Search for Higgs boson pair production in the bbττ final state with the ATLAS detector

RENAFAE Workshop 2022

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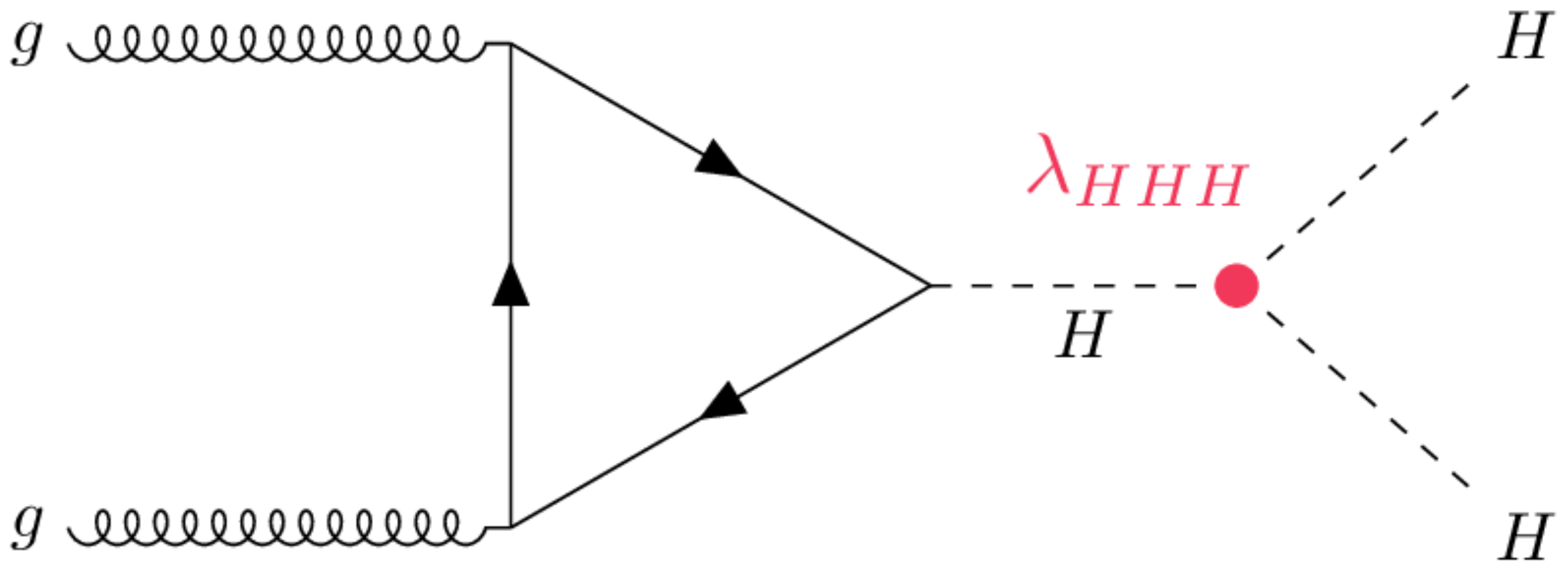
Search for HH production - SM

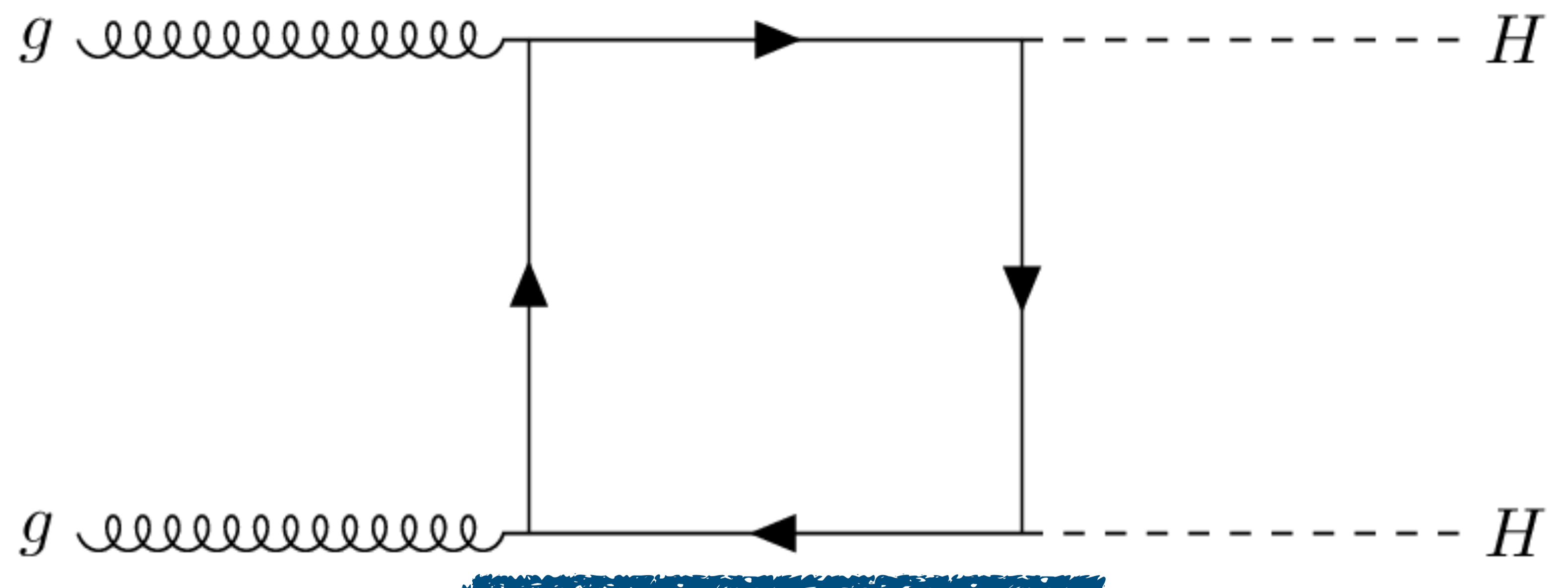
$$\mathcal{L} = -\tfrac{1}{4} F_{\mu\nu} F^{\mu\nu} + i\bar{\psi}\not{D}\psi + \psi_i y_{ij} \psi_j \phi + h.c. + |D_\mu \phi|^2 - V(\phi)$$

$$V(\phi) = -\mu^2\phi^2 + \lambda\phi^4$$

- HH final states search within the **Standard Model**
- SM predicts trilinear Higgs self-coupling λ_{HHH}
- Direct probe of electroweak symmetry breaking potential



Higgs boson self-coupling



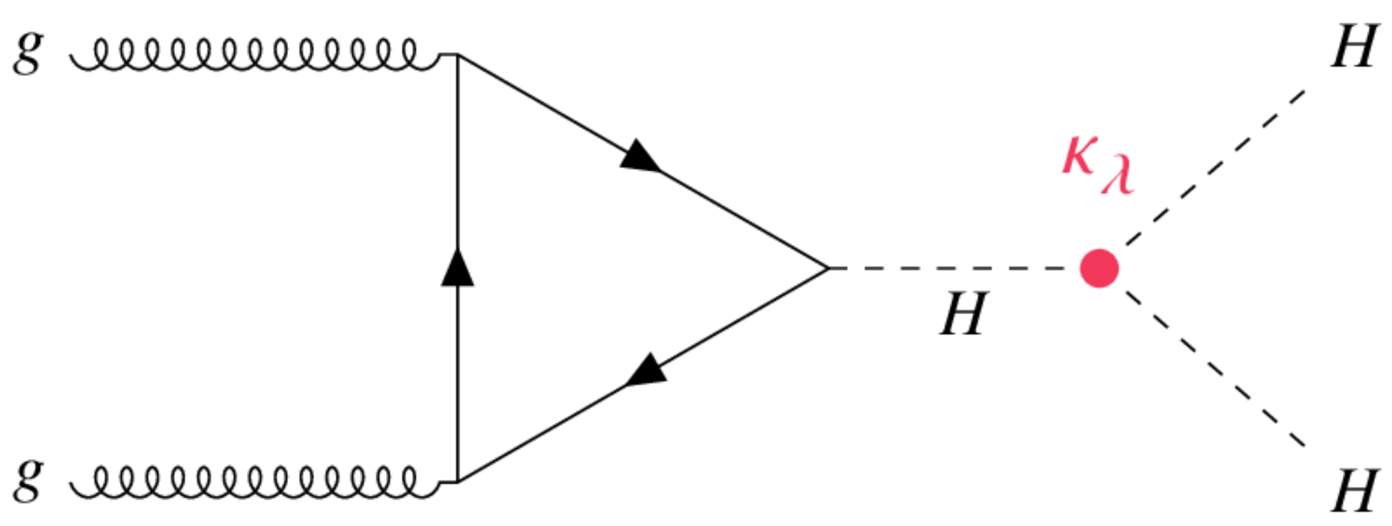
Higgs-fermion Yukawa coupling

$$\sigma^{SM}_{ggF}(HH) = 31.05^{+6\%}_{-23\%}(\text{scale}+m_{top}) \pm 3.0\%(\text{PDF}+\alpha_s)\ \text{fb}$$

$m_H = 125$ GeV and $\sqrt{s} = 13$ TeV.

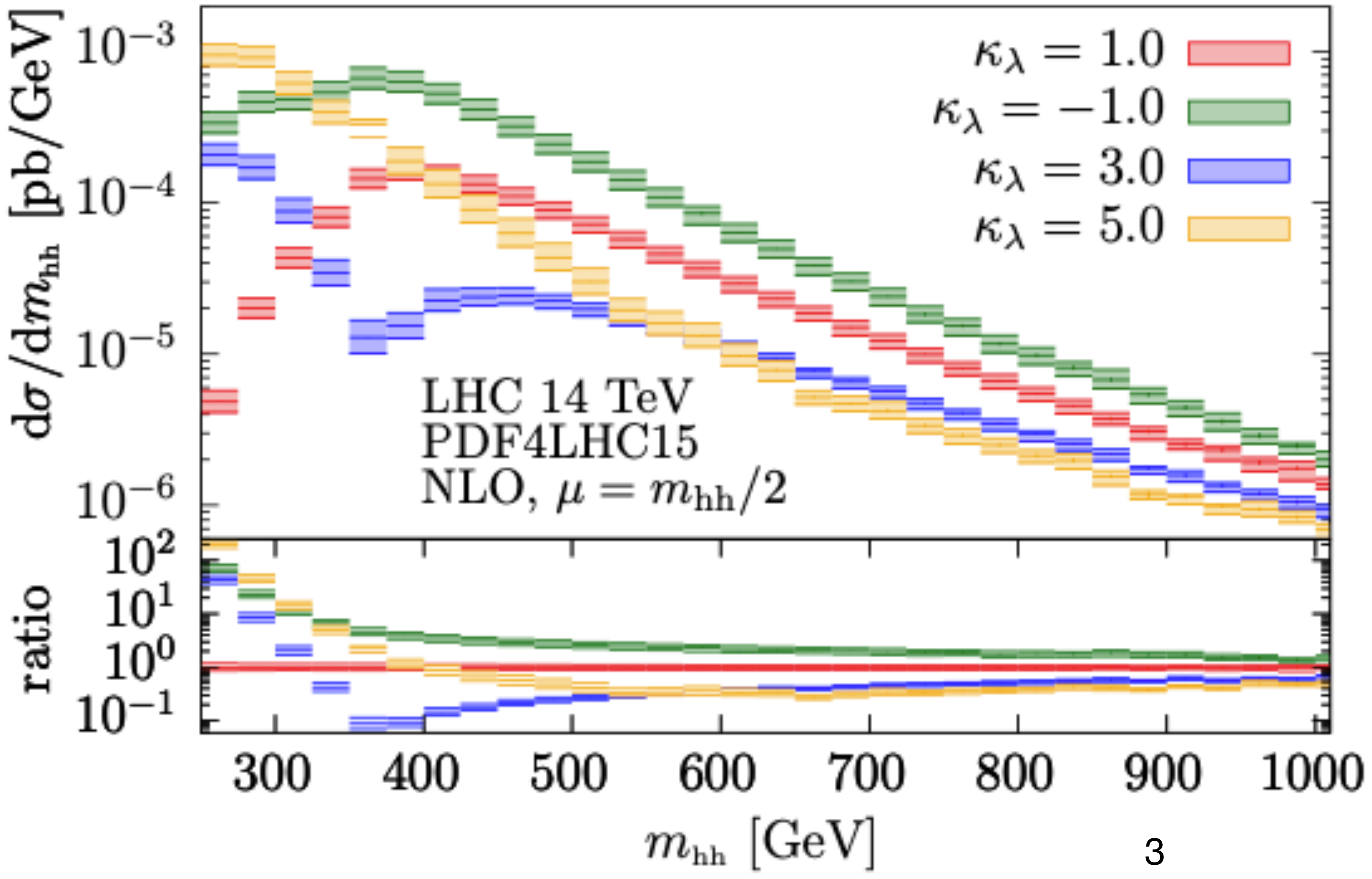
- ggF dominant production mode at LHC
- $\sigma_{ggF}(pp \rightarrow HH)$ small due to destructive interference between top quark loop and HH self-coupling diagrams
  - about 1000 times smaller than that of single Higgs bosons
- Major goal of HL-LHC: measure HH cross section and trilinear self-coupling λ_{HHH}

