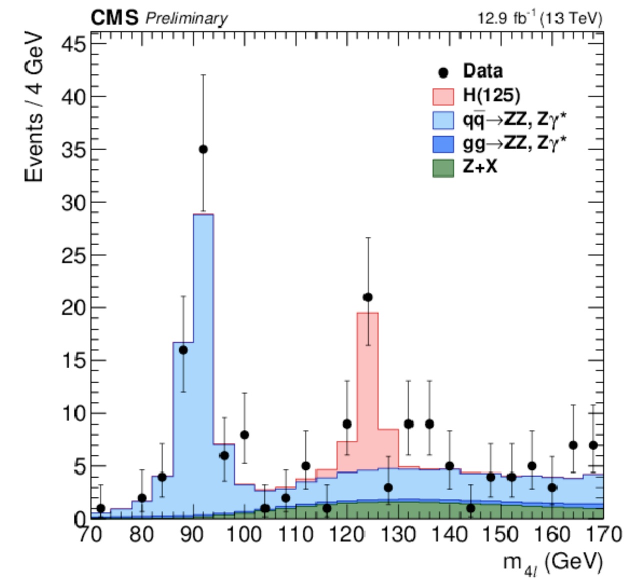


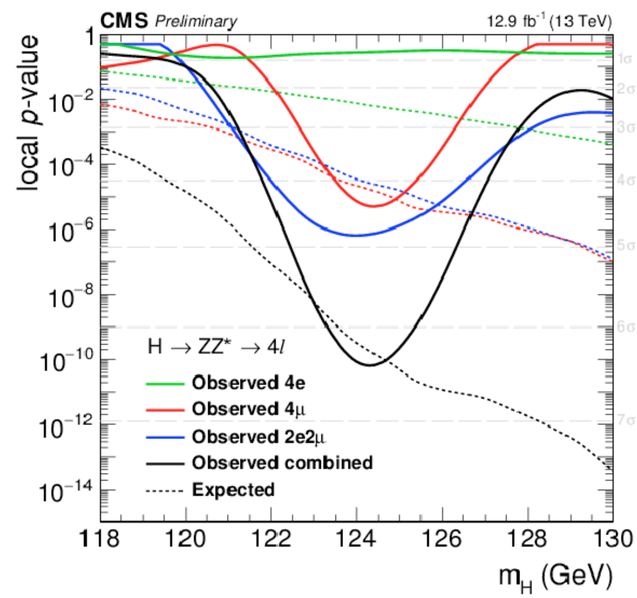




H→ZZ→4l, Run II

- Golden channel at LHC
  - Two pairs of same flavor, opposite sign, isolated leptons
  - Large S/B, excellent resolution
  - Narrow peak over a flat background
- All main production modes probed: ggF, VBF, VH, ttH
- Extraction of signal through fit of m_{4l}, together with various kinematics discriminants, which enhance the signal purity in different production modes



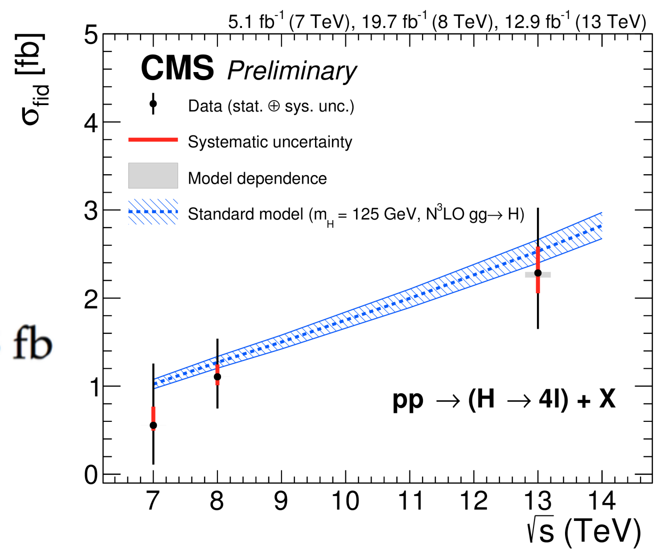


The Higgs boson rediscovered: > 5 σ

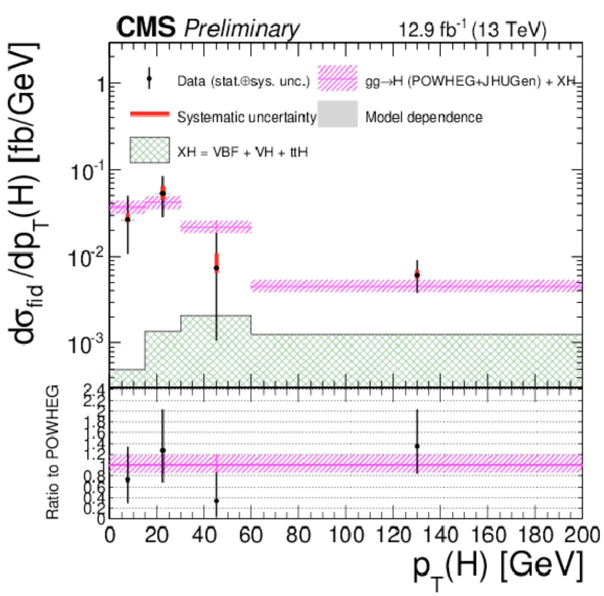
H→ZZ→4l: cross sections (Run I and II)

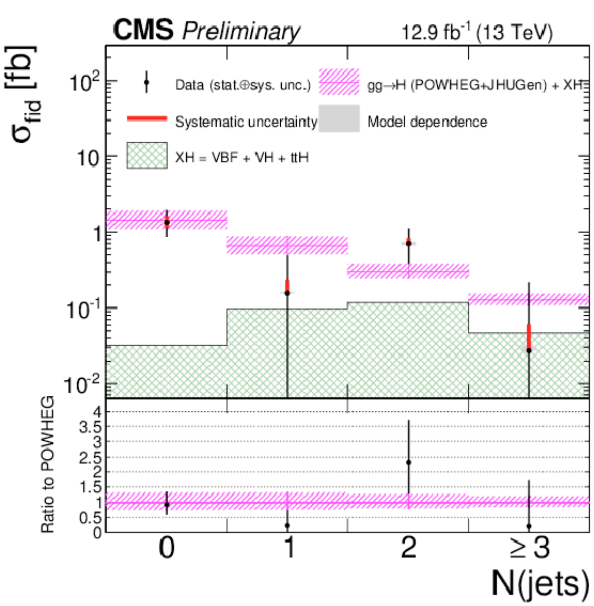
- Fiducial volume defined to closely match reconstruction level
- $\sigma_{\text{fid.}} = 2.29^{+0.74}_{-0.64}(\text{stat.})^{+0.30}_{-0.23}(\text{sys.})^{+0.01}_{-0.05}(\text{model dep.})\ \text{fb}$

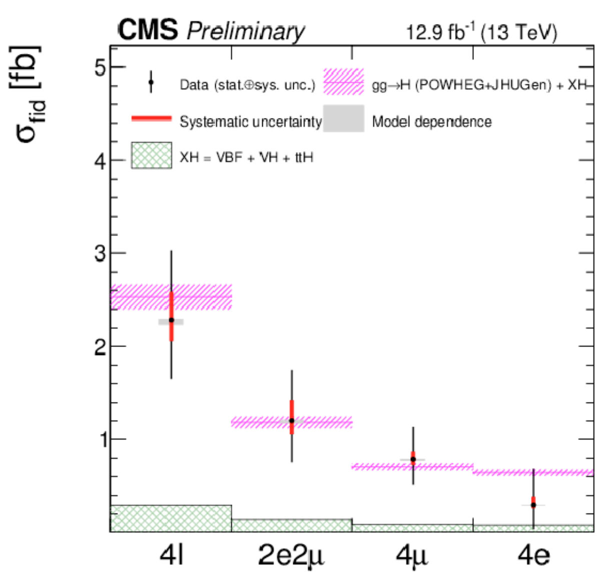
SM expectation (Run II) $\sigma^{\text{SM}}_{\text{fid.}} = 2.53 \pm 0.13\ \text{fb}$



