Higgs studies in ATLAS and CMS

LIU Kun (TDLI/SJTU)

on behalf of the ATLAS and CMS collaborations

2019.09.02

CMS Compact Muon Solenoid

上海交通大學 SHANGHAI JIAO TONG UNIVERSITY

ATLAS EXPERIMENT

Outline

- ✦ Brief introduction of Higgs boson at LHC

- ✦ Higgs mass and width measurements
- ✦ Higgs cross section measurements
- ✦ Combined measurement of Higgs couplings

- ✦ Recent updates on ttH and tH searches
- ✦ Higgs to charm-quark pair and muon pair searches
- ✦ Di-Higgs searches
- ✦ Higgs to invisible searches
- ✦ Prospects at High-Luminosity LHC

- ✦ Summary

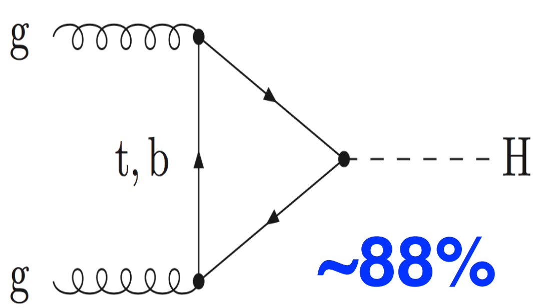
Disclaimer: not covering all topics, this talk is going to present a few selected recent updates since Corfu2018 conference.

The Higgs boson production and decay at LHC

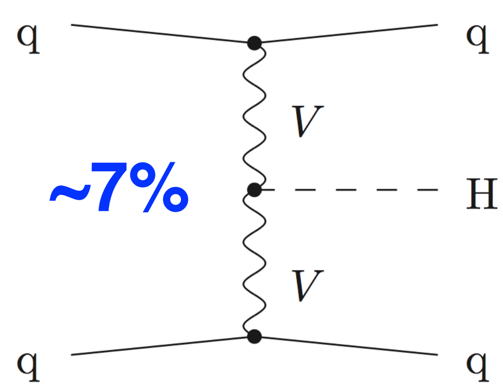
Higgs boson production at LHC
at 13 TeV centre-of-mass energy

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

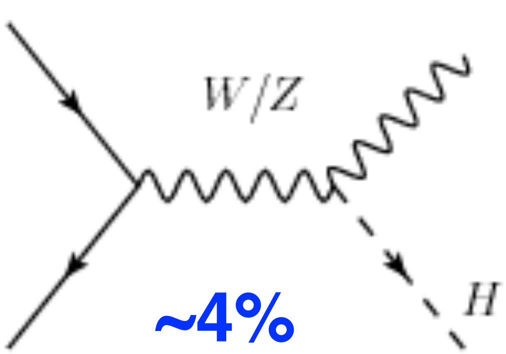
gluon-gluon fusion(ggF)



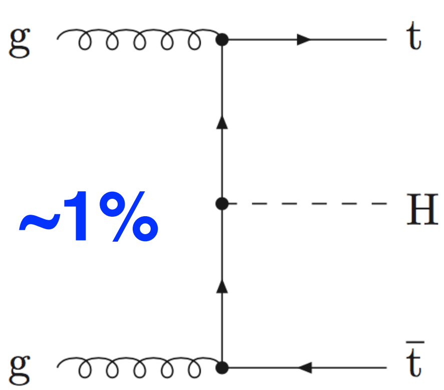
Vector boson fusion(VBF)



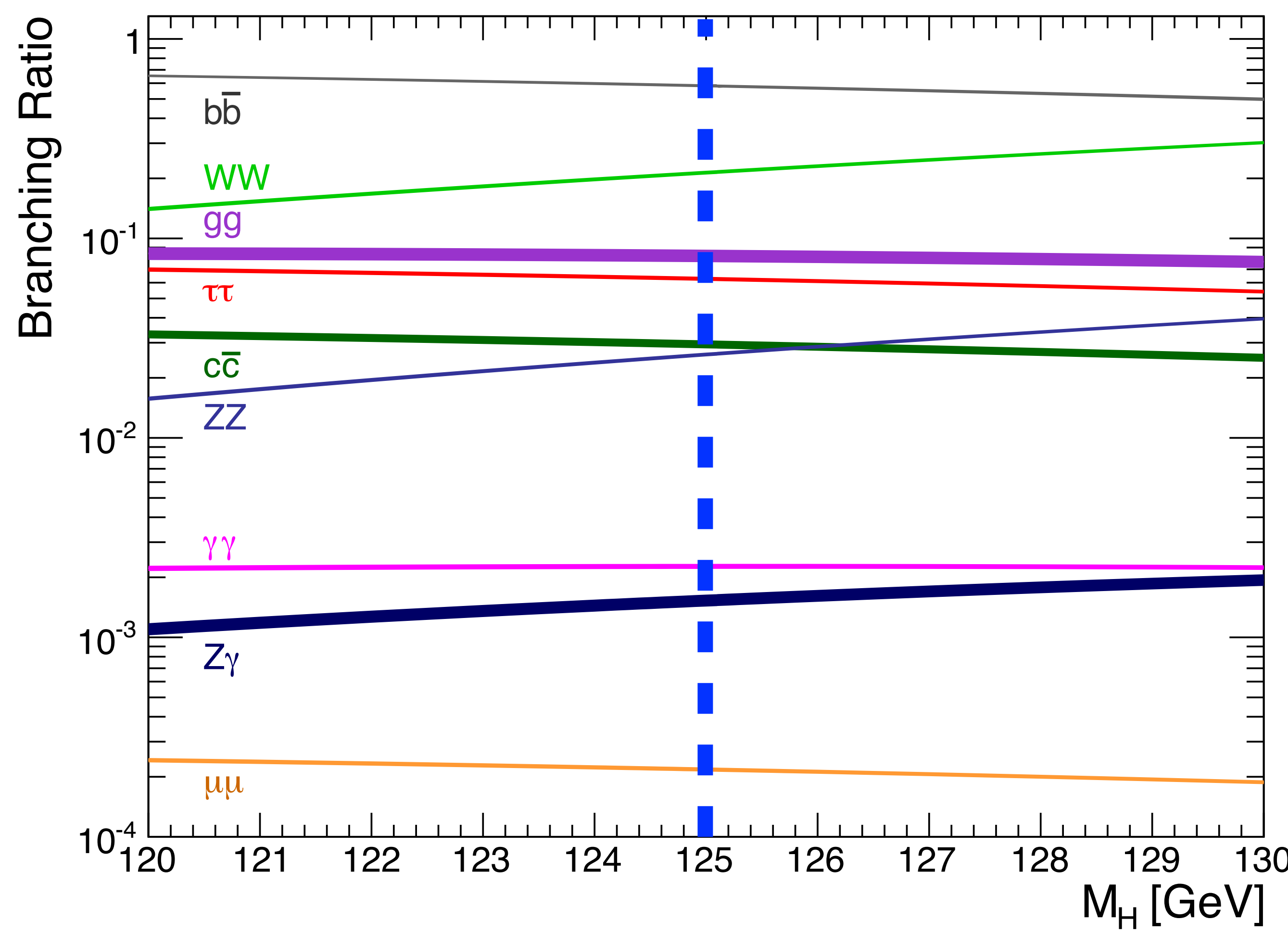
Higgs associated production with vector bosons (VH)



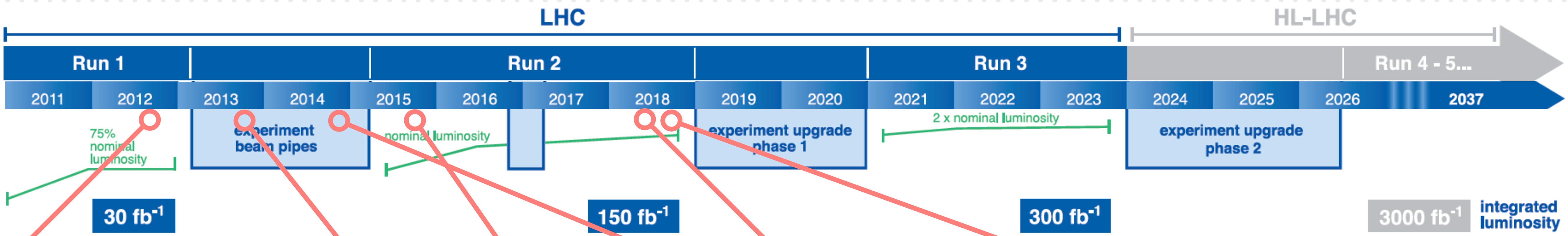
Higgs associated production with a top-quark pair (ttH)



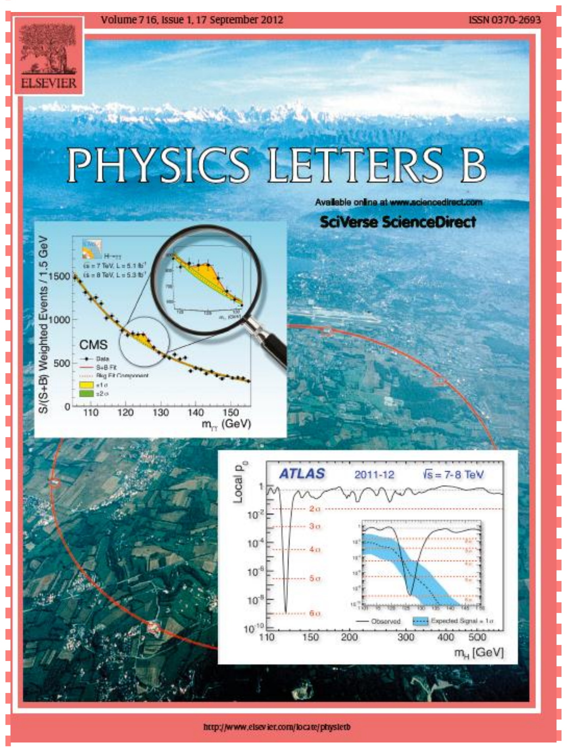
Higgs boson decay modes



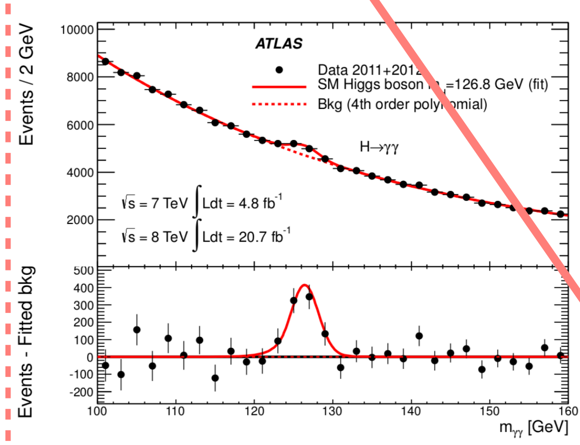
The Higgs boson observations timeline at the LHC

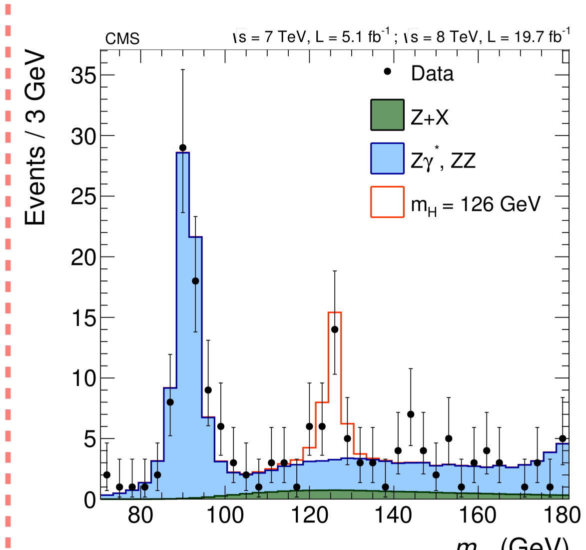


SM-like Higgs discovery
(ggF → $\gamma\gamma$ + ZZ + WW)

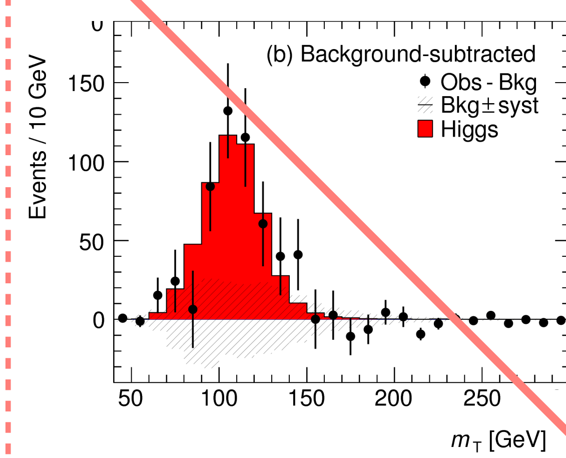


H→$\gamma\gamma$, ZZ→4l observation
(spin-0 and parity +)