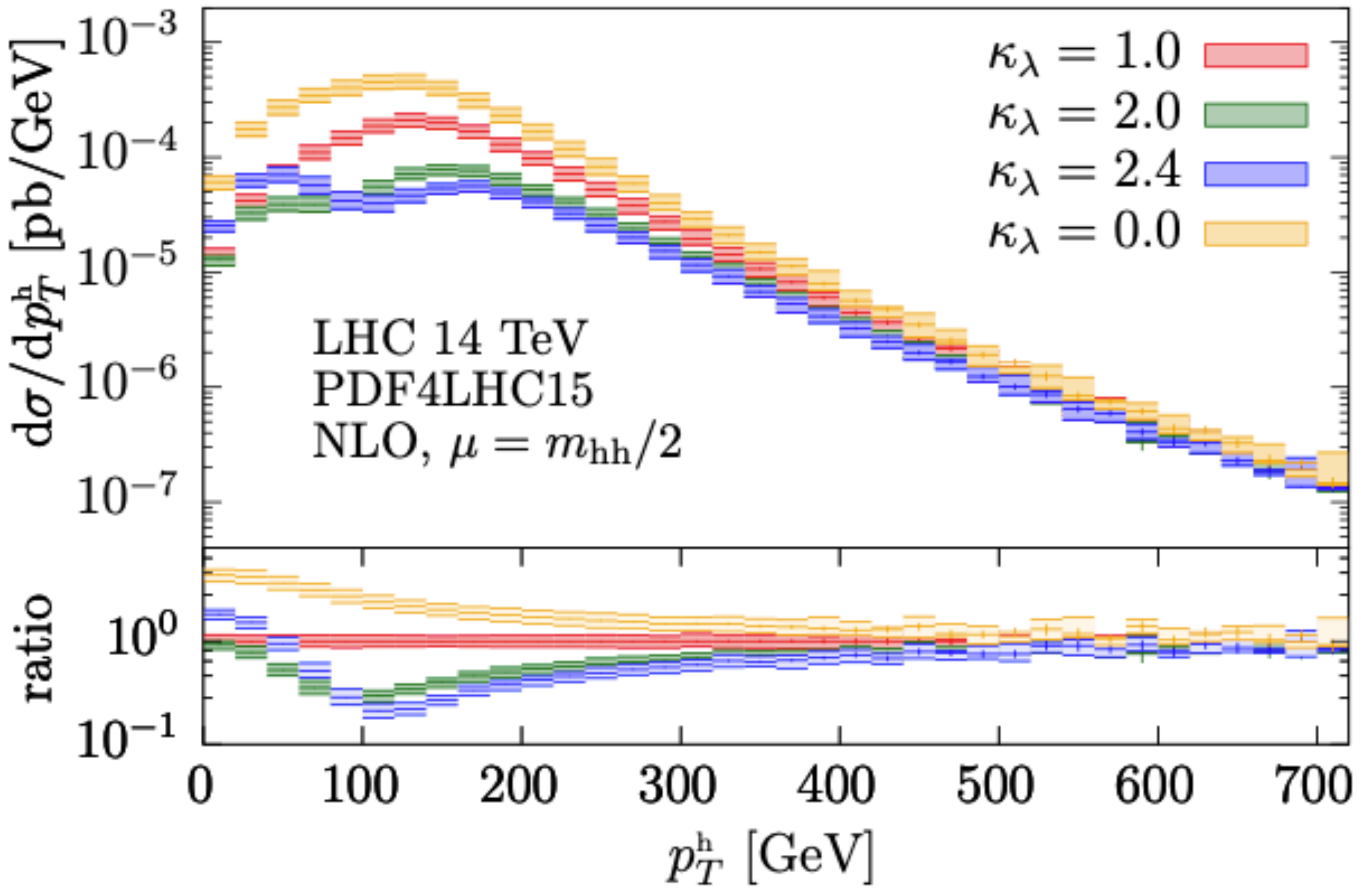
Search for HH production - anomalous couplings



- LHC experiments are currently not sensitive to SM HH production
- Non-resonant searches can be already sensitive to BSM effects on HH physics
  - HH final states search within **anomalous couplings**
  - sensitive to anomalous deviations of the coupling strength $\kappa_\lambda = \lambda_{HHH}/\lambda^{SM}_{HHH}$
- **Higgs boson trilinear self-coupling modifier κ_λ** has large impact on cross section and kinematics

JHEP06(2019)066



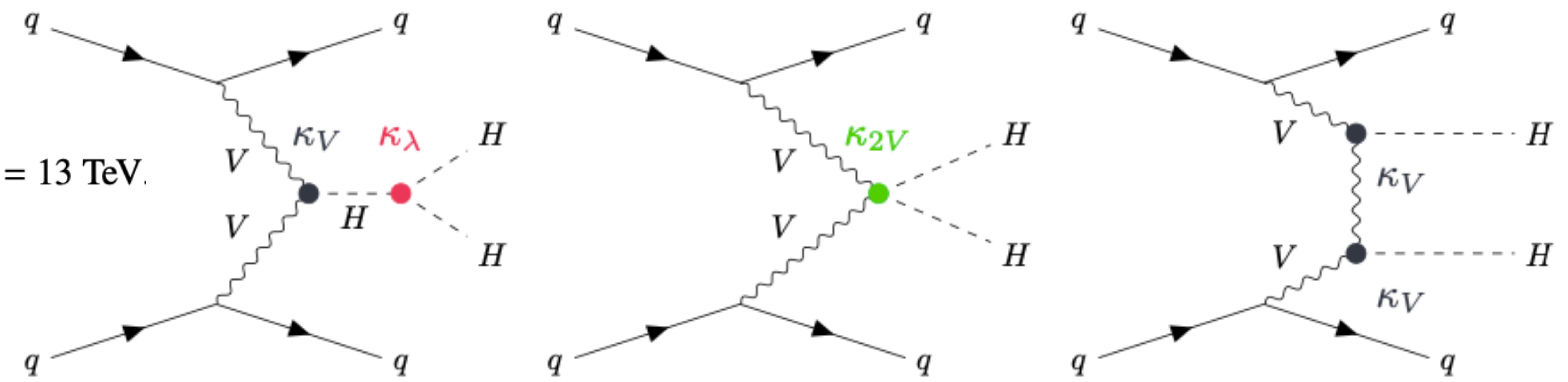


Search for HH production - SM

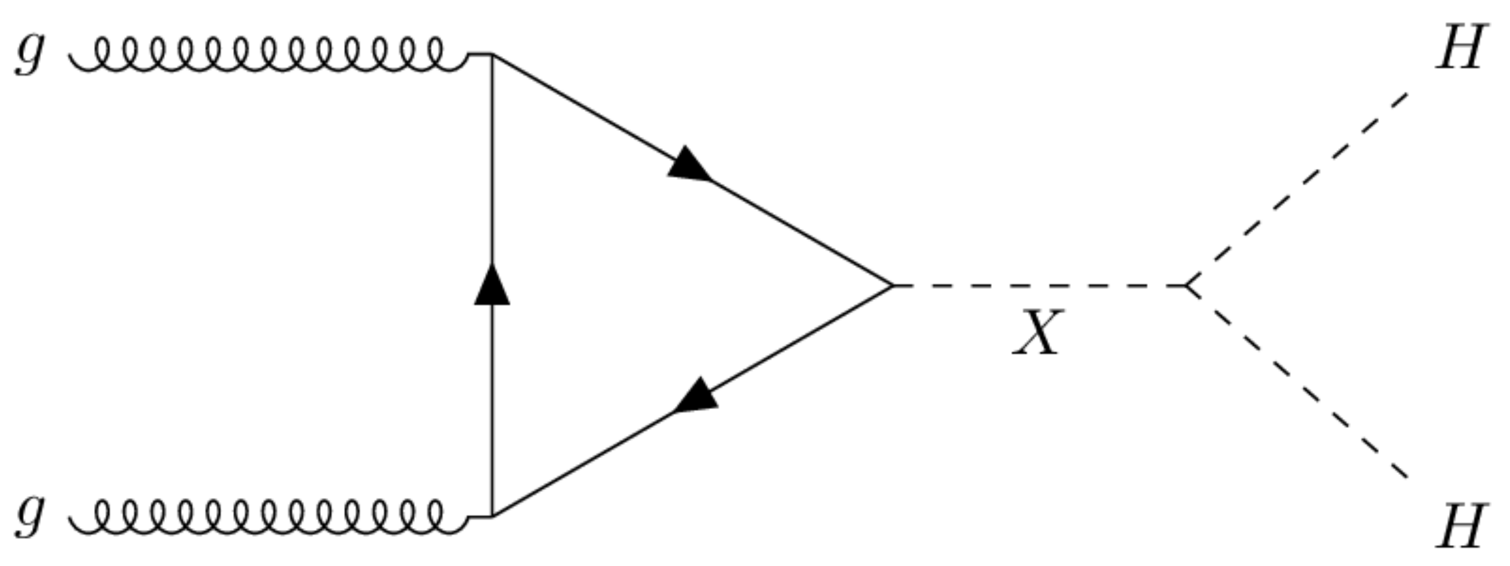
- Next leading production mode is Vector-Boson-Fusion (VBF)
  - sensitive to κ_λ and to quartic VVHH coupling (κ_{2V})

$$\sigma^{SM}_{VBF}(HH) = 1.73^{+0.03\%}_{-0.04\%}\,(\text{scale}) \pm 2.1\%\,(\text{PDF} + \alpha_s)\ \text{fb}$$

$m_H = 125$ GeV and $\sqrt{s} = 13$ TeV



Search for HH production - BSM

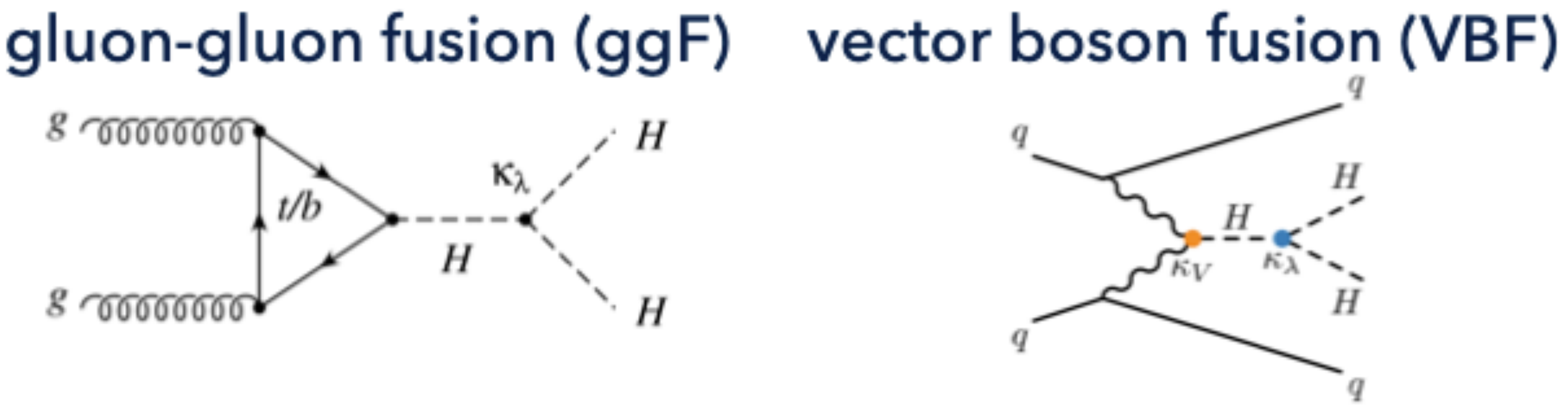


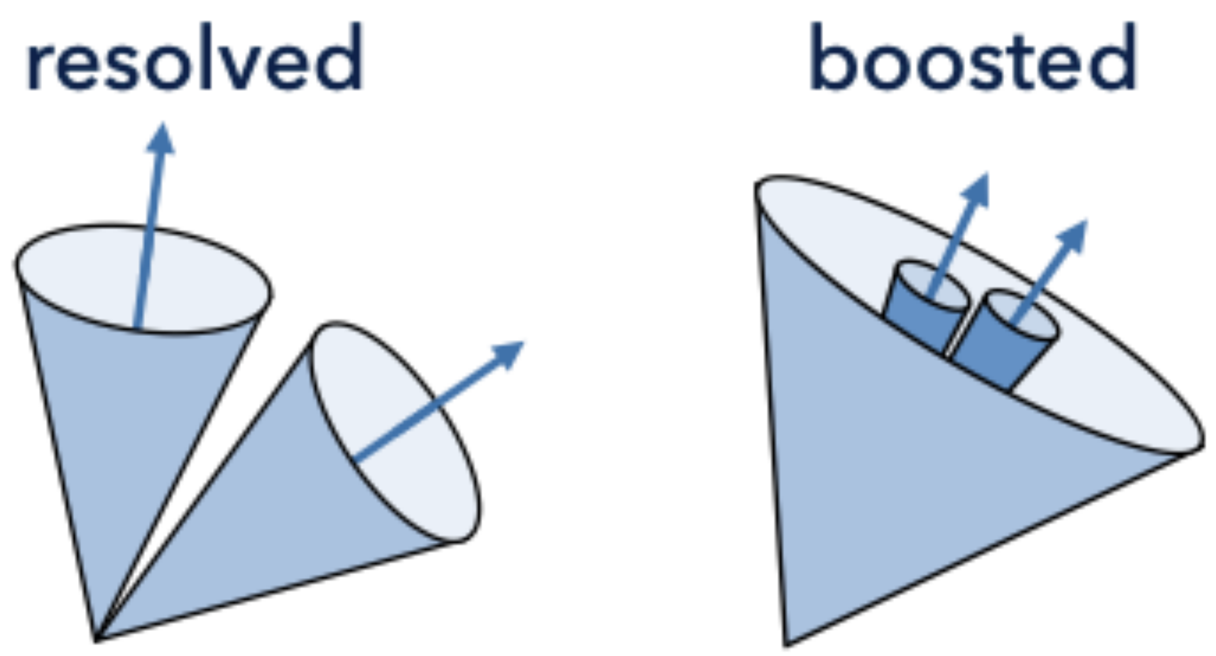
Resonant production

- HH final states search within **Beyond-the-Standard-Model resonances**
- Several BSM models predict existence of heavy particles decaying into 2 Higgs bosons
- Spin-0 resonance: predicted by Two-Higgs-Doublet Models (e.g. MSSM) and Electroweak Singlet Models
- Spin-2 resonance: Kaluza-Klein graviton, predicted in the Randall-Sundrum model of warped extra dimensions

HH experimental signatures

- Analyses challenge: compromise between BR and higher purity. No golden channel!!
- Variety of final states
- Hbb highest BR
- Leptonic final states: high background suppression
- Dominant production modes and different regimes are considered

