What have we learned in Run-2 about the Higgs boson

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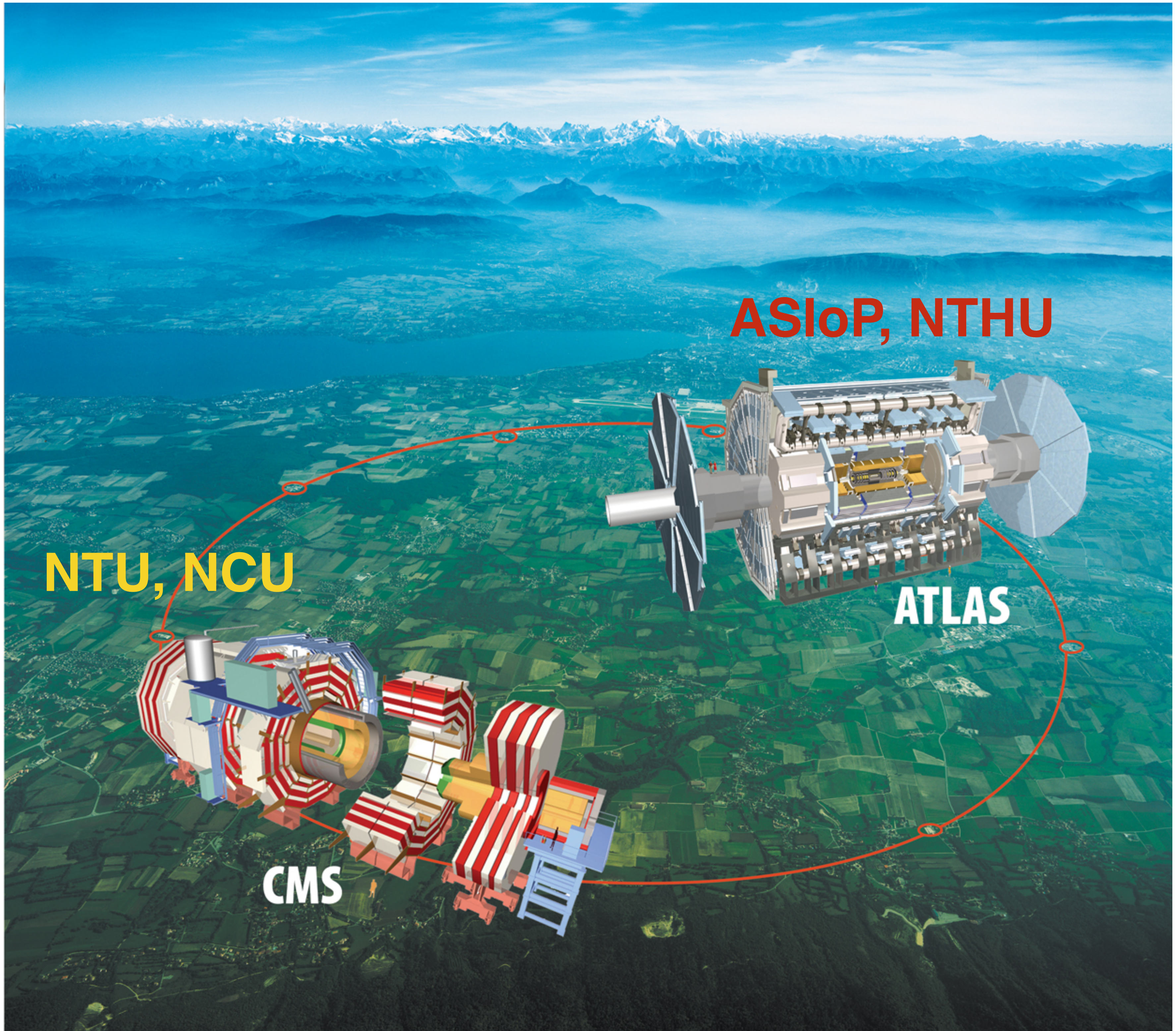
Outline

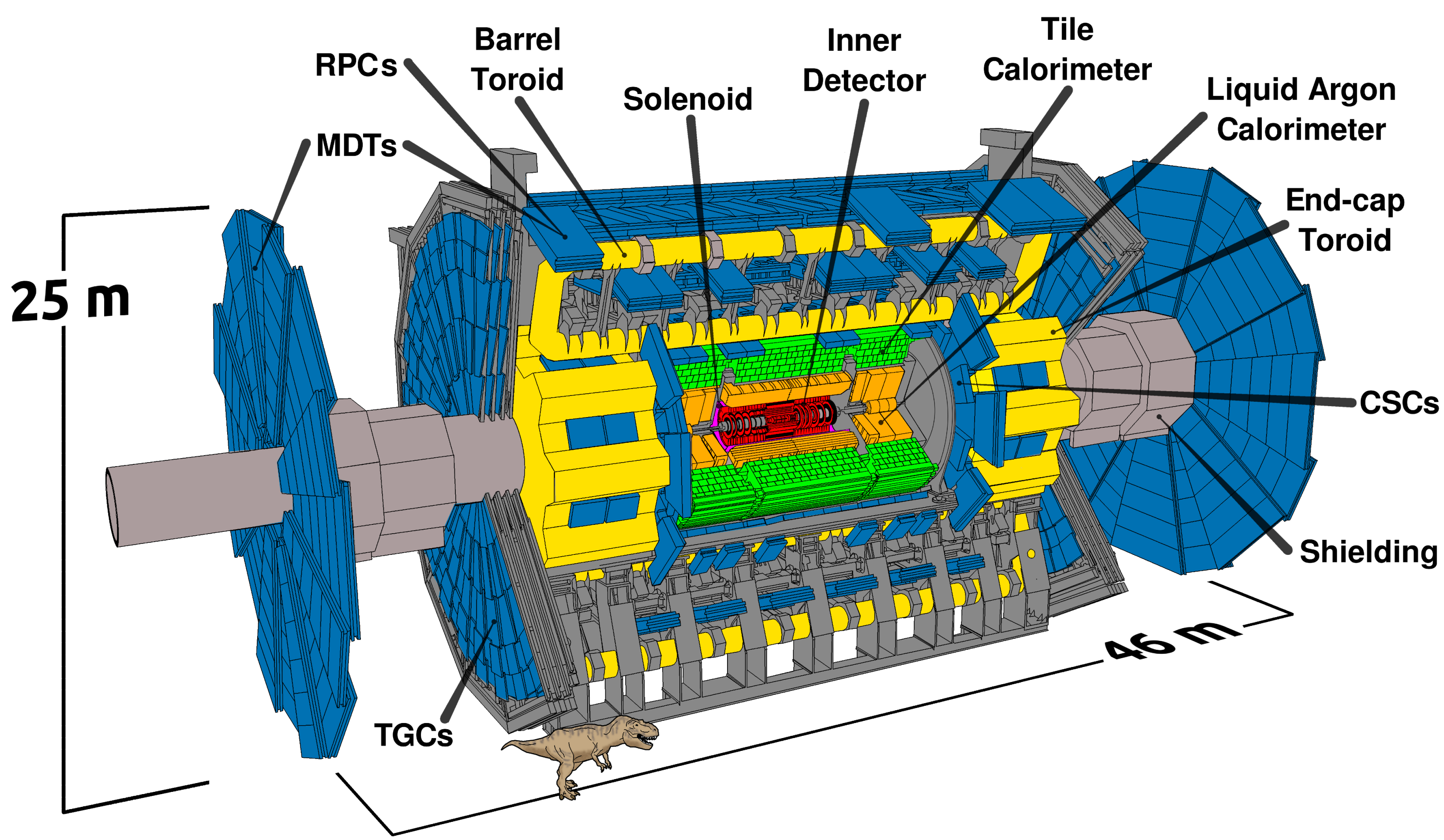
- The Experiments at the Large Hadron Collider
- The Higgs boson: What do we know now?
- Latest results (mostly from Higgs Couplings 2020)
- Summary and Outlook

TW@LHC

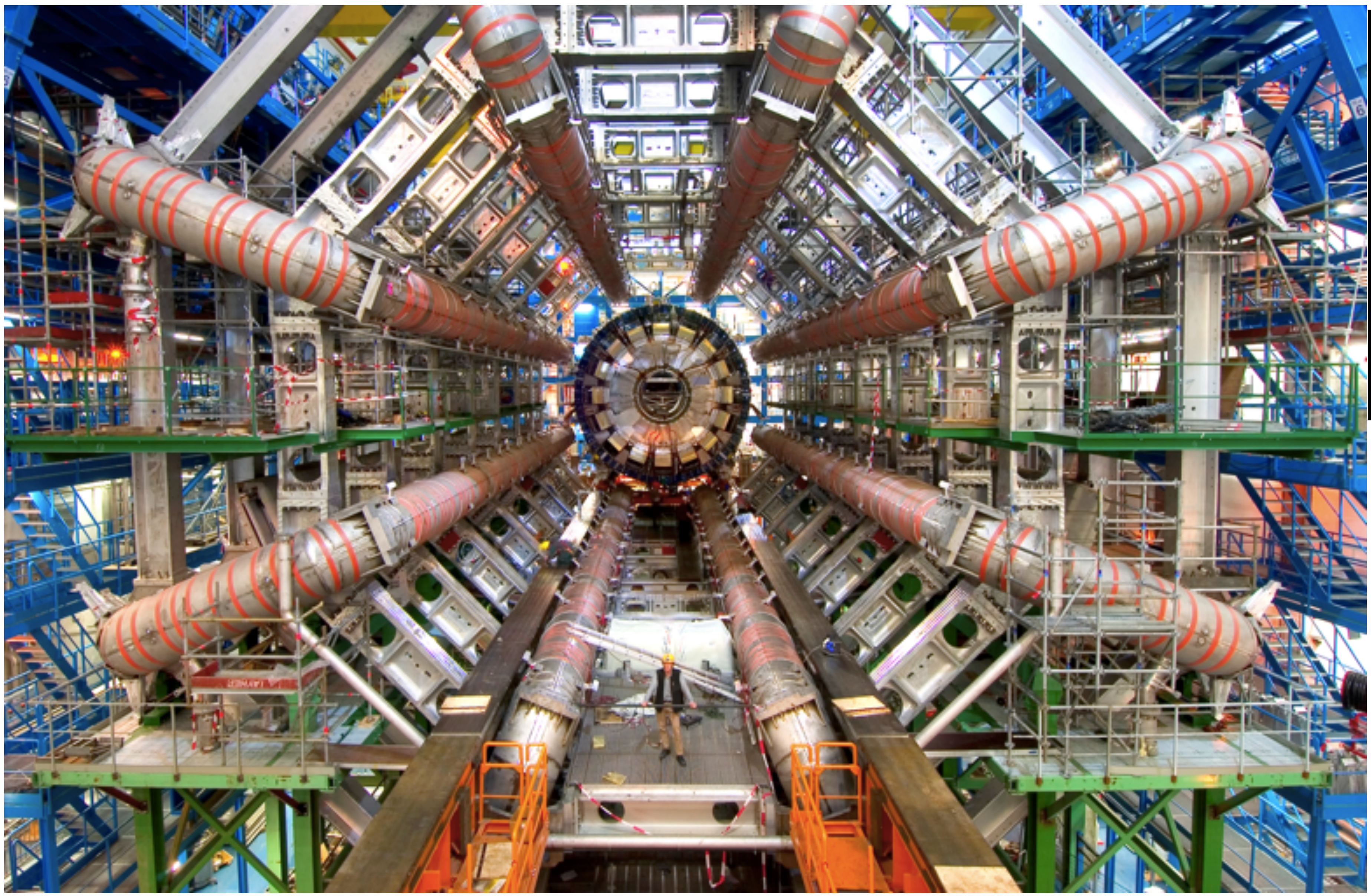


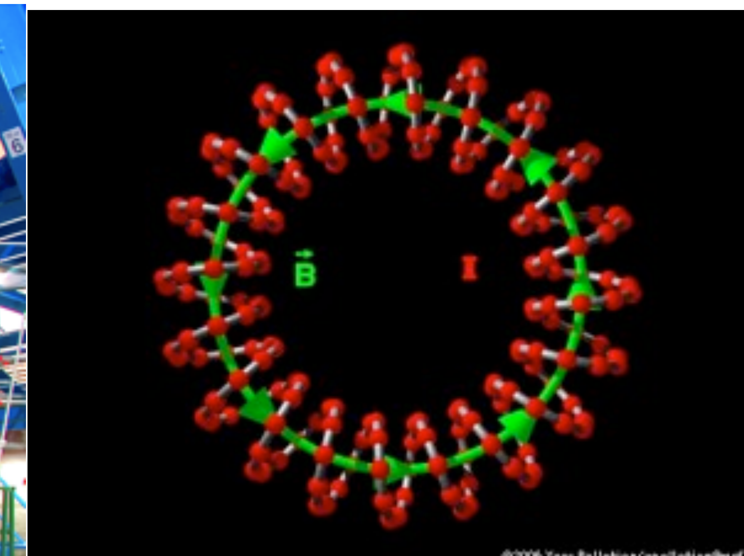
The ATLAS Detector

- ATLAS = *A Toroidal LHC ApparatuS*
- Feature: A giant toroidal magnet (in yellow below)



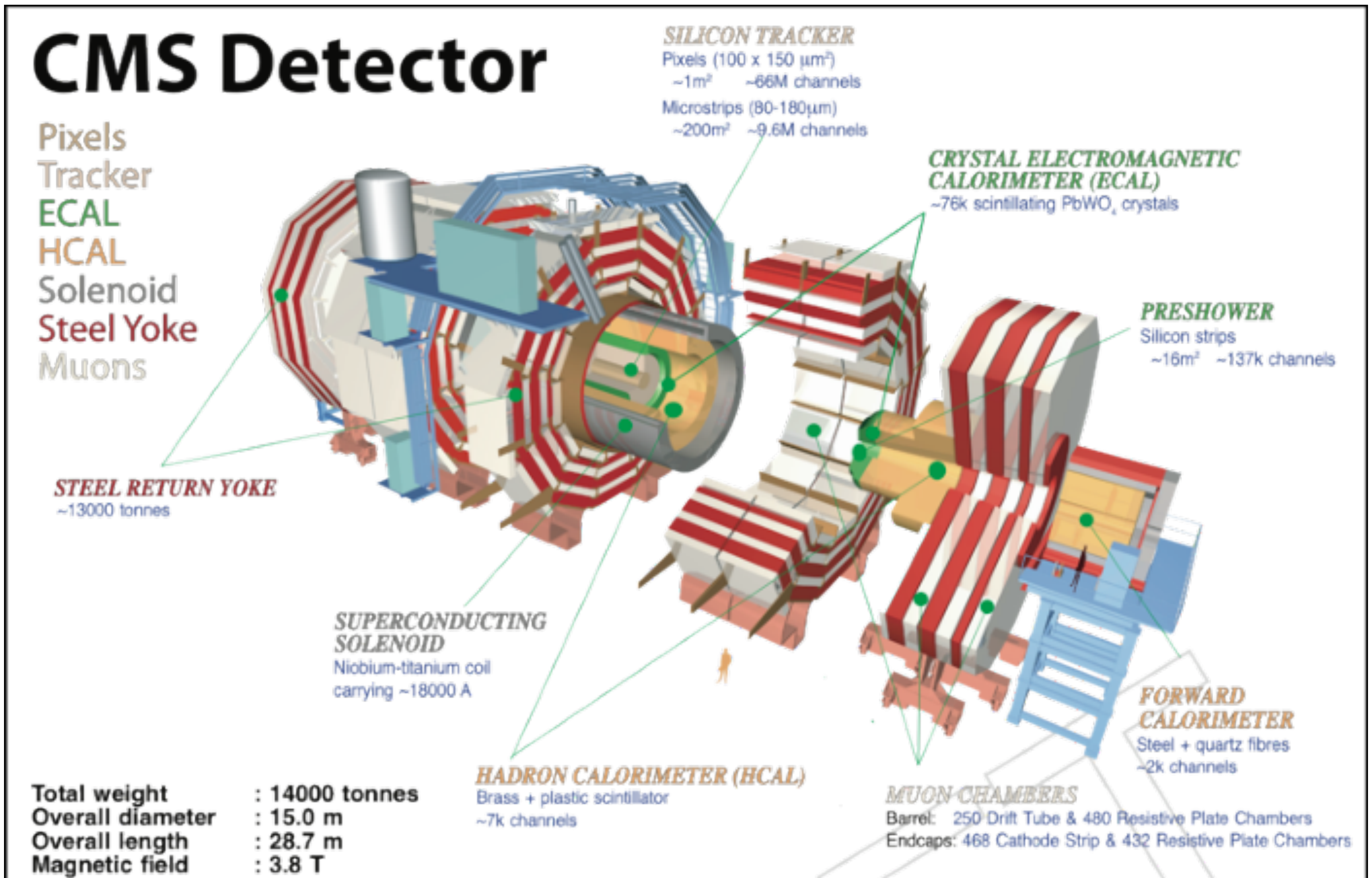
The ATLAS Detector





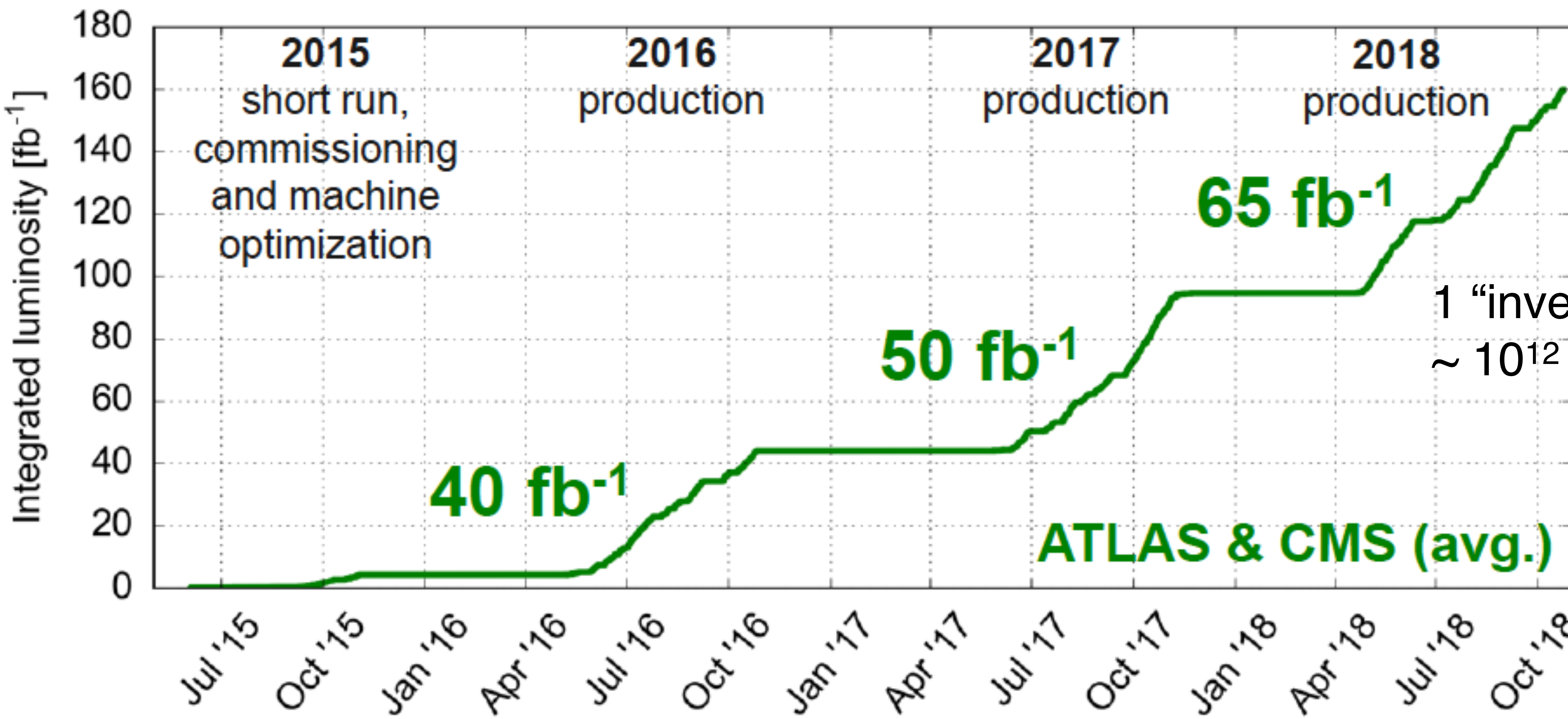
The CMS Detector

- CMS = The *C*ompact *M*uon *S*olenoid



Run-2 of the LHC (2015-2018)

- Proton collision at center-of-mass energy of 13 TeV!
- Collected more than 6x of Run-1 data

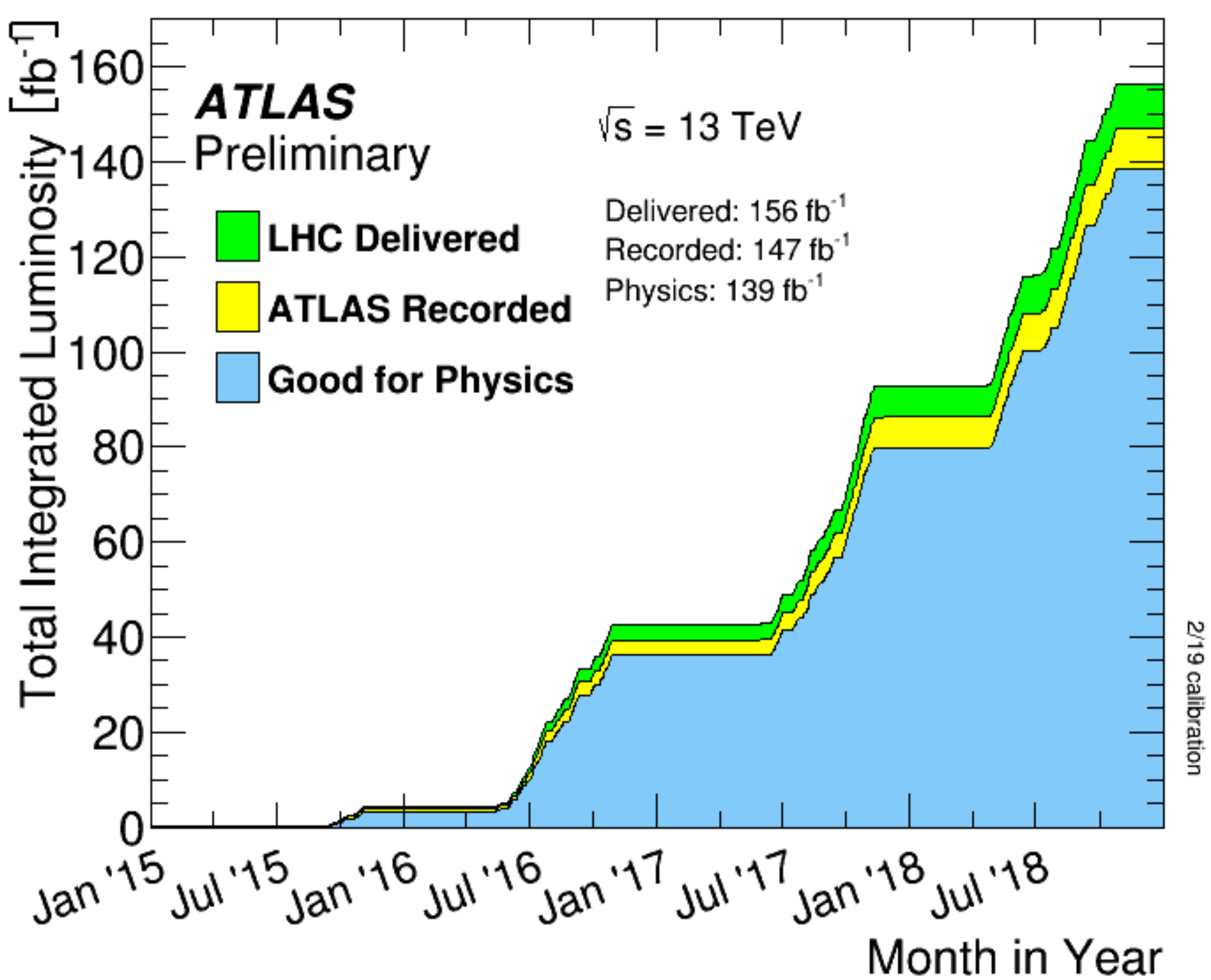


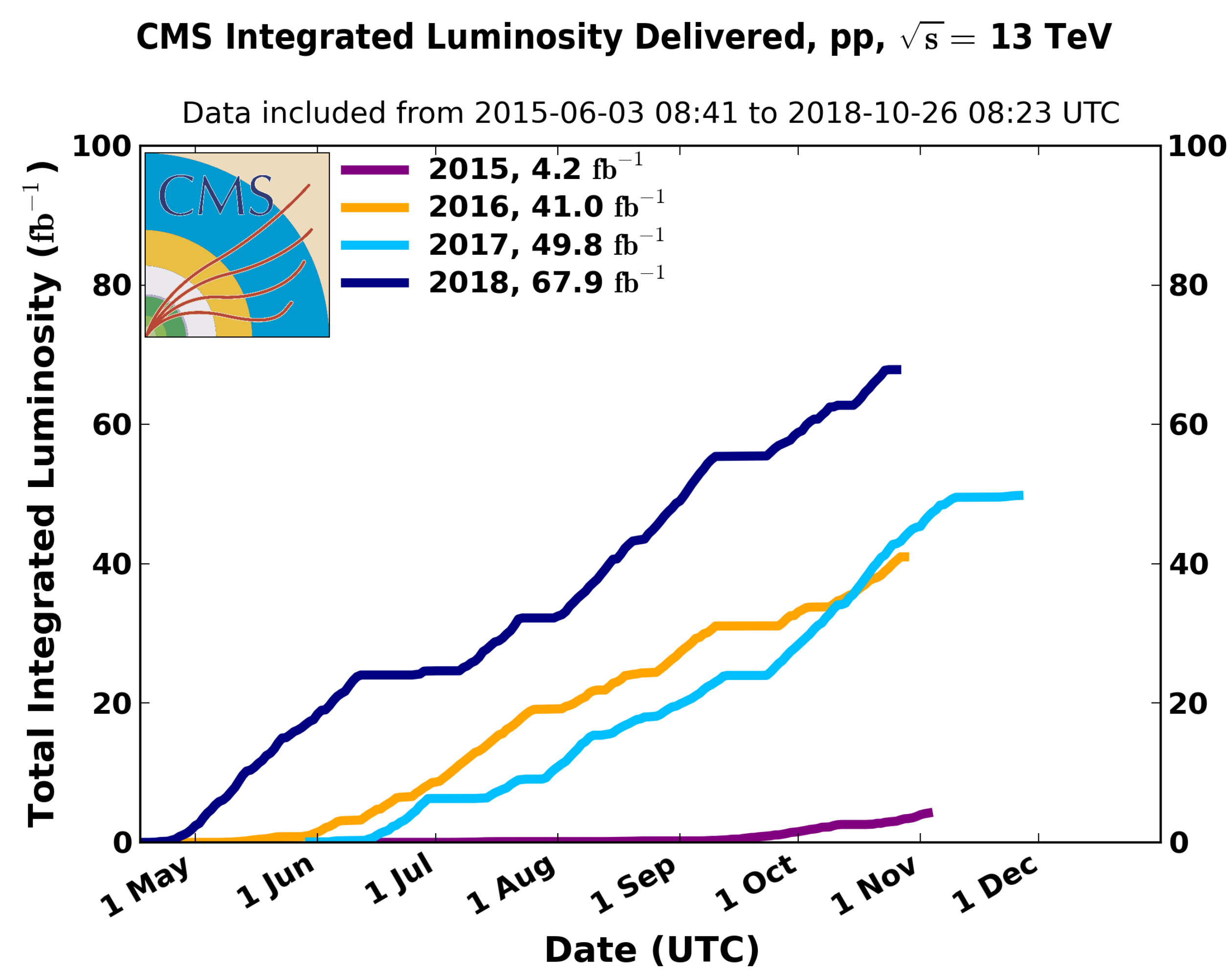
total 160 fb^{-1}

1 "inverse femtobarn" ~ 10^{12} p-p collisions

Run-2 of the LHC (2015-2018)

