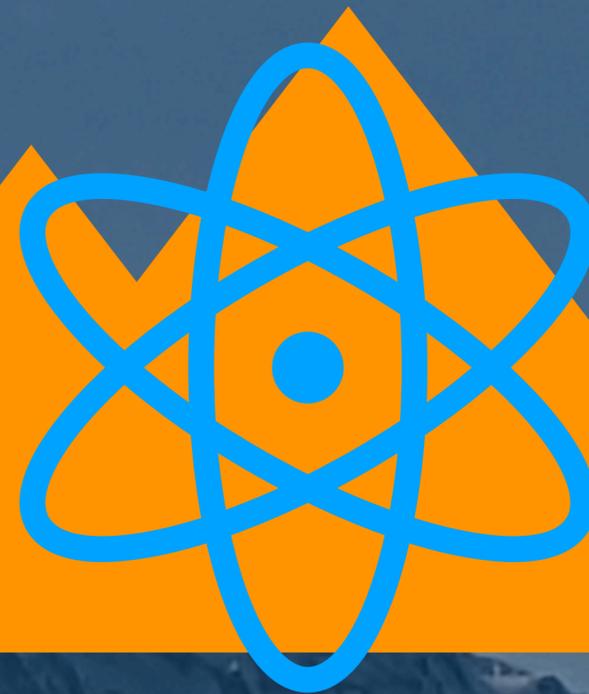


# Projections for Higgs analyses - HL-LHC Results



**Saptaparna Bhattacharya**

**On behalf of CMS and ATLAS Collaborations**

**Northwestern University**

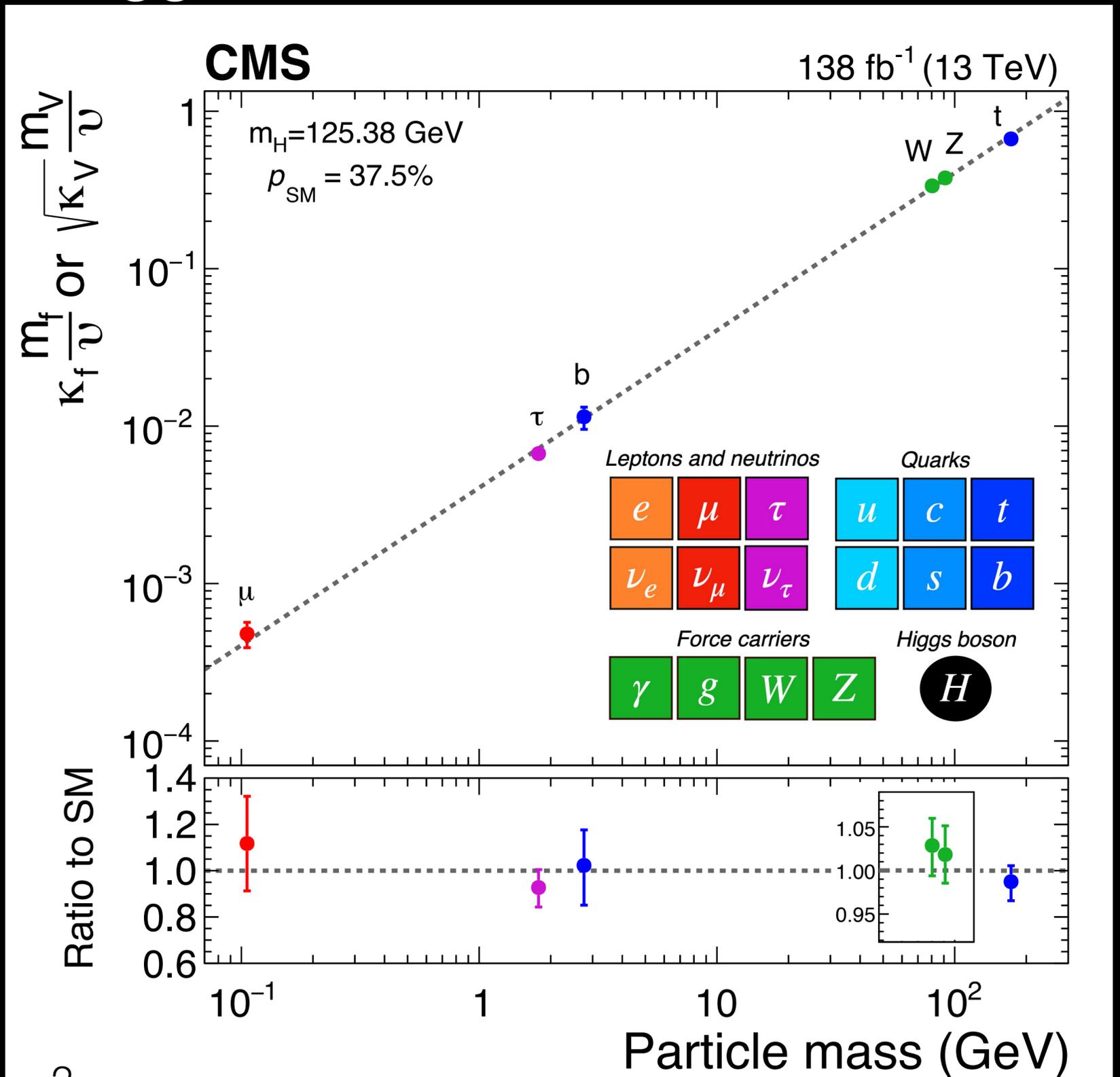
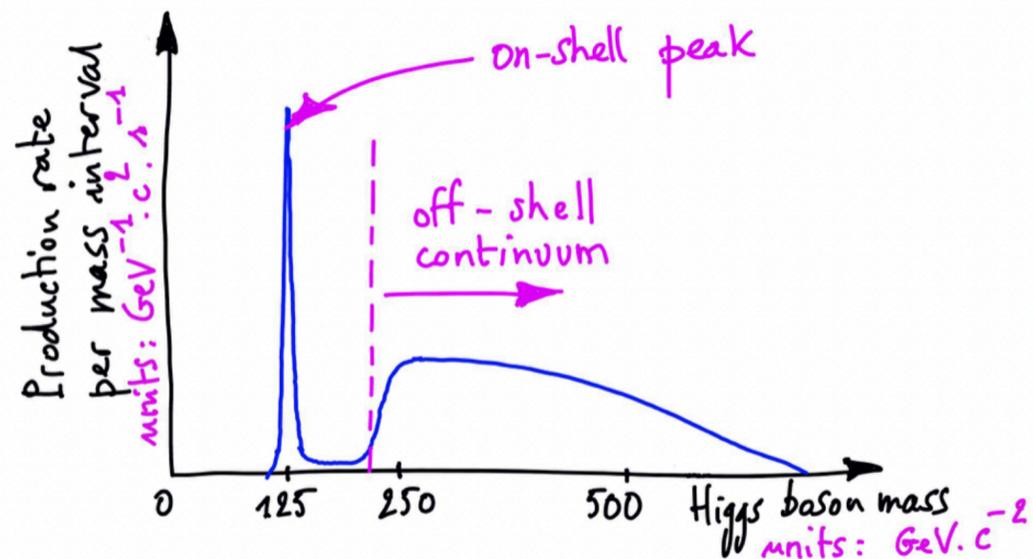
**Snowmass Meeting in Seattle**

**July 17<sup>th</sup>-July 26<sup>th</sup>, 2022**



# Where do we stand w.r.t Higgs Boson @ Run II

- Mass known to a precision of 0.11% ( $m_H = 125.38 \pm 0.14$  GeV)
- Width measured to be  $\Gamma_H = 3.2^{+2.4}_{-1.7}$  MeV (including off-shell and on-shell modes)



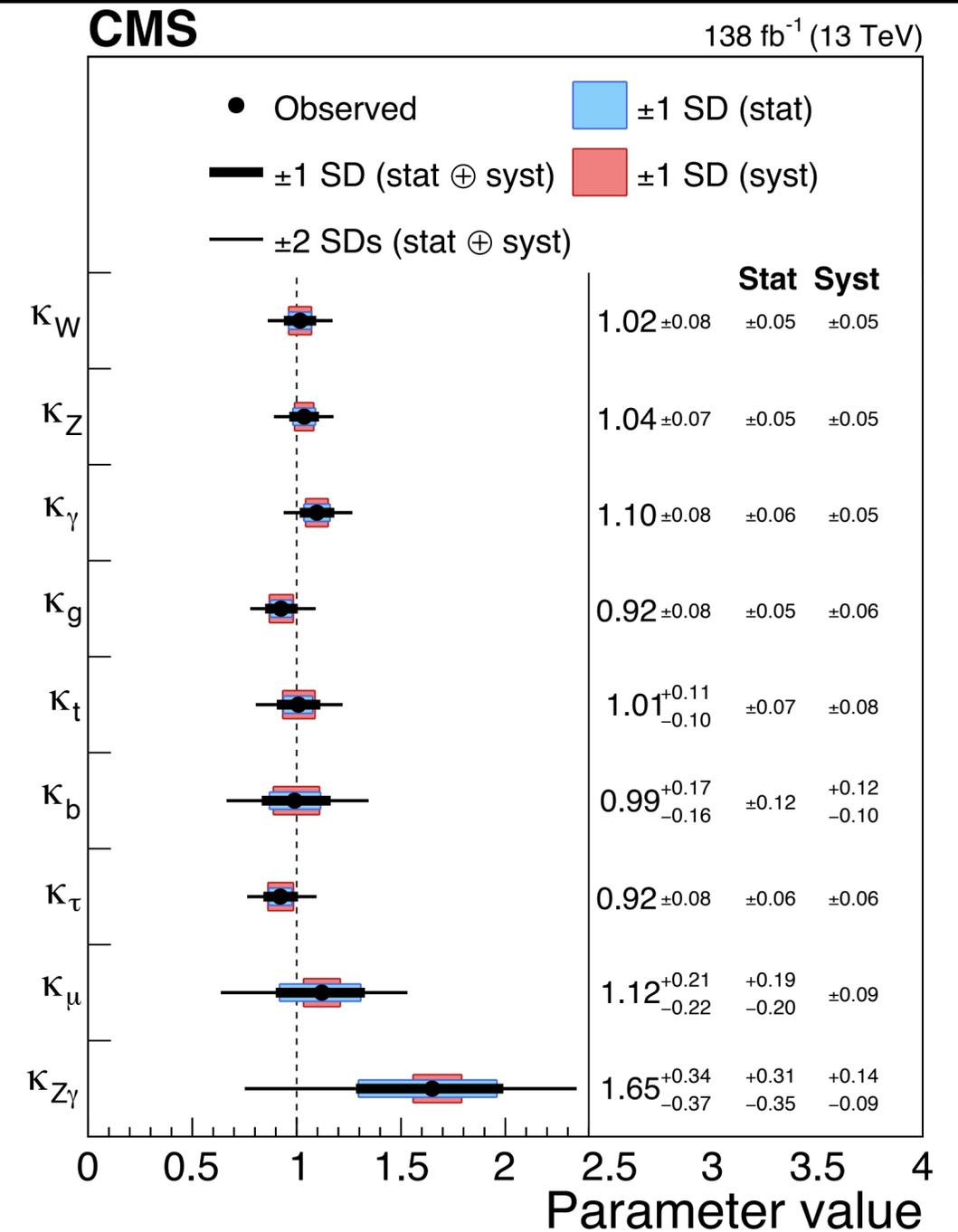
# The Higgs Boson as predicted in the Standard Model

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i\bar{\psi}\not{D}\psi + h.c.$$

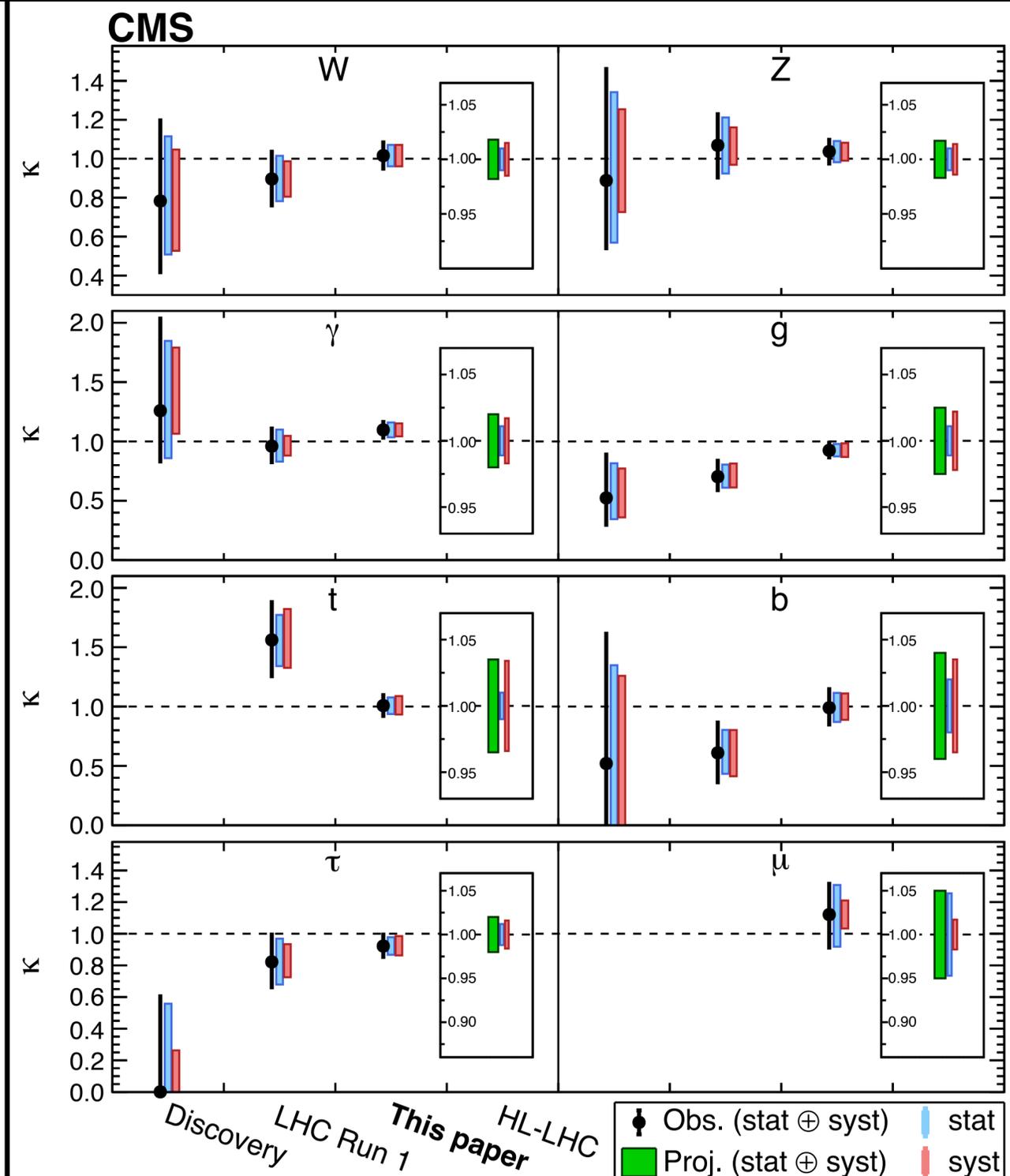
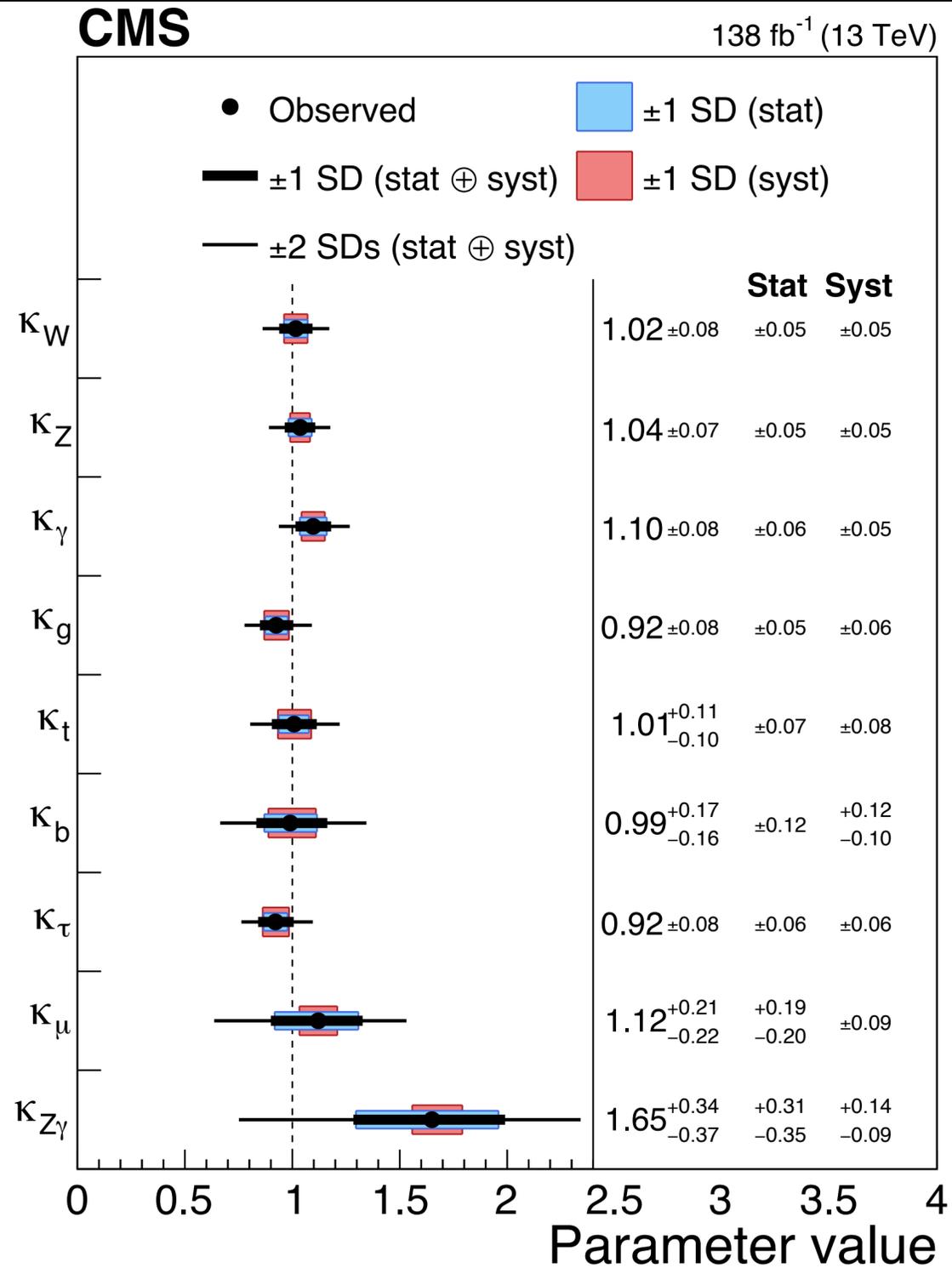
$$+ \chi_i y_{ij} \chi_j \phi + h.c.$$

$$+ |D_\mu \phi|^2 - V(\phi)$$

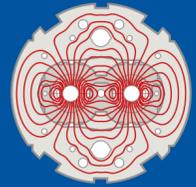
- $\kappa$ -framework: coupling strength modifiers



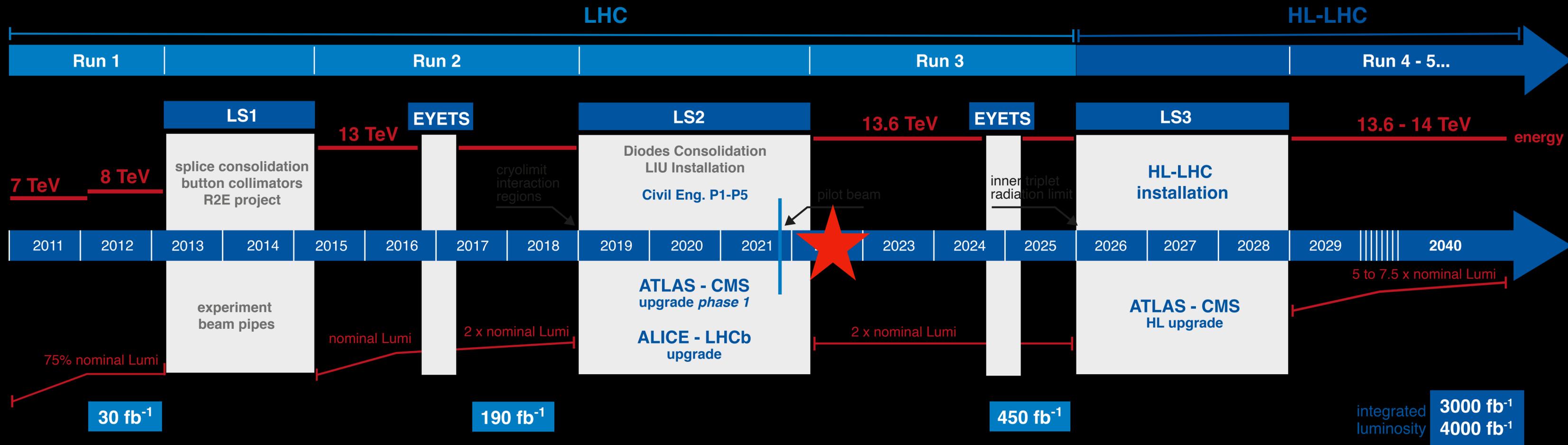
# The Higgs Boson as predicted in the Standard Model



# The LHC upgrade schedule



## LHC / HL-LHC Plan



### HL-LHC TECHNICAL EQUIPMENT:



DESIGN STUDY

PROTOTYPES

CONSTRUCTION

INSTALLATION & COMM.

