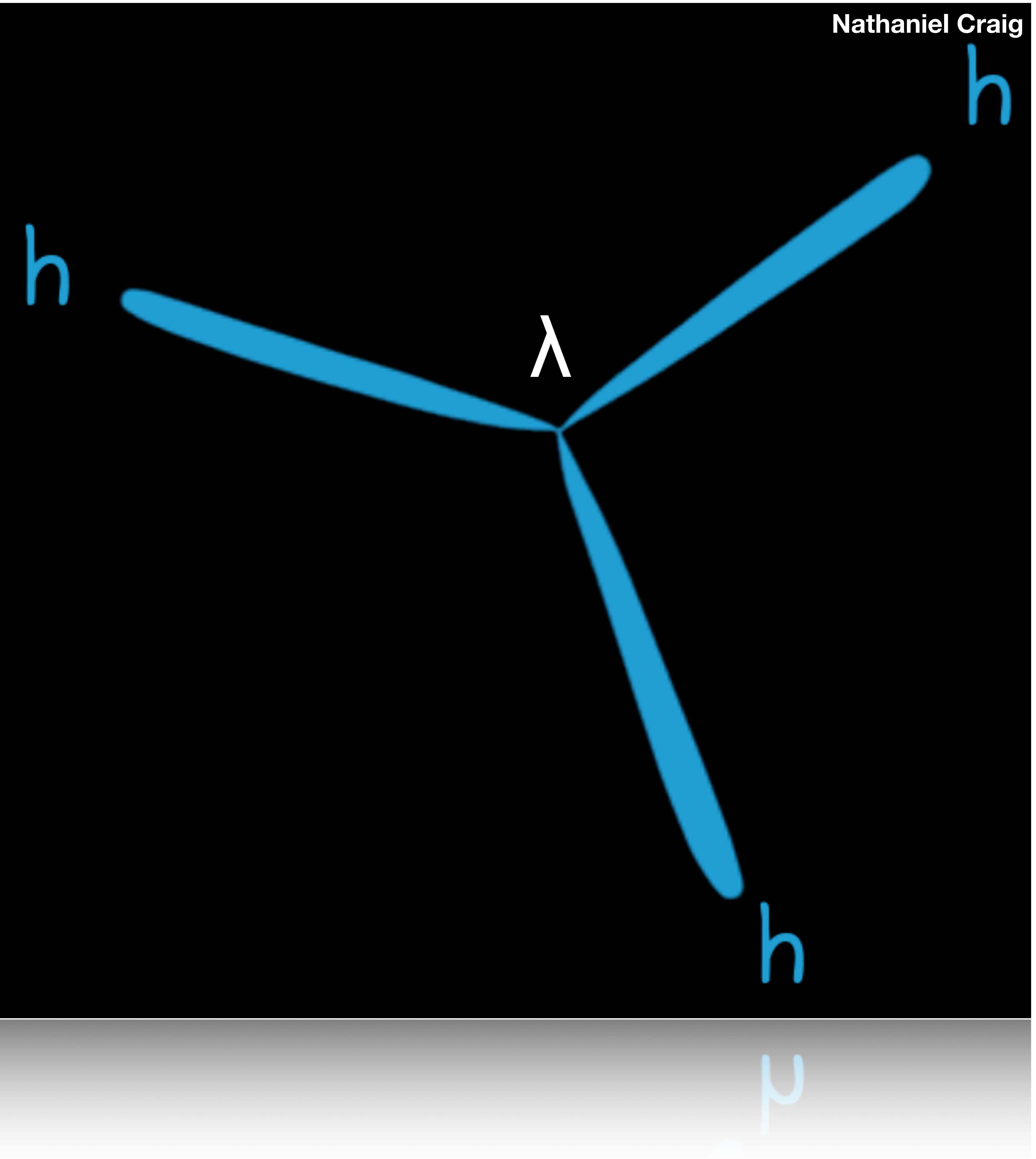
Probing the Higgs self-coupling with the ATLAS detector

Elementary Particle Physics Seminar, University of Warwick

Xiaohu SUN (孙小虎)
University of Manchester
February 6, 2019

Contents



The Higgs boson

Discovered in summer 2012

125.09 GeV, 0 charge, 0 spin

The SM predicts its **self-interacting**

Very unique feature

Not like any other massive particle

Can we probe it at the LHC? 🔎

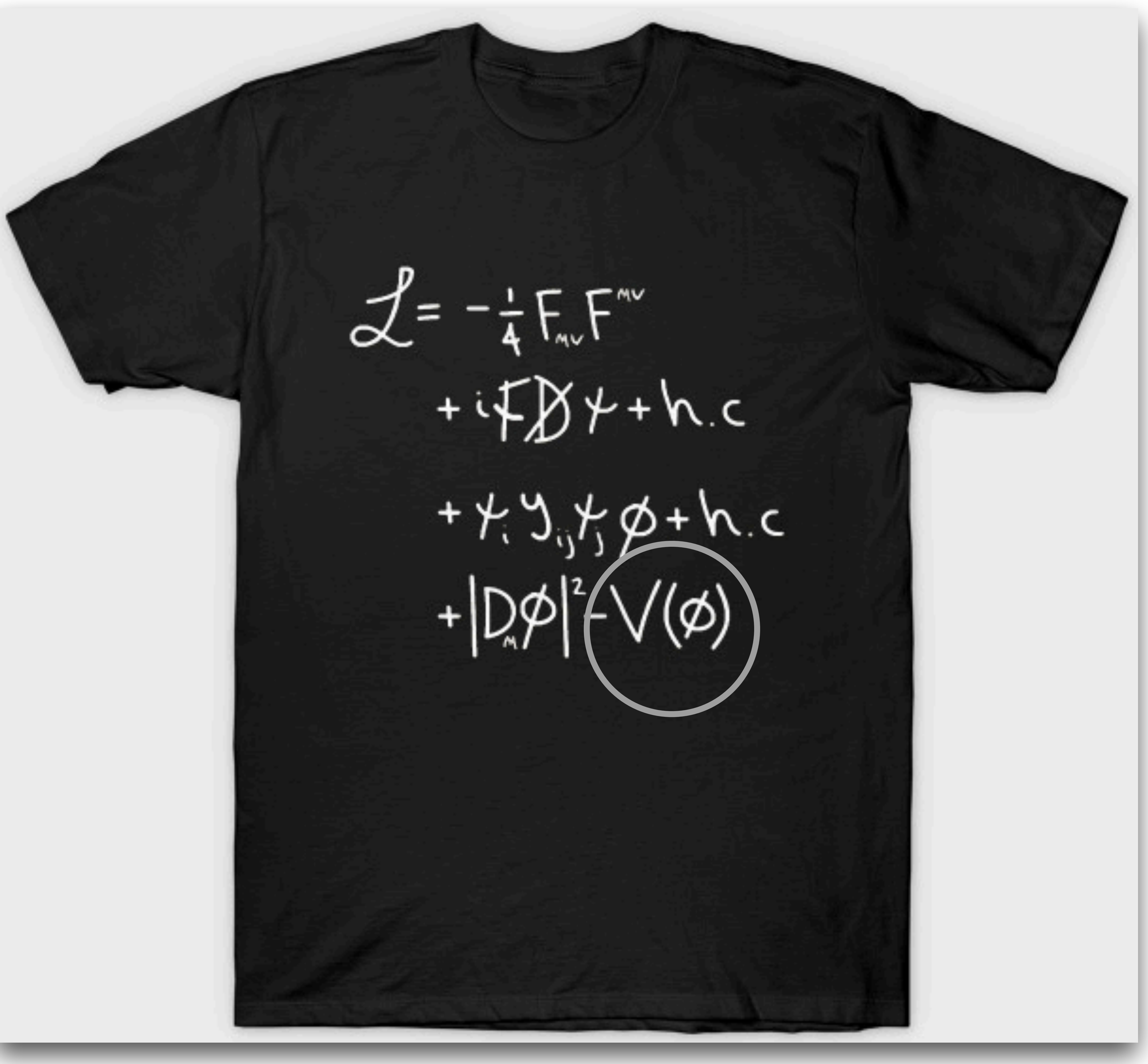
Direct probe

- Double Higgs (di-Higgs) production

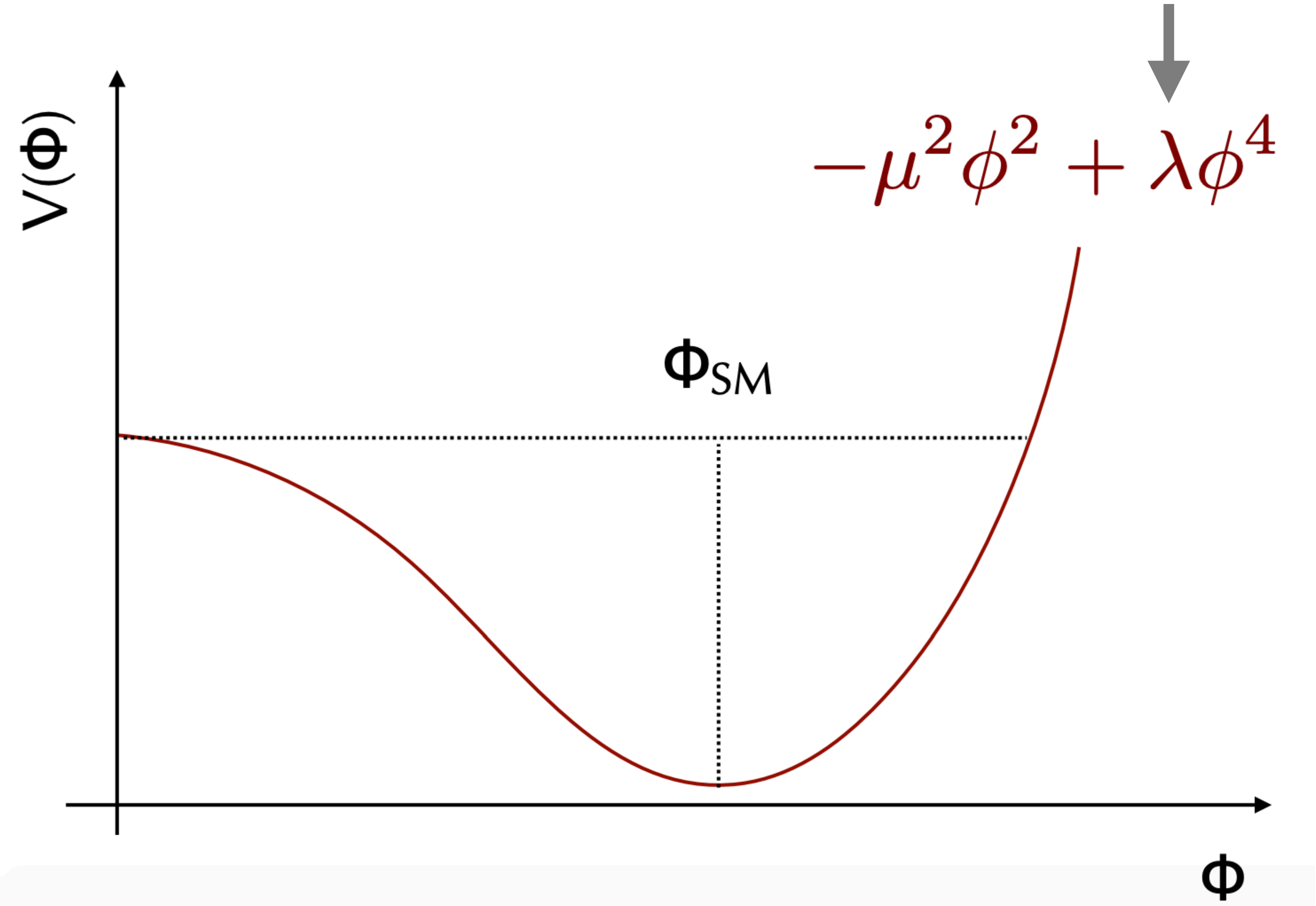
Indirect probe

- Single Higgs production with EWK correction

The Standard Model



- Force carriers γ,W,Z,g, all discovered
- Fermion interactions, largely measured
- Yukawa couplings that determine fermion masses, largely discovered and measured
- Higgs kinematic: WZ masses, all measured
- Higgs potential: <u>Higgs self-coupling</u>, **not yet!**

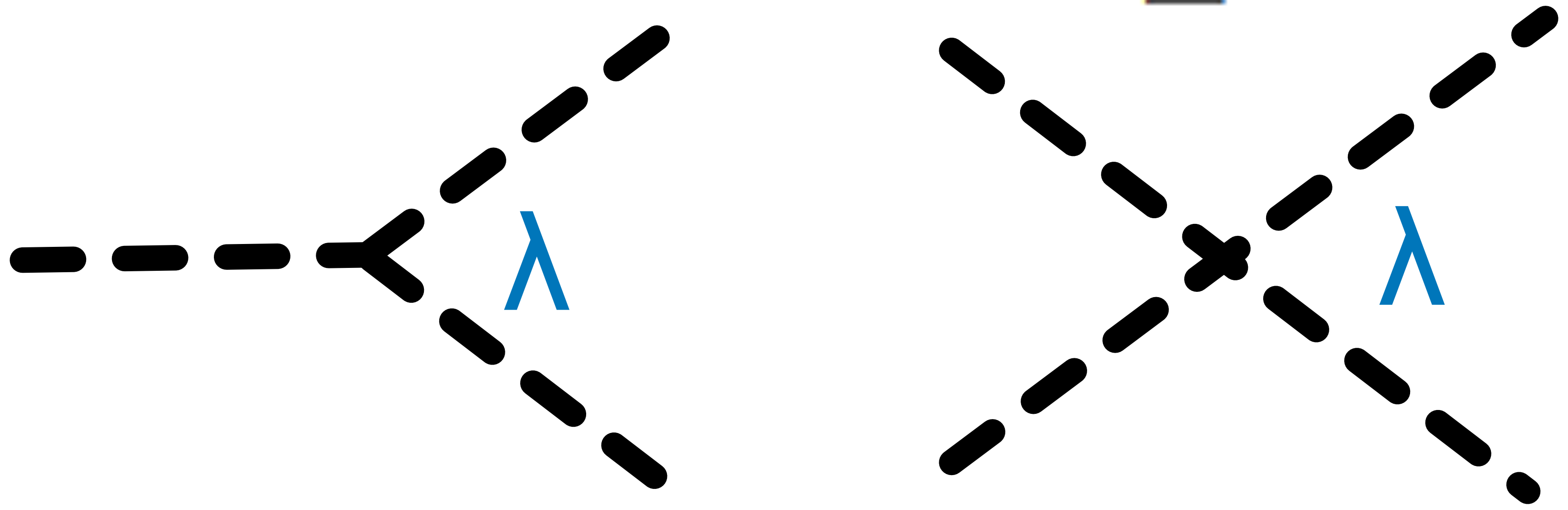


The Higgs potential

After EWSB Higgs potential becomes

$$\lambda v^2 h^2 + \lambda v h^3 + \frac{\lambda}{4} h^4$$

Higgs mass



Higgs self-coupling λ: Double Higgs Triple Higgs or Higgs scattering

pp→HH is the first accessible production mode to probe Higgs self-coupling λ at the LHC

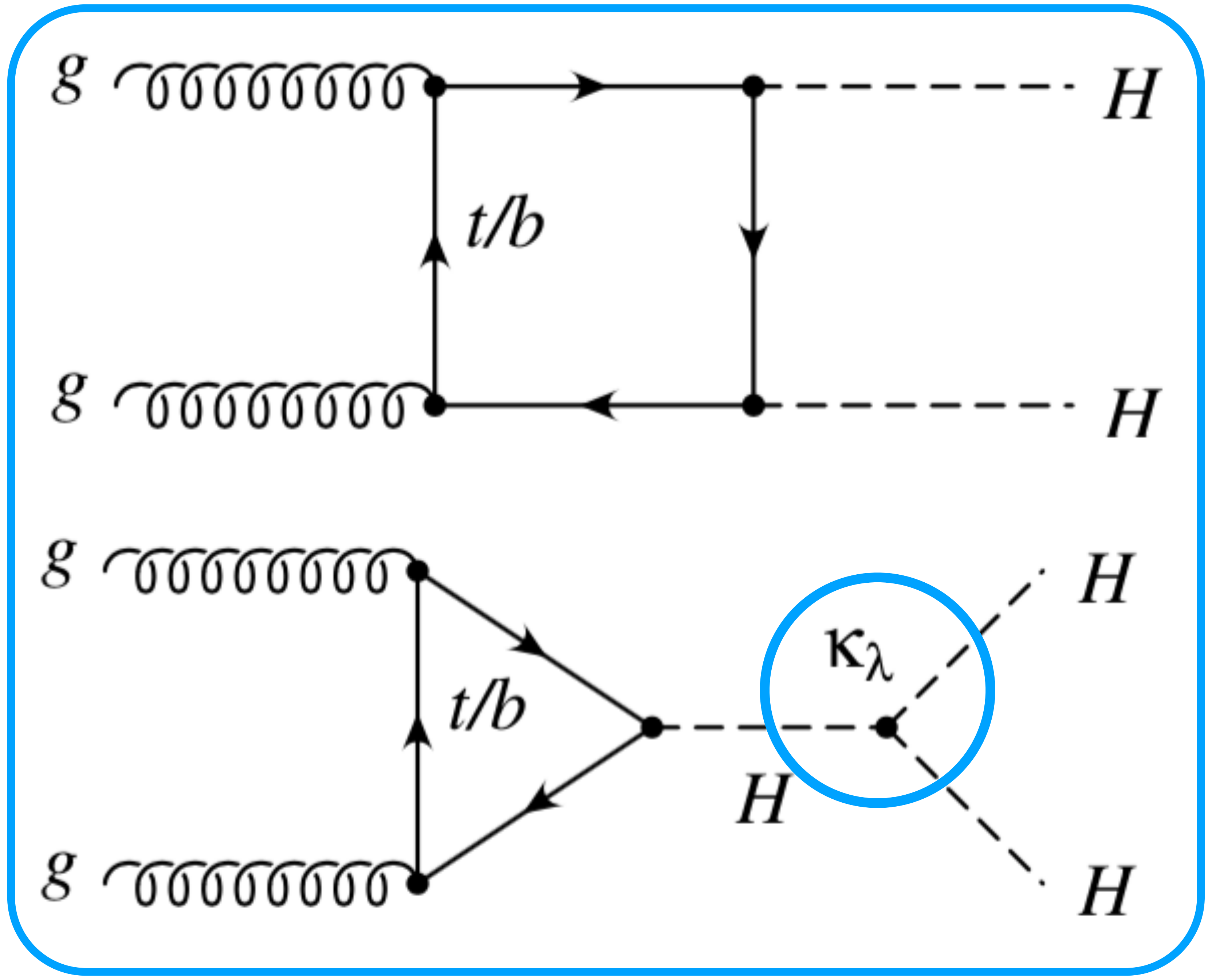
In practice, one only needs to measure the relative value κ_λ

Thus, if measurement agrees SM, then $\kappa_\lambda \sim 1$

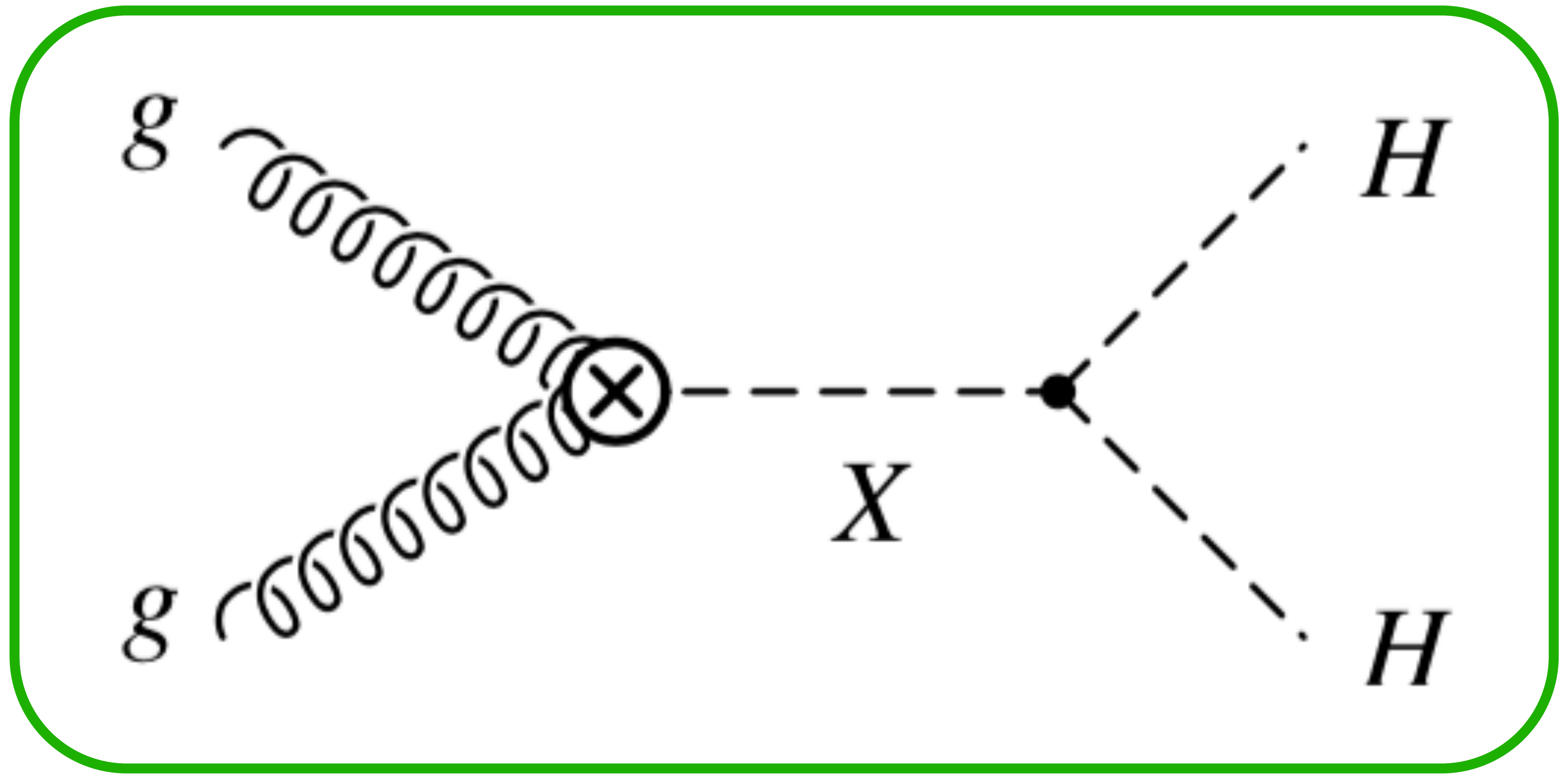
$$\kappa_\lambda = \frac{\lambda_{\text{measured}}}{\lambda_{\text{SM}}}$$

Di-Higgs

- Standard Model (SM) **non-resonant** di-Higgs (HH) allows to directly probe Higgs self-coupling κ_λ (=$\lambda_3/\lambda_{3,SM}$), study the Higgs potential structure

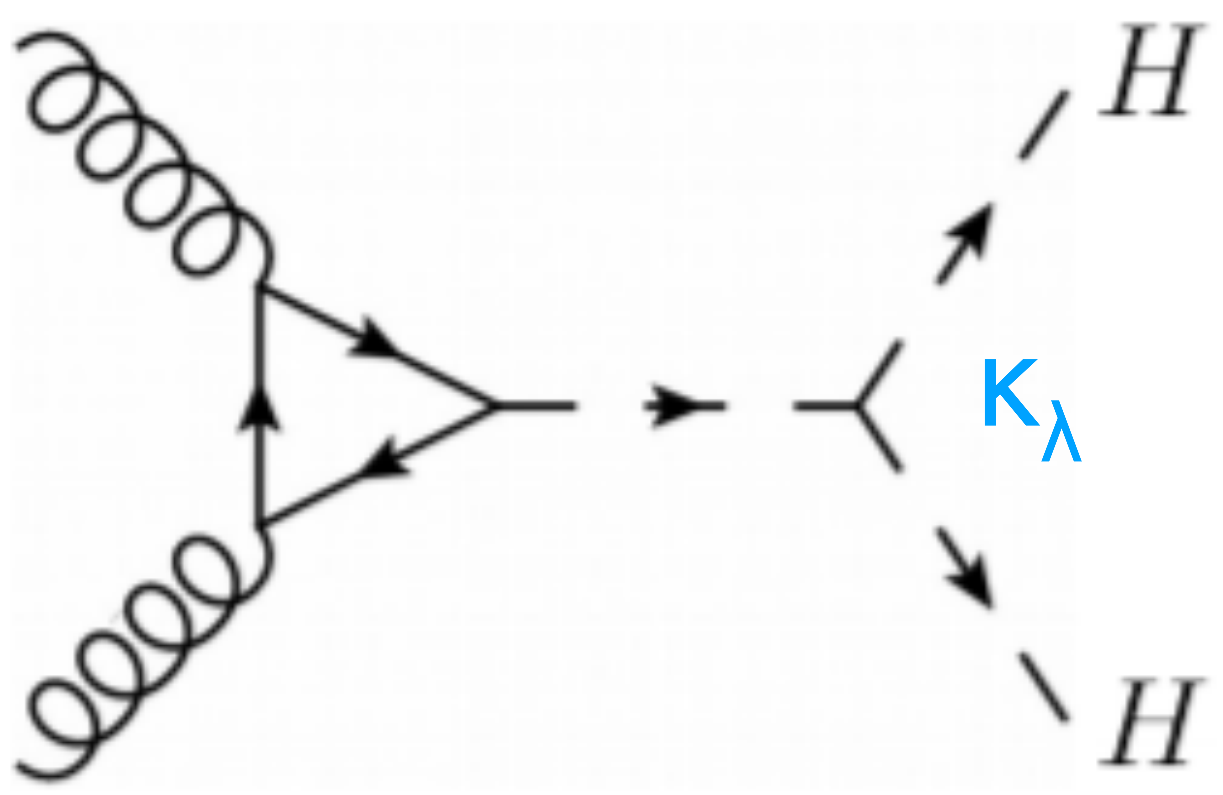


- BSM **resonant** di-Higgs originates from a heavy Higgs or graviton (EWK singlet, MSSM, 2HDM, RS KK graviton models etc.)

