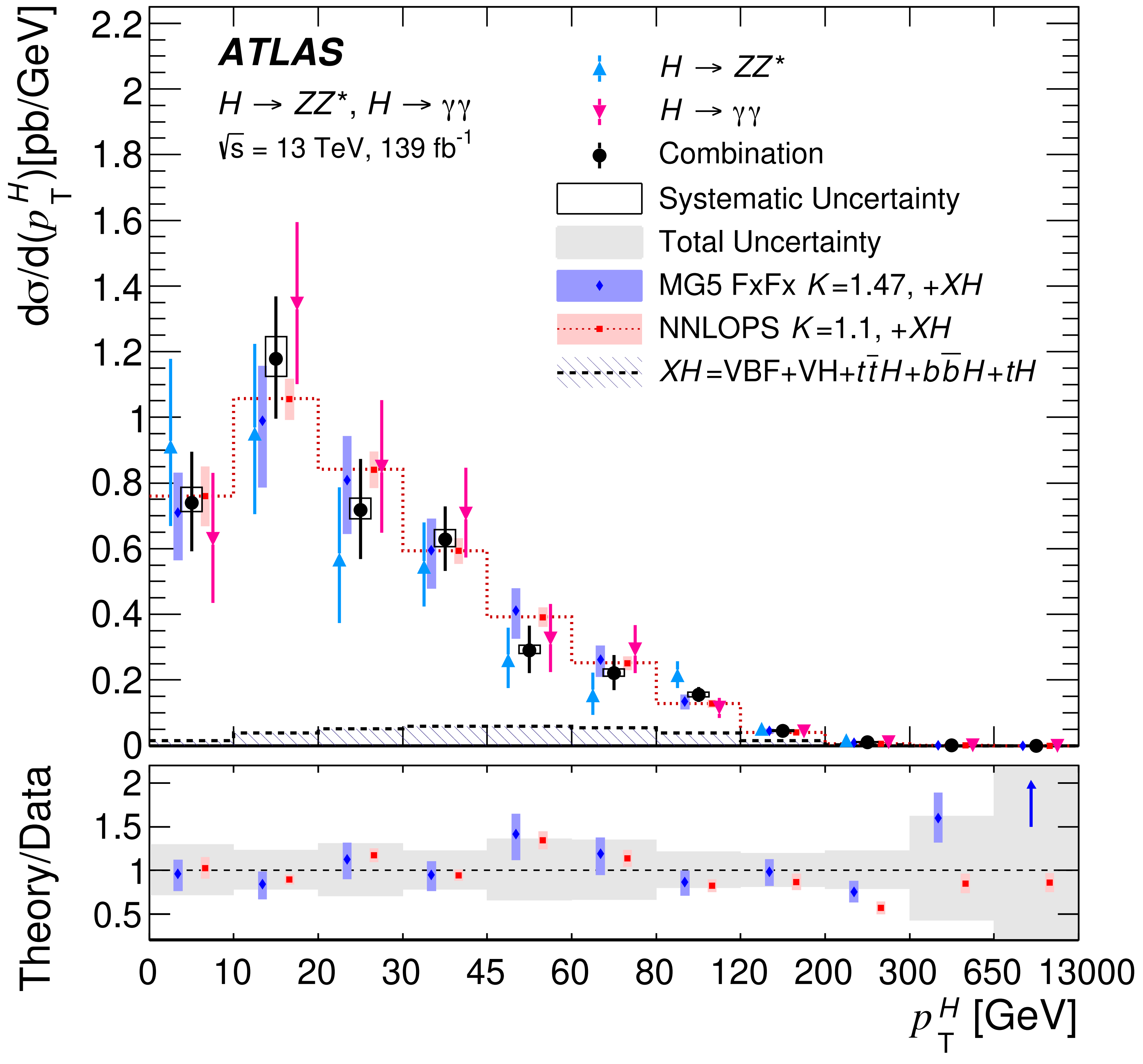
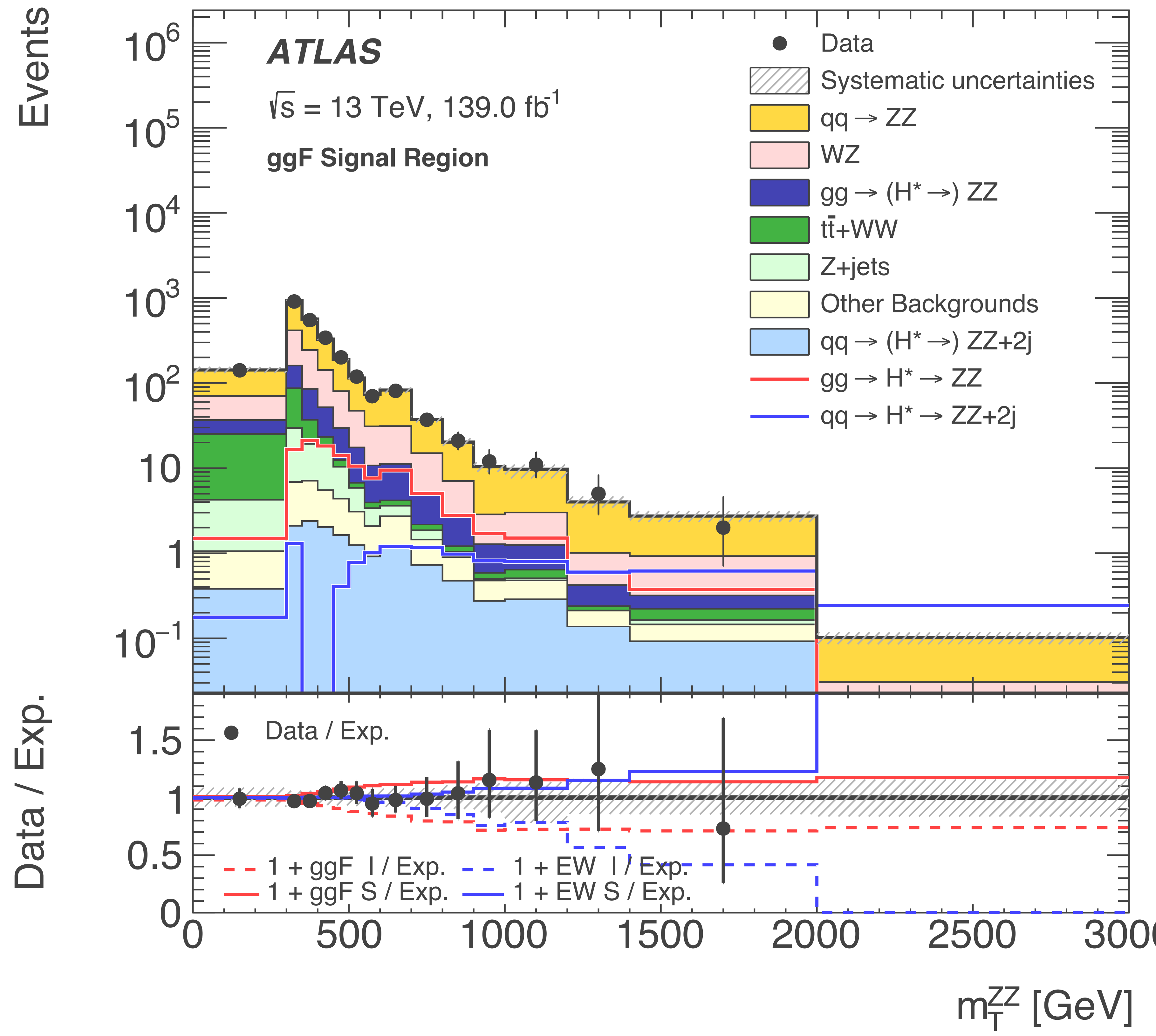
Uli Haisch, MPI Project Review 2024, 9.12.24

Higgs precision physics @ LHC

[ATLAS, 2207.08615]



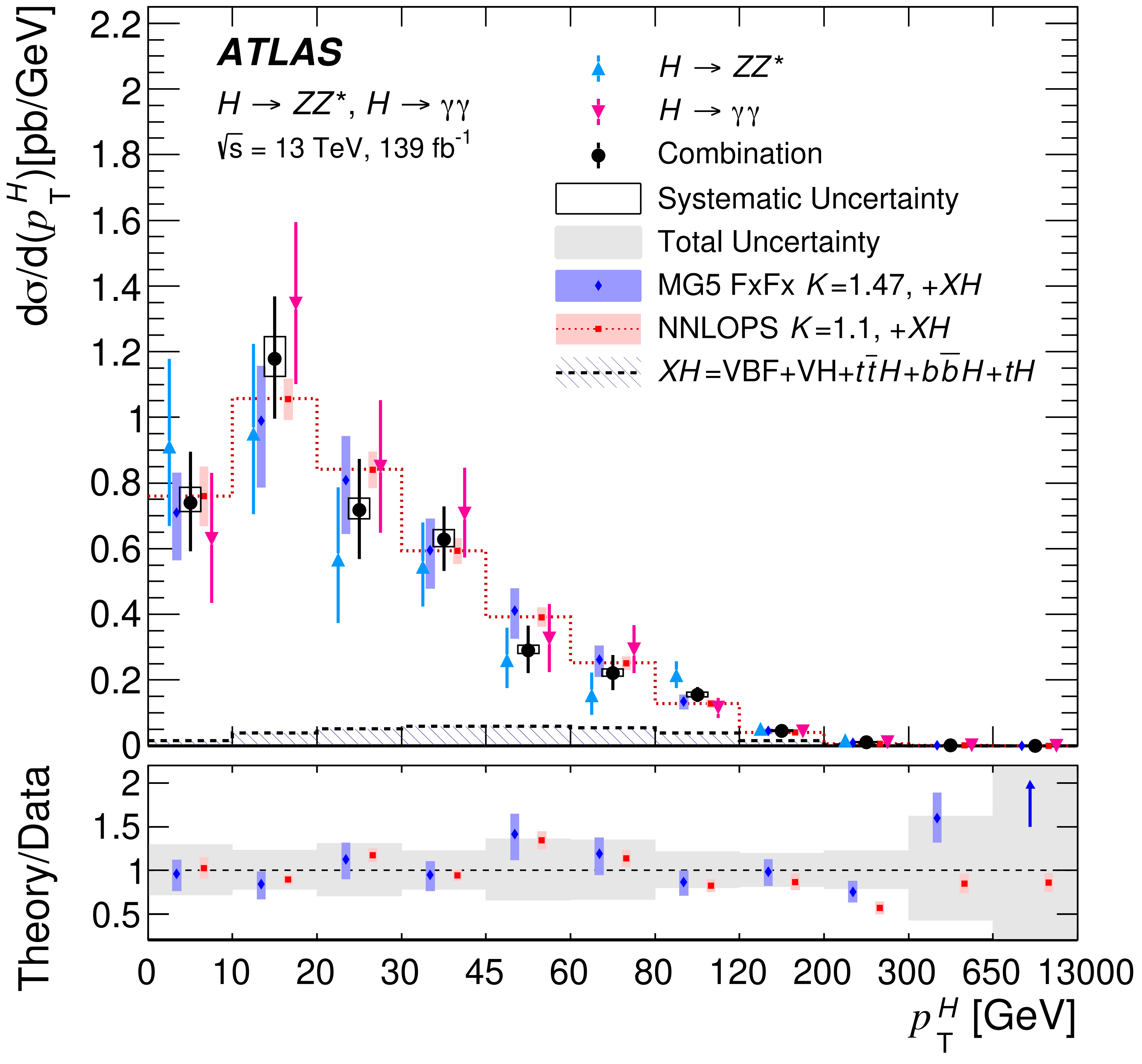
[ATLAS, 2304.01532]



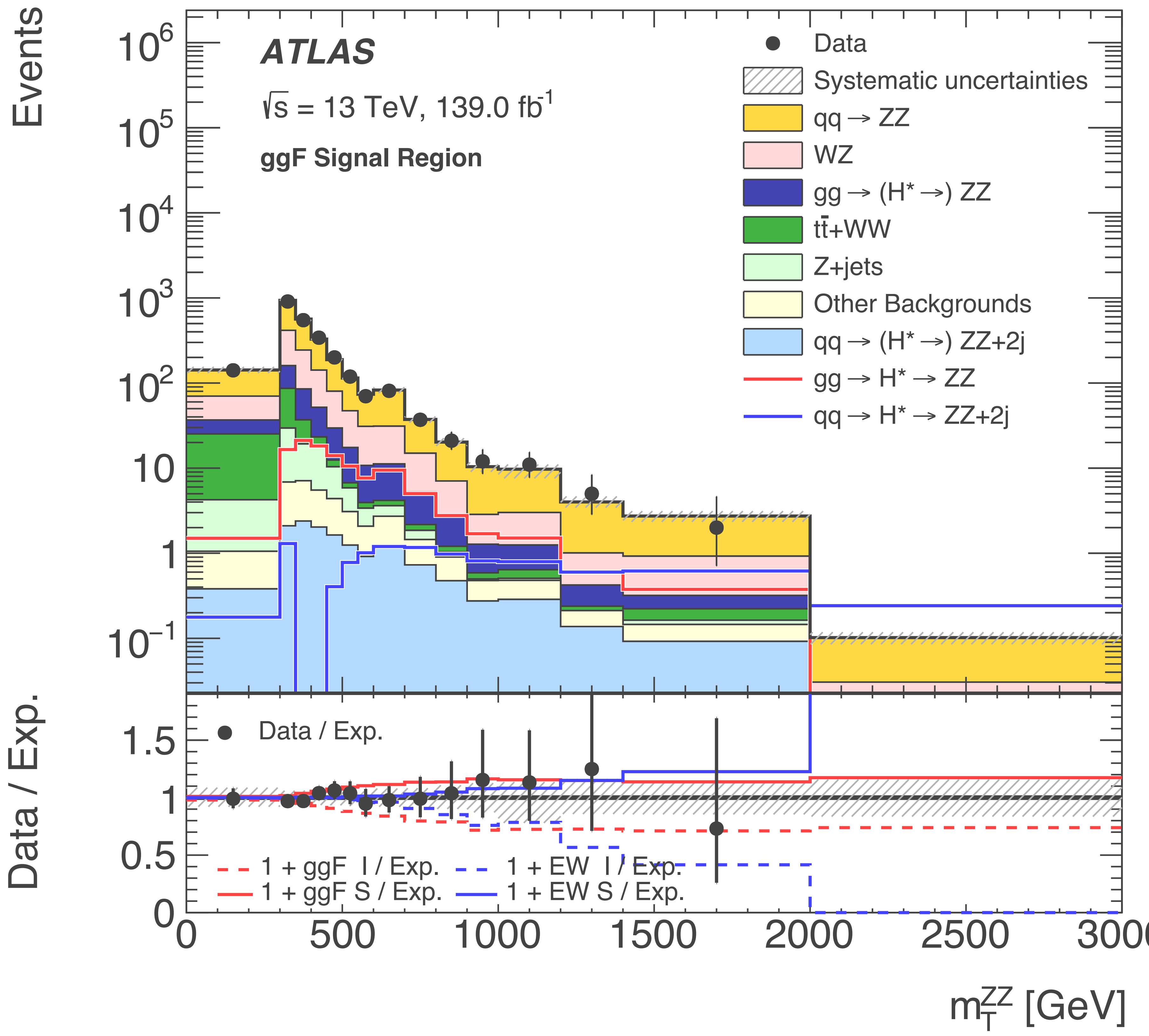
Higgs measurements @ LHC improve steadily & become more differential

Higgs precision physics @ LHC

[ATLAS, 2207.08615]

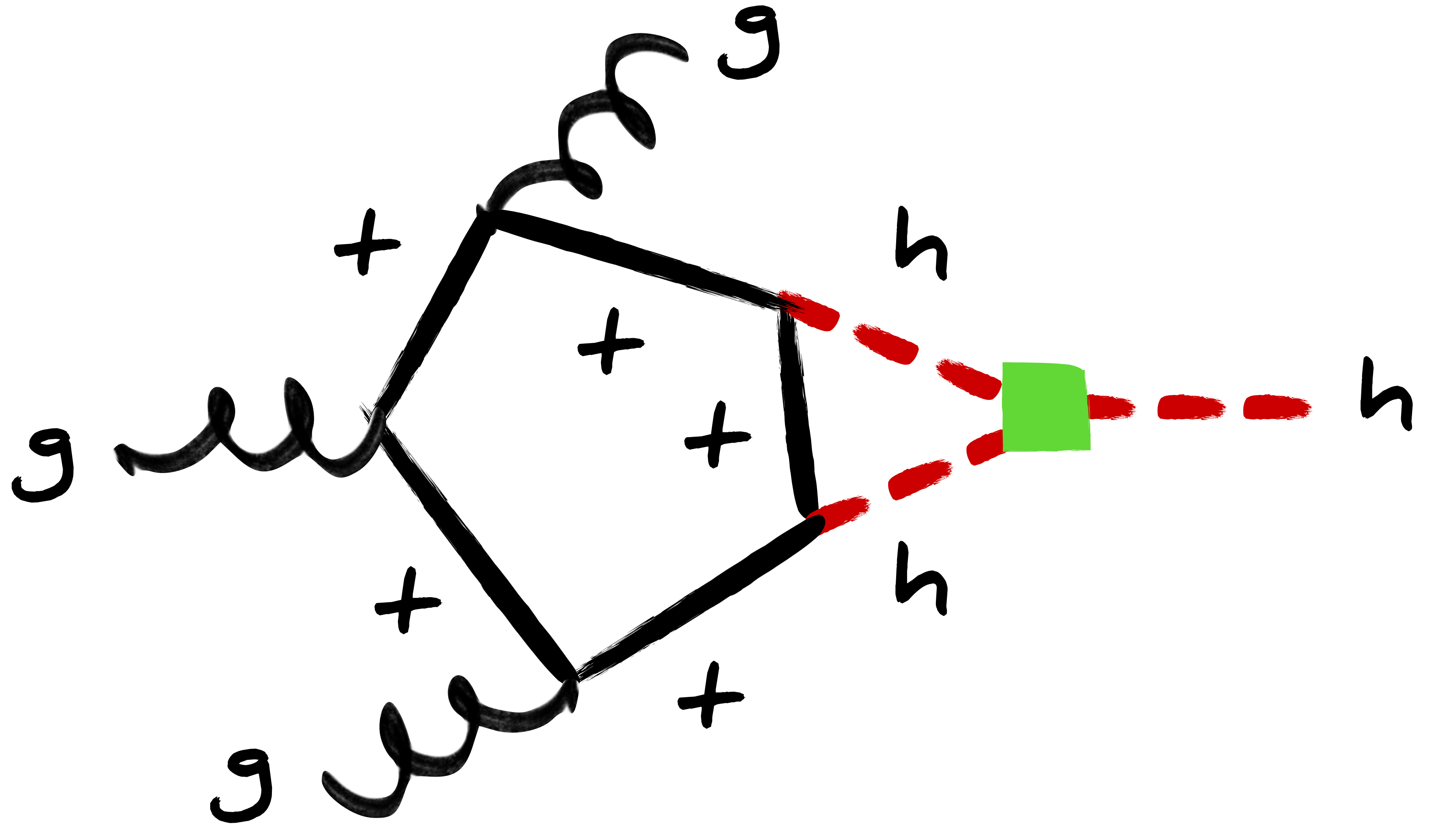


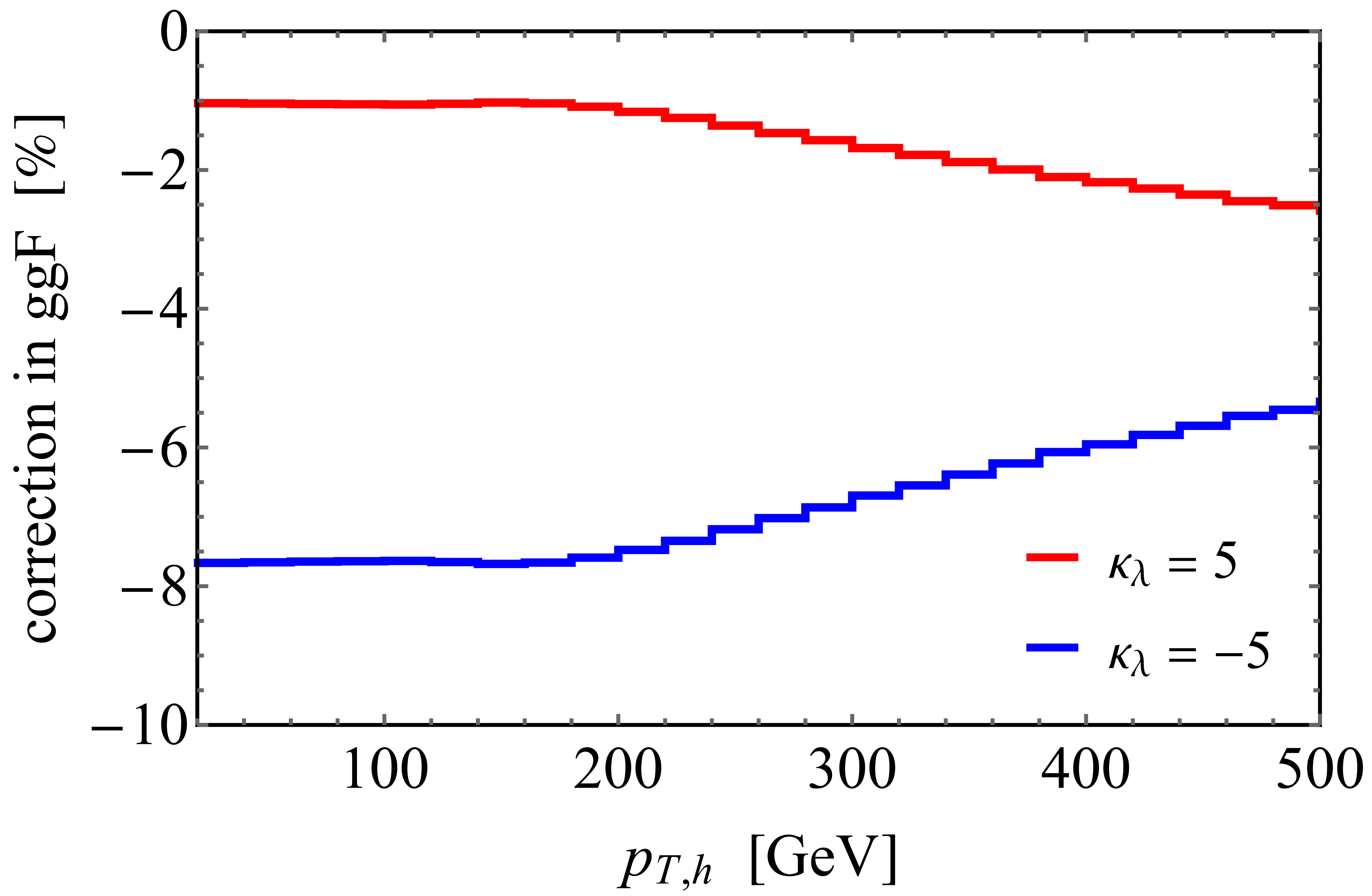
[ATLAS, 2304.01532]



What can we learn from measurements such as $p_{T,h}$ or off-shell rate?

