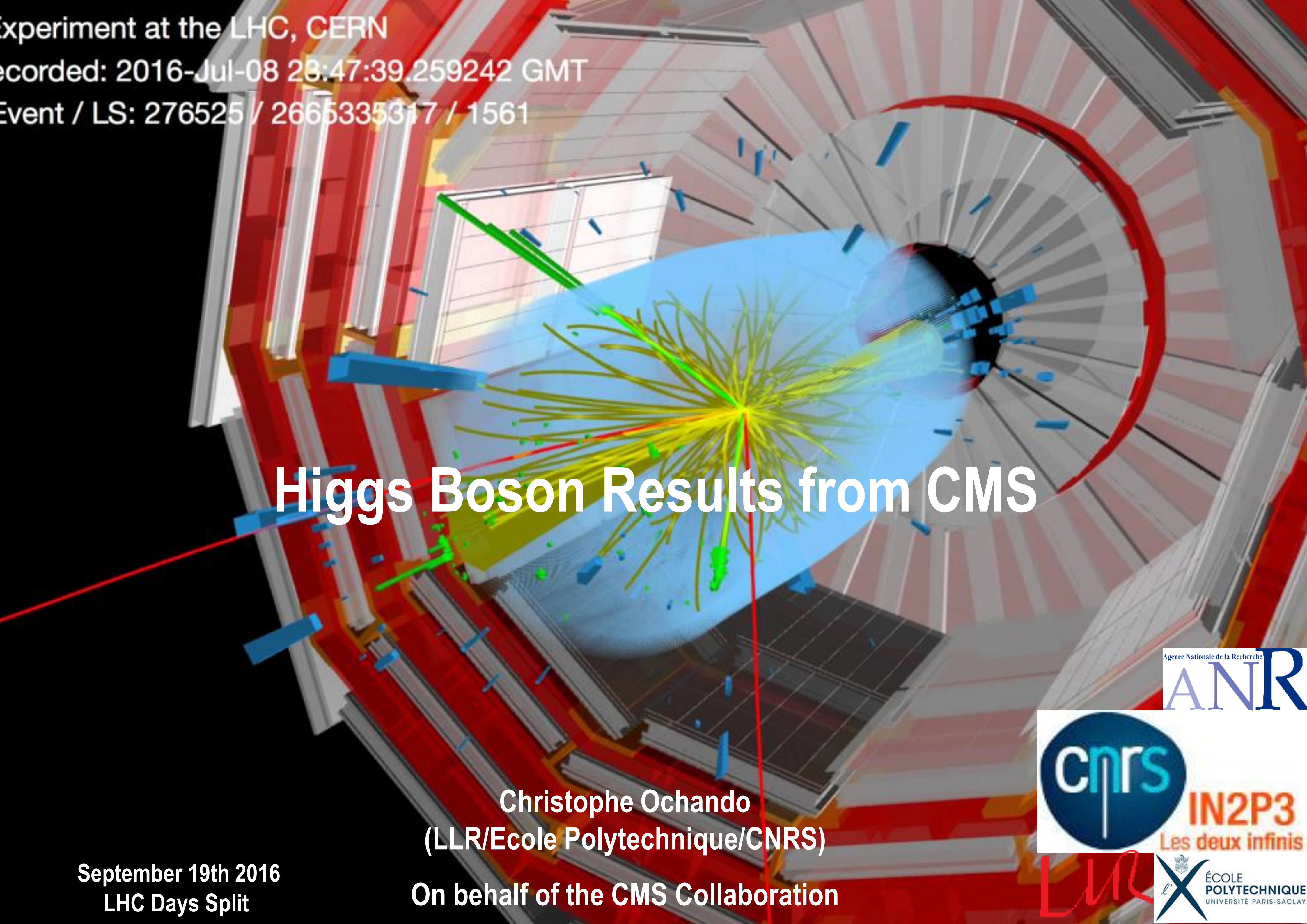


Higgs Boson Results from CMS

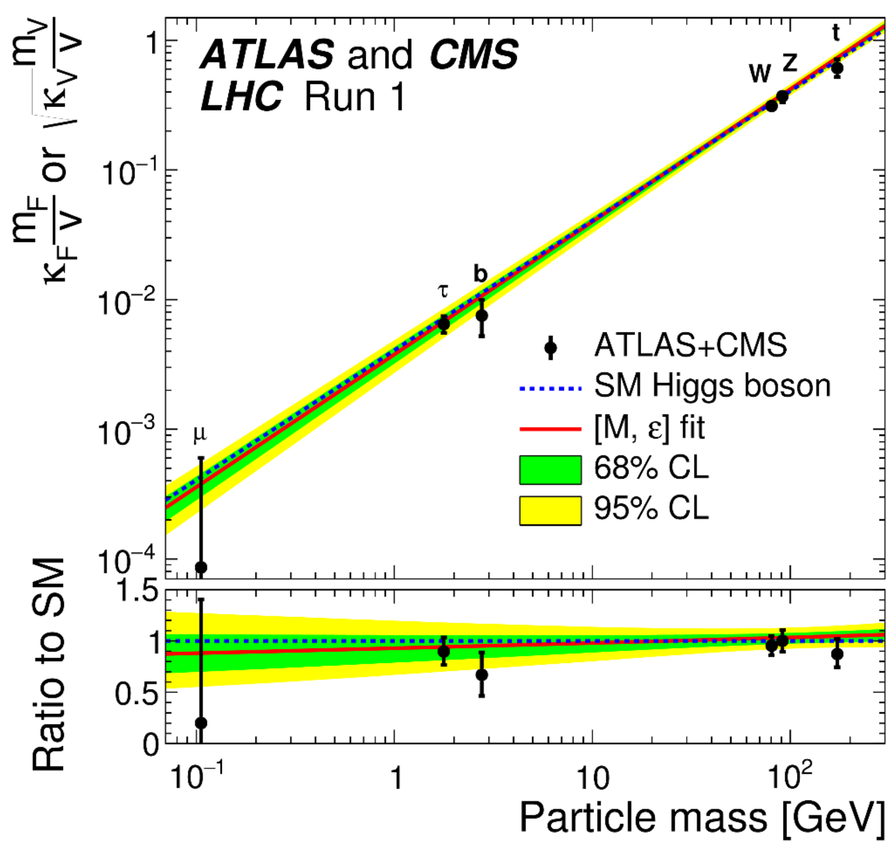
Christophe Ochando
(LLR/Ecole Polytechnique/CNRS)

On behalf of the CMS Collaboration

September 19th 2016
LHC Days Split

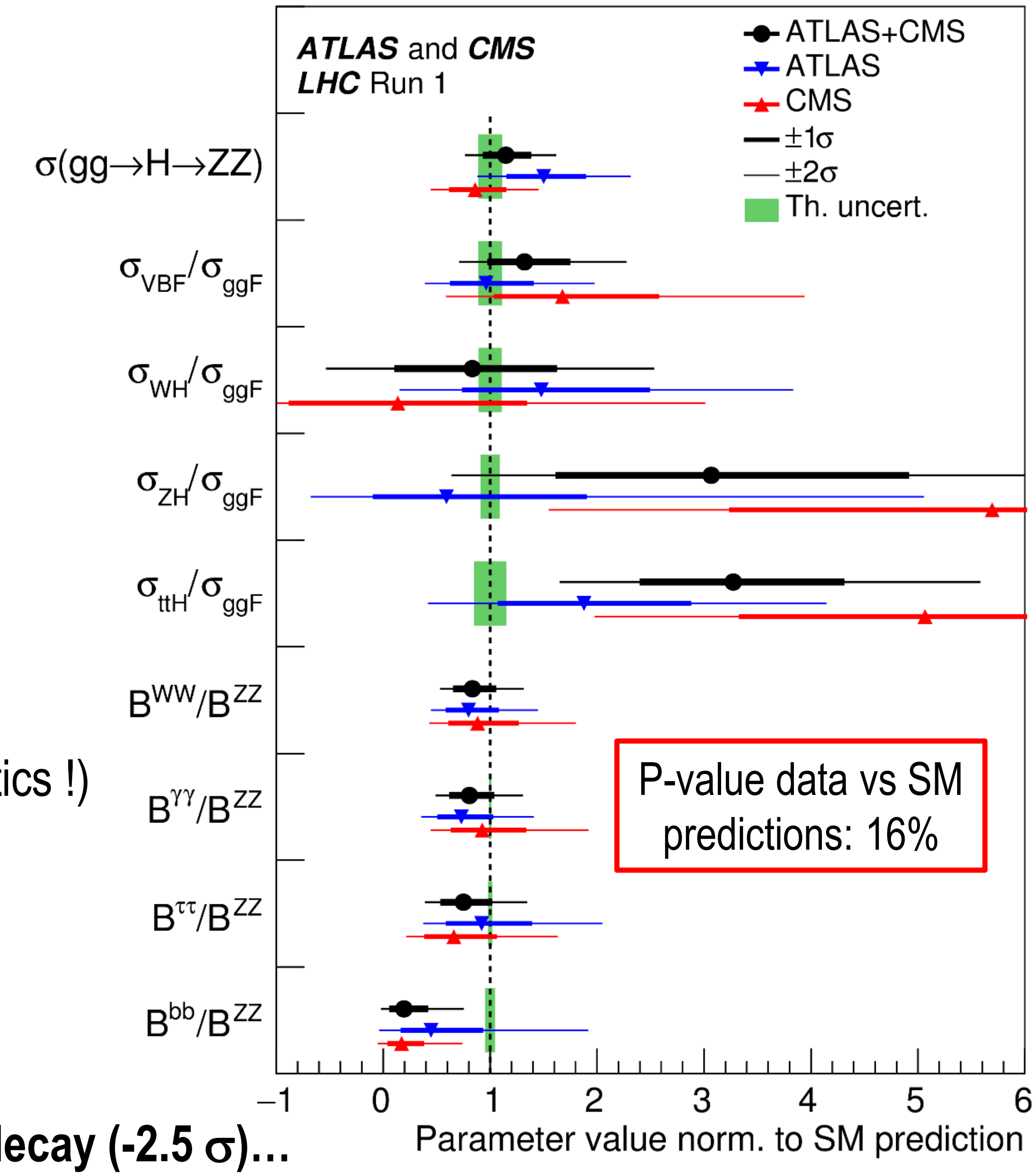
Run I Higgs boson Grand Summary

JHEP 08(2016)045



Using gg→H→ZZ as a reference:

$$(\sigma_i . BR_j) = \sigma(gg \rightarrow H \rightarrow ZZ) \frac{\sigma_i}{\sigma_{ggF}} \frac{BR^j}{BR^{ZZ}}$$



- **Higgs boson discovery with bosonic decays,**
  - **now also observation with taus**
- m_H=125.09 with 0.2% precision (dominated by statistics !)
- 0+ state favoured over other J^{PC} hypothesis
- narrow width (Γ_H< ~20 MeV @ 95% CL)
- Couplings to third-generation fermions and W/Z known with 10-30% precision.
- **Slight excess in ttH (3 σ)… slight deficit in bbar decay (-2.5 σ)…**

From Run I to Run II

- **Change in data taking conditions:** See talk from A. Zabi
  - 8 TeV → 13 TeV

@m_H=125 GeV:

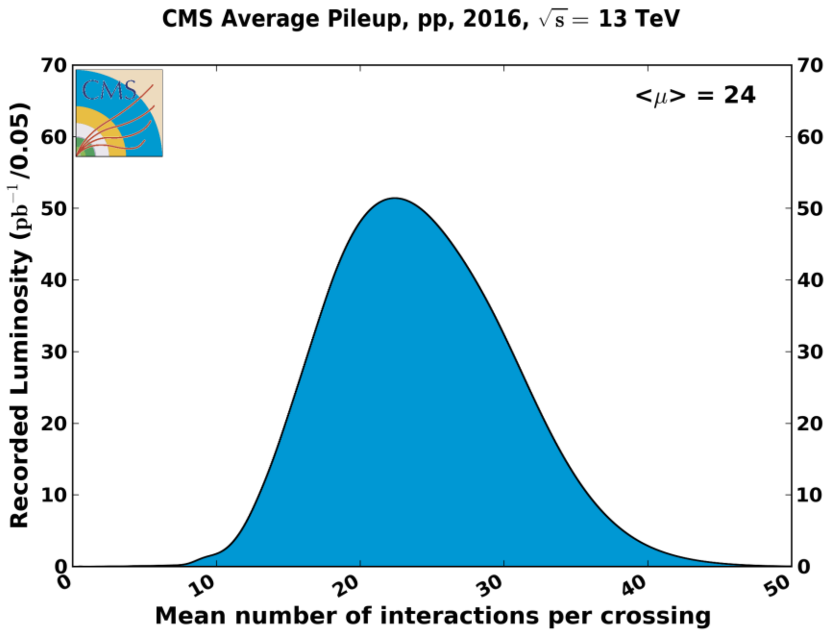
	σ_{13TeV} (pb)	σ_{13TeV} / σ_{8TeV}
gg→H	43.9	**2.3**
qq→qqH (VBF)	3.8	**2.4**
qq→VH (WH/ZH)	2.3	**~2**
gg→ttH	0.13	**3.9**

Factor 2-4 increase of Higgs production cross section !
(background too…)

Makes life easier

But…
- Increase of Instantaneous luminosity,
- Bunch spacing: 50ns → 25 ns
- Increase of Pile-Up (in and out-of-time)

Makes life harder



+ Detector Upgrades (L1 Trigger, …)

From Run I to Run II: Exploring new territories…

Higher energy and higher integrated luminosity opens up many possibilities to study the scalar sector:

- **Precision measurements:** (anomalous) couplings, differential distributions,
  - main modes: ZZ, WW, $\gamma\gamma$, $\tau\tau$, bb
  - Observation of all production modes: VBF, VH, ttH, tqH, bbH, …
  - Rare decay modes ($H\rightarrow\mu\mu$, $H\rightarrow Z\gamma$, …) or forbidden ($H\rightarrow\tau\mu$)
  - Di-Higgs non-resonant searches

- **Extension of the scalar sector (2HDM, nMSSM, …)**
  - Additional (pseudo-) scalar bosons,
  - neutral or charged, low or high mass

See talk from S. Nikitenko

- **Portal to new physics ?**
  - SUSY, Dark Matter, …

See talks from C. Collard, D. Kovalsky

(some) Recent CMS Higgs Results

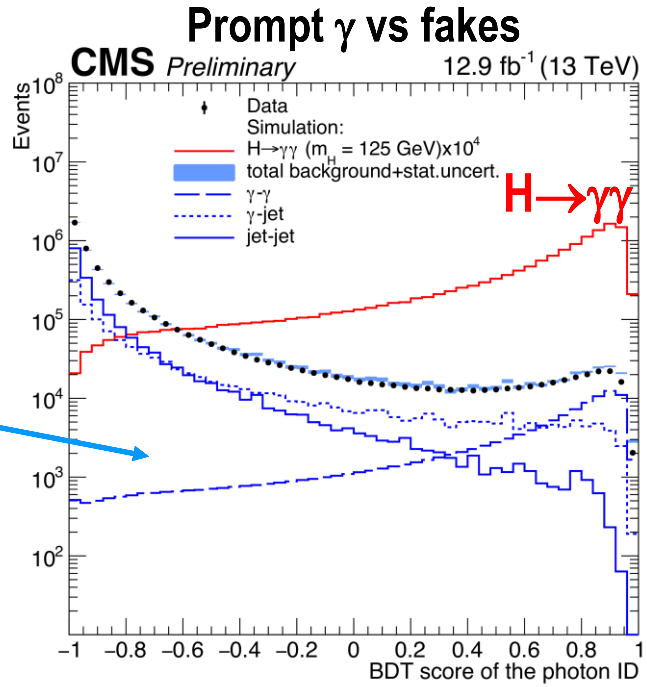
HIG-16-026	non-resonant $HH\rightarrow bbbb$	2.3 fb^{-1}	
HIG-16-030	non-resonant $HH\rightarrow bb\gamma\gamma$	2.7 fb^{-1}	
HIG-16-024	$HH\rightarrow bbWW$	2.3 fb^{-1}	
HIG-16-028	$HH\rightarrow bb\tau\tau$	12.9 fb^{-1}	✓
HIG-16-022	$ttH\rightarrow$multileptons	12.9 fb^{-1}	✓
HIG-16-019	tH, $H\rightarrow bb$	2.3 fb^{-1}	
HIG-16-033	$H\rightarrow ZZ^*\rightarrow4$ leptons	12.9 fb^{-1}	✓
HIG-16-020	$H\rightarrow\gamma\gamma$	12.9 fb^{-1}	✓

✓ : Covered in this talk

Tools for discovery and measurements (1)

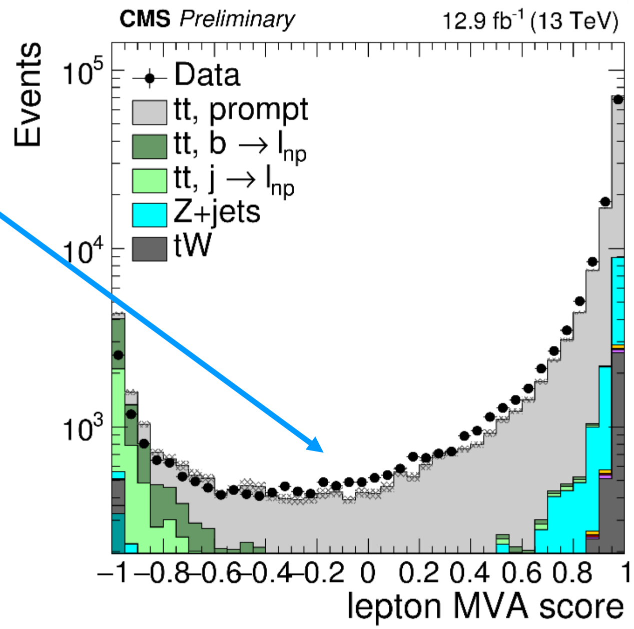
Higgs Physics is a challenge at LHC:

- Many different final states, low yields, low S/B (in general), low pT leptons,
- Development of advanced tools & technics to improve sensitivity/precision



➢ MultiVariate Analysis for objects:

- Regression to improve e/γ momentum/energy ($H\rightarrow\gamma\gamma$, $H\rightarrow ZZ\rightarrow 4l$)
- Vertex ID ($H\rightarrow\gamma\gamma$)
- Electron Identification ($H\rightarrow ZZ\rightarrow 4l$), Photon ID ($H\rightarrow\gamma\gamma$), Tau ID ($HH\rightarrow bb\tau\tau$)
- Lepton ID ($ttH\rightarrow$multileptons)
  - ID, Isolation, Impact parameters from leptons + associated jets information
- B-tagging of jets ($HH\rightarrow bb\tau\tau$, ttH, …)
- MVA also used to categorize events or extract signal



Prompt leptons
vs non-prompt
(from b-jets, conversion…)

Tools for discovery and measurements (2)

➢ **Signal Extraction via Matrix Element Methods (MEM):**

- Event-by-event discriminator built upon Matrix Elements. Combined with reco level info.

$$w_{i,\alpha}(\Phi') = \frac{1}{\sigma_\alpha} \int d\Phi_\alpha \cdot \delta^4\left(p_1^\mu + p_2^\mu - \sum_{k\geq 2} p_k^\mu\right) \cdot \frac{f(x_1,\mu_F) f(x_2,\mu_F)}{x_1 x_2 s} \cdot \left|\mathcal{M}_\alpha(p_k^\mu)\right|^2 \cdot W(\Phi'|\Phi_\alpha)$$

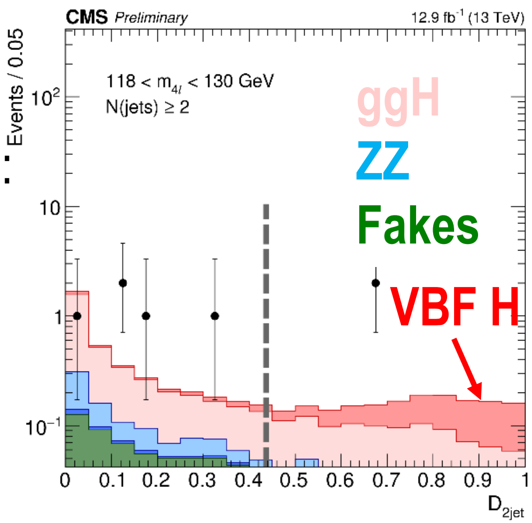
Phase Space | Momentum conservation | PDF's | LO ME from Madgraph5_aMC@NLO | Transfer Function (relates parton and reco quantities)

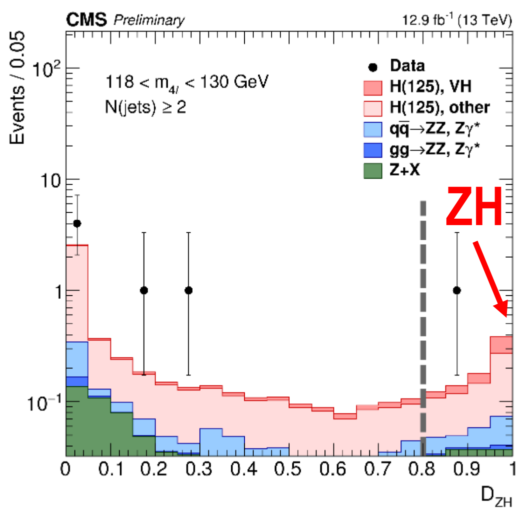
- **MEM weights** used in ttH→multileptons (**see later**) as input to BDT.