- Differential cross section for $p_T(H)$ and N(jets), Run II

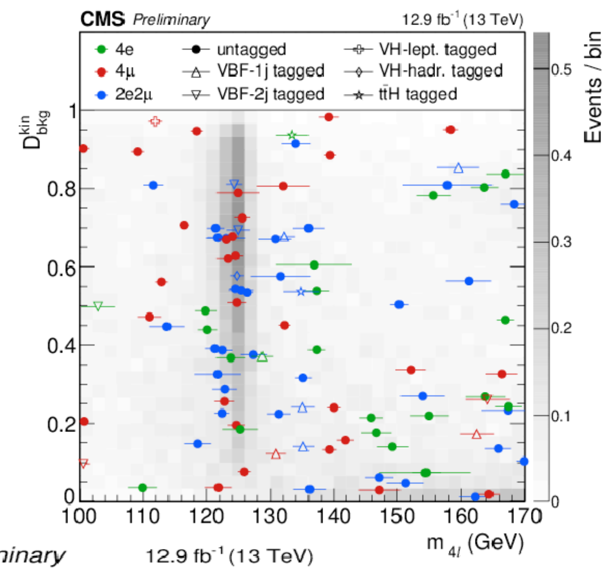


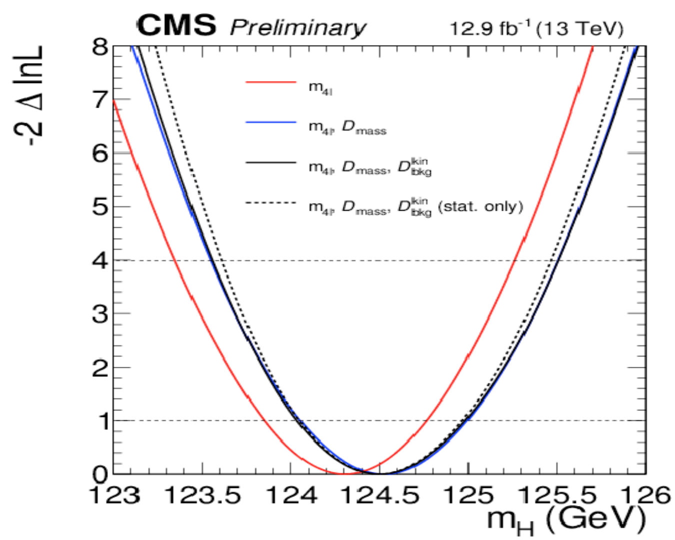


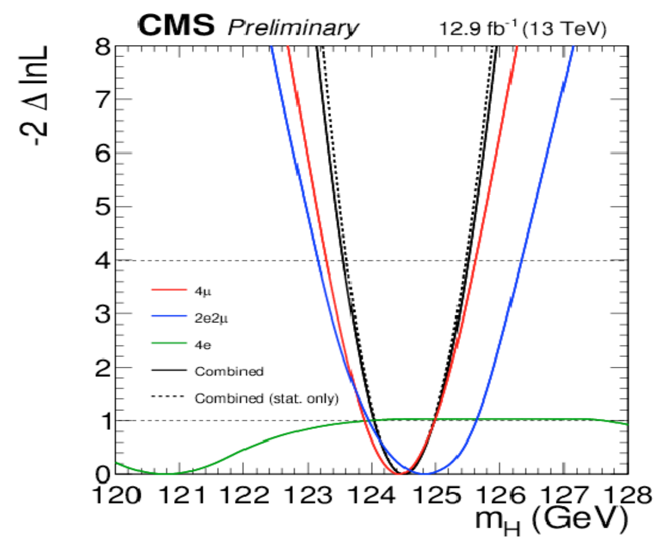


H→ZZ→4l: mass from 13 Tev

- Exploit event-by-event mass resolution $\mathcal{D}_{mass}$
  - defined by propagating per-lepton momentum error to the 4-lepton candidate; calibrated in data and MC using Z events
  - $\mathcal{D}_{mass}$ brings **8%** exp. improvement
- 3D fit based for mass $\mathcal{L}(m_{4\ell}, \mathcal{D}_{mass}, \mathcal{D}_{bkg}^{kin})$



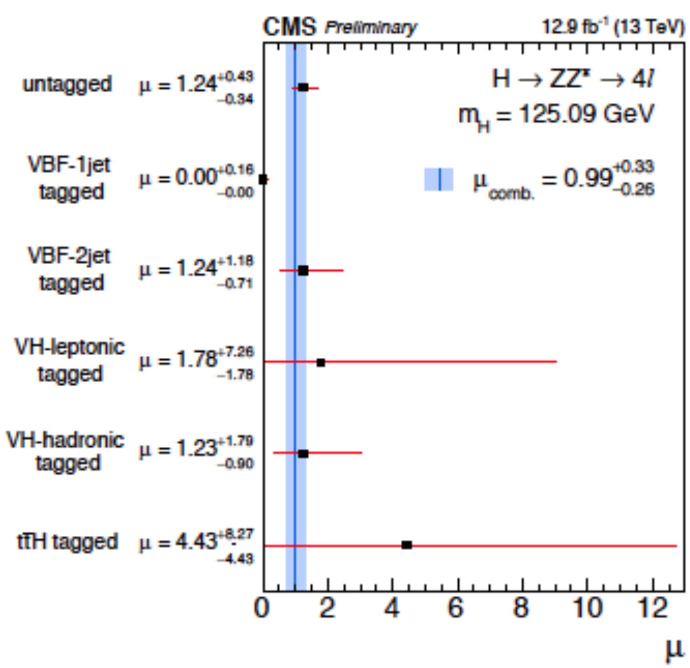


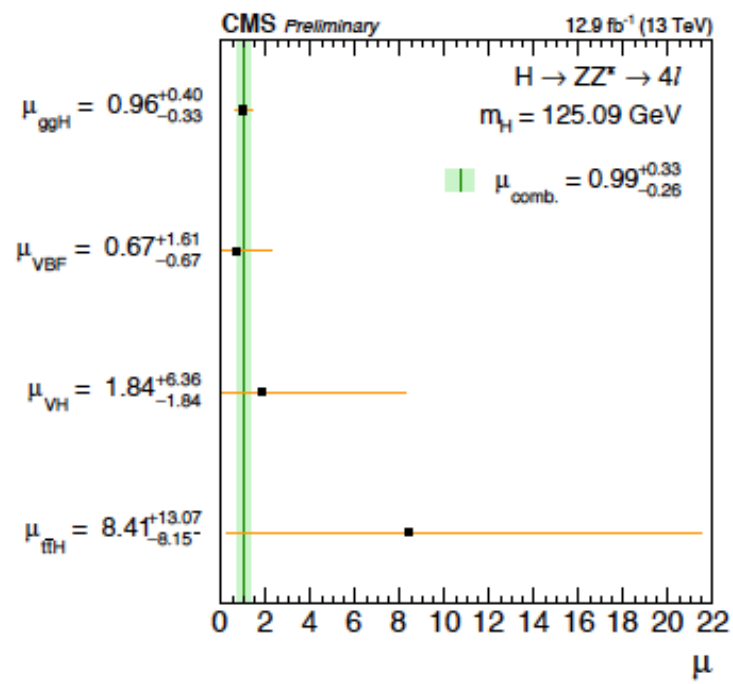


$$m_H = 124.50^{+0.48}_{-0.46}\ \text{GeV} = 124.50^{+0.47}_{-0.45}(\text{stat.})^{+0.13}_{-0.11}(\text{sys.})\ \text{GeV}$$

H → 4l at 13 TeV

Category	Untagged	VBF-1j	VBF-2j	VH-lept.	VH-hadr.	$t\bar{t}H$	Total
$q\bar{q} \to ZZ$	7.27	0.82	0.06	0.10	0.11	0.01	8.36
$gg \to ZZ$	0.62	0.11	0.01	0.01	0.01	0.00	0.77
$Z + X$	3.83	0.32	0.24	0.05	0.08	0.10	4.64
Sum of backgrounds	11.73	1.25	0.32	0.16	0.20	0.11	13.77
Signal ($m_H = 125$ GeV)	15.51	3.62	1.45	0.14	0.70	0.19	21.61
Total expected	27.24	4.87	1.77	0.30	0.90	0.30	35.38
Observed	29	1	2	0	1	0	33

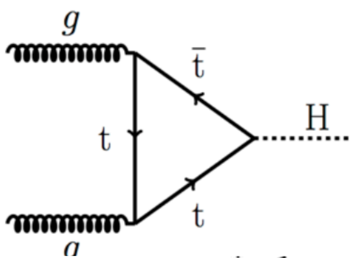




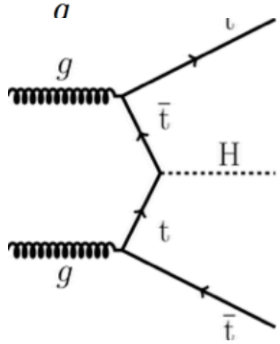
ttH

- Probing the top-Higgs Yukawa coupling at LHC

  – via gluon fusion cross section, assuming no BSM particles running in the loop



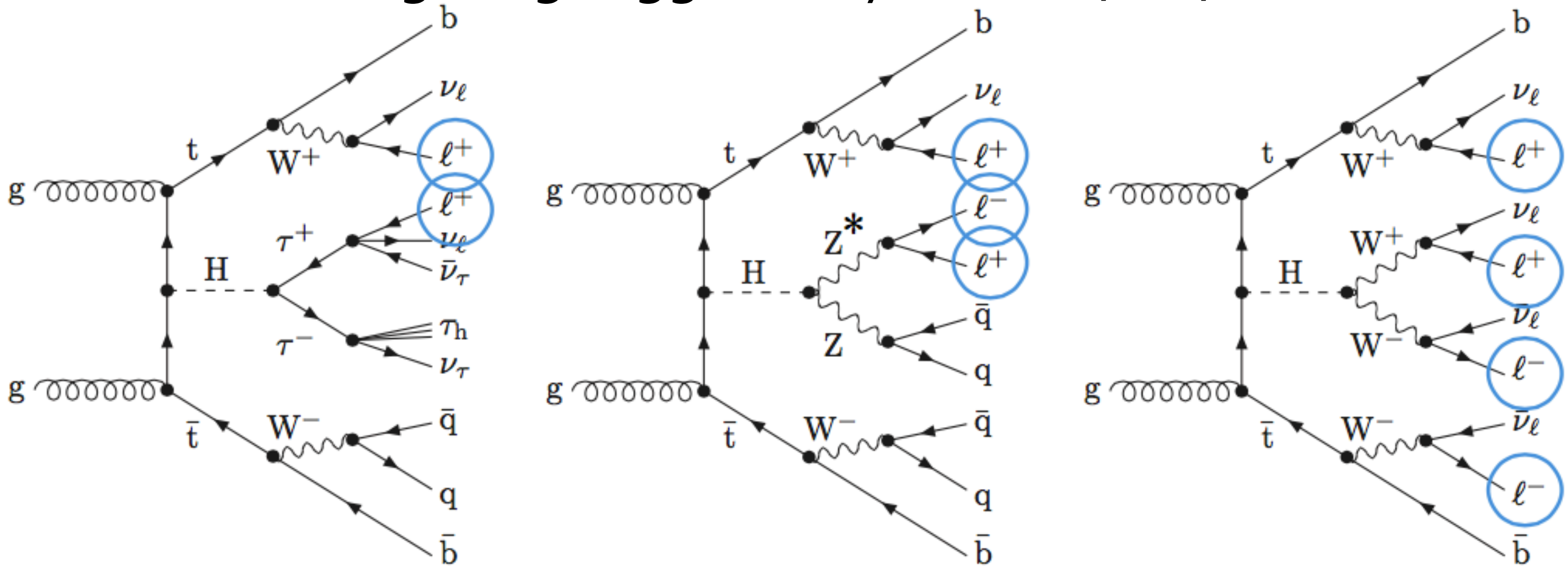
  – directly at tree level, via associated productions