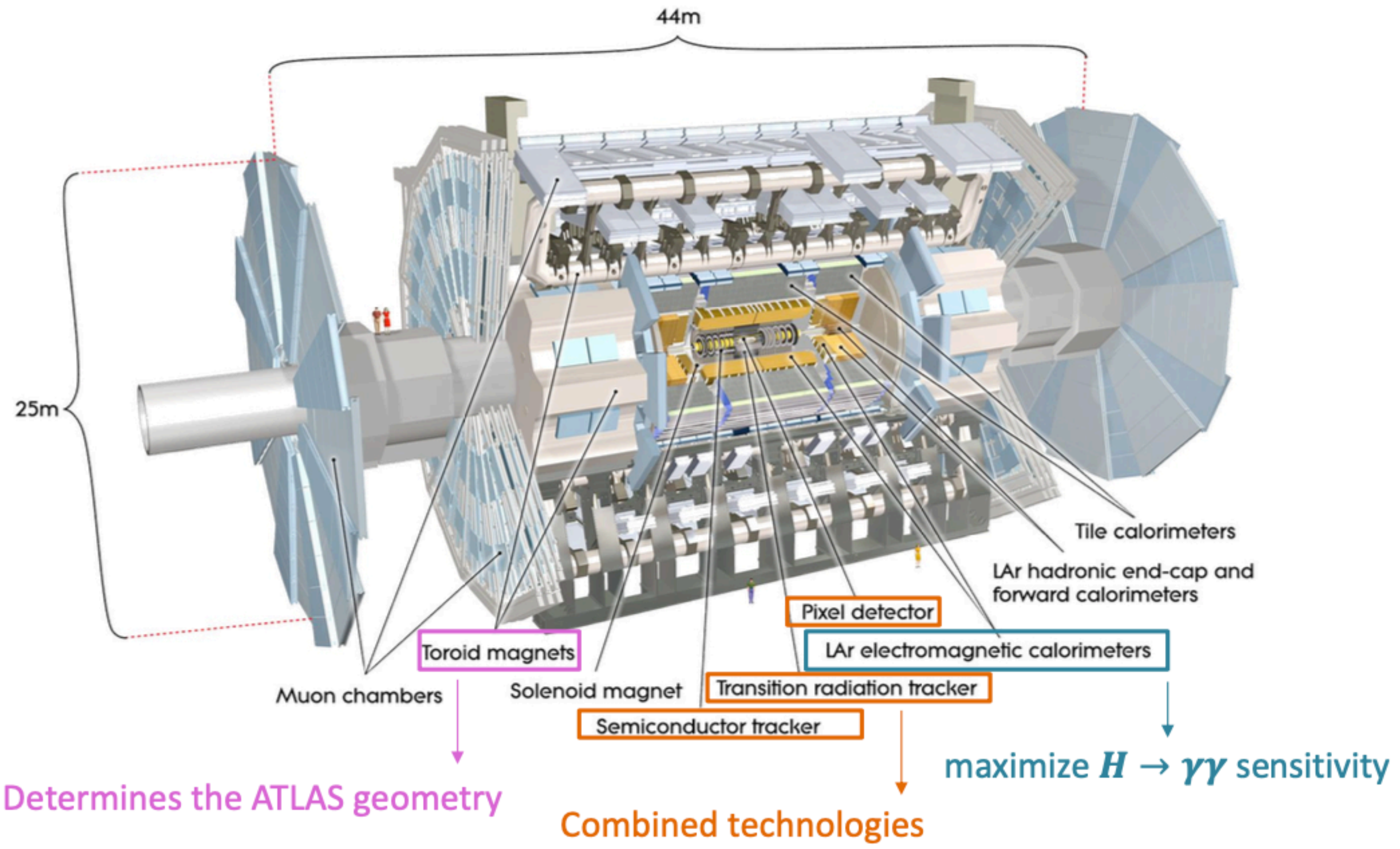


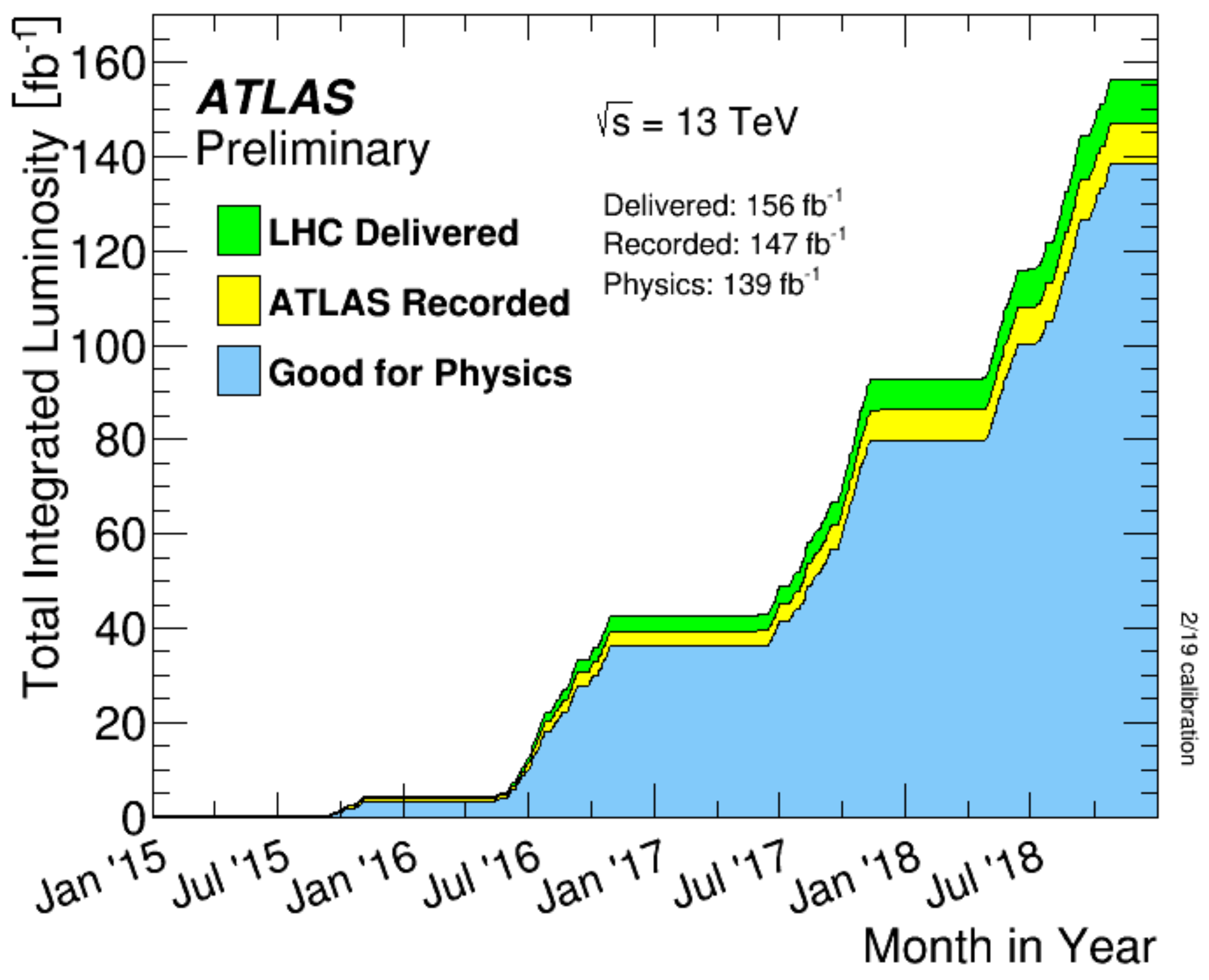


	bb	WW	ττ	ZZ	γγ
bb	34%				
WW	25%	4.6%			
ττ	7.3%	2.7%	0.39%		
ZZ	3.1%	1.1%	0.33%	0.07%	
γγ	0.26%	0.10%	0.03%	0.01%	0.0005%

published by ATLAS

ATLAS Detector and Run 2 data-taking period





Physics benchmarks drove the design of the detector

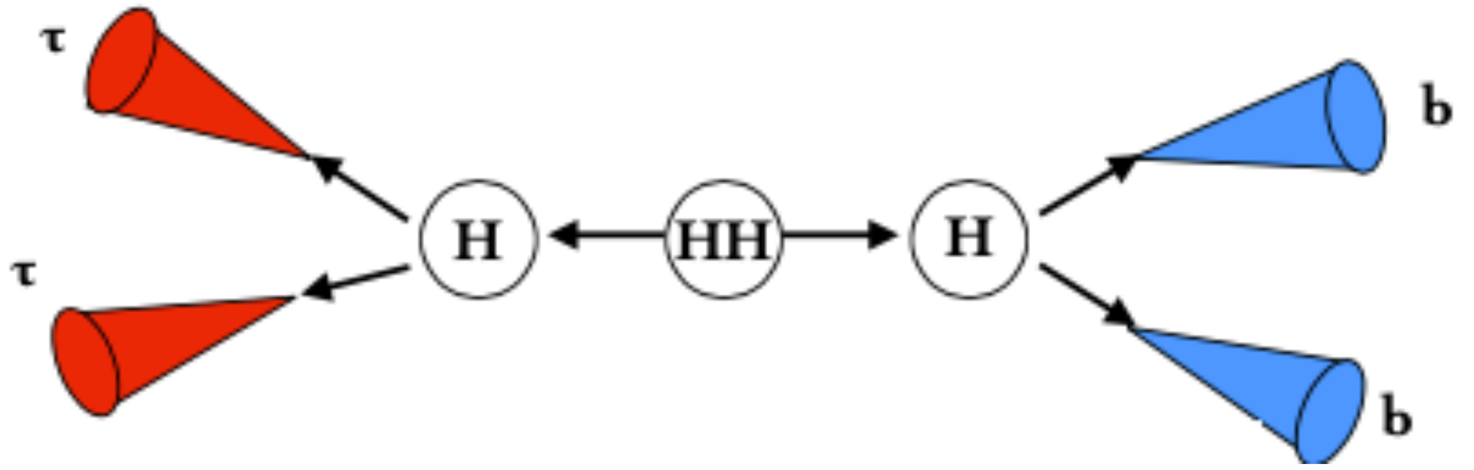
Excellent stand-alone reconstruction capabilities