- **Matrix Element Likelihood Analysis** (H→ZZ→4l):
  - Simplified MEM. No integration, no transfer function

$$\mathcal{D}_{\rm bkg}^{\rm kin} = \left[1 + \frac{\mathcal{P}_{\rm bkg}^{q\bar{q}}(\vec{\Omega}^{H\to 4\ell}|m_{4\ell})}{\mathcal{P}_{\rm sig}^{gg}(\vec{\Omega}^{H\to 4\ell}|m_{4\ell})}\right]^{-1}$$

  - ME from JHUGen or MCFM
  - Several discriminants (**see later**) built to separate:
    - ❖ gg vs qq→4 leptons
    - ❖ ggH vs VBF or VH or ttH
    - ❖ Different J^{PC} hypothesis, …





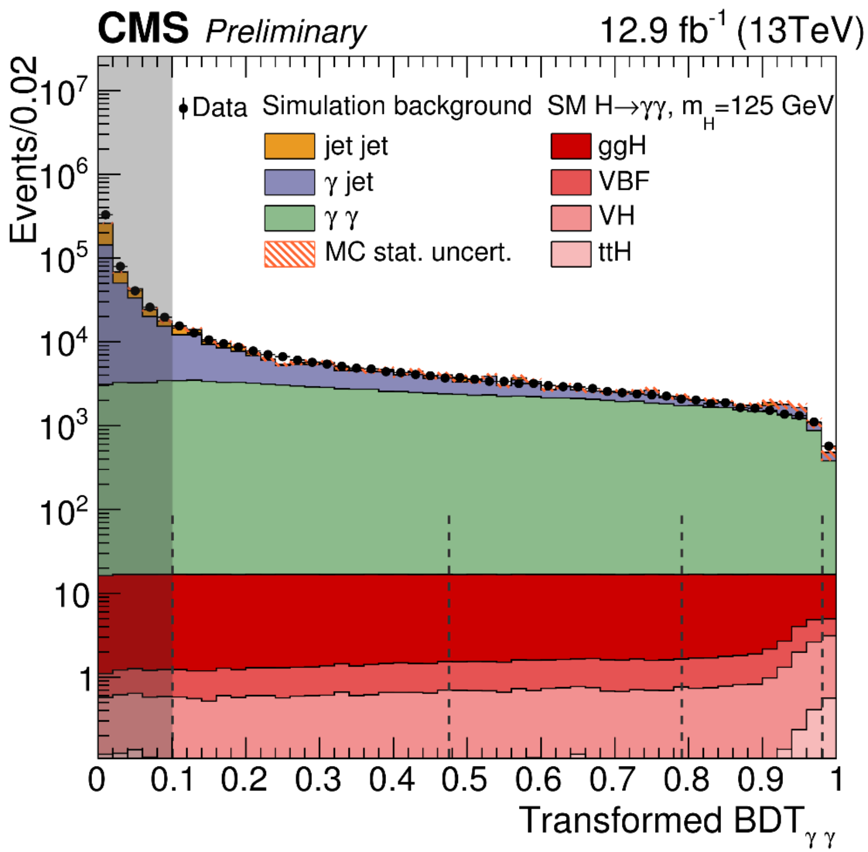
H→γγ overview

HIG-16-020

- 2 high energetic isolated photons ($pT_1>m_{\gamma\gamma}/3$, $pT_2>m_{\gamma\gamma}/4$)
- **Narrow peak** over a large falling background, S/B~(O)%

➢ Analysis Strategy:

- BDTγγ: Separate H→γγ from background
  - use kinematics, mass resolution, γID…
- **Events categorized into 8 exclusive classes:**
  - Optimize S/B, separate production mode
  - ttH-tagged: additional leptons, (b-)jets + cut on BDTγγ
  - VBF: 2 jets, cut on BDTjjγγ (mjj, Δϕ(jj,γγ), …)
  - Untagged: cut on BDTγγ



➢ Signal Extraction:

- Fit of mγγ in each category

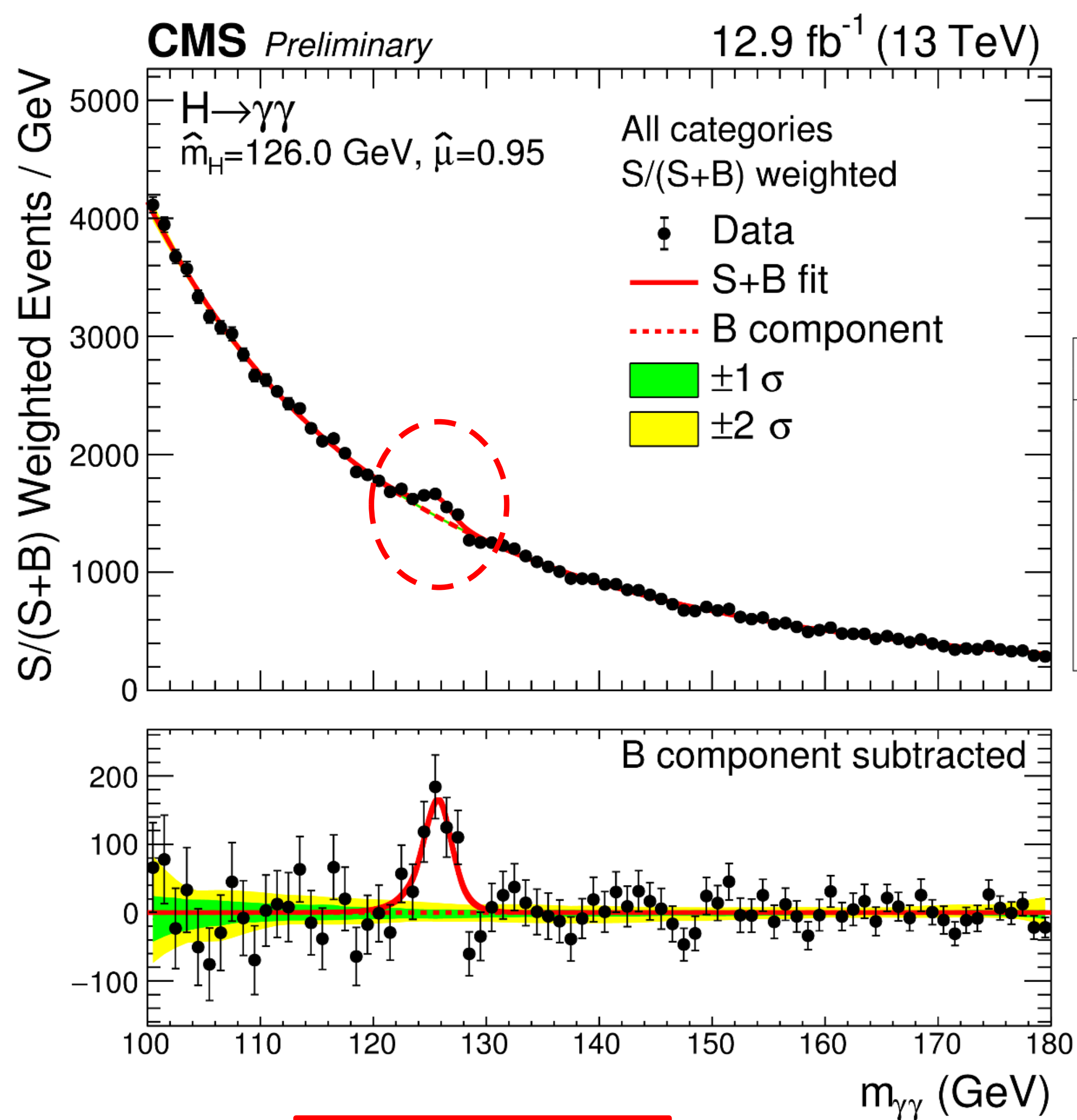
➢ Main Backgrounds:

- Irreducible: prompt di-photons production
- Reducible: γ+jets, QCD multijets

Estimated from DATA
(discrete profiling method)

H→γγ mass spectrum

HIG-16-020



Event Categories	SM 125GeV Higgs boson expected signal								Bkg (GeV^{-1})
	Total	ggh	vbf	wh	zh	tth	σ_{eff}	σ_{HM}	
Untagged Tag 0	11.92	79.10 %	7.60 %	7.11 %	3.59 %	2.60 %	1.18	1.03	4.98
Untagged Tag 1	128.78	85.98 %	7.38 %	3.70 %	2.12 %	0.82 %	1.35	1.20	199.14
Untagged Tag 2	220.12	91.11 %	5.01 %	2.18 %	1.23 %	0.47 %	1.70	1.47	670.44
Untagged Tag 3	258.50	92.35 %	4.23 %	1.89 %	1.06 %	0.47 %	2.44	2.17	1861.23
VBF Tag 0	9.35	29.47 %	69.97 %	0.29 %	0.07 %	0.20 %	1.60	1.33	3.09
VBF Tag 1	15.55	44.91 %	53.50 %	0.86 %	0.38 %	0.35 %	1.71	1.40	22.22
TTH Hadronic Tag	2.42	16.78 %	1.28 %	2.52 %	2.39 %	77.02 %	1.39	1.21	1.12
TTH Leptonic Tag	1.12	1.09 %	0.08 %	2.43 %	1.06 %	95.34 %	1.61	1.35	0.42
Total	647.77	87.93 %	7.29 %	2.40 %	1.35 %	1.03 %	1.88	1.52	2762.65

5.6σ (6.2σ exp.)
@ 125.09 GeV

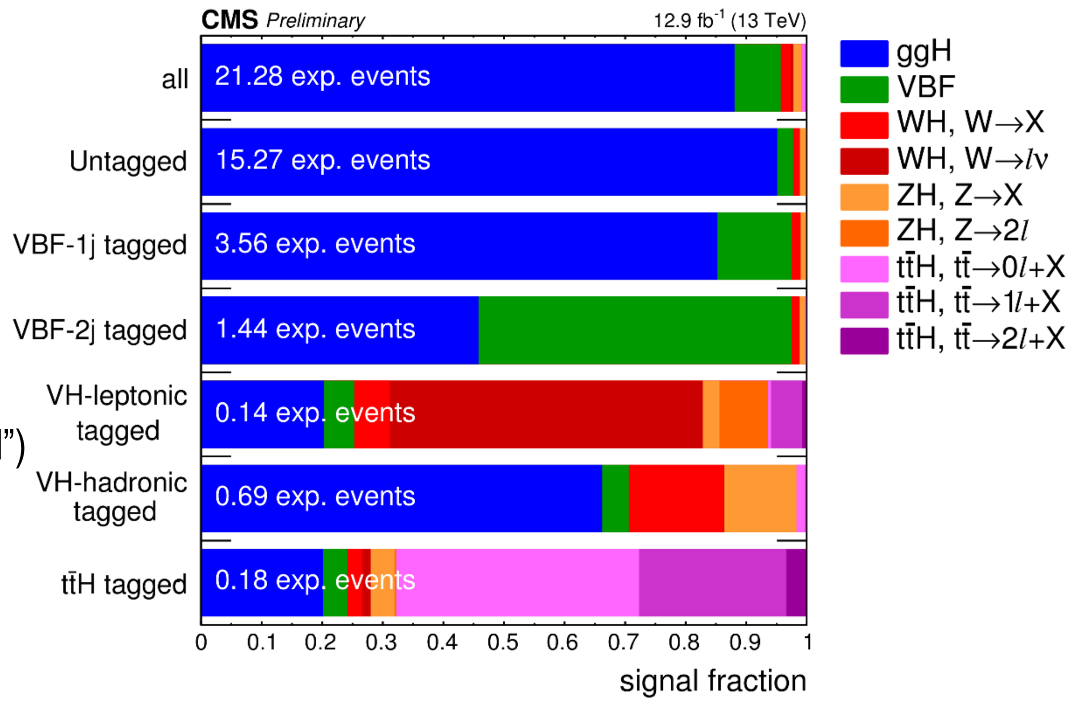
Best fit signal strength @125.09 GeV: $\mu = 0.91 \pm 0.17\ (\text{stat.})\ ^{+0.09}_{-0.07}\ (\text{syst.})\ ^{+0.08}_{-0.05}\ (\text{theo.})$.

H→ZZ(*)→4 leptons: overview

➢ 4 primary isolated leptons (e,μ)
- **Narrow resonance** over ~flat background, S/B ~ 2. Small yields (~6 events / fb)
- **Extremely demanding on selection.**
  - Leptons pT down to 5 (7) GeV for muons (electrons)
  - FSR γ Recovery
  - Open Phase space: 40(12)<mZ1 (mZ2)<120 GeV

Analysis Strategy:

- **Target most production modes (new!)**
- 6 exclusive categories.
  - based on number of (b-)jets, additional leptons
  - + cuts on kinematic discriminants (K_D)
- K_D: Matrix Element based (JHUGen, MCFM).
  Discriminate ggH vs ZZ ("untagged"),
  VBF/VH/ttH vs ggH ("production-mode-tagged")



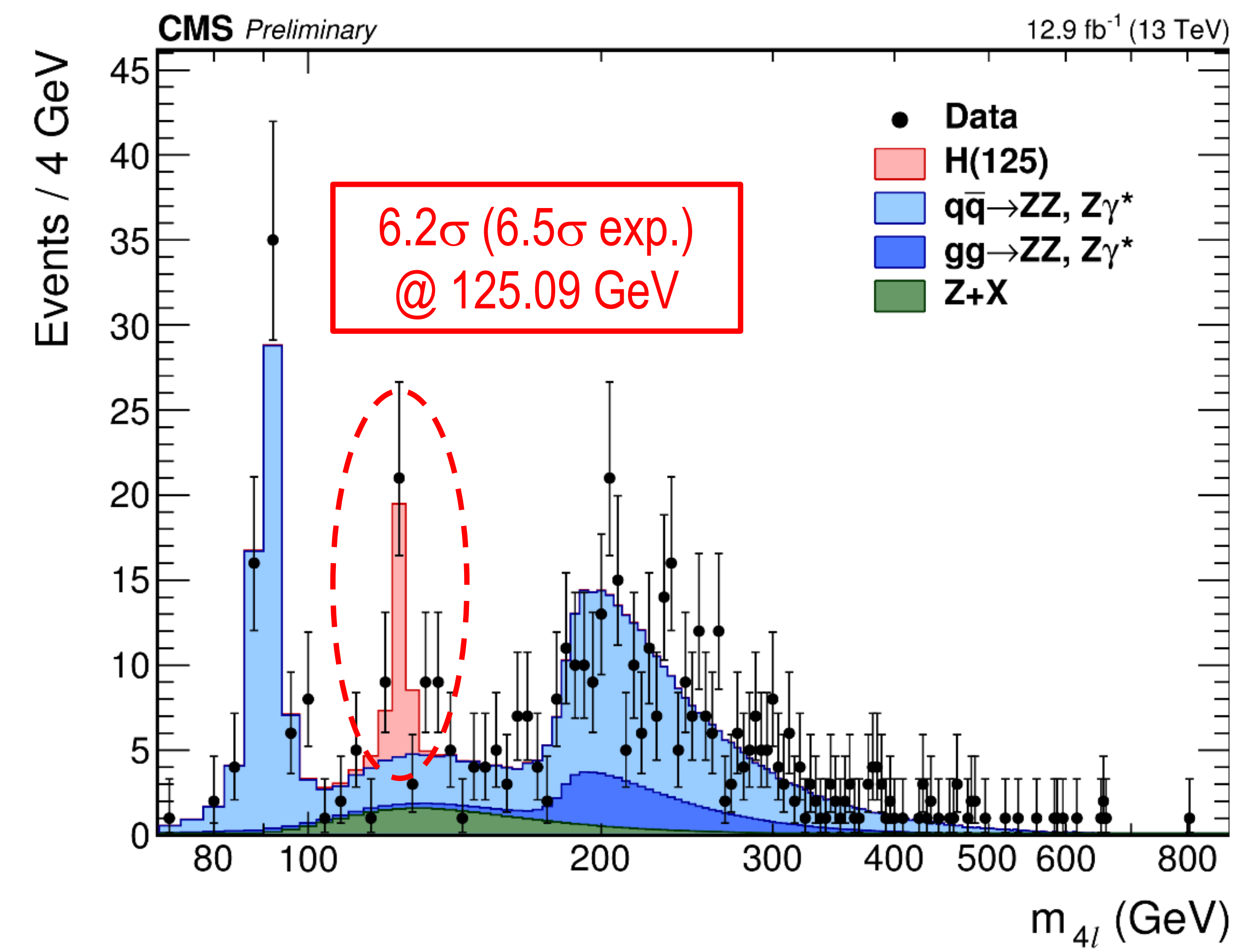
Signal Extraction:

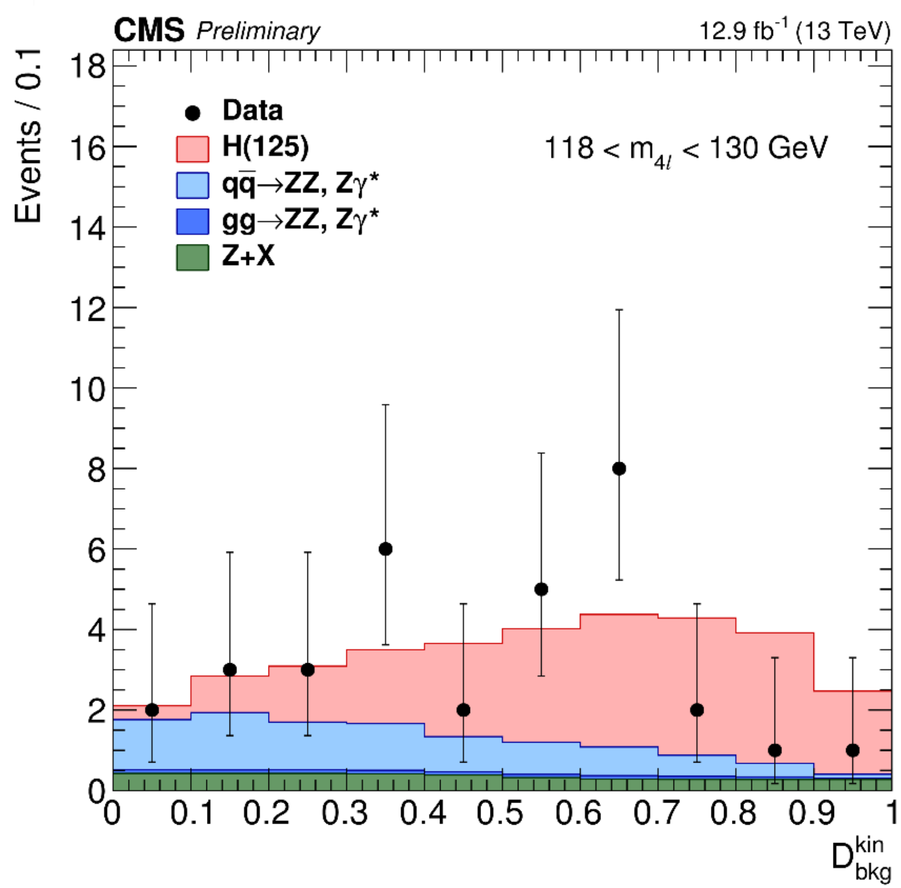
- 2D fit (m4l, K_D) in each category

Main Backgrounds:

- qq→ZZ*, gg→ZZ*: from MC, with mZZ-dependant k-factors
- Fakes from Z+jets,Z+bb, ttbar, … ("Z+X"): from DATA. 2 independent methods.