  – σ for ttH has the largest boost going from 8 to 13 TeV among the 5 main Higgs production modes (σ_{ttH} ~510 fb@13 TeV)
  – Challenging due to the presence of additional jets and leptons from top decay
- ttH in CMS
  – ttH(multilepton); ttH(→bb) (2015), ttH(→γγ) included in Hγγ analysis

ttH in multi-lepton final states

Targeting Higgs decays to WW, ZZ, ττ

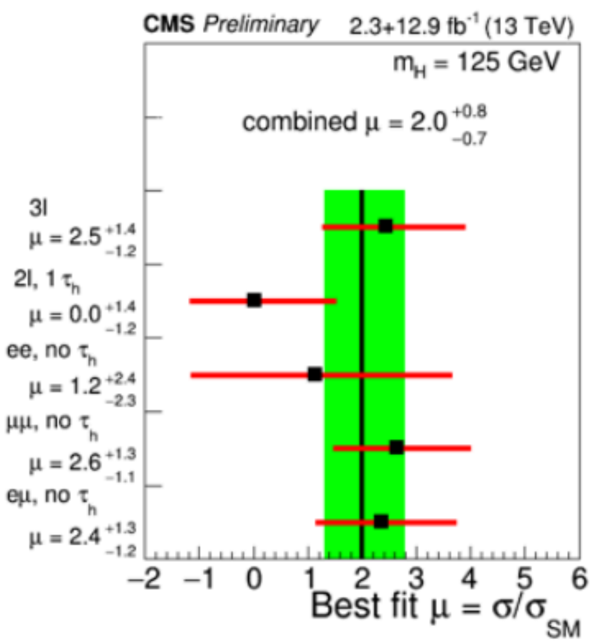


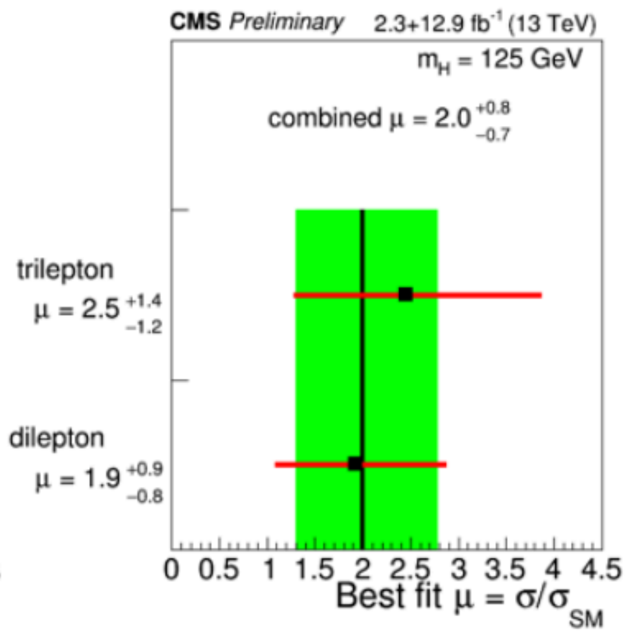
- Events with at least 2 loose or 1 medium b-tagged jets categorized into
  - two same-sign leptons + 4 jets
  - at least three leptons (with Z veto) + 2 jets
- Main backgrounds
  - **irreducible**: ttV (from MC), di-boson (validated in data)
  - **reducible**: non-prompt leptons in tt events and charge mis-ID, data-driven

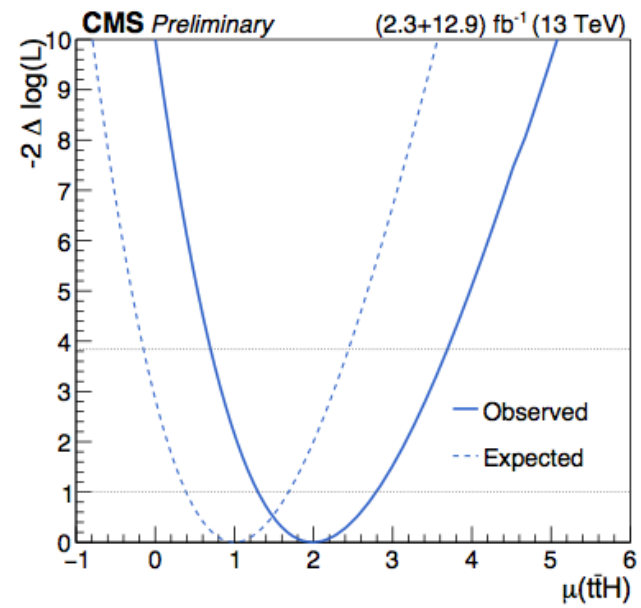
ttH(multileptons) results, 13 Tev

- Results with 2015 + 2016 data

Category	Obs. limit	Exp. limit $\pm 1\sigma$	Best fit $\mu \pm 1\sigma$
Same-sign dileptons	4.6	$1.7^{+0.9}_{-0.5}$	$2.7^{+1.1}_{-1.0}$
Trileptons	3.7	$2.3^{+1.2}_{-0.7}$	$1.3^{+1.2}_{-1.0}$
Combined categories	3.9	$1.4^{+0.7}_{-0.4}$	$2.3^{+0.9}_{-0.8}$
Combined with 2015 data	3.4	$1.3^{+0.6}_{-0.4}$	$2.0^{+0.8}_{-0.7}$

