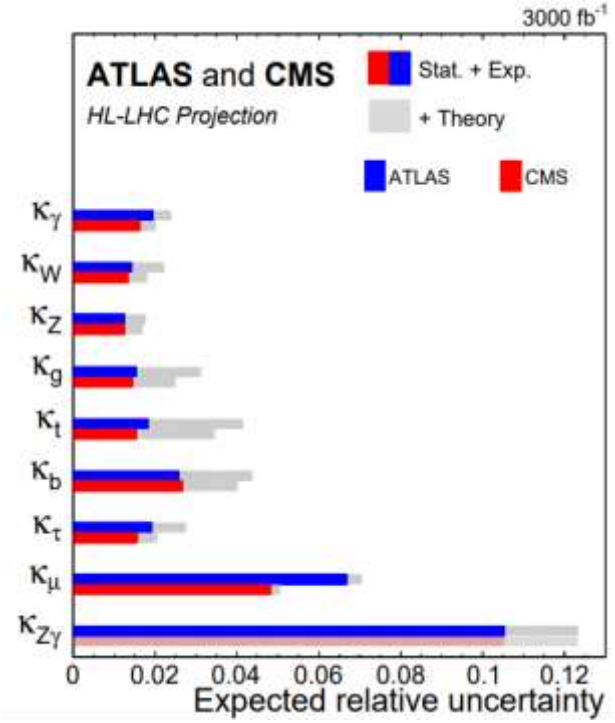
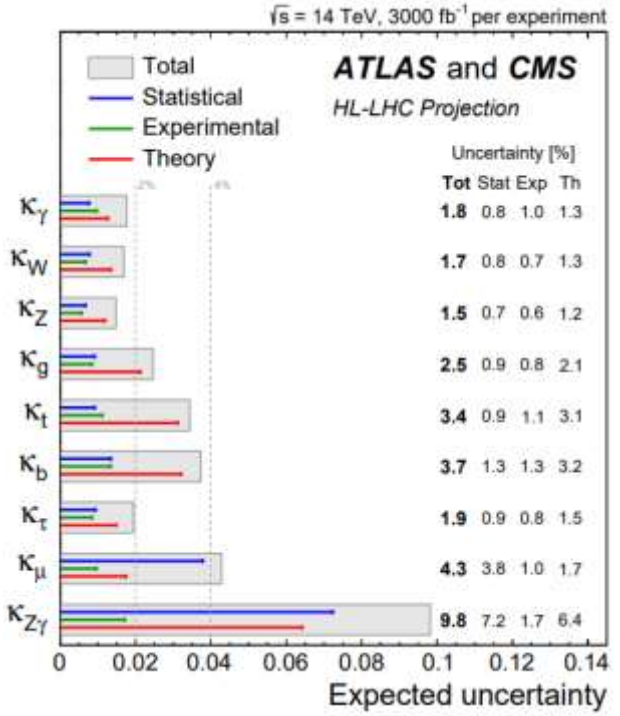
# Prospects for Higgs measurements and HH,HY searches at the HL-LHC with CMS

Zhengliang Guo

on behalf of CMS Collaboration



# Higgs physics prospect

- improvement Higgs mass measurements
- Ongoing researches on Higgs self-coupling
- Search for BSM Higgs models
- Search for invisible decays
- Search for CP structure
- Search for YH process
- ……

# Improvements on CMS detector

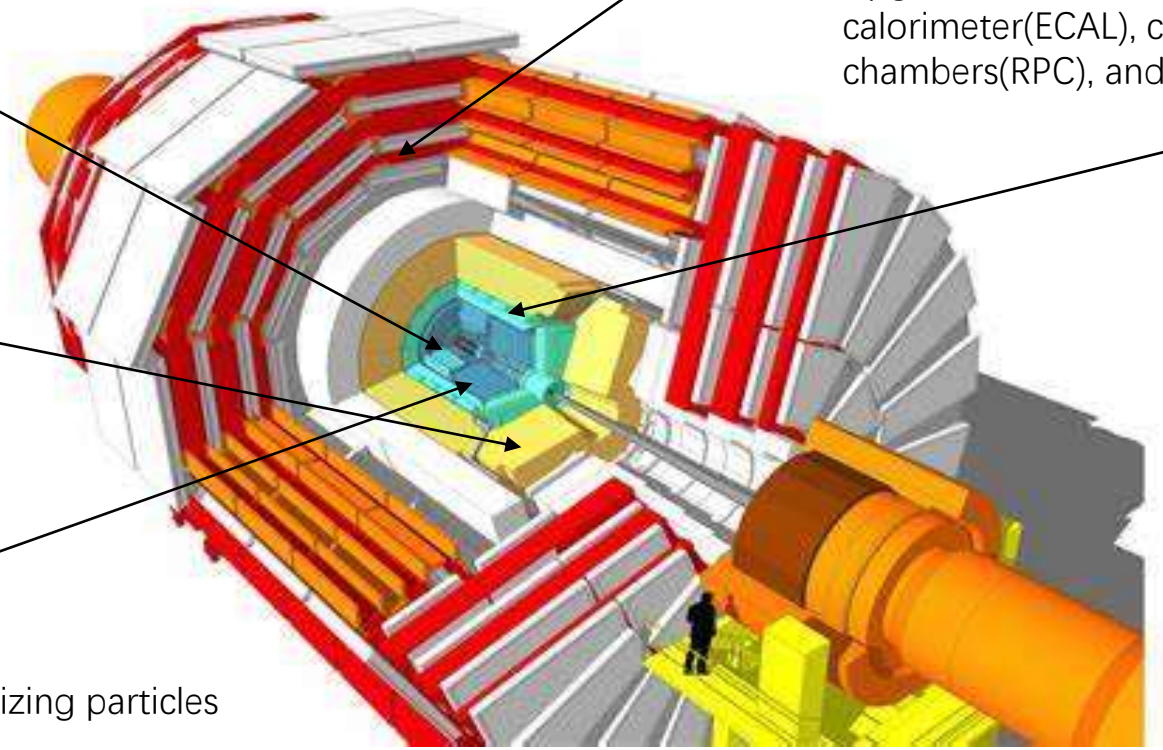
Replace L1 trigger (rate→750kHz, latency→12.5μs, HLT rate→7.5kHz)

New muon detectors based on RPC and gas electron multiplier(GEM)

Replace pixel and strip tracker detectors

Upgrade front-end electronics of the barrel electromagnetic calorimeter(ECAL), cathode strip chambers(CSC), resistive plate chambers(RPC), and drift tubes(DT) for muon detection

Replace endcap electromagnetic and hardon calorimeters



New timing detector for minimum ionizing particles

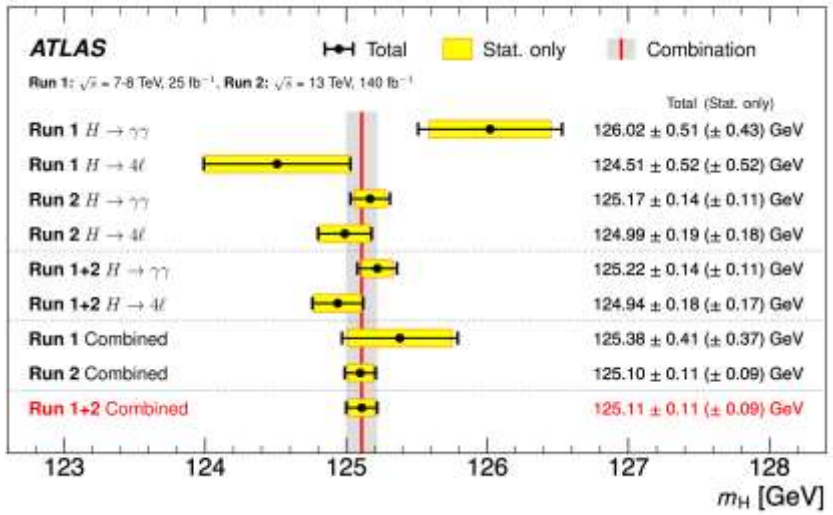
# Higgs boson mass

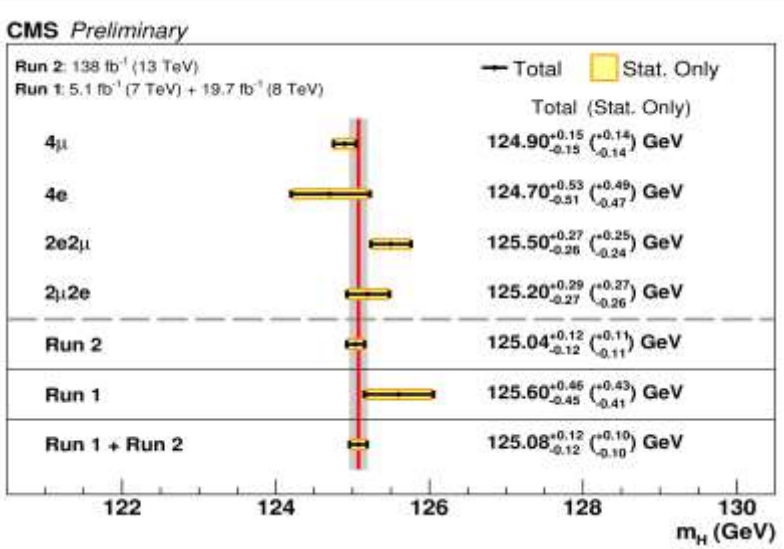
Higgs boson mass:
- fundamental parameter in SM
- not predicted by SM theory

