LATEST HIGGS BOSON PHYSICS RESULTS @ LHC

AND PROSPECTS FOR PHYSICS PERFORMANCE @ HL-LHC

P. Milenovic (CERN), on behalf of ATLAS and CMS Collaborations

~~AWLC'17, SLAC, 26-30 June 2017~~

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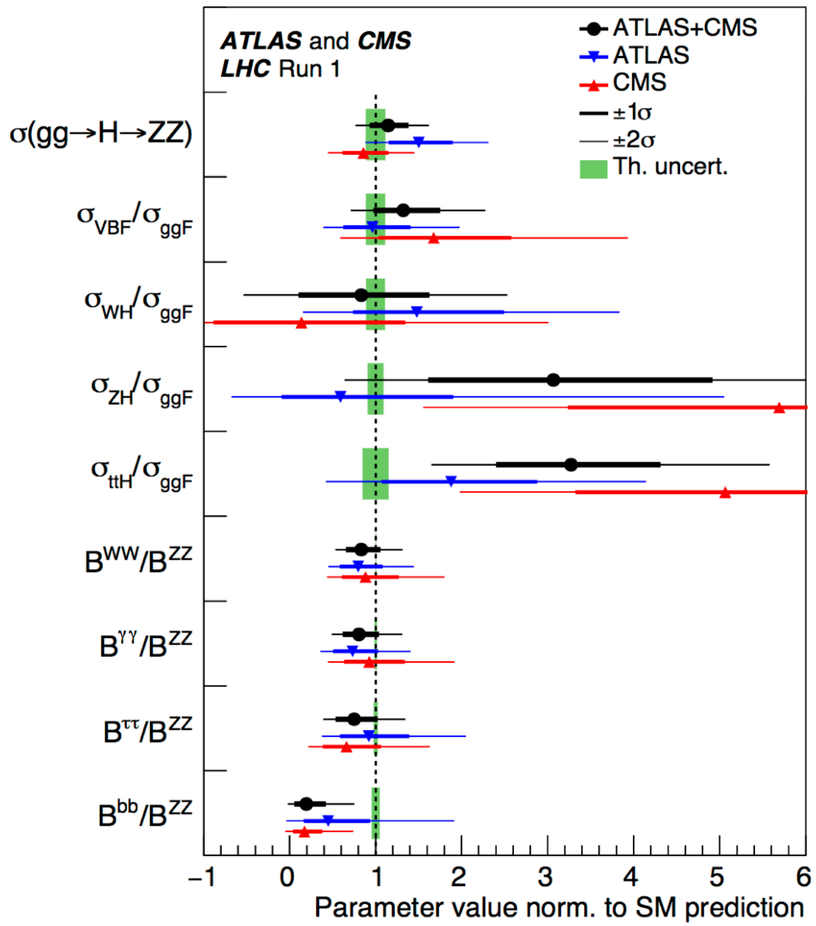
Preface

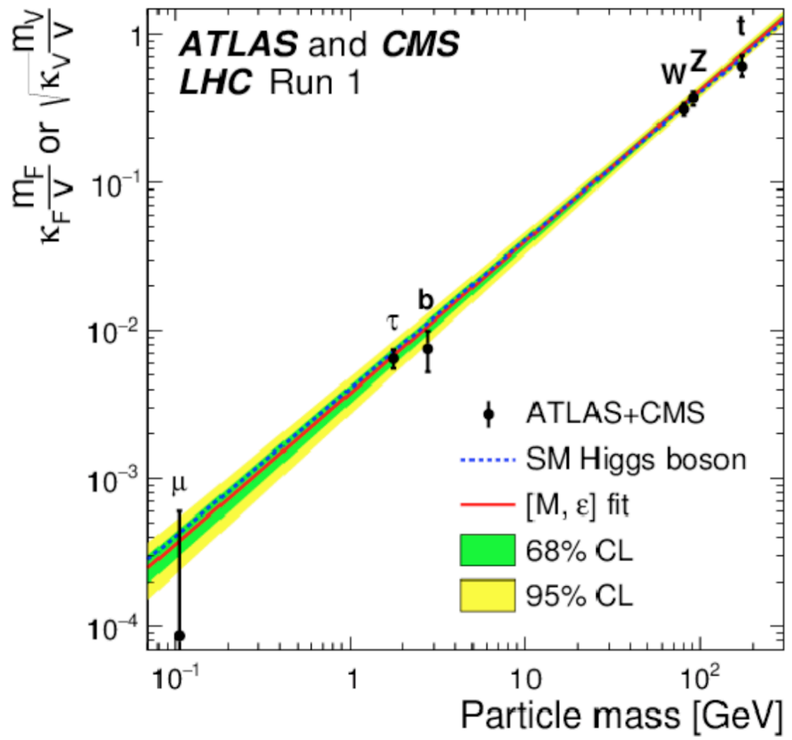
Higgs discovery: Triumph of LHC and its experiments @ Run 1

- After the discovery, **emphasis shifted towards measurements of properties** of the new particle.
- All Run1 results indicate **SM-like Higgs boson!**

Cross-sections & branching ratios:



Couplings to fermions/bosons:



Mass @ Run 1 LHC combination:
m_H = 125.09 ± 0.21(stat.) ± 0.11(sys.) GeV

Run 2: Further characterisation of the Higgs boson

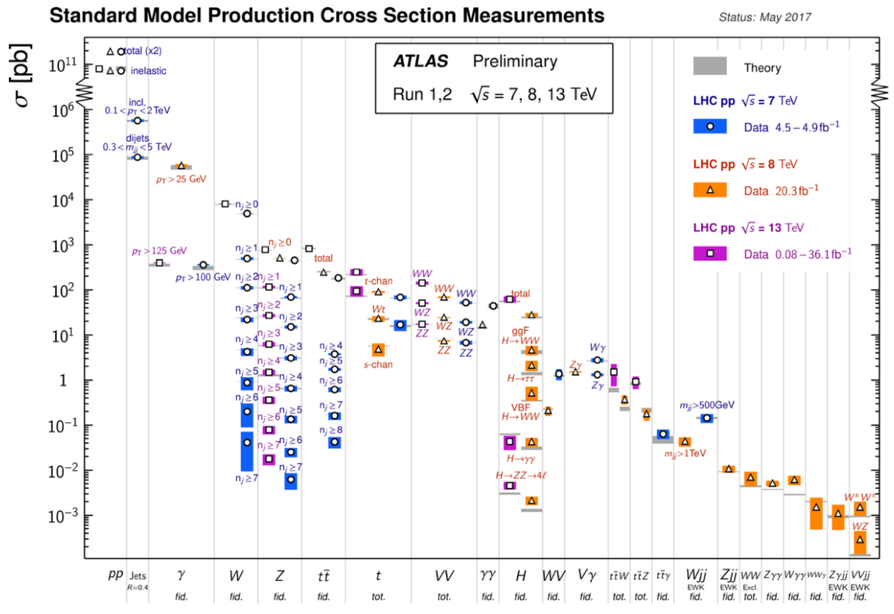
Preface

Excellence of LHC and its experiments: Enabled quick start and rich physics program @ 13 TeV in early years of Run 2

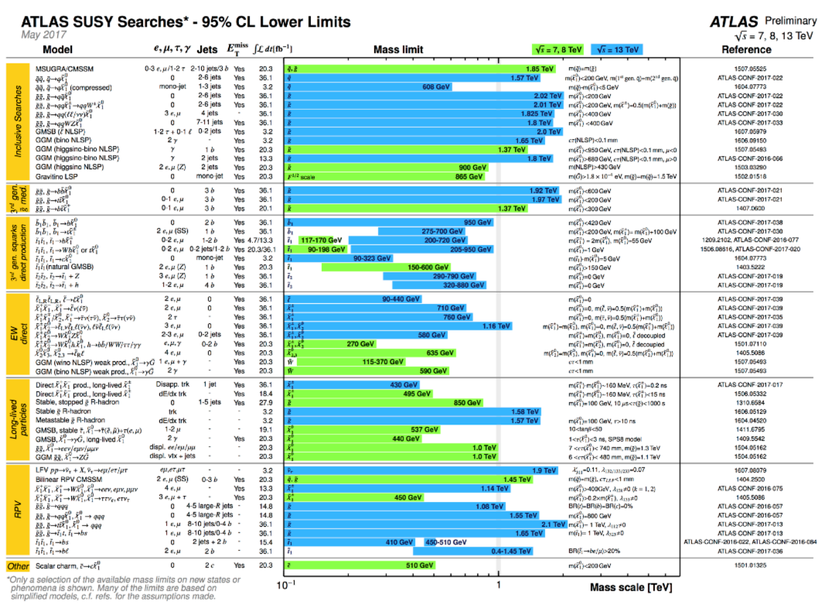
- **LHC**: more effective bunch collision schemes, increased machine availability (x2).
- **Experiments**: improved performance at high pile-up (and operation efficiency).

Performed a plethora of SM measurements and searches for new physics:

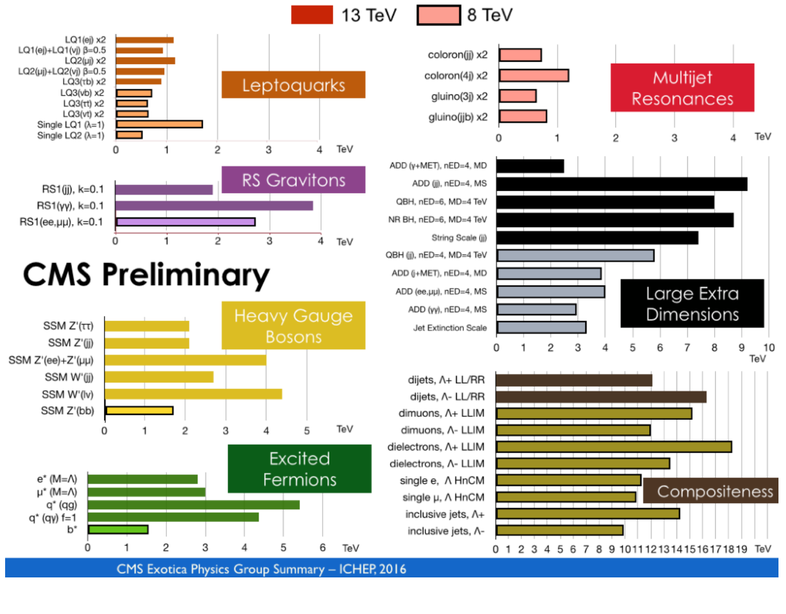
SM measurements



SUSY searches



Exotic searches



No deviation from SM

No indications for new physics phenomena

Run 2: Exploit the Higgs boson as a tool to probe for new physics

Latest Higgs boson measurements @ 13TeV

Characterisation of the SM Higgs boson:

- **Measurement of properties in $H \to 4\ell$, and $H \to \gamma\gamma$**
- **Probing of Yukawa interactions in ttH, $H \to \mu\mu$, $H \to \tau\tau$, and $H \to bb$**
- **Probing of its self-couplings in $pp \to HH$**

[*] predominantly presented results obtained with 36 fb^{-1}

H → 4ℓ measurements

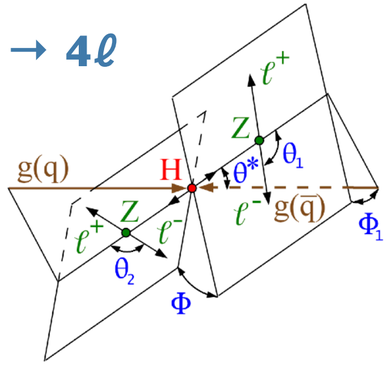
H → 4ℓ: Analyses approaches

CMS-HIG-16-041

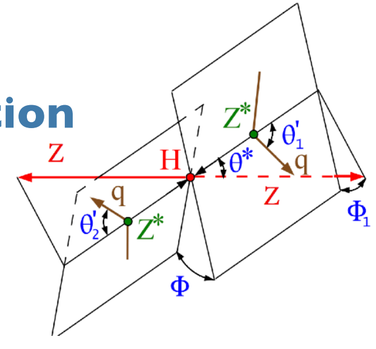
Exploit full decay-, production-, and object-related information:

- Clean signature, good $m_{4\ell}$ resolution (1-2%). Low irreducible/reducible backgrounds (estimated from MC/data).
- **Even categorisation**: Based on **event topology** and **ME-based discriminants**

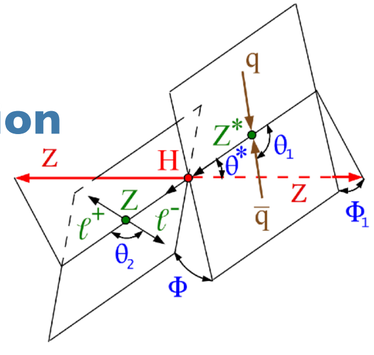
H → ZZ → 4ℓ decay



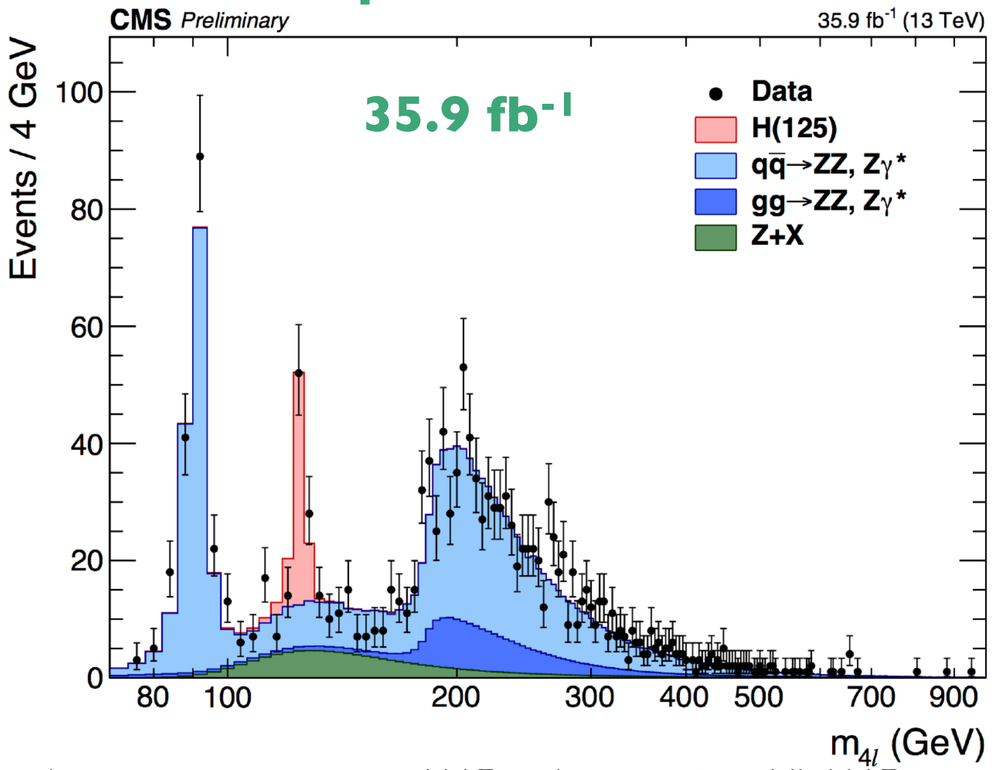
VBF production



VH production

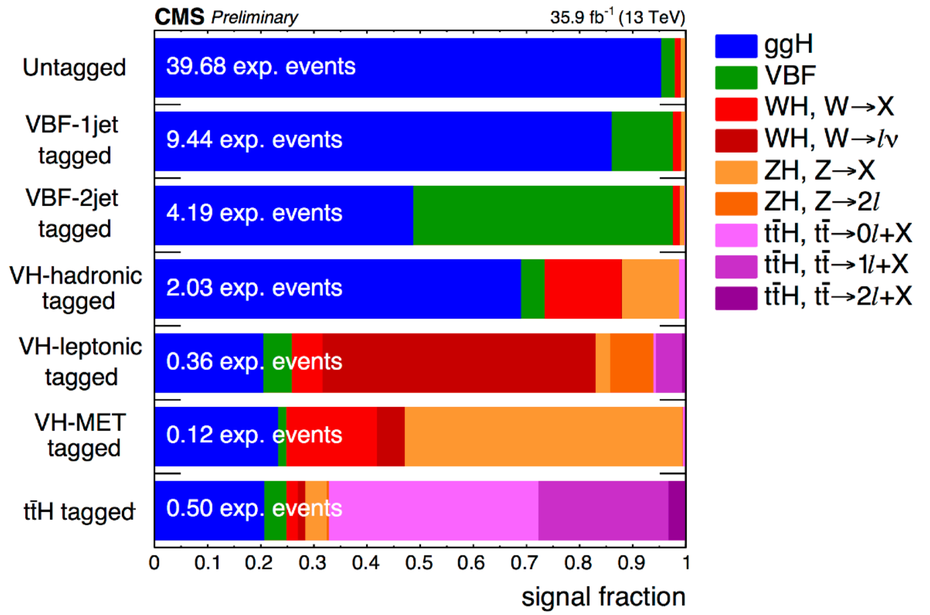


Four-lepton invariant mass:



Even categorisation

7 categories targeting 5 production modes:

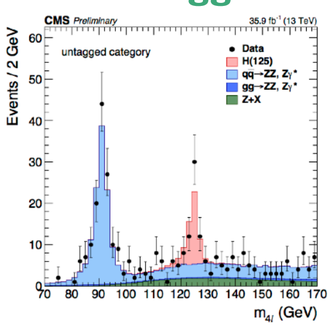


H → 4ℓ: Production modes

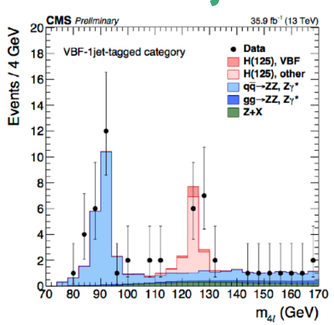
CMS-HIG-16-041

Extract info on H couplings by performing simultaneous 2D fit in seven categories:

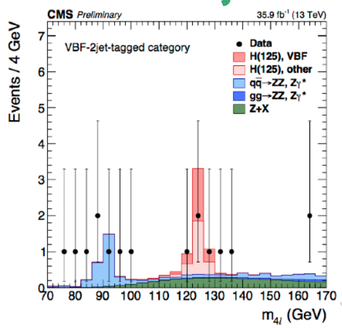
Untagged



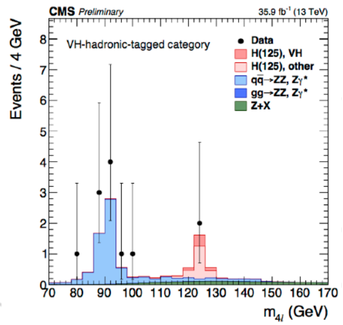
VBF 1-jet



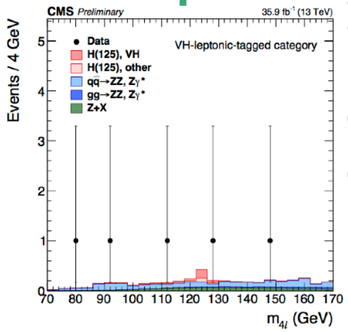
VBF 2-jet



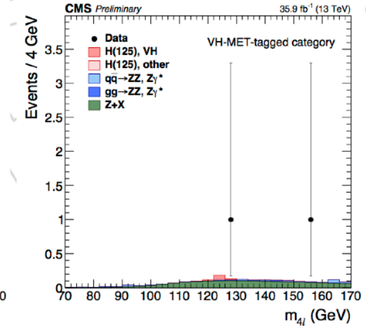
VH hadronic



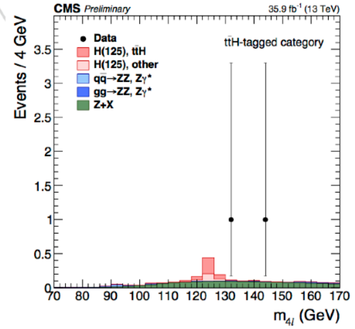
VH leptonic



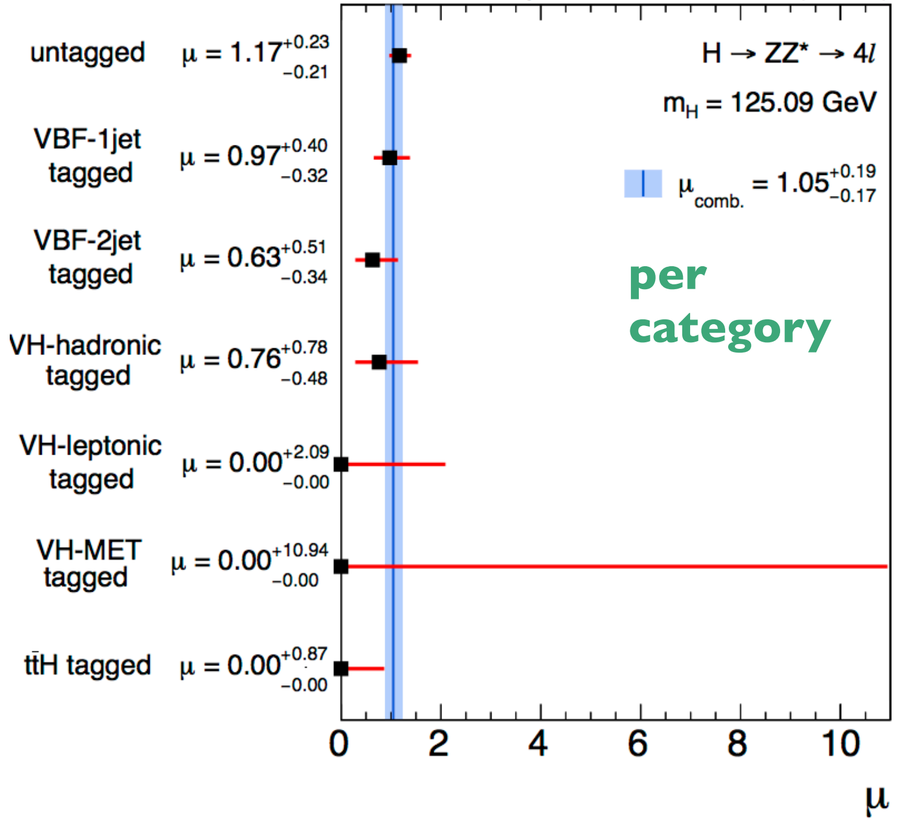
VH MET

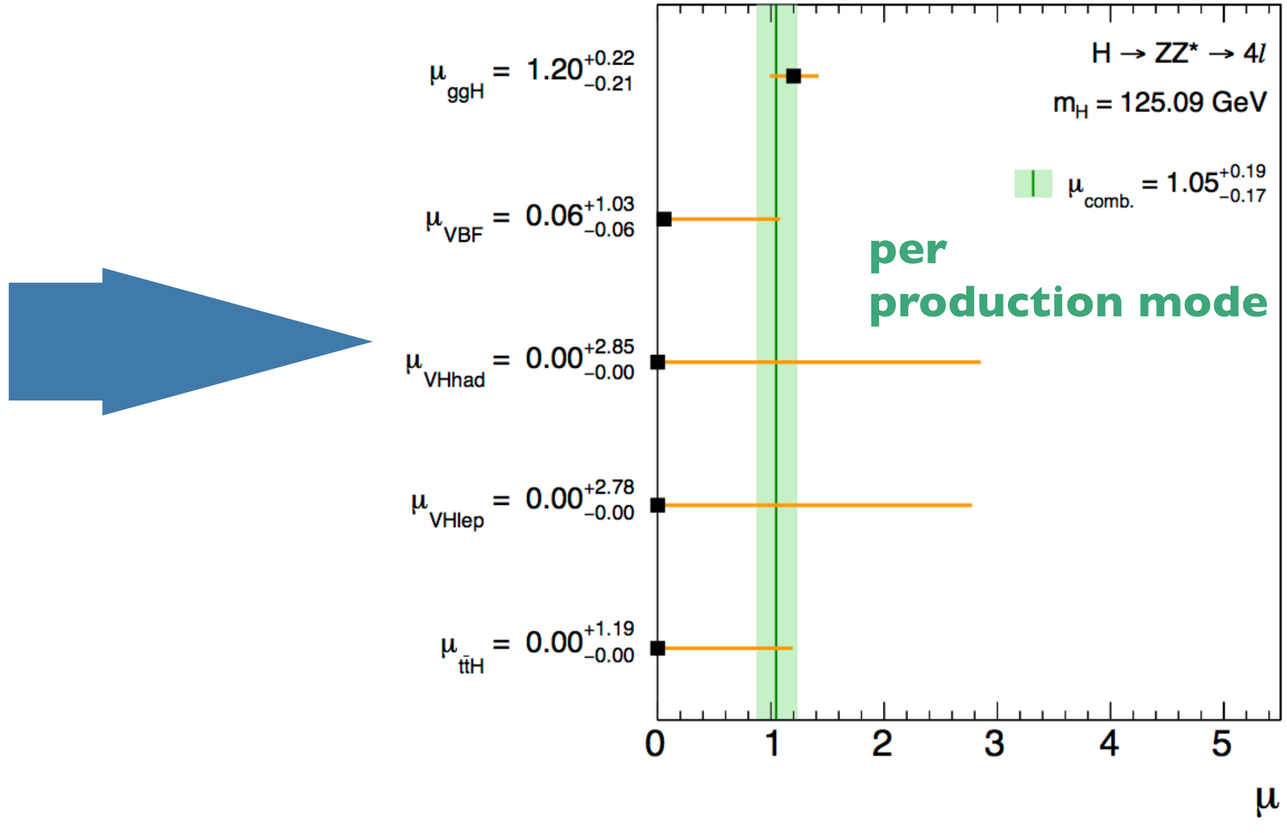


ttH



Sig. strengths per category + per production mode.





H → 4ℓ: Production modes

CMS-HIG-16-041

Extract info on H couplings by performing simultaneous 2D fit in seven categories:

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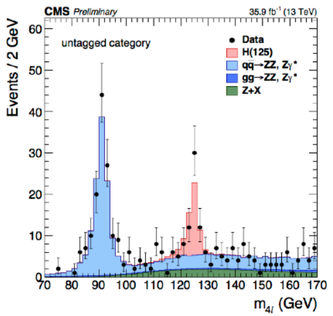
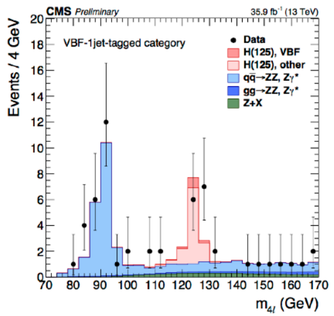
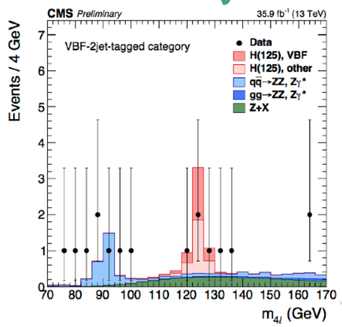


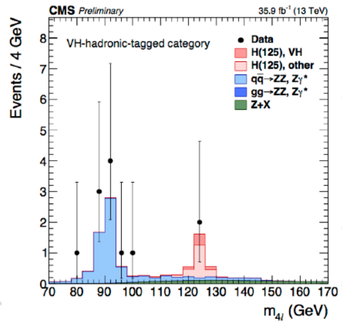
VBF 1-jet



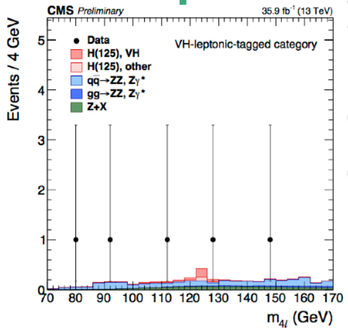
VBF 2-jet



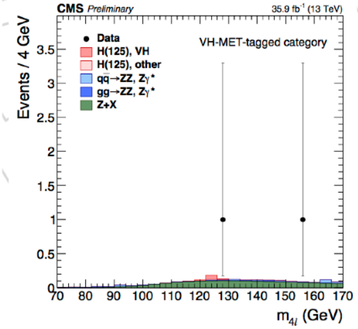
VH hadronic



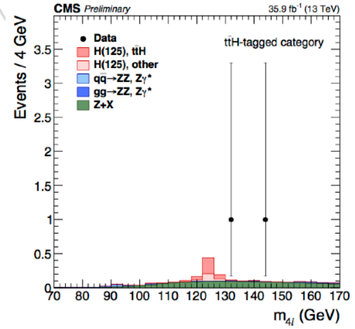
VH leptonic



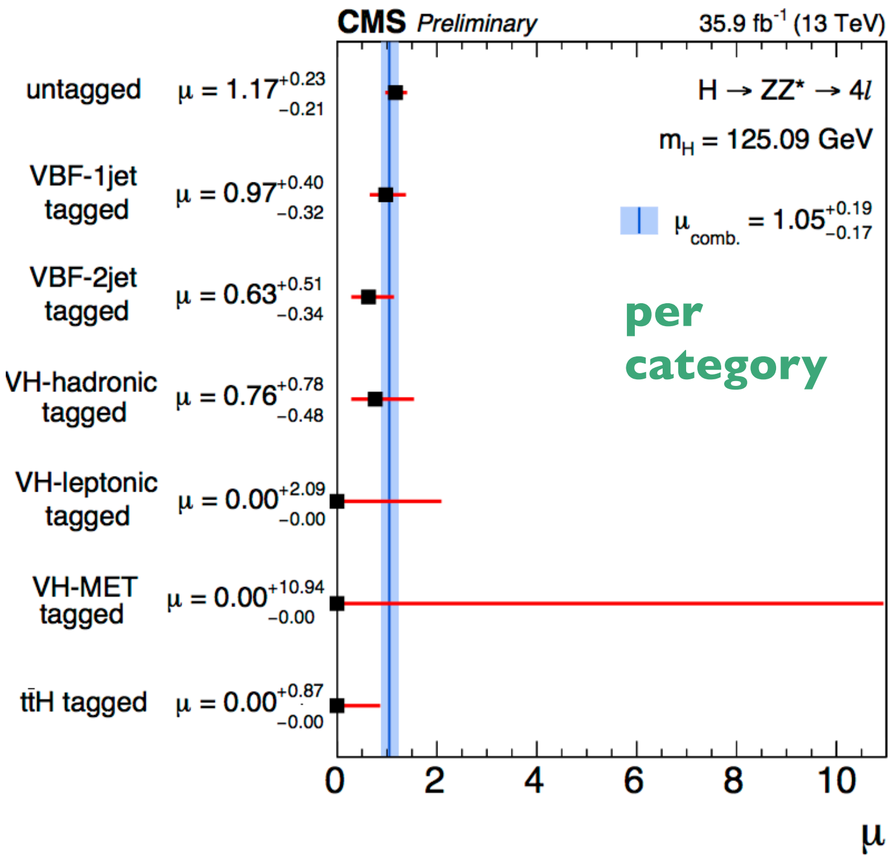
VH MET

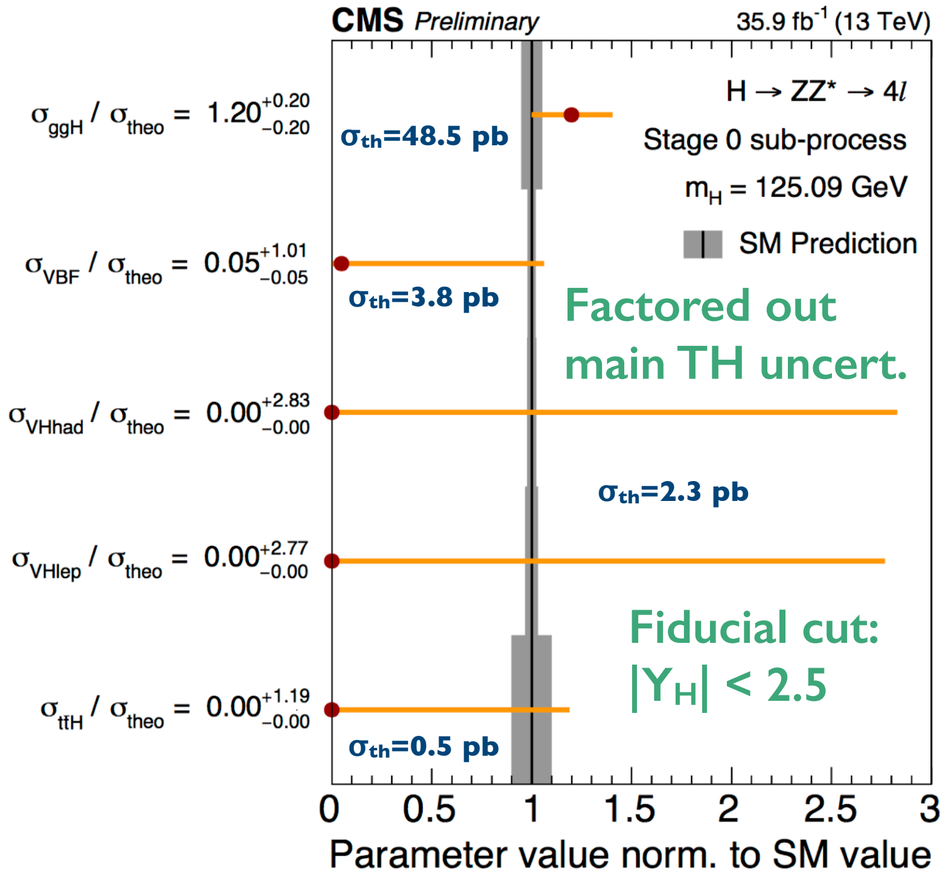


ttH



Sig. strengths per category + per production mode. And as "simplified" cross sections:





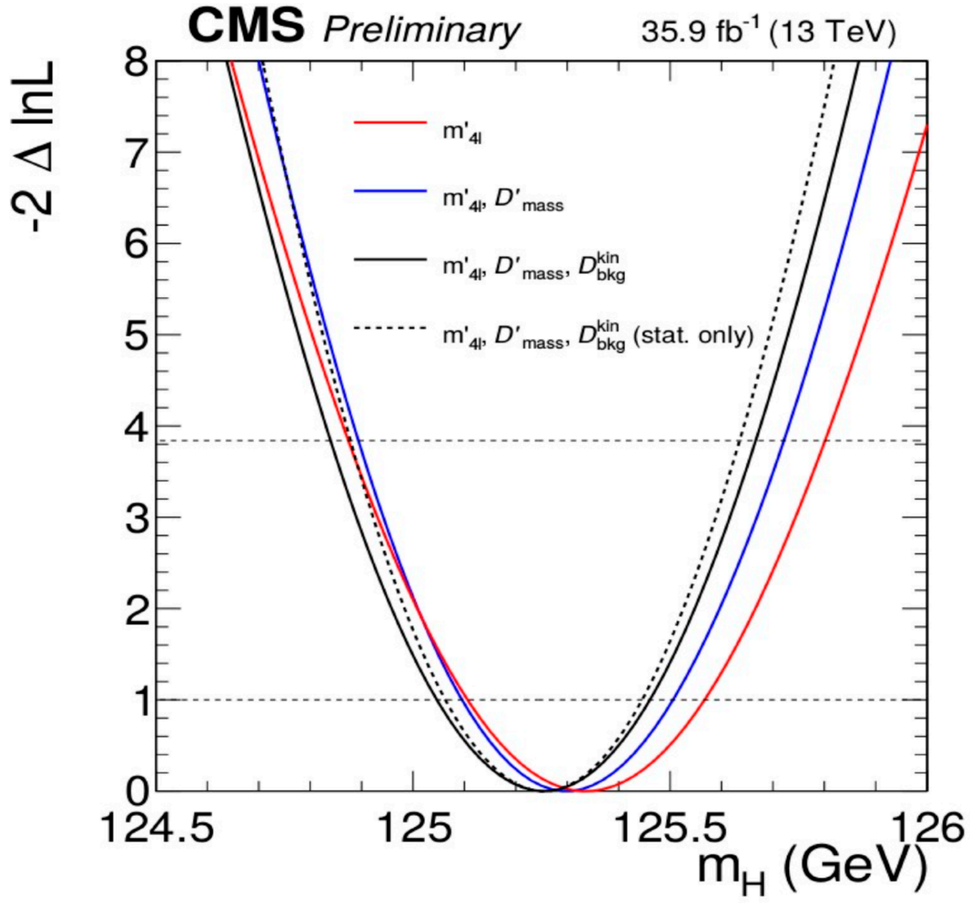
H → 4ℓ: Mass

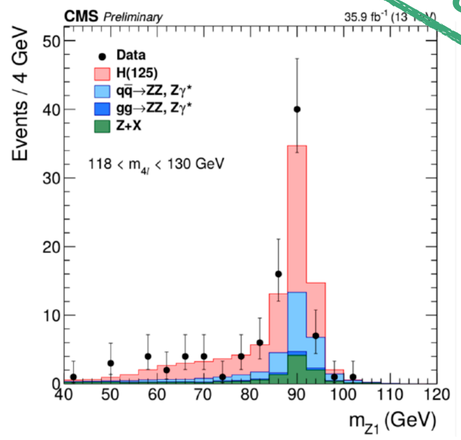
CMS-HIG-16-041

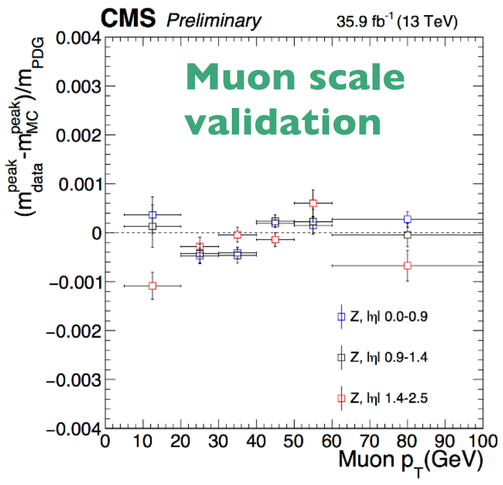
Perform 3D fit (m_{4l}, D_{m4l}, D^{kin}_{bkg}) using the Z-mass constraint:

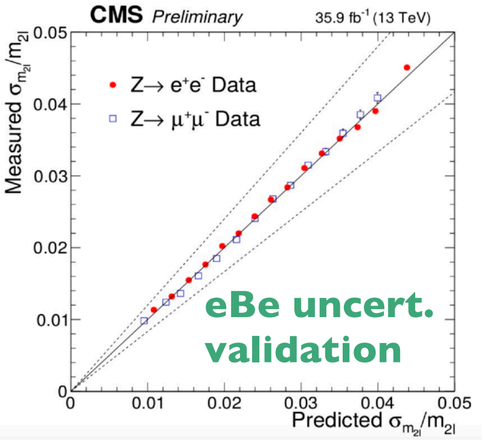
- **Per-event m_{4l} uncertainty D_{m4l}:** From lepton p_T uncertainties (corr. $Z \to \ell^+\ell^-$)
- **Z-mass constraint:** Kinematic refitting of Z_1 lepton p_T, to exploit m_{Z1} expectation

Expected **improvement 21%** over 1D m_{4l} fit









m_H = 125.26 ± 0.20 (stat) ± 0.08 (syst) GeV **(0.18% precision)**

49 MeV better then expected

Run I LHC combination: m_H = 125.09 ± 0.21(stat.) ± 0.11(sys.) GeV

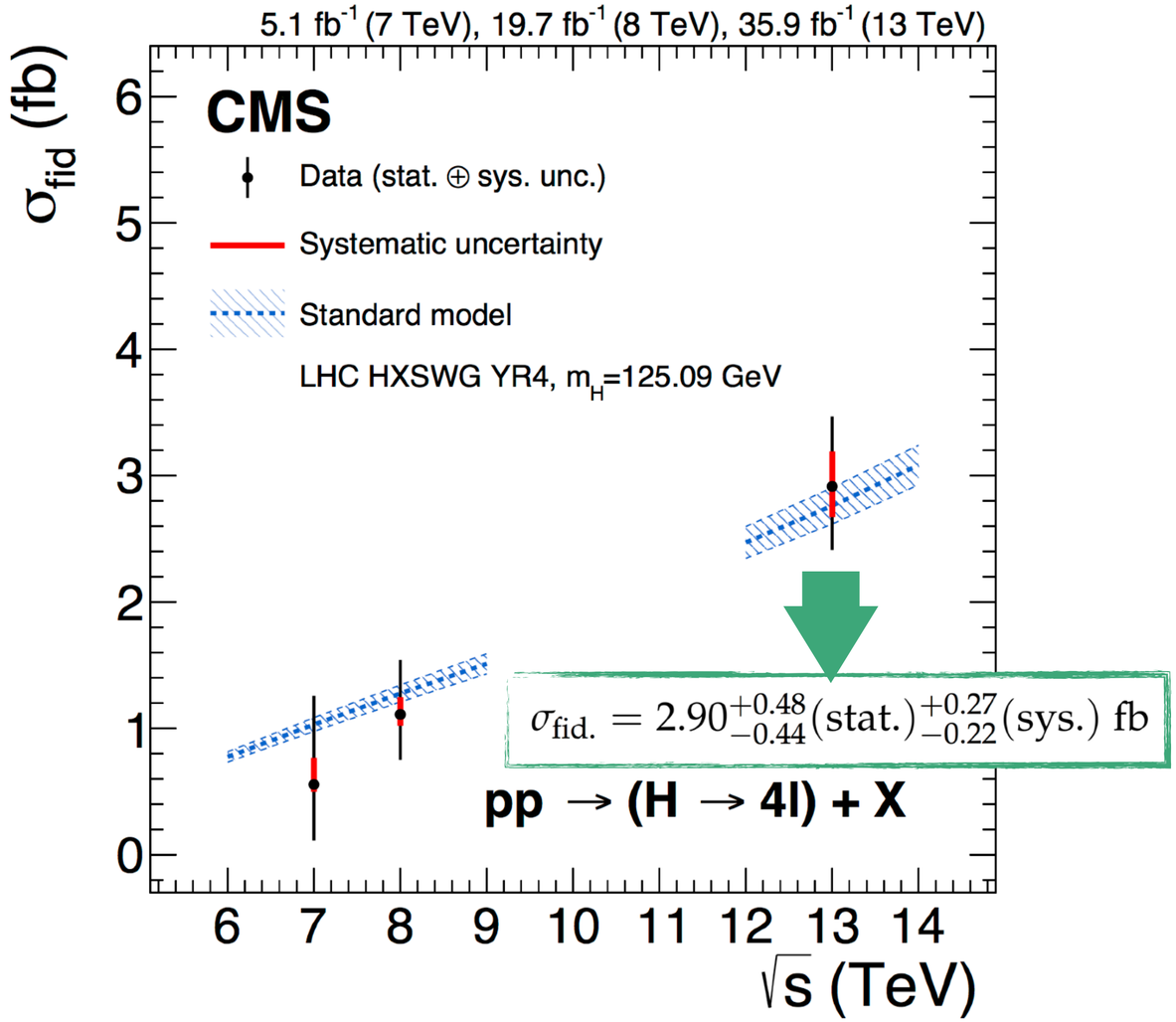
H → 4ℓ: Fiducial cross sections

CMS-HIG-16-041
ATLAS-CONF-2017-032

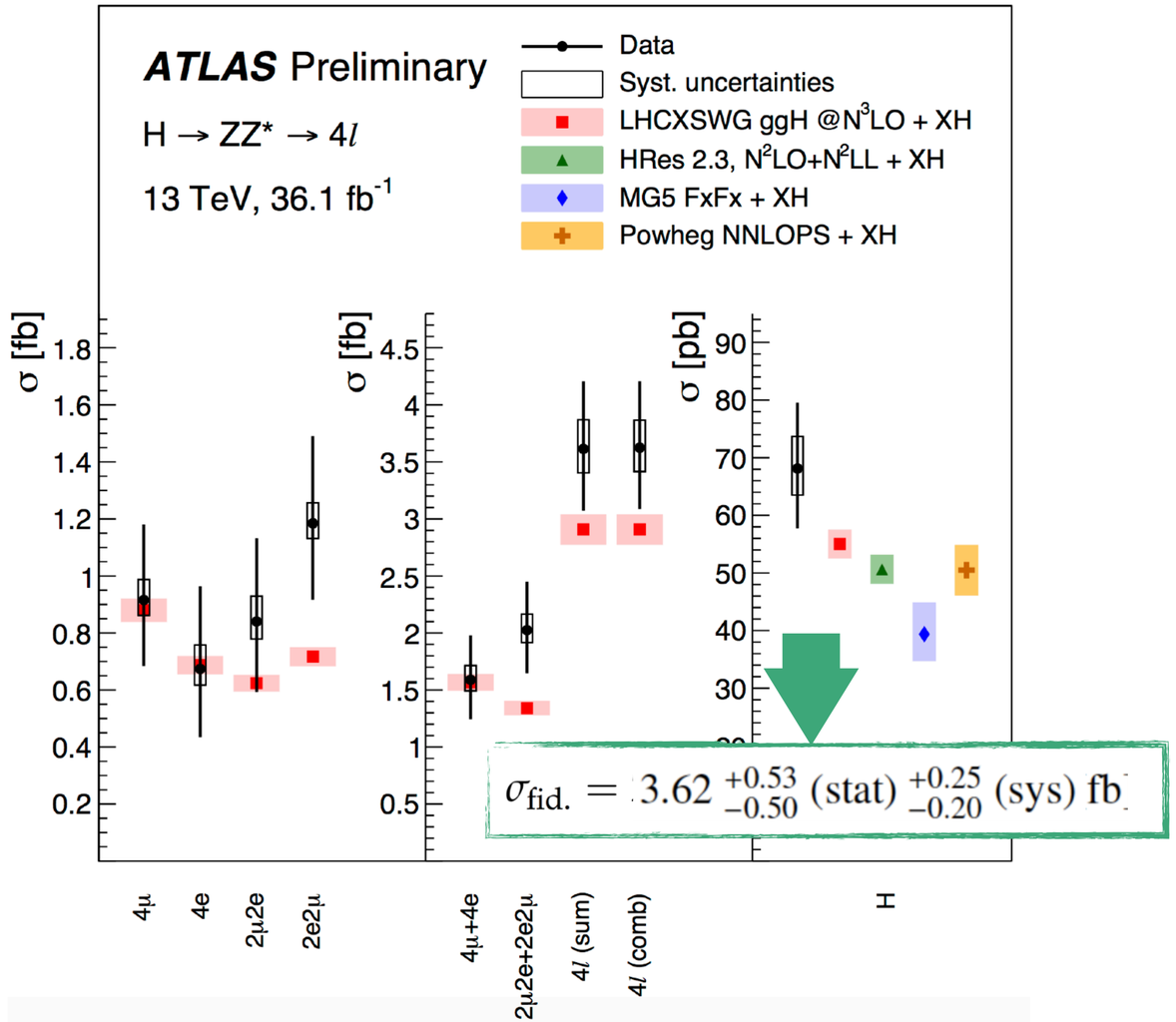
Measurements of a fiducial cross section:

- Measure within fiducial phase space to minimise model dependence
- Not sensitive to production mechanism, but expected to be dominated by gluon fusion

Fiducial XS @ 7, 8, 13 TeV



Fiducial XS @ 13 TeV



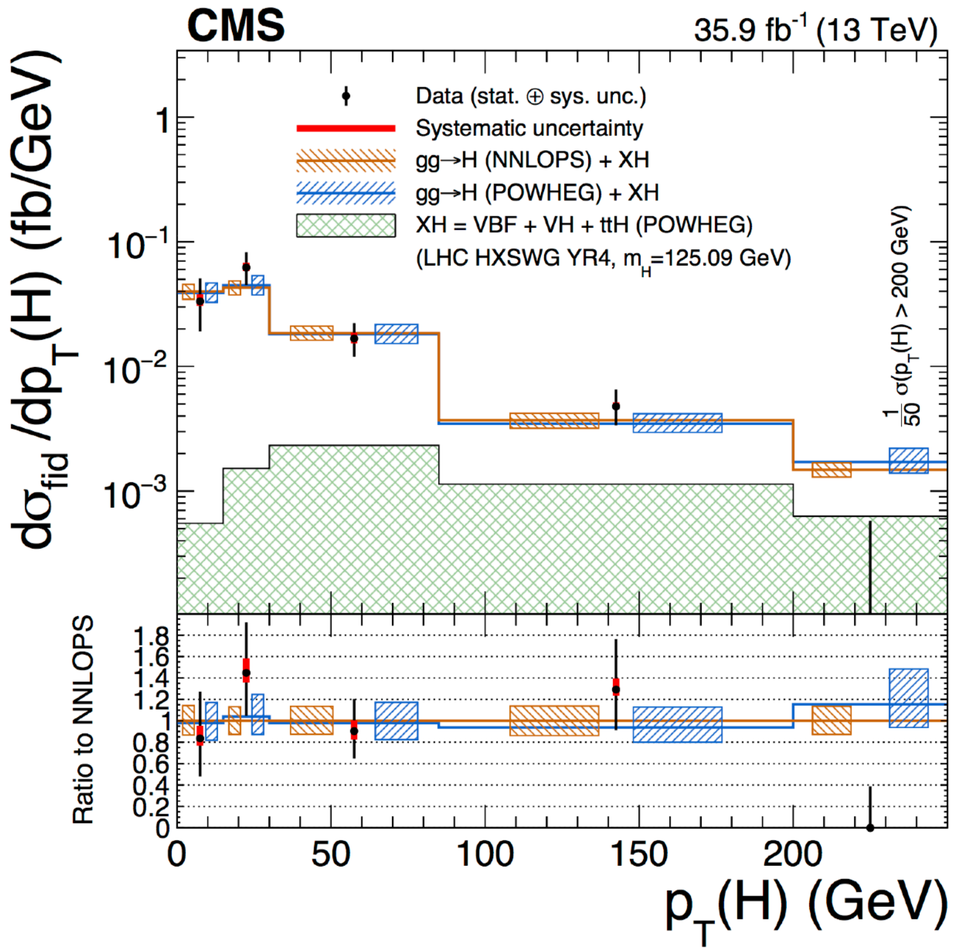
H → 4ℓ: Fiducial cross sections

CMS-HIG-16-041
ATLAS-CONF-2017-032

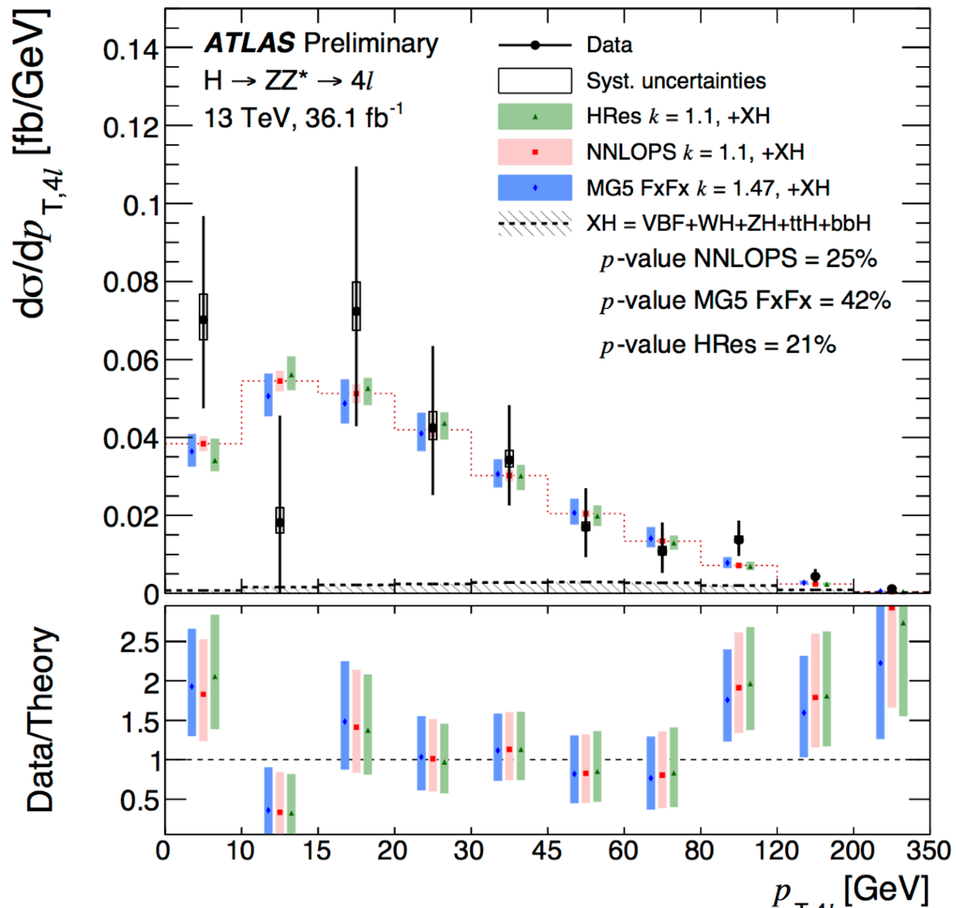
Measurements of a fiducial cross section:

- Measure within fiducial phase space to minimise model dependence
- **Differential measurements** for: **$p_T(4l)$, N(jets), p_T(jet), Y(4l), |cosθ*|, Δφ(jj) and m_{34}**
- Sensitive to modelling of hard quark and gluon radiation, relative contributions of different production modes, BSM effects in the loops, PDFs, etc.

$p_T(4l)$: CMS



$p_T(4l)$: ATLAS



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CMS-HIG-16-041
ATLAS-CONF-2017-032

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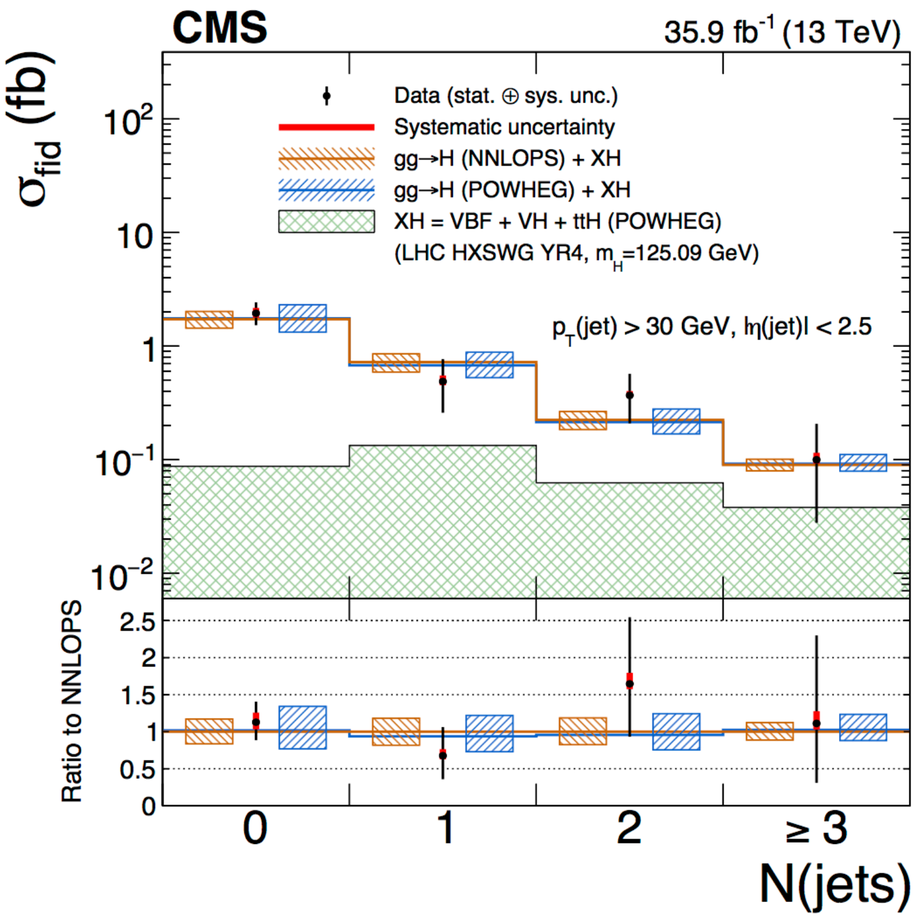
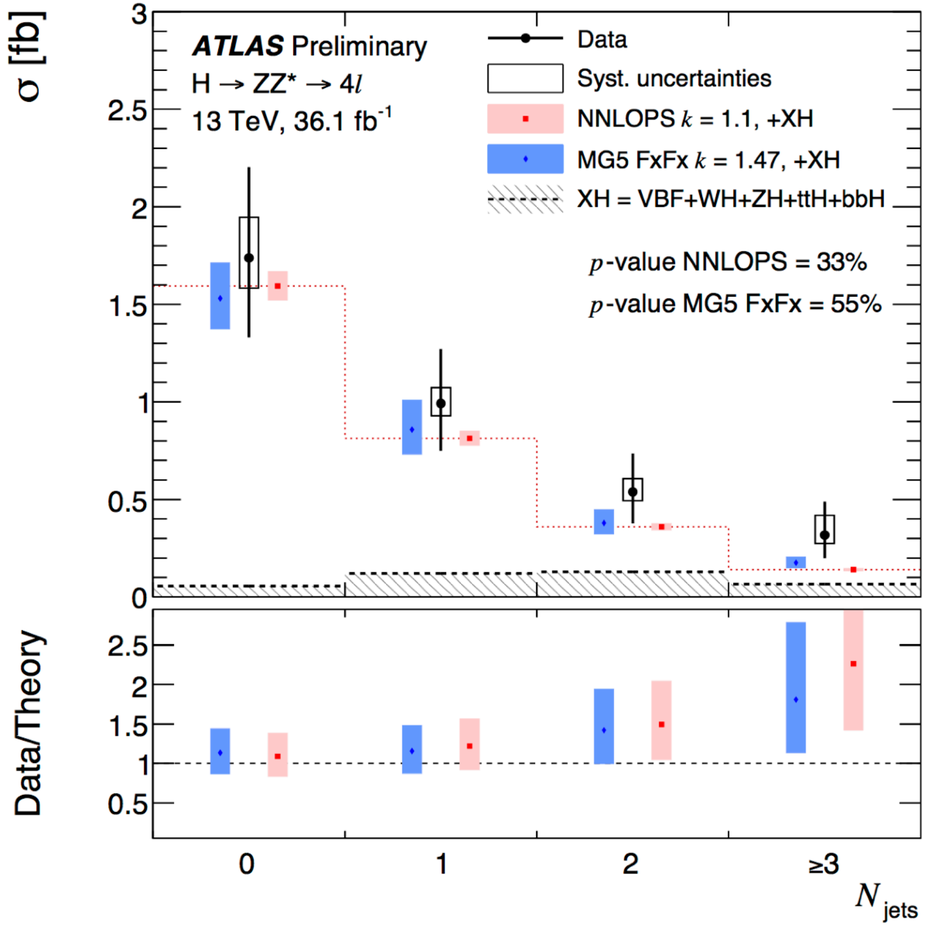
N(jets) : CMS



N(jets) : ATLAS



H → γγ measurements

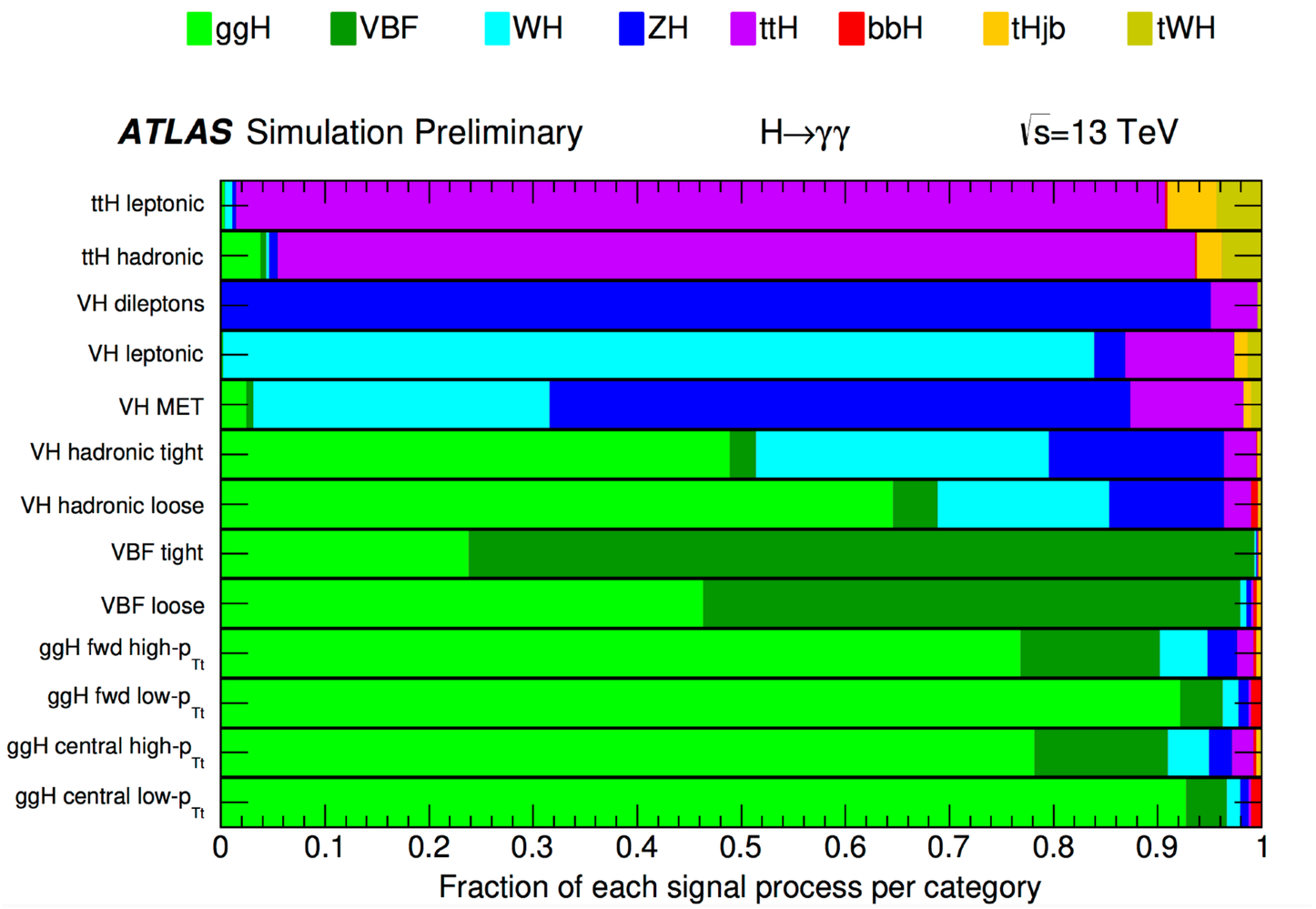
H → γγ: Analysis approaches

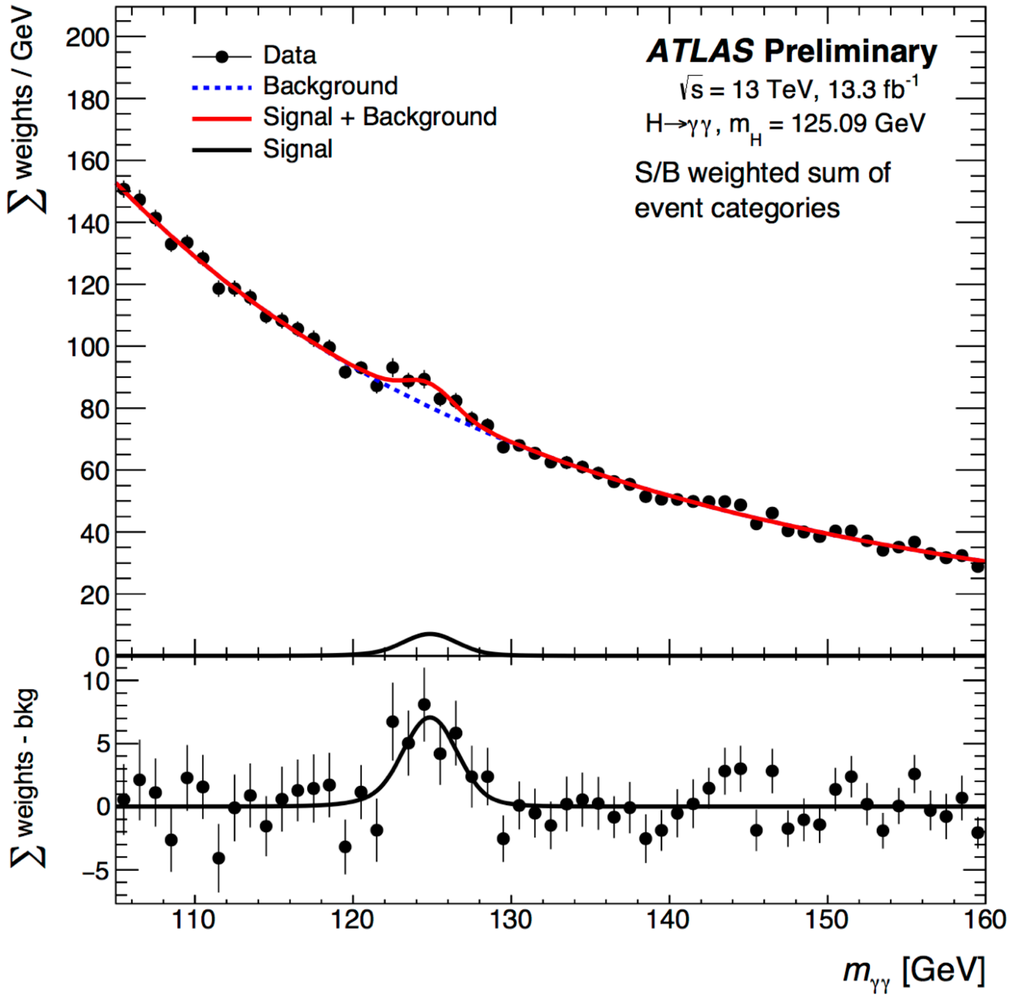
ATLAS-CONF-2016-067

Exploit clean signature and good $m_{\gamma\gamma}$ resolution

- **Even categorisation:** Based on mass resolution and S/B in the VBF, VH, ttH and gluon fusion categories
- Simultaneous fit to the di-photon $m_{\gamma\gamma}$ spectra in all cats.