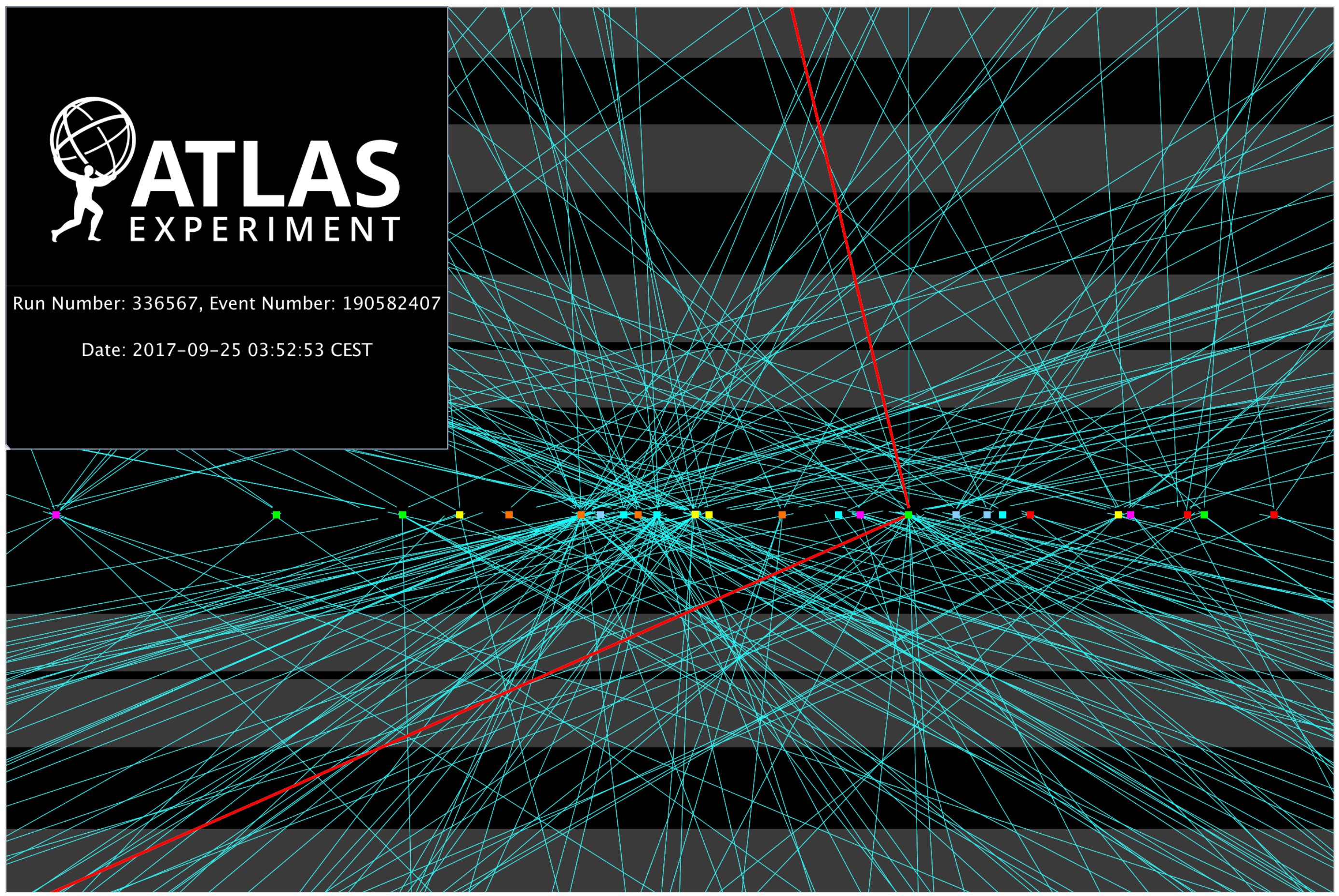
- Detectors performed very well; ~95% recording efficiencies
- ~140 fb^{-1} "good-for-physics" 13-TeV data



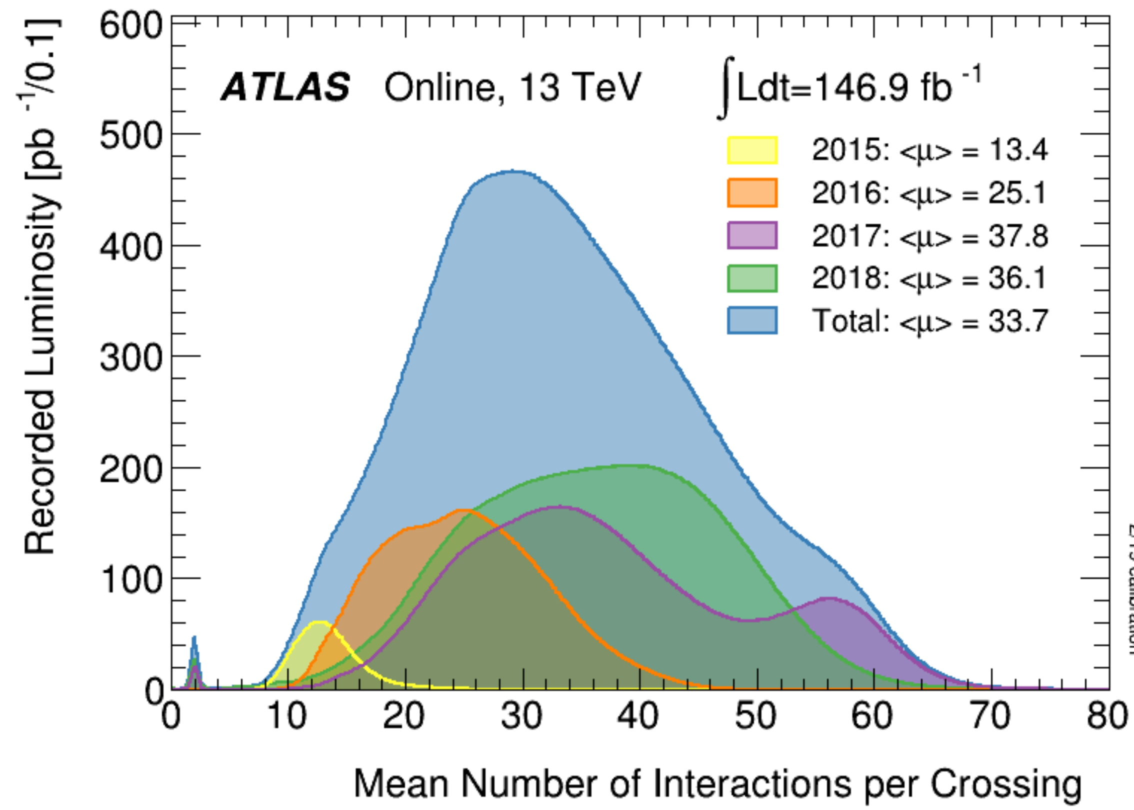


Challenges for Run-2: Pileup

A typical $Z \to \mu\mu$ event with 24 additionally reconstructed vertices



ATLAS Run-2

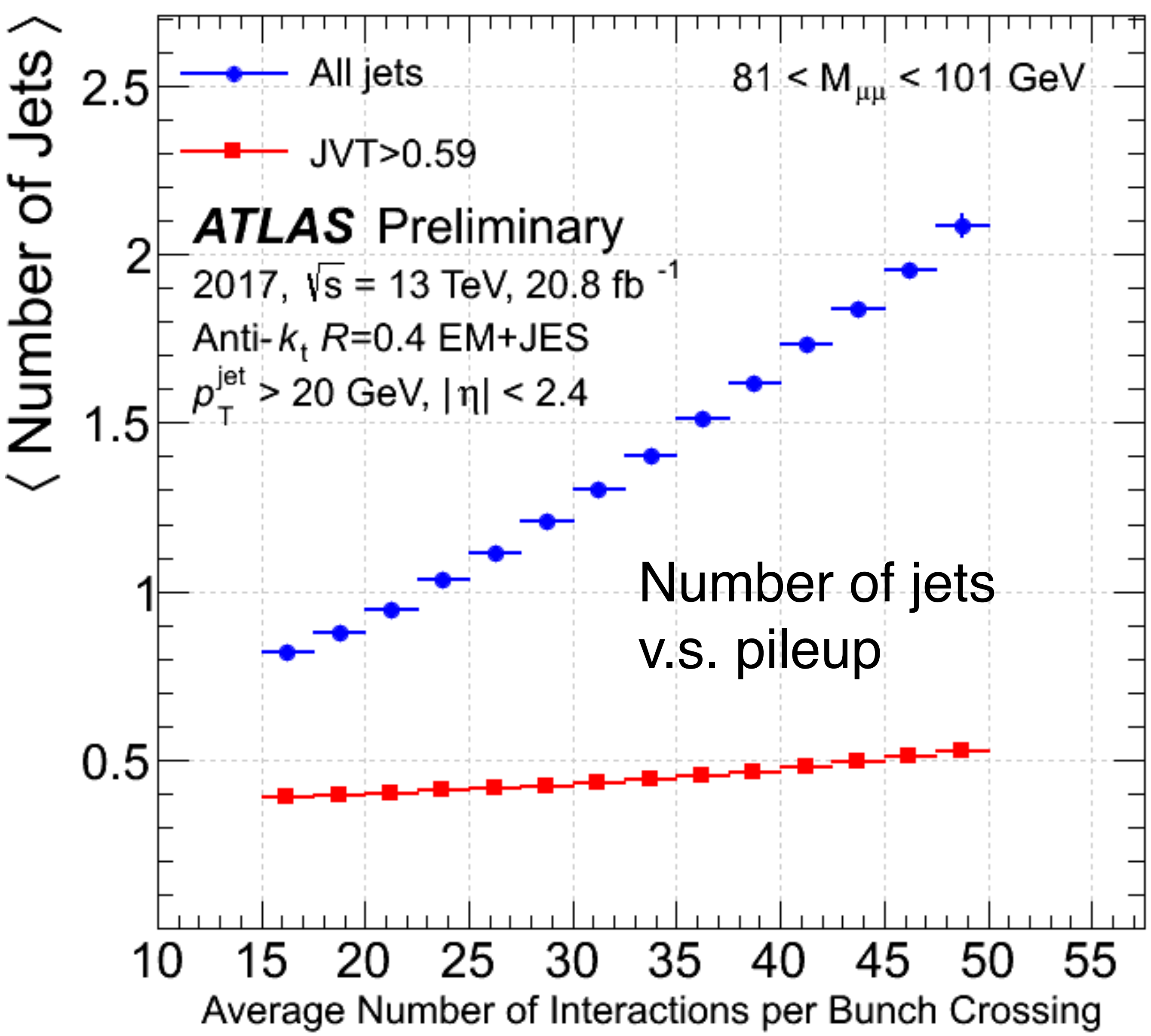


CMS

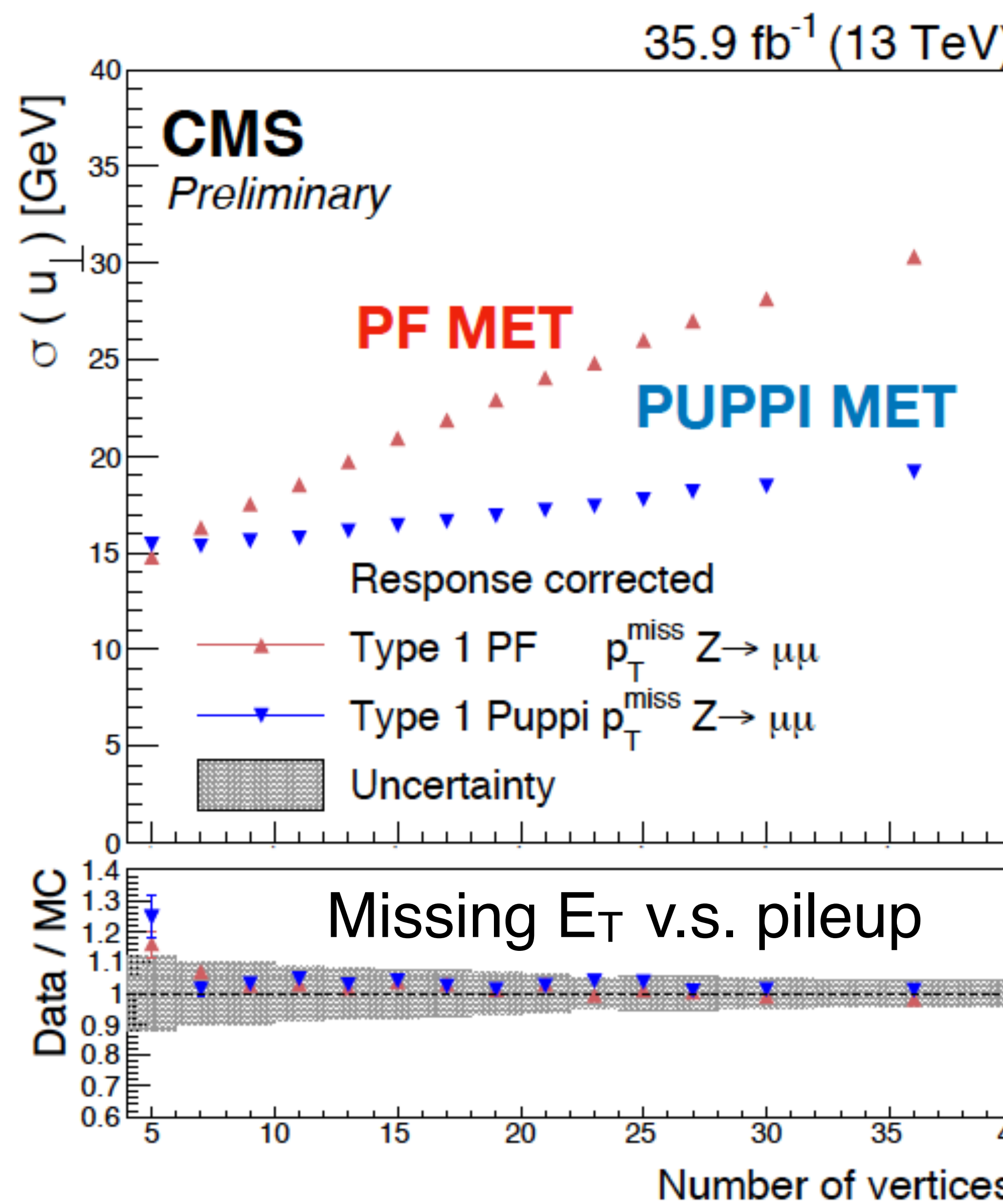
	Int. lumi	$<\mu>$
7 TeV	6.1 fb^{-1}	10
8 TeV	23.3 fb^{-1}	21
13 Tev	162.9 fb^{-1}	37

Challenges for Run-2: Pileup

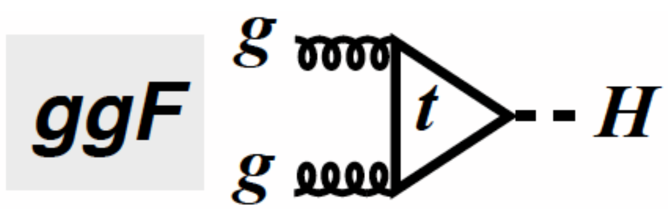
ATLAS: Jet Vertex Tagger (JVT)



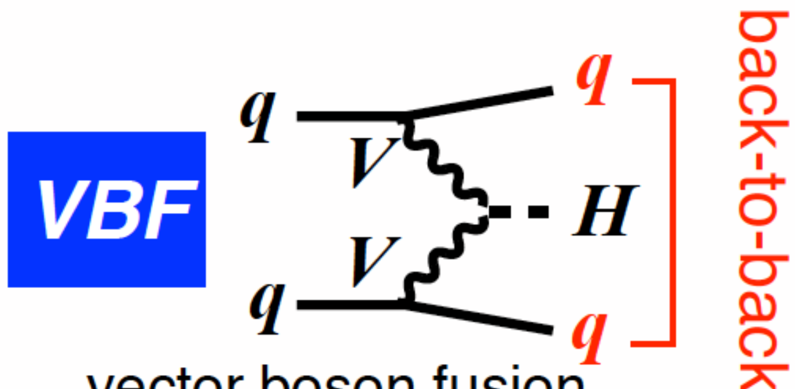
CMS: Particle Flow (PF) jets with PUPPI (Pileup Per Particle Identification) weights



Higgs Production

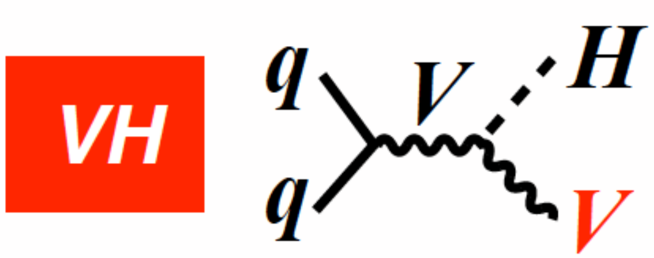
1. 

gluon-fusion

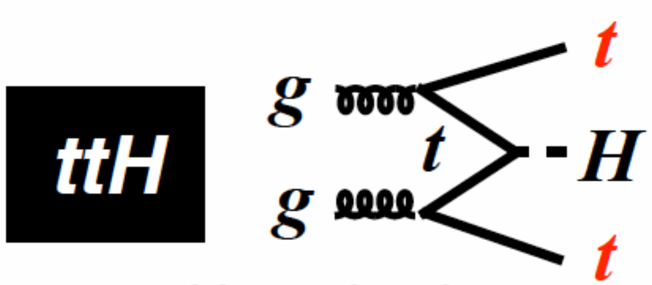
2. 

vector boson fusion

$V = W, Z$

3. 

WH/ZH production

4. 

ttH production

For a 125-GeV Higgs boson in an pp collider

87%

7%

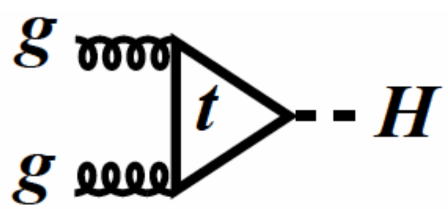
5%

1% rest (incl. *ttH*)

Higgs Production

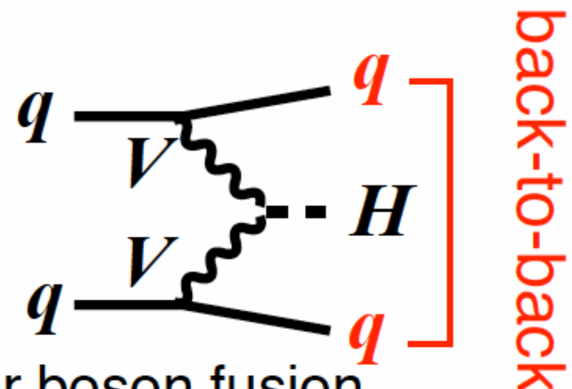
For a 125-GeV Higgs boson in an pp collider

1. ggF



gluon-fusion

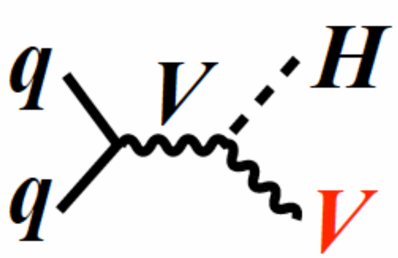
2. VBF



vector boson fusion

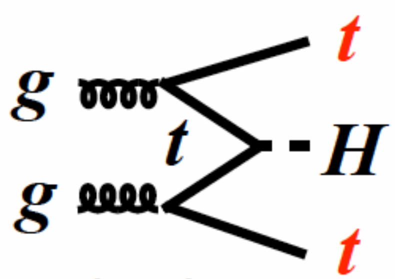
$V = W, Z$

3. VH

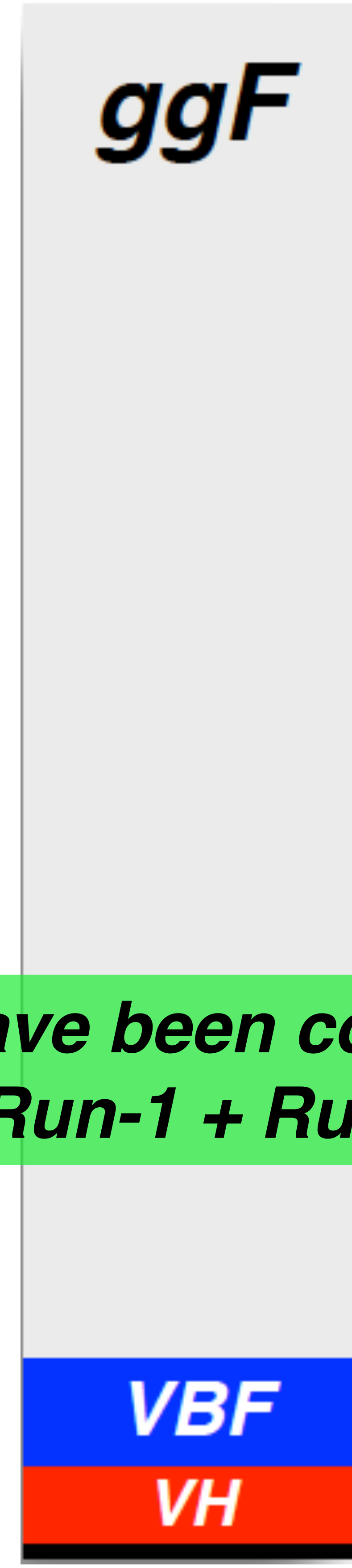


WH/ZH production

4. ttH



ttH production



87%

7%

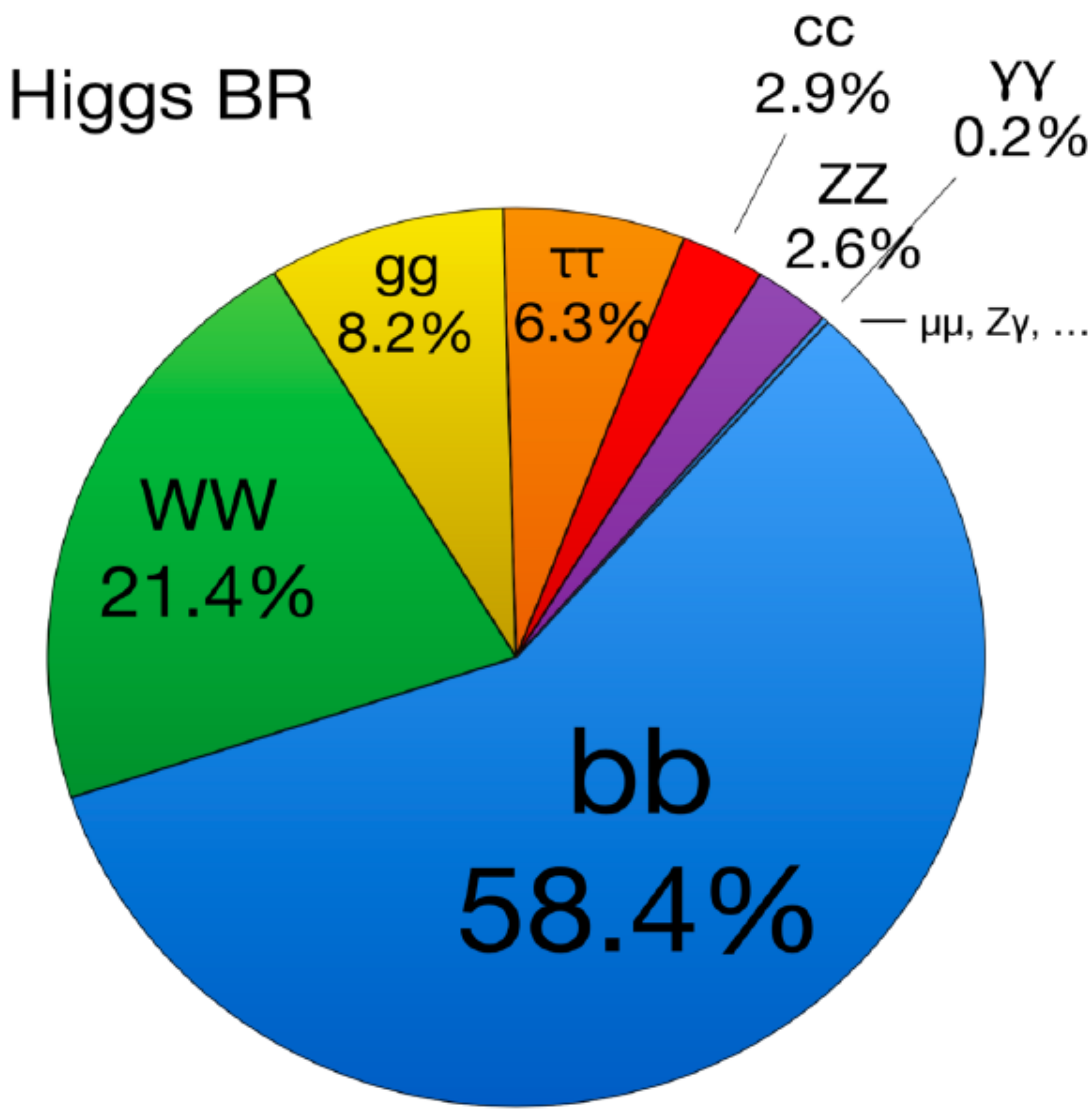
5%

1% rest (incl. *ttH*)

All have been confirmed with Run-1 + Run-2 data

Higgs Decay

mH = 125 GeV



Higgs Decay

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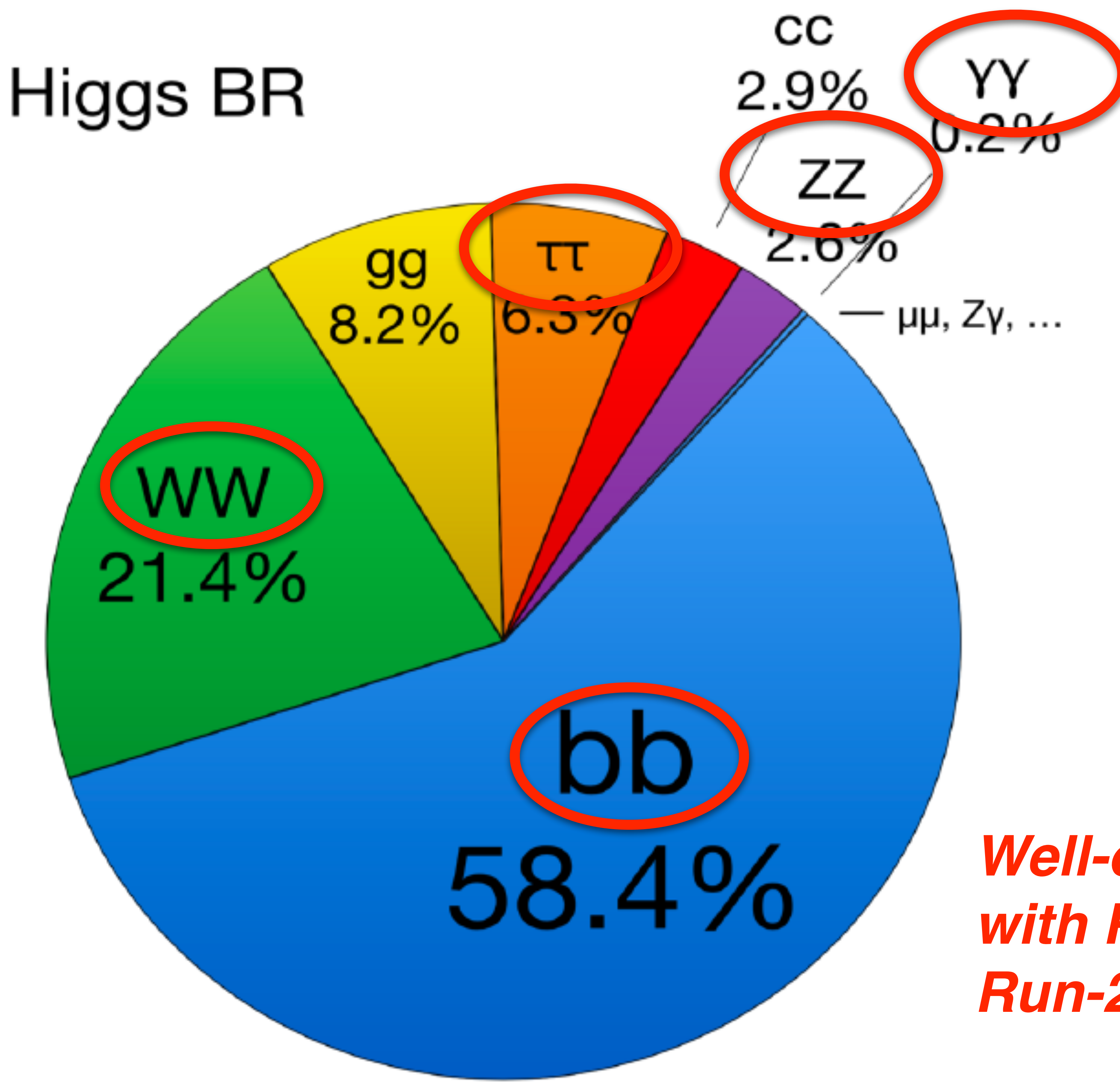
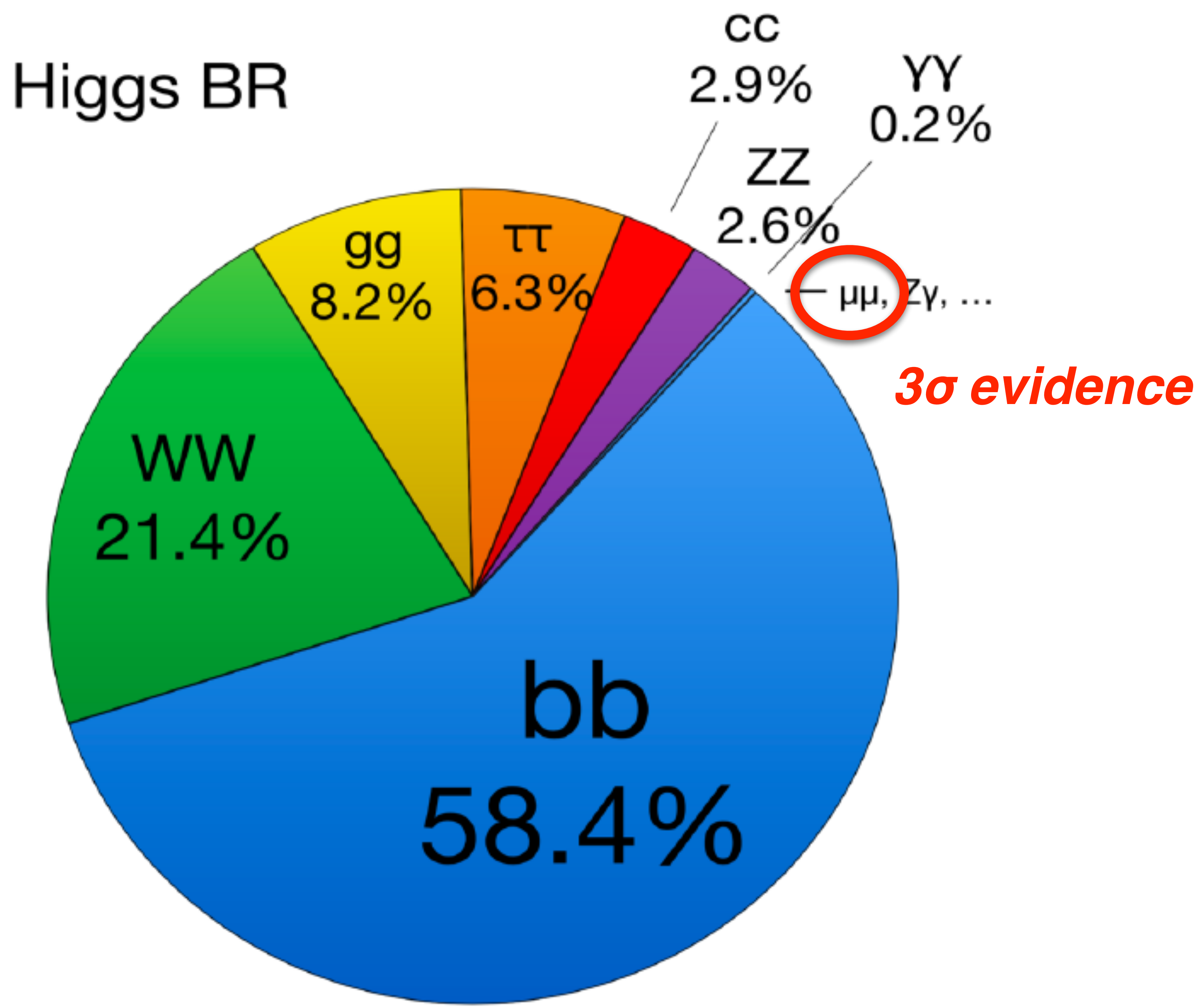