Motivation for precise measurement:
- help with the understanding of SM
- help with explorations into BSM

Current precision from Full Run-2 (+Run-1) data at ATLAS (CMS):

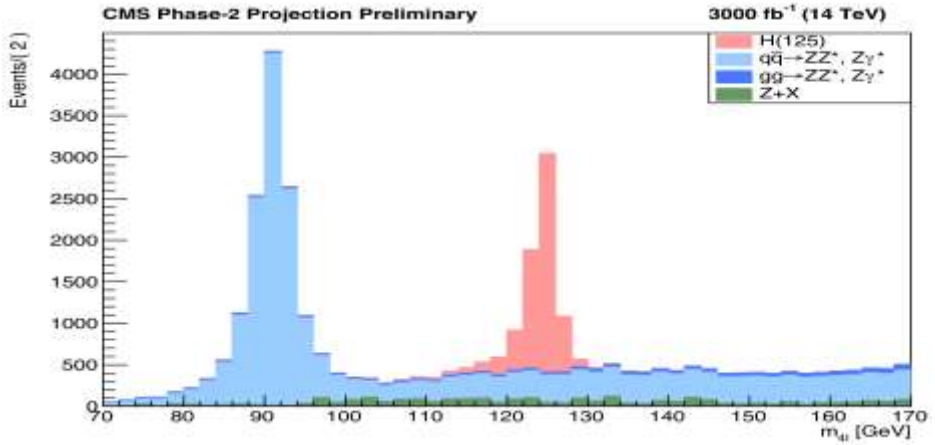
| | |
|---|---|
| **ATLAS H→4l+H→γγ (**arXiv:2308.04775**)** | $\boldsymbol{m_H}$ **= 125.11 ± 0.11 GeV** |
| **CMS H→4l (**CMS-PAS-HIG-21-019**)** | $\boldsymbol{m_H}$ **= 125.08 ± 0.12 GeV** |

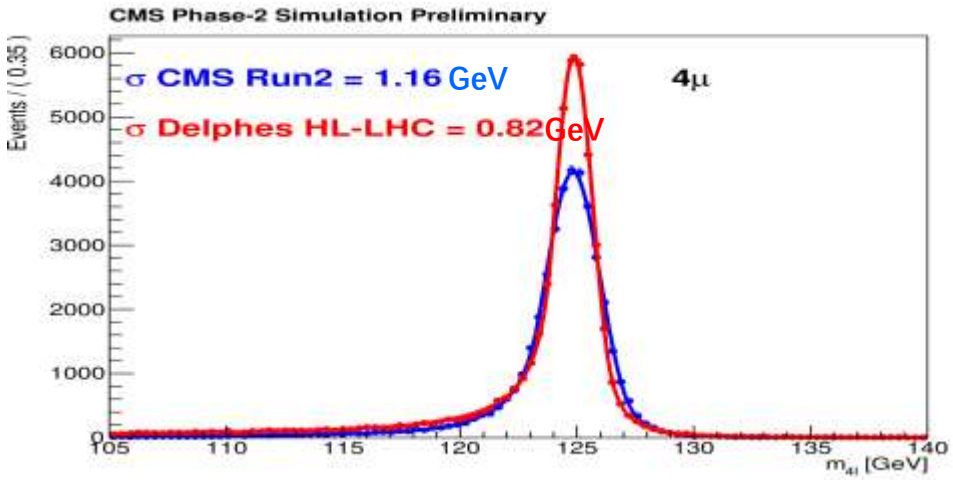


# Higgs boson mass measurement prospects

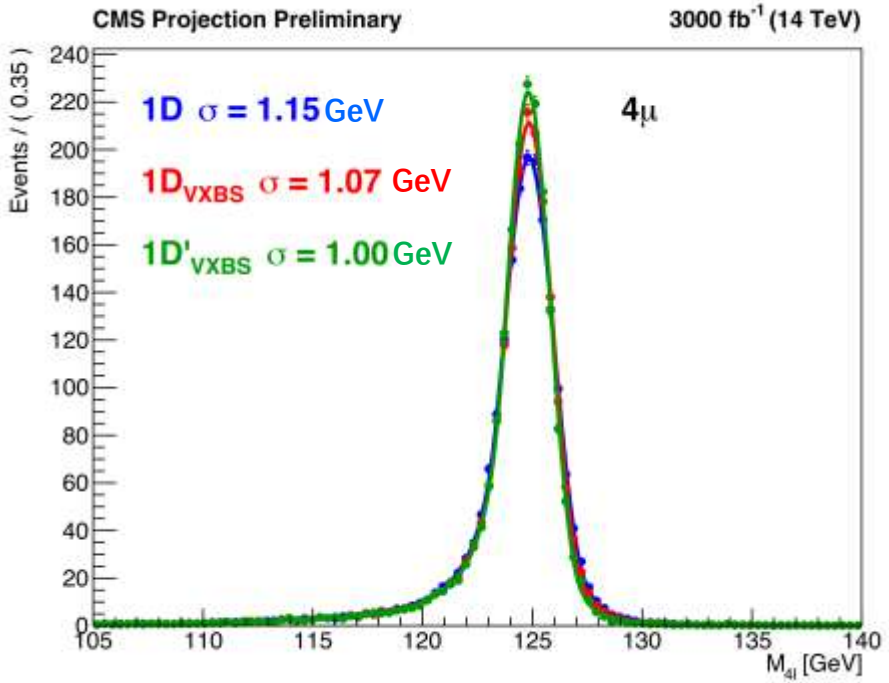
- H→ZZ→4l channel




· 25% improvement for 4μ invariant mass resolution thanks to new trackers

· improved 4l fits due to VXBS (vertex beam spot constraint) and $Z_1$ mass constraint

