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TSUNG-DAO LEE INSTITUTE

# Higgs cross-sections and properties (mass & width)

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on behalf of the ATLAS and CMS Collaborations

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30<sup>th</sup> Anniversary of the  
Recontres du Vietnam, 2023.8.7

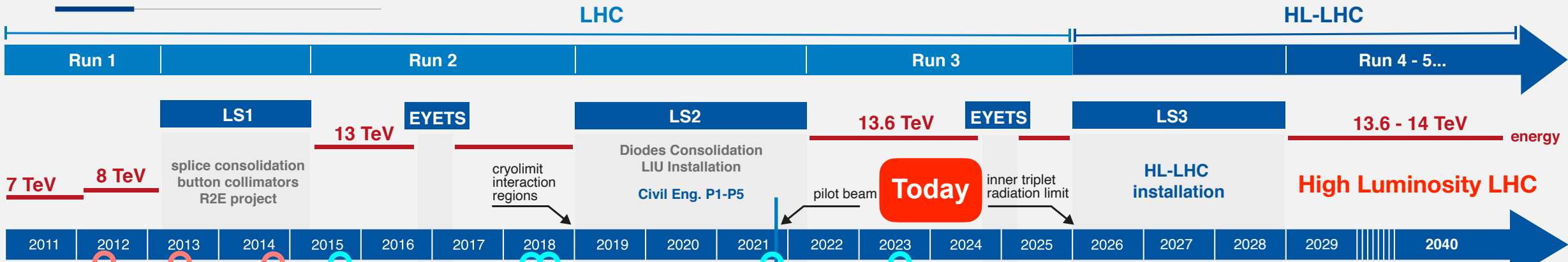


- **Brief overview of the Higgs boson discoveries at the LHC**
- **The Higgs boson mass and width measurements**
- **Higgs inclusive cross-section measurement**
- **Higgs Simplified Template Cross Section measurement**
- **Higgs differential cross sections measurement**
- **Searching for Higgs rare decay channels**

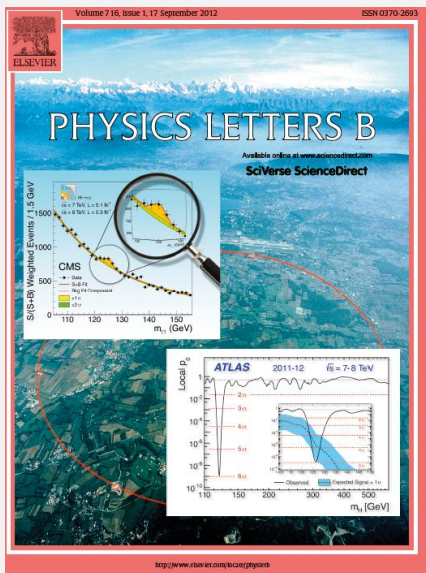
*— including updates in the last one year —*



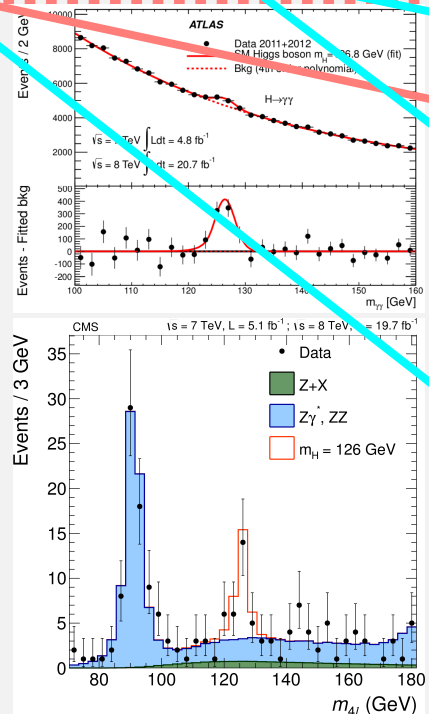
# The Higgs boson discoveries at the LHC (2012-2023)



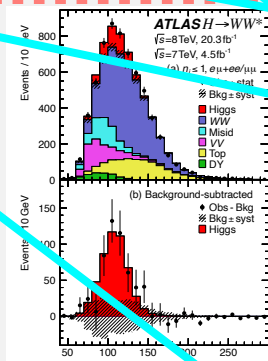
**SM-like Higgs discovery**  
( $ggF H \rightarrow \gamma\gamma + ZZ + WW$ )



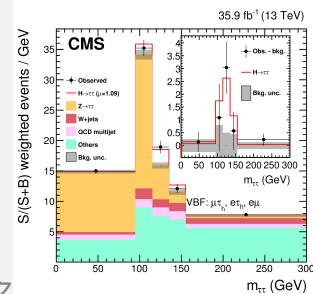
$H \rightarrow \gamma\gamma, ZZ \rightarrow 4l$  observation ( $0^+$ )



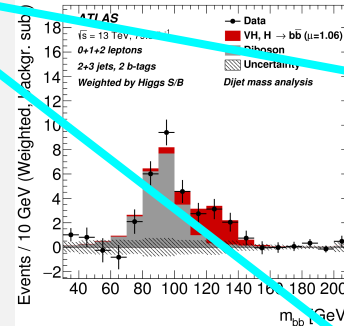
$H \rightarrow WW$  observation



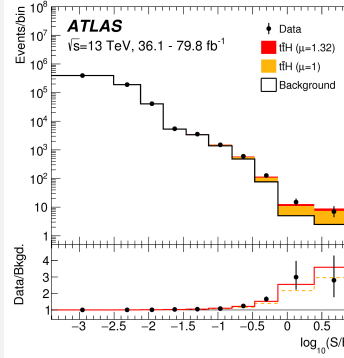
VBF H obs.,  $H \rightarrow \tau\tau$  obs.



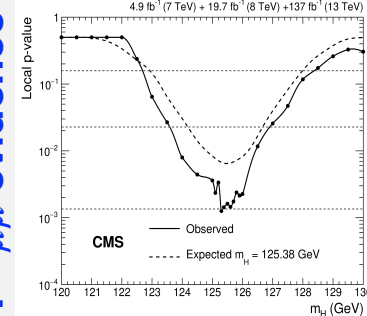
$VH, H \rightarrow bb$  obs.



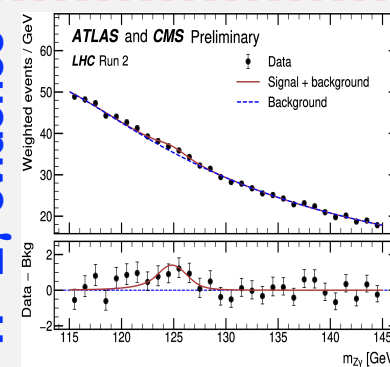
$t\bar{t}H$  observation



$H \rightarrow \mu\mu$  evidence



$H \rightarrow Z\gamma$  evidence



# The Higgs boson discoveries at the LHC (2012-2023)

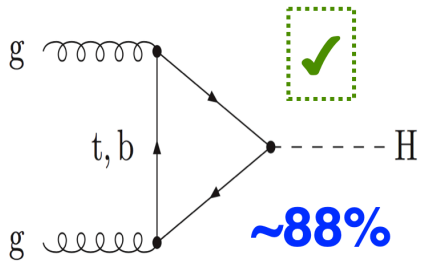
Higgs boson production at LHC at 13 TeV centre-of-mass energy



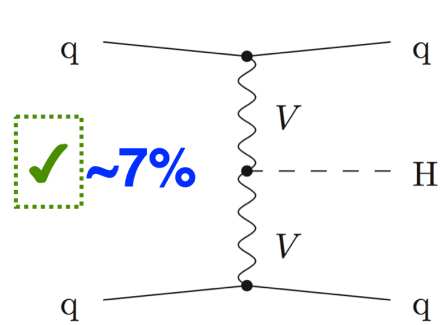
Higgs boson decay channels

✓ marks for 5 sigma discovery

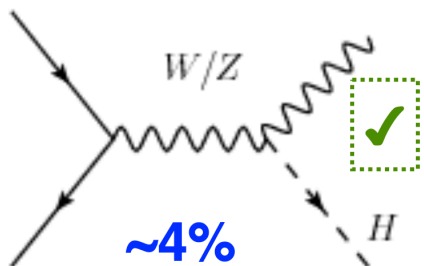
gluon-gluon fusion



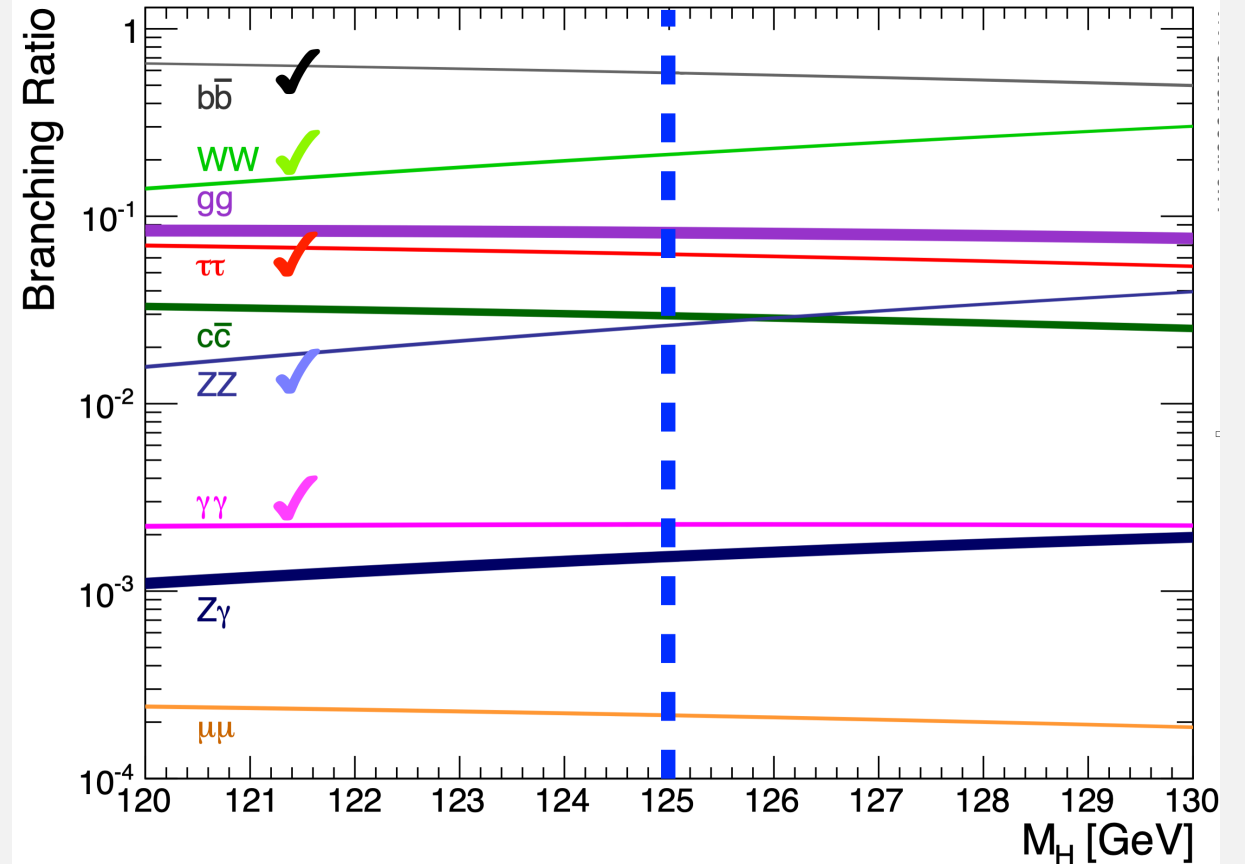
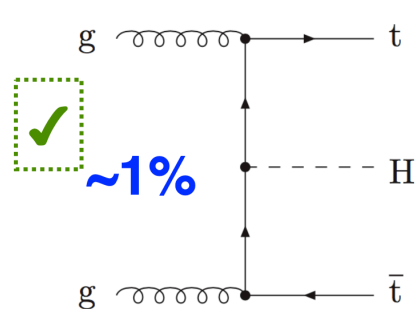
Vector boson fusion