Well-observed with Run-1 + Run-2 data

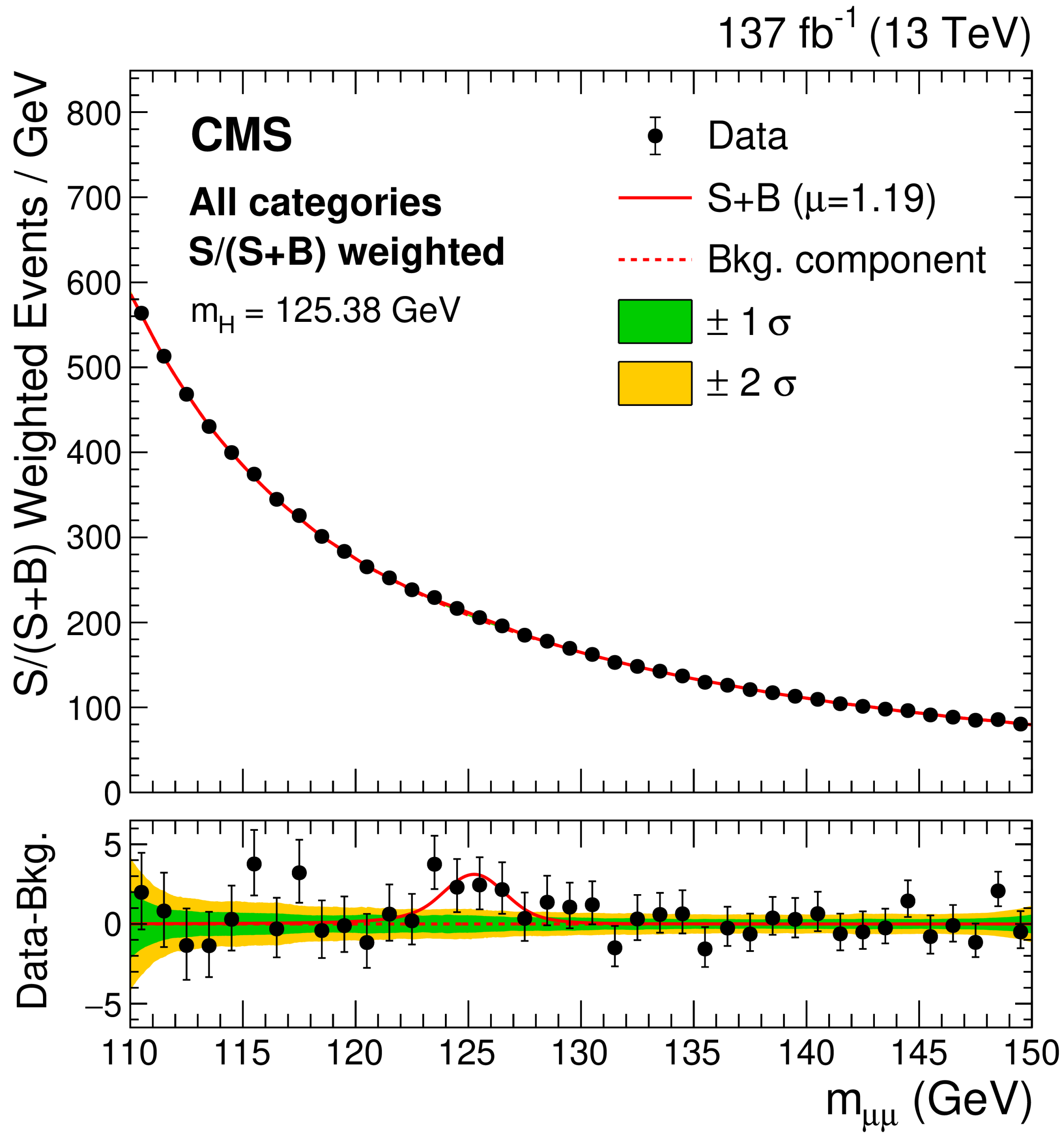
Higgs Decay

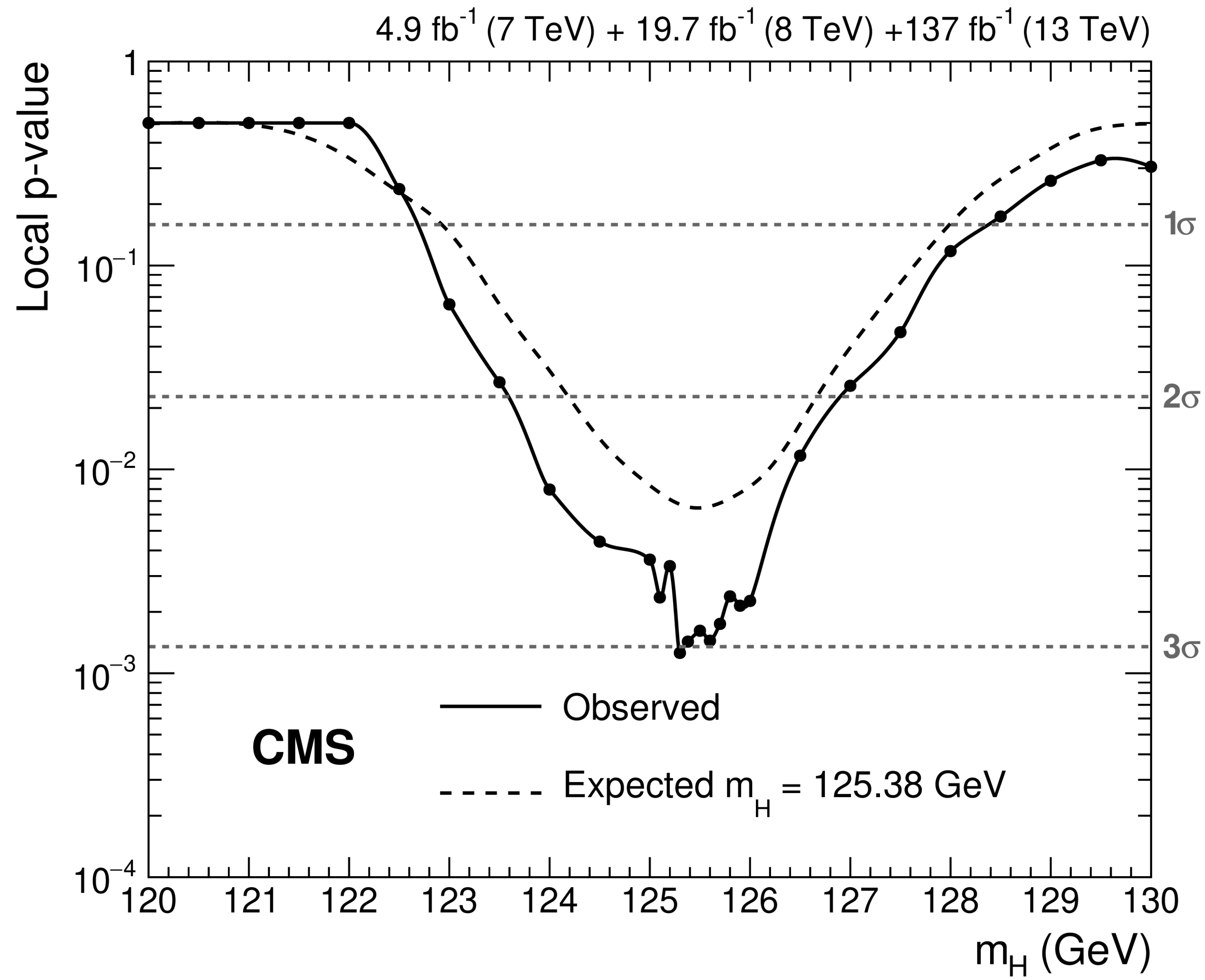
mH = 125 GeV



H → μμ

CMS-HIG-19-006

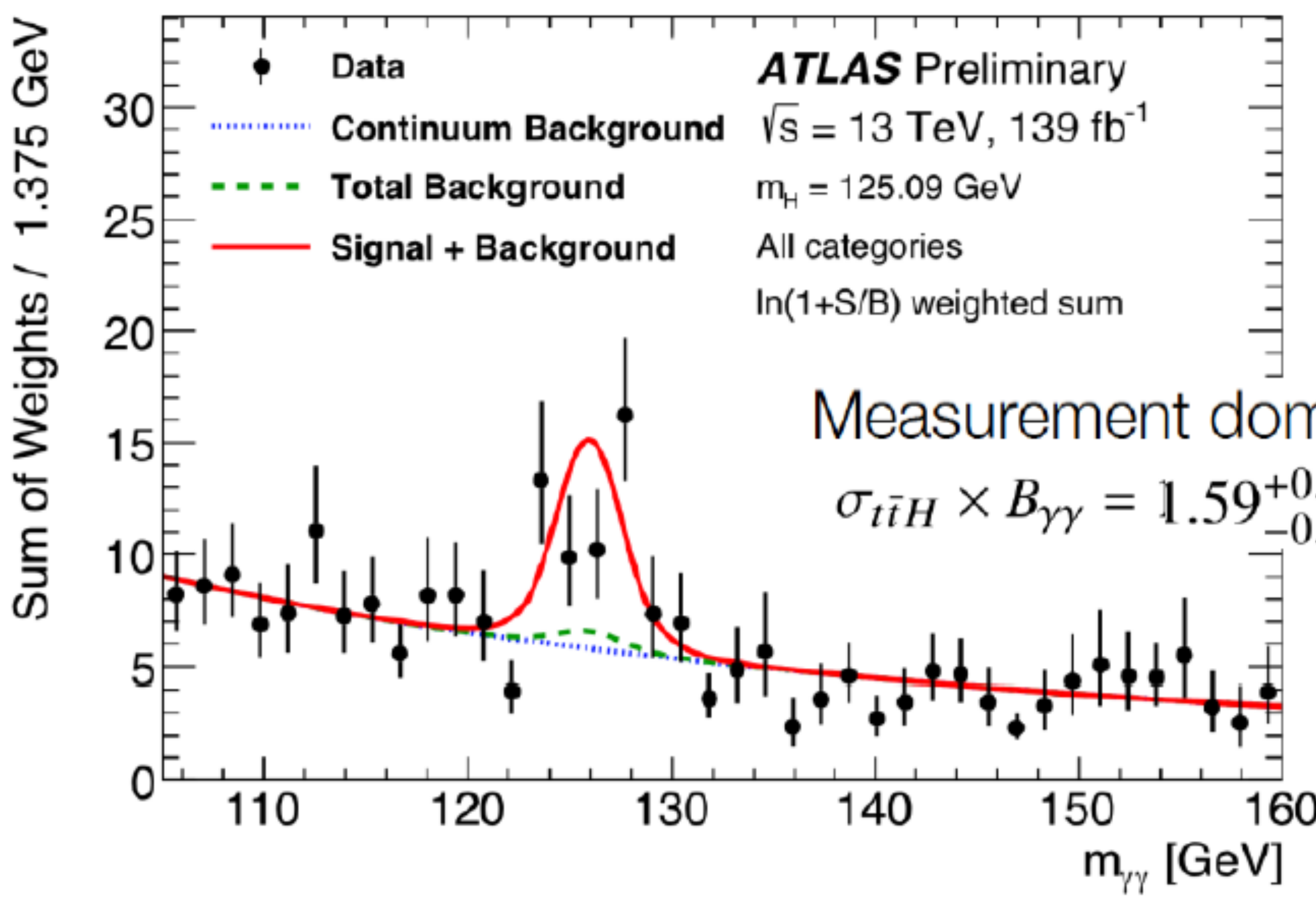




Higgs Production and Decay: Full Run-2 Data

ttH → γγ

Observation and measurement of ttH production in the diphoton channel with 139 fb-1 of data at Run 2 ATLAS-CONF-2019-04



Observed Expected

4.9σ (4.2σ)

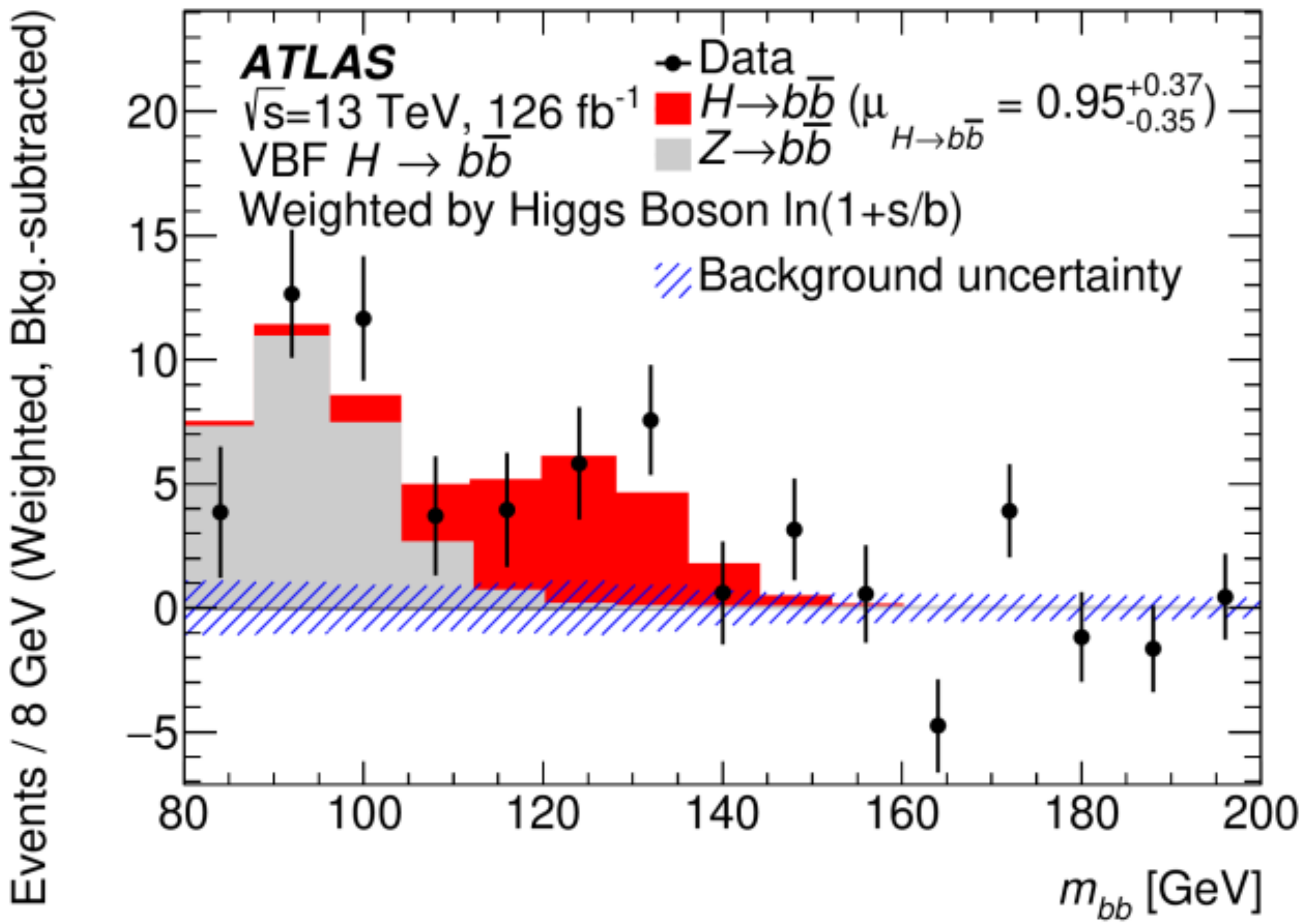
Measurement dominated by statistical uncertainties:

$$\sigma_{t\bar{t}H} \times B_{\gamma\gamma} = 1.59^{+0.38}_{-0.36}\,(\text{stat.})\;^{+0.15}_{-0.12}\,(\text{exp.})\;^{+0.15}_{-0.11}\,(\text{theo.})\;\text{fb}$$