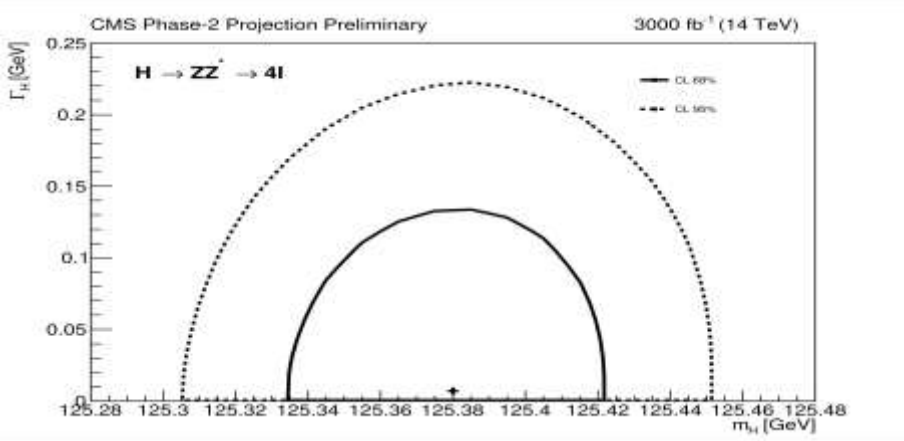


# Higgs boson mass measurement prospects

***Uncertainty down to 26MeV!***

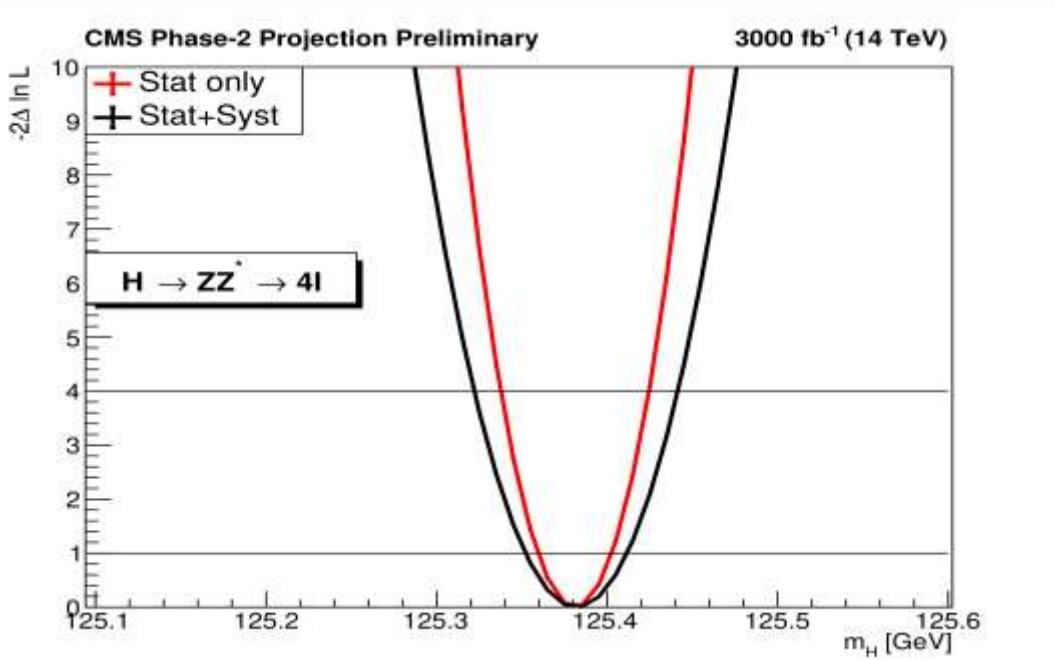
Uncertainties are evaluated for the 3000 $fb^{-1}$ case

| Systematic uncertainty | Baseline | Optimistic | Pessimistic | YR |
|---|---|---|---|---|
| Muon momentum scale | 0.01% | 0.005% | 0.01% | 0.05% |
| Electron momentum scale | 0.15% | 0.05% | 0.15% | 0.10-0.30% |
| Lepton momentum resolution | 10% | 5% | 10% | 5% |




Higgs width

*From CMS-PAS-FTR-21-007




| $m_{4\ell}$ expected uncertainty (MeV) | inclusive | $4\mu$ | 4e | $2e2\mu$ | $2\mu2e$ |
|---|---|---|---|---|---|
| *Optimistic* | | | | | |
| Total | 26 | 30 | 105 | 60 | 67 |
| Syst impact | 16 | 11 | 64 | 31 | 32 |
| Stat only | 22 | 28 | 83 | 51 | 59 |
| *Pessimistic* | | | | | |
| Total | 30 | 32 | 206 | 107 | 112 |
| Syst impact | 20 | 15 | 189 | 94 | 95 |
| Stat only | 22 | 28 | 83 | 51 | 59 |

# Higgs boson mass measurement prospects

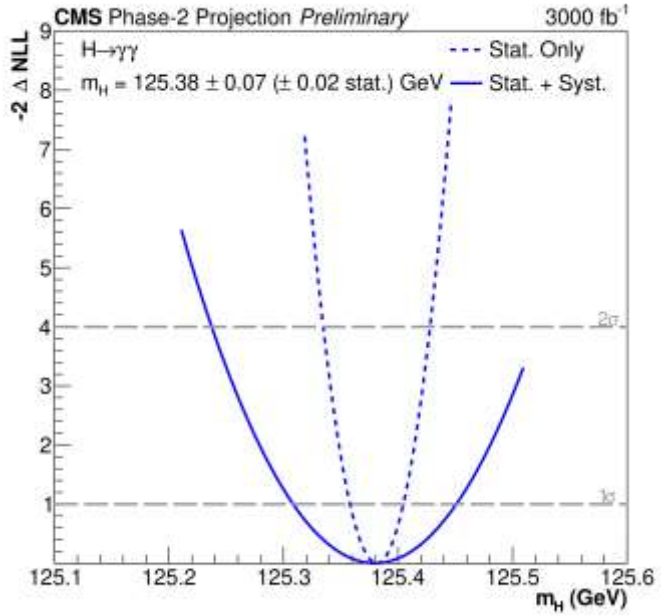
***Uncertainty down to 70MeV!***

- H→γγ channel: Projection based on 2016 analysis correcting for expected improvements in photon energy resolution
- Better performance on photon energy calibration lead to a more precise reconstruction of photon energy scale

| Sources of systematic uncertainty | Contribution [GeV] |
|---|---|
| Electron energy scale and resolution corrections | 0.06 |
| Residual $p_T$ dependence of the photon energy scale | 0.05 |
| Modelling of the material budget | 0.02 |
| Statistical uncertainty | 0.02 |
| Total uncertainty | 0.07 |

Projected leading uncertainty for $m_H$ in 3000$fb^{-1}$ scenario

*From CMS-PAS-FTR-21-008



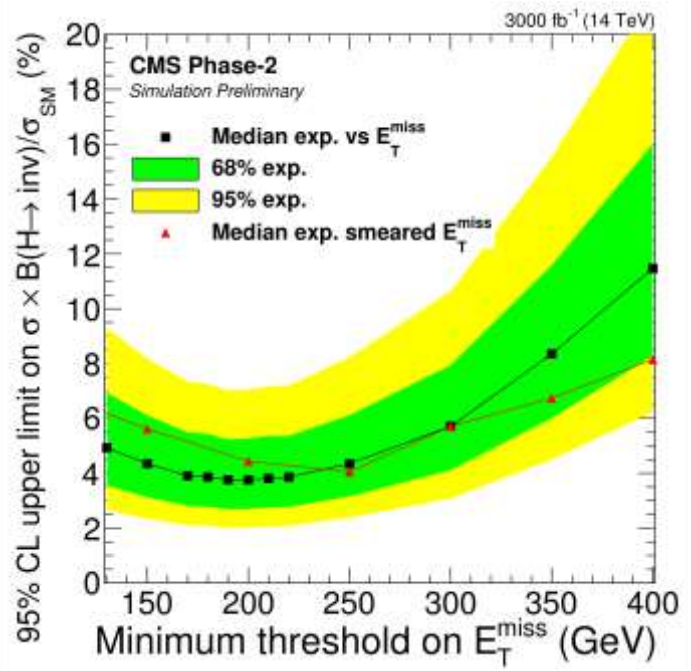
# Invisible decays of Higgs

- Direct searches for VBF →invisible decays benefit from improved forward tracking & calorimetry
- Sensitivity limited by trigger/selection thresholds achievable at HL-LHC

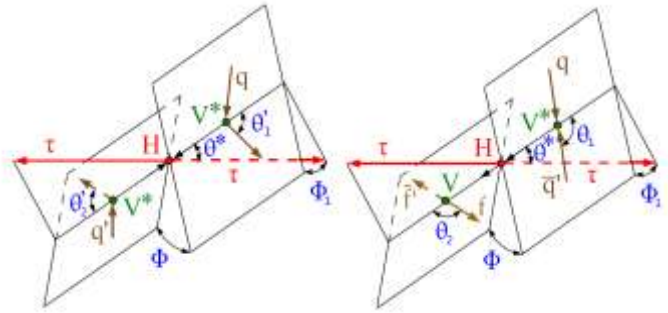
| Systematic | From Ref. [14] | This analysis |
|---|---|---|
| e-ID | 1%(gsf)⊕1%(idiso) | 1% |
| $\mu$-ID | 1%(reco)⊕1%(id)⊕0.5%(iso) | 0.5% |
| e-veto | 0.6%(gsf)⊕1.5%(idiso) | 1% |
| $\mu$-veto on QCD V+jets | 5%(reco)⊕5%(id)⊕2%(iso) | 2% |
| $\mu$-veto on EWK V+2jets | 10%(reco)⊕10%(id)⊕6%(iso) | 6% |
| $\tau$-veto | 1–1.5% for QCD–EWK | 0.5–0.75% |
| b-tag-veto | 0.1% (sig) 2% (top) | 0.05% (sig) 1% (top) |
| JES | 14%(sig) 2%(W/W) 1%(Z/Z) | 4.5%(sig) 0.5%(W/W) 0.2%(Z/Z) |
| Integrated luminosity | 2.5% | 1% |
| QCD multijet | 1.5% | 1.5% |
| Theory on W/Z ratio | 12.5% | 7% |
| ggH normalisation | 24% | 20% |

different sources of systematic uncertainty considered in Ref. [14] and for the HL-LHC setup considered in this analysis.