Constraining κ_λ using $p_{T,h}$ distribution

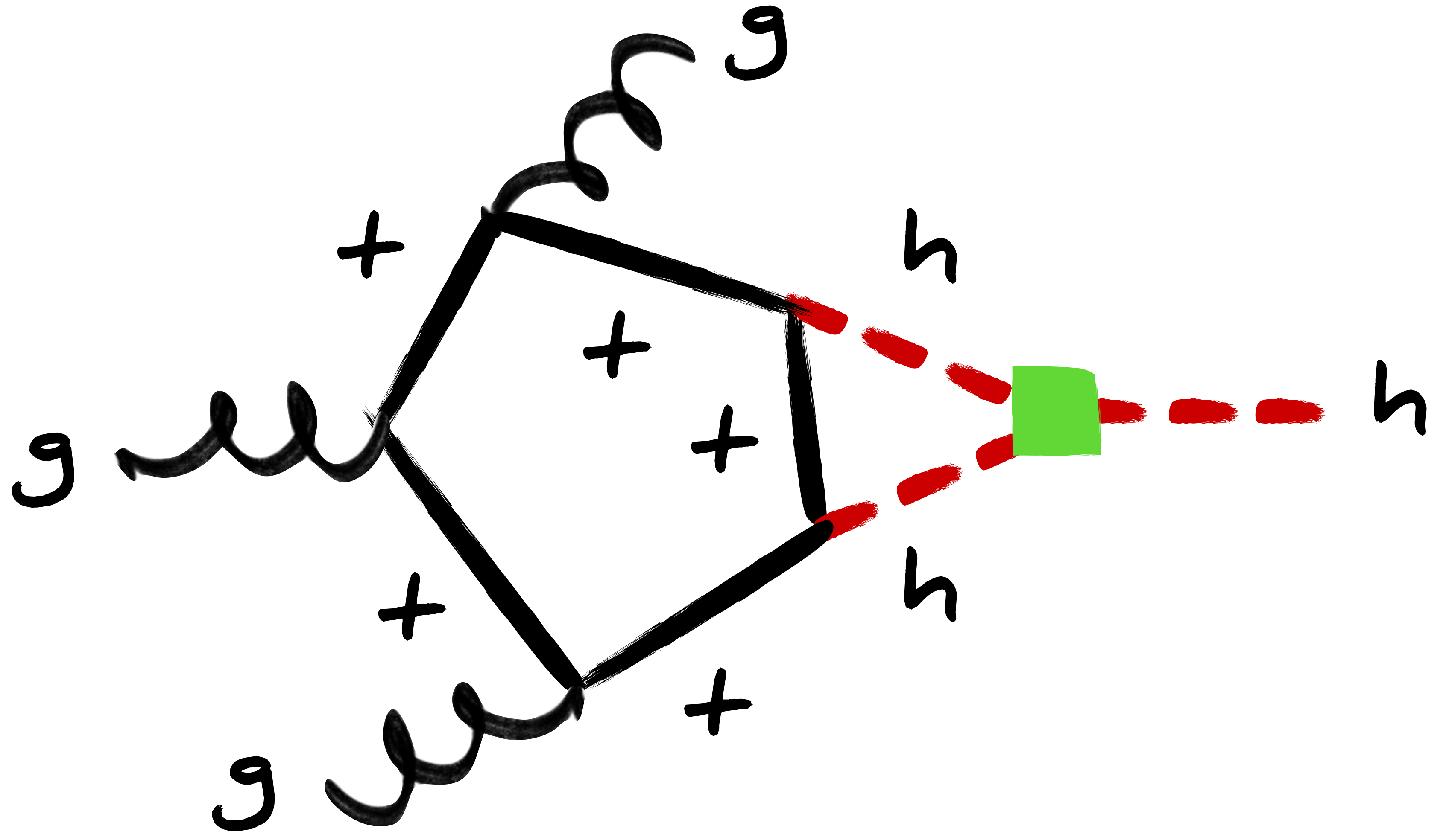


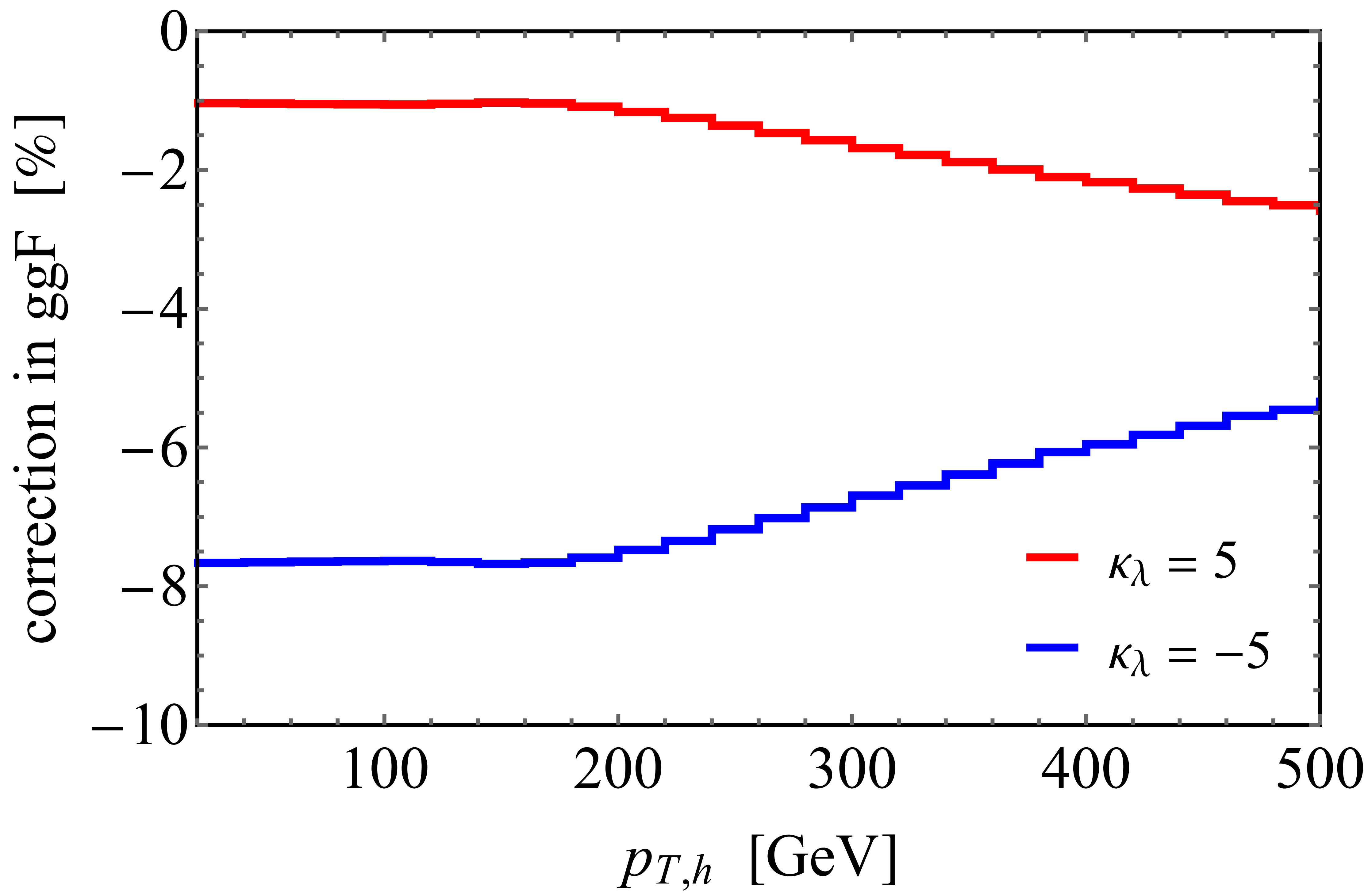


Non-trivial shape change of $p_{T,h}$ spectrum in ggF Higgs production due to 2-loop diagrams involving a trilinear Higgs self-coupling modifier (κ_λ)

[UH & Marco Niggetiedt, 2408.13186]

Constraining κ_λ using $p_{T,h}$ distribution





Dedicated studies planned to quantify precise impact of differential single-h measurements in global hh+h analyses to put constraints on κ_λ

[We are trying to convince Tae Park, a post-doc in Sandra Kortner's group, to help us]

Higgs portal interactions

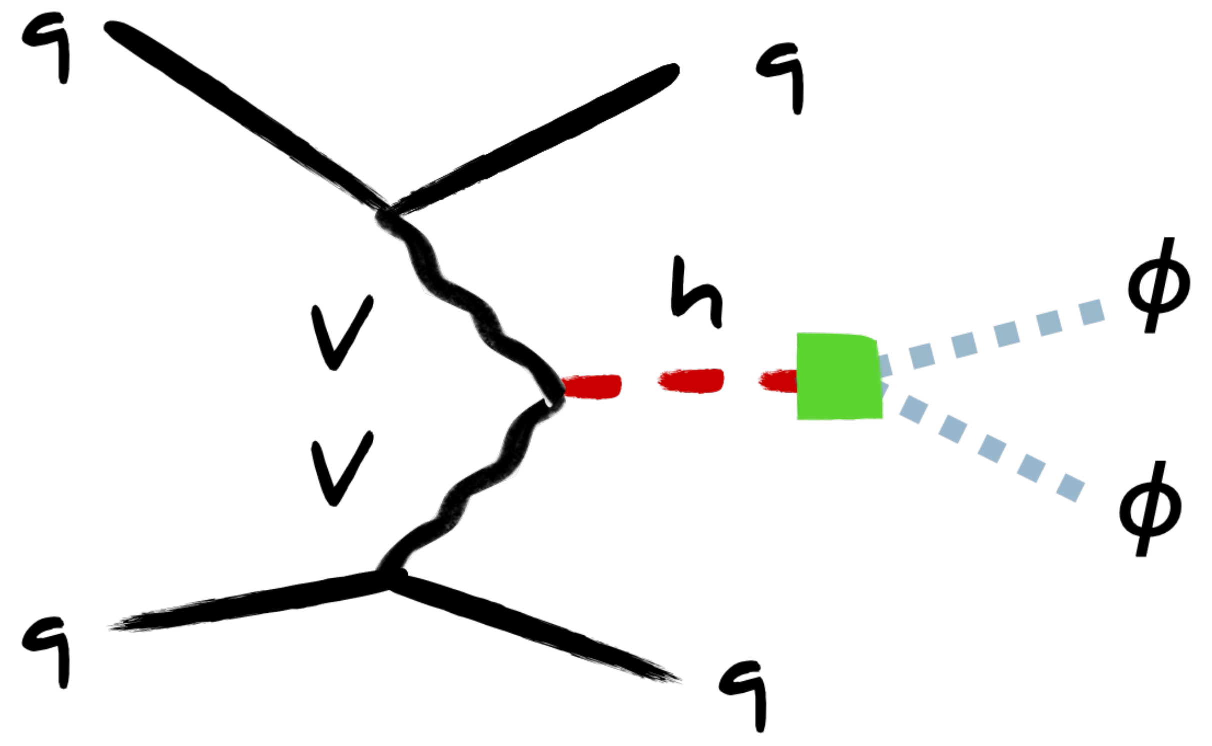
scalar — fermion — vector

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

$|H|^2$ 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, as dark matter (DM) direct detection (DD) cross section momentum suppressed

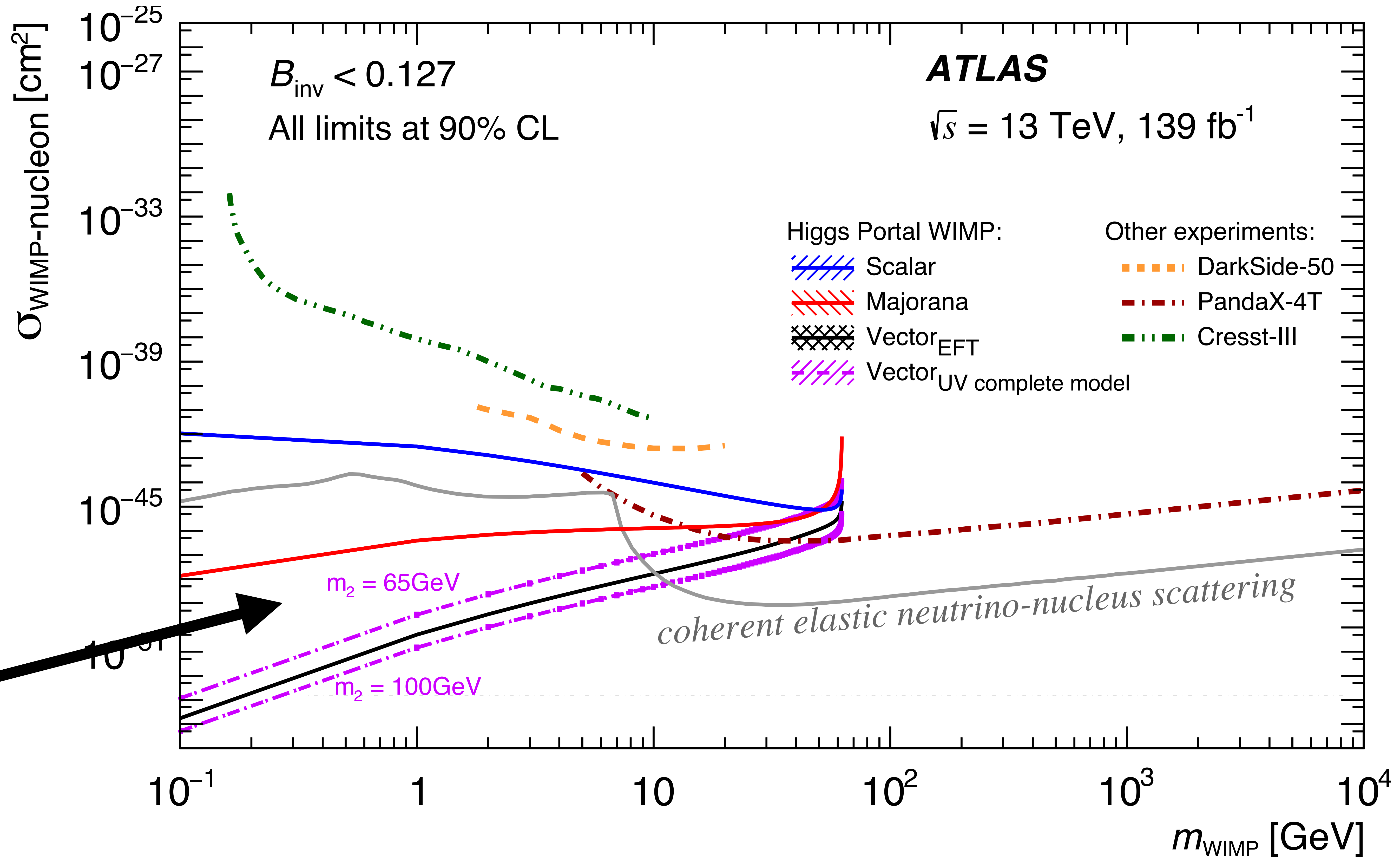
[for a recent review see for instance Spyros Argyropoulos, Oleg Brandt & UH, 2109.13597]

Higgs portal searches @ LHC

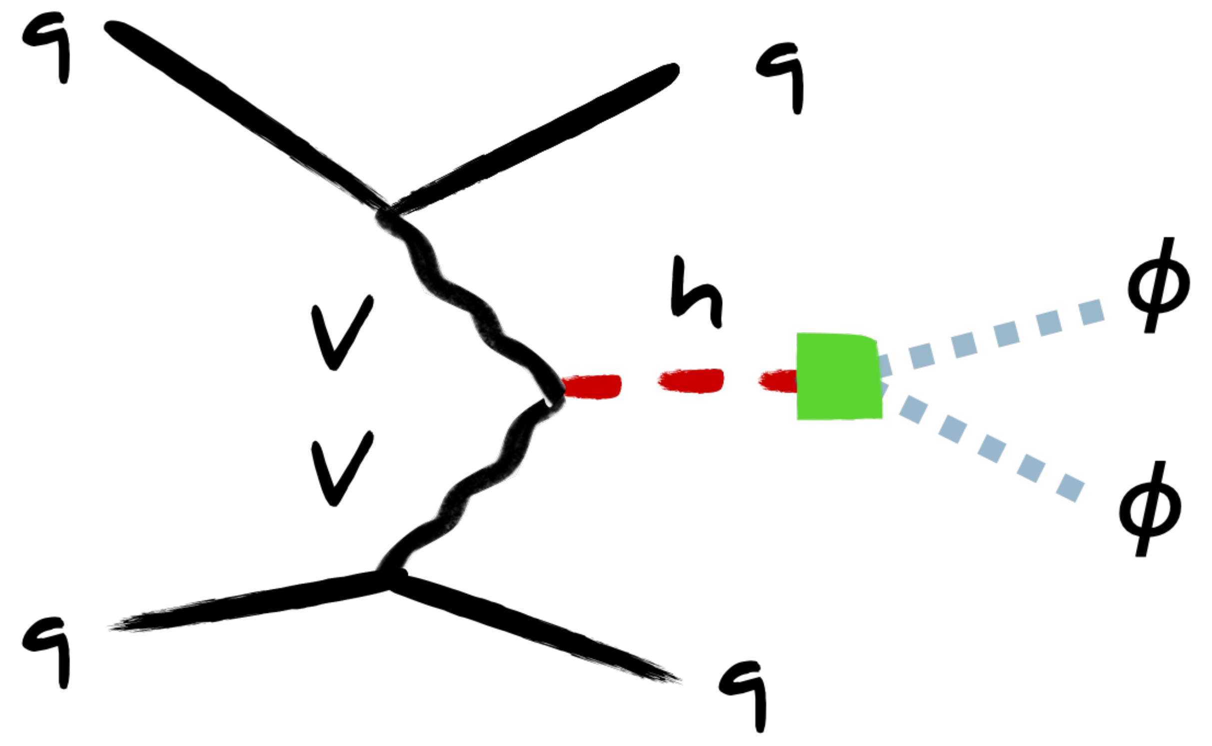


If DM states are kinematically accessible in Higgs decays, LHC searches for h→invisible superior to present DD limits

