Higgs self-coupling and prospects for HH and HHH

Carlo Pandini on behalf of the ATLAS and CMS Collaborations

23/10/2024 - CERN

Extended Scalar Sectors From All Angles 2024

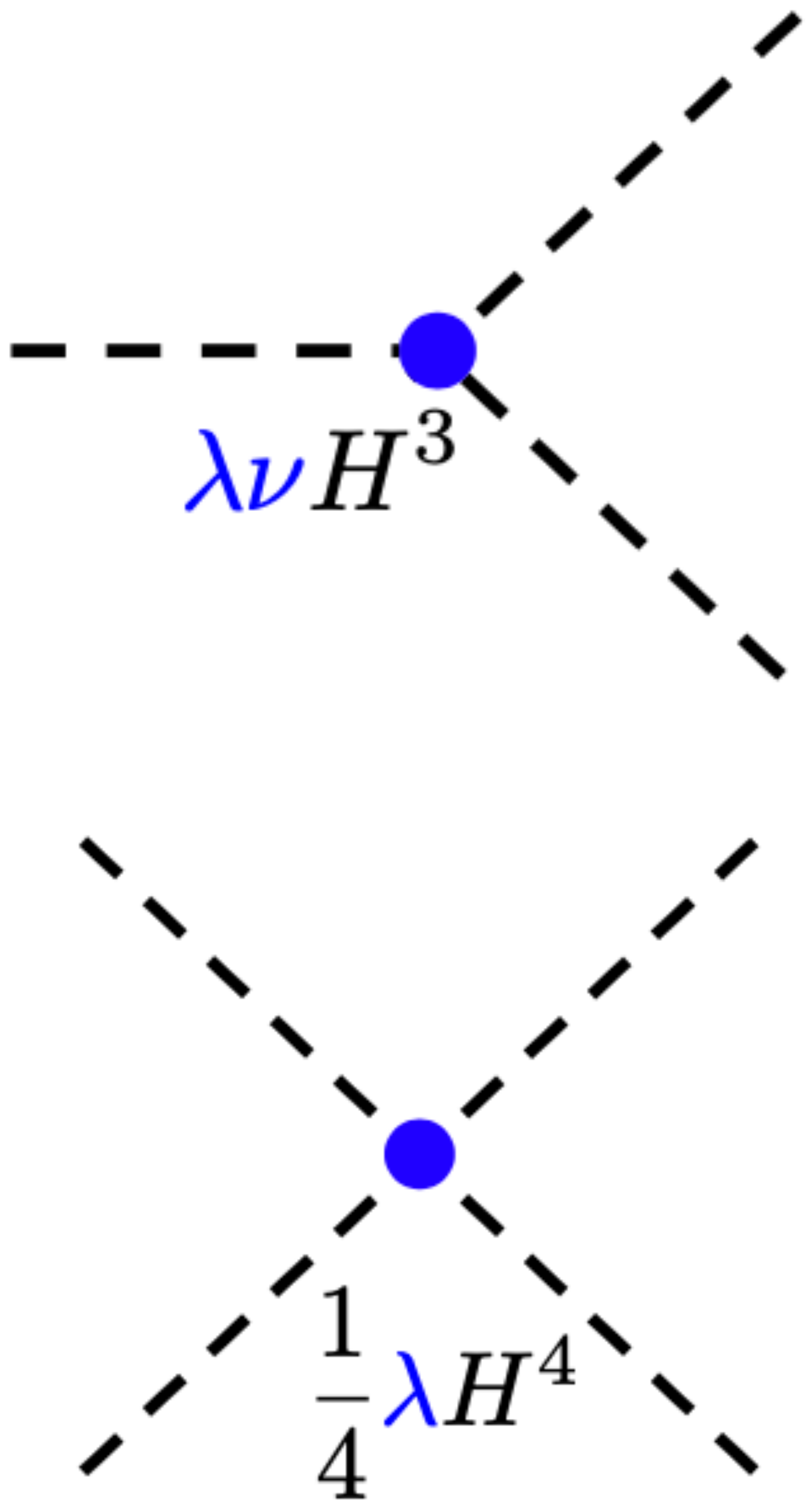
Introduction
&
Outline

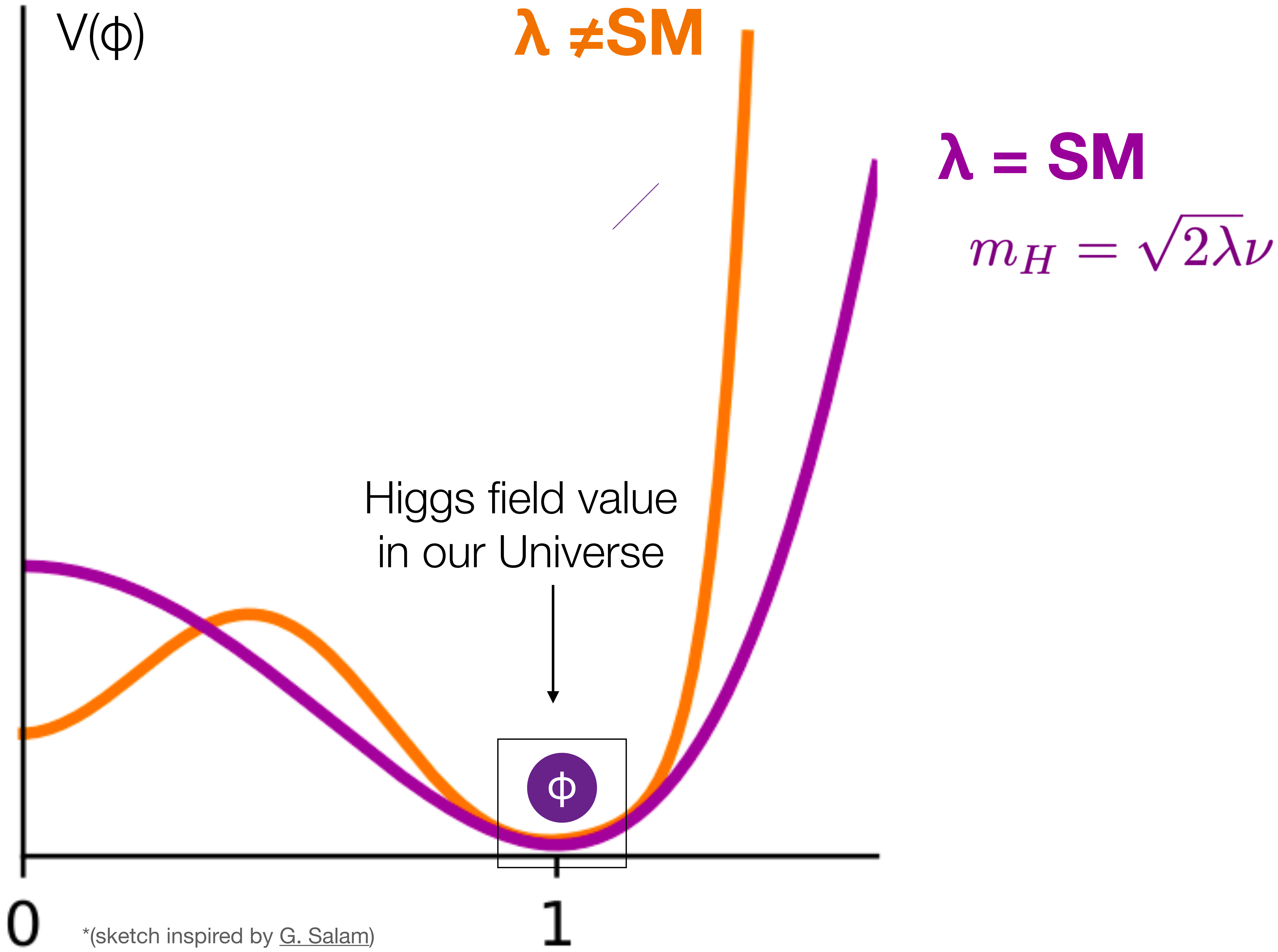
Trilinear self-coupling
Experimental overview

Quartic self-coupling
Brief experimental considerations

$$V(\Phi) = V_0 + \frac{1}{2}m_H^2 H^2 + \lambda\nu H^3 + \frac{1}{4}\lambda H^4$$

Higgs self-interactions

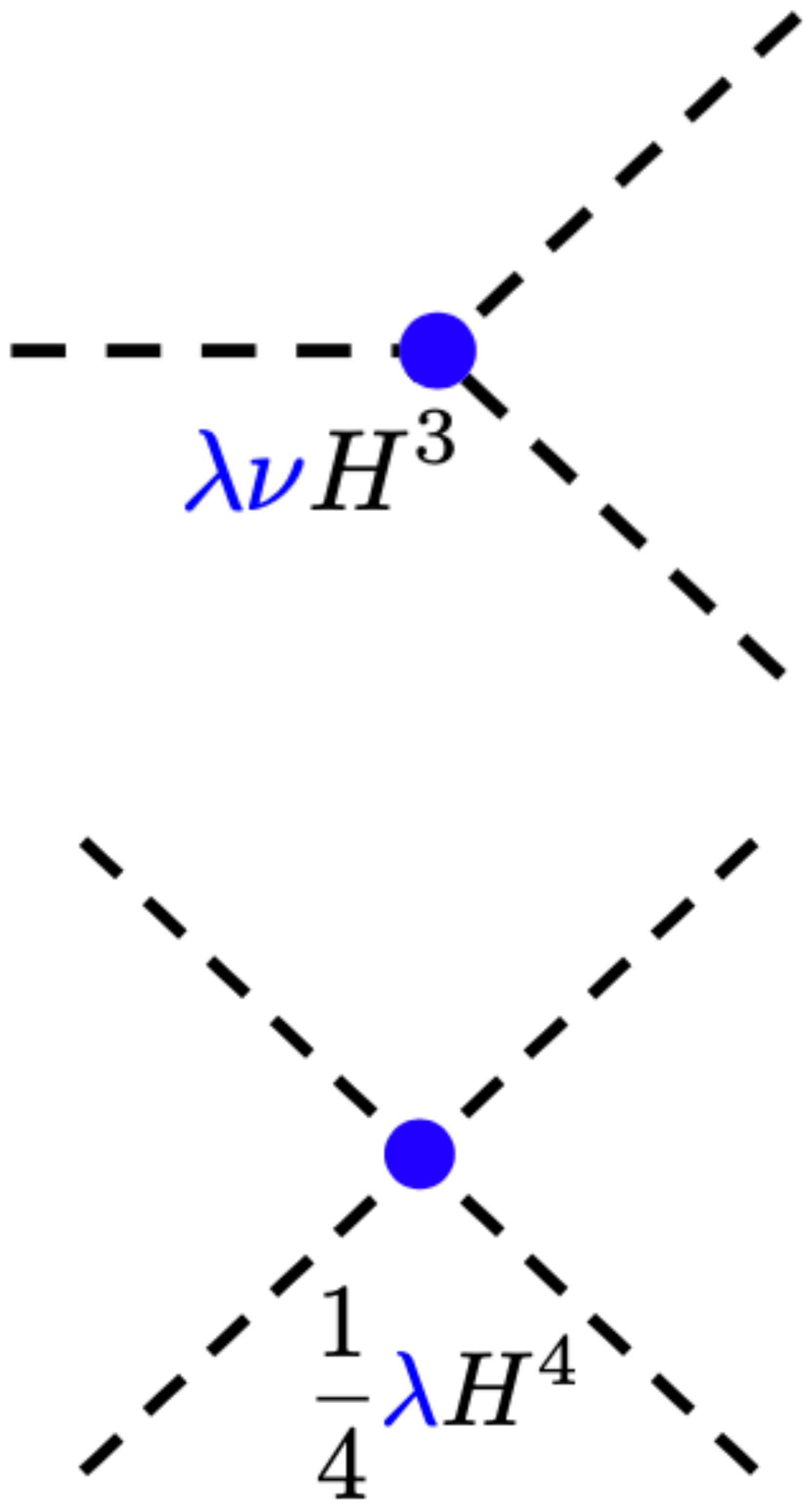


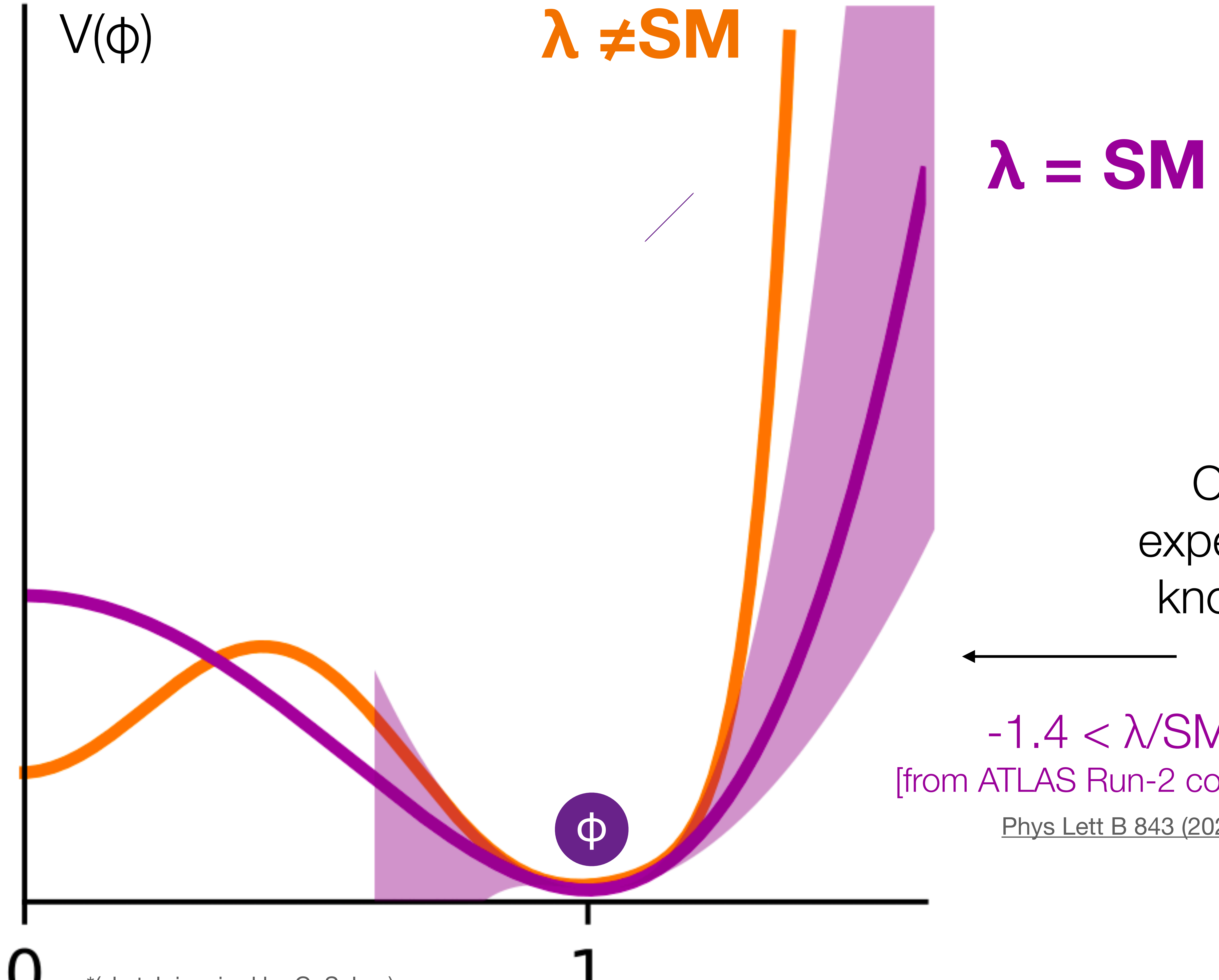


*(sketch inspired by G. Salam)

$$V(\Phi) = V_0 + \frac{1}{2}m_H^2 H^2 + \lambda\nu H^3 + \frac{1}{4}\lambda H^4$$

Higgs self-interactions





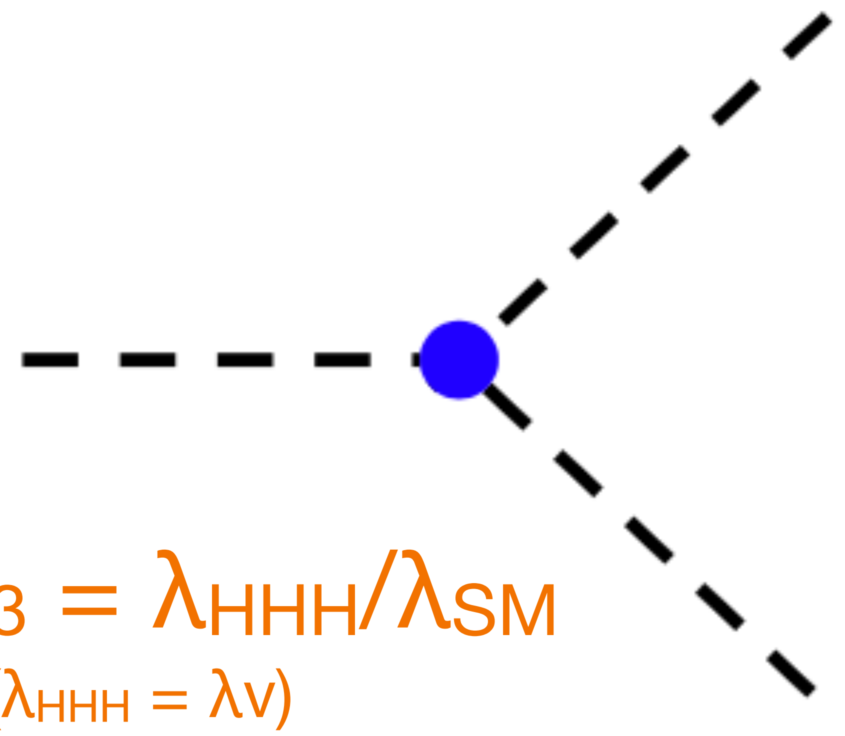
*(sketch inspired by G. Salam)

Current experimental knowledge

-1.4 < λ/SM < 6.1
[from ATLAS Run-2 combined results]
Phys Lett B 843 (2023) 137745

Several processes at the LHC sensitive to Higgs self-coupling

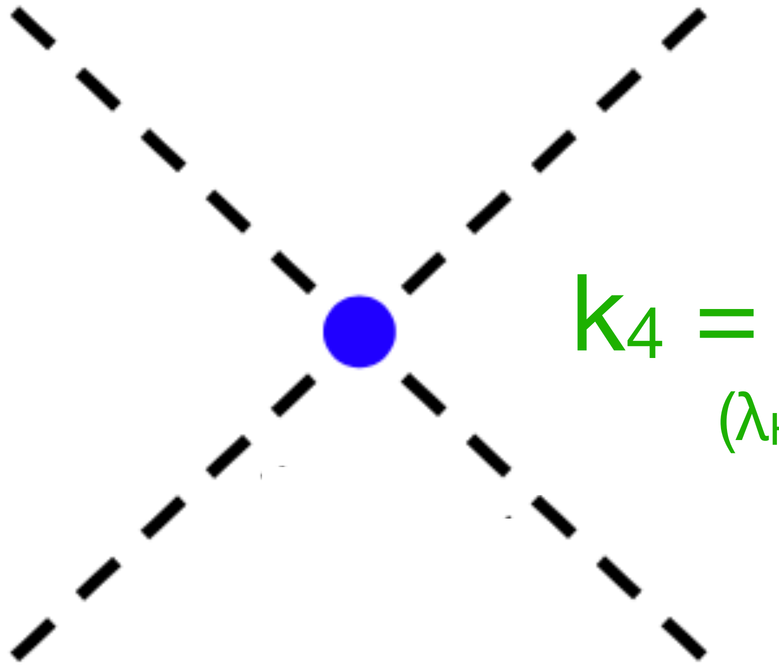
Trilinear self-coupling



$k_\lambda = k_3 = \lambda_{HHH}/\lambda_{SM}$

($\lambda_{HHH} = \lambda v$)

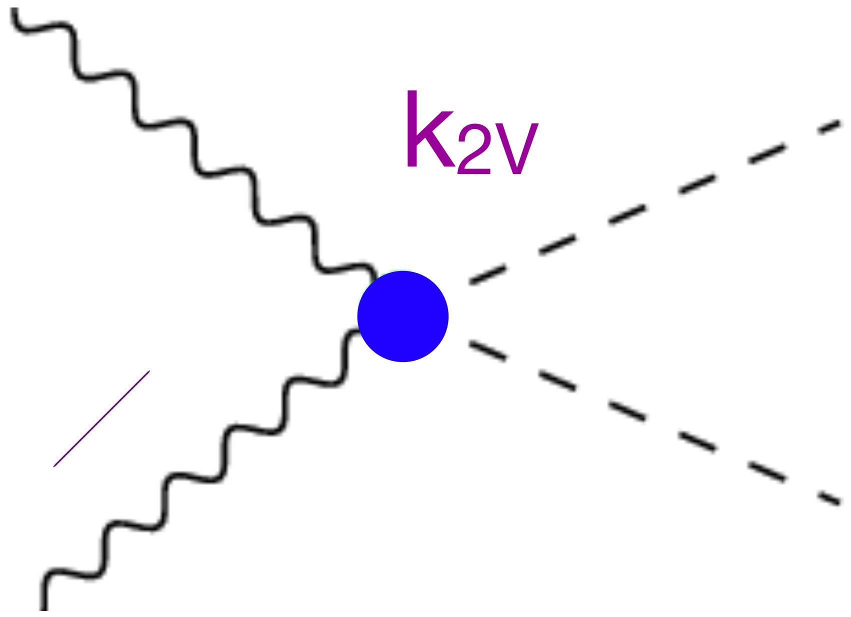
Quartic self-coupling



$k_4 = \lambda_{HHHH}/\lambda_{SM}$

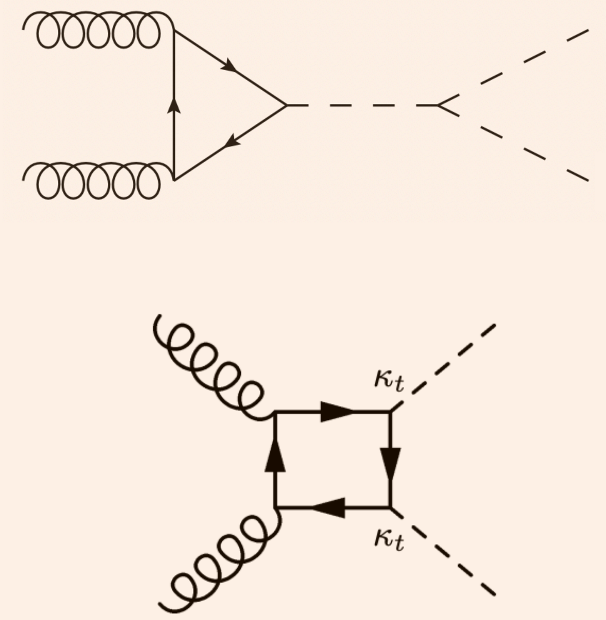
($\lambda_{HHHH} = ¼ \lambda$)

HH to vector boson coupling (gauge)



ggHH

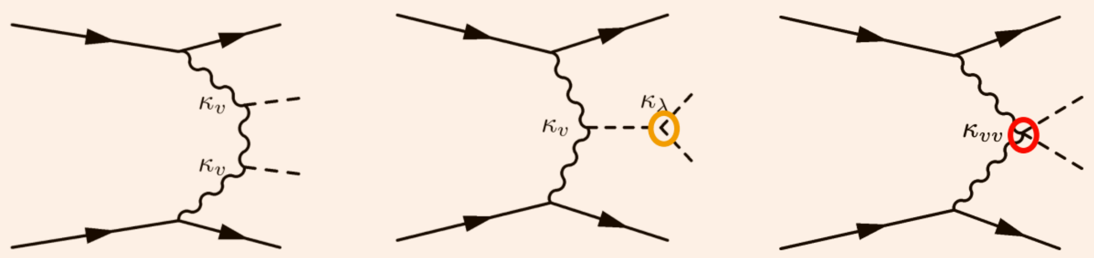
[σ_{HH}~31fb]



VBF HH

[σ_{VBF}~1.7fb]

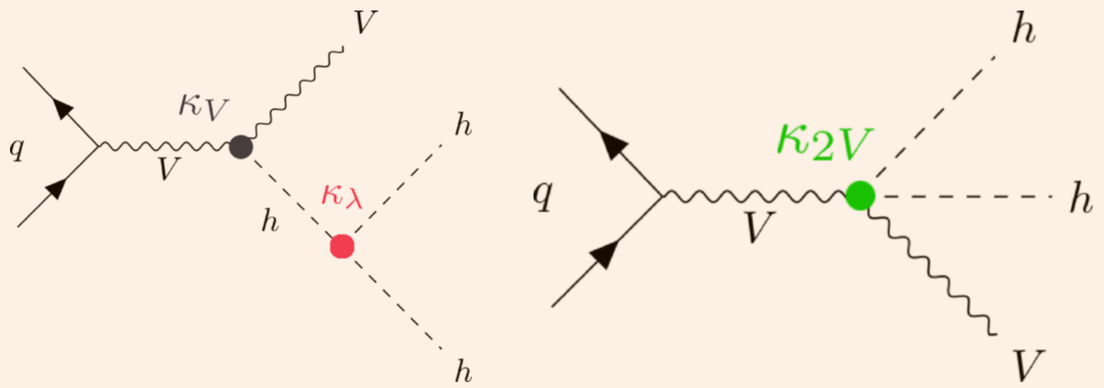
sensitive to VVHH **k_{2V} coupling**



VHH

[σ_{VHH}~0.86fb]

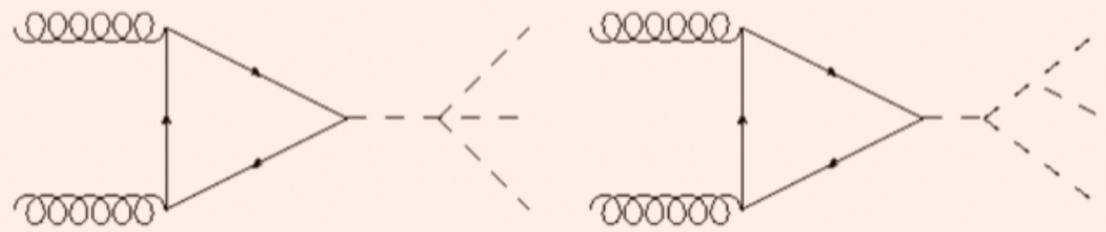
sensitive to VVHH **k_{2V} coupling**



HHH

[σ_{HHH}~0.08fb]

unique sensitivity to λ_{HHHH},
interference with λ_{HHH}

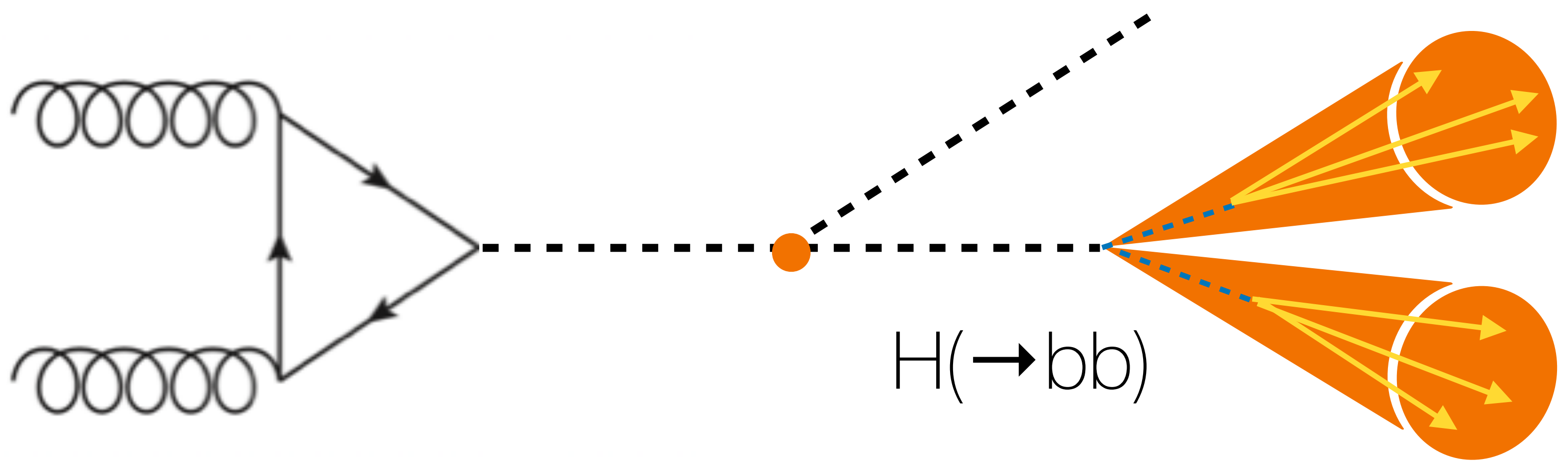


HH Quick Review

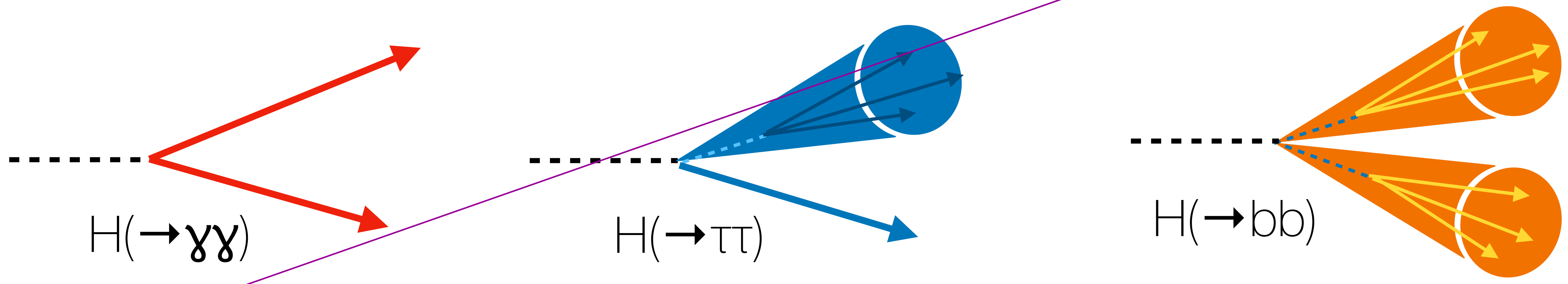
3 golden channels across
ATLAS and CMS

HH Experimental Signatures: “golden channels”

1st Higgs decaying to **bottom-quarks**:
largest branching ratio, coarse energy resolution



2nd Higgs determines the nature of the experimental search:
cleaner signature vs higher statistics …



BRs	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%

Three “golden” experimental channels:

- **H(→bb)H(→bb)**
  largest branching ratio (34%)
  huge QCD multi-jet background
- **H(→bb)H(→ττ)**
  moderate branching ratio (7.3%)
  multi-jet rejected thanks to tau leptons
- **H(→bb)H(→γγ)**
  tiny branching ratio (<1%)
  clean signature and great resolution

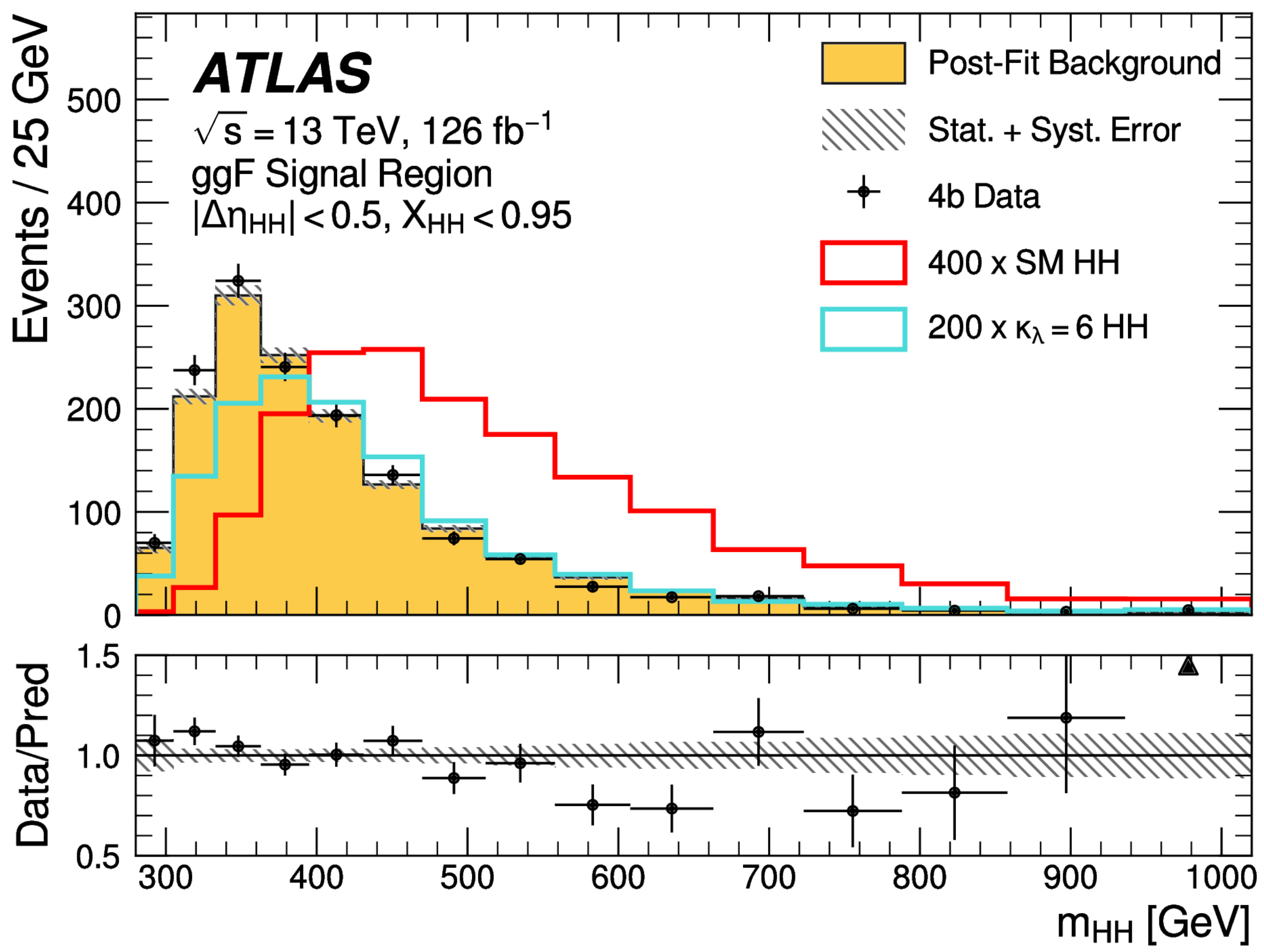
Combining with all channels will be important to achieve first evidence!

HH(→bbbb): resolved topologies

- **largest total BR(~34%)**, very large QCD background: **acceptance x efficiency ~ 1%**
- **b-tagging algorithms** and b-jet pairing are critical, data-driven background estimate
- targeting **ggHH** (low/high-m_{HH}) and **VBF** categories simultaneously
- ATLAS: fit to m_{HH} distribution / CMS: fit to dedicated BDT discriminant for ggHH (m_{HH} for VBF)

BR	bb
bb	34%

ATLAS — PhysRev D 108 (2023) 052003

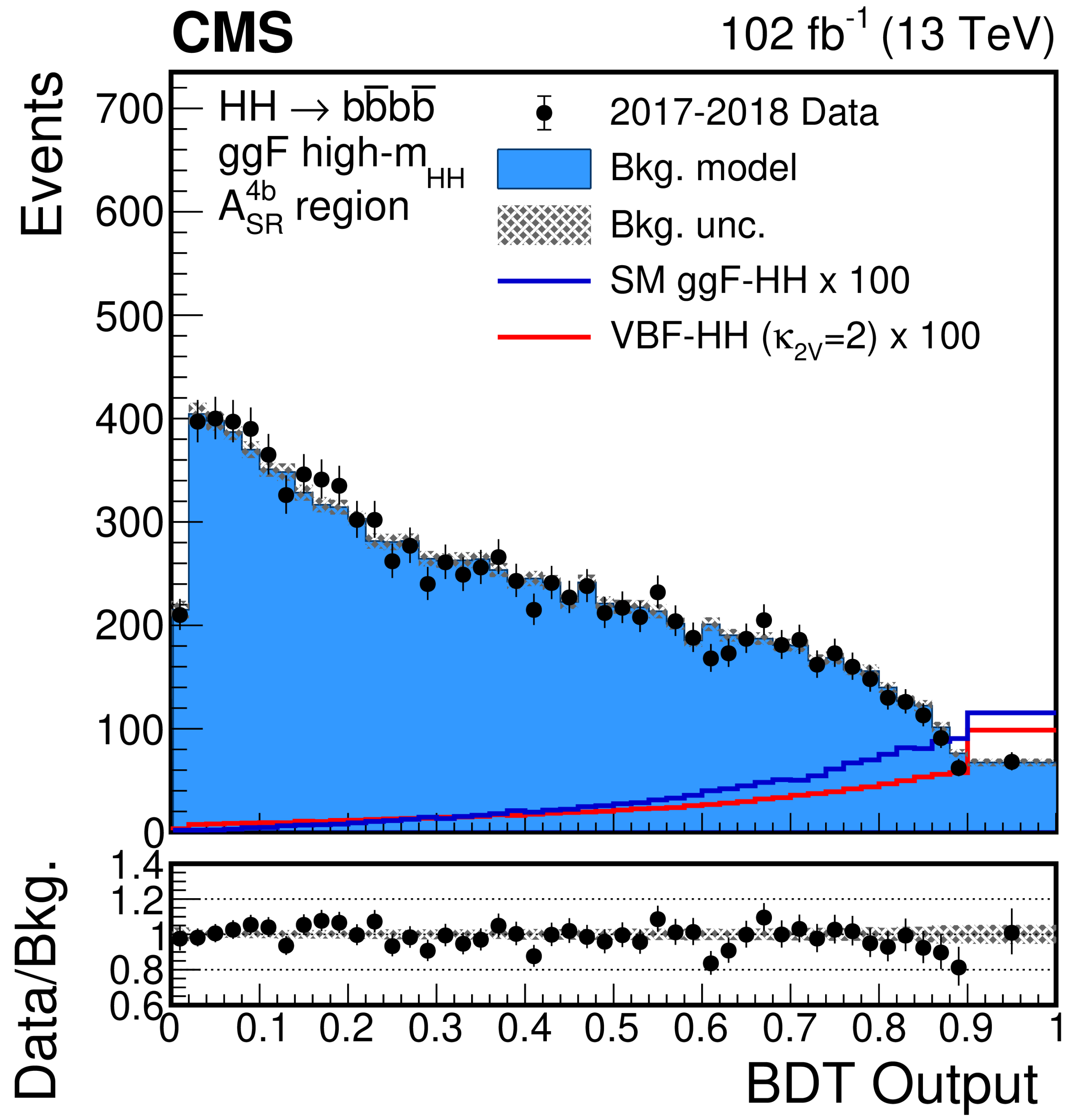


μ_{HH} < 5.4 (8.1)

$k_\lambda \in [-3.5, 11.3]_{obs}$ $(-5.4, 11.4)_{exp}$

$k_{2V} \in [0.0, 2.1]_{obs}$ $(-0.1, 2.1)_{exp}$

CMS — PhysRev D 129 (2022) 081802



μ_{HH} < 3.9 (7.8)

$k_\lambda \in [-2.3, 9.4]_{obs}$ $(-5.0, 12.0)_{exp}$

$k_{2V} \in [-0.1, 2.2]_{obs}$ $(-0.4, 2.5)_{exp}$

HH(→bbbb): boosted topologies

- **large-radius QCD jet: Higgs reconstruction as boosted system → strong background suppression**
- combined information from: **Higgs kinematics, Higgs mass, QCD jet sub-structure, b-tagging**
- strong sensitivity to **k2V** coupling (large boost when k2V deviates from SM)

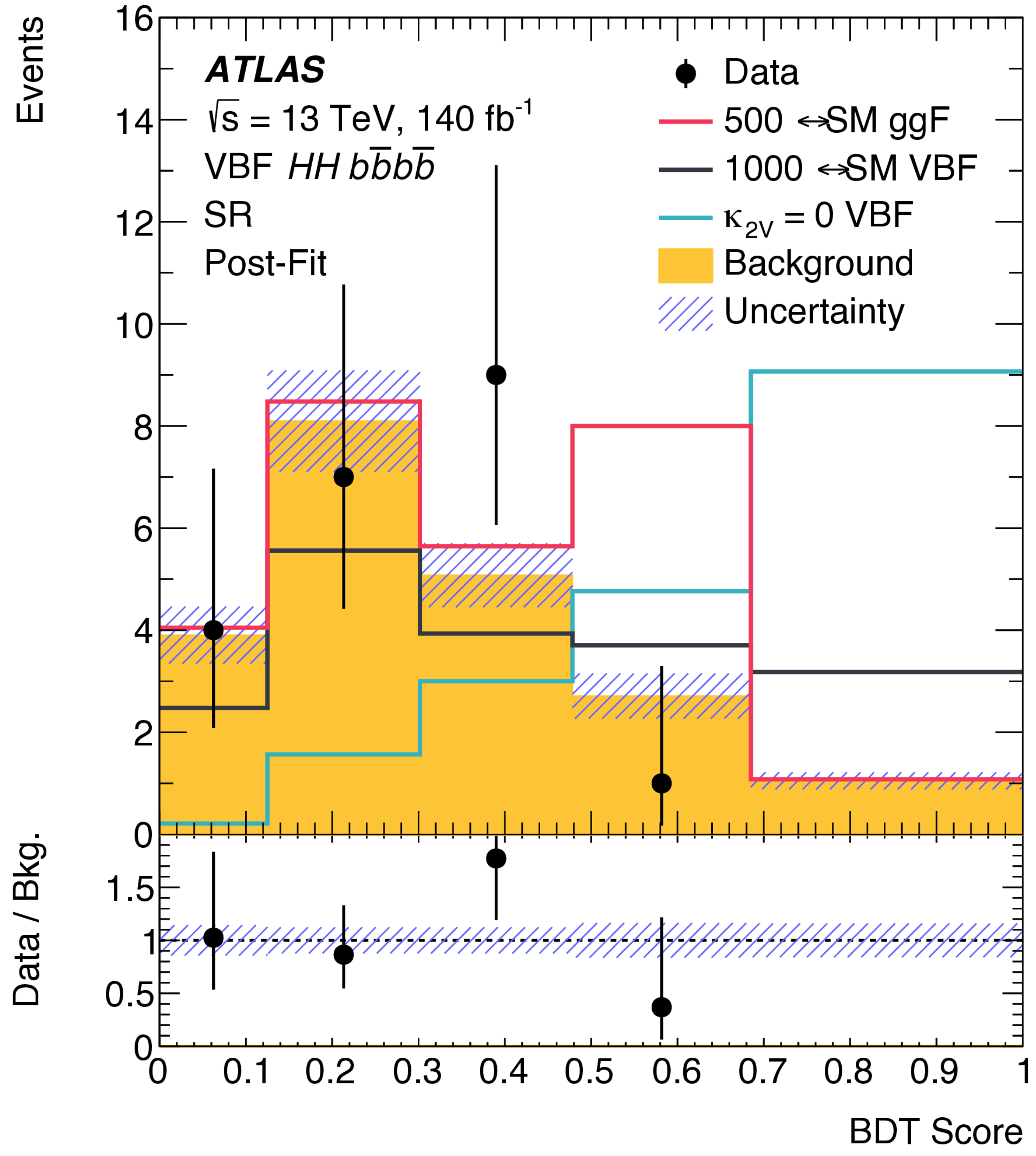
BR	bb
bb	34%

PhysLett B 858 (2024) 139007

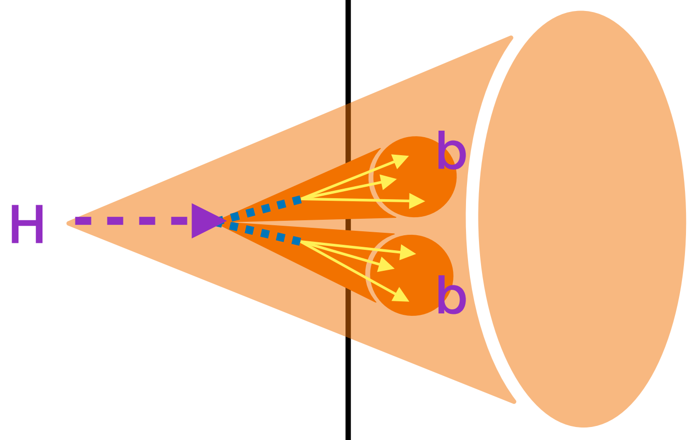
ATLAS

CMS

PhysLett 131 (2023) 041803

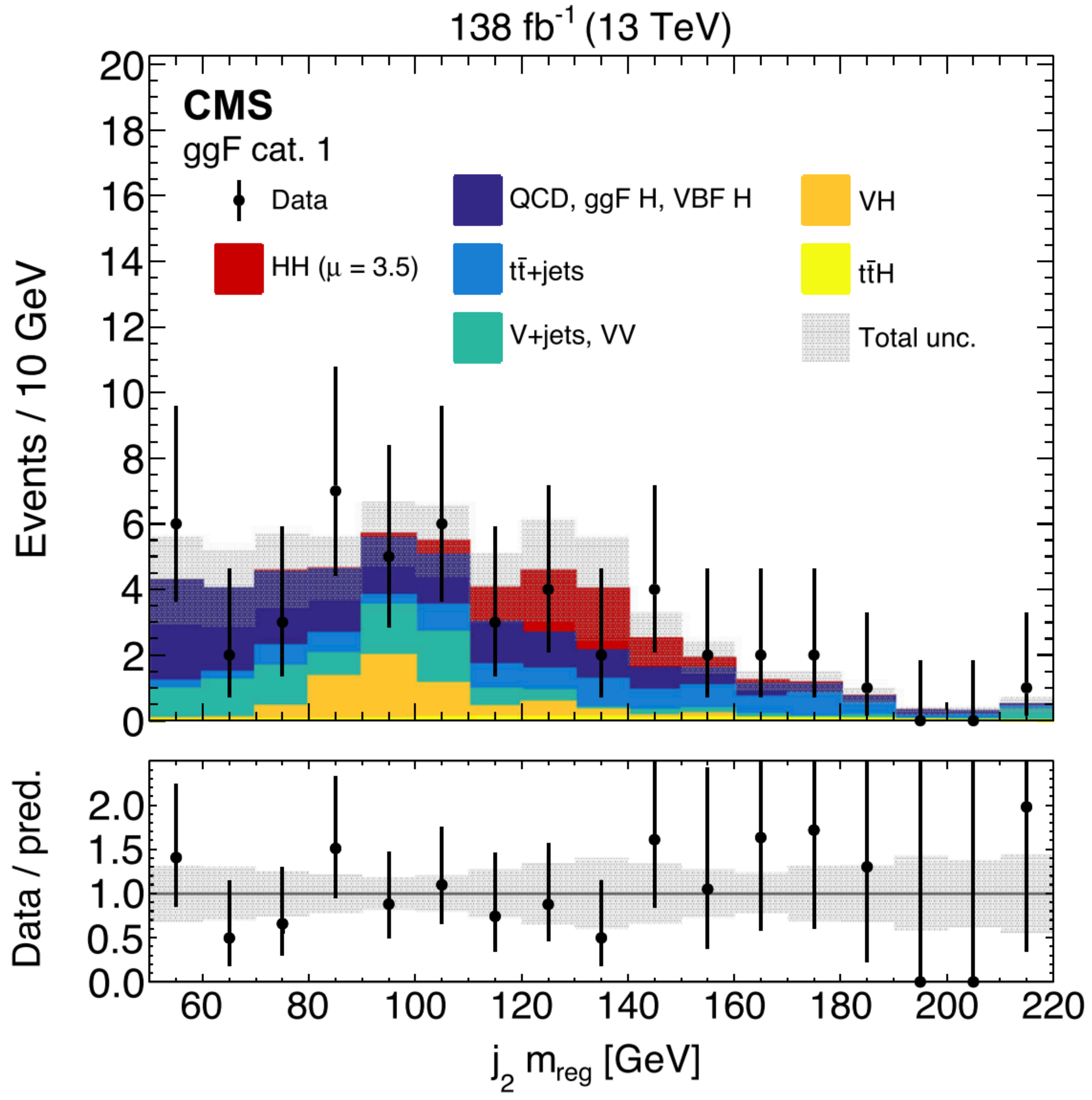


ATLAS analysis focusing only on VBF regime



CMS covers both VBF regime and ggHH production

(very competitive limits on μ_{HH}: as powerful as resolved ggHH)



$k_{2V} \in [0.55, 1.49]_{obs}$ $(0.37, 1.67)_{exp}$

$\mu_{HH} < 9.9$ (5.1)

$k_\lambda \in [-9.9, 16.9]_{obs}$ $(-5.1, 12.2)_{exp}$

$k_{2V} \in [0.62, 1.41]_{obs}$ $(0.66, 1.37)_{exp}$

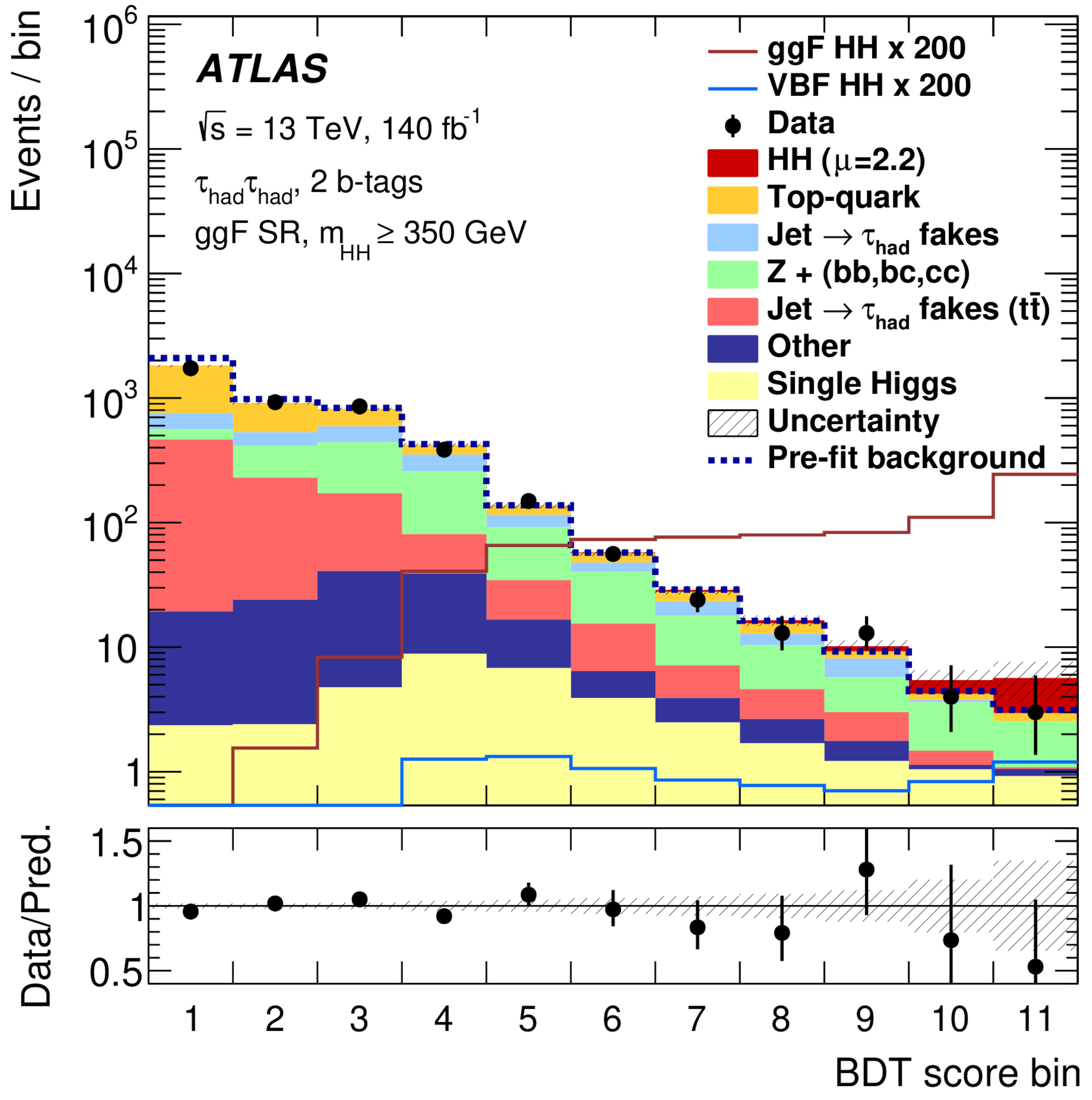
Assuming the SM: k2V =0 excluded at more than 6σ

HH(→bbττ)

- combining **fully hadronic (dominant)** and **semi-leptonic** decay channels
- large ttbar and data-driven fake-tau background
- targeting **ggHH** (low/high-m_{HH}) and **VBF** categories simultaneously

BR	ττ
bb	7.3%

Phys Rev D 110 (2024) 032012 — **ATLAS**

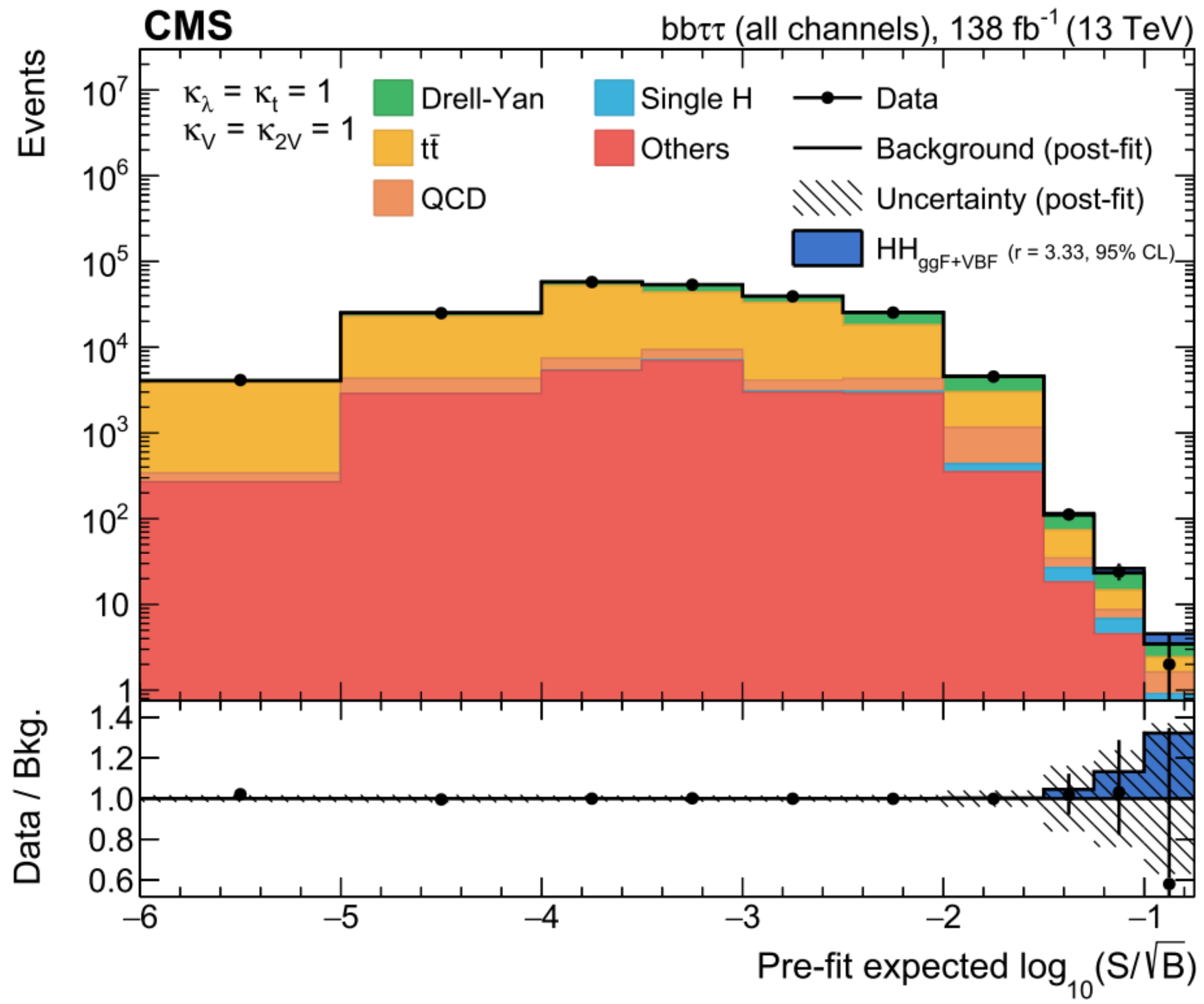


μ_{HH} < 5.9 (3.3)

$k_\lambda \in [-3.2, 9.1]_{obs}$ $(-2.5, 9.2)_{exp}$

$k_{2V} \in [-0.4, 2.6]_{obs}$ $(-0.2, 2.4)_{exp}$

CMS — Phys Lett B 832 (2023) 137531



μ_{HH} < 3.3 (5.2)

$k_\lambda \in [-1.7, 8.7]_{obs}$ $(-2.9, 9.8)_{exp}$

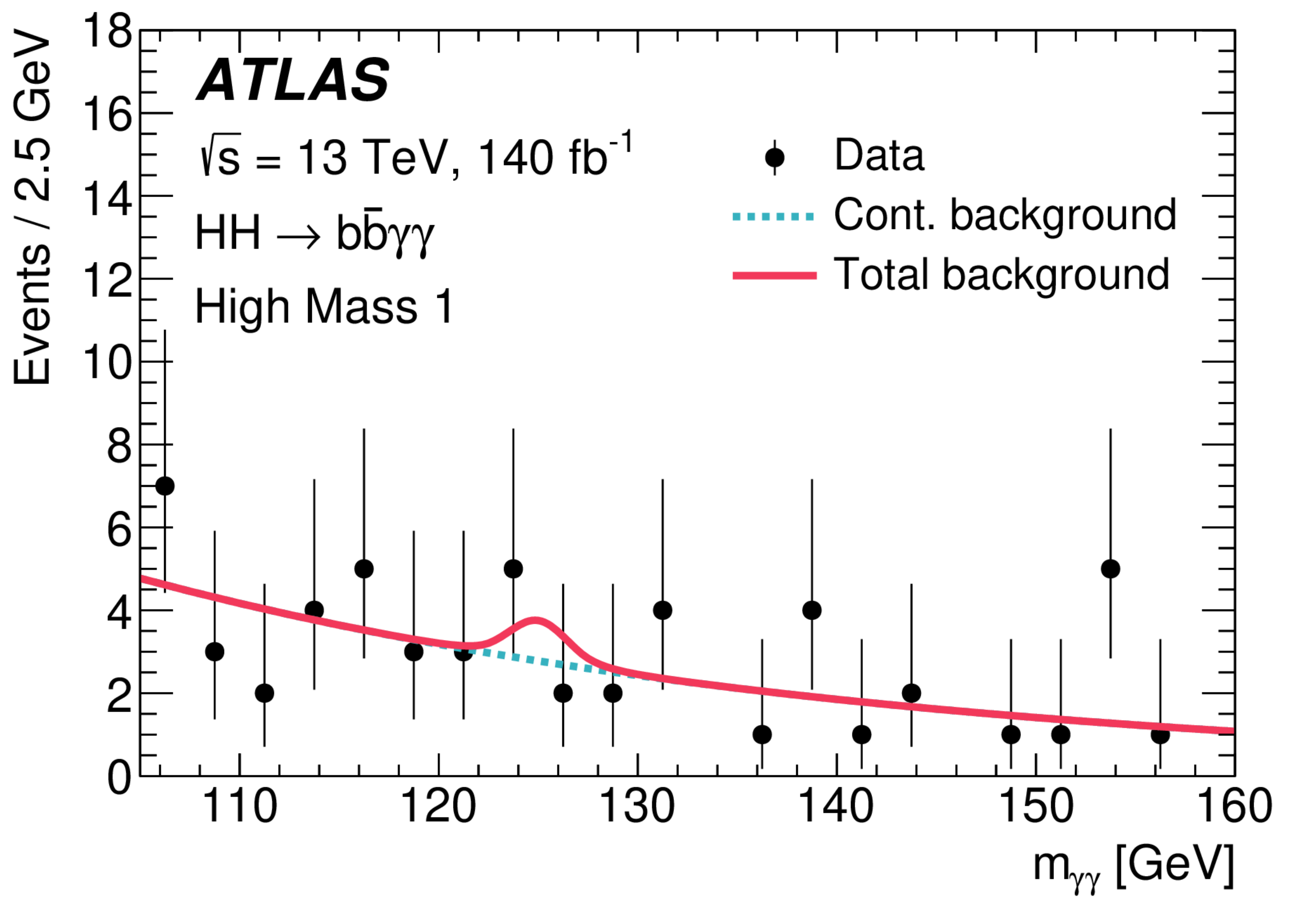
$k_{2V} \in [-0.4, 2.6]_{obs}$ $(-0.6, 2.8)_{exp}$

HH(→bbγγ)

- MVA techniques to distinguish signal from continuum γγ background
- targeting **ggHH** (low/high-m_{HH}) and **VBF** categories
- fit $m_{\gamma\gamma}$ distribution to control the background and extract the HH signal

BR	γγ
bb	0.26%

JHEP 01 (2024) 066 **ATLAS**



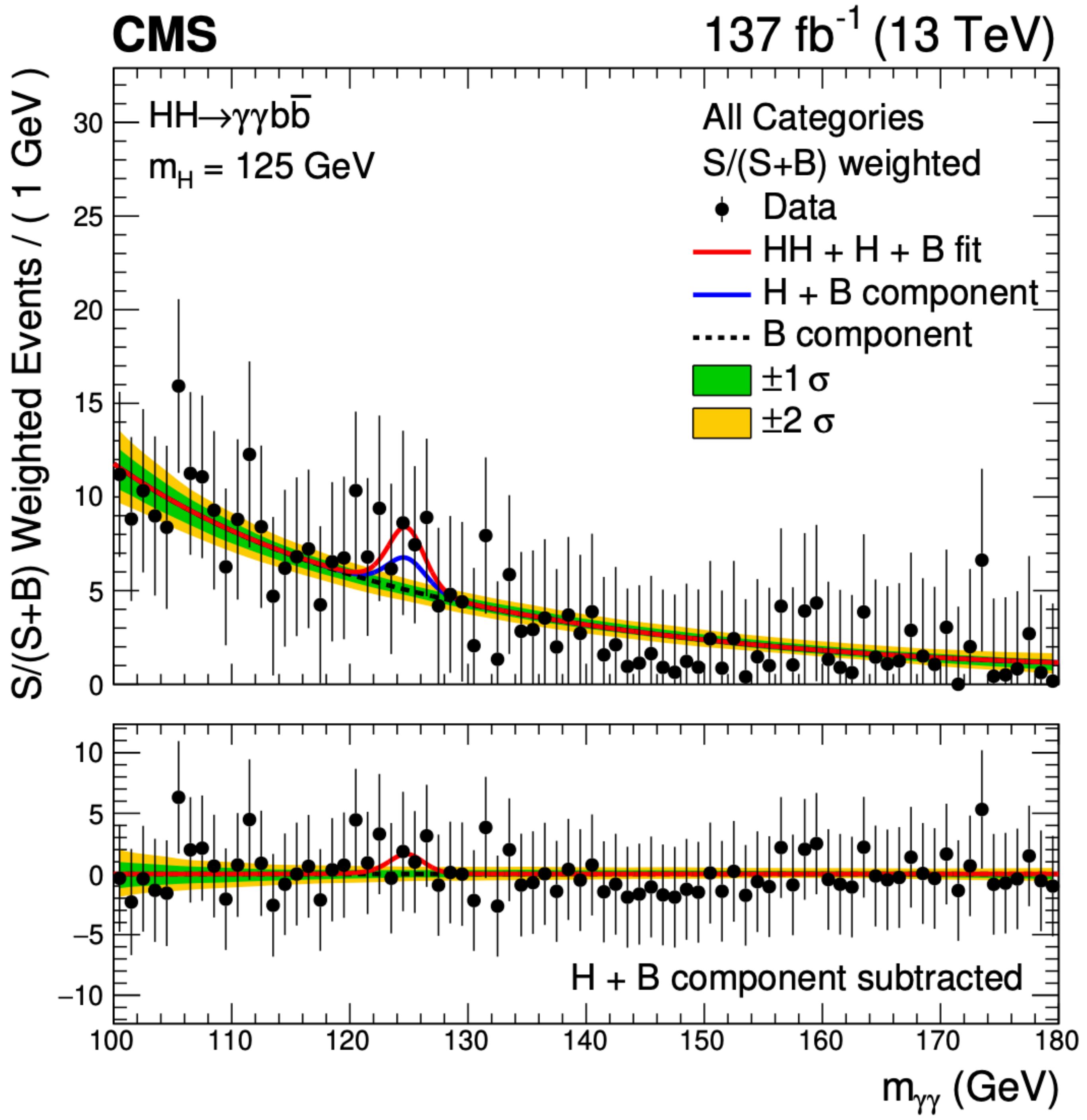
μ_{HH} < 5.0 (6.4)

$k_\lambda \in [-1.4, 6.9]_{obs}$ $(-2.8, 7.8)_{exp}$

$k_{2V} \in [-0.5, 2.7]_{obs}$ $(-1.1, 3.3)_{exp}$

CMS JHEP 03 (2021) 257

Fully dominated by statistical uncertainties



μ_{HH} < 7.7 (5.2)

$k_\lambda \in [-3.3, 8.5]_{obs}$ $(-2.5, 8.2)_{exp}$

$k_{2V} \in [-1.3, 3.5]_{obs}$ $(-0.9, 3.1)_{exp}$

Focus on recent results from ATLAS and CMS

what can we gather from other decay modes?

