HASCO Summer School 2017, University of Göttingen, 16-21 July 2017

Higgs Physics

Lecture 2

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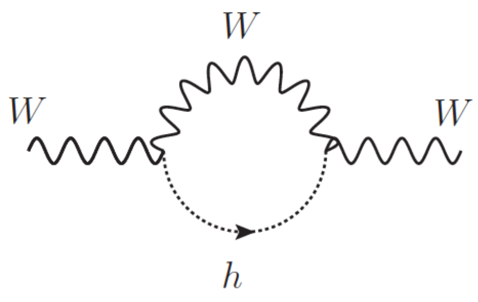
ICREA/IFAE, Barcelona

Much more to Higgs physics than the LHC

Indirect precision EW



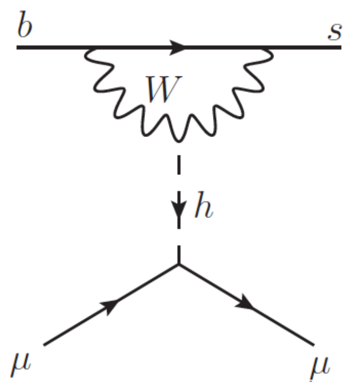
Direct Search Programs

- LEP
- TeVatron
- SLC
- Etc…

$$H^0$$

LHC

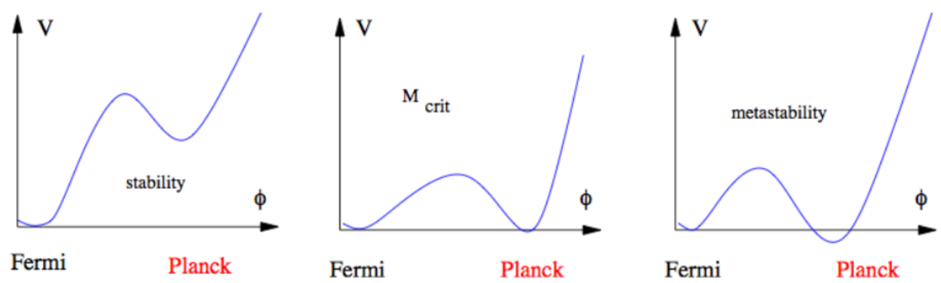
Indirect Flavor



(Higgs penguin)

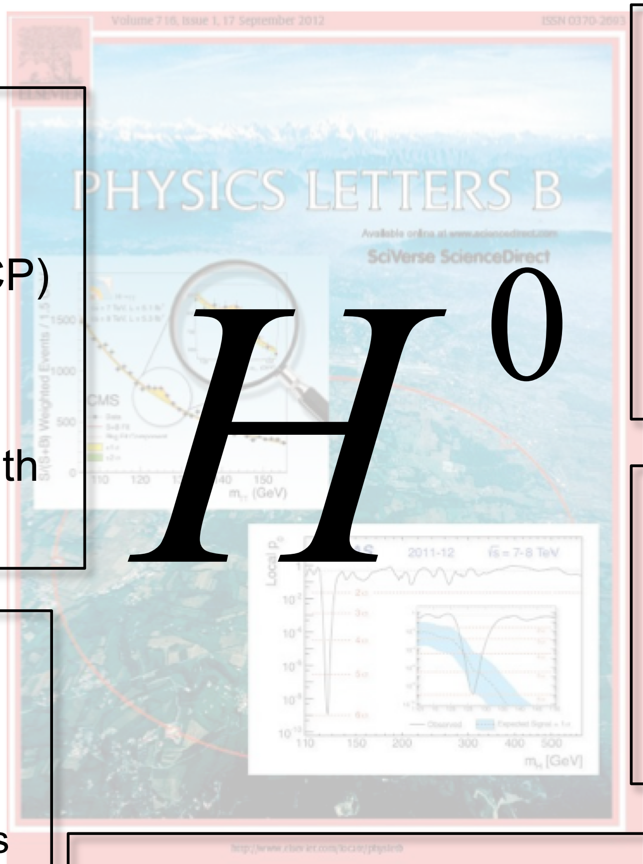
Indirect cosmology

- Vacuum stability
- Higgs Inflation
- Etc…



Explosion of the Higgs Physics landscape!

- Since the discovery of the Higgs boson, an entire new field has emerged.



Precision measurements

- Mass and width
- Quantum numbers (spin, CP)
- Coupling properties
- Differential cross sections
- Off-shell couplings and width
- Interferometry

Is the SM minimal?

- 2HDM searches
- MSSM, NMSSM searches
- Doubly-charged Higgs bosons

Rare / BSM decays

- $H^0 \rightarrow \mu\mu$
- $H^0 \rightarrow Z\gamma$
- $H^0 \rightarrow J/\psi\gamma$, $\Upsilon(ns)\gamma$
- LFV $H^0 \rightarrow \mu\tau$, $e\tau$, $e\mu$
- $H^0 \rightarrow aa$

…and more!

- FCNC $t \rightarrow H^0 q$ decays
- Di-Higgs production
- Trilinear coupling
- … etc

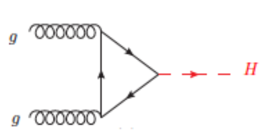
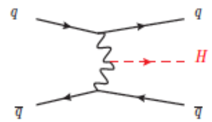
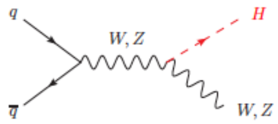
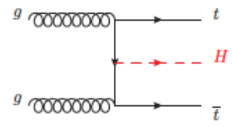
Tool for discovery

- Portal to DM (invisible Higgs)
- Portal to hidden sectors
- Portal to BSM physics with H^0 in the final state (VH^0, H^0H^0)

Overview of main Higgs analyses

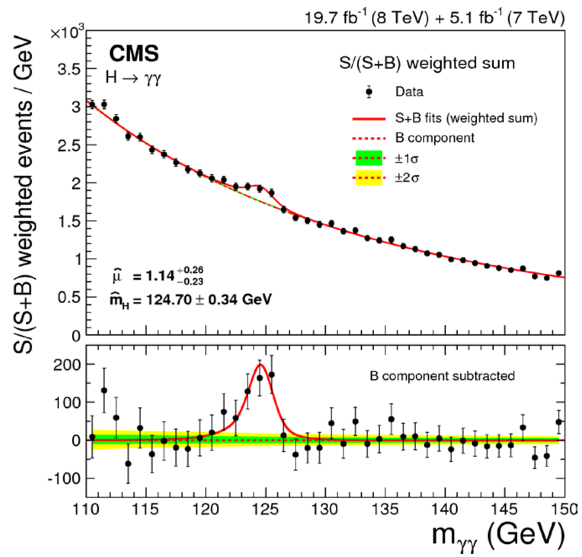
Production modes

Decay modes

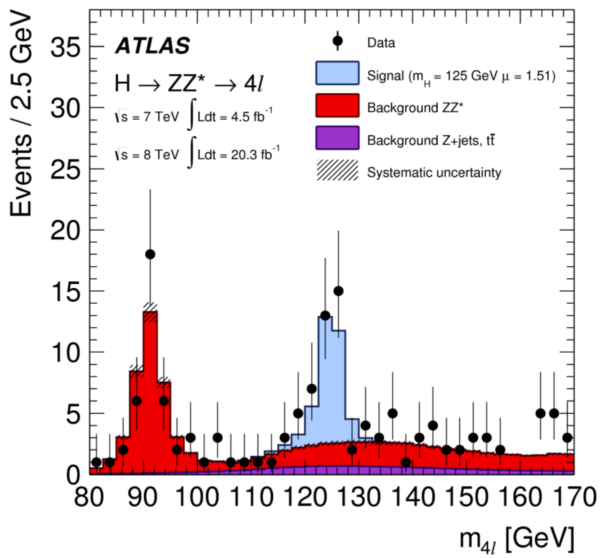
Channel categories	ggF 	VBF 	VH 	ttH 
γγ	✓	✓	✓	✓
ZZ (llll)	✓	✓	✓	✓
WW (lνlν)	✓	✓	✓	✓
ττ				
bb				
Zγ				
μμ				
Invisible	✓			

Discovery channels

γγ



ZZ* → 4l



Overview of main Higgs analyses

Production modes

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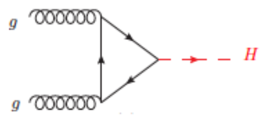
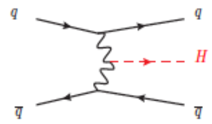
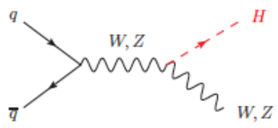
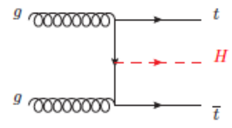
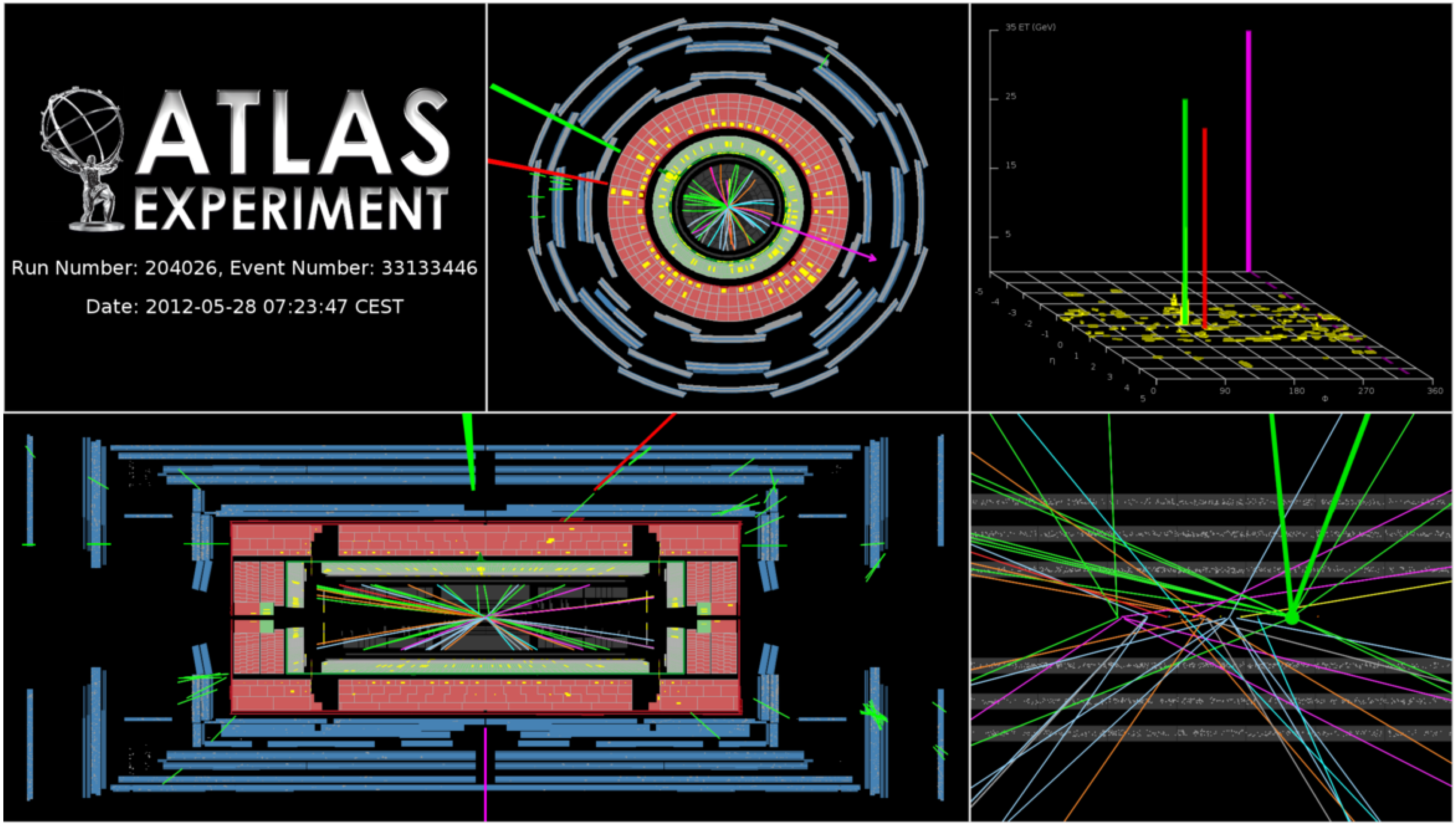
Channel categories	ggF 	VBF 	VH 	ttH 
γγ	✓	✓	✓	✓
ZZ (llll)	✓	✓	✓	✓
WW (lνlν)	✓	✓	✓	✓
ττ	✓			✓
bb		✓	✓	✓
Zγ	✓	✓		
μμ	✓	✓		
Invisible	✓ (monojet)	✓	✓	

A different kind of discovery channel…

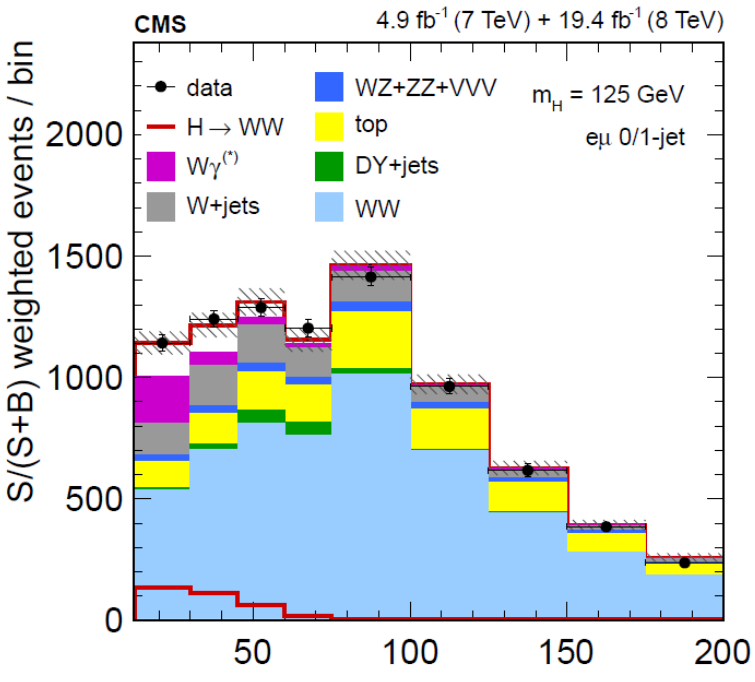
$H \rightarrow WW^* \rightarrow l\nu l\nu$



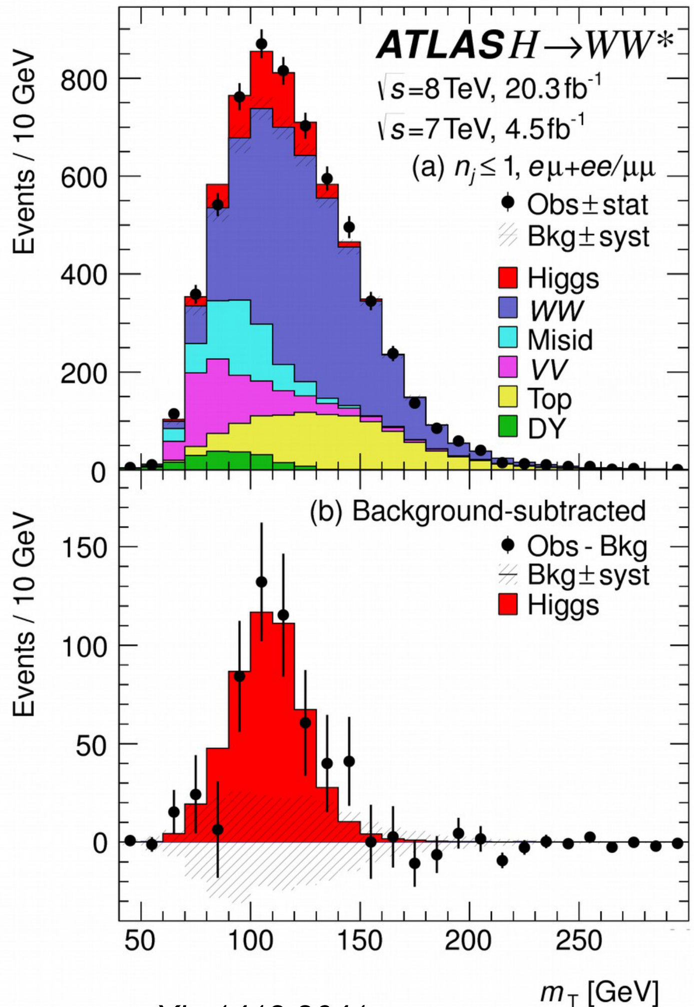
Requires exquisite background understanding!

$H \rightarrow WW^* \rightarrow l\nu l\nu$

- High-sensitivity channel for $130<m_H<200$ GeV.
- Clean dilepton plus E_T^{miss} signature but low S/B.
- Main backgrounds: Z+jets, WW, W+jet/γ, top.
  ➔ normalization in data control regions.
- No direct reconstruction of Higgs mass possible (neutrinos) ➔ use transverse mass variable.
- Exploit spin correlation between W bosons:
  spin 0 ➔ small angular separation between leptons



arXiv:1312.1129

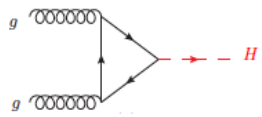
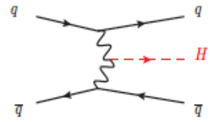
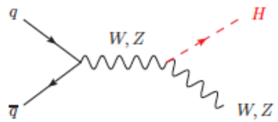
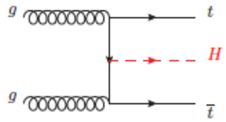


arXiv:1412.2641

Overview of main Higgs analyses

Production modes

Decay modes

Channel categories	ggF 	VBF 	VH 	ttH 
γγ	✓	✓	✓	✓
ZZ (llll)	✓	✓	✓	✓
WW (lνlν)	✓	✓	✓	✓
ττ	✓	✓	✓	✓
bb		✓	✓	✓
Zγ	✓	✓		
μμ	✓	✓		
Invisible	✓ (monojet)	✓	✓	

The rest of the channels are crucial to establish the nature of the particle

Precision measurements

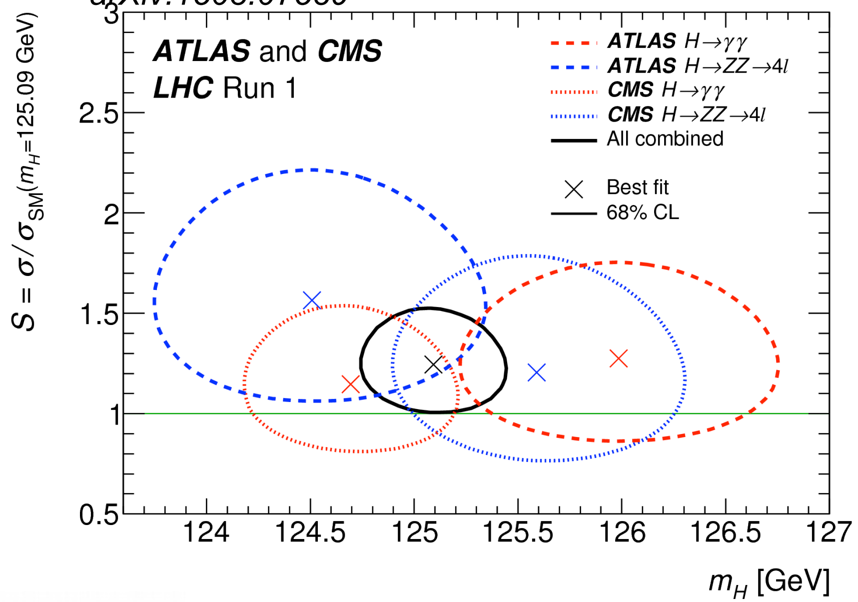
Higgs boson mass

- Measurement of the Higgs boson mass performed in the two channels with the best mass resolution: H→γγ and H→ZZ*→4l using final Run 1 calibrations.
- Signal yield left free to avoid biasing mass measurement.

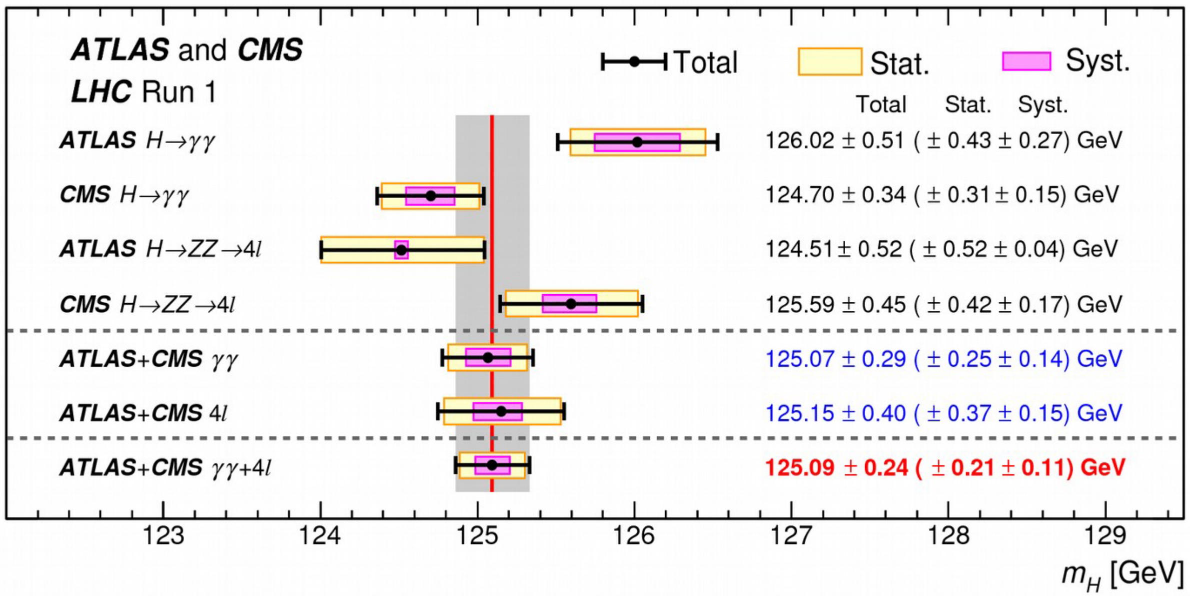
m_H = 125.09 ± 0.24 GeV

2 per-mille accuracy!

arXiv:1503.07589



arXiv:1503.07589



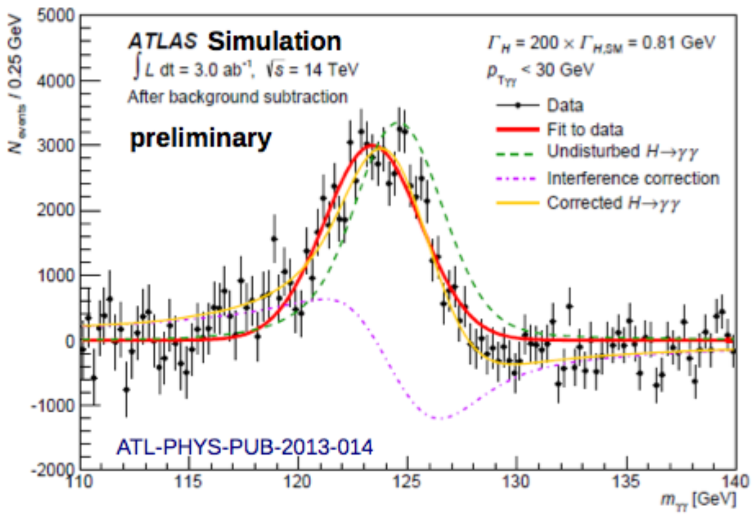
- Compatibility of the four measurements ~10%.
- Measurement still dominated by the statistical uncertainty.
- Main systematic uncertainty related to photon and lepton energy scales.

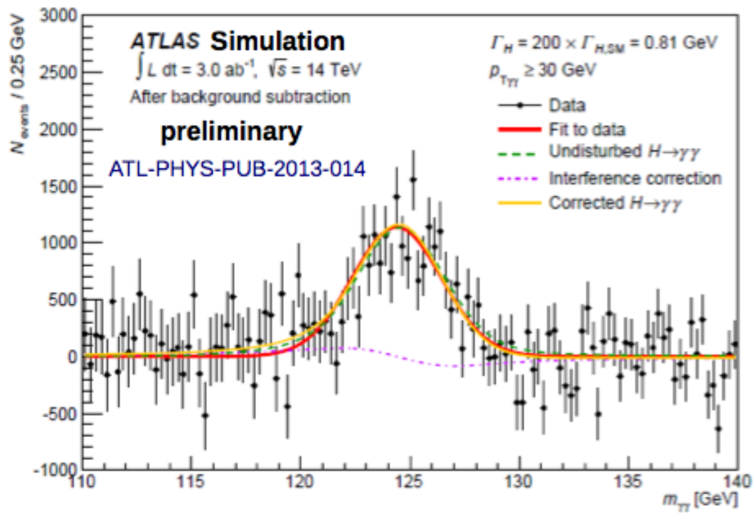
Higgs boson width

Γ_H(SM)=4.2 MeV (~3 orders of magnitude smaller than $\Gamma_{W,Z}$!)

- A precise and model-independent determination at the LHC through rate measurements is not possible, since what is measured is σ x BR. [Much better prospects at an e^+e^- collider.]
- Existing direct bounds are quite weak:
  - $\Gamma_H > 3.6 \times 10^{-9}$ MeV (from lifetime in $H \rightarrow ZZ^{(*)} \rightarrow 4l$)
  - $\Gamma_H < 1.7$ GeV (from width of invariant mass distribution in $H \rightarrow ZZ^{(*)} \rightarrow 4l$)
- Other possibilities:
  - Coupling measurements (with some assumptions)
  - Constraints from invisible (and exotic) decays
  - Interferometry in $\gamma\gamma$: interference with background shifts mass by ~30 MeV.

    ➔ Use p_T dependence of shift: exp limit $\Gamma_H < 200$ MeV (3 ab^{-1}).





Main quantum numbers: J^{CP}

- **Goal**: verify scalar and CP-even nature ($J^{CP}=0^+$) of the new boson.
  - Spin is a property of the particle. Possibilities:
    J=0 and J=2 allowed
    J=1 forbidden by Landau-Yang theorem (since $H\rightarrow\gamma\gamma$ is observed)
  - CP is a property of the interaction ➔ here will discuss about CP tests in the HVV interaction

- Many options to probe J^{CP} from angular (or threshold behavior) distributions:
  - From the associated production modes (VH, VBF or $gg\rightarrow H$+jets)
  - From the production angle $\cos\theta^*$ distribution
  - From the decay angles and the spin correlation when applicable

- Basic idea:
  - Measure compatibility with the 0^+ hypothesis.
  - Try to exclude alternative hypotheses (in favor of the 0^+ hypothesis) simulated using an effective Lagrangian including higher order couplings.

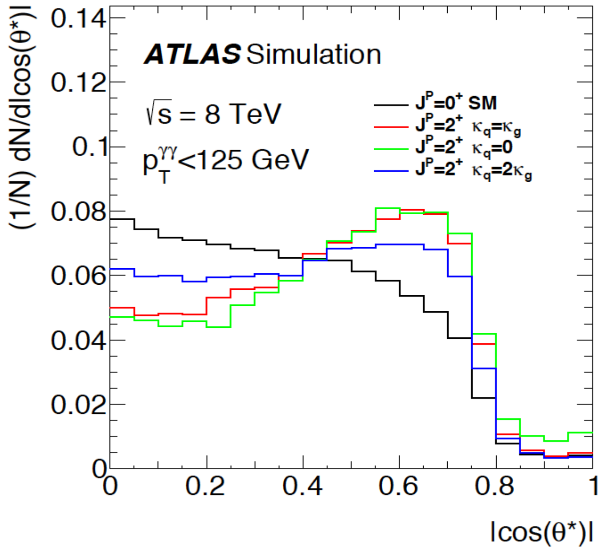
Main quantum numbers: J^{CP}

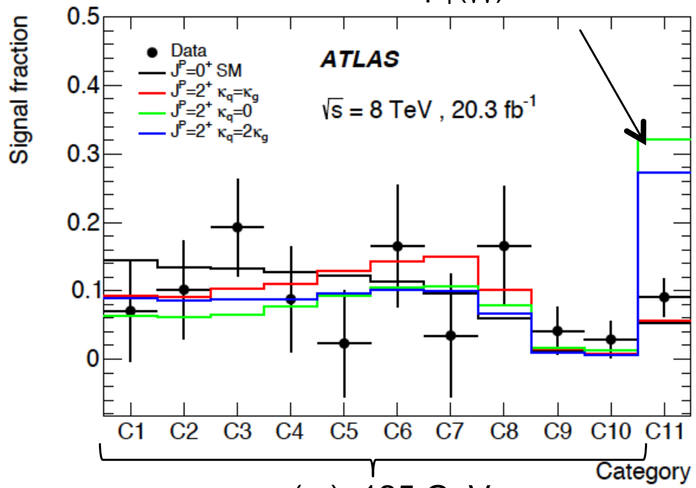
- Use $H \to \gamma\gamma$, ZZ^* and WW^* analyses re-optimized for J^{CP} tests.
  Different kinematic distributions used.

arXiv:1506.05669

125<$p_T(\gamma\gamma)$<300 GeV

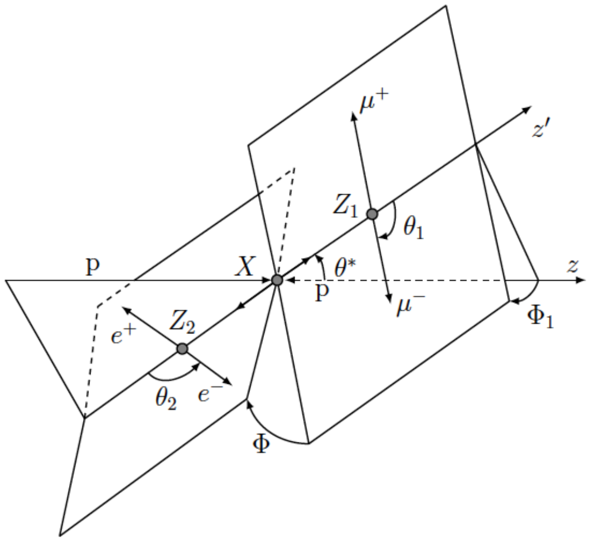
$H \to \gamma\gamma$:
mostly sensitive to spin.
Uses $p_T(\gamma\gamma)$ and photon decay angle in $\gamma\gamma$ rest frame.