13 categories targeting 5 production modes:





H → γγ: Analysis approaches

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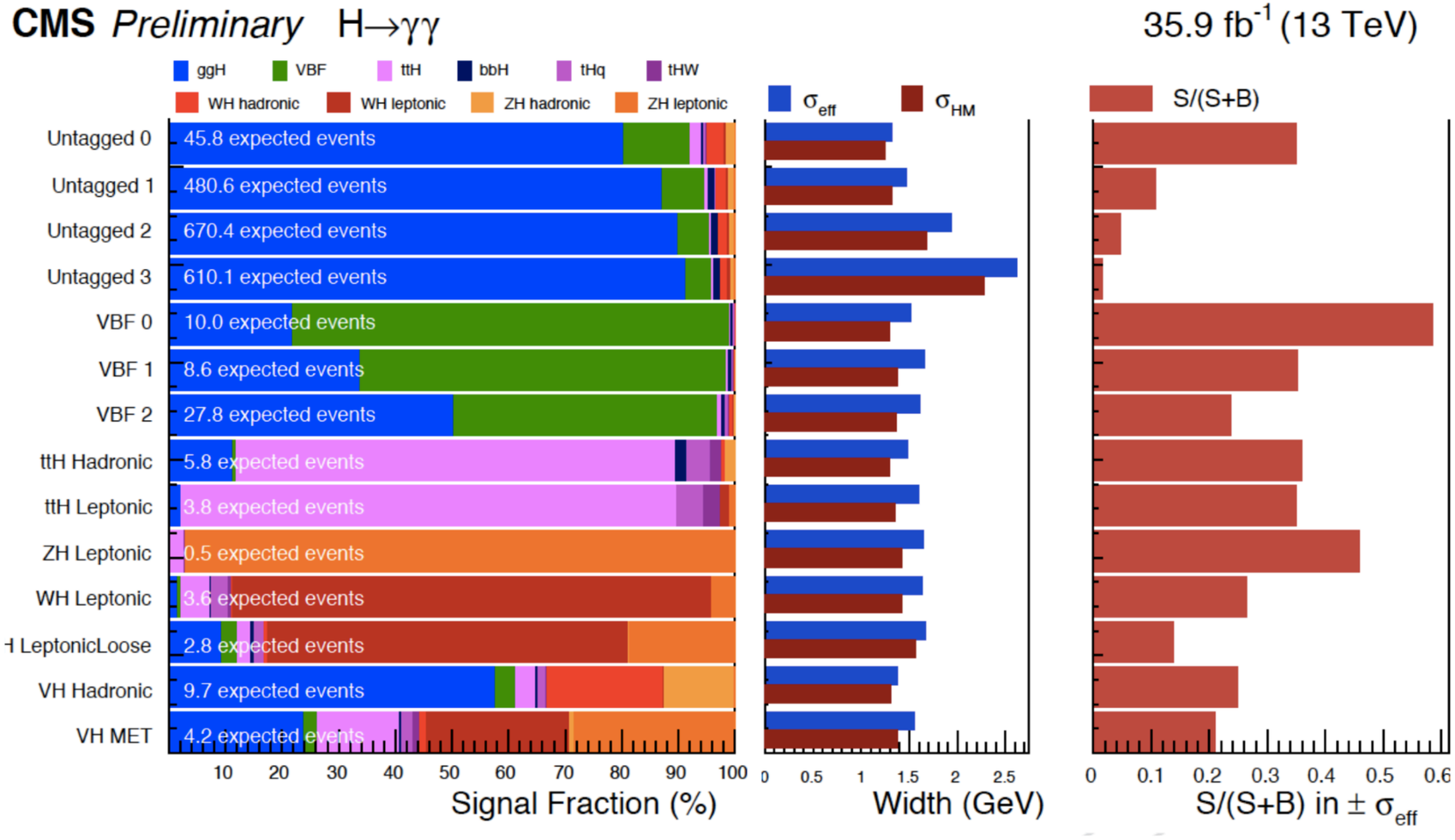
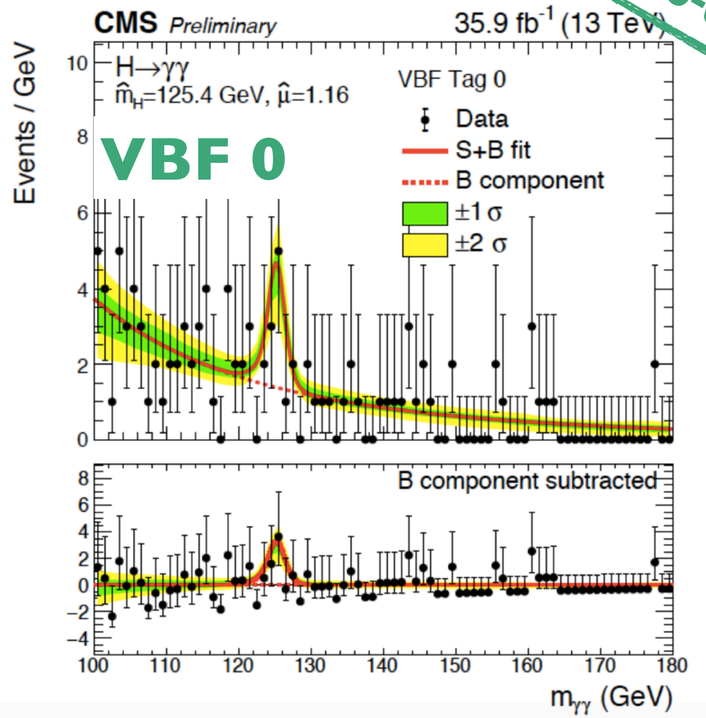
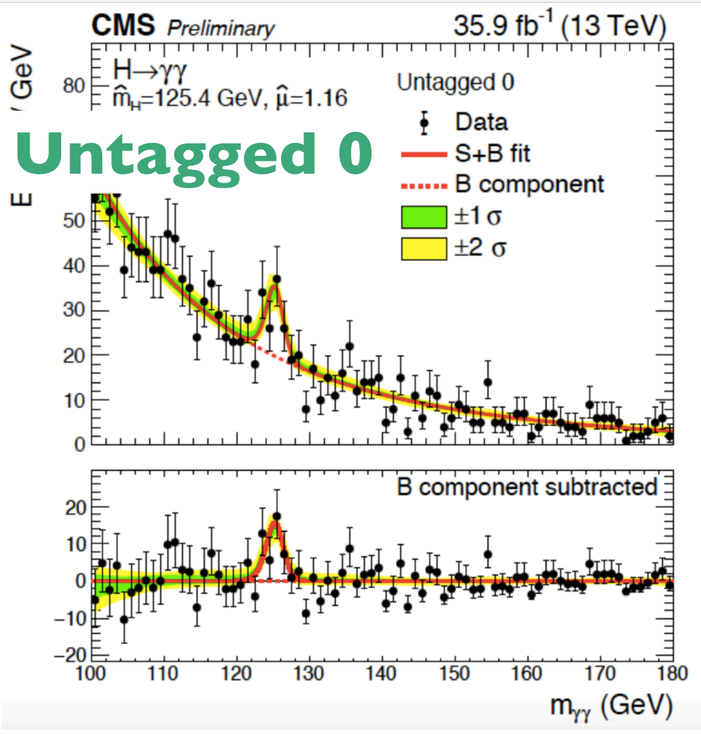
- Simultaneous fit to the di-photon $m_{\gamma\gamma}$ spectra in all cats.

14 categories targeting 5 production modes:







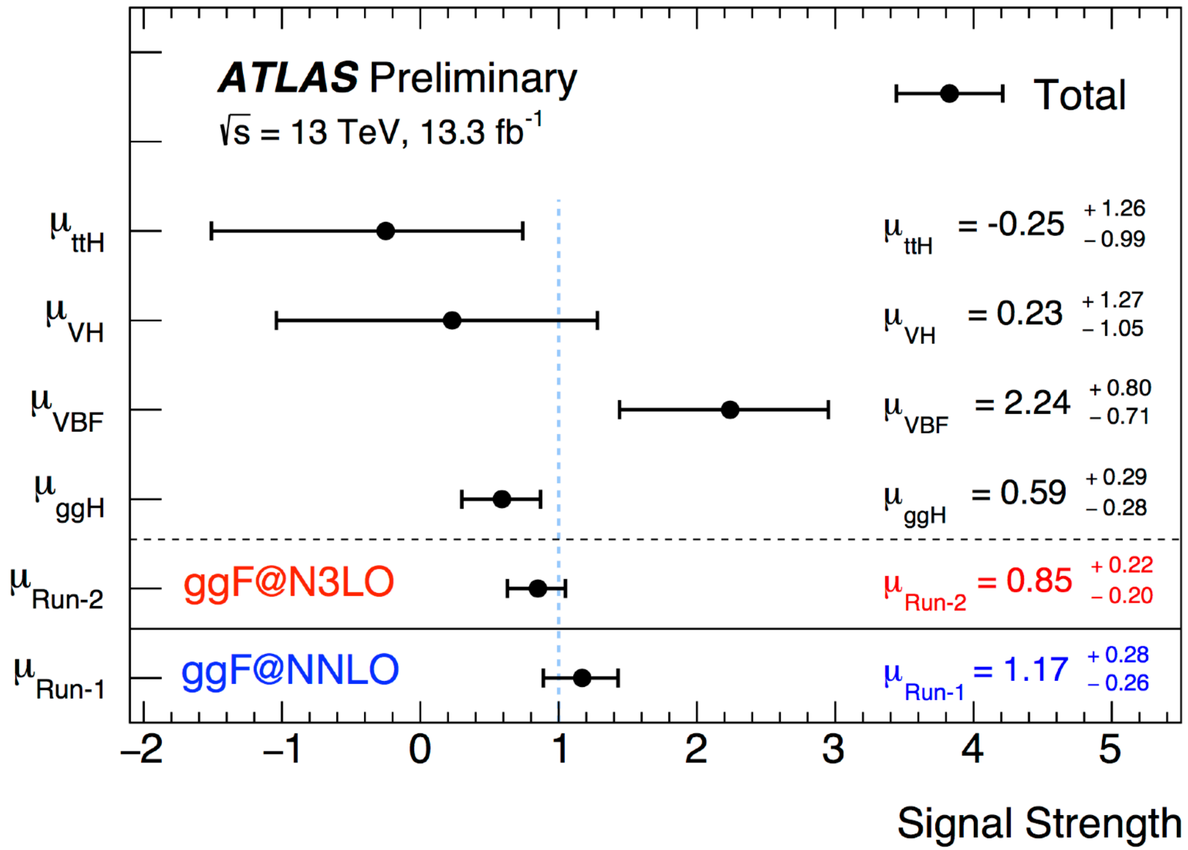
H → γγ: Production modes

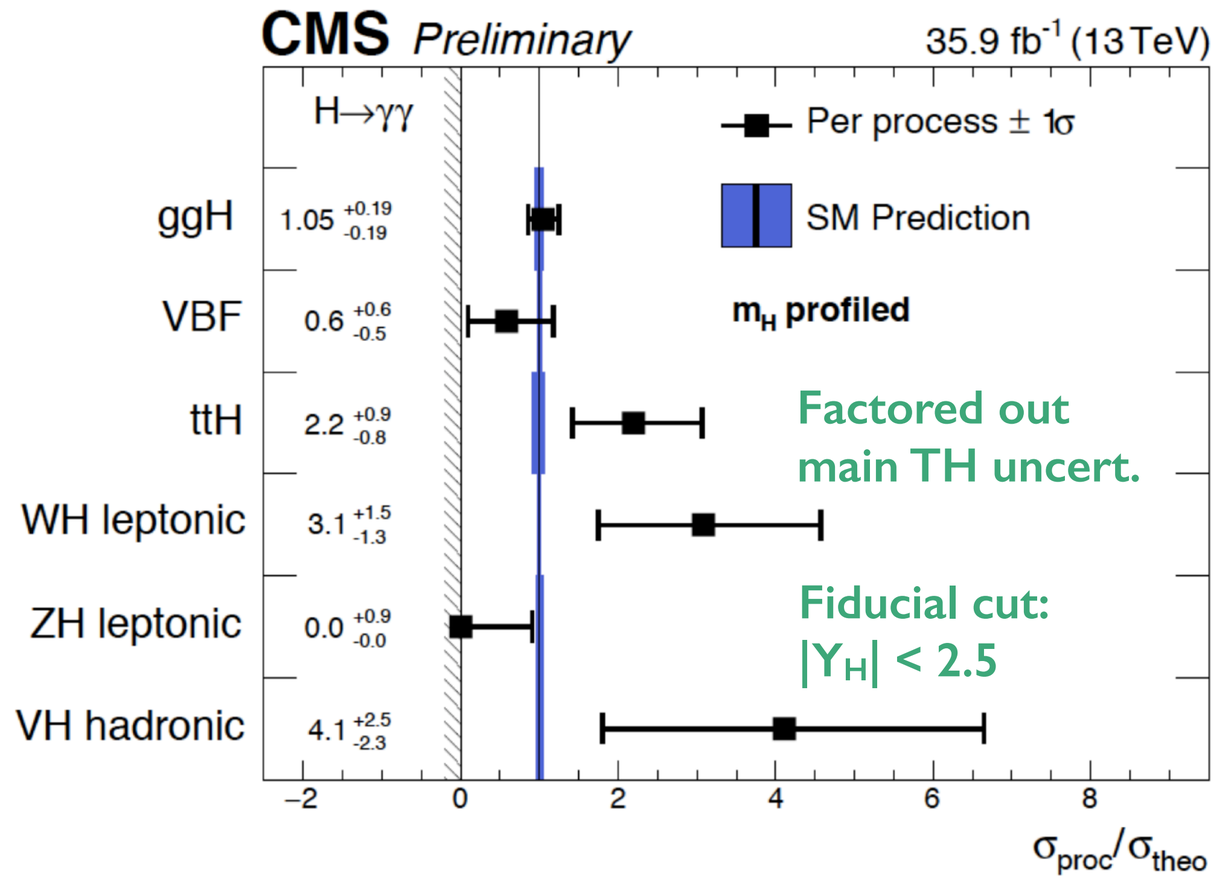
CMS-PAS-HIG-16-040
ATLAS-CONF-2016-067

Extract info on H production by performing simultaneous fit in 14 categories:

- A likelihood scan of the signal strength is performed, profiling all other nuisances including the Higgs mass.

Results presented in form of signal strengths per production mode, coupling modifiers, and as "simplified" cross sections:





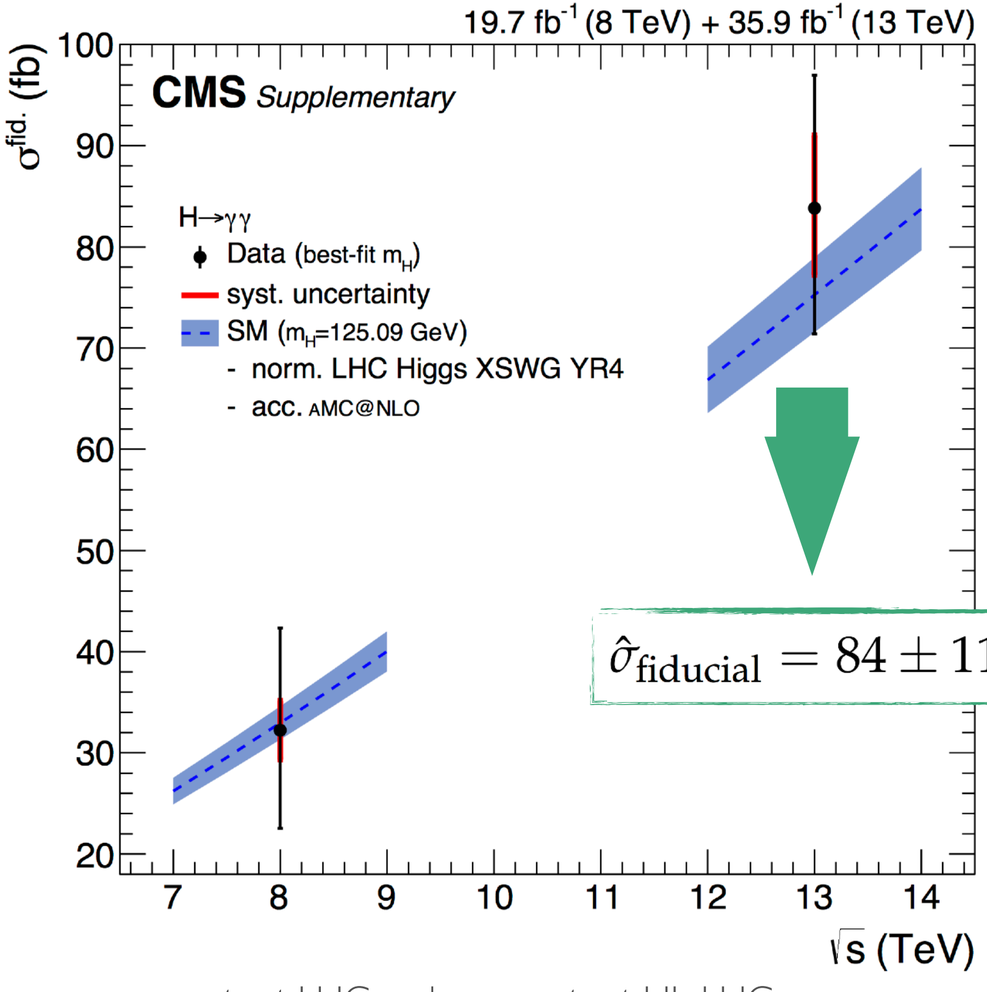
H → γγ: Fiducial cross sections

CMS-PAS-HIG-17-015

Performed measurement of fiducial cross sections (XS)

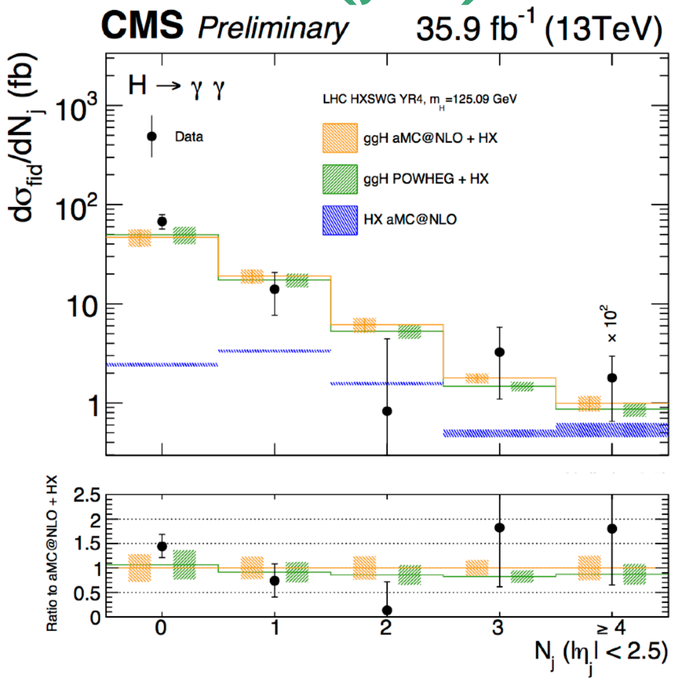
- **3 categories** to optimize signal significance based on mass resolution estimator (decorelated from di-photon inv. mass)
- Measured within fiducial phase space to minimise model dependence
- **Differential measurements** of **$p_T(\gamma\gamma)$, Y(γγ), N(jets)**

Integrated fiducial XS @ 8, 13 TeV

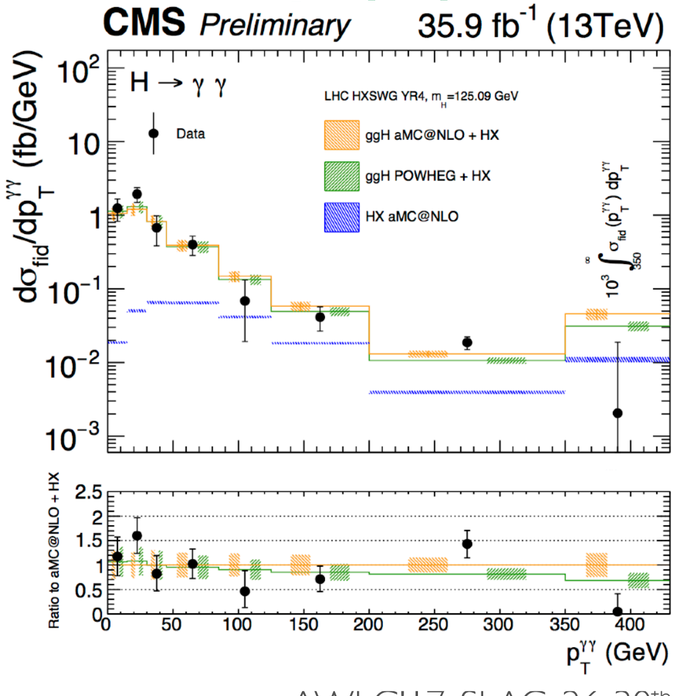


$$\hat{\sigma}_{\text{fiducial}} = 84 \pm 11\ (\text{stat}) \pm 7\ (\text{syst})\ \text{fb}$$

N(jets)



$p_T(\gamma\gamma)$



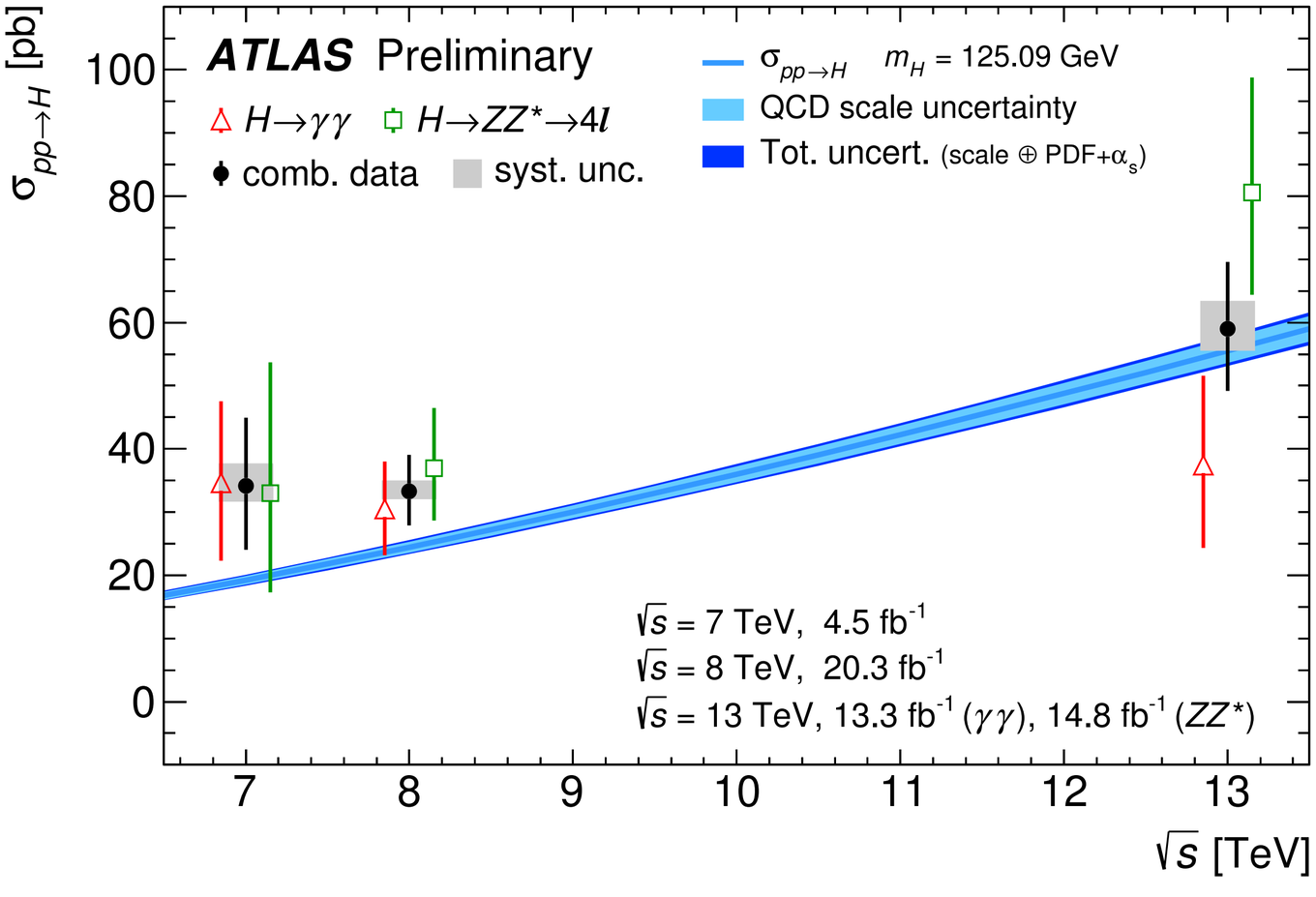
H → γγ: Fiducial cross sections

ATLAS-CONF-2016-067

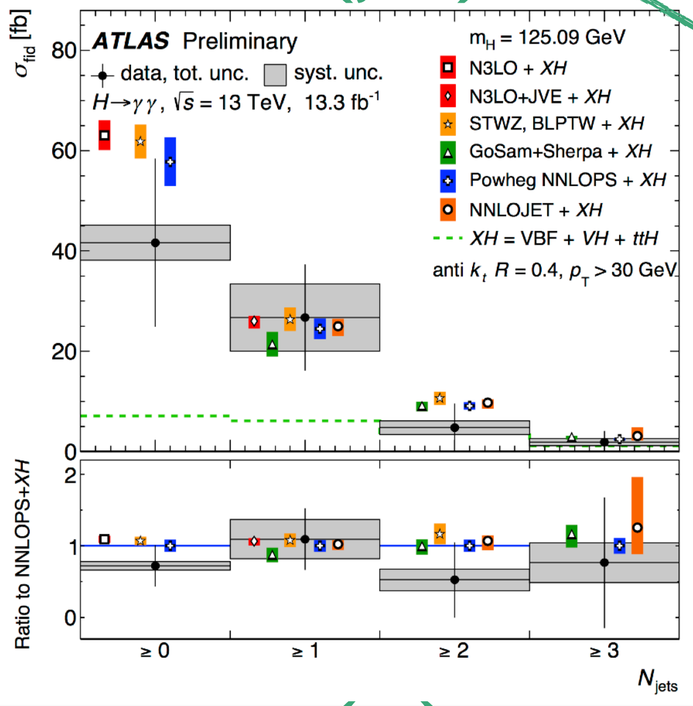
Performed measurement of fiducial cross sections (XS):

- Measured within fiducial phase space to minimise model dependence
- **Differential measurements** of **$p_T(\gamma\gamma)$, $Y(\gamma\gamma)$, N(jets)**
- Good agreement between H → 4l and H → γγ results in all variables
  - p-values higher than 56%

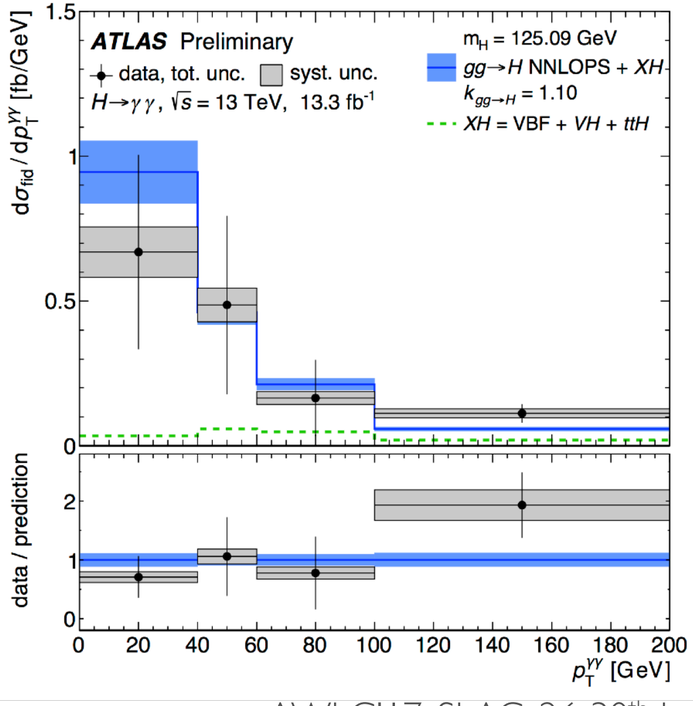
H→γγ + H→ZZ→4l @ 7, 8, 13 TeV



N(jets)



$p_T(\gamma\gamma)$



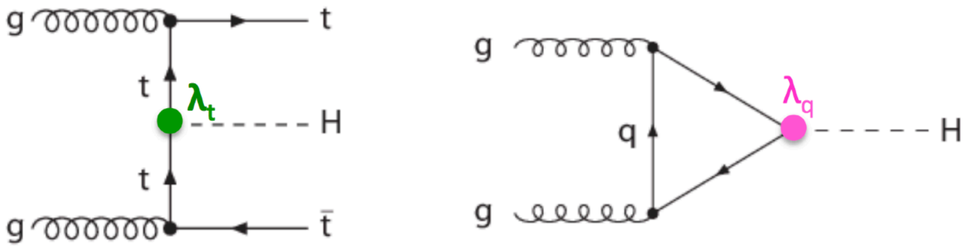
Search for H production in association with top quark

ttH: Analyses approaches

CMS-PAS-HIG-17-004
CMS-PAS-HIG-17-003

ttH production - direct probe of top Yukawa coupling:

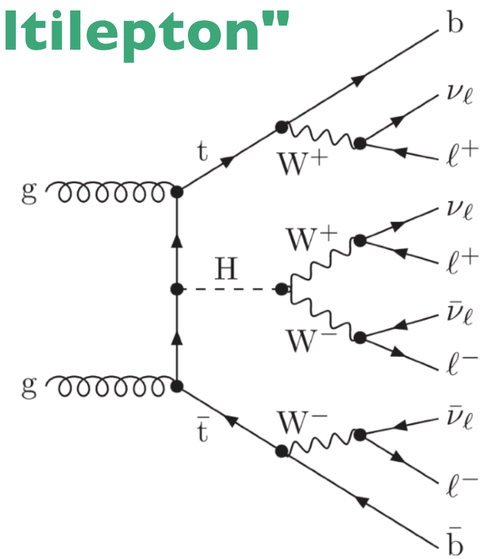
- **Tree-level process, XS proportional to λ_t^2**. Complementary evidence to loop-induced ggH.



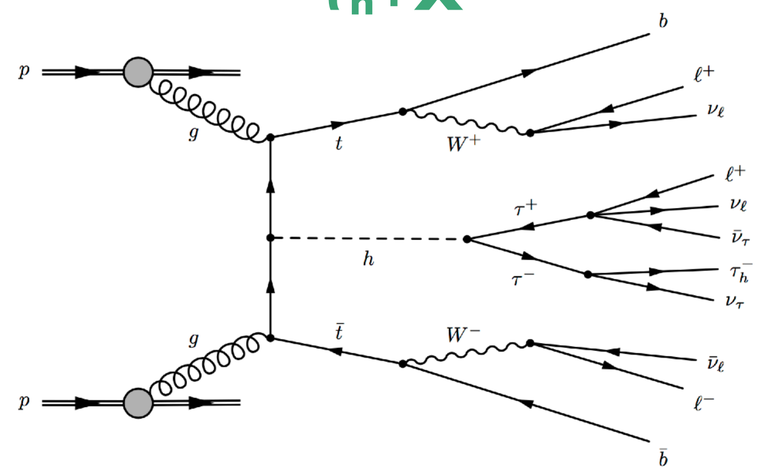
σ_{ttH} ~ 507 fb^{-1} @ 13TeV

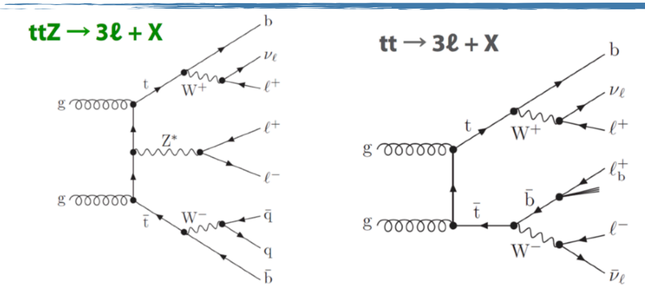
- Several decay modes. Updated results for **leptonic searches for ttH production (H → WW/ZZ/ττ)**.