Recent results: ATLAS HH multi-leptons

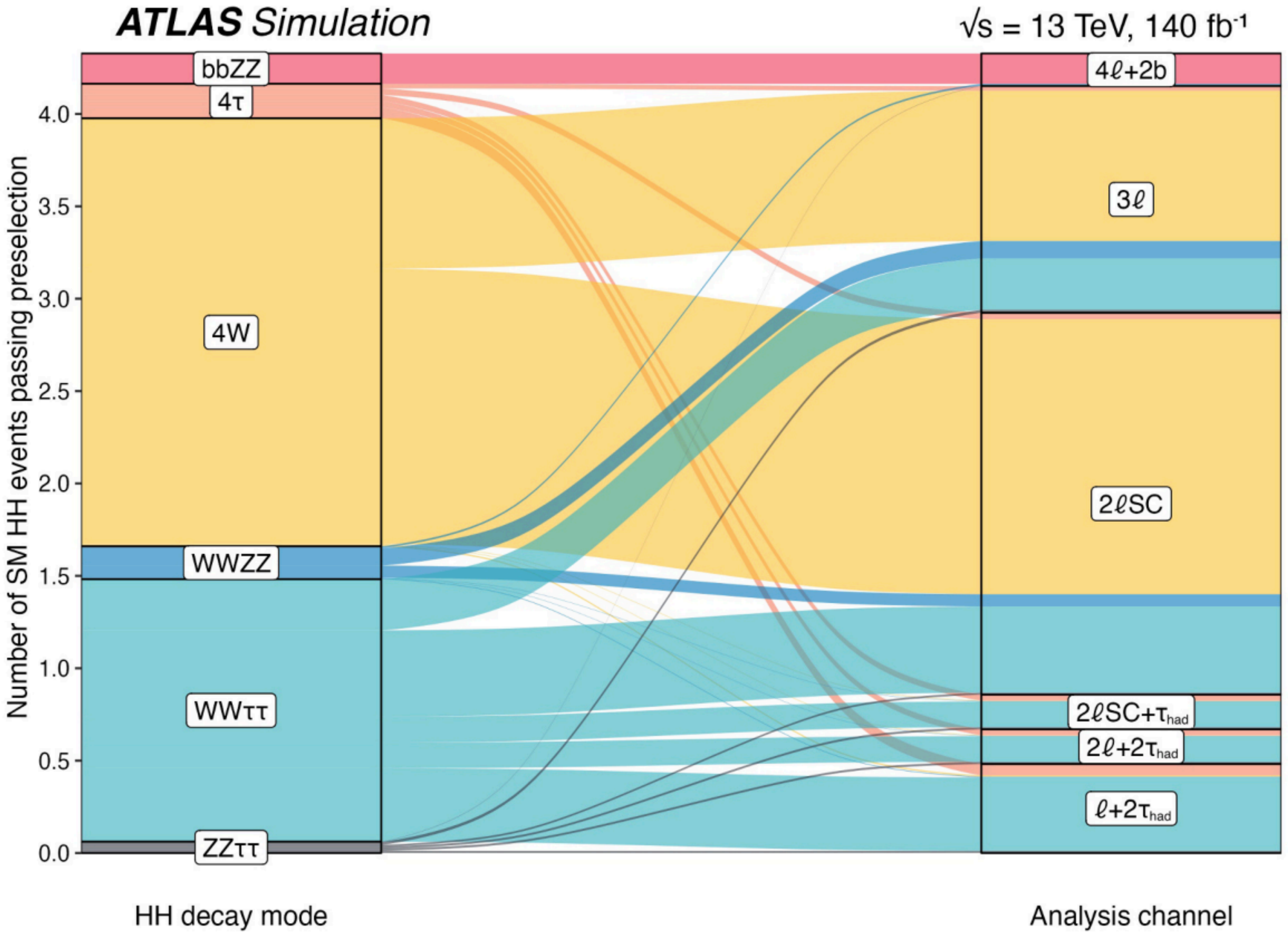
JHEP08(2024)164

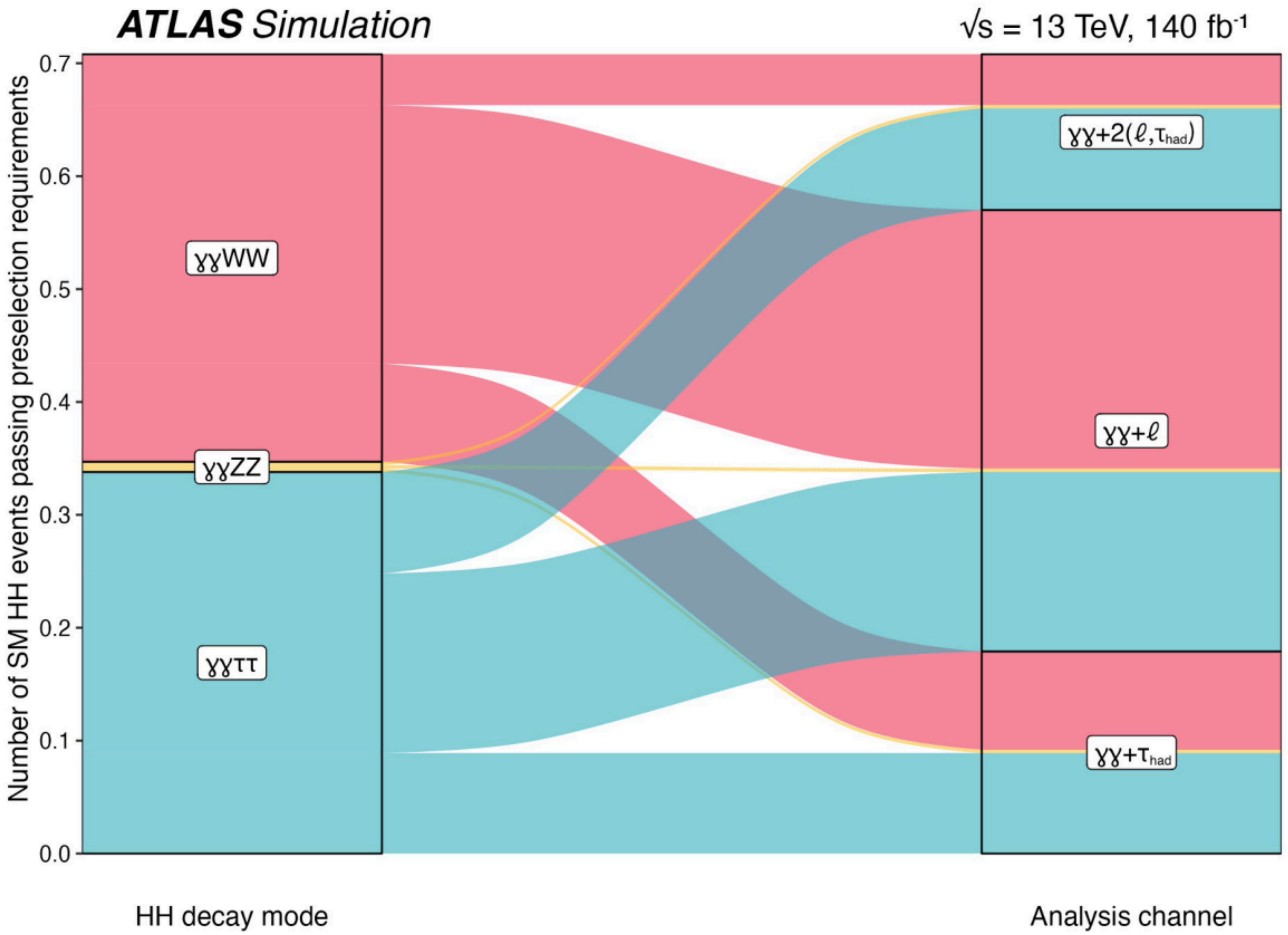
BR [%]	bb	WW	ττ	ZZ
WW		4.6		
ττ		2.7	0.39	
ZZ	3.1	1.1	0.33	
γγ		0.1	0.03	0.01

Several decay modes included:
non-negligible BRs (<1% - ~5%): hard to reconstruct final states

→ 6 categories fully multi-lepton
→ 3 categories with γγ+leptons

(each category can receive contribution from multiple decay modes)

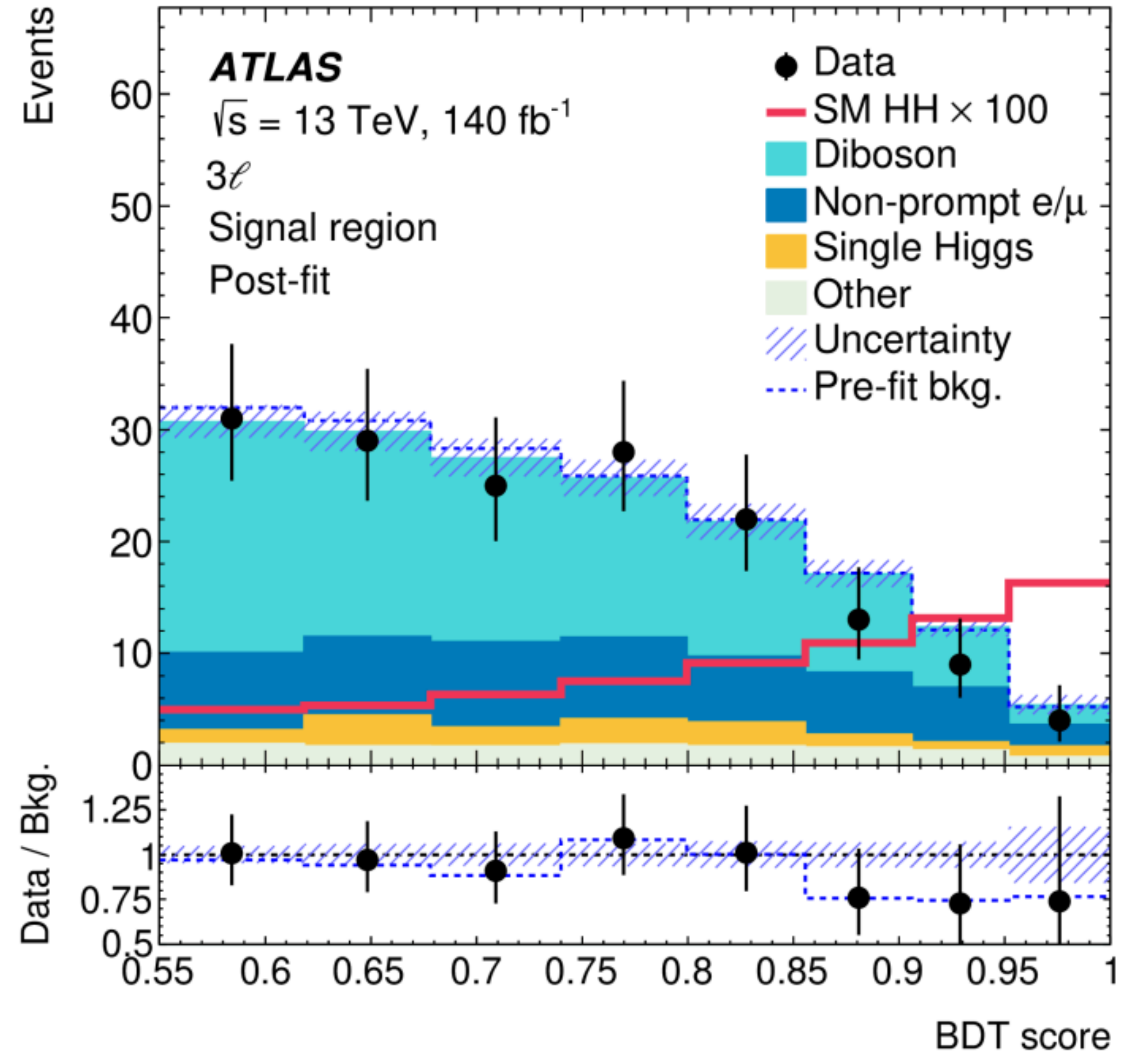




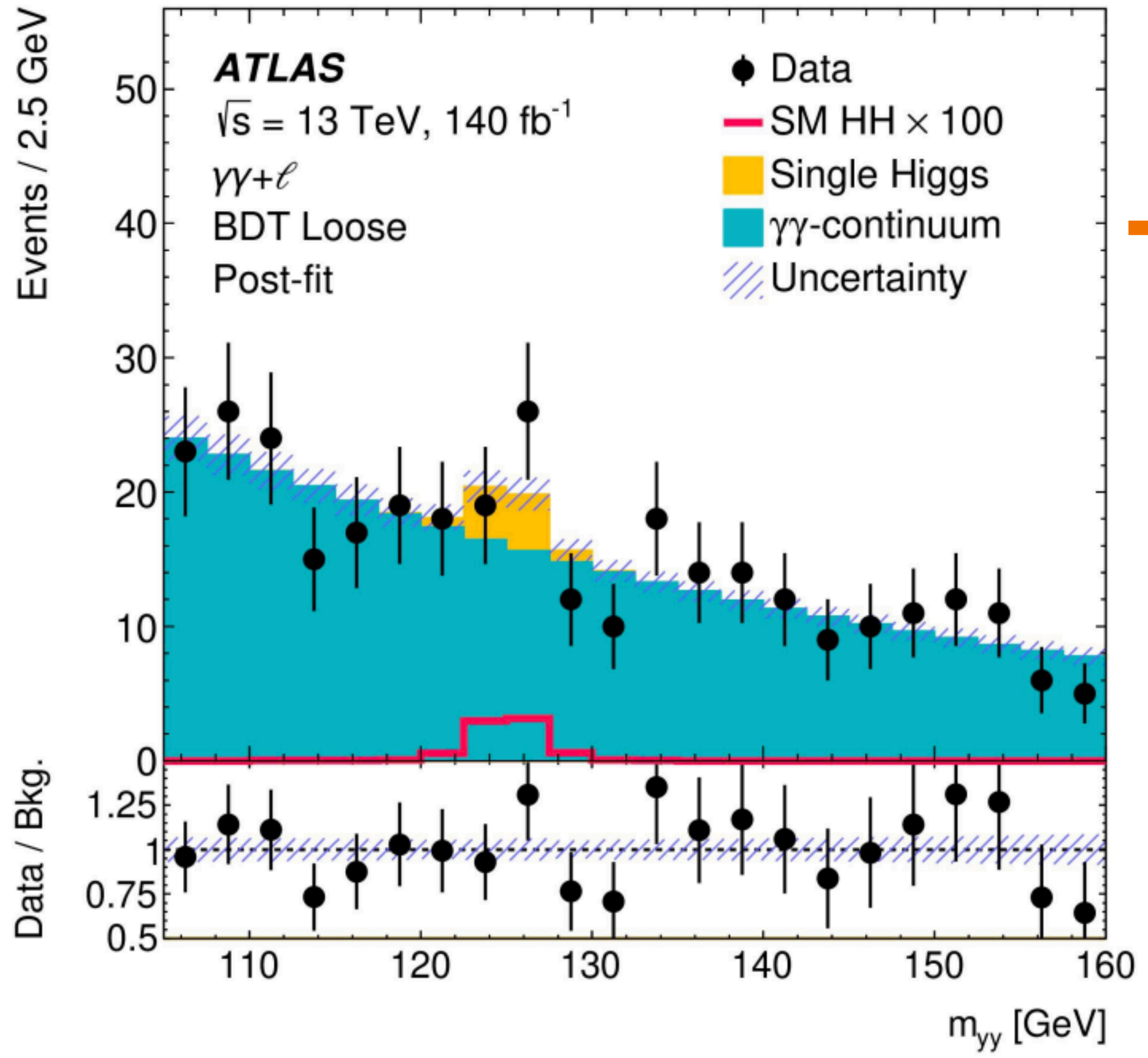
Recent results: ATLAS HH multi-leptons

JHEP08(2024)164

BDT fit in ML channels

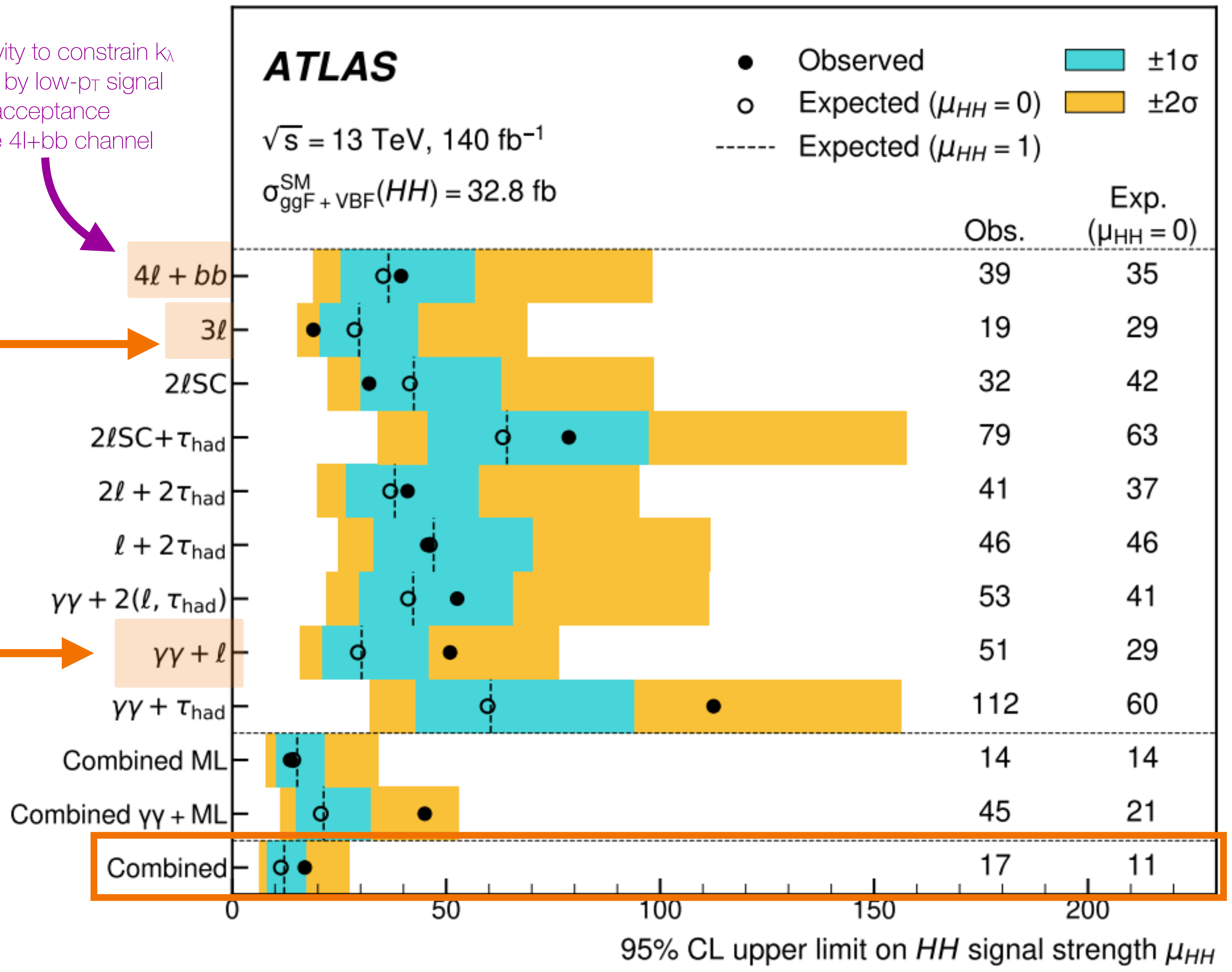


$m_{\gamma\gamma}$ fit in ML channels



Important contributions from all channels

Sensitivity to constrain k_λ driven by low-p_T signal acceptance in the 4l+bb channel



$k_\lambda \in [-6.2, 11.6]_{obs}$ $(-4.5, 9.6)_{exp}$

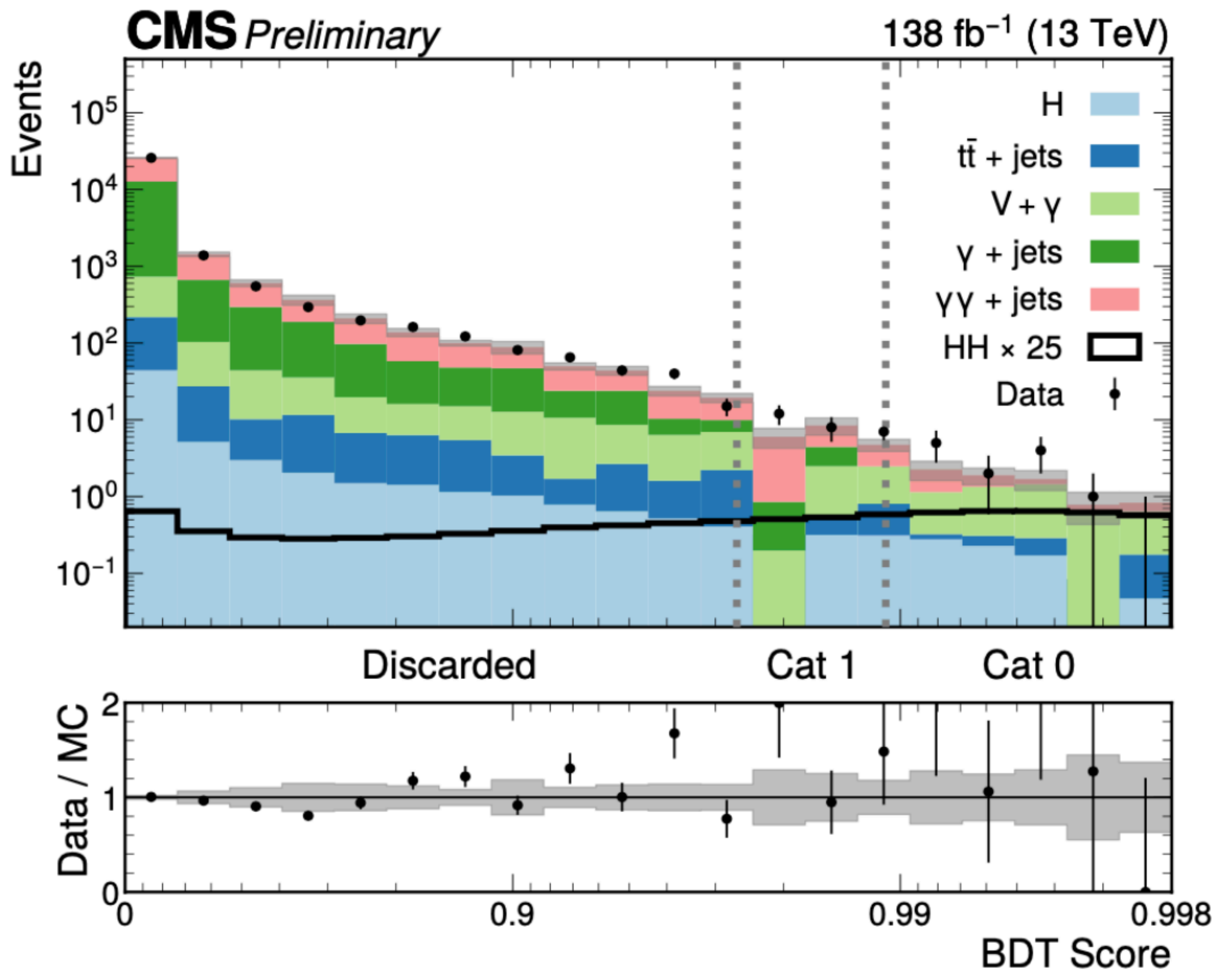
$k_{2V} \in [-2.5, 4.6]_{obs}$ $(-1.9, 4.1)_{exp}$

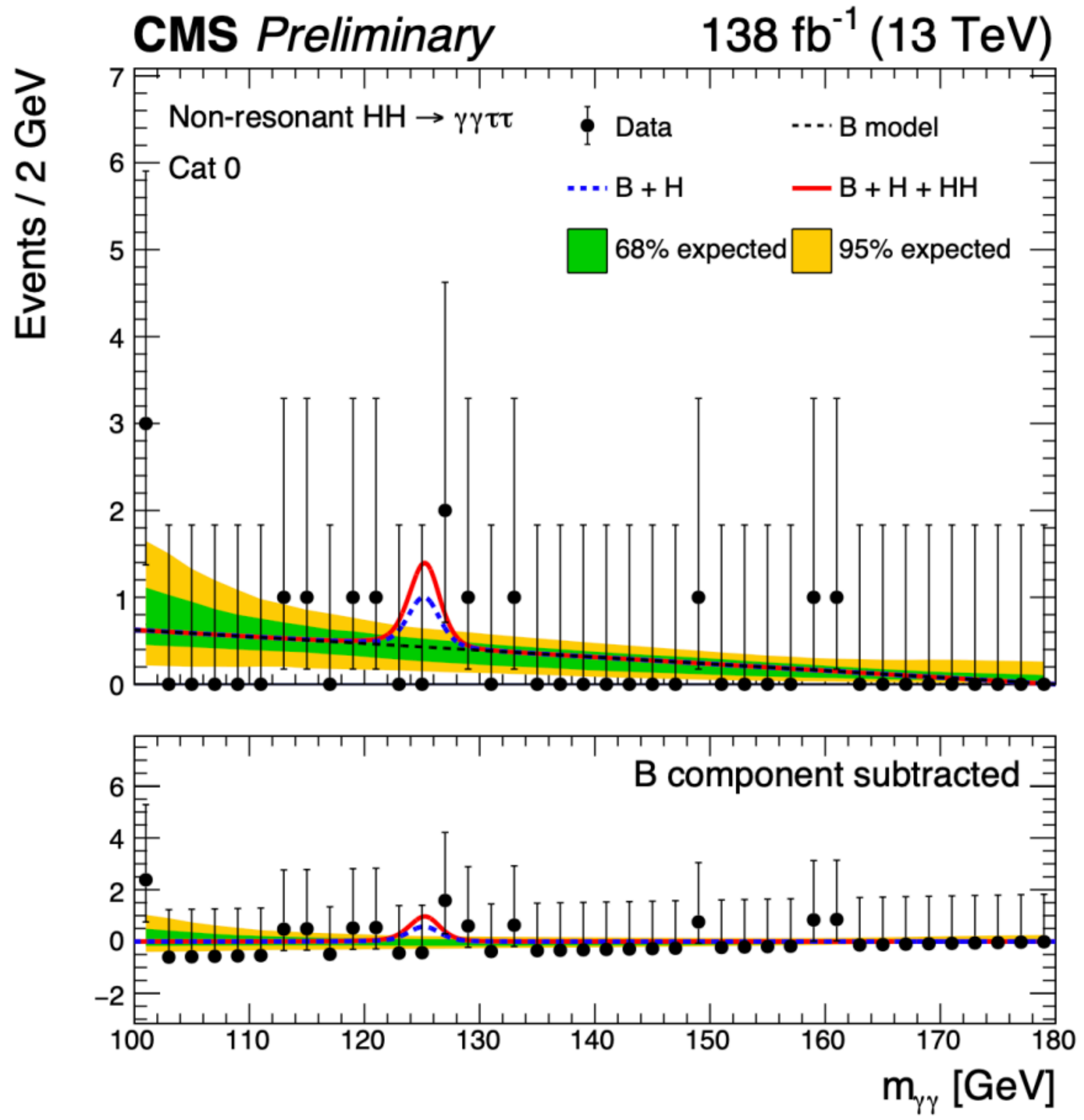
Recent results: CMS HH(→ττɣɣ)

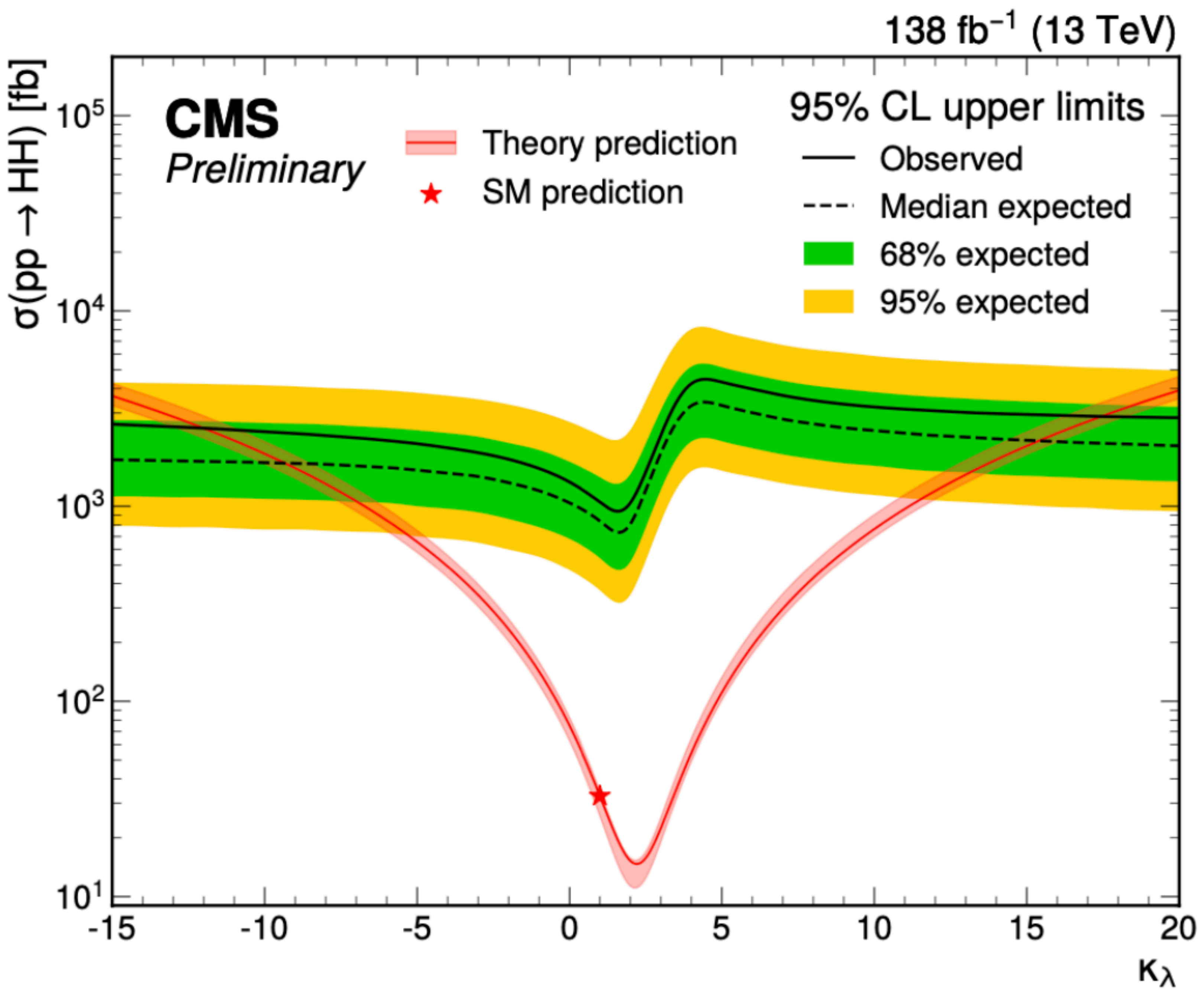
CMS PAS HIG-22-012 (2024)

CMS targets ττγγ with a specific analysis: 5 dedicated channels based on tau decay signatures

BDT trained to categorise signal → Fit of $m_{\gamma\gamma}$ spectrum → Limit on self-coupling







μ_{HH} < 33 (26)

$k_\lambda \in [-13, 18]_{obs}$ $(-11, 16)_{exp}$

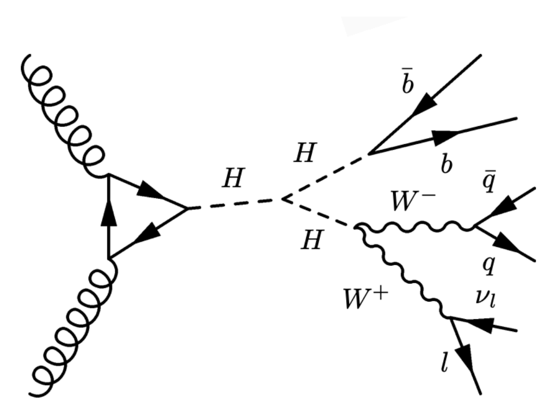
Recent results: CMS HH(→bbWW)

JHEP 07 (2024) 293

Second largest HH BR after 4b final state: ~ ¼ of HH pairs decay to bbWW !
Nevertheless, very hard to reconstruct experimentally due to complex WW decays

*including fully hadronic W decays (not covered in the analysis)

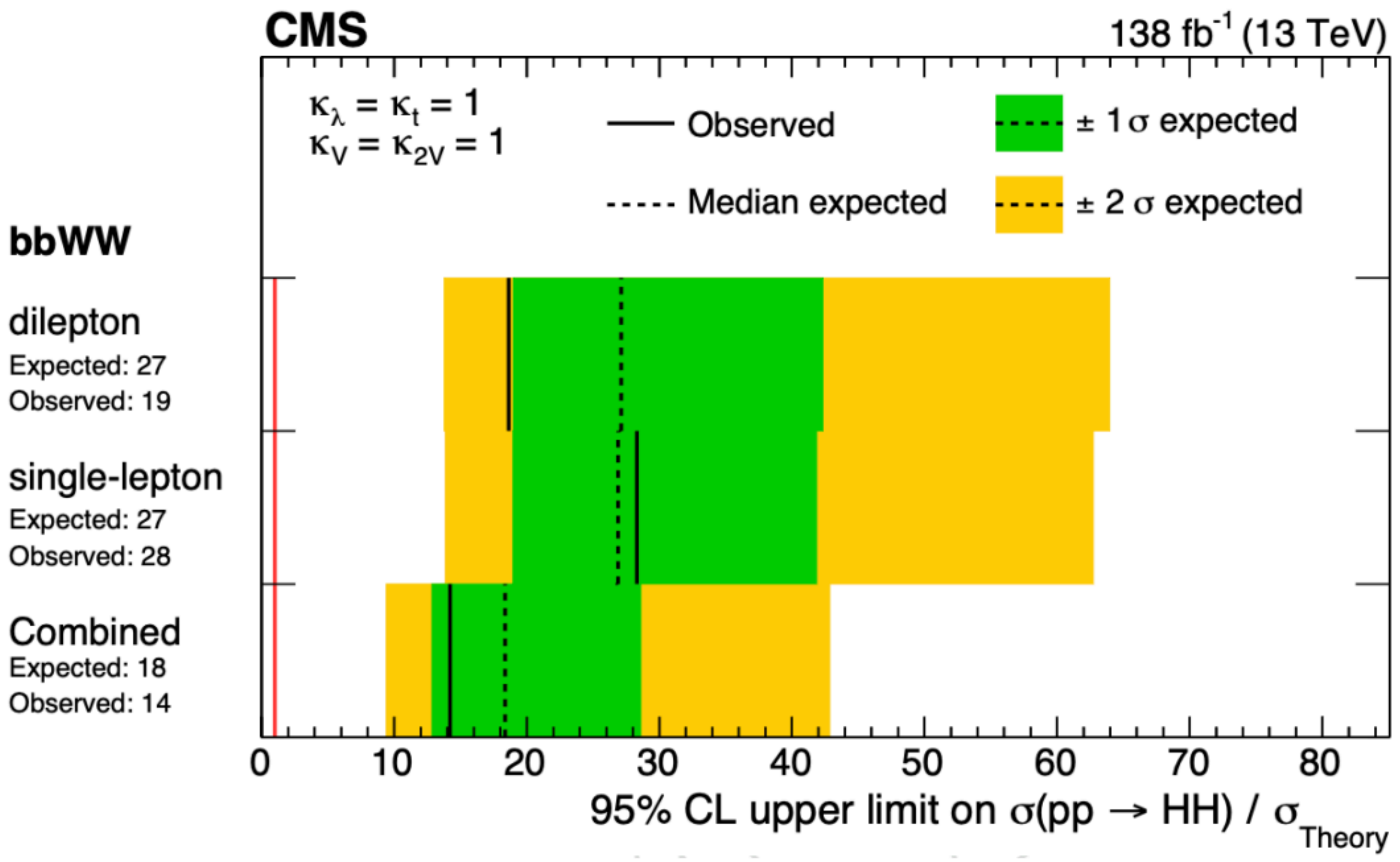
BR	WW
bb	25%



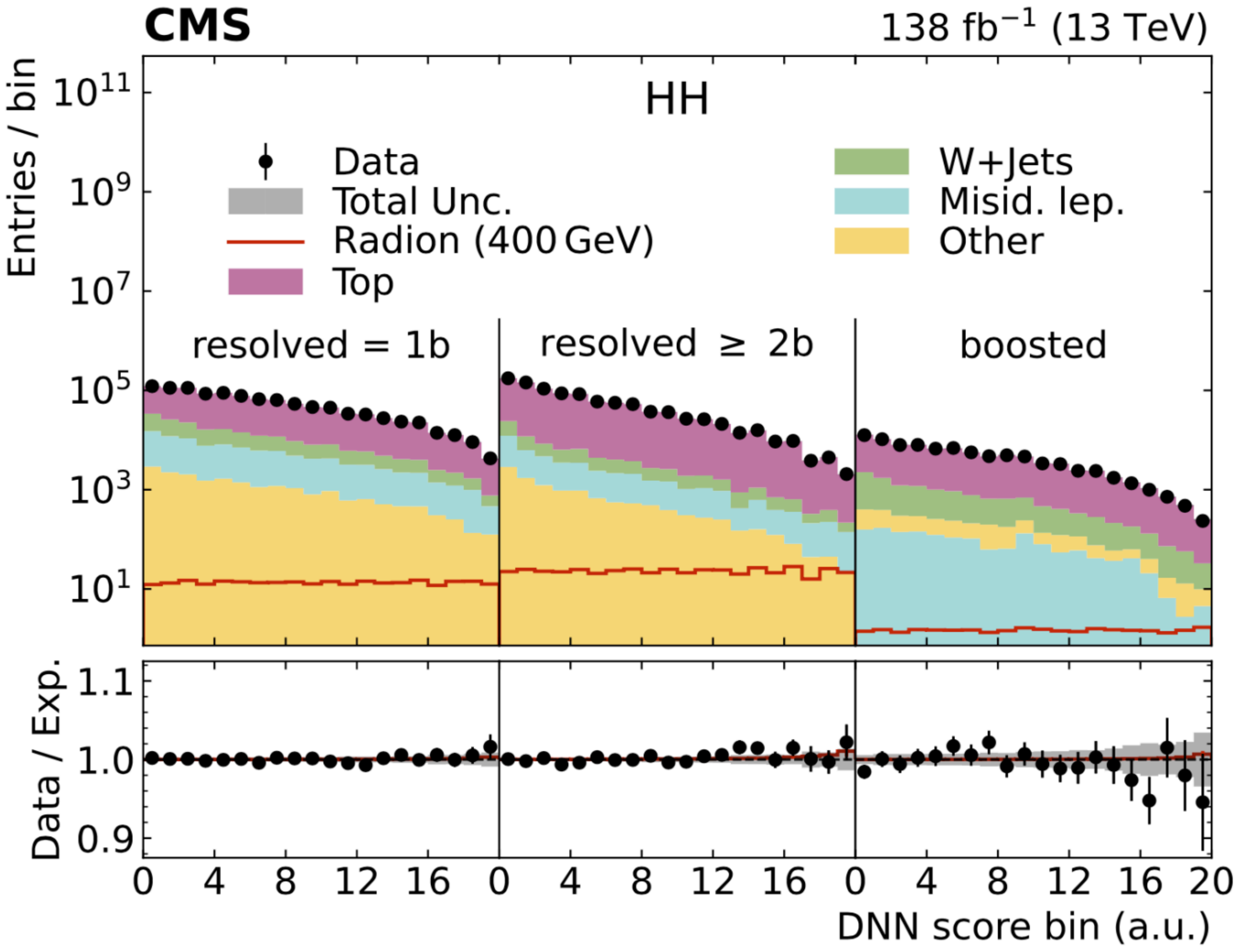
Combination of:

- resolved topologies according to #b-jets
- boosted topologies (large-R jets)

Simultaneous fit of DNN classifier in all categories



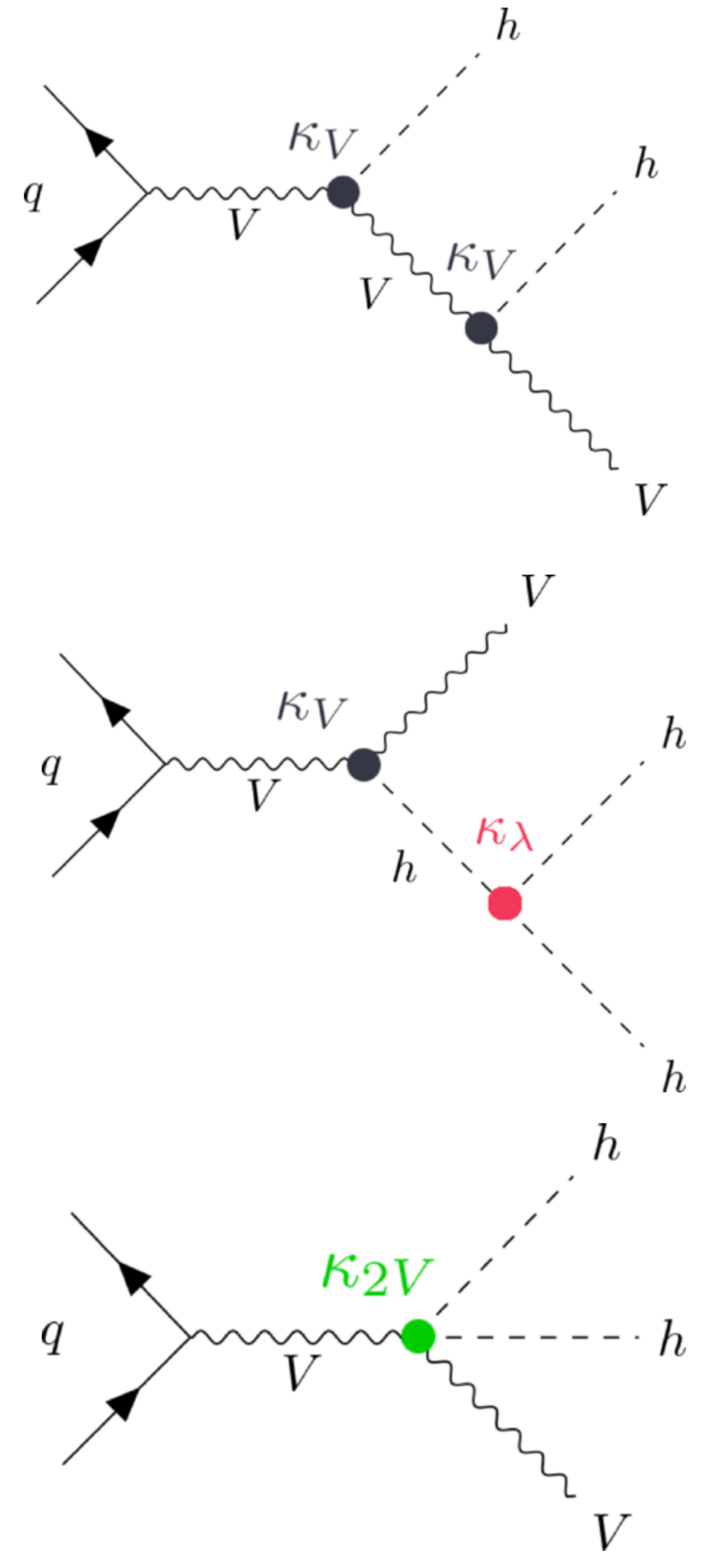
$k_\lambda \in [-7.2, 13.8]_{obs}$ $(-8.7, 15.2)_{exp}$



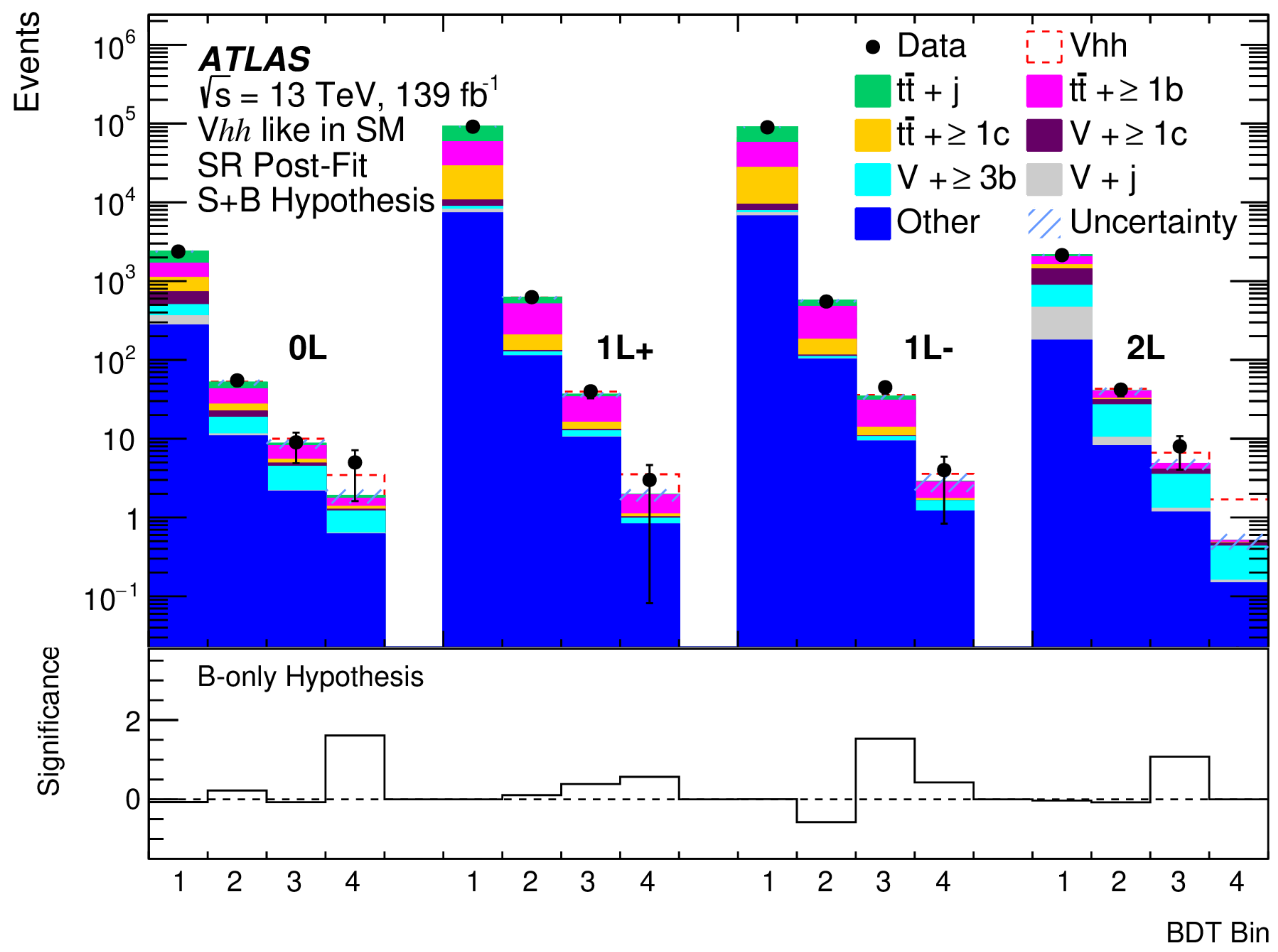
Recent results: ATLAS VHH(4b)

Eur. Phys. J. C 83 (2023) 519

ZHH and **WHH** production in the 4b final state (small XS, maximising BR)



0-lepton	1-lepton	2-lepton
Z(νν)HH	W(lν)HH	Z(ll)HH



$k_{2Z} \in [-9.9, 11.3]_{obs}$ $(-7.1, 8.5)_{exp}$

$k_{2W} \in [-12.3, 13.5]_{obs}$ $(-8.6, 9.8)_{exp}$

$k_{2V} \in [-8.6, 10]_{obs}$ $(-5.7, 7.1)_{exp}$

Not competitive for combined k_{2V}, nor k_λ, but uniquely sensitive to separate Z and W couplings

Similar results from CMS VHH

… and projections towards the LHC future

Combinations …

HH combinations - signal strength

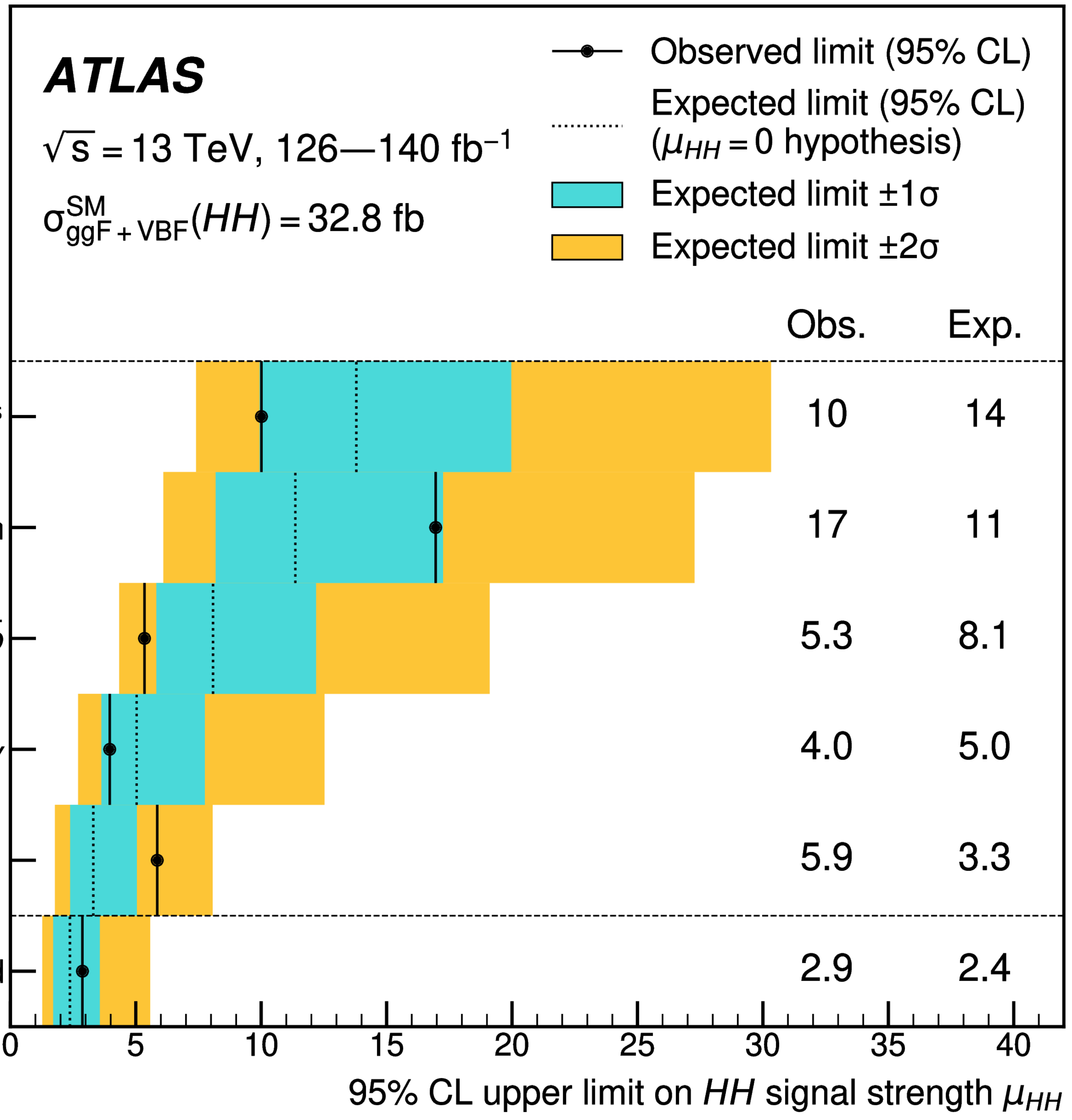
No single golden channel: HH combinations will be the key towards evidence and observation

Phys. Rev. Lett. 133 (2024) 101801

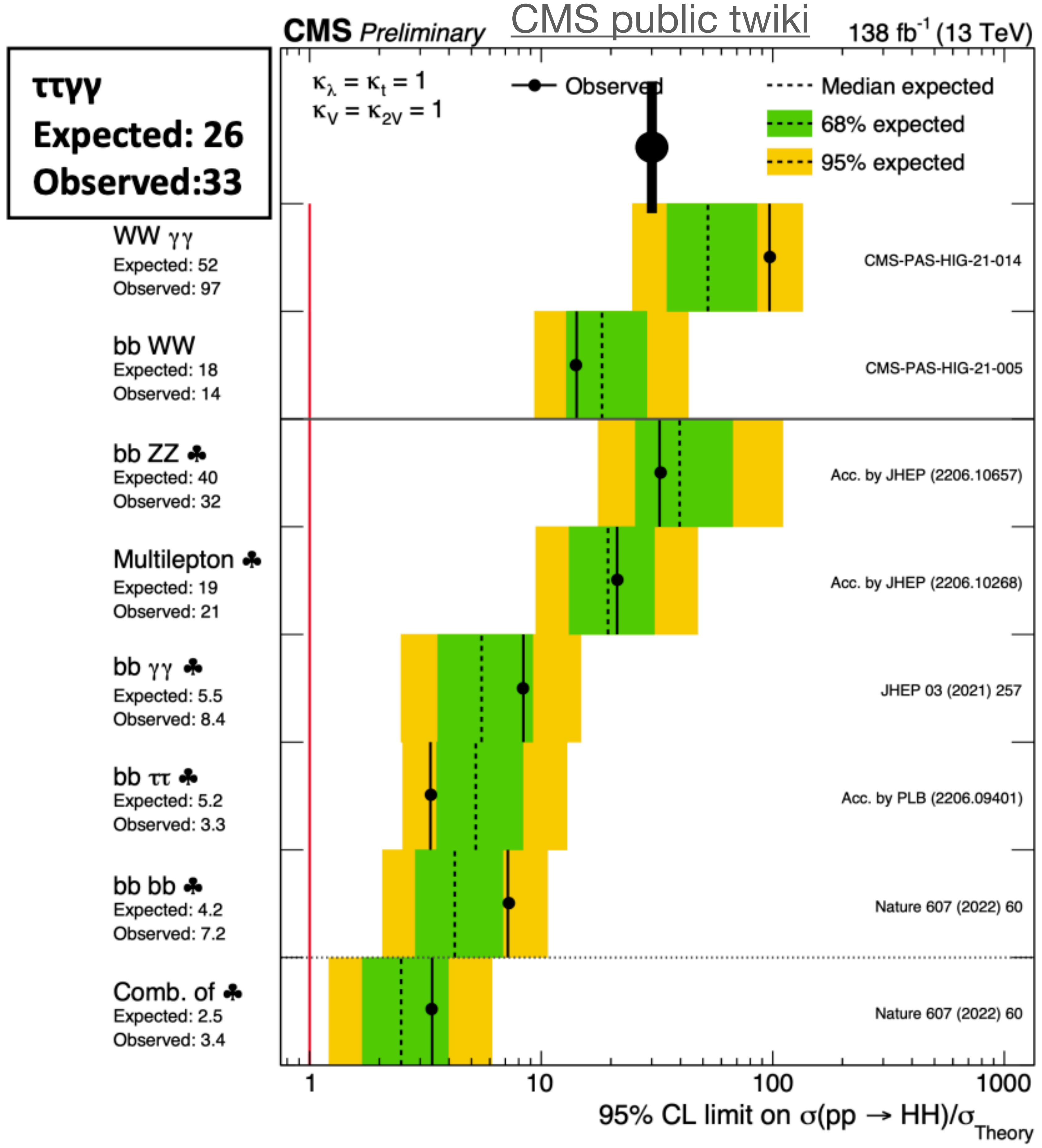
new results wrt previous combination

new boosted VBF(4b) added to bbbb

re-optimised Run-2 results for both channels



CMS public twiki



New results for:
- WWγγ
- bbWW
- ττγγ (added by hand in the combination plot, stolen from A. Bethani's talk at HH24)

(not yet in total combined)

$\mu_{HH}^{ATLAS} < 2.9\ (2.4)$

$\mu_{HH}^{CMS} < 3.4\ (2.5)$*

*missing (WWγγ, bbWW, ττγγ) - expected small improvements

HH combinations - self-coupling parameters

No single golden channel: HH combinations will be the key towards evidence and observation

ATLAS (HH updated constraint) - $k_\lambda \in [-1.2, 7.2]_{obs}$

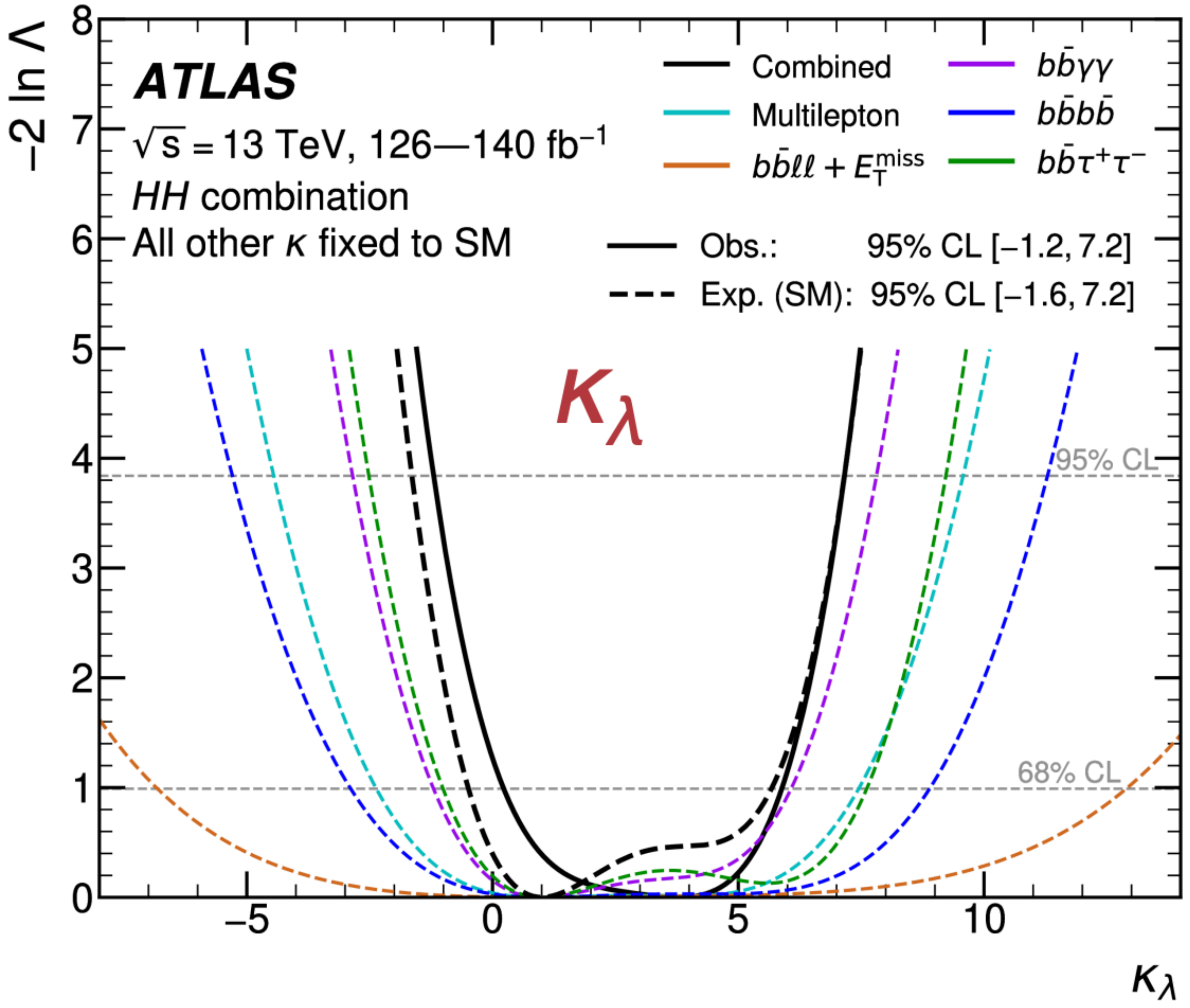
CMS (HH only constraint) - $k_\lambda \in [-1.24, 6.49]_{obs}$

CMS Nature paper

$k_{2V} \in [0.67, 1.38]_{obs}$

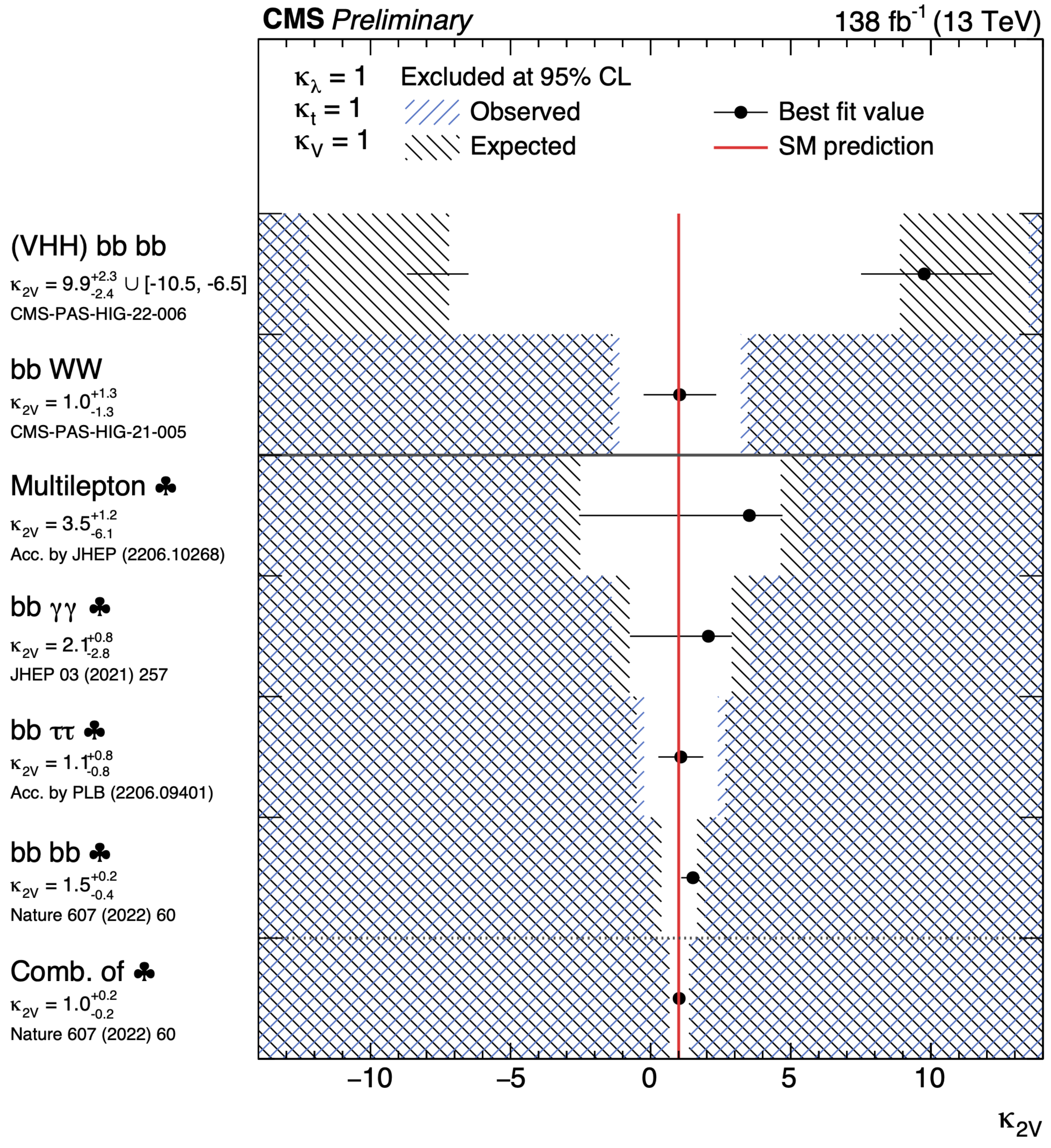
Assuming the SM: k2V =0 excluded with more than 6σ

Phys. Rev. Lett. 133 (2024) 101801



CMS public twiki

k_{2V}



bbyy (and bbττ) dominant for **k_λ** determination

(VBF) boosted HH(4b) largely dominant for **k_{2V}** constraints

HH production: looking towards LHC Run-3

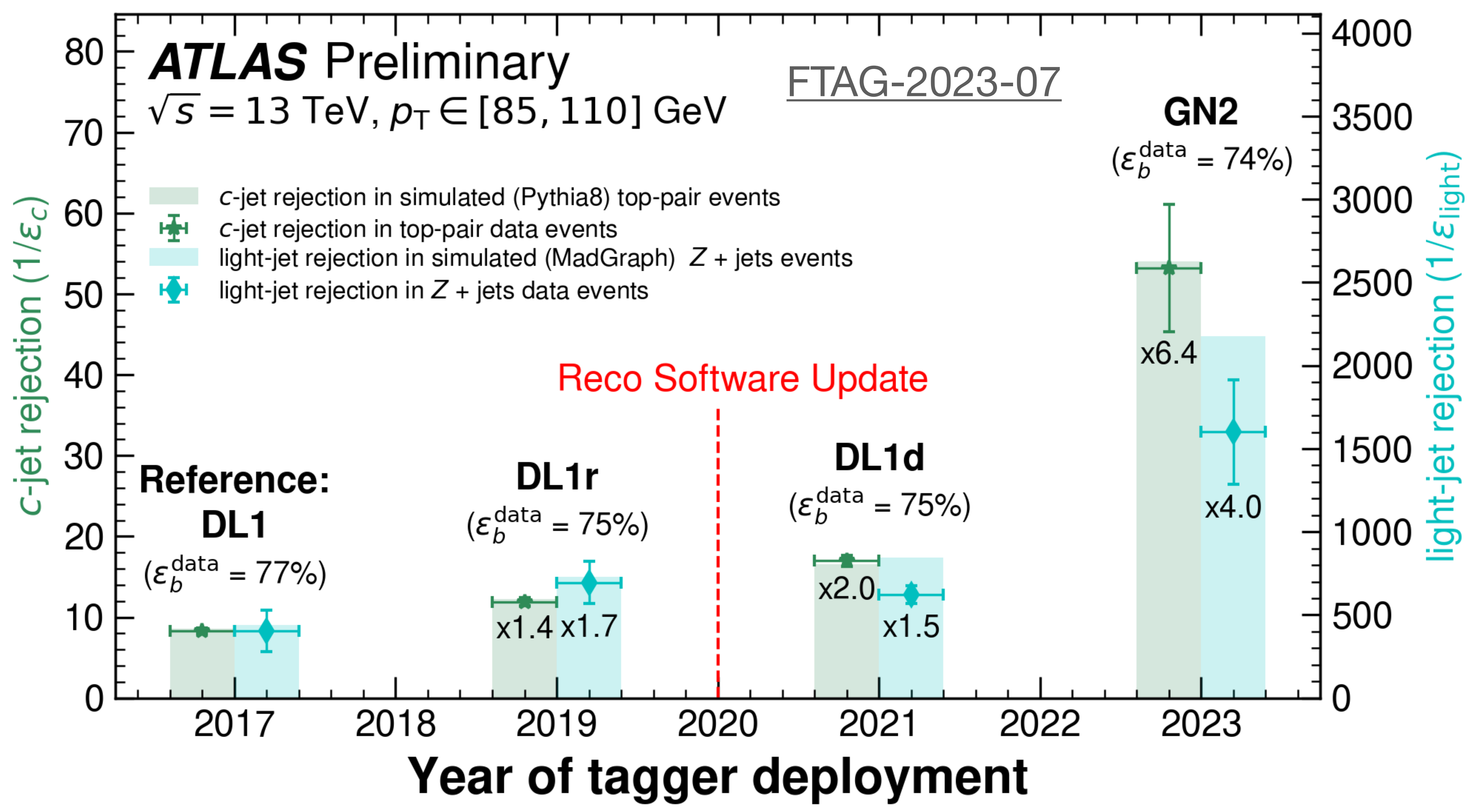
HH searches limited by statistics (5-20% impact of systematics):
additional O(300/fb) of collected luminosity will result in an O(70%) improvement in analysis sensitivity

Experimental improvements: main focus on signal acceptance - **can we retain more HH events?**

see talk from Frank this afternoon !

Example: ATLAS b-tagging algorithms

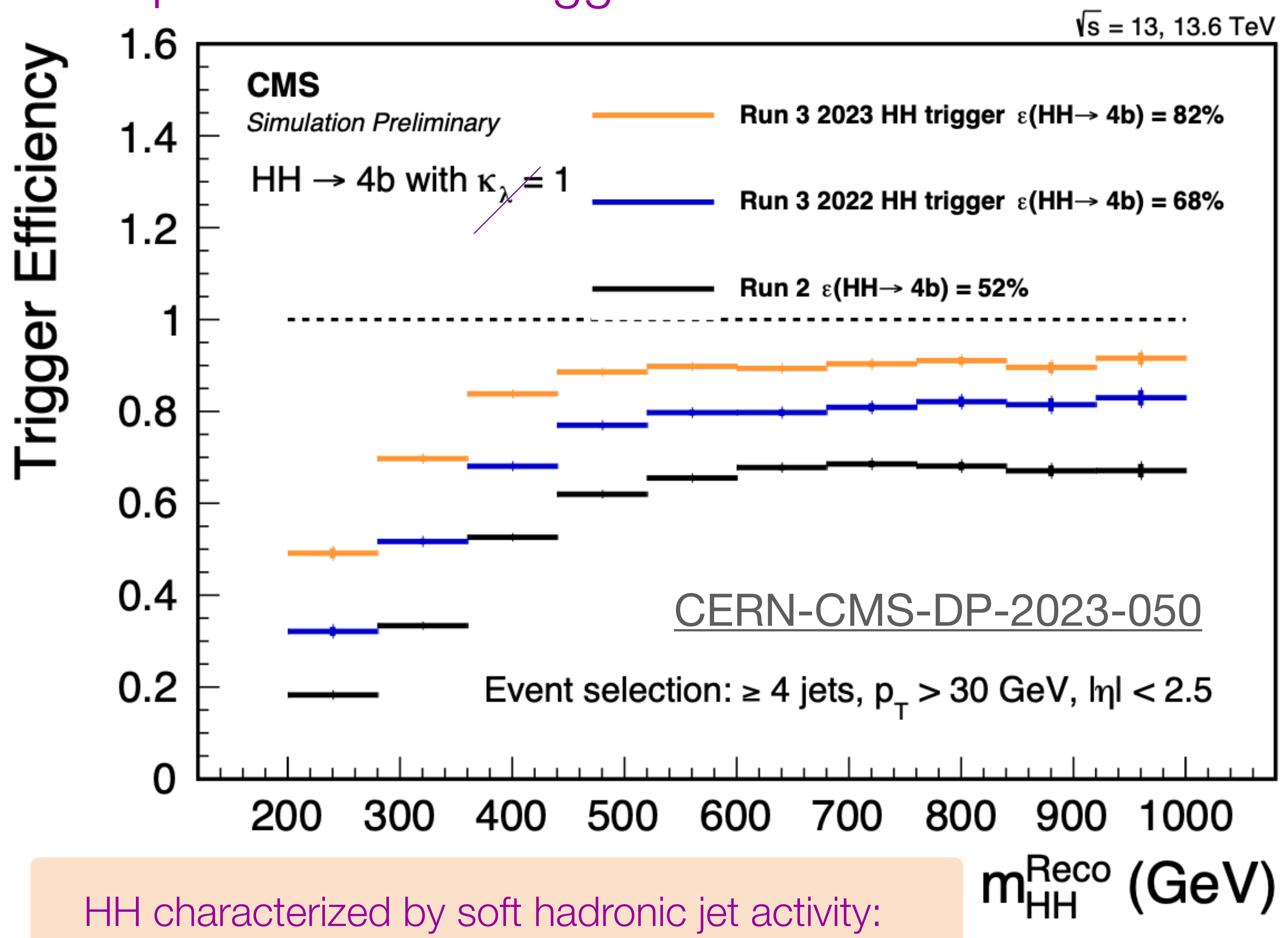
Eur. Phys. J. C 83 (2023) 681



used in current analyses

4x better background rejection for the same signal efficiency !