PHYSICS

### HL-LHC CIVIL ENGINEERING:

DEFINITION

EXCAVATION

BUILDINGS



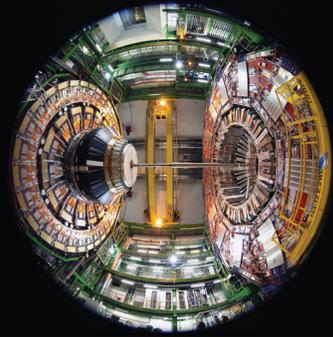
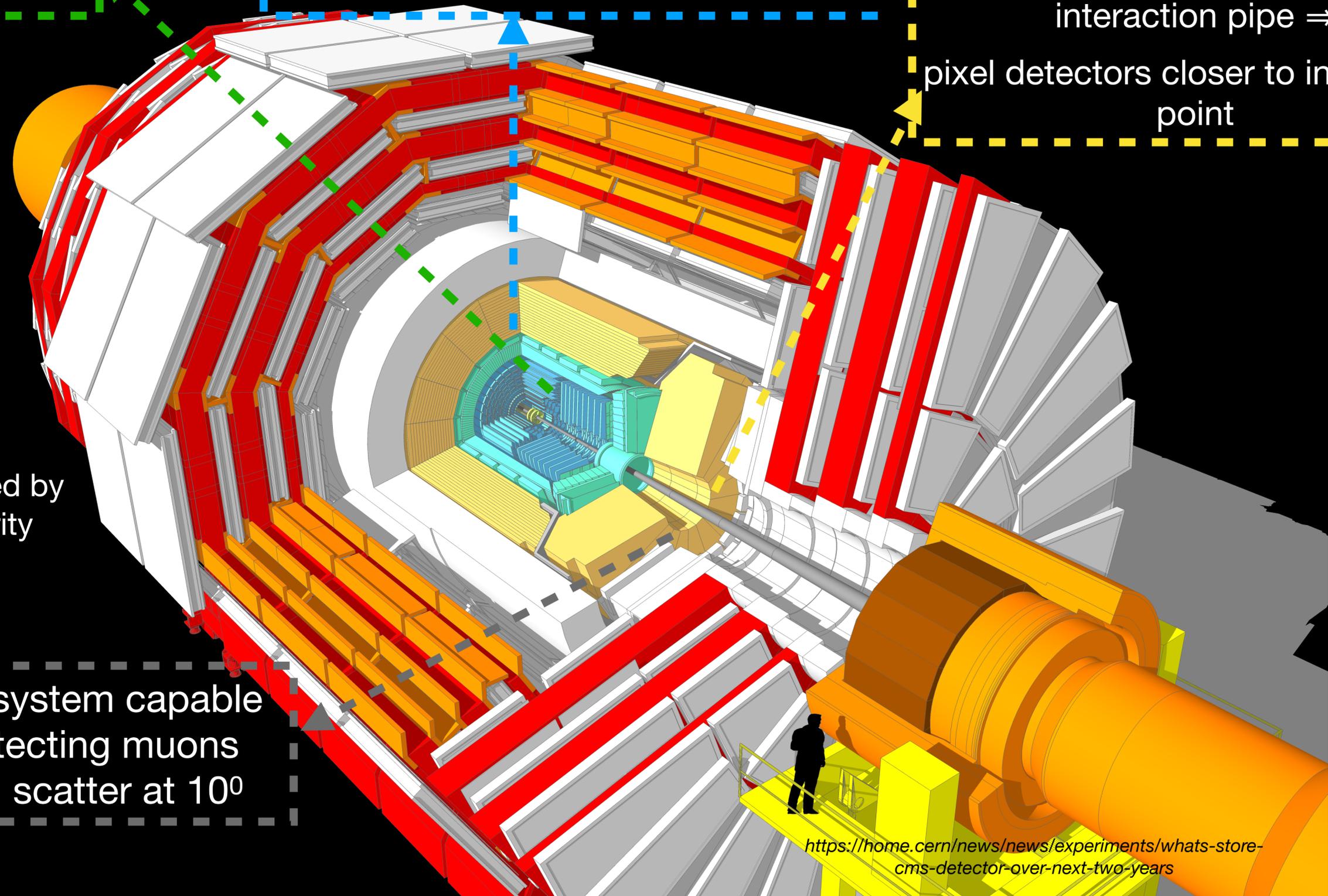
**We are here**

# The upgraded CMS Detector

Pixel detectors will be replaced

Hadron Calorimeter: upgraded readout electronics

Beam pipe: closer to the interaction pipe  $\Rightarrow$  pixel detectors closer to interaction point

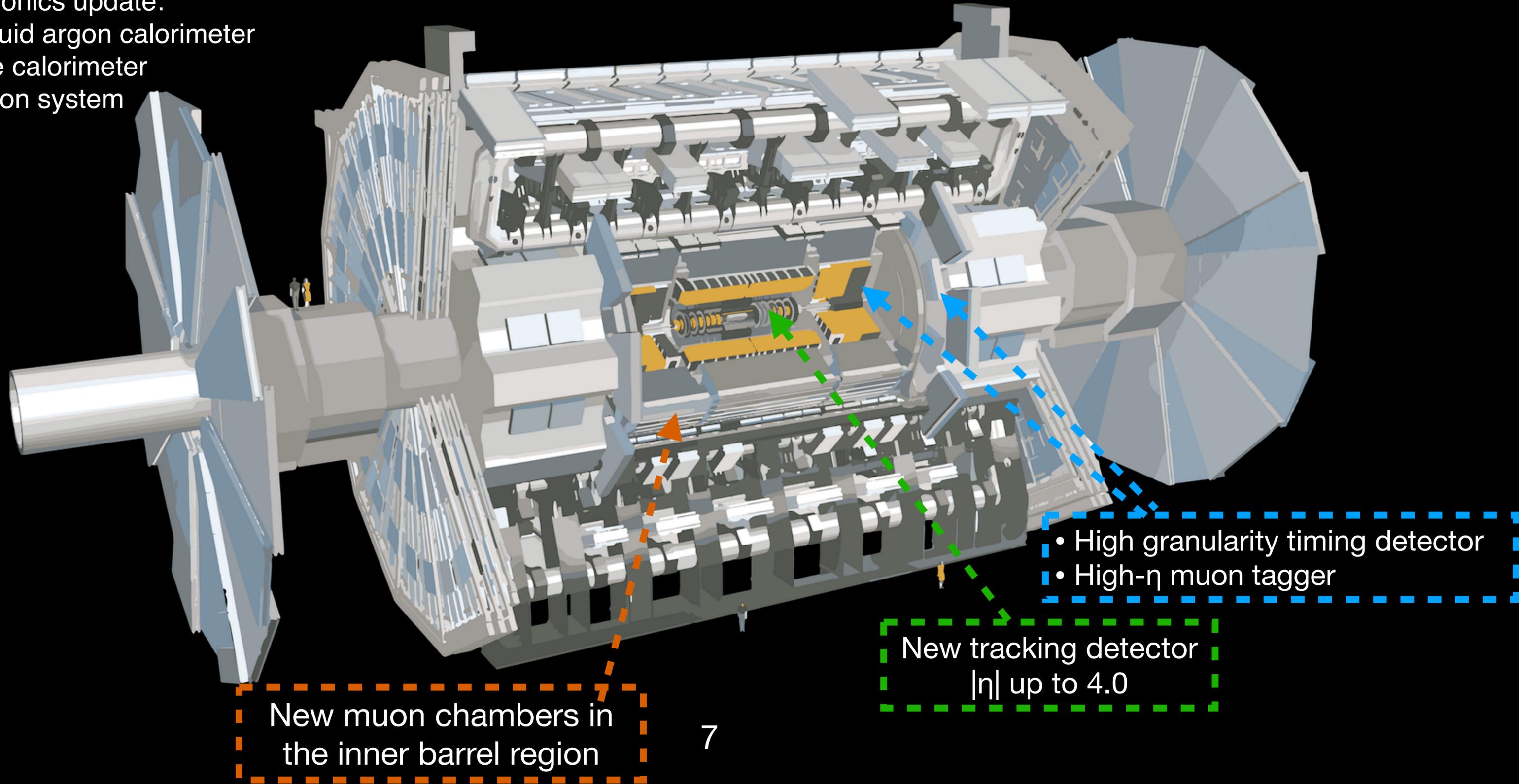


Endcaps to be replaced by the new High Granularity Calorimeter, HGCAL (2024-2026)

Muon system capable of detecting muons which scatter at  $10^0$

# The upgraded ATLAS Detector

- Upgraded trigger and data acquisition system:
  - Improved high-level trigger
- Electronics update:
  - Liquid argon calorimeter
  - Tile calorimeter
  - Muon system



# Outline of the talk

- Projection of the Higgs boson mass and on-shell width measurements

- $H \rightarrow ZZ \rightarrow 4\ell$  

- $H \rightarrow \gamma\gamma$  

- Prospects for  $H \rightarrow \tau^+\tau^-$  

- Study of  $H \rightarrow \mu^+\mu^-$  

- Projection of  $VH, H \rightarrow c\bar{c}, H \rightarrow b\bar{b}$  

- Prospects for  $t\bar{t}H, H \rightarrow b\bar{b}$  

- Prospects for non resonant  $HH$  in  $W^+W^-\gamma\gamma, \tau^+\tau^-\gamma\gamma$  and  $bb\gamma\gamma$  and  $t\bar{t}HH, H \rightarrow b\bar{b}$  

- Search for rare Higgs boson with mesons 

- Search for high-mass resonances decaying to  $W^+W^-$  

Targeting precision



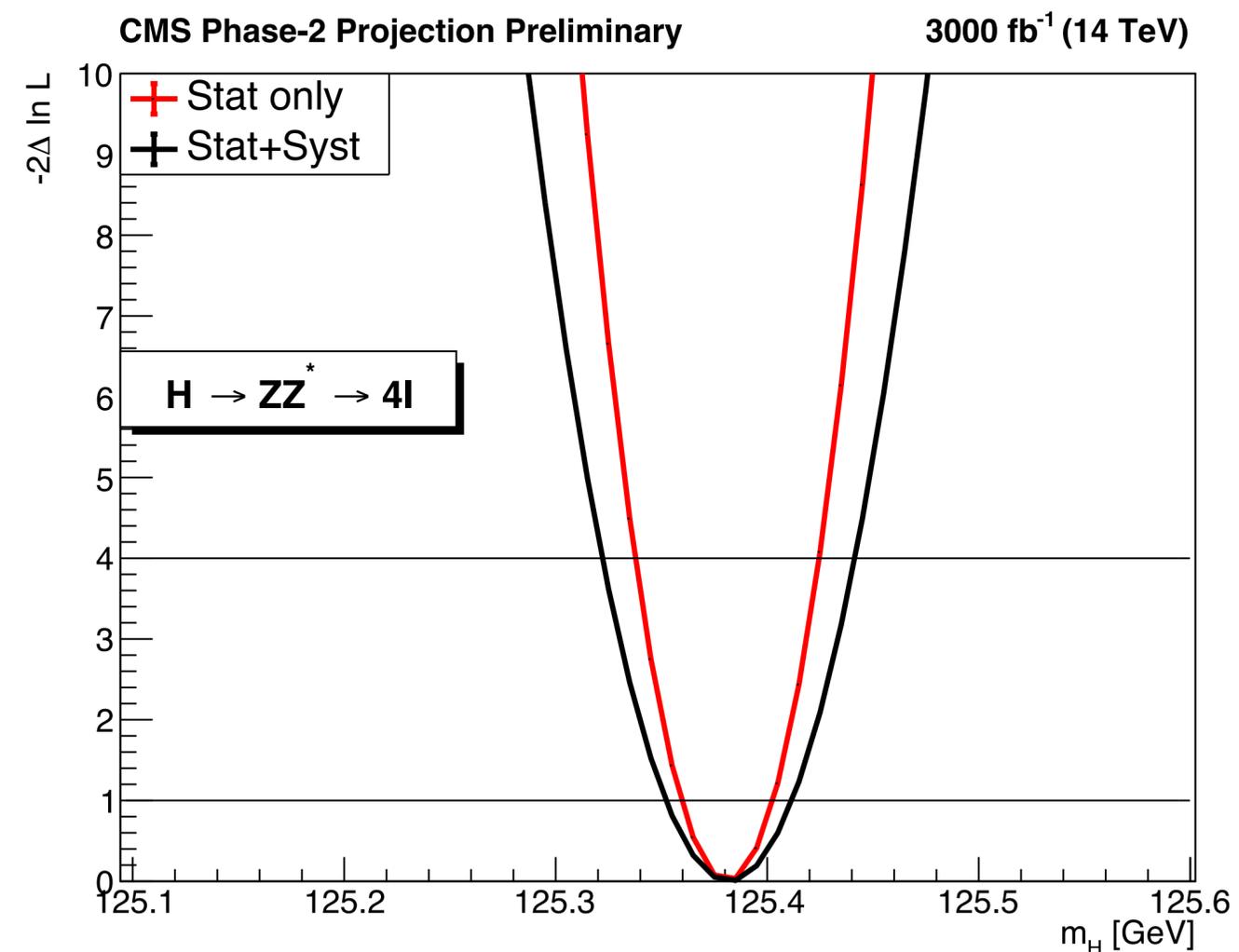
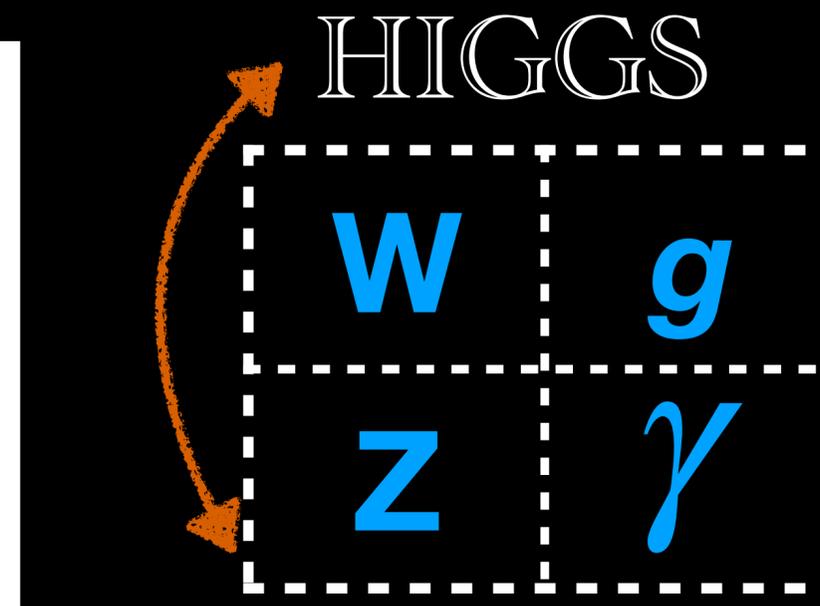
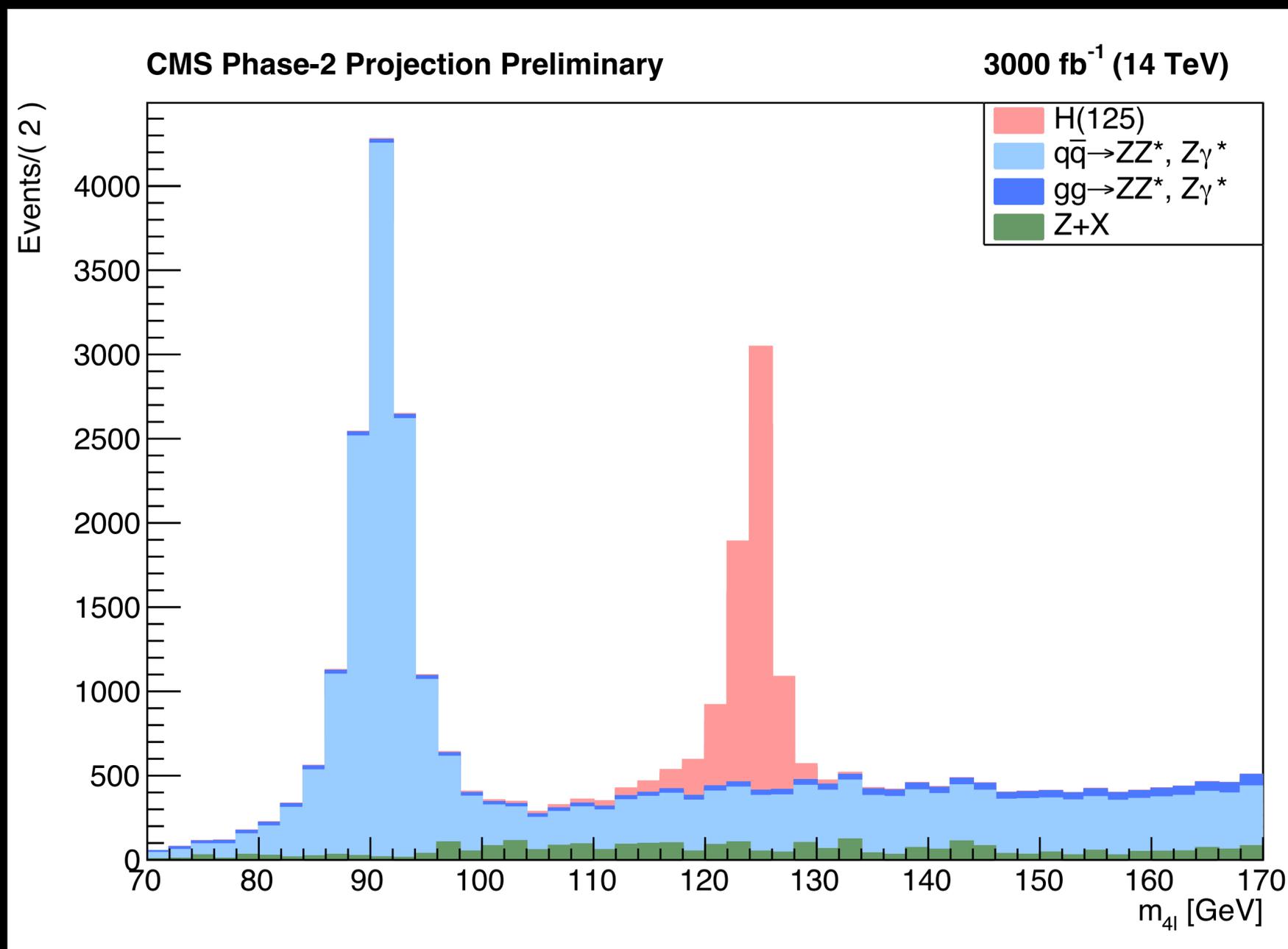
Novel ML based methodology



All new results summarized in white paper: <https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PUBNOTES/ATL-PHYS-PUB-2022-018/ATL-PHYS-PUB-2022-018.pdf>



$$H \rightarrow ZZ \rightarrow 4\ell$$

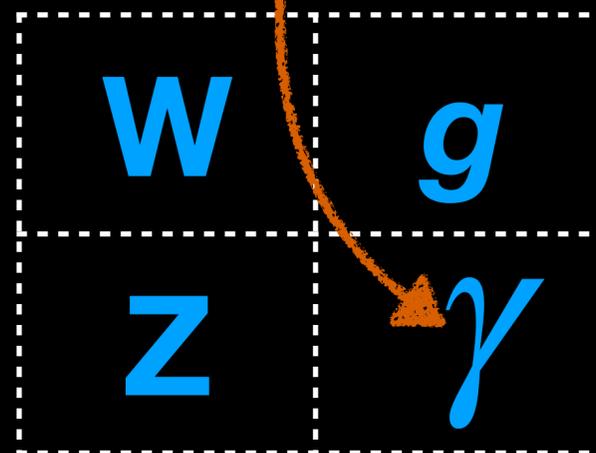


- Expect order of magnitude reduction in Higgs Mass uncertainty (in 4l final state):  
 $m_H = 125.38 \pm 0.03 \text{ GeV} [0.022 \text{ (stat.)} \pm 0.020 \text{ (syst.)}] \text{ GeV}$
- Width ( $\Gamma_H$ ) < 0.09 (0.18) GeV at 68 (95)% C.L.
- Uncertainties associated with mass resolution and lepton identification



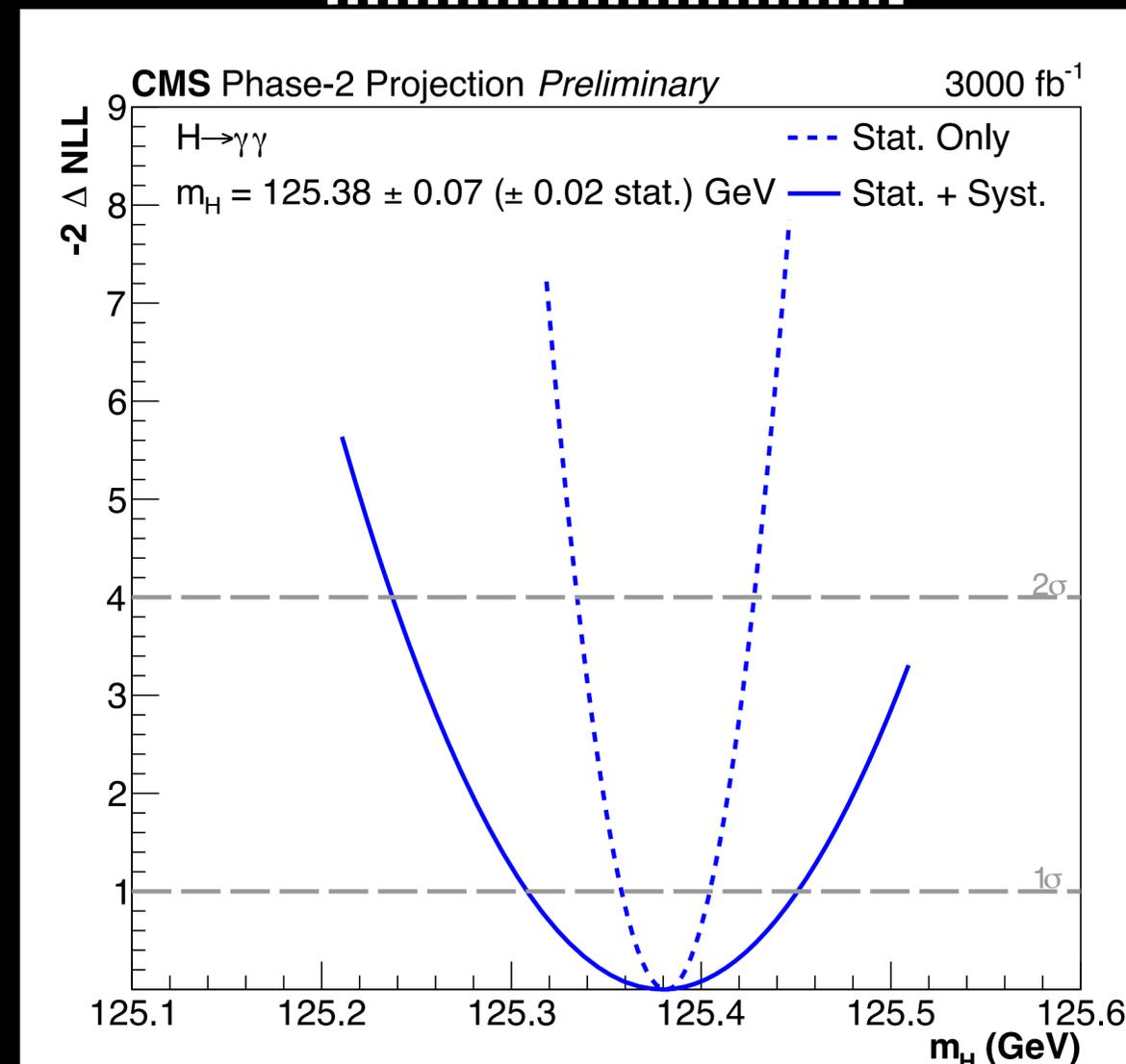
$$H \rightarrow \gamma\gamma$$

HIGGS



- Mass computation:
  - $m_H = 125.38 \pm 0.02$  (stat.)  $\pm 0.07$  (syst.)
- Improvement by a factor of 3 compared to current measurement, due to,
  - Factor of  $\sim 10$  luminosity
  - Improved tracker with lower material budget
  - Precision of the HGCAL
  - Pileup suppression with timing detectors
  - New algorithms for improved electromagnetic object reconstruction and calibration