Higgs Production and Decay: Full Run-2 Data

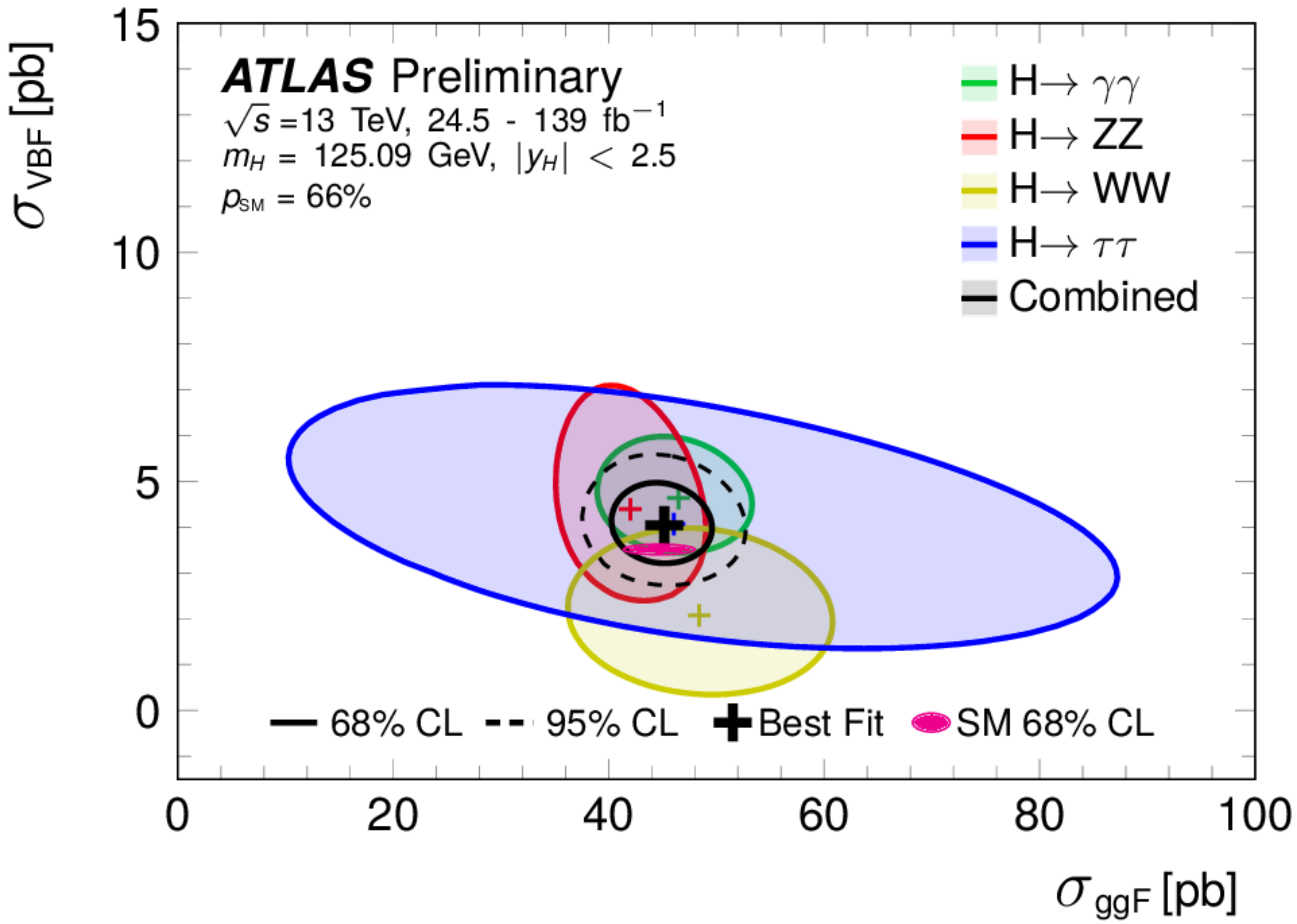
VBF H → bb: 3σ evidence

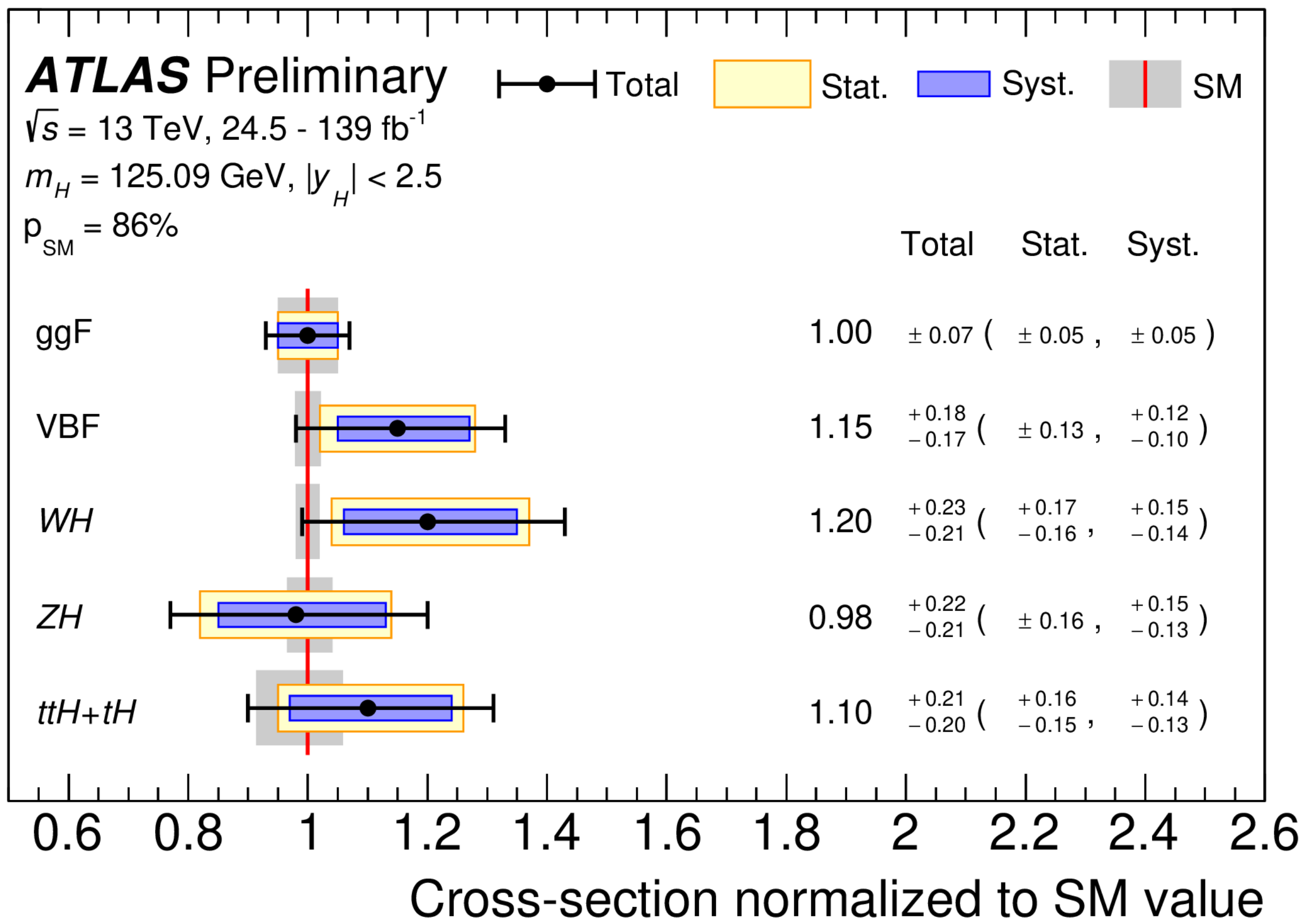
arXiv:2011.08280



Higgs Couplings

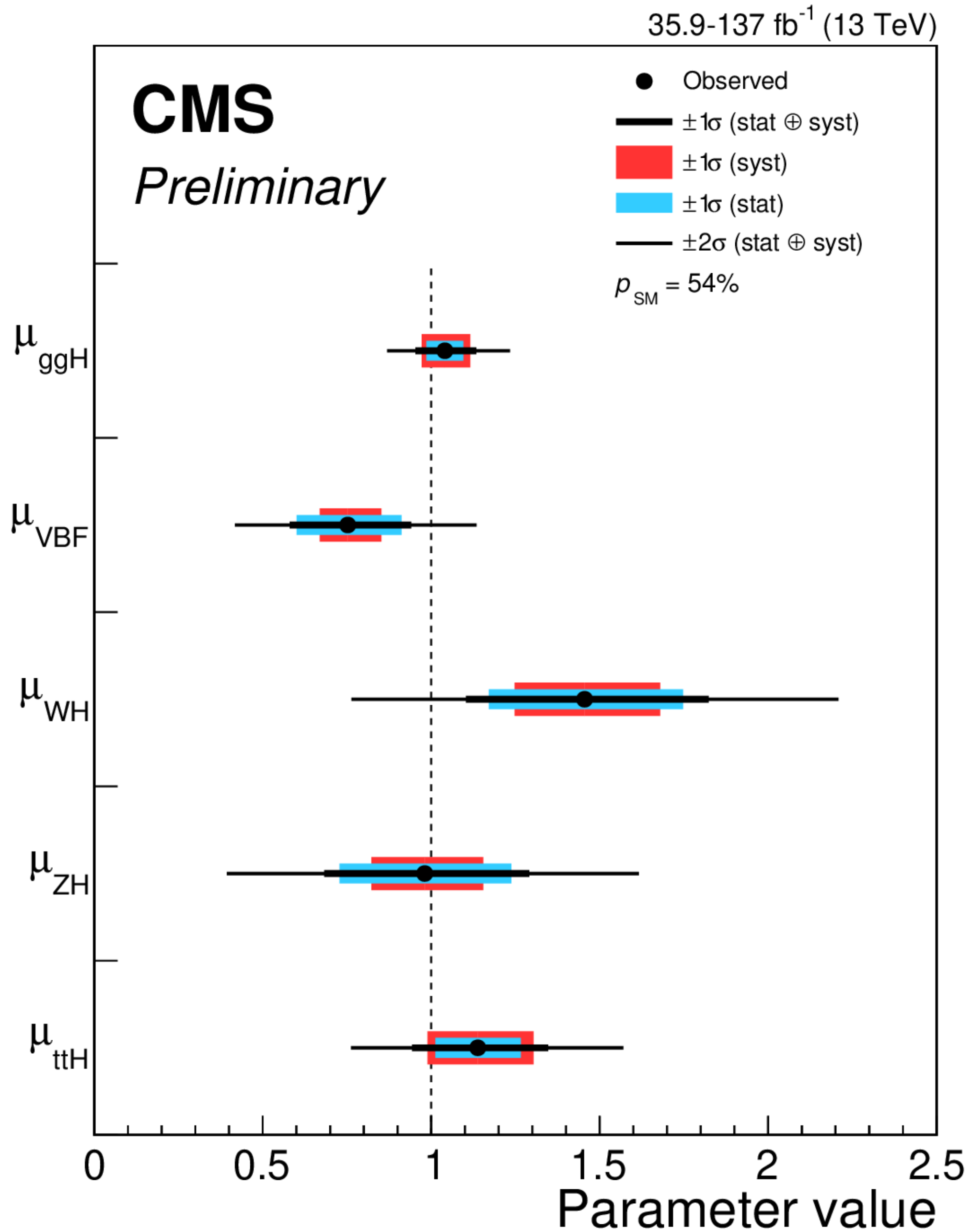
ATLAS-CONF-2020-027

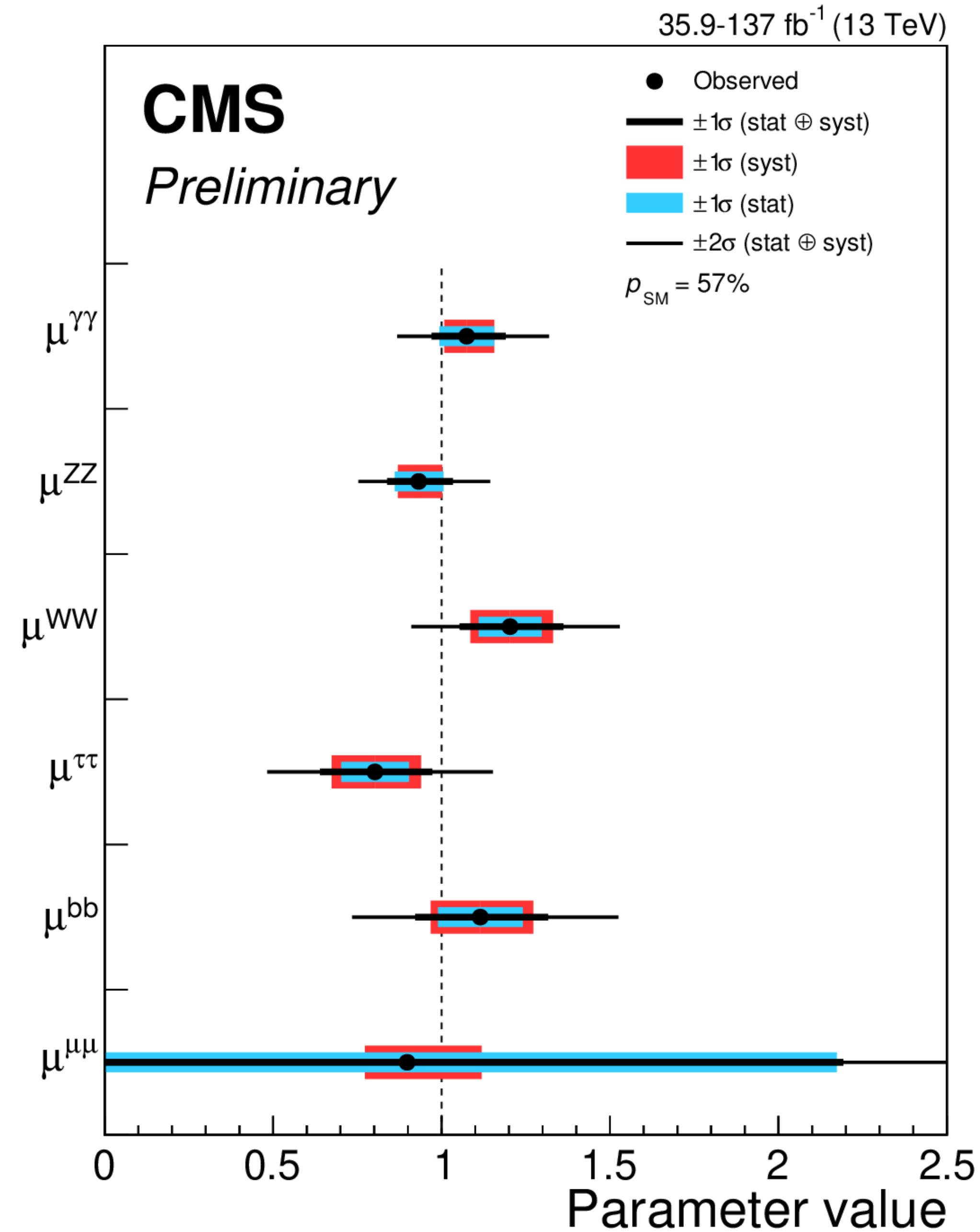




Higgs Couplings

CMS-PAS-HIG-19-005

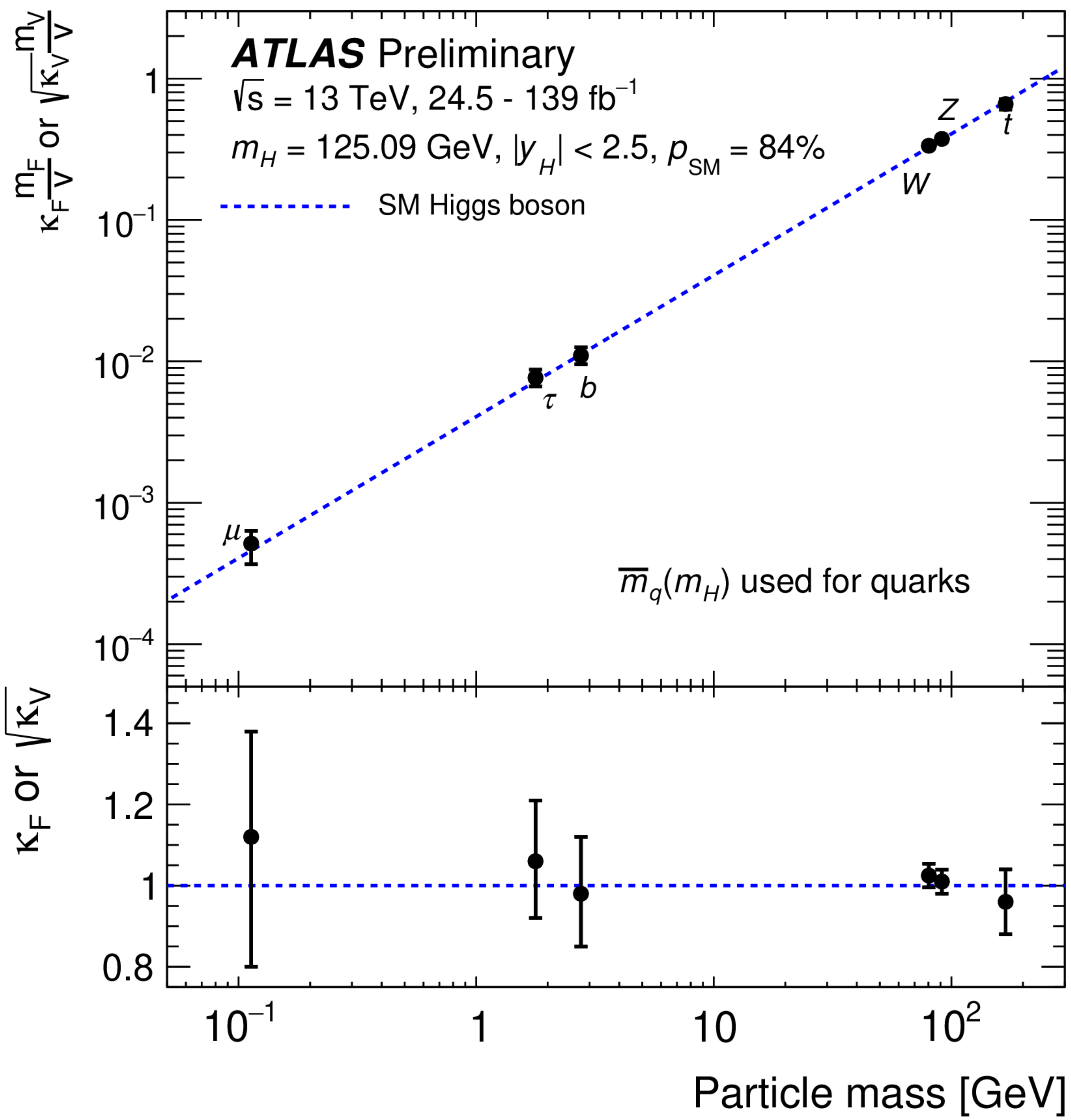




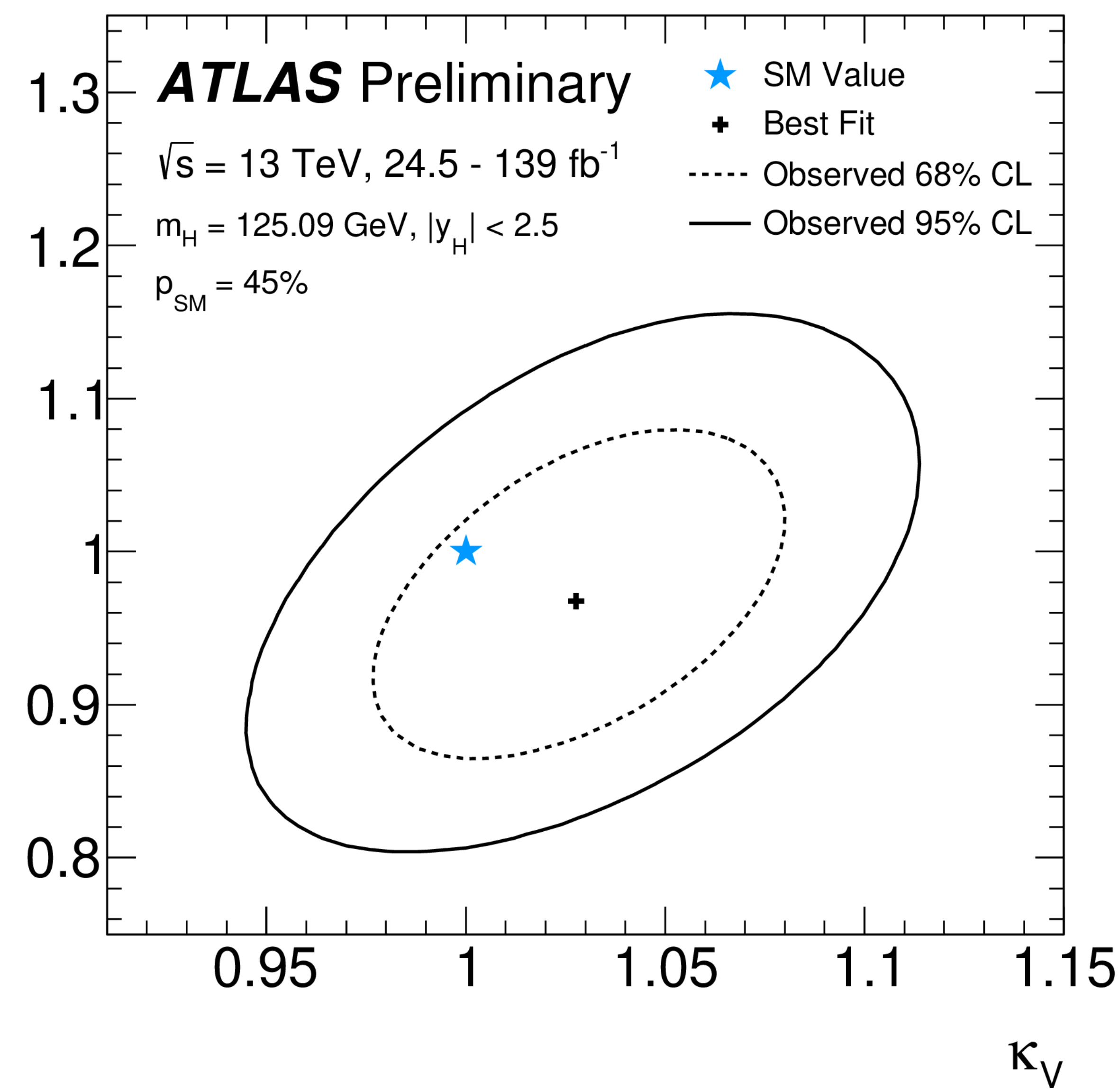
Higgs Couplings

$$\kappa^2 = \sigma/\sigma^{SM}$$

ATLAS-CONF-2020-027



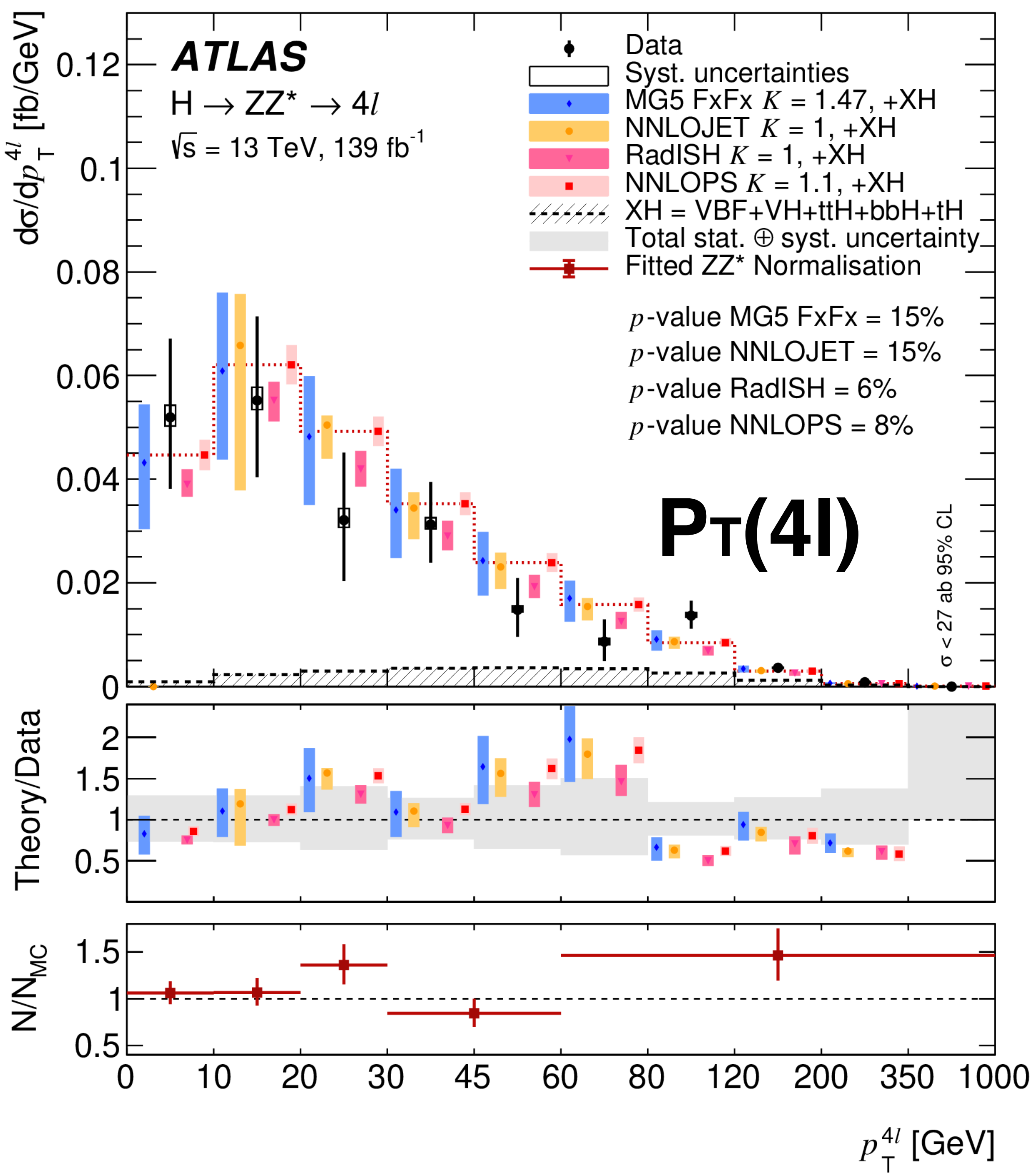
fermions vs vector bosons

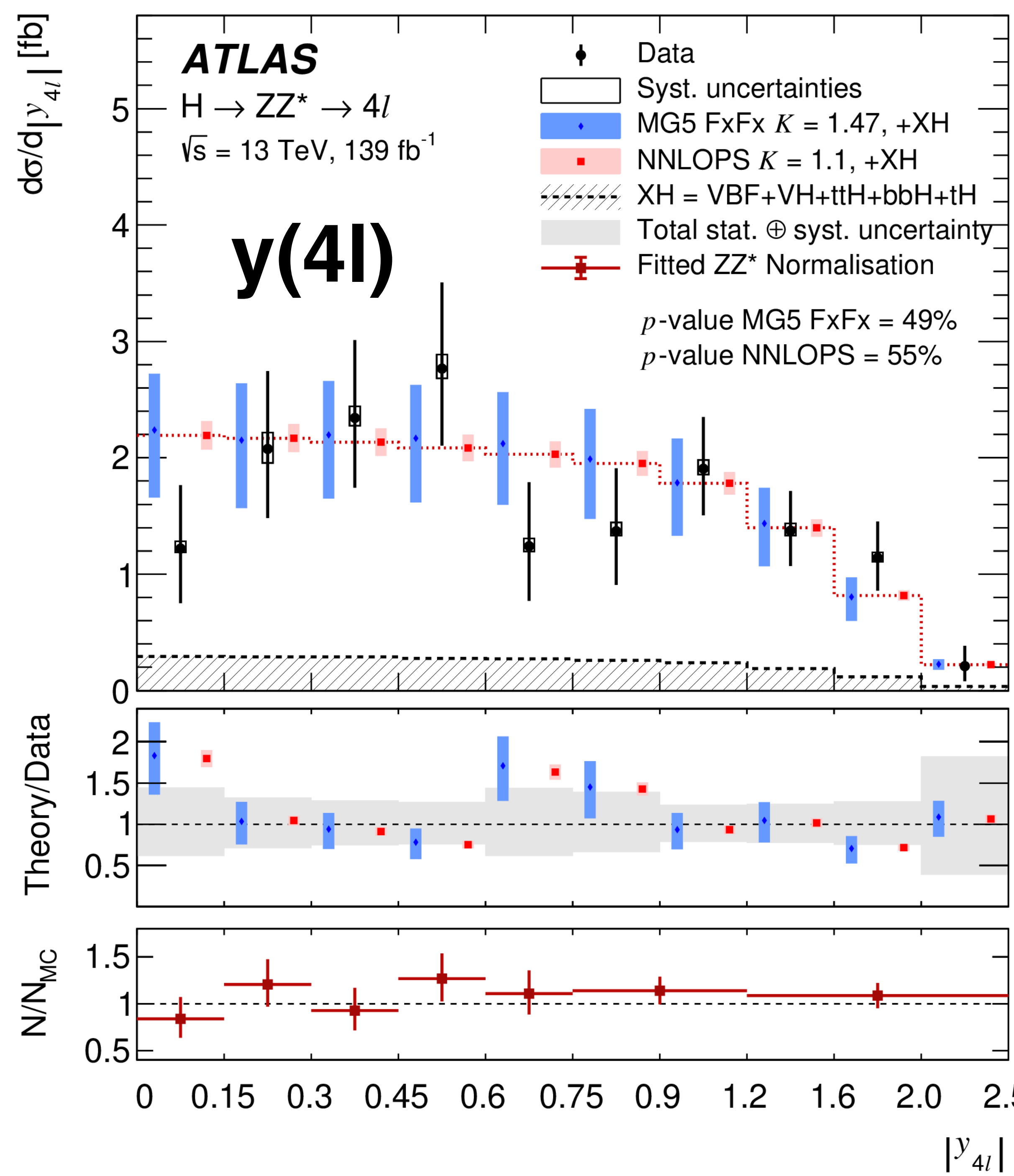


Differential Cross section

- Latest results from ATLAS H->4l channel with full Run-2 data

Eur. Phys. J. C 80 (2020) 941





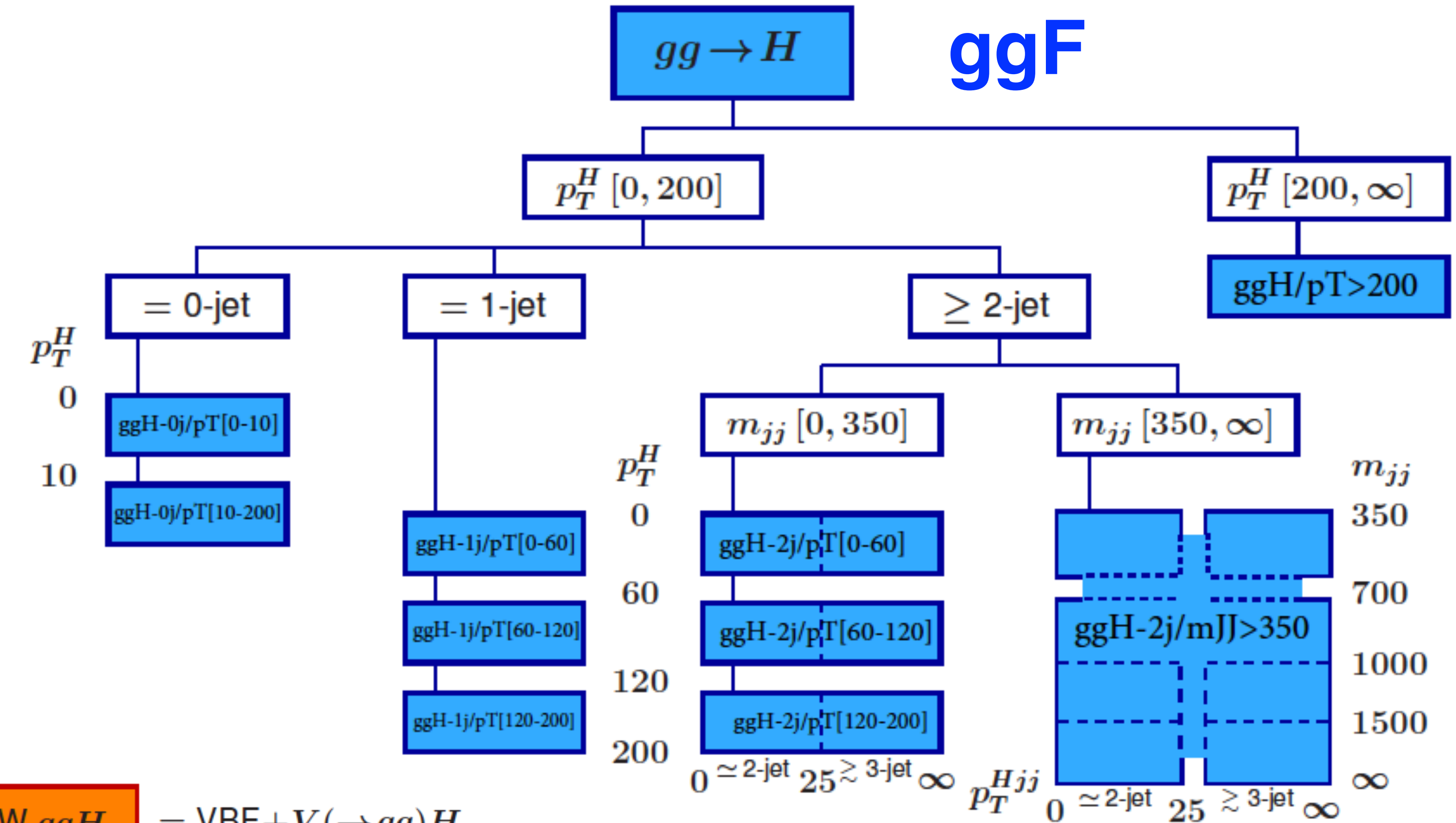
N

Simplified Template Cross Section (STXS)

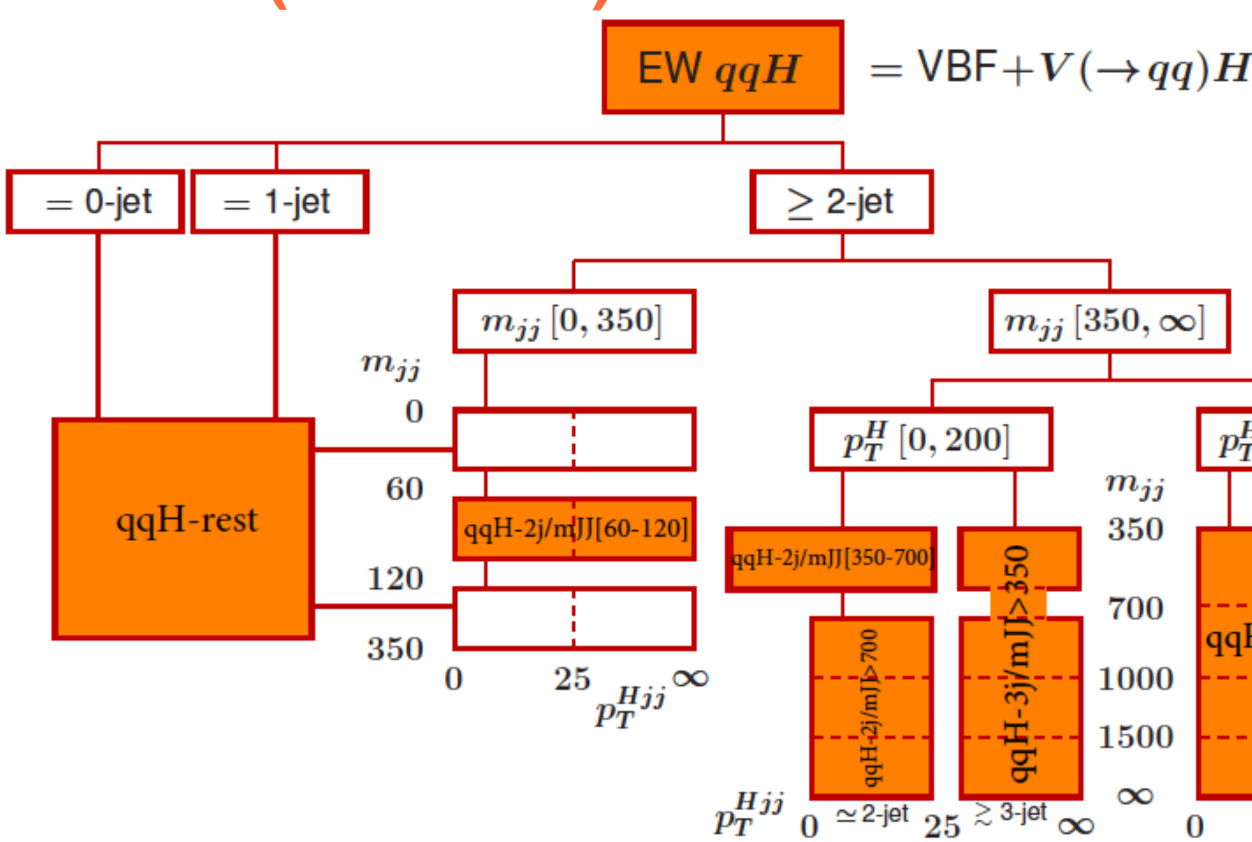
- Measure Higgs X-sec*BR in exclusive phase space (bins).
- Bins chosen to maximize precision and sensitivities of BSM
- Allow combinations of different decay modes.
- A new standard to communicate LHC Higgs data to phenomenologists.

