DESY Particle and Astroparticle Physics Colloquium, 10 Sept 2018

Recent Higgs results from LHC

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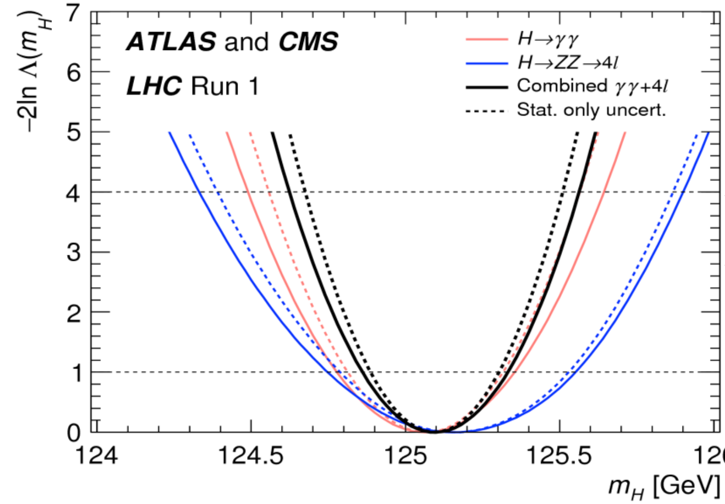
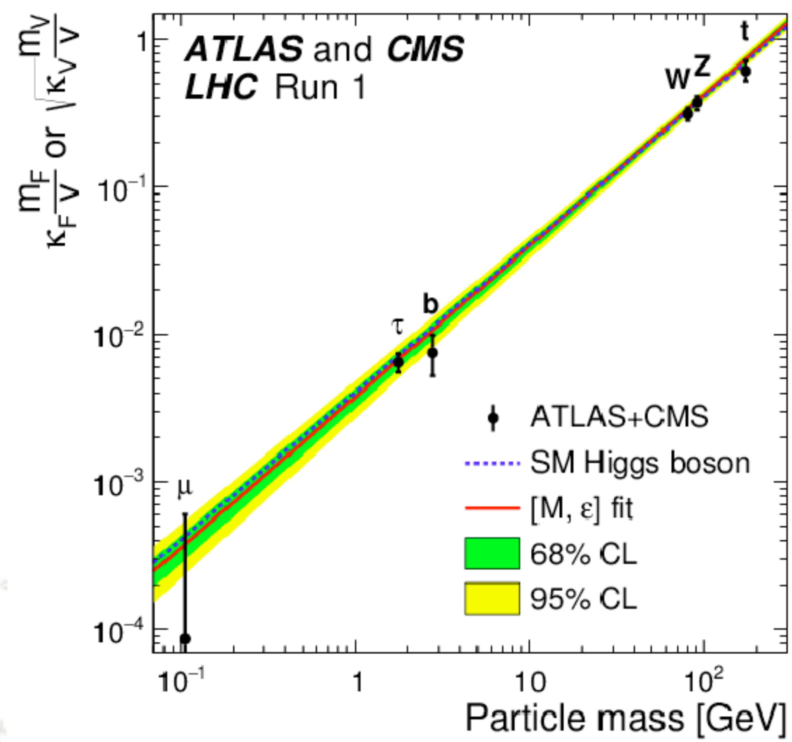
(CERN)

LHC Run 1

- 2012: a Higgs boson discovered at LHC
- Full LHC Run 1 data:
  - H mass measurement 125.09 ± 0.24 GeV (0.2%)
  - Excluded alterative J^{CP} hypotheses (e.g. 0^-, 2^+)
  - Inclusive production and couplings to W/Z/γ, t/b/τ probed at 10–30% level



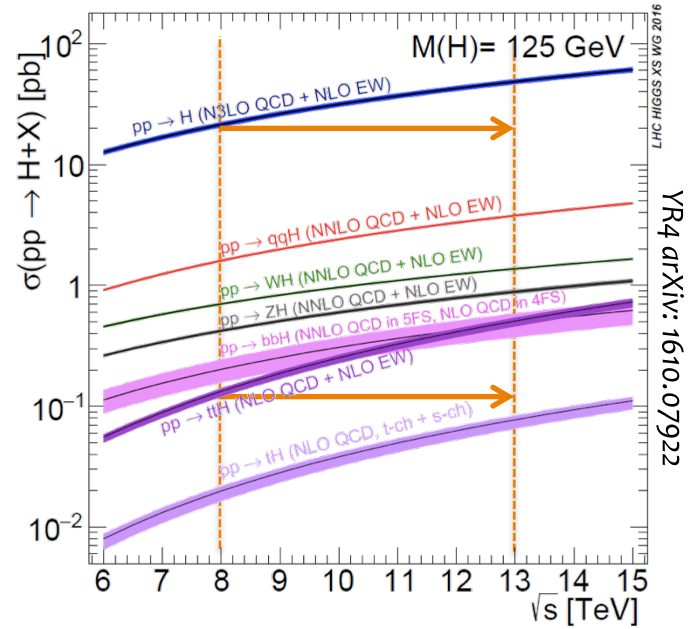
PRL 114 (2015) 191803

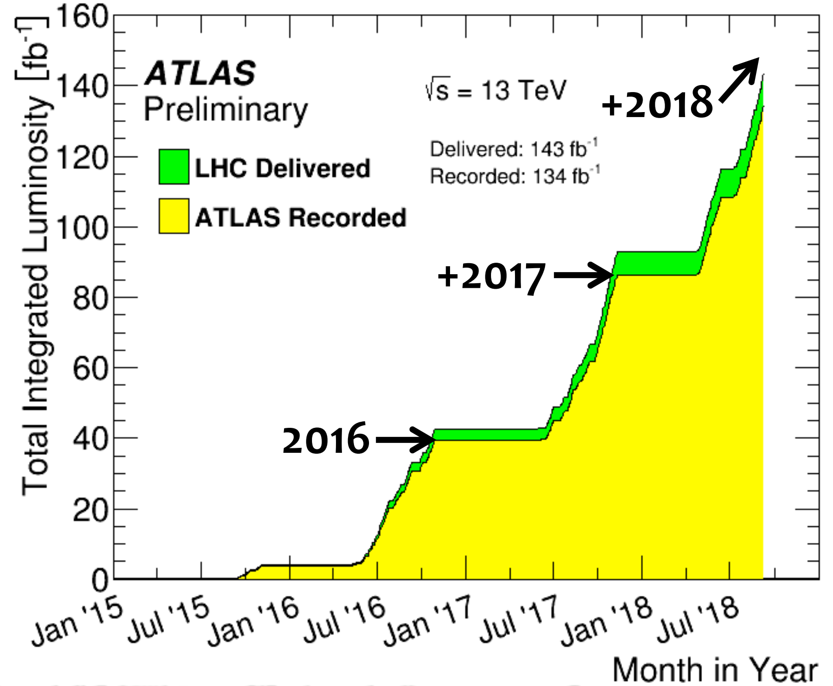


JHEP 08 (2016) 045

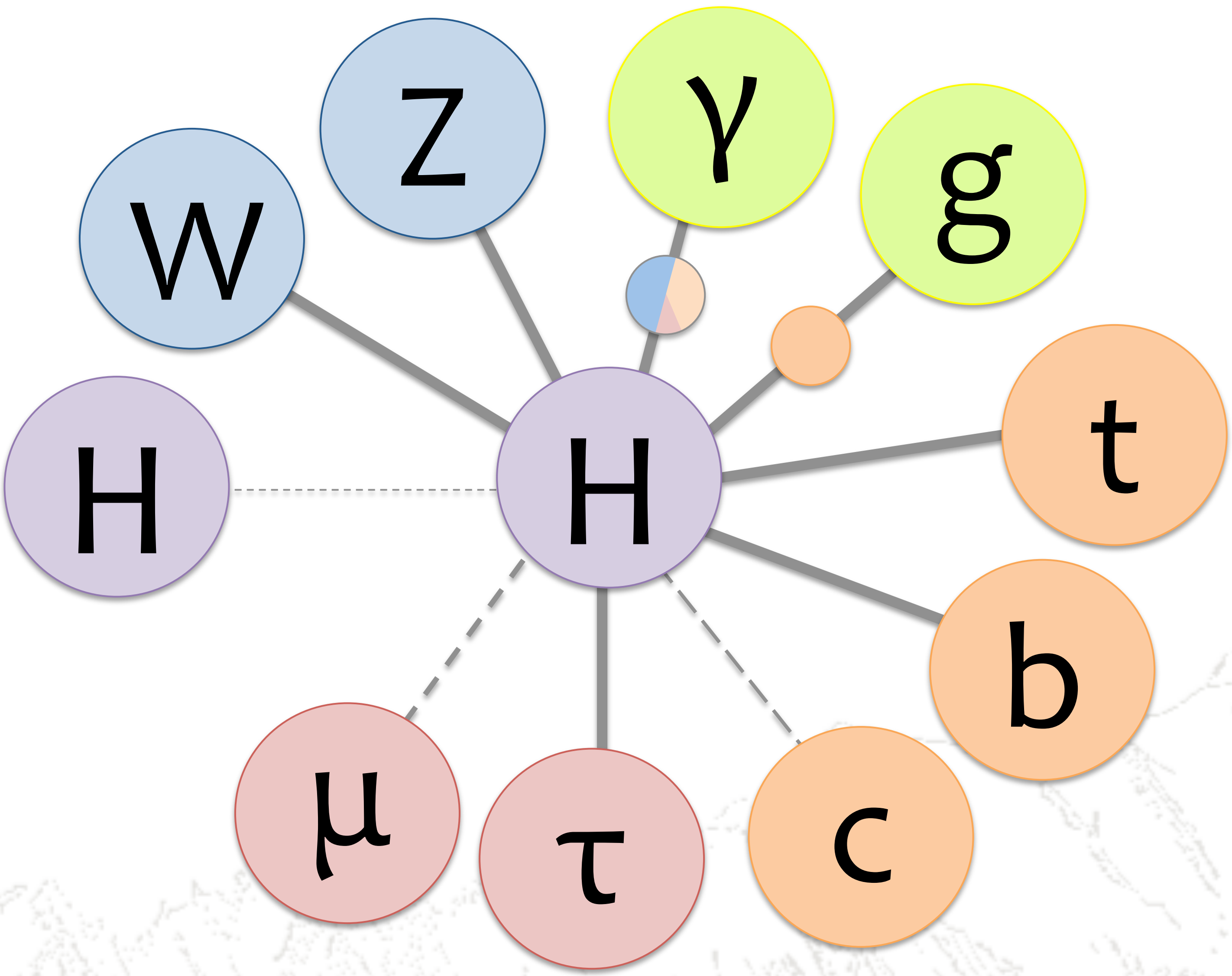
LHC Run 2

- $\sqrt{s}$: 7-8 TeV → 13 TeV
  - ×2-4 increase in σ(H)
- Higher inst. luminosity: ~ $8 \cdot 10^{33}$ → ~ $2 \cdot 10^{34}$
  - factor 2 above LHC design
- Larger datasets:
  - **2016** data: L_{int} ~36 fb^{-1} (most results based on this)
  - **+ 2017**: total L_{int} ~80 fb^{-1}
  - **+ 2018**: L_{int} ~150 fb^{-1} in reach (×4 compared to 2016 data)





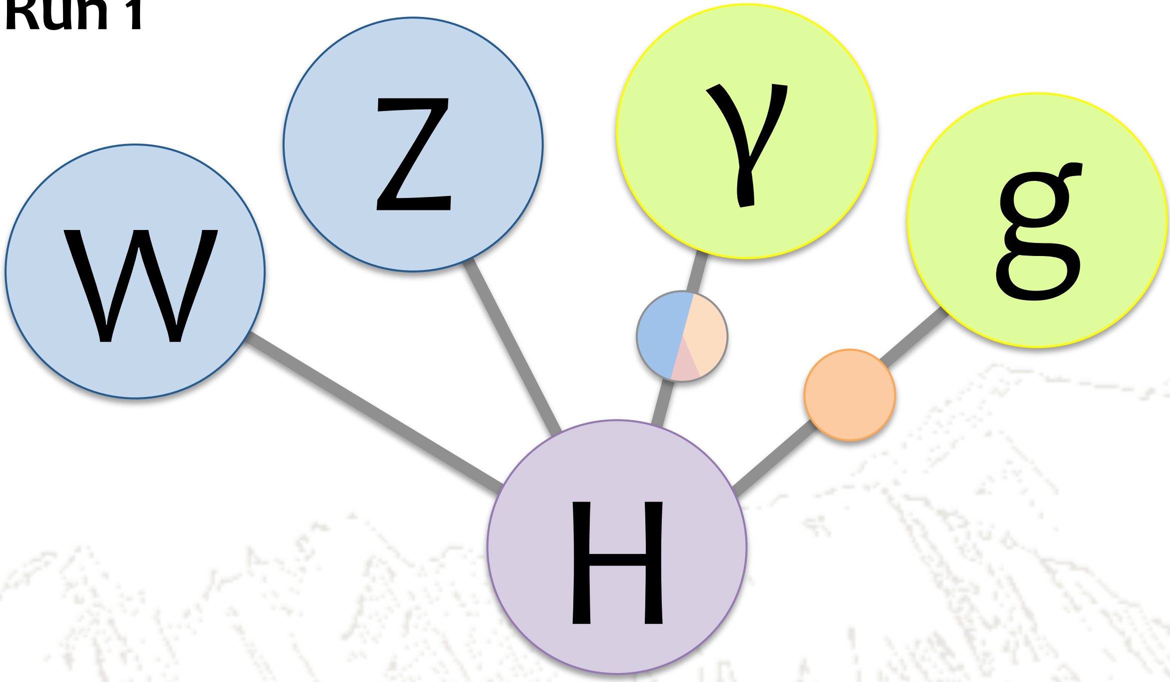
Higgs boson interactions



H – Vector boson interactions

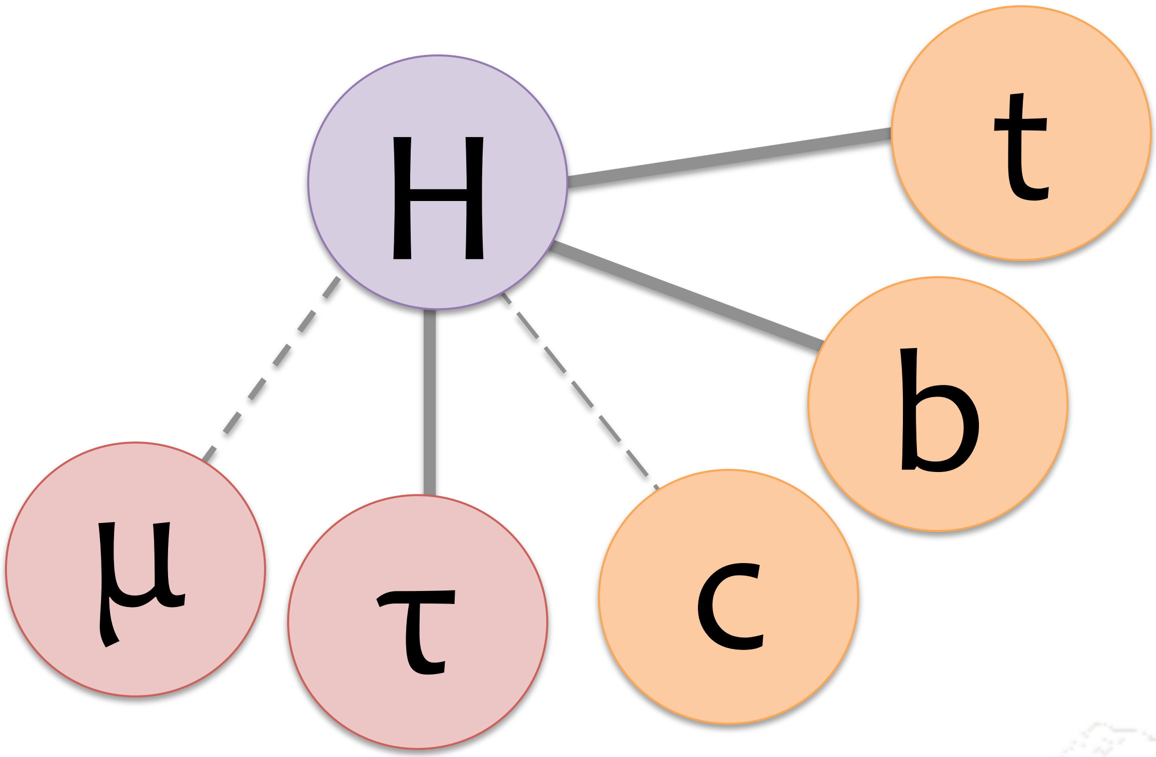
- **H–W** and **H–Z** are the most essential Higgs boson couplings.
- **Clearly established from WW/ZZ decays, already since Run 1**

- **H–γ** and **H–g** interaction in SM only realized via loops
  - **H → γγ clearly established in Run 1**
  - "Inclusive" H production in good agreement with SM predictions, dominantly from **gg → H**



