Higgs physics at LHC

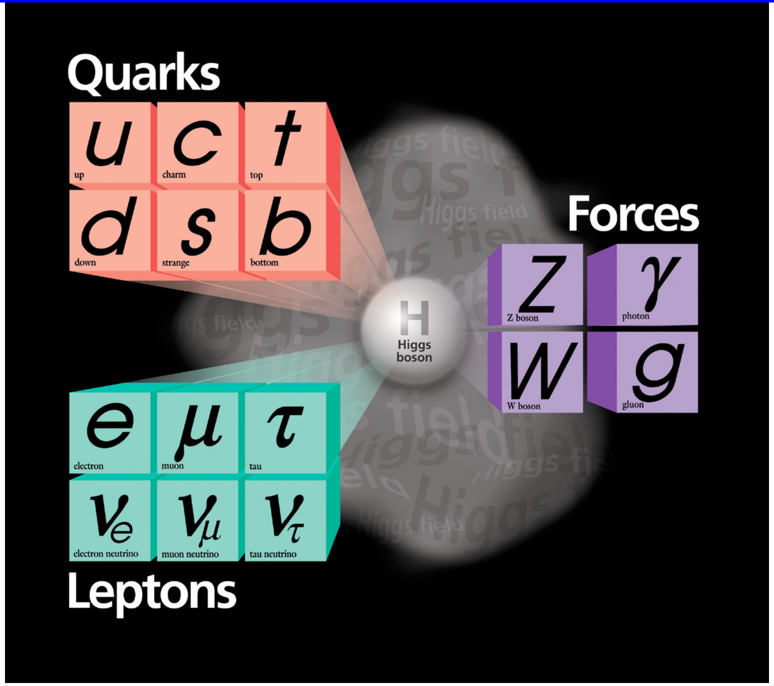
Lei Zhang (张雷)

School of Physics, Nanjing University

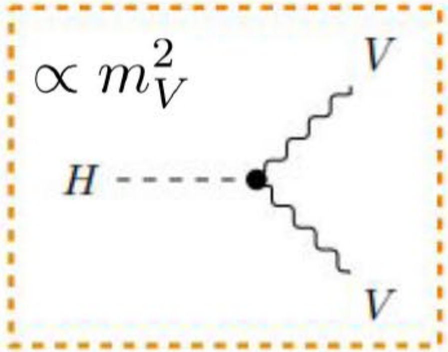
29th Mini-workshop on the frontier of LHC，福州，15 Dec 2024

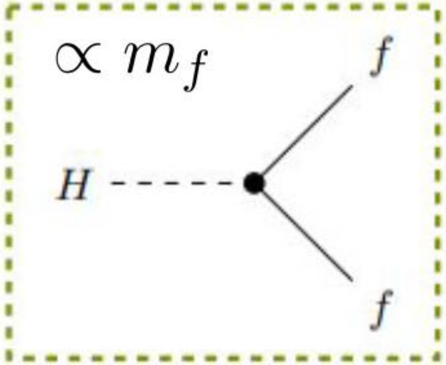
Higgs: the lord of Standard Model

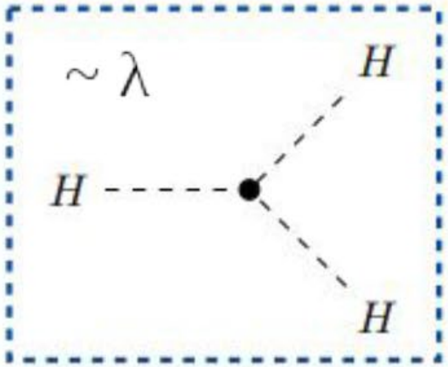
$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu}$$
$$+ i \bar{\psi} \not{D} \psi + h.c.$$
$$+ \bar{\psi}_i y_{ij} \psi_j \phi + h.c.$$ Yukawa terms
$$+ |D_\mu \phi|^2 - V(\phi)$$ Brout-Englert-Higgs mechanism

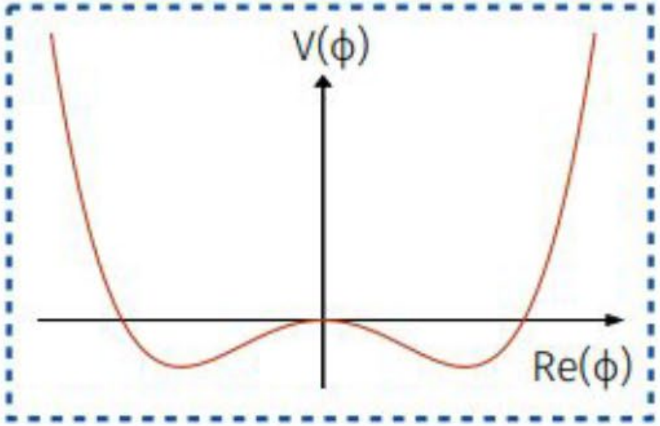


Higgs boson
CP-even scalar
⇒ elementary
⇒ electrically neutral
⇒ spin 0
⇒ parity even









⇒ 15 out of the 19 free parameters of the SM are connected to the Higgs boson

self-coupling λ
HH production

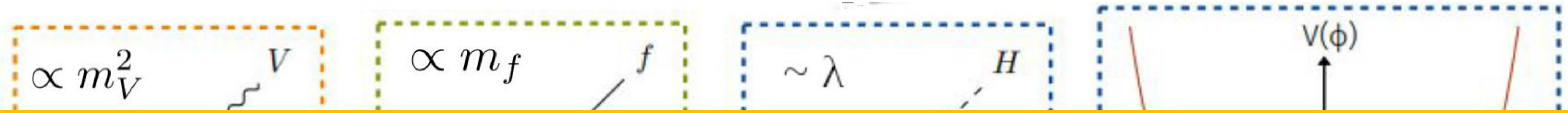
Higgs: the lord of Standard Model

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i\bar{\psi}\not{D}\psi + h.c. + \bar{\psi}_i y_{ij} \psi_j \phi + h.c. + |D_\mu \phi|^2 - V(\phi)$$

once m_H is known, it can be well tested

Couples to all massive bosons and fermions with a strength related to the particles' mass

- production cross-section
- branching ratios
- total decay width
- …

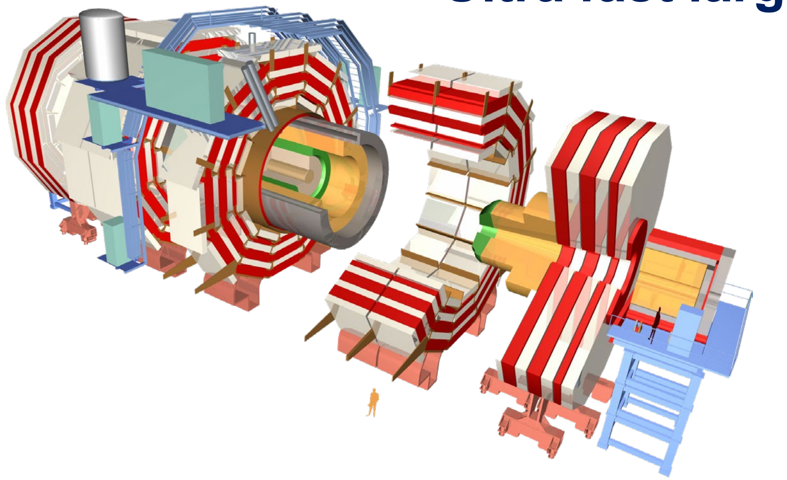


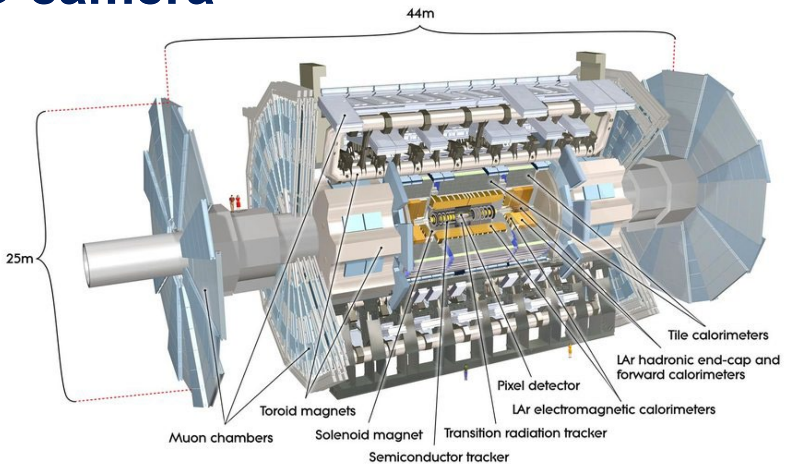
- ➢ Investigating with better precision and granularity, probing rarer processes and more extreme phase-spaces, etc.
- ➢ In this talk, I will try to give an overview over current best knowledge and most recent results - strong & personal selection!

⇒ 15 out of the 19 free parameters of the SM are connected to the Higgs boson

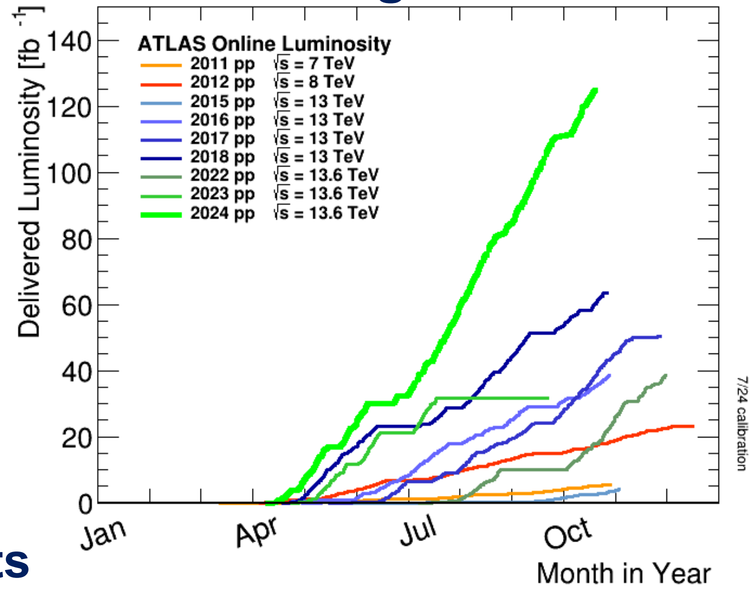
ATLAS and CMS: exploring at energy frontier

Ultra fast large 3D camera

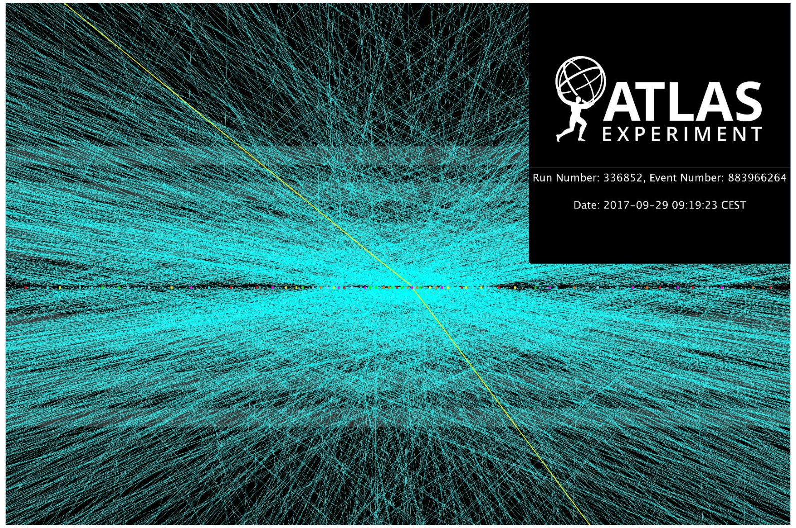




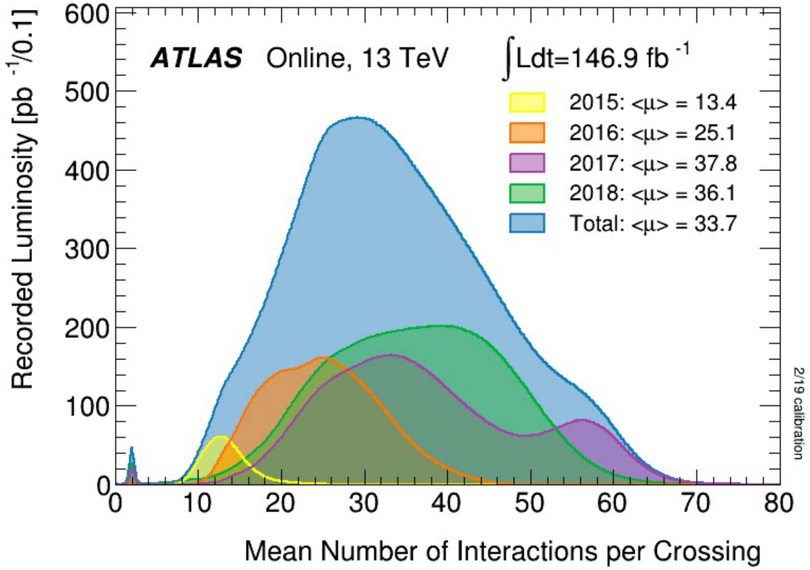
Huge dataset

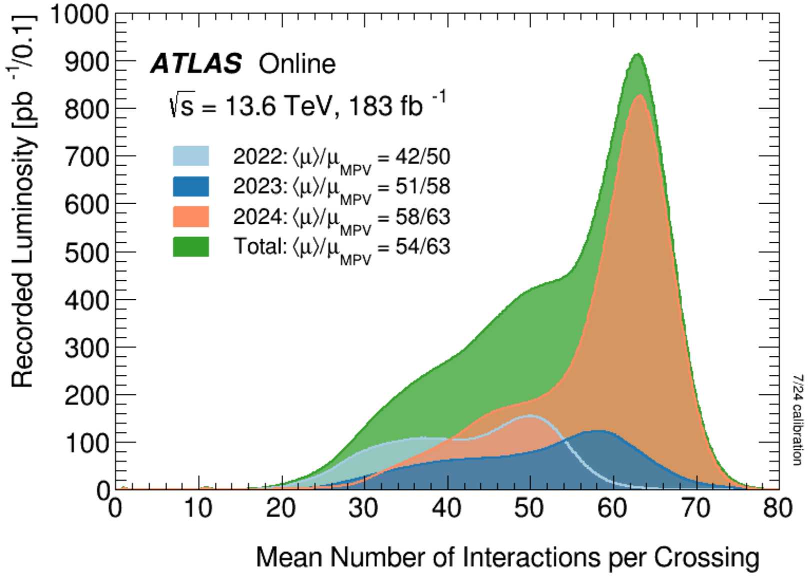


Busy environment



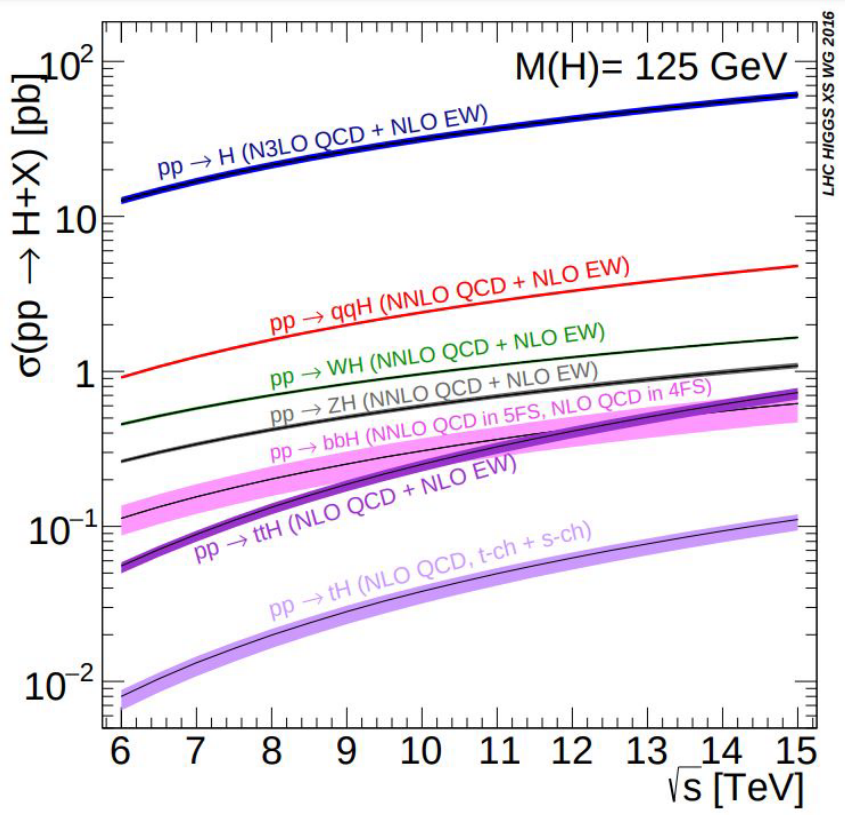
Pileup events

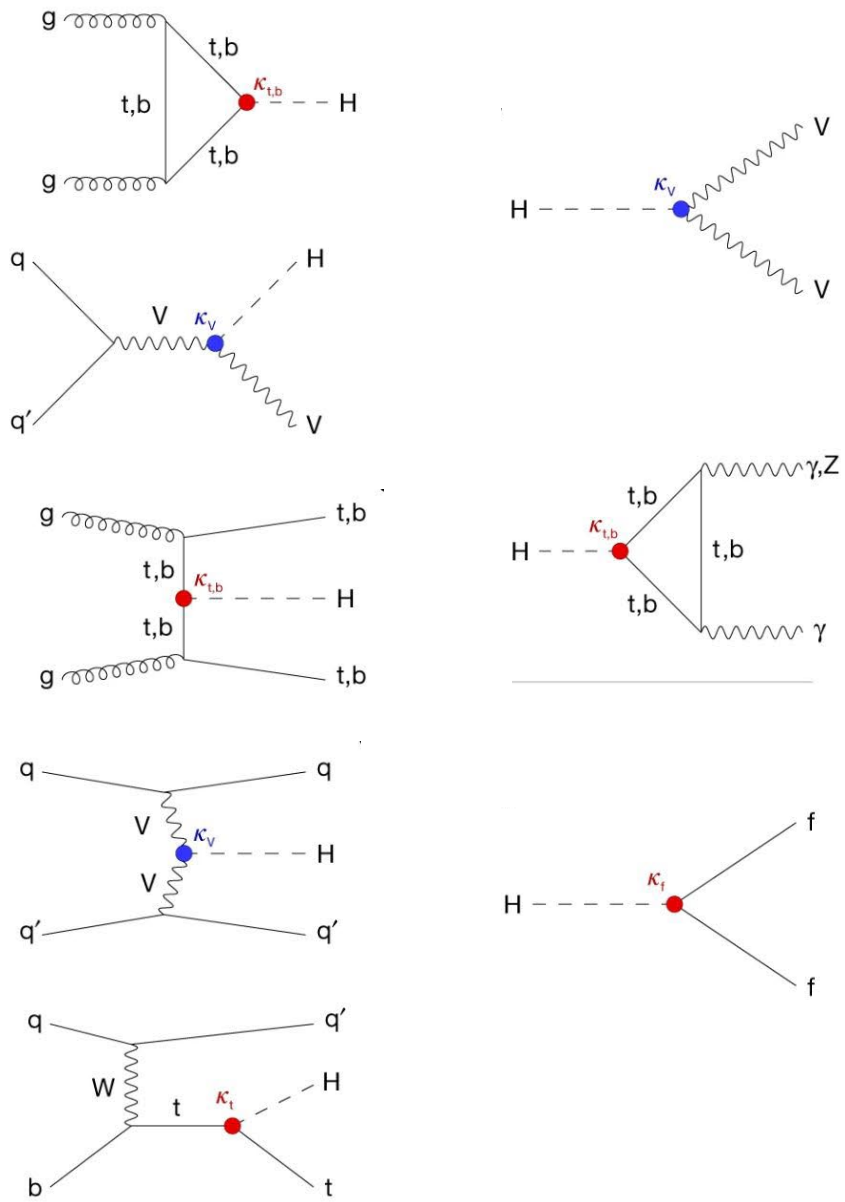




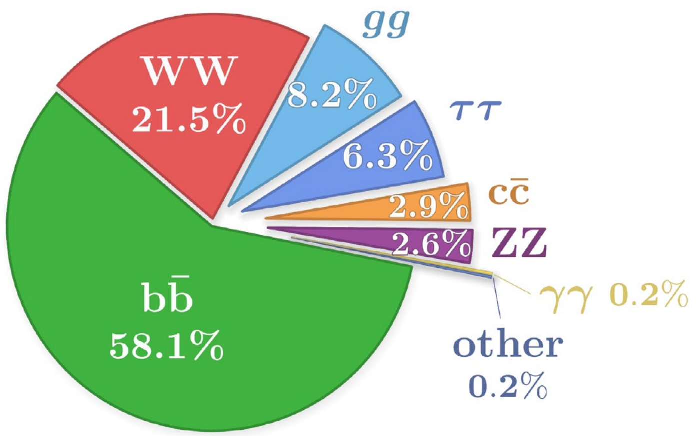
Rich phenomenology at the LHC

A variety of production modes



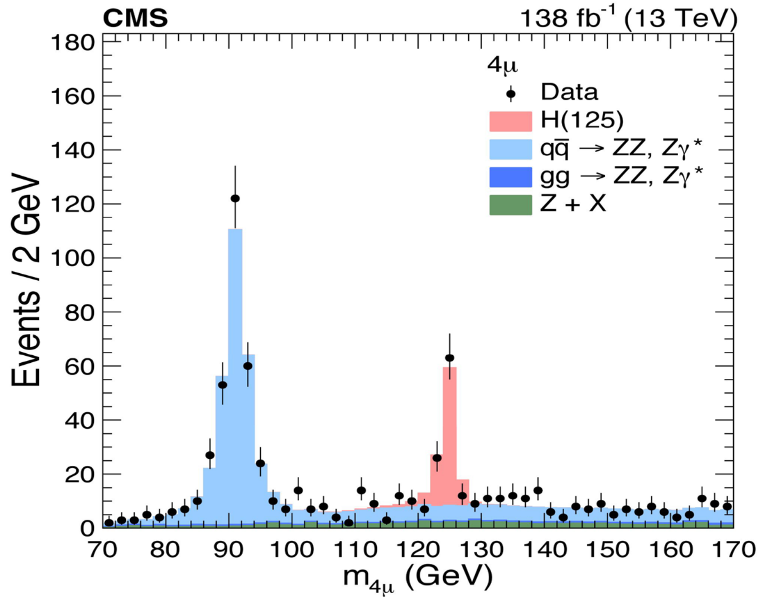


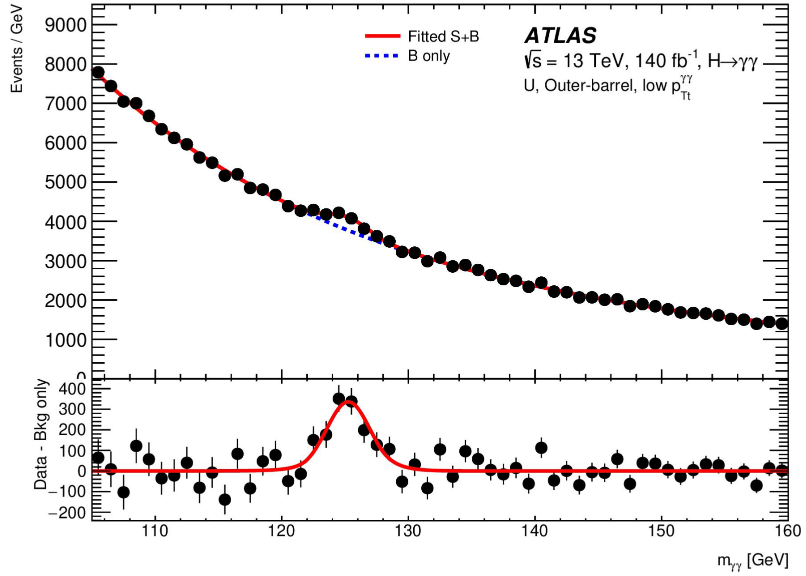
A variety of decay modes



Higgs property: mass

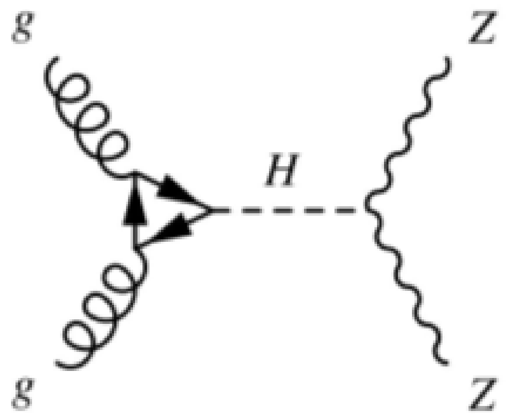
- Measured in clean final states with Higgs boson fully reconstructed
- CMS: H→ZZ*→ 4 leptons (e/μ) [arXiv:2409.13663]
  - $m_H = 125.08 \pm 0.10\ (\text{stat.}) \pm 0.05\ (\text{syst.})$ GeV
- ATLAS: combination [PRL 131 (2023) 251802]
  - H→γγ and H→ZZ*→ 4 leptons (e/μ)
  - $m_H = 125.11 \pm 0.09\ (\text{stat.}) \pm 0.06\ (\text{syst.})$ GeV
- Most precise measurements to date
  - Mass resolution: < 1‰
  - in very good agreement with each other