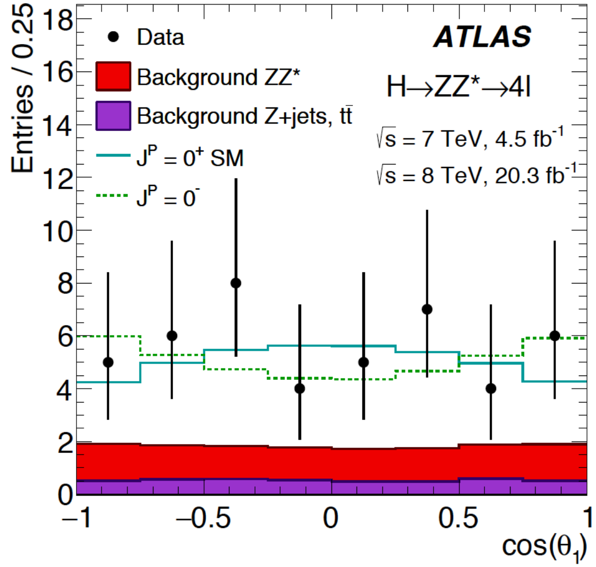




$p_T(\gamma\gamma)$<125 GeV

$H \to ZZ^* \to 4l$:
mostly sensitive to parity.
Uses the distribution of 5 production and decay angles combined in a BDT or Matrix Element (MELA) discriminants



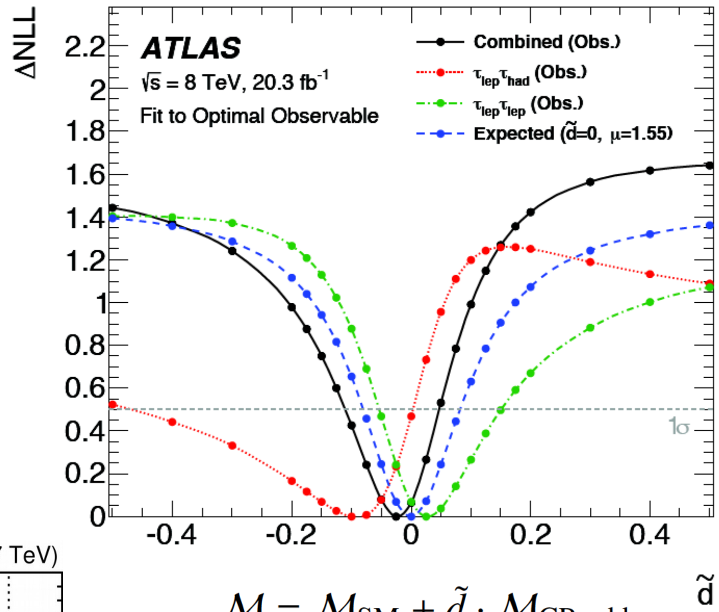


Main quantum numbers: J^{CP}

- Alternative spin hypotheses are disfavored by >3σ combining $H \rightarrow \gamma\gamma$, $H \rightarrow ZZ^*$, and $H \rightarrow WW^*$ analyses.

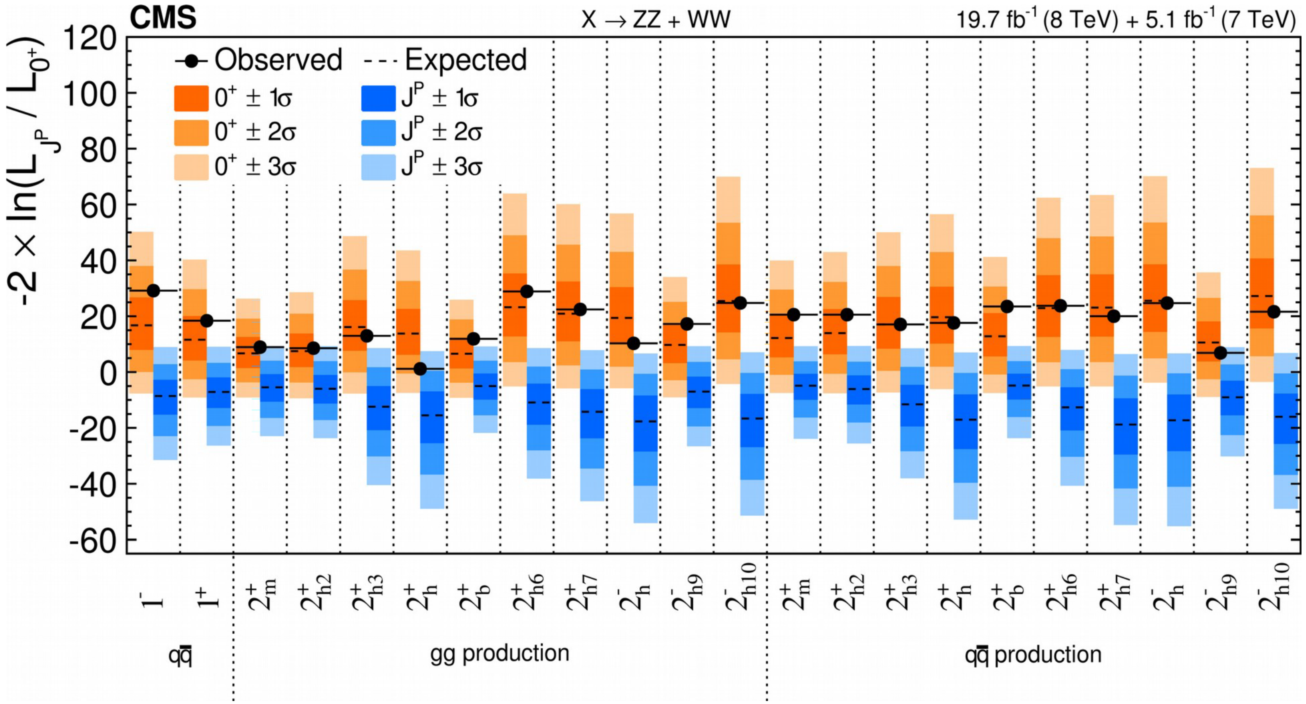
- Tensor structure of the HVV interaction has been tested using $H \rightarrow ZZ^*$ and $H \rightarrow WW^*$ analyses, including CP-odd contributions.

arXiv:1602.04516



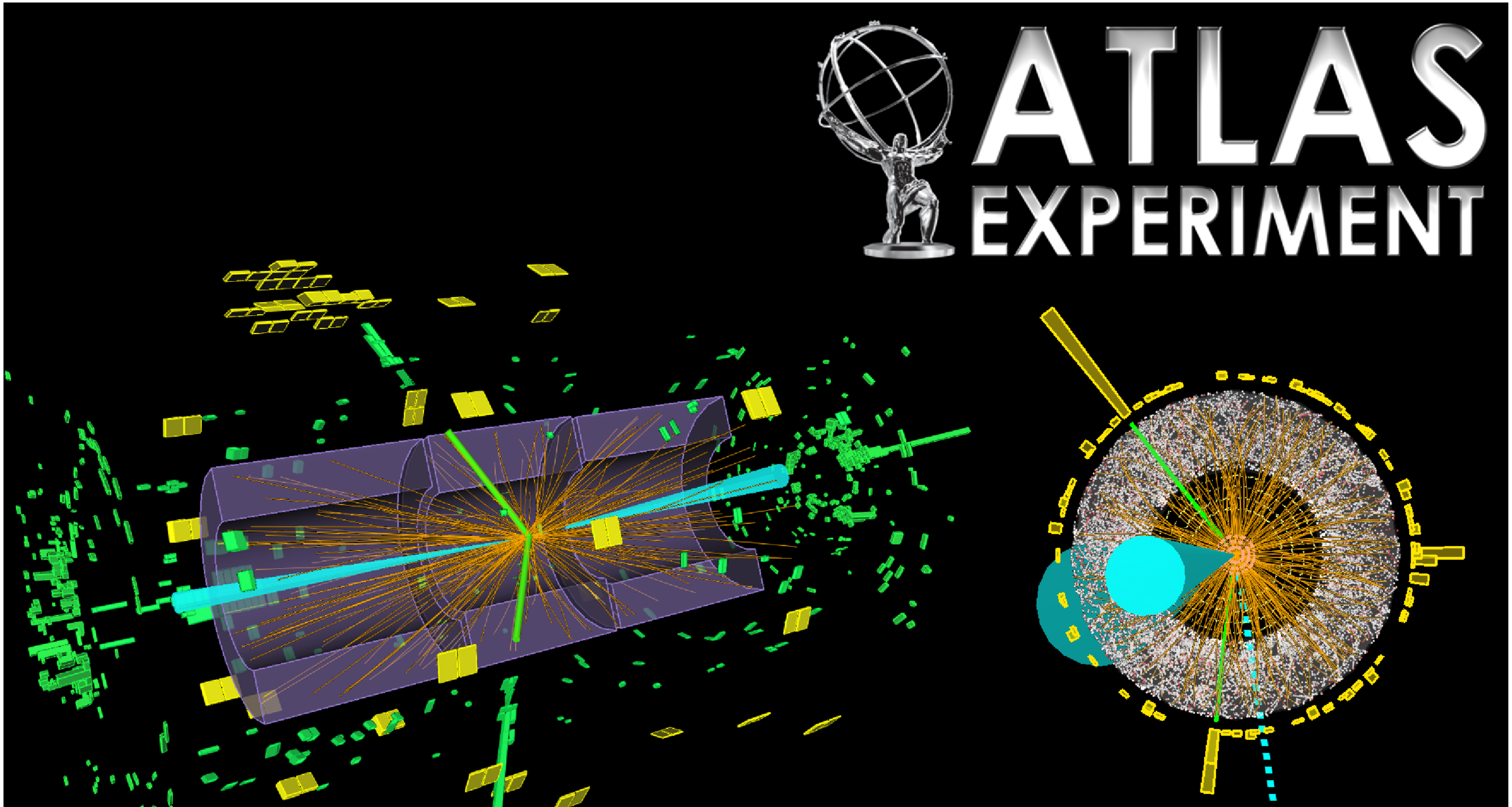
$$\mathcal{M} = \mathcal{M}_{SM} + \tilde{d} \cdot \mathcal{M}_{CP\text{-odd}}$$

arXiv:1411.3441



- Additional constraints on CP-odd contributions have been obtained using the VBF, $H \rightarrow \tau\tau$ process.

Higgs couplings to fermions: H→$\tau^+\tau^-$

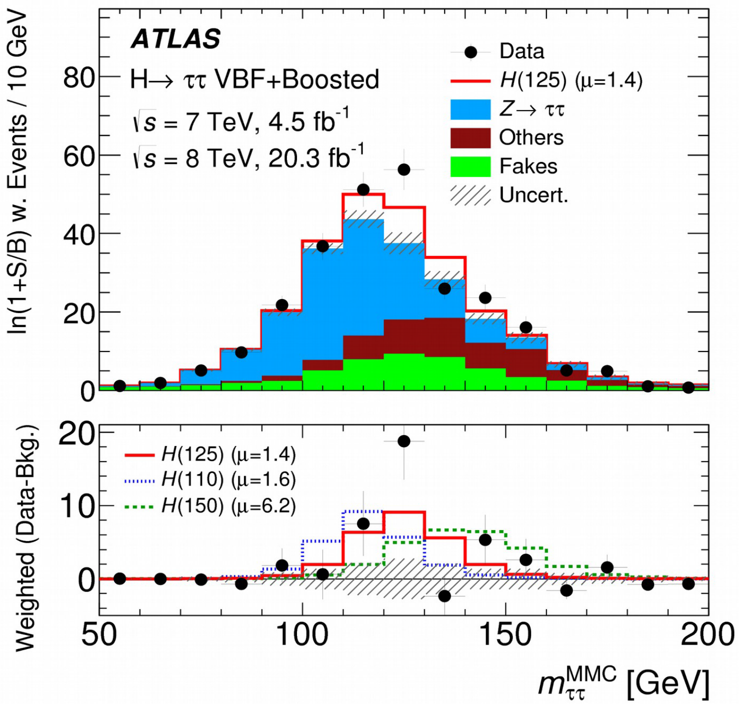


H→$\tau_{had}\tau_{had}$ candidate in VBF channel (m_{MMC} = 131 GeV)

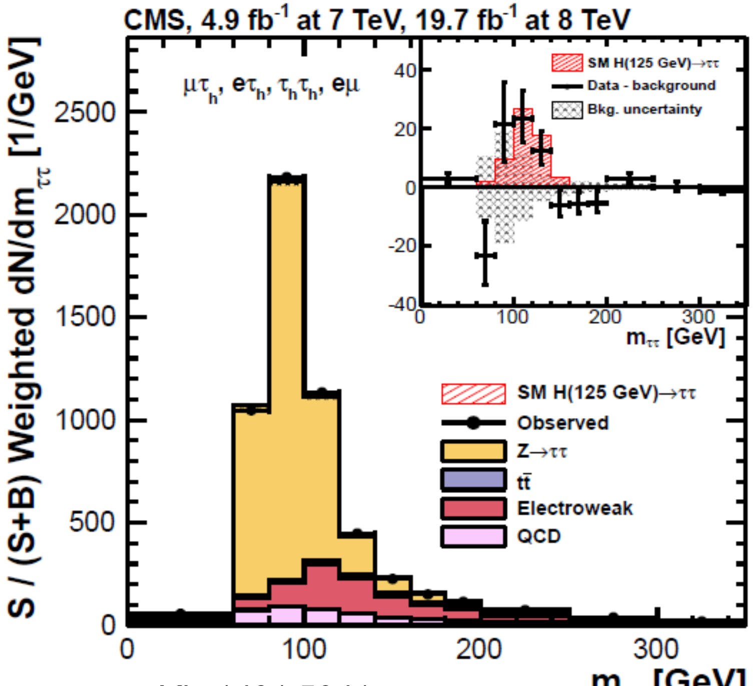
Higgs couplings to fermions: $H \rightarrow \tau^+\tau^-$

- The most sensitive of the fermionic decay modes.
- Events categorized depending on the tau decay modes (leptonic, hadronic) and the jet multiplicity to enhance the sensitivity to VBF and gluon fusion production of highly-boosted Higgs bosons.
- Main background is $Z \rightarrow \tau\tau$, modeled from $Z \rightarrow \mu\mu$ data replacing muons by simulated tau decays ("τ embedding").

arXiv:1501.4943



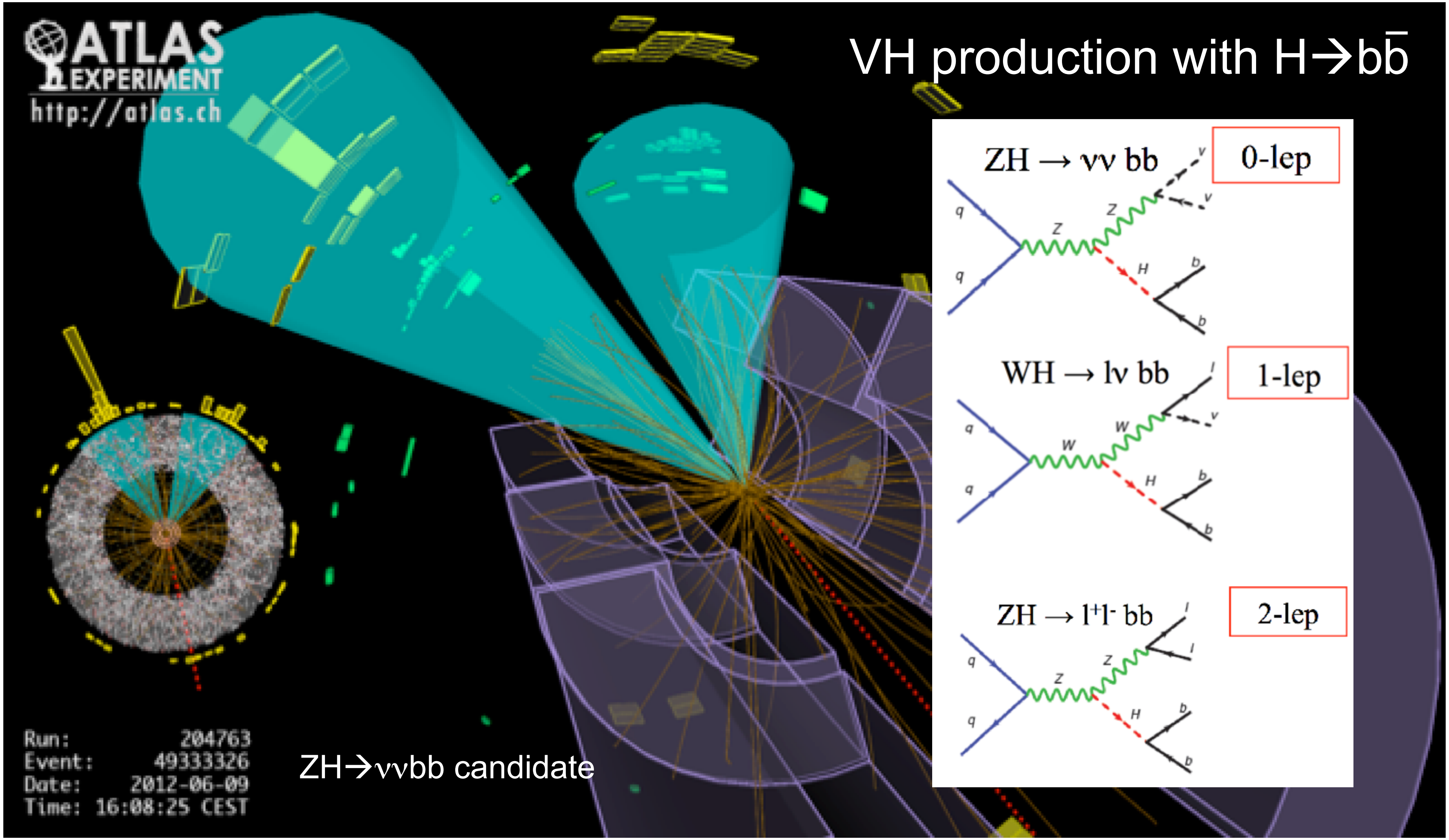
Obs (exp) significance: 4.5σ (3.4σ)



arXiv:1401.5041

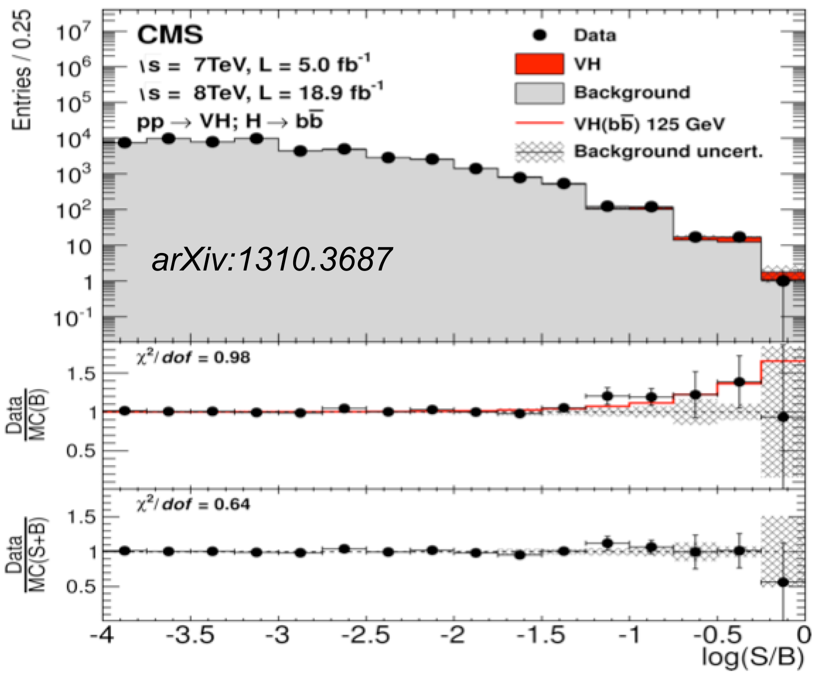
Obs (exp) significance: 3.2σ (3.7σ)

Higgs couplings to fermions: $H \rightarrow b\bar{b}$



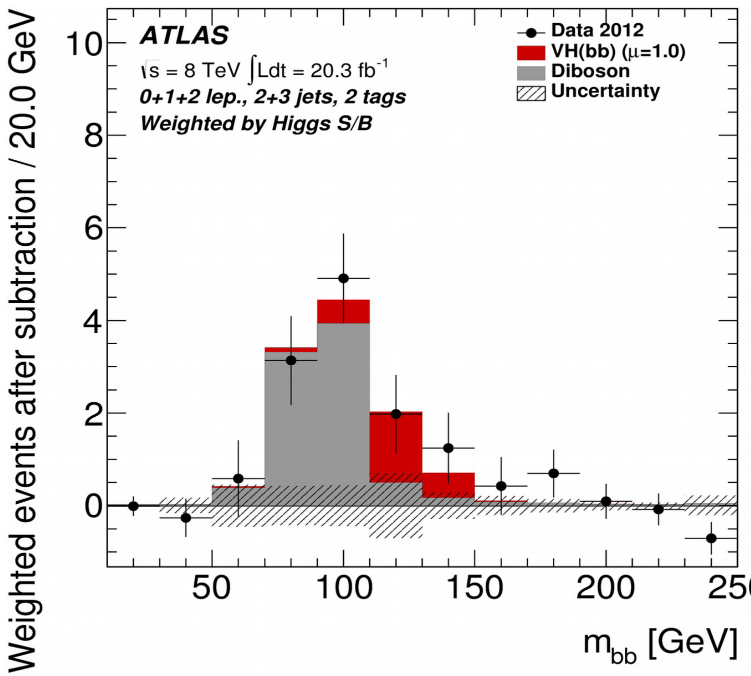
Higgs couplings to fermions: H→b$\bar{b}$

- Most abundant decay mode: BR(H→b$\bar{b}$)~58%.
- Exploit three leptonic W/Z decay modes in VH associated production
  ➔ categorize events by lepton multiplicity (0-lepton, 1-lepton, 2-lepton).
- Broad di-b-jet resonance over large background from W+heavy-flavor and t$\bar{t}$ production.
- Multivariate analyses to increase sensitivity.
- Use VZ(Z→b$\bar{b}$) to validate search strategy.



Obs (exp) significance: 2.1σ (2.1σ)

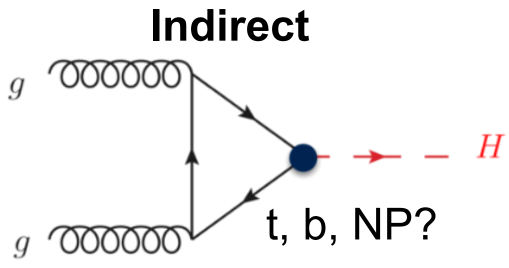
arXiv:1409.6212

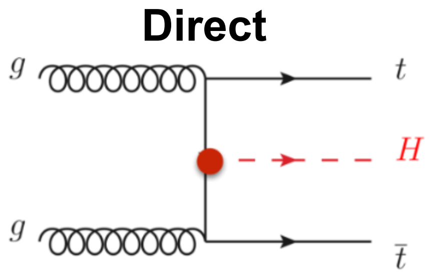


Obs (exp) significance: 1.4σ (2.6σ)

Higgs couplings to fermions: $t\bar{t}H$

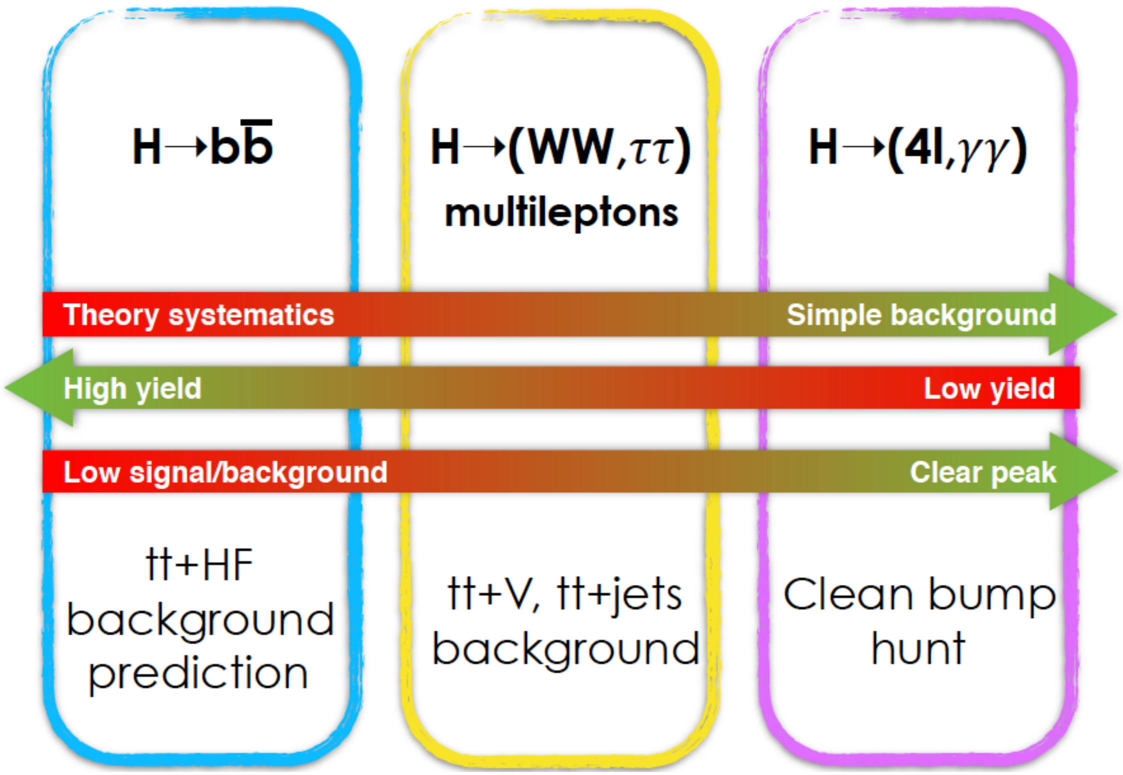
- Associated $t\bar{t}H$ production allows direct measurement of the top-Higgs Yukawa coupling.





$$\sigma_{t\bar{t}H} \propto \lambda_t^2$$

- Very rich experimental signature, depending on the decay of the top quarks and the Higgs boson. Analyses characterized by large number of categories and control regions.



Higgs couplings to fermions: $t\bar{t}H$

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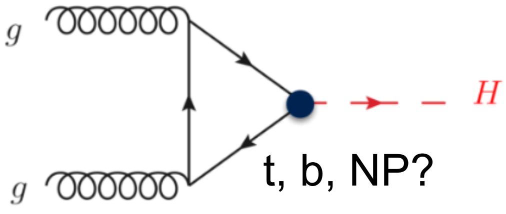
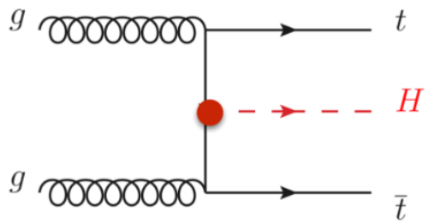
Indirect



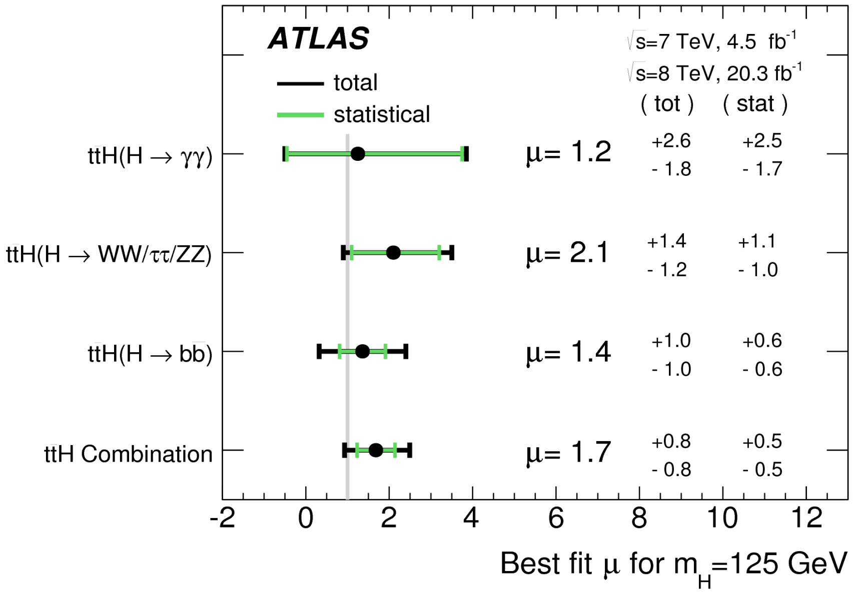
Direct

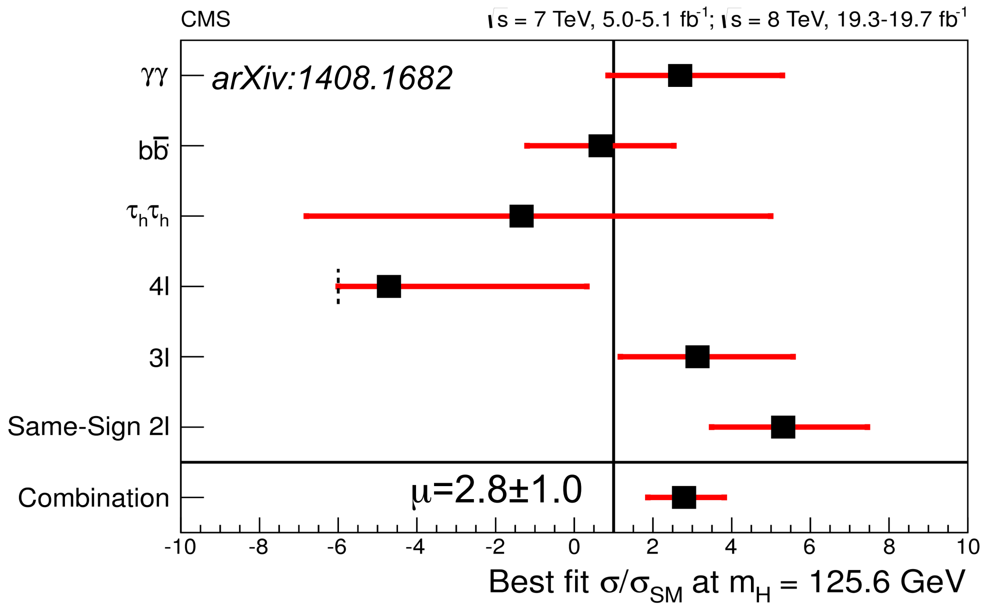


$$\sigma_{t\bar{t}H} \propto \lambda_t^2$$

- Very rich experimental signature, depending on the decay of the top quarks and the Higgs boson. Analyses characterized by large number of categories and control regions.

arXiv:1310.3687





Obs (exp) significance: 2.5σ (1.5σ)

Obs (exp) significance: 3.4σ (1.2σ)

Total cross section

- At the LHC only products of cross section times branching ratios are measured. There is no model-independent way to determine the cross section and the branching ratio separately.

