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8 November 2024

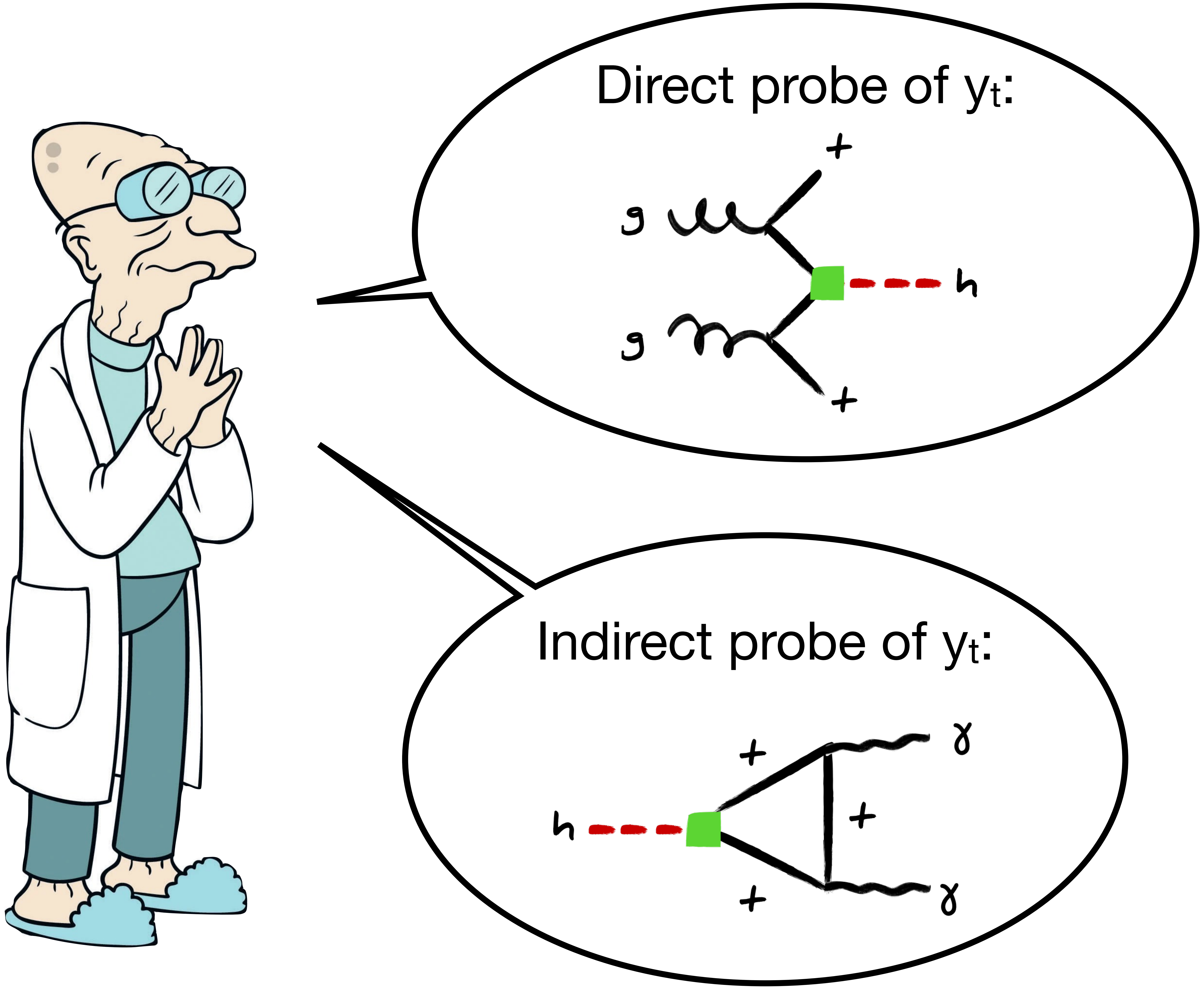
Indirect probes of the Higgs sector

(In)direct probes: theorist's view

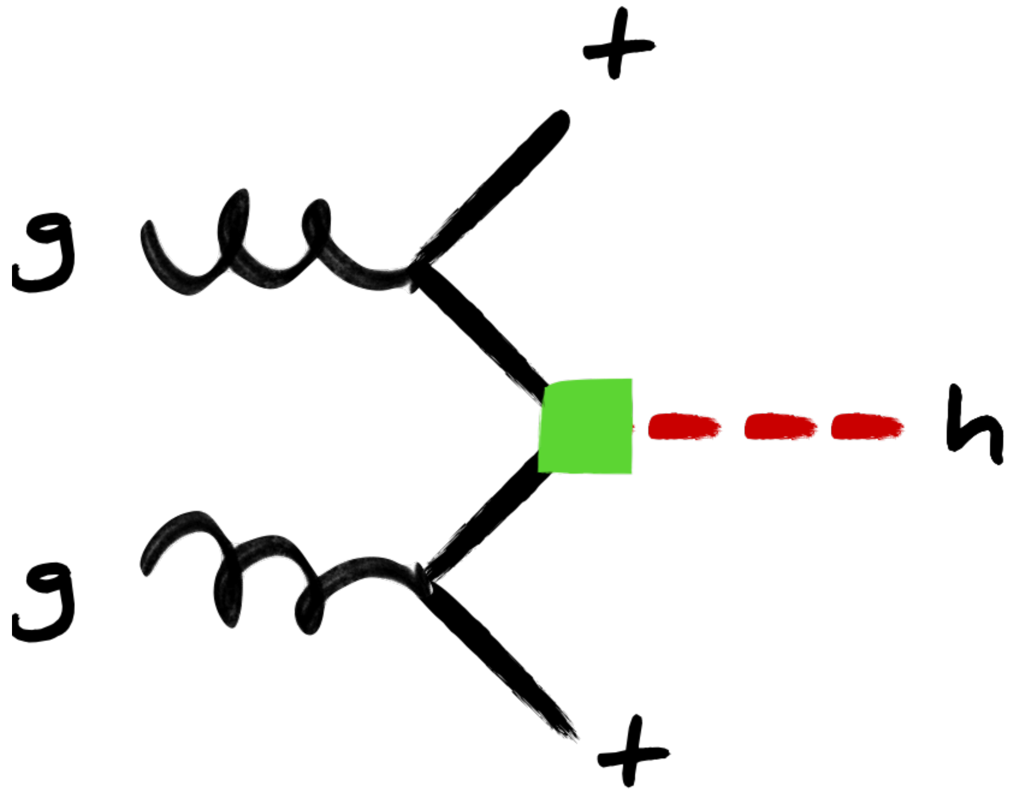
Direct probes: tests of
tree-level interactions

Indirect probes: tests of loop
modifications of interactions

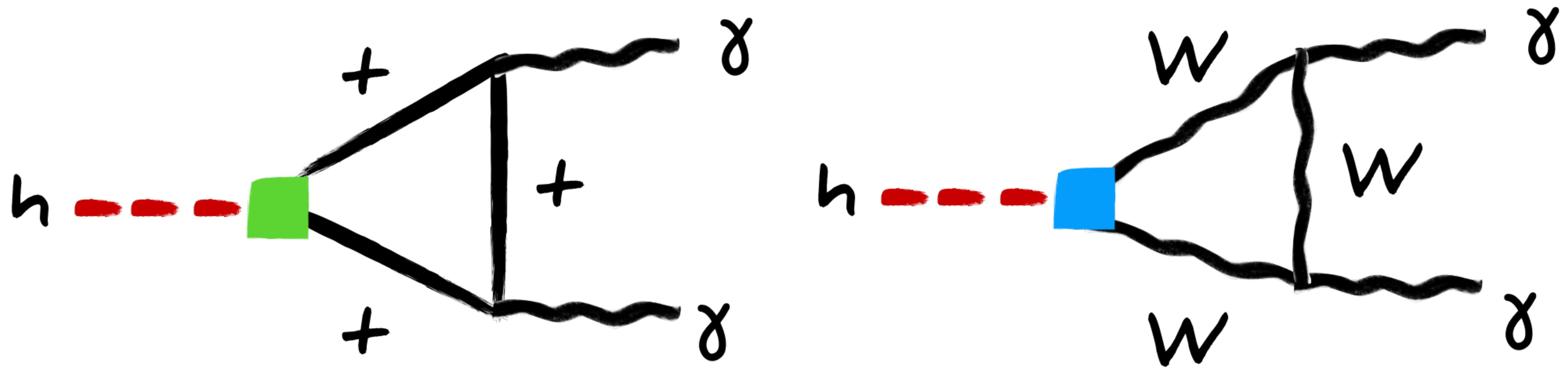
(In)direct probes: example top Yukawa (y_t)



(In)direct probes: synergy & complementarity



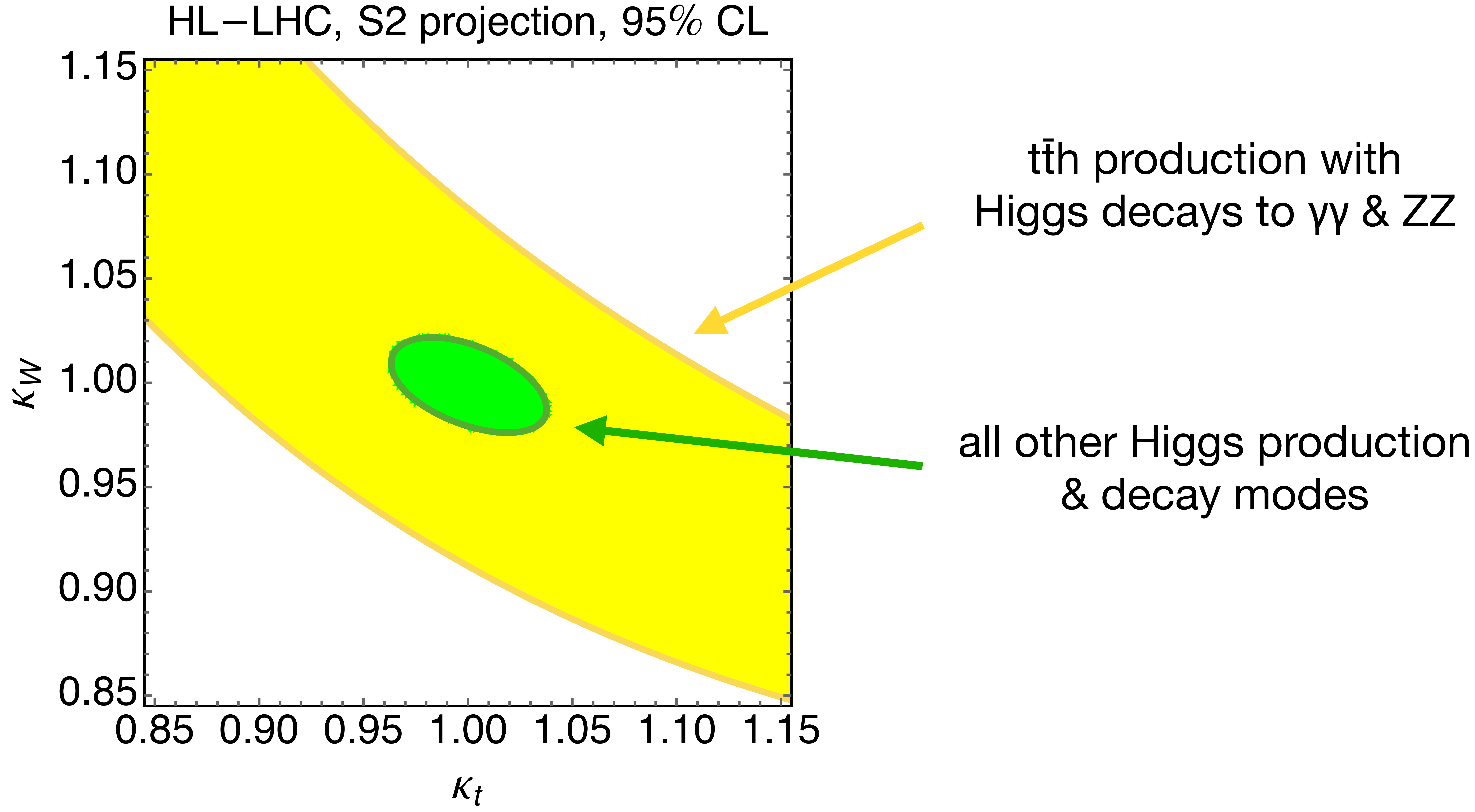
$$\propto \kappa_t^2$$



$$\propto \quad 0.07\kappa_t^2 + 1.59\kappa_W^2 - 0.66\kappa_W\kappa_t$$

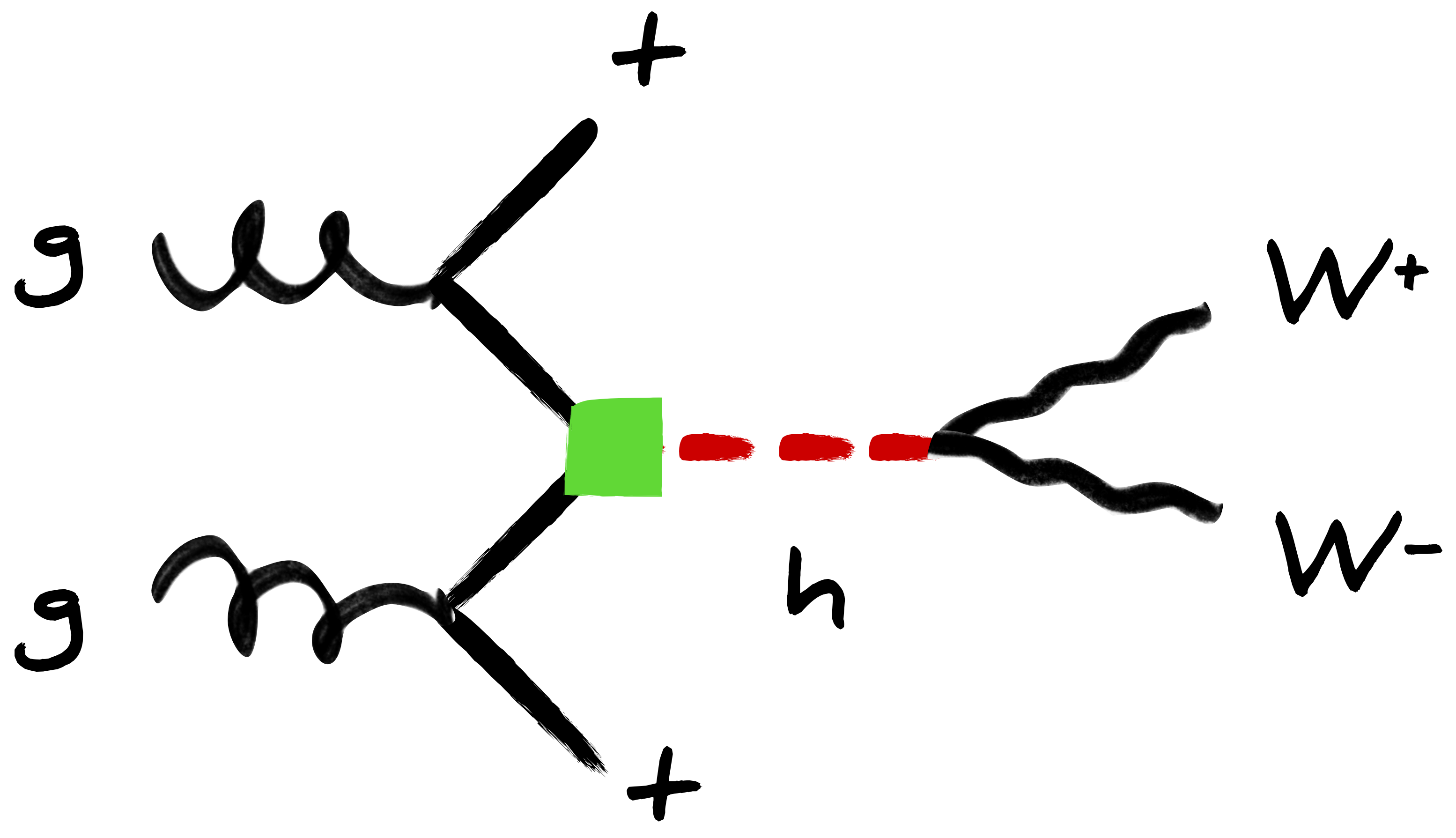
Under a given new-physics hypothesis, say for example κ framework, it is always possible to combine direct & indirect probes to strengthen constraints

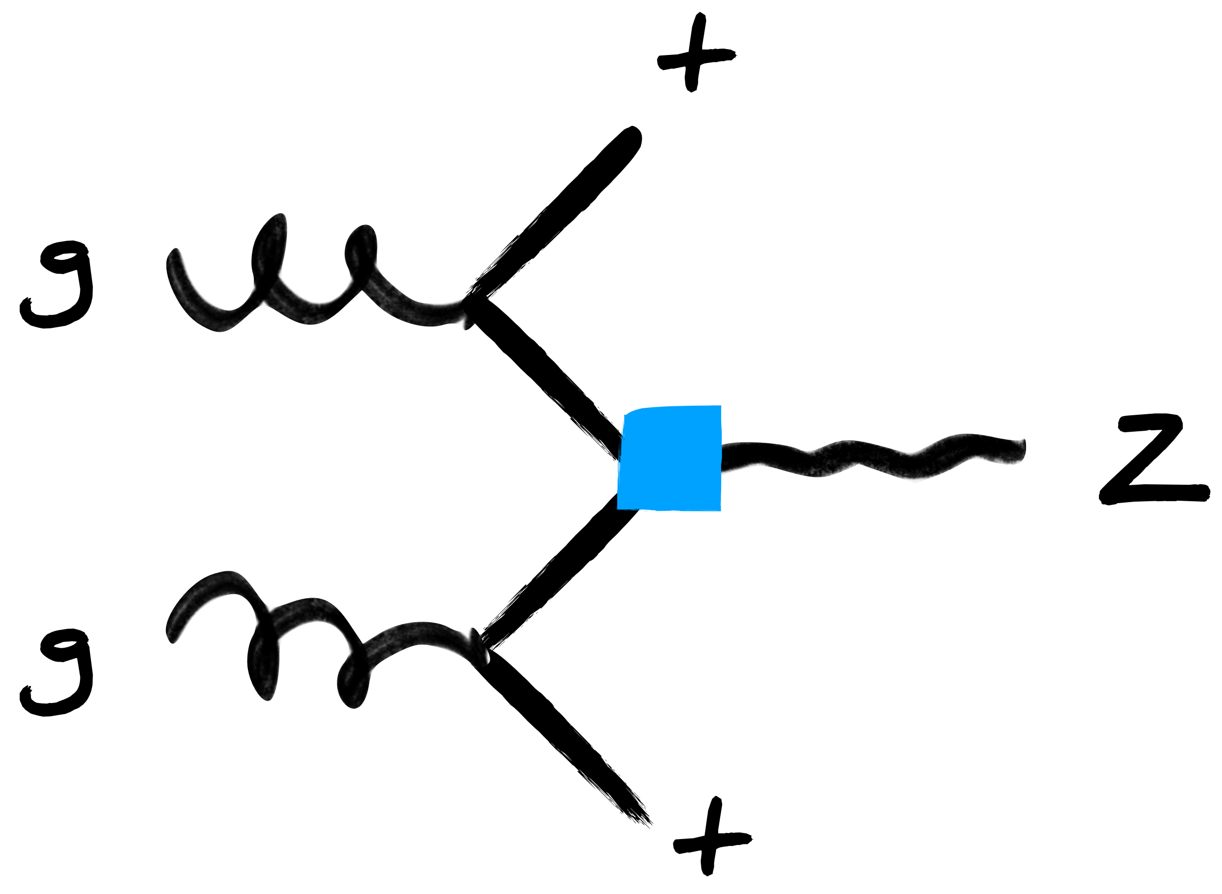
(In)direct probes: synergy & complementarity



(In)direct probes: experimentalist’s view

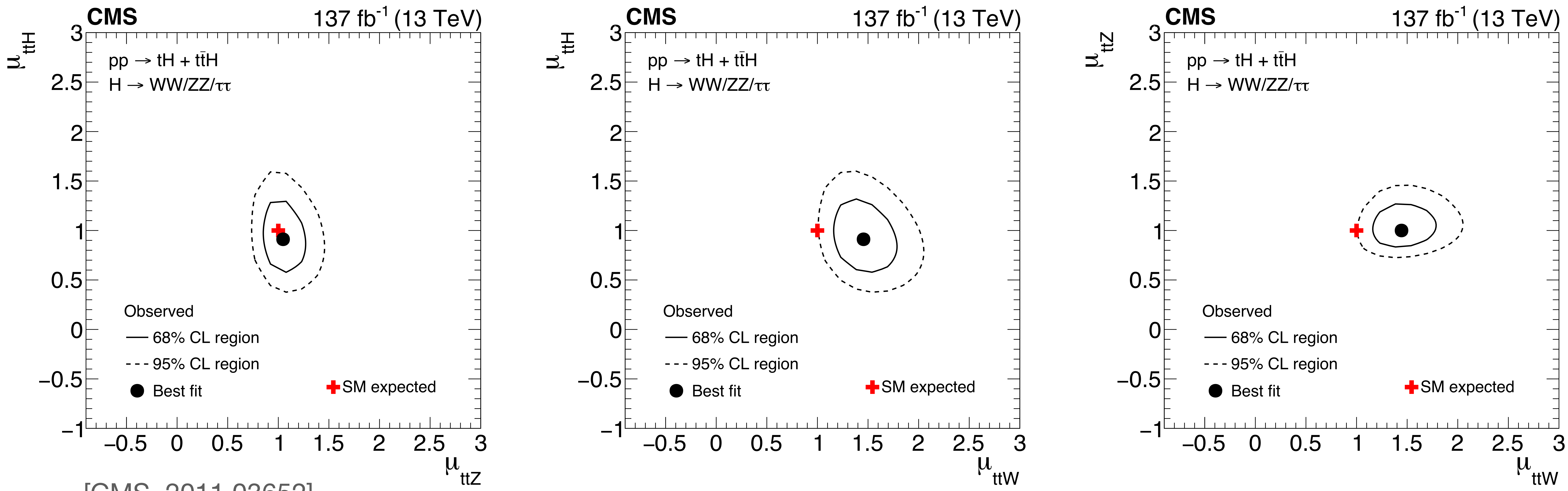
(In)direct probes: experimentalist’s view





Important constraint on $t\bar{t}h$ production provided by multilepton search, resulting from Higgs decays to W^+W^-, ZZ & $\tau^+\tau^-$. Background from $t\bar{t}Z$ production, which depends on Z-boson coupling to top quarks, which is not very well known

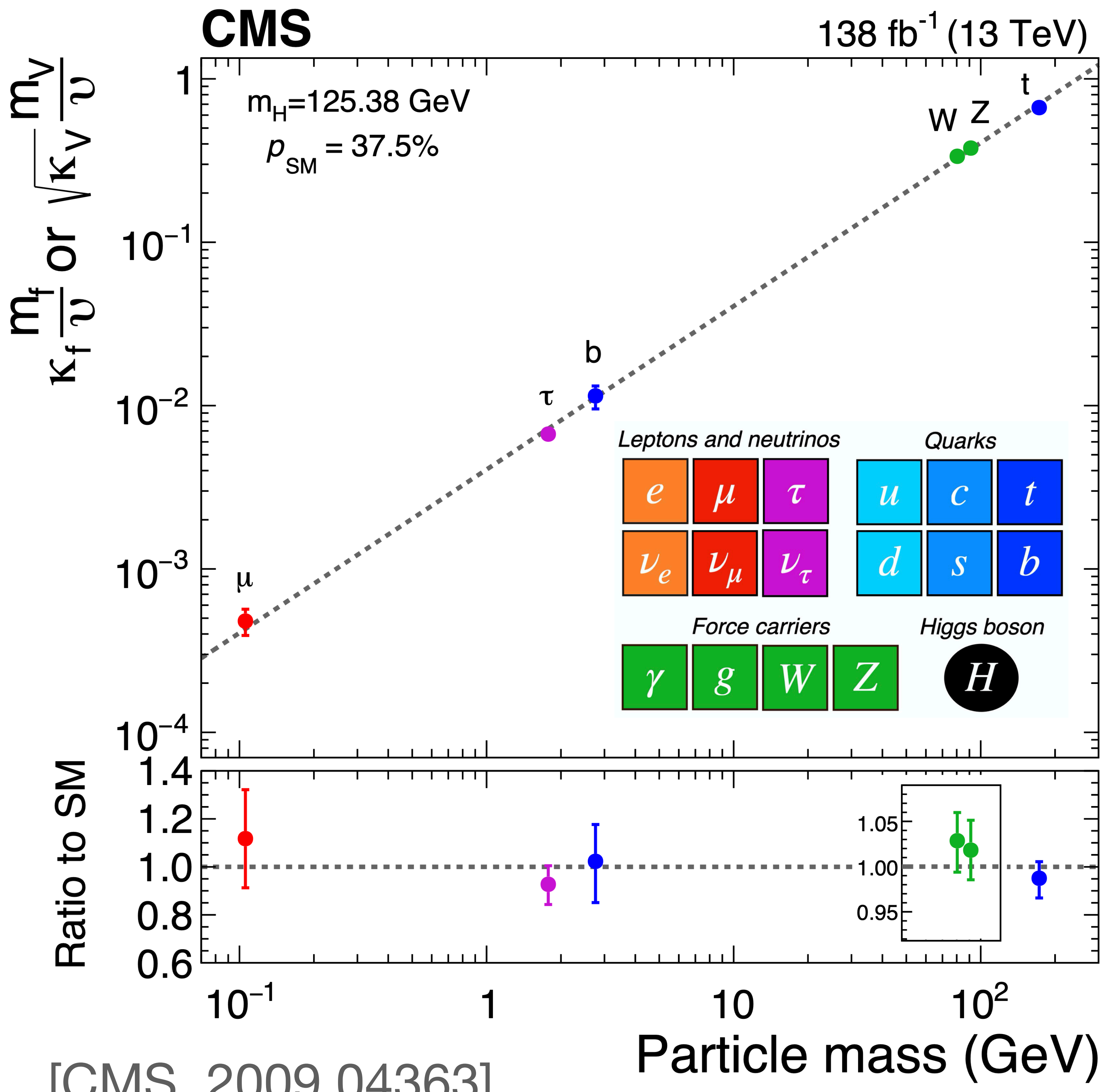
(In)direct probes: experimentalist's view



[CMS, 2011.03652]

Extraction of y_t in $t\bar{t}h$ production direct only under model assumptions. Consider $t\bar{t}h$, $t\bar{t}Z$, $t\bar{t}W$, etc. together to extract bounds on y_t, Z-boson coupling to top-quarks, etc.

When are indirect probes helpful?



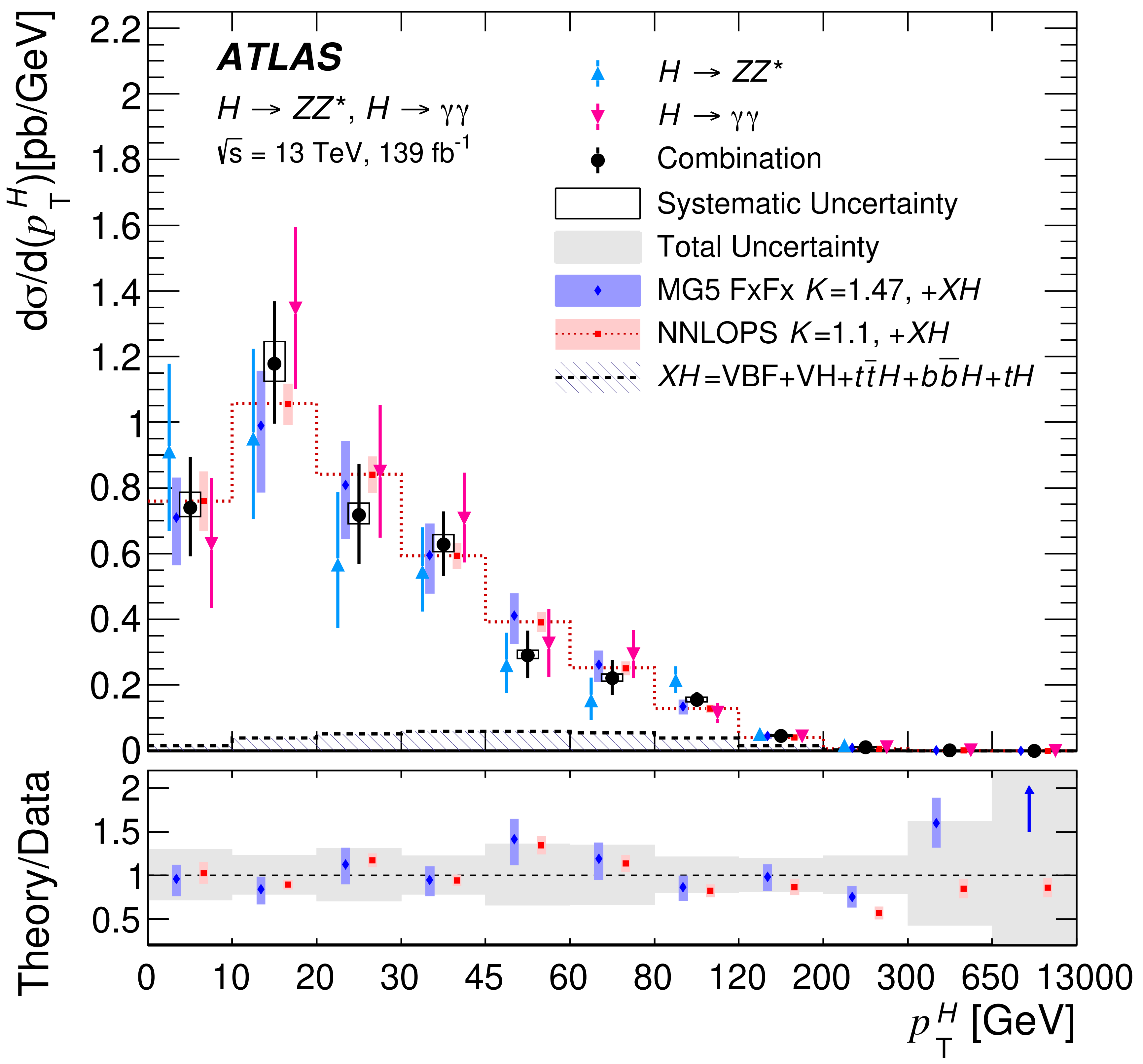
[CMS, 2009.04363]

Yukawa couplings of light fermions, Higgs self-couplings, …

If present LHC data is only able to put very loose bounds on a given coupling

When are indirect probes helpful?