$H \to ZZ^{(*)} \to 4$ leptons mass spectrum





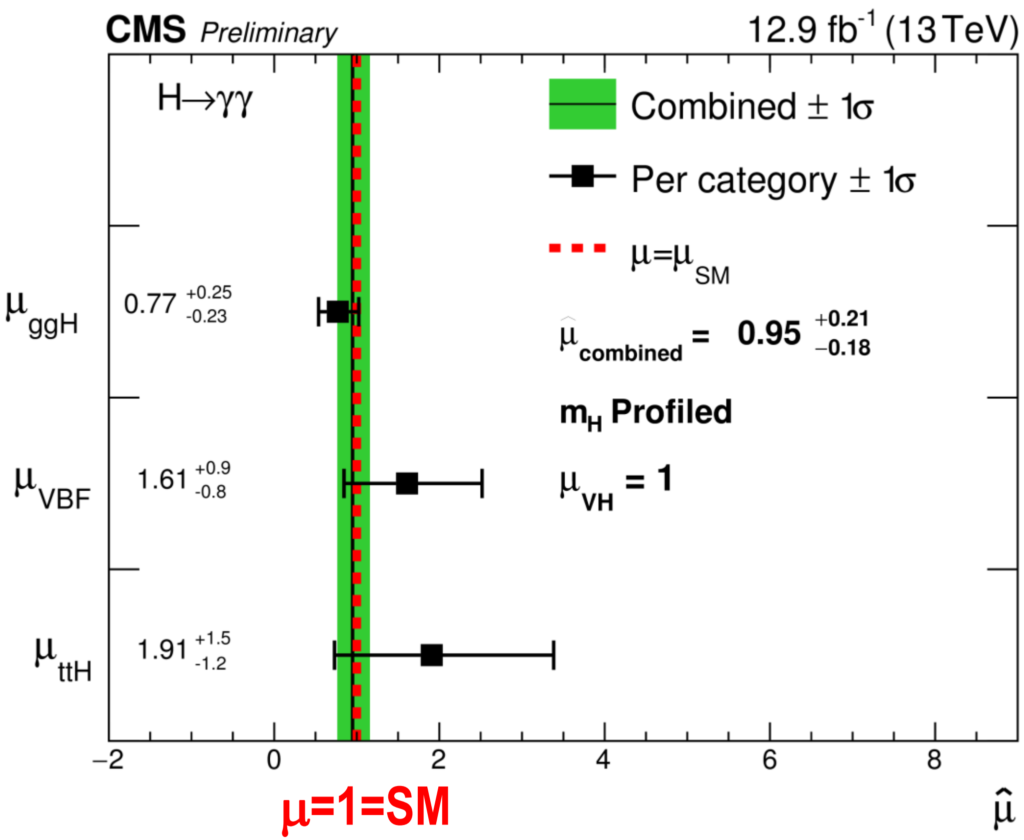
118 <m4l<130 GeV

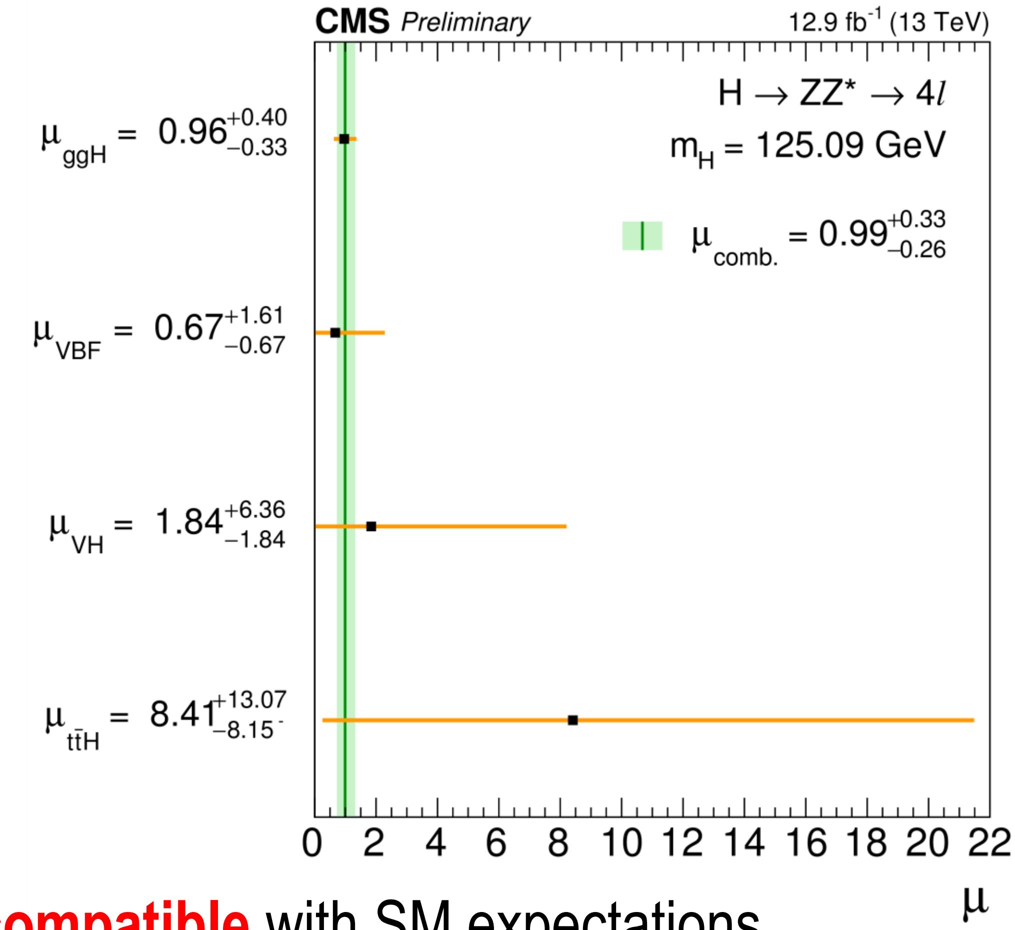
Category	Untagged	VBF-1j	VBF-2j	VH-lept.	VH-hadr.	$t\bar{t}H$	Total
$q\bar{q} \to ZZ$	7.27	0.82	0.06	0.10	0.11	0.01	8.36
$gg \to ZZ$	0.62	0.11	0.01	0.01	0.01	0.00	0.77
Z + X	3.83	0.32	0.24	0.05	0.08	0.10	4.64
Sum of backgrounds	11.73	1.25	0.32	0.16	0.20	0.11	13.77
Signal ($m_H = 125$ GeV)	15.51	3.62	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

Best fit signal strength @125.09 GeV: $\mu = 0.99^{+0.33}_{-0.26}$

HZZ, Hγγ: Production Modes

HIG-16-020, HIG-16-033





Production mechanism signal strength **compatible** with SM expectations

➢ Also, several measurements:

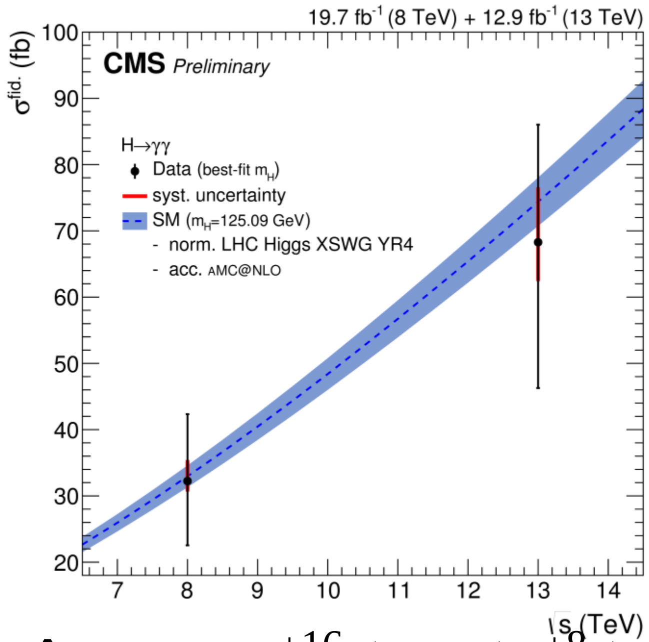
- Mass: $m_{\mathrm{H}} = 124.50^{+0.48}_{-0.46}$ GeV
- Width (from off-shell ZZ): $\Gamma_{\mathrm{H}} < 41$ MeV @ 95% CL
- Anomalous HZZ couplings…
- Fiducial/Differential cross-section (**see next slides**)

with H→ZZ→4l see back-up slides

HZZ, Hγγ: Fiducial / Differential Cross Sections

H→γγ

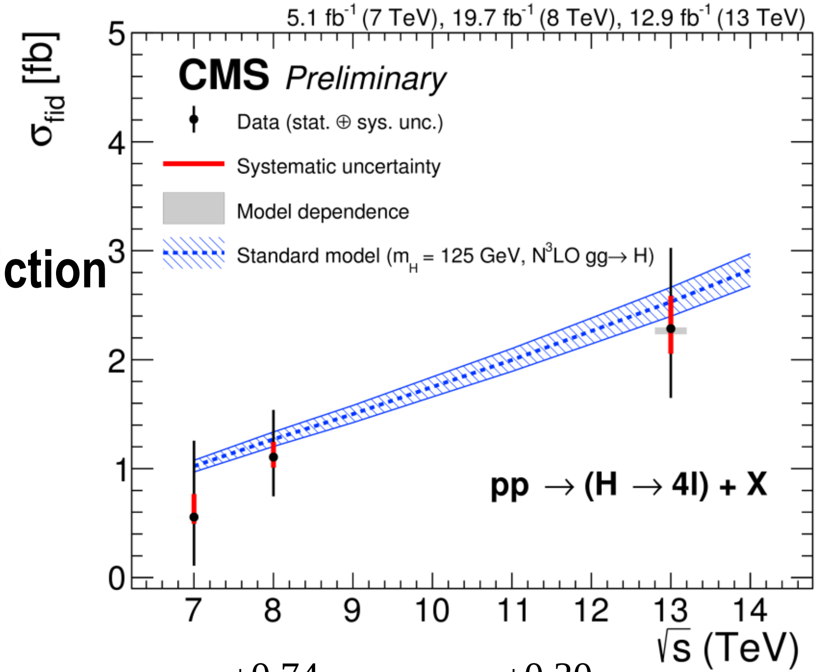
Different categorization (3 based on mass resolution)



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

H→ZZ*→ 4l

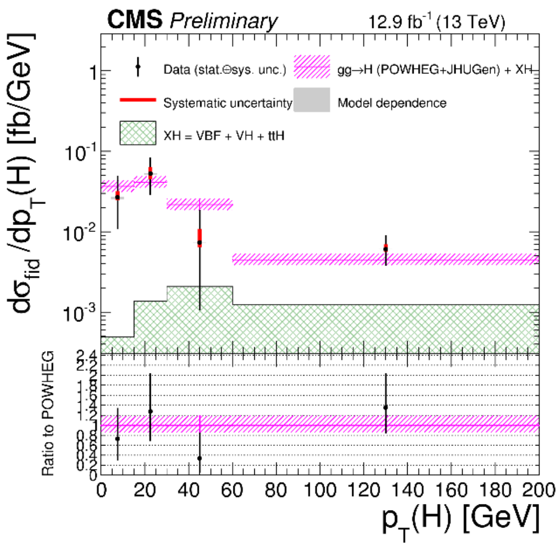
No category. Fiducial volume closely matches reco level.

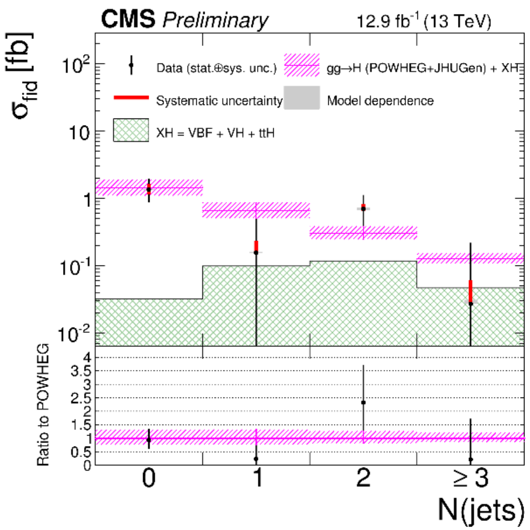


$$\hat{\sigma}_{fid} = 2.29^{+0.74}_{-0.64}\,(\text{stat.})\,^{+0.30}_{-0.23}\,(\text{syst.})\ \text{fb}$$

In agreement with SM prediction (N^{3}LO), 30% precision

- Also, differential measurements:
  - pT(H), N(jets) from H→ZZ

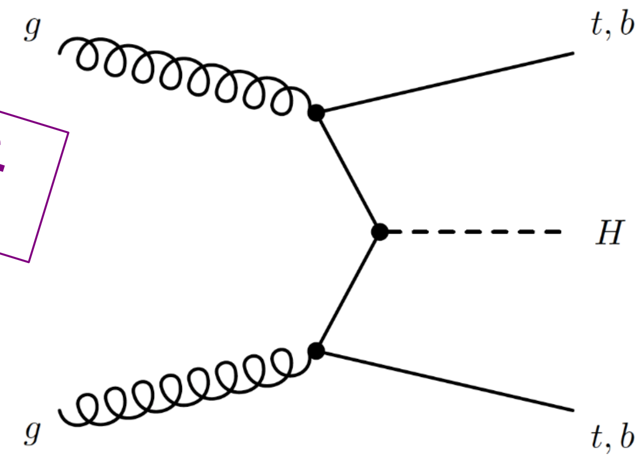




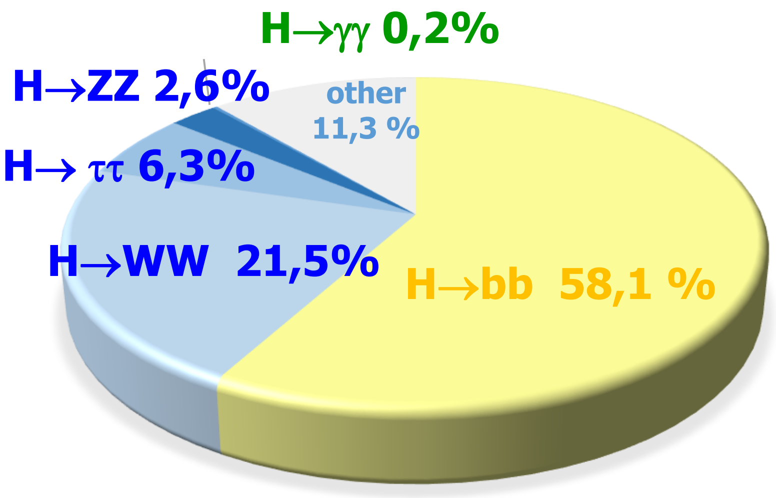
ttH: overview

- **Motivation:**
  - directly probe top Yukawa coupling at tree level, looking at associated production (thus, avoiding assumptions on the loop content in ggH production)

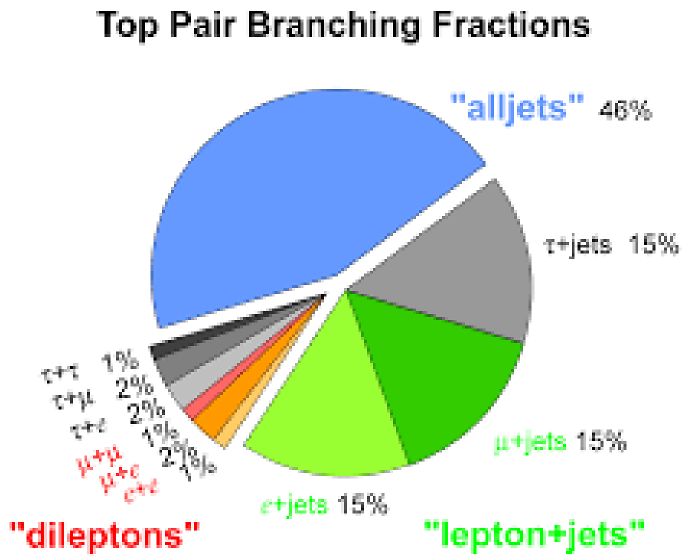
More details in C. Contreras talk



RunII ttH analysis in CMS:
Final states combine Higgs & Top decay



X

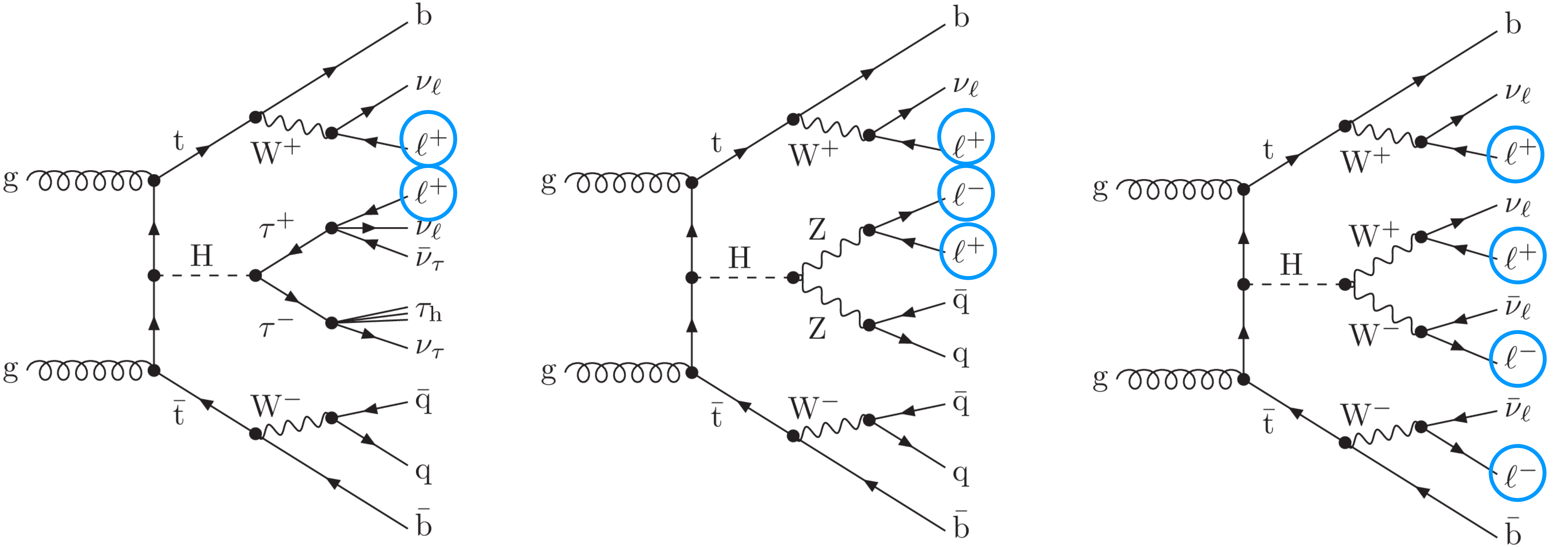


ttH, H→bb (2.7 fb-1)
- with 1 or 2 W→eυ or μυ

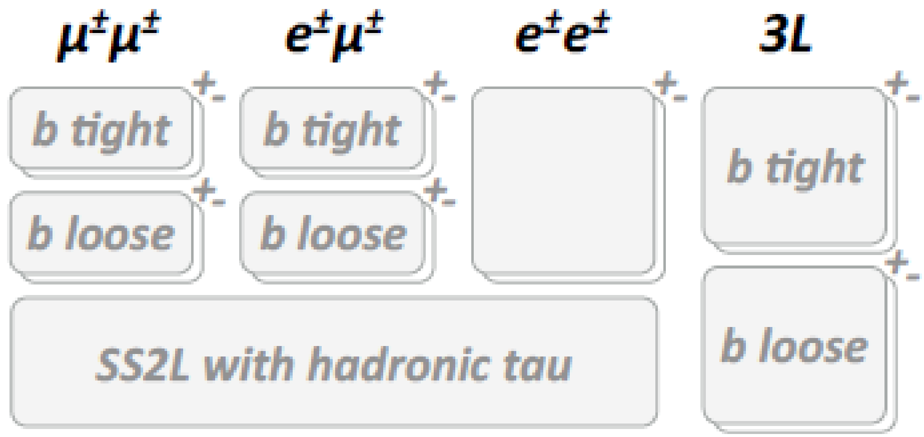
ttH→multileptons (12.9 fb-1)
- Target H→WW, ZZ, ττ + additional leptons from top decay

ttH→γγ (12.9 fb-1)
Included as categories in H→γγ

ttH->multi-leptons (1)



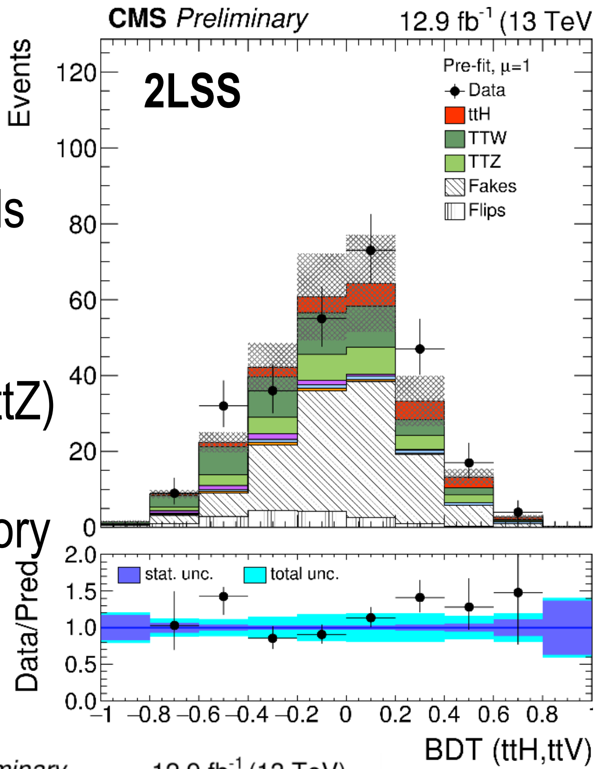
- **Analysis Strategy:**
  - 2 channels:
    - 2 same-sign leptons + 4 jets (**2LSS**)
    - >= 3 leptons (with Z veto) + 2 jets (**3L**)
  - At least 2 loose or 1 medium b-tagged jets
  - Further categories based on lepton flavor, charge, hadronically-decaying taus, …