STXS

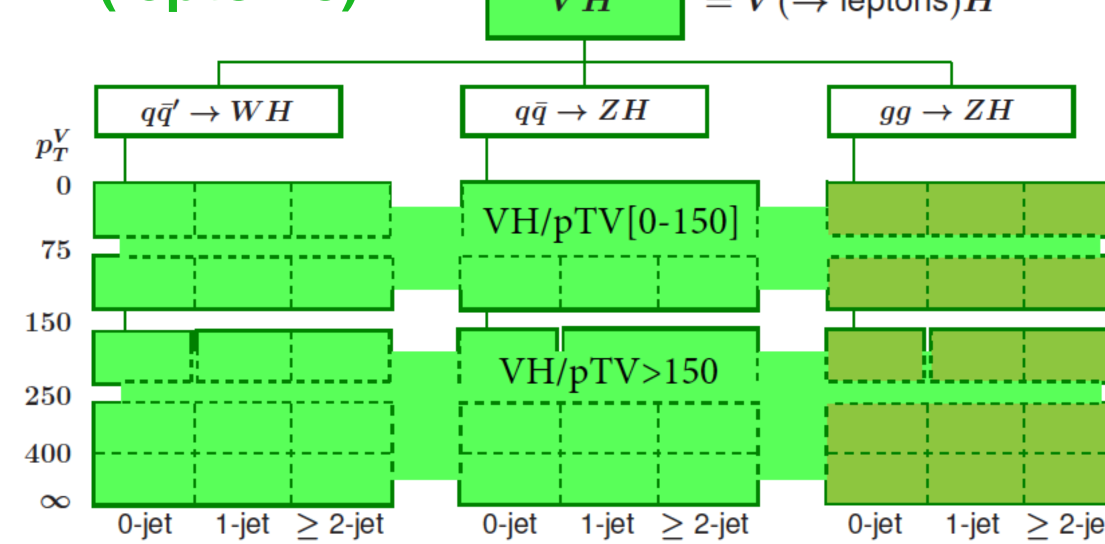
ggF



VBF+V(hadronic)H



V(leptonic)H

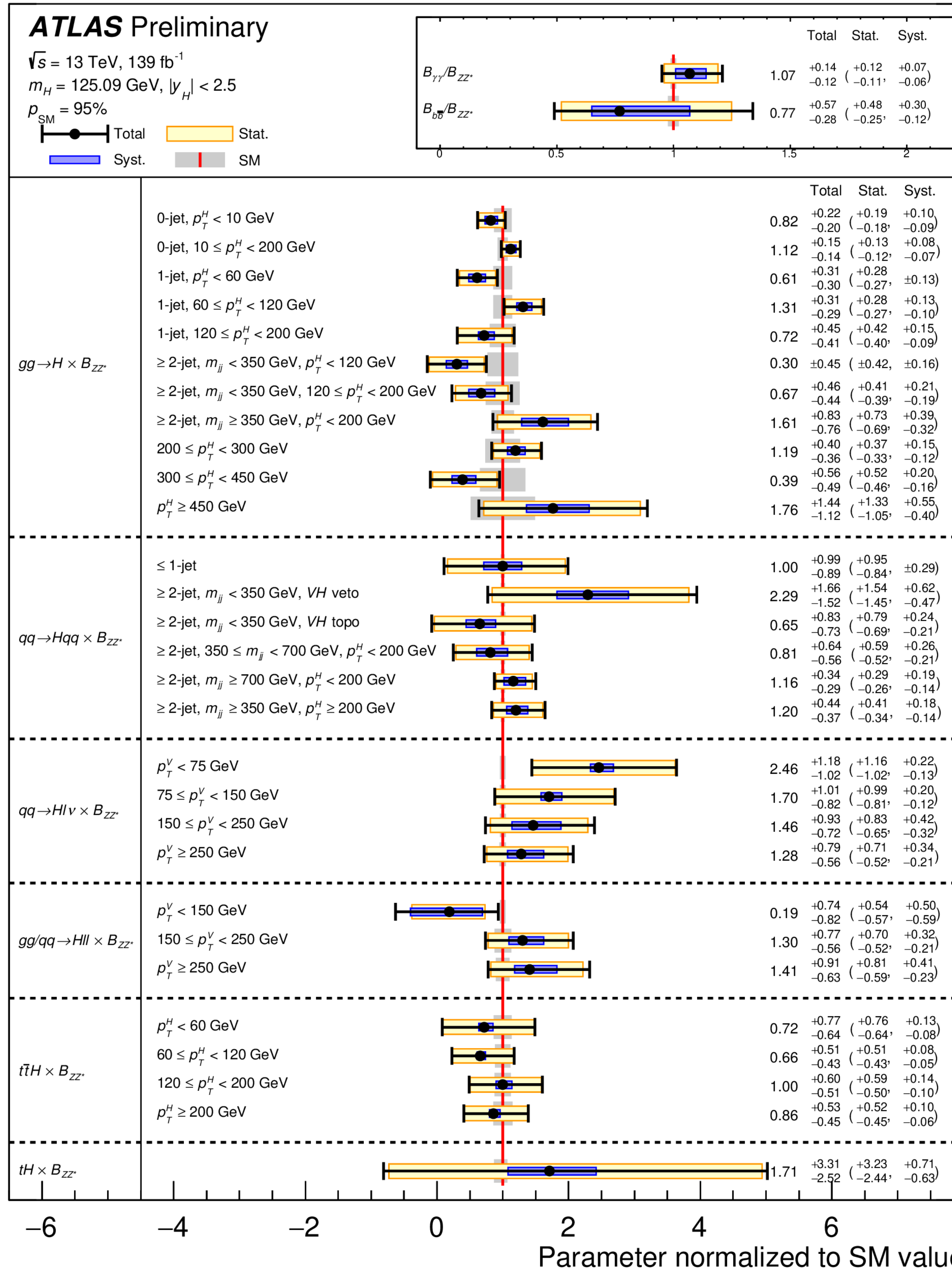


STXS

- **Differential measurements in gg→H and pp→VH**

→ Bins at high $p_T^{H,V}$ sensitive to BSM

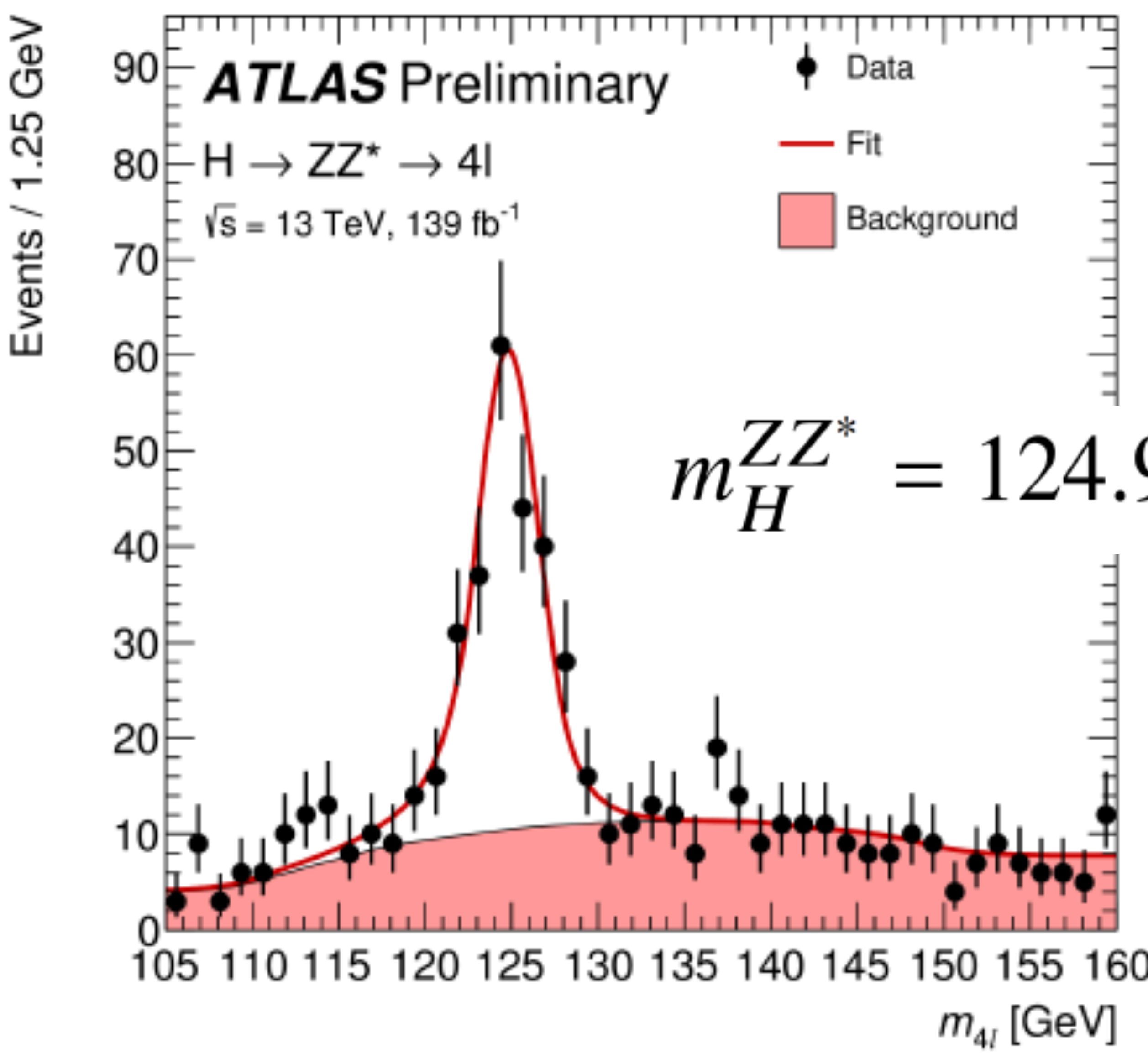
- **Stat unc. > Syst almost everywhere**



ATLAS-CONF-2020-027

Higgs Mass

ATLAS-CONF-2020-005



$$m_H^{ZZ^*} = 124.92 \pm 0.19\ (\text{stat})^{+0.09}_{-0.06}\ (\text{syst})\ \text{GeV}$$

Higgs Mass

Exp.	channel	Dataset	Measure-ment (GeV)	Reference
ATLAS-CMS	H->γγ, H->ZZ*	Run-I	$125.09^{+/-0.240}$	Phys. Rev. Lett. 114, 191803
ATLAS	H->γγ, H->ZZ*	Run-I + ‘15 + ‘16	$124.97^{+/-0.240}$	Phys. Lett. B 784
CMS	H->ZZ*	‘16	$125.62^{+/-210}$	JHEP 11 (‘17) 047
CMS	H->γγ, H->ZZ*	Run-I, ’16	$125.38^{+/-140}$	Phys. Lett. B 805 135425
ATLAS	H->ZZ*	Run-II	124.92^{+210}_{-200}	ATLAS-CONF-2020-005

M. Van De Klundert’s talk at Higgs Couplings 2020

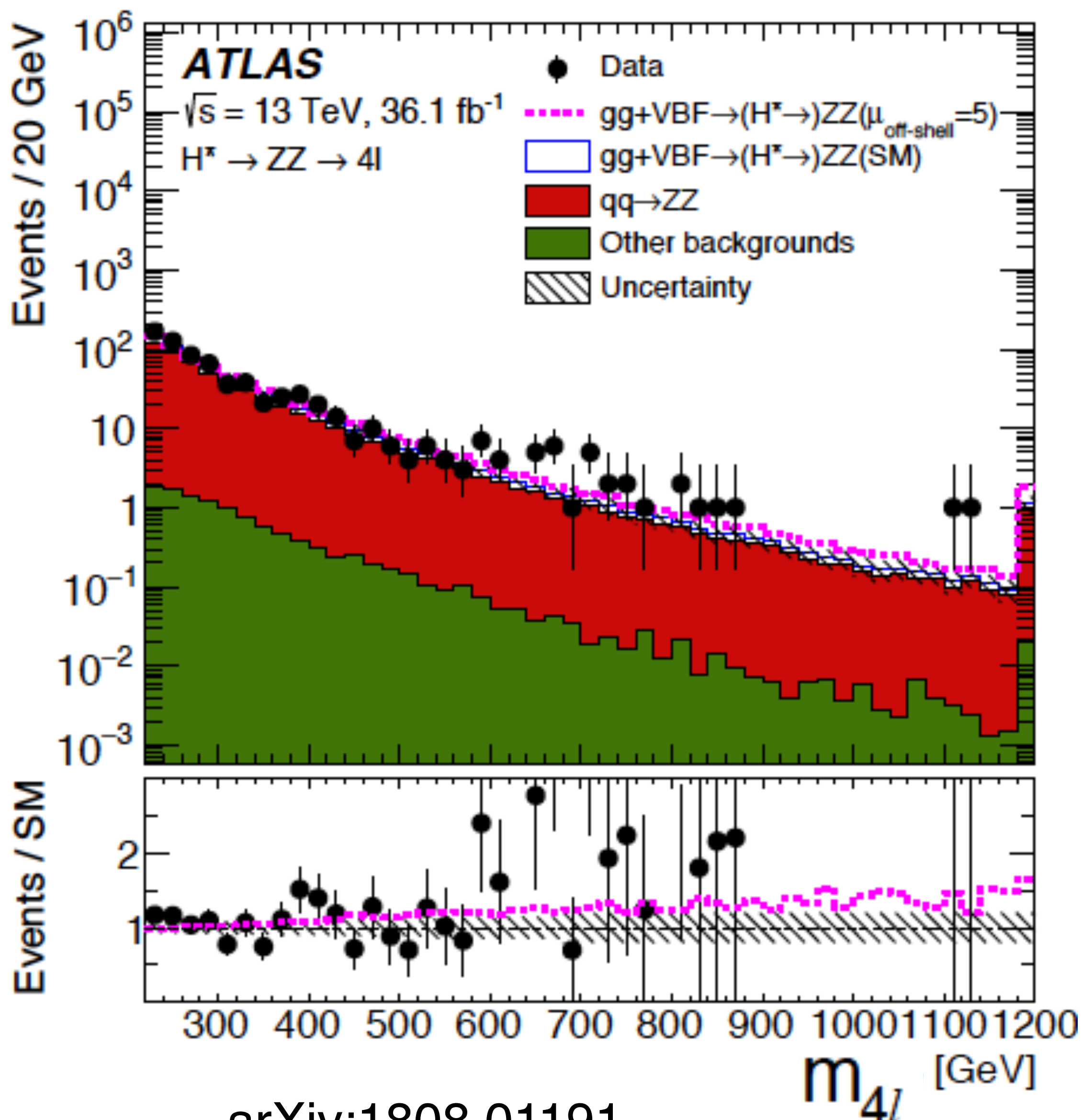
Higgs Width

- Measured by ratio of on-shell and off-shell signal strengths in H → ZZ*
$$\frac{\mathrm{d}\,\sigma_{gg\to H\to ZZ}}{\mathrm{d}\,m^2_{ZZ}} \sim \frac{g^2_{\mathrm{ggH}} g^2_{\mathrm{HZZ}}}{(m^2_{ZZ}-m^2_H)^2+m^2_H {\Gamma_H}^2}$$
- Larger width may indicate BSM decays (e.g. H → invisible), new resonances, or anomalous HVV couplings

Higgs Width

ATLAS ($4\ell+2\ell2\nu$)

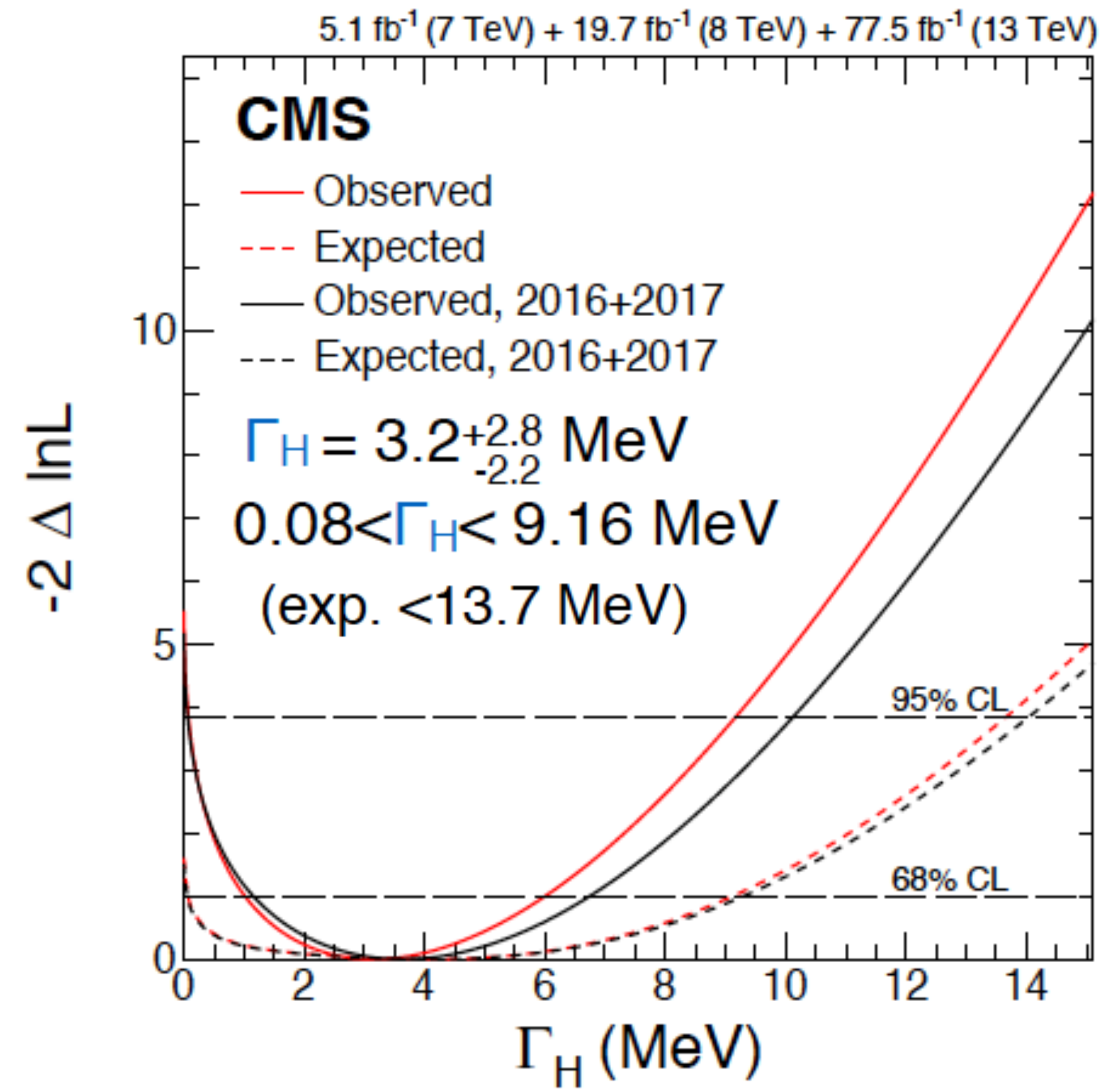
Γ_H < 14.4 MeV (exp. <15.2 MeV)



arXiv:1808.01191
(2015+2016 data)

CMS ($H \to 4\ell$)

arXiv:1901.00174
(2016 + 2017 data)



Higgs CP properties

Run 1 results excluded spin-1 and spin-2 hypotheses, focusing now on scalar vs. pseudoscalar with the larger datasets in Run 2.

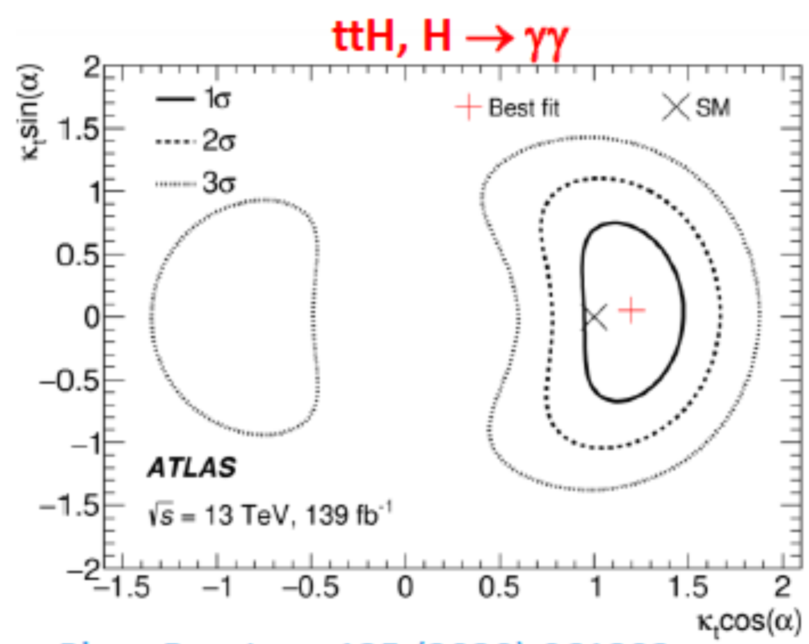
Recent results on CP structure in Higgs-fermion couplings via ttH and ττ.

<u>Lagrangian with CP-odd comp: $\tilde{\kappa}$</u>

$$\mathcal{L}(Hf\bar{f}) = -\frac{m_f}{v}\bar{\psi}_f\left(\kappa_f + \mathrm{i}\,\tilde{\kappa}_f\gamma_5\right)\psi_f\,H$$

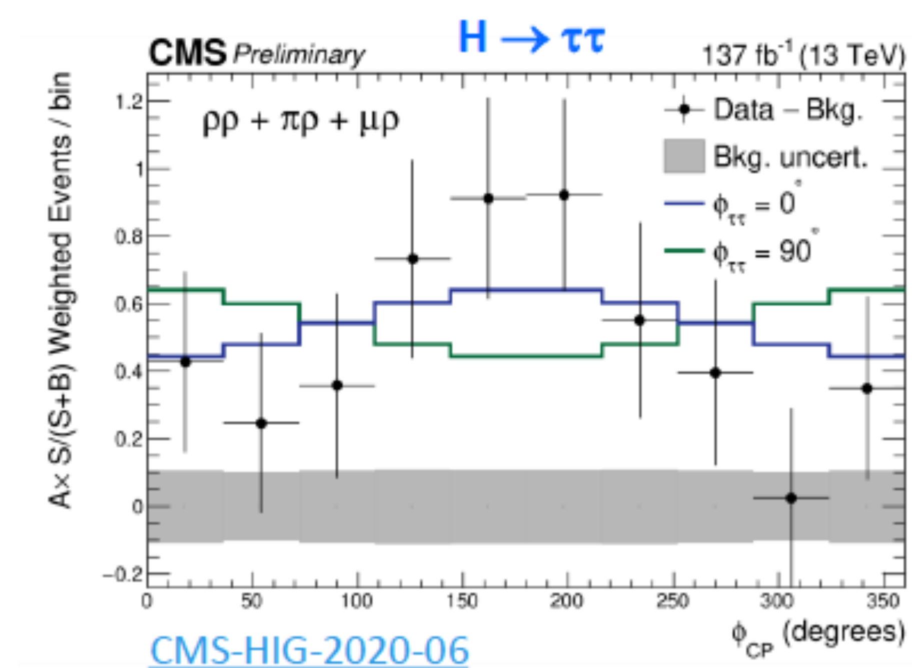
<u>CP mixing angle</u>

$$\phi_{CP} = \arg(\tilde{\kappa}_f/\kappa_f)$$



[Phys. Rev. Lett. 125 (2020) 061802]

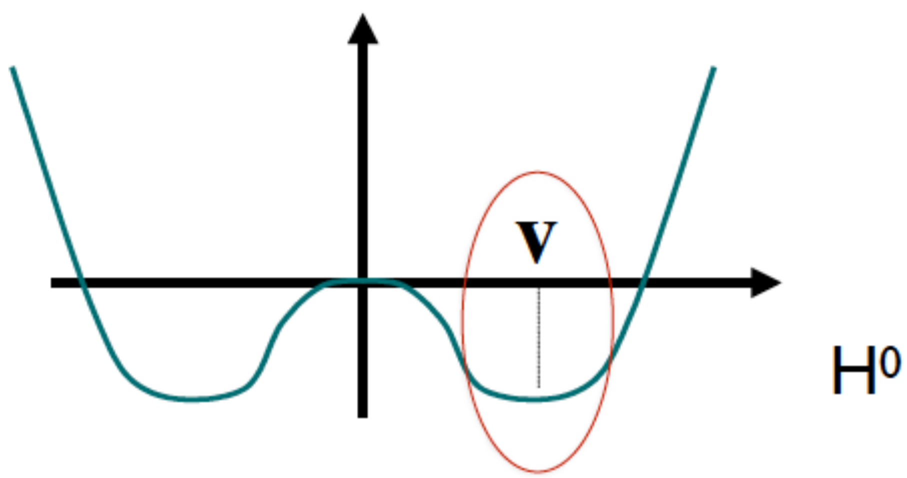
-43° < α < 43° @ 95% C.L.



[CMS-HIG-2020-06]

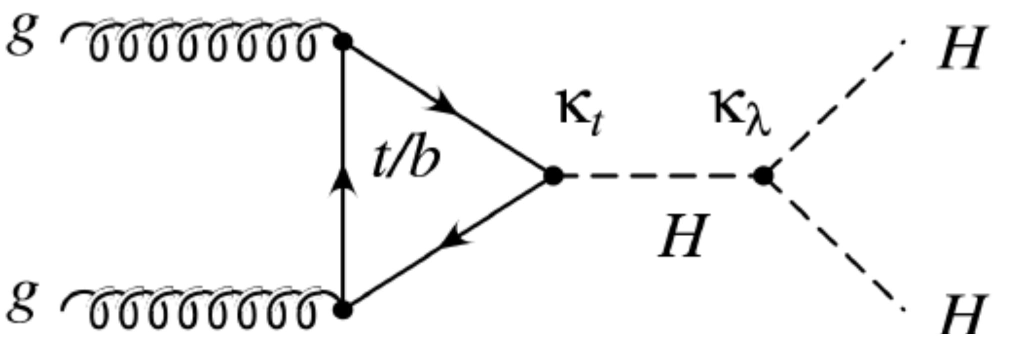
$\phi_{\tau\tau} = (4 \pm 17)^o$

Higgs self couplings

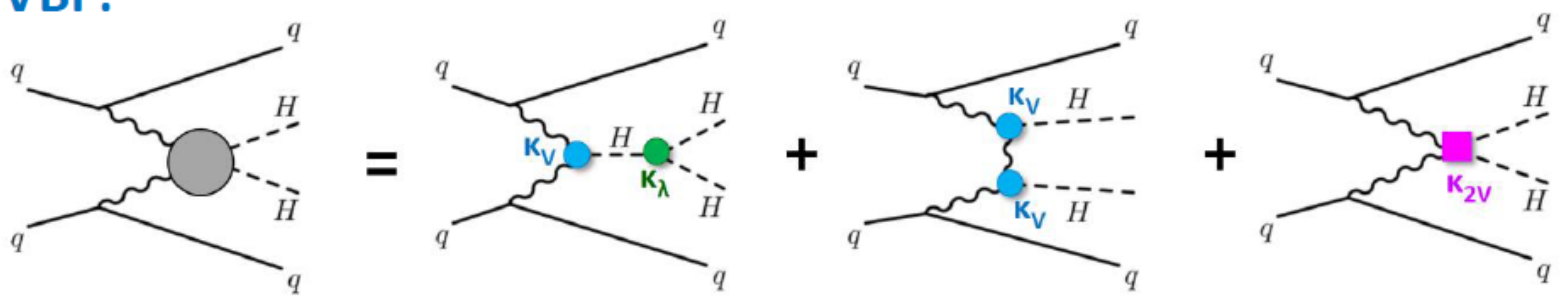


$$V(H) = -\mu^2 |H|^2 + \lambda |H|^4$$

Who ordered that ?