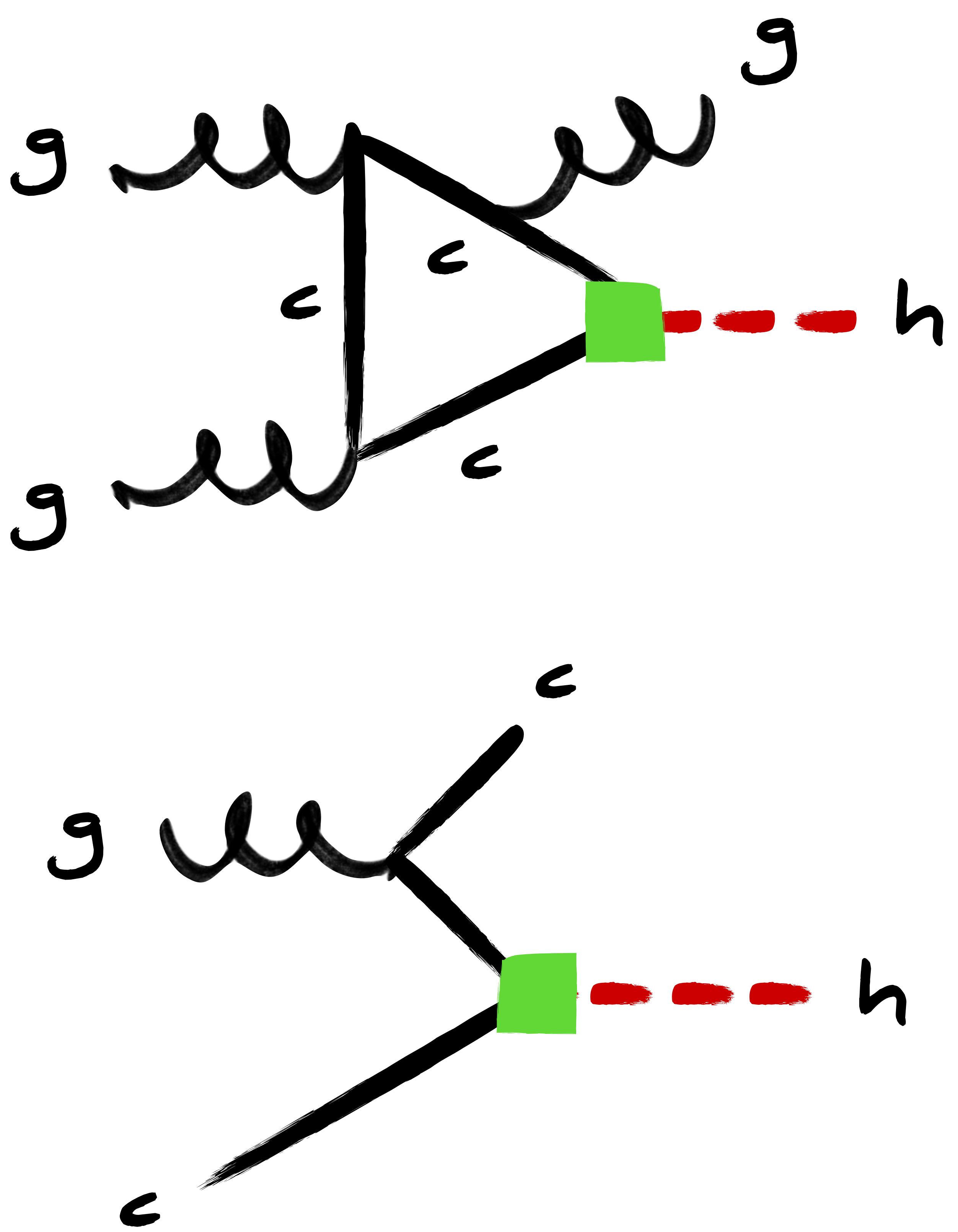
[ATLAS, 2207.08615]



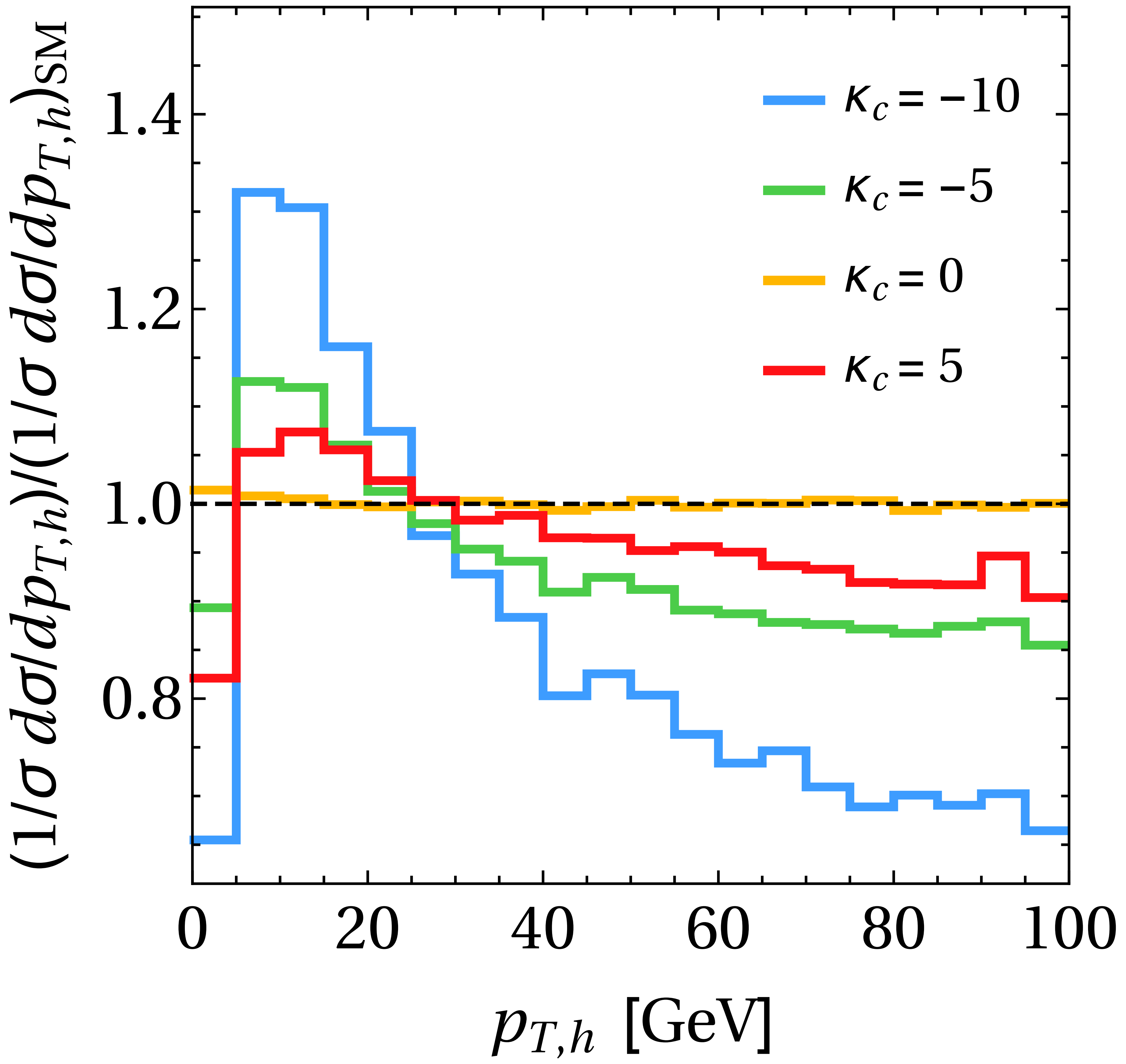
transverse momentum (p_T) spectrum of Higgs, Higgs off-shell measurements, …

If LHC able to measure a theoretically clean, differential Higgs observable precisely

Charm Yukawa coupling (y_c) from Higgs p_T



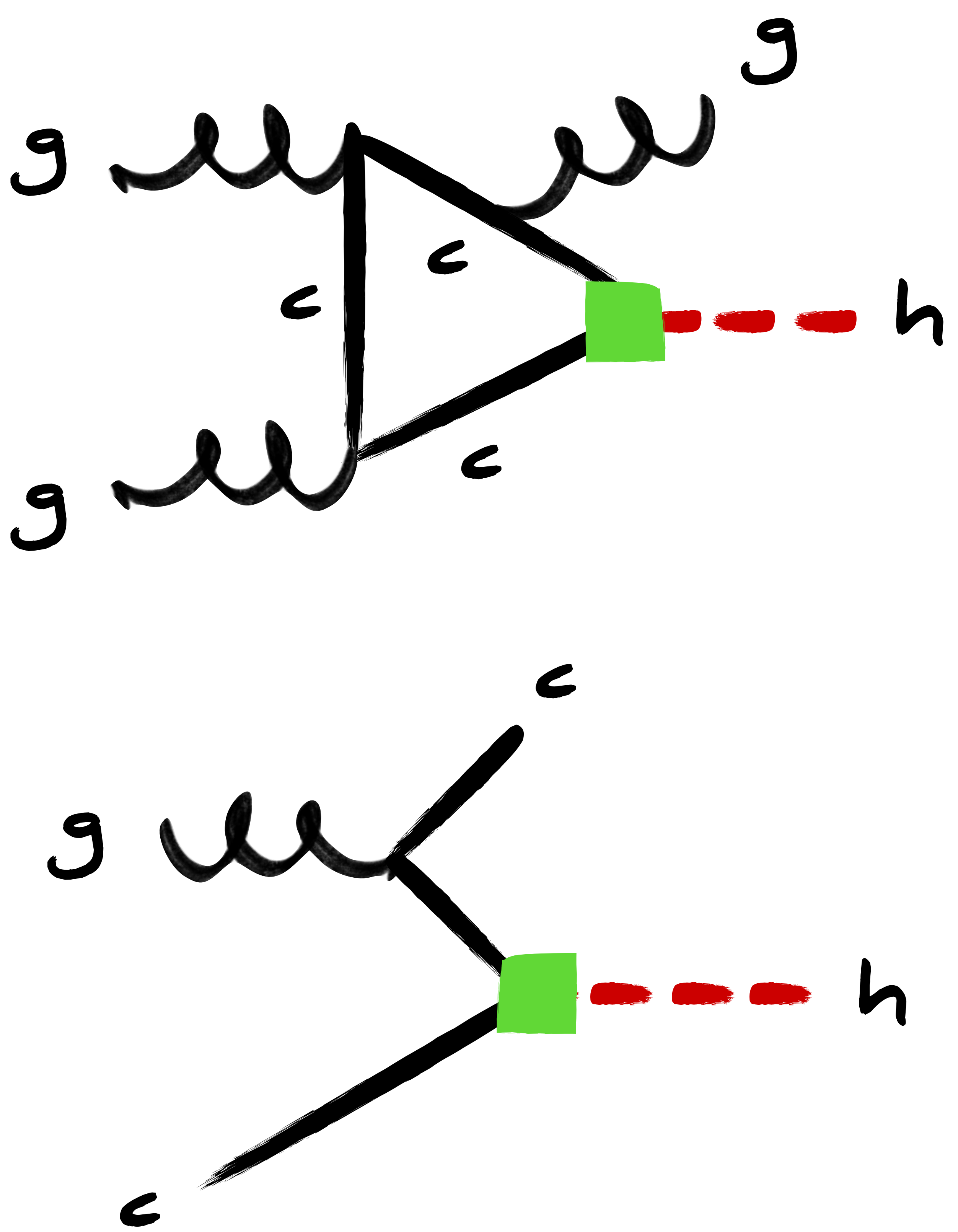
[Bishara, UH, Monni & Re, 1606.09253]



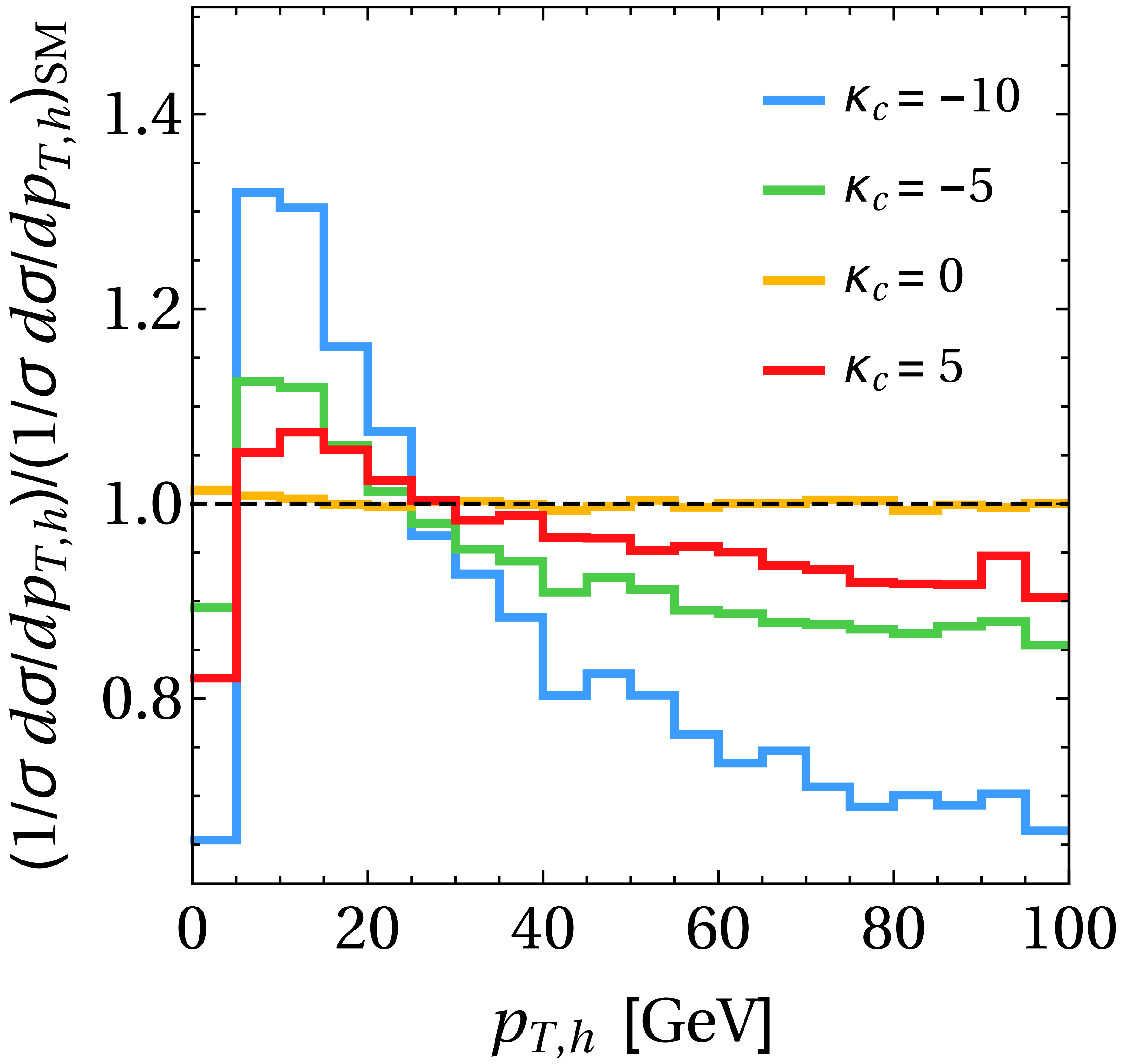
Emissions from charm loops or charm-initiated production distort $p_{T,h}$ spectrum

[see also Soreq, Zhu & Zupan, 1606.09621]

Charm Yukawa coupling (y_c) from Higgs p_T



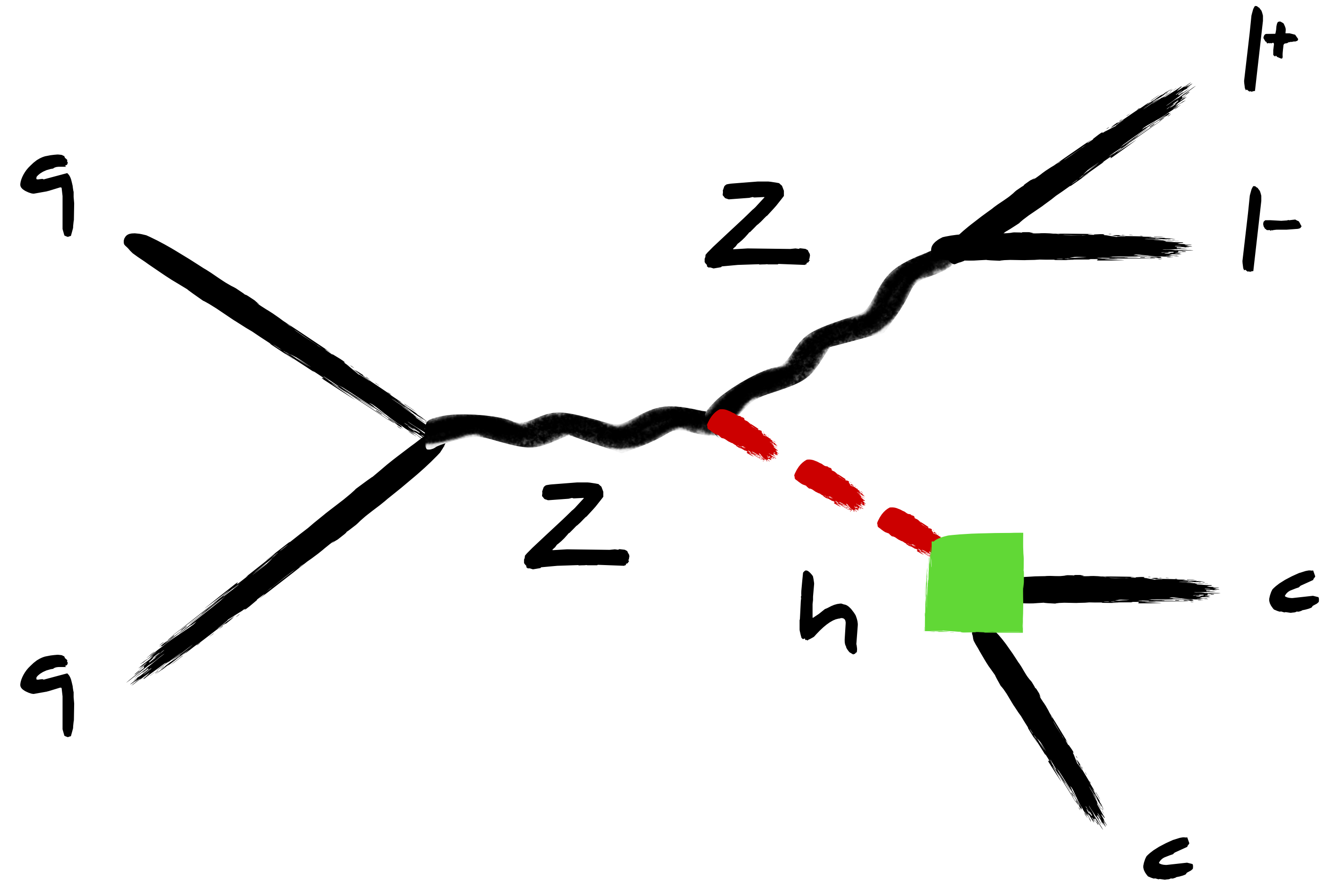
[Bishara, UH, Monni & Re, 1606.09253]



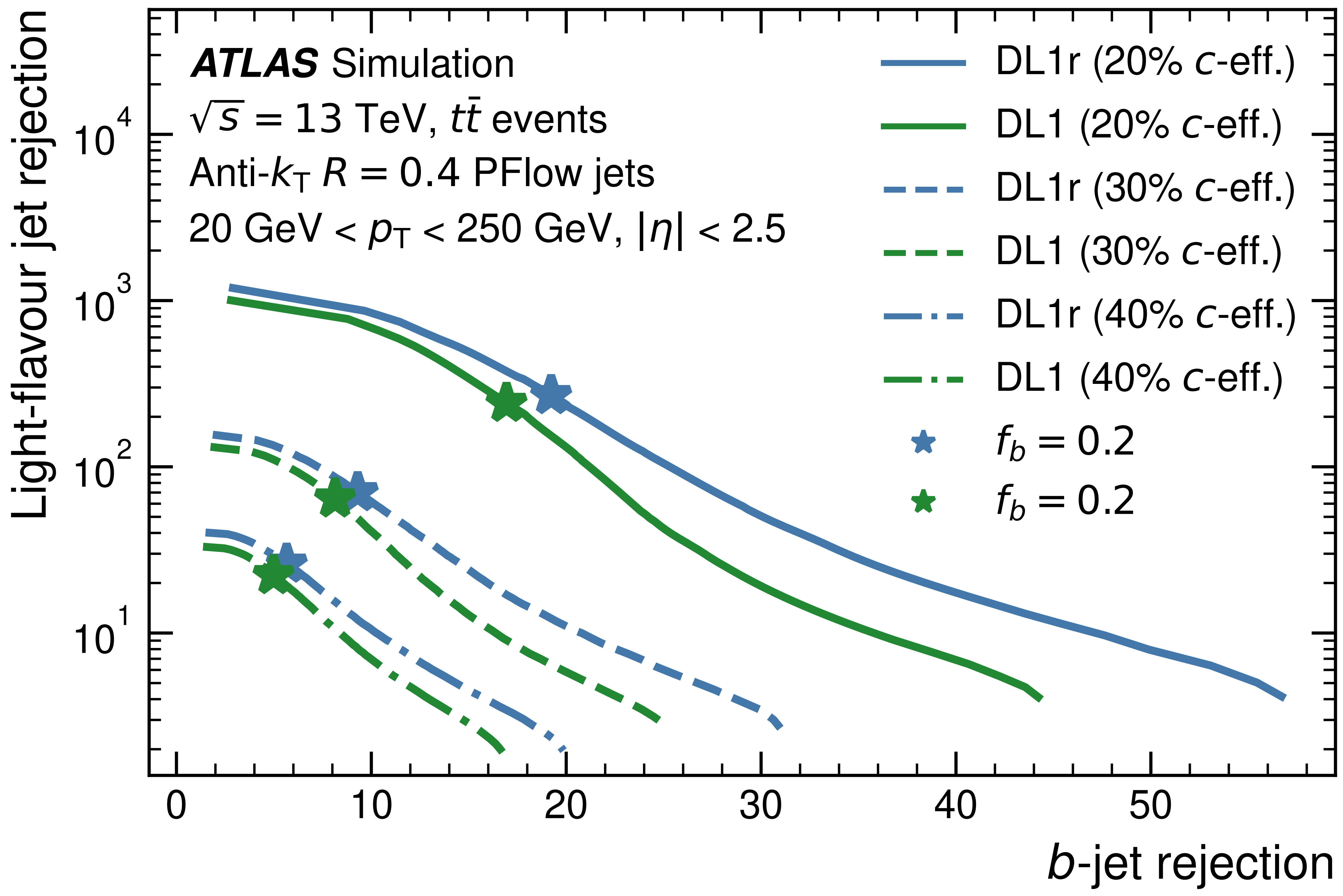
Same idea applies in light-quark case, but detectable effects only for very large κ_q

[see also Soreq, Zhu & Zupan, 1606.09621]

Constraints on y_c from Vh production



[ATLAS, 2211.16345]

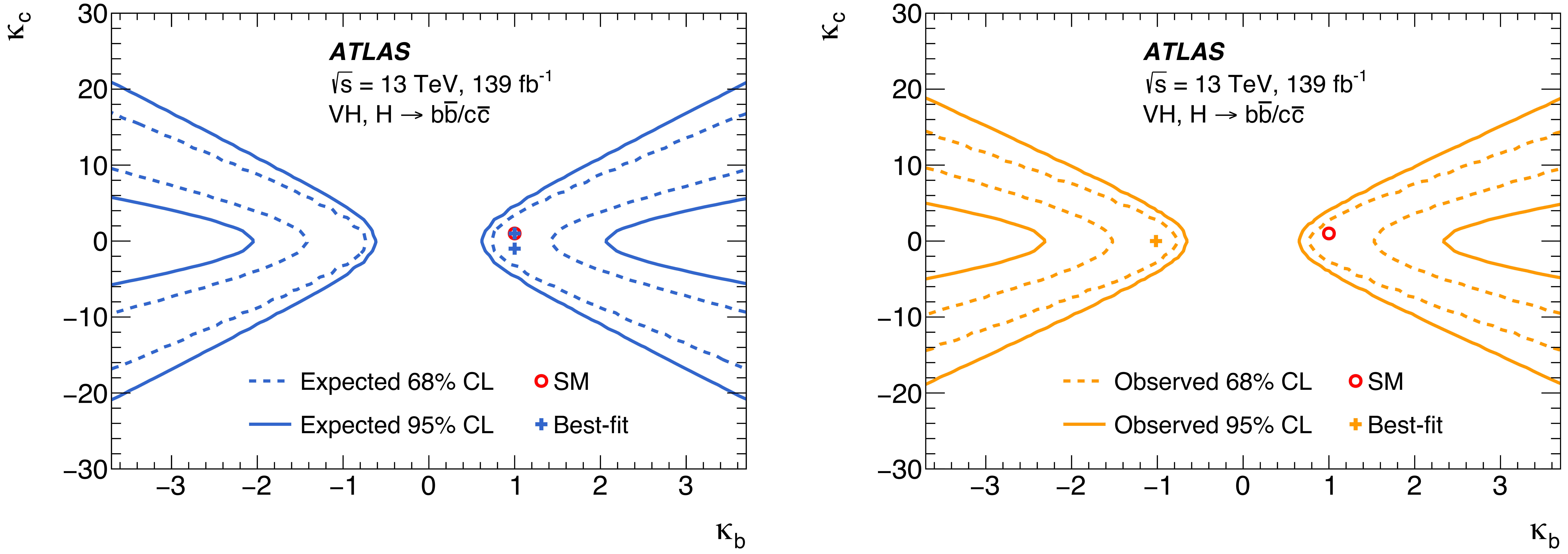


Charm-tagging enables to probe y_c directly @ LHC in associated Vh production

[idea developed in Delaunay, Golling, Perez & Soreq, 1310.7029; Perez, Soreq, Stamou & Tobioka, 1503.00290, 1505.06689]

Direct constraints on κ_b & κ_c @ LHC

[ATLAS, 2201.11428]

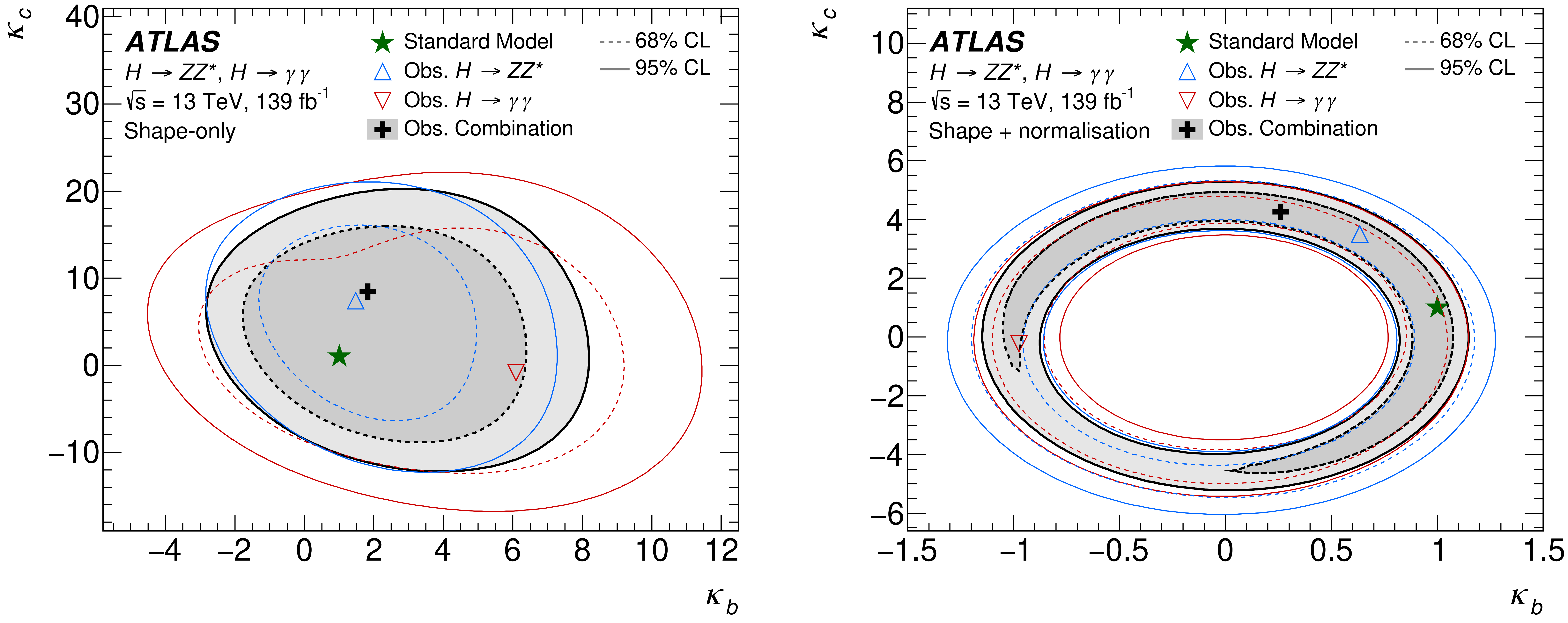


Vh production constrains κ_b & κ_c to two hyperbola-like strips in 2D plane

[see also CMS, 2205.05550; ATLAS, 2410.19611; talks by Missio, Ördek & Wuchterl]

Indirect constraints on κ_b & κ_c @ LHC

[ATLAS, 2207.08615]

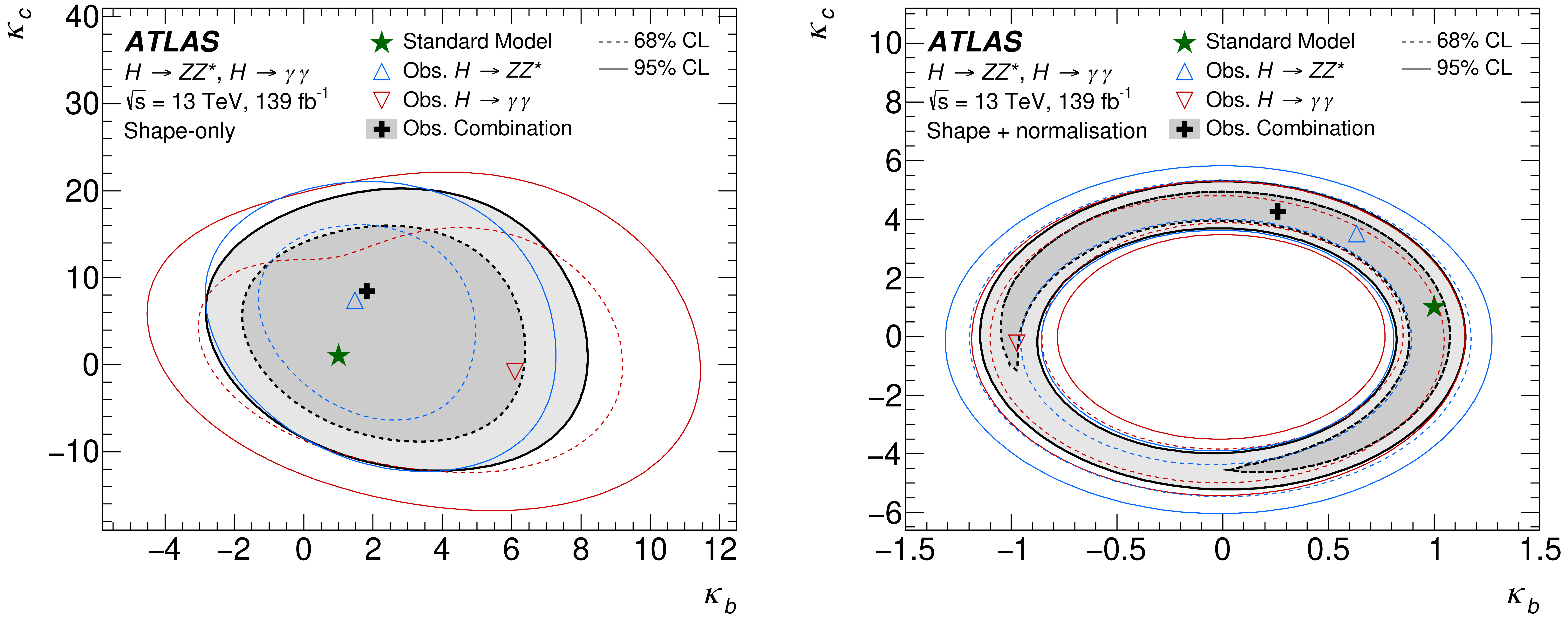


At present, shape changes in $p_{T,h}$ spectrum lead only to weak oval exclusions

[see also CMS, 2305.07532; CMS-PAS-HIG-23-013; talks by Galli, Winterbottom & Wuchterl]

Indirect constraints on κ_b & κ_c @ LHC

[ATLAS, 2207.08615]

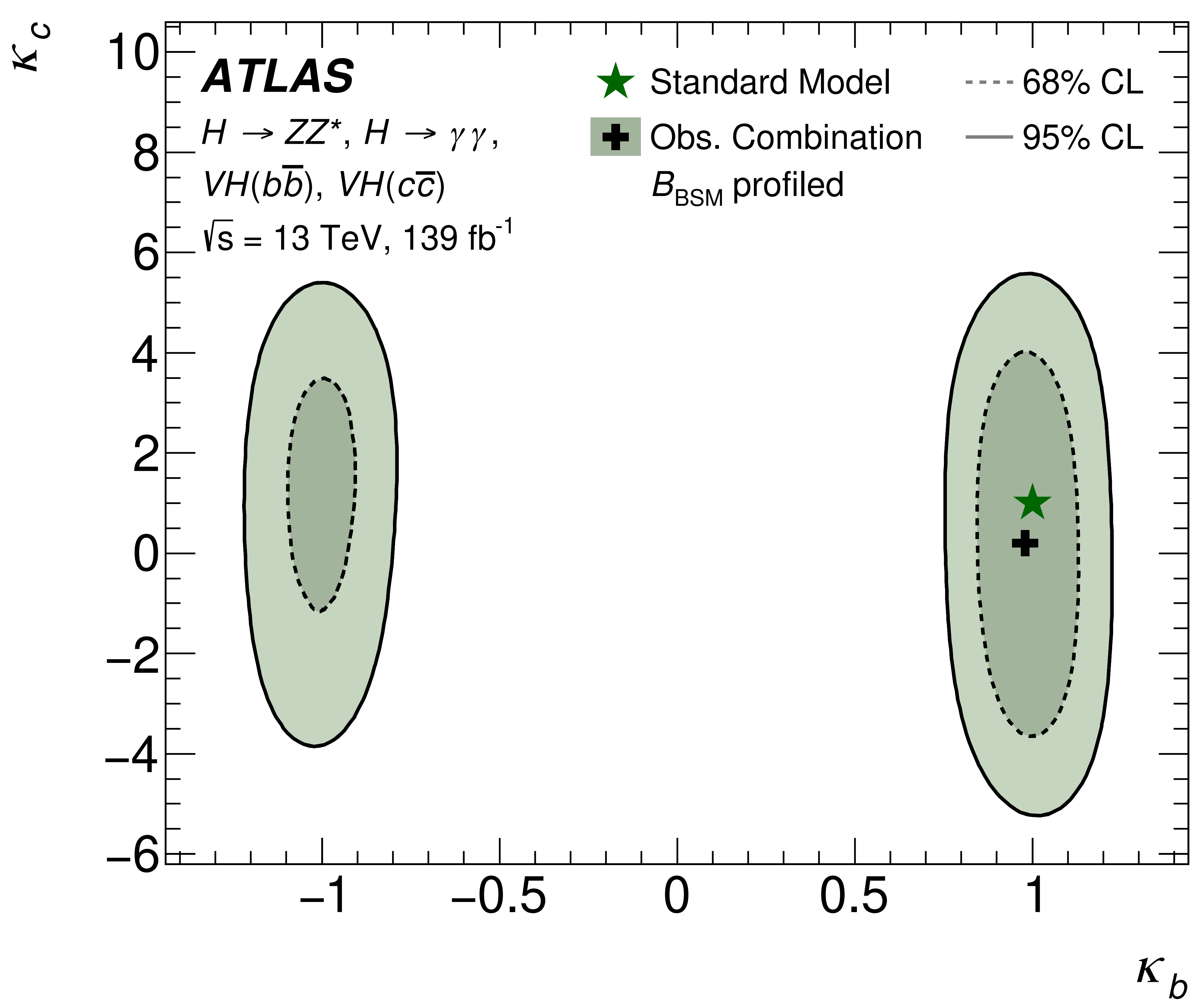


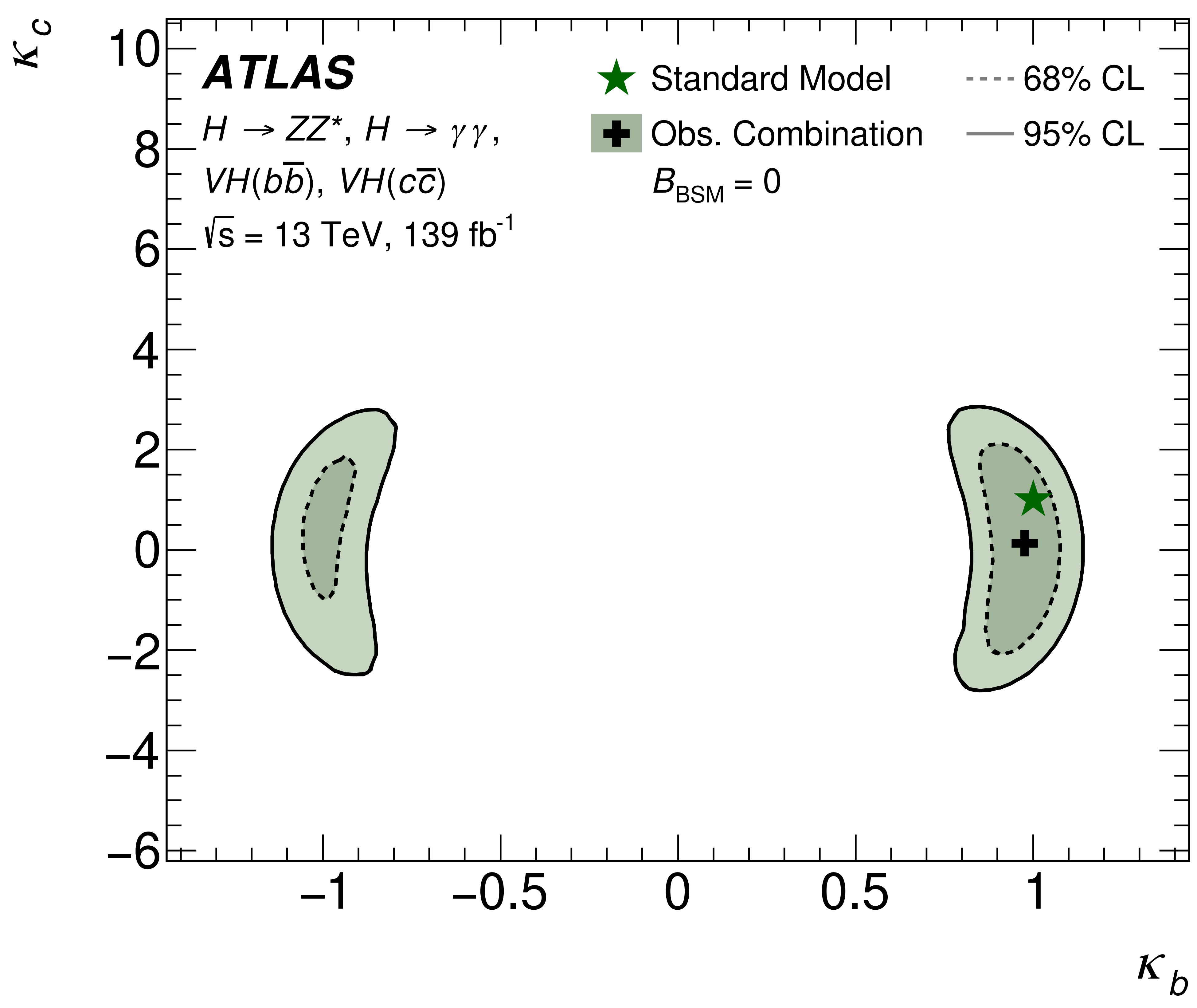
Adding information on normalisation, constrains κ_b & κ_c to elliptic band in 2D plane