Sources of systematic uncertainty	Contribution [GeV]
Residual $p_T$ dependence of the photon and electron energy scale	0.06-0.05
Modeling of the material budget	0.02
Statistical uncertainty	0.02

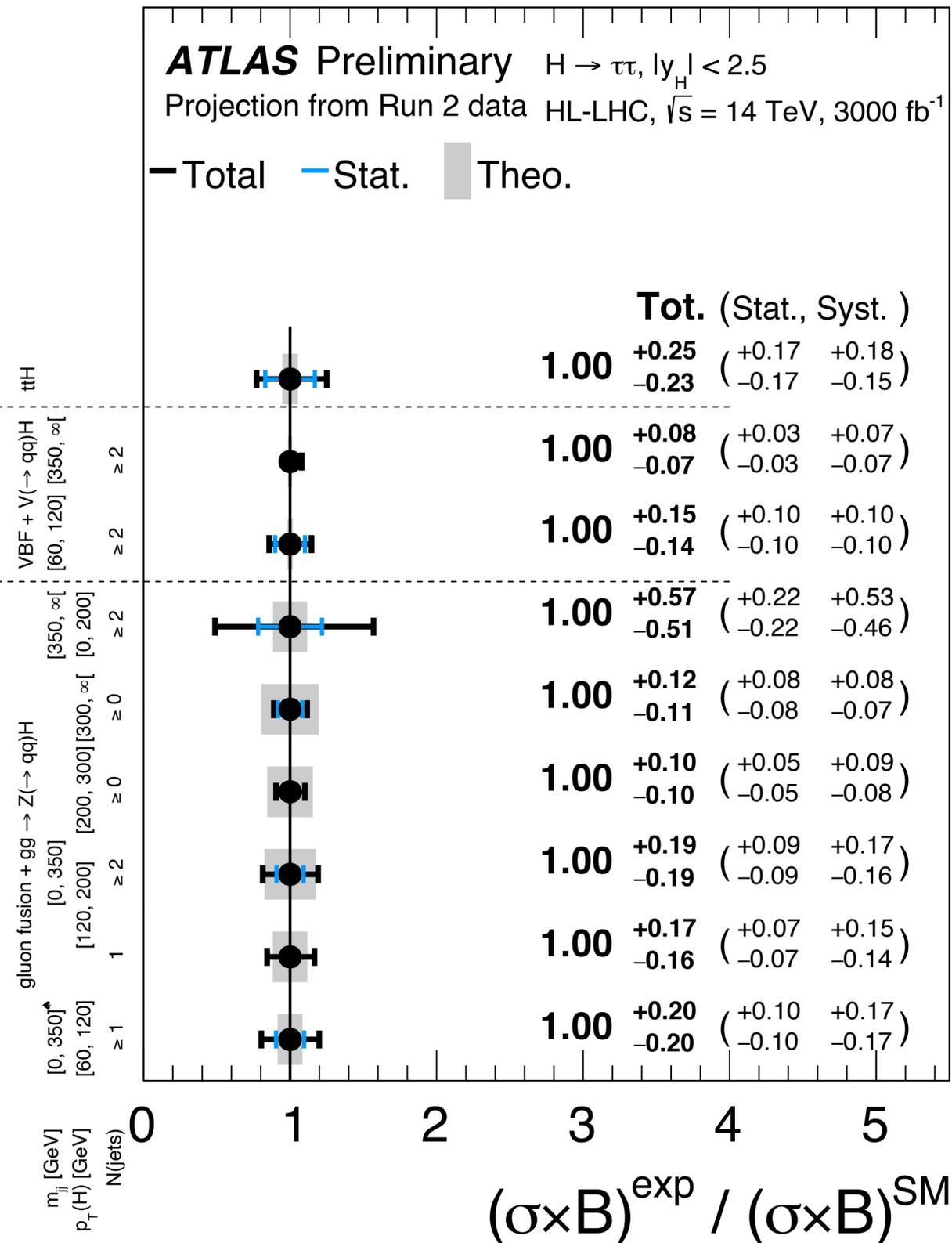
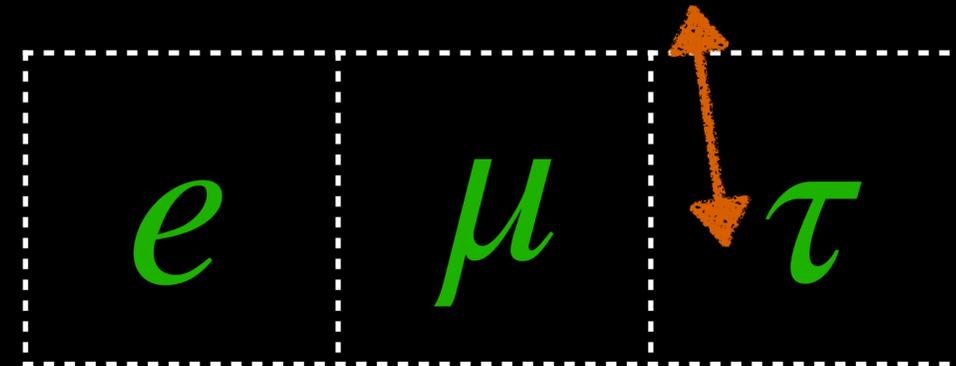




$$H \rightarrow \tau^+ \tau^-$$



# HIGGS



- Most precise mode for studying  $H \rightarrow \tau^+ \tau^-$ :
  - vector boson fusion (7% uncertainty)
- Uncertainties:
  - theoretical uncertainty on the signal
  - hadronic  $\tau$  decay



# CP structure of the Yukawa coupling between the Higgs and the tau leptons

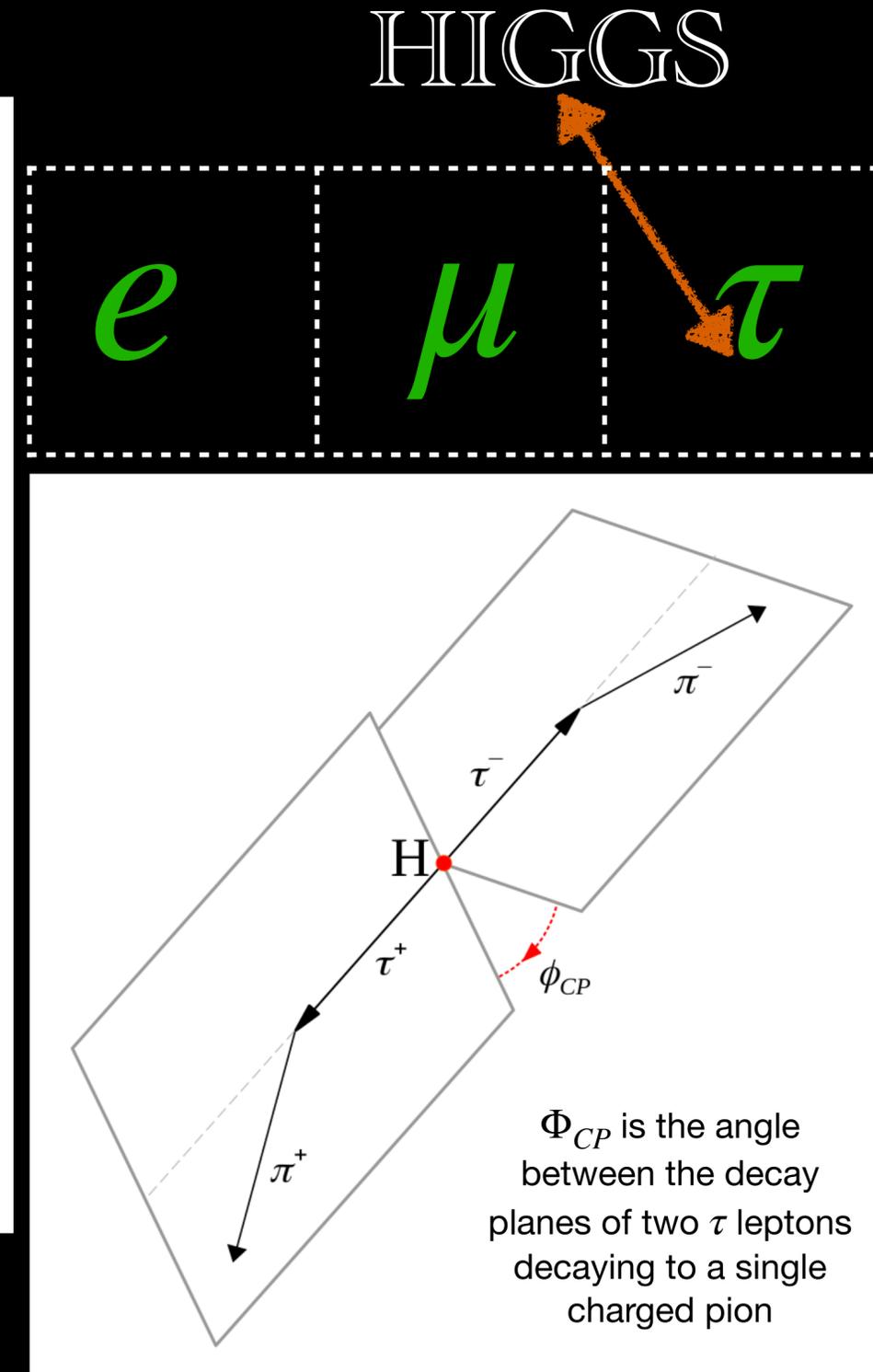
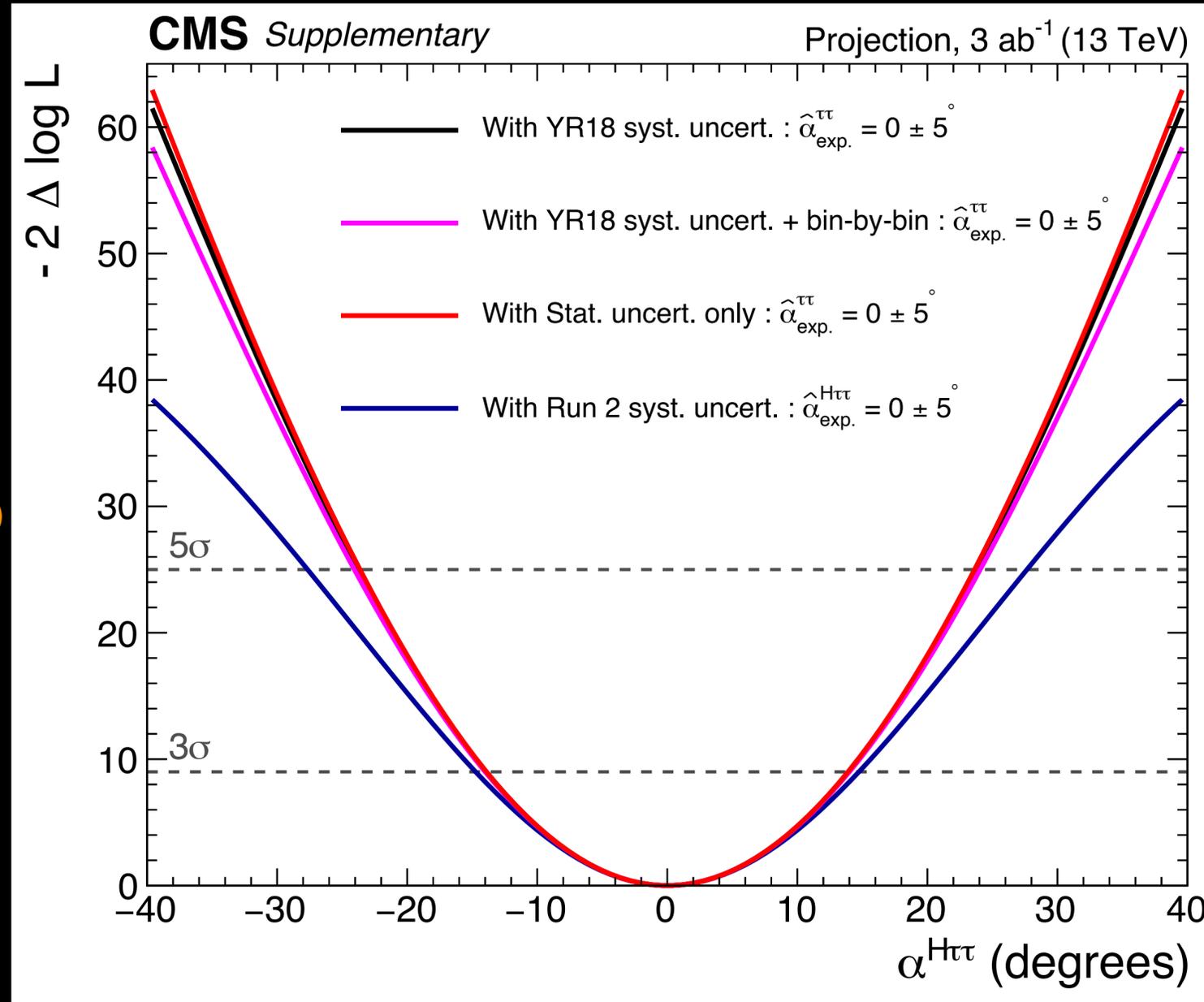
- SM Higgs is even under charge-parity (CP) inversion
- Deviation from pure CP-even state  $\Rightarrow$  new physics!

- $\mathcal{L}_Y = -\frac{m_\tau}{v} H(\kappa_\tau \bar{\tau} \tau + \tilde{\kappa}_\tau \bar{\tau} i \gamma_5 \tau)$

and mixing angle defined in terms of the coupling strength

as  $\tan(\alpha^{H\tau\tau}) = \frac{\tilde{\kappa}_\tau}{\kappa_\tau}$

- Pure scalar:  $\alpha^{H\tau\tau} = 0$
- Pseudo scalar:  $\alpha^{H\tau\tau} = 90^\circ$

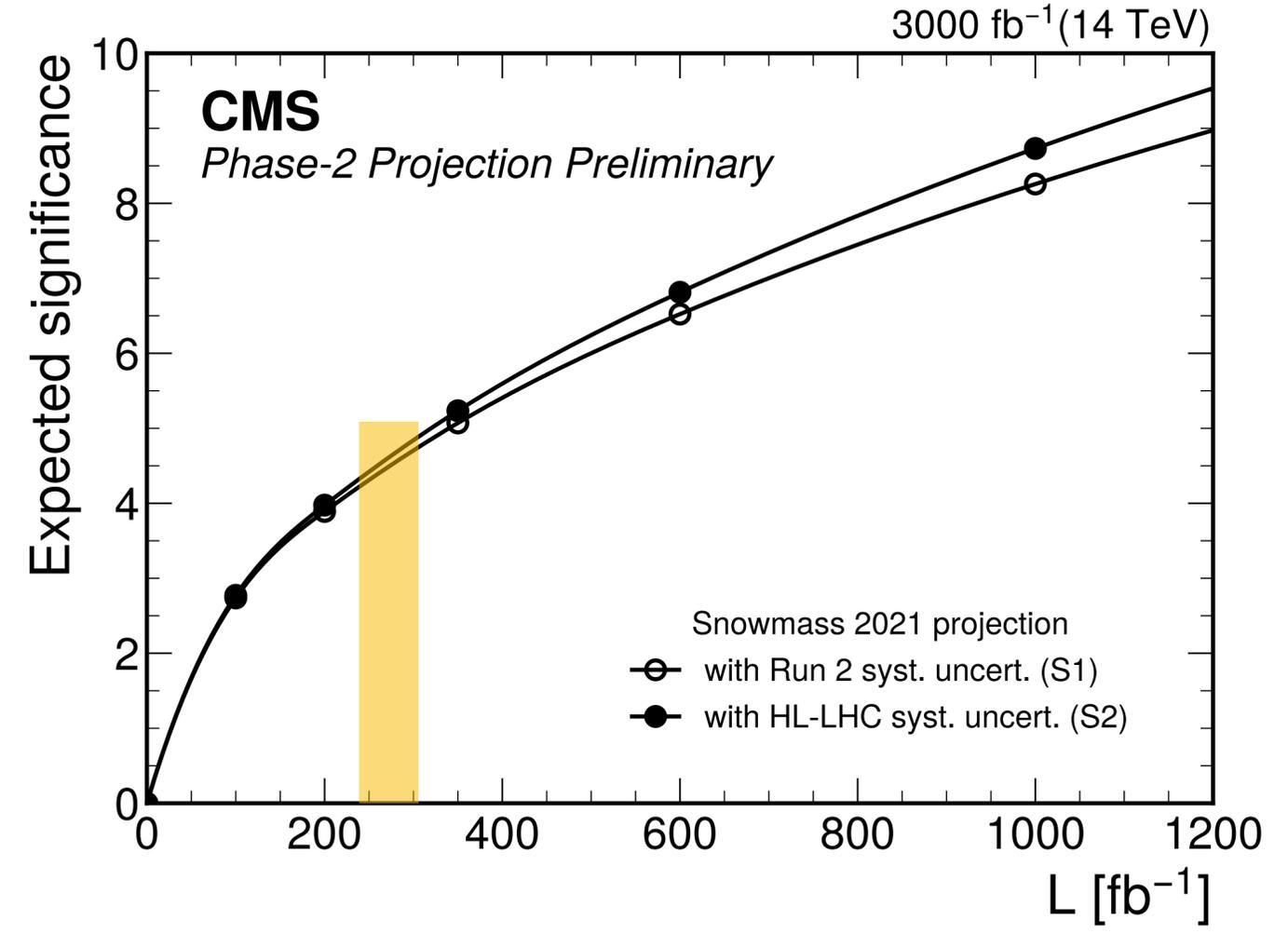
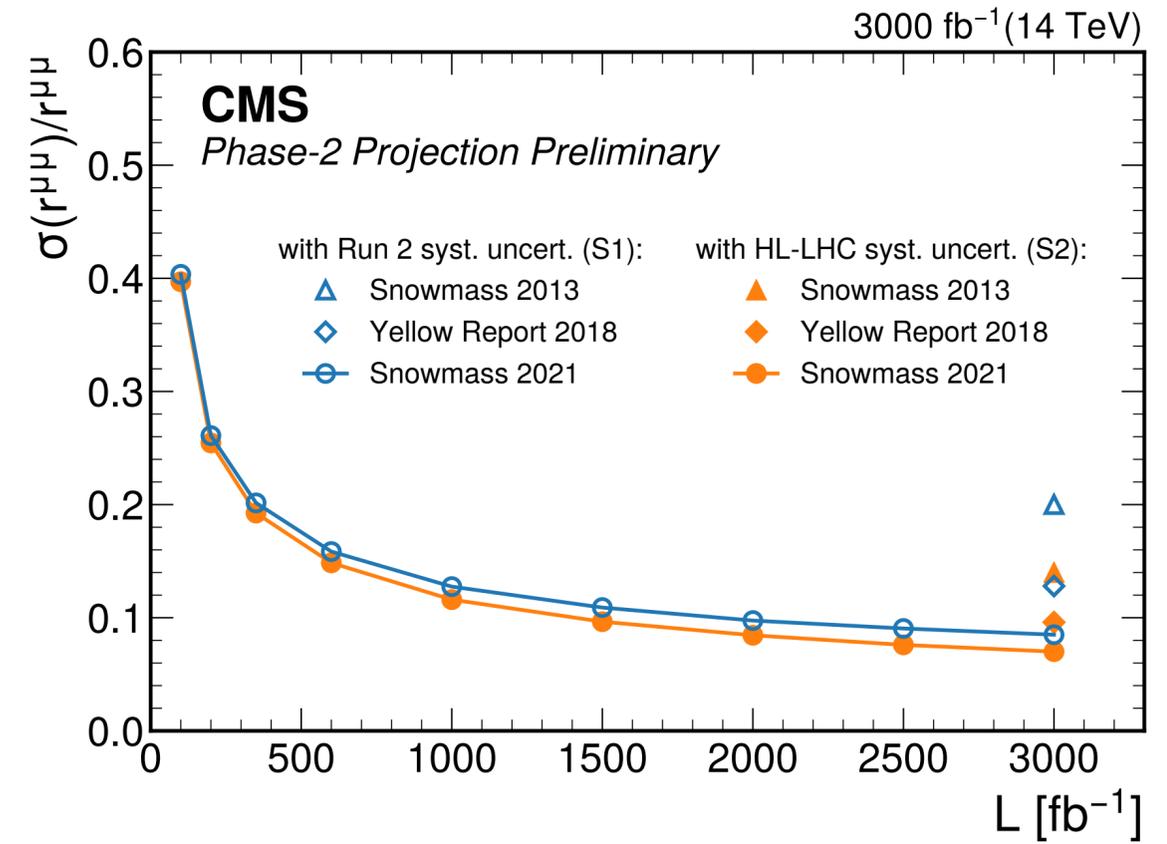
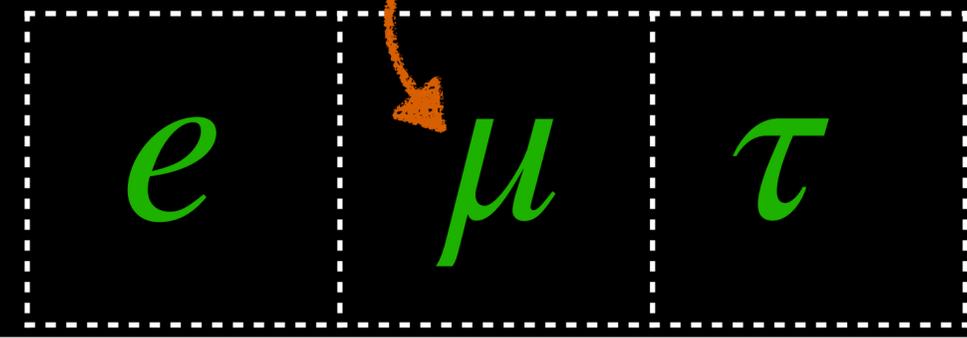