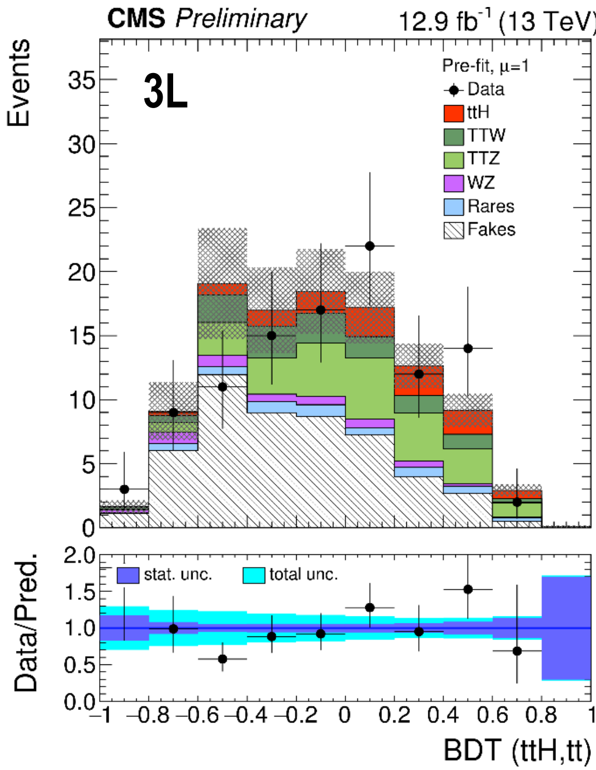


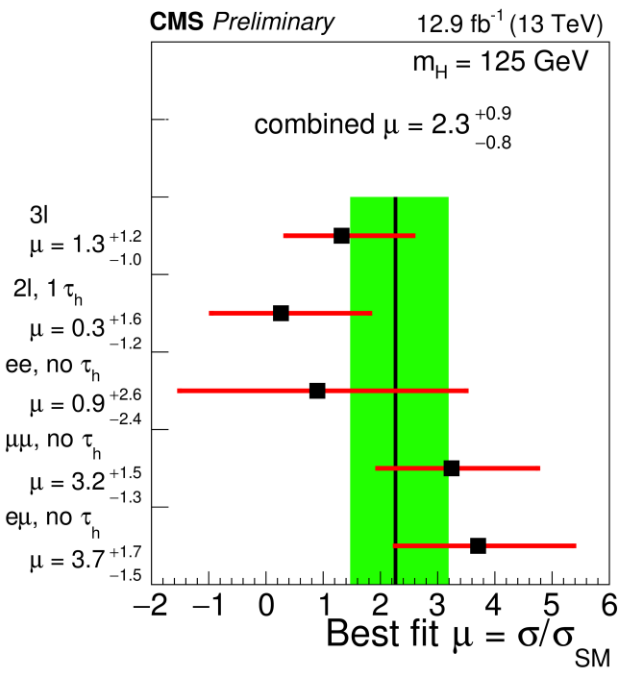
- **Main backgrounds:**
  - **Irreducible:** ttV (from MC), di-boson (validated in data)
  - **Reducible**: non-prompt leptons in tt events and charge mis-ID (from DATA)

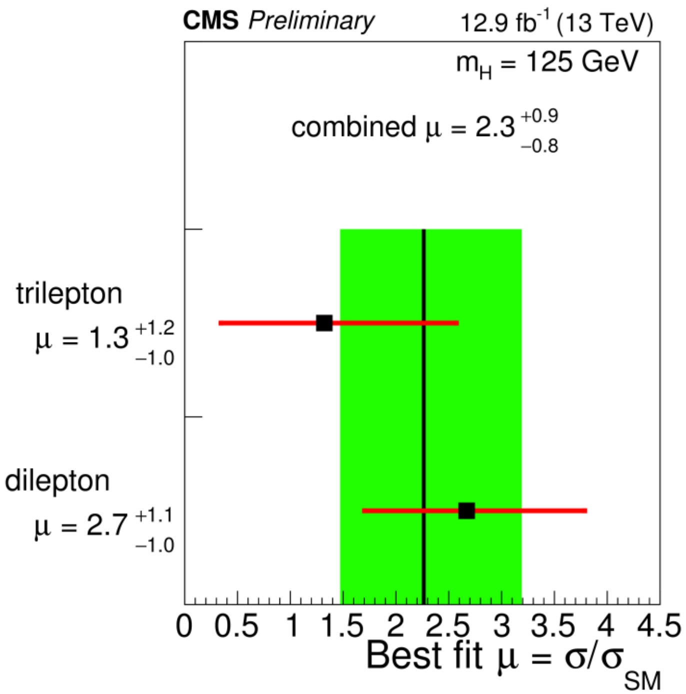
ttH->multi-leptons (2)

- **Signal Extraction:**
  - 2 BDT's: ttH vs tt, ttH vs ttV
  - Trained separately for 2LSS and 3L channels
  - Use topological and kinematic differences between signal and backgrounds
    - + log of MEM weights in 3L (ttH, ttW, ttZ)
  - Simultaneous 2D fits of BDTs in each category









Best fit signal strength @125 GeV:

$$\mu = 2.3^{+0.9}_{-0.8}$$

(μ=1=SM)

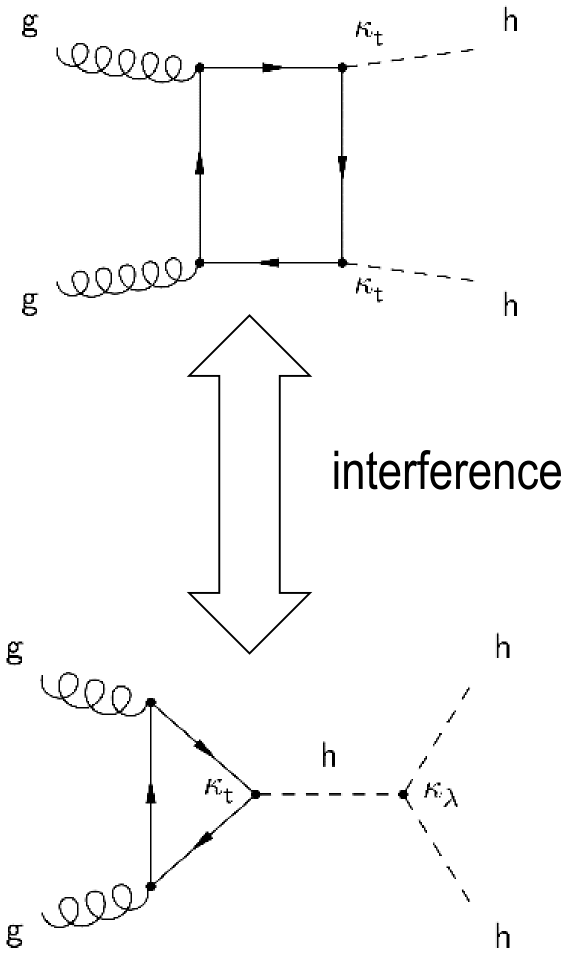
Local p-value: 3.2σ (1.7σ)

(non-resonant) HH: overview

➢ **Motivation:**

- Probe trilinear Higgs couplings (λ_{HHH})
- BSM physics. Modeled in EFT adding 6-dim operators.
    - Described by 6 parameters (non-SM top yukawa and λ_{HHH} couplings, …)

$$\sigma^{SM}_{hh}(13\text{TeV}) = 33.45\text{fb}^{+4.3\%}_{-6.0\%}(\text{scale unc.}) \pm 3.1\%(\text{PDF}+\alpha_S\text{ unc})$$



Run II Analyses in CMS (13 TeV):

➢ **bbbb** (resonant, non-resonant(*)): 2.3 fb-1
- Highest BR, high QCD/tt contamination

➢ **bbWW** (resonant, non-resonant(*)): 2.3 fb-1
- High BR, large irreducible tt background

➢ **bb$\gamma\gamma$** (resonant, non-resonant(*)): 2.7 fb-1
- High purity, very low BR

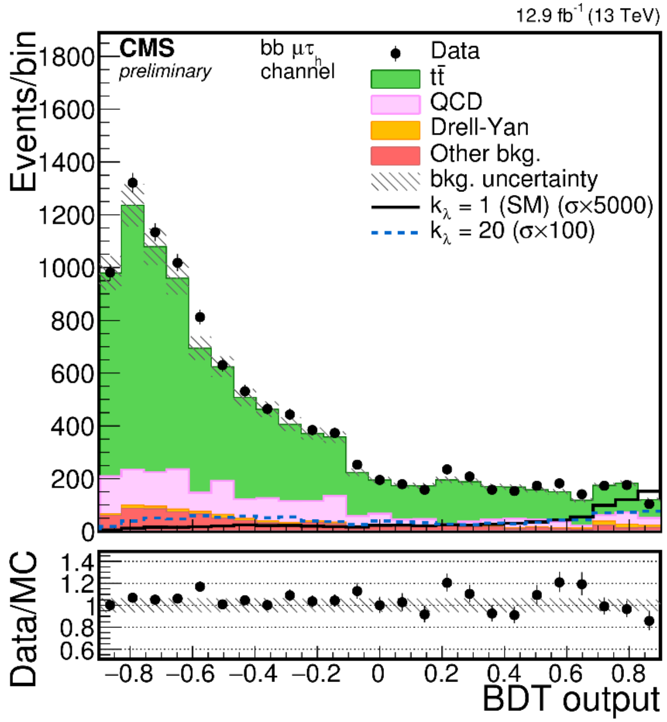
➢ **bb$\tau\tau$ (resonant, non-resonant(*)):** 12.9 fb-1
- Relatively low background and BR. **(see next slide)**

(*) resonant = BSM Analysis where X→HH

(non-resonant) HH→bbττ

➢ Analysis Strategy:

- 1 τ_H + 1 isolated lepton (e, μ, τ_H) + 2 b-jets
- 3 final states: $e\tau_H$, $\mu\tau_H$, $\tau_H\tau_H$
- Cut on BDT discriminant (angular information): reduce ttbar

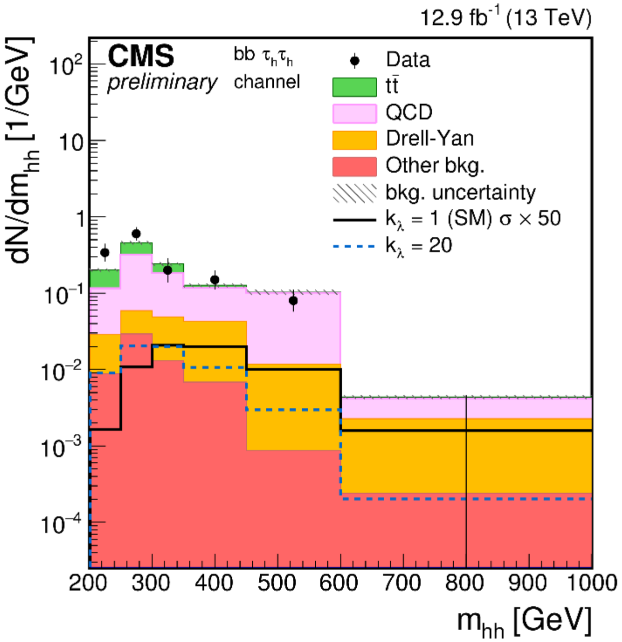


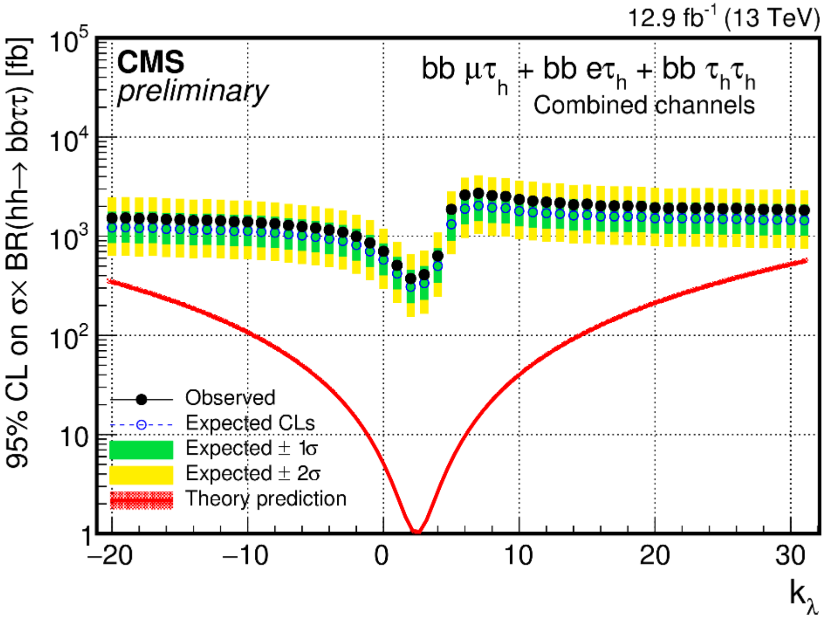
➢ Main Backgrounds:

- ttbar: estimated from MC
- QCD multijet: estimated from DATA in control regions

➢ Signal Extraction:

- Visible mass as final variable



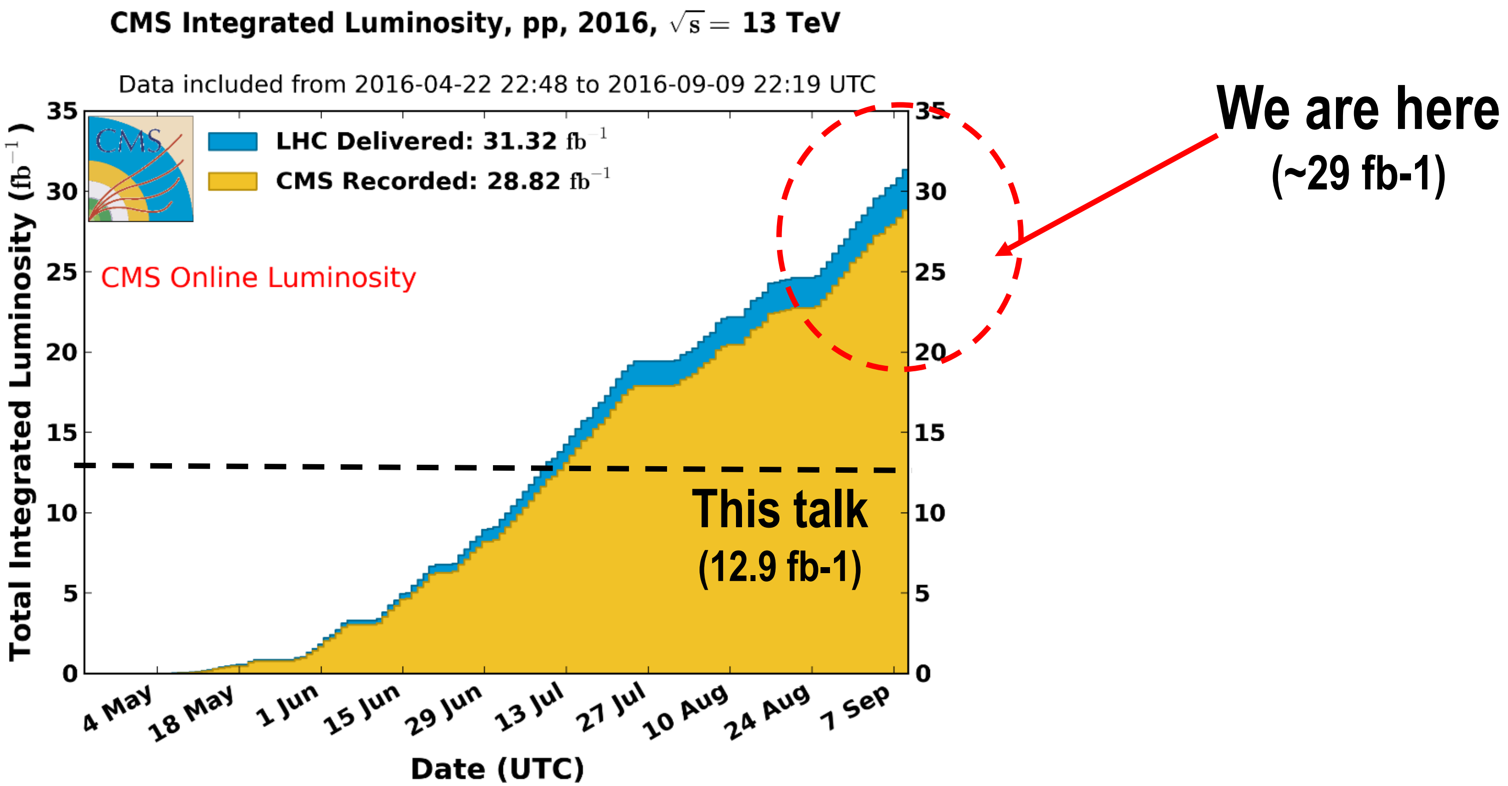


At $k_\lambda = \lambda_{HHH} / \lambda_{SM} = 1$,
95%CL upper limit is:
508 fb (420 fb exp.).
~200xSM (170xSM exp.)

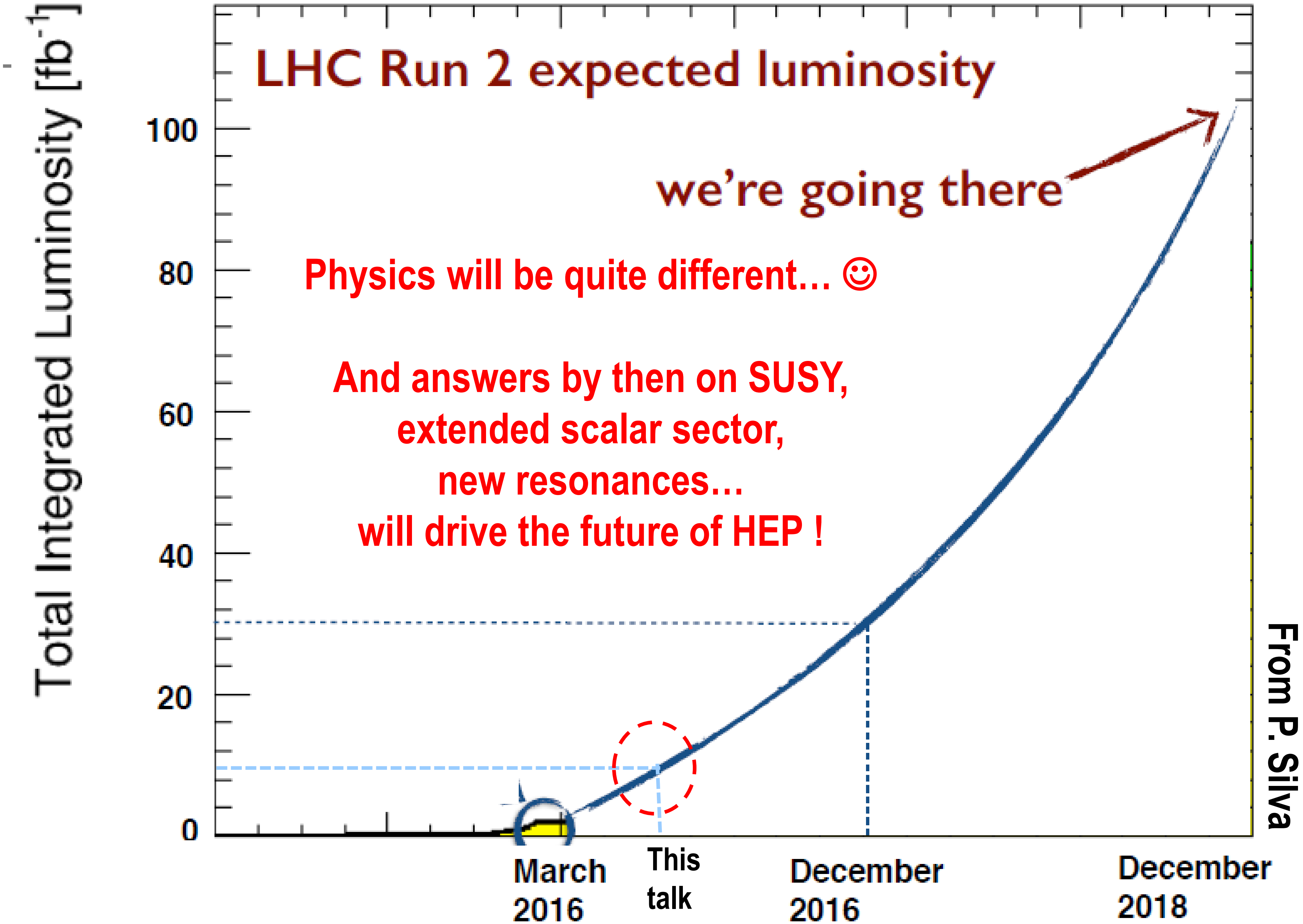
Summary

- **Higgs particle is special in our theory of fundamental interactions**
  - Higgs Mechanism is ad-hoc… but necessary !
  - Possibly at the origin of flavor structure, all SM problems (hierarchy, …),
  - Links to Dark Matter ? Cosmology ?