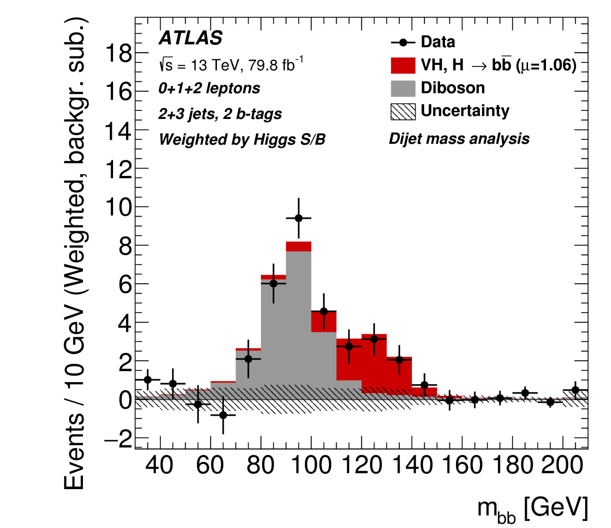




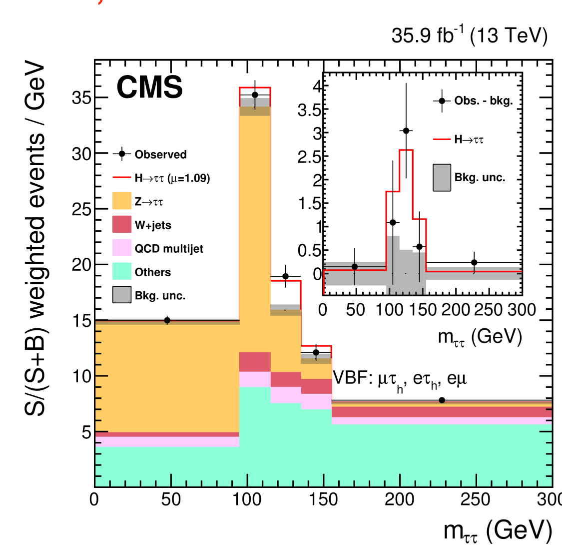
H→WW observation



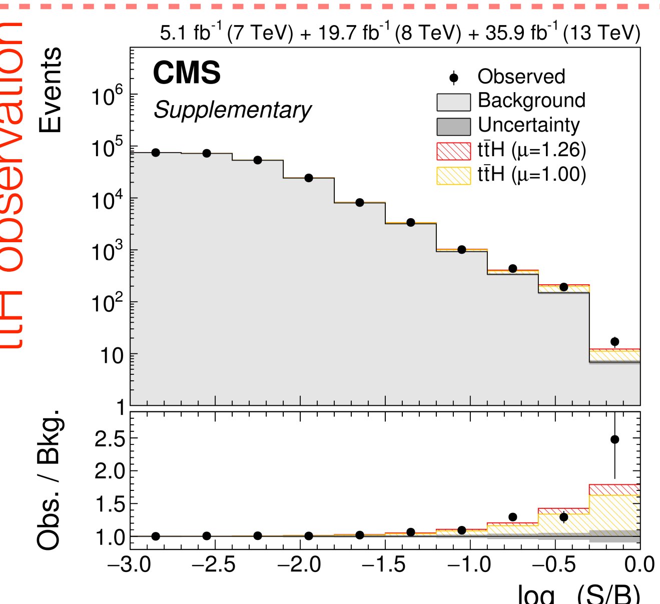
VH, H→bb observation



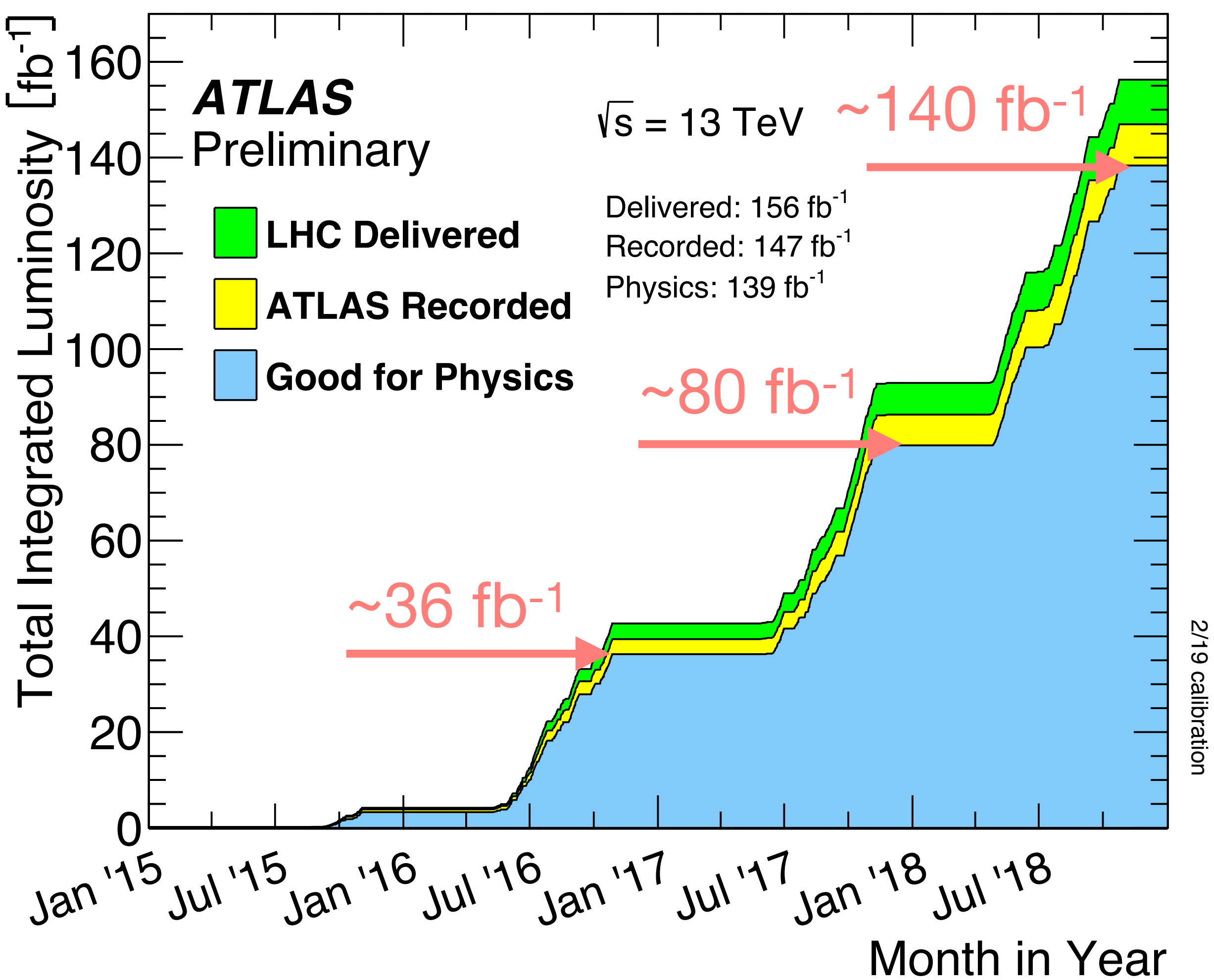
VBF, H→$\tau\tau$ observation

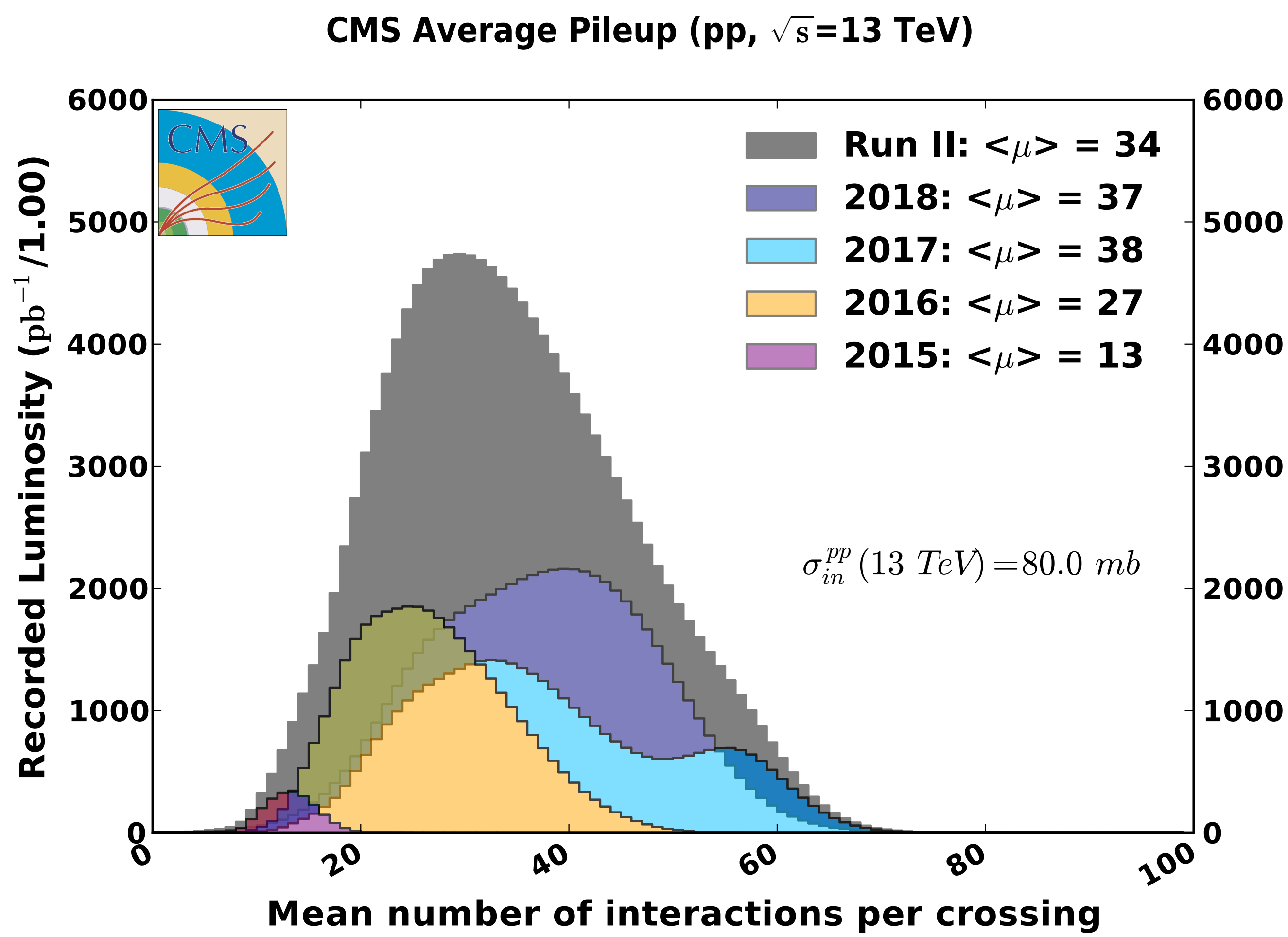


ttH observation



ATLAS and CMS Run II luminosity





- ✦ ATLAS and CMS experiments have successfully collected 140 fb^{-1} luminosity at 13 TeV centre-of-mass energy in full Run 2 period → Thanks to LHC machine !
- ✦ Run 2 dataset has been used in stage for published analyses, i.e 36 / 80 / 140 fb^{-1}.

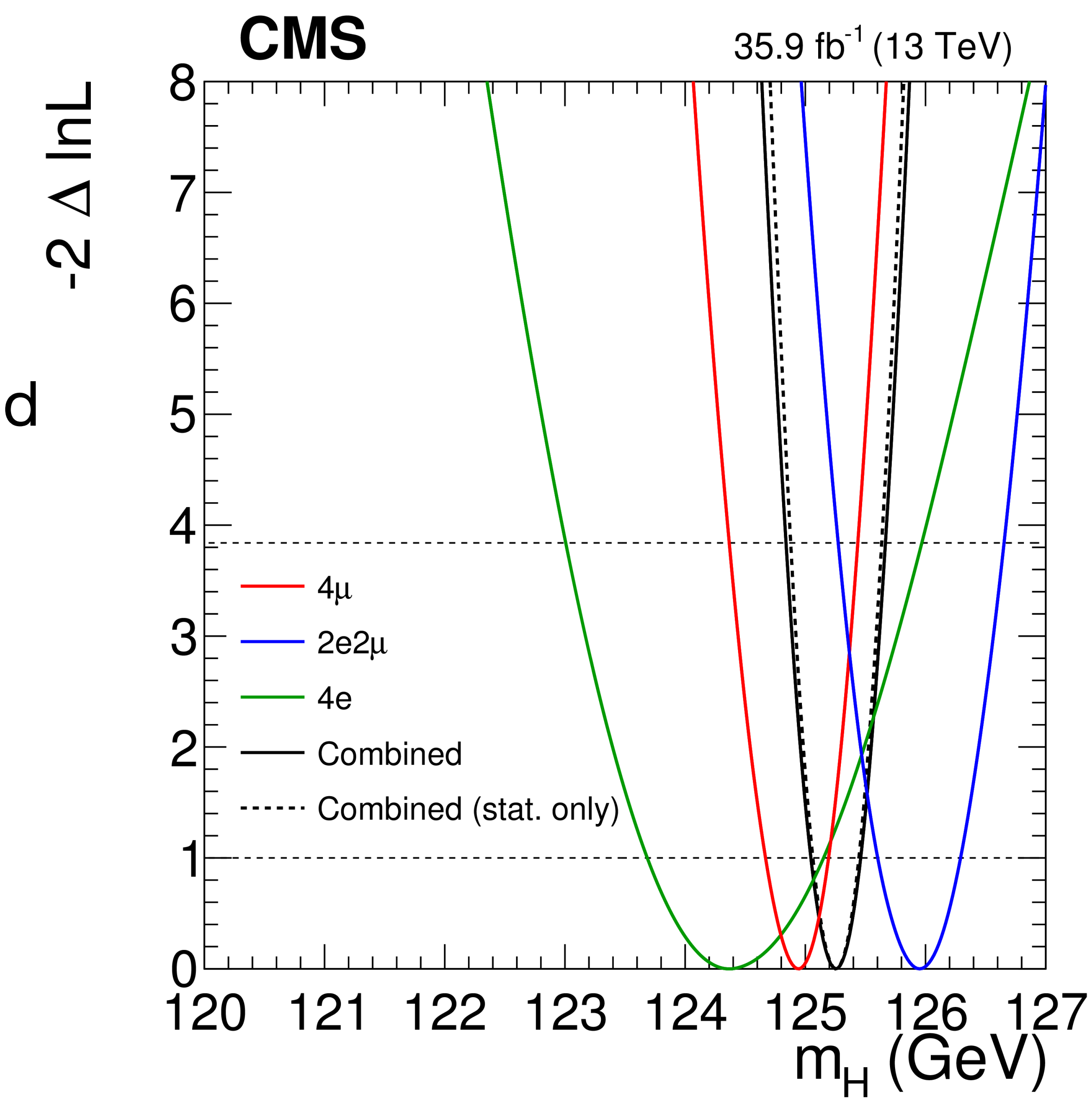
Higgs boson mass measurement

PRL 114 (2015) 191803
PLB 784 (2018) 345
JHEP 11 (2017) 047

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

$$125.09 \pm 0.24\ (\pm 0.21 \pm 0.11)\ \text{GeV}$$

Stat. Syst.



- ATLAS Run 2 measurement in $H\to ZZ\to 4l$ and $H\to\gamma\gamma$ combination, using 36 fb^{-1} dataset:

$$124.86 \pm 0.27\ (\pm 0.18)\ \text{GeV}$$

Stat. only

- CMS Run 2 measurement in $H\to ZZ\to 4l$ channel, using 36 fb^{-1} dataset:

$$125.26 \pm 0.21\ (\pm 0.20 \pm 0.08)\ \text{GeV}$$

Stat. Syst.

→ this result is better than ATLAS+CMS Run 1 combination.

All measurements are in good agreement !

Constraints on Higgs boson width

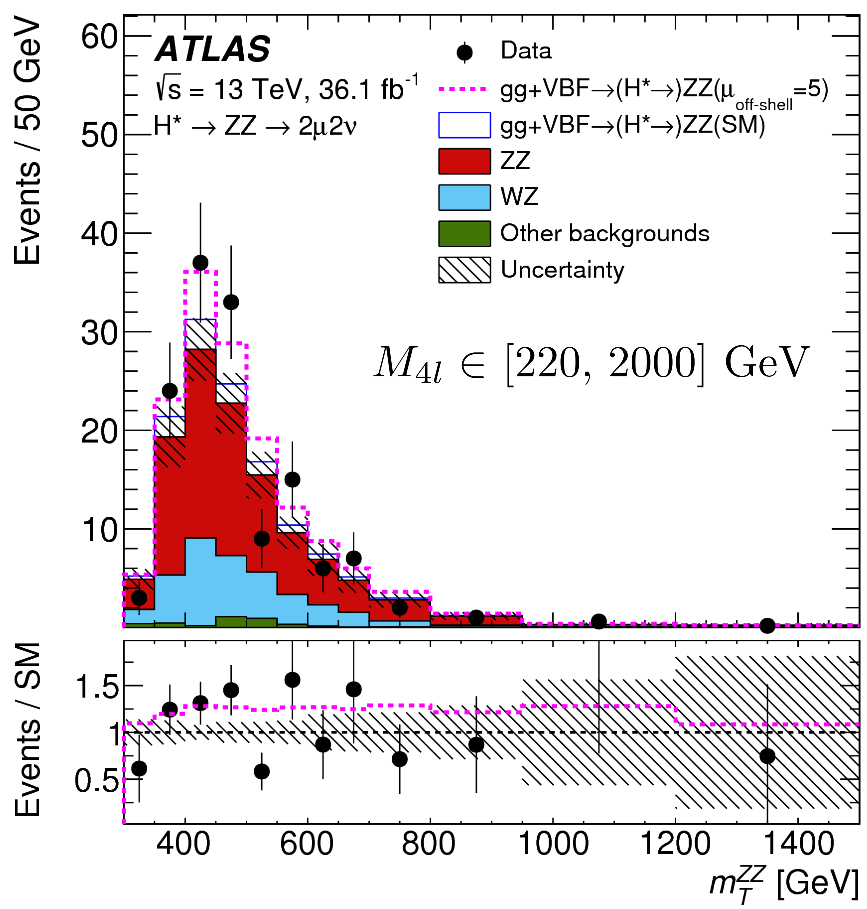
PRD 99 (2019) 112003
PLB 786 (2018) 223
ATL-PHYS-PUB-2015-024
CMS-PAS-FTR-18-011

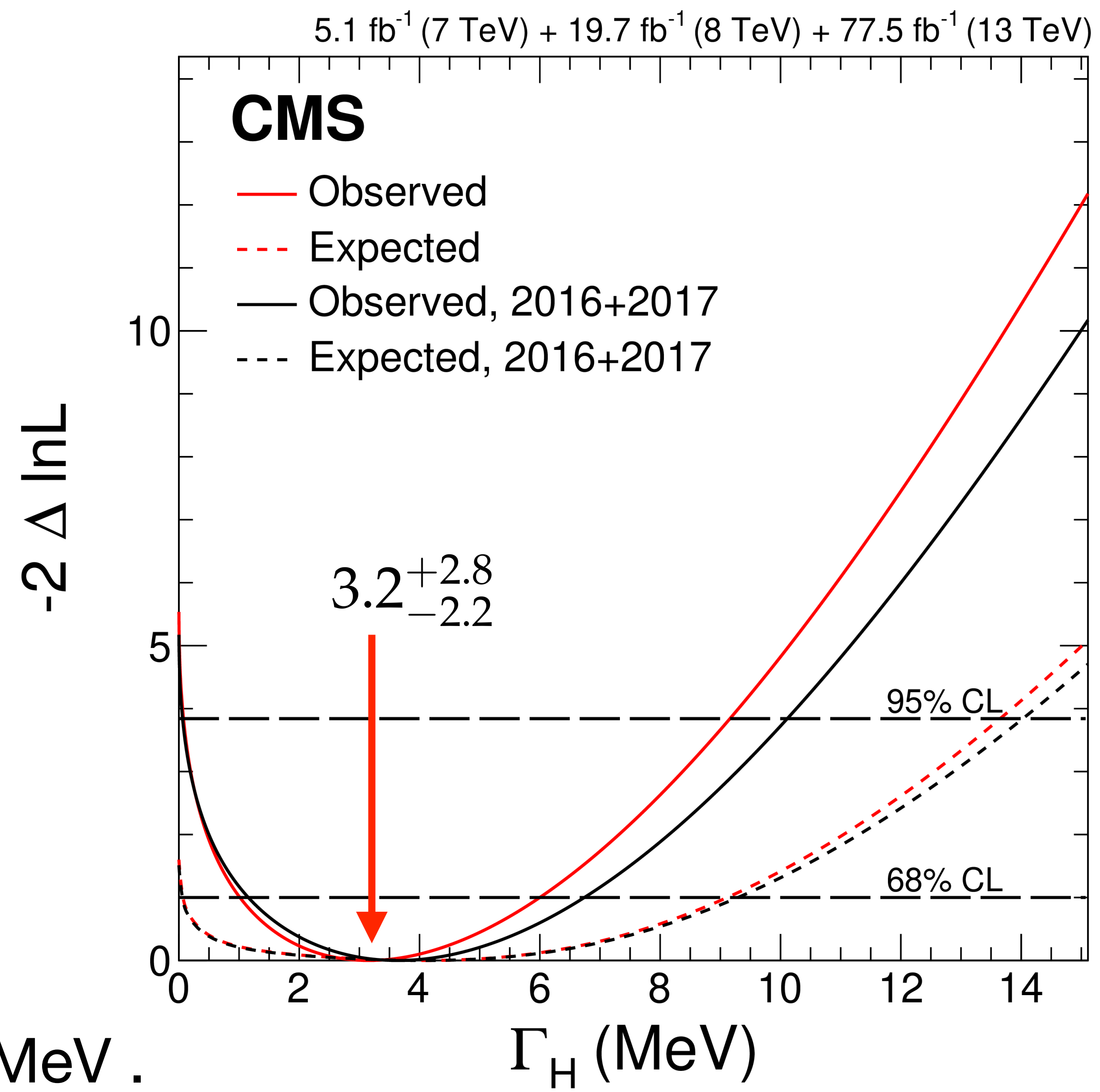
Indirect measurement from off-shell production in H→ZZ→4l channel. Obs. limit on Higgs width:

- 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.

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



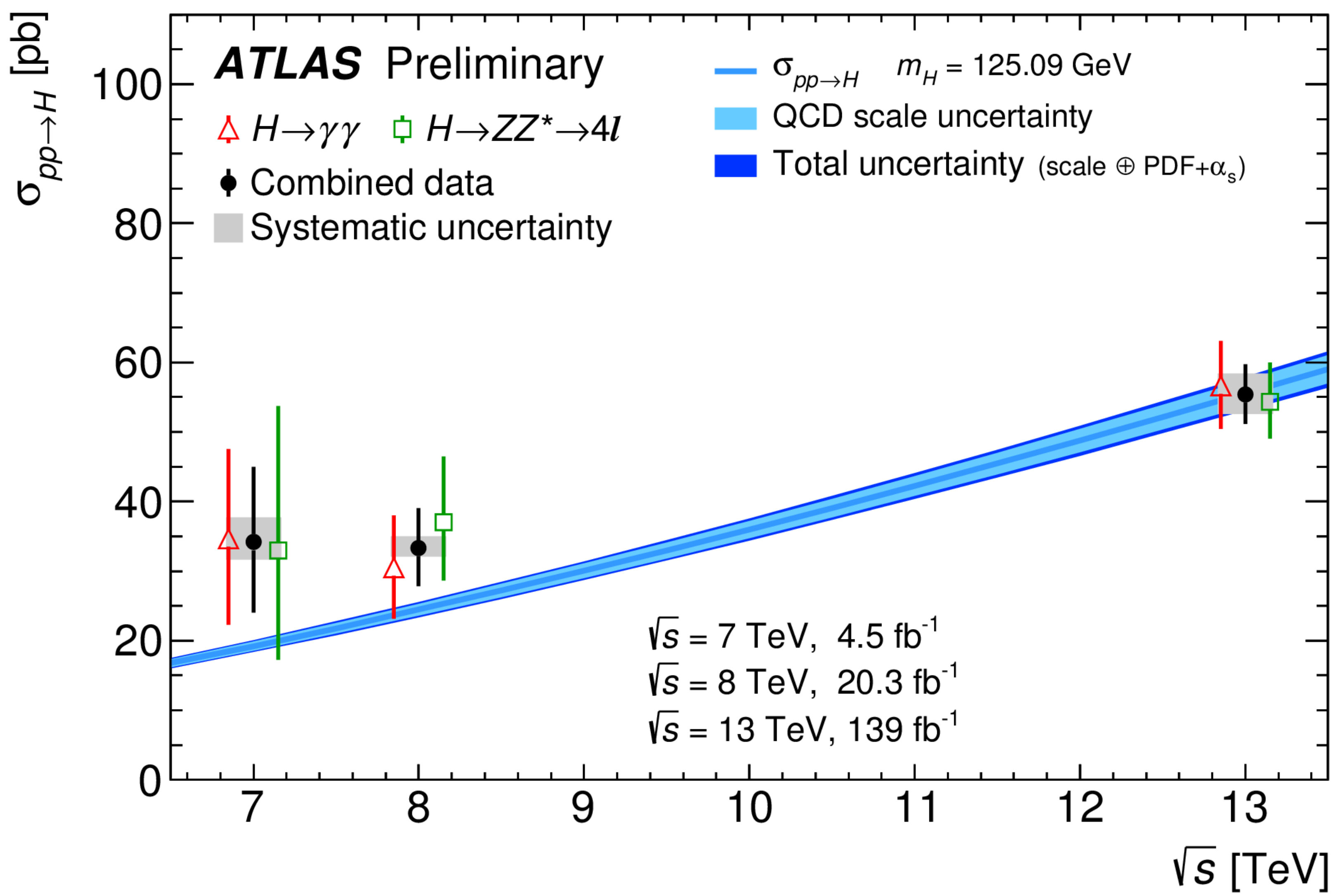


Prospects w/ 3 ab^{-1} at HL-LHC, Γ_H can be measured in CMS (ATLAS): $4.1^{+1.0}_{-1.1}$ $(4.2^{+1.5}_{-2.1})$ MeV .

