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Exploring BSM via Higgs Measurements

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Higgs Potential 2024

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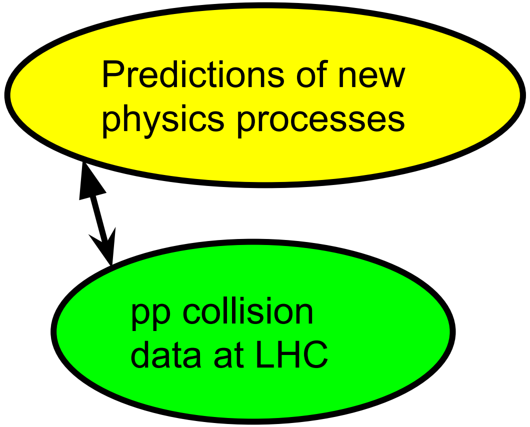
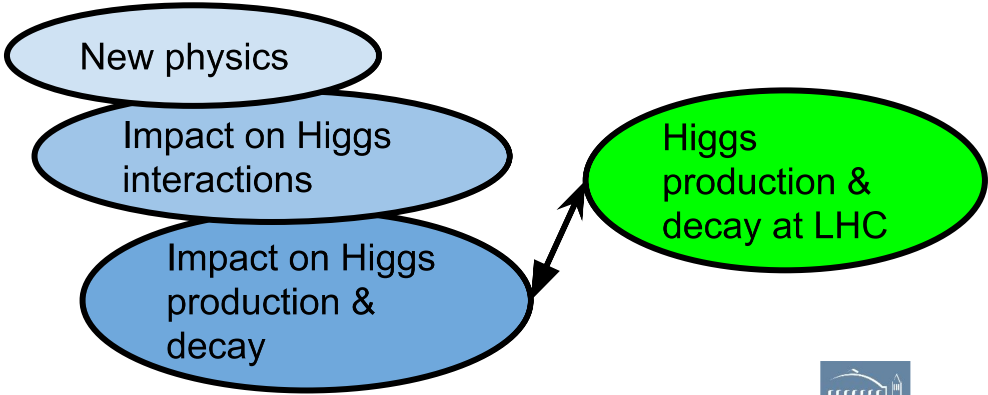
The indirect searches of BSM

- BSM theories can be investigated both directly / indirectly
- Advantages of indirect searches over direct approaches:
  - **Model independence**: general exploration and does not rely on specific assumptions
  - **Broader coverage:** possible to probe inaccessible energy scales, or the theories without accessible new particle predictions
  - **Re-optimization of existing analyses**
- Higgs boson is a important probe of BSM, making indirect searches of BSM a crucial task of Higgs property measurements





Landscape

BSM impact on Higgs couplings

- Effective Field Theory (EFT) : Jiayin's talk
- CP violation in Higgs couplings : Fangyi's talk
- Anomalous Higgs couplings: Jeffery's talk

BSM impact on Higgs rare decays

- Higgs width measurement : Hongtao's talk
- Higgs rare decay measurements: Qiuping's talk

Indirect BSM searches

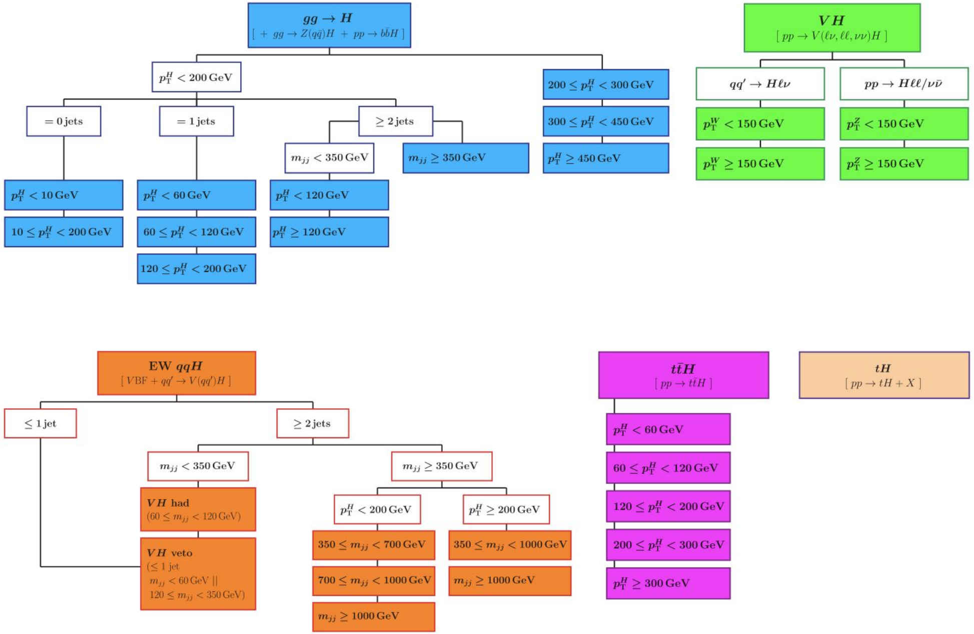
- Long-live particles with Higgs boson: Kang's talk
- Model-independent searches with Higgs boson

Caveat: the talk only introduces a few examples in each direction

Higgs couplings

Constraint on SMEFT with STXS measurements

- Precise measurements of Higgs properties can verify SM and probe BSM models.
- The simplified template cross-section (STXS) divides Higgs cross-section measurements in various kinematic regions, with optimized definition for reducing theoretical uncertainties, multivariate analysis, and the combined measurements.