HIGGS



- $H \rightarrow \mu^+ \mu^-$  branching fraction low ( $\mathcal{B}_{SM}(H \rightarrow \mu\mu) = 2.18 \times 10^{-4}$ )
- Observed significance of  $3.0 \sigma$  possible due to excellent muon momentum resolution of the CMS detector
- Expect improved performance at the HL-LHC
- Muon  $|\eta| = 2.8 \Rightarrow 10\%$  increase in signal acceptance
- Mass resolution expected to improve by 30%



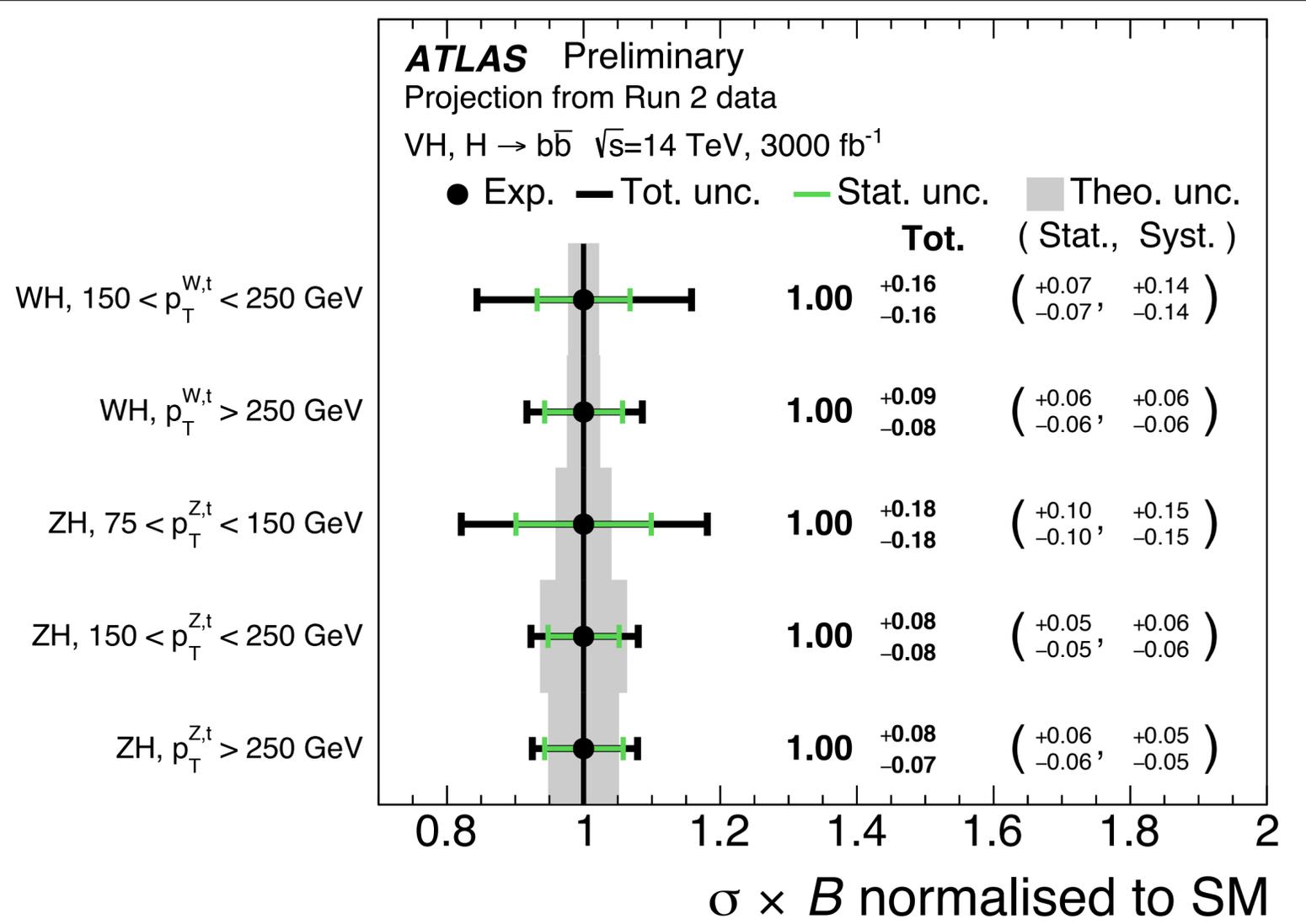
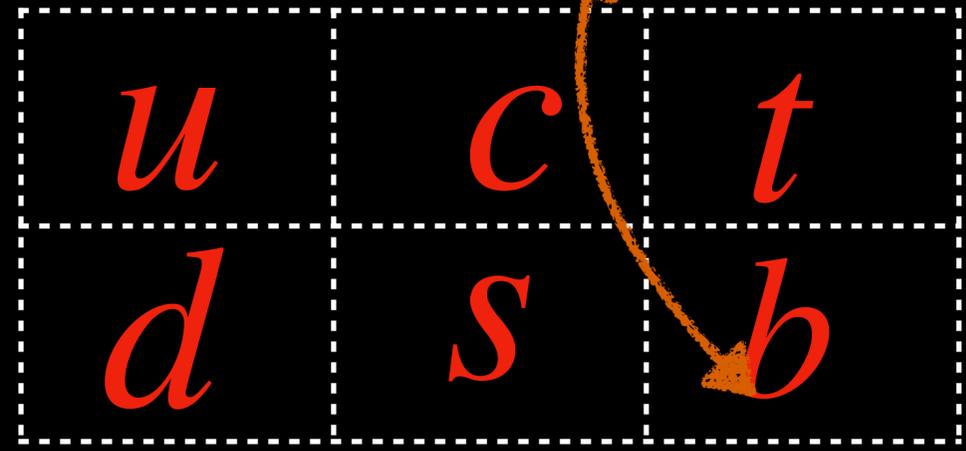


# $H \rightarrow b\bar{b}$

## HIGGS



- Higgs production in association with a vector boson  $\rightarrow$  most sensitive channel for studying  $H \rightarrow b\bar{b}$ 
  - $ZH, H \rightarrow b\bar{b}$  observed (expected) 5.3 (5.1)  $\sigma$  at Run II
- At the HL-LHC:
  - $\mu_{WH}^{b\bar{b}} = 1.00 \pm 0.04$  (stat.)  $\pm 0.07$  (syst.)
  - $\mu_{ZH}^{b\bar{b}} = 1.00 \pm 0.03$  (stat.)  $\pm 0.06$  (syst.)



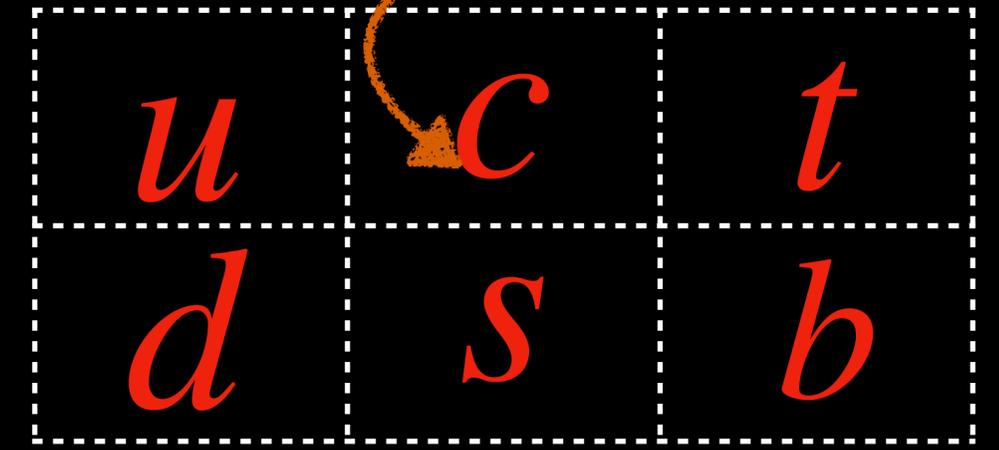
Sources of systematic uncertainty	$\Delta\mu_{ZH}^{b\bar{b}}$	$\Delta\mu_{WH}^{b\bar{b}}$
Total	0.070	0.081
Statistical	0.034	0.039
Systematic	0.063	0.070

Systematic uncertainties arise from theoretical and modeling uncertainties, experimental uncertainties and flavor tagging

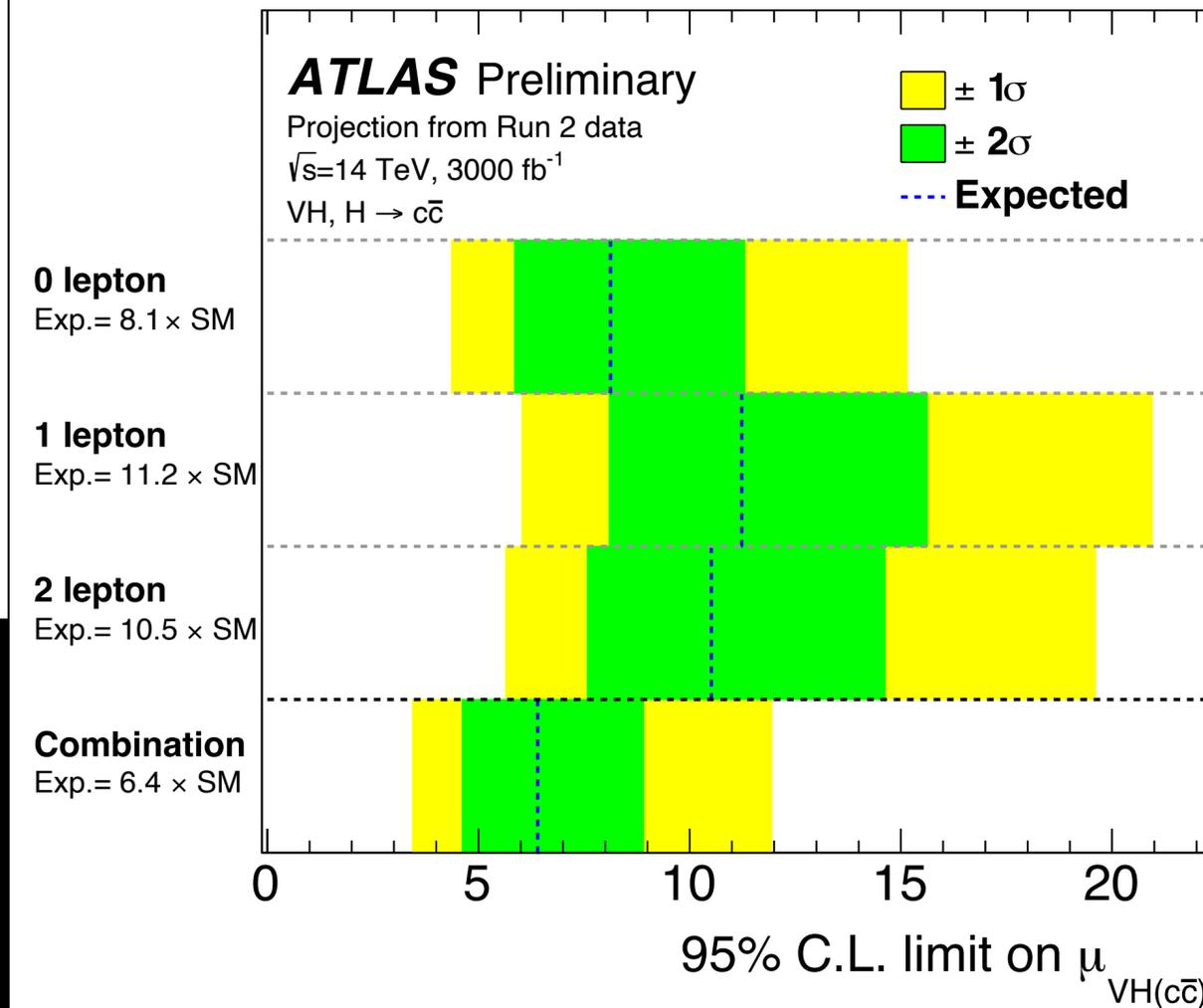
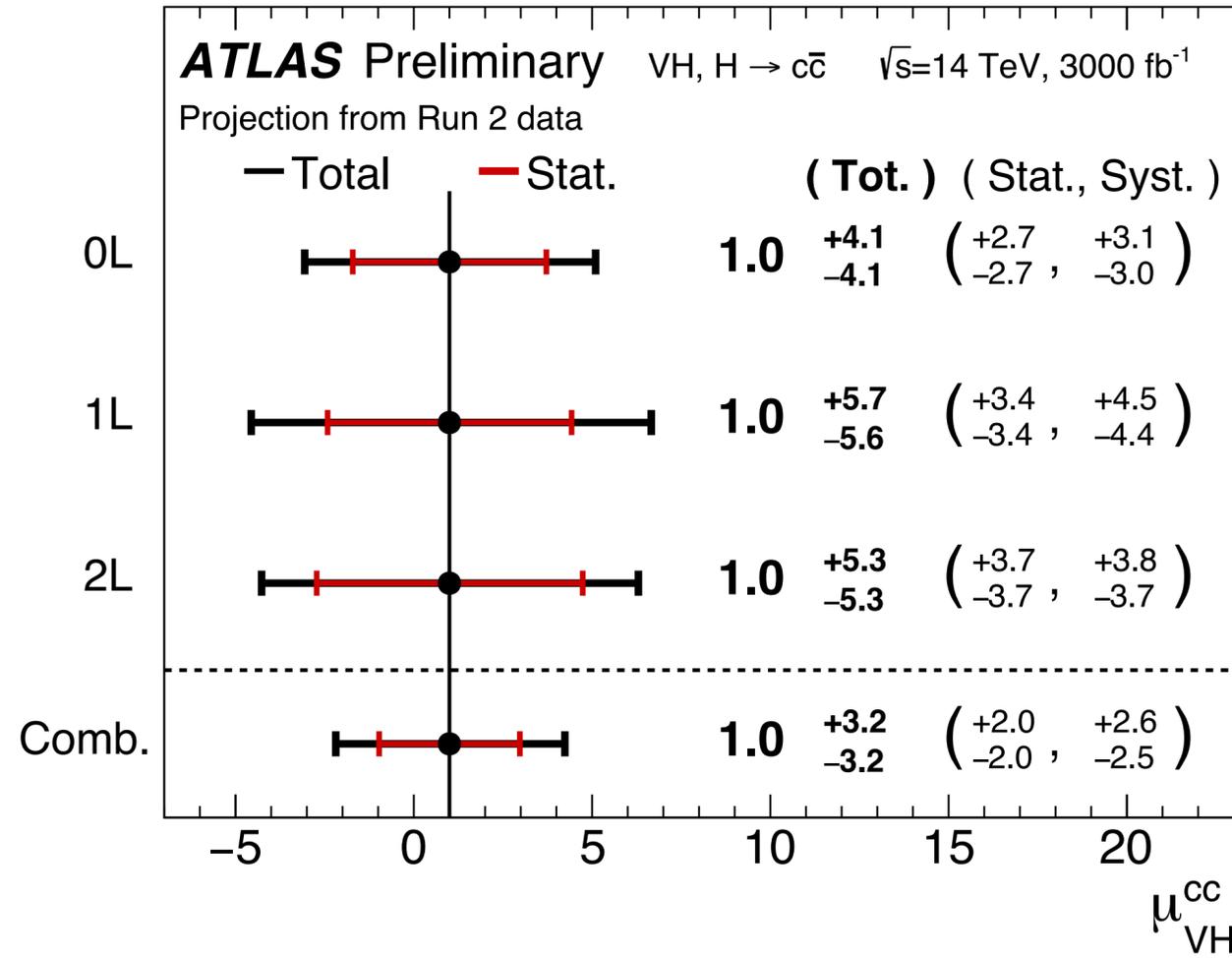


# $H \rightarrow c\bar{c}$

HIGGS



- $H \rightarrow c\bar{c}$  branching fraction is low
  - $\mathcal{B}_{SM}(H \rightarrow c\bar{c}) = 2.89 \times 10^{-2}$
- $VH, H \rightarrow c\bar{c}$  not observed yet
- Expected significance at the HL-LHC: 6.4 X SM



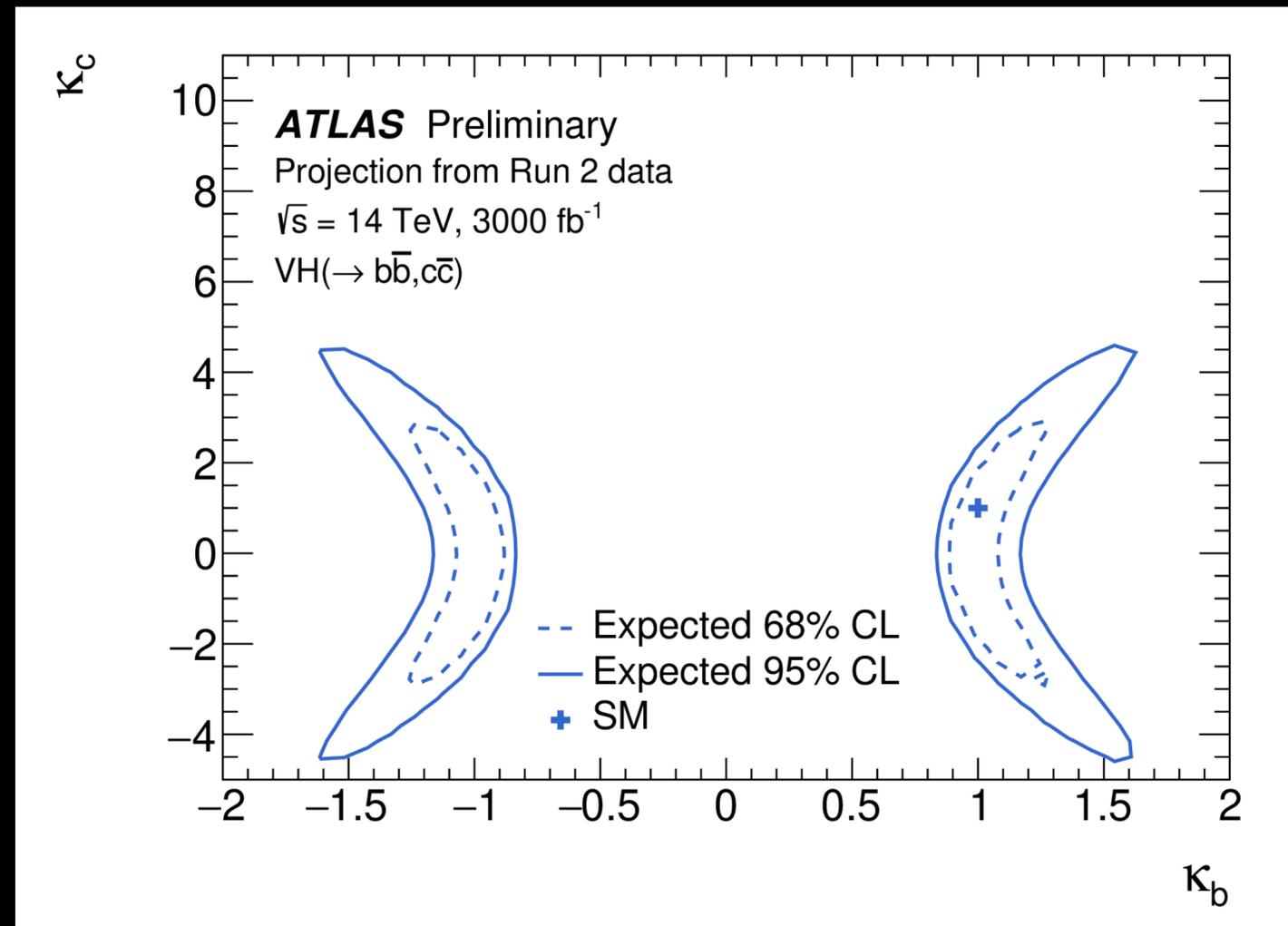
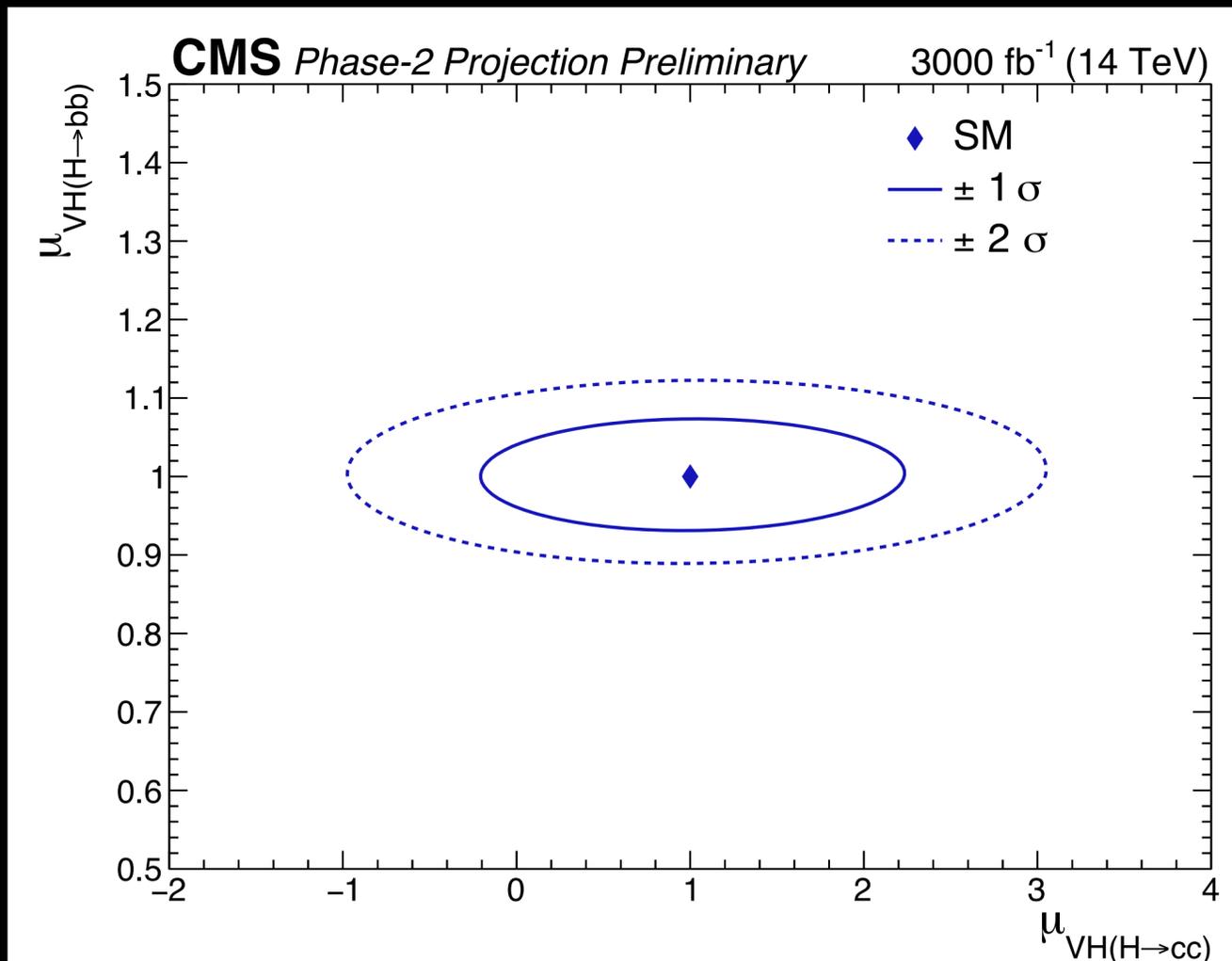
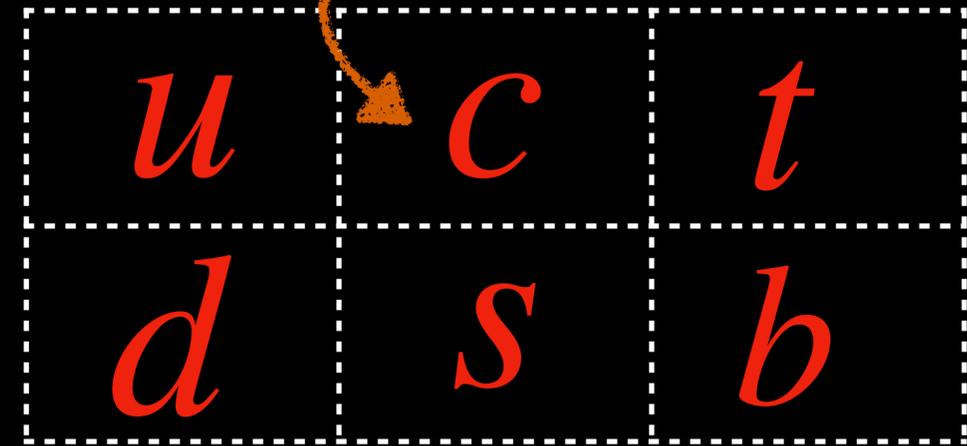
- $ZH, H \rightarrow \nu\nu b\bar{b}$ : 0 leptons
- $WH, H \rightarrow \ell\nu b\bar{b}$ : 1 lepton
- $ZH, H \rightarrow \ell\ell b\bar{b}$ : 2 leptons