*From CMS-PAS-FTR-18-016

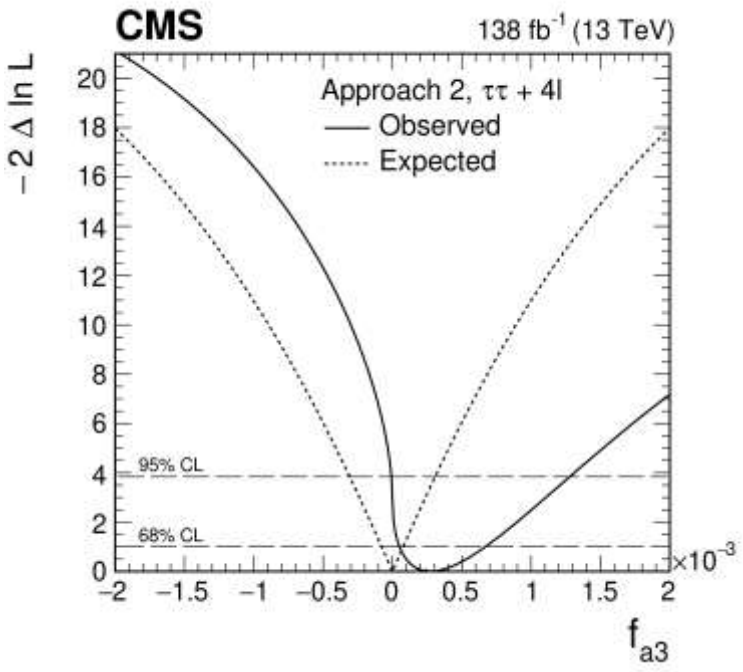


# CP in H→ττ

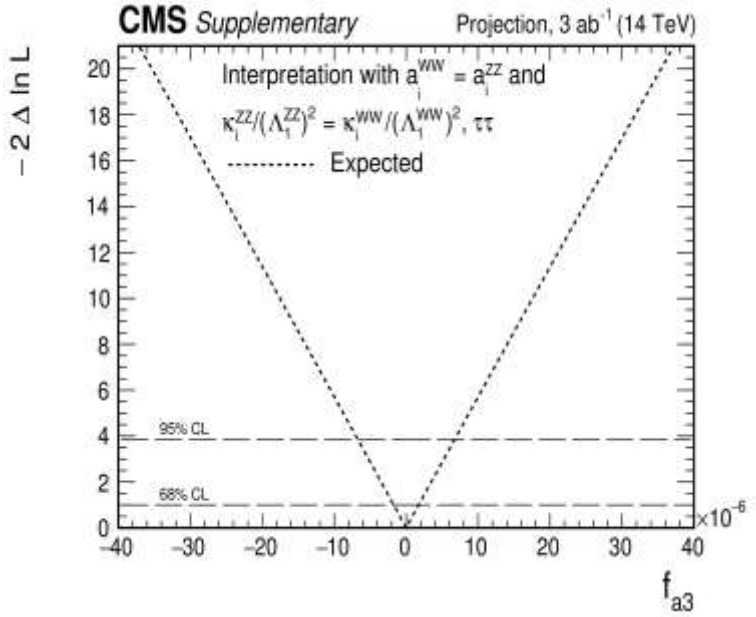


$*f_{a3}$ = fraction of xsec by CP-odd couplings (BSM)

VBF, VH production modes



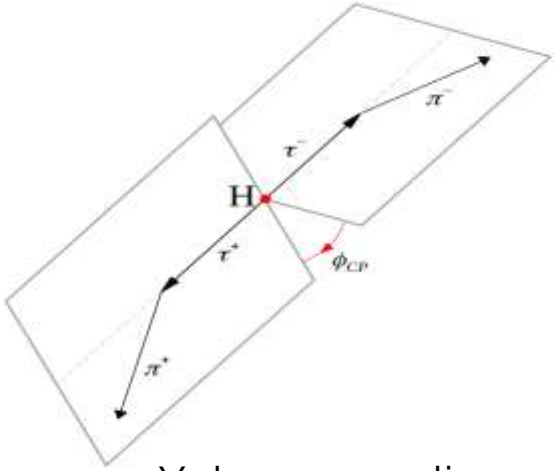

**50 times better constraints expected!**



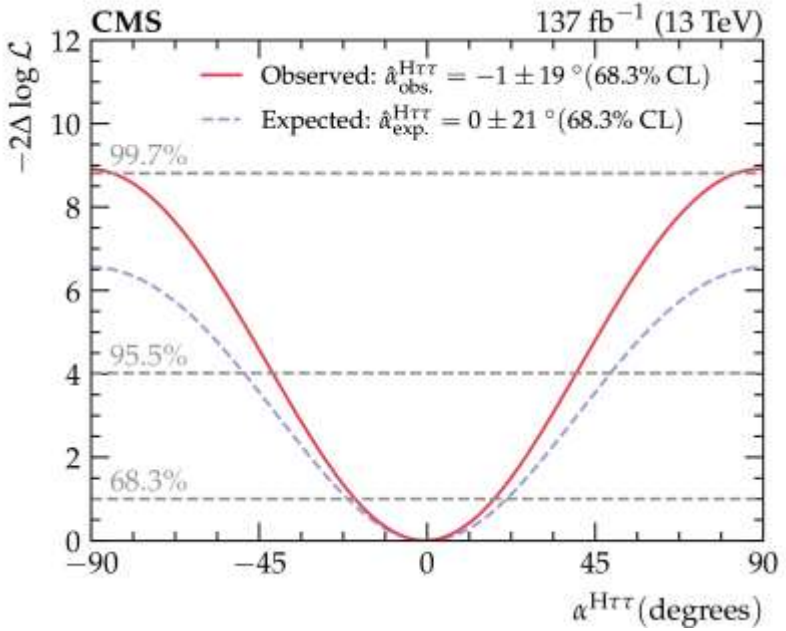

$3ab^{-1}$projection for the likelihood scan for $CP$ odd parameters

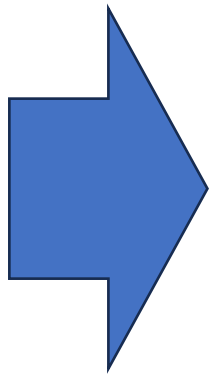
*From CMS-HIG-20-007

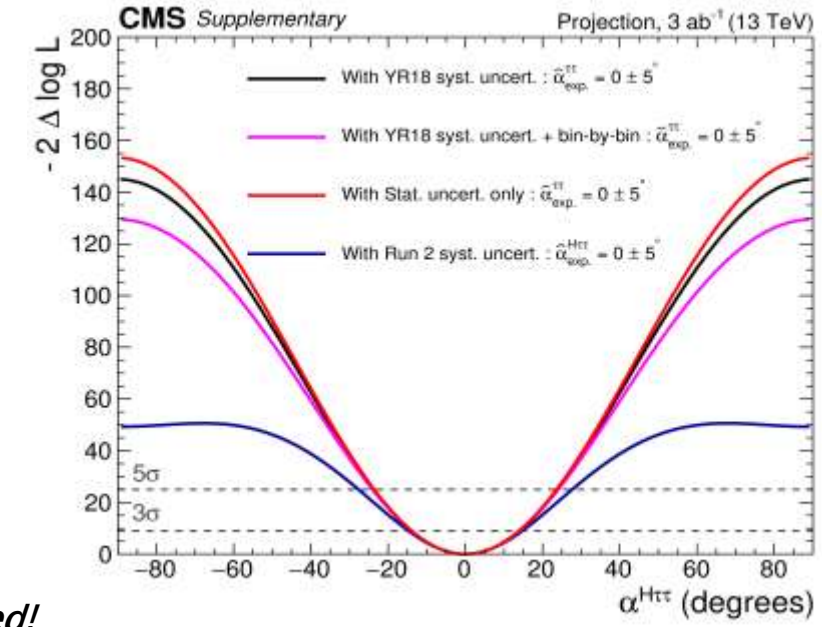
# CP in H→ττ




τ Yukawa coupling






***4 times better constraints expected!***

$3ab^{-1}$projection for the likelihood scan for $CP$ odd parameters

*From CMS-HIG-20-006

# Prospect for HH measurements

- HH→bbbb, bbWW, bbττ, bbγγ, and bbZZ combination

| Channel | Significance | | 95% CL limit on $\sigma_{HH}/\sigma_{HH}^{SM}$ | |
|---|---|---|---|---|
| | Stat. + syst. | Stat. only | Stat. + syst. | Stat. only |
| bbbb | 0.95 | 1.2 | 2.1 | 1.6 |
| bb$\tau\tau$ | 1.4 | 1.6 | 1.4 | 1.3 |
| bbWW($\ell\nu\ell\nu$) | 0.56 | 0.59 | 3.5 | 3.3 |
| bb$\gamma\gamma$ | 1.8 | 1.8 | 1.1 | 1.1 |
| bbZZ($\ell\ell\ell\ell$) | 0.37 | 0.37 | 6.6 | 6.5 |
| Combination | 2.6 | 2.8 | 0.77 | 0.71 |

