What we (don’t) know about Higgs boson

LIU Kun

2020.06.19

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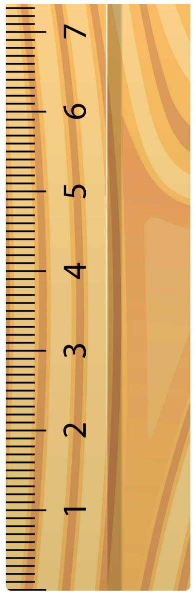
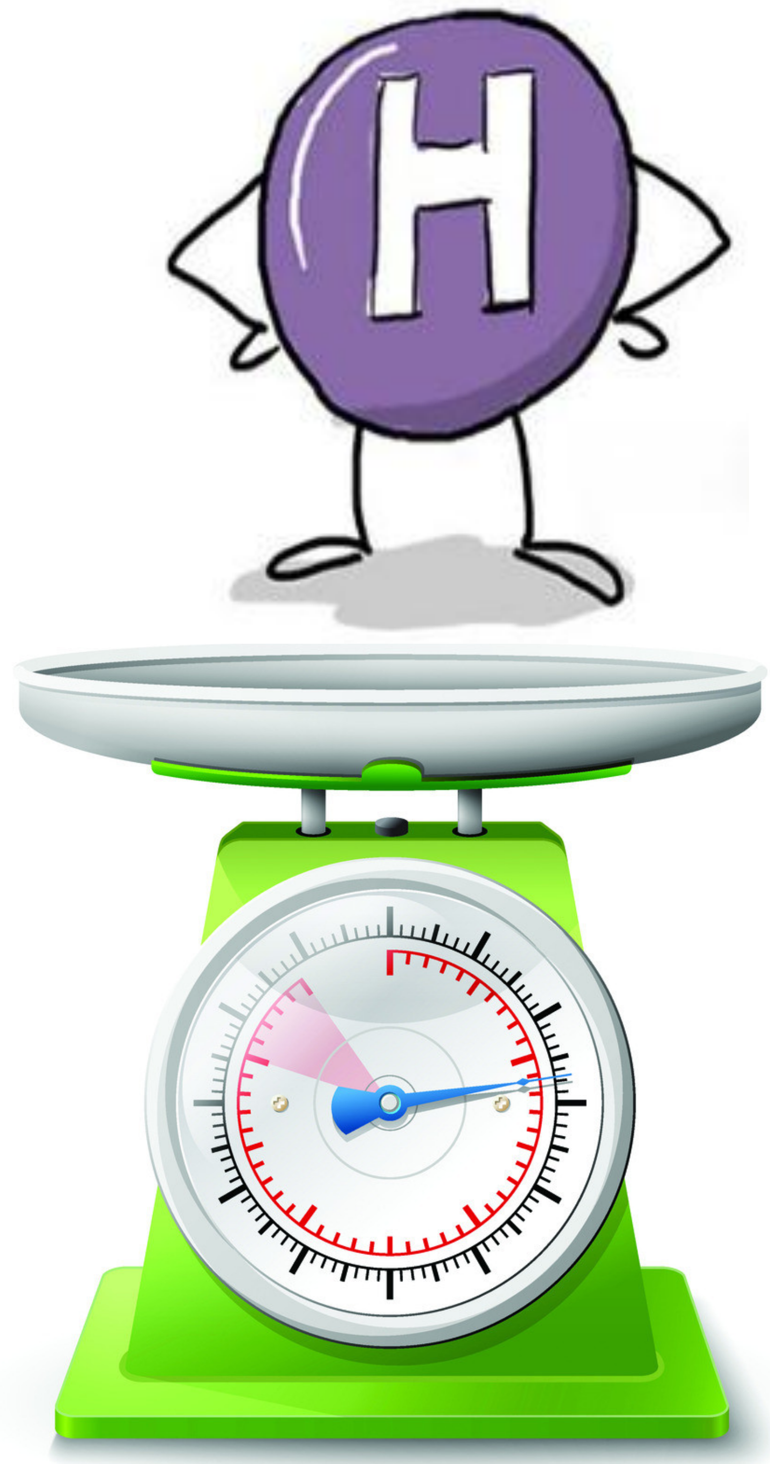




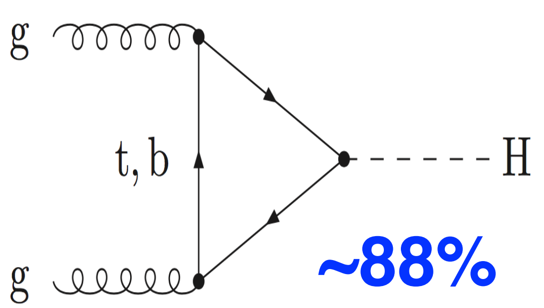
- Mass
- Width
- Cross sections
- Production&decays
- Couplings
- …

The Higgs boson production and decay at LHC

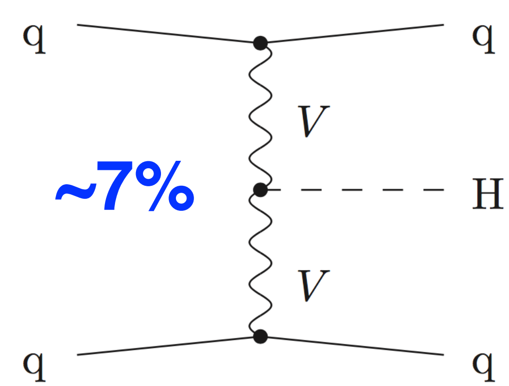
Higgs boson production at LHC
at 13 TeV centre-of-mass energy

~ 8 millions Higgs bosons have been produced per experiment (~200 per hour)

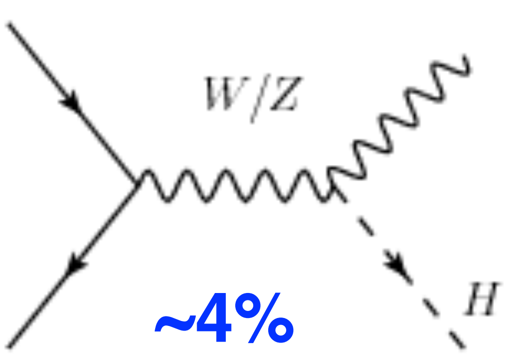
gluon-gluon fusion(ggF)



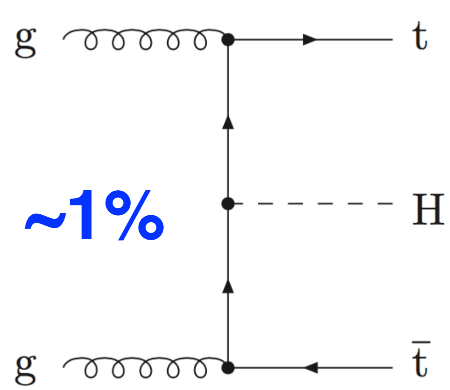
Vector boson fusion(VBF)



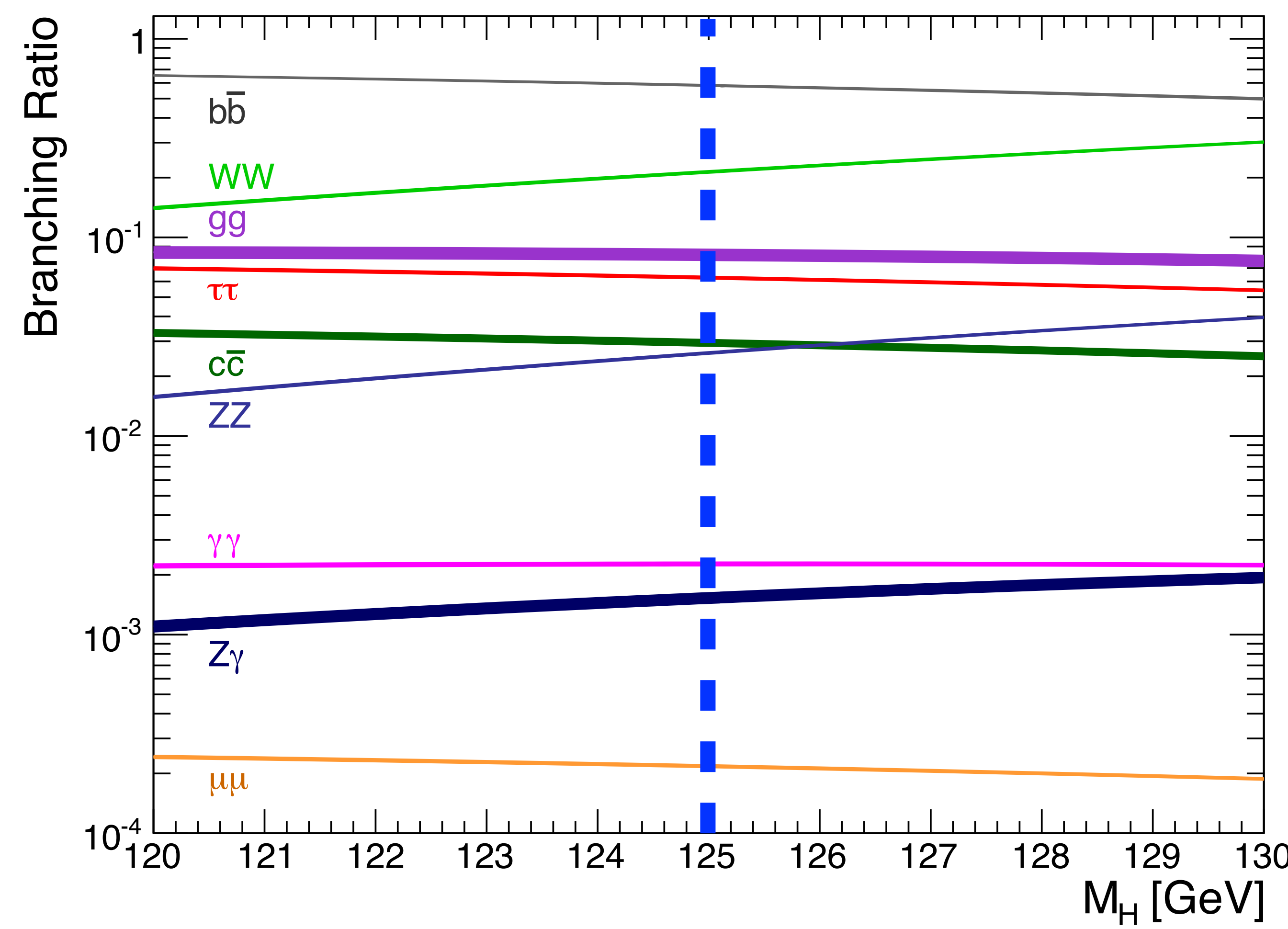
Higgs associated production with vector bosons (VH)



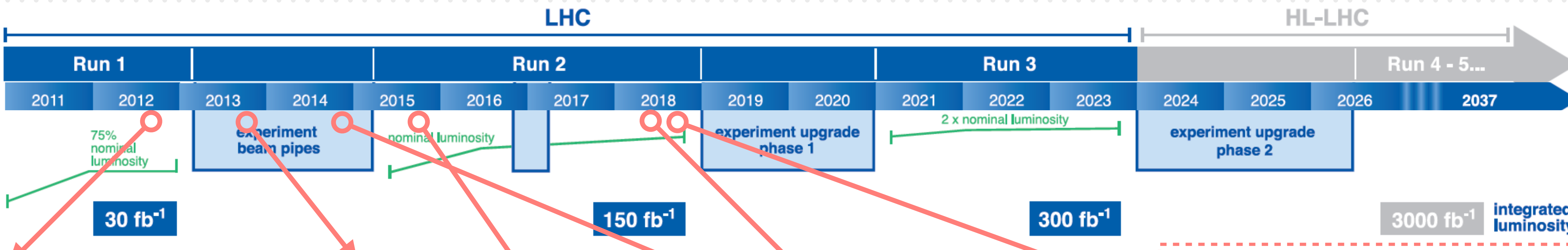
Higgs associated production with a top-quark pair (ttH)



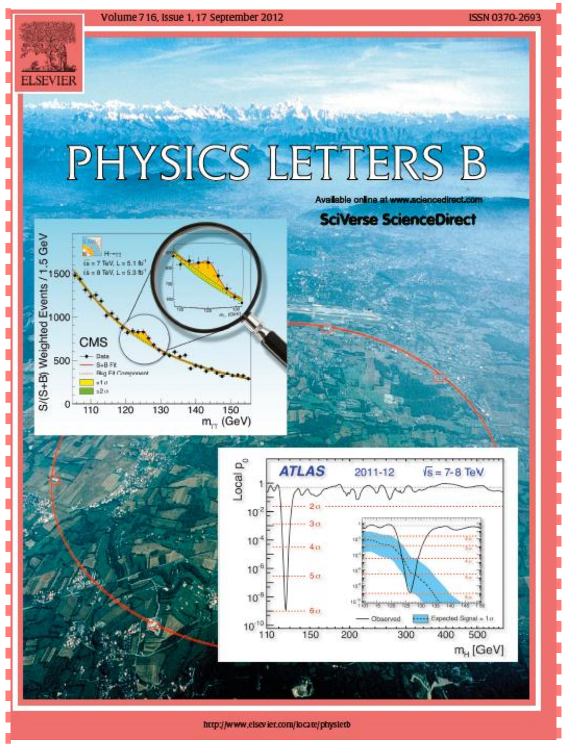
Higgs boson decay modes



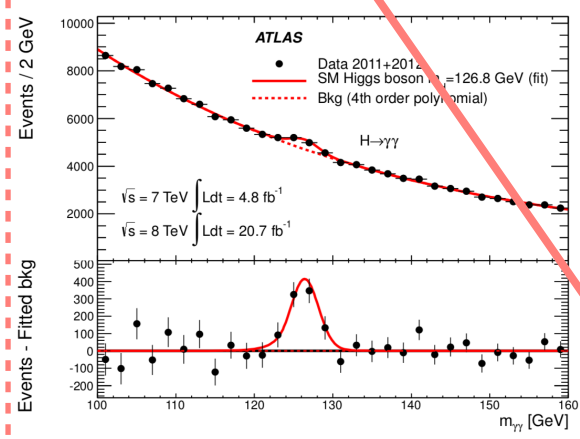
Higgs boson observation at LHC

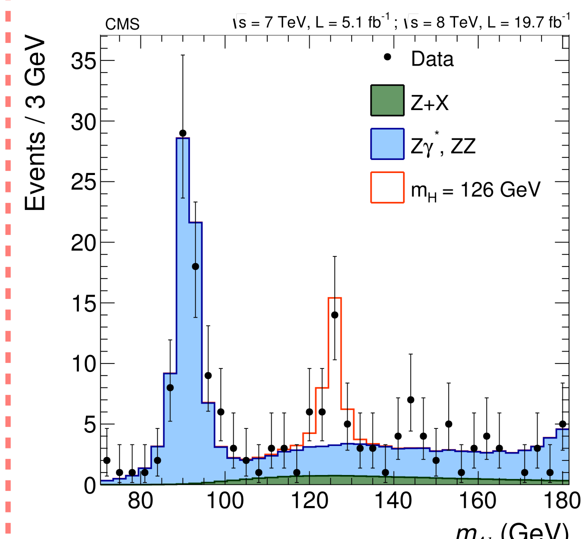


SM-like Higgs discovery
(ggF → $\gamma\gamma$ + ZZ + WW)

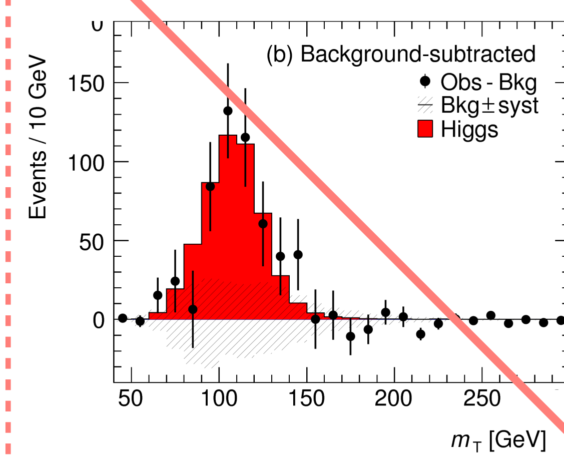


H→$\gamma\gamma$, ZZ→4l observation
(spin-0 and parity +)