- Combined total cross section (including 7 and 8 TeV measurements) assuming SM kinematics, SM ratios for production cross sections, and SM branching ratios:

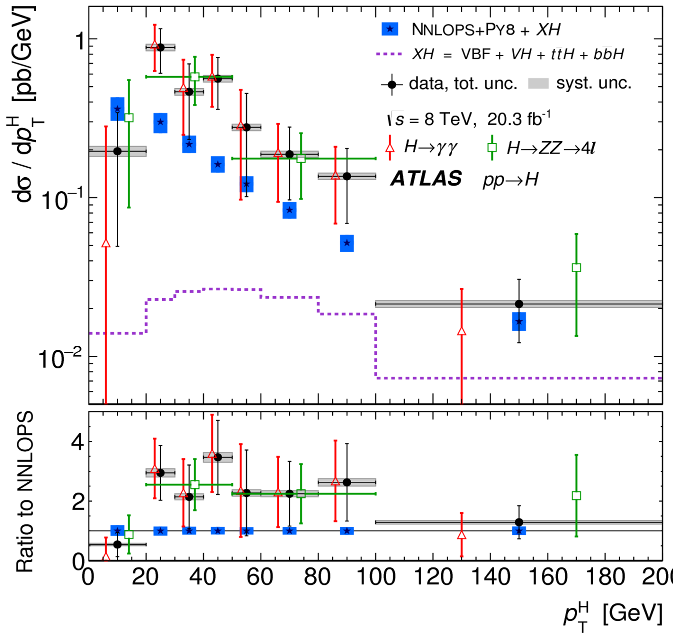
$\mu = \sigma / \sigma_{SM}$ arXiv:1606.02266

Combined	μ	$=$	$1.09^{+0.11}_{-0.10}$	$=$	$1.09^{+0.07}_{-0.07}\,(\text{stat})\,^{+0.04}_{-0.04}\,(\text{expt})\,^{+0.03}_{-0.03}\,(\text{thbgd})\,^{+0.07}_{-0.06}\,(\text{thsig})$
ATLAS	μ	$=$	$1.20^{+0.15}_{-0.14}$	$=$	$1.20^{+0.10}_{-0.10}\,(\text{stat})\,^{+0.06}_{-0.06}\,(\text{expt})\,^{+0.04}_{-0.04}\,(\text{thbgd})\,^{+0.08}_{-0.07}\,(\text{thsig})$
CMS	μ	$=$	$0.98^{+0.14}_{-0.13}$	$=$	$0.98^{+0.10}_{-0.09}\,(\text{stat})\,^{+0.06}_{-0.05}\,(\text{expt})\,^{+0.04}_{-0.04}\,(\text{thbgd})\,^{+0.08}_{-0.07}\,(\text{thsig})$

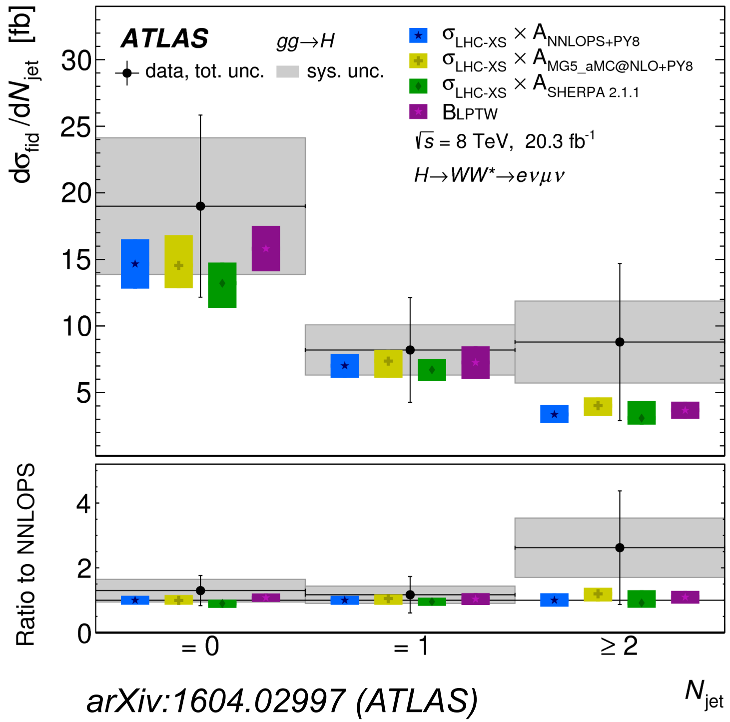
➔ Good agreement with the SM prediction (μ=1)

Differential cross sections

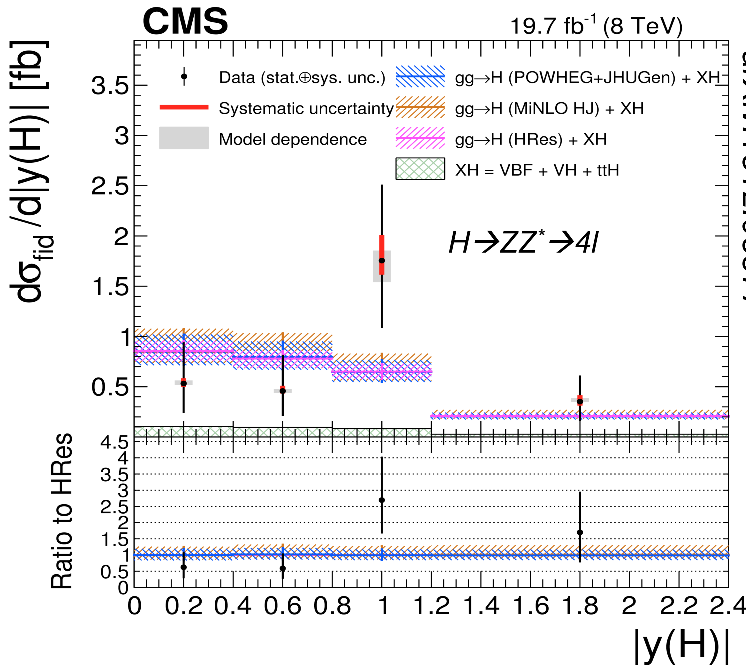
- Measurements of differential cross sections using Run 1 data for quantities such as p_T^H, $|y_H|$, or jet multiplicity, unfolded to the particle level.
- Using $H \rightarrow \gamma\gamma$, ZZ^* and even WW^* decay channels.
- Run 1 measurements still dominated by the statistical uncertainty.



arXiv:1512.08377



arXiv:1604.02997 (ATLAS)
arXiv:1606.01522 (CMS)



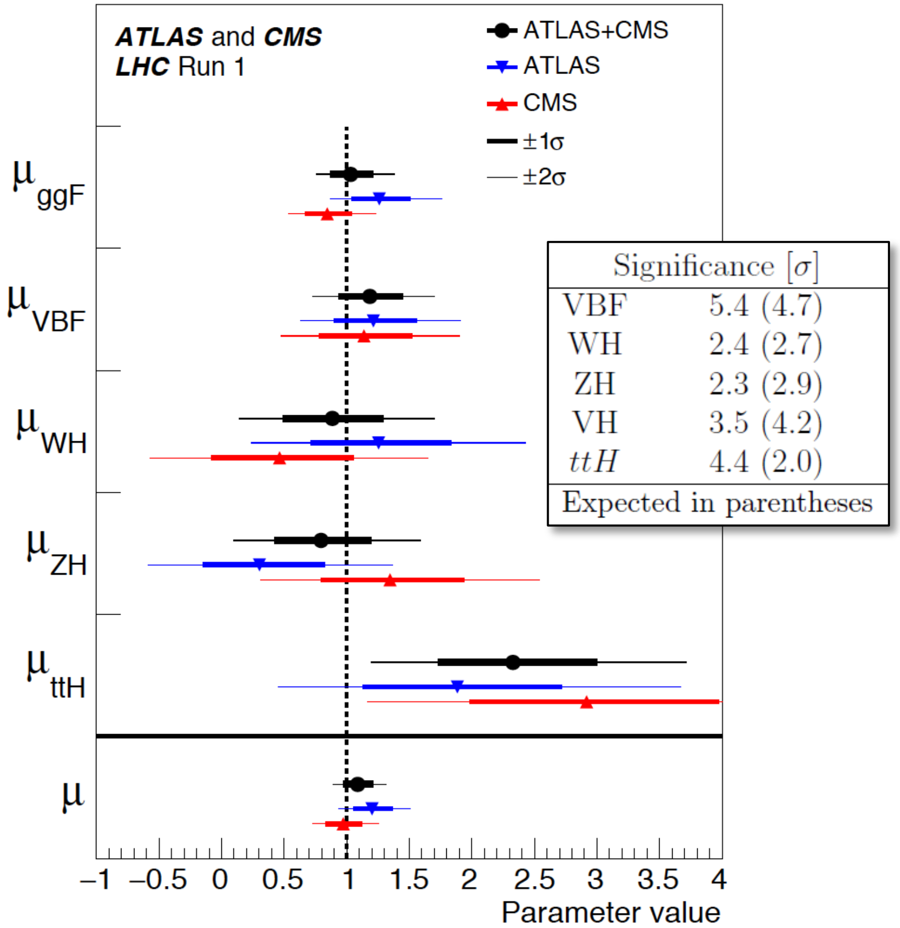
arXiv:1512.08377

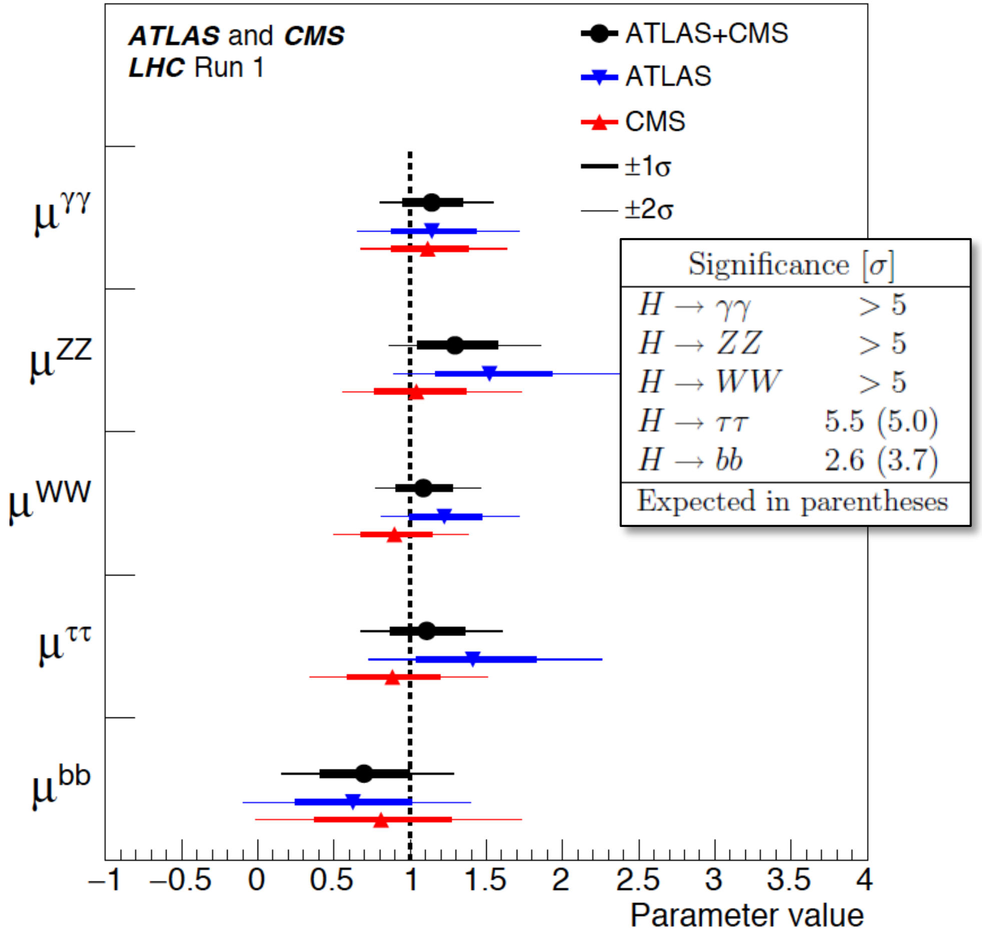
Signal strengths by production and decay

$\sigma_{meas}/\sigma_{SM}$ per production mode
(assuming SM decay)

BR_{meas}/BR_{SM} per decay mode
(assuming SM production)

arXiv:1606.02266





Good agreement with the SM prediction (μ=1)

Probing Higgs couplings

- Several production and decay mechanisms contribute to signal rates per channel
  ➔ interpretation is difficult

$$n_s^c = \underline{\mu}\left(\sum_{i\in\{processes\}} \underline{\mu^i}\sigma_{SM}^i \times A^{ic} \times \varepsilon^{ic}\right) \times \underline{\mu^f} Br^f \times L^c$$

- A better option: measure deviations of couplings from the SM prediction using an effective Lagrangian (*arXiv:1209.0040*).

$$\begin{aligned}
\mathcal{L} = {} & \kappa_3 \frac{m_H^2}{2v} H^3 + \kappa_Z \frac{m_Z^2}{v} Z_\mu Z^\mu H + \kappa_W \frac{2m_W^2}{v} W_\mu^+ W^{-\mu} H \\
& + \kappa_g \frac{\alpha_s}{12\pi v} G_{\mu\nu}^a G^{a\mu\nu} H + \kappa_\gamma \frac{\alpha}{2\pi v} A_{\mu\nu} A^{\mu\nu} H + \kappa_{Z\gamma} \frac{\alpha}{\pi v} A_{\mu\nu} Z^{\mu\nu} H \\
& + \kappa_{VV} \frac{\alpha}{2\pi v} \left(\cos^2\theta_W Z_{\mu\nu} Z^{\mu\nu} + 2\, W_{\mu\nu}^+ W^{-\mu\nu}\right) H \\
& - \left(\kappa_t \sum_{f=u,c,t} \frac{m_f}{v} f\bar{f} + \kappa_b \sum_{f=d,s,b} \frac{m_f}{v} f\bar{f} + \kappa_\tau \sum_{f=e,\mu,\tau} \frac{m_f}{v} f\bar{f}\right) H
\end{aligned}$$

Probing Higgs couplings

- Several production and decay mechanisms contribute to signal rates per channel
  ➔ interpretation is difficult

$$n_s^c = \mu \left(\sum_{i \in \{processes\}} \mu^i \sigma_{SM}^i \times A^{ic} \times \varepsilon^{ic} \right) \times \mu^f Br^f \times L^c$$

- MOTIVATION:
  Precision Higgs coupling measurements can provide an indirect probe for NP.

◻ SUSY (tanβ=5): $\frac{g_{hbb}}{g_{h_{SM}bb}} = \frac{g_{h\tau\tau}}{g_{h_{SM}\tau\tau}} \simeq 1 + 1.7\% \left(\frac{1\ \mathrm{TeV}}{m_A}\right)^2$

◻ Composite Higgs: $\frac{g_{hff}}{g_{h_{SM}ff}} \simeq \frac{g_{hVV}}{g_{h_{SM}VV}} \simeq 1 - 3\% \left(\frac{1\ \mathrm{TeV}}{f}\right)^2$

◻ Top partners: $\frac{g_{hgg}}{g_{h_{SM}gg}} \simeq 1 + 2.9\% \left(\frac{1\ \mathrm{TeV}}{m_T}\right)^2, \quad \frac{g_{h\gamma\gamma}}{g_{h_{SM}\gamma\gamma}} \simeq 1 - 0.8\% \left(\frac{1\ \mathrm{TeV}}{m_T}\right)^2$

Expected deviations in general small. How well can the LHC do?

Probing Higgs couplings

- Basic assumptions:
  - there is only one underlying state with m_H=125.09 GeV,
  - it has negligible width,
  - it is a CP-even scalar (only allow for modification of coupling strengths, leaving the Lorentz structure of the interaction untouched).

- Under these assumptions all production cross sections and branching ratios can be expressed in terms of a few common multiplicative factors to the SM Higgs couplings.

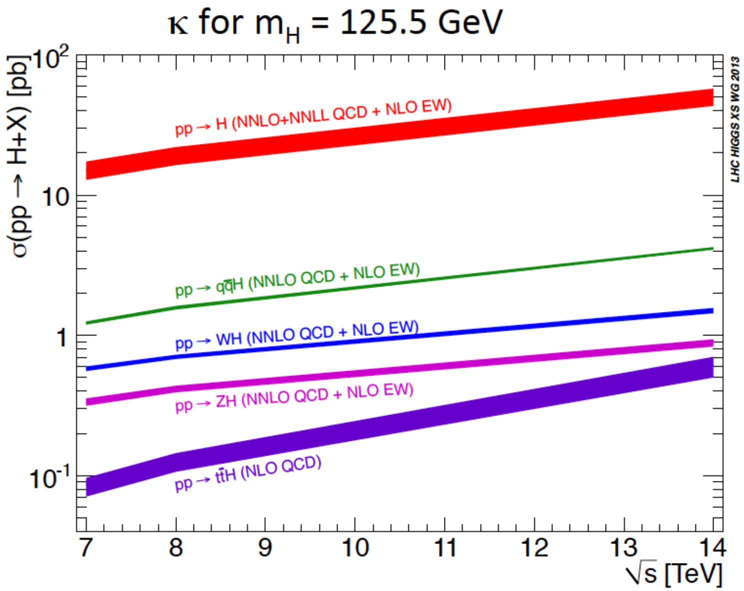
  Examples:

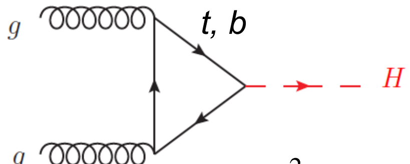
$$\sigma(gg \to H)BR(H \to WW) = \sigma_{SM}(gg \to H)BR_{SM}(H \to WW)\frac{\kappa_g^2 \kappa_W^2}{\kappa_H^2}$$

$$\sigma(WH)BR(H \to bb) = \sigma_{SM}(WH)BR_{SM}(H \to bb)\frac{\kappa_W^2 \kappa_b^2}{\kappa_H^2}$$

where $$\kappa_H^2 = \frac{\sum_i \kappa_i^2 \Gamma_{i,SM}}{\sum_i \Gamma_{i,SM}}$$

Parameterizing Higgs production cross sections



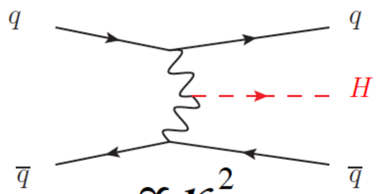


Gluon fusion process

NNnLO ~O(10%)

$$\propto \kappa_g^2 = 1.06\kappa_t^2 - 0.07\kappa_t\kappa_b + 0.01\kappa_b^2$$

(when assuming no colored BSM in the loop)

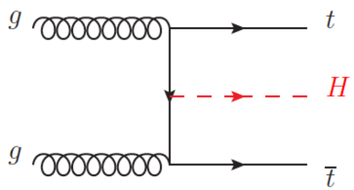


$\propto \kappa_V^2$

Vector Boson Fusion

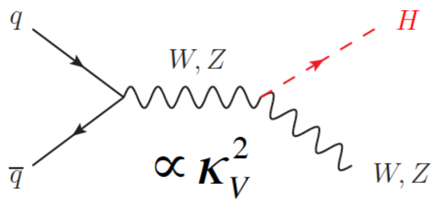
NLO TH uncertainty ~O(5%)

Two forward jets and a large rapidity gap



$\propto \kappa_t^2$

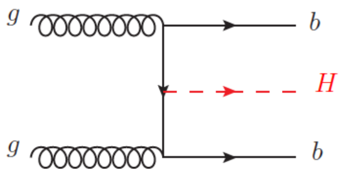
Top Assoc. Prod.



$\propto \kappa_V^2$

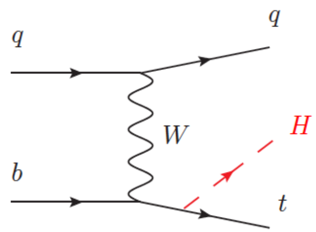
W and Z Associated Production

NNLO TH uncertainty ~O(5%)

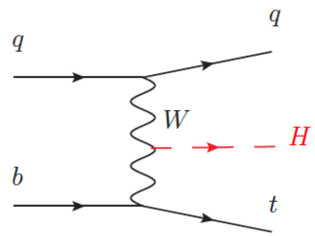


$\propto \kappa_b^2$

B-quark Assoc. Prod.



tH



$$\propto 3.3\kappa_W^2 - 5.1\kappa_t\kappa_W + 2.8\kappa_t^2$$

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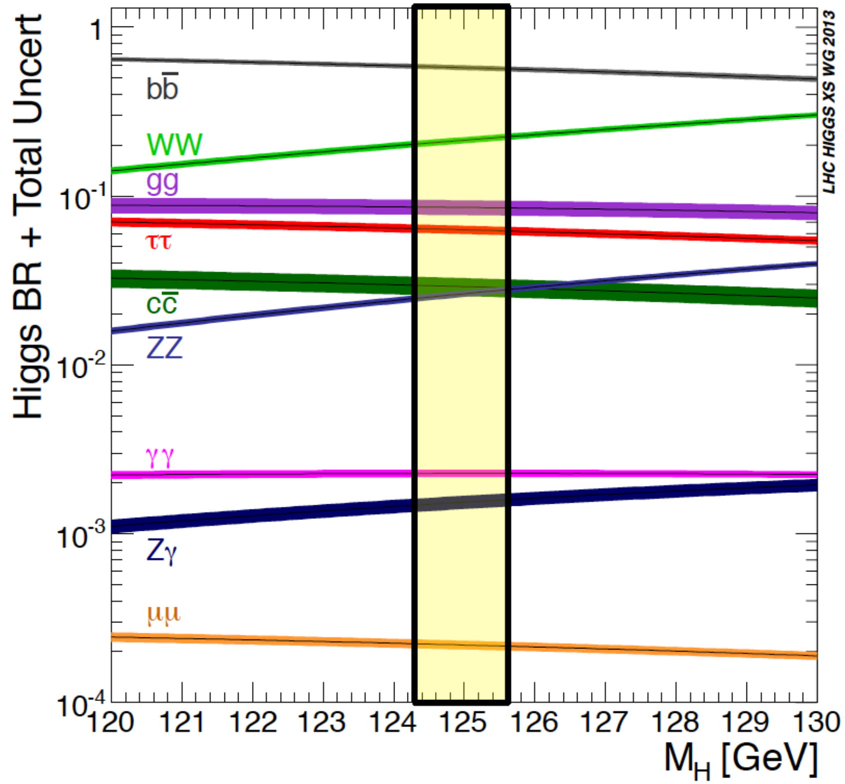
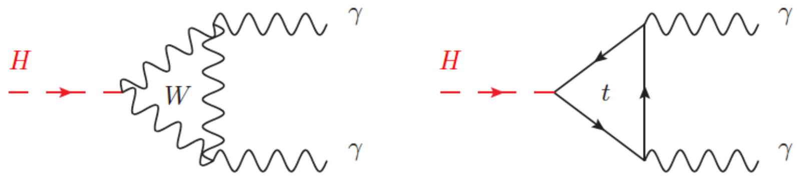
Parameterizing Higgs branching ratios

- Dominant: bb (57%) $\propto \kappa_b^2 / \kappa_H^2$
- WW channel (22%) $\propto \kappa_W^2 / \kappa_H^2$
- ττ channel (6.3%) $\propto \kappa_\tau^2 / \kappa_H^2$
- ZZ channel (3%) $\propto \kappa_Z^2 / \kappa_H^2$
- cc channel (3%) $\propto \kappa_c^2 / \kappa_H^2$
  Extremely difficult
- The γγ channel (0.2%) $\propto \kappa_\gamma^2 / \kappa_H^2$





$$\kappa_\gamma^2 \propto 1.6\kappa_W^2 - 0.7\kappa_t\kappa_W + 0.1\kappa_t^2$$

(when assuming no charged BSM in the loop)

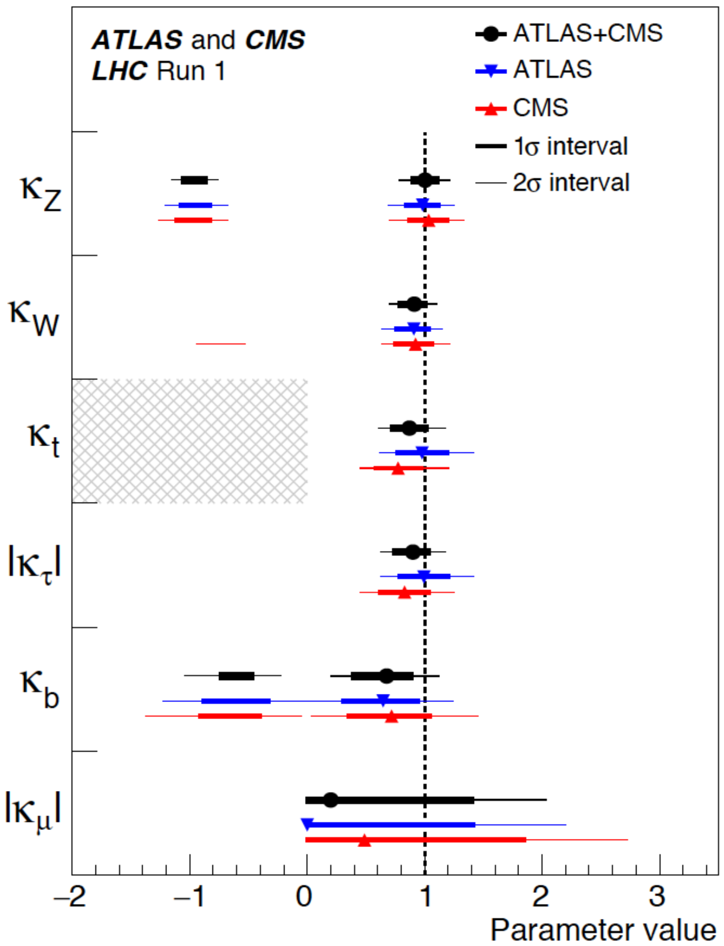
- The Zγ (0.2%) $\propto \kappa_{Z\gamma}^2 = 1.12\kappa_W^2 - 0.15\kappa_t\kappa_W + 0.03\kappa_t^2$
- The μμ channel (0.02%) $\propto \kappa_\mu^2 / \kappa_H^2$

Standard Model fit

- Resolve all loops.
- One coupling parameters per SM particle.
- No beyond-SM decays.

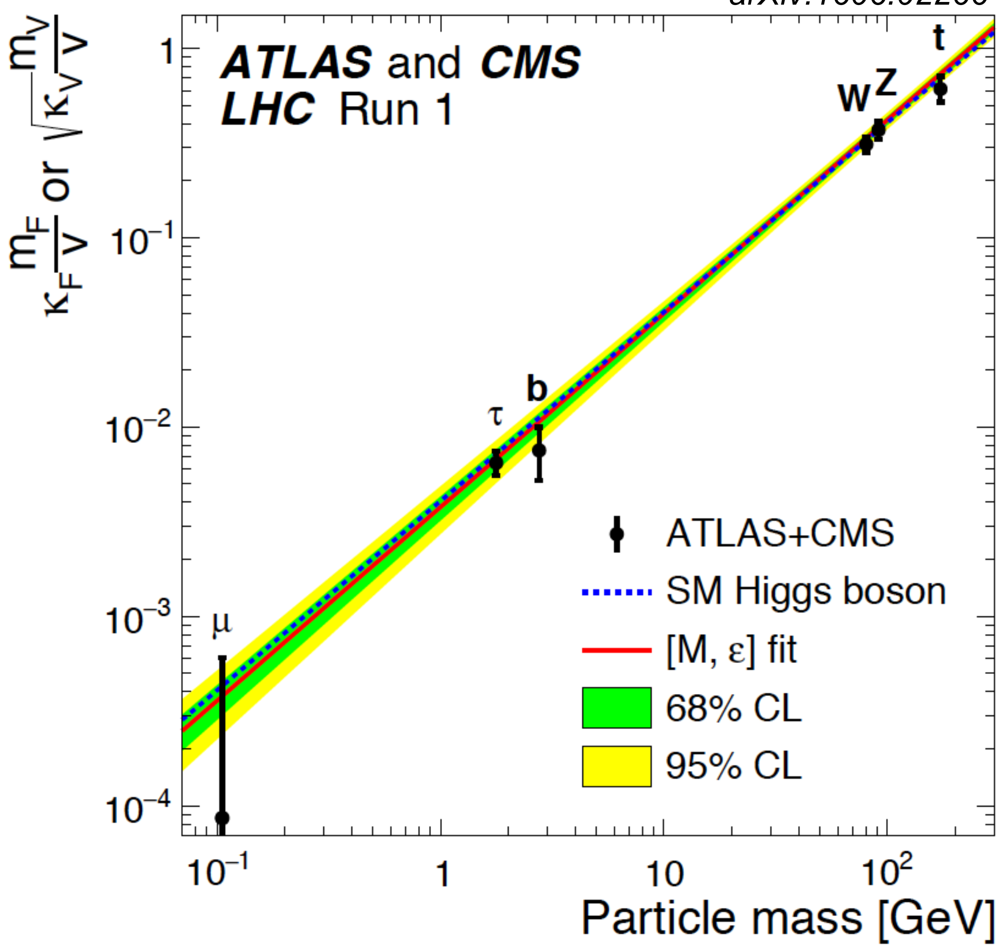
$\kappa_Z, \kappa_W, \kappa_t,$
$\kappa_b, \kappa_\tau, \kappa_\mu$

arXiv:1606.02266



Compatibility with the SM: 74%

arXiv:1606.02266



Beyond Standard Model fit

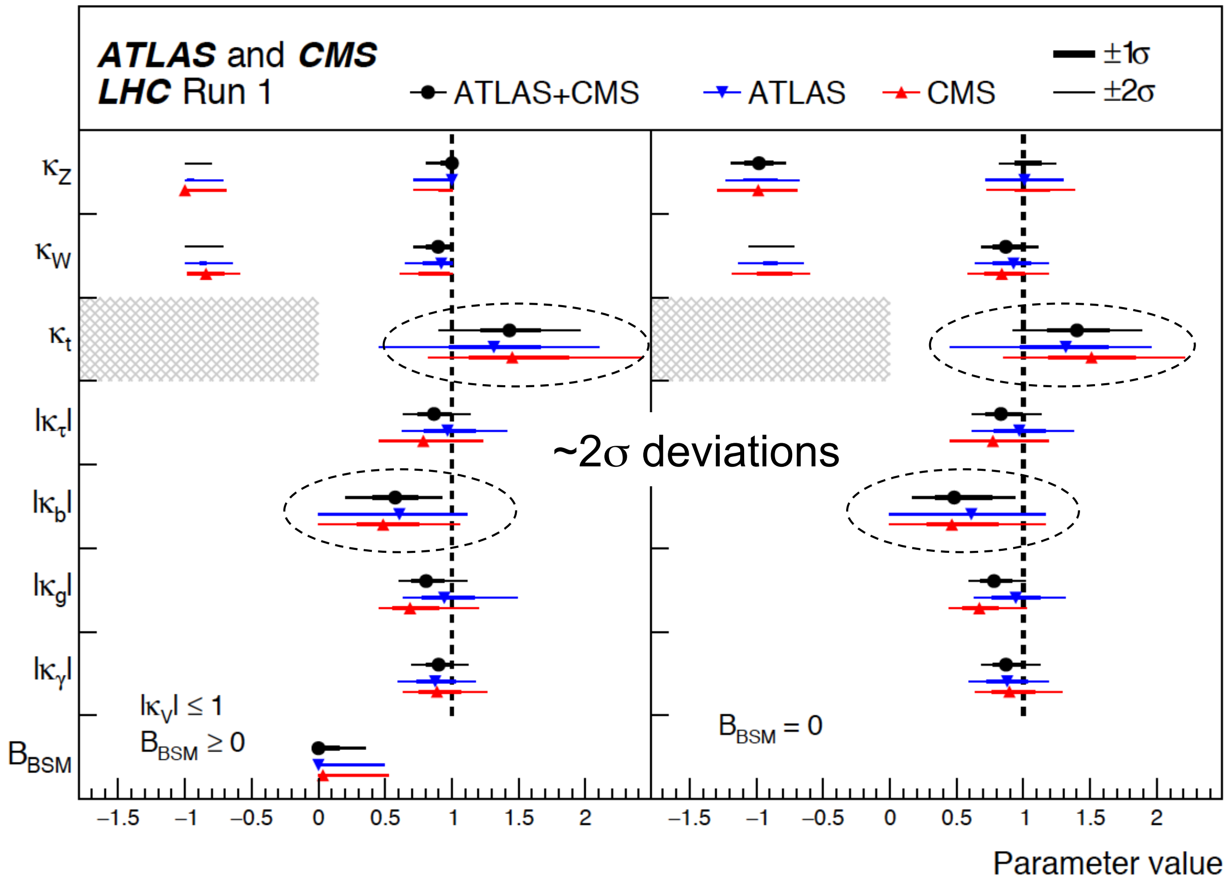
- Allow deviations in all tree-level couplings.
- Allow independent deviations in loop couplings.
- Allow beyond-Standard-Model decays.