[see also CMS, 2305.07532; CMS-PAS-HIG-23-013; talks by Galli, Winterbottom & Wuchterl]

Combined constraints on κ_b & κ_c @ LHC

[ATLAS, 2207.08615]

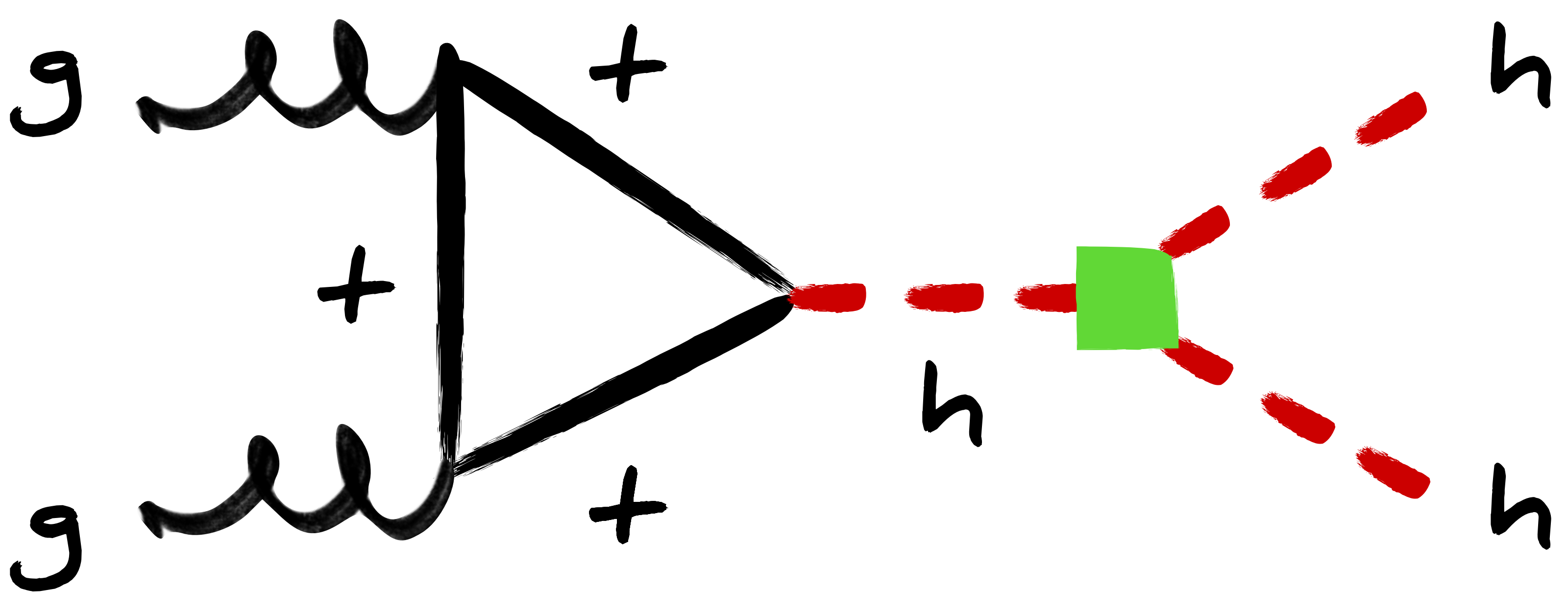


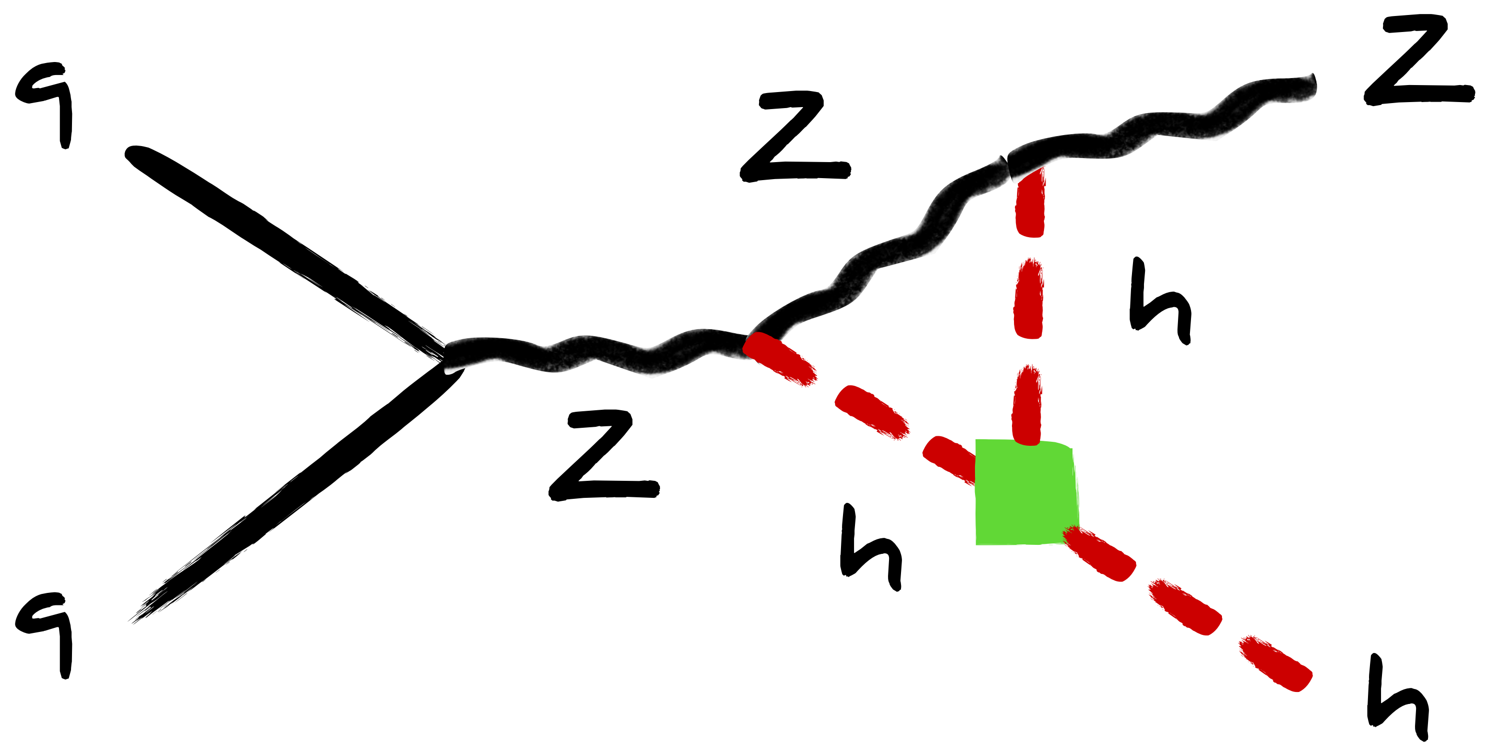


Combination of bounds leads to two island of solution centred around (1,1) & (-1,-1).

Limits depend on assumption about size of new-physics effects in Higgs width

(In)direct probes of κ_λ

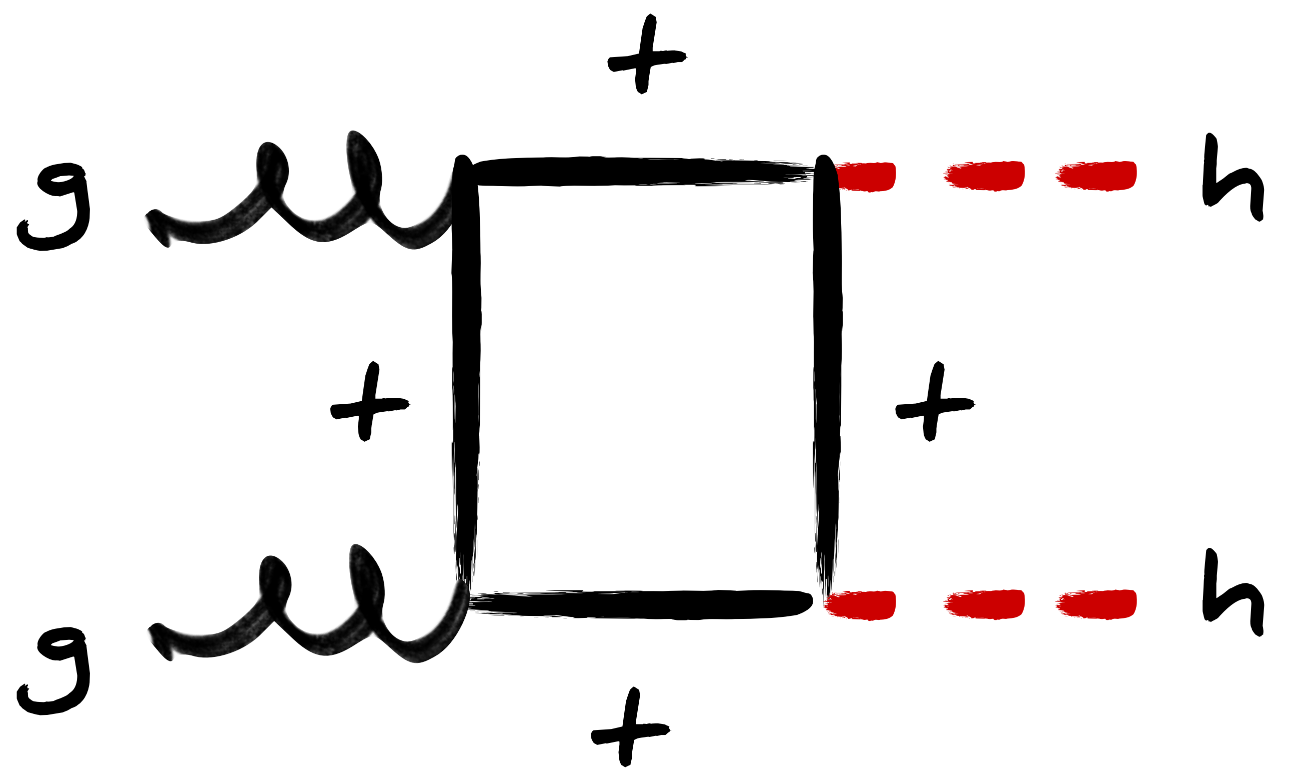


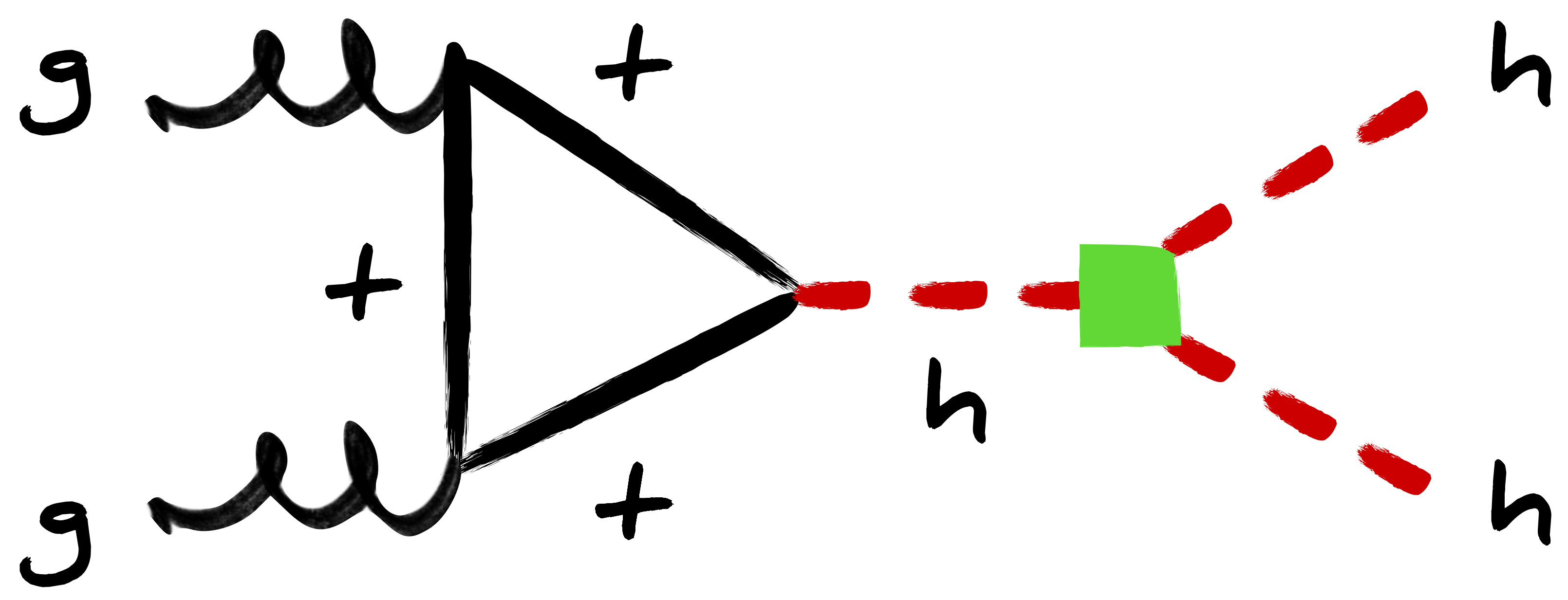


Direct probe of trilinear Higgs self-coupling (κ_λ) provided by hh production, while all single-h production & decay channels @ LHC become indirectly sensitive to κ_λ at 1-loop (Vh, VBF, $t\bar{t}h$, $h\rightarrow b\bar{b}$, etc.) or 2-loop level (ggF, $h\rightarrow\gamma\gamma$, etc.)

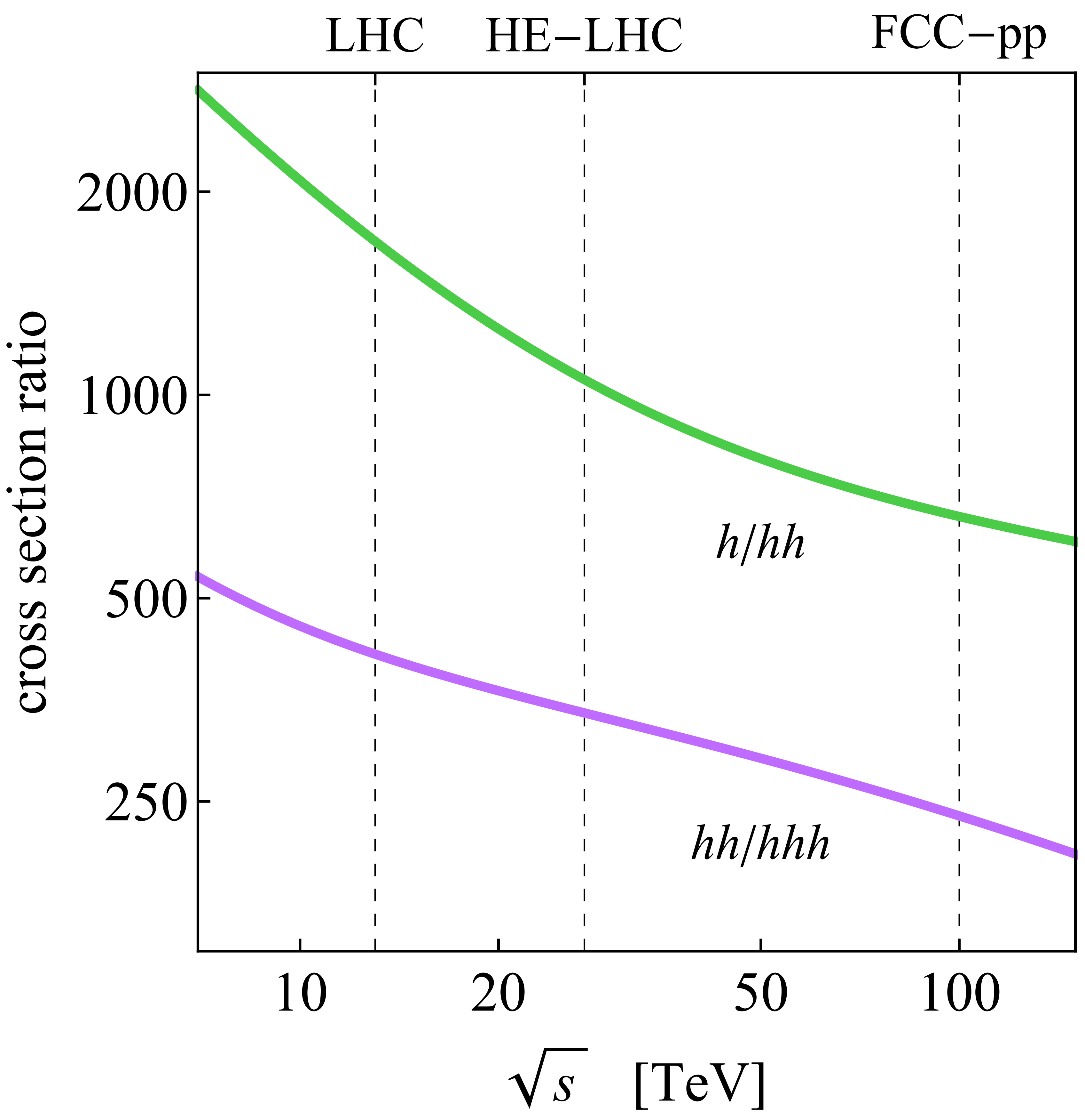
[see for instance McCullough, 1312.3322; Gorbahn & UH, 1607.03773; Degrassi et al., 1607.04251; Bizon et al., 1610.05771; …]

(In)direct probes of κ_λ



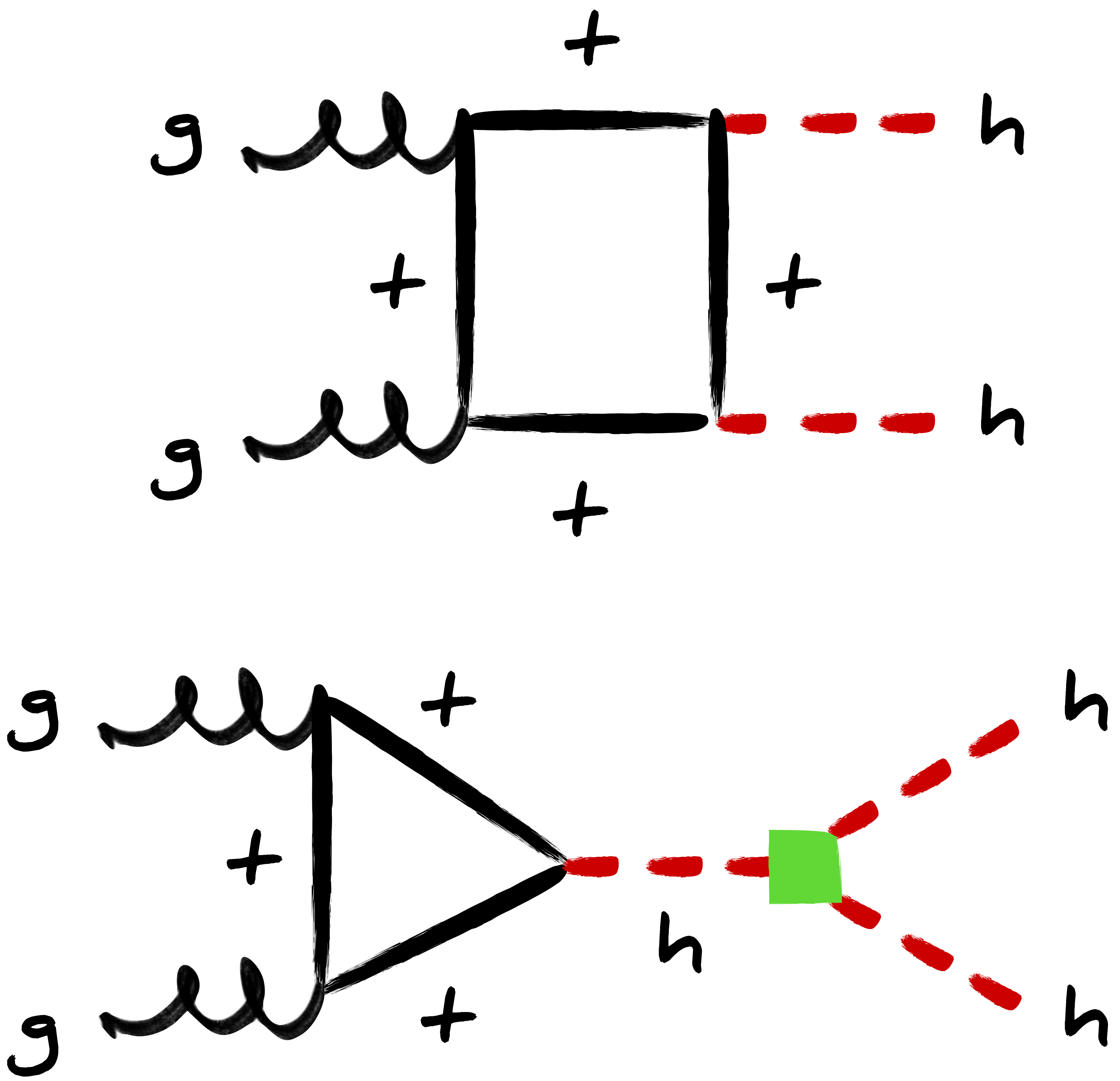


[Bizon, UH & Rottoli, 1810.04665]



Loop probes of κ_λ can only compete with hh production because of destructive interference between box & triangle contribution in gg→hh amplitude

(In)direct probes of κ_λ



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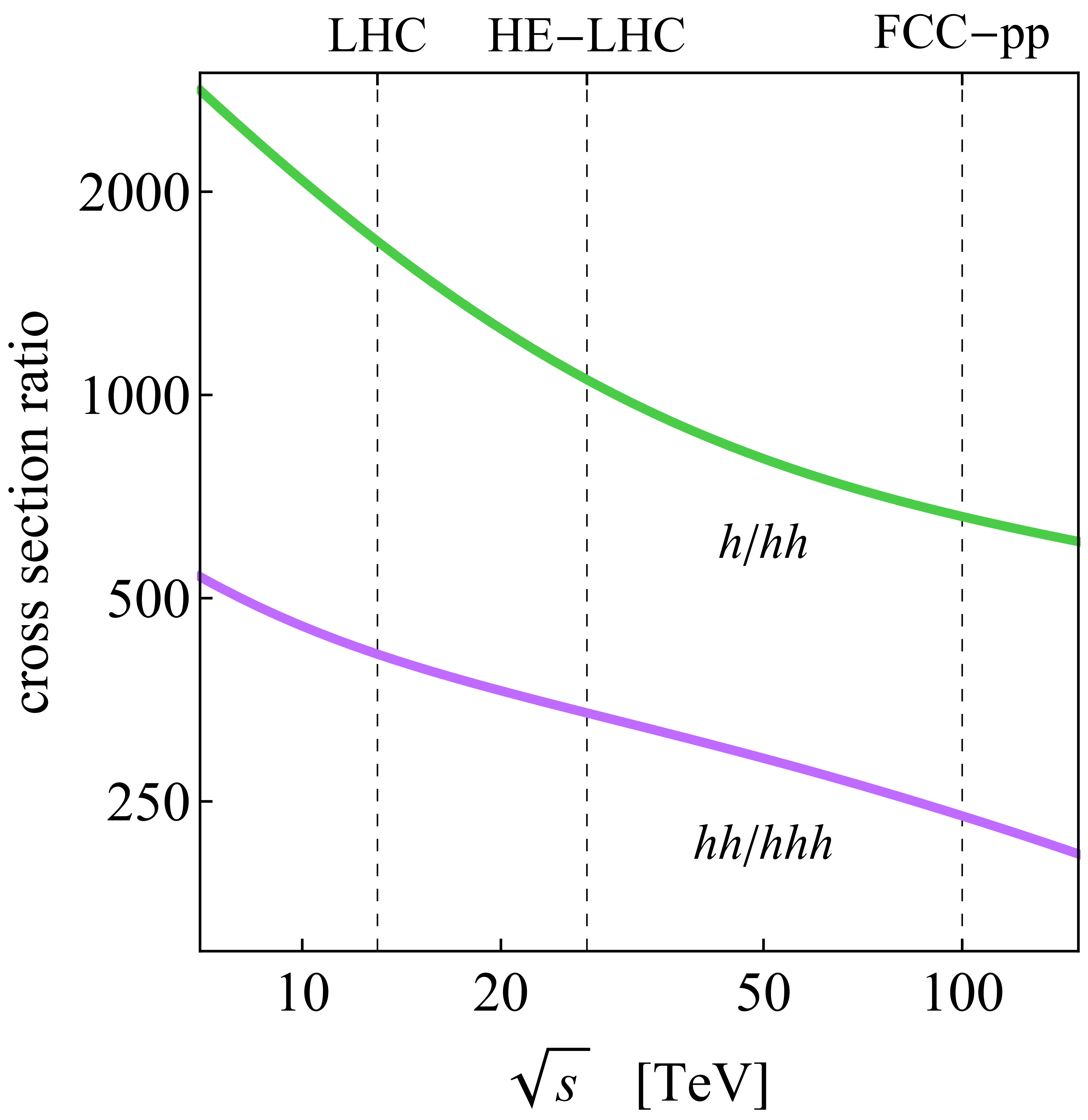


Suppression of pp→hh rate more pronounced @ LHC than @ HE-LHC or FCC-pp energies, rendering indirect tests of Higgs self-couplings more promising @ LHC

Combined constraints on κ_λ @ LHC

[ATLAS, 2211.01216]

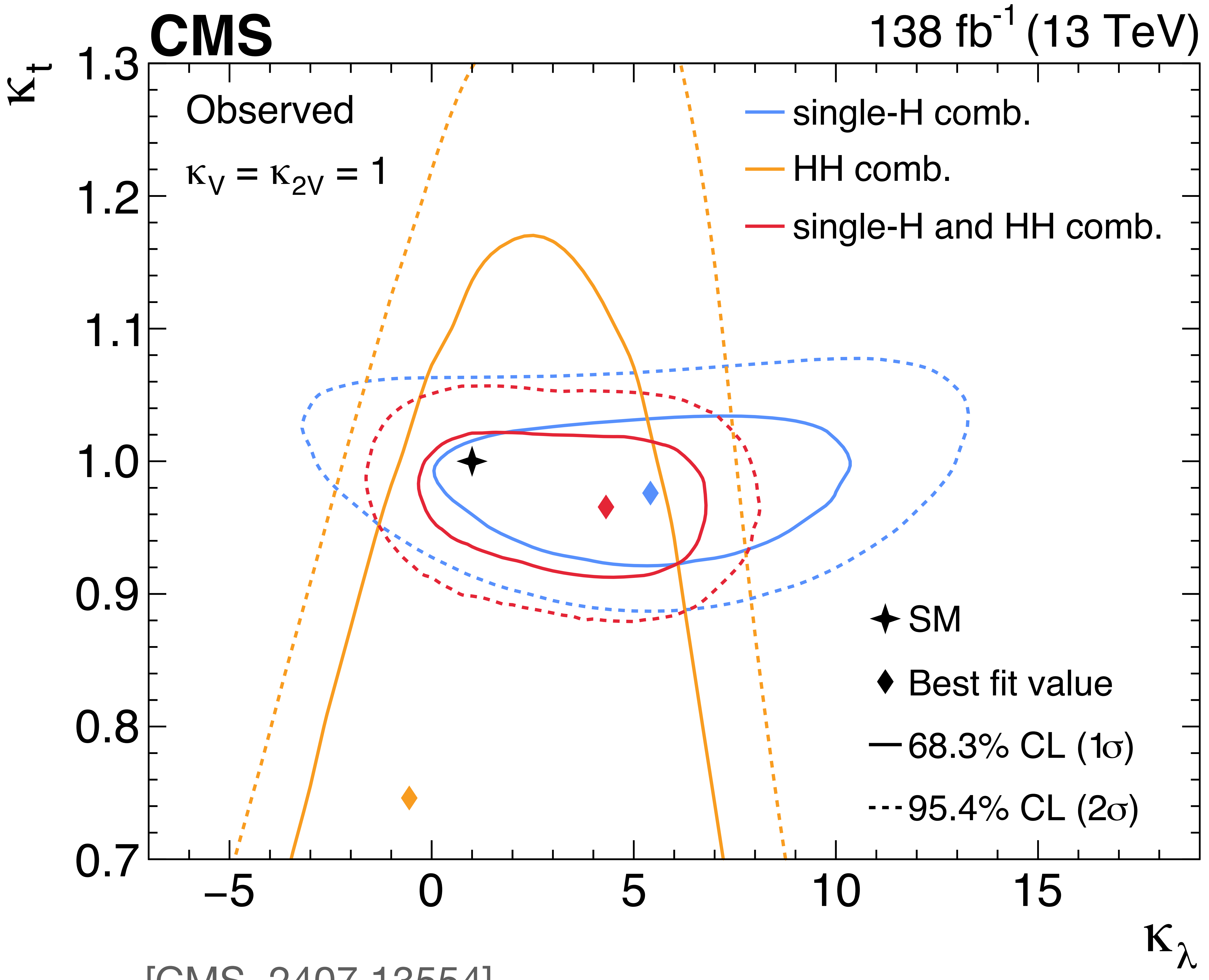
Combination assumption	Obs. 95% CL	Exp. 95% CL	Obs. value$^{+1\sigma}_{-1\sigma}$
HH combination	$-0.6 < \kappa_\lambda < 6.6$	$-2.1 < \kappa_\lambda < 7.8$	$\kappa_\lambda = 3.1^{+1.9}_{-2.0}$
Single-H combination	$-4.0 < \kappa_\lambda < 10.3$	$-5.2 < \kappa_\lambda < 11.5$	$\kappa_\lambda = 2.5^{+4.6}_{-3.9}$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

If only κ_λ is considered, constraints from hh production are notable better than bounds that arise from combination of single-h measurements

[see also CMS, 2407.13554; talks by Balunas, Galli & Motta]

Combined constraints on κ_λ @ LHC

But, large degeneracy of hh production cross section to κ_λ & κ_t, limits κ_λ sensitivity of hh process in 2D plane. Instead, single-h combination provides stringent bounds on κ_t, which is utilized in hh+h combination

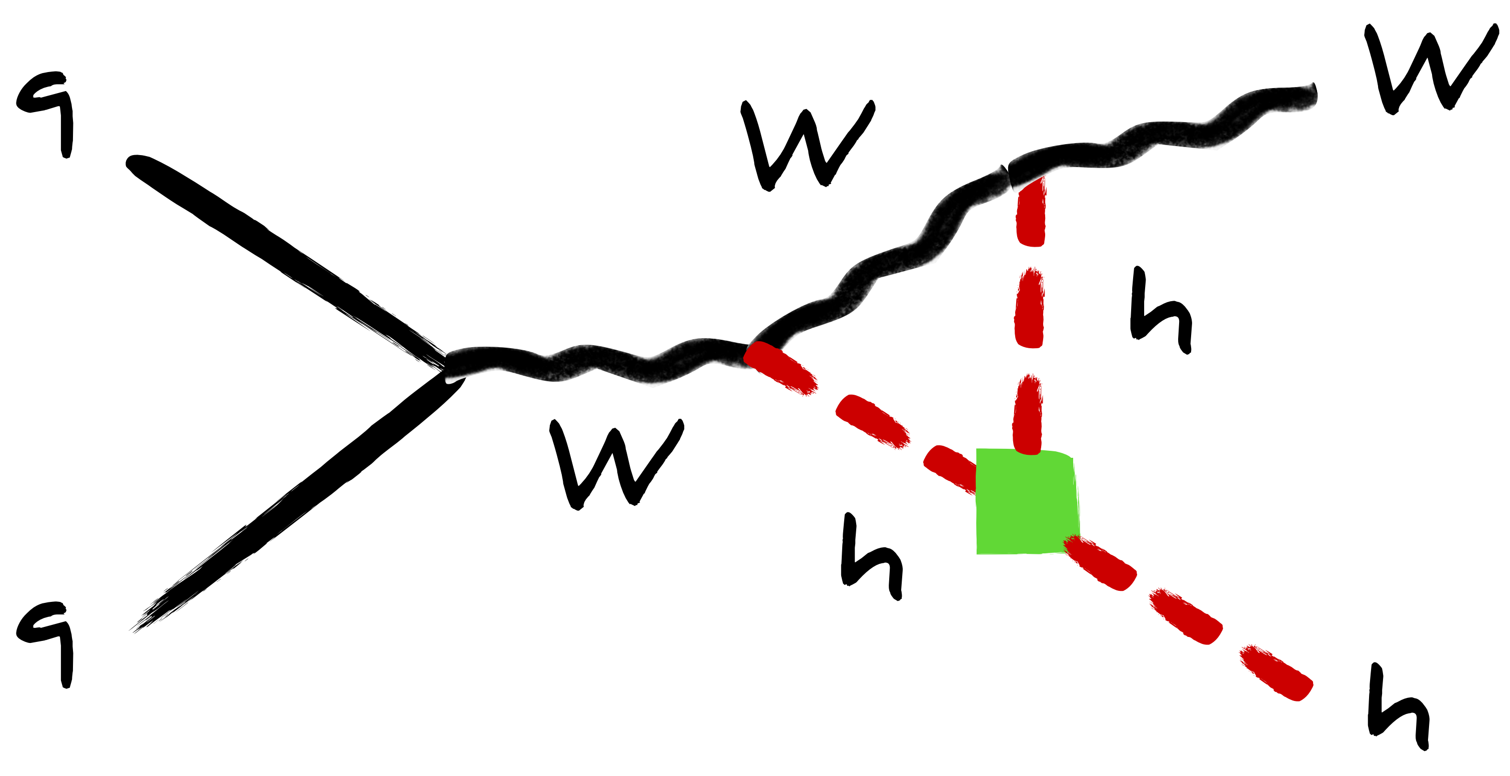


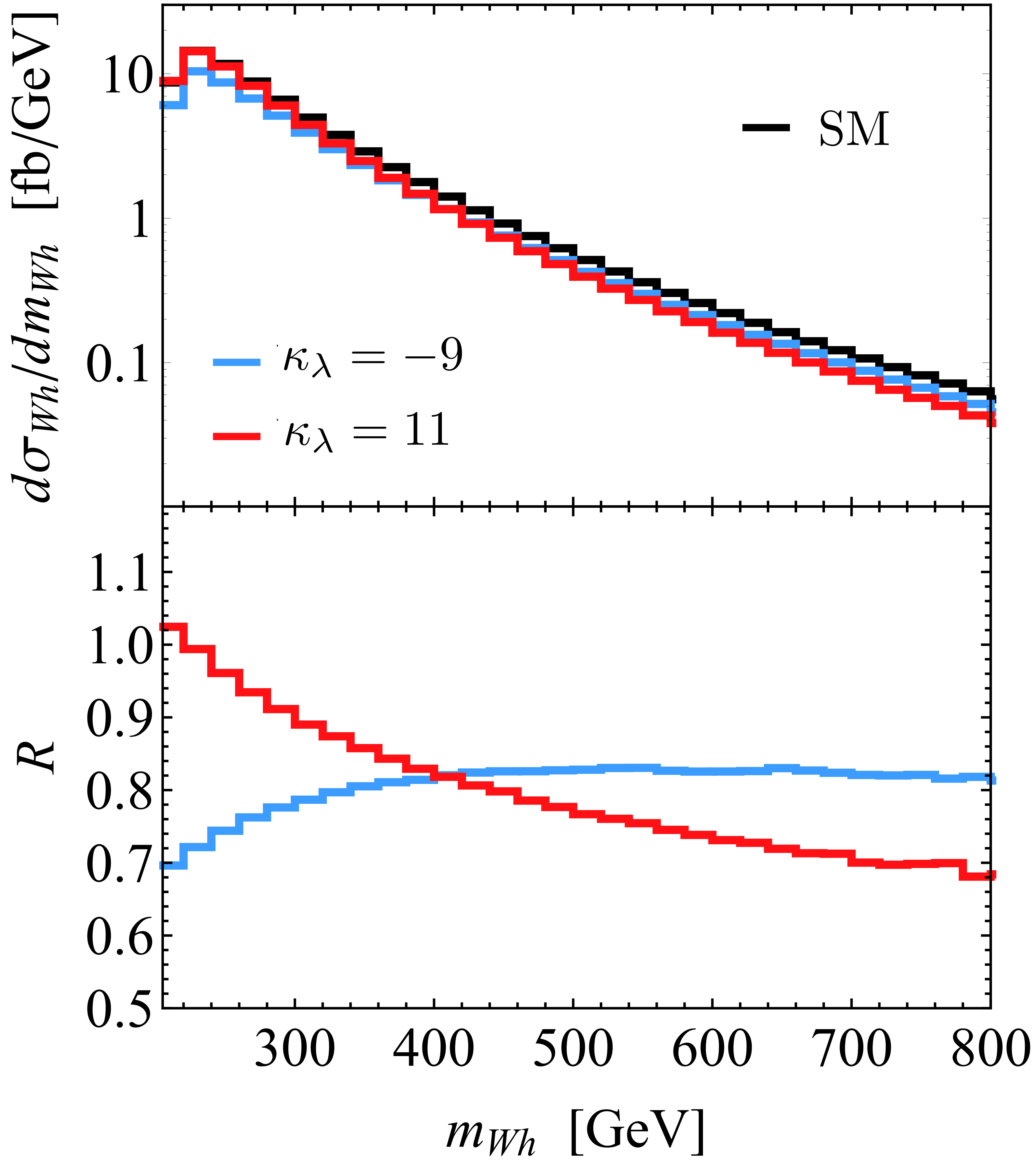
[CMS, 2407.13554]