Example: CMS new triggers



HH characterized by soft hadronic jet activity:
data-parking approach allows to drastically improve signal efficiency

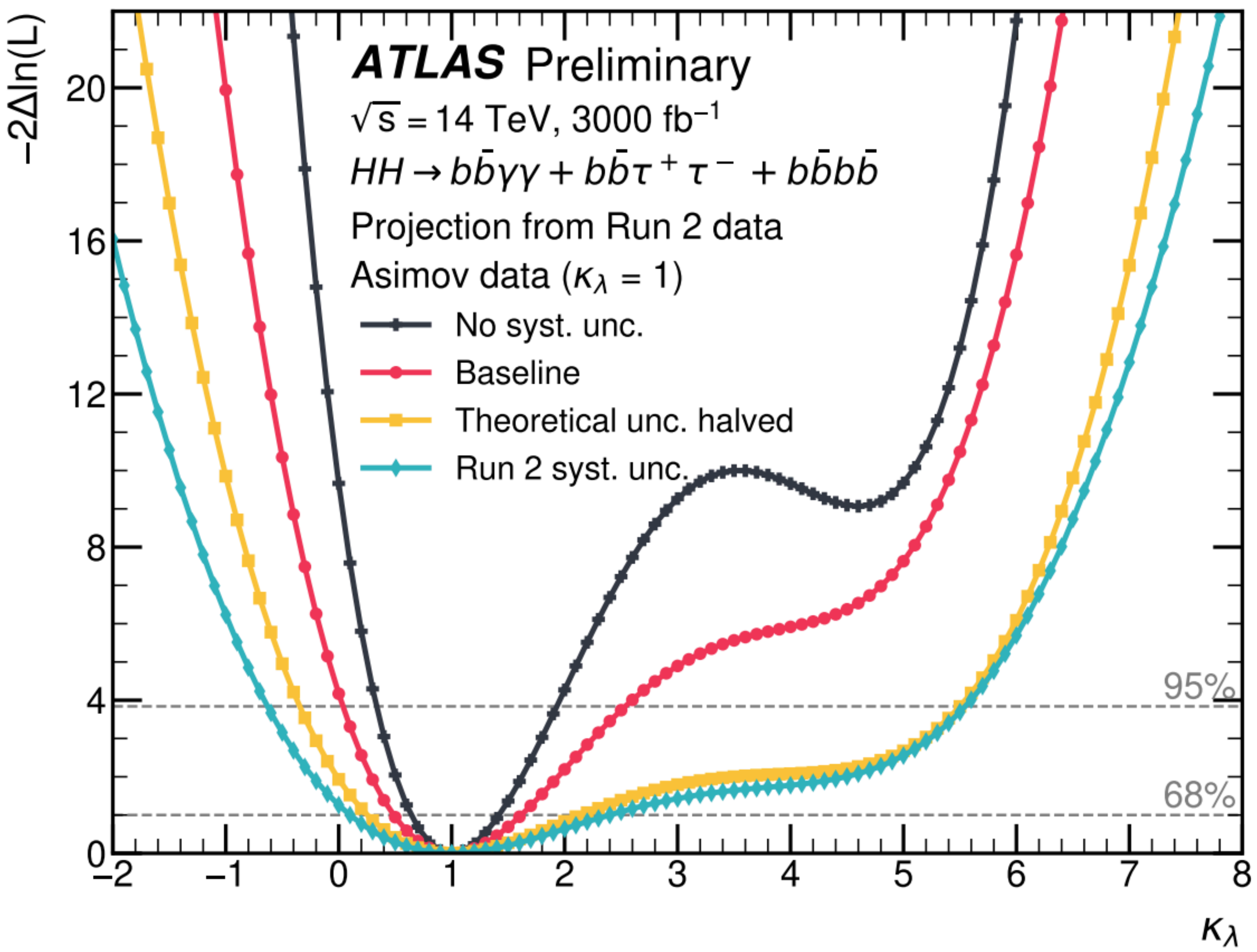
Many more (*not public*) advancements in experimental techniques: we can do better than simple lumi-scaling (as shown during Run-2)
Full Run-2+3 results can close in on μ_{HH} limits around (1) - possible first 3σ from ATLAS+CMS combination? *(this is of course personal divination)

HH production: looking towards HL-LHC

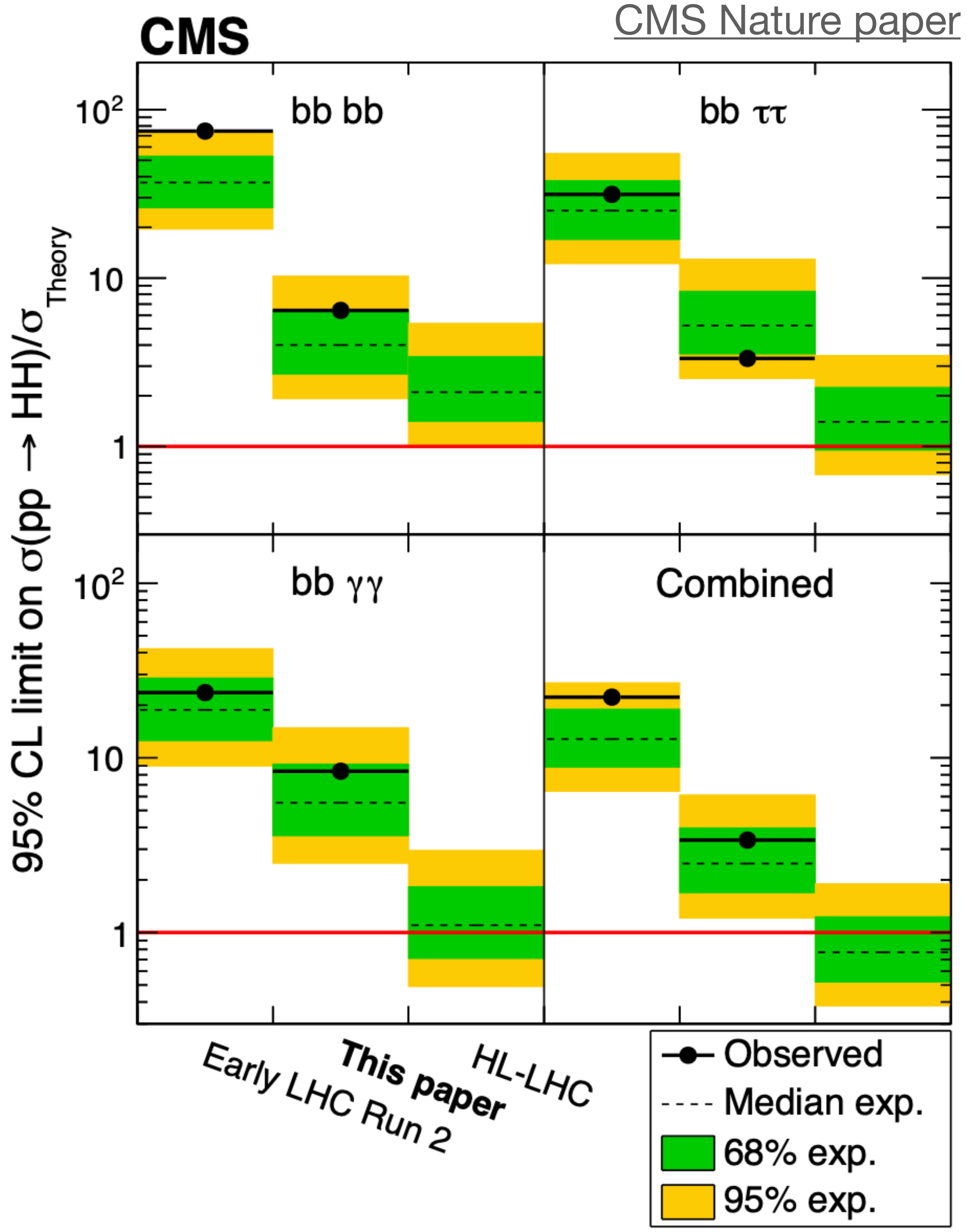
Both experiments provide important HL-projections for HH searches:
not based on the most up-to-date results, so to be taken with a grain of salt !
(this is essentially a lumi-scaling with different scenarios for systematics)

Large effort from both ATLAS and CMS to update the HL-LHC HH projections *shortly* !

ATL-PHYS-PUB-2022-053



CMS Nature paper

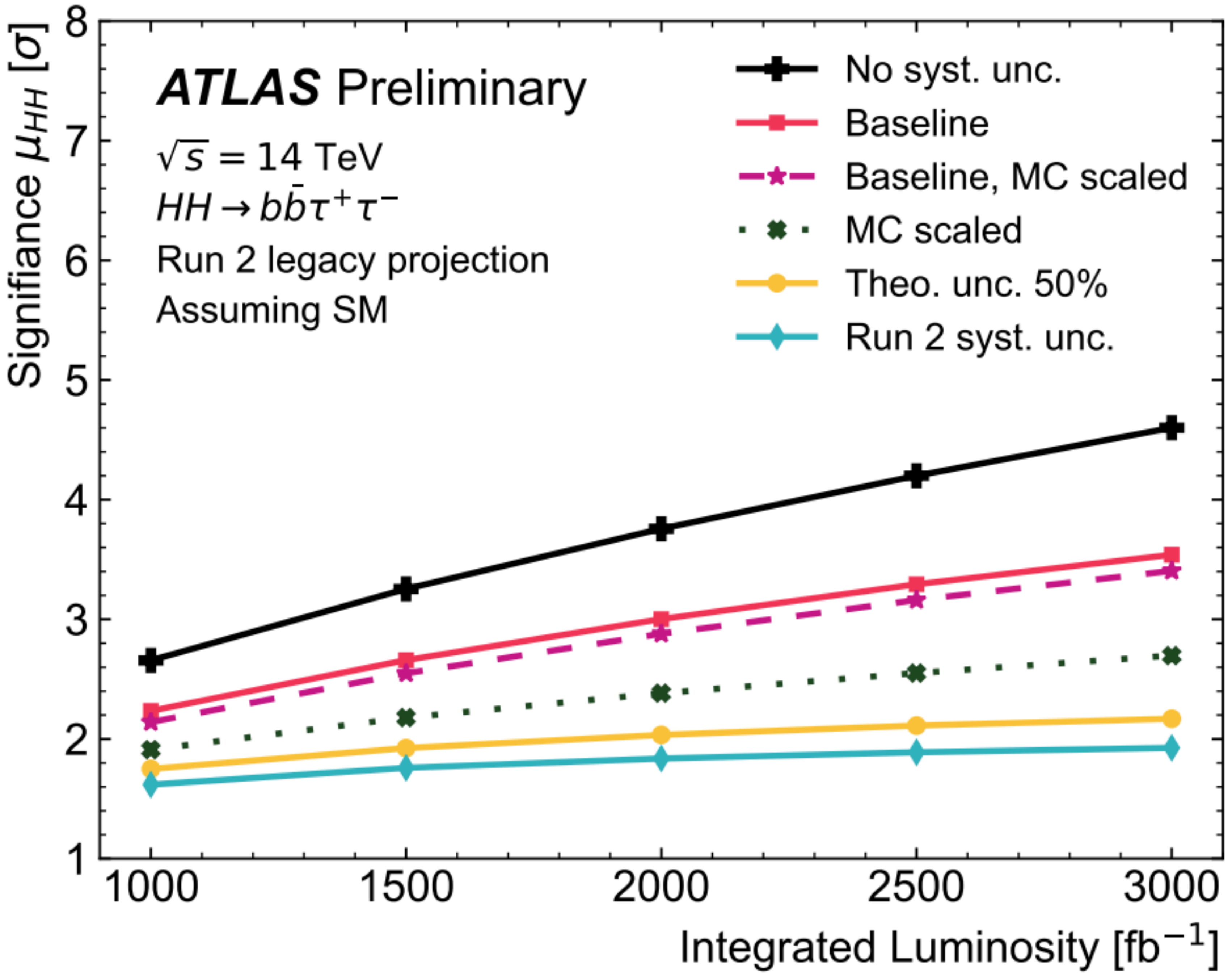


Of course with a drastic improvement of luminosity the hierarchy among HH changes (largest improvements to bbyy, due to limited stats)

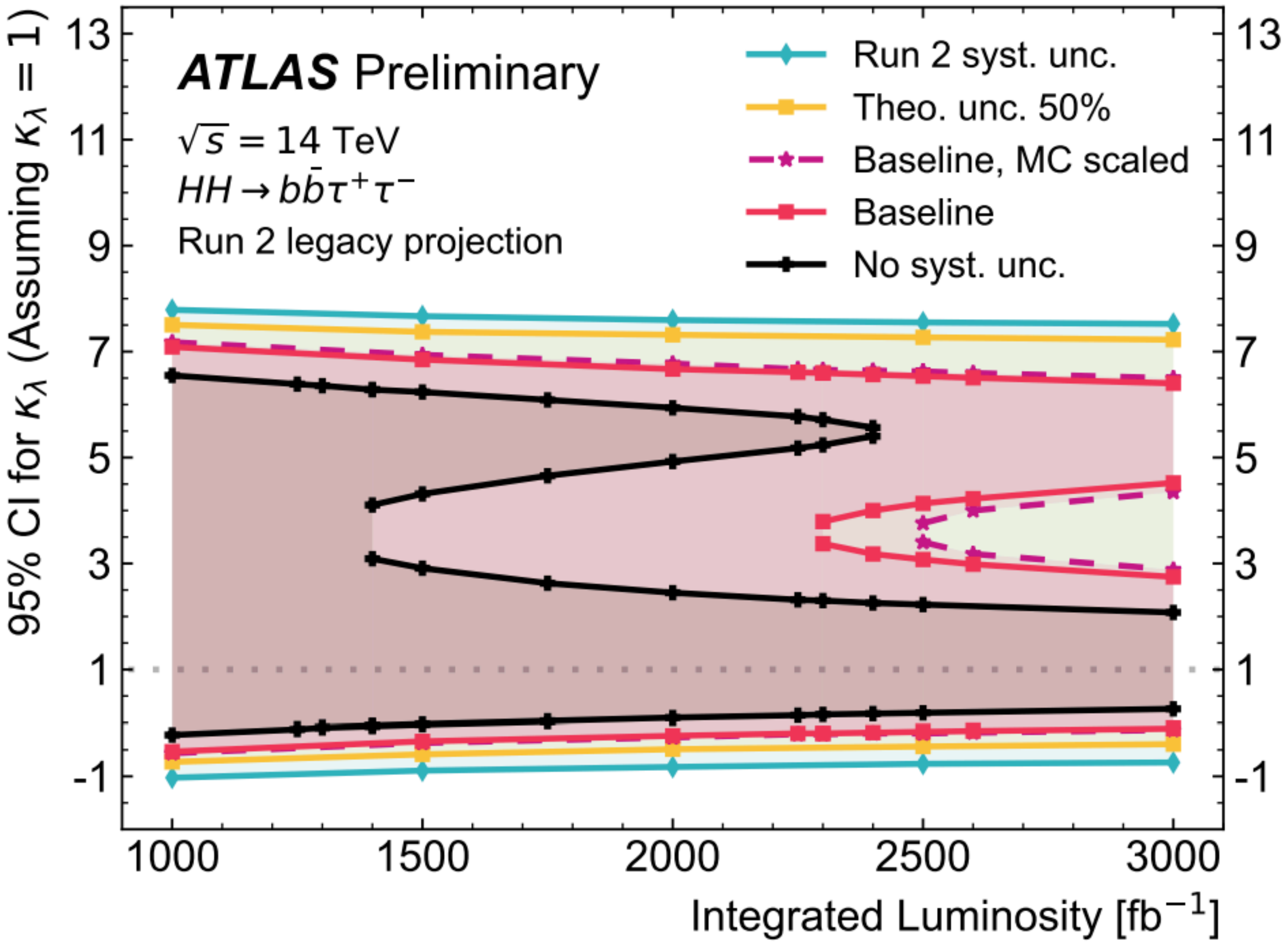
HH production: looking towards HL-LHC

Updated HH(bbττ) HL-LHC projections from ATLAS: in-depth work to account for experimental advancements !

(assuming SM)



(assuming SM)



Bounds Higgs self-coupling vs LHC luminosity (assuming SM)

(different colours = different systematic uncertainties scenarios)

→ in absence of systematics we could resolve the **k_λ** degeneracy with O(2.5/ab)

(stronger impact of bbyy expected here!)

Close to 3σ from single channel:
HH(bbττ) alone is close to the previous HL-LHC projection from 3 golden channels combined !

- Run-2 syst. unc. = same uncertainties used in Run-2 analyses
- MC scaled = Run-2 syst. + MC stat. unc. scaling with luminosity
- Theo. unc. 50% = Run-2 syst. + halving signal and bkg uncertainties
- baseline = Snowmass recommendations expected HL-LHC perf. (no MC stat. unc.)
- baseline, MC scaled = “” + MC stat. unc. scaling with luminosity

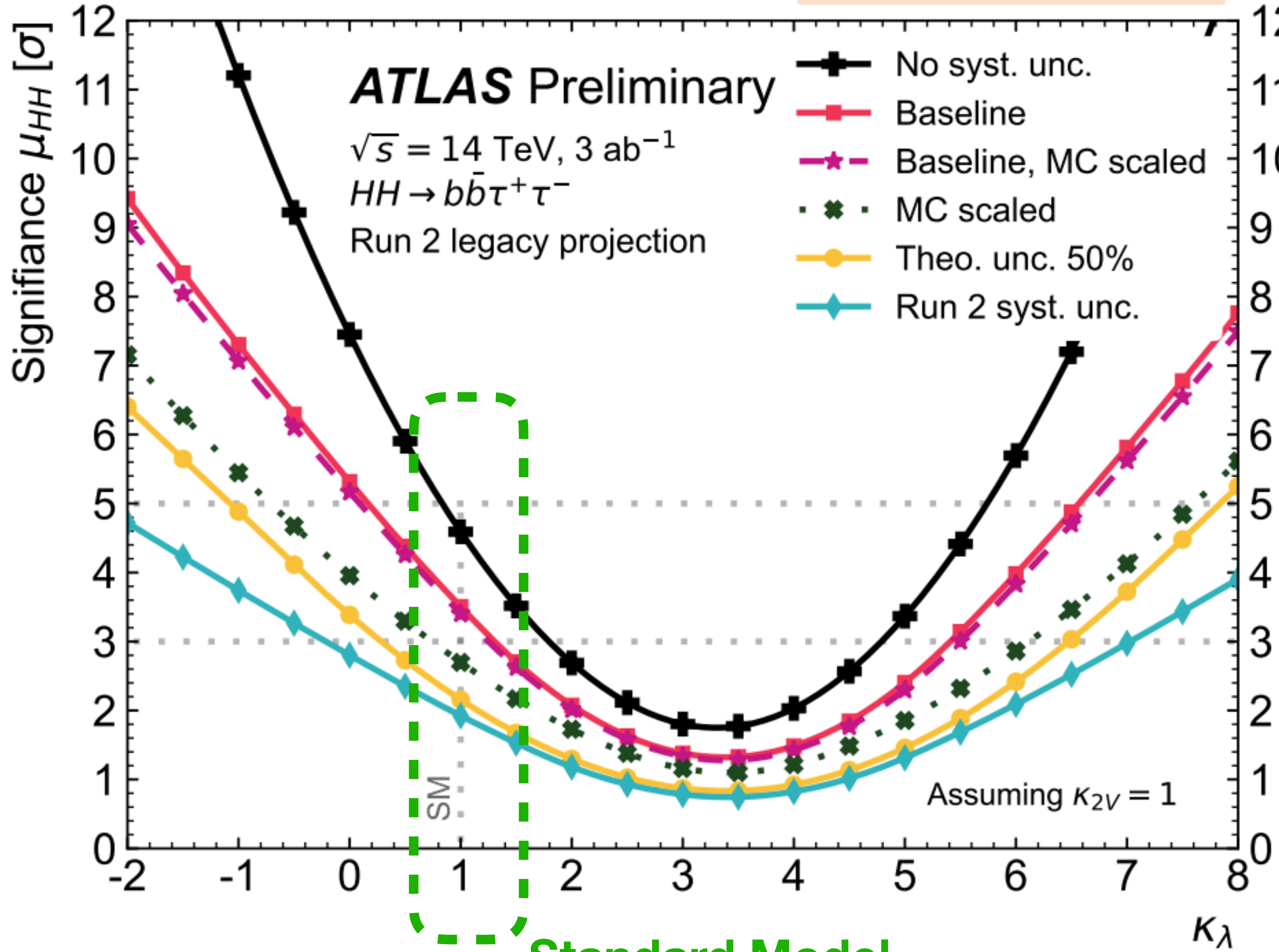
Showing the important of updated projections, accounting for:
increased luminosity, com energy, algorithmic improvements in object reconstruction, theory and MC improvements, analysis techniques

HH production: looking towards HL-LHC

ATL-PHYS-PUB-2024-016

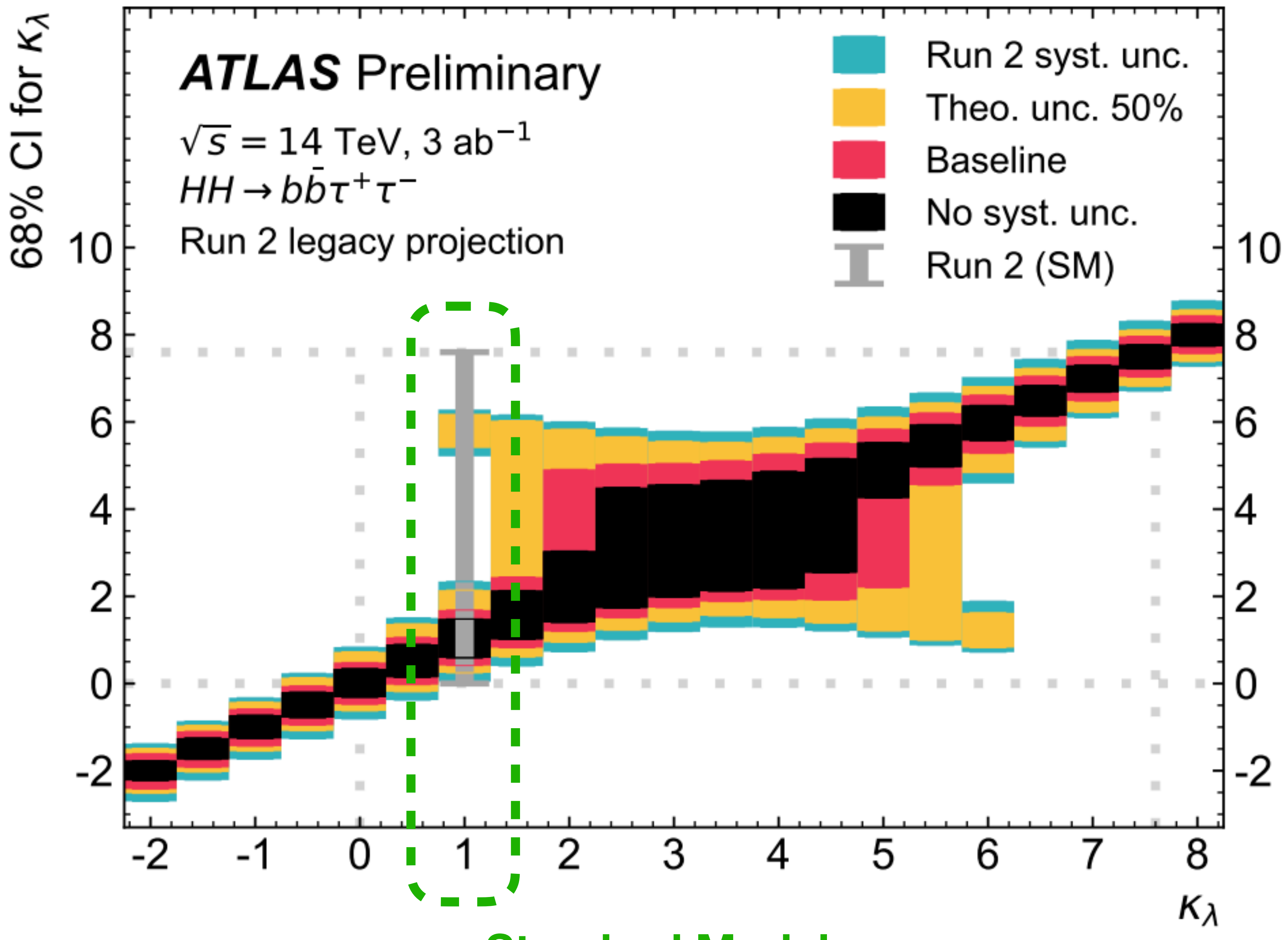
Updated HH(bbττ) HL-LHC projections from ATLAS: in-depth work to account for experimental advancements !

(not assuming SM)



Standard Model

(not assuming SM)



Standard Model

→ our knowledge of k_λ at the end of the HL-LHC will very much depend on the universe's implementation of Higgs self-interactions !

Will we observe HH production?

yes*, if k_λ is lower or equal to the SM, or much larger

significantly reduced sensitivity for k_λ ~ 3.5

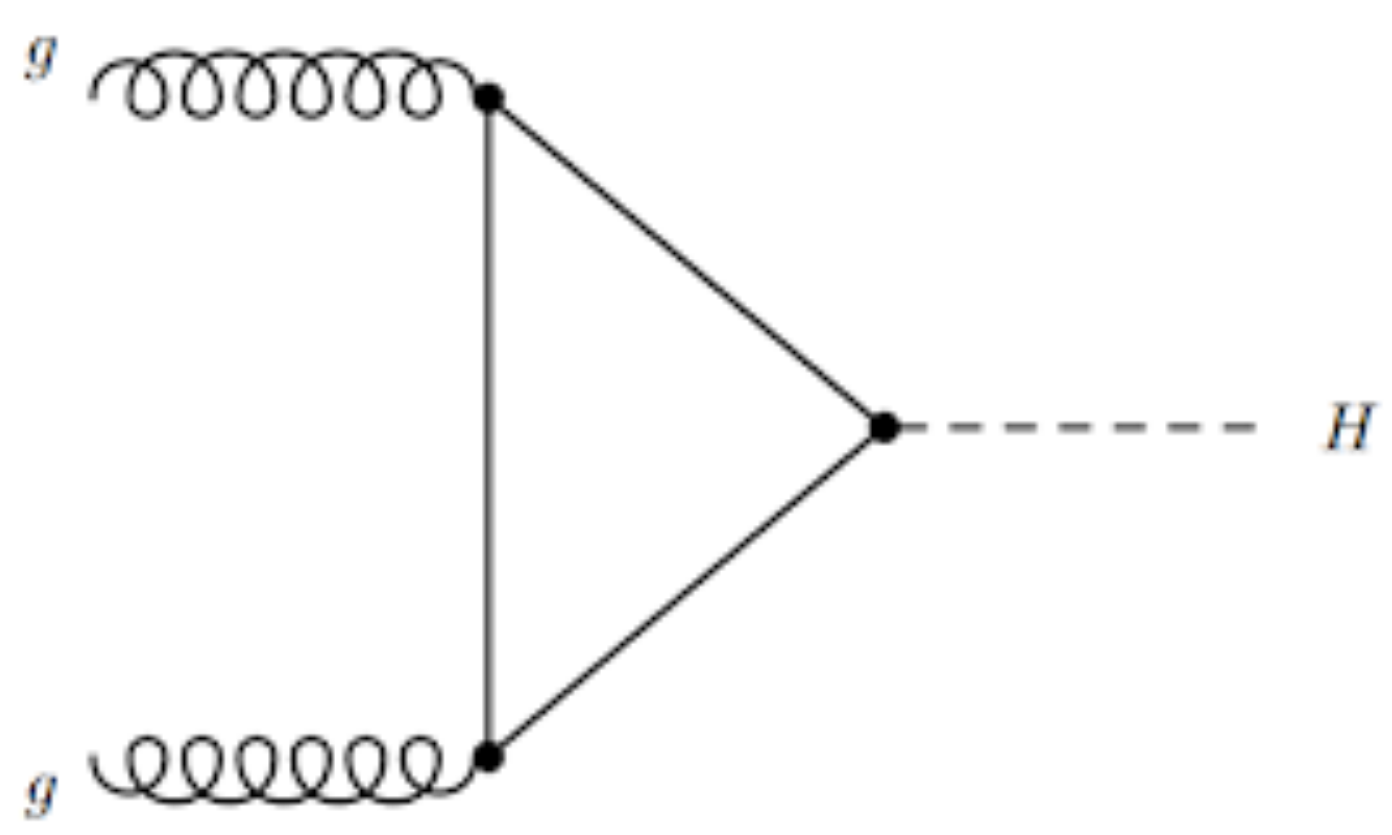
Showing the important of updated projections, accounting for:
increased luminosity, com energy, algorithmic improvements in object reconstruction, theory and MC improvements, analysis techniques

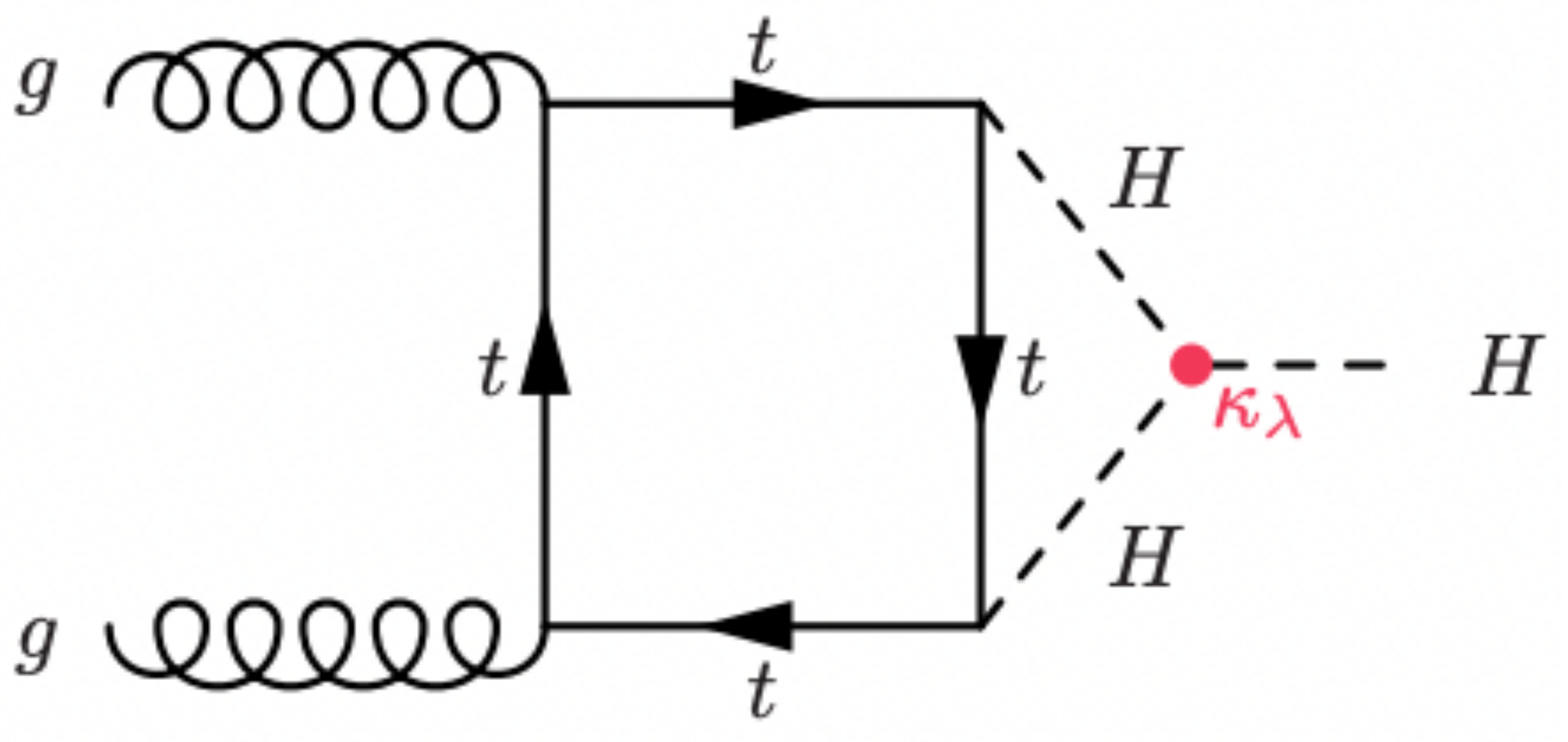
*yes = potentially

Indirect probe of Higgs self-coupling

via corrections to single-Higgs production

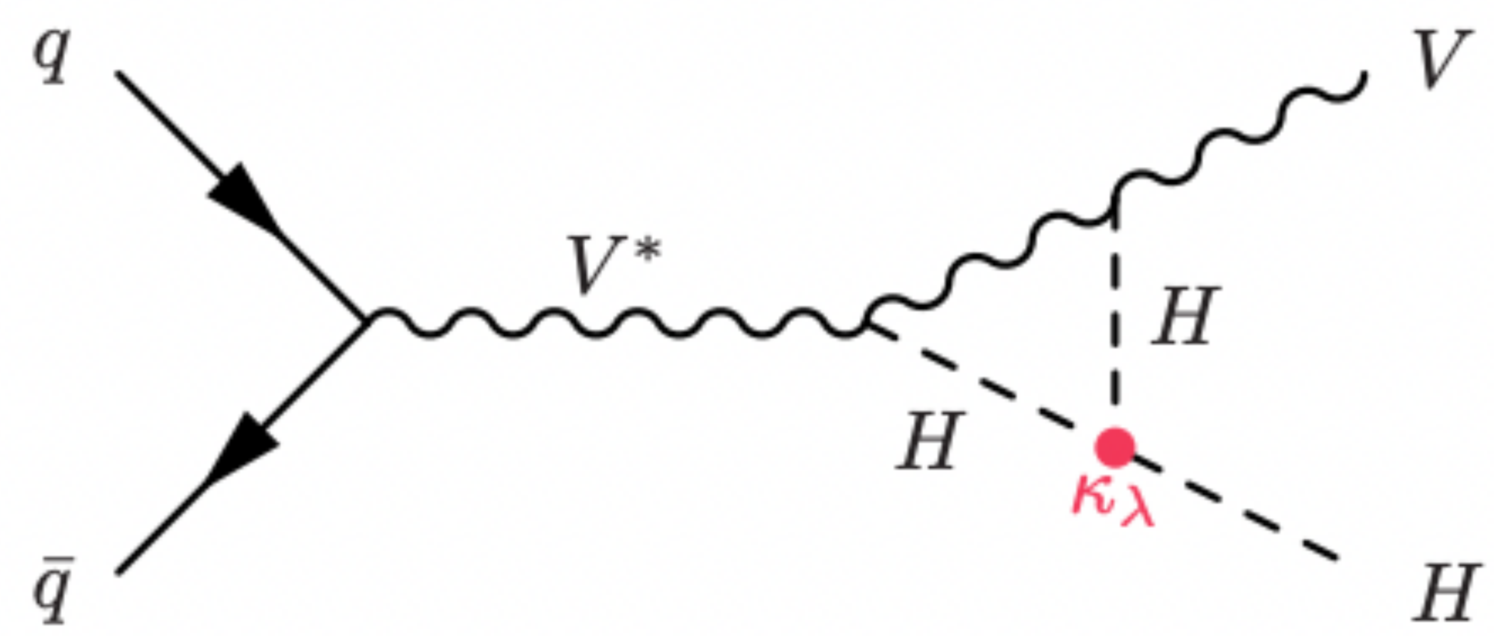
Consider the main Higgs production mechanism at the LHC: Higgs gluon-fusion ggH

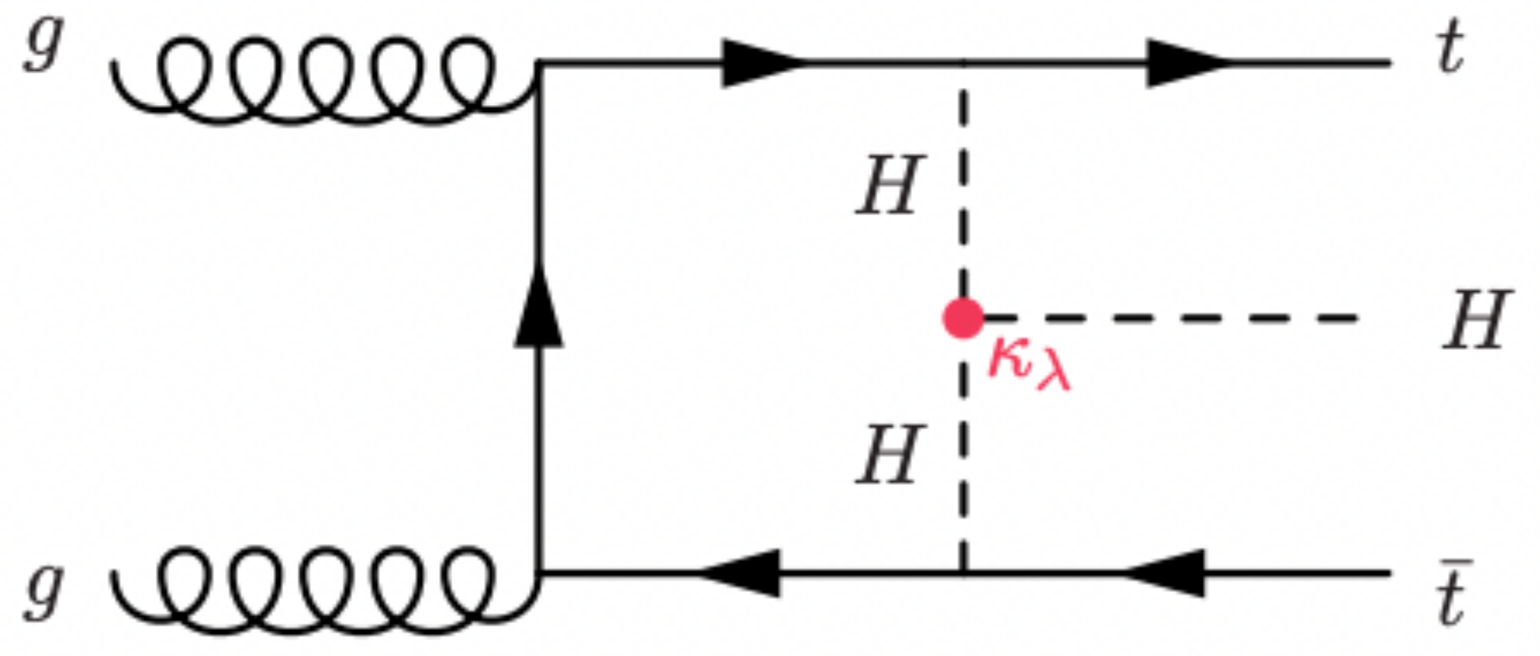




Higher-order corrections introduce a dependency on scalar-self-interactions !

(Higgs loops: much lower cross-section - but sizeable differential effects)

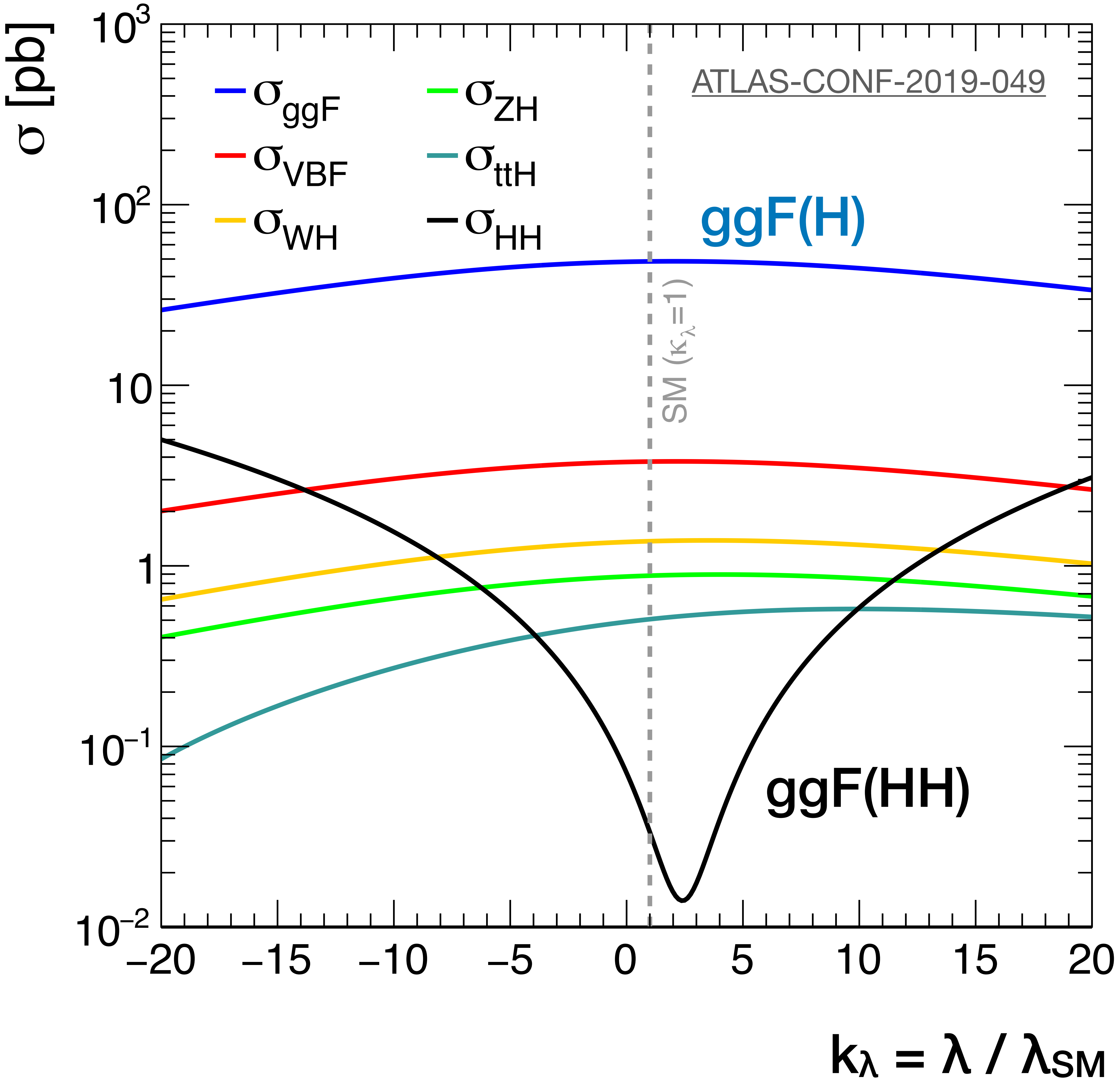




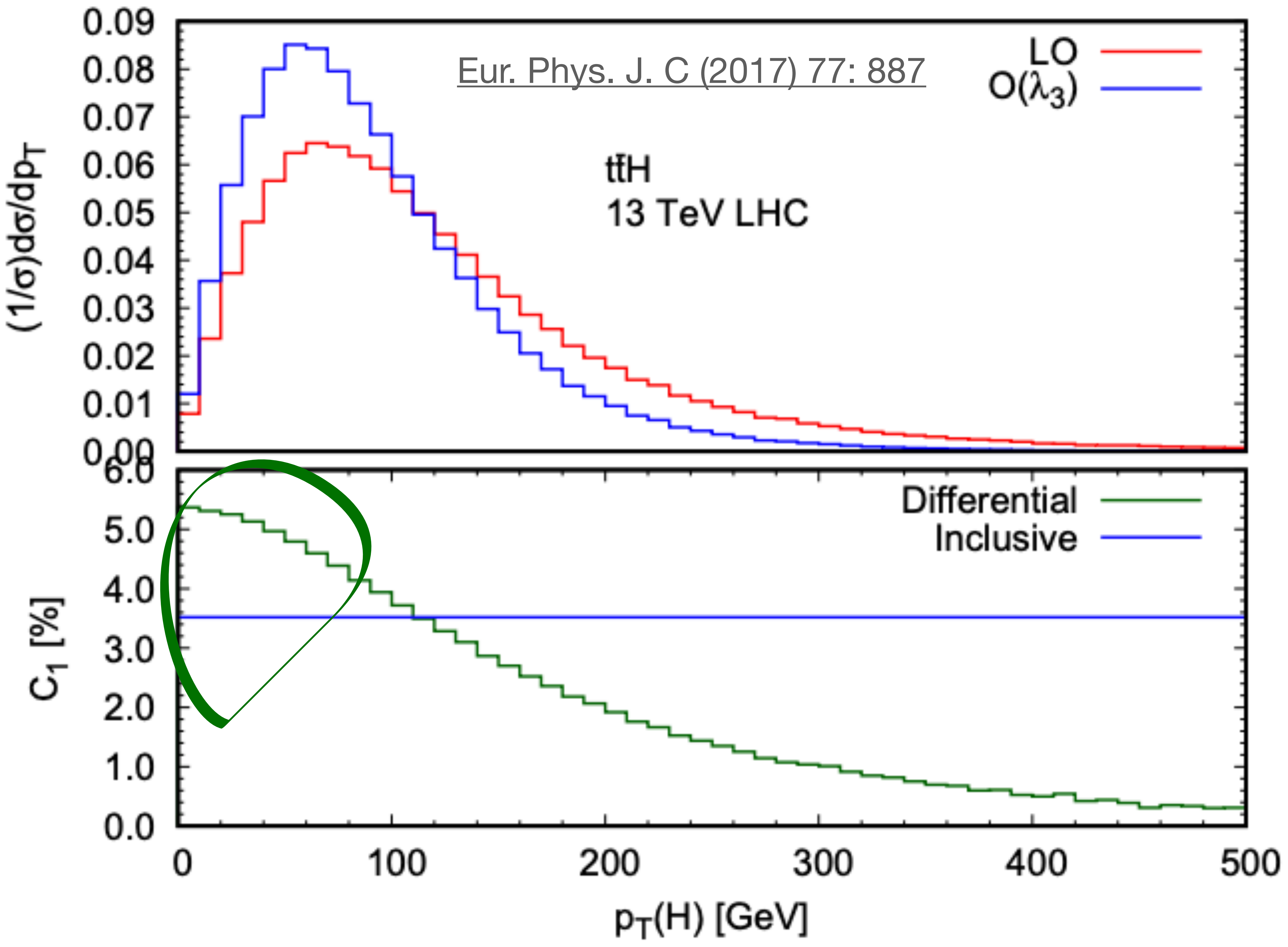
This is true for all Higgs production modes, as well as decay diagrams

Alternative probes: single-Higgs production

Total cross-section variations moderate compared to HH



O(5%) effects on Higgs differential cross-sections



Single-Higgs measurements much more precise than HH: some sensitivity to moderate variations of yields (and shapes)

Note: no differential parametrisation of self-coupling effects in ggH (only yield variations)

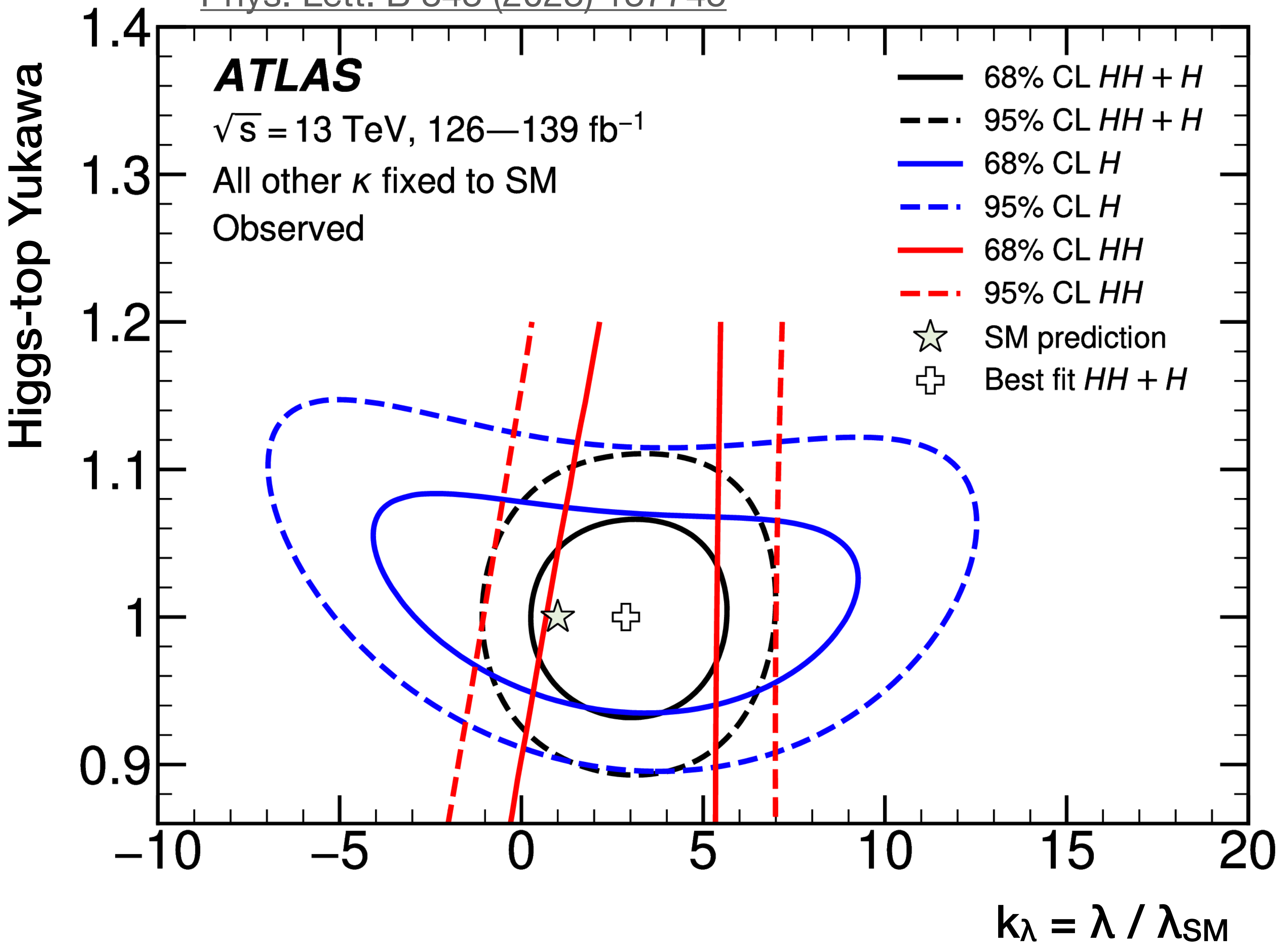
Simultaneous measurement of top Yukawa and Higgs self-coupling

HH cross section
largely degenerate in the top-Yukawa and Higgs self-coupling

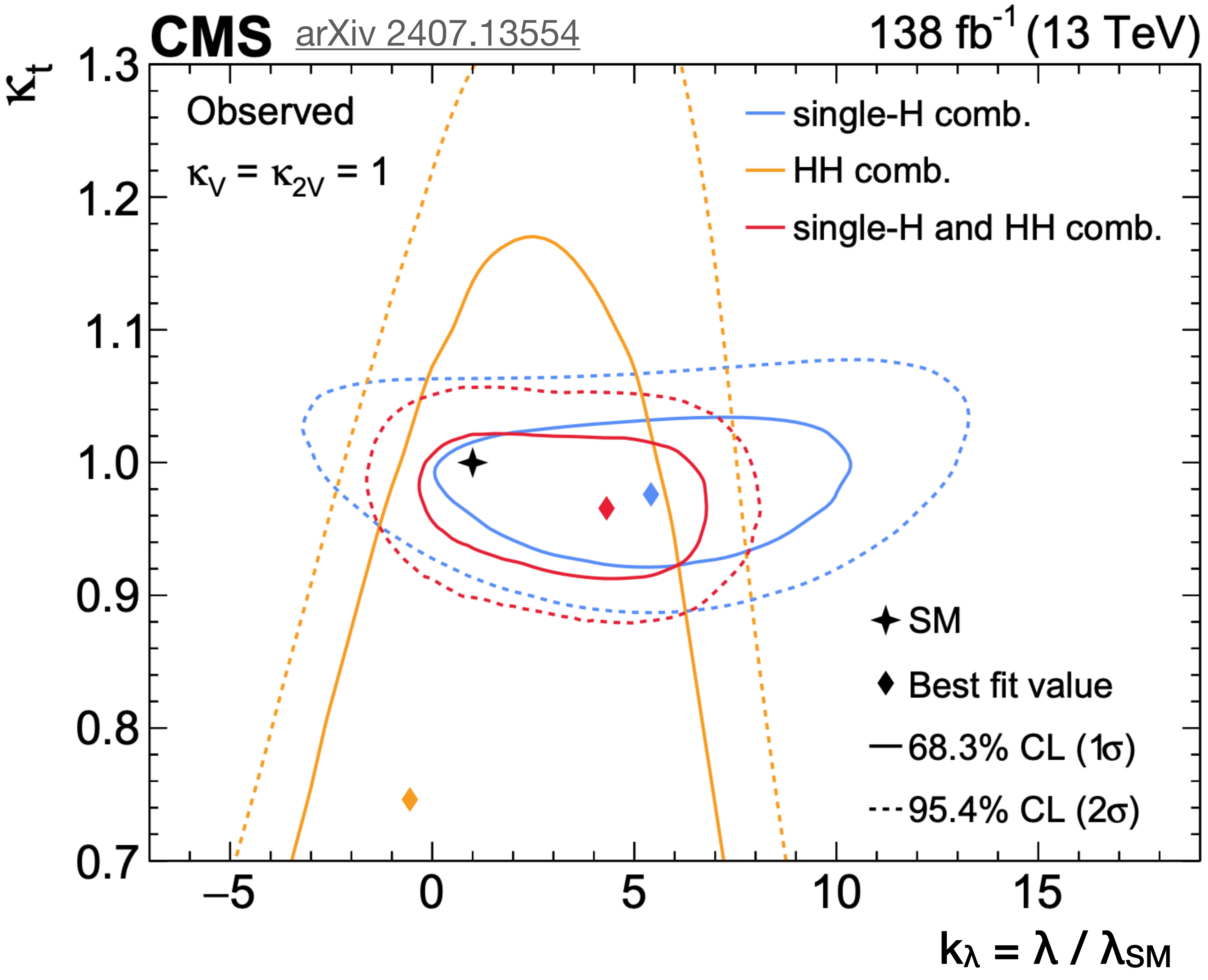
Single-H cross-section
looser bounds on k_λ but sensitive to Higgs-top Yukawa

Combined H+HH
model independent constraints on Higgs coupling
(Yukawa + gauge + self-interaction)

Phys. Lett. B 843 (2023) 137745



CMS arXiv 2407.13554



ATLAS (H+HH constraint) - $k_\lambda \in [-1.25, 6.85]_{obs}$
(with k_t, k_V, k_b, k_τ floating)

CMS (H+HH constraint) - $k_\lambda \in [-1.4, 7.8]_{obs}$
(with k_t, k_V, k_b, k_τ, k_{2V}, k_μ floating)

Simultaneous measurement of k_V and k_{2V}

HH cross section

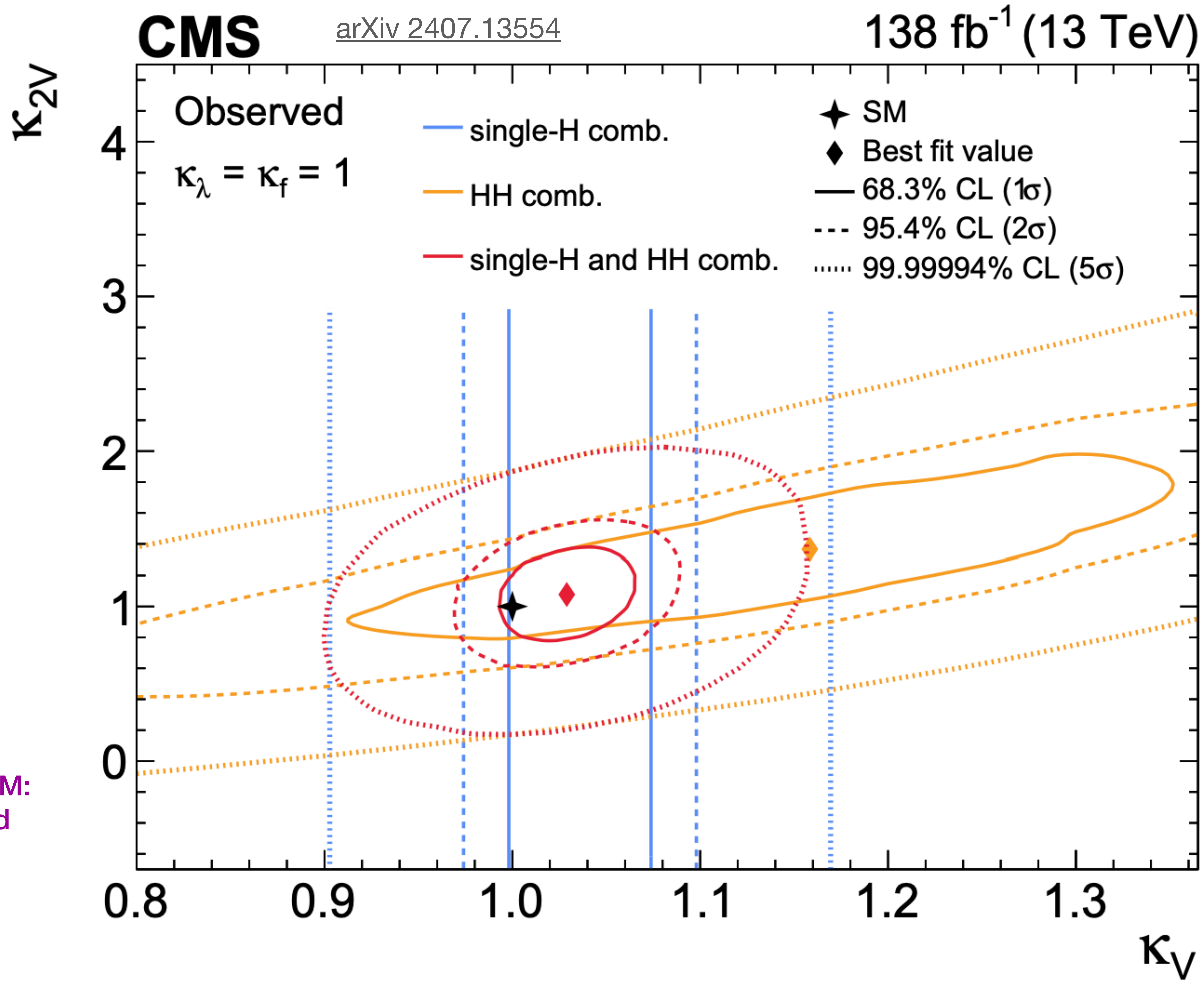
largely degenerate in the k_V and k_{2V}

Single-H cross-section

looser bounds on k_{2V} but sensitive to k_V

Combined H+HH

model independent constraints on Higgs coupling (Yukawa + gauge + self-interaction)



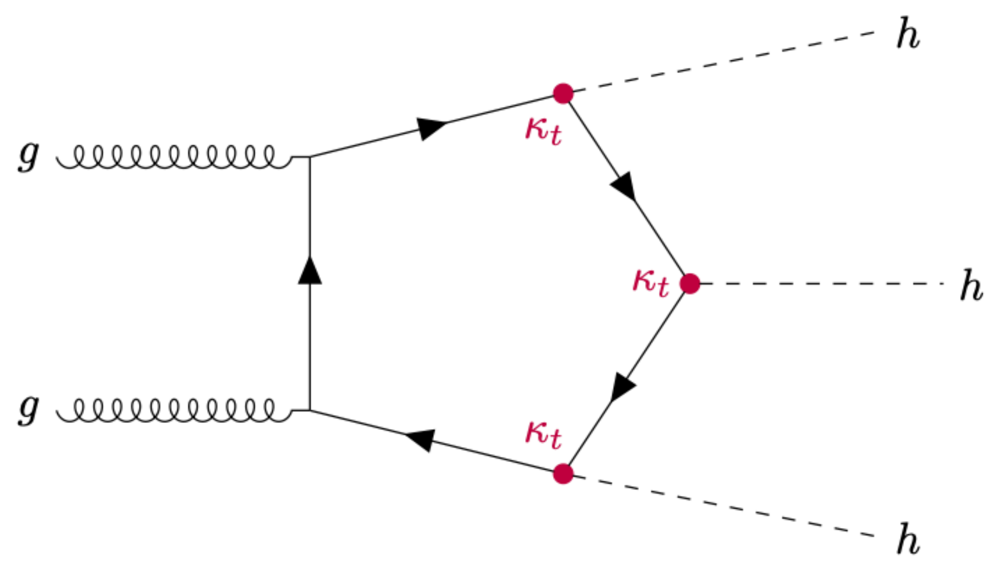
Assuming the SM:
k2V =0 excluded
at CL > 99.99%

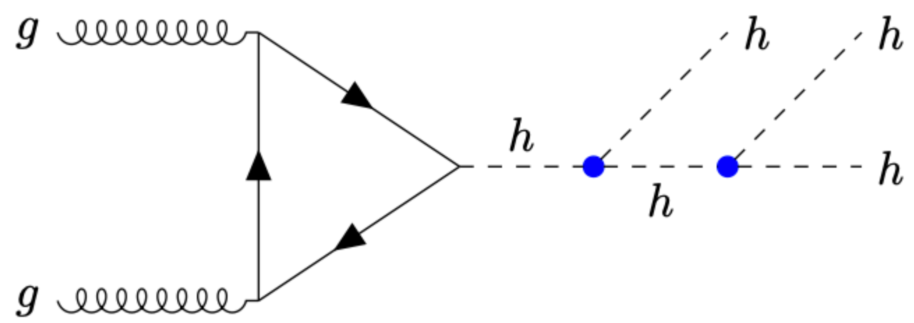
ATLAS does not consider single-H constraint in k_{2V} measurements *yet*

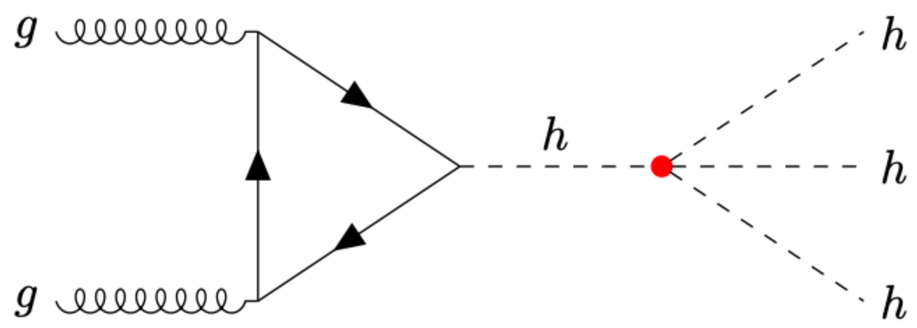
Quartic coupling and HHH experimental considerations

SM HHH production: experimental overview

Currently unexplored at the LHC
(interest from both ATLAS and CMS with current dataset)





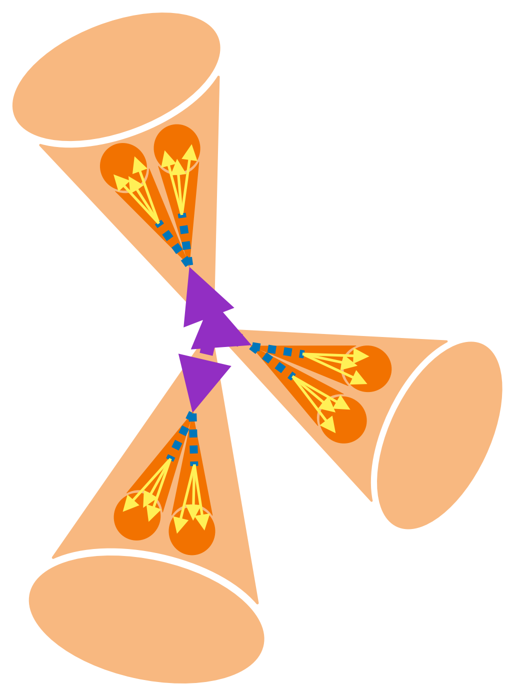


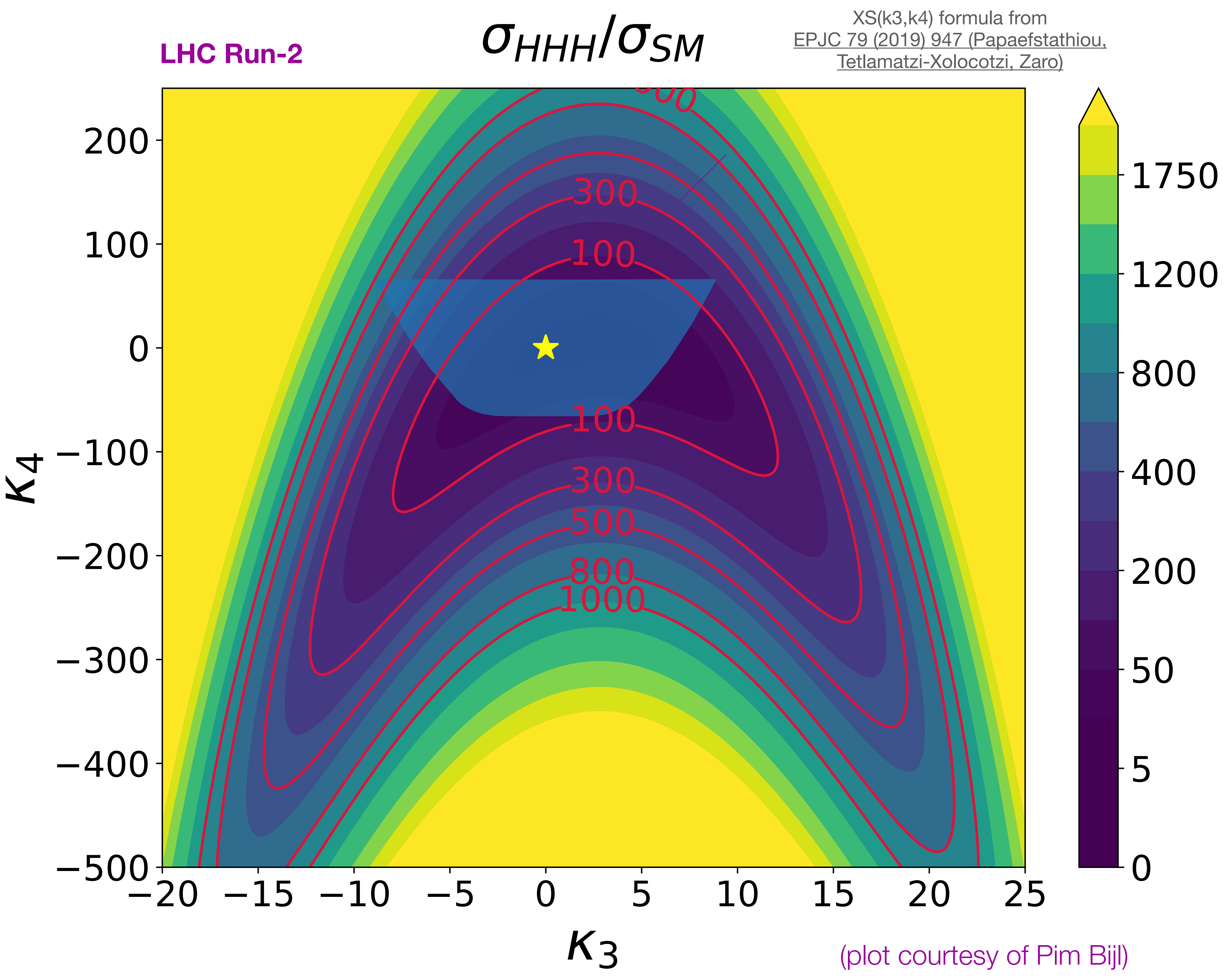
Note: currently *no* HHH cross-section calculation at 13 and 13.6 TeV!

- possible sensitivity to O(500-1000)xSM already with Run(2-3)? [~40-80fb around HH territory]
- interesting bounds on k_3 as well (competitive with single-H / minor HH decay modes]
- see HHH whitepaper for more details!

Tiny cross-section (~0.08fb) extremely challenging

- relying on H(bb) decays for maximum statistics [HH(4b)H(yy)?]
- non-trivial Higgs reconstruction (jet-pairing)
- large-radius-jet might bring large improvements ?