- **Understanding EWSB & its consequences is the beginning of a long journey…**
  - … with the Run II, we are just scratching the surface.
  - Rich program is ahead of us (precision measurements, rare/forbidden decays, HH, discoveries, …)
  - Many more results to come with 2016 data…
    - In particular, 13 TeV data crucial to understand ttH production



Towards 2018…

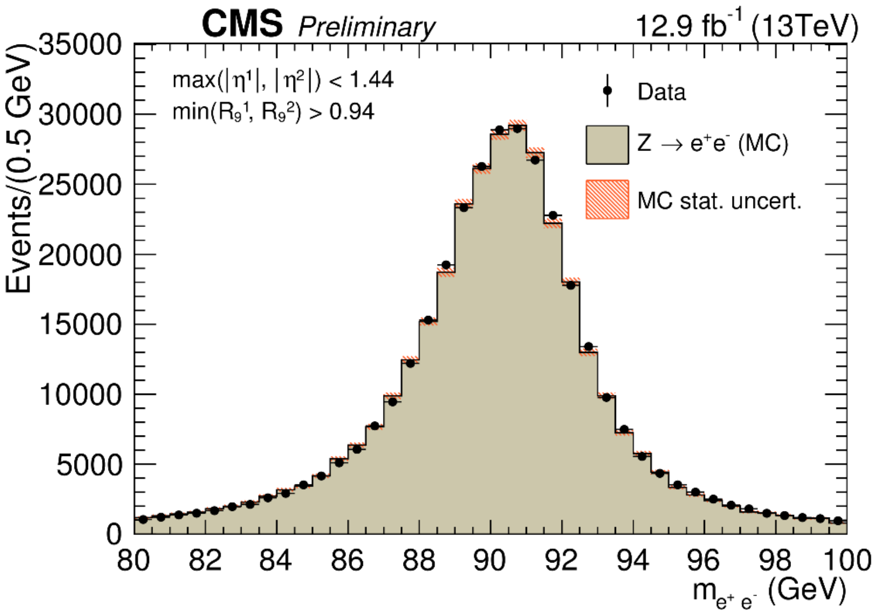


BACK UP SLIDES

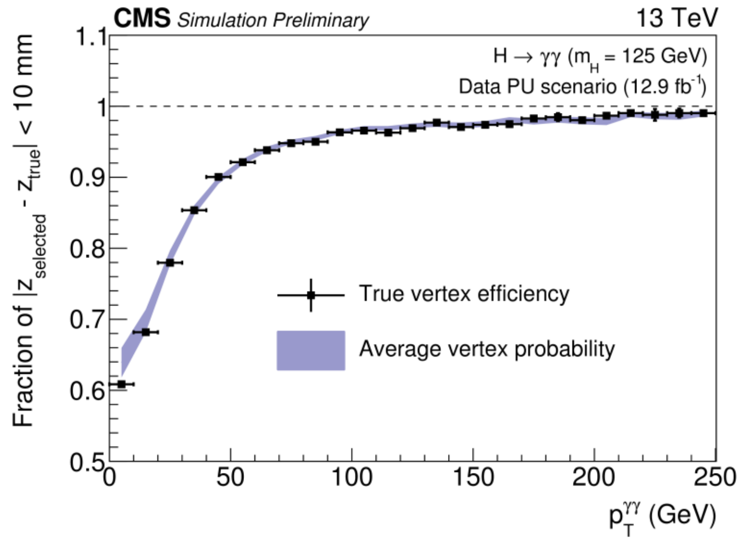
H→γγ mass resolution

$$m\gamma\gamma = \sqrt{2E_1E_2(1-\cos\theta)}$$

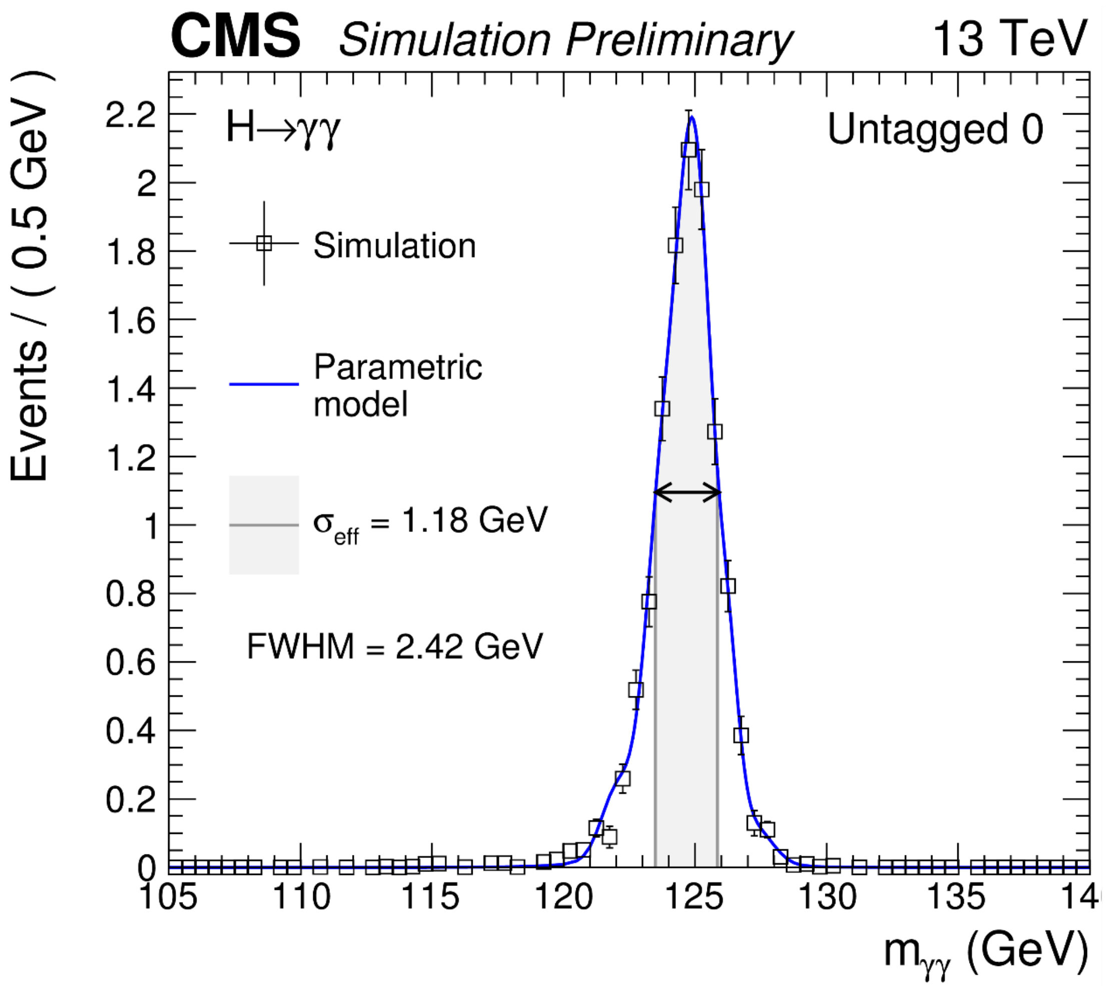
- ECAL response:
  - Corrected for change in time,
  - Inter-calibration (η/φ)
  - Absolute scale
- Scale vs time and resolution calibration:
  - Z→ee peak as reference

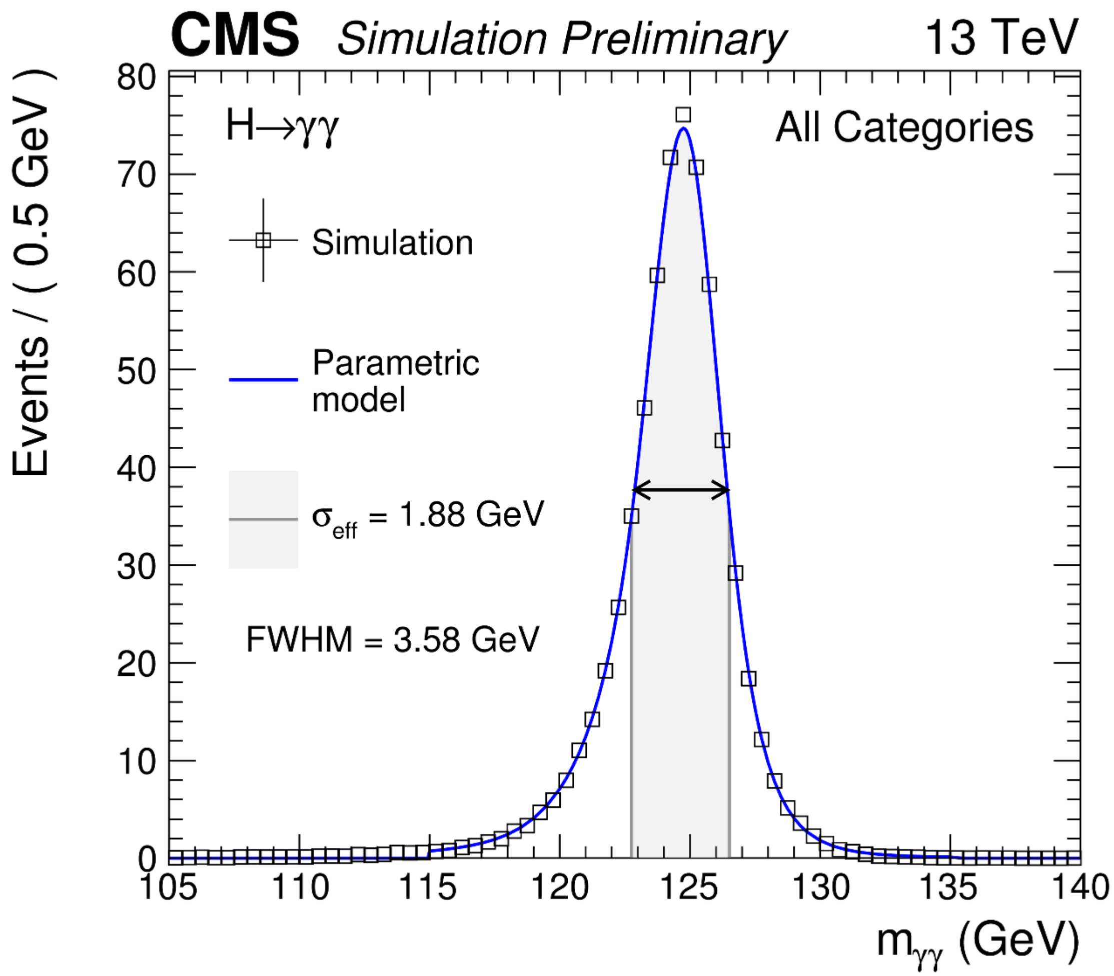


- Vertex assignment correct within 1cm →**negligible impact** on mass resolution
- MVA for VertexID
  - Kinematic correlations and track distribution imbalance
  - Direction of conversion tracks (if present)
- Second MVA: probability of correct vertex choice (used in BDTγγ)
- Validated with Z→μμ events



H→γγ mass resolution





σ_{eff} = 1.18 GeV in best category

(was 1.05 GeV at 8 TeV+ FWHM=1.86 GeV. But with final calibration/alignment!

https://twiki.cern.ch/twiki/bin/view/CMSPublic/Hig13001PubTWiki#8_TeV_dataset

$H \to \gamma\gamma$: Systematic uncertainties

➢ Experimental Uncertainties:

Luminosity	6.2%
Trigger efficiency	<0.1%
Photon pre-selection	0.1%-2.3% (depending on γ cat.) Up to 4% (depending on event cat.)
Vertex Finding efficiency	1.5%
Energy Scale and resolution	0.15-0.5% (dep. On γ cat.). Effect of 6% in signal strength
Non-uniformity of light collection	0.07% on γ energy scale
GEANT4	0.05% on γ energy scale
Material budget	0.17% on γ energy scale
Shower shape correction	0.064% on γ energy scale
Jet energy scale and resolution	JES:4-15% migrations within VBF cat., same between VBF and untagged, 5% in ttH cat. JER: <2% for all migrations
B-tag efficiency	2% in lepton-tagged cat., 5% in hadronic-tagged cat.
LeptonID	<1% in ttH cat.

Also: BDT ID, per-photon resolution estimate

➢ Theory Uncertainties:

PDF	< 2%
αS	3.7%
Underlying Event Parton Shower	Inside VBF: 7% VBF->other: 9%
QCD scale	5-10 %
BR ($H \to \gamma\gamma$)	2.08%
ggH contamination in VBF	Norm. 39% migration: 10%
ggH contamination in ttH	10% stat PS modeling: up to 45% Gluon splitting:18%

H→ZZ*→4 leptons: Categories

6 mutually exclusive categories,
defined applying following criteria in this exact order:

1. exactly 4 leptons + {2-3 jets with ≤1 b-tag or ≥4 jets with 0 b-tag} + high D_{2jet} value ➔ **VBF-2jet tagged category**

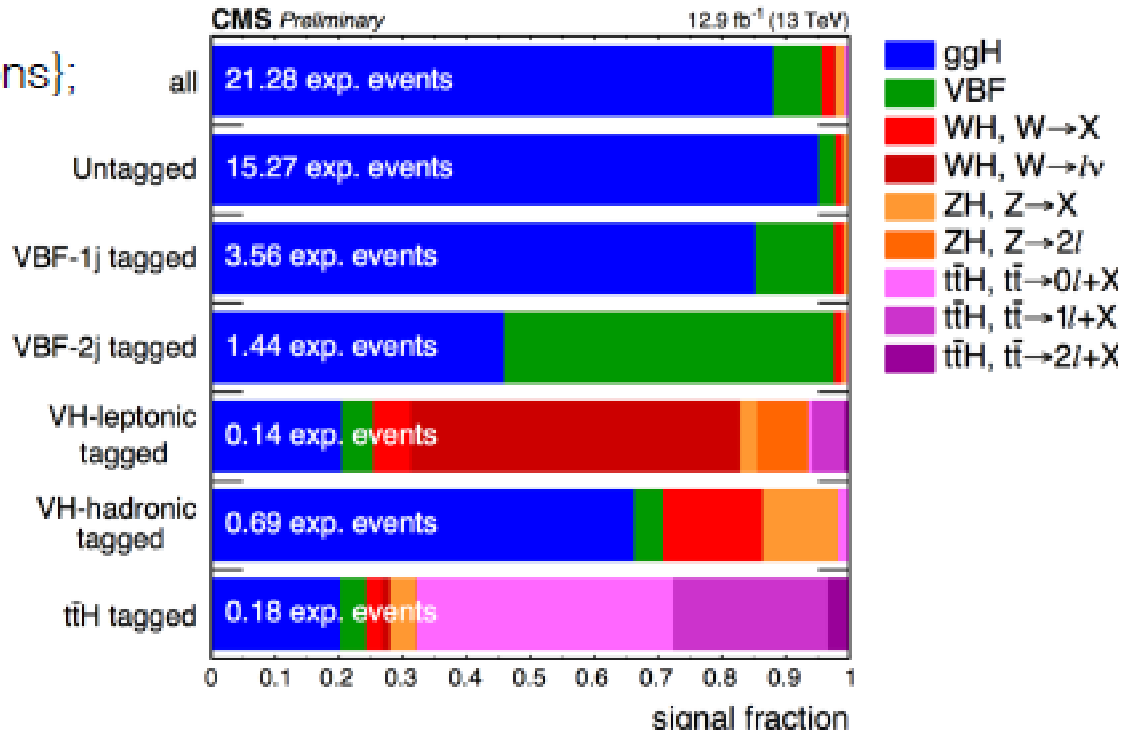
2. exactly ≥4 leptons + {2-3 jets with ≤1 b-tag or 4 jets with 0 b-tag} + high D_{WH} or D_{ZH} value;
   or 2-3 jets + 2 b-tags
   ➔ **VH-hadronic tagged category**

3. ≤3 jets + 0 b-tag + {exactly 5 leptons or ≥1 pair of additional opposite-sign leptons};
   or 0 jet + ≥5 leptons
   ➔ **VH-leptonic tagged category**

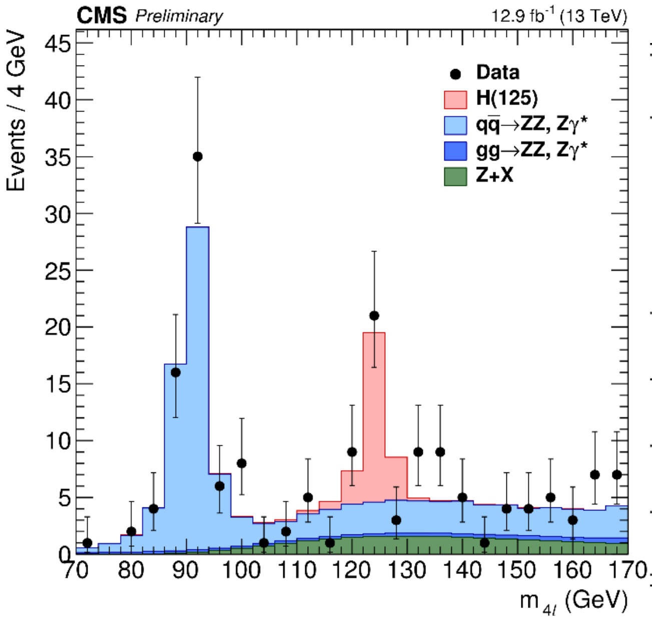
4. ≥4 jets + ≥1 b-tag;
   or ≥5 leptons ➔ **ttH tagged category**

5. exactly 4 leptons + exactly 1 jet + high D_{1jet} value
   ➔ **VBF-1jet tagged category**