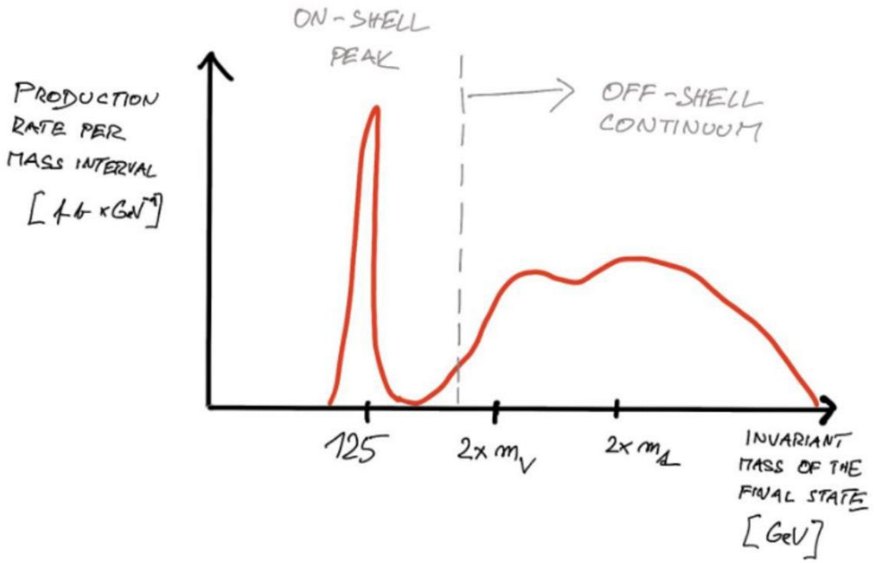


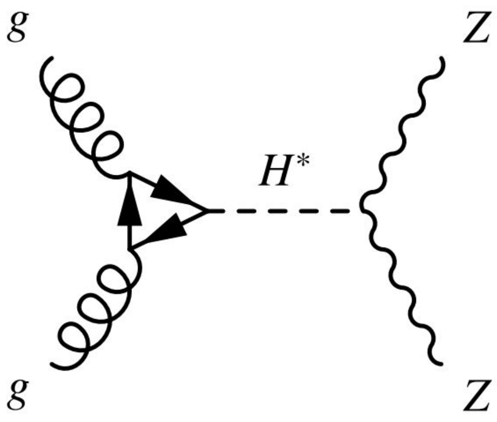


Higgs-boson total width

- Assuming SM: Γ_H = 4.1 MeV for m_H ~ 125 GeV
  - Constrain unmeasured/able decays, modified by BSM decays, e.g. dark-matter
  - At LHC, direct measurements from line shape or flight distance, is impossible
- Constrain via $\Gamma_H \propto \sigma$(off-shell) / σ(on-shell)
  - Assumption: same couplings between off- and on-shell

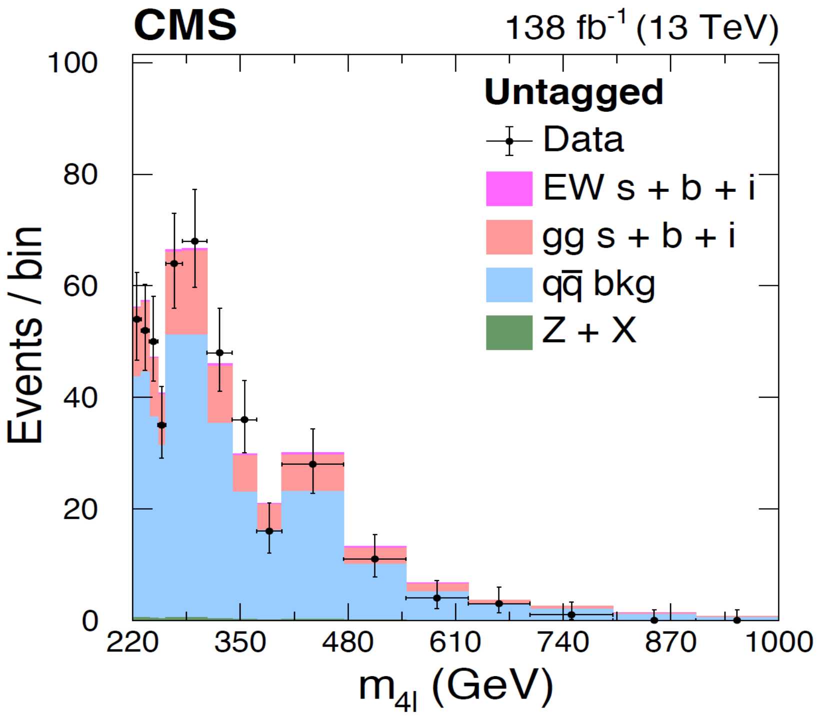


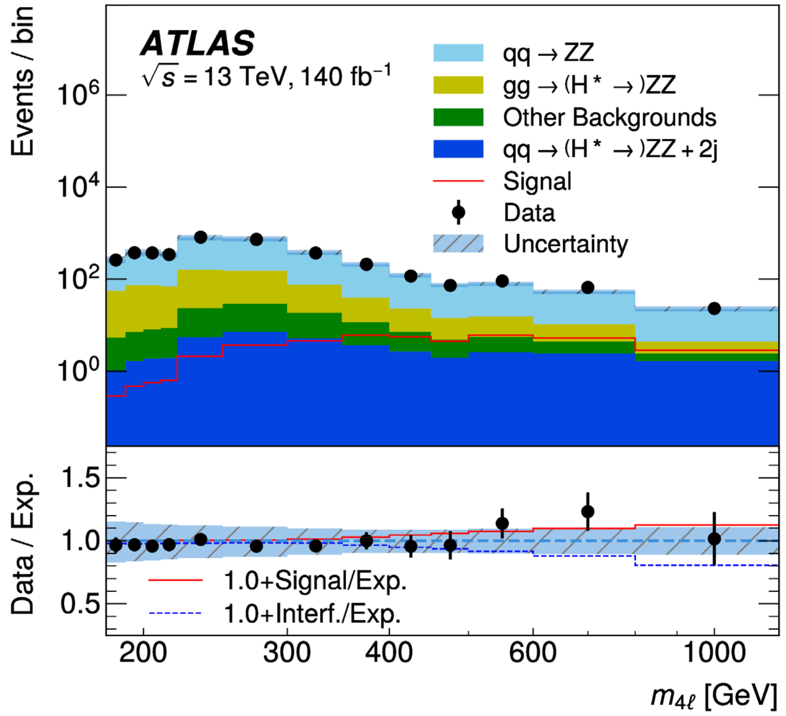


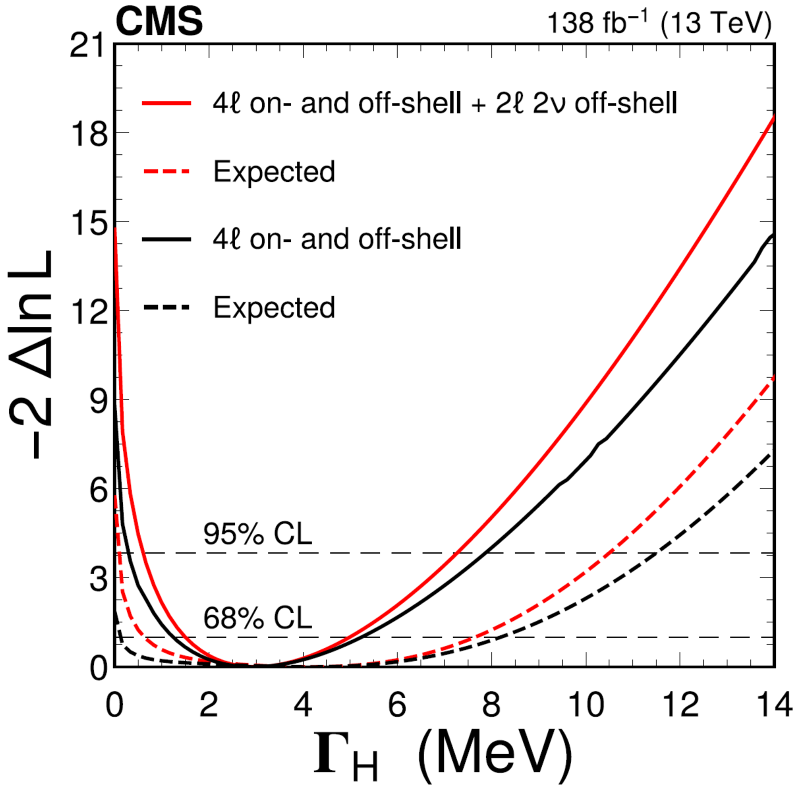


Higgs-boson total width

- ATLAS: $\Gamma_H = 4.3^{+2.7}_{-1.9}$ [arXiv:2412.01548]
- CMS: $\Gamma_H = 3.0^{+2.0}_{-1.5}$ [arXiv:2409.13663]



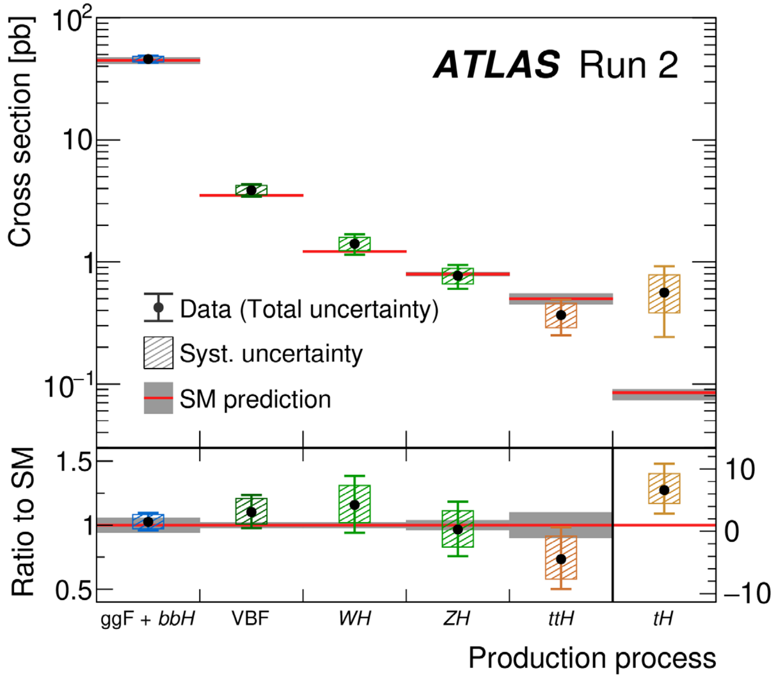


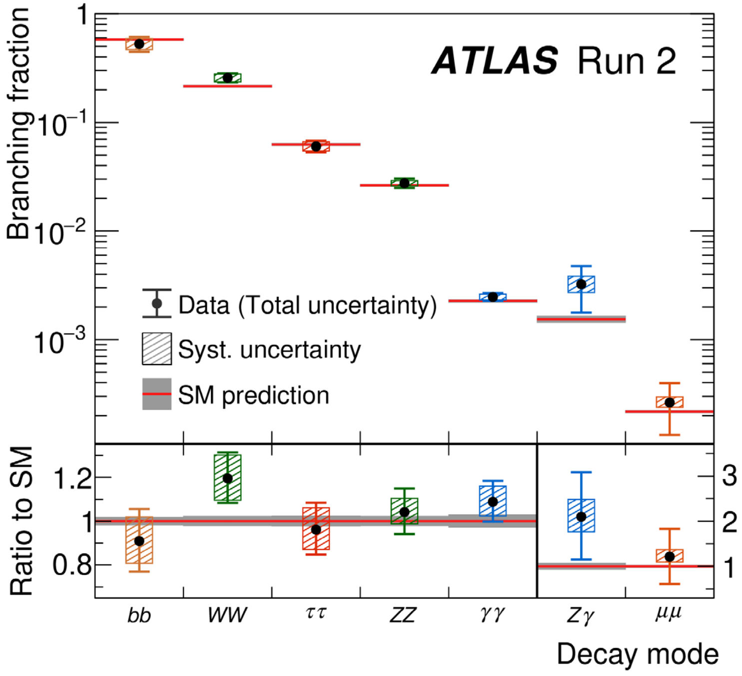


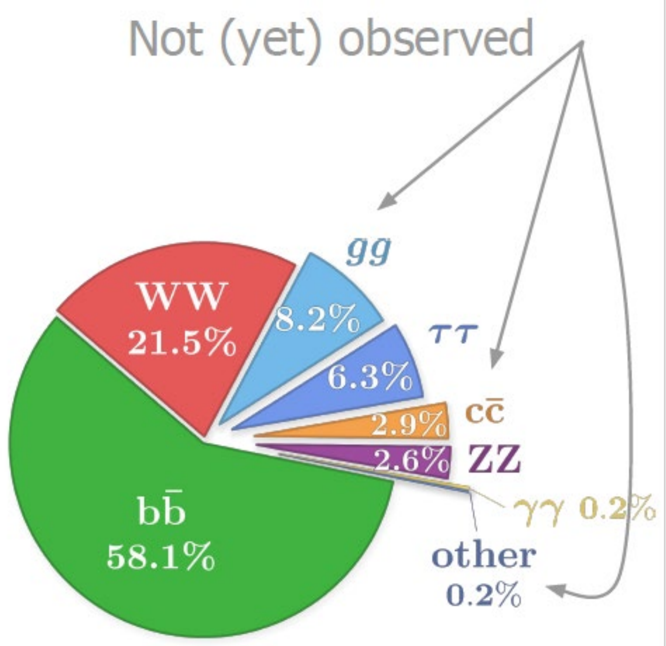
Higgs property: production and decay

- Dominant production modes and > 88% of potential SM decays observed
  - with < 10-20% precision

- ATLAS: Nature 607 52 (2022)
- CMS: Nature 607 60 (2022)

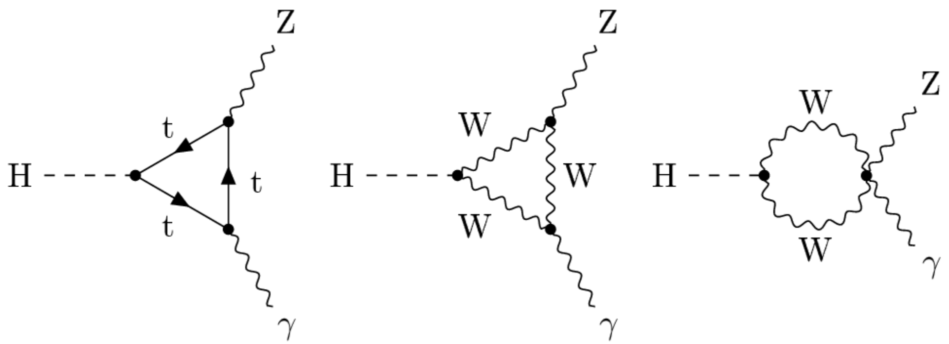


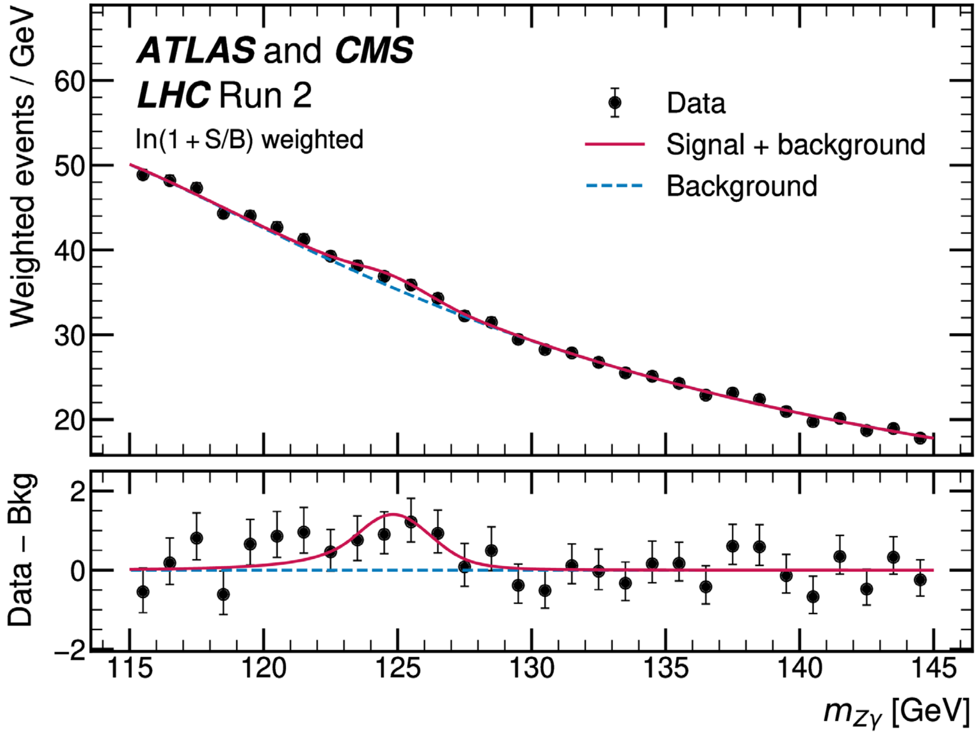




Higgs property: production and decay

- $H\rightarrow Z\gamma$: $Br(H\rightarrow Z\gamma) = 1.54\times10^{-3}$
  - rare H decay via loop diagrams sensitive to new physics



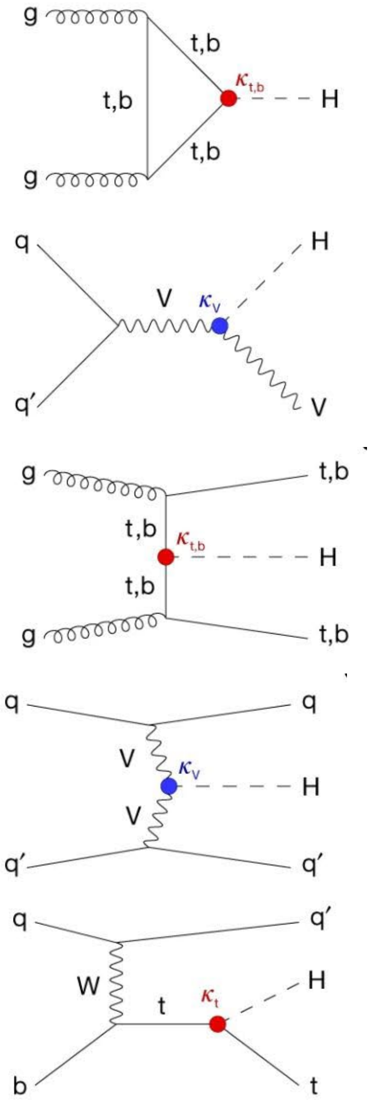


- ATLAS and CMS combination
  - Obs. (exp.) significance of 3.4 (1.6)
  - First evidence of H decay
  - μ= 2.2$\pm$0.6 (stat) (syst)
- Agrees with SM prediction within 1.9 σ