The definition of kinematic regions are based on:

- Higgs production modes
- Higgs pT, Higgs+jet pT or Higgs+dijet pT
- Number of jets, mass of di-jet
- vector boson pT

Constraint on SMEFT with STXS measurements

- Model-independent description of the deviations in Higgs measurements. Probing general interactions between Higgs and new physics

- The Higgs STXS measurements are sensitive to particular Wilson coefficients

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_k \frac{c_k}{\Lambda^2} O_k$$

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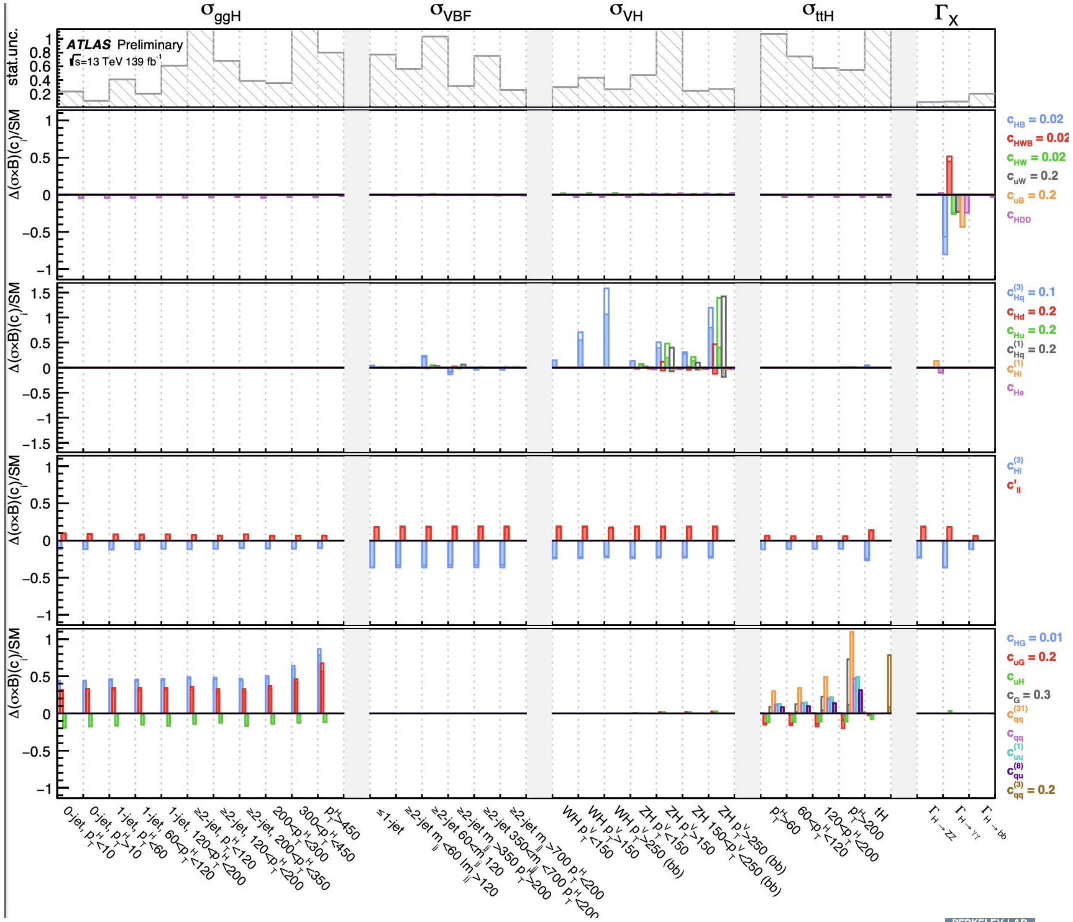
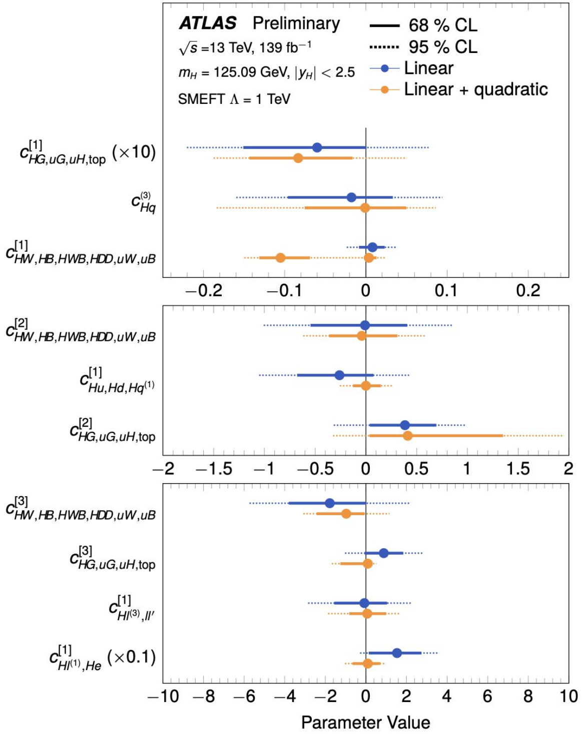
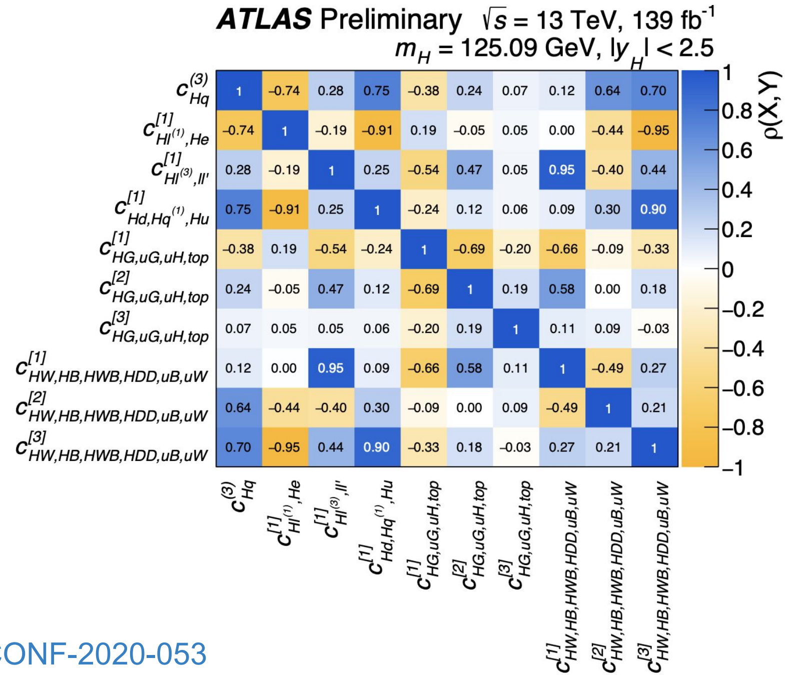