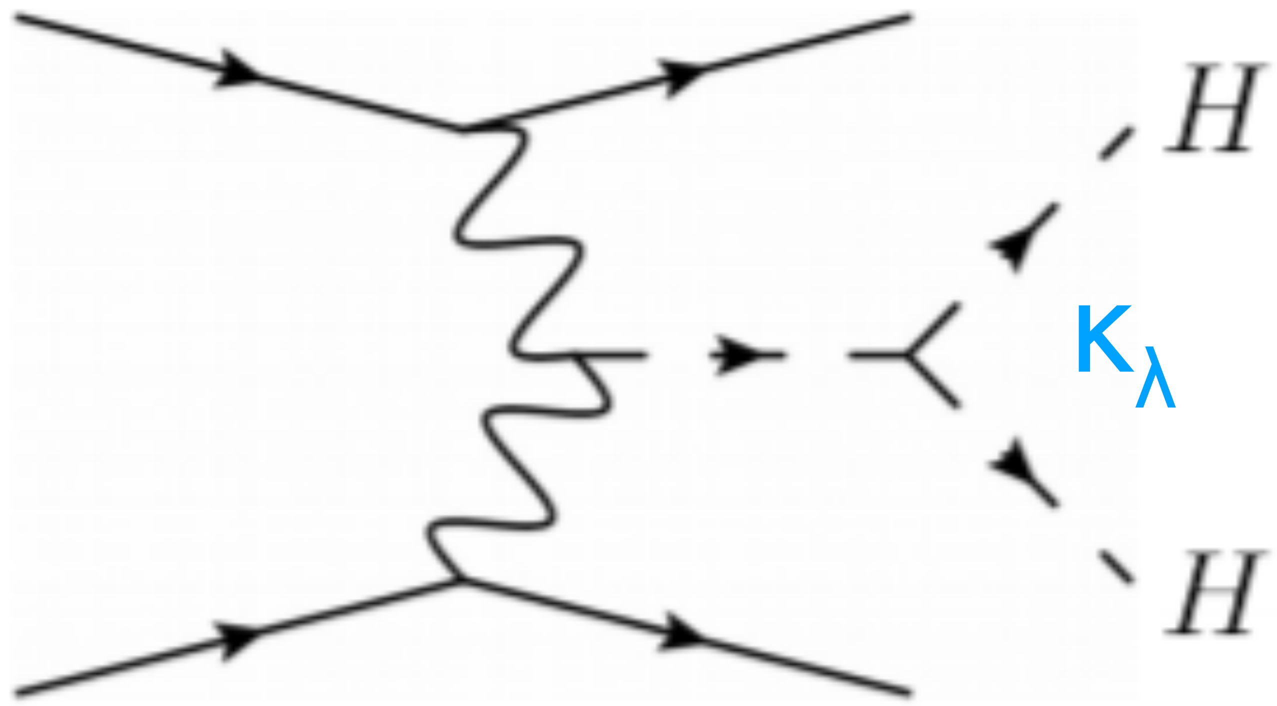


Di-Higgs production modes

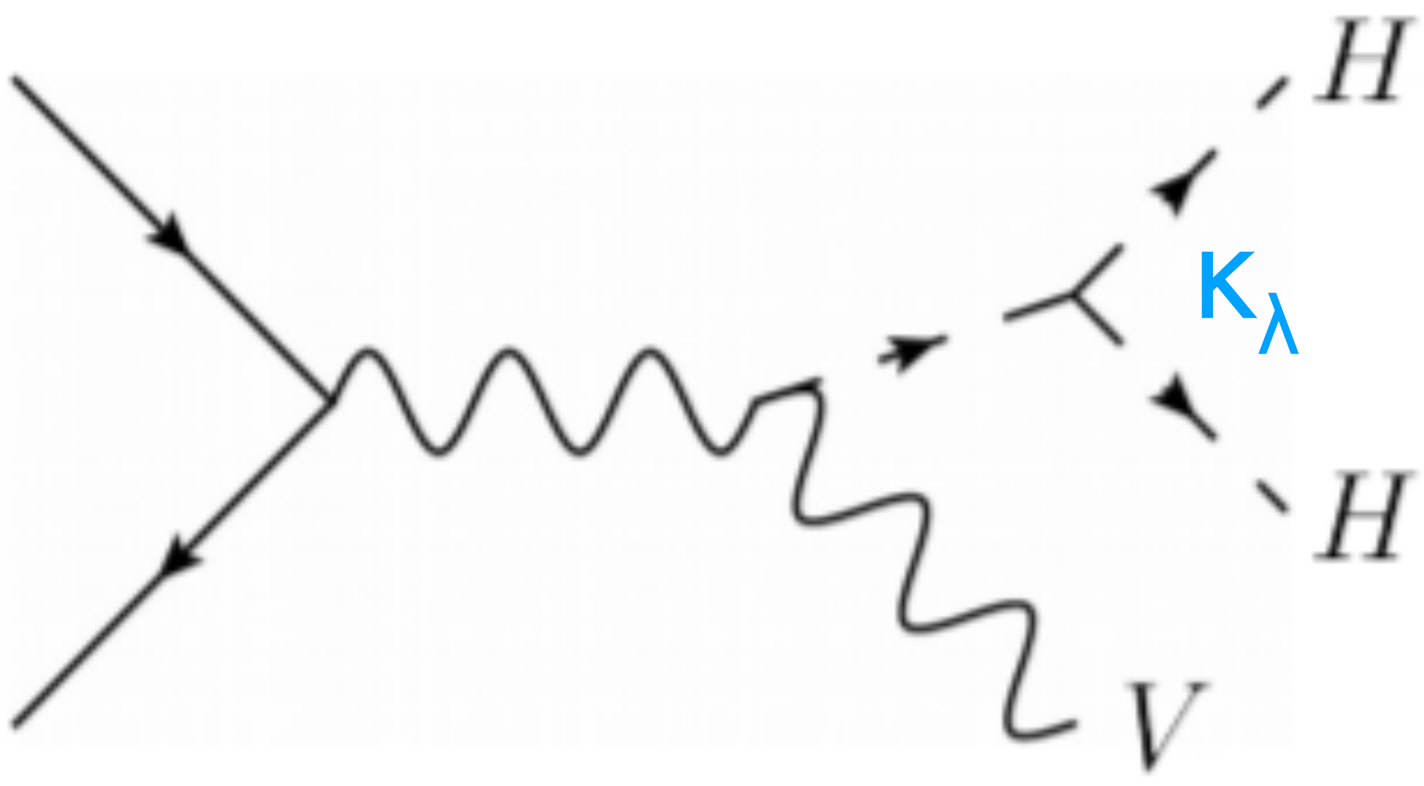
Gluon fusion



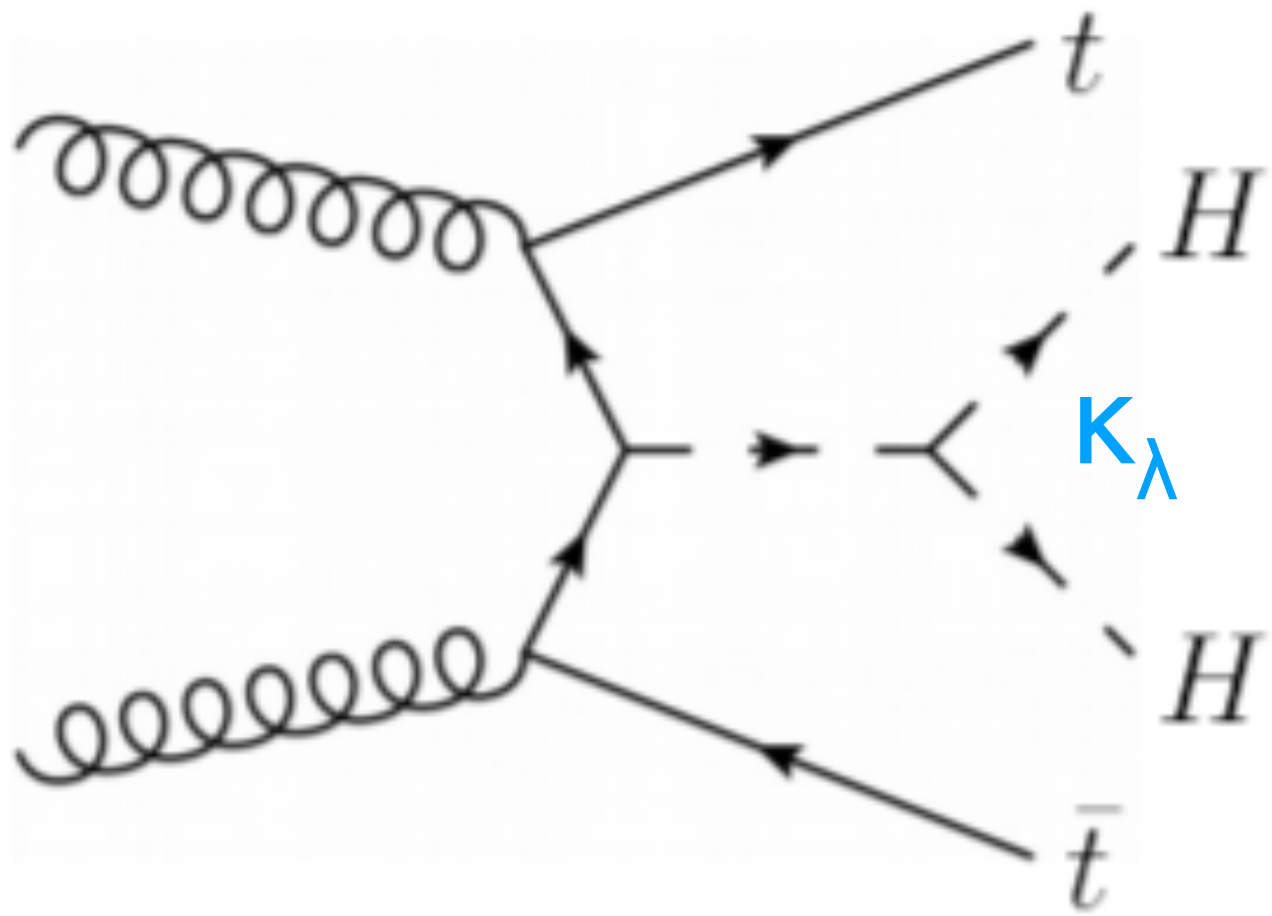
Vector boson fusion



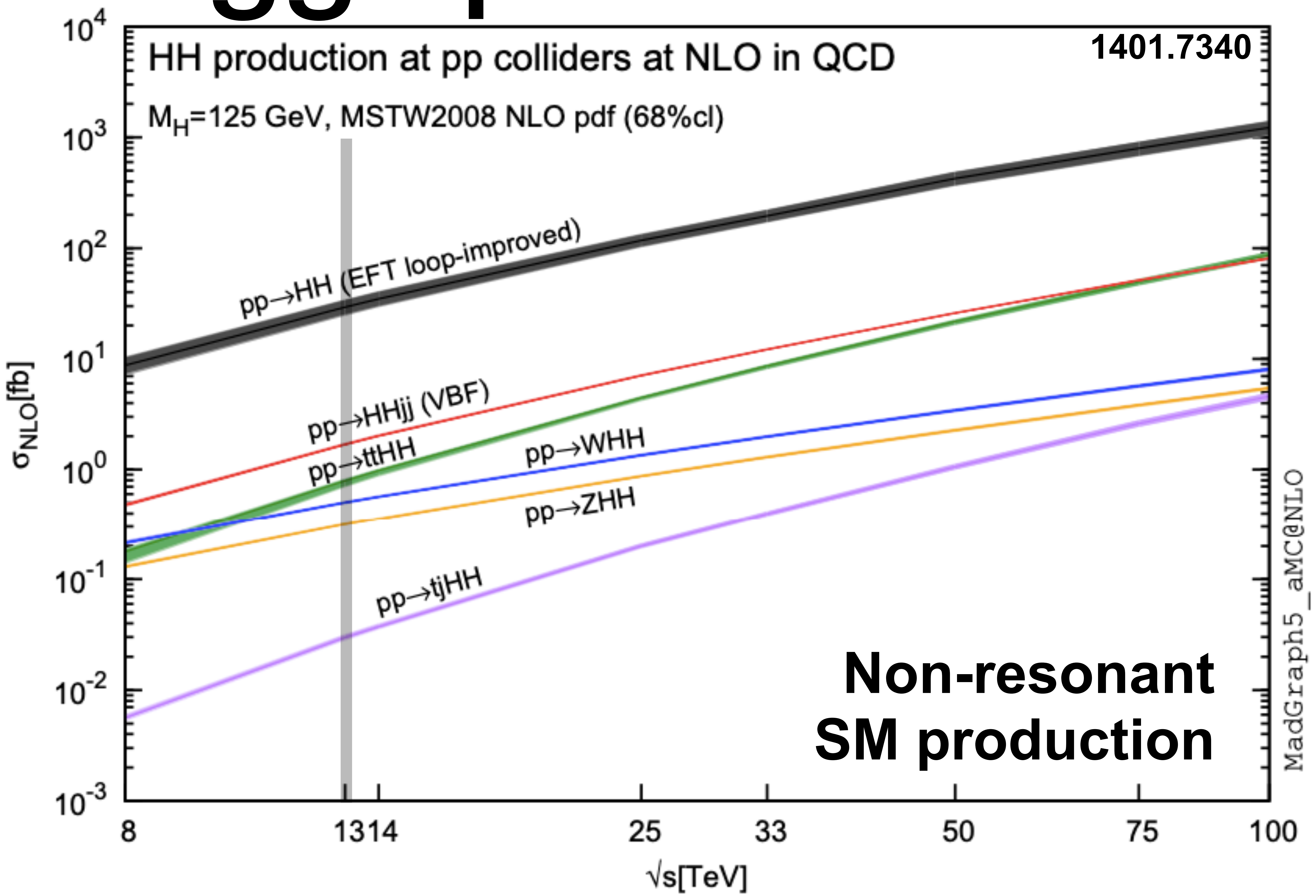
Higgs–strahlung



Top associated

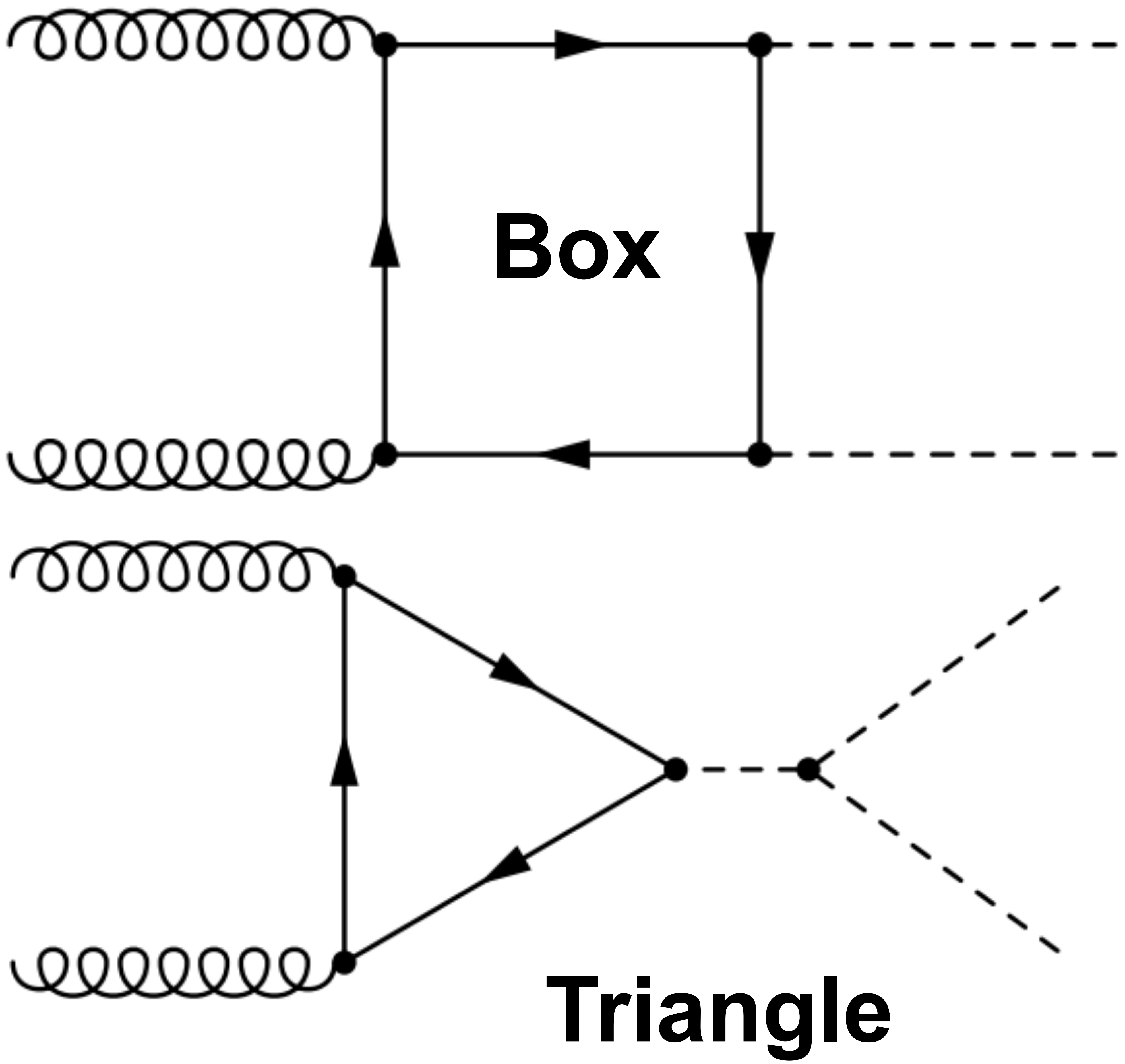


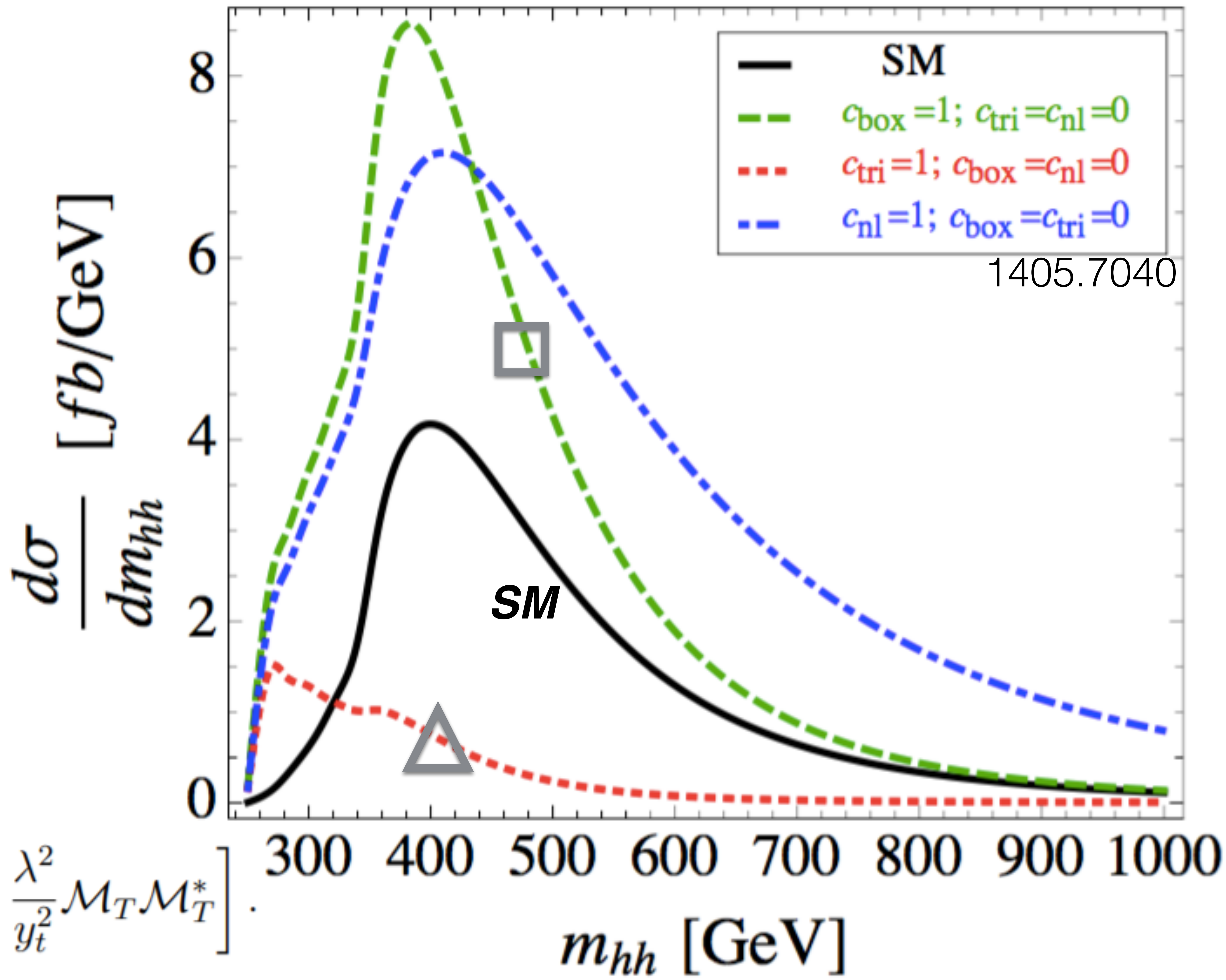
Di-Higgs production rates



ggF is the leading HH production, but its cross-section is still 3 orders of magnitude smaller than single Higgs production, still challenging!

The destructive interference





$$|\mathcal{M}|^2 = y_t^4 \left[\mathcal{M}_B\mathcal{M}_B^* + \frac{\lambda}{y_t}(\mathcal{M}_B\mathcal{M}_T^* + \mathcal{M}_T\mathcal{M}_B^*) + \frac{\lambda^2}{y_t^2}\mathcal{M}_T\mathcal{M}_T^*\right].$$

The decays

$(H\to bb,\ H\to WW,\ H\to ZZ,\ H\to tautau,\ H\to \gamma\gamma,\ \ldots)^2$

$= HH\to bbbb,\ HH\to WWWW,\ HH\to ZZZZ,\ \ldots,$

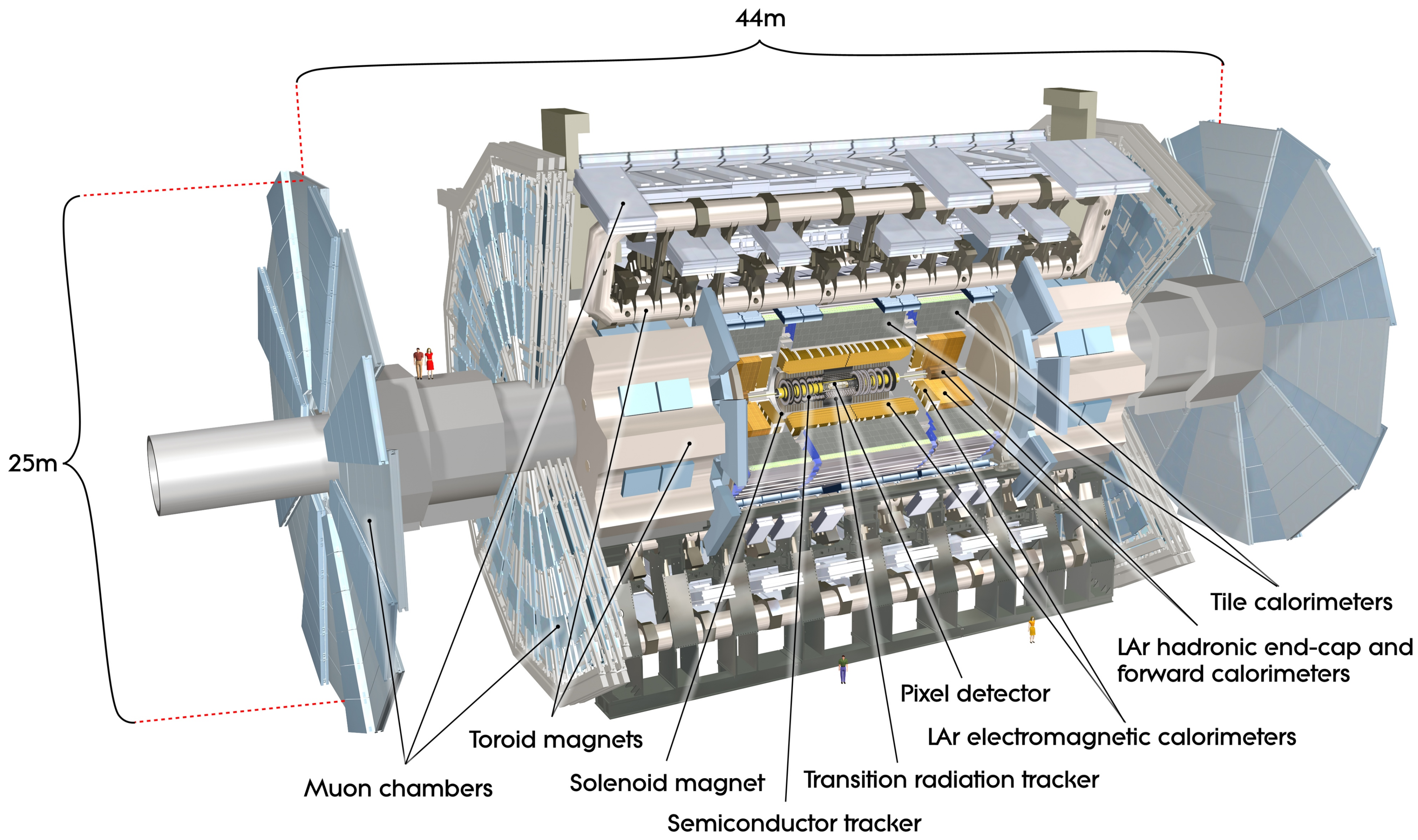
$HH\to bbtautau,\ HH\to bb\gamma\gamma,\ \ldots,$

…

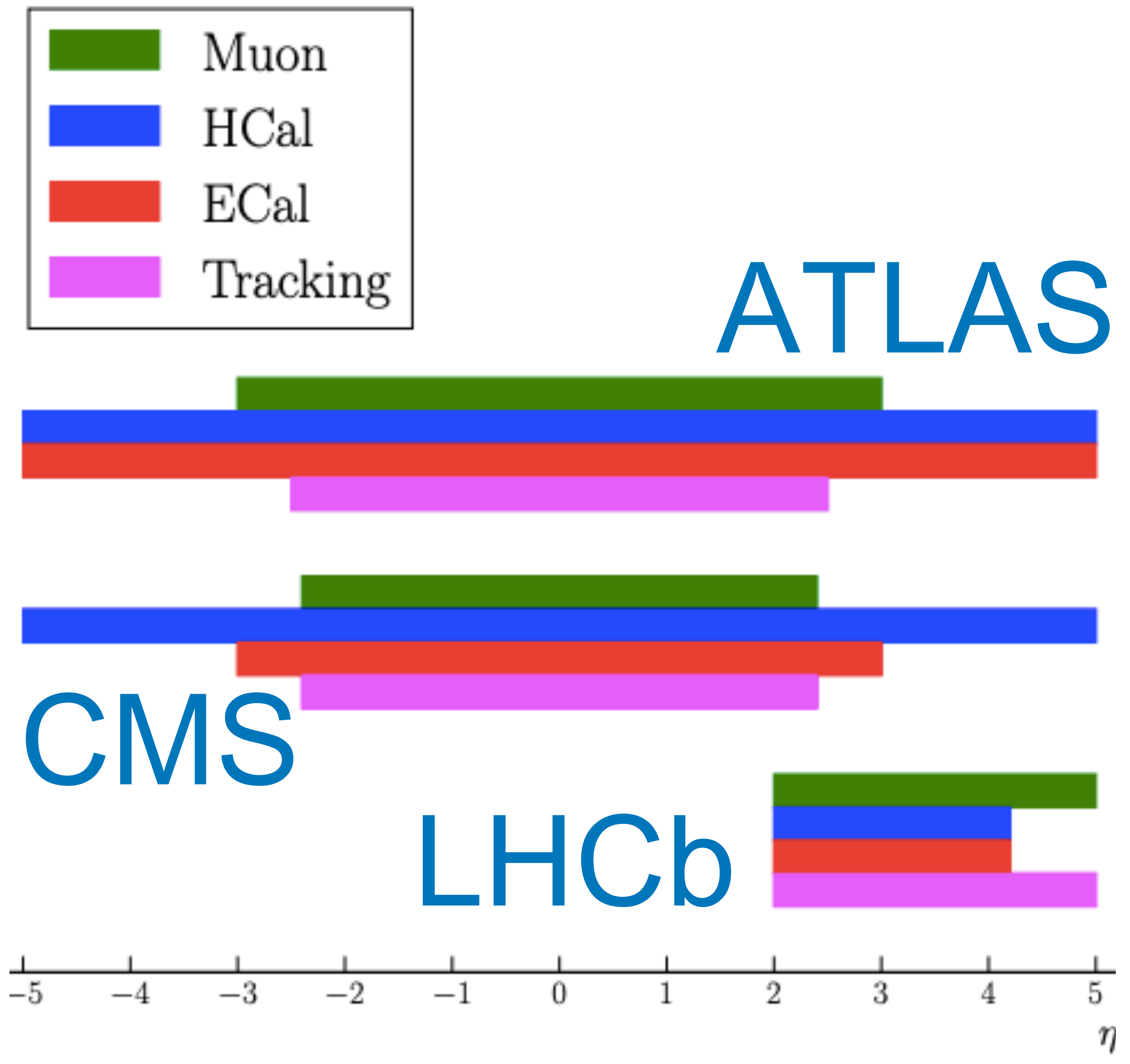
Assuming 5 dominant Higgs decay channels results in 15 double Higgs decay channels

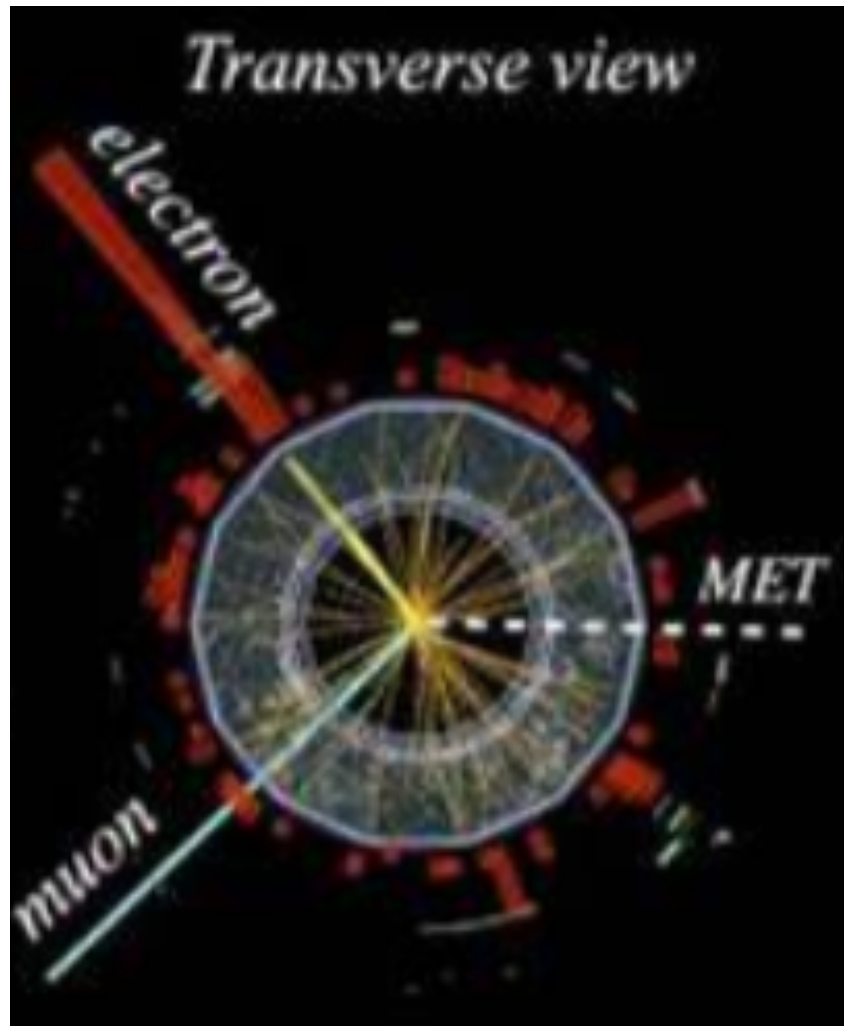
But the BR is also squared, leading to smaller rates

The ATLAS detector



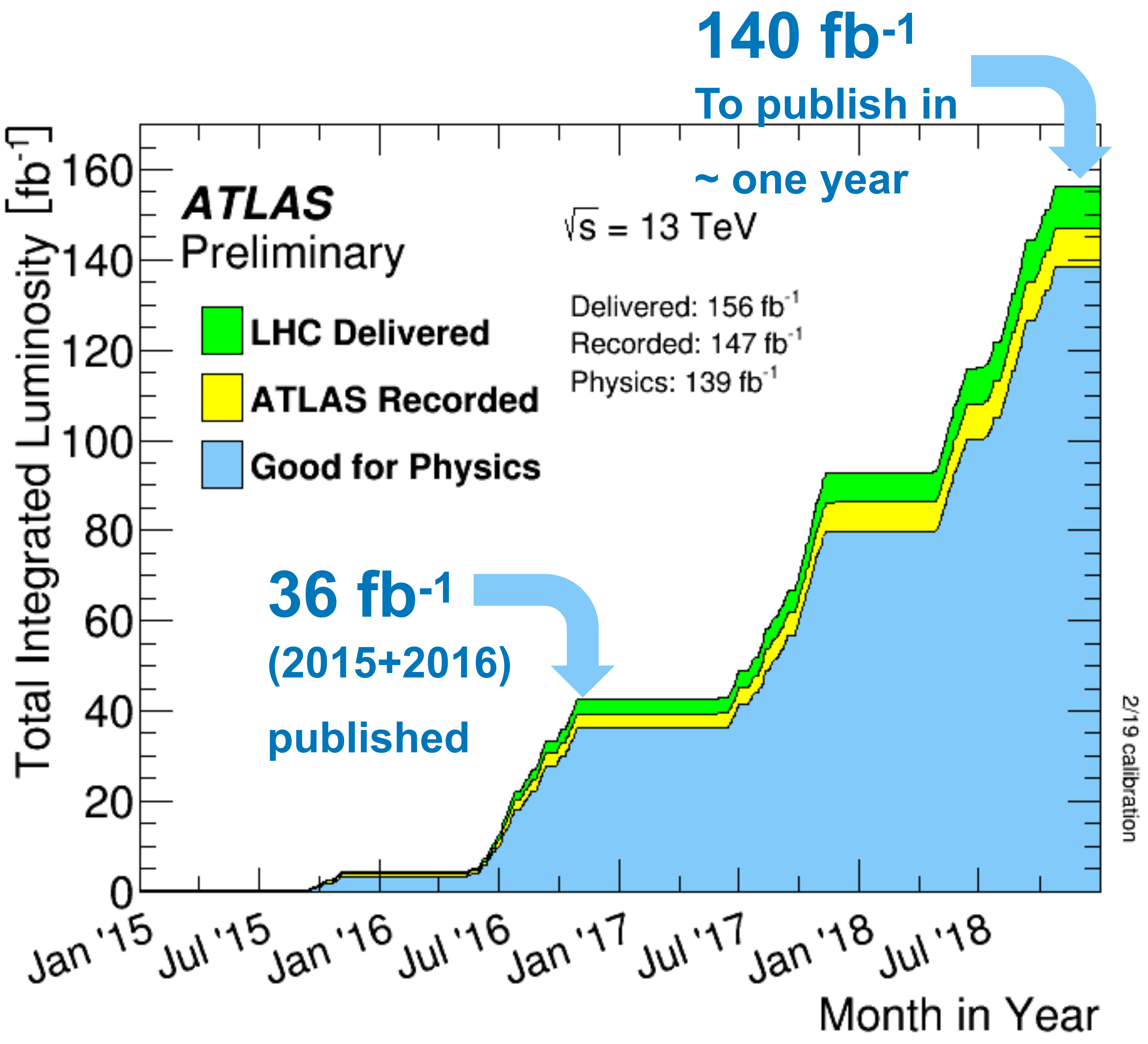
η coverage





H→WW→eνμν

Data taking - Run2



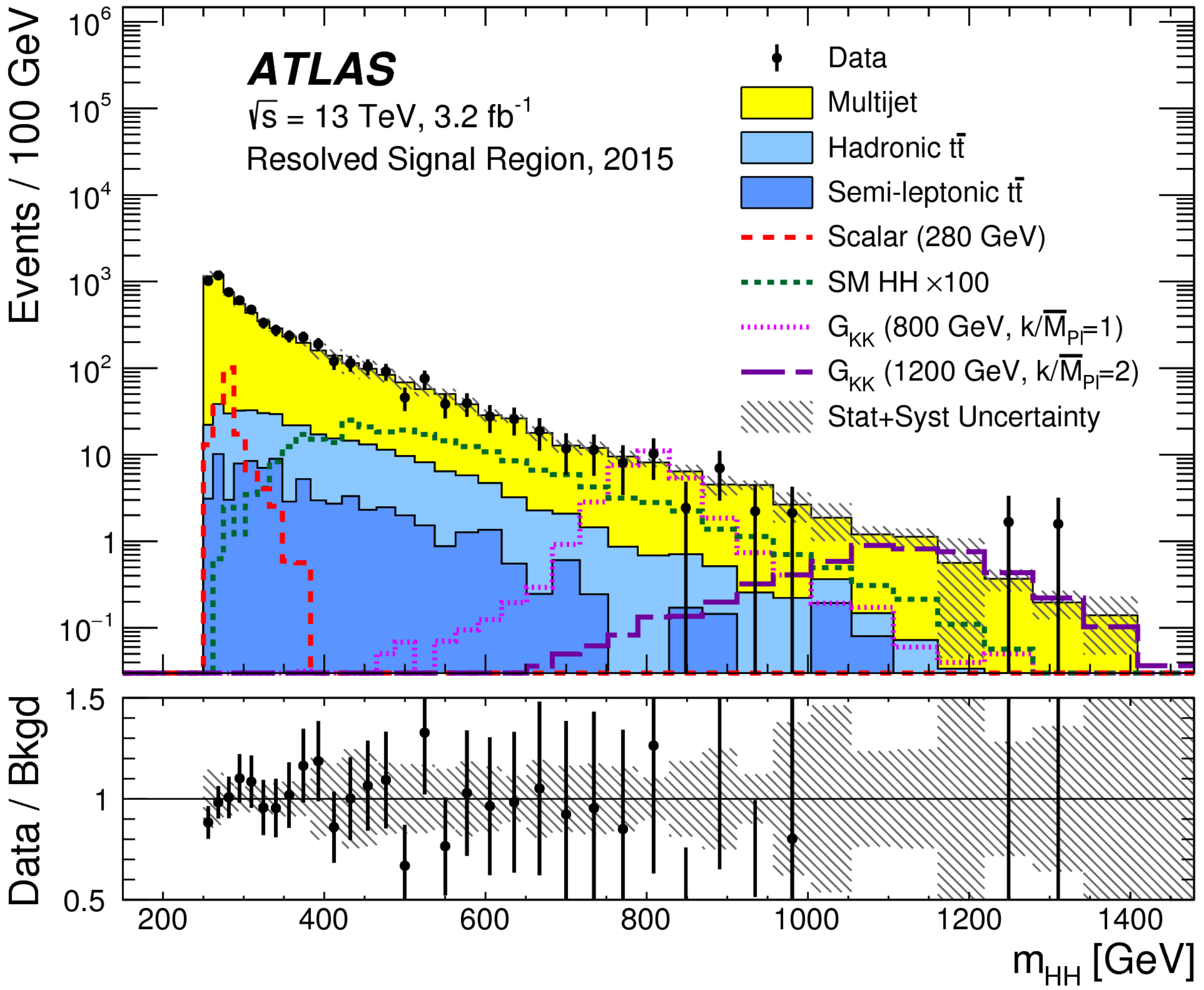
- 36 fb^{-1} means ~1200 HH events
- 140 fb^{-1} means ~5000 HH events
  - ~7M single Higgs events
- SM is assumed

Contents

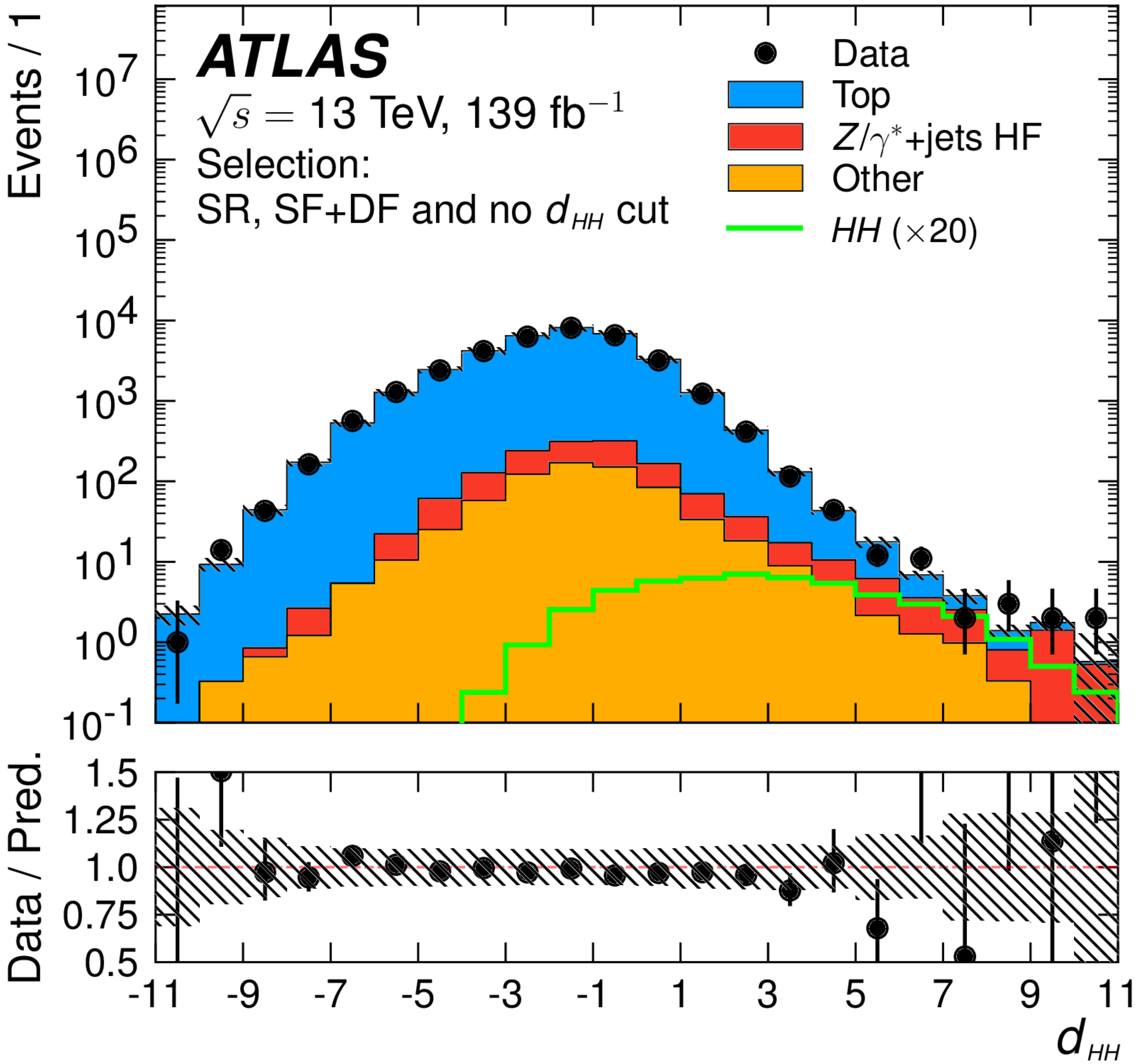
- Introduction
- HH searches
- Higgs self-coupling in single Higgs
- Prospects HL(HE)-LHC ee-colliders