6. other events ➔ **untagged category**

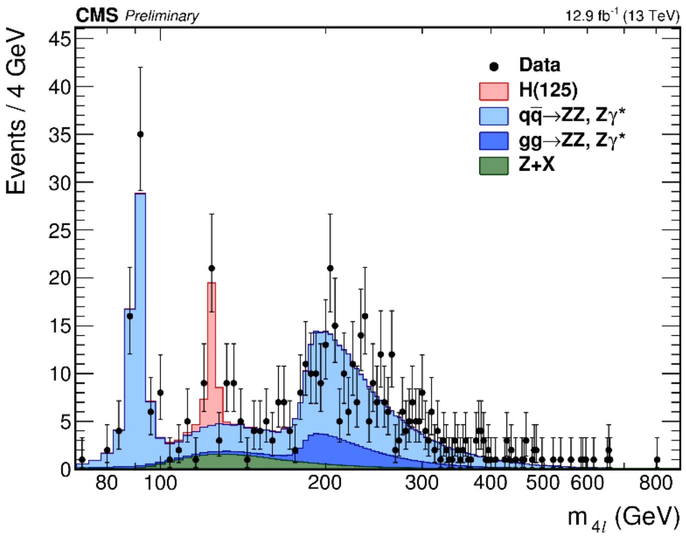


$H \to ZZ^* \to 4$ leptons: yields



118<m4l<130 GeV

Channel	4e	4μ	$2e2\mu$	4ℓ
$q\bar{q} \to ZZ$	$1.37^{+0.16}_{-0.15}$	$3.09^{+0.27}_{-0.27}$	$3.90^{+0.46}_{-0.43}$	$8.36^{+0.81}_{-0.79}$
$gg \to ZZ$	$0.16^{+0.03}_{-0.03}$	$0.32^{+0.05}_{-0.05}$	$0.30^{+0.05}_{-0.05}$	$0.77^{+0.12}_{-0.12}$
Z + X	$0.90^{+0.38}_{-0.37}$	$1.40^{+0.52}_{-0.51}$	$2.34^{+0.91}_{-0.89}$	$4.64^{+1.11}_{-1.09}$
Sum of backgrounds	$2.42^{+0.42}_{-0.40}$	$4.81^{+0.59}_{-0.59}$	$6.54^{+1.03}_{-1.00}$	$13.77^{+1.41}_{-1.38}$
Signal ($m_H = 125$ GeV)	$3.90^{+0.53}_{-0.54}$	$7.92^{+0.88}_{-0.93}$	$9.80^{+1.34}_{-1.36}$	$21.61^{+2.63}_{-2.71}$
Total expected	$6.32^{+0.78}_{-0.76}$	$12.73^{+1.21}_{-1.24}$	$16.34^{+1.92}_{-1.90}$	$35.38^{+3.43}_{-3.45}$
Observed	5	12	16	33



m4l>70 GeV

Channel	4e	4μ	$2e2\mu$	4ℓ
$q\bar{q} \to ZZ$	$71.3^{+8.4}_{-8.0}$	$132.6^{+11.6}_{-11.6}$	$173.3^{+20.6}_{-19.3}$	$377.2^{+36.6}_{-35.7}$
$gg \to ZZ$	$14.8^{+2.6}_{-2.5}$	$25.3^{+3.9}_{-3.9}$	$36.8^{+6.5}_{-6.5}$	$76.9^{+12.6}_{-12.6}$
Z + X	$9.8^{+4.2}_{-4.0}$	$10.2^{+3.8}_{-3.8}$	$20.4^{+7.9}_{-7.7}$	$40.4^{+9.7}_{-9.5}$
Sum of backgrounds	$95.9^{+10.9}_{-10.4}$	$168.0^{+14.1}_{-14.0}$	$230.5^{+25.5}_{-24.2}$	$494.4^{+44.6}_{-43.3}$
Signal ($m_H = 125$ GeV)	$4.6^{+0.6}_{-0.6}$	$8.7^{+1.0}_{-1.0}$	$11.2^{+1.5}_{-1.5}$	$24.5^{+2.9}_{-3.0}$
Total expected	$100.5^{+11.4}_{-10.8}$	$176.7^{+14.8}_{-14.7}$	$241.7^{+26.6}_{-25.2}$	$518.9^{+46.6}_{-45.3}$
Observed	111	178	244	533

H→ZZ →4l: Background Control

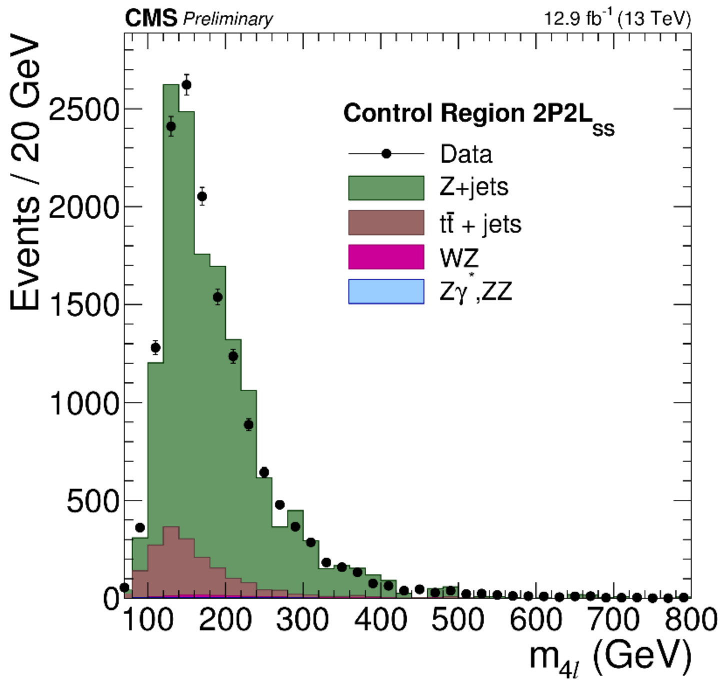
- **qq/gg→ZZ**: from MC (POWHEG & MCFM)

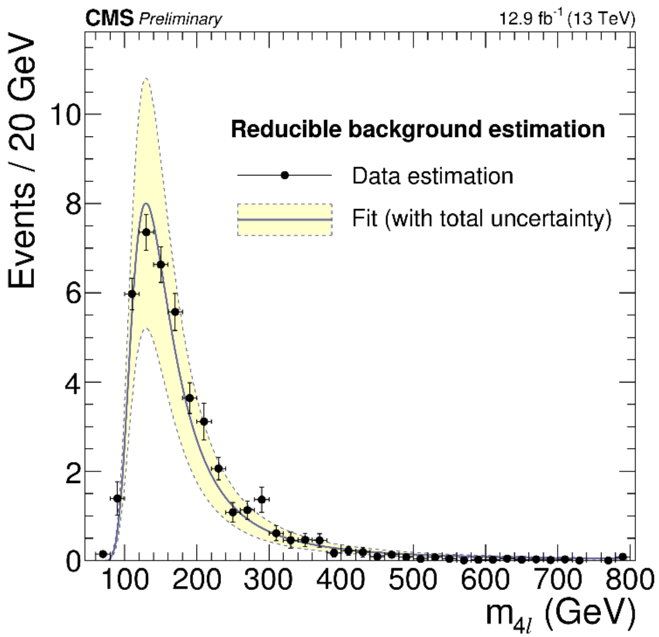
- **Reducible (Z+jets, tt, WZ,…):** from DATA.
- 2 "fake rate" methods:

- **Method A:**
  - Control Regions:
    - Z1+2 OS-SF "failing" leptons (2P2F, 2 "prompt" + 2 failed")
    - 3 prompt + 1 failing leptons (3P+1F):
      - target estimation of background WZ, $Z\gamma^*$, …
  - Extrapolation to signal region: lepton mis-identified probability

- **Method AA:**
  - Control Region (CR):
    - Z1+ 2 SS-SF "loose" leptons
  - Extrapolation to signal region:
    - SS/OS factor from MC, cross-checked with data
    - lepton mis-identified probability (corrected for difference in composition of converted photon between CR & sample to extract misID probability)

- **Final estimate:** combination of the two methods (yields&shapes) (yields in control regions & part of the uncertainties un-correlated)

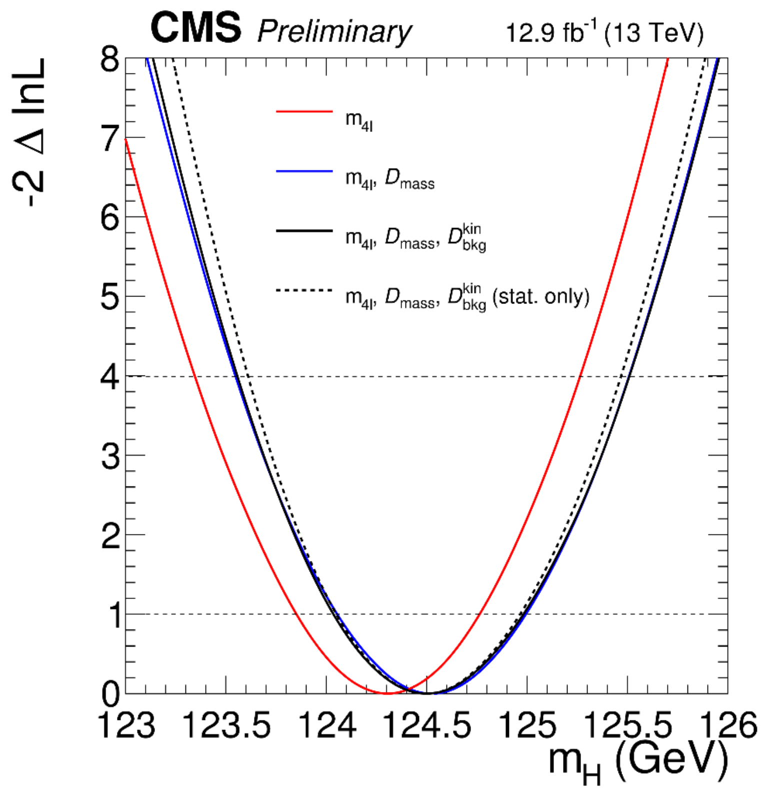




$H \to ZZ \to 4l$: systematic uncertainties

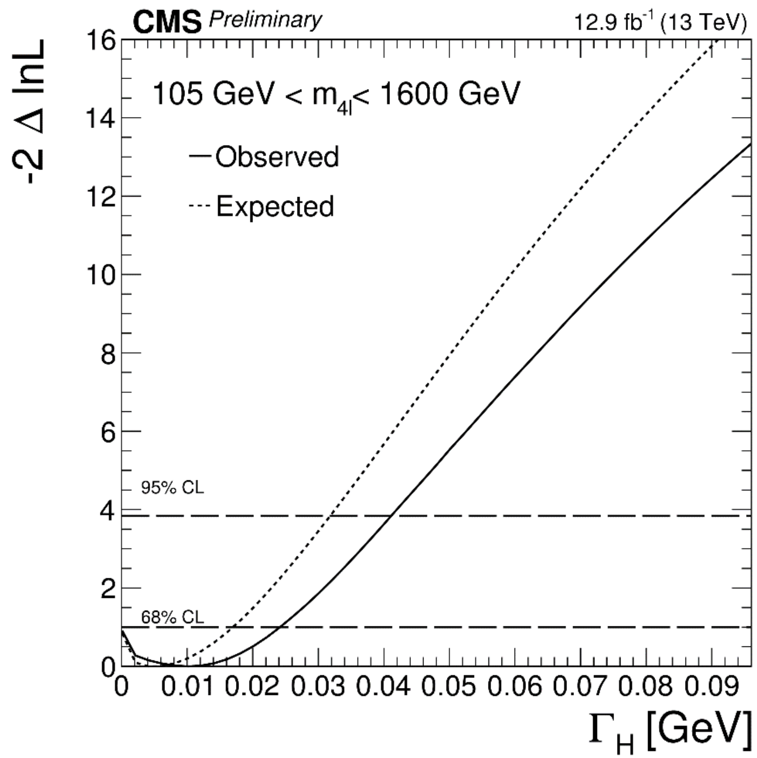
Summary of relative systematic uncertainties	
Common experimental uncertainties	
Luminosity	6.2 %
Lepton identification/reconstruction efficiencies	6 – 11 %
Background related uncertainties	
QCD scale ($q\bar{q} \to ZZ$, $gg \to ZZ$)	3 – 10 %
PDF set ($q\bar{q} \to ZZ$, $gg \to ZZ$)	3 – 5 %
Electroweak corrections ($q\bar{q} \to ZZ$)	1 – 15 %
$gg \to ZZ$ K factor	10 %
Reducible background (Z+X)	40 – 55 %
Event categorization (experimental)	2 – 18 %
Event categorization (theoretical)	3 – 20 %
Signal related uncertainties	
QCD scale ($q\bar{q} \to$ VBF/VH, $gg \to$ H/$t\bar{t}$H)	3 – 10 %
PDF set ($q\bar{q} \to$ VBF/VH, $gg \to$ H/$t\bar{t}$H)	3 – 4 %
BR($H \to ZZ \to 4\ell$)	2 %
Lepton energy scale	0.04 – 0.3 %
Lepton energy resolution	20 %
Event categorization (experimental)	2 – 15 %
Event categorization (theoretical)	8 – 20 %

H→ZZ →4l: Mass & Width



Channel	1D: $\mathcal{L}(m_{4l})$ (GeV)	2D: $\mathcal{L}(m_{4l}, \mathcal{D}_{\text{mass}})$ (GeV)	3D: $\mathcal{L}(m_{4l}, \mathcal{D}_{\text{mass}}, \mathcal{D}^{\text{kin}}_{\text{bkg}})$ (GeV)
4ℓ	$124.31^{+0.46}_{-0.45}$	$124.52^{+0.47}_{-0.47}$	$124.50^{+0.47}_{-0.45}(\text{stat.})^{+0.13}_{-0.11}(\text{sys.})$

Parameter	$m_{4\ell}$ range	Observed	Expected
Γ_H (GeV)	$[100, 1600]$	$0.010^{+0.014}_{-0.010}$ $[0.000, 0.041]$	$0.004^{+0.013}_{-0.004}$ $[0.000, 0.032]$
Γ_H (GeV)	$[105, 140]$	$0.3^{+1.4}_{-0.0}$ $[0.0, 3.9]$	$0.0^{+1.1}_{-0.0}$ $[0.0, 2.7]$

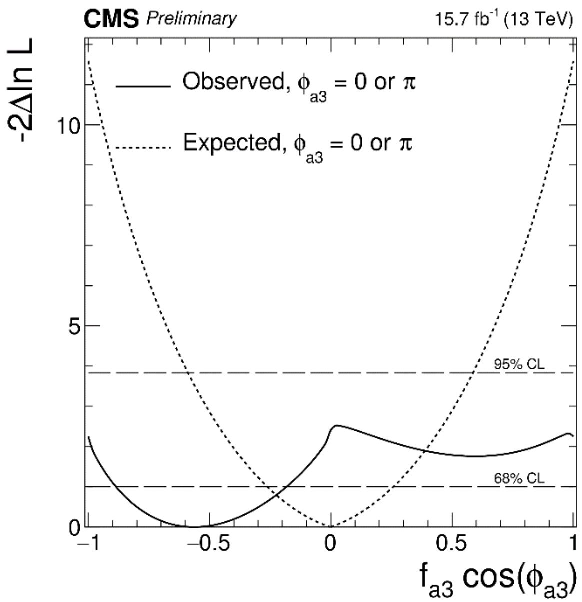


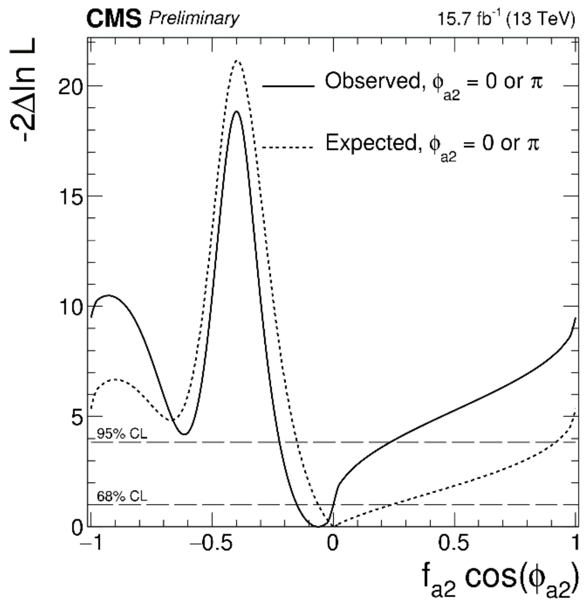
H→ZZ →4l: Anomalous couplings

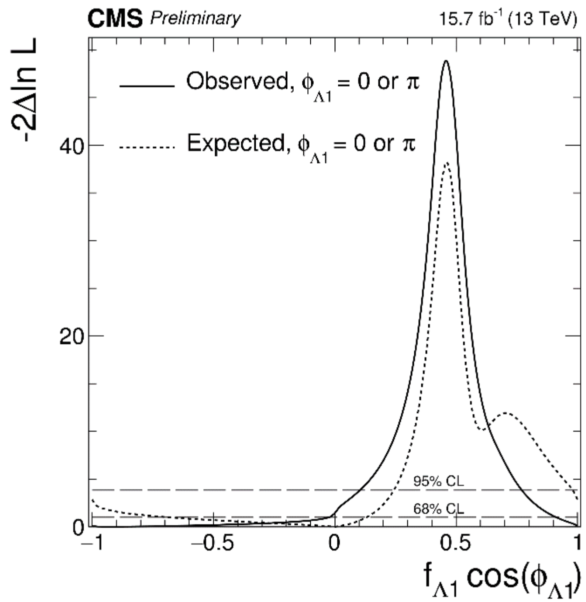
$$f_{a3} = \frac{|a_3|^2\sigma_3}{|a_1|^2\sigma_1 + |a_2|^2\sigma_2 + |a_3|^2\sigma_3 + \tilde{\sigma}_{\Lambda1}/\left(\Lambda_1\right)^4 + \ldots}, \qquad \phi_{a3} = \arg\left(\frac{a_3}{a_1}\right),$$

$$f_{a2} = \frac{|a_2|^2\sigma_2}{|a_1|^2\sigma_1 + |a_2|^2\sigma_2 + |a_3|^2\sigma_3 + \tilde{\sigma}_{\Lambda1}/\left(\Lambda_1\right)^4 + \ldots}, \qquad \phi_{a2} = \arg\left(\frac{a_2}{a_1}\right),$$

$$f_{\Lambda1} = \frac{\tilde{\sigma}_{\Lambda1}/\left(\Lambda_1\right)^4}{|a_1|^2\sigma_1 + |a_2|^2\sigma_2 + |a_3|^2\sigma_3 + \tilde{\sigma}_{\Lambda1}/\left(\Lambda_1\right)^4 + \ldots}, \qquad \phi_{\Lambda1},$$

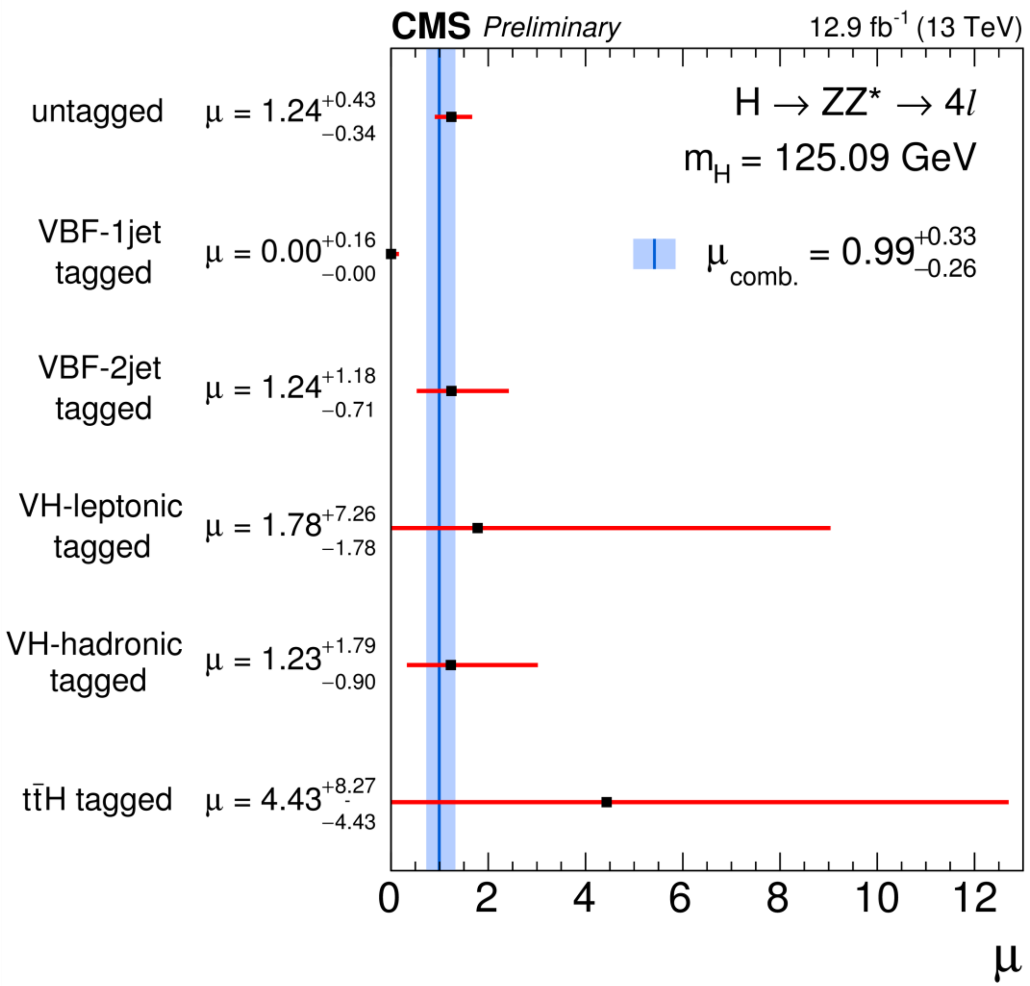


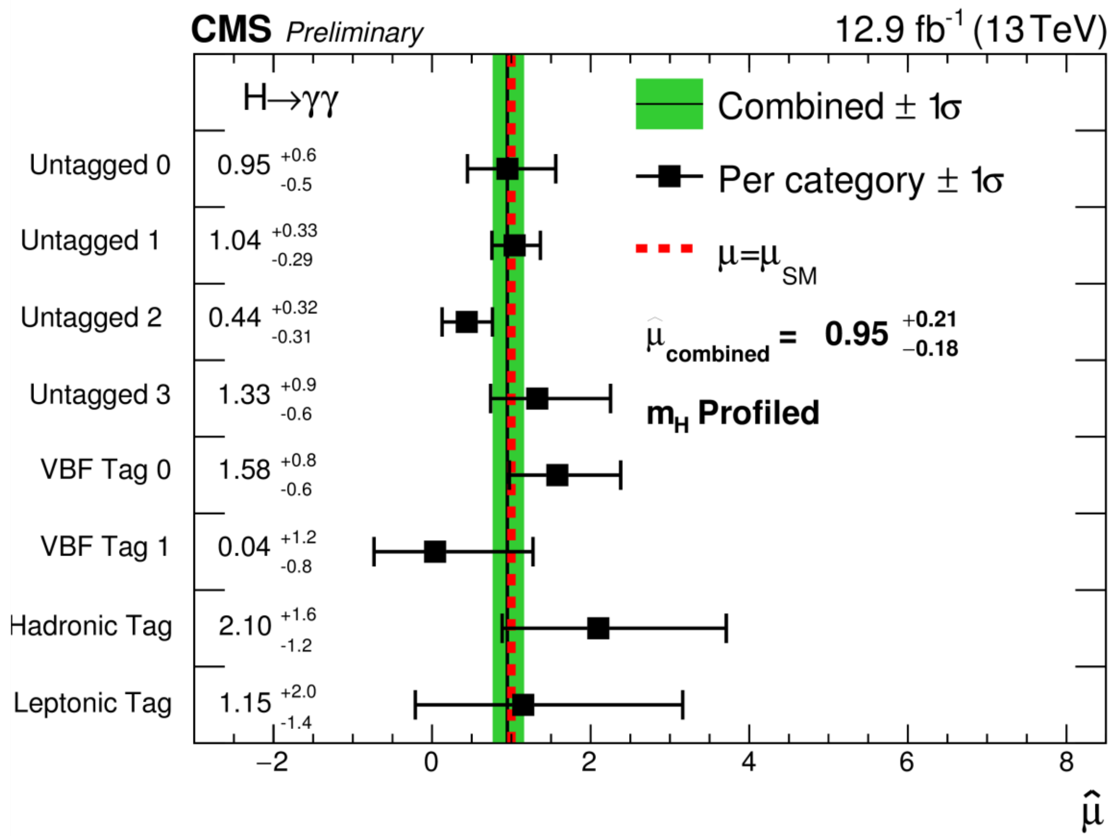




Parameter	Observed	Expected
$f_{a3}\cos(\phi_{a3})$	$-0.56^{+0.38}_{-0.32}$ $[-1.00, 1.00]$	$0.00^{+0.26}_{-0.26}$ $[-0.59, 0.59]$
$f_{a2}\cos(\phi_{a2})$	$-0.06^{+0.06}_{-0.09}$ $[-0.22, 0.24]$	$0.00^{+0.24}_{-0.06}$ $[-0.15, 0.92]$
$f_{\Lambda1}\cos(\phi_{\Lambda1})$	$-0.93^{+0.90}_{-0.16}$ $[-1.00, 0.10] \cup [0.77, 1.00]$	$0.00^{+0.13}_{-0.69}$ $[-1.00, 0.24] \cup [0.98, 1.00]$

HZZ, Hγγ: signal strength per categories





Why double Higgs?