[see also ATLAS, 2211.01216; talks by Balunas, Galli & Motta]

Differential single-h measurements & κλ

[Bizon et al., 1610.05771]

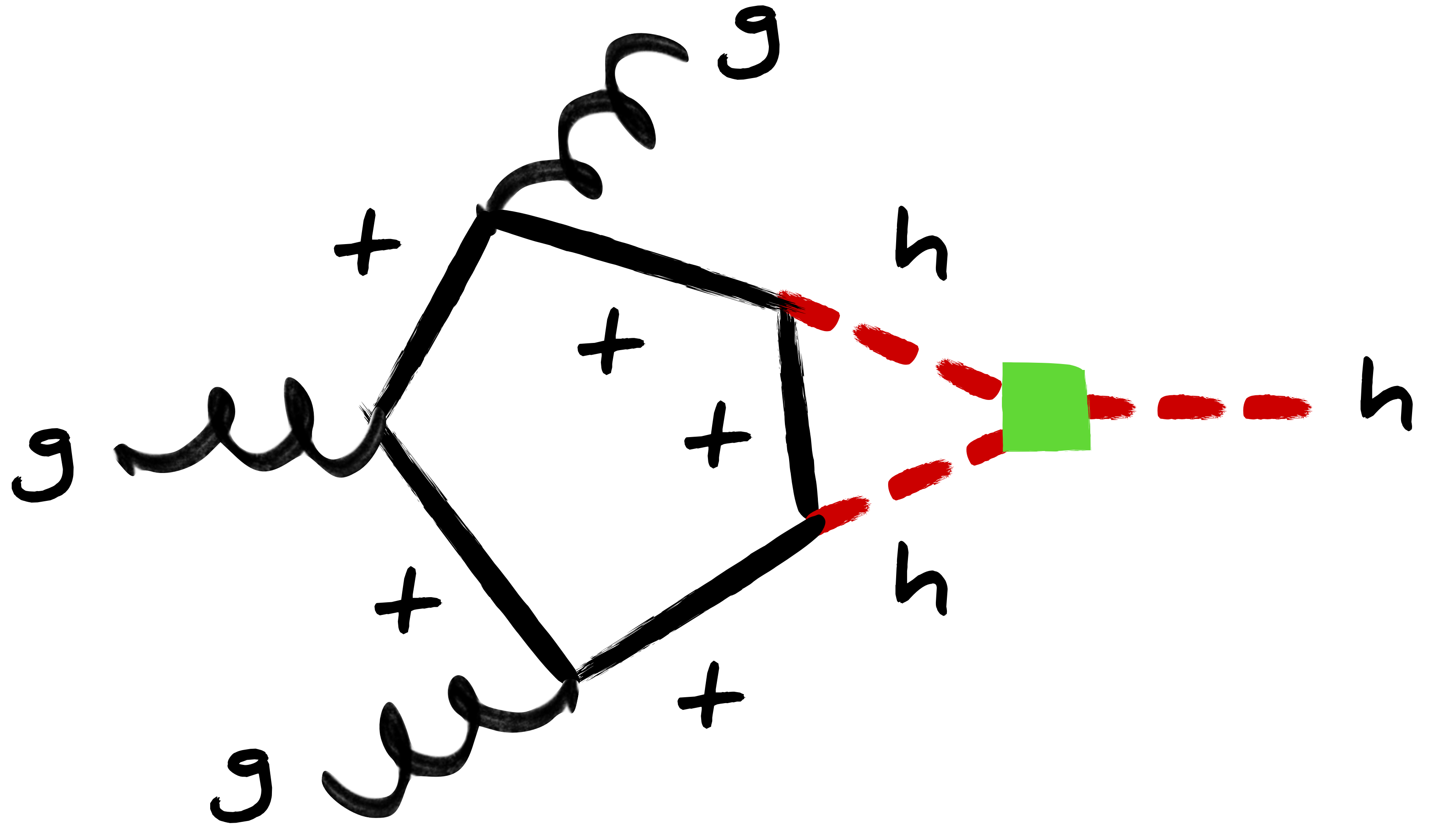




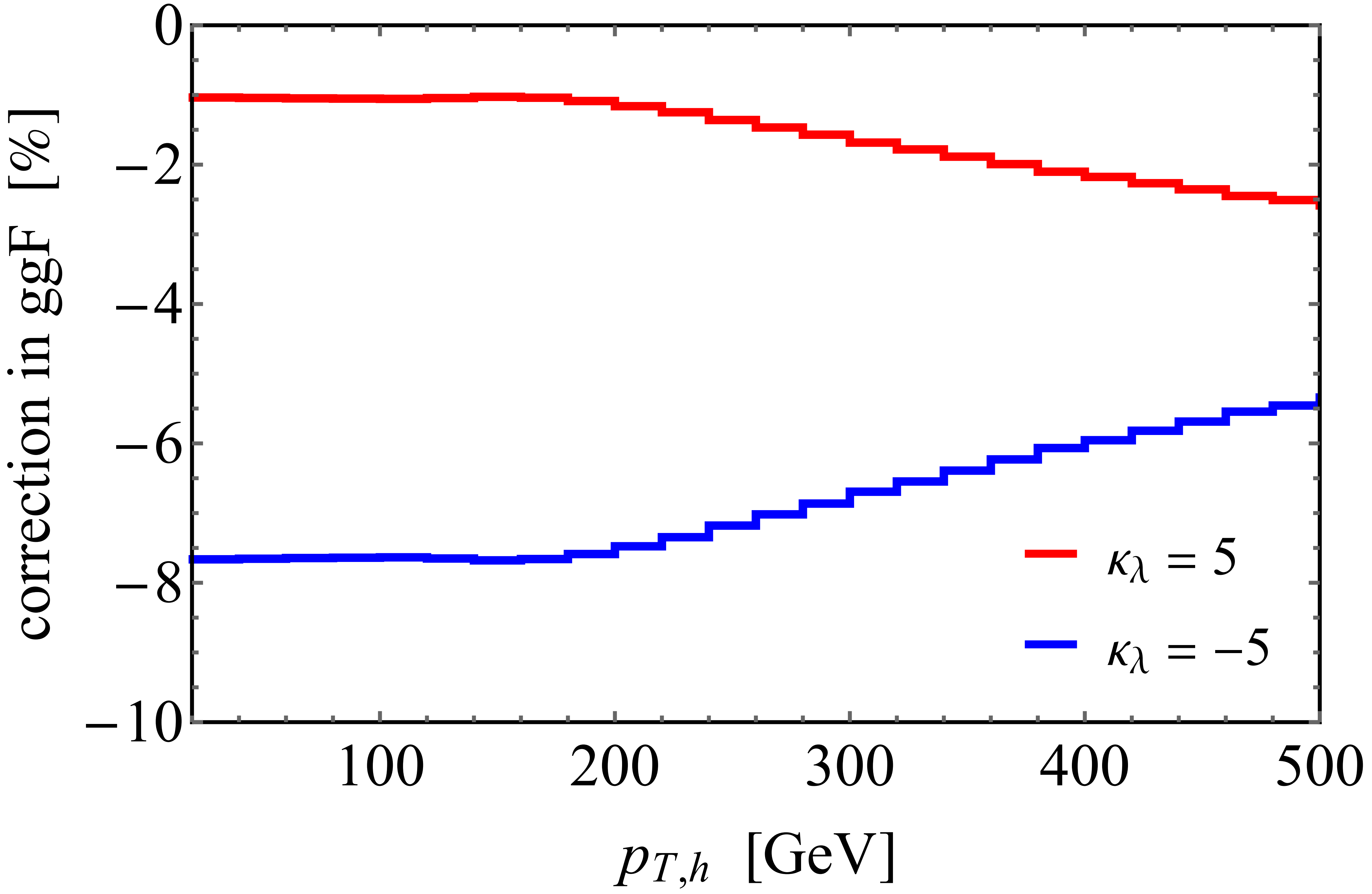
Non-trivial modifications of kinematic distributions due to heavy particles in loops of single-h probes

[see also Maltoni, Pagani, Shivaji & Zhao, 1709.08649]

Differential single-h measurements & κ_λ



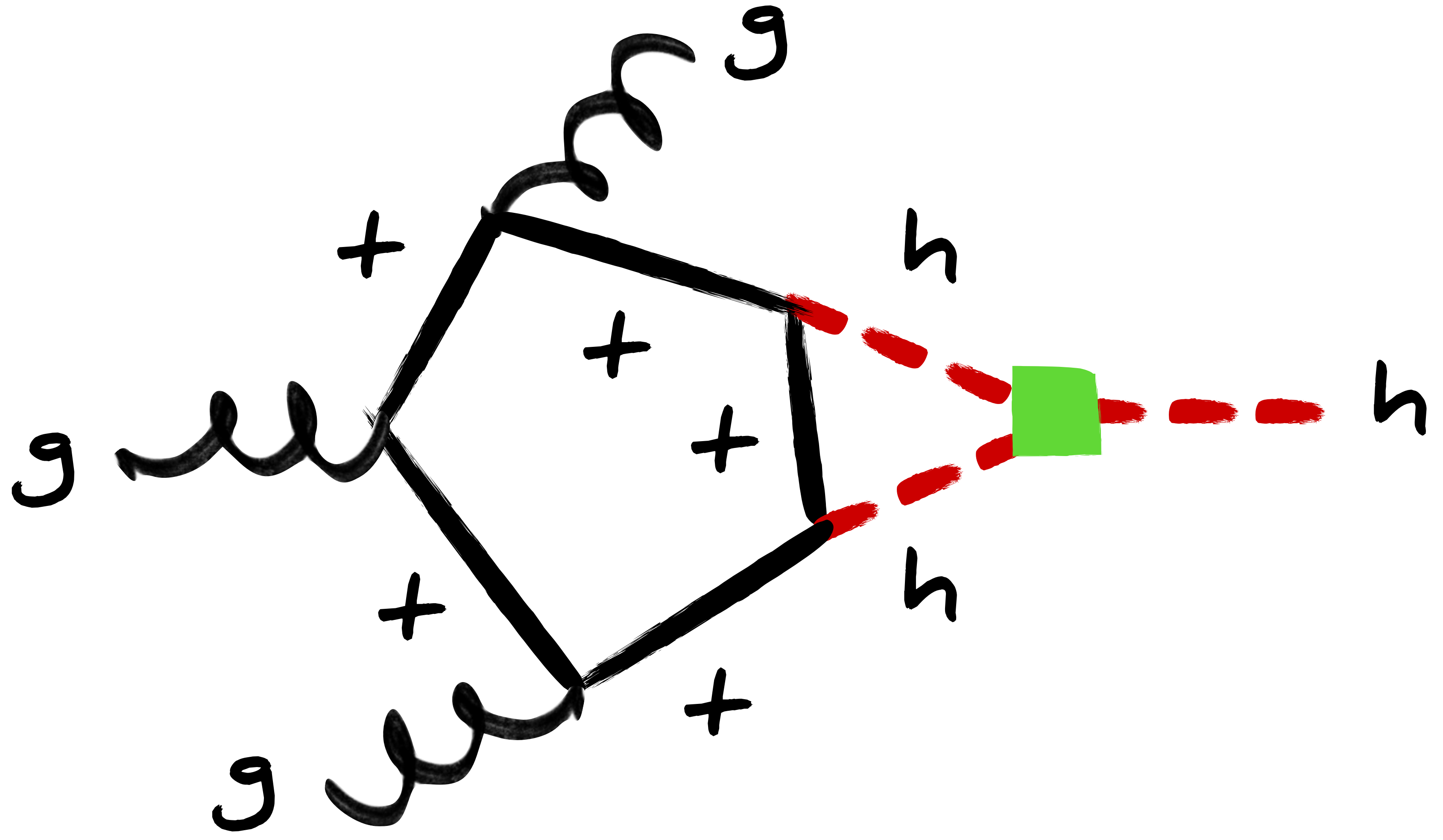
[based on UH & Niggetiedt, 2408.13186]



Exact κ_λ dependence computed for differential single-Higgs predictions in all cases relevant for LHC, i.e. ggF, Vh, VBF, $t\bar{t}h$ & th production

[Bizon et al., 1610.05771, Maltoni et al., 1709.08649; UH & Niggetiedt, 2408.13186]

Differential single-h measurements & κ_λ



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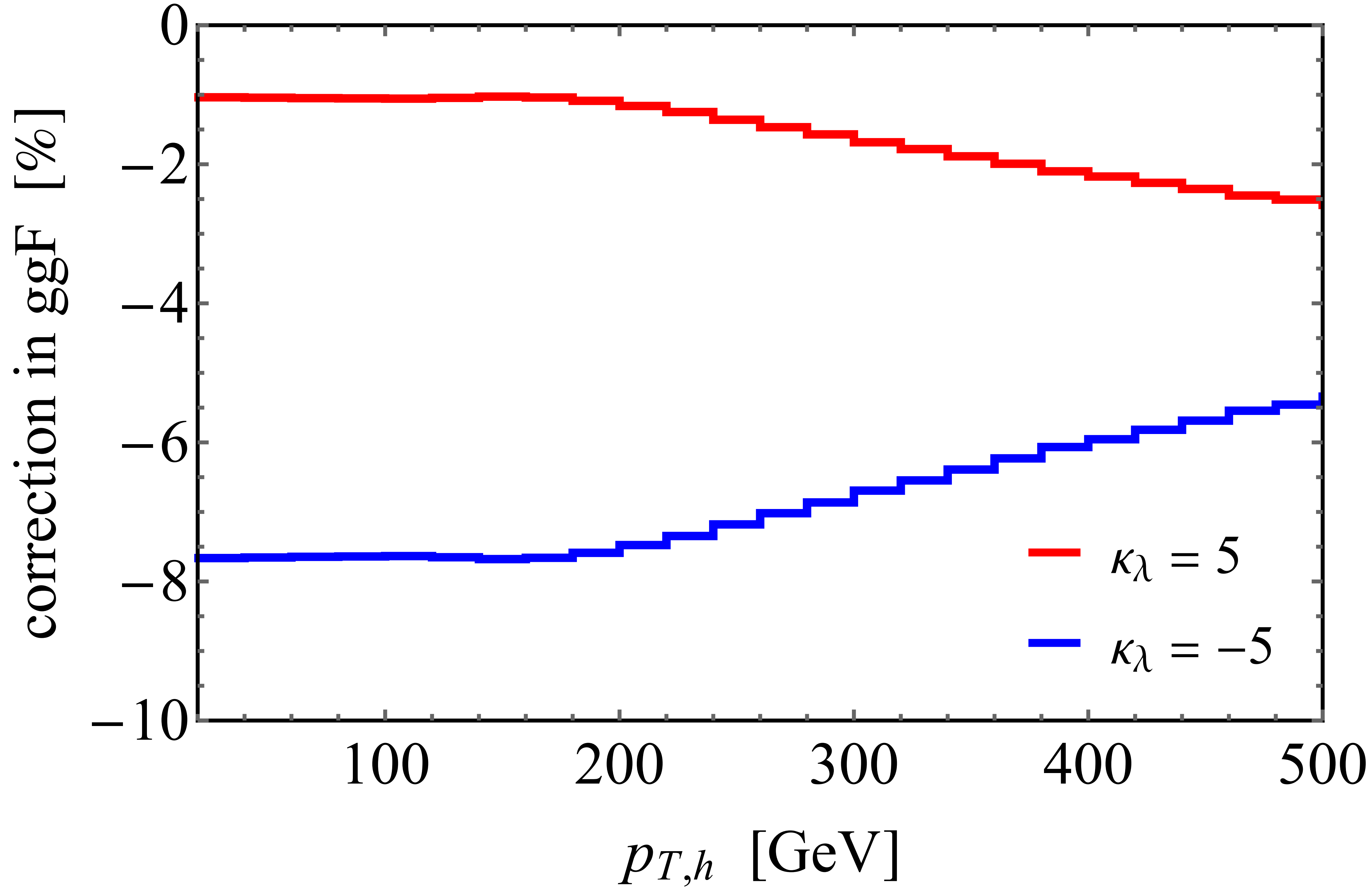
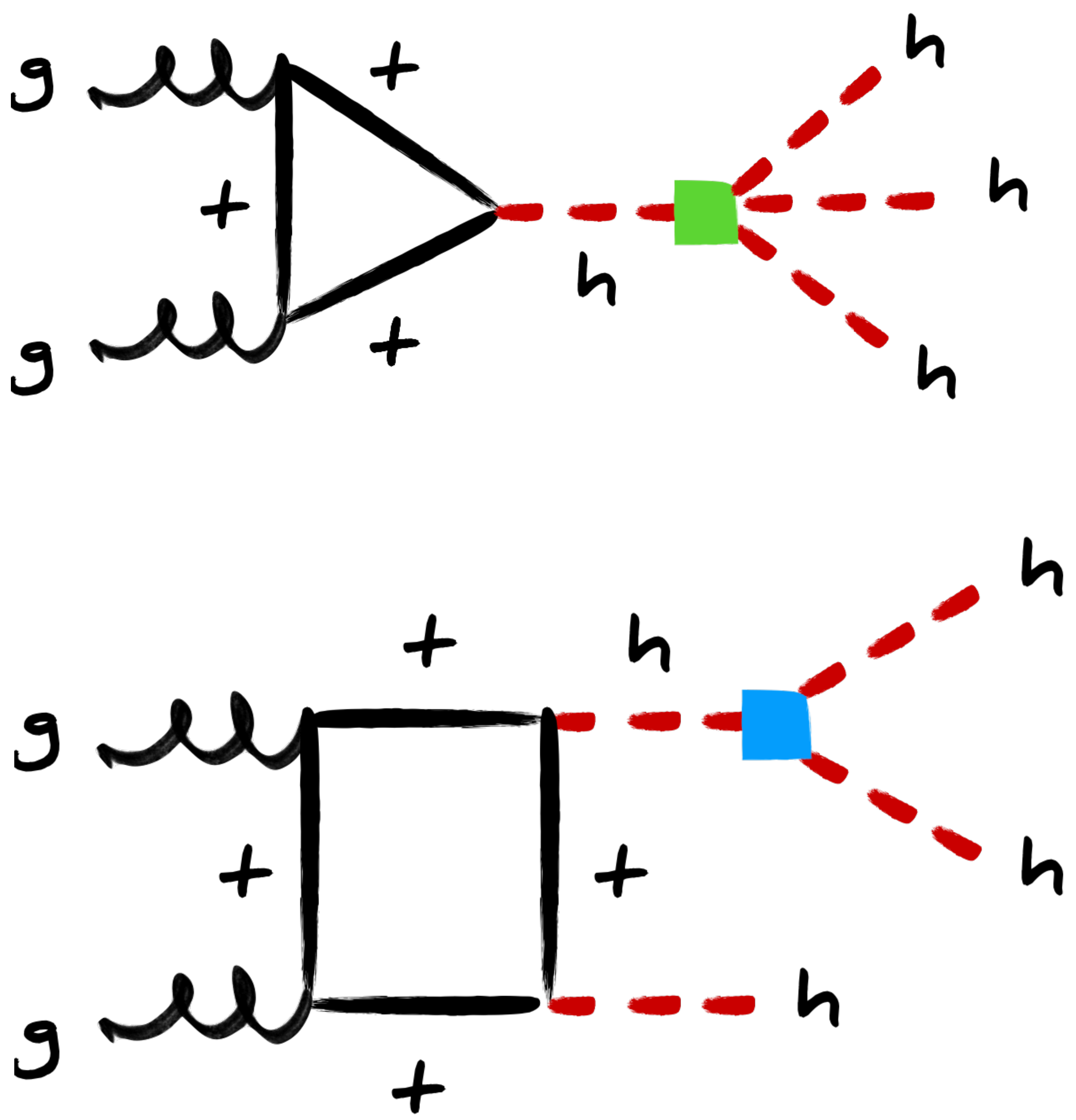


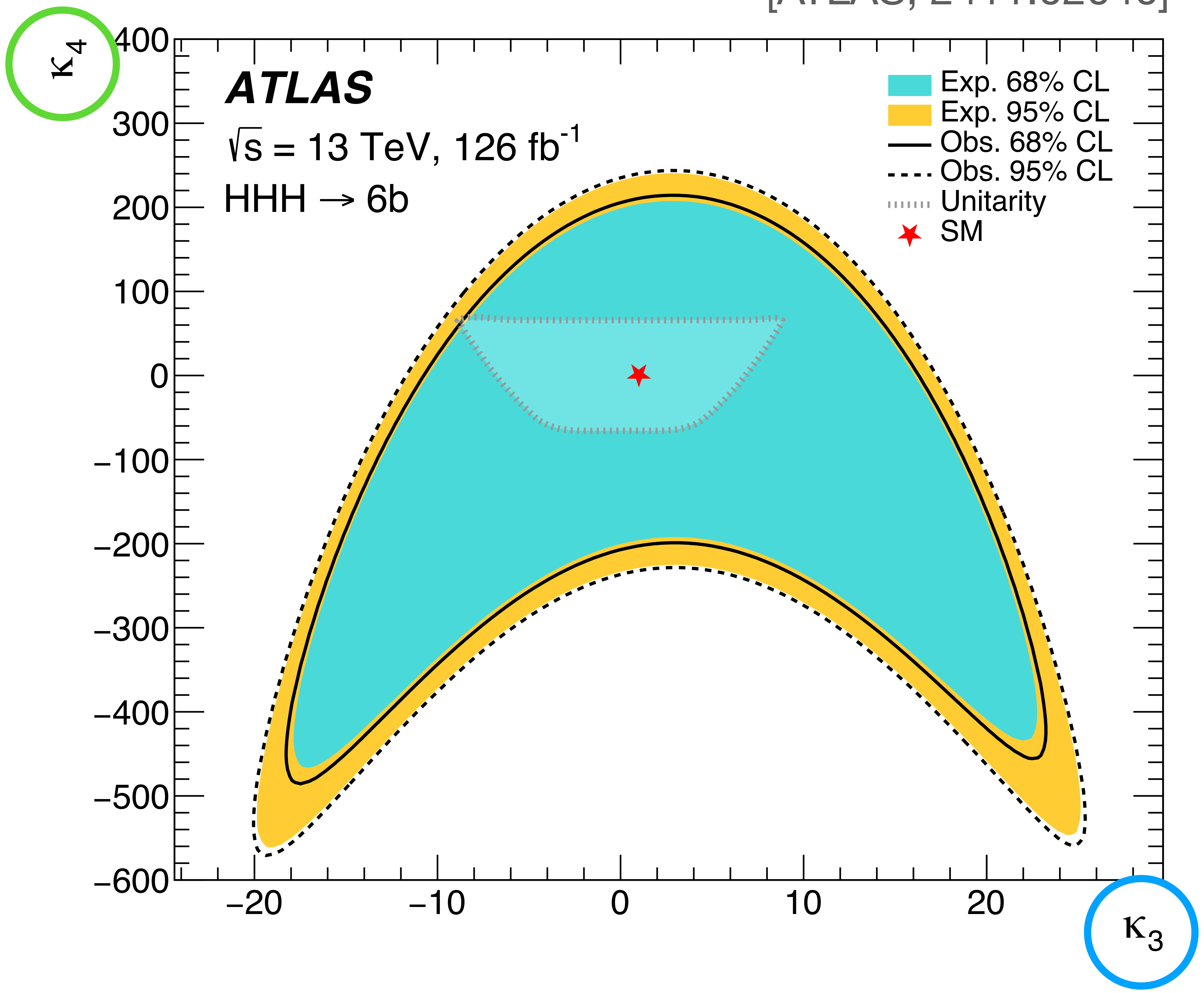
Dedicated studies needed to quantify precise impact of differential single-h measurements in global hh+h analyses to constrain κ_λ

[Bizon et al., 1610.05771, Maltoni et al., 1709.08649; UH & Niggetiedt, 2408.13186]

Nice, first LHC limit on 3h production!



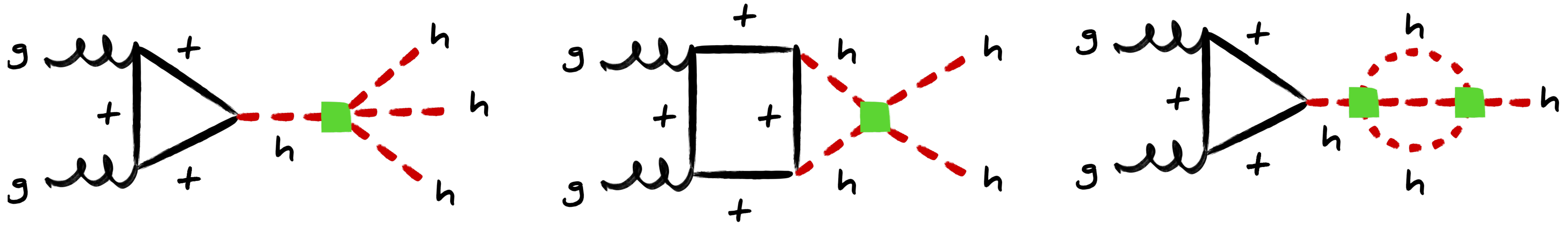
[ATLAS, 2411.02040]



ATLAS puts first constraint on 3h production & interprets its result in κ_3-κ_4 plane

[see also talk by Balunas & Chen]

(In)direct probes of κ4

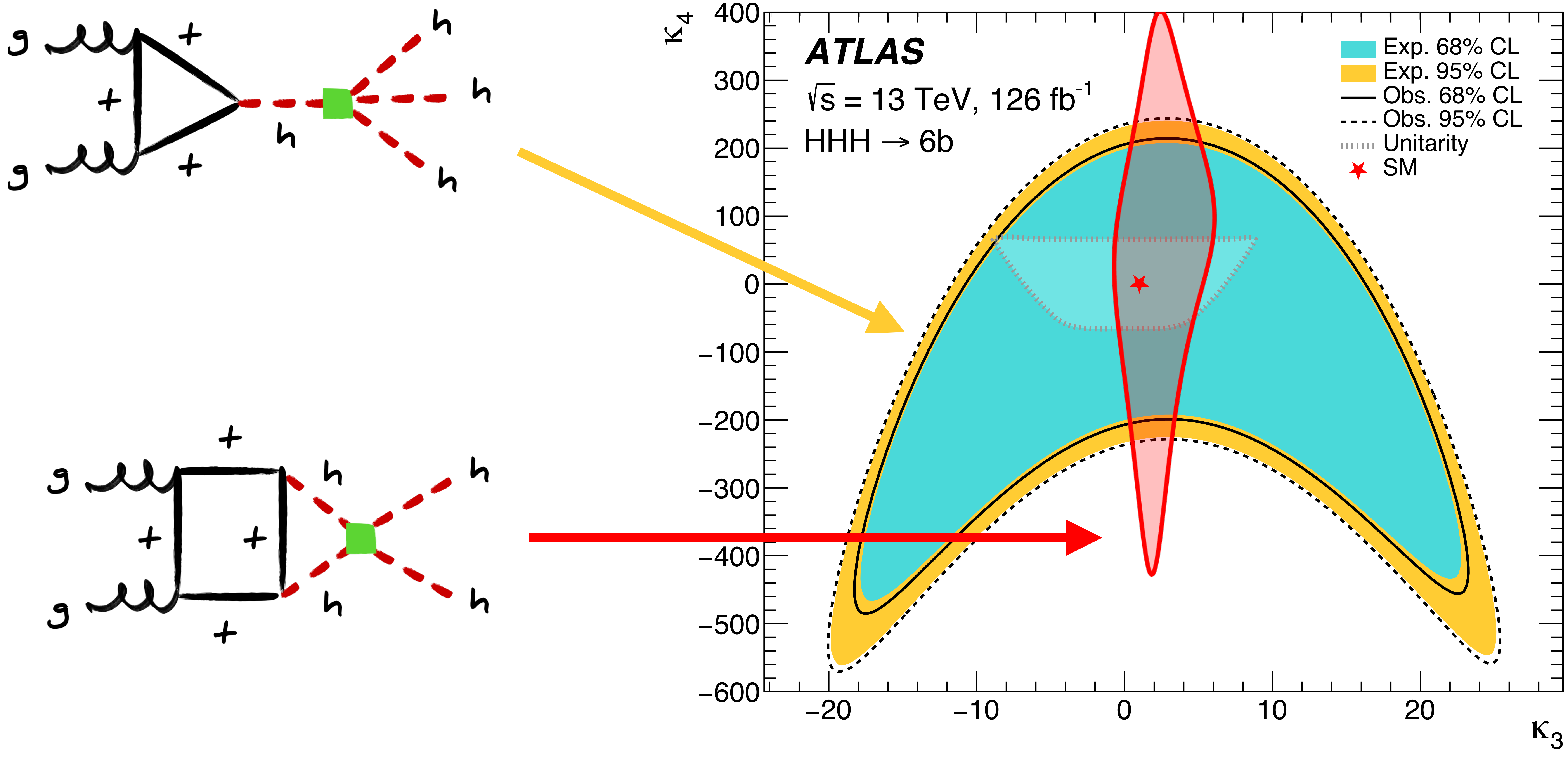


Direct probe of quartic Higgs self-coupling (κ4) provided @ 1-loop by 3h production, while indirect sensitivity in hh & h production through 2-loop & 3-loop corrections

[see for instance Bizon et al., 1810.04665, 2402.03463; Borowka et al., 1811.12366]

Higgs self-couplings after LHC Run 2

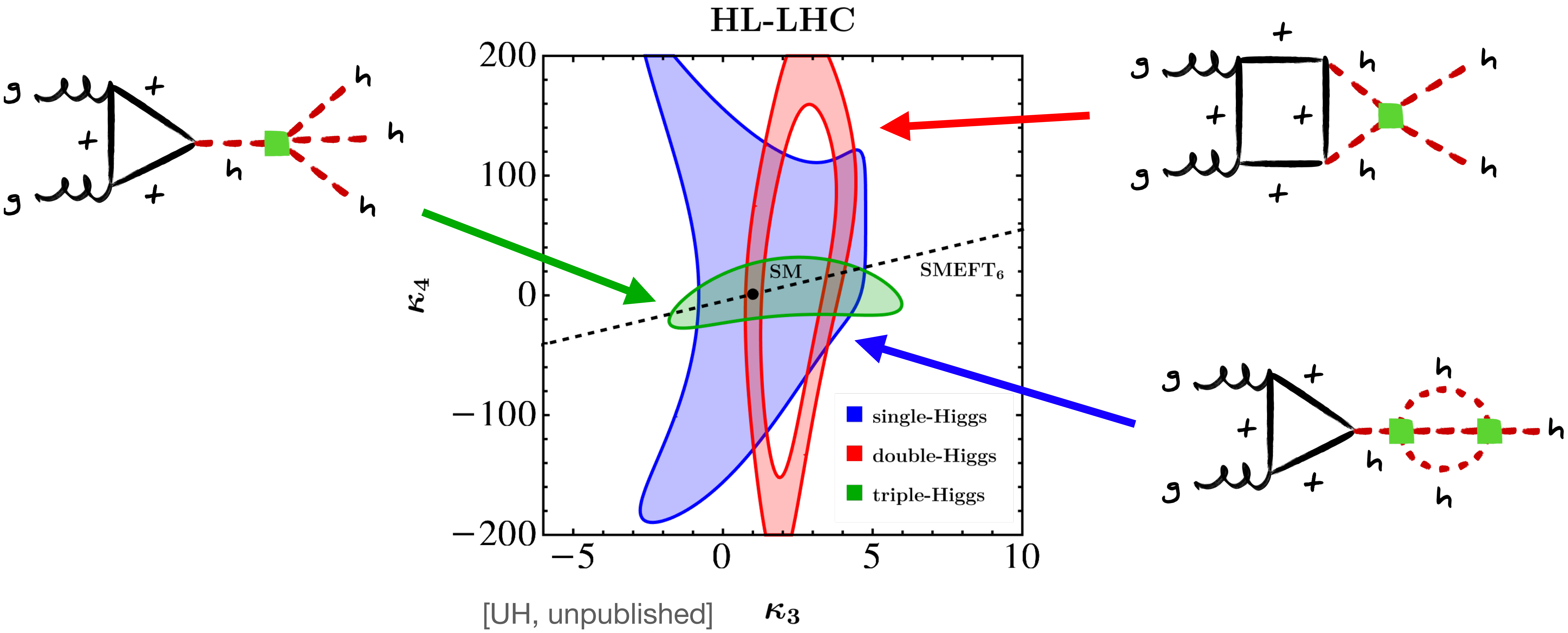
[ATLAS, 2411.02040]



Bounds on Higgs self-couplings from hh & 3h production orthogonal in κ_3-κ_4 plane

[pp→hh bound obtained using results from Bizon et al., 2402.03463]