Constraint on SMEFT

- Principal Component Analysis (PCA) is performed to re-compute Wilson coefficients
- Measurement is performed on the eigenvectors from PCA
- No deviations from SM is found yet, more studies in [Jiayin's talk]





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CP properties in Higgs couplings

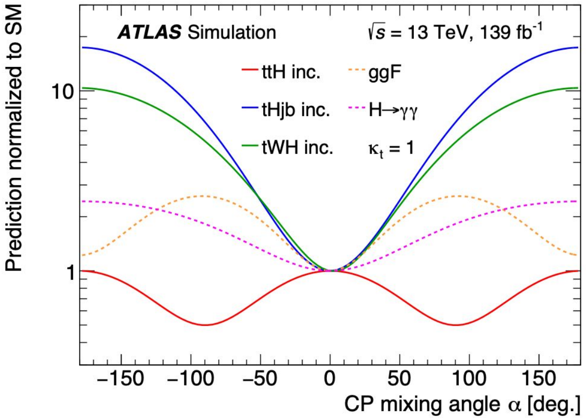
- In the SM, the Yukawa interactions are CP-even. In BSM, CP-odd component arises
- The CP-odd contribution can vary Higgs production and kinematics
- CP violation can offer more understanding of matter-antimatter asymmetry

$$\mathcal{L}_t = -\frac{m}{v}\kappa_t(\cos(\alpha)\bar{t}t + i\sin(\alpha)\bar{t}\gamma_5 t)H,$$

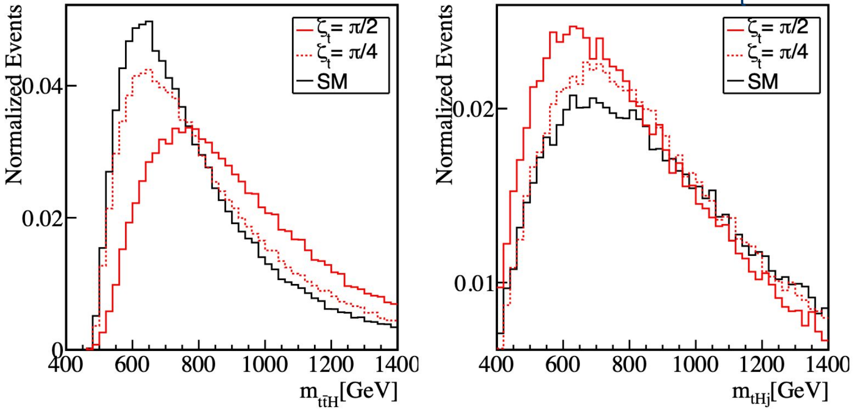
Standard model : $\alpha = 0$, $\kappa_t = 1$

CP even CP odd

ttH and tH cross-section as function of (κ_t, α)



tops + Higgs kinematics as function of (κ_t, α)



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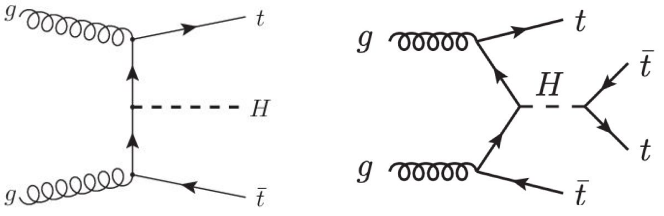
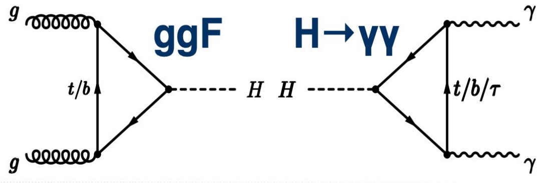
Measuring CP properties with top-Higgs coupling

- The top-Higgs coupling can be measured with
  - $H \to \gamma\gamma$, $H \to bb$, multi-lepton, and tttt (off-shell Higgs)