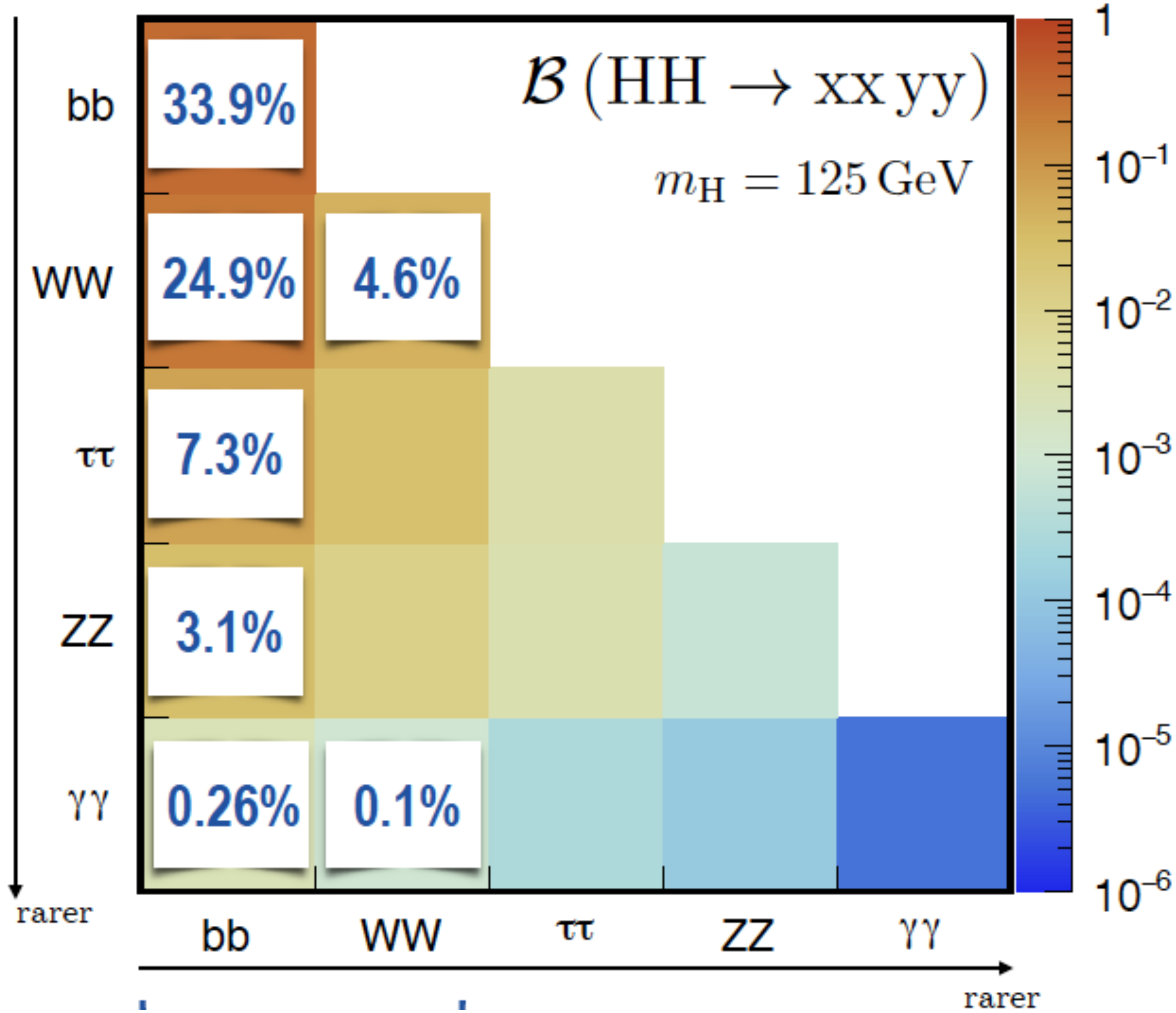


VBF:



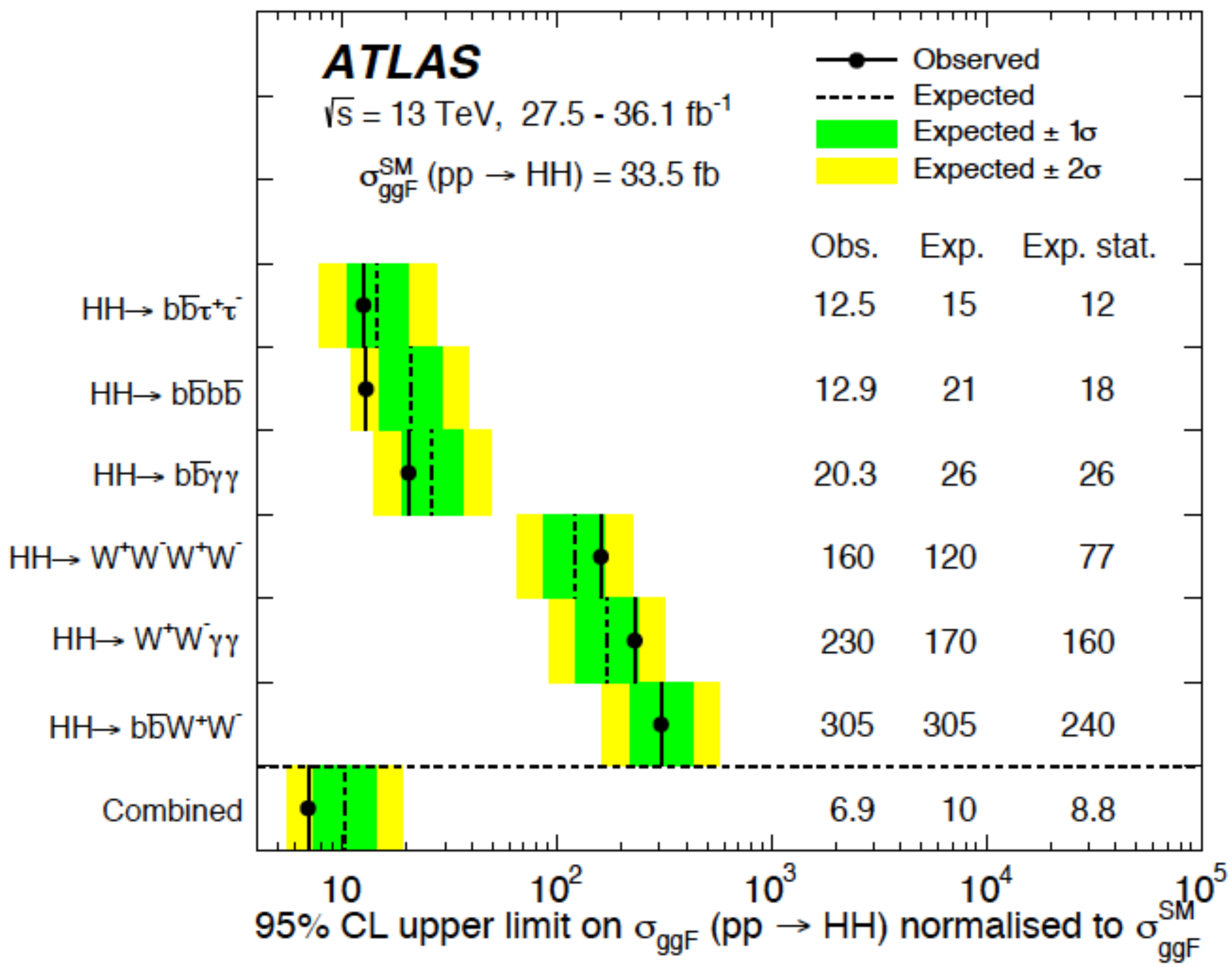
Higgs self couplings

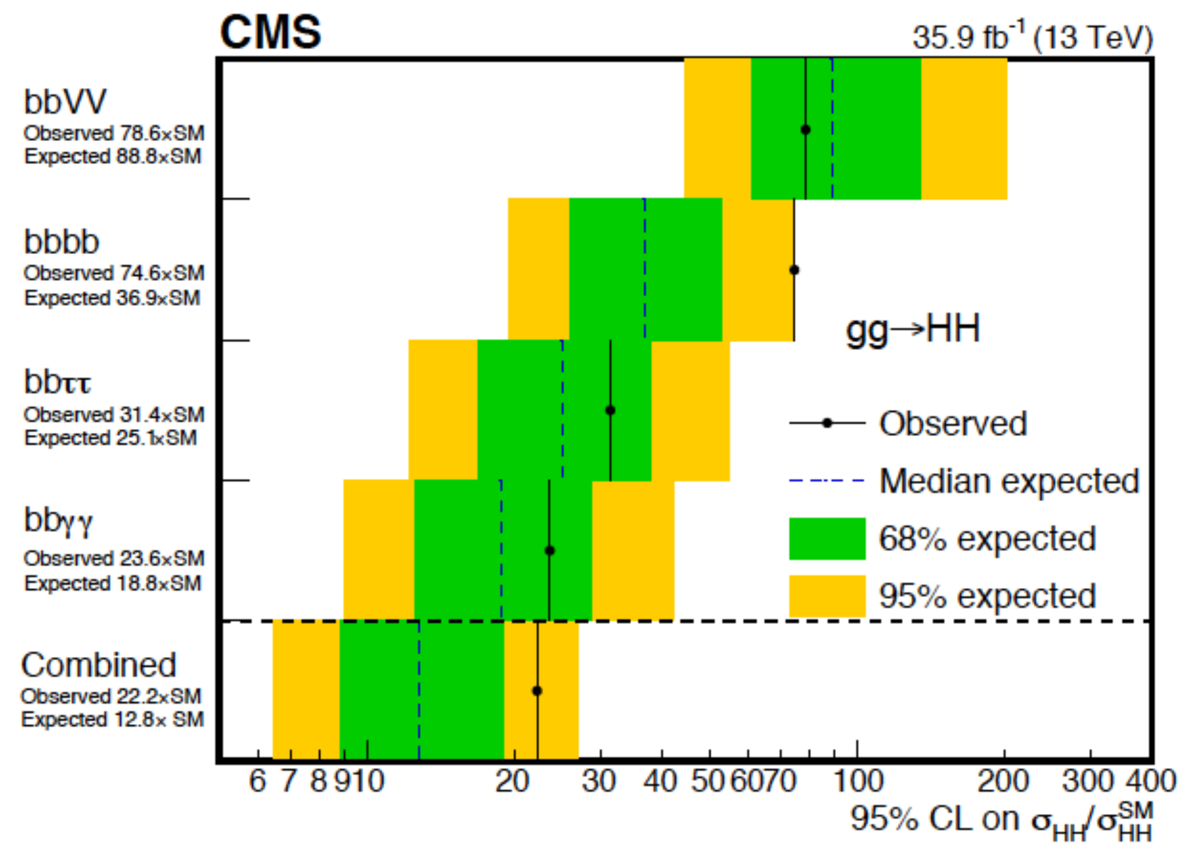
- Di-Higgs production measurement: most feasible with at least one $H \to bb$



Higgs self couplings

arXiv:1906.02025
PRL 122, 121803 (2019)





$\sigma^{hh}/\sigma^{hh}_{sm}$: ATLAS < 6.9, CMS < 22.2

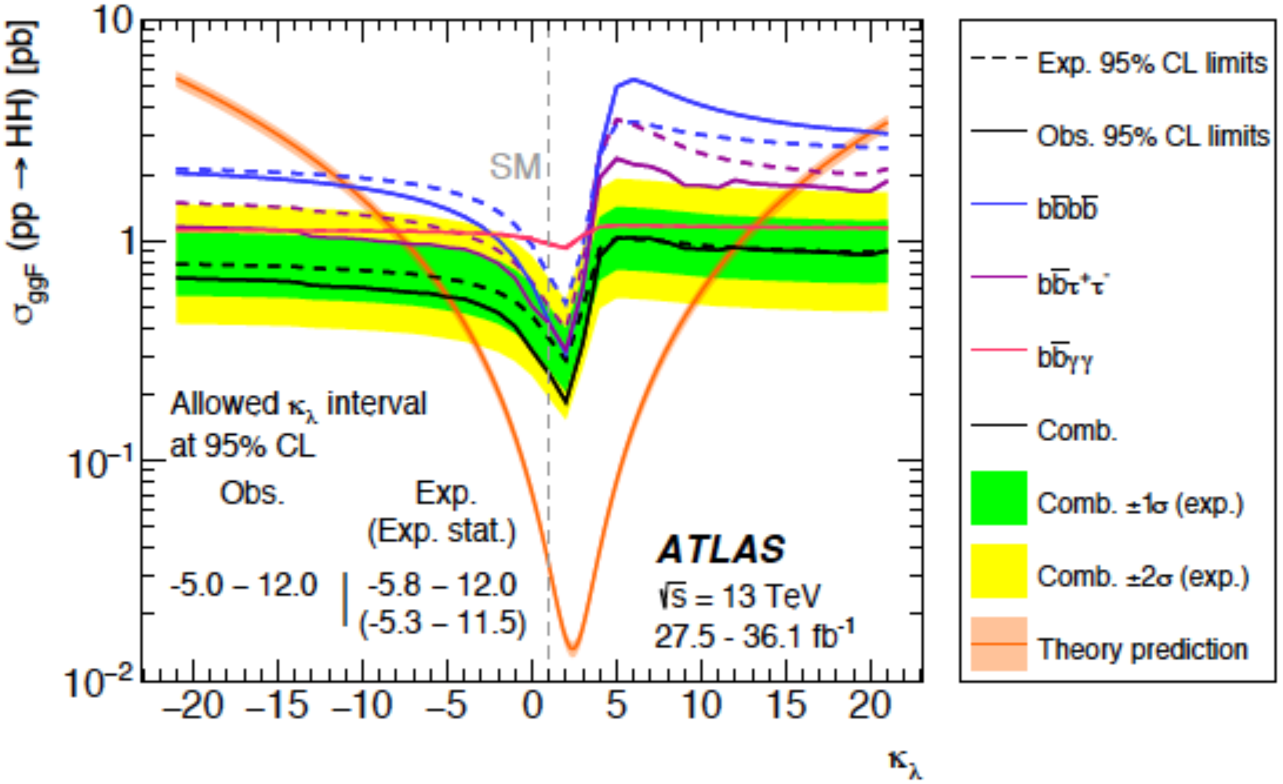
Higgs self couplings

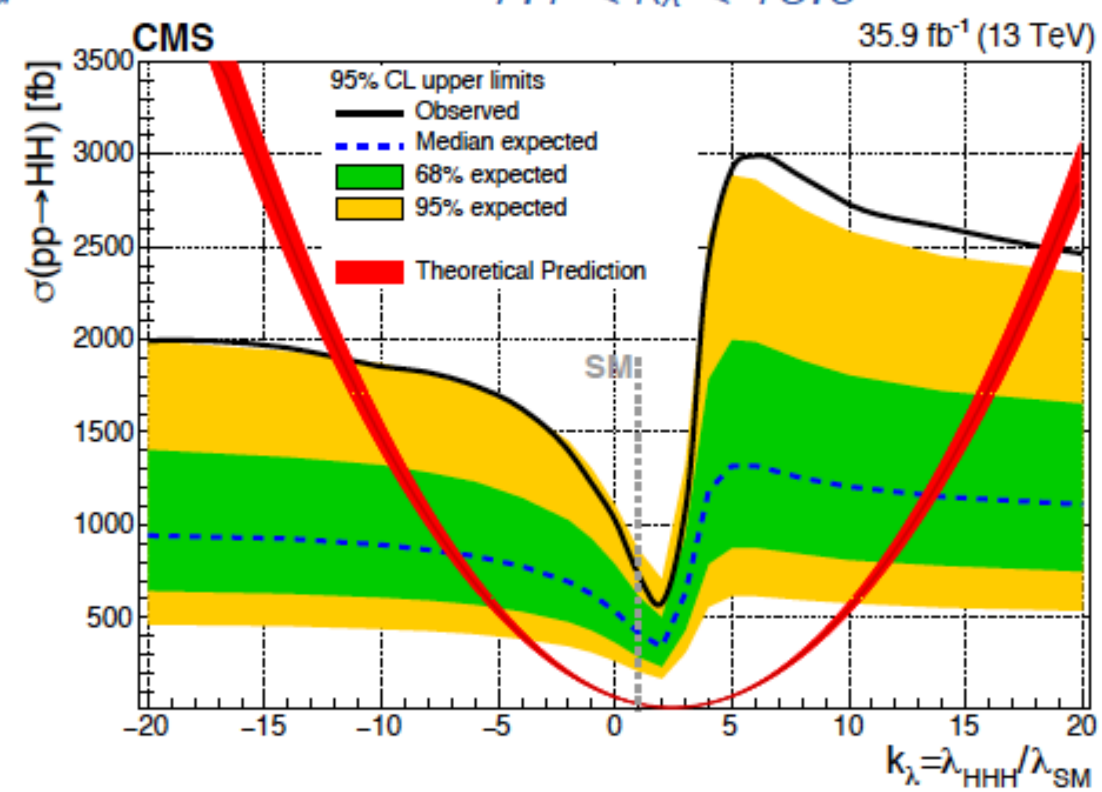
arXiv:1906.02025

PRL 122, 121803 (2019)

$\kappa_\lambda = \lambda_{HHH} / \lambda_{HHH}^{SM}$

$-5.0 < \kappa_\lambda < 12$	***Observed***	**$-11.8 < \kappa_\lambda < 18.8$**
$-5.8 < \kappa_\lambda < 12$	*Expected*	$-7.1 < \kappa_\lambda < 13.6$

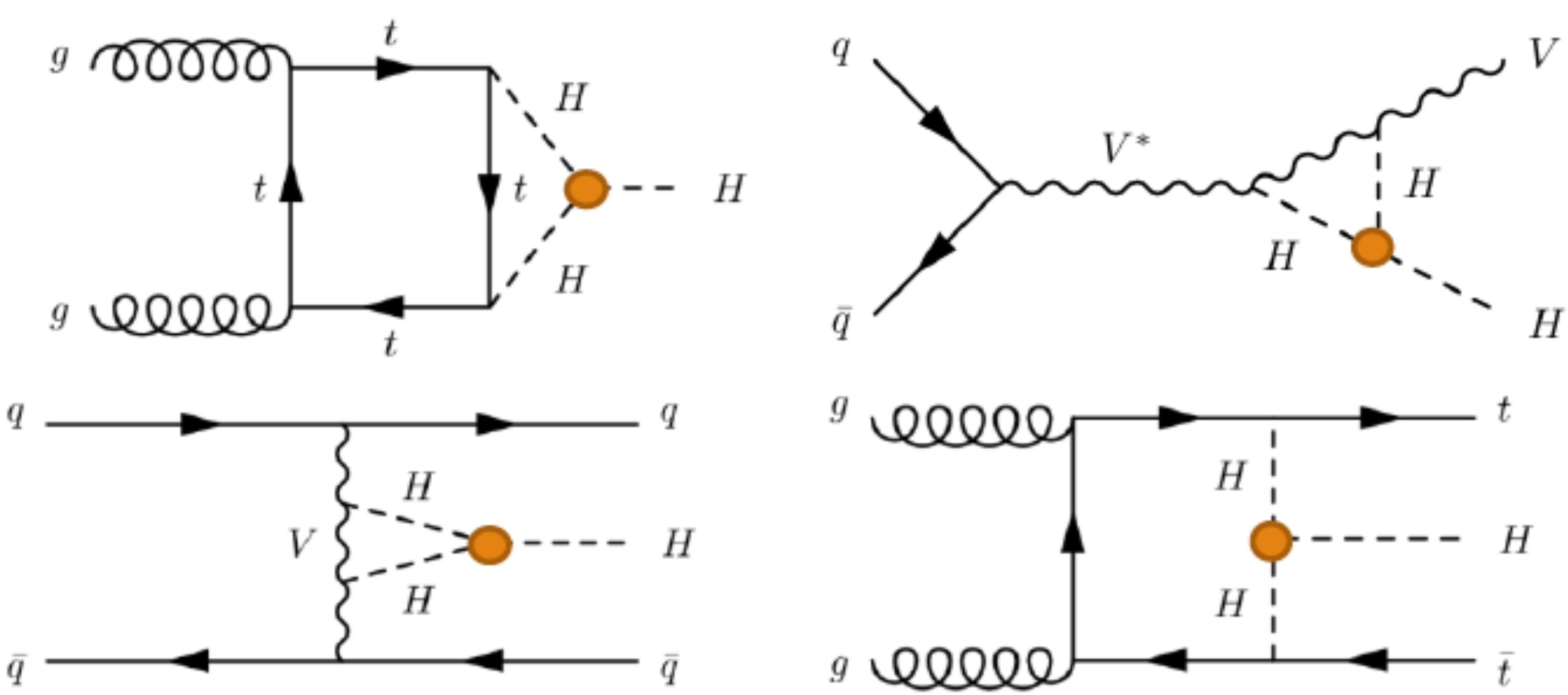




Higgs self couplings

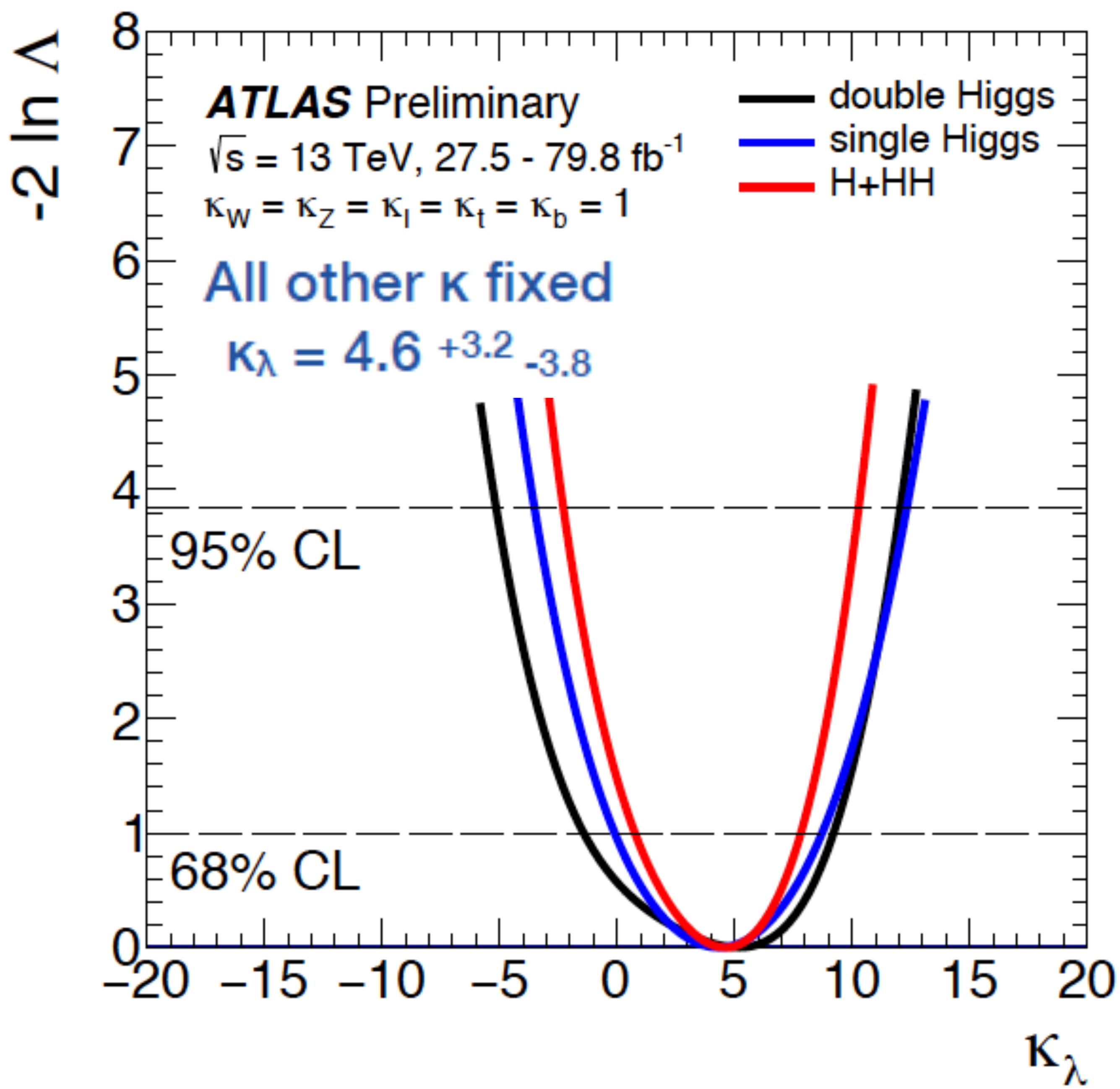
Combining H and HH maximises the sensitivity to λ_{HHH}

Single H production sensitive to λ at the one-loop level.



Higgs self couplings

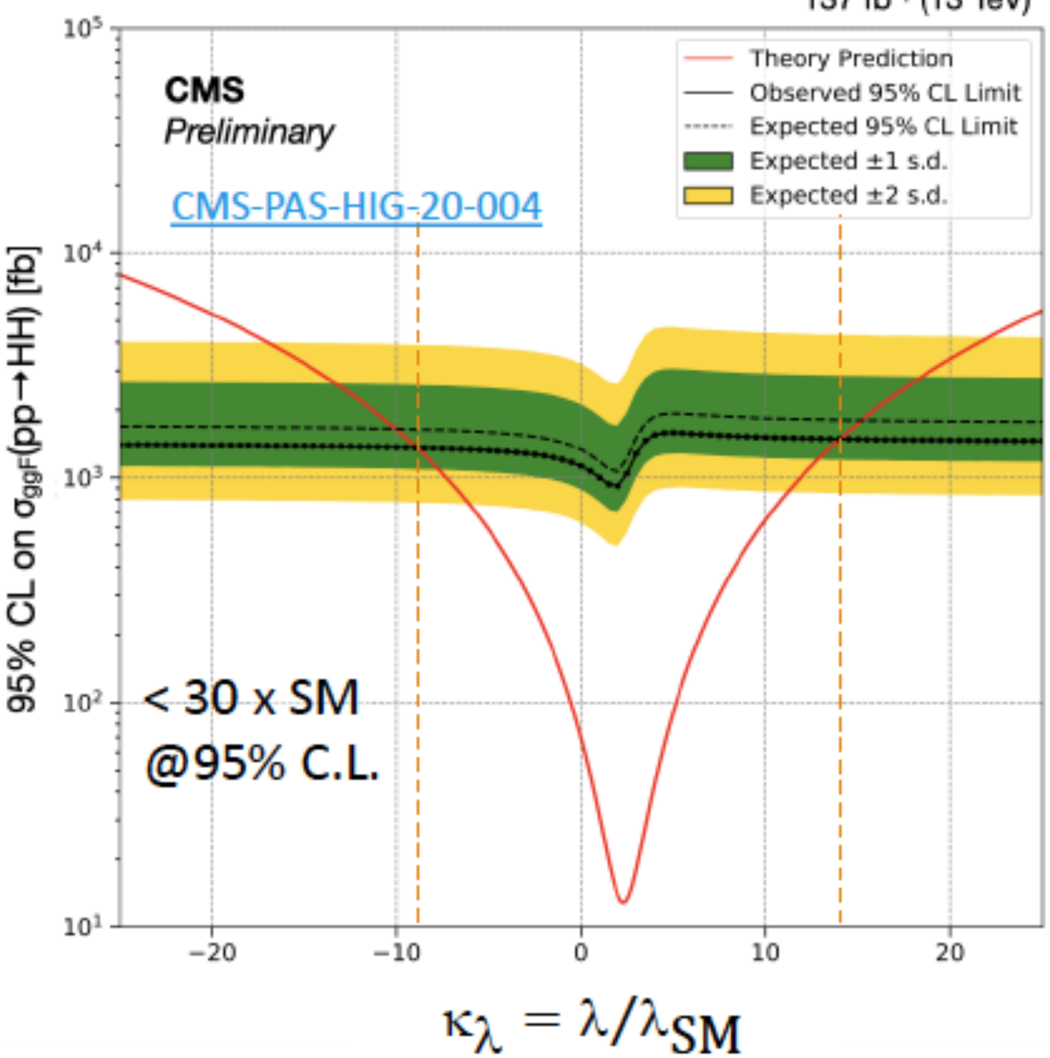
Combining H and HH maximises the sensitivity to λ_{HHH}