  Impose weak constraint $\kappa_V \leq 1$.

$\kappa_Z, \kappa_W, \kappa_t, \kappa_b, \kappa_\tau, \kappa_g, \kappa_\gamma, BR_{BSM}$

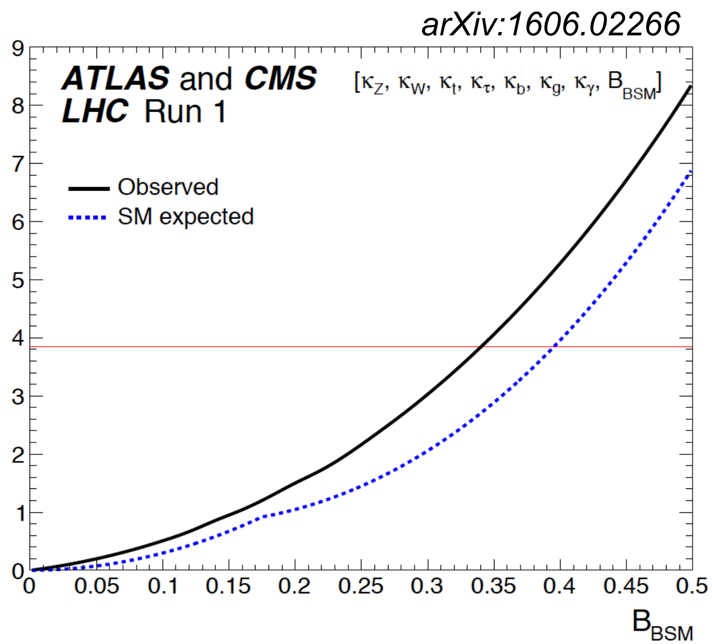
$$\Gamma_H = \Gamma_H^{SM} \times \frac{\kappa_H^2}{1 - BR_{BSM}}, \quad BR(H \to xx) = BR_{SM}(H \to xx) \times (1 - BR_{BSM}) \cdot \frac{\kappa_x^2}{\kappa_H^2}$$

arXiv:1606.02266



Compatibility with the SM: 11%

arXiv:1606.02266



Obs (exp) limit: $BR_{BSM} < 0.34$ (0.39)

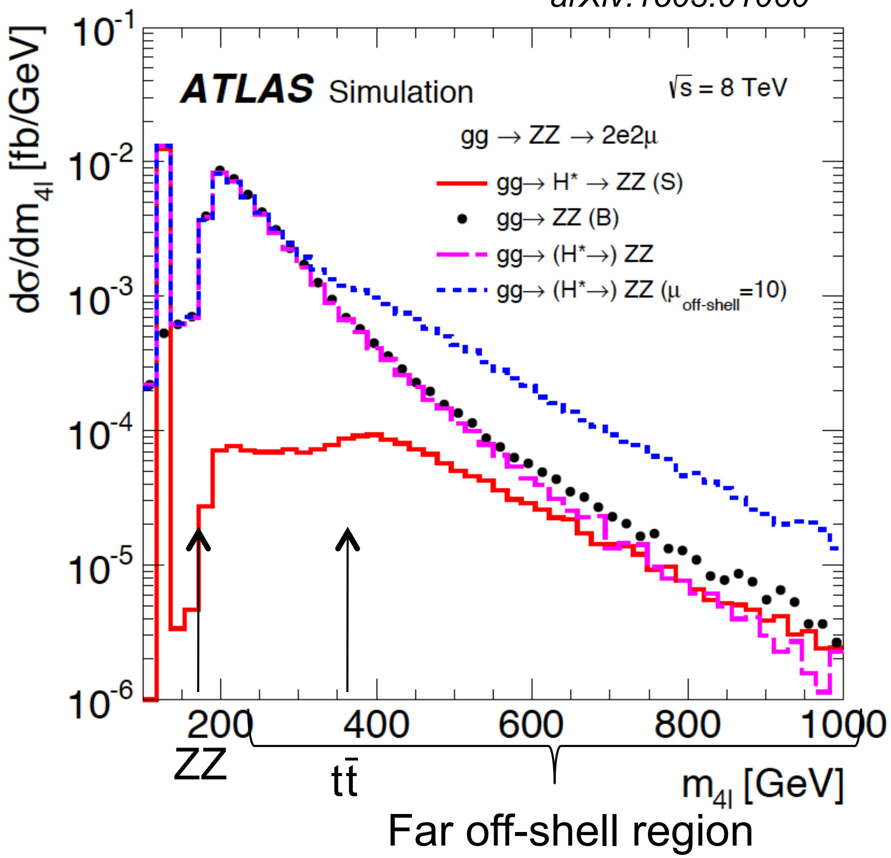
Off-shell Higgs coupling measurement

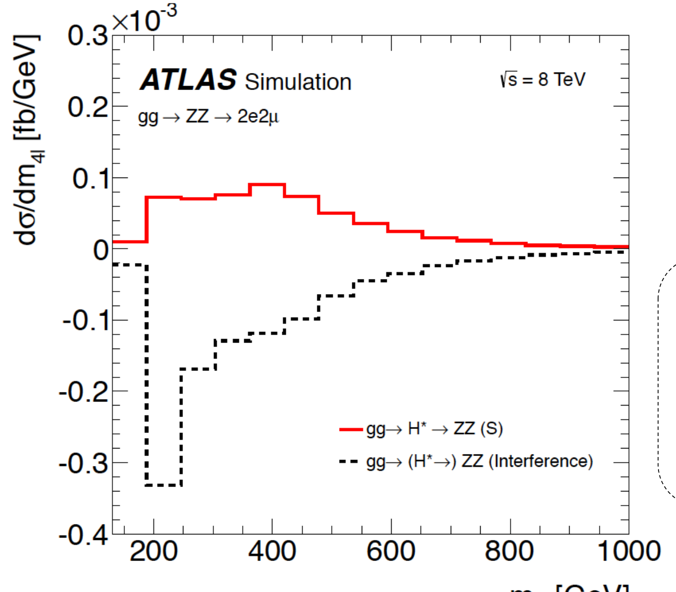
- Measure Higgs signal strength in the far off-shell region in H→VV decays (V=W,Z).

$$\mu_{\text{off-shell}}(\hat{s}) \equiv \frac{\sigma^{gg\to H^*\to VV}_{\text{off-shell}}(\hat{s})}{\sigma^{gg\to H^*\to VV}_{\text{off-shell, SM}}(\hat{s})} = \kappa^2_{g,\text{off-shell}}(\hat{s}) \cdot \kappa^2_{V,\text{off-shell}}(\hat{s})$$

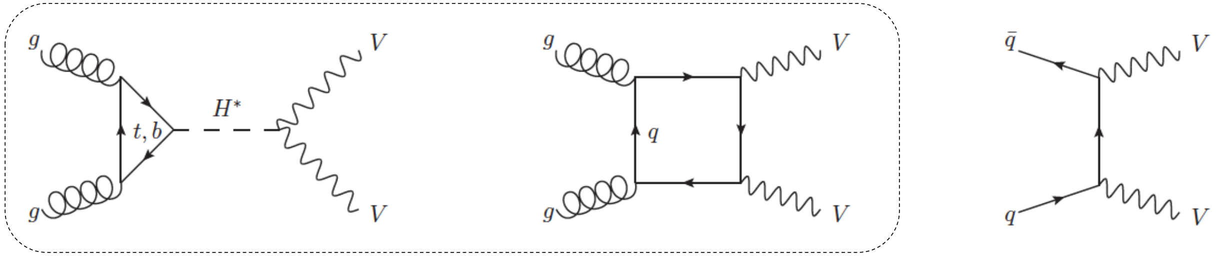
- Probes NP that affects just the Higgs couplings and not the continuum background.
- Need to take into account interference effects with the gg→ZZ background, which can be significant.

arXiv:1503.01060





arXiv:1503.01060

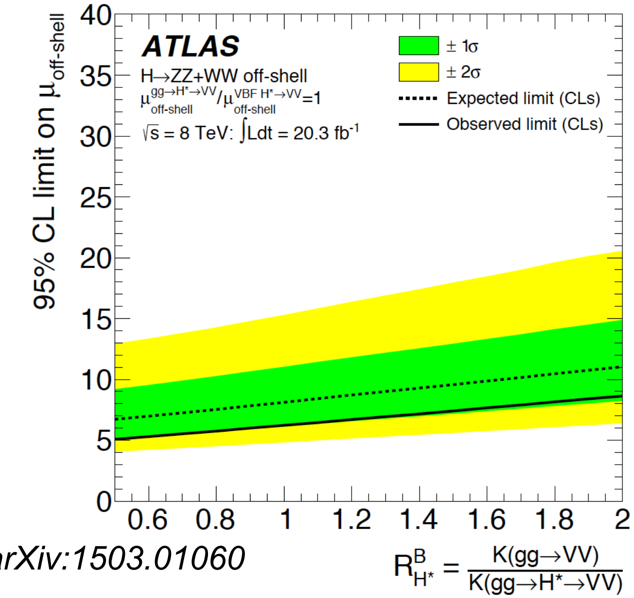


Interference!

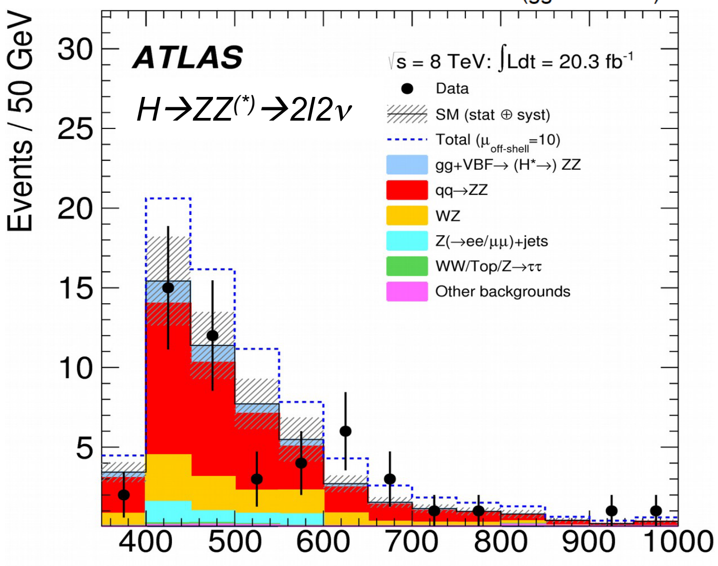
Off-shell Higgs coupling measurement

- Since gg→VV continuum described at LO, derive $\mu_{\text{off-shell}}$ limit as a function of the unknown k-factor between gg→VV and gg→H*→VV.
- Assuming $\mu_{\text{on-shell}} = \mu_{\text{off-shell}}$ can derive indirect limit on total Higgs width since:

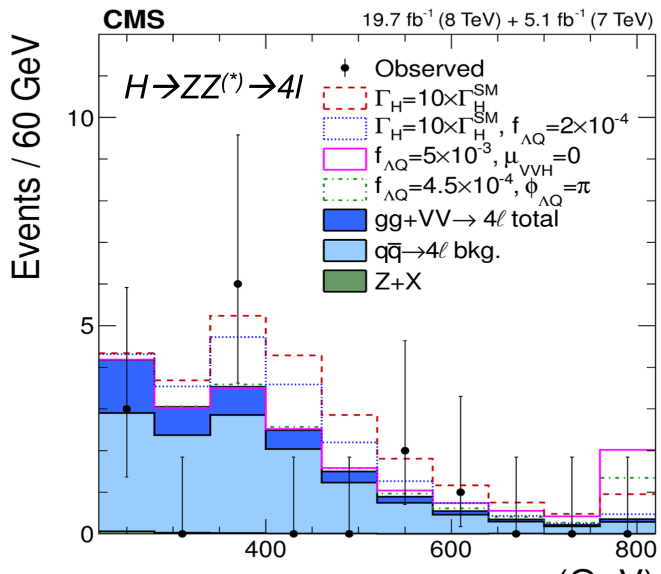
$$\mu_{\text{on-shell}} \equiv \frac{\sigma^{gg\to H\to VV}_{\text{on-shell}}}{\sigma^{gg\to H\to VV}_{\text{on-shell, SM}}} = \frac{\kappa^2_{g,\text{on-shell}} \cdot \kappa^2_{V,\text{on-shell}}}{\Gamma_H/\Gamma_H^{SM}}$$



arXiv:1503.01060



arXiv:1503.01060



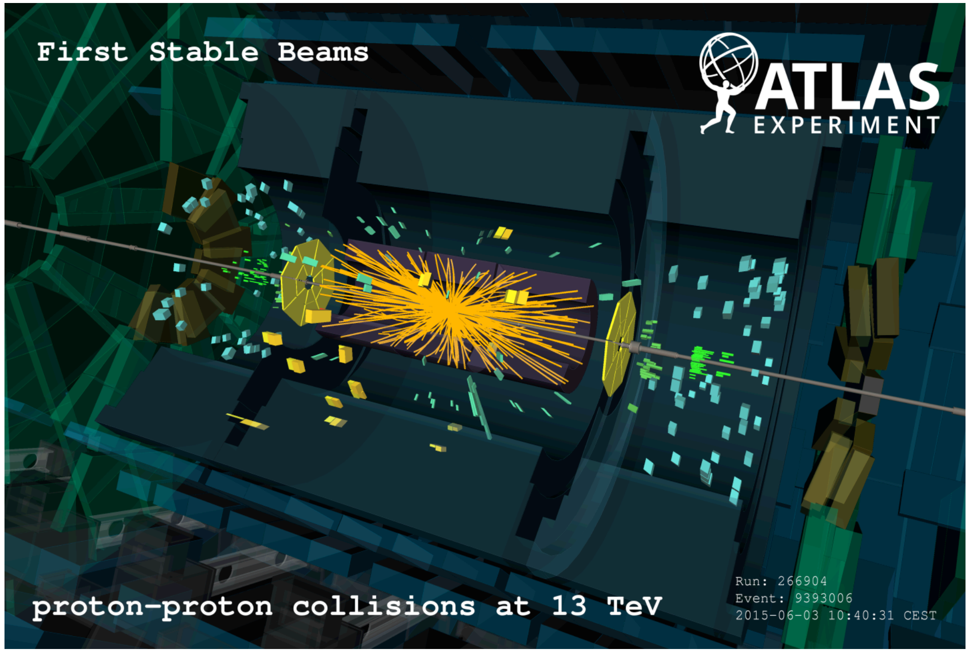
arXiv:1507.06656, 1605.02329

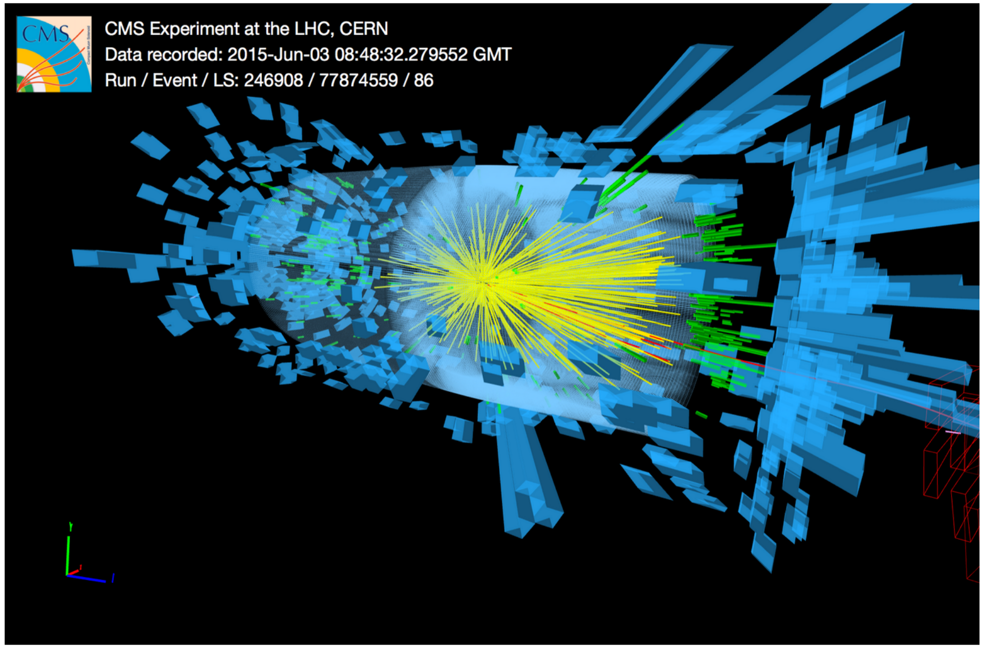
Obs (exp) limit: Γ_H<23 (33) MeV

Obs (exp) limit: Γ_H<13 (26) MeV

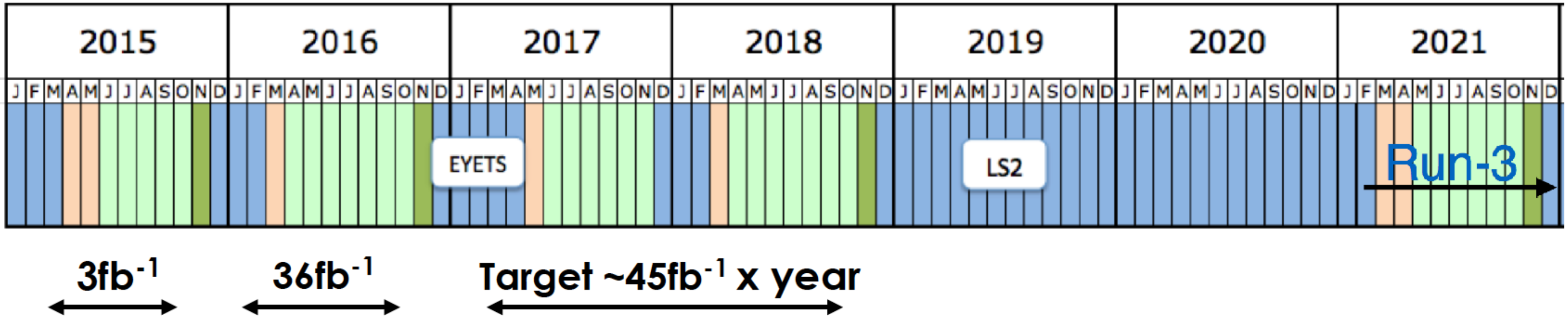
Run 2: Towards the Higgs precision physics era

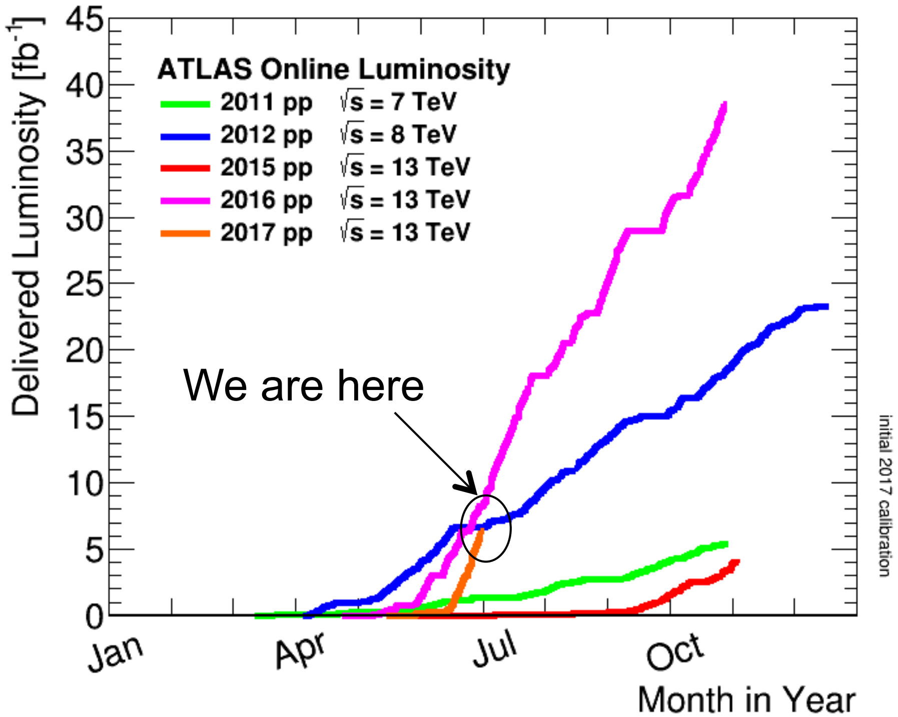
June 3, 2015: Run 2 starts!





Run 2 status/plans





Outstanding performance!

13 TeV pp 2015 dataset (at 25 ns):

- Highest inst. luminosity: 5×10^{33} cm^{-2}s^{-1} (Run 1: $7\text{-}8 \times 10^{33}$ cm^{-2}s^{-1})
- ~3.9 fb^{-1} recorded

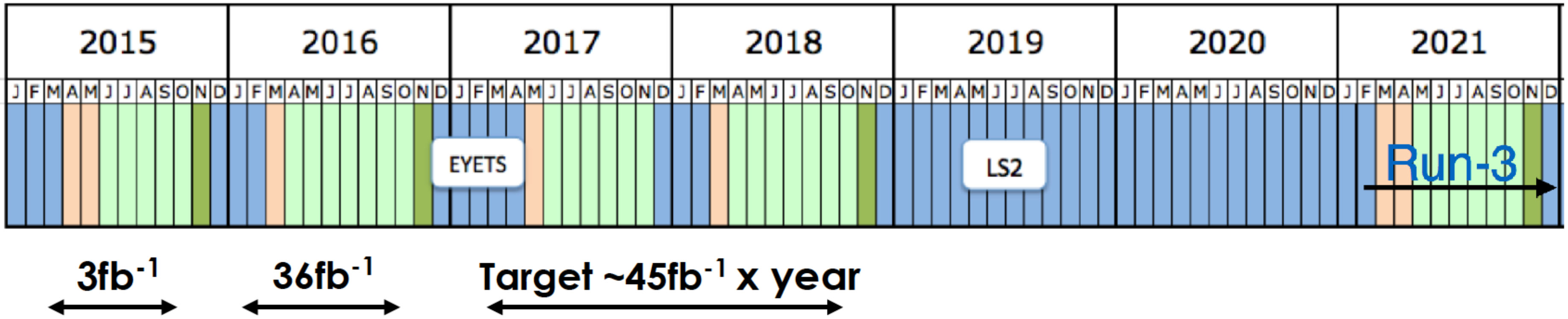
13 TeV pp 2016 dataset:

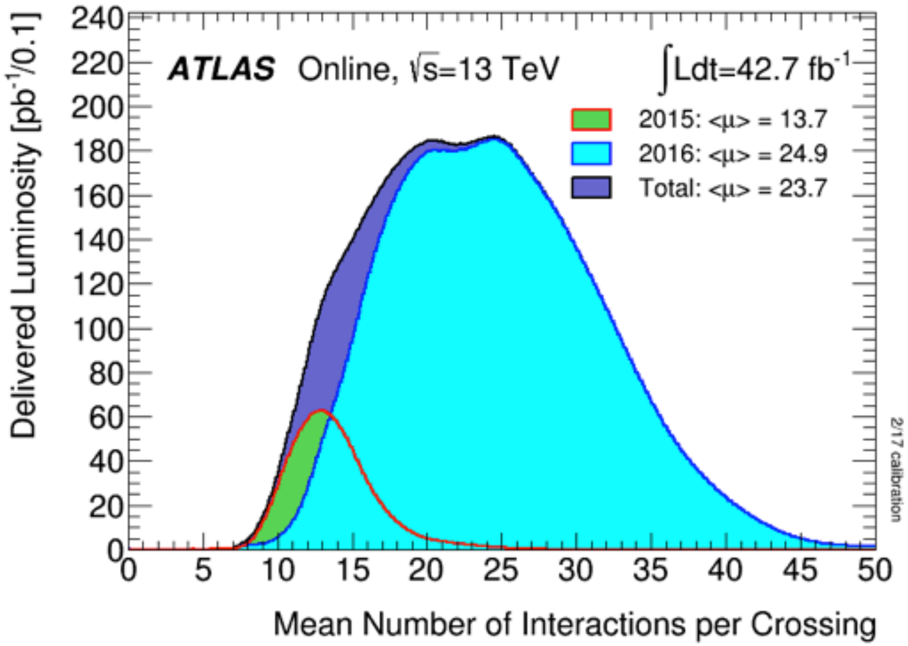
- Record inst luminosity of ~1.4×10^{34} cm^{-2}s^{-1}.
- Record daily delivered luminosity of ~0.6 fb^{-1}.
- ~36 fb^{-1} recorded

13 TeV pp 2017 dataset:

- Collisions restarted on May 23, 2017.
- Inst. luminosity already at ~1.6×10^{34} cm^{-2}s^{-1}.

Run 2 status/plans





Key challenge: average (maximum) pileup ~25 (45-50) interactions per bunch crossing

13 TeV pp 2015 dataset (at 25 ns):

- Highest inst. luminosity: 5×10^{33} cm^{-2}s^{-1} (Run 1: 7-8x10^{33} cm^{-2}s^{-1})
- ~3.9 fb^{-1} recorded

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13 TeV pp 2017 dataset:

- Collisions restarted on May 23, 2017.
- Inst. luminosity already at ~1.6×10^{34} cm^{-2}s^{-1}.

Run 2 milestones in Higgs physics

Precision
Cross-sections
Couplings
Mass

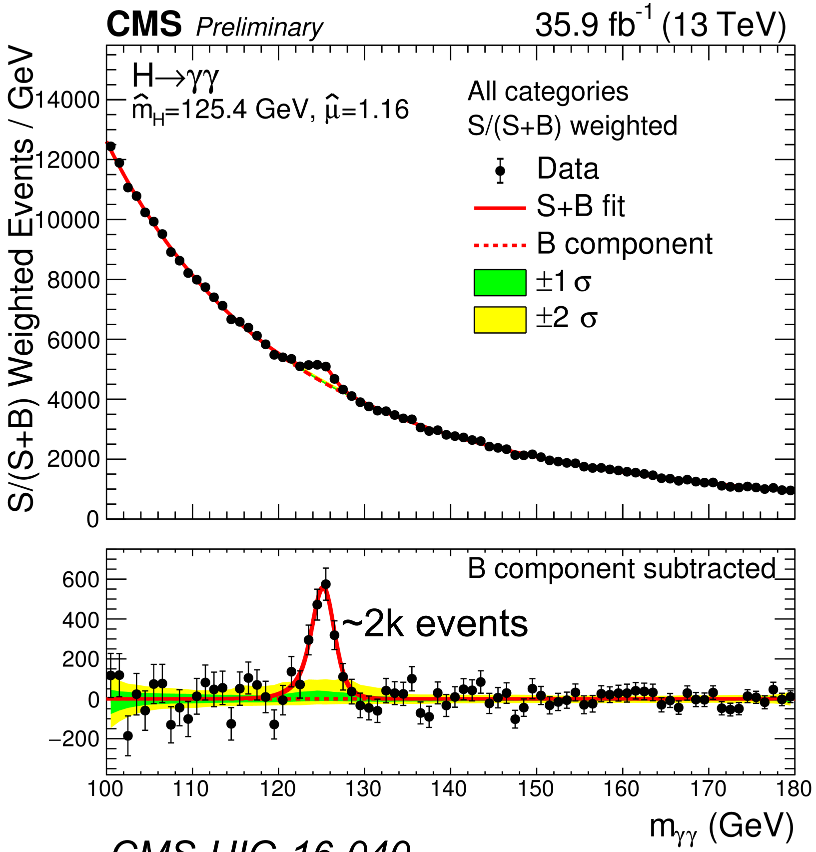
Discovery
Couplings to
fermions

Other scalars
Charged/neutral
Heavy/light

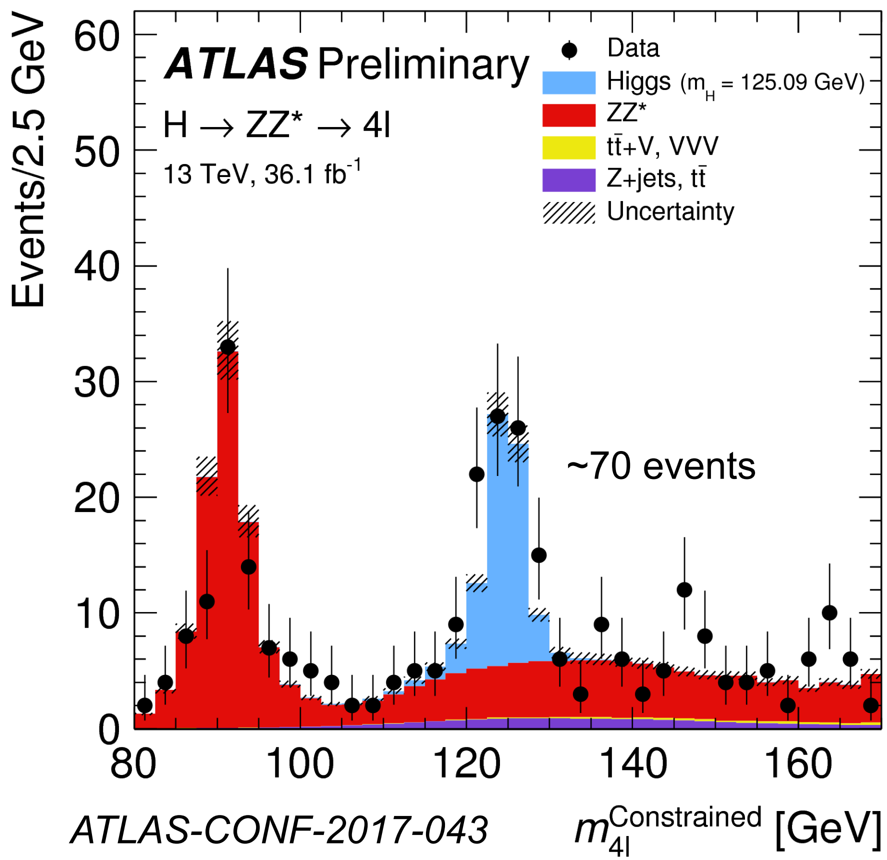
Known unknowns
Rare decays
Self-couplings

Unknown unknowns
BSM couplings
BSM decays

Early Run 2 results: H→γγ and H→ZZ*→4l



CMS-HIG-16-040



ATLAS-CONF-2017-043

$\mu = 1.16^{+0.15}_{-0.14} = 1.16^{+0.11}_{-0.10}(\text{stat})^{+0.09}_{-0.08}(\text{exp})^{+0.06}_{-0.05}(\text{theo})$

$\mu = 1.28^{+0.18}_{-0.17}(\text{stat})^{+0.08}_{-0.06}(\text{exp})^{+0.08}_{-0.06}(\text{theo})$

Improvements on overall precision ~x2 wrt Run 1
Starting to approach SM theory uncertainty

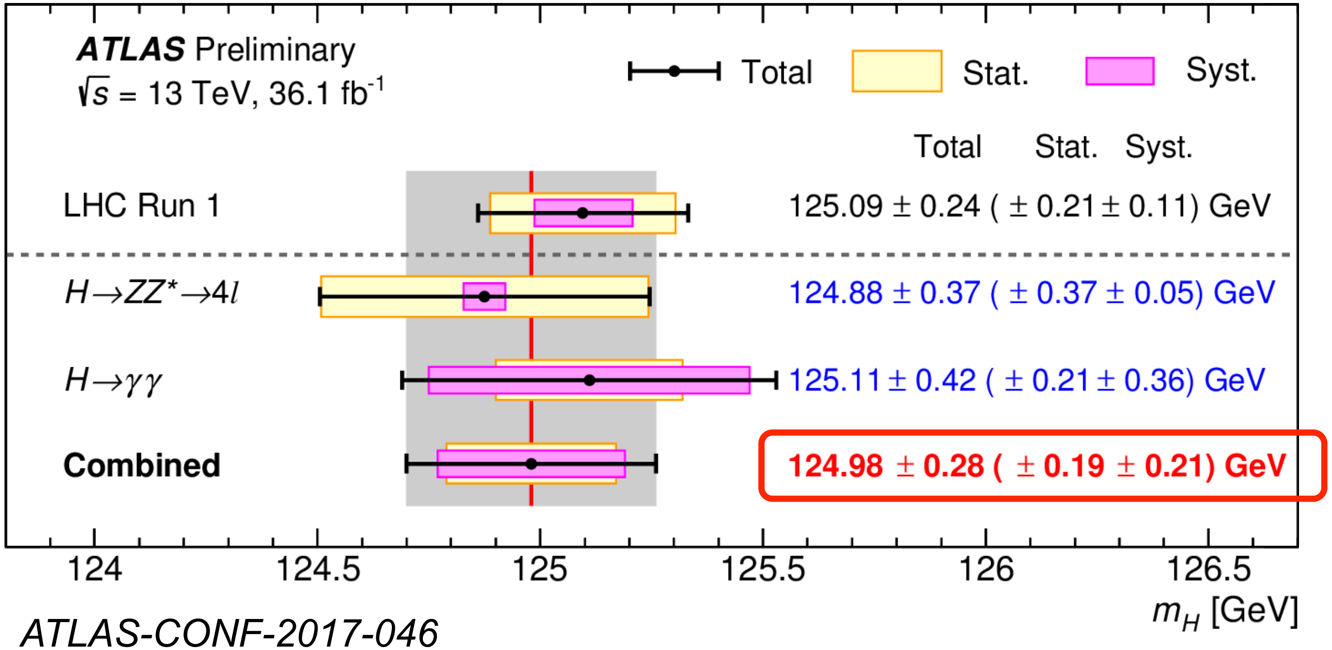
Early Run 2 results: Higgs mass

- Individual experiment measurements already comparable or better than Run 1 combination!