Higgs associated production with vector bosons

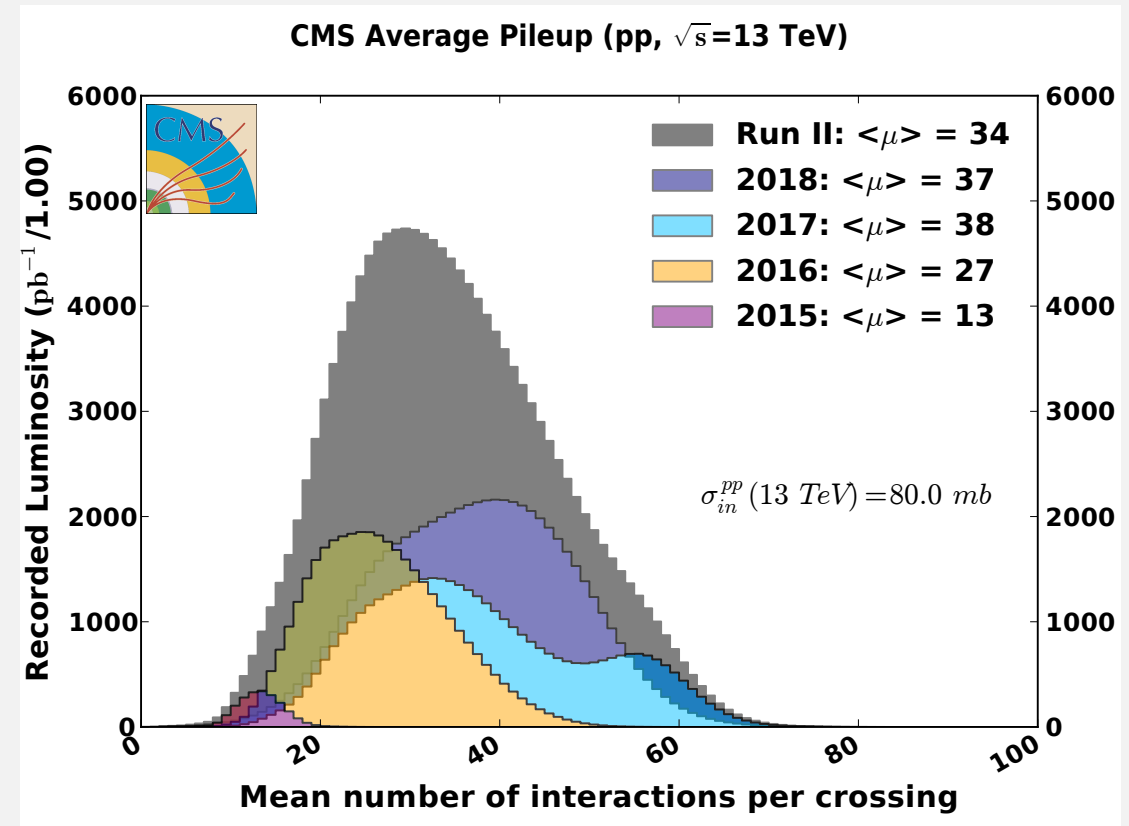
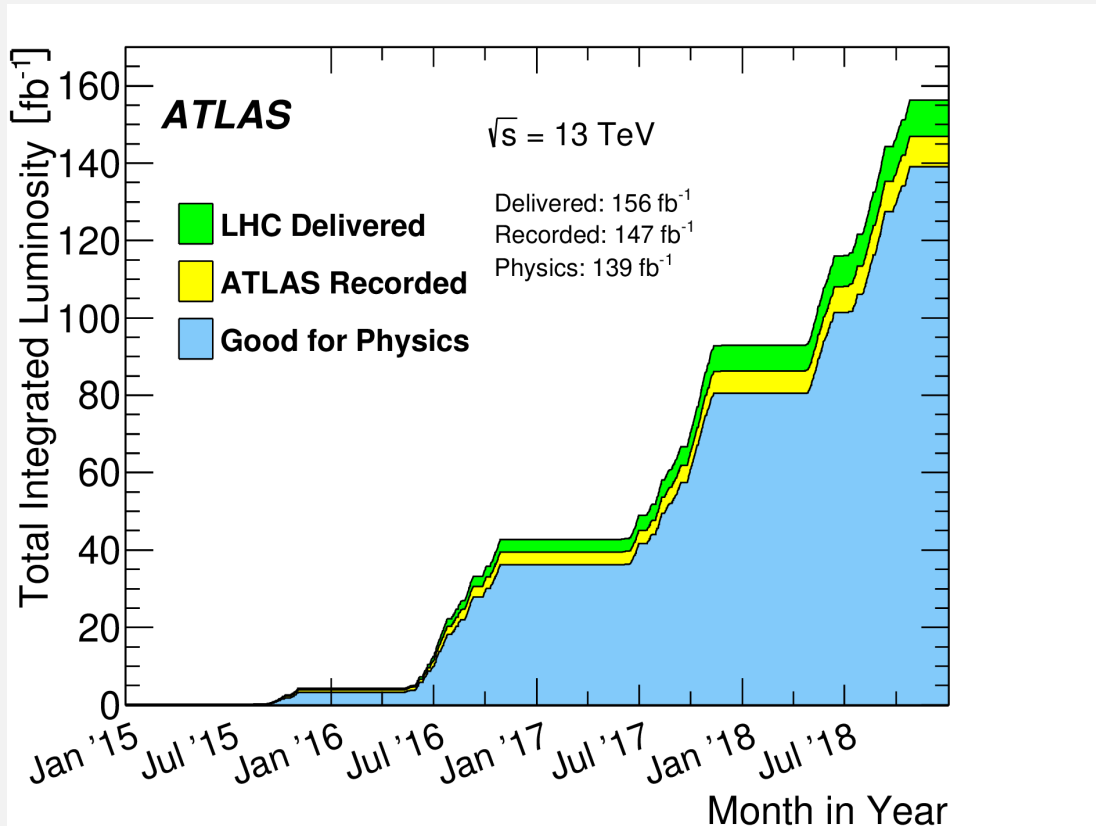


Higgs associated production with a top-quark pair





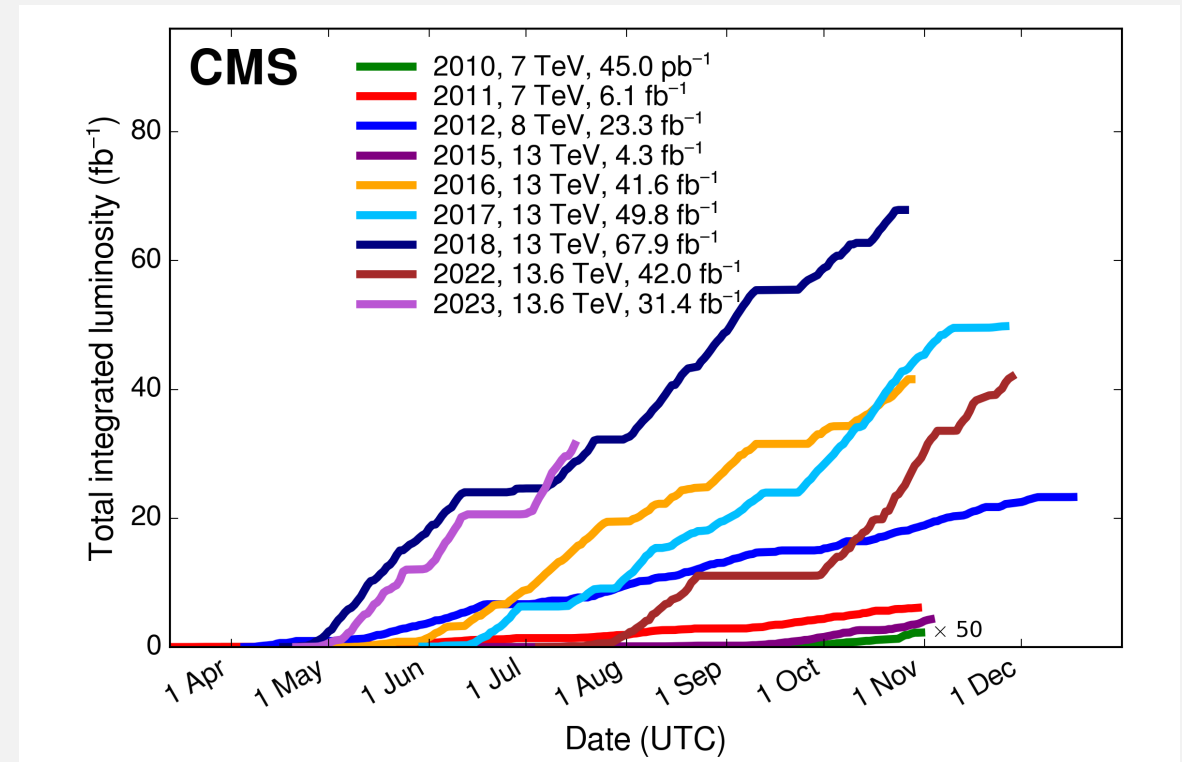
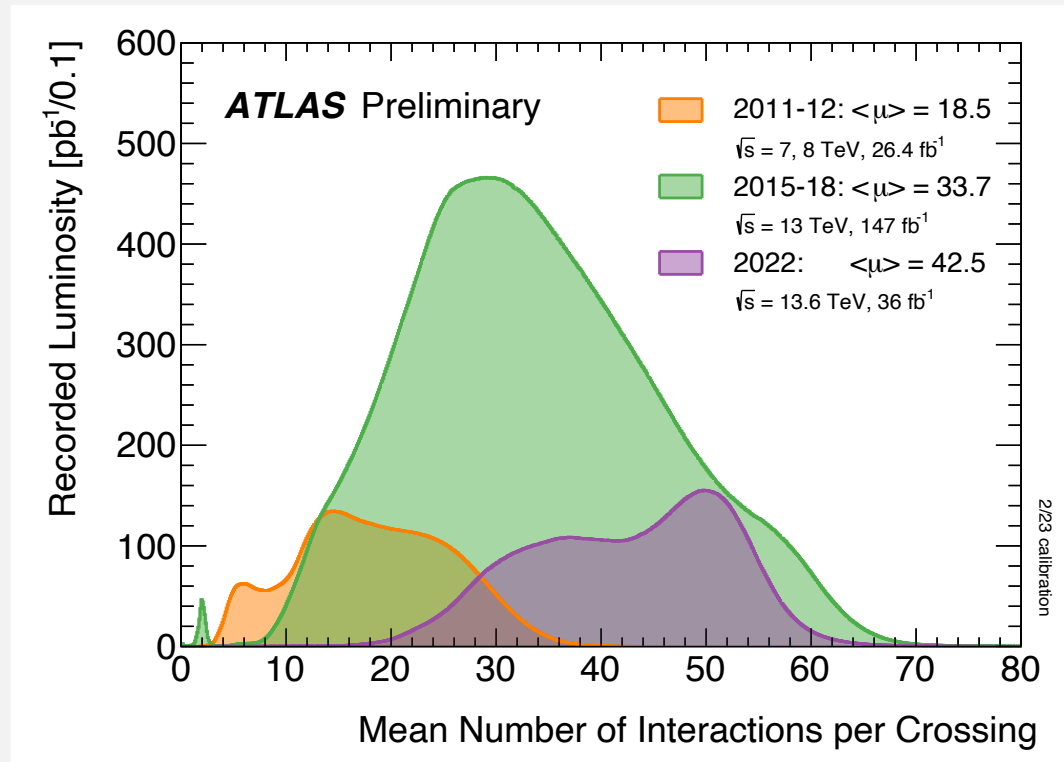
# ● ATLAS and CMS Run 2 datasets (2015 - 2018)



- **~140 fb<sup>-1</sup> datasets have been collected at  $\sqrt{s} = 13$  TeV in full Run 2 period**
- **Thanks to the CERN accelerator and technical teams for excellent LHC performance!**

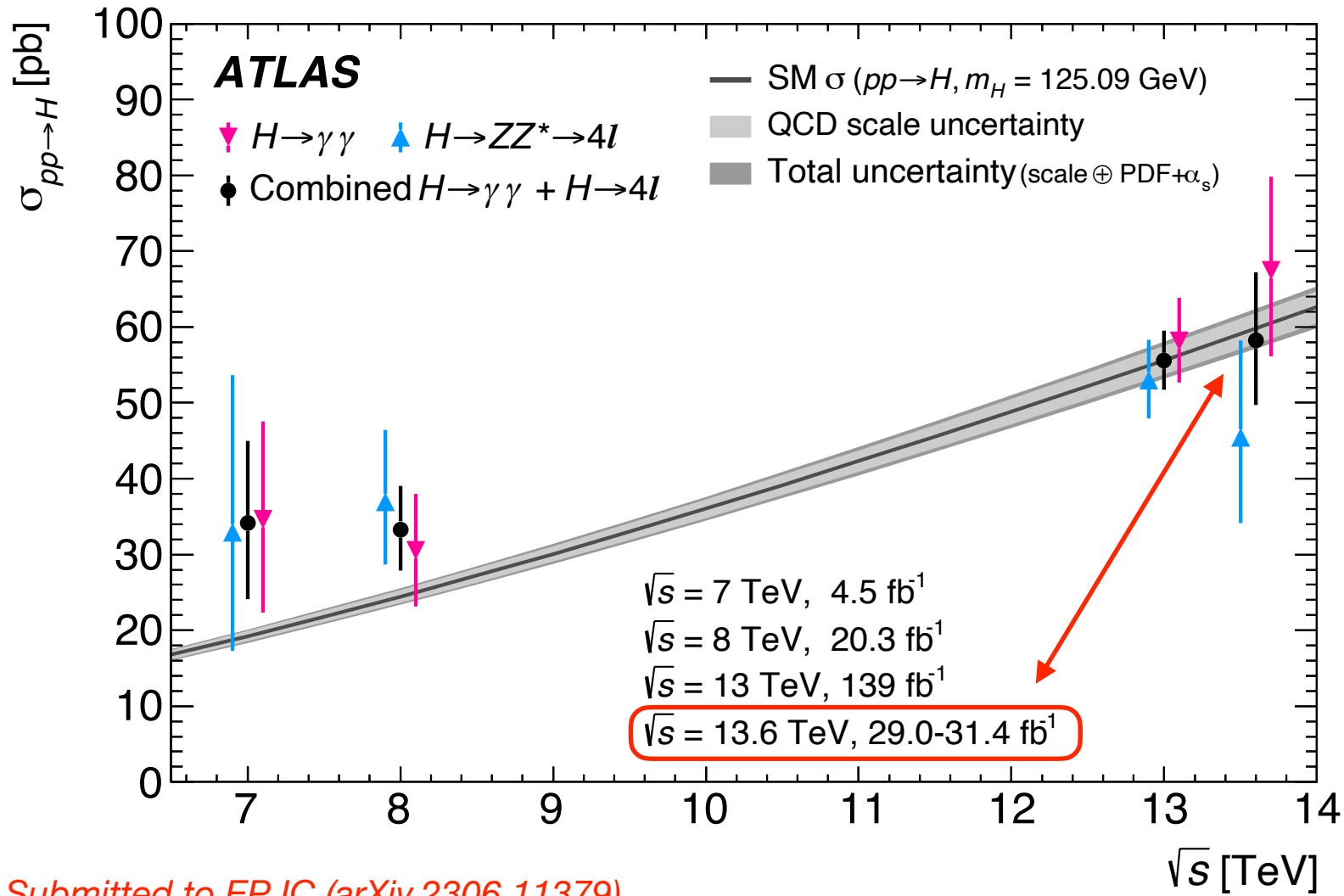
# ● ATLAS and CMS Run 3 datasets (2022 - now)

- The Large Hadron Collider machine is running at record energy 13.6 TeV!