Inner Detector - Tracking e PI em $|\eta| < 2.5$

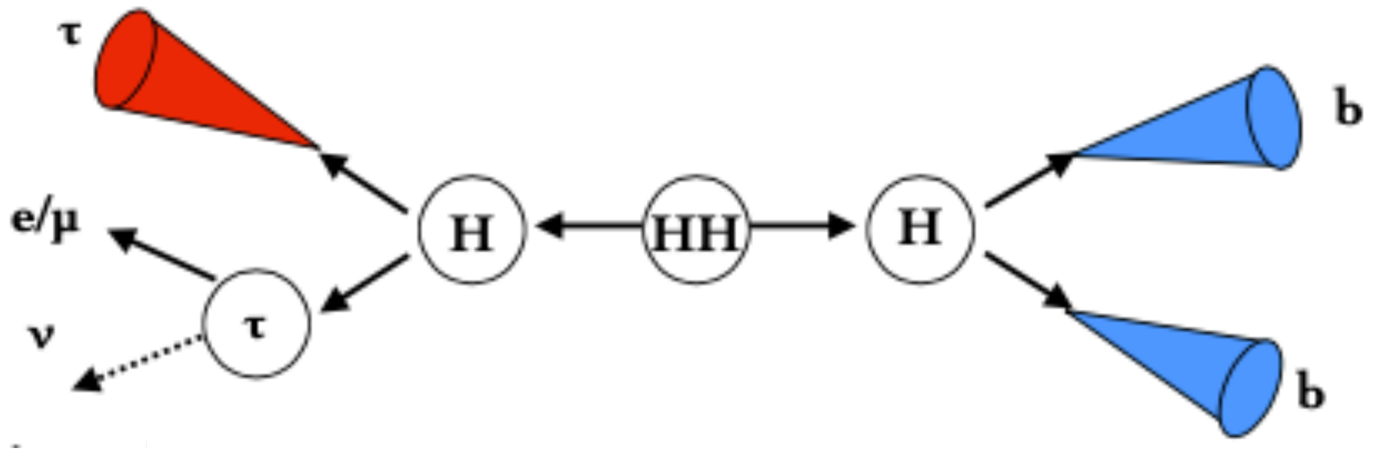
Calorimetry - $|\eta| < 4.9$

Muon Spectometer - $|\eta| < 2.7$

Publication: ATLAS-CONF-2021-030



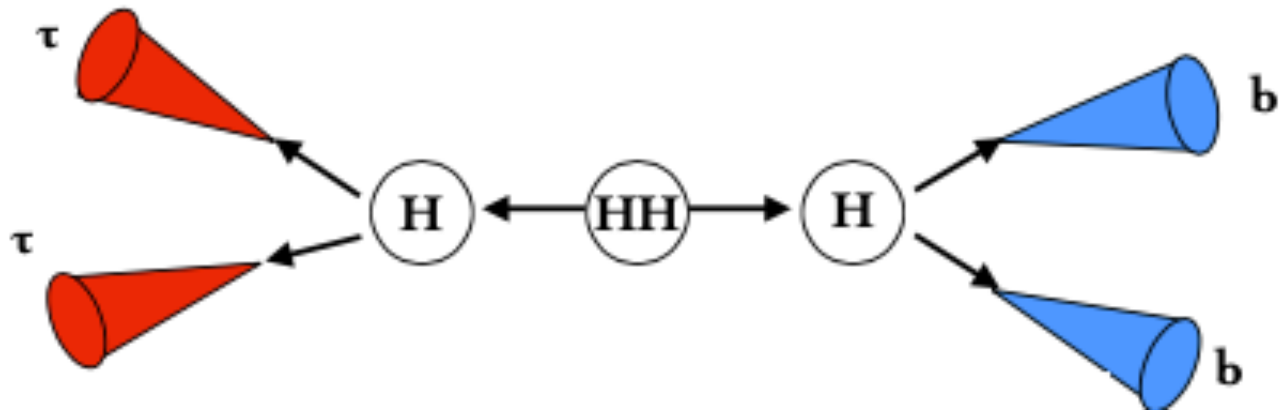
$HH \rightarrow bb\tau_{had}\tau_{had}$

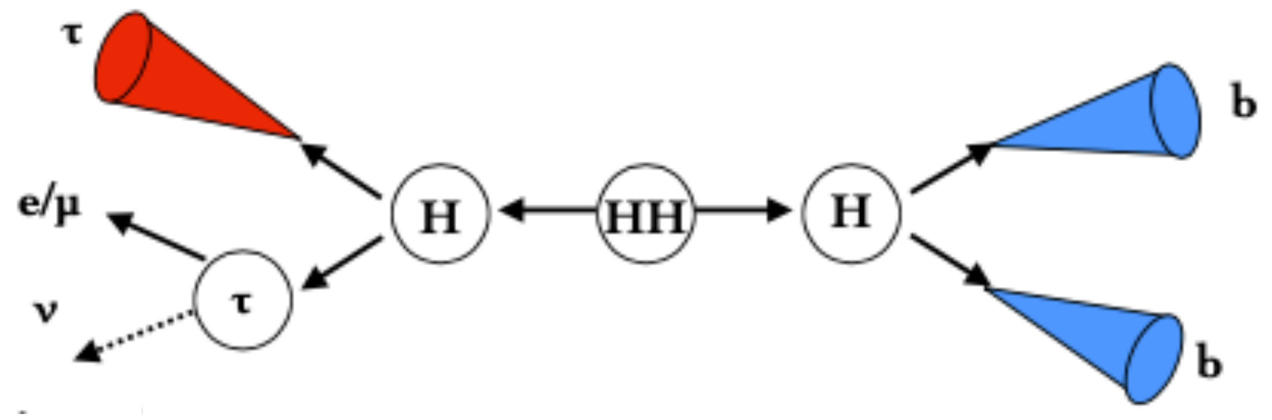


$HH \rightarrow bb\tau_{lep}\tau_{had}$

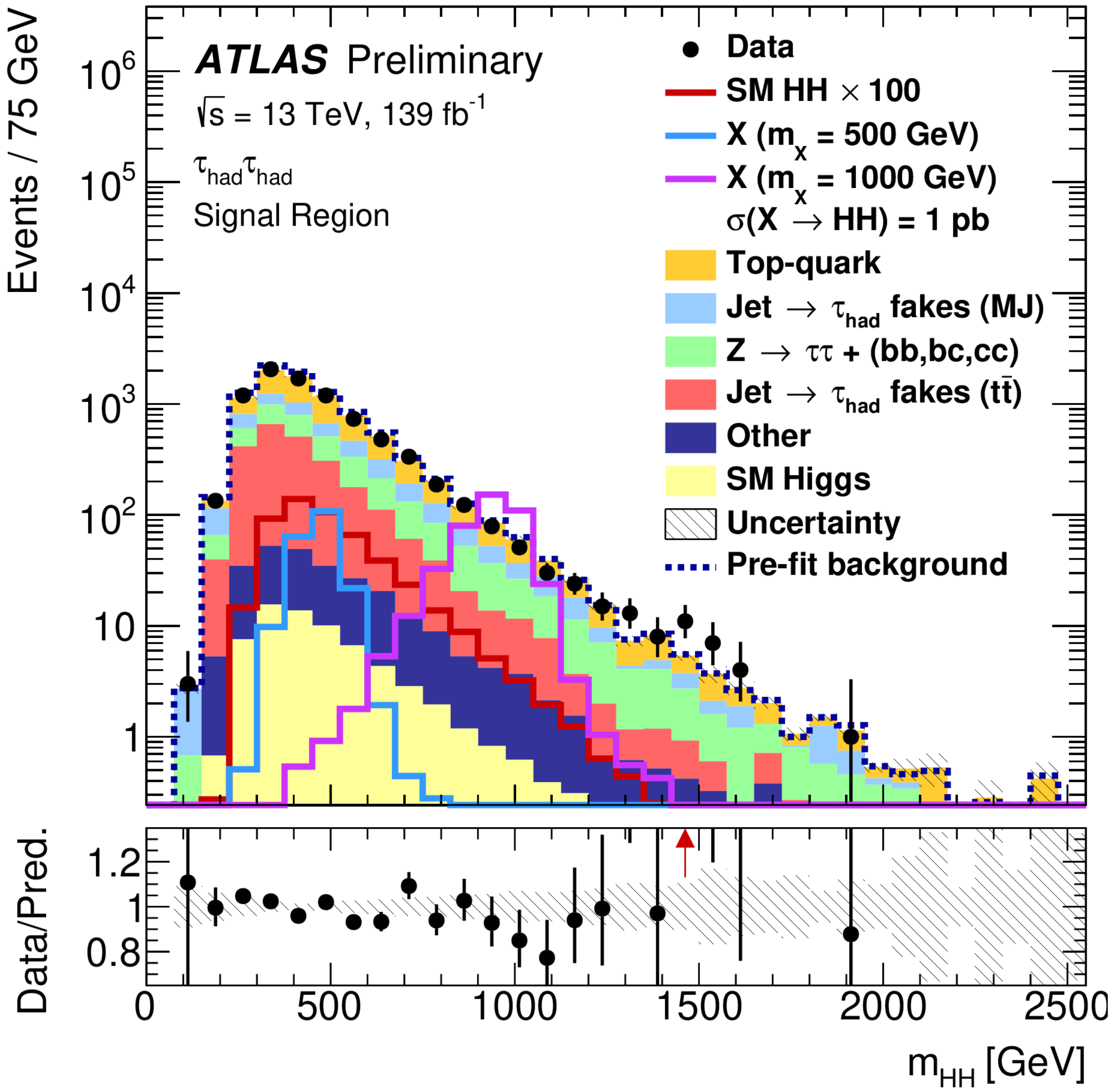
Analysis Strategy

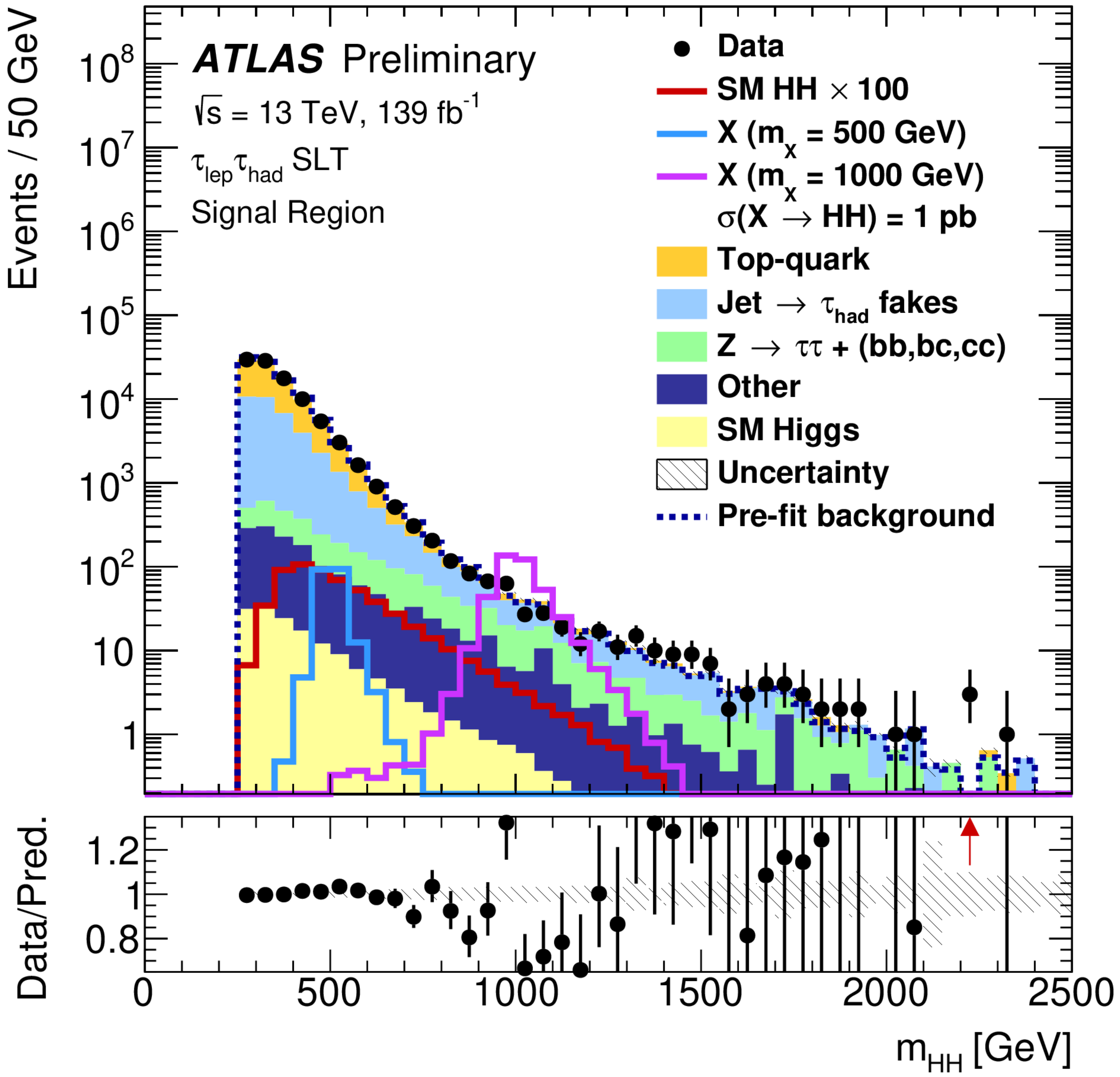
ATL-CONF-2021-030





- bb$\tau\tau$ has the 3rd largest BR of accessible channels
  - challenging τ_{had} reco and triggering
  - neutrinos in τ decays
- **lephad**: τ_{lep} τ_{had} **(46%)**
- **hadhad: τ_{had} τ_{had} (42%)**
- **non-resonant** and **resonant (251-1600 GeV)** analyses





Main backgrounds:

- **true-τ** : ttbar and Z+heavy flavour
- single H contributions
- fake-τ

Channel	Triggers	Properties
HadHad	single-τ and di-τ triggers	high purity
LepHad (SLT)	single-lepton trigger	high acceptance, large $t\bar{t}$ background
LepHad (LTT)	lepton+τ trigger	lower p_T^ℓ increases low-mass sensitivity

Results - I

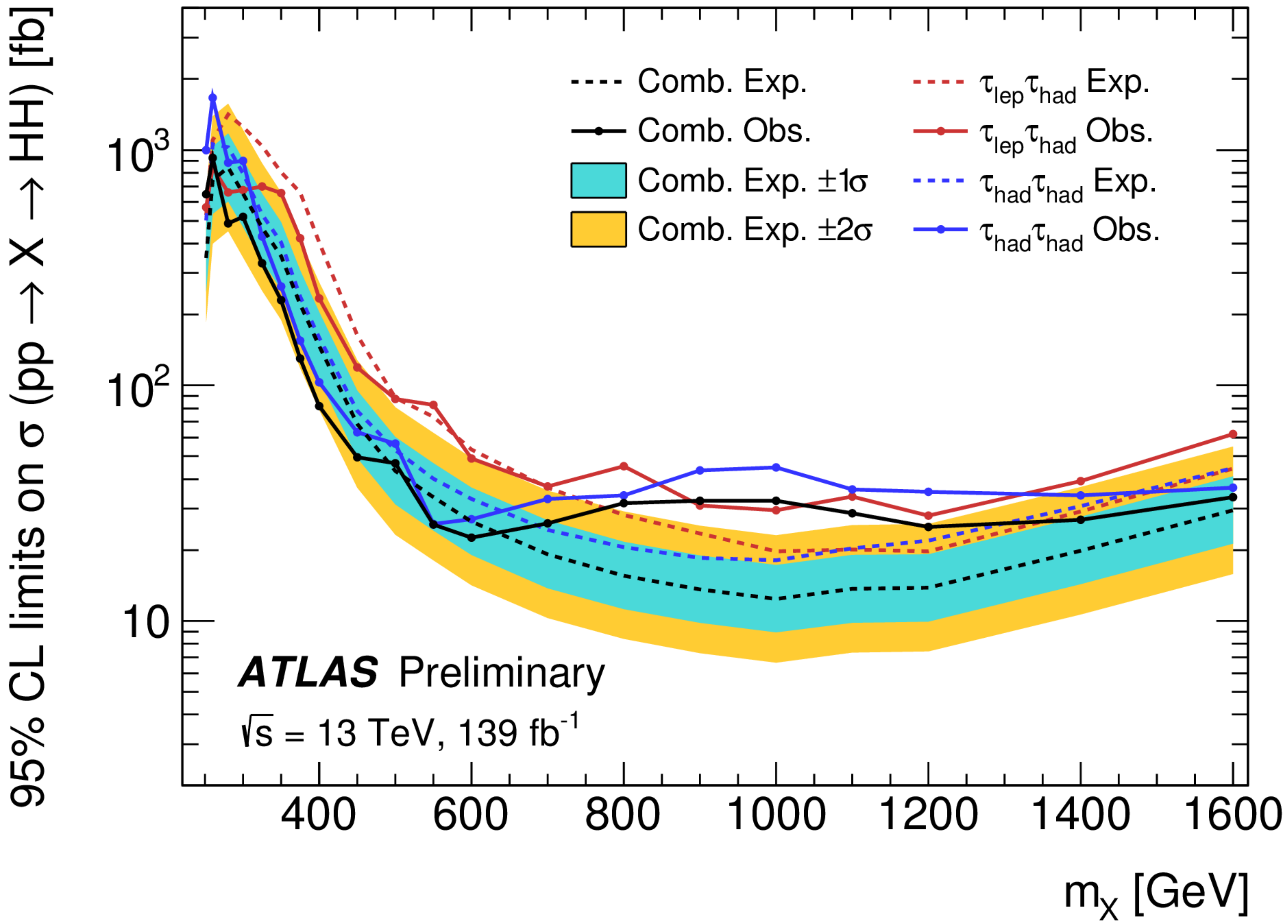
ATL-CONF-2021-030

non-resonant obs (exp) 4.7 (3.9) x SM

		Observed	$-2\ \sigma$	$-1\ \sigma$	Expected	$+1\ \sigma$	$+2\ \sigma$
$\tau_{\text{had}}\tau_{\text{had}}$	$\sigma_{\text{ggF+VBF}}$ [fb]	145	70.5	94.6	131	183	245
	$\sigma_{\text{ggF+VBF}}/\sigma^{\text{SM}}_{\text{ggF+VBF}}$	4.95	2.38	3.19	4.43	6.17	8.27
$\tau_{\text{lep}}\tau_{\text{had}}$	$\sigma_{\text{ggF+VBF}}$ [fb]	265	124	167	231	322	432
	$\sigma_{\text{ggF+VBF}}/\sigma^{\text{SM}}_{\text{ggF+VBF}}$	9.16	4.22	5.66	7.86	10.9	14.7
Combined	$\sigma_{\text{ggF+VBF}}$ [fb]	135	61.3	82.3	114	159	213
	$\sigma_{\text{ggF+VBF}}/\sigma^{\text{SM}}_{\text{ggF+VBF}}$	4.65	2.08	2.79	3.87	5.39	7.22

- factor **4** improvement compared to previous non-resonant Run 2 result with 36 fb^{-1} (PRL 121(2018)191801), **obs (exp) 12.7 (14.8)**
  - 50% due to luminosity increase
  - 50% due to improved τ_{had} and **b-jet** reconstruction and identification techniques, new triggers and a number of analysis-level improvements

Resonant (Spin-0): obs (exp) 23 - 920 fb (12 - 840 fb)



- local excess @ 1.0 (1.1) TeV in the $\tau_{had}\tau_{had}$ ($\tau_{lep}\tau_{had}$) channel of 2.8σ (1.5σ)
- combined at 1 TeV: **local (global)** excess of **3.0σ (2.0σ)**