Higgs cross section measurement

EPJC 79 (2019) 421
ATLAS-CONF-2019-005
ATLAS-CONF-2019-032

- Inclusive Higgs signal strength from all analysis 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 channels at 7,8 and 13 TeV:

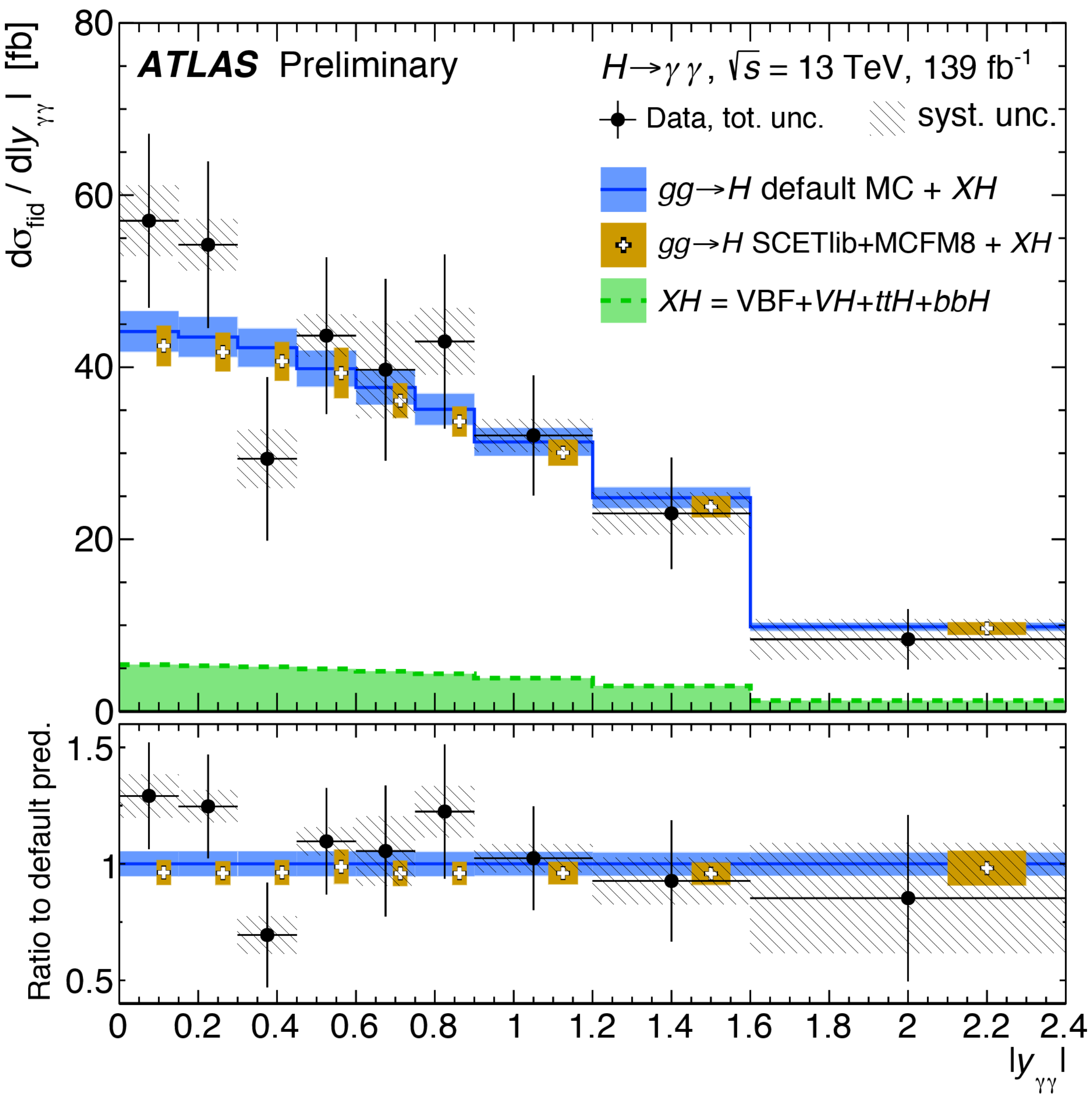


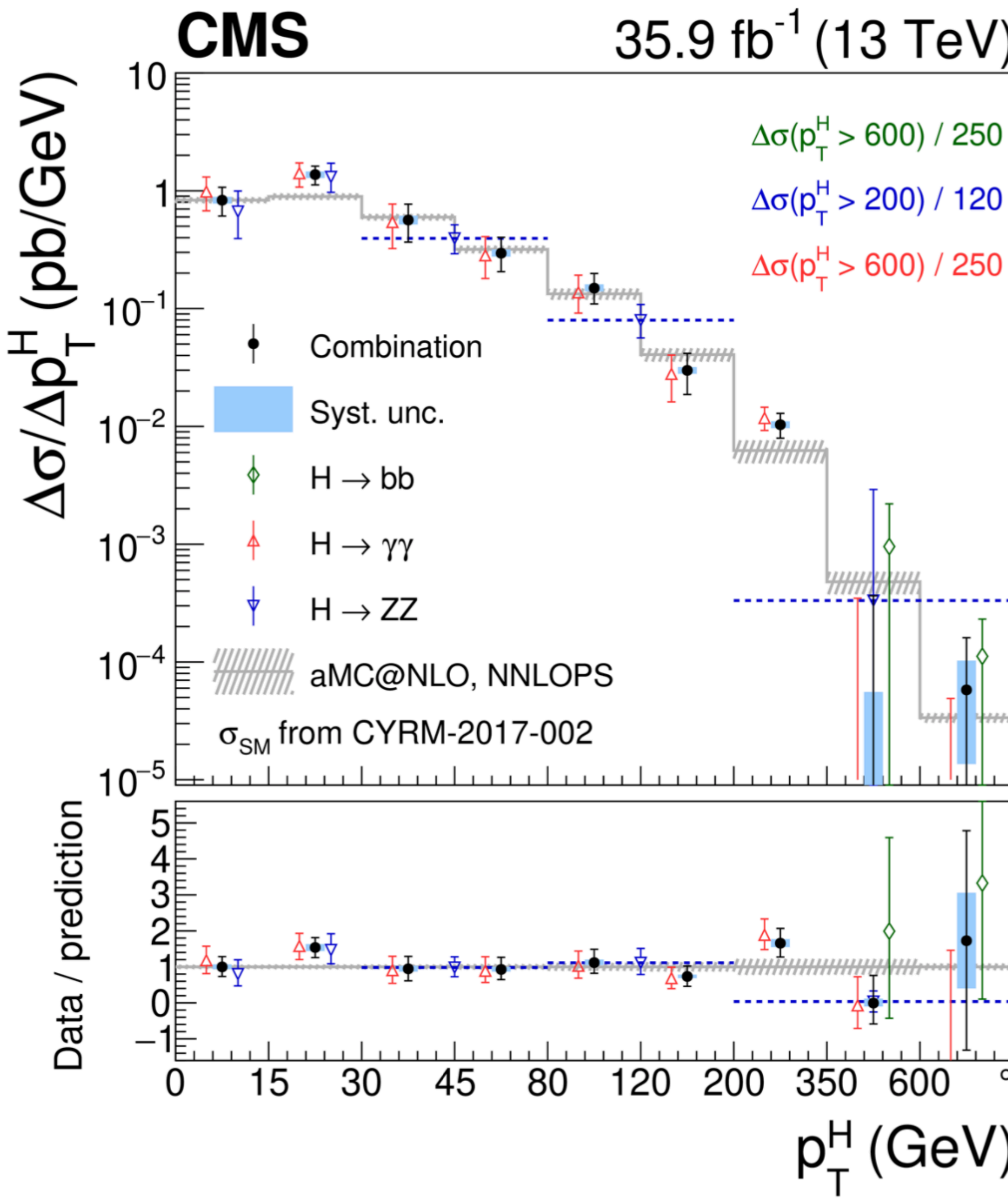
➡ Inclusive X-section measurements are in good agreement with the SM prediction.

Higgs cross section vs Higgs rapidity, p_T

PLB 792 (2019) 369
ATLAS-CONF-2019-032
ATLAS-CONF-2019-029

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





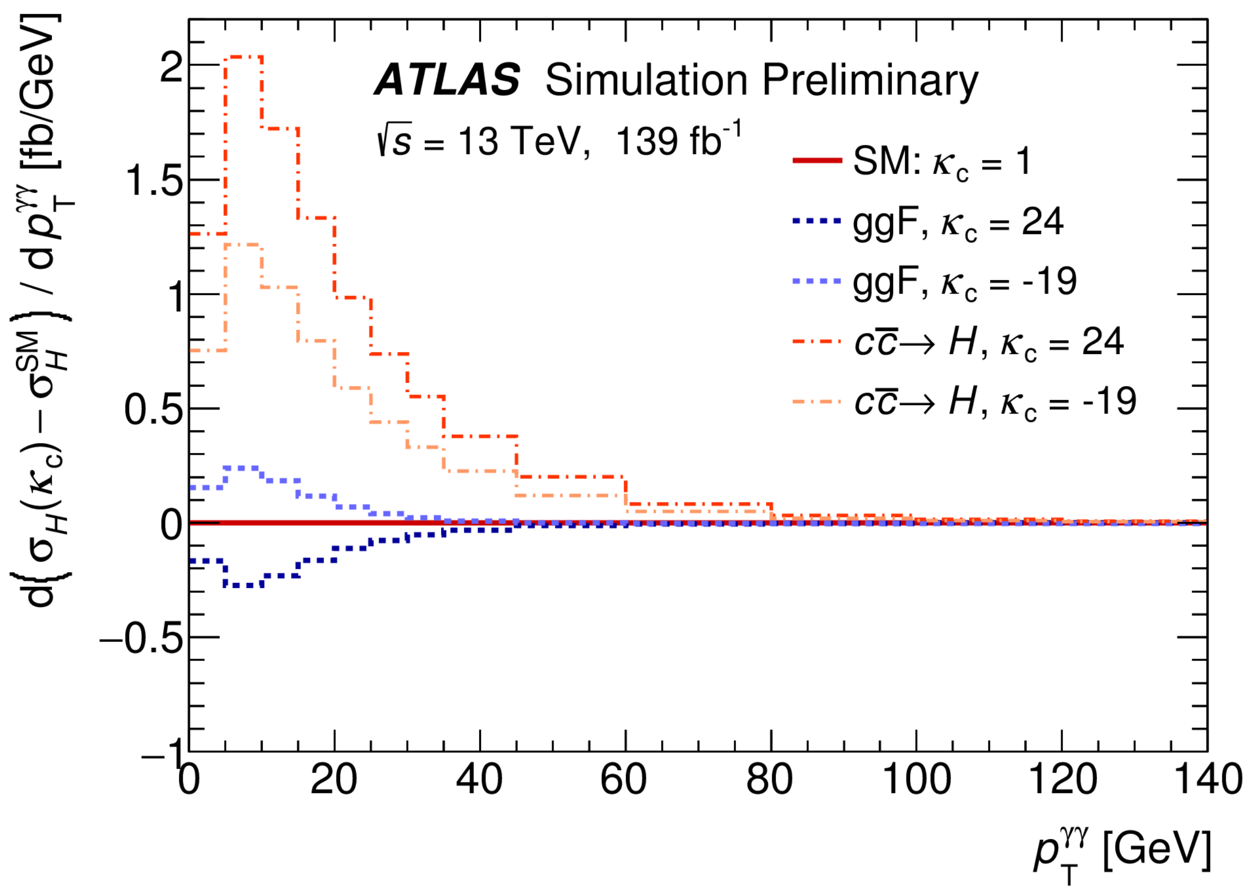
➡ Measurements are in good agreement with the SM predictions.

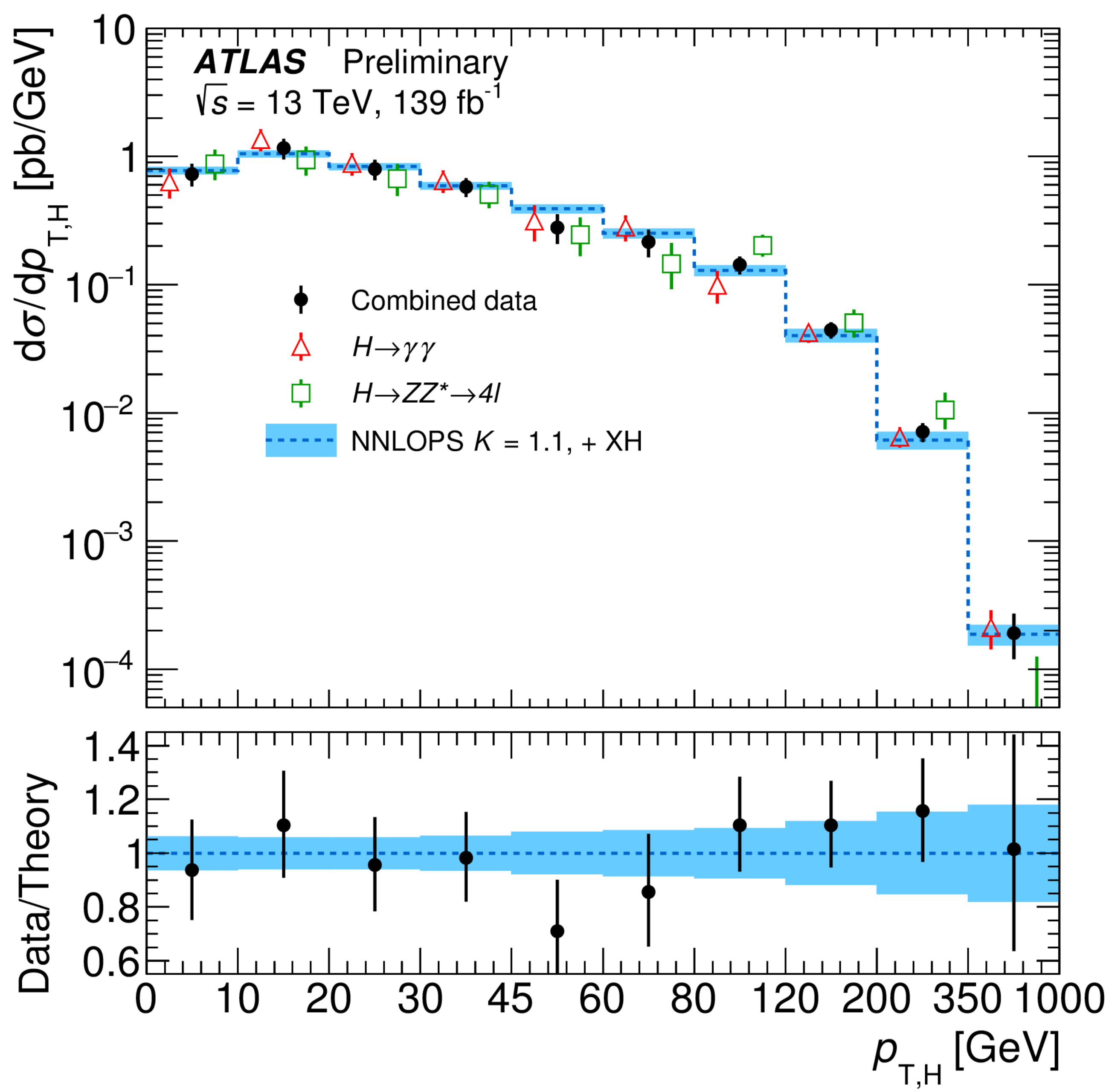
Higgs cross section vs Higgs rapidity, p_T

PLB 792 (2019) 369
ATLAS-CONF-2019-029

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

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

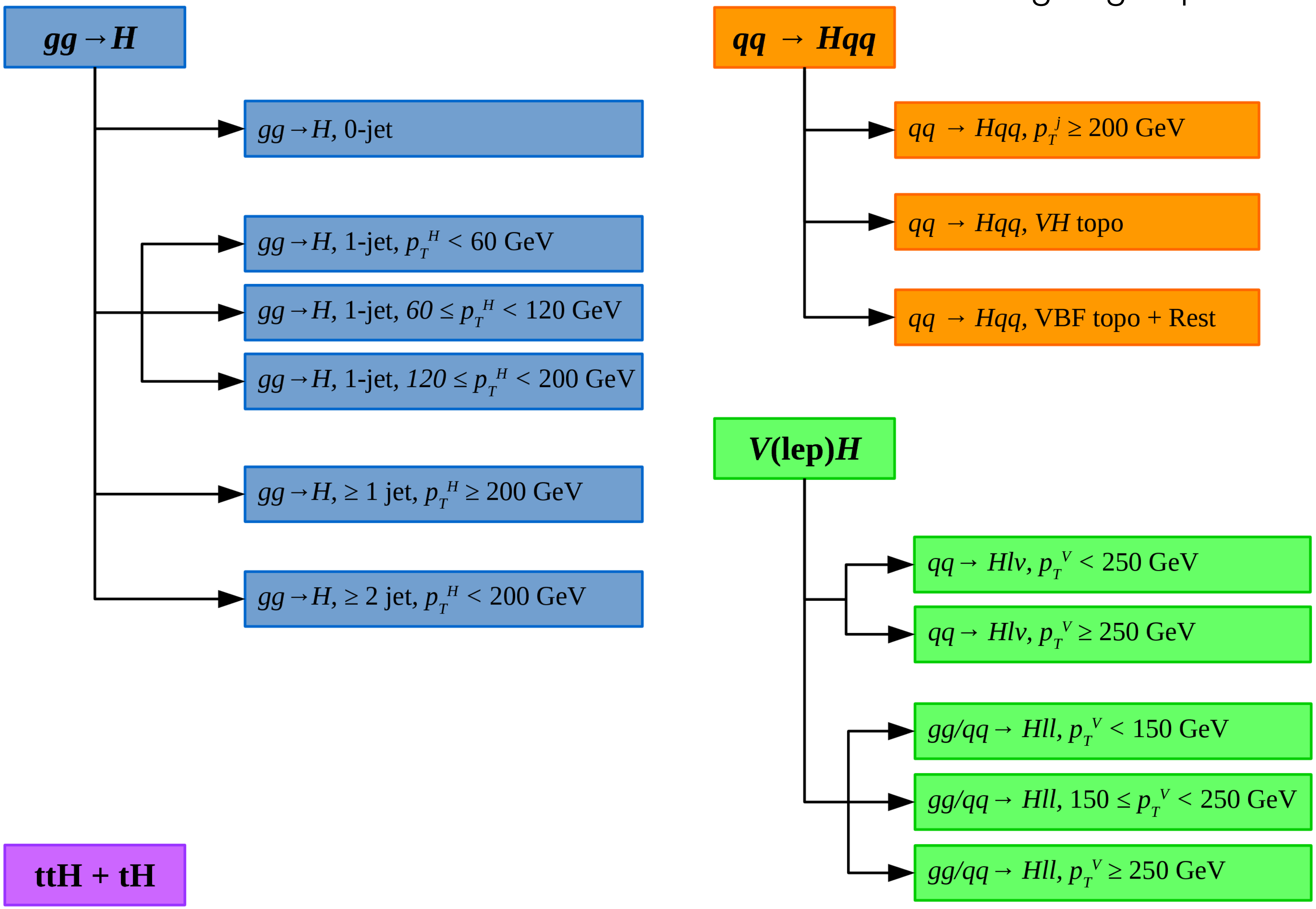




p_T differential X-section measurement is used to extract limit on charm Yukawa coupling strength modifier: $\kappa_c(y_c/y_c^{SM}) \in$ [-19,24] @ 95% C.L. (similar results in CMS).