Higgs self-couplings in HL-LHC era

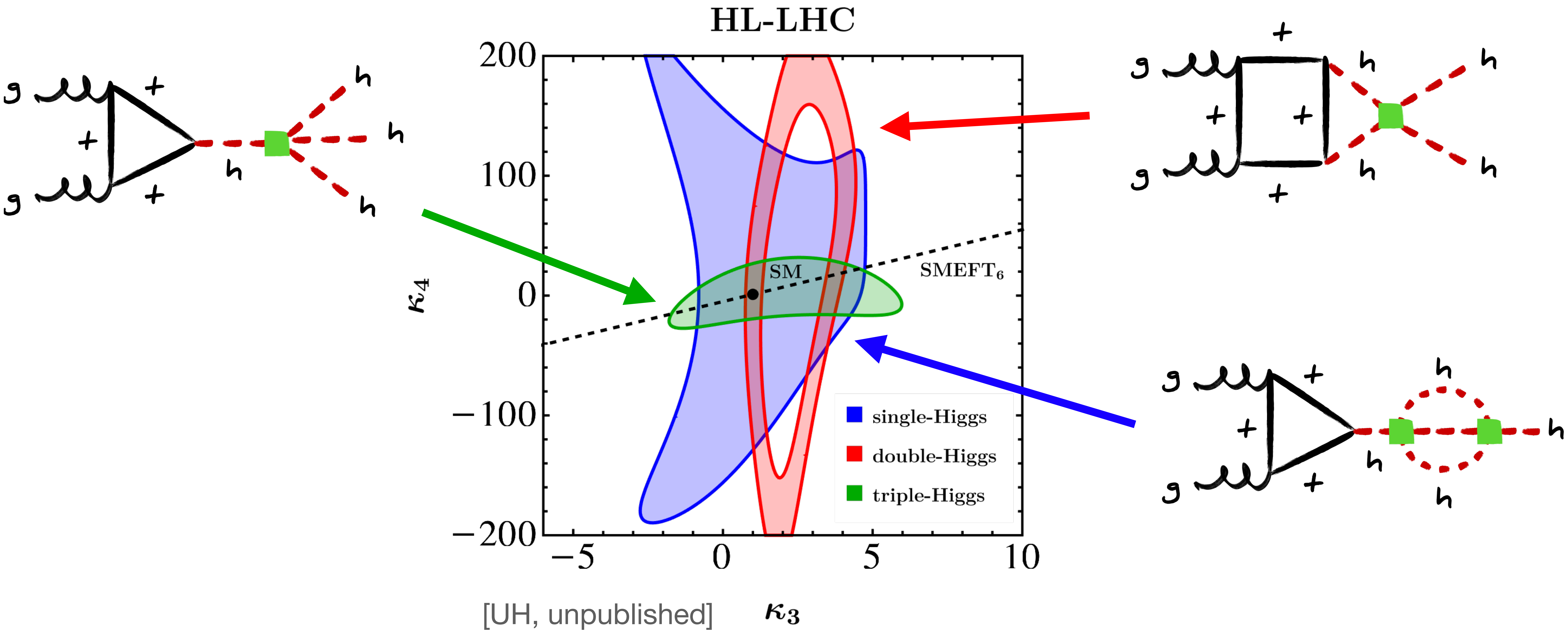


[UH, unpublished]

Hypothetical HL-LHC bound of O(10) on 3h signal strength will set best bound on κ4

[see Stylianou & Weiglein, 2312.04646; Papaefstathiou & Tetlalmatzi-Xolocotzi, 2312.13562 for pp→3h HL-LHC studies]

Higgs self-couplings in HL-LHC era

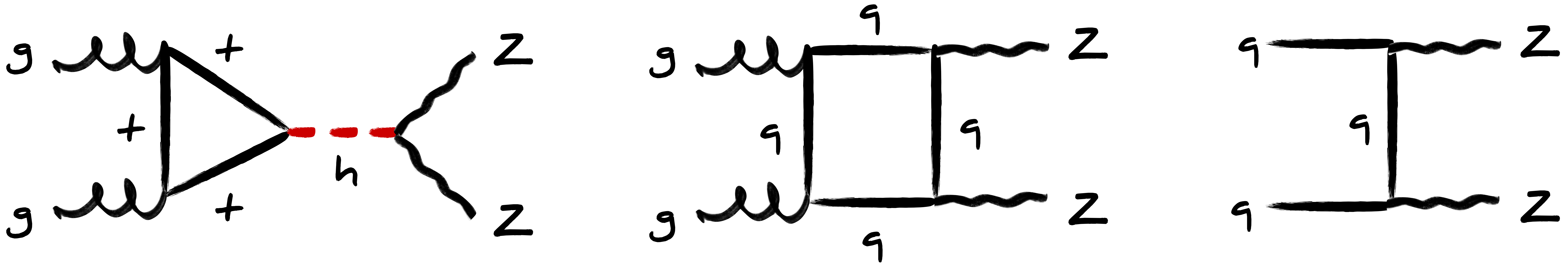


[UH, unpublished]

Flat direction in κ_3 of 3h constraint, partly resolved by indirect hh & h probes

[see Stylianou & Weiglein, 2312.04646; Papaefstathiou & Tetlalmatzi-Xolocotzi, 2312.13562 for pp→3h HL-LHC studies]

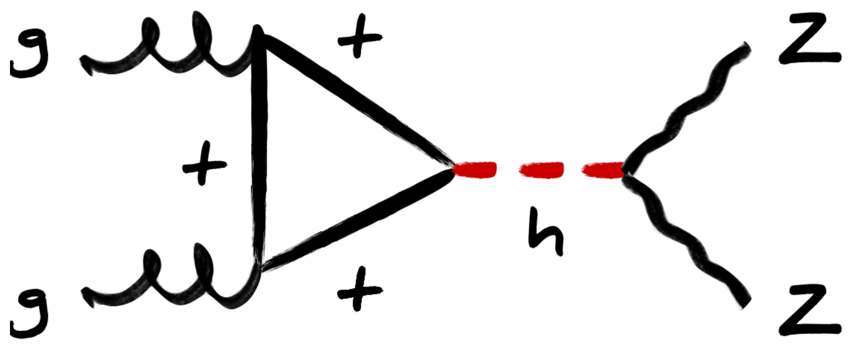
Higgs off-shell measurements



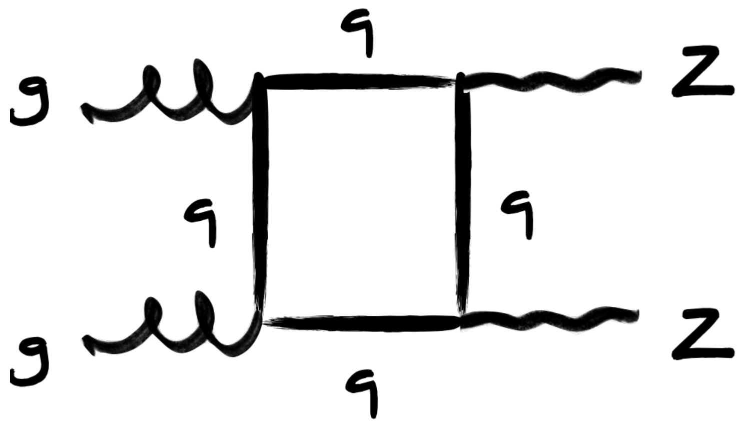
For $m_{4l} > m_h$, pp→ZZ→4l distributions have an enhanced sensitivity to gg→h→ZZ process & its interference with gg→ZZ channel. Assuming that on-shell Higgs signal strengths are SM-like, possible to set bounds on total Higgs width @ LHC

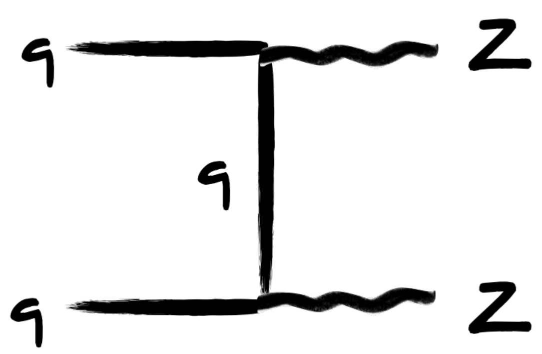
[idea developed in Kauer & Passarino, 1206.4803; Caolo & Melnikov, 1307.4935; Campbell, Ellis & Williams, 1311.3589, 1312.1628]

Higgs width measurements @ LHC

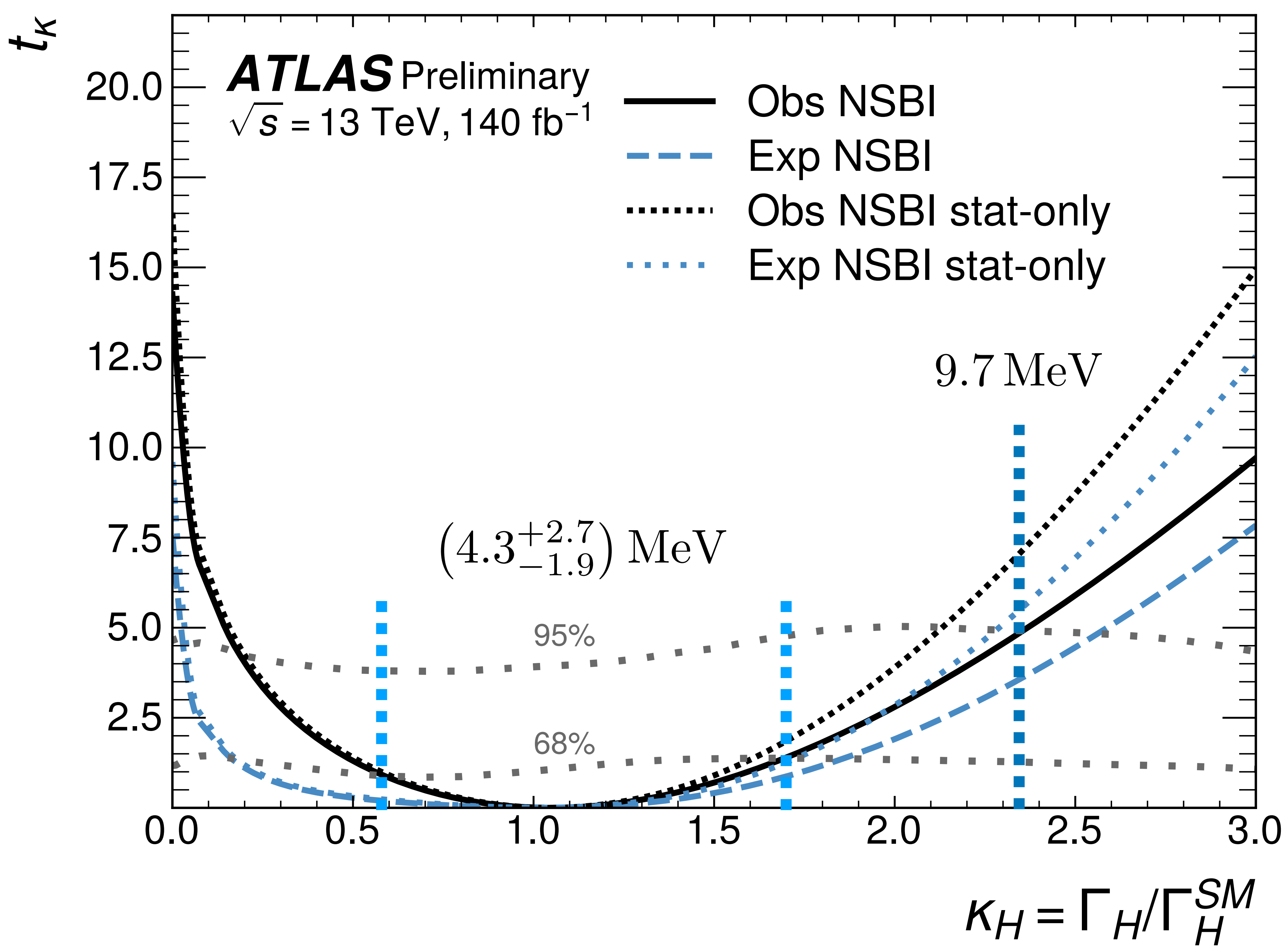


$$O_{\mathrm{NN}} = \log_{10}\left(\frac{P_{\mathrm{S}}}{P_{\mathrm{B}} + P_{\mathrm{NI}}}\right)$$





[ATLAS-CONF-2024-016]



To enhance sensitivity to Higgs contribution with respect to m4l, latest LHC searches for ZZ→4l use machine learning approaches to matrix-element method

[see also CMS, 2409.13663; talks by Gargiulo, Leight, Sandesara & Winterbottom]

Trilinear Higgs self-coupling from pp→4l

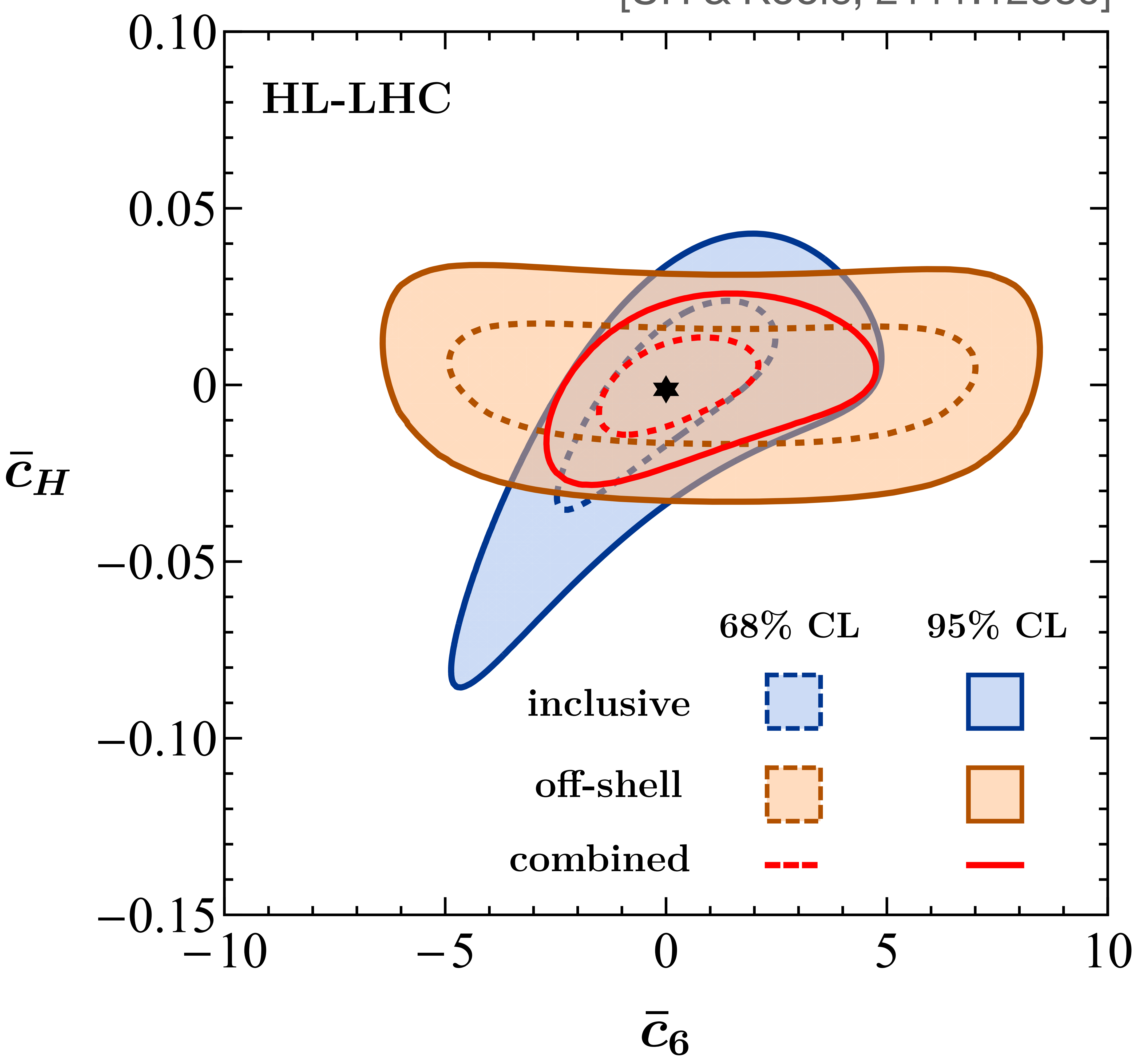
$$\mathcal{L}_{\rm SMEFT} \supset -\frac{\lambda \bar{c}_6}{v^2}|H|^6 + \frac{\bar{c}_H}{2v^2}\left(\partial_\mu |H|^2\right)^2$$

$$\Downarrow$$

$$\mathcal{L} \supset -\lambda \kappa_\lambda v h^3\,, \qquad \kappa_\lambda = 1 + \bar{c}_6 - \frac{3}{2}\bar{c}_H$$

In SM effective field they (SMEFT), κ_λ receives contributions from more than a single Wilson coefficient

[UH & Koole, 2111.12589]



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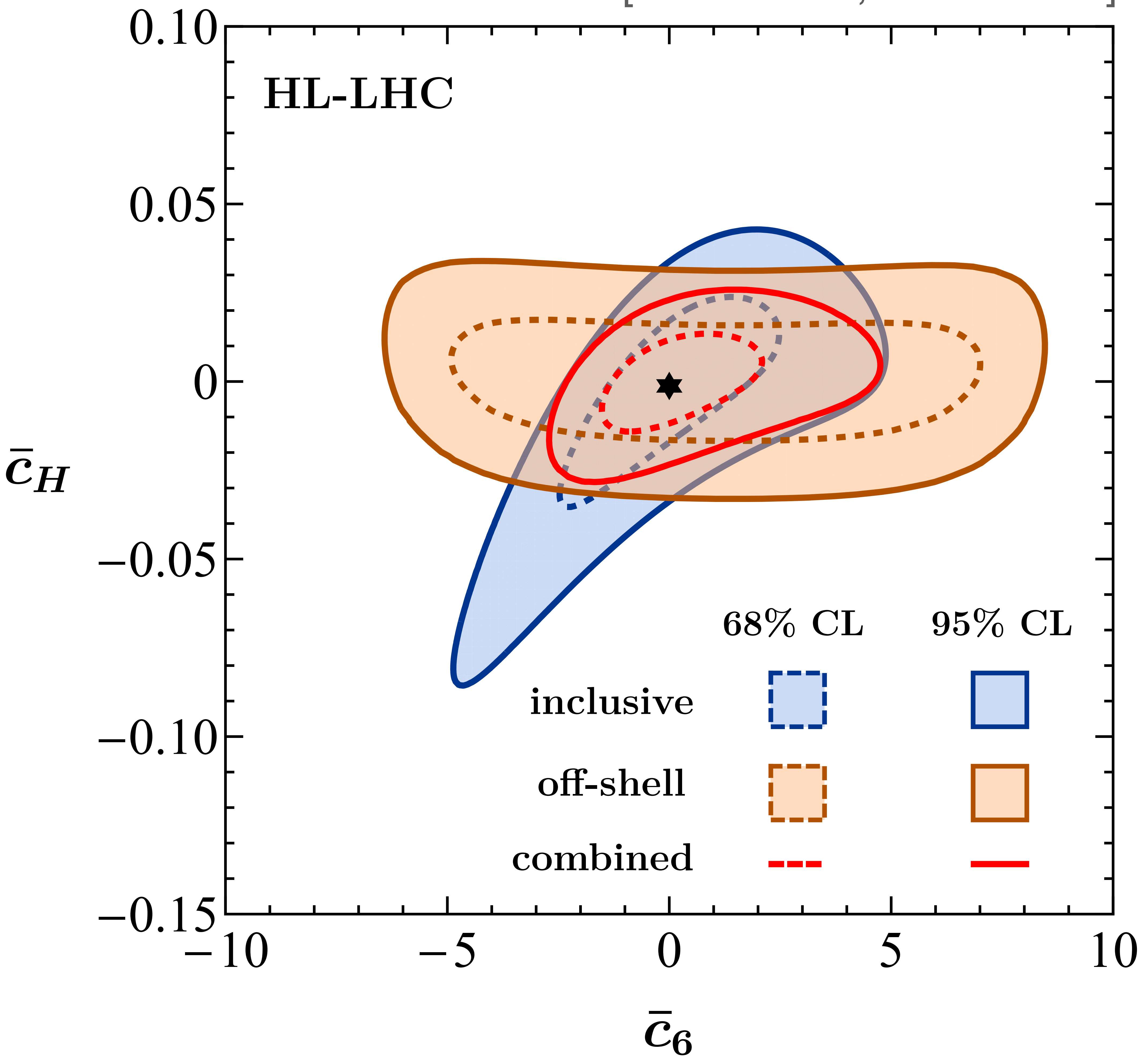
On-shell & off-shell measurements depend differently on O_6 & O_H operators.
Combination improves 2D constraints

[UH & Koole, 2111.12589]



Higgs portal interactions

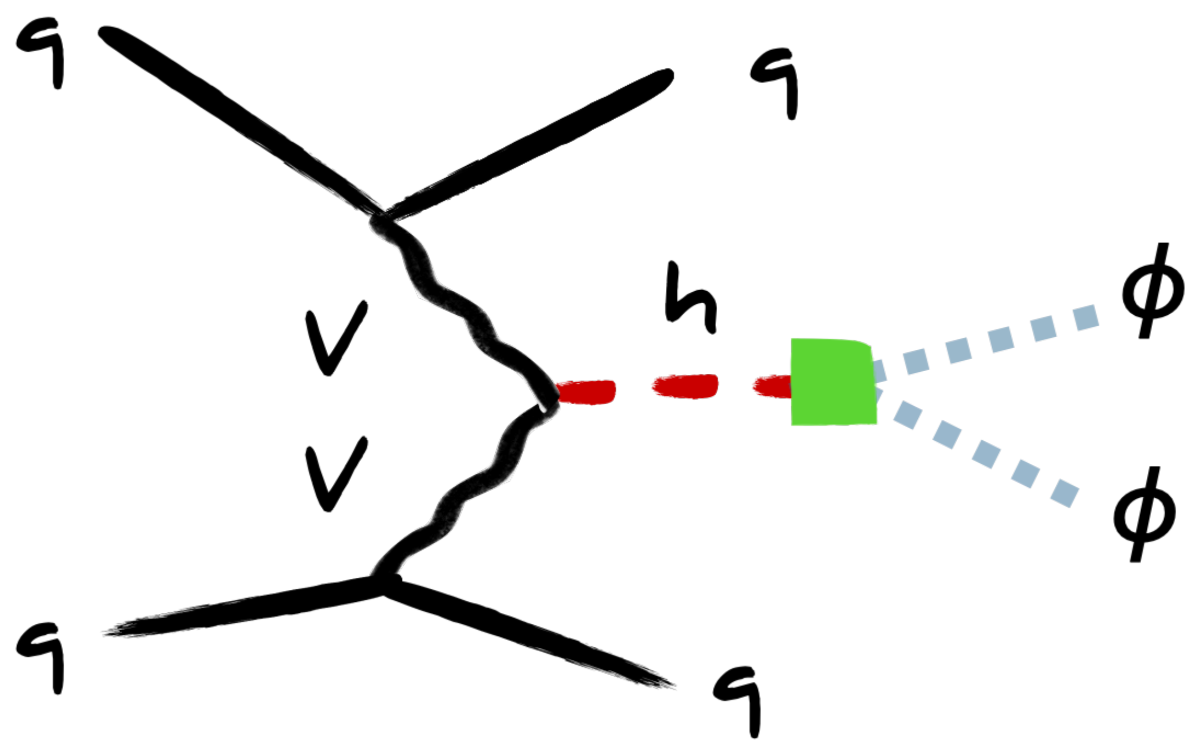
scalar — fermion — vector

$$\mathcal{L} \supset c_\phi |H|^2 |\phi|^2 + \frac{c_{\partial\phi}}{f^2} \left(\partial_\mu |H|^2\right) \left(\partial^\mu |\phi|^2\right) + \frac{c_\psi}{f} |H|^2 \bar{\psi}\psi + c_V |H|^2 V_\mu V^\mu$$

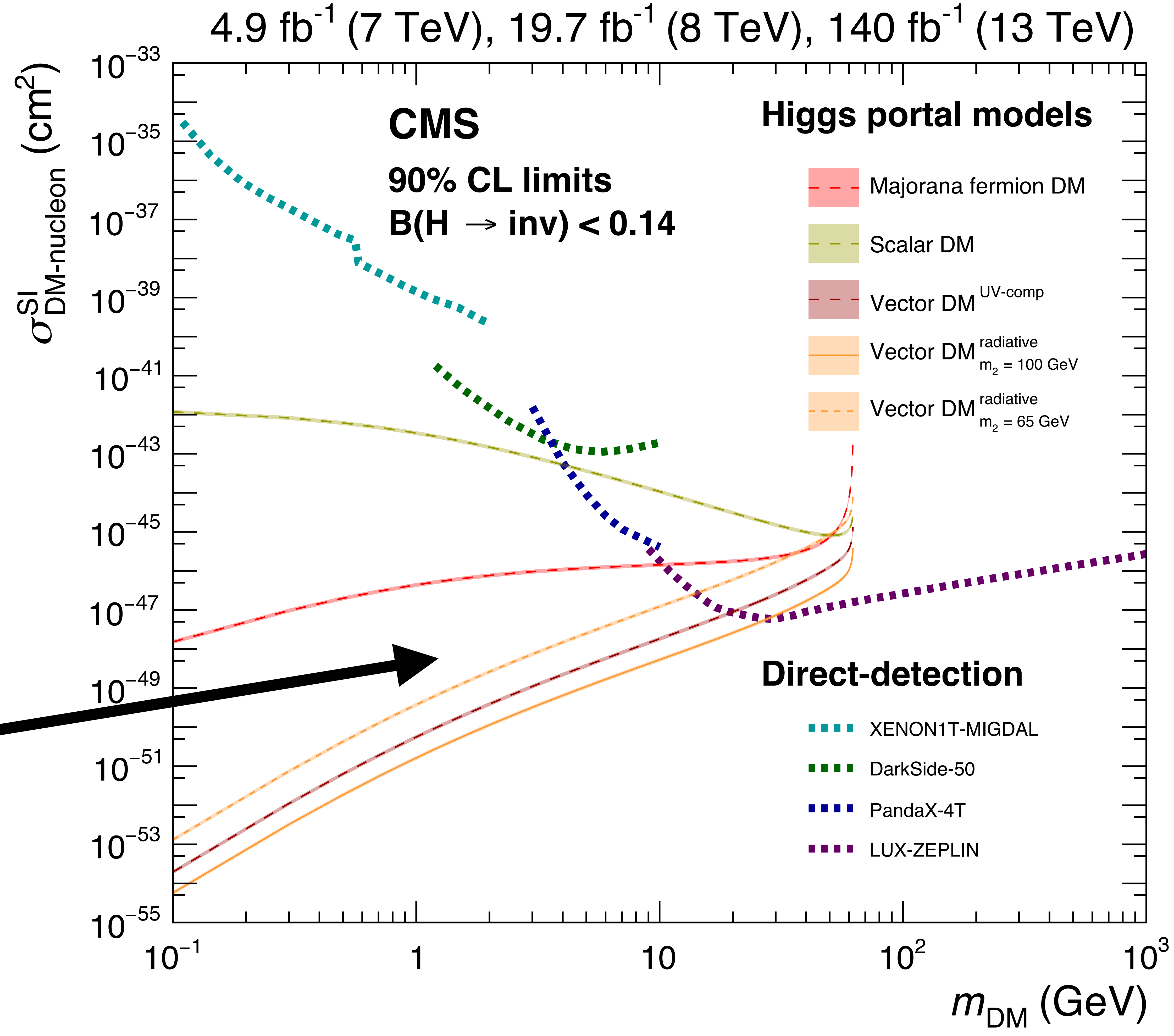
$|H|^2$ provides a simple portal to dark or hidden sectors. At dimension four one has couplings of $|H|^2$ to spin-0 & spin-1 fields, while interactions with spin-1/2 fields are of dimension five. Dimension-six derivative spin-0 coupling also interesting, since dark matter (DM) direct detection (DD) cross section momentum suppressed

[for a recent review see for instance Argyropoulos, Brandt & UH, 2109.13597]

Higgs portal searches @ LHC



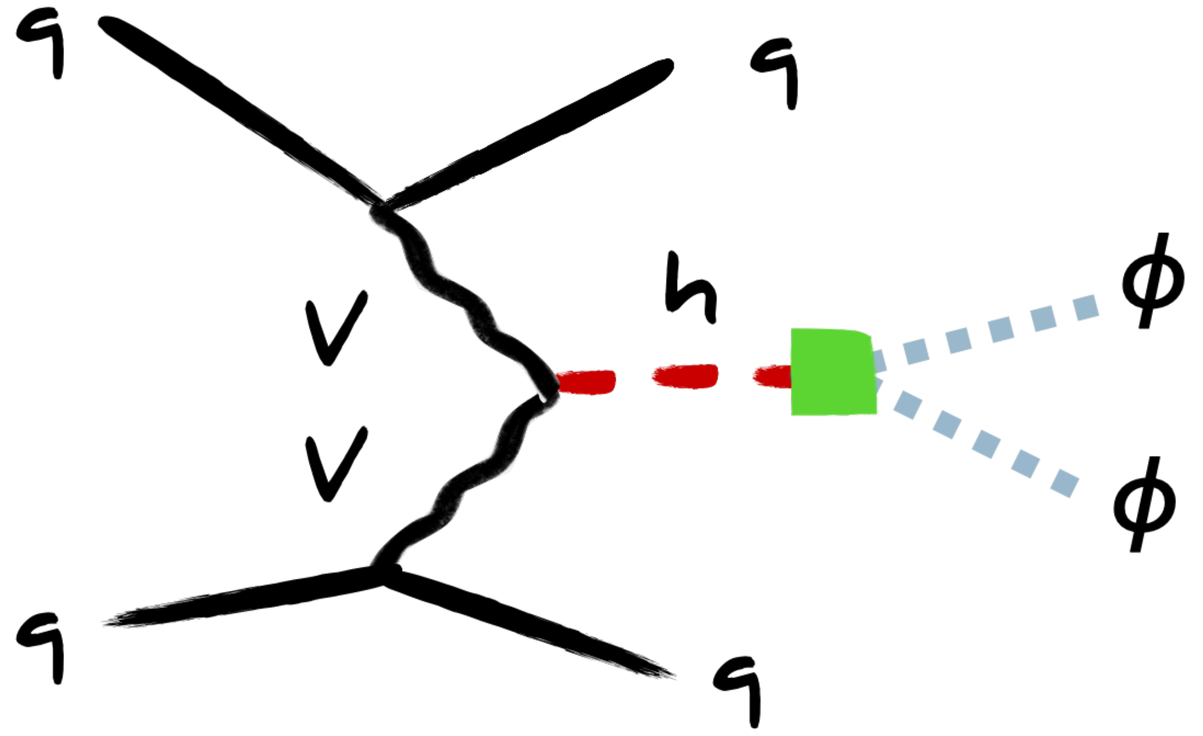
If DM states are kinematically accessible in Higgs decays, LHC searches for h→invisible superior to present DD limits



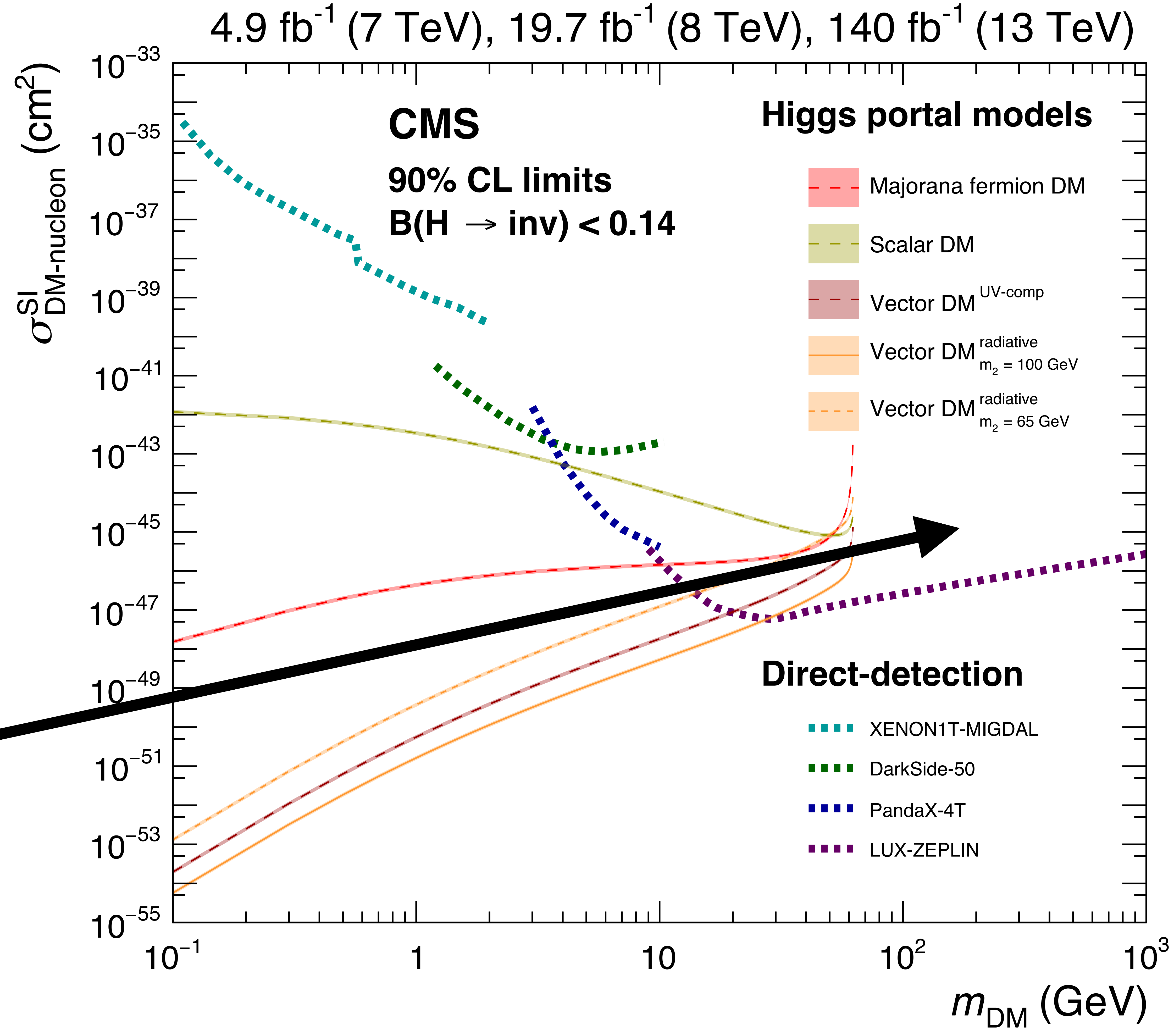
[CMS, 2303.01214]

[see also ATLAS, 2202.07953]

Higgs portal searches @ LHC



Can LHC say something about region where DM is inaccessible in h→invisible?