ATLAS combination of H→ZZ*→4l & H→γγ

Statistically limited

Systematics limited



ATLAS-CONF-2017-046

CMS H→ZZ*→4l

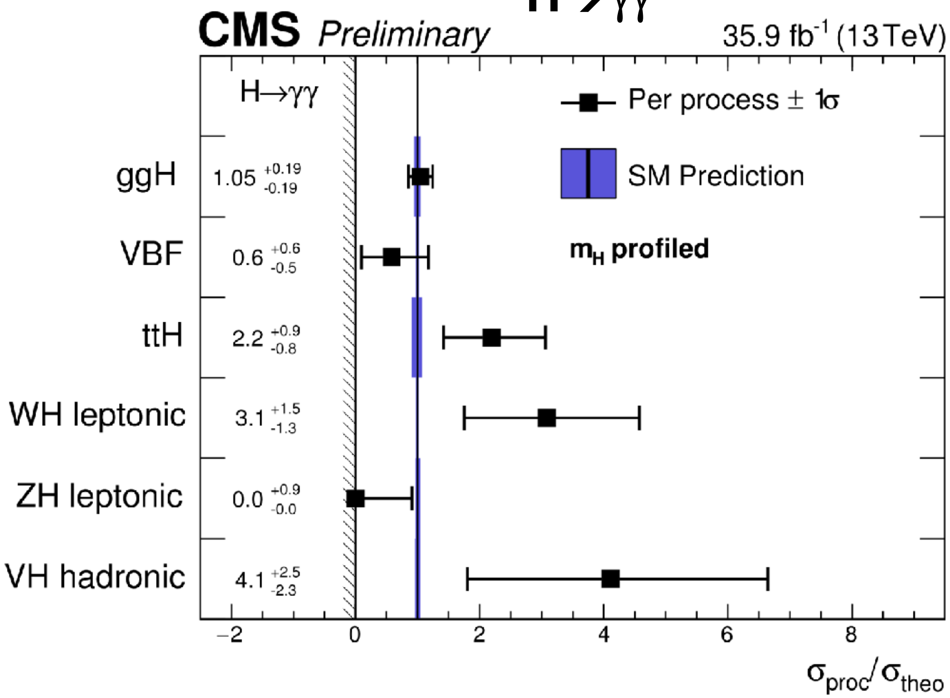
$$m_H = 125.26 \pm 0.20(\mathrm{stat}) \pm 0.08(\mathrm{syst})\ \mathrm{GeV}$$

arXiv:1706.09936

Early Run 2 results: Cross sections by production modes

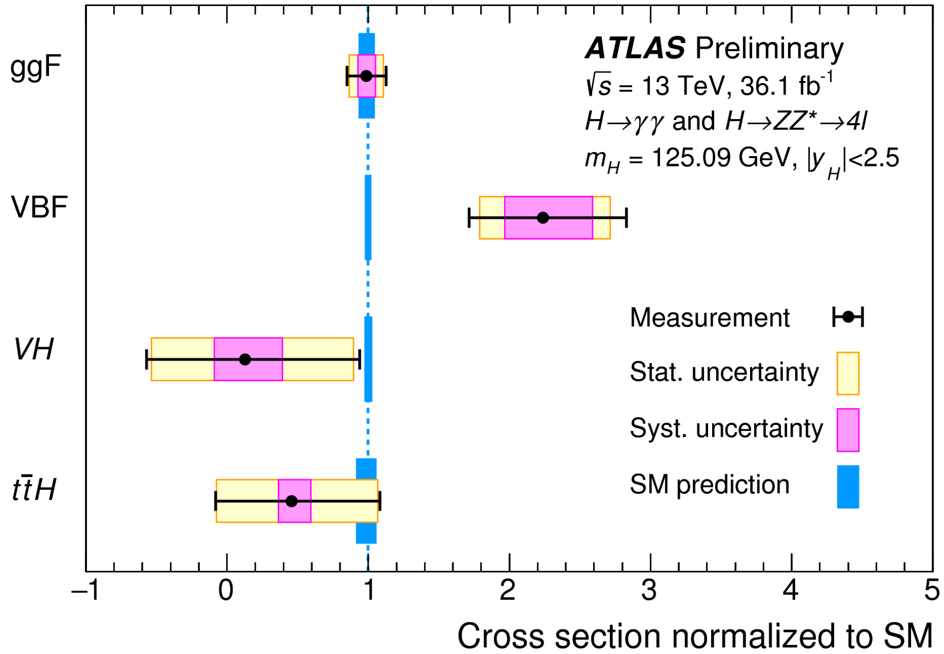
- Events split in different categories to increase sensitivity to various production modes.

H→γγ



CMS-HIG-16-040

H→γγ and H→ZZ*→4l



ATLAS-CONF-2017-047

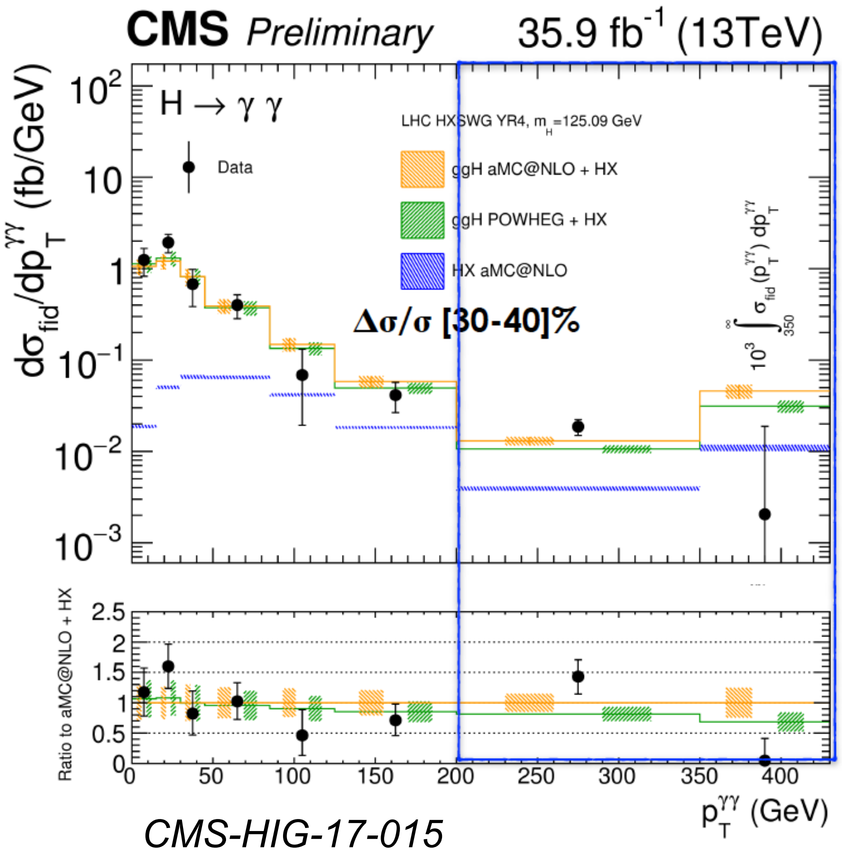
Precision improvements ~x2 wrt Run 1

ATLAS: Excess in VBF (both H→γγ and H→4l)
SM compatibility p-value 5%

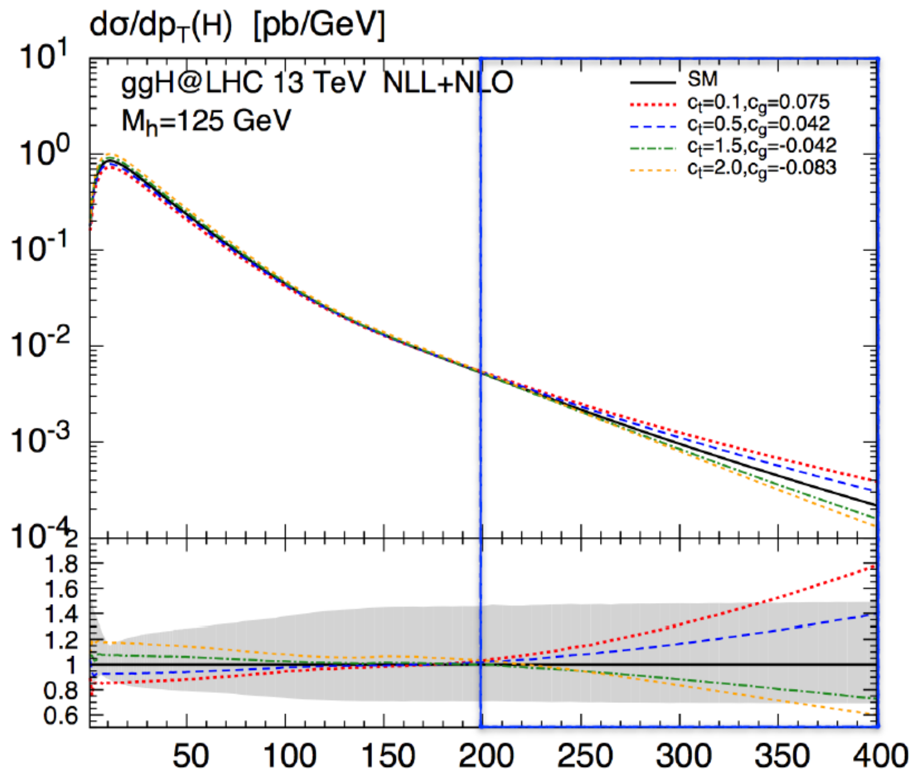
Increased scrutiny allowed by the larger statistics

Early Run 2 results: Differential cross sections

- Significantly improved precision in differential cross section distributions, particularly in the tails.



CMS-HIG-17-015



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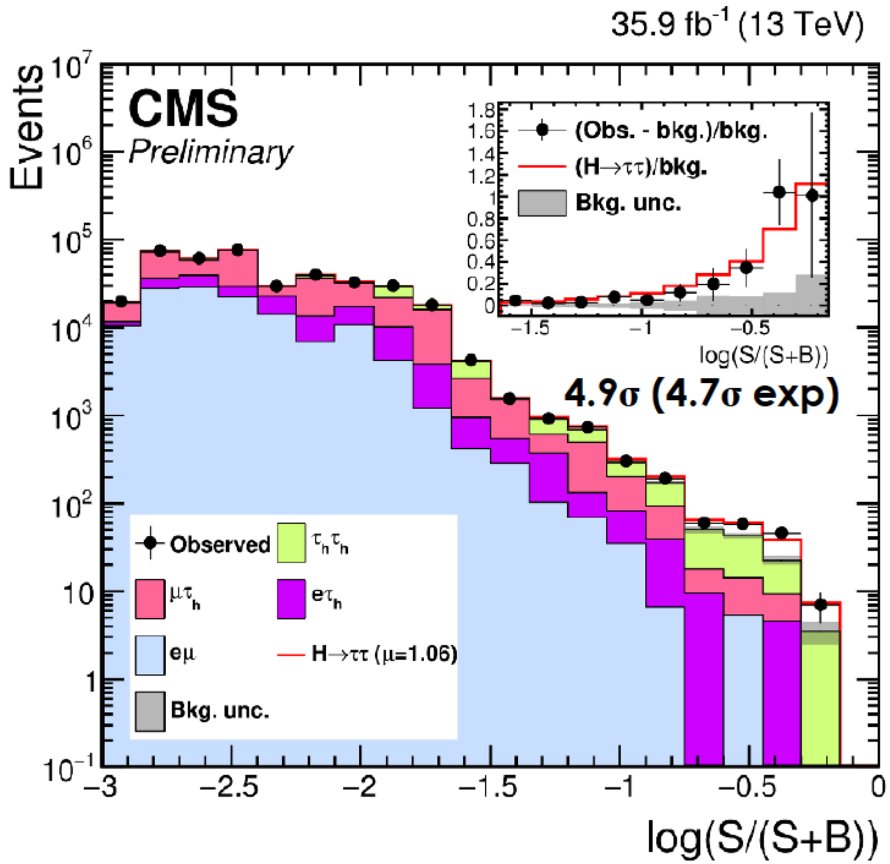
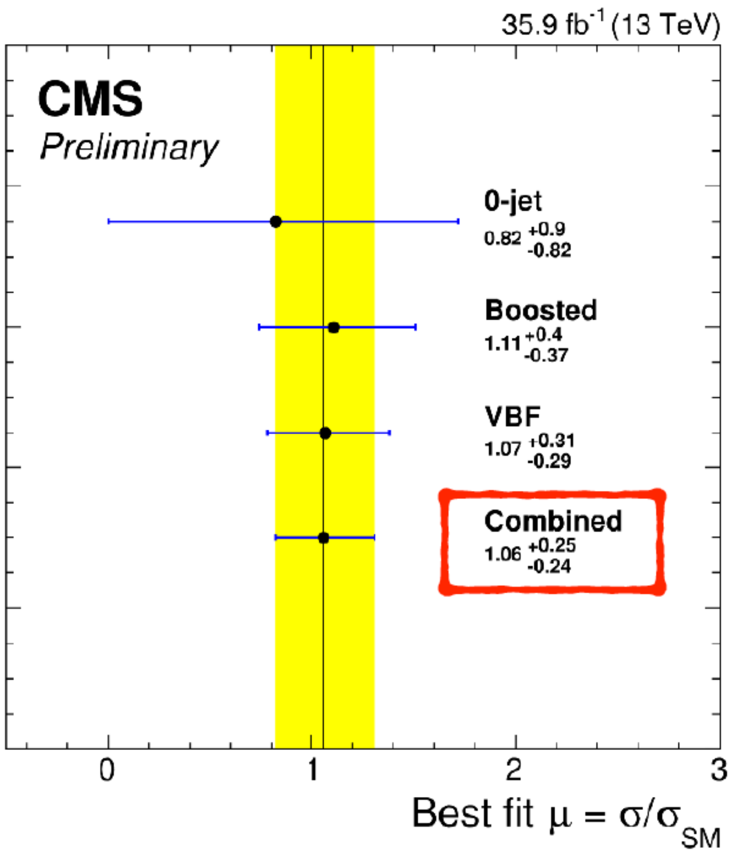
$d\sigma/dp_{T,H}$ sensitive to perturbative QCD calculations but will also allow probing in a model-independent way the ggH vertex!

Early Run 2 results: Observation of H→ττ

CMS-HIG-16-043



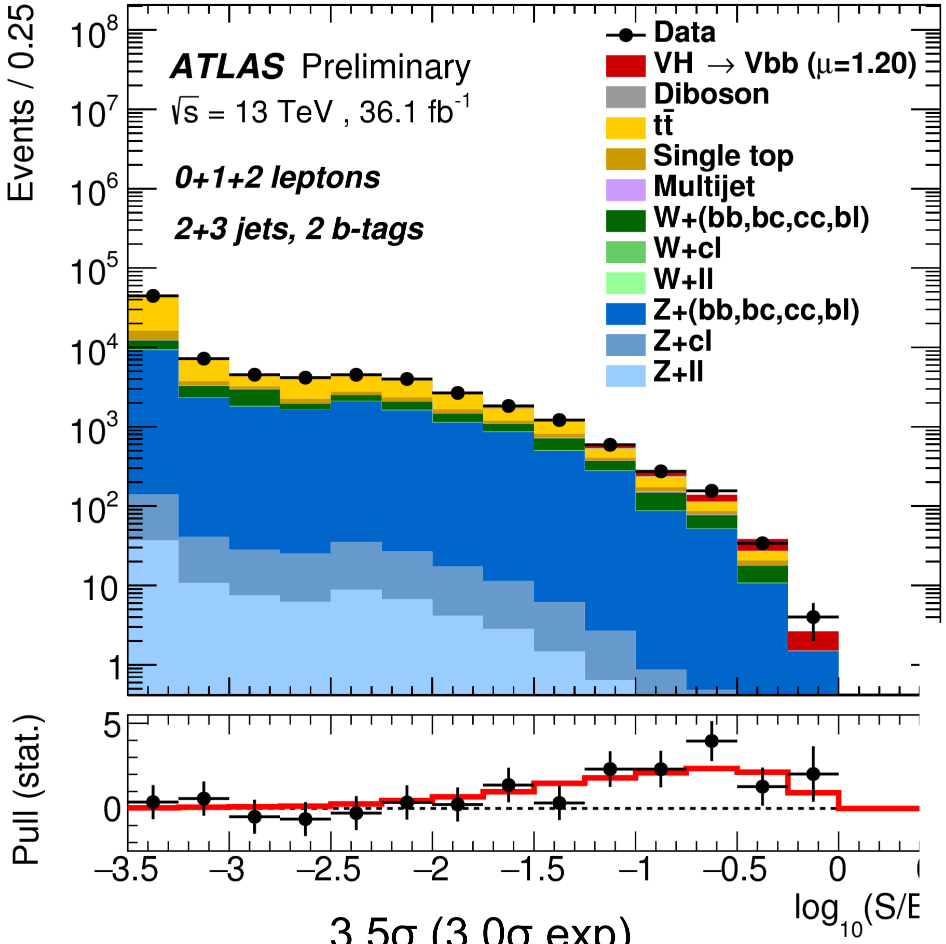


4 $\tau\tau$ channels ($\tau_h\tau_h$, $e\tau_h$, $\mu\tau_h$, eμ) x 3 categories (0-jet, boosted, VBF)
2D fit signal extraction: $m_{\tau\tau}$ vs (τ decay mode, p_T, dijet mass)

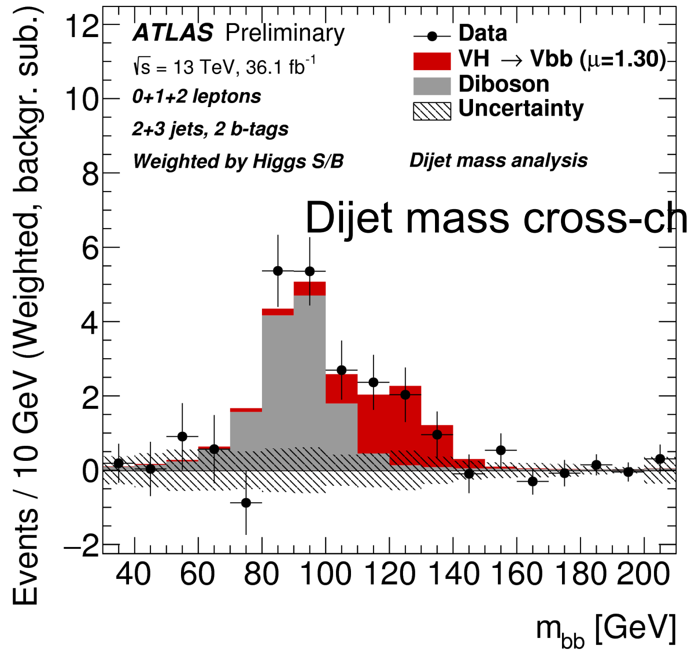
Observation of $\tau\tau$ decay mode from a single experiment:
4.9σ (4.7σ exp) [5.9σ when combined with CMS Run 1]

Early Run 2 results: Evidence for H→b$\bar{b}$

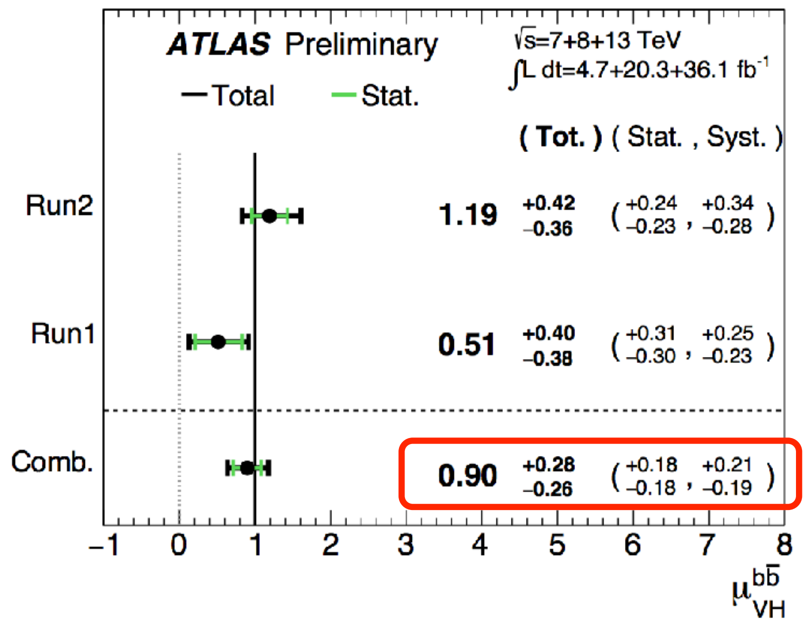
ATLAS-CONF-2017-041



3.5σ (3.0σ exp)



Dijet mass cross-check



Evidence for VH(bb):

3.6σ when combined with ATLAS Run 1

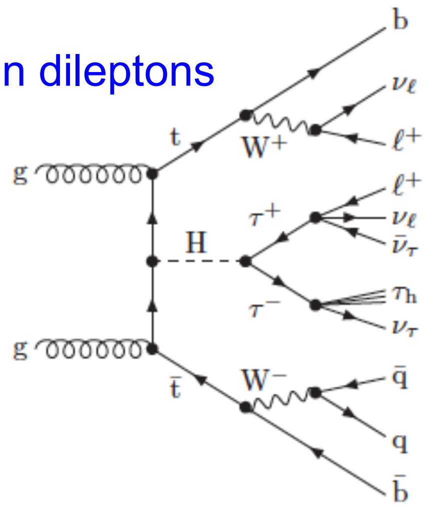
[Run 1 ATLAS+CMS 2.6σ (3.7 exp)]

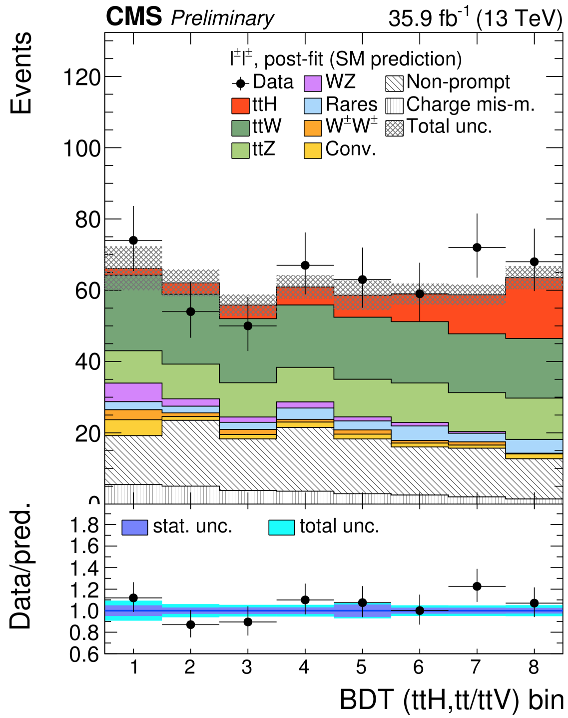
Early Run 2 results: Evidence for tt̄H?

- Increasingly more sophisticated analyses bring significant improvements in sensitivity. Example: multileptons

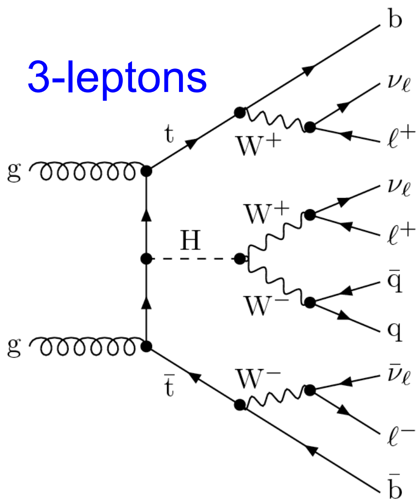
CMS-HIG-17-004

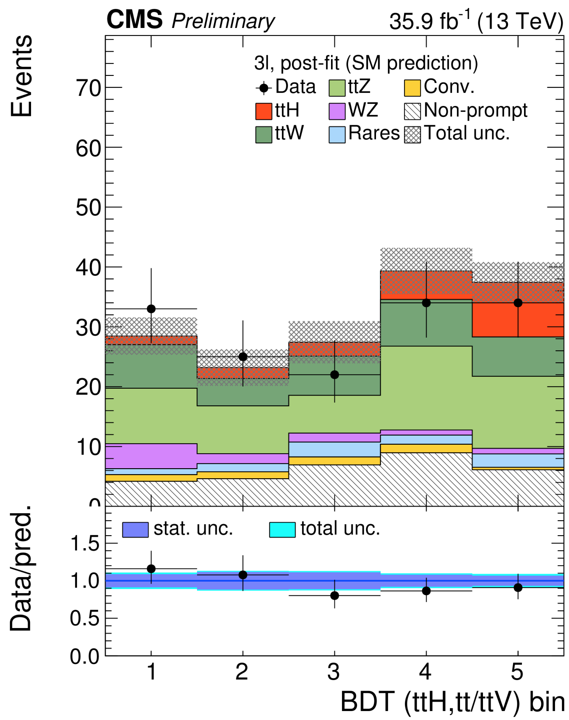
Same-sign dileptons





3-leptons





Early Run 2 results: Evidence for $t\bar{t}H$?

Run1 (yellow)

Run2: 13 fb^{-1} (green), 36 fb^{-1} (red)

$$\mu_{ttH}=\sigma_{ttH}/\sigma_{SM}$$

	ATLAS	CMS	
Run1 comb.	$2.3^{+0.7}_{-0.6}$		← 4.4σ (2.0σ exp)
bb	$2.1^{+1.0}_{-0.9}$	-0.2 ± 0.8	
multileptons	$2.5^{+1.3}_{-1.1}$	1.5 ± 0.5	← 3.3σ (2.5σ exp)
τ_h+X		$0.7^{+0.6}_{-0.5}$	
γγ	$0.5^{+0.6}_{-0.6}$	$2.2^{+0.9}_{-0.8}$	← 3.3σ (1.5σ exp)
ZZ	<7.5 @ 95%CL	$0.0^{(*)+1.2}_{-0.0}$	

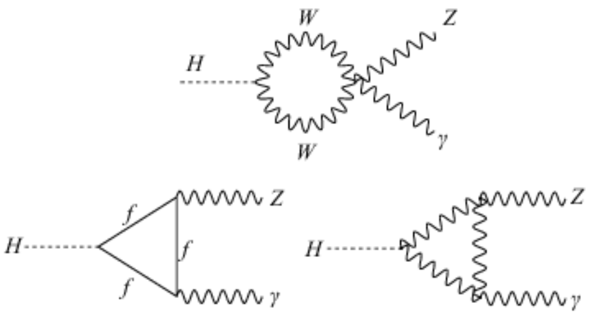
(*): 68% CL interval with $\mu \geq 0$

- Individual analyses are already exceeding the sensitivity of the Run 1 combination.
- Evidence for ttH? Statistically a combination would be largely incompatible with μ_{ttH}=0.

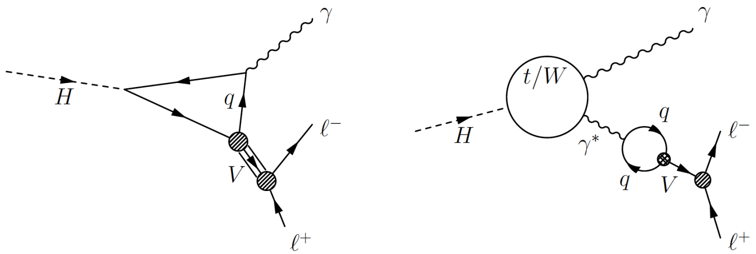
Rare processes

Rare Decays

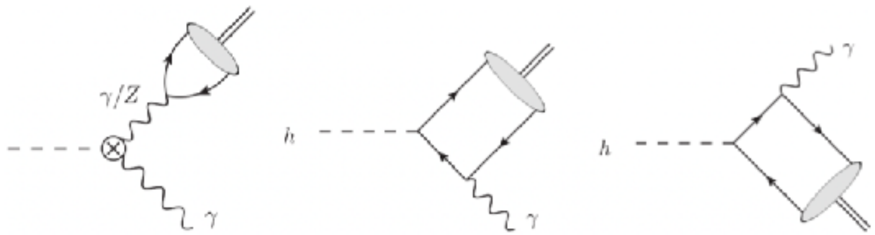
H→Zɣ, H→ɣ*ɣ: access BSM in loops



H→J/Ψɣ: coupling to charm



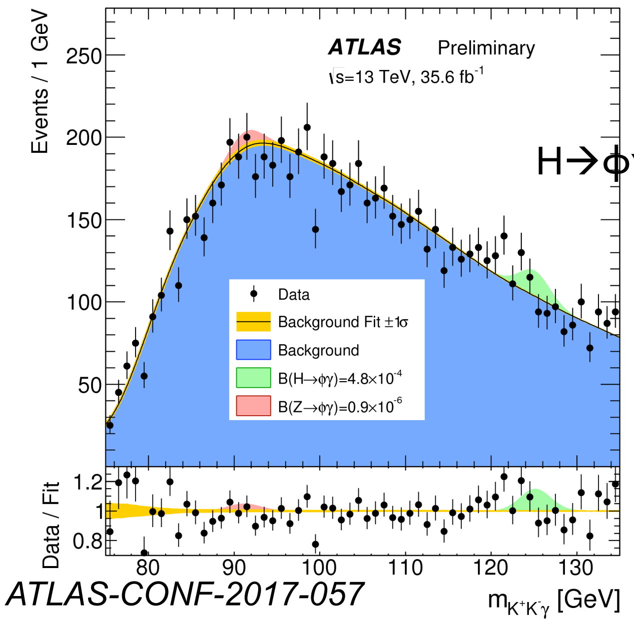
H→ρɣ & H→ϕɣ: couplings to light quarks



Observation would imply BSM!