HH→bbbb and HH→bbWW

Trigger on b-jets
Look at bbbb
Fit on m(bbbb)

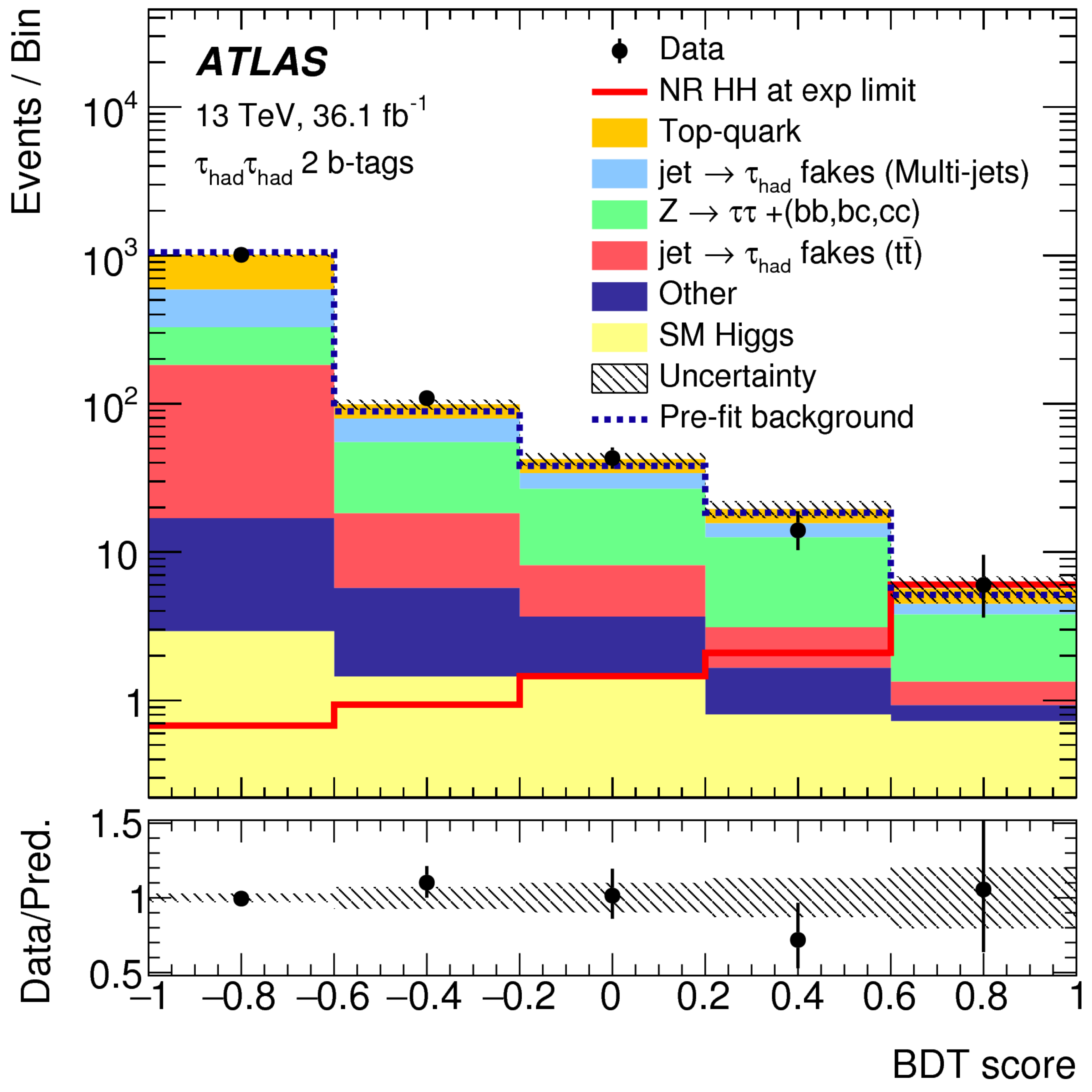


Trigger on lepton
Look at bbll+MET; Fit on ~DNN score

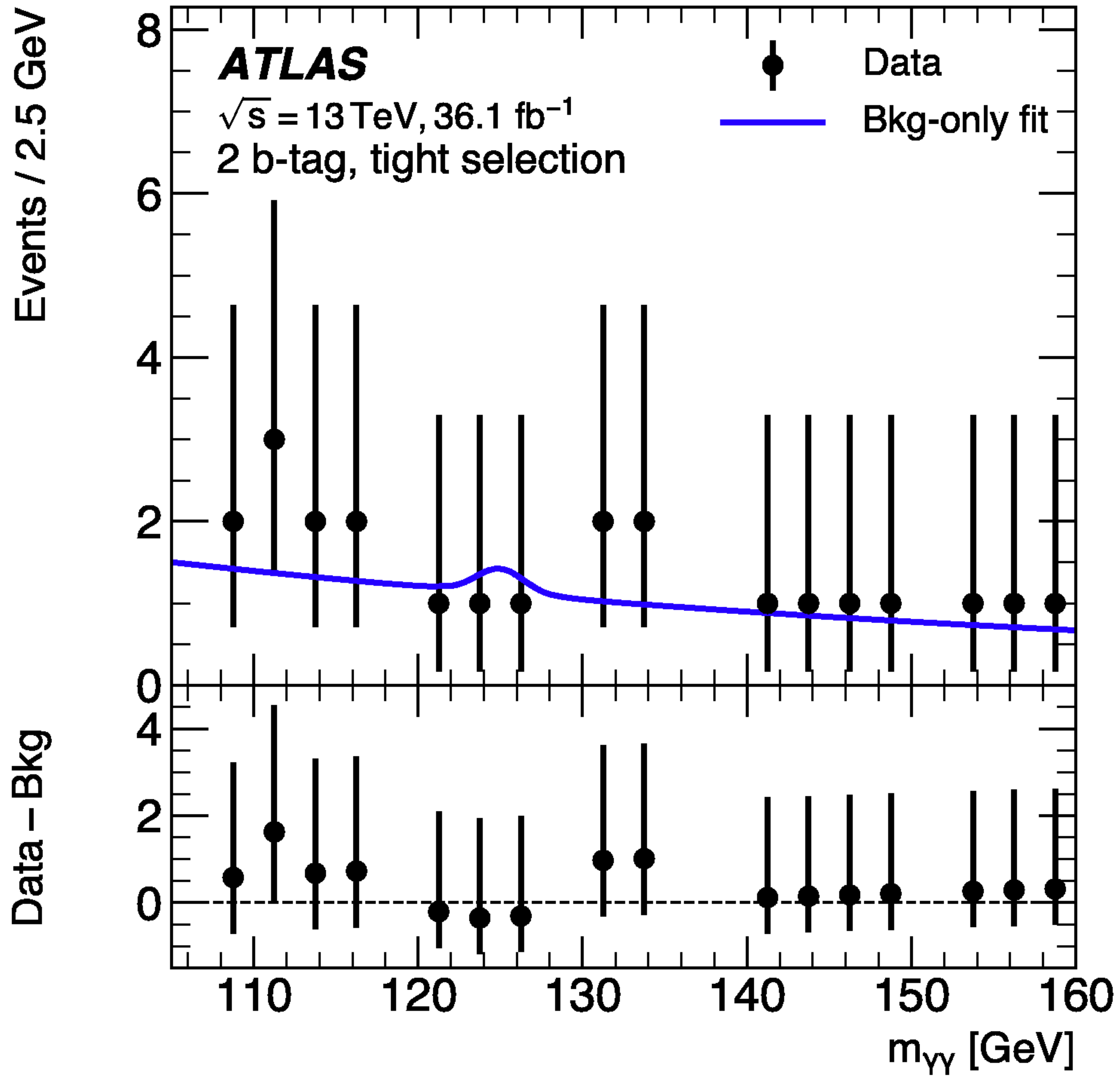


HH→bbττ and HH→bbγγ

Trigger on lepton, τ_{had}
Look at bbττ; Fit on BDT score



Trigger on diphoton
Look at bbγγ and bjγγ
Fit on m(γγ)



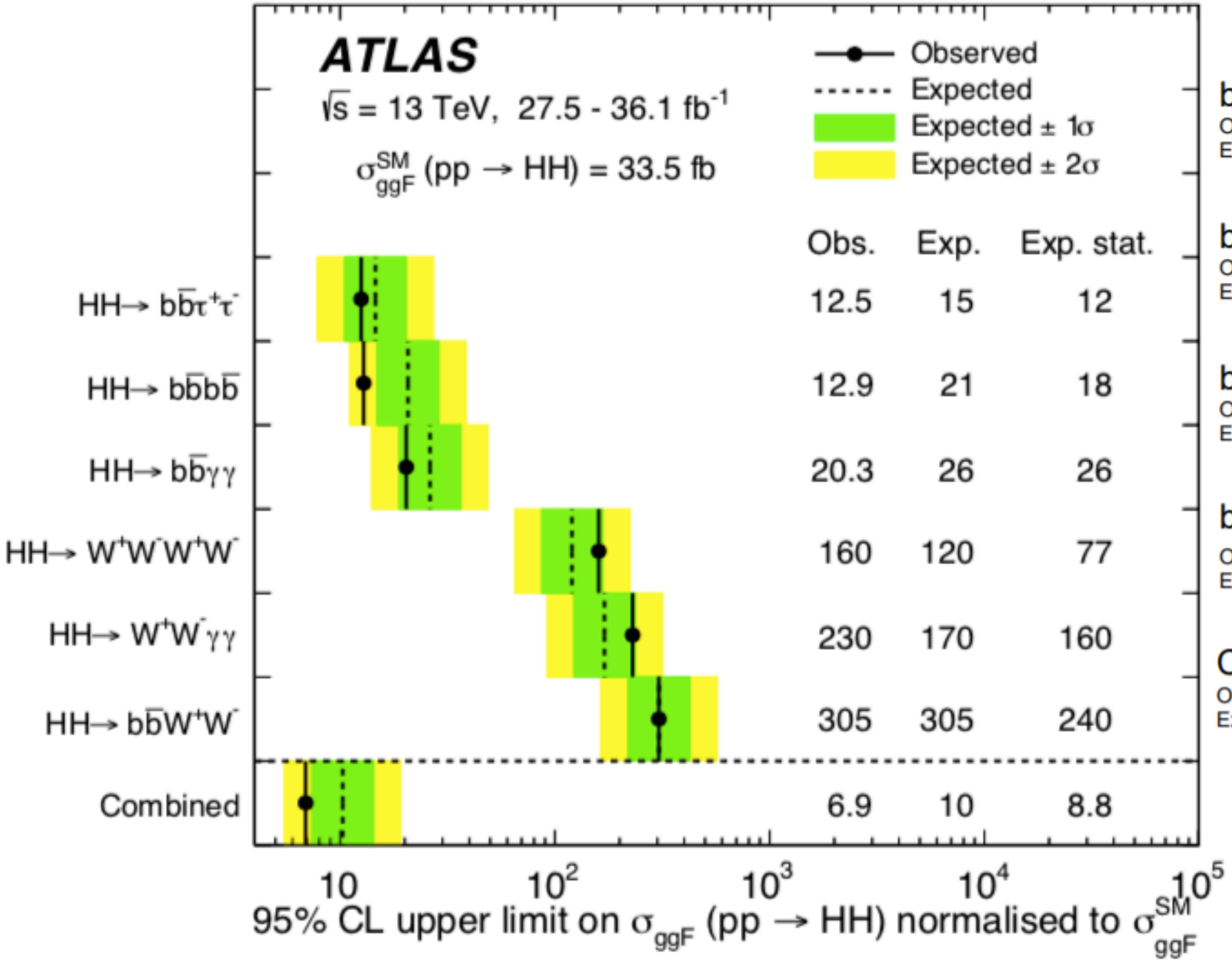
Di-Higgs combination

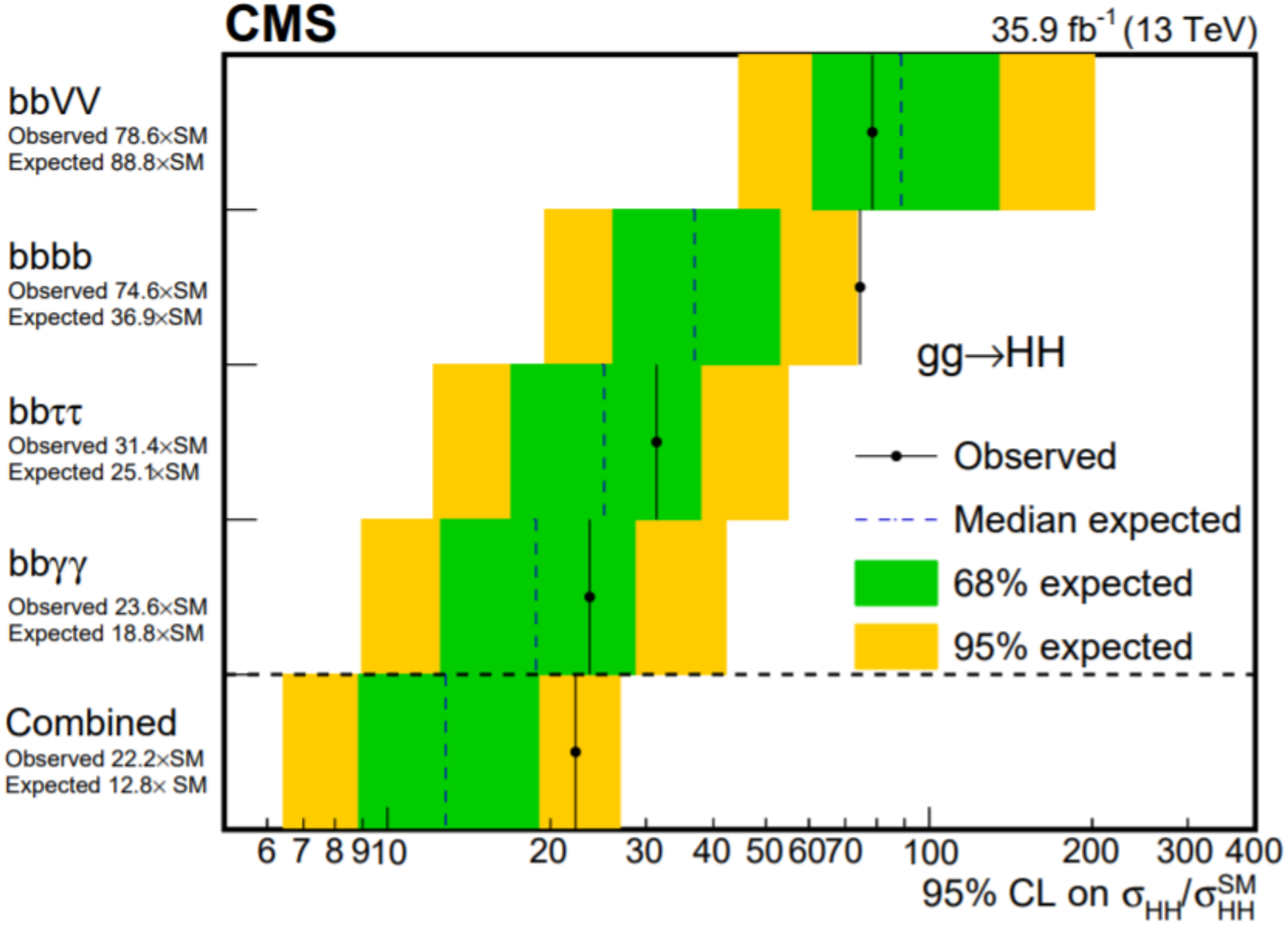
- The most sensitivity comes by statistically combining all decay channels
  - Correlate cross section as a parameter of interest
  - Correlate experimental and theoretical uncertainties
  - Extract the statistical power and experimental sensitivity simultaneously from all the channels

	$b\bar{b}b\bar{b}$	$b\bar{b}W^+W^-$	$b\bar{b}\tau^+\tau^-$	$W^+W^-W^+W^-$	$b\bar{b}\gamma\gamma$	$W^+W^-\gamma\gamma$
$\mathcal{B}(HH \to x\bar{x}y\bar{y})$	0.34	0.25	0.073	0.046	$2.6 \cdot 10^{-3}$	$1.0 \cdot 10^{-3}$
$\mathcal{L}_{\text{int}}$ [fb^{-1}]	27.5 [36.1]	36.1	36.1	36.1	36.1	36.1
Categories	2 [2–5]	1 [1]	3 [2–3]	9 [9]	2 [2]	1 [1]
Discriminant	m_{HH} [m_{HH}]	c.e. [m_{HH}]	BDT [BDT]	c.e. [c.e.]	$m_{\gamma\gamma}$ [m_{HH}]	$m_{\gamma\gamma}$ [$m_{\gamma\gamma}$]
Model	NR [S/G]	NR [S/G]	NR [S/G]	NR [S]	NR [S]	NR [S]
$m_{S/G}$ [TeV]	[0.26–3.00]	[0.50–3.00]	[0.26–1.00]	[0.26–0.50]	[0.26–1.00]	[0.26–0.50]

NEW on 10 January 2020 Phys. Lett. B 800 (2020) 135103

HH: non-resonant

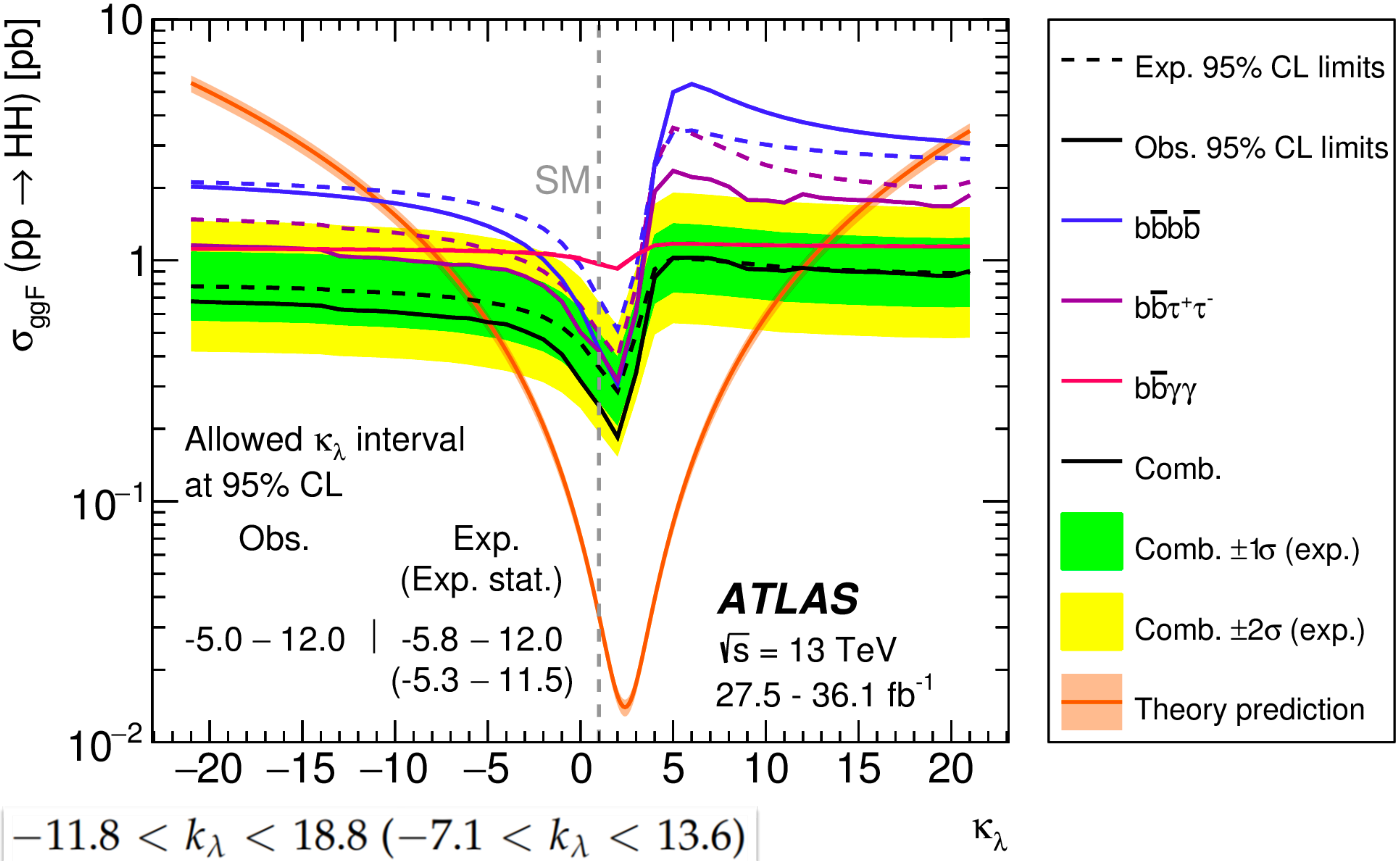




Non-resonant xs limits
Combined limits ~**10**xSM (exp) ~7xSM (obs)

Non-resonant xs limits
Combined limits ~**13**xSM (exp) ~22xSM (obs)

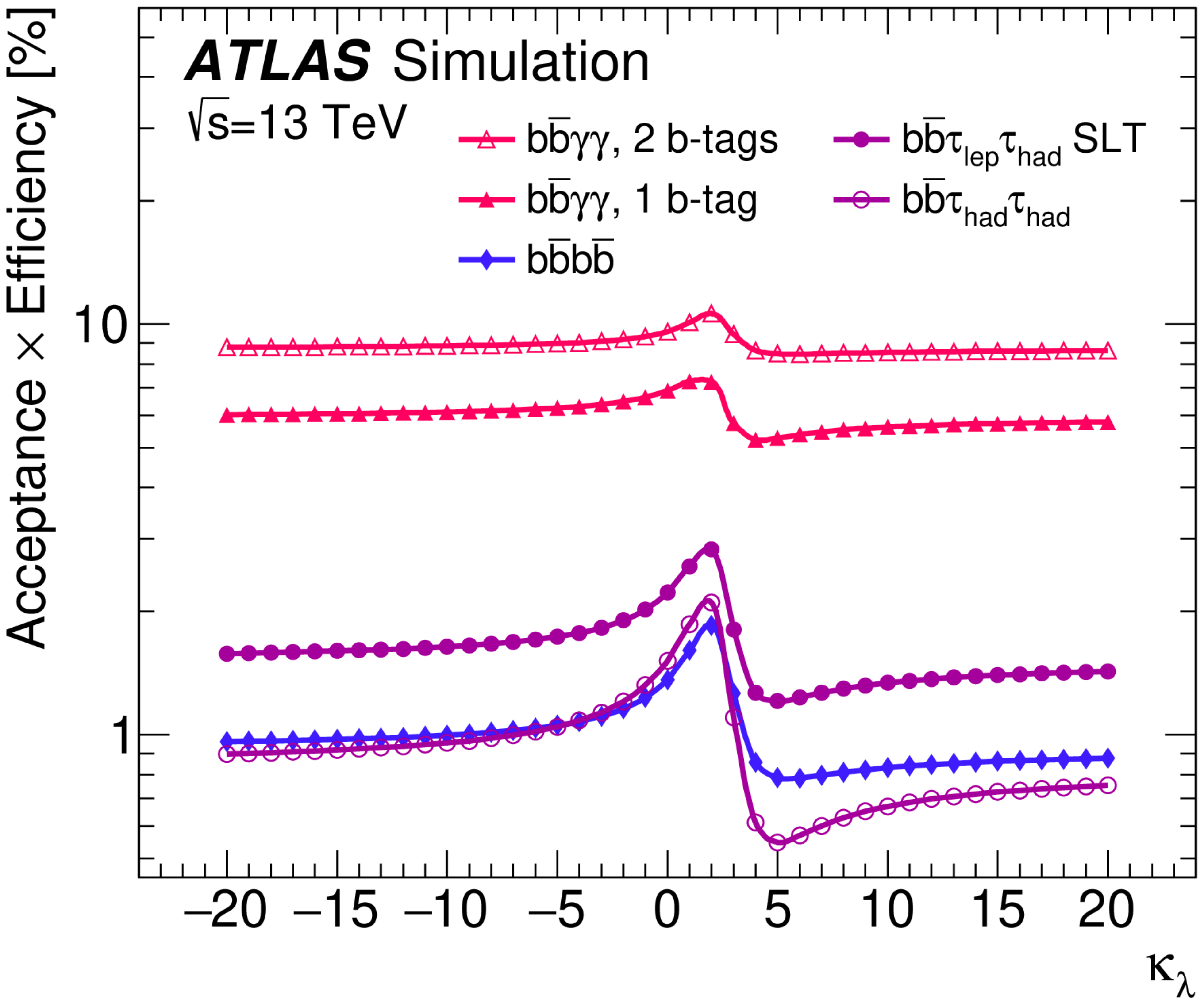
HH: Higgs self-coupling



CMS $-11.8 < k_\lambda < 18.8 \; (-7.1 < k_\lambda < 13.6)$

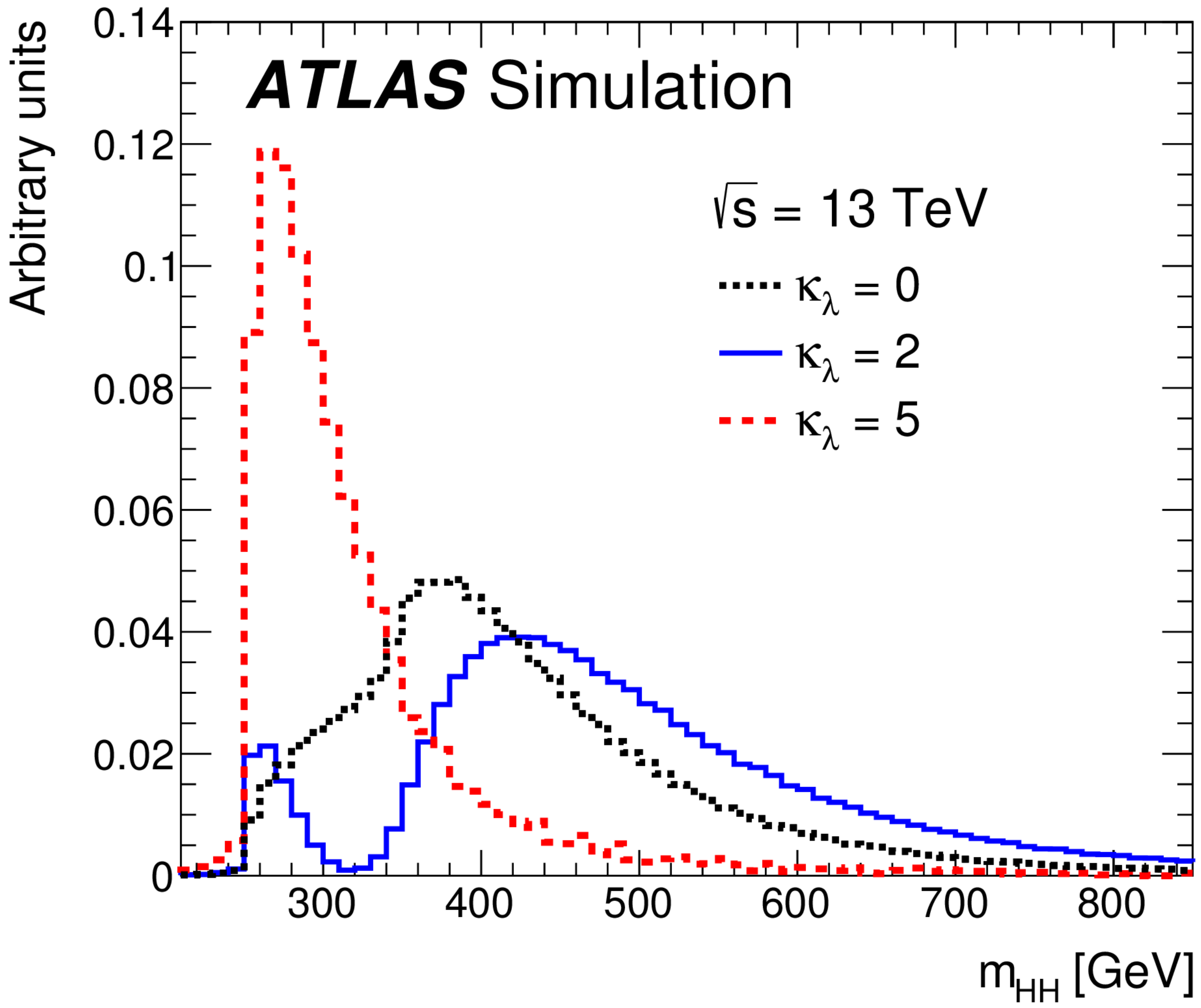
κ_λ constraints obtained by xs limits with fixed κ_λ values

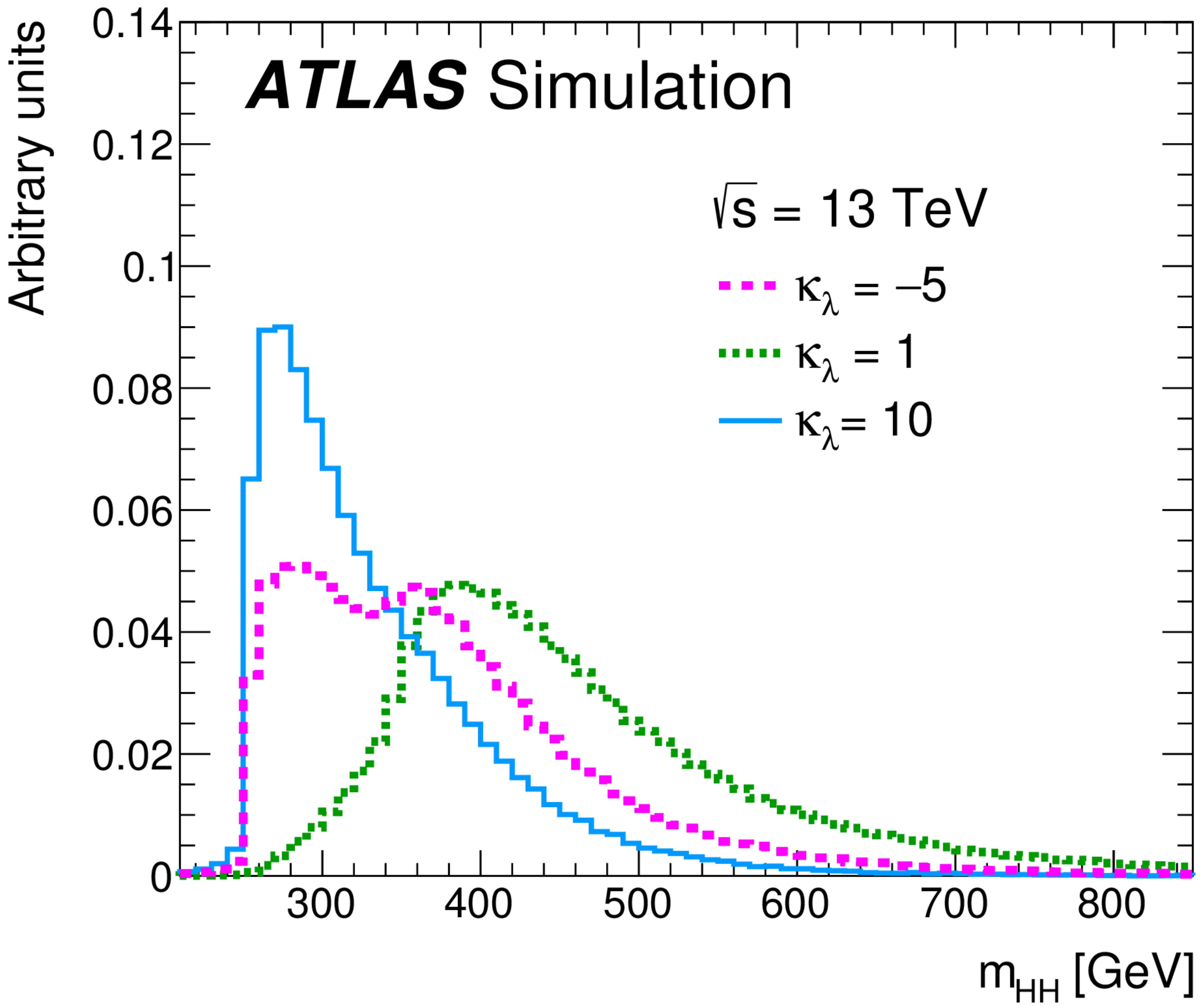
HH: efficiency vs self-coupling



bbγγ not most sensitive in $\kappa_\lambda = 1$ (SM) but strong in higher $|\kappa_\lambda|$ given its flat efficiency