Results - II

ATL-CONF-2021-030
ATL-CONF-2021-052

non-resonant obs (exp) 4.7 (3.9) x SM

		Observed	-2σ	-1σ	Expected	$+1\sigma$	$+2\sigma$
$\tau_{had}\tau_{had}$	$\sigma_{ggF+VBF}$ [fb]	145	70.5	94.6	131	183	245
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  - 50% due to luminosity increase
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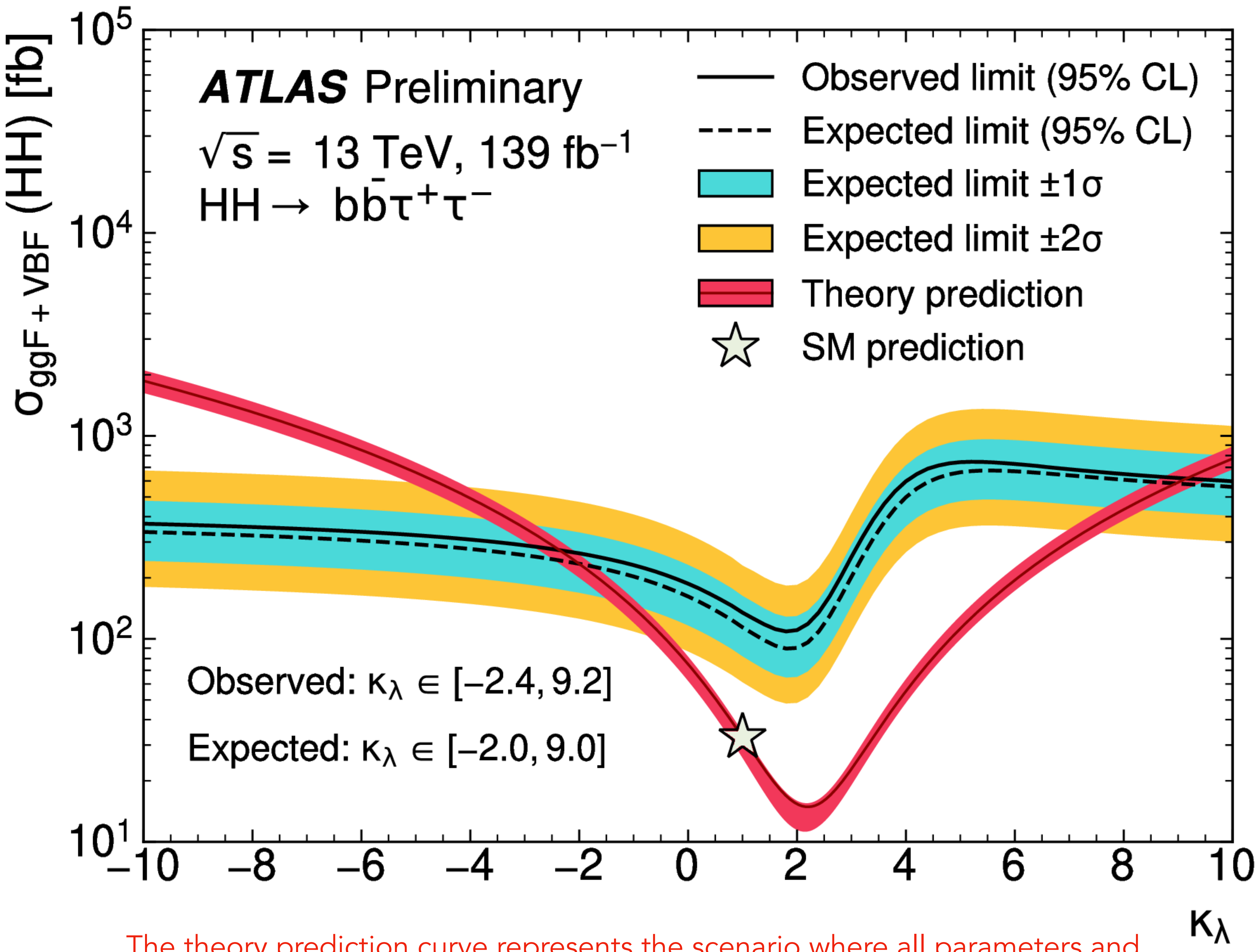
obs κ_λ excluded outside the interval [-2.4, 9.2]

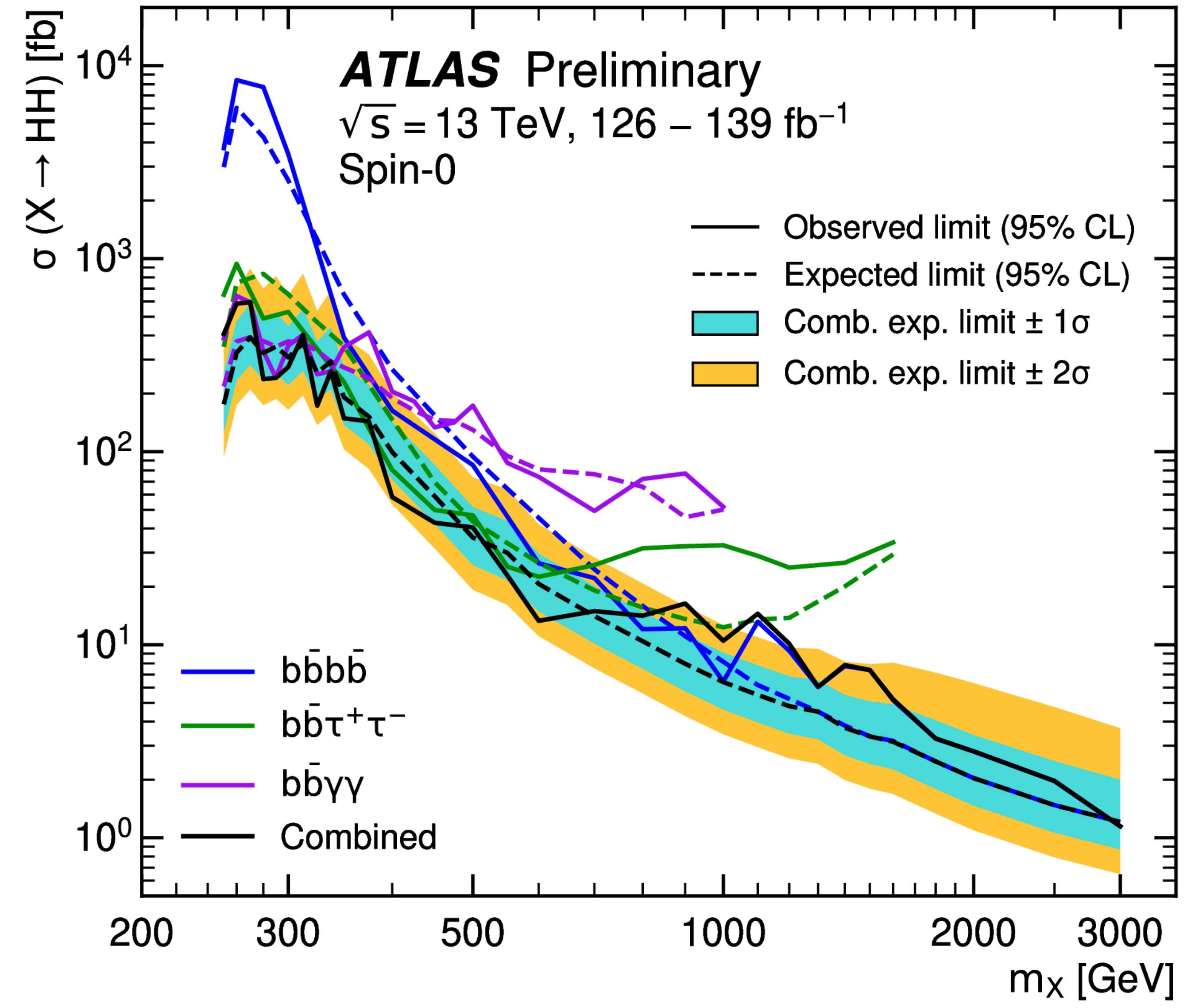


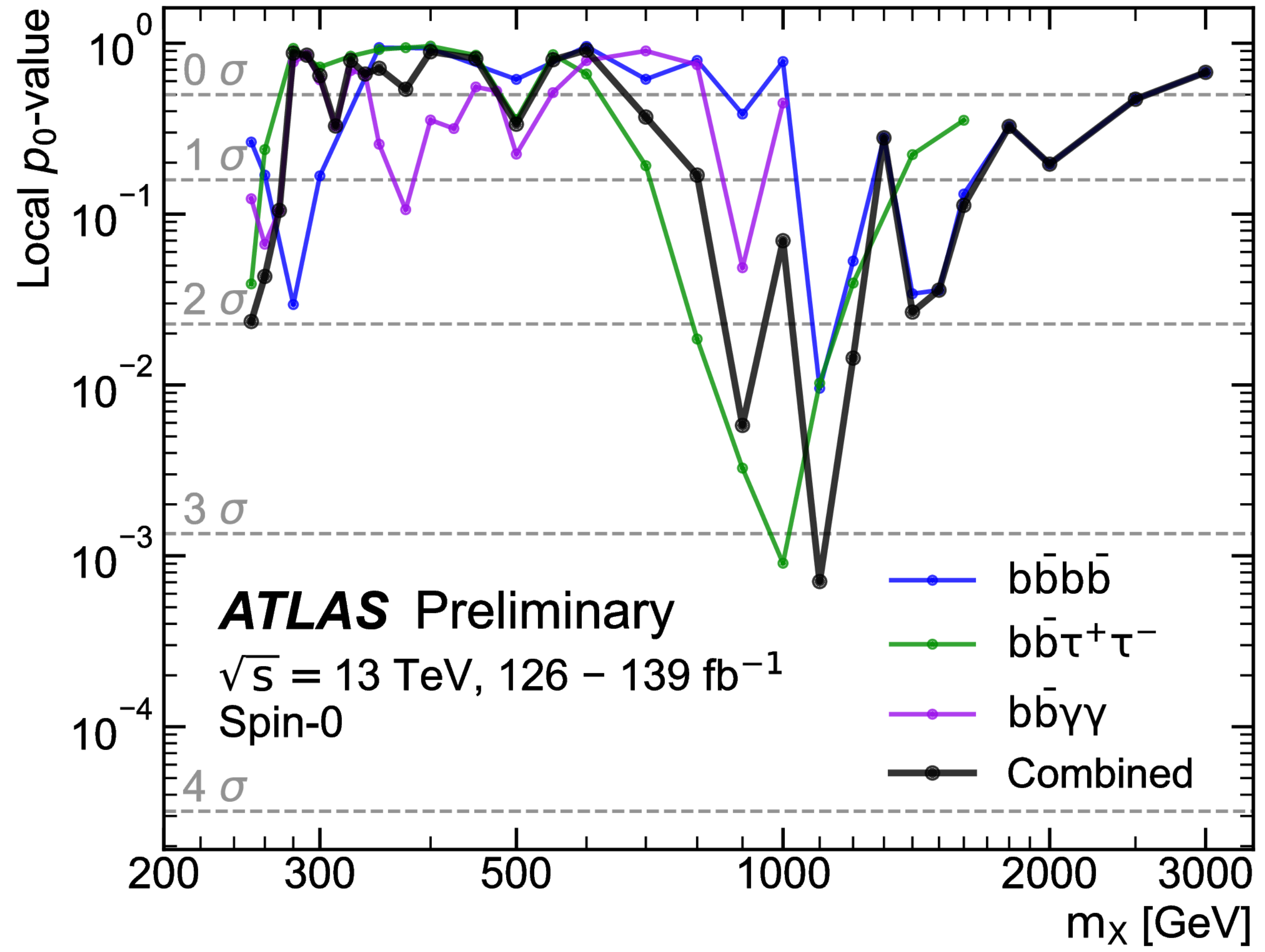
The theory prediction curve represents the scenario where all parameters and couplings are set to their SM values except for κ_λ. Expected limits assume no HH production.