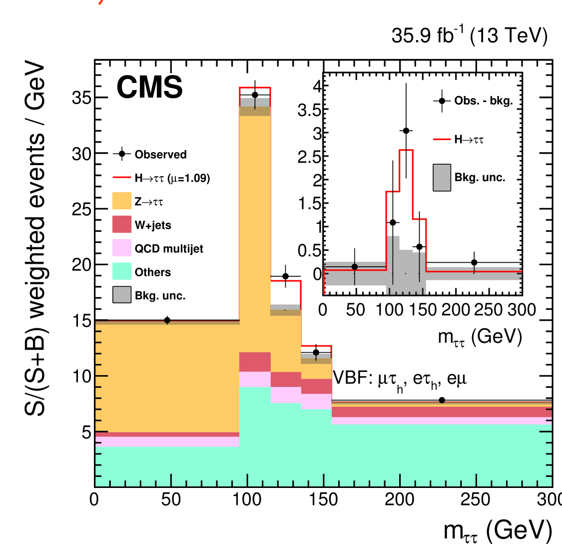




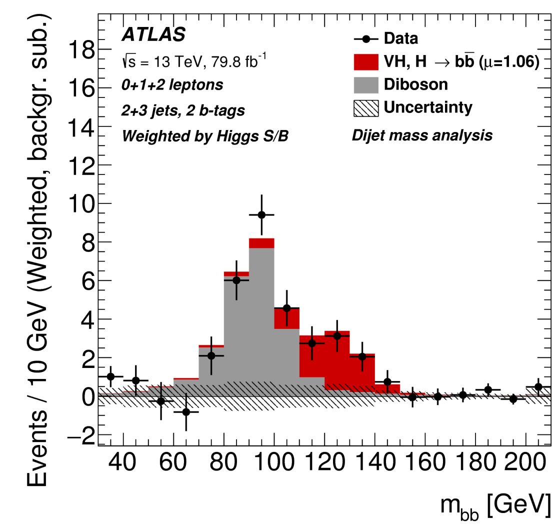
H→WW observation



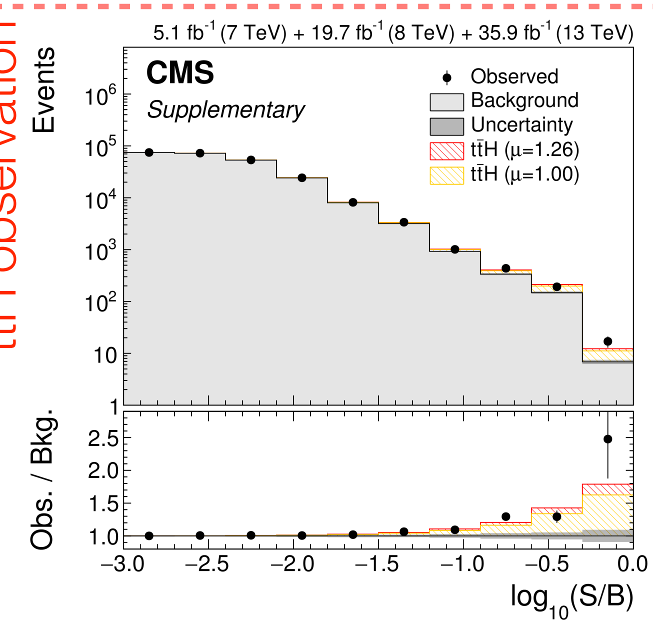
VBF, H→$\tau\tau$ observation



VH, H→bb observation



ttH observation

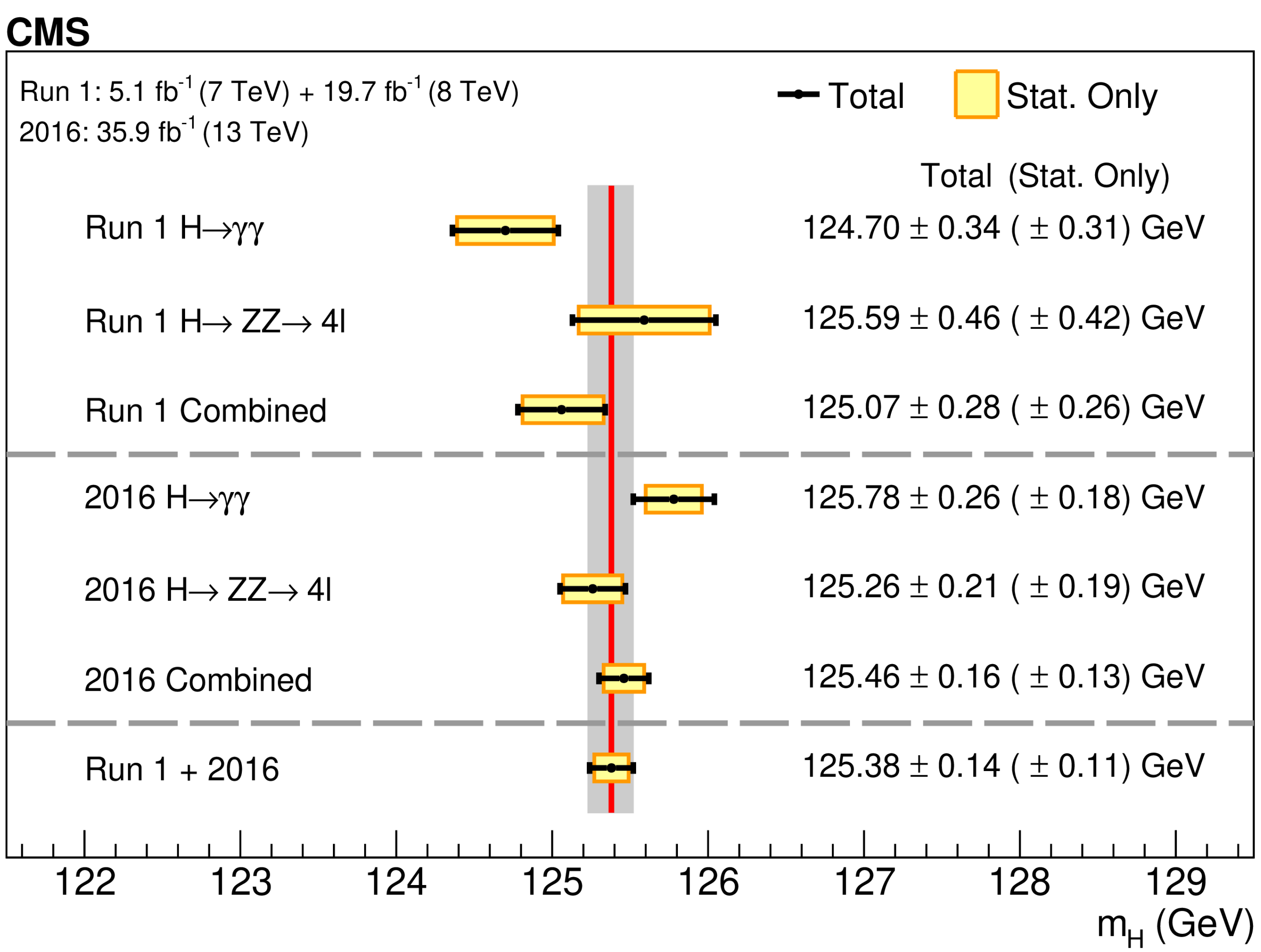


Higgs boson mass measurement

PRL 114 (2015) 191803
ATLAS-CONF-2020-005
PLB 805 (2020) 135425

The **Higgs boson mass** has been measured **at 0.2% accuracy in Run 1** (ATLAS+CMS):

$$125.09 \pm 0.24\ (\underbrace{\pm 0.21}_{\text{Stat.}} \underbrace{\pm 0.11}_{\text{Syst.}})\ \text{GeV}$$



- ✦ **ATLAS Run 2** H→ZZ→4l channel uses 139 fb^{-1} dataset:

$$124.92 \pm 0.19(\text{stat.})^{+0.09}_{-0.06}(\text{syst.})\ \text{GeV}$$

- ✦ **CMS Run 2** measurement in H→$\gamma\gamma$ and H→ZZ→4l combination, using 35.9 fb^{-1} dataset:

$$125.46 \pm 0.13\,(\text{stat}) \pm 0.10\,(\text{syst})\,\text{GeV}$$

→ combination with CMS Run 1 measurements gives the most precise measurement at present (0.11%):

$$\boxed{125.38 \pm 0.11\,(\text{stat}) \pm 0.08\,(\text{syst})\,\text{GeV}}$$

Constraints on Higgs boson width

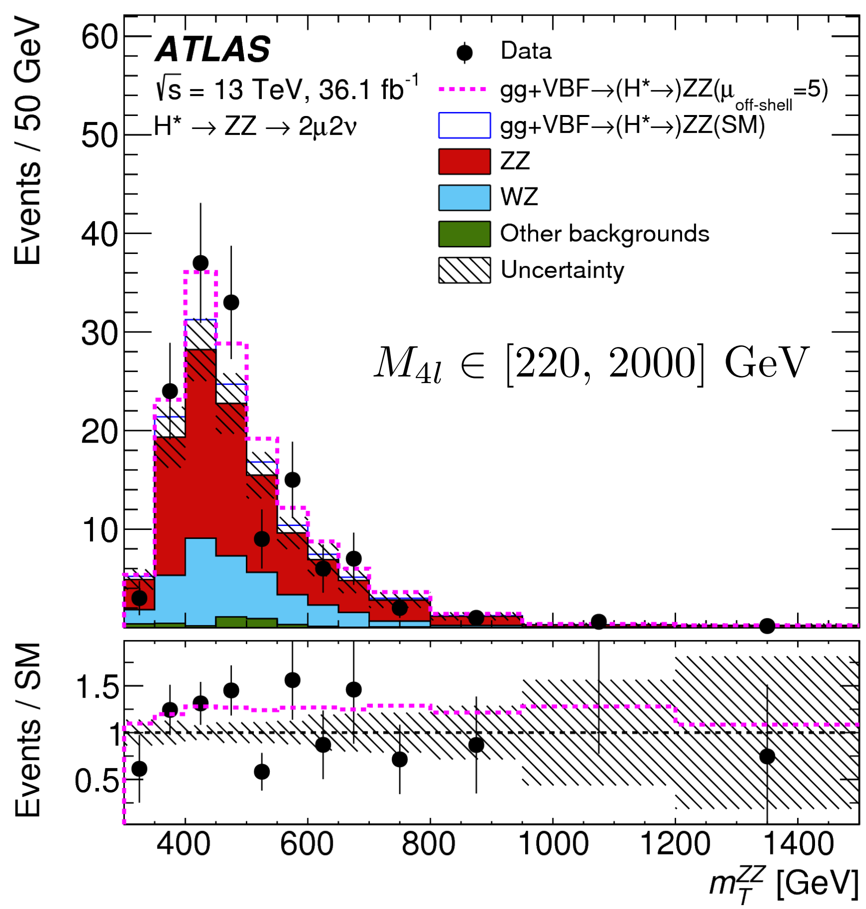
PRD 99 (2019) 112003
PLB 786 (2018) 223
ATL-PHYS-PUB-2015-024
CMS-PAS-FTR-18-011

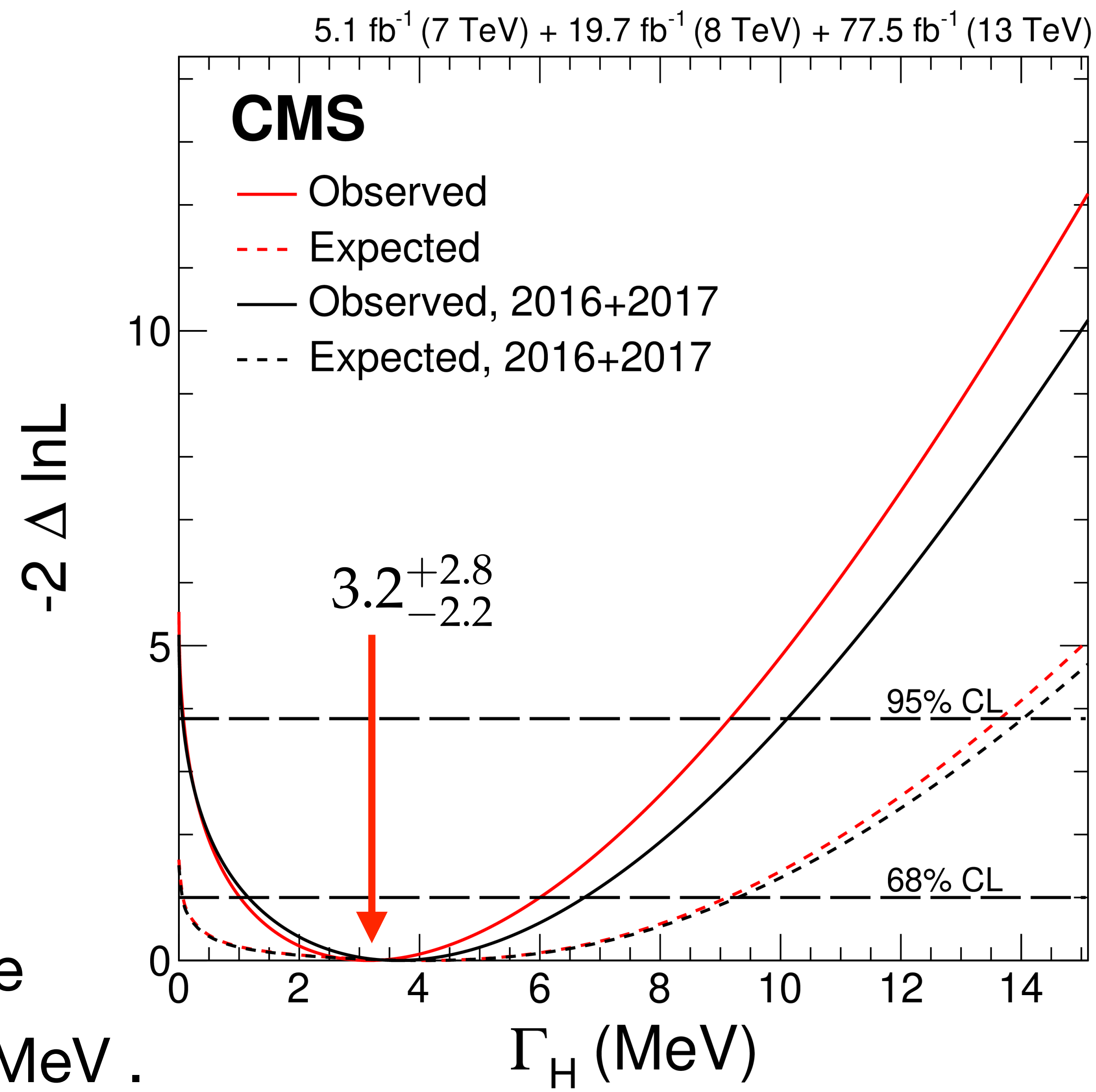
Indirect measurement from off-shell production in H→ZZ→4l channel. Obs. limit on Higgs width:

- ATLAS Run 2 (36.1fb^{-1}): < 14.4 MeV
- CMS Run 1+2 (77 fb^{-1}): [0.08, 9.16] MeV

➡ comparing to the SM prediction: 4.1 MeV.

$$\frac{\sigma^{on-shell}_{gg\to H\to ZZ^*} \sim \frac{g^2_{ggH}\, g^2_{HZZ}}{m_H \Gamma_H}}{\sigma^{off-shell}_{gg\to H^*\to ZZ} \sim \frac{g^2_{ggH}\, g^2_{HZZ}}{(2m_Z)^2}}$$



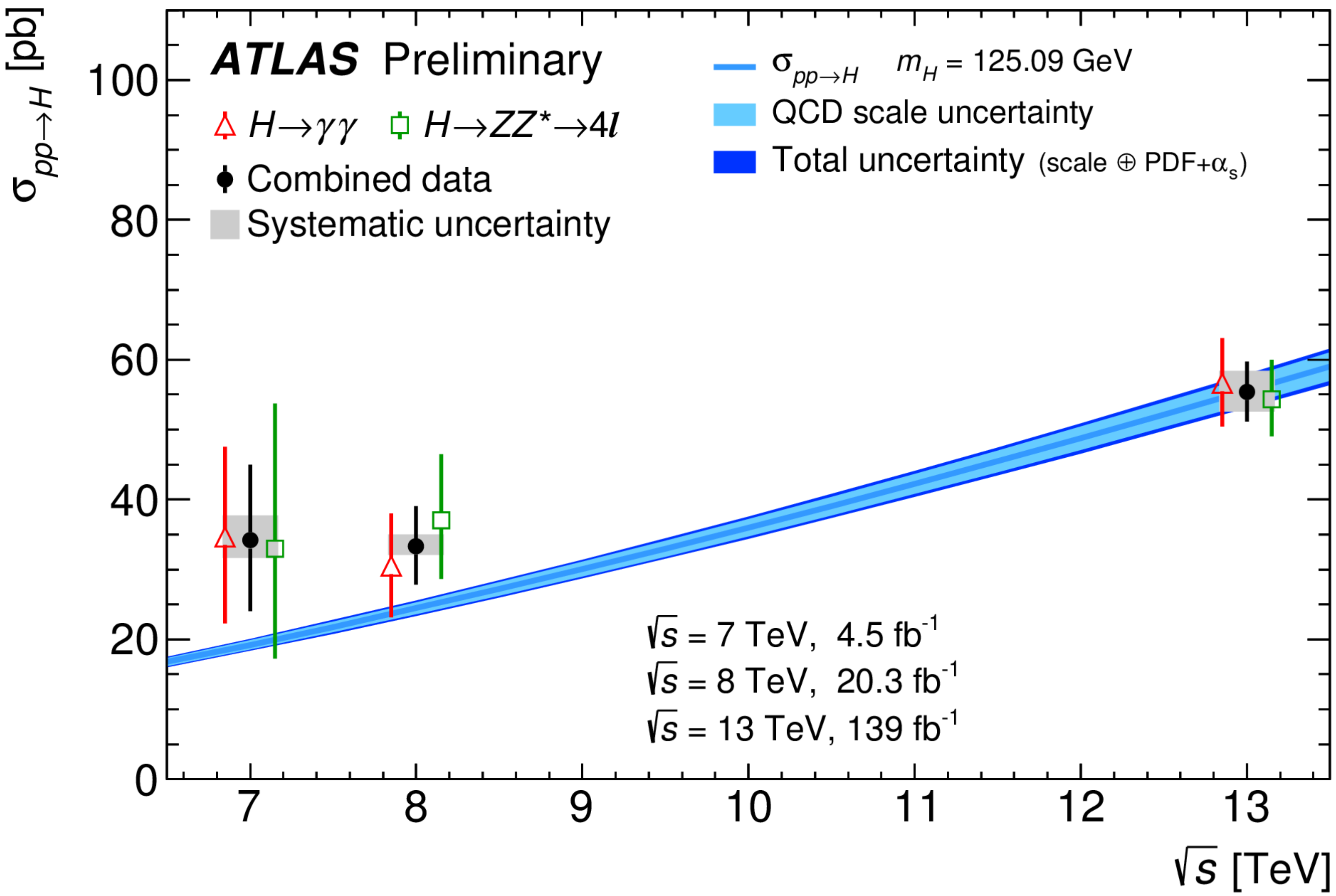


Prospects with 3 ab^{-1} at HL-LHC, Γ_H can be measured in CMS (ATLAS): $4.1^{+1.0}_{-1.1}$ $(4.2^{+1.5}_{-2.1})$ MeV .