<u>Less obvious answers:</u>

- ✦ extract **non-linear couplings** not accessible in single Higgs
- ✦ alternative measurement of **single-Higgs vertices**
- ✦ probe the **strength of EWSB dynamics** at high energy $E \gg m_h$

Non resonant
$gg \to hh$
$pp \to hh + jj$

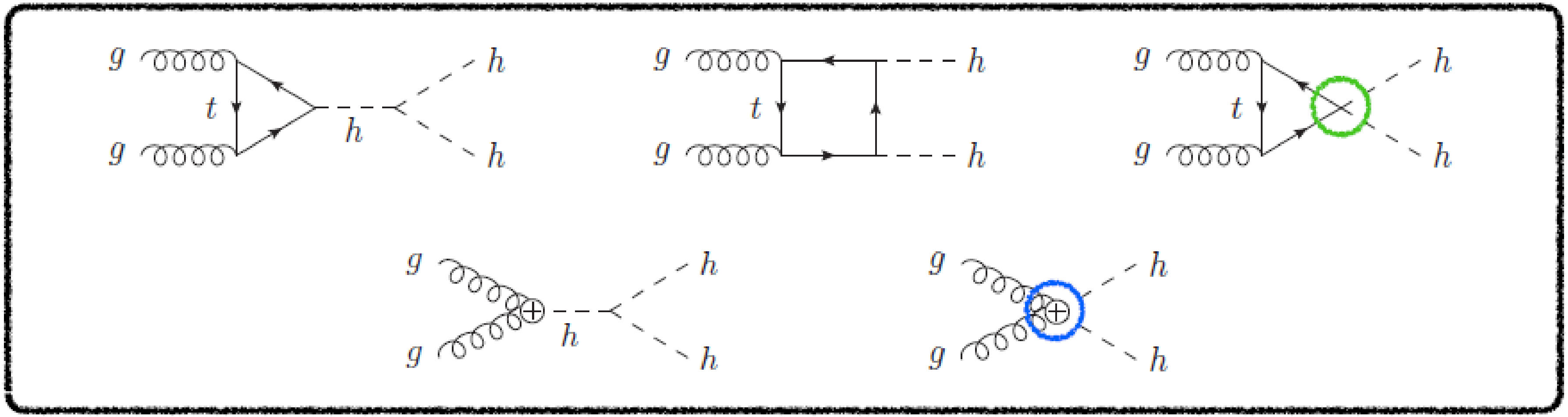
- ✦ explore **extended Higgs sectors**

Resonant
$pp \to H \to hh$

Non-linear Higgs couplings

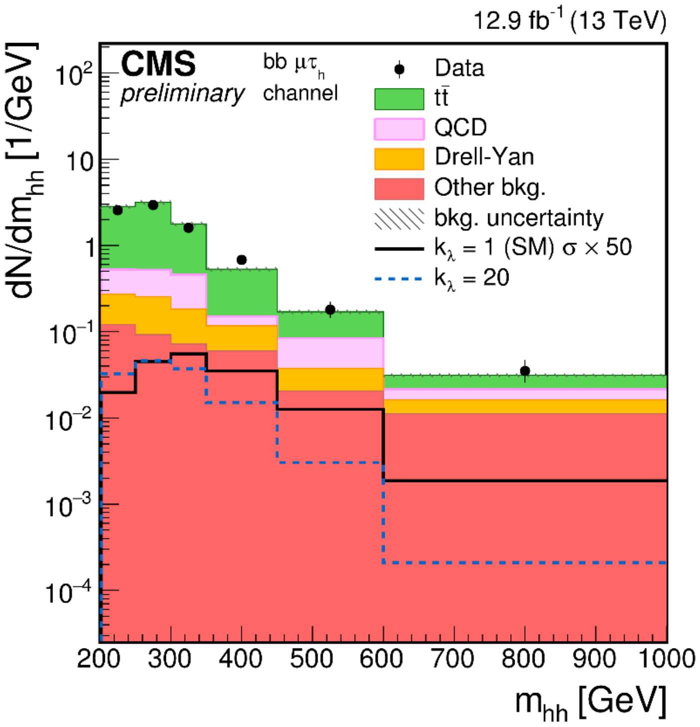
Several vertices contribute to double Higgs production in GF

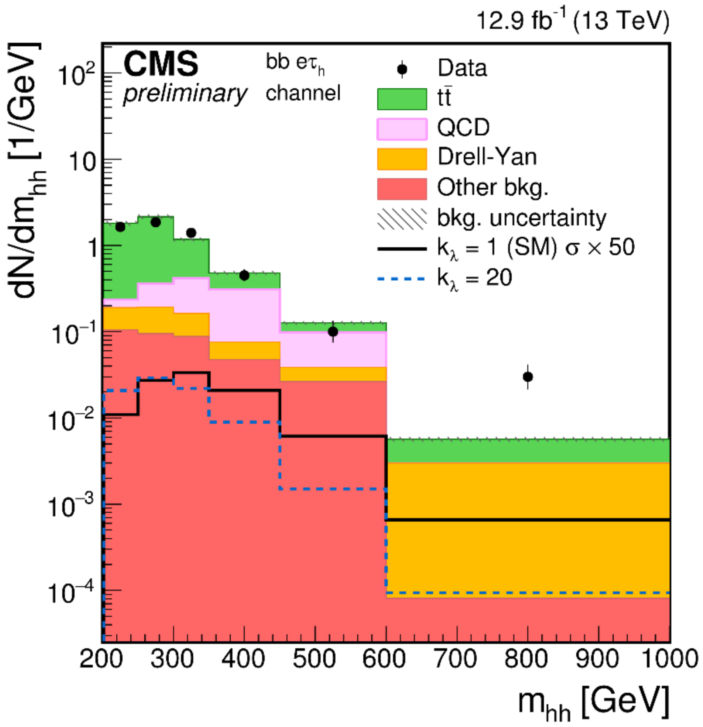
$$\mathcal{L} \supset -m_t \bar{t}t \left(c_t \frac{h}{v} + c_{2t} \frac{h^2}{2v^2} \right) - \lambda_3 \frac{m_h^2}{2v} h^3 + \frac{g_s^2}{4\pi^2} \left(c_g \frac{h}{v} + c_{2g} \frac{h^2}{2v^2} \right) G_{\mu\nu} G^{\mu\nu}$$

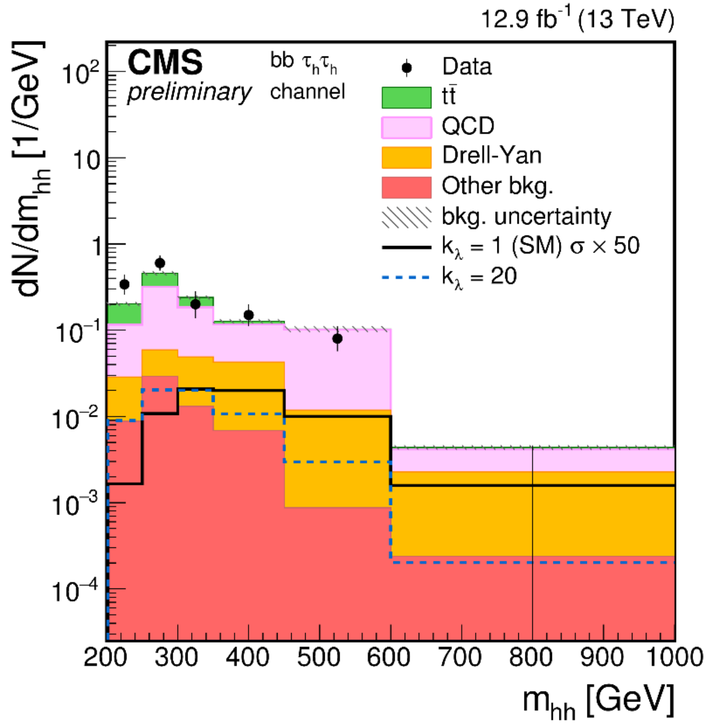


- modifications of the single Higgs couplings can affect HH production (eg. $\bar{t}th$)
- some vertices can be probed independently only in HH processes (eg. $\bar{t}thh$, $h^2 G_{\mu\nu} G^{\mu\nu}$)

HH→bbττ: yields







Process	$bb\mu\tau_h$	$bbe\tau_h$	$bb\tau_h\tau_h$
$t\bar{t}$	368.1 ± 37.2	228.5 ± 23.4	15.3 ± 1.7
multijet	52.2 ± 6.5	55.7 ± 4.6	45.7 ± 4.1
Z+jets	31.5 ± 3.0	18.7 ± 1.9	10.3 ± 1.1
W+jets	13.0 ± 1.0	11.0 ± 0.9	1.4 ± 0.1
single top	11.6 ± 1.0	10.7 ± 1.0	1.5 ± 0.2
di-boson	3.1 ± 0.4	1.4 ± 0.2	0.7 ± 0.1
Total expected background	480.0 ± 37.9	326.0 ± 24.4	74.8 ± 4.6
$k_\lambda = 1$	0.24	0.13	0.12
$k_\lambda = 20$	7.8	4.8	4.1
DATA	464	317	84

HH→bbττ: systematic uncertainties

Normalization:

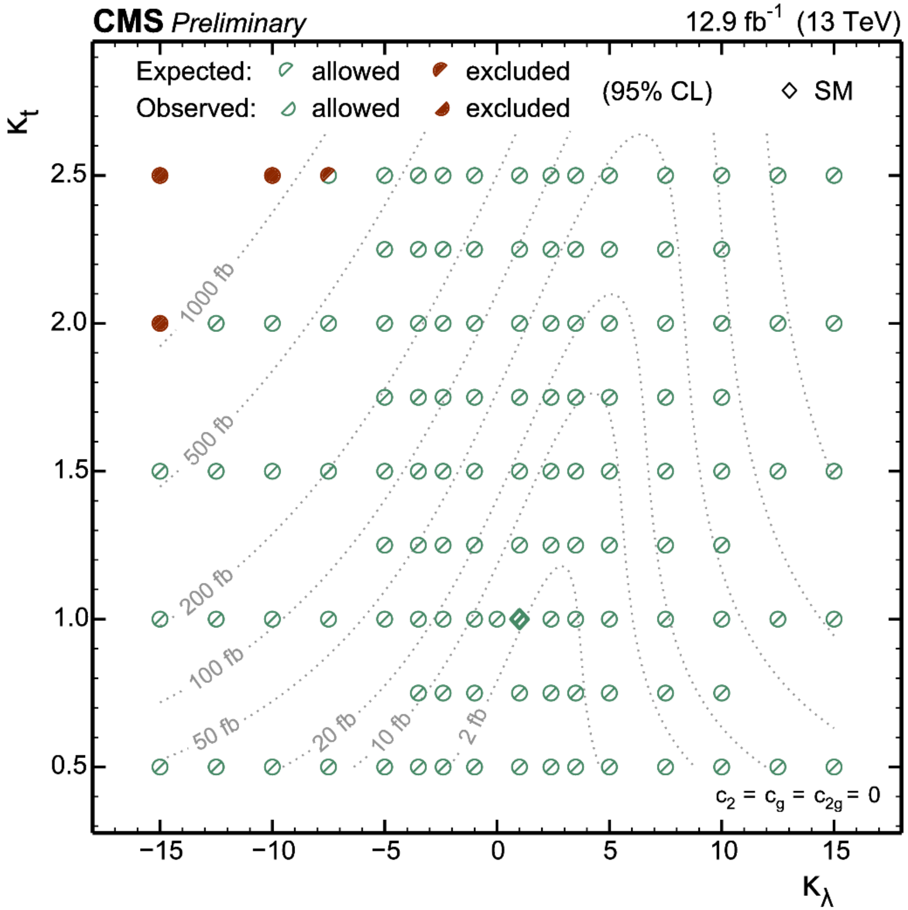
Systematic	value	processes
luminosity	6.2%	all but multijet, Z+jets
Jet energy scale	2-4%	all
MC cross-section	1-10%	backgrounds, not Z+jets, multijet
b-tag efficiency	2-6%	all
lepton efficiency	2-6%	all
Z+jets SF uncertainty	1-10%	Z+jets
τ energy scale	3-10%	all
scale unc.	$+4.3/-6\%$	theory
PDF variation	3.1%	theory

Shape:

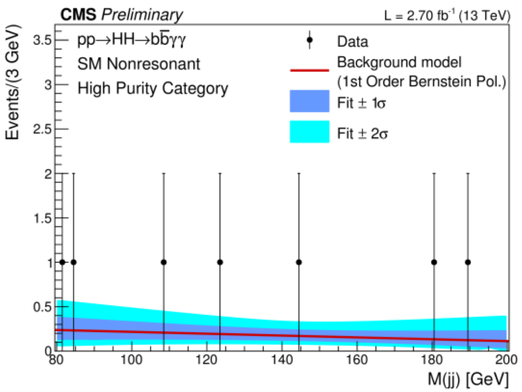
- DATA/MC Difference in pT distribution for ttbar
- Multijet background shape
- Uncertainties due to limited statistics (MC or data control region)
- Visible mass distribution change (up/down tau energy scale)

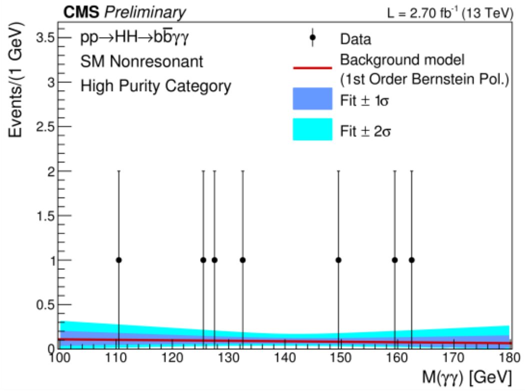
HH→bbττ: constraints on BSM

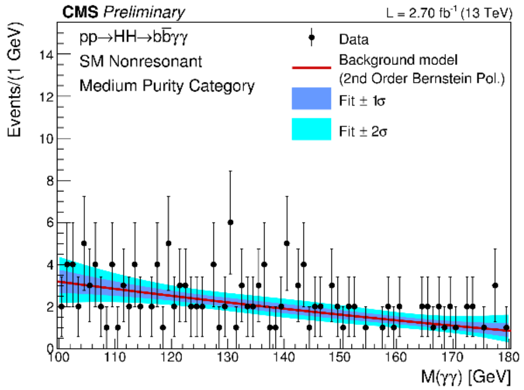
Exclusion of Higgs boson pair production in the EFT parametrization as a function of the coupling modifiers
kλkλ and ktkt, fixing the other EFT parameters to cg=c2g=c2=0cg=c2g=c2=0.
Each marker denotes a point in the bidimensional (kλ,ktkλ,kt) plane for which the corresponding prediction has been tested with the available data.
Open green semicircles denote points compatible with the current data while red full semicircles denote points excluded with the current data.
The two halves of the circles denote the expected and observed exclusion as reported in the plot legend.
The diamond shaped marker refers to the prediction of the SM.
The dotted lines indicate trajectories in the plane with equal Higgs boson pair production cross section and are labeled
with the corresponding value of σ(gg→hh)×BR(hh→bbττ)σ(gg→hh)×BR(hh→bbττ).