H – fermion interactions

In the SM, $\boldsymbol{\lambda_f = m_f / v}$ for all fermions



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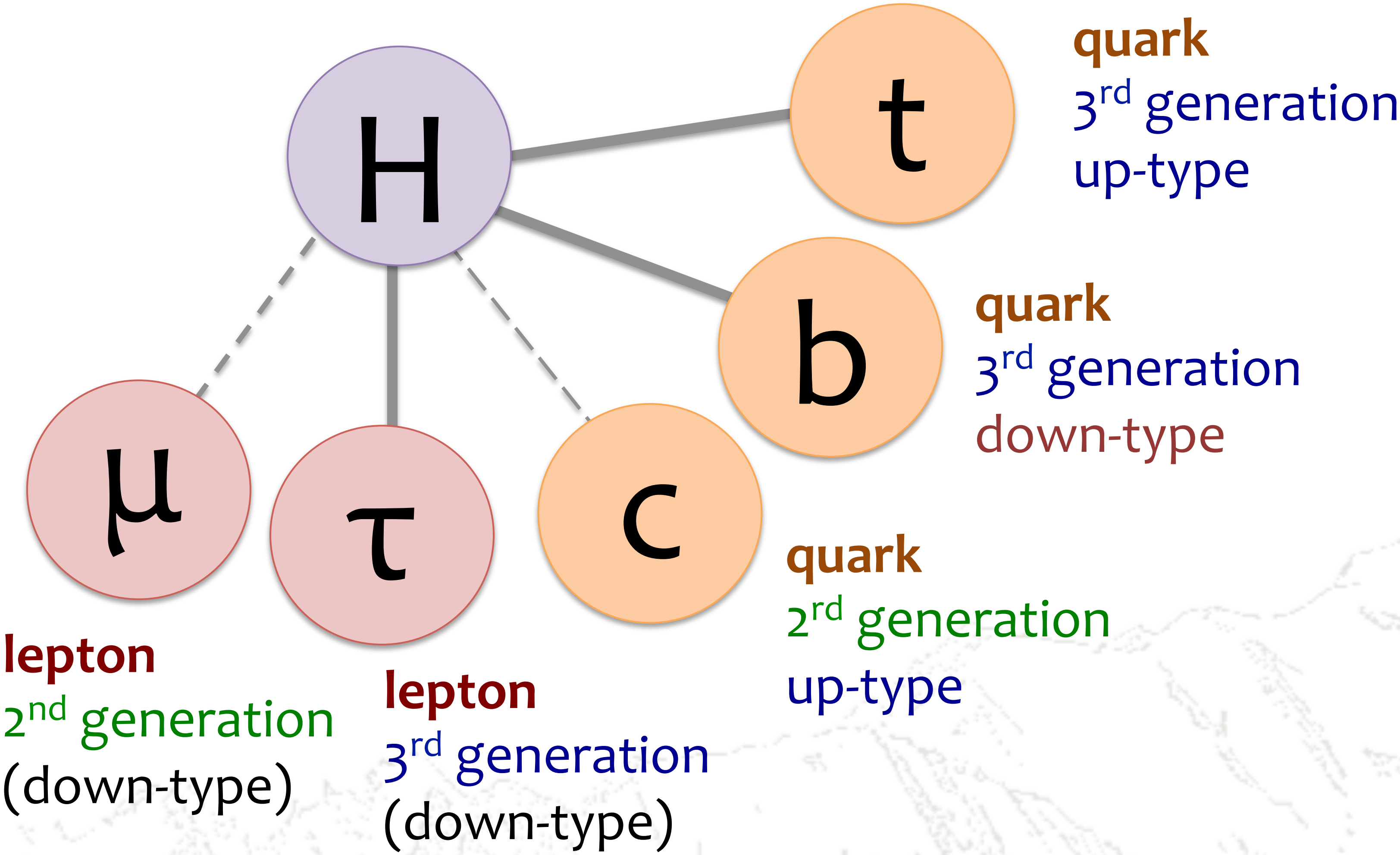
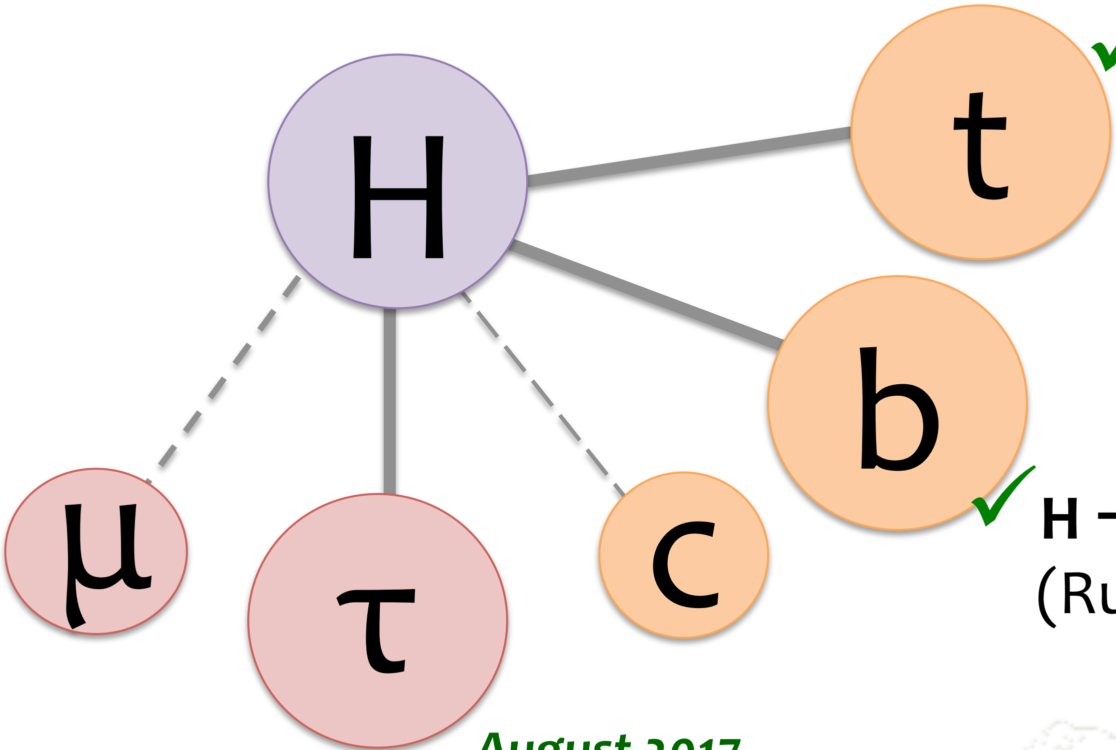


H–fermion interaction



April 2018

✓ Direct **H–t** coupling **observed** via **ttH** production
(Run 1 + 2016 data)

August 2018

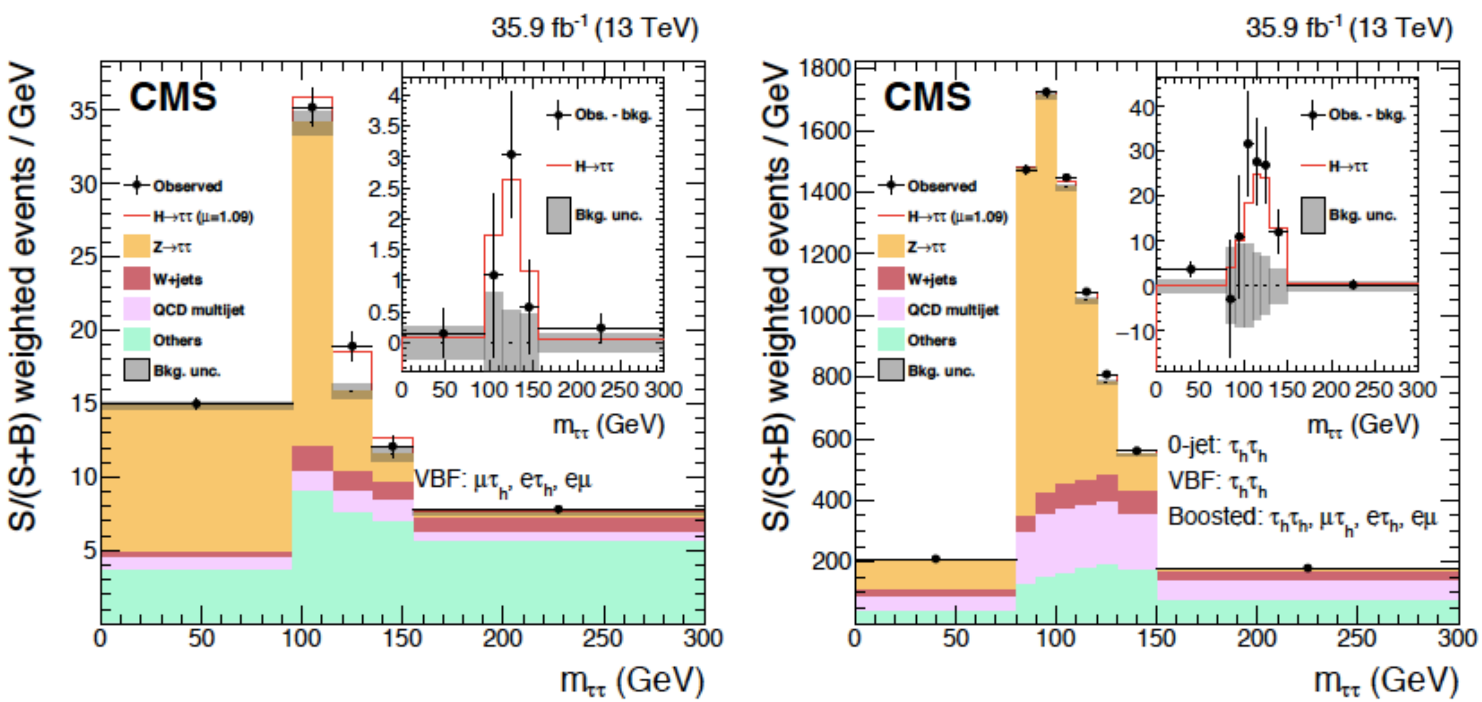
✓ **H → bb observed**
(Run 1 + 2016+ 2017)

August 2017

✓ **H → ττ observed**
(Run 1 + 2016 data)

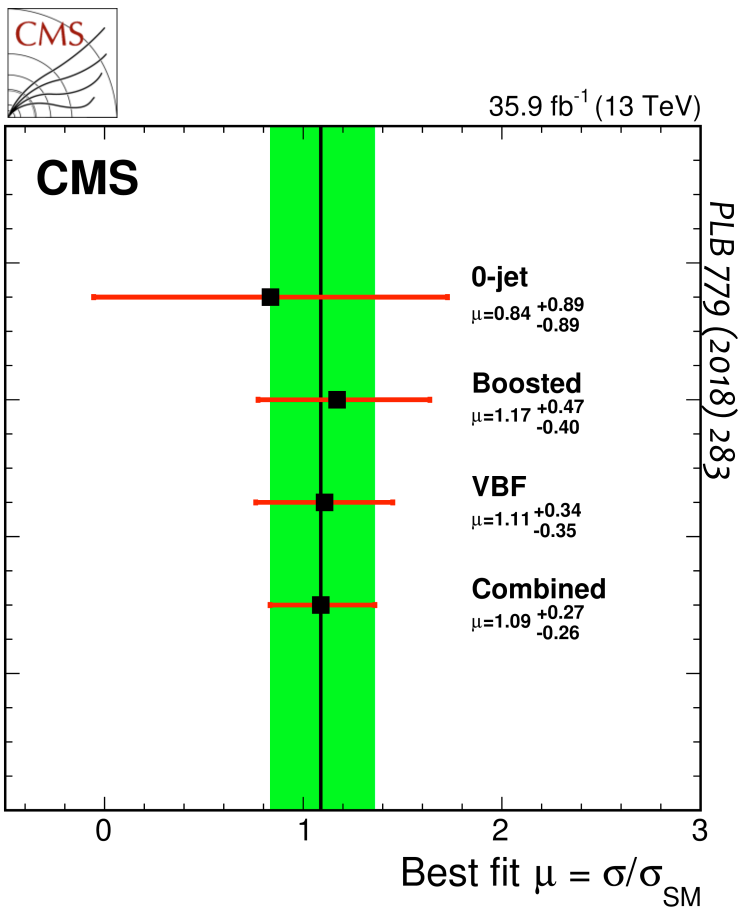
$H \rightarrow \tau\tau$ observation

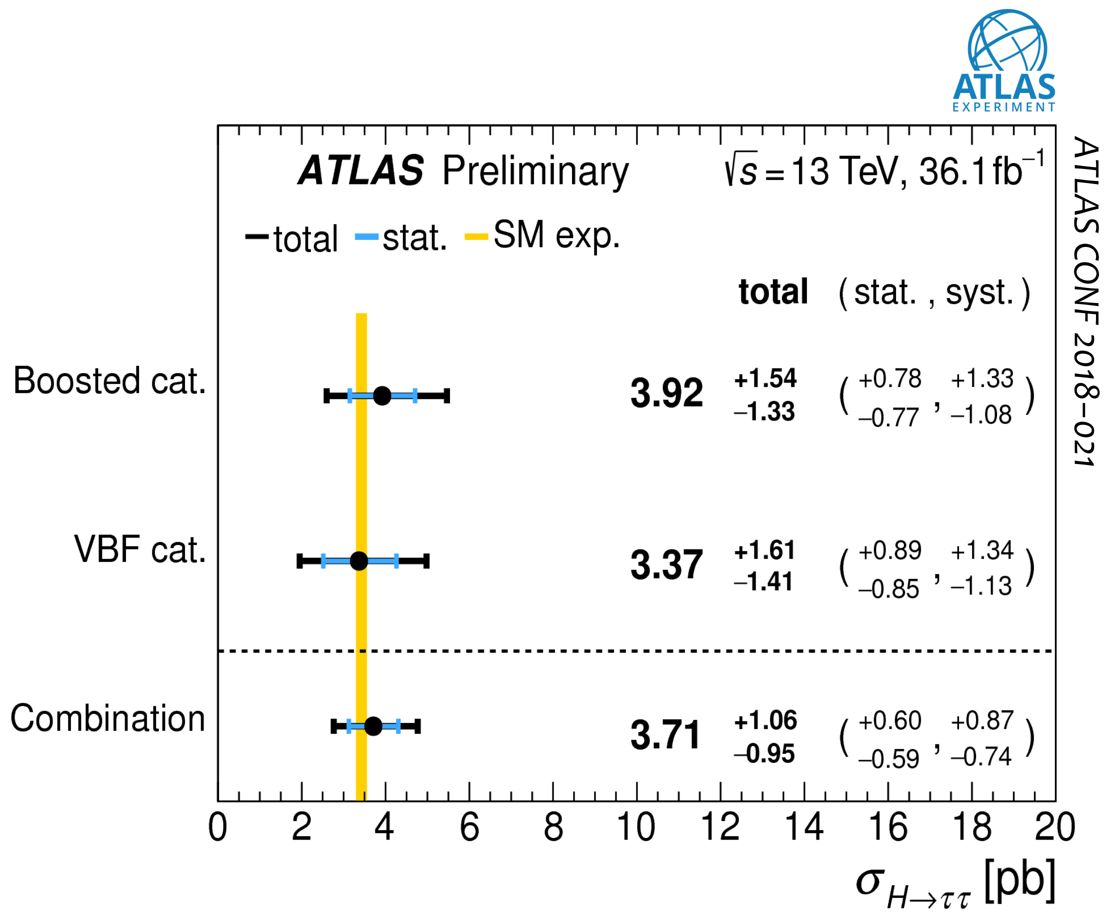
- First individual fermion coupling to be established with ≥5σ significance
  (already achieved with the LHC Run 1 combination)



PLB 779 (2018) 283

$H \rightarrow \tau\tau$





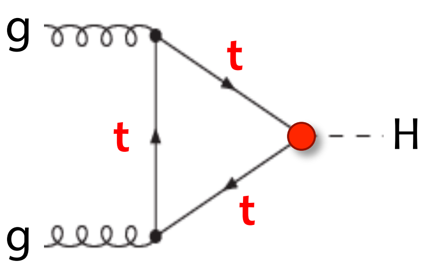
$\sigma/\sigma_{SM} = 1.09^{+0.27}_{-0.26}$

