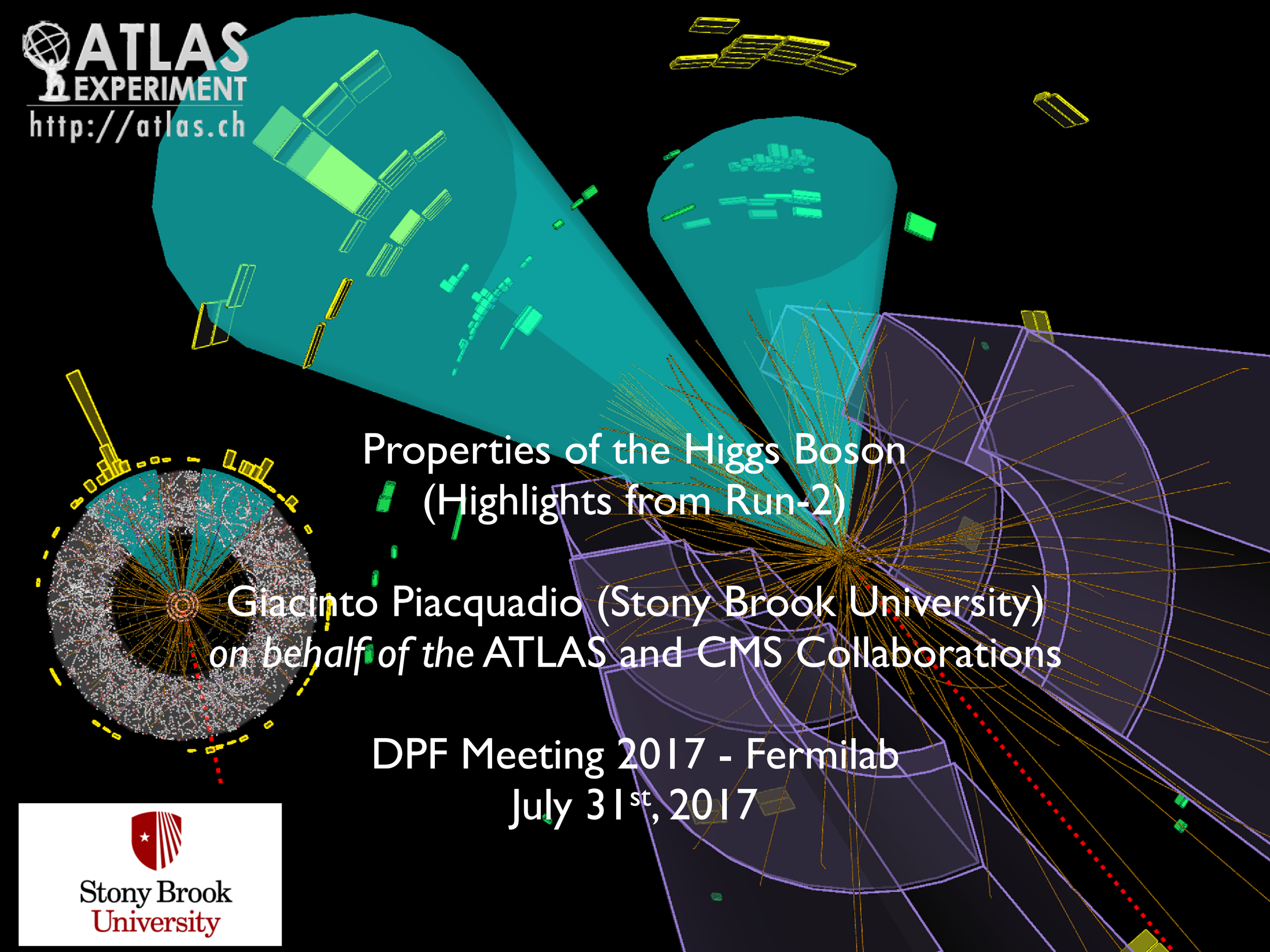

Properties of the Higgs Boson (Highlights from Run-2)

Giacinto Piacquadio (Stony Brook University)
on behalf of the ATLAS and CMS Collaborations

DPF Meeting 2017 - Fermilab
July 31st, 2017

5 years ago: Higgs Boson Discovery announced by ATLAS and CMS at CERN (July 4th, 2012)

The Higgs boson in the SM

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu}$$

$$+ i \bar{\psi} \not{D} \psi$$

$$+ |D_\mu \phi|^2 - V(\phi)$$

$$+ \bar{\psi}_i y_{ij} \psi_j \phi + h.c.$$

- The Higgs boson discovery
  - confirmed the Higgs mechanism that provides masses to elementary particles
  - opened the way to the exploration of a **new sector** of the SM Lagrangian!

The Higgs boson in the SM

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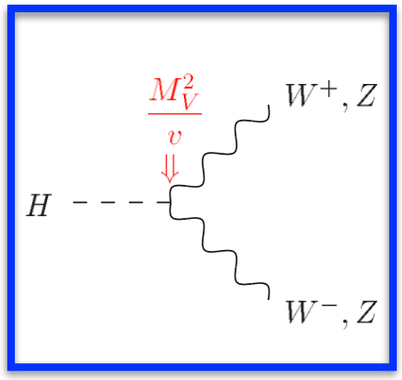
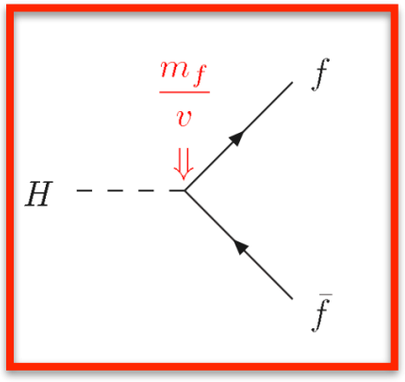
- The Higgs boson discovery
  - confirmed the Higgs mechanism that provides masses to elementary particles
  - opened the way to the exploration of a **new sector** of the SM Lagrangian!
- Two types of tree-level coupling to other SM particles:



to Bosons



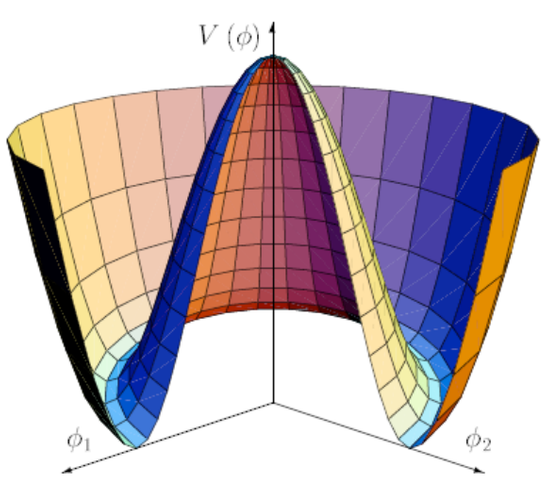
to Fermions

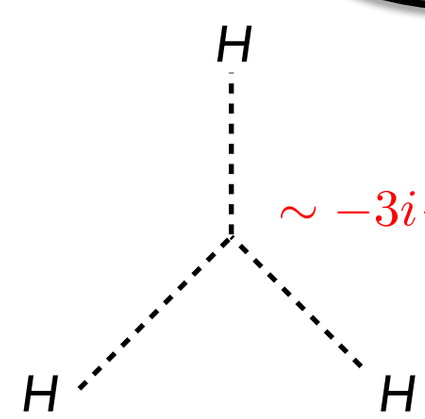
The Higgs boson in the SM

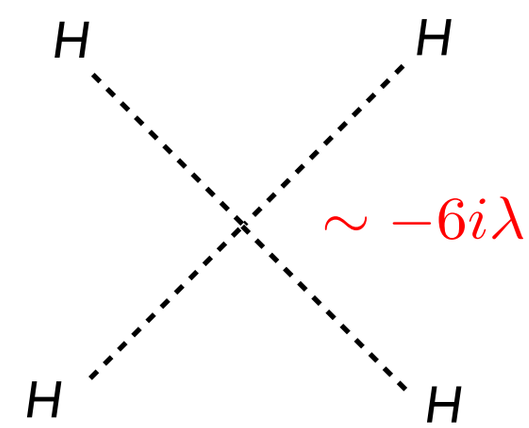
$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu}$$
$$+ i \bar{\psi} \not{D} \psi$$
$$+ |D_\mu \phi|^2 - V(\phi)$$
$$+ \bar{\psi}_i y_{ij} \psi_j \phi + h.c.$$

- The Higgs boson discovery
  - confirmed the Higgs mechanism that provides masses to elementary particles
  - opened the way to the exploration of a **new sector** of the SM Lagrangian!
- Higgs boson can also interact with itself, through quartic term in Higgs potential
  - Very suppressed in SM! Difficult to probe…

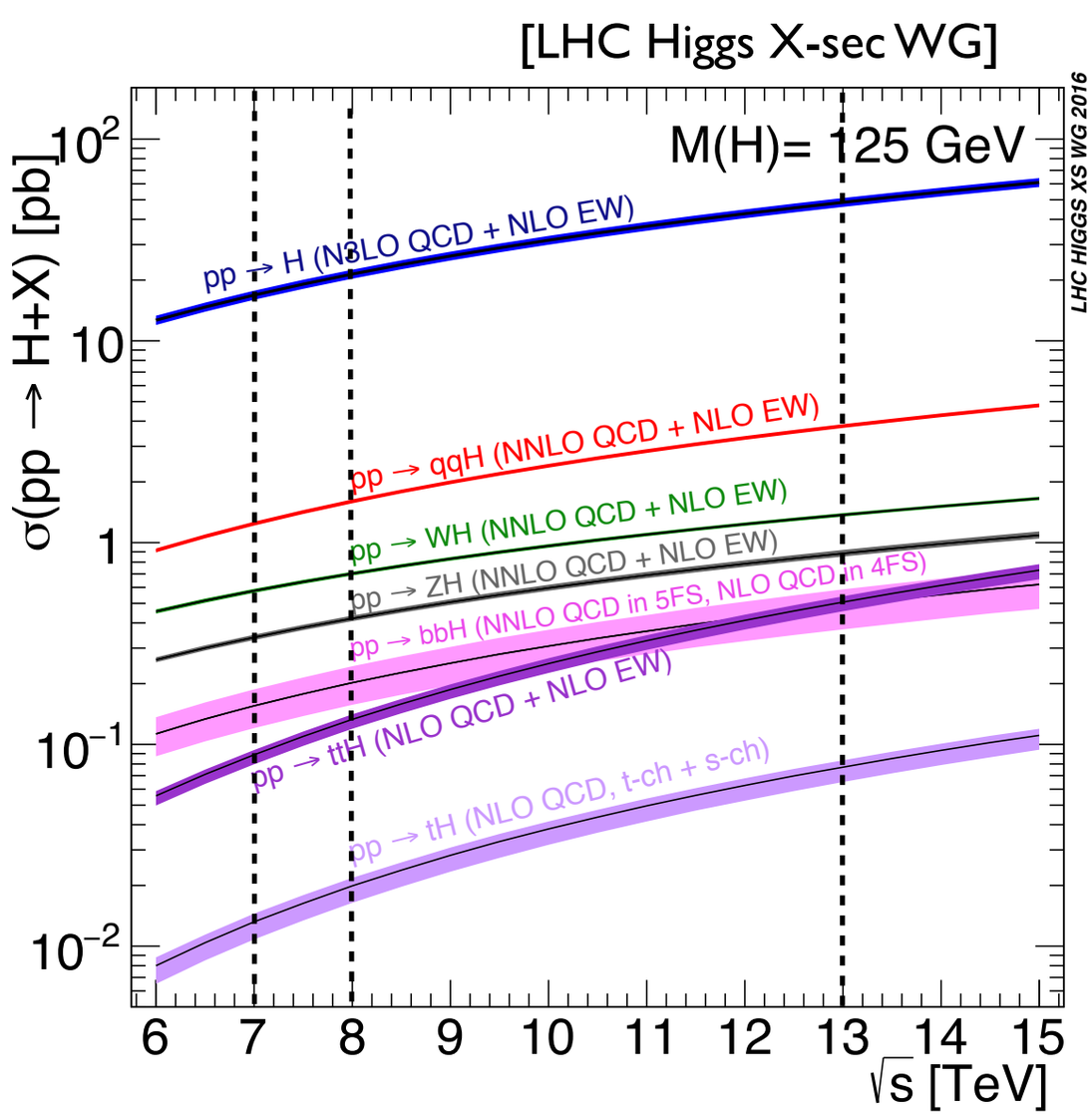
$$V(\phi) \sim -\mu^2 \left(\phi\phi^\dagger\right) + \lambda \left(\phi\phi^\dagger\right)^2$$



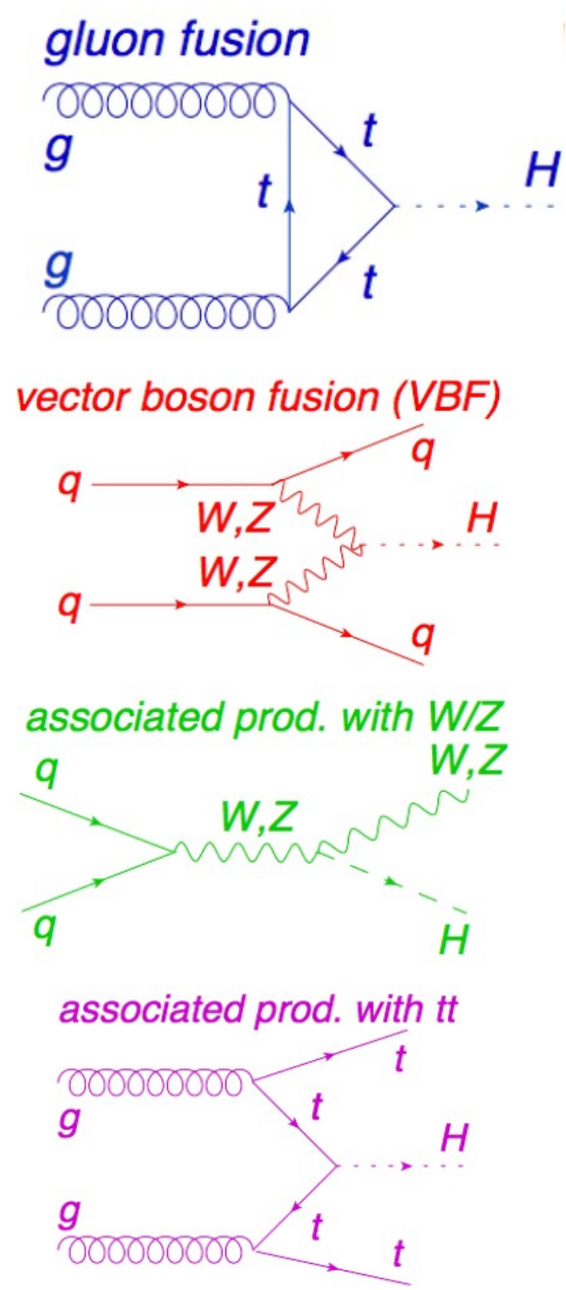




Higgs boson production at the LHC



Production modes



Higgs bosons produced in Run 2 (2015+2016)