Higgs Simplified Template X-Section measurement

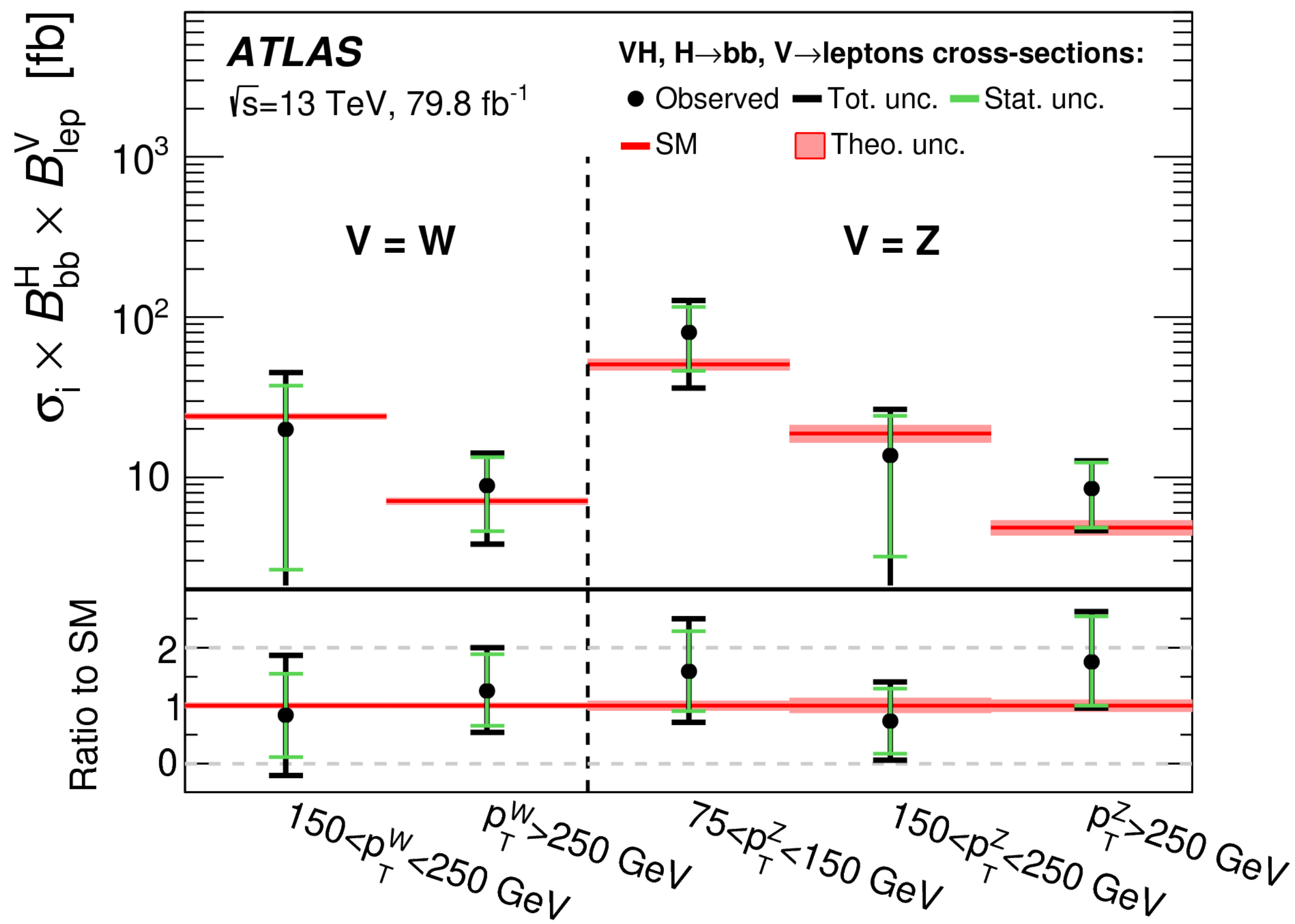
Merged groups of Stage-1 bins



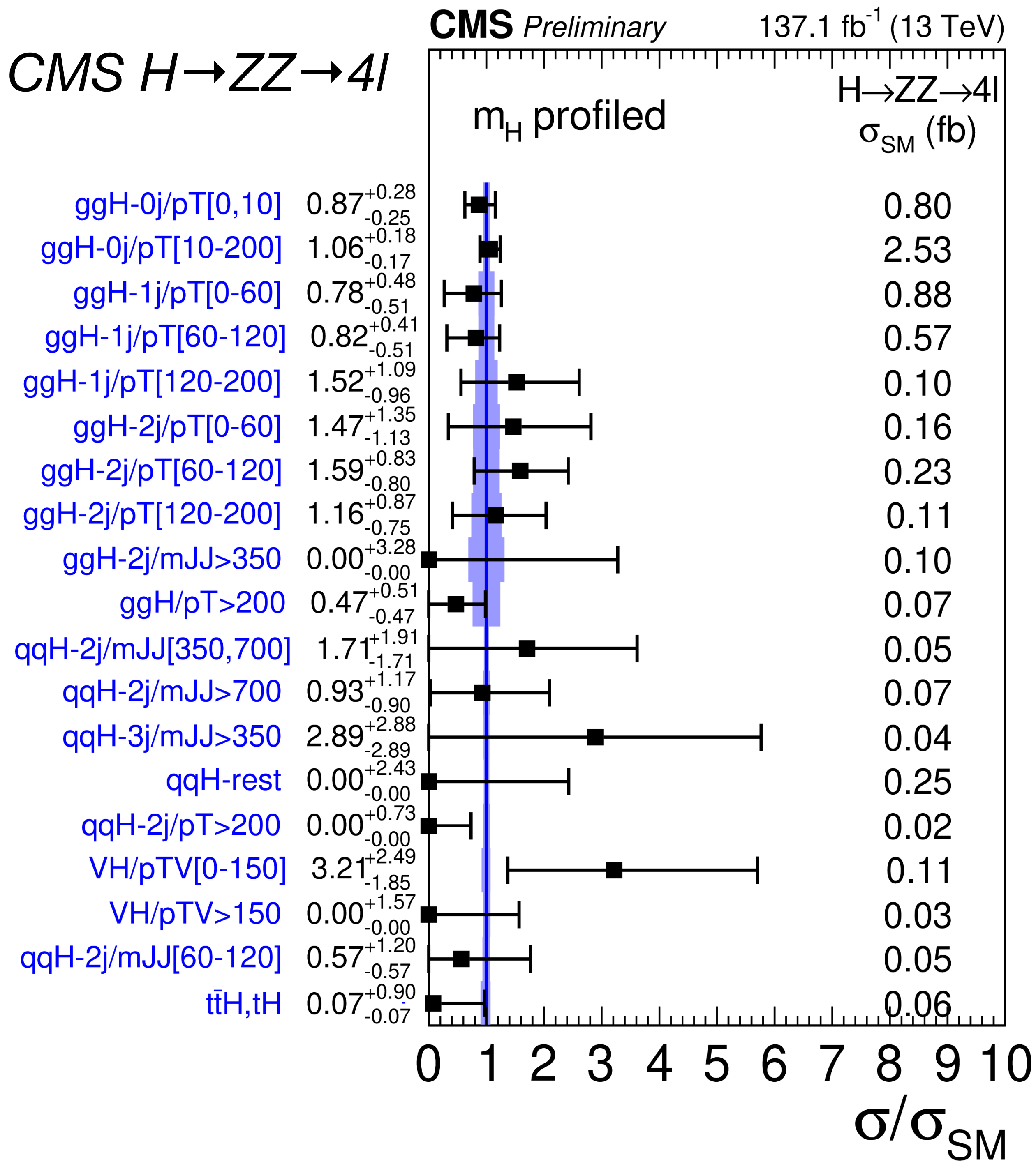
Higgs Simplified Template X-Section measurement

EPJC 05 (2019) 141, CMS-PAS-HIG-19-001

ATLAS VH, H→bb



CMS H→ZZ→4l



Measurements are in good agreement with the SM predictions !

Combined measurement of Higgs coupling properties

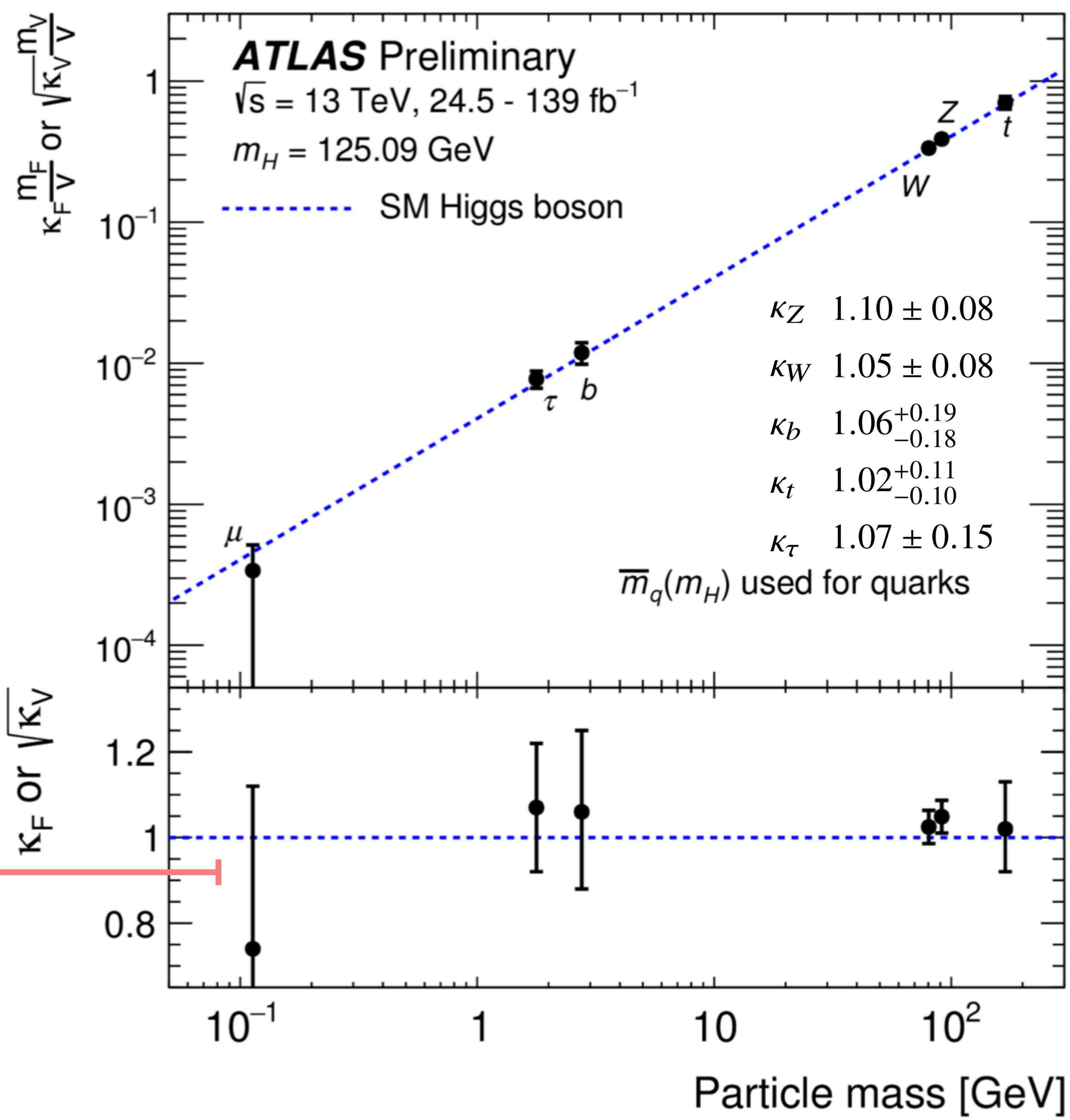
EPJC 79 (2019) 421, ATLAS-CONF-2019-005

- ATLAS and CMS have performed global fit of coupling modifiers, using kappa framework:
  - using 36 - 140 fb^{-1}
  - all production&decay channels.

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

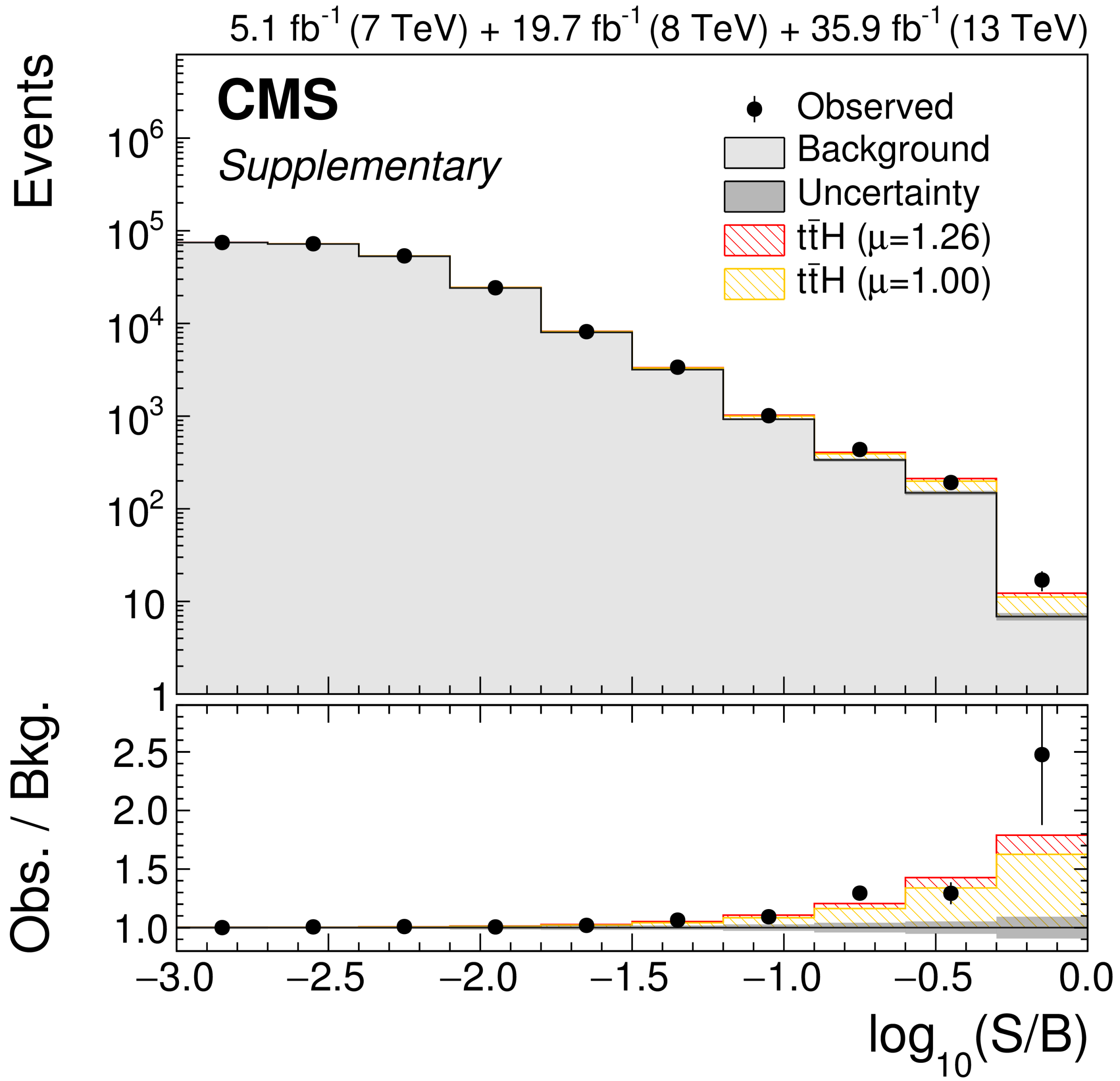
✓ ~10-20% uncertainty on Higgs to the 3rd generation fermion couplings.