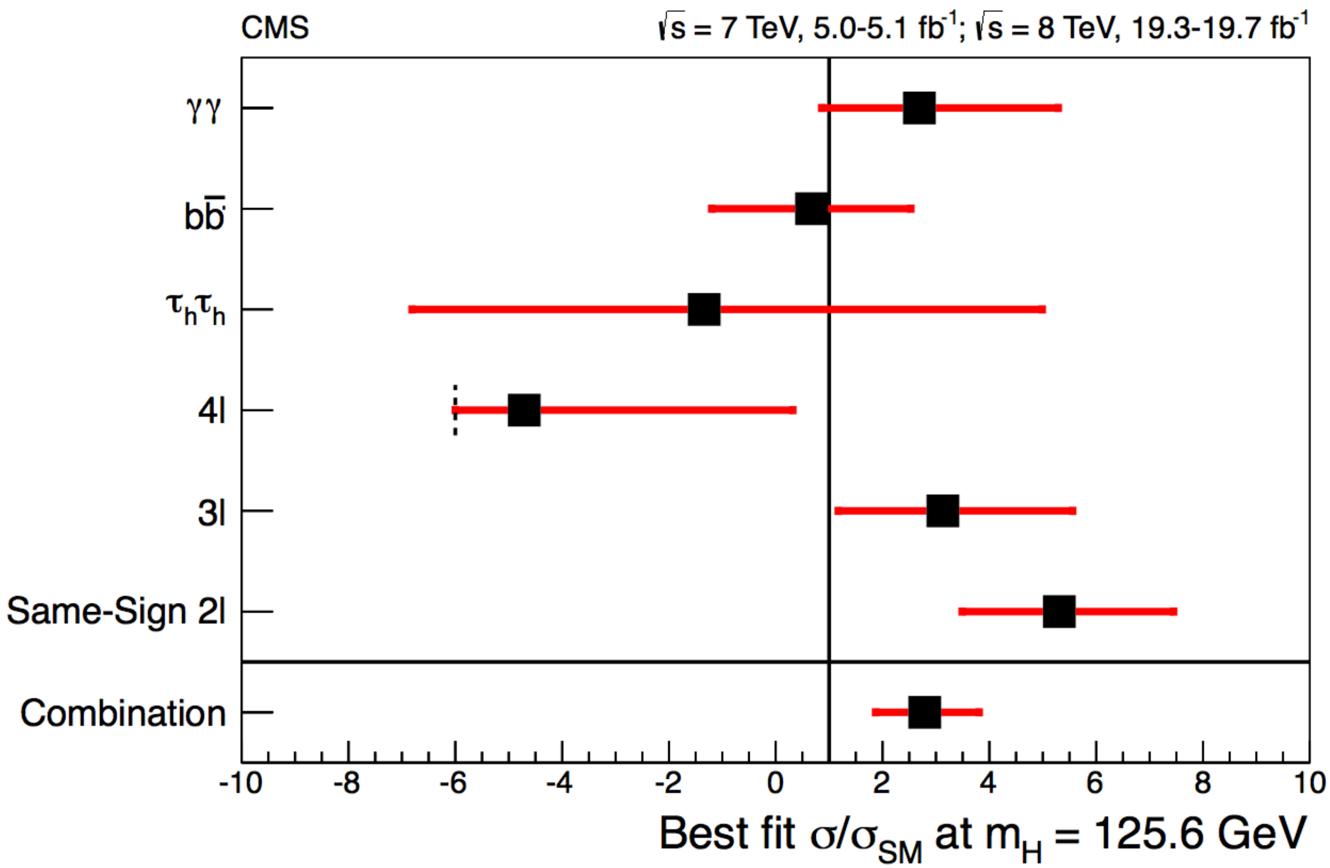






Observed (expected) significance: 3.2 (1.7) σ

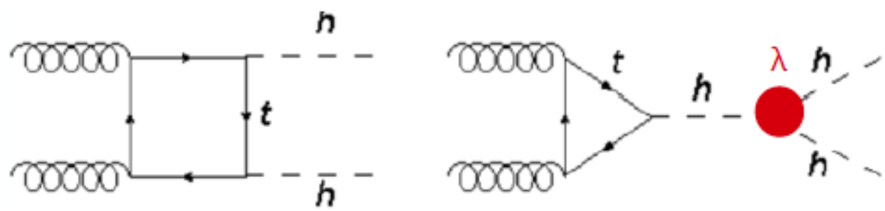
CMS Run I, ttH



Observed (expected) 3.4 (2.0) σ

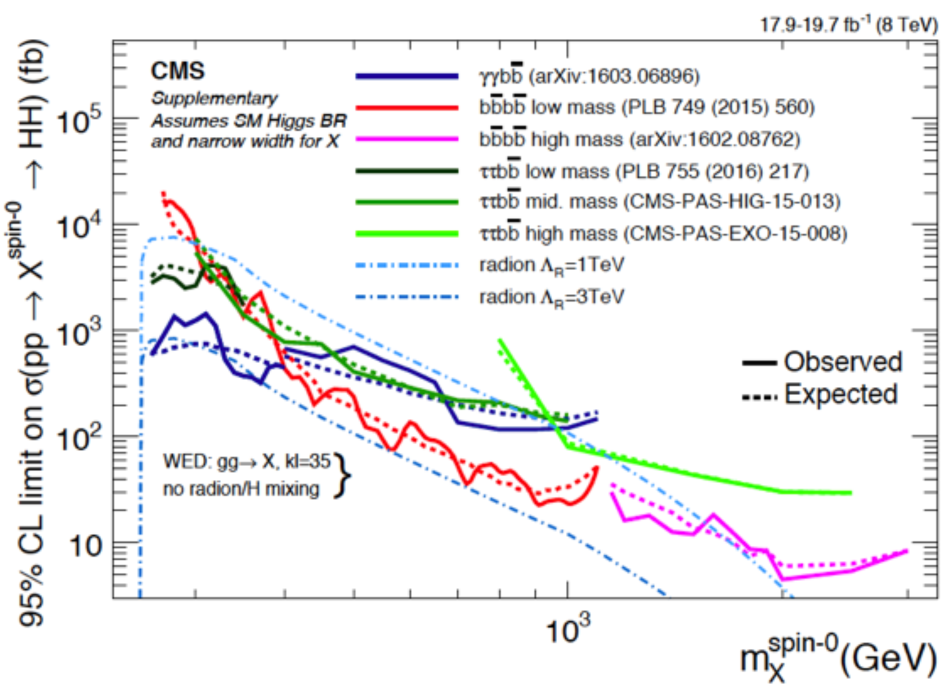
Di-Higgs Searches

- **Study of Higgs self-coupling in SM possible at HL LHC, large (BSM) coupling may show up already in Run II**
  - Gluon fusion cross section ~40fb
  - Vector boson fusion cross section ~2fb



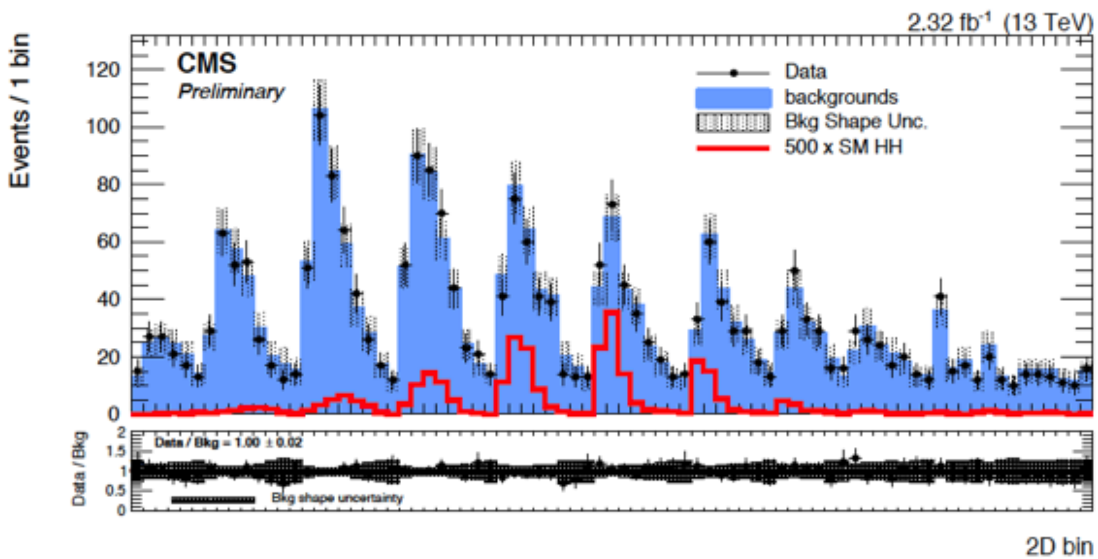
- **Enhancement possible in new physics scenarios**
  - Large progress in analyses, resonant and non-resonant searches for Run-II, different final states analyzed

Summary of Run-I resonant searches

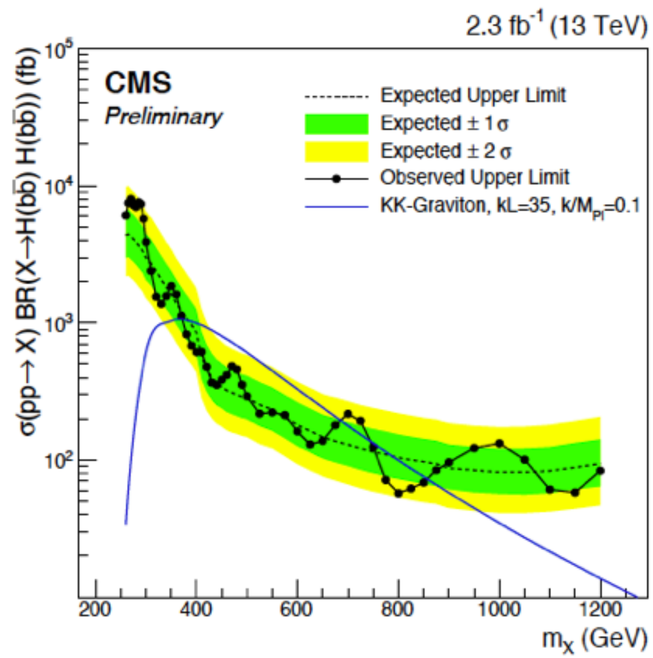


Di-Higgs Searches

- **Non-resonant production**
  - binned shape fit to the 2D $m(b_1,b_2)$, $m(b_3,b_4)$ distribution
  - pairing by minimizing $|m(b_i,b_j)-m(b_k,b_l)|$
- **Resonant production**
  - search for narrow resonance
  - reconstructed 4b mass used for signal extraction



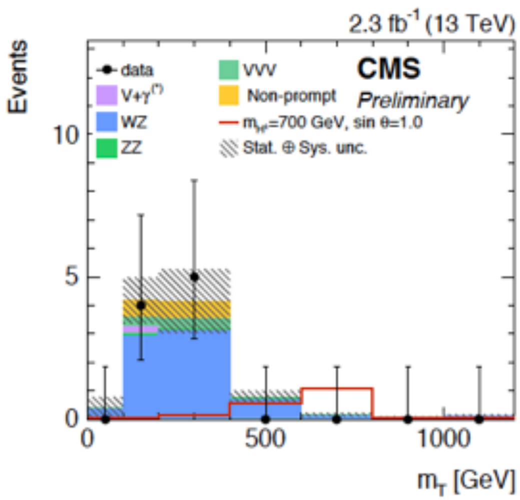
Category	Observed	Expected	-2σ	-1σ	$+1\sigma$	$+2\sigma$
			[fb]			
SM $H(b\bar{b})H(b\bar{b})$	3880	3490	2140	2540	5350	8350

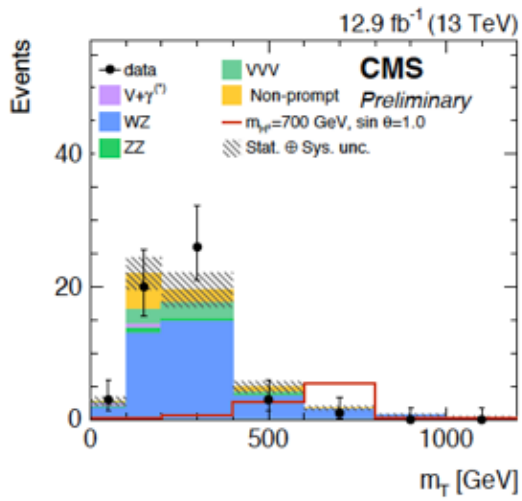


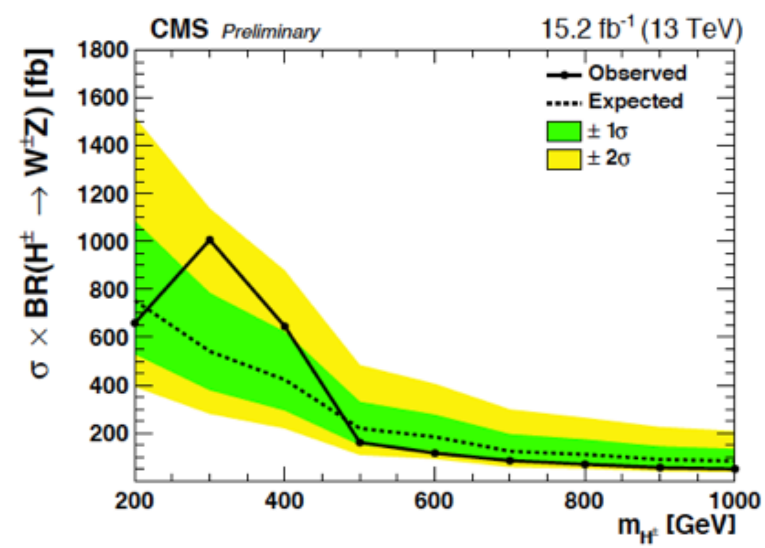
Charged Higgs Searches

- **Charged Higgs program in CMS**
  - search channels motivated by 2HDM (MSSM):
    $H^{\pm} \rightarrow tb$, $H^{\pm} \rightarrow \tau\nu$
  - other channels studied
    $H^{\pm} \rightarrow cs$, $H^{\pm} \rightarrow cb$
  - first time in Run-II:
    $H^{\pm} \rightarrow W^{\pm}Z$ using VBS topology,
    motivated by Higgs triplet models,
    complements doubly charged Higgs search