$\sigma/\sigma_{SM} = 1.09^{+0.36}_{-0.30}$

top – Higgs interaction

- Largest Yukawa interaction in SM, important in several production and decay processes:

gluon fusion



- **gg → H** has the largest cross section among all Higgs boson production modes at LHC
- In the SM, the top quark loop gives the dominant contribution
- Production cross section is sensitive to any heavier BSM particles with QCD interactions

top – Higgs interaction

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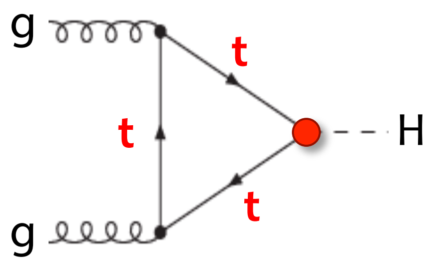
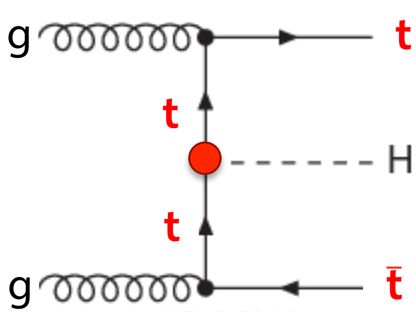
gluon fusion



ttH production



- **ttH:** direct assessment of top-Hig coupling at tree level
- also, final state similar to that of many BSM physics searches (e.g. supersymmetry)

top – Higgs interaction

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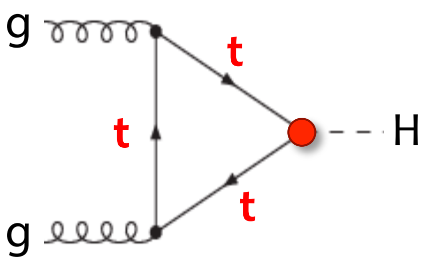
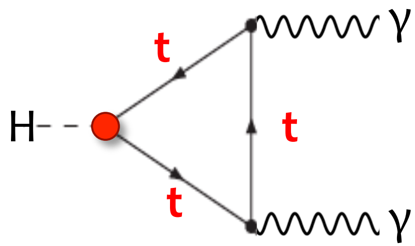
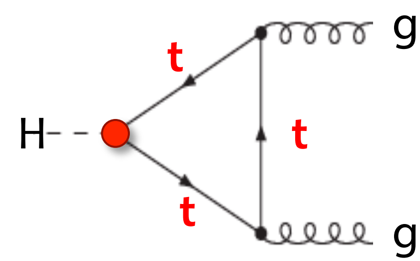
gluon fusion



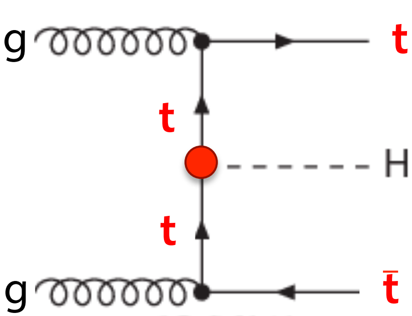
H → γγ decay



H → gg decay



ttH production

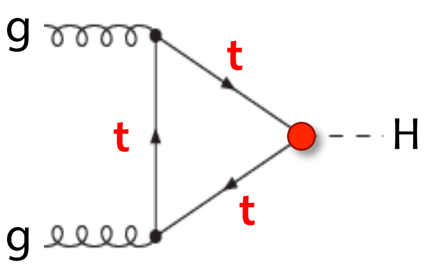


- BR's sensitive to heavy BSM particles
- top quark second largest contributor to H → γγ (after the W loop), and dominant in H → gg

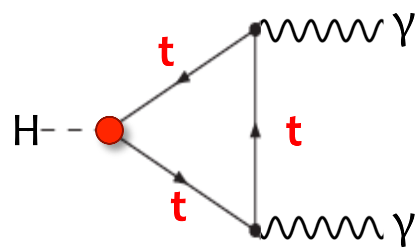
top – Higgs interaction

- Largest Yukawa interaction in SM, important in several production and decay processes:

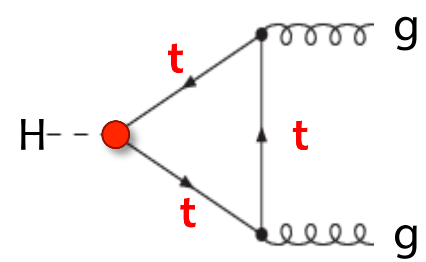
gluon fusion



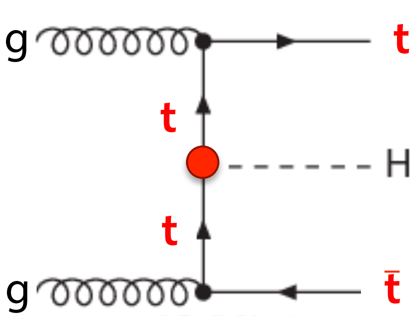
H → γγ decay



H → gg decay

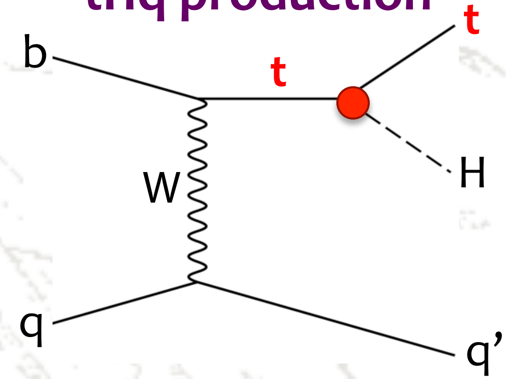


ttH production



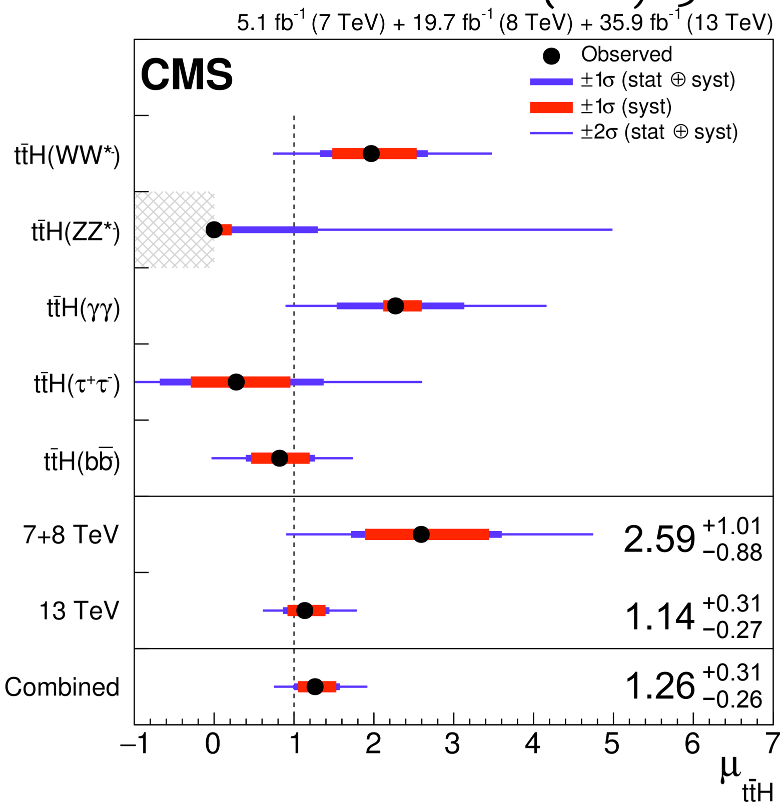
- probe interference between t–H and V–H couplings at tree level

tHq production



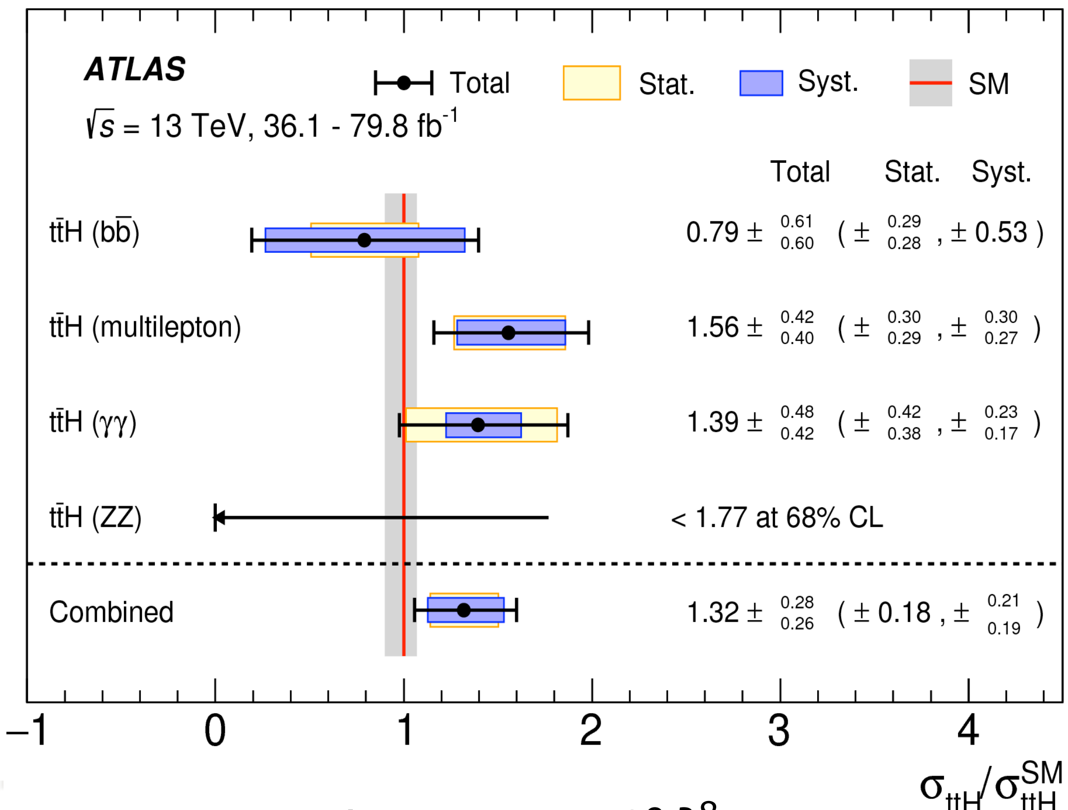
ttH observation

PRL 120 (2018) 231801



$$\sigma/\sigma_{SM} = 1.26\,^{+0.31}_{-0.26}$$

PLB 784 (2018) 173



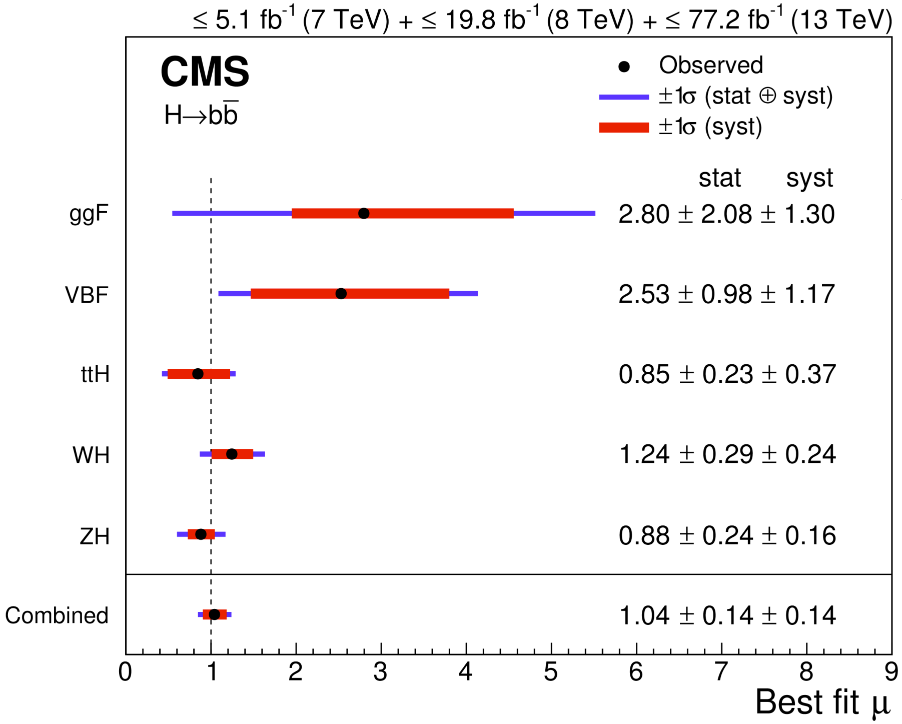
$$\sigma/\sigma_{SM} = 1.32\,^{+0.28}_{-0.26}$$

$H \rightarrow bb$

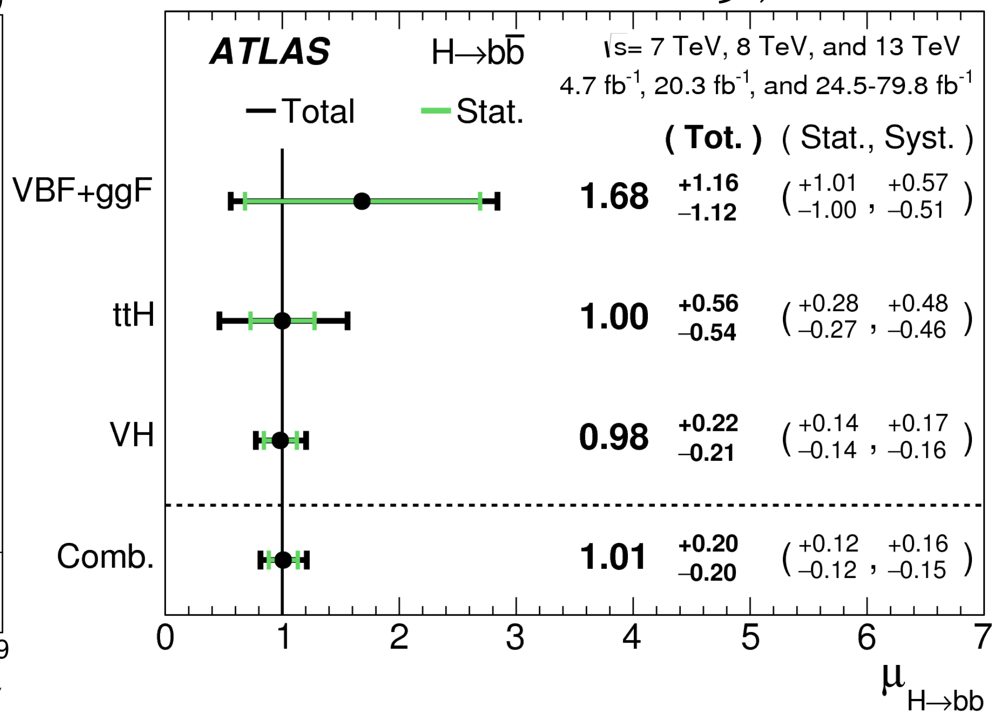
- Largest BR among all the decays:
  - Dominates total width of SM Higgs
  - Once the decay is established, it can be used to probe Higgs production at very high p_T
- Probably the only Yukawa coupling to a down-type quark within LHC reach