1.7M

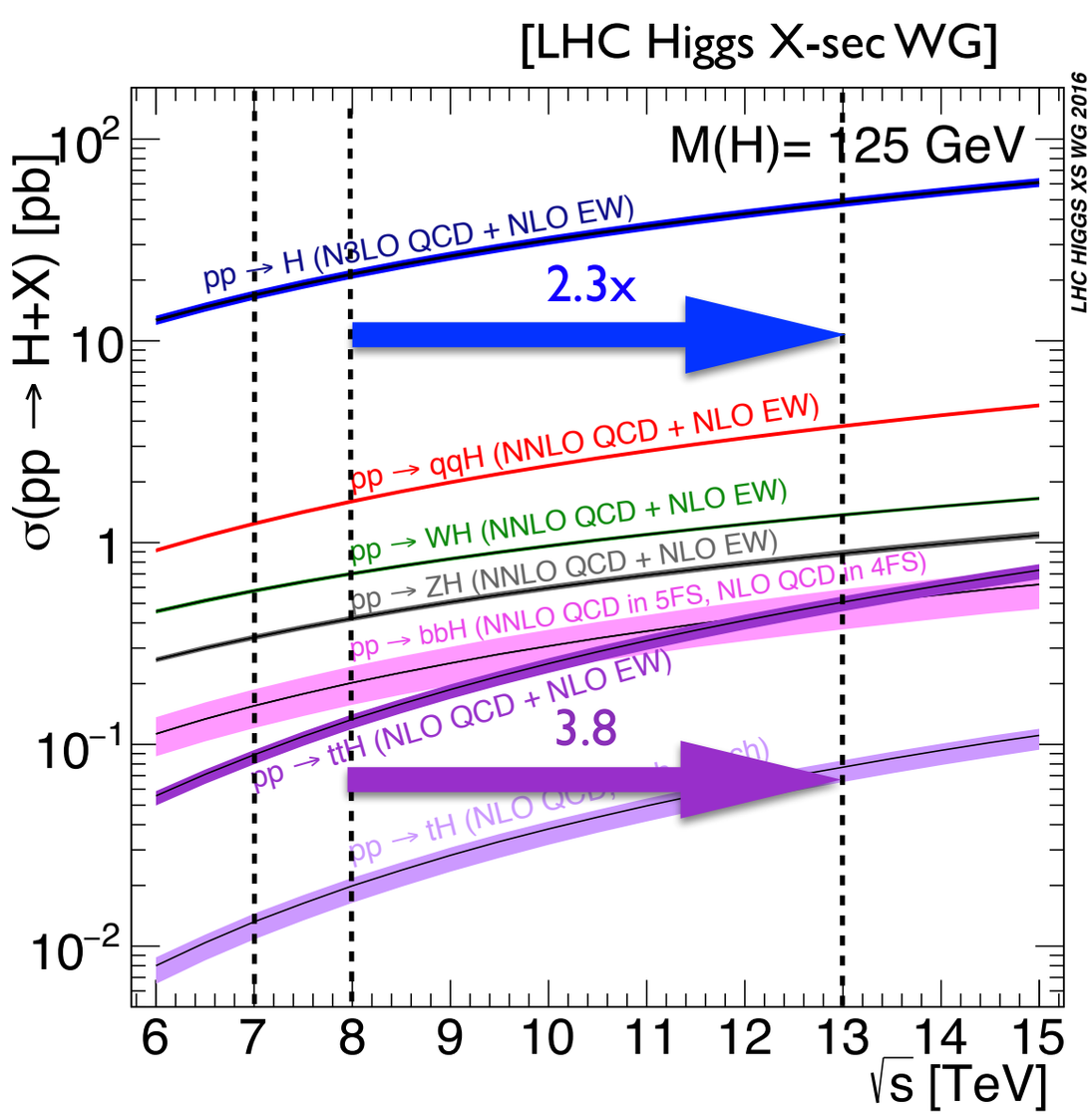
137k

81k

18k

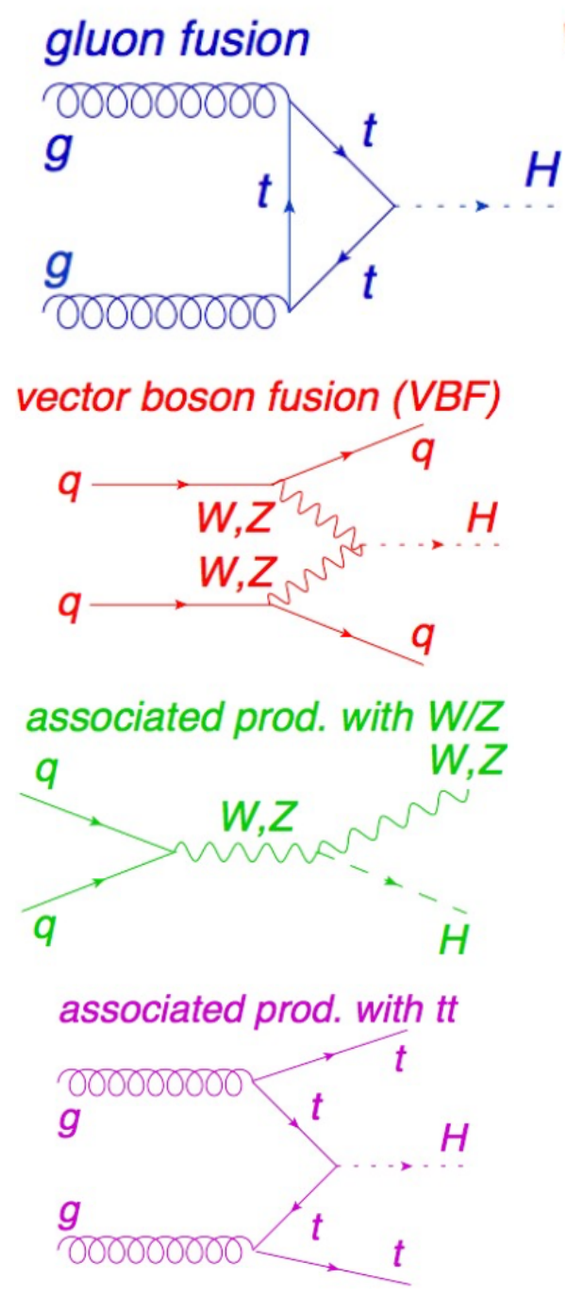
6

Higgs boson production at the LHC



- Significant increase in production rate due to higher center of mass energy from LHC Run-1 to Run-2!

Production modes



Higgs bosons produced in Run 2 (2015+2016)

1.7M

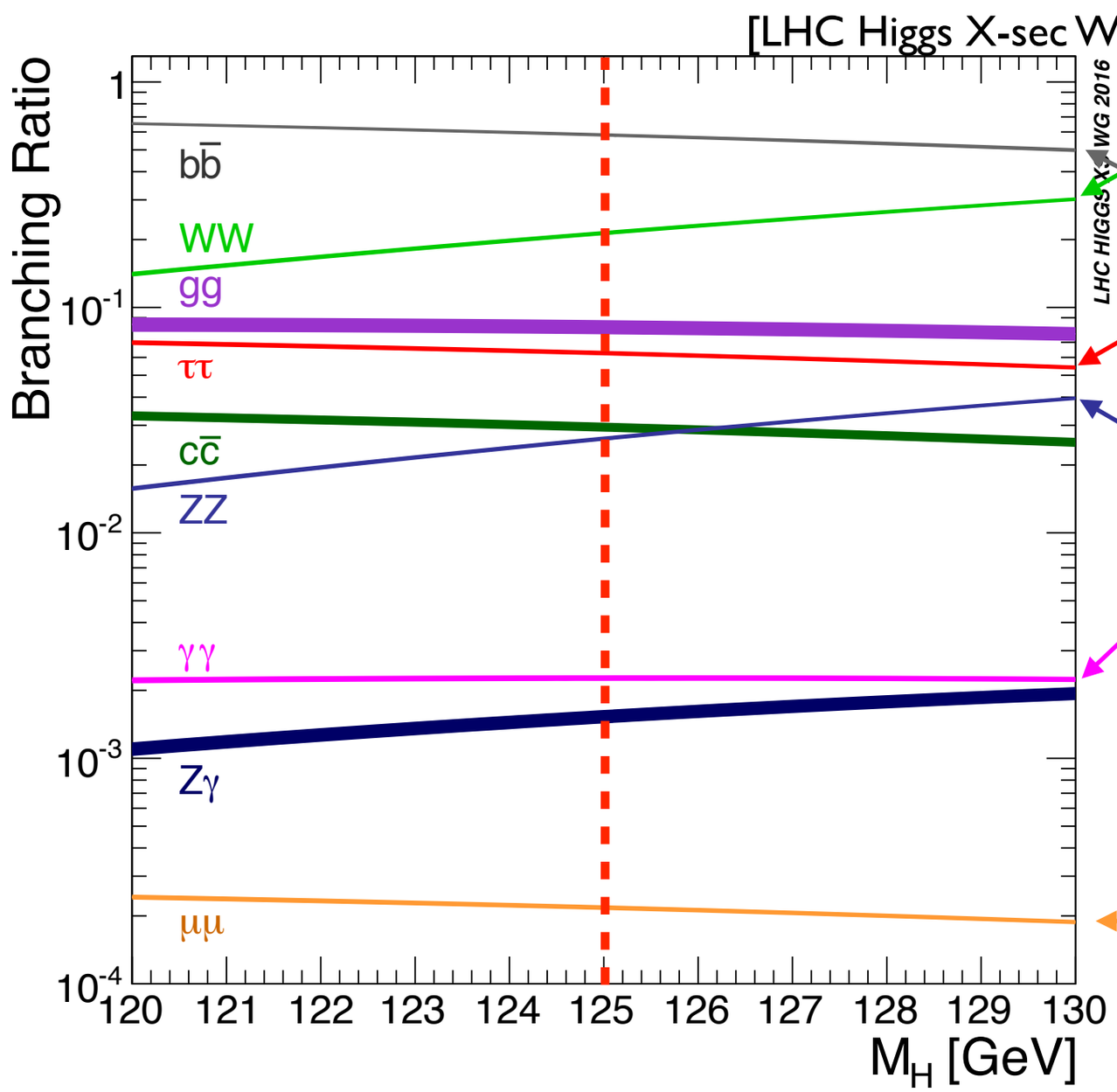
137k

81k

18k

7

How can we identify a Higgs boson?



WW: High BR, but low mass resolution

bb, ττ: high BR, but low S/B, important to directly probe Higgs coupling to fermions

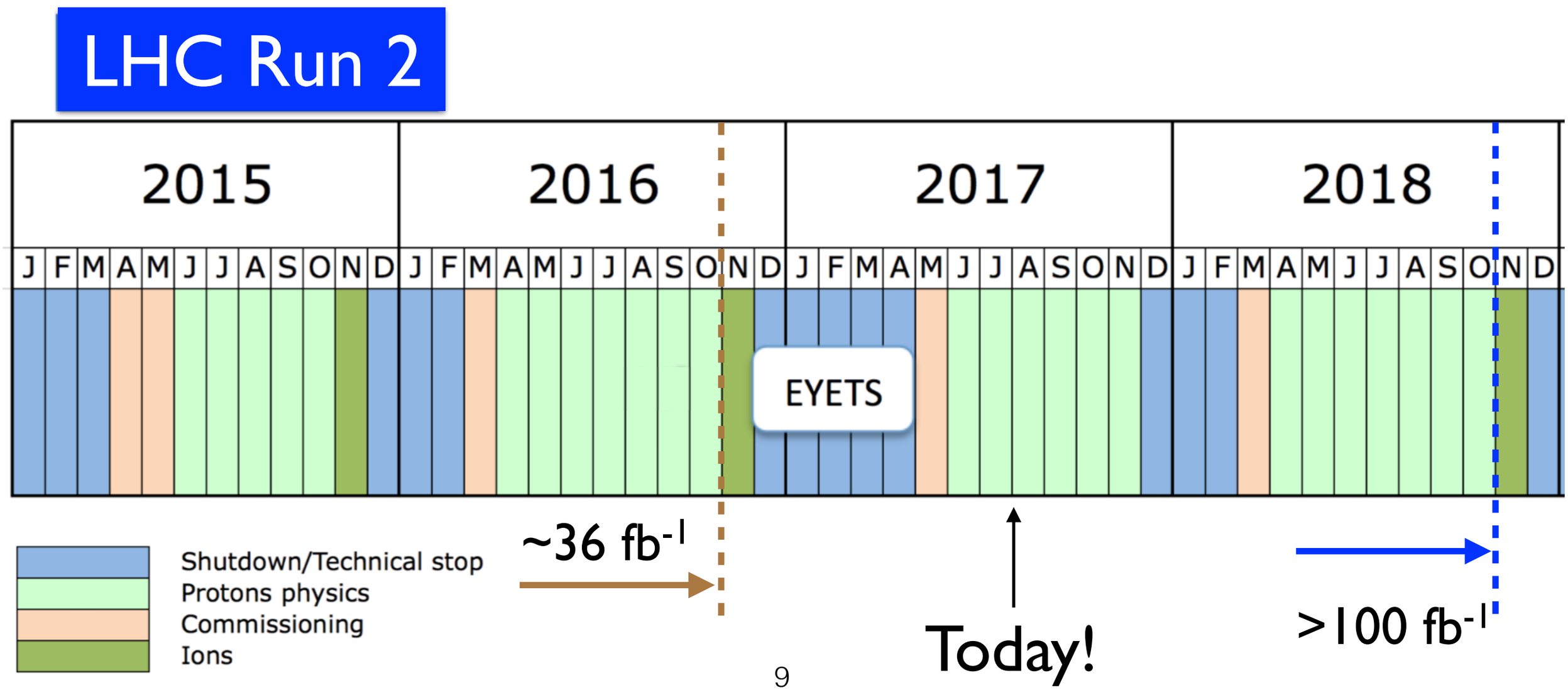
ZZ, γγ (the two discovery channels): high mass resolution channels, with fully reconstructed final states

μμ: very small BR, but gives access to coupling to 2nd generation fermions

- All SM predictions fixed once mass is known (125.09 ± 0.24 GeV from Run-1)
- Any observed deviation in Higgs boson properties would be a sign of New Physics!

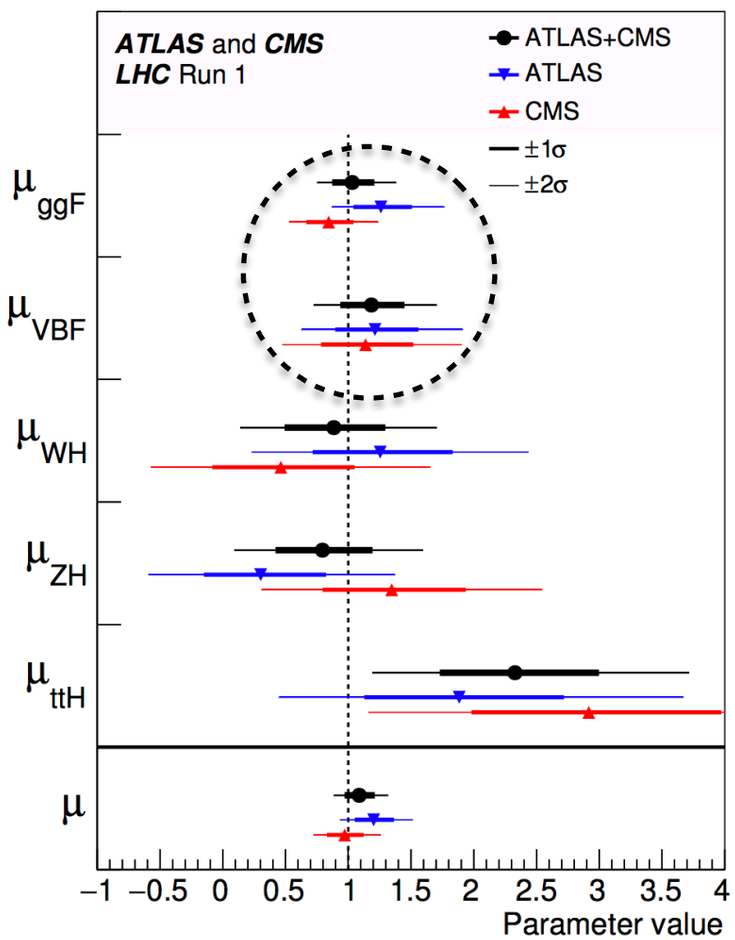
Where are we today?

- LHC Run-1 provided 29 fb^{-1} of pp collision data at $\sqrt{s}$ of 7 and 8 TeV
- The results presented today are based on 36 fb^{-1} of Run-2 data at $\sqrt{s}$ of 13 TeV
  - LHC is running extremely well: already >9 fb^{-1} available for 2017 (not included yet)
  - This is only 1/3 of the data expected by the end of Run 2

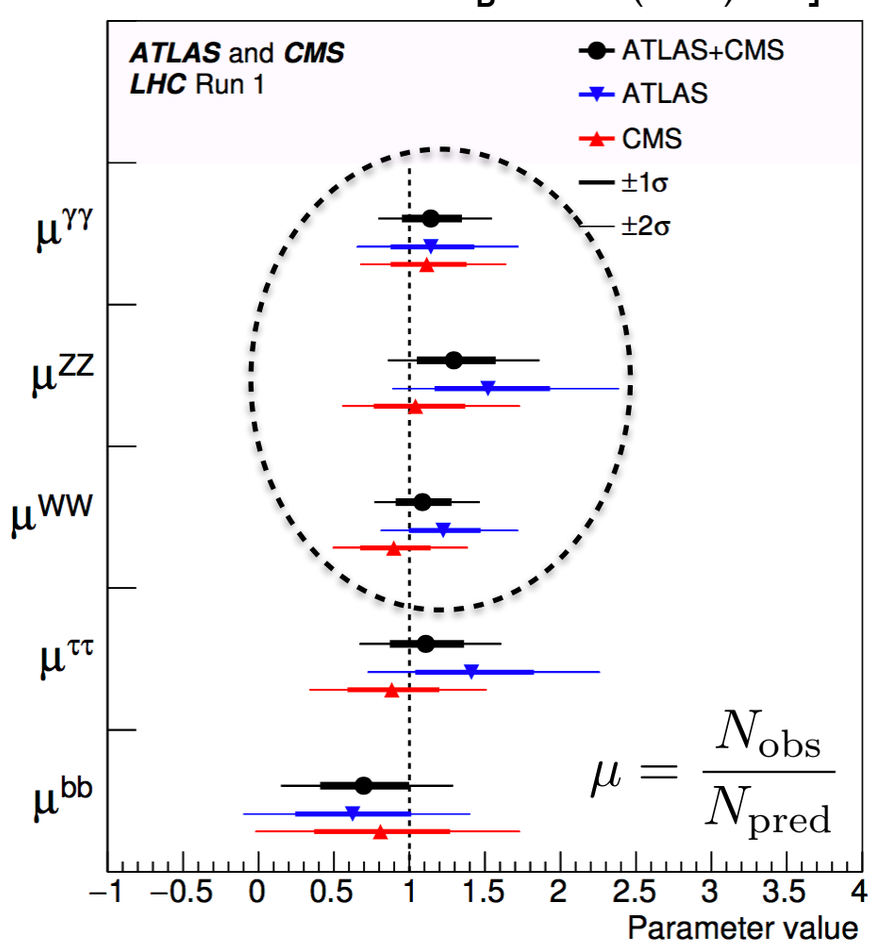


The Run 1 legacy

- Mass determined to 0.2% precision.



[JHEP 08 (2016) 045]



- Observation of gluon fusion and vector boson fusion
- Observation of $H \to ZZ$, $H \to WW$, $H \to \gamma\gamma$
- Coupling to fermions *not fully established*
  - $H \to \tau\tau$ observed through ATLAS+CMS combination
  - $H \to bb$ below 3σ
  - ttH not observed

- Absolute Higgs boson couplings determined with precisions of 10-25%
- Overall cross section $\Delta\sigma \sim 10\%$, first differential distributions measured
- Spin 1 and 2 hypotheses, and additional Spin 0 BSM couplings, excluded at >95% C.L.

The Quest for New Physics

- So far all measurements are compatible with the SM.
- The Standard Model works beautifully, but there are many phenomena it cannot explain!
  - Dark Matter
  - Neutrino masses
  - Large Matter-Antimatter asymmetry observed in the Universe
  - Mass hierarchy
  - Hierarchy problem
  - ....
- However, the expected deviations in Higgs boson couplings depend on the New Physics scale:

$$\frac{g_{HXX}}{g_{HXX}^{SM}} \sim 1 + \delta \cdot \left(\frac{1\ \mathrm{TeV}}{\Lambda_{\mathrm{NP}}} \right)^2$$

with $\delta < 5\%$ (depending on model)

- So for $\Lambda = 1$ TeV, we need to probe Higgs couplings to better than 5%.
- After Run-1 measured within 10-25%… higher precision needed!

New Run 2 results - Highlights!