Direct constraint

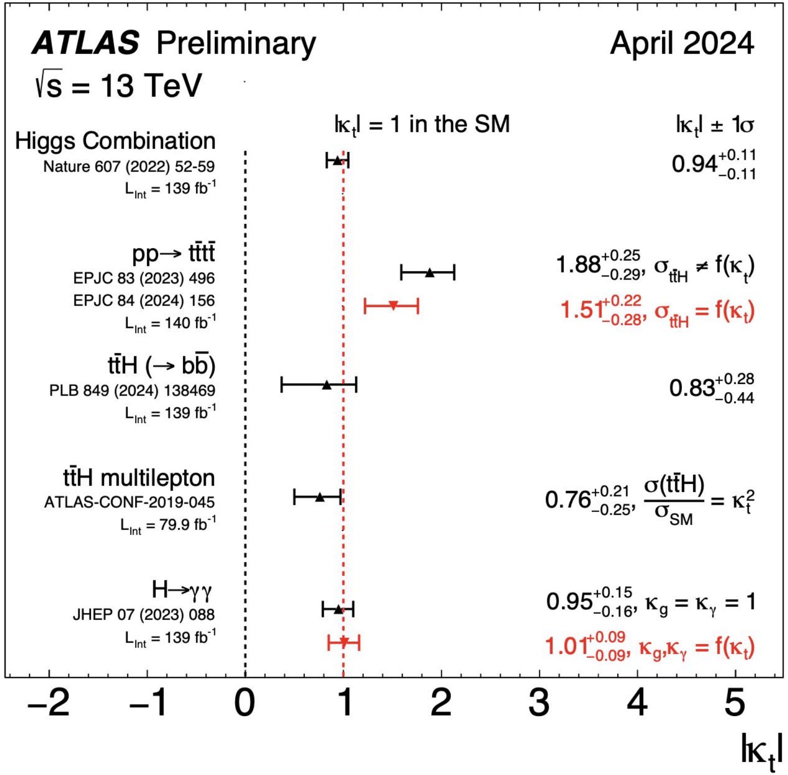


Indirect constraint

$$\sigma_{tttt} = c_0 + c_1 a_t^2 + c_2 b_t^2 + c_3 a_t^4 + c_4 a_t^2 b_t^2 + c_5 b_t^4$$

$$\sigma_{ttH} = A\, a_t^2 + B\, b_t^2$$

(b_t terms are the CP-odd contributions)



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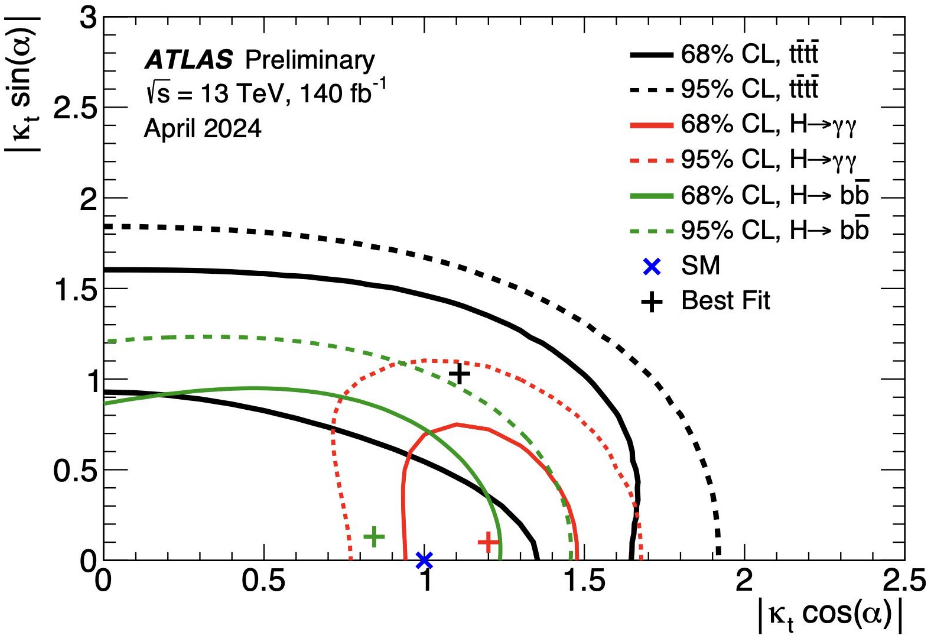
Measuring CP properties with top-Higgs coupling

- No CP-odd contribution observed yet for Htt
- In the most sensitive channel (Hyy) the total CP-odd (α=90°) is excluded by 3.9σ, 95% C limit on CP mixing: |α| < 43°
- More studies (Hgg, HVV, Htautau..) studies in [Fangyi's talk]



Higgs rare decays

Why Higgs width is important?

- Sensitive to the potential presence of beyond SM Higgs boson decays that are **not covered by direct searches**

- In the SM, Higgs width is **4.1 MeV**, which is inaccessible via most of the direct measurement at ATLAS/CMS due to limited detector resolution

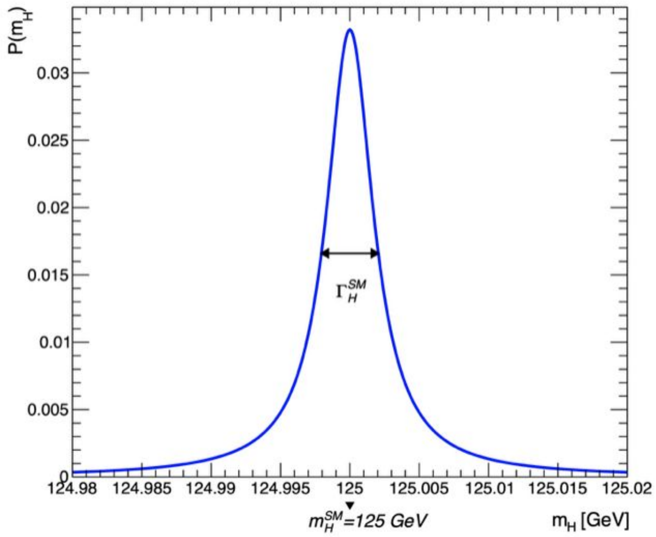


Figure 1: The relativistic Breit-Wigner distribution of the Higgs boson resonance with a width (Γ_H) of 4.1 MeV. For comparison, the width of the Z boson is more than 600 times larger (2.495 GeV), allowing us to measure it directly from the Breit-Wigner line shape. (Image: M. Javurkova/ATLAS Collaboration)