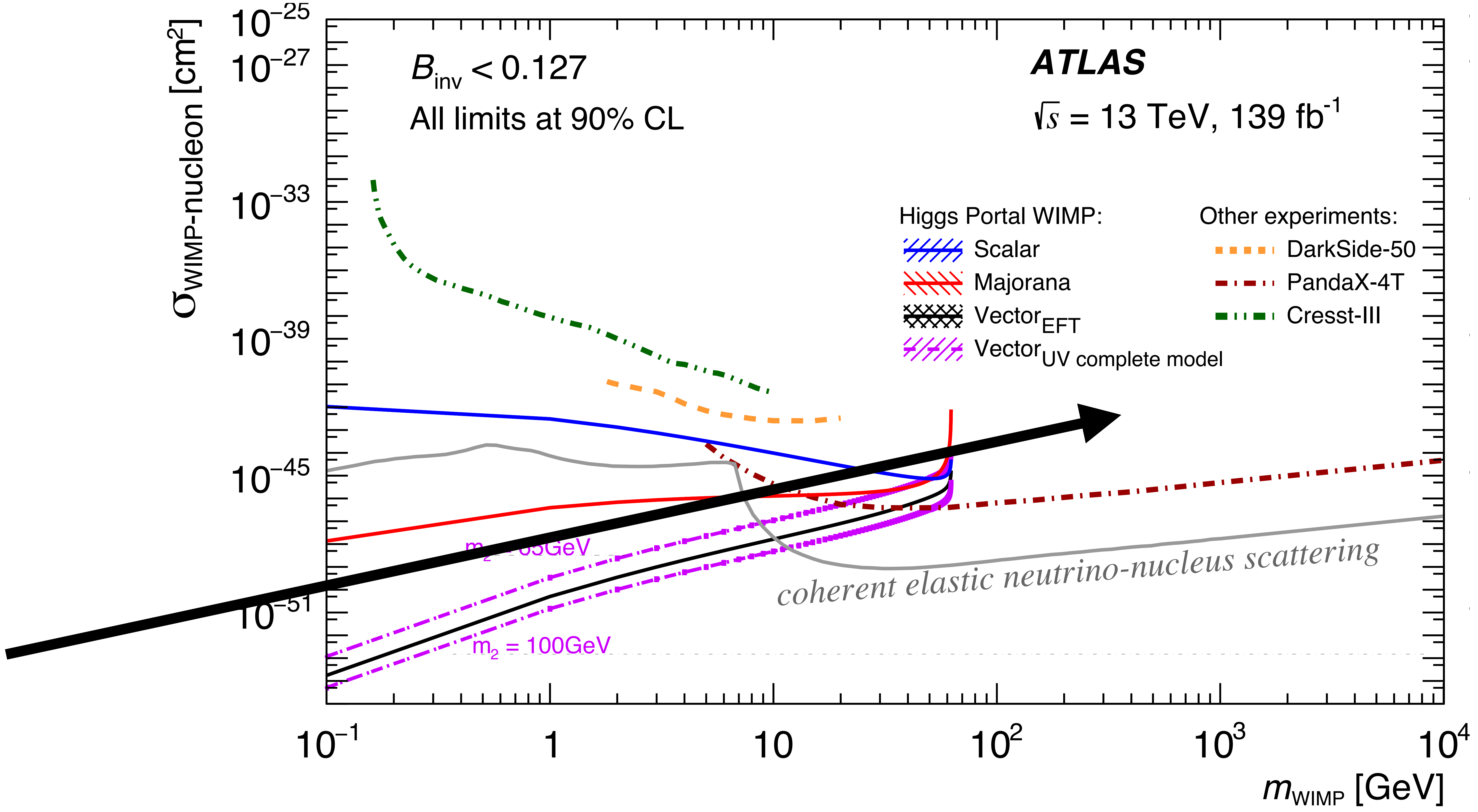
[ATLAS, 2202.07953]



Higgs portal searches @ LHC



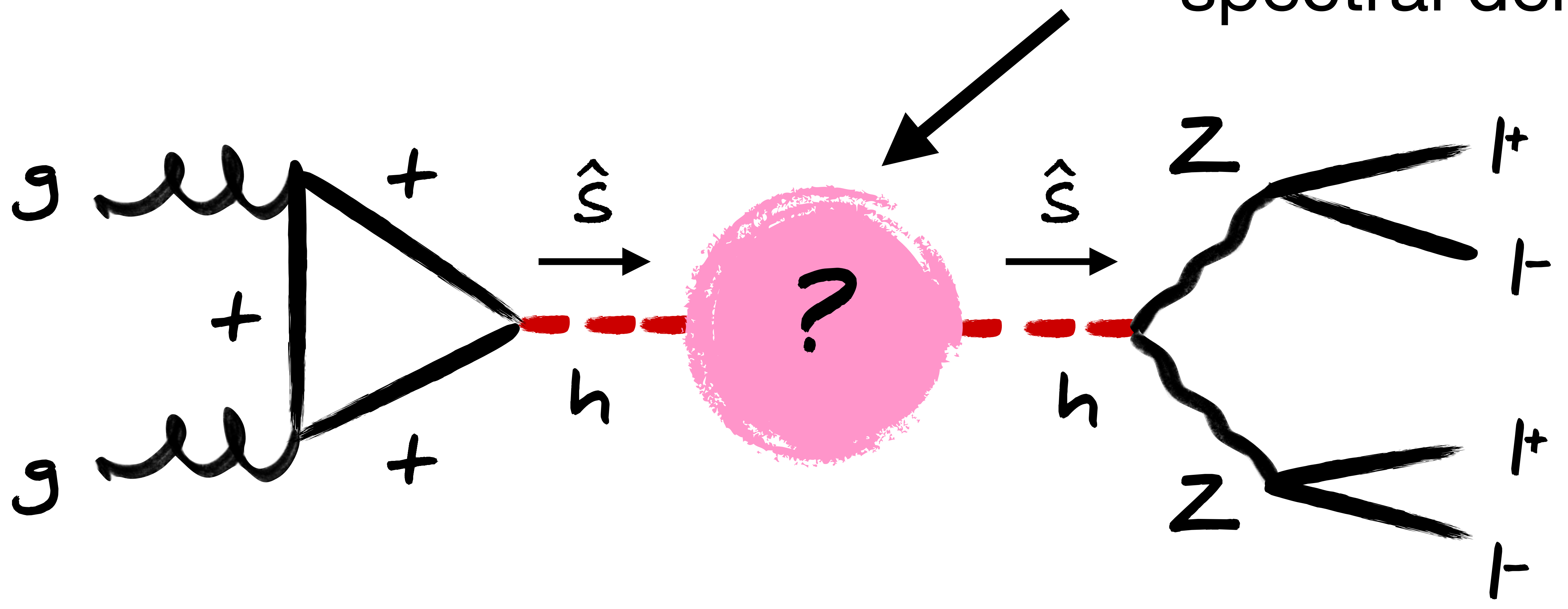
[ATLAS, 2202.07953]



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

Searches for Higgsphilics in pp→4l

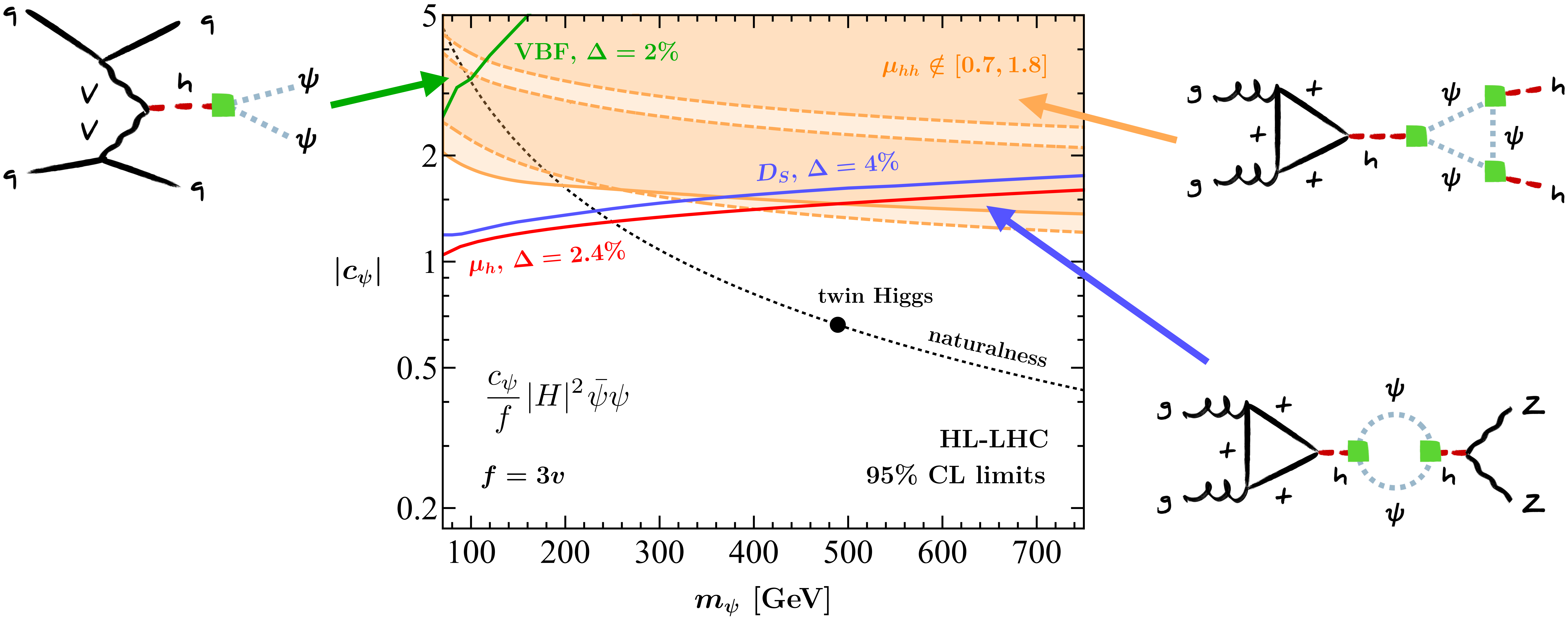
DM particles, top partners, …,
spectral density of Higgs



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

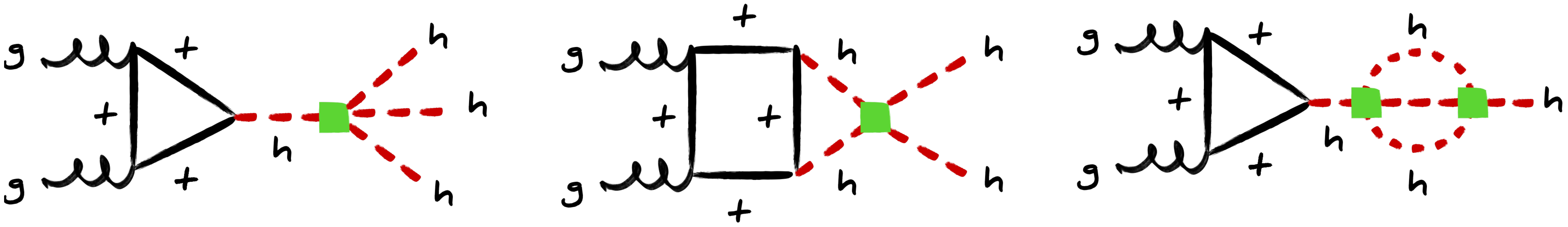
[UH & Gabriel Koole, 2201.09711; UH, Max Ruhdorfer, Konstantin Schmid & Andi Weiler; 2311.03995]

HL-LHC bounds on fermionic Higgs portal



[UH, Max Ruhdorfer, Konstantin Schmid & Andi Weiler; 2311.03995]

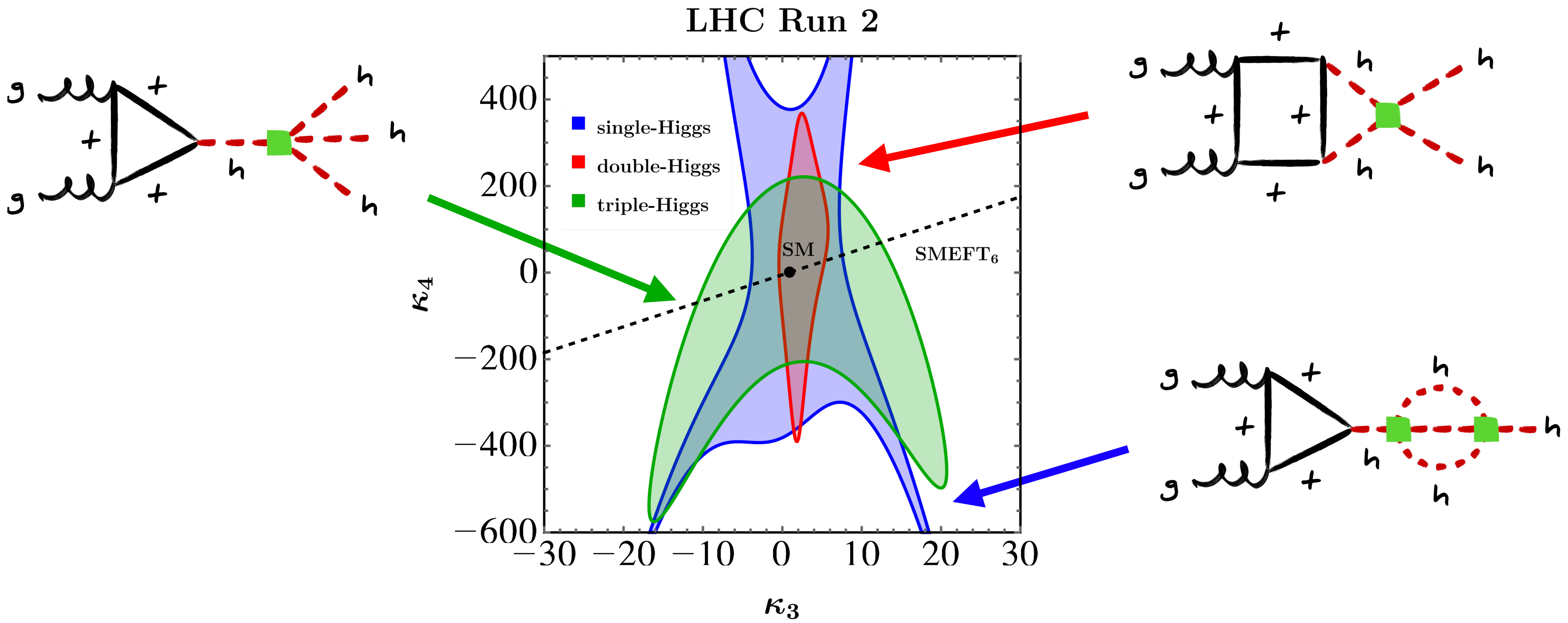
What about quartic Higgs self-coupling?



Direct probe of quartic Higgs self-coupling (κ_4) provided @ 1-loop by 3h production, while indirect sensitivity in hh & h production through 2-loop & 3-loop corrections

[UH, Aparna Sankar & Giulia Zanderighi, ongoing]

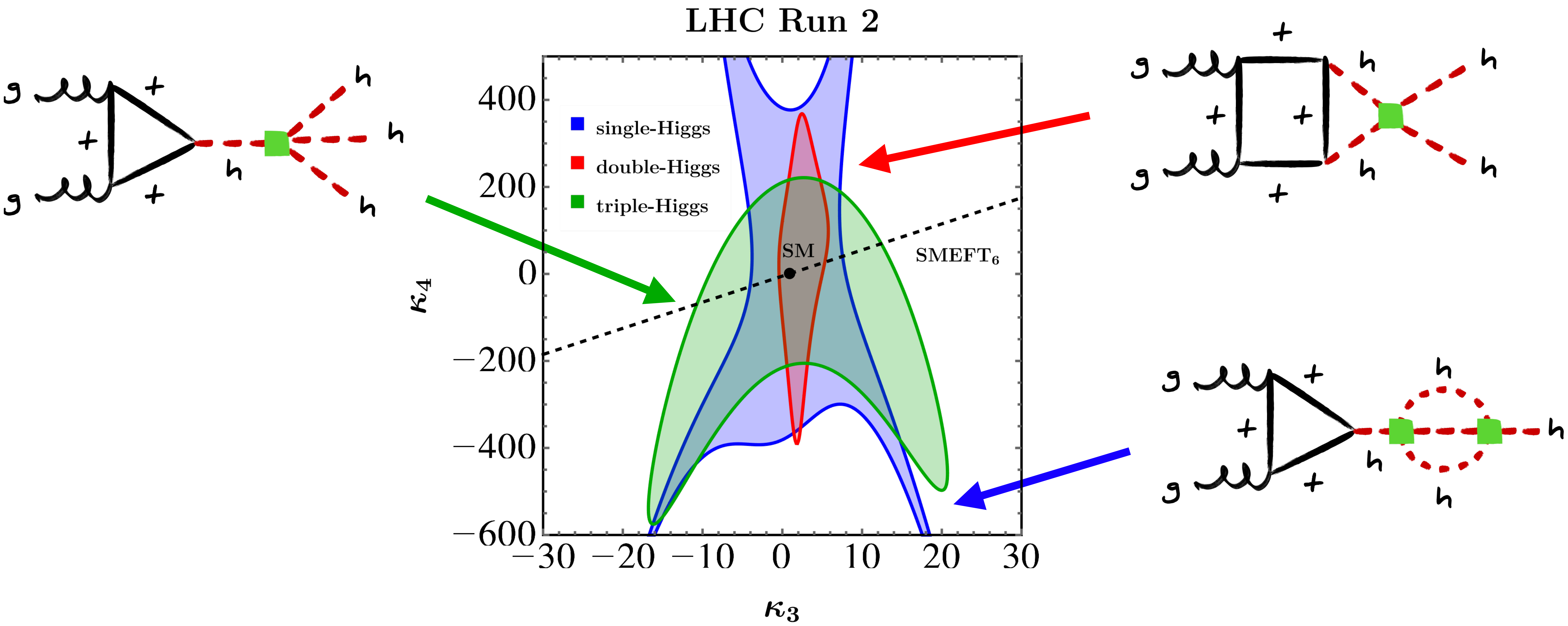
Higgs self-couplings after LHC Run 2



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

[UH, Aparna Sankar & Giulia Zanderighi, ongoing; pp→3h bound from ATLAS, 2411.02040]

Higgs self-couplings after LHC Run 2



New limit from h production poor as LHC Run 2 measurements not precise enough

[UH, Aparna Sankar & Giulia Zanderighi, ongoing; pp→3h bound from ATLAS, 2411.02040]

Vh production in SMEFT @ NNLO+PS

Q_{HW} Q_{HB} Q_{HWB}

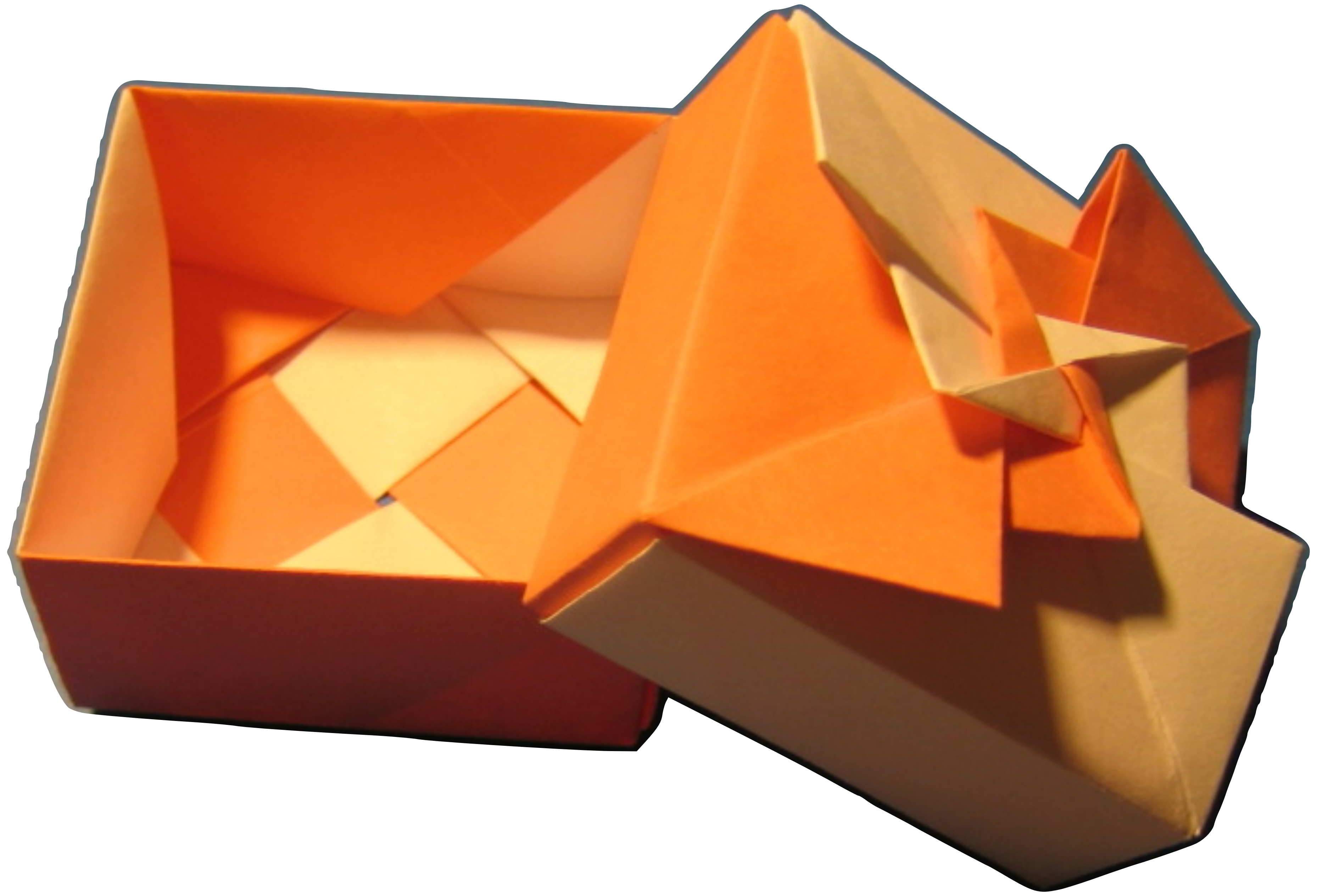
$Q_{Hq}^{(1)}$ $Q_{Hq}^{(3)}$ Q_{Hu} Q_{Hd}