"Multilepton"



"τ_h+X "





Irreducible: tt+W/Z/γ* - from simulation, O(10%) uncertainty

Reducible: tt+jets or charge mis-assignment - from data, O(30%) uncertainty

Similar strategy for background estimate in the two analyses

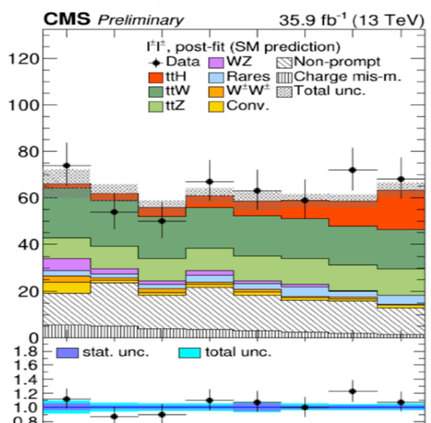
ttH: Multileptonic and semi-had. H → ττ

CMS-HIG-17-003/004

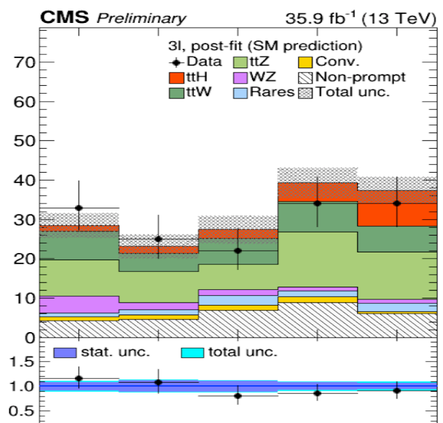
Extensive use of MVA and ME-based methods for signal extraction:

- **Multileptonic categories (2ℓss , 3ℓ , 4ℓ):** use **kinematic BDTs** against **ttbar** & **ttW/Z**, and/or **ME likelihood ratio** for additional **ttW/Z** separation (counting experiment in 4ℓ category)

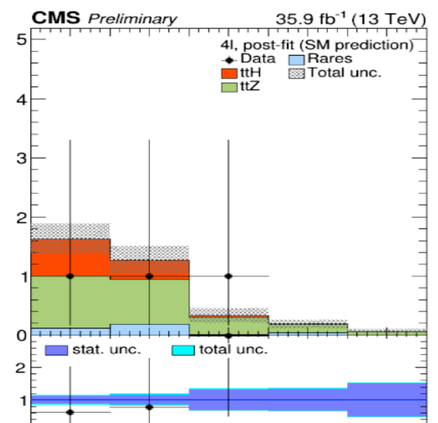
2ℓss:



3ℓ:

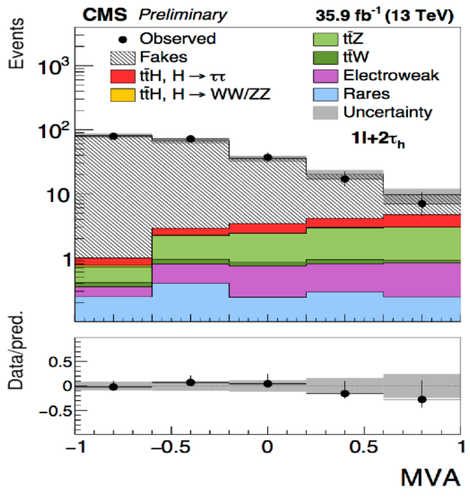


4ℓ:

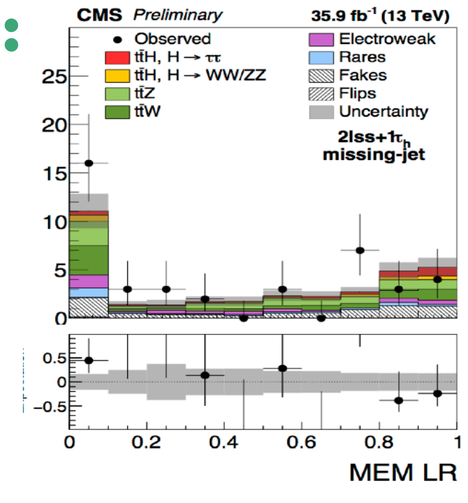


- **Semi-nadronic categories (3ℓ + 1τh, 2ℓss + 1τh, 1ℓ + 2τh):** use **kinematic BDTs** against **ttbar** & **ttW/Z**, and/or **ME likelihood ratio** for additional **ttW/Z** separation

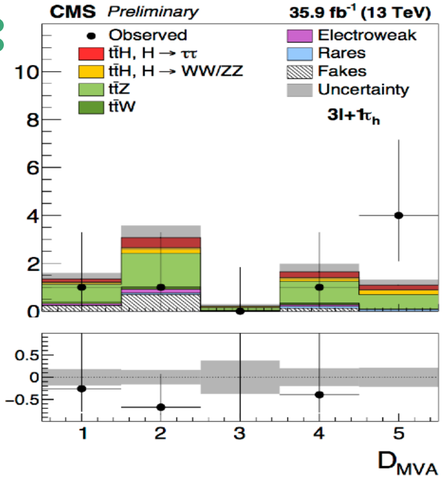
1ℓ + 2τh:



3ℓ + 1τh:



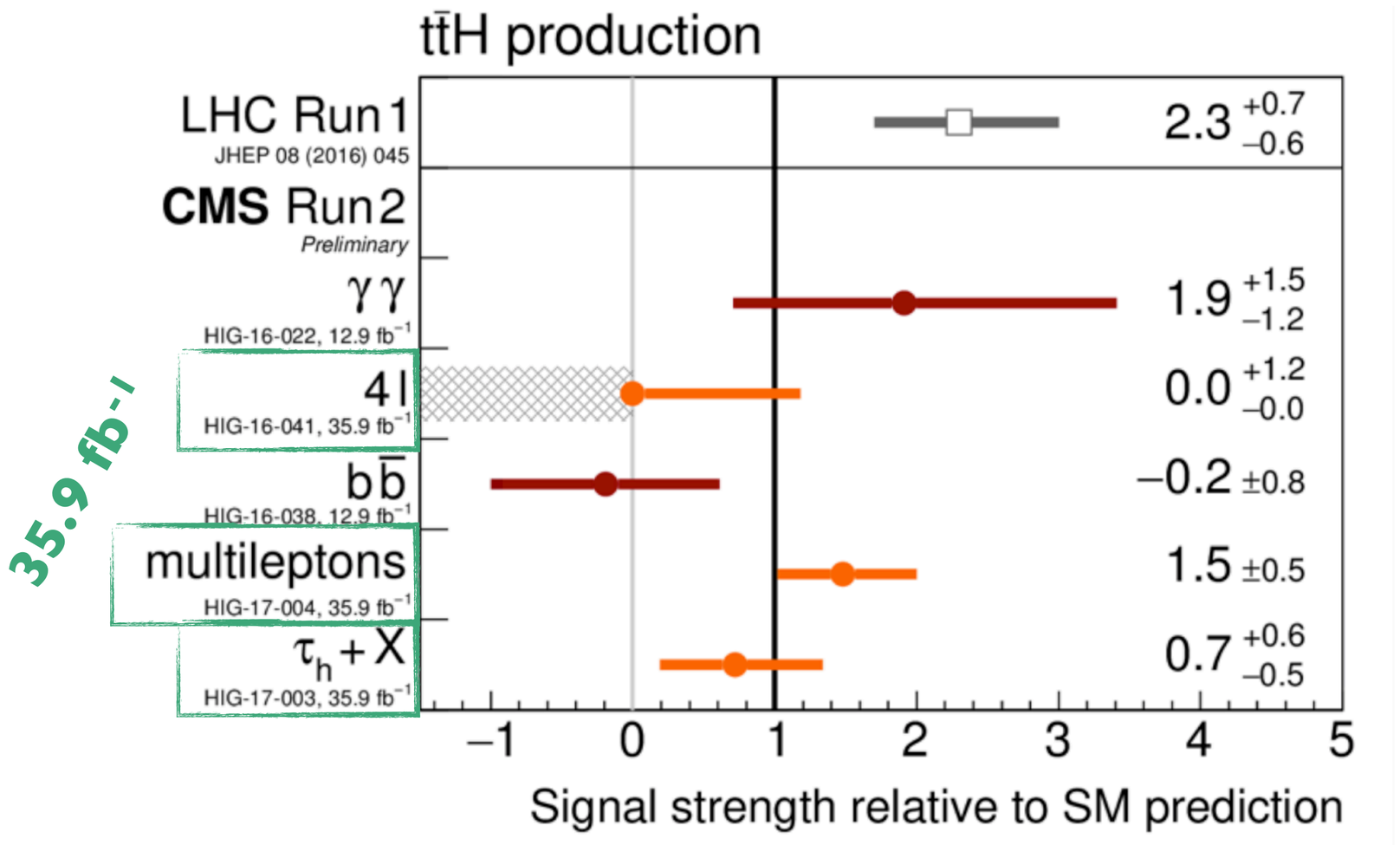
2ℓss + 1τh:



ttH: Results

CMS-PAS-HIG-17-004
CMS-PAS-HIG-17-003
CMS-PAS-HIG-16-041

First indication for ttH production in multi-lepton final states:



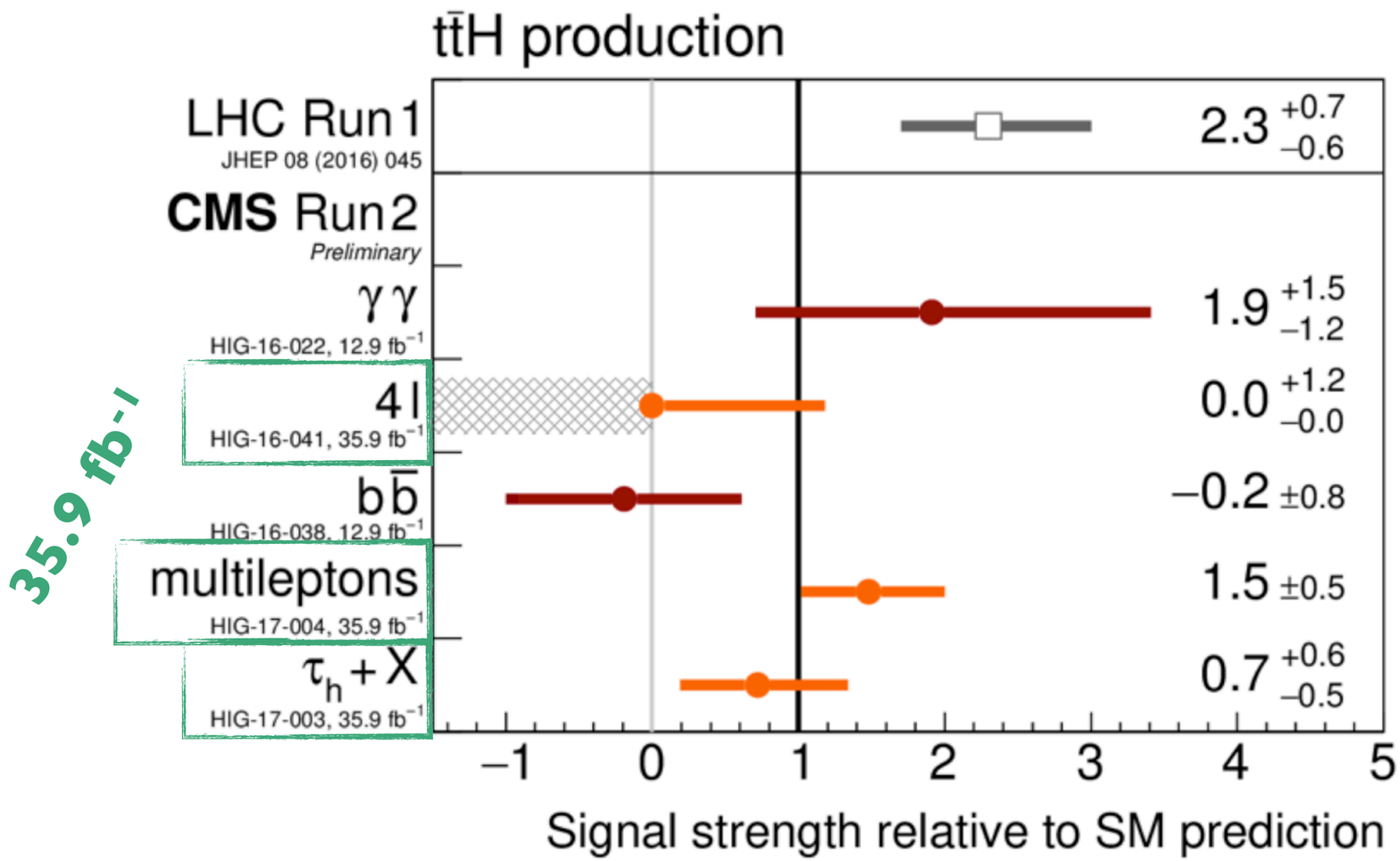
ttH, multilepton final states (electrons, muons):		
significance	3.3σ (observed)	2.5σ (expected)

ttH, semi-hadronic H→ττ		
significance	1.4σ (observed)	1.8σ (expected)

ttH: Results

CMS-PAS-HIG-17-004
CMS-PAS-HIG-17-003
CMS-PAS-HIG-16-041

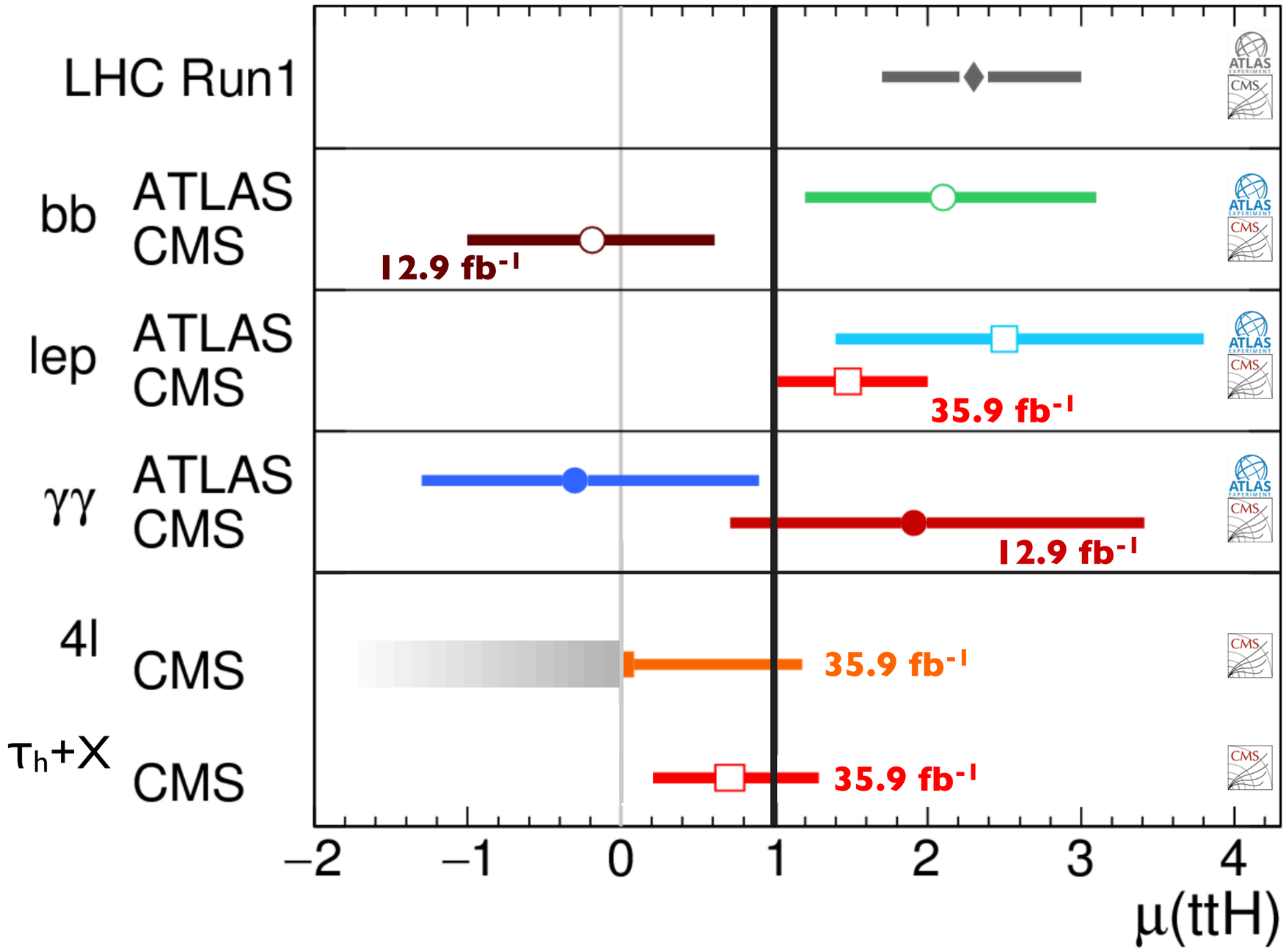
First indication for ttH production in multi-lepton final states:



There's still not a single analysis with a strong & unambiguous ttH signal, and it will take time and effort to get there...

ttH: Results

Overview of measurements of ttH production by CMS and ATLAS @ 13 TeV:



Probing of H → μμ couplings

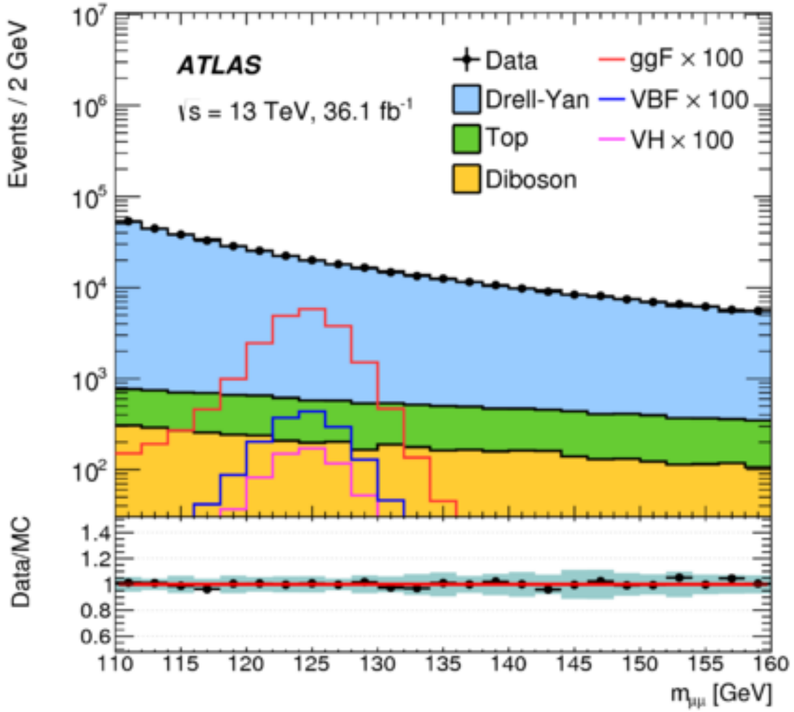
H → μμ: Analyses & Results

ATLAS-CONF-2017-014

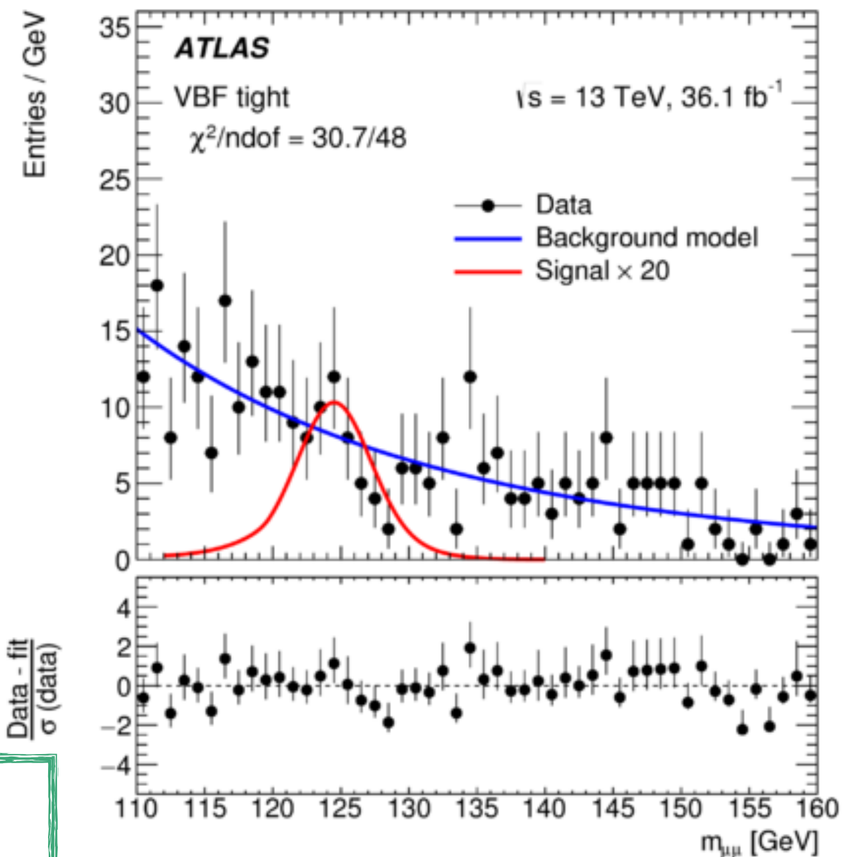
Sensitivity to measure Higgs couplings to 2nd generation fermions:

- Clean signature, good $m_{2\ell}$ resolution. Small BR of ~10^{-4}. Irreducible background mainly Z/γ* → μμ
- **Event cats.**: Use **BDTs** to separate VBF-like events. ggH-dominated cats. based on **p_T and η of μμ**
- Simultaneous fit to the di-muon $m_{\mu\mu}$ spectra

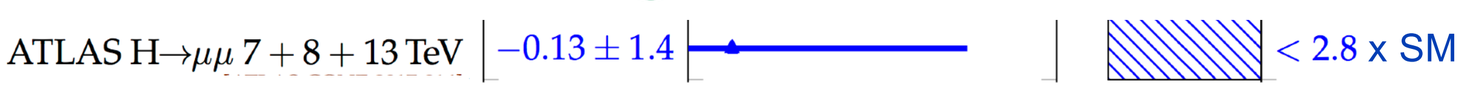
Inclusive in categories



VBF tight category:



Combination of results @ 7, 8, 13 TeV:



Probing of H → ττ couplings

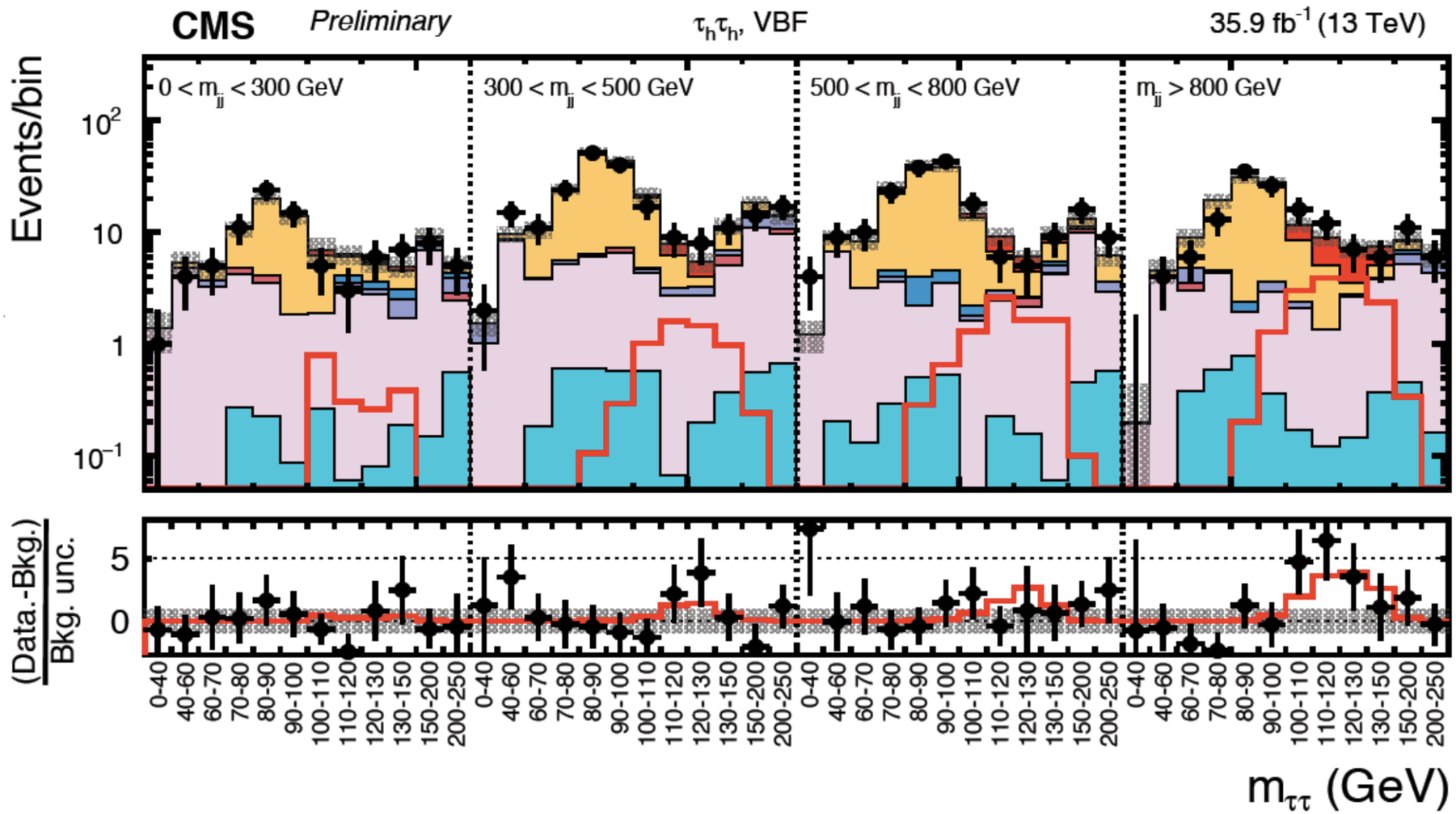
H → ττ: Analyses & Results

CMS-PAS-HIG-16-043

Sensitivity to measure Higgs couplings to 3rd generation fermions:

- **Event cats.:** 4 final states (**eμ, μτ_h, eτ_h, $\tau_h\tau_h$**) and 3 categories (**0-jet, VBF and Boosted**)
- Simultaneous fit in two kinematic observables that yield the best sensitivity for each signal region (2D) plus control regions (1D) for the tt, QCD and W+jets backgrounds.

VBF category, $\tau_h\tau_h$ final state:

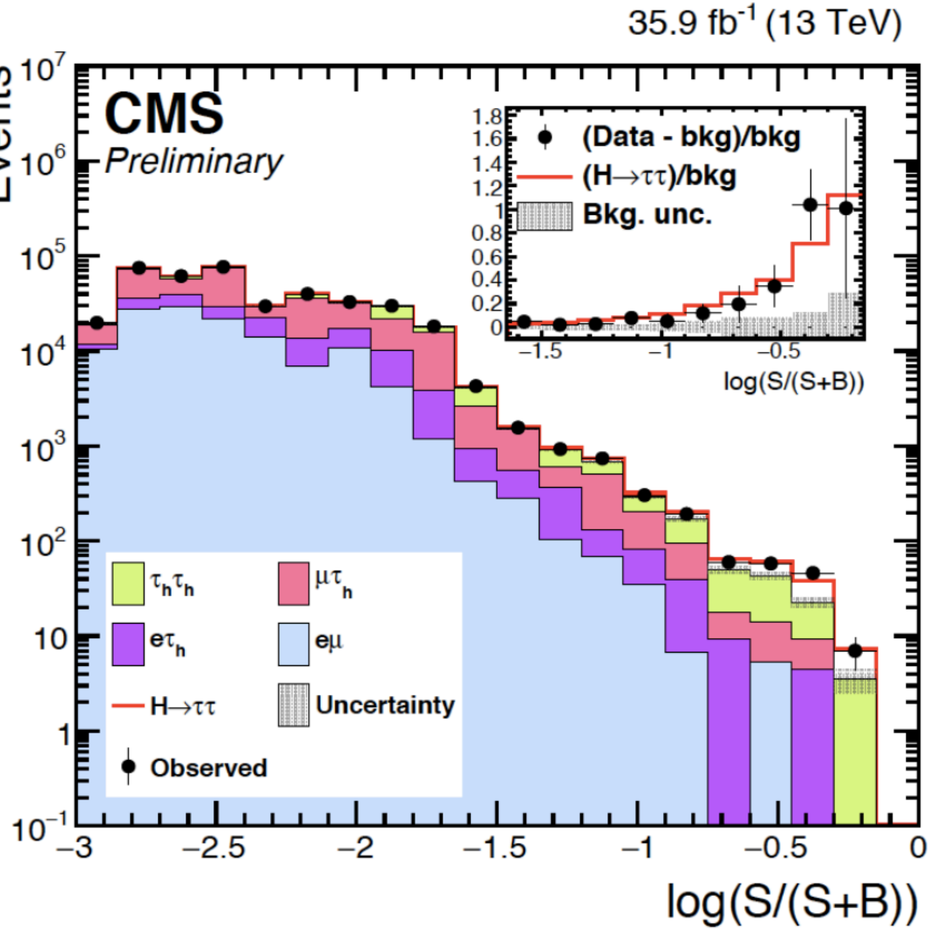


H → ττ: Analyses & Results

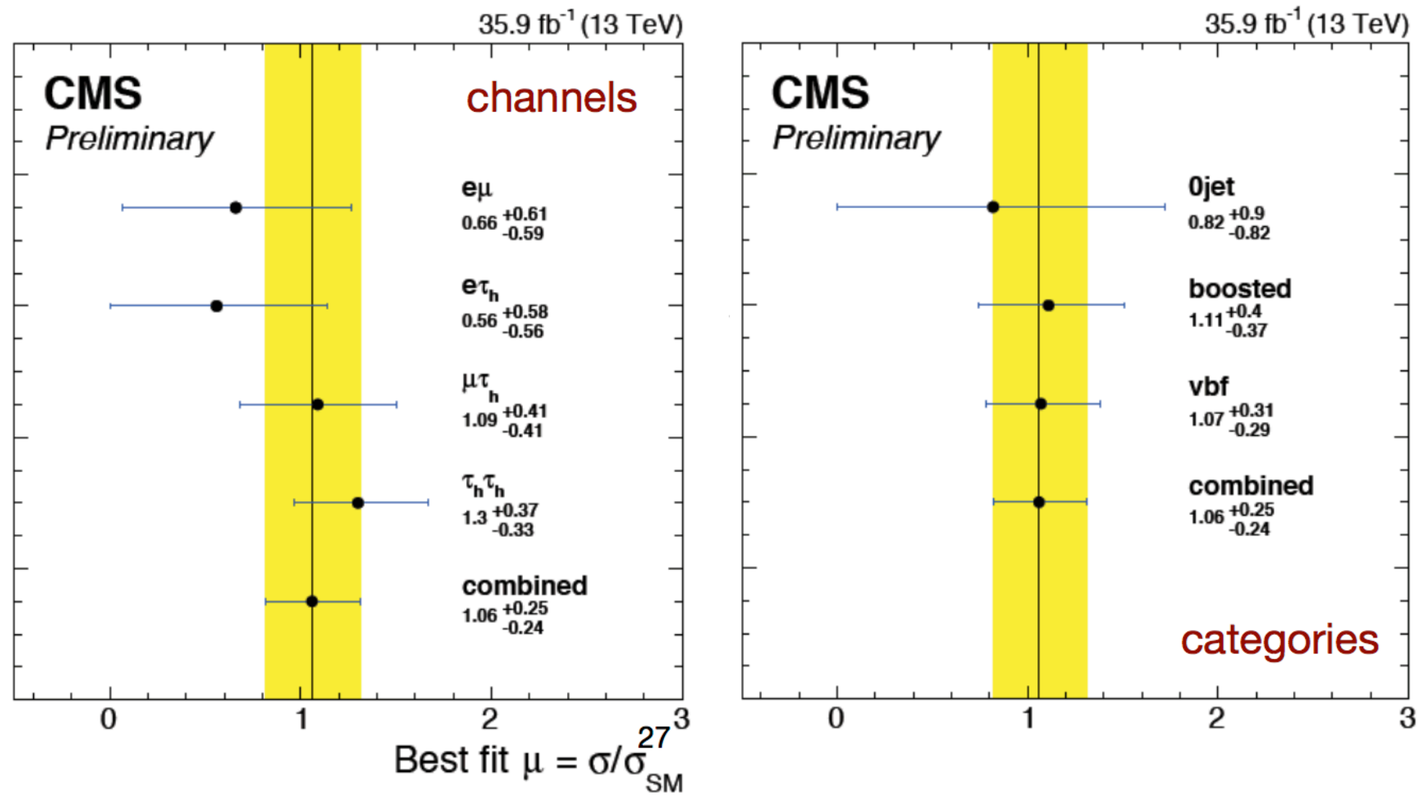
CMS-PAS-HIG-16-043

Sensitivity to measure Higgs couplings to 3rd generation fermions:

- **Event cats.:** 4 final states (**eμ, μτ_h, eτ_h, $\tau_h\tau_h$**) and 3 categories (**0-jet, VBF and Boosted**)
- Simultaneous fit in two kinematic observables that yield the best sensitivity for each signal region (2D) plus control regions (1D) for the tt, QCD and W+jets backgrounds.



Signal strength per category and final state:



Observed (expected) significance of 4.9σ (4.7σ) for m_H = 125 GeV.

Run 1 LHC combination: observed with > 5σ significance

Probing of H → bb couplings

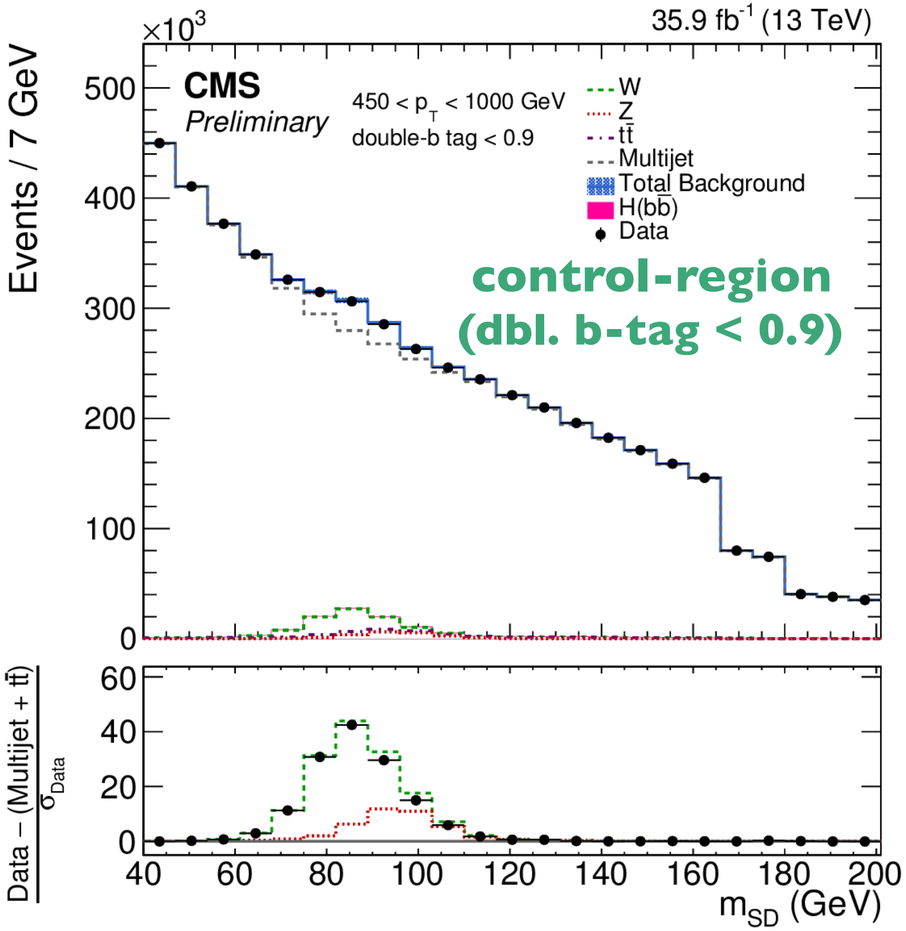
H → bb: Analyses & Results

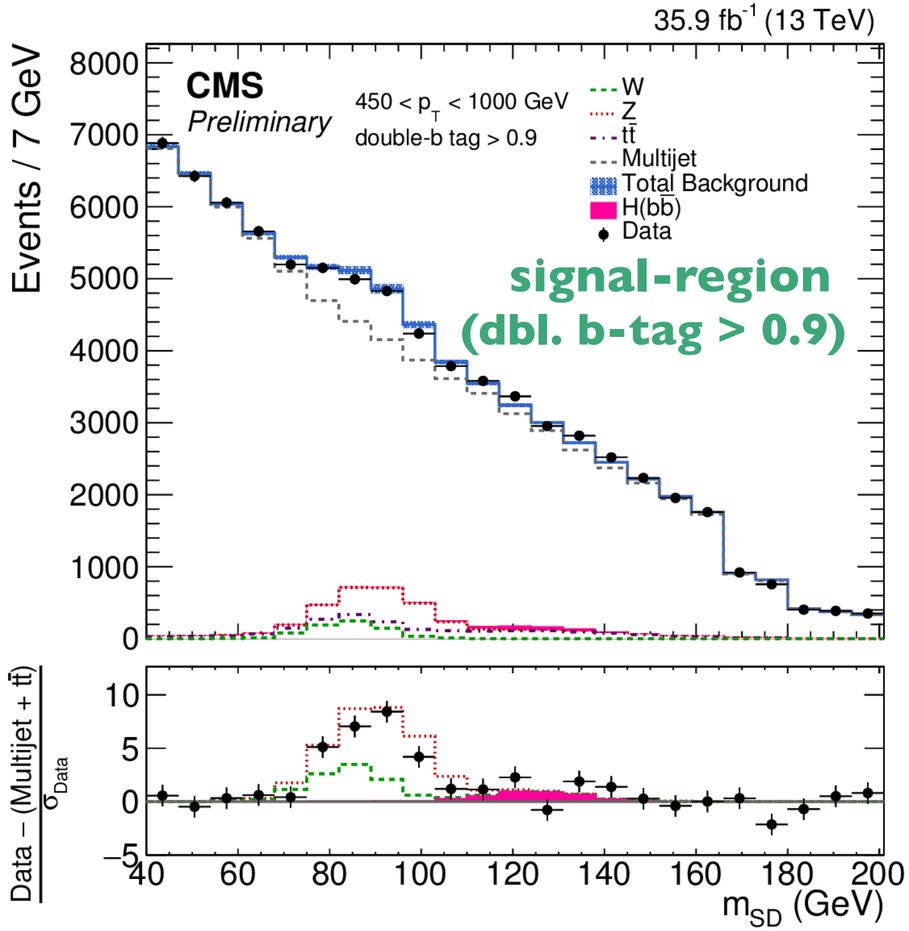
CMS-PAS-HIG-17-010

Sensitivity to measure Higgs couplings to 2nd generation fermions :

- **"boosted" gg→H→bb:** Exploit boosted topologies: aim for H(125) produced with **high p_T**
- H → bb reconstructed as a single jet (using jet substructure & b-tagging techniques).
- Simultaneous fit of jet mass distribution (both for events that pass and fail b-tagging - to extract QCD bkg).