$$H \rightarrow c\bar{c}$$

HIGGS

- Advanced tagging algorithms used to identify c-quark jets
- Leading uncertainty due to misidentification
- Best fit signal value:
  - $\mu_{VH} = 1.0 \pm 0.6$  (stat.)  $\pm 0.5$  (syst.)
- Interpretation in terms of the  $\kappa$ -framework



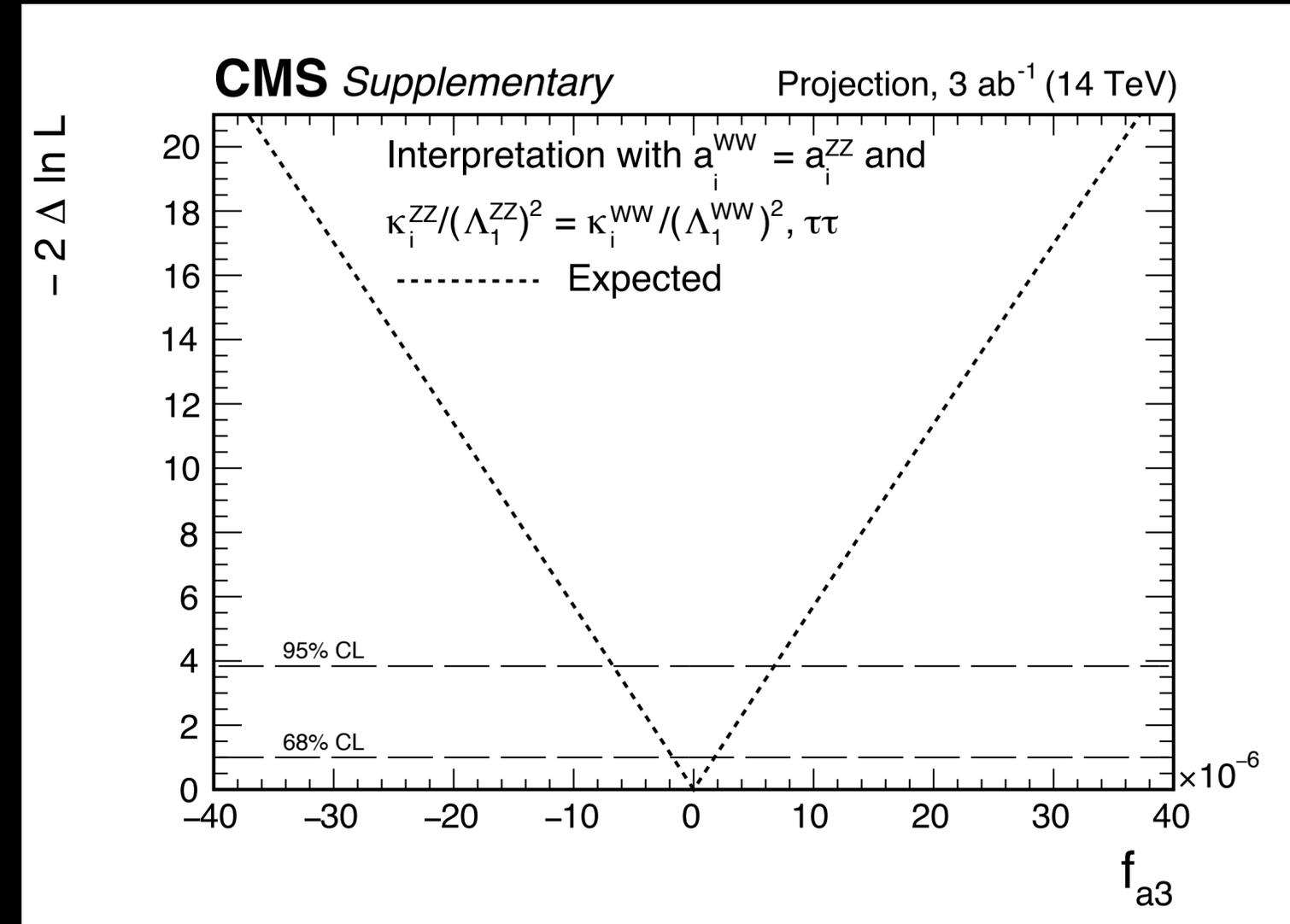


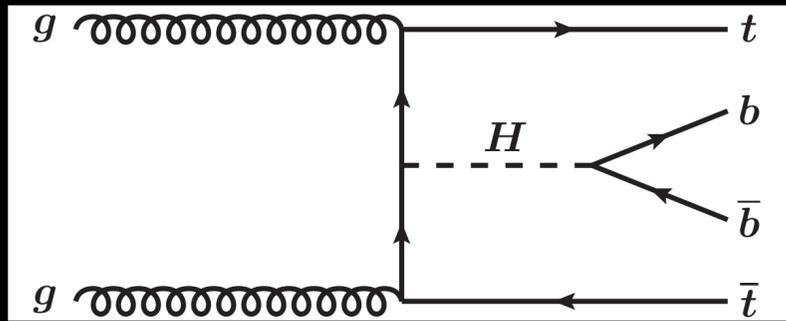
# Anomalous contributions to Higgs couplings

- $H \rightarrow \tau^+ \tau^-$  decay where the Higgs is produced by gluon fusion or associated production can be used to look for anomalous couplings
- Scattering amplitude can be parametrized as a function of coupling coefficients  $a_i^{VV}$

$$a_i^{VV} = \frac{k_i^{VV}}{(\Lambda_i^{VV})^2}$$

- Under custodial symmetry, assume  $a_i^{WW} = a_i^{ZZ}$
- Anomalous contributions expressed as a function of effective fractional contributions ( $f_{a3}$ )
- Alternate scenario takes possible CP-violation into account also explored
- Improvement by three orders of magnitude w.r.t Run II at the HL-LHC





CMS Experiment at the LHC, CERN  
 Data recorded: 2017-Oct-24 05:30:27.213248 GMT  
 Run / Event / LS: 305518 / 207815469 / 107

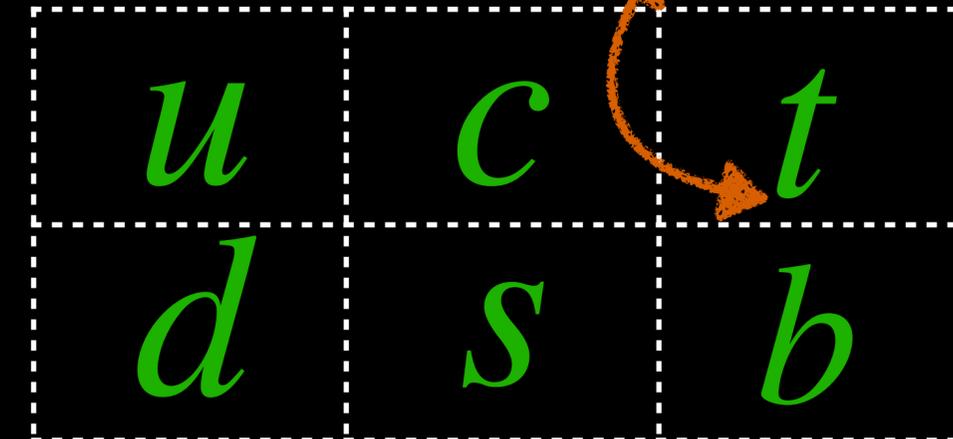
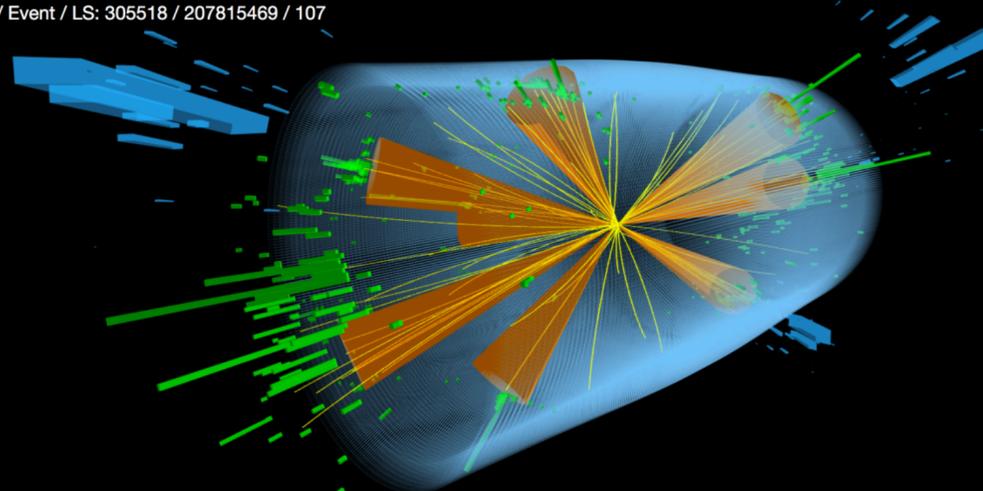
# The Higgs and the top

HIGGS

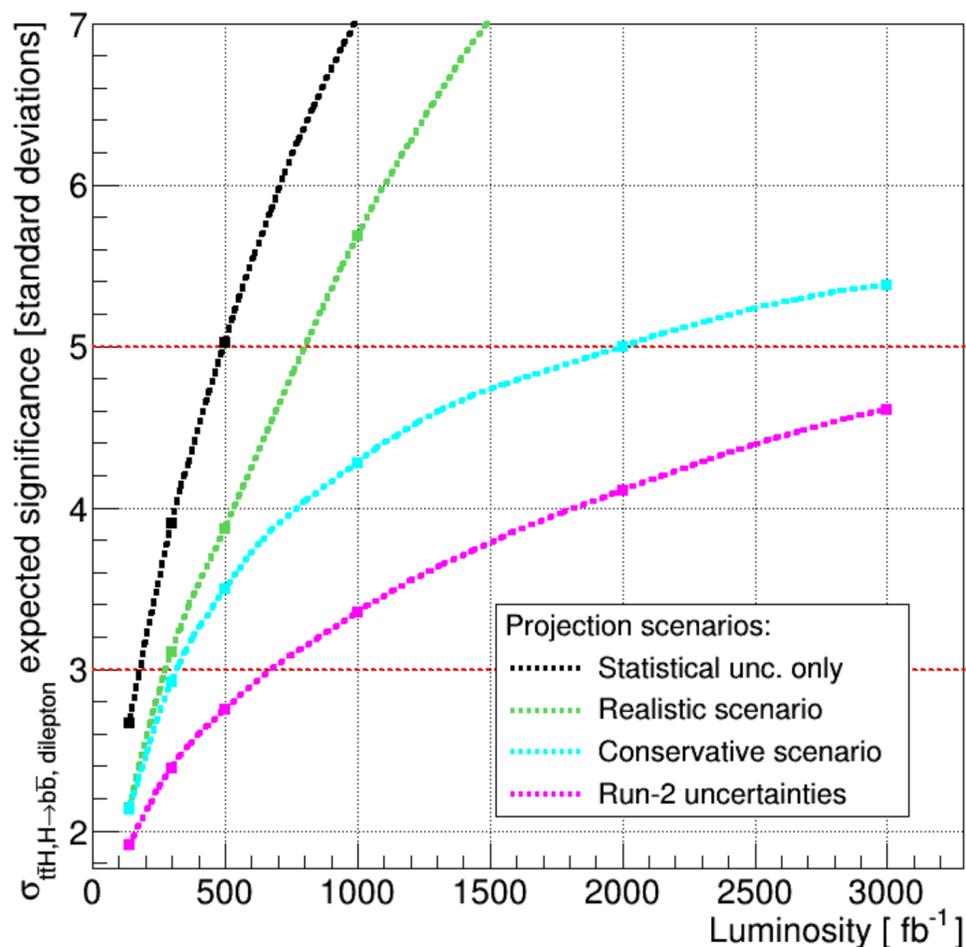


+ Delphes

$t\bar{t}H$  event in Run II  
 $t\bar{t}H$  observed with 5.2  
 $\sigma$  significance



CMS Phase-2 Projection Preliminary 14 TeV



- Evidence for  $t\bar{t}H$ ,  $H \rightarrow b\bar{b}$  at 3.9 (3.5) observed (expected)  $\sigma$  at Run II
- Projection studies performed with the use of a neural network discriminator to suppress  $t\bar{t} + b\bar{b}$  background
- Discovery with dilepton channel possible with 1/3<sup>rd</sup> of the HL-LHC integrated luminosity

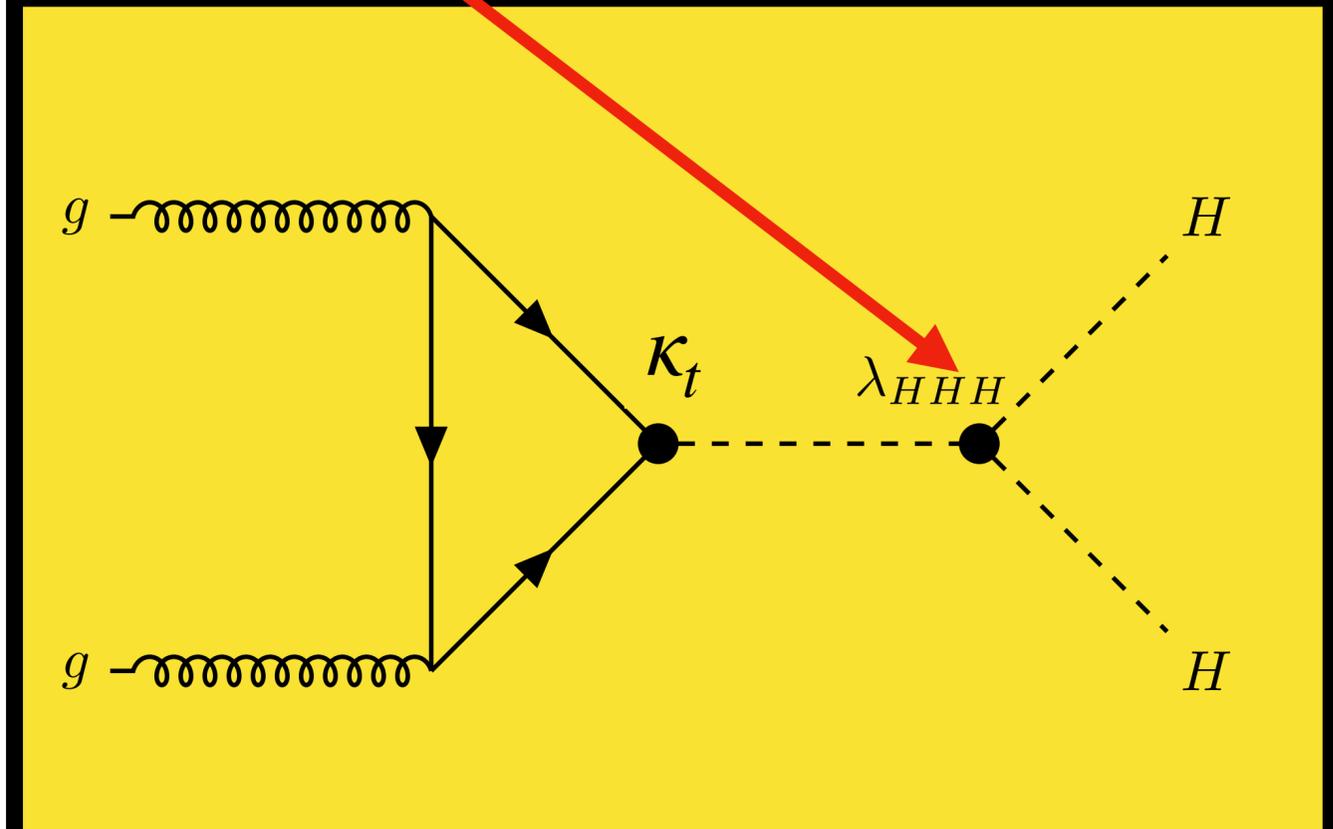
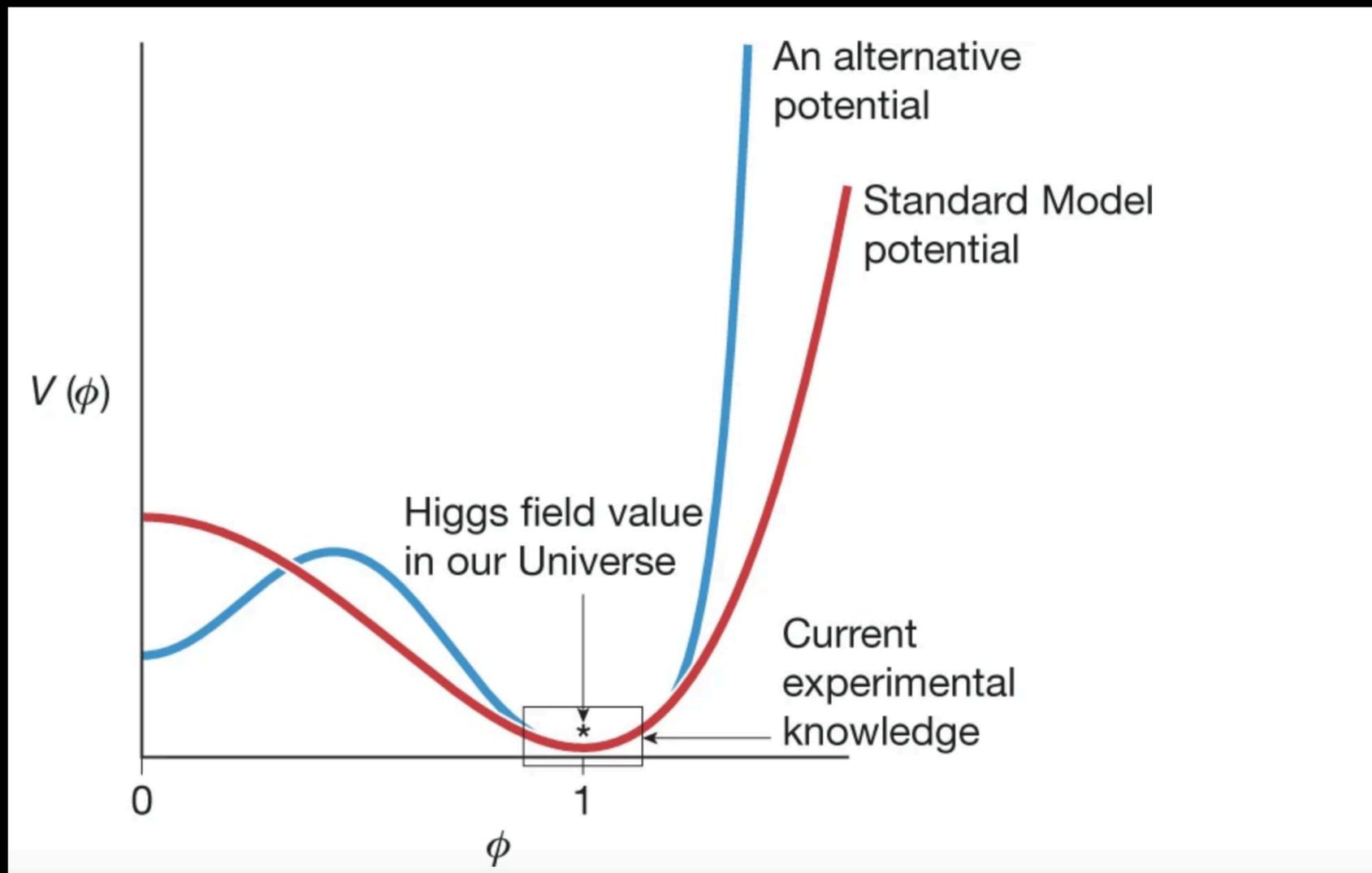
CMS Phase-2 Projection Preliminary