Combining ATLAS results

ATL-CONF-2021-052

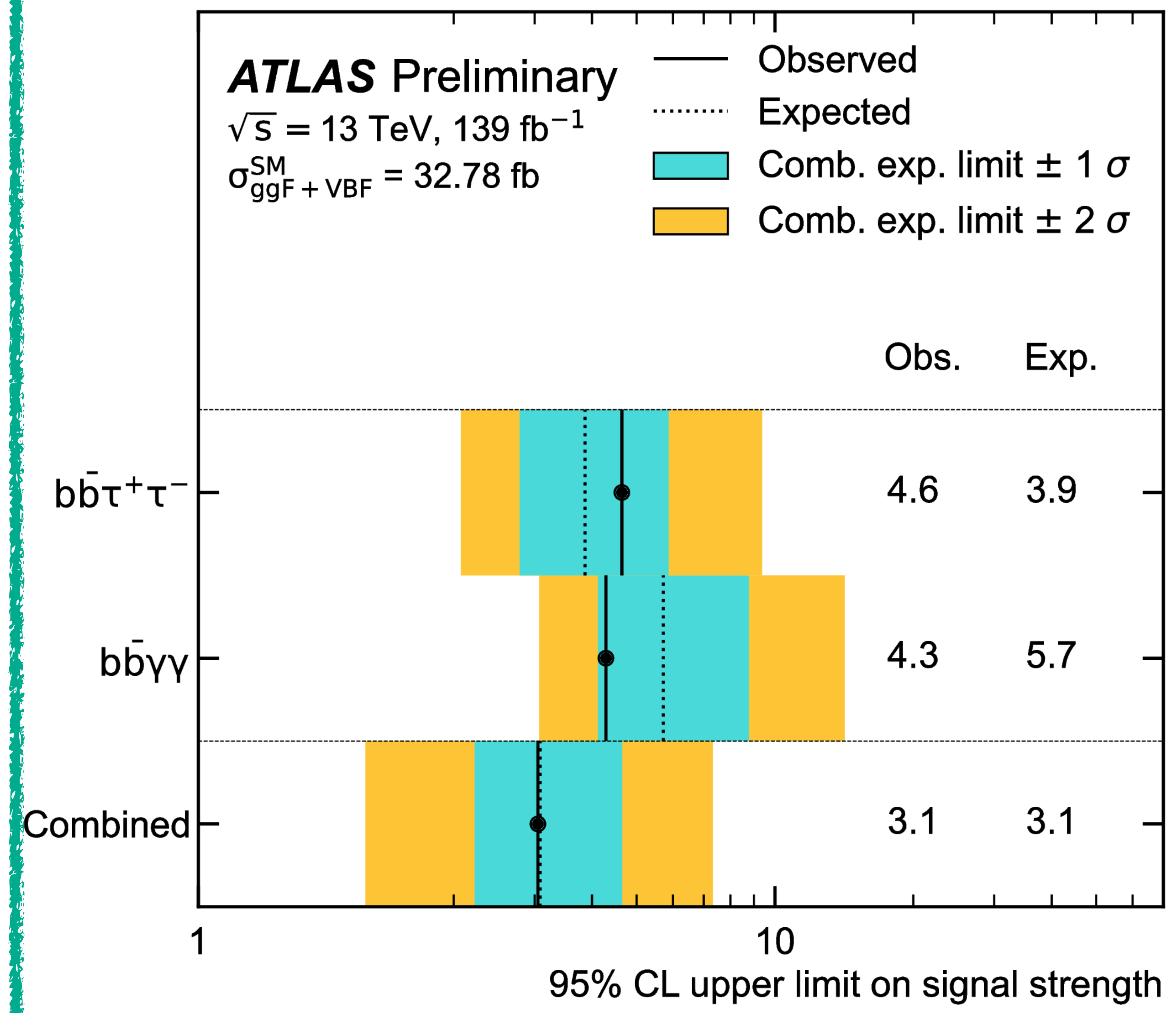
Resonant (Spin-0): bbb, bbγγ and bbττ

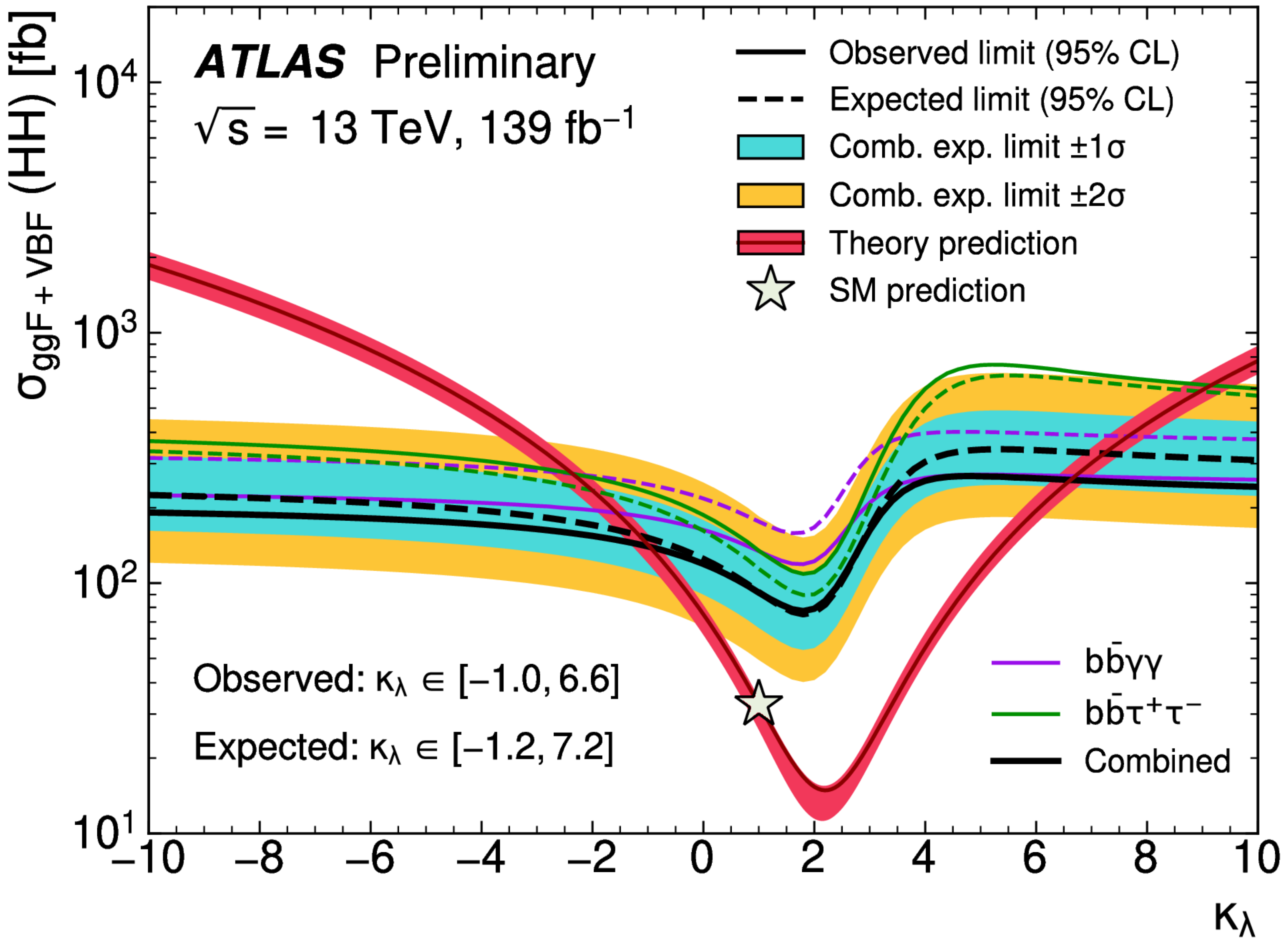




- complementarity between channels allows to obtain optimal exclusion across m_X
- largest excess at m_X = 1.1 TeV: **local (global)** excess of **3.2σ (2.1σ)**

bbγγ and bb**ττ** full Run 2 analyses combination

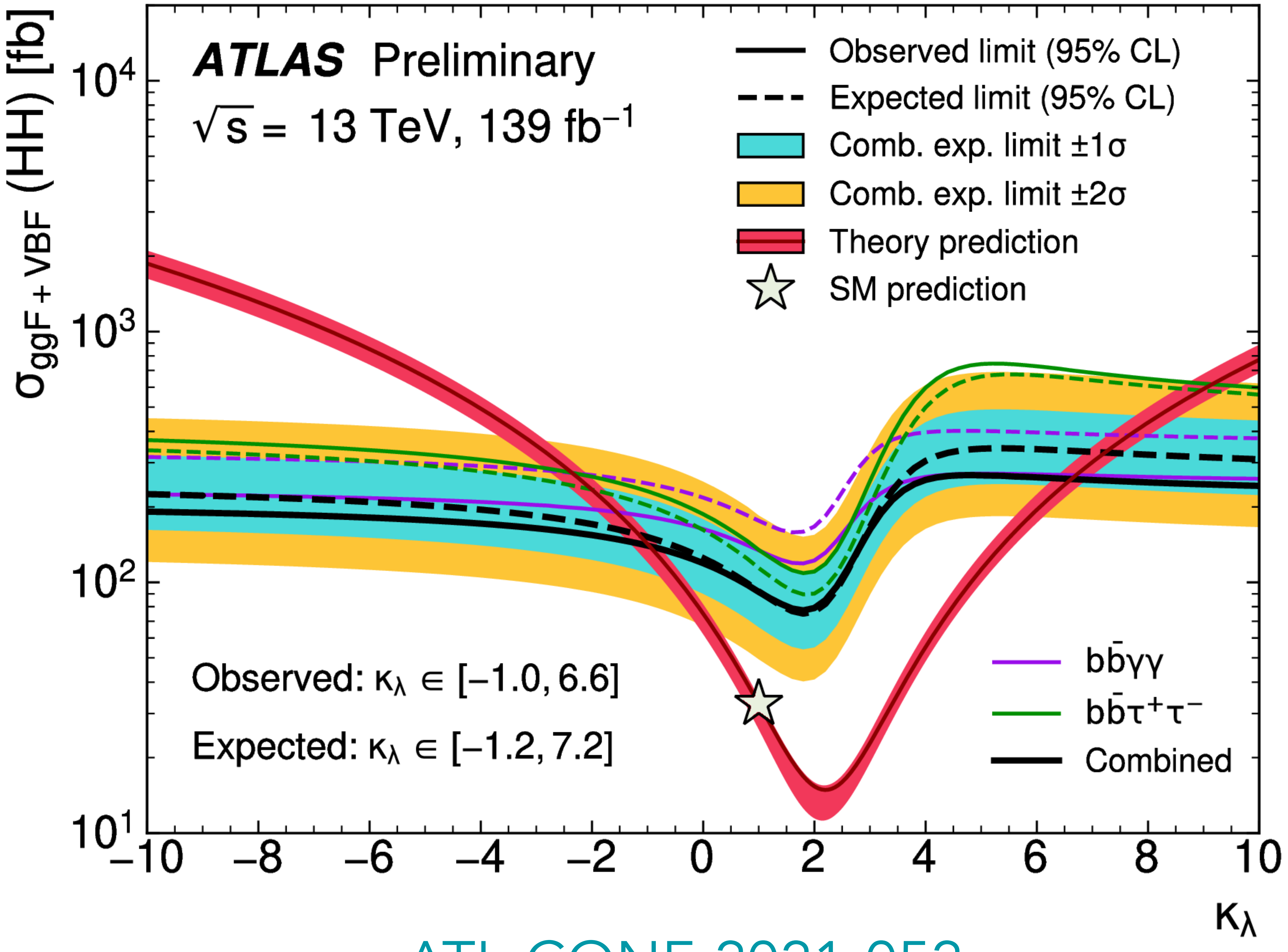




- current most stringent limits on HH signal strength and **κ_λ**
- **obs (exp) 3.1 (3.1) X σ^{SM}_{HH}**
- **obs (exp): -1.0 (-1.2) < κ_λ < 6.6 (7.2)**

Why are EFTs interesting for HH production?

- The Effective Field Theory (EFT) framework can be used as a tool to:
  - make a more general measurement of the Higgs self-coupling
  - explore Beyond-the-Standard-Model scenarios produced at $E >> E_{LHC}$

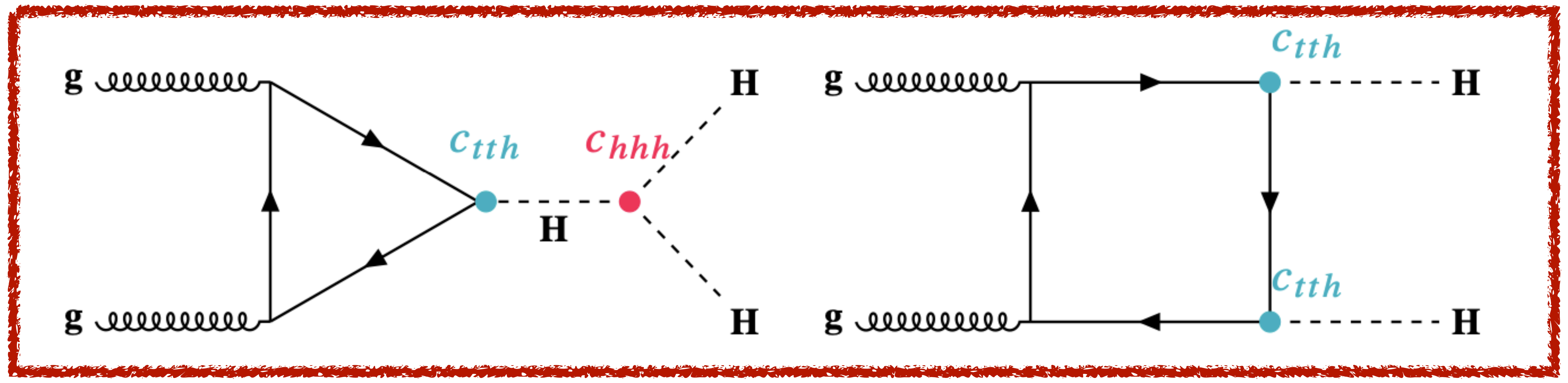


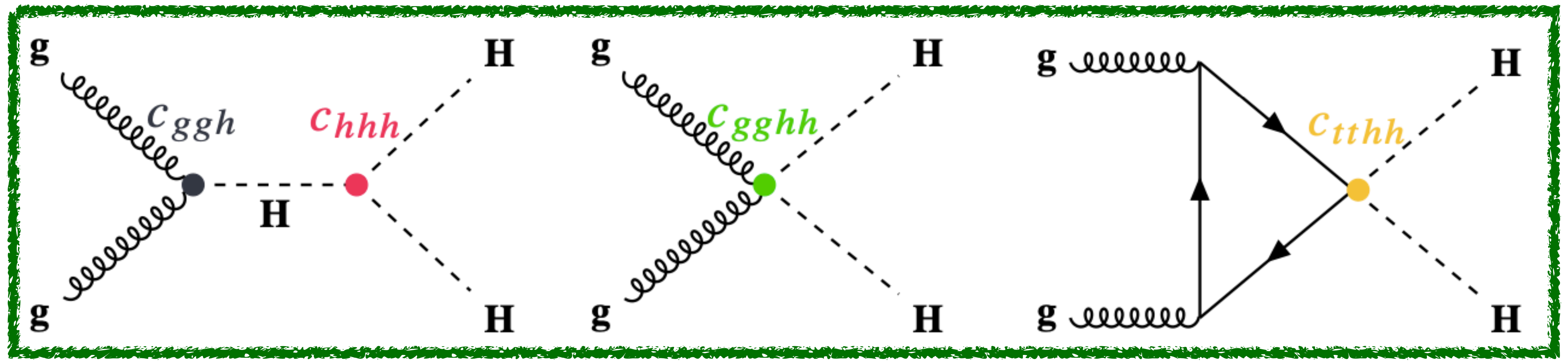
ATL-CONF-2021-052

- HH searches present constraints on $\kappa_\lambda = c_{hhh} / c_{hhh}^{SM}$ while assuming that all other couplings have their SM values (kappa framework)
- Two frameworks are available in HH:
  - Higgs EFT: Higgs is a singlet (more general)
  - SM EFT: Higgs is a doublet (more SM-like)

ggF HH - HEFT interpretation ATL-PHYS-PUB-2022-019

- interpretation of ggF $HH \to bb\tau\tau$ ATLAS Run-2 search in **Higgs EFT framework**
- in the HEFT Lagrangian, ggF HH production is described at LO with 5 operators and their corresponding Wilson coefficients c:

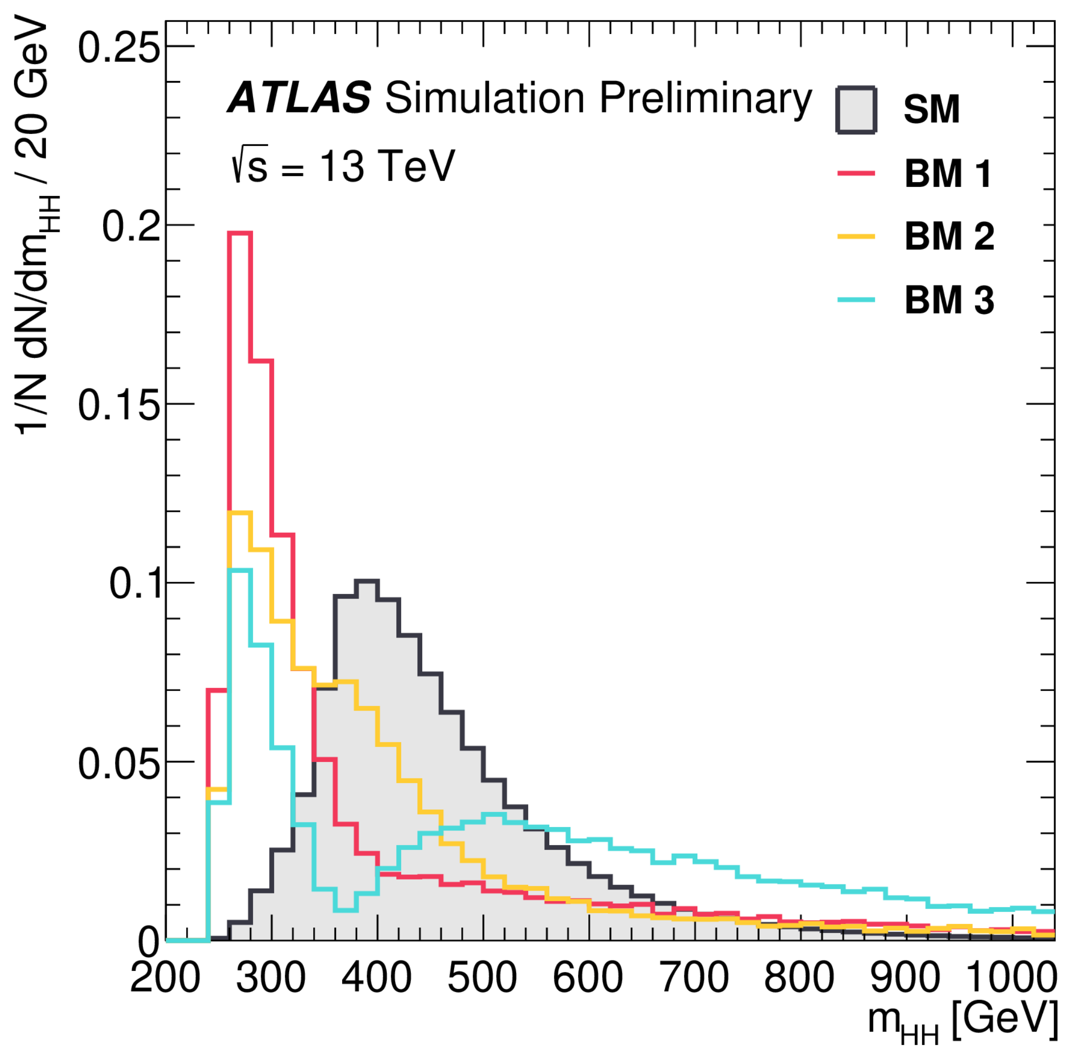


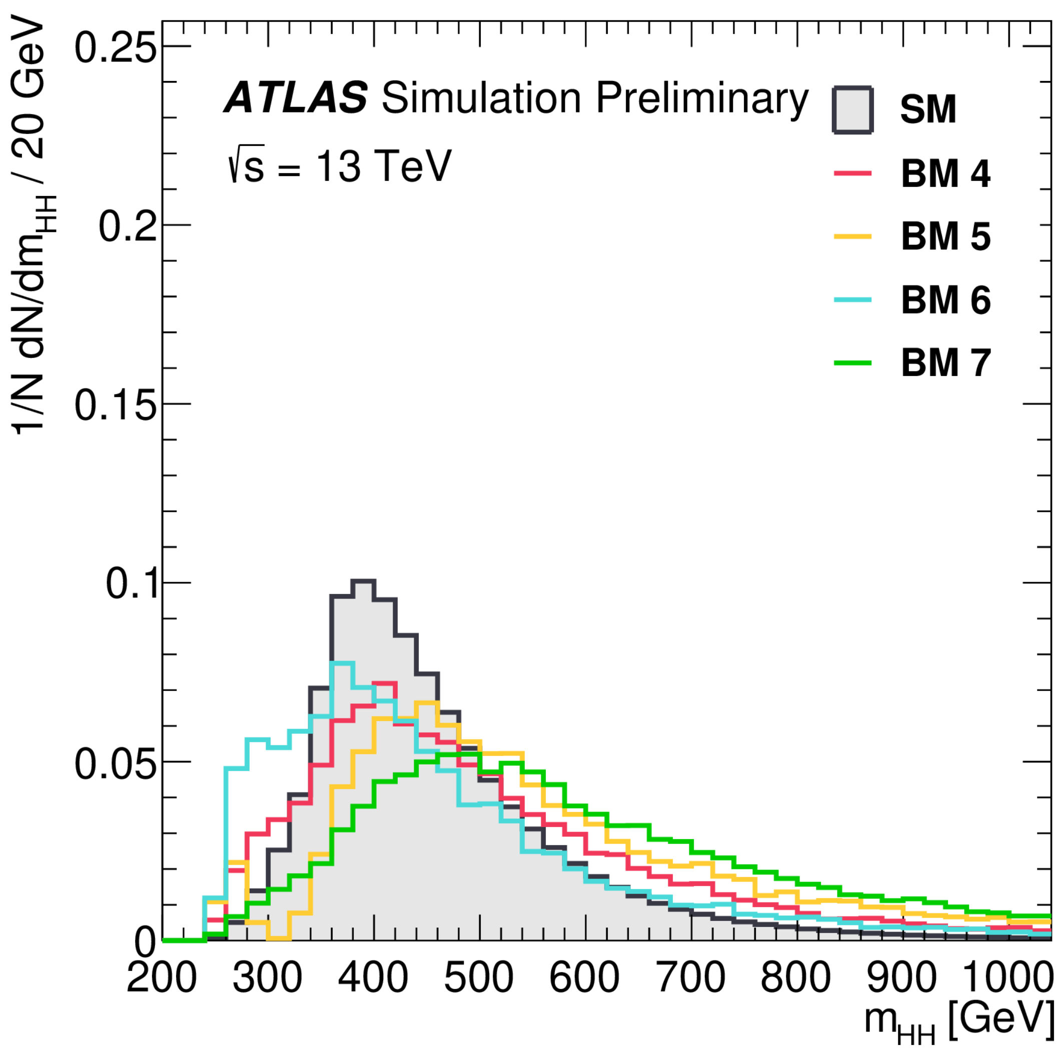


- chhh, ctth, cggh , ctthh, cgghh where chhh = κ_λ and ctth= κ_t
  - smooth transition from kappa framework to EFTs (both contain κ_λ)
  - theorists have suggested a set of 7 benchmarks that fairly represent the different shapes obtained by the variations of chhh, ctth, cggh , ctthh, cgghh in HEFT at NLO.

Benchmark	c_{hhh}	c_{tth}	c_{tthh}	c_{ggh}	c_{gghh}
SM	1	1	0	0	0
BM 1	3.94	0.94	−1/3	0.5	1/3
BM 2	6.84	0.61	1/3	0.0	−1/3
BM 3	2.21	1.05	−1/3	0.5	0.5
BM 4	2.79	0.61	1/3	−0.5	1/6
BM 5	3.95	1.17	−1/3	1/6	−0.5
BM 6	5.68	0.83	1/3	−0.5	1/3
BM 7	−0.10	0.94	1	1/6	−1/6