Higgs cross section measurement

EPJC 79 (2019) 421
P.R.D 202 (2020) 012002
ATLAS-CONF-2019-032

- Inclusive Higgs signal strength from all channels combination:
  - ATLAS Run 2 (80fb^{-1}): $\mu = 1.11^{+0.09}_{-0.08} = 1.11 \pm 0.05\,(\text{stat.})\,^{+0.05}_{-0.04}\,(\text{exp.})\,^{+0.05}_{-0.04}\,(\text{sig. th.}) \pm 0.03\,(\text{bkg. th.})$
  - CMS Run 2 (36fb^{-1}): $\mu = 1.17 \pm 0.10 = 1.17 \pm 0.06\,(\text{stat})\,^{+0.06}_{-0.05}\,(\text{sig theo}) \pm 0.06\,(\text{other syst})$
- Inclusive X-section measurement in $\gamma\gamma$ and ZZ channel at 7,8 and 13 TeV:

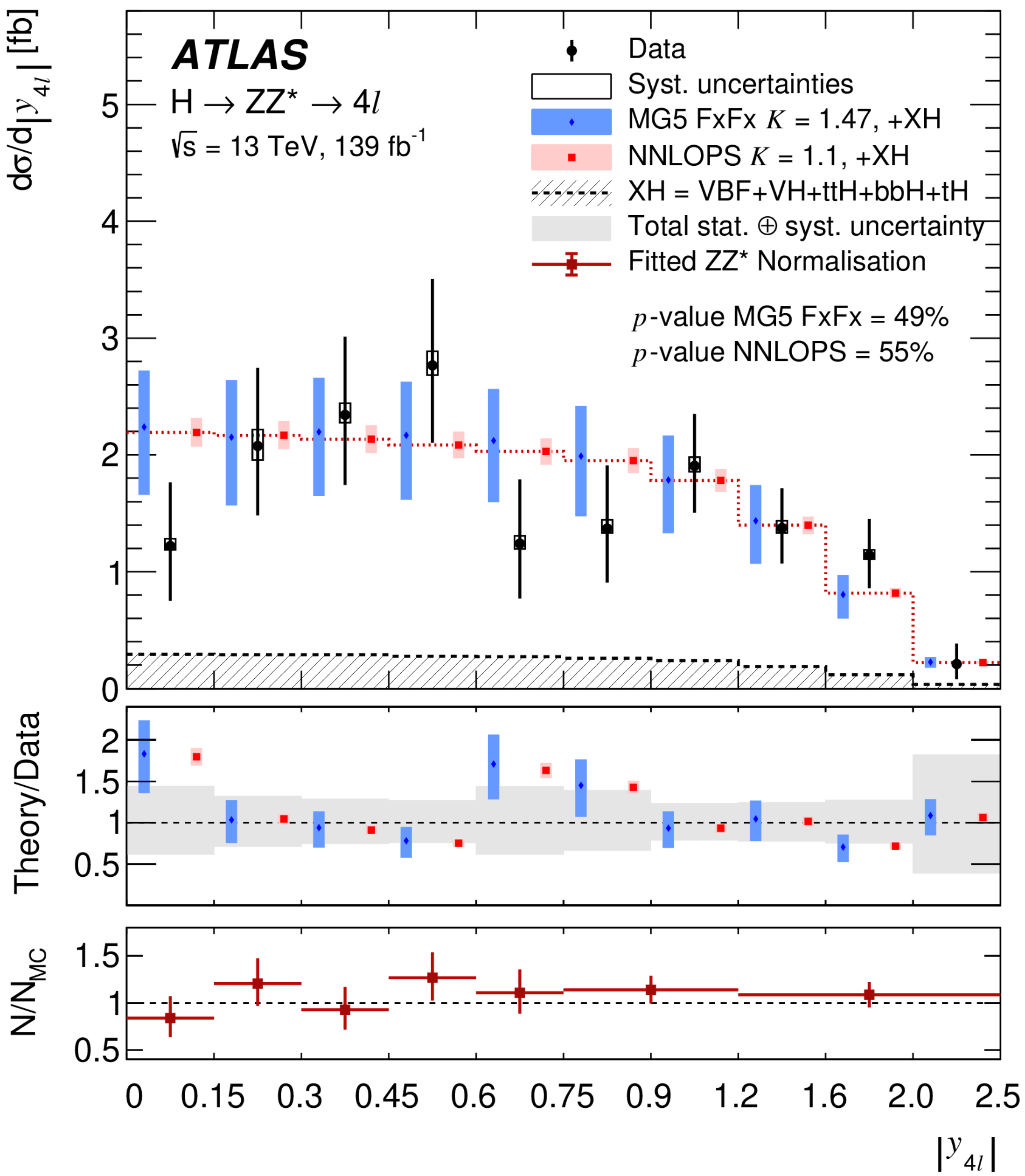


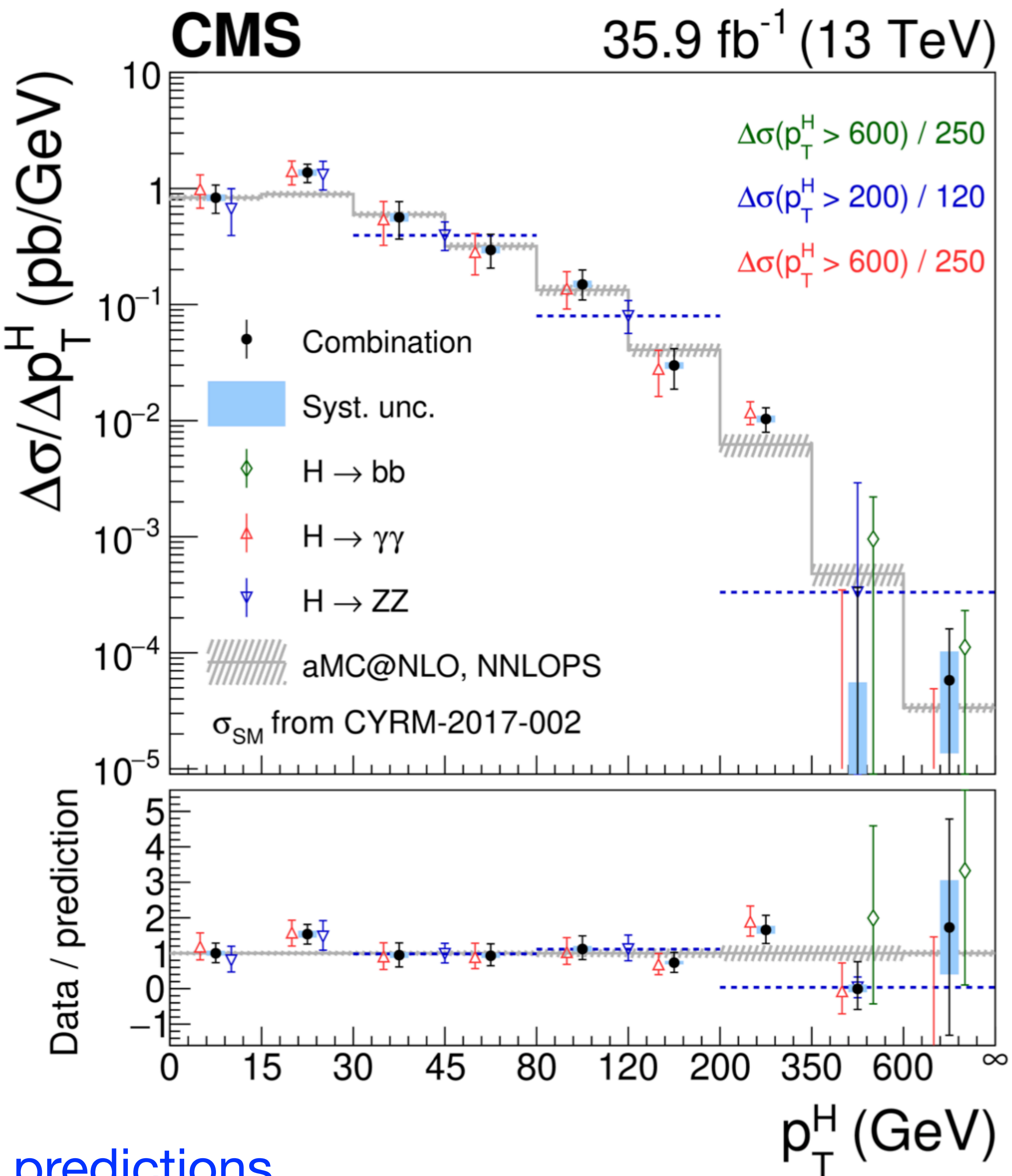
➡ Inclusive X-section measurements are in agreement with the SM prediction.

Higgs cross section vs Higgs rapidity, p_T

PLB 792 (2019) 369
Submitted to: EPJC

- Differential X-section measurement in $H\to\gamma\gamma$, ZZ (and bb) channels.

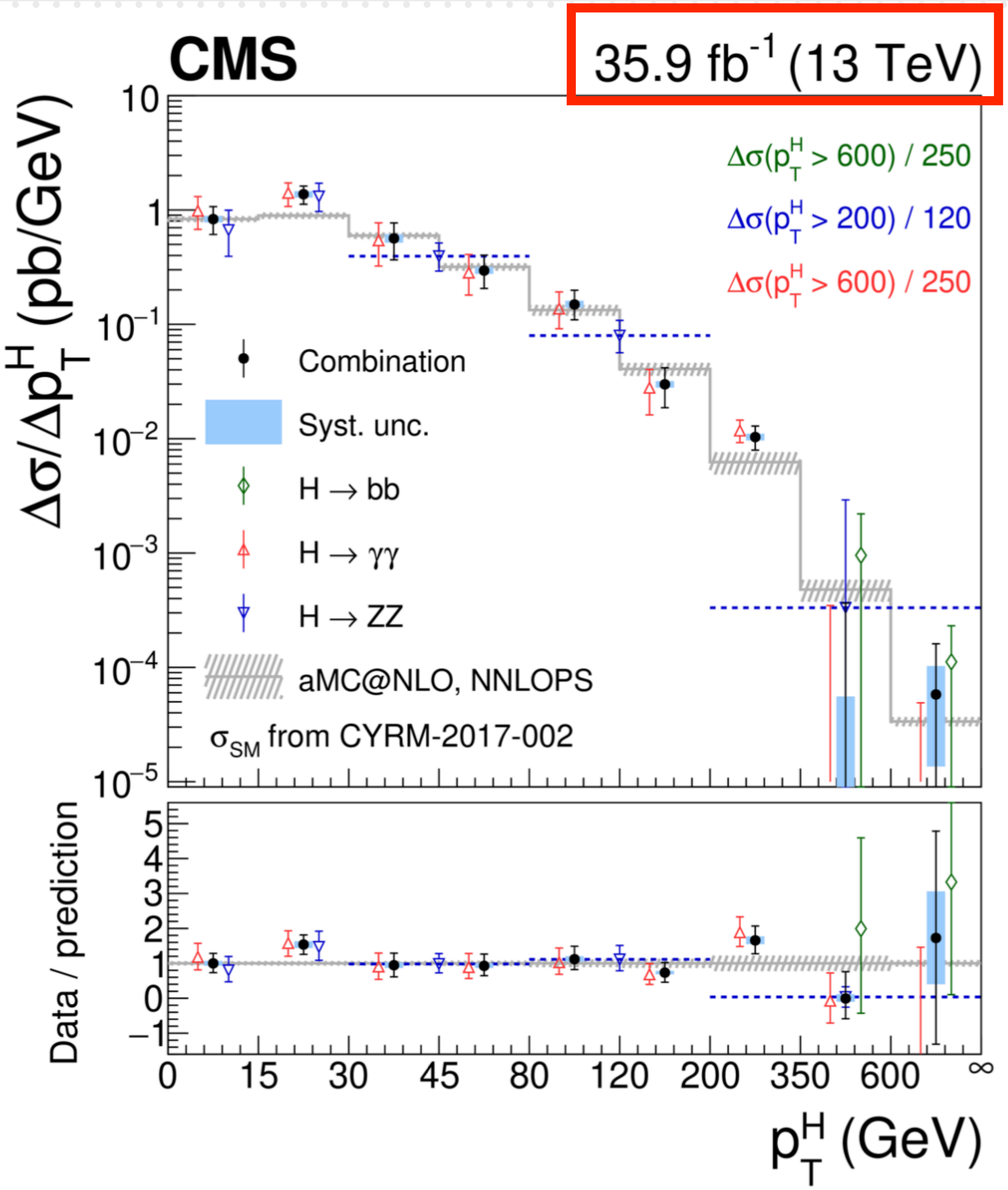


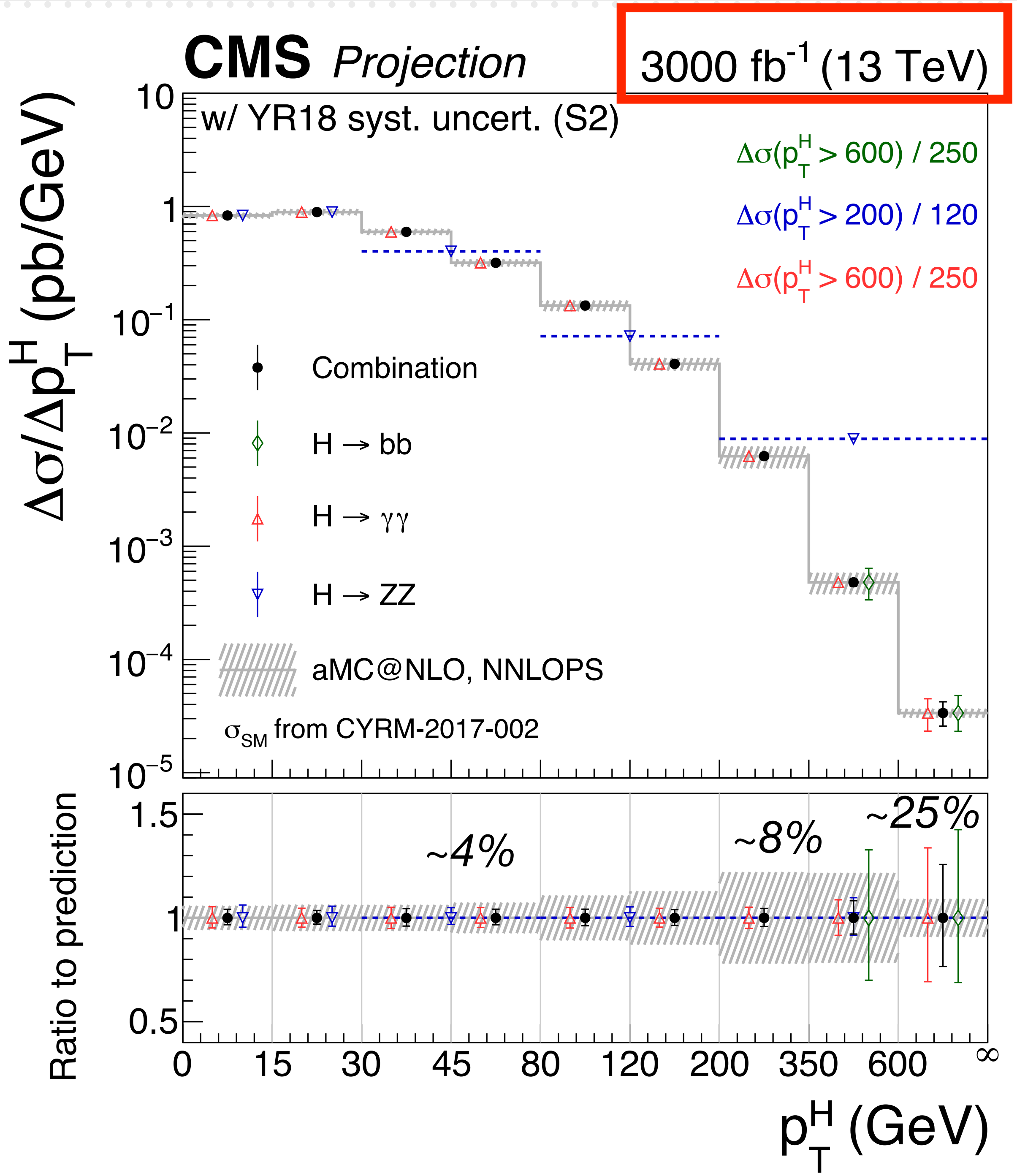


➡ Measurements are in agreement with predictions.

Prospects at High Luminosity LHC (3000 fb^{-1})

CMS-PAS-FTR-18-011





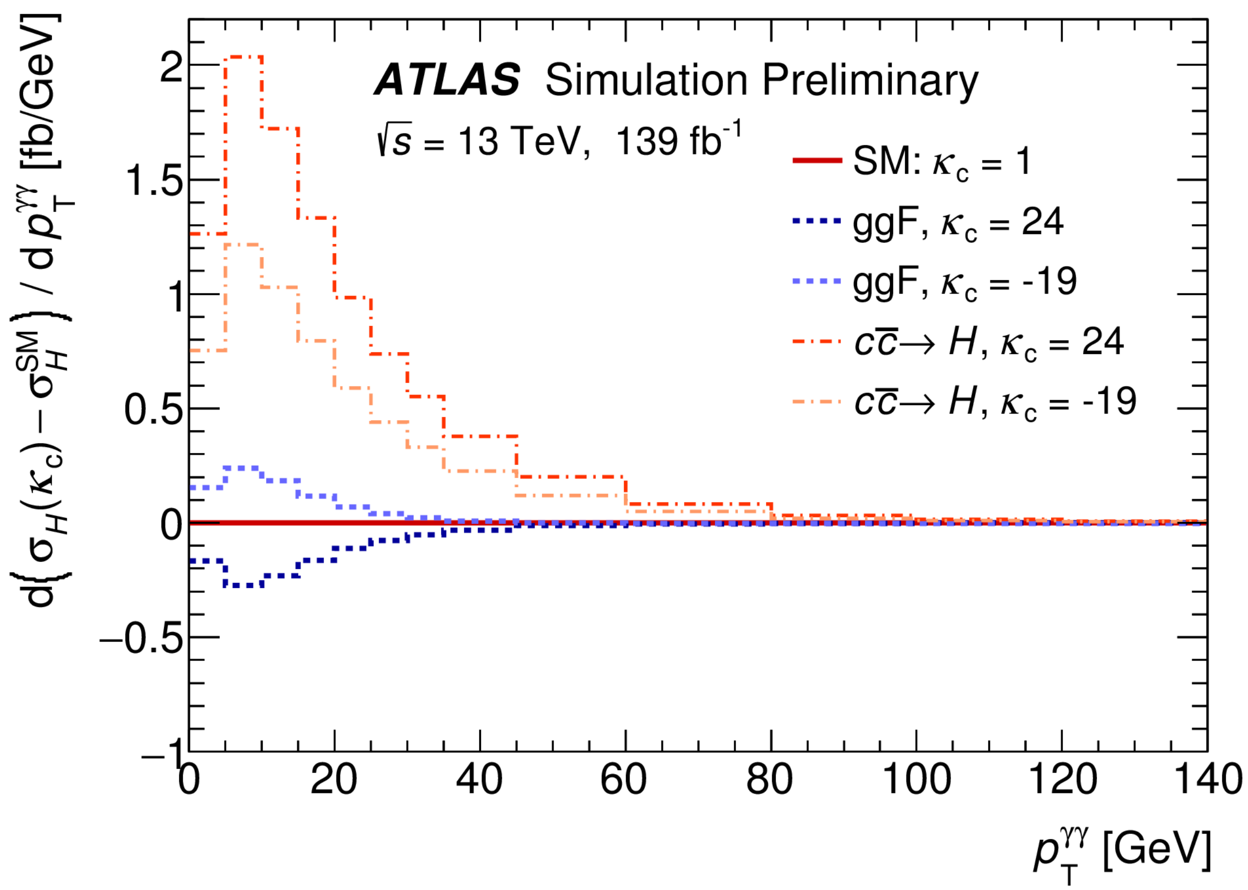
➡ Uncertainties in the high Higgs p_T region can be reduced by a factor of 10 (w.r.t 20-30% with full Run 2 dataset).