CMS-PAS-HIG-18-030 dilepton channel	$\mu$	tot	stat	syst
35.9 fb <sup>-1</sup> (2016) + 41.5 fb <sup>-1</sup> (2017)	1.04	+0.74 -0.71	+0.39 -0.38	+0.63 -0.59
<b>13 TeV</b>				
Realistic scenario L = 300 fb <sup>-1</sup>	1.00	+0.36 -0.33	+0.27 -0.26	+0.24 -0.20
Run-2 unc. scenario L = 3000 fb <sup>-1</sup>	1.00	+0.25 -0.23	+0.09 -0.09	+0.23 -0.21
Conservative scenario L = 3000 fb <sup>-1</sup>	1.00	+0.22 -0.17	+0.09 -0.09	+0.20 -0.14
Realistic scenario L = 3000 fb <sup>-1</sup>	1.00	+0.13 -0.12	+0.09 -0.09	+0.09 -0.08

$\hat{\mu} = \hat{\sigma} / \sigma_{SM}$

# Higgs self interaction as a probe for new physics

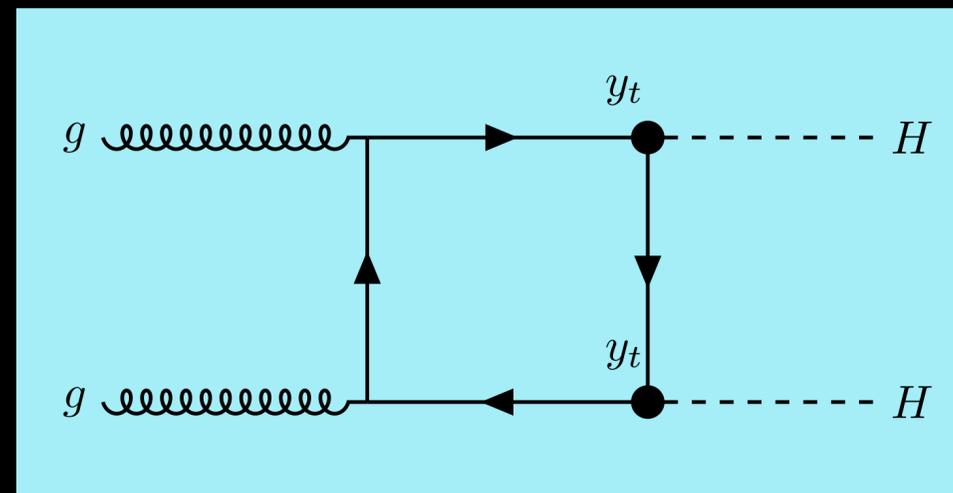
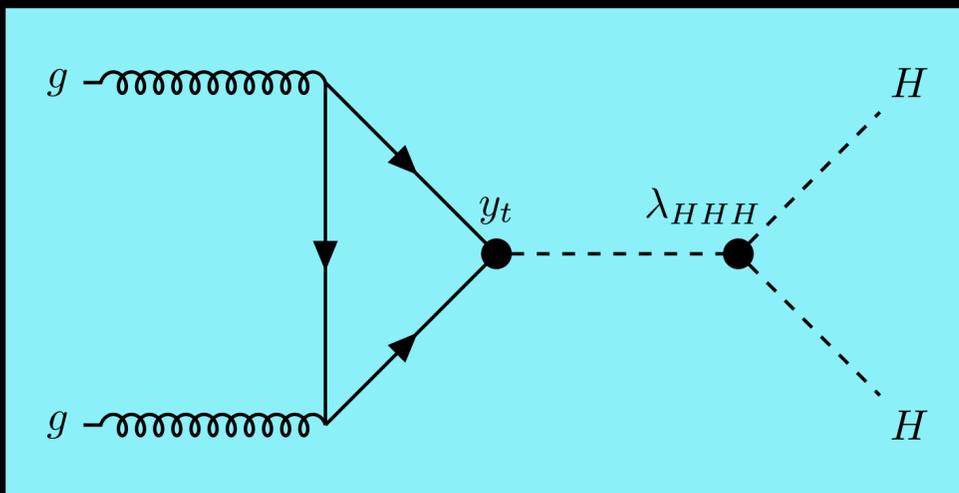
$$V = \frac{m_h^2}{2} h^2 + \frac{m_h^2}{2v} h^3 + \frac{m_h^2}{8v^2} h^4$$



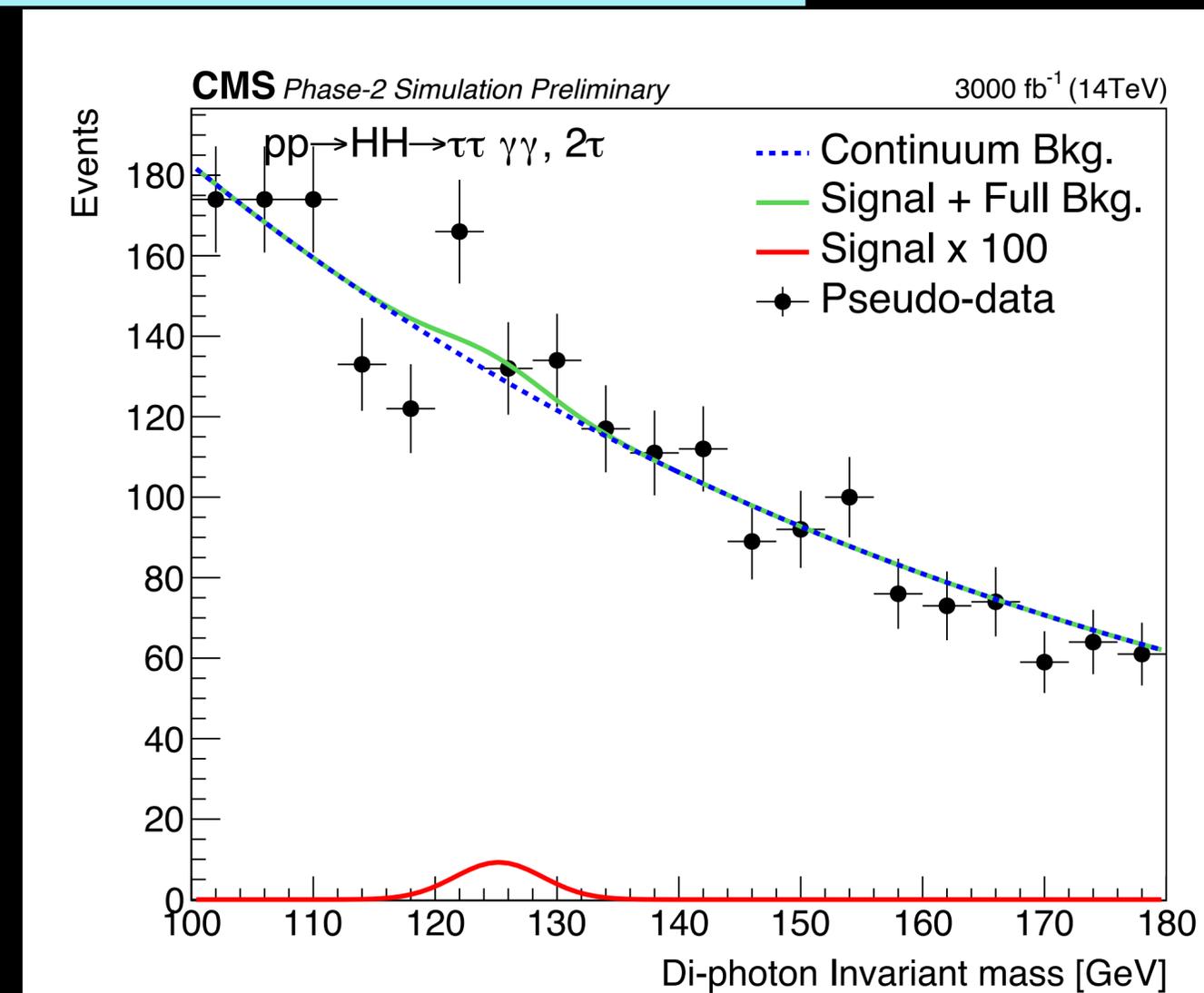
# Di-Higgs



Delphes based

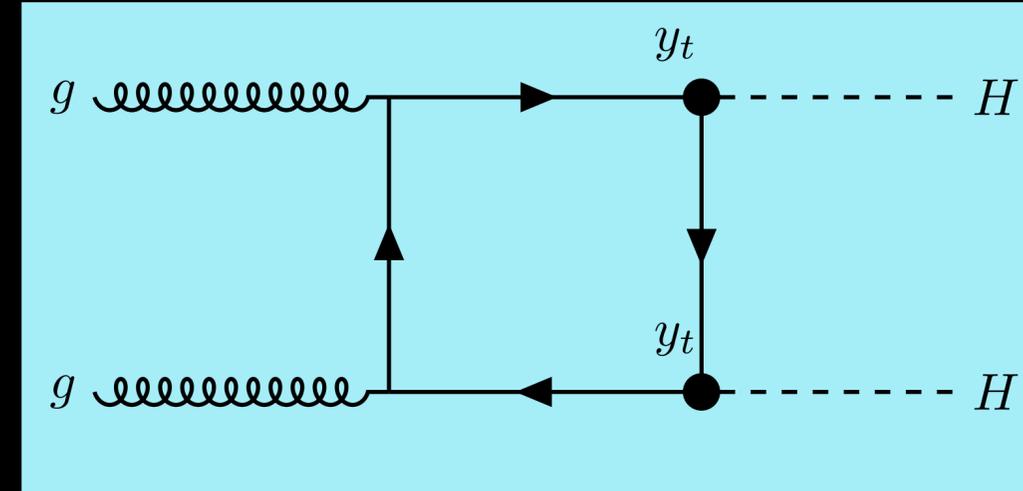
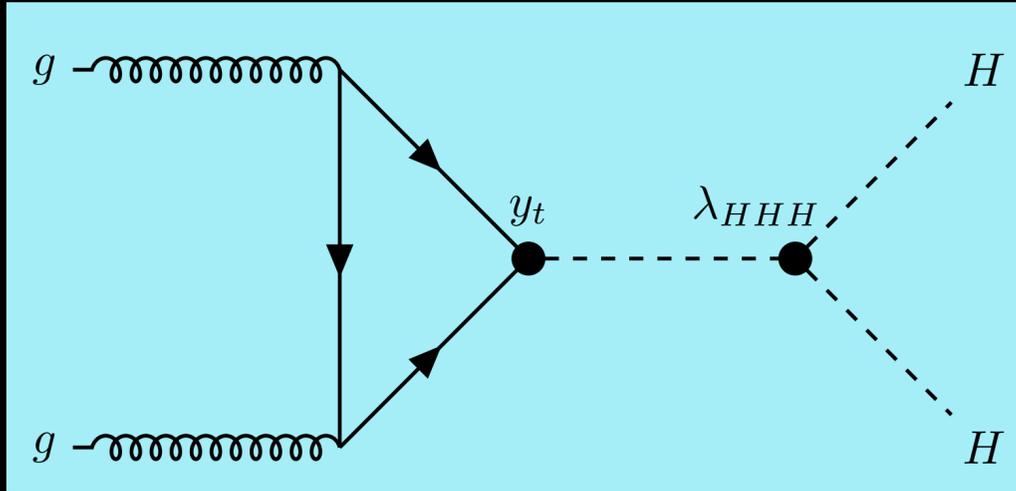


- $HH, H \rightarrow WW, H \rightarrow \gamma\gamma$  and  $HH, H \rightarrow \tau\tau, H \rightarrow \gamma\gamma$ 
  - Events further categorized after requiring diphoton pair based on # of leptons
- Deep neural network used to suppress backgrounds
- Uncertainty arises from jet energy scale,  $m_{\gamma\gamma}$  resolution, PDF +  $\alpha_s$  associated with  $ggHH$  and single  $H$  processes
- Expected significance:  $0.22\sigma$

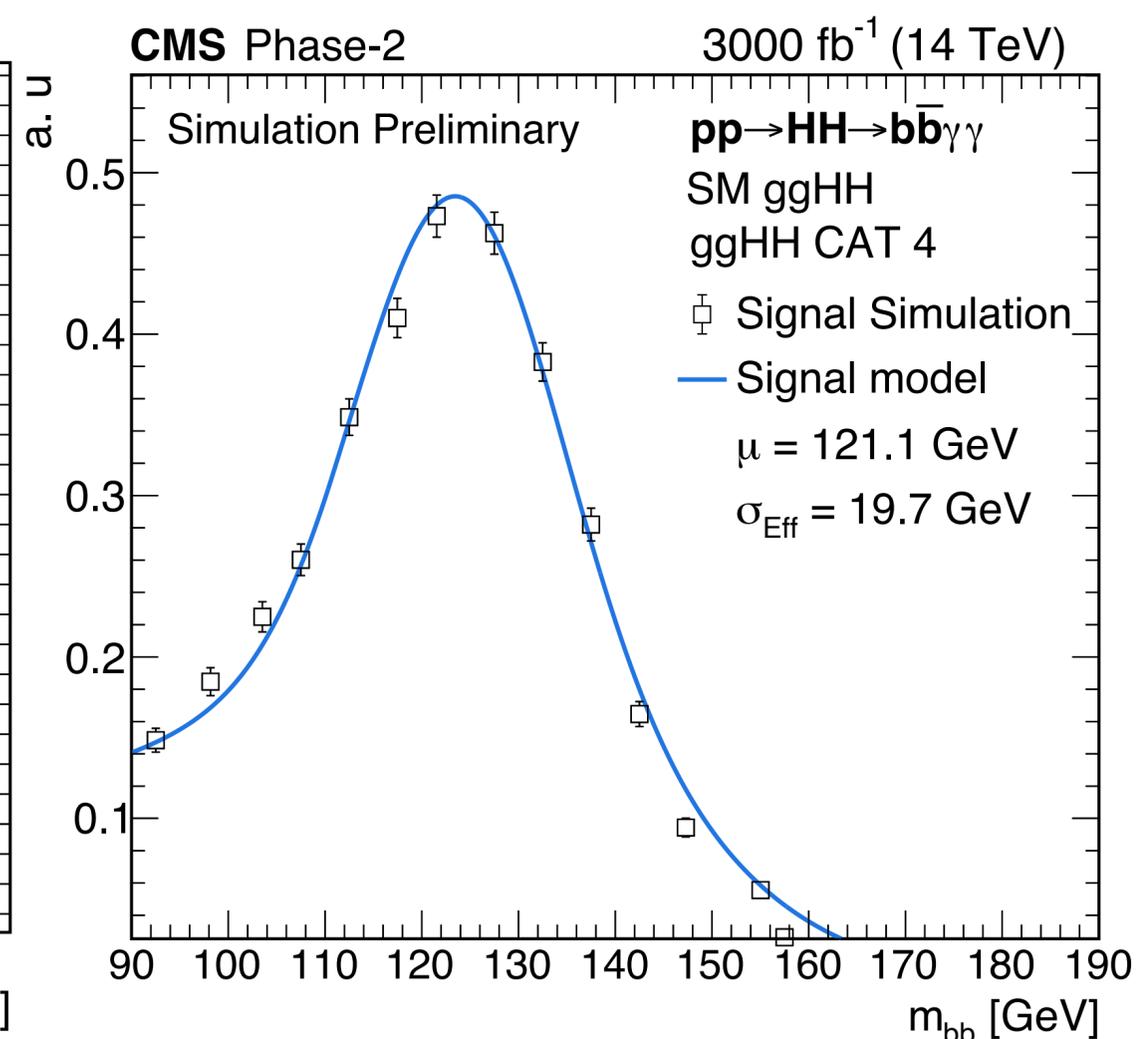
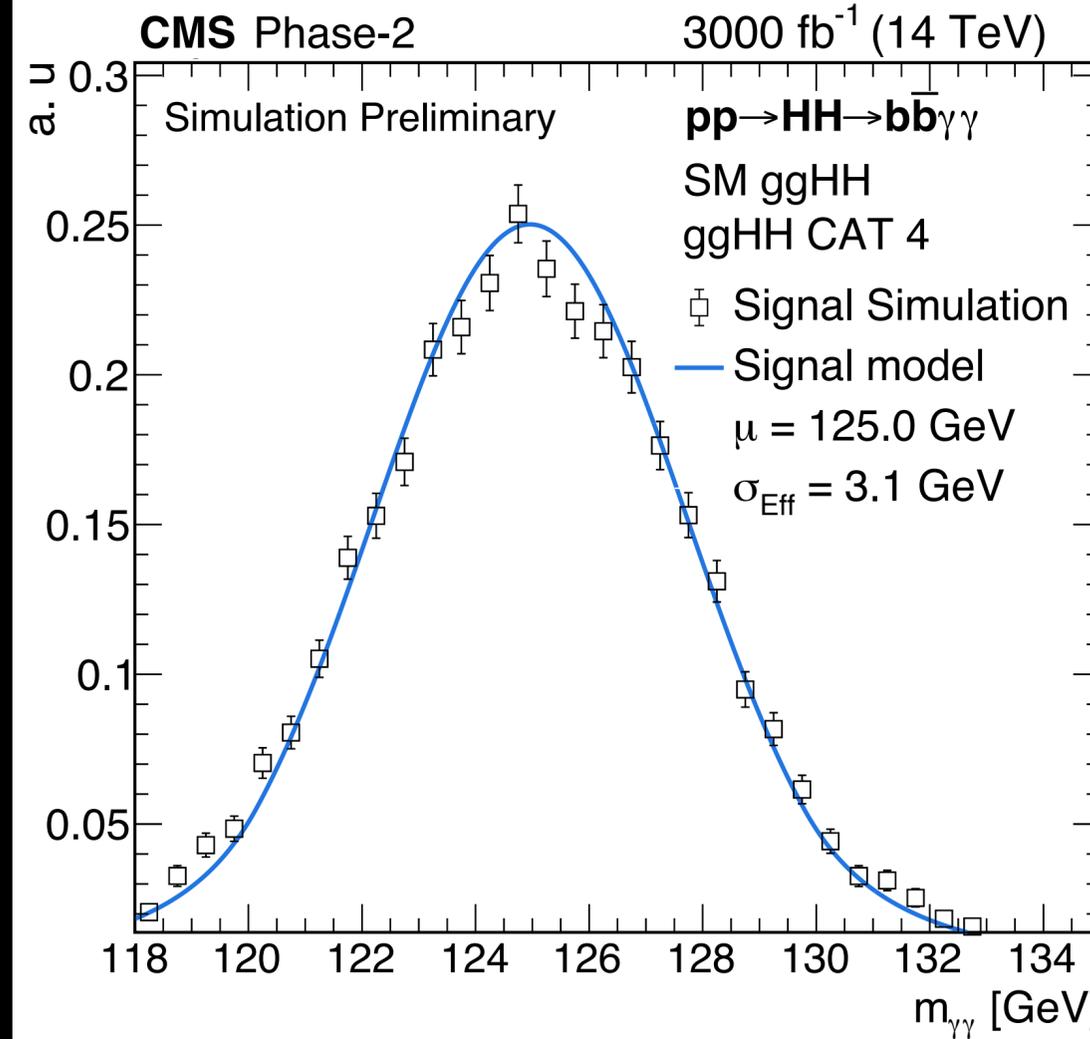