*From CMS-PAS-FTR-18-019

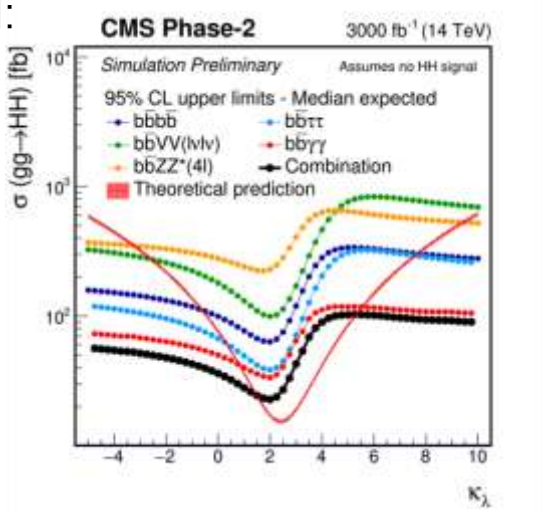
Reach a corresponding significance of the signal of 2.6σ

# Prospect for HH measurements

- HH→bbbb, bbWW, bbττ, bbγγ, and bbZZ combination(2018 analysis)

**Prospects for the measurement of the $\lambda_{HHH}$:**

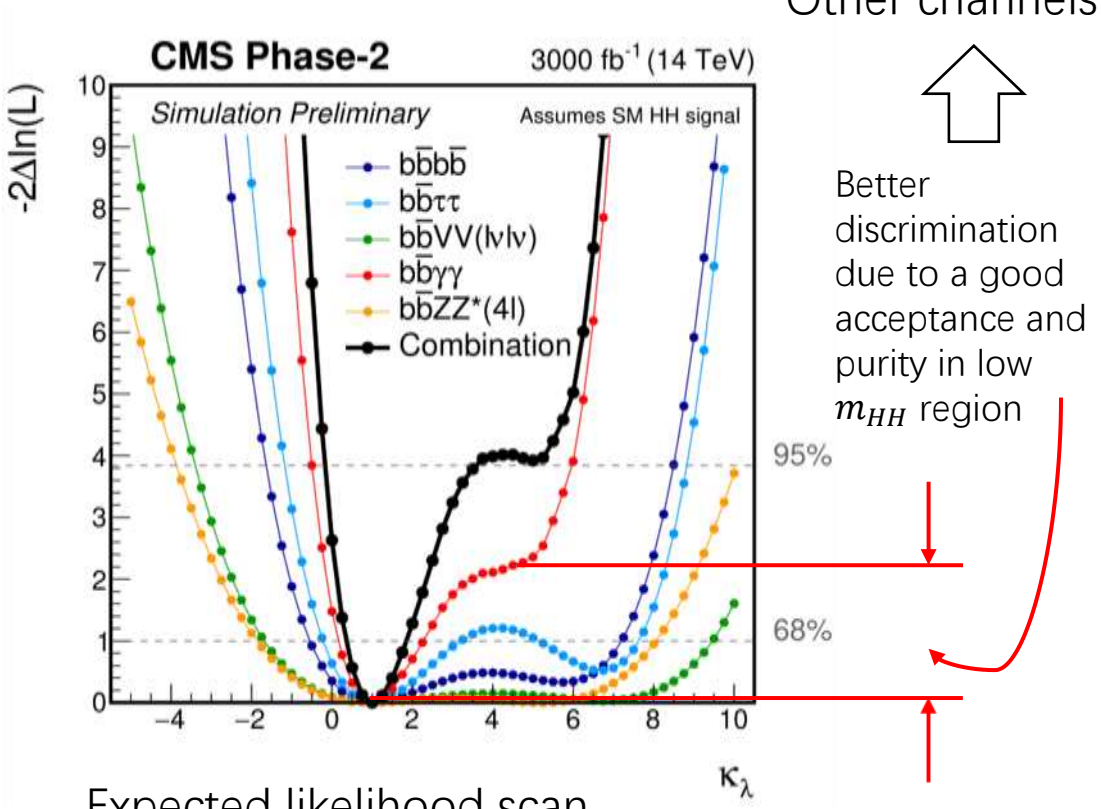
If no HH signal:




Parametrisation techniques can be used to mitigate the change of excluded cross sections with the variation of $\kappa_\lambda$

*From CMS-PAS-FTR-18-019

Other channels?

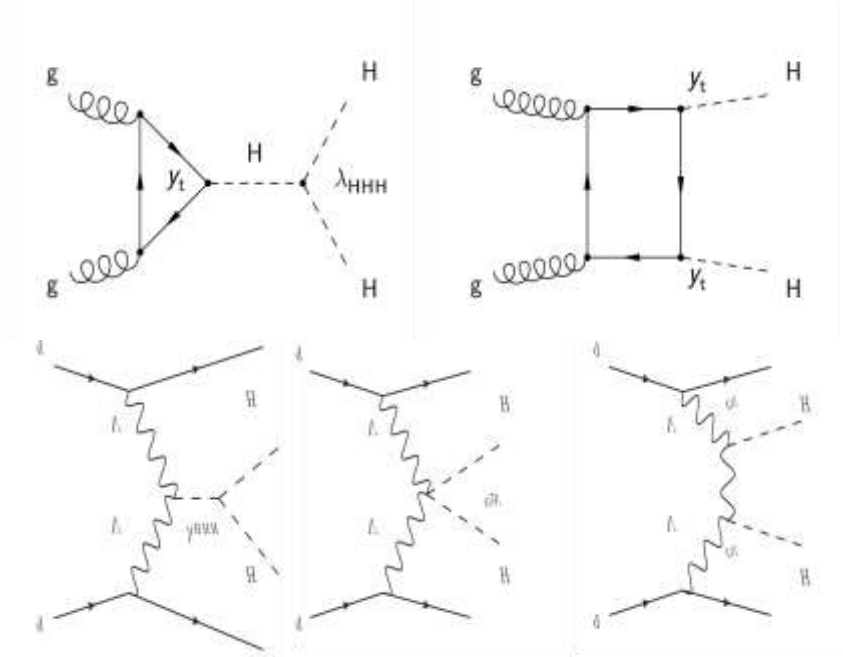


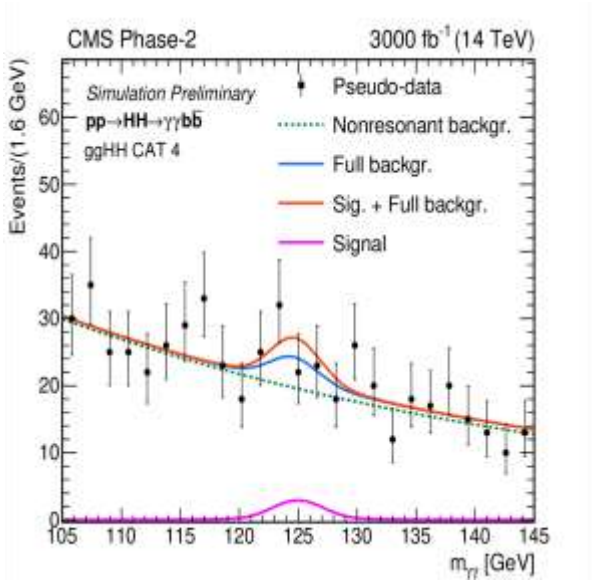

Better discrimination due to a good acceptance and purity in low $m_{HH}$ region

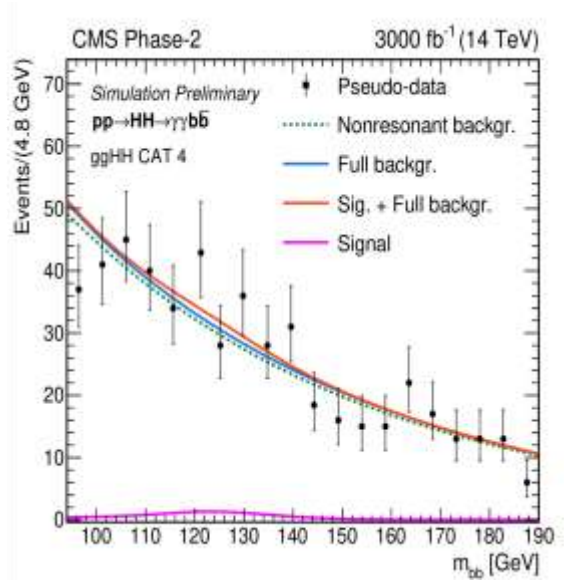
Expected likelihood scan assuming HH signal