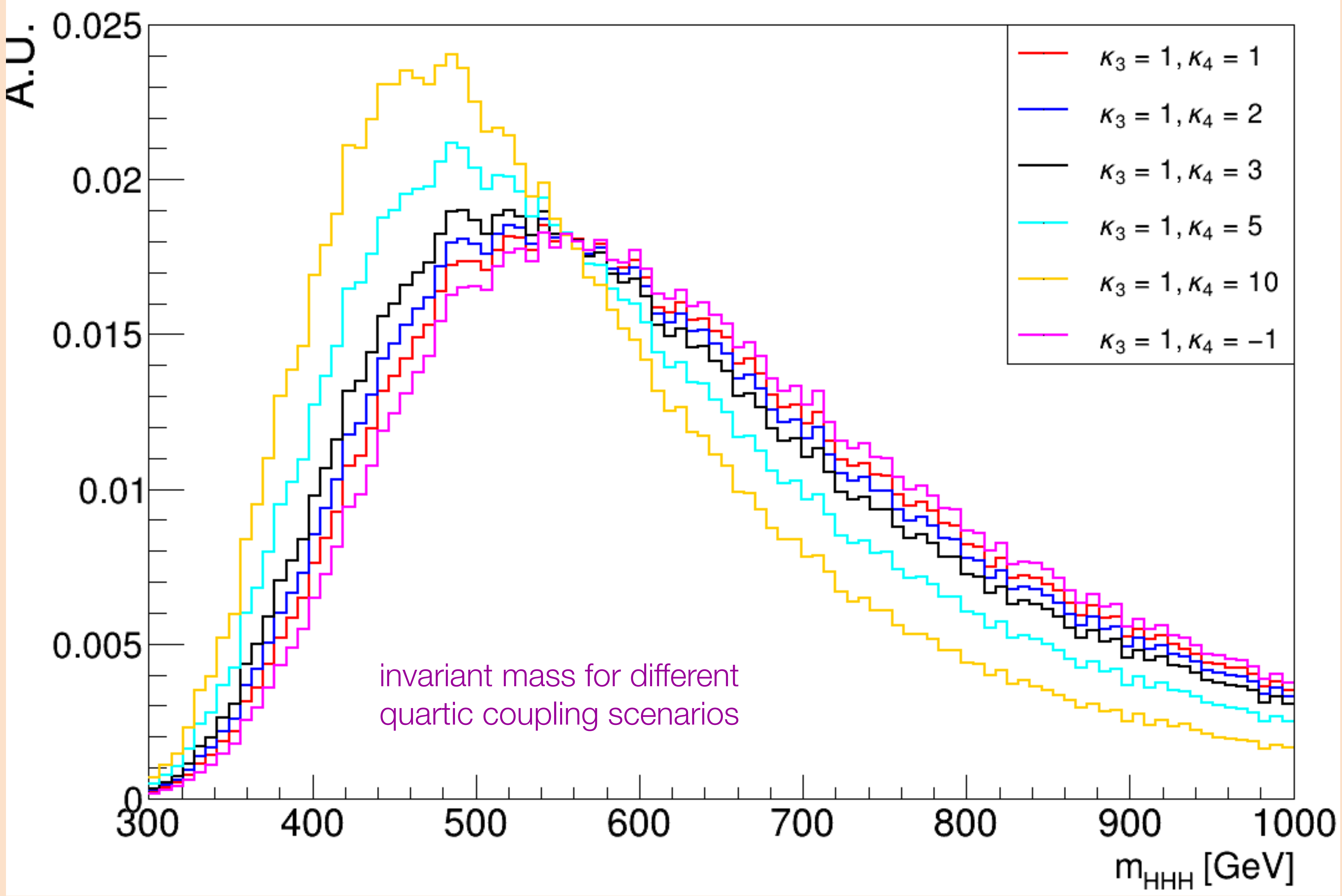


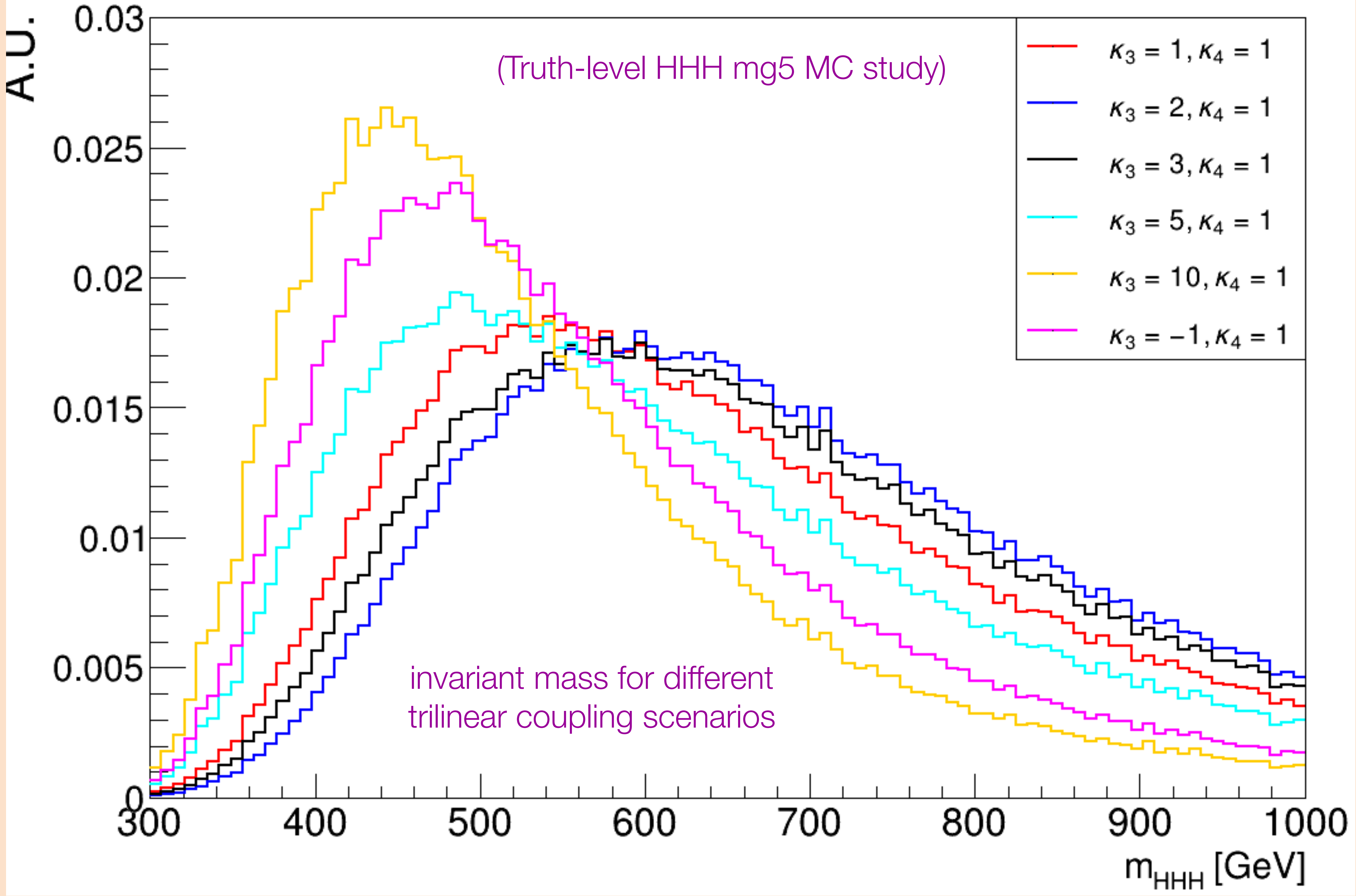
*shaded blue area represents bounds on self-coupling parameters from perturbative unitarity (EPJC 84 (2024) 366)

(plot courtesy of Pim Bijl)

HHH production: experimental overview

Kinematic information can provide additional sensitivity to k3 and (to a lesser extent) k4 coupling modifiers (similar to HH)





Interest from ATLAS/CMS collaborations - only way to access quartic coupling / complementary sensitivity to trilinear coupling stay tuned for experimental results soon !

Conclusions

Conclusions & Outline

Large research program for ATLAS and CMS to investigate Higgs self-couplings and scalar self-interactions, from current Run-2 results - to Run-3 and HL-LHC projections !

Huge advancements in our experimental investigation of HH production during the LHC Run-2: building confidence and expertise to reach results we thought only possible with the HL-phase !

Focus on golden channels, but not only: important contributions from all decay modes.
Critical role of combinations to extract the full information from data (in the most model independent way)

Projections towards HL-LHC are important to convey the physics reach of this research program.

Growing interest towards HHH production: a first look at the Higgs quartic coupling? Not for today - but stay tuned!

Thank you for your attention !

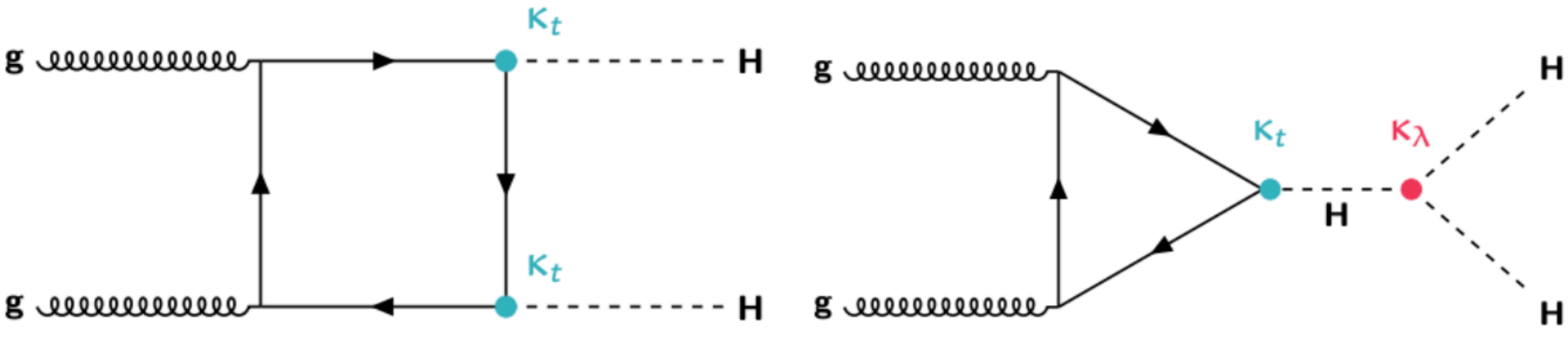
BACK

UP

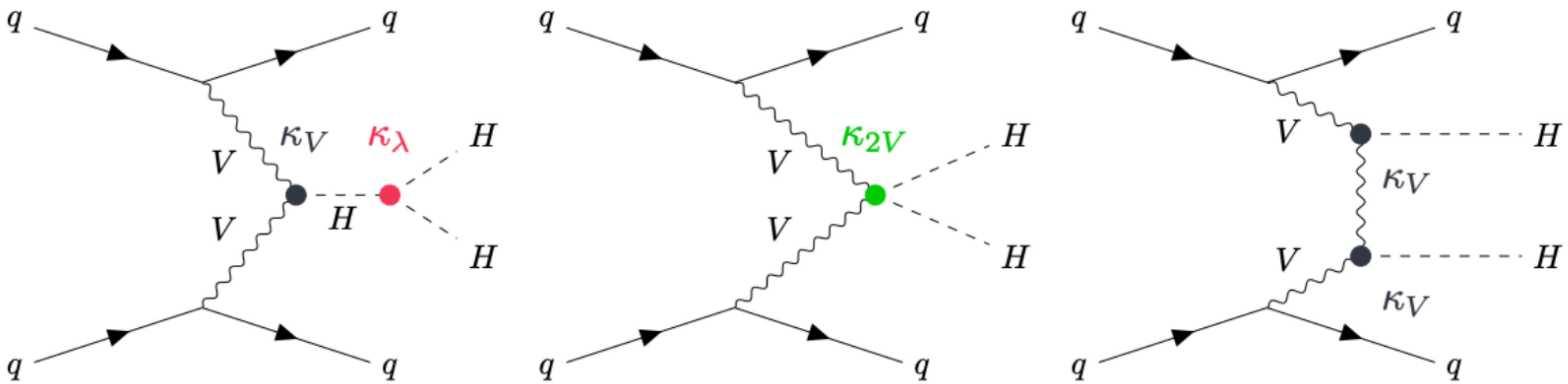
HH signal phenomenology

HH signal phenomenology

- main production mode through gluon fusion (ggHH)
    - XS(ggHH) = 31.05 fb at com = 13TeV
    - strongly suppressed by interference effect
    - sensitive to trilinear self-coupling and its variations

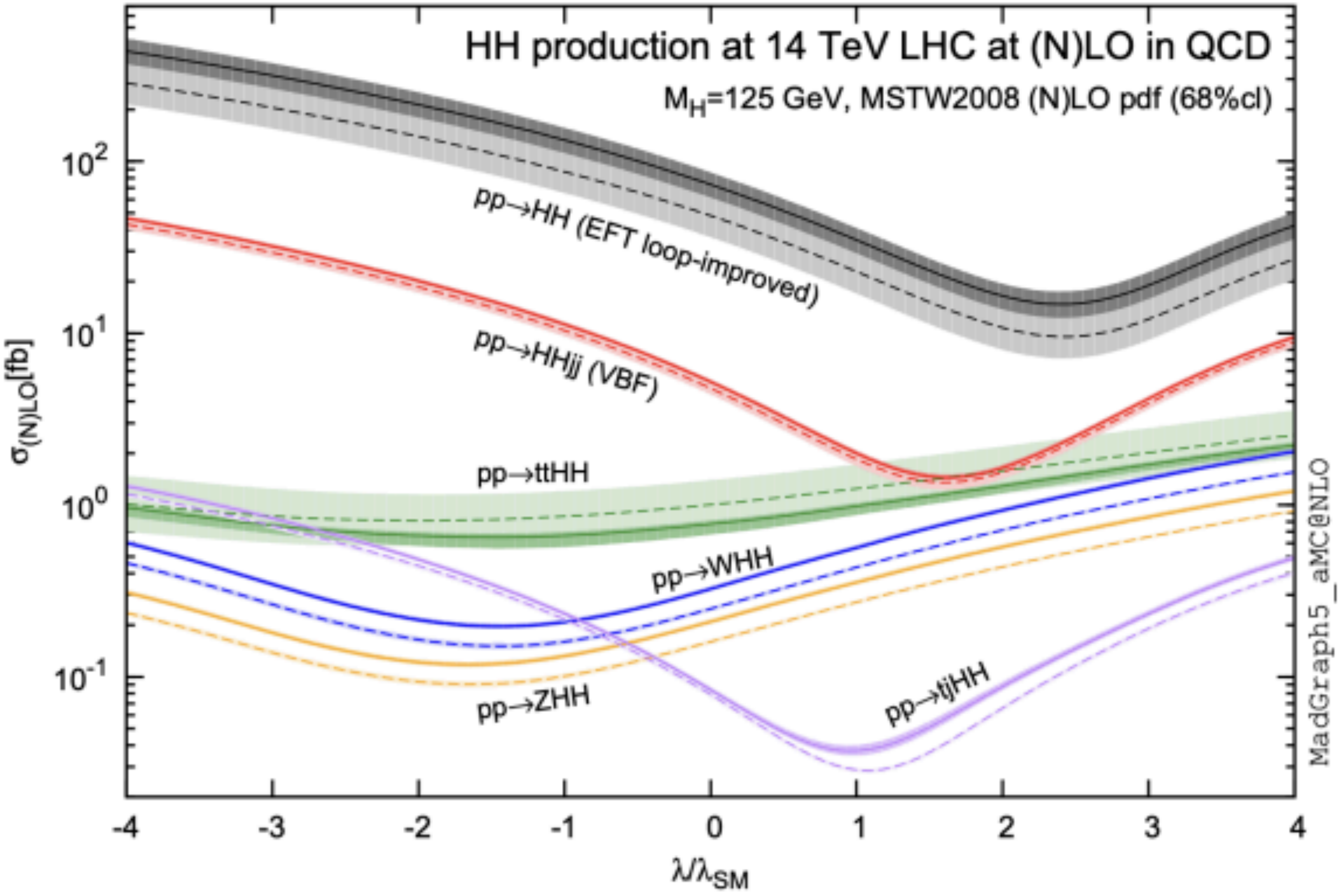


- next leading production mode is vector-boson-fusion (VBF)
    - XS(VBF) = 1.726fb at com = 13TeV
    - sensitive to trilinear self-coupling and quartic VVHH coupling (k2V)



HH signal phenomenology: HH Cross-Section

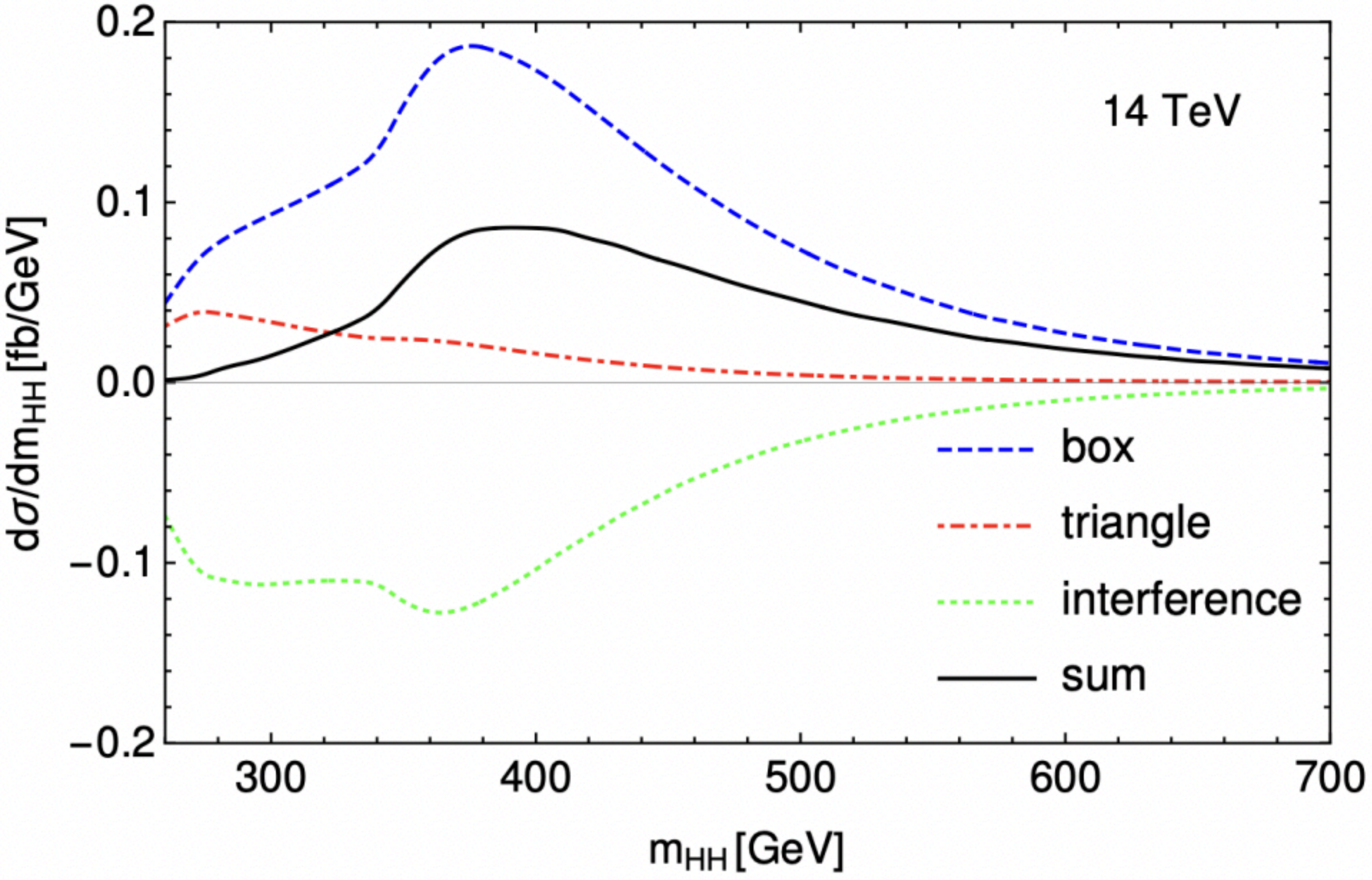
back-up

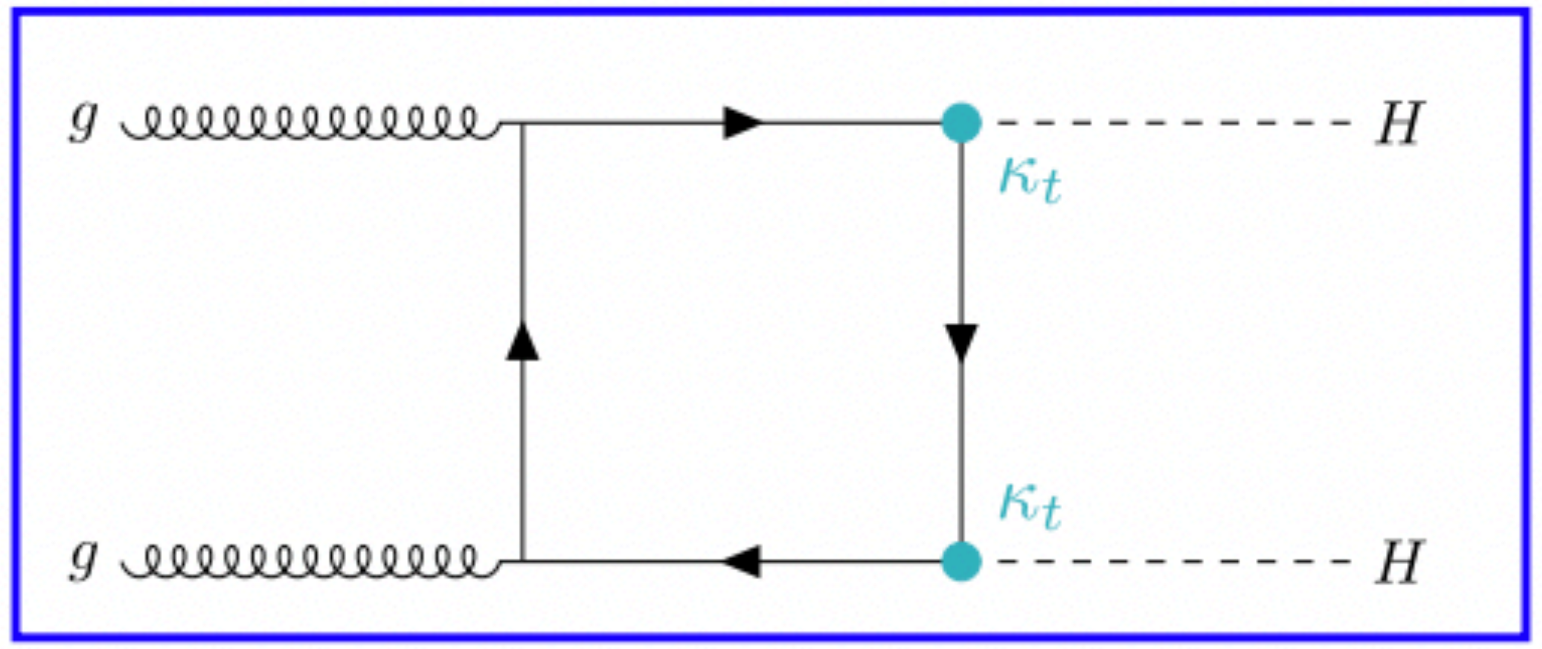


HH signal phenomenology: interference and variati

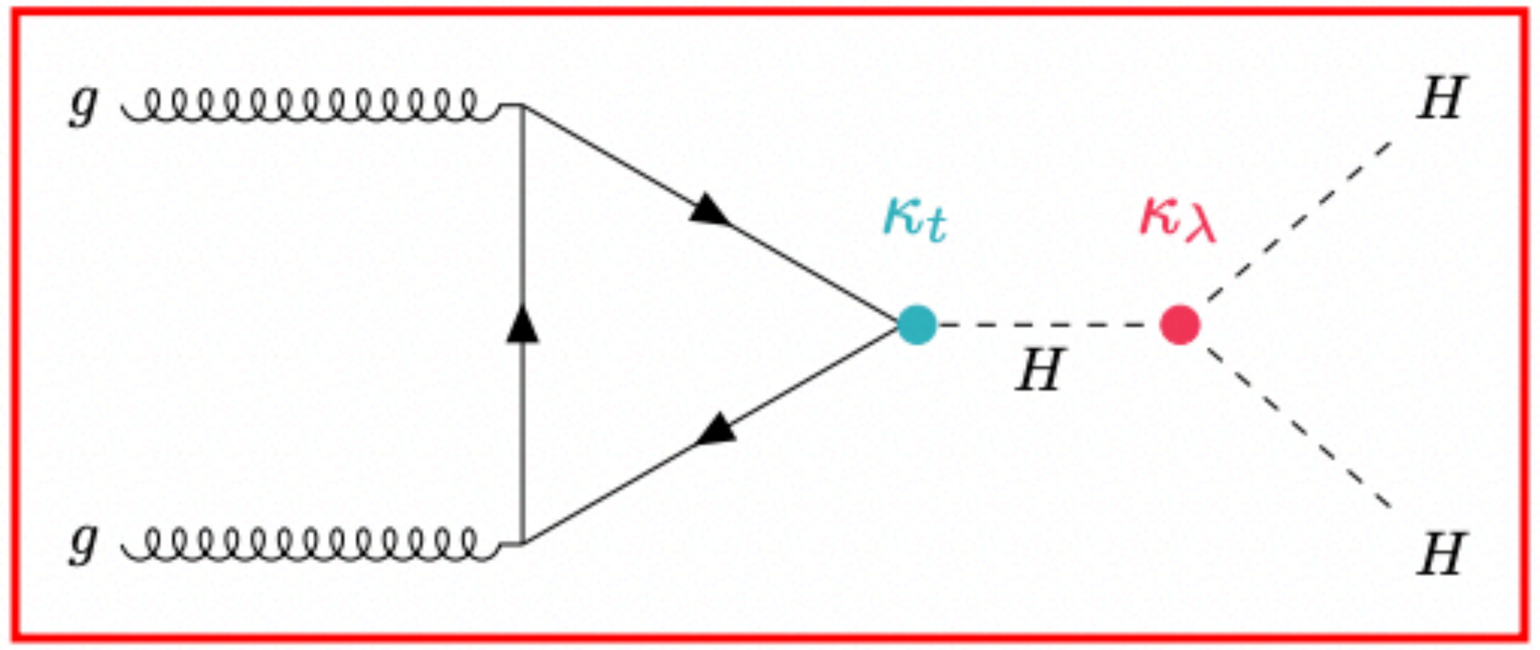
back-up

destructive interference between triangle and box terms





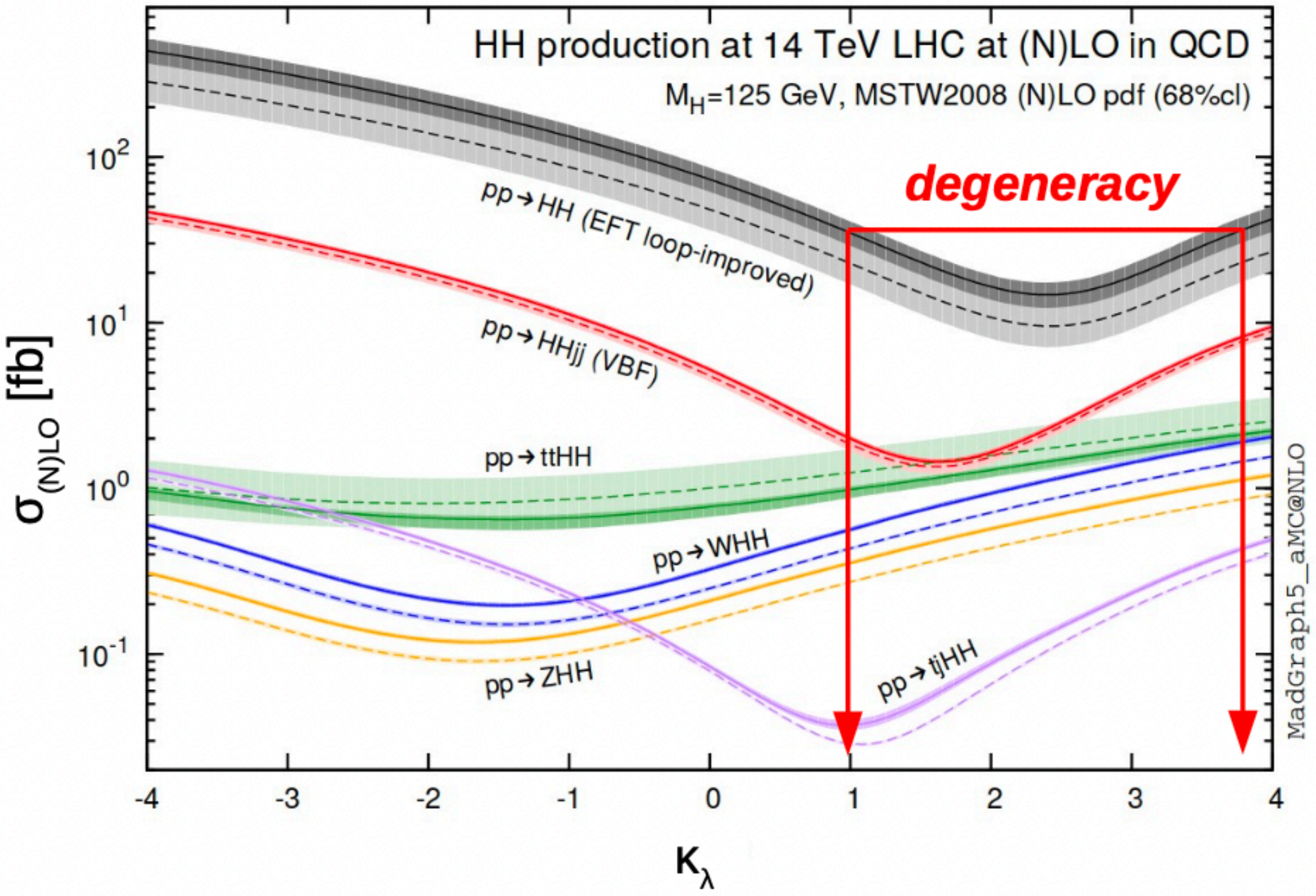
$$\sigma \sim |B|^2 + |T|^2 + 2\mathrm{Re}(B^*T)$$



HH signal phenomenology: interference and variati

back-up

destructive interference between triangle and box terms



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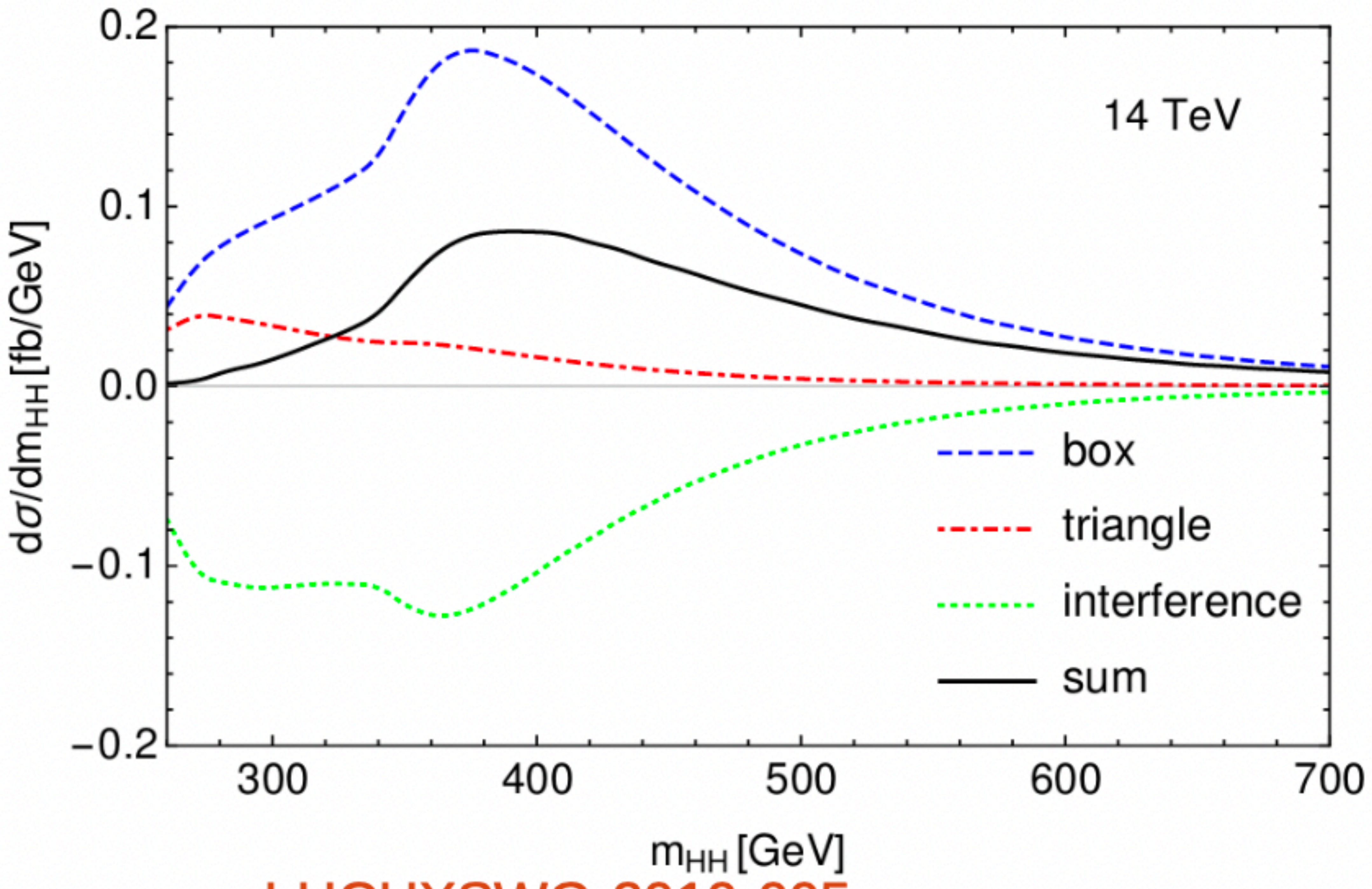
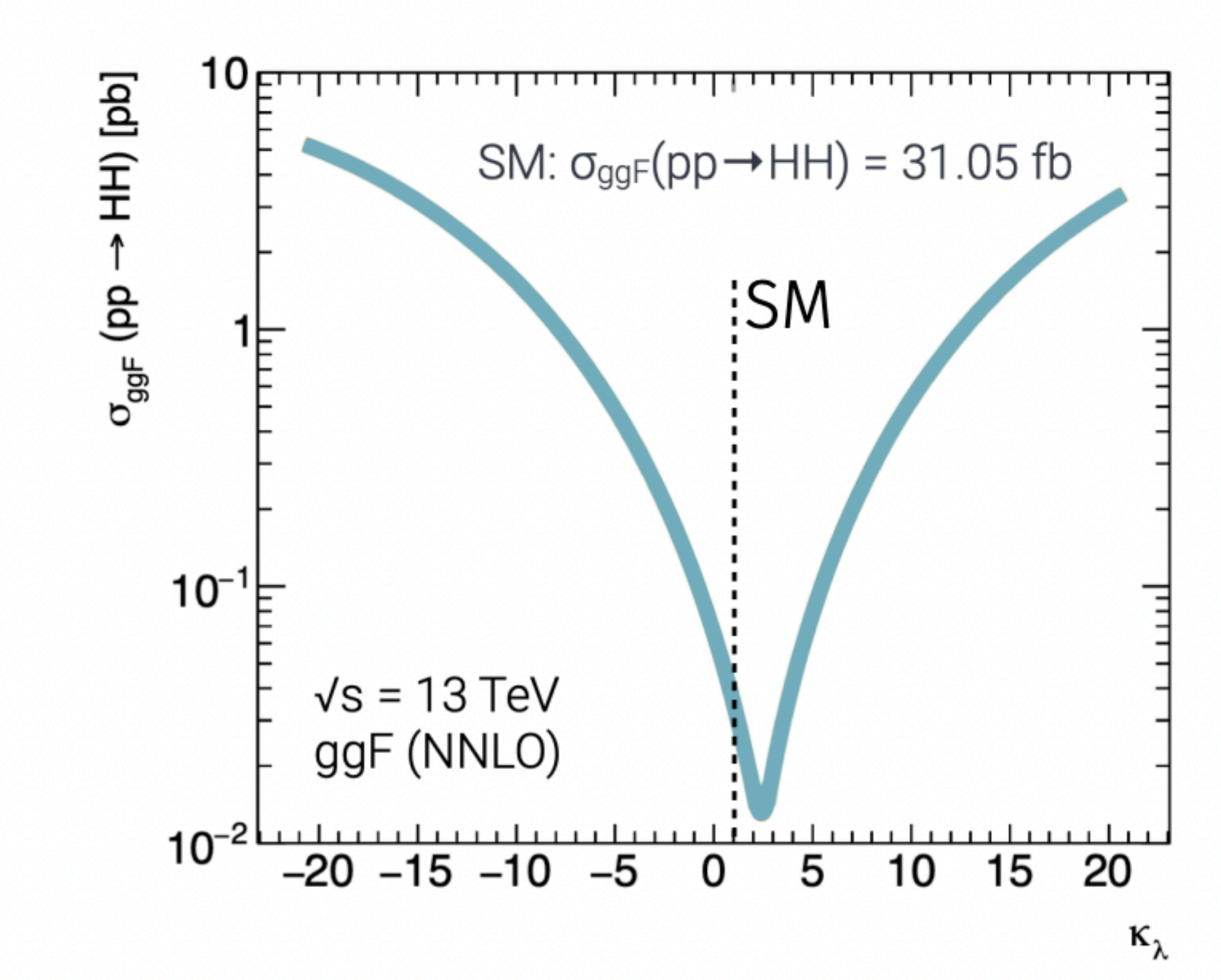


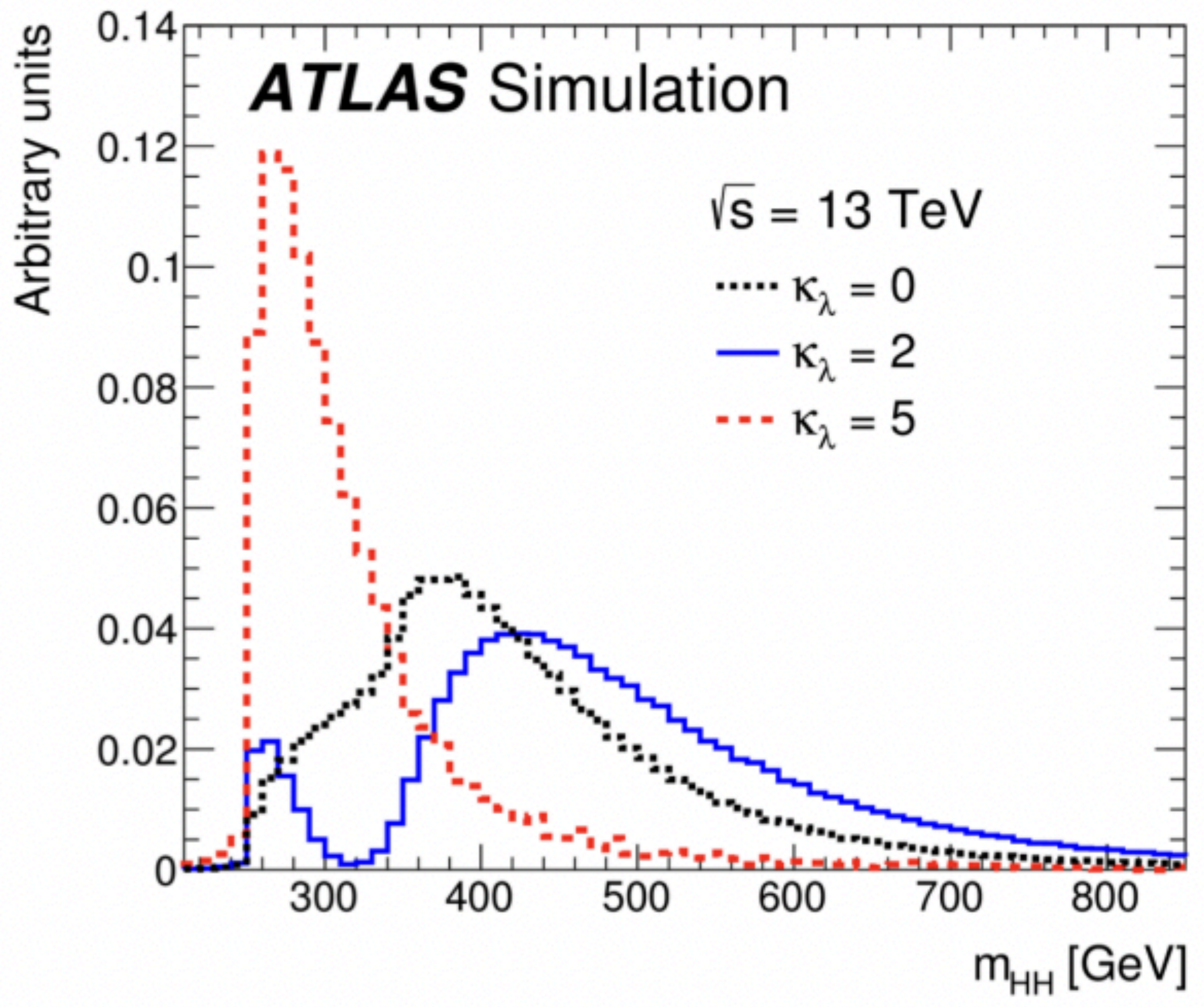
LHCHXSWG-2019-005

HH signal phenomenology: ggF HH

cross-section shows strong dependence on the tri-linear coupling

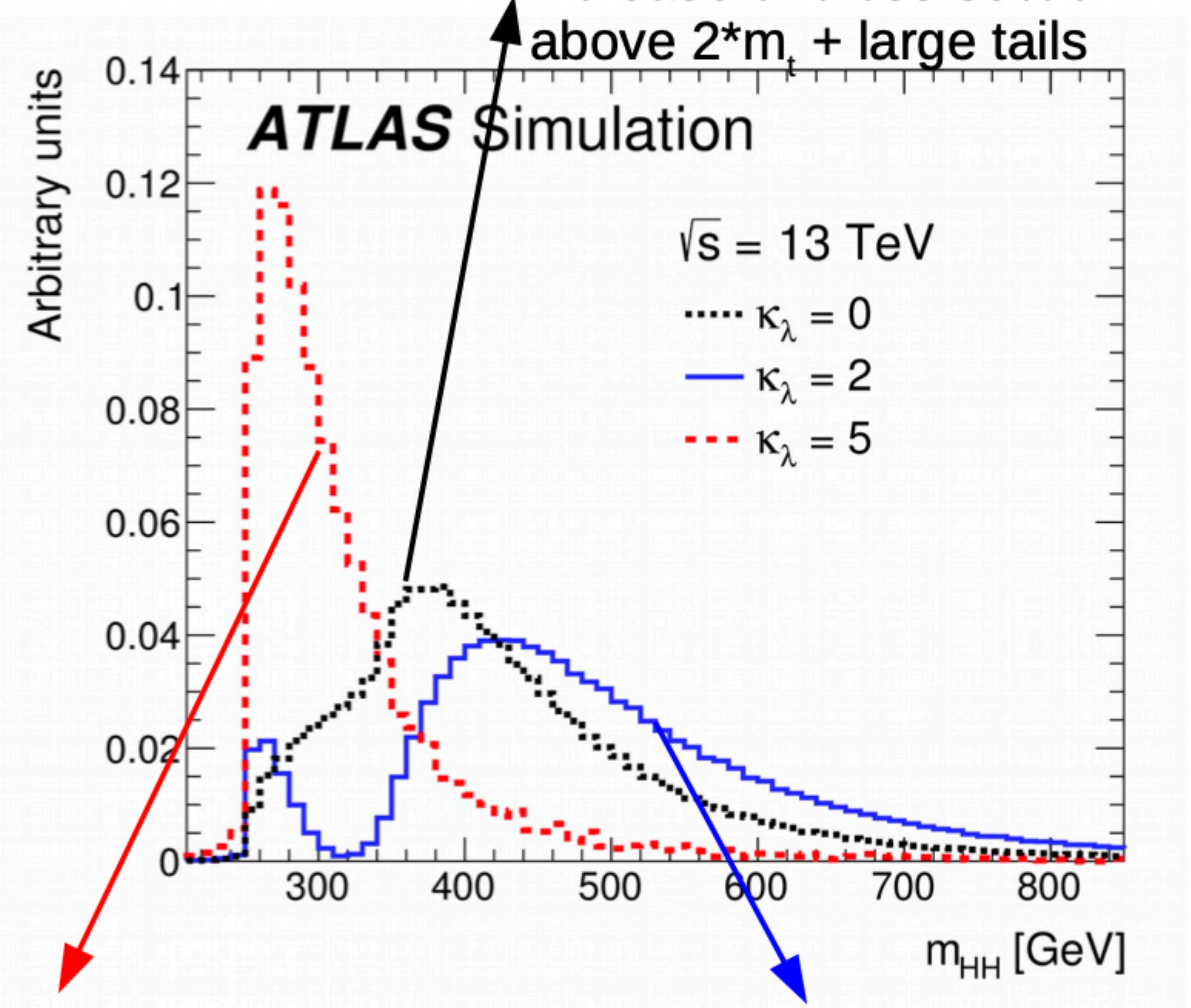


significante shape variations for the m(HH) variable, as a function of the tri-linear coupling



HH signal phenomenology: ggF HH

κ_λ=0: no triangle ⇒ increase of cross-section above 2*m_t + large tails

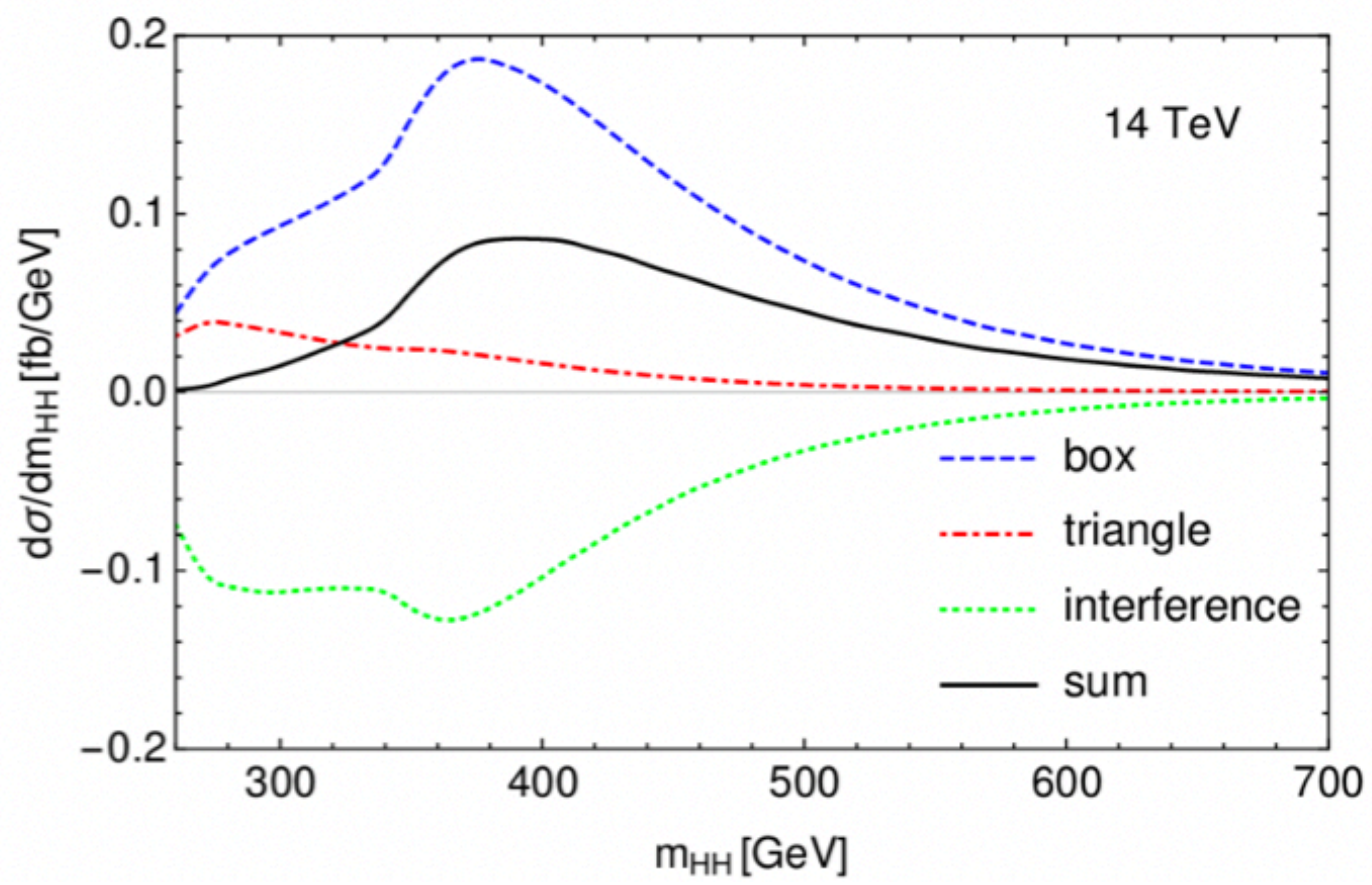


κ_λ=5: interference at high m_{HH} ⇒ soft spectrum

κ_λ=2: max interference ⇒ deficit between 2*m_H and 2*m_t + large tails

|κ_λ|>10: trilinear dominant ⇒ peaks at 2*m_H

significante shape variations for the m(HH) variable, as a function of the tri-linear coupling

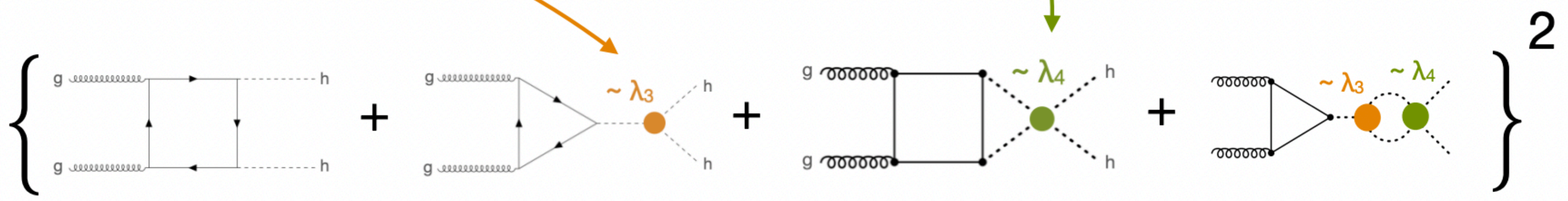


HH signal phenomenology: ggF HH and quartic coupling

- We got a private POWHEG model from Luca Rottoli (one of the authors) which implements the coupling modifiers κ_3 and κ_4 at LO order in QCD

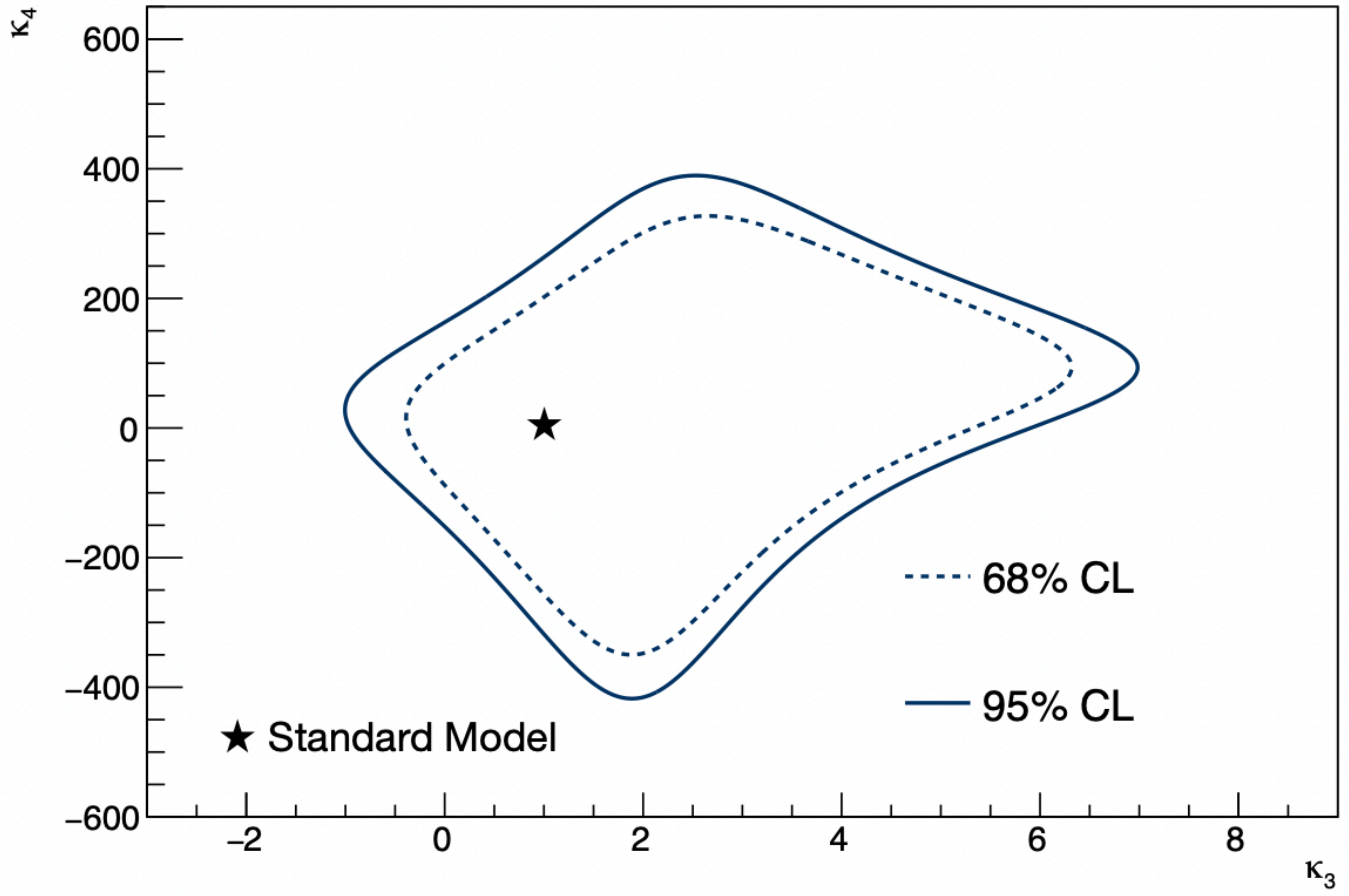
$$\kappa_3 = \frac{\lambda_3}{\lambda_3^{\mathrm{SM}}} = 1 + \Delta\kappa_3 \qquad \kappa_4 = \frac{\lambda_4}{\lambda_4^{\mathrm{SM}}}$$

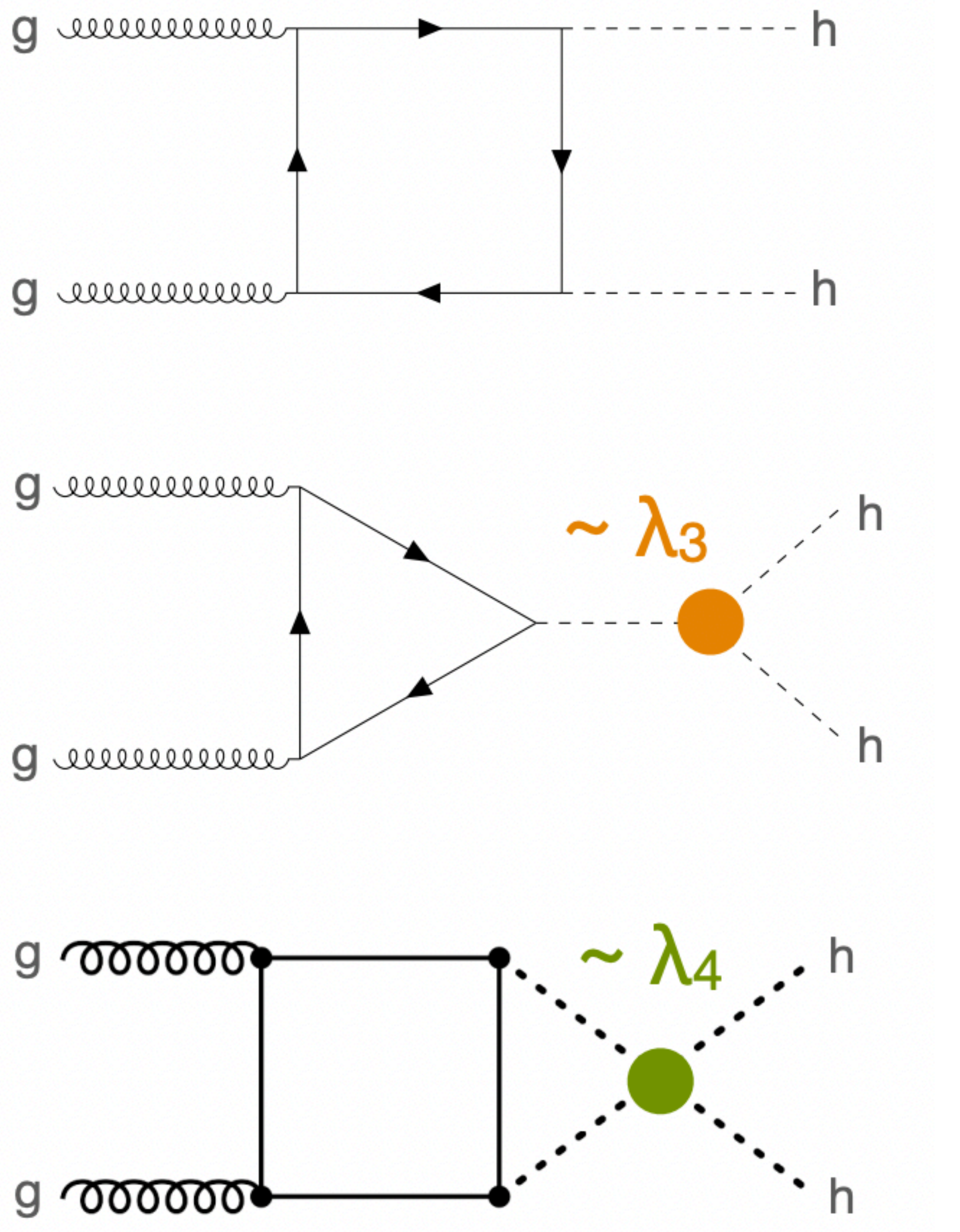
- Cross-section for pp→hh ~



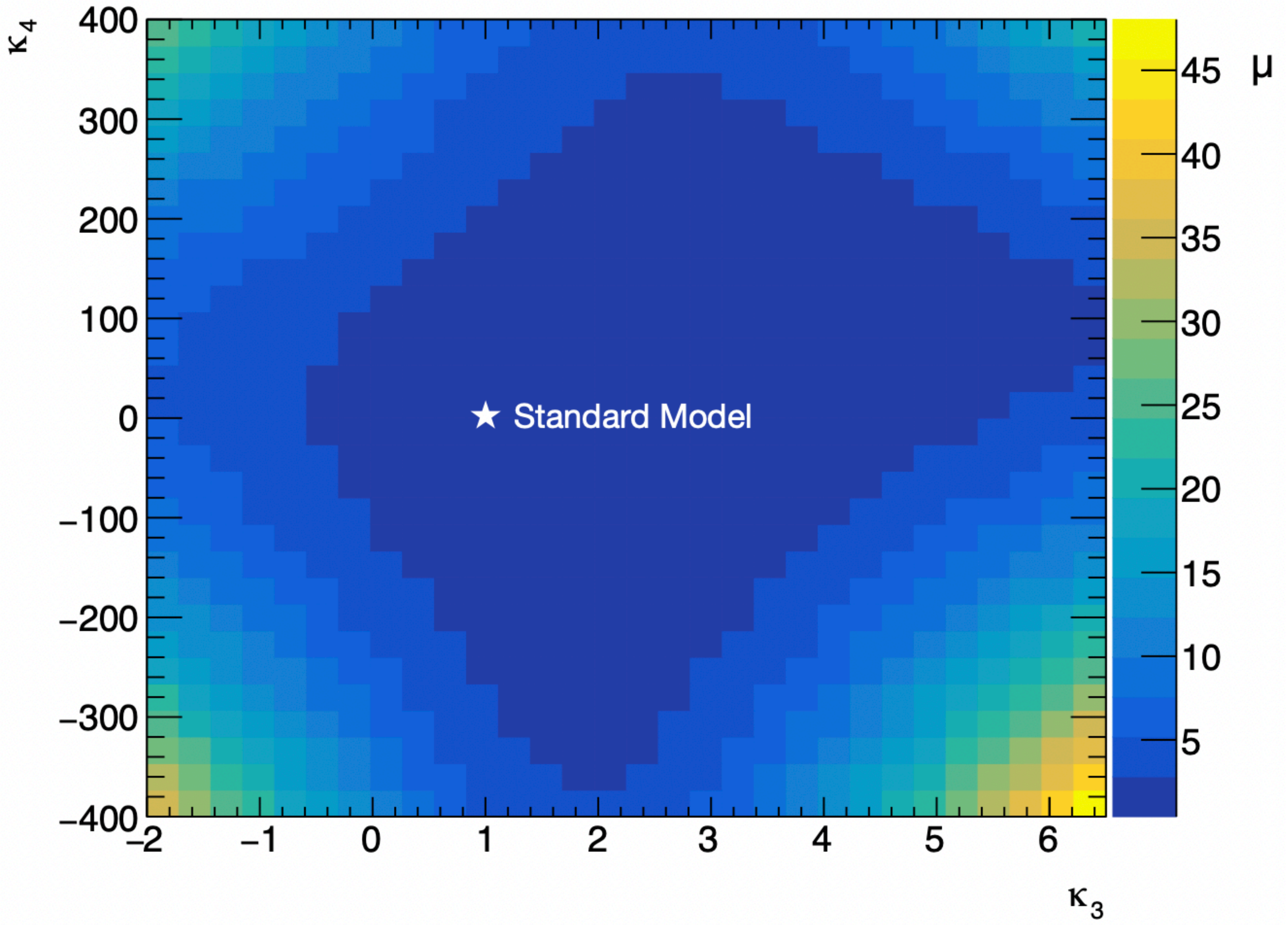
- Cross-section for pp→hh ~ $p_0 + p_1\ \kappa_3 + p_2\ \kappa_4 + p_3\ \kappa_3^2 + p_4\ \kappa_3\kappa_4 + p_5\ \kappa_4^2 + p_6\ \kappa_3^2\kappa_4 + p_7\ \kappa_3\kappa_4^2 + p_8\ \kappa_3^2\kappa_4^2$ [polynomial in κ_3 and κ_4]

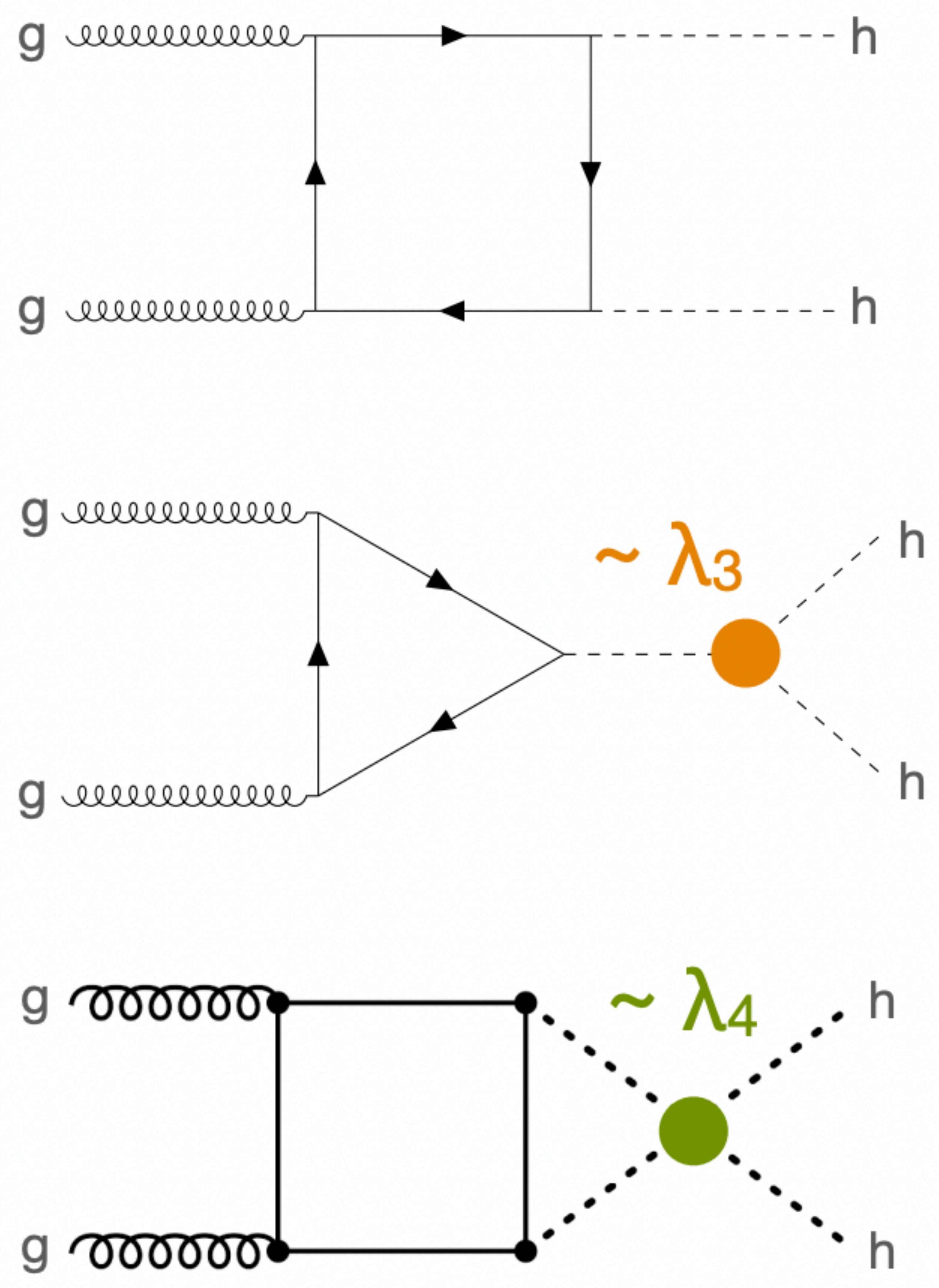
- Generated cross-section values for combinations of (κ_3, κ_4) and fit a polynomial through the points