Dataset	2015	2016
Data	9	53
WZ	7.7 ± 1.8	34.5 ± 7.9
Non-prompt	1.2 ± 1.1	8.8 ± 2.7
$Z\gamma$	0.2 ± 0.2	1.0 ± 0.7
ZZ	0.2 ± 0.0	1.6 ± 0.1
VVV	0.8 ± 0.1	$5.3 \pm$
Total Bkg.	10.1 ± 2.1	51.3 ± 8.4
Signal $(m(H^{+}) = 700\ \text{GeV})$	1.8 ± 0.2	8.9 ± 0.9







Invisible Higgs Decays

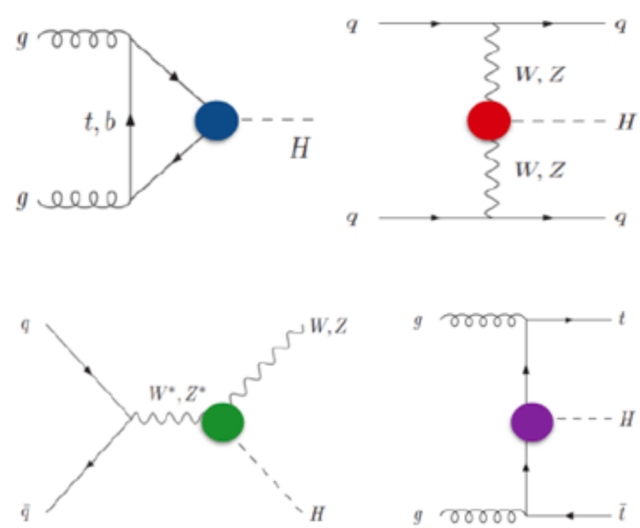
- **Connecting the Higgs and the Dark Matter sector**

  observation would be clear evidence for BSM with many interpretations possivble, including:
  - LSP in SUSY,
  - other Dark Matter particles candidates,
  - extra dimensions

- **Search strategy:**

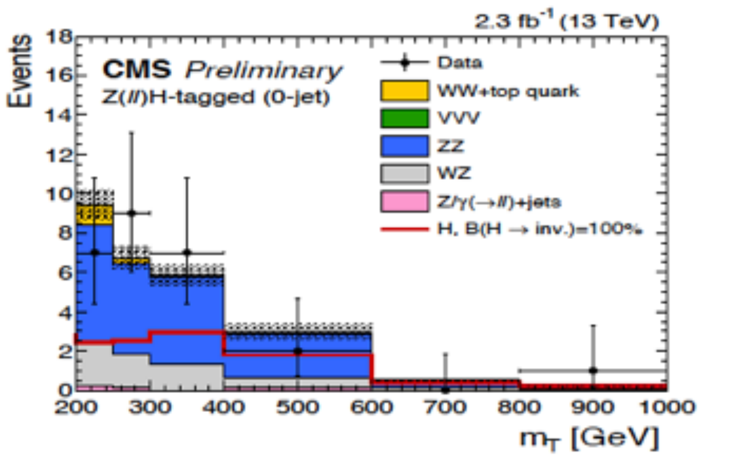
  large missing transverse energy is a common signature, different Higgs production modes explored to tag events:

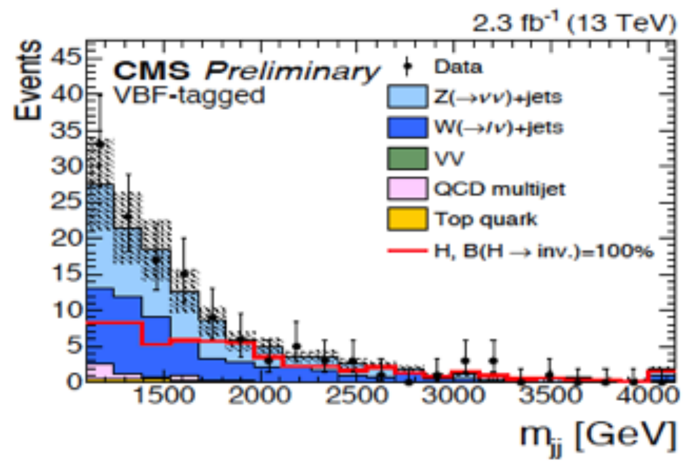
  - qqH: VBF signature with two forward jets and rapidity gap and large di-jet mass
  - Z(ll/bb)H: two leptons / b-jets compatible with Z boson hypothesis
  - Z/W(jj)H: two jets compatible with Z or W boson hypothesis
  - ttH: two top quark candidates
  - gF Higgs: mono-jet search

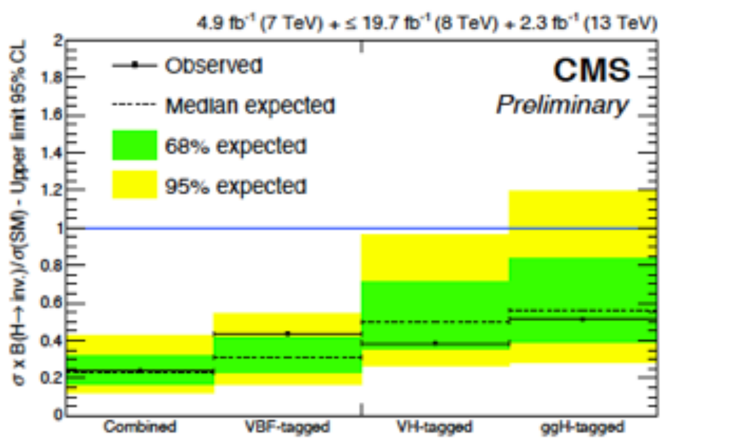


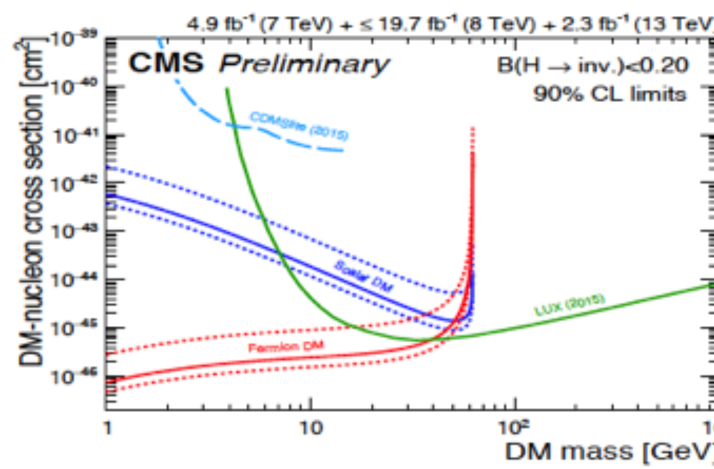
Invisible Higgs Decays

- control of backgrounds is crucial:
  use combined fits of signal and background regions





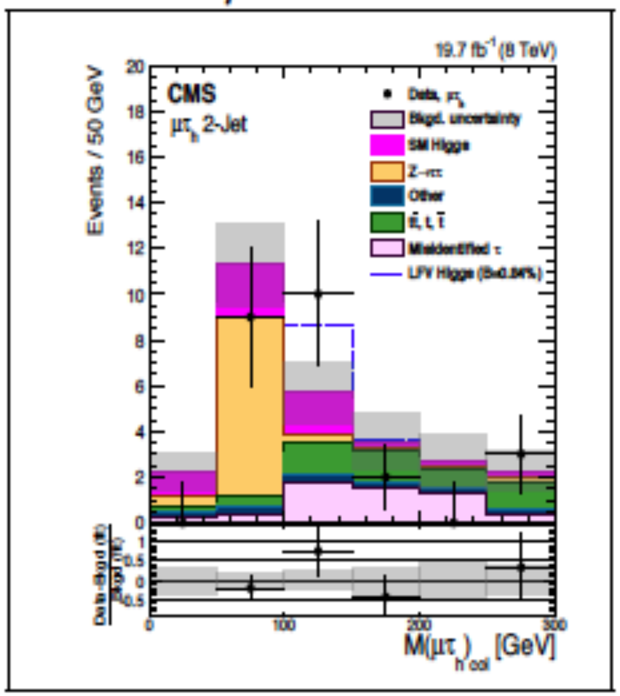




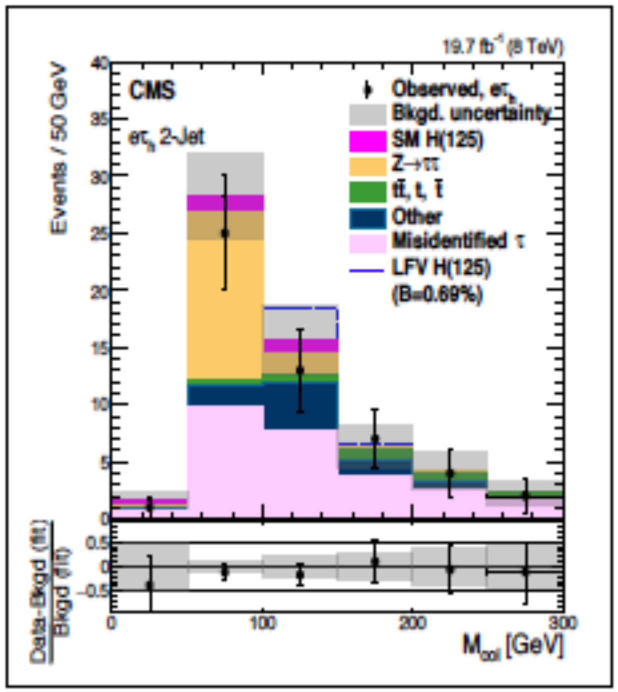
Lepton flavor violating Higgs decays

- Search for mass peak at mH ~ 125 GeV in $\mu\tau$ / $e\tau$ / $e\mu$ pairs
- Analysis leaning on SM Higgs H→$\tau\tau$ measurements
- Direct limits on BR (H→ $\mu\tau$ / $e\tau$ / $e\mu$) established
- Fluctuation in $\mu\tau$ final state at 8 TeV ?