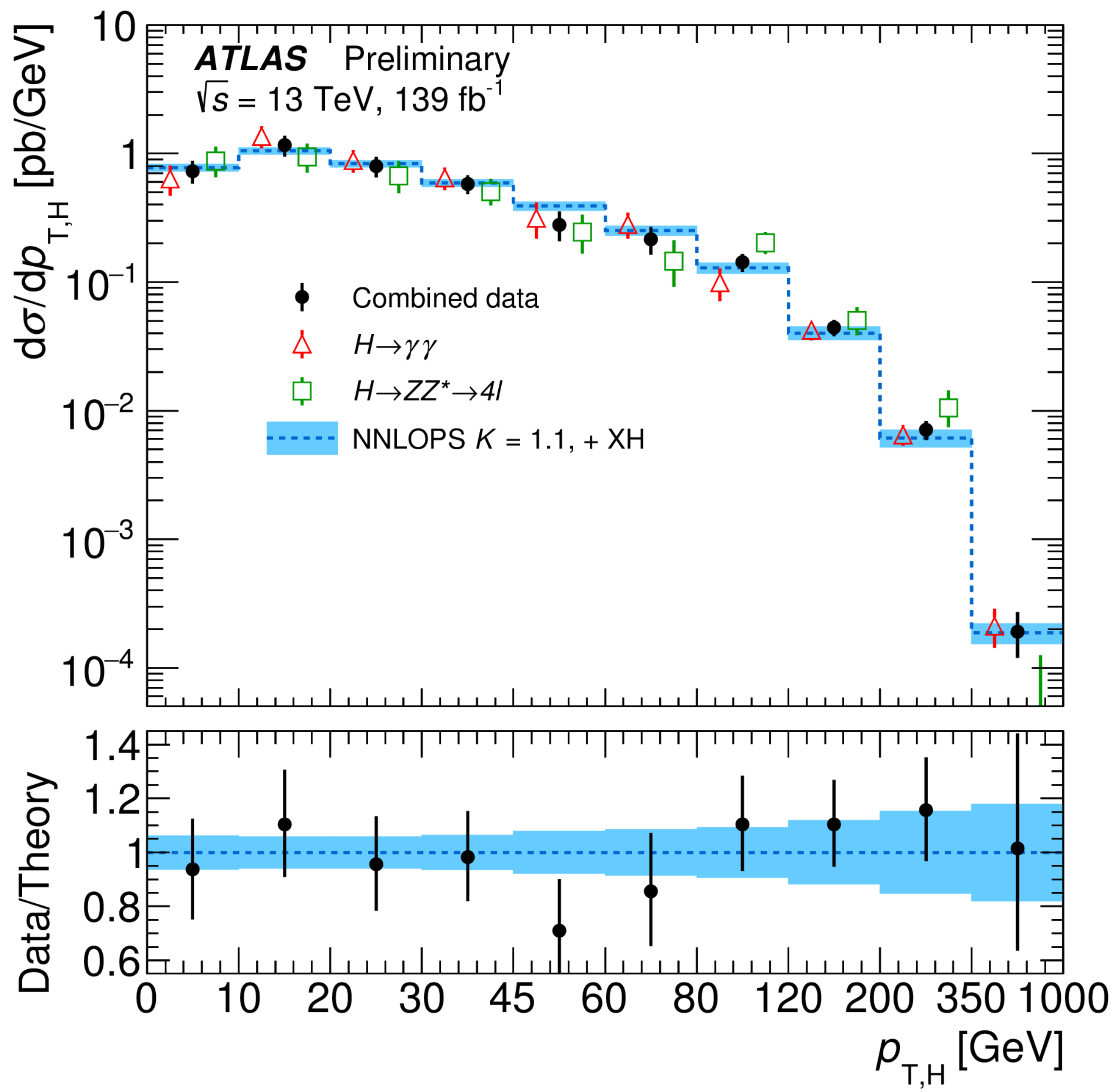
Higgs cross section measurement interpretation

ATLAS-CONF-2019-029

Higgs differential cross section measurement in H→$\gamma\gamma$ and H→ZZ→4l channels.

Higgs differential X-section at low p_T is sensitive to Charm Yukawa coupling:

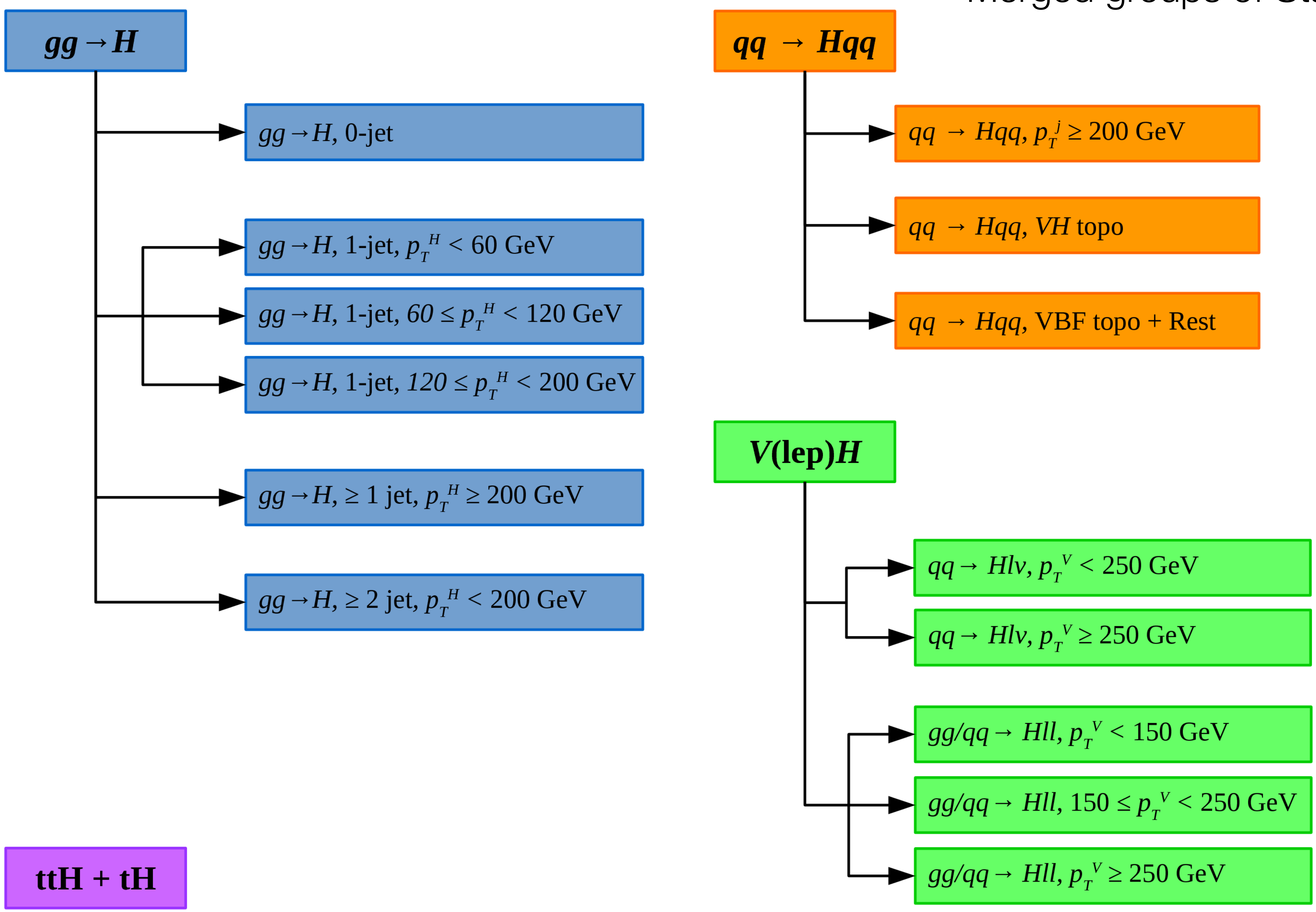




p_T differential X-section measurement is used to extract limit on charm Yukawa coupling strength modifier: $\kappa_c(y_c/y_c^{SM}) \in$ [-19,24] @ 95% C.L. (similar result in CMS).

Higgs Simplified Template X-Section measurement

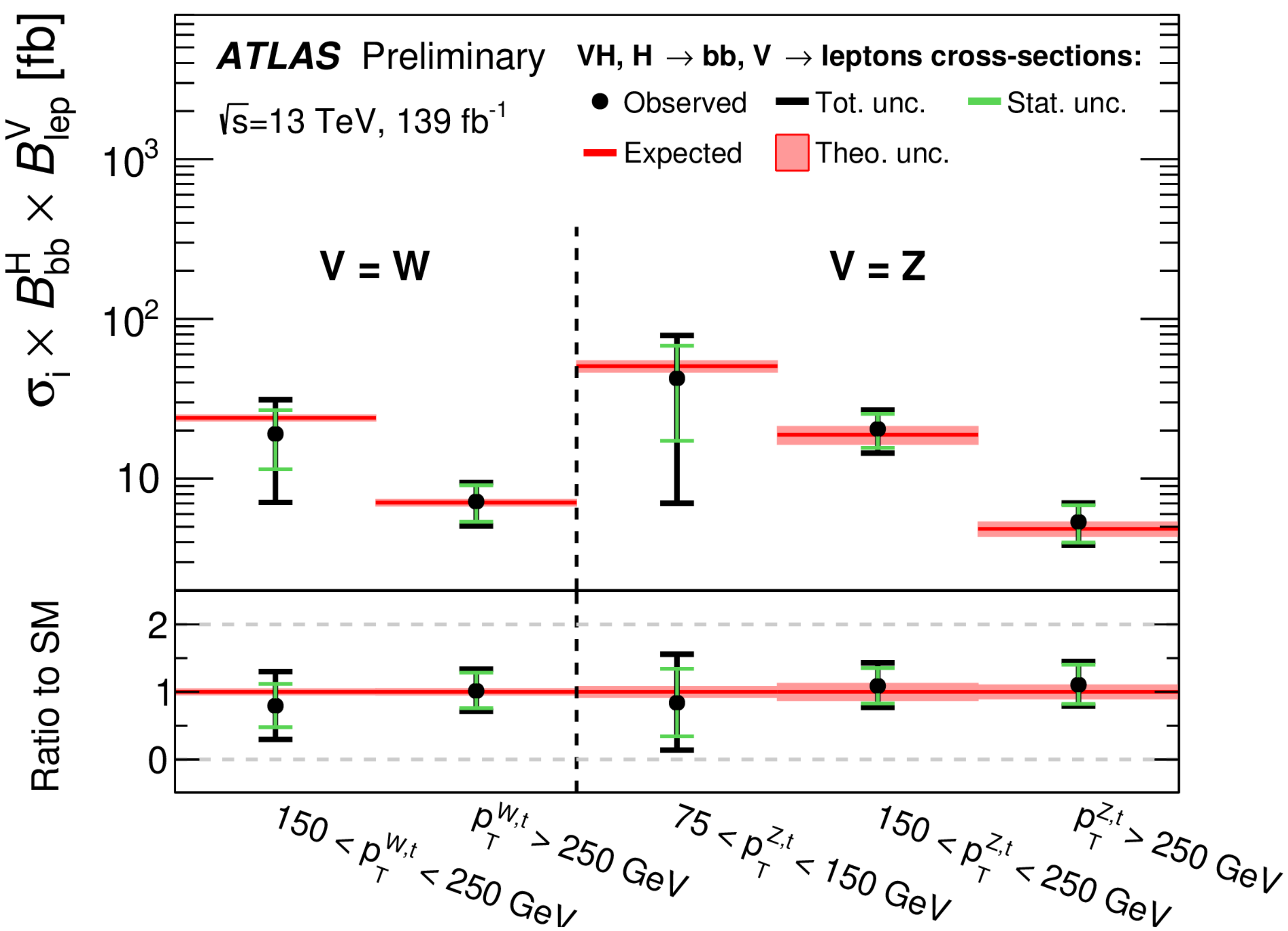
Merged groups of Stage-1 bins



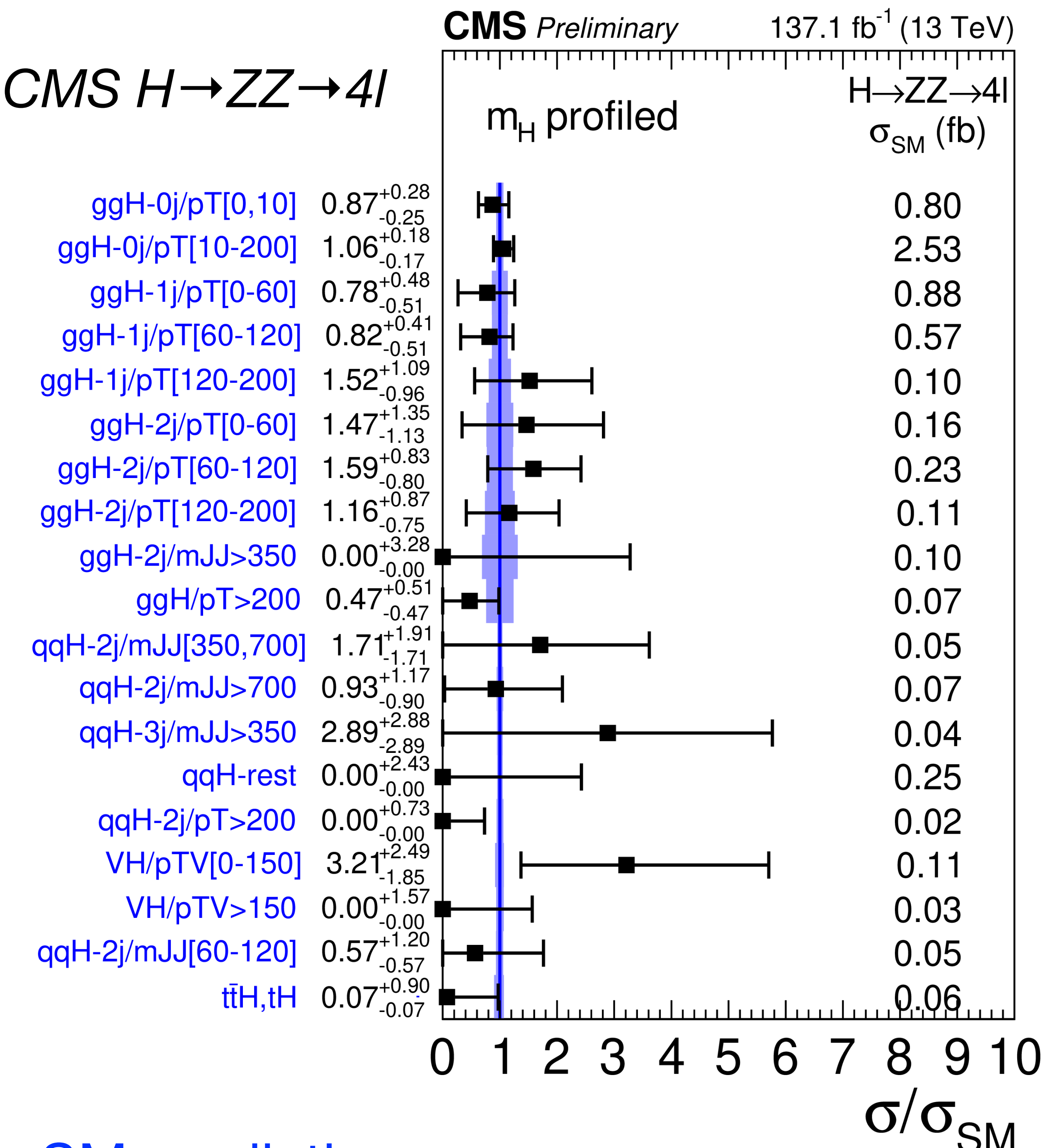
Higgs Simplified Template X-Section measurement

ATLAS-CONF-2020-006, CMS-PAS-HIG-19-001

ATLAS VH, H→bb



CMS H→ZZ→4l



➡ Measurements are in agreement with the SM predictions.

Combined measurement of Higgs coupling properties

CMS-PAS-HIG-19-005, P.R.D 101 (2020) 012002

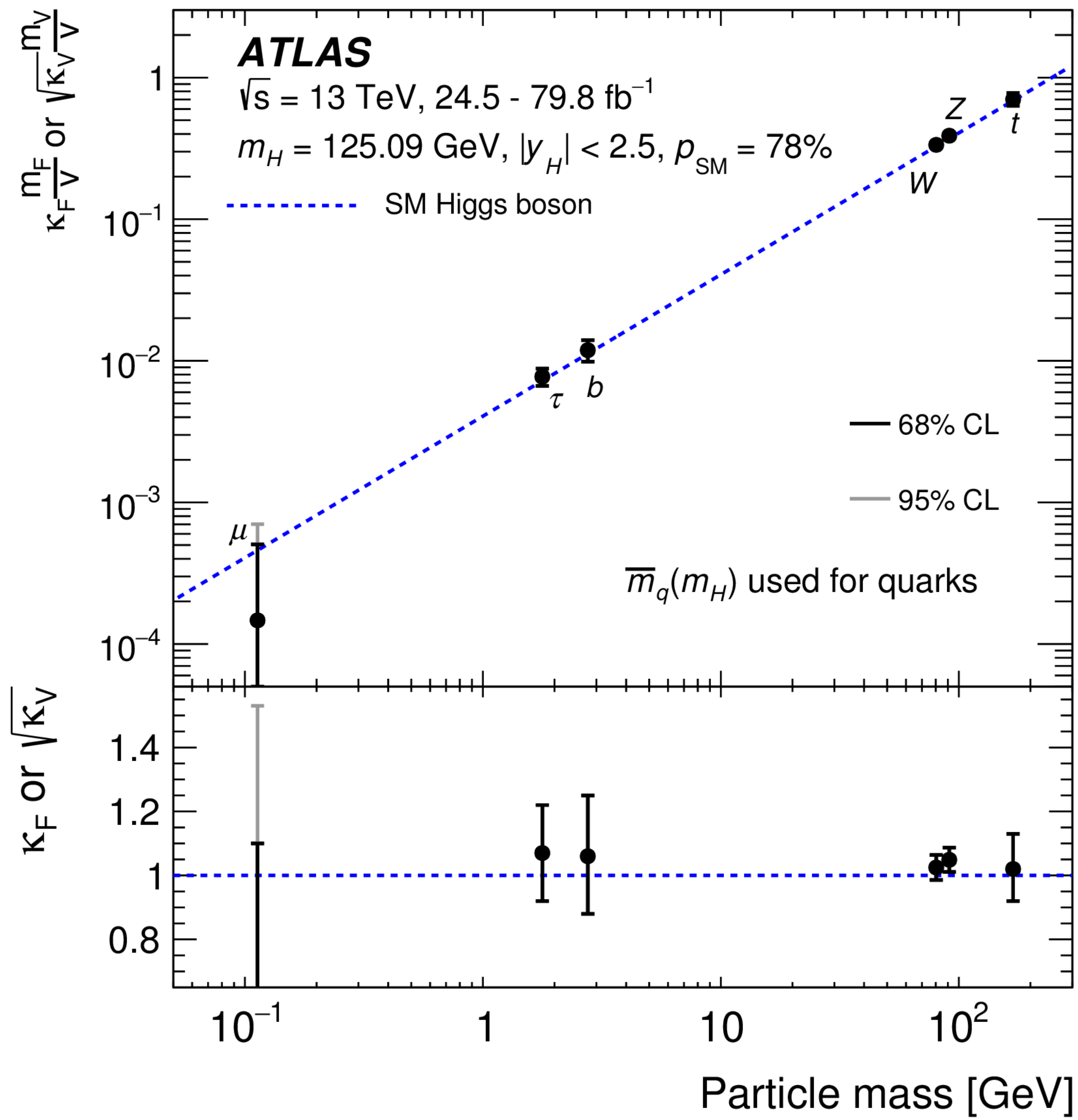
- ATLAS and CMS have performed global fit of coupling modifiers, using kappa framework:
  - using 36 - 80 fb^{-1}
  - all production&decay channels

✓ ~10% uncertainty on Higgs to W/Z boson couplings

✓ ~10-20% uncertainty on Higgs to the 3rd generation fermion couplings.