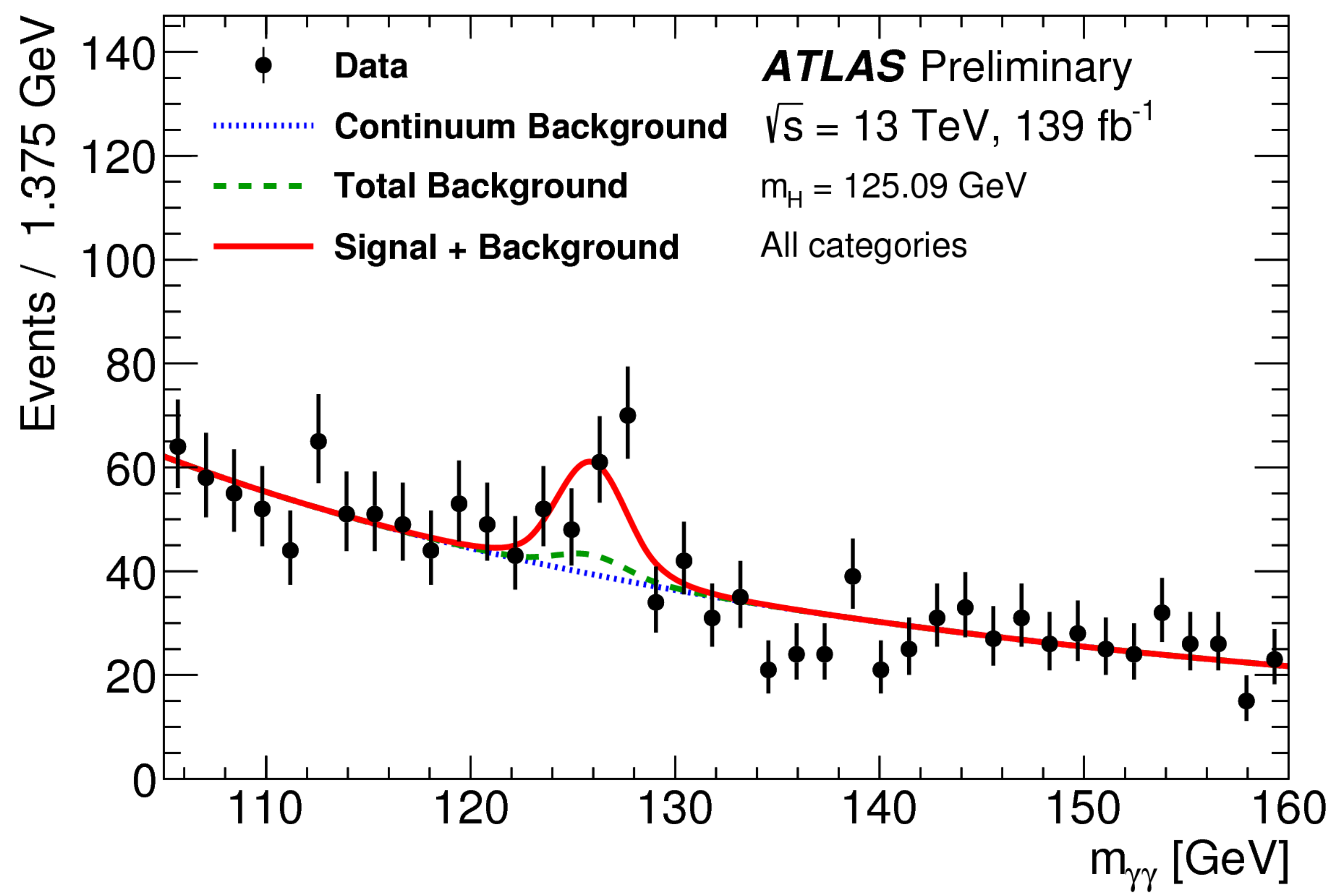
- The obs.(exp.) significance for H→$\mu\mu$ is 0.8σ (1.5σ) from ATLAS using 140 fb^{-1} data, and 0.9σ (1.0σ) from CMS using 36 fb^{-1} dataset.



Observation of ttH production channel

PLB 784 (2018) 173
PRL 120 (2018) 231801
ATLAS-CONF-2019-004



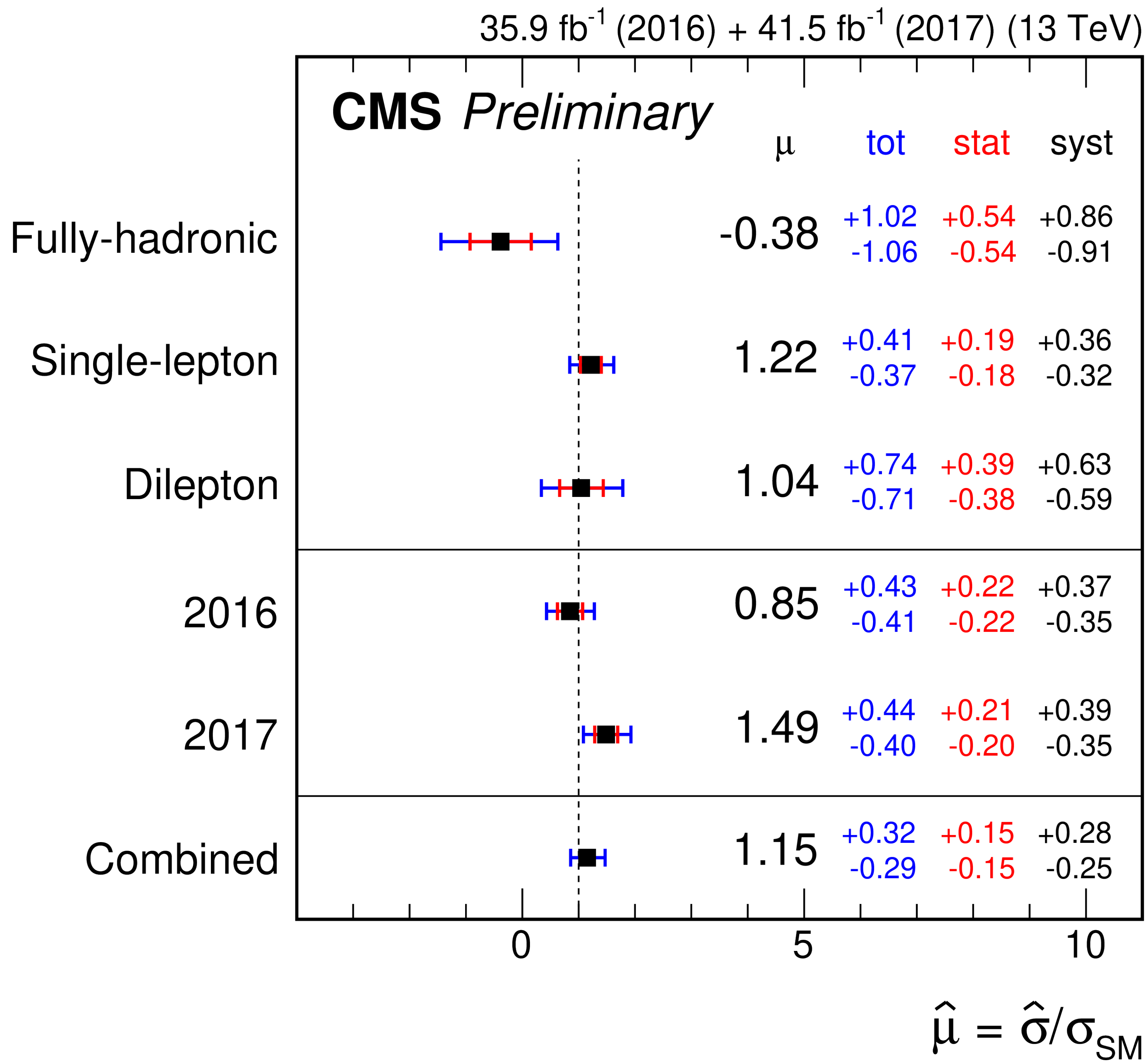


- ttH observation in both ATLAS and CMS in 2018 from combination of H→bb, $\gamma\gamma$ and multi-leptons channels with Run 1+ (partially) Run 2 luminosity.
- With full Run 2 luminosity, ATLAS ttH (H→$\gamma\gamma$) has 4.9σ observed significance.

ttH, H→bb channel evidence in CMS

CMS-PAS-HIG-18-030

- CMS ttH, H→bb channel has been updated to 80 fb^{-1} luminosity.
- The Obs.(exp.) significance is 3.7σ (2.6σ) → Evidence for ttH, H→bb channel !
- The measured ttH, H→bb cross section is in good agreement with the SM prediction.

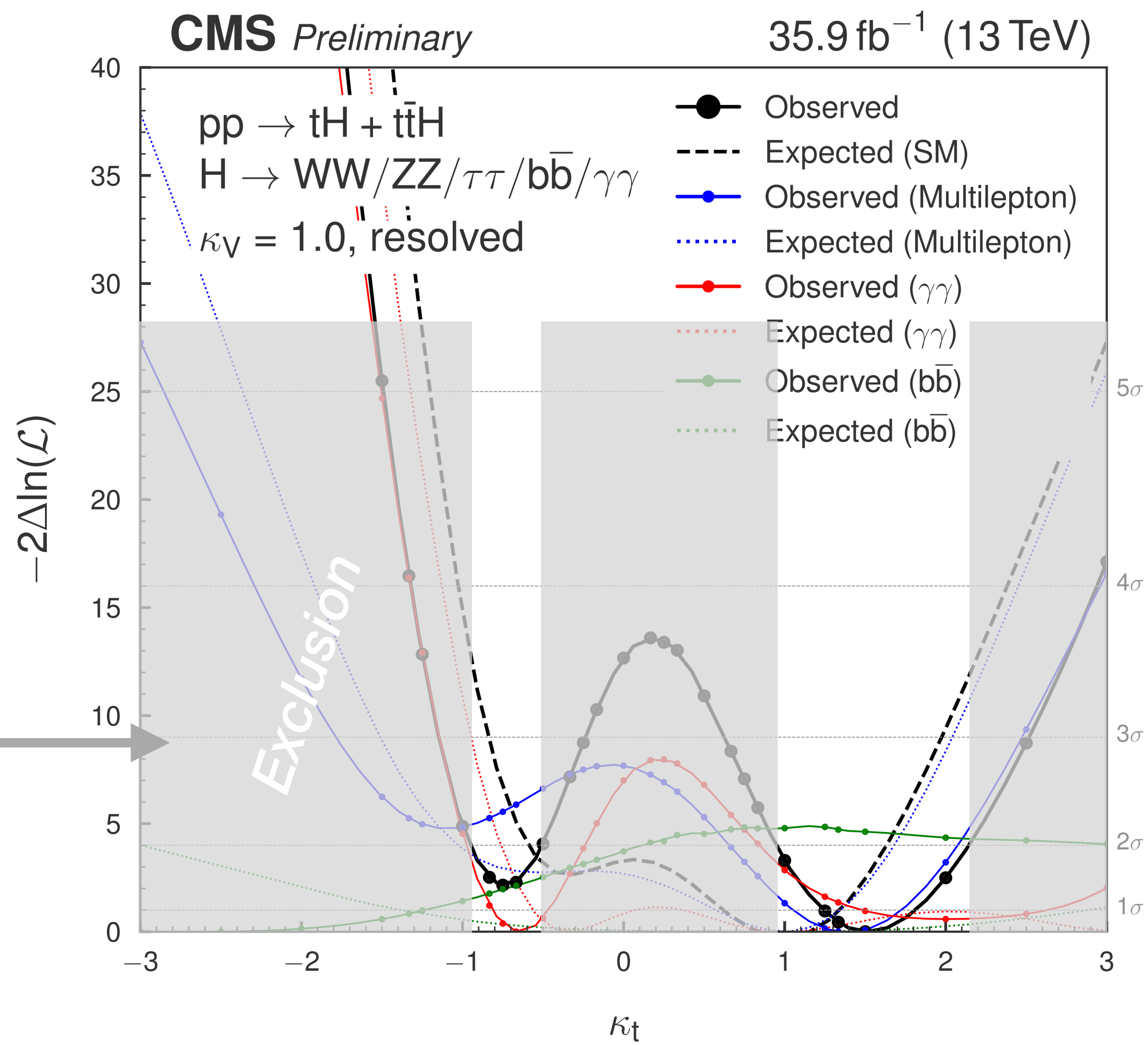


Search for tH production channel in CMS

PRD 99 (2019) 092005

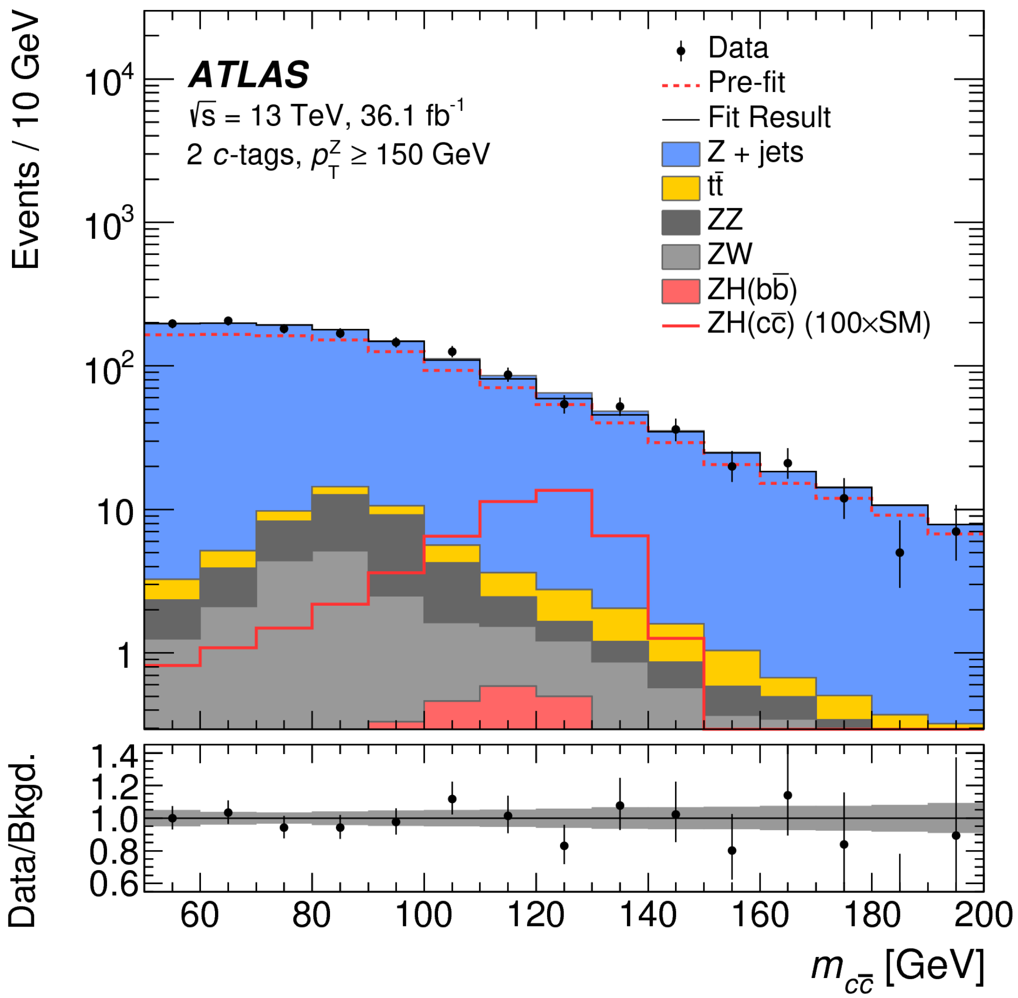
- tH channel is sensitive to Higgs-top Yukawa coupling sign.
- CMS analysis combines H→bb, $\gamma\gamma$ and multi-leptons channels.
- 95% C.L upper limit on SM-like tH signal strength: 25 (12) obs.(exp.).
- ttH+tH combination favours positive κ_t over negative by ~1.5 σ (4.0σ expected).

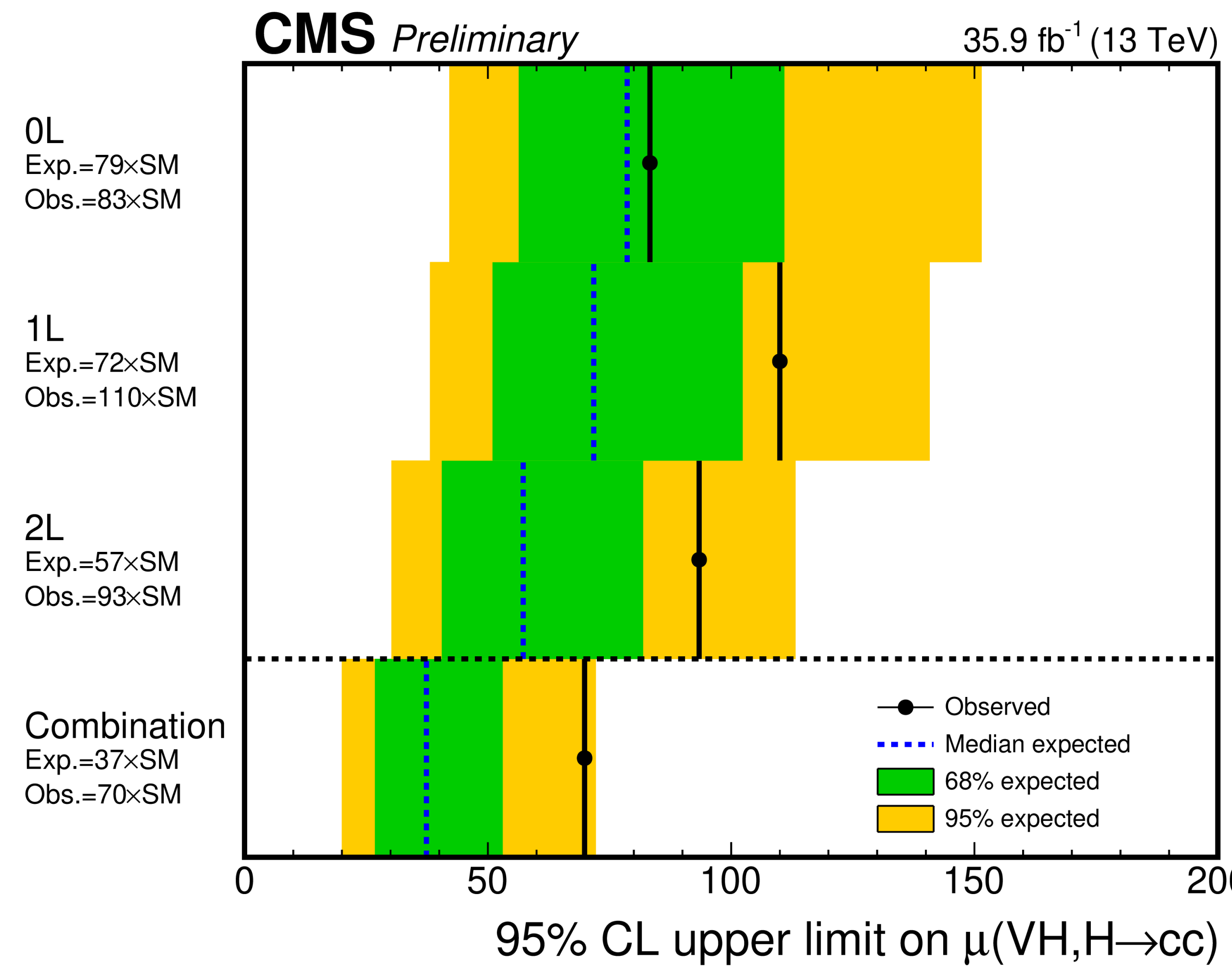
2-sigma exclusion bands



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

PRL 120 (2018) 211802
CMS-PAS-HIG-18-031
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.