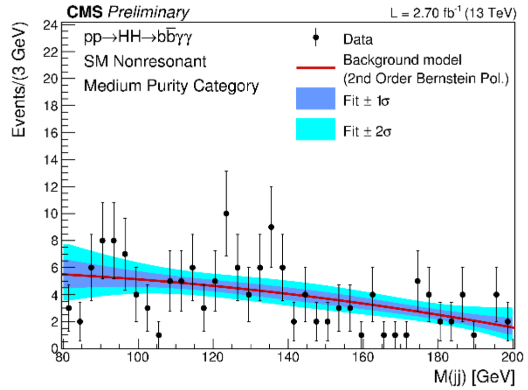


HH→bbγγ (2015)

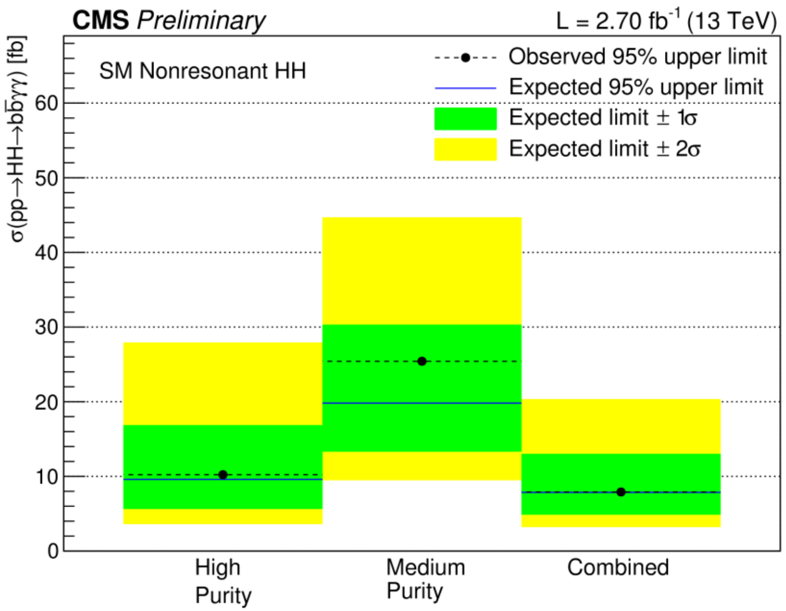






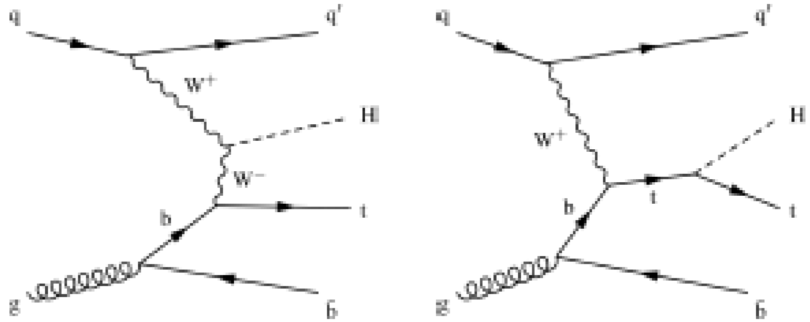


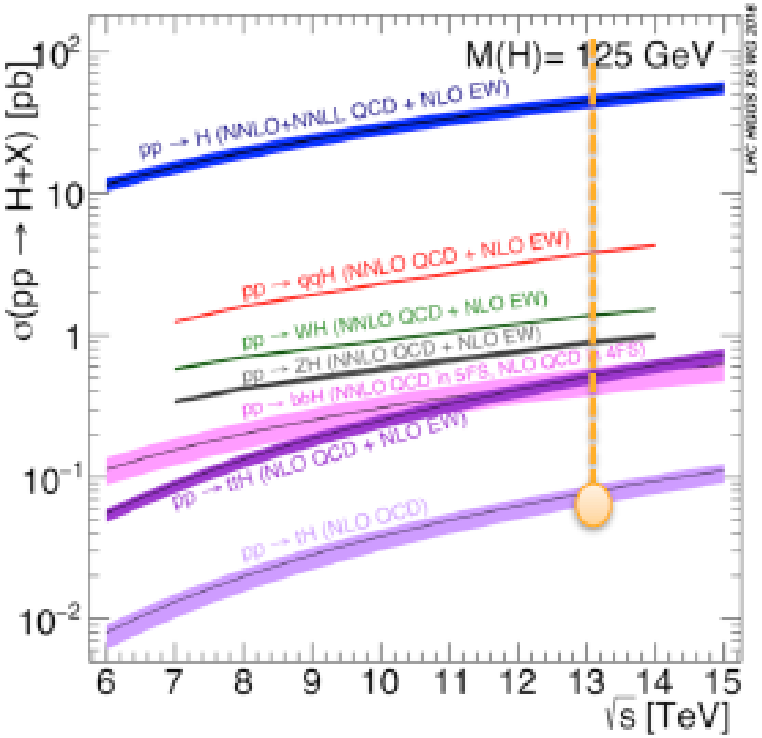
Signal hypothesis	# categories	Extra Selection
Resonance, $M_X \leq 500\,\text{GeV}$	2 (b tags)	$\tilde{M}_X$ Window
Resonance, $M_X \geq 500\,\text{GeV}$	-	$\tilde{M}_X$ Window
Nonresonant	2 (b tags)	$\tilde{M}_X > 350$ GeV



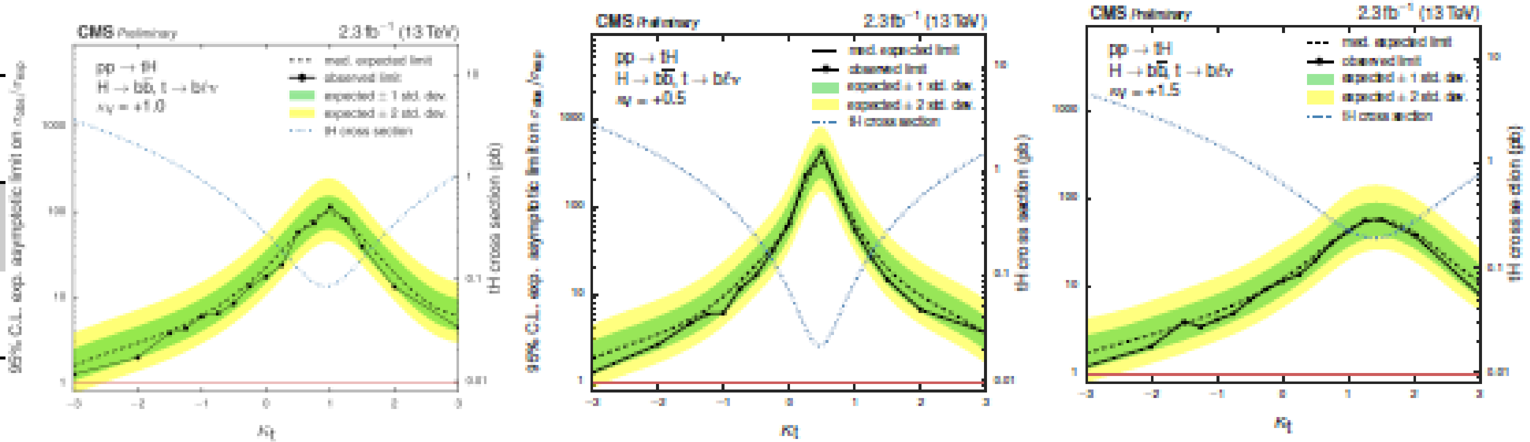
tH(→bb)

- Smallest SM production cross section
  - Diagrams are interfering in SM
  - While it is constructive for inverted top coupling (ITC) κ_{top}=-1



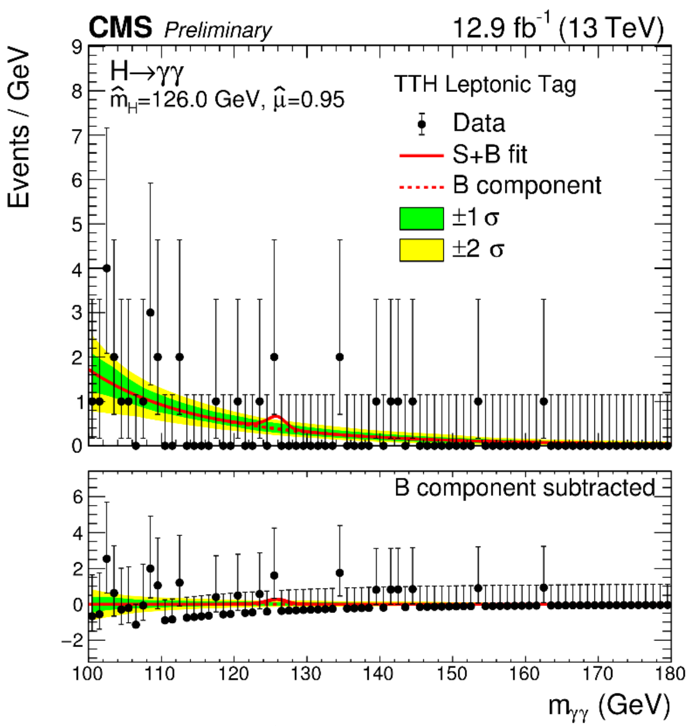


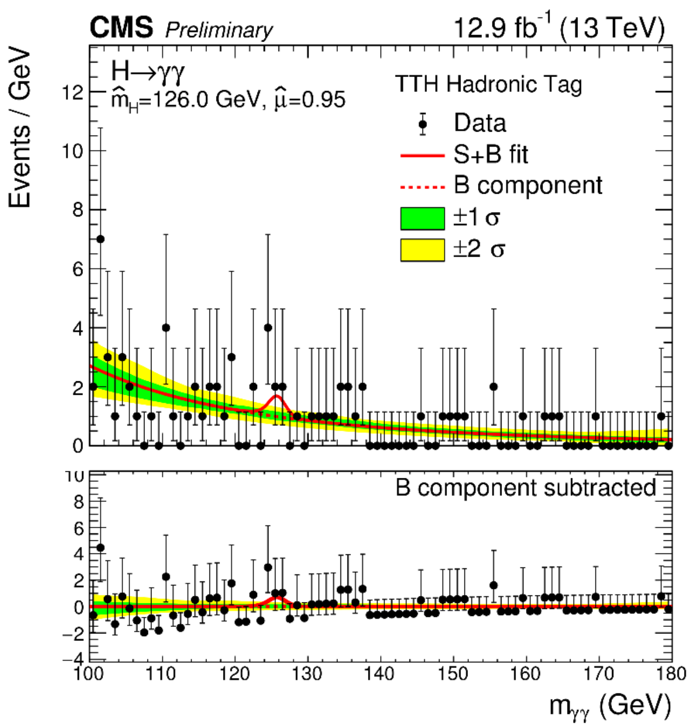
CMS	Upper limit x SM (expected)
SM	113.7 (98.6)
ITC	6.0 (6.4)

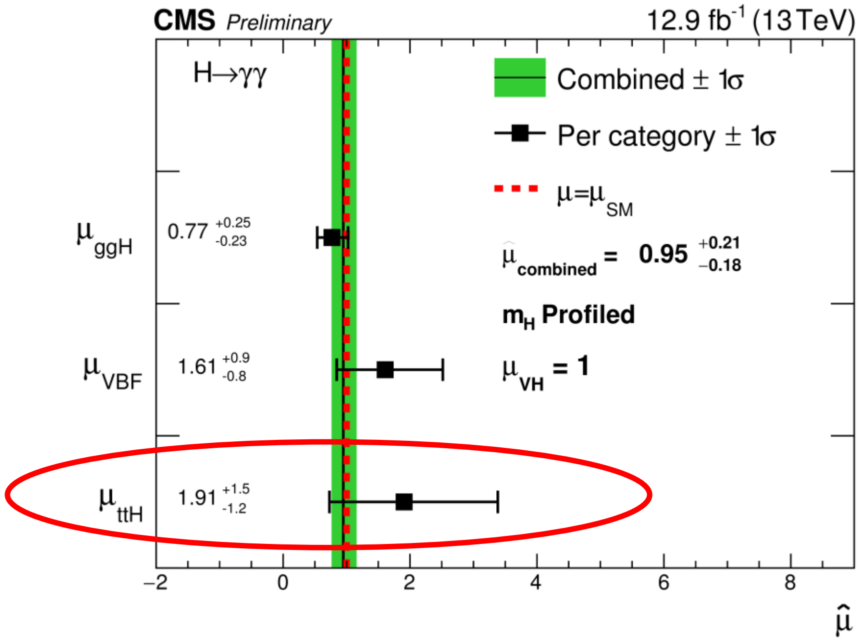


ttH, H→γγ

- Categories from H→γγ (**see previous slides**), targeting leptonic or hadronic decay of top.







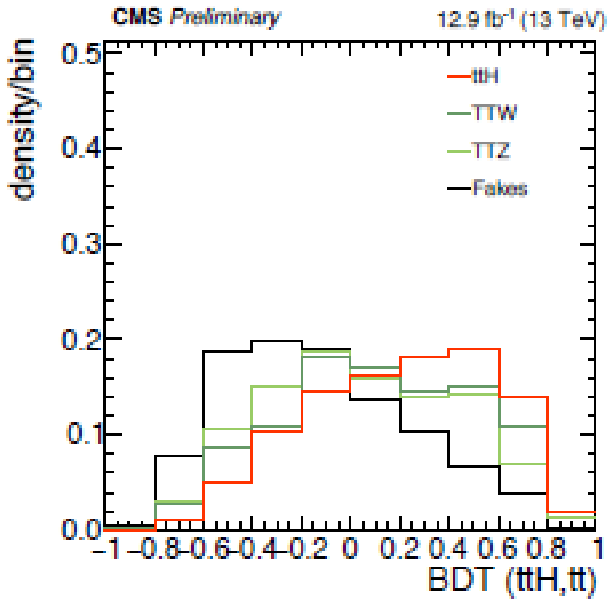
Kinematic discrimination

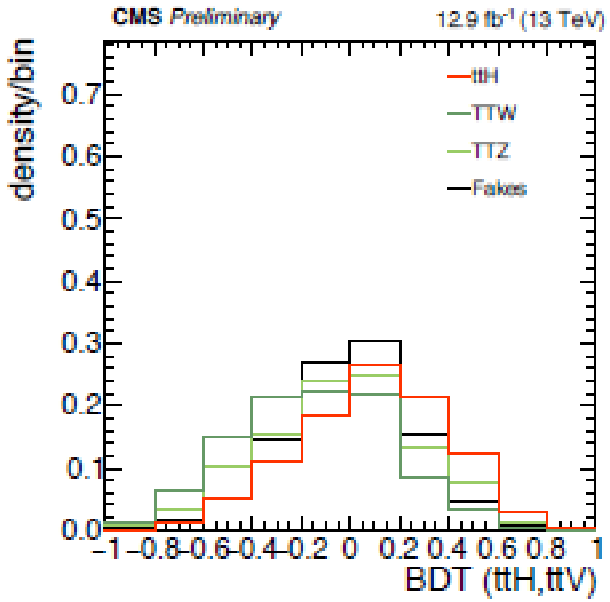
CMS PAS HIG-16-022

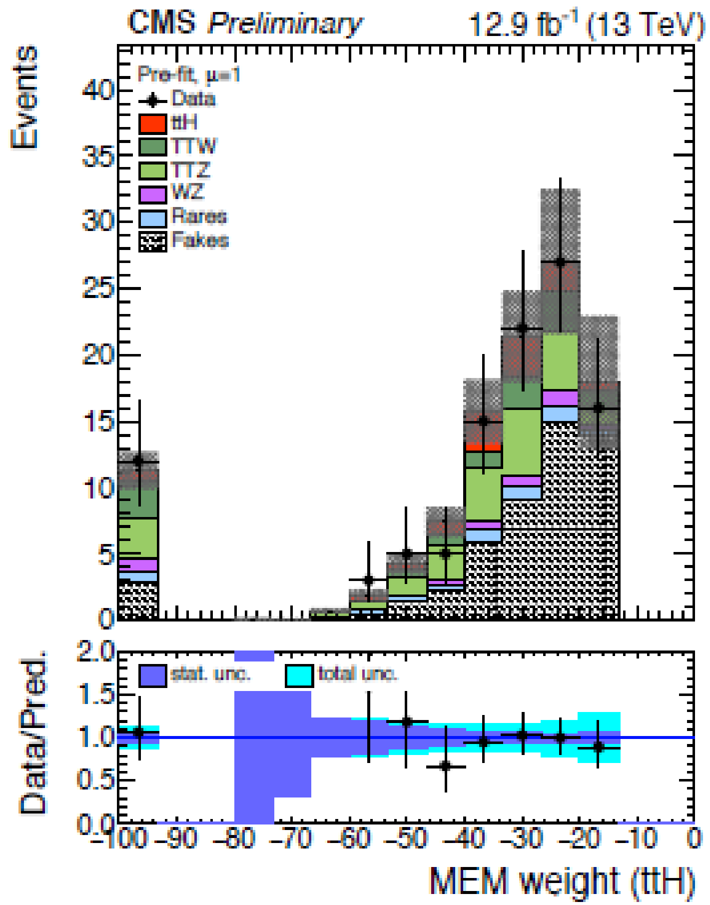
- Using **kinematic observables to improve discrimination against tt and ttV events**: jet multiplicity, lepton/jet angular separation, MET, lepton p_T
- New for 2016 analysis **in 3l: matrix element weights for ttH and ttV hypotheses**

$$w_{i,\alpha}(\Phi') = \frac{1}{\sigma_\alpha} \int d\Phi_\alpha \cdot \delta^4\left(p_1^\mu + p_2^\mu - \sum_{k>2} p_k^\mu\right) \cdot \frac{f(x_1,\mu_F) f(x_2,\mu_F)}{x_1 x_2 s} \cdot \left|\mathcal{M}_\alpha(p_k^\mu)\right|^2 \cdot W(\Phi'|\Phi_\alpha)$$

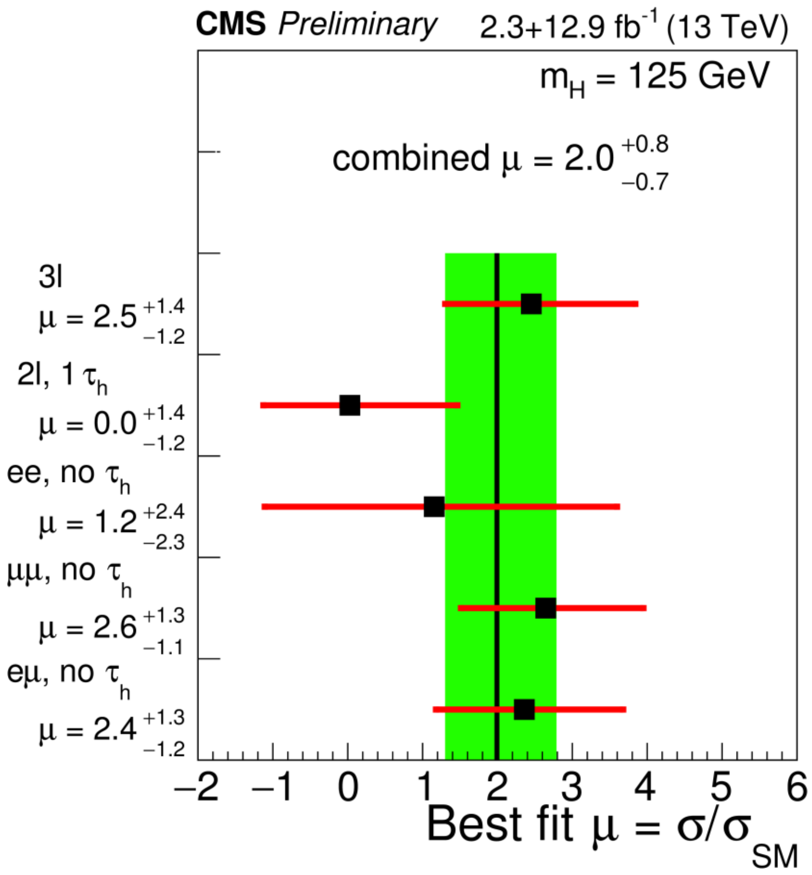
- Separate **BDT discriminators** against tt and ttV:

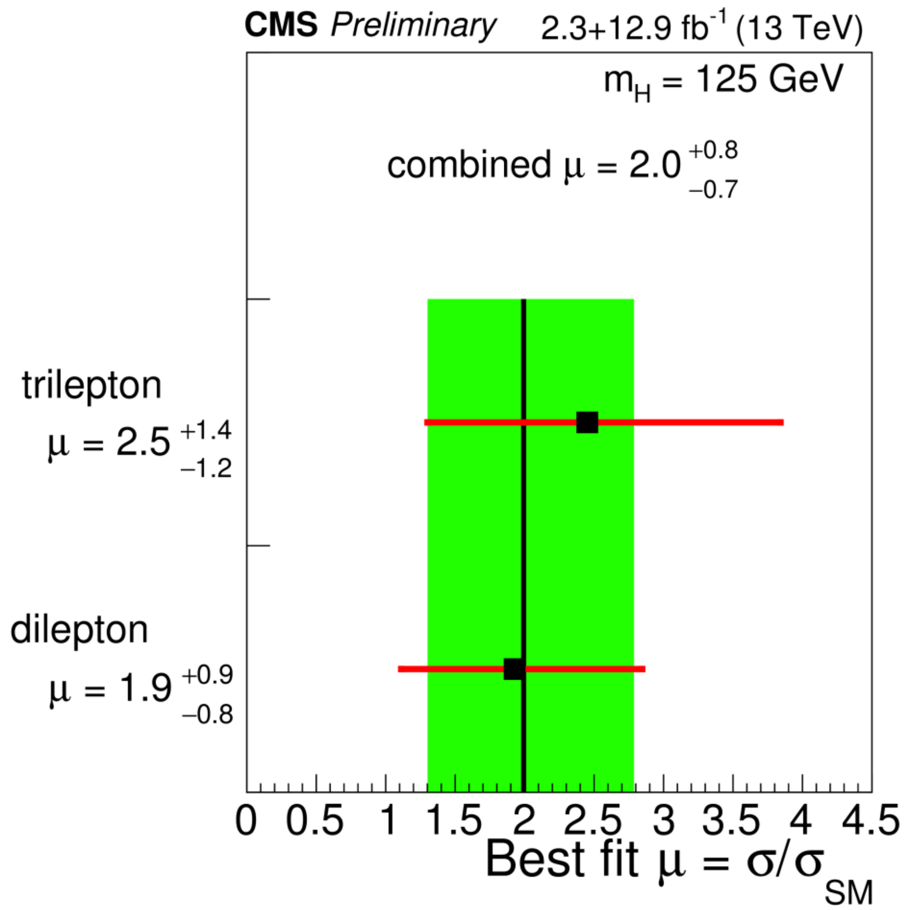






ttH->multileptons Summary (2015+2016)





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	$1.3^{+0.6}_{-0.4}$	$2.0^{+0.8}_{-0.7}$

ttH: 2015 results

- Higgs to bb

$$\hat{\mu}_{obs} = -2.0^{+1.8}_{-1.8}$$

- Higgs to γγ

$$\hat{\mu}_{obs} = 3.8^{+4.5}_{-3.6}$$

- Multi-lepton

$$\hat{\mu}_{obs} = 0.6^{+1.4}_{-1.1}$$