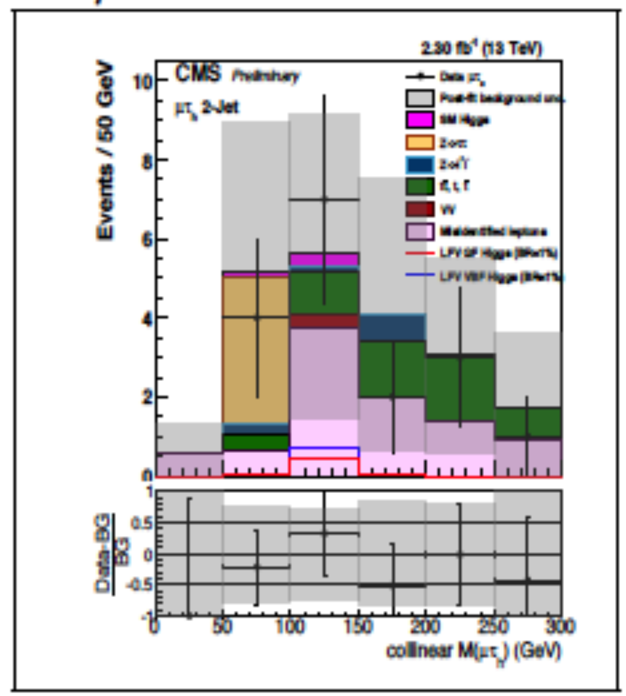
$\mu\tau$ 8 TeV



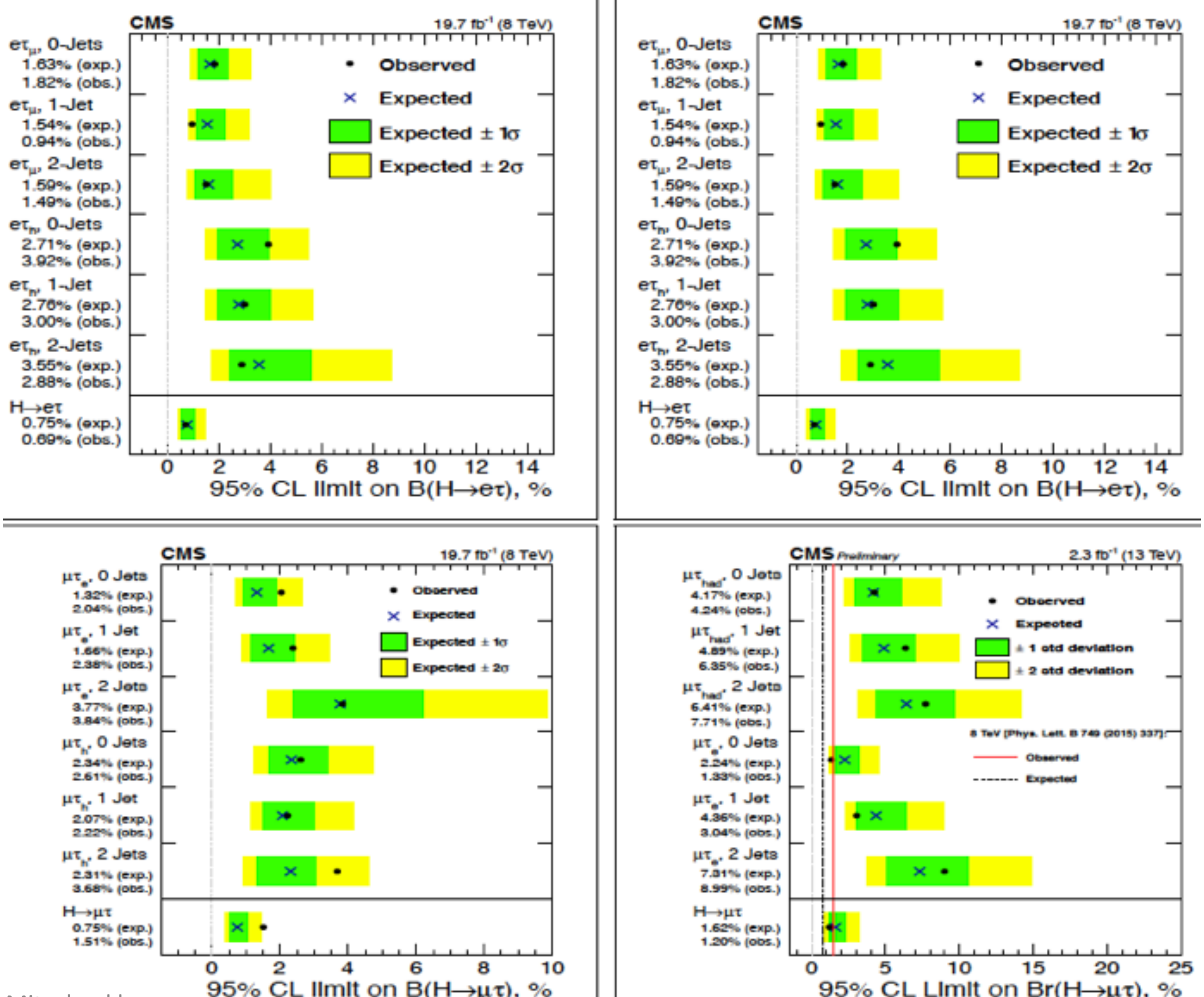
$e\tau$ 8 TeV



$\mu\tau$ 13 TeV

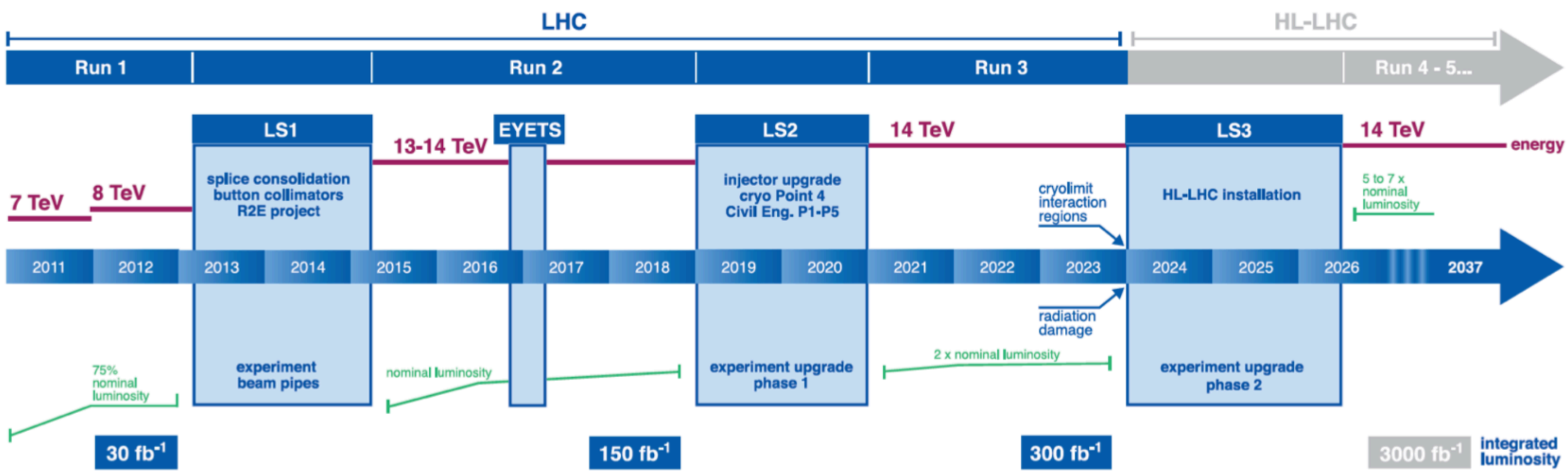


Lepton flavor violating Higgs decays



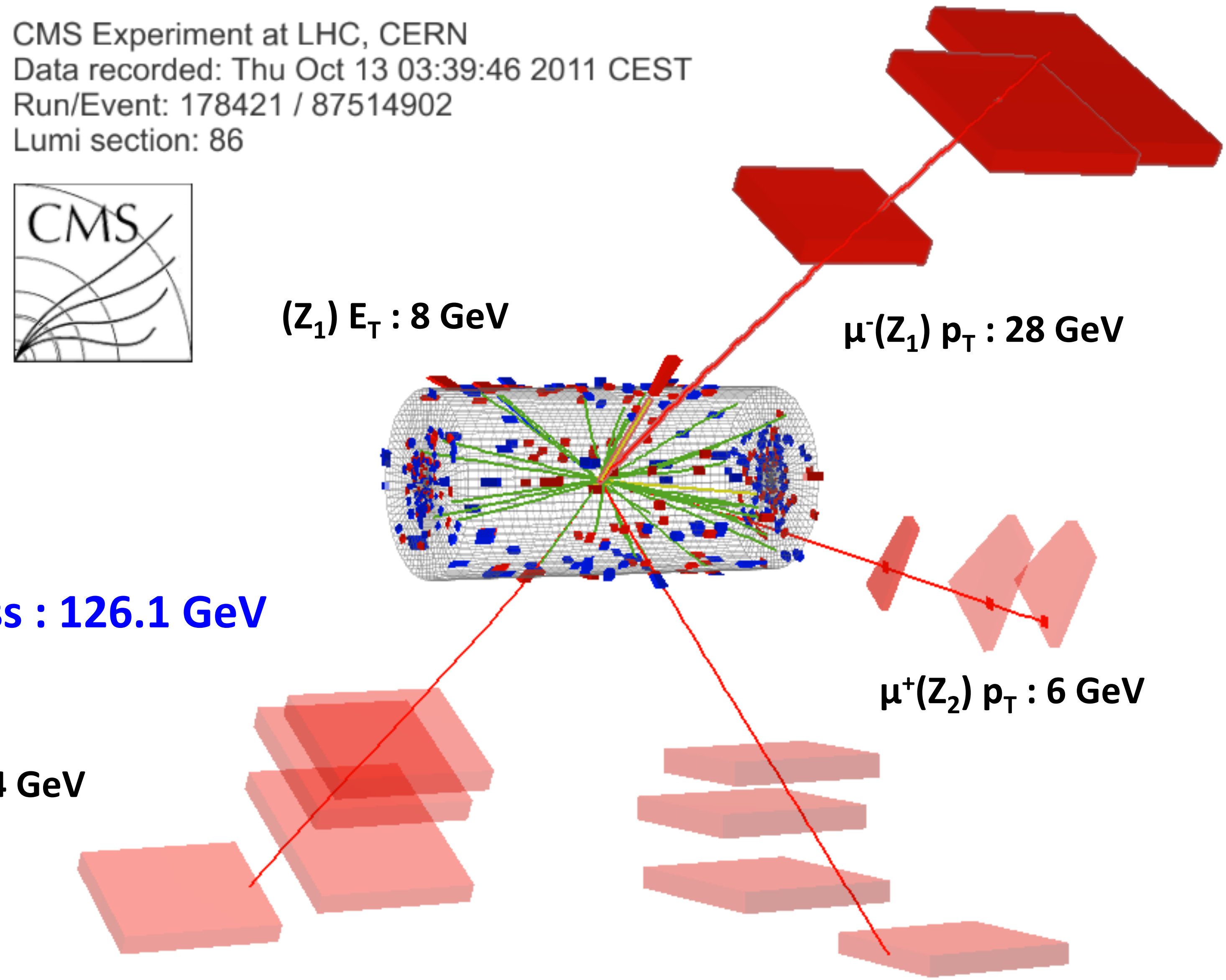
Summary

- Exploration of the new energy regime of 13 TeV has just started, CMS is extending the scope of the Higgs studies
- The Higgs boson has been rediscovered and several measurements performed
- No significant deviations from the Standard model from this first look. Most results limited by statistics.
- ~10x more data by end of 2018 (End of Run II), stay tuned



Backup