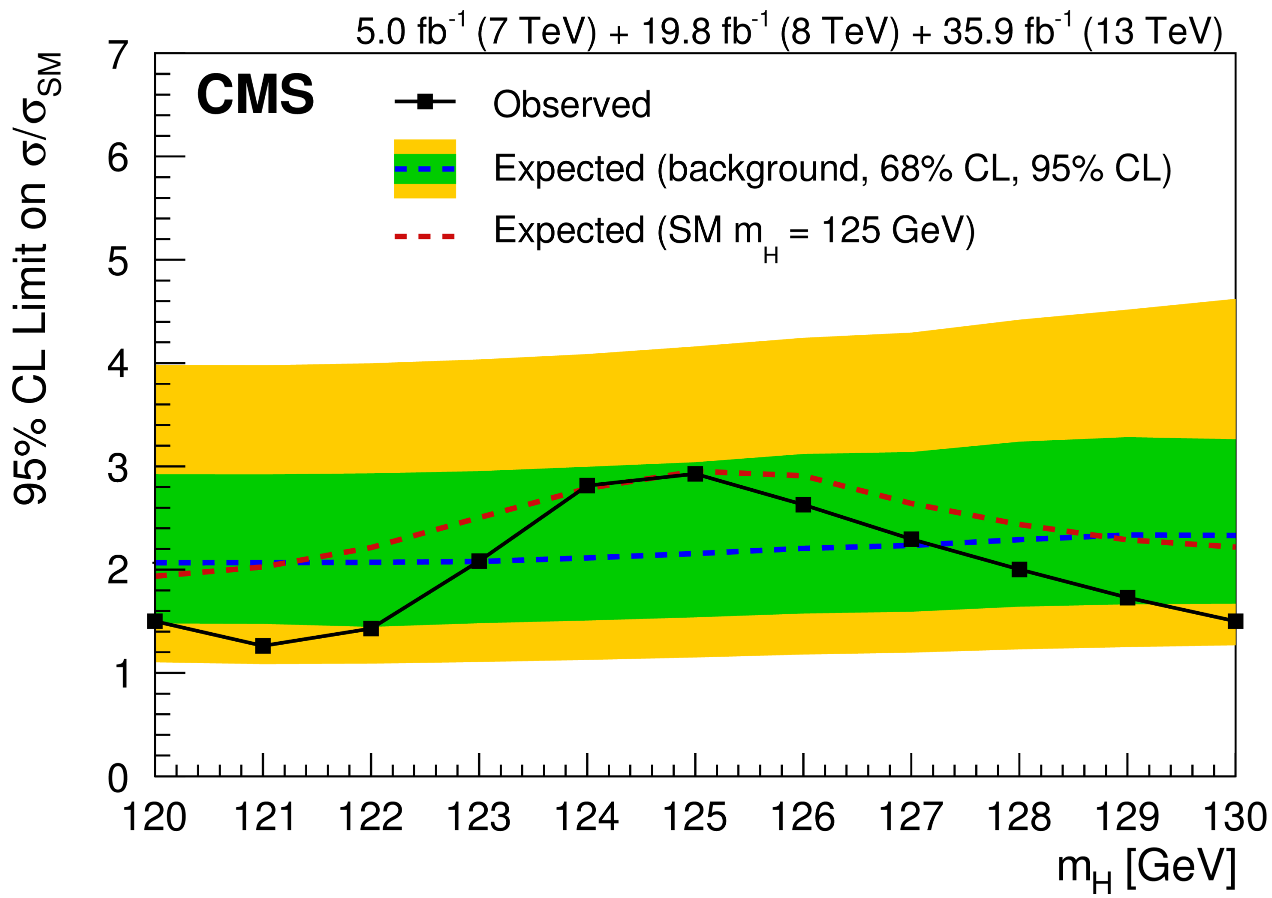
➡ Statistical uncertainty dominates !

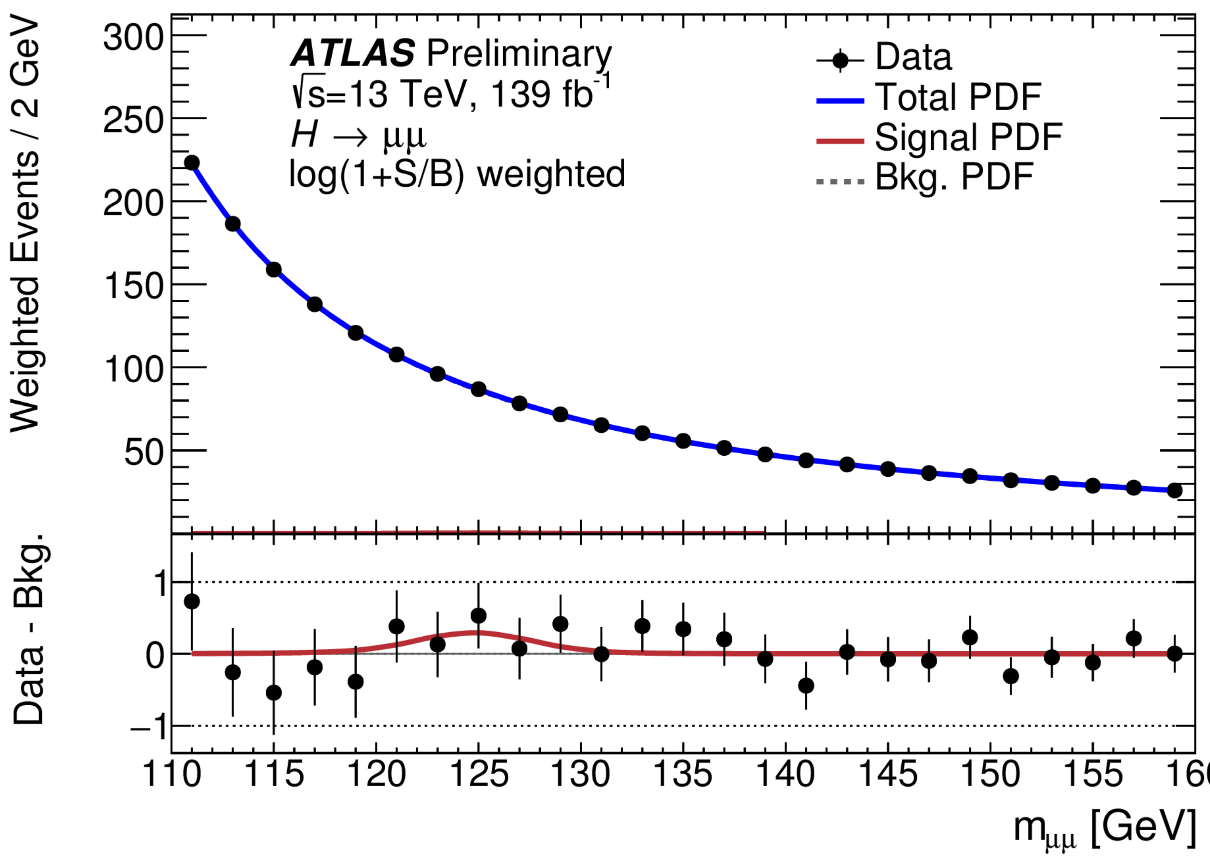
Limits on H→J/Ψ+γ, Ψ(2S)γ and Υ(1S,2S,3S)γ BR at 95% C.L (36.1 fb^{-1}): 3.5x10^{-4}, 2x10^{-3} and (4.9,5.9,5.7)x10^{-4} → about 100, 500, 10^{5} times the SM predictions.

Search for H→$\mu\mu$ 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 140 fb^{-1}: 1.7 (1.3) x SM prediction.



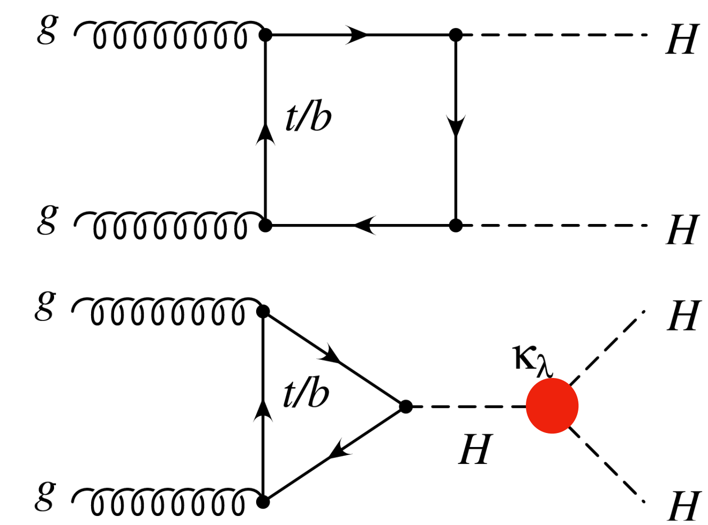


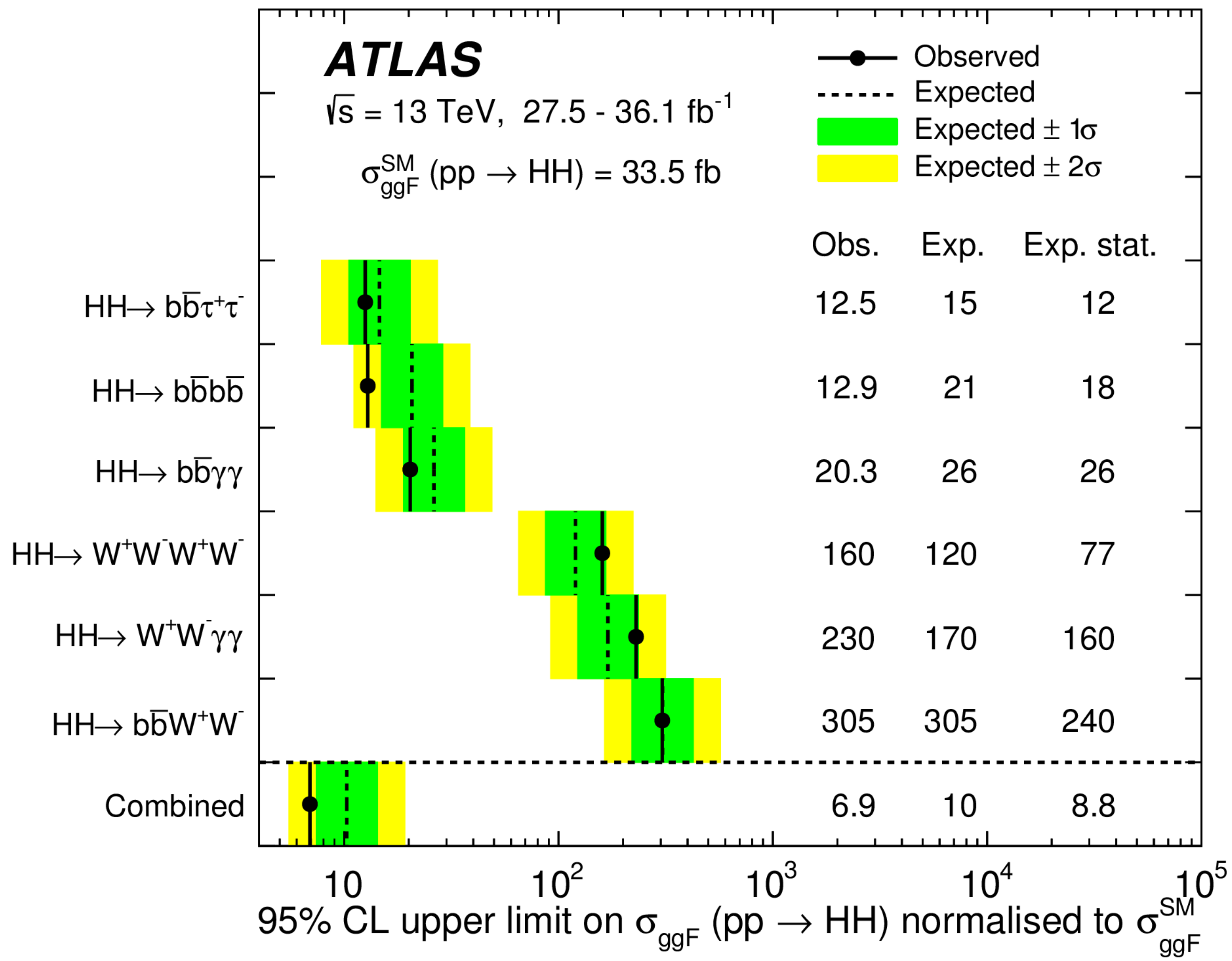
➡ Statistical uncertainty dominates !

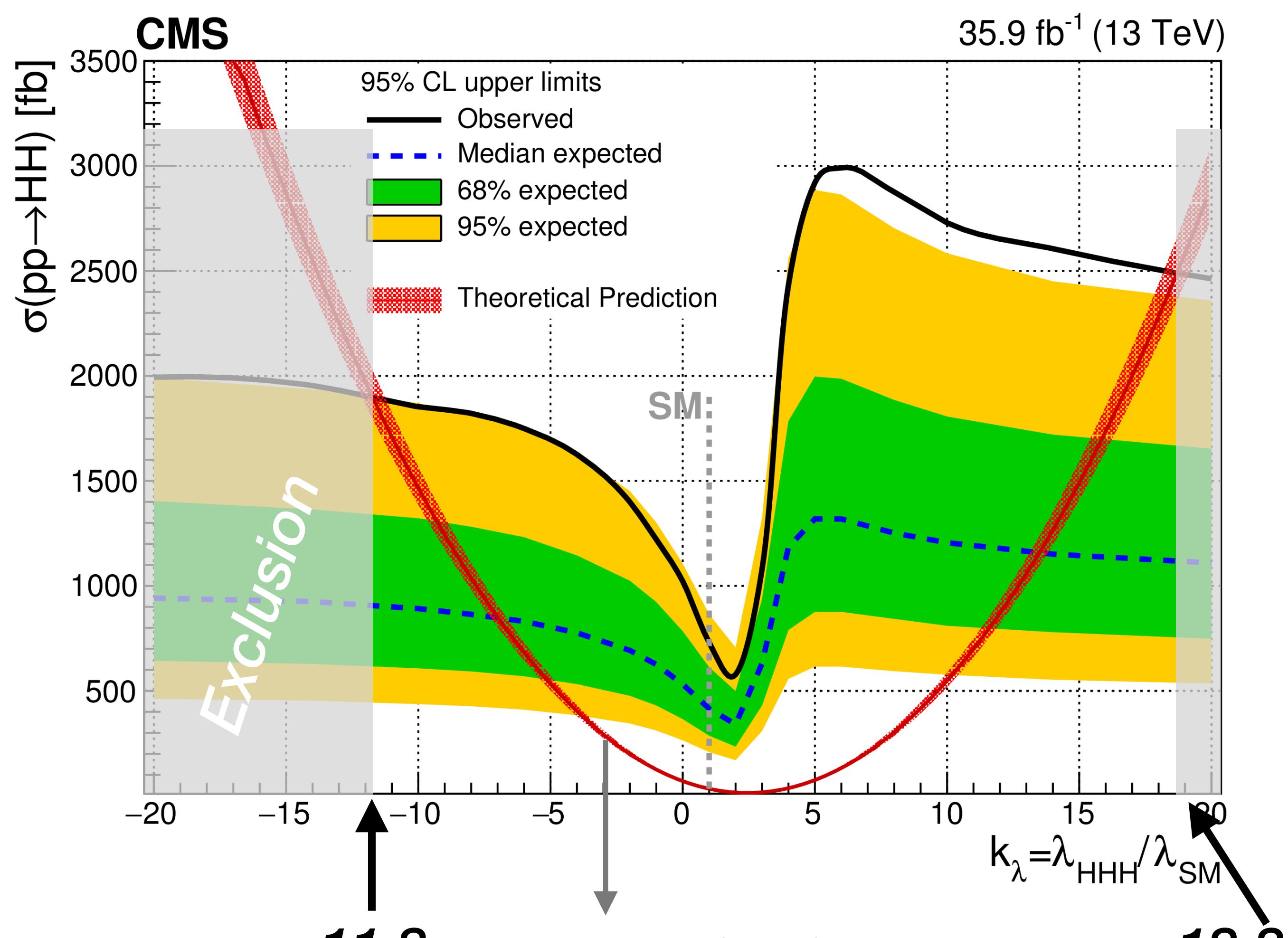
Search for Di-Higgs production channel

arXiv:1906.02025
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 !