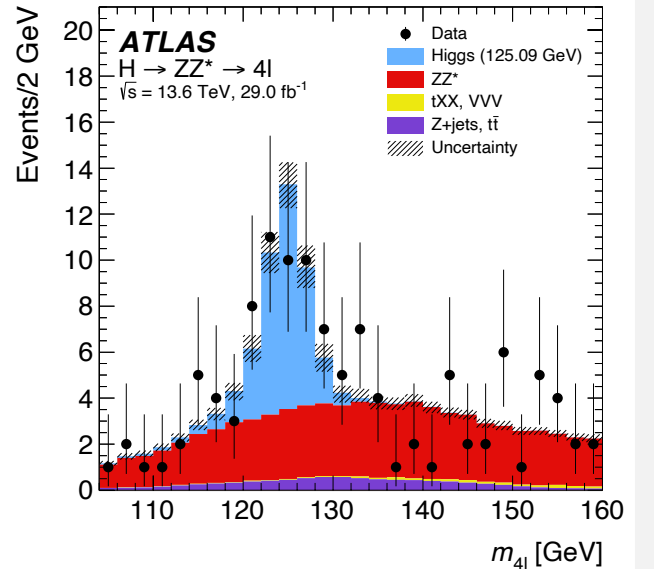
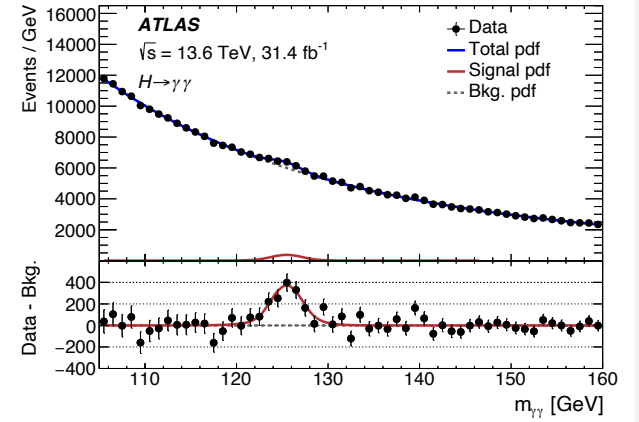


- 42 fb<sup>-1</sup> and 31.4 fb<sup>-1</sup> datasets have been collected in 2022 and 2023 (til July 21) with average mean number of interactions per crossing being 46 and 52.

# Higgs cross section measurement vs pp collision energy



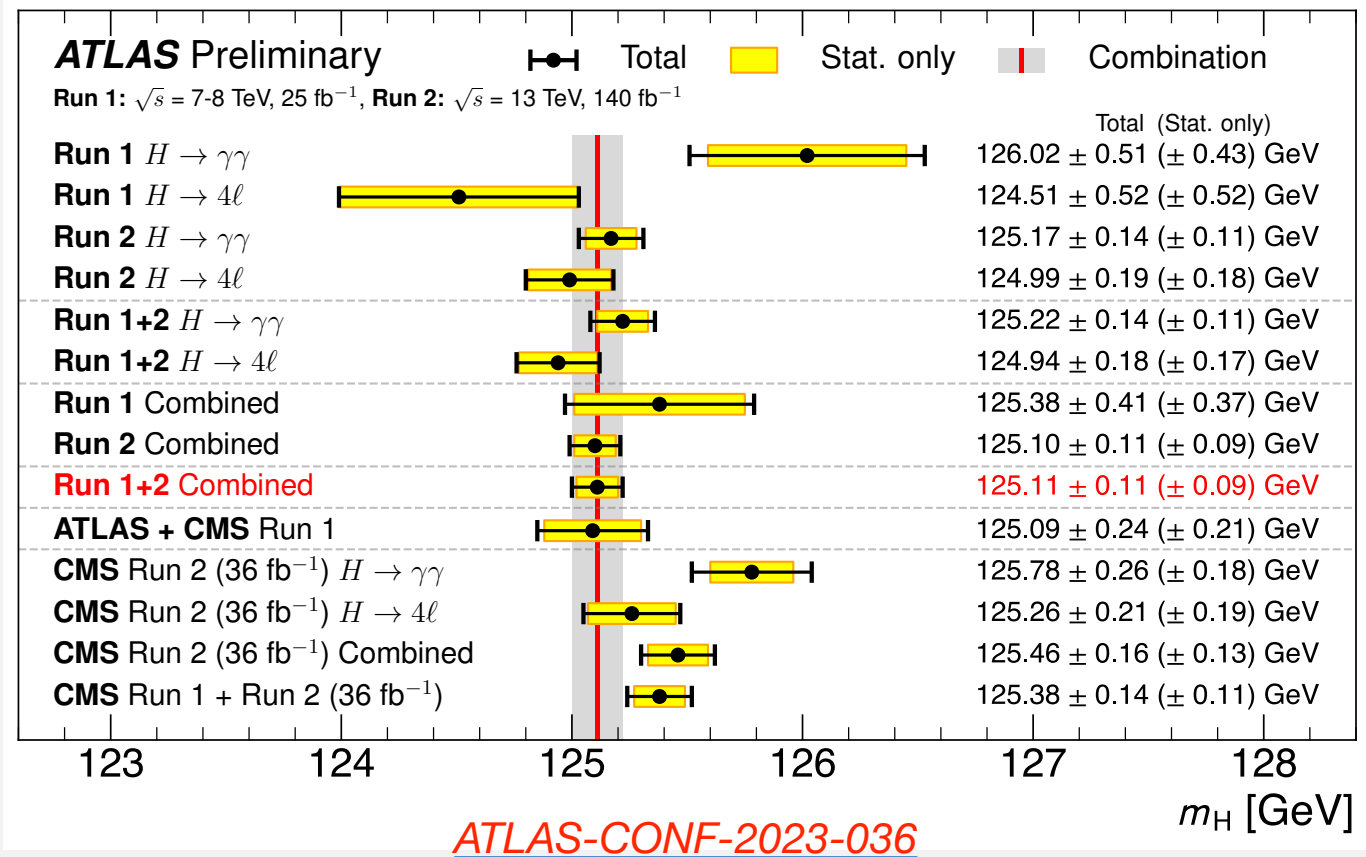
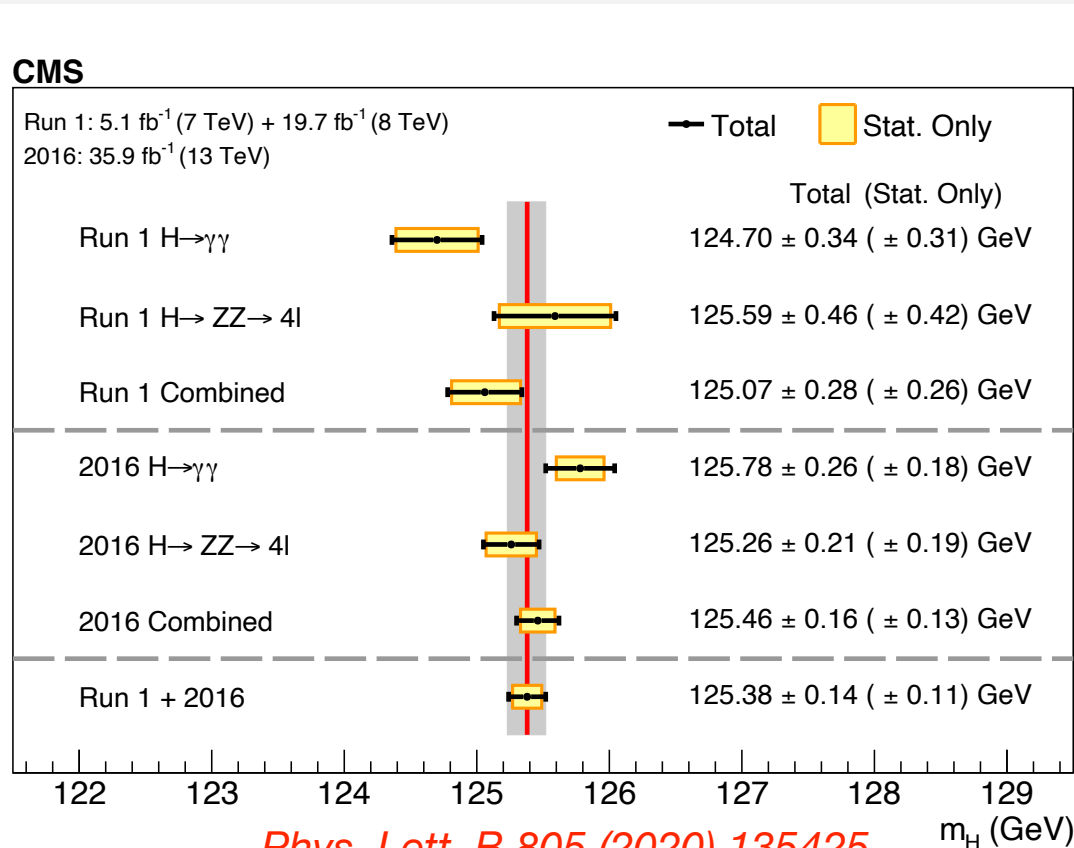
Submitted to EPJC (arXiv.2306.11379)



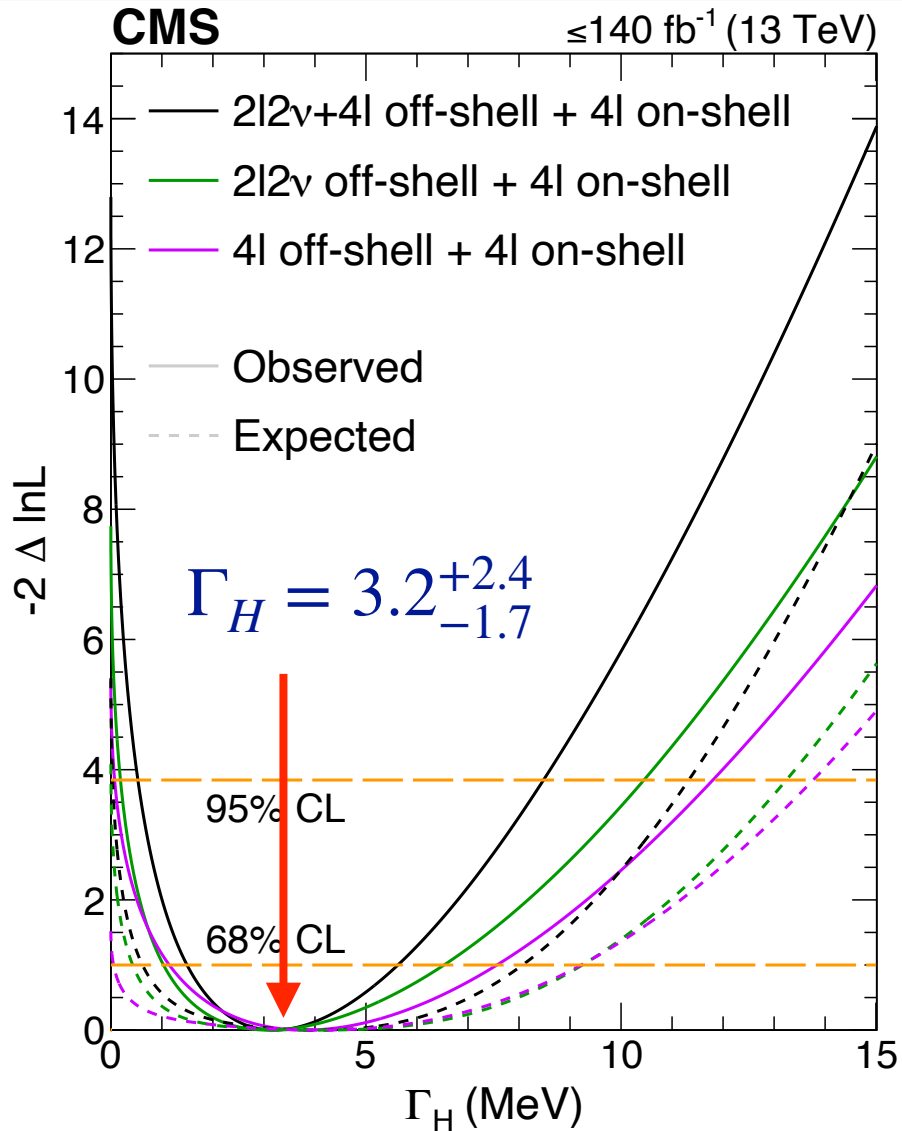


# • The Higgs boson mass measurement at 0.09% precision

- **CMS combination of  $H \rightarrow \gamma\gamma$  and  $H \rightarrow ZZ^* \rightarrow 4\ell$  channels using 35.9 fb<sup>-1</sup> Run 2 + Run 1 dataset:**  $125.38 \pm 0.11$  (stat.)  $\pm 0.08$ (syst.) GeV
- **ATLAS  $H \rightarrow \gamma\gamma$  139 fb<sup>-1</sup> Run 2+Run 1 dataset:**  $125.11 \pm 0.09$  (stat.)  $\pm 0.06$ (syst.) GeV