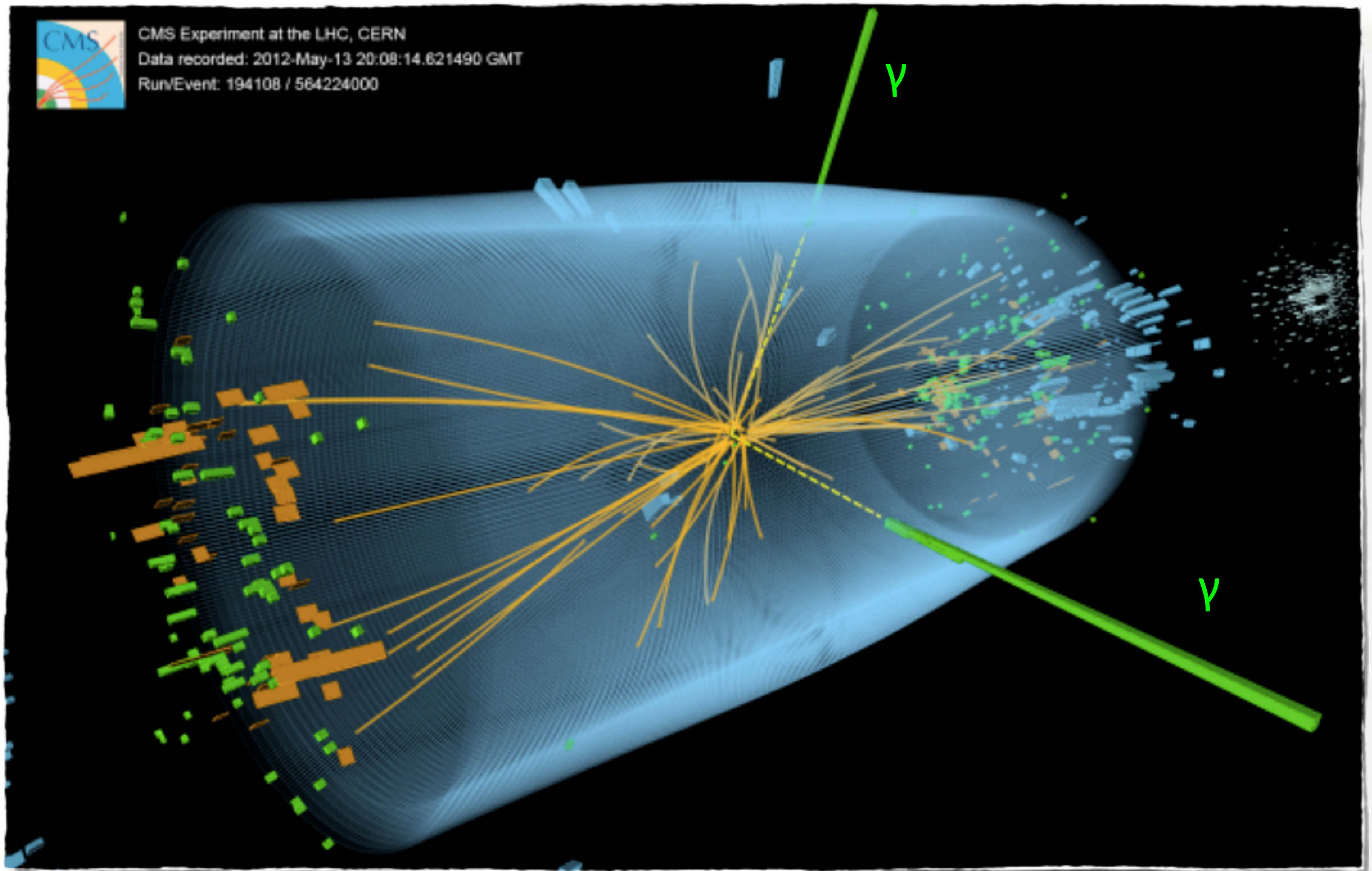
4μ+γ computer event display



7 TeV DATA

4μ+γ Mass : 126.1 GeV

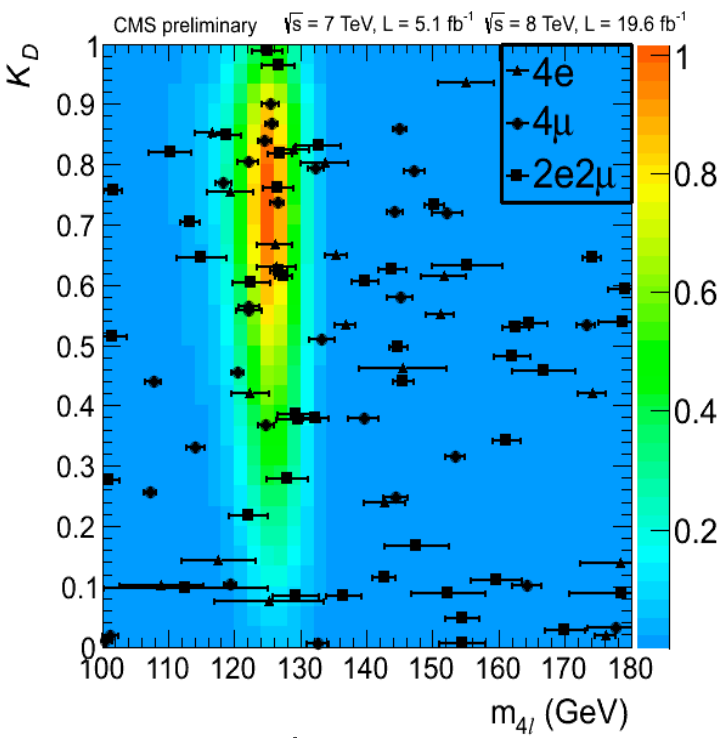
Event display $H \to \gamma\gamma$



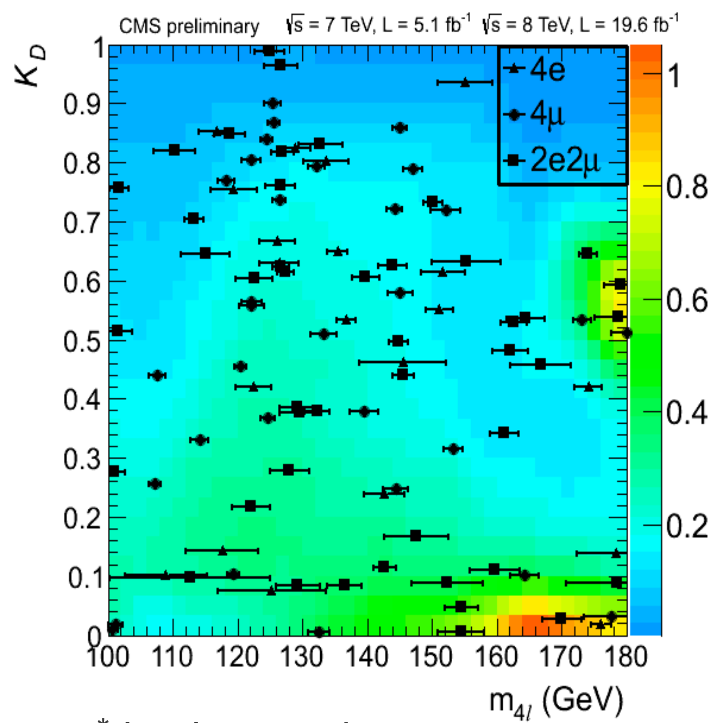
S/B improvement: Kinematic Discriminant (Run I data)

- To further improve signal to background ratio, we use a discriminant based on kinematic 4l information

$$\mathrm{KD} = \frac{\mathcal{P}_{\mathrm{sig}}}{\mathcal{P}_{\mathrm{sig}} + c \times \mathcal{P}_{\mathrm{bkg}}} = \left[1 + \frac{c \times \mathcal{P}_{\mathrm{bkg}}(m_1, m_2, \vec{\Omega} | m_{4\ell})}{\mathcal{P}_{\mathrm{sig}}(m_1, m_2, \vec{\Omega} | m_{4\ell})} \right]^{-1}$$