CONF-2019-049

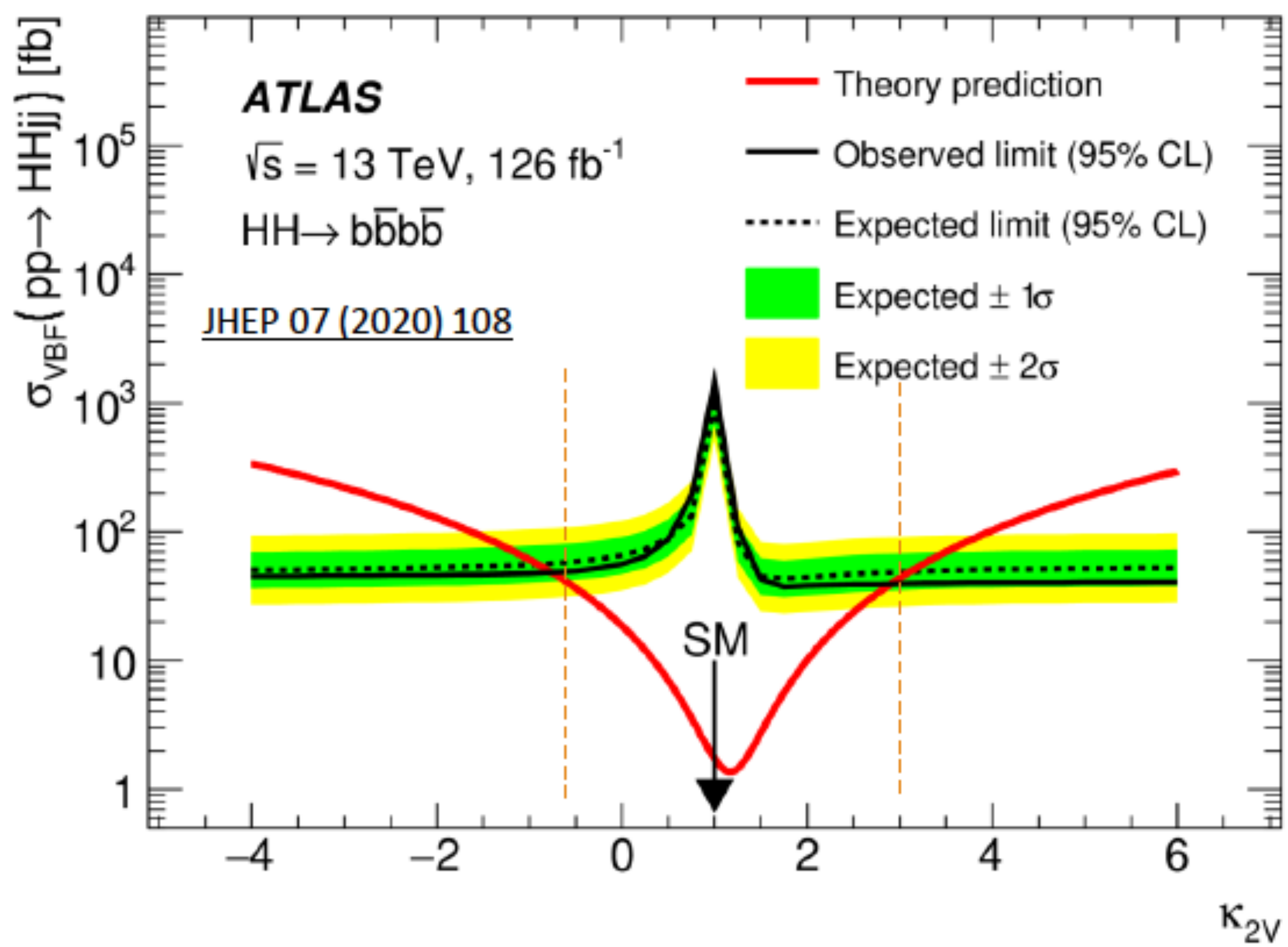
Higgs self couplings: Full Run-2 data

$HH \to b\bar{b}ZZ^* \to b\bar{b}4l$



First search in this final state: $-9 < \kappa_\lambda < 14$

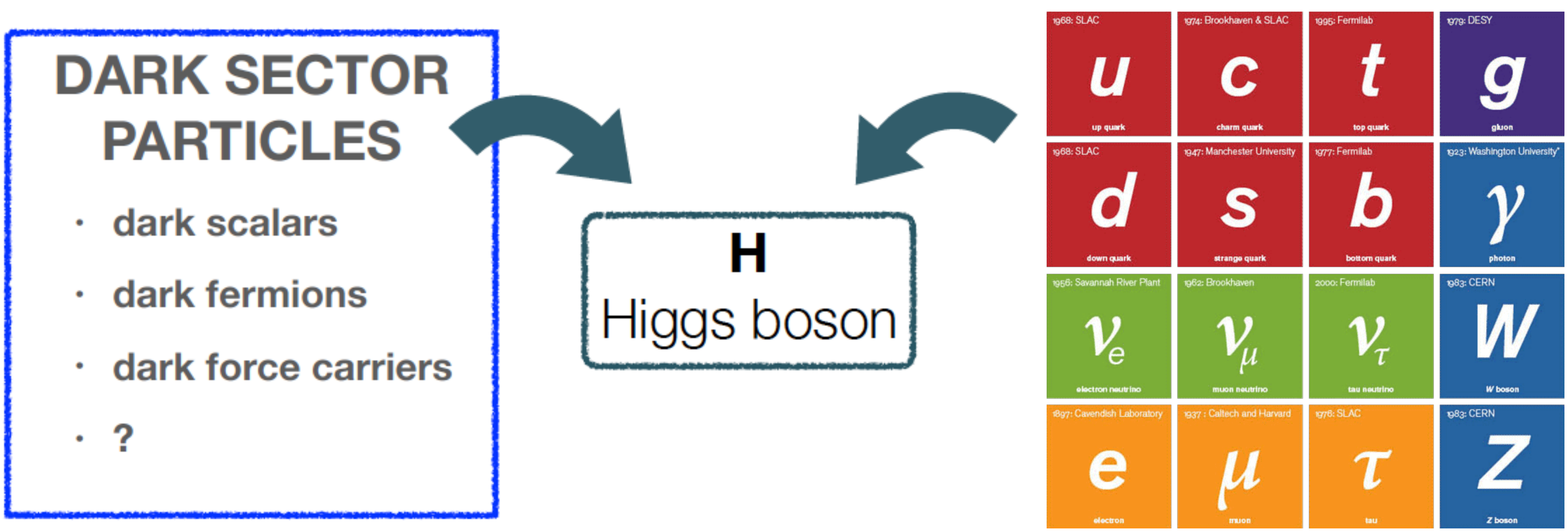
$pp \to qqH(b\bar{b})H(b\bar{b})$



First constraint on κ_{2V}: $-0.76 < \kappa_{2V} < 2.90$

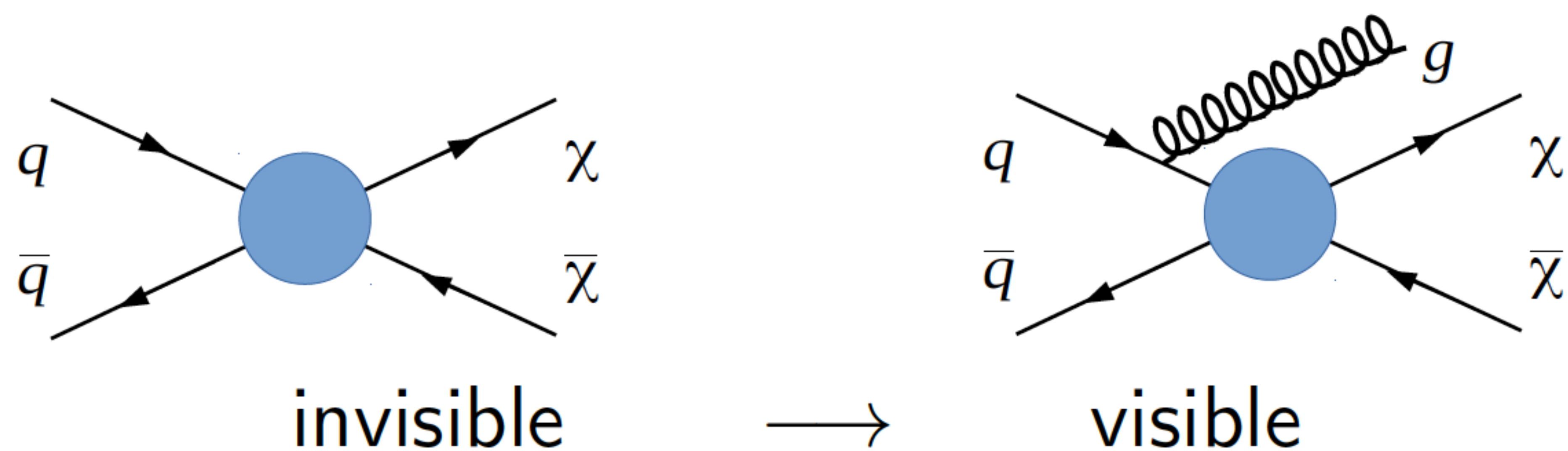
Higgs as a Portal to New Physics

- New particles may interact with SM only via Higgs



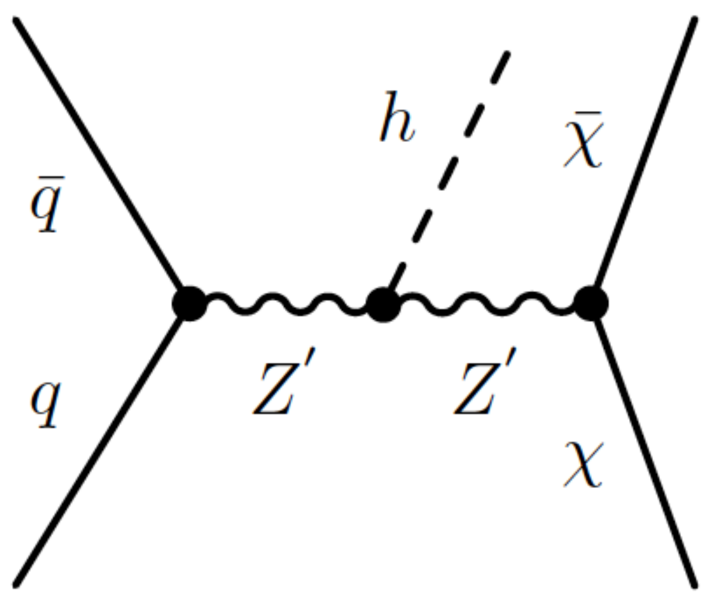
Search for Dark Matter (DM)

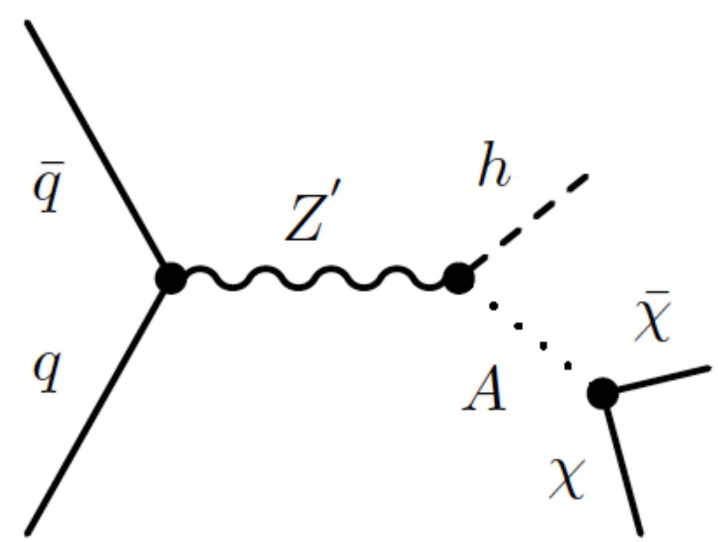
- DM are invisible for detectors (do not interact with ordinary materials). —Signatures as missing energy.
- Pair production: Need a known, visible particle in association with the DM.



Search for Dark Matter (DM)

- Mono-X (DM recoiling against X)
  Generic experimental signature:
  $pp \to E_T^{\text{miss}} + X$, where X =jet, γ, W/Z ($\to$ lep/jets), t/b or H

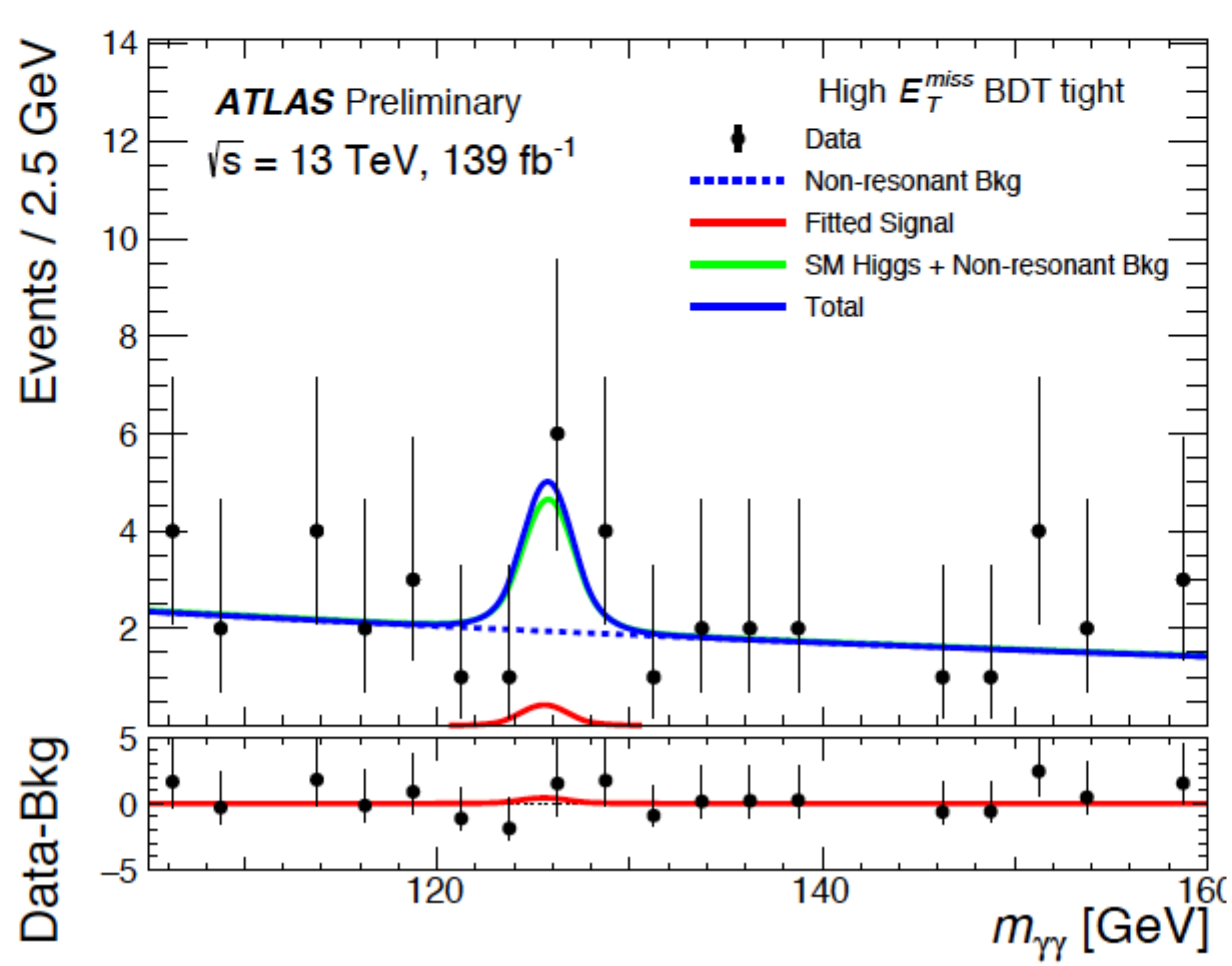


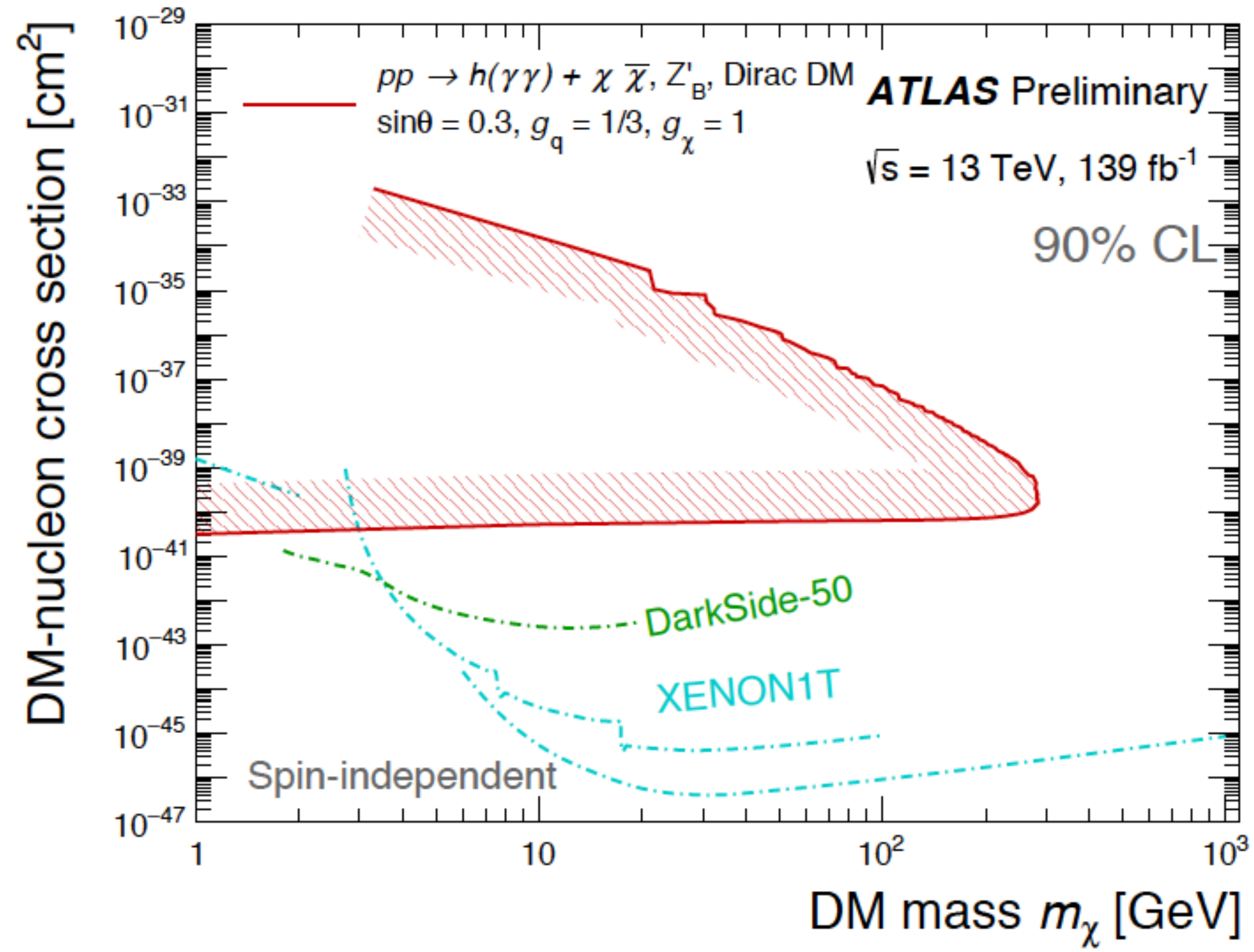


Search for Dark Matter (DM)

- ATLAS mono-H->γγ channel with full Run-2 data

ATLAS-CONF-2020-054

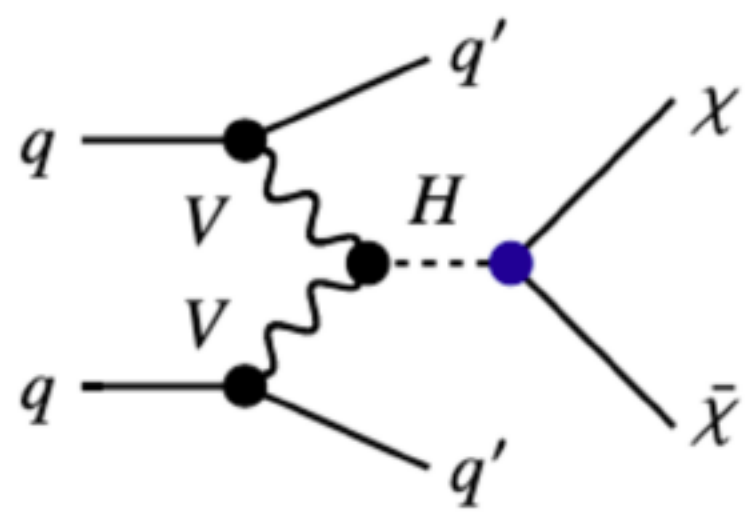


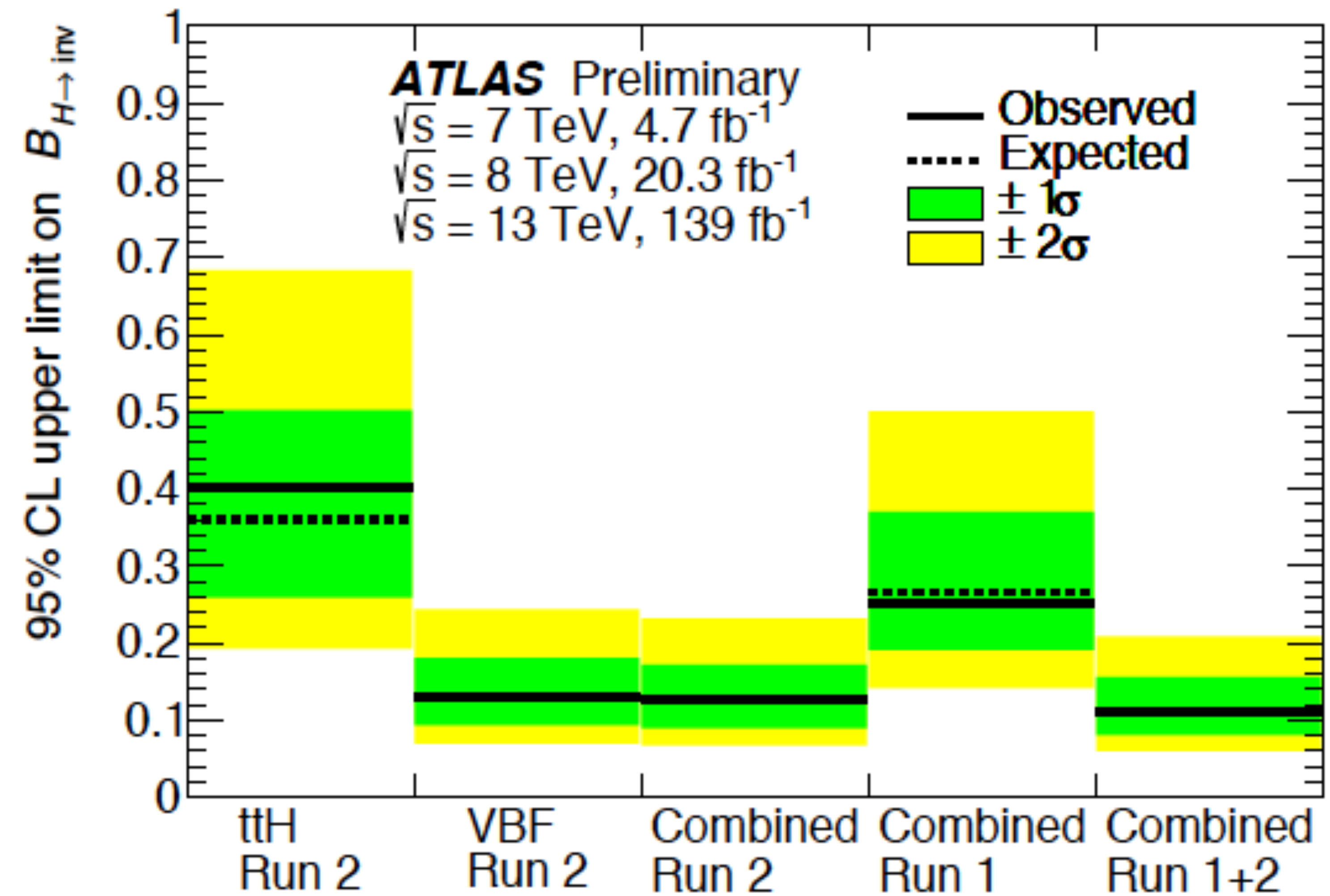


Search for Dark Matter (DM)

- VBF H->invisible

ATLAS-CONF-2020-052

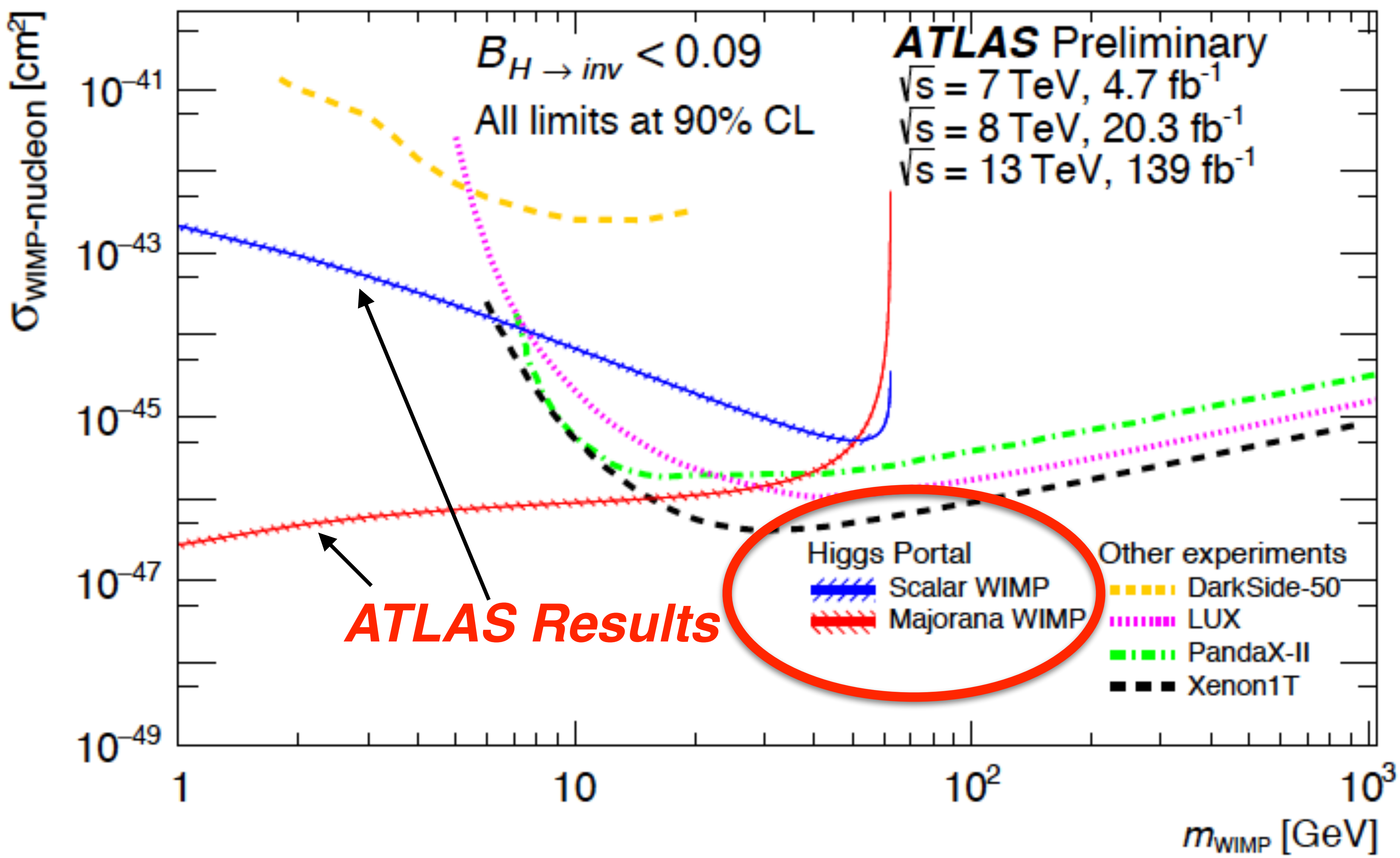




Search for Dark Matter (DM)

- VBF H->invisible

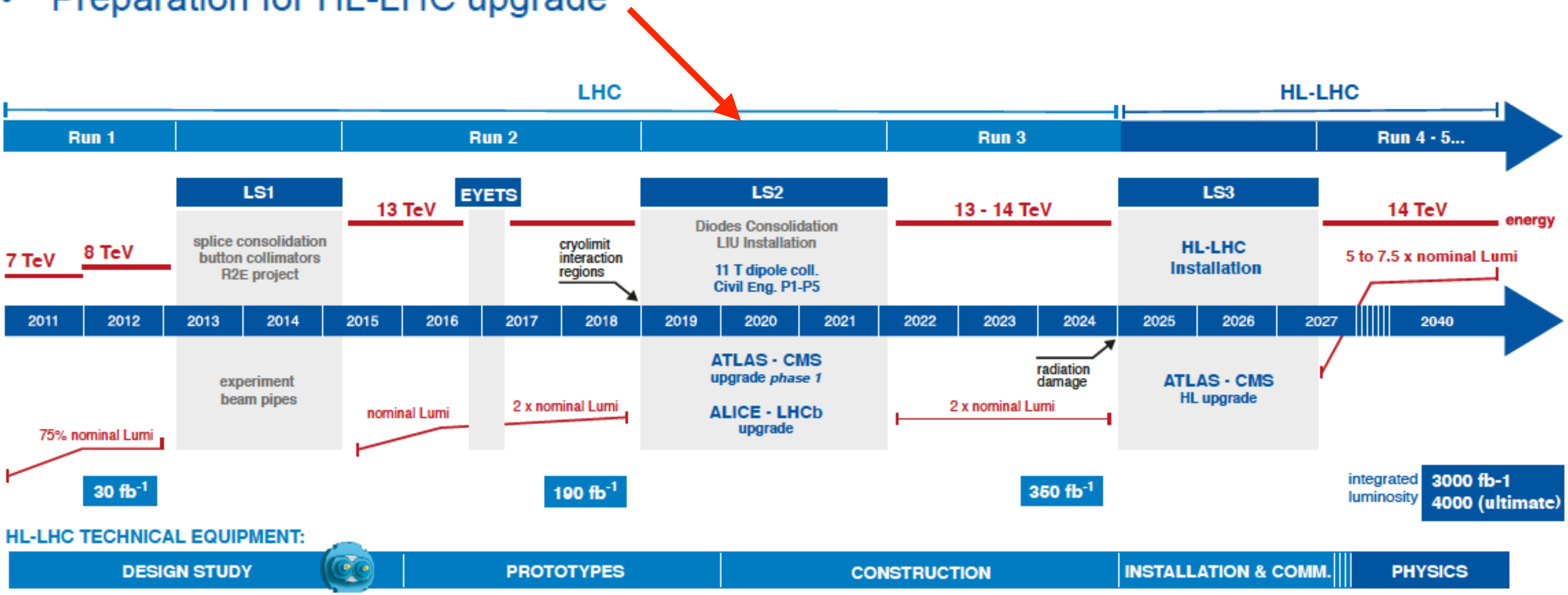
ATLAS-CONF-2020-052



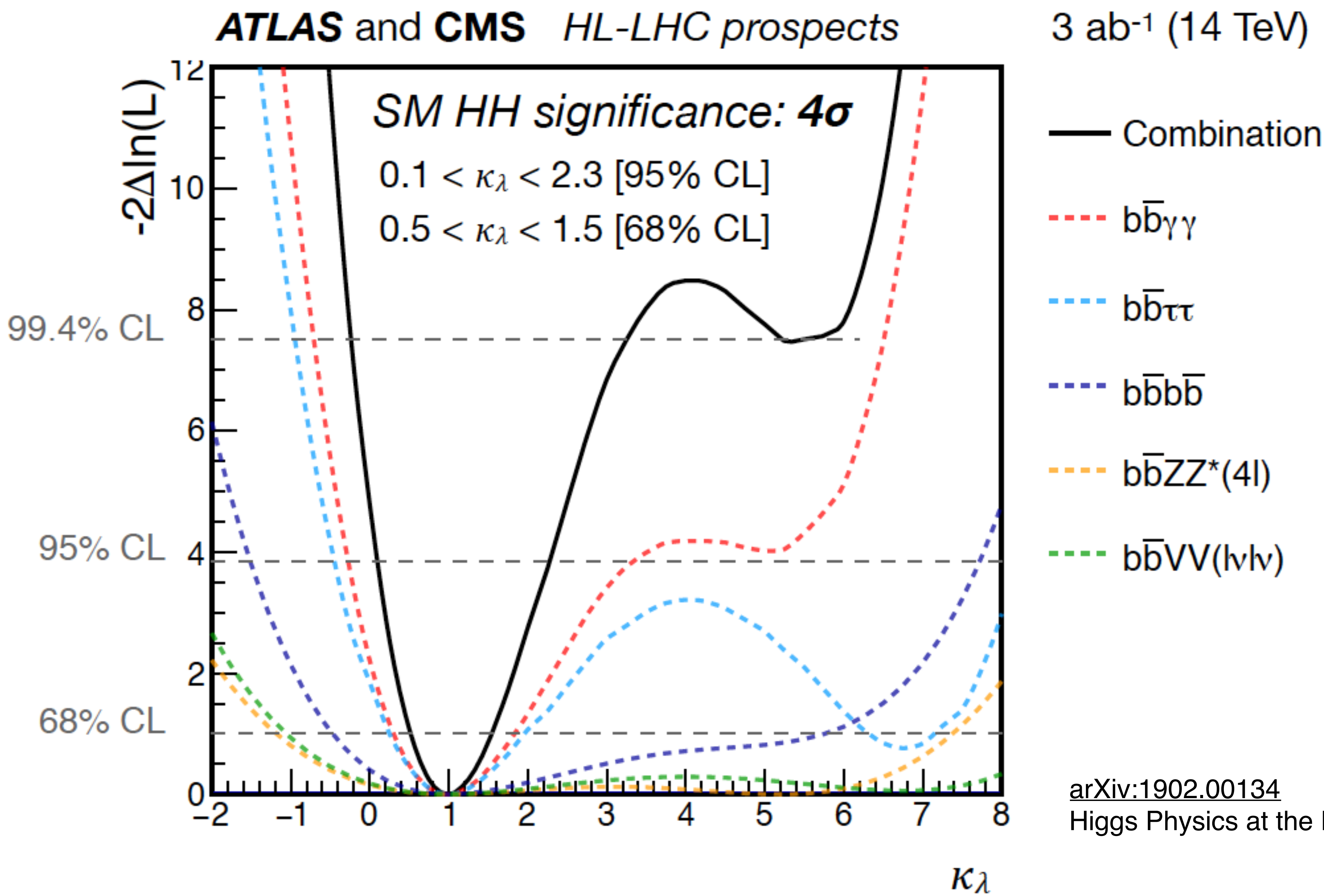
Outlook

Long Shutdown 2 (now):

- Maintenance and consolidations works
- Preparation for HL-LHC upgrade



Higgs self couplings @ HL-LHC



arXiv:1902.00134
Higgs Physics at the HL-LHC and HE-LHC

Summary

- The Higgs boson is a benchmark in Run-2
- Probe new physics via precision measurements of the Higgs boson, or use it as a new handle to exotic signals.
- Goals for Run-3/HL-LHC: $H\to\mu\mu$, $H\to cc$, $H\to Z\gamma$, Higgs self-couplings, Higgs width…

  —Inputs/Ideas from the theory side will make the list longer and richer!