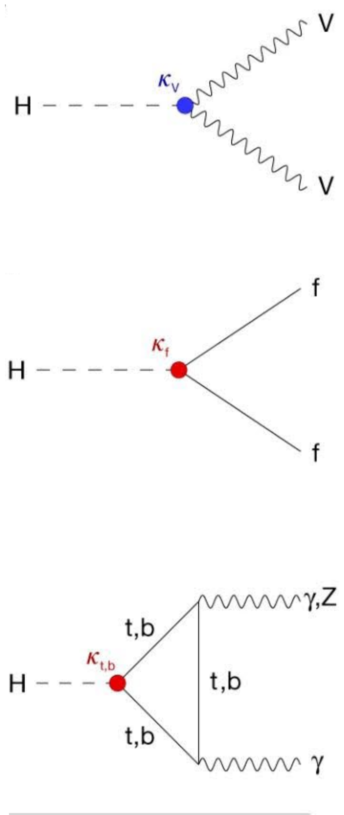
Phys. rev. Lett. 132 (2024) 021803

Higgs property: coupling

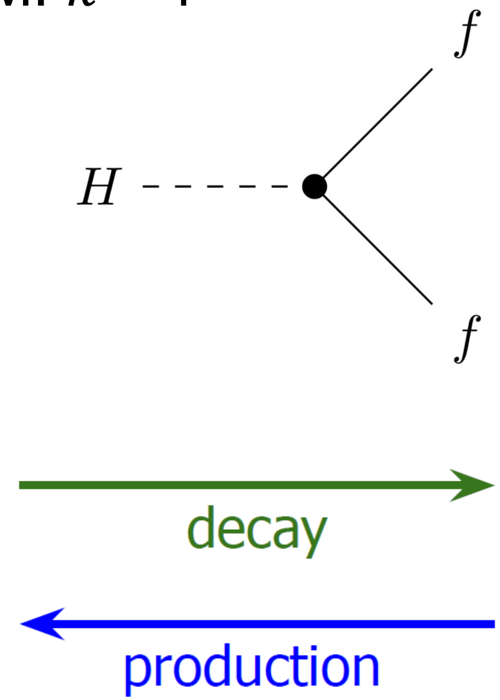
Production modes



Decay modes



- Coupling-strength modifier κ
  - SM: κ = 1

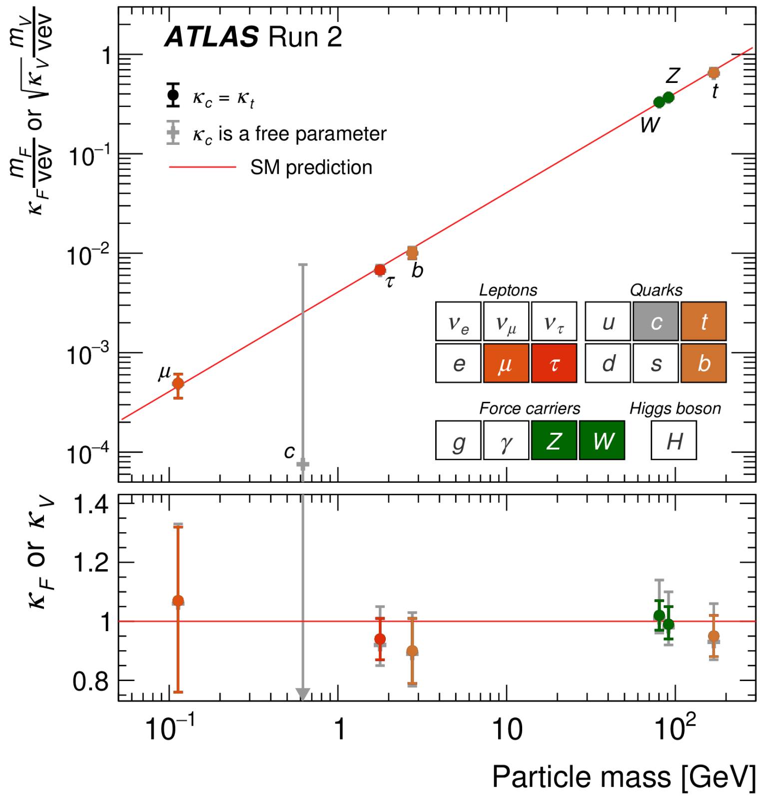


$$\kappa_j^2 = \frac{\sigma_j}{\sigma_j^{\mathrm{SM}}}$$

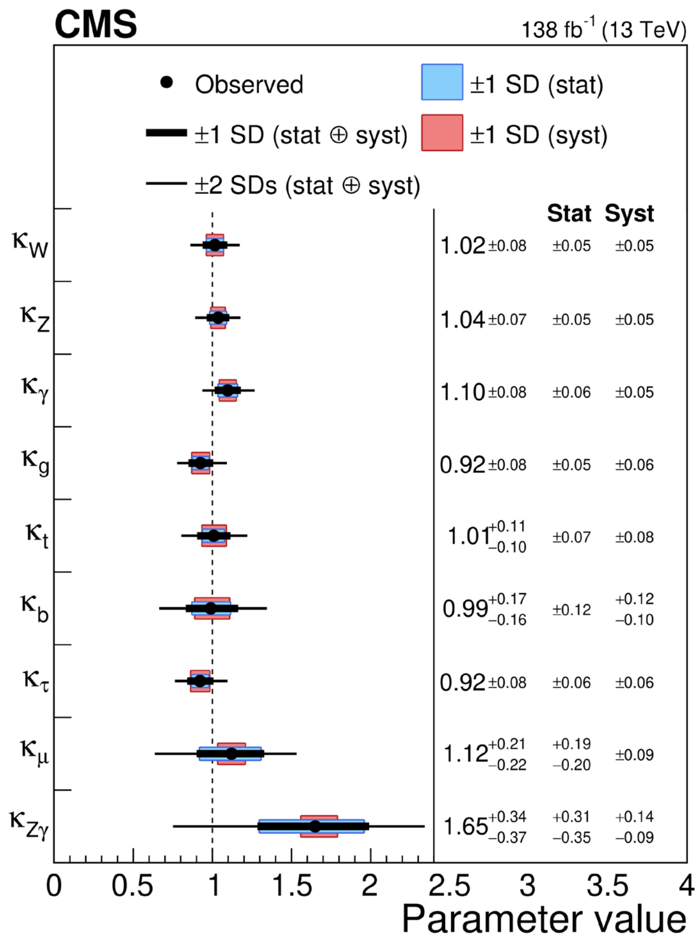
$$\kappa_j^2 = \frac{\Gamma_j}{\Gamma_j^{\mathrm{SM}}}$$

Higgs property: coupling

- ➢ Good agreement with SM prediction, within < 10% uncertainty
  - Still many missing pieces…



ATLAS: Nature 607 52 (2022)



CMS: Nature 607 (2022) 60

Higgs: new territory to explore

Why is the electroweak interaction so much stronger than gravity?

- Are there new particles close to the mass of the Higgs boson?
- Is the Higgs boson elementary or made of other particles?
- Are there anomalies in the interactions of the Higgs boson with the *W* and *Z* bosons?

Why is there more matter than antimatter in the Universe?

- Are there charge-parity violating Higgs decays?
- Are there anomalies in the Higgs self-coupling that would imply a strong first-order early-Universe electroweak phase transition?
- Are there multiple Higgs sectors?

Higgs boson

What is dark matter?

- Can the Higgs boson provide a portal to dark matter or a dark sector?
- Is the Higgs lifetime consistent with the Standard Model?
- Are there new decay modes of the Higgs boson?

What is the origin of the vast range of quark and lepton masses in the Standard Model?

- Are there modified interactions to the Higgs boson and known particles?
- Does the Higgs boson decay into pairs of quarks or leptons with distinct flavours (for example, $H \to \mu^+\tau^-$)?

What is the origin of the early Universe inflation?

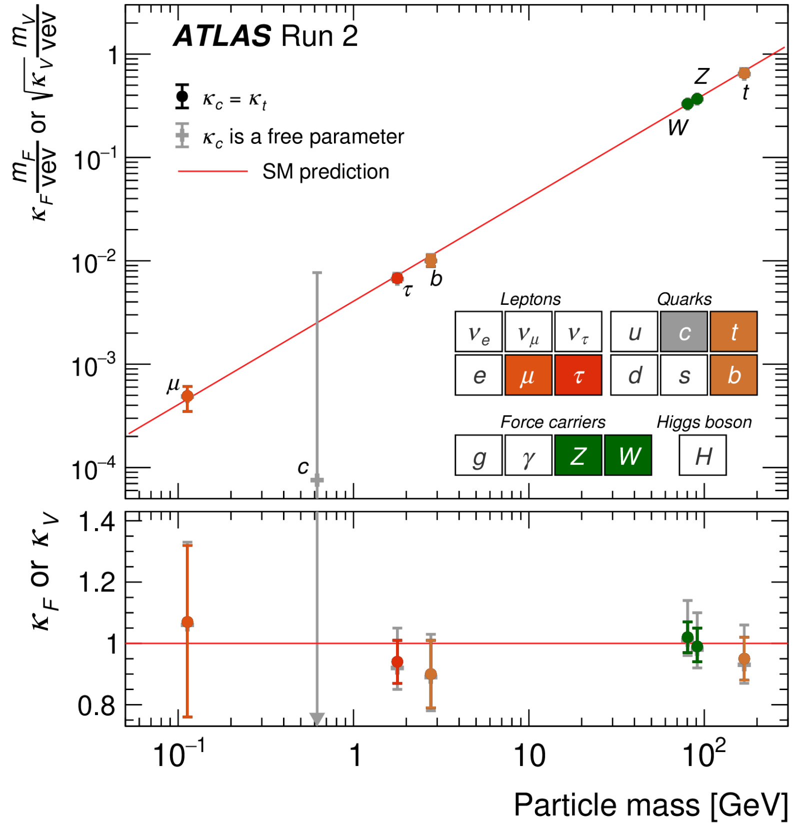
- Any imprint in cosmological observations?

Adapted from G. Salam, L.T. Wang, G. Zanderighi; Nature 607, 41 (2022)

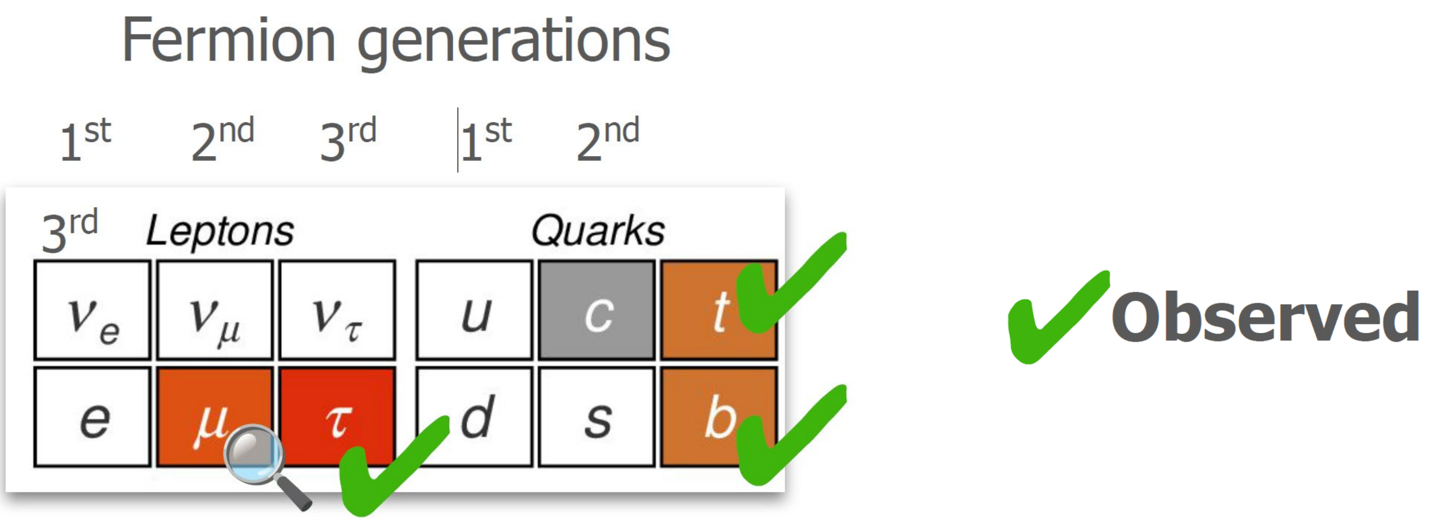
- Higgs boson might be key to answering many open questions
  - Self-coupling, Couplings to other particles, CP violation? Total width, +much more, + direct searches for new physics
  - Keep investigating with better precision and granularity, probing rarer processes, more extreme phase-spaces, etc.

Beyond the 3rd generation

- Yukawa coupling: 9 out of 19 free parameters of SM

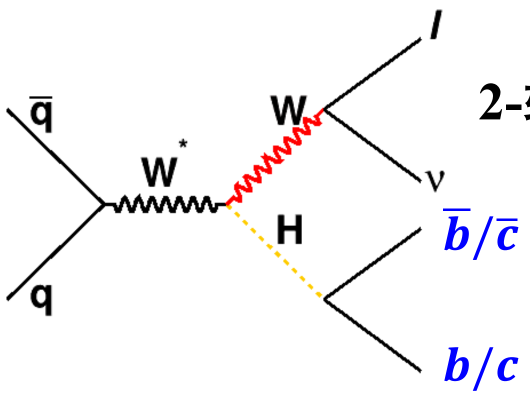


- On the way to probe all Yukawa couplings
  - the charm quark standing at the frontier

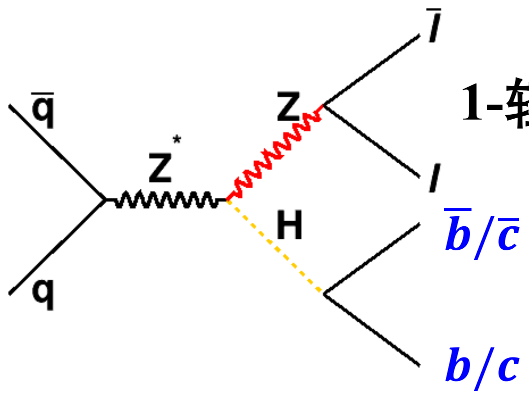


VH(→cc): ATLAS final Run-2

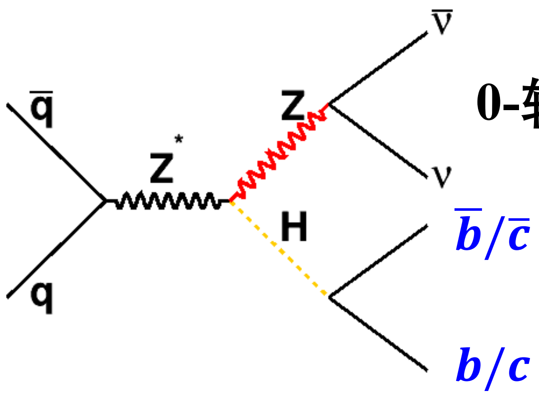
- BR(H→cc)=2.9%, 2nd largest BR not yet observed [ATLAS-CONF-204-010]
  - Most direct & sensitive probe of Higgs-charm coupling
  - Quark final state: huge multi-jet backgrounds
- V(→leptons)H: golden channel for H→bb/cc
  - Significant XS and effective multi-jet background suppression



2-轻子道



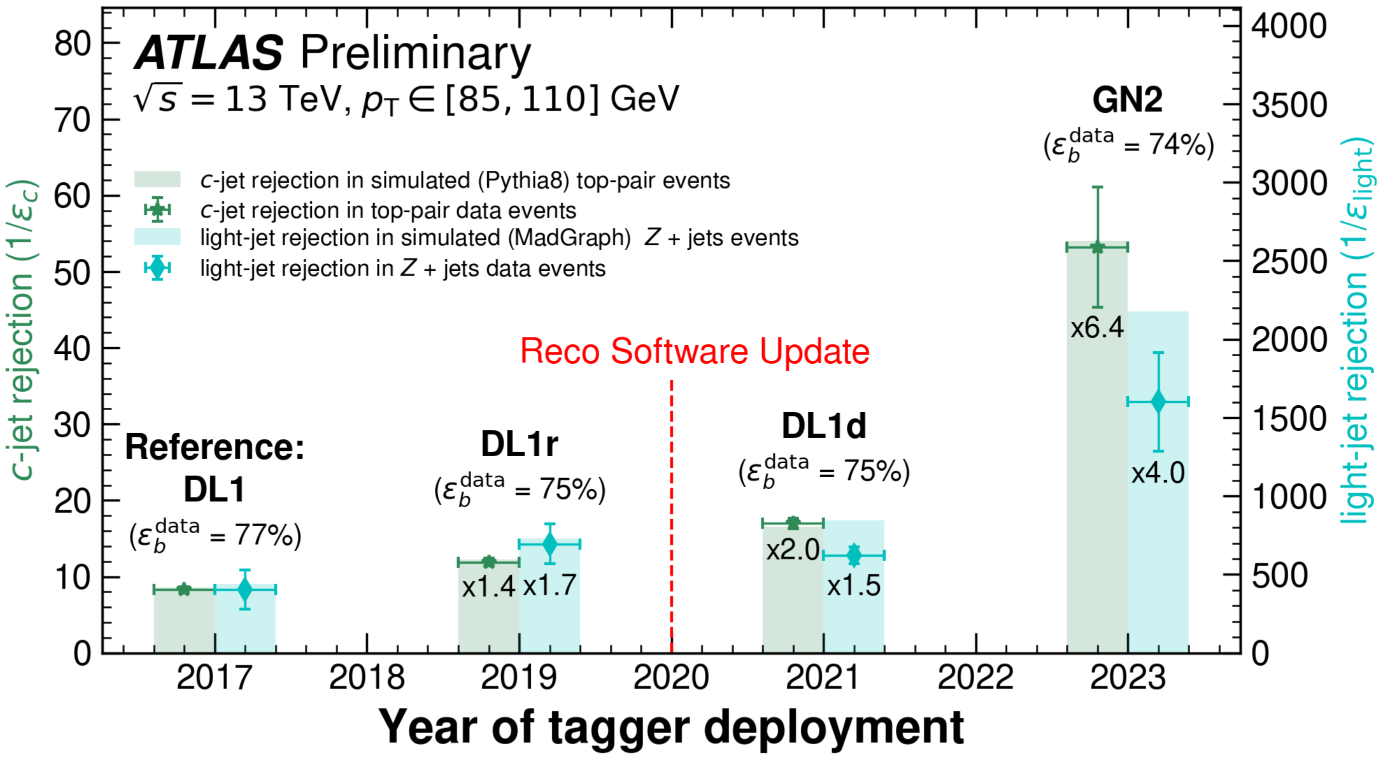
1-轻子道

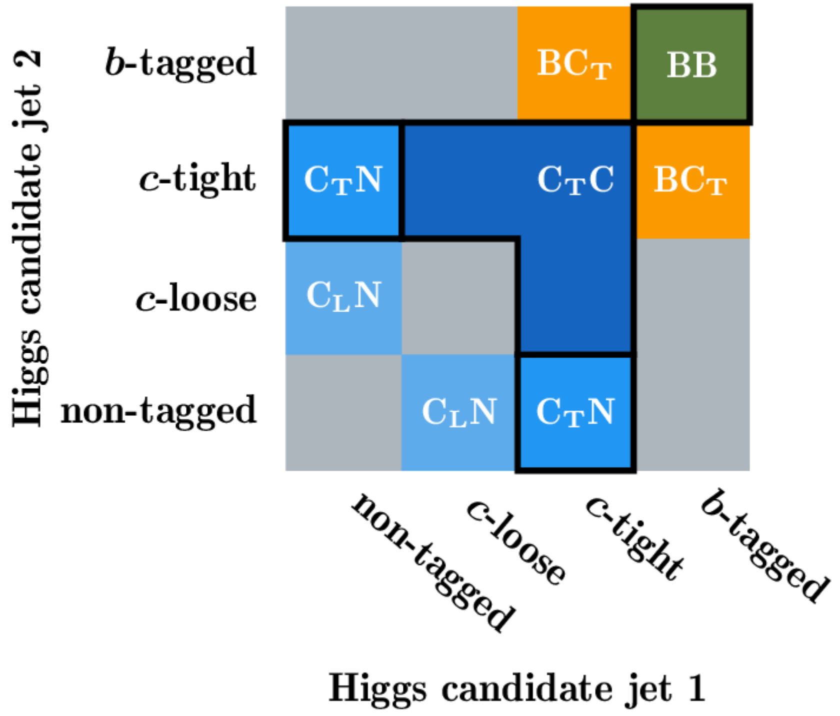


0-轻子道

VH(→cc): ATLAS final Run-2

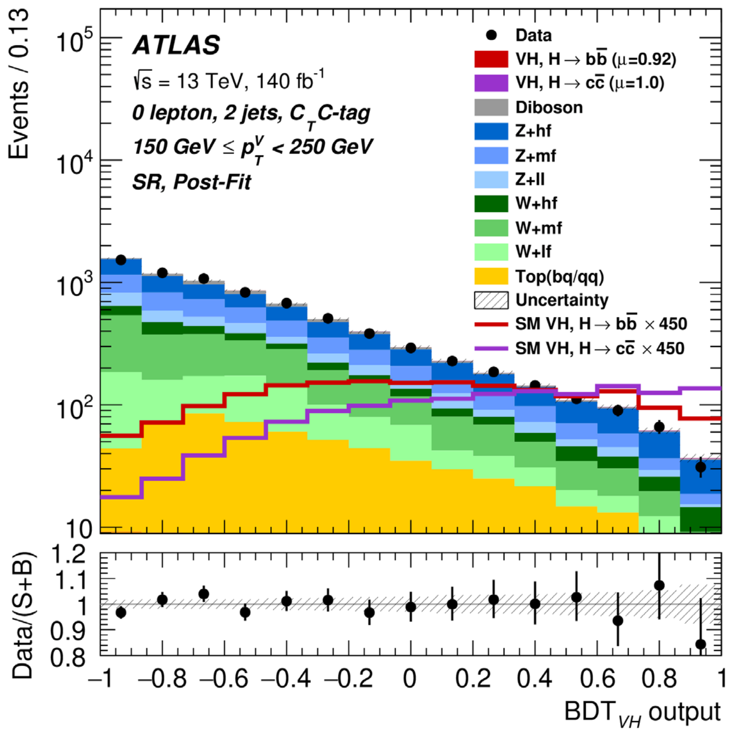
- Flavor tagging is the key experimental technique
  - Novel ML based tagging, refined calibration with better precision
  - Finer categorization and simultaneously b/c tagging

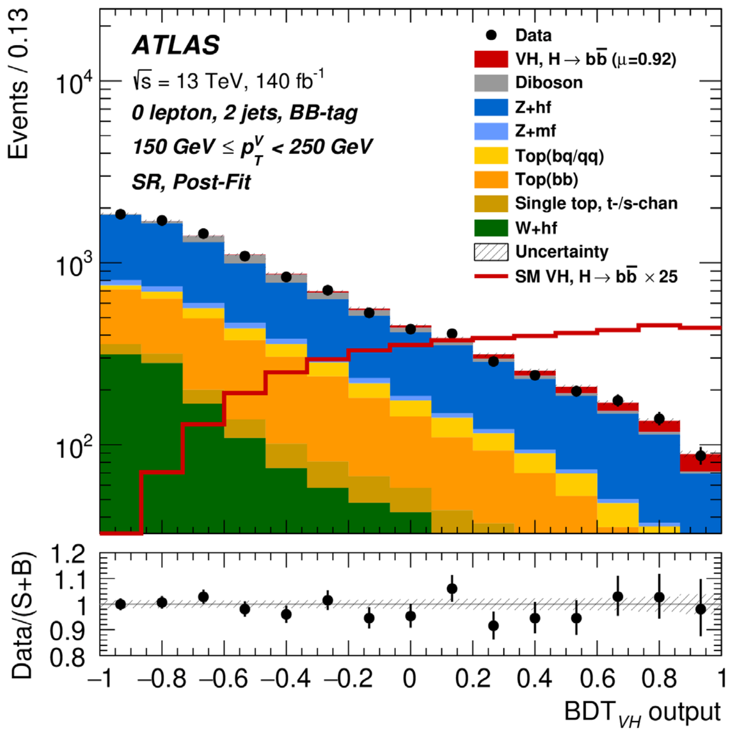


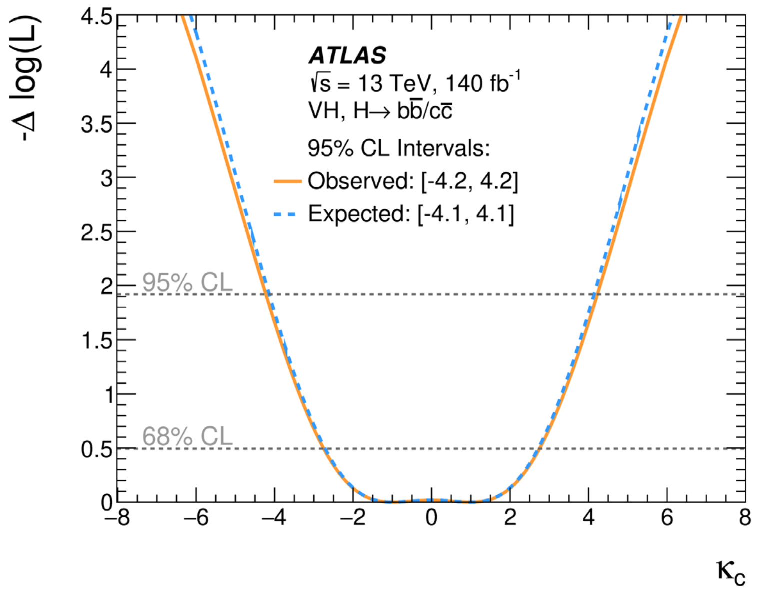


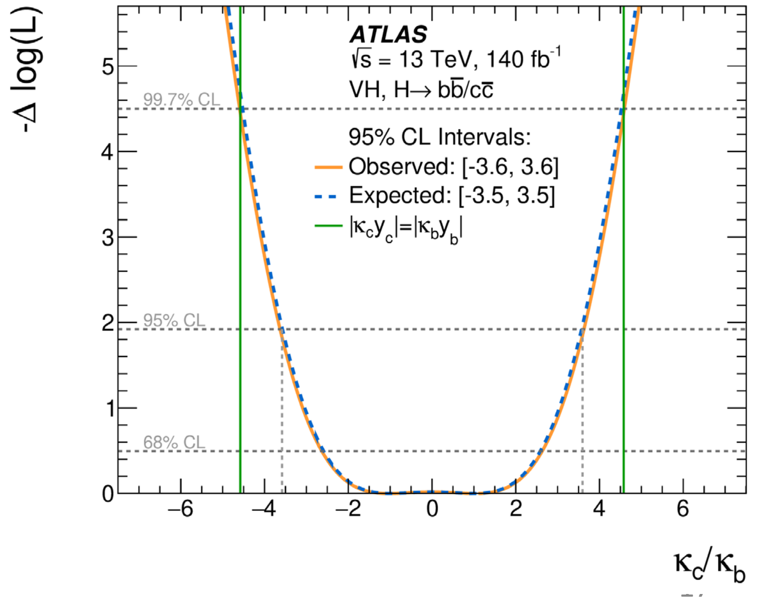
VH(→cc): ATLAS final Run-2

- Simultaneous analysis of VH, H→bb and H→cc
  - First direct constrain on the ratio of κ_c and κ_b