Inclusive fit results:





Events categorised in bins of the jet p_T (450 - 1000 GeV)

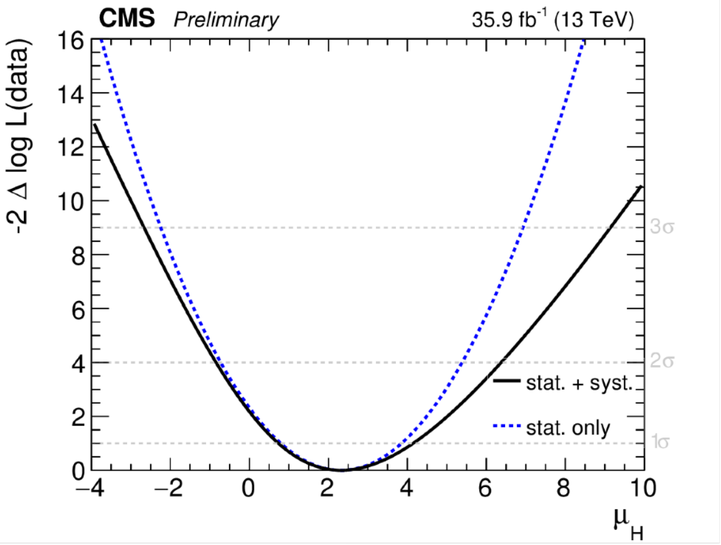
Sensitivity to Z→ bb process in single-jet topology

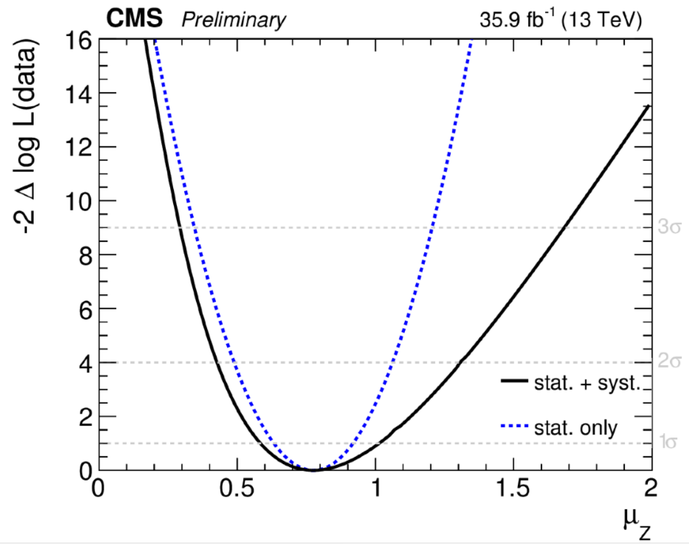
H → bb: Analyses & Results

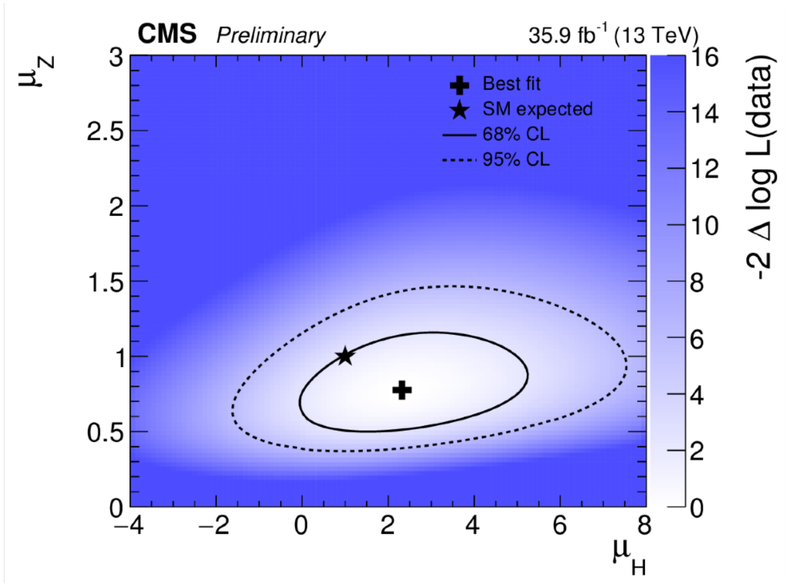
CMS-PAS-HIG-17-010

Sensitivity to measure Higgs couplings to 2nd generation fermions :

- **"boosted" gg→H→bb:** Exploit boosted topologies: aim for H(125) produced with **high p_T**
- H → bb reconstructed as a single jet (using jet substructure & b-tagging techniques).
- Simultaneous fit of jet mass distribution (both for events that pass and fail b-tagging - to extract QCD bkg).







	H	Z
Observed best fit	$\mu H = 2.3^{+1.8}_{-1.6}$	$\mu Z = 0.78^{+0.23}_{-0.19}$
Expected significance	0.7σ $(\mu H = 1)$	5.8σ $(\mu_Z = 1)$
Observed significance	1.5σ	5.1σ

First observation of Z→ bb in the single-jet topology

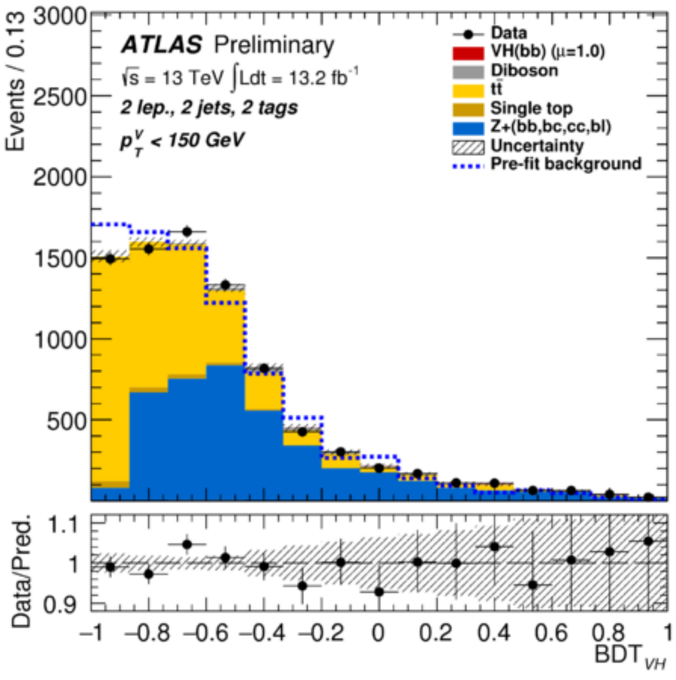
H → bb: Analyses & Results

ATLAS-CONF-2016-091

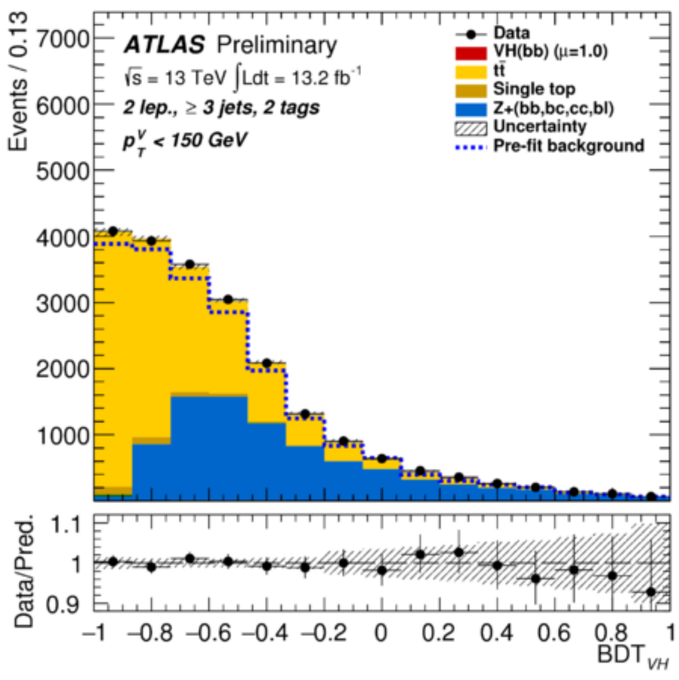
Sensitivity to measure Higgs couplings to 2nd generation fermions :

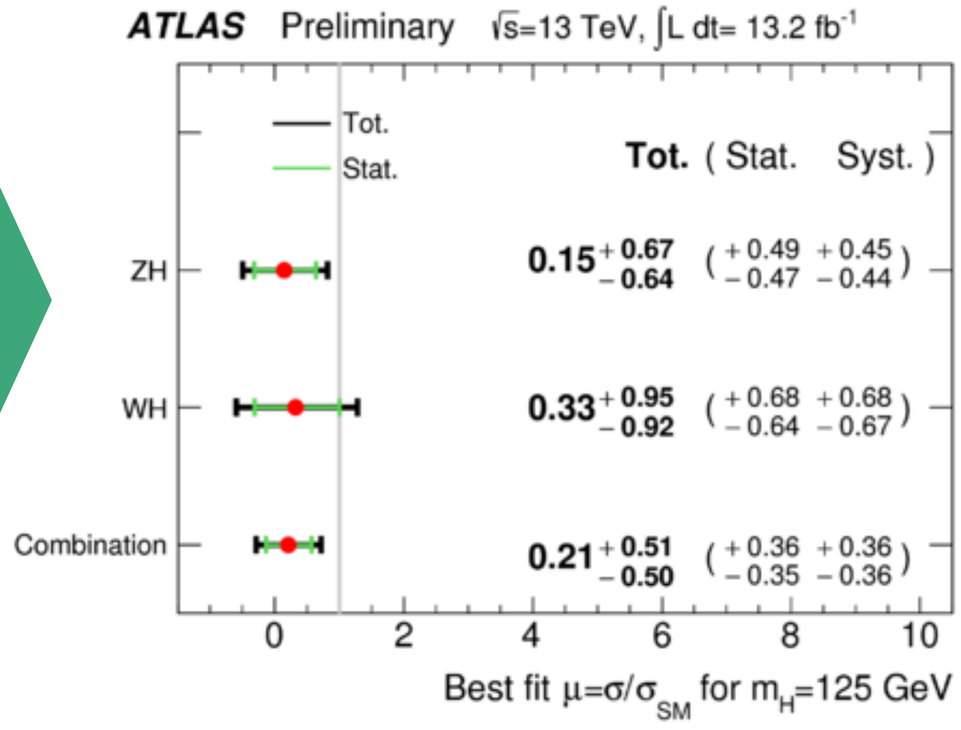
- Aim for SM Higgs boson produced **in association with W or Z** ($Z\to\nu\nu$, $W\to\ell\nu$, and $Z\to\ell\ell$).
- **Event cats:** based on b-tagging, number of leptons, number of jets, and kinematics.
- Simultaneous fit of several MVA discriminants (one per cat.).

N_{jets} = 2



$N_{jets} \geqq 3$





Verified by extracting the W/Z→ bb process

Obs. (exp.) significance 0.4 (1.9)
[still limited statistics of 13 fb^{-1}]

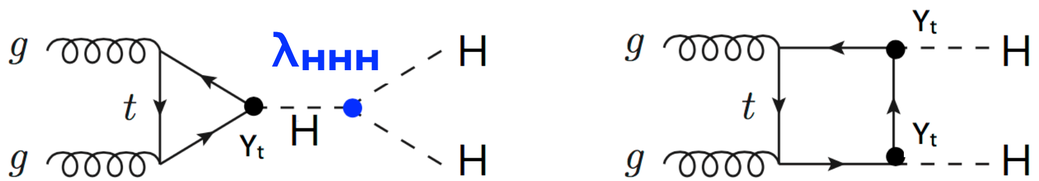
Searching for pp → HH pair production

HH: Analyses approaches

CMS-PAS-HIG-17-002
CMS-PAS-HIG-17-006
ATLAS-CONF-2016-049

Tool to extract Higgs boson trilinear coupling λ_{HHH}:

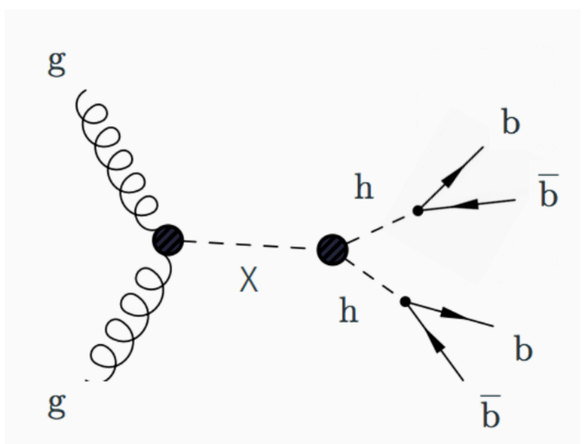
- Probe the shape of the scalar Higgs potential.



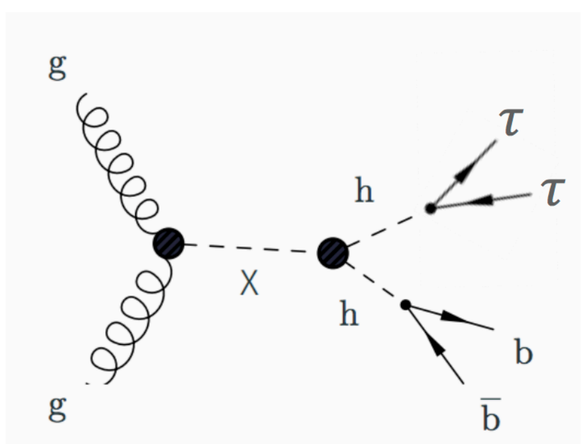
$\sigma_{HH} \sim 33.5$ fb^{-1} @ 13TeV (NNLO + NNLL)

- **Resonant production X→HH**: Probe for BSM phenomena.
- **Non-resonant production:** Probe for anomalous λ_{HHH} and Y_t couplings and 3 new contact interactions.
- Several decay modes. Strongest limits from **HH → bbbb**.
  New results for **HH → bbττ** and **HH → bbVV($\ell\nu\ell\nu$)** searches.

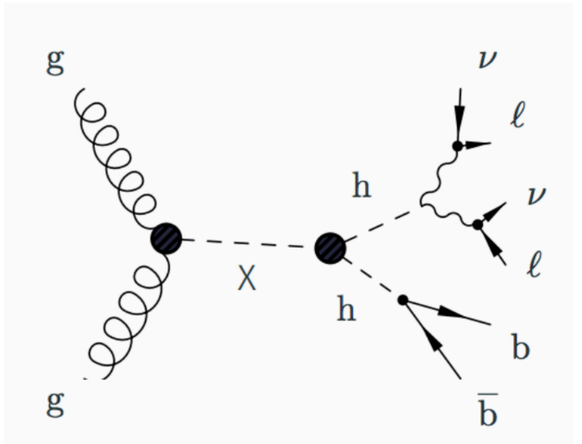
HH → bbbb



HH → bbττ



HH → bbVV(2l2ν).

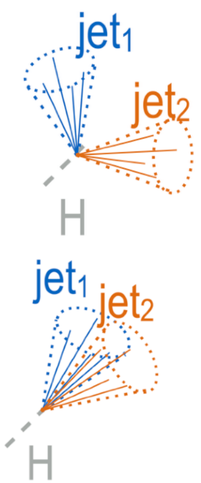


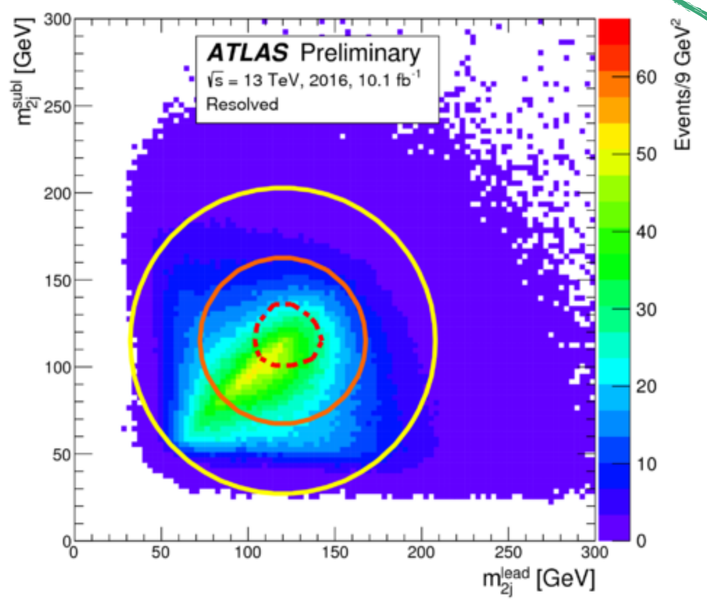
HH: HH → bbbb

ATLAS-CONF-2016-049

Analysis approach:

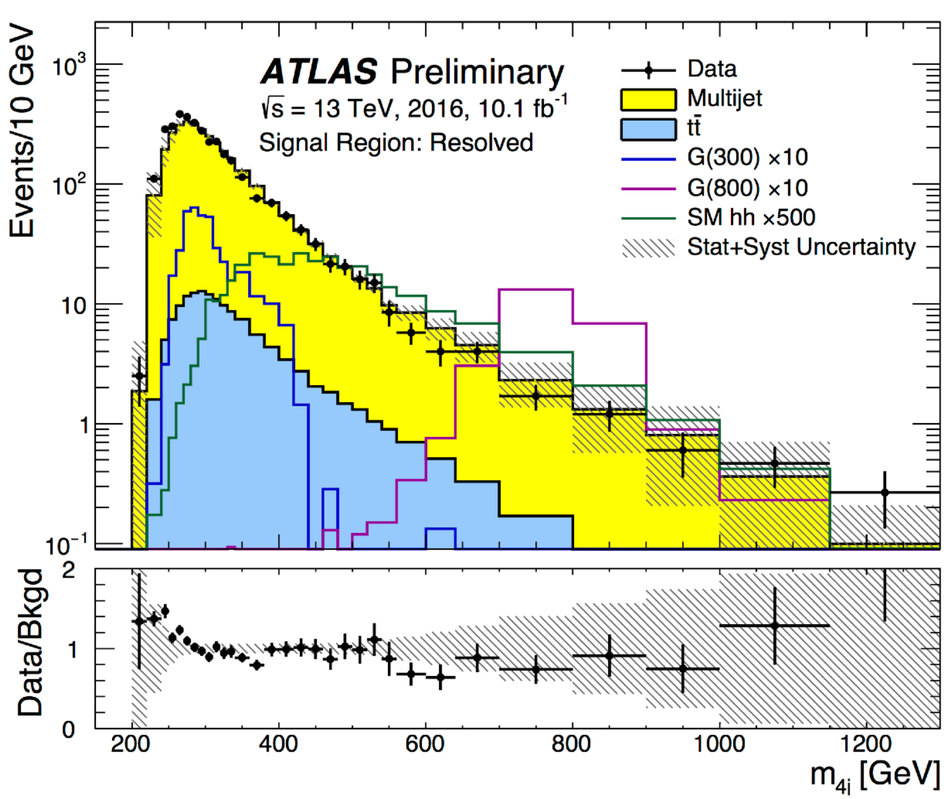
- **Topologies: 4 resolved jets, and two pairs of boosted jets (from H → bb)**
  - jet sub-structure and b-tagging techniques
- **1D fits:** invariant masses the (sub)jets

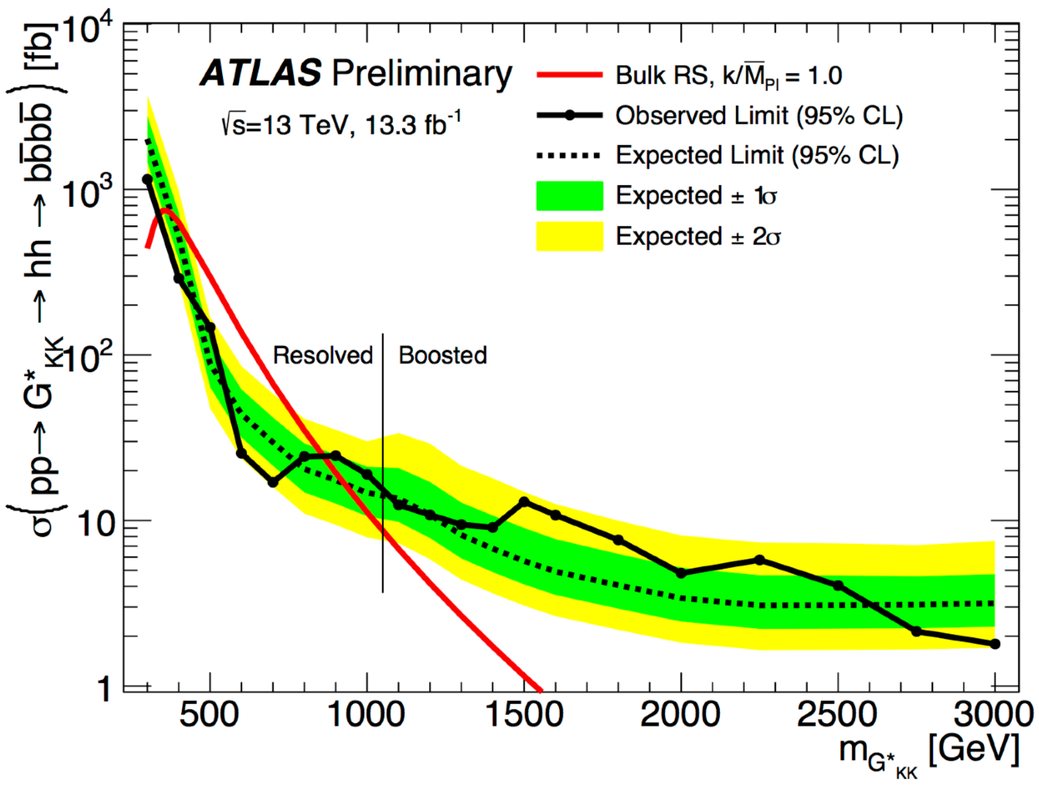




Results:

- For non-resonant searches limits: **$\sigma/\sigma_{SM} \sim 29$** (with ~36fb^{-1}, still the strongest limits).





HH: HH → bbττ

CMS-PAS-HIG-17-002

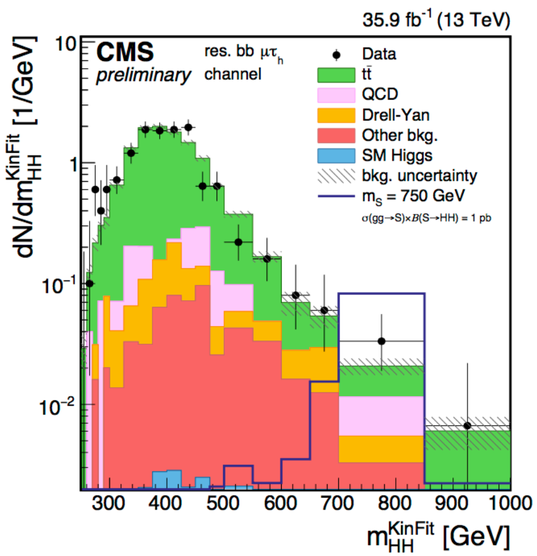
Analysis approach:

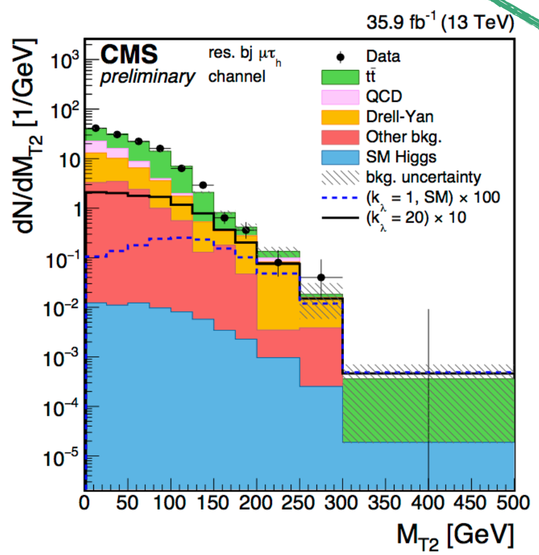
- **3 ττ flavors: $e\tau_h$, $\mu\tau_h$, $\tau_h\tau_h$**
- **bb cats.: 2 btag, 1 btag, 1 boosted jet**
- **1D fit: m_{HH}** (resonant), **m_{T2}** (non-resonant)

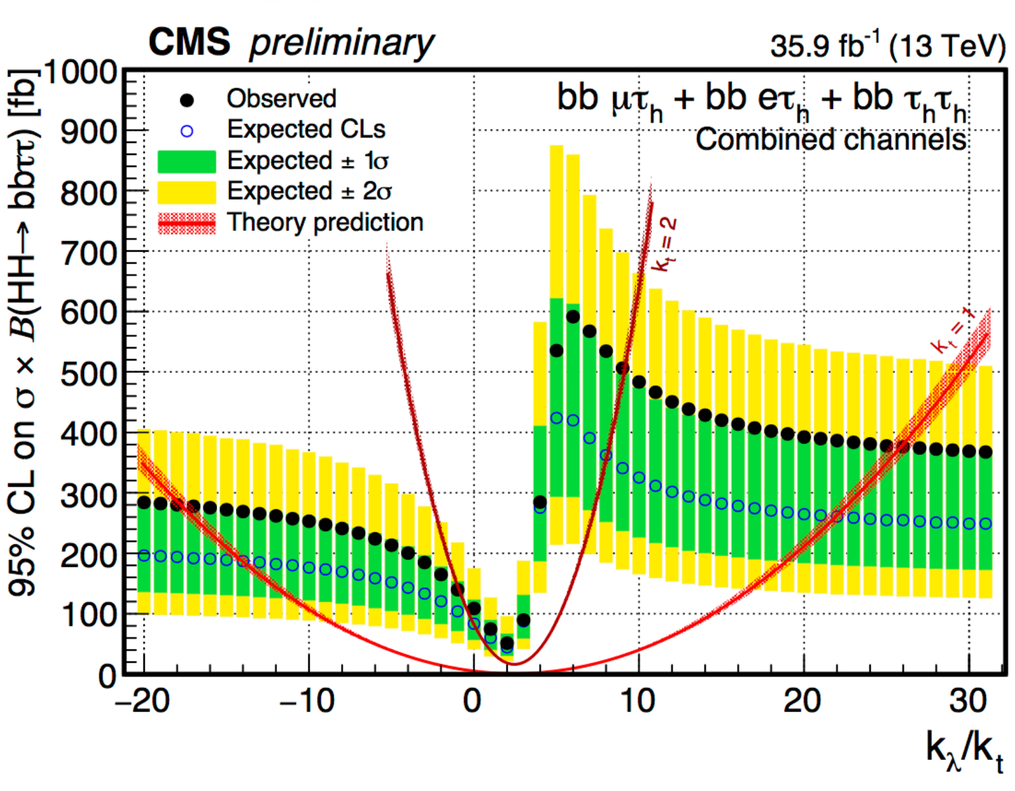
Results:

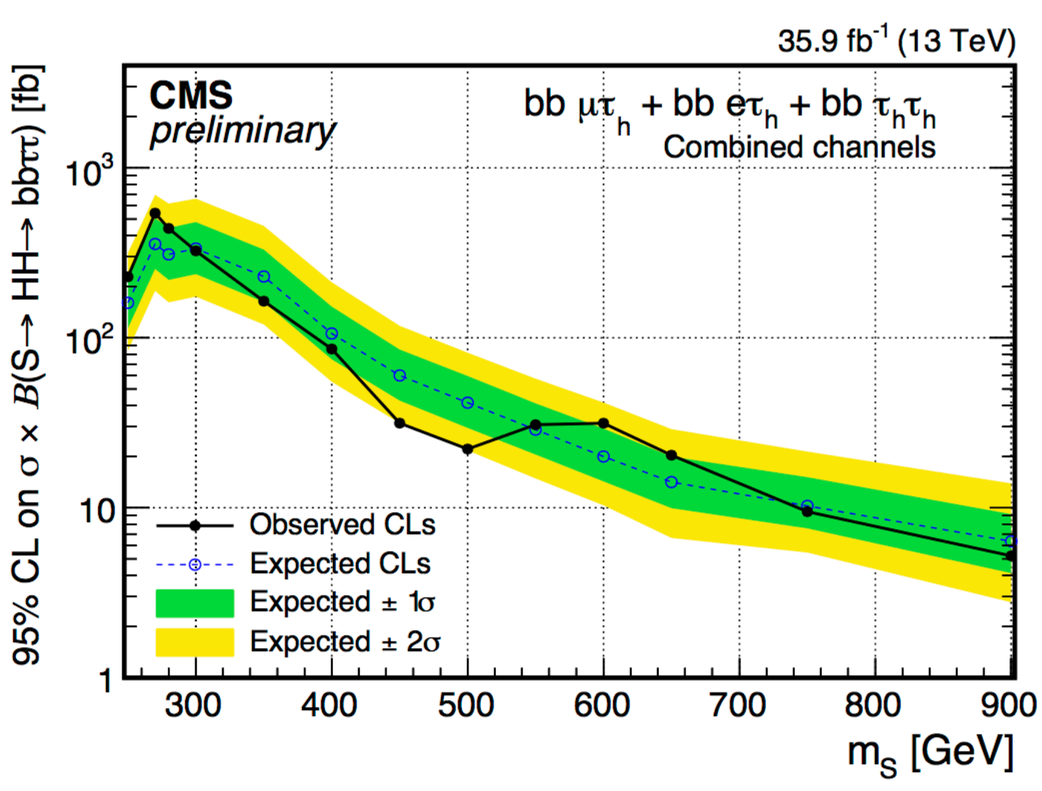
- Limits on **σ/σ_{SM}** as function of **m_S** and **(k_T, k_λ)**

$\sigma_{HH}/\sigma_{SM} < 28$ (25 exp.)