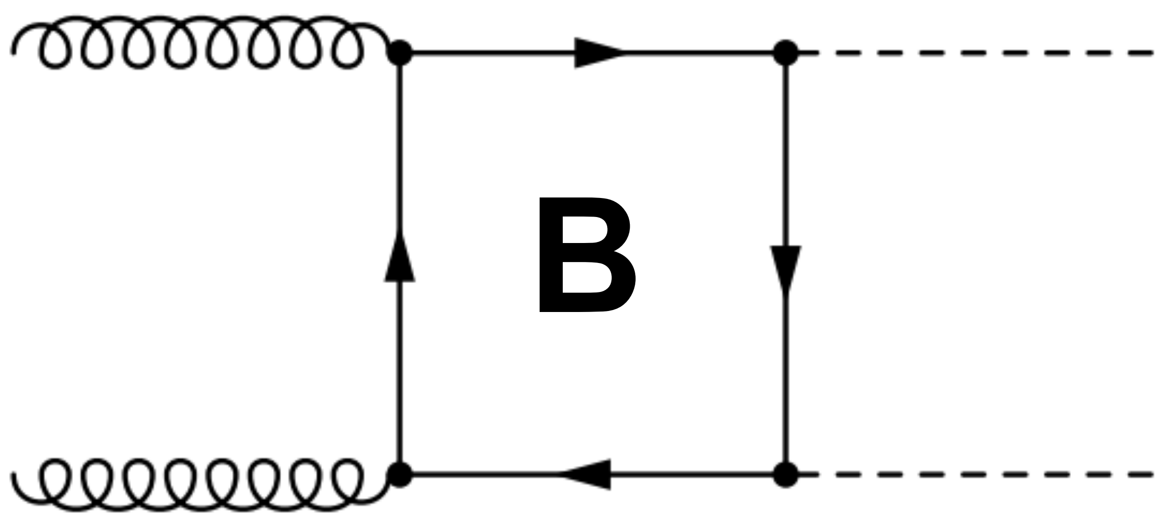
HH: Higgs self-coupling on mHH

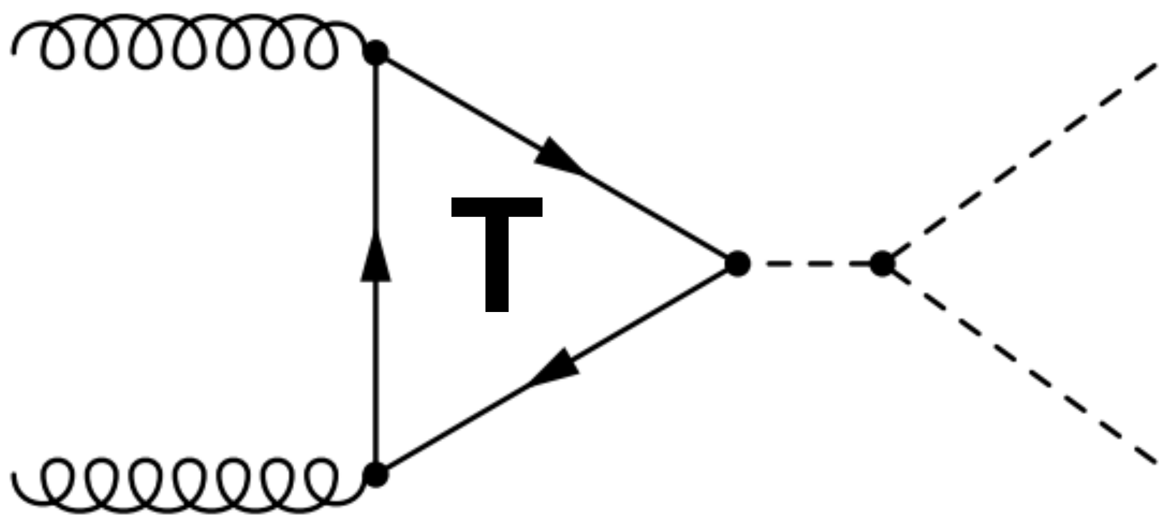




In general, larger $|\kappa_\lambda|$ tends to have softer m_{HH} given more contributions from the triangle diagram

HH: Higgs self-coupling "morphing"





$$|\mathcal{M}|^2 = y_t^4 \left[\mathcal{M}_B\mathcal{M}_B^* + \frac{\lambda}{y_t}(\mathcal{M}_B\mathcal{M}_T^* + \mathcal{M}_T\mathcal{M}_B^*) + \frac{\lambda^2}{y_t^2}\mathcal{M}_T\mathcal{M}_T^*\right].$$

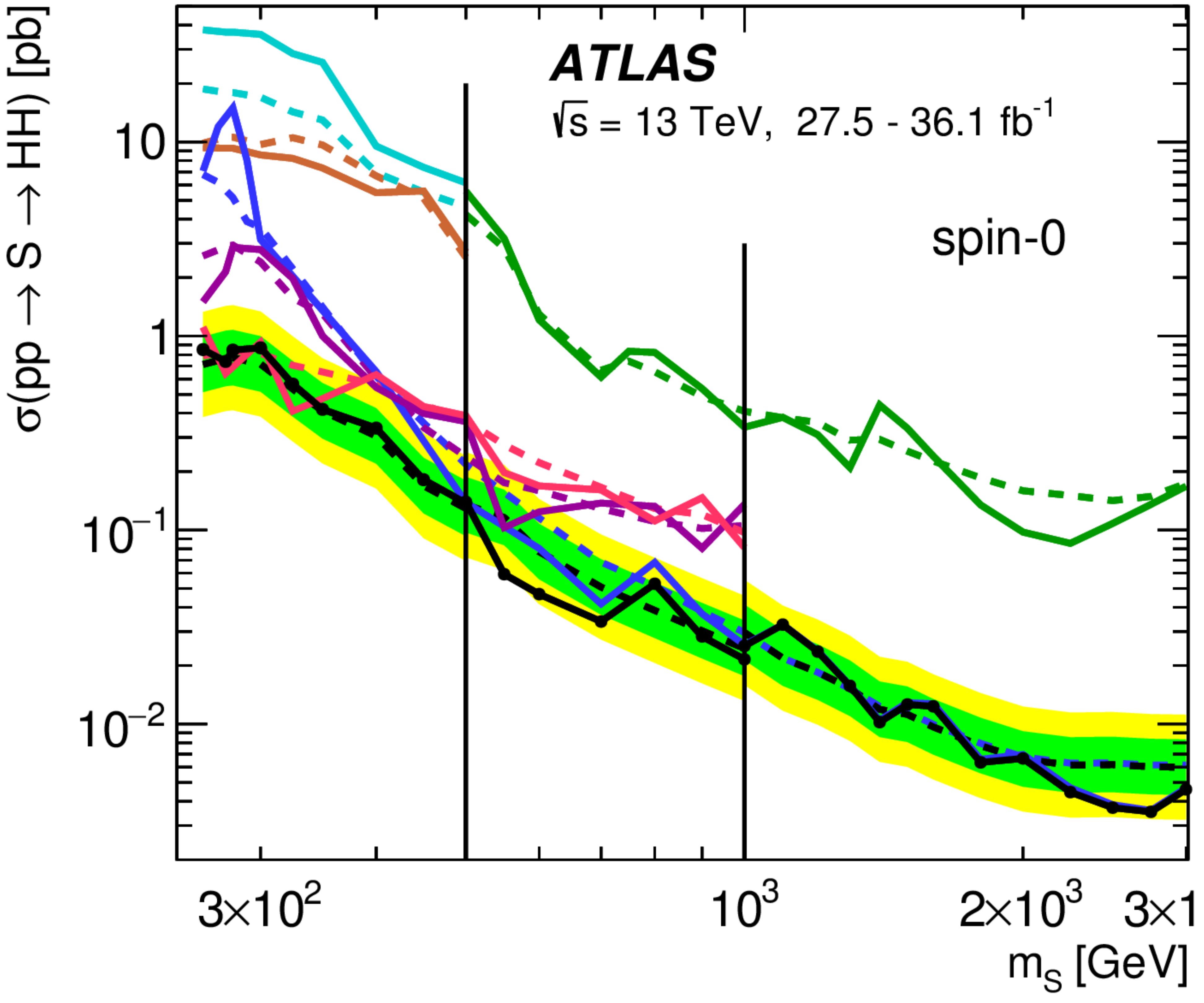
For example, $\sigma(y_t = 1.2, \kappa_\lambda = 1) = (1.2)^4\,\sigma(y_t = 1, \kappa_\lambda = 1/1.2)$.

In practice, one only needs to generate three samples that can be combined into a sample with any κ_t, κ_λ values. See below

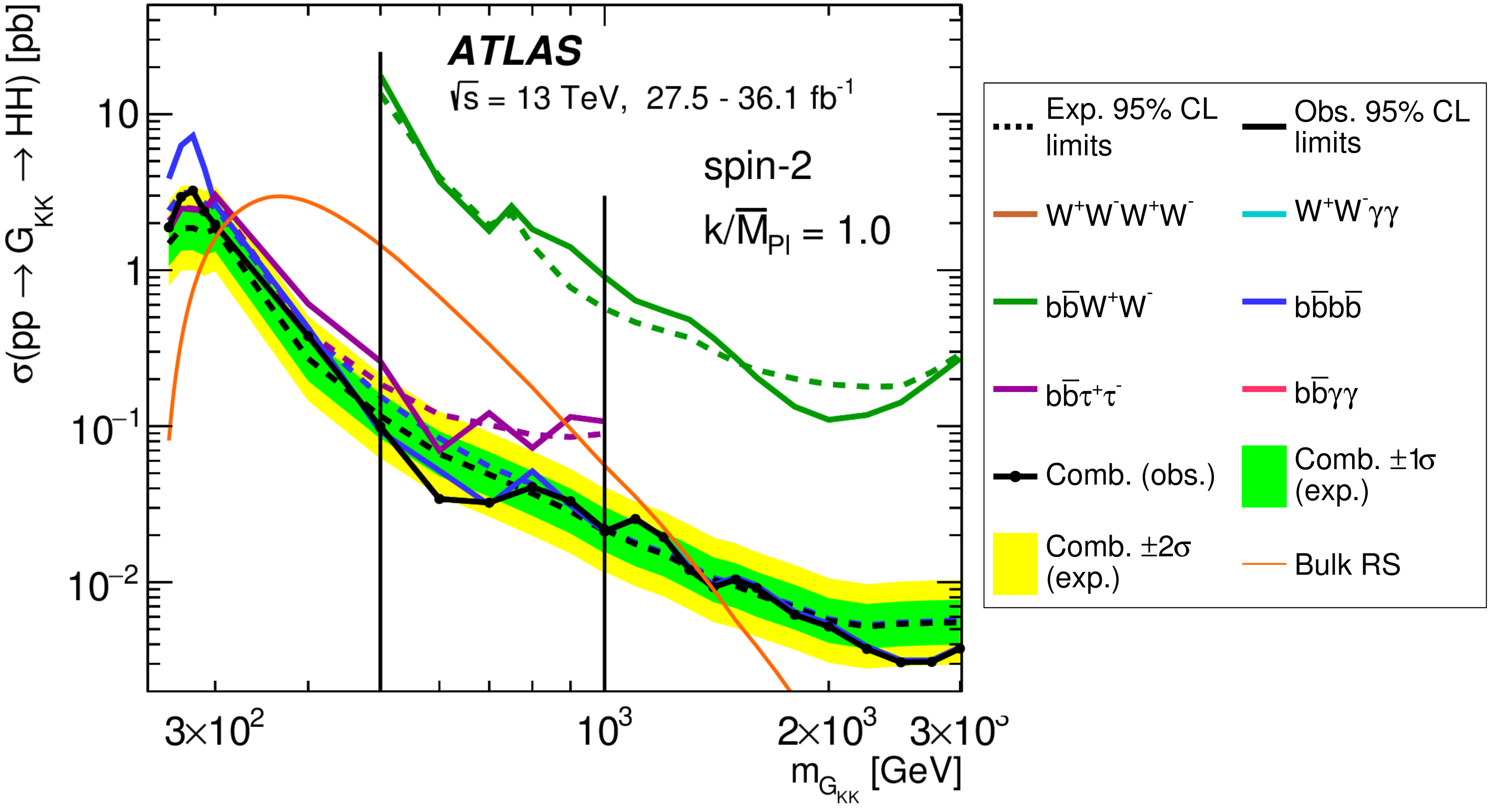
The combined samples are compared to generated ones and good closure is found in general

$$|A(k_t, k_\lambda)|^2 = k_t^2\left[\left(k_t^2 + \frac{k_\lambda^2}{20} - \frac{399}{380}k_t k_\lambda\right)|A(1,0)|^2 + \left(\frac{40}{38}k_t k_\lambda - \frac{2}{38}k_\lambda^2\right)|A(1,1)|^2 + \frac{k_\lambda^2 - k_t k_\lambda}{380}|A(1,20)|^2\right]$$

HH: heavy Higgs, graviton



Heavy Higgs



Graviton

HH: systematic uncertainties

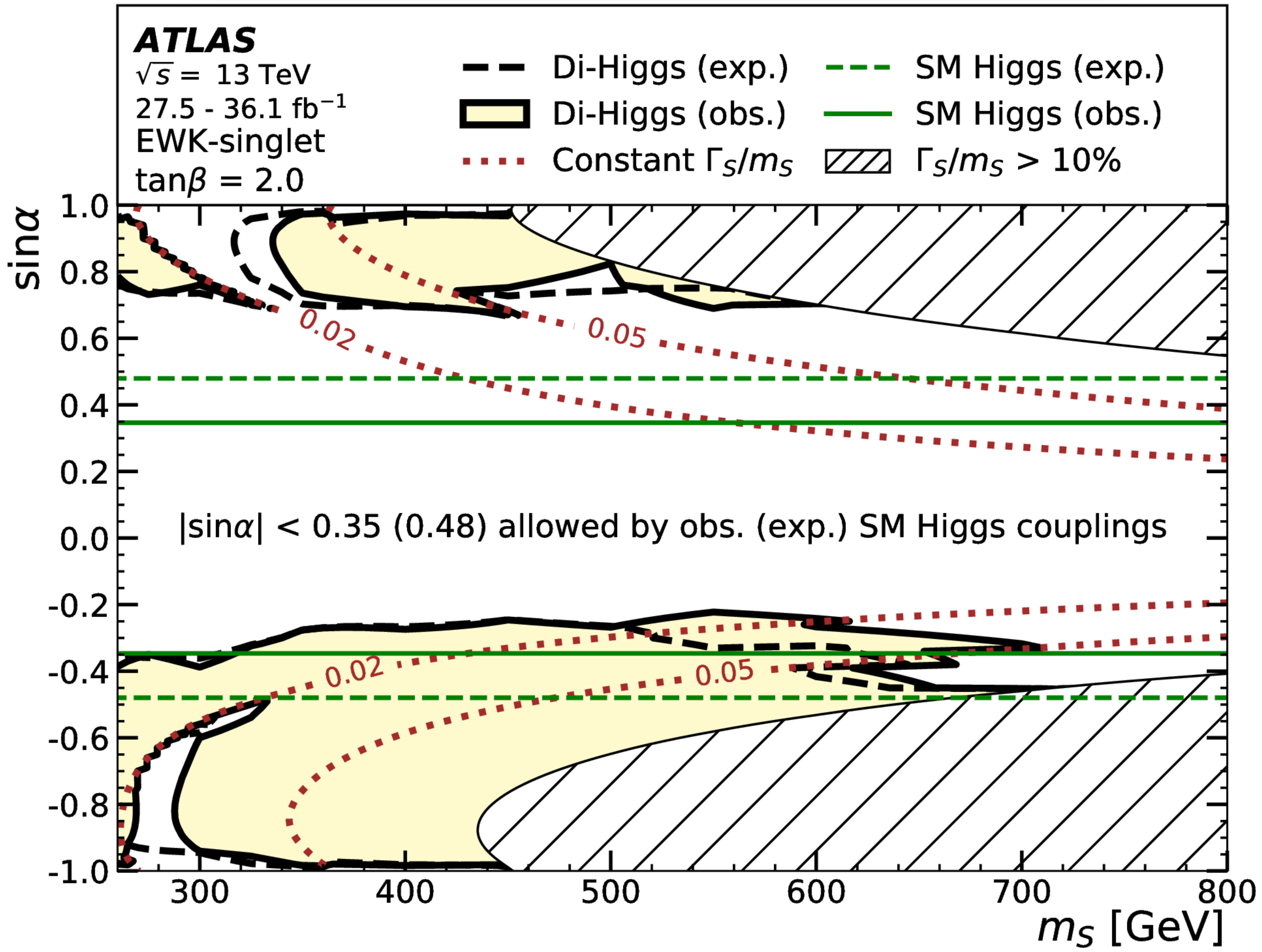
- Currently, HH is still statistically limited
- It will be still the same case in many channels with HL-LHC
- Among the systematic uncertainties, background modeling dominates

Upper limit percentage variation	NR	Spin-0		Spin-2 $k/\overline{M}_{\mathrm{Pl}} = 1$		Spin-2 $k/\overline{M}_{\mathrm{Pl}} = 2$	
		1 TeV	3 TeV	1 TeV	3 TeV	1 TeV	3 TeV
Simulation statistics	3%	1%	-	2%	-	1%	-
Background modelling	5%	7%	9%	11%	15%	16%	21%
Signal theory	1%	-	-	-	1%	-	-
Tau	2%	-	-	-	-	1%	-
Jet	-	1%	2%	2%	3%	5%	4%
b-tagging	1%	2%	-	3%	-	4%	-
All	13%	12%	11%	19%	18%	29%	25%

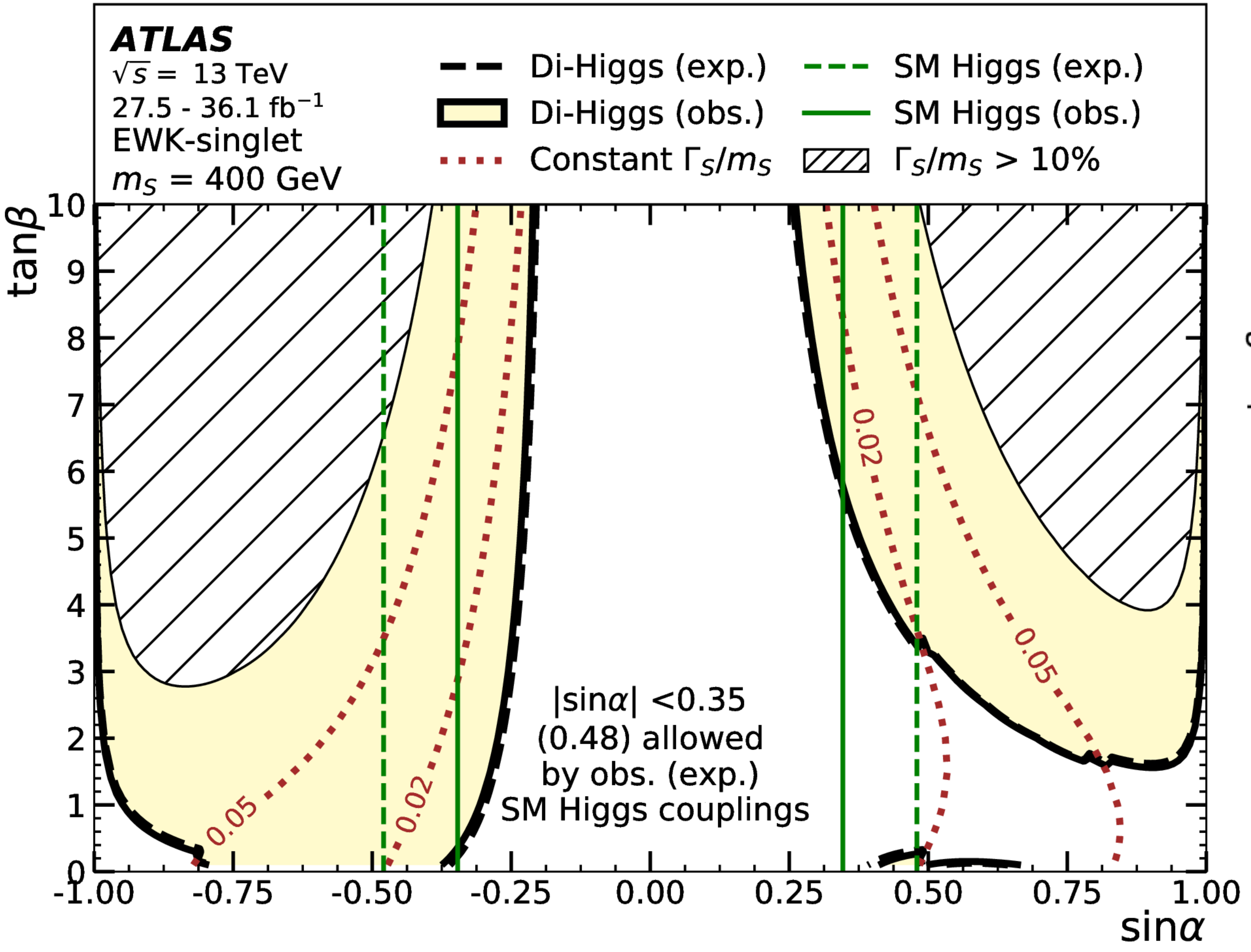
HH: EWK-singlet

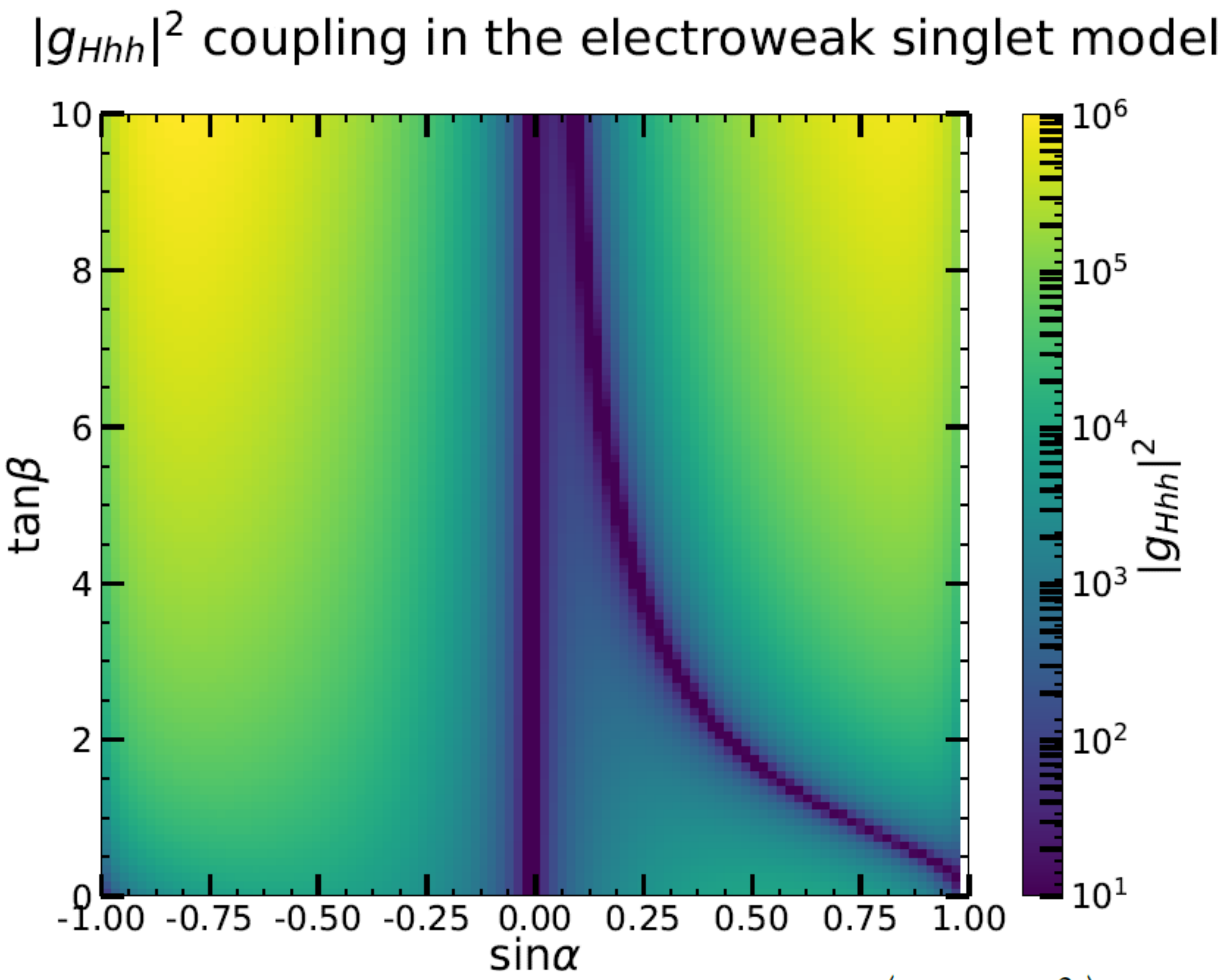
- Additional electroweak singlet model (EWK-singlet) is a very simple extension to the Higgs sector in SM
  - Add one more real (or complex) electroweak singlet to the Higgs double
- This model (in the simplest scenario) predicts one SM Higgs and one heavier Higgs
- The parameters include
  - m_S (the mass of the heavier Higgs)
  - sinα (mixing angle of the two Higgs states)
  - tanβ (the ratio of vev)
- The HH combined limits targeting at spin0 is used to interpret EWK-singlet

$$\mathcal{V} = m^2\Phi^\dagger\Phi + \lambda_1\left(\Phi^\dagger\Phi\right)^2 + \\ + \mu^2 S^2 + \lambda_2 S^4 + \\ + \lambda_3\left(\Phi^\dagger\Phi\right)S^2$$



HH: EWK-singlet





$$g_{SHH} = -\frac{\sin 2\alpha}{2v_d v_s}(-\sin\alpha v_d + \cos\alpha v_s)\left(m_H^2 + \frac{m_S^2}{2}\right)$$

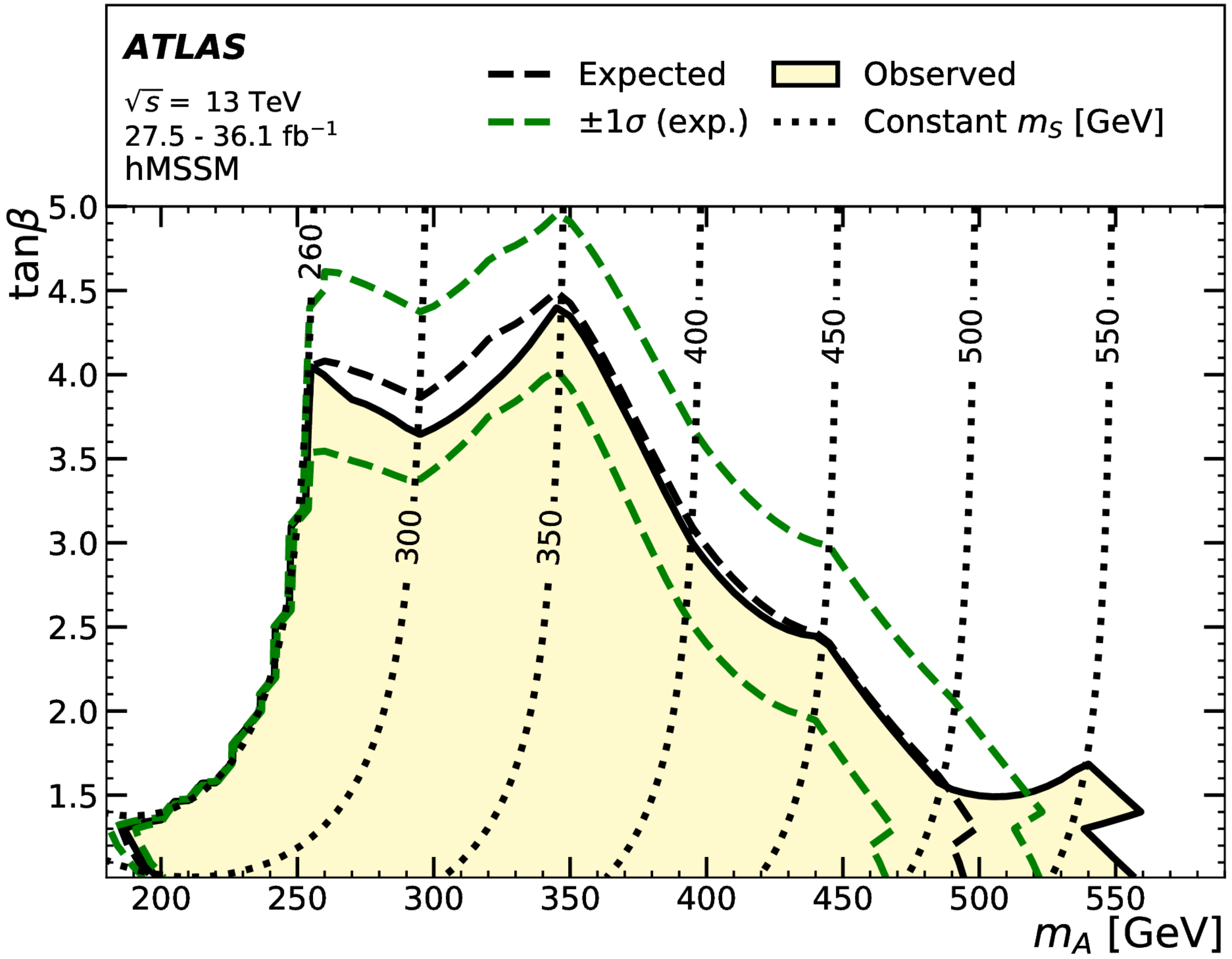
The coupling diminishes at

- $\sin\alpha = 0$, or
- $-\sin\alpha v_d + \cos\alpha v_s = 0 \implies \tan\beta = \frac{\cos\alpha}{\sin\alpha}$

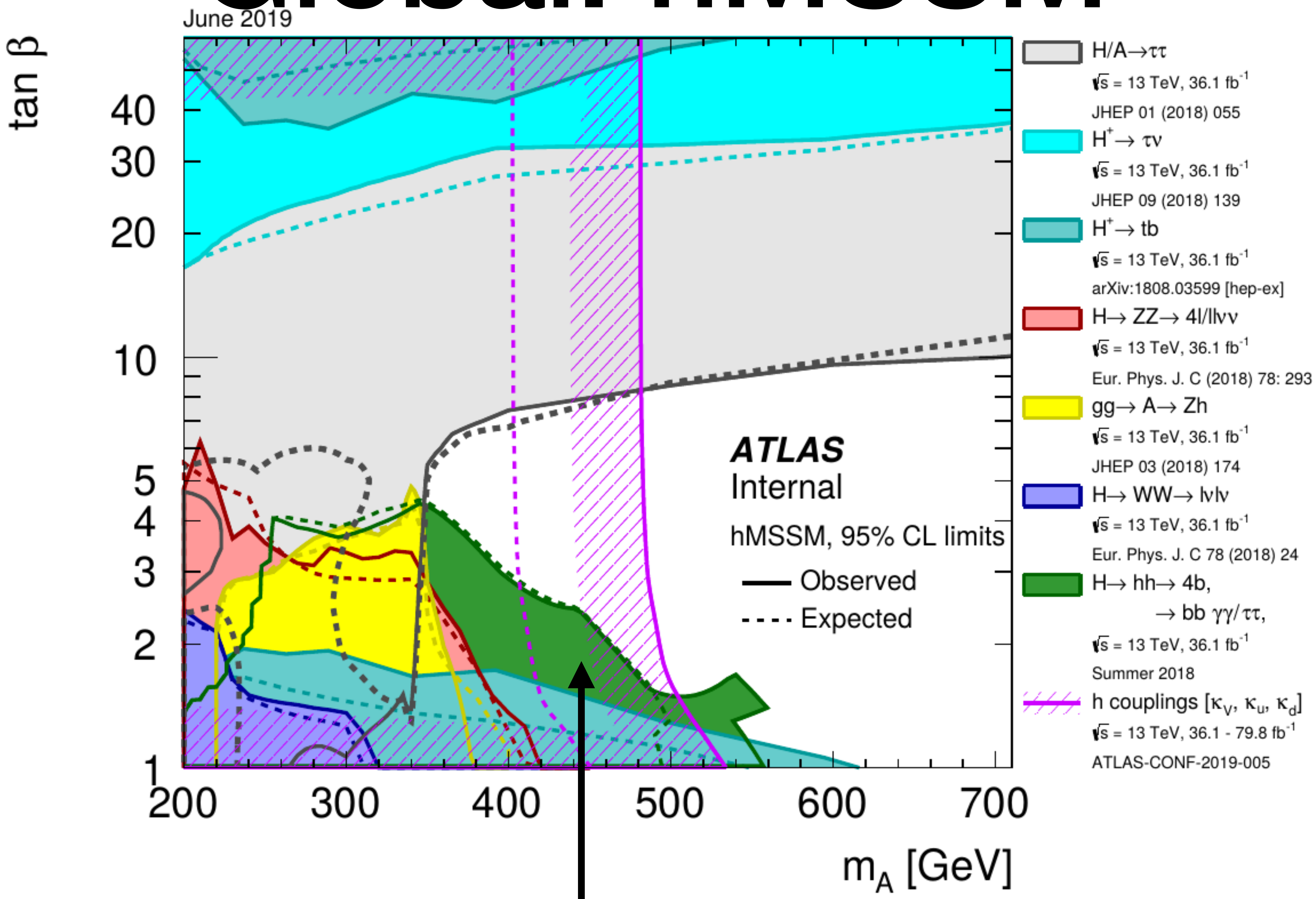
HH: hMSSM

- hMSSM is a simplified MSSM (Minimal Supersymmetric Standard Model), its Higgs sector is equivalent to Type II 2HDM (Two-Doublet-Higgs Models)
- This benchmark predicts five Higgs bosons
  - Heavier Higgs: CP-even S, CP-odd A, a pair of charged
  - SM Higgs: H
- Only two parameters can build up the model
  - m_A (mass of A)
  - tanβ (the ratio of vev)
- The HH combined limits targeting at spin0 is used to interpret hMSSM

$$m_S = \frac{(m_A^2 + m_Z^2 - m_H^2)(m_Z^2 c_\beta^2 + m_A^2 s_\beta^2) - m_A^2 m_Z^2 c_{2\beta}^2}{m_Z^2 c_\beta^2 + m_A^2 s_\beta^2 - m_H^2}$$