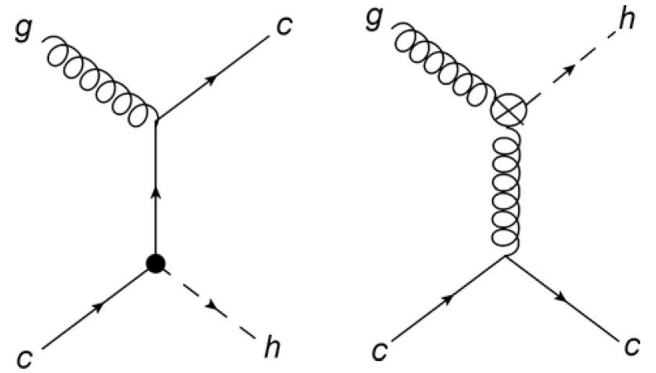




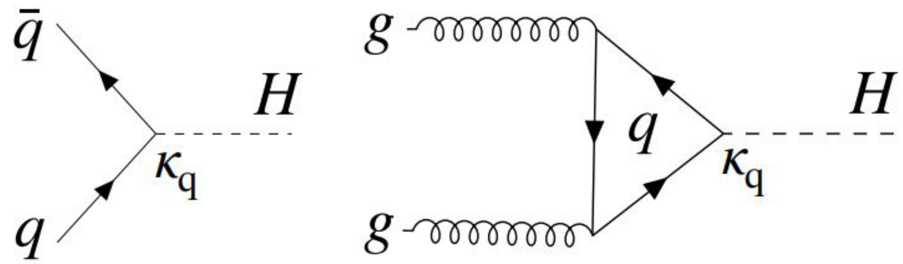
- Similar result obtained by CMS [PRL 131 (2023) 061801]

Attempts for probing κ_c and other light quarks

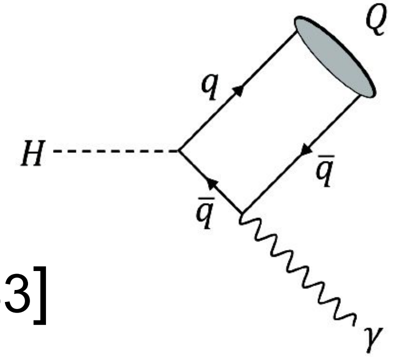
- H+c, proposed in [PRL 115 (2015) 211801]
  - Dominant diagram not sensitive to κ_c (~99%)
  - ATLAS [arXiv:2407.15550] and CMS [HIG-23-010]
  - σ(H+c) < ~10 pb [< ~4 × SM] ⇒ κ_c: < ~100 @95% CL

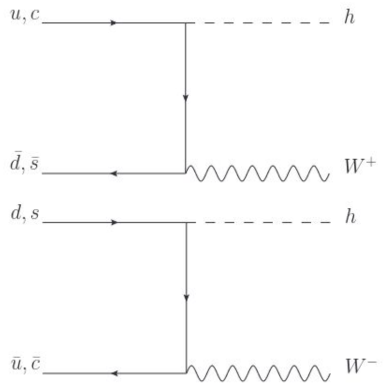


- Light-quark Yukawa in inclusive H production
  - H→ZZ* →4l: CMS [HIG-23-011]
  - κ_q affects the production and width
  - Simultaneous constraints on κq for q = u, d, s, c



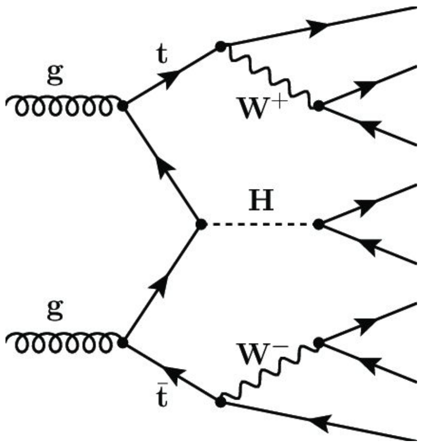
- Exclusive H→Qγ*: [idea: PRD 88, 053003]
- W±H charge asymmetry: [idea: JHEP 02 (2017) 083]



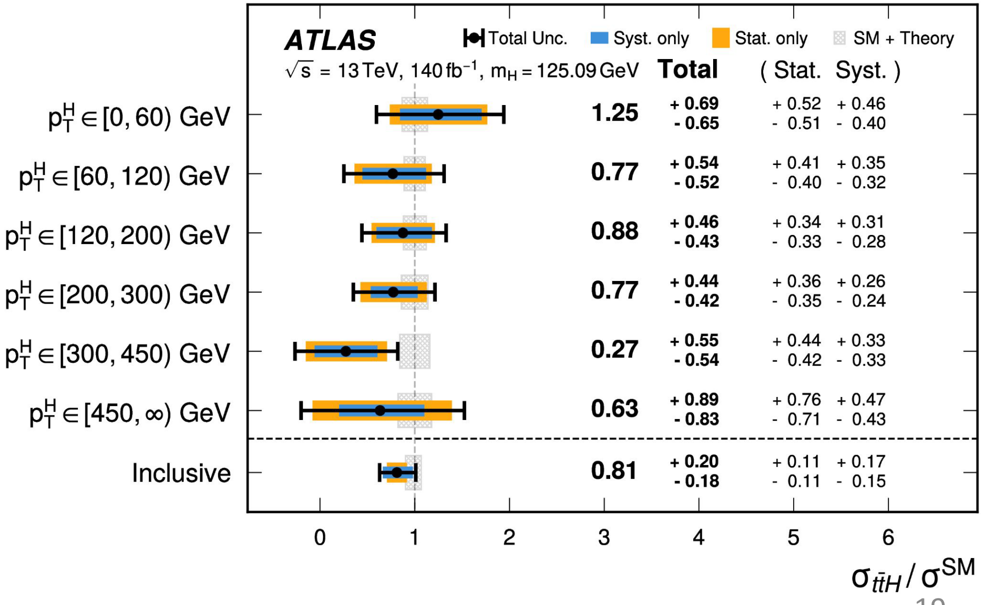


ttH(→bb): ATLAS final Run-2 [HIGG-2020-24]

- ttH: most sensitive probe of Higgs-top quark coupling
  - H→bb: dominant decay
- Extremely difficult final state
  - Reco/ID of 4 b-jets and Higgs candidate
  - Major background: tt + b-jets

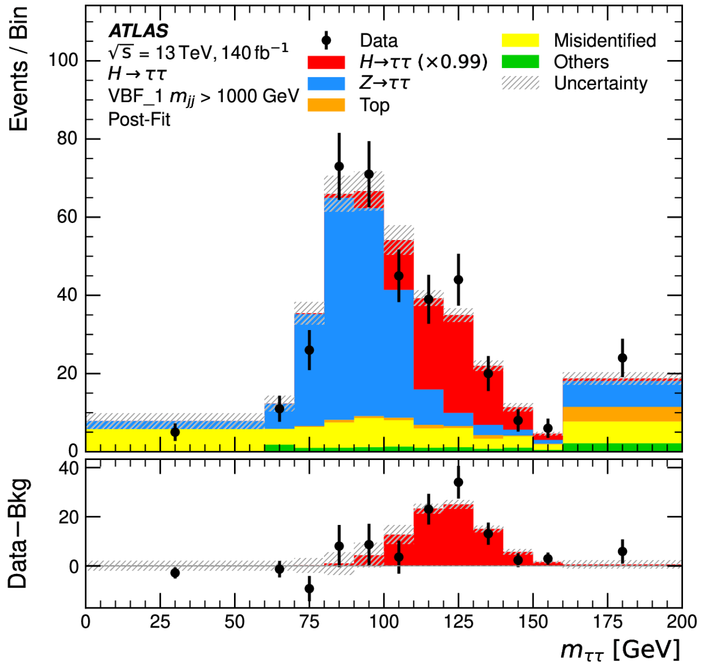


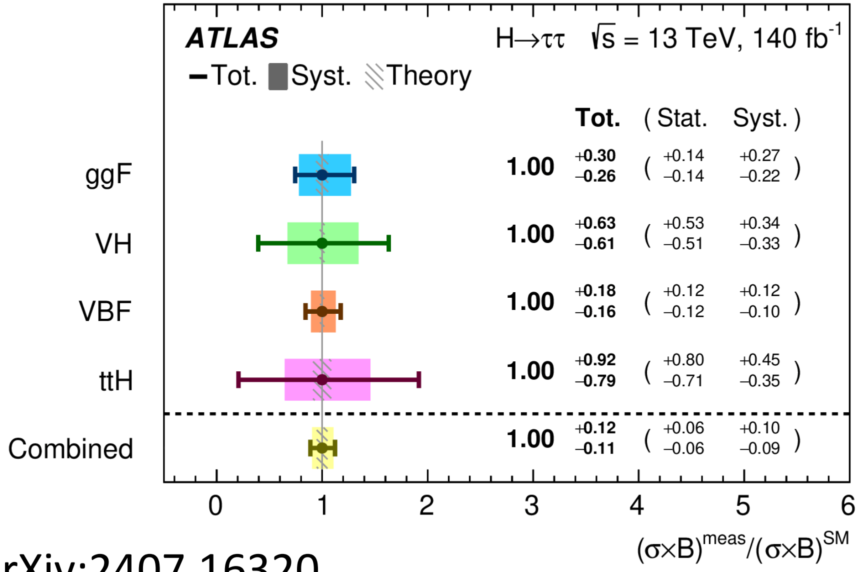
- Best single measurement to date!
  - Obs. (exp.) sign. 4.6 (5.4)σ
  - Uncertainty ~halved ; increased granularity
  - Consistent with SM prediction - up to high energy!



Precision test of Yukawa coupling

- Yukawa coupling predicts: $y_f \sim m_f$
  - Quark mass difficult to measure precisely due to non-perturbative effect
  - Lepton mass can be measured precisely, used to test Yukawa coupling
- $H \rightarrow \tau\tau$ decay has largest BR to leptons, Re-analysis of Run 2 data
  - Strongest decay mode for measuring VBF xsec (+ ≈ 15% wrt last round)



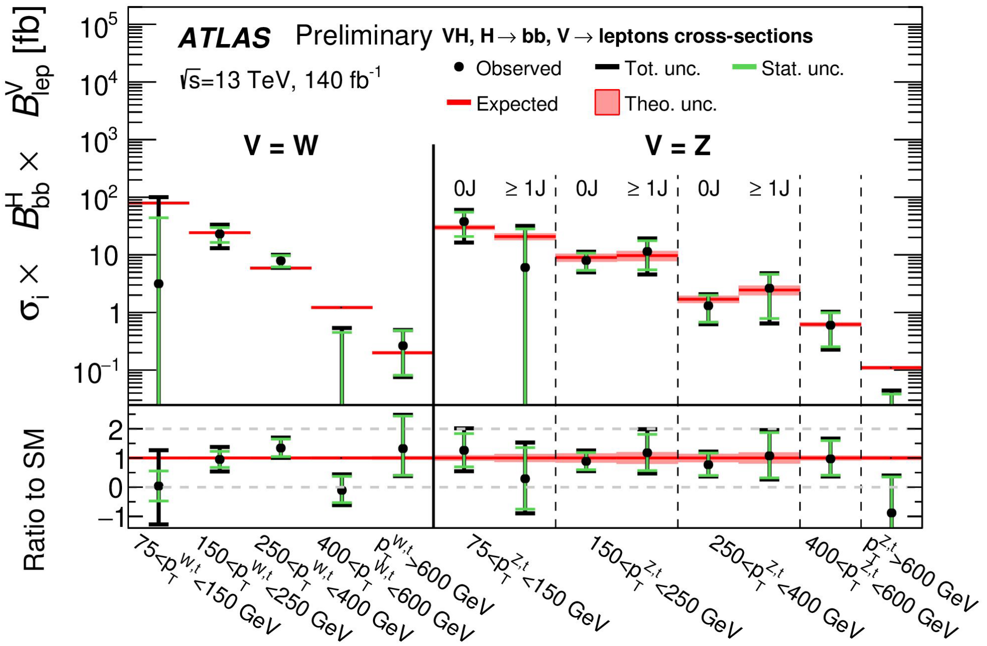


arXiv:2407.16320

Studying the Higgs-boson's kinematics

- ➢ Differential cross-section measurements as function of kinematic variables
  - Reveal subtle deviations from SM prediction
- ➢ Two types of differential measurements:
  - Unfolded fiducial differential measurements
  - Simplified Template Cross-Sections (STXS)

- ➢ ATLAS V(→leptons)H(→bb) STXS
  - Most granular and precise STXS measurement of VH



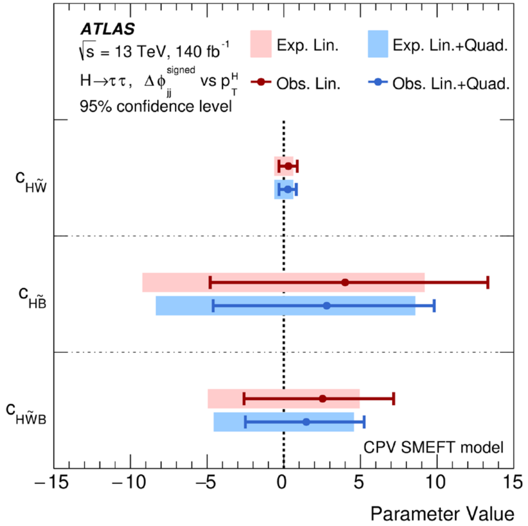
[ATLAS-CONF-2024-010]

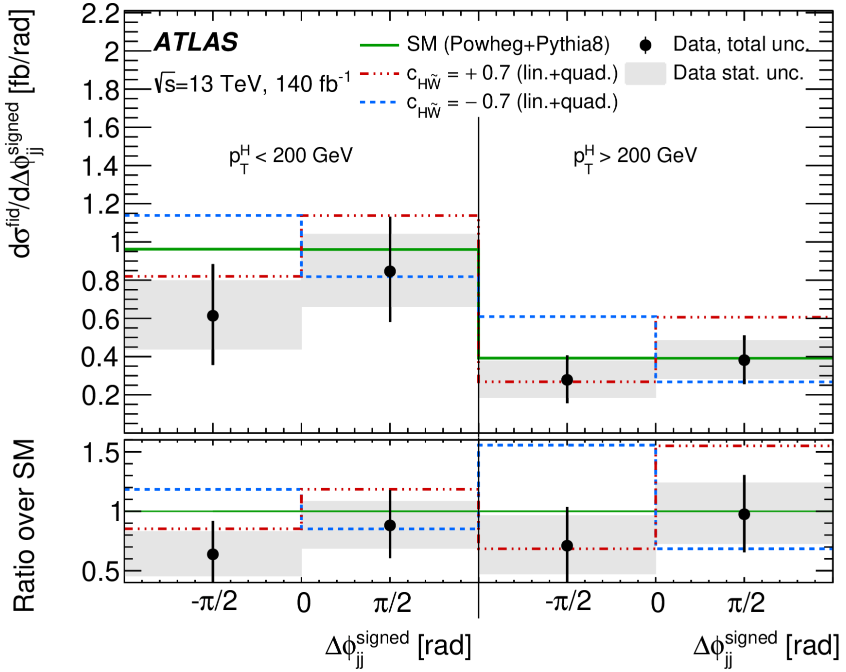
Studying the Higgs-boson's kinematics

- Differential cross-section measurements as function of kinematic variables
  - Reveal subtle deviations from SM prediction
- Two types of differential measurements:
  - Unfolded fiducial differential measurements
  - Simplified Template Cross-Sections (STXS)

arXiv:2407.16320

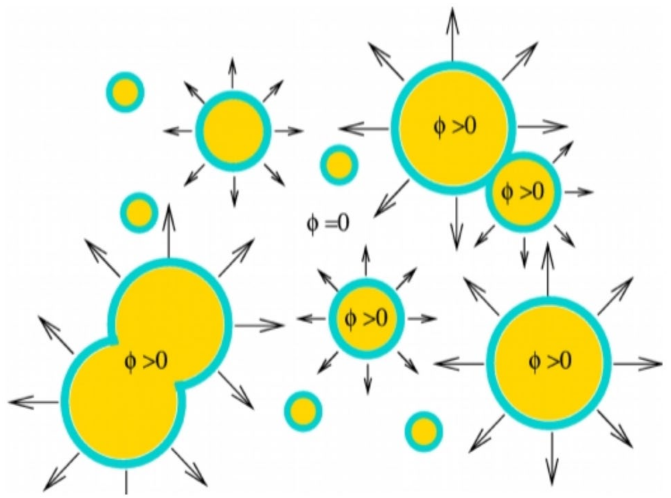
- $H \rightarrow \tau\tau$: unfolded differential cross-section measurements
  - SMEFT interpretation: constrain CP odd operators



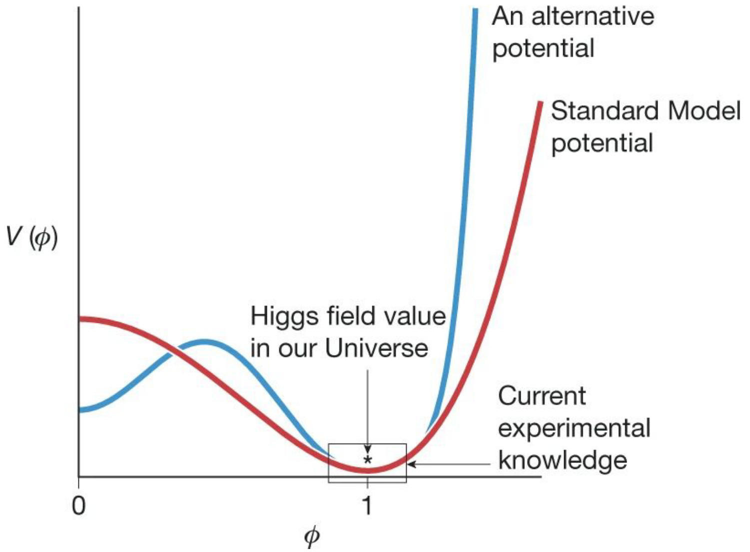


Baryogenesis and Higgs potential

- Why matter far more than anti-matter?
- Requests from Sakharov Conditions
  - More CP violation than SM
  - First order phase transition, departure from Thermal Equilibrium

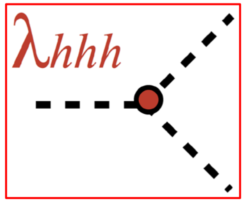


- Higgs potential determined EW symmetry breaking: 1st or 2nd order?