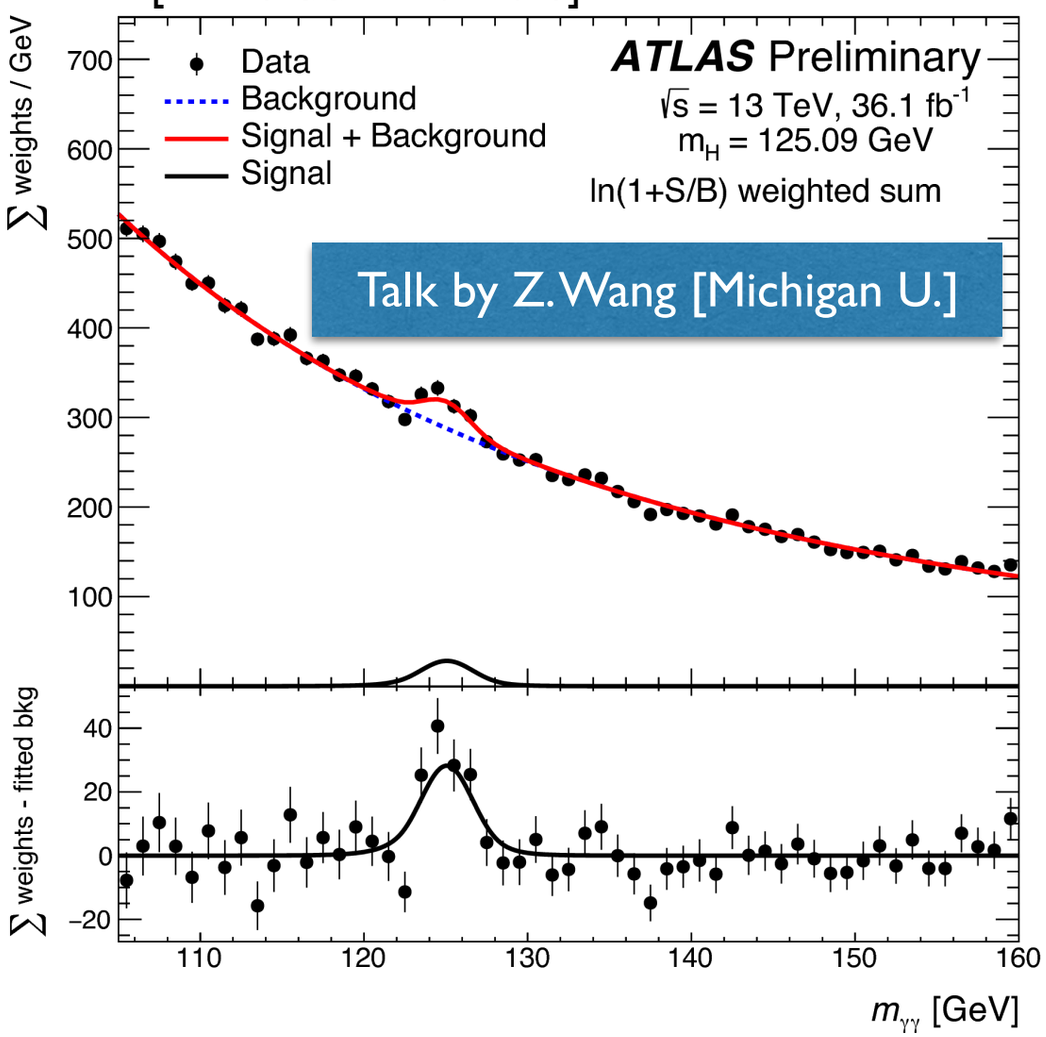
- H → bosons: towards the precision era
  - Cross section, inclusive and differential
  - Mass measurement
  - First "simplified template" cross-section measurements
- H → fermions: direct coupling to fermions
  - Observation of H → ττ
  - Evidence of H → bb
  - ttH production
  - Coupling to 2nd generation fermions
- Double Higgs production: status and prospects

H → bosons: towards the precision era

H → γγ

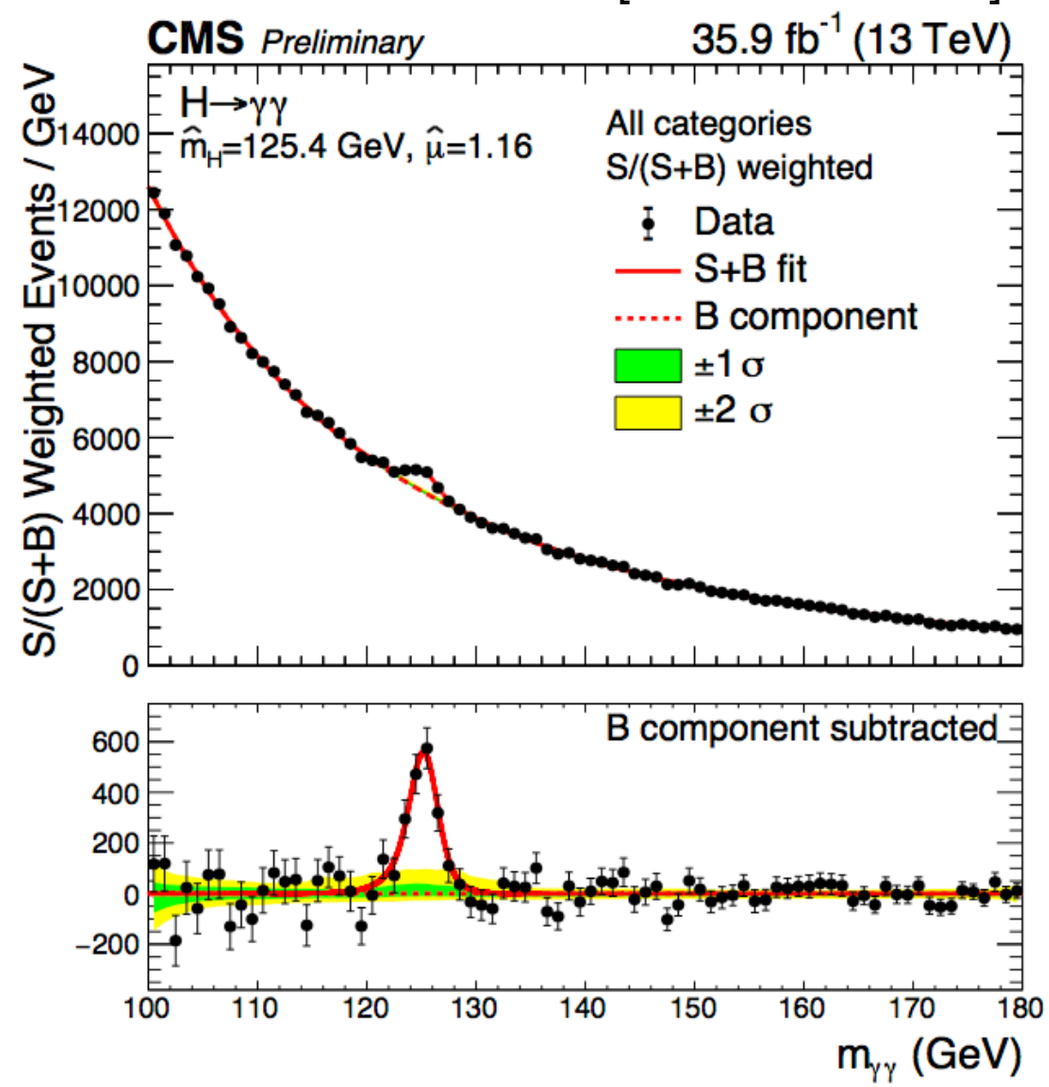
- Fit in 31 (14) categories in ATLAS (CMS) provides improved sensitivity, including to different production modes

[ATLAS-CONF-2017-045]



$$\mu = 0.99\,^{+0.14}_{-0.14} = 0.99\,^{+0.12}_{-0.11}\,(\text{stat.})\,^{+0.06}_{-0.05}\,(\text{exp.})\,^{+0.06}_{-0.05}\,(\text{theory})$$

[CMS PAS HIG-16-040]

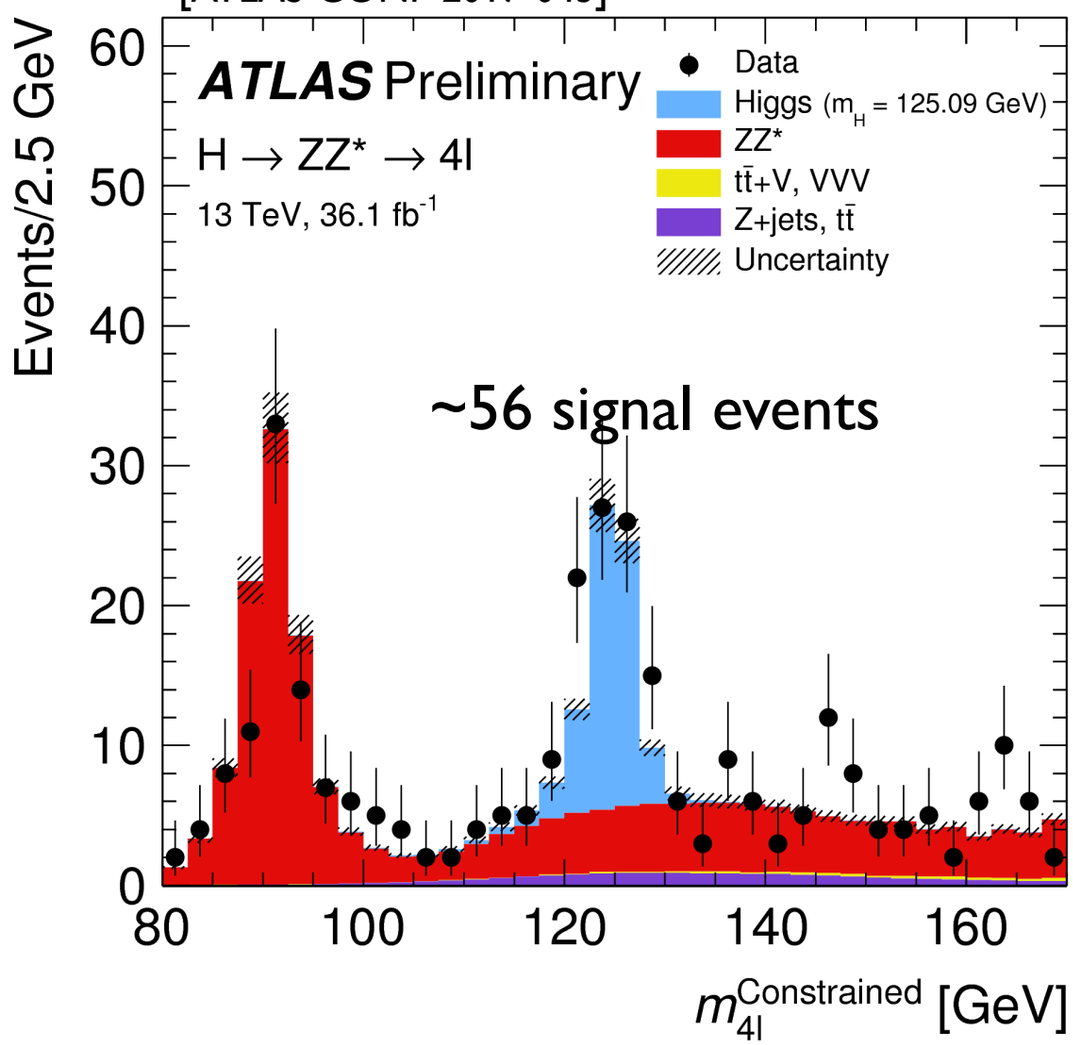


$$\mu = 1.16^{+0.15}_{-0.14} = 1.16^{+0.11}_{-0.10}(\text{stat})^{+0.09}_{-0.08}(\text{exp})^{+0.06}_{-0.05}(\text{theo})$$

- Uncertainty on μ reduced by a factor of 2 with respect to Run 1 (compatible with increase in statistics by almost a factor of 4)

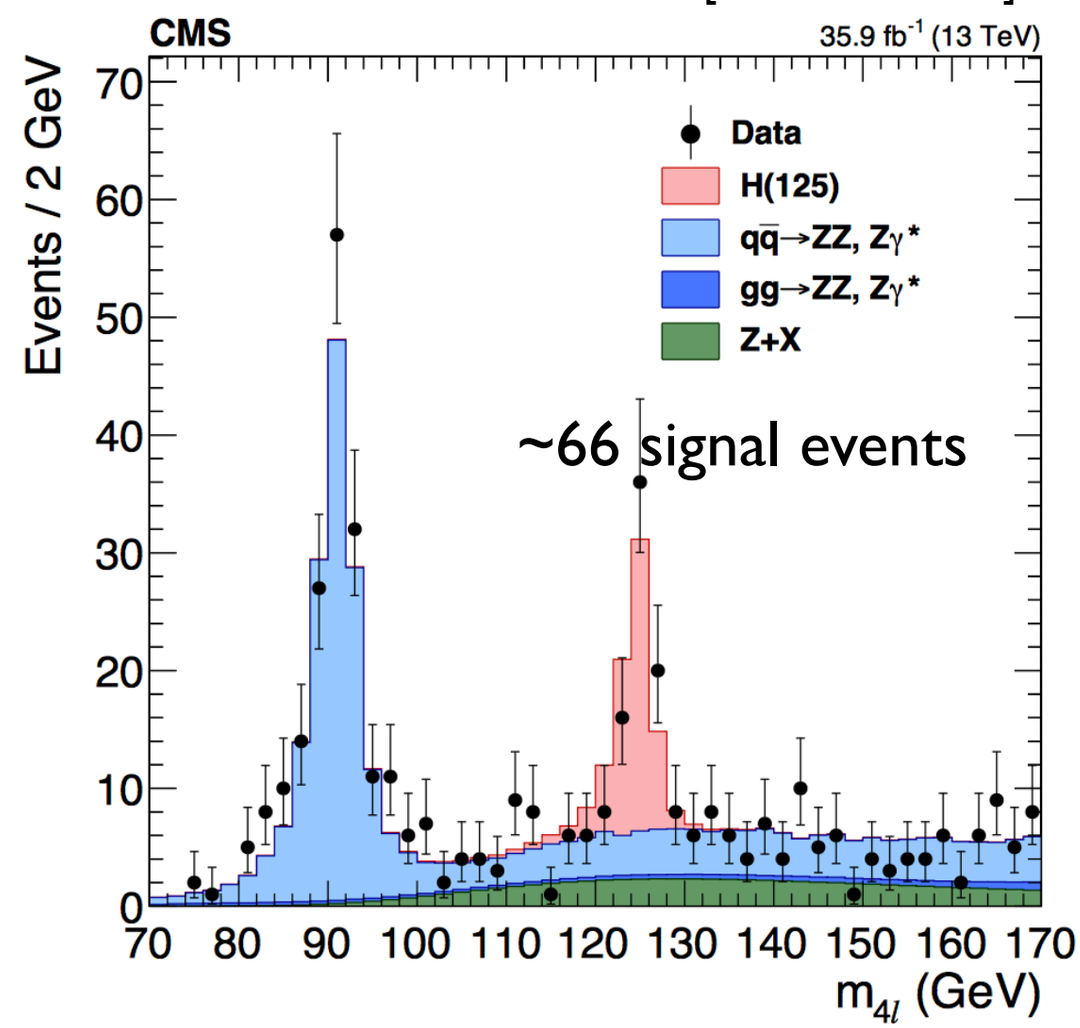
H → ZZ* → 4 leptons

[ATLAS-CONF-2017-043]



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

[arXiv:1706.09936]

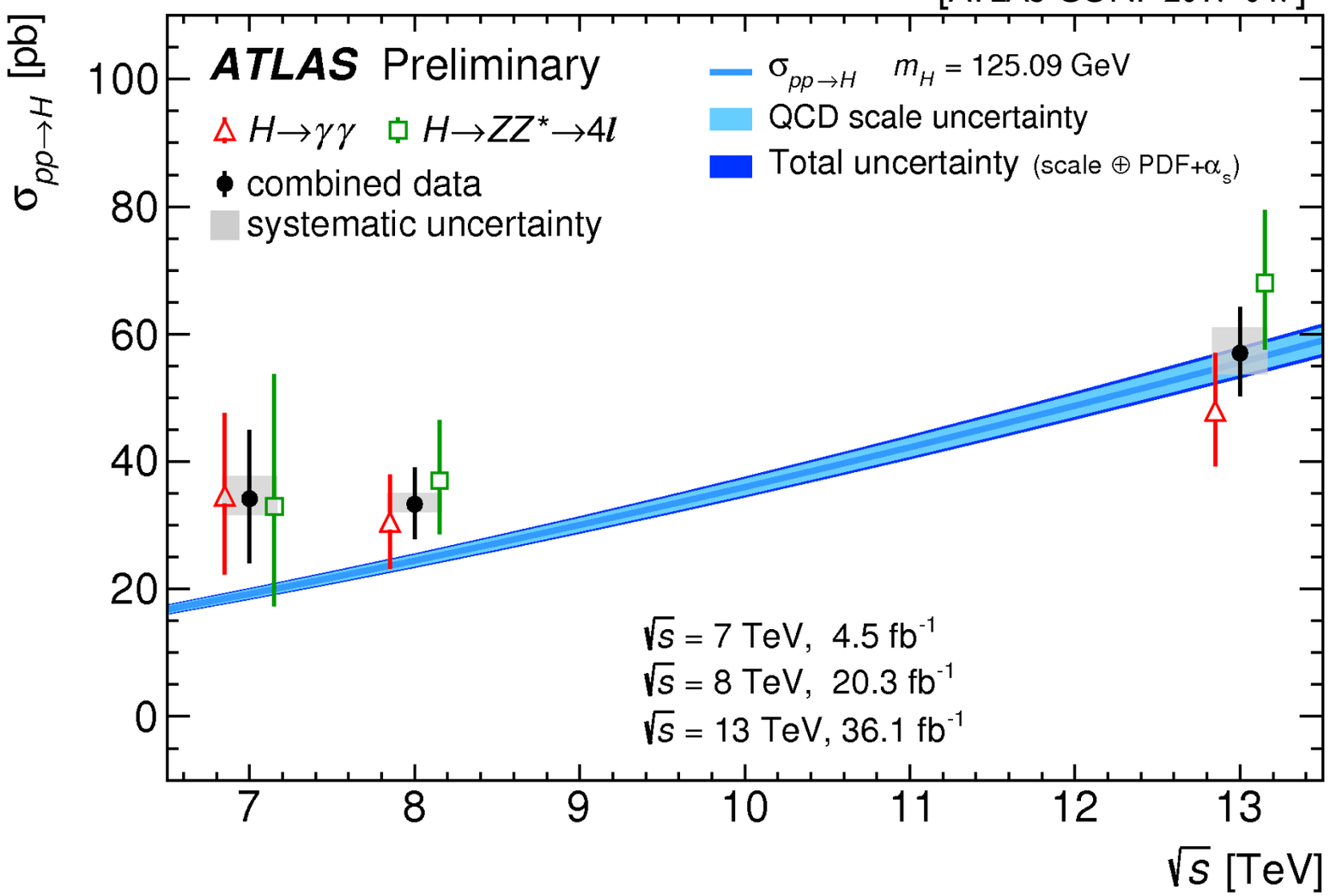


$$\mu = 1.05^{+0.15}_{-0.14}(\text{stat})^{+0.11}_{-0.09}(\text{syst})$$

- Low Signal yield, but S/B ~ 2
- Again, uncertainty on signal strength reduced by nearly factor ~2 with respect to Run I