H → bb observation

arXiv:1808.08242, acc. by PRL

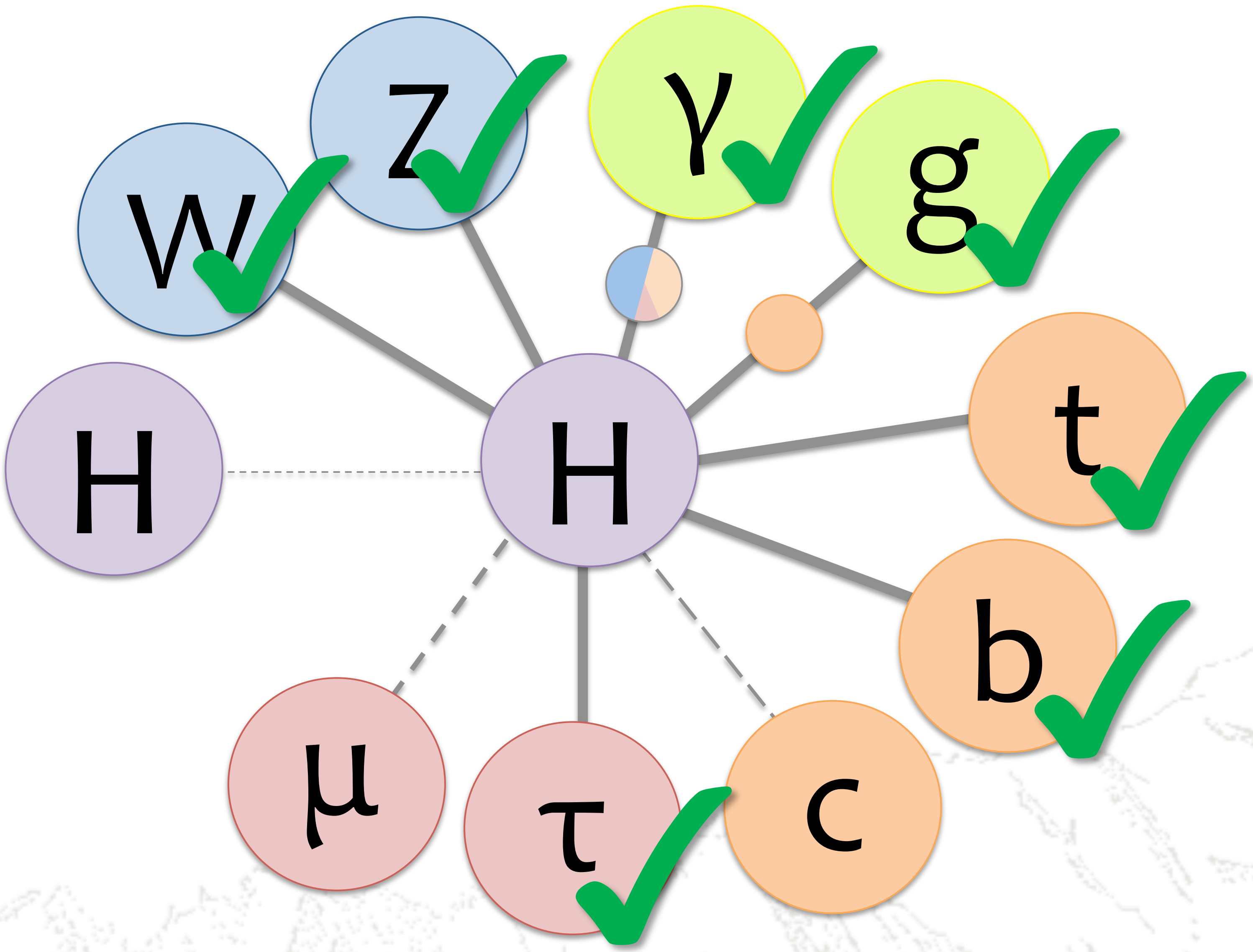


arXiv:1808.08238, sub. to PLB



$\sigma/\sigma_{SM} = 1.04 \pm 0.20$

$\sigma/\sigma_{SM} = 1.01 \pm 0.20$

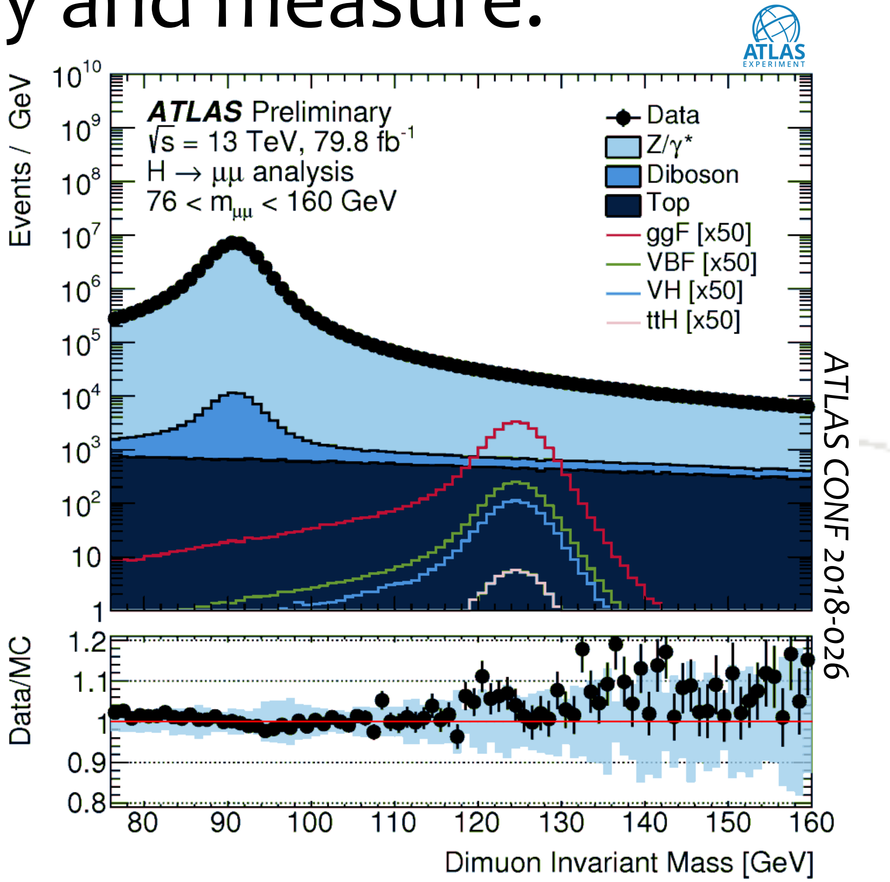

Z
γ
g
W
H
H
t
b
μ
τ
c

What next?


Bottom, 80 fb^{-1}
Higgs trilinear
(via ferrata)
82
6
Tau 40 fb^{-1}
Top 40 fb^{-1}
Muon 3σ 150 fb^{-1}
Charm ??
6

$H \rightarrow \mu\mu$

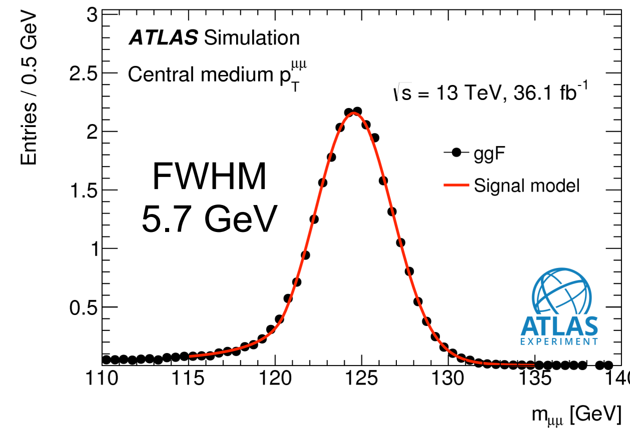
- In principle, an easy analysis: muons are the easiest object to identify and measure.
- $BR(\mu\mu)_{SM} = 2.2 \times 10^{-4}$
- Main challenge: the irreducible $Z^{*} \rightarrow \mu\mu$ background
  - $\sigma \times BR(H \rightarrow \mu\mu) = 12$ fb
  - $\sigma \times BR(Z \rightarrow \mu\mu) \sim 1.9$ nb **(1.6 × 10^5 times larger)**



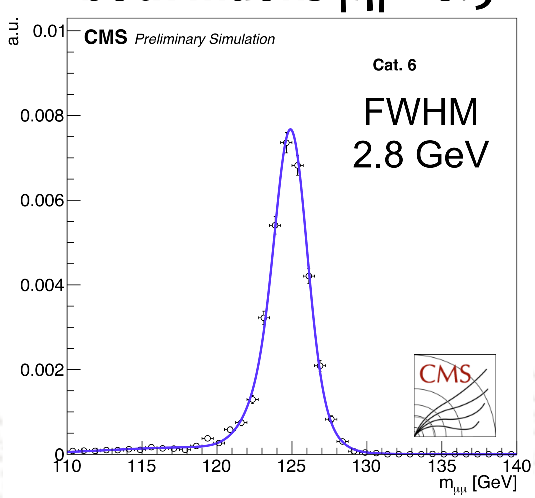
H → μμ: methods

- Good muon momentum resolution is critical
  - Categorize events according to muon |η|

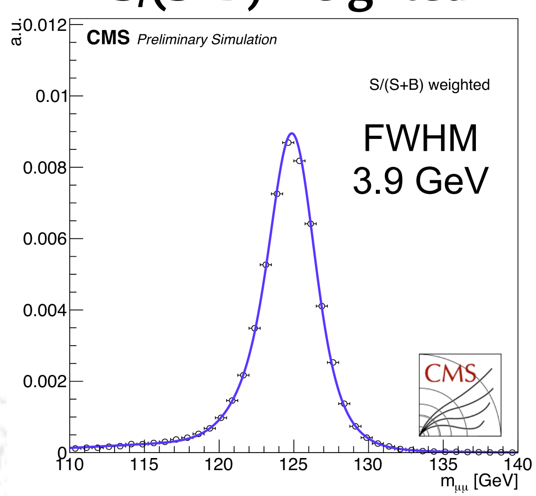
both muons |η| < 1.05



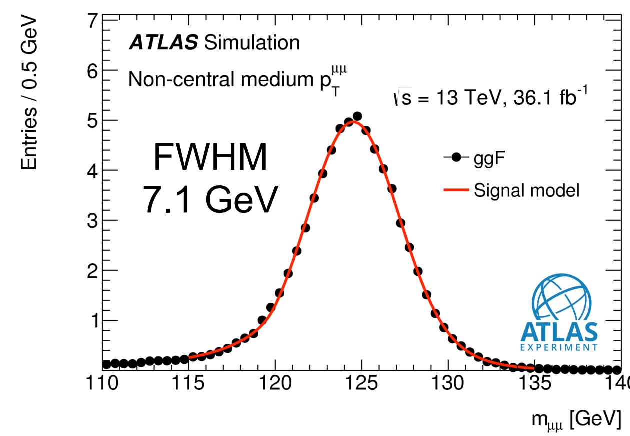
best mass resolution both muons |η| < 0.9



all categories, S/(S+B) weighted



one muon 1.05 < |η| < 2.5

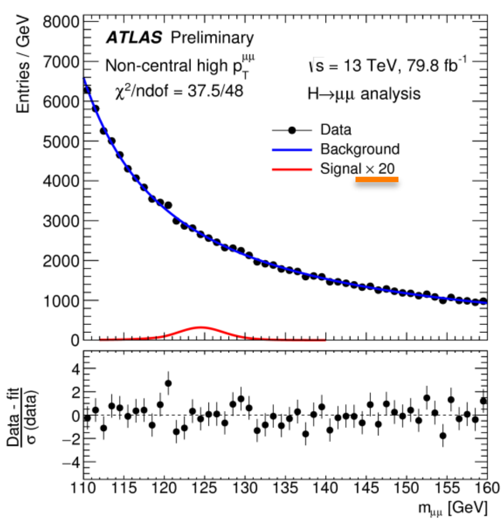


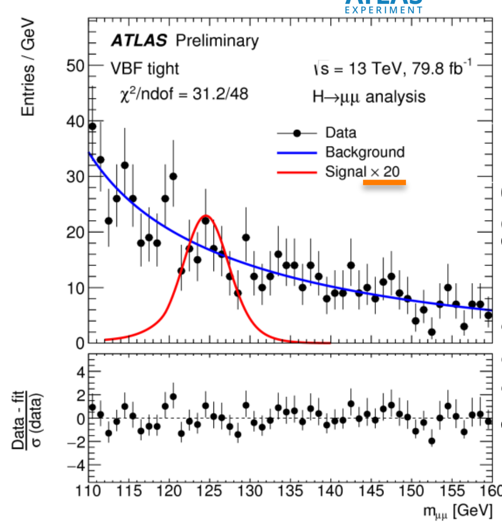
H → μμ: methods

- Suppress tt→μμννbb using b-tagging, E_T^{miss}
- Select phase space regions with best S/B:
  - high $p_T(\mu\mu)$ or VBF production
- Different approaches in ATLAS & CMS:
  - ATLAS: MVA selection to target VBF events, simple $p_T(\mu\mu)$ categorization for the rest, b-jet veto and E_T^{miss} cuts against tt
  - CMS: inclusive MVA discriminator using muons, jets, b-tag, E_T^{miss} trained against all backgrounds

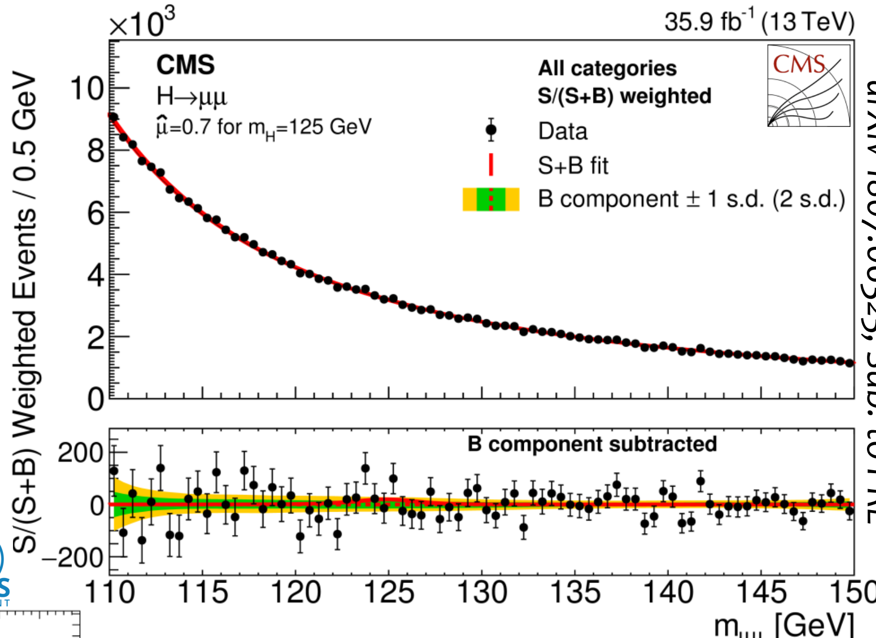
H → μμ: a look at the data

ATLAS : plot of two categories with highest discovery sensitivity





ATLAS CONF 2018-026



arXiv 1807.06325, Sub. to PRL

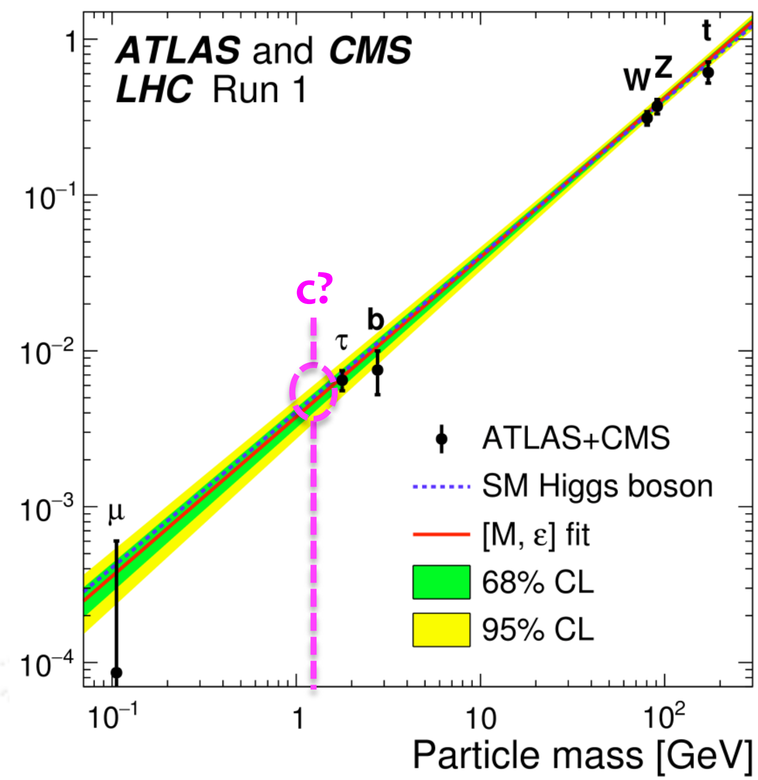
CMS: weighted sum plot of all categories

$H \rightarrow \mu\mu$: results

- ATLAS result based on 2016 + 2017 data, CMS result on Run 1 + 2016 data
  - Comparable sensitivity
- Best fit values of signal strength $\mu = \sigma/\sigma_{SM}$:
  - ATLAS: $\mu = 0.1 \pm 1.0$
  - CMS: $\mu = 0.9 \pm 1.0$
- Observed & expected upper limits (95% CL)
  - ATLAS: $\mu < 2.1$ obs (2.0 exp. for $\mu = 0$)
  - CMS: $\mu < 2.9$ obs (2.2 exp. for $\mu = 0$)

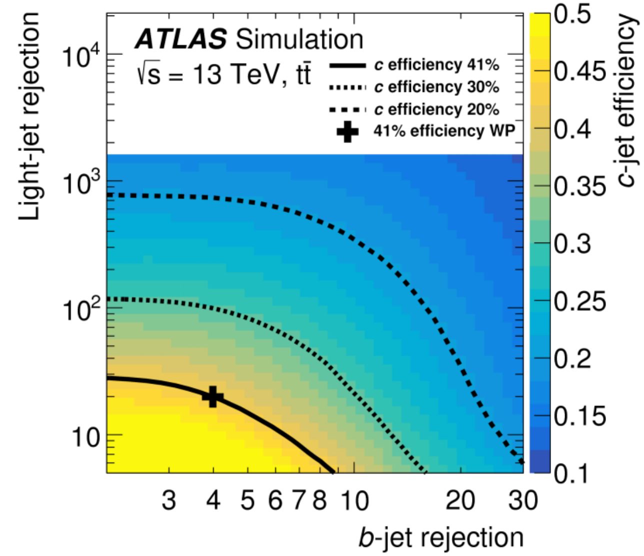
H → cc ?