Global: hMSSM

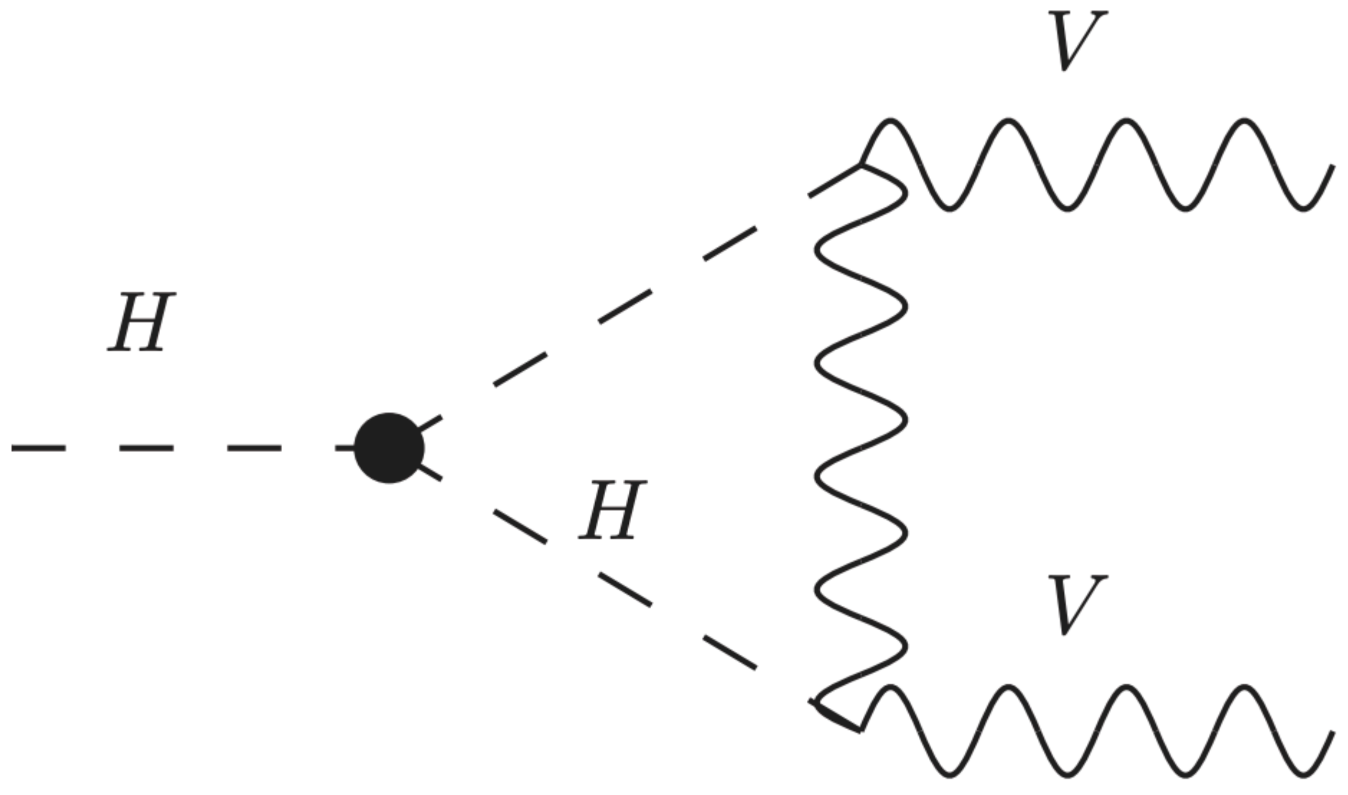


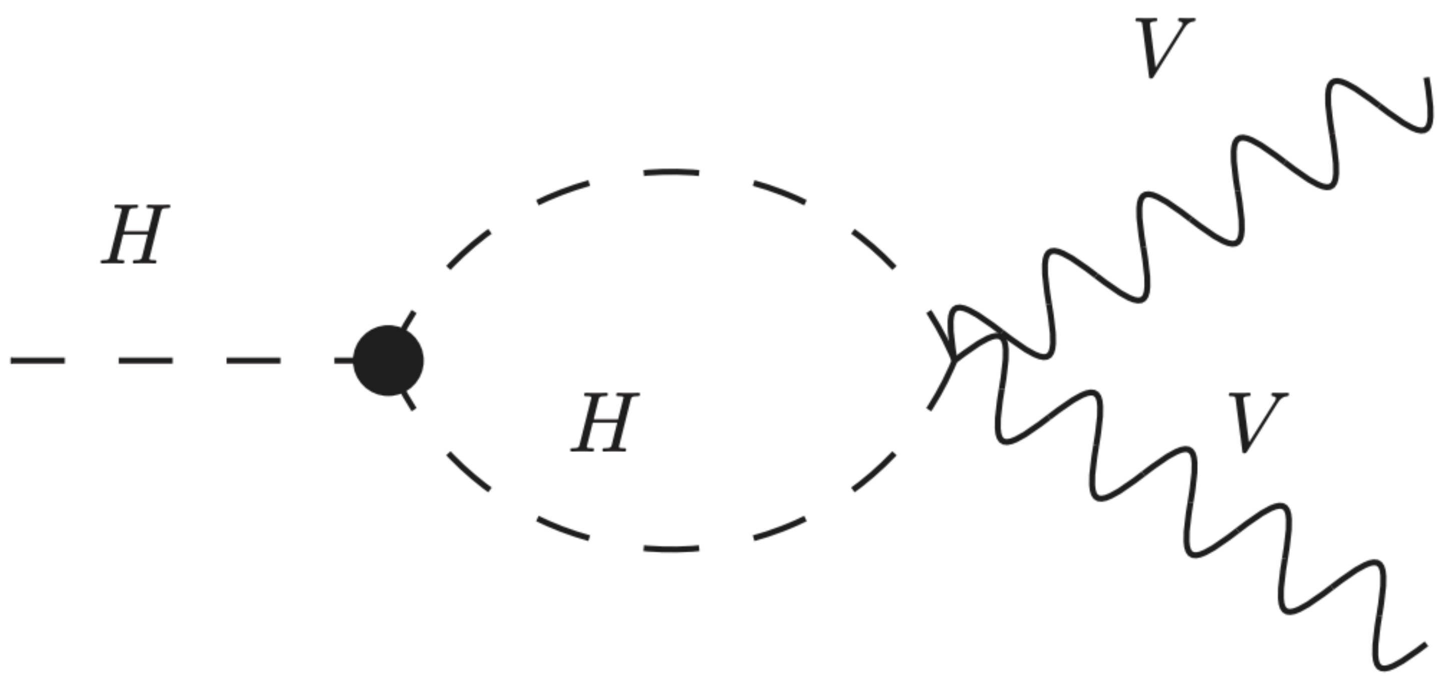
In the global picture of hMSSM exclusion with all available ATLAS heavy particle searches, the HH leads in the intermediate mass range

Contents

EWK correction on single Higgs productions

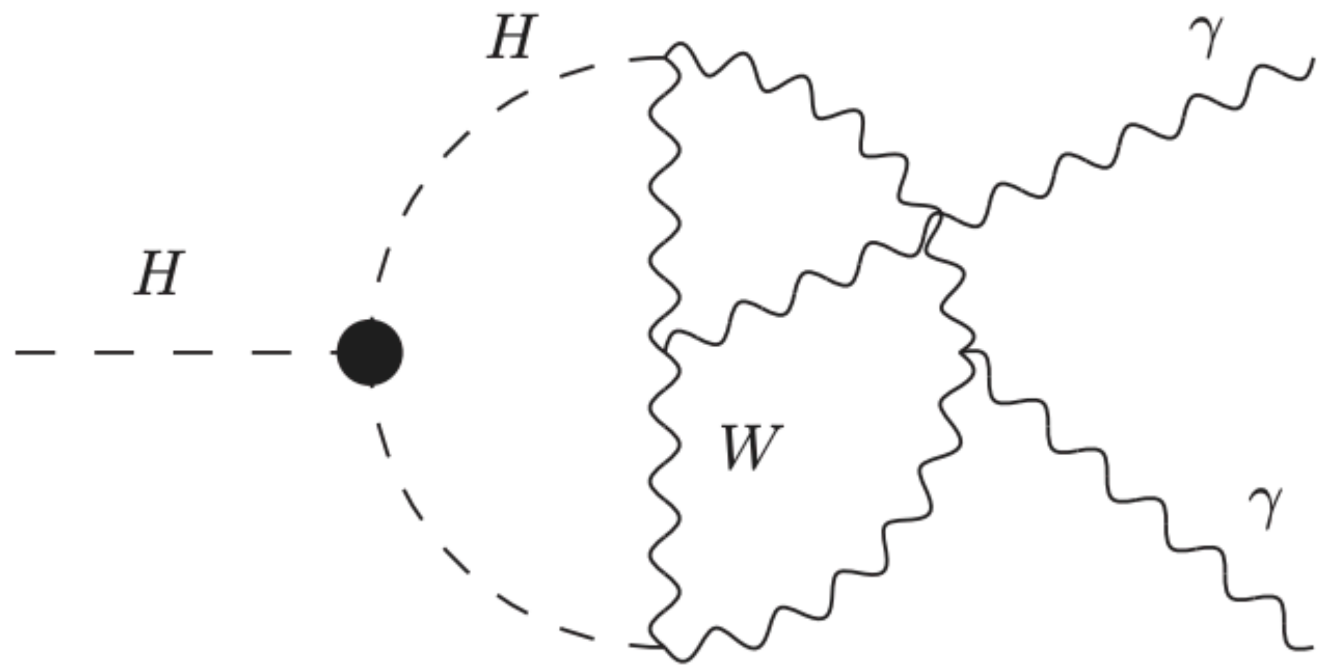
EWK correction on single Higgs decays

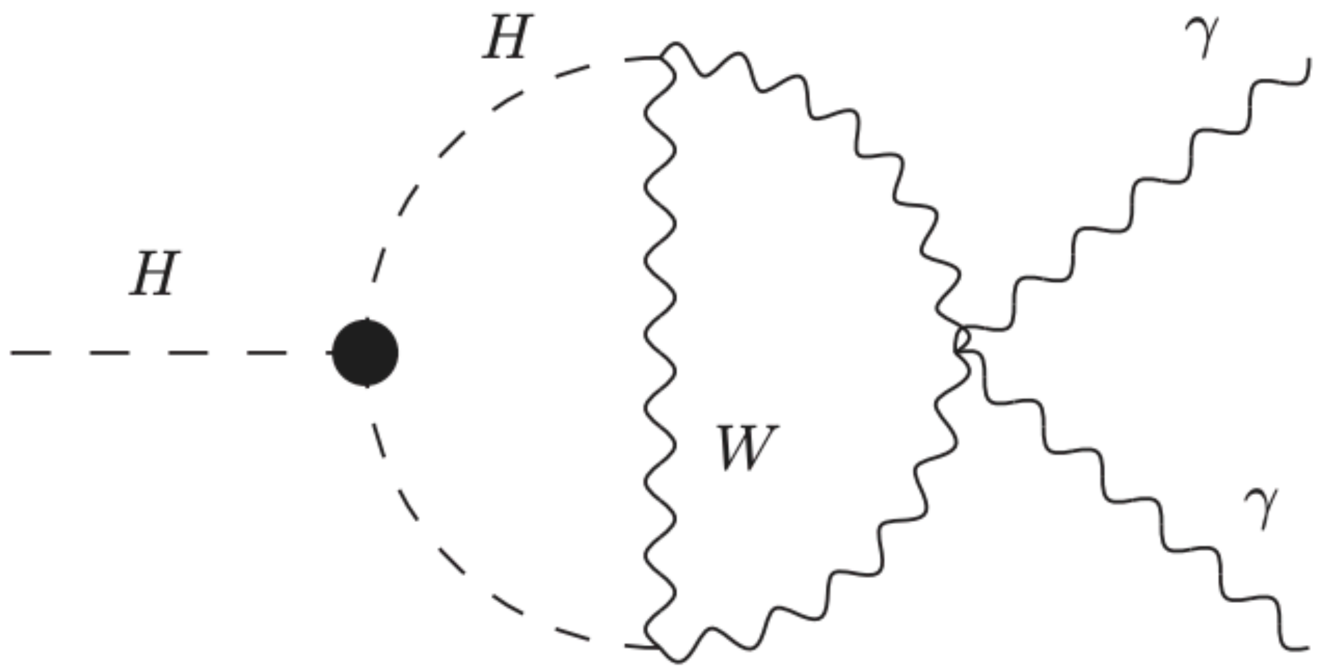


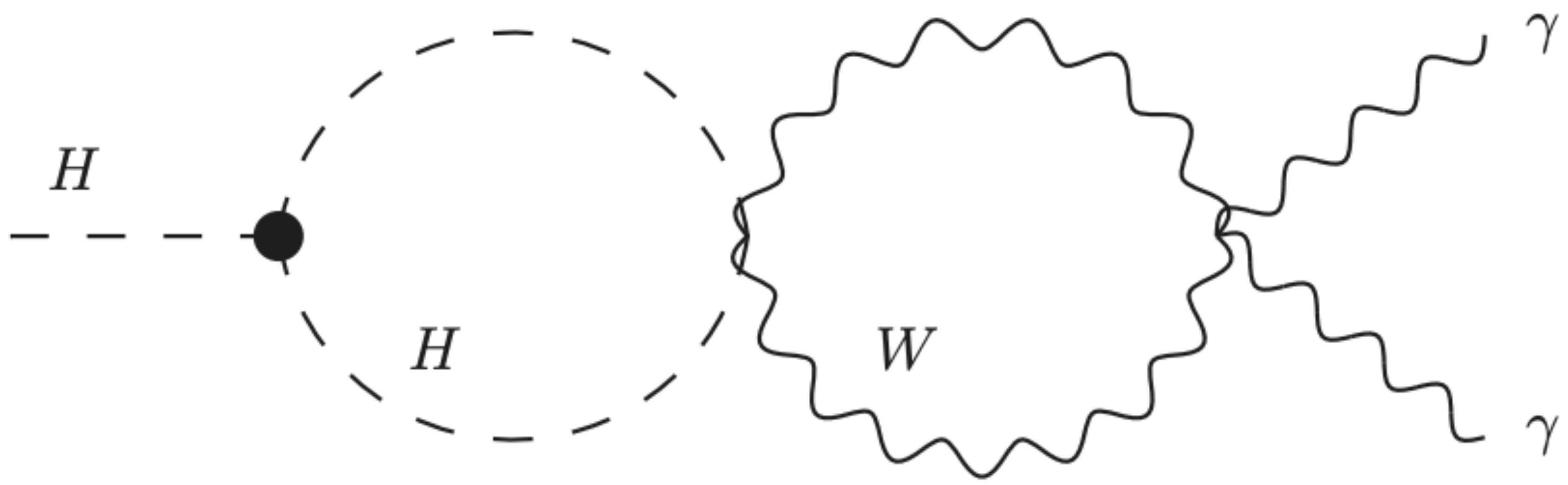


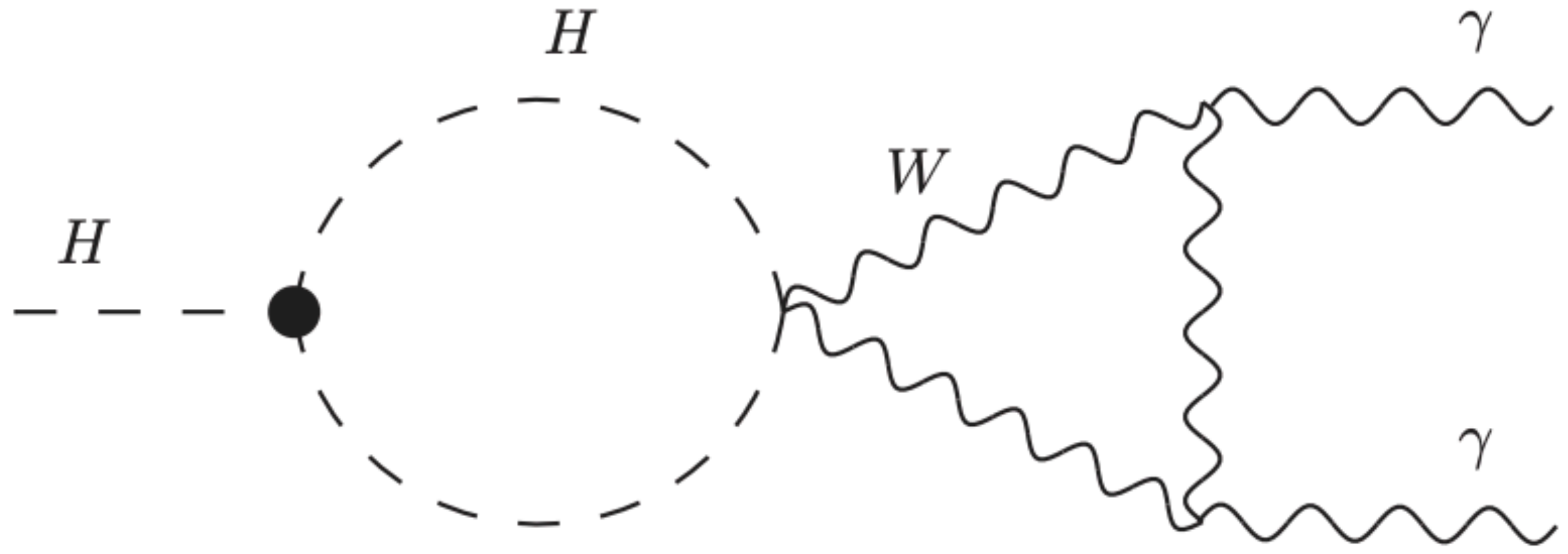
Directly change bosonic decays

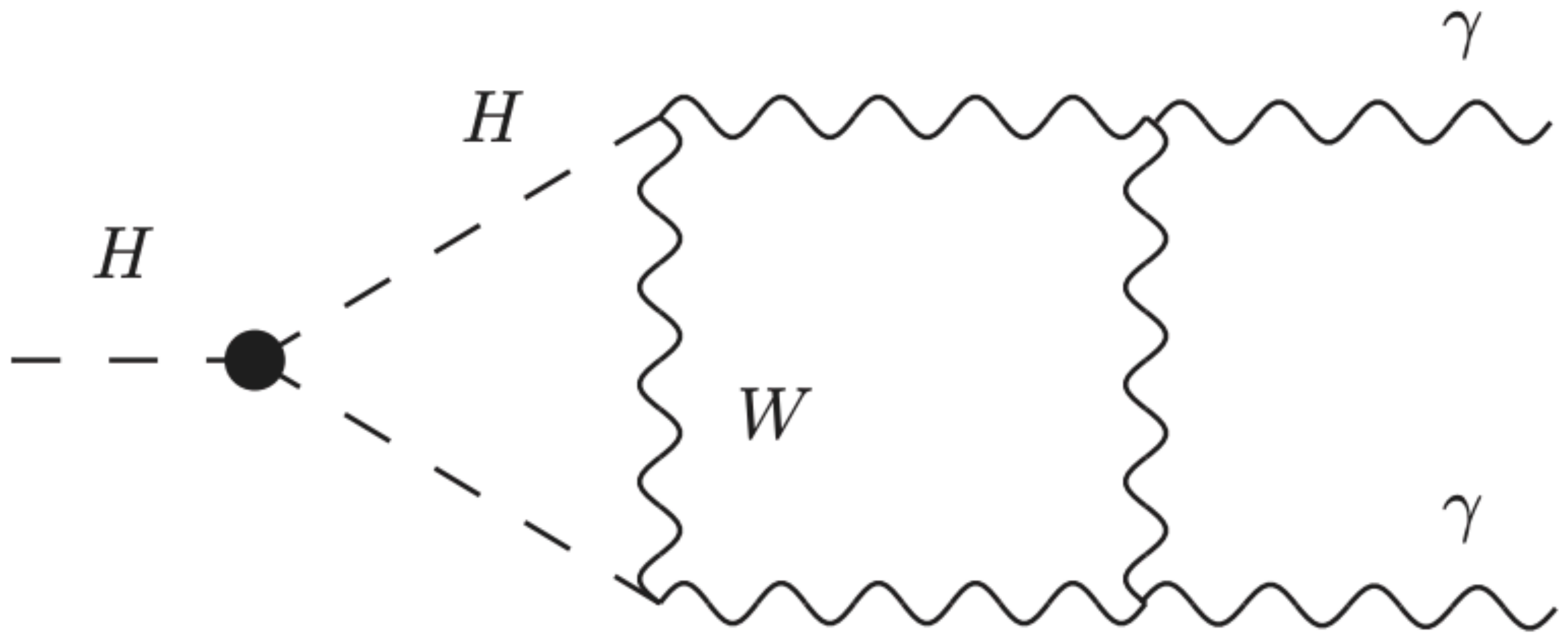
Indirectly change fermionic decays





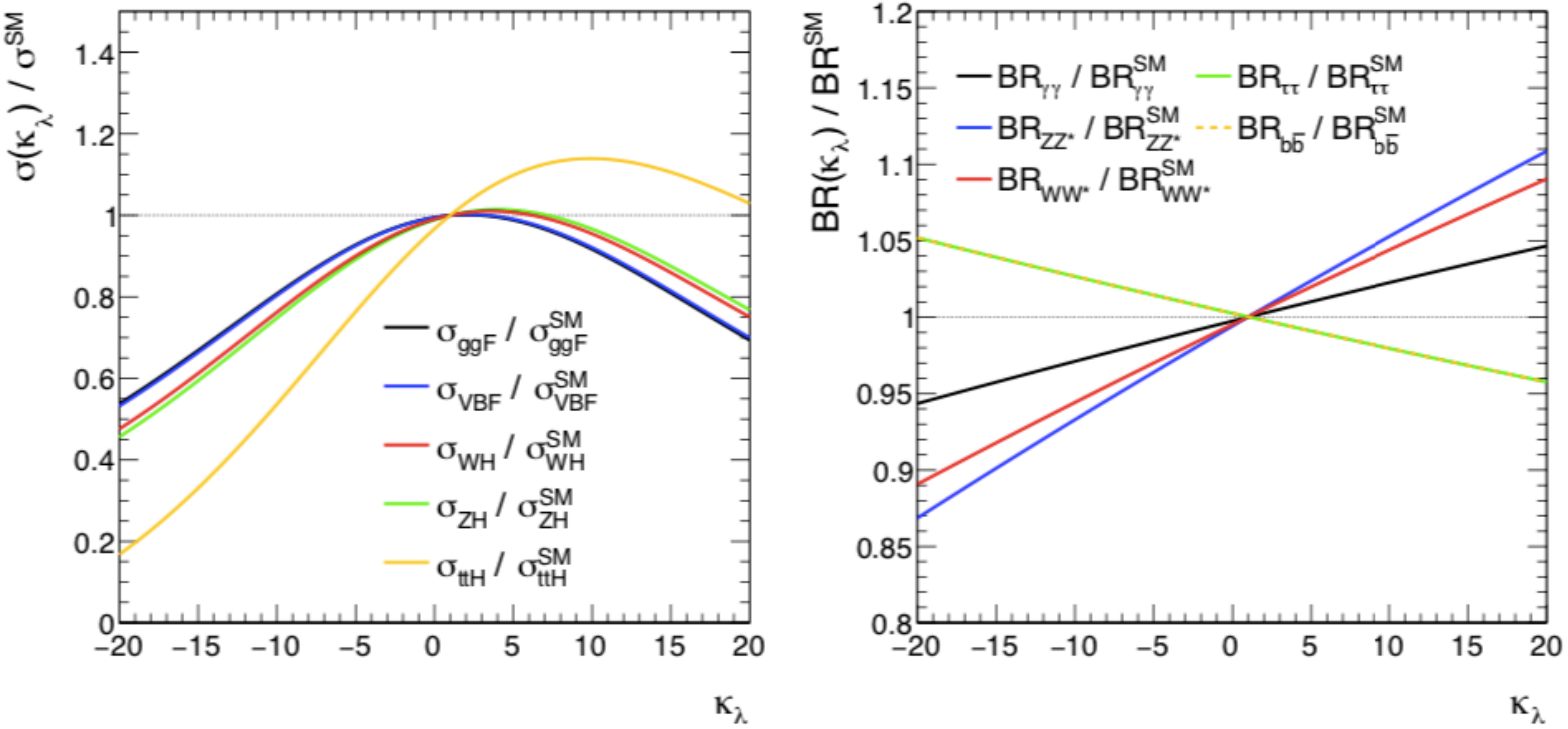






Indirect self-coupling measurement from single Higgs

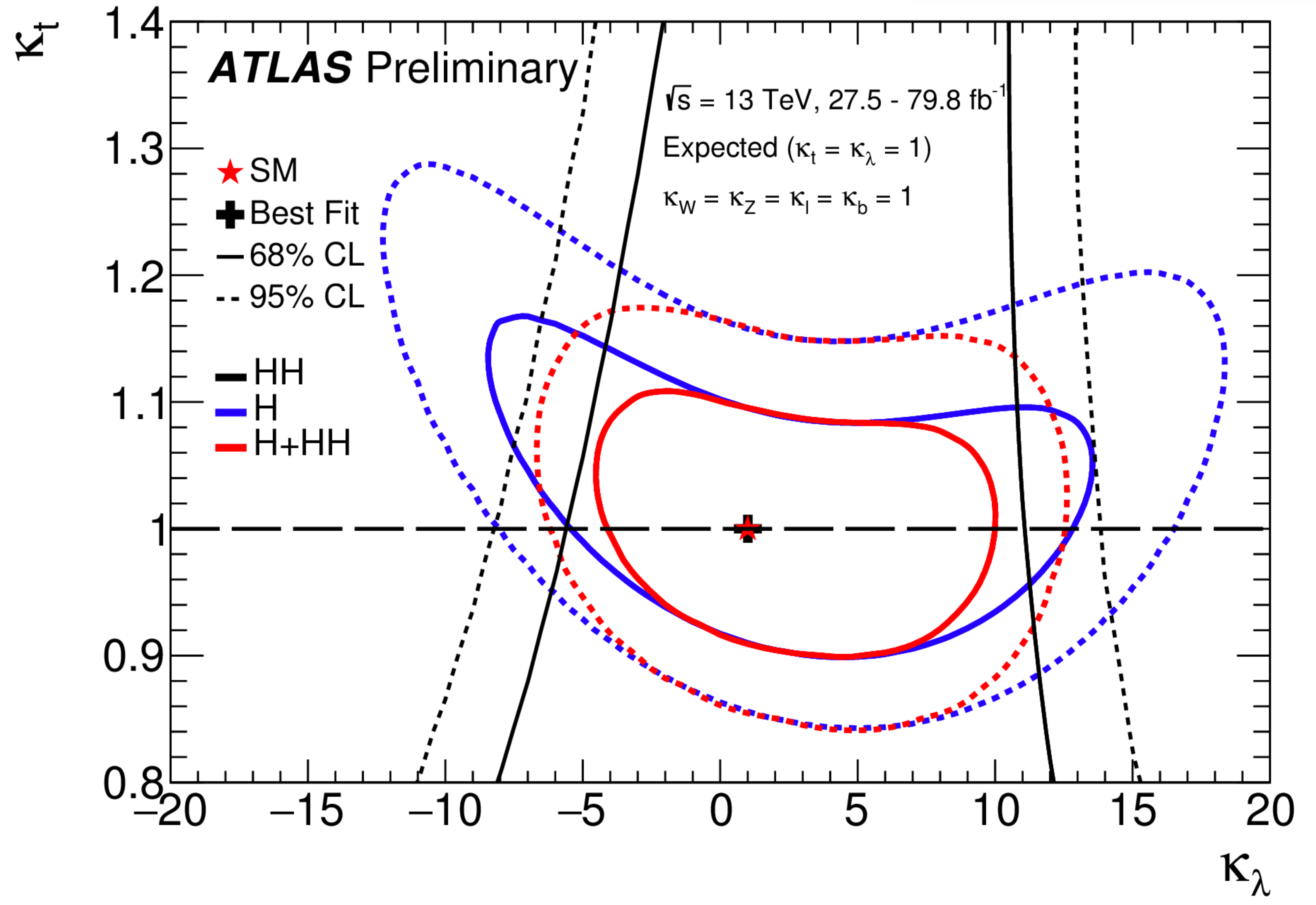
- Single Higgs coupling measurements can **indirectly** influence the Higgs self-coupling, **via EW loop corrections**

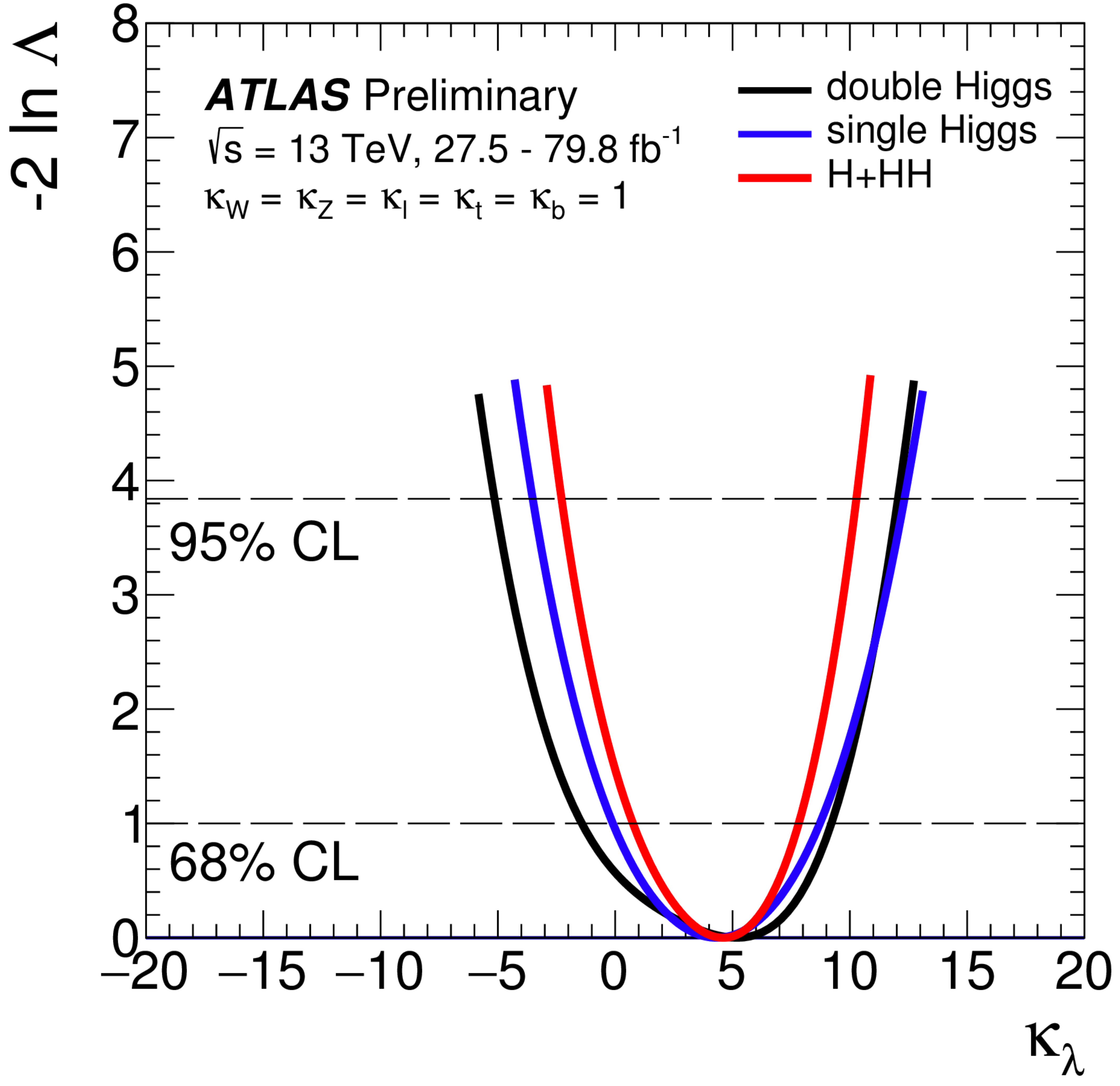


Combined HH+H

HH (36/fb)	$-5.0 < \kappa_\lambda < 12.0$
H (80/fb)	$-3.2 < \kappa_\lambda < 11.9$