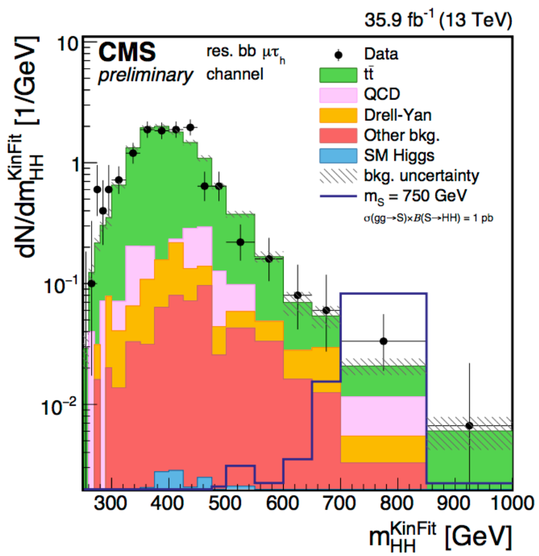


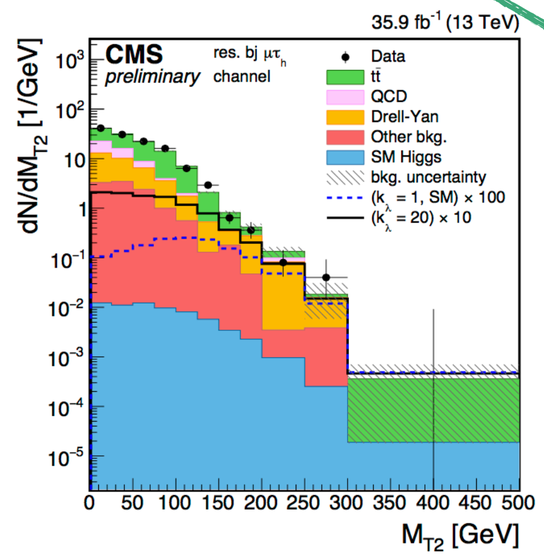
HH: HH → bbττ

CMS-PAS-HIG-17-002

Analysis approach:

- 3 ττ flavors: $e\tau_h$, $\mu\tau_h$, $\tau_h\tau_h$
- bb cats.: 2 btag, 1 btag, 1 boosted jet
- 1D fit: m_{HH} (resonant), m_{T2} (non-resonant)

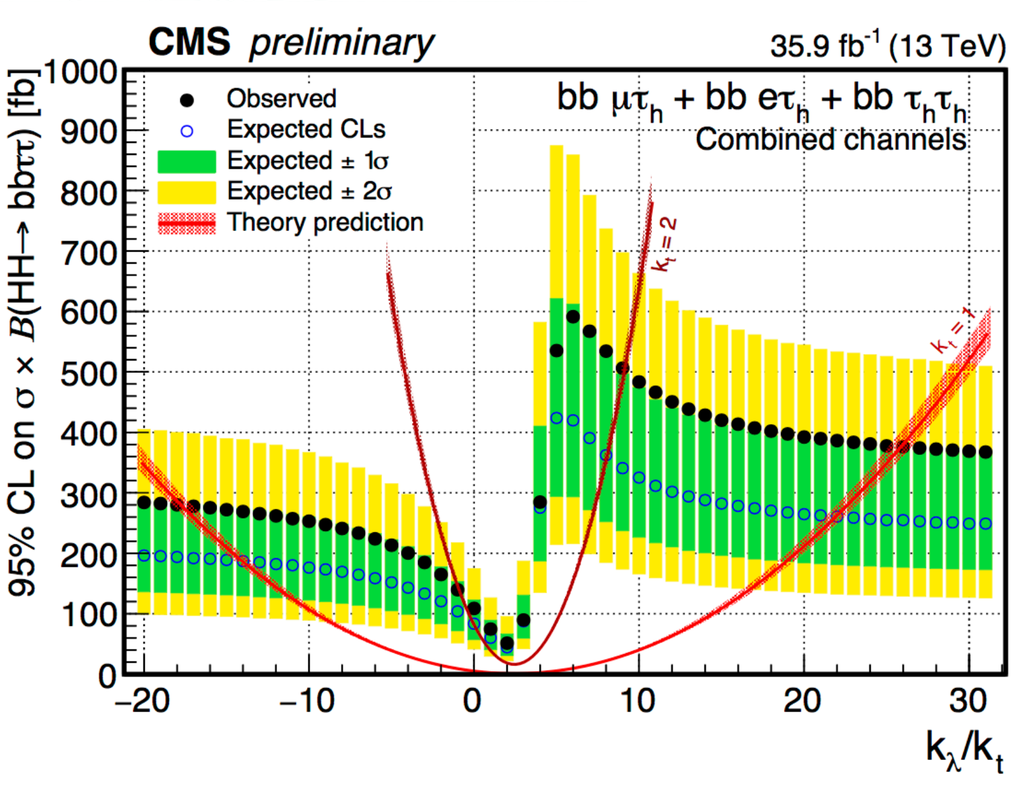


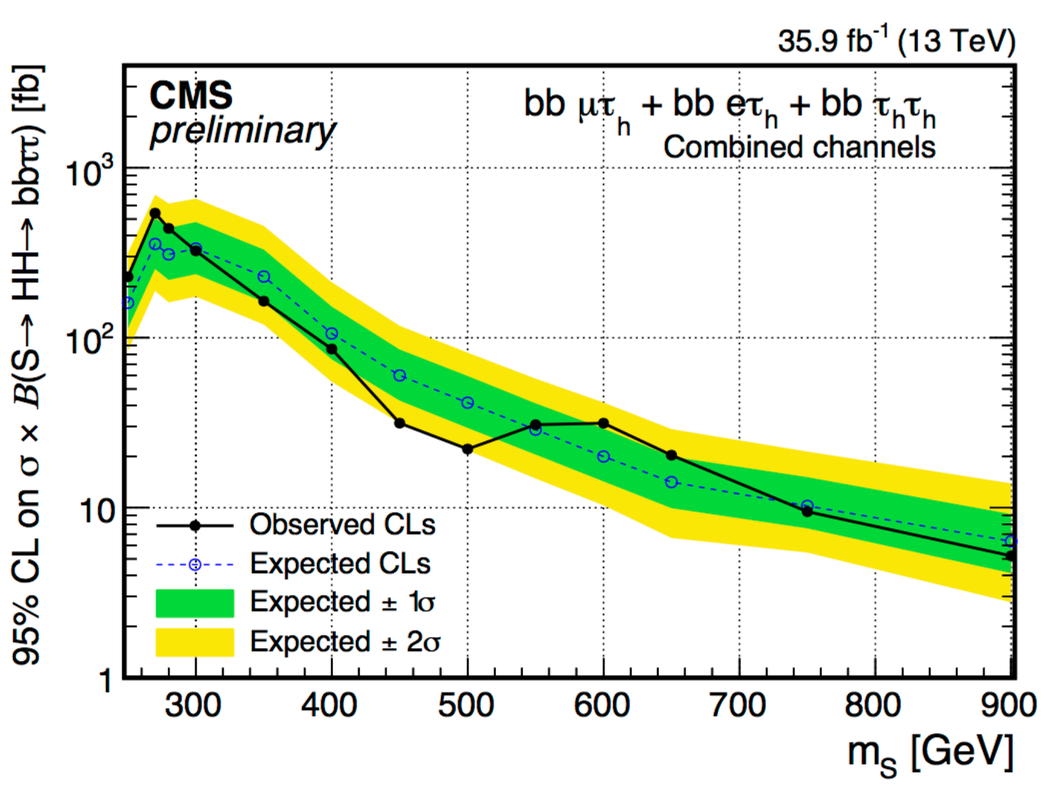


Results:

- Limits on σ/σ_{SM} as function of m_S and (k_T, k_λ)

$\sigma_{HH}/\sigma_{SM} < 28$ (25 exp.) Run I ATLAS combination: $\sigma_{HH}/\sigma_{SM} < 70$ (48 exp.)





HH: HH → bbVV(ℓνℓν)

CMS-PAS-HIG-17-006

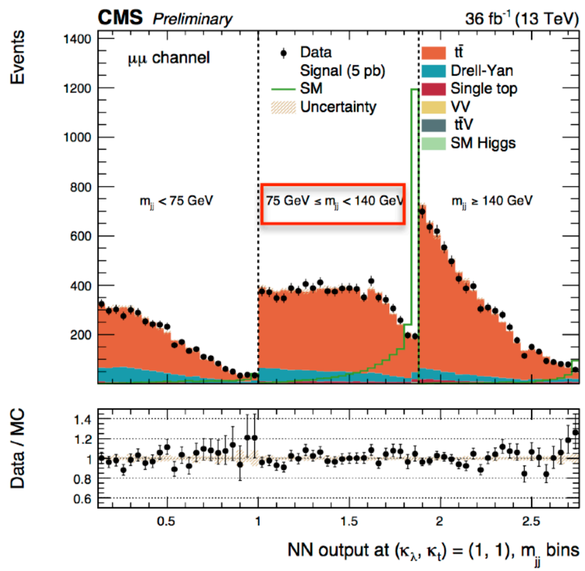
Analysis approach:

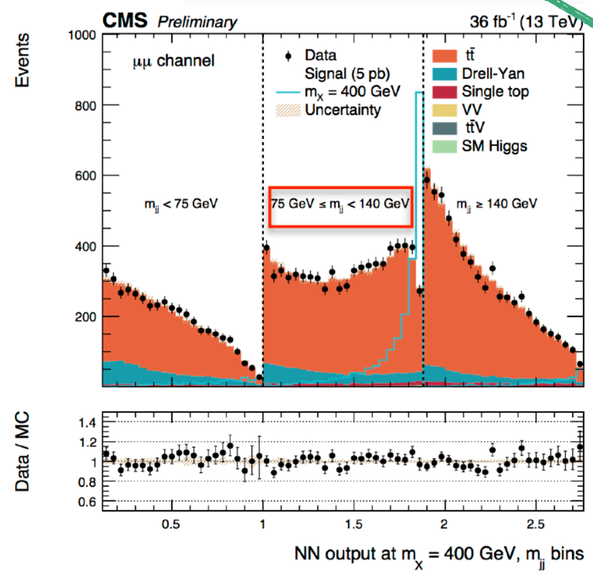
- **3 ℓℓ flavors: e^+e^-, $\mu^+\mu^-$, $e^\pm\mu^\mp$**
- **1D fit** with parameterized **DNN** output

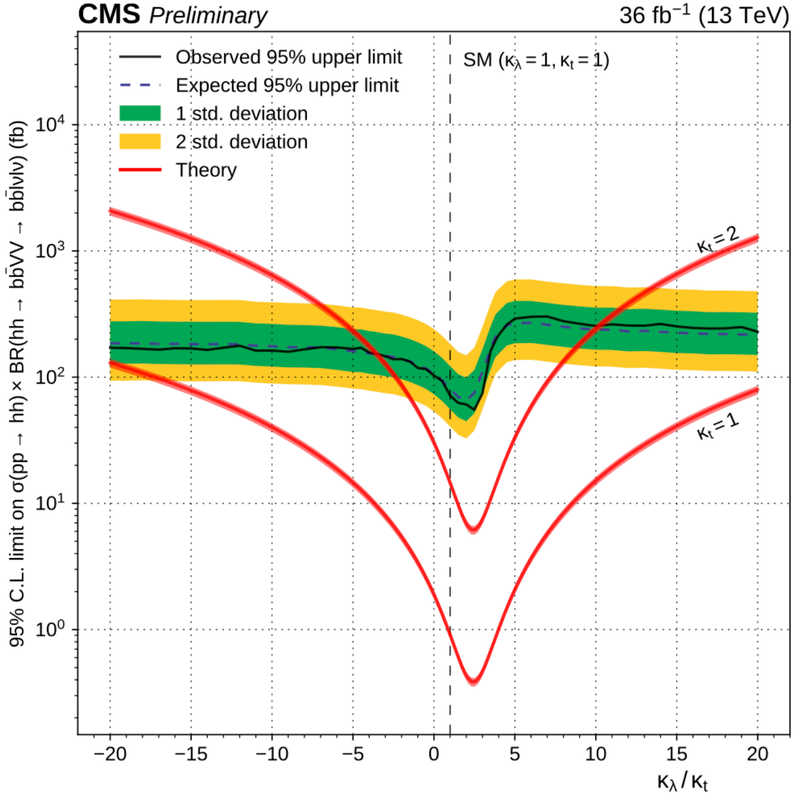
Results:

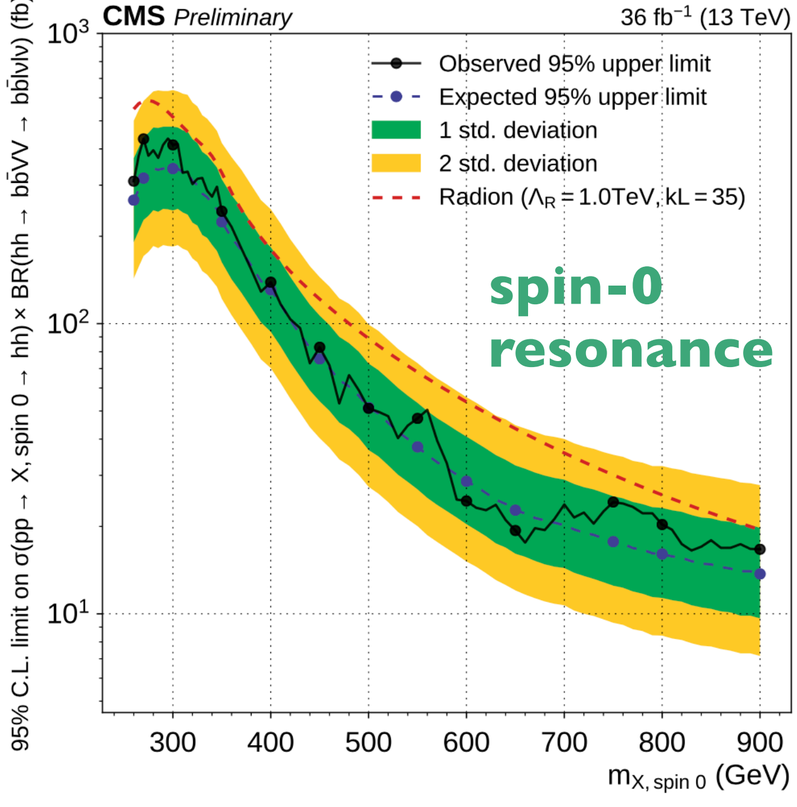
- Limits on **σ/σ_{SM}** as function of **m_X** and **(k_T, k_λ)**

$\sigma_{HH}/\sigma_{SM} < 79$ (89 exp.)



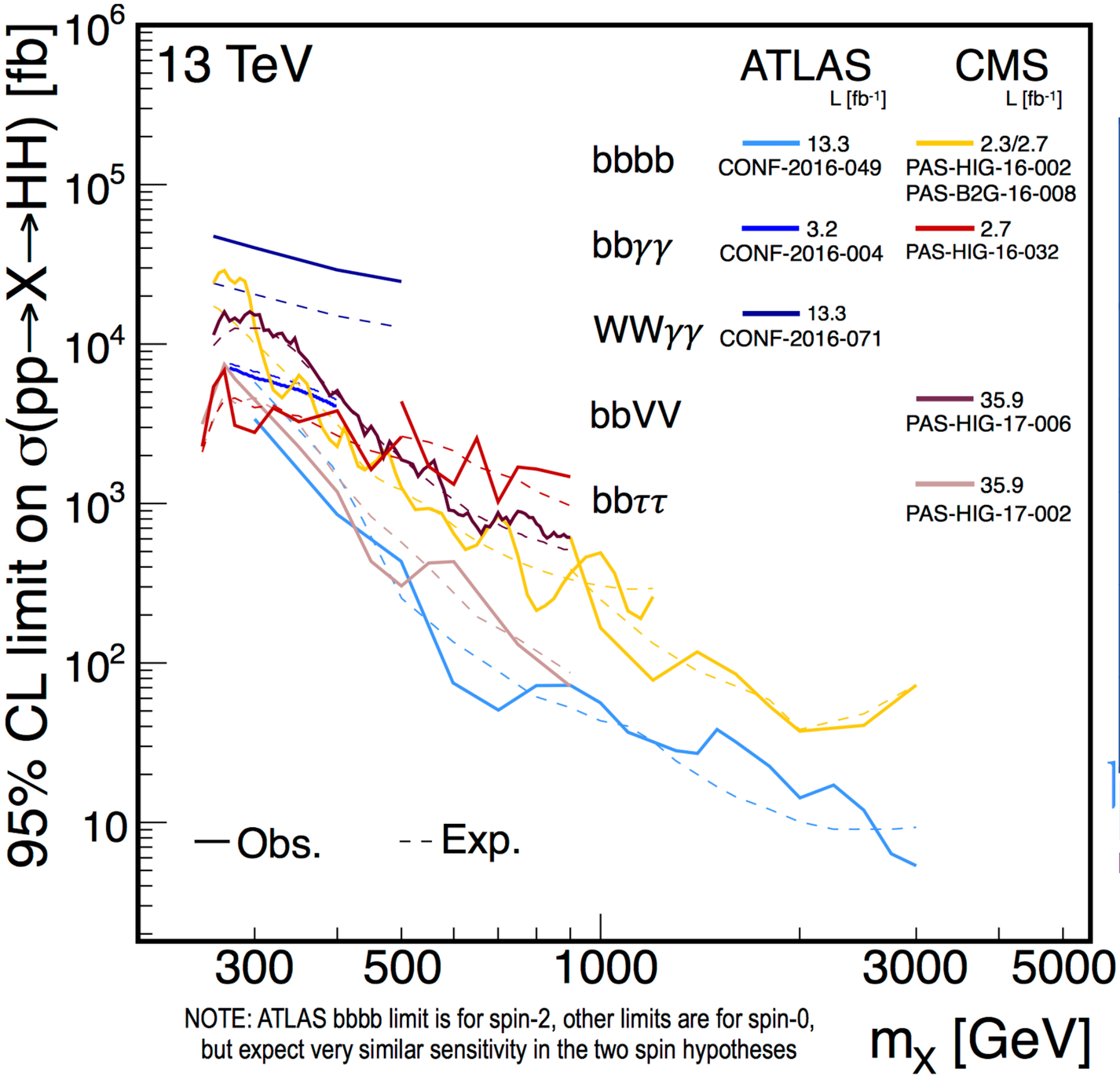






HH: Results (ATLAS + CMS)

CMS-PAS-HIG-17-002
CMS-PAS-HIG-17-006
ATLAS-CONF-2016-049



Chan.	Obs. (exp.) 95% C.L. limit on σ/σ_{SM} ATLAS EXPERIMENT	CMS
bbbb	29 (38)	342 (308)
bbVV	-	79 (89) ⊡
bb$\tau\tau$	-	28 (25) ⊡
bb$\gamma\gamma$	117 (161)	91 (90)
WW$\gamma\gamma$	747 (386)	-
	2.3-3.2 fb^{-1}	13.3 fb^{-1}	35.9 fb^{-1}

⊡: Test of anomalous HH couplings

Latest Higgs boson measurements @ 13TeV

Search for BSM phenomena in Higgs physics:

- Probing for anomalous HVV interactions in $H \to 4\ell$
- Searching for additional scalar resonances
- Search for BSM signatures of the Higgs boson in:
  $H \to \gamma\gamma/bb + E_{T}^{miss}$ (DM) and $H \to \mu\tau/e\tau$ (LFV)

[*] predominantly presented results obtained with 36 fb^{-1}

H → 4ℓ: Anomalous couplings

CMS-PAS-HIG-17-011

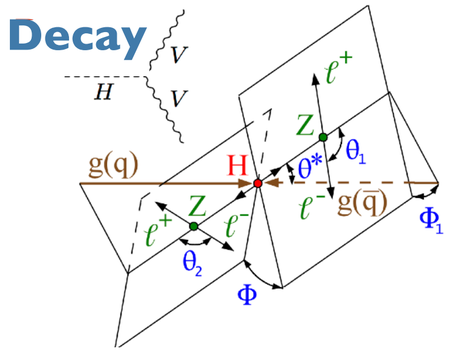
Exploit full decay-, and production-related information:

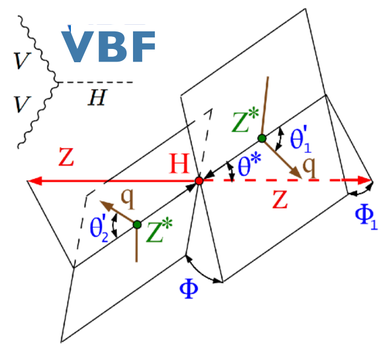
- Parametrisation of decay amplitude:

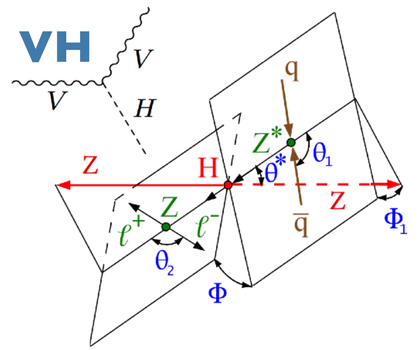
$$A = \frac{1}{v}\left[a_1^{VV} + \frac{\kappa_1^{VV} q_1^2 + \kappa_2^{VV} q_2^2}{\left(\Lambda_1^{VV}\right)^2} + \frac{\kappa_3^{VV}(q_1+q_2)^2}{\left(\Lambda_Q^{VV}\right)^2}\right] m_{V1}^2 \epsilon_{V1}^* \epsilon_{V2}^* + a_2^{VV} f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + a_3^{VV} f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu}$$

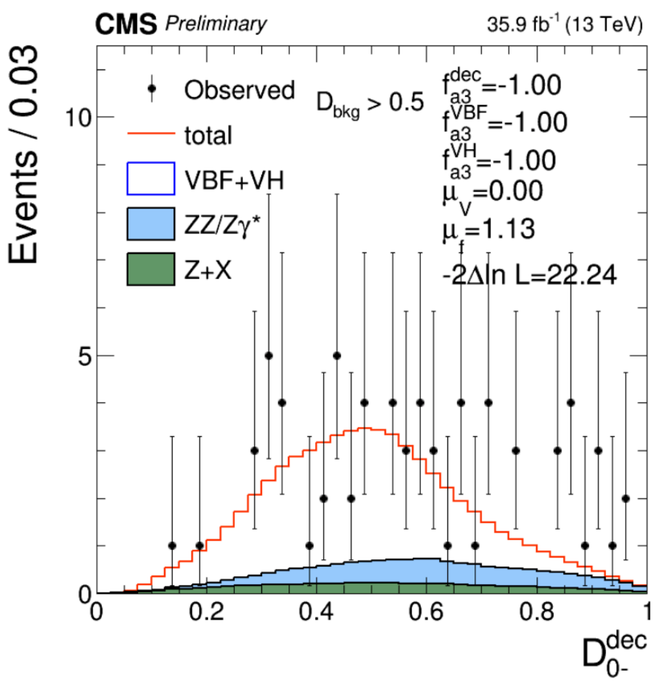
SM | leading momentum expansion | higher order cp-even | cp-odd

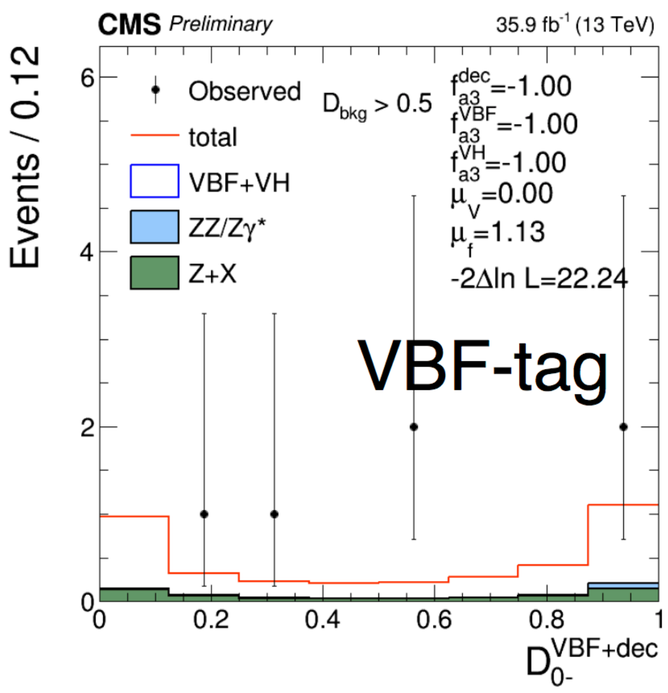
- Untagged, VBF, VH categories: 3 ME-based discriminants encoding both decay and production information

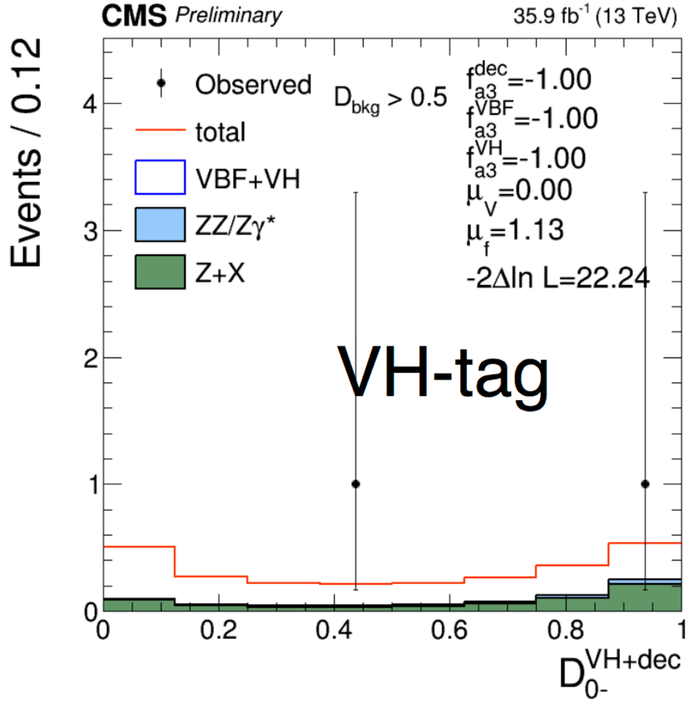








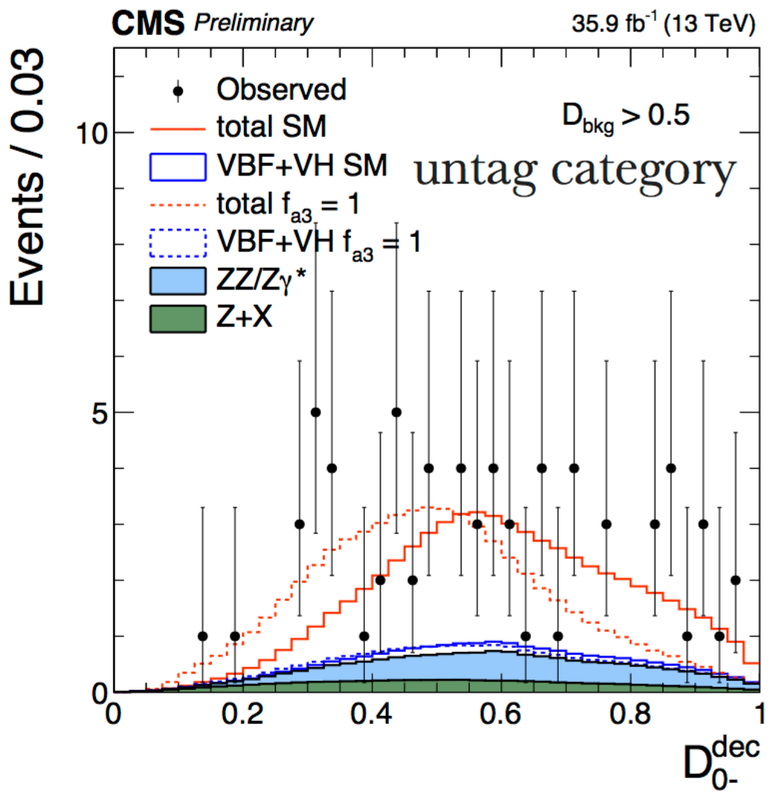


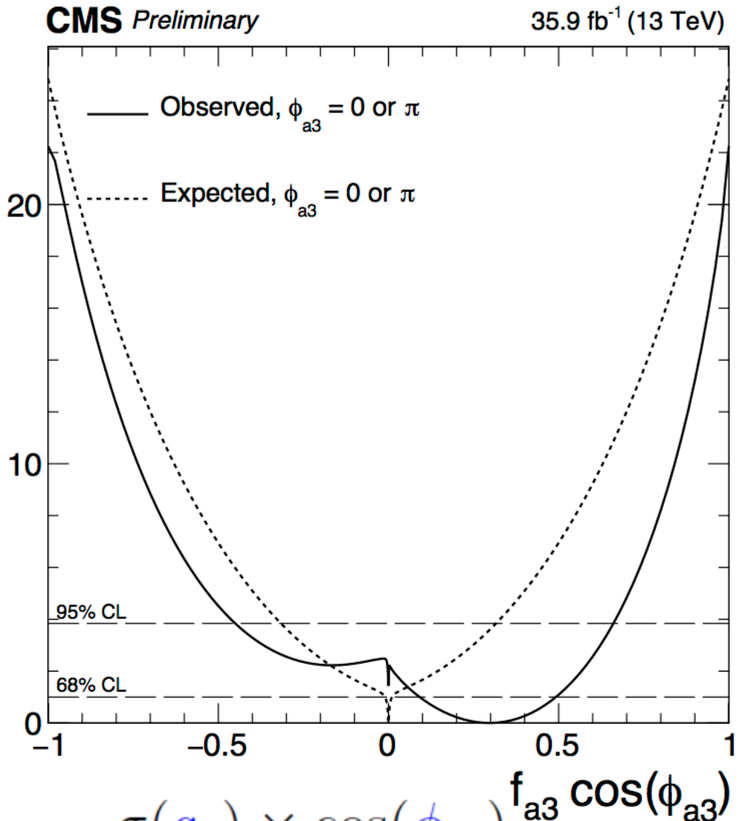


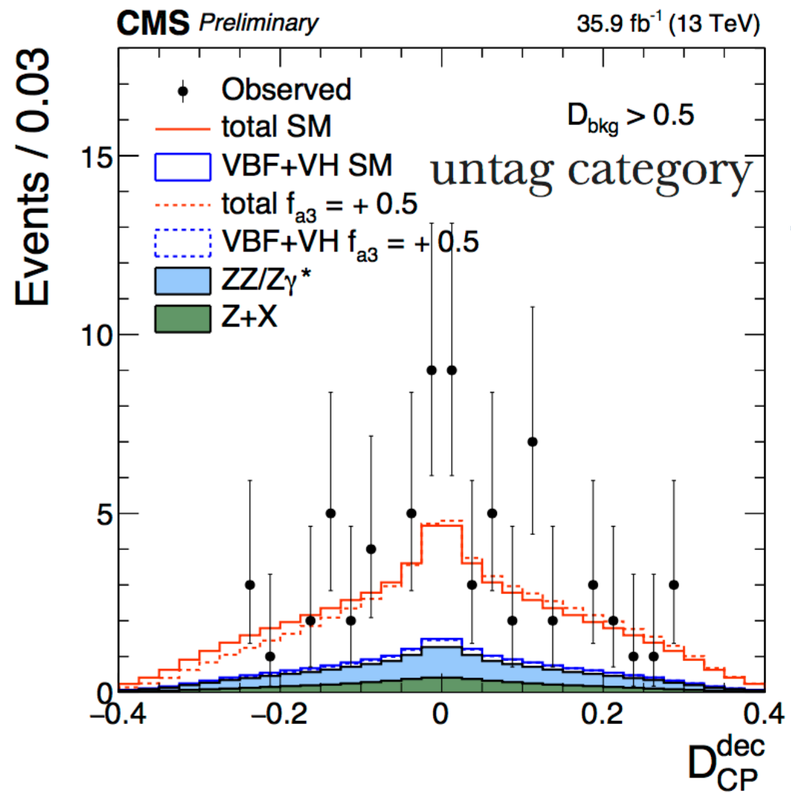
H → 4ℓ: Anomalous couplings

CMS-PAS-HIG-17-011

Exploit full decay-, and production-related information:







$$f_{a3} \Rightarrow \frac{\sigma(a_3) \times \cos(\phi_{a3})}{\sigma(a_1) + \sigma(a_3)}$$

Parameter	Observed	Expected
$f_{a3}\cos(\phi_{a3})$	$0.30^{+0.19}_{-0.21}$ $[-0.45, 0.66]$	$0.000^{+0.017}_{-0.017}$ $[-0.32, 0.32]$
$f_{a2}\cos(\phi_{a2})$	$0.04^{+0.19}_{-0.04}$ $[-0.69, -0.64] \cup [-0.04, 0.64]$	$0.000^{+0.015}_{-0.014}$ $[-0.08, 0.29]$
$f_{\Lambda 1}\cos(\phi_{\Lambda 1})$	$0.00^{+0.06}_{-0.33}$ $[-0.92, 0.15]$	$0.000^{+0.014}_{-0.014}$ $[-0.79, 0.15]$
$f_{\Lambda 1}^{Z\gamma}\cos(\phi_{\Lambda 1}^{Z\gamma})$	$0.16^{+0.36}_{-0.25}$ $[-0.43, 0.80]$	$0.000^{+0.020}_{-0.024}$ $[-0.49, 0.80]$

Run1 exp (HZZ+HWW):

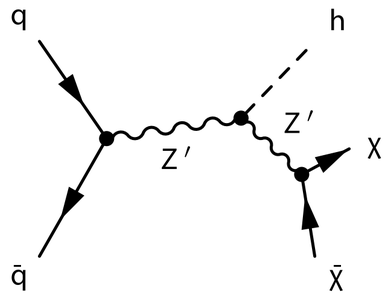
$0^{+0.23}_{-0.23}$
$0^{+0.08}_{-0.03}$
$0^{+0.15}_{-0.08}$

"Dark Matter": H → γγ + E_{Tmiss}

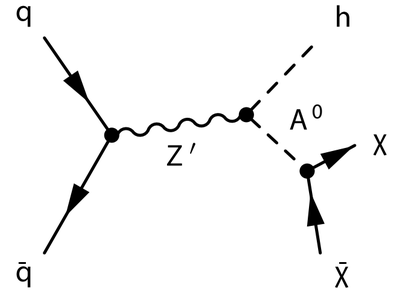
ATLAS-CONF-2017-024

Searches for BSM phenomena (DM) with H → γγ and E_{Tmiss} signature:

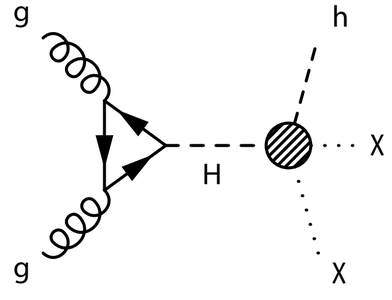
Z'_B model



Z' 2HDM

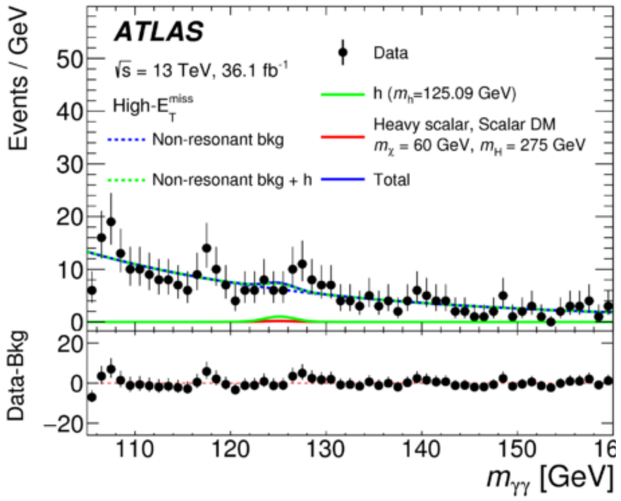


Heavy scalar

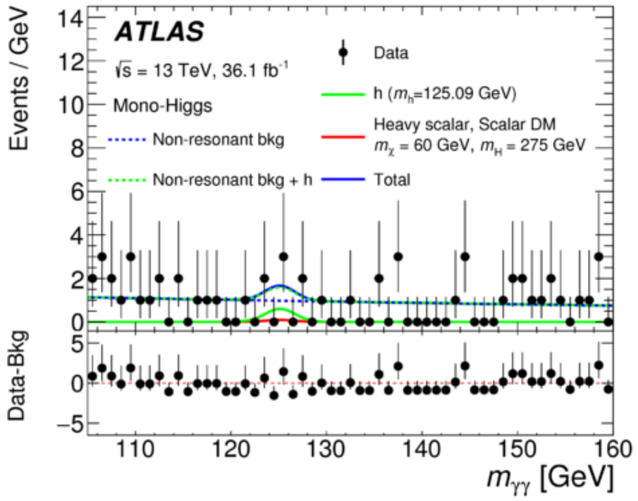


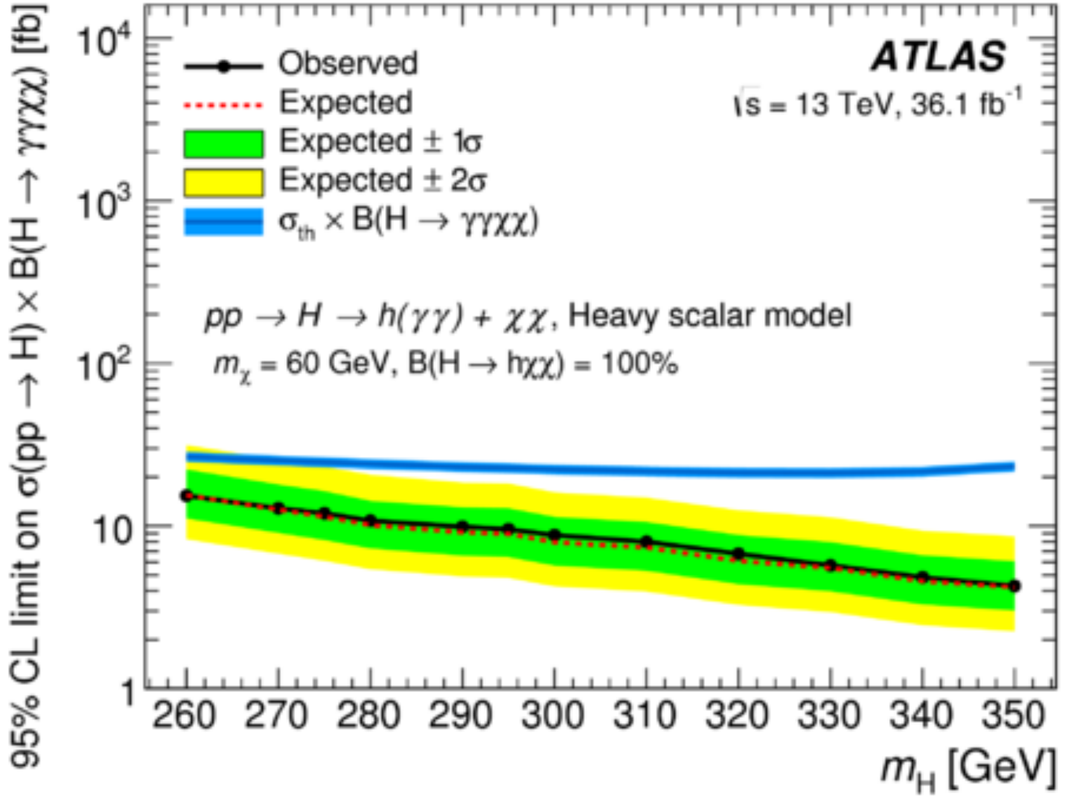
- **Event categorisation**: Use **E_{Tmiss} significance** and magnitude of **vectorial sum of γ and jets.**
- Simultaneous fit to the di-photon $m_{γγ}$ spectra.