Run1 (yellow)
Run2 (red): 36 fb^{-1}

Process	σ/σ_{SM} (95% CL)
H→Zɣ (ATLAS) 36fb^{-1}@ 13 TeV	<6.6
H→Zɣ (CMS) Run1	<9
H→ɣ*ɣ (CMS) Run1	<7.7
H→J/Ψɣ (ATLAS) Run1	<540
H→J/Ψɣ (CMS) Run1	<540
H→ρɣ (ATLAS) 36 fb-1 @ 13 TeV	<52
H→ϕɣ (ATLAS) 36 fb-1 @ 13 TeV	<208
H→ee (CMS) Run1	<~10^5



H→ϕɣ (ϕ→K⁺K⁻)

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Double-Higgs production

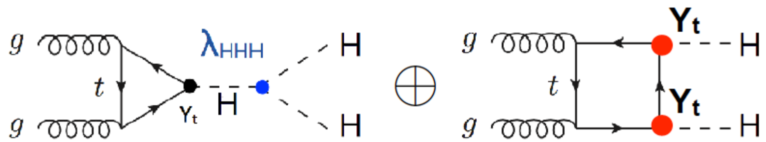
- Determination of the scalar potential ➔ self couplings!

  λ_4: currently hopeless at any planed experiment

  λ_3 : in principle possible via double-Higgs production, but very challenging because of negative interference among diagrams

$$\mathcal{L} \supset -\frac{m_h^2}{2}h^2 - \lambda_3^{SM} v h^3 - \lambda_4^{SM} h^4,$$

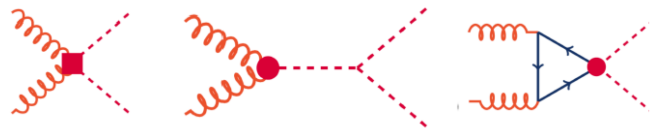
$$\lambda_3^{SM} = \frac{m_h^2}{2v^2}, \qquad \lambda_4^{SM} = \frac{m_h^2}{8v^2},$$



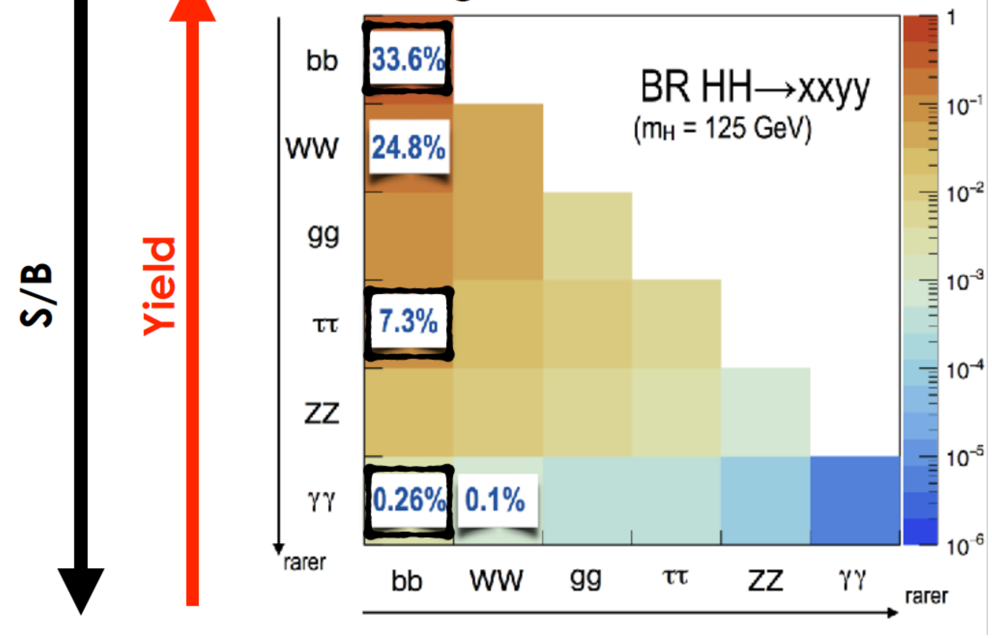
$\sigma_{gg\to HH}$ = 33.49$^{+4.3}_{-6.0}$ (scale) ± 2.1 (PDF) ± 2.3 (α_s) fb

[13 TeV, NNLO + NNLL with top mass effects, HXSWG, arXiv:1610.07922]

sensitive to possible BSM contributions



A large matrix of final states



bbbb largest statistics

bb(γγ,ττ) good compromise between statistics and S/B

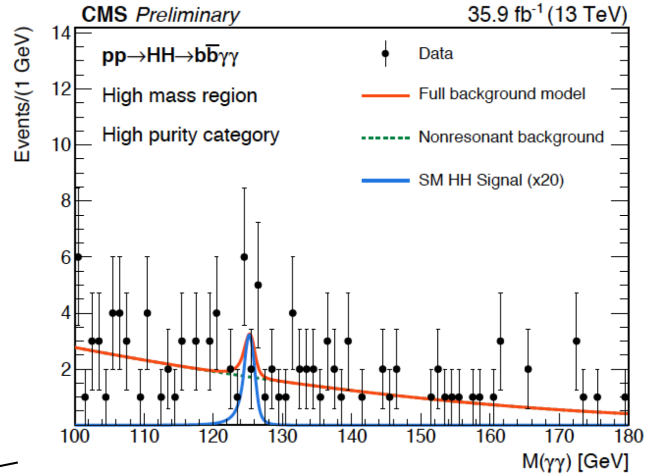
Double-Higgs production

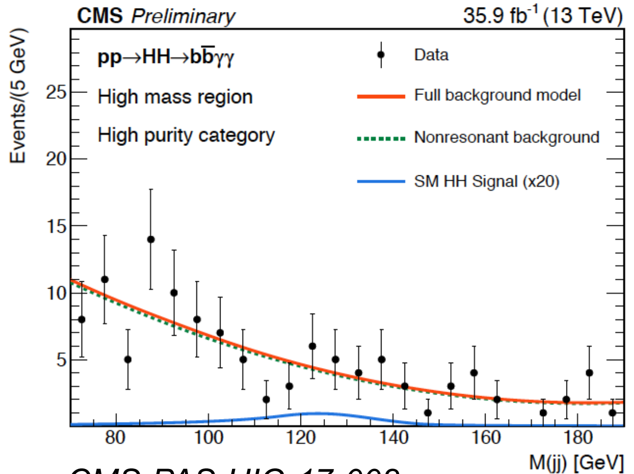
σ/σ_{SM} 95% CL (exp)

	ATLAS	CMS
bbbb	<29 (38)	<342 (308)
bbWW		<79 (89)
bbττ		<28 (25)
bbγγ	<117 (161)	<19 (17) NEW
WWγγ	<747 (386)	

Run2: 3 fb^{-1} | 13 fb^{-1} | 36 fb^{-1}

$HH \rightarrow b\bar{b}\gamma\gamma$





CMS-PAS-HIG-17-008

Reaching ~ O(10)xSM sensitivity

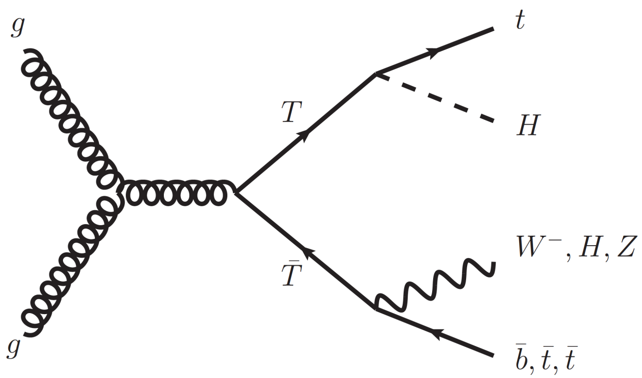
Will require full HL-LHC statistics to approach SM sensitivity

Higgs as a tool for discovery

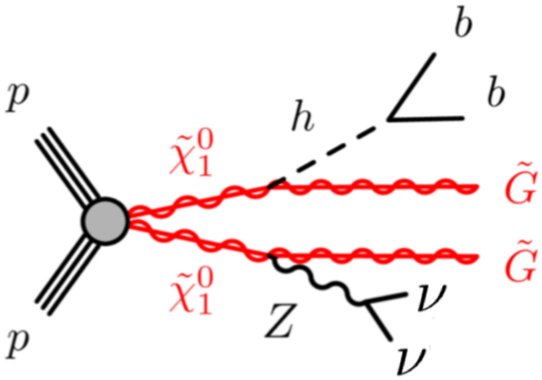
Probing NP through the Higgs boson

- In many NP scenarios the Higgs boson couples preferentially to new particles:
  - $m_X > m_h$: the Higgs boson may appear in decays of X or is produced in association with X.
  - $m_X < m_h$: Higgs boson may decay into X.

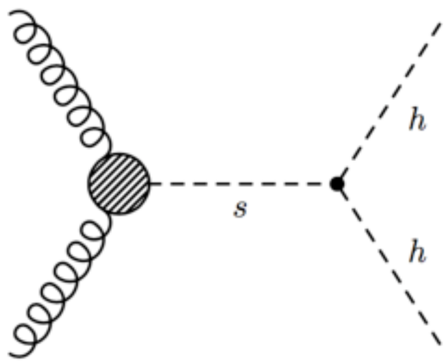
Some examples:



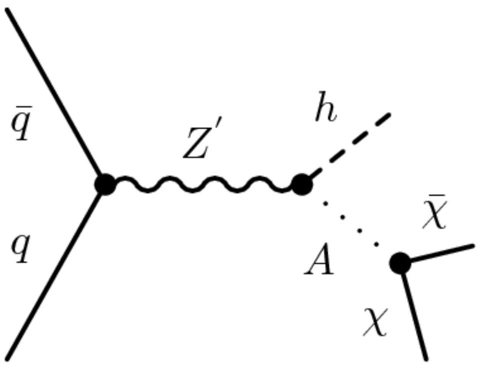
Vector-like quark decay



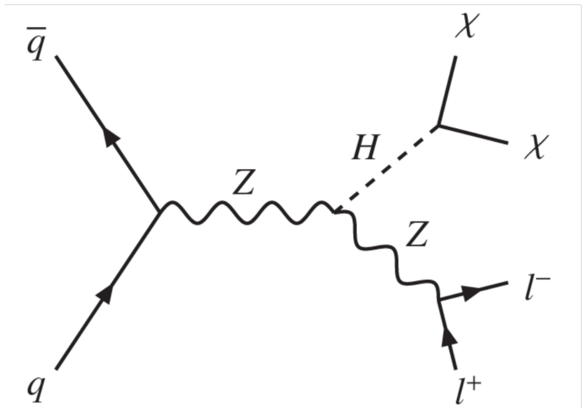
Higgsino decay



Di-higgs resonances



Mono-Higgs production



Invisible Higgs decays

Mono-Higgs searches

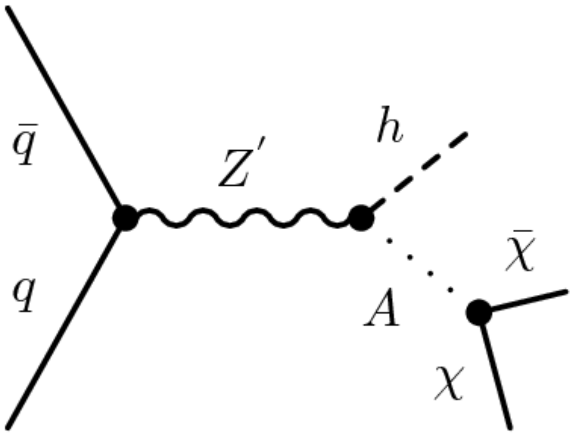
h→γγ:

- Require H→γγ candidates ($120<m_{\gamma\gamma}<130$ GeV), large $p_T(\gamma\gamma)$ and significant E_T^{miss}.
- Counting experiment.

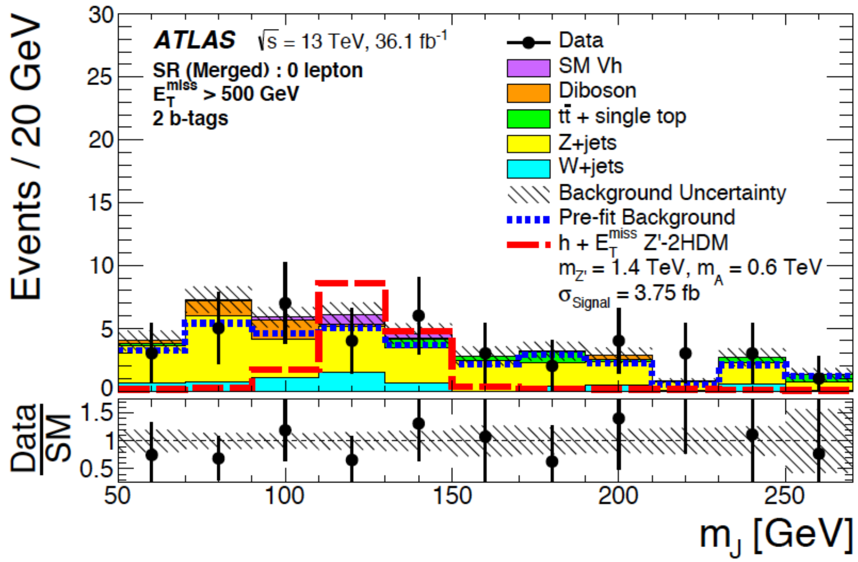
h→b$\bar{b}$:

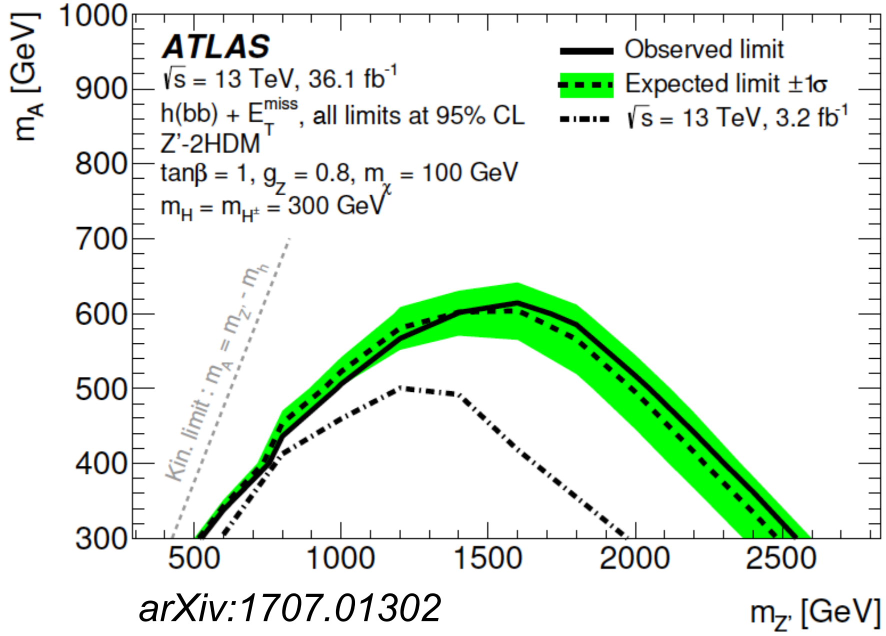
- Require 2 b-tagged jets and high E_T^{miss}.
- Analyze di-jet(fat jet) mass spectrum in different E_T^{miss} bins.

Results interpreted in the context of various simplified models, e.g. Z'-2HDM.



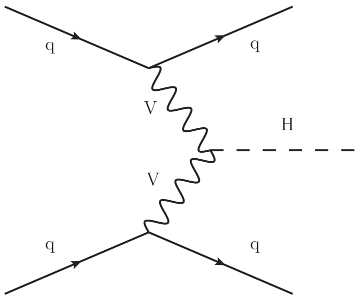
h(→b$\bar{b}$)+E_T^{miss}

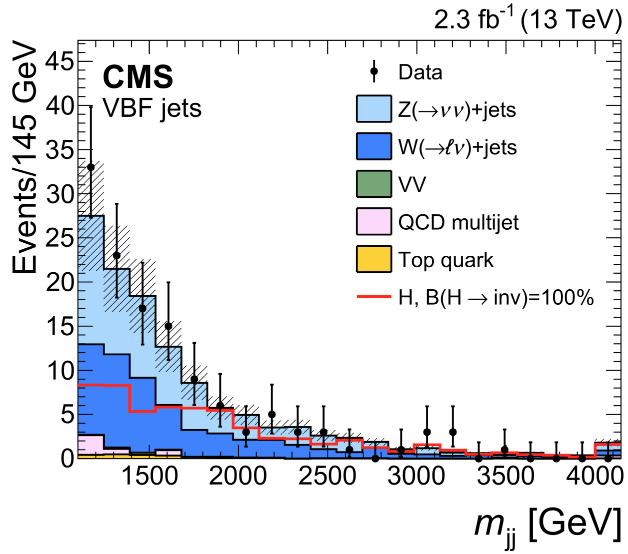




Invisible Higgs decays

- Most sensitive searches use VBF production.
  - Main selection on m_{jj}, $\Delta\eta_{jj}$, and large E_T^{miss}.
- Derive upper limit on BR(H→inv), under the assumption of SM production cross section.
- Result also interpreted in the context of a Higgs-portal model of dark matter interactions.





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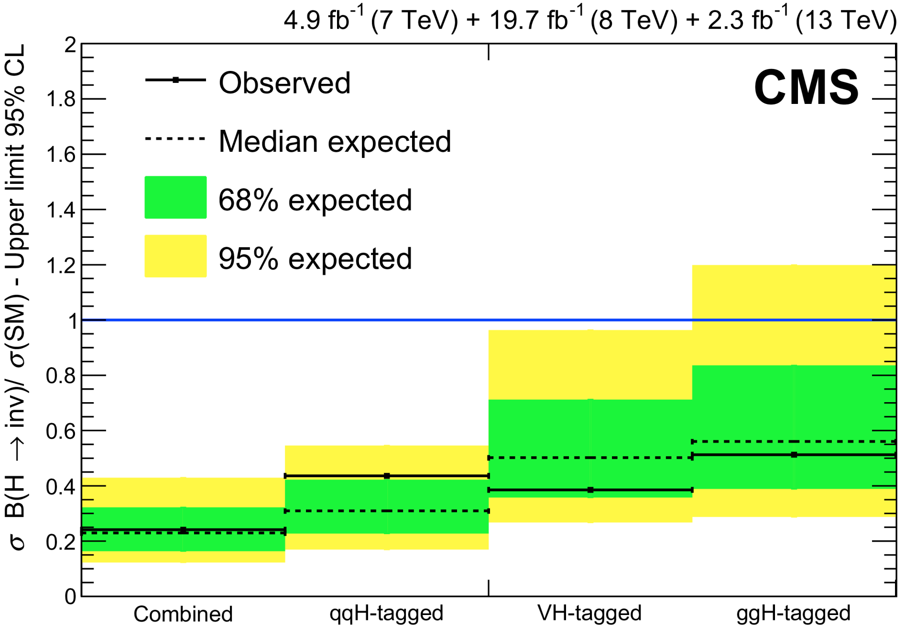

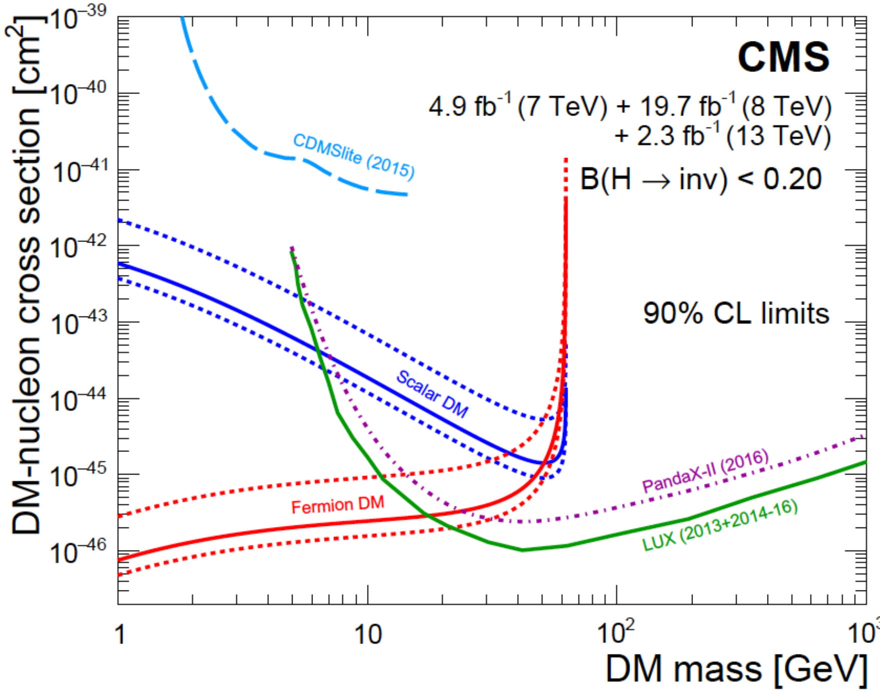

BR(H→inv) < 0.24 (0.23 exp) at 95% CL

Is the Higgs sector minimal?

Extended Higgs sectors

Many possibilities beyond the SM!

- **EWS** (EW singlet): add a Higgs singlet real scalar field to the SM
  → 2 neutral physical states (h and H).

- **2HDM** (Two Higgs Doublet Model): add 2nd Higgs doublet to the SM
  → 5 physical states: 2 neutral CP-even (h and H), 1 neutral CP-odd (A), 2 charged ($H^{\pm}$).
  6 free parameters in minimal model:
  m_h, m_H, m_A, $m_{H\pm}$, $\tan\beta = v_1/v_2$ (ratio of doublet vacuum expectation values),
  α (mixing angle between CP-even states)

- **MSSM** (Minimal Supersymmetric SM): extended Higgs sector is a particular case of a 2HDM type II.

Type	Description	up-type quarks couple to	down-type quarks couple to	charged leptons couple to	remarks
Type I	Fermiophobic	Φ_2	Φ_2	Φ_2	charged fermions only couple to second doublet
Type II	MSSM-like	Φ_2	Φ_1	Φ_1	up- and down-type quarks couple to separate doublets
X	Lepton-specific	Φ_2	Φ_2	Φ_1	
Y	Flipped	Φ_2	Φ_1	Φ_2	
Type III		Φ_1, Φ_2	Φ_1, Φ_2	Φ_1, Φ_2	Flavor-changing neutral currents at tree level

By convention, Φ_2 is the doublet to which up-type quarks couple.

Extended Higgs sectors

Many possibilities beyond the SM!

- **EWS** (EW singlet): add a Higgs singlet real scalar field to the SM
  ➔ 2 neutral physical states (h and H).

- **2HDM** (Two Higgs Doublet Model): add 2nd Higgs doublet to the SM
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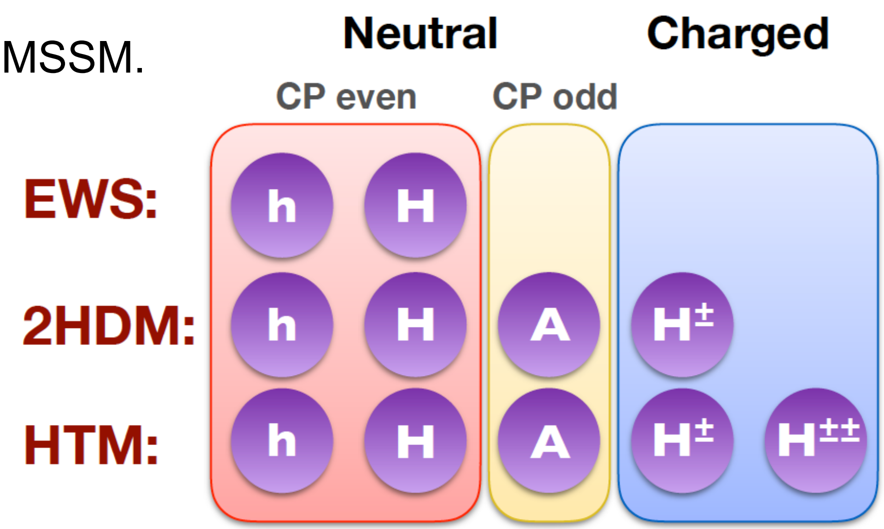
  m_h, m_H, m_A, $m_{H\pm}$, $\tan\beta = v_1/v_2$ (ratio of doublet vacuum expectation values),
  α (mixing angle between CP-even states)

- **MSSM** (Minimal Supersymmetric SM): extended Higgs sector is a particular case of a 2HDM type II.

- **NMSSM** (next-to-MSSM): add Higgs singlet to MSSM.
  ➔ 7 physical states: CP-even H_1, H_2, H_3,
  CP-odd A, and $H^{\pm}$.

- **HTM** (Higgs Triplet Model): add Higgs triplet to SM (motivation: generate Majorana mass terms for neutrinos)
  ➔ 7 physical states: h, H, A, $H^{\pm}$, and $H^{\pm\pm}$.



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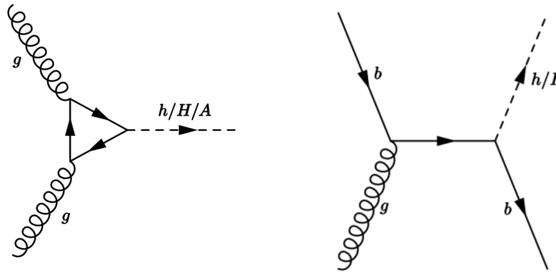
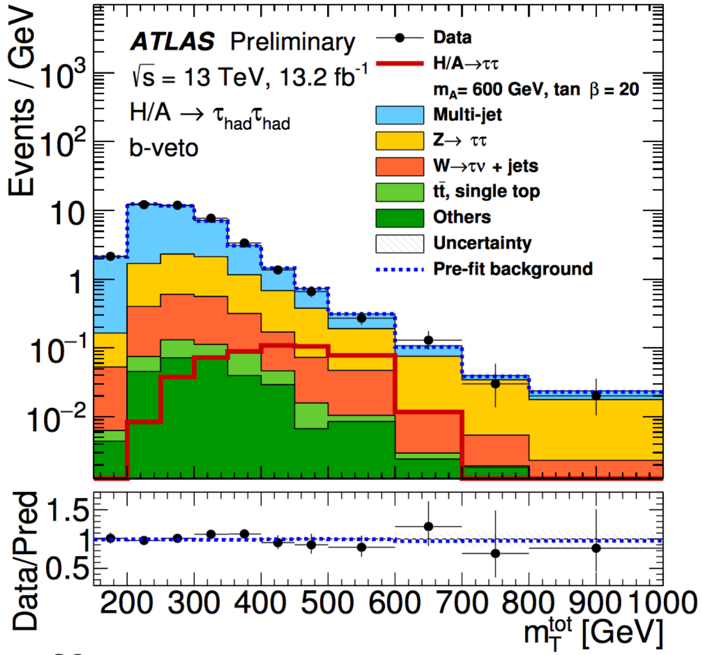
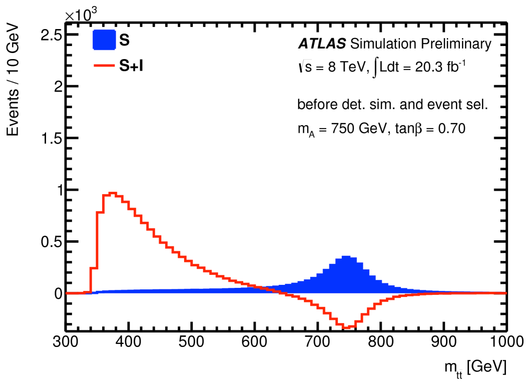
Neutral Higgs: fermionic decays

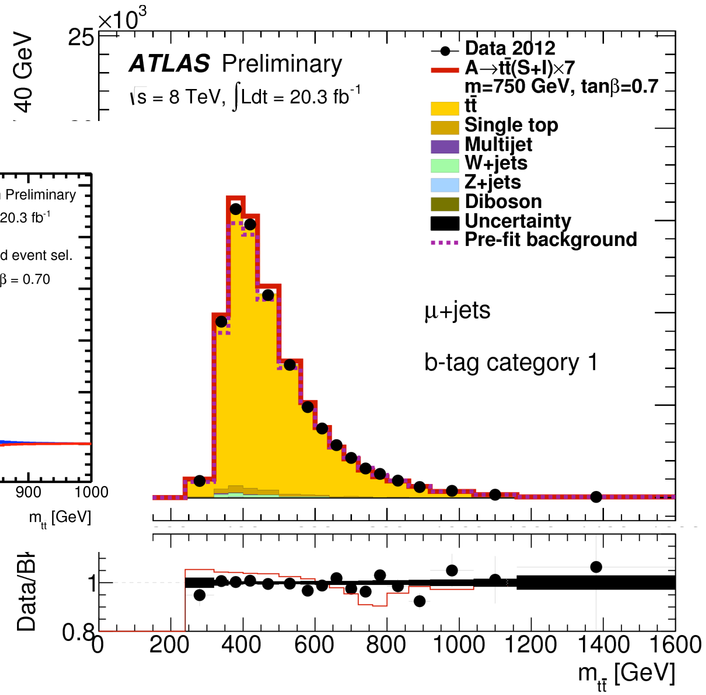


In Type II 2HDM:

- **High tanβ**: main search mode is H/A(b)→ττ(b) (also H/A(b)→b$\bar{b}$(b) but lower sensitivity)
- **Low tanβ**: main search mode is H/A→t$\bar{t}$
  - Challenging due to strong interference between gg→H/A signal and gg→t$\bar{t}$ bkg that creates peak-dip structure.