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How to measure the Higgs width

$$\frac{d\sigma}{dm^2} = \frac{g_i^2 g_f^2}{(m^2 - m_H^2)^2 + m_H^2 \Gamma_{\mathrm{H}}^2}$$

Higgs boson lineshape

$$\sigma \propto \frac{g_i^2 g_f^2}{m_H \Gamma}$$

On-shell Higgs: coupling and width correlated

$$\frac{d\sigma}{dm^2} \propto \frac{g_i^2 g_f^2}{(m^2 - m_H^2)^2}$$

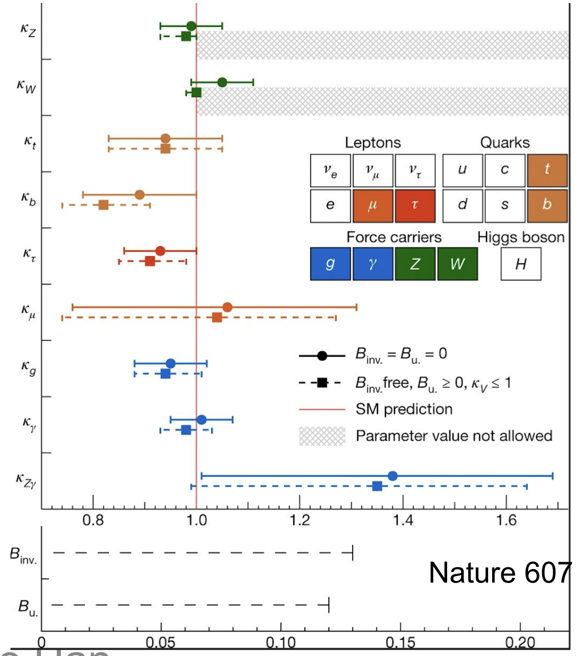
Off-shell Higgs: coupling and width uncorrelated

Combined measurement of on-shell and off-shell Higgs boson : $R_\Gamma = \frac{\Gamma_{\mathrm{H}}}{\Gamma_{\mathrm{H,SM}}} = \frac{\mu_{\text{off-shell}}}{\mu_{\text{on-shell}}}$

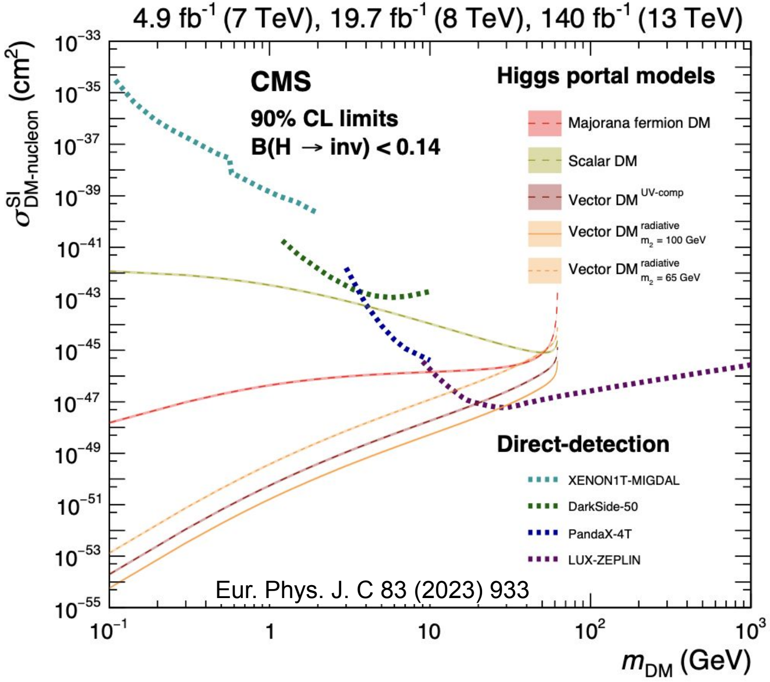
- Higgs width with off-shell HZZ:
  - ATLAS: PLB 846 (2023) 138223 (95% CL limit of Γ_H < 10.2 MeV)
  - CMS: Nature Phys. 18 (2022) 1329 (limit of Γ_H < 8.5 MeV)
- New result in ATLAS based on top-Higgs coupling: arxiv:2407.10631
  - Solving the problem that the loop-induced effective Higgs-gluon coupling could vary differently between on-shell and off-shell production processes
- More studies and details in Hongtao's talk

Search for Higgs rare decays

- Higgs to invisible is a rare decay channel in the SM
- However, the H->invisible Br will be enhanced with interactions between Higgs and DM
- No evidence found for DM candidates, constraints are set on the Br (see Qiuping's talk)