Fit results for Higgs boson coupling modifiers:

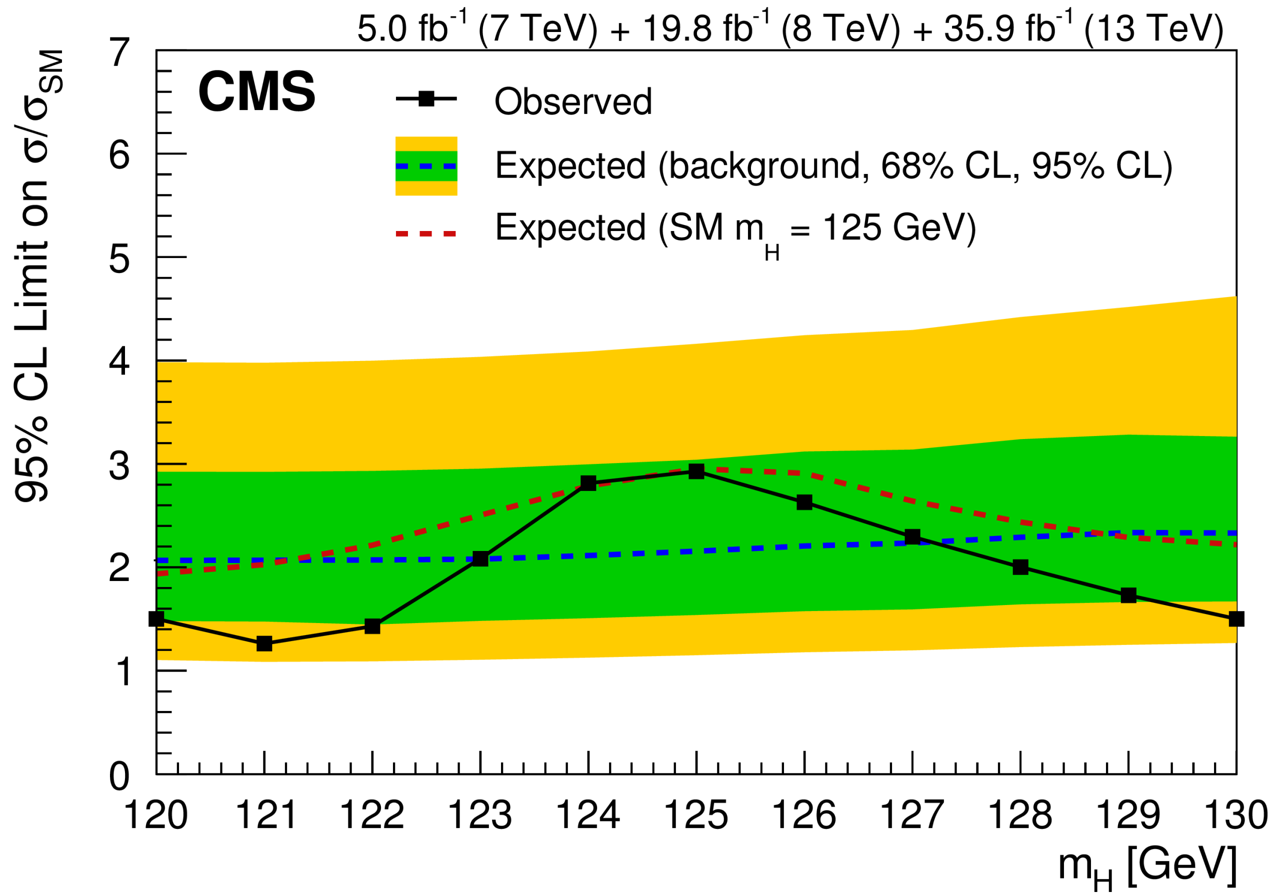
κ_Z	1.10 ± 0.08
κ_W	1.05 ± 0.08
κ_b	$1.06\ ^{+\,0.19}_{-\,0.18}$
κ_t	$1.02\ ^{+\,0.11}_{-\,0.10}$
κ_τ	1.07 ± 0.15
κ_μ	< 1.53 at 95% CL

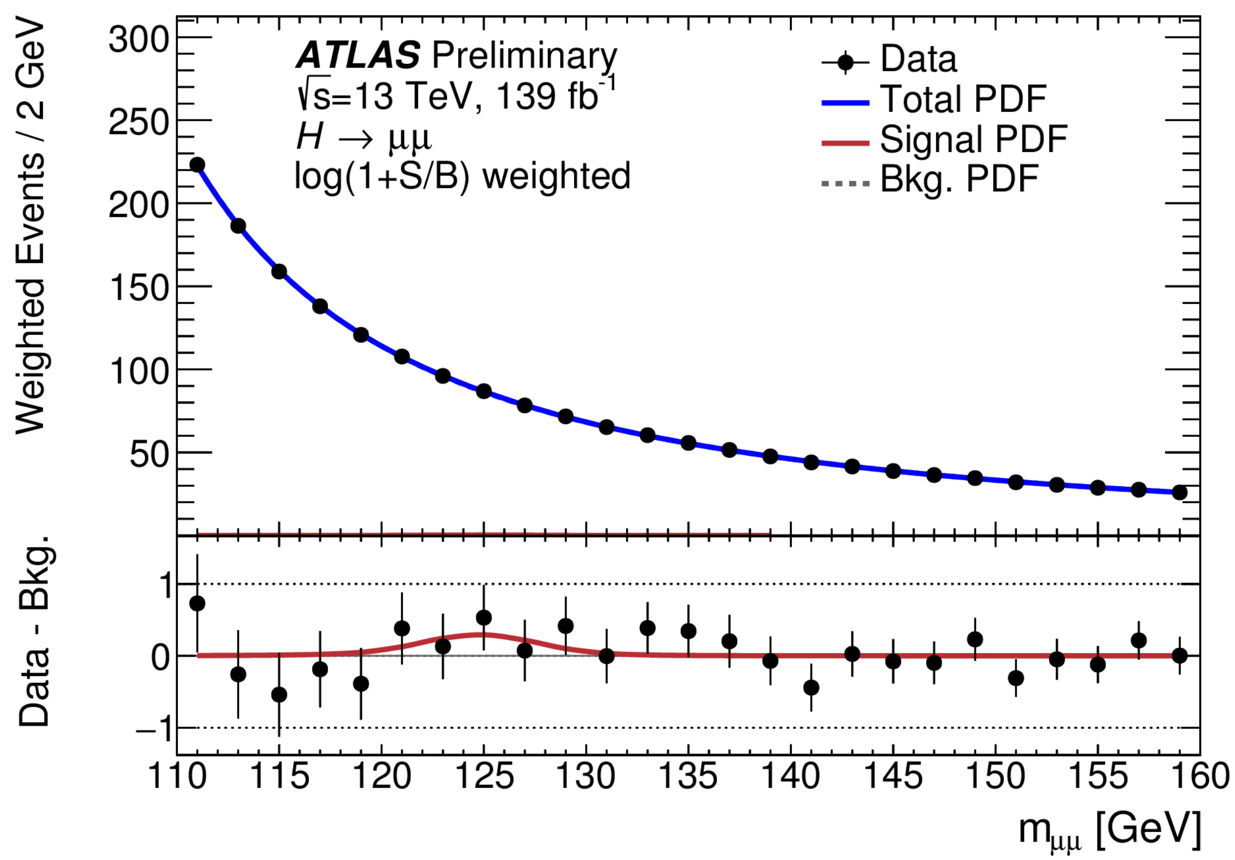


Search for H→$\mu\mu$ decay mode

PRL 122 (2019) 021801
ATLAS-CONF-2019-028

- Obs.(exp.) limit from CMS (Run 1+ 36fb^{-1}): 2.95 (2.16) x SM prediction.
- ATLAS analysis has been updated to 139 fb^{-1}: 1.7 (1.3) x SM prediction.



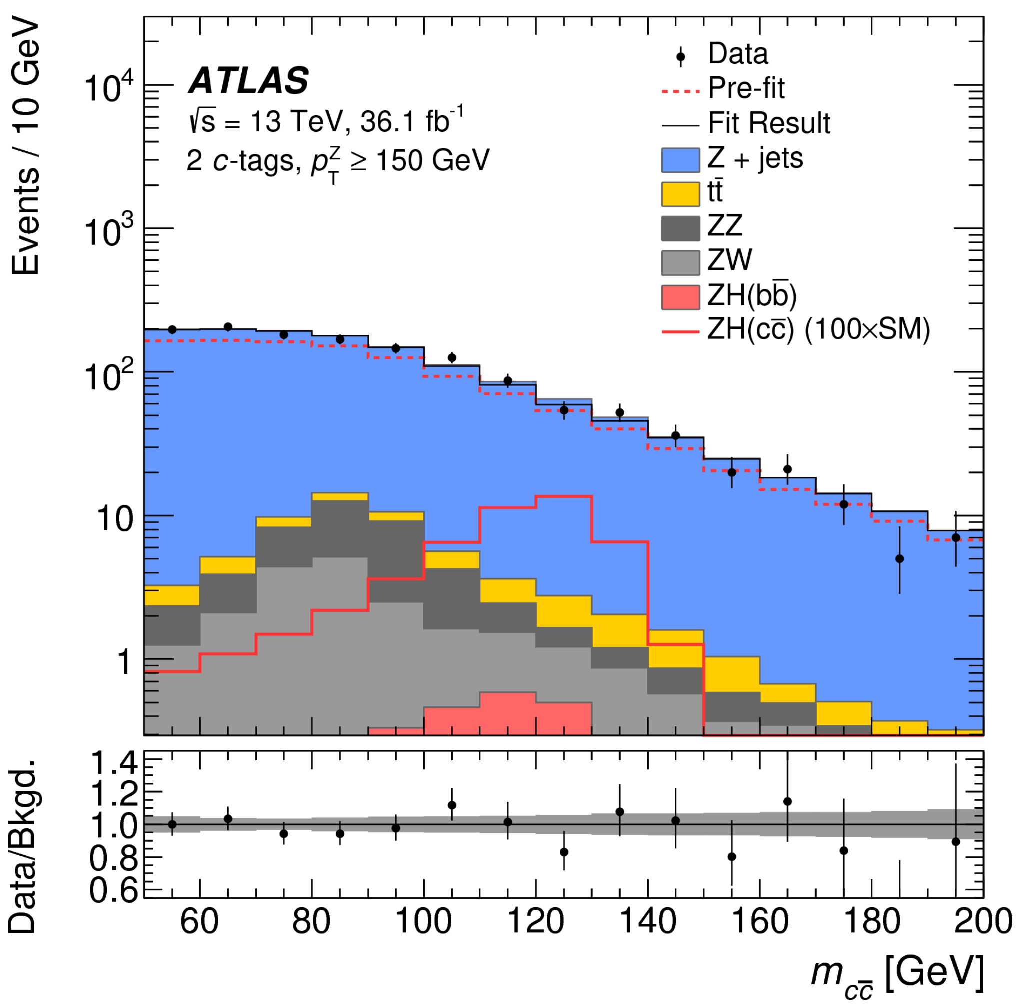


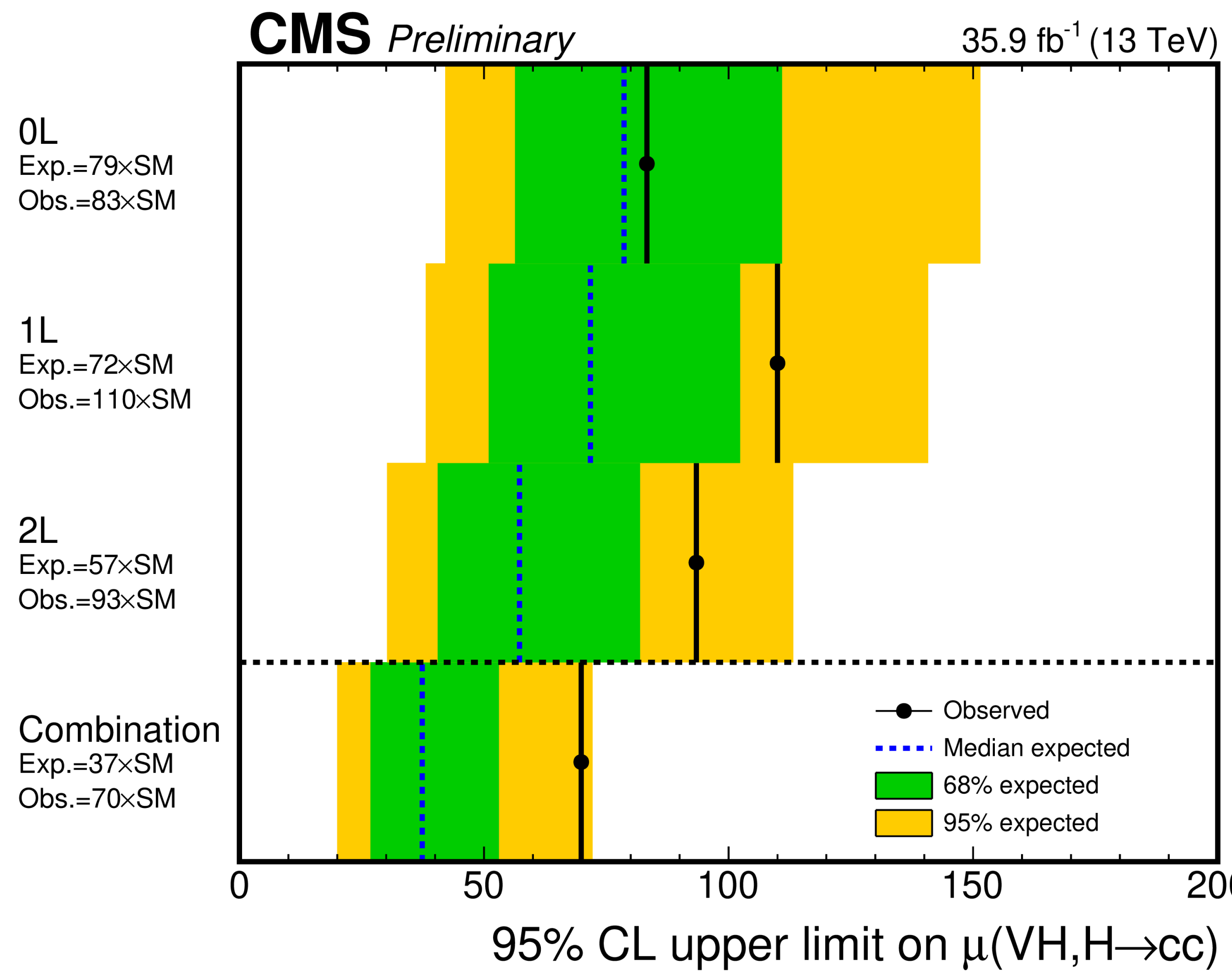
➡ Statistical uncertainty dominates !

- The obs.(exp.) significance for H→$\mu\mu$ is 0.8σ (1.5σ) from ATLAS using 139 fb^{-1} data, and 0.9σ (1.0σ) from CMS using 36 fb^{-1} dataset.

Search for H→cc decay mode (36 fb^{-1})

PRL 120 (2018) 211802
JHEP 03 (2020) 31
PLB 786 (2018) 134





- 95% C.L limit from ATLAS ZH(H→cc): 110 (150) obs.(exp.) x SM prediction.
- 95% C.L limit from CMS W/ZH(H→cc): 70 (37) obs.(exp.) x SM prediction.

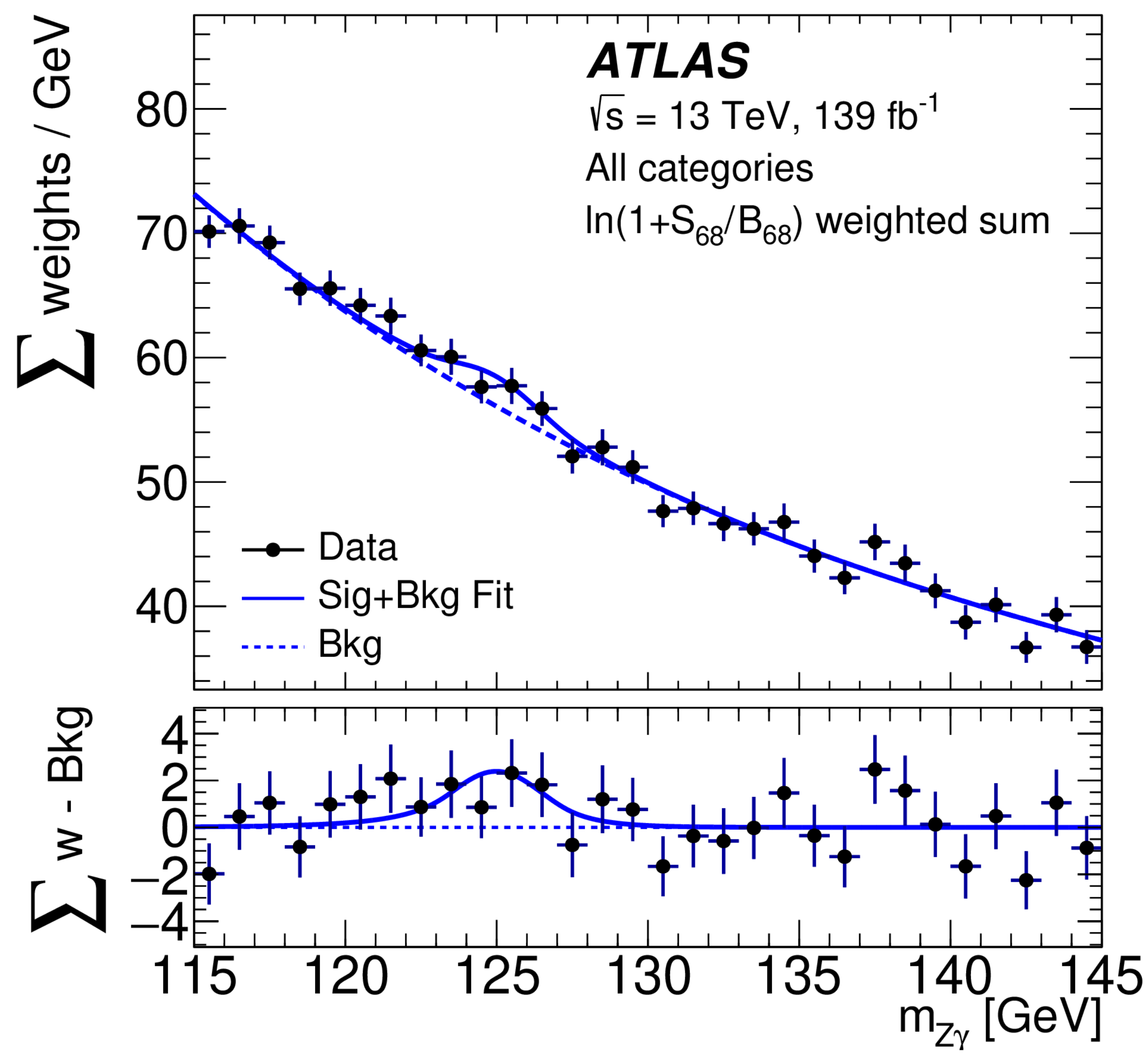
➡ Statistical uncertainty dominates !