# Prospect for HH measurements

- HH→bbγγ (with a projected result of 2.16 σ exceeding a previous projection showing a result of 1.83)
- 5σ discovery potential(ATLAS+CMS) for Higgs pair production on HL-LHC with phase2 detector



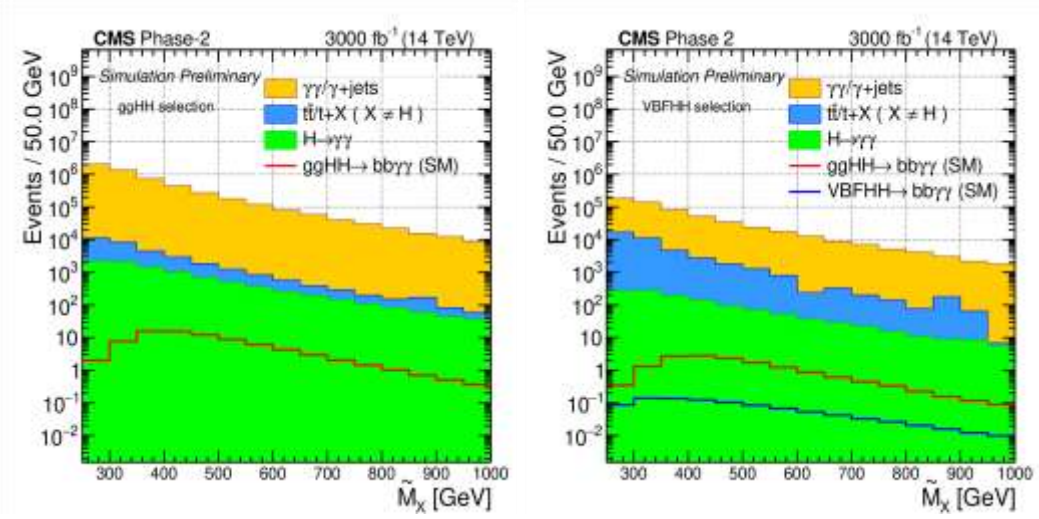




*From CMS-PAS-FTR-18-019

# Prospect for HH measurements

- HH→bbγγ

Improved ttH rejection, VBF-HH categories, photon and b-jet identification from MTD detector help with the analysis




Systematic uncertainties

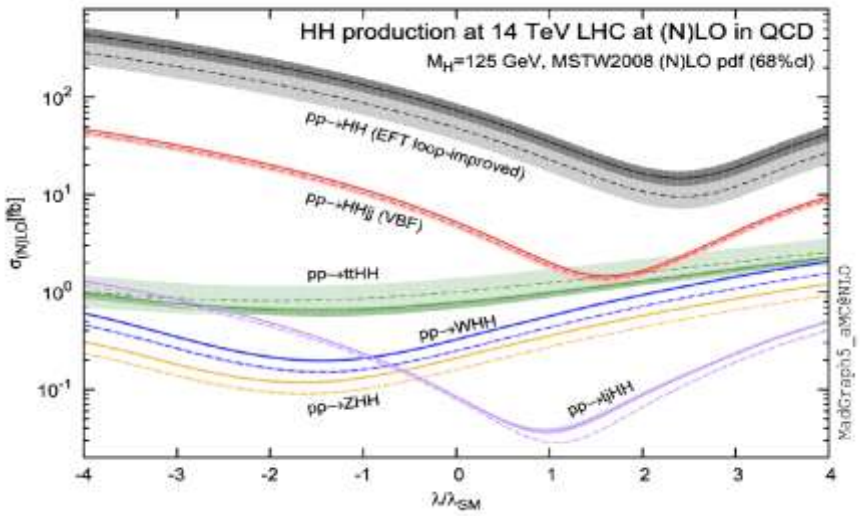
| Systematic unc. | Impacts on yields (%) |
|---|---|
| $m_{\gamma\gamma}$ resolution | 5.0 |
| $m_{bb}$ resolution | 5.0 |
| Diphoton trigger efficiency | 2.0 |
| Photon energy scale | 2.0 |
| Jet energy scale | 1.0 |
| b-tag efficiency | 1.0 |
| Photon Id | 0.5 / photon |
| $m_{\gamma\gamma}$ scale | 0.5 |
| Luminosity | 1.0 |

| Systematic unc. | Impacts on yields (%) |
|---|---|
| Effect of various uncertainties on ggHH signal | |
| PDF + $\alpha_s$ | 3.0 |
| QCD scale | 2.1/-4.9 |
| $m_{top}$ | 4.0/-18.0 |
| Effect of various uncertainties on VBFHH signal | |
| PDF + $\alpha_s$ | 2.1 |
| QCD scale | 0.3/-0.4 |
| Dipole recoil | 2.0 |
| Effect of QCD scale unc. for single H background | |
| ggH | 4.6/-6.7 |
| VBF | 0.5/-0.3 |
| VH | 0.4/-0.7 |
| ttH | 6.0/-9.2 |
| tHq | 6.4/-14.7 |
| Effect of PDF+$\alpha_s$ unc. for single H background | |
| ggH | 3.2/-3.2 |
| VBFH | 2.1/-2.1 |
| VH | 1.8/-1.8 |
| ttH | 3.5/-3.5 |
| tHQ | 3.6/-3.6 |

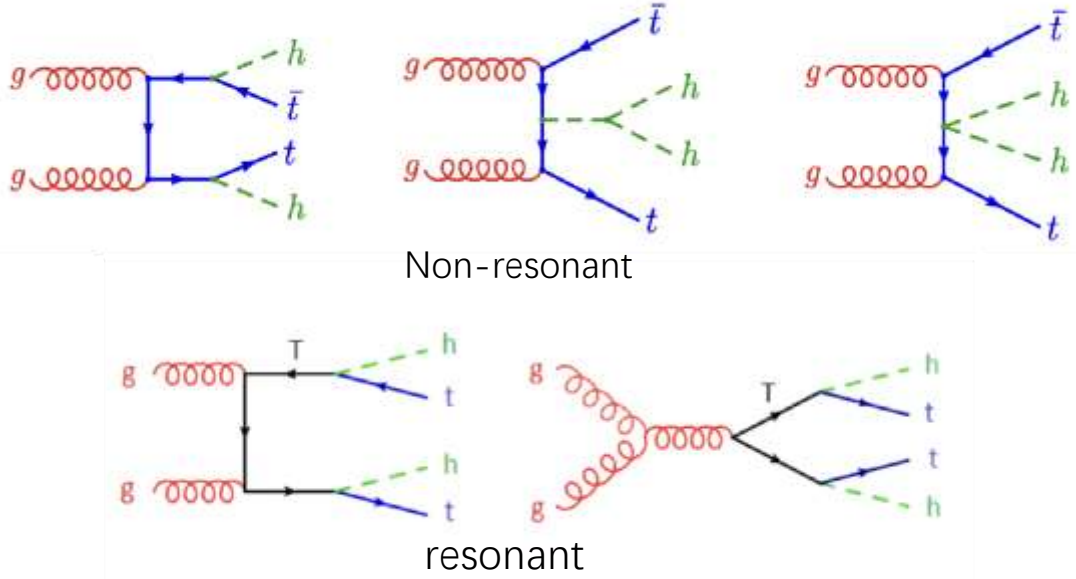
*From CMS-PAS-FTR-18-019

# Searches for ttHH production within BSM

Different di-higgs production modes




ttHH production process at LO within MCHM




ttHH:
· tiny cross section
· small sensitivity to deviations in λ
· combinations with other channels
· additionally radiated Higgs boson allowing more dependence on BSM effects