HH signal phenomenology: ggF HH and quartic coupling



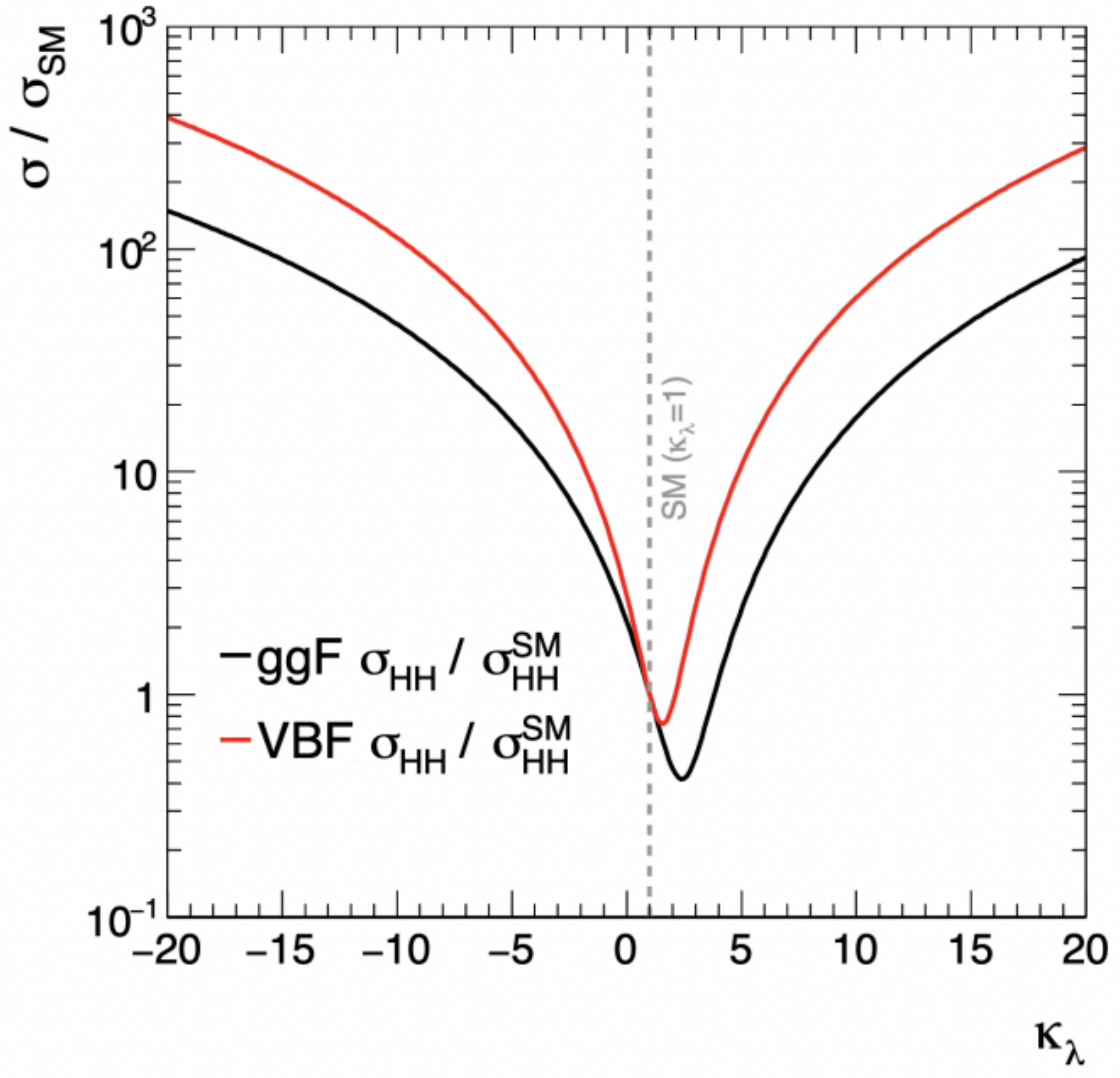


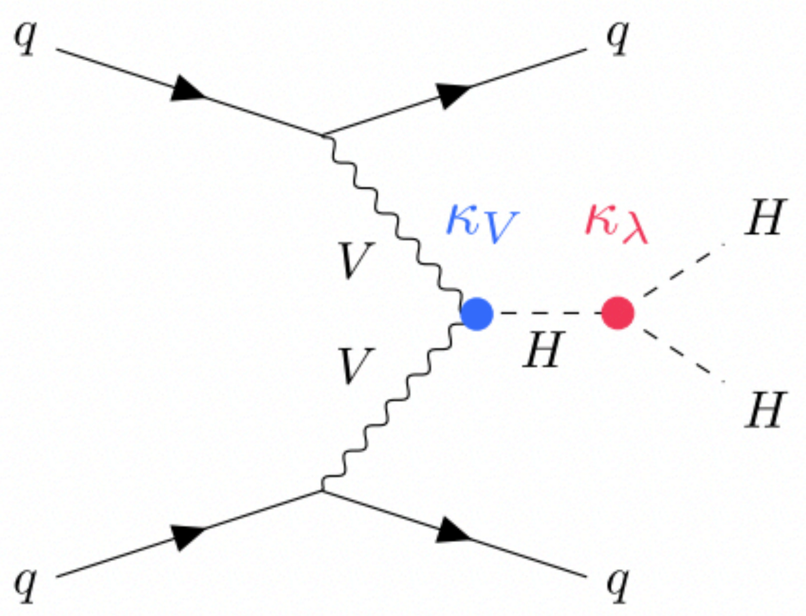
HH signal phenomenology: VBF HH

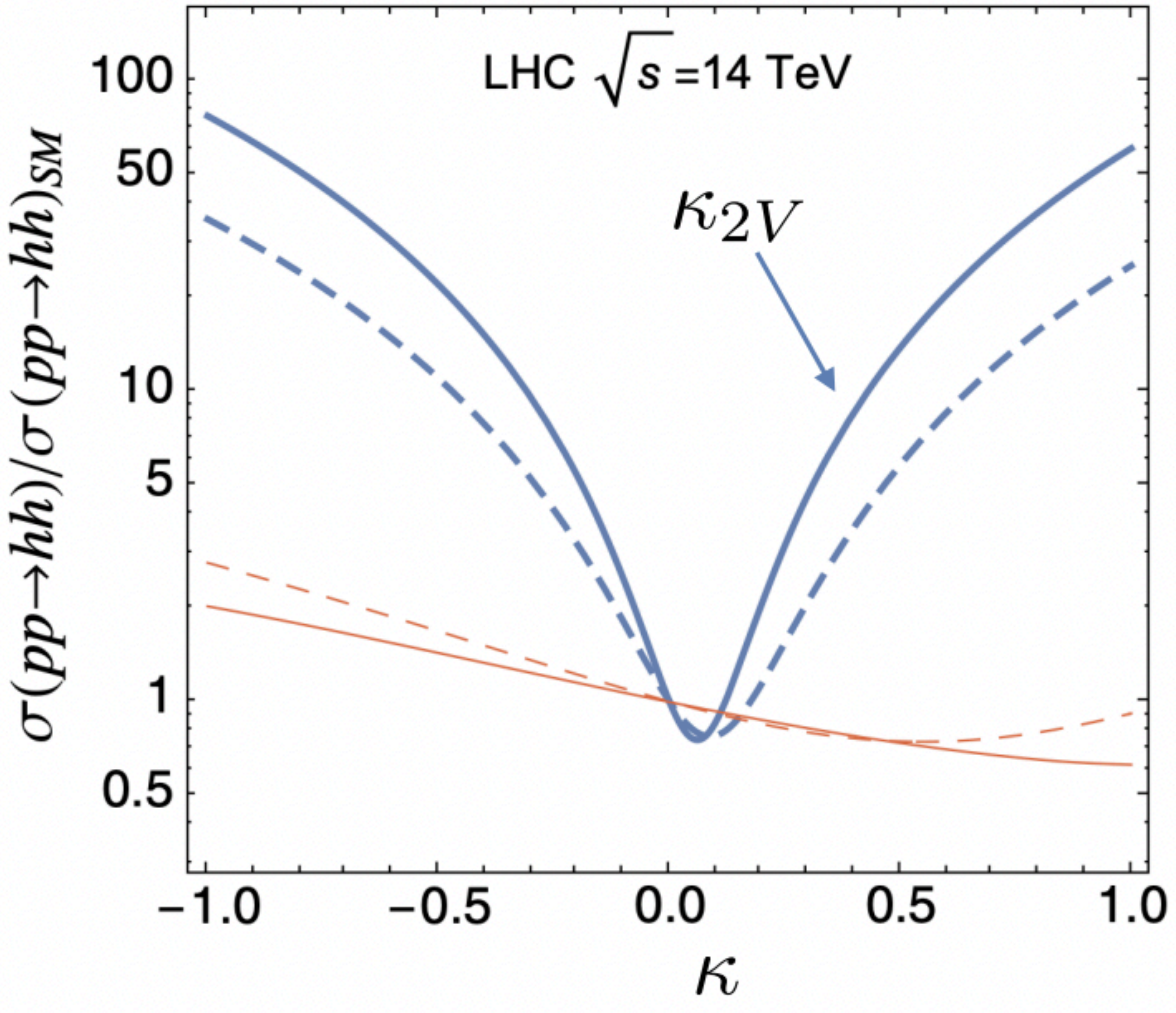
back-up

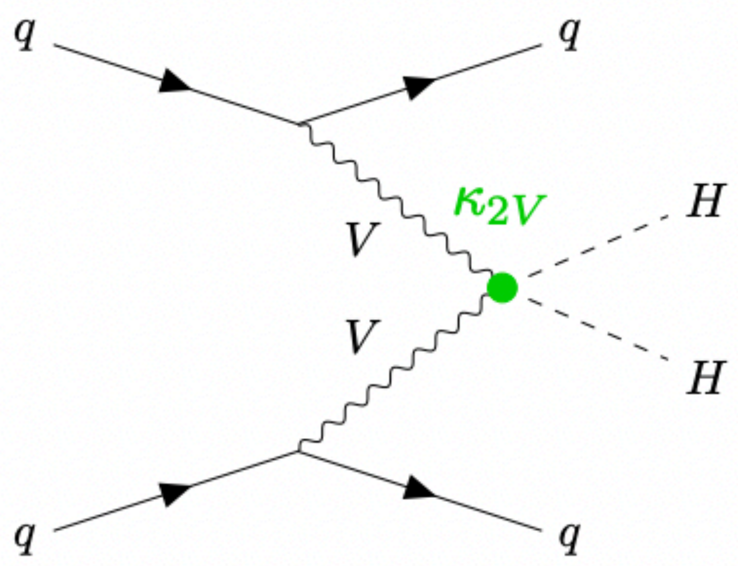
VBF(HH) is also sensitive to the tri-linear coupling
(XS always lower than ggHH though)

unique sensitivity to the VVHH coupling k2V
(e.g. if we see deviations in kV, we can use k2V to determine if H is part of a doublet)



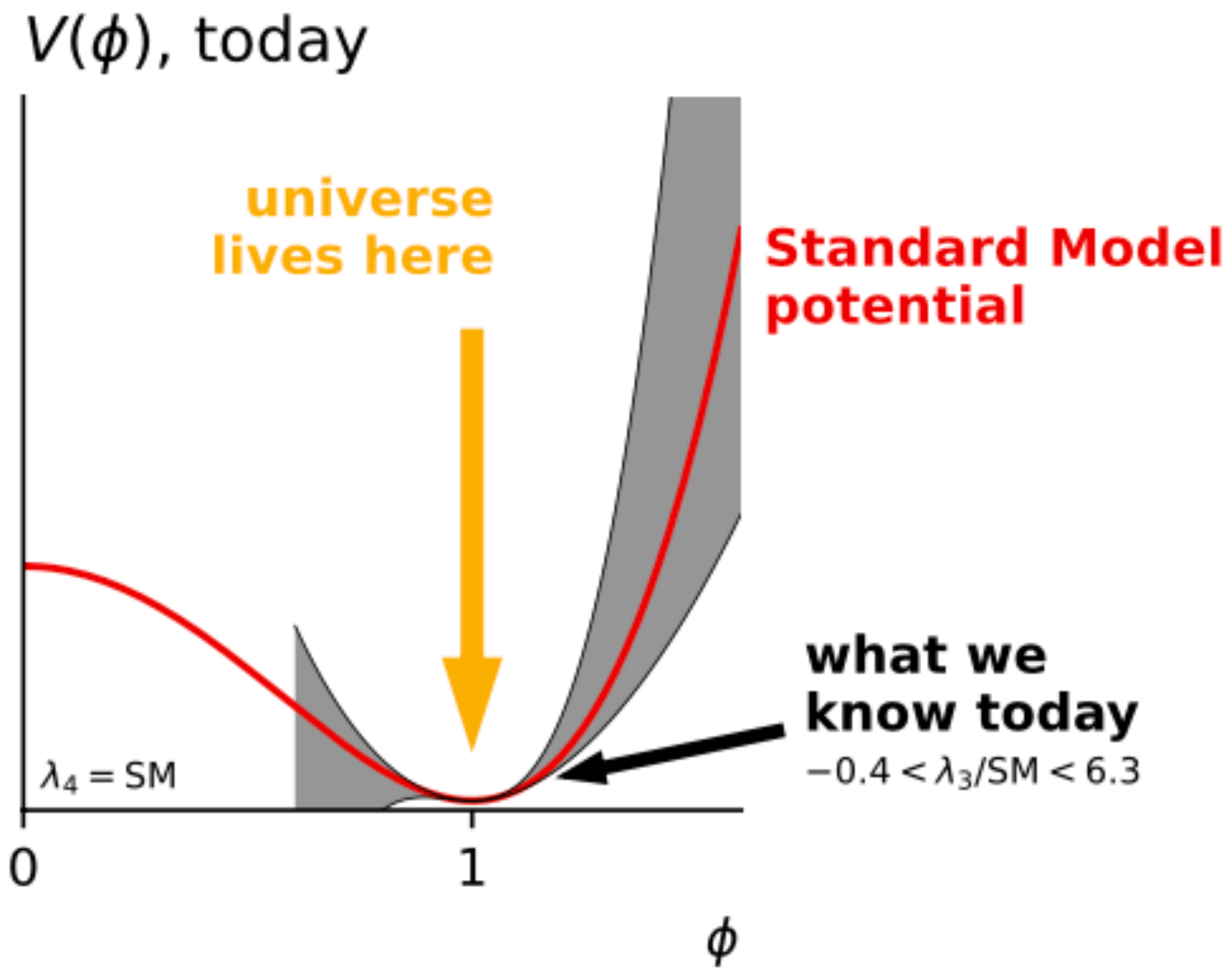


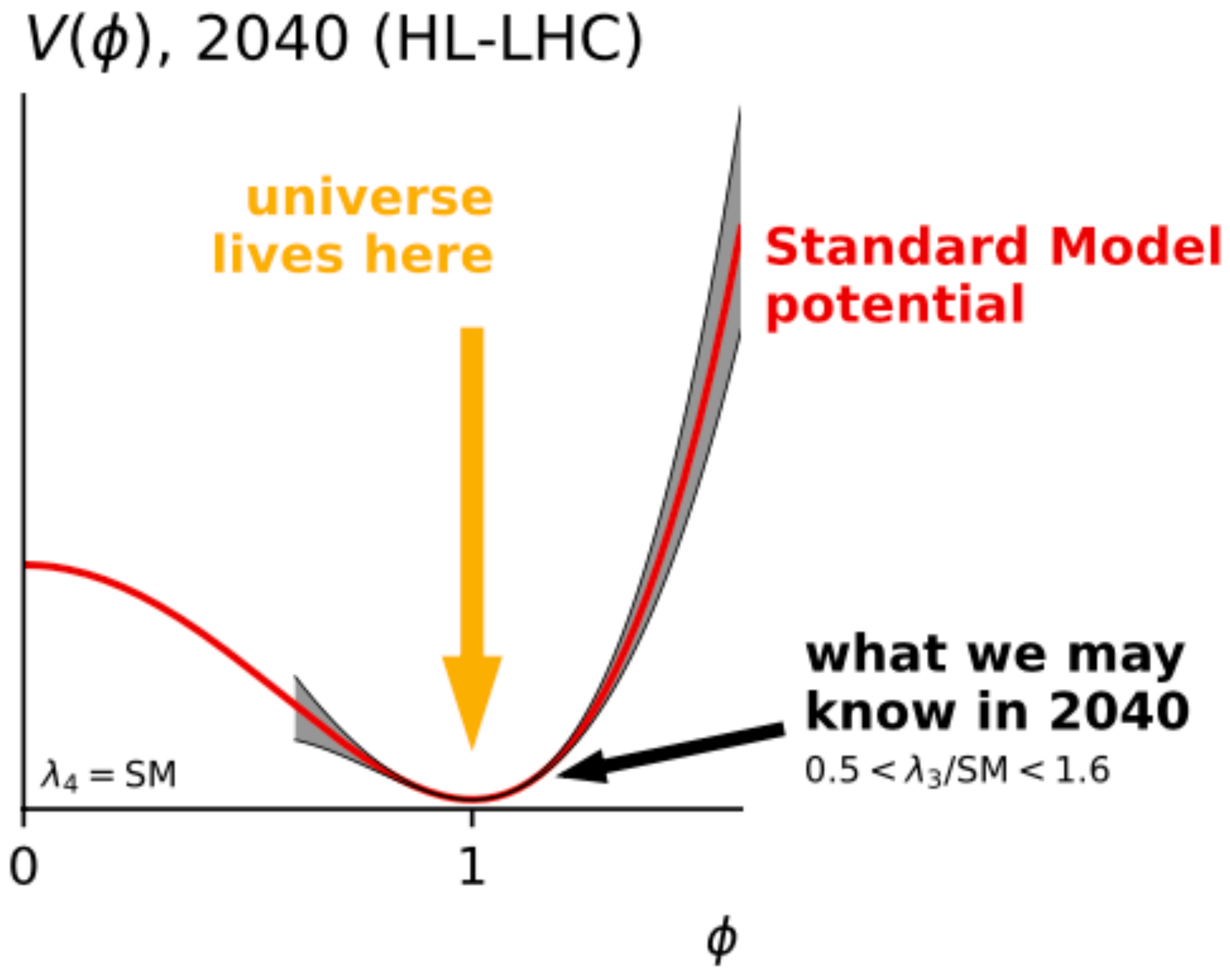


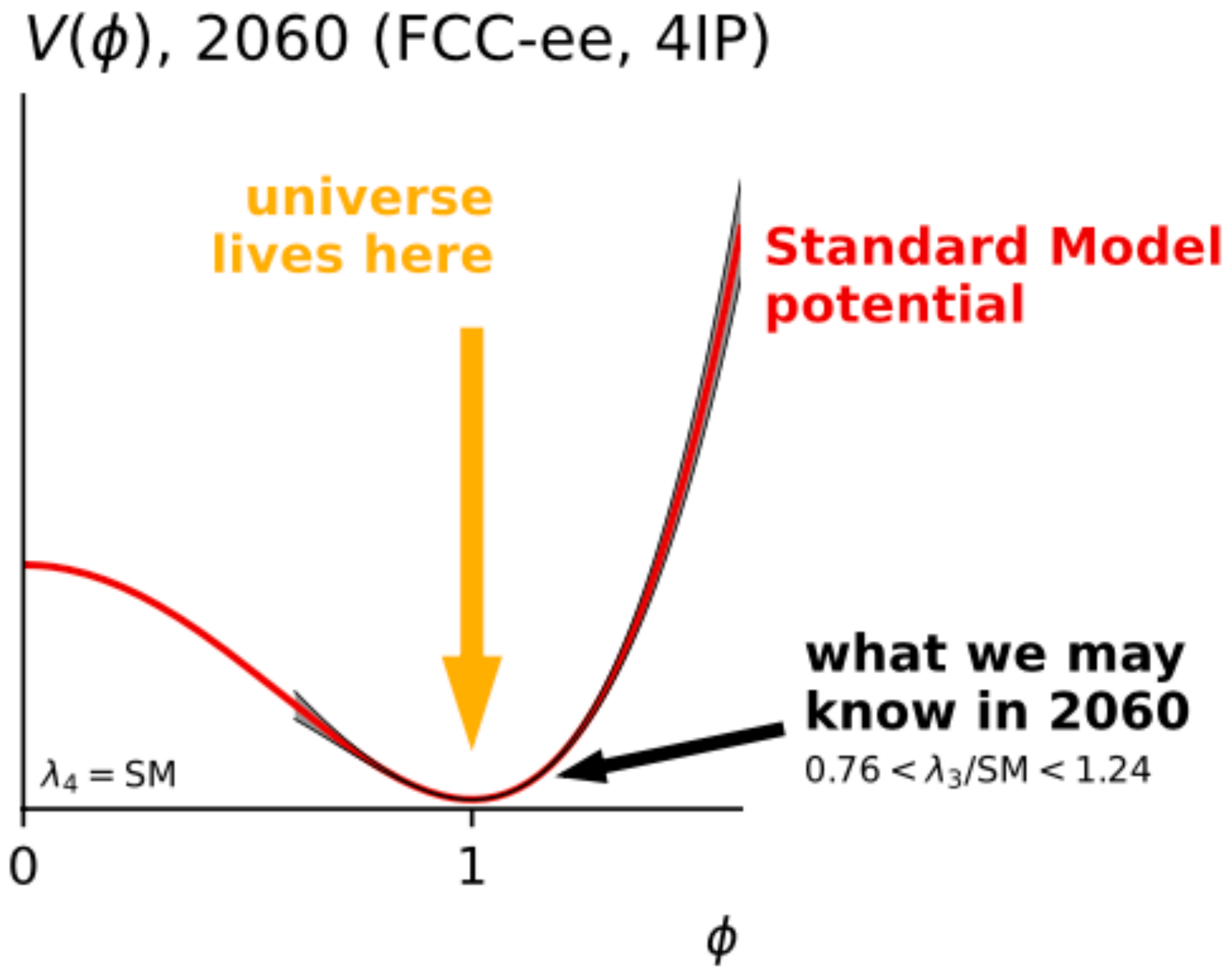


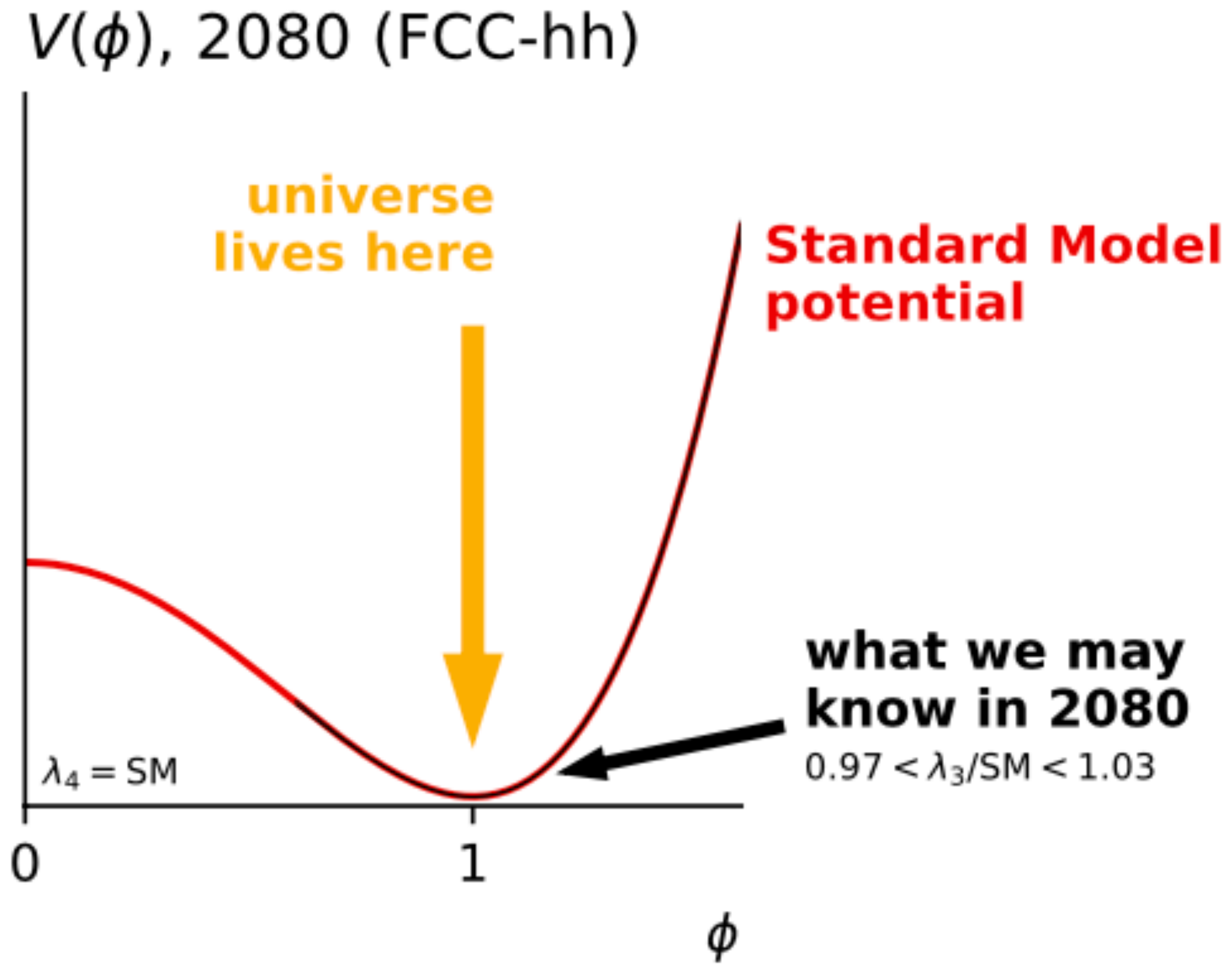
Higgs self-interactions and Higgs potential

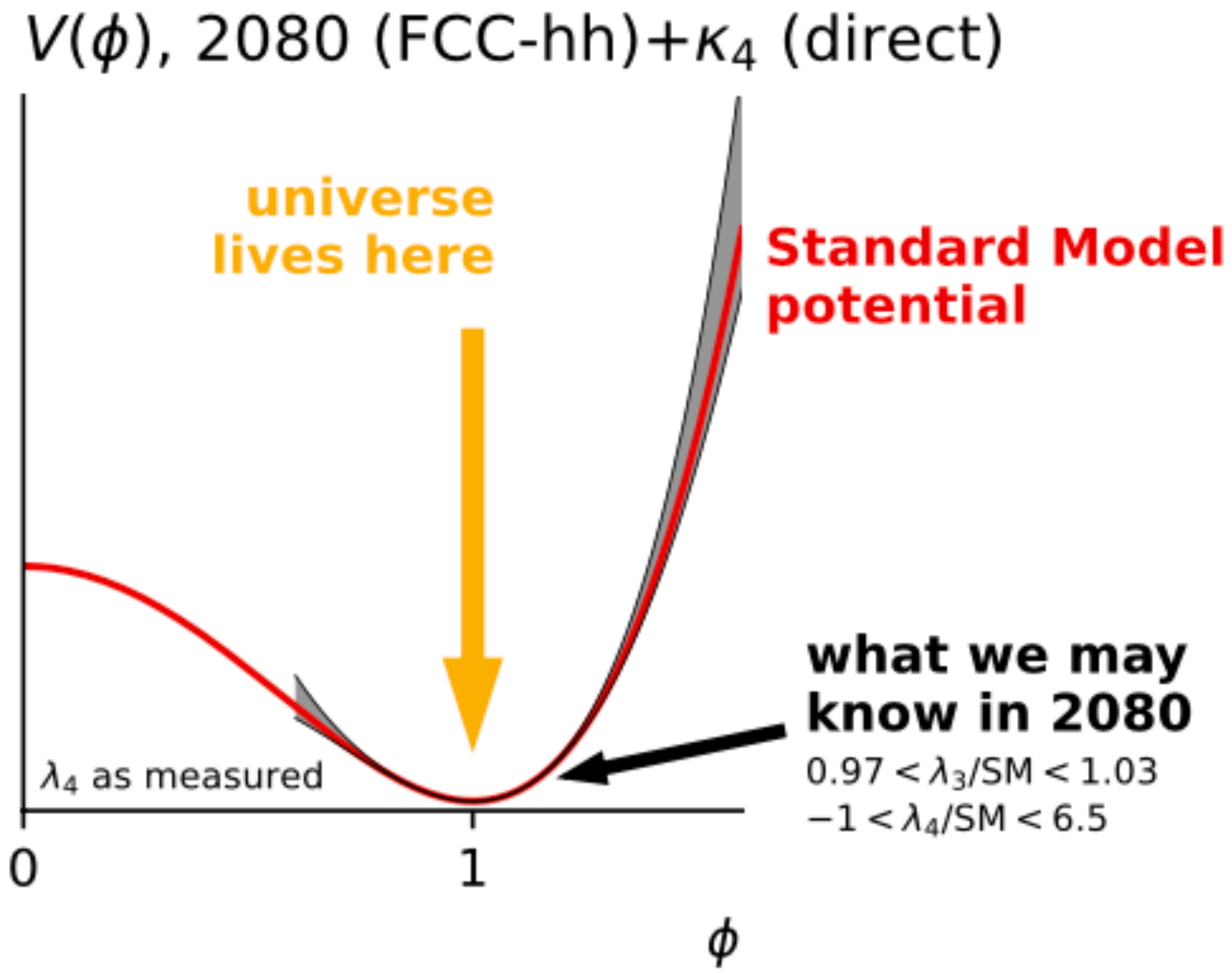
The Higgs Potential





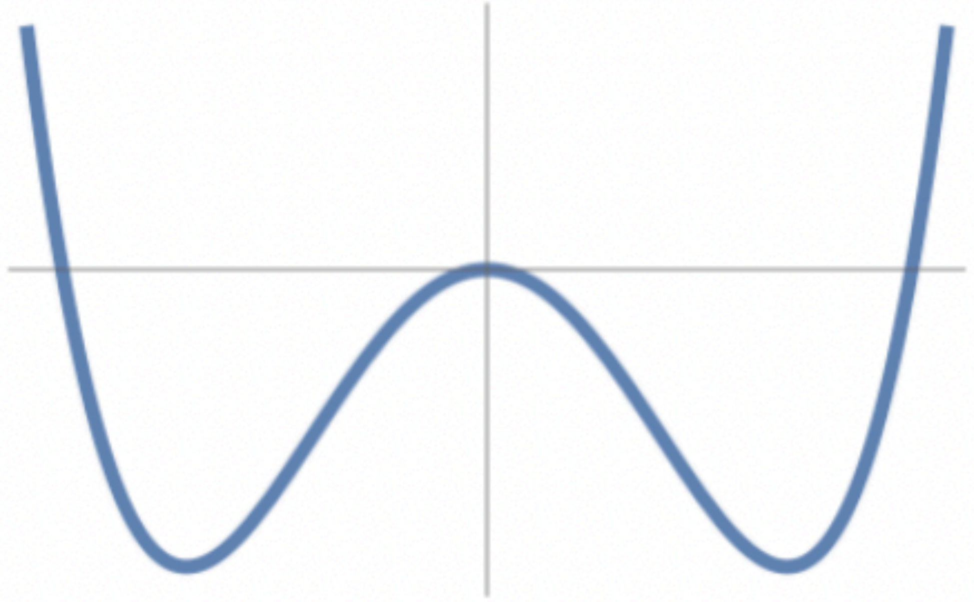




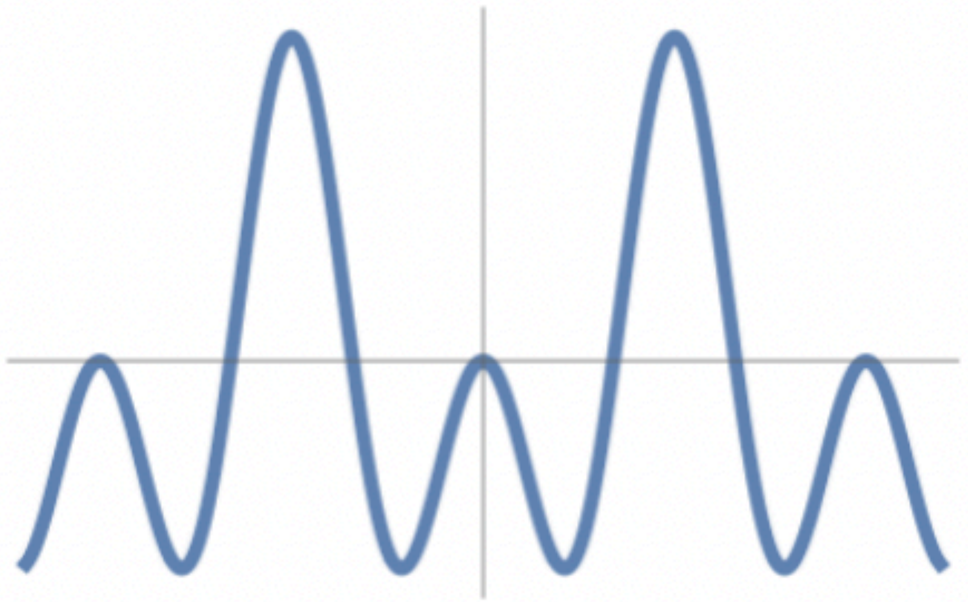


The Higgs Potential

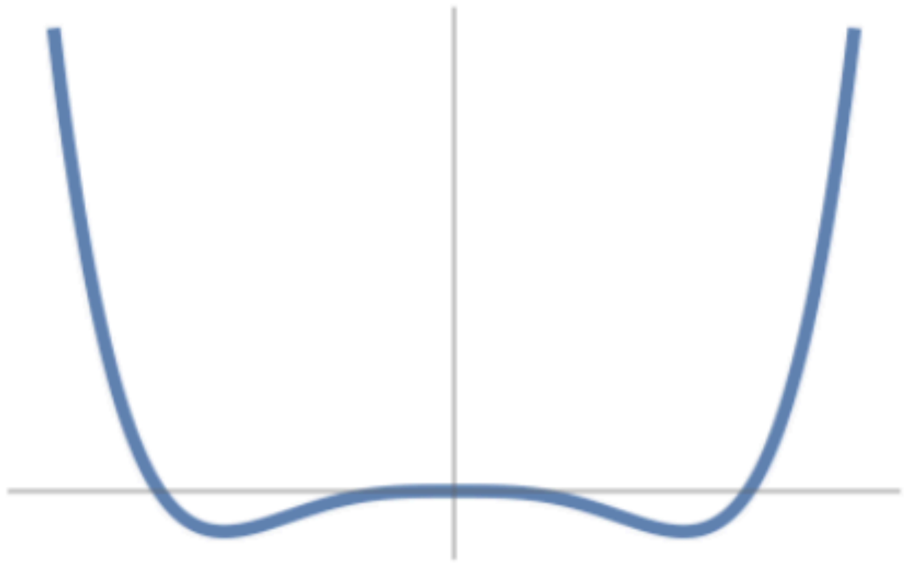
The Higgs Potential in QFT textbooks of the future
(might still be the Standard Model realisation)



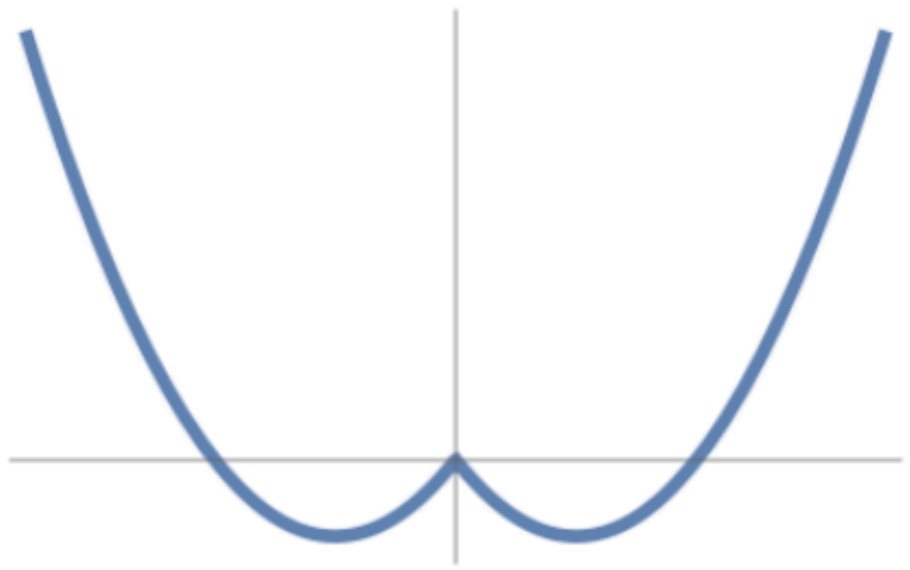
Landau-Ginzburg Higgs



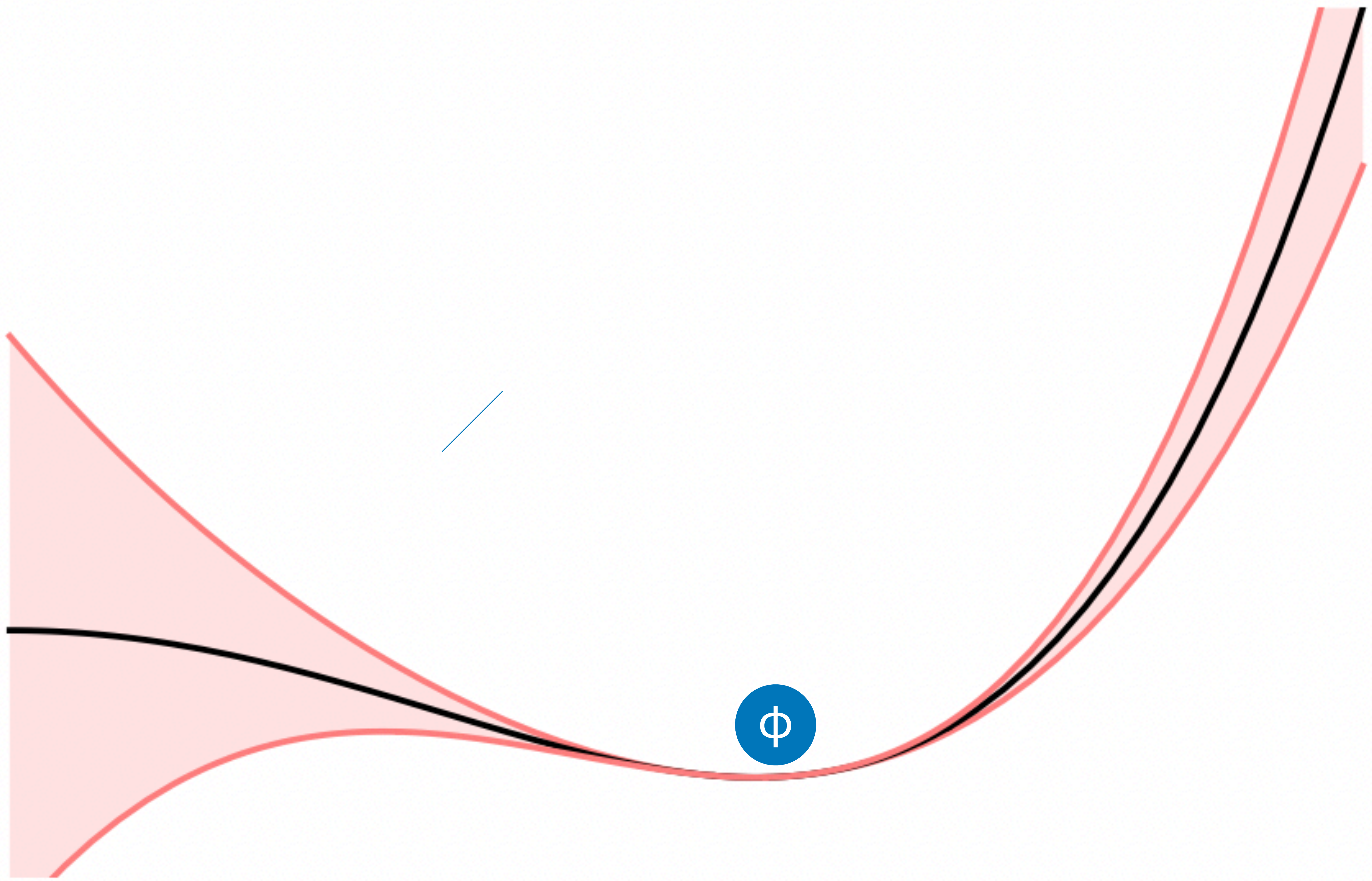
Nambu-Goldstone Higgs



Coleman-Weinberg Higgs



Tadpole-Induced Higgs



1907.02078

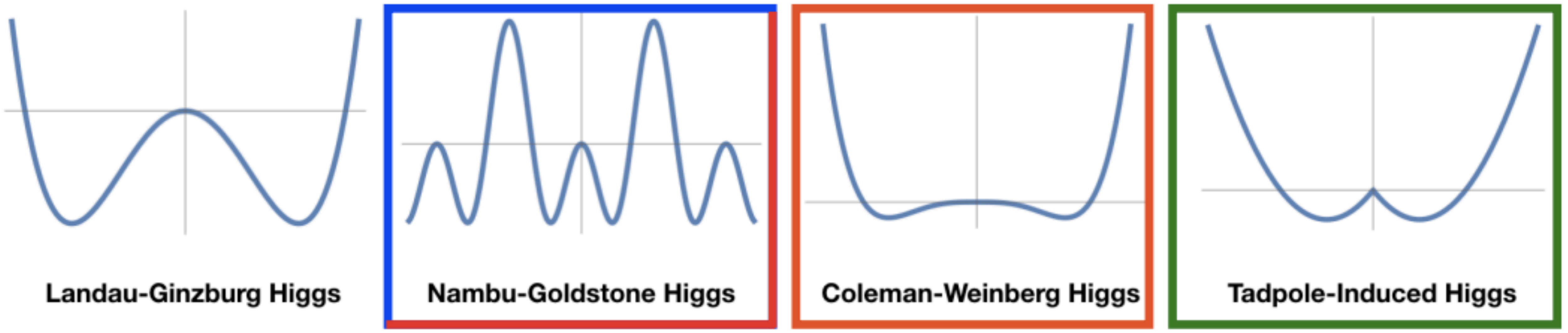
Higgs self-interactions and Higgs potential

https://arxiv.org/pdf/1907.02078.pdf

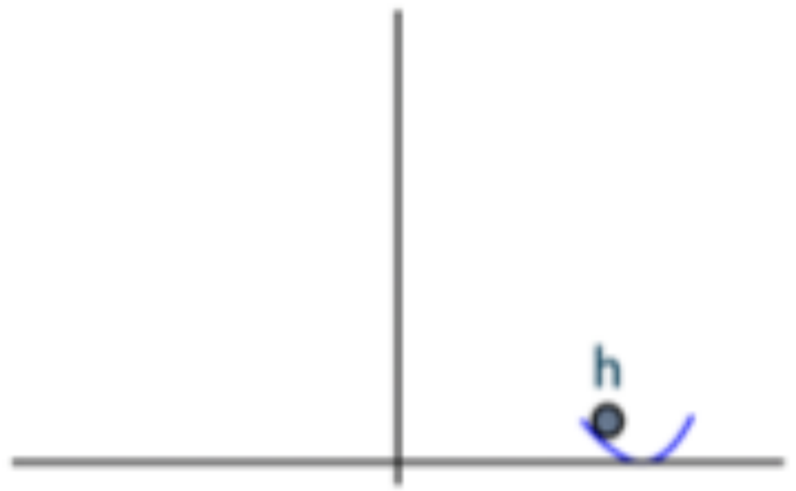
Alternative Higgs potential models

$$V(H) \simeq \begin{cases} -m^2 H^\dagger H + \lambda (H^\dagger H)^2 + \frac{c_6 \lambda}{\Lambda^2}(H^\dagger H)^3, & \text{Elementary Higgs} \\ -a \sin^2(\sqrt{H^\dagger H}/f) + b \sin^4(\sqrt{H^\dagger H}/f), & \text{Nambu-Goldstone Higgs} \\ \lambda (H^\dagger H)^2 + \epsilon (H^\dagger H)^2 \log \frac{H^\dagger H}{\mu^2}, & \text{Coleman-Weinberg Higgs} \\ -\kappa^3 \sqrt{H^\dagger H} + m^2 H^\dagger H, & \text{Tadpole-induced Higgs} \end{cases}$$

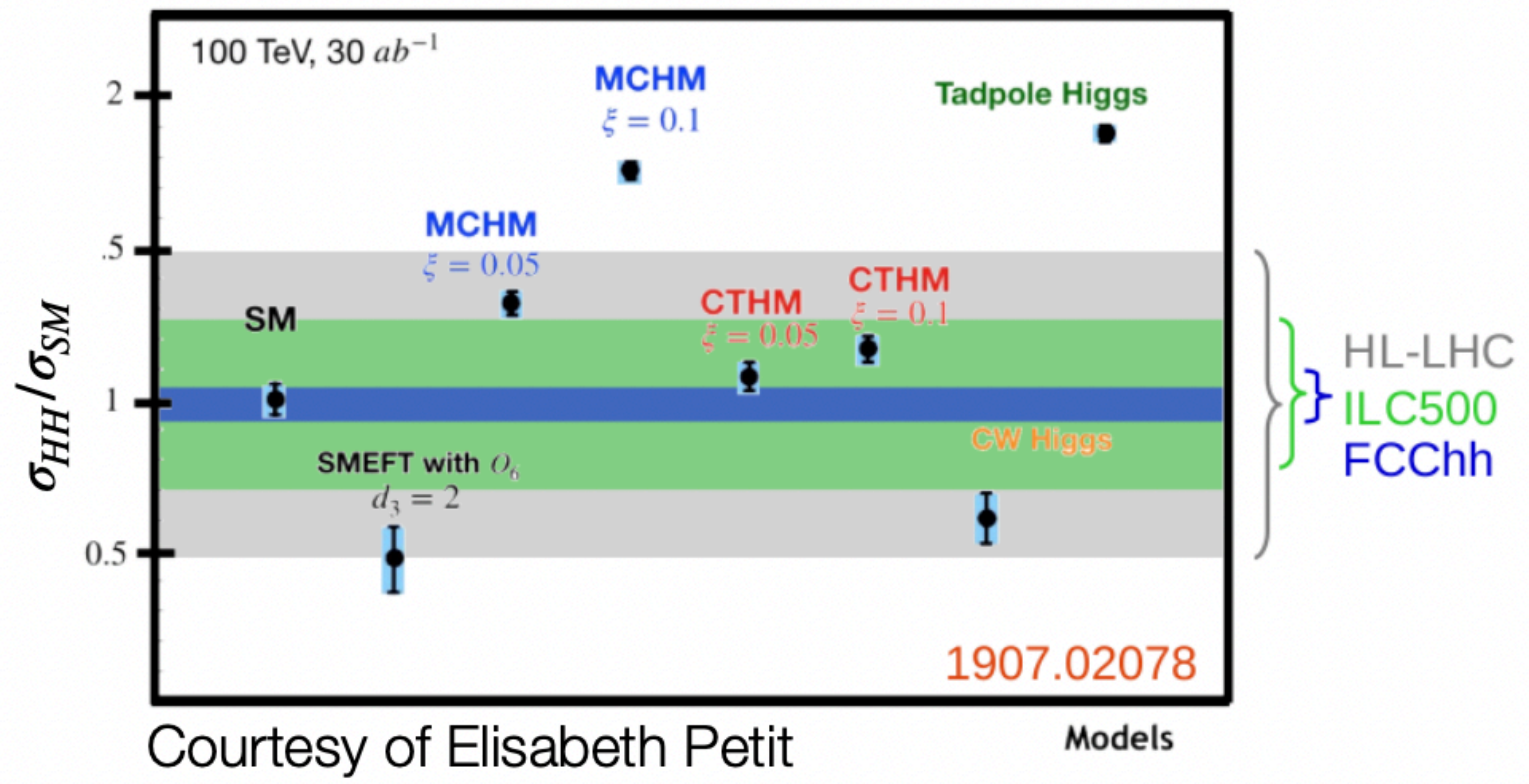
- Nambu-Goldstone Higgs: pseudo Nambu-Goldstone boson emerging from strong dynamics at a high scale
- Coleman-Weinberg Higgs: EWSB is triggered by renormalization group (RG) running effects
- Tadpole-induced Higgs: EWSB is triggered by the Higgs tadpole



minimal composite Higgs model/ composite twin Higgs model : different coupling to top quark



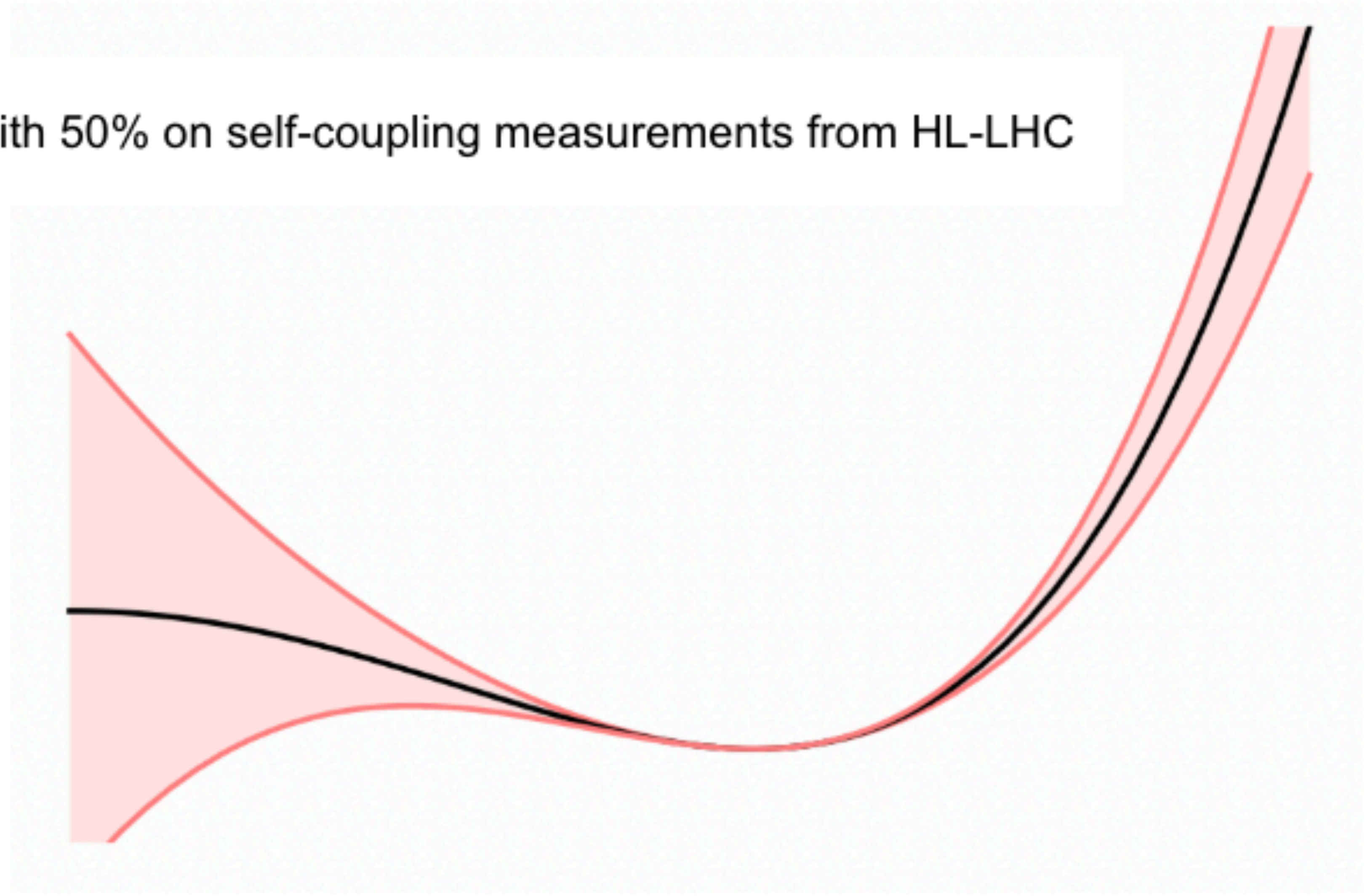
[arXiv:1511.06495]



Courtesy of Elisabeth Petit

Assuming a measurement of the HH cross-section with a 1-sigma 5% precision

Precision in Higgs self-coupling measurements



$\delta\kappa_\lambda \sim \mathcal{O}(\%)$ — **First order phase transition at EW scale**

$\delta\kappa_\lambda \lesssim \mathcal{O}(\%)$ — **EW symmetry restoration vs non-restoration**

*The questions we can answer (**completely**) are limited with current colliders !*

Can we do better than coupling variations? Yes (of course): Effective Field Theory approach

$$\mathscr{L} = \mathscr{L}_{SM} + \frac{h^6}{\Lambda^2} \qquad \delta\kappa_\lambda \sim \frac{v^2}{\lambda\Lambda^2}, \qquad \Lambda \sim 1\,\mathrm{TeV} \implies \boxed{\delta\kappa_\lambda \sim .5}$$

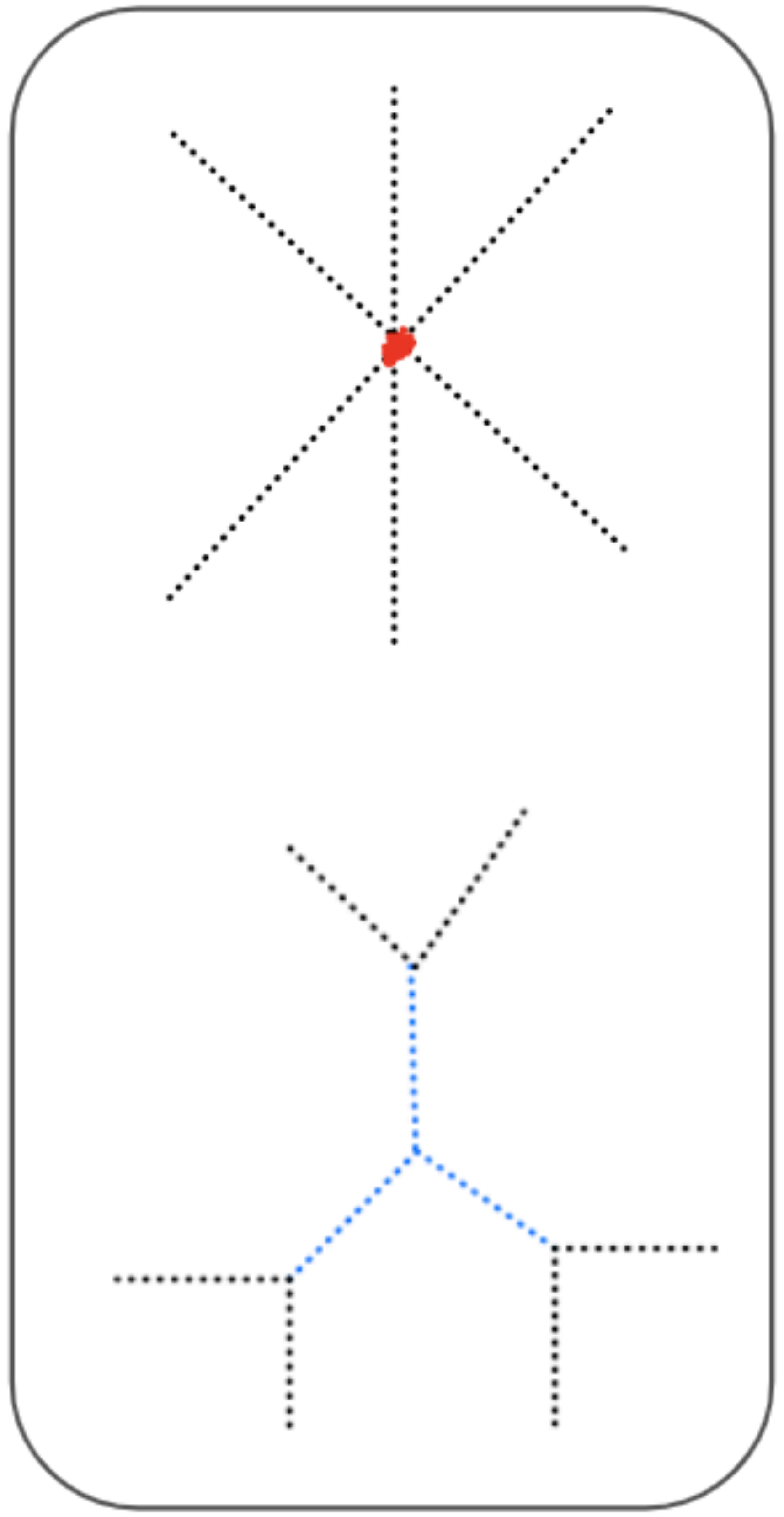
New physics at the TeV scale would be barely visible through self-coupling effects … (50%)

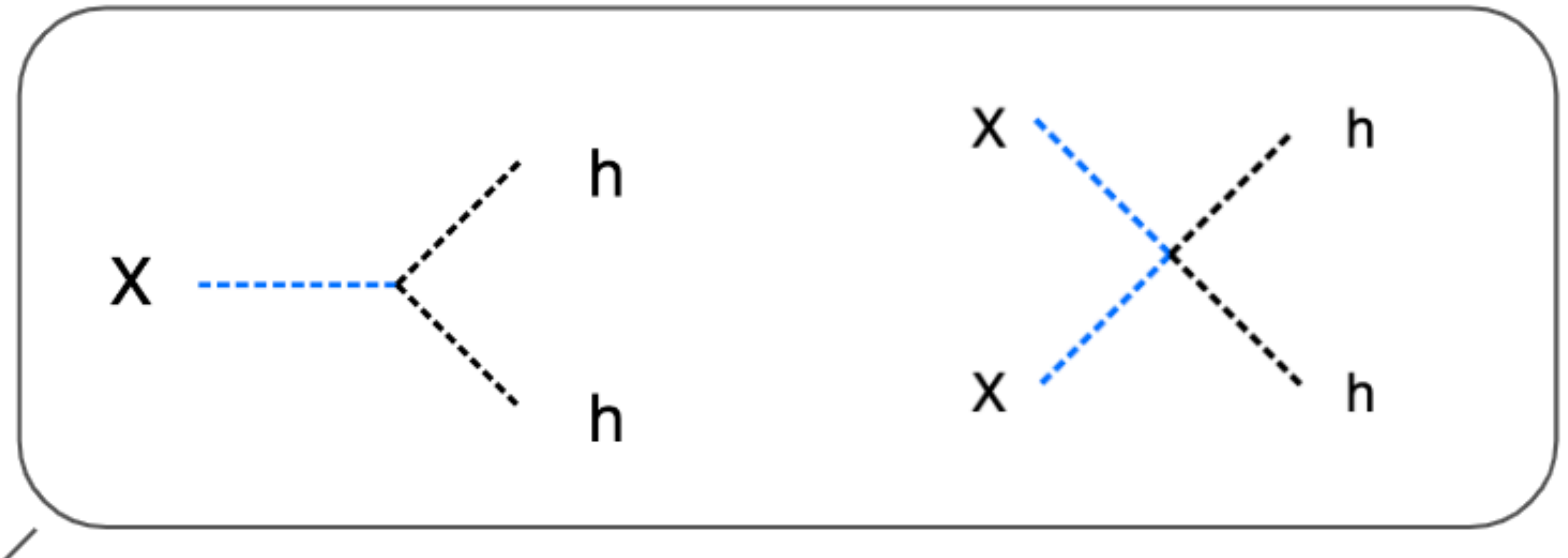
Precision in Higgs self-coupling measurements

back-up

Leading Order operator for HH: what new physics (coupling to H) live here that can generate this new interaction?

$$\frac{h^6}{\Lambda^2}$$





$$\delta\kappa_\lambda \sim \frac{\lambda_{X^3}\lambda_{Xhh}^3}{\lambda_{SM} m_X^4}\frac{v^2}{m_X^2}$$

There's a chance

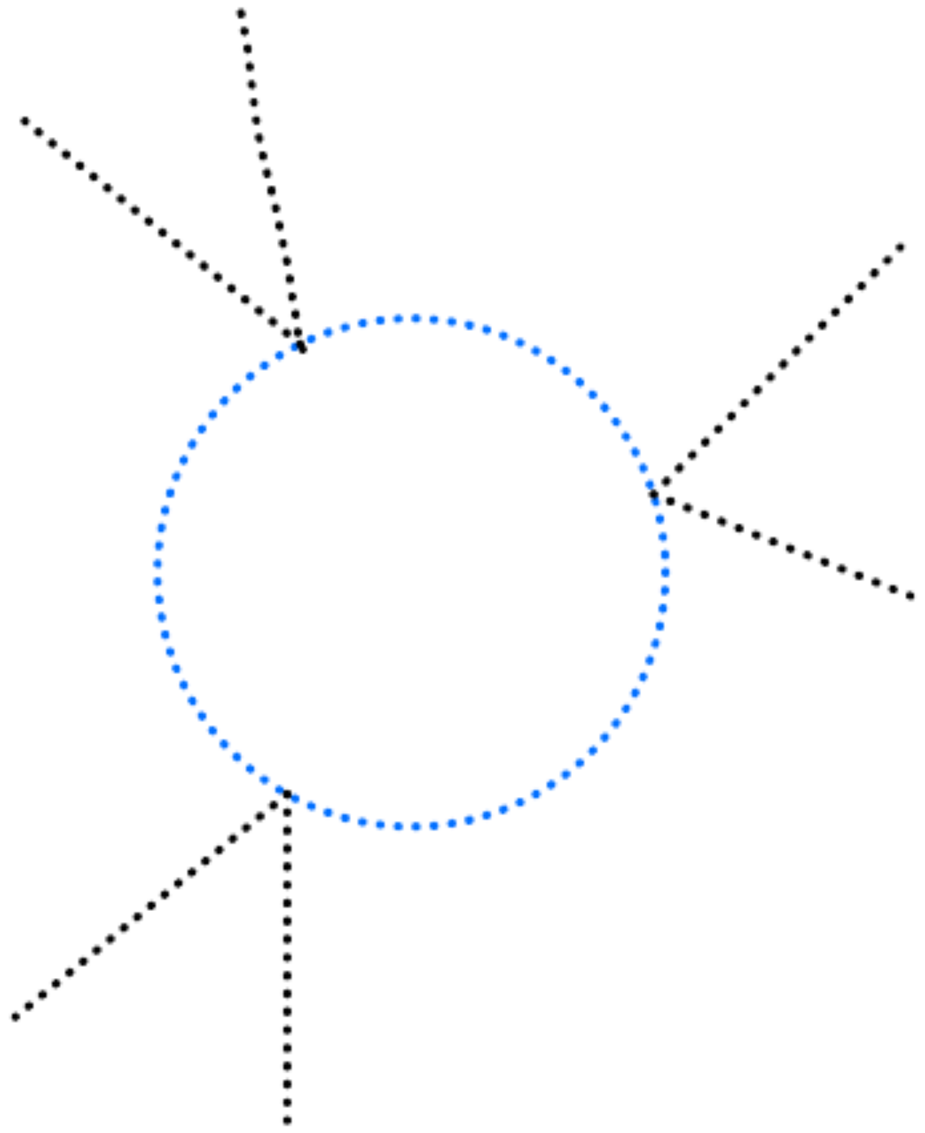
O(50-100%)

This new scalar state mixes with the Higgs, hence modifications enter in all Higgs couplings (gauge, Yukawa):
important to account for this with model-independent combinations (H+HH) and further with EFTs

https://indico.cern.ch/event/1359386/

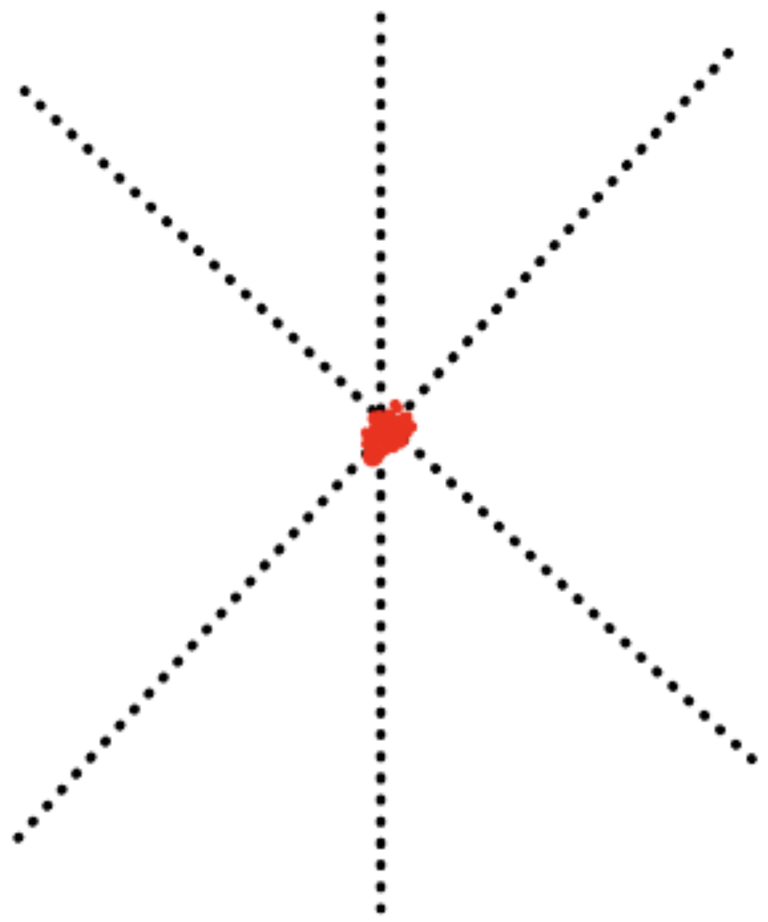
Precision in Higgs self-coupling measurements

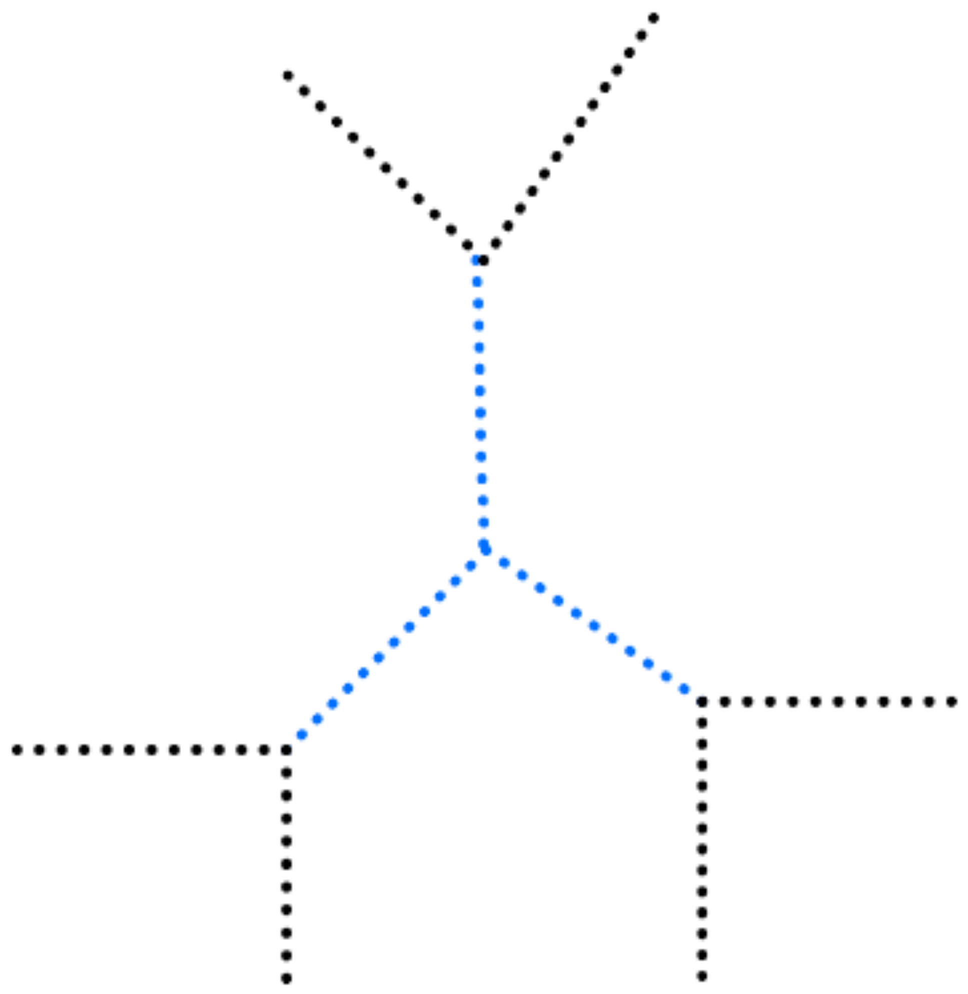
back-up



(Loop contribution is also present, but much smaller effect than tree)

$$\delta\kappa_\lambda \sim \frac{\lambda_{HX}^3}{24\pi^2\lambda_{SM}} \frac{v^2}{m_X^2} \implies 10^{-3} \to 10^{-1}$$



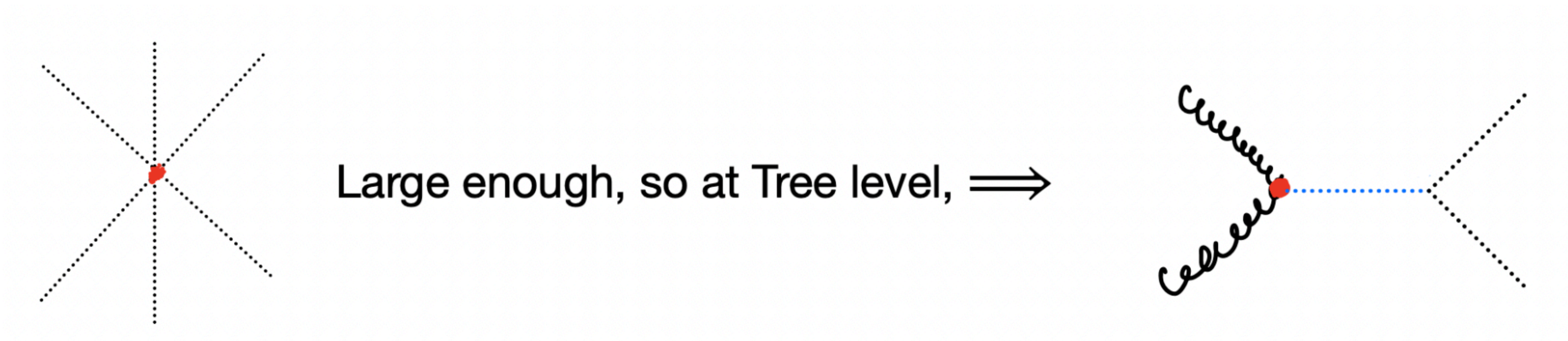


$$\delta\kappa_\lambda \sim \frac{\lambda_{X^3}\lambda_{Xhh}^3}{\lambda_{SM} m_X^4} \frac{v^2}{m_X^2} \implies$$

There's a chance

Precision in Higgs self-coupling measurements

If we add dim6 operators to obtain large (visible) self-coupling variations: we have a new scalar state coupling at tree-level



Mixing with SM Higgs, and producing HH final states:
resonant production important to consider in combined interpretations with non-resonant HH production

(due to the level of achievable precision and the model-dependedness we want)

Final message: HH (resonant + non-resonant) good probe for wide set of simplified models (e.g. 2HDMs)
a common interpretation can be beneficial in setting the scope
(energy + precision)

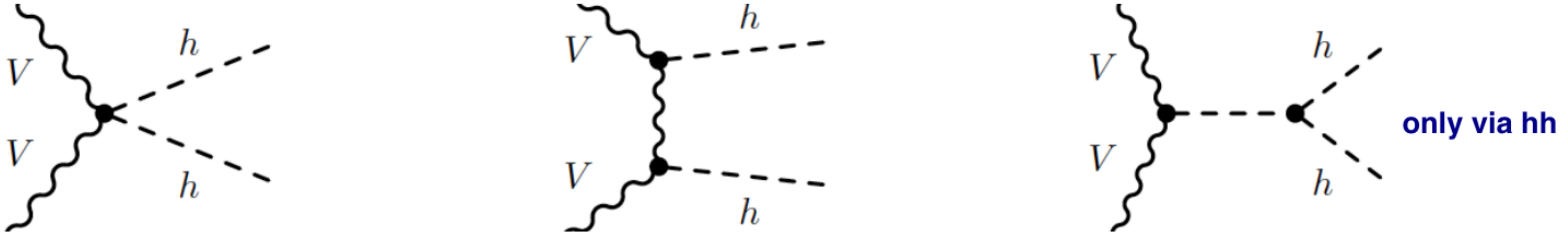
Vector Boson Scattering

back-up

- In the SM, the Higgs boson is part of a $SU(2)_L$ doublet, connecting **Higgs with vector boson interactions**

$$c_{2V} hhVV \quad \& \quad c_V hVV \quad \rightarrow \quad c_{2V} \text{ linked to } c_V$$

$\propto c_{2V}$ $\quad$ $\propto c_V^2$ $\quad$ $\propto c_V c_3$



- However, this is not necessarily the case, the Higgs-like scalar found at the LHC could be instead a singlet under the SM gauge groups is EWSB is **realised in a non-linear manner**

$$\phi = \frac{v+h}{\sqrt{2}} U \begin{pmatrix} 0 \\ 1 \end{pmatrix} = \sqrt{2}\Phi \begin{pmatrix} 0 \\ 1 \end{pmatrix}, \qquad \text{where } \; U = \exp\left\{ i \frac{2\, T_a \varphi_a}{v} \right\}$$

Goldstone bosons

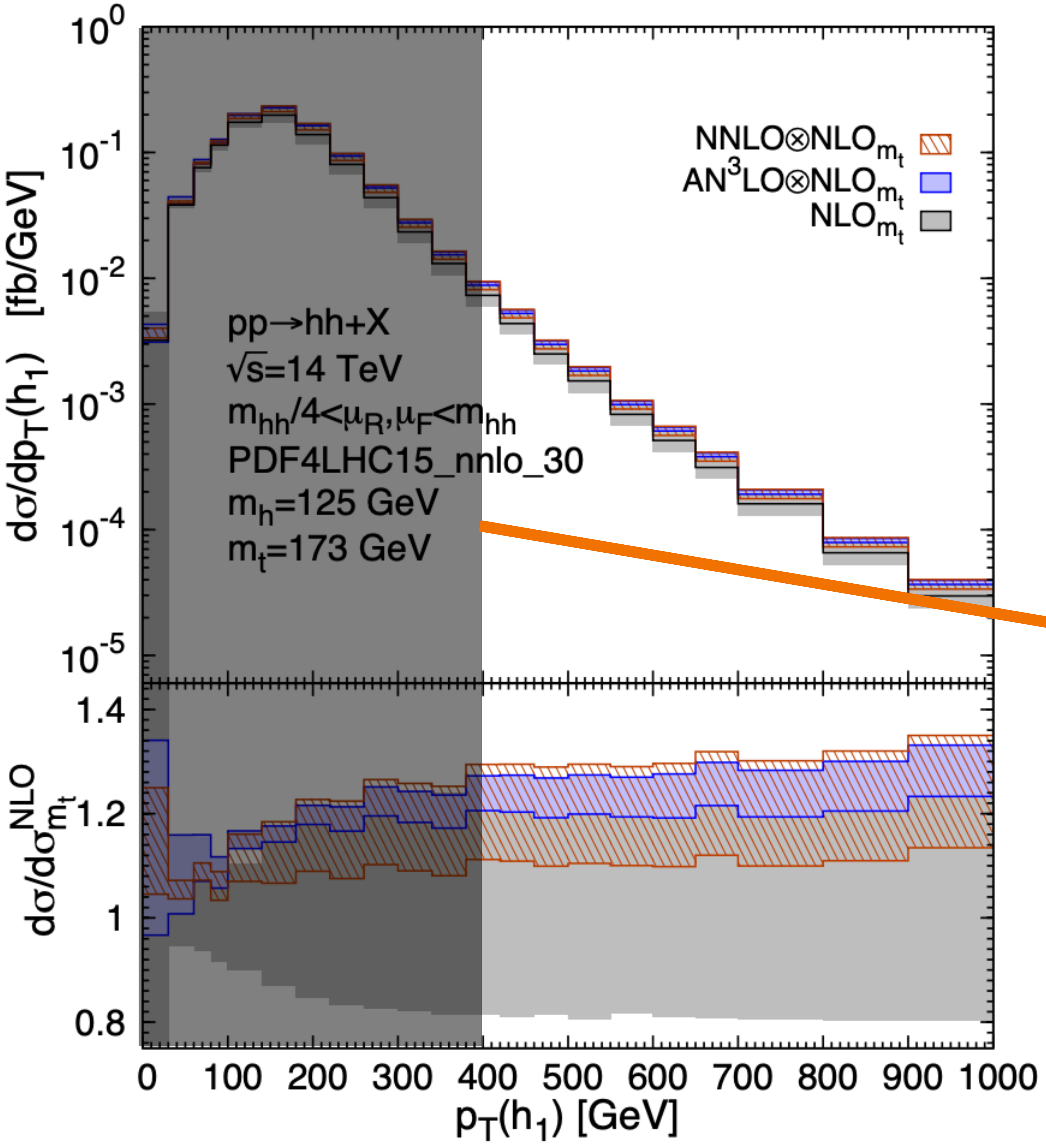
Higgs field

physical Higgs particle

In this scenario e.g. the hhVV and hVV couplings become independent model parameters

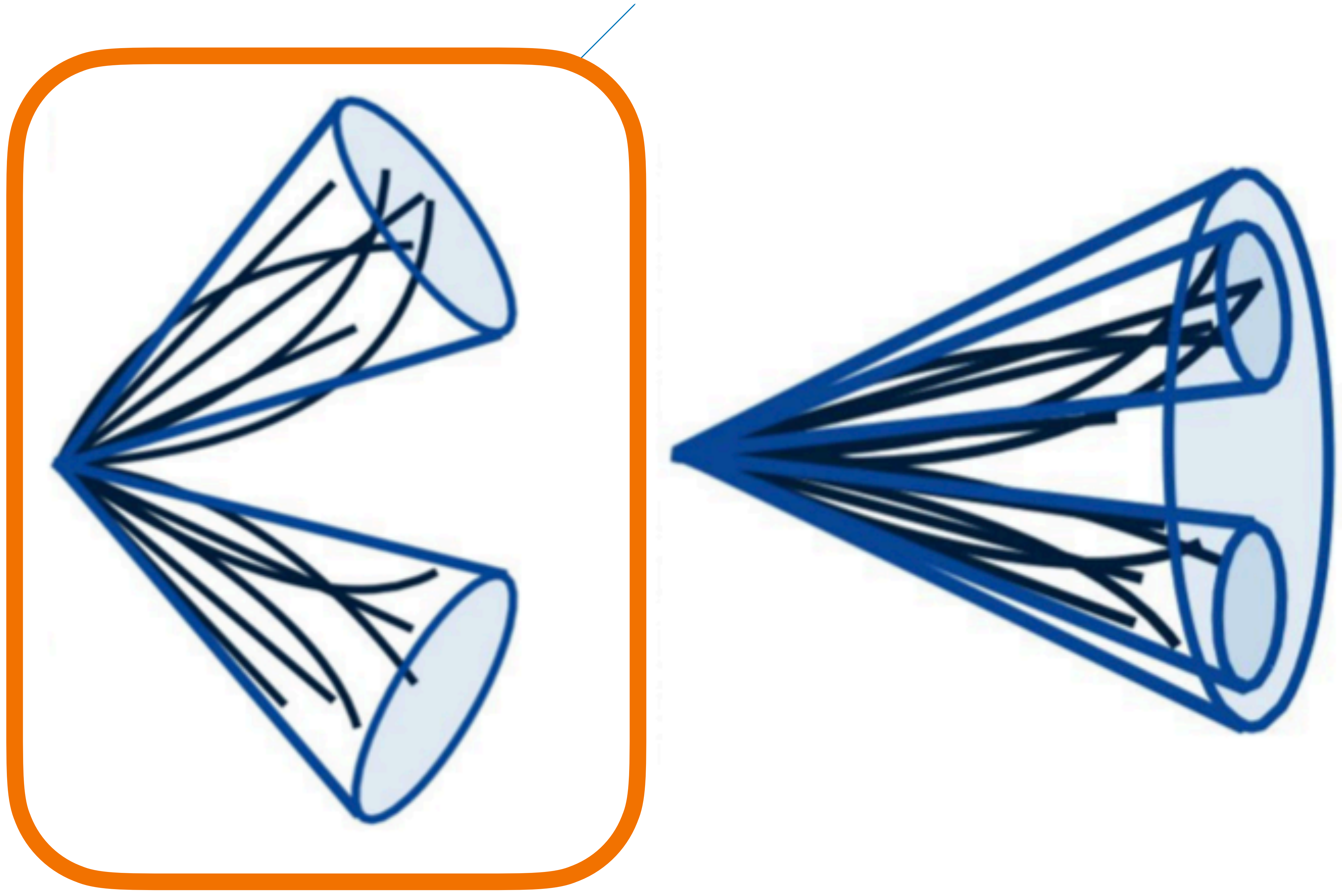
Feasibility of HHH at LHC Run-3 - (3) proof-of-principle HH(4b)

SM double(triple)-Higgs production happens at low transverse momentum !