Limits on H→J/Ψ+γ, Ψ(2S)γ and Υ(1S,2S,3S)γ BR at 95% C.L (36.1 fb^{-1}): 3.5x10^{-4}, 2x10^{-3} and (4.9,5.9,5.7)x10^{-4} → about 100, 500, 10^5 times the SM predictions.

Search for H→Zγ decay mode

submitted to: P.L.B

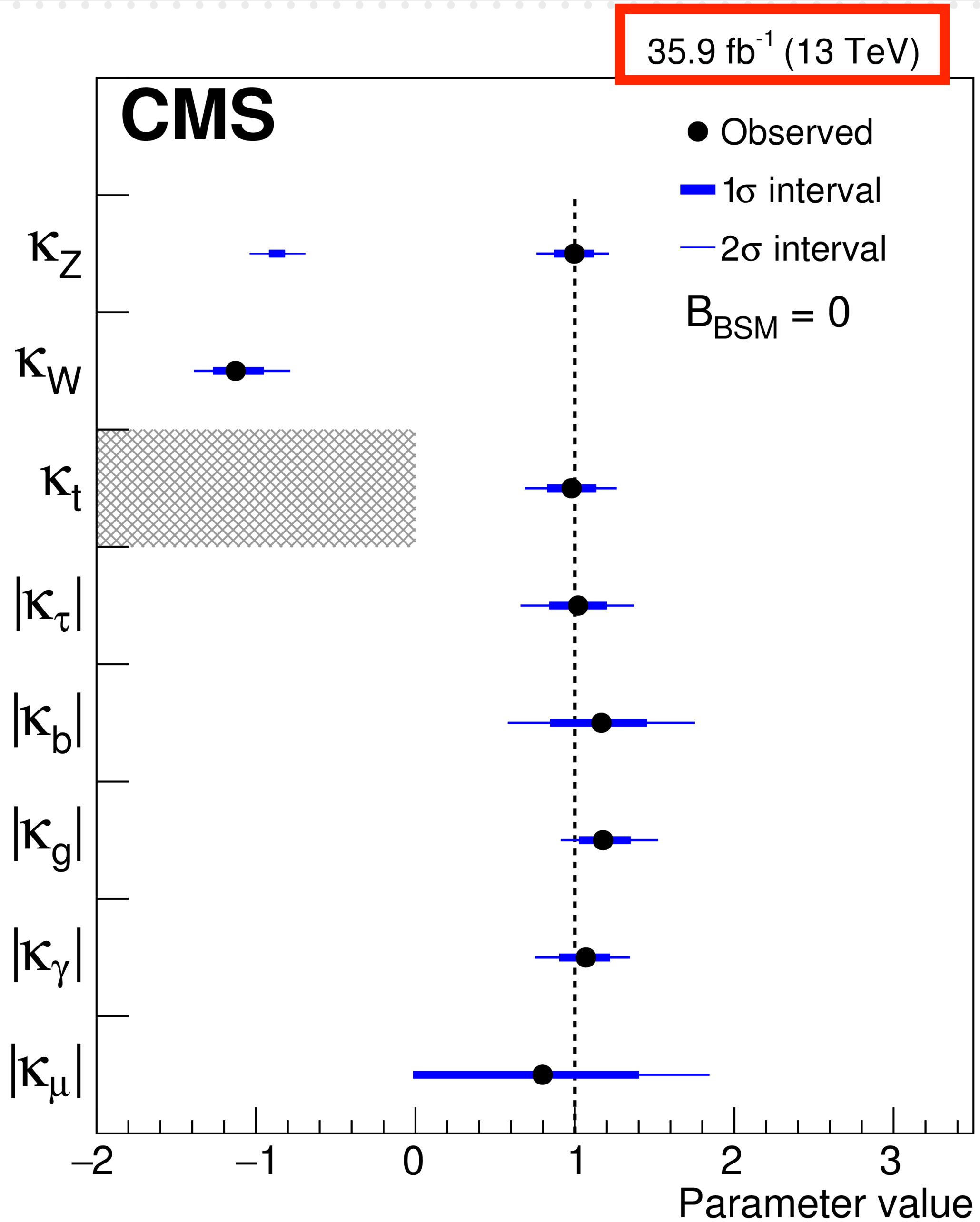
- ATLAS has updated H→Zγ search with 139 fb^{-1} full Run 2 luminosity.
- Upper limit at 95% C.L. on pp→H→Zγ X-section: 3.6 times the SM prediction.

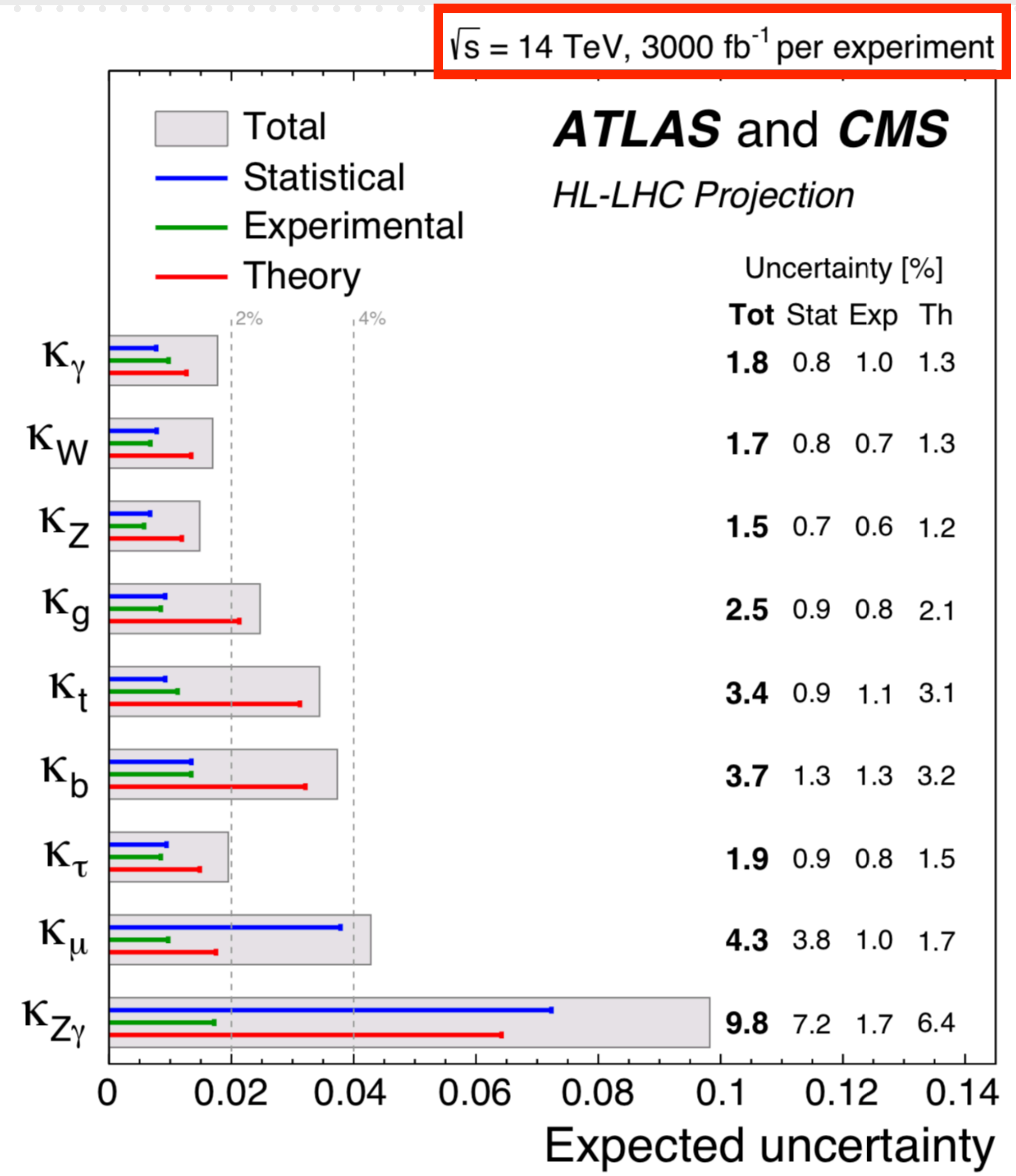


- The best-fit value for the signal strength is $2.0^{+1.0}_{-0.9}$.

Prospects at High Luminosity LHC (3000 fb^{-1})

arXiv:1902.00134
EPJC 79 (2019) 421

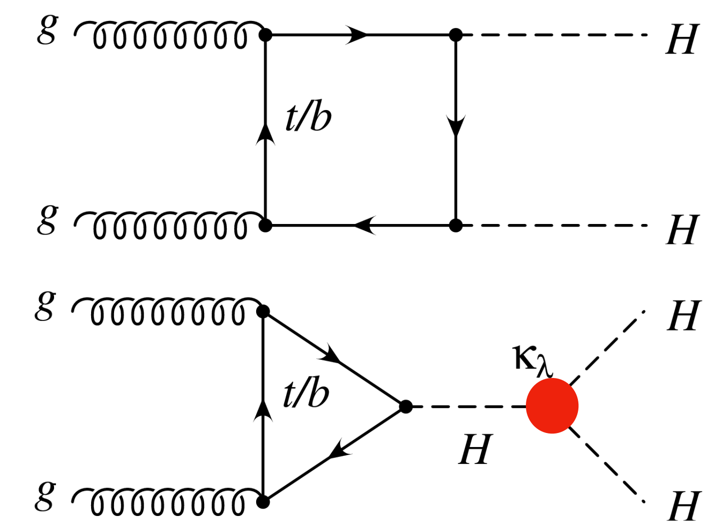




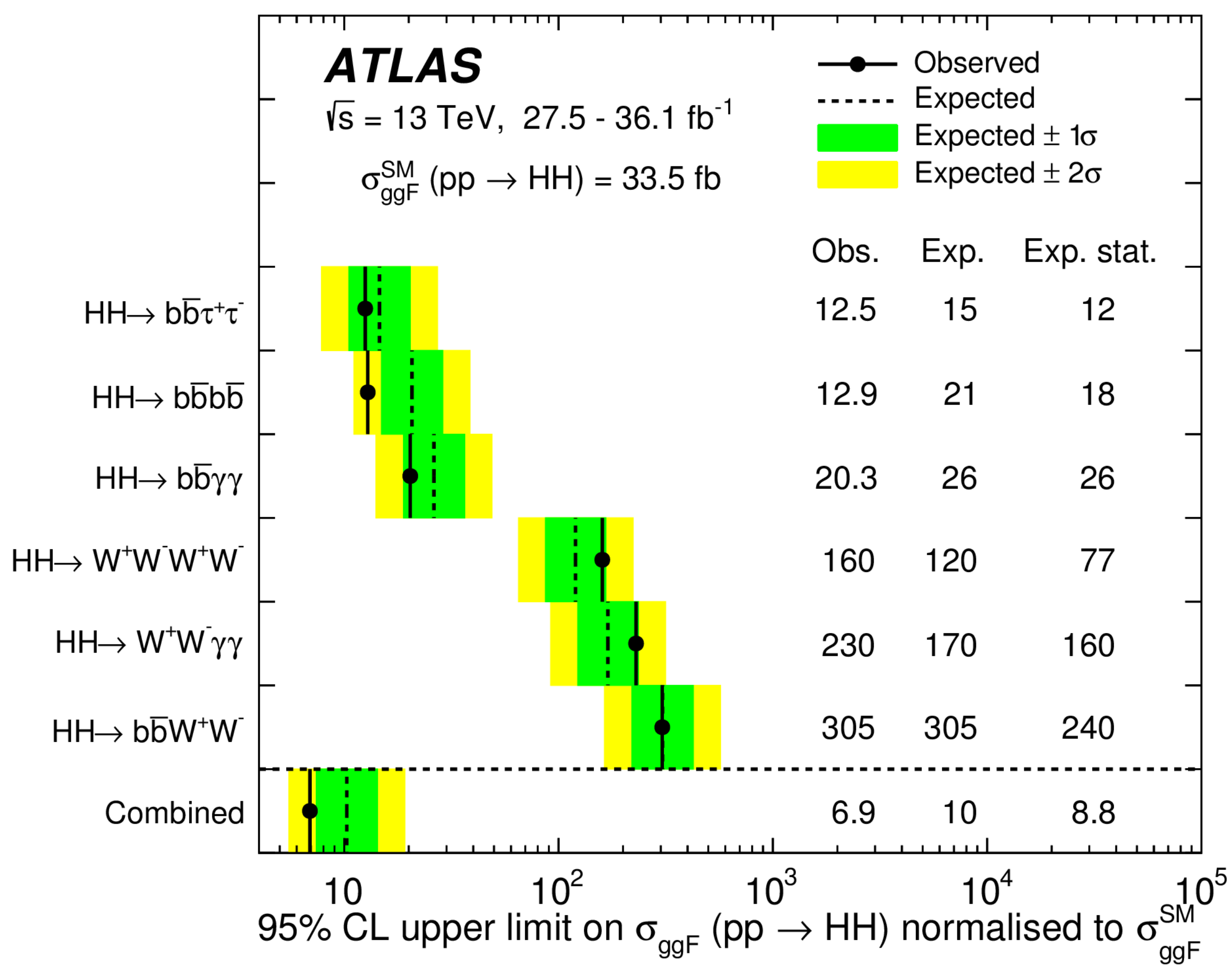
- 2-4 % precision of Higgs couplings to W/Z, 3rd gen. fermions, γ/g and muon.
- Discovery for H→μμ and H→Zγ decays.
- H→cc : $\sigma/\sigma_{SM} < 6.3$ from ATLAS Run 2 result extrapolation.

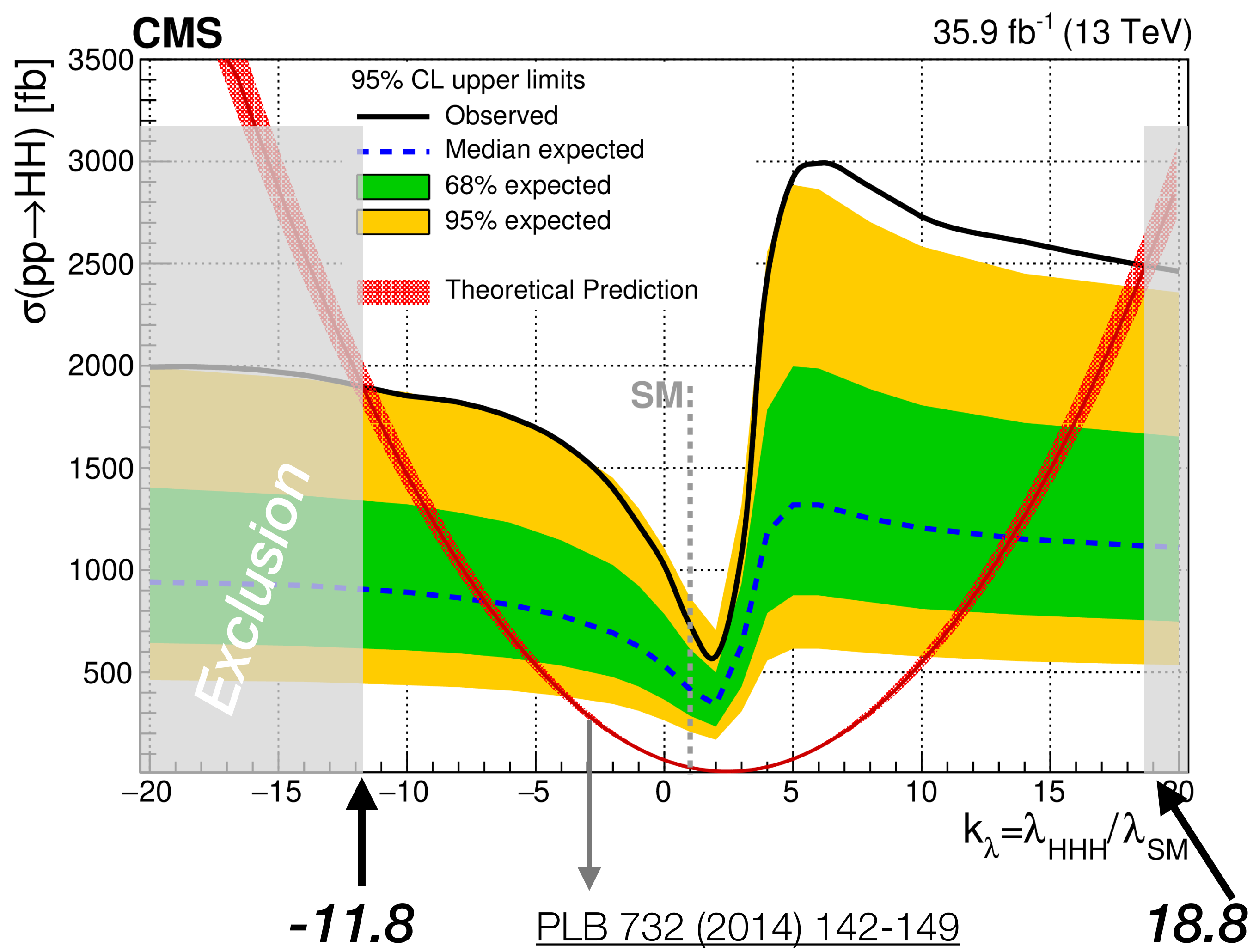
Search for Di-Higgs production channel

PLB 800 (2020) 135103
PRL 122 (2019) 121803



- HH channel is sensitive to Higgs self-coupling property.
- Both ATLAS and CMS have performed HH searches using 36 fb^{-1} luminosity datasets.
  - ➡ Statistical uncertainty dominates !