$Q_{H\ell}^{(1)}$ $Q_{H\ell}^{(3)}$ Q_{He}

Q_{HD} $Q_{H\Box}$ $Q_{\ell\ell}$

→

Vh MiNNLO$_{\text{PS}}$ generator

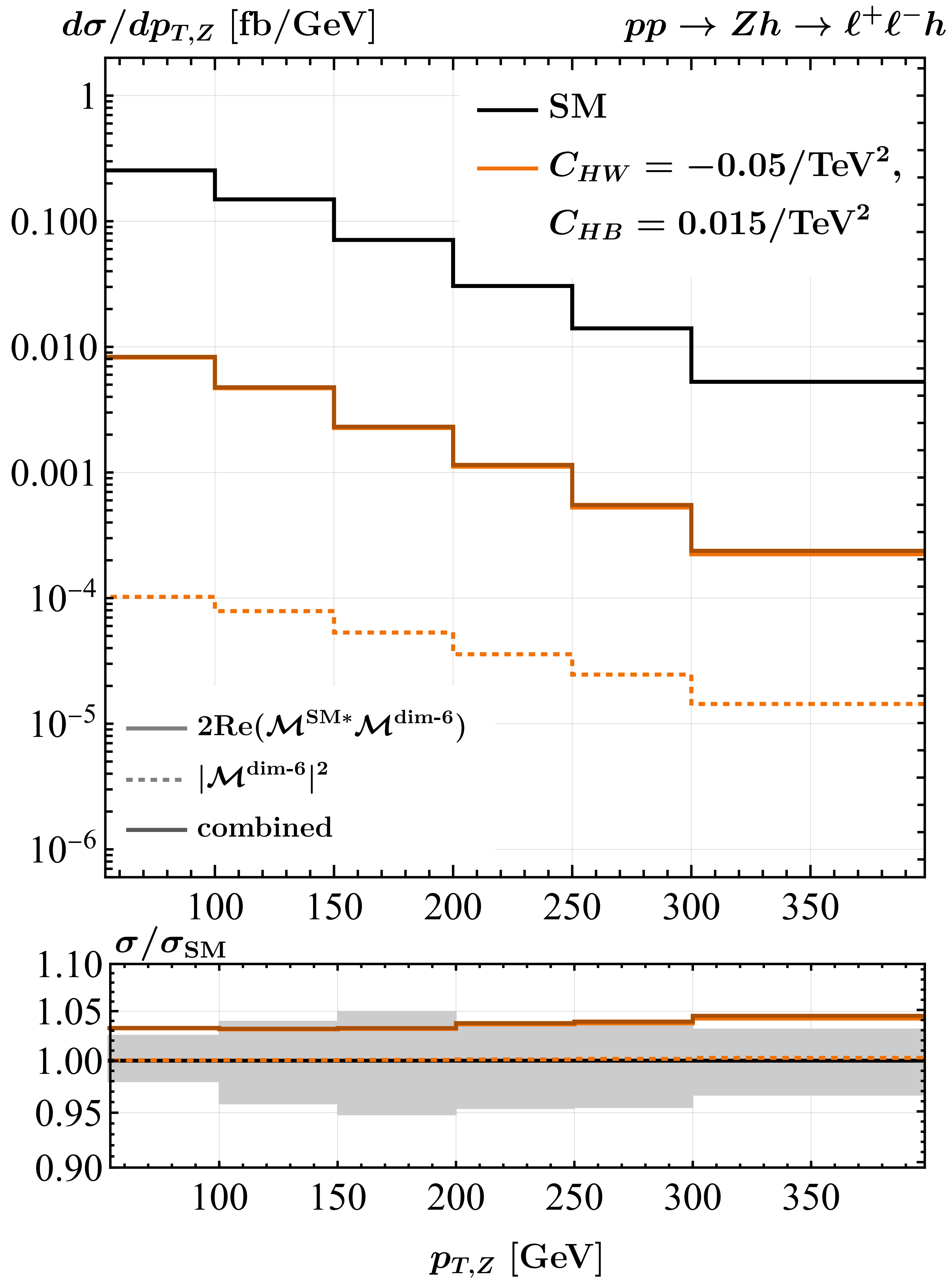


POWHEG-BOX

[Rhorry Gauld, UH & Luc Schnell, 2311.06107]

Vh production in SMEFT @ NNLO+PS

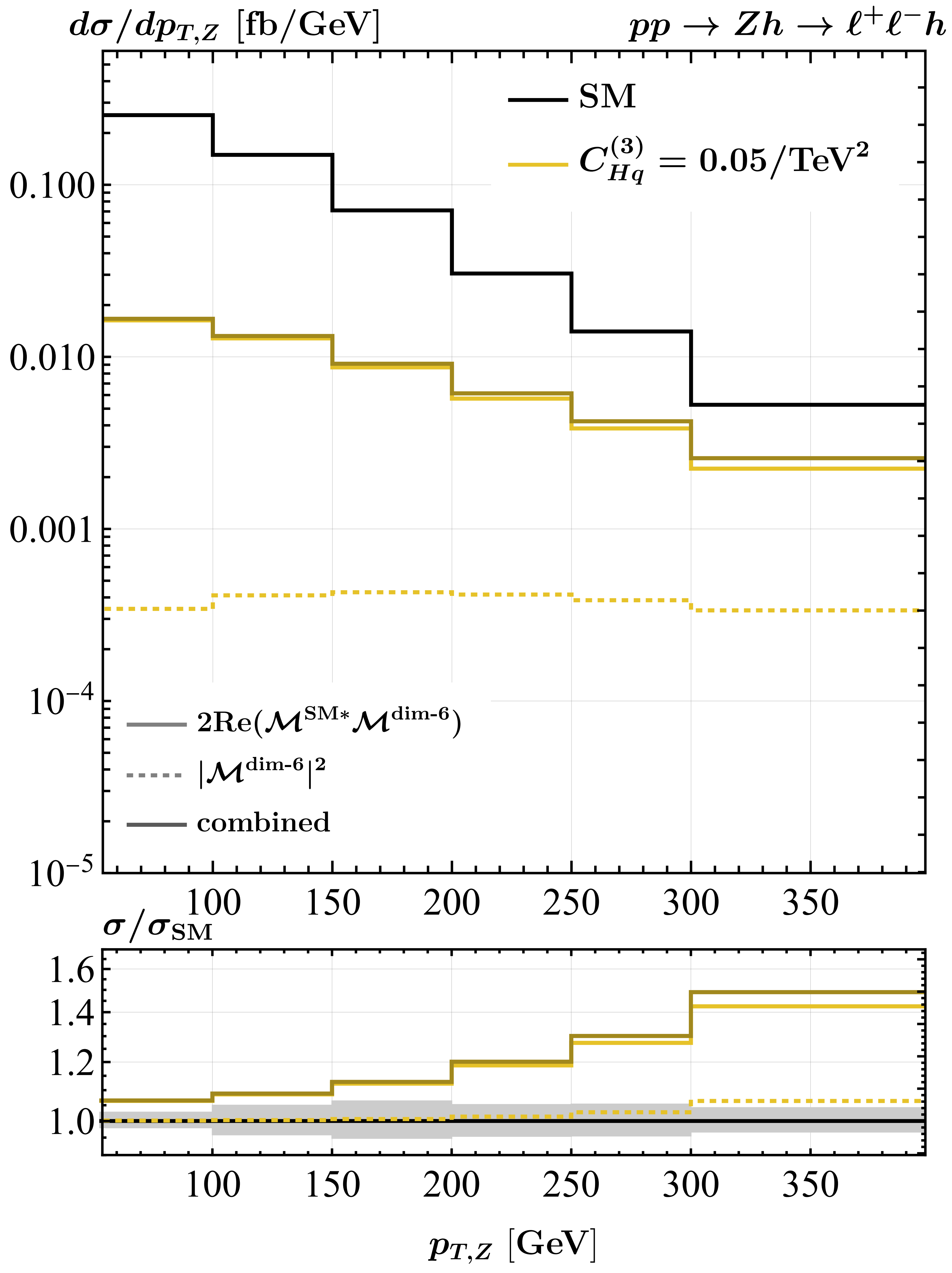
If stringent constraints from M_W, h→γγ & h→γZ are imposed, numerical impact of Wilson coefficients C_{HW}, C_{HB} & C_{HWB} on kinematic distributions in pp→Zh→l^+l^-h rather limited, amounting to relative deviations of no more than 5%



[Rhorry Gauld, UH & Luc Schnell, 2311.06107]

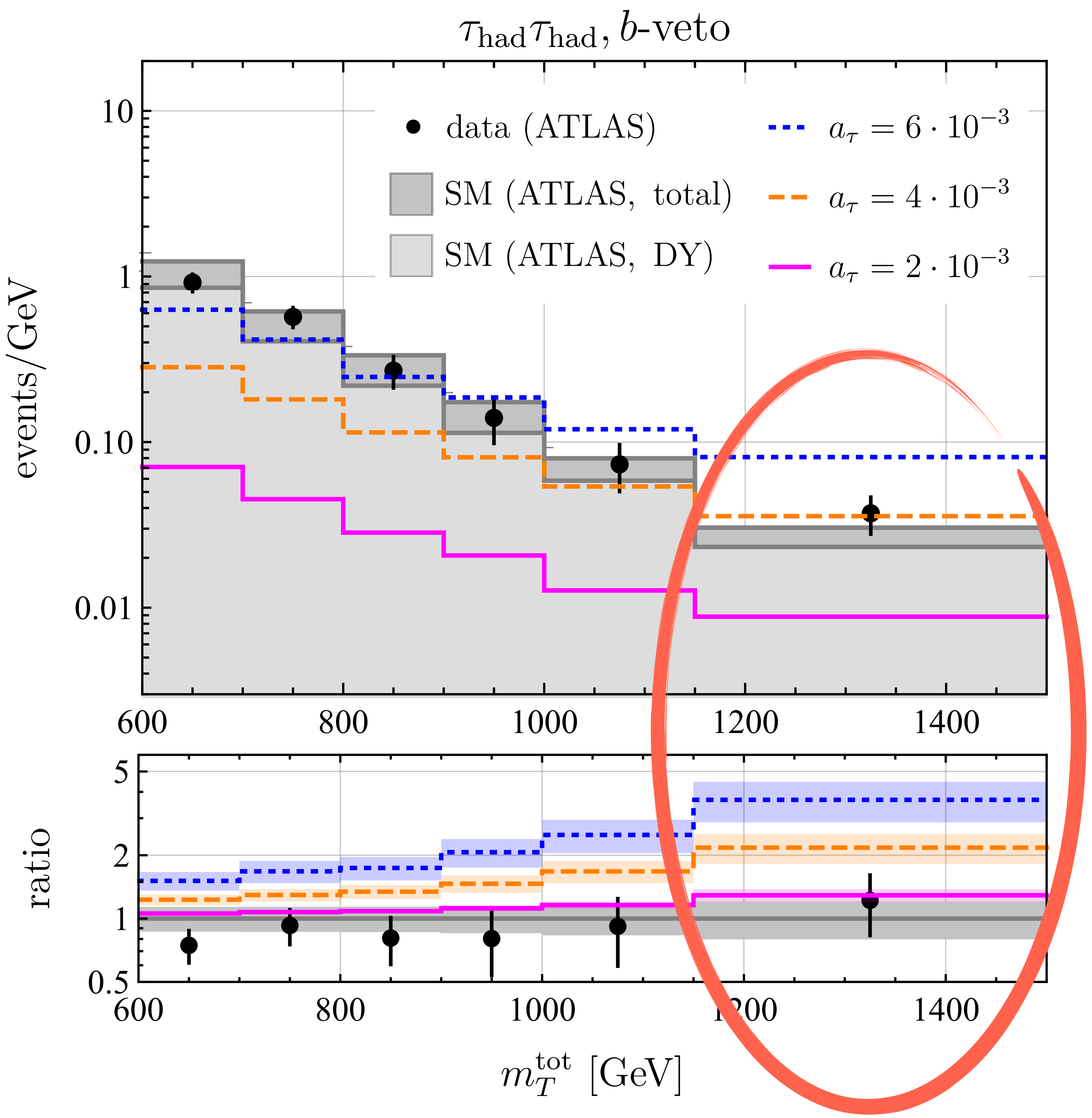
Vh production in SMEFT @ NNLO+PS

Enhanced sensitivity of $pp \to Zh \to l^+l^-h$ to $C_{Hq}^{(1)}$, $C_{Hq}^{(3)}$, C_{Hu} & C_{Hd} arises from energy growth of amplitudes. Effects can reach 50% in $p_{T,Z}$ spectrum in region where Higgs decay products are significantly boosted. Vh production @ HL-LHC may allow to constrain Z-boson couplings to light quarks as well as SLC & LEP



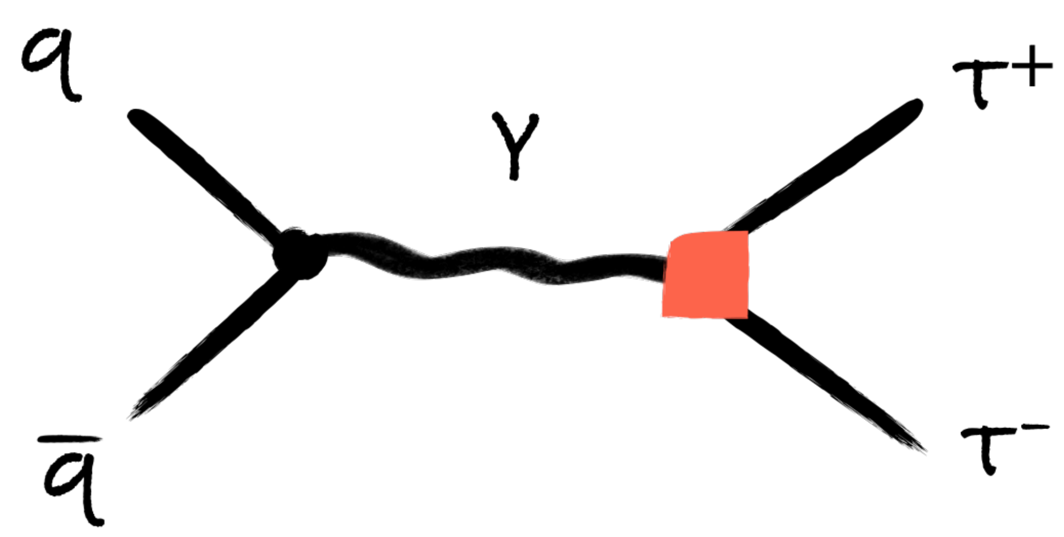
[Rhorry Gauld, UH & Luc Schnell, 2311.06107]

LHC tau-pair production constraints on a_τ



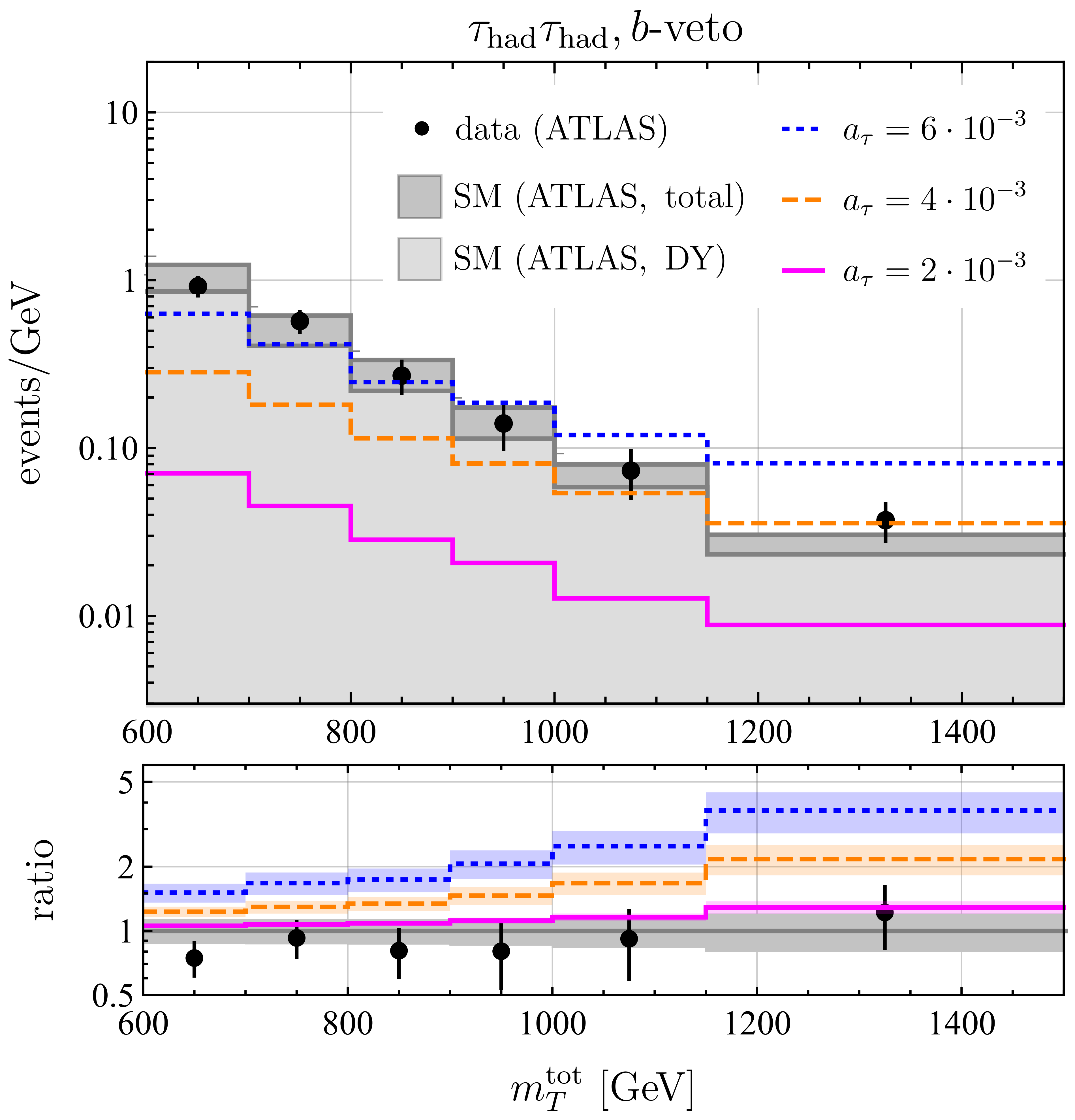
$$\mathcal{L} \supset \frac{c_{\tau\gamma} v}{\sqrt{2}\Lambda^2} \left(\bar{\tau}_L \sigma_{\mu\nu} \tau_R\right) F^{\mu\nu} + \text{h.c.}$$

$$a_\tau = \frac{2\sqrt{2} m_\tau v}{e} \frac{\text{Re}\left(c_{\tau\gamma}\right)}{\Lambda^2}$$



[UH, Luc Schnell & Joachim Weiss, 2307.14133; pp→$\tau^+\tau^-$ data from ATLAS, 2002.12223]