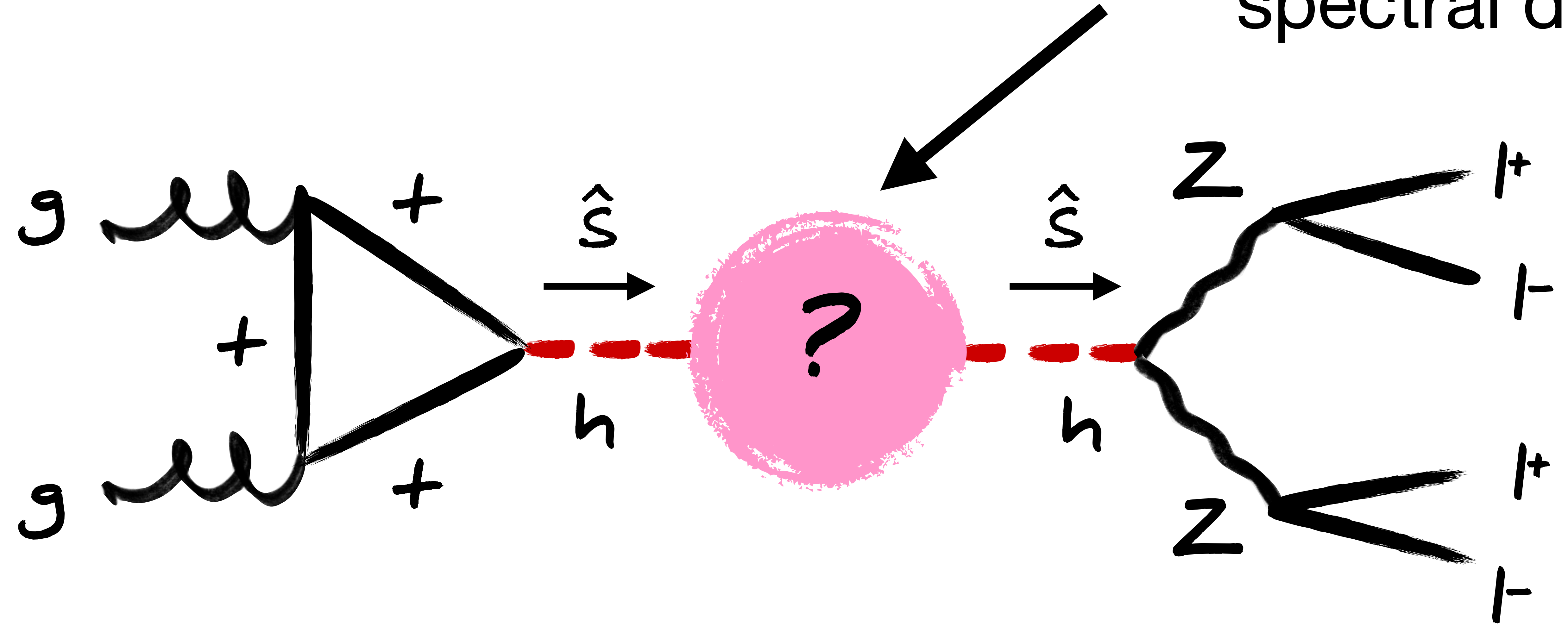


[CMS, 2303.01214]

[see also ATLAS, 2202.07953]

Searches for Higgsphilics in pp→4l

DM particles, top partners, ...,
spectral density of Higgs

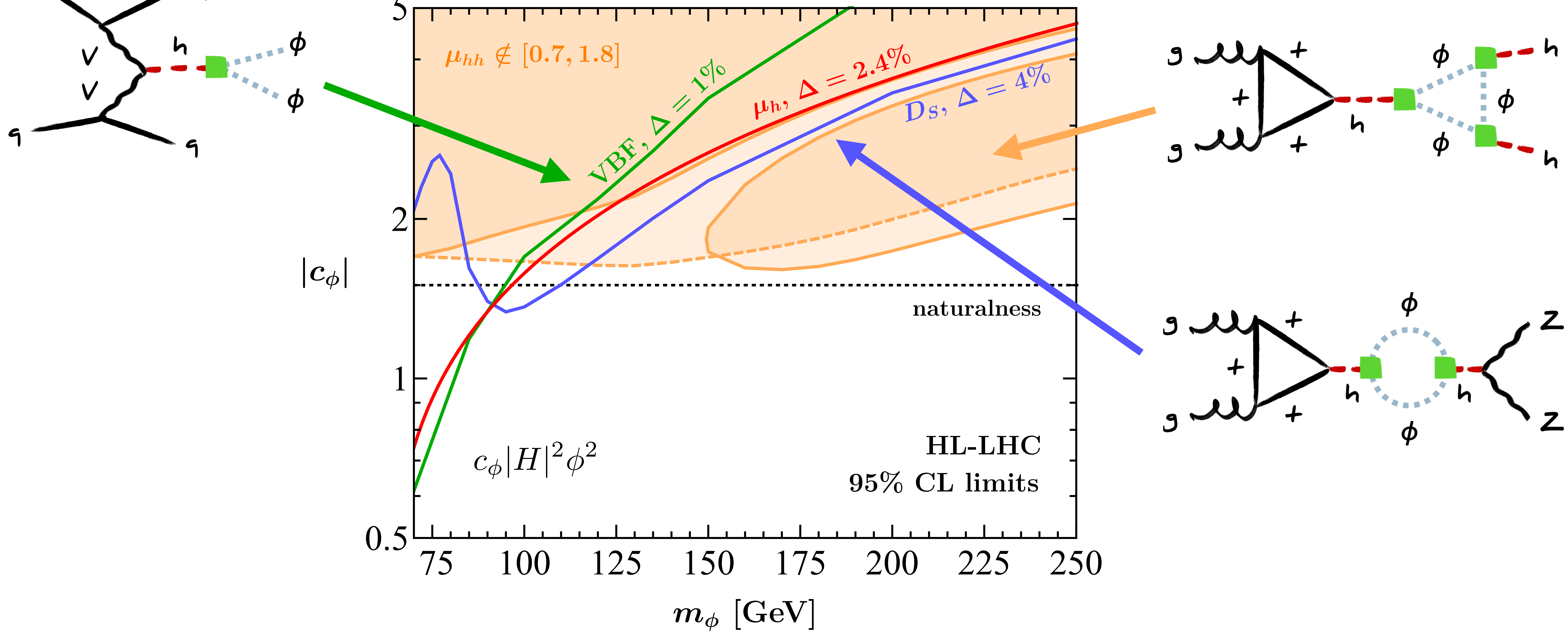


Off-shell Higgs measurements in pp→4l allow to scan ŝ-dependence of Higgs propagator, which is sensitive to virtual exchange of light Higgsphilic states

[Goncalves, Han & Mukhopadhyay, 1710.02149, 1803.09751; UH & Koole, 2201.09711; UH, Ruhdorfer, Schmid & Weiler; 2311.03995]

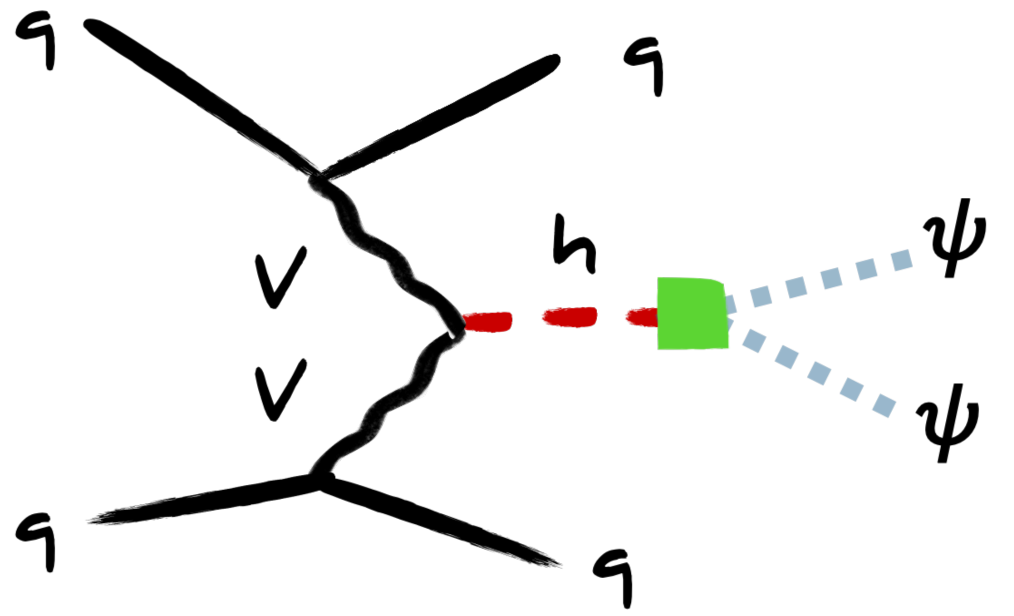
HL-LHC bounds on marginal Higgs portal

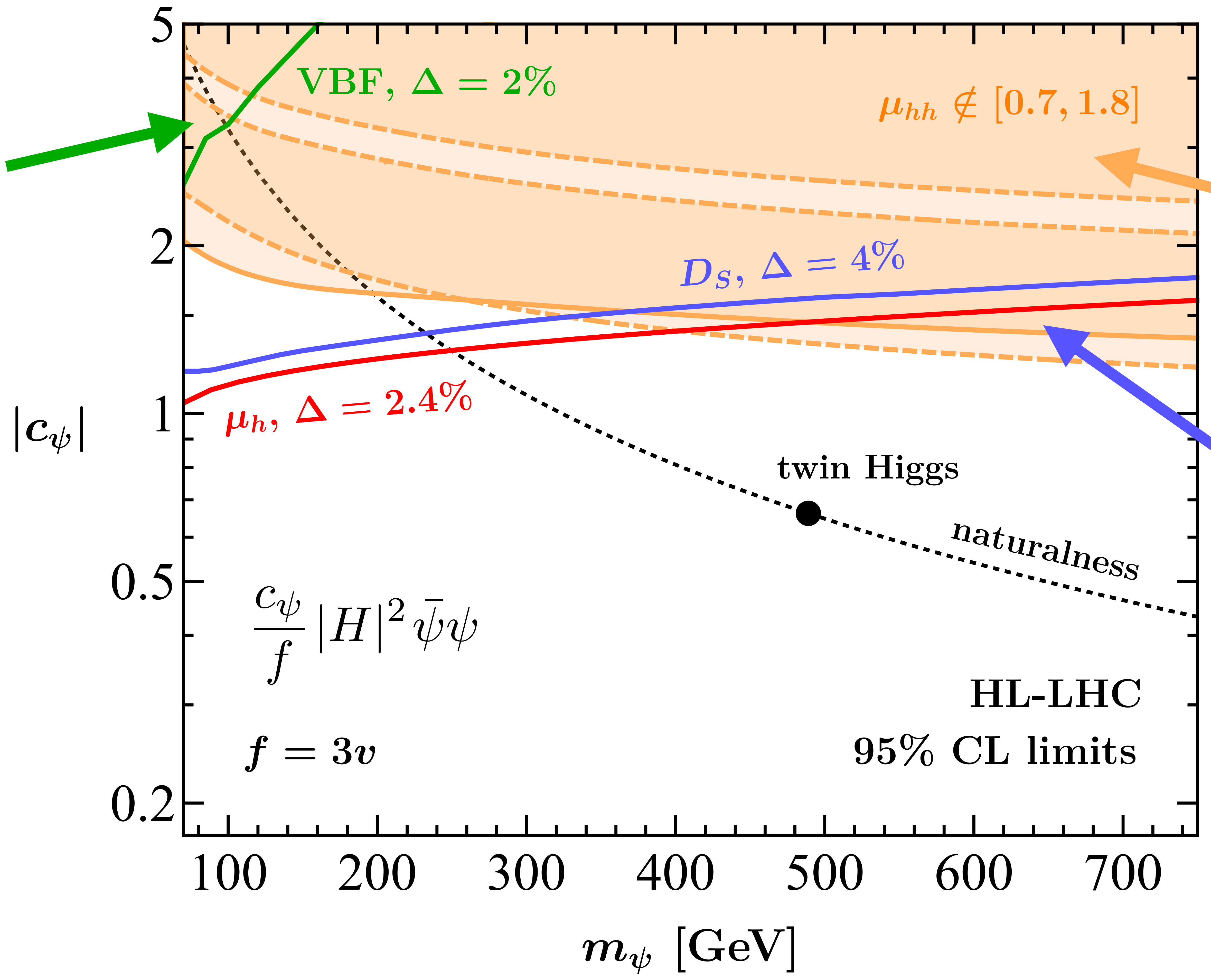
[UH & Koole, 2201.09711]

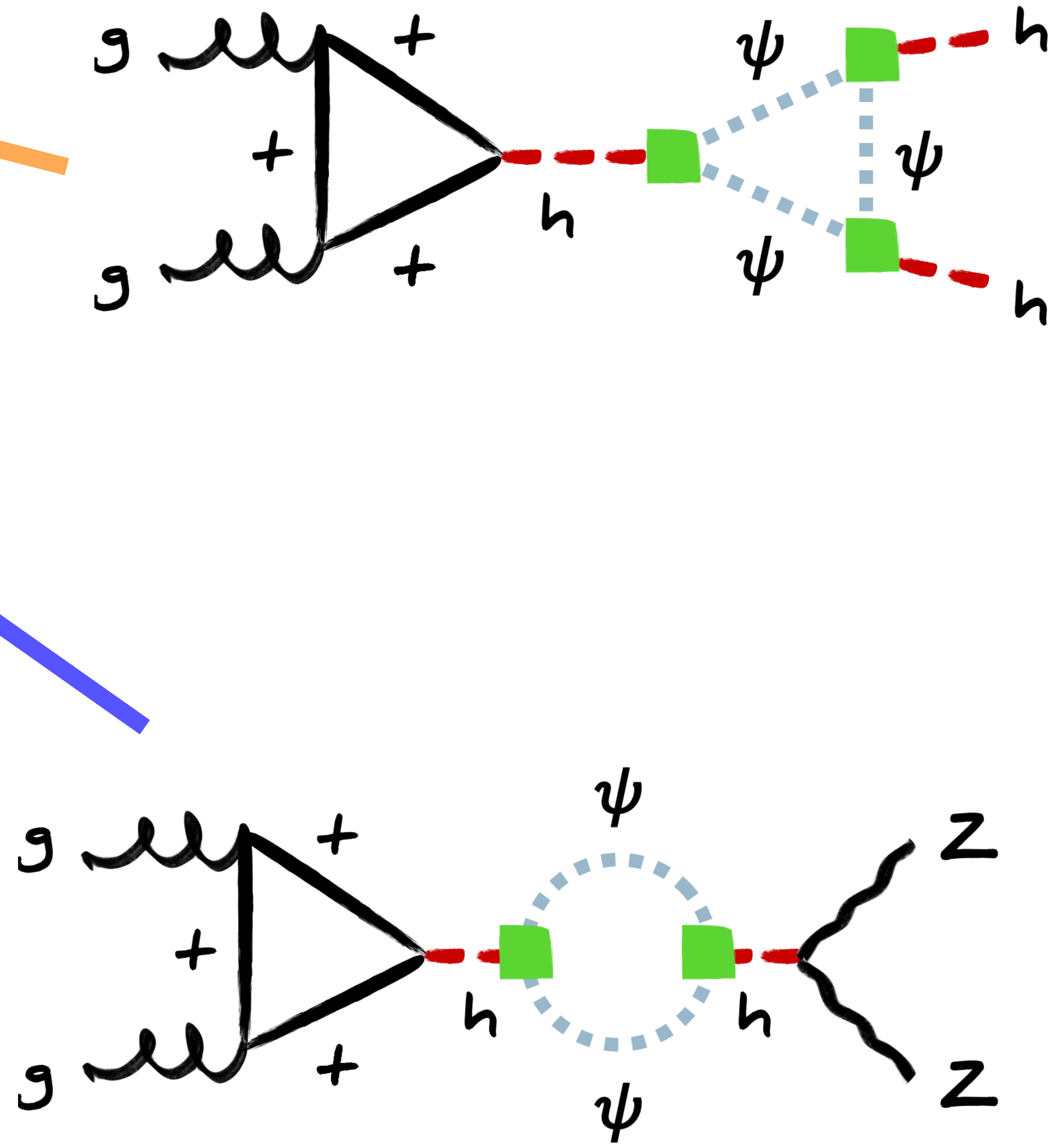


[off-shell VBF bound taken from Ruhdorfer, Salvioni & Weiler, 1910.04170]

HL-LHC bounds on fermionic Higgs portal







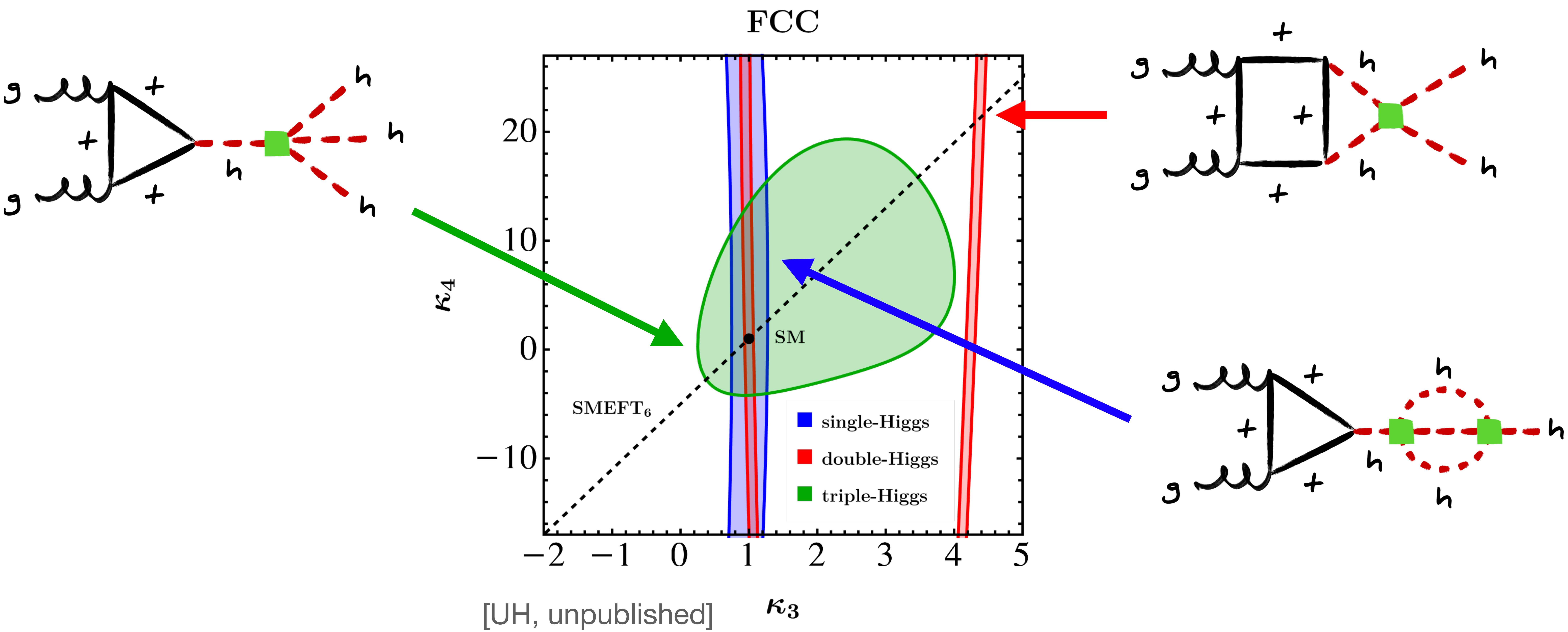
[UH, Ruhdorfer, Schmid & Weiler; 2311.03995]

Conclusions

- Distinction between direct & indirect Higgs probes academic, because in practice both strategies test same physics in a given beyond SM model
- Indirect Higgs probes well-established @ LHC & employed by both ATLAS & CMS to extractions of charm Yukawa & trilinear Higgs self-coupling
- Differential & off-shell Higgs measurements @ HL-LHC will allow to tighten indirect constraints on κ's, Wilson coefficients, light Higgsphilic physics, etc. Measurements have not been fully exploited experimentally @ LHC Run 2

Backup

Higgs self-couplings in FCC era

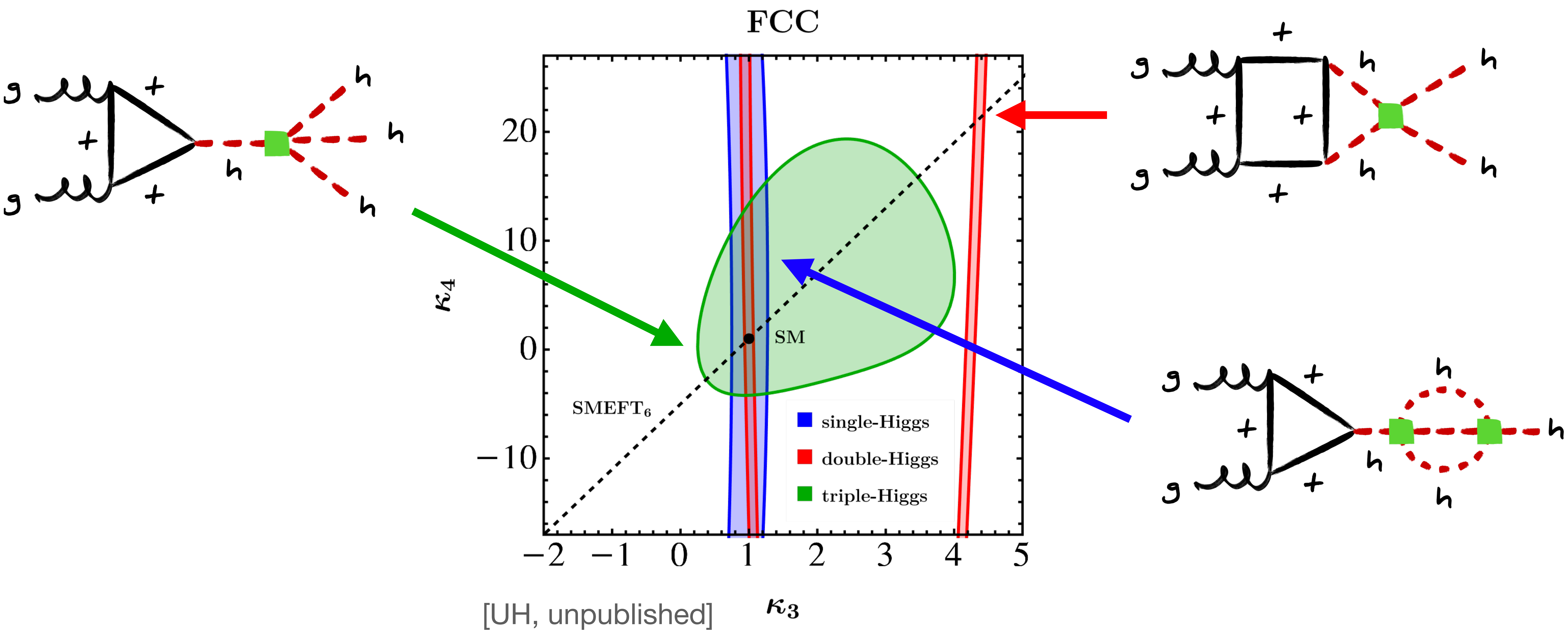


[UH, unpublished]

Single-h bounds notable improved due to permille accuracy of Zh @ FCC-ee

[see Bizon et al., 1810.04665, 2402.03463 for pp→hh & pp→3h FCC studies]

Higgs self-couplings in FCC era

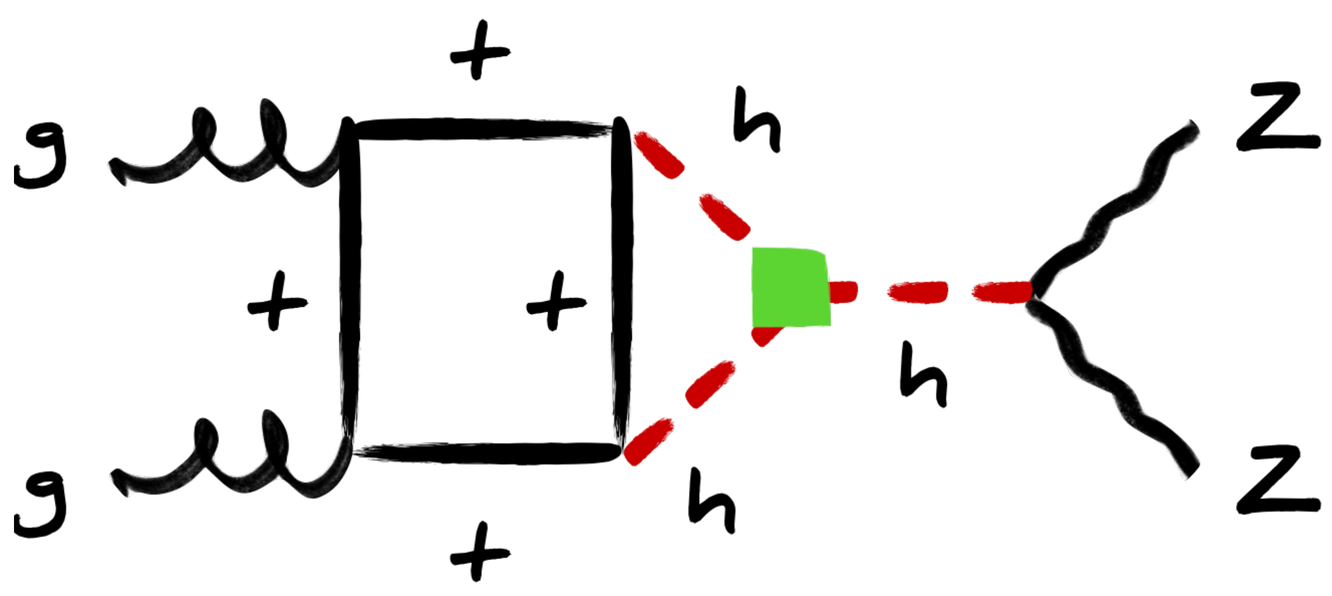


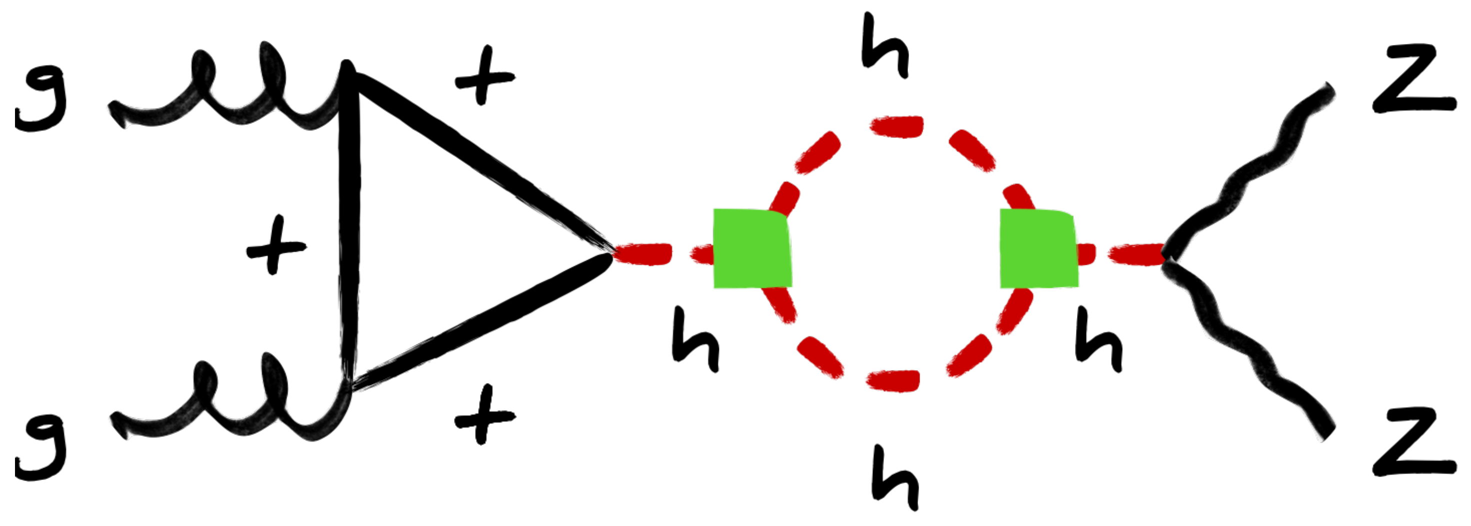
[UH, unpublished]

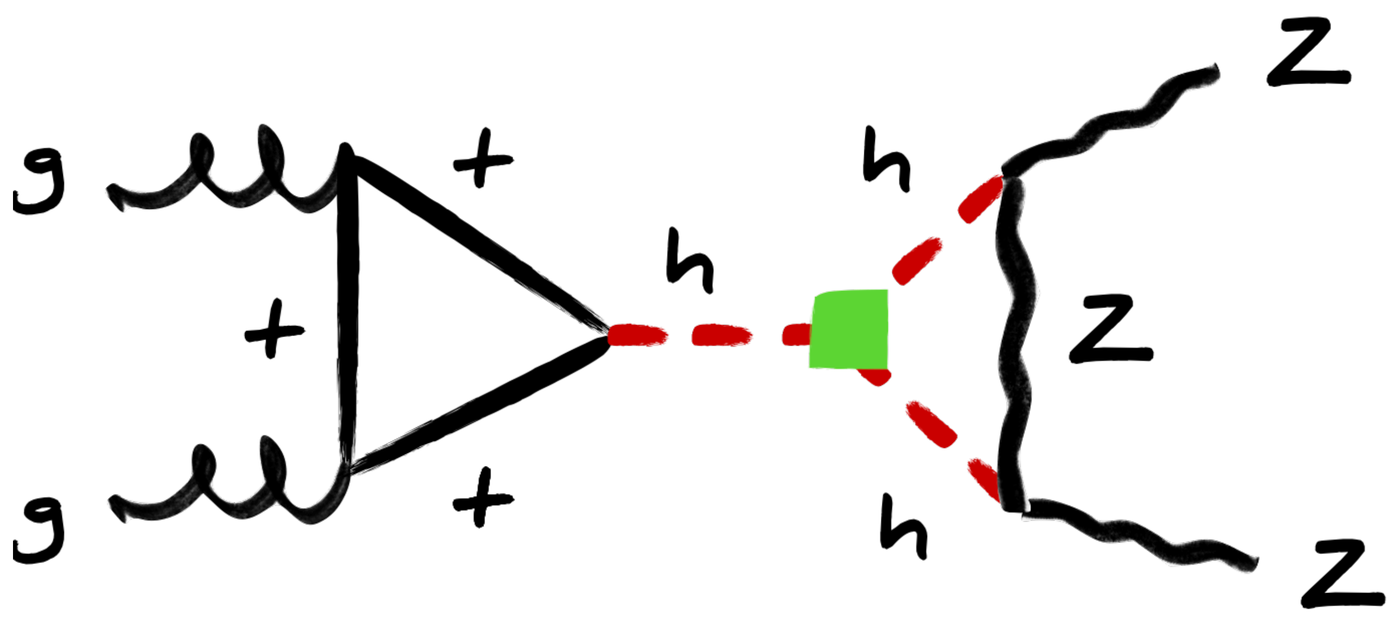
Indirect probes remove degeneracy of direct pp→3h constraint in κ_3-κ_4 plane

[see Bizon et al., 1810.04665, 2402.03463 for pp→hh & pp→3h FCC studies]

Anatomy of κλ corrections







<u>production side:</u>

non-universal correction,
linear κλ dependence

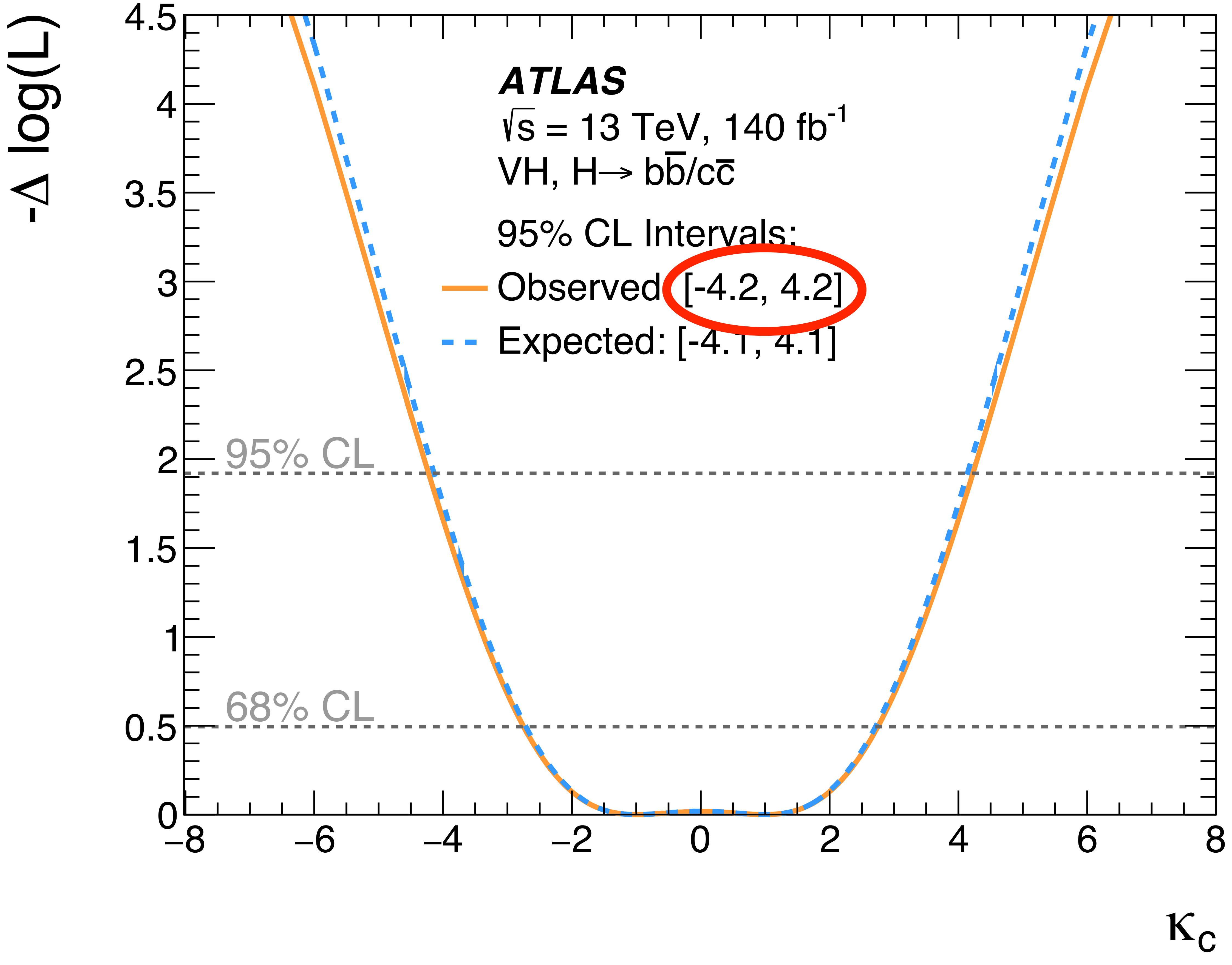
<u>Higgs propagator:</u>

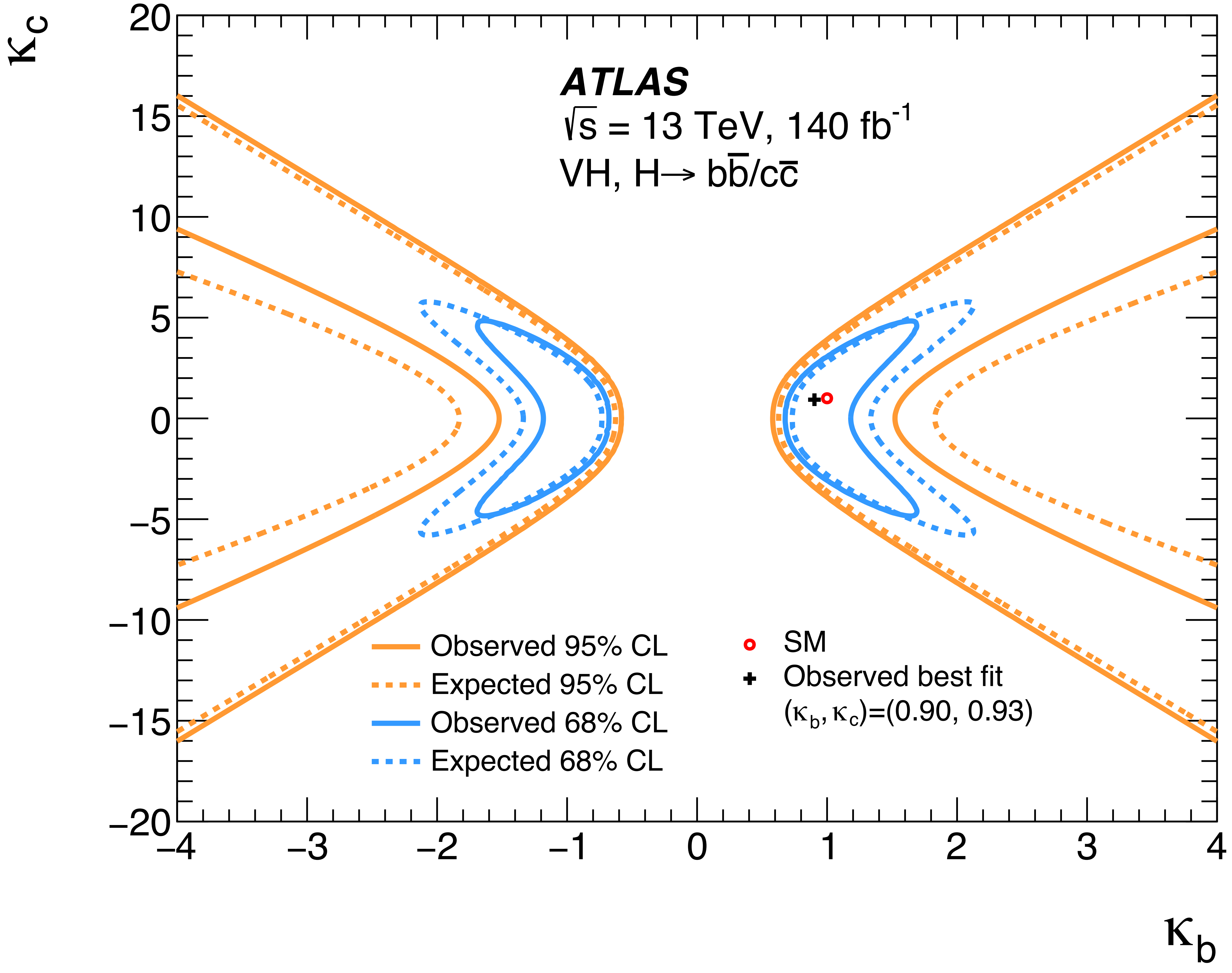
universal correction,
quadratic κλ dependence