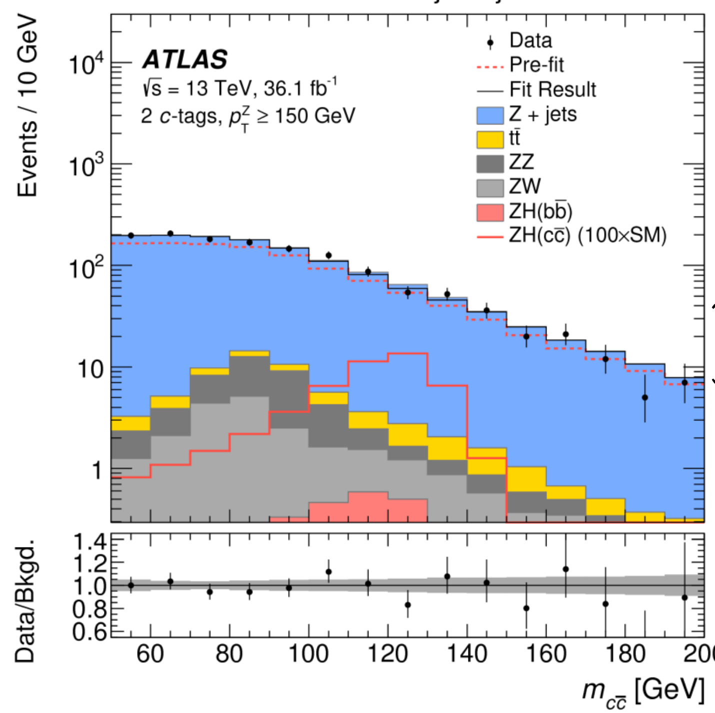
- Charm coupling $\lambda_c \sim \lambda_\tau$, but way harder to probe:
  - BR(cc) ~ 0.05 × BR(bb)
  - and, H → bb background!
- Three approaches have been explored so far:
  - Direct searches for inclusive H → cc decays, as H → bb
  - Searches for charmonium decays: H → J/Ψ γ
  - Extract constraints on λ_c from kinematics



inclusive H → cc

- So far attempted only by ATLAS, to demonstrate charm tagging performance
- Much simpler approach compared to VH→bb:
  - use only Z(ℓℓ)H production
  - fit m(cc) distribution in cut-based categories, instead of a full MVA-based analysis
- Limits on $\mu = \sigma\times BR / \sigma_{SM}\times BR_{SM}$ from analysis on 2016 data
  - **μ < 110 obs. (μ < 150 exp.)**

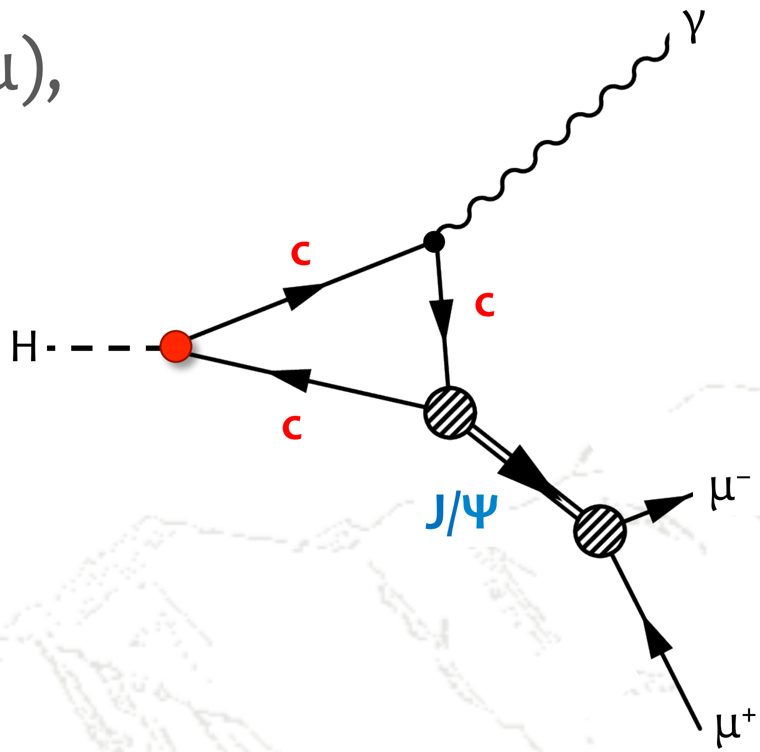




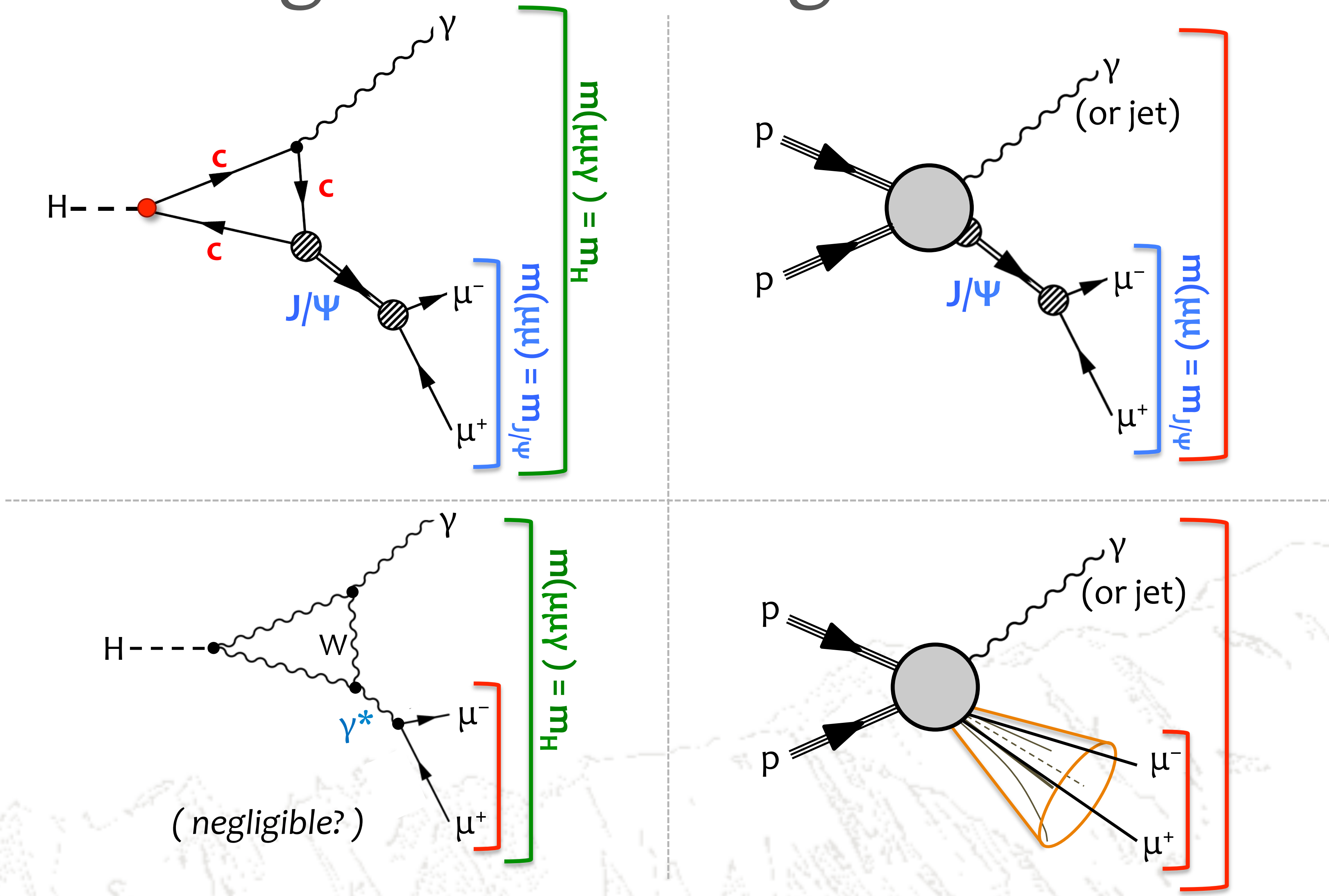
PRL 120 (2018) 211802

$H \rightarrow J/\Psi\ \gamma$

- Very rare decay in the SM: $BR(H \rightarrow J/\Psi\ \gamma) \sim 3{\times}10^{-6}$
  - 1.8×10^{-7} with $BR(J/\Psi \rightarrow \mu\mu)$, factor 13000 / 180 smaller than $H \rightarrow \gamma\gamma$ / 4μ
- Resonant signal, and no $H \rightarrow bb$ background



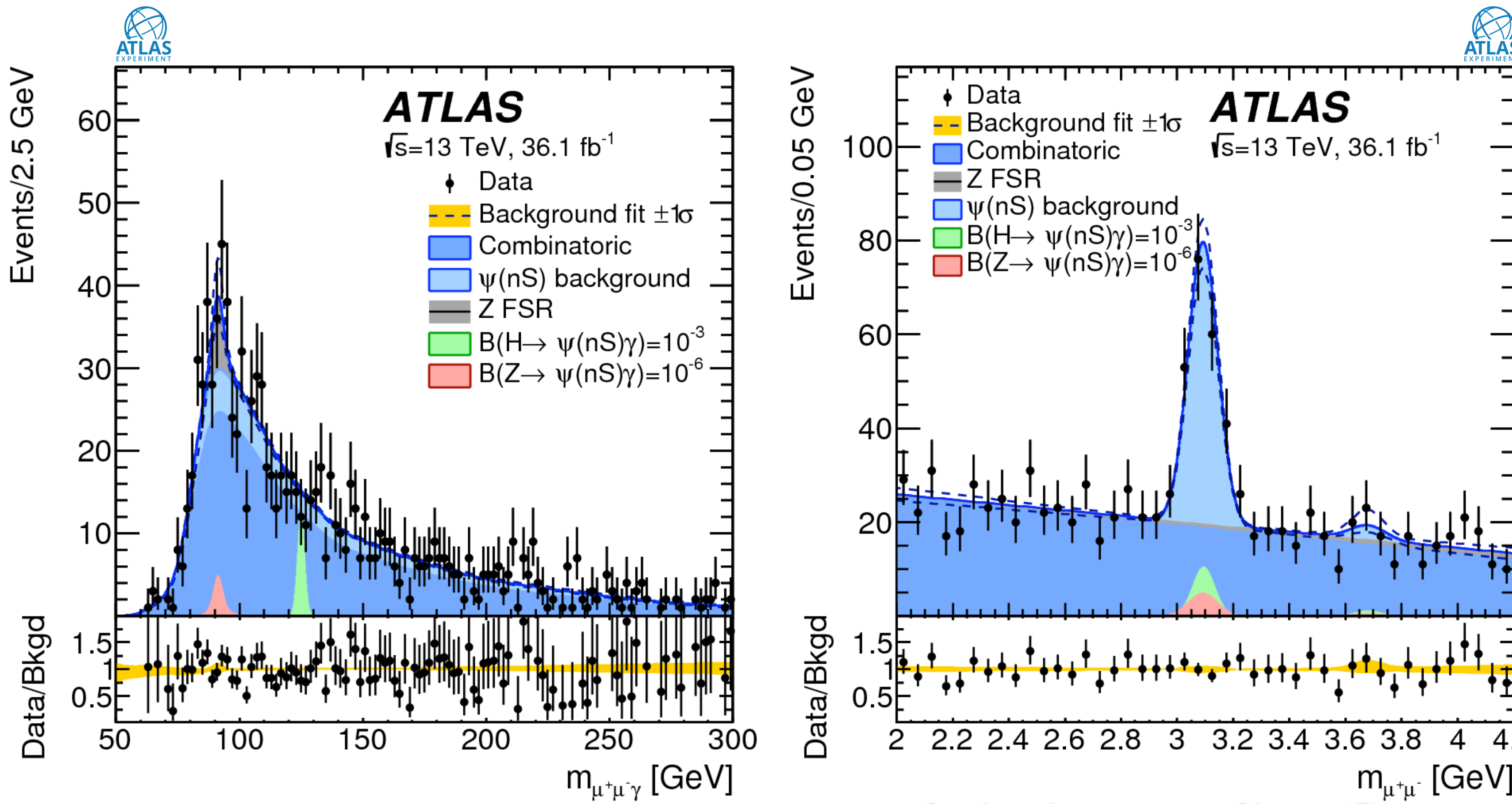
Signal and backgrounds



$H \to J/\Psi\ \gamma$

- Currently the most recent & advanced analysis is by ATLAS, on 2016 data
  - signal extraction using bi-dimensional fit in $m(\mu\mu)$ vs $m(\mu\mu\gamma)$ plane
  - background model for continuum $\mu\mu\ \gamma$ and $J/\Psi\ \gamma$ built by sampling probability densities extracted in data from relaxed selection
- CMS performed same search on 2016 data, with simpler approach, 1D fit of $m(\mu\mu\gamma)$
- Both analyses also search for $Z \to J/\Psi\ \gamma$

H → J/Ψ γ: look at the data



arXiv:1807.00802, sub. to PLB

- 1D projections on m(μμγ) and m(μμ)
- Higgs signal shown for BR 10^{-3} (~300 × SM)

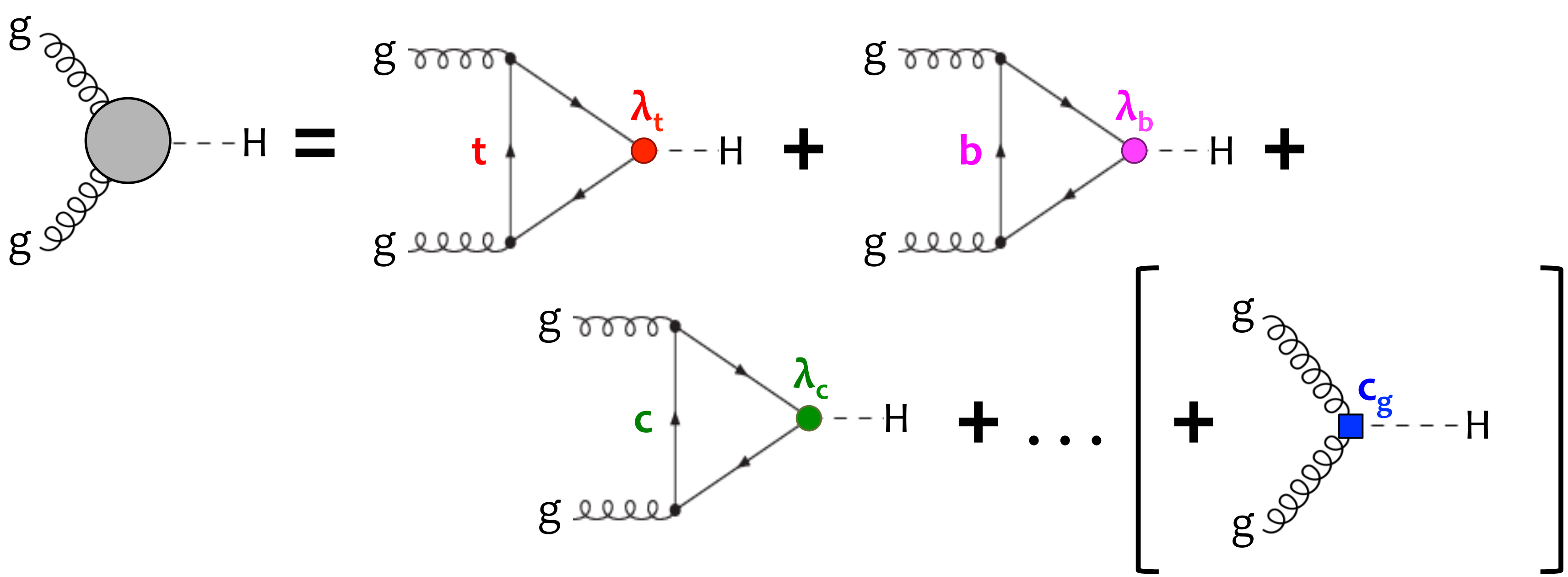
$H \rightarrow J/\Psi\ \gamma$: results

- ATLAS upper limit on BR($H \rightarrow J/\Psi\ \gamma$)
  - BR < 3.5×10^{-4} observed (3.0×10^{-4} expected), corresponding to < **120 (100) × BR_{SM}**
- CMS upper limit on BR($H \rightarrow J/\Psi\ \gamma$)
  - BR < 7.6×10^{-4} observed (5.2×10^{-4} expected), corresponding to < 260 (170) × BR_{SM}
  - Combination with Run 1: < **220 (160) × BR_{SM}**

arXiv:1807.00802, sub. to PLB

CMS PAS SMP–17–002

constrain λ_c from H kinematics?