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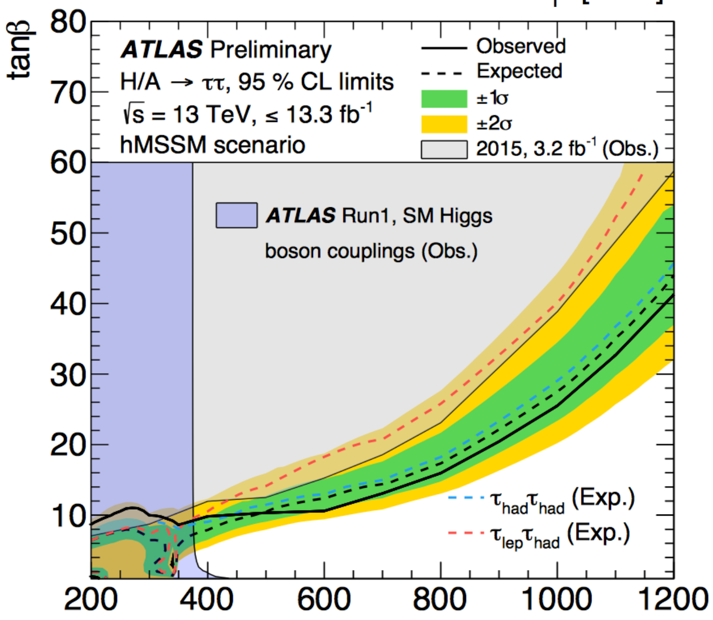
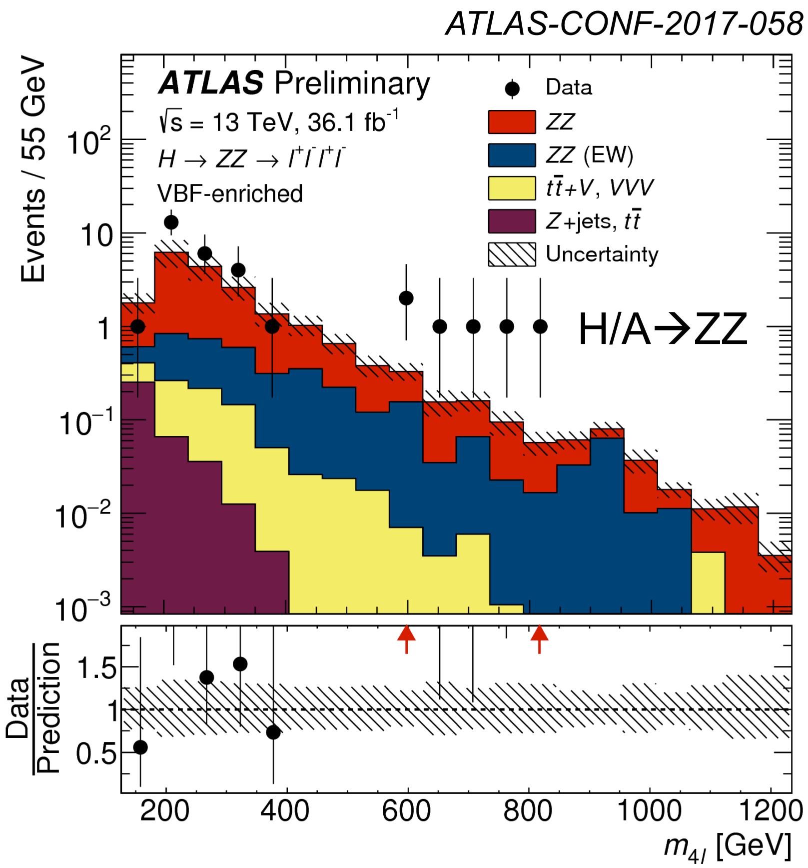
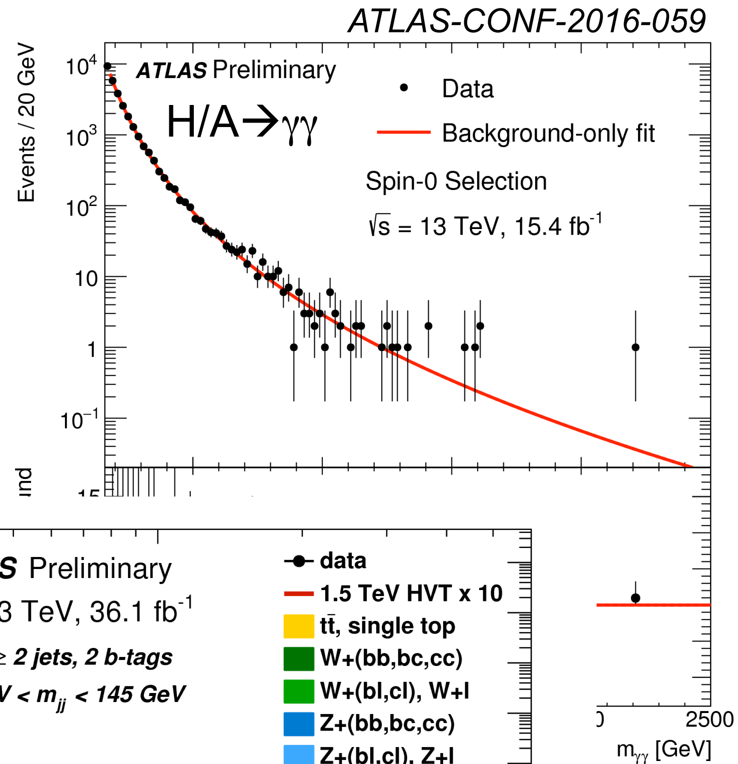
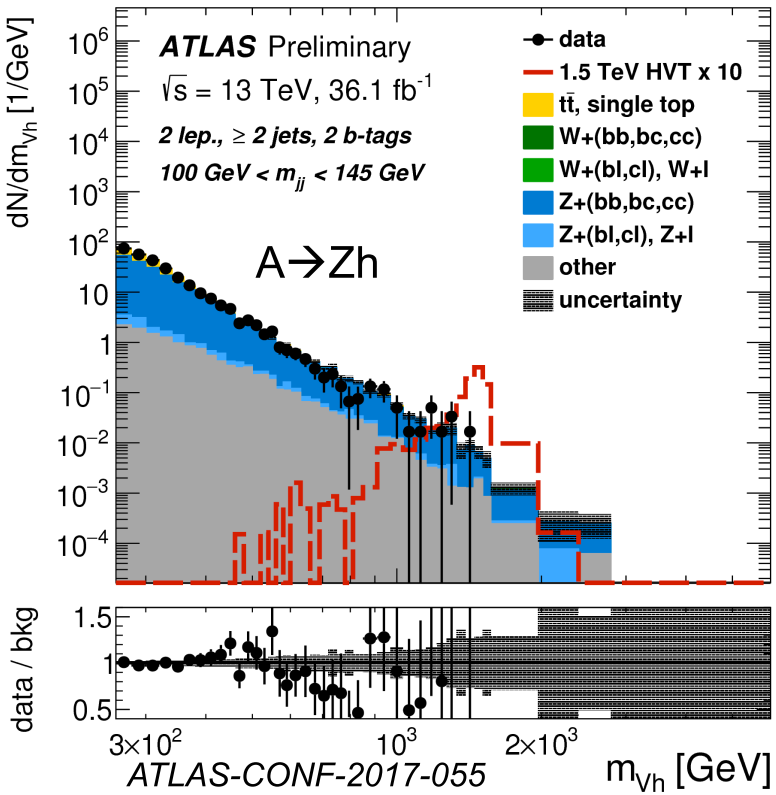


ATLAS-CONF-2016-085

Neutral Higgs: bosonic decays





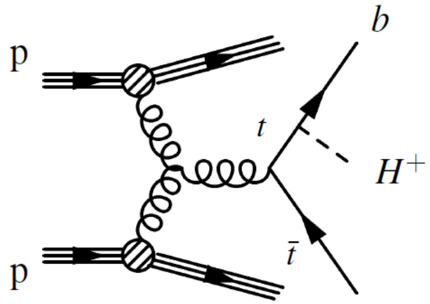


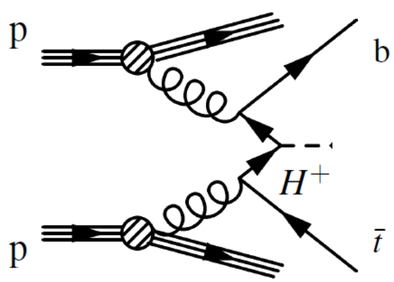
Many searches in many channels, considering both gg→H/A and VBF.

Also H/A→WW, Zγ, hh.

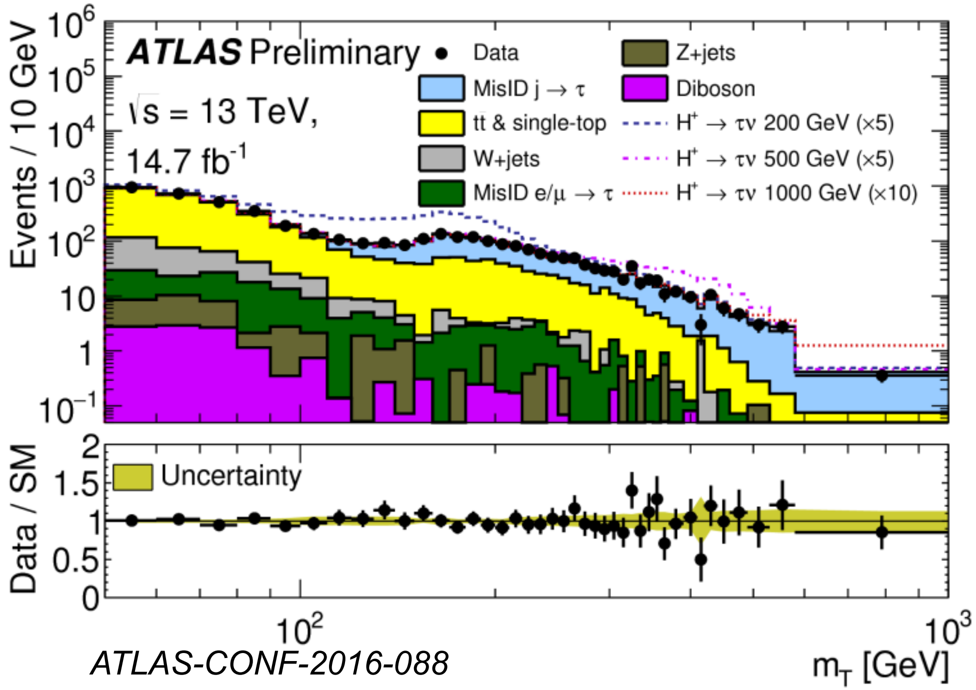
Charged Higgs

- Production modes:
  - $m_{H\pm} < m_t$-m_b: $t\bar{t} \rightarrow WbH^{\pm}b$
  - $m_{H\pm} > m_t$-m_b: associated $tbH^{\pm}$
- Decay modes:
  - High $\tan\beta$: $H^{\pm} \rightarrow \tau\nu$
  - Low $\tan\beta$: $H^{\pm} \rightarrow tb$
  - Also possible: $H^{\pm} \rightarrow Wh$, WZ





$H^{\pm} \rightarrow \tau\nu$ (assoc. prod)



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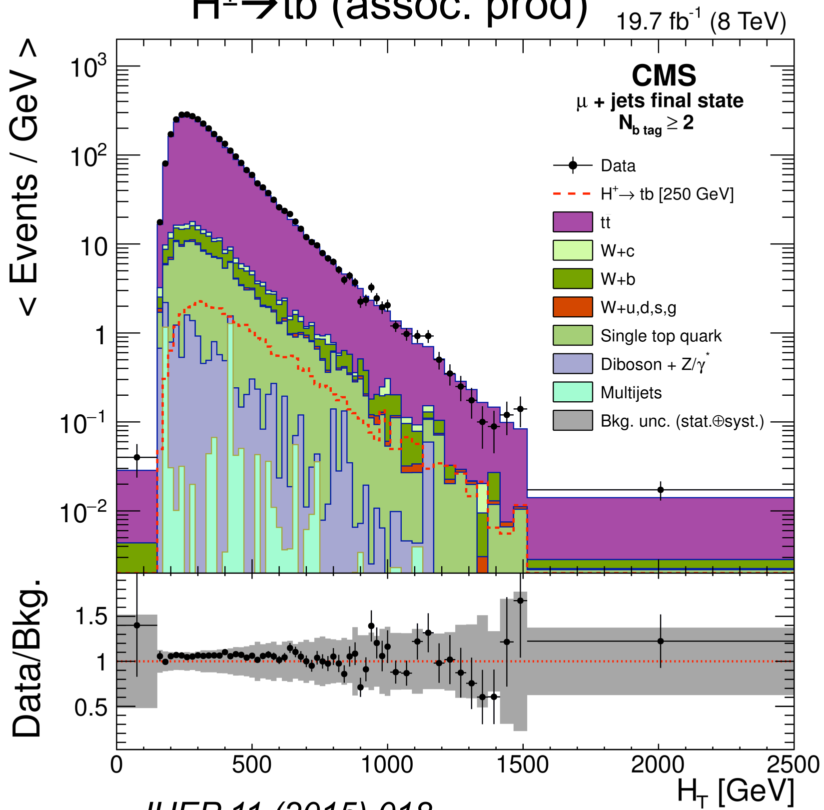
$H^{\pm} \rightarrow tb$ (assoc. prod)



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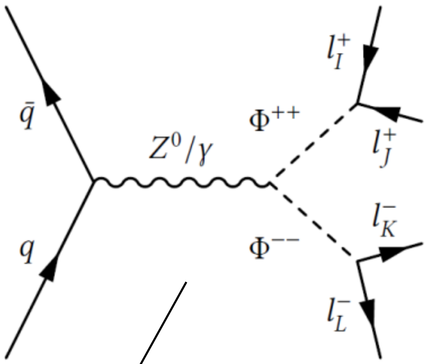
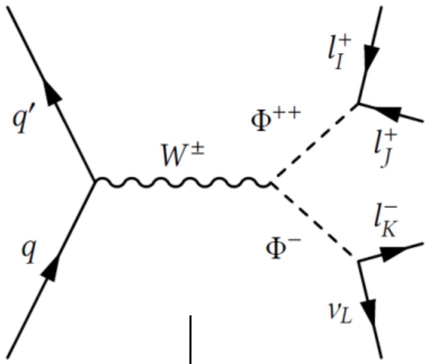
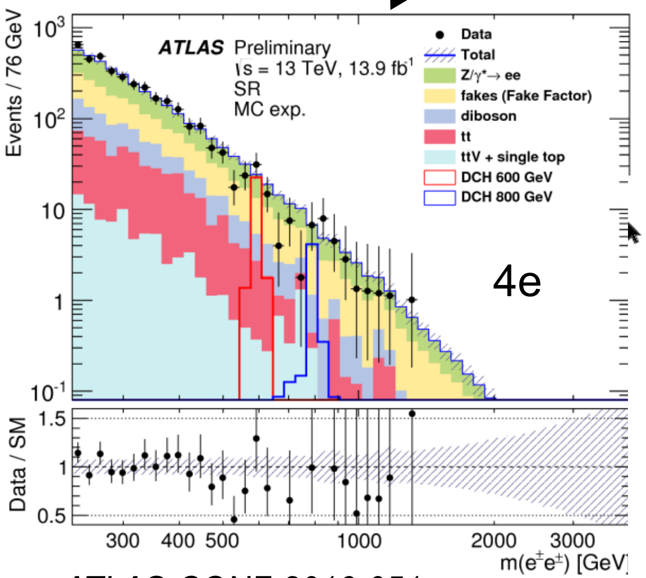
Doubly-charged Higgs







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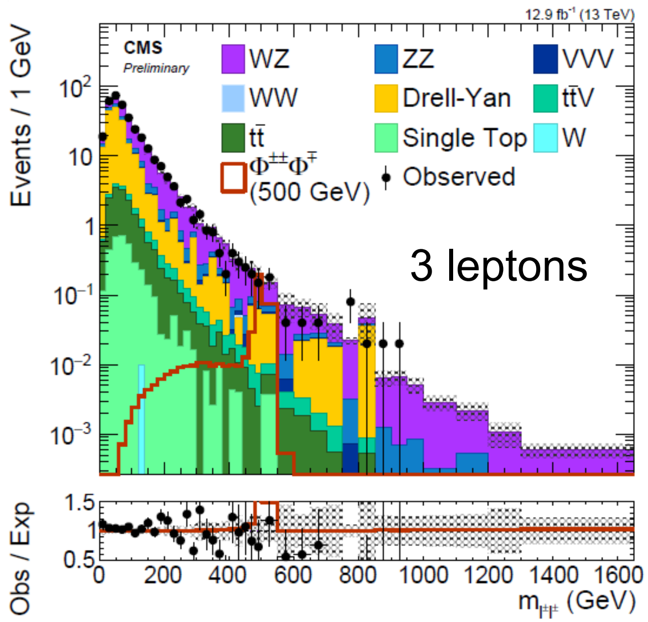
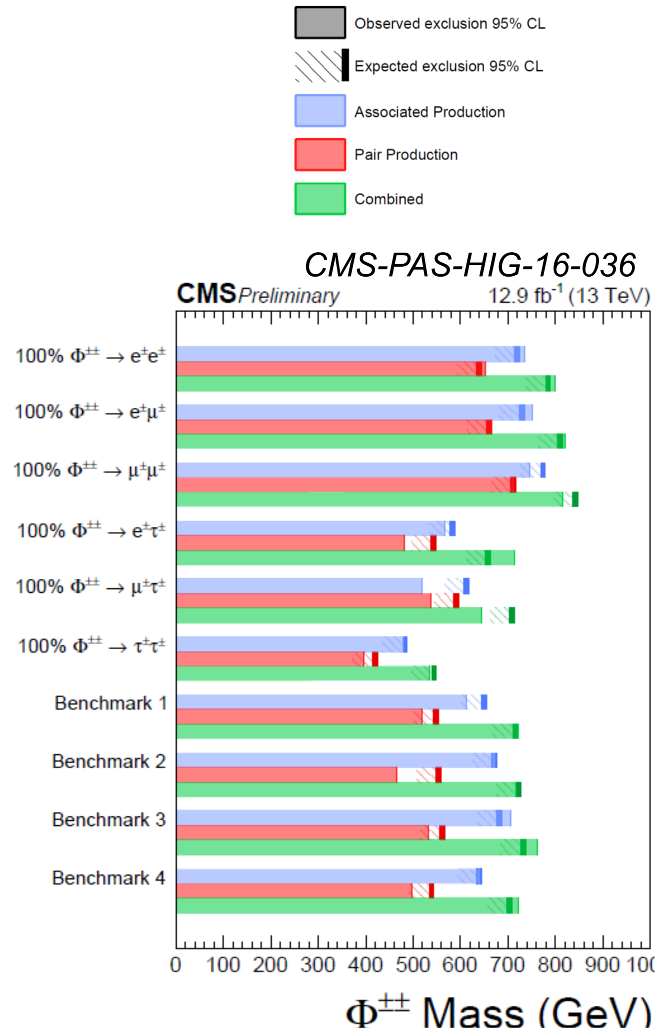
CMS-PAS-HIG-16-036



(a) $\ell^\pm\ell^\pm\ell^\mp$

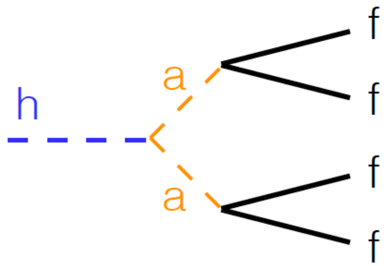


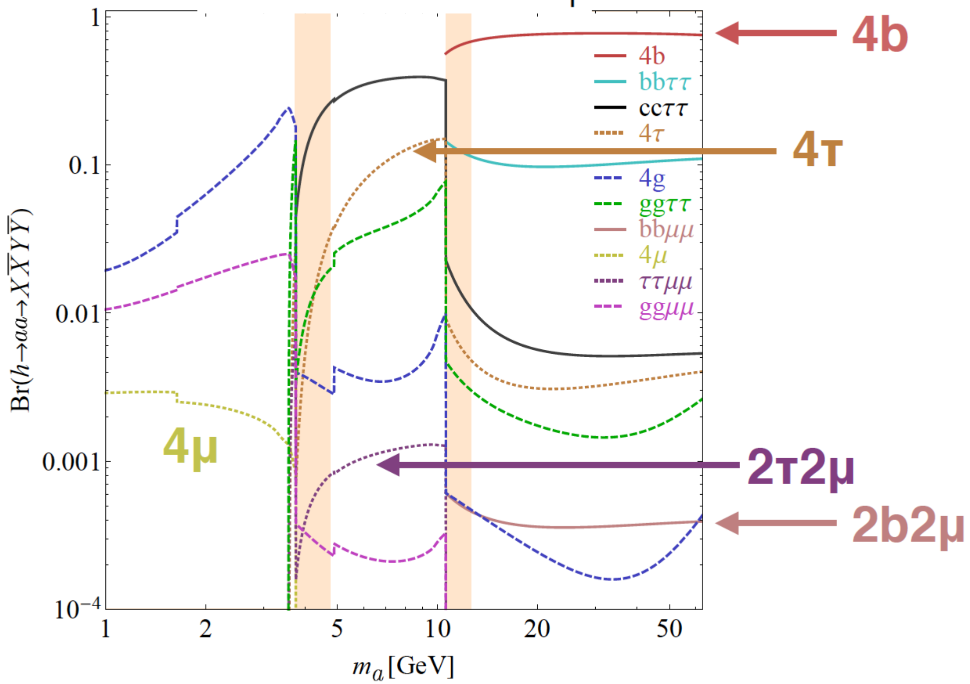
Benchmark Point	ee	$e\mu$	$e\tau$	$\mu\mu$	$\mu\tau$	$\tau\tau$
BP1	0	0.01	0.01	0.30	0.38	0.30
BP2	1/2	0	0	1/8	1/4	1/8
BP3	1/3	0	0	1/3	0	1/3
BP4	1/6	1/6	1/6	1/6	1/6	1/6

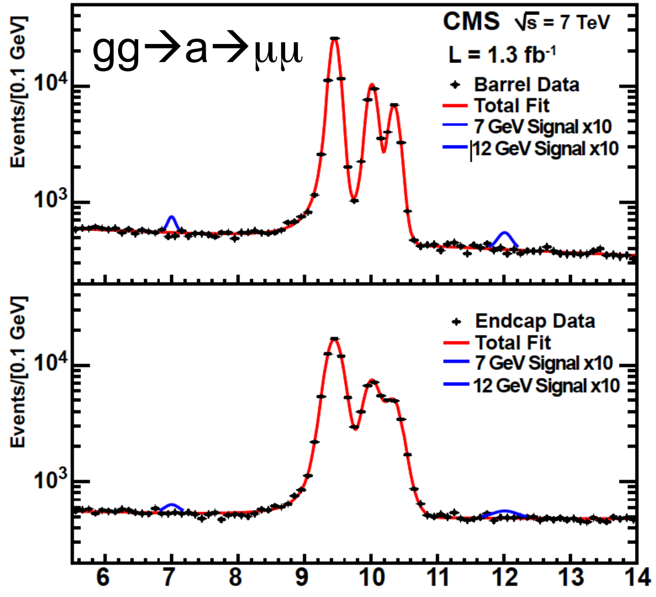
Correspond to different neutrino mass hierarchies

Light scalars

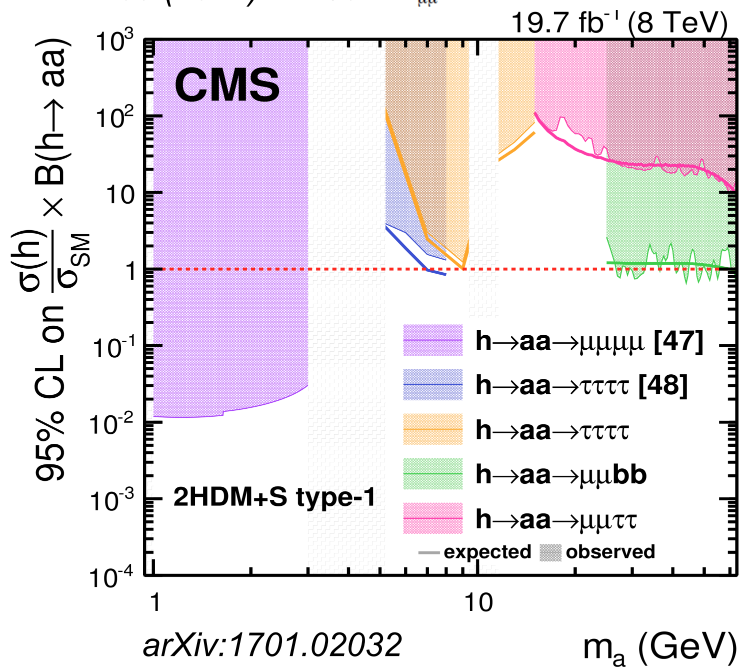
- Production modes for light CP-odd scalars (e.g. from NMSSM):
  - Direct production: $gg \rightarrow a$, $b\bar{b}a$, $t\bar{t}a$
  - In Higgs decays: $h \rightarrow aa$
    - Decay modes are model dependent.







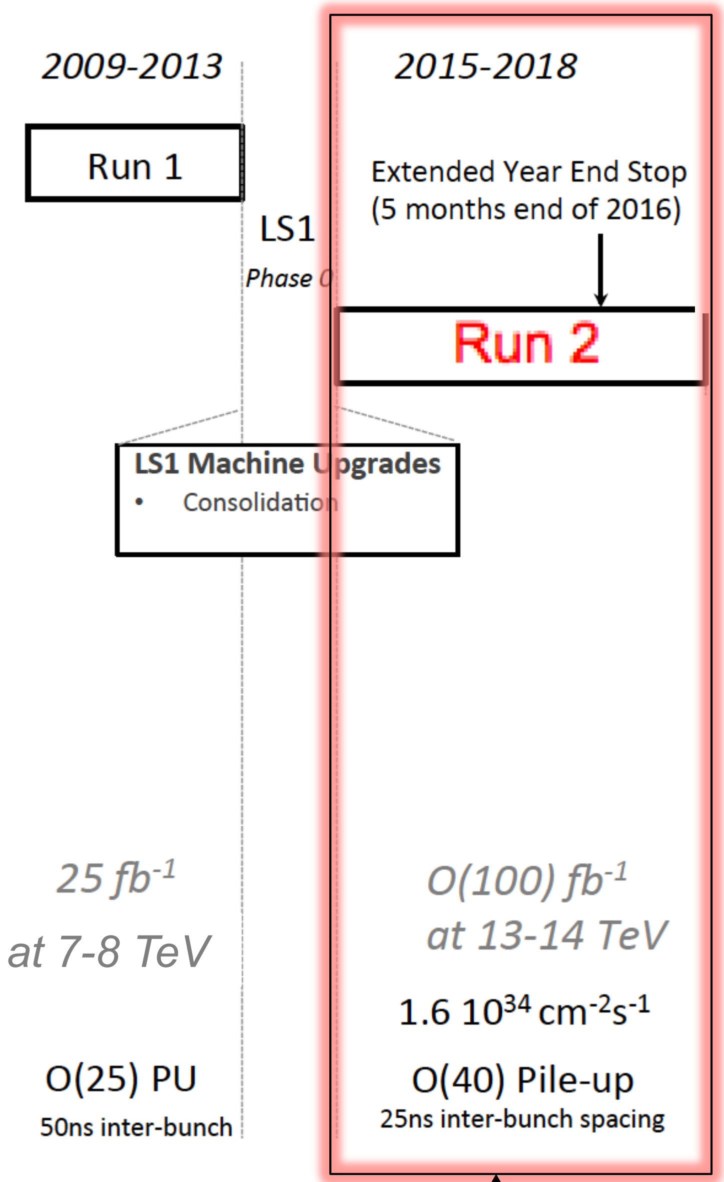
PRL 109 (2012) 121801 $m_{\mu\mu}$ [GeV]



arXiv:1701.02032

Future prospects

Recall: LHC Run 2 Prospects



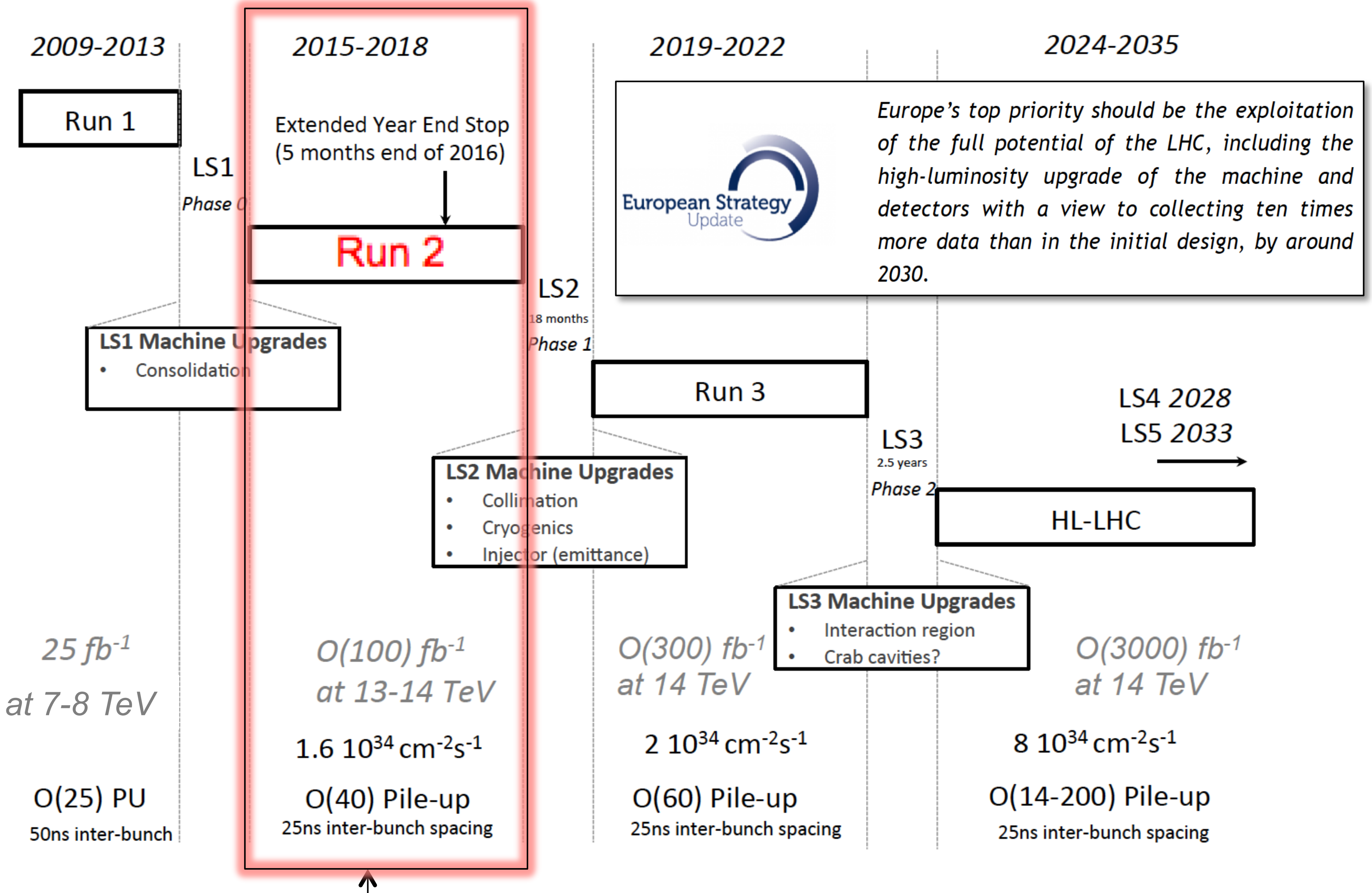
We are here…

By end of 2018 will multiply by ~x3 currently analyzed dataset

Run 2 Milestones in Higgs Physics:

- Improved precision in Higgs boson mass.
- Improved precision in Higgs coupling measurements, including observation of couplings to 3rd generation quarks (Hbb and Htt).
- Detailed studies of Higgs boson production via fiducial and differential cross section measurements.
- Detailed studies on production yields and kinematics to search for non-SM interactions (EFT, pseudo-observables, CP-odd admixture, ...)
- Extensive searches for rare and BSM decay modes.

LHC Beyond Run 2

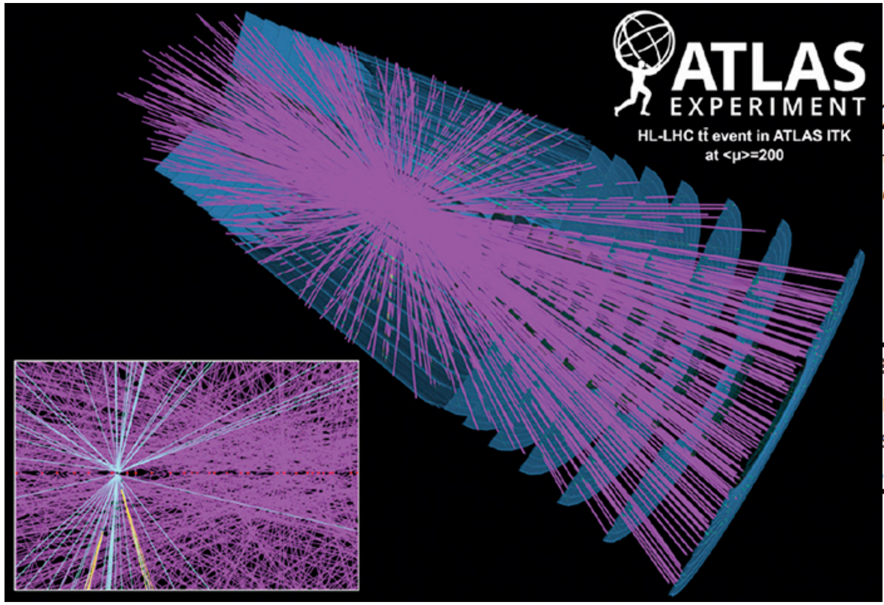


We are at the beginning of a ~20 year program!