LHC tau-pair production constraints on a_τ



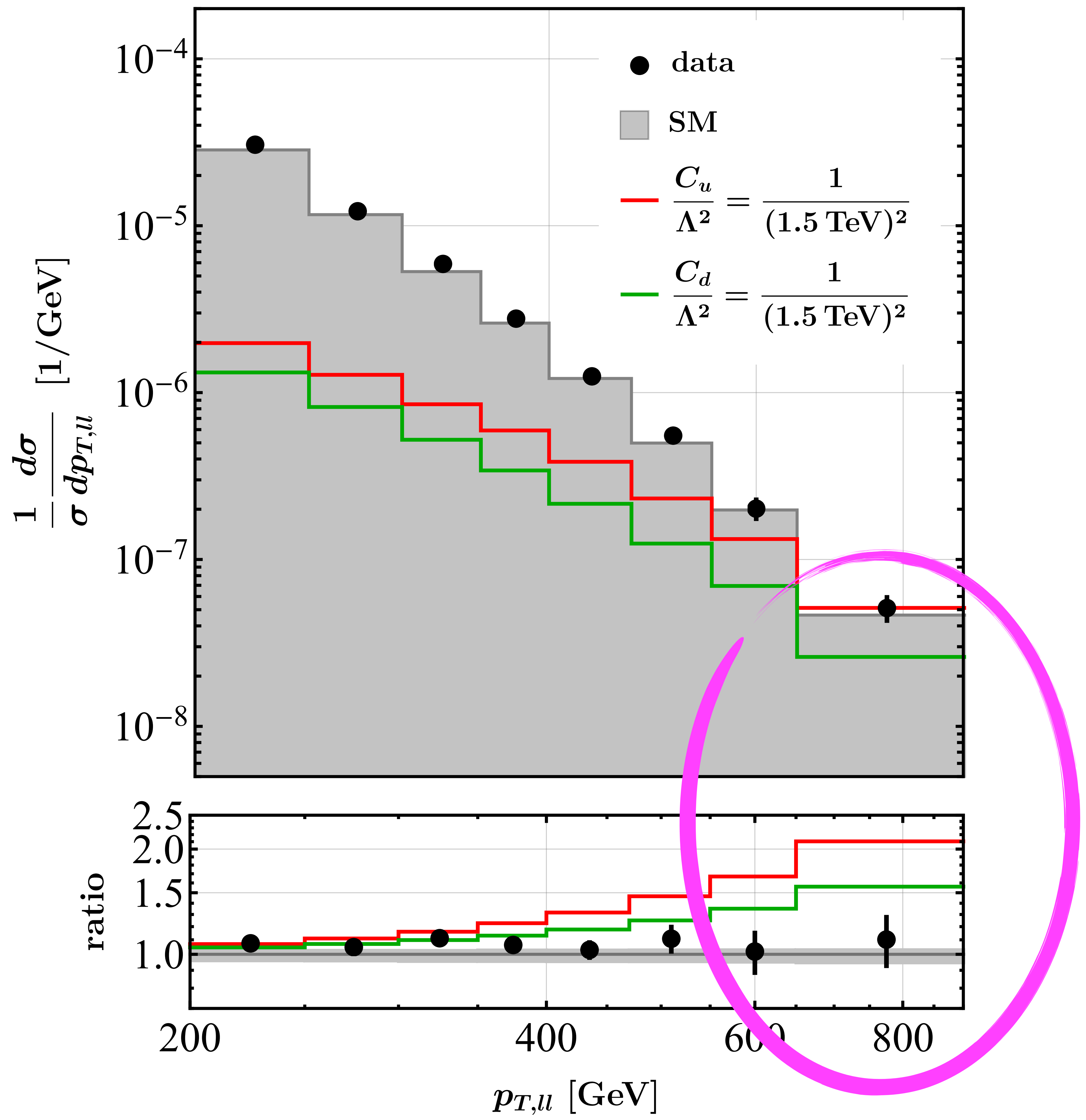
$$\frac{|c_{\tau\gamma}|}{\Lambda^2} < \frac{1}{(1.5\,\mathrm{TeV})^2}$$

$$a_\tau < 1.8 \cdot 10^{-3} \simeq 1.5 \cdot a_\tau^{\mathrm{SM}}$$

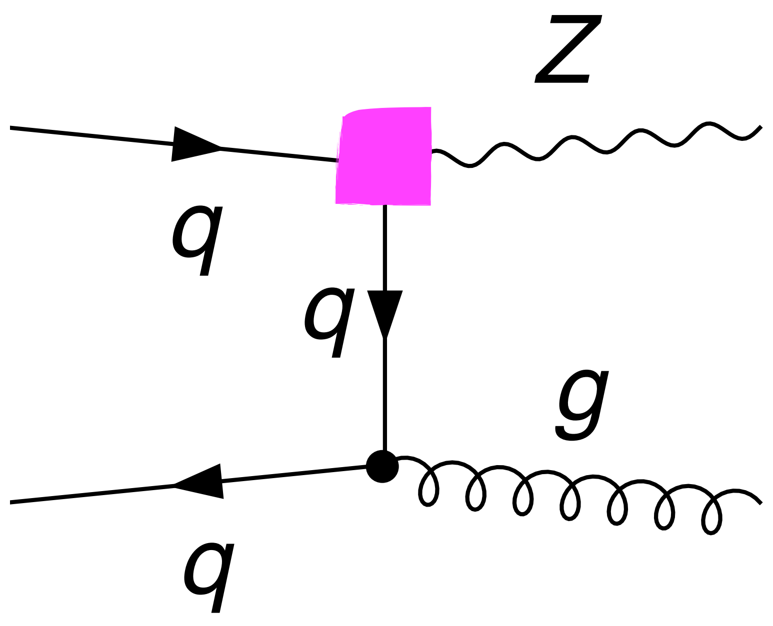
Limit on a_τ better than those from DELPHI (e^+e^-), ATLAS & CMS (PbPb, pp) in $\gamma\gamma \to \tau^+\tau^-$

[UH, Luc Schnell & Joachim Weiss, 2307.14133; $pp \to \tau^+\tau^-$ data from ATLAS, 2002.12223]

SMEFT effects & Lam-Tung relation

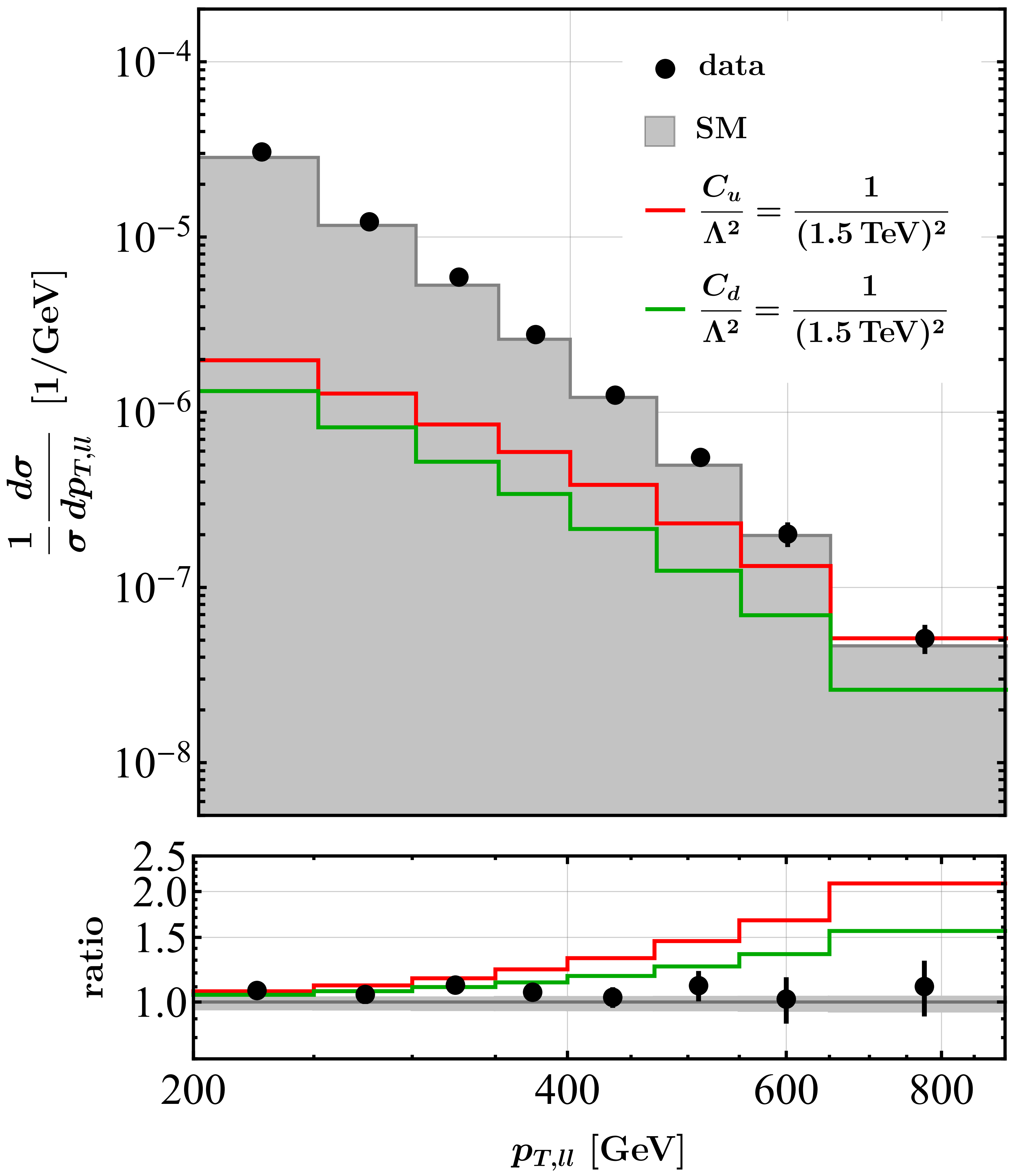


$$\mathcal{L} \supset \frac{v}{\sqrt{2} s_w \Lambda^2} \sum_{q=u,d} C_q \bar{q}_L \sigma_{\mu\nu} q_R Z^{\mu\nu} + \text{h.c.}$$



[Rhorry Gauld, UH & Joachim Weiss, ongoing; Drell-Yan data from ATLAS, 1912.02844]

SMEFT effects & Lam-Tung relation

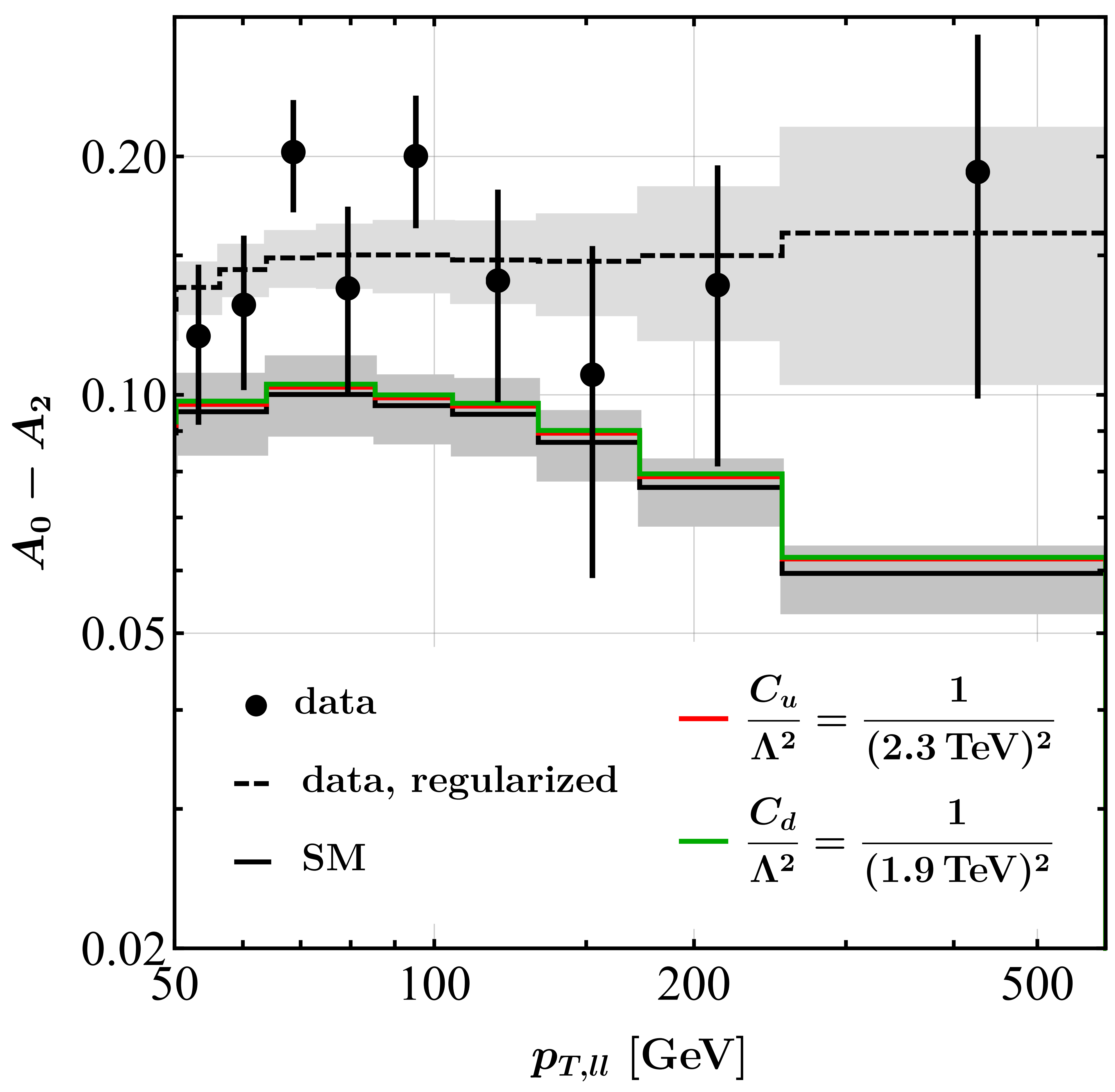


$$\frac{|C_u|}{\Lambda^2} < \frac{1}{(2.3\,\text{TeV})^2}$$

$$\frac{|C_d|}{\Lambda^2} < \frac{1}{(1.9\,\text{TeV})^2}$$

[Rhorry Gauld, UH & Joachim Weiss, ongoing; Drell-Yan data from ATLAS, 1912.02844]

SMEFT effects & Lam-Tung relation



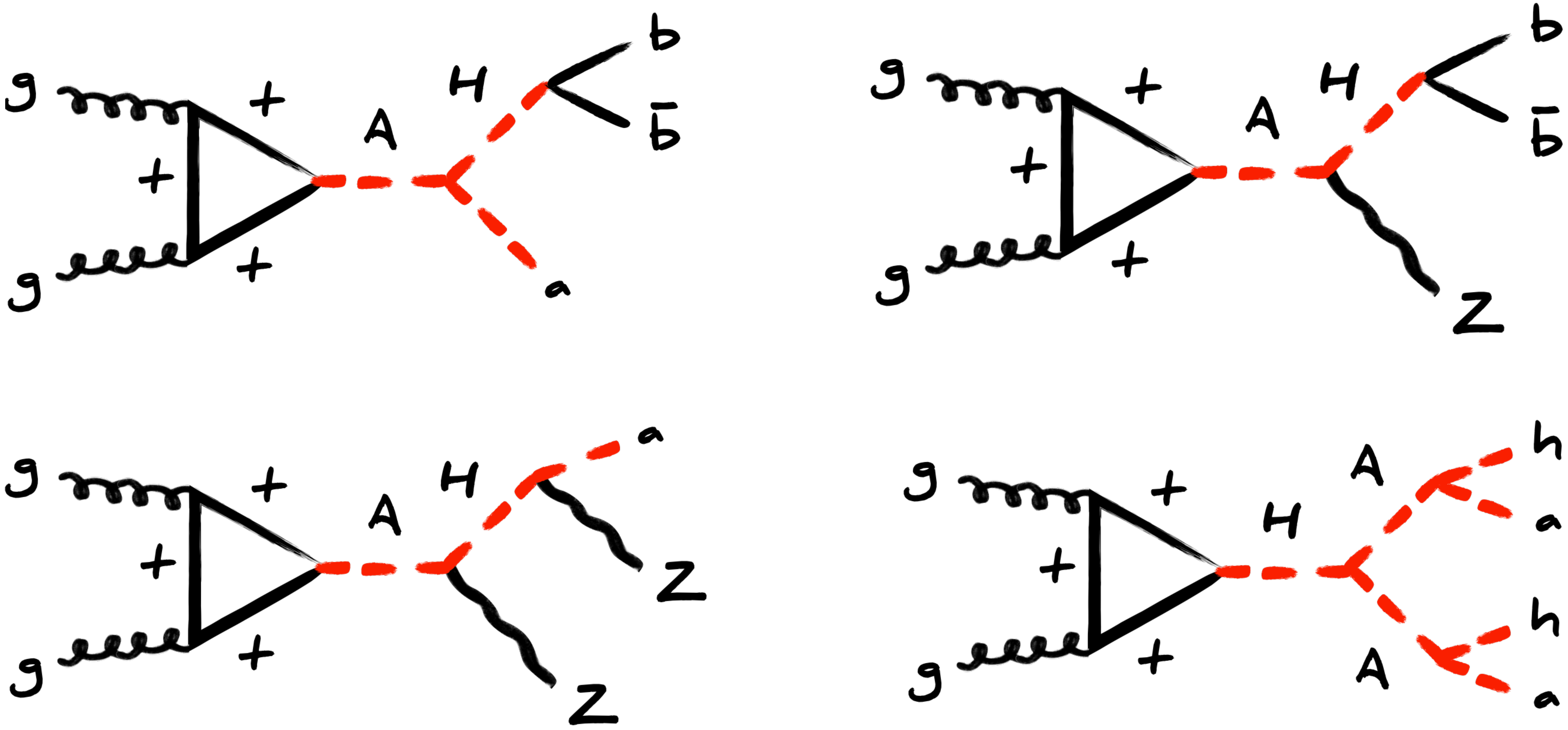
Light-quark dipole effects far too small to account for discrepancy between SM prediction & ATLAS data for Lam-Tung combination A_0 - A_2 of angular coefficients in high-$p_{T,ll}$ tail of spectrum

[Rhorry Gauld, UH & Joachim Weiss, ongoing; measurement of the angular coefficients from ATLAS, 1606.00689]

2HDM+a model reloaded @ LHC

- 2HDM+a model is a cornerstone of both ATLAS & CMS interpretations of missing transverse energy (MET) aka DM searches
- All Run 2 benchmarks feature type-II Yukawas & degenerate 2HDM Higgs mass spectrum. Degenerate 2HDM Higgs masses avoid constraints from EW precision observables, but in type II lead to TeVish 2HDM spectrum, as flavor physics requires charged Higgs to be heavier than about 600 GeV

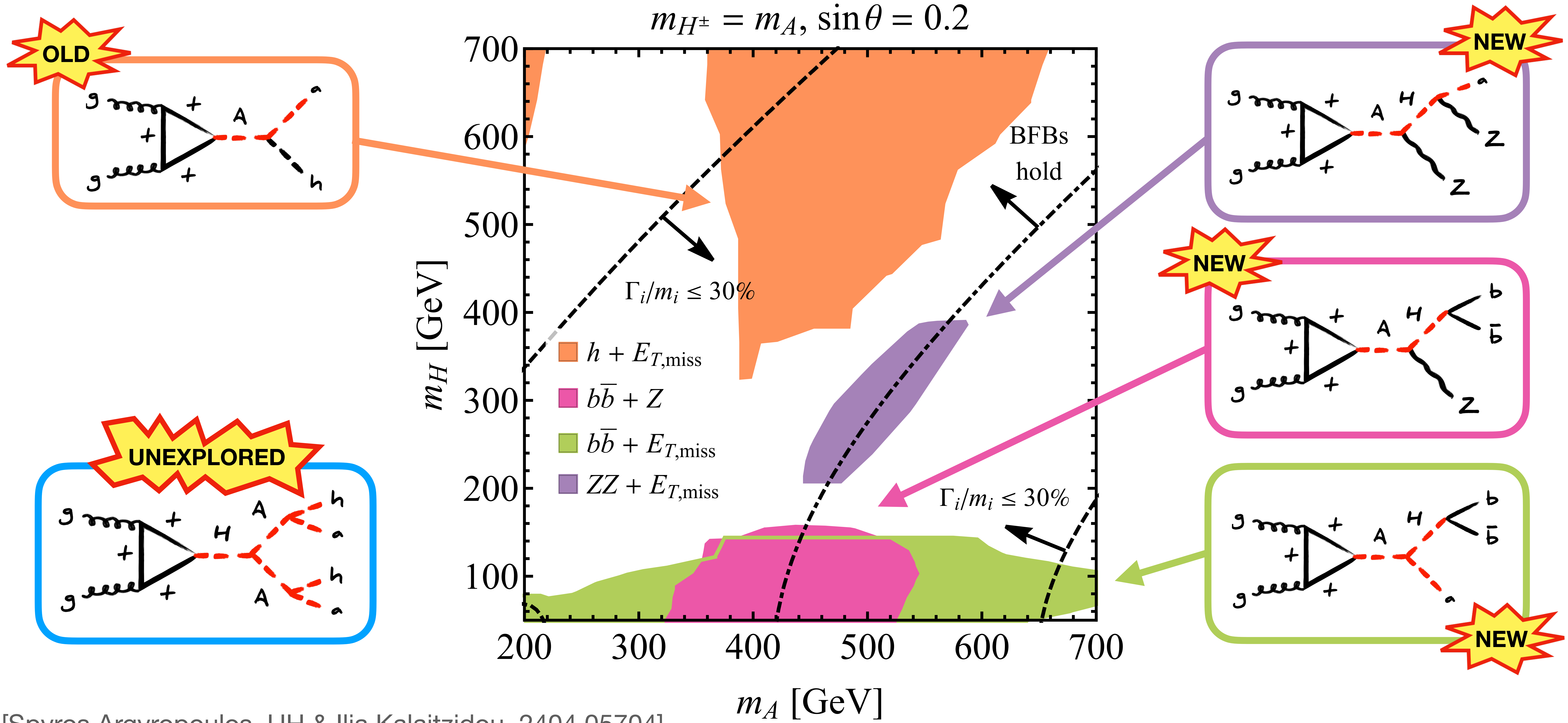
2HDM+a model reloaded @ LHC



In case of non-degenerate 2HDM Higgses, new MET & non-MET channels open up

[Spyros Argyropoulos, UH & Ilia Kalaitzidou, 2404.05704]

Old & new 2HDM+a signatures in type I



[Spyros Argyropoulos, UH & Ilia Kalaitzidou, 2404.05704]