<u>decay side:</u>

non-universal correction,
linear κλ dependence

Direct constraints on κ_b & κ_c @ LHC

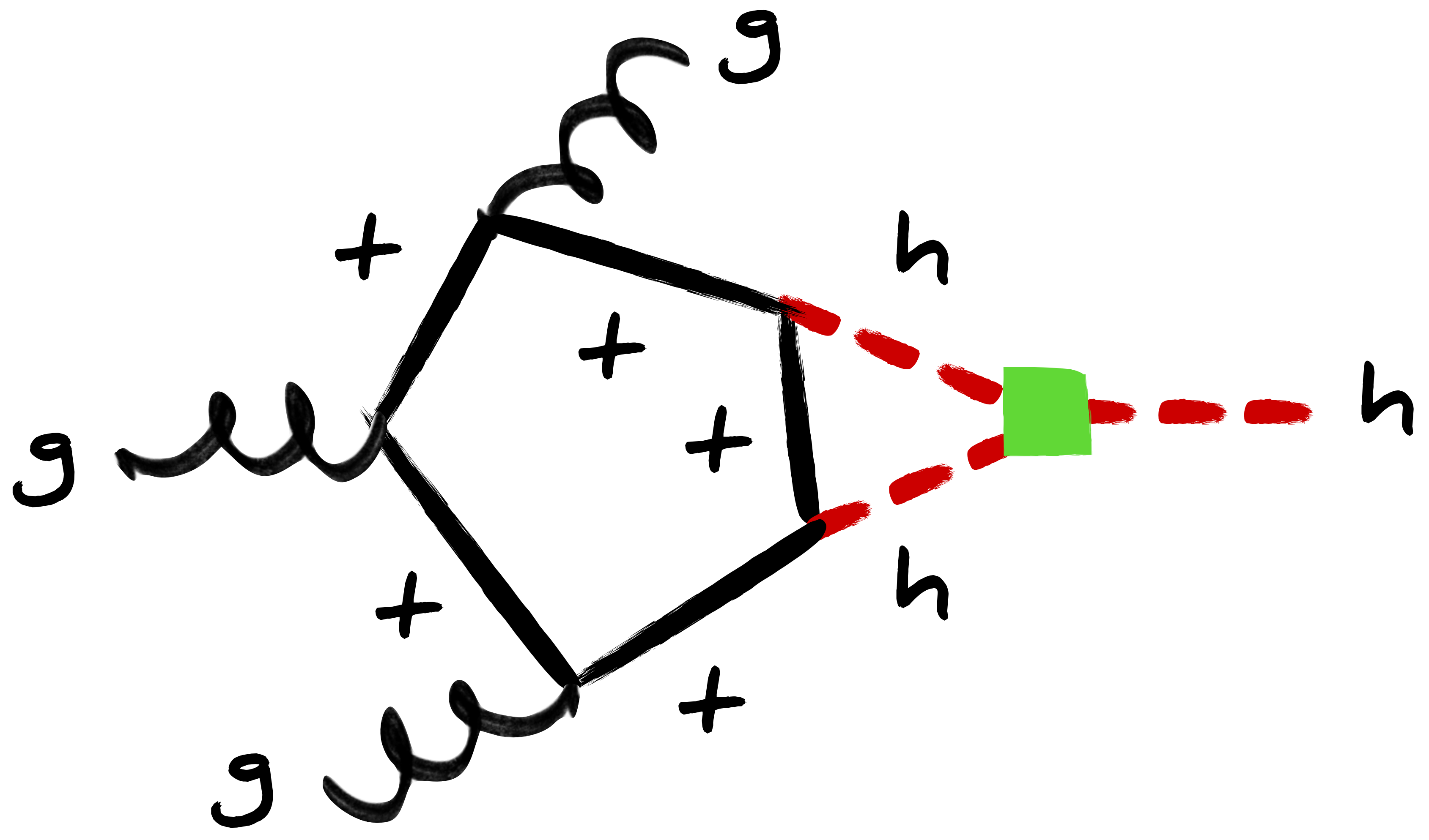


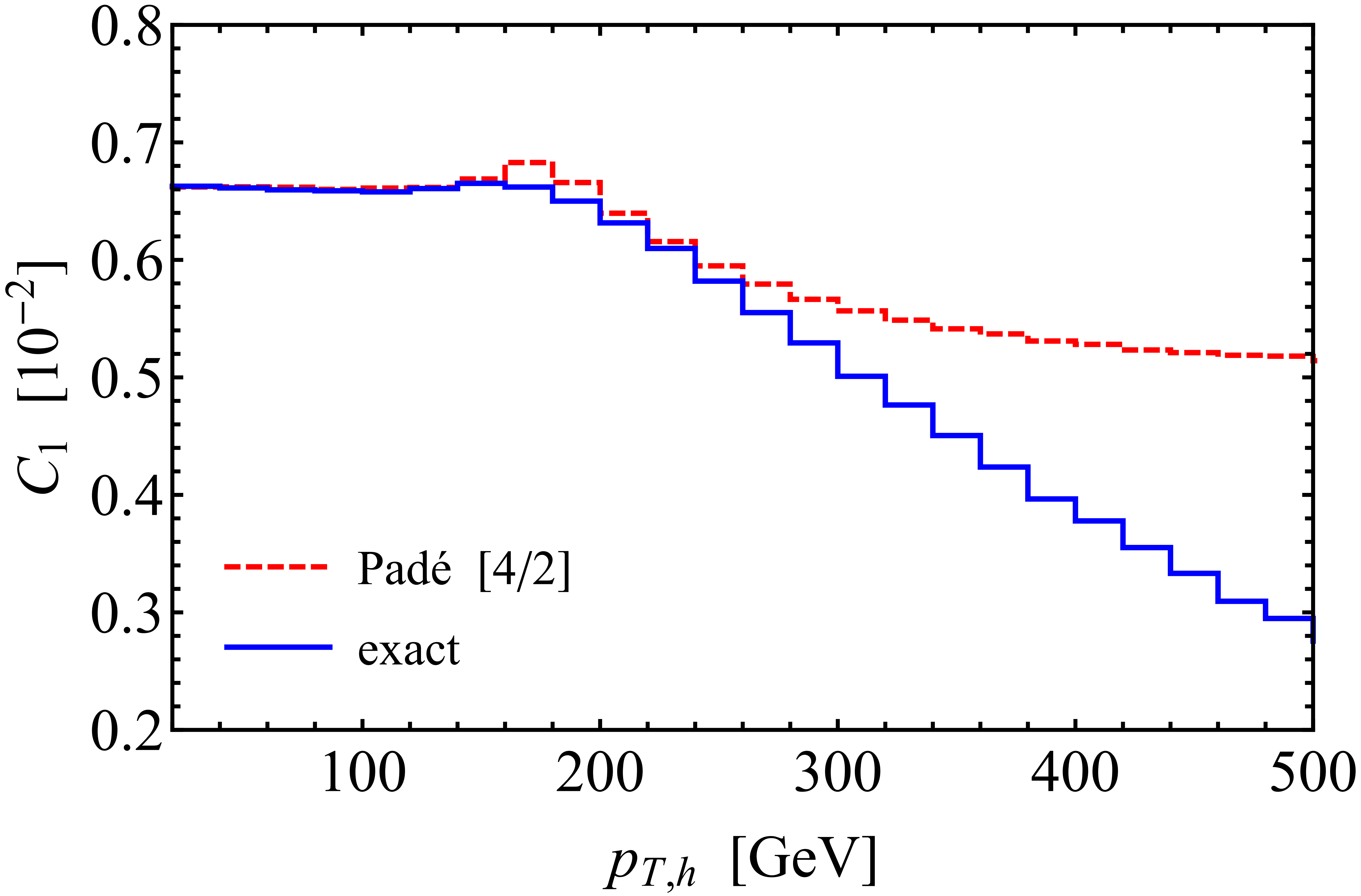


[ATLAS, 2410.19611]

Non-universal κ_λ effects in h+jet production

[UH & Niggetiedt, 2408.13186]





Only exact calculation of linear κ_λ terms allows to describe $p_{T,h}$ spectrum above m_t

[Padé approximation obtained in Gao, Shen, Wang, Yang & Zhou, 2302.04160]

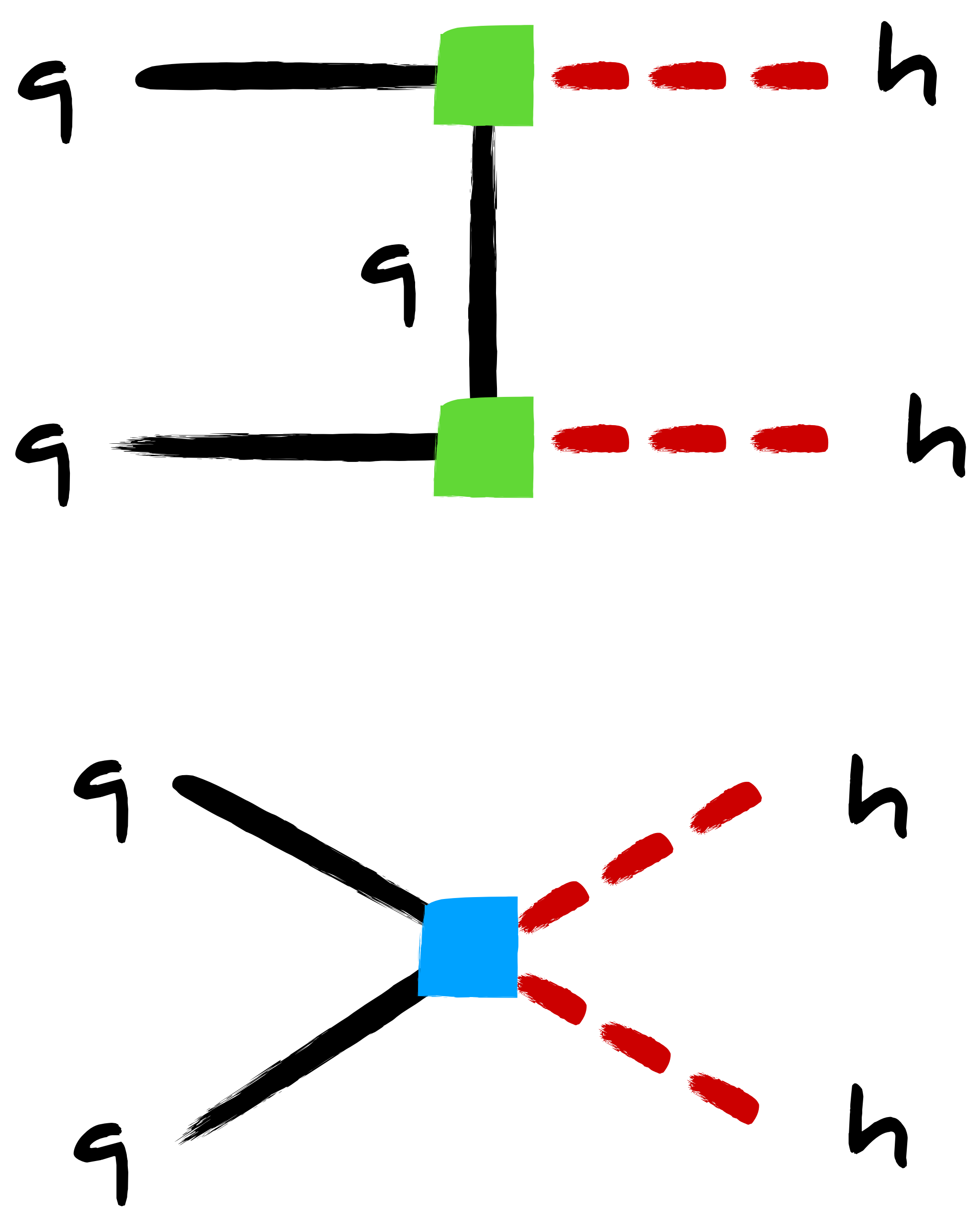
LHC constraints on light-quark Yukawas

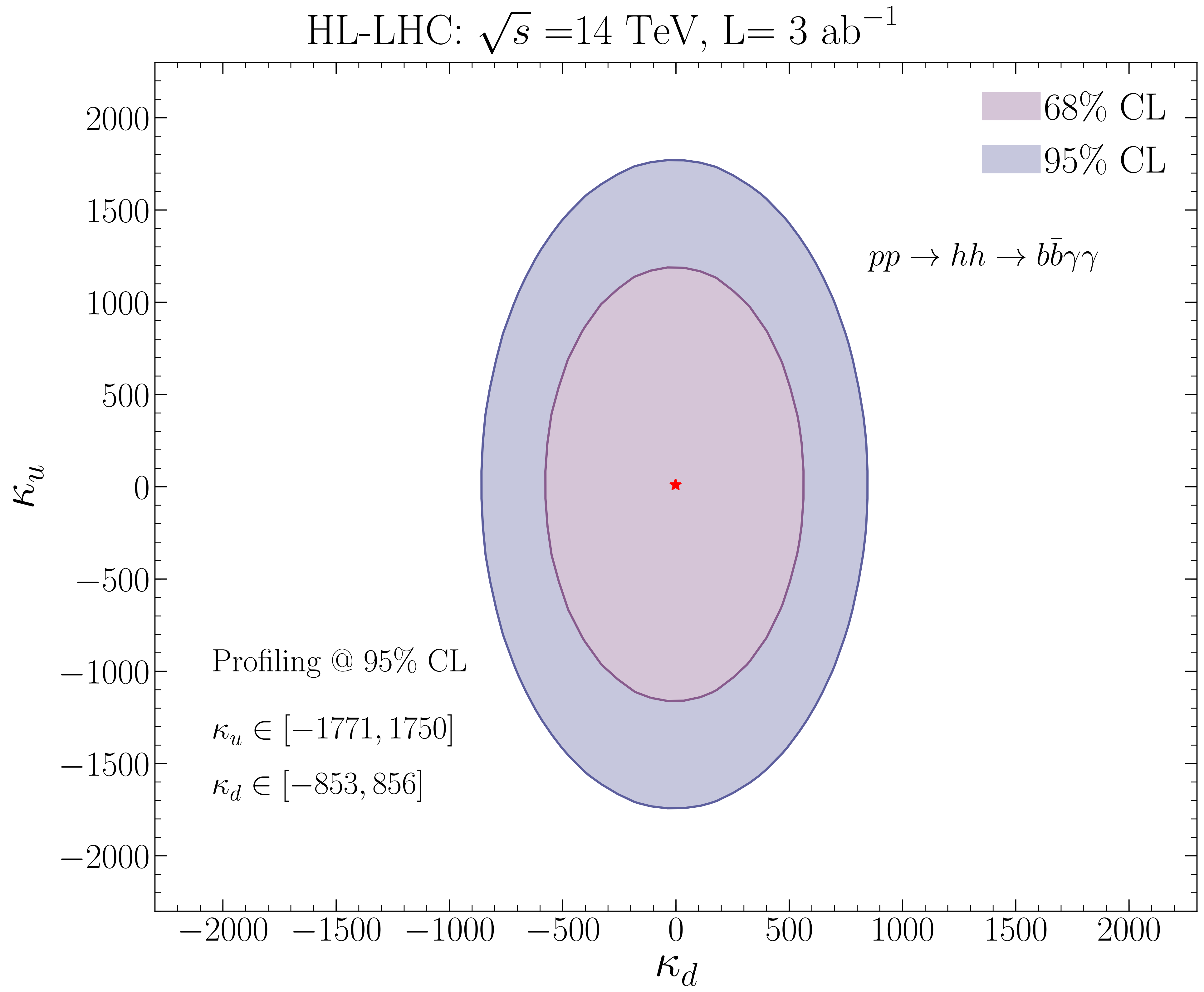
[CMS-PAS-HIG-23-011]

Parameter	Scenario	Observed		Expected	
κ_u	float all	$(0.0 \pm 1.5) \times 10^3$	$[-2.4, 2.4] \times 10^3$	$(0.0 \pm 1.8) \times 10^3$	$[-2.6, 2.6] \times 10^3$
κ_u	fix others	$(0.0 \pm 1.4) \times 10^3$	$[-2.3, 2.3] \times 10^3$	$(0.0 \pm 1.6) \times 10^3$	$[-2.5, 2.5] \times 10^3$
κ_d	float all	$(0.0 \pm 7.1) \times 10^2$	$[-1.0, 1.0] \times 10^3$	$(0.0 \pm 7.4) \times 10^2$	$[-1.0, 1.0] \times 10^3$
κ_d	fix others	$(1.5^{+5.0}_{-8.0}) \times 10^2$	$[-9.7, 9.7] \times 10^2$	$(0.0 \pm 6.5) \times 10^2$	$[-9.7, 9.7] \times 10^2$
κ_s	float all	0^{+33}_{-34}	$[-46, 44]$	1^{+32}_{-31}	$[-44, 42]$
κ_s	fix others	11^{+19}_{-42}	$[-44, 42]$	1^{+26}_{-30}	$[-41, 40]$
κ_c	float all	$0.0^{+2.7}_{-3.0}$	$[-4.0, 3.4]$	$1.0^{+1.4}_{-3.8}$	$[-3.8, 3.2]$
κ_c	fix others	$1.4^{+1.2}_{-4.4}$	$[-4.0, 3.5]$	$1.0^{+1.3}_{-3.8}$	$[-3.8, 3.2]$
Γ_H^{BSM} (MeV)	float all	$0.0^{+0.9}_{-0.0}$	< 1.6	$0.0^{+0.7}_{-0.0}$	< 1.4

First indirect bounds on κ_q modifiers obtained from production rate of h→4l

hh constraints on light-quark Yukawas

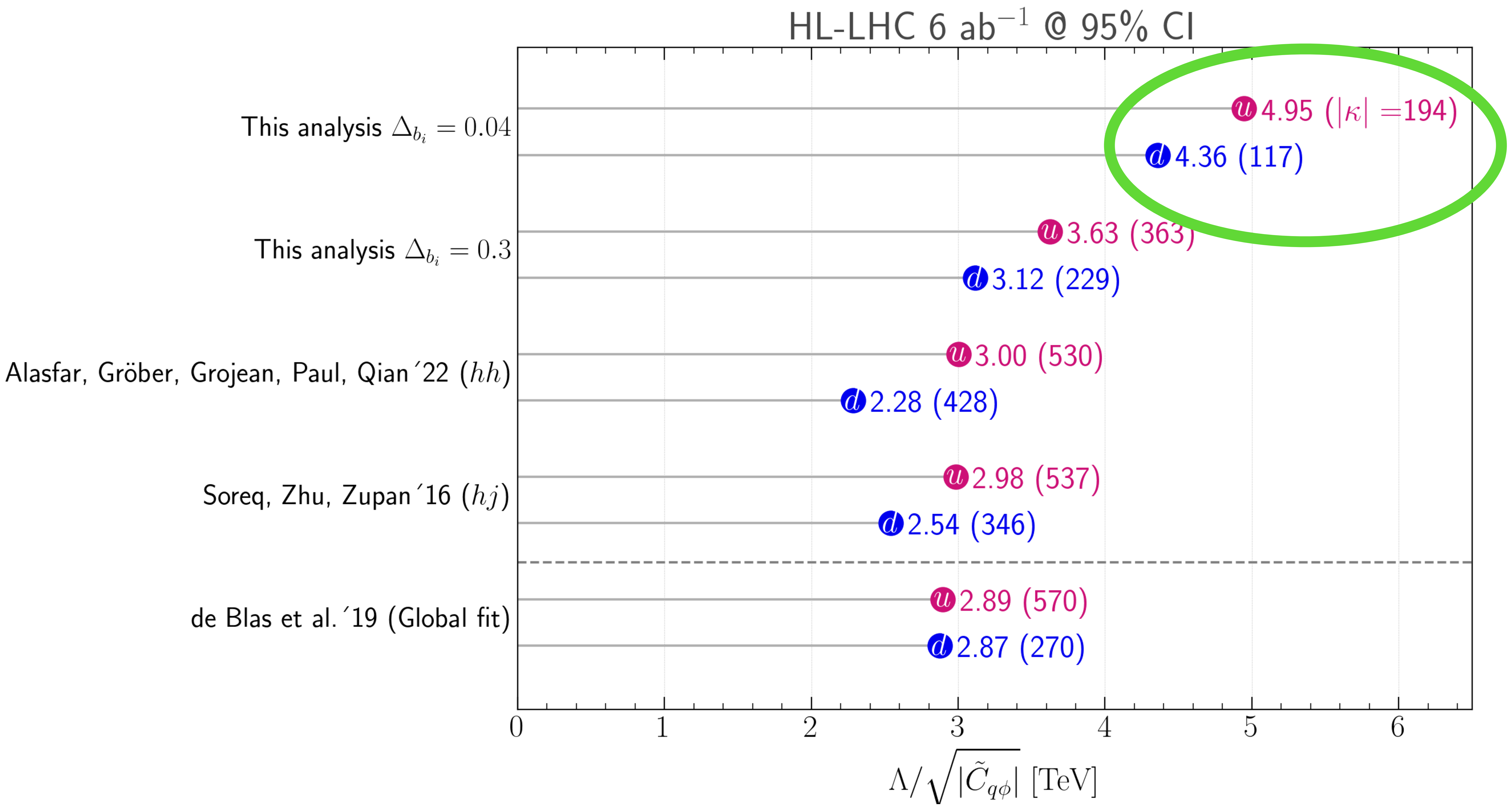


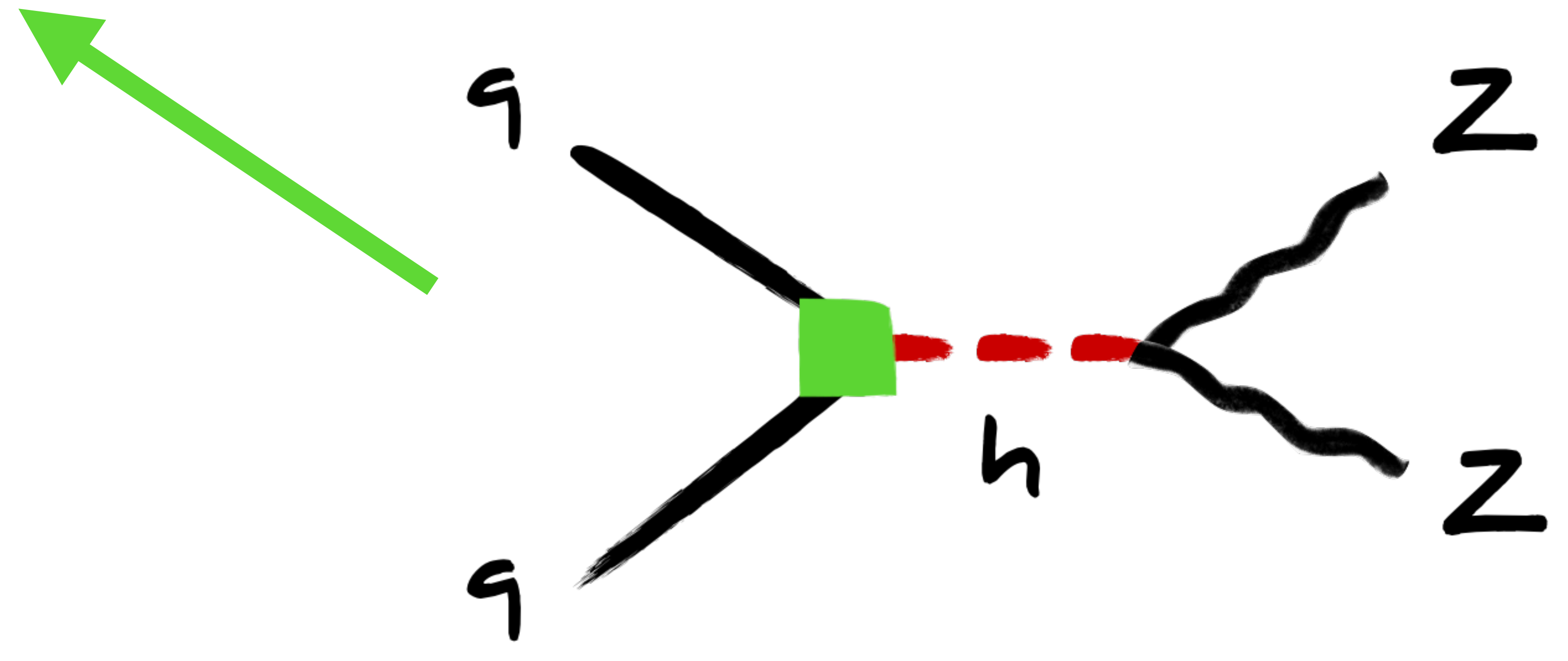


qq̄→hh process gives access to light-quark Yukawas. Dominant effect arises from possible Higgs non-linearities, which induce a 4-point interaction

[Alasfar, Lopez & Gröber, 1909.05279]

Light-quark Yukawas from pp→4l

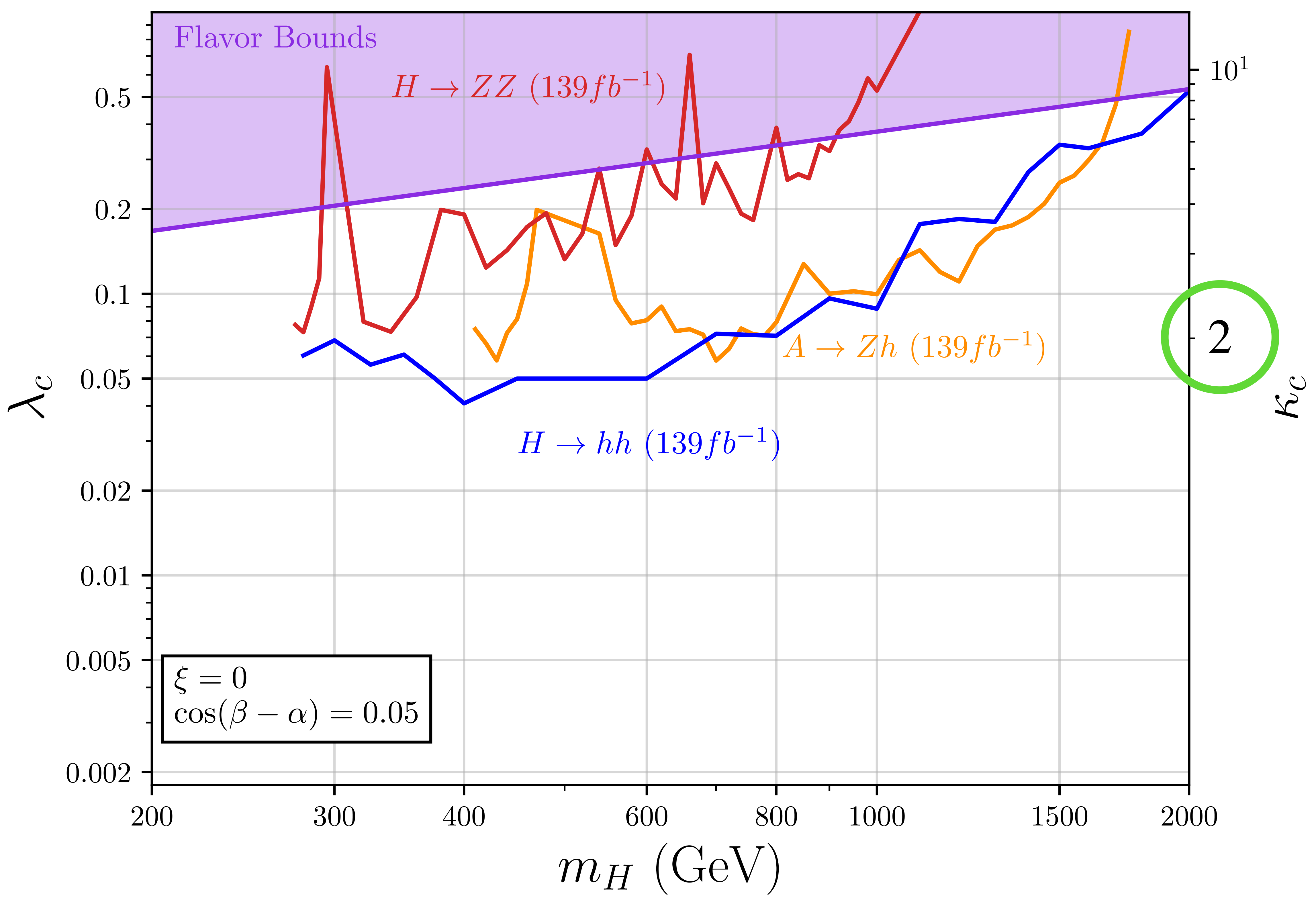


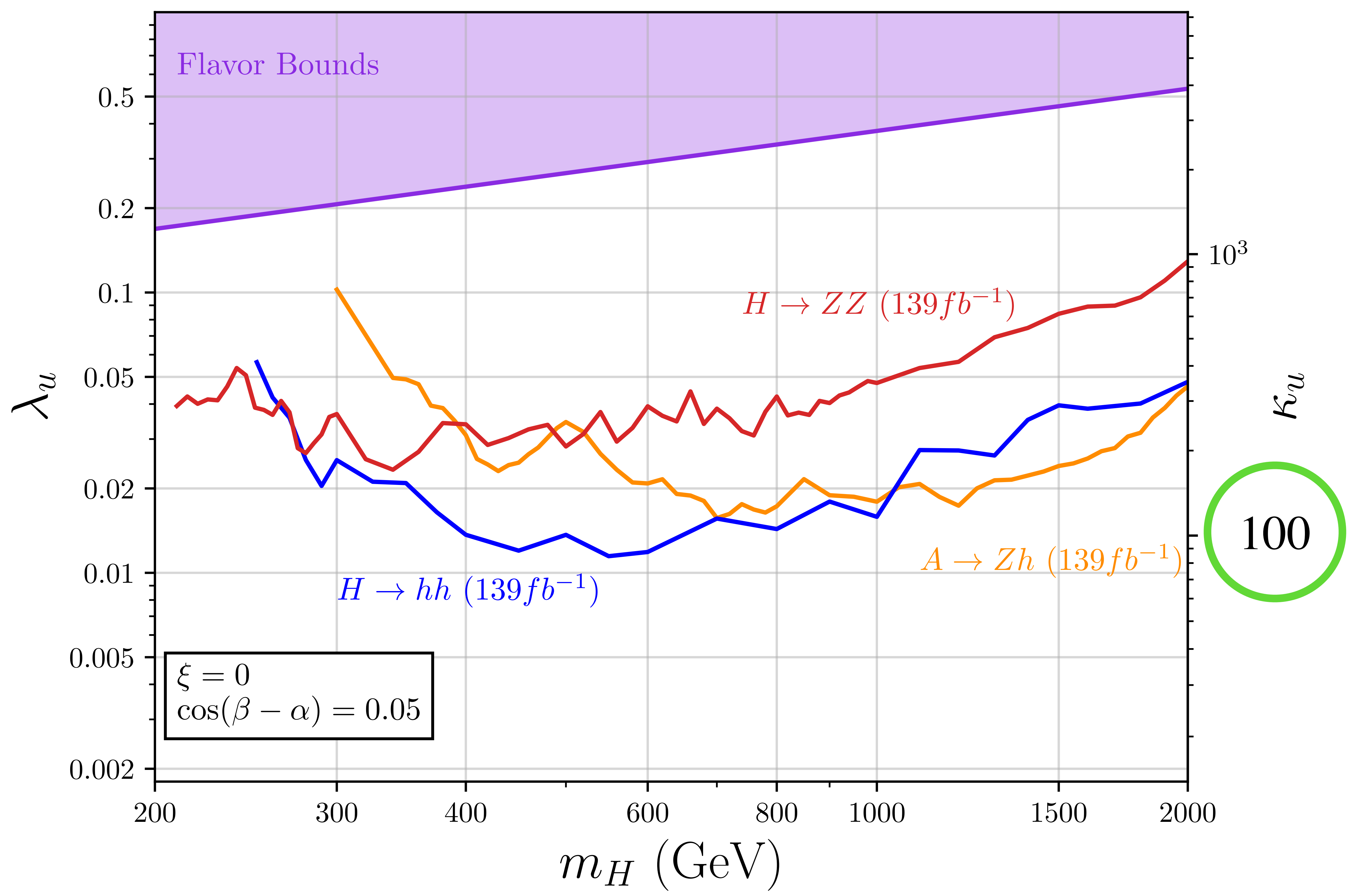


Using DS, pp→4l found to be promising channel to extract information on κ_q's

[Balzani, Gröber & Vitti, 2304.09772]

How charming/upsy can Higgs be?