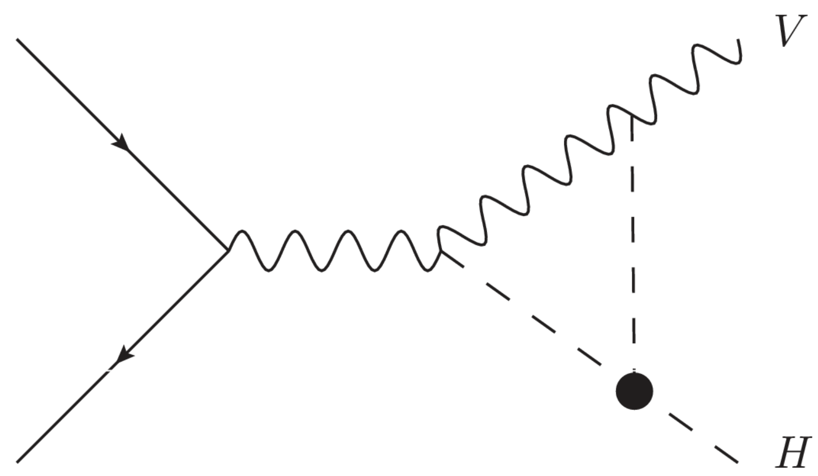


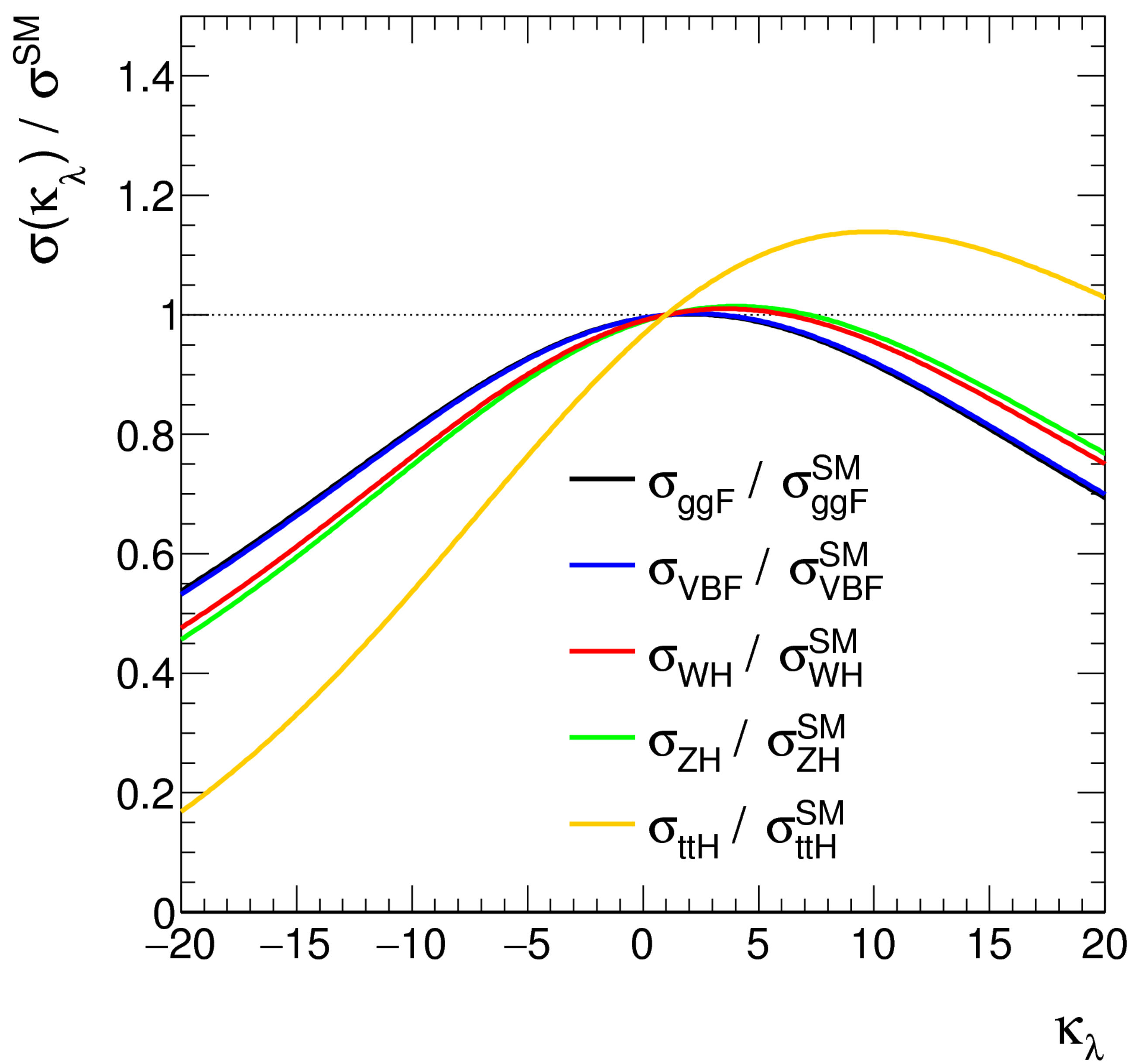
PLB 732 (2014) 142-149

Self-coupling constraints from single Higgs production

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

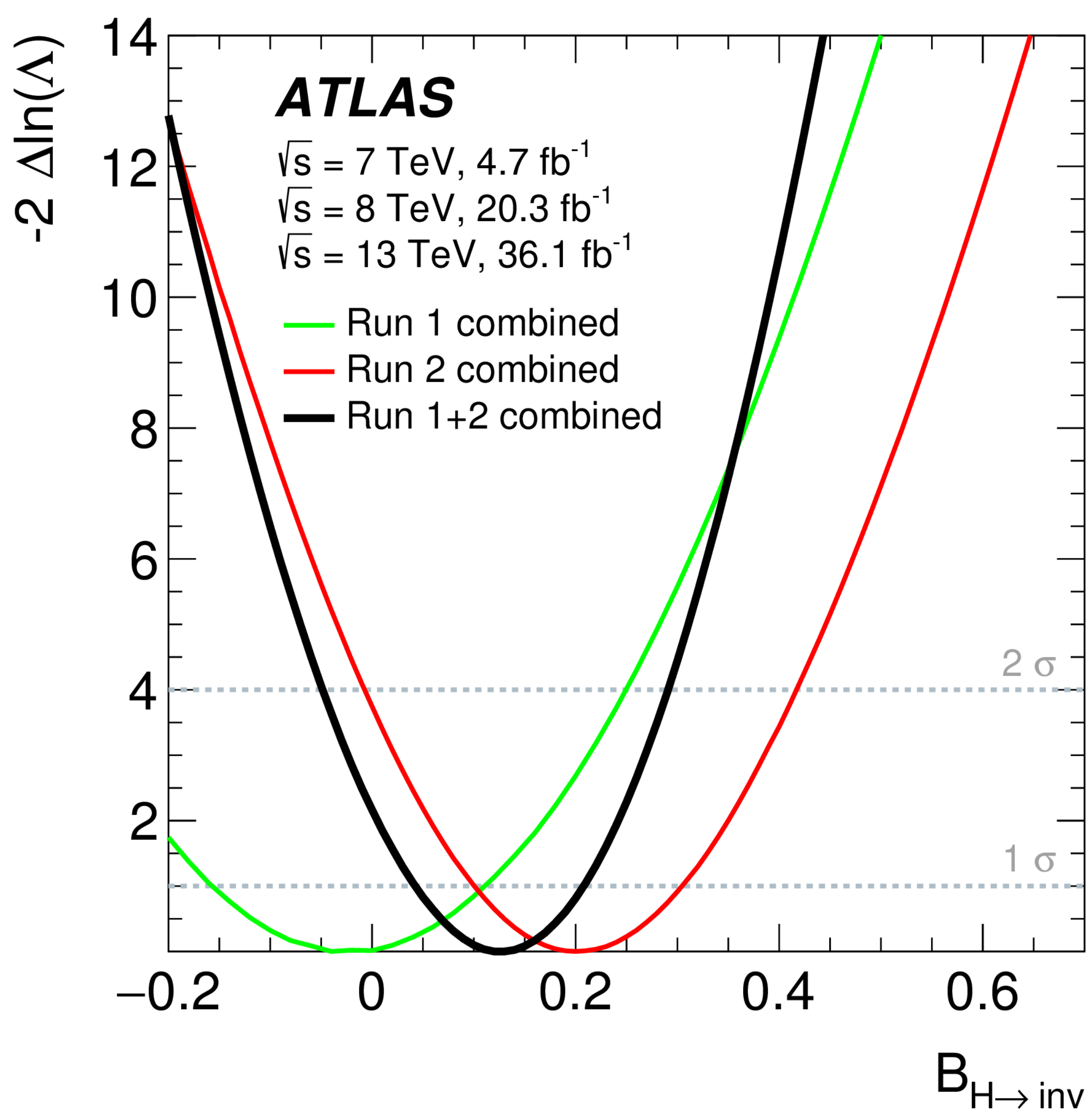
$$\kappa_\lambda \ (\lambda_3/\lambda_3^{SM}) \in [\text{-}3.2, 11.9] \ @ \ 95\% \ \text{C.L.}$$

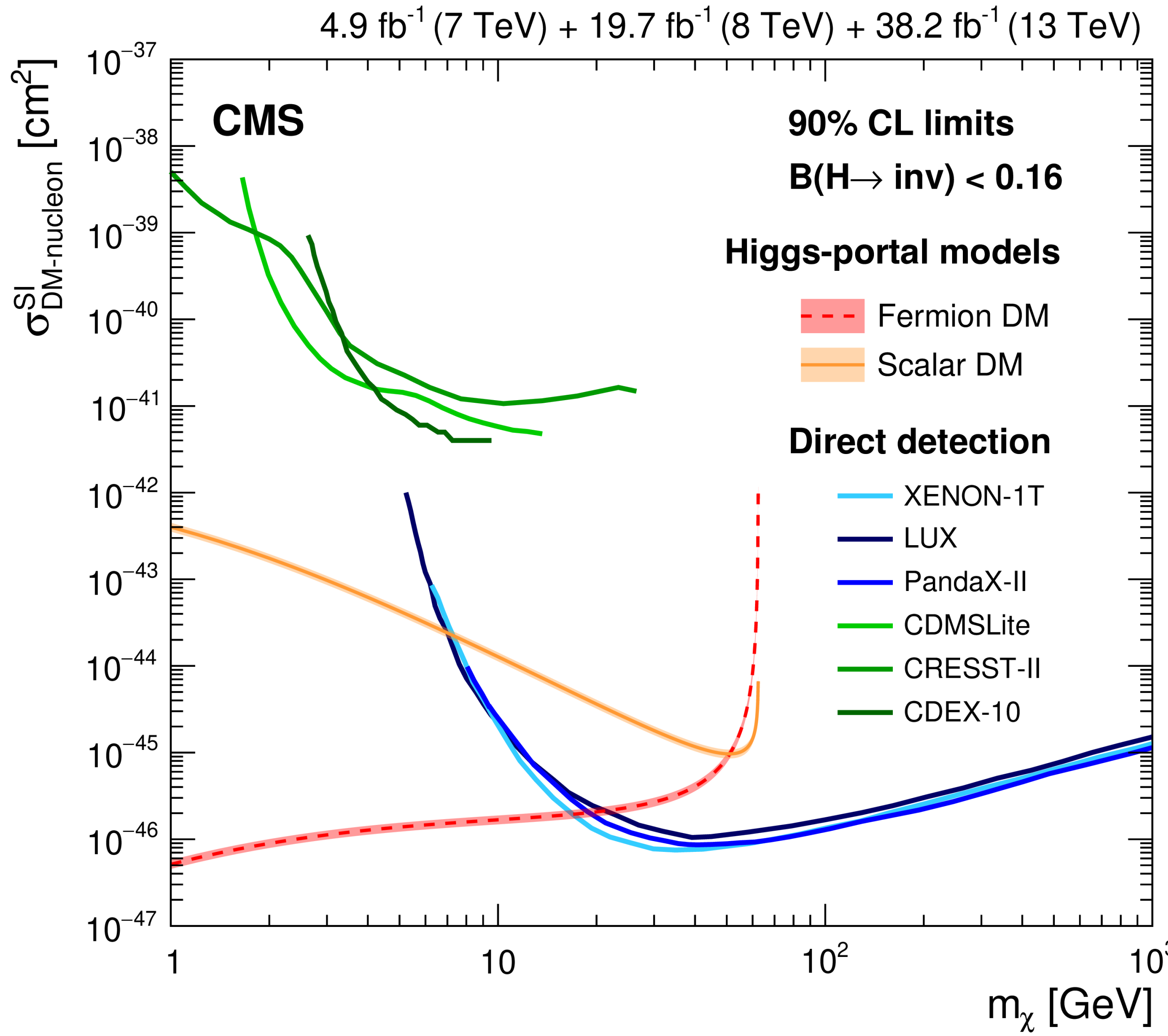
→ this result is comparable with direct measurement from Di-Higgs channel with 36 fb^{-1} luminosity.

Higgs to invisible searches

PRL 122 (2019) 231801
PLB 793 (2019) 520

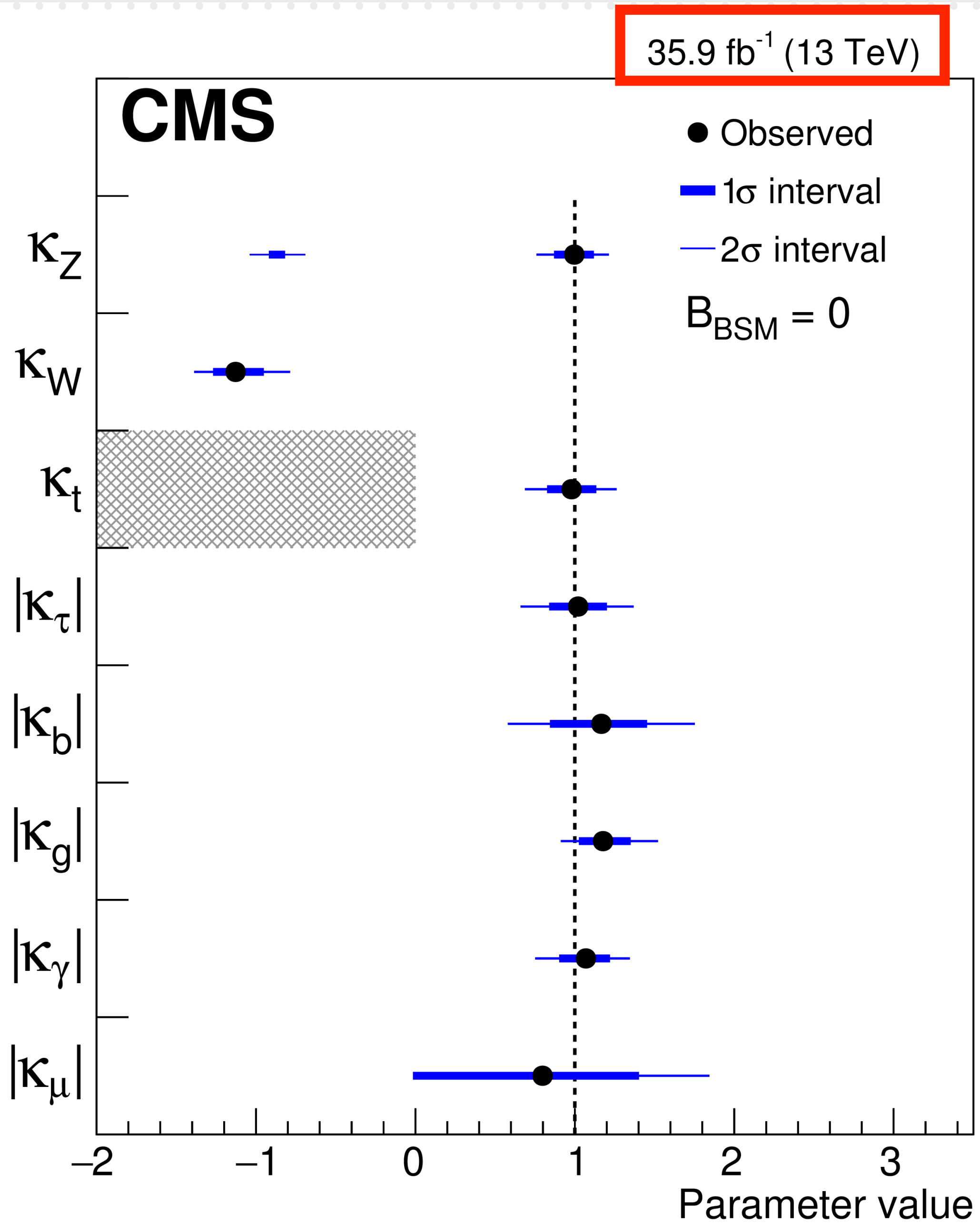
- Searches have been done in VH (and also VBF) channel by ATLAS (CMS).
- This channel is sensitive to BSM phenomena that can be recast in Dark Matter limits under certain assumptions (e.g H→DM in case $M_{DM} < M_H/2$).
- LHC has the best limit for low mass dark matter in model-specific scenarios.

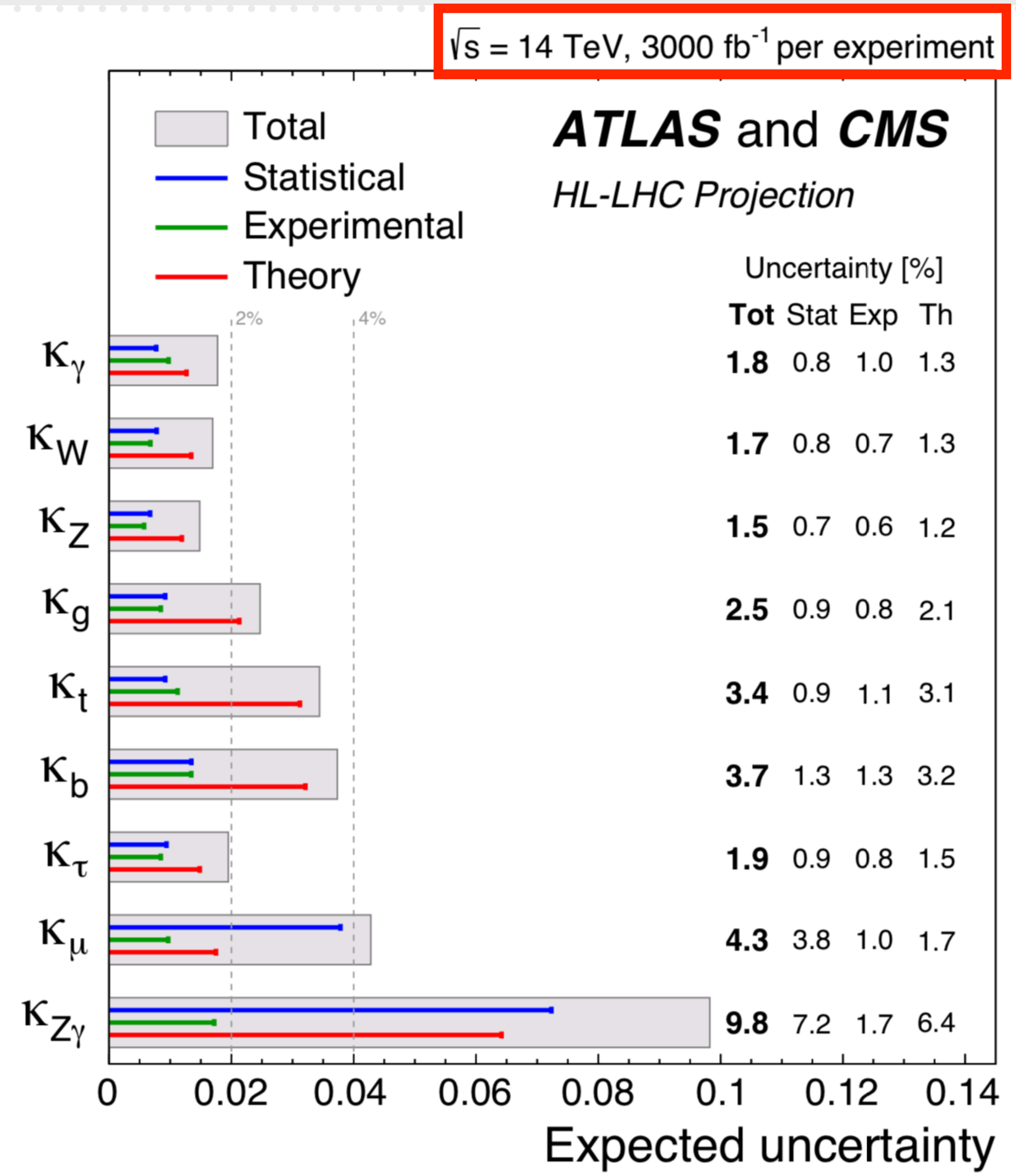




Towards to High Luminosity LHC (3000 fb^{-1})