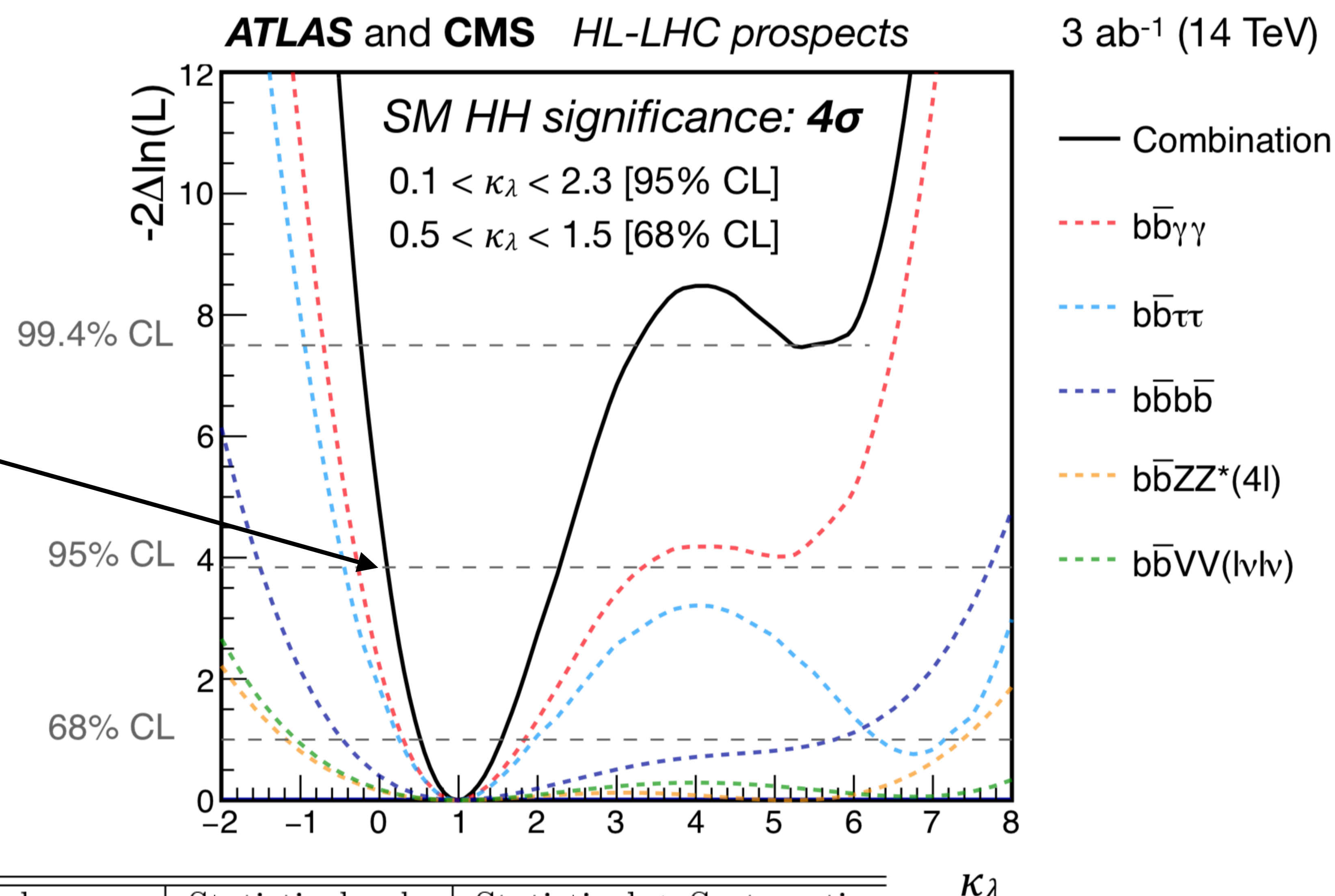


Prospects at High Luminosity LHC (3000 fb^{-1})

arXiv:1902.00134
ATL-PHY-PUB-2018-053

- 4-sigma evidence for SM di-Higgs production (3-sigma from each experiment).
- Constraints on Higgs self-coupling property: $\kappa_\lambda(\lambda_3/\lambda_3^{SM}) \in [0.1,\ 2.3]$ @ 95% C.L

At 95% C.L, ATLAS+CMS is anticipated to exclude no Higgs trilinear coupling with full HL-LHC dataset.



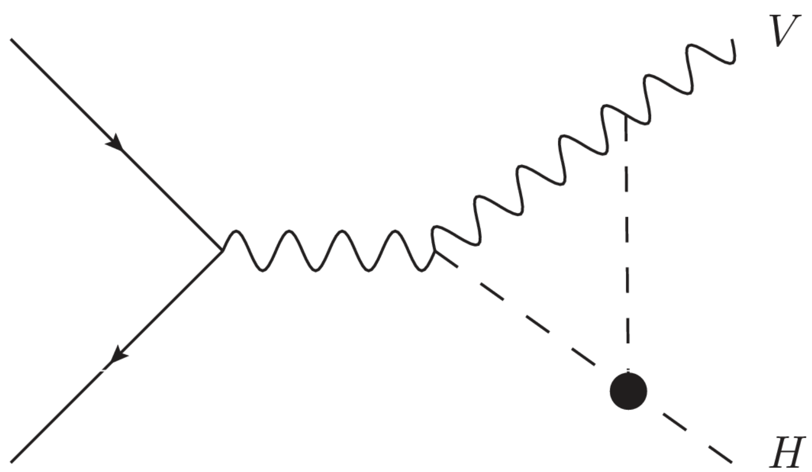
ATLAS 3 ab^{-1} prospects extrapolated from 36 fb^{-1} analyses

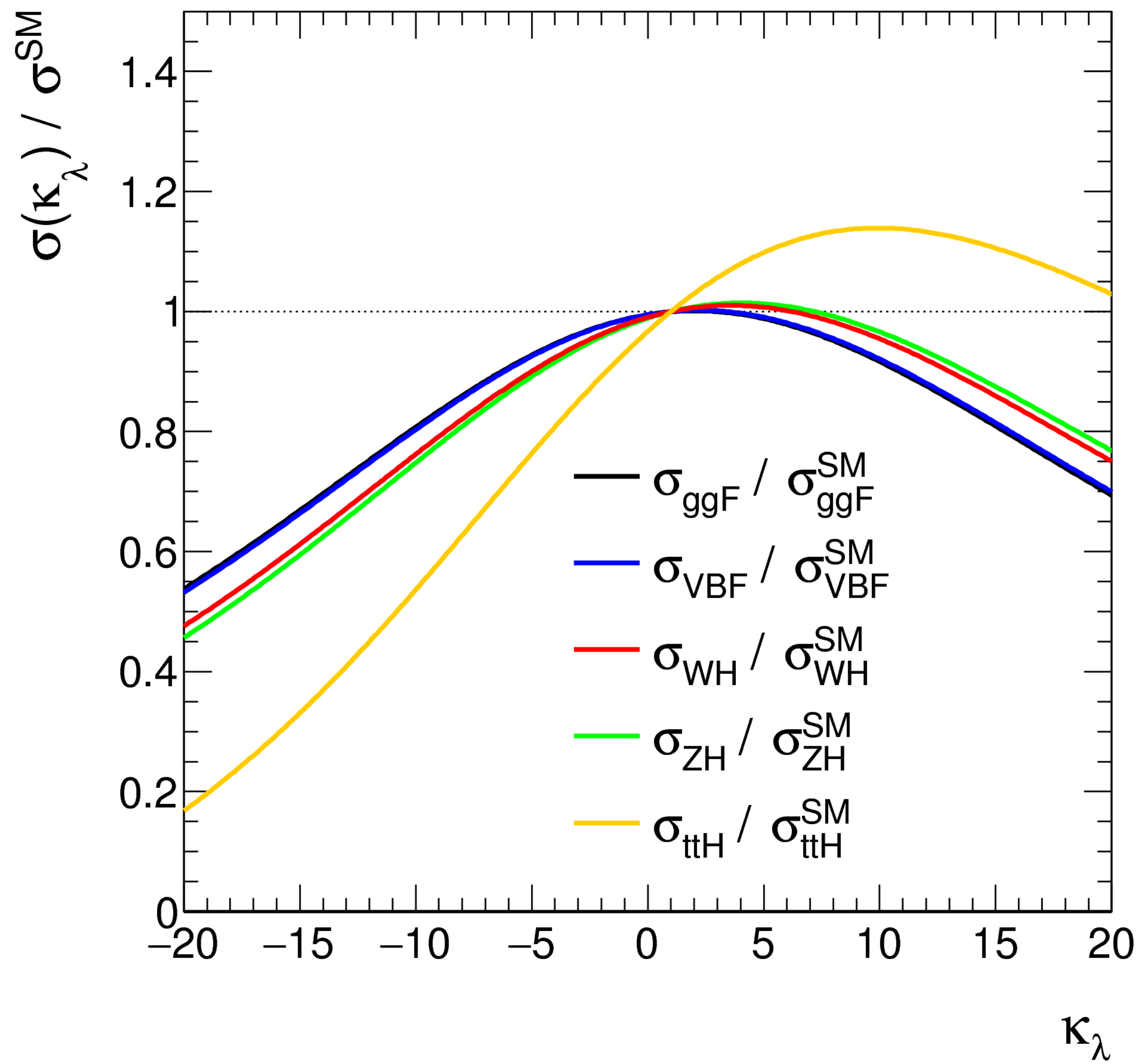
Channel	Statistical-only	Statistical + Systematic
$HH \to b\bar{b}b\bar{b}$	1.4	0.61
$HH \to b\bar{b}\tau^+\tau^-$	2.5	2.1
$HH \to b\bar{b}\gamma\gamma$	2.1	2.0
Combined	3.5	3.0

Self-coupling constraints from single Higgs production

ATL-CONF-2019-049, ATL-PHYS-PUB-2019-009

A varied Higgs trilinear coupling effects not only inclusive Higgs production/decay rates but also their kinematics, through NLO EW corrections.





ATLAS measurement as inputs (80fb^{-1}):

- inclusive X-section for ggF, ttH
- STXS measurements for VBF and VH.

Constraints on self-coupling modifier

$$\kappa_\lambda \ (\lambda_3/\lambda_3^{SM}) \in [\text{-}3.2{,}11.9] \ @ \ 95\% \text{ C.L.}$$

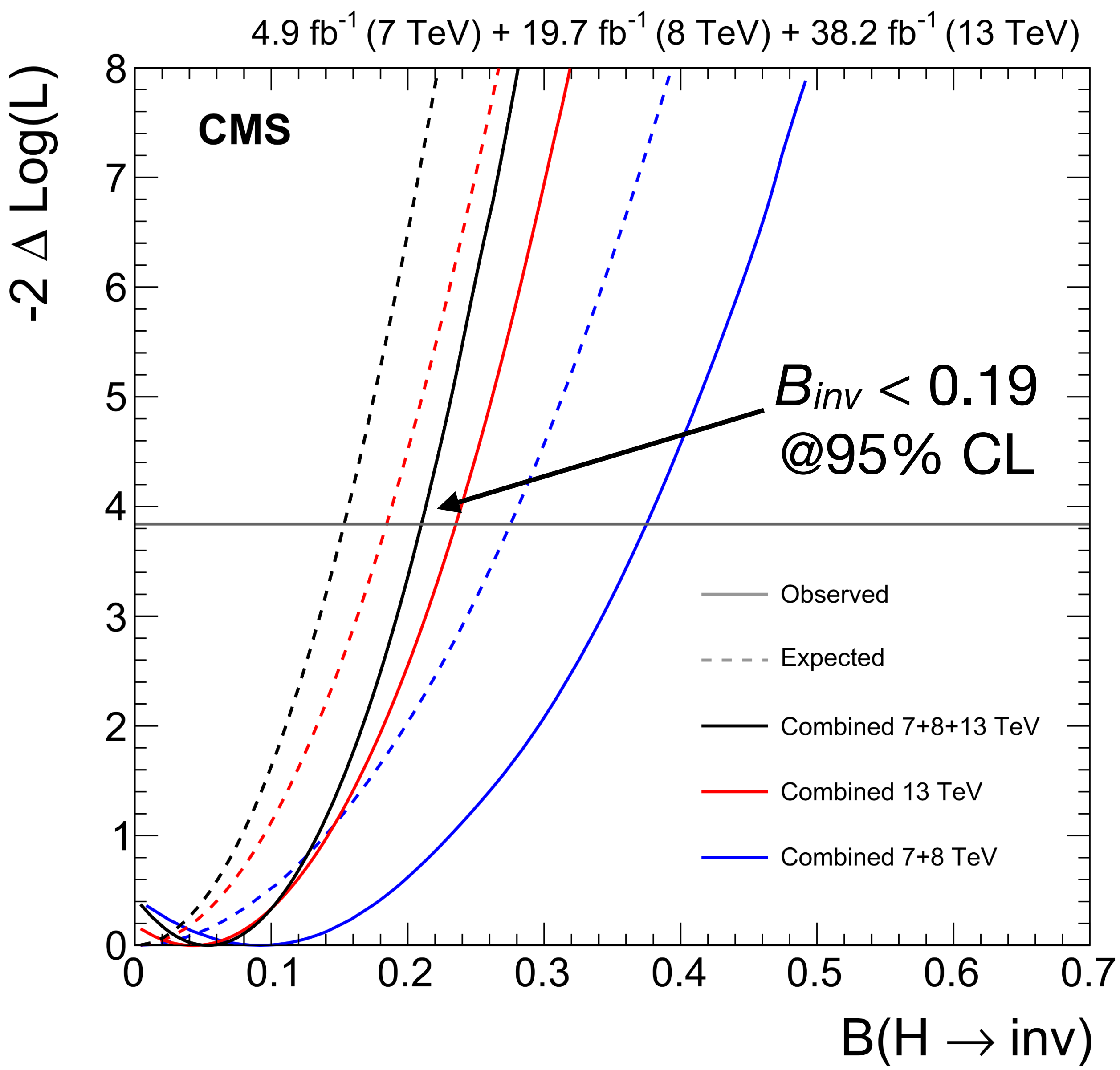
→ this result is comparable with direct measurement from Di-Higgs channel with 36 fb^{-1} luminosity, combination:

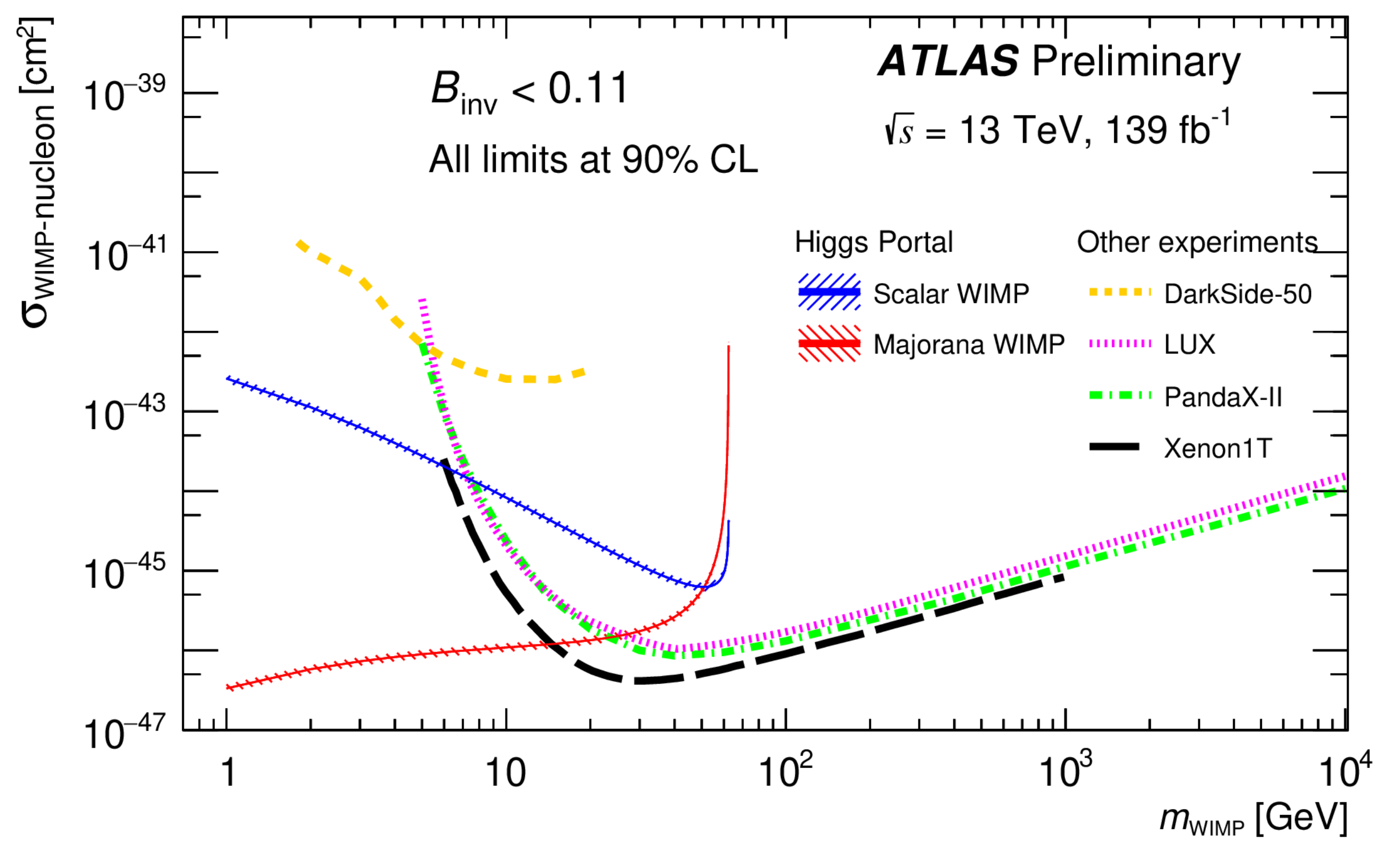
$$-2.3 < \kappa_\lambda < 10.3 \text{ at } 95\% \text{ CL}$$

Higgs to invisible searches

ATLAS-CONF-2020-008
PLB 793 (2019) 520

- Searches have been performed in VH and VBF channel in both ATLAS and CMS.
- Higgs to invisible is sensitive to BSM phenomena that can be recast in Dark Matter limits under certain assumptions (e.g H→DM in case $M_{DM} < M_H/2$).
- LHC has the best limit for low mass dark matter in model-specific scenarios.