Conclusions

- Broad range of activities with a strong focus on LHC BSM phenomenology. Ongoing collaborations with internal & external ATLAS researchers & LHC DM working group
- Due to lack of time, I have not discussed research on flavor physics done in last year

Backup

Trilinear Higgs self-coupling from pp→4l

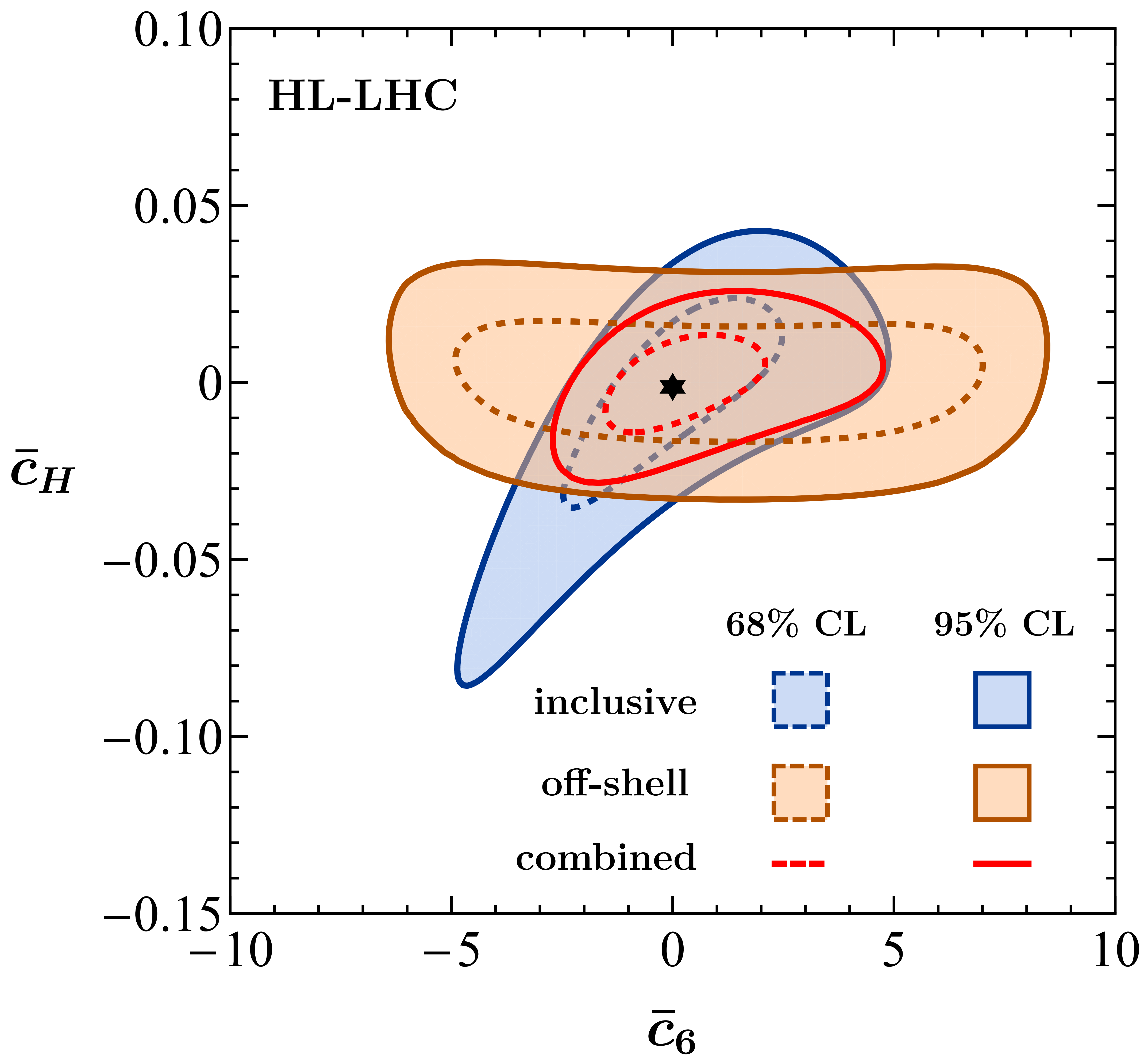
[UH & Gabriel Koole, 2111.12589]

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

$$\Downarrow$$

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

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



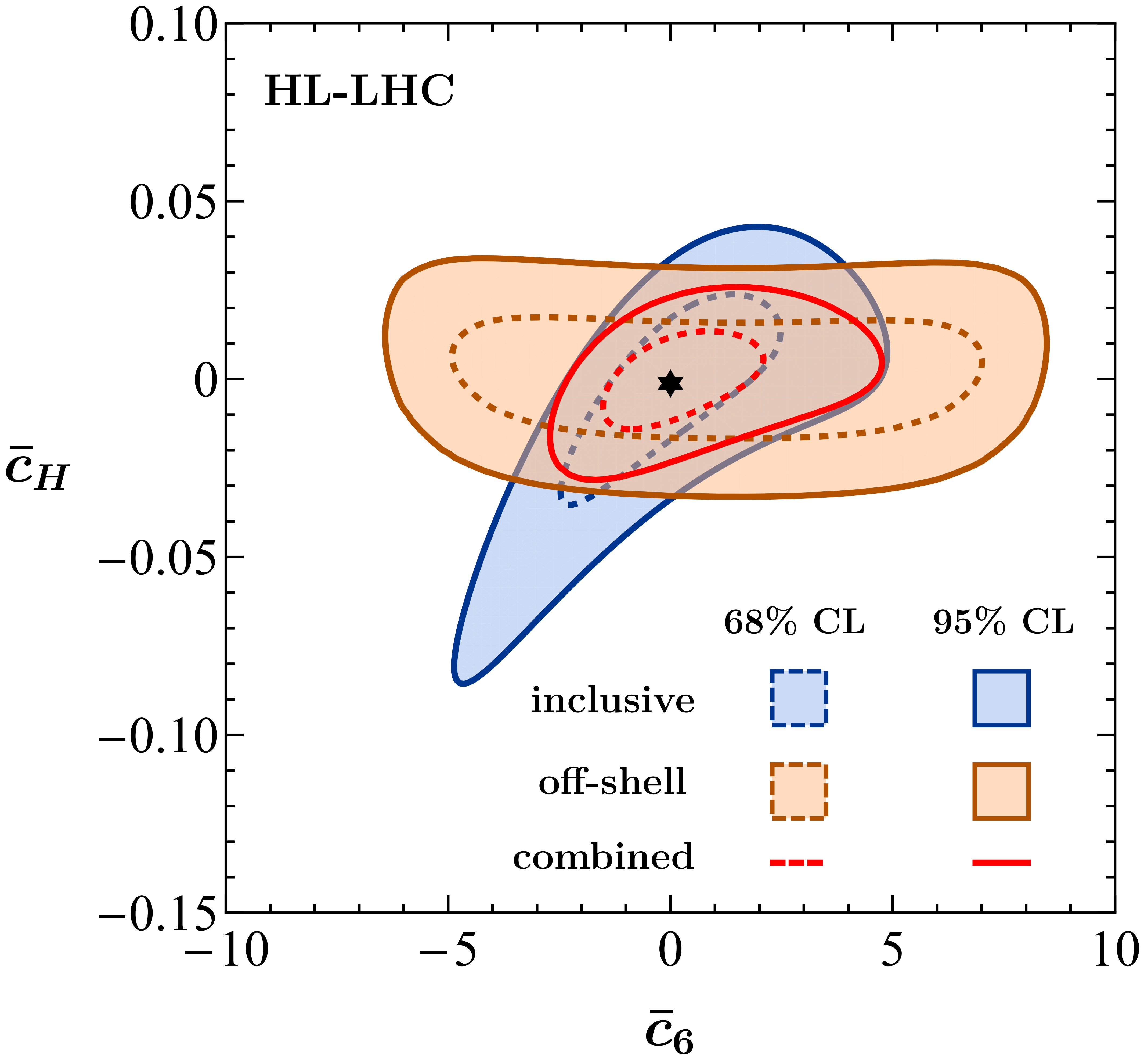
Trilinear Higgs self-coupling from pp→4l

[UH & Gabriel Koole, 2111.12589]

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

$$\Downarrow$$

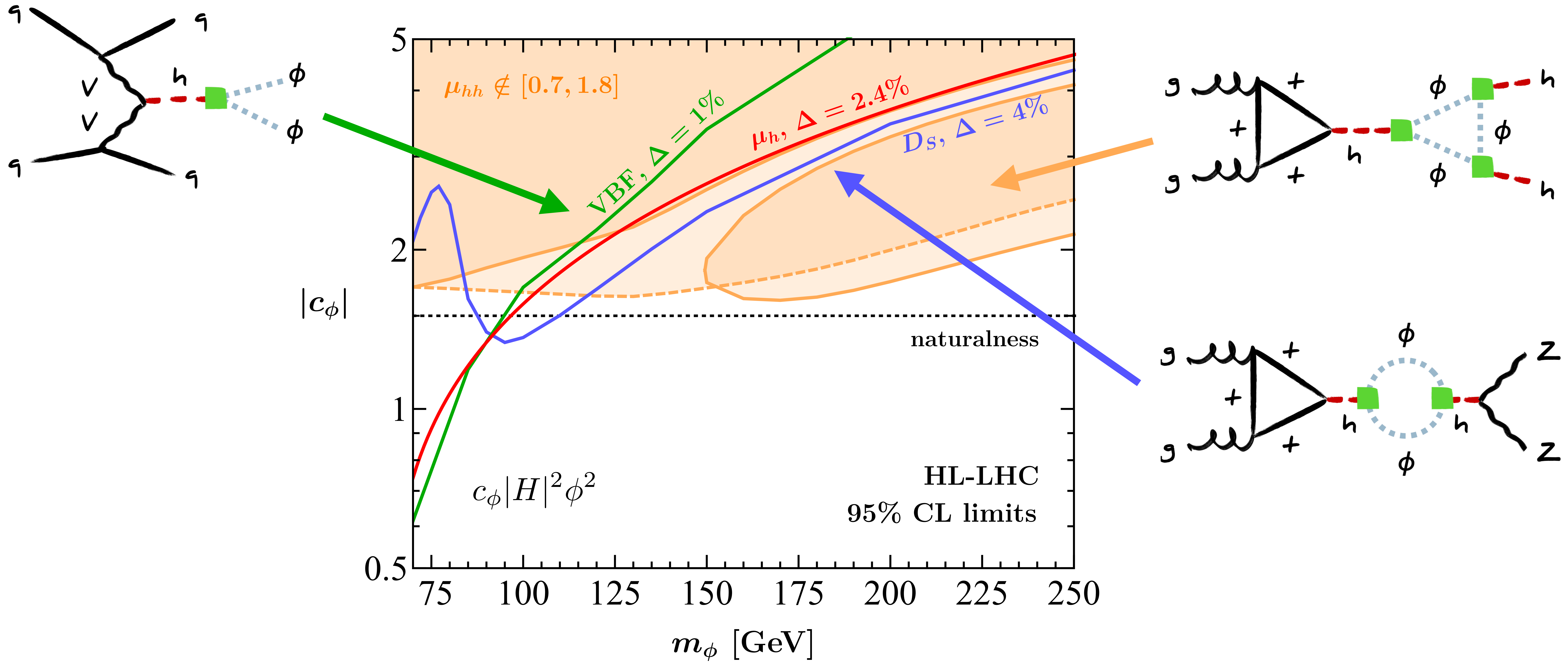
$$\mathcal{L} \supset -\lambda \kappa_\lambda v h^3\,, \qquad \kappa_\lambda = 1 + \bar{c}_6 - \frac{3}{2}\,\bar{c}_H$$



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

[Ongoing effort with Tae Park to make old analysis more realistic]

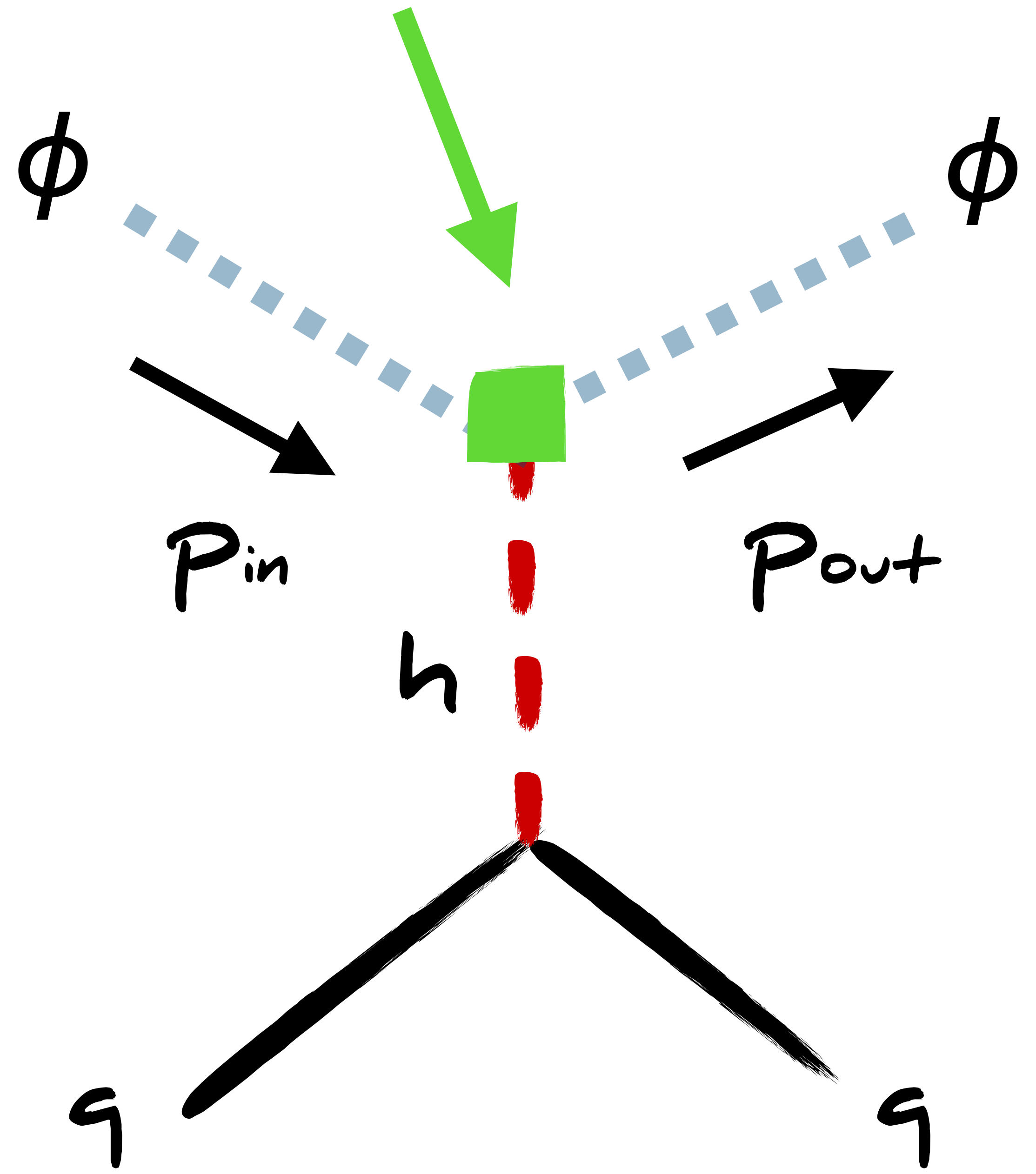
HL-LHC bounds on marginal Higgs portal



[UH & Gabriel Koole, 2201.09711]

Derivative Higgs portal: DM-N scattering

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

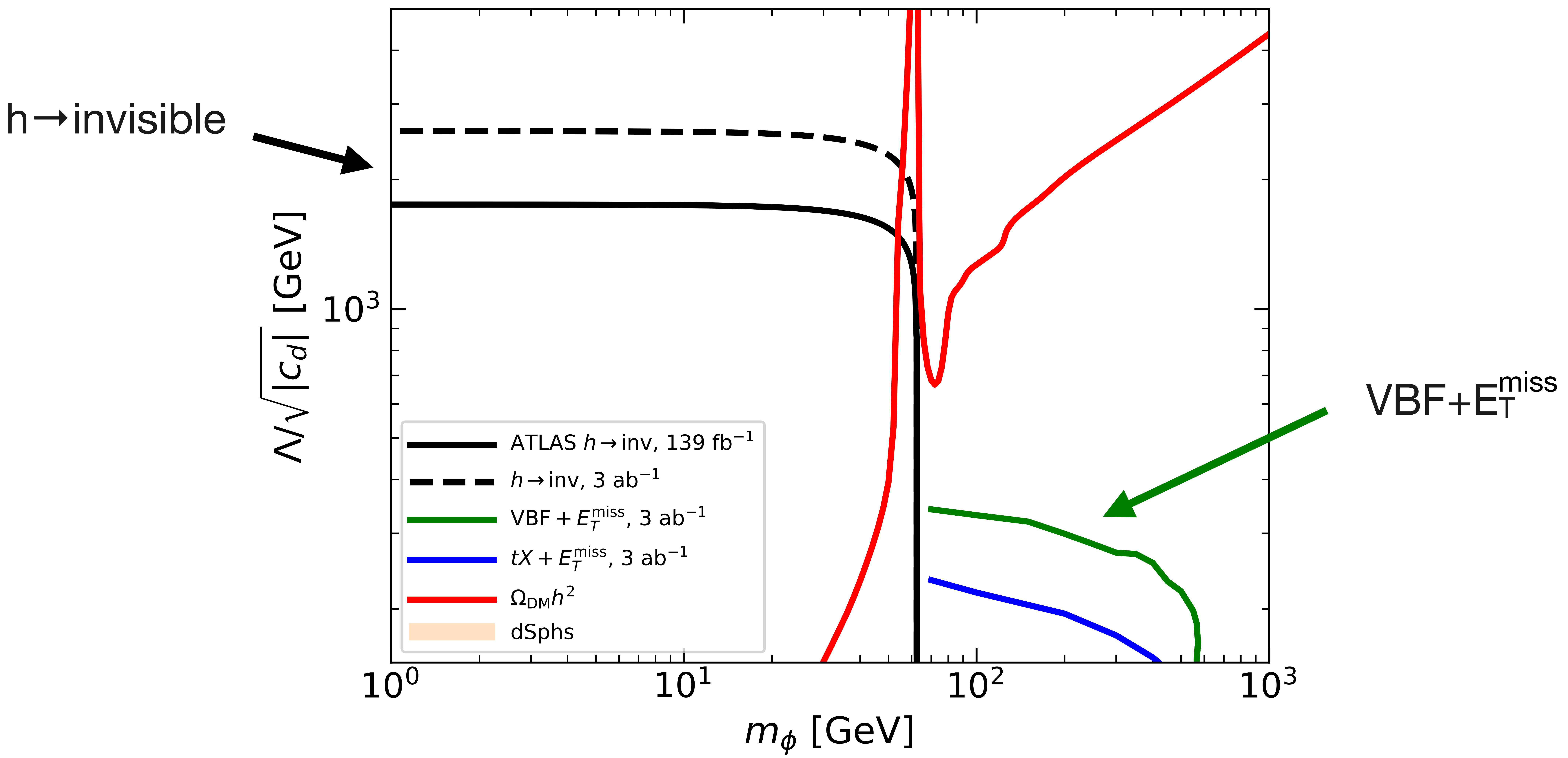


$$\propto \frac{(p_{\rm in} - p_{\rm out})^2}{f^2} \lesssim \frac{(100\,{\rm MeV})^2}{f^2}$$