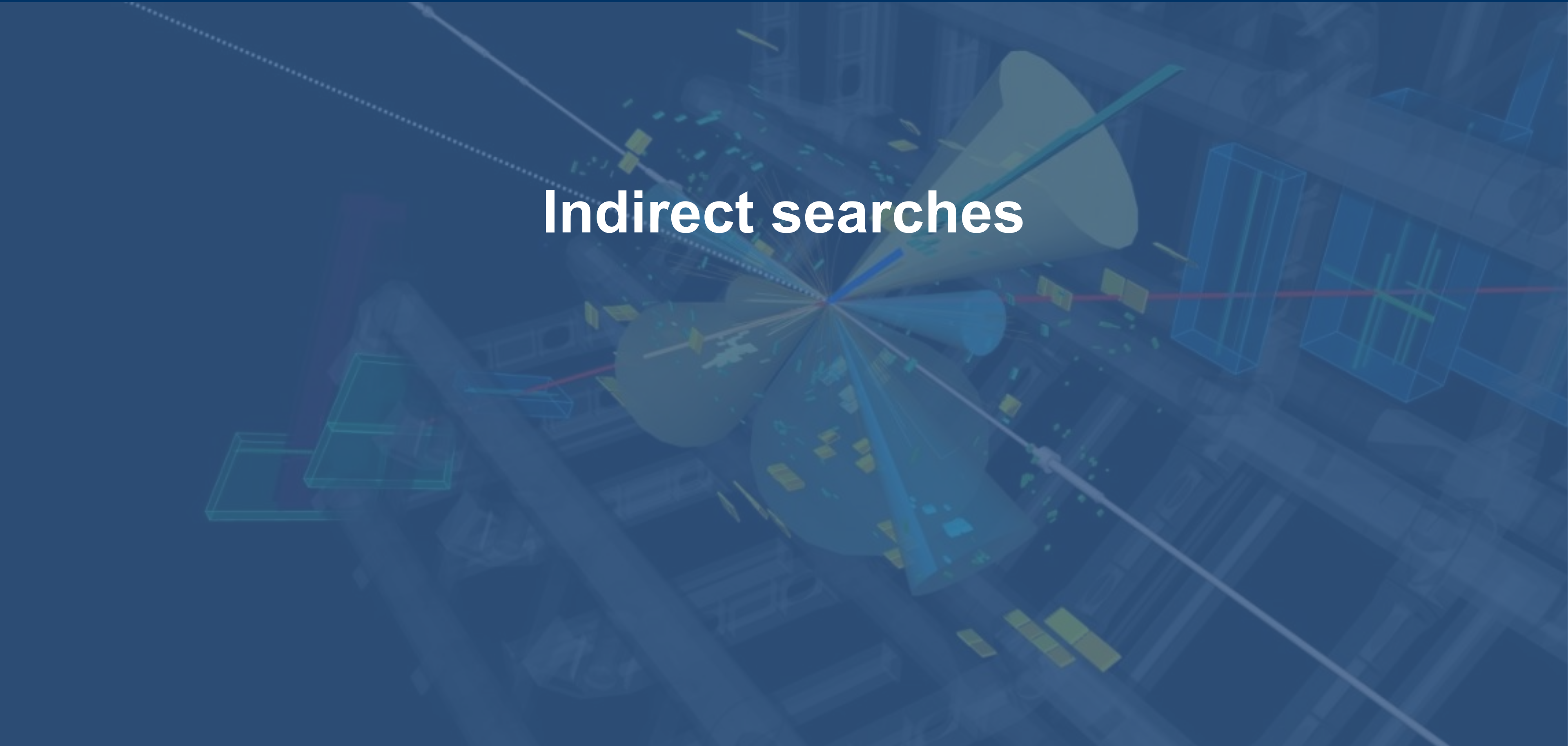


Nature 607 52-59 (2022)



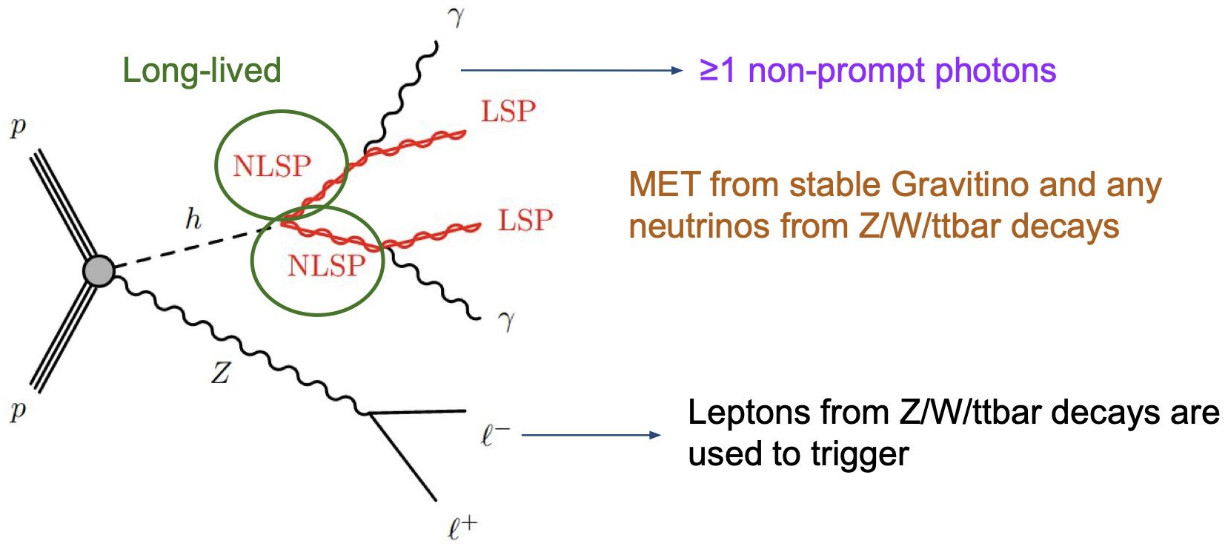
Eur. Phys. J. C 83 (2023) 933

Indirect searches



Higgs decay to long live particles

- The searches for Higgs exotic decays are also important for the new physics study with SM-like Higgs boson and photons in the final state.
- SUSY models can predict Higgs decay to displaced photons and invisible new particles as missing transverse energy.
- **The photon pointing, and photon timing, can be defined as the observables.**