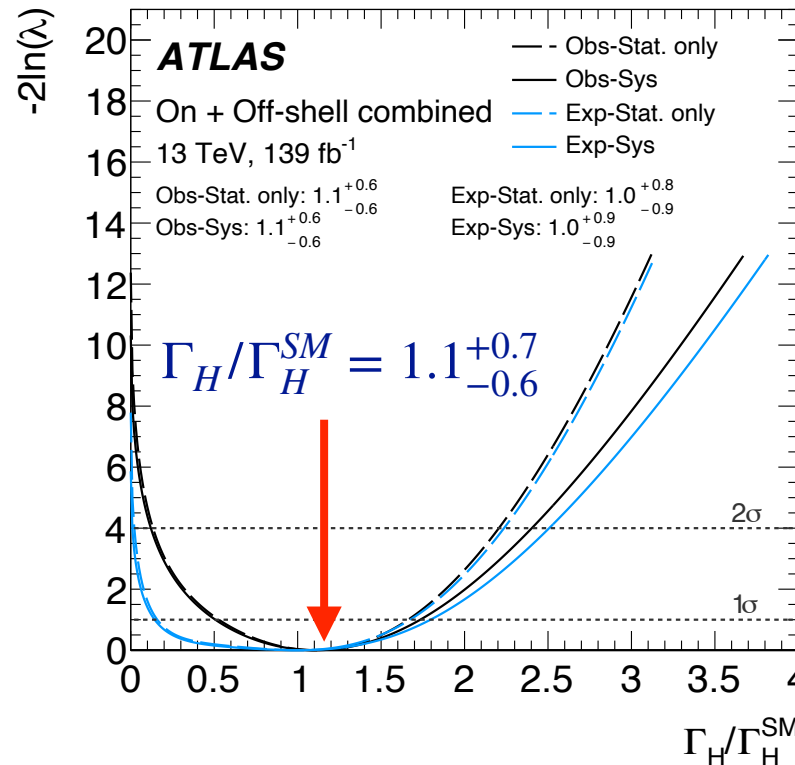


# The Higgs boson width measurement



- Indirect measurement from off-shell production in the  $H \rightarrow ZZ \rightarrow 4\ell / 2\ell 2\nu$  channels

- CMS, ATLAS observed  $\Gamma_H = 3.2^{+2.4}_{-1.7}, 4.5^{+3.3}_{-2.5}$  MeV



- No off-shell scenario is excluded at 3.6 standard deviations.
- Observed (expected) upper limit on  $\Gamma_H$  at 95% C.L. is 10.5 (10.9).

$$\sigma_{gg \rightarrow H \rightarrow ZZ^*}^{on-shell} \sim \frac{g_{ggH}^2 g_{HZZ}^2}{m_H \Gamma_H}$$

$$\sigma_{gg \rightarrow H^* \rightarrow ZZ}^{off-shell} \sim \frac{g_{ggH}^2 g_{HZZ}^2}{(2m_Z)^2}$$

# The Higgs boson production cross section measurement

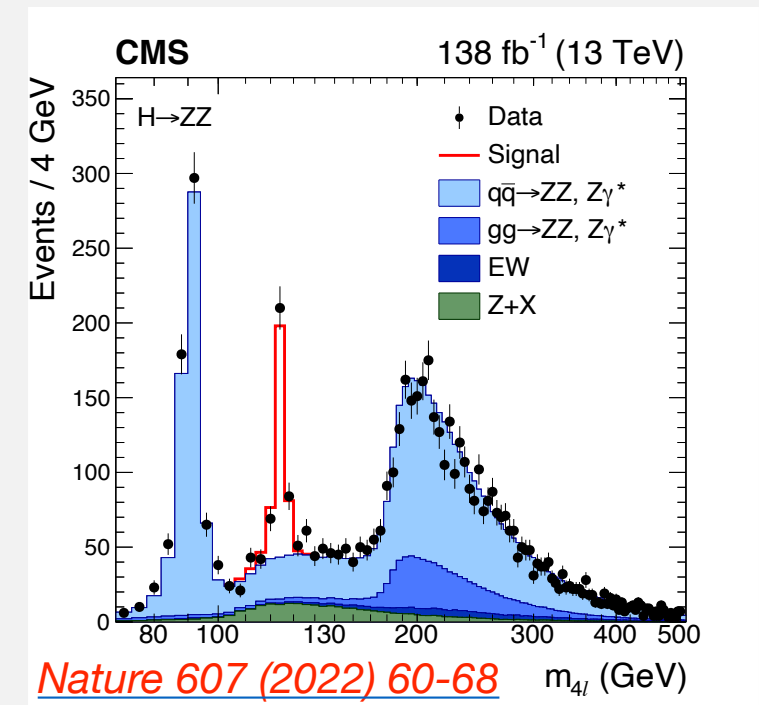
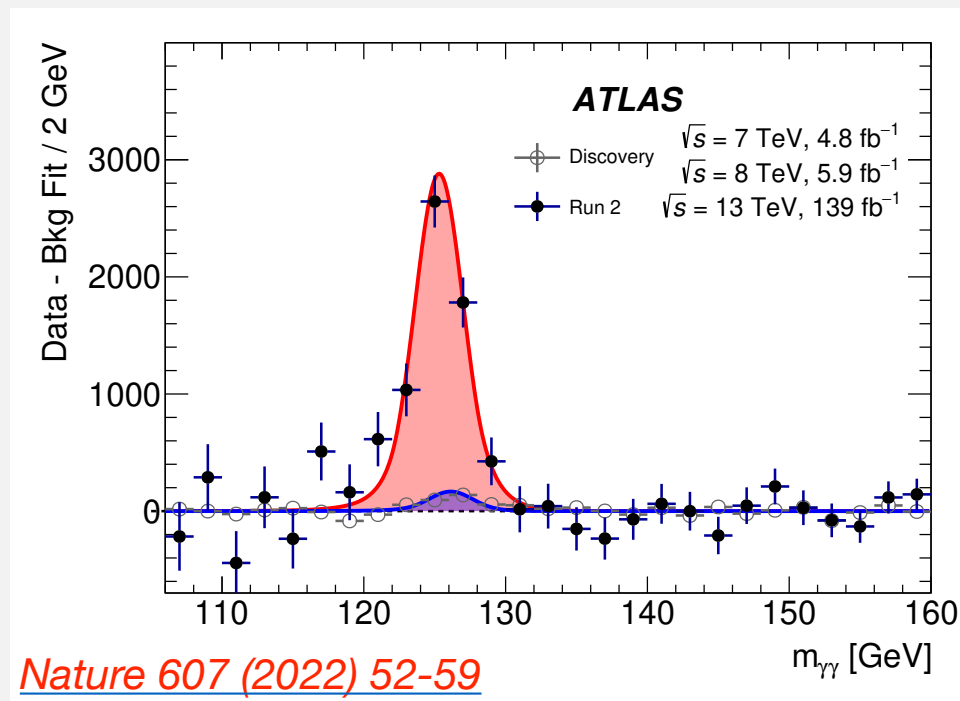
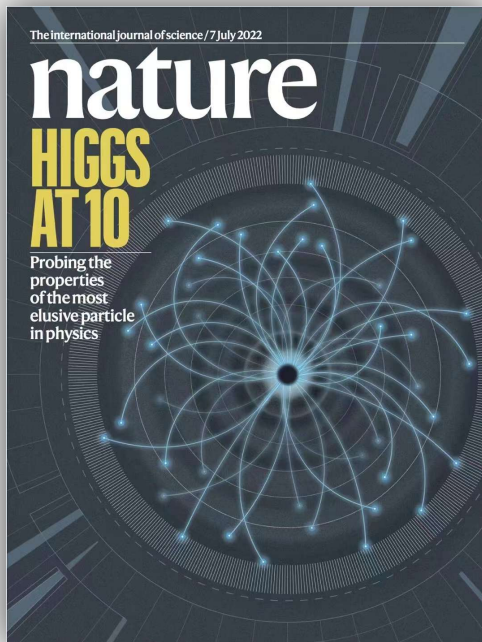
## Inclusive Higgs production cross section (signal strength $\mu$ ) at 13 TeV in Run 2:

### ATLAS result with 139 fb<sup>-1</sup>

$$\mu = 1.05 \pm 0.06 = 1.05 \pm 0.03(\text{stat.}) \pm 0.03(\text{exp.}) \pm 0.04(\text{sig. th.}) \pm 0.02(\text{bkg. th.})$$

### CMS result with 138 fb<sup>-1</sup>

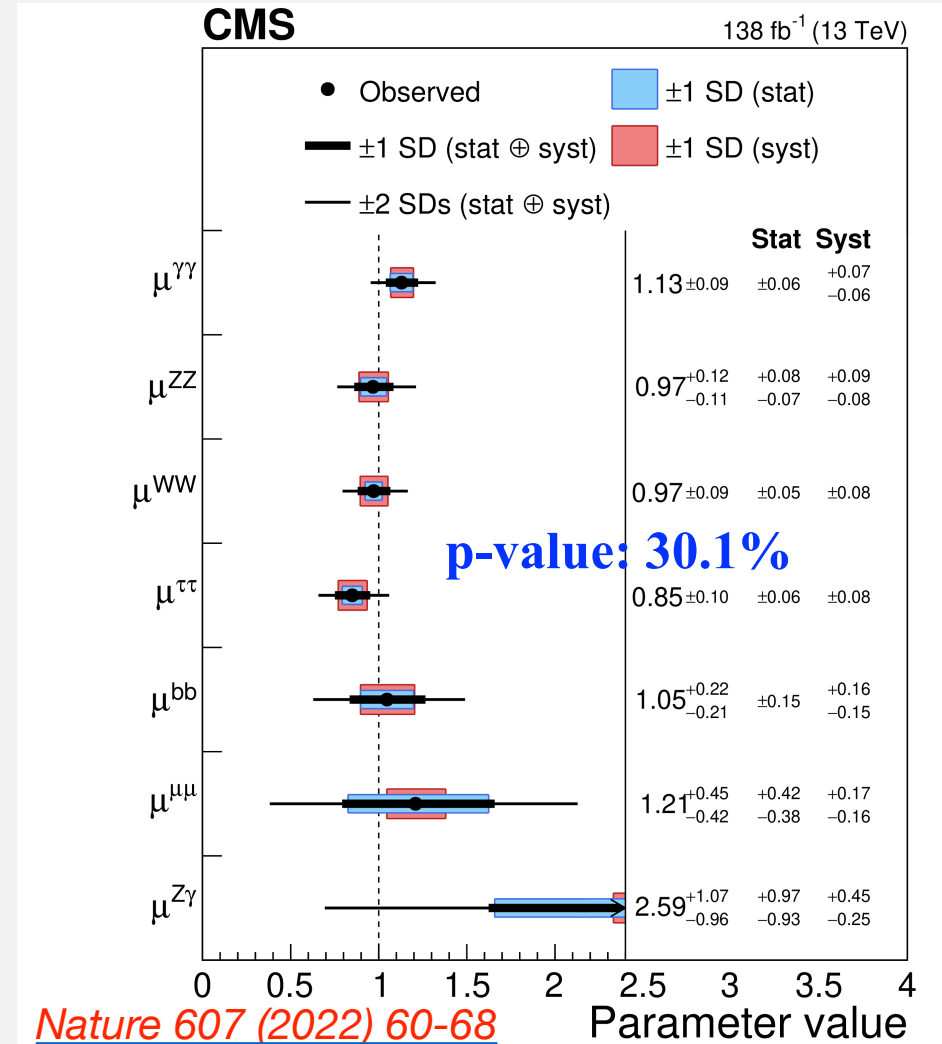
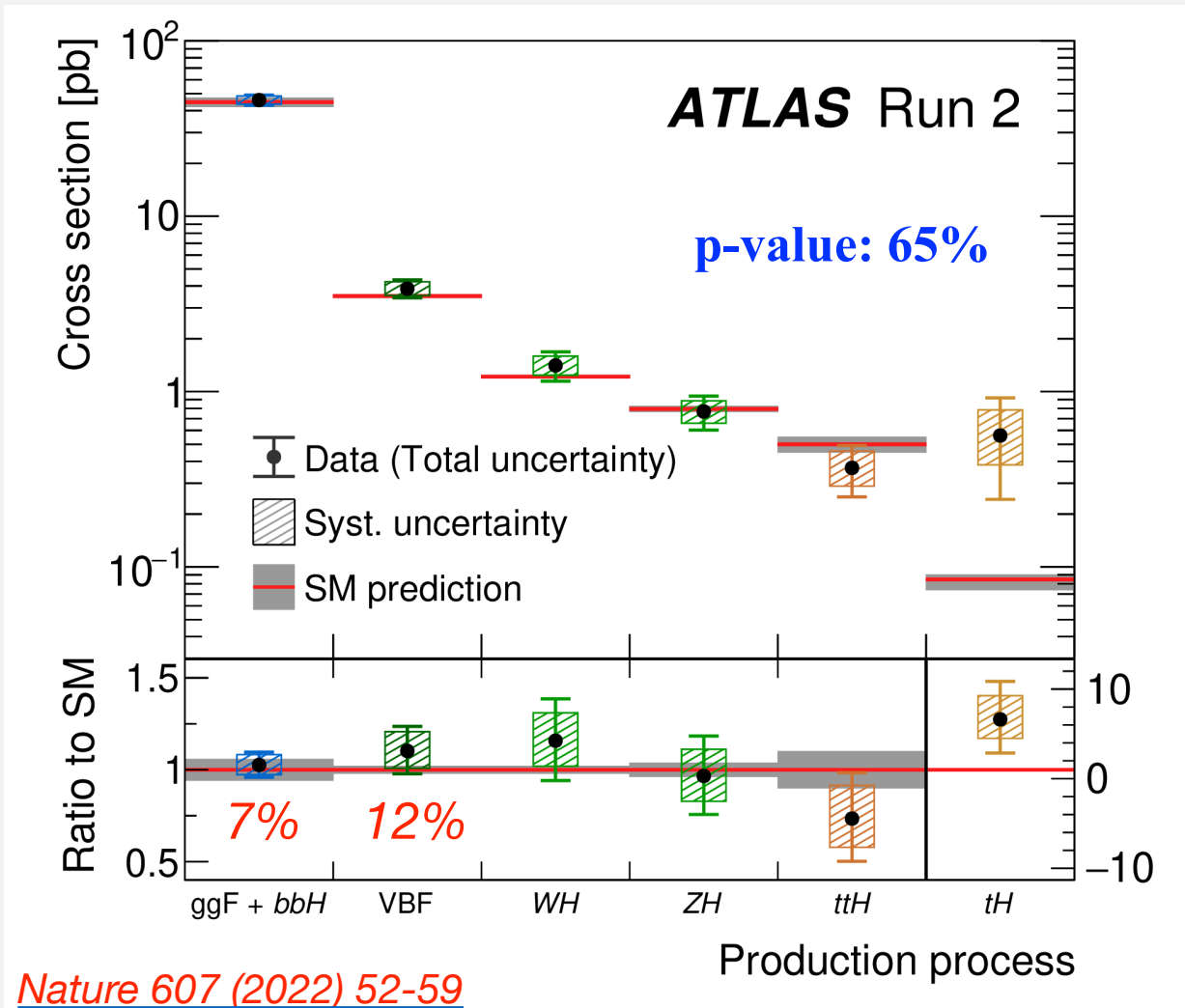
$$\mu = 1.002 \pm 0.057 = 1.002 \pm 0.029(\text{stat.}) \pm 0.033(\text{exp.}) \pm 0.036(\text{sig. th.})$$