Probe Higgs potential

- Expand Higgs potential about the minimum

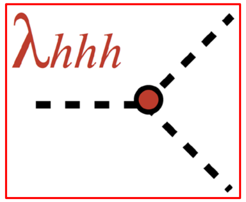


m_H对应曲率

$$V(\phi) = -\mu^2\phi^2 + \lambda\phi^4 \Rightarrow V_0 + \frac{1}{2}m_h^2 h^2 + \frac{m_h^2}{2v^2} v h^3 + \frac{1}{4}\frac{m_h^2}{2v^2} h^4$$

Probe Higgs potential

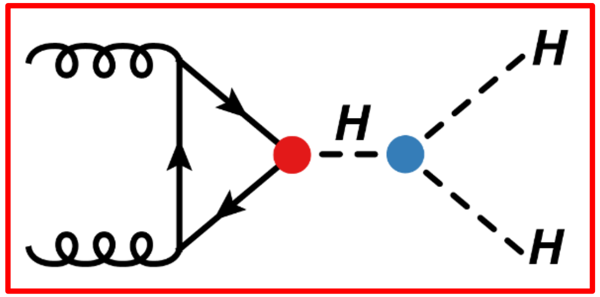
- Expand Higgs potential about the minimum

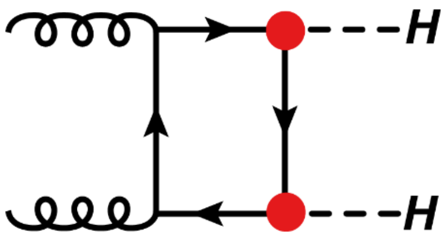


m_H对应曲率

$$V(\phi) = -\mu^2\phi^2 + \lambda\phi^4 \Rightarrow V_0 + \frac{1}{2}m_h^2 h^2 + \frac{m_h^2}{2v^2} v h^3 + \frac{1}{4}\frac{m_h^2}{2v^2} h^4$$

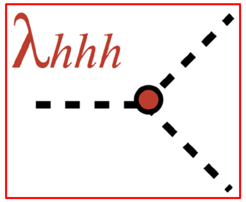
- Higgs-self coupling (λ_{hhh}) is crucial for probing Higgs potential
  - Measured in double Higgs production (di-Higgs) at LHC





Probe Higgs potential

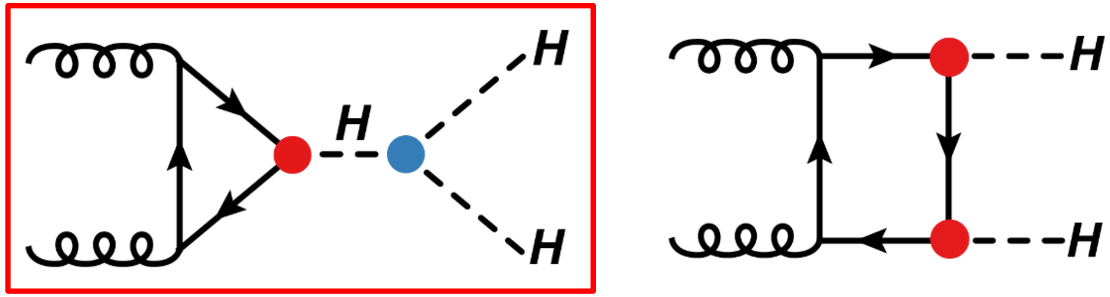
- Expand Higgs potential about the minimum



m_H对应曲率

$$V(\phi) = -\mu^2\phi^2 + \lambda\phi^4 \Rightarrow V_0 + \frac{1}{2}m_h^2 h^2 + \frac{m_h^2}{2v^2} v h^3 + \frac{1}{4}\frac{m_h^2}{2v^2} h^4$$

- Higgs-self coupling (λ_{hhh}) is crucial for probing Higgs potential
  - Measured in double Higgs production (di-Higgs) at LHC

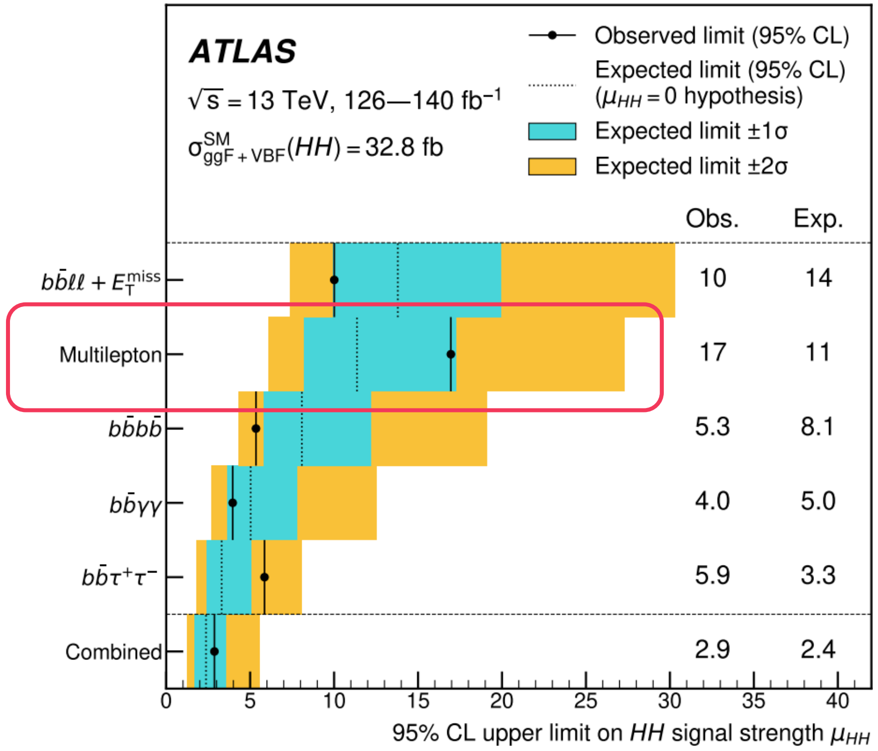


	bb	WW	ττ	ZZ	γγ
bb	34%				
WW	25%	4.6%			
ττ	7.3%	2.7%	0.39%		
ZZ	3.1%	1.1%	0.33%	0.069%	
γγ	0.26%	0.10%	0.028%	0.012%	0.0005%

- Di-Higgs at LHC: σ(HH) ~40fb
  - ggF dominant mode (90%), VBF (5%)
  - Complex decay products

Higgs self-coupling

- All HH channels explored
  - Multi lepton channel included for the first time at ATLAS [JHEP 08 (2024) 164]

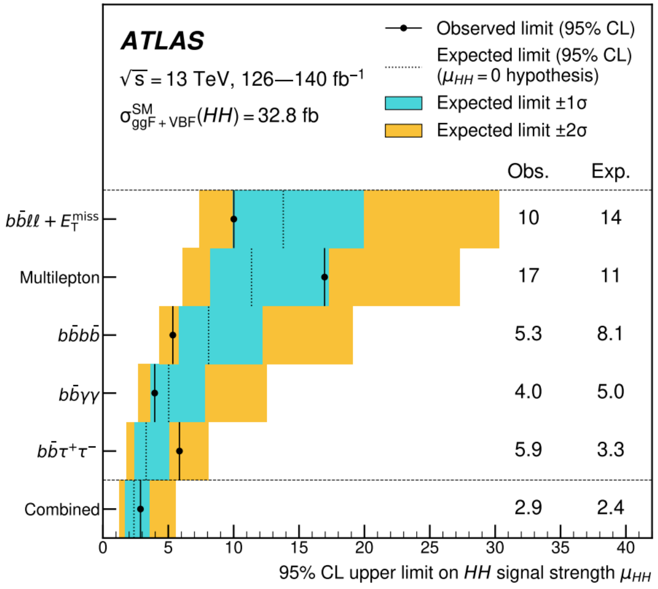


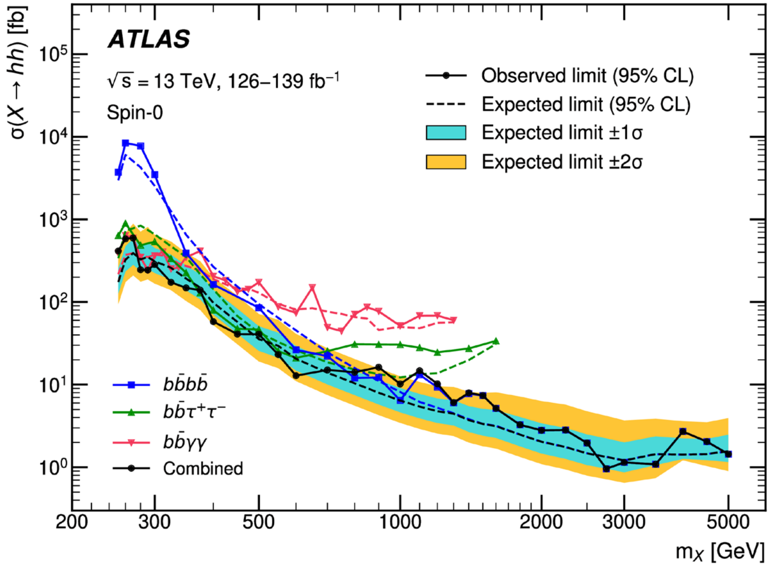
	bb	WW	ττ	ZZ	γγ
bb	34%				
WW	25%	4.6%			
ττ	7.3%	2.7%	0.39%		
ZZ	3.1%	1.1%	0.33%	0.069%	
γγ	0.26%	0.10%	0.028%	0.012%	0.0005%

Higgs self-coupling

- Statistics combination to maximize the sensitivity
  - Non-resonant HH ATLAS [PRL 133, 101801 (2024)]
  - BSM resonant HH ATLAS [PRL 132, 231801 (2024)]

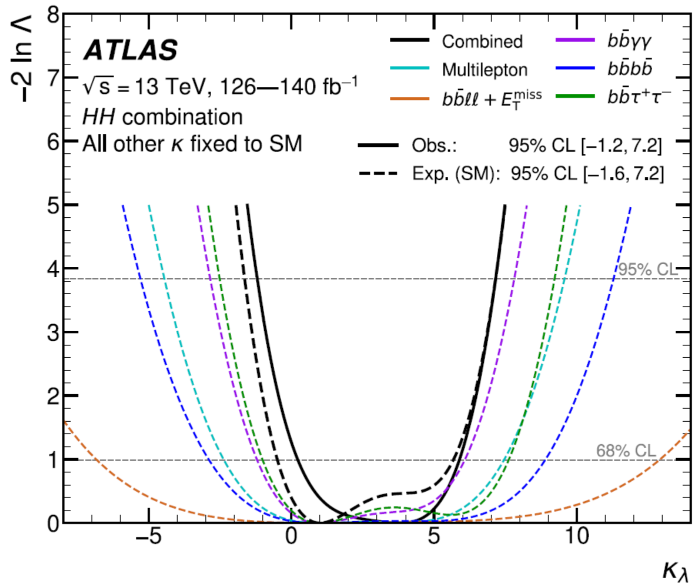
	bb	WW	ττ	ZZ	γγ
bb	34%				
WW	25%	4.6%			
ττ	7.3%	2.7%	0.39%		
ZZ	3.1%	1.1%	0.33%	0.069%	
γγ	0.26%	0.10%	0.028%	0.012%	0.0005%

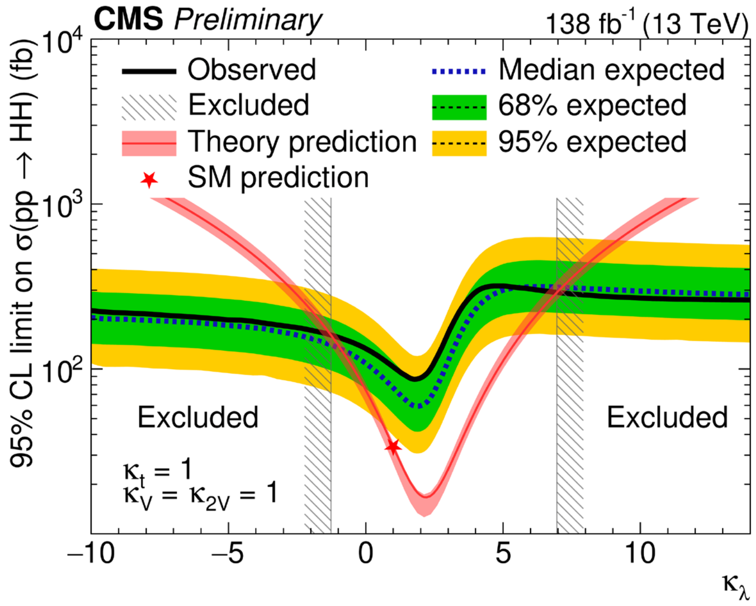


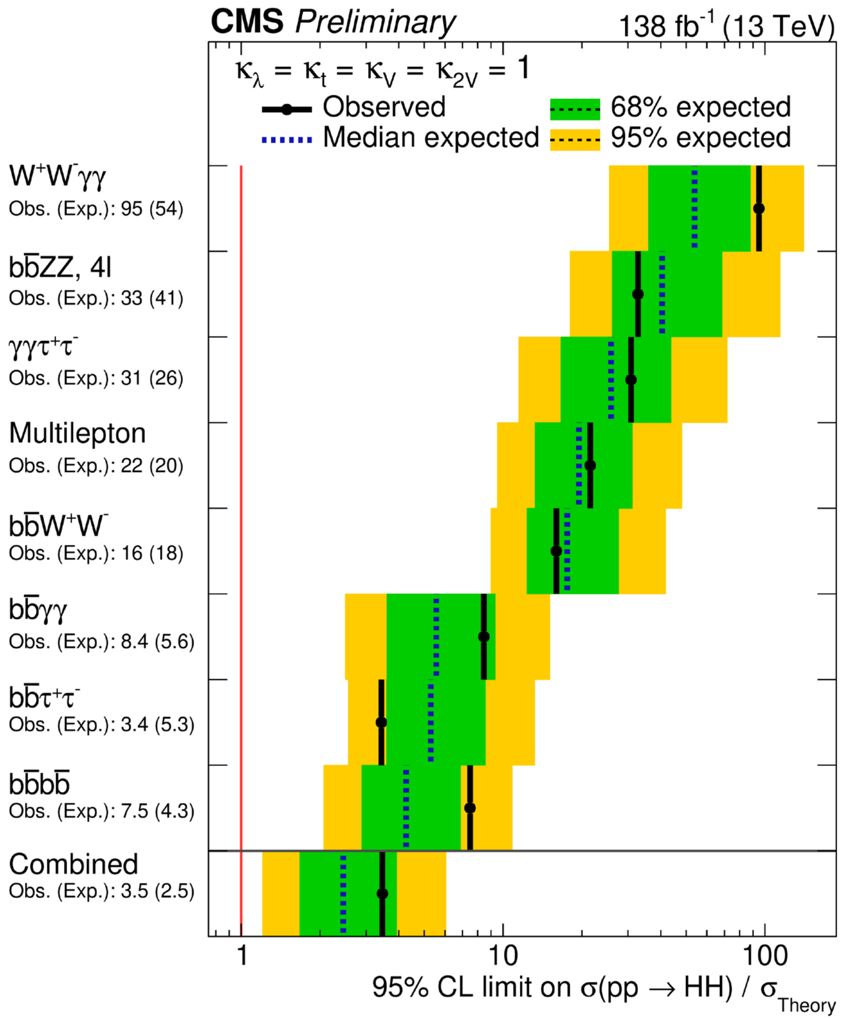


Higgs self-coupling

- CMS also release new results [CMS-PAS-HIG-20-011]
  - adds additional channels: bbWW, WWγγ, and ττγγ, and additional VHH production mode for 4b channel
- 95% CL limit on κ_λ
  - ATLAS: $-1.2<\kappa_\lambda<7.2$ $(-1.6<\kappa_\lambda<7.2)$
  - CMS: $-1.39<\kappa_\lambda<7.02$ $(-1.02<\kappa_\lambda<7.19)$





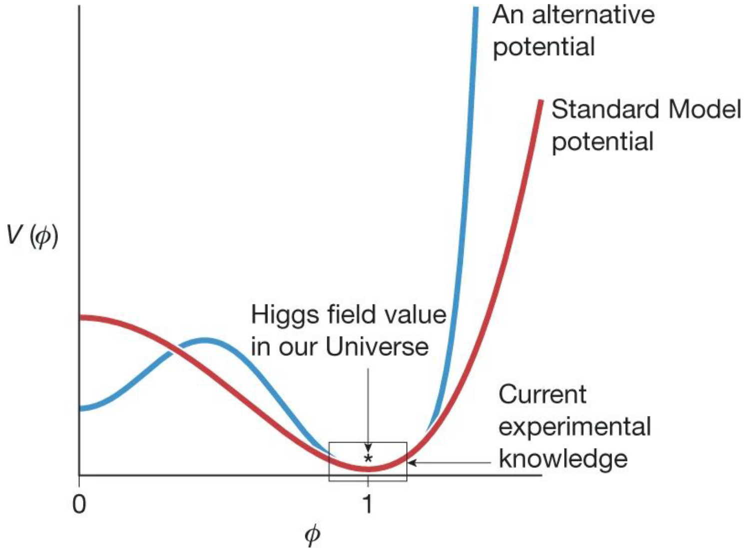


Extended Higgs sector

- Extension of Higgs sector could change the Higgs potential.
  - For example, SM plus one singlet extension, allow first order EW phase transition

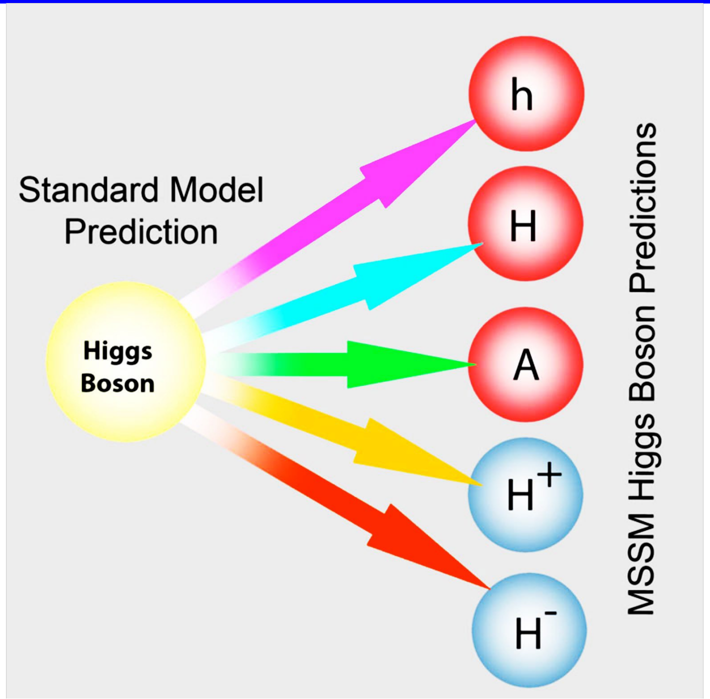
$$V_{\rm CxSM} = \frac{m^2}{2}{\rm H}^\dagger{\rm H} + \frac{\lambda}{4}({\rm H}^\dagger{\rm H})^2$$

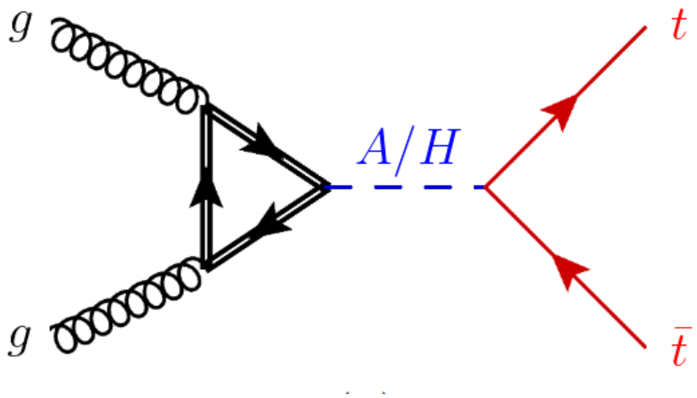
$$+\frac{\delta_2}{2}{\rm H}^\dagger{\rm H}|\mathbb{S}|^2 + \frac{b_2}{2}|\mathbb{S}|^2 + \frac{d_2}{4}|\mathbb{S}|^4 + \left(\frac{b_1}{4}\mathbb{S}^2 + a_1\mathbb{S} + c.c.\right)$$

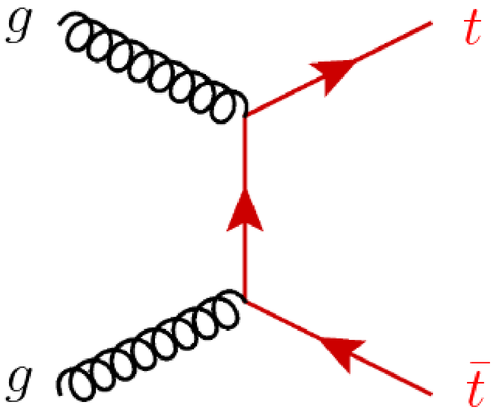


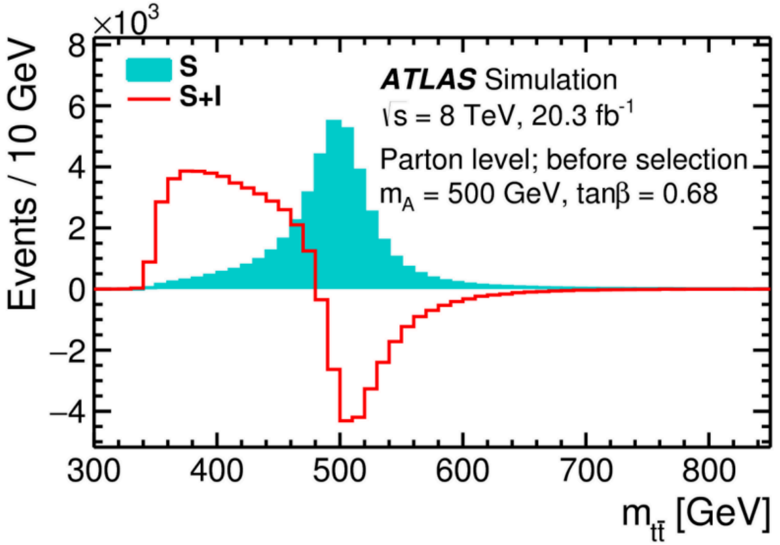
BSM Higgs boson

- Two-Higgs Doublets Model (2HDM)
  - Minimum extension of Higgs sector
  - Requested by MSSM
  - Two free parameters at tree level: m_A, tan $\beta = \nu_u/\nu_d$
- Top quark, heaviest particle, sensitive to BSM Higgs
  - Severe interference with SM
  - Signature difficult to detector



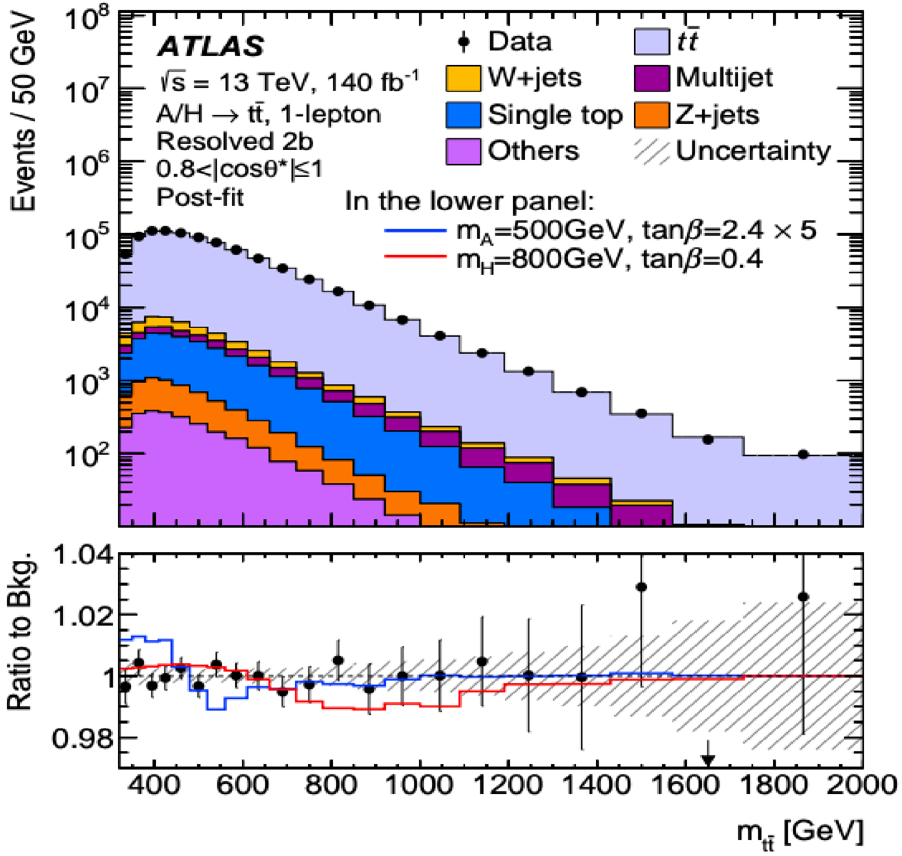


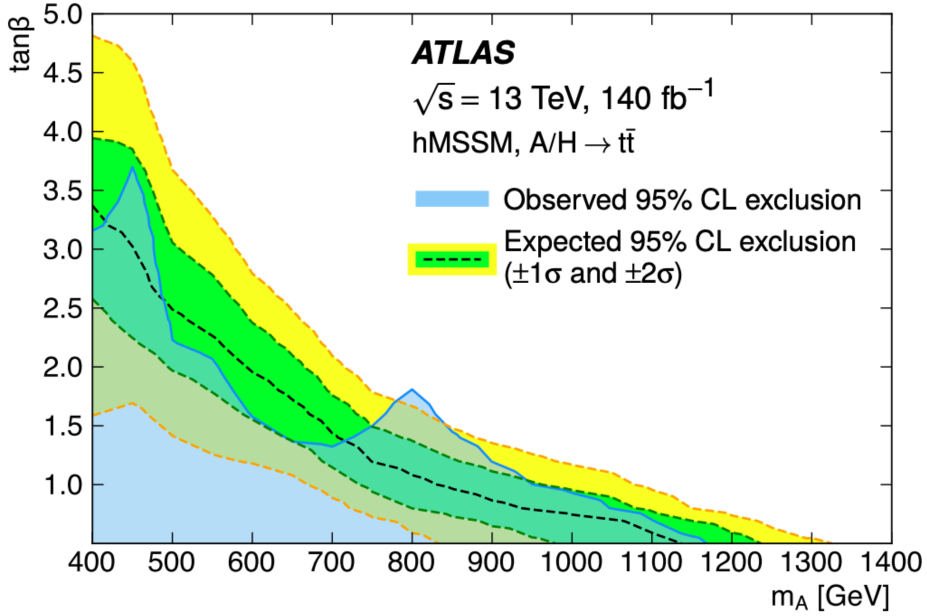




BSM Higgs boson

- Develop new analysis methods
  - Precise modeling signal theoretically and new statistics analysis for interference effect