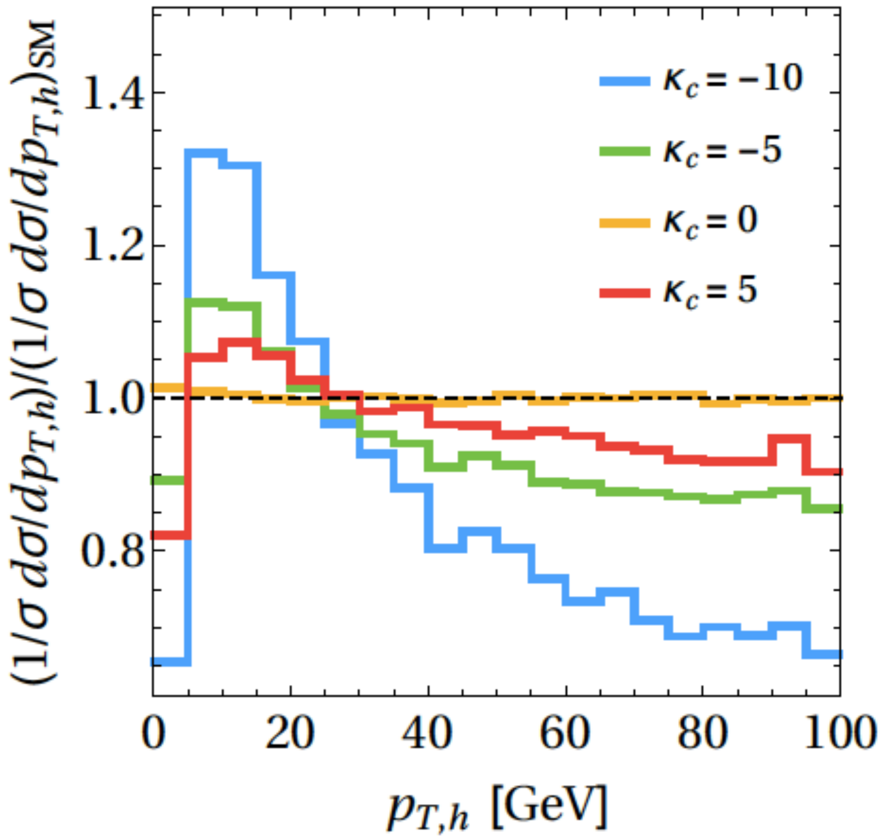
- σ(ggH) and p_T(H) dependent on λ_t, λ_b, λ_c,
  - O(1%) effects from charm, mostly at low p_T
  - Possible extra contact term c_g from heavy BSM physics, at scale $\Lambda >> m_h$, can be probed at high p_T

constrain λ_c from $p_T(H)$

CMS analysis, 2016 data:

- p_T(ggH) predictions provided by theorists in terms of $\kappa_q := \lambda_q / \lambda_q^{SM}$
  - p_T range [0, 120] GeV, well below m_{top}
- Parameterization as quadratic polynomial in κ_t, κ_b, κ_c at each p_T

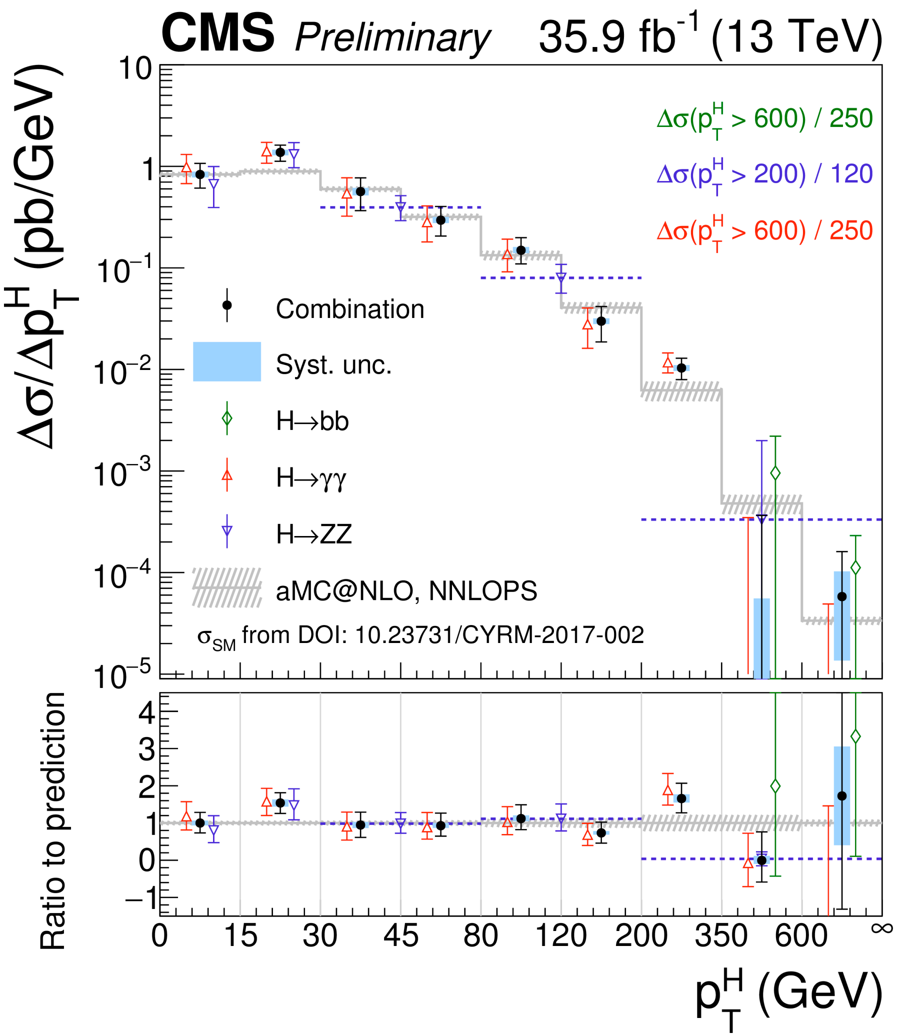
Bishara, Haisch, Monni, Re PRL 118, 121801 (2017)



measure $p_T(H)$

- Combined fit of $p_T(H)$ measurements from γγ and ZZ final states
  - H→bb measurement starting from 350 GeV
- Likelihood unfolding, no regularization.
- Theory uncertainties on $p_T(H)$ included

CMS PAS HIG-17-028

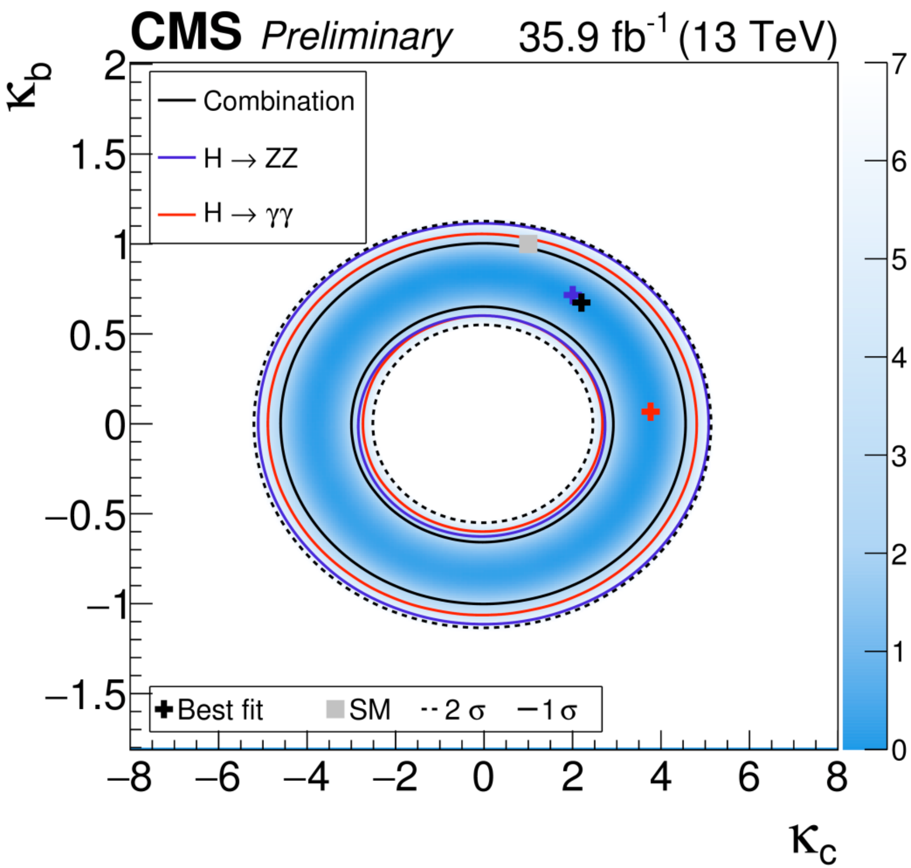


Model assumptions

- Vary only κ_b, κ_c: fix $\kappa_t = 1$ in σ(ggH)
  - VBF, WH, ZH, ttH as in SM (with uncertainties)
  - σ(bbH) scaled from SM prediction as κ_b^2
- Modifications to couplings also affect BR's. Considered two extreme scenarios:
  1. Only SM decays, all other coupling modifiers κ_i fixed to 1: BR(γγ, ZZ) strongly sensitive to κ_b, κ_c
  2. BR(γγ) and BR(ZZ) considered free parameters i.e. rely only on $p_T(H)$ shape information

Results

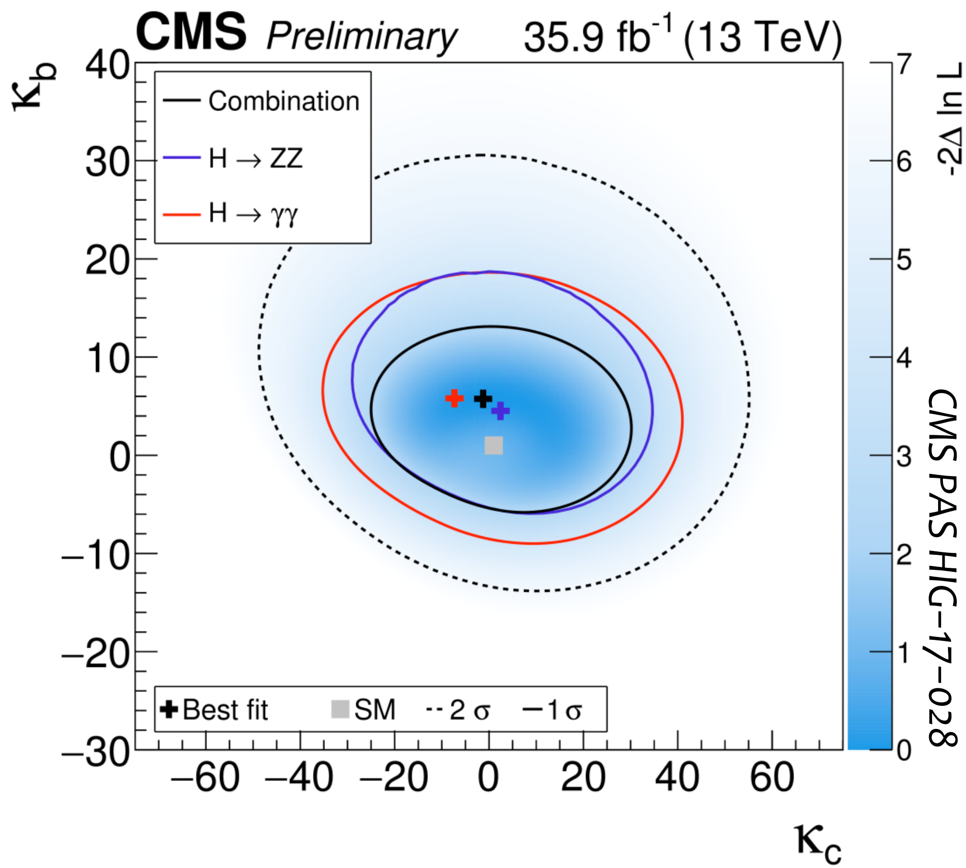
Scenario 1: BR = BR(κ_b, κ_c)



$-4.3 < \kappa_c < 4.3$ observed

($-5.4 < \kappa_c < 5.3$ expected)

Scenario 2: free BR's

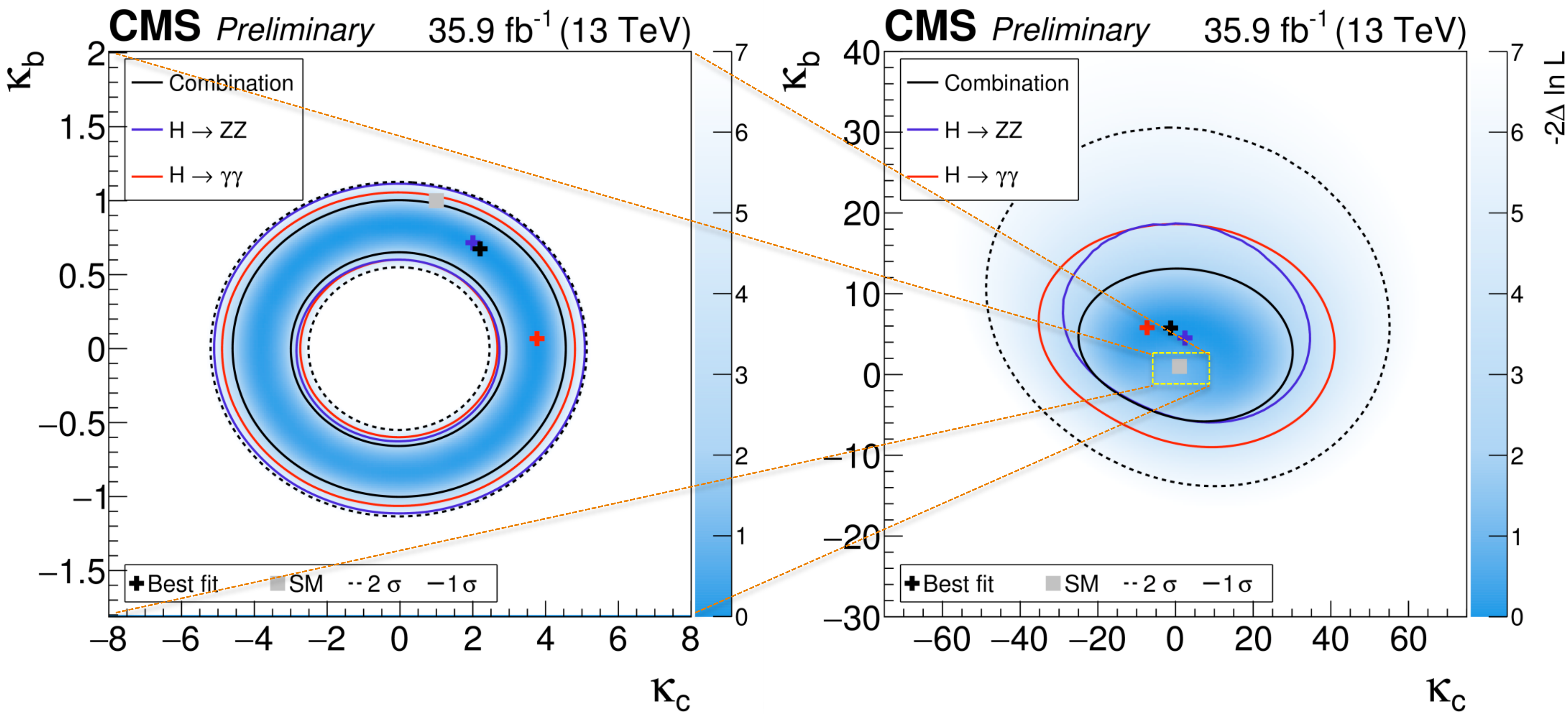


$-18 < \kappa_c < 23$ observed

($-16 < \kappa_c < 19$ expected)

Results

Scenario 1: BR = BR(κ_b, κ_c) **Scenario 2: free BR's**



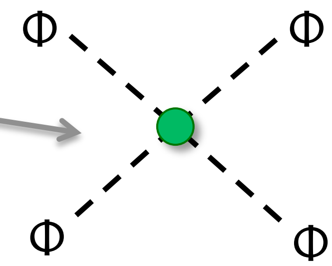
$-4.3 < \kappa_c < 4.3$ observed
($-5.4 < \kappa_c < 5.3$ expected)

$-18 < \kappa_c < 23$ observed
($-16 < \kappa_c < 19$ expected)