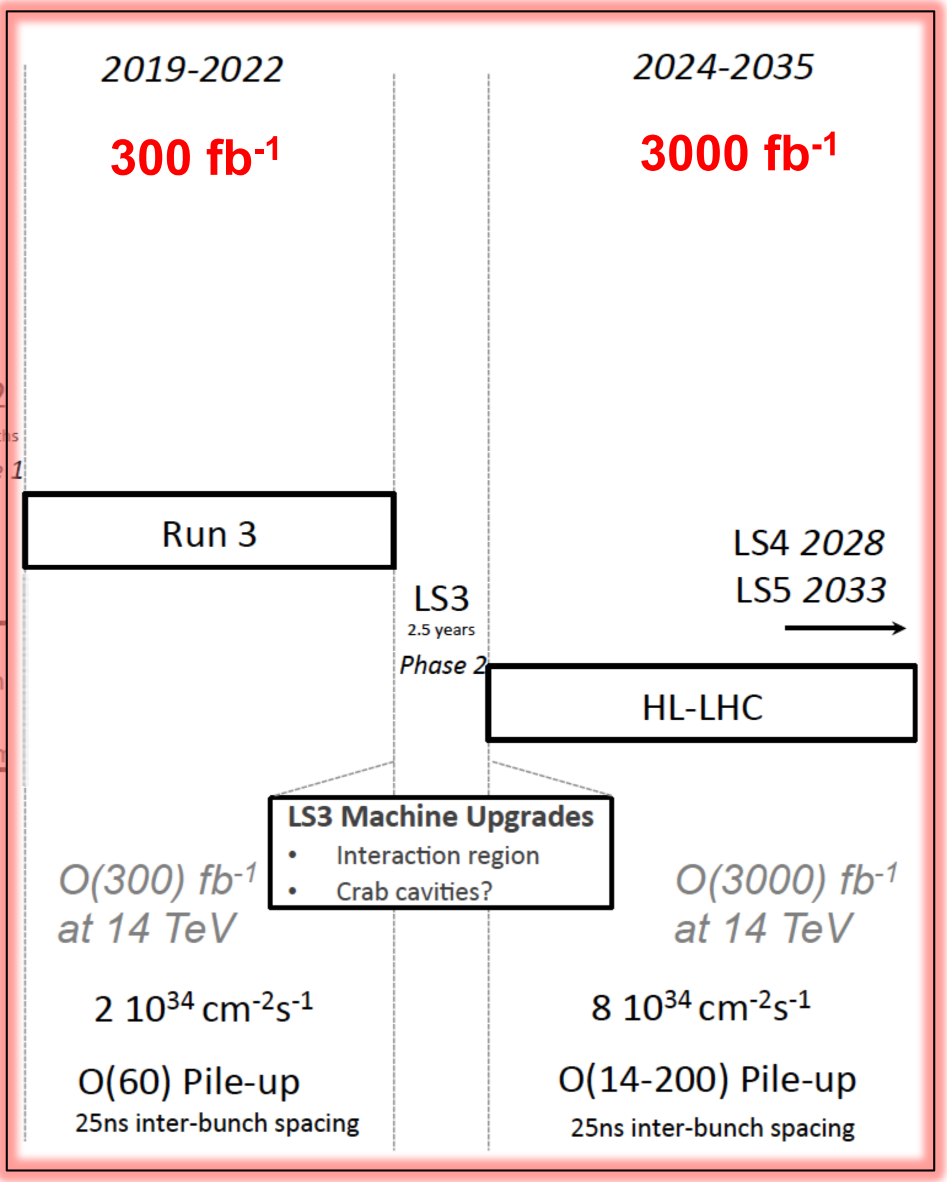
The perfect time to start a PhD at the LHC!

LHC Beyond Run 2

Significant detector upgrades being planned to cope with high pileup at HL-LHC



$t\bar{t}$ event with 200 pileup interactions overlaid in ATLAS Phase-II tracker



LHC Beyond Run 2

Beyond-Run 2 Prospects:

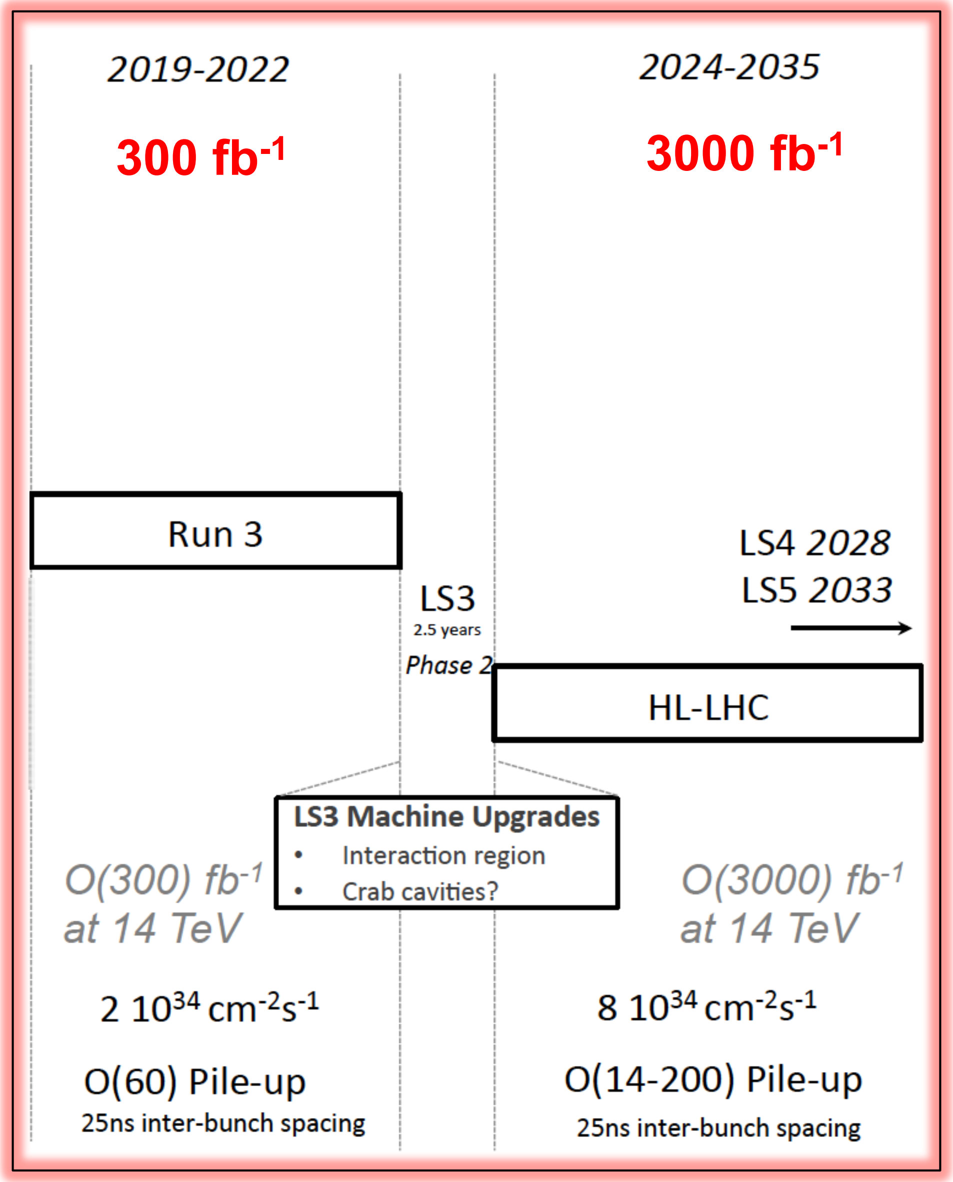
- Precision Higgs couplings:

Projected accuracy per experiment
(arXiv:1307.7135 and ATL-PHYS-PUB-2014-016)

Coupling modifier	300 fb^{-1}	3000 fb^{-1}
$\kappa_{W,Z}$, κ_γ	6%	3%
κ_b	12%	5%
κ_t	15%	7%
κ_τ	10%	5%
κ_μ	22%	7%

(*) Assuming Run 1 experimental uncertainty, theory uncertainty reduced by x2.

- Observation of rare decay modes ($H\rightarrow\mu\mu$, $Z\gamma$).
- Possibly evidence for SM di-Higgs production.
- Studies on vector-boson scattering.



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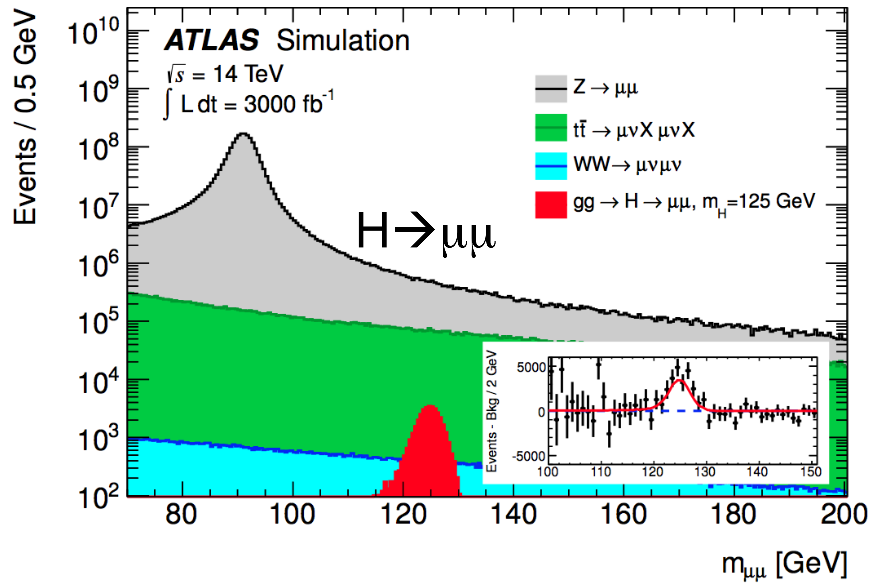
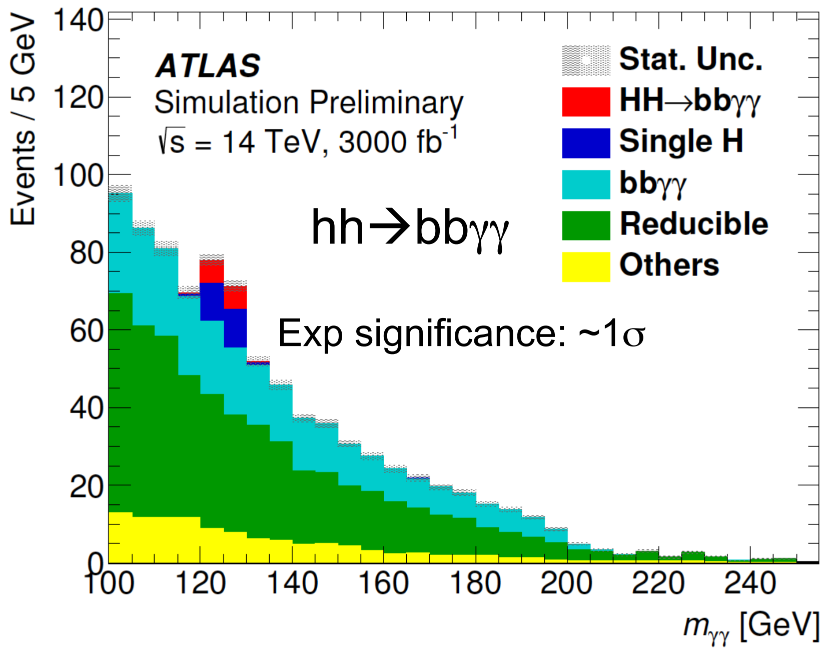


ATL-PHYS-PUB-2017-001



Beyond LHC programs

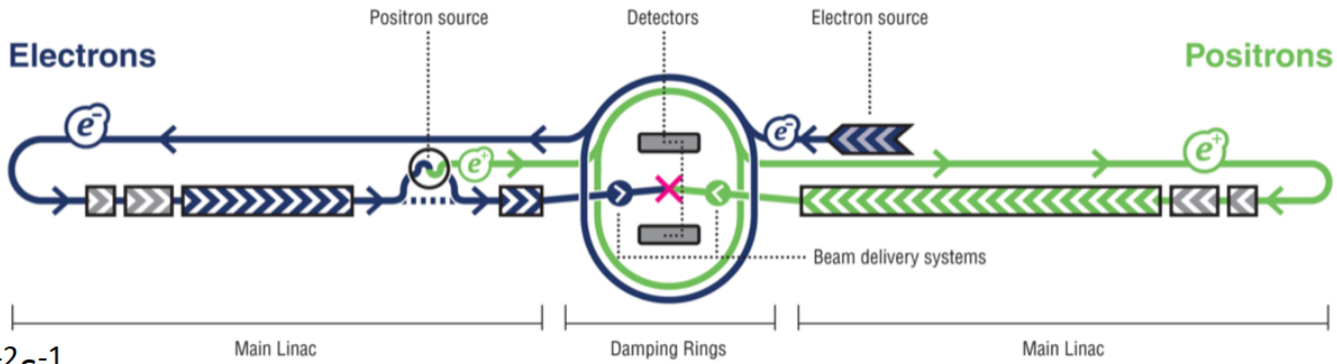
e$^+$e$^-$ colliders

ILC

Three scenarios

- 250 GeV
- 500 GeV
- 1000 GeV

Lumi 0.7 to 5 10^{34} cm^{-2}s^{-1}

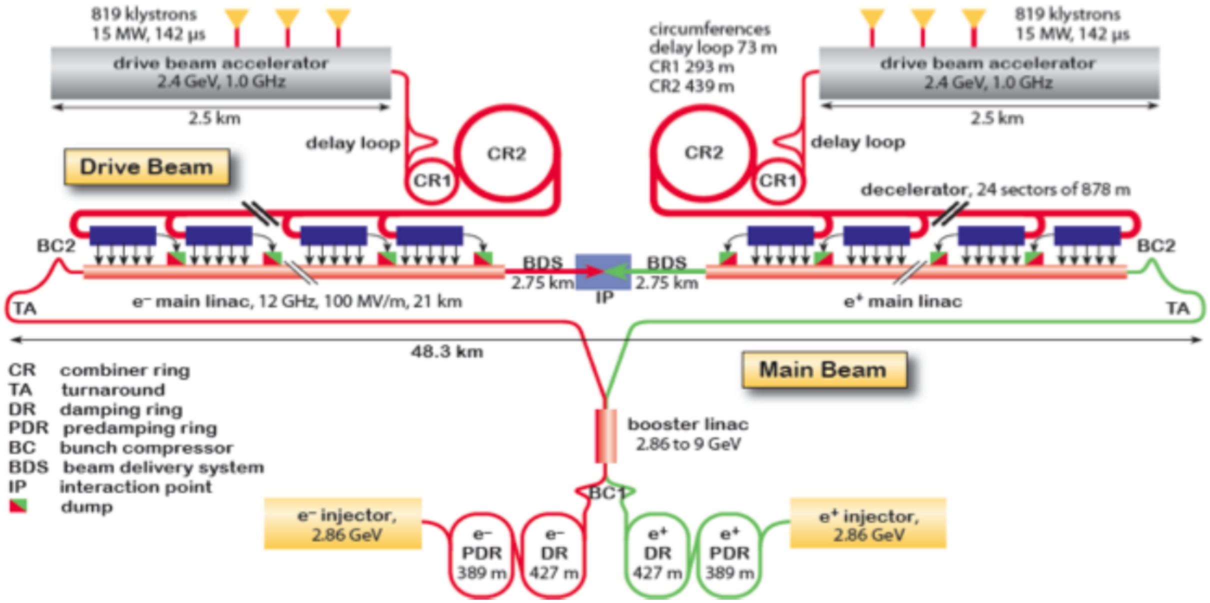


CLIC

Three scenarios

- 500 GeV
- 1500 GeV
- 3000 GeV

Lumi 1.3 to 6 10^{34} cm^{-2}s^{-1}



Beyond LHC programs

Future circular collider VHE-LHC including e^+e^- collider

FCC-ee

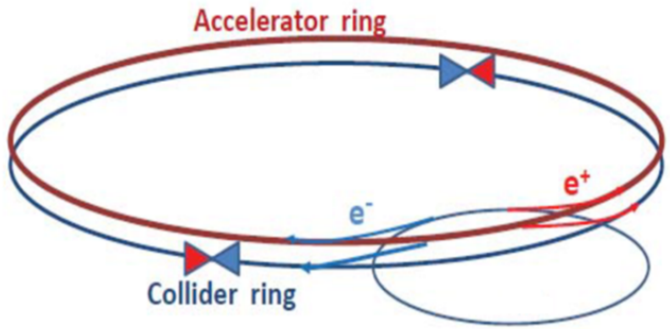
Two scenarios

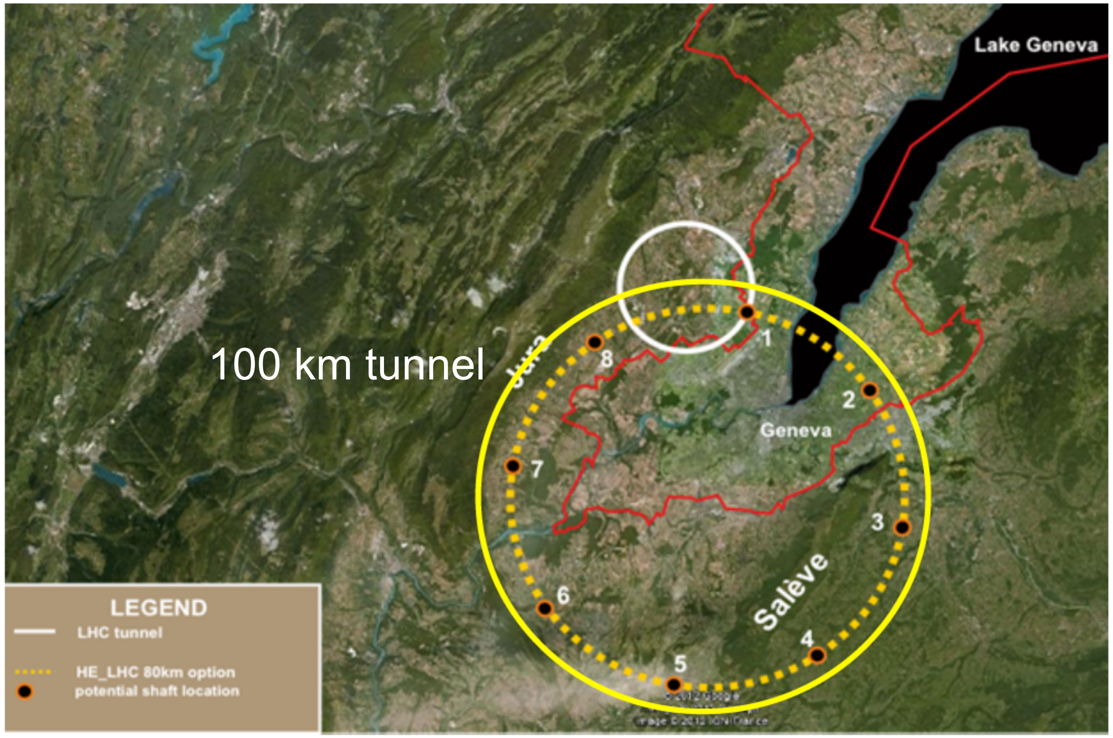
- 240GeV
- 350GeV
- Even more?

Lumi 5-7x10^{34} $cm^{-2}s^{-1}$
(but 4 IPs)

FCC-hh

100 TeV Collider
(~20T magnets)





Beyond LHC programs

e^+e^- colliders

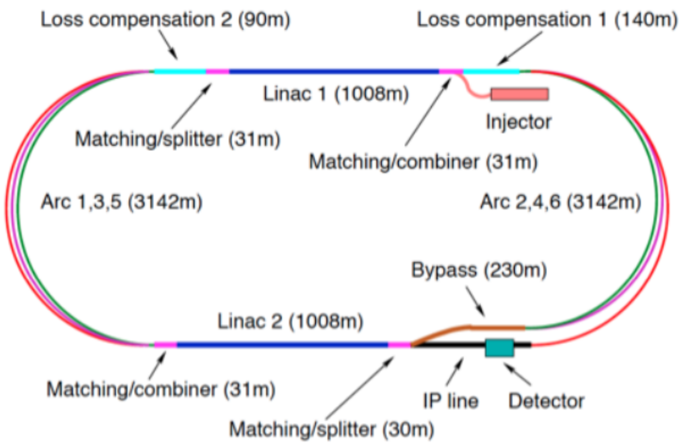
Facility	ILC			ILC(LumiUp)	TLEP (4 IP)		CLIC		
$\sqrt{s}$ (GeV)	250	500	1000	250/500/1000	240	350	350	1400	3000
$\int \mathcal{L}dt$ (fb^{-1})	250	+500	+1000	1150+1600+2500‡	10000	+2600	500	+1500	+2000
Γ_H	12%	5.0%	4.6%	2.5%	1.9%	1.0%	9.2%	8.5%	8.4%
κ_γ	18%	8.4%	4.0%	2.4%	1.7%	1.5%	–	5.9%	<5.9%
κ_g	6.4%	2.3%	1.6%	0.9%	1.1%	0.8%	4.1%	2.3%	2.2%
κ_W	4.9%	1.2%	1.2%	0.6%	0.85%	0.19%	2.6%	2.1%	2.1%
κ_Z	1.3%	1.0%	1.0%	0.5%	0.16%	0.15%	2.1%	2.1%	2.1%
κ_μ	91%	91%	16%	10%	6.4%	6.2%	–	11%	5.6%
κ_τ	5.8%	2.4%	1.8%	1.0%	0.94%	0.54%	4.0%	2.5%	<2.5%
κ_c	6.8%	2.8%	1.8%	1.1%	1.0%	0.71%	3.8%	2.4%	2.2%
κ_b	5.3%	1.7%	1.3%	0.8%	0.88%	0.42%	2.8%	2.2%	2.1%
κ_t	–	14%	3.2%	2.0%	–	13%	–	4.5%	<4.5%
BR_{inv}	0.9%	< 0.9%	< 0.9%	0.4%	0.19%	< 0.19%			

C. Grojean

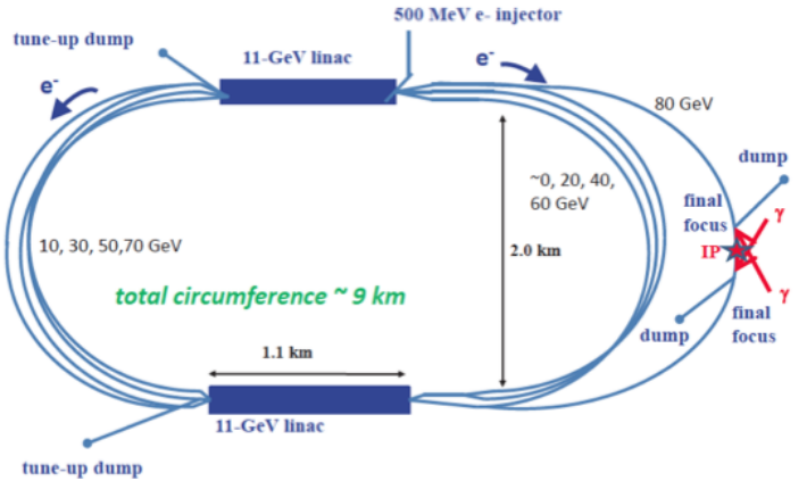
- Reaching few permil to percent level precision on the couplings
- Direct measurement of branching fractions

Further Programs

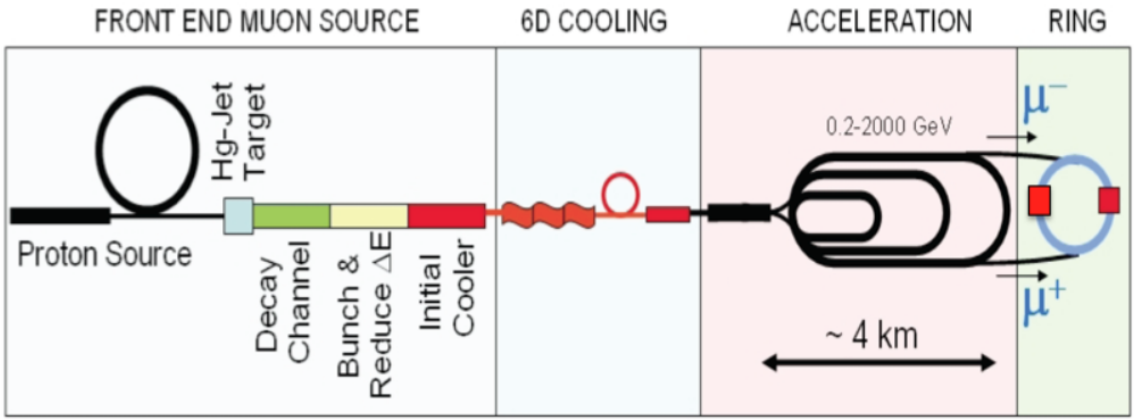
ep Collider



γγ Collider



Ultimate Higgs factory μμ Collider

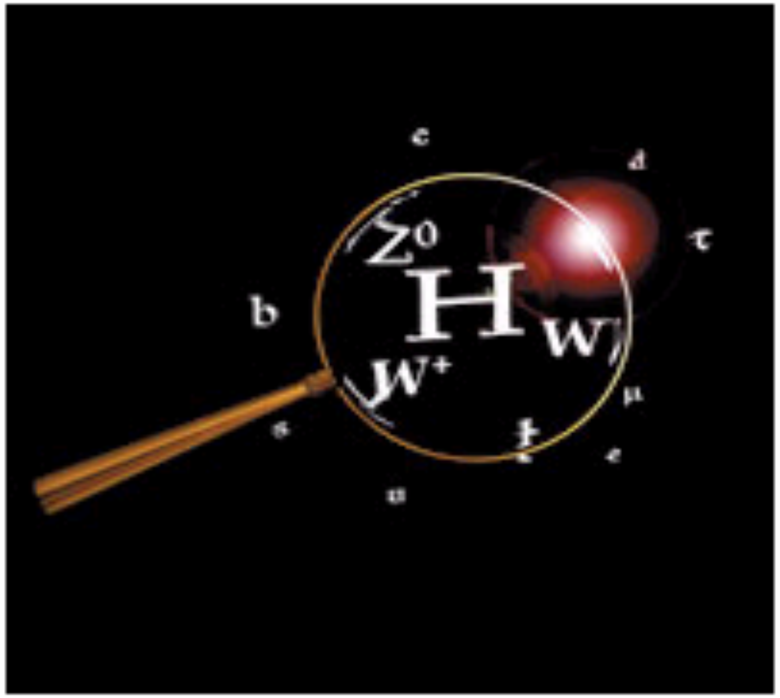


Conclusions

- Since the discovery of the Higgs boson, and entire new field of research has emerged.

- The LHC Run 1 program allowed outlining the experimental profile of the Higgs boson:
    - Mass measured to 0.2% accuracy.
    - Evidence of CP-even scalar nature.
    - Observation of coupling to W, Z and taus.
    - Evidence for non-universal couplings.
    - First studies on Higgs production.
    - First constraints on Higgs width and rare/ BSM decay modes.

  Greatly benefited from strong experiment-theory connection.



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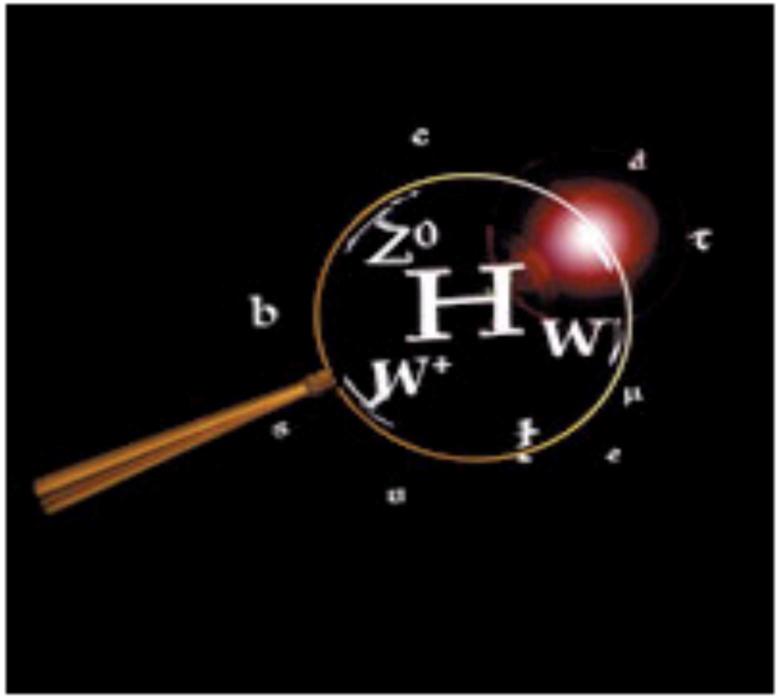

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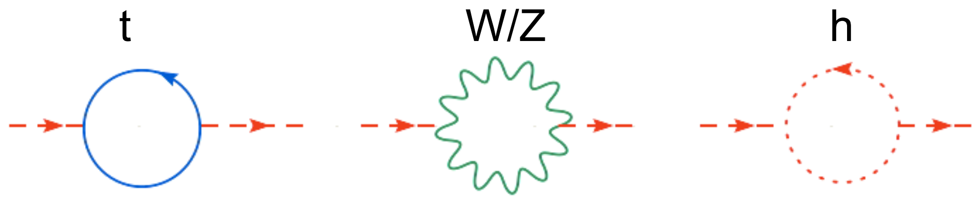
A deep exploration of the Higgs sector is a top priority of the LHC Run 2 and beyond

Join us!

Backup

Digression: Hierarchy problem

- The Higgs potential is fully renormalizable, but loop corrections to the Higgs boson mass are quadratically divergent:



$$(125\,\mathrm{GeV})^2 = m^2_{H0} + \left[-(2\,\mathrm{TeV})^2 + (700\,\mathrm{GeV})^2 + (500\,\mathrm{GeV})^2\right]\left(\frac{\Lambda}{10\mathrm{TeV}}\right)^2$$

The top quark has the largest contribution because of the large Yukawa coupling

$$\lambda_t = \frac{\sqrt{2}m_t}{v} = 0.9965 \pm 0.0044$$

(for $m_t \sim 173.34 \pm 0.76$ GeV)

- If the scale at which the SM breaks down is large, the Higgs natural mass should be of the order of the cut-off (e.g. the Planck Scale)

  ➔ Requires huge cancellation among unrelated contributions to the Higgs boson mass (a.k.a. "fine tuning") which makes the theory "unnatural".

Note: technicolor models are not concerned by this problem since the Higgs boson is not an elementary scalar.