H+HH → $-2.3 < \kappa_\lambda < 10.3$

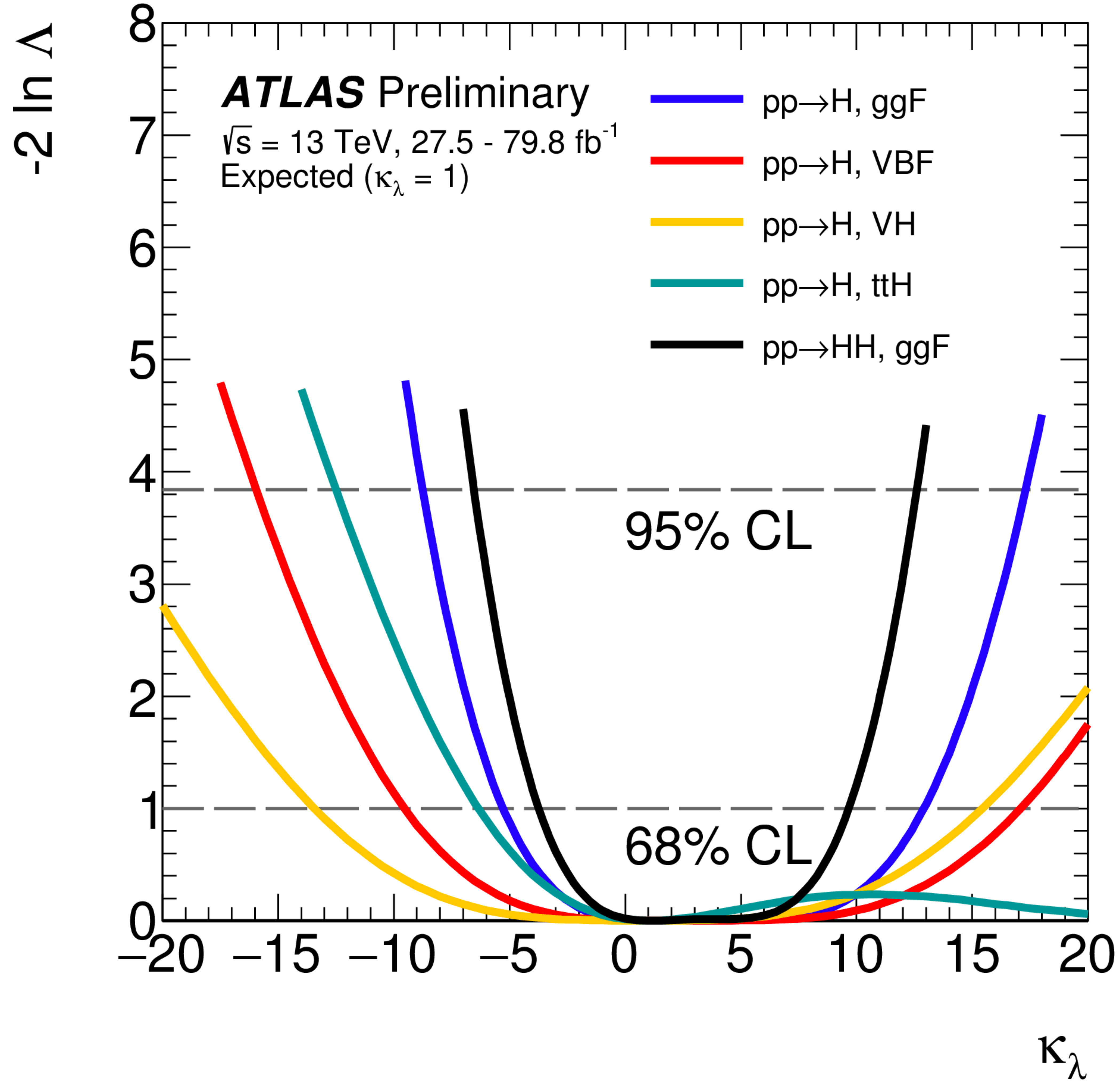


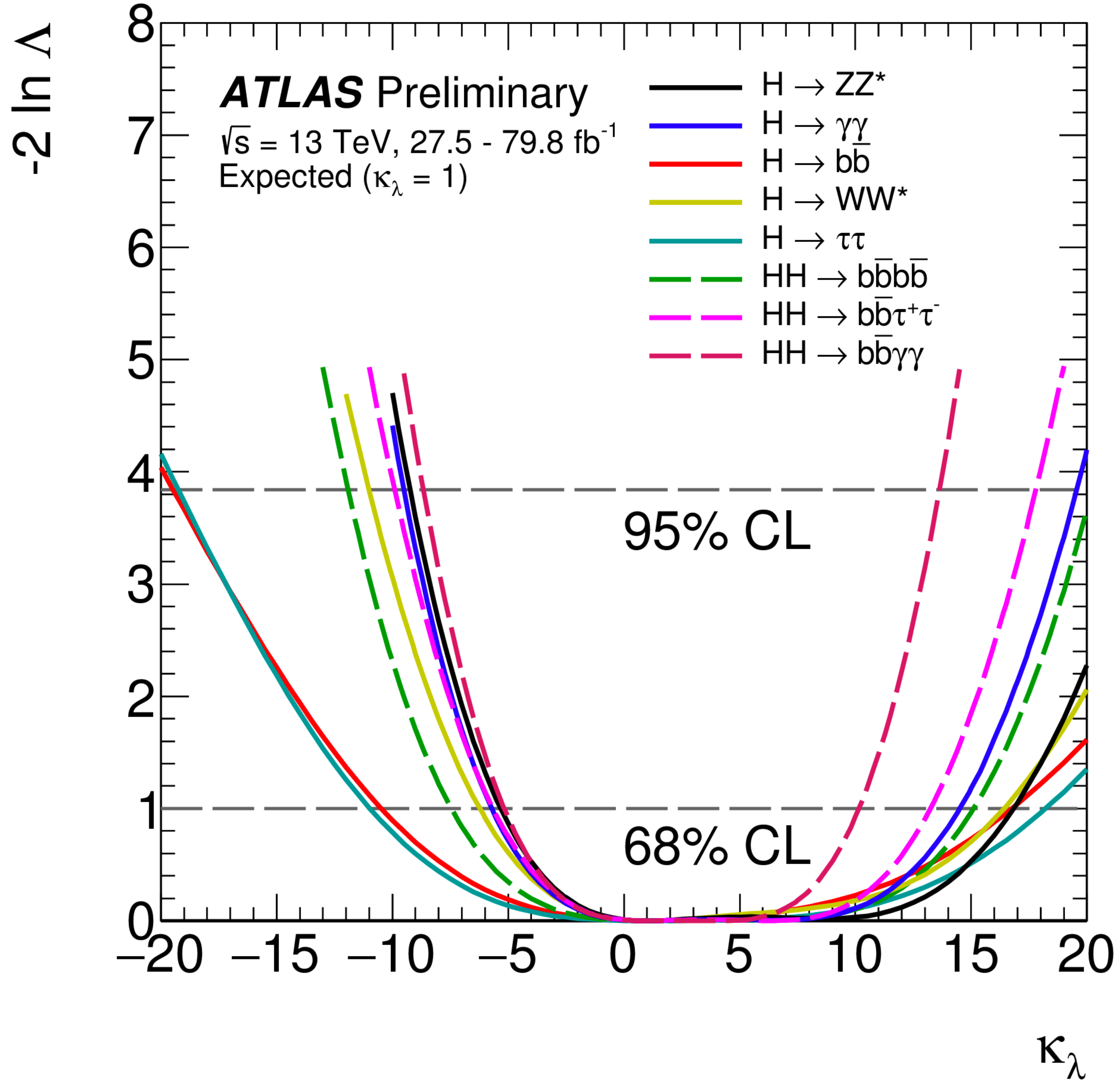


NEW on “Higgs hunting 2019” Sep

ATLAS-CONF-2019-049

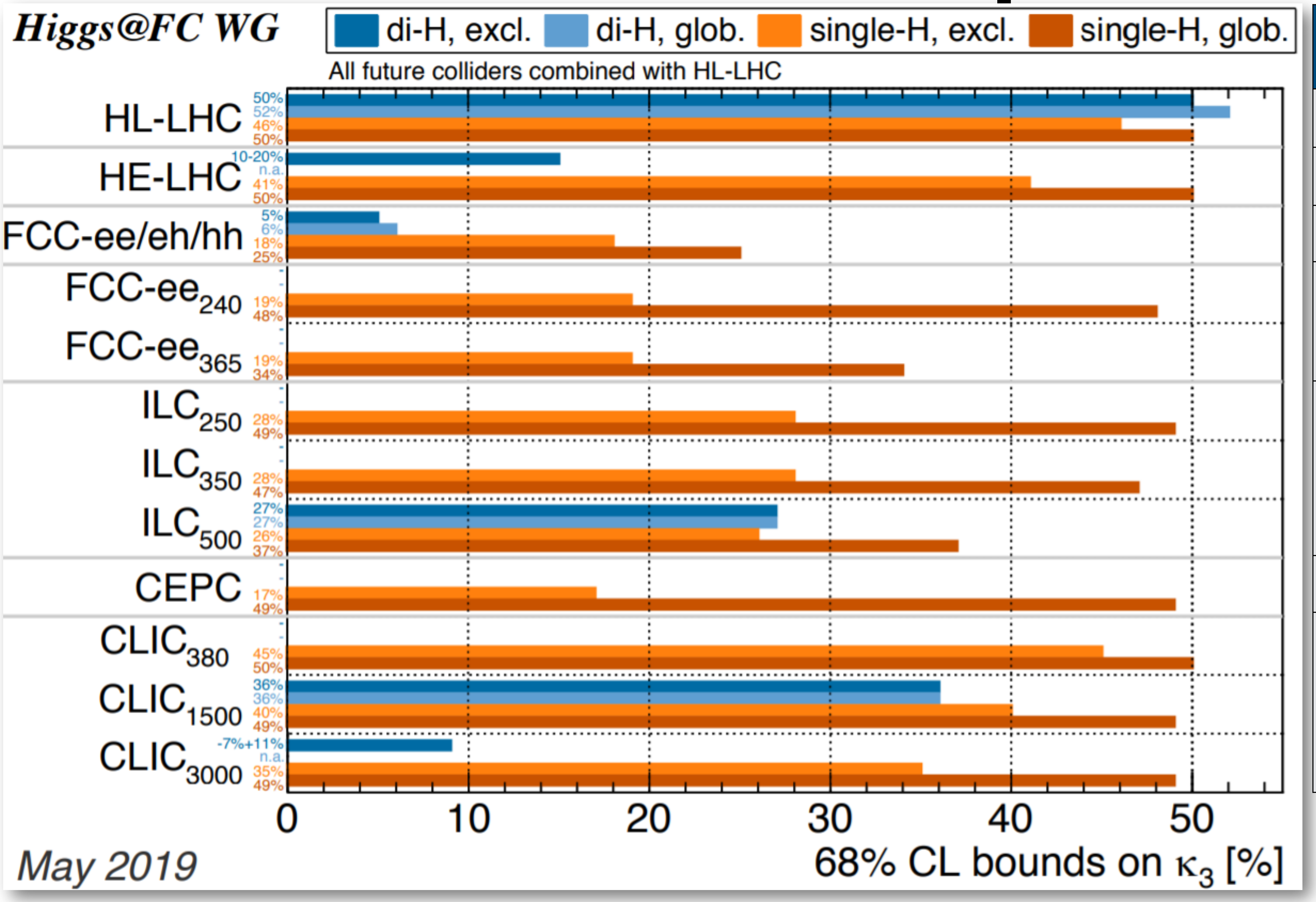
Breakdown


-2 ln Λ
ATLAS Preliminary
√s = 13 TeV, 27.5 - 79.8 fb-1
Expected (κλ = 1)
pp→H, ggF
pp→H, VBF
pp→H, VH
pp→H, ttH
pp→HH, ggF
95% CL
68% CL
κλ


-2 ln Λ
ATLAS Preliminary
√s = 13 TeV, 27.5 - 79.8 fb-1
Expected (κλ = 1)
H → ZZ*
H → γγ
H → bb̄
H → WW*
H → ττ
HH → bb̄bb̄
HH → bb̄τ+τ-
HH → bb̄γγ
95% CL
68% CL
κλ

Contents

"All" future possibilities



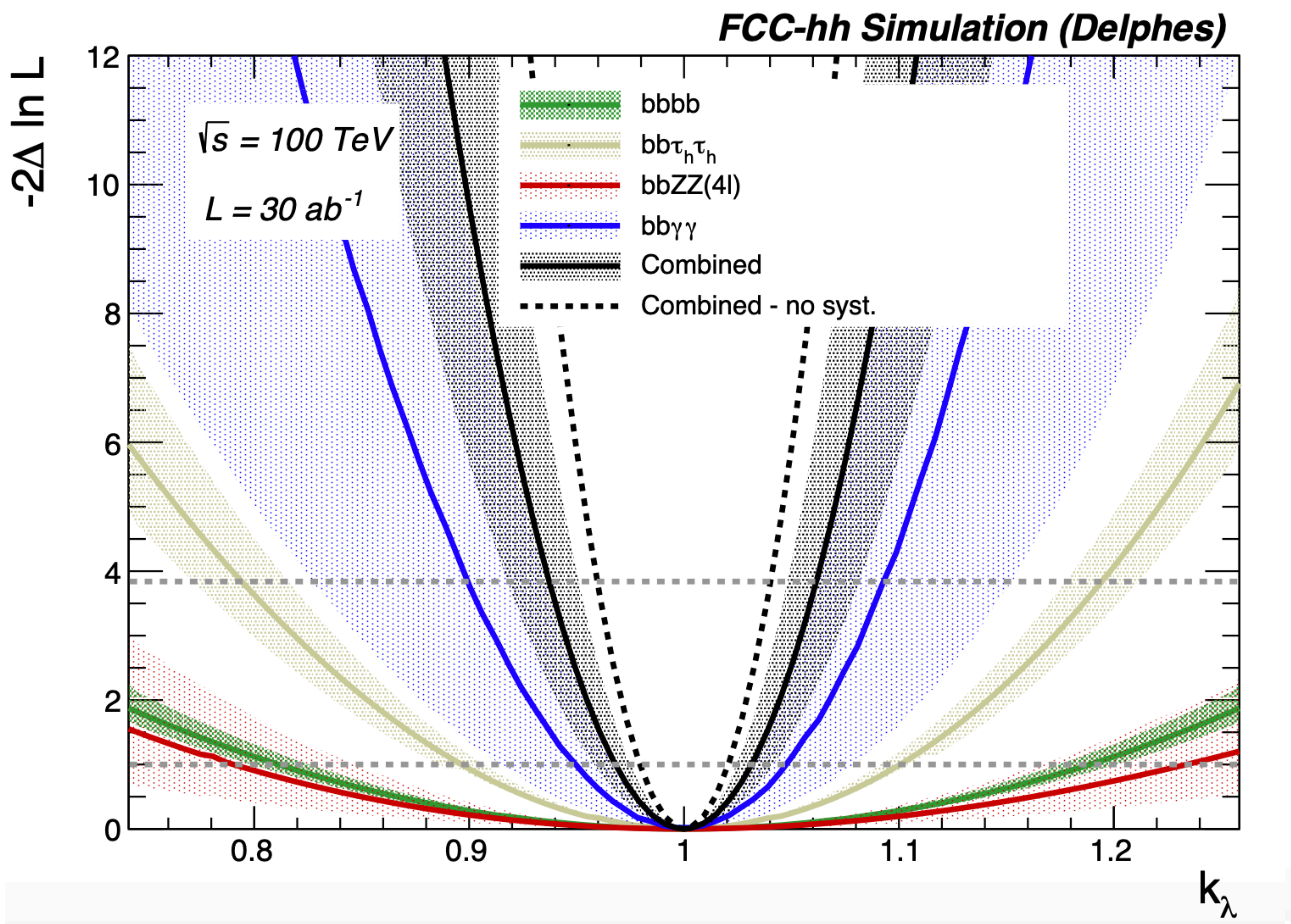
HH	H
~50%	~50%
~15%	~40%
~5%	~20%
-	~20%
~25%	~25%
-	~15%
~10%	~35%

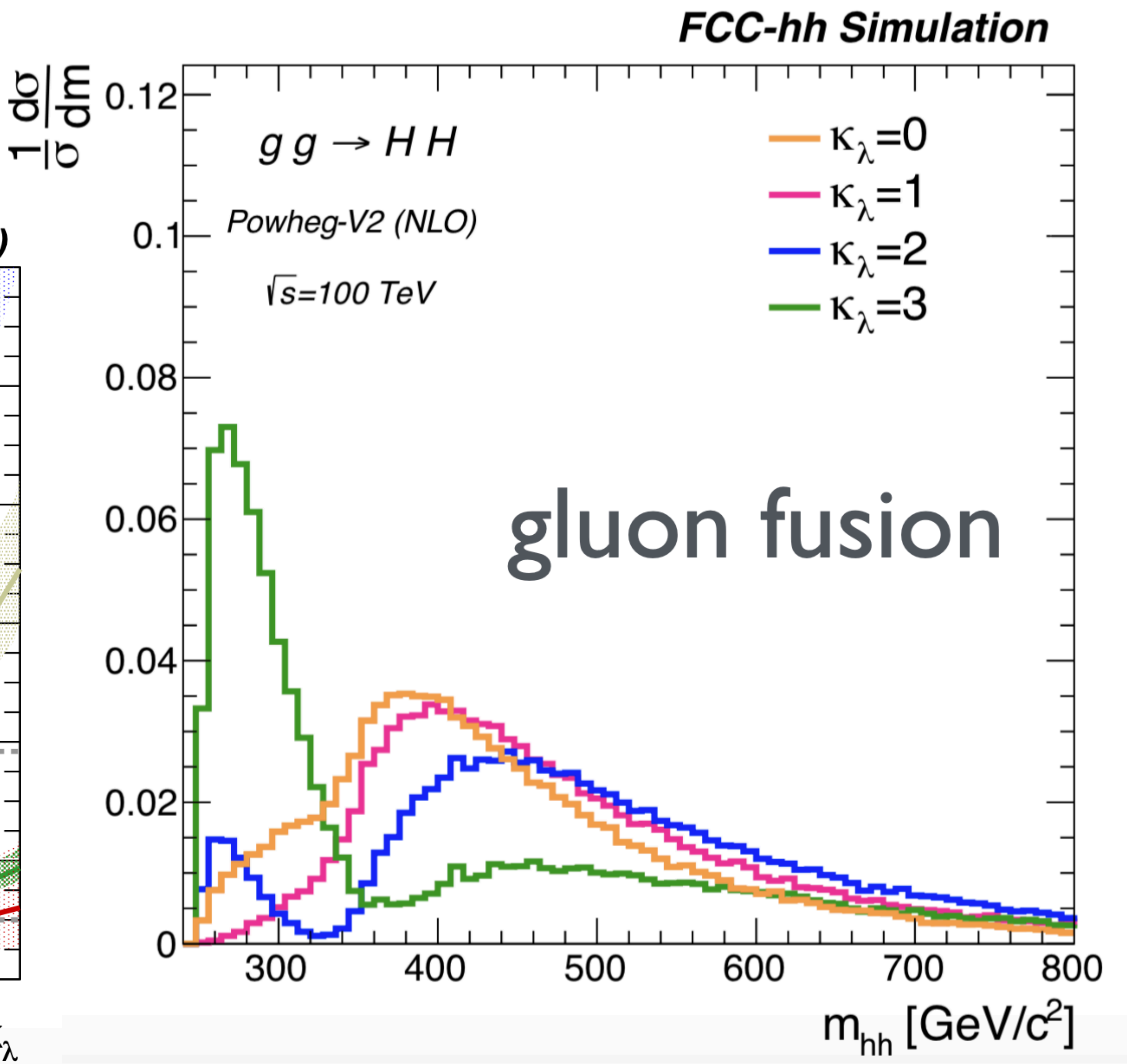
The best precision in each category

HH is robust w.r.t other Higgs couplings

FCC-hh

The ggF HH xsec will reach O(1) pb
The Higgs self-coupling will finally reach precision measurement in FCC-hh

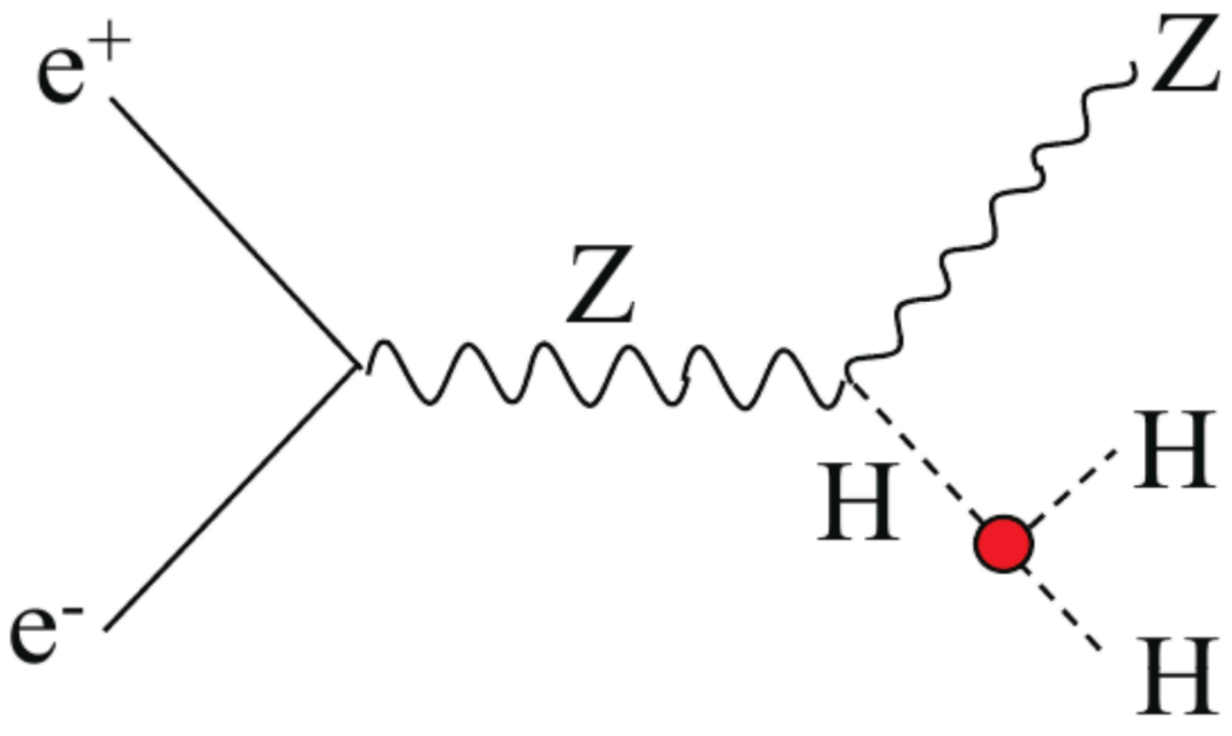


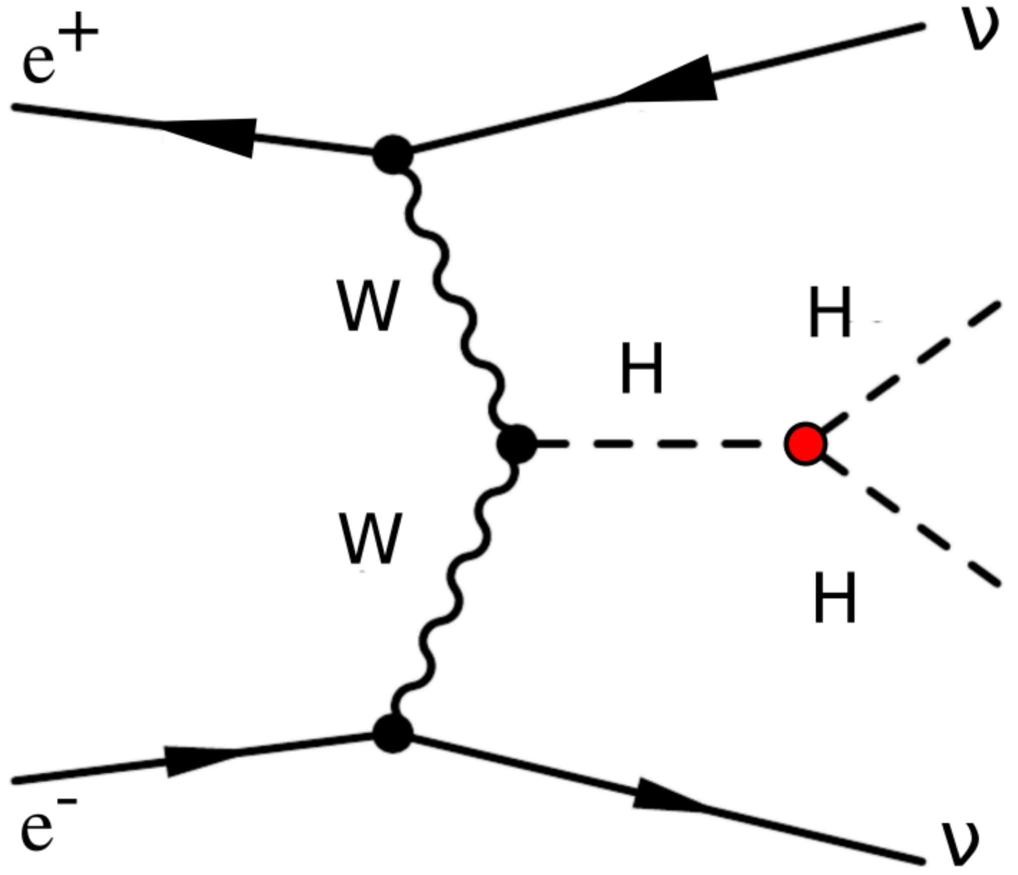


ee-collider HH

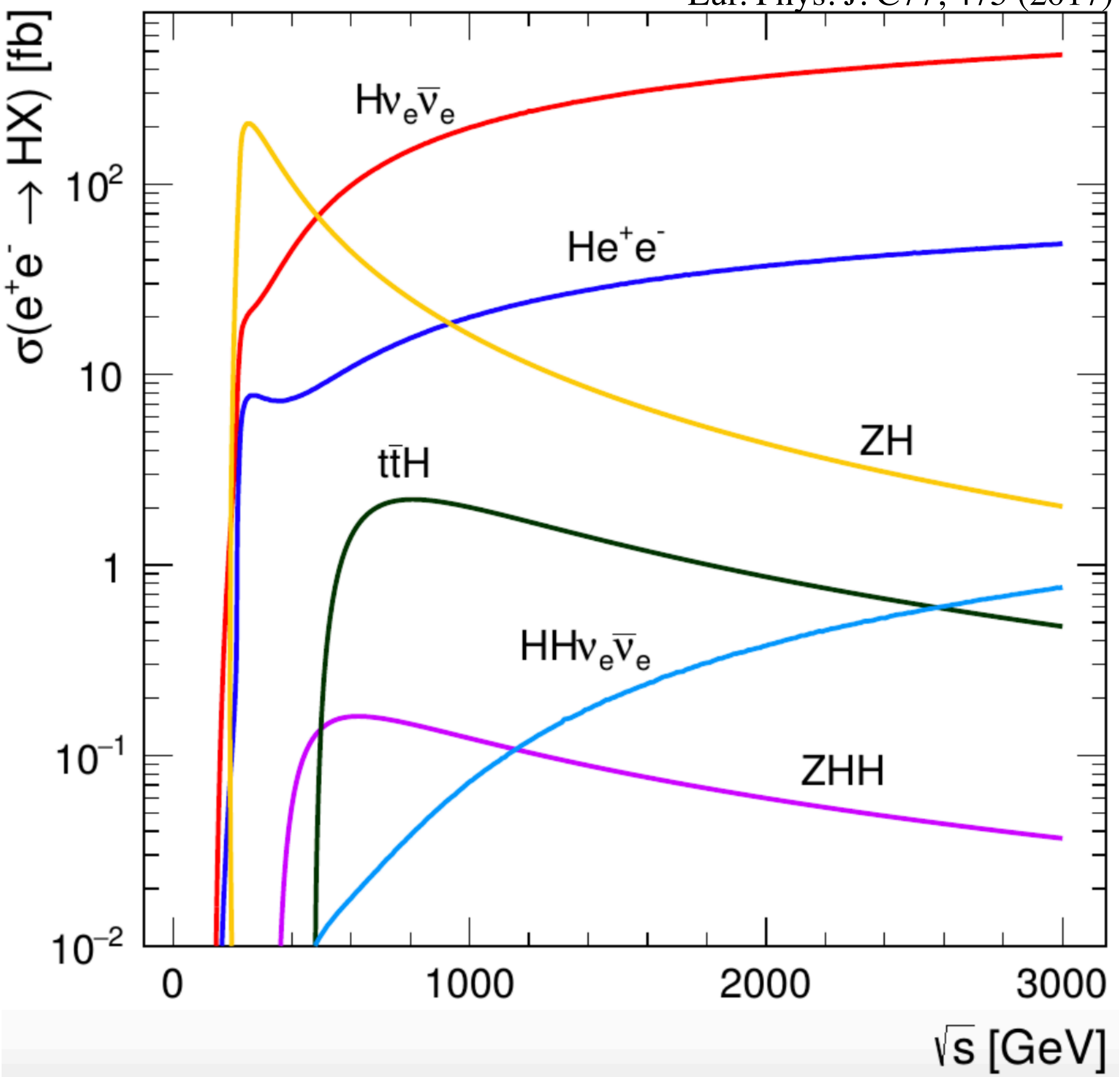
Dominant production
ZHH Higgsstrahlung and VBF HHvv

Accessible >~ 500 GeV





Eur. Phys. J. C77, 475 (2017)

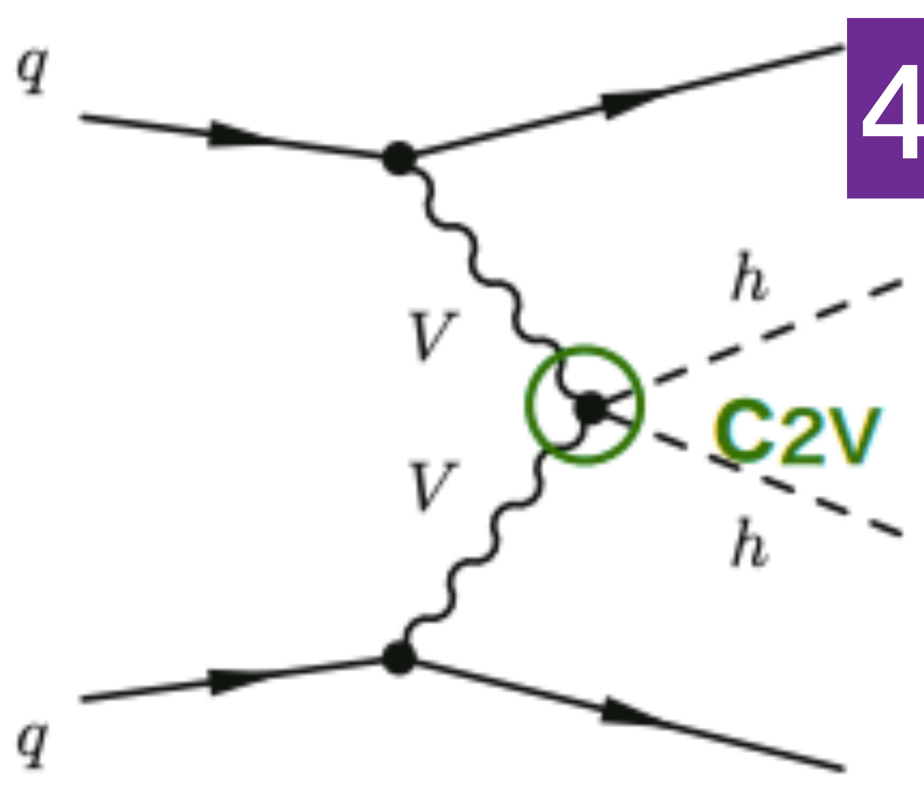


Summary

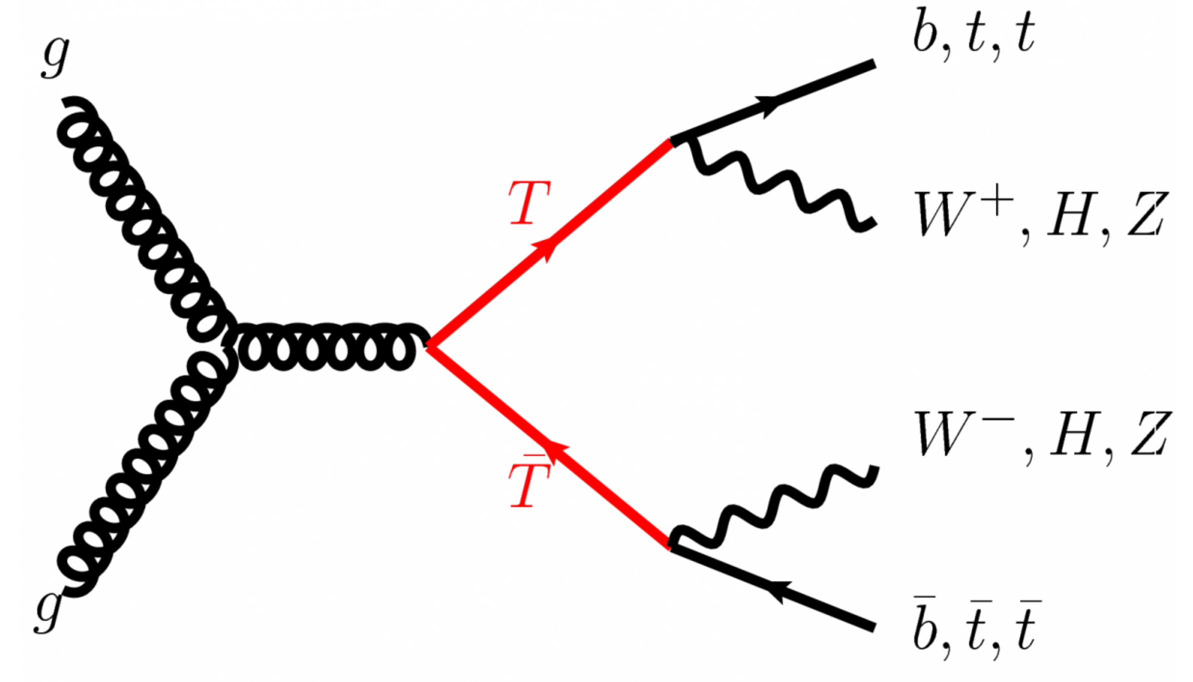
- Higgs self-coupling being one of the largest motivations drive the HH searches
  - This can complete the missing piece of the SM, reveal the Higgs potential and indicate the evolution of the early Universe
- There were/are a large number of HH search programs on the hadron collider
  - These analyses already impose influencing impact in the domain and the related
- A variety of new physics beyond Higgs self-coupling can be probed using HH
- HH+H combination is very meaningful
  - With the current statistics, single Higgs is in a similar level of sensitivity to HH
- Look forward to fruitful results in near future

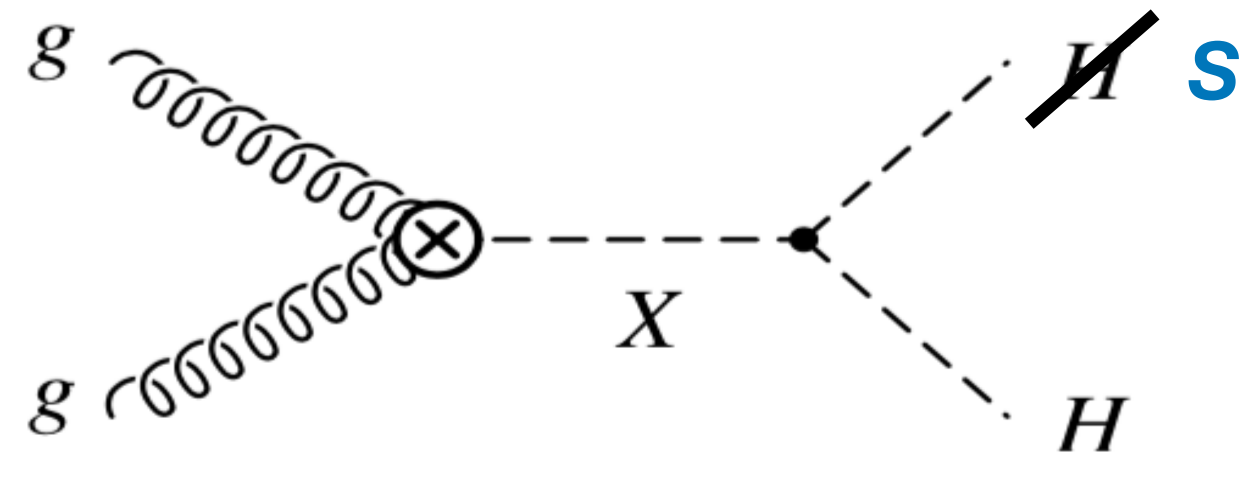
Backup

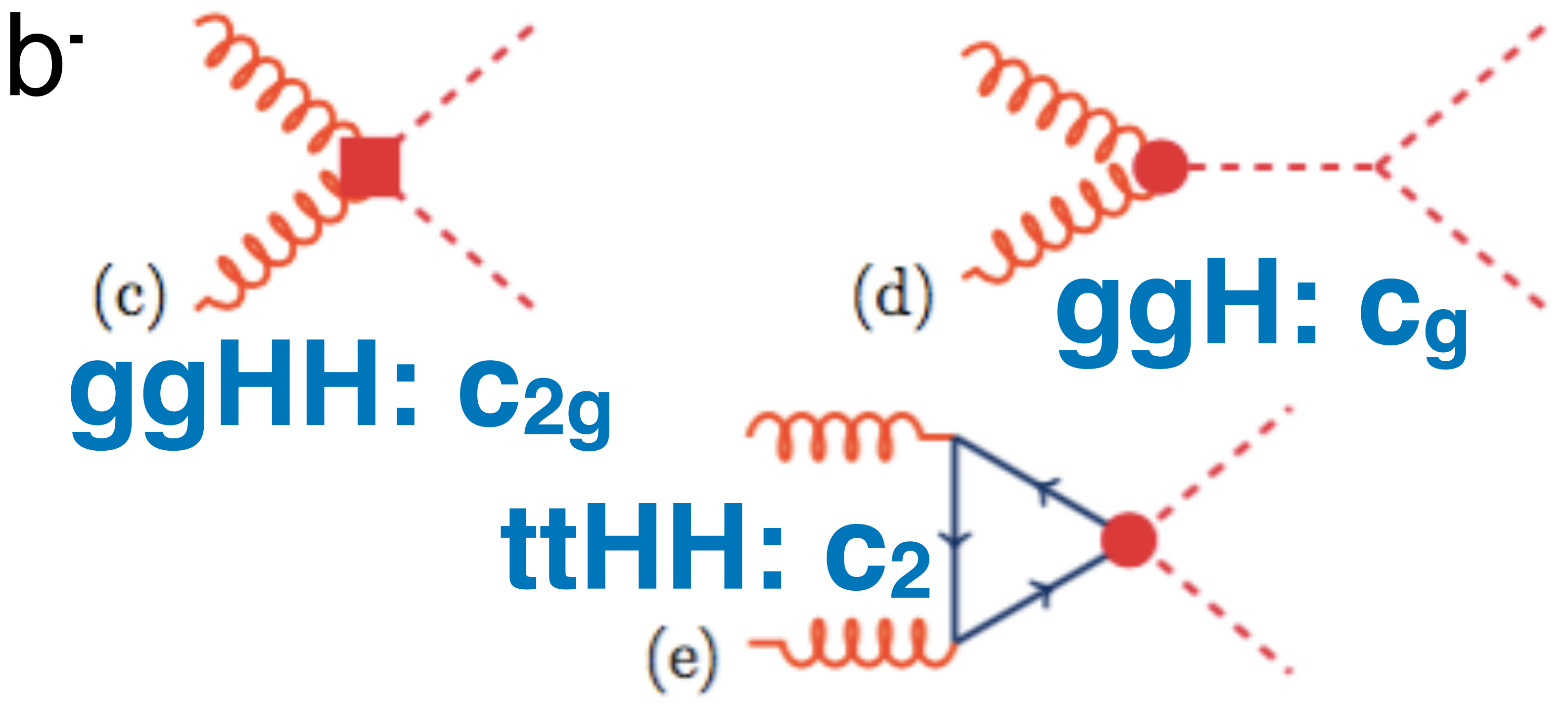
HH@LHC: new ideas?