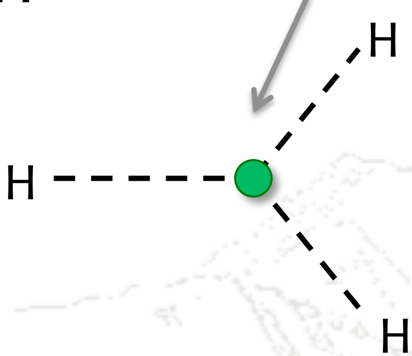
Higgs boson self-coupling

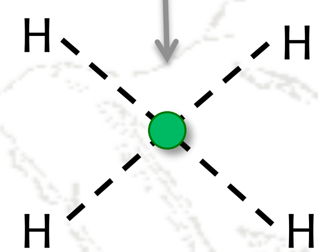
- Self-coupling essential in the EWSB potential

$$V(\varphi) = -\mu^2 (\Phi^\dagger \Phi)^2 + \lambda (\Phi^\dagger \Phi)^2$$



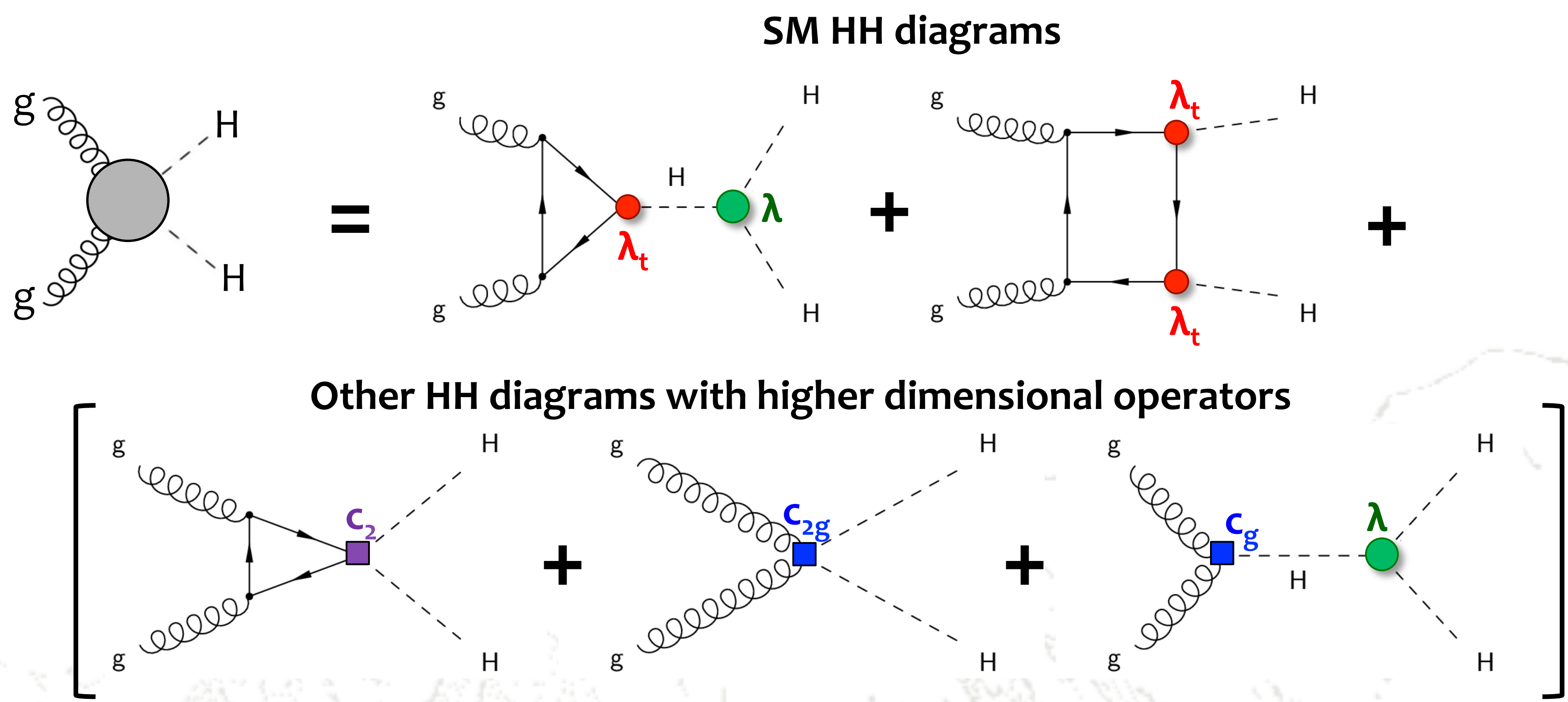
$$= V_0 + \tfrac{1}{2} m_H{}^2 H^2 + \lambda v H^3 + \tfrac{1}{4} \lambda H^4$$





Higgs boson self-coupling

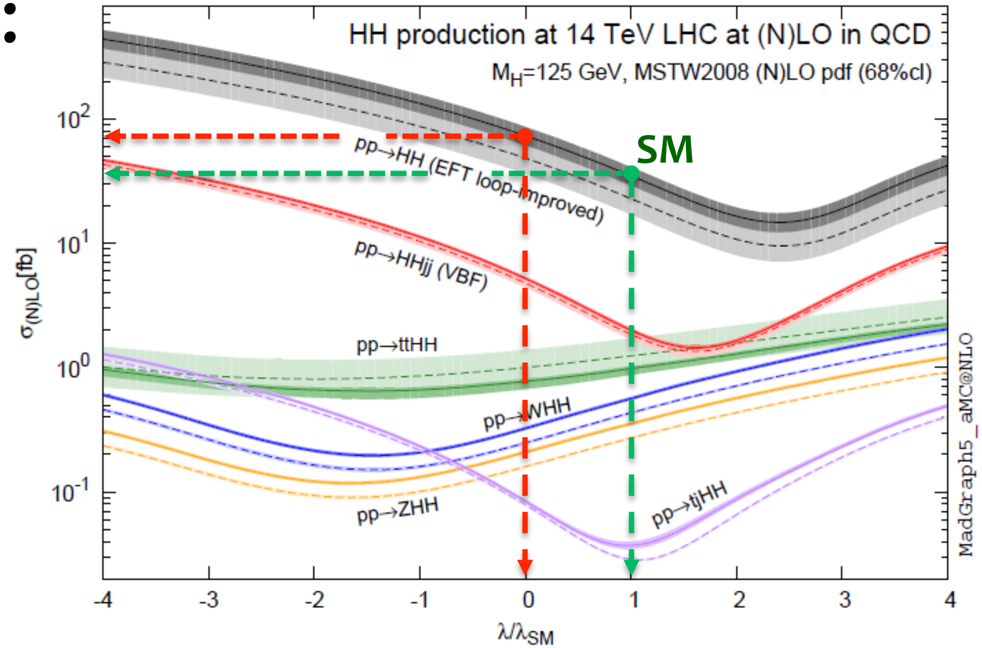
- Trilinear λ can be probed in HH production
  - With a caveat: other couplings affect HH too!



HH production

- SM σ(ggHH): 33.5 fb:
  - factor ~200 smaller than σ(ggH)
- Smallness of SM HH due to destructive interference
  - Larger σ for λ = 0

[PLB 732 (2014) 142-149]

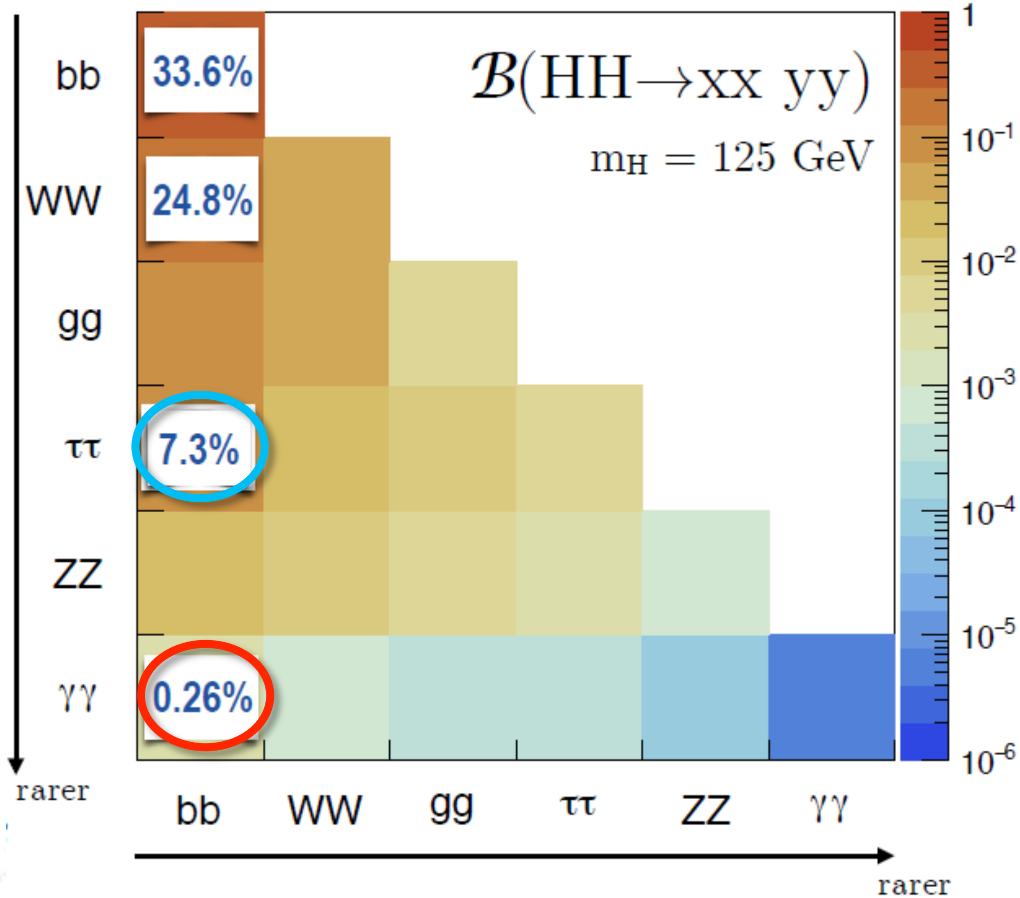


$$\sigma/\sigma_{SM} \sim 2.09\,\kappa_t^4 - 1.36\,\kappa_\lambda\kappa_t^3 + 0.28\,\kappa_\lambda^2\kappa_t^2$$

$[\kappa_t := \lambda_t / \lambda_t^{SM}\ ;\ \kappa_\lambda := \lambda / \lambda_{SM}\ ]$

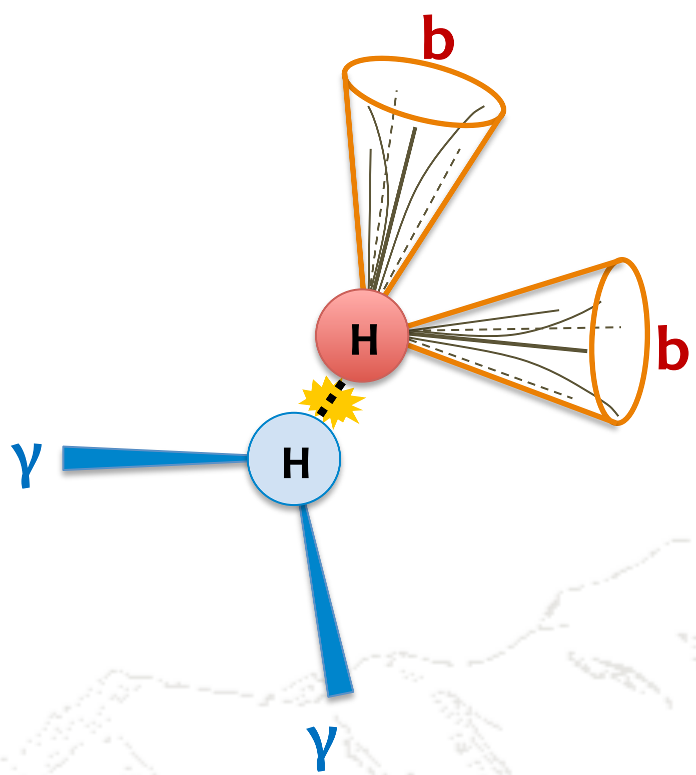
HH production

- Smallness of σ requires using larger BR decays
- Currently best sensitivity for SM-like HH in: **bbττ** (ATLAS), **bbγγ** (CMS)



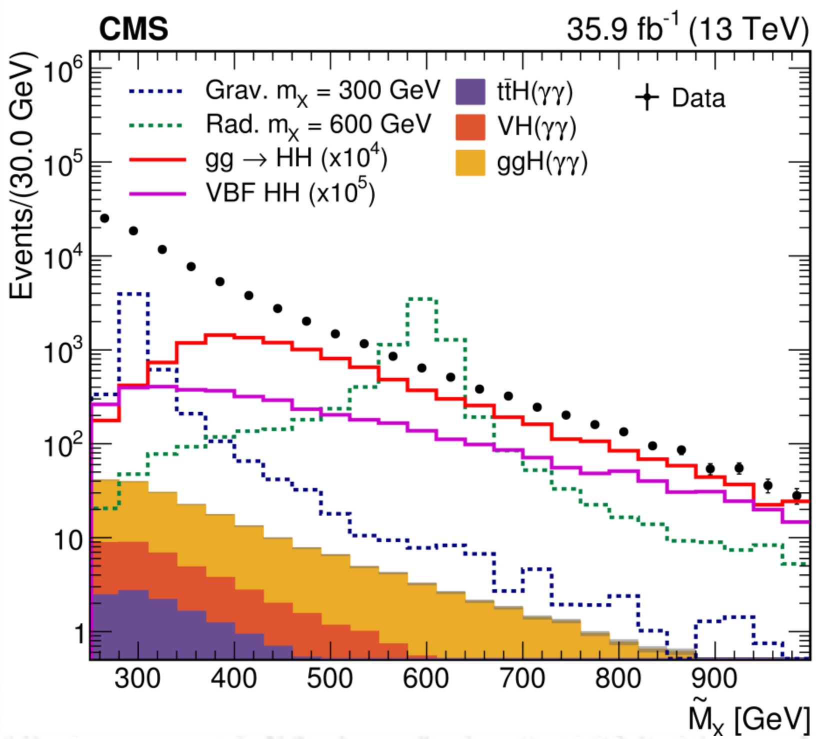
CMS HH → bb γγ

- $\sigma_{ggHH} \times BR = 0.087$ fb
  - expect ~ 3 events / 2016 dataset
- Rely on the two invariant masses:
  - **m(γγ)**: discriminate between signal and continuum γγ + jets
  - **m(bb)**: discriminate against H + jets (including VBF, VH, ttH, …)
- Exploit tools developed for the H → γγ and H → bb analyses:
  - vertex selection, photon MVA identification & energy calibration
  - b-jet energy regression: dedicated version using also E_T^{miss} to balance the event (as $Z_{\ell\ell}H_{bb}$)



CMS HH → bb γγ

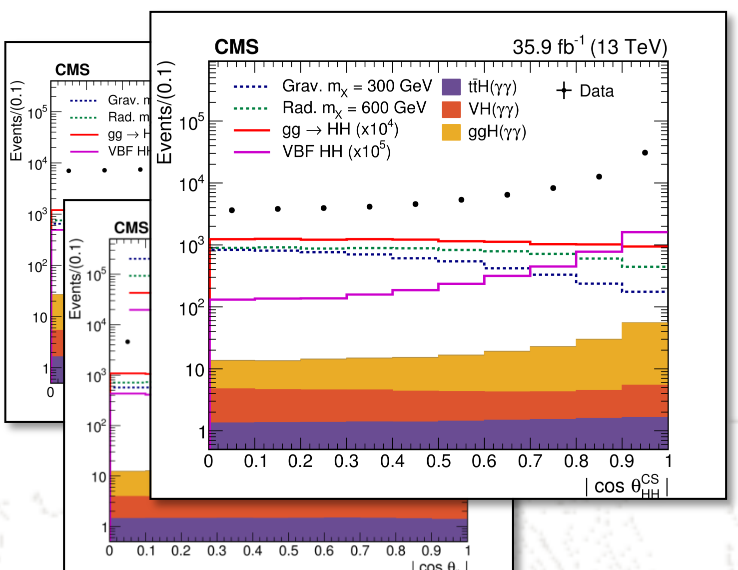
- Build additional variables to improve purity:
  1. $\mathbf{M_X := m_{\gamma\gamma jj}} + (m_H - m_{jj}) + (m_H - m_{\gamma\gamma})$

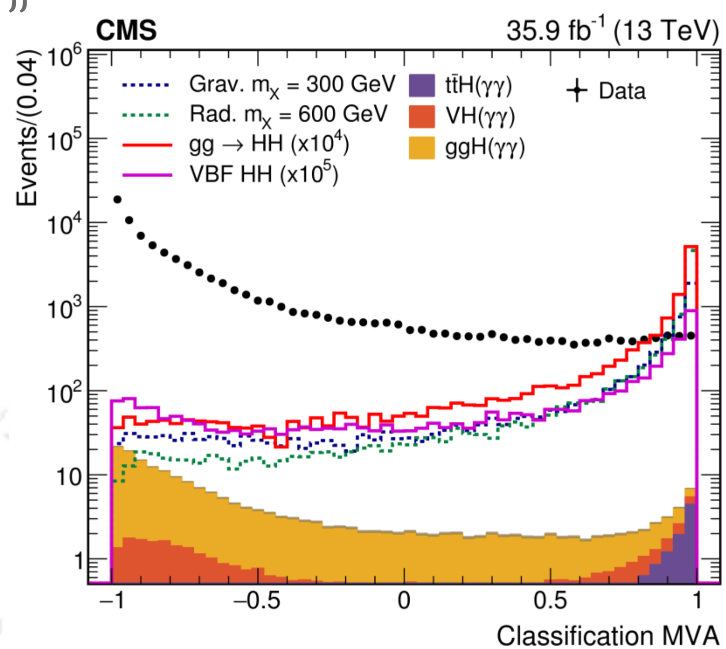


correction to reduce correlation with m_{jj}, $m_{\gamma\gamma}$ and improve resolution (simple approximation of a kinematic fit)