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

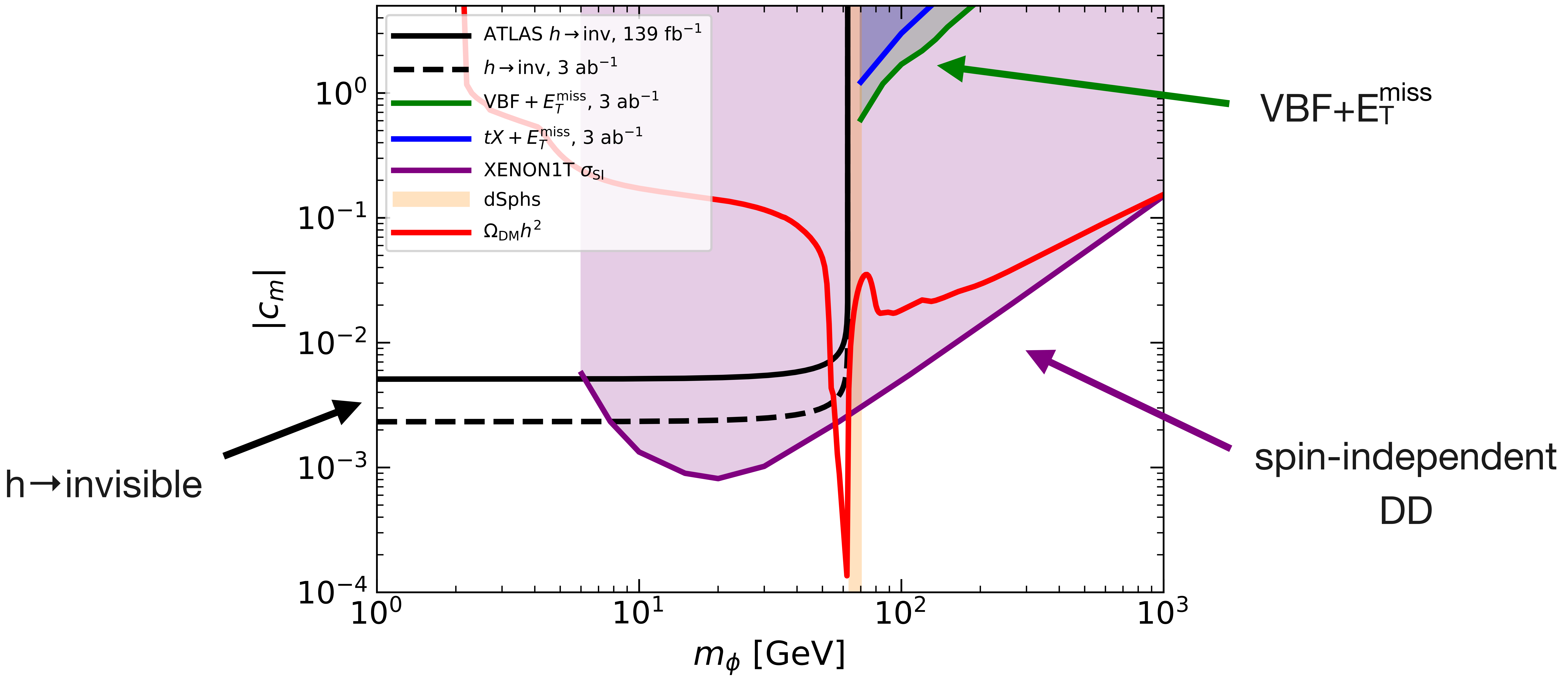
[see for example Reuven Balkin, Max Ruhdorfer, Ennio Salvioni & Andi Weiler, 1809.09106]

Global picture of derivative Higgs portal



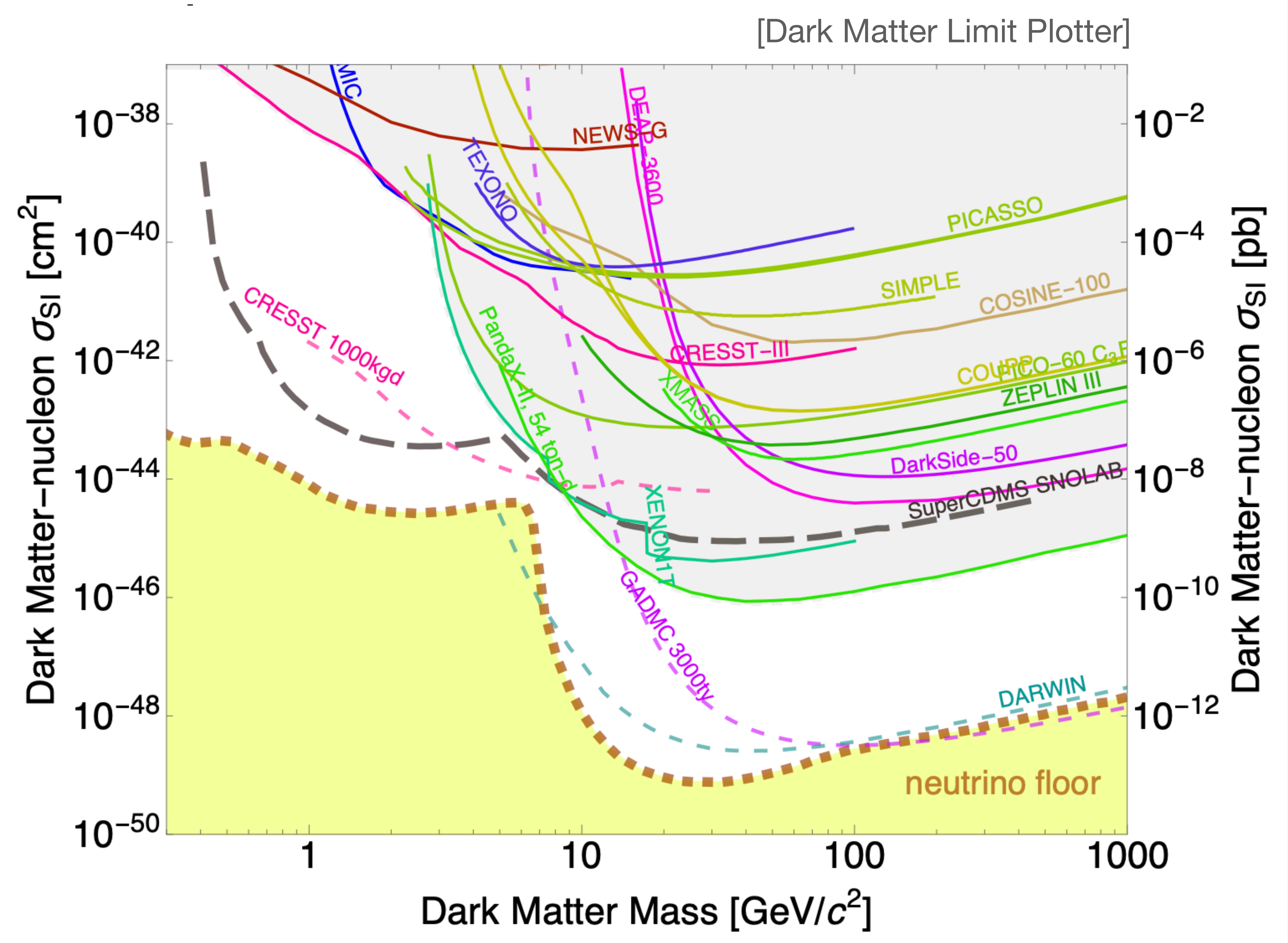
[Spyros Argyropoulos, Oleg Brandt & UH, 2109.13597]

Global picture of marginal Higgs portal

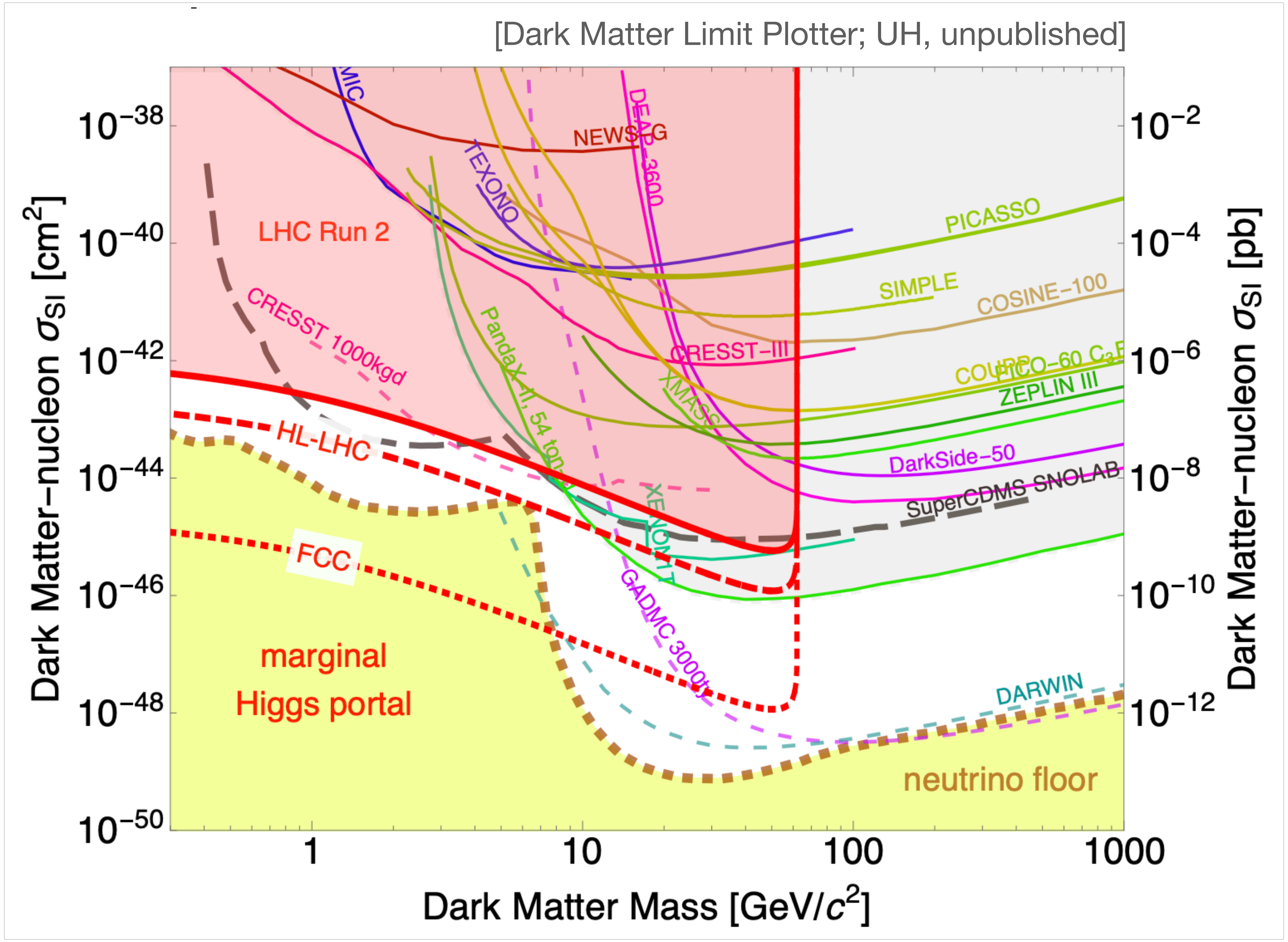


[Spyros Argyropoulos, Oleg Brandt & UH, 2109.13597]

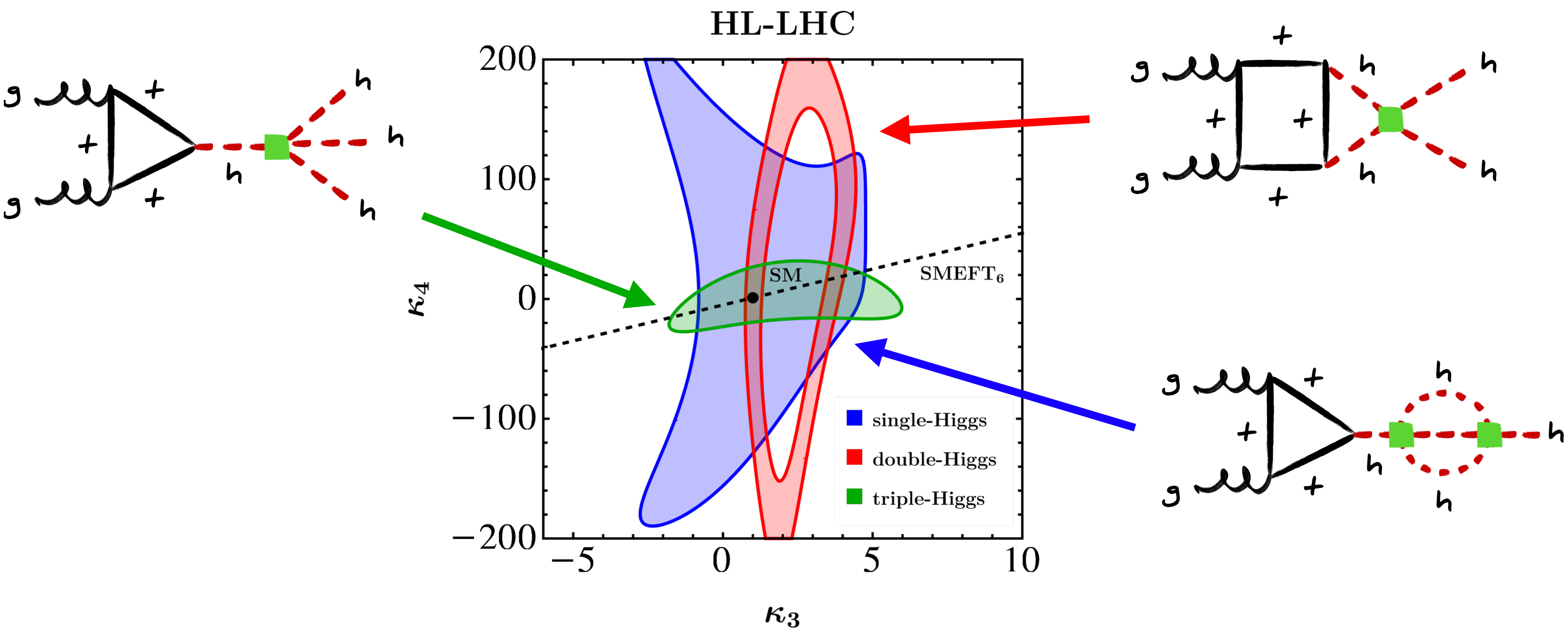
Future probes of neutrino floor



Future probes of neutrino floor



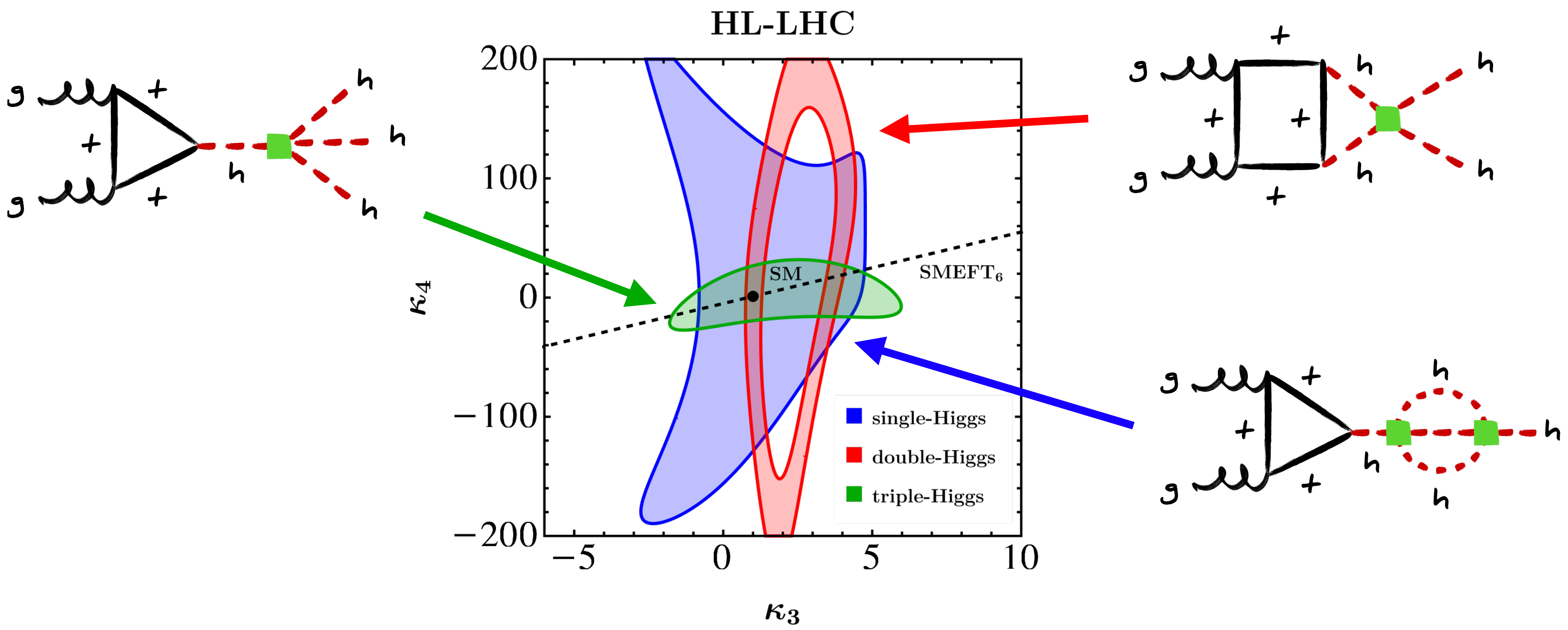
Higgs self-couplings in HL-LHC era



Hypothetical HL-LHC bound of O(10) on 3h signal strength will set best bound on κ_4

[UH, Aparna Sankar & Giulia Zanderighi, ongoing]

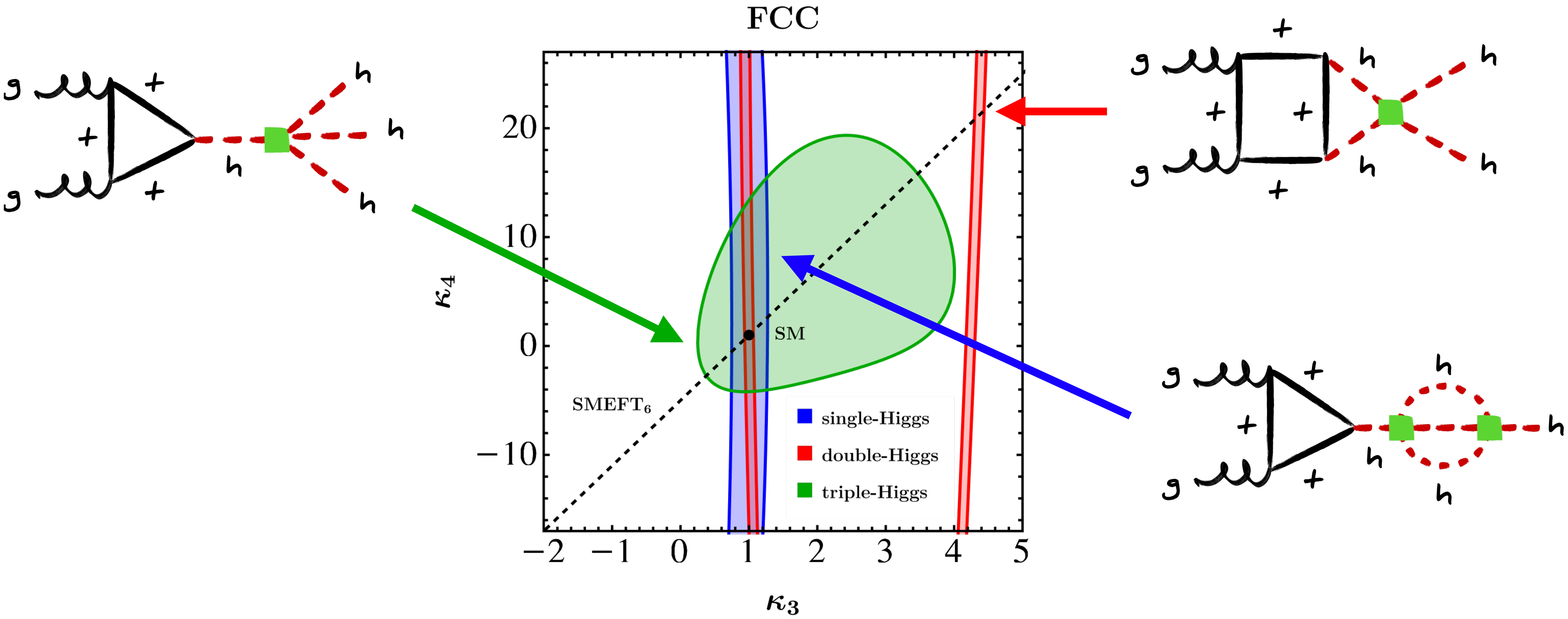
Higgs self-couplings in HL-LHC era



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

[UH, Aparna Sankar & Giulia Zanderighi, ongoing]

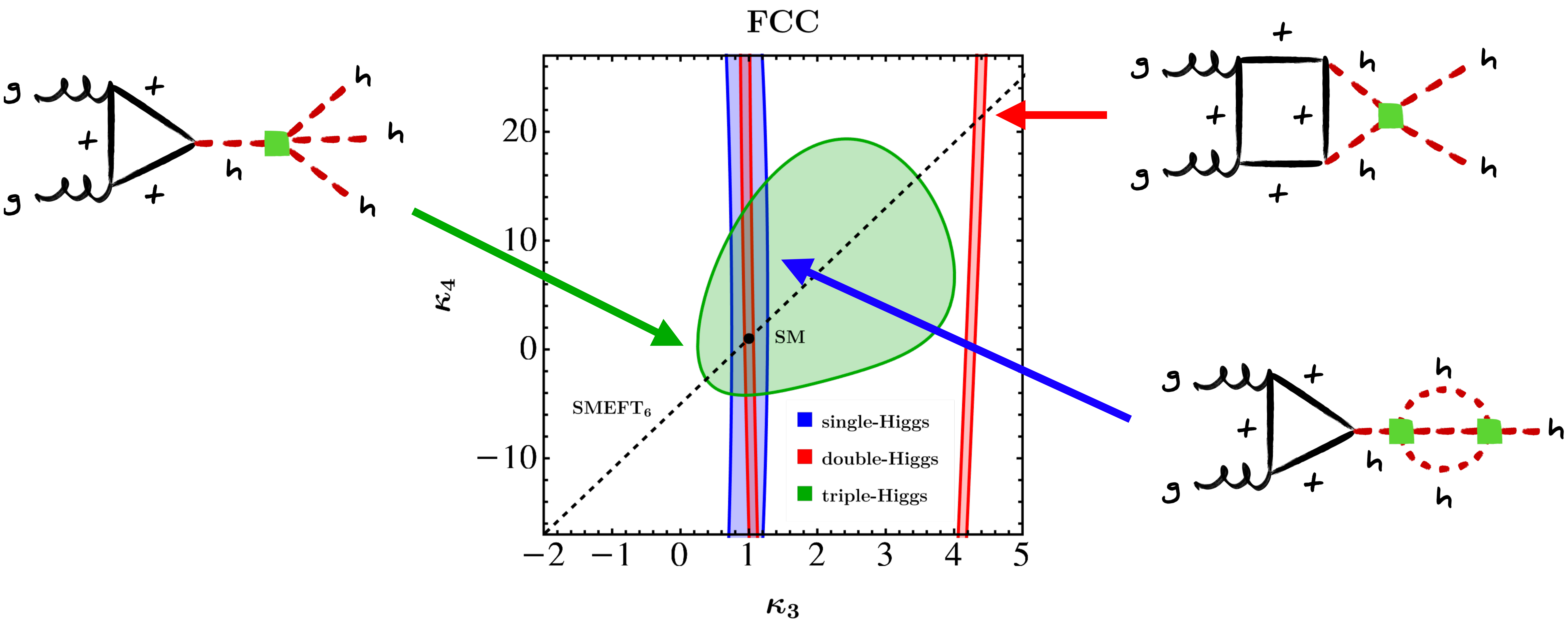
Higgs self-couplings in FCC era



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

[UH, Aparna Sankar & Giulia Zanderighi, ongoing]