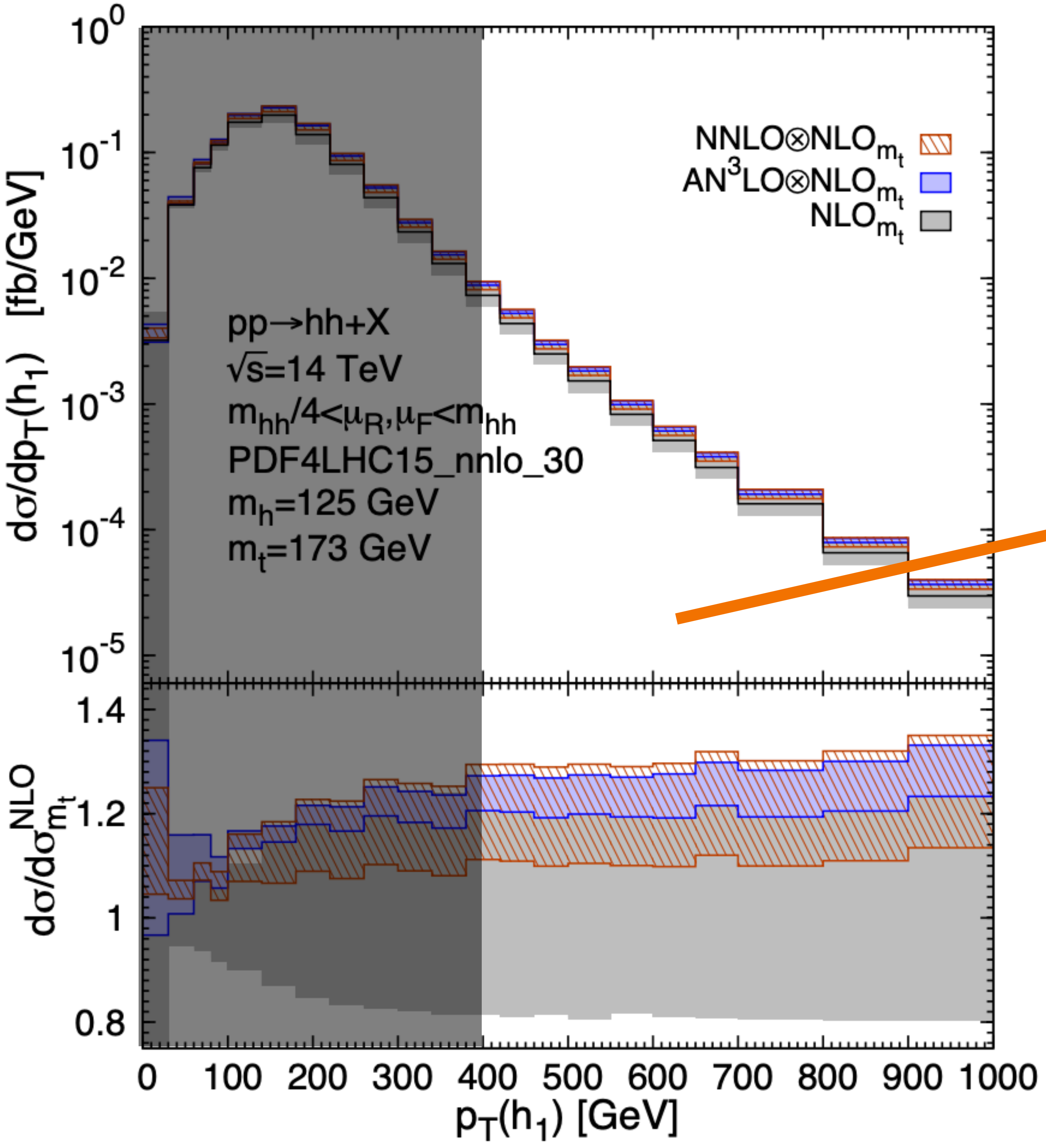
Transverse momentum of one Higgs boson produced in HH events (theory calculation)

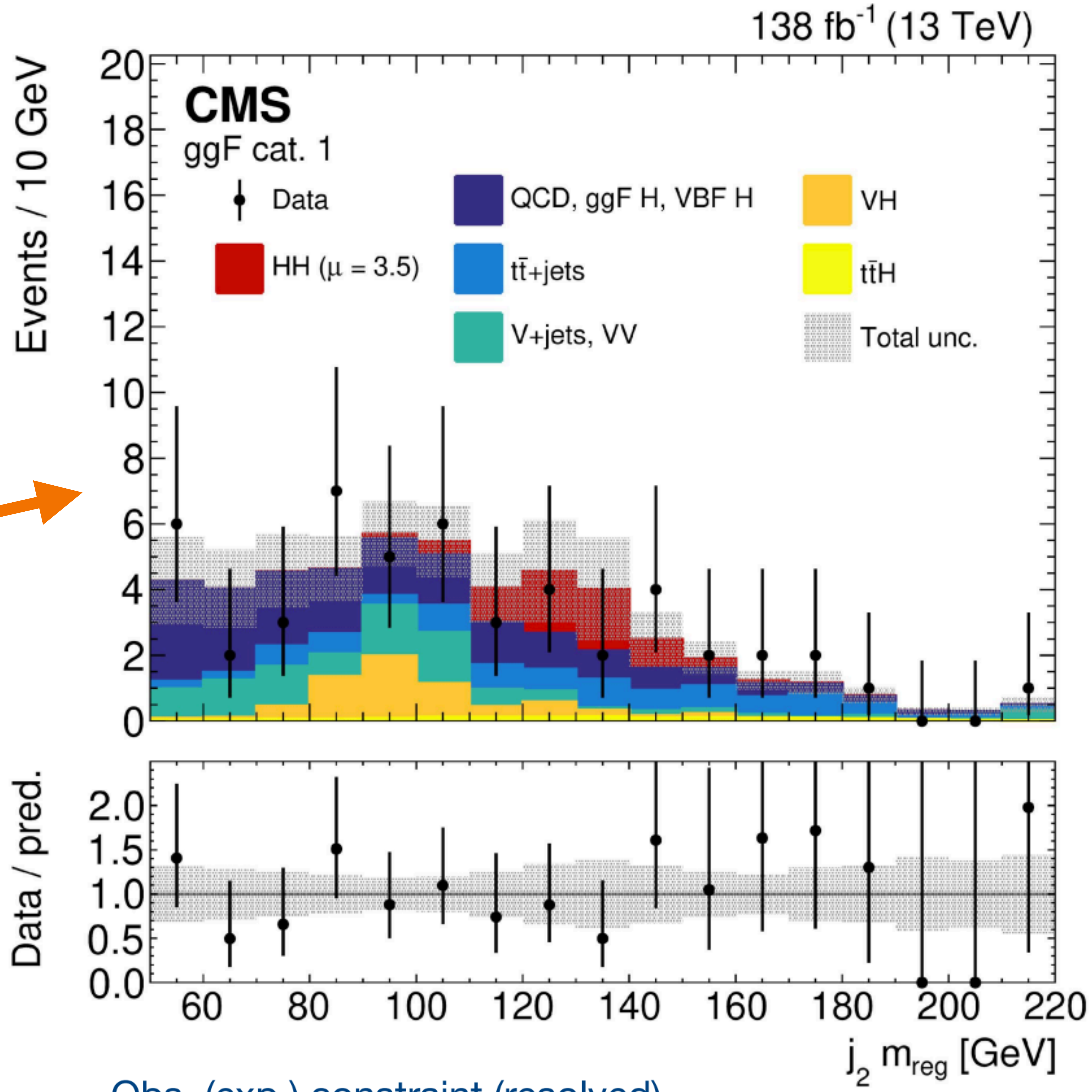
Bulk of the cross-section is lower than the “boosted” regime!



Feasibility of HHH at LHC Run-3 - (3) proof-of-principle HH(4b)

CMS HH4b manages to extract sensitivity **from the tail as from the bulk**



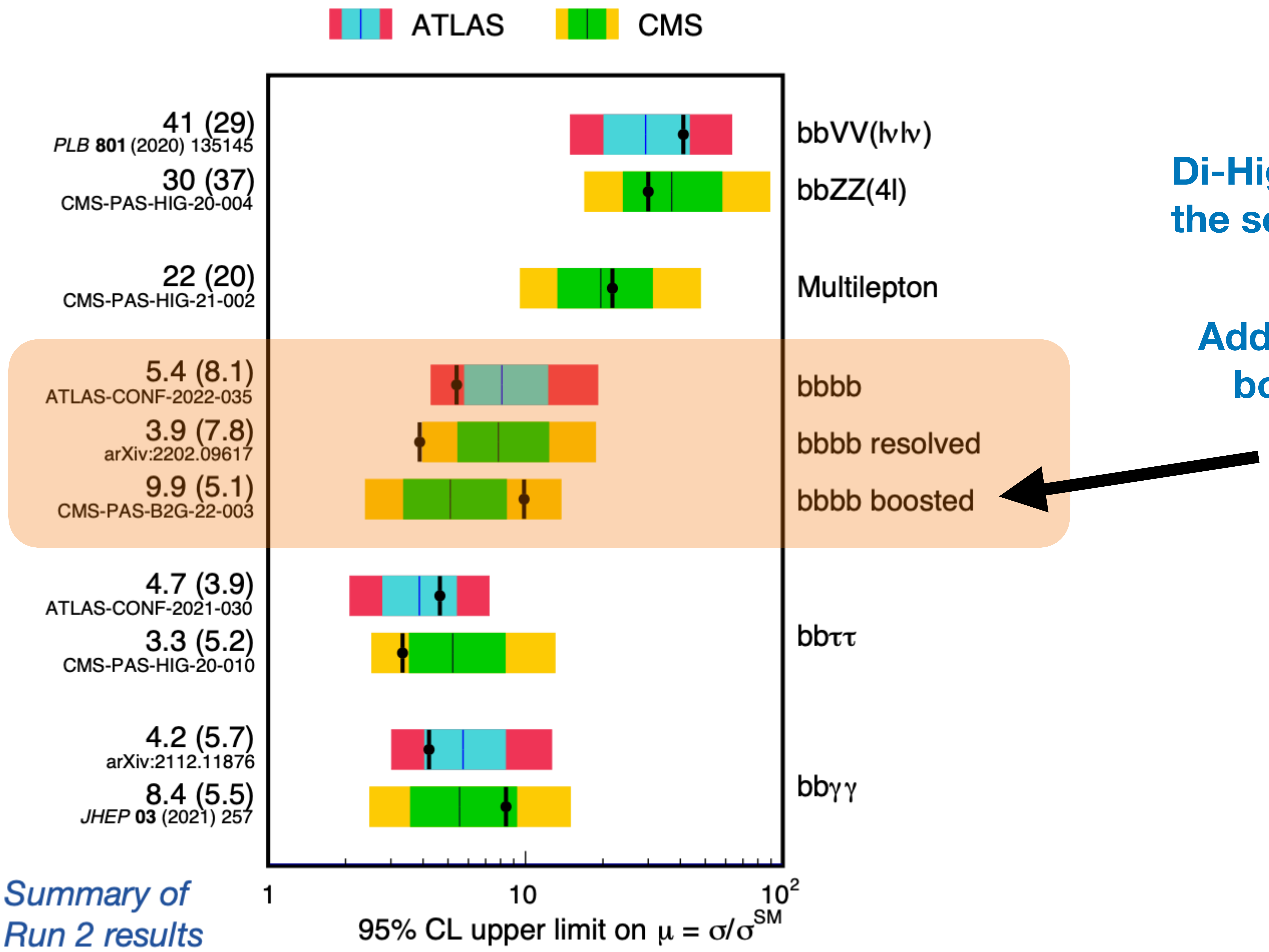


Obs. (exp.) constraint (resolved)
[-2.3, 9.4] ([-5.0,12.0])
Obs. (exp.) constraint (boosted)
[-9.9,16.9] ([-5.1,12.2])

x30 improvement wrt previous analysis

Feasibility of HHH at LHC Run-3 - (3) proof-of-principle

back-up



Summary of Run 2 results

Di-Higgs has no golden channel leading the sensitivity in a dominant way

Add an extra channel by including the boosted 4b regime with such high sensitivity

Feasibility of HHH at LHC Run-3 - (3) proof-of-principle

back-up

CMS manages to exploit **simultaneously & complementary**

- event kinematic
- large-R jet substructure
- flavour tagging
- mass information

Powerful tagger is not only key to disentangle very high pT regimes

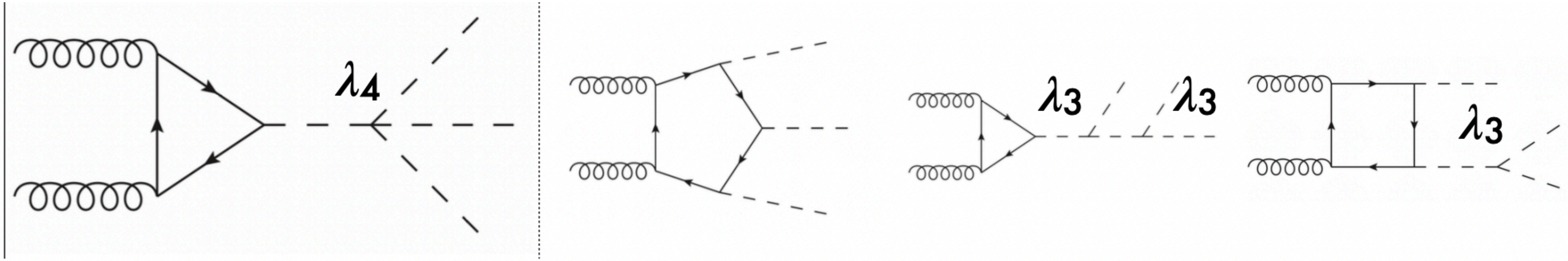
The HH(4b) results show how this approach can replace the “analysis MVA” very successfully, by tagging very rare signal events and suppressing backgrounds even for moderate pT.

→ the tagger does better than the custom-designed analysis high-level MVA
then better go as low as possible in pT with large-R jets and let the tagger disentangle S/B

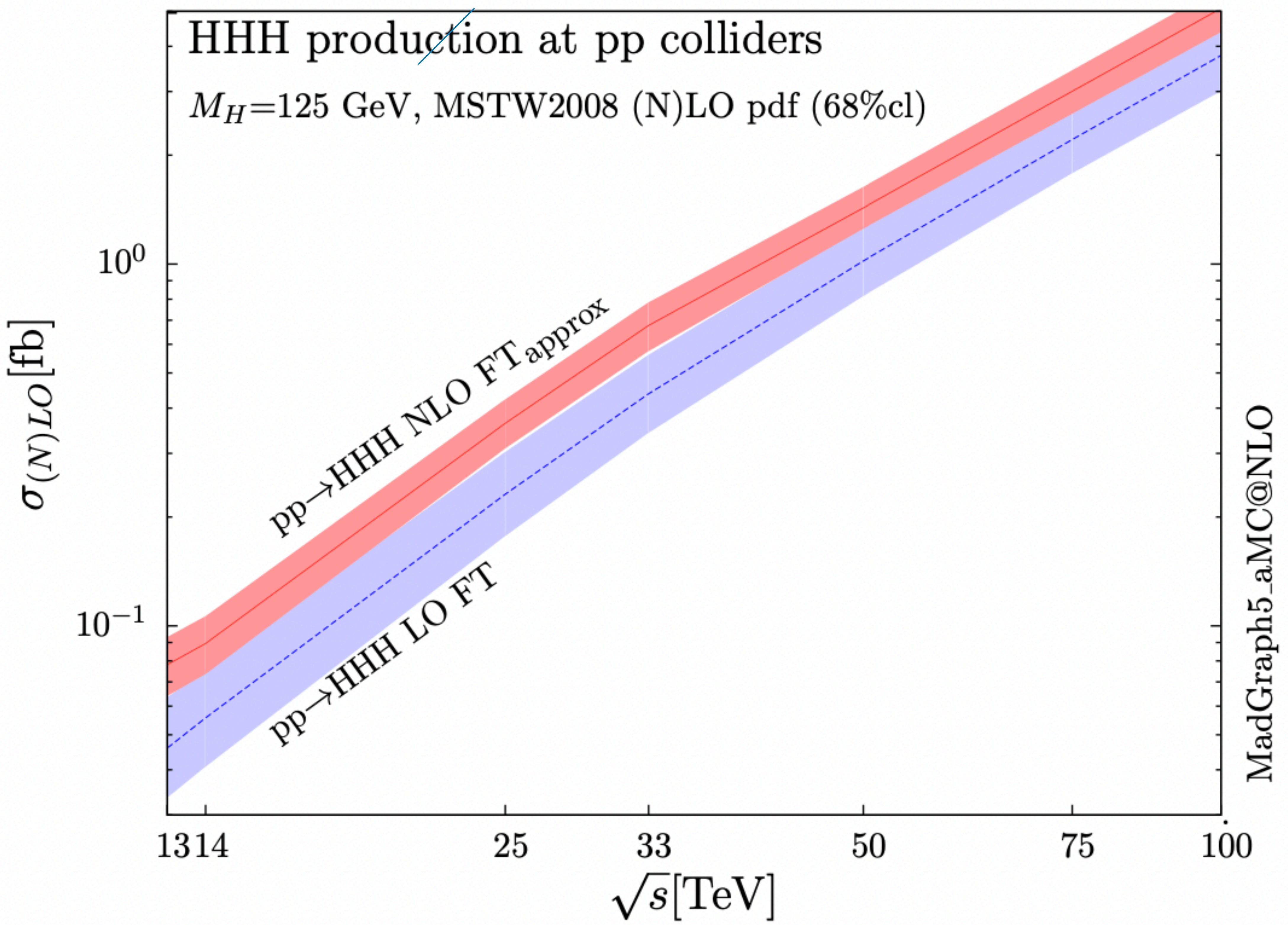
HHH signal phenomenology

HHH signal phenomenology

Triple Higgs

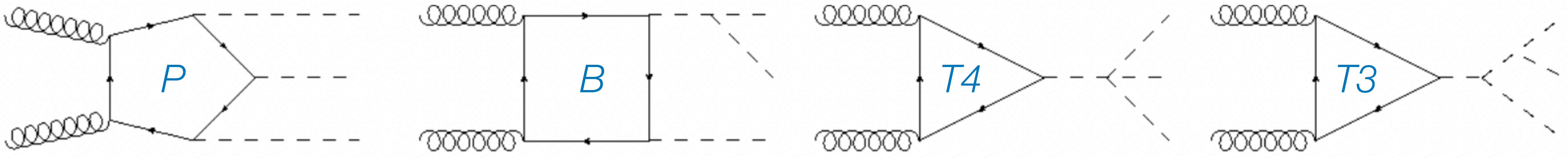


$\sigma(HHH)$ [fb]	$\sqrt{s} = 14$ TeV	$\sqrt{s} = 33$ TeV	$\sqrt{s} = 100$ TeV
LO FT	$0.0557\,^{+34.5+2.5\%}_{-24.0-2.7\%}$	$0.438\,^{+26.8+1.5\%}_{+20.0-2.0\%}$	$3.78\,^{+24.1+0.9\%}_{-18.7-1.7\%}$
NLO $\mathrm{FT}_{\mathrm{approx}}$	$0.0894\,^{+16.5+2.5\%}_{-14.6-3.2\%}$	$0.677\,^{+14.5+1.4\%}_{-13.4-1.7\%}$	$5.09\,^{+13.5+1.0\%}_{-12.7-1.3\%}$

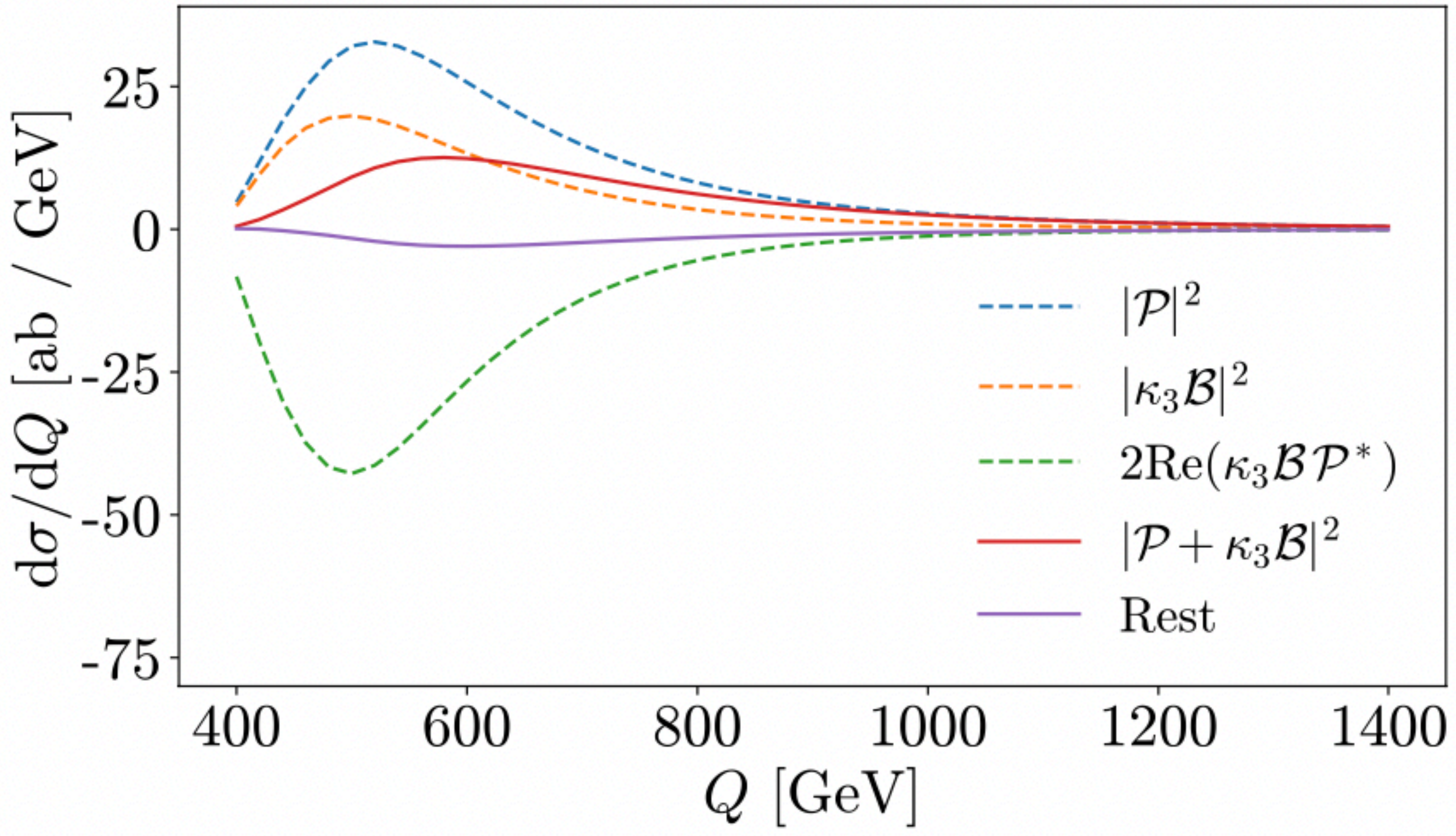


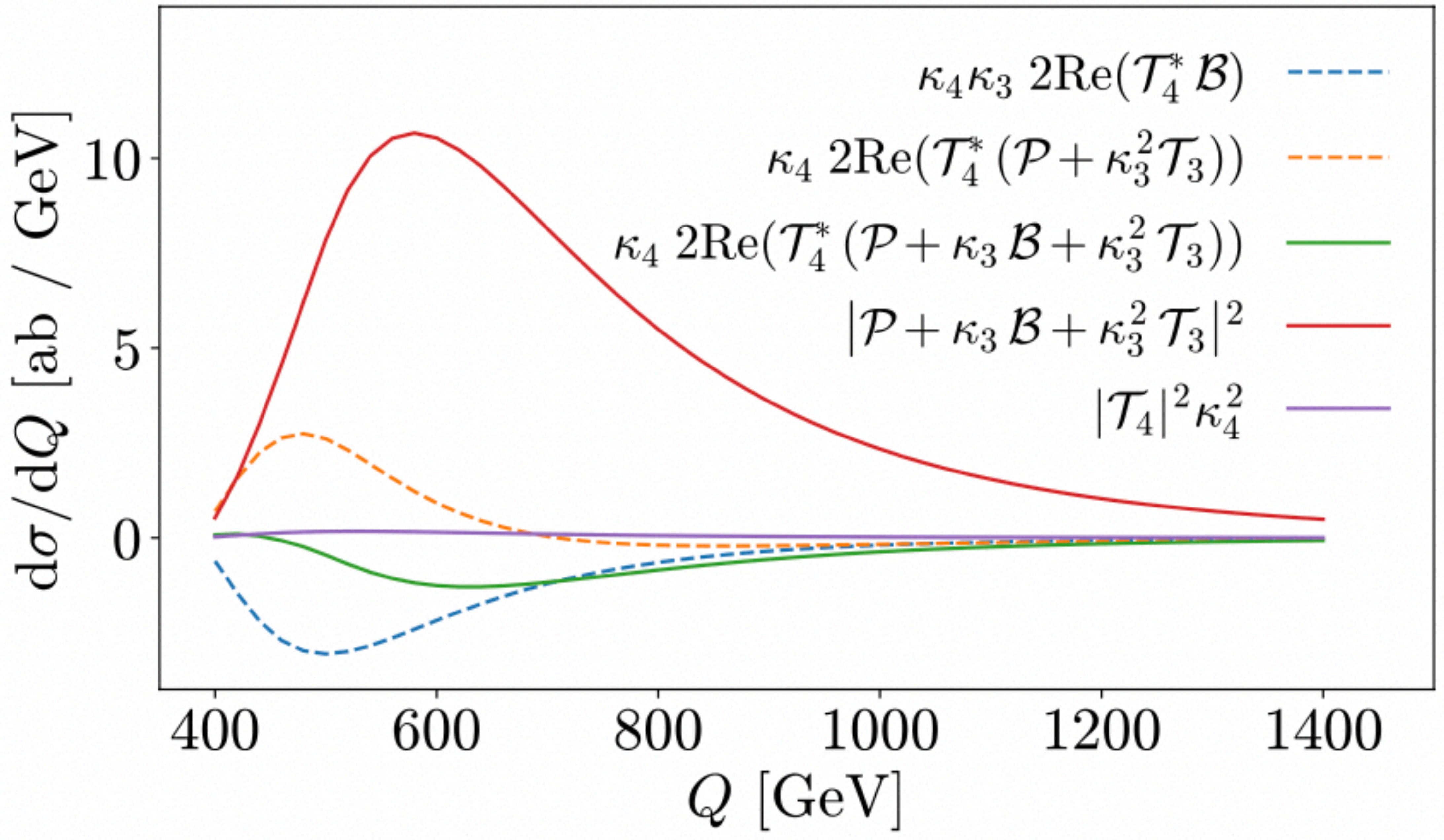
HHH signal phenomenology

back-up

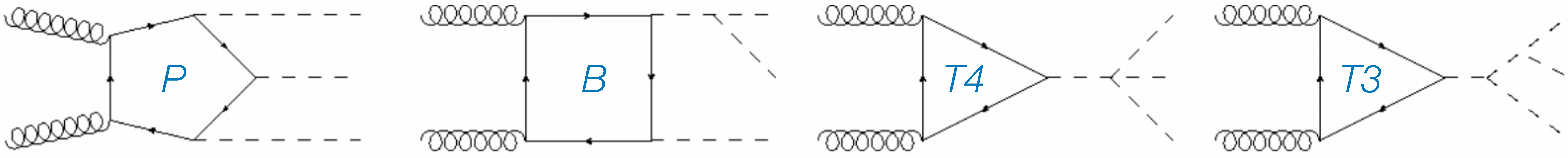


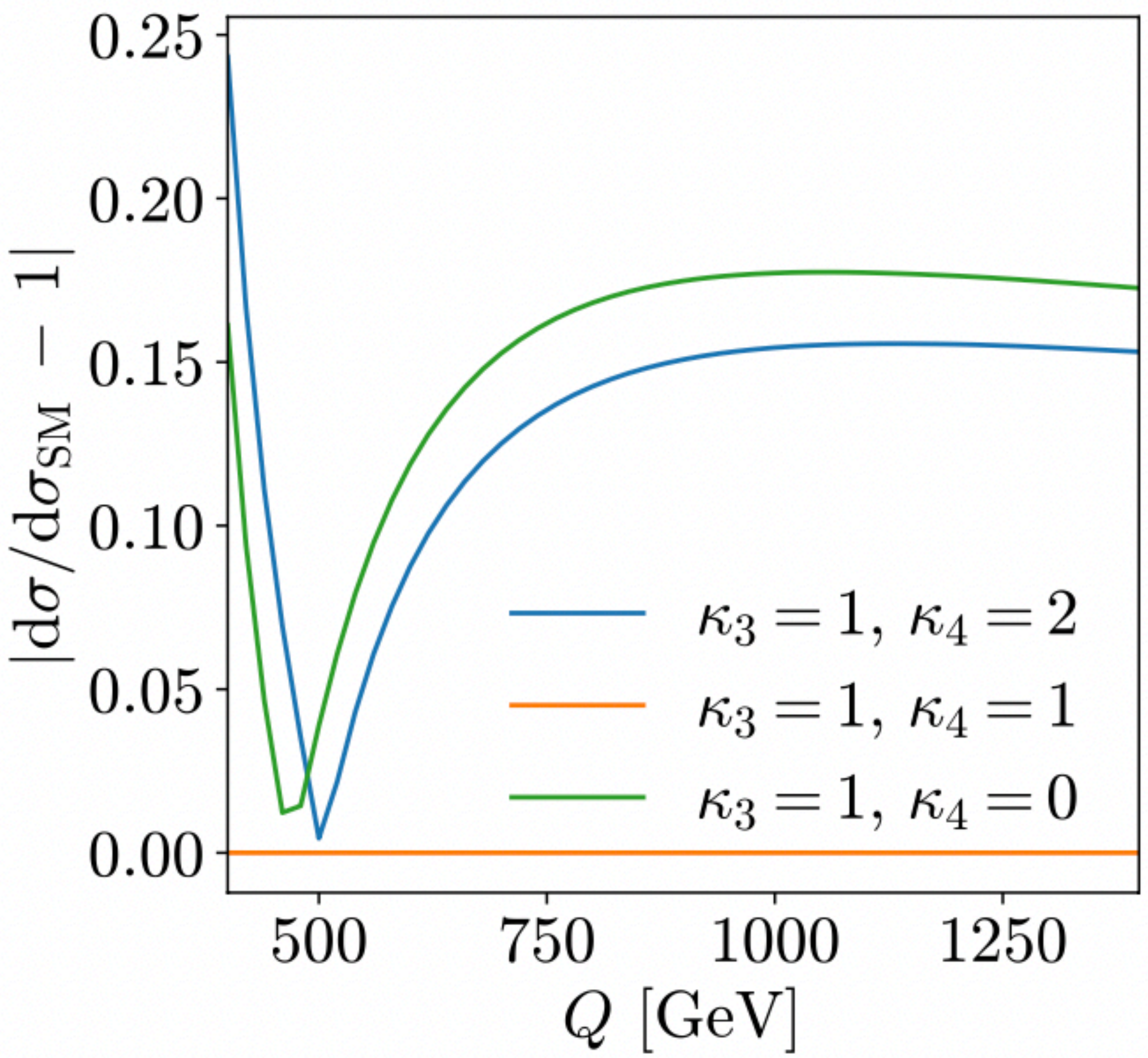
$$\mathcal{M} = \mathcal{P} + \kappa_3\,\mathcal{B} + \kappa_3^2\,\mathcal{T}_3 + \kappa_4\,\mathcal{T}_4.$$

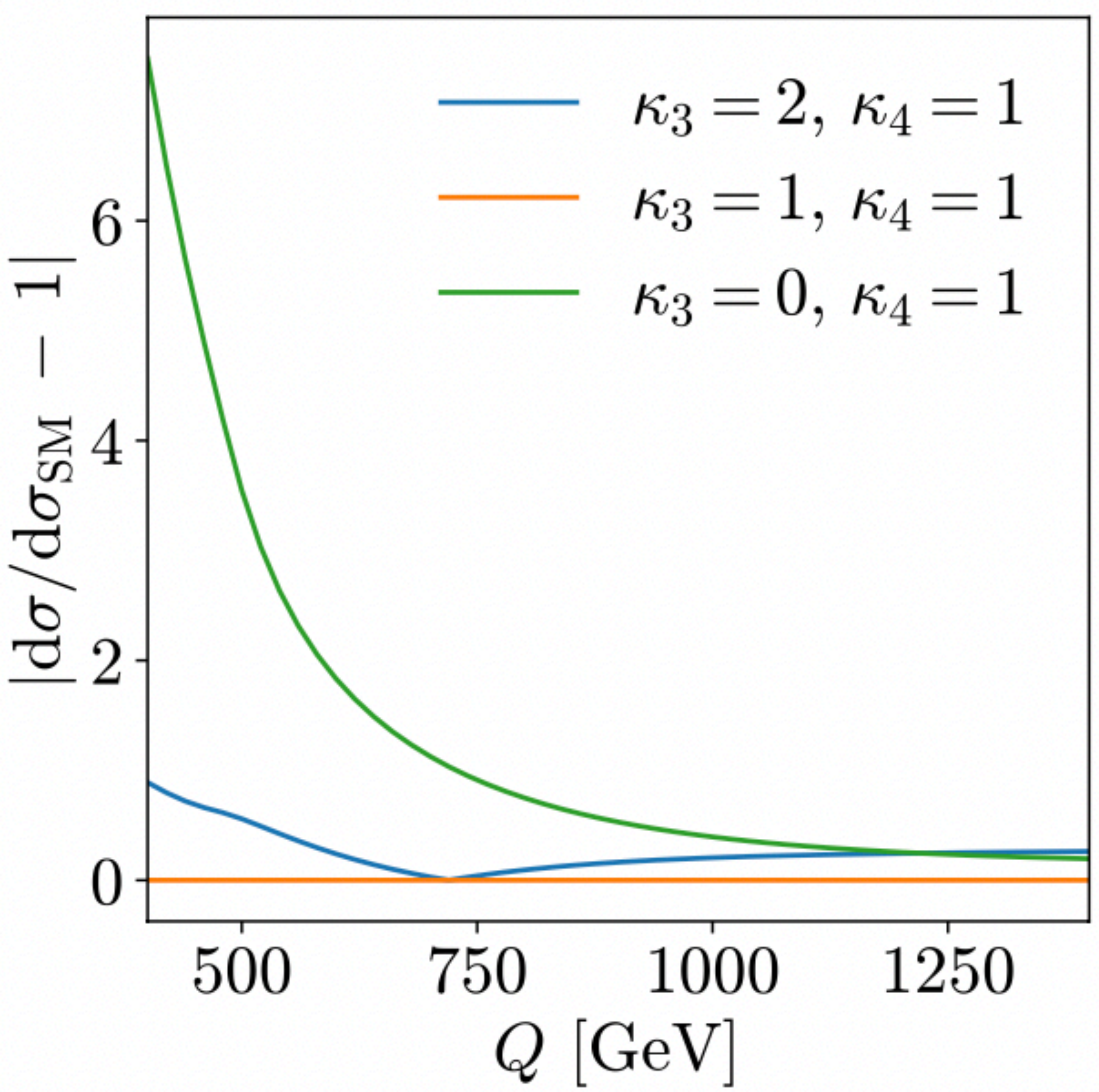


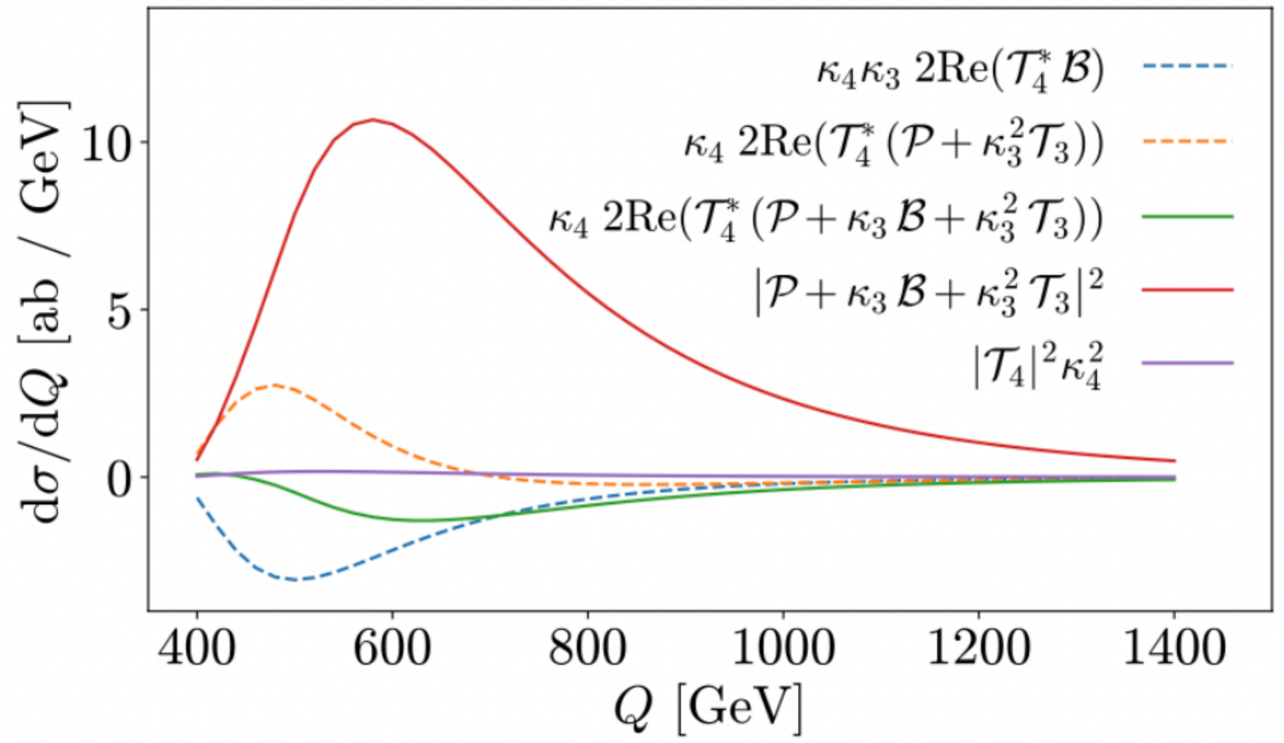


HHH signal phenomenology









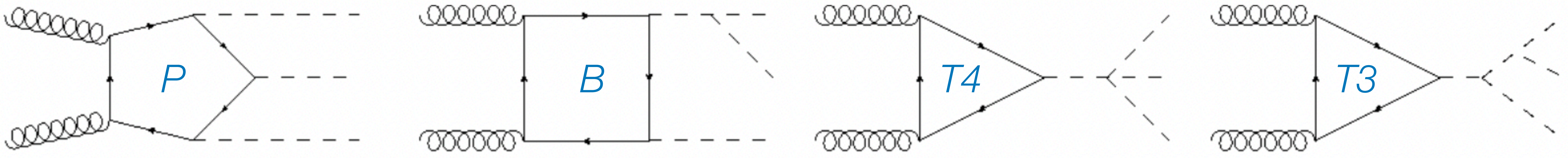
quartic sensitivity when P and B are smallest:
production threshold (low mHHH)
and high tails (large mHHH)

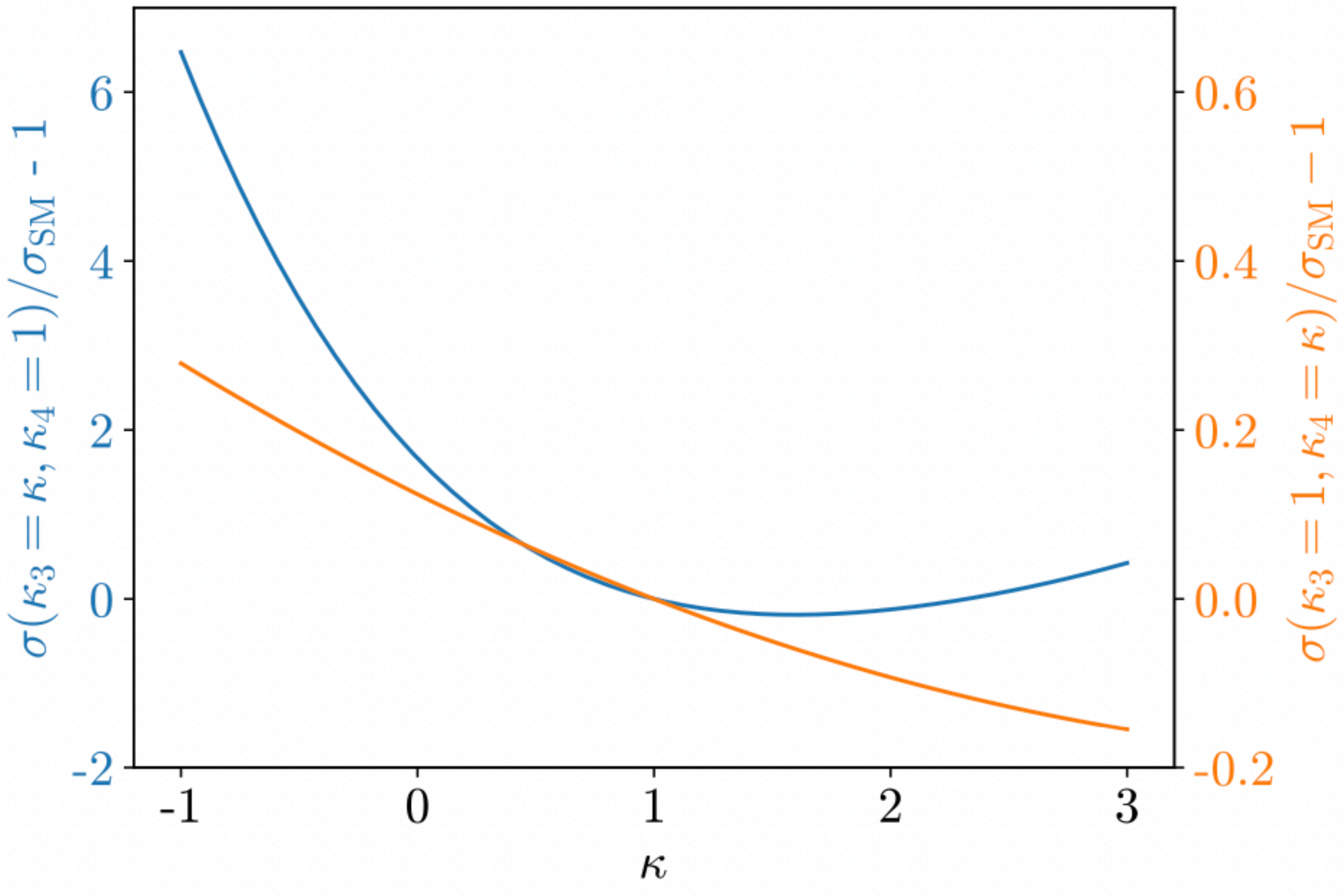
trilinear sensitivity rather large

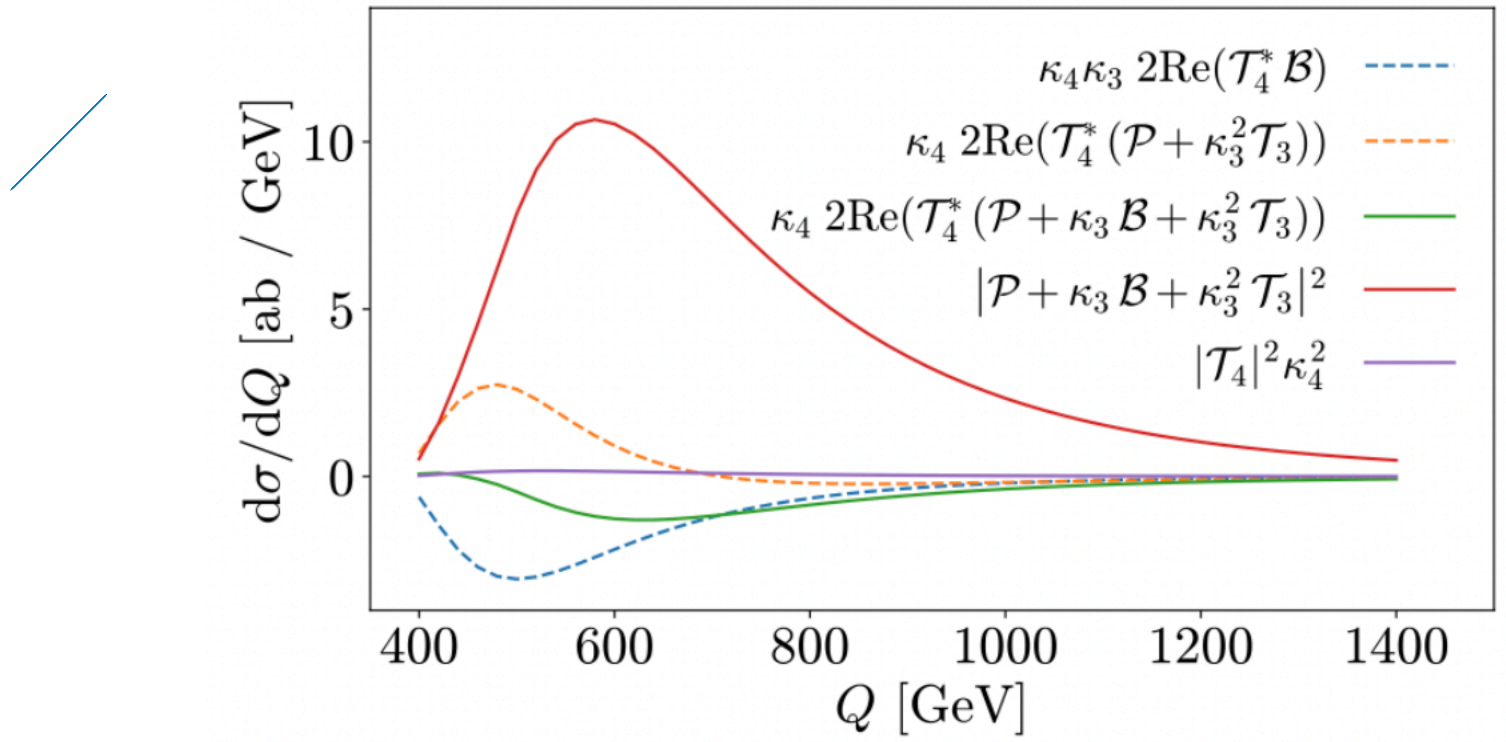
thanks to spoiling of the cancellation effects

HHH signal phenomenology

back-up







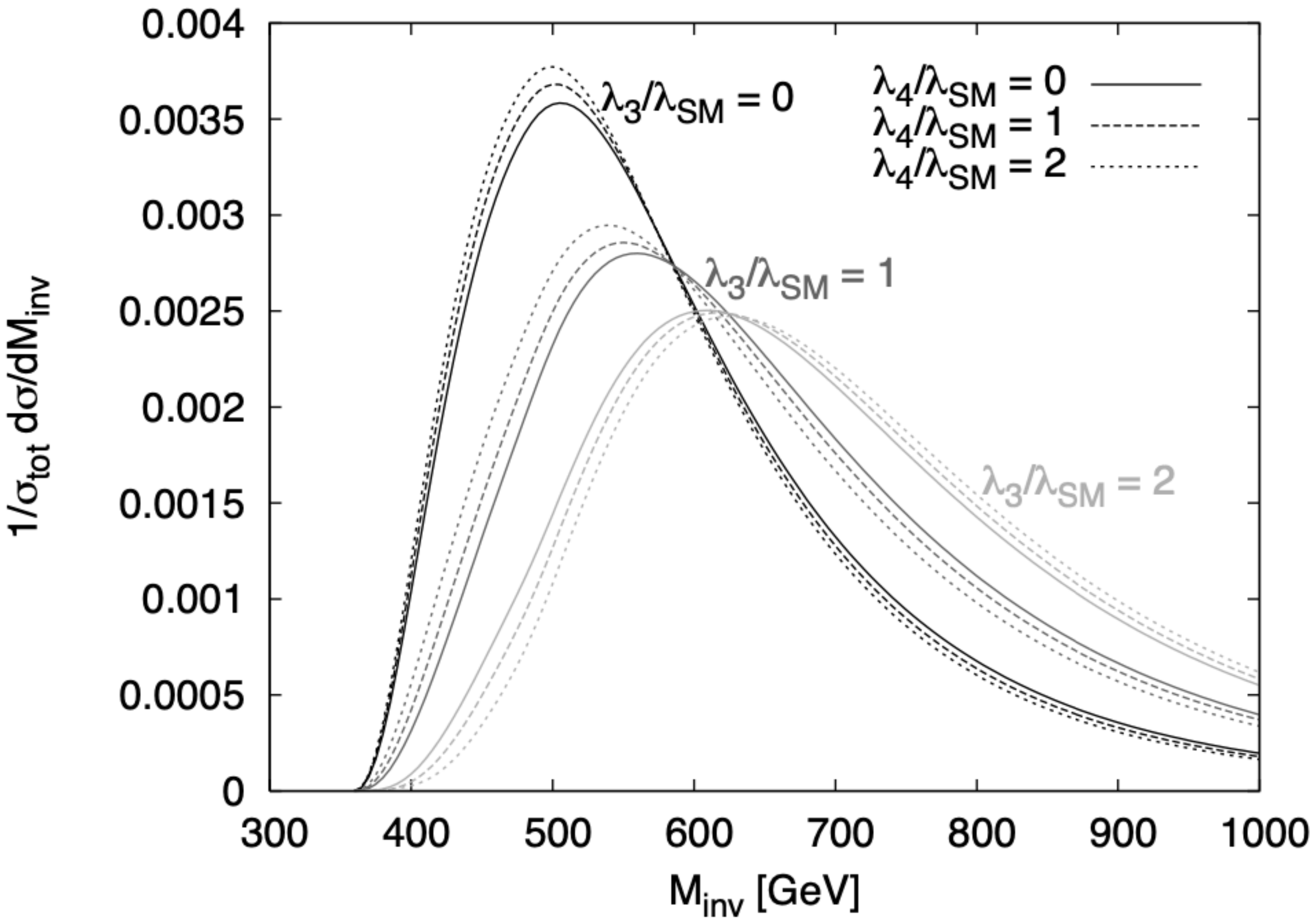
quartic sensitivity when P and B are smallest:
production threshold (low mHHH) and high tails (large mHHH)

trilinear sensitivity rather large

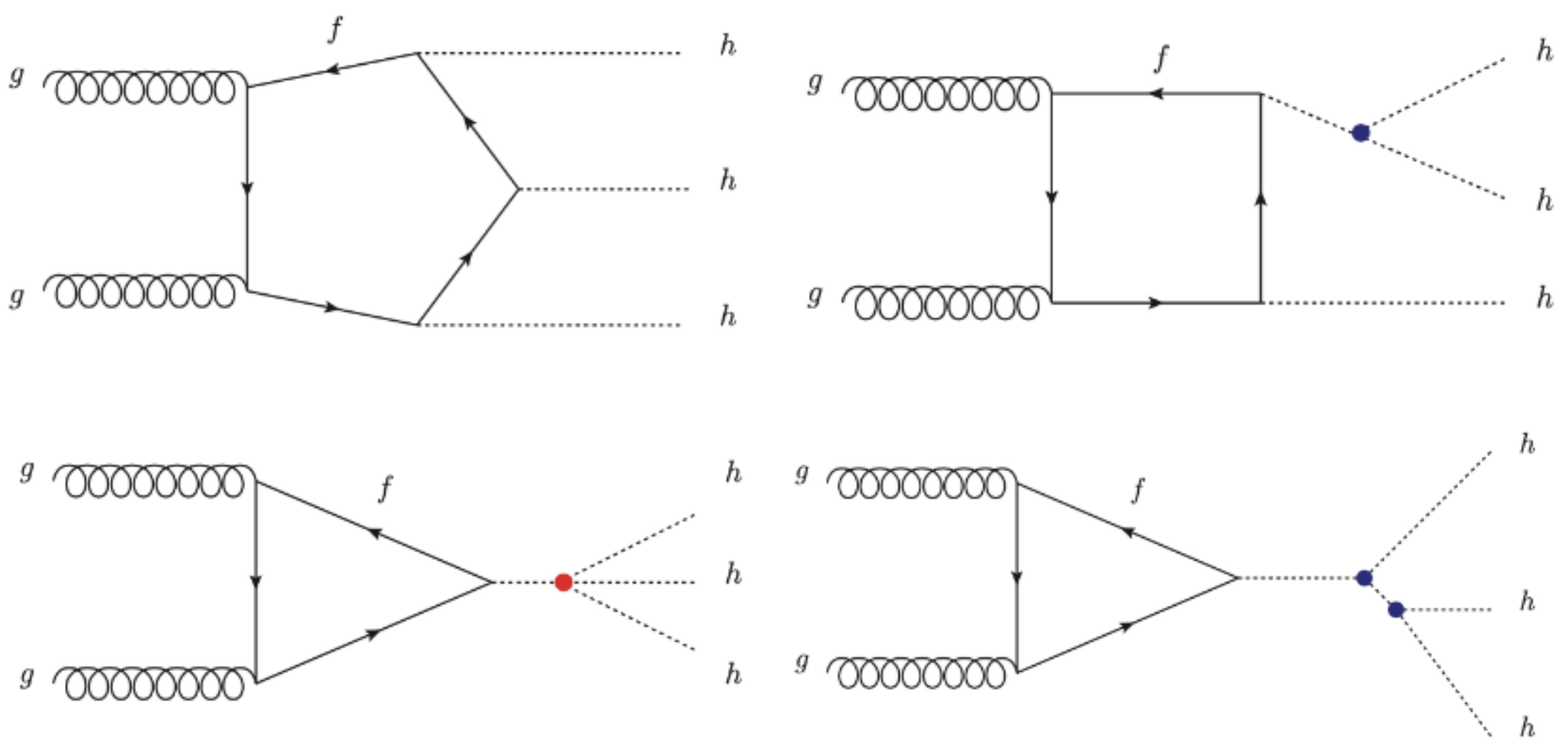
thanks to spoiling of the cancellation effects

HHH signal phenomenology

m(HHH) variations as a function of tri-linear and quartic Higgs couplings



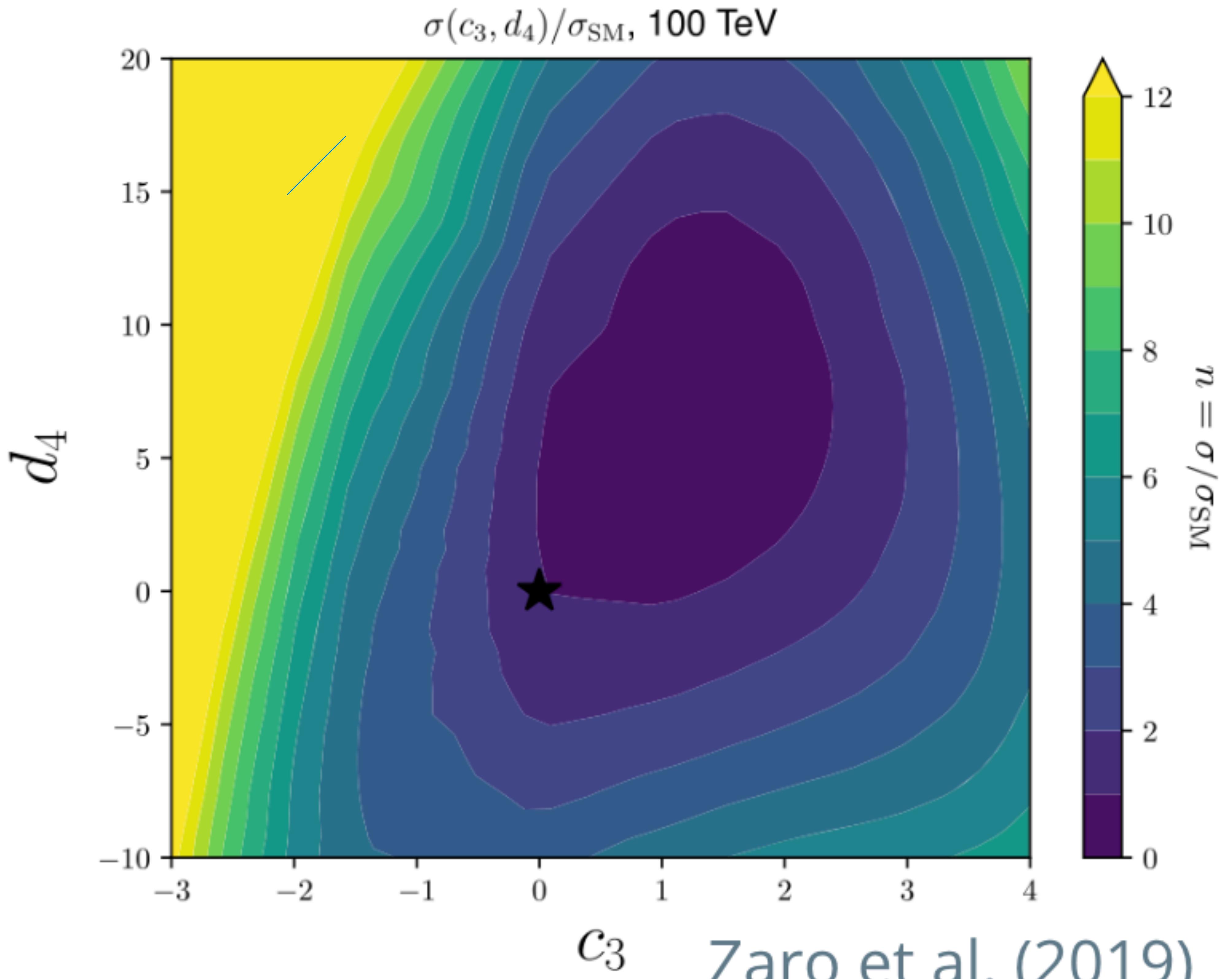
HHH signal phenomenology



$\kappa_3 = \lambda_3/\lambda_{SM}$ $\kappa_4 = \lambda_4/\lambda_{SM}$

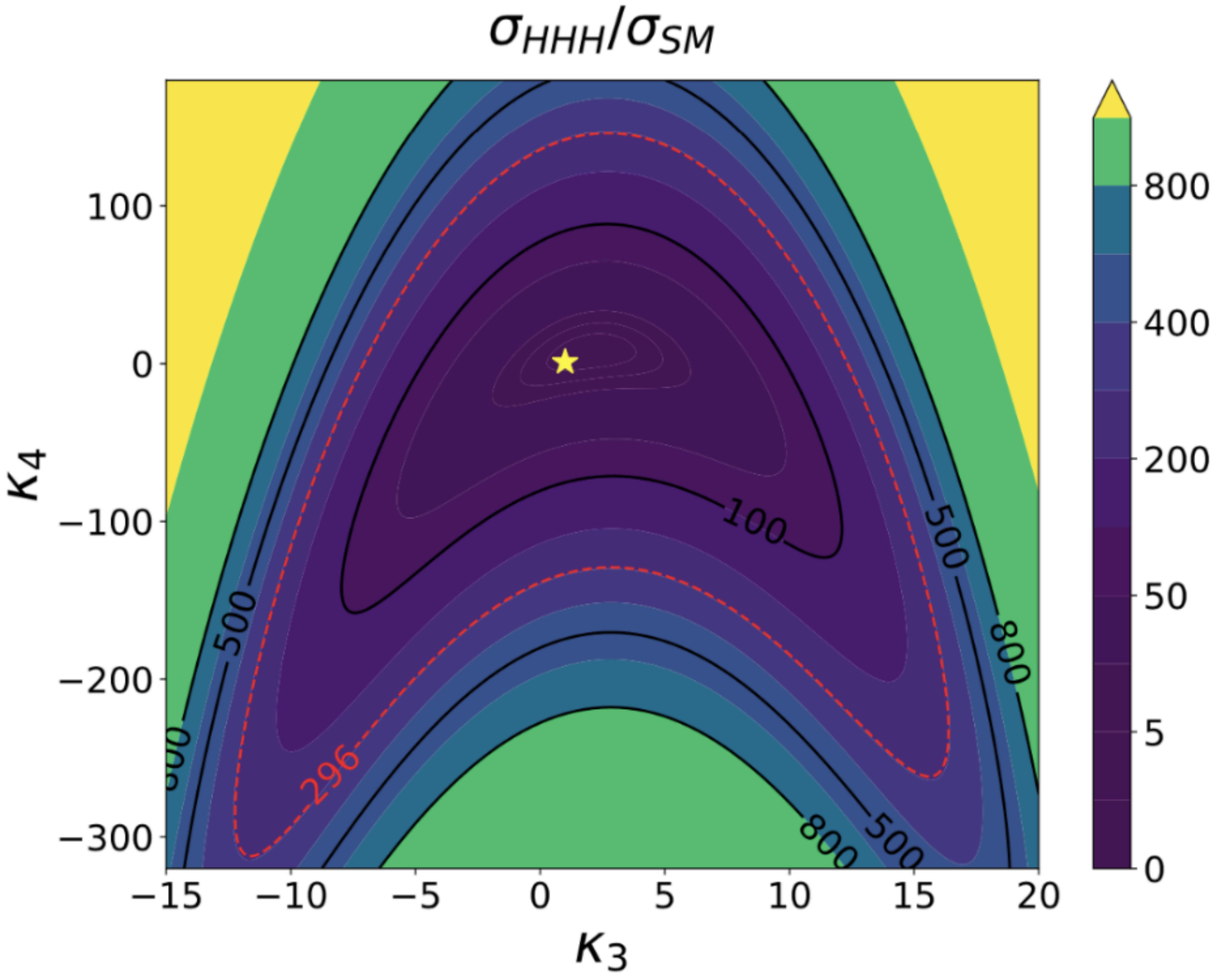
SM σ_{HHH} @ 13 TeV ~ 0.1 fb (NNLO)

So far only studied in literature at 100 TeV colliders: we want to investigate it in Run-2 and Run-3



Zaro et al. (2019)

How does σ_{HHH}/σ_{SM} change?