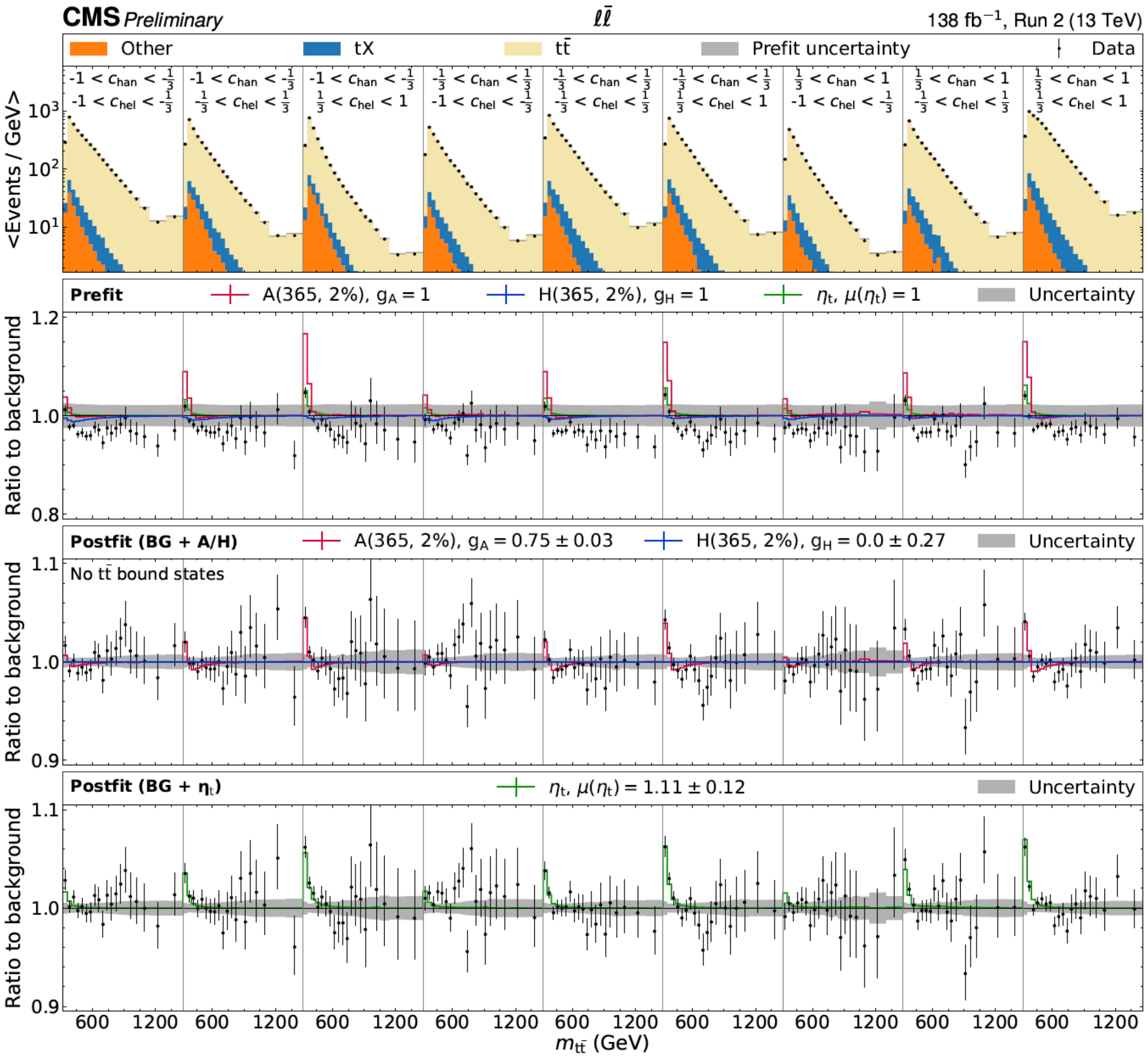




- Most sensitive channel at high mass and low $\tan\beta$

CMS results on $\mathbf{A/H \to tt}$

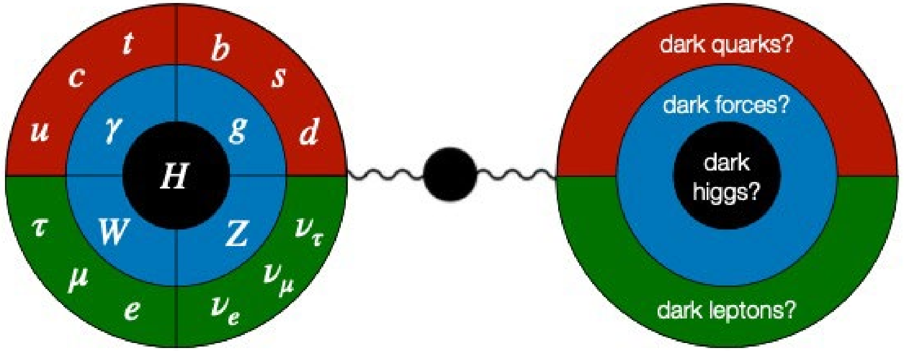
- CMS preliminary results show
  - Excess at around ttbar threshold
  - A/H boson?
  - $\boldsymbol{t\bar{t}}$ bound state ($\boldsymbol{\eta_t}$)?
- Both CMS and ATLAS refining analysis near ttbar threshold
  - Stay tuned

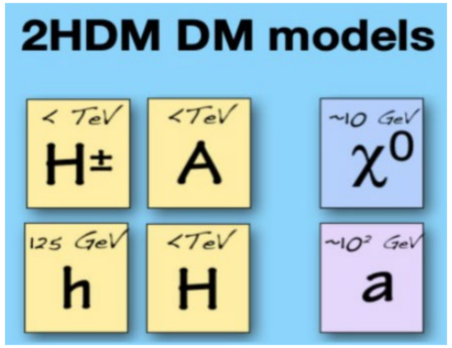


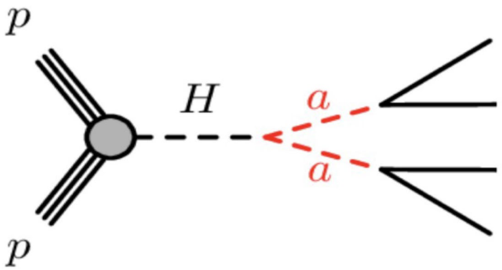
CMS-PAS-HIG-22-013

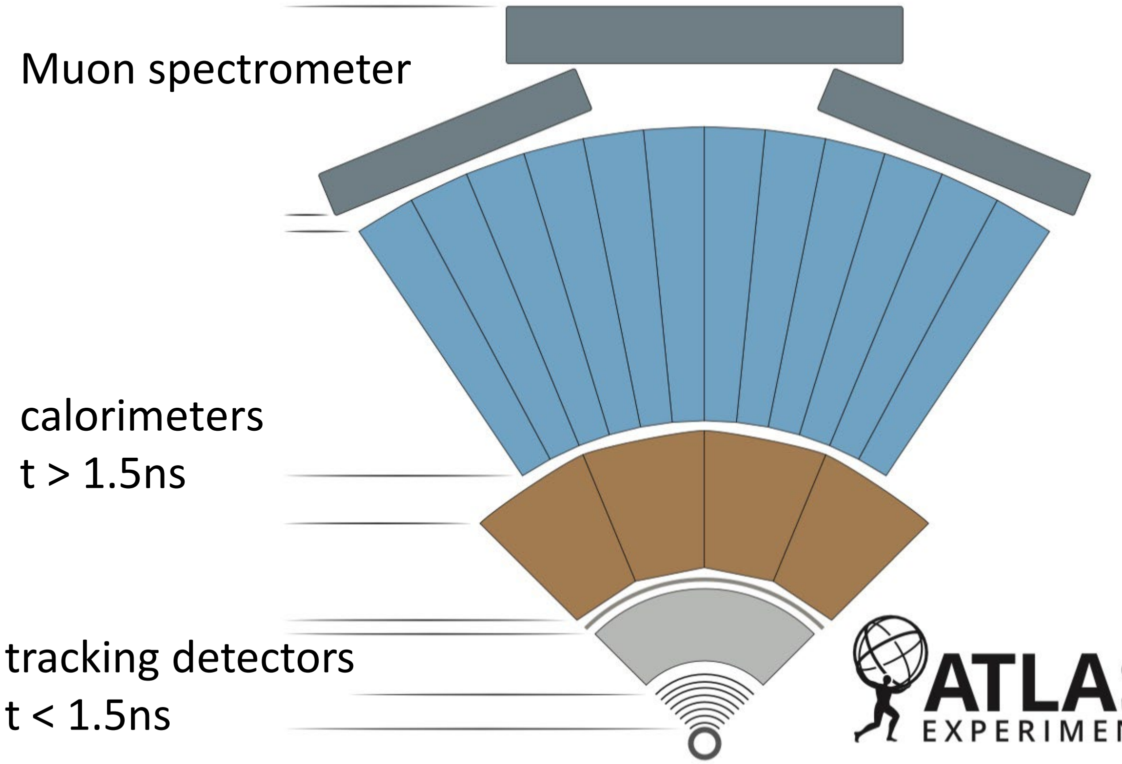
Higgs portal

- Higgs as a portal to dark matter, e.g. 2HDM+a
  - Pseudoscalar(a) via Higgs decay
  - With long life time, aka, long lived particles (LLP)



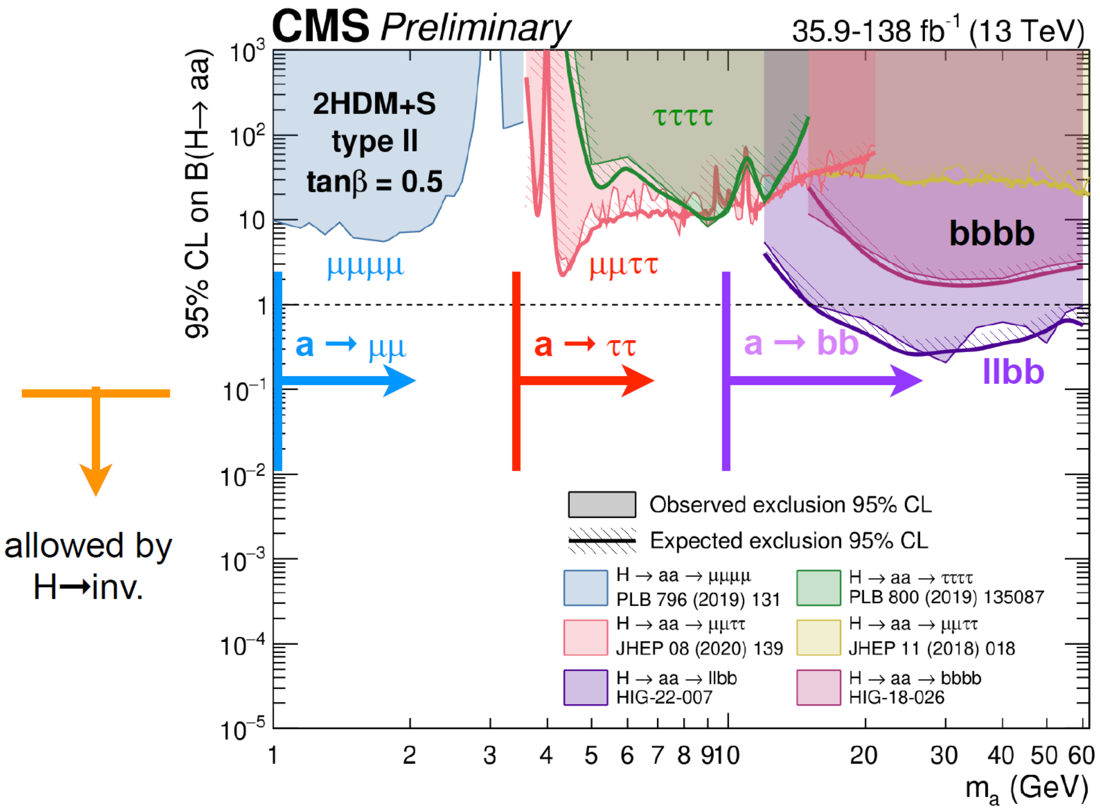






Higgs portal

➢ Pseudoscalars (a) via Higgs decays



- all consider H→aa, channels are complementary
- y=1 means Higgs decays 100% into new scalars

https://twiki.cern.ch/twiki/bin/view/CMSPublic/Summary2HDMSRun2

Interpretation: SMEFT

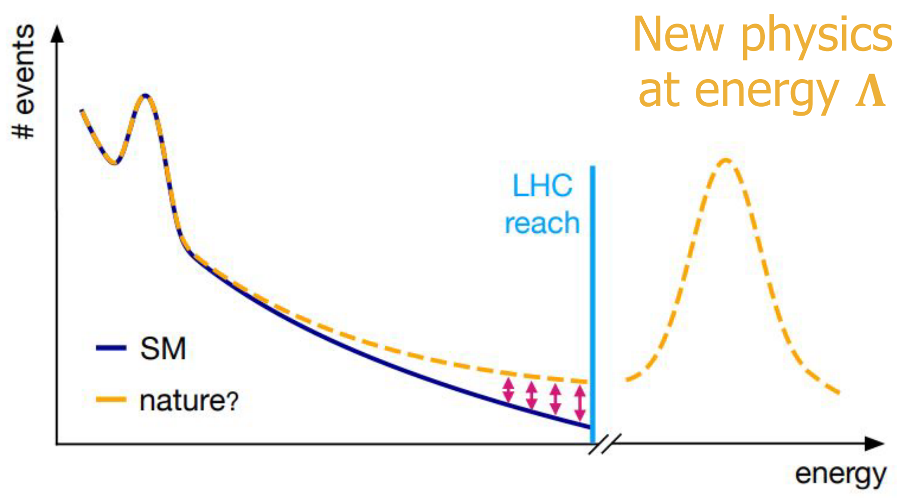
- Standard Model Effective Field Theory (SMEFT)
  - model-independent way to parametrise effects of new physics appearing at high energy Λ ($\gg$ vev) at much lower energy (E $\ll \Lambda$)

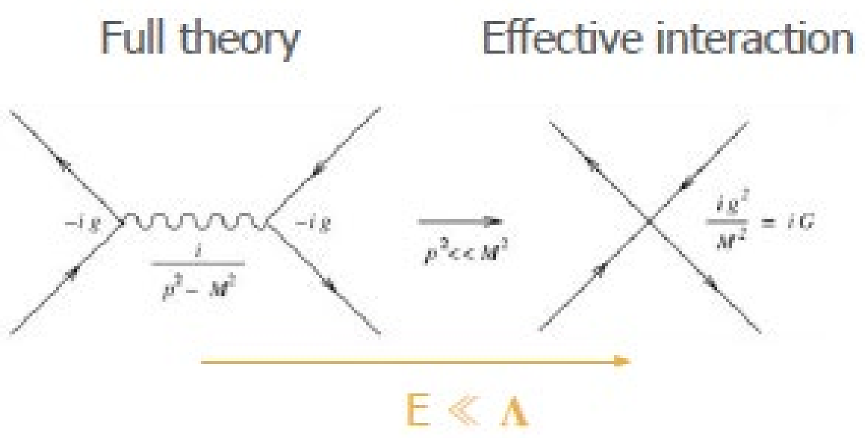
$$\mathcal{L}_{eff} = \mathcal{L}^{SM} + \mathcal{L}^{D=6}, \qquad \mathcal{L}^{D=6} = \frac{1}{\Lambda^2}\sum_i c_i^{(6)} \mathcal{O}_i^{(6)}$$

  - O_i: operators built from SM fields and respect SM symmetries
  - c_i: Wilson coefficients ~ strength of effective interaction (SM: 0)
- Observables
  - e.g. cross-section

$$\sigma_{\text{STXS}} = \sigma_{\text{SM}} + \sigma_{\text{int}} + \sigma_{\text{BSM}}$$

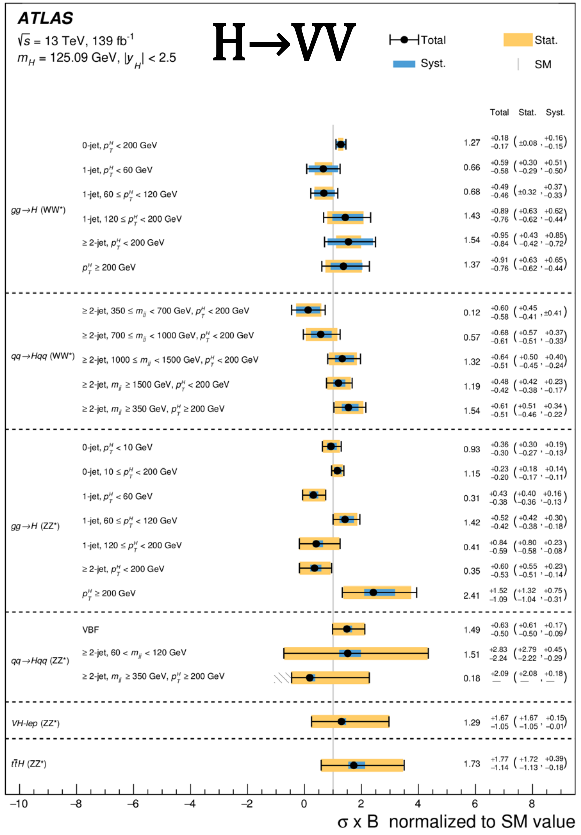
  - SM-BSM interference ~$1/\Lambda^2$ ⇒"linear"
  - BSM~$1/\Lambda^4$ ⇒"quadratic"