High E_{Tmiss} cat.:



Mono-Higgs cat.:



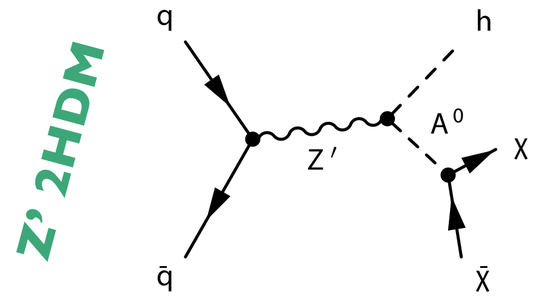


- Upper limits on the (simplified) DM production and on heavy scalar production

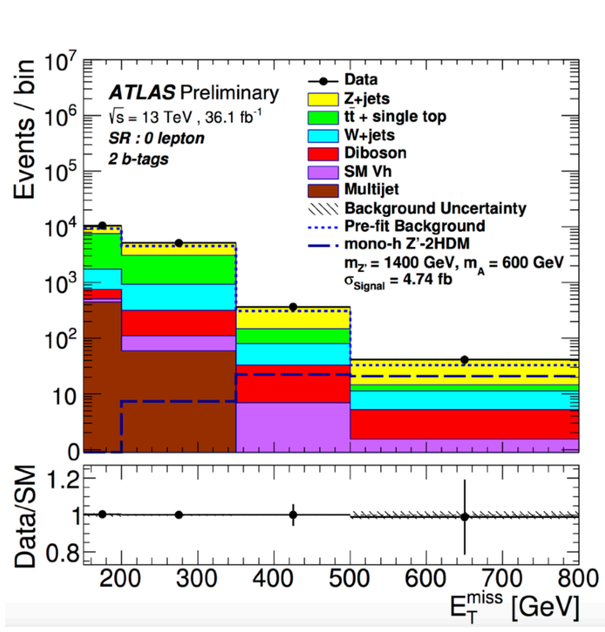
"Dark Matter": H → bb + E_{Tmiss}

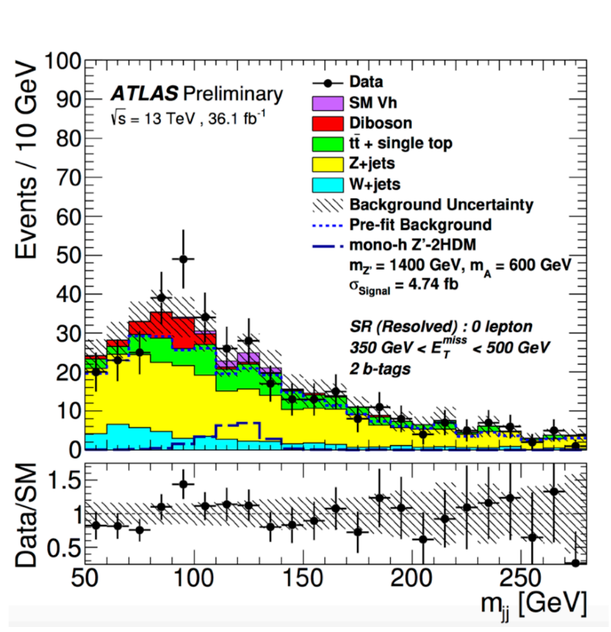
ATLAS-CONF-2017-028

Searches for BSM phenomena (DM) with H → bb and E_{Tmiss} signature:

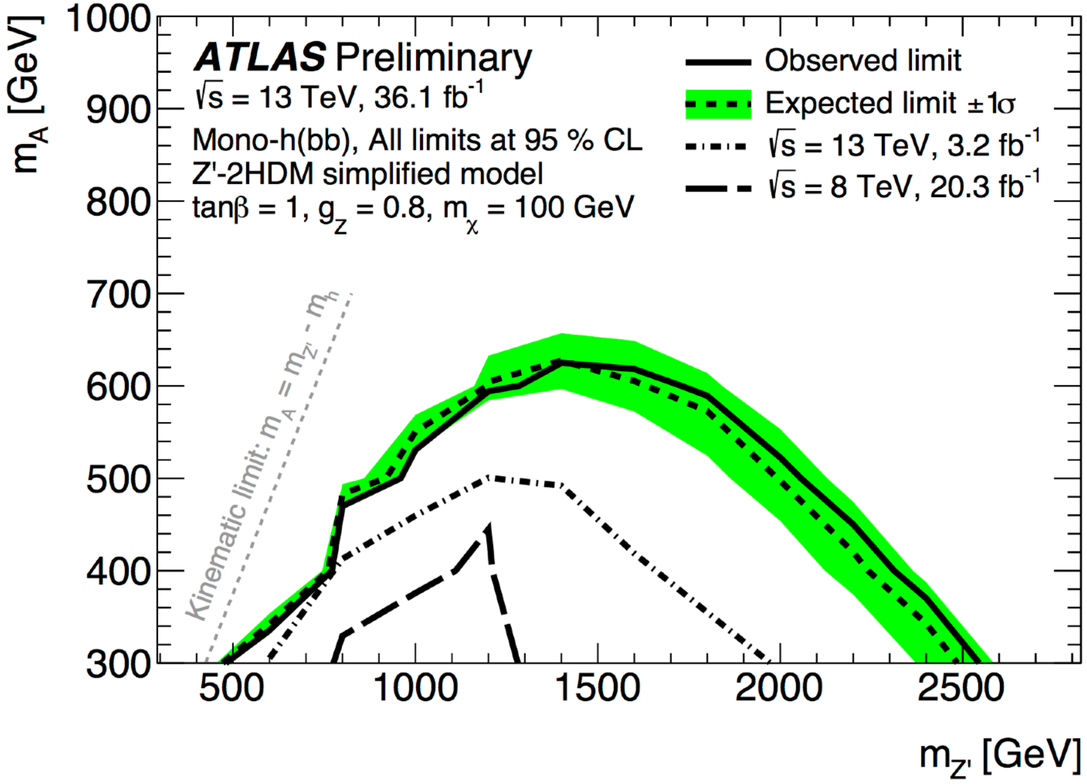


- **Two categories**: with **resolved jets (MET < 500 GeV)** and **merged jets (MET > 500 GeV)**.
- Simultaneous fit to the di-jet m_{JJ} spectra.



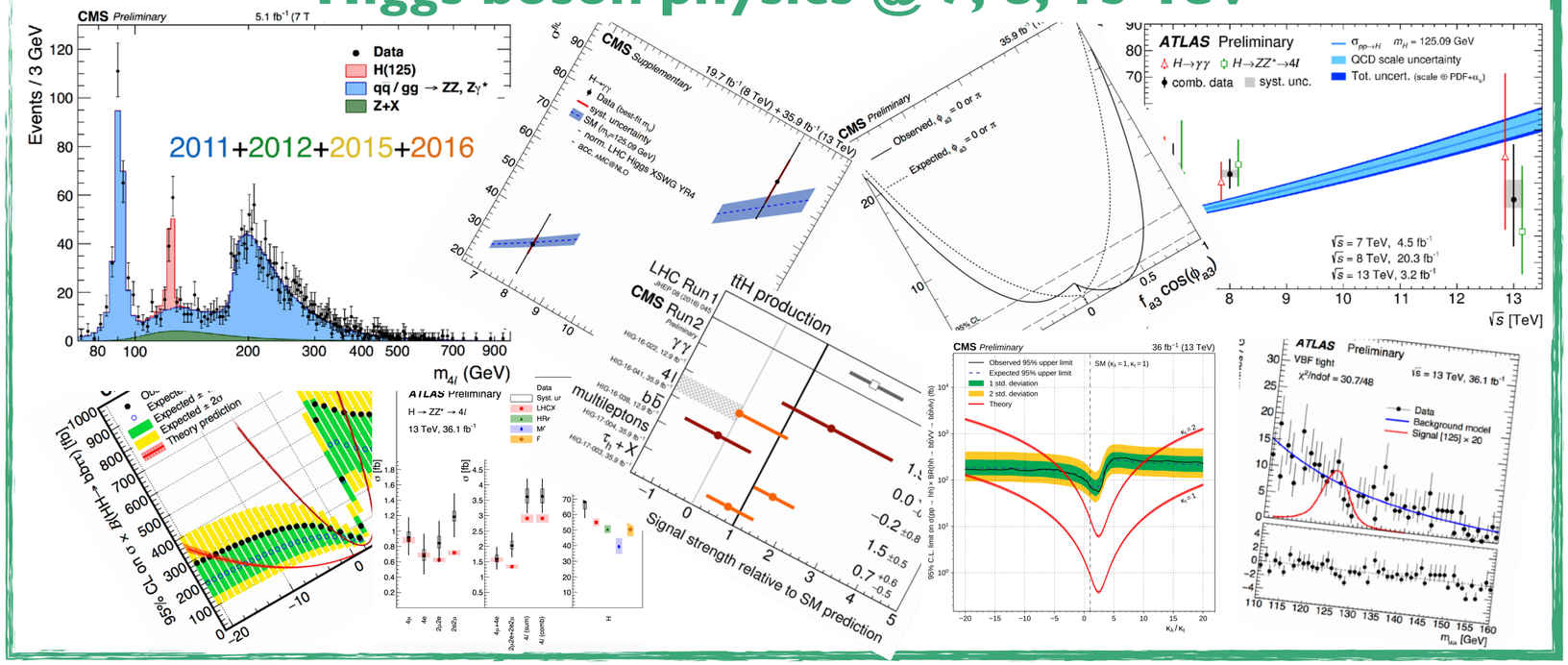


- Upper limits on the (simplified) DM production



From here into the (near-term) future...

Higgs boson physics @ 7, 8, 13 TeV



so far, compatible with Standard Model...

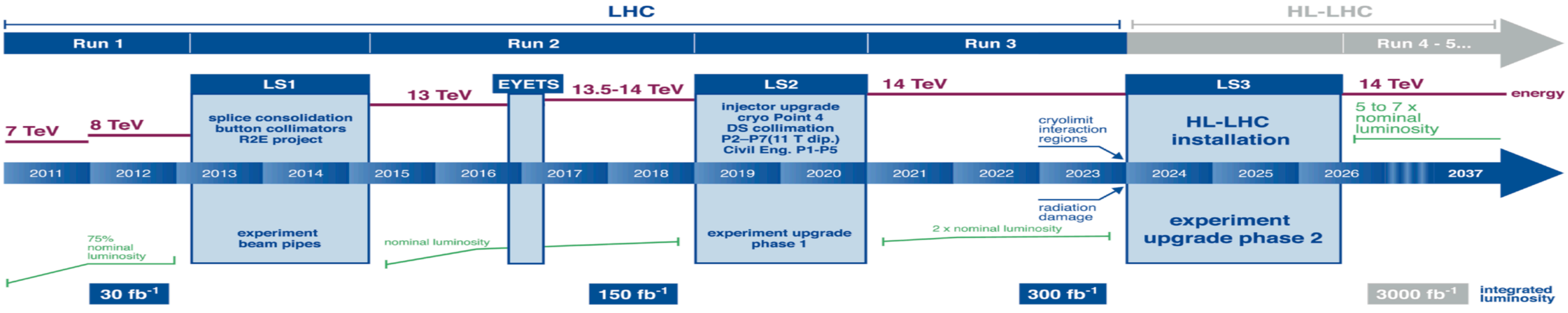
LHC goals for 2017 and 2018: **45 fb^{-1} per year** (with ~50% availability of stable beams)

Immediate attention by experiments:

- **Readiness for data taking** and analysis in 2017 (and for **Phase II Upgrade TDRs**)
- Preparatory discussions between experiments (and TH colleagues) **for LHC combination:**
  - **mass and differential fiducial XS** (towards the end of 2017),
  - **overall couplings and simplified cross sections** (end of 2017 or after).

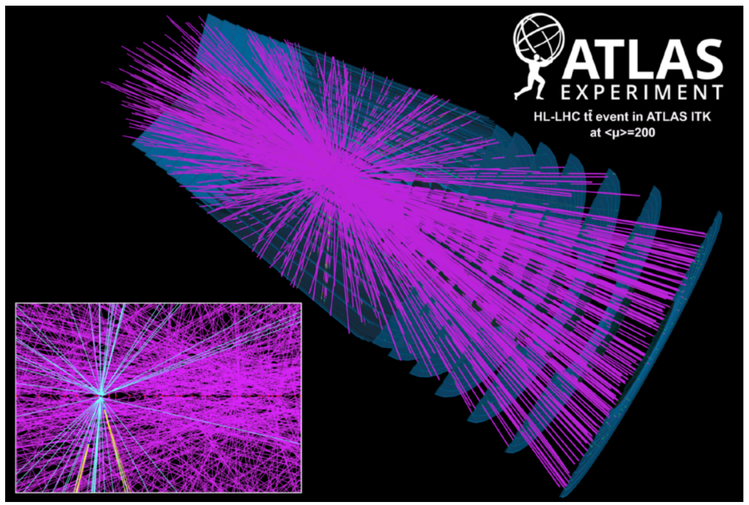
Towards the long-term future: HL-LHC

From the early discovery machine ... to the Higgs factory and its full discovery potential



HL-LHC - topography of our particle physics knowledge:

- Deeper understanding of the Higgs boson (couplings, potential).
- Precision measurements in QCD, EWK, Higgs (ultimate goal O(1%)).
- Probing new physics phenomena (directly & via precision measurements).



Challenges for the experiments:

- Major experiment upgrades needed to improve radiation hardness, replace detectors at end-of-life or extend coverage,
- Provide handles to mitigate pileup and maintain/improve trigger acceptance.

Physics performance @ HL-LHC

No phenomenon is a true phenomenon
until it is an observed phenomenon.
John A. Wheeler

Prospects for Higgs boson physics at HL-LHC:

- Precision measurements of H(125) properties in **H → γγ** and **H → 4ℓ**
- Probing/measurement of rare decays and couplings
- Measurement of its self-couplings in **pp → HH**

Analysis techniques & extrapolation strategies

ATLAS HL-LHC analysis techniques:

- 14 TeV collision energy and 140 or 200 PU
- Simulate detector response by **smearing p_T and E of physics objects,**
- **Emulate triggers** with trigger efficiency functions

Validated with full simulation

CMS fast simulation for HL-LHC:

- 14 TeV collision energy and 200 PU
- Parameterised **Delphes simulation**

Validated with full simulation

CMS extrapolation strategy:

- Public results @13 TeV are extrapolated to larger data sets (300 and 3000 fb^{-1}).
- Extrapolations are presented under different scenarios for the evolution of uncertainties.

	systematics unchanged	exp. sys. scaled* $1/\sqrt{L}$	theo. sys. scaled 1/2	high PU effects
ECFA16 S1	✓	✗	✗	✗
ECFA16 S1+	✓	✗	✗	✓
ECFA16 S2	✗	✓	✓	✗
ECFA16 S2+	✗	✓	✓	✓

H(125) properties in H → γγ @ HL-LHC

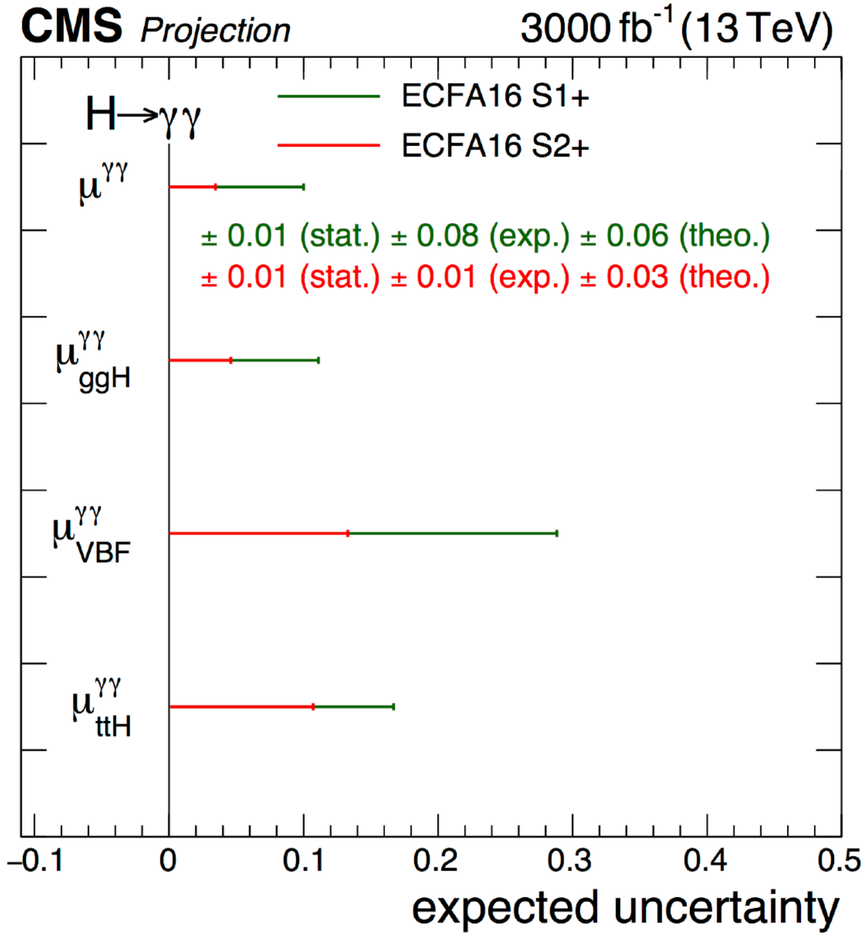
CMS-PAS-FTR-16-002

Performance estimated using the H→ γγ analysis @12.9 fb^{-1} (13 TeV).

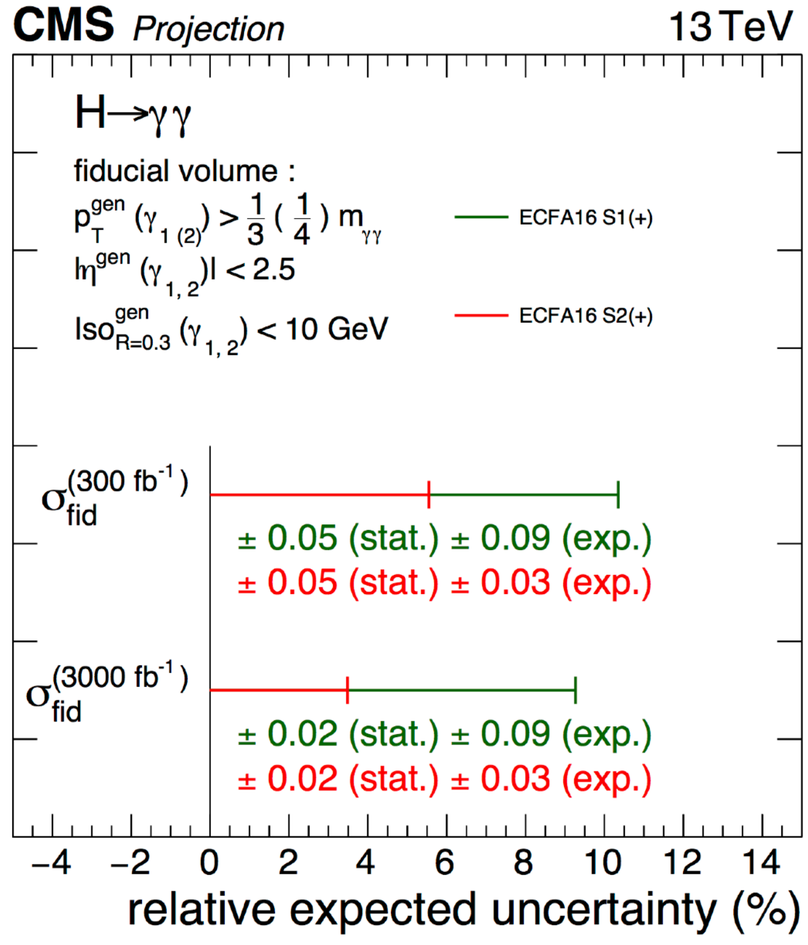
Effects of high pileup and detector performance @3ab^{-1} estimated:

- The beamspot is simulated to have σz ~ 5 cm
- Vertex identification reduced from 80% to 40%
- Photon ID efficiency decreased by 2.3% (10%) in EB (EE)

Signal strength per production mode



Fiducial XS measurements



H(125) properties in H → 4ℓ @ HL-LHC

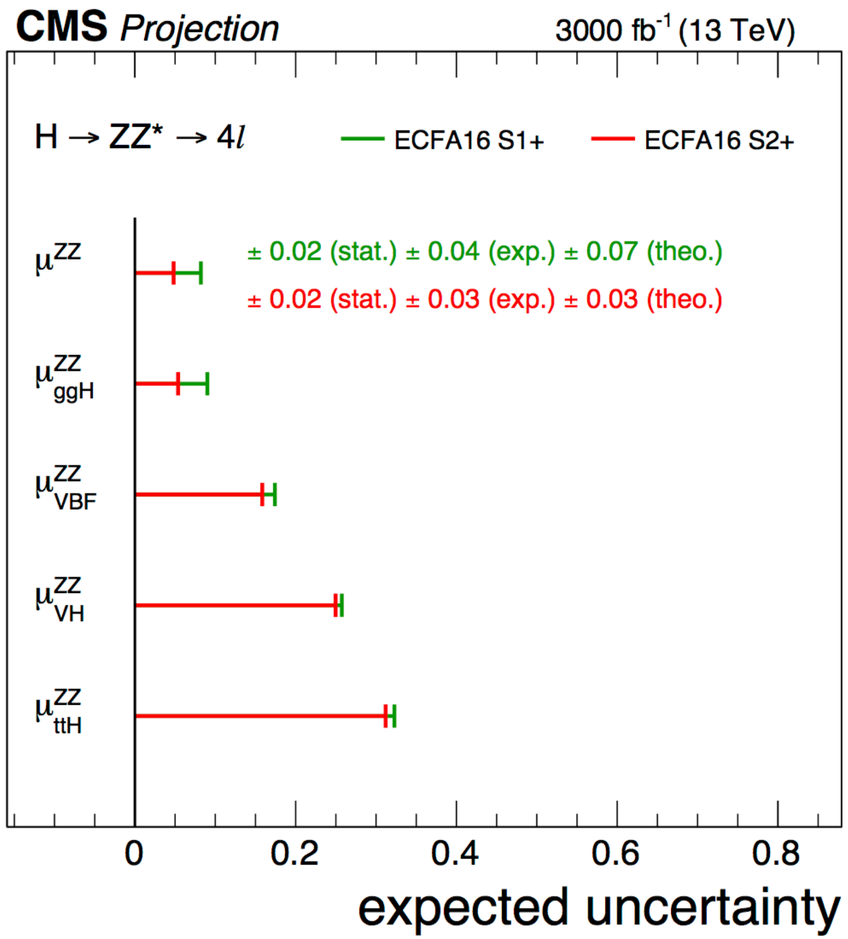
CMS-PAS-FTR-16-002

Performance estimated using the H→ 4ℓ analysis @12.9 fb^{-1} (13 TeV).

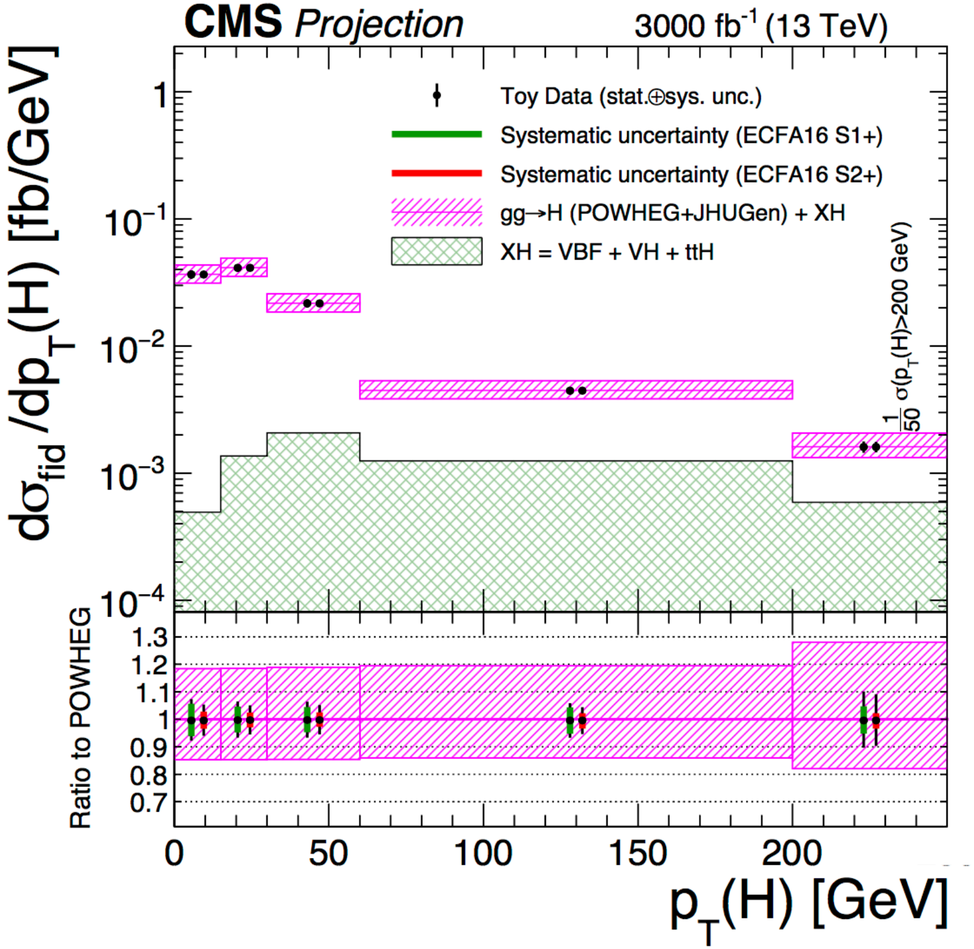
Effects of high pileup and detector performance @3ab^{-1} estimated:

- Lepton misidentification rates
- Lepton efficiencies decreased accordingly for muons/electrons

Signal strength per production mode



Differential p_T(H) cross section

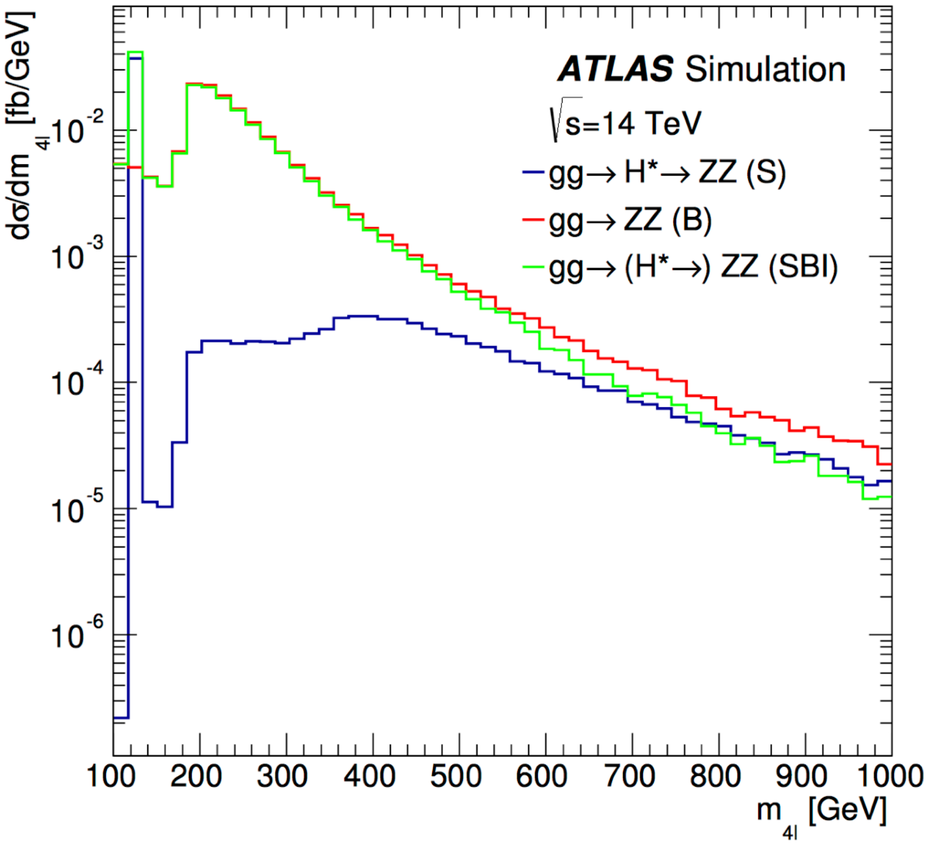


H(125) properties in H → 4ℓ @ HL-LHC

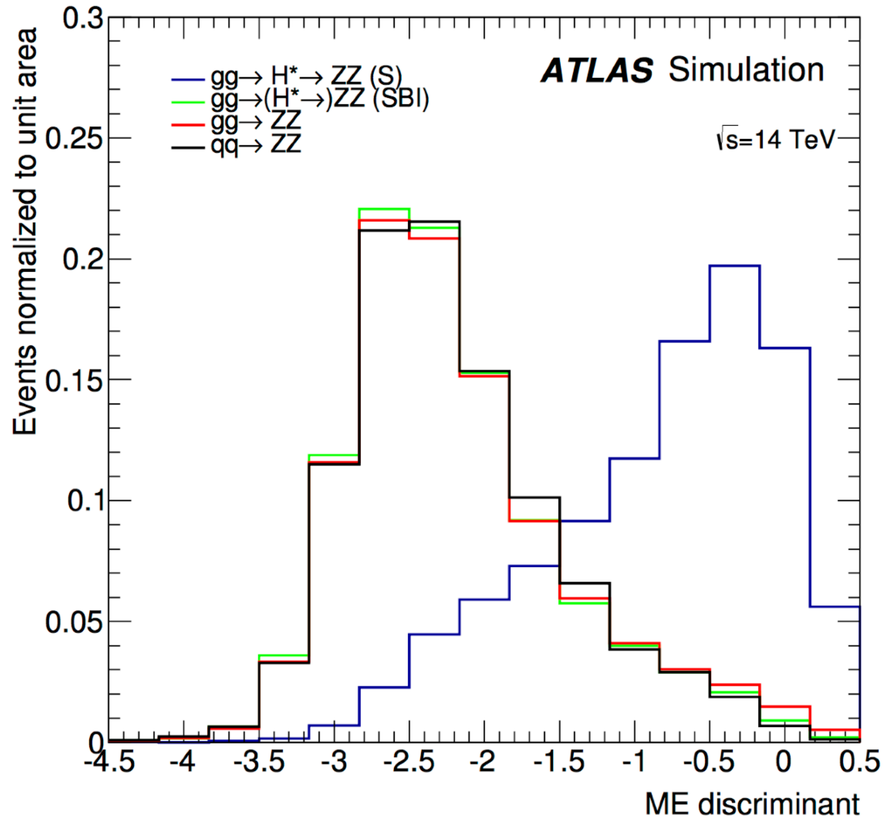
Performance estimated using the simplified version of H→ 4ℓ analysis @ 8 TeV.