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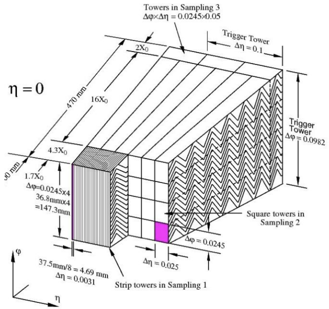
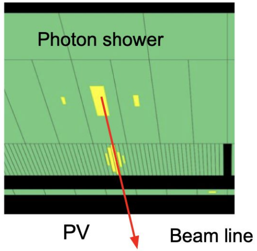
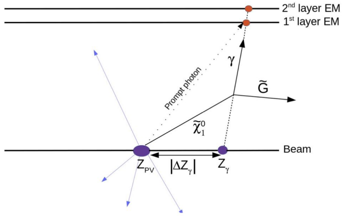
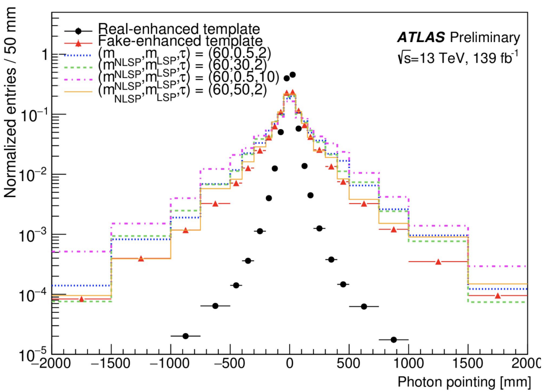
Photon pointing and timing

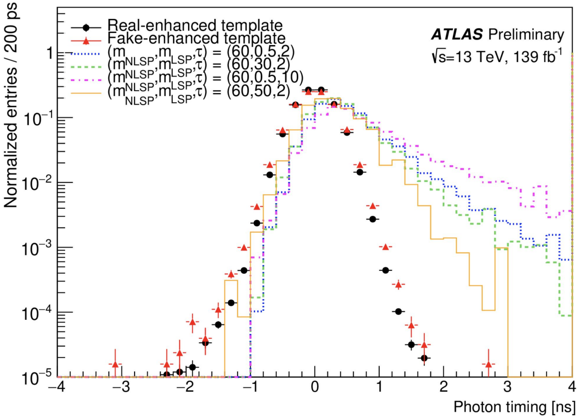
- **Photon pointing** is the separation along the beam line between the extrapolated origin of photon and the primary vertex. Multiple layers of EM calorimeter suggests photon's direction.
- **Photon timing** is defined as the delay in arrival time compared to prompt photon. The time of arrival of photon is measured in the highest energy cell of the second layer of EM-calorimeter.
- Since SUSY models has **displaced and delayed photons**, the pointing and timing can be











PhysRevD.108.032016

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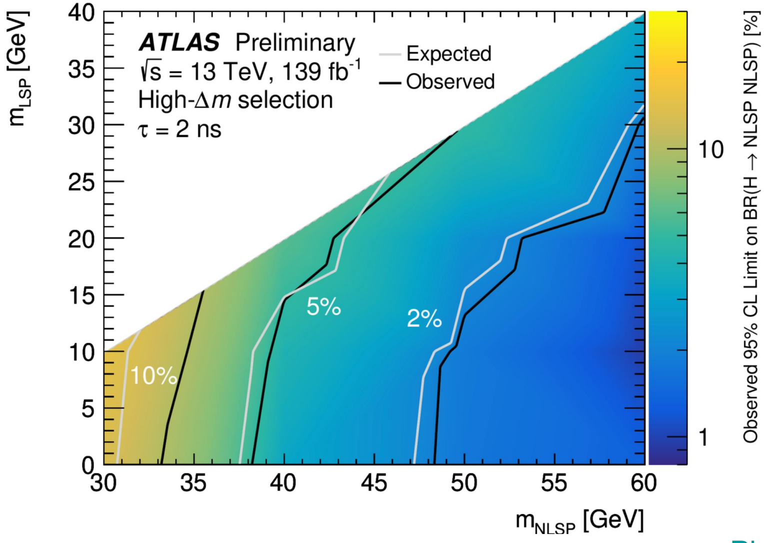
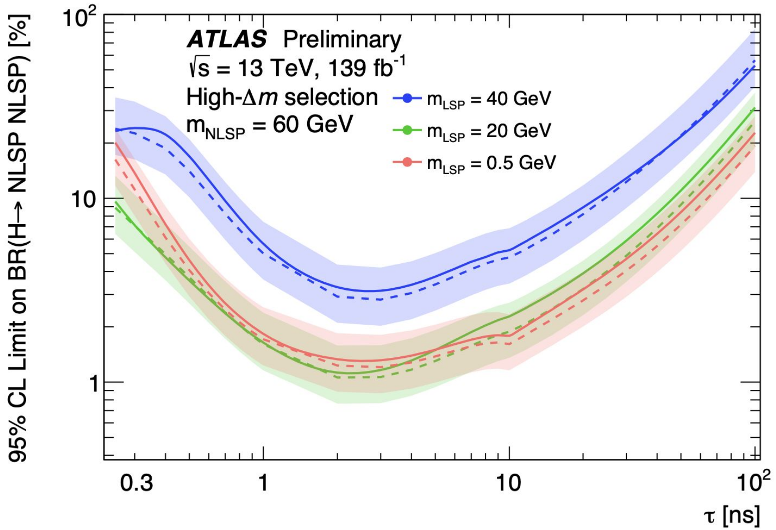
Results mNLSP-mLSP = 10 GeV

- In general, there's no excess found beyond SM.
- Limits are set on the Br of Higgs exotic decays, the sensitivities are higher when the mNLSP-mLSP is higher, or the NLSP lifetime is closer to 2ns.