Analytical formula $\sigma_{HHH}(\kappa_3, \kappa_4)/\sigma_{SM}$:

$$\frac{\sigma_{HHH}}{\sigma_{SM}} = 1 + 0.0309\,\kappa_3^4 - 0.2079\kappa_3^3 + 0.0407\kappa_3^2\kappa_4 + 0.7384\kappa_3^2 + 0.0156\kappa_4^2 - 0.01450\kappa_3\kappa_4 - 0.1078\kappa_4 - 0.6887\kappa_3$$

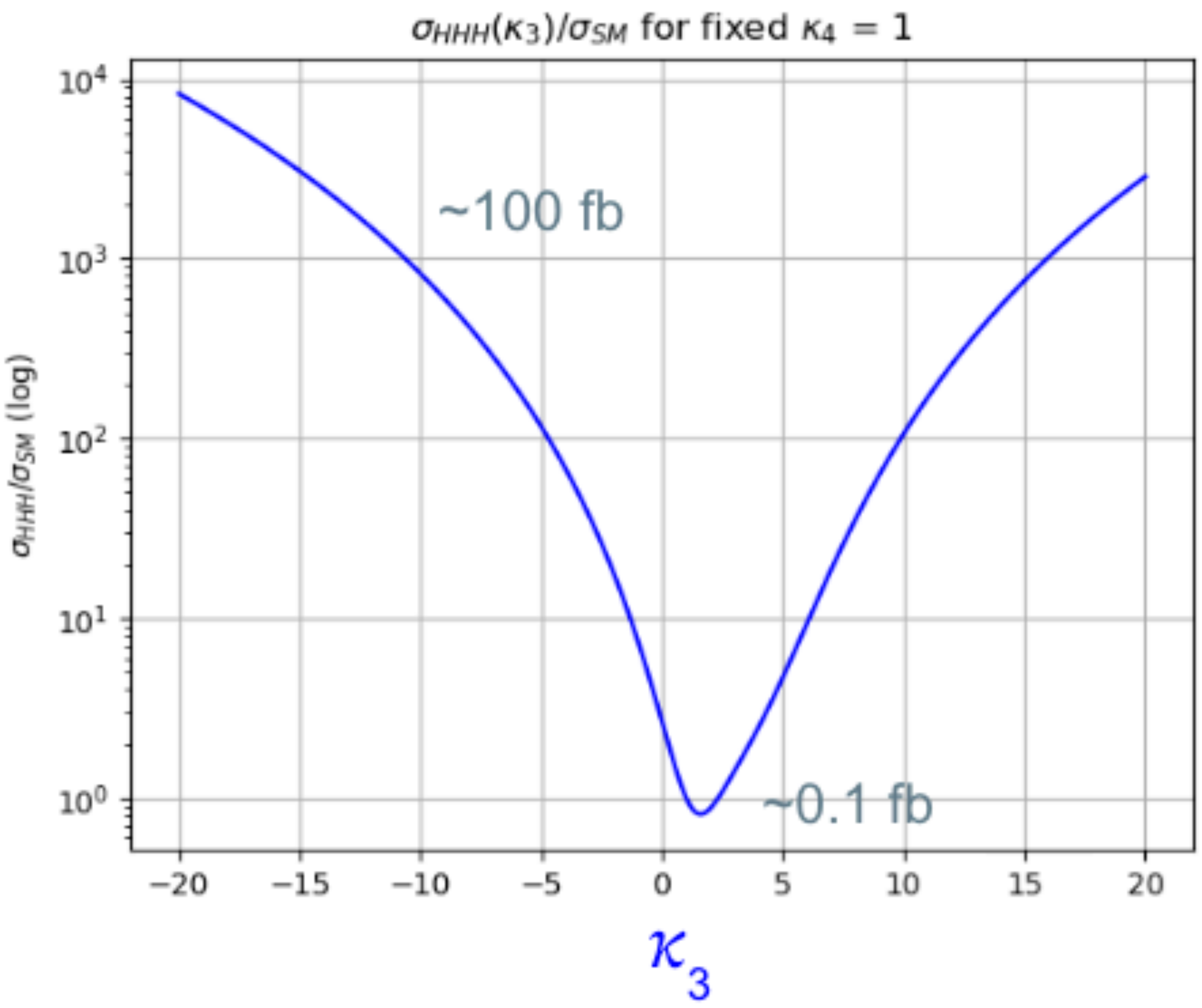
- κ_3: $\mathcal{O}$(10-20)
- κ_4: $\mathcal{O}$(100-200)

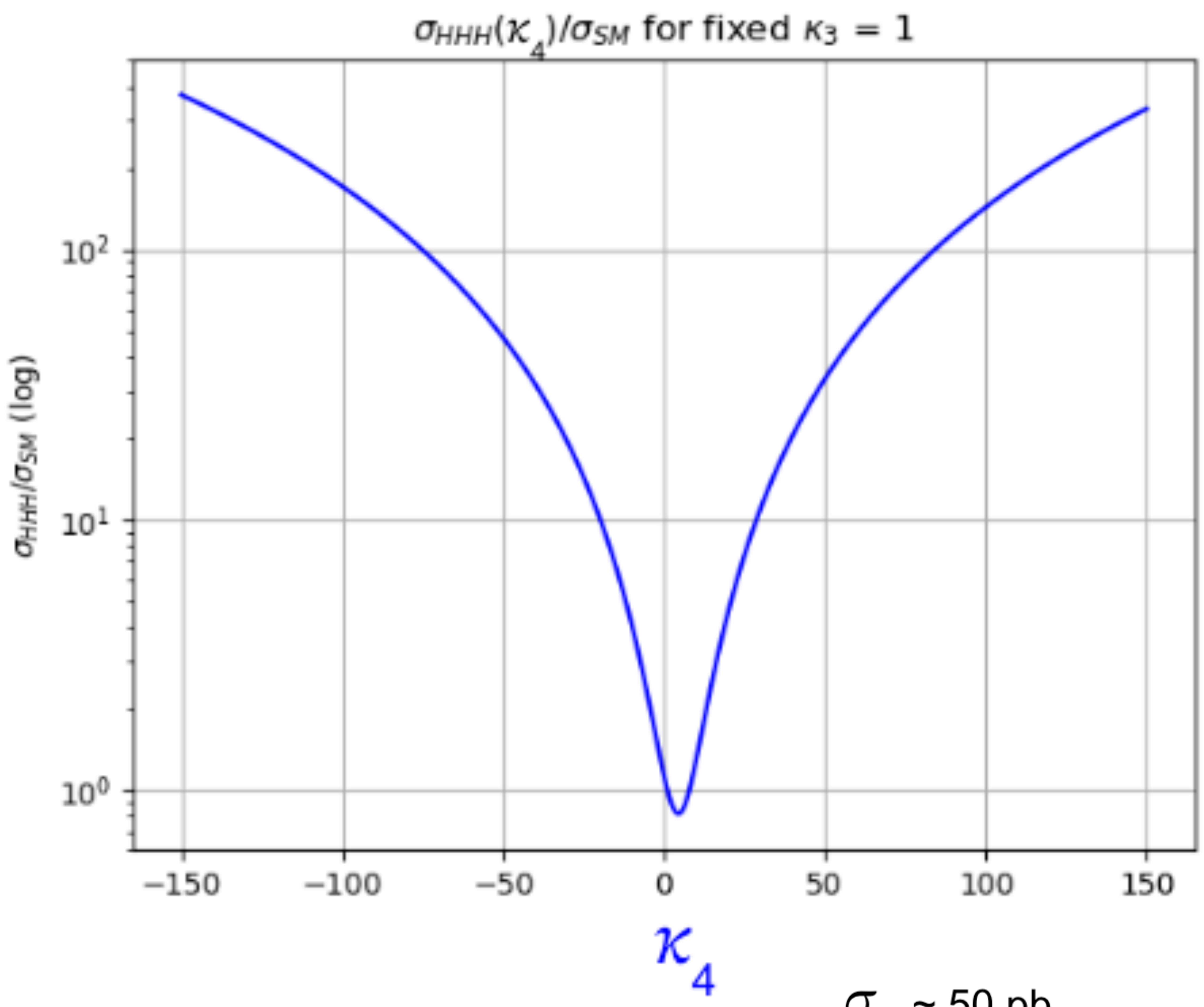
σ_{HHH} up to ~ 30 fb
(close to HH production)

Zaro et al. (2019)

HHH signal phenomenology

back-up

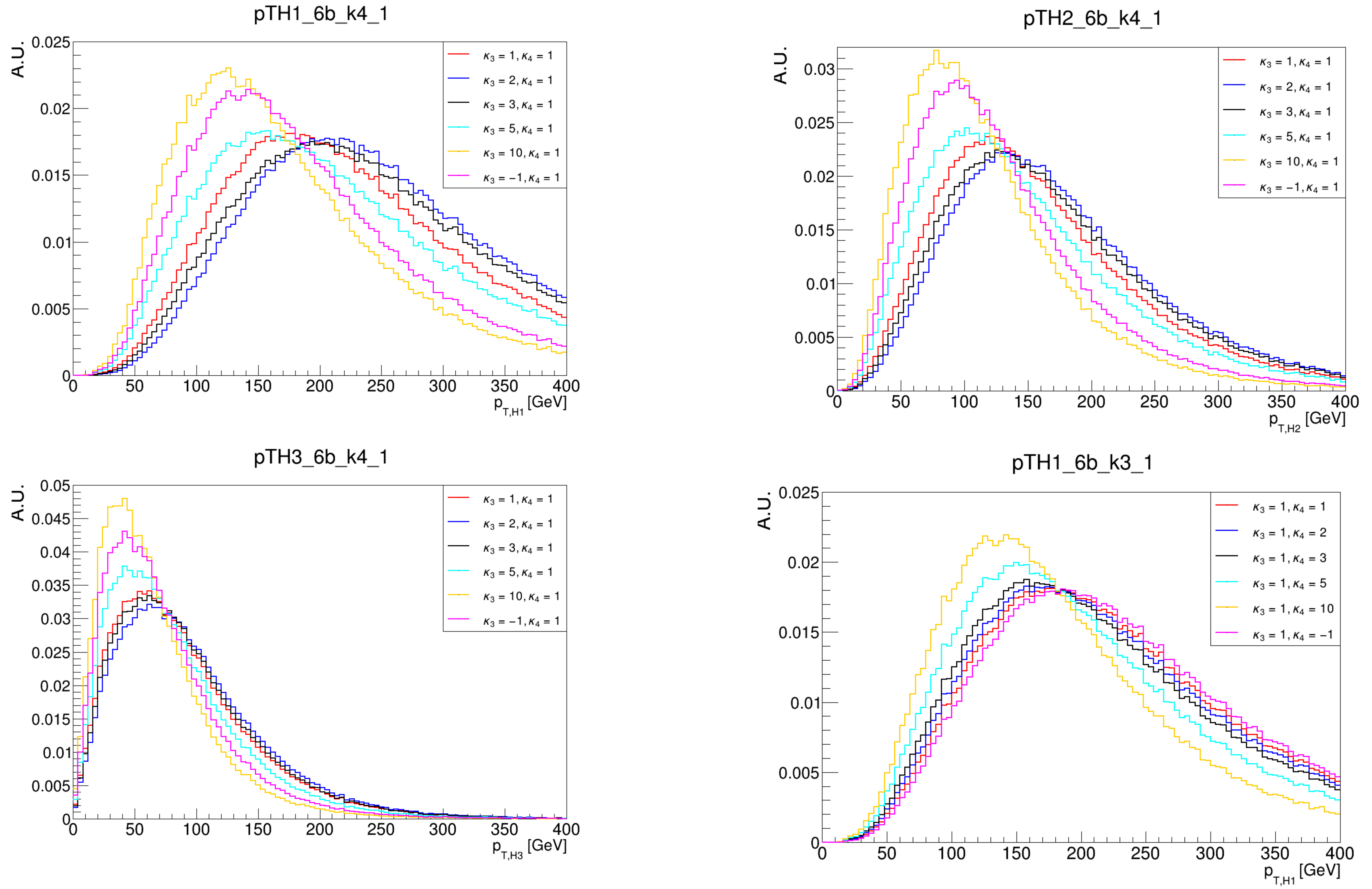




σ_H ~ 50 pb
σ_{HH} ~ 30 fb
σ_{HHH} ~ 0.1 fb

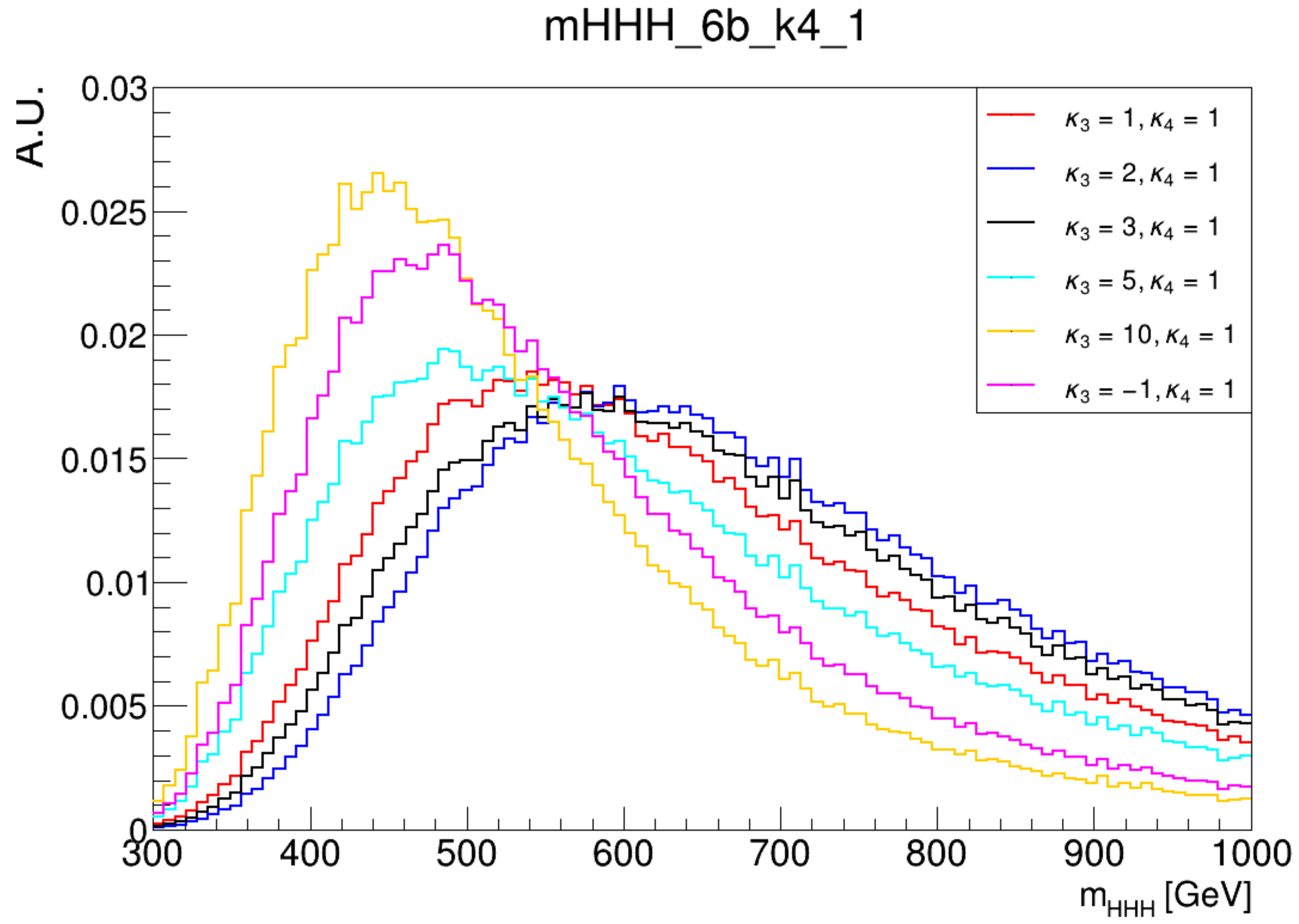
HHH signal phenomenology

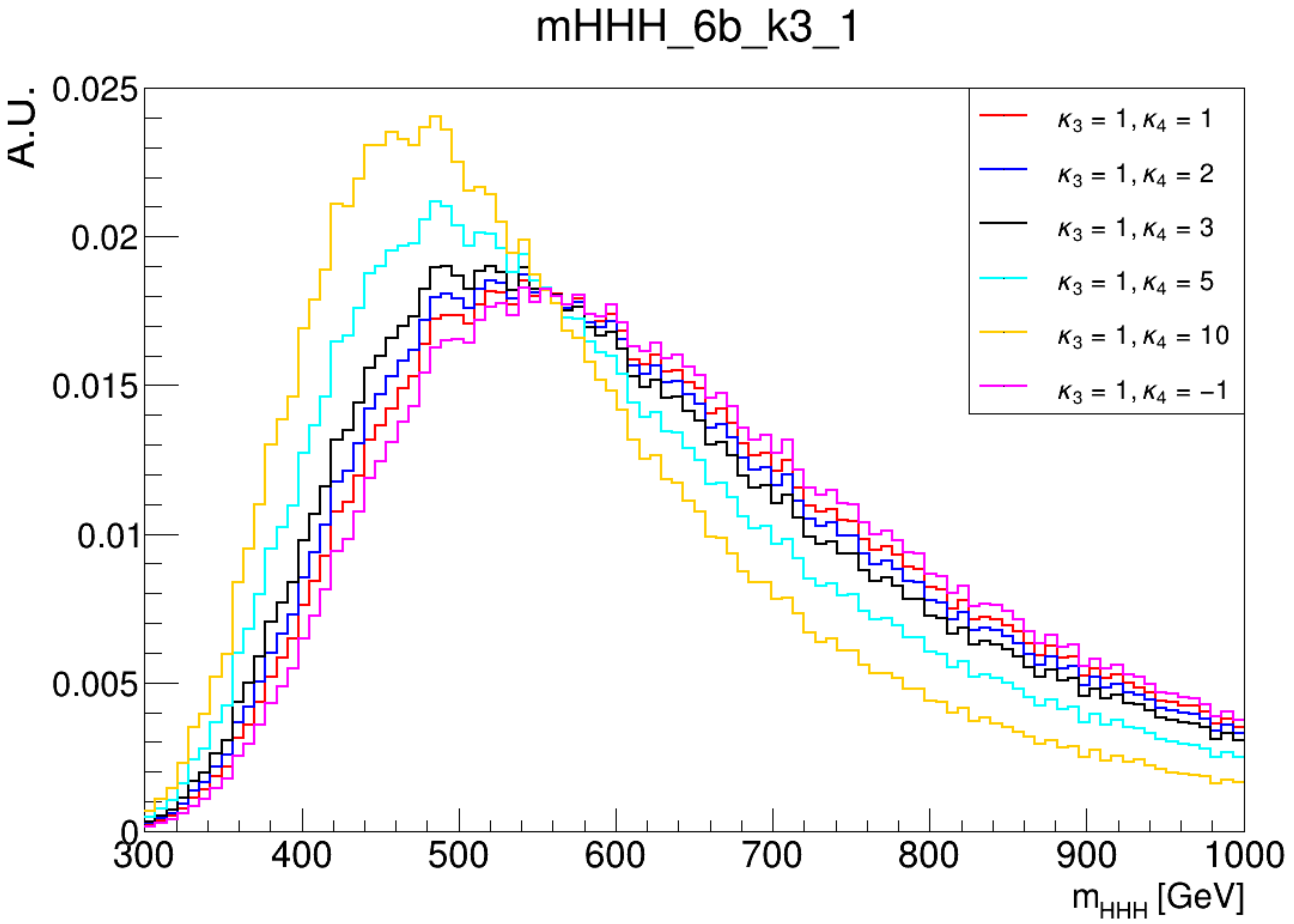
back-up



HHH signal phenomenology

back-up

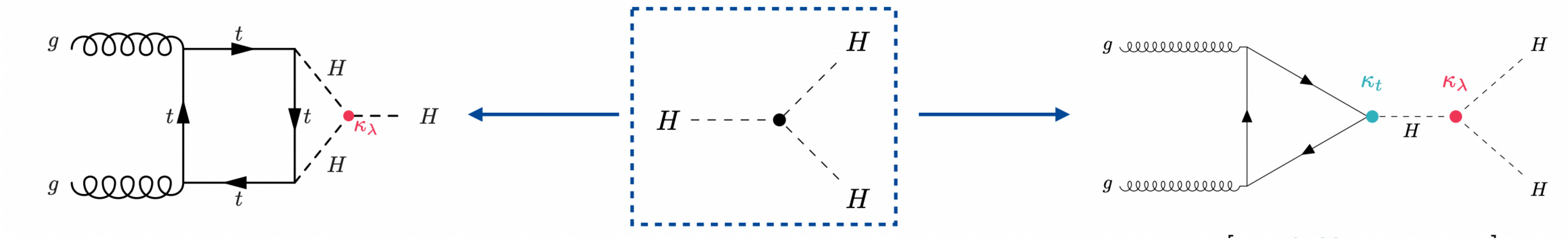




Zoom: single-H sensitivity to self-couplings

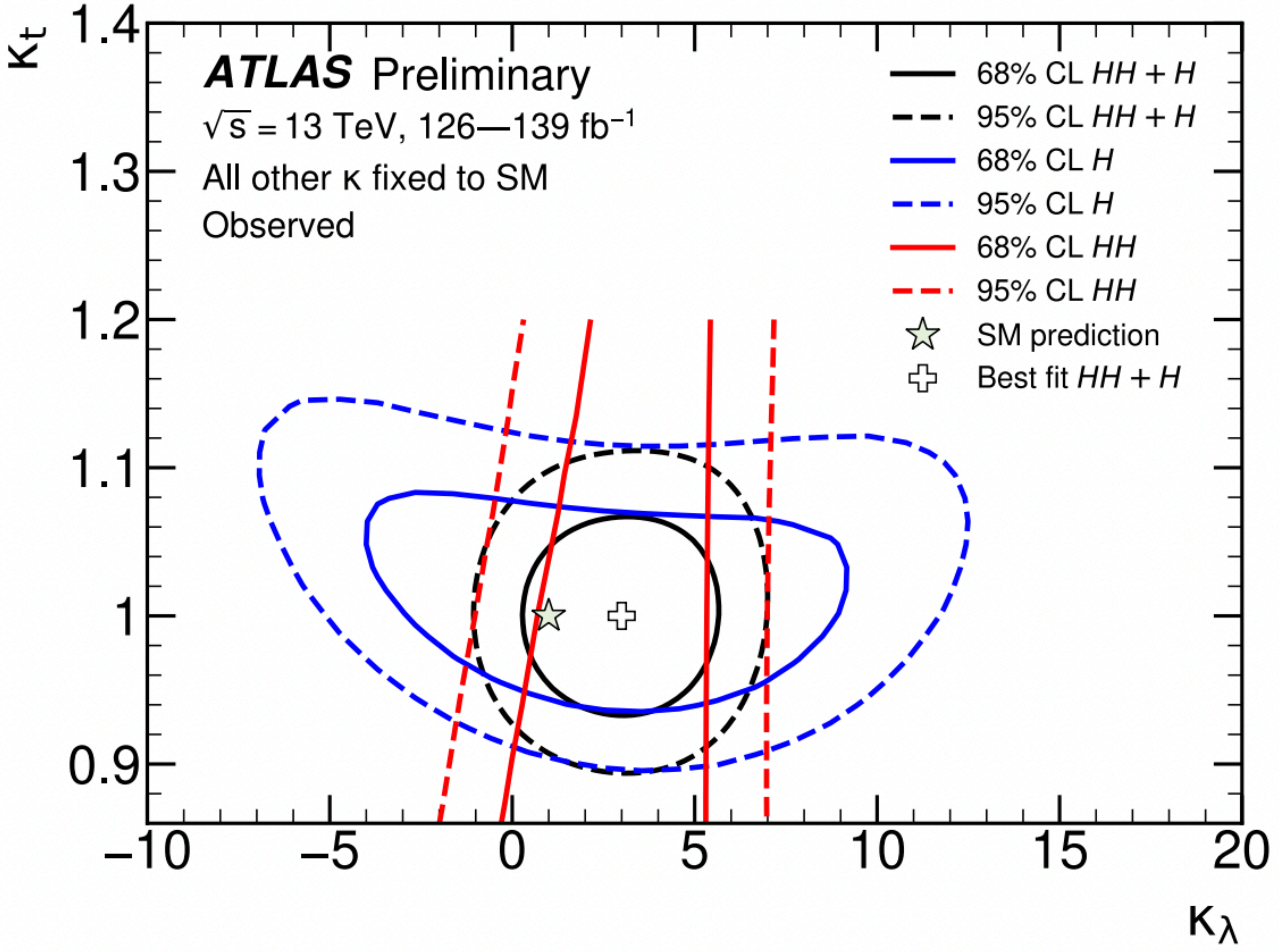
Self-couplings through single-H corrections

back-up



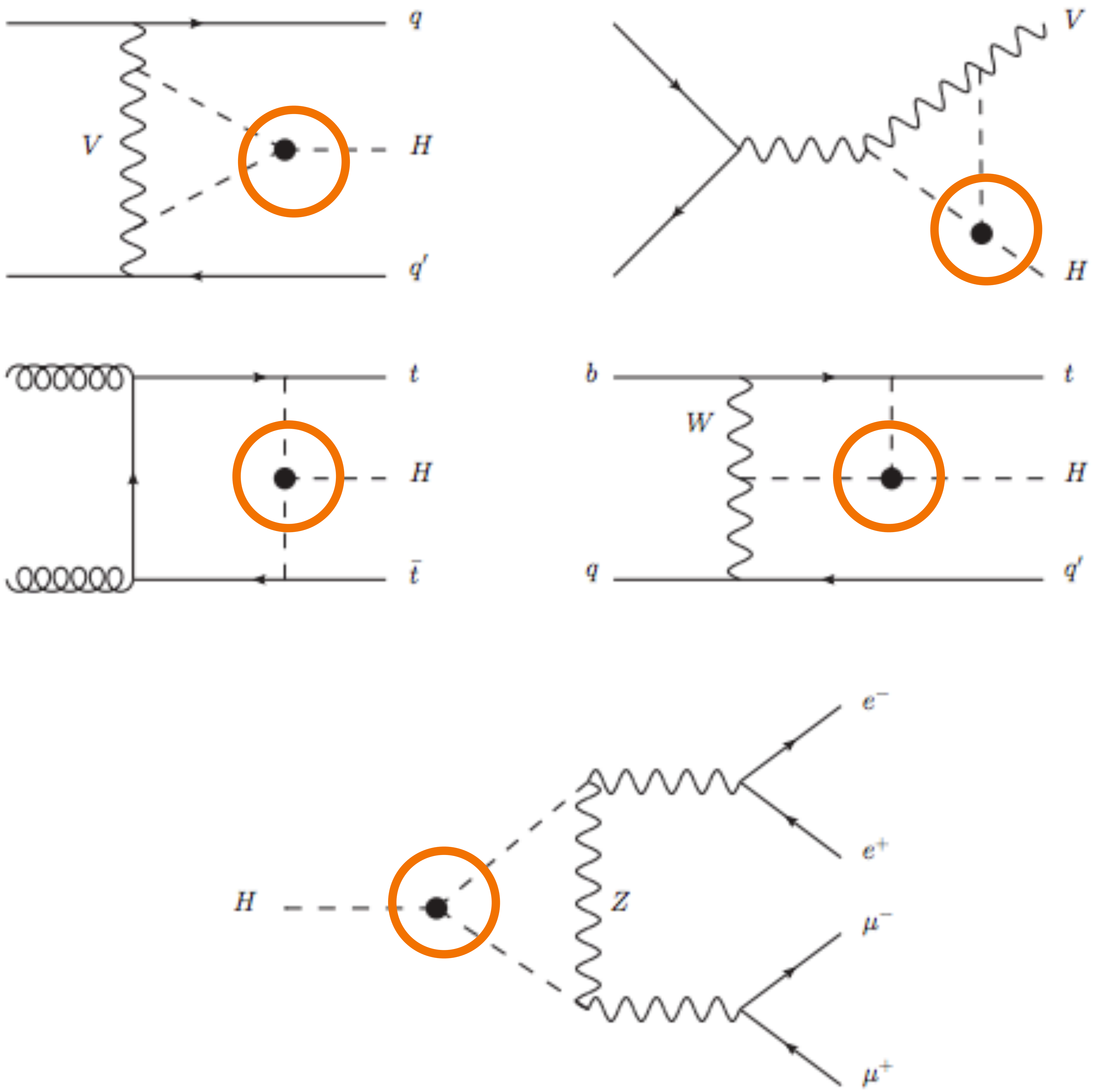
- higher order EW diagrams make single-H boson processes also dependent on the Higgs boson self coupling lambda
- combination of both H and HH (and HHH?) measurements allows to put stringent limits on lambda, while at the same time relaxing assumptions about other Higgs couplings (e.g. top-Higgs couplings in particular)

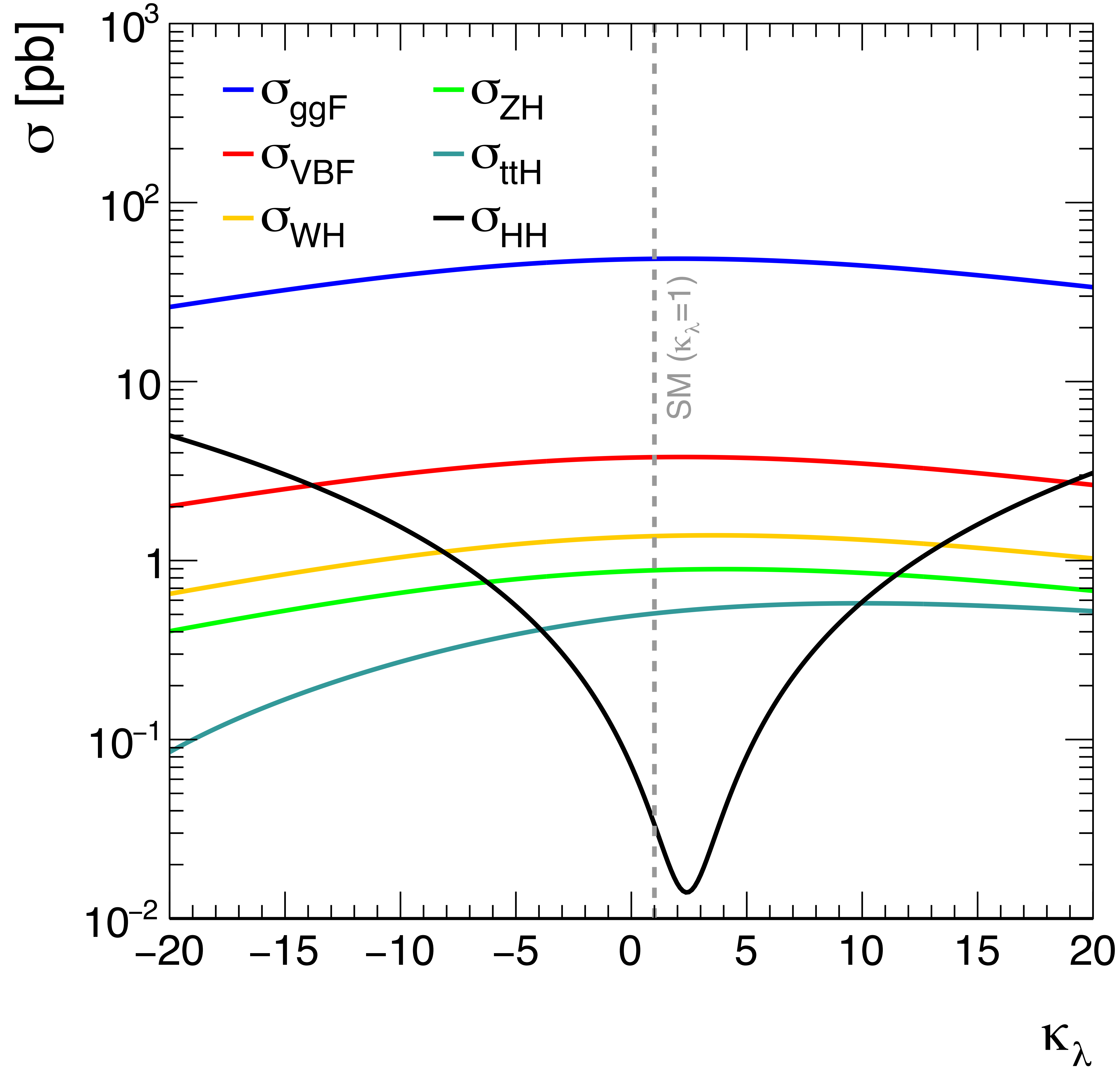
[ATLAS-CONF-2022-050]



Self-couplings through single-H corrections

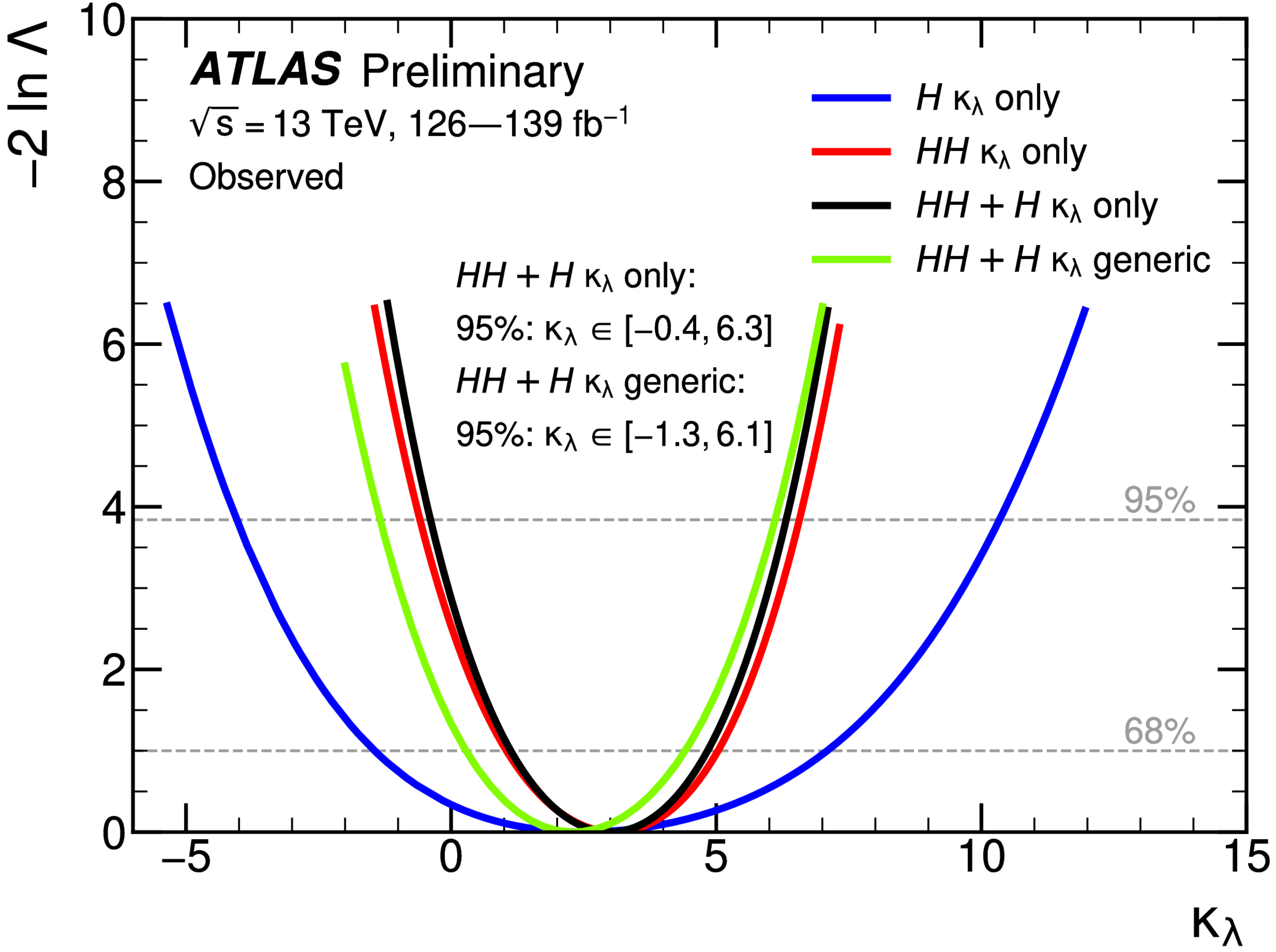
Indirect sensitivity to Higgs self-couplings - tiny effects up to O(5%) - but lots of single-H events produced at LHC !





Self-couplings through single-H corrections

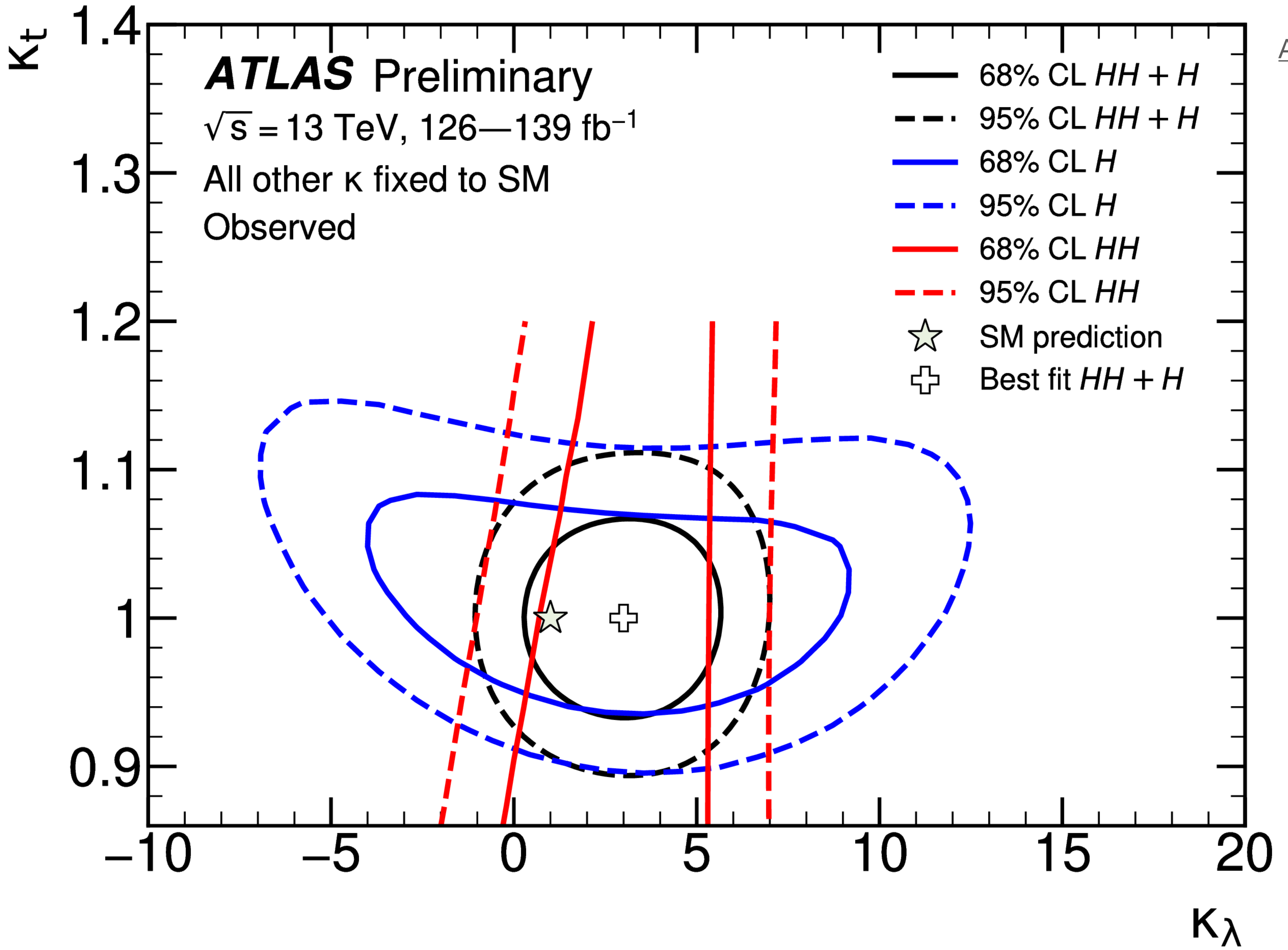
Di-Higgs analysis channels currently combined ⊕ **Single-Higgs results from Nature paper**



ATLAS-CONF-2022-050

Self-couplings through single-H corrections

Di-Higgs analysis channels currently combined ⊕ **Single-Higgs results from Nature paper**



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Self-couplings through single-H corrections

back-up

Di-Higgs analysis channels currently combined ⊕ **Single-Higgs results from Nature paper**

Combination assumption	Obs. 95% CL	Exp. 95% CL	Obs. value$^{+1\sigma}_{-1\sigma}$
HH combination	$-0.6 < \kappa_\lambda < 6.6$	$-2.1 < \kappa_\lambda < 7.8$	$\kappa_\lambda = 3.1^{+1.9}_{-2.0}$
Single-H combination	$-4.0 < \kappa_\lambda < 10.3$	$-5.2 < \kappa_\lambda < 11.5$	$\kappa_\lambda = 2.5^{+4.6}_{-3.9}$
HH+H combination	$-0.4 < \kappa_\lambda < 6.3$	$-1.9 < \kappa_\lambda < 7.5$	$\kappa_\lambda = 3.0^{+1.8}_{-1.9}$
HH+H combination, κ_t floating	$-0.4 < \kappa_\lambda < 6.3$	$-1.9 < \kappa_\lambda < 7.6$	$\kappa_\lambda = 3.0^{+1.8}_{-1.9}$
HH+H combination, κ_t, κ_V, κ_b, κ_τ floating	$-1.3 < \kappa_\lambda < 6.1$	$-2.1 < \kappa_\lambda < 7.6$	$\kappa_\lambda = 2.3^{+2.1}_{-2.0}$

ATLAS-CONF-2022-050

Higgs trilinear self-interaction parameter constrained

$-0.4 < k_\lambda < 6.3$ [most-stringent]

$-1.3 < k_\lambda < 6.1$ [most-general]

Self-couplings through single-H corrections

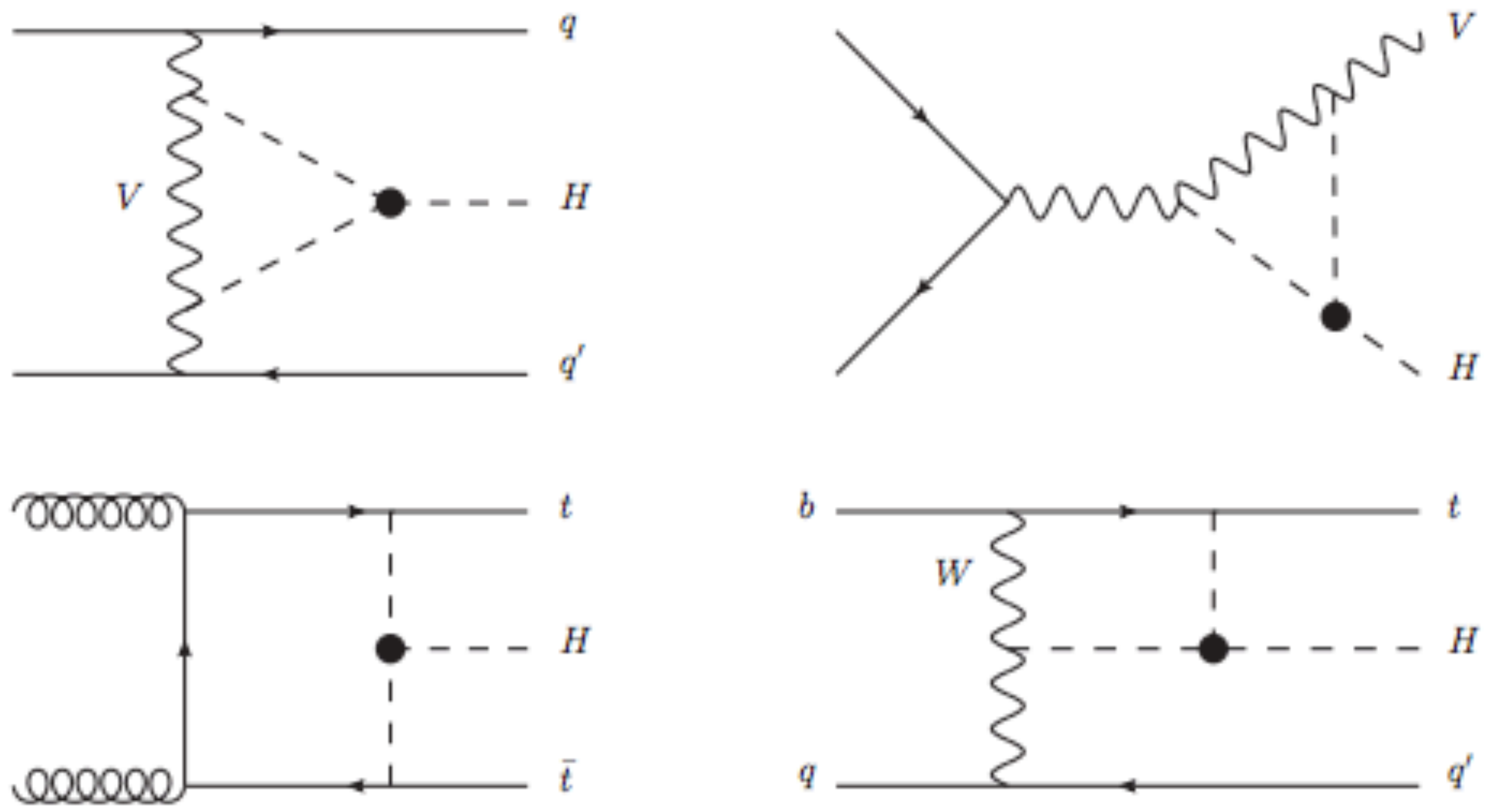
Higgs potential

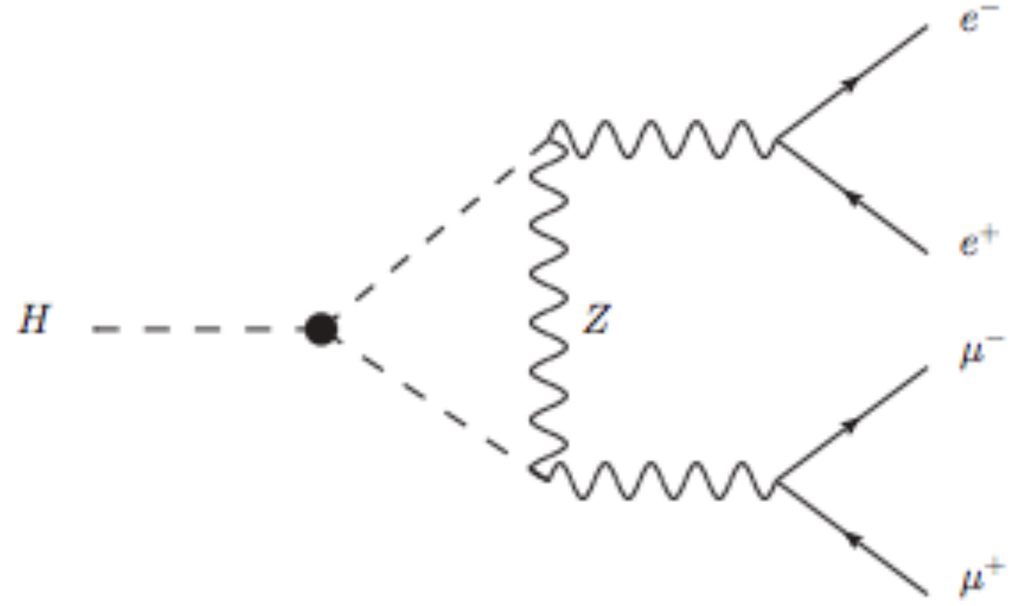
$$V(H) = \frac{1}{2}m_H^2 H^2 + \lambda_3 v H^3 + \frac{1}{4}\lambda_4 H^4 + O(H^5),$$

$\lambda_3^{\mathrm{SM}} = \lambda_4^{\mathrm{SM}} \simeq 0.13$

$$V^{\mathrm{SM}}(\Phi) = -\mu^2(\Phi^\dagger\Phi) + \lambda(\Phi^\dagger\Phi)^2$$

- sensitivity to Higgs tri-linear coupling from (1) direct HH measurements, or (2) NLO EW corrections to single-H production





Single-H XS parametrised as function of tri-linear coupling modifications

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

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

1. universal $O(\lambda_3^2)$ correction from wave function renormalisation, encoded in Z_H^{BSM}
2. process and kinematic dependent $O(\lambda_3)$ linear correction from above type of diagram, encoded in **C1 coefficients**

- **$k_\lambda = \lambda_3 / \lambda_3^{SM}$**

- paper Maltoni et al., 2016
- paper Maltoni et al., 2018
- ATLAS CONF 2019
- ATLAS PUB 2019

Self-couplings through single-H corrections

- **C1** :process and kinematic dependent O(λ_3) linear correction, from interference between LO amplitude and NLO EW λ_3 corrections
- evaluated through MG5 HiggsSelfCoupling tools

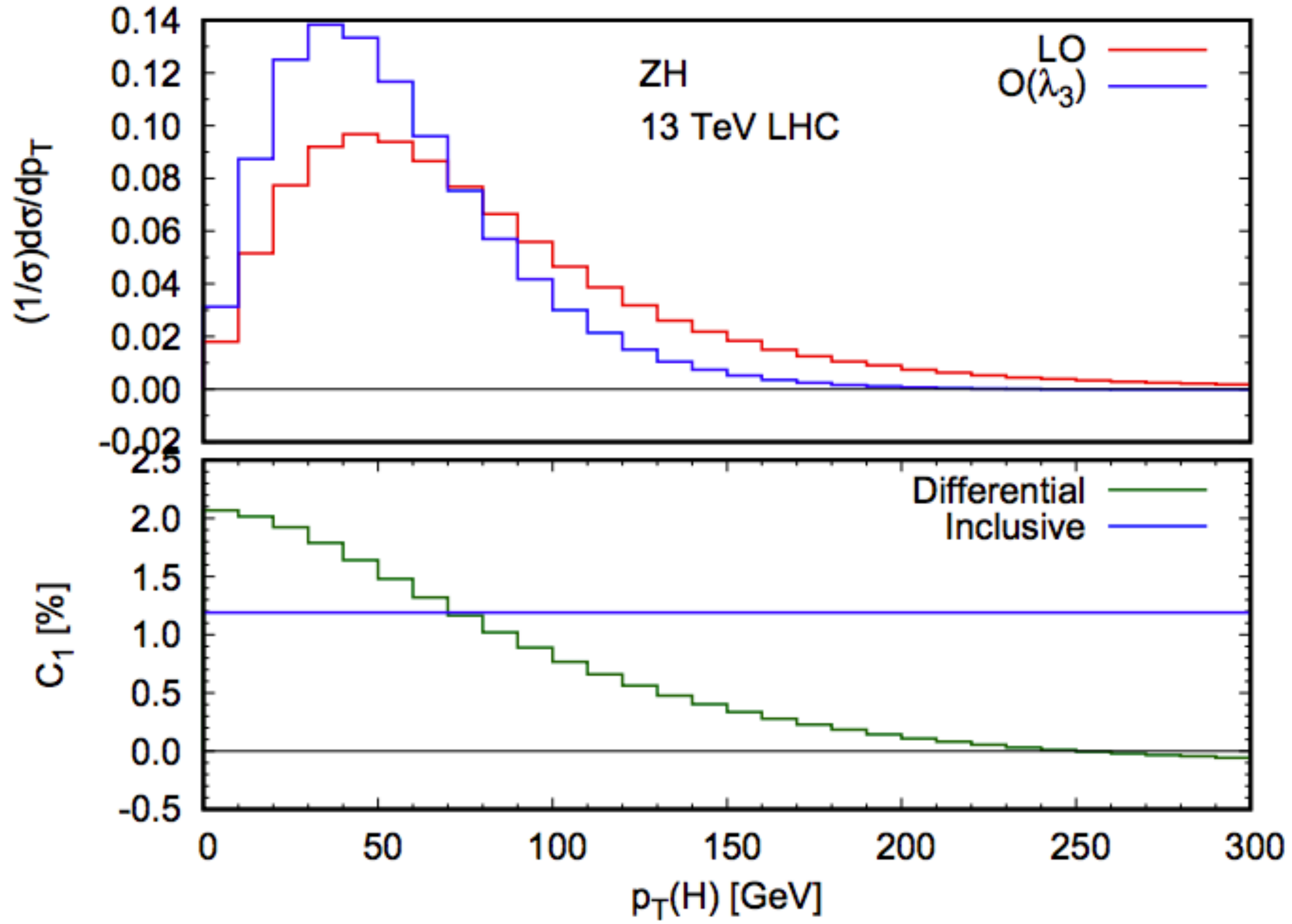
$$\mu_i(\kappa_\lambda, \kappa_i) = \frac{\sigma^{\rm BSM}}{\sigma^{\rm SM}} = Z_H^{\rm BSM}(\kappa_\lambda)\left[\kappa_i^2 + \frac{(\kappa_\lambda - 1)C_1^i}{K_{\rm EW}^i}\right]$$

$$C_1(p_i) \equiv w_i = \frac{2\Re(\mathcal{M}^{0*}\mathcal{M}^1_{\lambda_3^{\rm SM}})}{|\mathcal{M}^0|^2}$$

signal strength as a function of k_λ :
C1 coefficients encode the sensitivity of the measurement to k_λ

Small correction to the total rate, but sizable effect on kinematic: key to account for differential effects ...

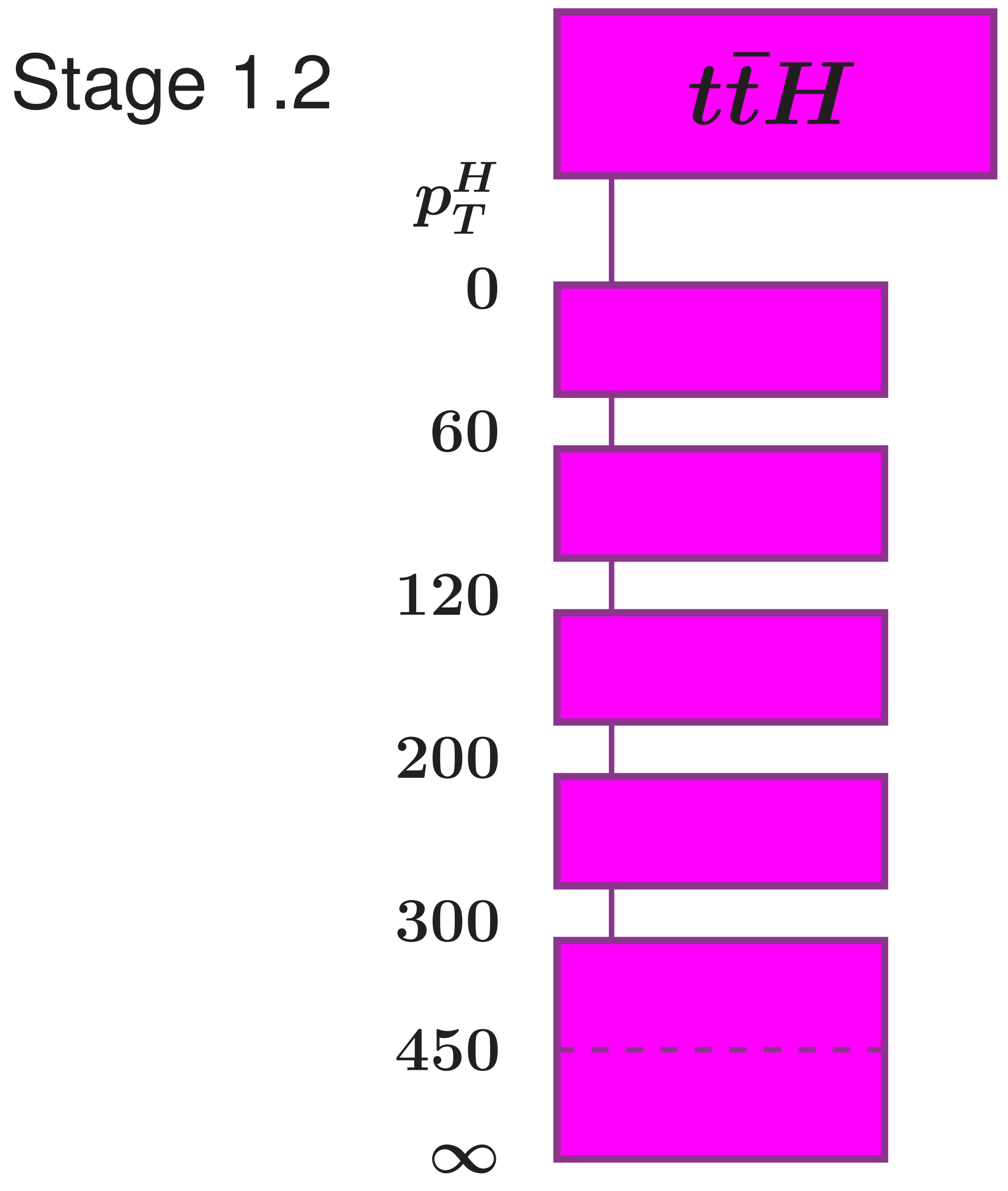
already the case in past ATLAS results (2019, partial Run-2 stat) with first STXS bin measurements

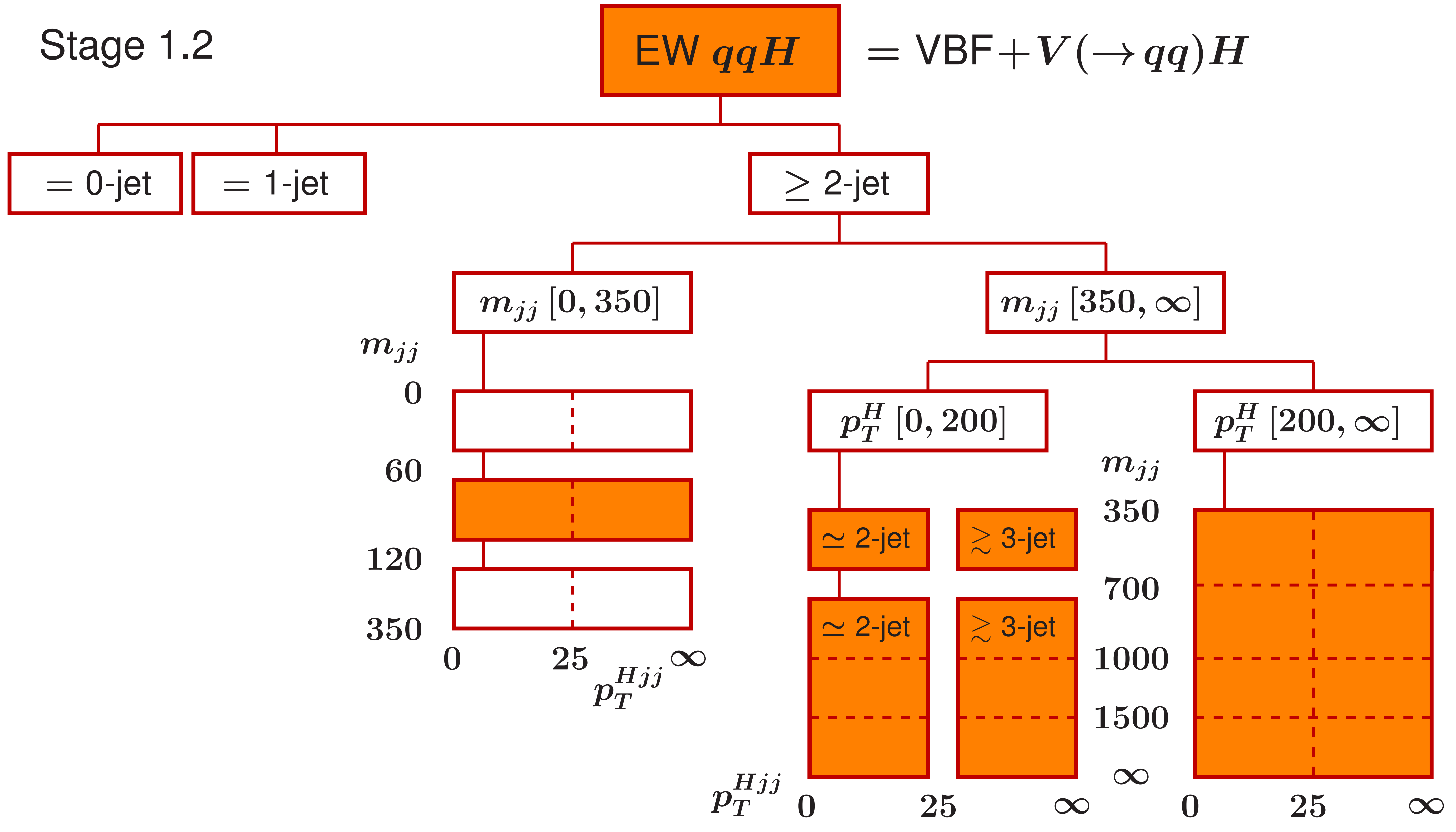


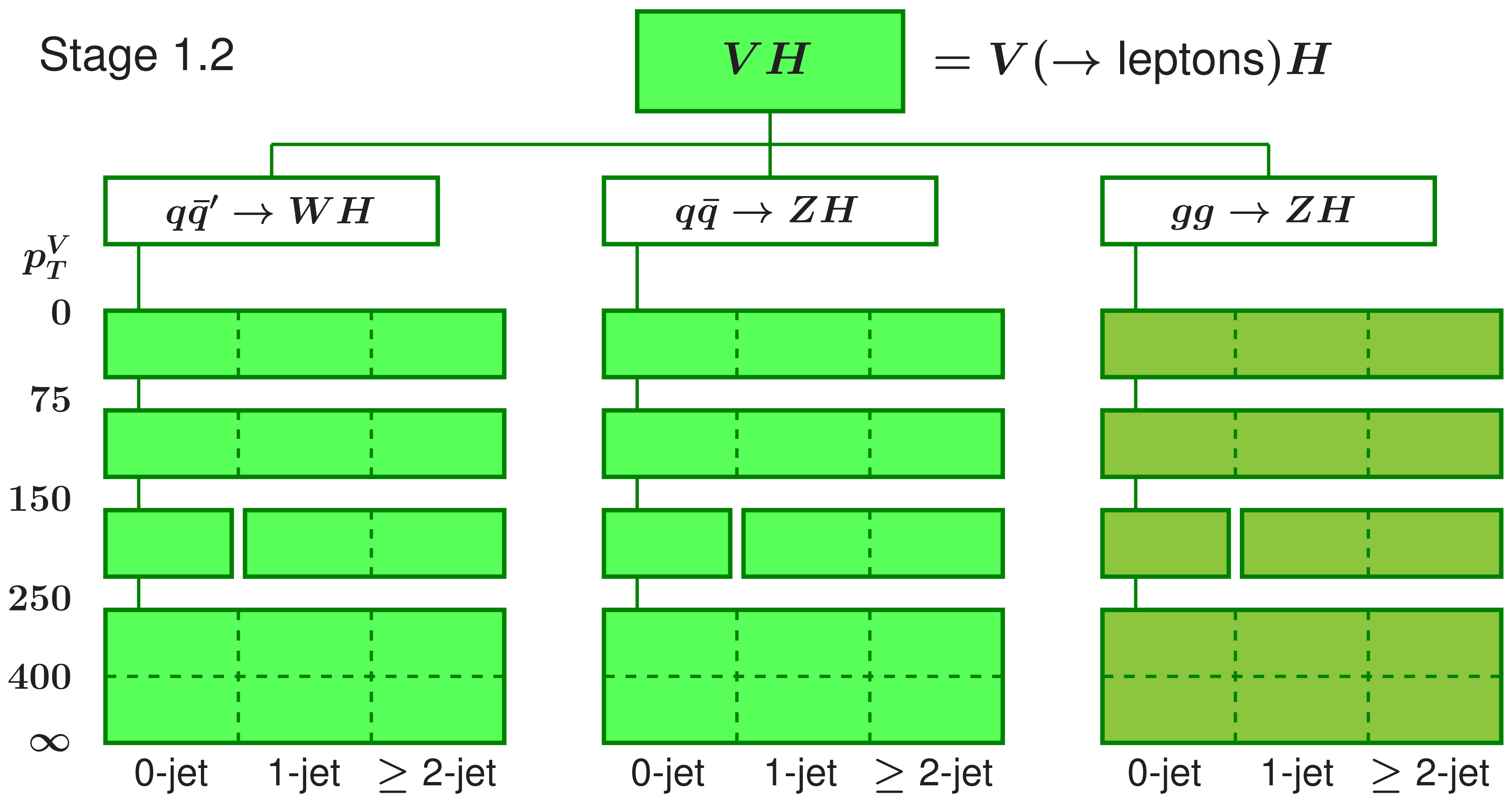
Self-couplings through single-H corrections

Gain from kλ measurement in the current single-H combination?