H → γγ and H → ZZ* combination

[ATLAS-CONF-2017-047]

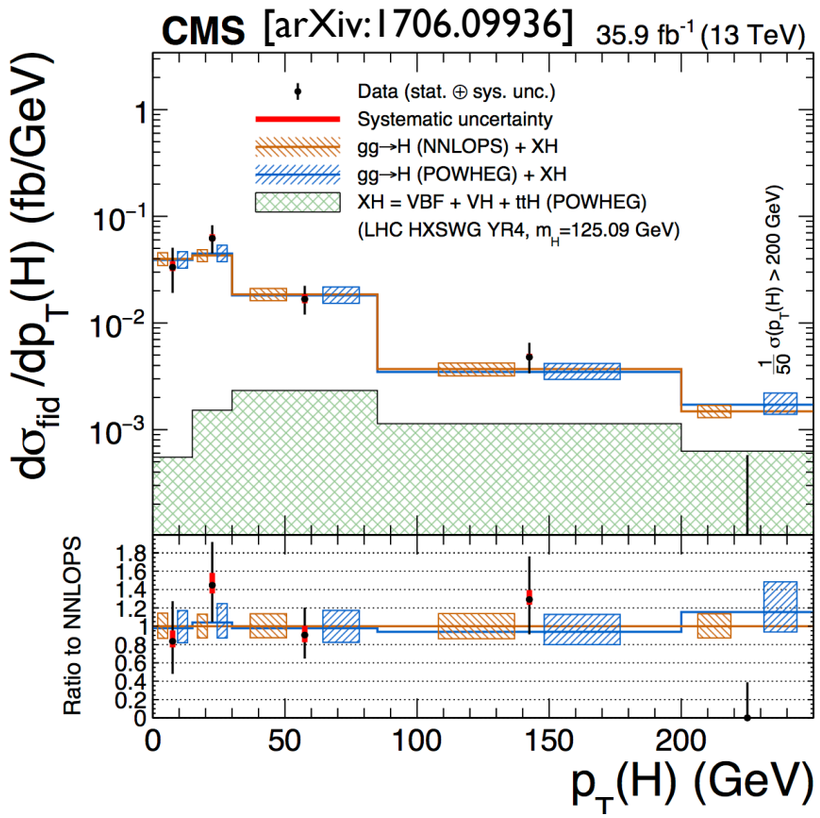


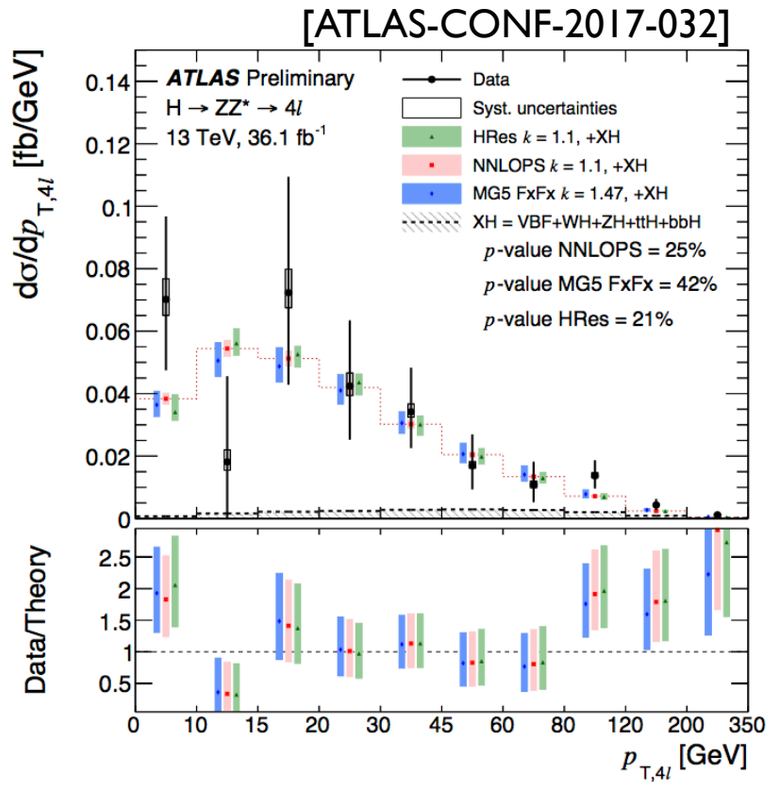
Talk by H.Yang (LBNL)

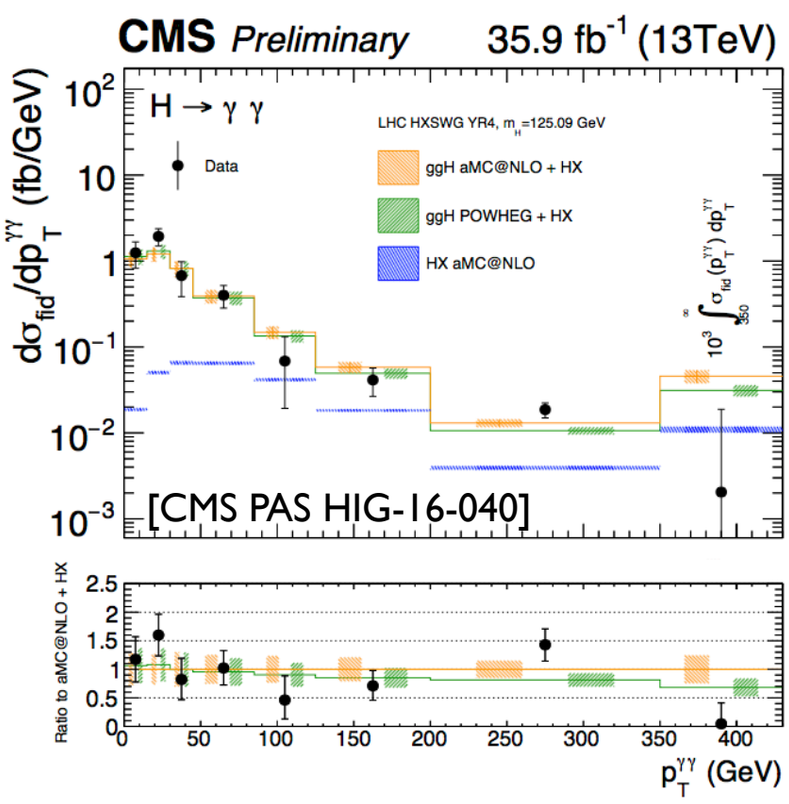
- Total cross section for pp —> H + X determined to be: $57.0^{+6.0}_{-5.9}$ (stat.) $^{+4.0}_{-3.3}$ (syst.) pb
  - Still compatible with theory prediction: $55.6^{+2.4}_{-3.4}$ pb !
- Experimental uncertainty is ~12%, theory uncertainty is ~5% (thanks to N³LO + PDF4LHC)
  - Experimental uncertainty will improve further (combination with CMS, other channels, more data)

"Higgs-boson physics @ LHC: from discovery to precision" L. Reina

Differential measurements

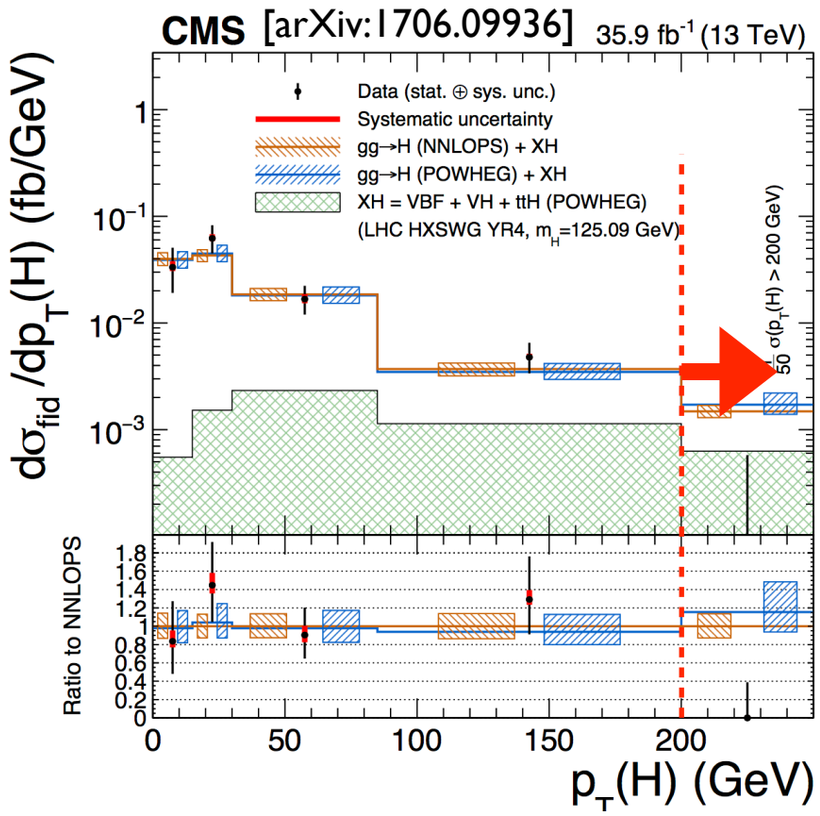


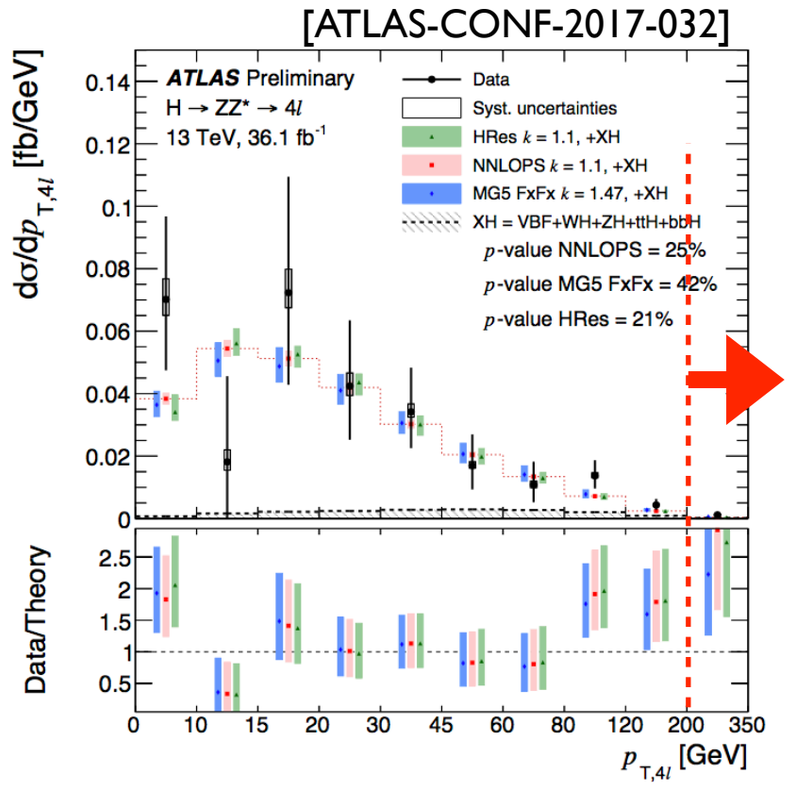


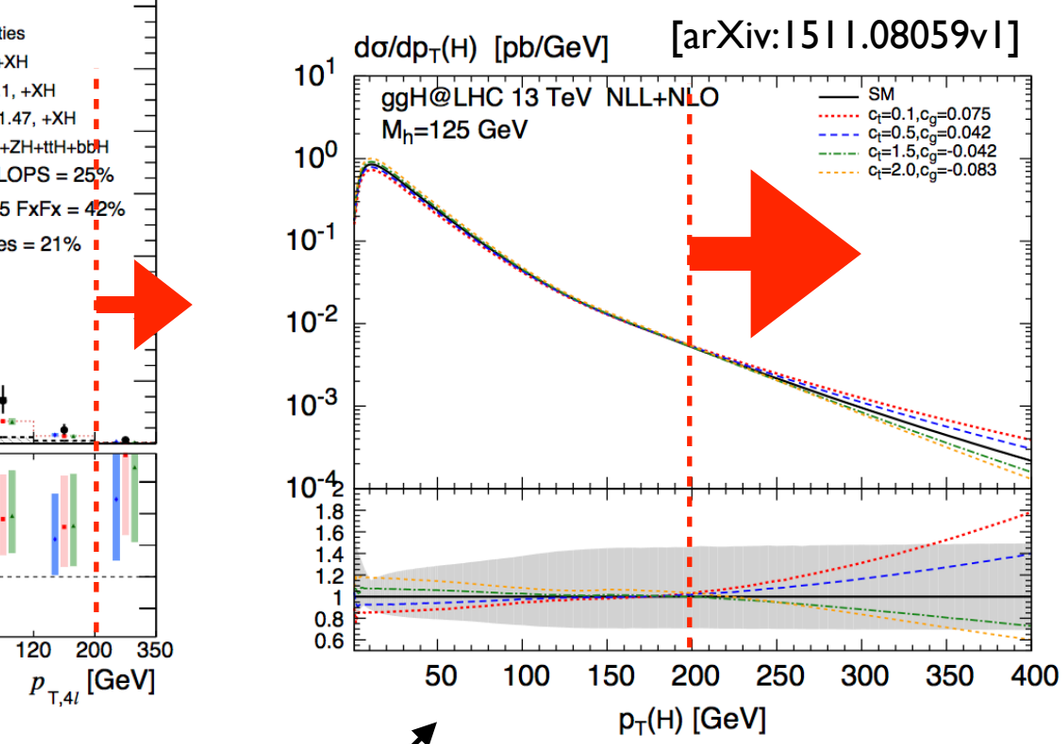


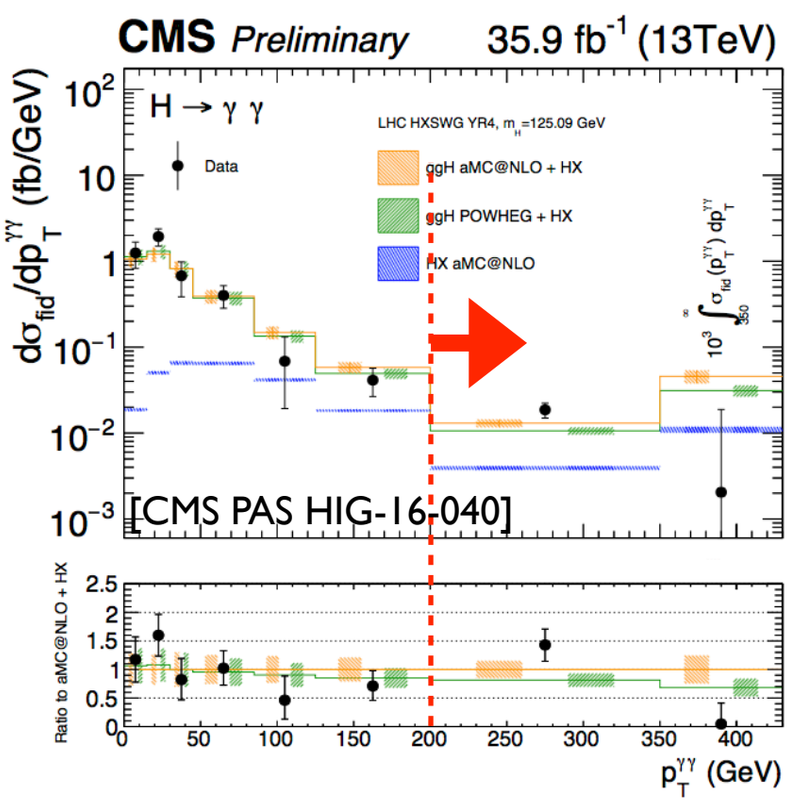
- In general good agreement between theory and experiment, precision significantly increased w.r.t. Run 1.