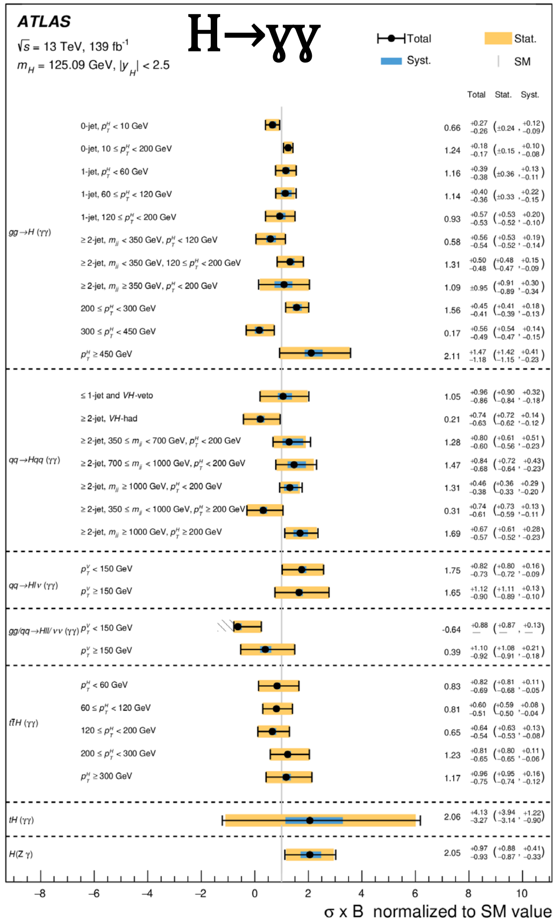


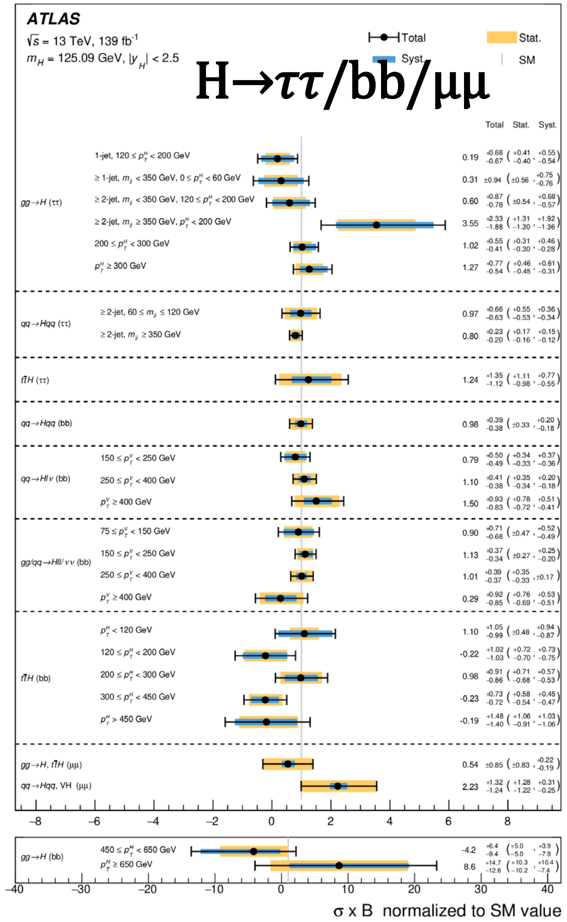


Interpretation of ATLAS STXS measurements

- STXS: p_T^H (and m_{jj} for ggF/VBF), sensitive to O(50) SMEFT operators O_i



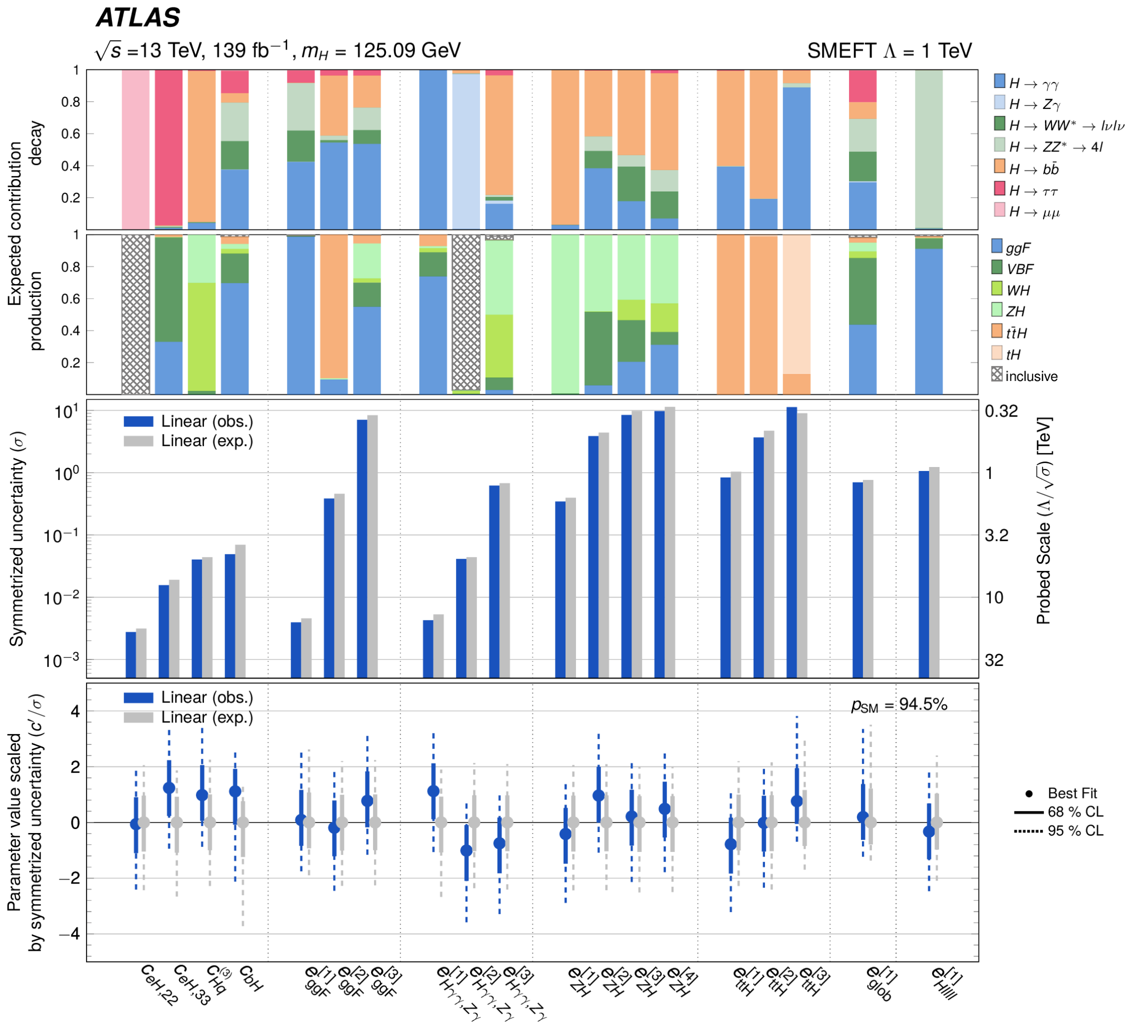




Interpretation of ATLAS STXS measurements

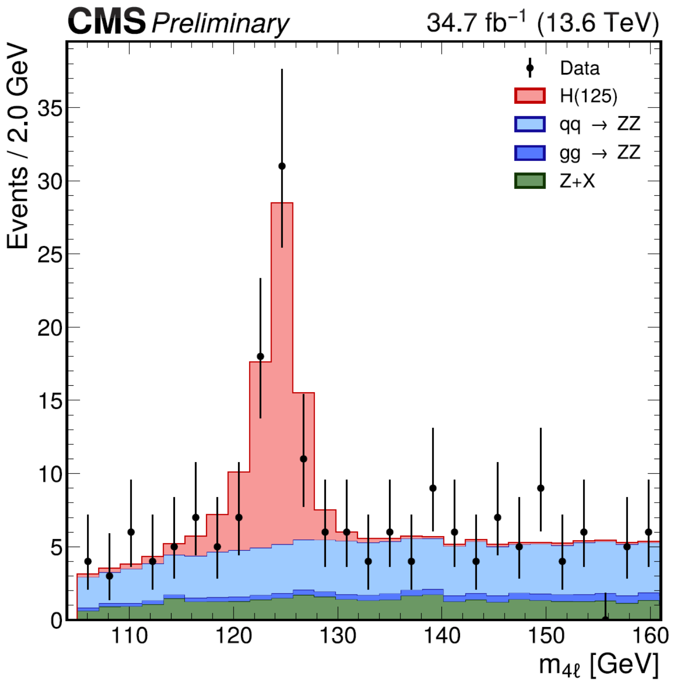
- STXS: p_T^H (and m_{jj} for ggF/VBF), sensitive to O(50) SMEFT operators O_i

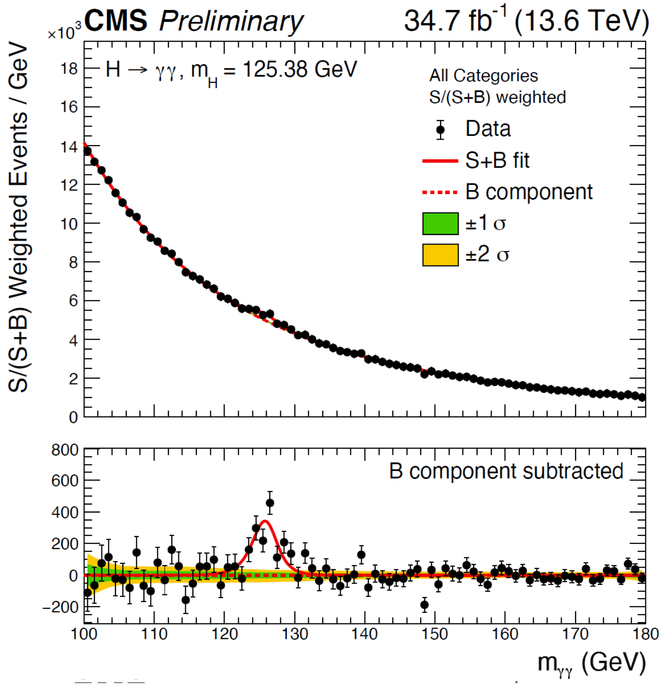
- Constrain a subset of 19 coefficients or linear combinations of coefficients
  - Principal Component Analysis (PCA) ⇒ Linear combinations of Wilson coefficients e_j

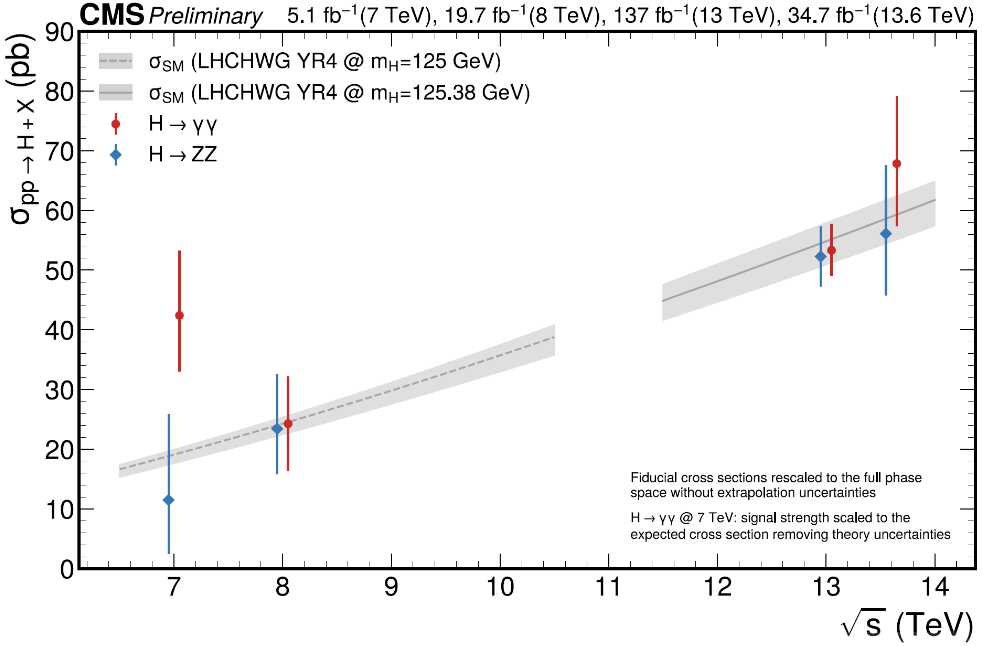


- Only CP-even operators

Run-3 efforts are gaining momentum







- First (differential) cross-section measurements
  - With Run 3 data in $H \rightarrow ZZ^* \rightarrow 4l$ and $H \rightarrow \gamma\gamma$ by CMS.
  - Similar results from ATLAS [EPJC 84 (2024) 78]

CMS-PAS-HIG-24-013
CMS-HIG-PAS-23-014

Conclusions

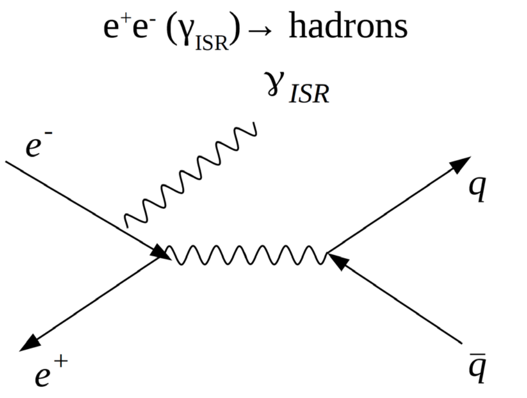
- Higgs properties and couplings probedmore broadly and precisely
  - Some recent highlighted results reported
  - Plenty of unprobed areas where deviations could occur
- On-going Run-3 will quick triplicate the data size
  - with higher energy and better experimental techniques
  - promise a new push of the current frontiers: Self-coupling, 2^{nd} Yukawa coupling ...
  - Besides, HL-LHC upgrade on the horizon …
- We have exciting times ahead of us!

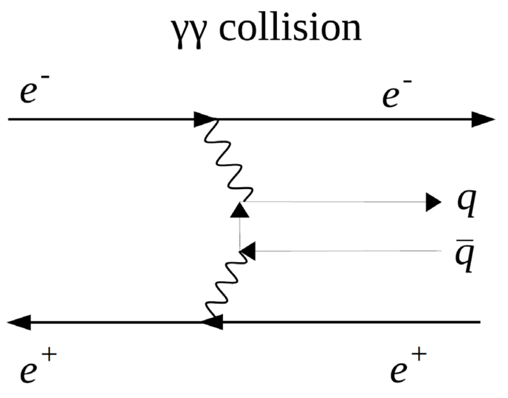
Conclusions

- Higgs properties and couplings probedmore broadly and precisely
  - Some recent highlighted results reported
  - Plenty of unprobed areas where deviations could occur
- On-going Run-3 will quick triplicate the data size
  - with higher energy and better experimental techniques
  - promise a new push of the current frontiers: Self-coupling, 2nd Yukawa coupling ...
  - Besides, HL-LHC upgrade on the horizon …
- We have exciting times ahead of us!

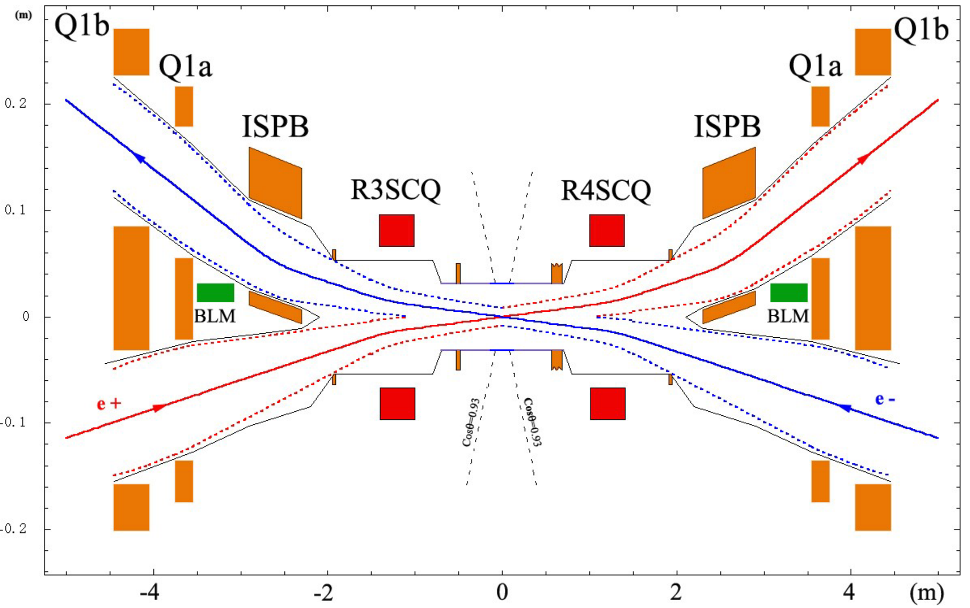
Thank you for your attention

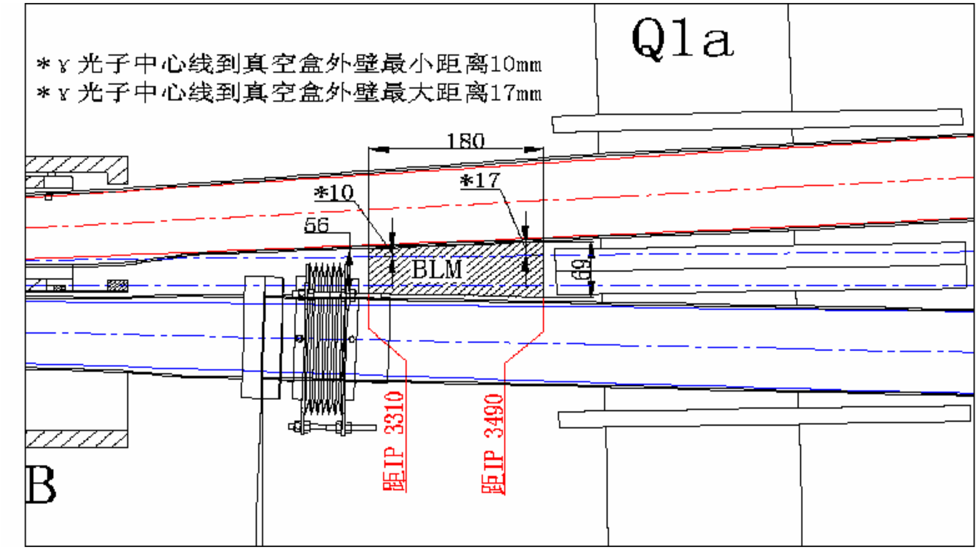
BEPCII-BESIII forward physics





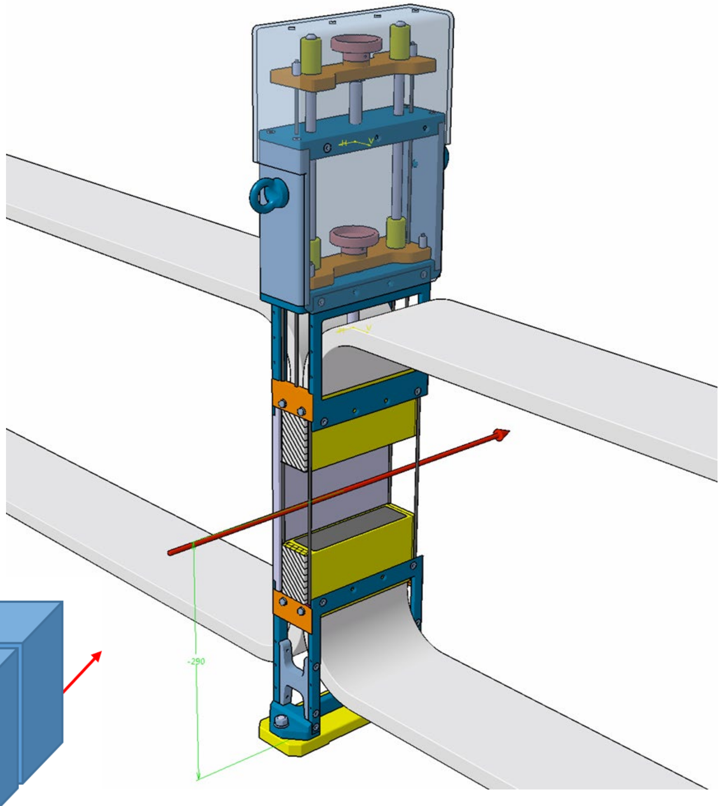
- Forward detector
  - 3.3m <z<3.5 m, θ=0 in CMS frame
  - Fast Luminosity Monitor as baseline
- Physics potential
  - ISR physics: photon tagging
  - Di-Photon physics: electron tagging

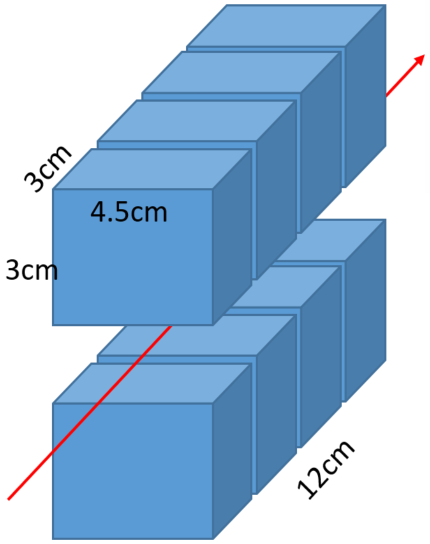




BEPCII-BESIII forward physics

- Preliminary conceptual design: LYSO + SiPM
  - Modular design: 10*9*30mm crystal bar assembled in 3*5 array
  - Four same detector modules on each side, with ~240 ch in total
  - Timescale: ~ 2 years
- Key advantage: synchronized with BESIII TDAQ
  - High energy photon source
  - Harsh environment for novel detector R&D
- Physics potential
  - ISR, di-photon, what about others?
  - Axion? dark matter? Exotic hadron? …
- With strong physics case, further detector upgrade is possible

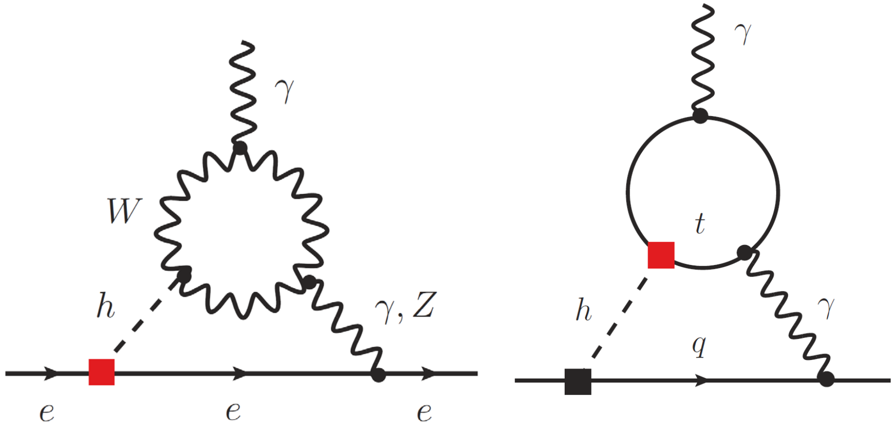




- Overview of Higgs coupling and property measurement
- Highlight the latest H->bb/cc, tautau Yukawa coupling, ttH(bb)
- Higgs CP
- Higgs self coupling:
  - Highlight combination, multilepton, etc
- BSM Higgs: ttbar,
  - Ttbar puzzle, quantum business
- Higgs and flavor sector
- Higgs potential and EWPT
- Higgs rare decay: long lived, etc.
- BSM Higgs

Indirect constraint

- Low energy experiments, e.g. electron EDM, can constrain the Higgs CP indirectly



$$\mathcal{L} \supset -\frac{y_f}{\sqrt{2}} \left(\kappa_f \bar{f} f + i \tilde{\kappa}_f \bar{f} \gamma_5 f \right) h$$

ACME collaboration:

eEDM<1.1×10^{-29} e·cm

$$|\tilde{\kappa}_e| \lesssim 1.7 \times 10^{-2}$$
$$|\tilde{\kappa}_t| \lesssim 1.0 \times 10^{-2}$$

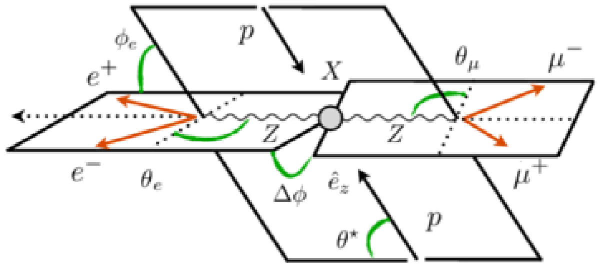
- But, very model dependent
  - Gauge-dependent contributions, UV-divergent diagrams, etc.