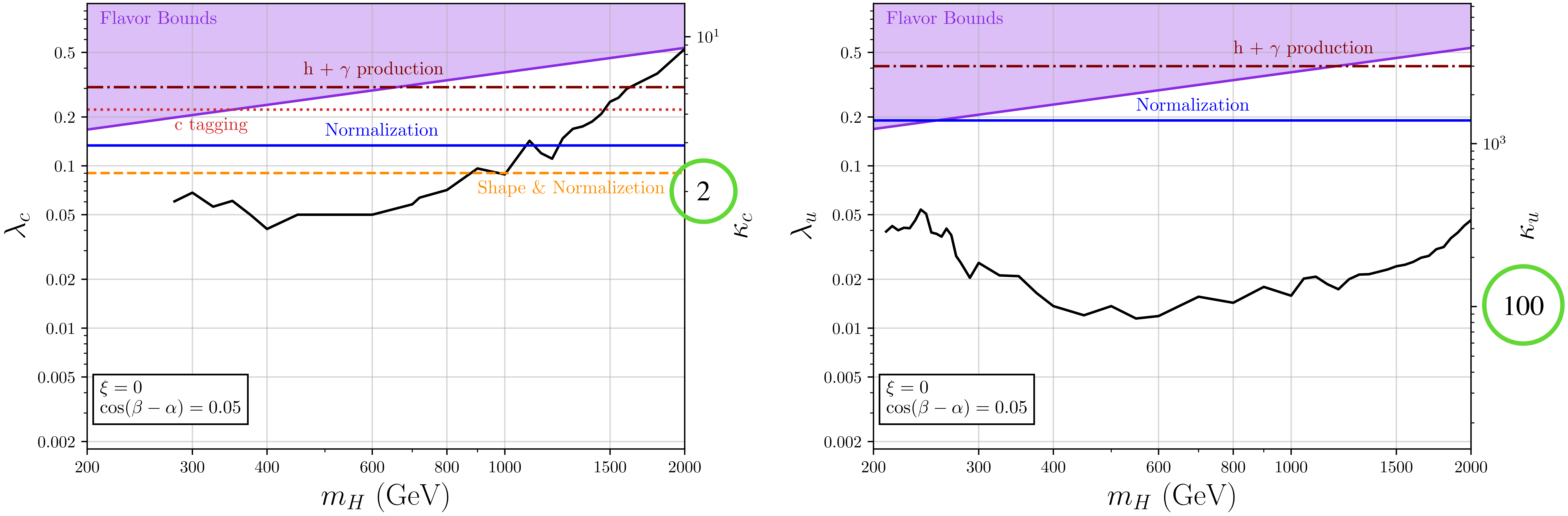




In 2HDM with non-alignment & down-type spontaneous flavor violation, LHC constraints from heavy Higgs searches stronger than flavor physics

[Giannakopoulou, Meade & Valli, 2410.05236]

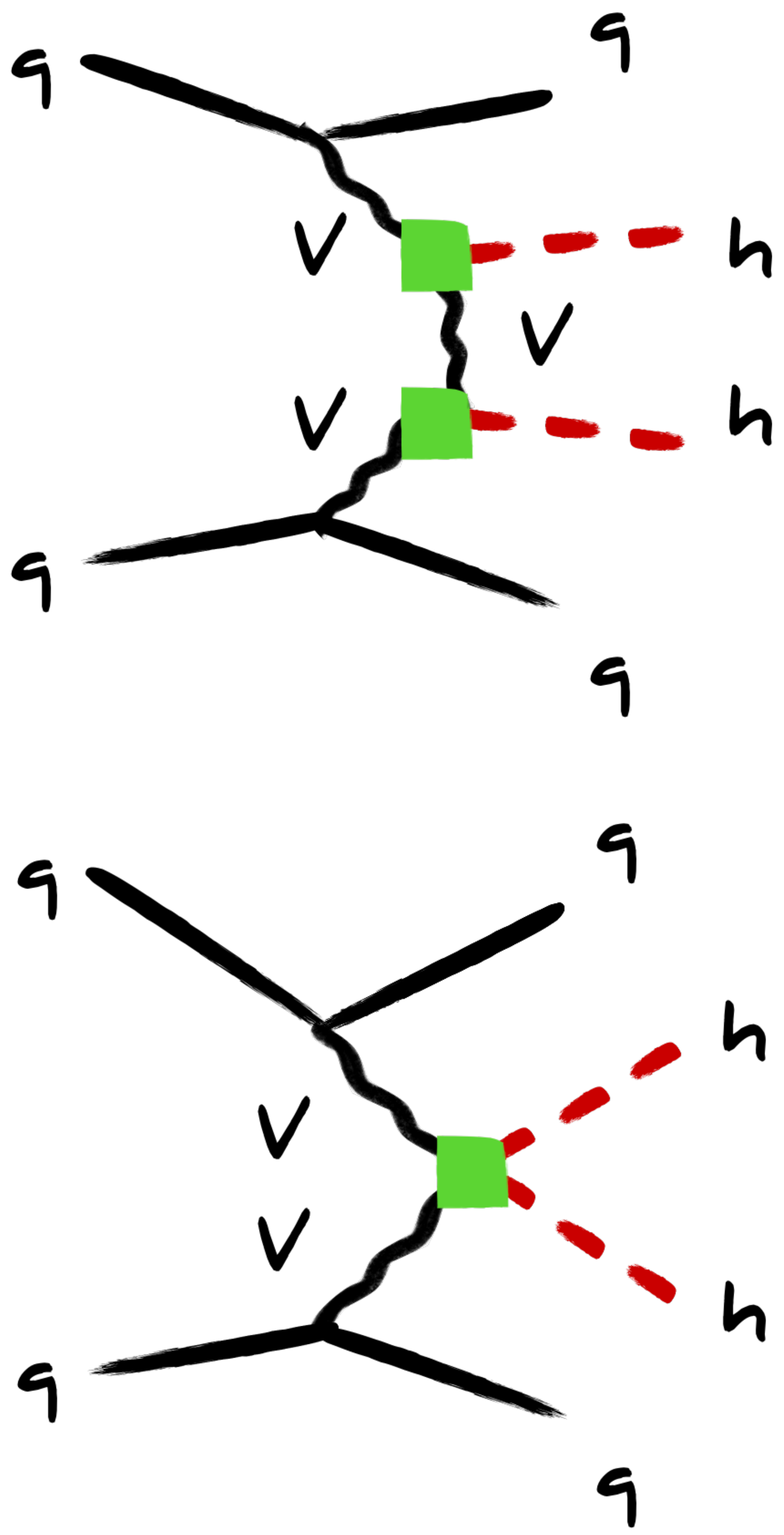
How charming/upsy can Higgs be?

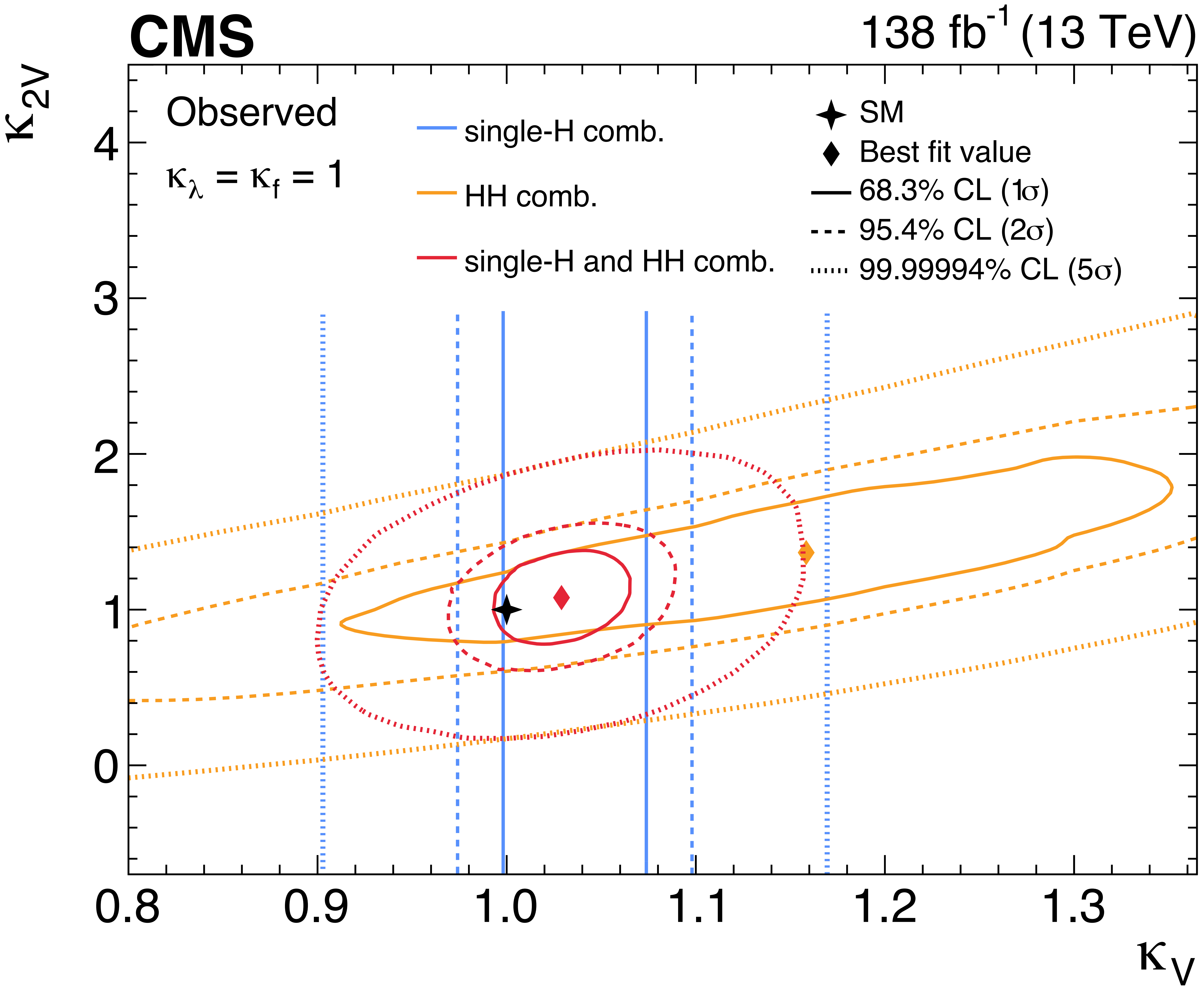


Direct resonant searches provide model-dependent bounds of $|\kappa_c| < O(2)$ & $|\kappa_u| < O(100)$, typically better what can be achieved by other means @ LHC

[Giannakopoulou, Meade & Valli, 2410.05236]

Synergy & complementarity: κ_V & κ_{2V}

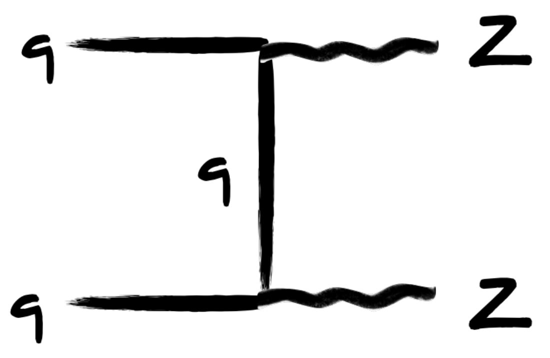


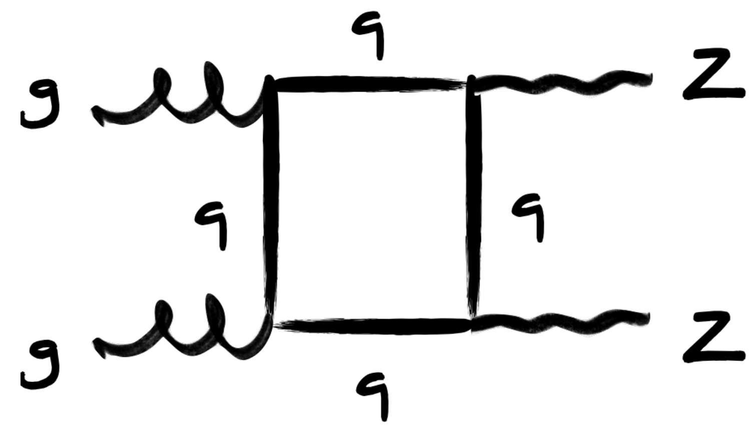


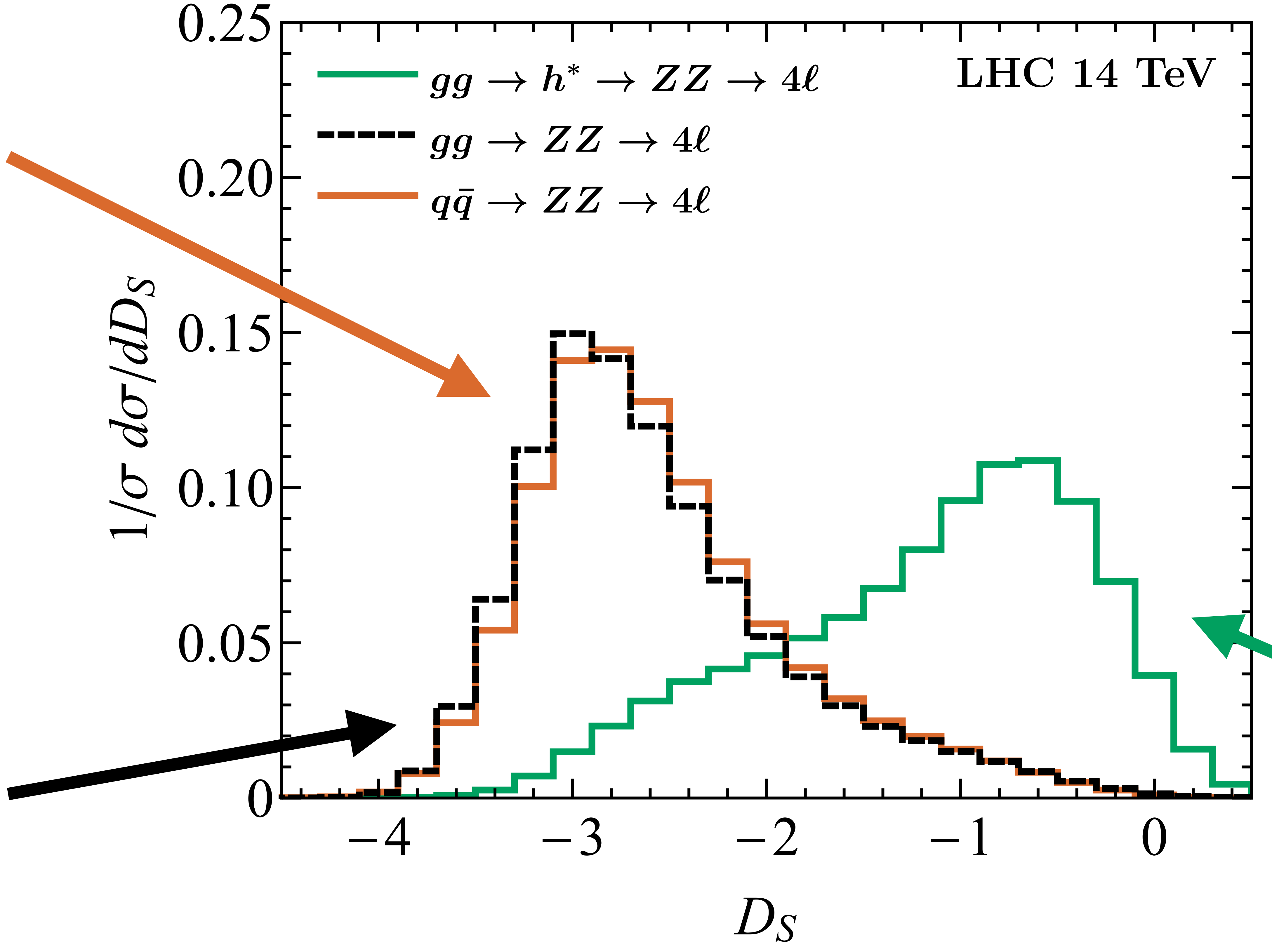
[CMS, 2407.13554]

Matrix-element based discriminators

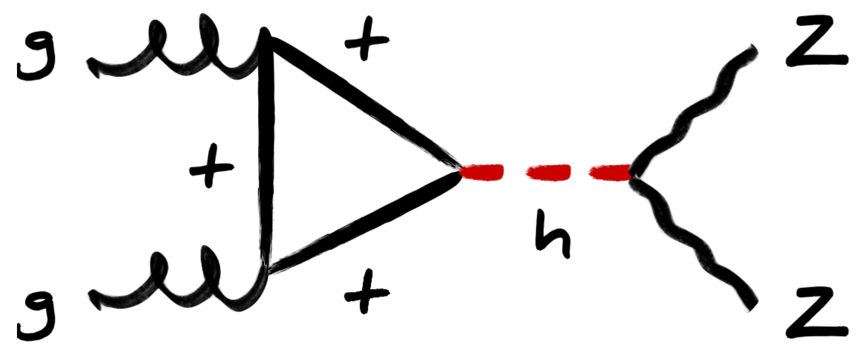
[UH & Koole, 2111.12589]







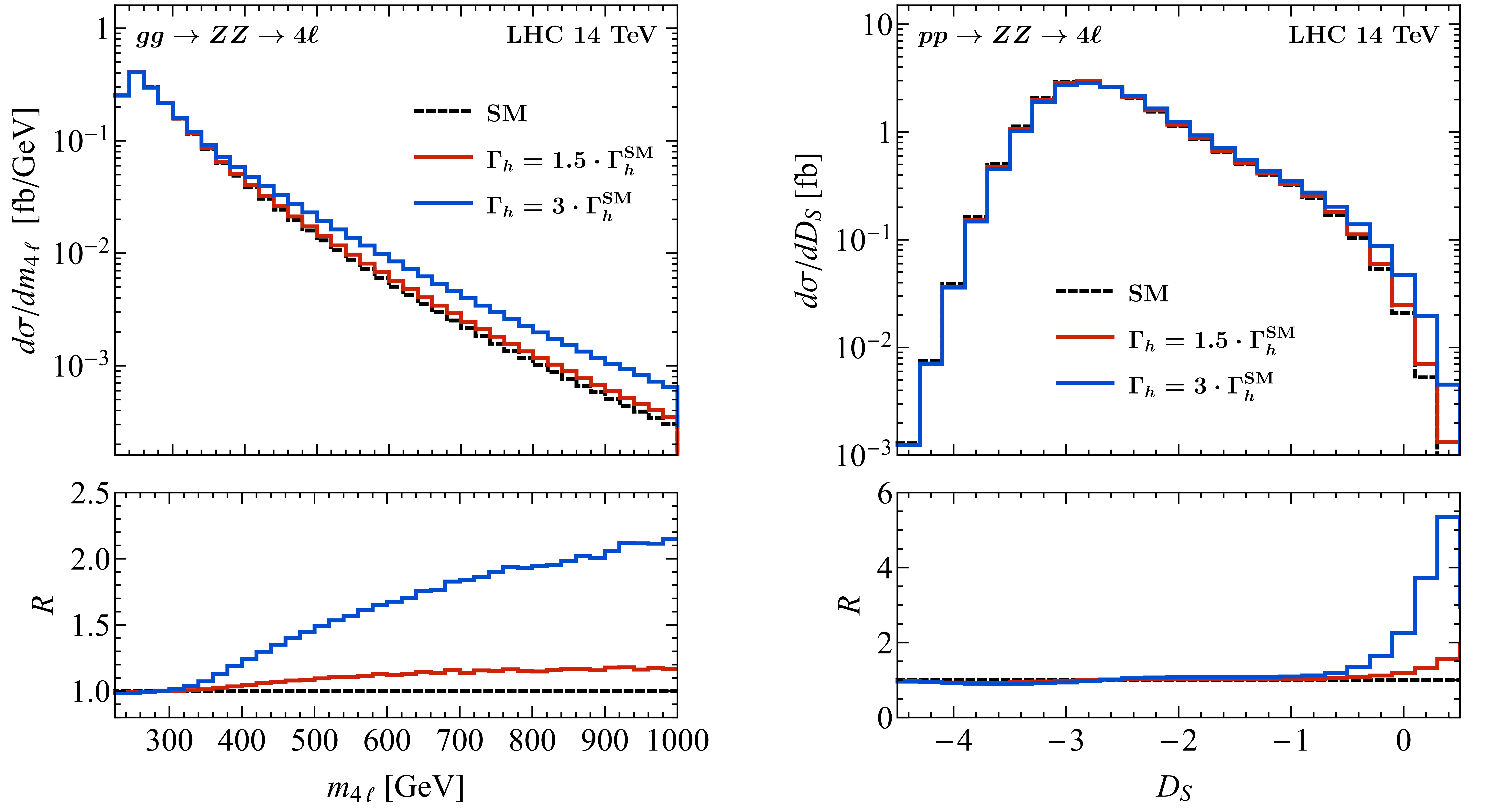
$$D_S = \log_{10}\left(\frac{P_h}{P_{gg} + c \cdot P_{q\bar{q}}}\right)$$



[D_S introduced in Campbell, Ellis & Williams, 1311.3589, 1312.1628]

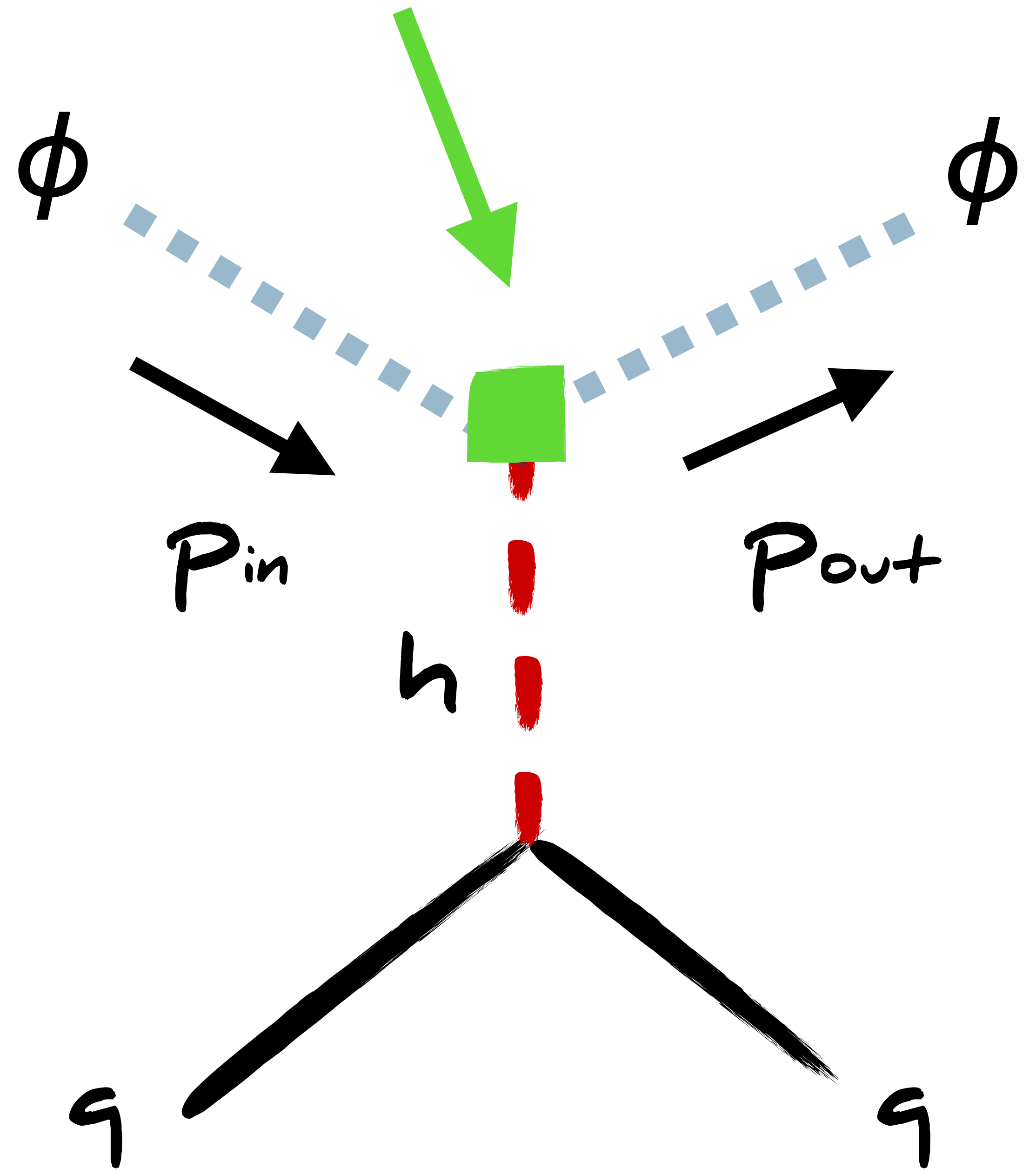
Higgs width measurements: m_{4l} vs. D_S

[UH & Koole, 2111.12589]



Derivative Higgs portal: DM-N scattering

$$\frac{c_d}{f^2}\left(\partial_\mu |H|^2\right)\left(\partial^\mu |\phi|^2\right)$$

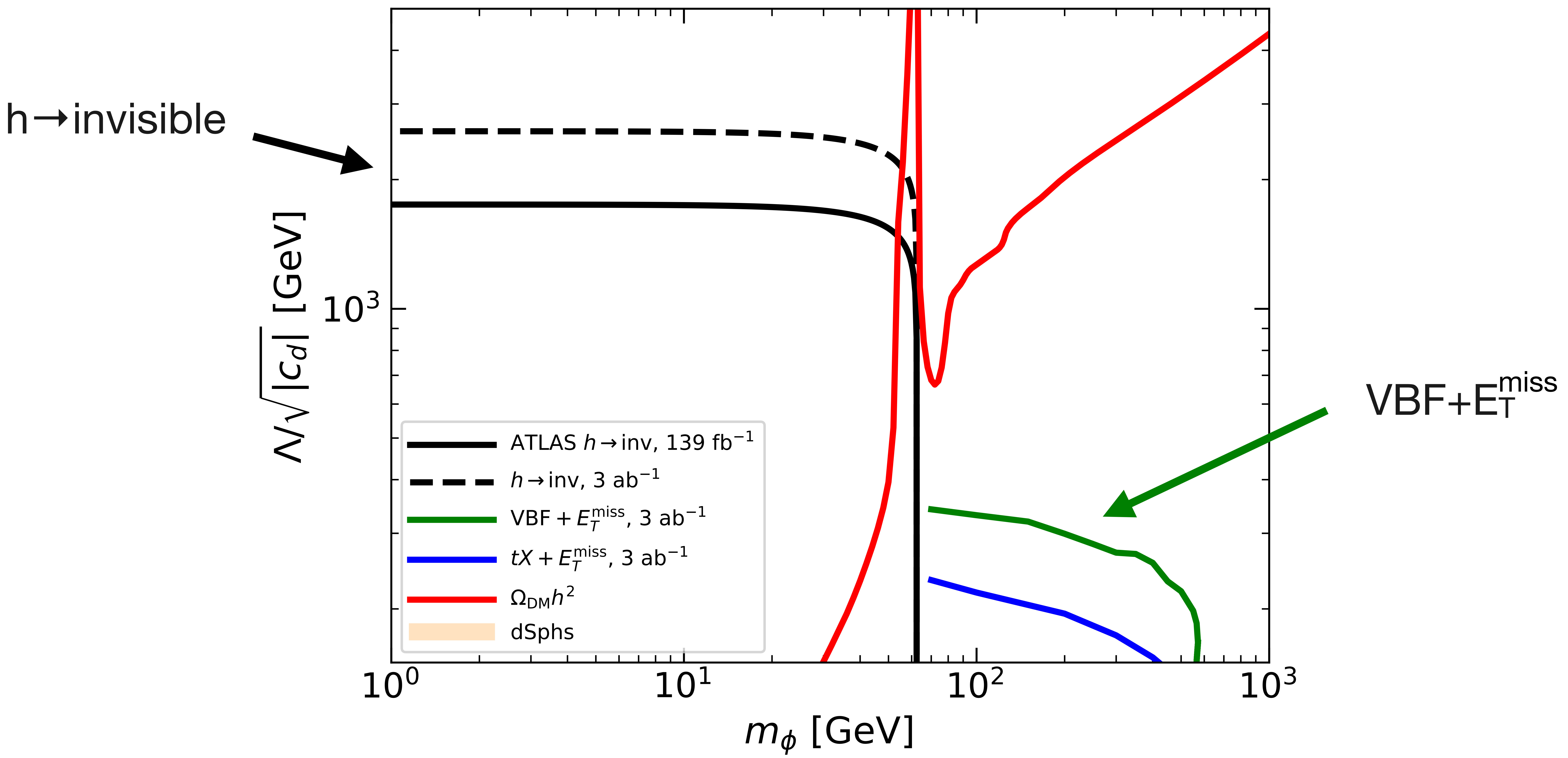


$$\propto \frac{(p_{\text{in}} - p_{\text{out}})^2}{f^2} \lesssim \frac{(100\,\text{MeV})^2}{f^2}$$

Due to momentum suppression, DD limits easily avoided for new-physics scales f of O(1 TeV)

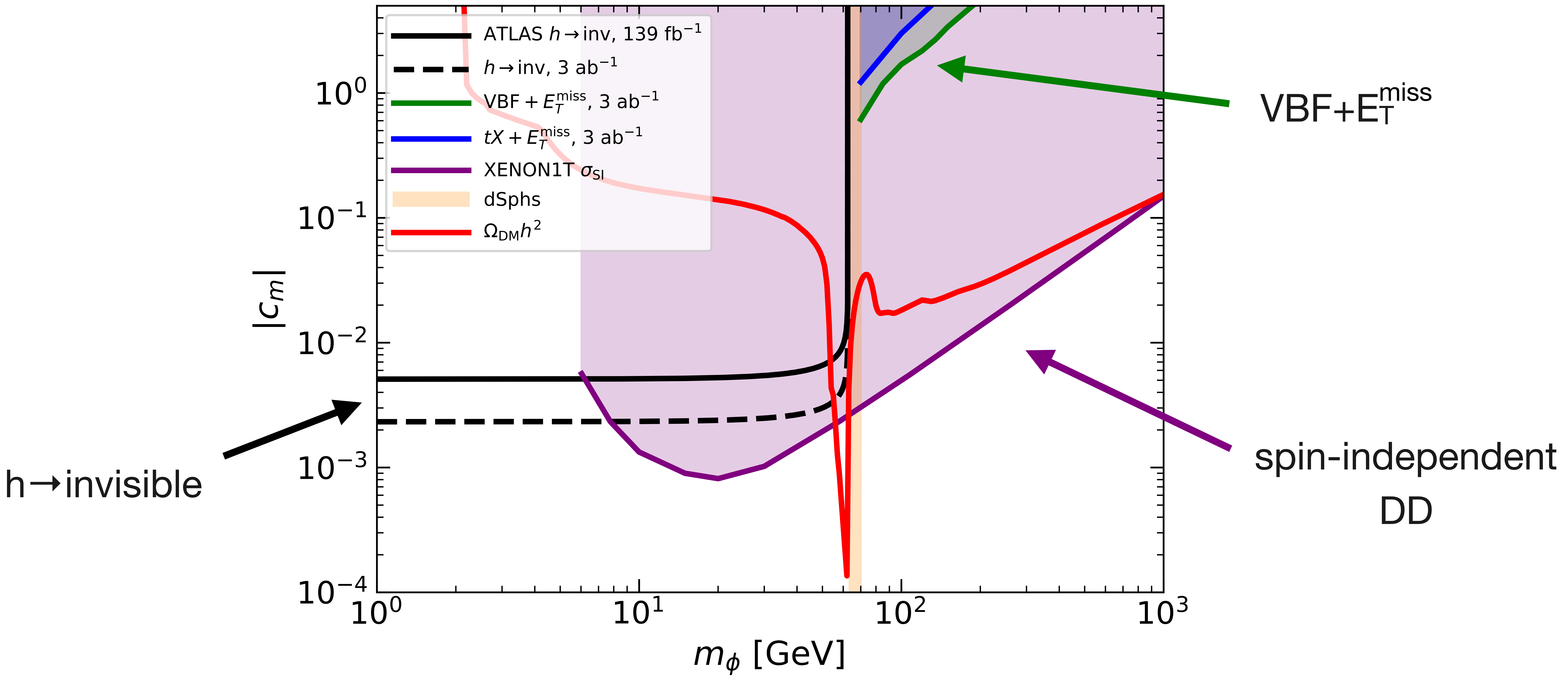
[see for example Balkin, Ruhdorfer, Salvioni & Weiler, 1809.09106]

Global picture of derivative Higgs portal



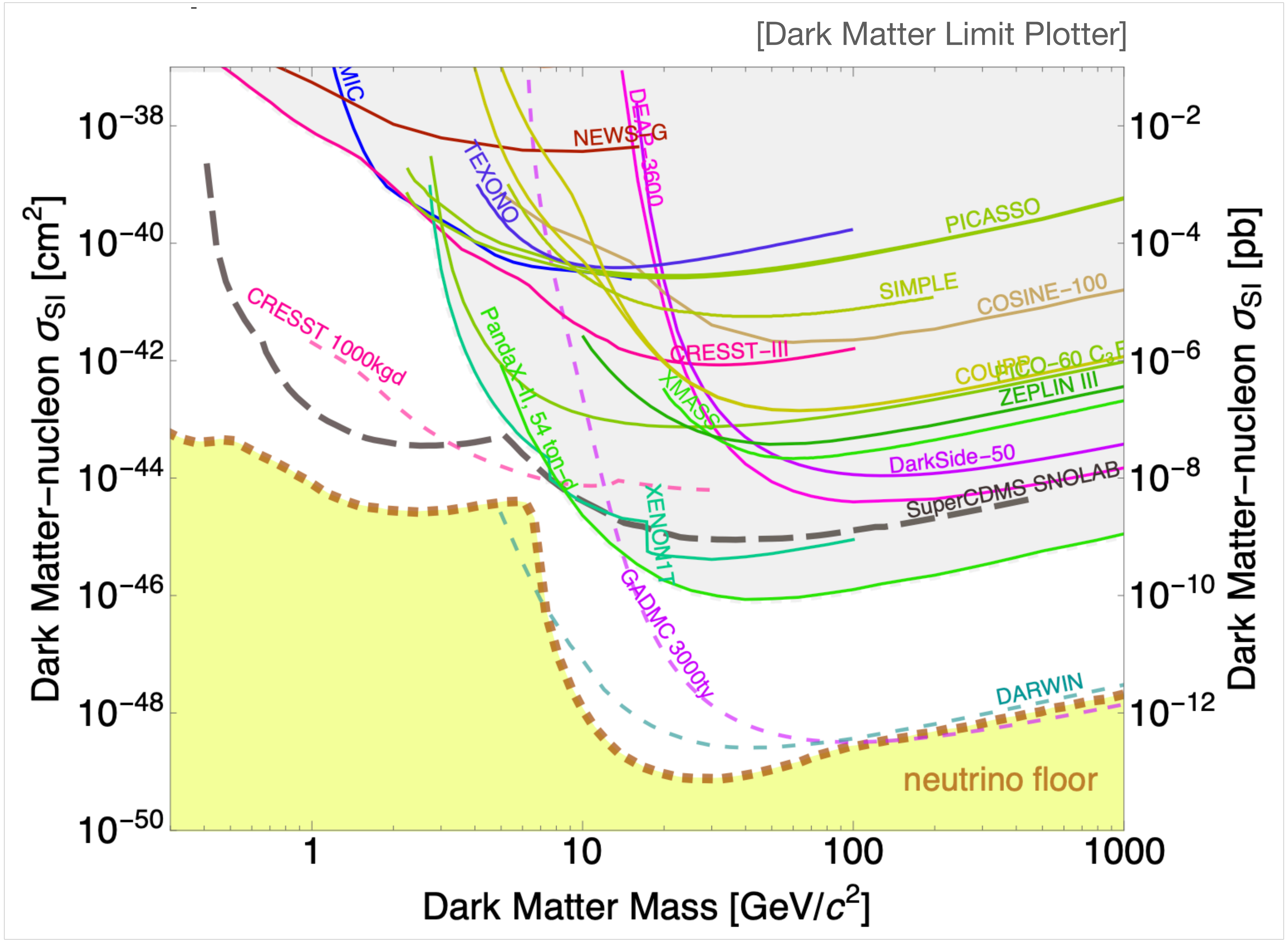
[Argyropoulos, Brandt & UH, 2109.13597]

Global picture of marginal Higgs portal



[Argyropoulos, Brandt & UH, 2109.13597]

Future probes of neutrino floor



Future probes of neutrino floor