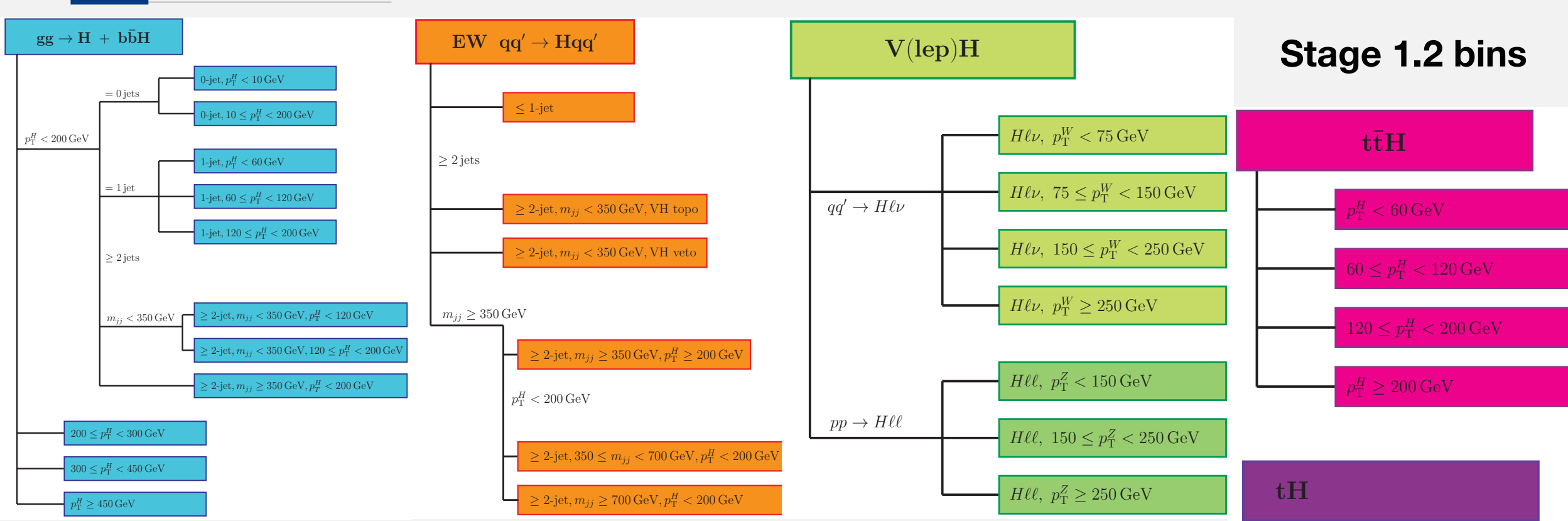


# The Higgs boson production and decay measurement

## Cross section measurements vs Higgs production channel and decay mode



# The Higgs boson simplified template cross section



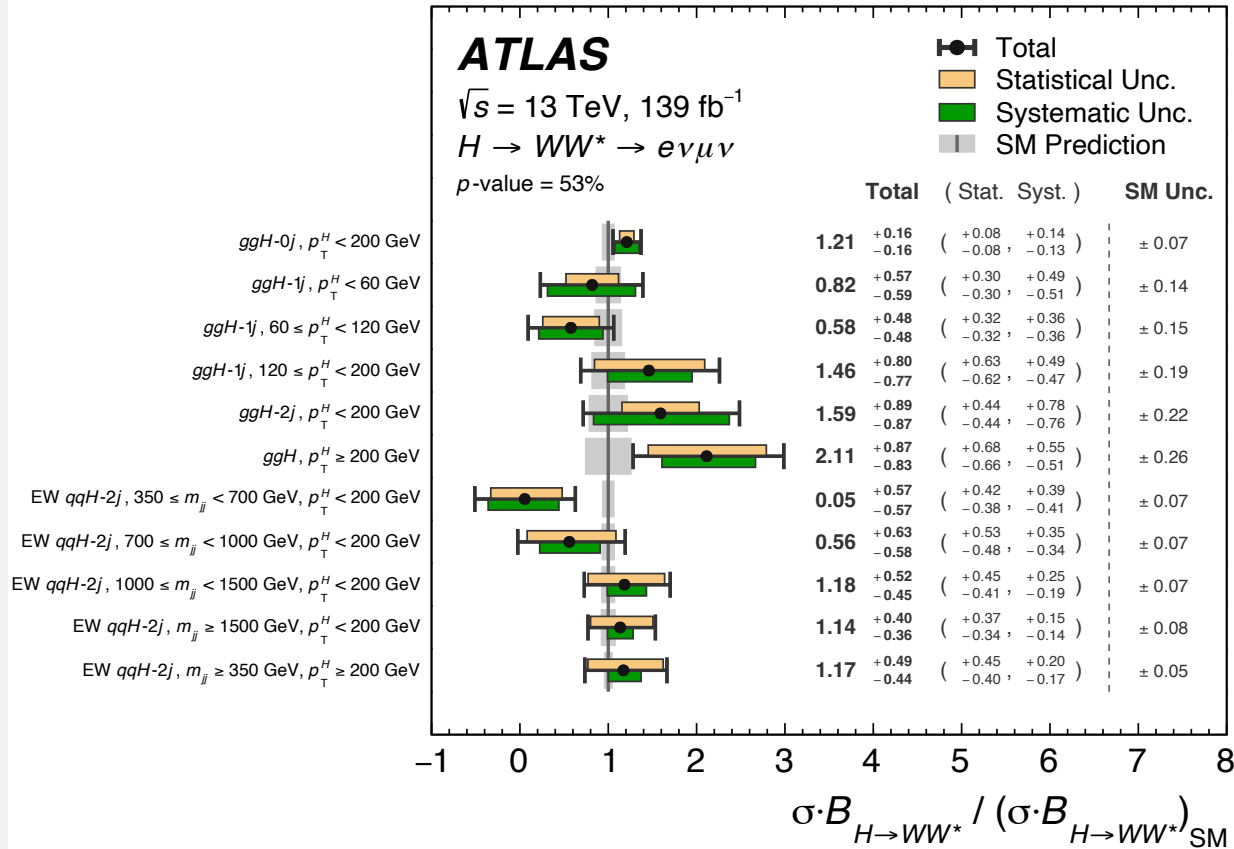
## Motivation of doing Simplified Template X-Section measurement (STXS):

- Sensitive to deviations from the SM expectation
- Minimize model-dependent extrapolations
- Avoidance of large theory uncertainties in the corresponding SM predictions

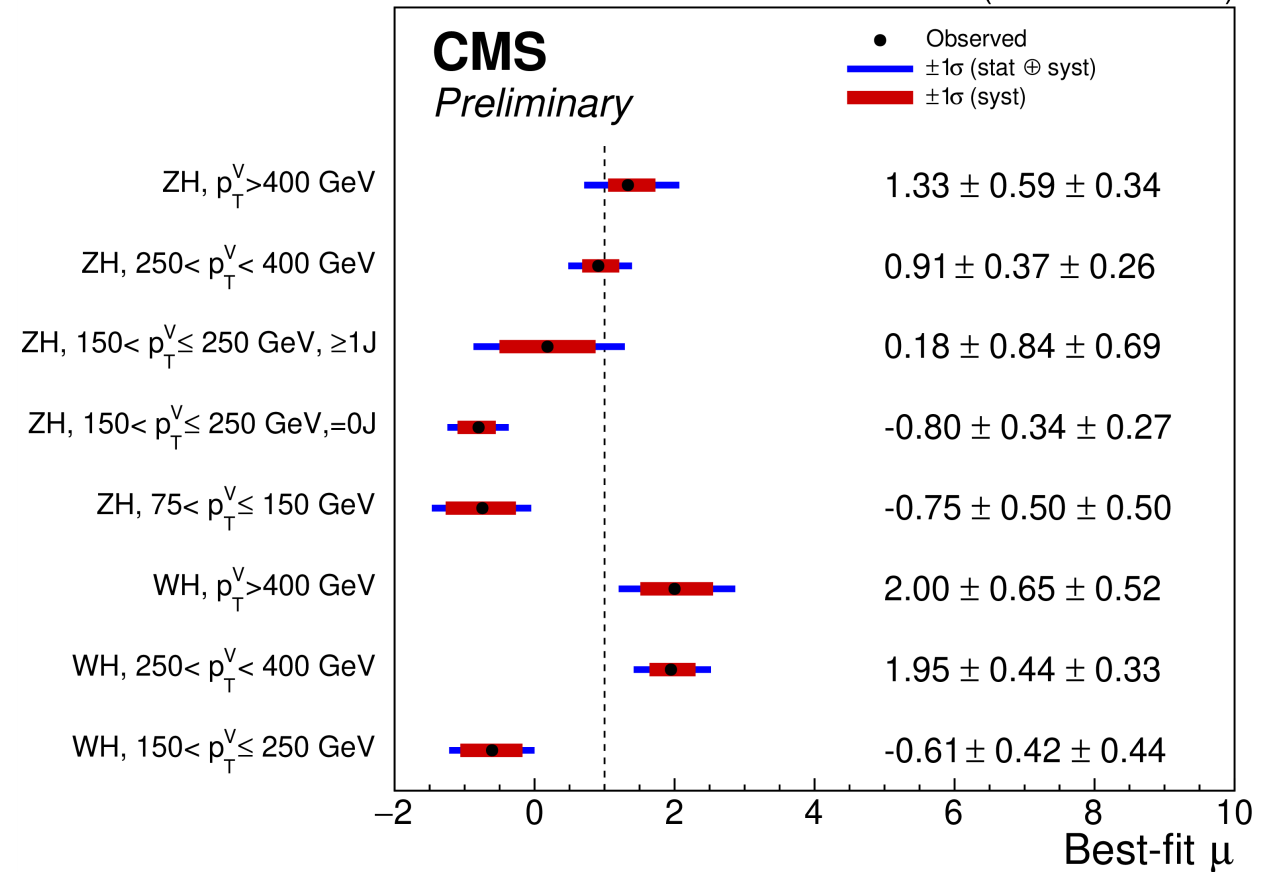
# The Higgs boson simplified template cross section

## ATLAS $H \rightarrow WW^* \rightarrow e\nu\mu\nu$ channel

## CMS $H \rightarrow bb$ channel



138 fb<sup>-1</sup> (13 TeV - Run 2)