CMS HH → bb γγ

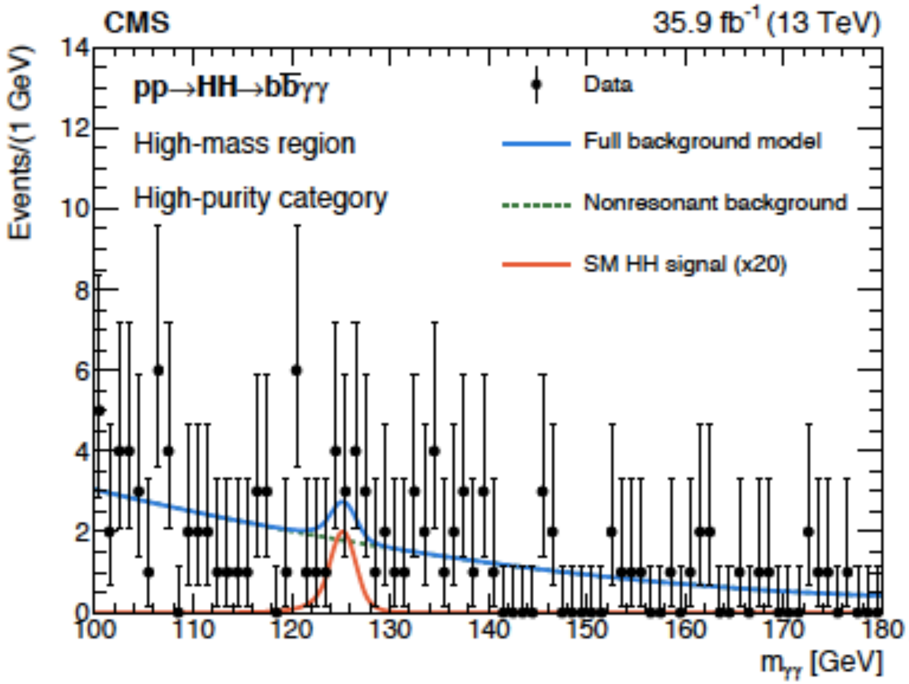
- Build additional variables to improve purity:
  1. $\mathbf{M_X := m_{\gamma\gamma jj}} + (m_H - m_{jj}) + (m_H - m_{\gamma\gamma})$
  2. **MVA** discriminant using b-tagging, helicity angles, $p_T^{\gamma\gamma}/m_{\gamma\gamma jj}$, $p_T^{bb}/m_{\gamma\gamma jj}$

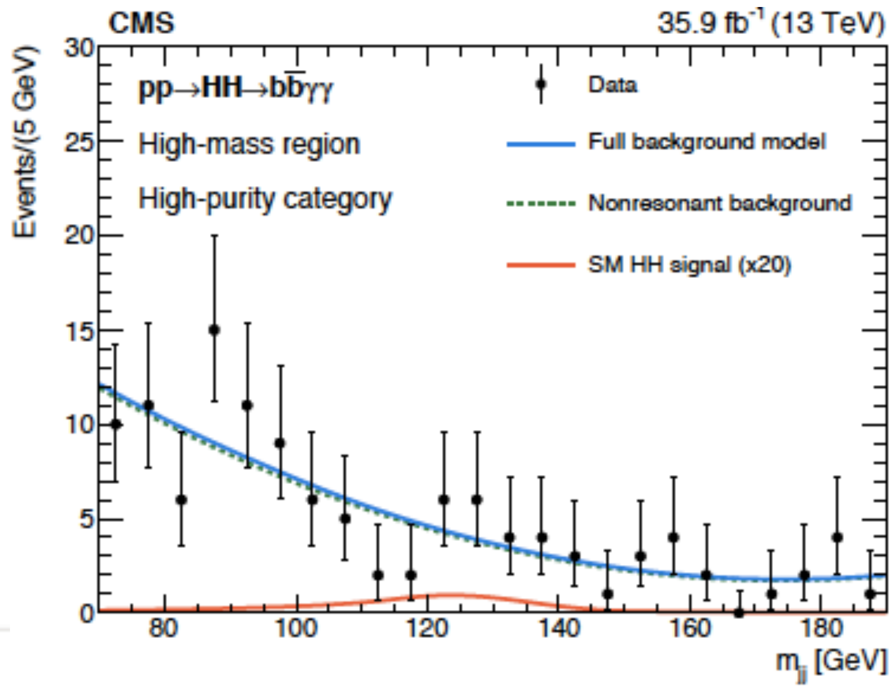




CMS HH → bb γγ

- Signal extraction: **2D fit of $m_{\gamma\gamma}$ vs m_{bb}** in categories defined by M_X & MVA





HH → bb γγ results

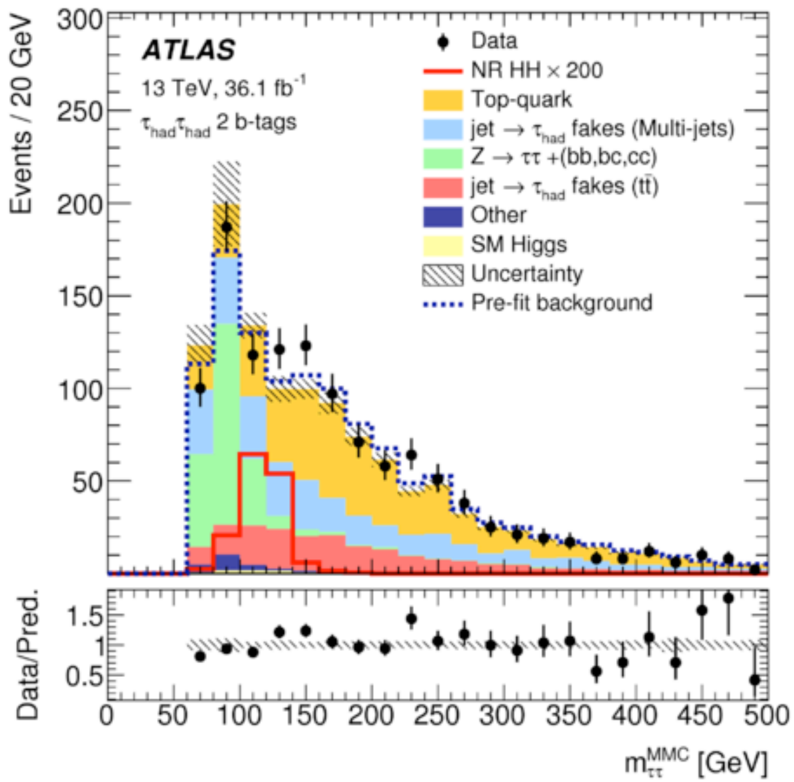
- CMS upper limit on σ_{ggHH}: 0.79 pb (expected upper limit 0.63 pb)
  - Corresponding to **24 × σ_{SM}** (**19 × σ_{SM}**)
  - Further ~1.3% improvement if including also expected signal from VBF HH
- ATLAS bbγγ analysis, simpler approach:
  - no m(bb) regession, mostly cut-based categorization, 1D fit of $m_{\gamma\gamma}$
  - Upper limit 0.73 pb (expected 0.93 pb), corresponding to **22 × σ_{SM}** (**24× σ_{SM}**)

arXiv 1806.00408, sub to PLB

arXiv 1807.04873, sub to JHEP

ATLAS HH → bb ττ

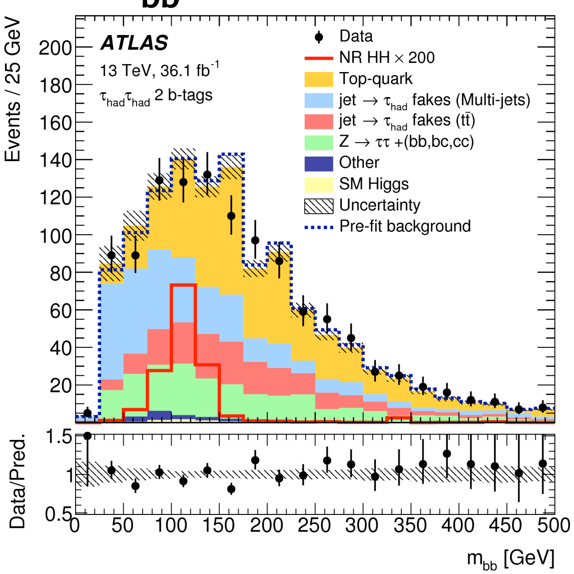
- Analysis in $bb\tau_\ell\tau_h$ and $bb\tau_h\tau_h$ final states
  - Relying on 1ℓ, $\ell + \tau_h$, $1\tau_h$, $2\tau_h$ triggers
  - $m_{\tau\tau}$ reconstruction with MMC algorithm
  - m_{HH} reconstructed with $m_{\tau\tau} = m_{bb} = m_H$ constraint
- Main backgrounds from tt, $Z_{\tau\tau}$ + b/c jets, fakes (jets mis-id as τ_h)



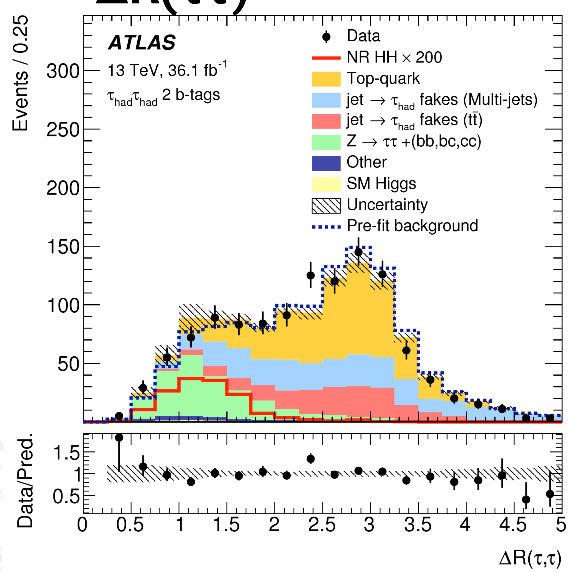
ATLAS HH → bb ττ

- BDT to separate HH from all backgrounds ($\tau_h\tau_h$), or dominant tt background ($\tau_\ell\tau_h$):
  - inputs: $m_{\tau\tau}$, m_{bb}, m_{HH}, ΔR_{bb}, $\Delta R_{\tau\tau}$, E_T^{miss} φ centrality ($\tau_h\tau_h$) or $m_T^{\ell\nu}$ ($\tau_\ell\tau_h$)

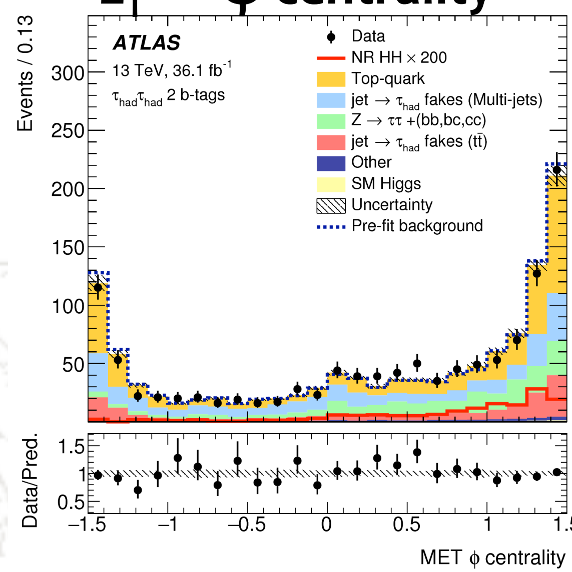
m_{bb}



$\Delta R(\tau\tau)$

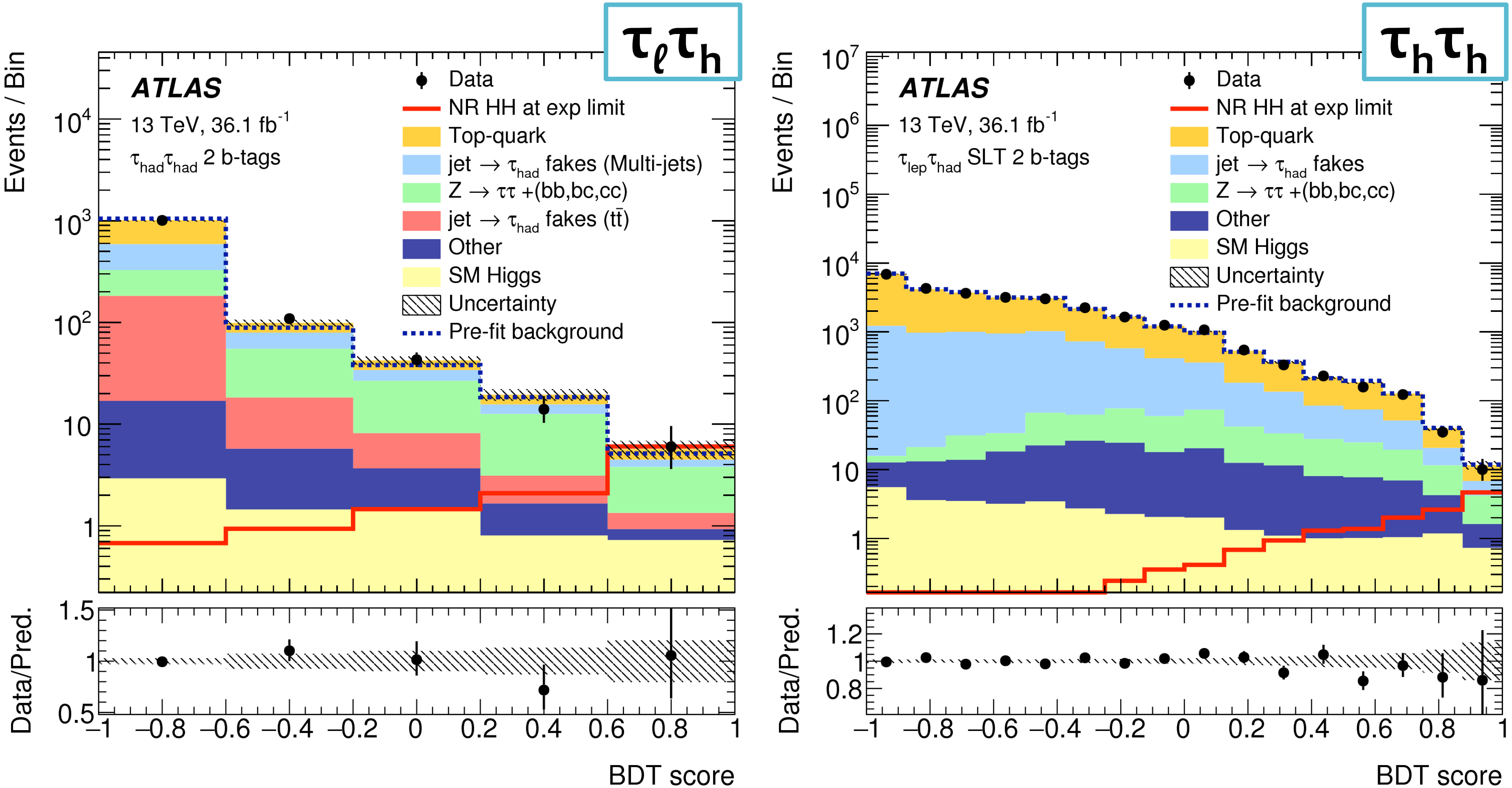


E_T^{miss} φ centrality



ATLAS HH → bb ττ

- Signal extraction from BDT output distribution



HH → bb ττ results

- ATLAS upper limit on $\sigma_{HH \to bb\tau\tau}$: 30.9 fb (expected upper limit 36.1 fb)
  - Corresponding to **12.7 × σ_{SM}** (**14.8 × σ_{SM}**)
  - Most sensitivity from $\tau_h\tau_h$ (exp. 17 × σ_{SM})
- Earlier CMS analysis, simpler approach:
  - Fit to m_{T2} instead after BDT cut ($\tau_\ell\tau_h$), or after cut-based selection ($\tau_h\tau_h$)
  - Upper limit 75.4 fb (expected 61.0 fb), corresponding to **30 × σ_{SM}** (**25× σ_{SM}**)

arXiv 1808.00336, sub. to PRL

arXiv 1707.02909 , PLB 778 (2018) 101

Conclusions

- Higgs boson coupling to all 3rd generation fermions have now been observed ($\geq 5\sigma$)
  - all results comparible with SM predictions
- Good prospects for $H \rightarrow \mu\mu$
  - analyses now approaching $O(1)\times$SM sensitivity, with only a fraction of run 2 data analyzed
- Several analyses exploring Higgs–charm couplings and HH, but it's a long way to go
  - currently at $O(100)\times$SM and $O(10)\times$SM