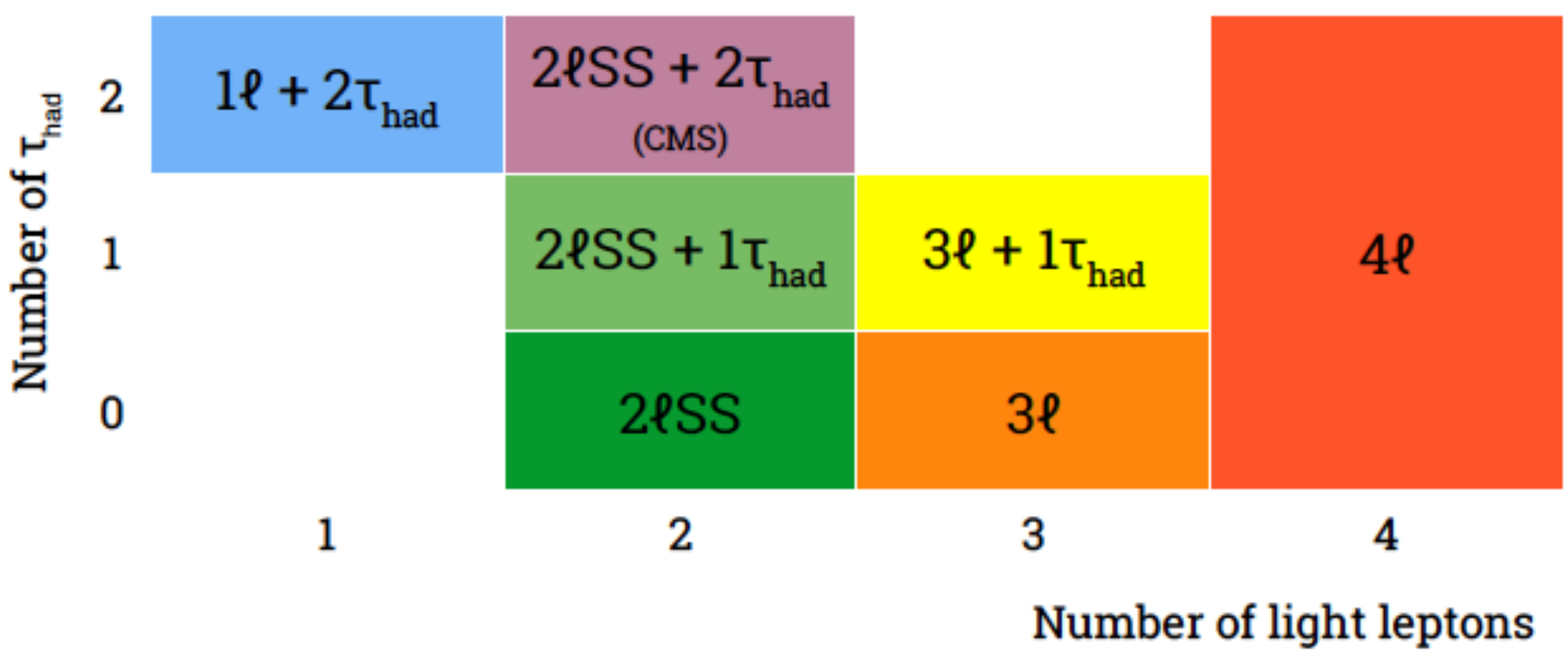
Backup

ttH multilepton couplings

ATLAS: ATLAS-CONF-2019-045 – 80 fb^{-1}
CMS: CMS-PAS-HIG-18-019 – 36+42 fb^{-1}

H → WW, ττ, ZZ decays (tt → ℓ+jets or dilepton)

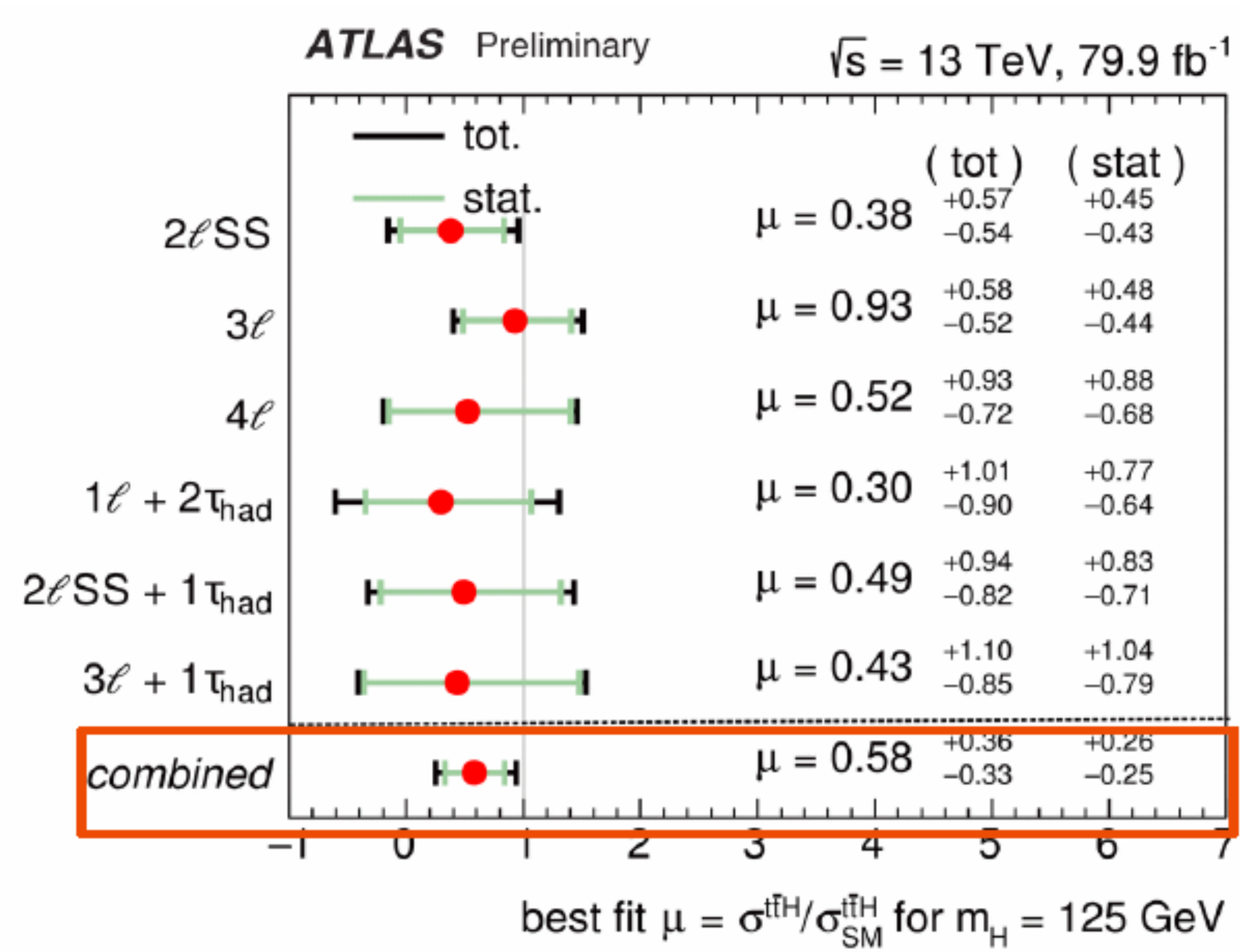
- Big backgrounds are $t\bar{t}W$, $t\bar{t}Z$, $t\bar{t}$ + "fake"/charge-misID leptons & τ_{had}
- MVA in each category (matrix element in CMS; BDT)
  - most powerful categories are 2ℓSS and 3ℓ



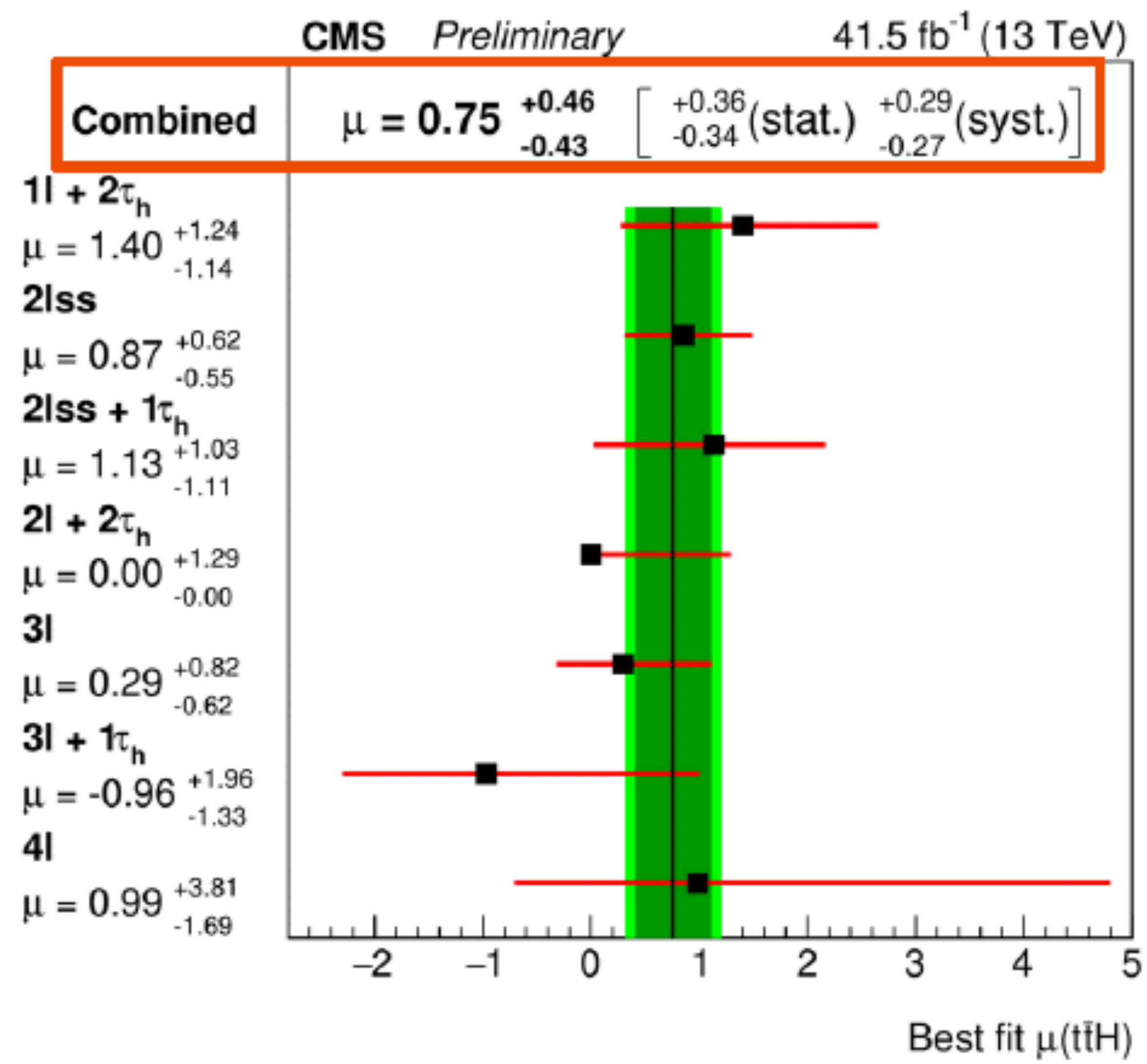
ttH multilepton couplings

ATLAS: ATLAS-CONF-2019-045 – 80 fb^{-1}
CMS: CMS-PAS-HIG-18-019 – 36+42 fb^{-1}

Biggest systematics are jet energy scale, $t\bar{t}V$ modeling

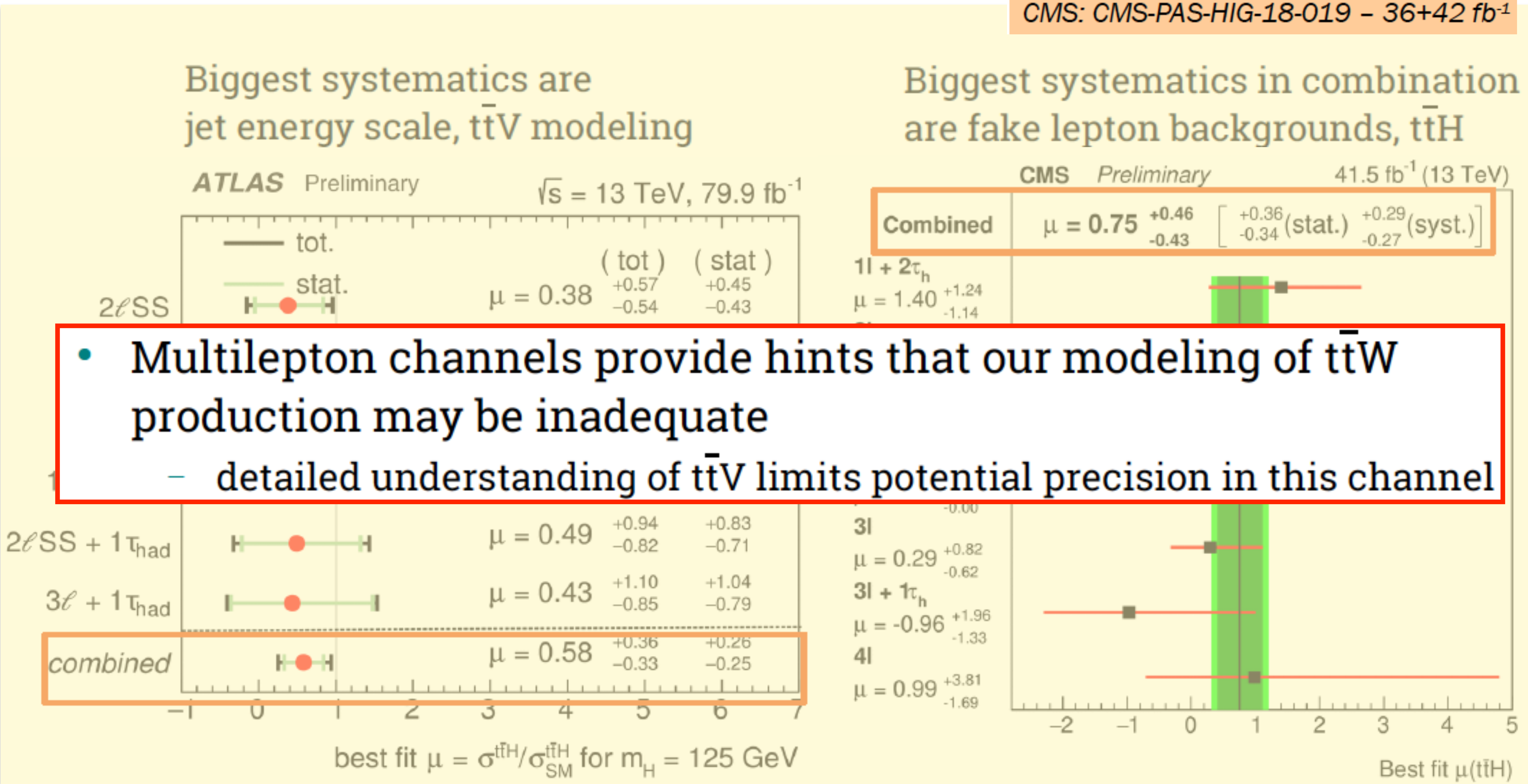


Biggest systematics in combination are fake lepton backgrounds, $t\bar{t}H$



ttH multilepton couplings

ATLAS: ATLAS-CONF-2019-045 – 80 fb^{-1}
CMS: CMS-PAS-HIG-18-019 – 36+42 fb^{-1}



- Multilepton channels provide hints that our modeling of $t\bar{t}W$ production may be inadequate
  - detailed understanding of $t\bar{t}V$ limits potential precision in this channel

Higgs Width

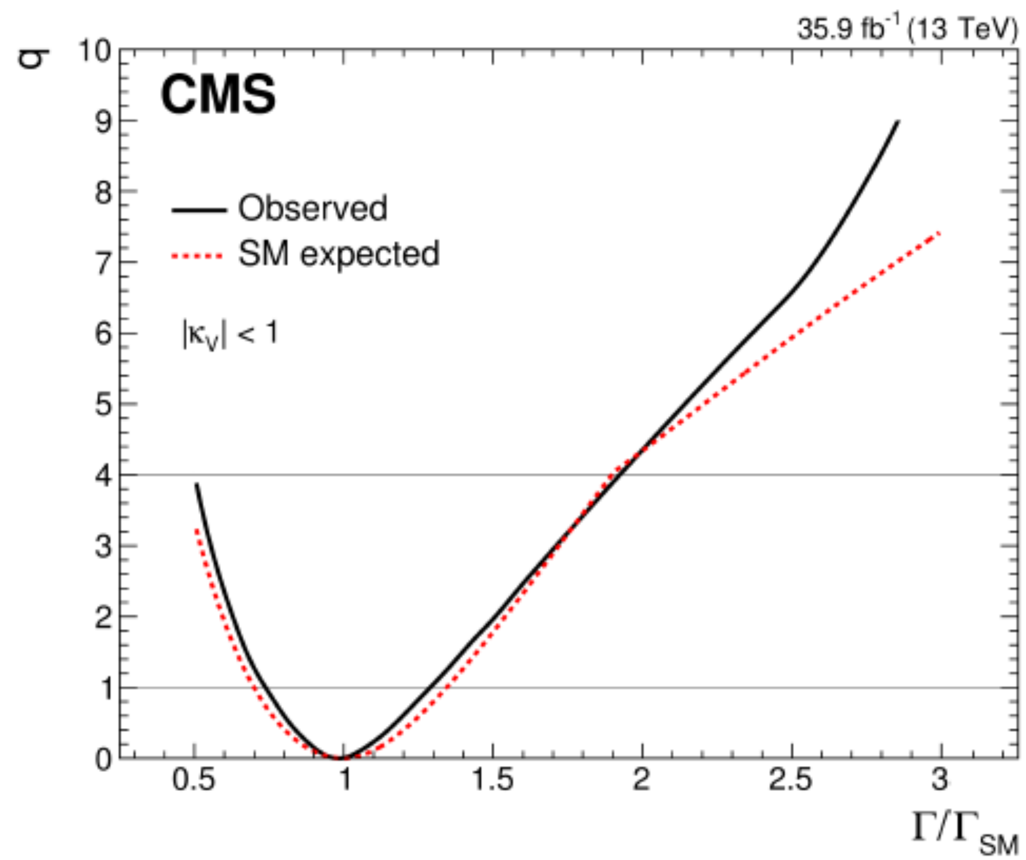
- Can extract Higgs width from Higgs couplings combination

Eur. Phys. J. C 79 (2019) 421

- **Derived within κ-framework, combination of the H→γγ, ZZ, WW, $\tau\tau$, bb, $\mu\mu$ and invisible decay channels using up to 36 fb^{-1}**
  - **Reinterpreting the model allowing for BSM decays of the Higgs boson.**

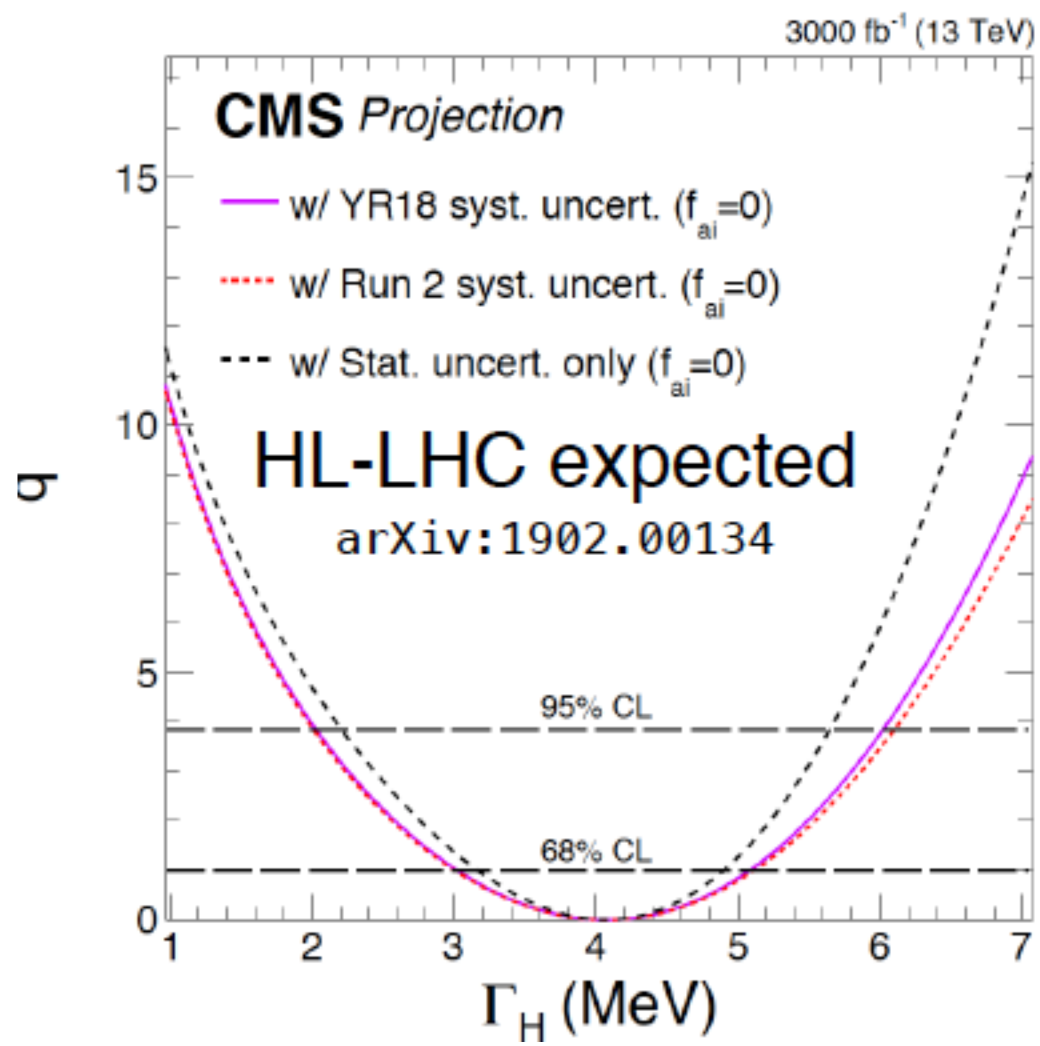
$$\frac{\Gamma_{\rm H}}{\Gamma_{\rm H}^{\rm SM}} = \frac{\kappa_{\rm H}^2}{1-(\mathcal{B}_{\rm undet}+\mathcal{B}_{\rm inv})}$$

- **~30% uncertainty on the total width constraint**



$$\Gamma_{\rm tot}/\Gamma_{\rm SM} = 0.98^{+0.31}_{-0.25}$$

Higgs width @ HL-LHC



arXiv:1902.00134

ATLAS+CMS

HL-LHC expect

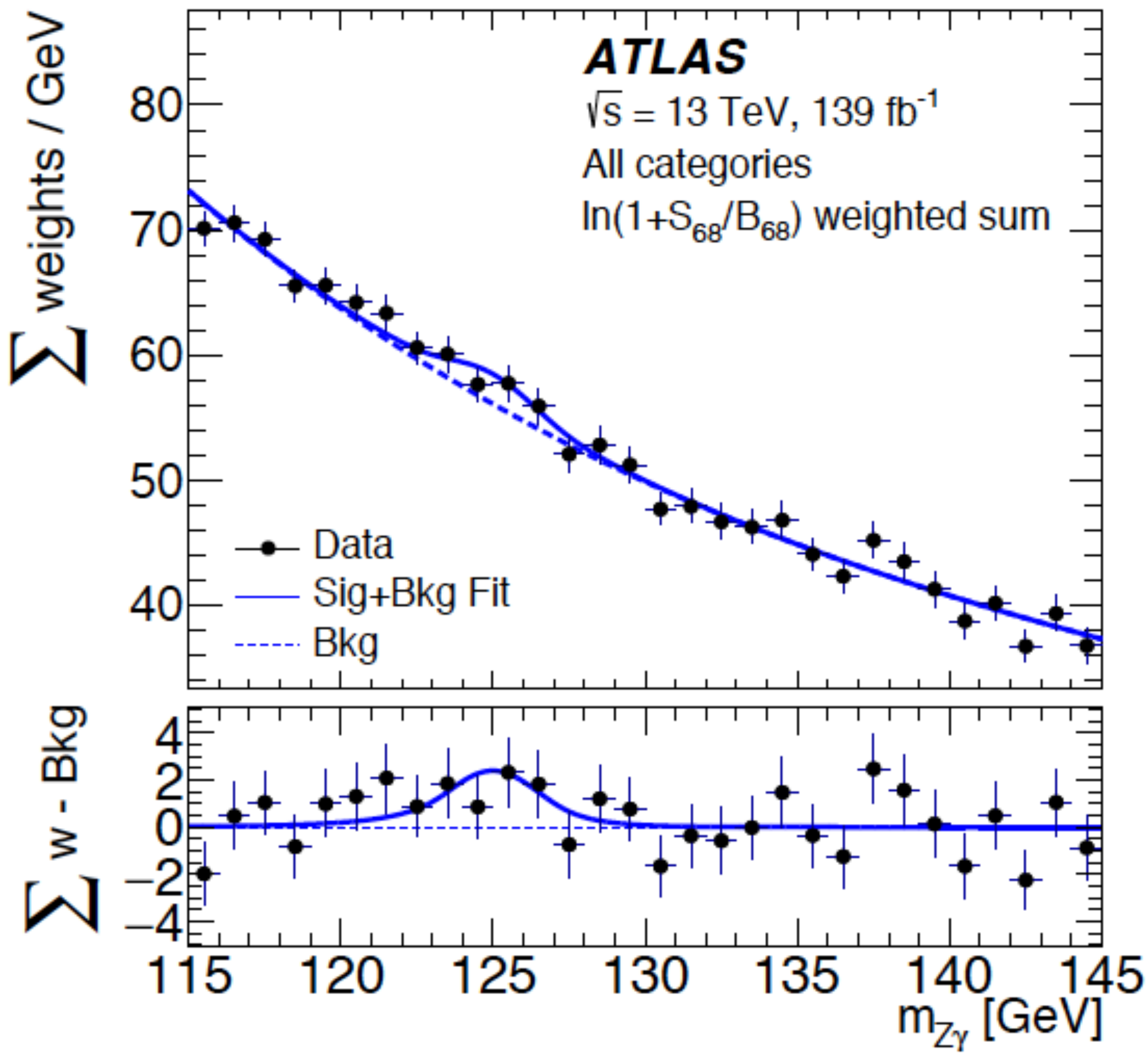
3000 fb^{-1}

$\Gamma_H = \boxed{4.1} \boxed{\pm 0.8 \text{ MeV}}$

expected uncertainty

expected in SM

H → Zγ



Phys. Lett. B 809 (2020) 135754

$2.2\,\sigma$

upper limit on
σ*BR = 3.6x SM

Higgs CP properties

CP structure of Higgs-τ Yukawa coupling (CMS)

$$A(\mathrm{Hff}) = -\frac{m_{\mathrm{f}}}{v}\bar{\psi}_{\mathrm{f}}\left(\kappa_{\mathrm{f}} + \mathrm{i}\,\tilde{\kappa}_{\mathrm{f}}\gamma_5\right)\psi_{\mathrm{f}}$$

$$\tan(\phi_{\tau\tau}) = \frac{\tilde{\kappa}}{\kappa}$$

- This correlation can be probed via the angle ϕ_{cp} between the τ **decay planes:**

$$\frac{d\Gamma}{d\phi_{\mathrm{CP}}} \propto \cos(\phi_{\mathrm{CP}} - 2\phi_{\tau\tau})$$

Latest Results on the Higgs Boson