- What else can we do with HH, besides what we are doing? New production modes, new BSM models etc.
- VBF HH (HHjj): strong contamination from ggH + jj events, but very sensitive to the C_{2V} coupling
  - Already started on 4b, can extend to more decay channels
- ttHH, the third largest production: fun to look at, huge number of final state particles
  - Alternative BSM target: tHtH for vector-like-quark T'→tH (indications from recent tension in SM **lepton universality** tests, such as R(D$^{(*)}$), R(K$^{(*)}$), and W→τν over W→eν+μν)
- HH→bbττ for alternative BSM target leptoquark with bτbτ, LQ→b
- SH models, where S is non-SM Higgs, mainly for enhanced bosonic decays
- Effective field theory (EFT) coupling constraints

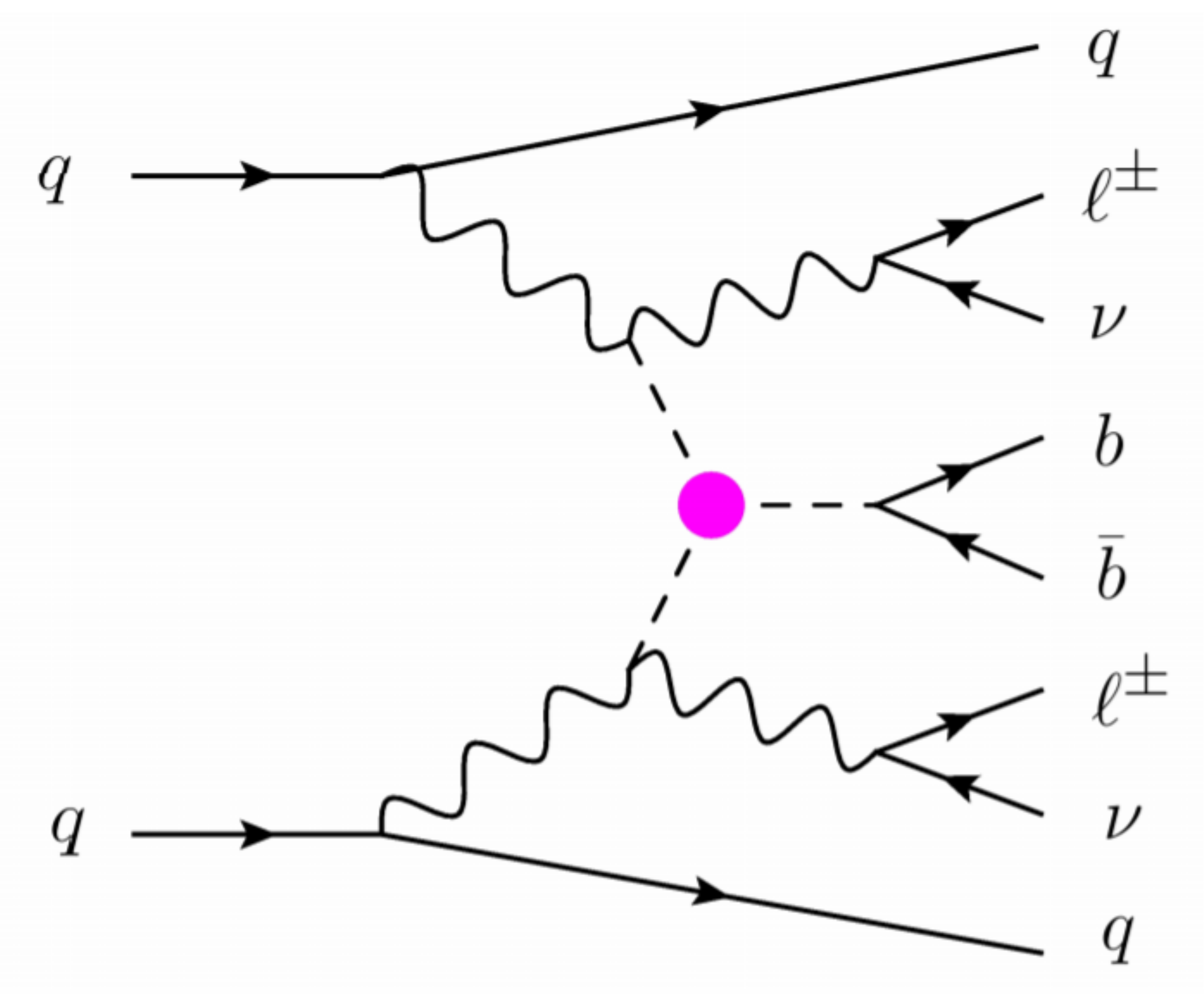


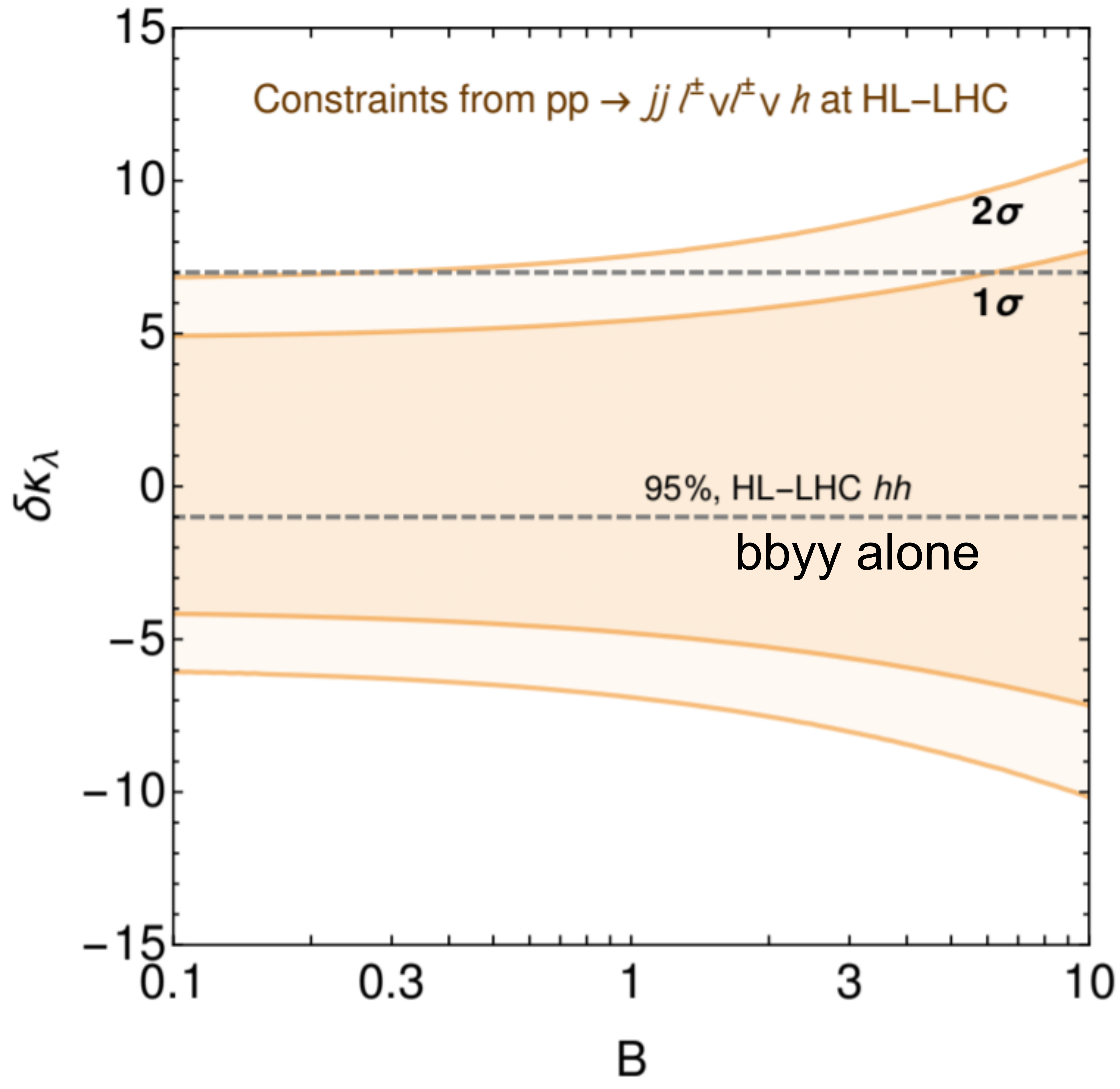




One more: when Higgs meets VBS

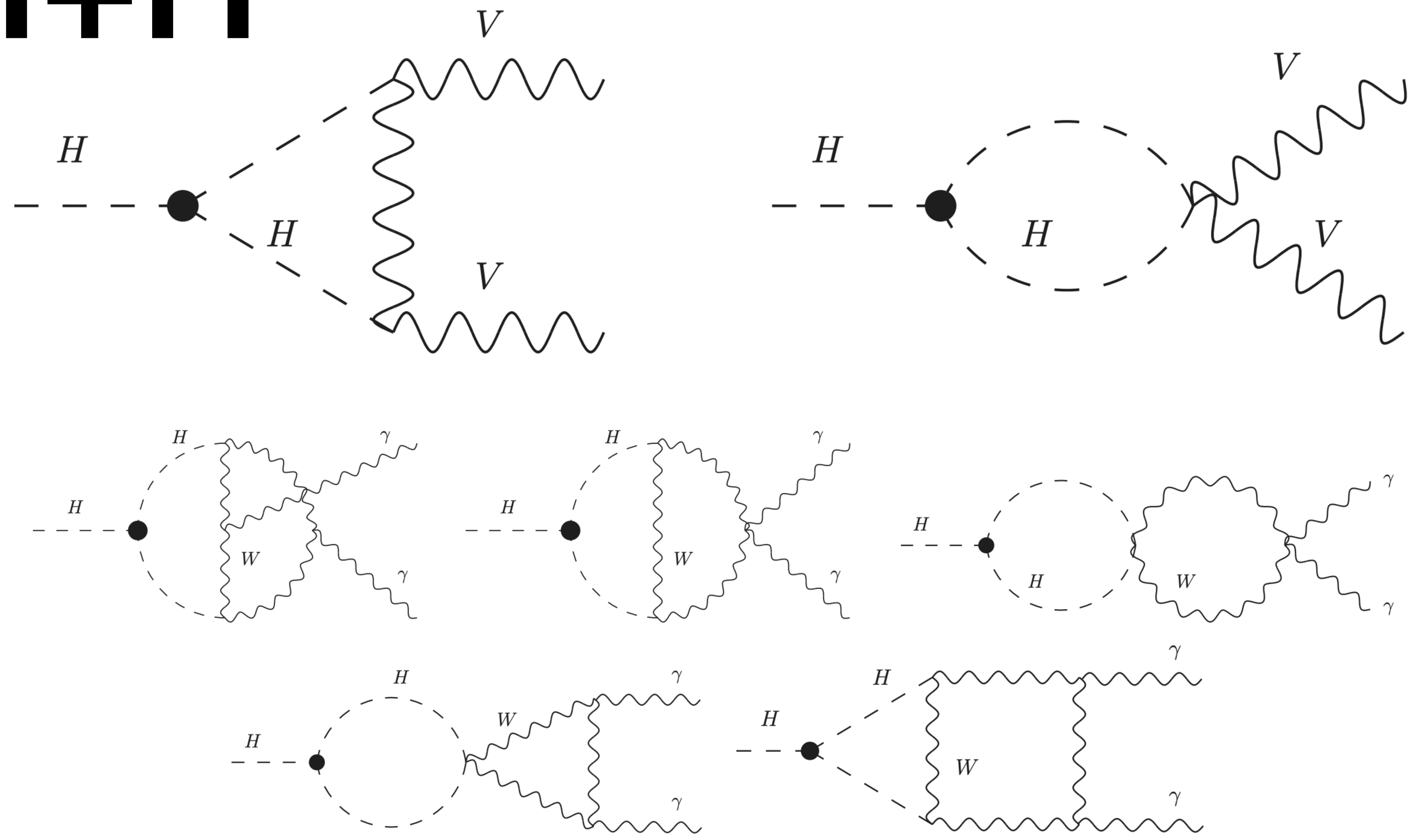
Higgs Couplings without the Higgs PhysRevLett.123.181801





HH+H

production mode	ggF	VBF	ZH	WH	$t\bar{t}H$
$C_1^i \times 100$	0.66	0.63	1.19	1.03	3.52
K_{EW}^i	1.049	0.932	0.947	0.93	1.014
κ_i^2	κ_F^2	κ_V^2	κ_V^2	κ_V^2	κ_F^2



$$\mu_i(\kappa_\lambda, \kappa_i) = \frac{\sigma^{\mathrm{BSM}}}{\sigma^{\mathrm{SM}}} = Z_H^{\mathrm{BSM}}(\kappa_\lambda)\left[\kappa_i^2 + \frac{(\kappa_\lambda - 1)C_1^i}{K_{\mathrm{EW}}^i}\right]$$

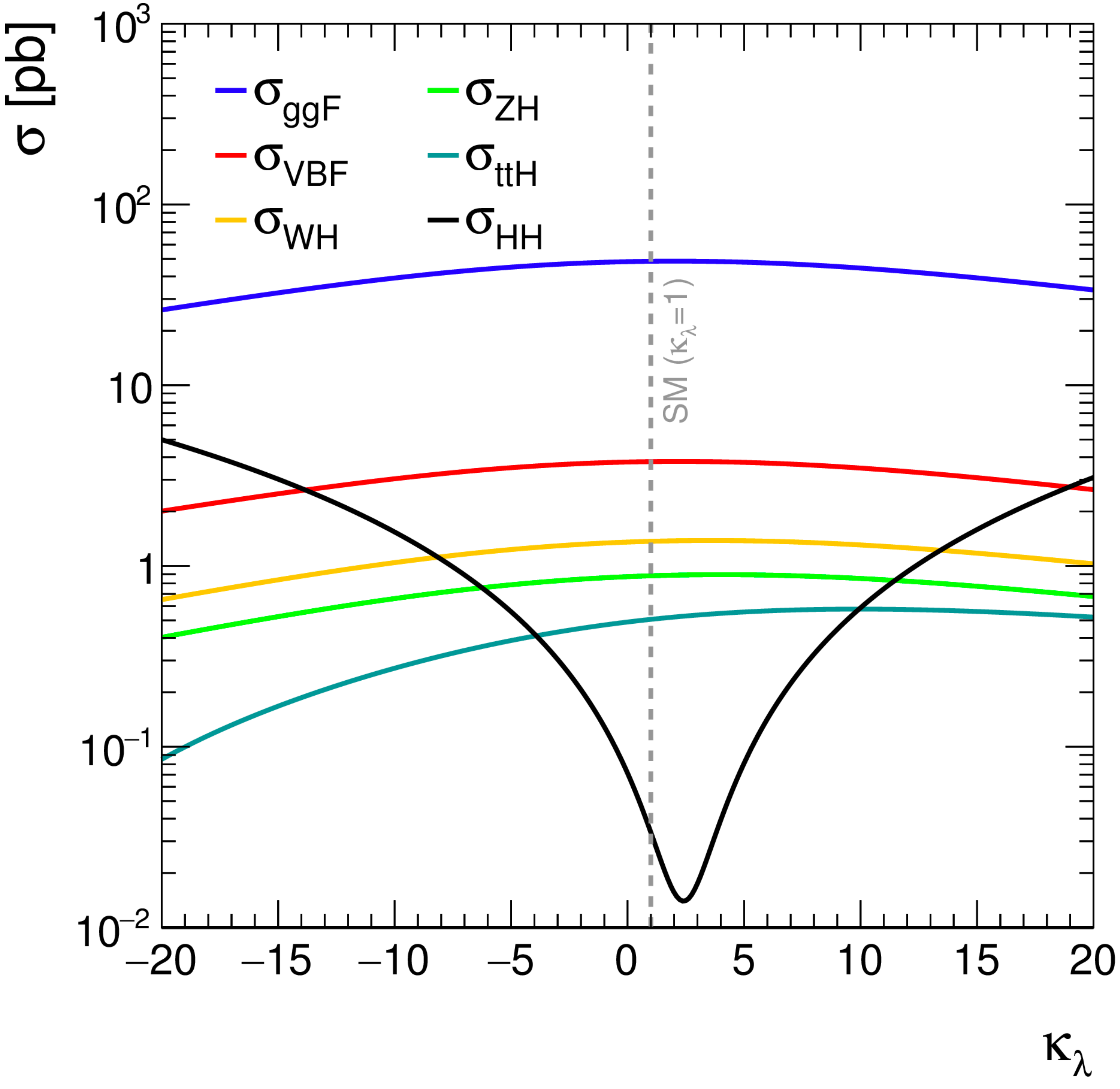
$$\mu_f(\kappa_\lambda, \kappa_f) = \frac{\mathrm{BR}_f^{\mathrm{BSM}}}{\mathrm{BR}_f^{SM}} = \frac{\kappa_f^2 + (\kappa_\lambda - 1)C_1^f}{\sum_j \mathrm{BR}_j^{\mathrm{SM}}\left[\kappa_j^2 + (\kappa_\lambda - 1)C_1^j\right]}$$

$$Z_H^{\mathrm{BSM}}(\kappa_\lambda) = \frac{1}{1 - (\kappa_\lambda^2 - 1)\delta Z_H} \quad \text{with} \quad \delta Z_H = -1.536 \times 10^{-3}$$

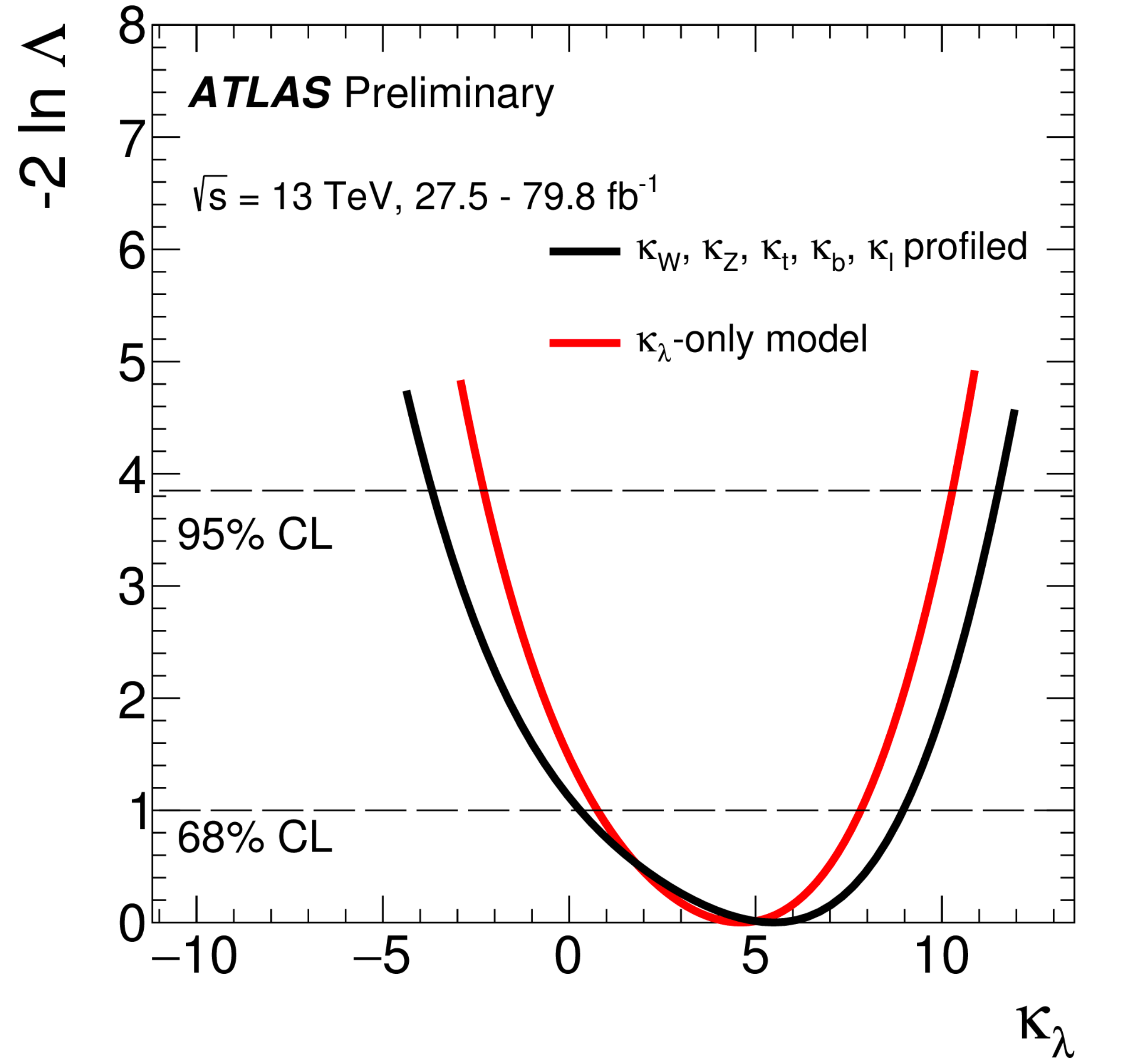
Not all decays are DIRECTLY corrected by κ_λ

decay mode	$H \to \gamma\gamma$	$H \to WW^*$	$H \to ZZ^*$	$H \to b\bar{b}$	$H \to \tau\tau$
$C_1^f \times 100$	0.49	0.73	0.82	0	0
κ_f^2	$1.59\kappa_V^2 + 0.07\kappa_F^2 - 0.67\kappa_V\kappa_F$	κ_V^2	κ_V^2	κ_F^2	κ_F^2

HH+H

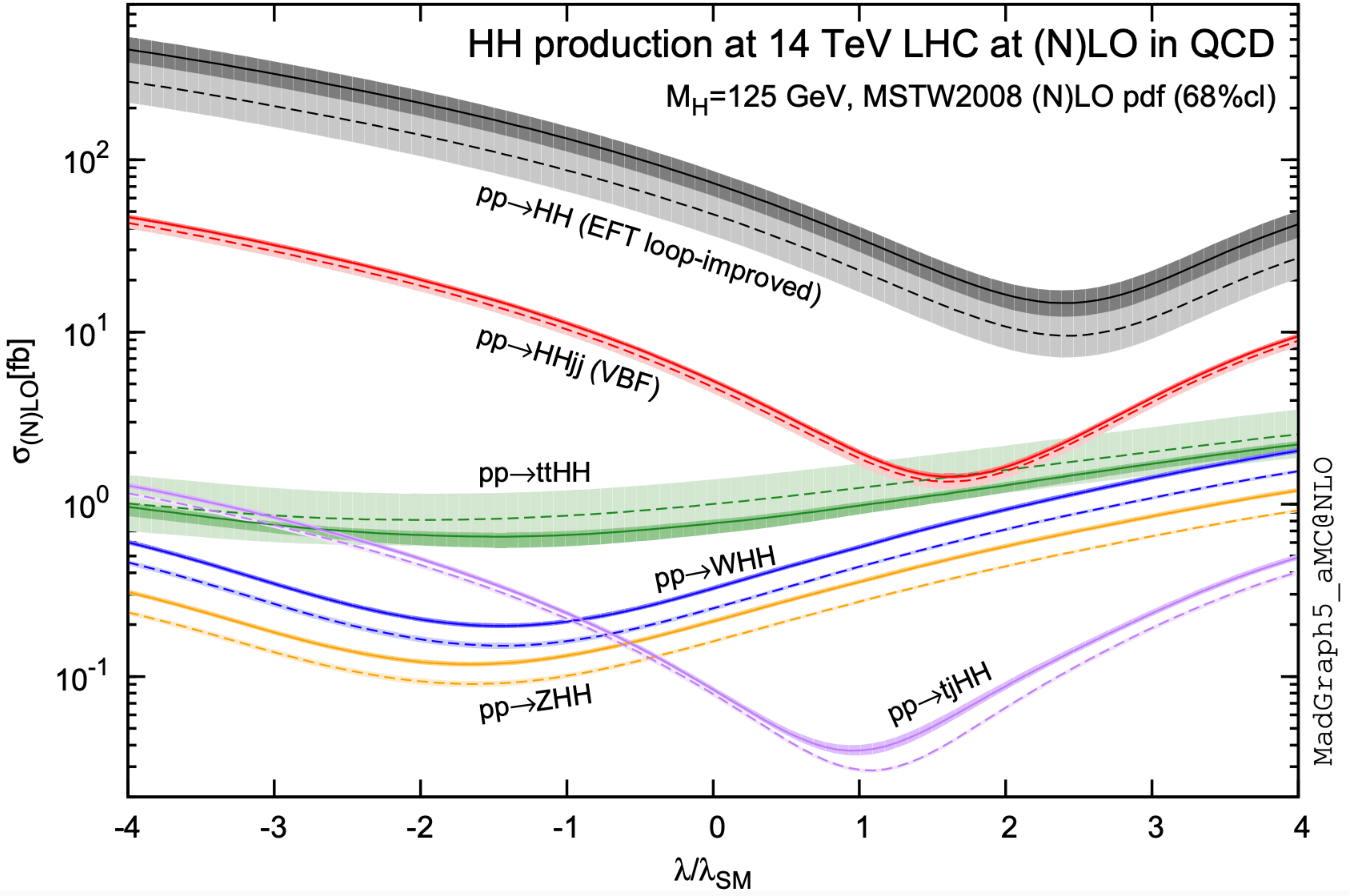


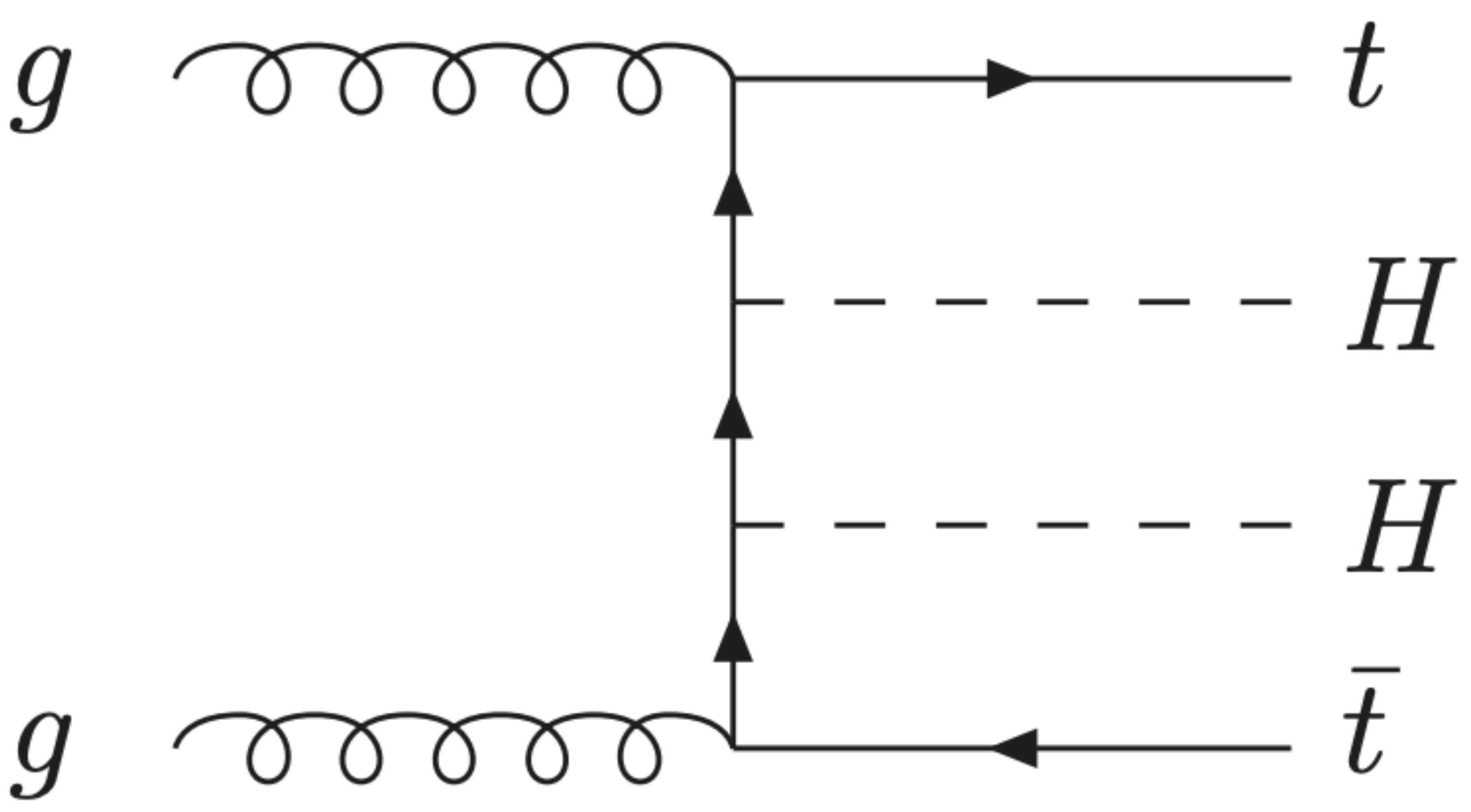
Analysis	Integrated luminosi
$H \to \gamma\gamma$ (excluding $t\bar{t}H$, $H \to \gamma\gamma$)	79.8
$H \to ZZ^* \to 4\ell$ (including $t\bar{t}H$, $H \to ZZ^* \to 4\ell$)	79.8
$H \to WW^* \to e\nu\mu\nu$	36.1
$H \to \tau^+\tau^-$	36.1
VH, $H \to b\bar{b}$	79.8
$t\bar{t}H$, $H \to b\bar{b}$	36.1
$t\bar{t}H$, $H \to$ multilepton	36.1
$HH \to bbbb$	27.5
$HH \to b\bar{b}\tau^+\tau^-$	36.1
$HH \to b\bar{b}\gamma\gamma$	36.1



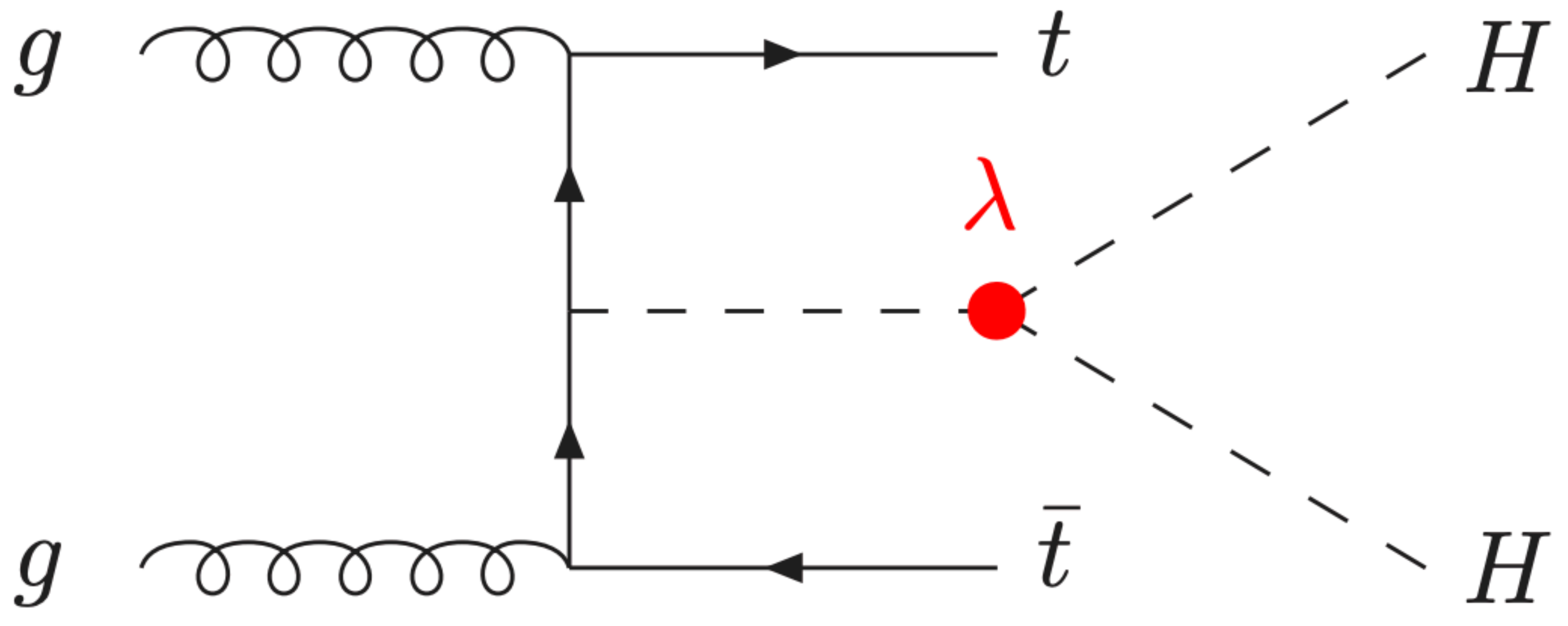
Model	$\kappa_{W\,-1\sigma}^{\ +1\sigma}$	$\kappa_{Z\,-1\sigma}^{\ +1\sigma}$	$\kappa_{t\,-1\sigma}^{\ +1\sigma}$	$\kappa_{b\,-1\sigma}^{\ +1\sigma}$	$\kappa_{\ell\,-1\sigma}^{\ +1\sigma}$	$\kappa_{\lambda\,-1\sigma}^{\ +1\sigma}$	κ_λ [95% CL]	
κ_λ-only	1	1	1	1	1	$4.6^{+3.2}_{-3.8}$	$[-2.3, 10.3]$	obs.
						$1.0^{+7.3}_{-3.8}$	$[-5.1, 11.2]$	exp.
Generic	$1.03^{+0.08}_{-0.08}$	$1.10^{+0.09}_{-0.09}$	$1.00^{+0.12}_{-0.11}$	$1.03^{+0.20}_{-0.18}$	$1.06^{+0.16}_{-0.16}$	$5.5^{+3.5}_{-5.2}$	$[-3.7, 11.5]$	obs.
	$1.00^{+0.08}_{-0.08}$	$1.00^{+0.08}_{-0.08}$	$1.00^{+0.12}_{-0.12}$	$1.00^{+0.21}_{-0.19}$	$1.00^{+0.16}_{-0.15}$	$1.0^{+7.6}_{-4.5}$	$[-6.2, 11.6]$	exp.