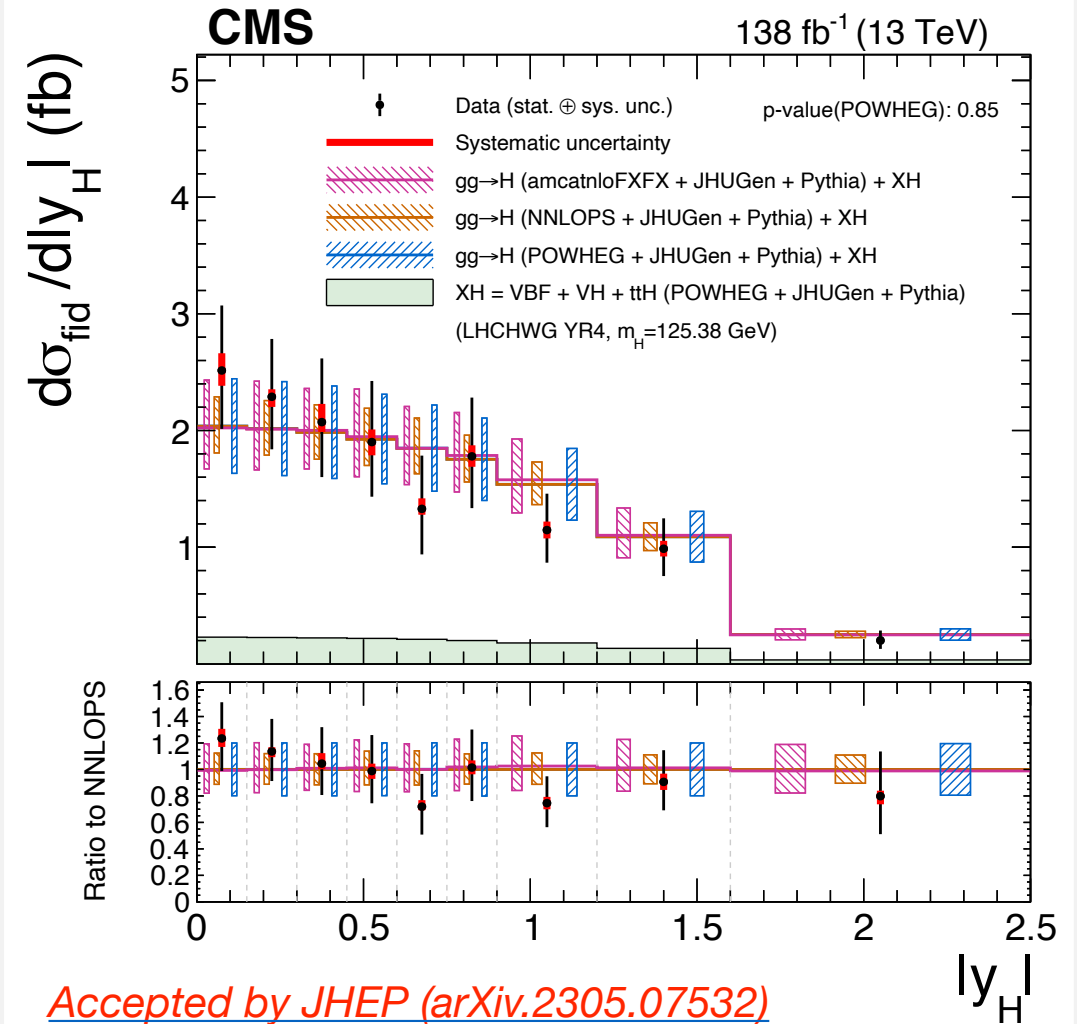
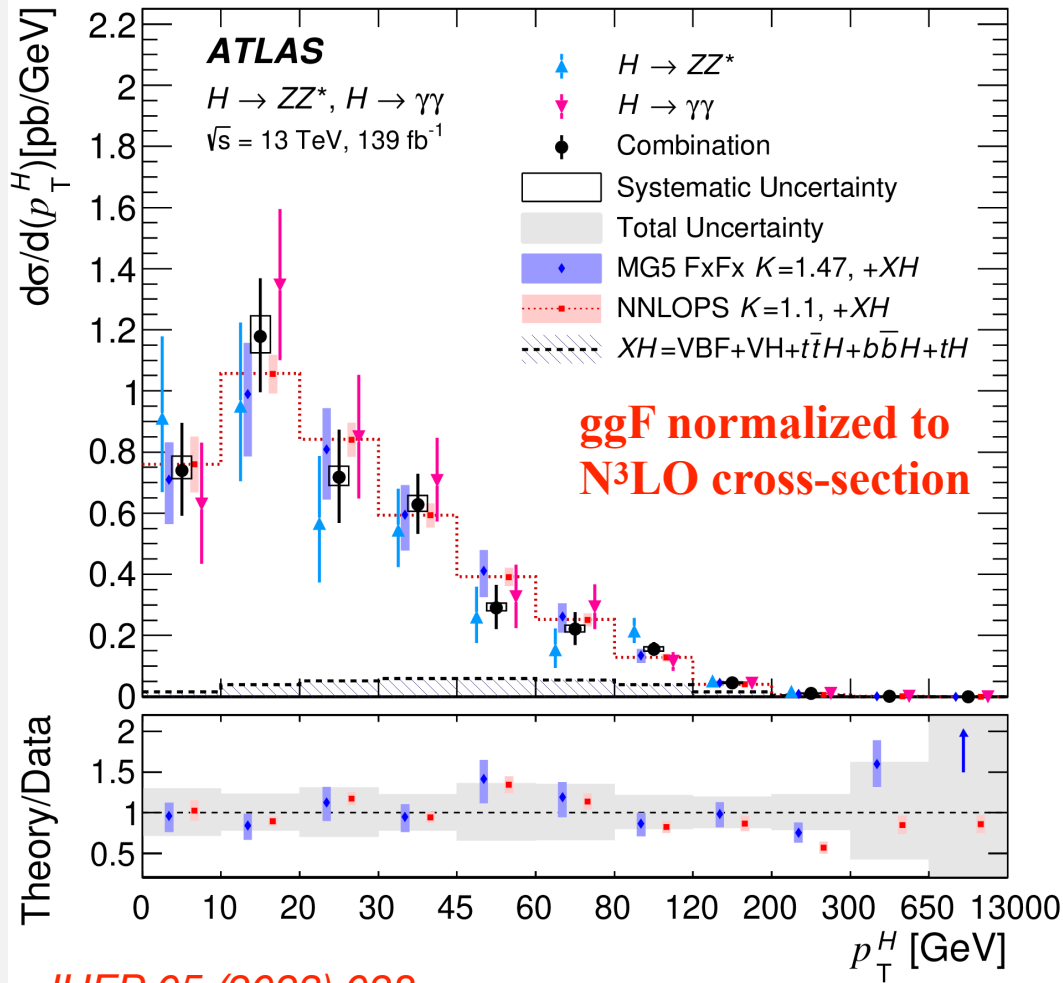
Submitted to PRD (arXiv.2207.00338)

CMS-PAS-HIG-20-001



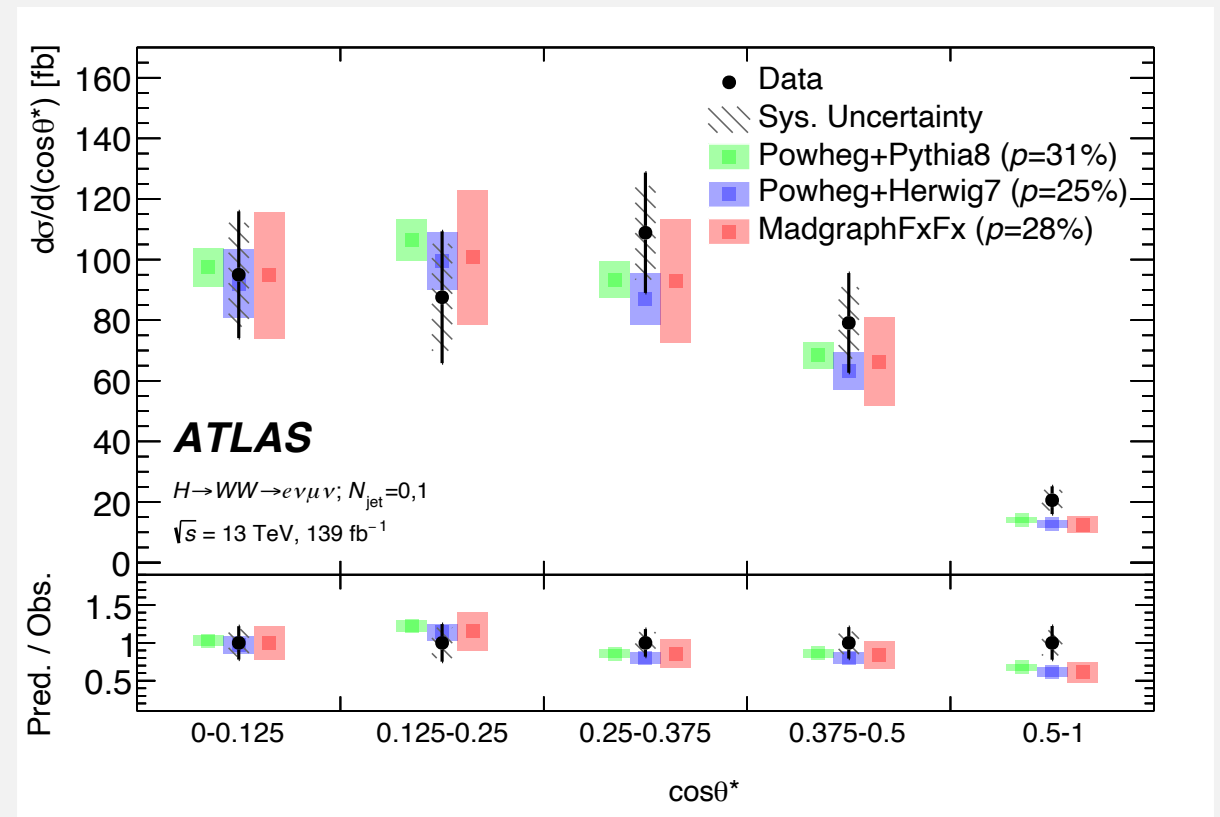
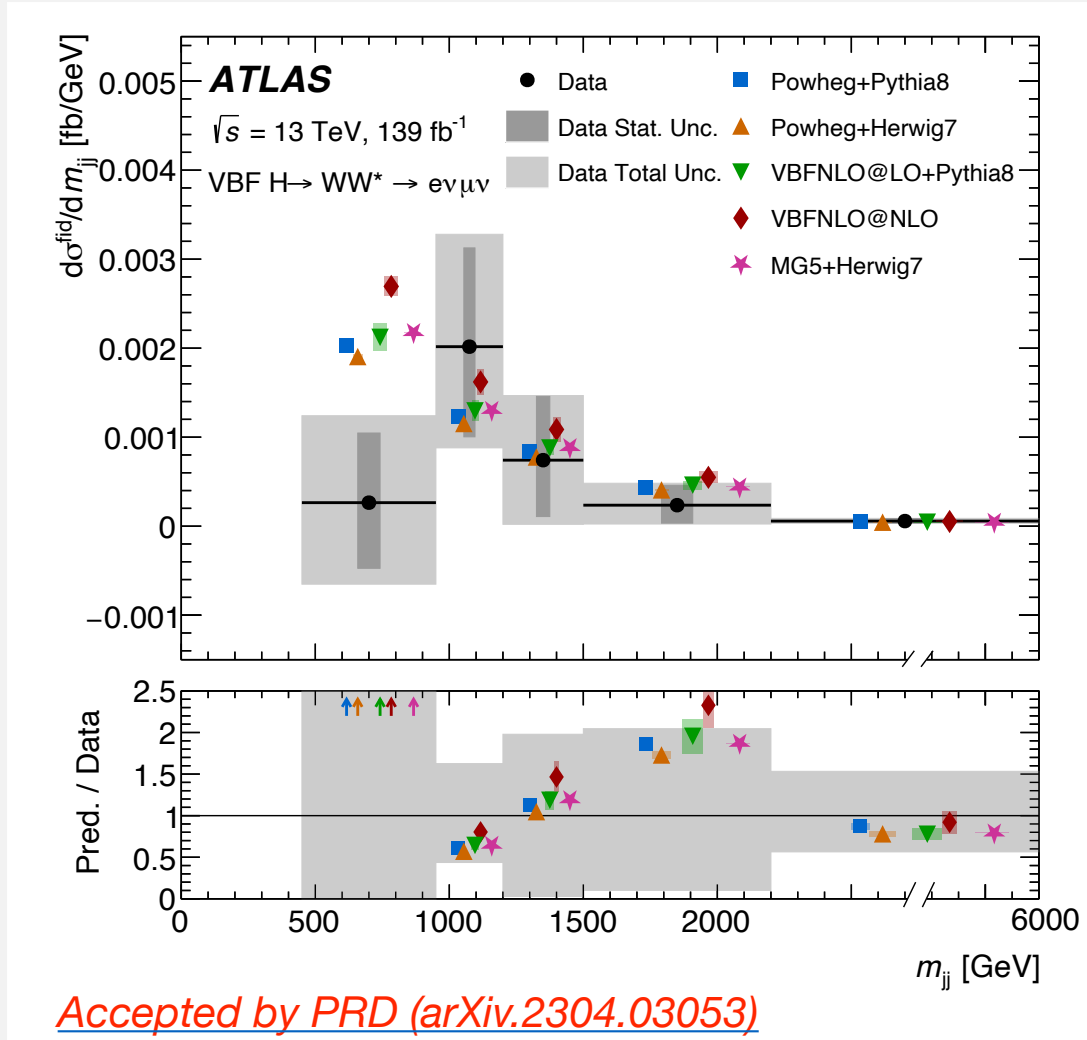
# The Higgs boson differential cross section measurement

- Differential  $pp \rightarrow H + X$  cross-sections measurement in  $H \rightarrow \gamma\gamma, ZZ^* \rightarrow 4\ell$  channels



# The Higgs boson differential cross section measurement

## Differential $pp \rightarrow H + X$ cross-sections measurement in $H \rightarrow WW \rightarrow \ell\nu\ell\nu$ channel