Delphes  
based

# Di-Higgs



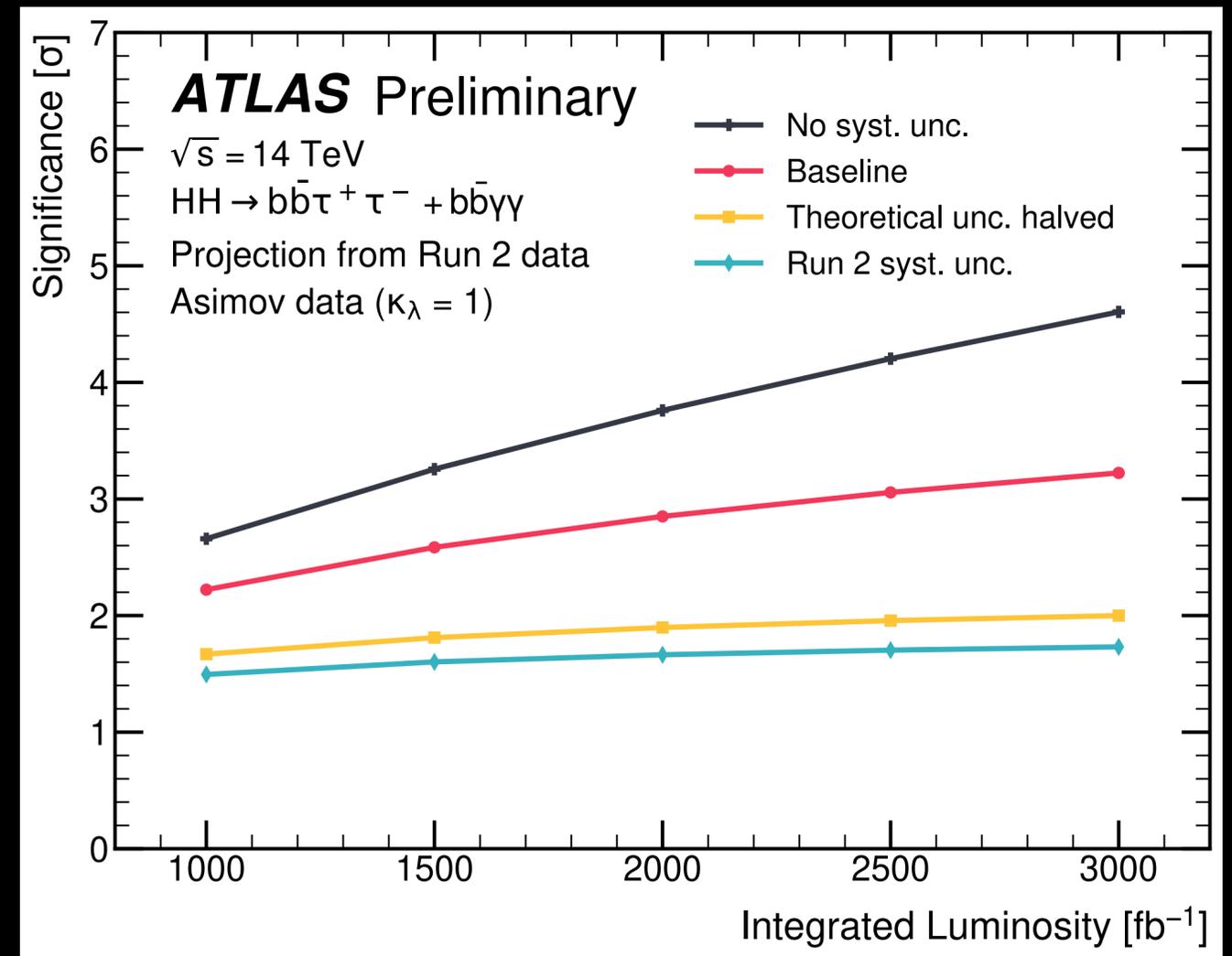
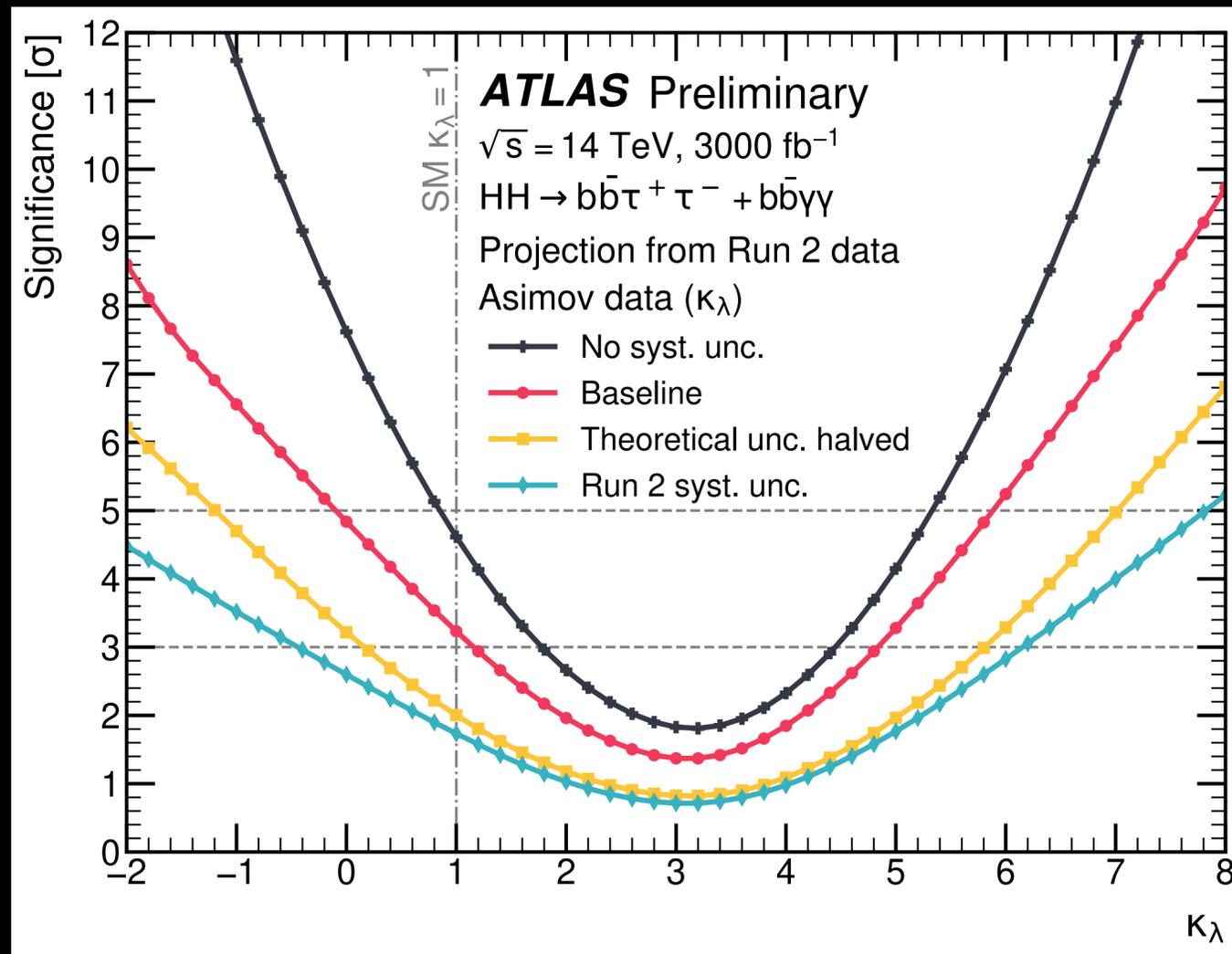
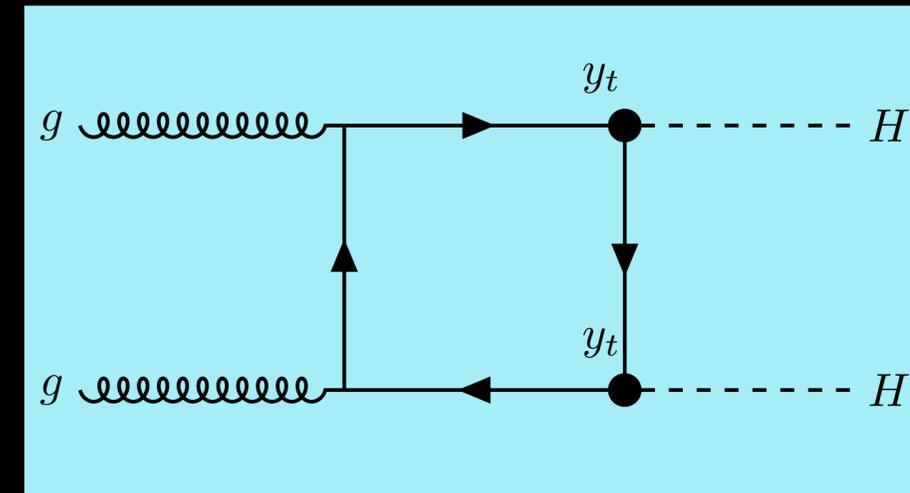
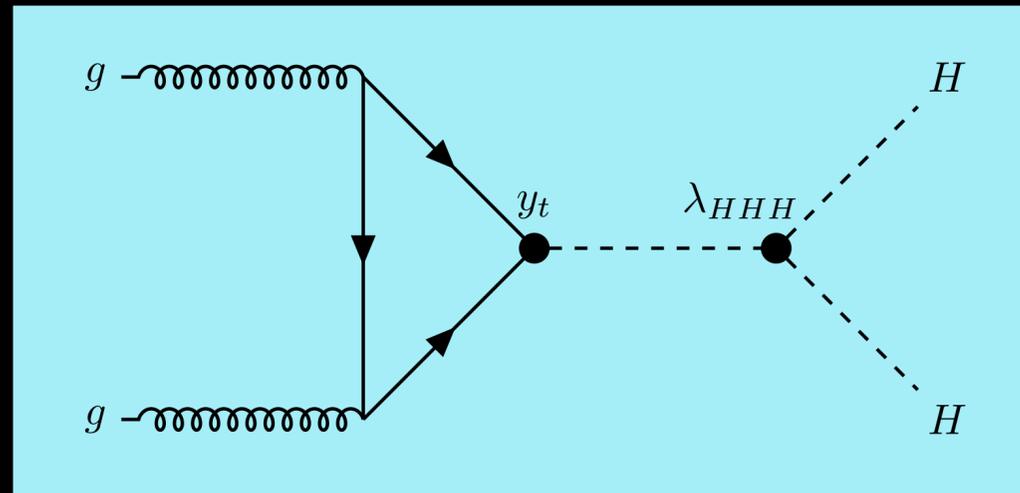
- $HH, H \rightarrow b\bar{b}, H \rightarrow \gamma\gamma$
- Uncertainty arises from  $m_{\gamma\gamma}$  and  $m_{bb}$  mass resolution
- Expected significance:
  - $2.16 \sigma$





# Di-Higgs

- $HH, H \rightarrow b\bar{b}, H \rightarrow \tau\tau$  and  $HH, H \rightarrow b\bar{b}, H \rightarrow \gamma\gamma$
- Uncertainty arises from photon efficiency,  $b$  and  $c$  tagging efficiency
- Expected significance:
  - $4.6 \sigma$  (without systematic uncertainty)
  - $3.2 \sigma$  (with systematic uncertainty)

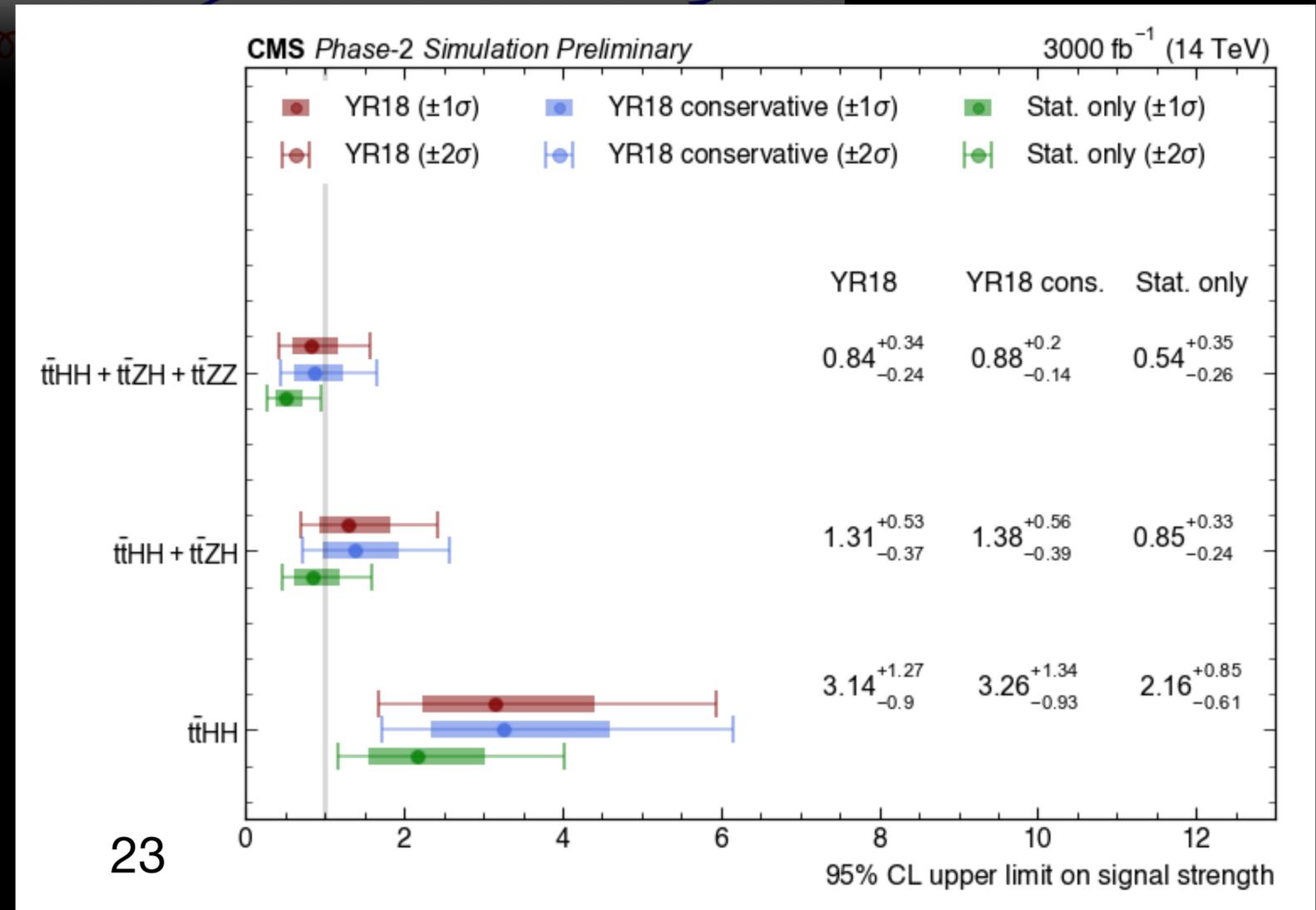
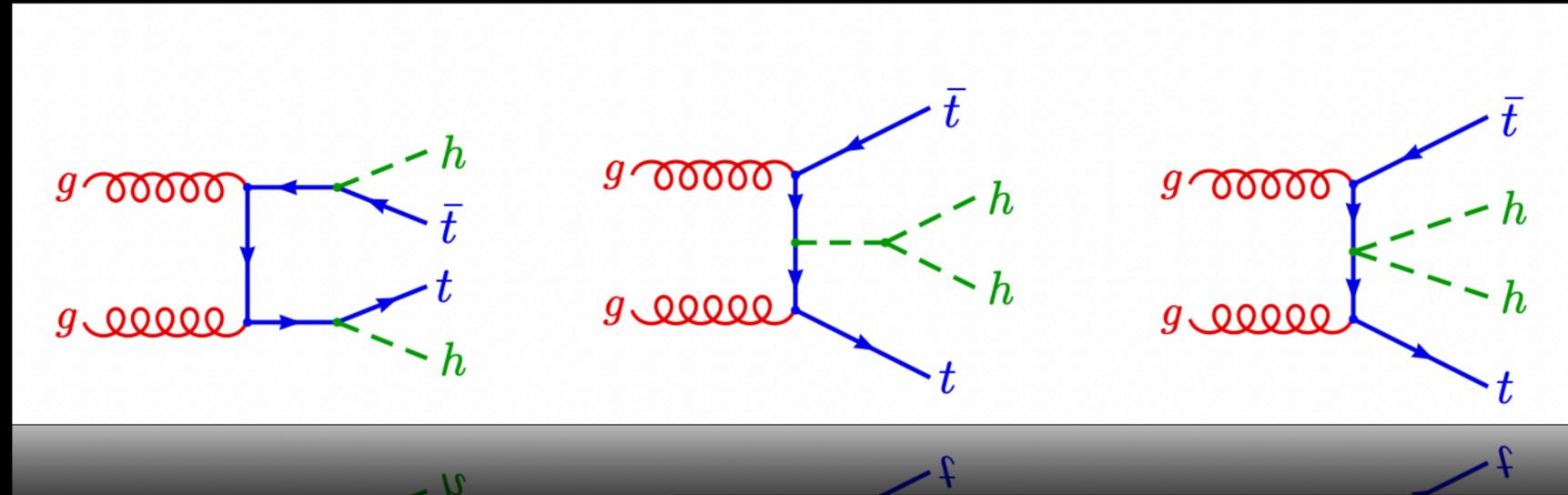


# The DiHiggs and the top

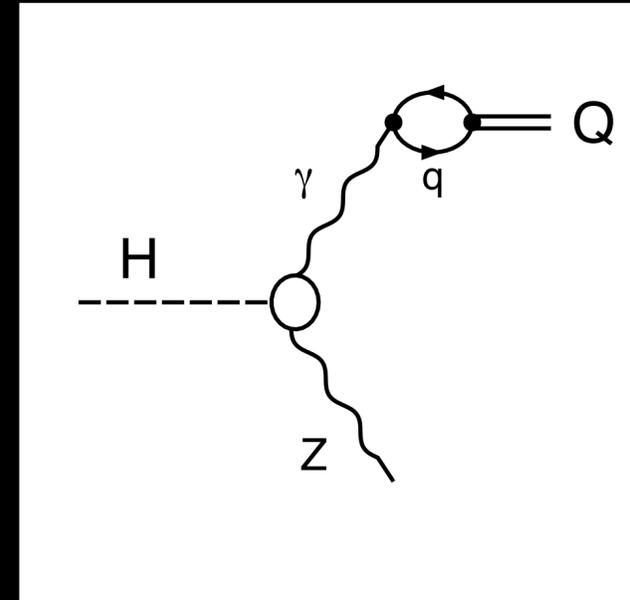
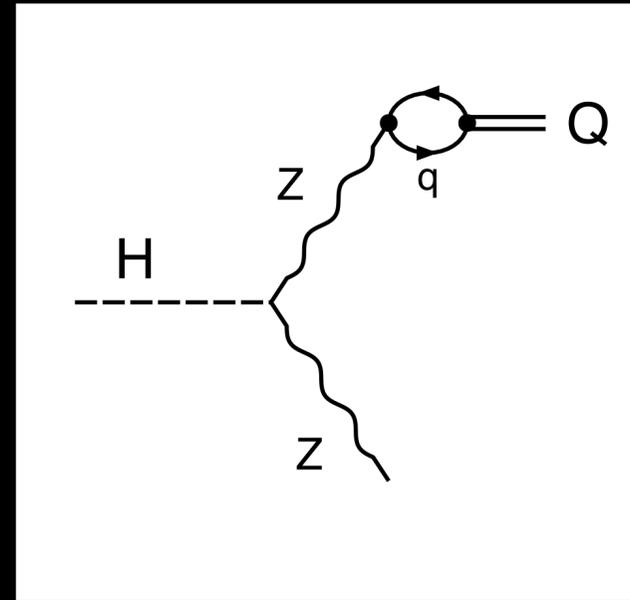
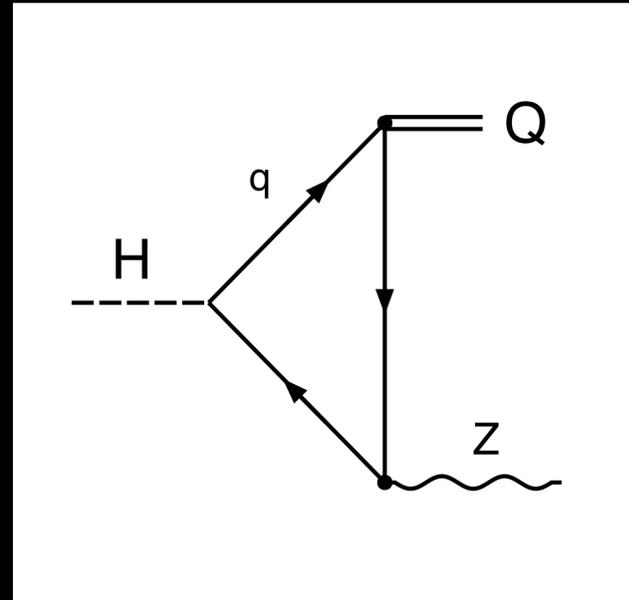


Delphes based

- Cross section of  $t\bar{t}HH$  is 0.948 fb
- Topology under exploration:
  - $H \rightarrow b\bar{b}, t \rightarrow Wb, (W \rightarrow l\nu, qq')$
- Deep neural network based discriminators used to separate signal from background
- Systematic uncertainties associated with jet energy scale, resolution and b-tagging
- Combined production  $t\bar{t}ZZ + t\bar{t}ZH + t\bar{t}HH$ : 0.84 X SM at 95% C.L. at HL-LHC

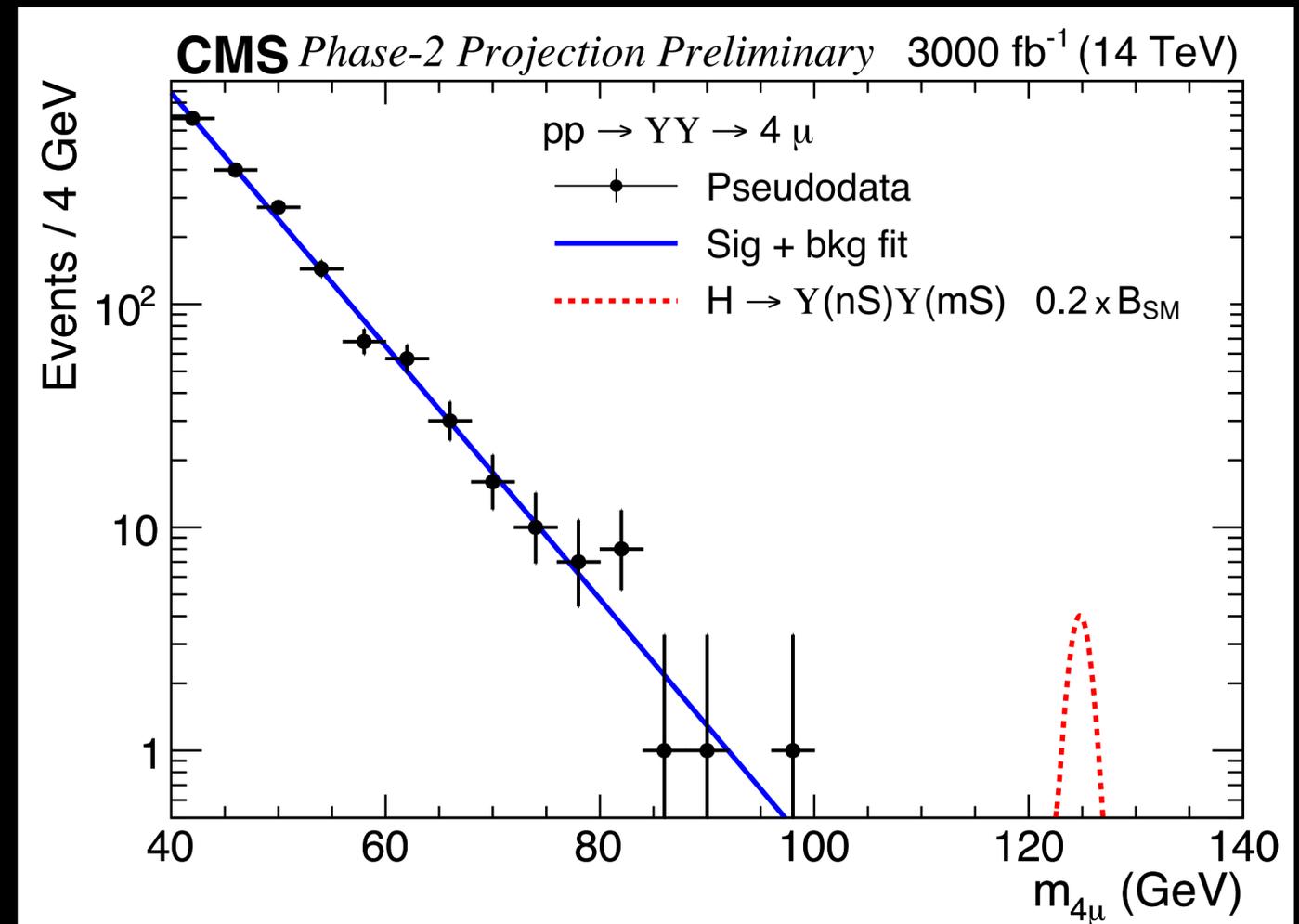


# Search for rare Higgs boson with mesons



- $H \rightarrow Z J/\psi$  and  $H \rightarrow \Upsilon\Upsilon$  studied
- Uncertainty arises from PDF +  $\alpha_s$