Differential measurements

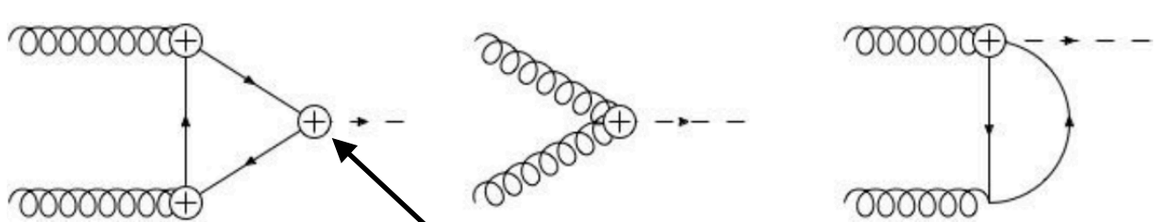








- In general good agreement between theory and experiment, precision significantly increased w.r.t. Run 1.
- The high pT(H) region most interesting, can be enhanced by new physics contributions [M. Grazzini et al.]:

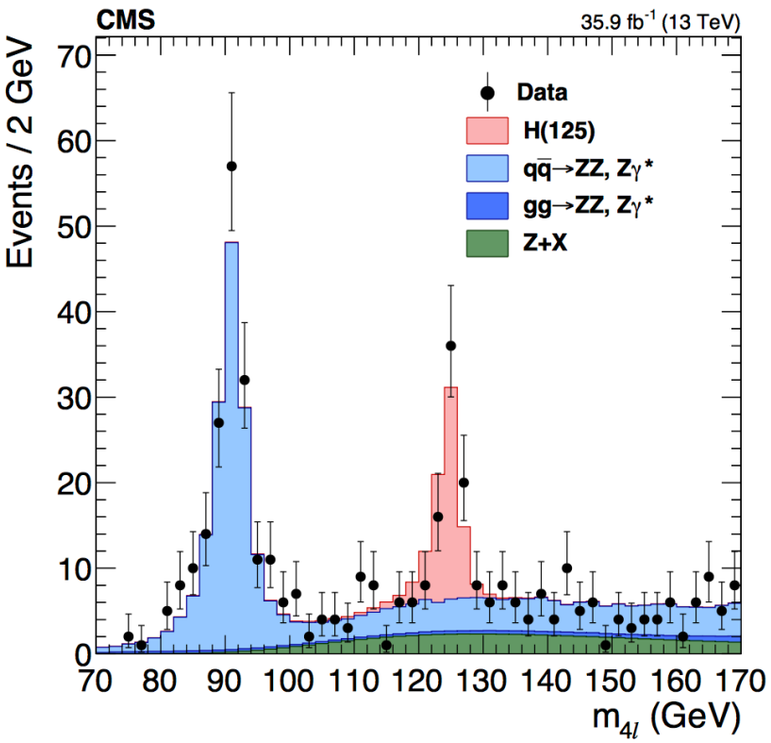


insertion of 6-dim operator

Mass measurement

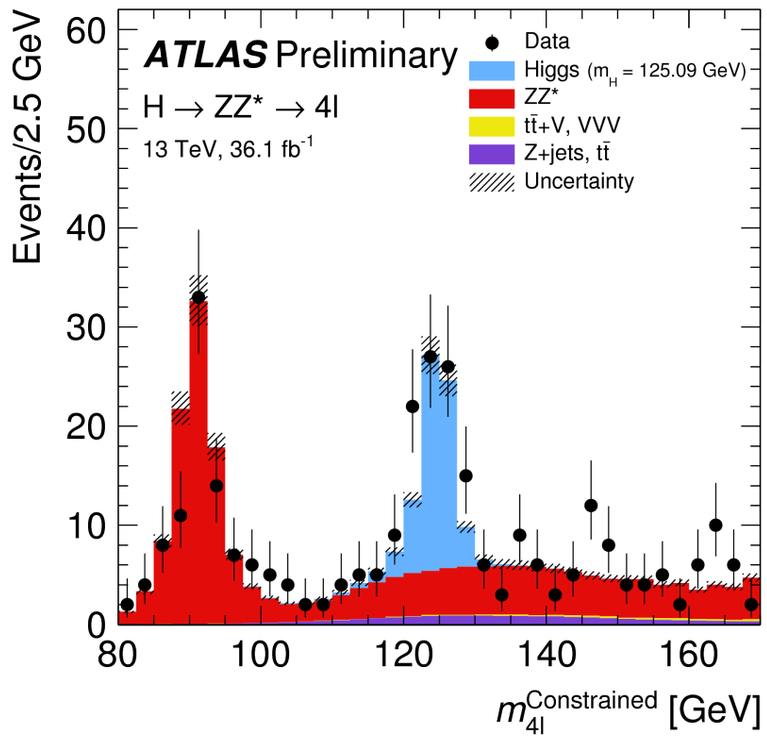
Mass measurement

$H \to ZZ^*$



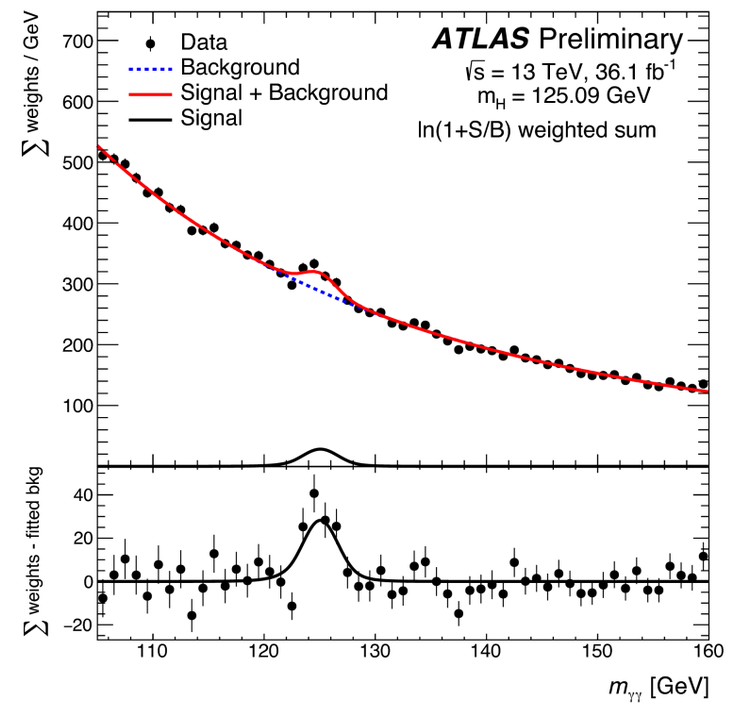
$125.26 \pm 0.20\ (\text{stat}) \pm 0.08\ (\text{syst})$ (GeV)

$H \to ZZ^*$



$124.88 \pm 0.37\ (\text{stat}) \pm 0.05\ (\text{syst})$

$H \to \gamma\gamma$



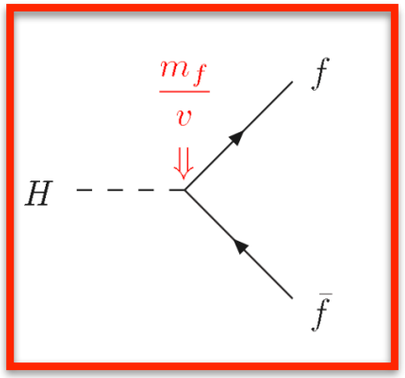
$125.11 \pm 0.21\ (\text{stat}) \pm 0.36\ (\text{syst})$

ATLAS comb.

$124.98 \pm 0.19\ (\text{stat.}) \pm 0.21\ (\text{syst.})$ (GeV)

- Both experiments now use per-event mass errors in H → ZZ* to improve mass resolution.
- Both results alone are compatible and already competitive with the ATLAS+CMS Run 1 result
  - 125.09 ± 0.21 (stat) ± 0.11 (syst) GeV

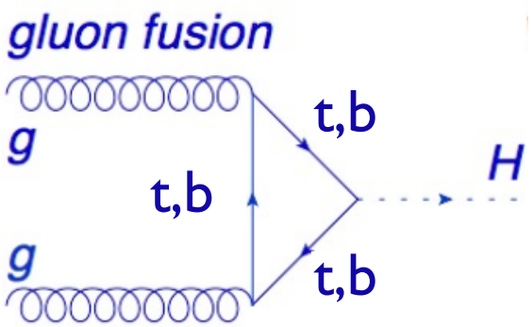
Coupling to fermions



Higgs boson coupling to fermions (Run-1)

Indirect probe (loop-induced)

$gg \to H$ Observed!



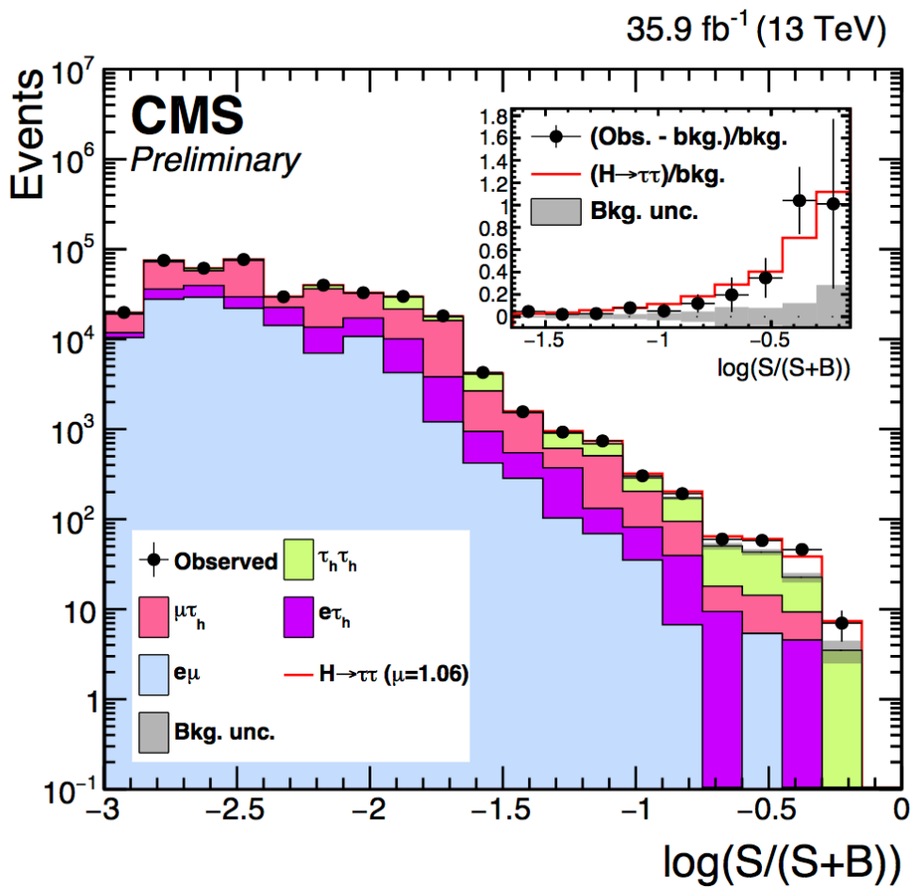
Direct probe (tree-level)

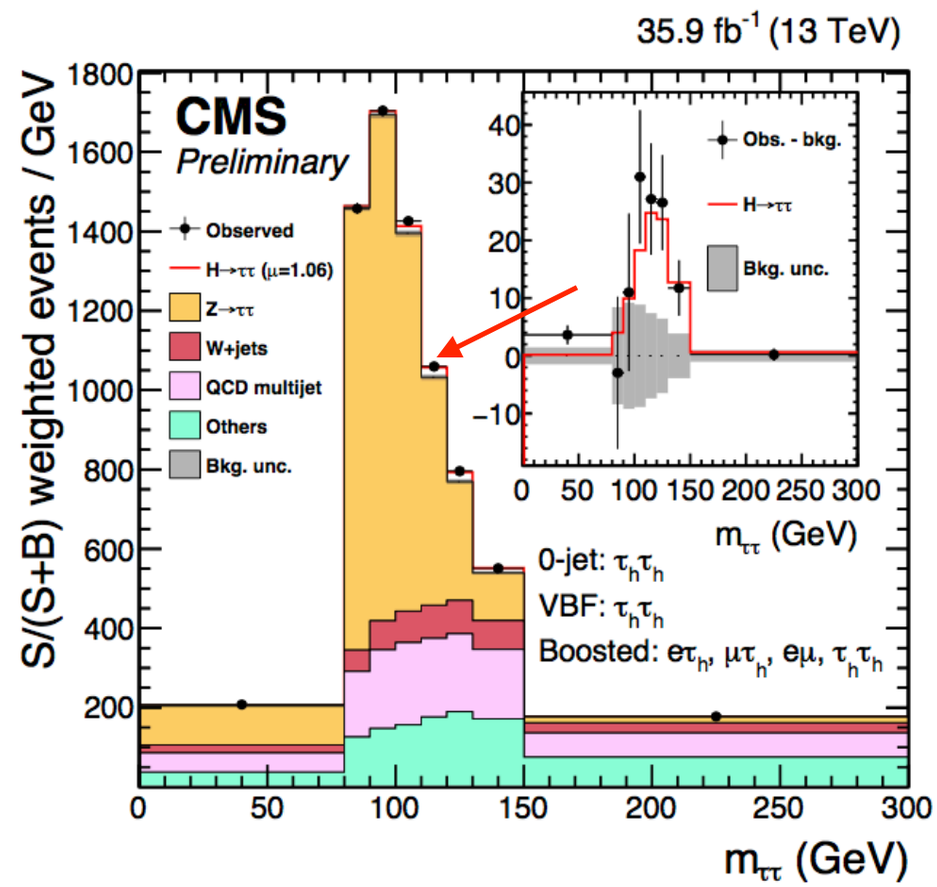
$H \to \tau\tau$	Observed!	(leptons)
$H \to b\bar{b}$	*Not observed yet*	(down-type quarks)
$gg \to t\bar{t}H$	*Not observed yet*	(up-type quarks)

[only 3rd generation fermions highlighted here]

[CMS-PAS-HIG-16-043]

Observation of H → ττ



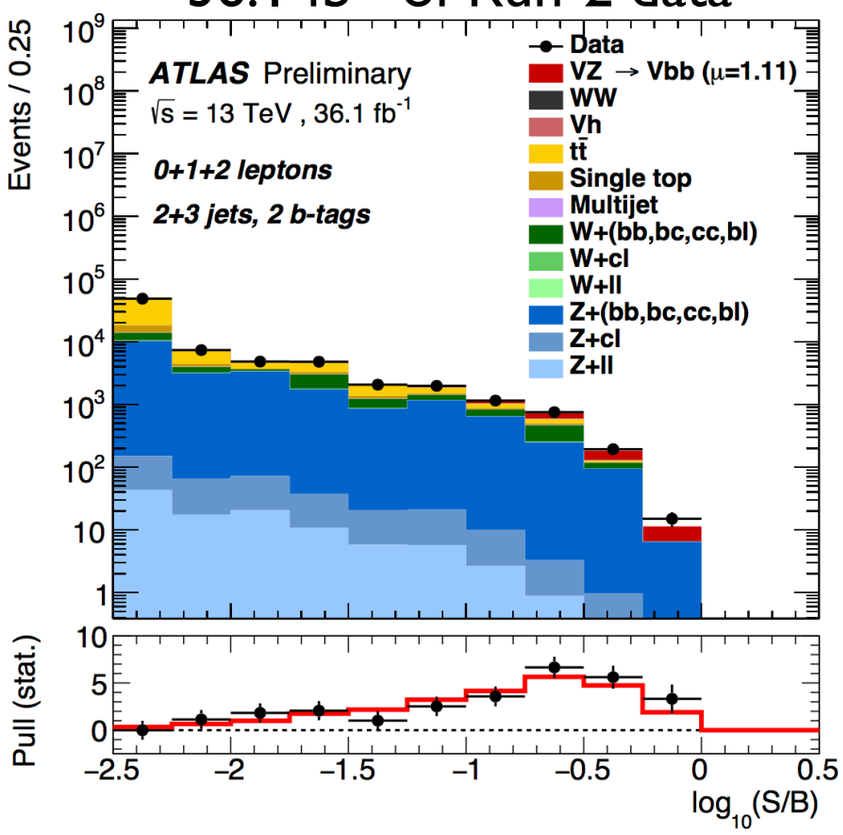


- Fit to 3 categories (0-jet, boosted, VBF) x 4 channels (eμ ,eτ_h, τ_h, $\tau_h\tau_h$)
  - 2D discriminant for signal extraction: ($m_{\tau\tau}$) x (τ decay mode, $p_T(\tau\tau)$, m_{jj})
- Run 2 significance: **4.9σ** (4.7σ expected), signal strength: $\mu = 1.06^{+0.25}_{-0.24}$
- First single experiment observation through combination with Run 1: **5.9σ**.

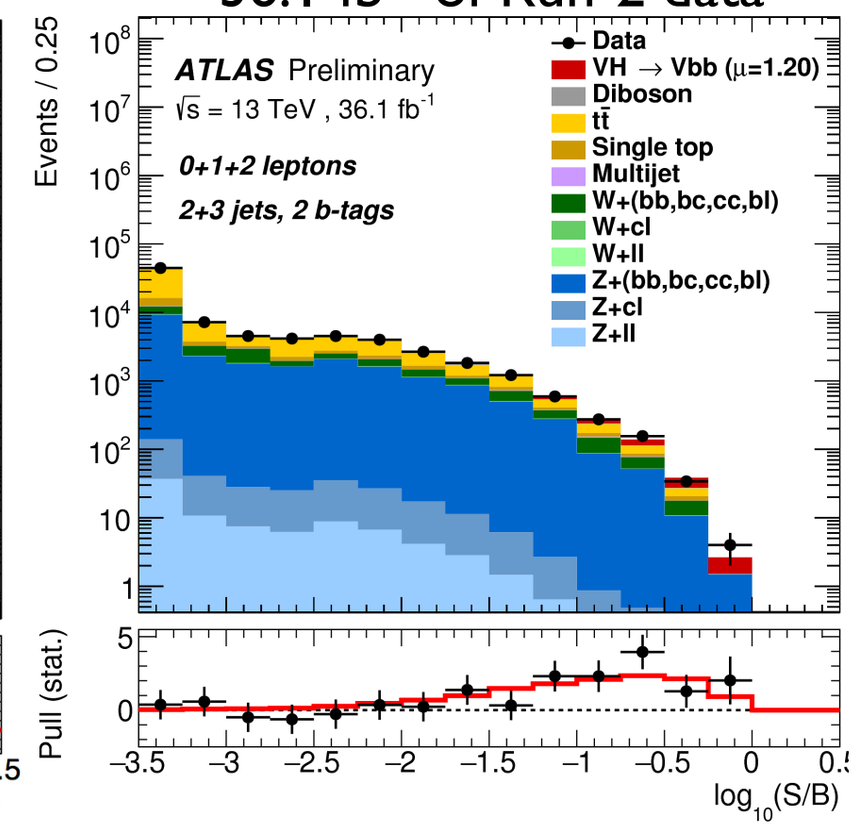
[ATLAS-CONF-2017-041]

Evidence for H → bb

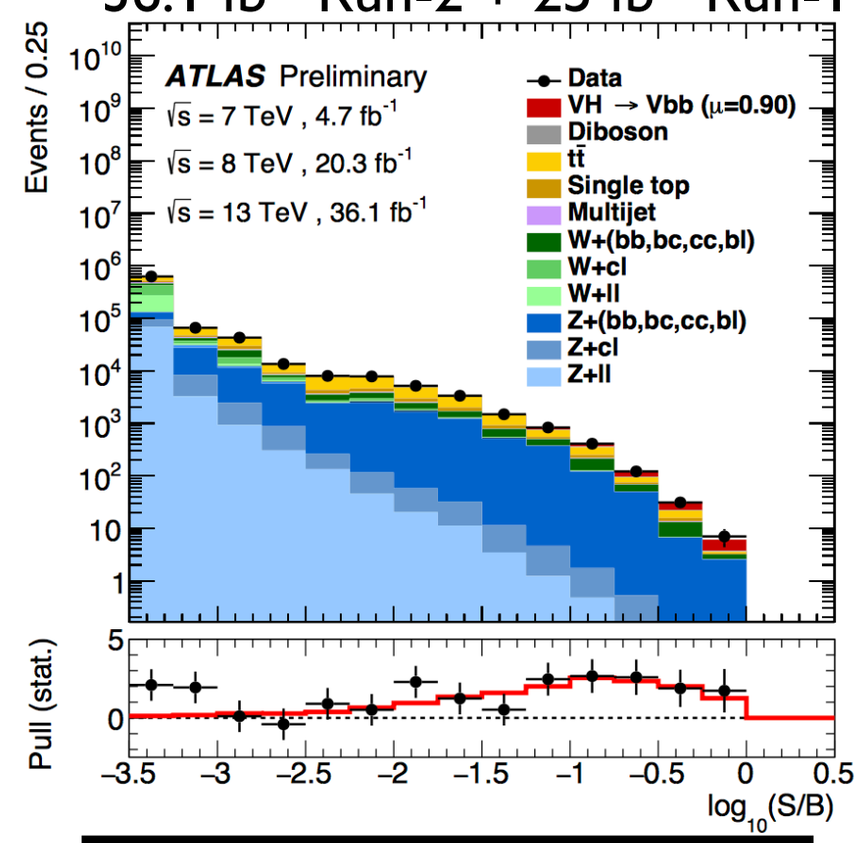
36.1 fb^{-1} of Run-2 data



36.1 fb^{-1} of Run-2 data



36.1 fb^{-1} Run-2 + 25 fb^{-1} Run-1



VZ, Z → bb: $\mu = 1.11^{+0.25}_{-0.24}$
5.8σ (5.3σ expected)