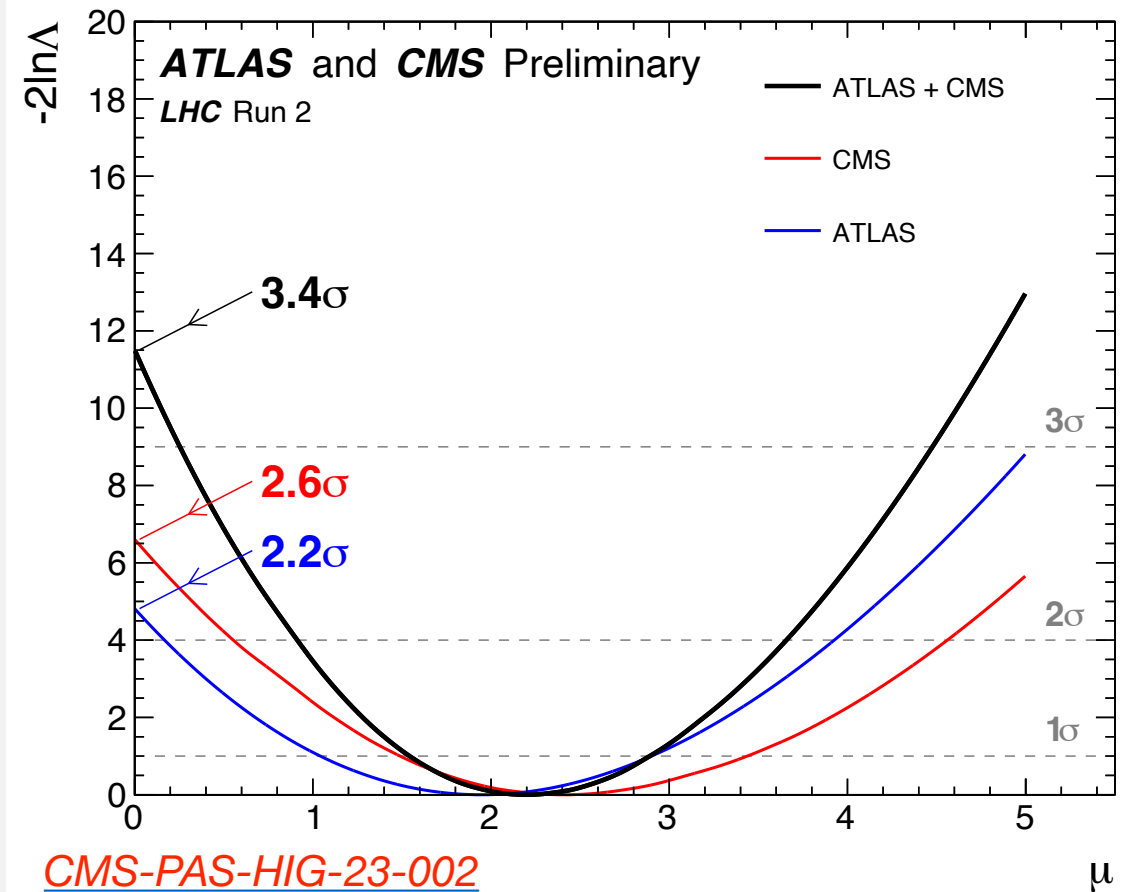
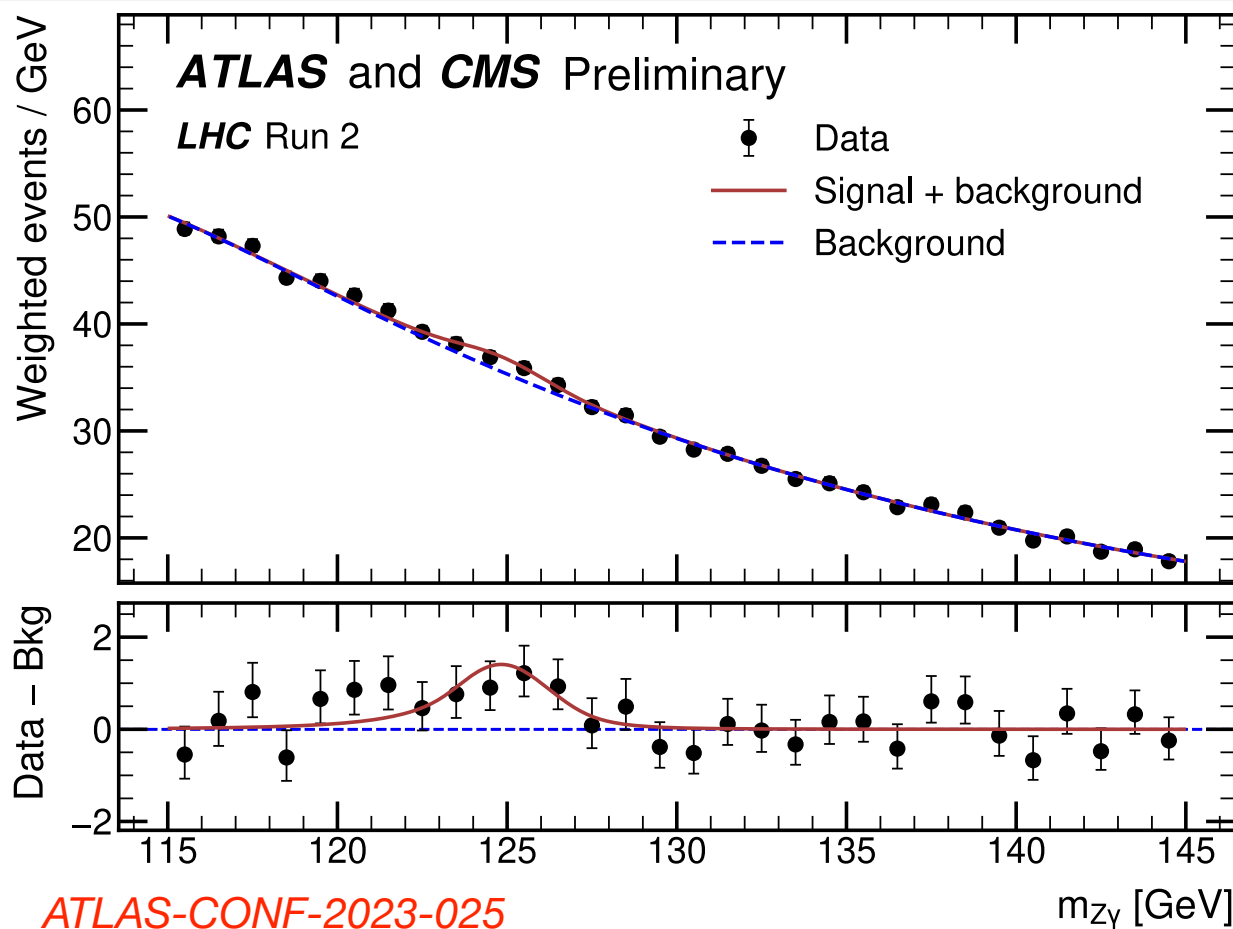


*Accepted by EPJC (arXiv.2301.06822)*

➔ **Statistical uncertainties dominate the experimental precision.**

# Evidence of the Higgs boson to Z and photon decay mode

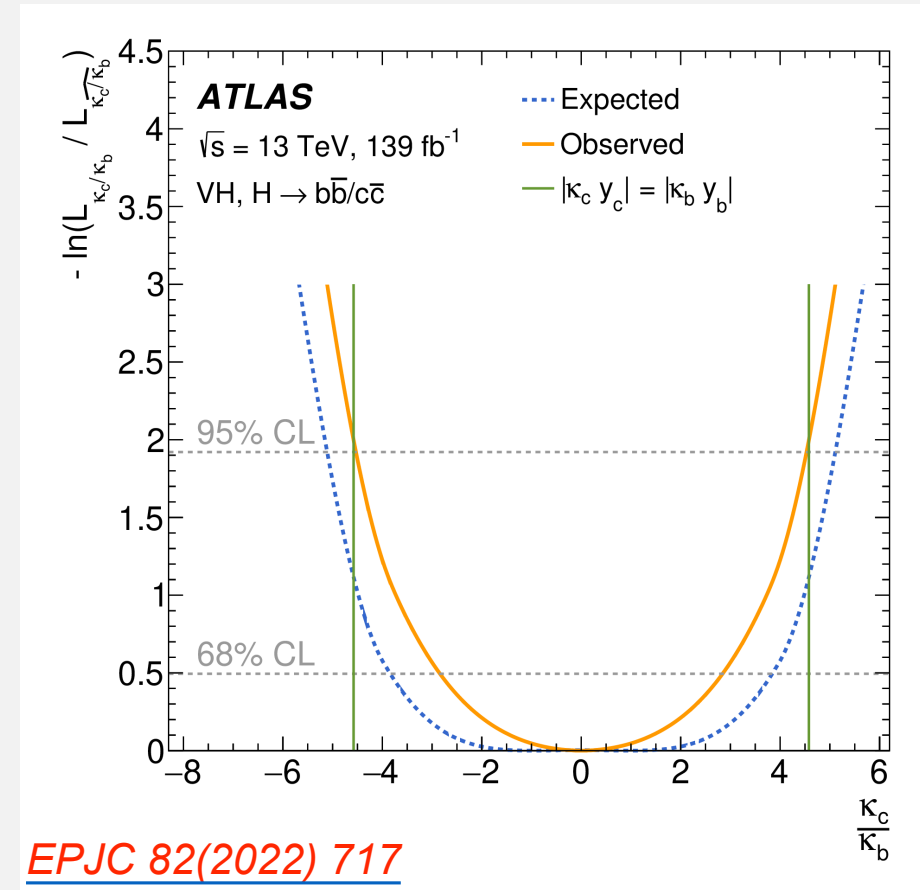
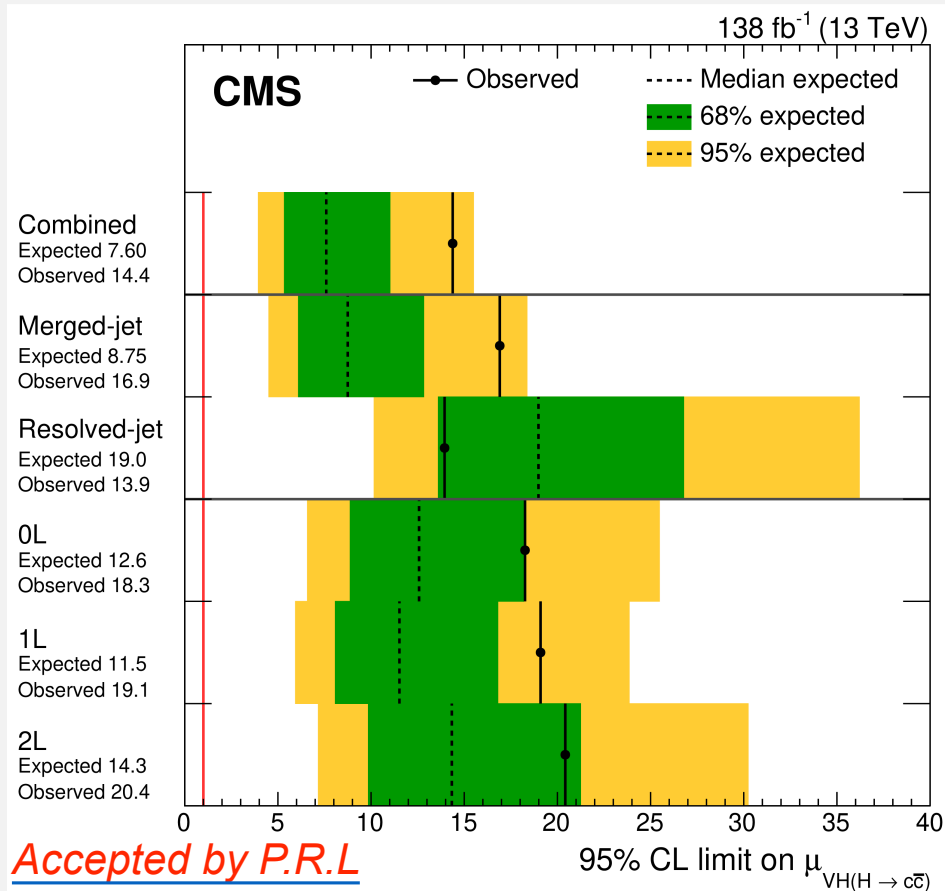
- Combination of ATLAS and CMS Run 2 dataset  $\rightarrow 3.4 \sigma$  significance!
- The measured signal strength  $\mu = 2.2 \pm 0.7$ , agrees with the SM within  $1.9 \sigma$ .