reweighting of SM and HEFT samples to obtain m_{HH} shape

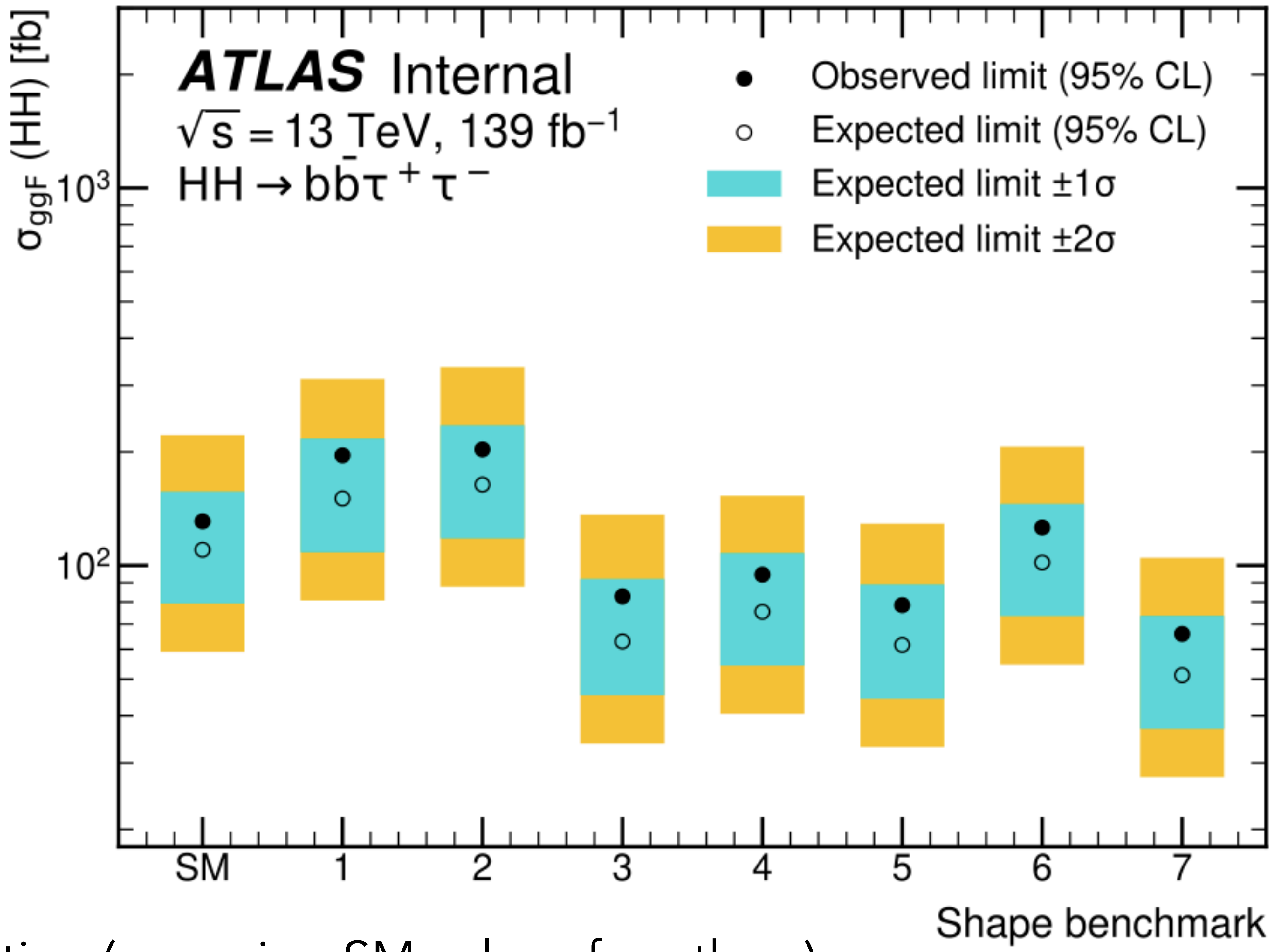




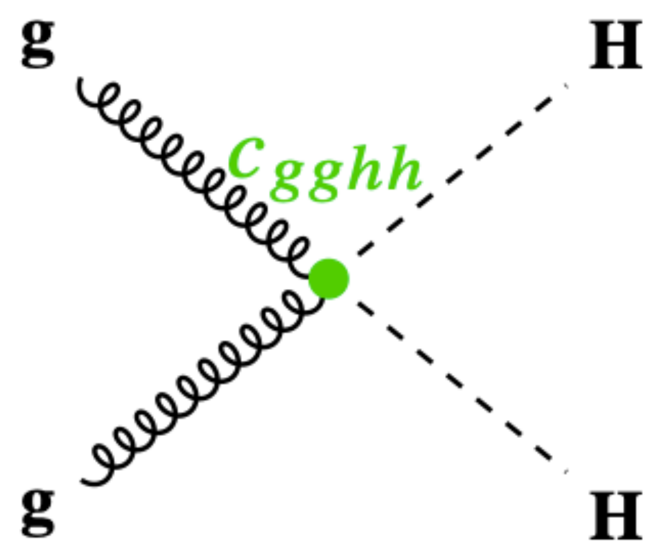
Results - III

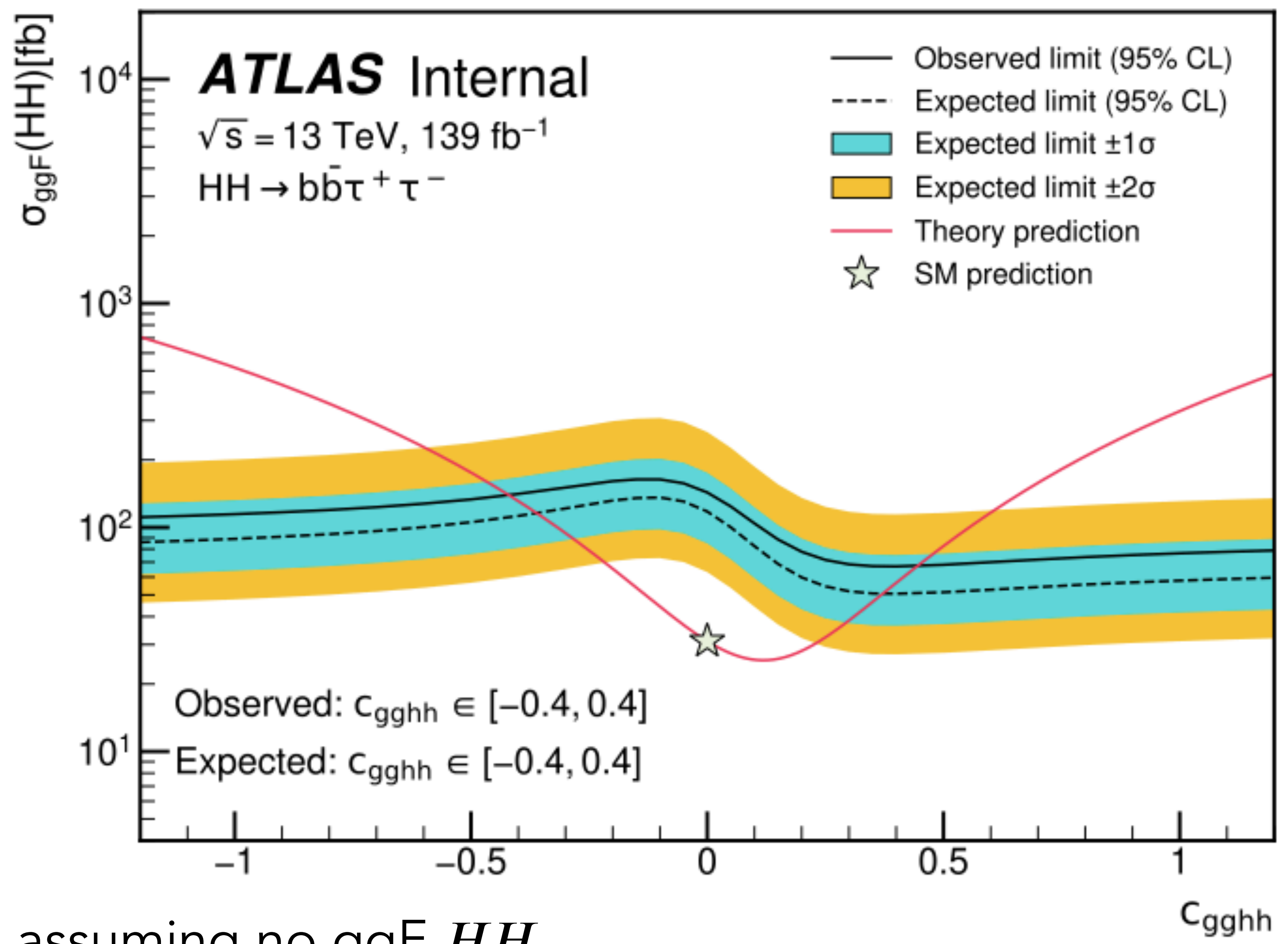
ATL-PHYS-PUB-2022-019

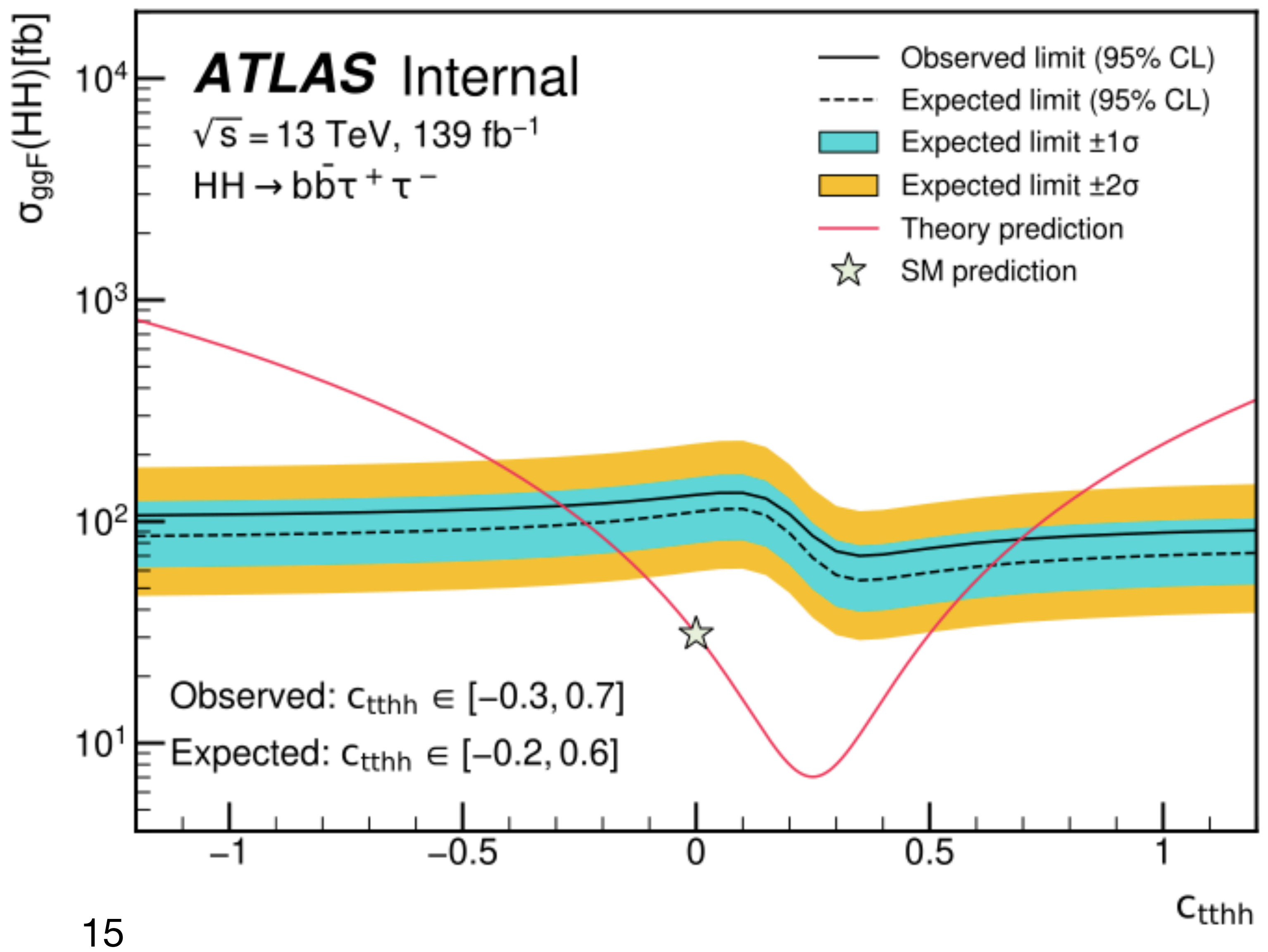
	95% CL upper limit on ggF HH cross-section [fb]					
Benchmark	Obs.	-2σ	-1σ	Exp.	$+1\sigma$	$+2\sigma$
SM	130.9	59.1	79.3	110.1	156.9	221.4
BM 1	195.8	80.8	108.4	150.5	216.9	312.0
BM 2	203.1	87.9	118.0	163.7	235.0	335.5
BM 3	82.8	33.8	45.3	62.9	92.1	136.3
BM 4	94.6	40.5	54.4	75.4	107.9	153.0
BM 5	78.5	33.1	44.4	61.6	89.1	129.1
BM 6	126.1	54.7	73.4	101.8	145.6	206.4
BM 7	65.9	27.5	36.9	51.2	73.5	104.8

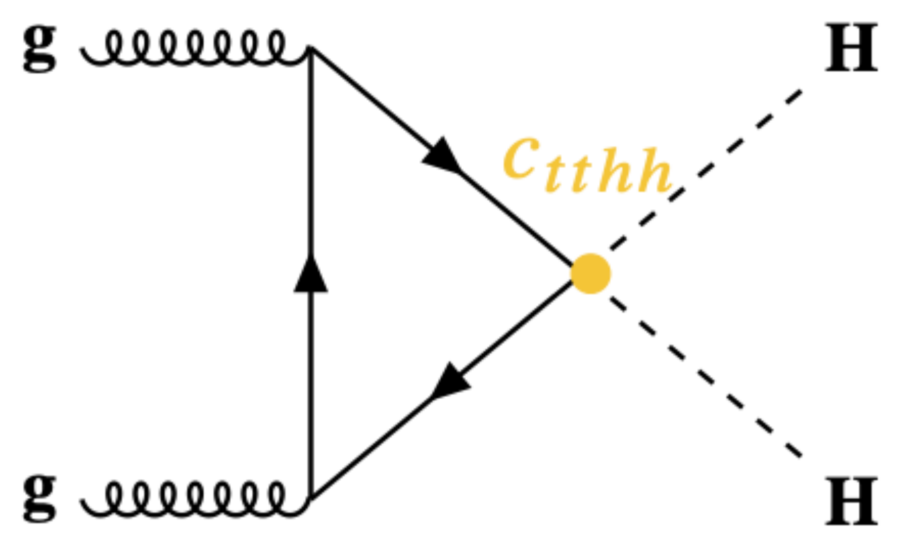


Scan sensitive BSM coefficients to HH production (assuming SM values for others)







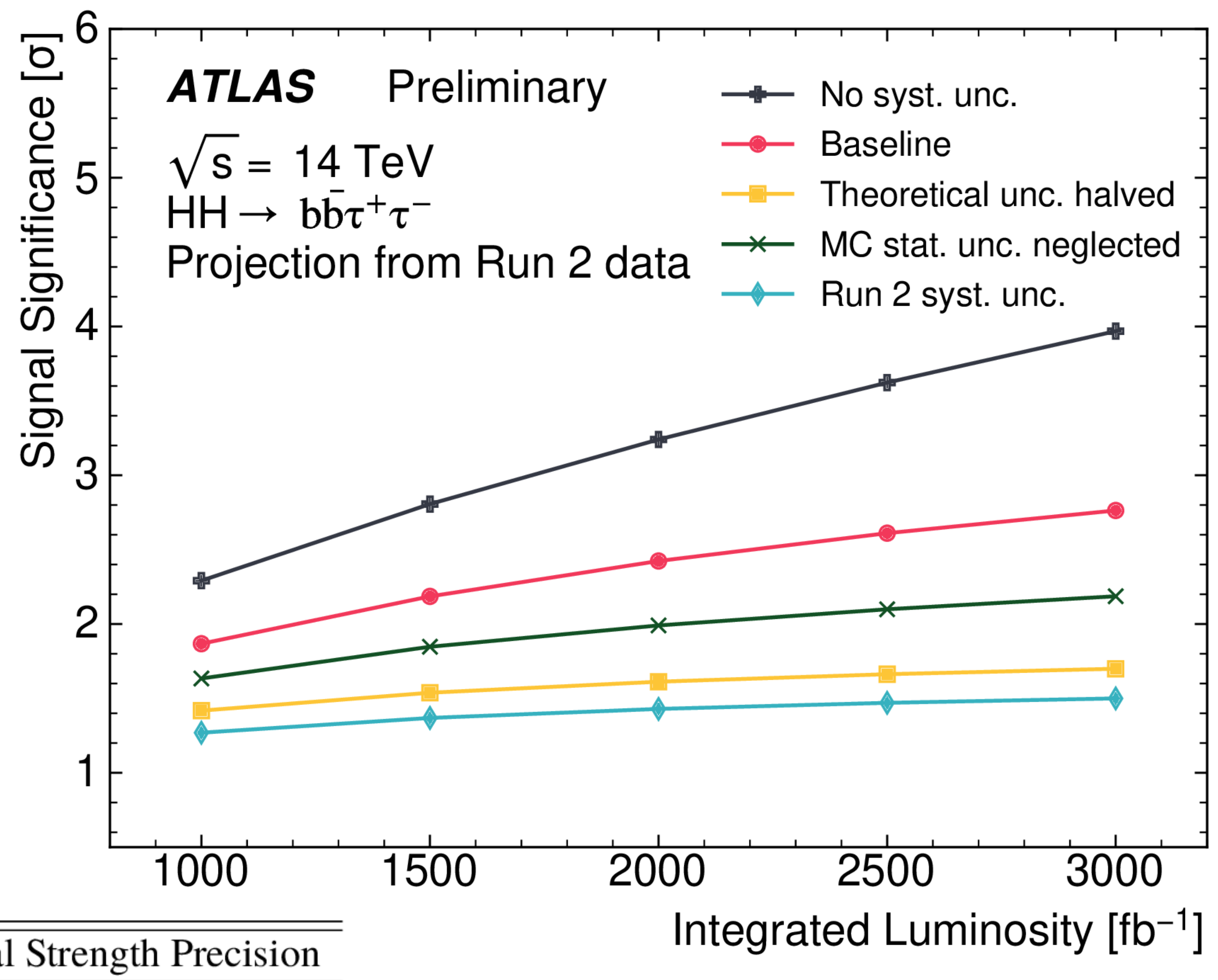


theory prediction curve represents the scenario where all Wilson coefficients are set to their SM values except for one under study.

expected limits are obtained assuming no ggF HH

HH→ bbττ @ HL-LHC

ATL-PHYS-PUB-2021-044

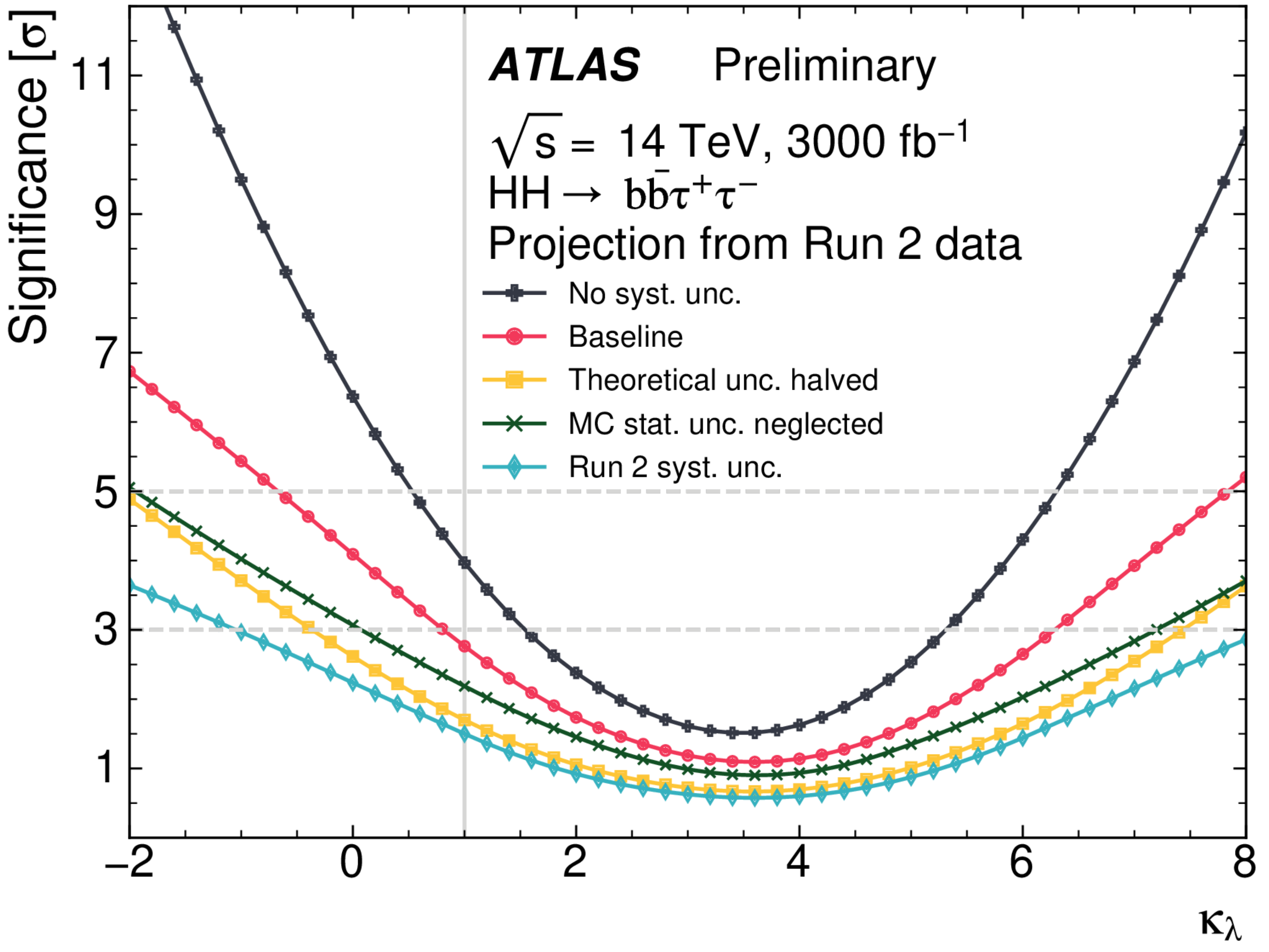


- assumptions for systematic uncertainties in different scenarios:
  - **no systematic uncertainties**
  - **baseline:** halved theoretical uncertainties + scaled Run 2 systematic uncertainties
  - **Run 2 systematic uncertainties**
  - **MC stat uncertainties neglected**
  - **halved theoretical uncertainties**

Uncertainty Scenario	95% CL Upper Limit	Significance [σ]	Signal Strength Precision
No syst. unc.	0.49	4.0	0.27
Baseline	0.71	2.8	0.39
Run 2 syst. unc.	1.37	1.5	0.69
MC stat. unc. neglected	0.99	2.2	0.51
Theoretical unc. halved	1.07	1.7	0.58

- new triggers, increased pile-up level, and detector upgrades effects not considered

- signal significance above the background only hypothesis in the **baseline** scenario:
  - **evidence** (> 3 σ) for HH production if $\kappa\lambda$ **< 0.8** or $\kappa\lambda$ **> 6.3**
  - **observation** (> 5 σ) for HH production if $\kappa\lambda$ **< –0.6 or** $\kappa\lambda$ **> 7.8**



Summary

- Strong *HH* → bb**ττ** results with 139 fb^{-1} ATLAS data
    - **non-resonant**: obs (exp) 4.7 (3.9) x SM
    - **resonant**: obs (exp) 23 - 920 fb (12 - 840 fb) with excess @ 1 TeV with global significance of **2.0σ**
    - obs (exp) $\boldsymbol{\kappa_\lambda}$ excluded outside the interval [-2.4, 9.2] ([-2.0,9.0])
    - **HEFT benchmarks:** observed (expected) 95% CL intervals:
        - $-0.4 < c_{gghh} < 0.4$ ($-0.4 < c_{gghh} < 0.4$) and $-0.3 < c_{tthh} < 0.7$ ($-0.2 < c_{tthh} < 0.6$)
- **Factor 4 improvement** compared to 36 fb^{-1}
    - 50% due to luminosity increase
    - 50% due to improved $\boldsymbol{\tau}_{had}$ and b-jet reconstruction and identification and analysis-level improvements
- HH→ bb**ττ** @ HL-LHC projection studies:
    - **HH signal significance** with (without) baseline systematic uncertainties: **2.8σ** (**4.0σ**)
    - **observation** for **HH production** with baseline systematic uncertainties if $\kappa\lambda$ **< –0.6 or** $\kappa\lambda$ **> 7.8**