- H(125) off-shell production exploited to constrain its decay width Γ_H
- Lepton efficiencies assumed to be preserved
- Limits on Γ_H extracted assuming SM-like Higgs boson (**YR4 : Γ_{SM} = 4.10 MeV @ m_H=125.09 GeV**)

$m_{4\ell}$ and off-shell production:



ME discriminant:



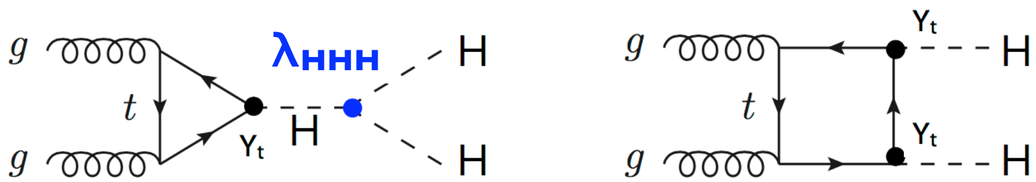
$\Gamma_H = 4.2^{+1.5}_{-2.1}$ MeV (stat+sys) [@3000 fb^{-1}]

H(125) self-couplings @ HL-LHC

CMS-PAS-FTR-16-002

Performance estimated using the pp → HH analyses with 2015 data (13 TeV).

- Probe the shape of the scalar Higgs potential.



$\sigma_{HH} \sim 33.5\ fb^{-1}$ @ 13TeV (NNLO + NNLL)

- Results for several decay modes: **HH → bbττ / bbγγ / bbVV / bbbb** .

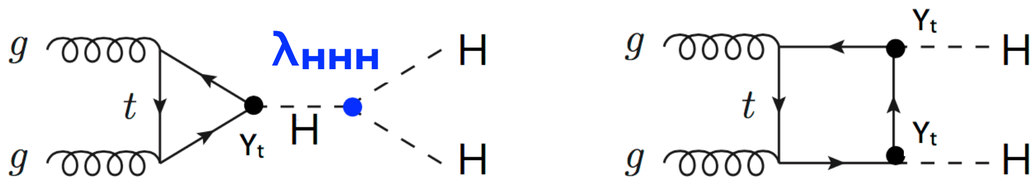
Channel	Median expected limits in μ_r		Z-value		Uncertainty as fraction of $\mu_r = 1$	
	ECFA16 S2	Stat. Only	ECFA16 S2	Stat. Only	ECFA16 S2	Stat. Only
$gg \to HH \to \gamma\gamma bb$ (S2+)	1.3	1.3	1.6	1.6	0.64	0.64
$gg \to HH \to \tau\tau bb$	5.2	3.9	0.39	0.53	2.6	1.9
$gg \to HH \to VVbb$	4.8	4.6	0.45	0.47	2.4	2.3
$gg \to HH \to bbbb$	7.0	2.9	0.39	0.67	2.5	1.5

H(125) self-couplings @ HL-LHC

CMS-PAS-FTR-16-002

Performance estimated using the pp → HH analyses with 2015 data (13 TeV).

- Probe the shape of the scalar Higgs potential.



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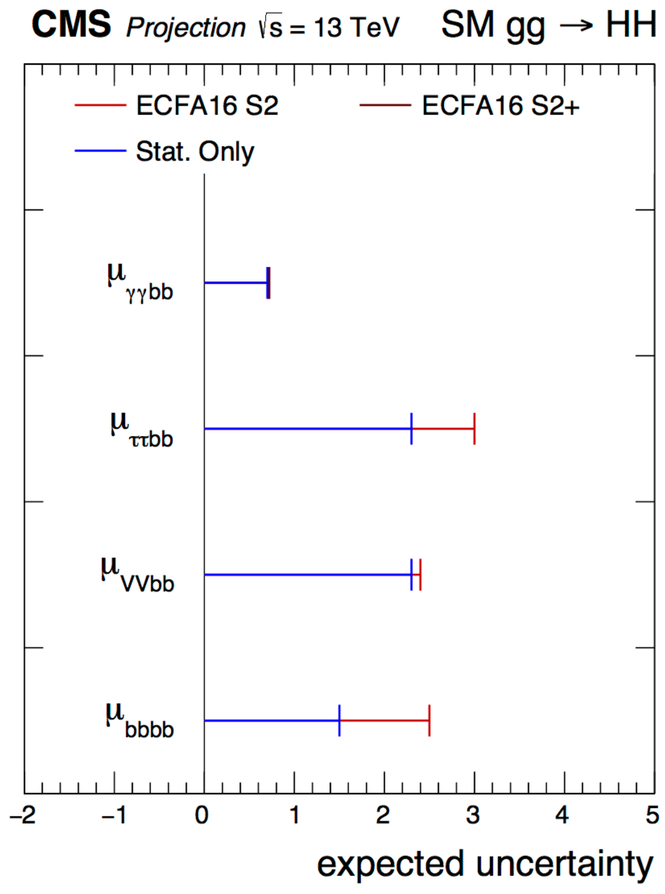
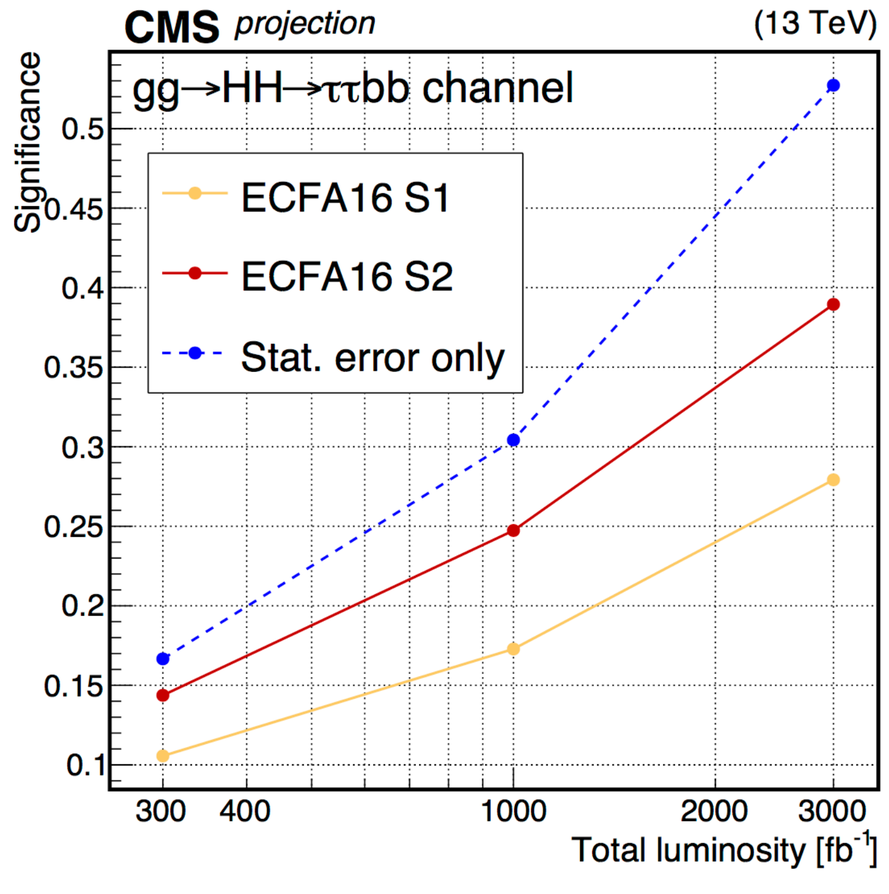


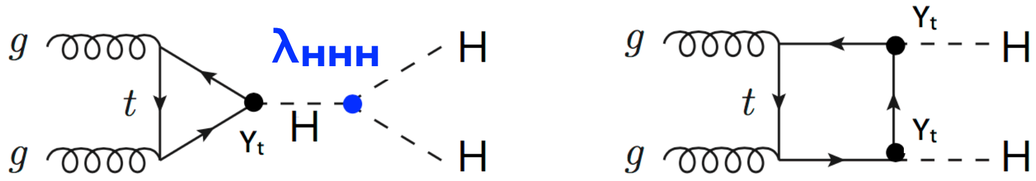


H(125) self-couplings @ HL-LHC

ATL-PHYS-PUB-2016-024
ATL-PHYS-PUB-2017-001

Performance estimated using the simplified pp → HH analyses (13 TeV).

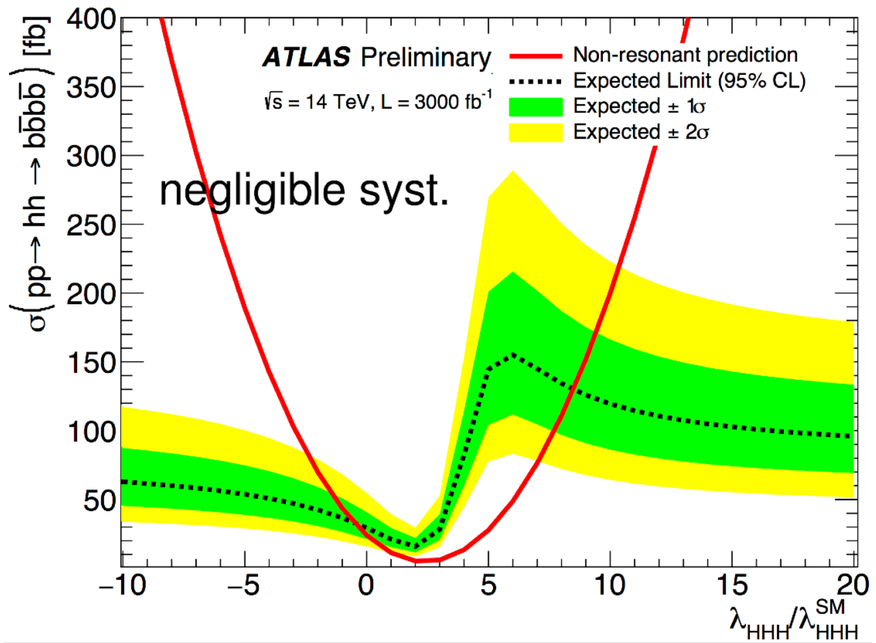
- Probe the shape of the scalar Higgs potential.



$\sigma_{HH} \sim 33.5\ fb^{-1}$ @ 13TeV (NNLO + NNLL)

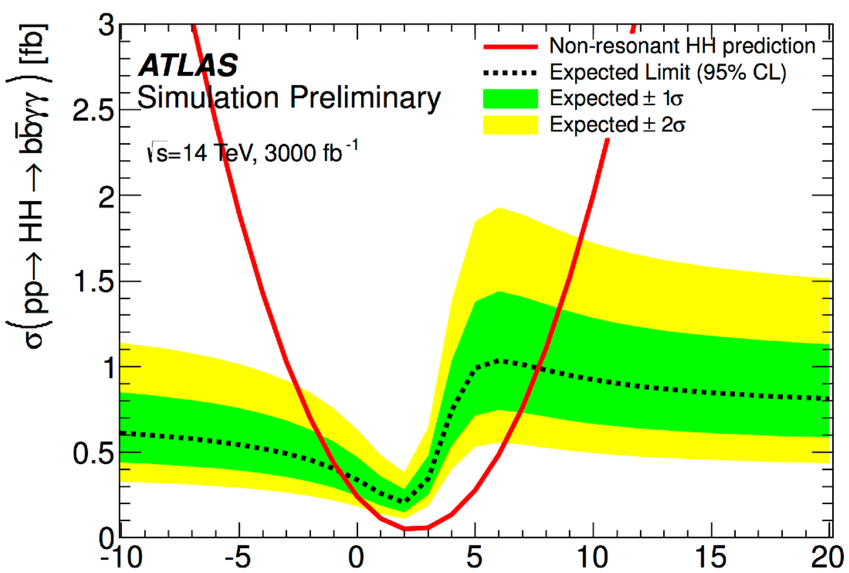
- Results for decay modes: **HH → bbγγ / bbbb**, and **ttHH** production **(HH → bbbb**, semi-leptonic tt**)**

HH → bbγγ



Expected to be constrained to:
$-0.8 < \lambda/\lambda_{SM} < 7.7$

HH → bbbb
(trigger p_T > 75 GeV)



Expected to be constrained to:
$-3.4 < \lambda/\lambda_{SM} < 12$

Physics performance @ HL-LHC

Good tests kill flawed theories; we remain alive to guess again.
Sir Karl Raimund Popper

Prospects for new physics at HL-LHC:

- Probing for anomalous HVV interactions in **H → 4ℓ**
- Searches for SUSY and DM signatures
- Direct observation of new resonances (**Z', W'**)

Anomalous HZZ interactions @ HL-LHC

CMS-PAS-FTR-16-002

Performance estimated using the H→ 4ℓ analysis @12.9 fb^{-1} (13 TeV).

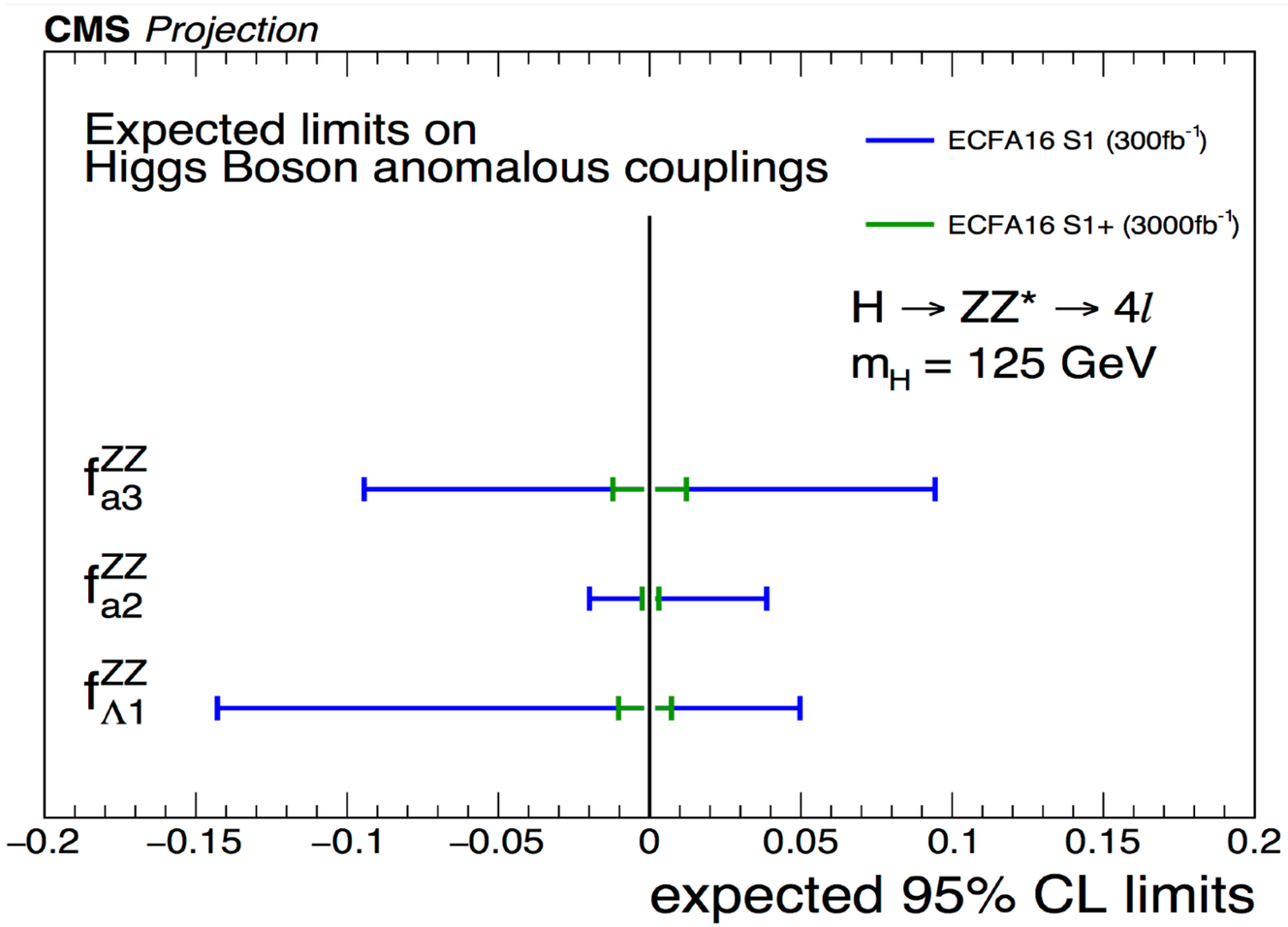
- Parameterisation of decay amplitude:

$$A = \frac{1}{v}\left[a_1^{VV} + \frac{\kappa_1^{VV} q_1^2 + \kappa_2^{VV} q_2^2}{\left(\Lambda_1^{VV}\right)^2} + \frac{\kappa_3^{VV}(q_1+q_2)^2}{\left(\Lambda_Q^{VV}\right)^2}\right] m_{V1}^2 \epsilon_{V1}^* \epsilon_{V2}^* + a_2^{VV} f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + a_3^{VV} f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu}$$

SM — leading momentum expansion — higher order cp-even — cp-odd

Effects of high pileup and detector performance @3ab^{-1} estimated:

- Lepton misidentification rates, and efficiencies



Towards the small values of fractional presence sensitivity pre-dominantly comes from the interference effects between different decay amplitude terms

Projected 95% CIs:

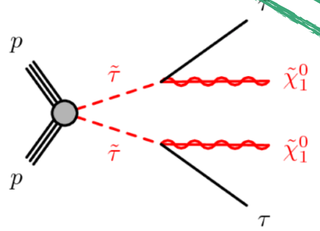
Parameter	300 fb^{-1}	3000 fb^{-1}
$f_{a3} \times cos\,(\phi_{a3})$	[-0.094, 0.094]	[-0.012, 0.012]
$f_{a2} \times cos\,(\phi_{a2})$	[-0.020, 0.039]	[-0.0025, 0.0031]
$f_{\Lambda 1} \times cos\,(\phi_{\Lambda 1})$	[-0.14, 0.05]	[-0.010, 0.0072]

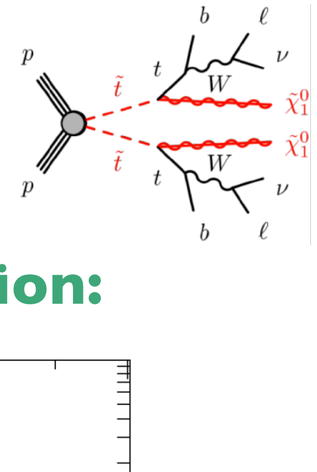
SUSY searches @ HL-LHC

ATL-PHYS-PUB-2016-021
ATL-PHYS-PUB-2016-022

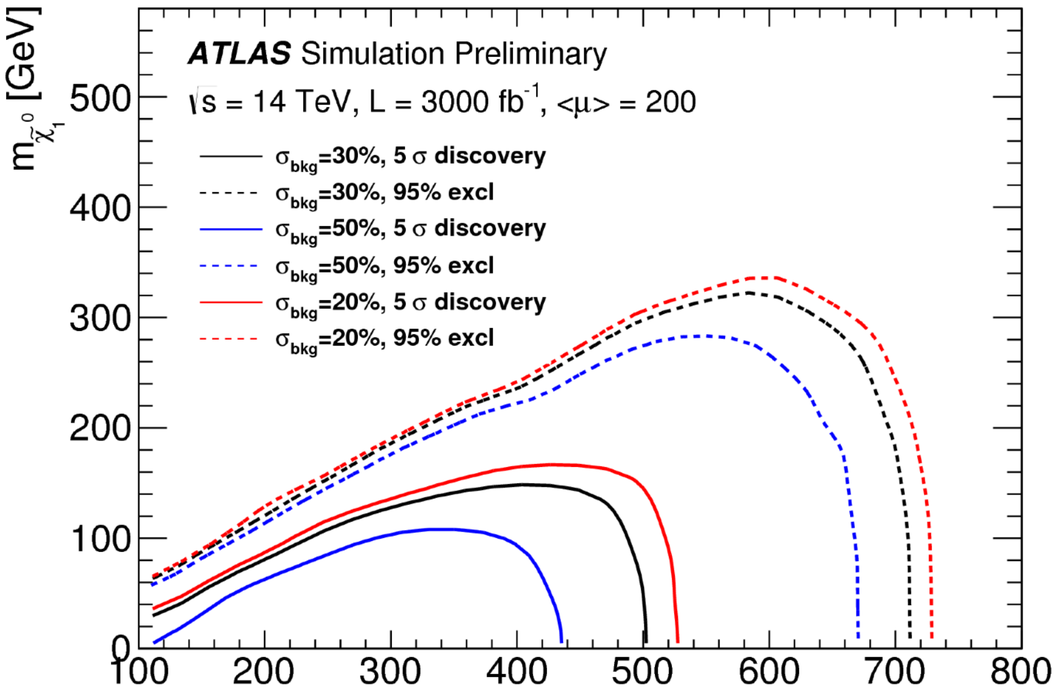
Performance estimated using the (simplified) analyses

- **Direct stau pair production:** Simplified models, assume 100% BR of $\tau \rightarrow \tau \chi^0_1$
  - Main background: W+jets, ttbar
- **Direct stop pair production:** Compressed mass spectra
  - Low stop - neutralino mass difference, channel needs high luminosity
- **Parameterised detector response** (resolution, efficiencies, misidentification rates)





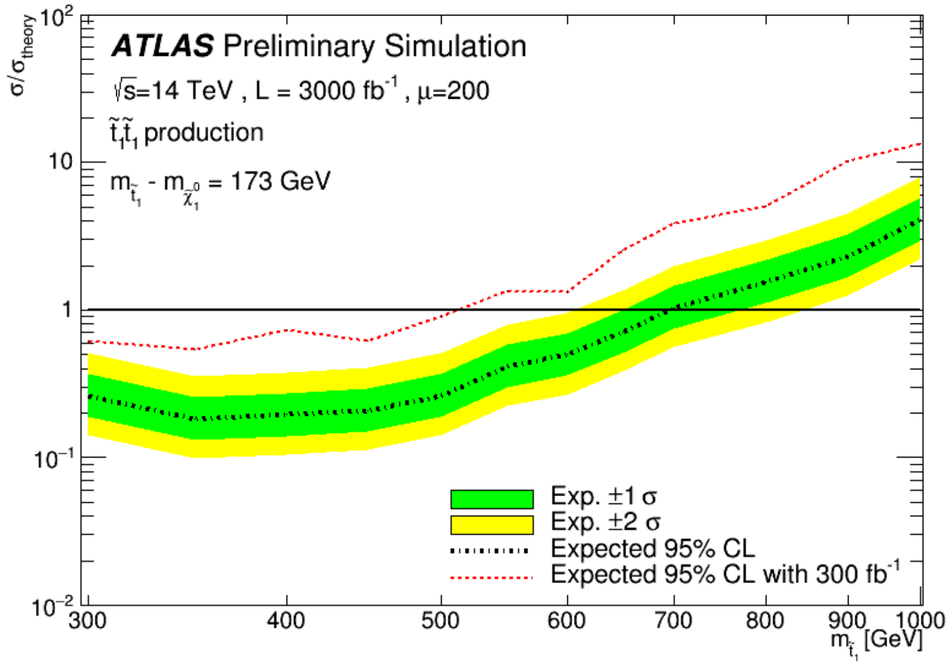
Direct stau pair production:



Discovery reach m(stau) < 430-520 GeV

current exclusion limits about 110 GeV

Direct stop pair production:



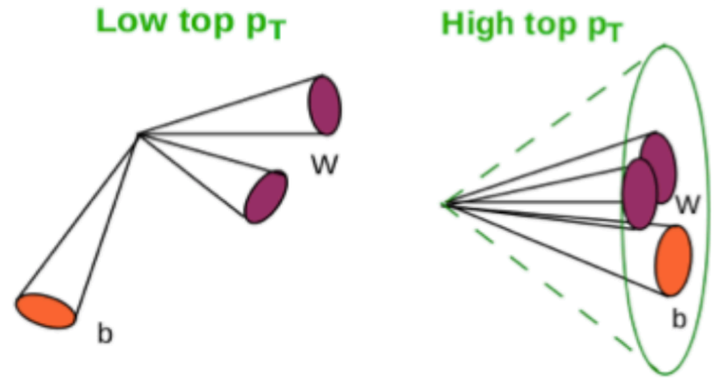
Discovery reach m(stop) < 500 GeV

New resonances @ HL-LHC

CMS-PAS-FTR-16-005
ATL-PHYS-PUB-2017-002

Performance estimated using the Z' and W' searches @ 13 TeV.

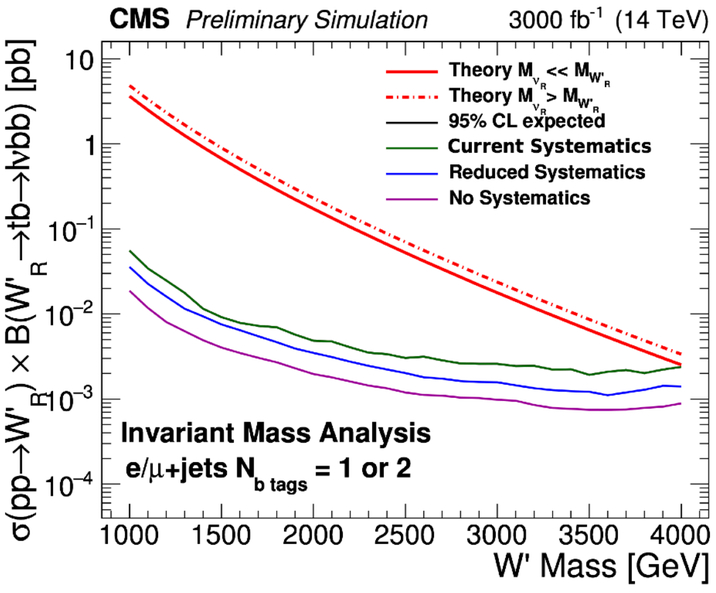
- **W' → tb → bbℓν :** high-p_T lepton, significant E_{Tmiss}, two b-jets
- **Z' → tt → ℓνb qq'b / qq'b qq'b :** Exploit boosted topologies



Effects of high pileup and detector performance @3ab^{-1}

- Lepton efficiencies assumed to be preserved, systematics (likely conservative) adopted to diff. scenarios.

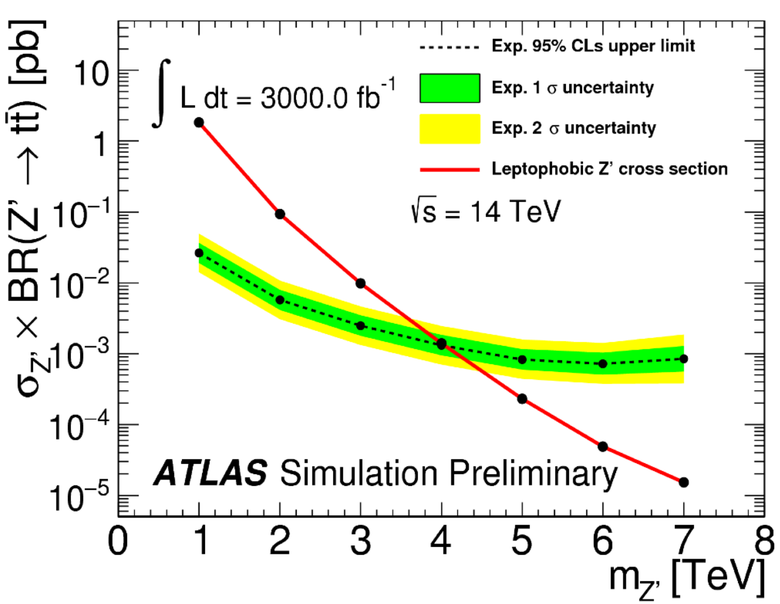
W' → tb → bbℓν



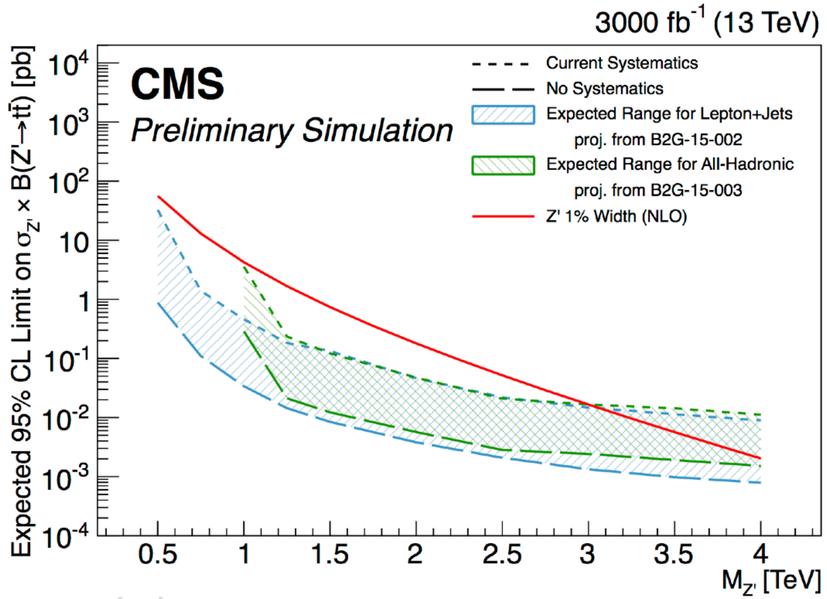
Exclusion: m(W') > 4 TeV

current limits about 2.7 TeV

Z' → tt (hadronic)



Z' → tt
(hadronic + semi-leptonic)



Exclusion: m(Z') > 4 TeV (similar to both final states)

current limits about 2 TeV

Summary

Measurements @ 7, 8, 13 TeV indicate the SM-like Higgs boson

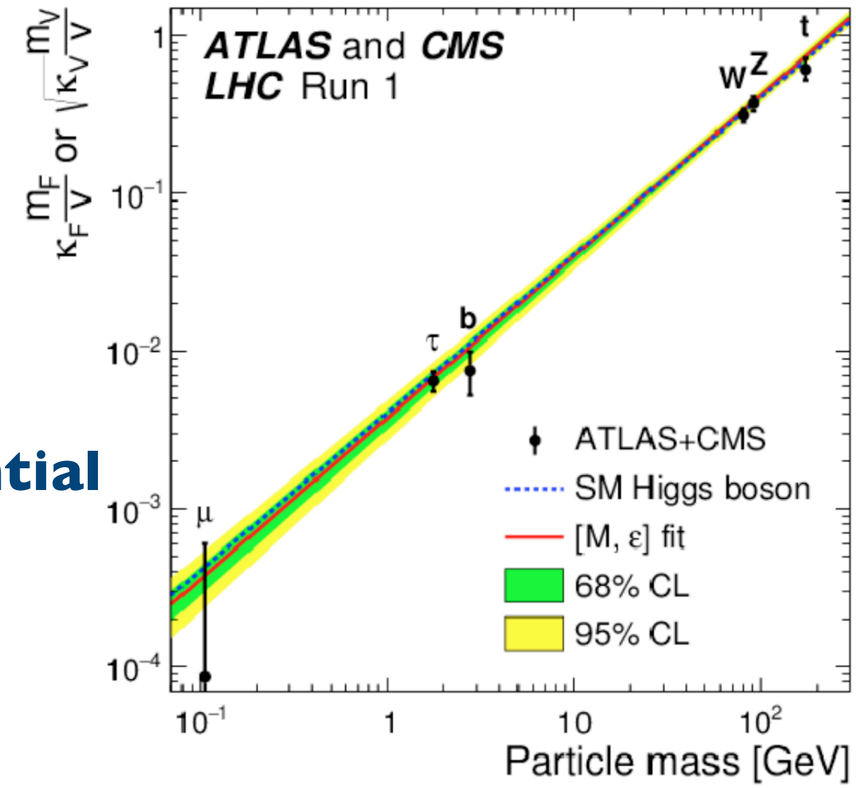
- Understanding of the true **nature of the Higgs boson** is one of the central subjects in the particles physics today

Near-term future measurements @ 13/14 TeV might provides us with some hints...

- Higgs boson might offer **a portal to the new physics** phenomena

Upgrades to HL-LHC will enable full discovery potential

- **Major effort of the community** of theoretical and experimental physicists is required (and is already ongoing)
- Estimates of the HL-LHC performance are already encouraging



Next-generation accelerators and experiments are key to the future of particles physics and to our understanding of the Nature

> If your experiment needs statistics,
> you ought to have done a better experiment.
> E. Rutherford