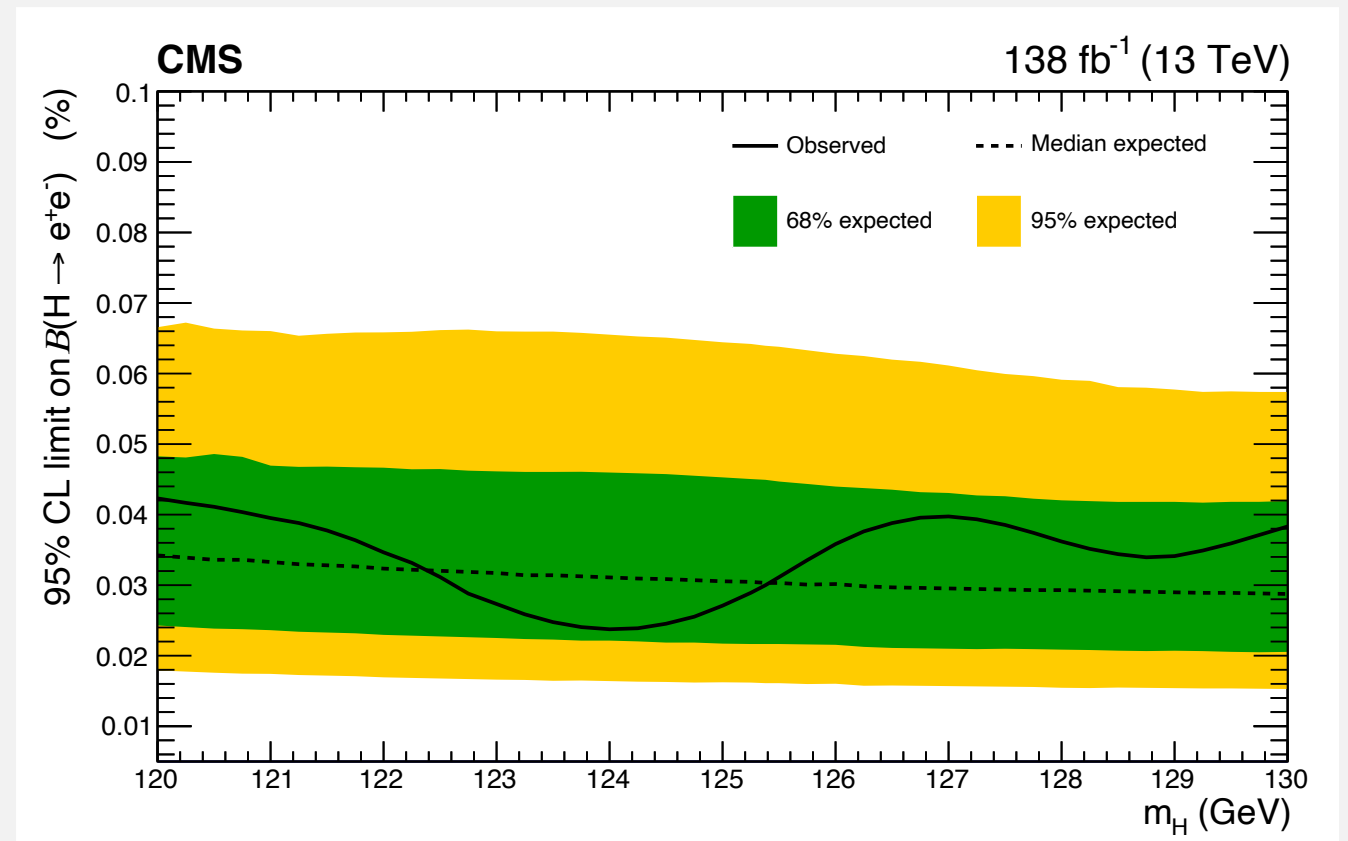
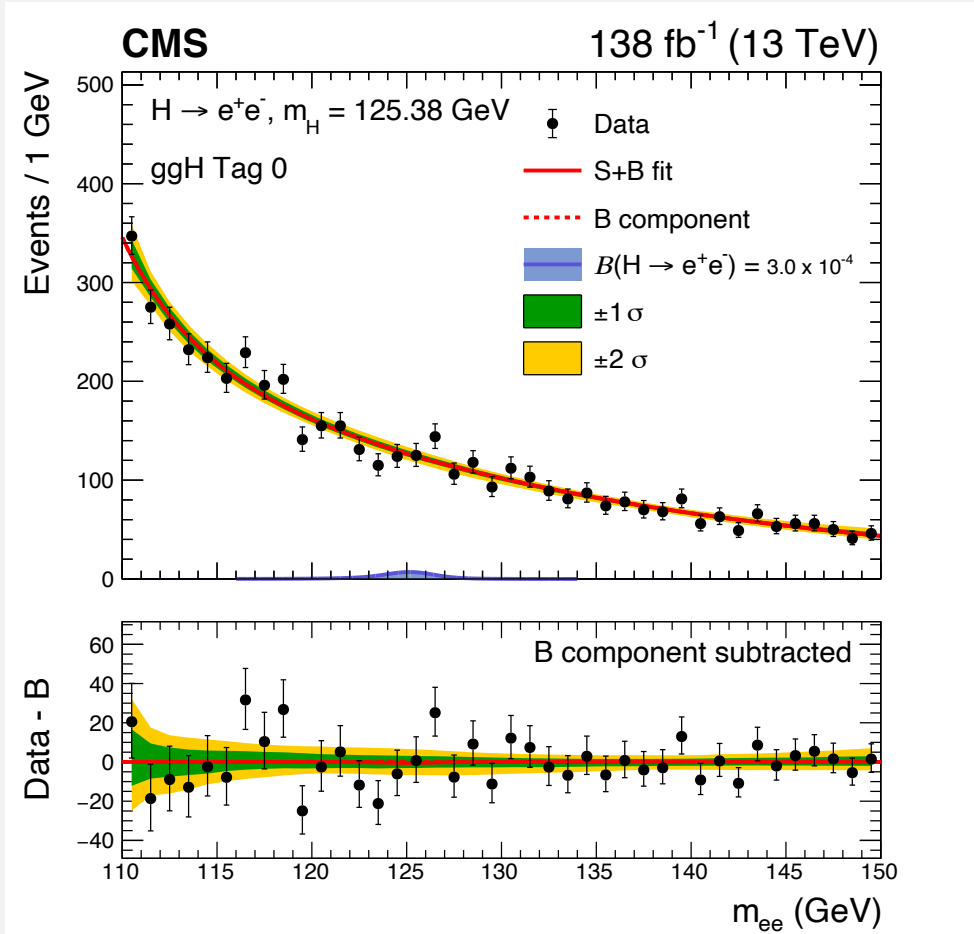
# Searching for Higgs decay to a pair of charm-quarks

- CMS VH(  $\rightarrow c\bar{c}$  ) channel observed (expected) limit is 14.4 (7.60) times the SM prediction.
- ATLAS VH(  $\rightarrow b\bar{b}, c\bar{c}$  ) constrains  $|\kappa_c/\kappa_b| < 4.5$  at 95% C.L.  $\rightarrow$  comparing to the ratio of b-quark and c-quark masses ( $m_b/m_c = 4.578 \pm 0.008$ , [Phys. Rev. D 98, 054517](#)).



# ● Searching for Higgs decay to a pair of electrons

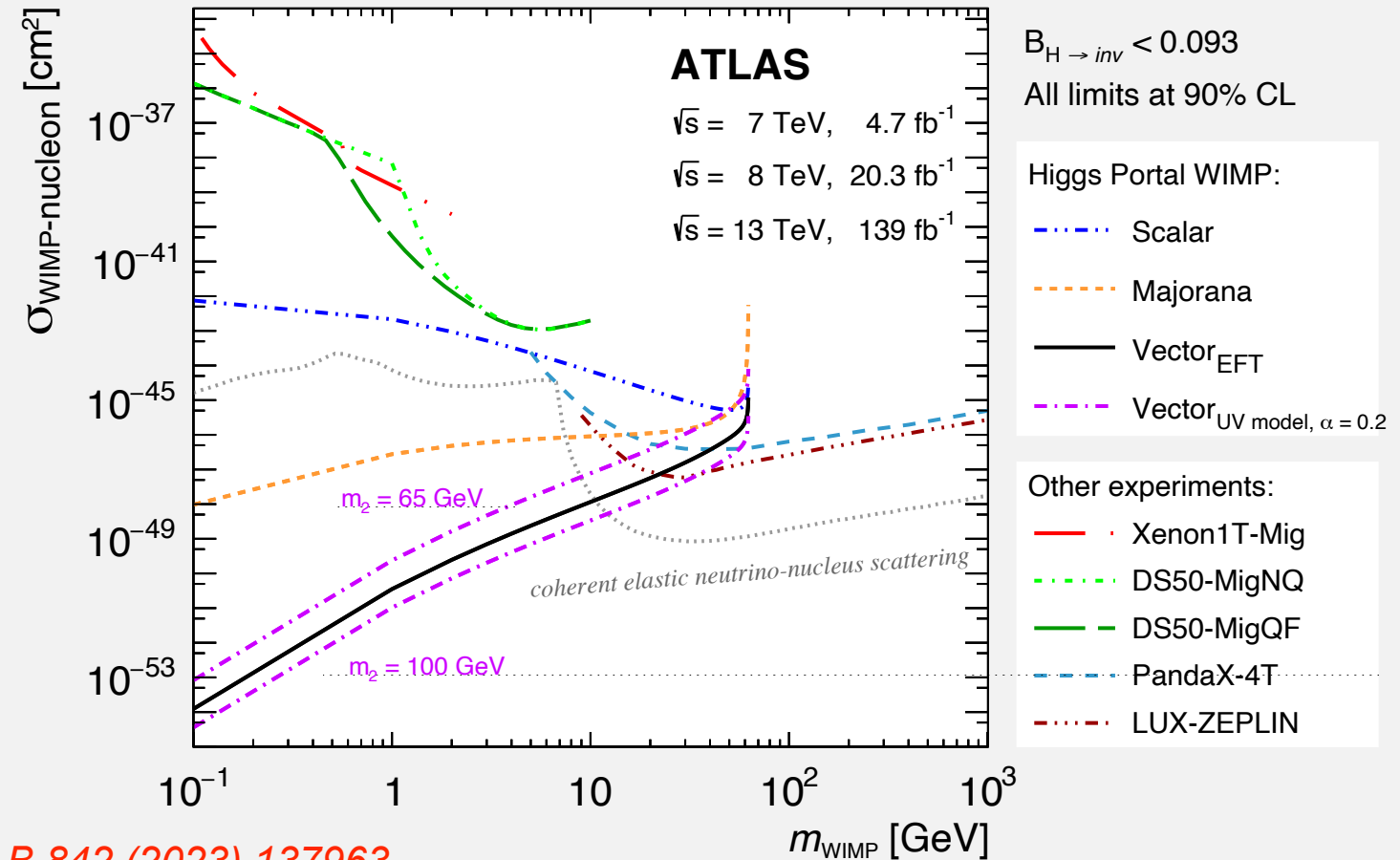
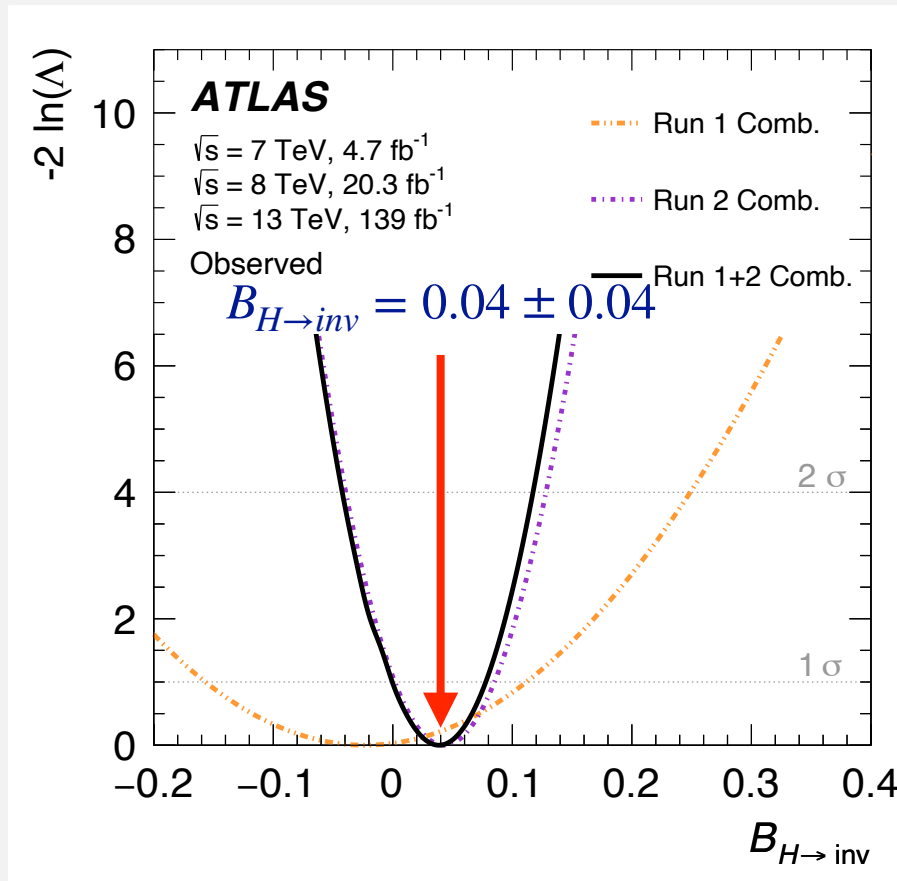
- The observed upper limit on the  $H \rightarrow e^+e^-$  branching ratio is  $3.0 \times 10^{-4}$  ( $3.0 \times 10^{-4}$  expected) at the 95% confidence level  $\rightarrow$  statistical uncertainty dominated!



*Accepted by PLB (arXiv.2208.00265)*

# ● Searching for the Higgs boson to invisible decay mode

- The observed (expected) upper limit on the  $H \rightarrow \text{invisible}$  BR is 0.107 (0.077) at 95% C.L.
- Competitive limits for low-mass dark matter candidates in model-specific scenarios.



[Phys. Lett. B 842 \(2023\) 137963](#)

## ● Summary

- **The major Higgs production and decay channels have been observed at the LHC**
  - ggF, VBF, WH, ZH, ttH+tH; H→bb, WW, ττ, ZZ, γγ; evidence for H→Zγ, H→μμ
- **The Higgs boson mass has been measured at 0.09% precision**
  - ATLAS latest measurement:  $125.11 \pm 0.09(\text{syst.}) \pm 0.06(\text{stat.}) \text{ GeV}$
  - CMS latest measurement:  $125.38 \pm 0.11(\text{syst.}) \pm 0.08(\text{stat.}) \text{ GeV}$
- **The Higgs boson width has been measured by CMS, ATLAS:  $\Gamma_H = 3.2_{-1.7}^{+2.4}, 4.5_{-2.5}^{+3.3} \text{ MeV}$**
- **Higgs inclusive production cross section has been measured at 6% precision**
- **Higgs differential cross sections have been measured with good precision**
- **Searching for Higgs rare productions have been performed**
  - Constraints on Higgs to a pair of charm-quarks and a pair of electrons branching ratios