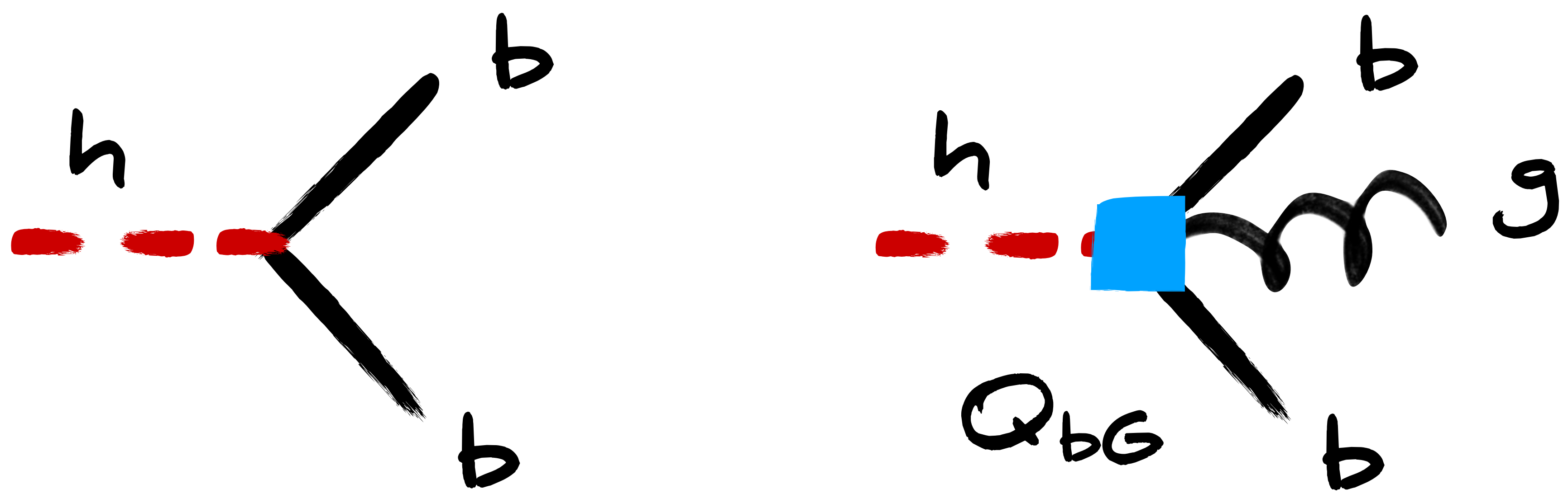
Higgs self-couplings in FCC era



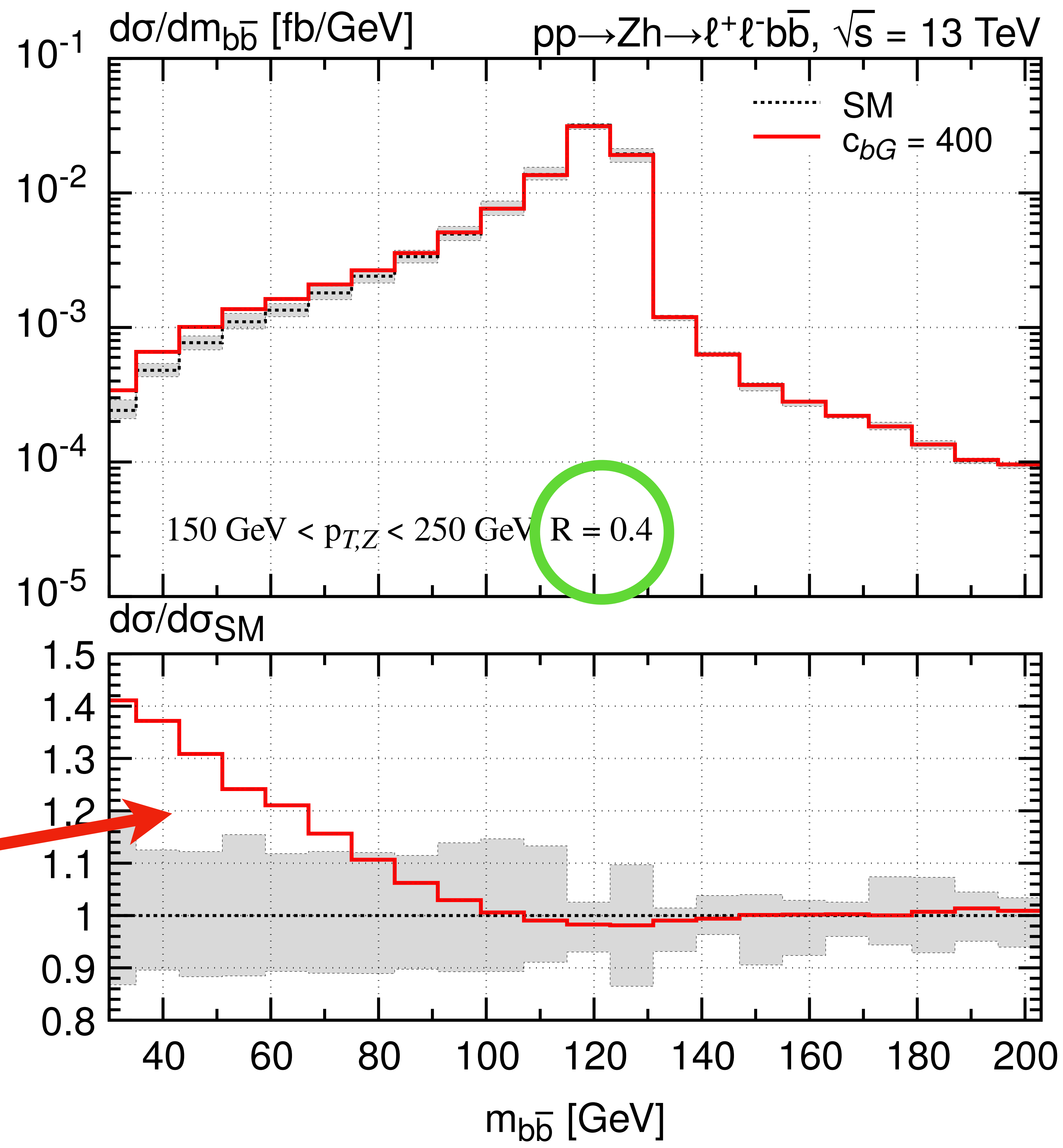
Indirect probes remove degeneracy of direct pp→3h constraint in κ_3-κ_4 plane

[UH, Aparna Sankar & Giulia Zanderighi, ongoing]

Bottom dipole in $pp \to Zh \to l^+l^-b\bar{b}$

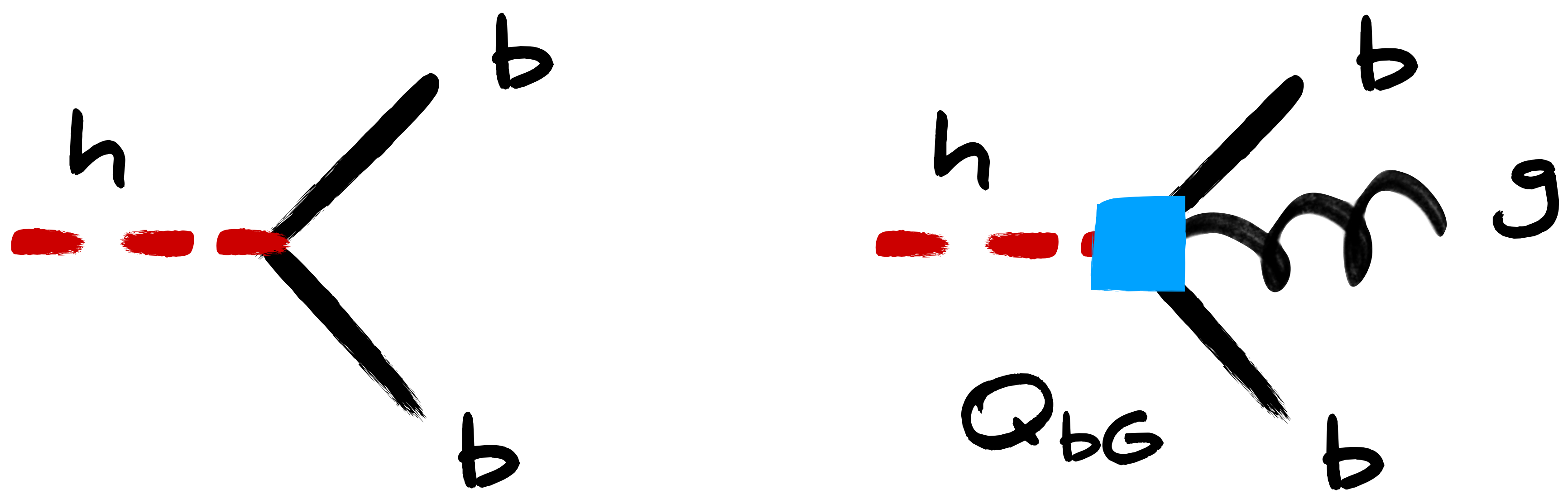


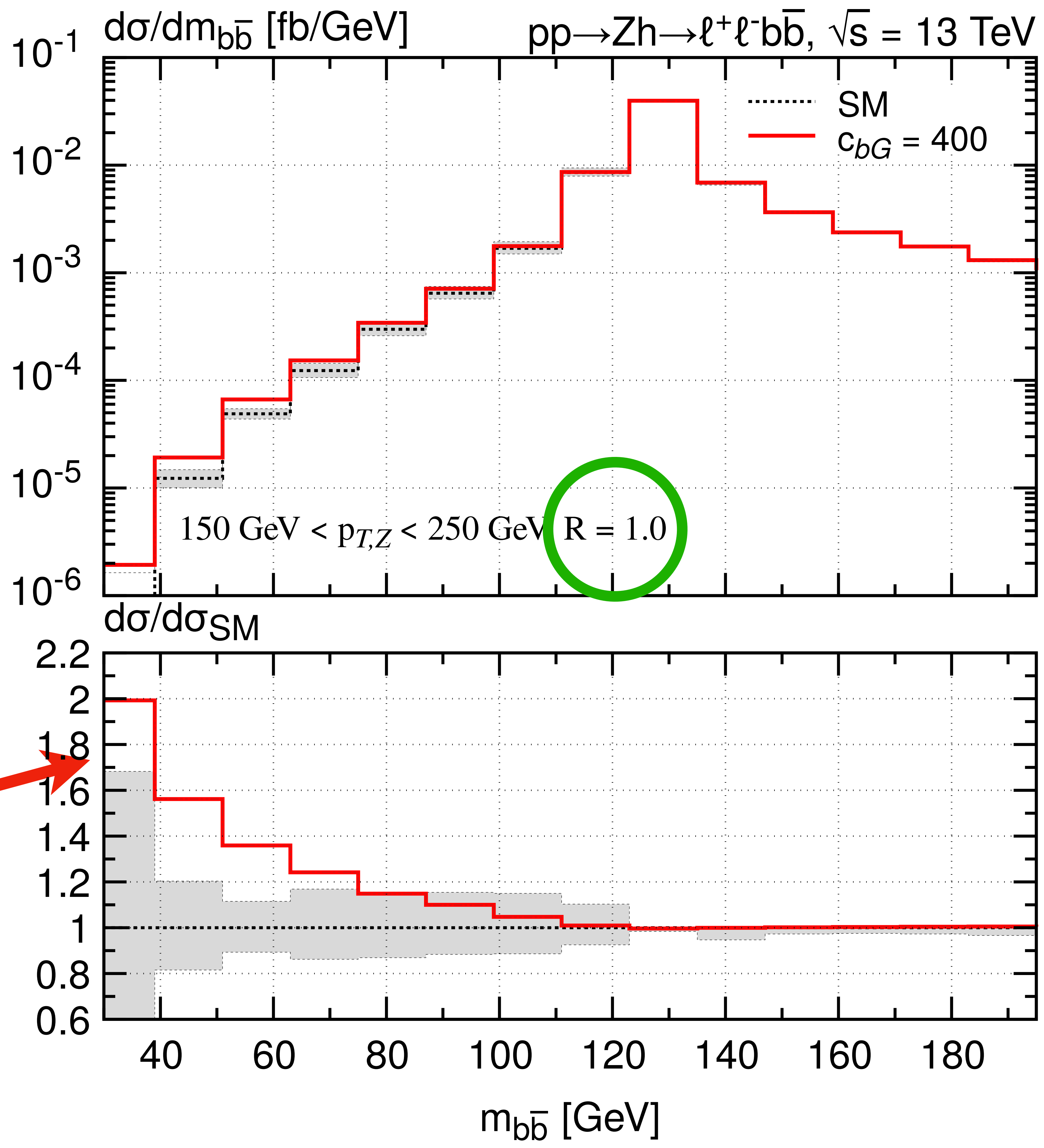
extra gluon emission in leading-order Q_{bG} contribution tends to reduce dibottom invariant mass relative to SM



[UH, Darren Scott, Marius Wiesemann, Giulia Zanderighi & Silvia Zanoli, 2204.00663]

Bottom dipole in pp→Zh→l+l-b$\bar{b}$





size of effect depends on radius parameter R used to reconstruct anti-k_t jets

[UH, Darren Scott, Marius Wiesemann, Giulia Zanderighi & Silvia Zanoli, 2204.00663]

Angular coefficients in Drell-Yan production

$$\frac{d\sigma}{dp_{T,ll}\,dy_{ll}\,dm_{ll}^2\,d\Omega} = \frac{3}{16\pi}\frac{d\sigma}{dp_{T,ll}\,dy_{ll}\,dm_{ll}^2}\Bigg[\left(1+\cos^2\theta\right) + \frac{A_0}{2}\left(1-3\cos^2\theta\right)$$

$$+ A_1\,\sin 2\theta\cos\phi + \frac{A_2}{2}\sin^2\theta\cos 2\phi + A_3\,\sin\theta\cos\phi$$

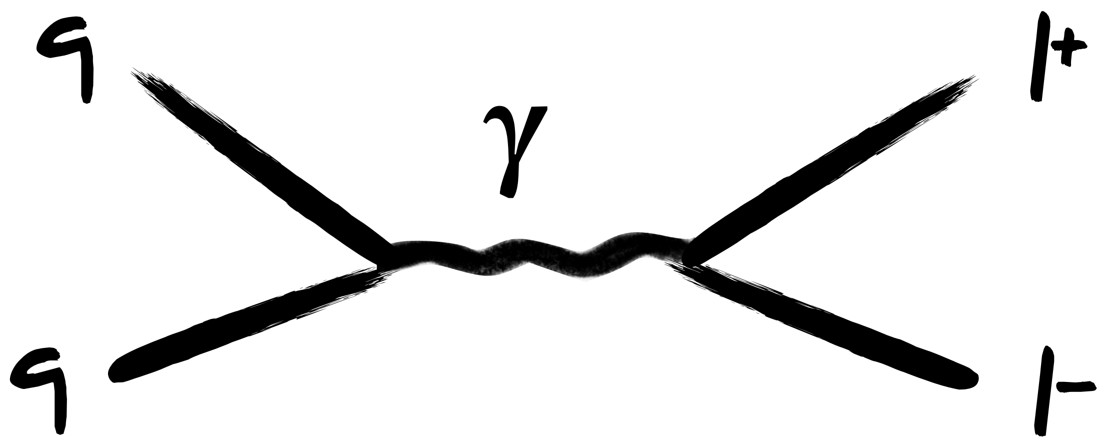
$$+ A_4\,\cos\theta + A_5\,\sin^2\theta\sin 2\phi + A_6\,\sin 2\theta\sin\phi + A_7\,\sin\theta\sin\phi\Bigg]$$

Angular coefficients in Drell-Yan production

$$\frac{d\sigma}{dp_{T,ll}\,dy_{ll}\,dm_{ll}^2\,d\cos\theta} = \frac{3}{8}\frac{d\sigma}{dp_{T,ll}\,dy_{ll}\,dm_{ll}^2}\left[\left(1+\frac{A_0}{2}\right)\left(1+\frac{2-3A_0}{2+A_0}\cos^2\theta\right)+A_4\cos\theta\right]$$

$$\frac{d\sigma}{dp_{T,ll}\,dy_{ll}\,dm_{ll}^2\,d\phi} = \frac{1}{2\pi}\frac{d\sigma}{dp_{T,ll}\,dy_{ll}\,dm_{ll}^2}\left[1+\frac{A_2}{4}\cos 2\phi+\frac{3\pi}{16}A_3\cos\phi\right.$$
$$\left.+\frac{A_5}{2}\sin 2\phi+\frac{3\pi}{16}A_7\sin\phi\right]$$

Angular coefficients in Drell-Yan production



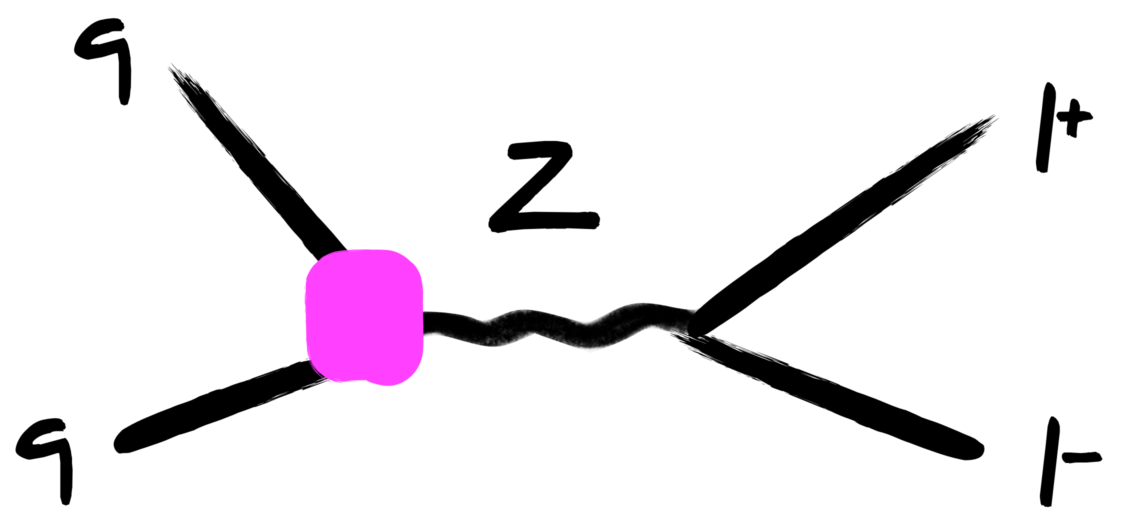
$$\frac{d\sigma}{d\hat{\Omega}} = \frac{\alpha^2 Q_q^2}{12\,\hat{s}} \left(1 + \cos^2\hat{\theta}\right)$$

$$\Downarrow$$

$$A_0 = 0\,, \qquad A_2 = 0$$

[Rhorry Gauld, UH & Joachim Weiss, ongoing]

Angular coefficients in Drell-Yan production



$$\frac{d\sigma}{d\hat{\Omega}} = \frac{\alpha\left(1 - 4s_w^2 + 8s_w^4\right) v^2 \, |C_q|^2}{192\pi \, s_w^4 \, c_w^2 \, \Lambda^4} \, \frac{\hat{s}^2}{\left(\hat{s} - M_Z^2\right)^2} \left(1 - \cos^2\hat{\theta}\right)$$

$$\Downarrow$$

$$A_0 \neq 0 \,, \qquad A_2 = 0$$

[Rhorry Gauld, UH & Joachim Weiss, ongoing]