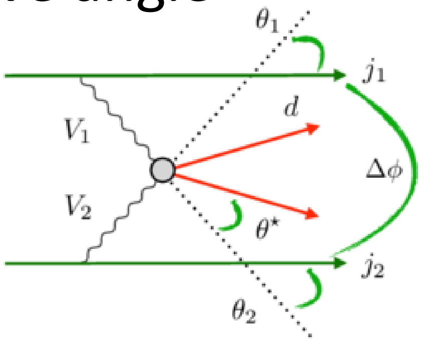
From J. Brod at Higgs 2020

CP violation in Higgs sector

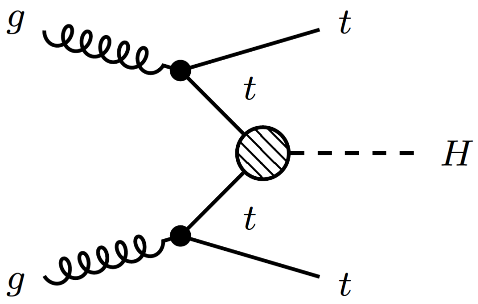
- General methodology:
  - using event topology to build some CP sensitive angle

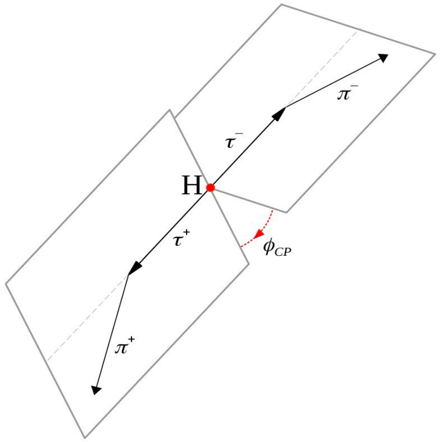
Higgs coupling to vector bosons (HVV)





Higgs coupling to fermions (Yukawa coupling: Hff)

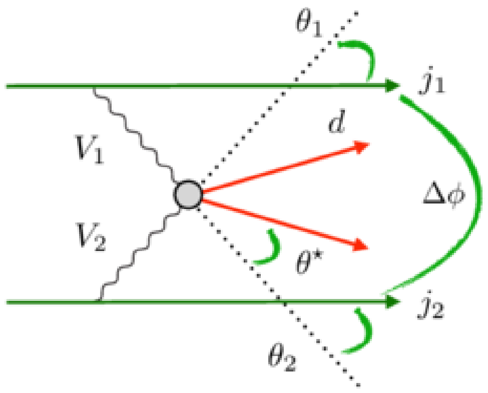




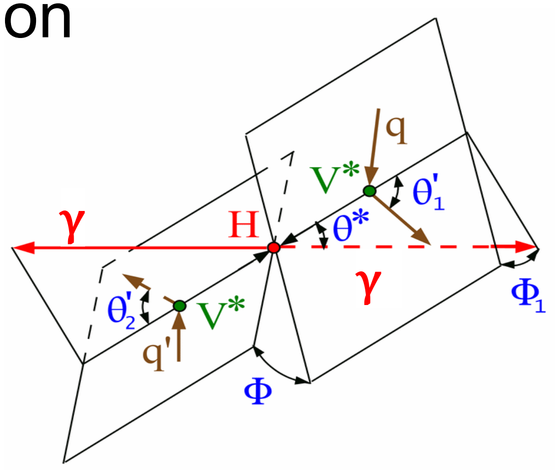
- Indirect measurements not discussed here
  - e.g. ggf loop, cross section, etc

Study HVV CP in VBF production

- HVV vertex in VBF Higgs production



To Higgs rest frame

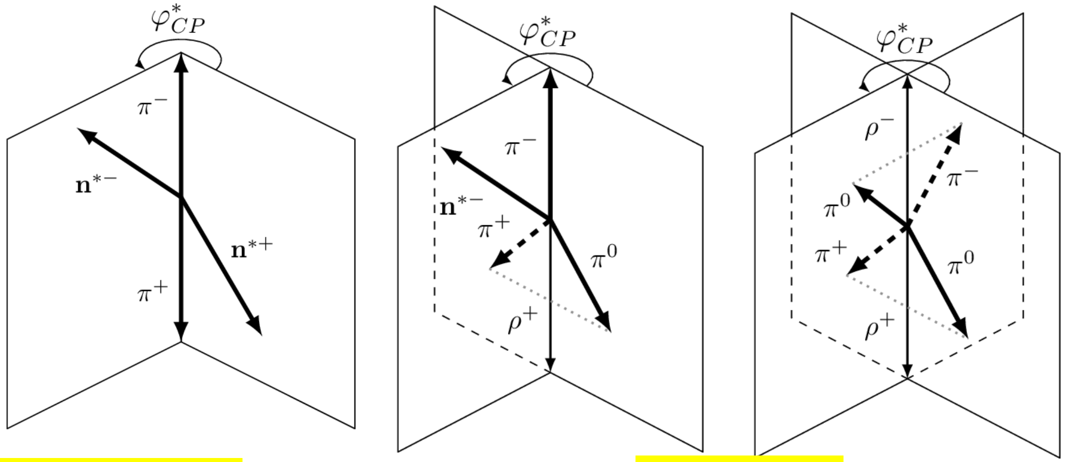


- Independent from Higgs decay: here, use H→γγ (SM Br)
- Interpretation with two EFT bases: Warsaw and HISZ

Warsaw: $\mathcal{L}_{\mathrm{SMEFT}}^{\mathrm{CP-odd}} \supset \frac{c_{H\tilde{W}}}{\Lambda^2} H^\dagger H \tilde{W}^I_{\mu\nu} W^{\mu\nu I} + \frac{c_{H\tilde{B}}}{\Lambda^2} H^\dagger H \tilde{B}^A_{\mu\nu} B^{\mu\nu} + \frac{c_{H\tilde{W}B}}{\Lambda^2} H^\dagger \sigma^I H \tilde{W}^I_{\mu\nu} B^{\mu\nu}$

CP sensitive observable

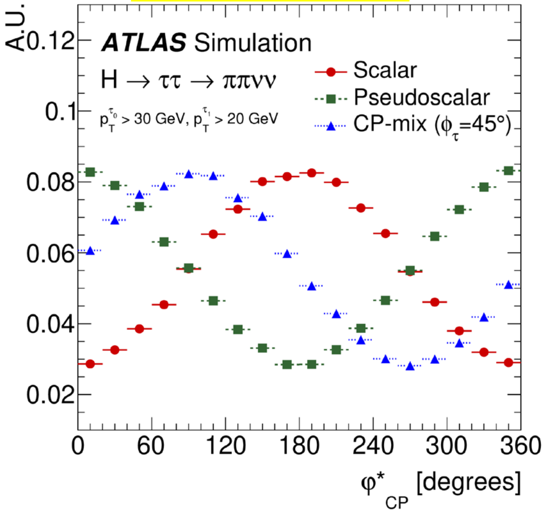
- φ^*_{CP} : angle between two tau decay planes, sensitive to ϕ_τ



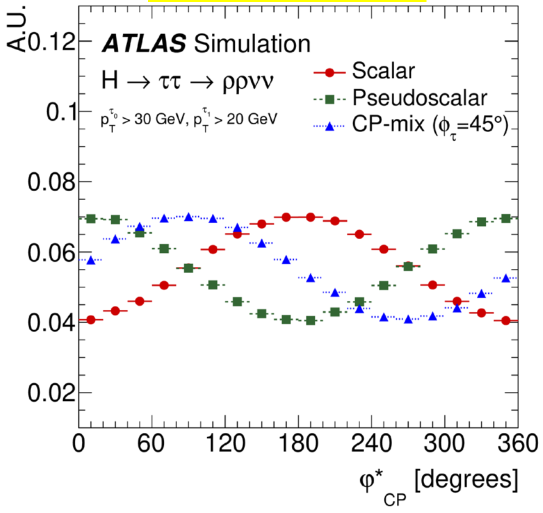
- **Combinations:**

1p0n–1p0n, ℓ–1p0n, 1p0n–1p1n, ℓ–1p1n, 1p1n–1p1n etc.

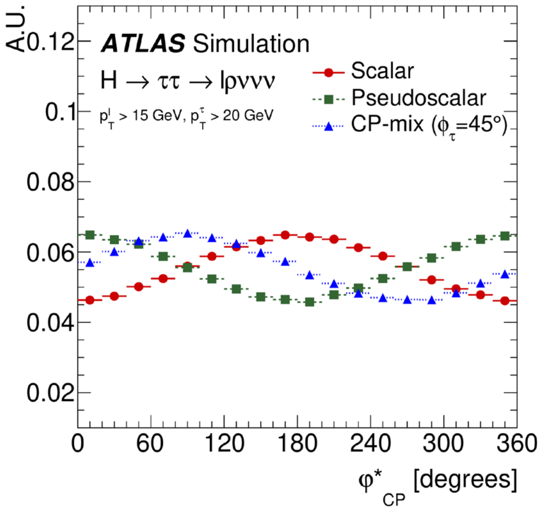
1p0n–1p0n



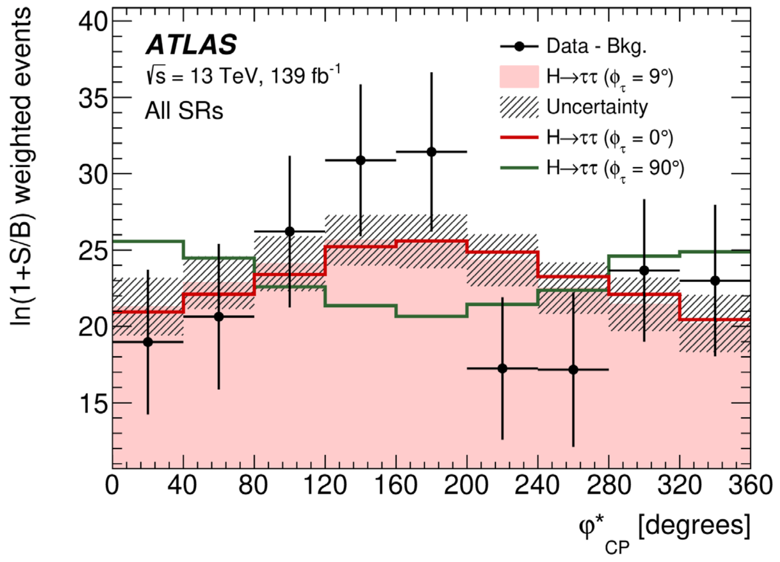
1p1n–1p1n

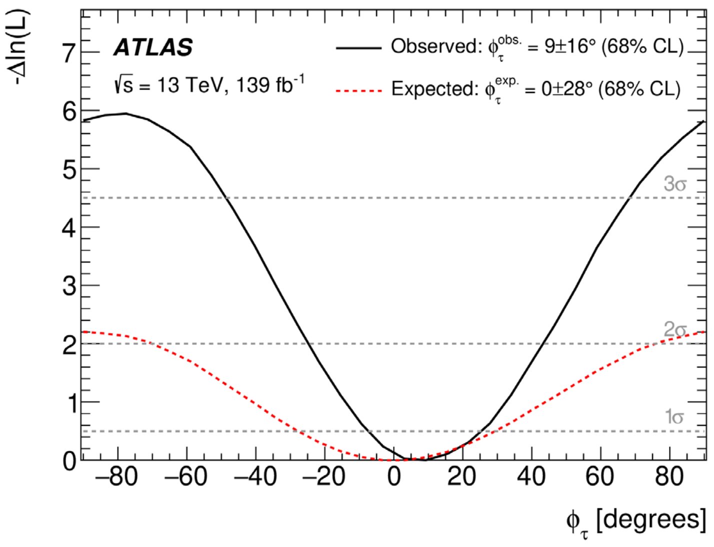


ℓ–1p1n



CP structure of H→ττ coupling





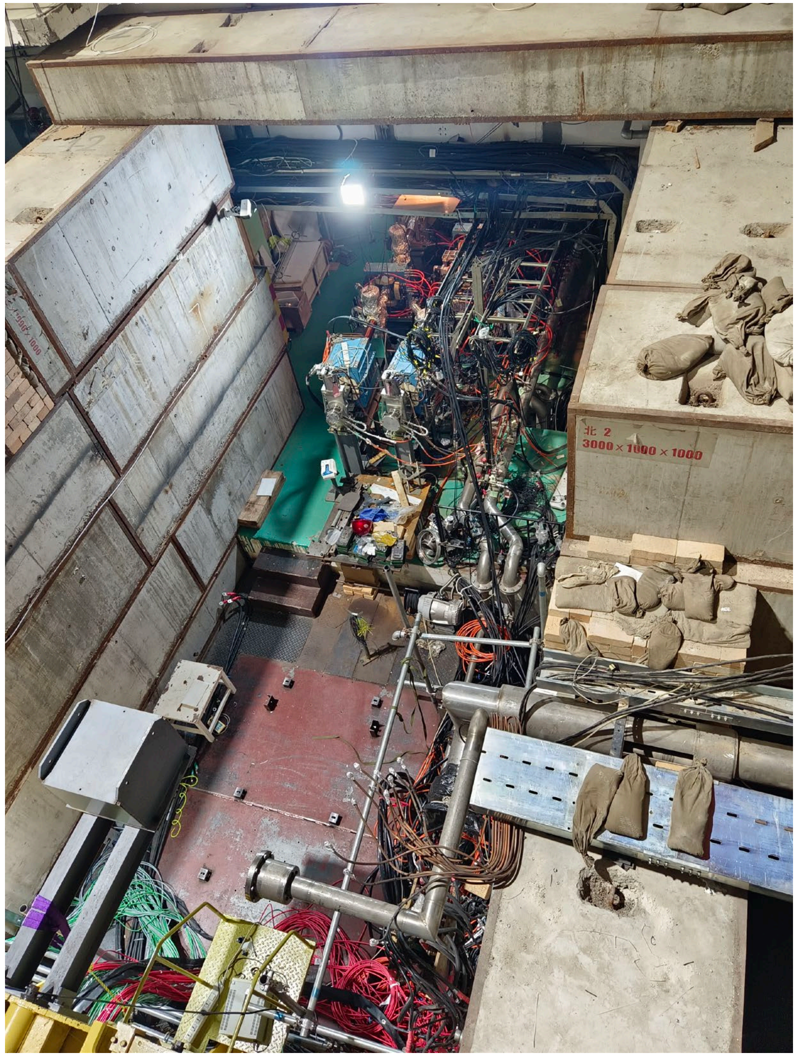
- Observed (expected) $\phi_\tau \approx 9° \pm 16°$ ($0° \pm 28°$) at the 68% CL
  - Results compatible with SM expectation within uncertainties
  - Excluded pure CP-odd state at 3.4σ significance

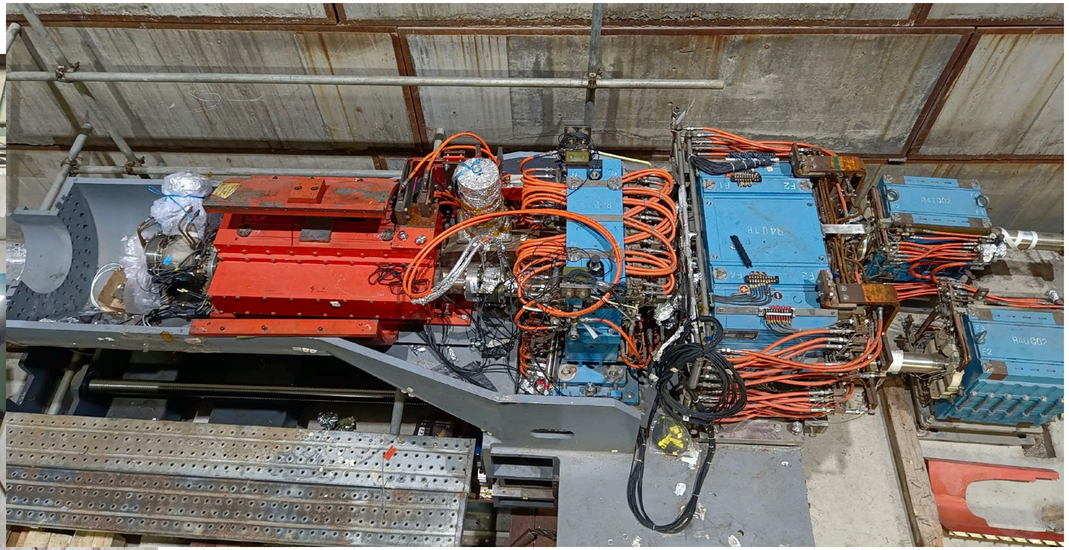
Study HVV CP in H→ZZ decay

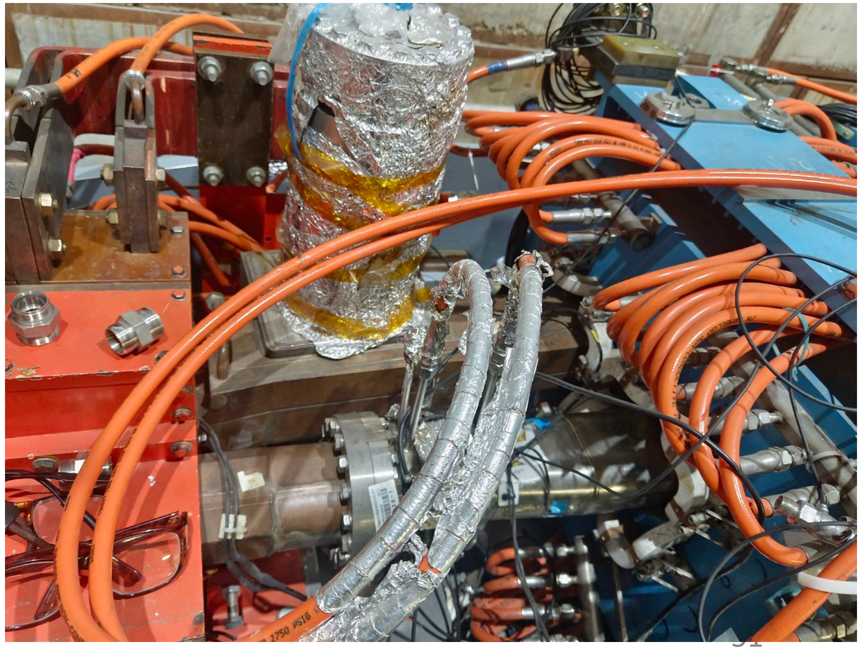
- Parameterize in terms of cross section fractions, f_{ai}
- For the V=W,Z,

$$f_{ai} = \frac{|a_i|^2 \sigma_i}{|a_1|^2 \sigma_1 + |a_2|^2 \sigma_2 + |a_3|^2 \sigma_3 + |\kappa_1|^2 \sigma_{\Lambda 1} + |\kappa_1^{Z\gamma}|^2 \sigma_{\Lambda 1}^{Z\gamma}} \operatorname{sgn}\left(\frac{a_i}{a_1}\right)$$

- Four fractions: f_{a2}, f_{a3}, $f_{\Lambda 1}$, and $f_{\Lambda 1}{}^{Z\gamma}$


北 2
3000×1000×1000

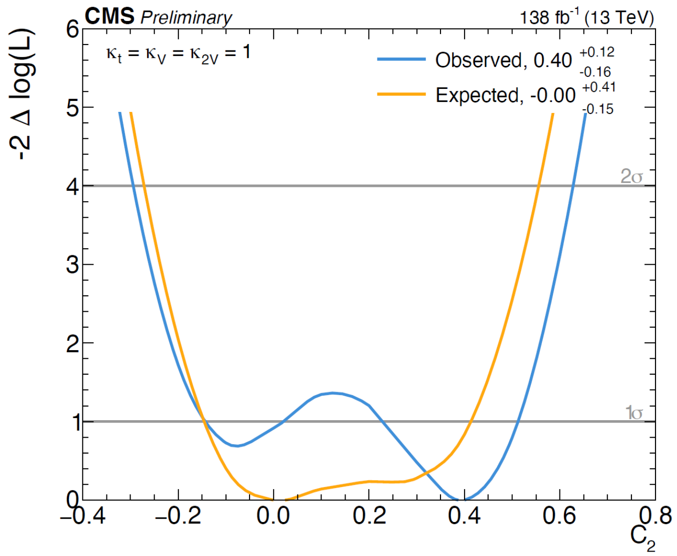


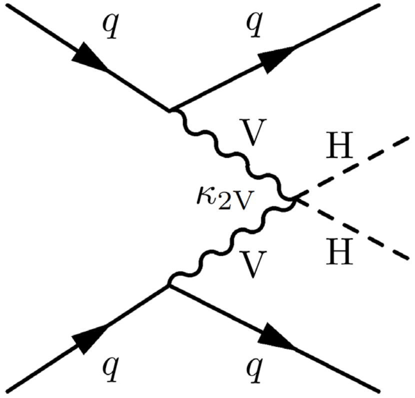


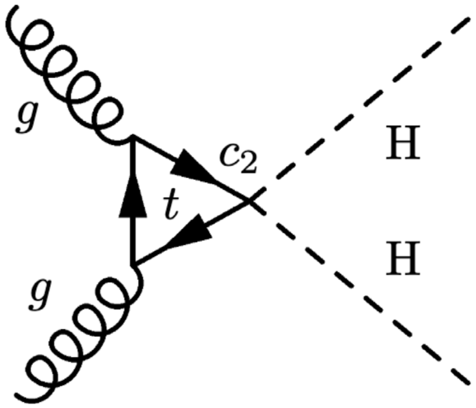
- Sensitivity to from VBF and VHH categories
- Obs. (Exp.) limit on cross-section of 79 (91) times the SM
- 95% CL limit on is set between 0.62 and 1.42 (expected 0.69 and 1.35)

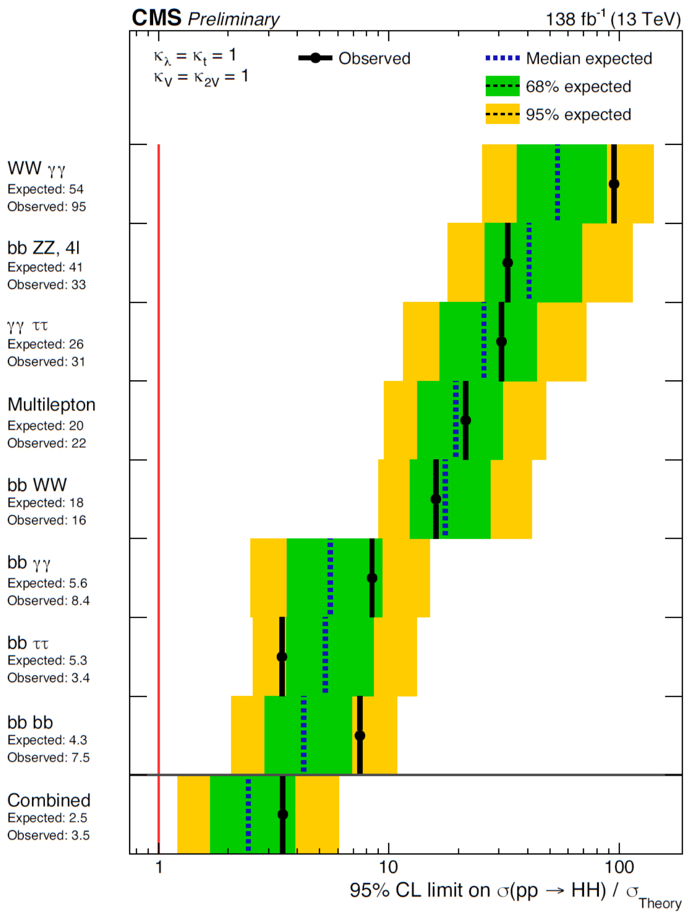
excluded by > 5σ!

We also provide 2D scans of parameters and interpretation in "Higgs Effective Field Theory" (HEFT) framework [*,**] (C_2 coefficient)



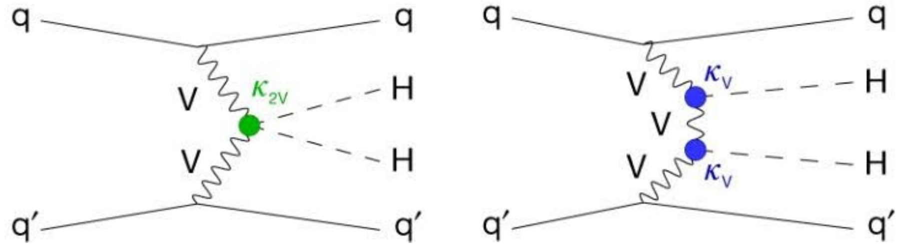






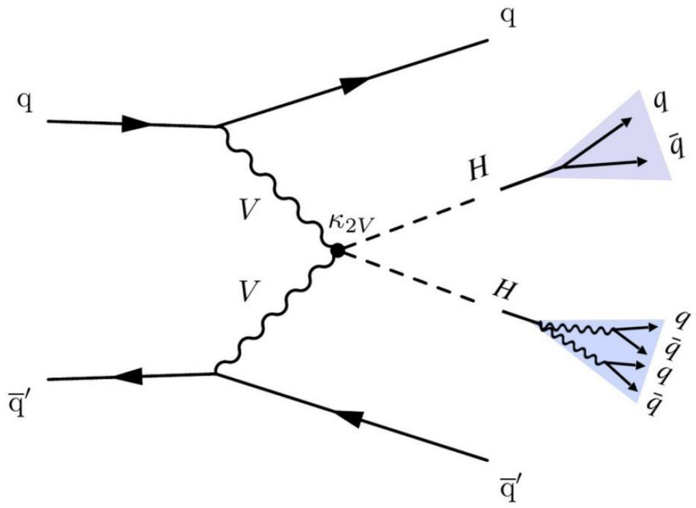
HHVV couplings - from HH

- HH also sensitive to other couplings, notably HHVV (κ_{2V})



- In SM (κ_{2V}=1): cancellation
  - BSM: potential enhancement of VBF HH (especially at high m_{HH})
- Current best constraint by CMS [Nature 607 (2022) 60]
  - 0.67<κ_{2V} <1.38 @95% CL; κ_{2V}=0 excluded with > 6σ
  - VBF HH combination; dominated by boosted 4b channel.
- Similar result obtained by ATLAS
  - [PRL 133 (2024) 101801]

- CMS new final state: [HIG-23-012]
  - all-hadronic bbVV boosted topology + new VV→4q tagging



- -0.04 < κ2V < 2.05 @95% CL
- (0.05 < κ2V <1.98 exp.)
- κ_{2V}=0 excluded with 1.1(0.9)σ