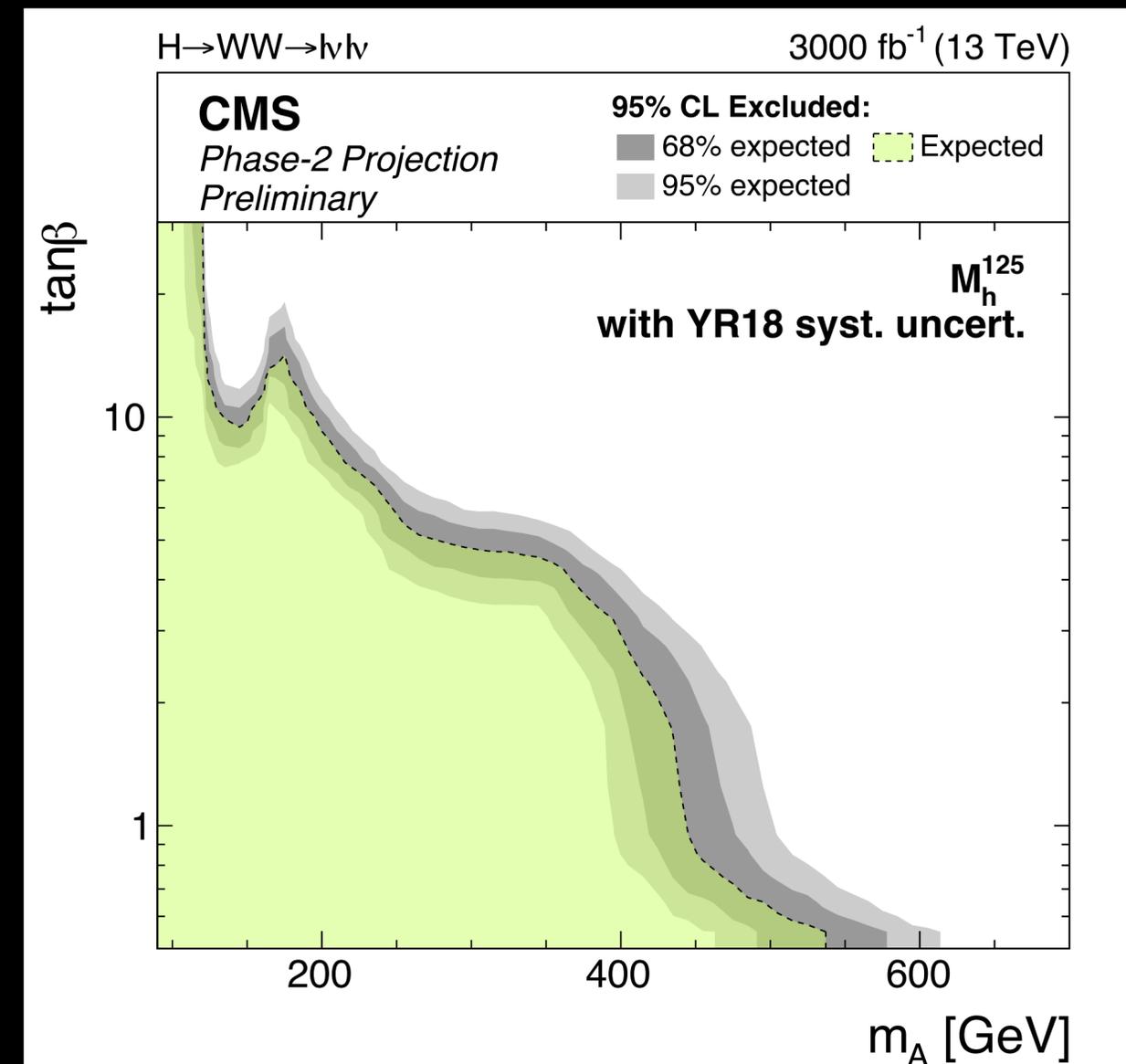
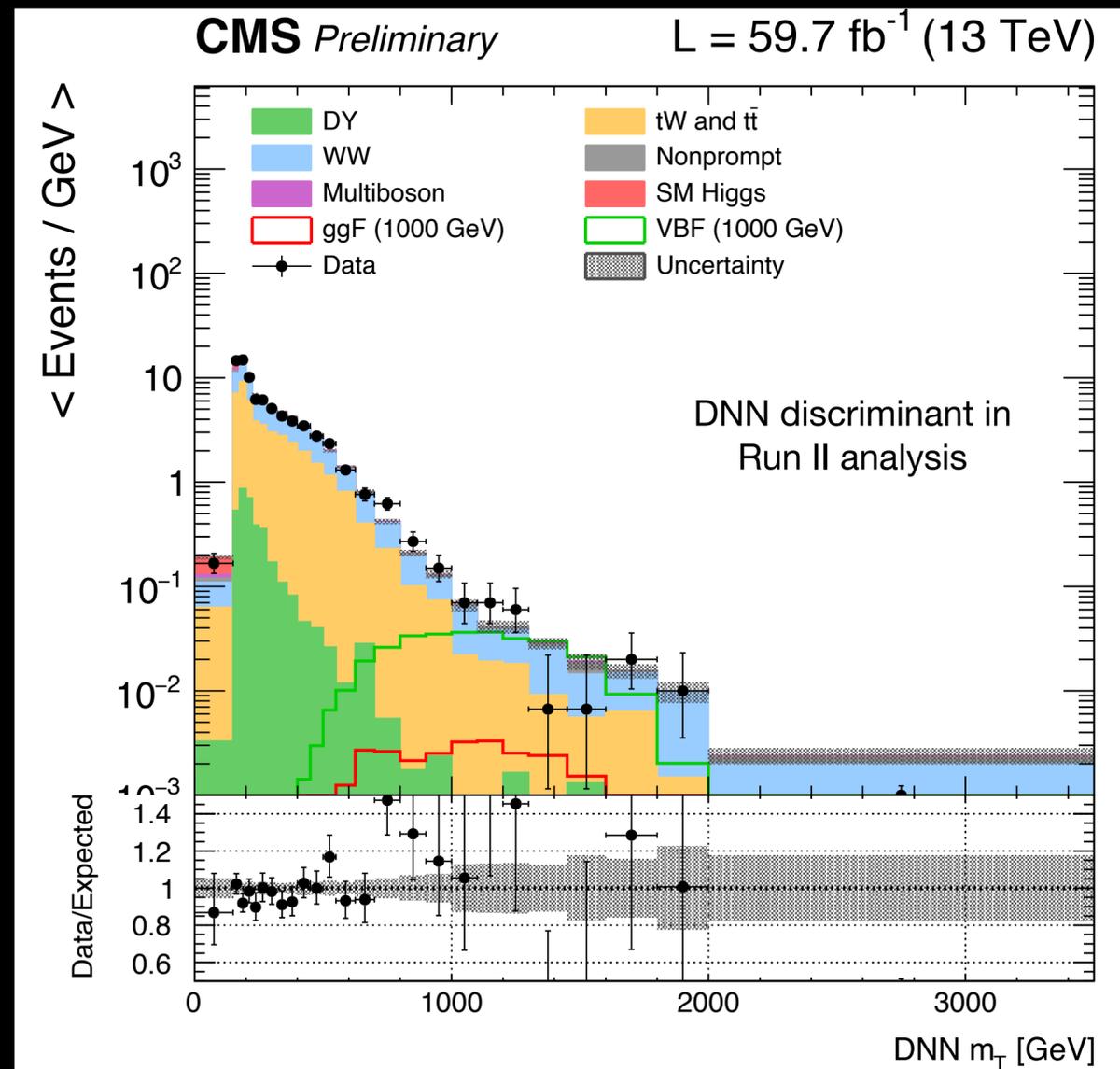
Channel	3000 fb <sup>-1</sup>	4500 fb <sup>-1</sup>
$H \rightarrow Z J/\psi$	$2.9 \times 10^{-4}$	$2.7 \times 10^{-4}$
$H \rightarrow \Upsilon\Upsilon$	$1.3 \times 10^{-5}$	$8.5 \times 10^{-6}$



# Search for high mass resonances decaying to $W^+W^-$



- Fully leptonic modes of the  $W$ -boson
- Mass range: 115 GeV - 5 TeV considered
- Classification of signal categories and backgrounds done using a deep neural network
  - DNN trained with kinematic variables
- MSSM scenarios: sensitive to low values of  $m_A$  and  $\tan\beta$

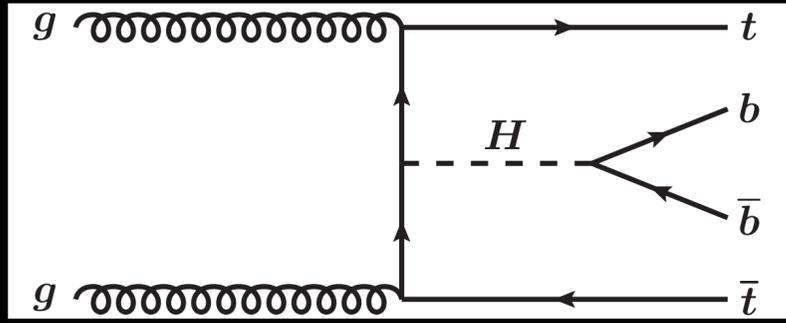


# Conclusion

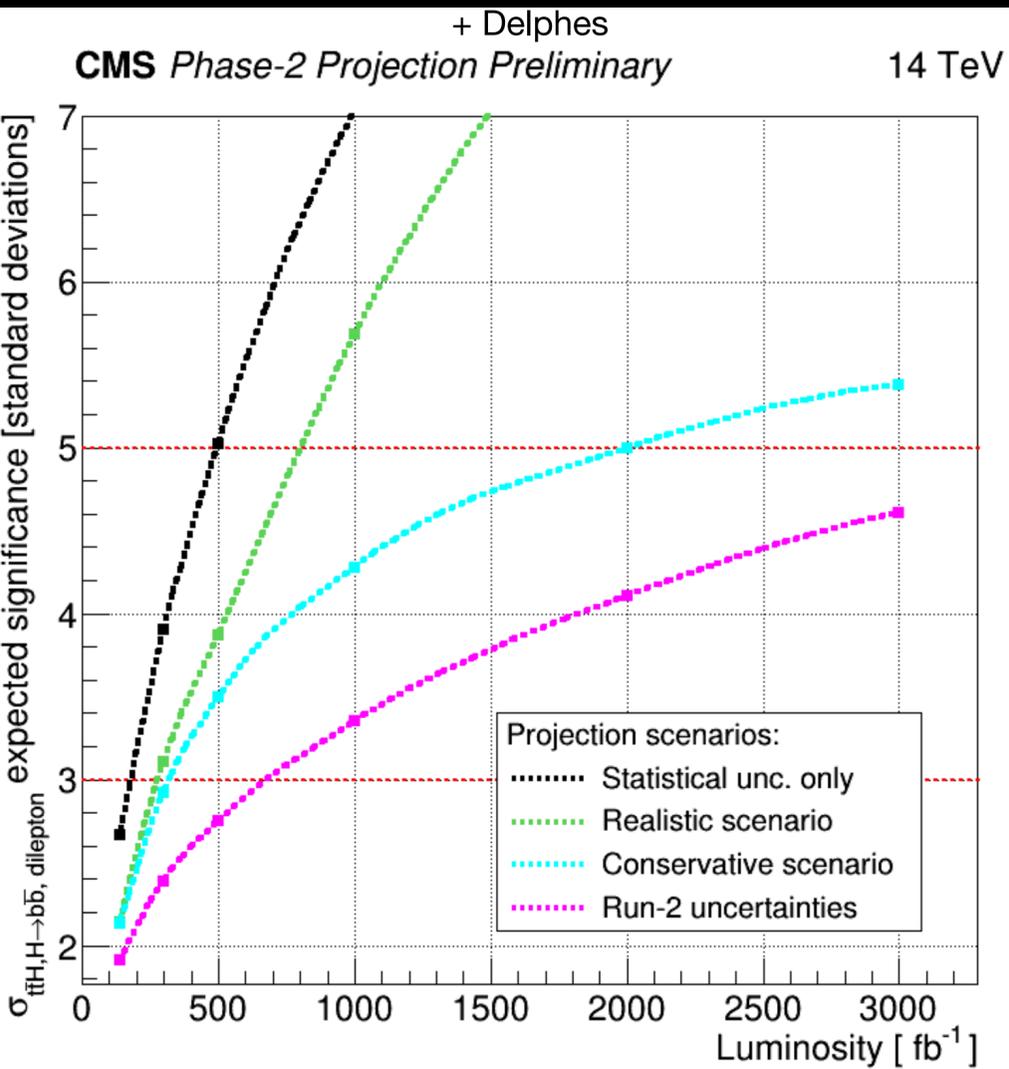
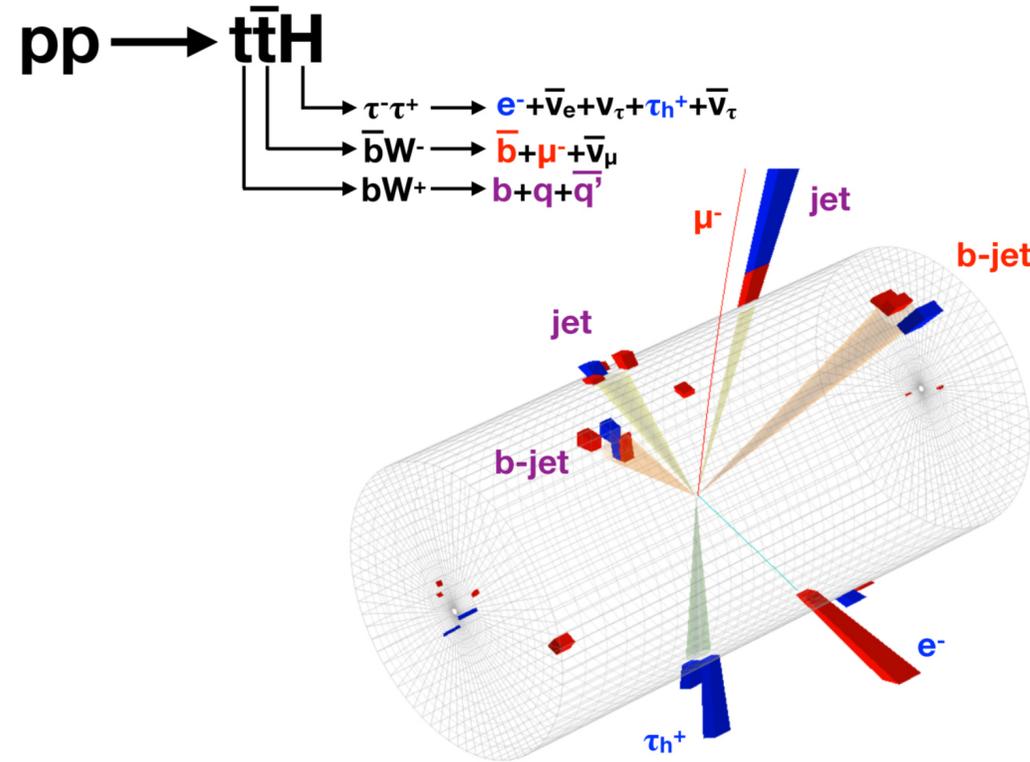
- ✓ New projections for HL-LHC presented
- ✓ Analysis target precision in computation of the Higgs mass, width and coupling
- ✓ Advanced ML methods explored to suppress backgrounds providing access to previously unexplored processes
- ✓ White paper: <https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PUBNOTES/ATL-PHYS-PUB-2022-018/ATL-PHYS-PUB-2022-018.pdf>

# Additional Material

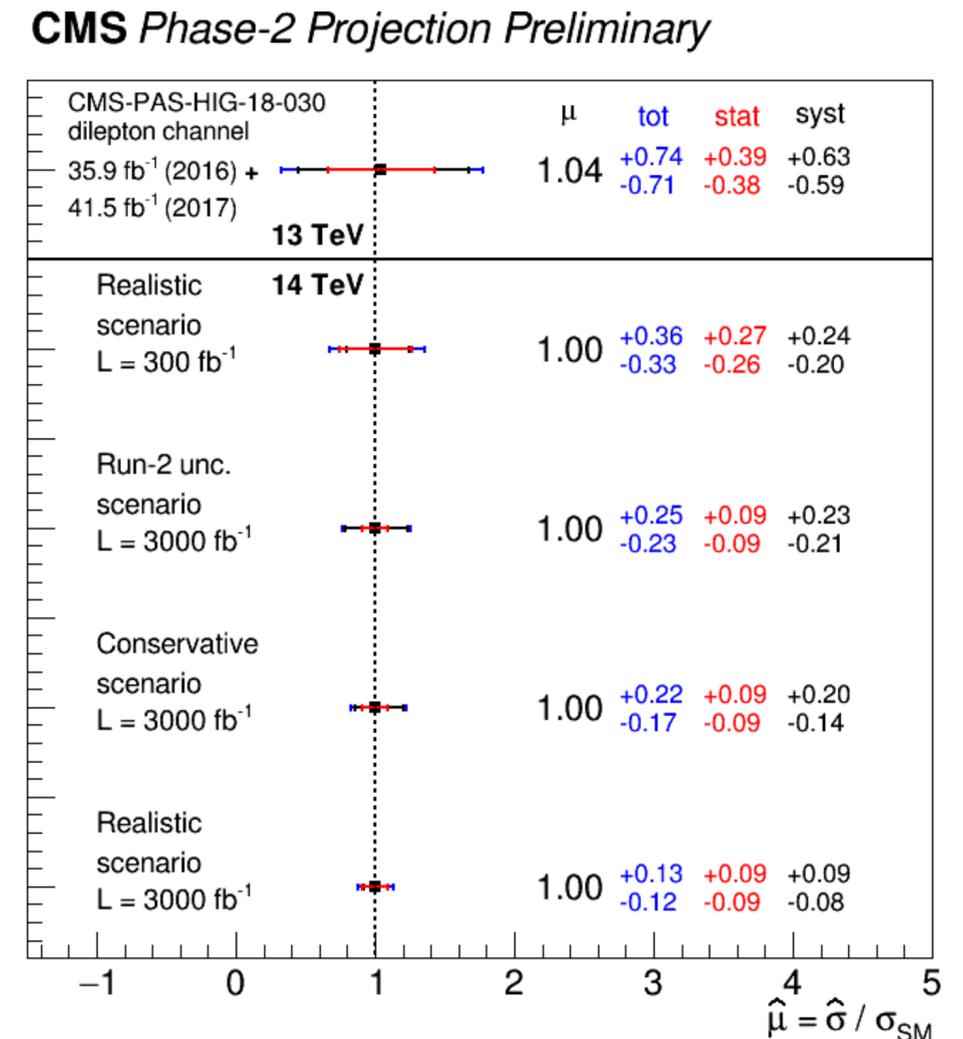
# The Higgs and the top



$t\bar{t}H$  event in Run II  
 $t\bar{t}H$  observed with 5.2  $\sigma$  significance



- Evidence for  $t\bar{t}H$ ,  $H \rightarrow b\bar{b}$  at 3.9 (3.5) observed (expected)  $\sigma$  at Run II
- Projection studies performed with the use of a neural network discriminator to suppress  $t\bar{t} + b\bar{b}$  background
- Discovery with dilepton channel possible with 1/3<sup>rd</sup> of the HL-LHC integrated luminosity



$$H \rightarrow ZZ \rightarrow 4\ell$$

- Conditions for projection:
  - The performance of the trigger system is considered to be the same as in the 2018 data taking period.
  - Detector performance such as acceptance, efficiency and resolution are considered to have the same values as for Run 2, even with an expected pile-up (number of interaction per bunch crossing) up to 200
  - Signal cross sections are scaled to 14 TeV
  - Background cross sections are scaled according to the parton luminosity ratio (1.13 for  $gg \rightarrow ZZ \rightarrow 4\ell$  and 1.10 for  $q\bar{q} \rightarrow ZZ \rightarrow 4\ell$ )
  - $\eta_\mu < 2.4$  and  $\eta_e < 2.5$

$$\begin{aligned}
f_{a3} &= \frac{|a_3|^2 \sigma_3}{|a_1|^2 \sigma_1 + |a_2|^2 \sigma_2 + |a_3|^2 \sigma_3 + |\kappa_1|^2 \sigma_{\Lambda 1} + |\kappa_1^{Z\gamma}|^2 \sigma_{\Lambda 1}^{Z\gamma}} \operatorname{sgn} \left( \frac{a_3}{a_1} \right), \\
f_{a2} &= \frac{|a_2|^2 \sigma_2}{|a_1|^2 \sigma_1 + |a_2|^2 \sigma_2 + |a_3|^2 \sigma_3 + |\kappa_1|^2 \sigma_{\Lambda 1} + |\kappa_1^{Z\gamma}|^2 \sigma_{\Lambda 1}^{Z\gamma}} \operatorname{sgn} \left( \frac{a_2}{a_1} \right), \\
f_{\Lambda 1} &= \frac{|\kappa_1|^2 \sigma_{\Lambda 1}}{|a_1|^2 \sigma_1 + |a_2|^2 \sigma_2 + |a_3|^2 \sigma_3 + |\kappa_1|^2 \sigma_{\Lambda 1} + |\kappa_1^{Z\gamma}|^2 \sigma_{\Lambda 1}^{Z\gamma}} \operatorname{sgn} \left( \frac{-\kappa_1}{a_1} \right), \\
f_{\Lambda 1}^{Z\gamma} &= \frac{|\kappa_2^{Z\gamma}|^2 \sigma_{\Lambda 1}^{Z\gamma}}{|a_1|^2 \sigma_1 + |a_2|^2 \sigma_2 + |a_3|^2 \sigma_3 + |\kappa_1|^2 \sigma_{\Lambda 1} + |\kappa_1^{Z\gamma}|^2 \sigma_{\Lambda 1}^{Z\gamma}} \operatorname{sgn} \left( \frac{-\kappa_2^{Z\gamma}}{a_1} \right),
\end{aligned}$$