- higher statistics, all analyses with full Run-2 dataset: finer granularity STXS split
- ttH is now binned in pTH: differential information sensitive to kλ effects







Self-couplings through single-H corrections

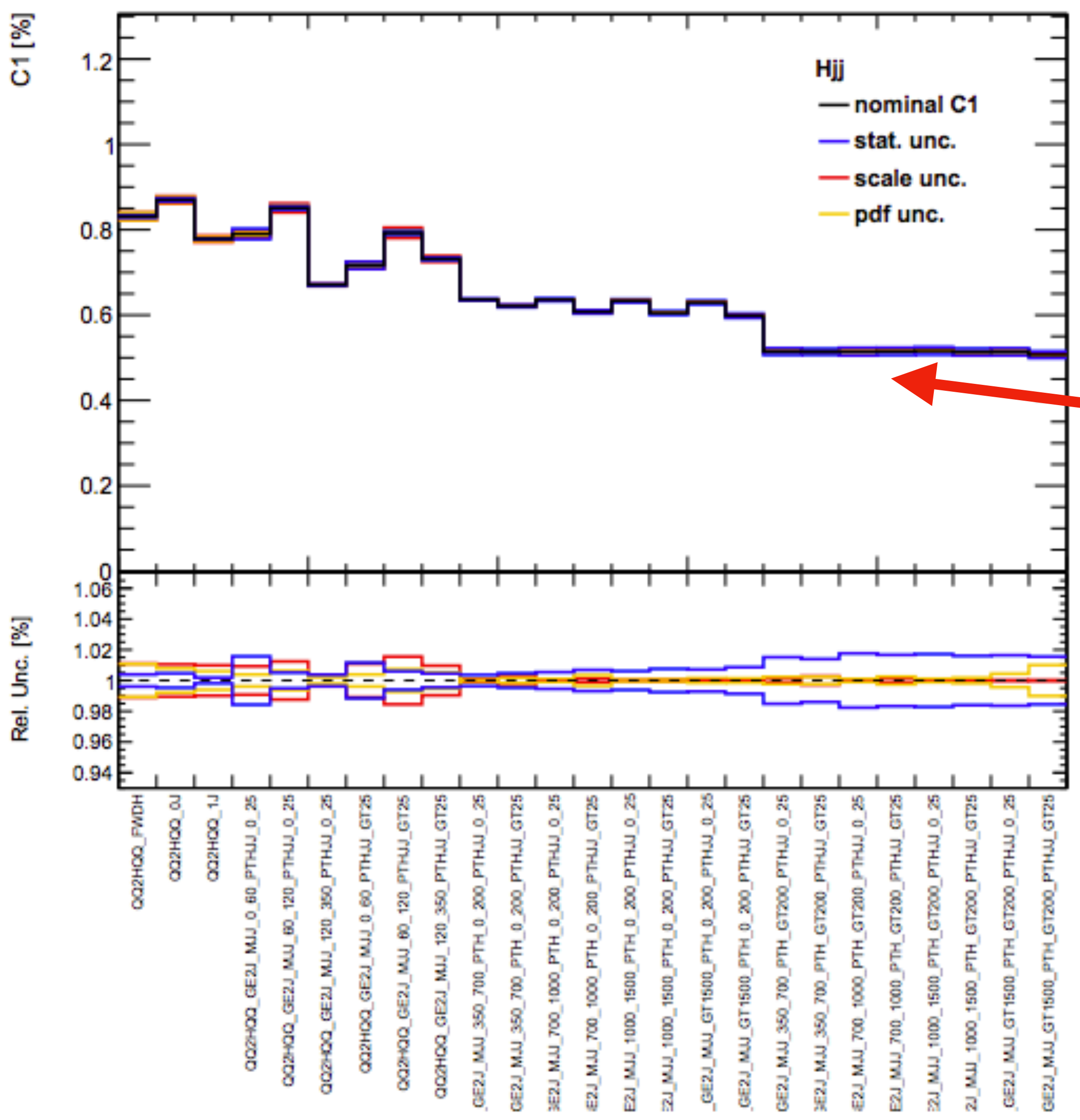
κ_λ fit relies on a parametrisation of the mu POIs from the combined workspace as functions of the self-coupling parameter

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

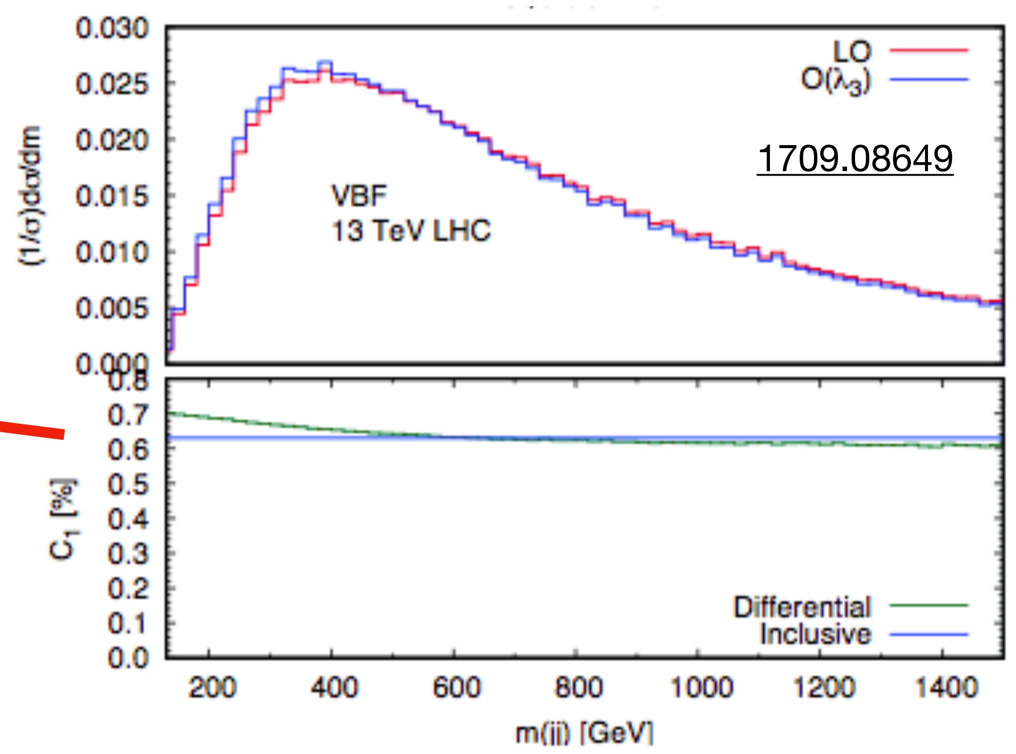
One word on the C1 coefficients:

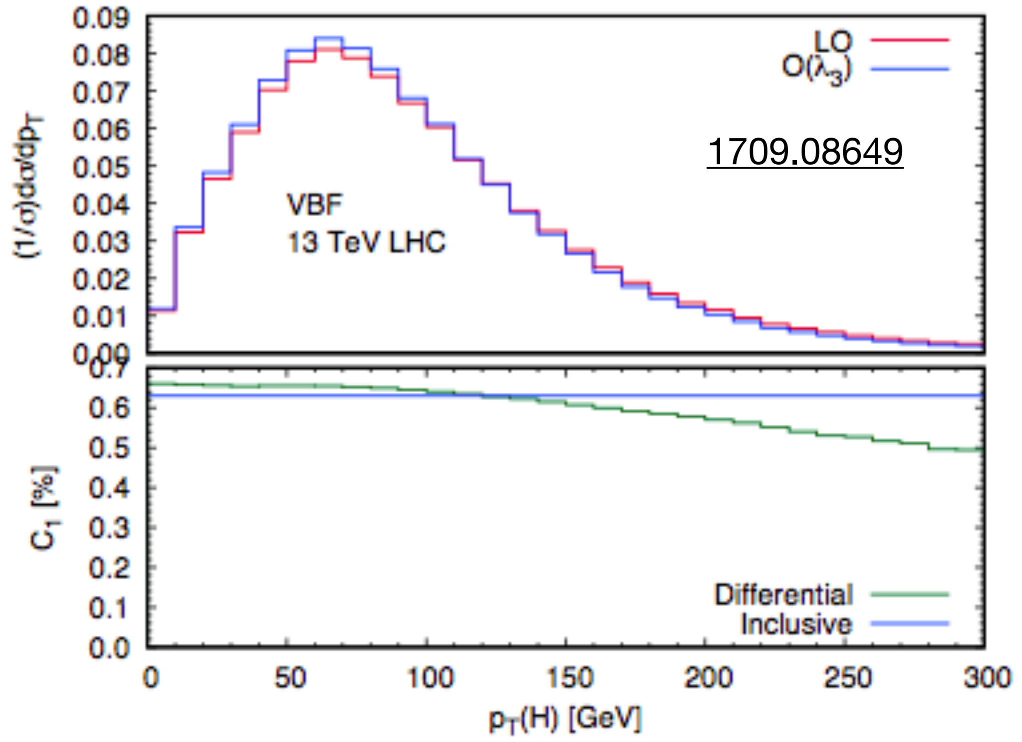
- goal is to produce a common C1 parametrisation between ATLAS and CMS
- C1 evaluated via standalone package under the hat of LHC-HXSWG2: **final validation ongoing**
  https://gitlab.cern.ch/LHCHIGGSXS/LHCHXSWG2/STXS/self-coupling-c1
  - MG5 HiggsSelfCoupling tools for LH event generation with κ_λ correction weights
  - showering independent from athena / ATLAS sw
  - STXS Rivet routine from LHC-HXSWG2 for classification
  - C1's evaluated from yoda files
- estimate of TH uncertainties (QCD scales, PDFs, shower tunes)

Self-couplings through single-H corrections

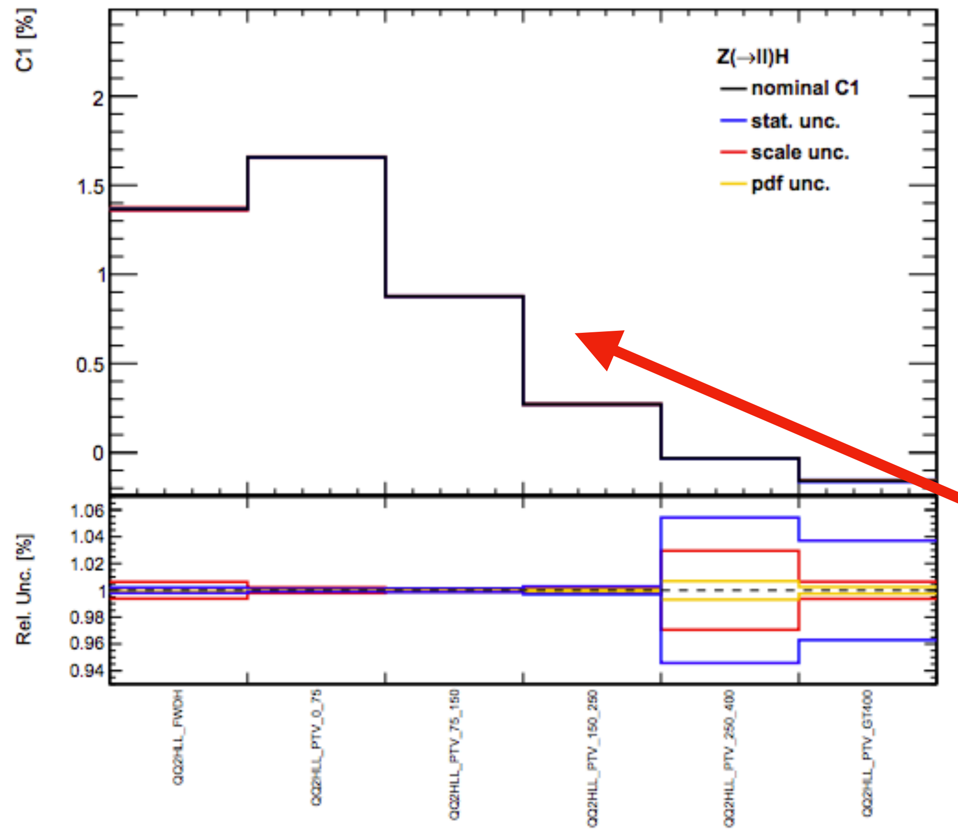


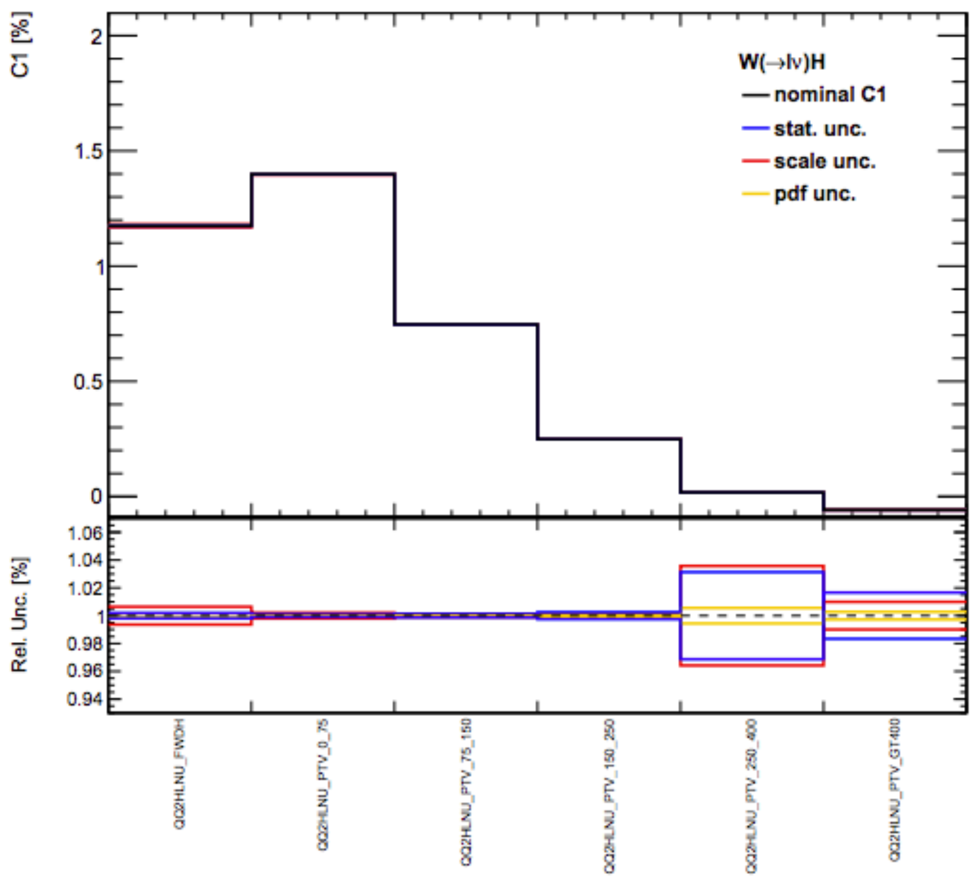
- small differential dependence for QQ2HQQ



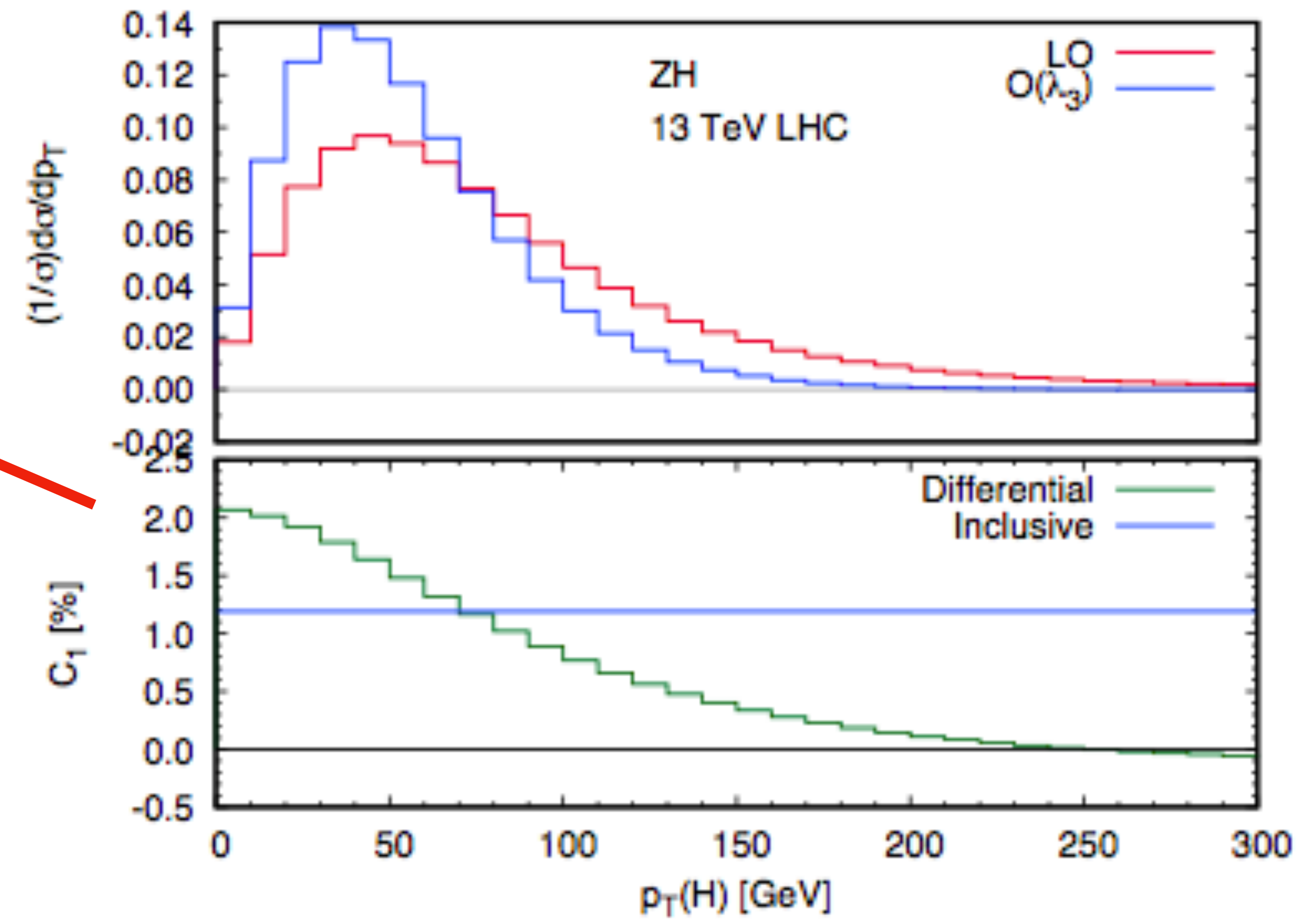


QQ2HLL/LNU STXS categories





ZH C1's from theory

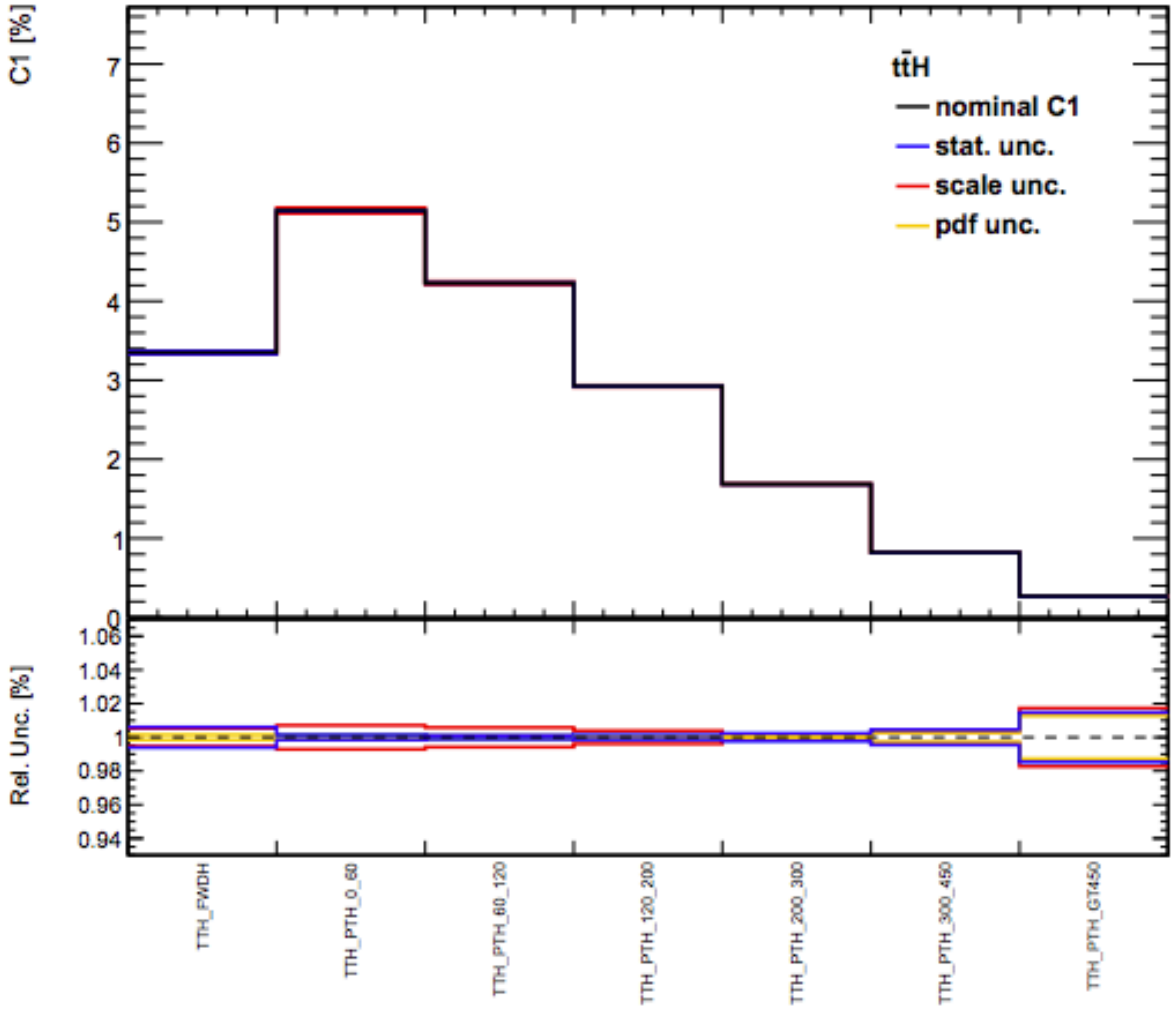


- strong dependence of C1 on the pT of the vector boson, captured by the STXS categorisation

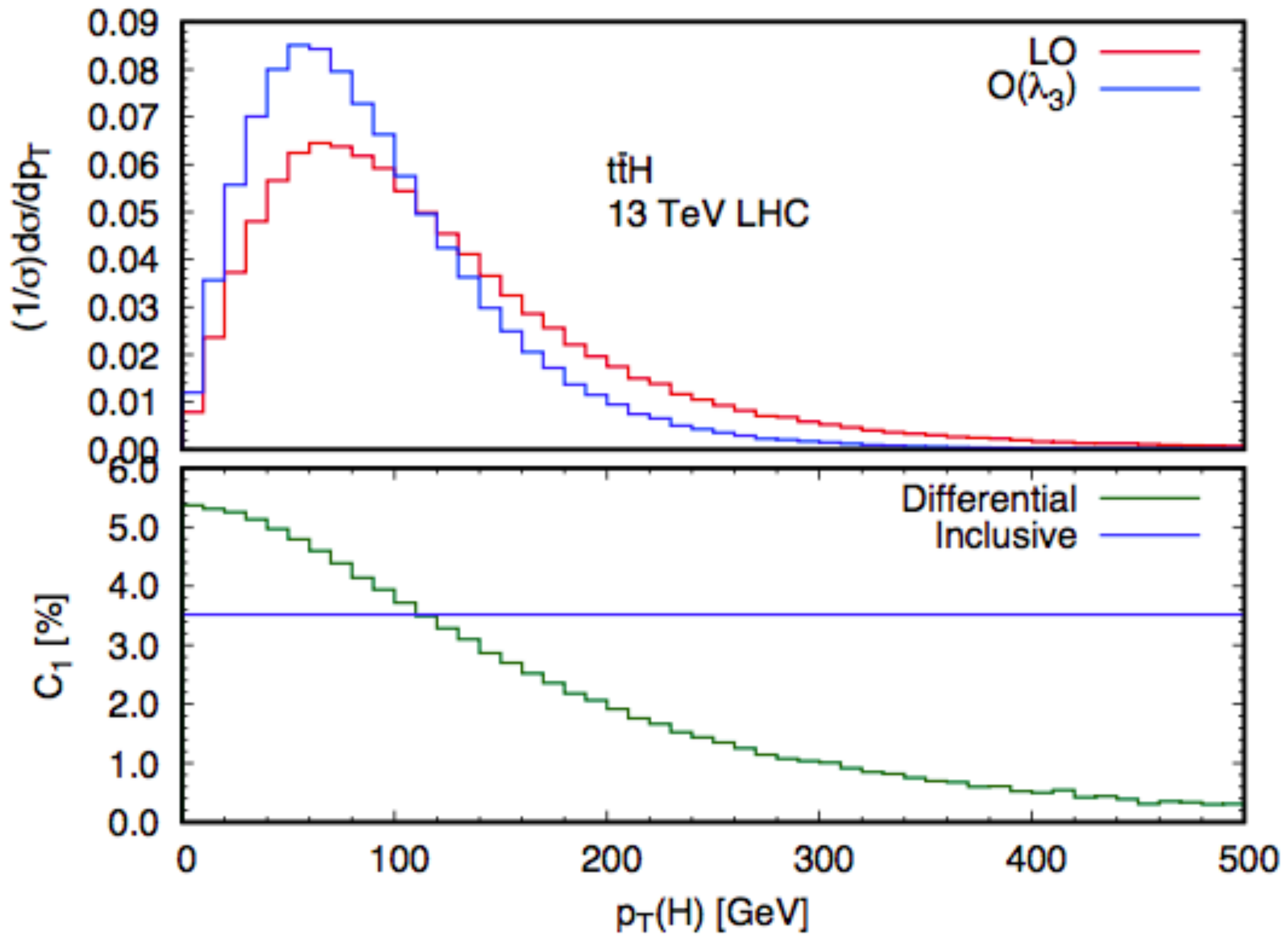
Self-couplings through single-H corrections

back-up

TTH STXS categories



TTH C1's from theory



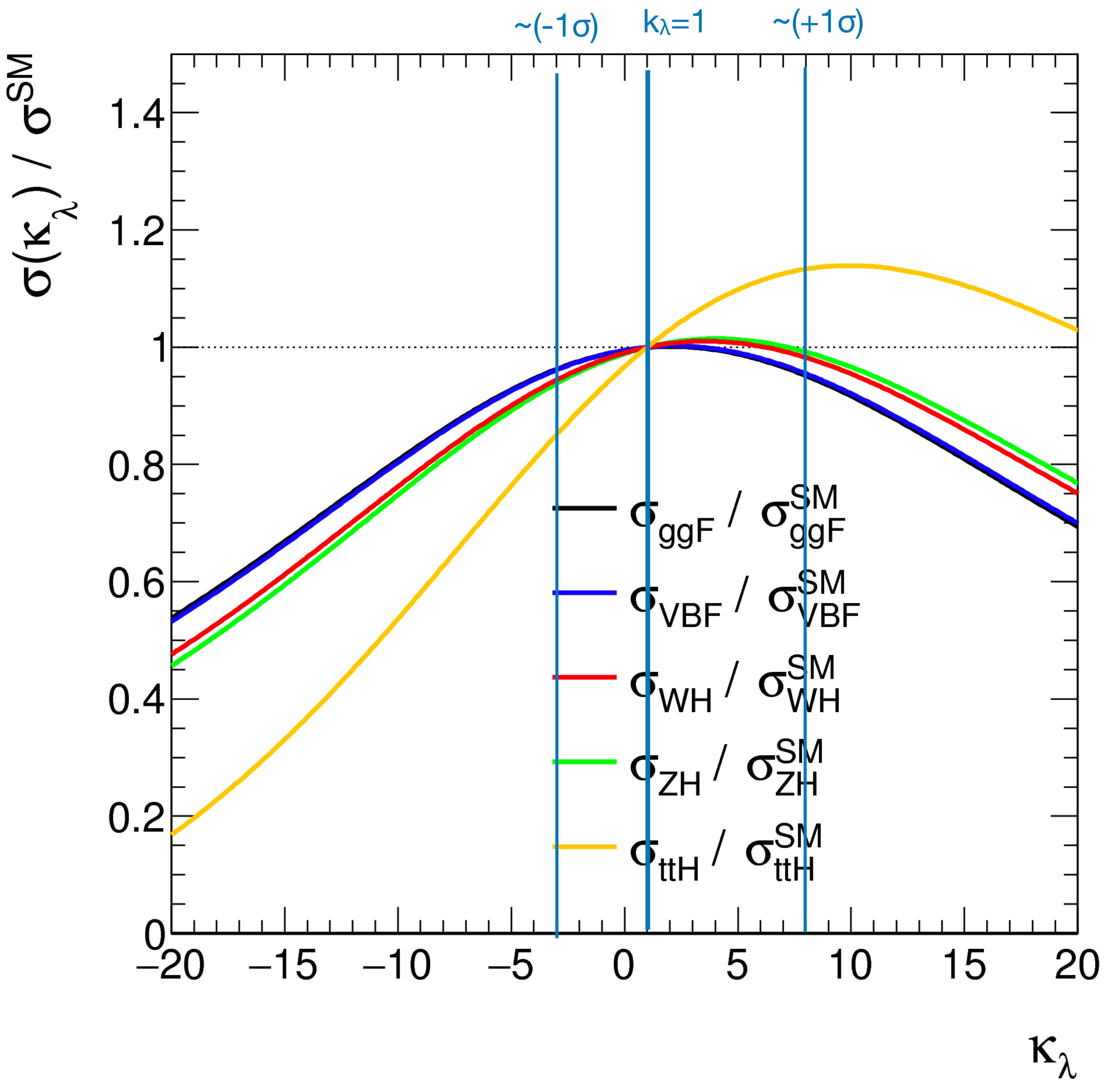
- strong dependence of C1 on the pT of the Higgs, captured by the STXS categorisation

Self-couplings through single-H corrections

First quick comment based on total XS dependence on k_λ

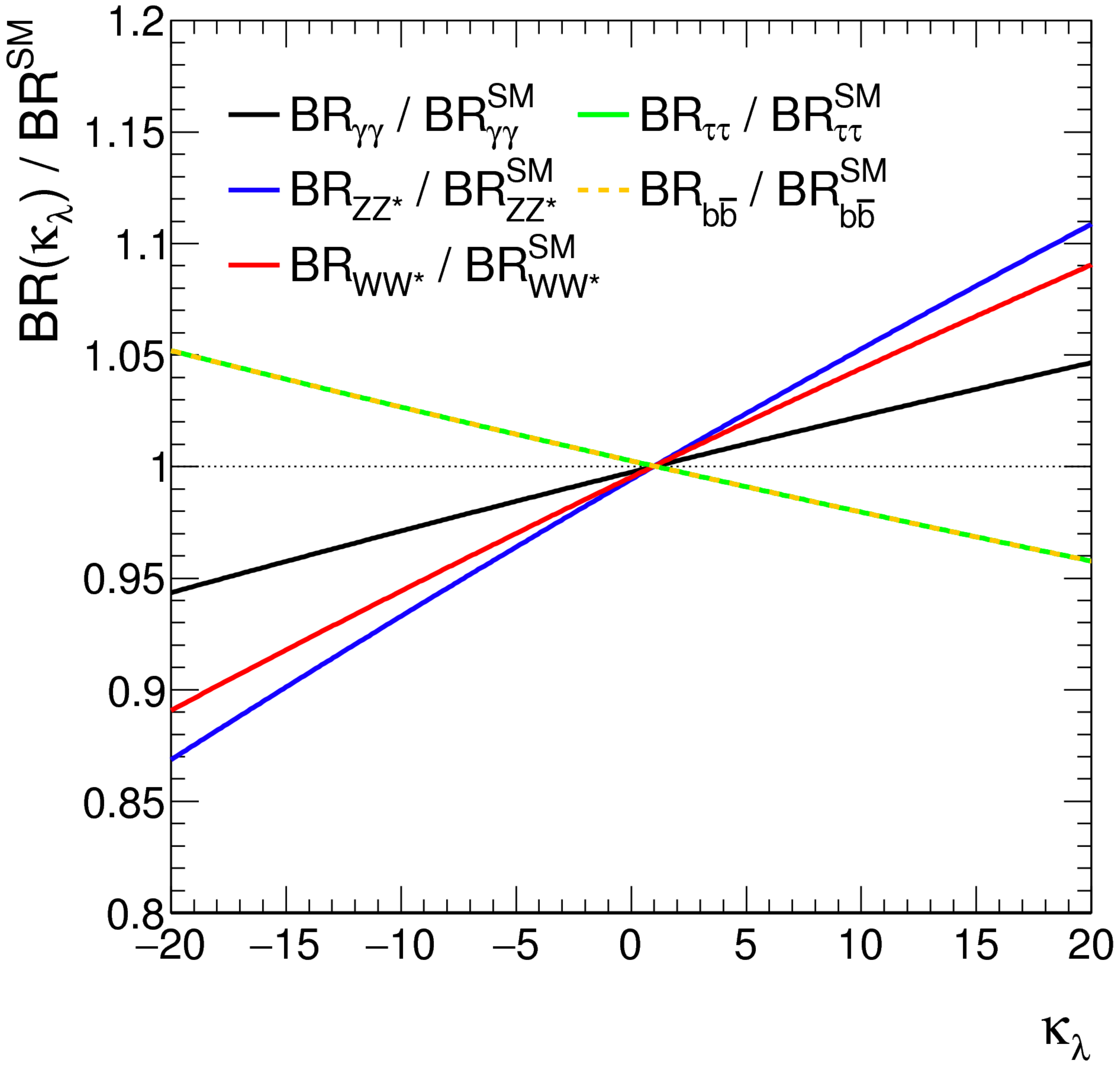
(no kinematic info here)

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



- Z_H^{BSM} dependence can only decrease the XS for k_λ values away from 0
  - $Z_H^{BSM} = 0.9$ for $k_\lambda \sim 8$
  - $Z_H^{BSM} = 0.99$ for $k_\lambda \sim -3$
- non-ttH XS fairly stable for positive k_λ values: larger error k_λ on the upper-side
- XS decreases on the lower-side uncertainty range for all prod. modes (rapidly for ttH): smaller error k_λ on the lower-side
- ttH behaviour rather different than other production modes: largest C1's positive increase for $k_\lambda > 1$

Self-couplings through single-H corrections



back-up

HH analyses and combination

HH combinations

BRs	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%

Three combinations typically favored:

H(→bb)H(→bb):
largest BR, but huge QCD multi-jet background

H(→bb)H(→ττ):
moderate BR, multi-jet rejection due to presence of ττ

H(→bb)H(→γγ):
small BR, but very clean signature + benefits from $m_{\gamma\gamma}$ resolution

HH combinations - self-coupling parameters

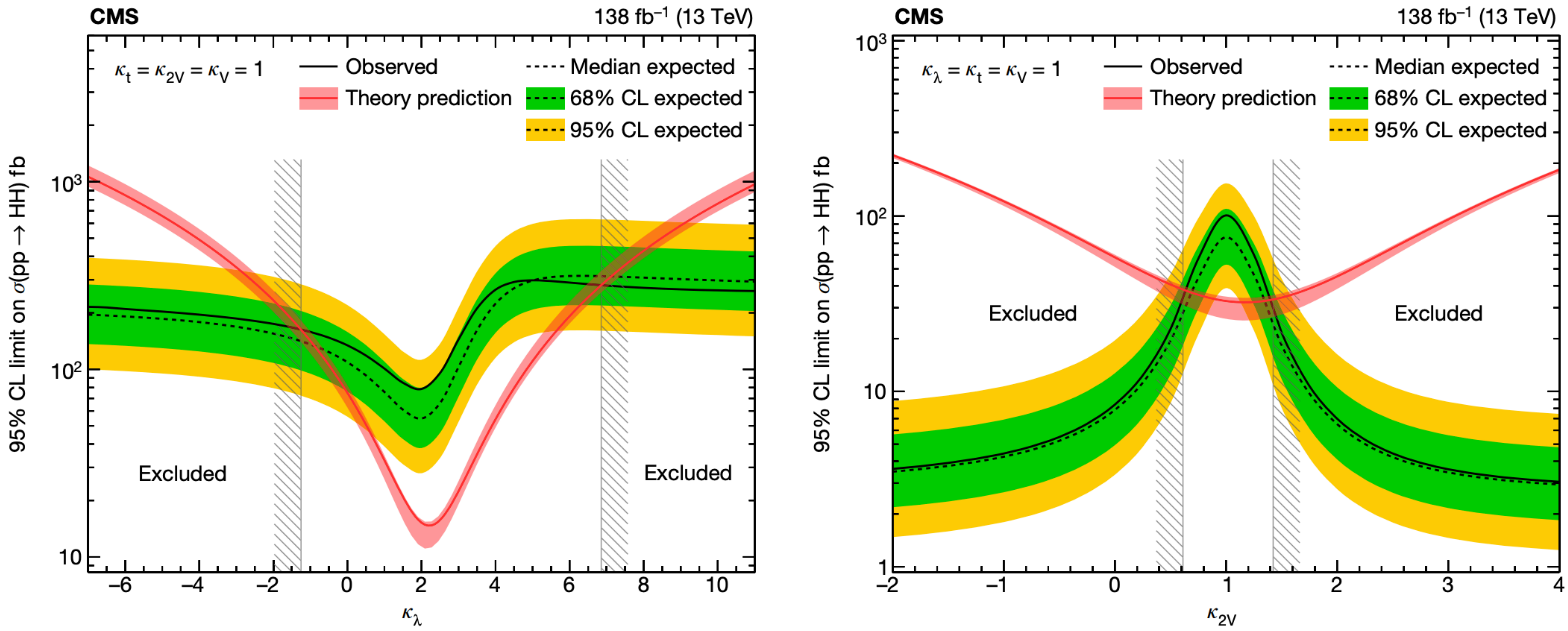
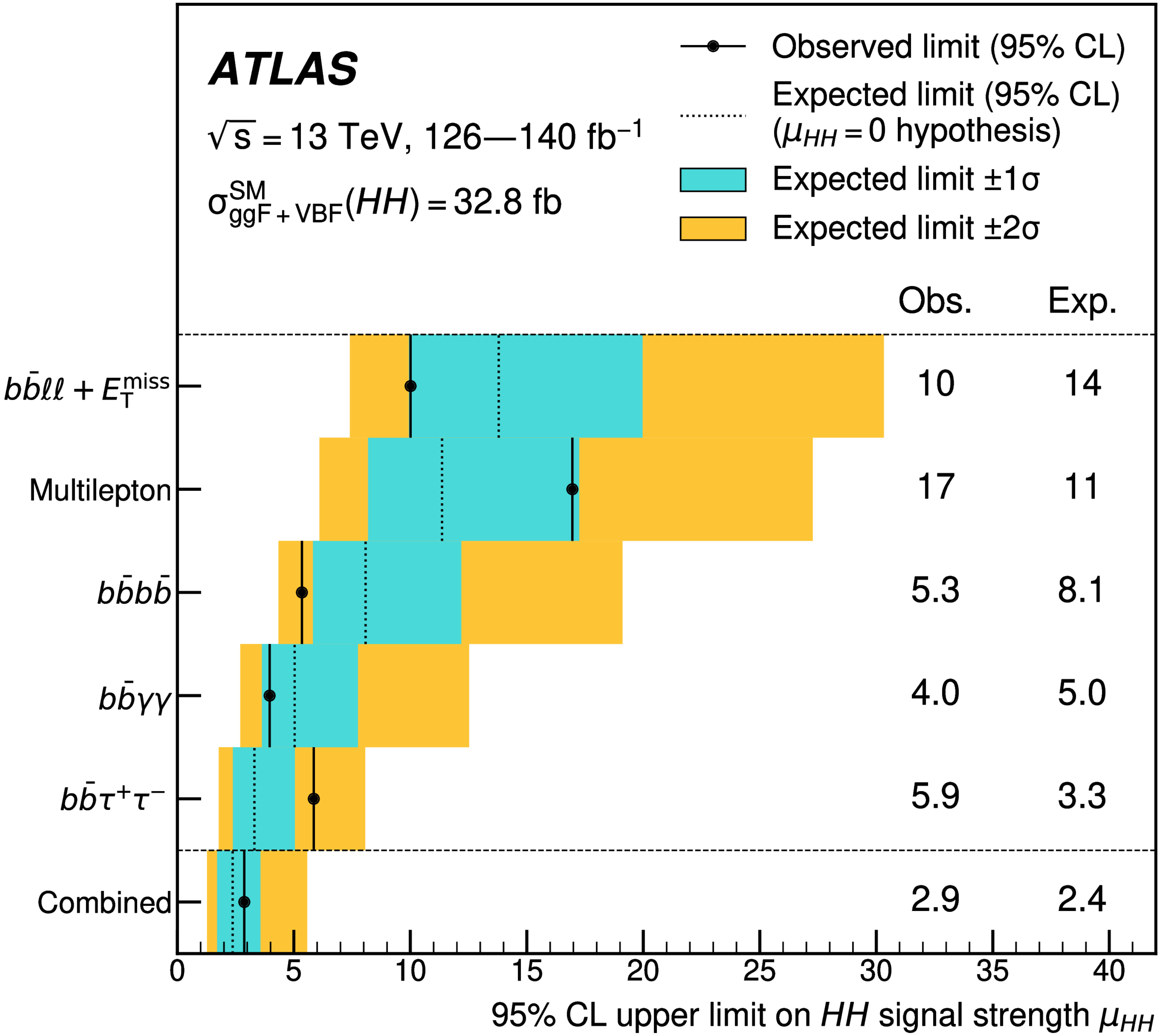


Fig. 6 | Limits on the Higgs boson self-interaction and quartic coupling. Combined expected and observed 95% CL upper limits on the HH production cross-section for different values of κ_λ (left) and κ_{2V} (right), assuming the SM values for the modifiers of Higgs boson couplings to top quarks and vector bosons. The green and yellow bands represent the 1-s.d. and 2-s.d. extensions beyond the expected limit, respectively; the red solid line (band) shows the theoretical prediction for the HH production cross-section (its 1-s.d. uncertainty). The areas to the left and to the right of the hatched regions are excluded at the 95% CL.

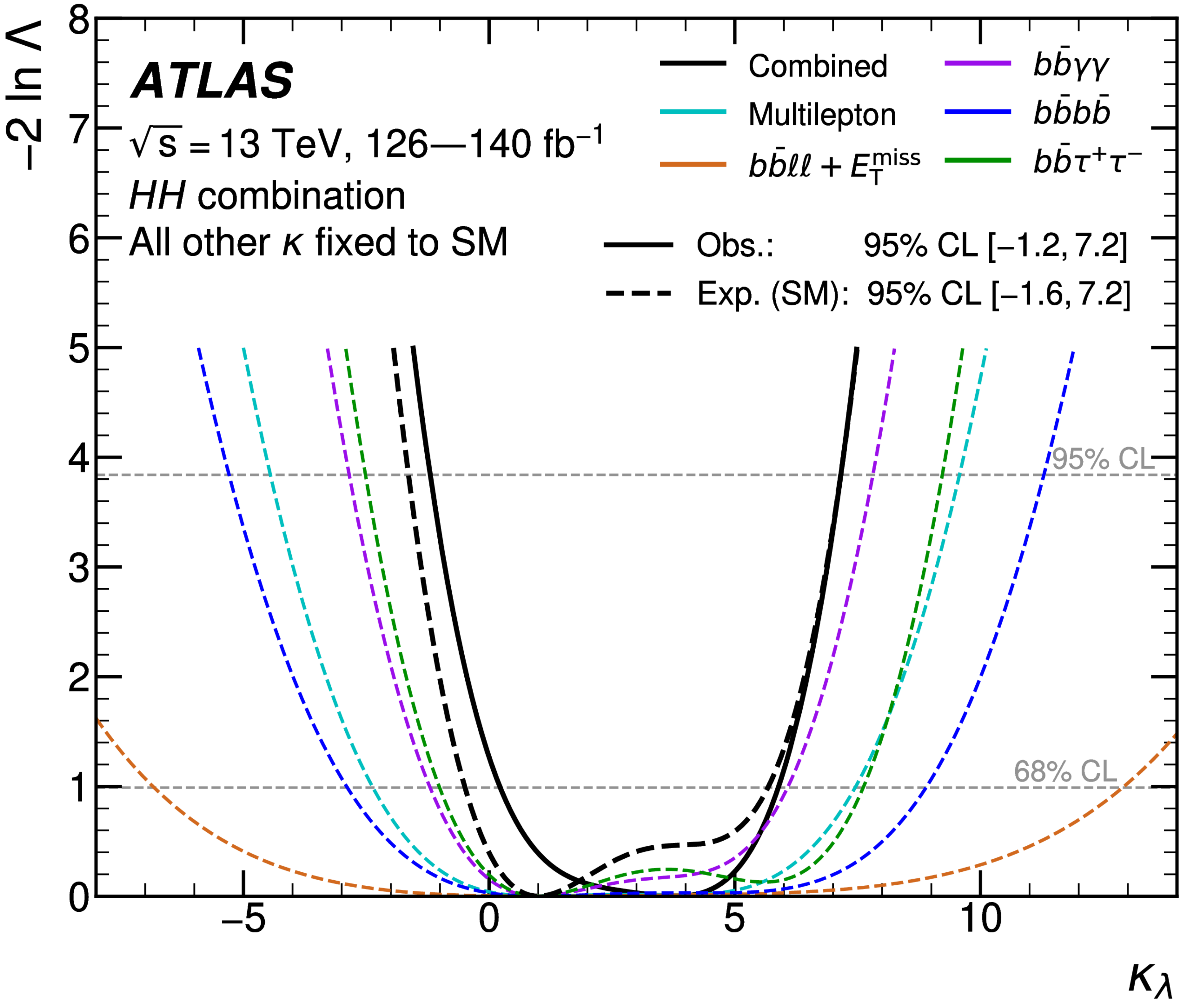
HH combinations

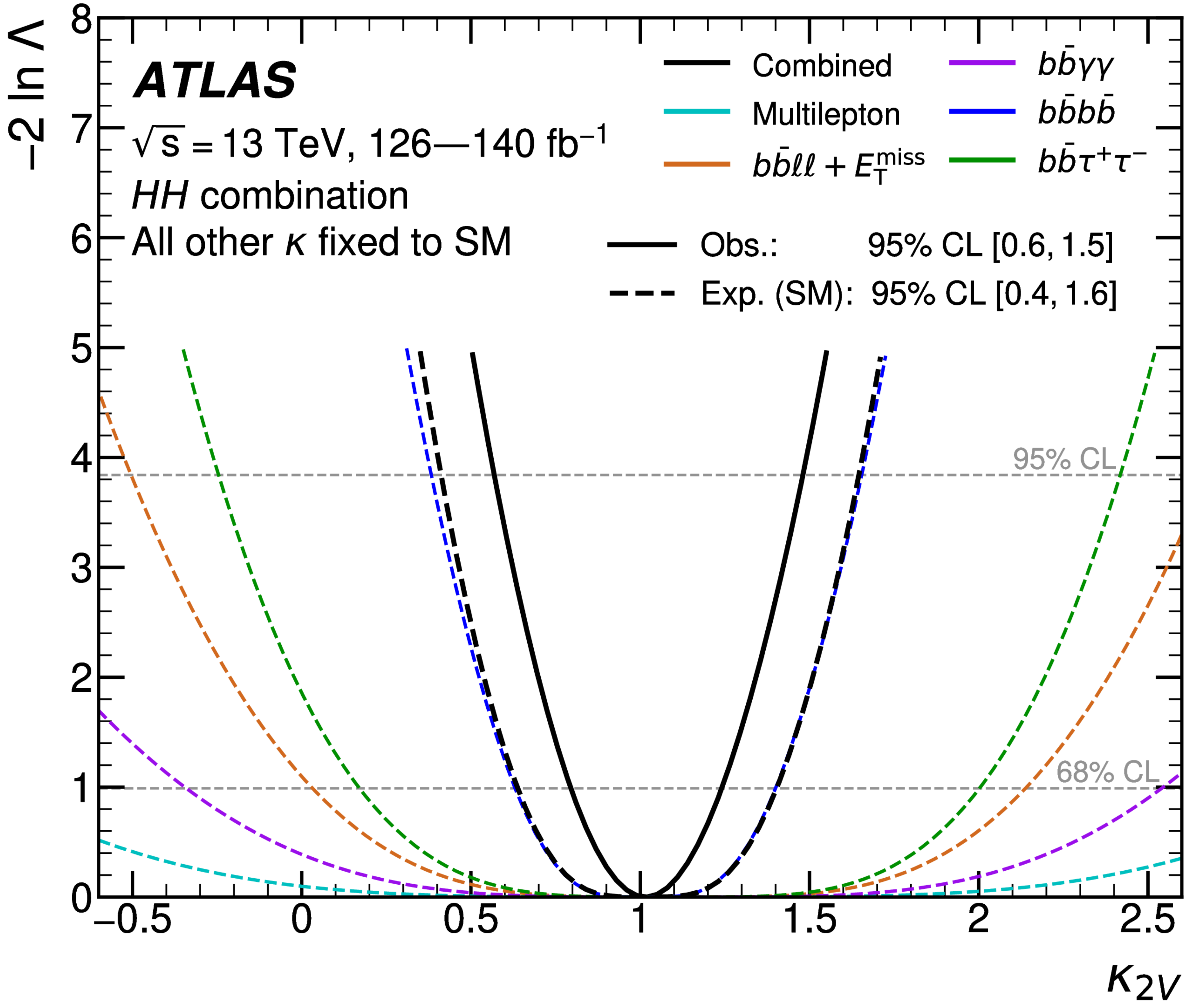
HDBS-2021-18



HH combinations

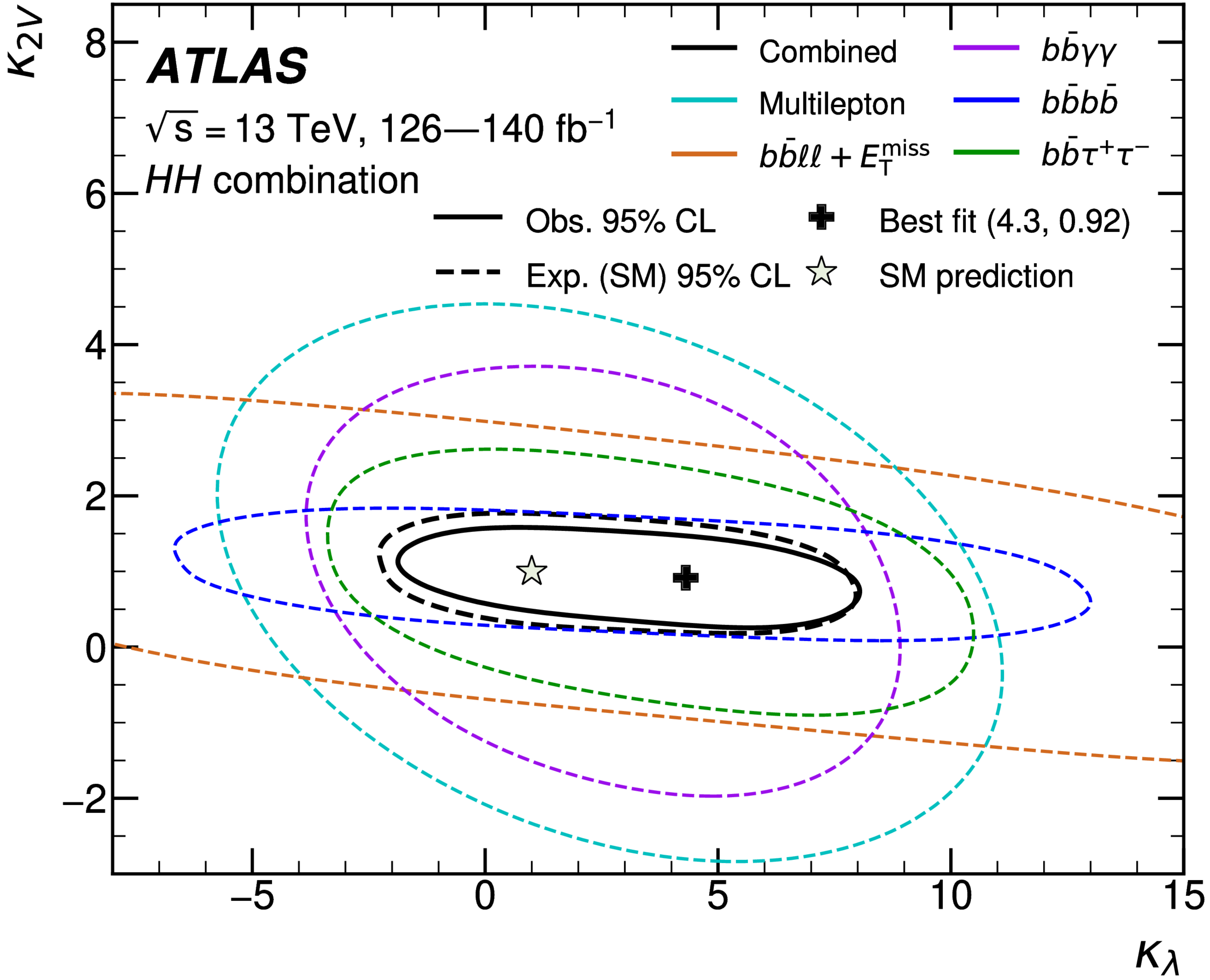
HDBS-2021-18



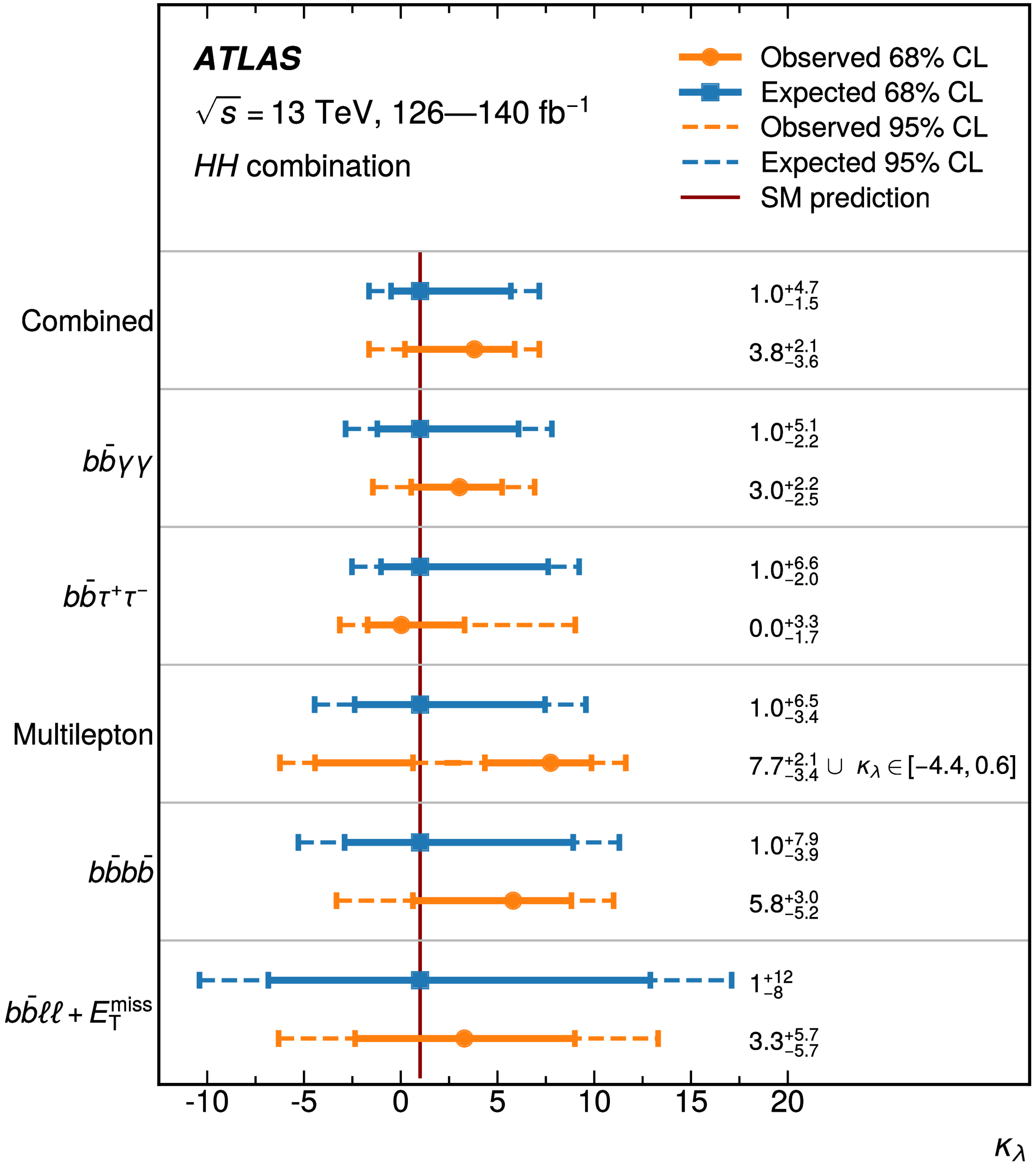


HH combinations

HDBS-2021-18



HH combinations

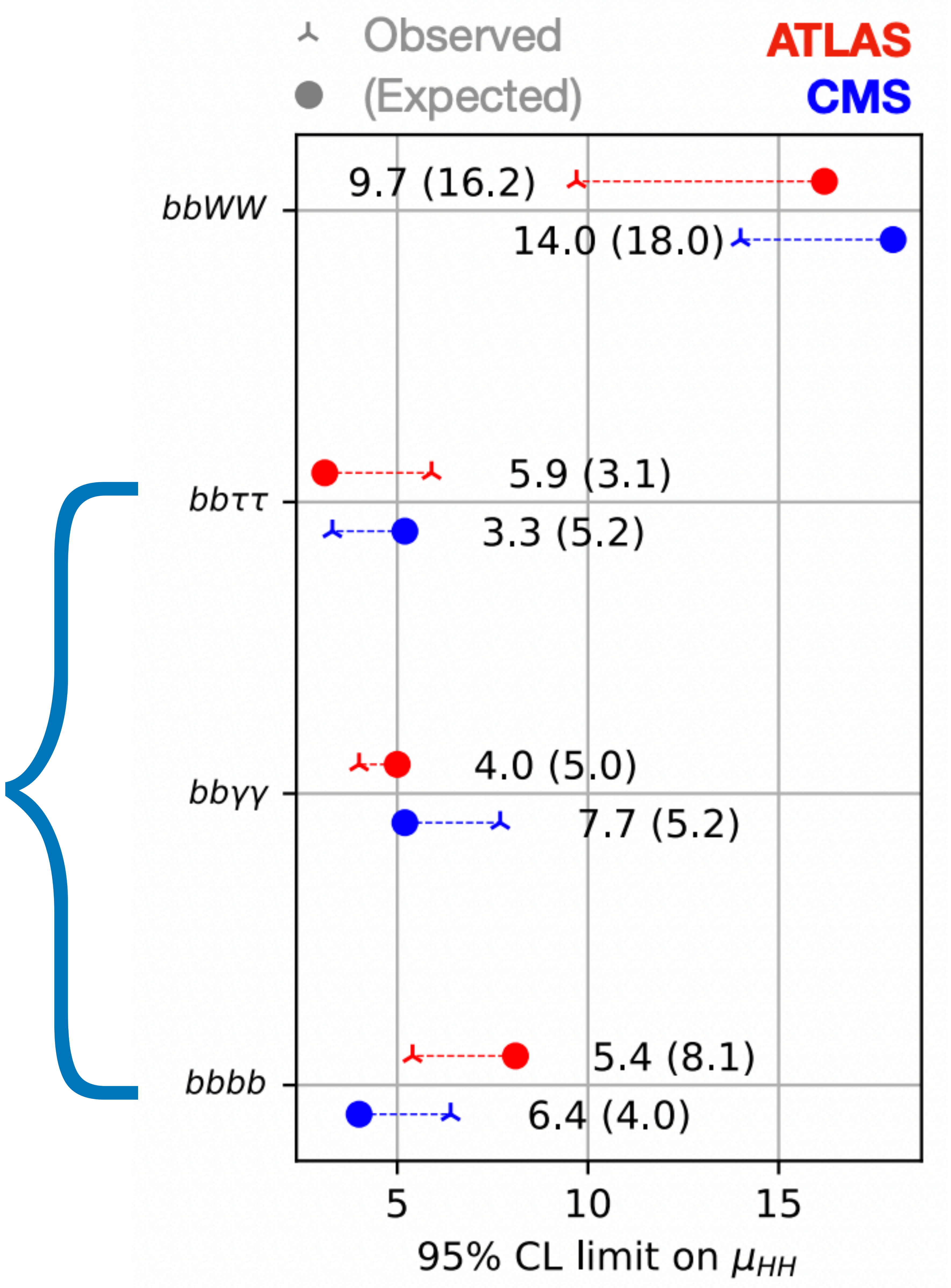


	Obs.	-2σ	-1σ	Exp.	$+1\sigma$	$+2\sigma$	Exp. SM
$b\bar{b}\tau^+\tau^-$	5.9	1.8	2.4	3.3	5.0	8.1	4.3
$b\bar{b}\gamma\gamma$	4.0	2.7	3.6	5.0	7.8	13	6.4
$b\bar{b}b\bar{b}$	5.3	4.3	5.8	8.1	12	19	9.1
Multilepton	17	6	8	11	17	27	12
$b\bar{b}\ell\ell + E_T^{miss}$	10	7	10	14	20	30	15
Combined	2.9	1.3	1.7	2.4	3.6	5.6	3.4

HH searches in ATLAS: a general overview

back-up

(plots courtesy of Luca Cadamuro from ATLAS HH workshop)



- Cross-section limits at **O(3-5)** the SM expectation
  some differences between ATLAS and CMS
- Golden channels performing ~ similarly
- Combined limits from ATLAS: μ_{HH} < **2.4** (2.9)

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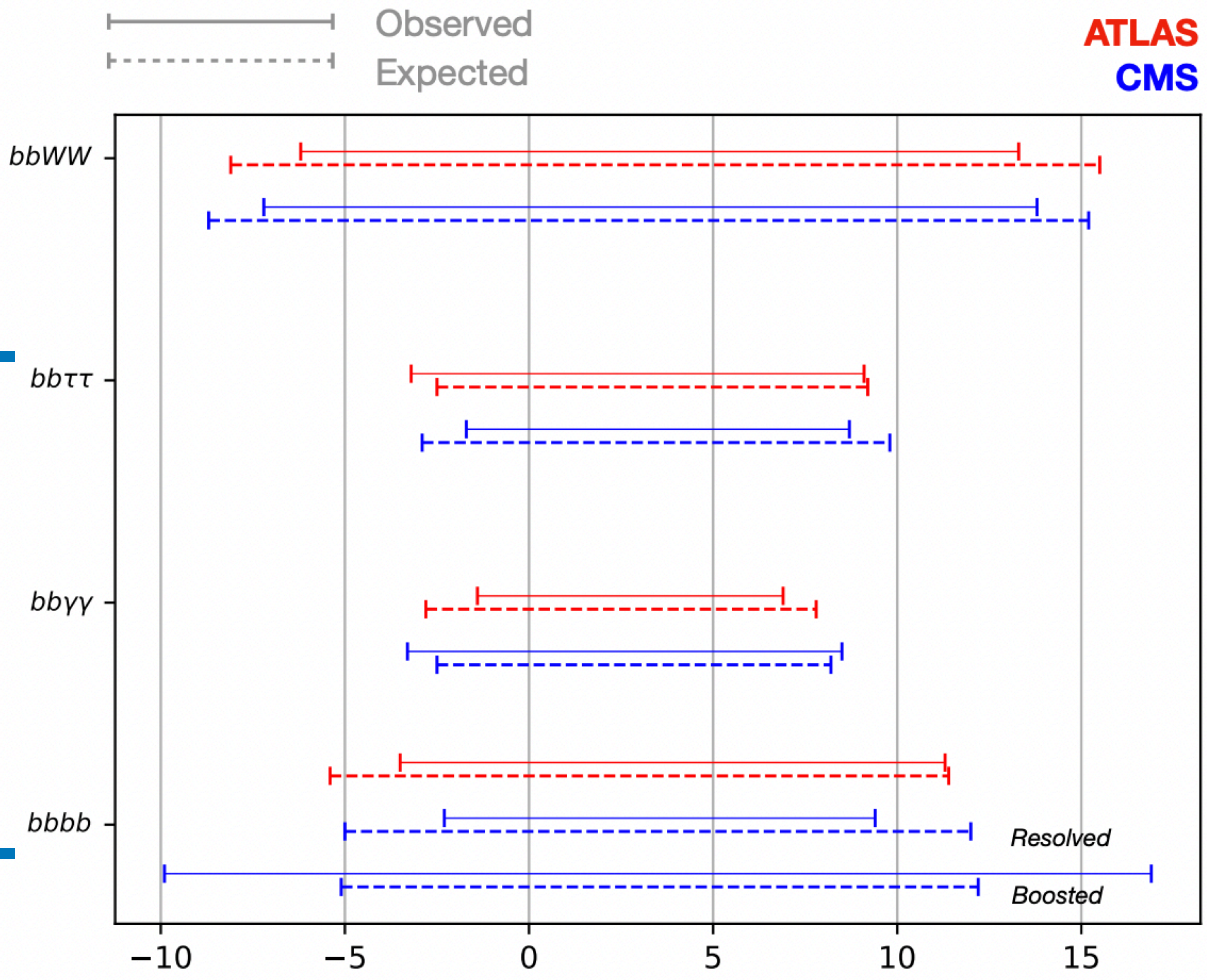
Remarkably:

back of the envelope combination +
scaling with LHC Run-3 luminosity (~300/fb) +
ATLAS & CMS combination

3σ evidence of HH production not out of reach

HH searches in ATLAS: a general overview

(plots courtesy of Luca Cadamuro from ATLAS HH workshop)



$k_\lambda = \lambda / \lambda_{SM}$

- Sensitivity to the Higgs self-coupling parameter still in the range of O(10)
- Combining all ATLAS analysis (plus single-Higgs, some assumptions)

$$-1.4 < \kappa_\lambda < 6.1$$

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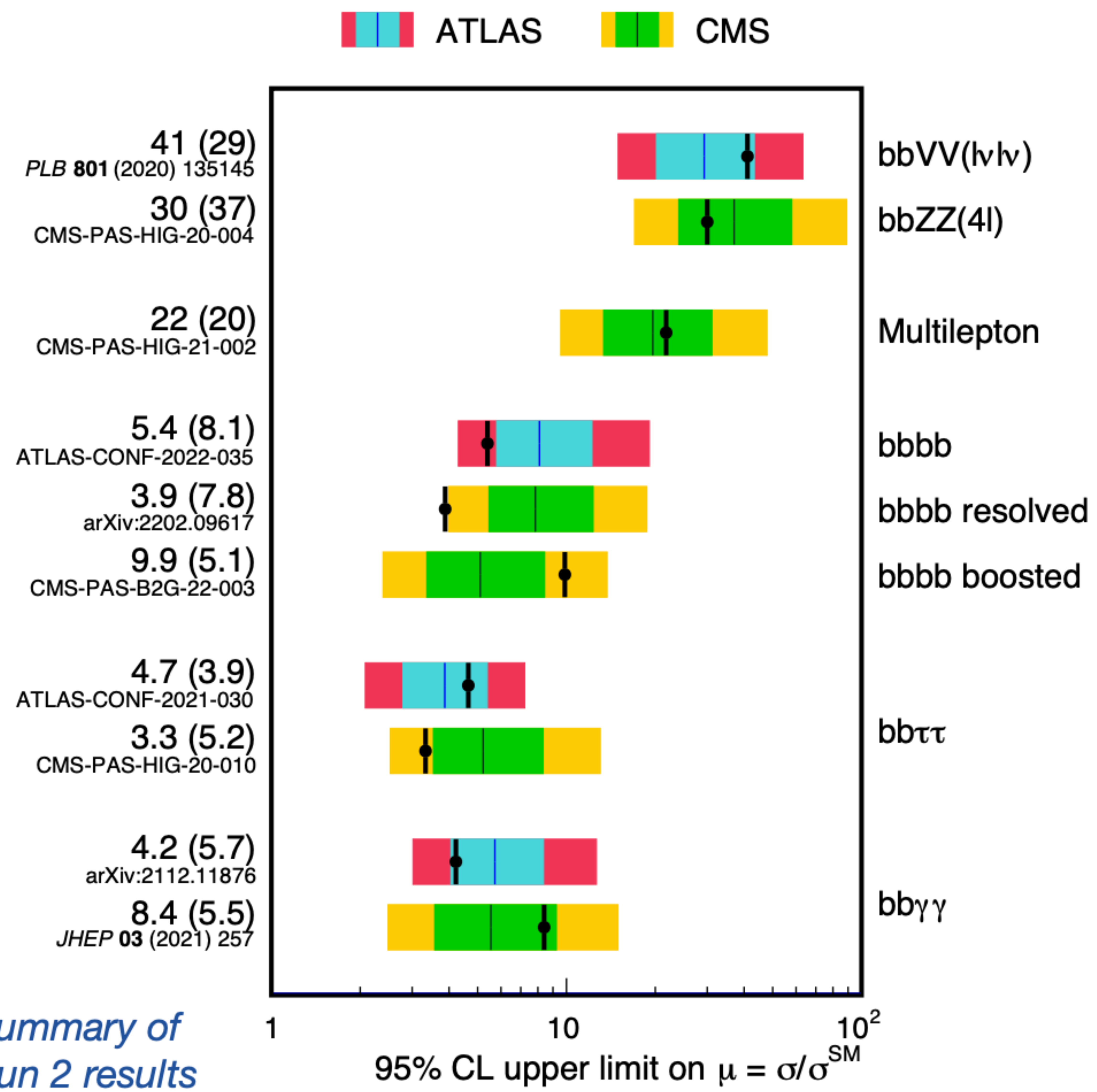
HH combinations

back-up



Summary of Run 2 results