HH

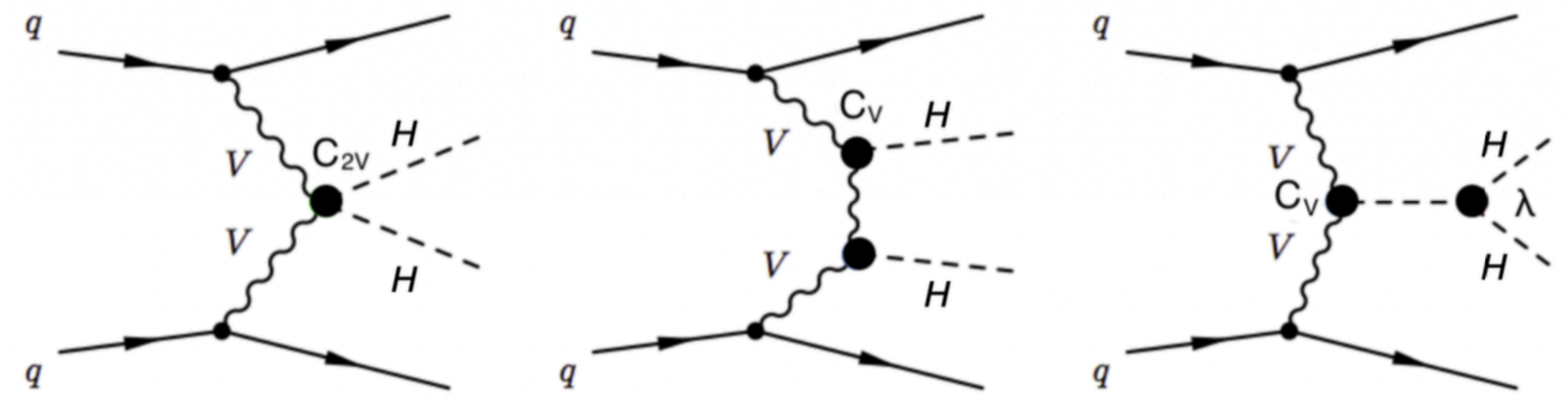

HH production at 14 TeV LHC at (N)LO in QCD
M_H=125 GeV, MSTW2008 (N)LO pdf (68%cl)
pp→HH (EFT loop-improved)
pp→HHjj (VBF)
pp→ttHH
pp→WHH
pp→ZHH
pp→tjHH
MadGraph5_aMC@NLO
σ(N)LO[fb]
λ/λSM


g
t
H
H
g
t̄

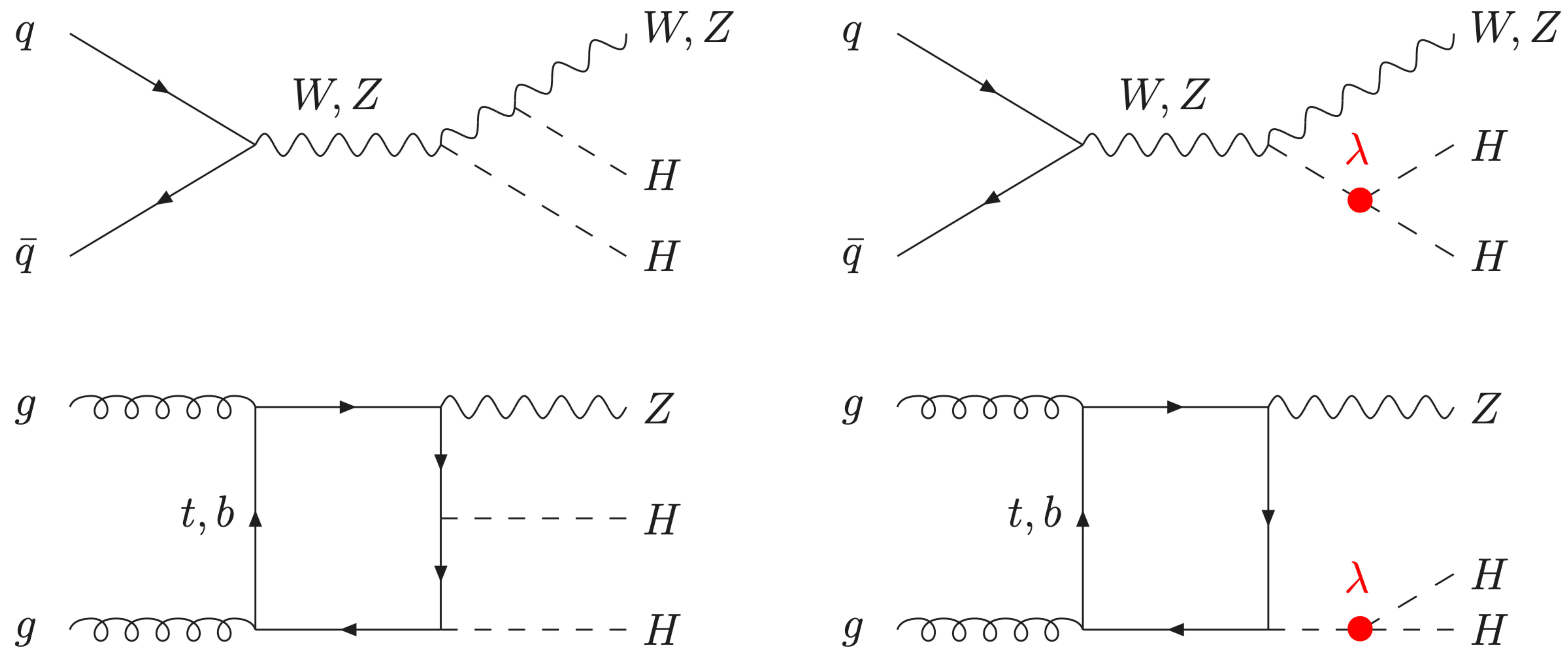
ttHH


g
t
H
λ
g
t̄
H

HH

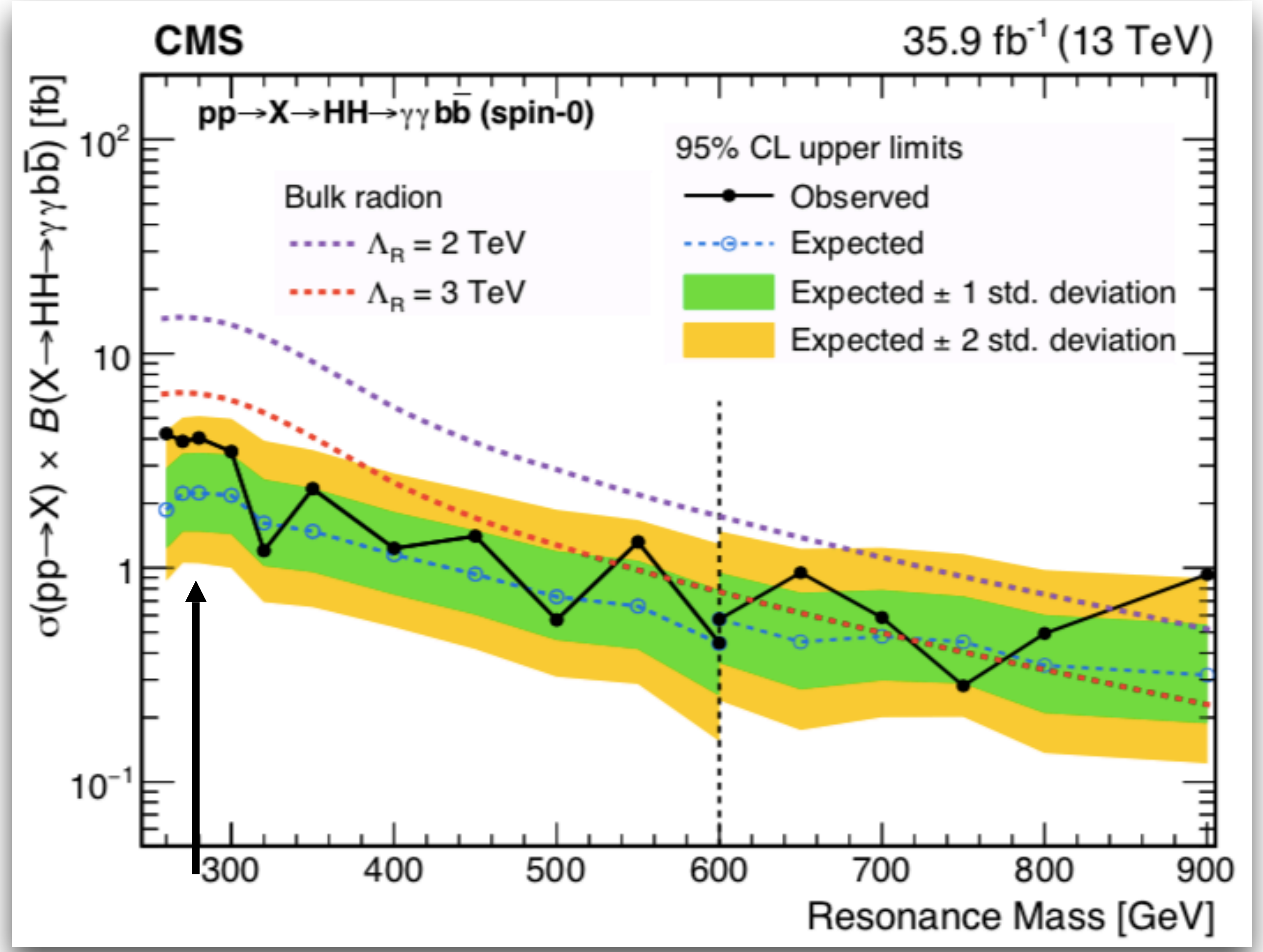


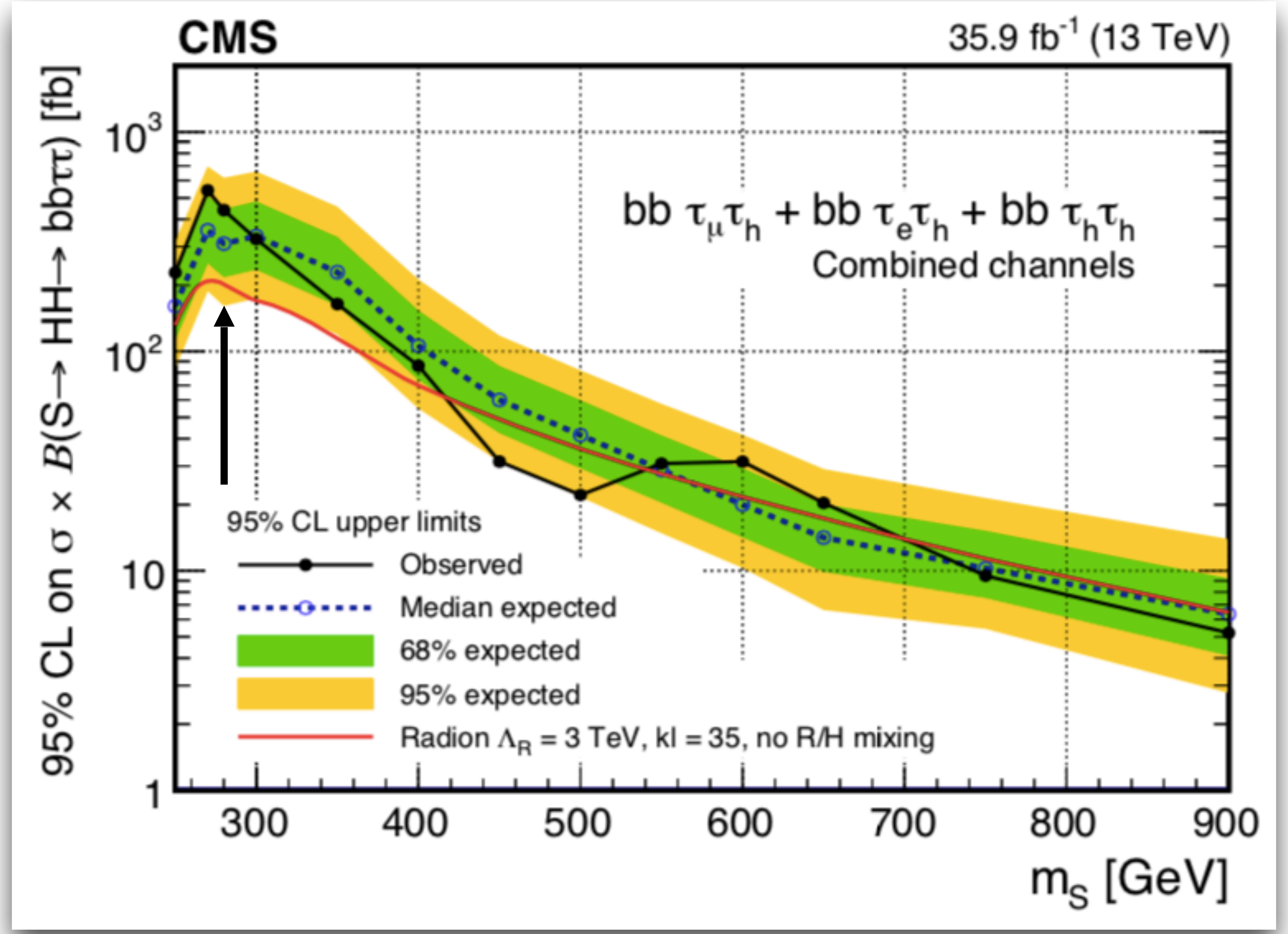
VBF



VHH

CMS HH: small excess ~300 GeV



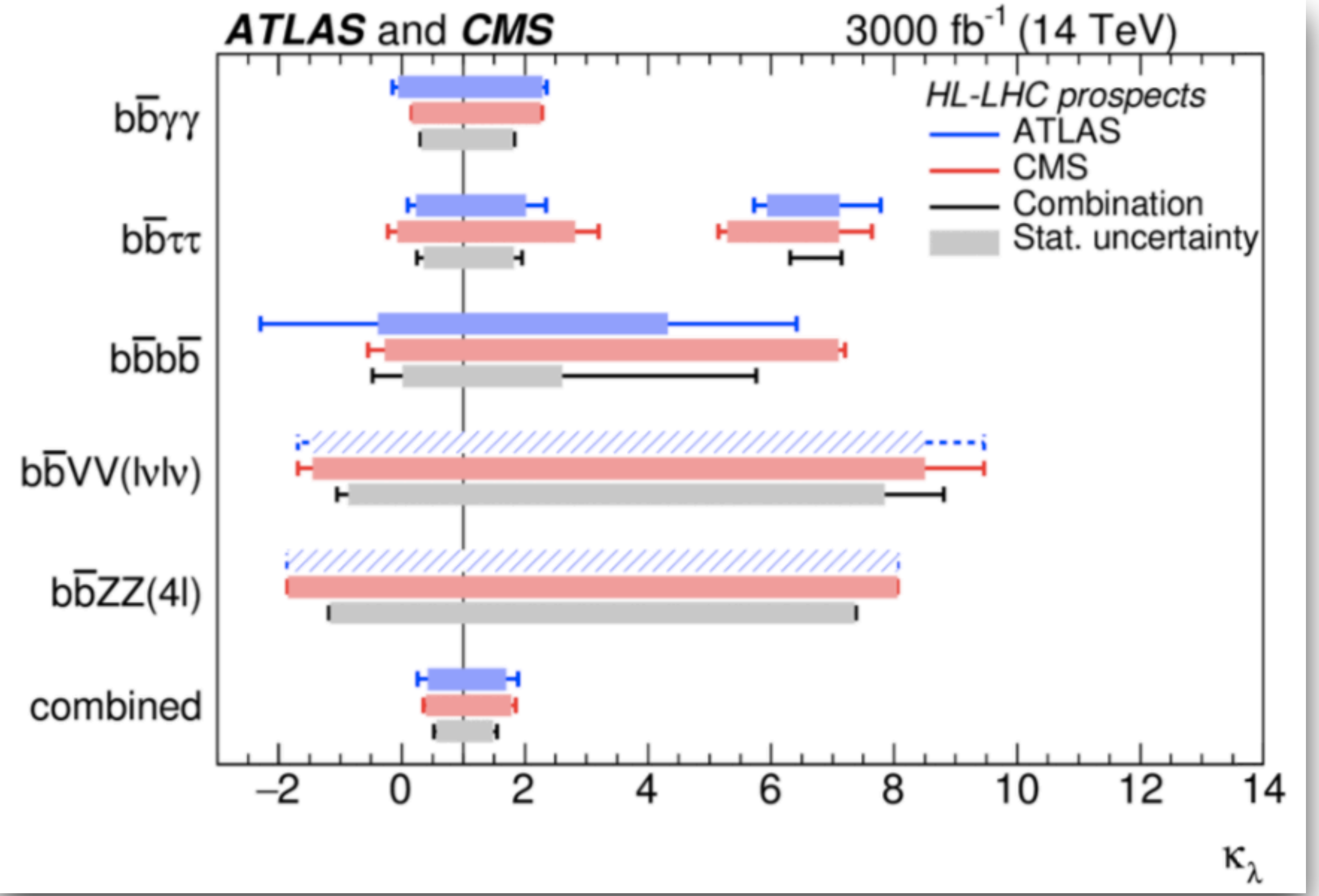


Prospects: HL-LHC

1902.00134
CMS-PAS-FTR-18-019
ATL-PHYS-PUB-2018-053

- ATLAS includes bbbb, bbττ and bbγγ
- CMS includes bbbb, bbττ, bbγγ, bbVV (2-lepton) and bbZZ (4-lepton)

	Statistical-only		Statistical + Systematic	
	ATLAS	CMS	ATLAS	CMS
$HH \to b\bar{b}b\bar{b}$	1.4	1.2	0.61	0.95
$HH \to b\bar{b}\tau\tau$	2.5	1.6	2.1	1.4
$HH \to b\bar{b}\gamma\gamma$	2.1	1.8	2.0	1.8
$HH \to b\bar{b}VV(ll\nu\nu)$	-	0.59	-	0.56
$HH \to b\bar{b}ZZ(4l)$	-	0.37	-	0.37
combined	3.5	2.8	3.0	2.6
	Combined 4.5		Combined 4.0	

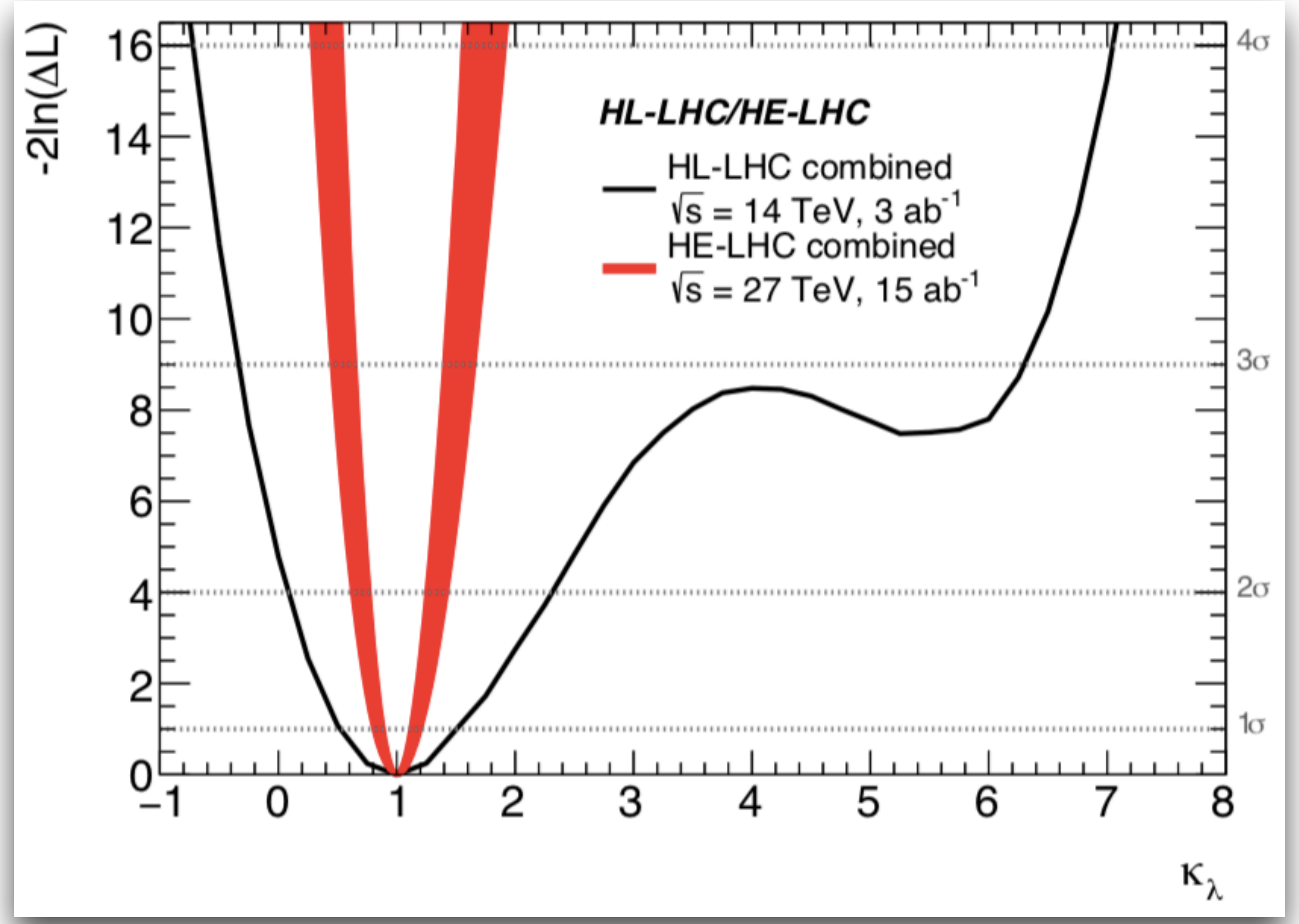


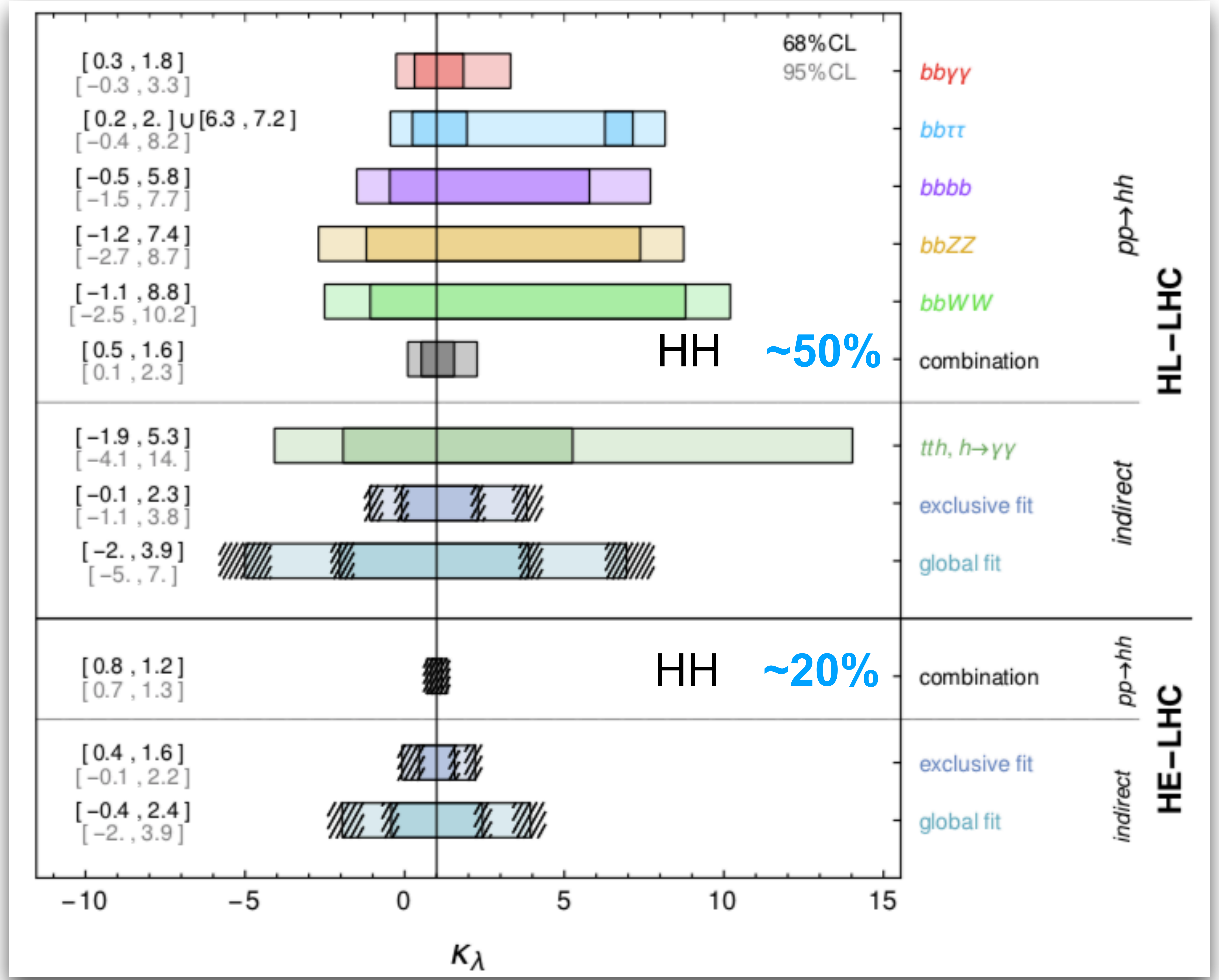
Combine ATLAS and CMS:
- Expected significance 4σ
- **Expected precision on pp→HH cross section ~25%**

Expected precision on κ_λ
~50% (double Higgs)
~110% (single Higgs)

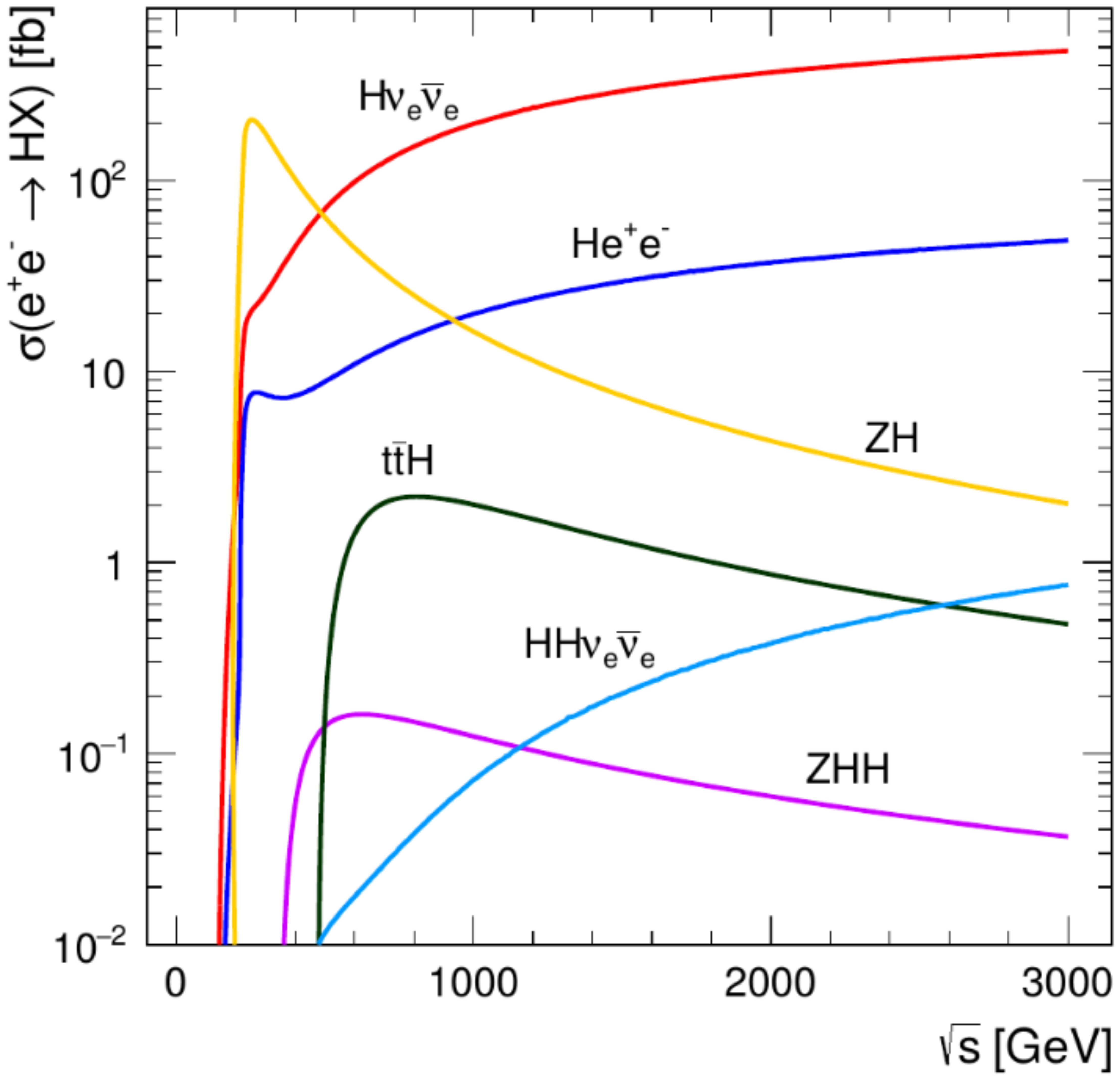
Prospects: HE-LHC

- Scale up to HE-LHC from HL-LHC: cross section x4, luminosity 15 ab^{-1}
- Studied **bbττ** and **bbγγ** with ATLAS assuming no systematic uncertainties
- Significance: 10.7σ in bbττ, 7.1σ in bbγγ
- **Precision on κ_λ: 20% (40%) in bbττ (bbγγ)**





Prospects: ee-colliders



- With lepton colliders, quite often only indirect measurements can be performed due to the energy threshold (~340GeV for VHH)
- Although much lower background level, the HH cross section is 2 orders of magnitude smaller than hadron collider
- Precision of κ_λ: CEPC/FCC-ee reaches ~50%; ILC/CLIC ~20%