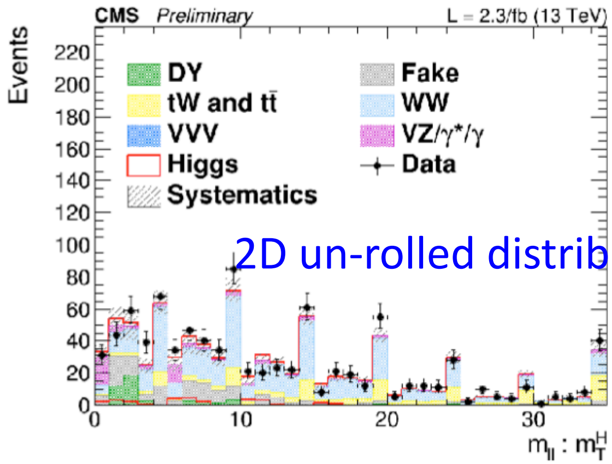
Higgs signal

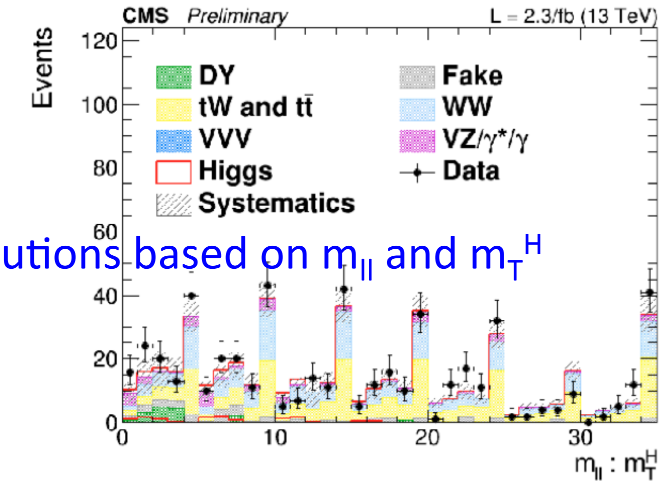


ZZ^* background

H→WW→2l2v (13 Tev, 2015)

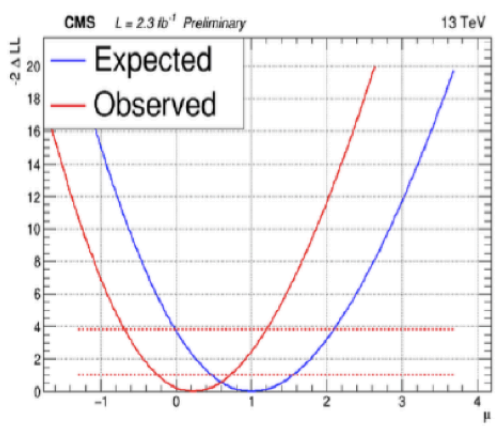
H→WW→eμ + νν : opposite-charge eμ in association with large MET for up to 1-jet.





2D un-rolled distributions based on m_{ll} and m_T^H

For m_H=125. GeV, obs. significance is 0.7σ (2.0σ expected); best fit signal strength σ/σ_{SM} = 0.3 ± 0.5



Category	Expected significance	Observed significance	Expected error on σ/σ_{SM}	σ/σ_{SM}
0-jet μe	1.1	1.3	$^{+0.91}_{-0.88}$	$1.13^{+0.9}_{-0.9}$
0-jet $e\mu$	1.3	0.4	$^{+0.82}_{-0.77}$	$0.33^{+0.7}_{-0.7}$
1-jet μe	0.8	0	$^{+1.30}_{-1.21}$	$-0.11^{+0.5}_{-1.7}$
1-jet $e\mu$	0.9	0	$^{+1.17}_{-1.10}$	$-0.54^{+1.4}_{-1.4}$
0-jet	1.6	1.3	$^{+0.63}_{-0.61}$	$0.71^{+0.6}_{-0.5}$
1-jet	1.2	0	$^{+0.87}_{-0.83}$	$-0.56^{+1.0}_{-1.0}$
Combination	2.0	0.7	$^{+0.53}_{-0.51}$	$0.33^{+0.5}_{-0.5}$

VBF Hbb

CMS-HIG-16-003

Analysis overview

- 2 scattered light jets
  - Expected to be close to beam line
  - EWK process ⇒ little QCD activity
- 2 b-jets from Higgs
  - Regression method reconstruction
  - m_{bb} final discriminant

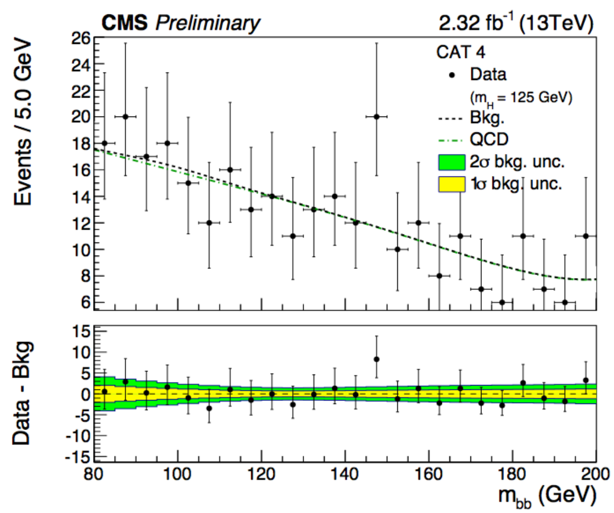
Hadronic triggers

QuadJet92,76,64,15, 1xCSV

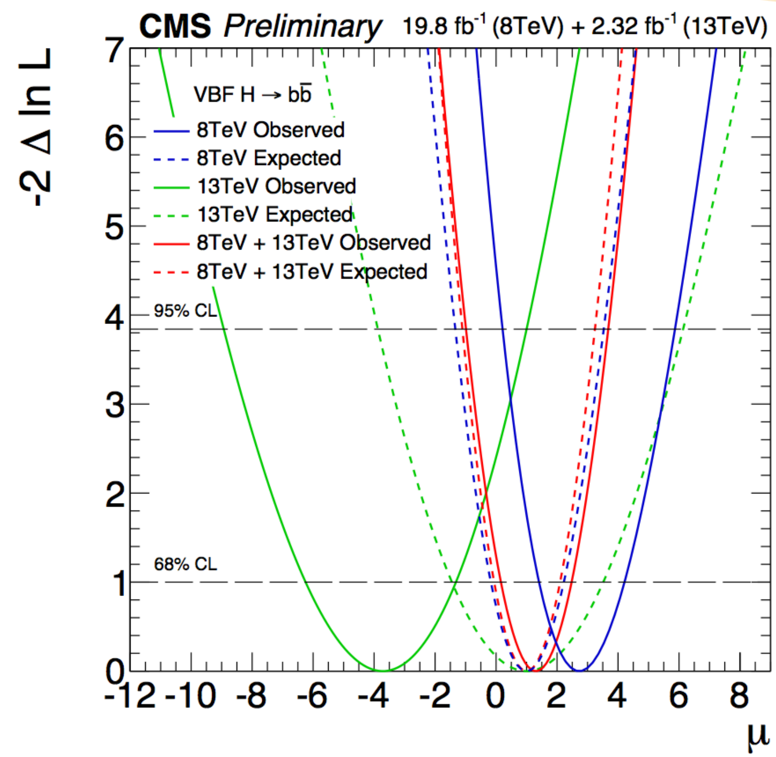
$\Delta\eta_{qq}>4.1$, $m_{qq}>460$, $\Delta\phi_{bb}<1.6$

QuadJet92,76,64,15, 2xCSV

$\Delta\eta_{qq}>1.2$, $m_{qq}>200$



Results – Run II



Combined Run I & Run II results:

Obs. (Exp.) limit: 3.4 (2.3) x SM

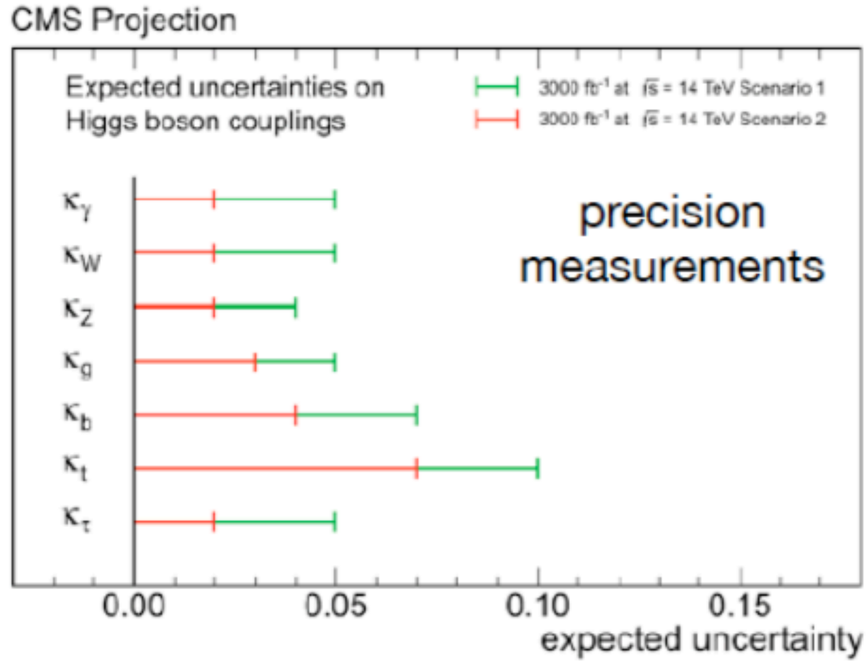
Best fit $\mu = \sigma/\sigma_{SM}$ = 1.3 +1.2/-1.1

Couplings measurement projection for HL-LHC

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

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

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



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]