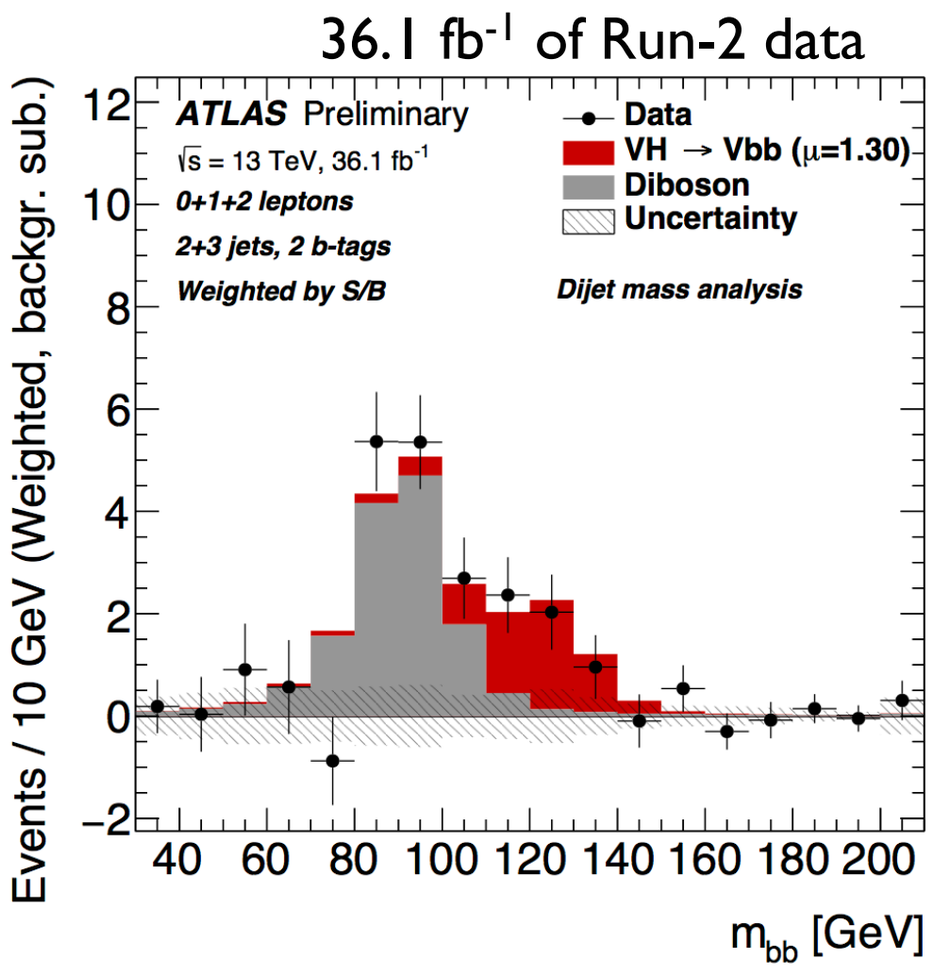
VH, H → bb: $\mu = 1.20^{+0.42}_{-0.36}$
3.5σ (3.0σ expected)

VH, H → bb: $\mu = 0.90^{+0.28}_{-0.26}$
3.6σ (4.0σ expected)

- Fit to 3 channels (0-, 1-, 2-lepton) targeting associated VH production at high $p_T(V)$
  - Multi Variate Analysis (BDT) based on m(bb), $p_T(V)$, ΔR(bb) as most important variables
- First evidence for H → bb at the LHC!
  - Previously evidence reported at Tevatron (2.8σ @ m_H=125 GeV, 3.1σ global, 1.5σ exp.)

[ATLAS-CONF-2017-041]

Evidence for H → bb



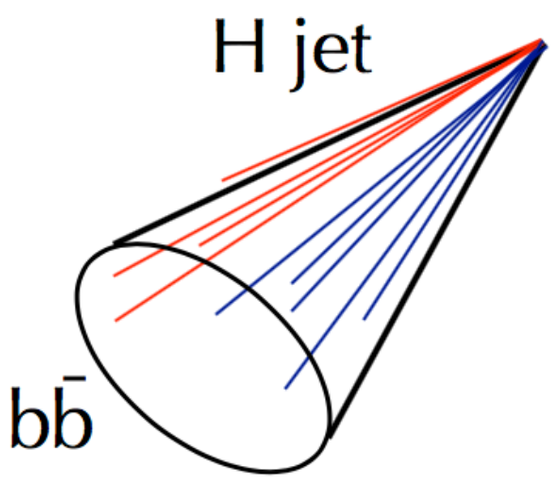
- Validated with m(bb) based analysis
  - 3.5σ evidence (2.8σ expected)
- Both VZ, Z → bb and VH, H → bb peaks clearly visible!

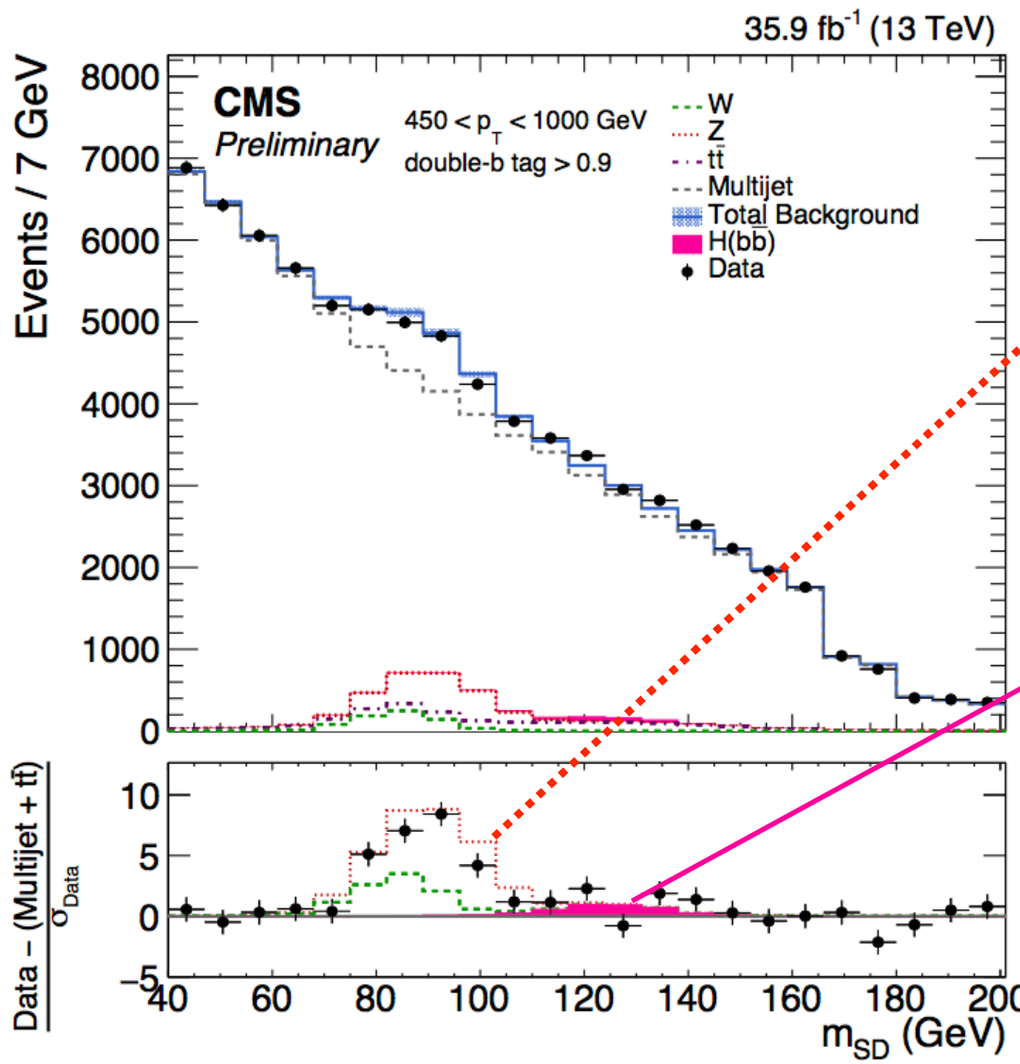
Talk by J. Duarte (Fermilab)

[CMS-PAS-HIG-17-010]

Inclusive H → bb

- Look for ggF, H → bb with $p_T(H)$ > 450 GeV (particularly sensitive to BSM physics!)





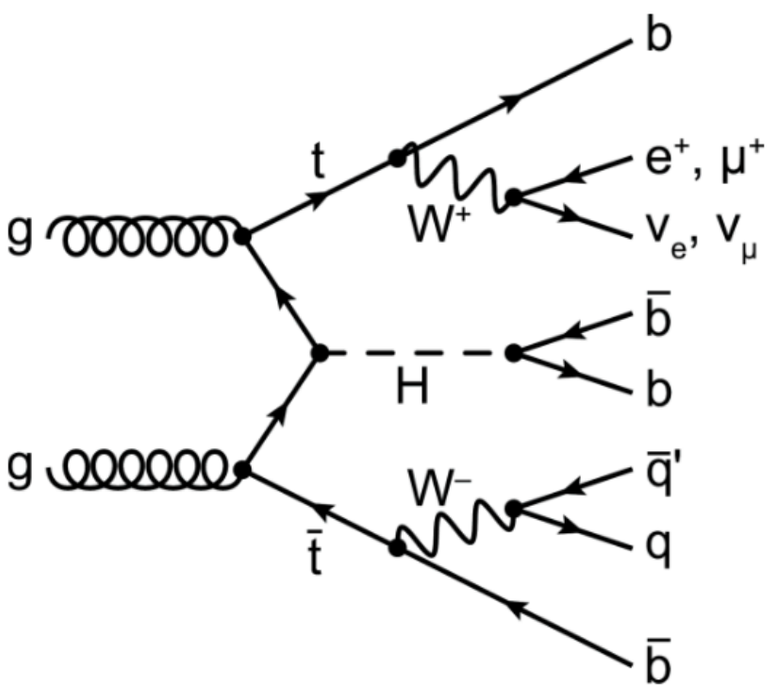
Z → bb: $\mu_Z = 0.78^{+0.23}_{-0.19}$
5.1σ (5.8σ expected)

ggF, H → bb: $\mu_H = 2.3^{+1.8}_{-1.6}$
1.5σ (0.7σ expected)

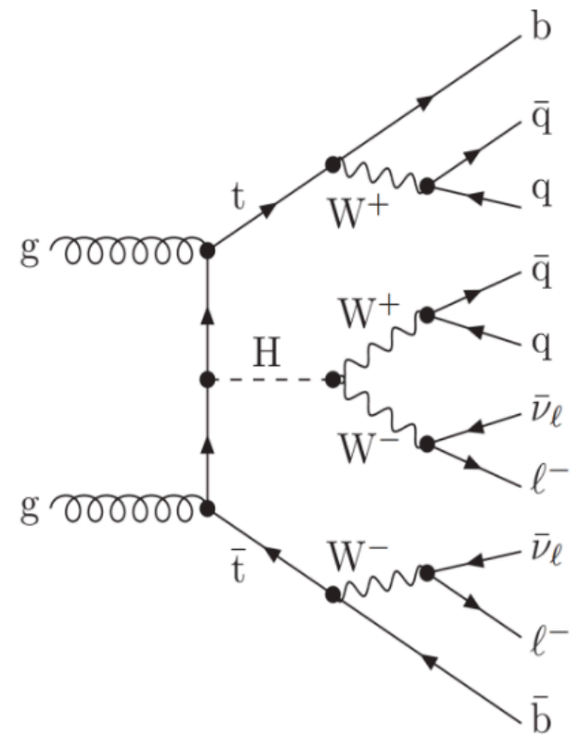
- Reconstruct Z/H → bb in a single R=0.8 AntiKt jet (remove soft activity, require a 2-prong decay, require double b-tagging)
- Clear observation of Z → bb peak! Demonstrates new technique to look for inclusive H → bb, and potential to extend differential measurements to pT(H)>450 GeV!

Measuring ttH production

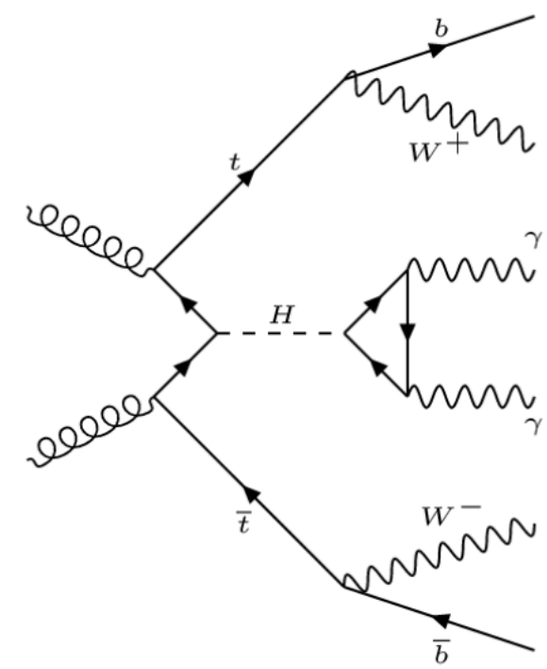
- Access production mode by measuring as many decays as possible:



$H \to b\bar{b}$



$H \to W^+W^-$
$H \to \tau\tau$
(multi-leptons)



$H \to \gamma\gamma$
$H \to ZZ$

Higher σ x BR

Higher purity

Run-2 ttH results

incomplete dataset (~13 fb^{-1})

	ATLAS		CMS	
	Signal strength	**Signif. obs (exp.)**	**Signal strength**	**Signif. obs (exp.)**
$H \to b\bar{b}$	$2.1^{+1.0}_{-0.9}$	2.3σ (1.2σ)	-0.2 ± 0.8	<0σ
multi-leptons	$2.5^{+1.3}_{-1.1}$	2.2σ (1.0σ)	1.5 ± 0.5	3.3σ (2.5σ)
1 or 2 τ_h + X			$0.7^{+0.6}_{-0.5}$	1.4σ (1.8σ)
$H \to \gamma\gamma$	0.5 ± 0.6	1.0σ (1.8σ)	$2.2^{+0.9}_{-0.8}$	3.3σ (1.5σ)
$H \to ZZ$	<6.9@95% CL	~0σ	$0.0^{+1.2}_{-0.0}$	≤0σ

- The ATLAS+CMS Run-1 combination left us with a signal strength of $2.3^{+0.7}_{-0.6}$ (4.4σ obs.)
- Run-2 analyses not yet all completed, but seem to hint at the presence of a ttH signal

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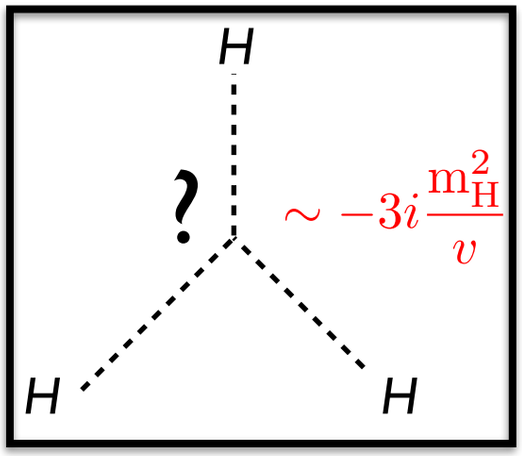
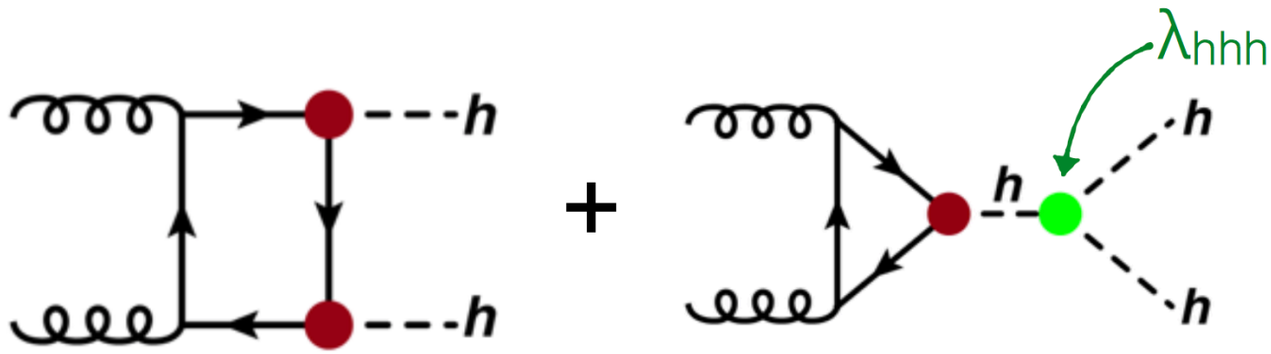
- Run-2 analyses not yet all completed, but seem to hint at the presence of a ttH signal
  - Several analyses already with expected sensitivity close or above 2σ.