MCHM:
· The minimal composite Higgs model
· the minimal model of the Higgs as a pseudo-Goldstone boson

# Searches for ttHH production within BSM

Better muon identification helps the reconstruction

| Object | ID | $p_T$ (GeV) | $\|\eta\|$ | Isolation ($I_{rel}^{PF}$) |
|---|---|---|---|---|
| Electrons (select) | medium | $> 30$ | $< 3$ | $< 0.3$ |
| Electrons (veto) | medium | 15-30 | $< 3$ | $< 0.3$ |
| Muons (select) | medium | $> 30$ | $< 2.8$ | $< 0.3$ |
| Muons (veto) | medium | 15-30 | $< 2.8$ | $< 0.3$ |
| Jets | loose | $> 30$ | $< 3$ | – |
| b jets (medium) | medium | $> 30$ | $< 3$ | – |
| b jets (loose) | loose and not medium | $> 30$ | $< 3$ | – |

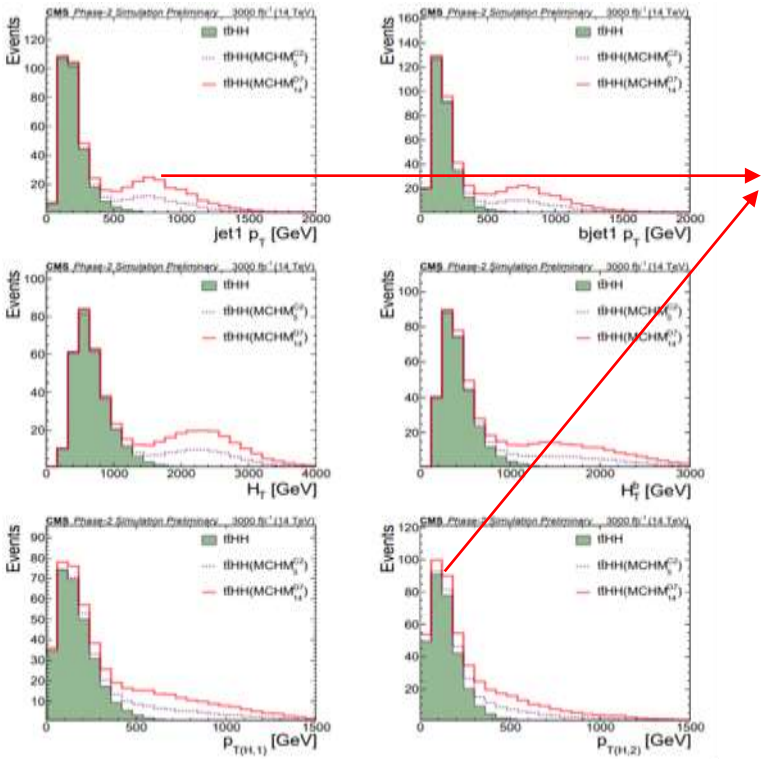
Systematic uncertainties(YR18)

| Uncertainty source | Uncertainty (%) | Variation | Impact on signal yield (%) | Impact on BG yield (%) |
|---|---|---|---|---|
| Jet energy scale | 0.4–3 | shape | $-0.5/+0.4$ | $-2.4/+2.3$ |
| Jet energy resolution | 0.4–3 | shape | $-0.02/-0.6$ | $-0.2/-2.2$ |
| b tagging | 1 | shape | $-1.3/+1.1$ | $-0.14/+0.16$ |
| Lepton identification | 0.5 | rate | $\pm 0.5$ | $\pm 0.5$ |
| Luminosity | 1 | rate | $\pm 1$ | $\pm 1$ |
| Theory uncertainties on cross section: Values from Table 4 | | | | |

*From CMS-PAS-FTR-21-010

# Three handles for the search for MCHM

· effect on kinematic distributions




Due to MCHM-like resonant process

· identification mass peaks

· large total cross section

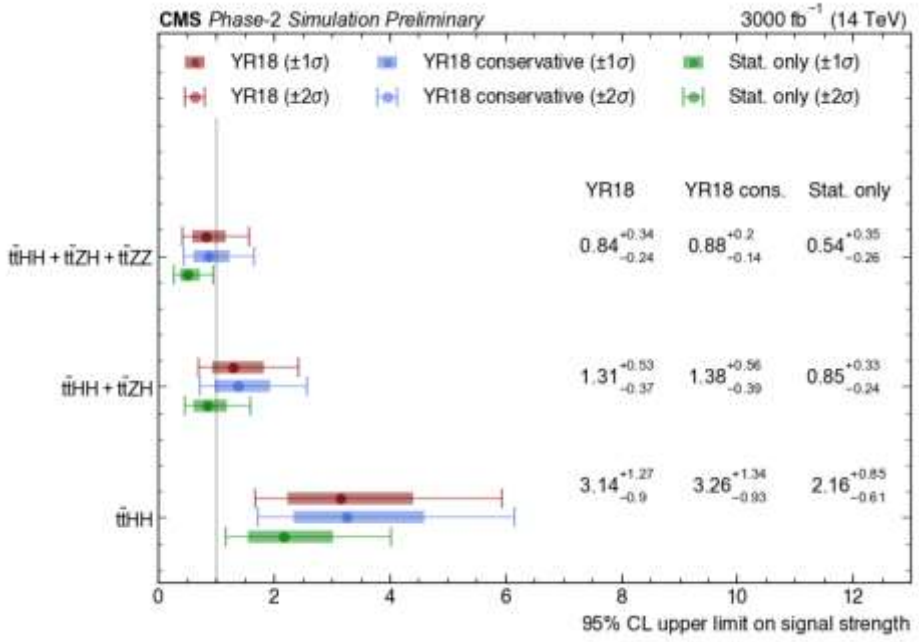
· charge 2/3 top partners in a proper mass range

· all decay within the reach of the HL-LHC

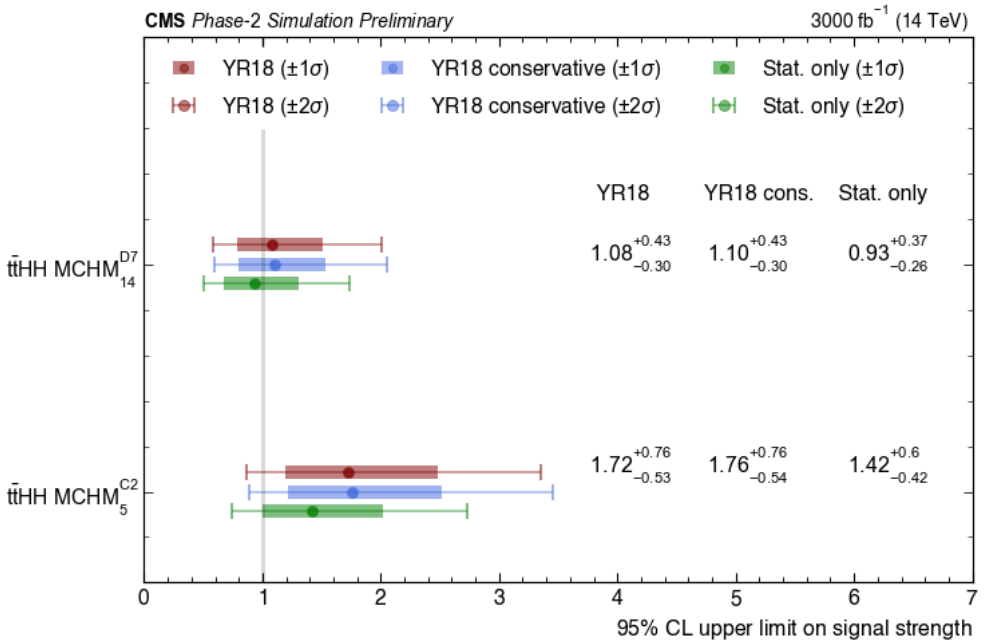
# Three handles for the search for MCHM

· upper limit on signal strength

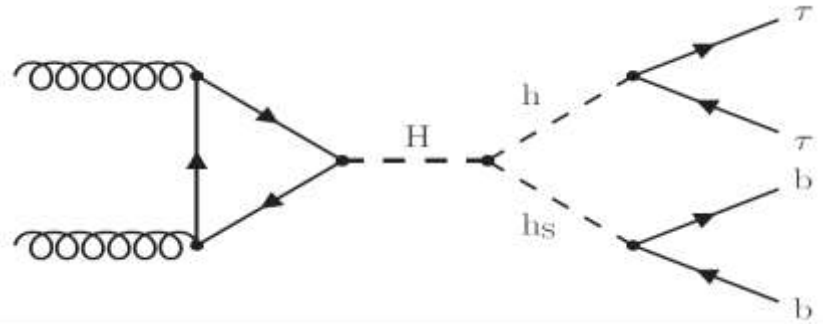
Projected upper limits for SM signals:

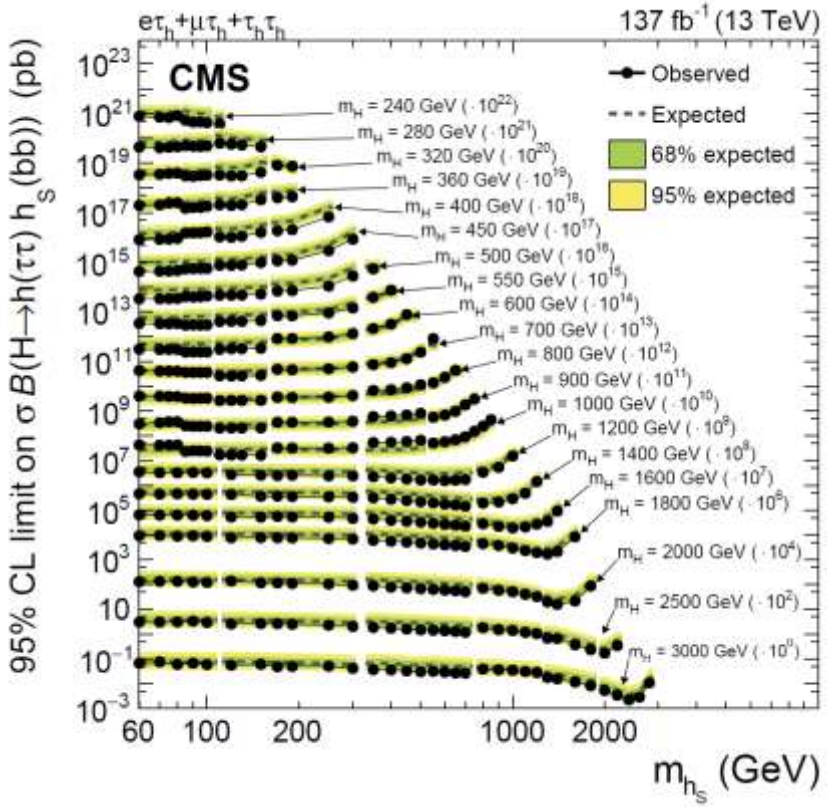


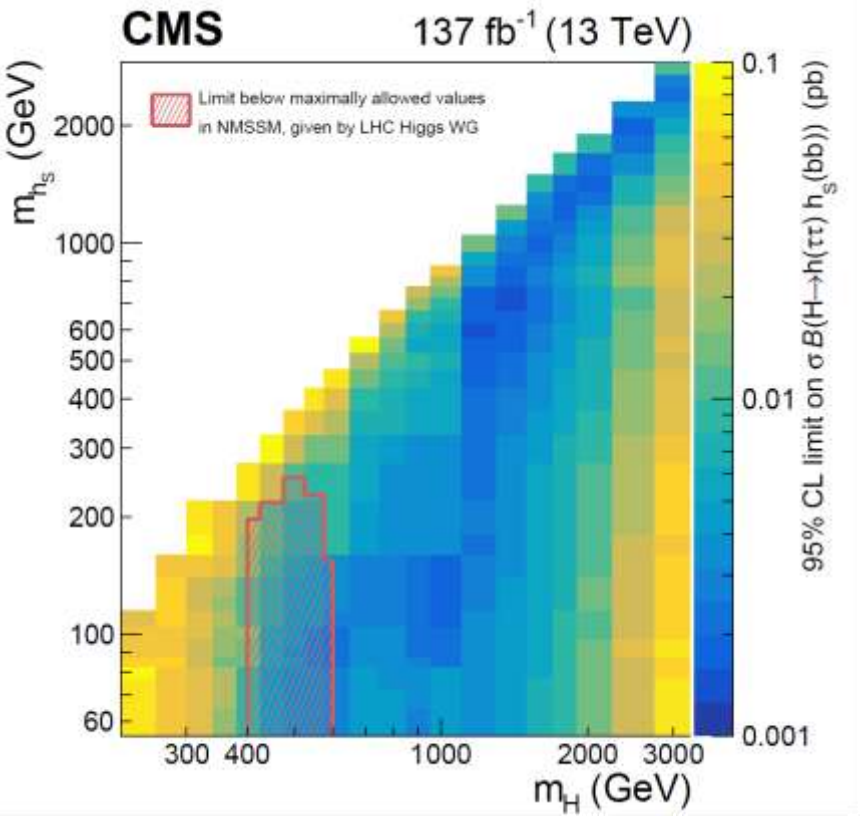

Prospect for BSM interpretation



# HY searches(NMSSM)




Larger exclusion regions would be found for multiple channels in HL-LHC with higher luminosity providing more data and better electron and muon detector aiding the reconstruction.

*From HIG-20-014

# summary

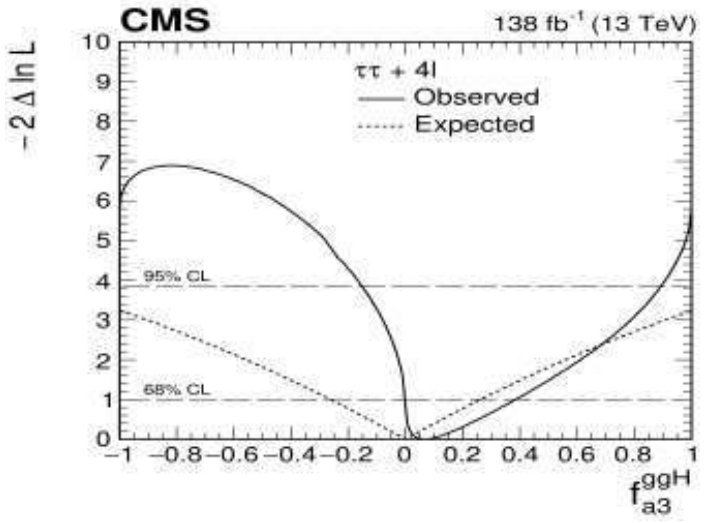
- Many properties such as Higgs mass and Higgs couplings can be measured in an advanced accuracy with higher luminosity and upgraded detectors
- BSM models can be further explored with larger datasets supporting or excluding them
- New analysis techniques are being utilized with the support of better data seized to further improve the evaluations.

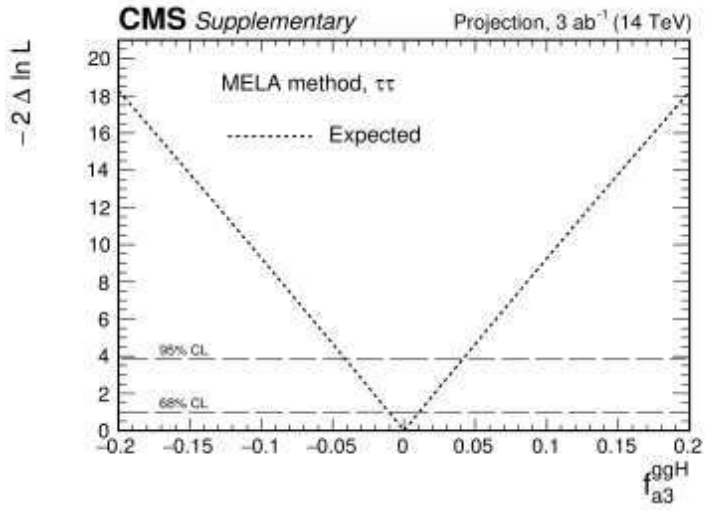
# Back Up

# CP in H⟶ττ(ggH)

$*f_{a3}$ = fraction of xsec by CP-odd couplings (BSM)

ggH production modes




**30 times better constraints expected!**

$3ab^{-1}$projection for the likelihood scan for $CP$ odd parameters

*From CMS-HIG-20-007

# Thank you