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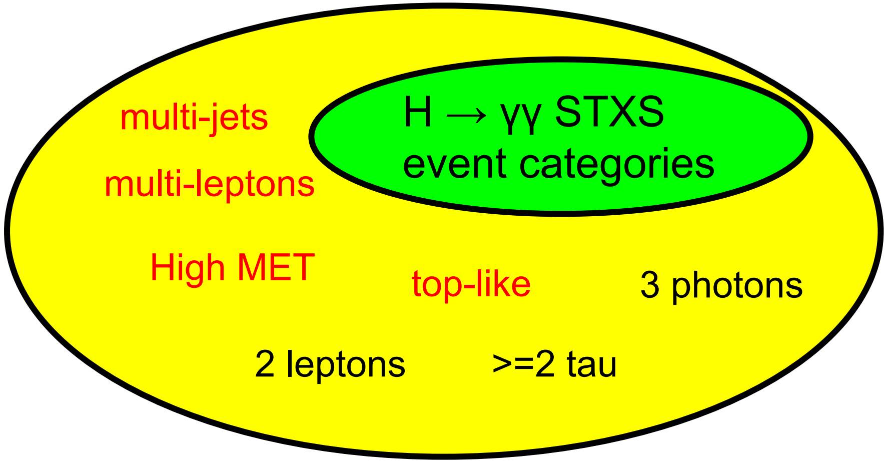
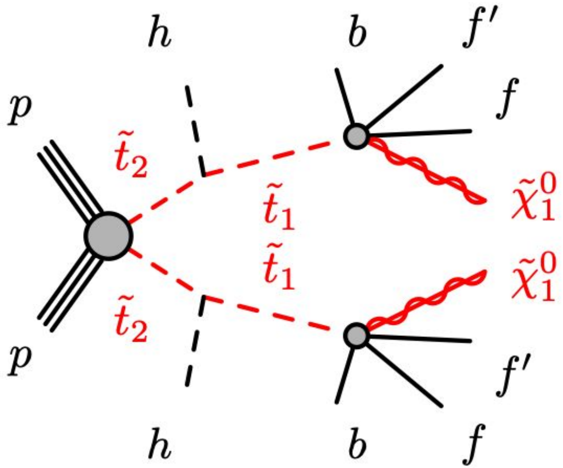
Model independent H+X search

- STXS measurement covers various phase spaces, but there are many regions uncovered..
- Various of BSM models, like EW or strong SUSY and Flavor Changing Neutral Currents (FCNC) expect the production of Higgs boson and new particles
  - Including the new physics that arise with the top-Higgs sector
- A search for H(→γγ)+X process can be model-independent JHEP 07 (2023) 176

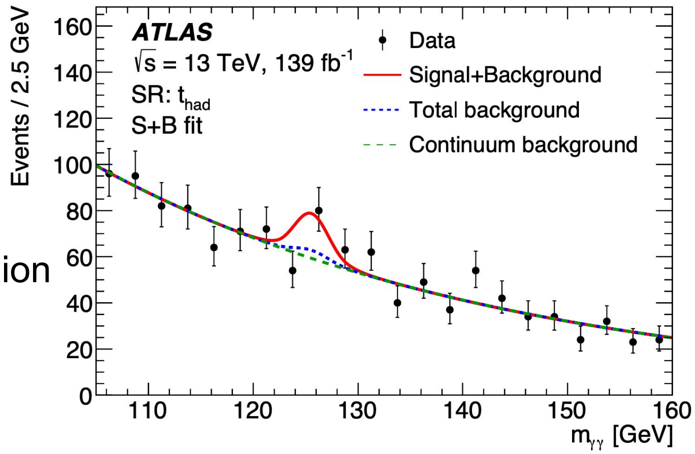


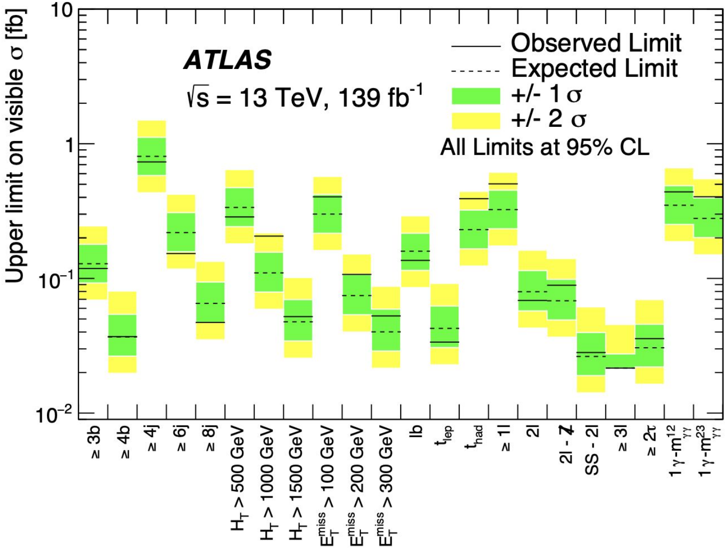


H+X search: results

- 22 cut-based categories are defined with different final states the searches are performed independently in all the signal regions, by S+B fits on the m(γγ)
- no obvious excess for H+X production.
  - The largest deviation from SM has a local significance 1.8σ in the HT > 1000 GeV region
  - There's 1.7σ local significance in the top hadronic decay region
- The detector level limits are set on the H+X cross-sections, and the detector efficiencies of various BSM models are reported to utilize the limits

1.7σ significance in the handronic top decay region





[JHEP 07 (2023) 176]

Summary

- Throughout history, deviations from the established models have often pointed to new physics, including the introduction of 2nd and 3rd generation particles, in our case the established model is the SM

- In general, the indirect searches of BSM have the advantages about model-independency, coverage of models, and the re-optimization of existing analyses

- The Indirect searches are introduced with 3 approaches: impact on Higgs couplings, Higgs rare decays, and indirect searches

- We haven’t found evidence of BSM yet, but the Higgs boson can play a central role in BSM studies, with many new ideas to be investigated through its production / decay

Backup

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