Di-Higgs production



Di-Higgs production

SM



$$\sigma(gg \to h) = 48.5 \text{ pb}$$

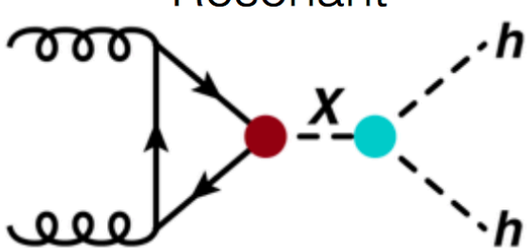
~1/1500

$$\sigma(gg \to hh) = 33.5 \text{ fb}$$

[Higgs Xsec WG Report 4]

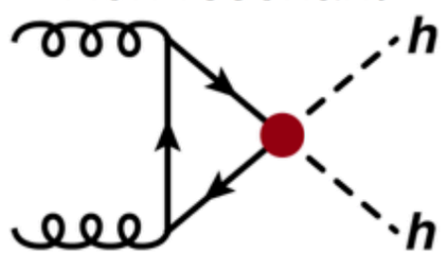
BSM

Resonant



KK gravitons, heavy higgs, …

Non-resonant



tthh vertex, coloured scalars, …

Where to look for Di-Higgs production?

hh decay branching ratios

bbbb	bbWW	bbττ	bbγγ
34%	25%	7%	0.26%
			WWγγ
			0.1%

Higher σ x BR

Higher purity

Di-Higgs production in Run-2

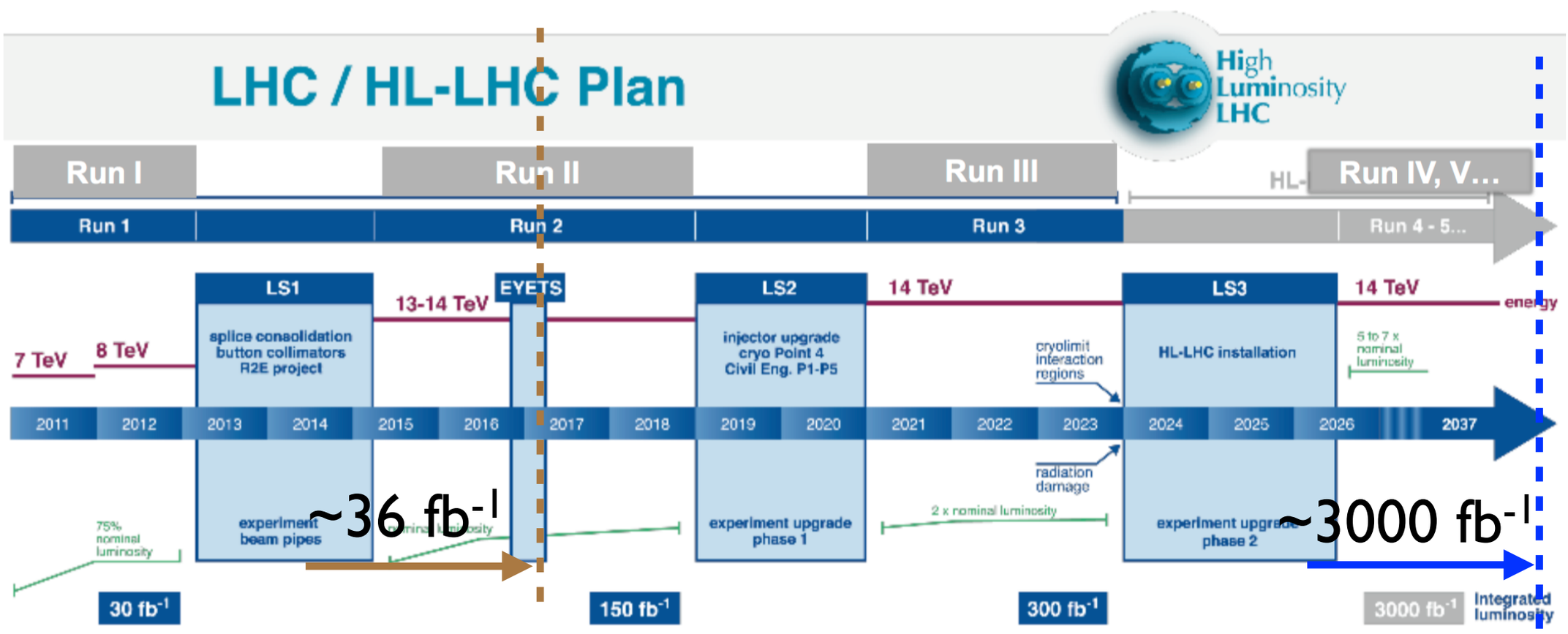
Limits on SM Di-Higgs production @ 95% CL	ATLAS	CMS
$HH \to bbbb$	< 29 (38)	<342 (308)
$HH \to bbWW$	Talk by B. Tannenwald (Ohio State U.)	< 79 (89)
$HH \to bb\tau\tau$		< 30 (25)
$HH \to bb\gamma\gamma$	< 116 (161)	< 19 (17)
$HH \to WW\gamma\gamma$	< 746 (385)	

complete dataset (~36 fb^{-1})
incomplete dataset (~13 fb^{-1})
incomplete dataset (~3 fb^{-1})

- Soon reaching x10 SM sensitivity (HH → bbγγ and HH → bbbb most promising)
- Important milestone to demonstrate sensitivity to Higgs self-coupling with ~3000 fb^{-1} (HL-LHC)

Conclusions

- Thanks to the first 36 fb^{-1} of Run-2 data:
  - The bosonic decay channels entered a precision era (x2 improvement in uncertainty)
  - Significant progress on coupling to fermions
    - Evidence for $H \rightarrow bb$, Single exp. observation of $H \rightarrow \tau\tau$, Emergence of ttH signal
  - Sensitivity to di-Higgs production approaching 10x SM
- Higgs physics an important indirect probe for New Physics: so far no deviations from SM…
- But still at the beginning of a long journey! Only analysed ~1/100 of the final LHC luminosity.

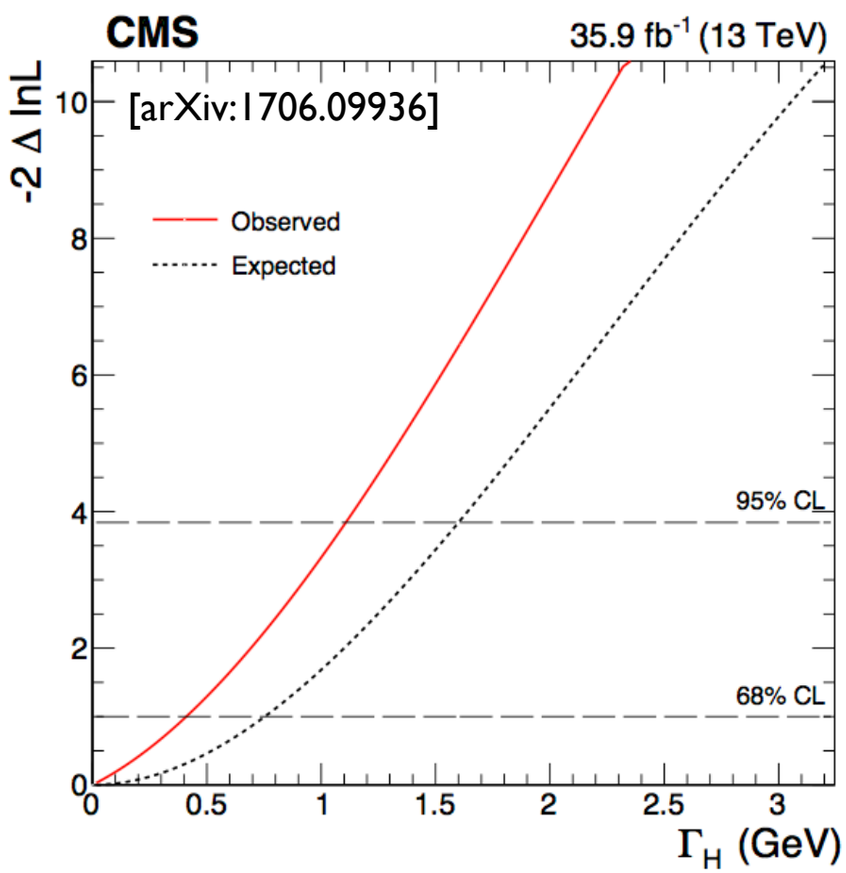


BACKUP

Mass measurement

Higgs boson width

$H \to ZZ^*$



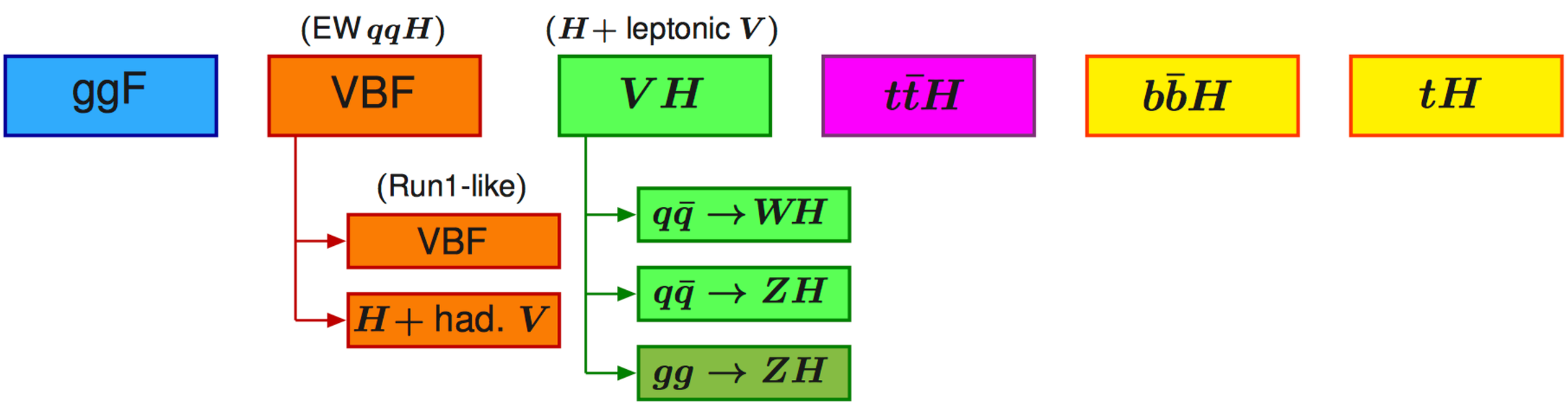
$$\Gamma_{\mathrm{H}} < 1.1 \text{ GeV } (95\% \text{ C.L.})$$

- Takes into account interference between signal and background.

Simplified template cross-section results

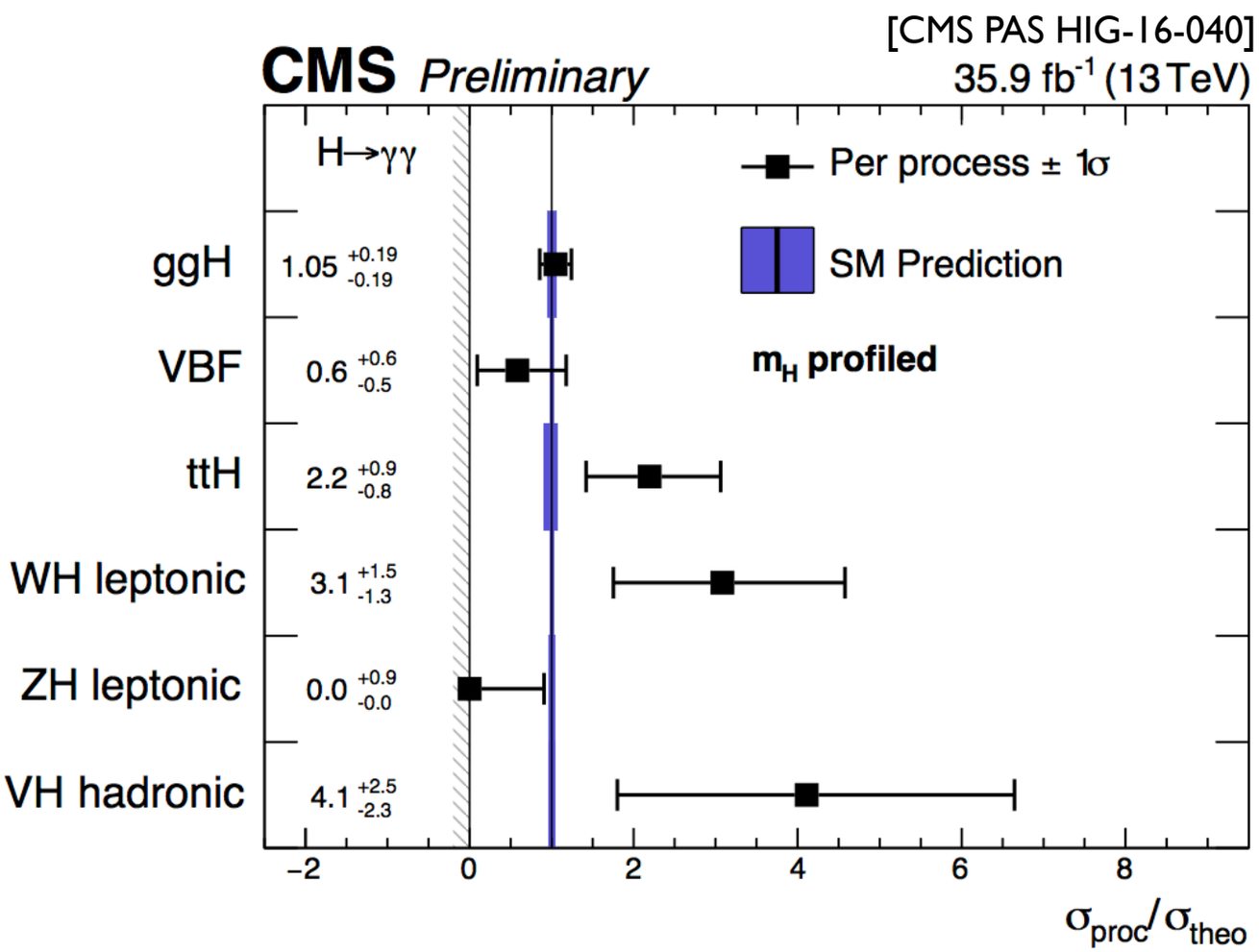
Simplified template cross-sections

- Proposed in LHC Higgs Cross Section WG Yellow Report 4 [M. Duehrssen et al.]
  - Extends the signal strength approach, sub-dividing the inclusive phase space into sub-spaces based on truth information
  - Defined in such a way to minimize dependence on theory assumptions
  - Maximize experimental sensitivity
  - Result (incl. full covariance matrix) can then be used for multiple interpretations
- Idea: proceed per stages, with more sub-divisions once data statistics allows for that
- Stage 0:

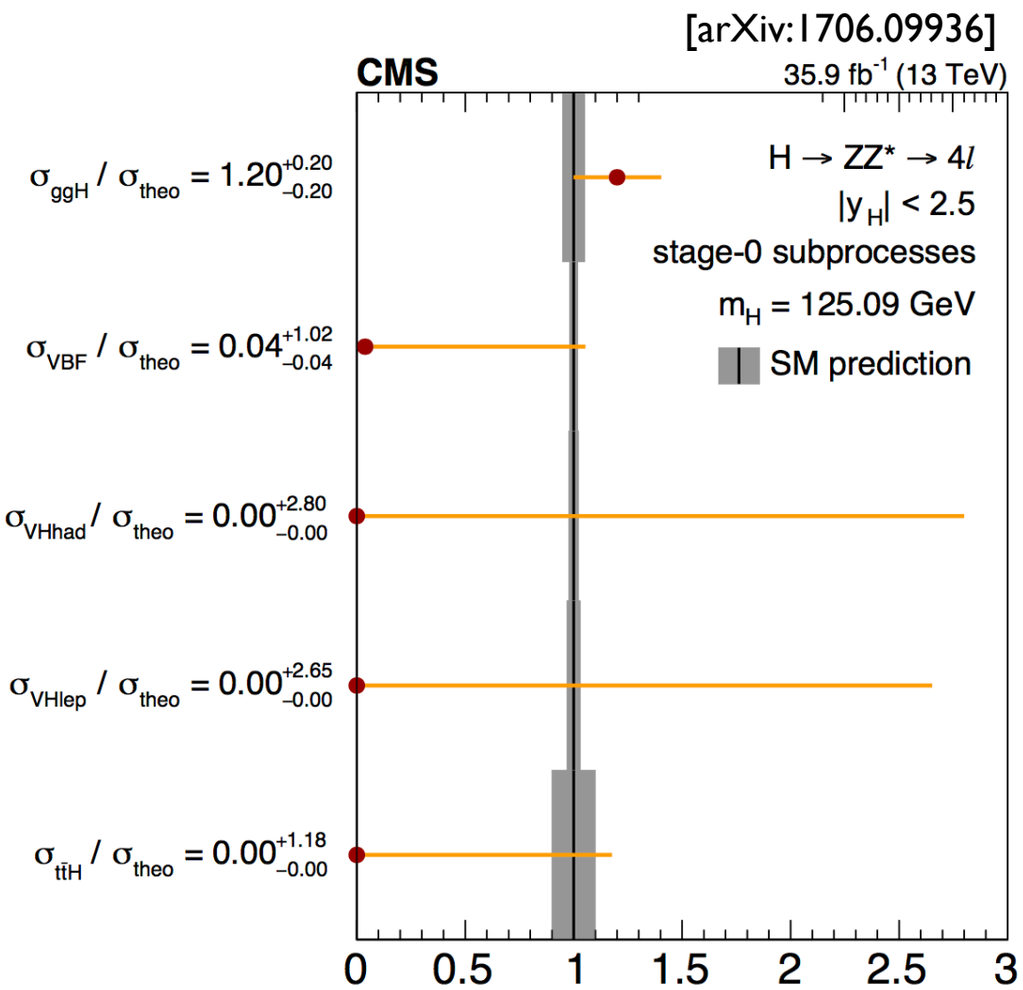


Stage 0 results

$H \to \gamma\gamma$



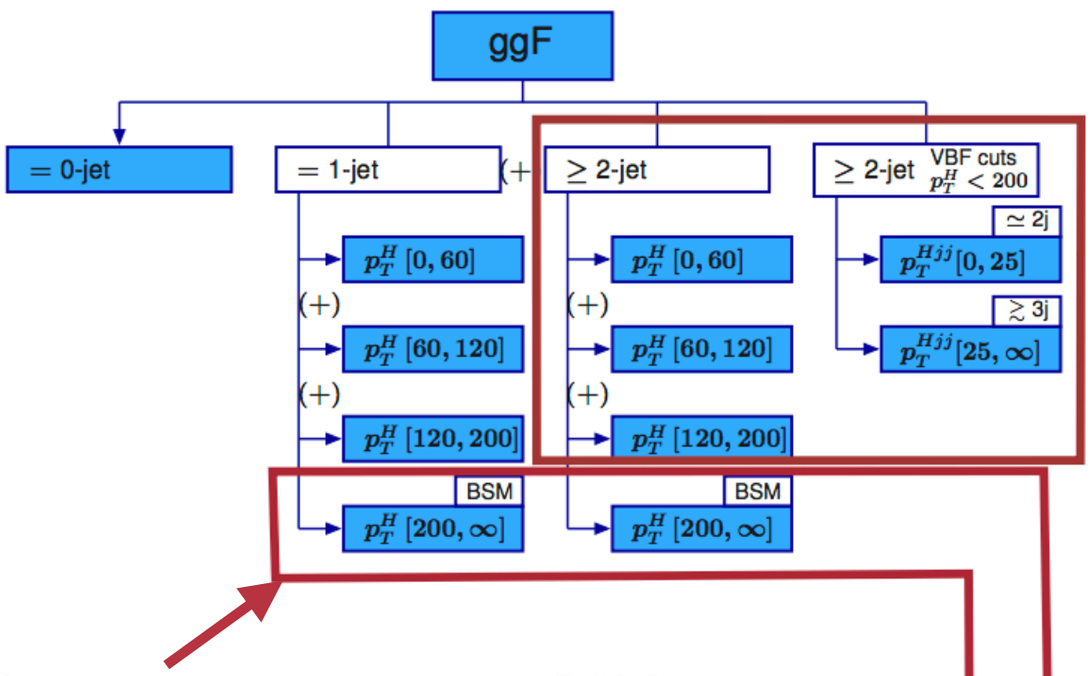
$H \to ZZ^*$



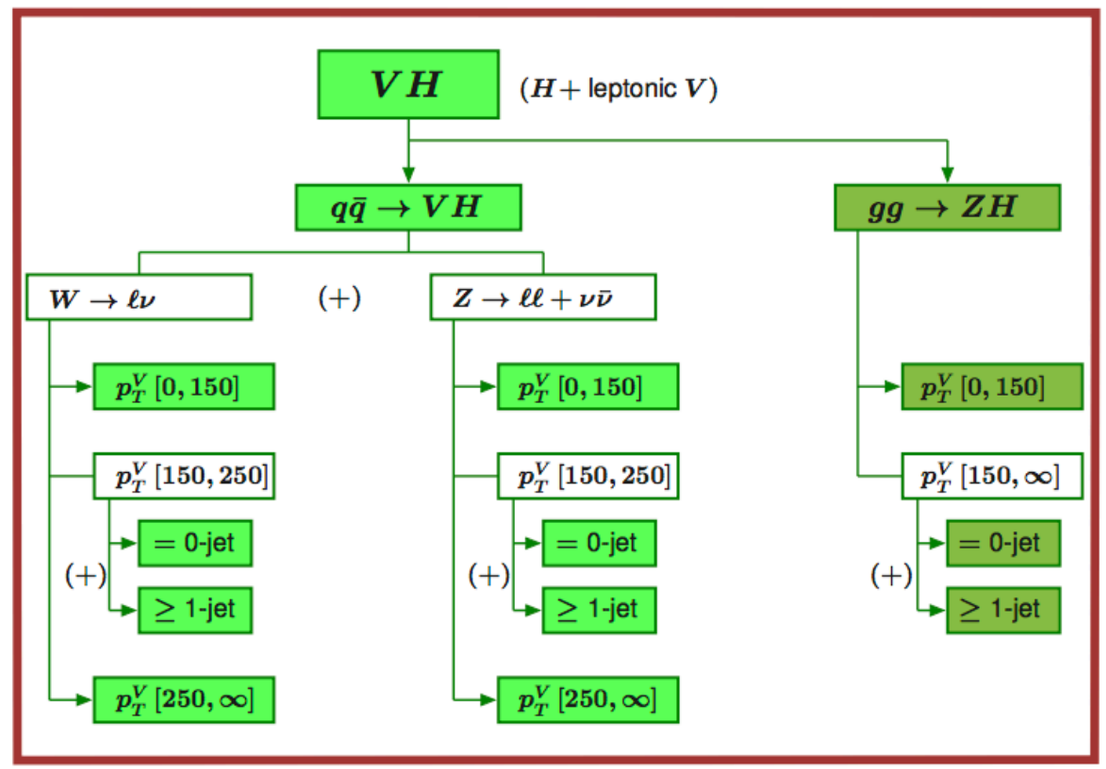
- Other decay channels, and experiment combination, will help constrain the subleading production modes.

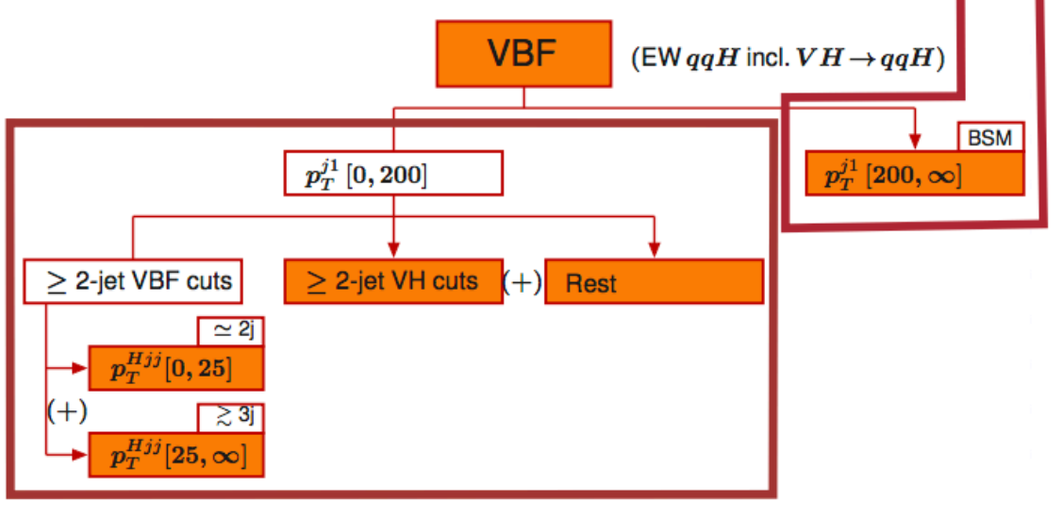
Going into further sub-divisions…

- Stage 1 (reduced by merging regions indicated by red boxes):



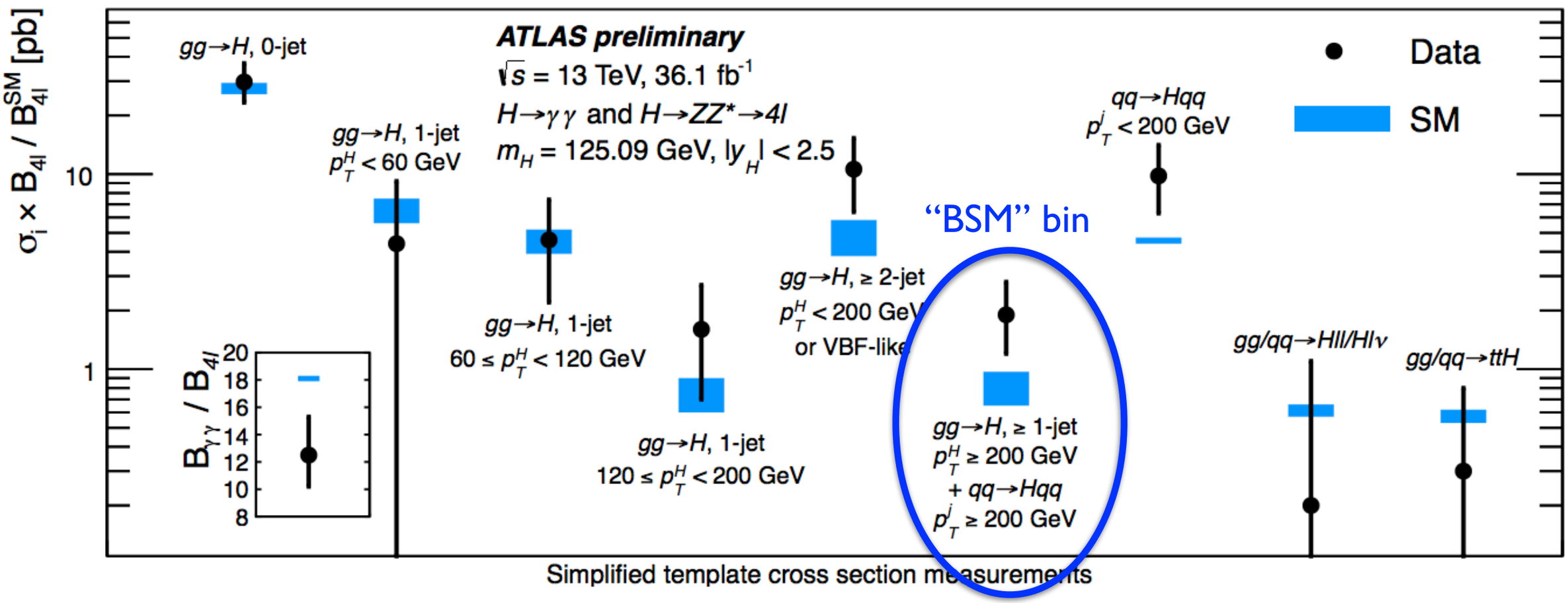
High p_T most sensitive to BSM





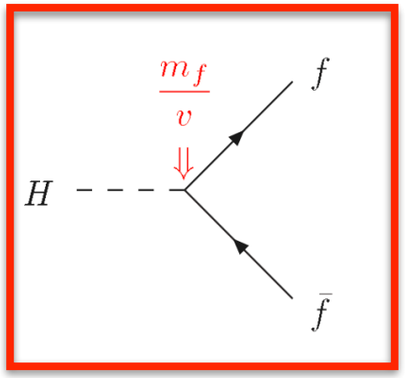
Results from H → ZZ* and H → γγ

[ATLAS-CONF-2017-047]

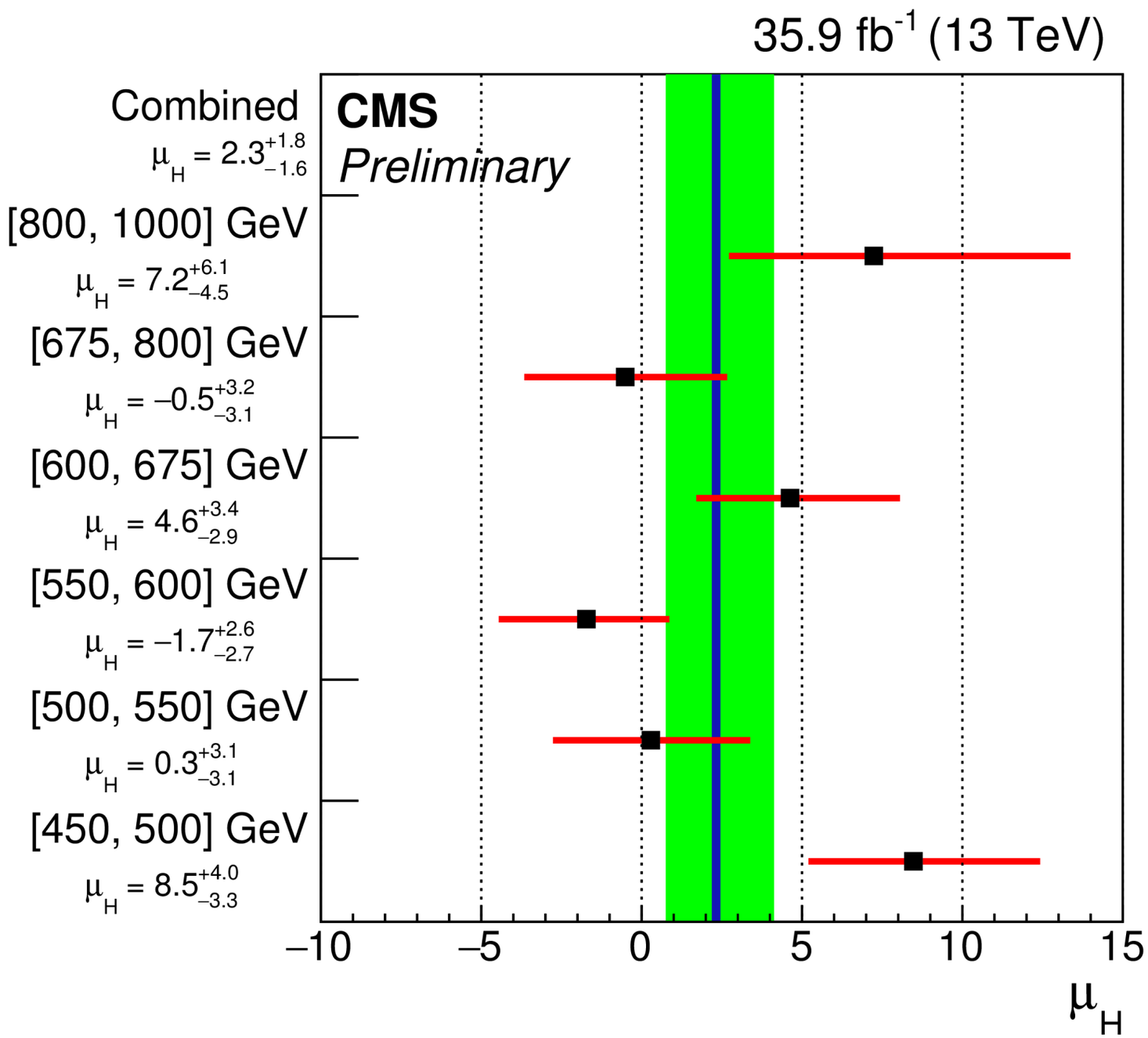


- Some measurements are slightly high, this is due to a small (~2σ) excess seen in 2 jet events, both in H → γγ and H → ZZ*
- First template cross-section measurements reality, but more work (combination with other channels and of two experiments) needed!

Coupling to fermions



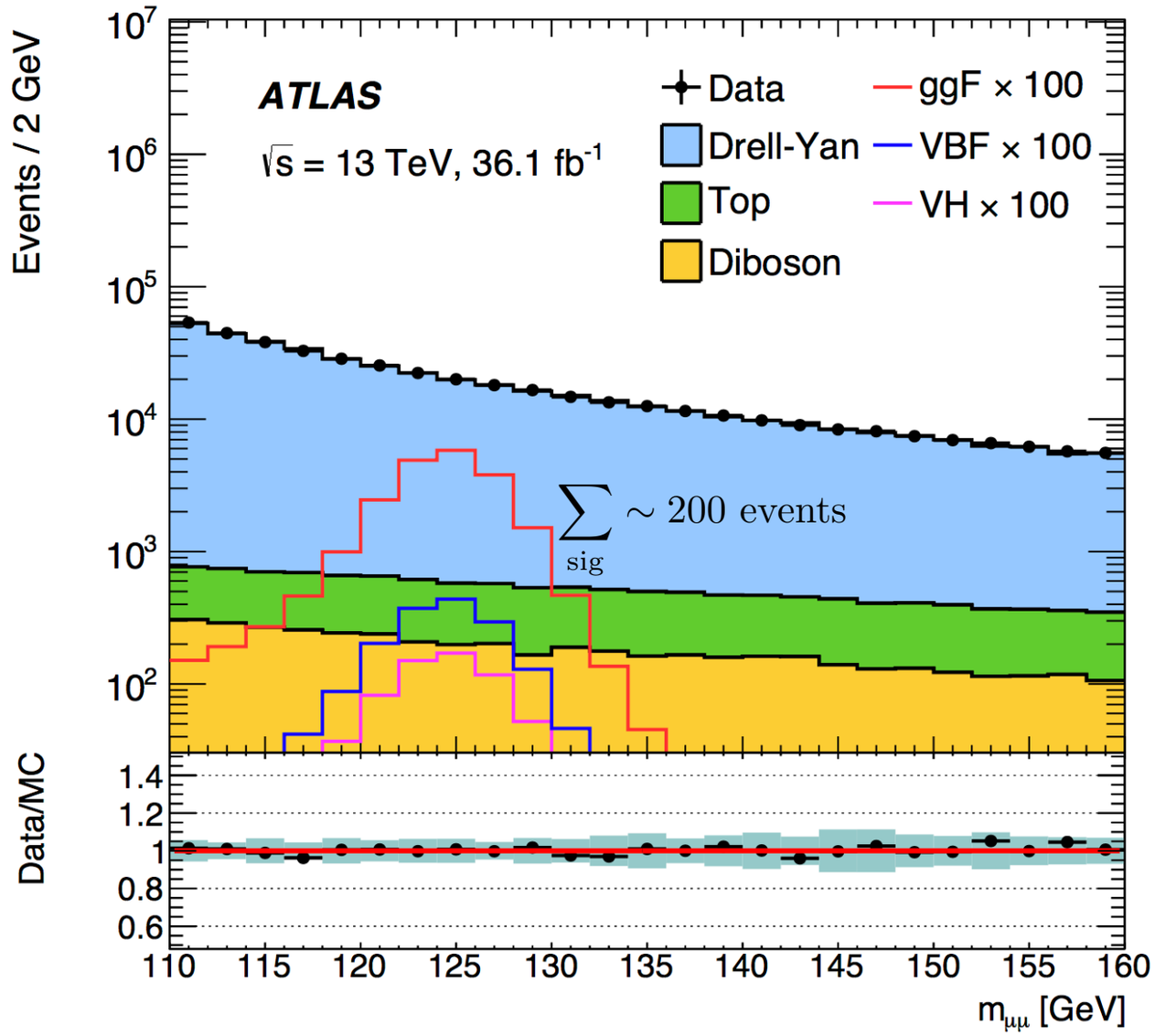
Search for ggF, H → bb



- "Boosted" H → bb search: can check for New Physics contributions arising at high pT(H)

Talk by A. White (U. Michigan)

[arXiv:1705.04582]

Coupling to 2nd generation fermions

- H → μμ: clear mass peak, but extremely small BR (~0.02%)
- Only a matter of statistics!
- ATLAS alone (Run-1+Run-2)
  - BR < 2.8xSM (exp. 2.9) @ 95% C.L.
- Getting closer to SM sensitivity!