arXiv:1902.00134
EPJC 79 (2019) 421

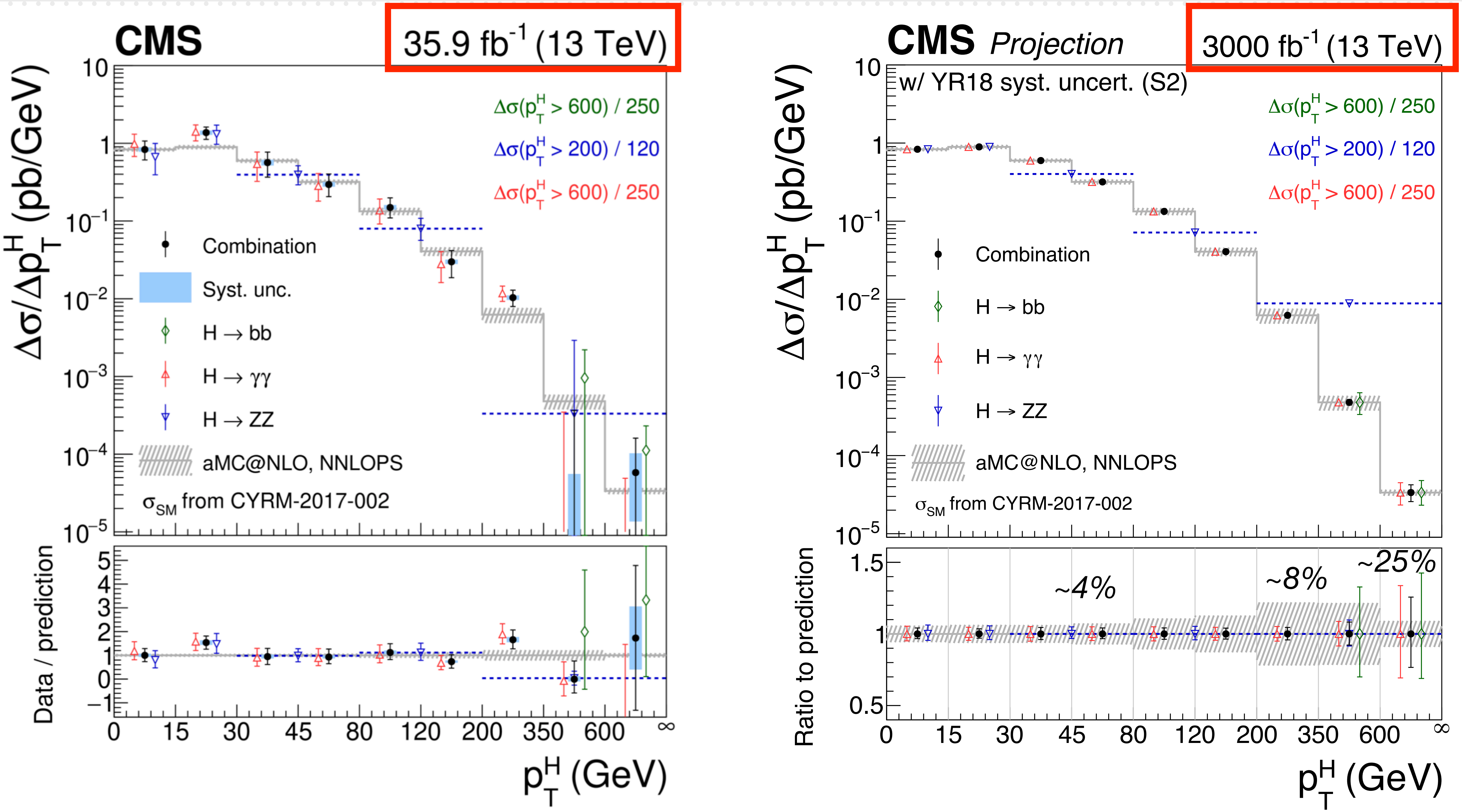




- 2-4 % precision of Higgs couplings to W/Z, 3rd gen. fermions, γ/g and muon.
- Discovery for H→μμ and H→Zγ decays.
- H→cc : $\sigma/\sigma_{SM} < 6.3$ from ATLAS Run 2 result extrapolation.

Towards to High Luminosity LHC (3000 fb^{-1})

CMS-PAS-FTR-18-011



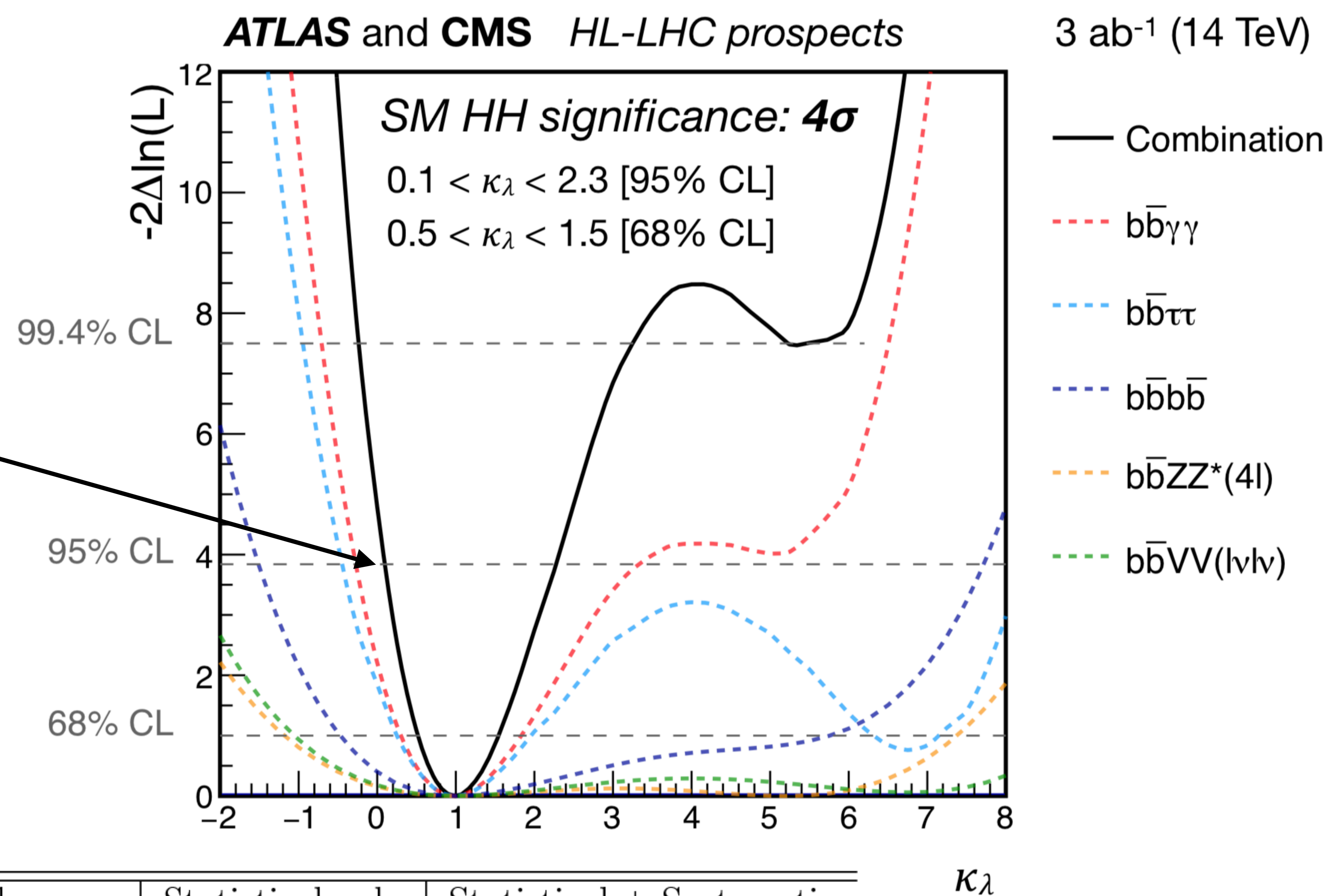
➡ Uncertainties in the high Higgs p_T region can be reduced by a factor of 10 (w.r.t 20-30% with full Run 2 dataset).

Towards to 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

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.
- LHC starts to have sensitivity to Higgs couplings to 2nd generation fermion.
- For Higgs physics, LHC has moved to precision measurement era.

- ~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)
  - sensitive to Di-Higgs production channel
  - set strong constraints on Higgs self-coupling parameter
  - ➡ Please stay tuned !

Backup

Constraints on Higgs coupling parameters

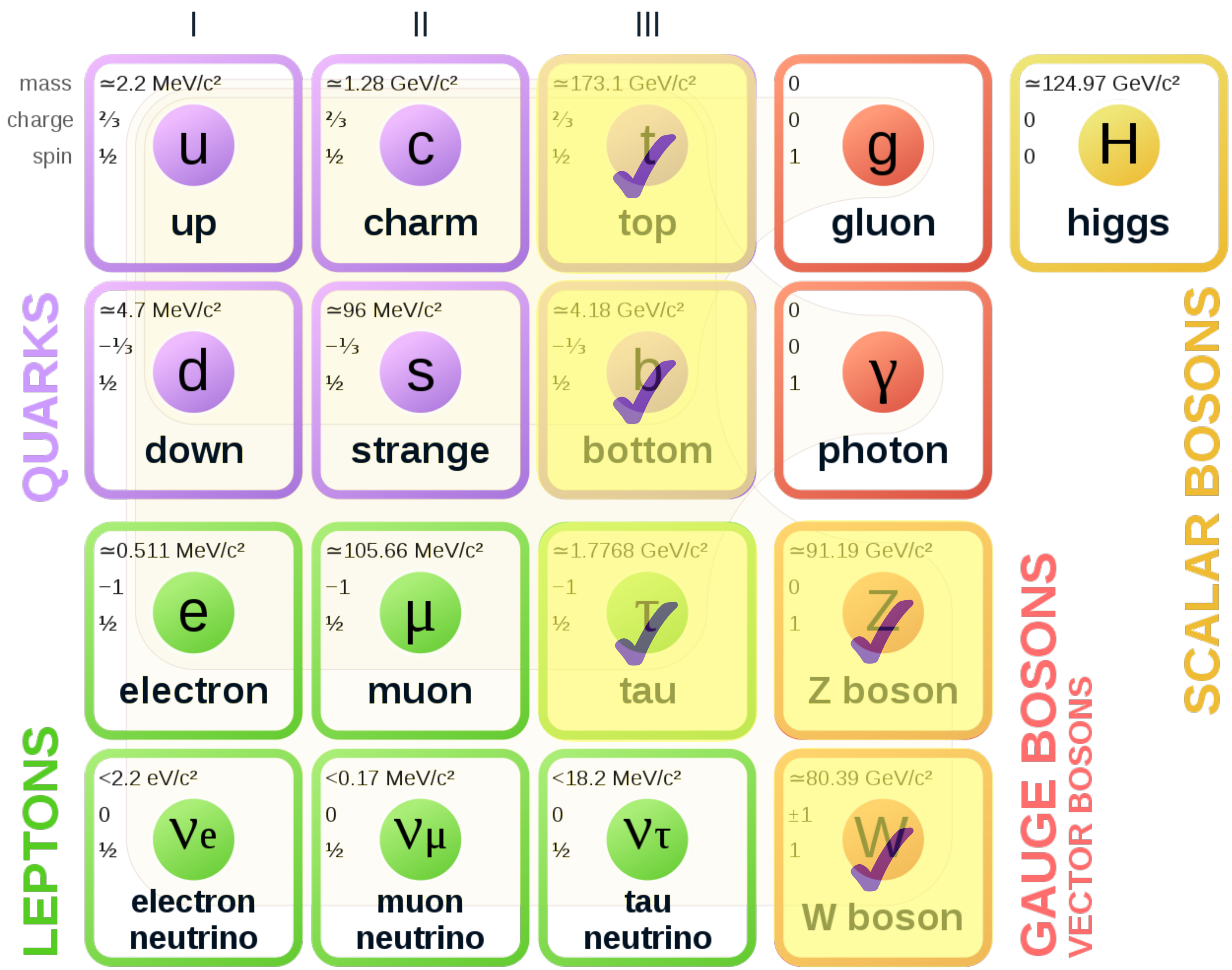
- Parameterisations of Higgs boson production X-section and decay width as functions of the coupling strength modifiers using kappa-framework

$$\kappa_j^2 = \frac{\sigma_j}{\sigma_j^{SM}} \quad \text{or} \quad \kappa_j^2 = \frac{\Gamma_j}{\Gamma_j^{SM}}$$

- Considering leading order contribution only.

Production	Loops	Interference	Effective modifier	Resolved modifier
$\sigma(\text{ggF})$	✓	$t-b$	κ_g^2	$1.04\,\kappa_t^2 + 0.002\,\kappa_b^2 - 0.04\,\kappa_t\kappa_b$
$\sigma(\text{VBF})$	-	-	-	$0.73\,\kappa_W^2 + 0.27\,\kappa_Z^2$
$\sigma(qq/qg \to ZH)$	-	-	-	κ_Z^2
$\sigma(gg \to ZH)$	✓	$t-Z$	$\kappa_{(ggZH)}$	$2.46\,\kappa_Z^2 + 0.46\,\kappa_t^2 - 1.90\,\kappa_Z\kappa_t$
$\sigma(WH)$	-	-	-	κ_W^2
$\sigma(t\bar{t}H)$	-	-	-	κ_t^2
$\sigma(tHW)$	-	$t-W$	-	$2.91\,\kappa_t^2 + 2.31\,\kappa_W^2 - 4.22\,\kappa_t\kappa_W$
$\sigma(tHq)$	-	$t-W$	-	$2.63\,\kappa_t^2 + 3.58\,\kappa_W^2 - 5.21\,\kappa_t\kappa_W$
$\sigma(b\bar{b}H)$	-	-	-	κ_b^2
Partial decay width				
Γ^{bb}	-	-	-	κ_b^2
Γ^{WW}	-	-	-	κ_W^2
Γ^{gg}	✓	$t-b$	κ_g^2	$1.11\,\kappa_t^2 + 0.01\,\kappa_b^2 - 0.12\,\kappa_t\kappa_b$
$\Gamma^{\tau\tau}$	-	-	-	κ_τ^2
Γ^{ZZ}	-	-	-	κ_Z^2
Γ^{cc}	-	-	-	$\kappa_c^2\ (=\kappa_t^2)$
$\Gamma^{\gamma\gamma}$	✓	$t-W$	κ_γ^2	$1.59\,\kappa_W^2 + 0.07\,\kappa_t^2 - 0.67\,\kappa_W\kappa_t$
$\Gamma^{Z\gamma}$	✓	$t-W$	$\kappa_{(Z\gamma)}^2$	$1.12\,\kappa_W^2 - 0.12\,\kappa_W\kappa_t$
Γ^{ss}	-	-	-	$\kappa_s^2\ (=\kappa_b^2)$
$\Gamma^{\mu\mu}$	-	-	-	κ_μ^2
Total width ($B_{inv} = B_{undet} = 0$)				
Γ_H	✓	-	κ_H^2	$0.58\,\kappa_b^2 + 0.22\,\kappa_W^2$ $+0.08\,\kappa_g^2 + 0.06\,\kappa_\tau^2$ $+0.03\,\kappa_Z^2 + 0.03\,\kappa_c^2$ $+0.0023\,\kappa_\gamma^2 + 0.0015\,\kappa_{(Z\gamma)}^2$ $+0.0004\,\kappa_s^2 + 0.00022\,\kappa_\mu^2$

Higgs boson is a real particle !

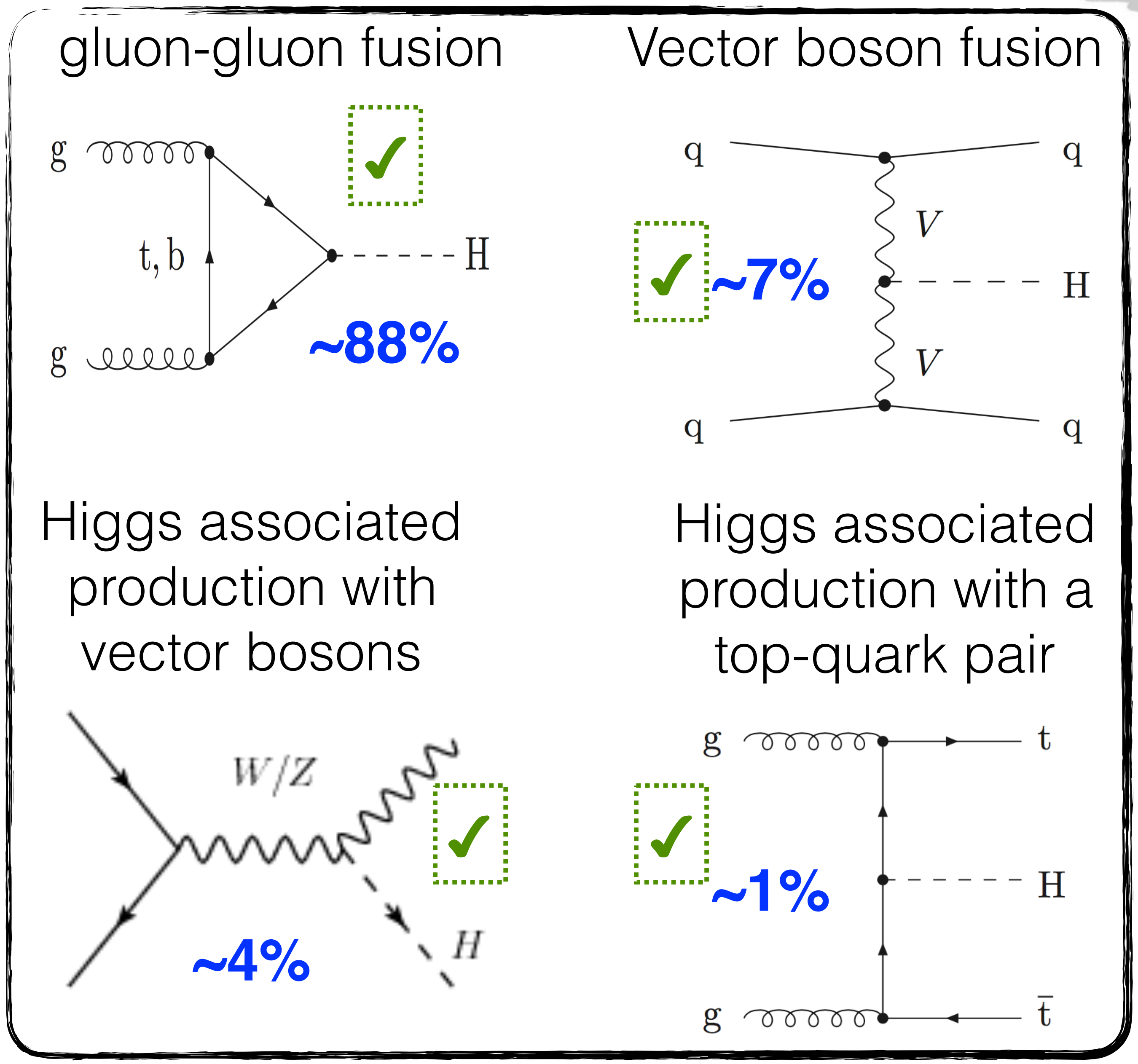


Higgs couplings with W/Z bosons and with the third generation fermions have been experimentally confirmed → in good agreement with the SM prediction.

Higgs boson is a real particle !

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

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



Higgs boson decay modes