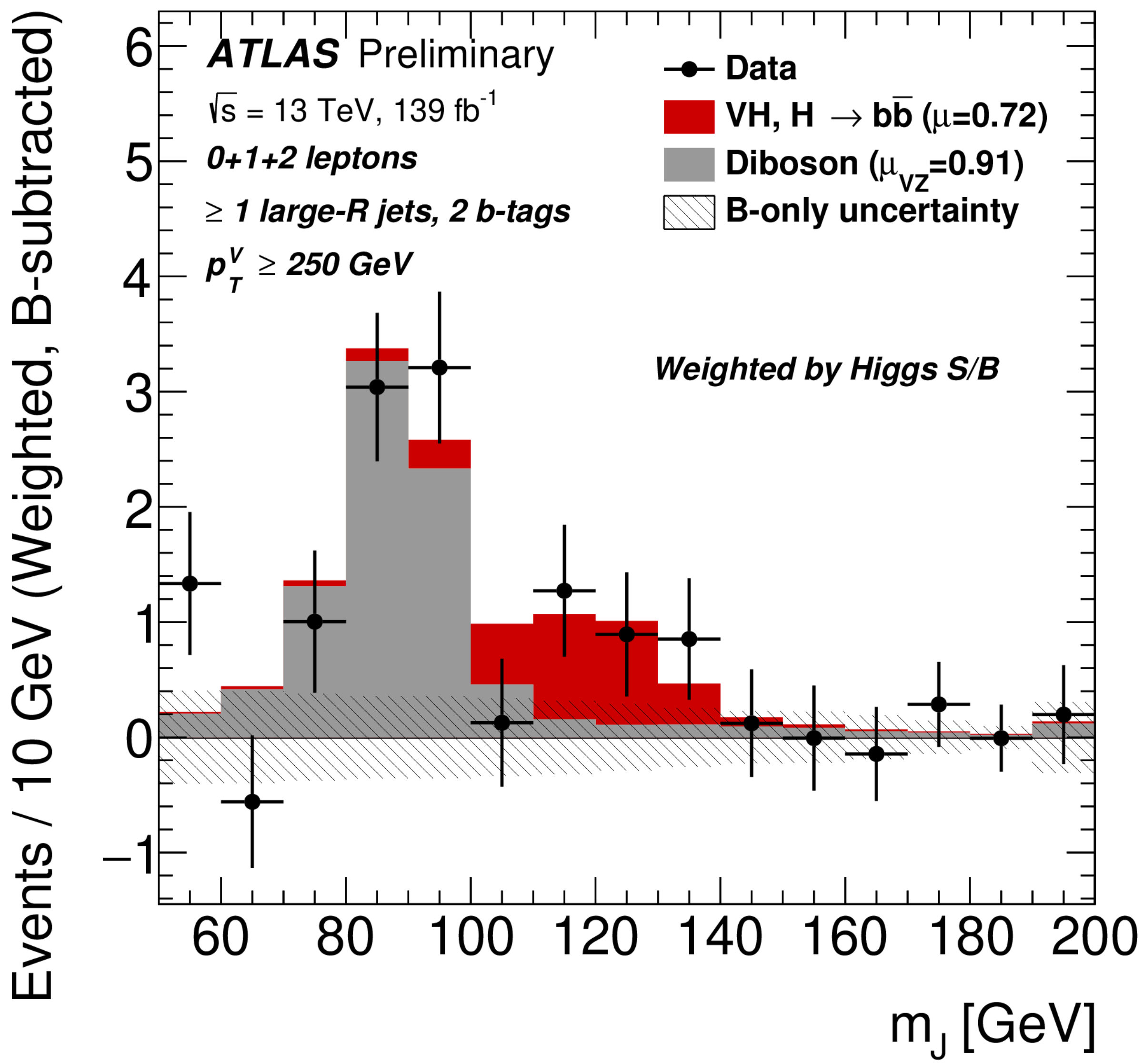


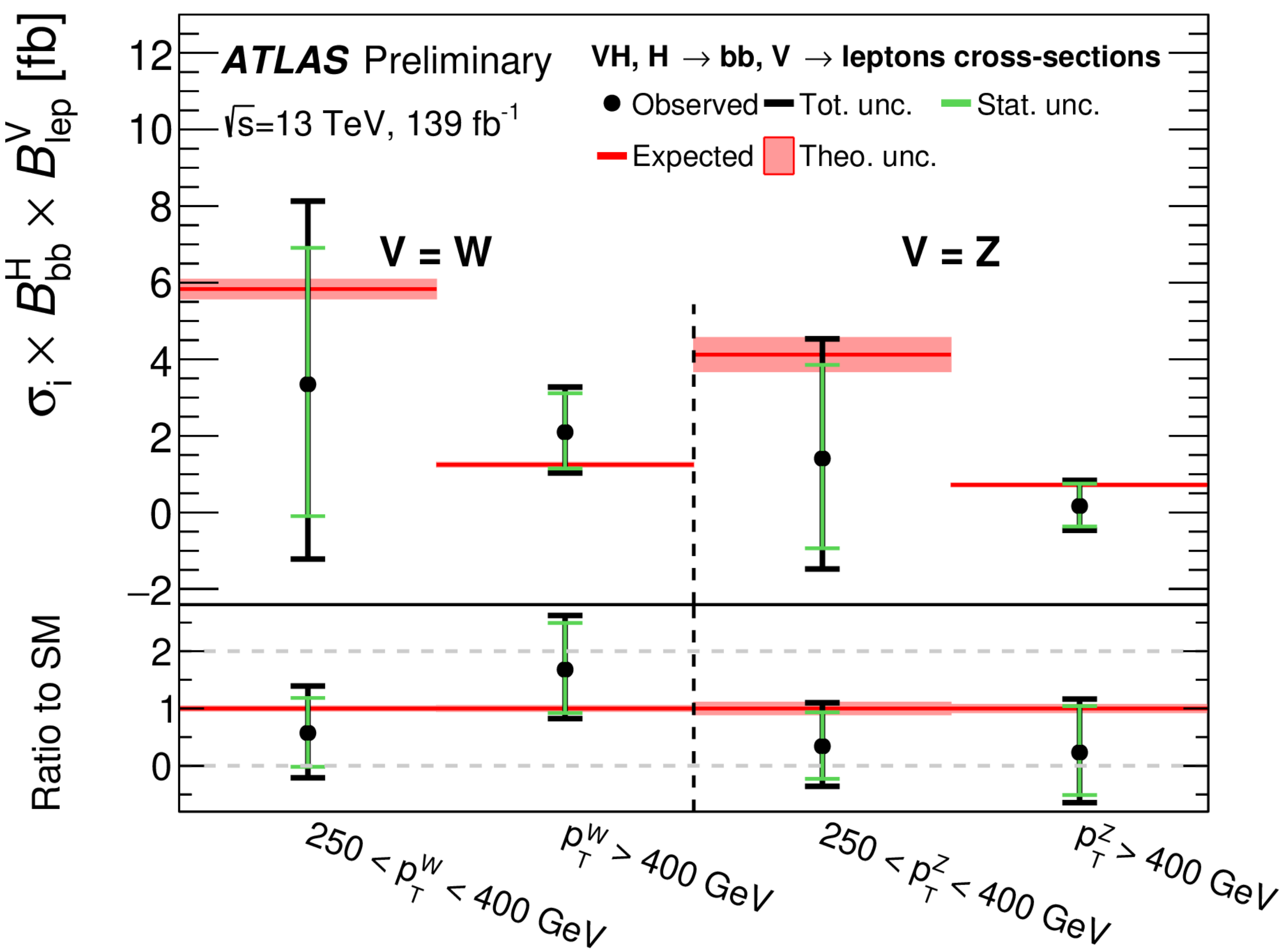


VH, H→bb analysis in boosted regime

ATLAS-CONF-2020-007

- ATLAS released the first preliminary VH, H→bb results in boosted regime, 139 fb^{-1}.
- The measured signal strength is $0.72^{+0.39}_{-0.36}$, abs. (exp.) significance of 2.1 (2.7) sigma.





Summary

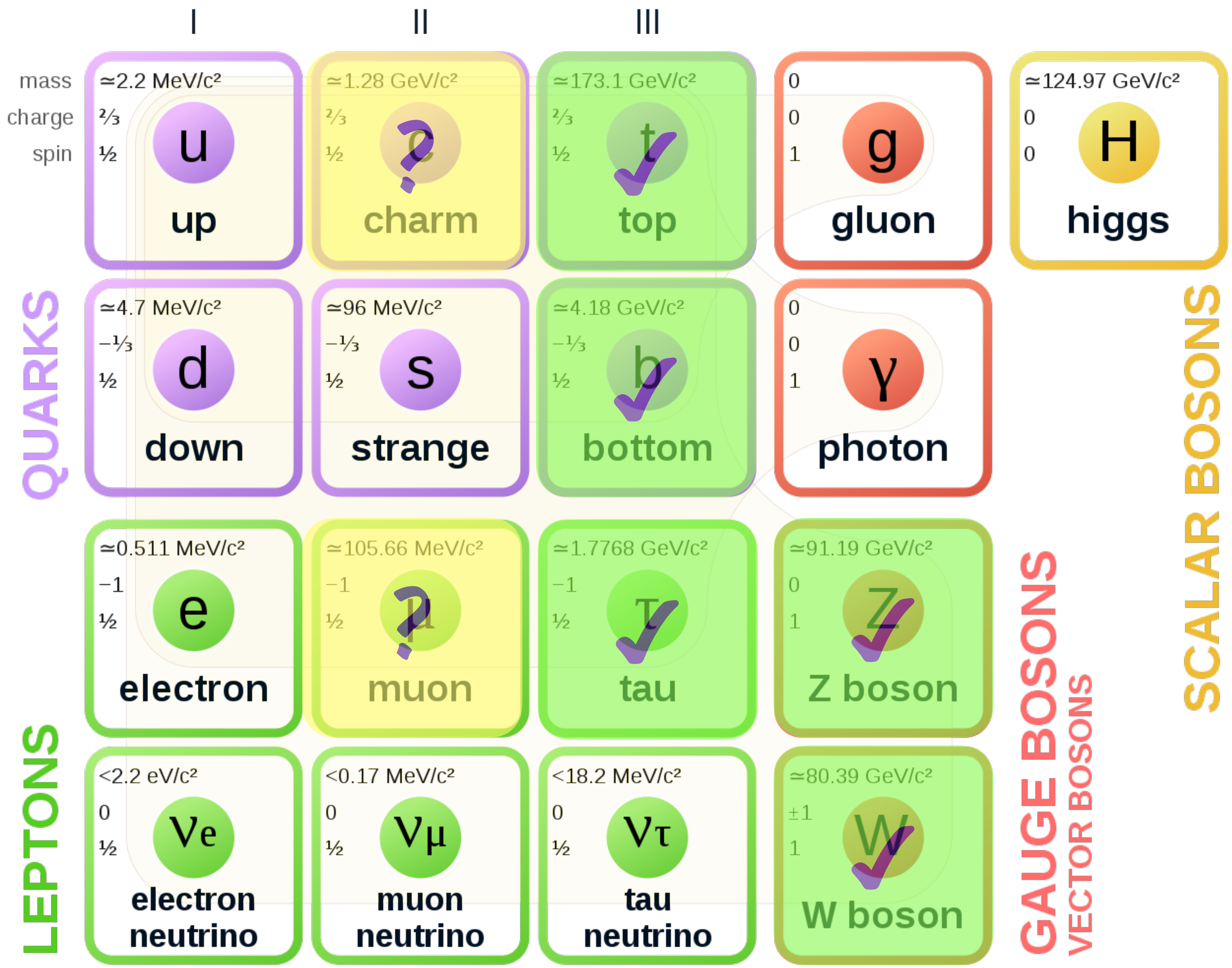
- The major Higgs production and decay channels have been observed in ATLAS and CMS using Run-1 and (partially) Run-2 datasets.

- Higgs couplings to the 3rd generation fermions, W/Z-bosons have been confirmed.
- Higgs physics at LHC has moved to precision measurement era.
- LHC starts to have sensitivity to Higgs couplings with 2nd generation fermions.

- ~5% of LHC designed luminosity has been achieved. High-Luminosity LHC will
  - be able to access Higgs couplings with the 2nd generation fermions (μ,c)
  - be sensitive to di-Higgs production channel
  - set strong constraints on Higgs self-coupling parameter
  - ➡ Please stay tuned !

Not talking about EFT in this talk, but this is something also very interesting !

Higgs boson shakes hands with other particles (?)



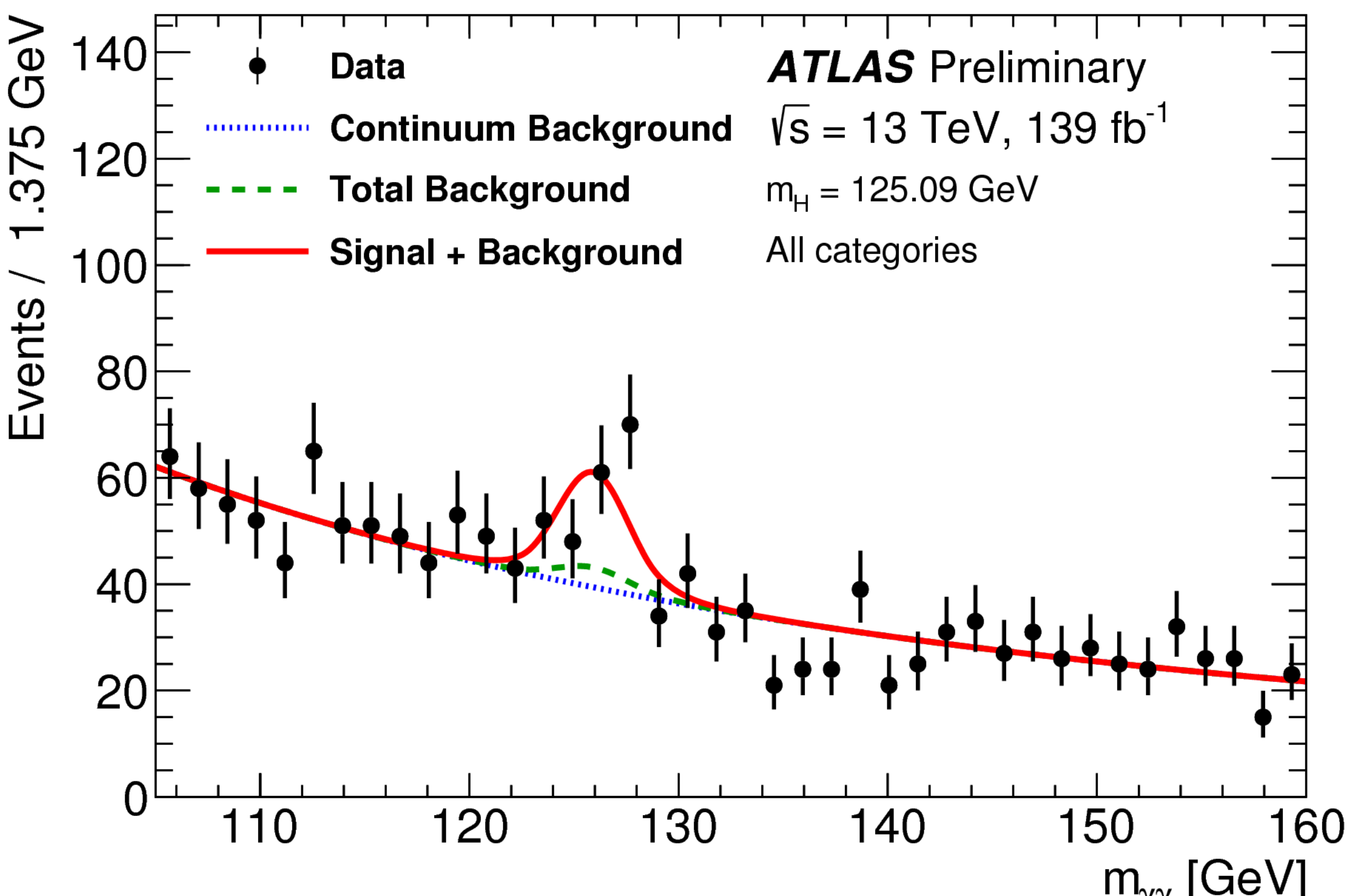
Higgs couplings with W/Z bosons and with the third generation fermions have been experimentally confirmed → in good agreement with the SM prediction.

Backup

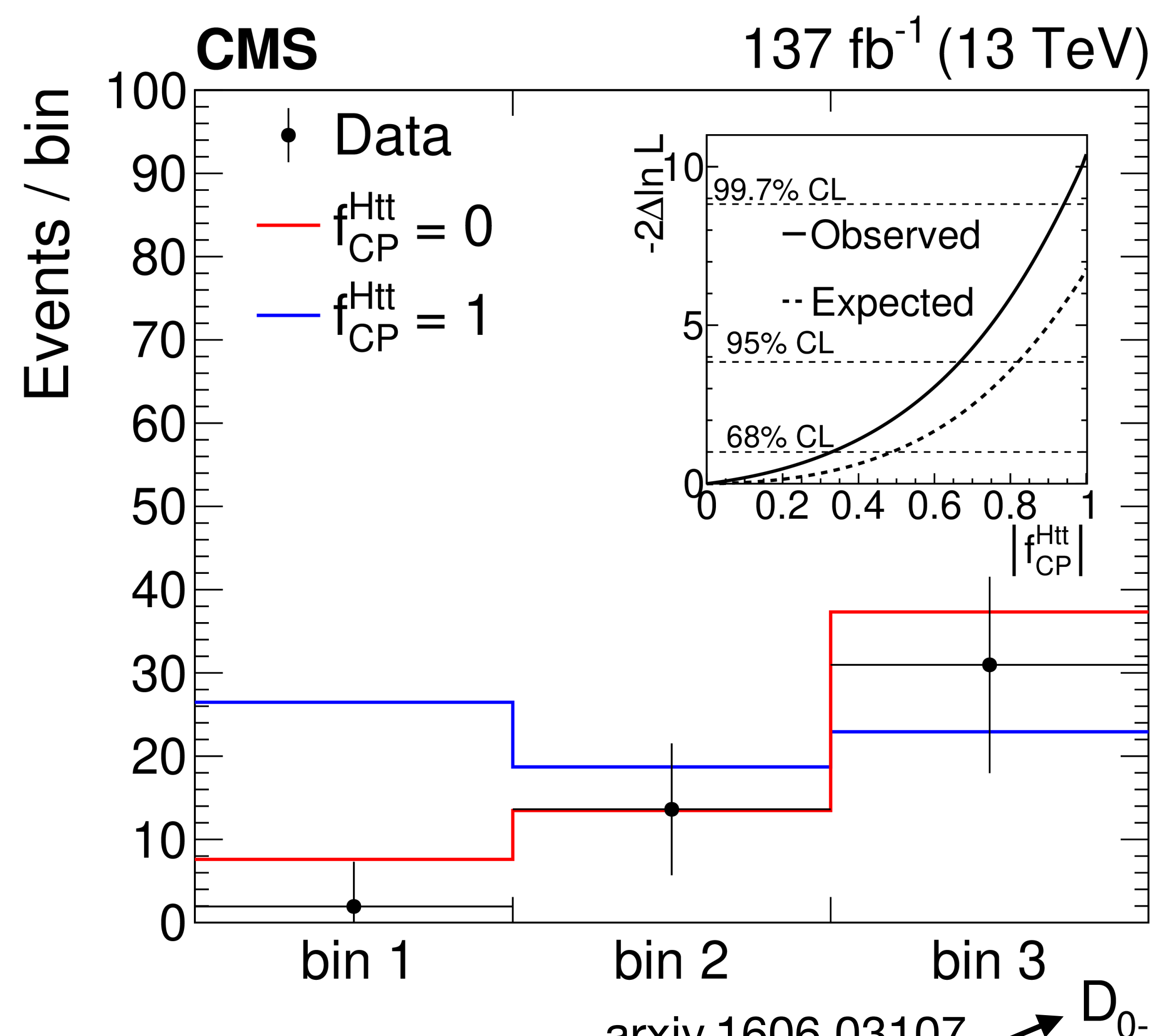
ttH observation in H→$\gamma\gamma$ channel

submitted to: PRL (ATLAS)
submitted to: PRL (CMS)

- ttH observation in 2018 from combination of H→bb, $\gamma\gamma$ and multi-lepton channels with Run 1+ (partially) Run 2 luminosity, in both experiments.
- With full Run 2 dataset, both ATLAS&CMS have observed ttH via H→$\gamma\gamma$ channel.



$$f_{CP}^{Htt} = \frac{|\tilde{\kappa}_t|^2}{|\kappa_t|^2 + |\tilde{\kappa}_t|^2}\,\mathrm{sign}(\tilde{\kappa}_t/\kappa_t)$$



arxiv.1606.03107

- ttH (H→$\gamma\gamma$) data disfavor the pure CP-odd model of the Htt coupling at 3.2σ in CMS (similar result in ATLAS).