SM/SMEFT, and Higgs theory overview

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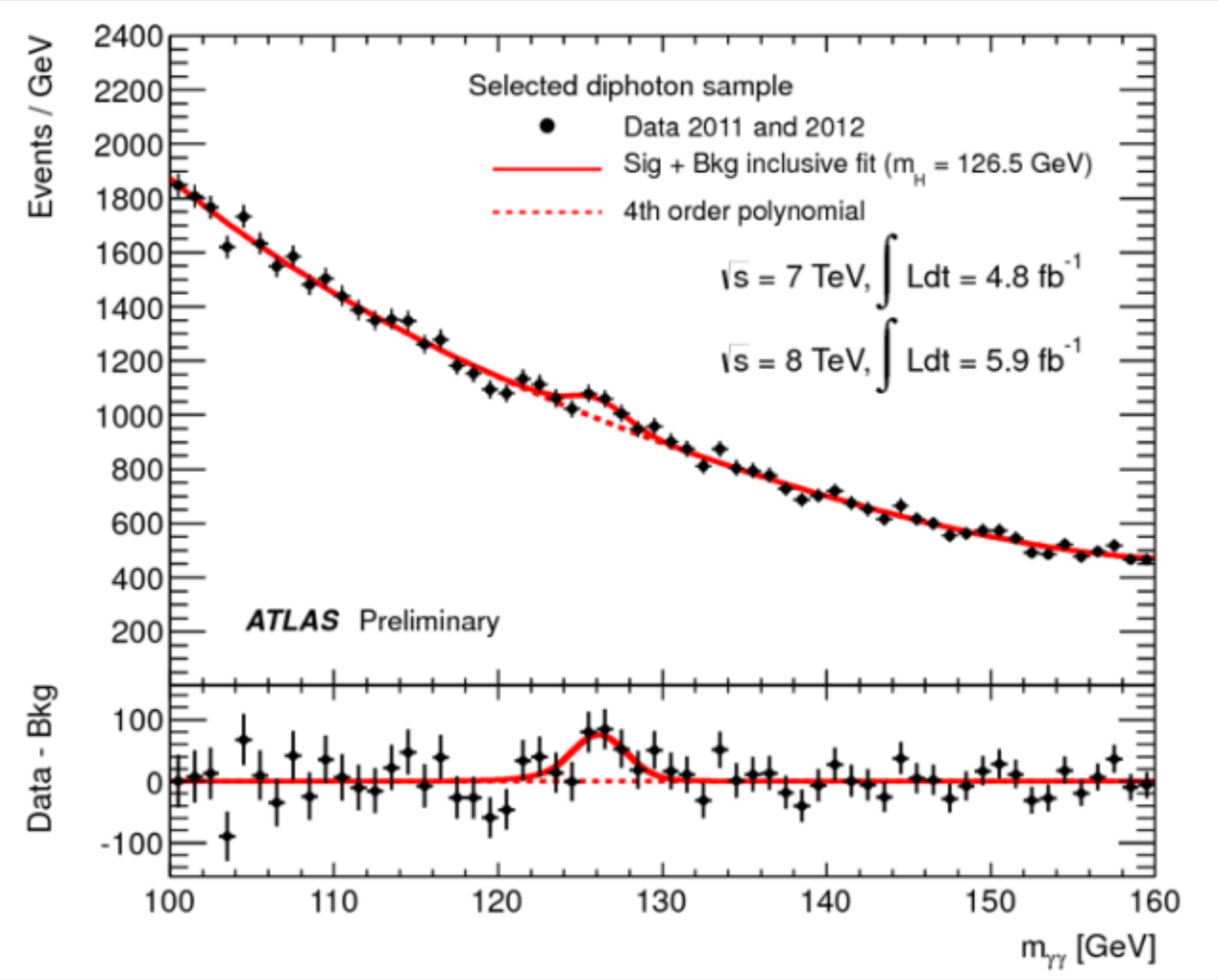
Sezione di Padova

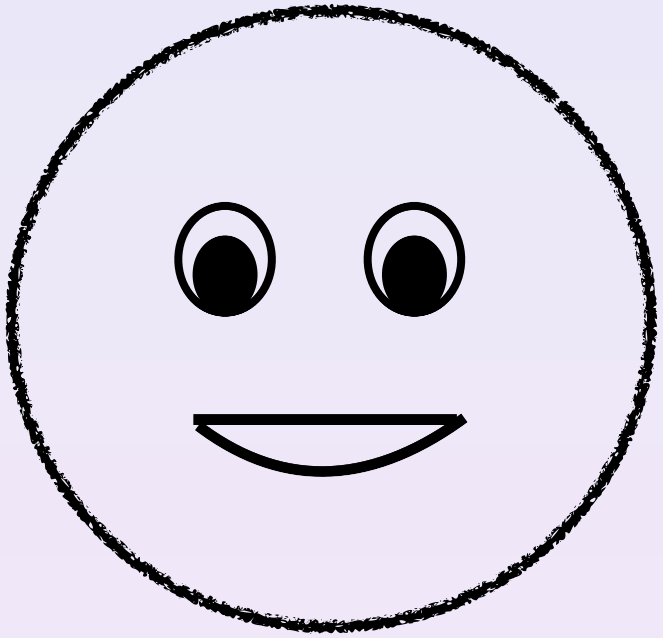
Higgs Boson discovery



Higgs boson as last missing ingredient of the Standard Model discovered in 2012

Higgs Boson discovery

But how does it behave? Is it the SM Higgs boson?



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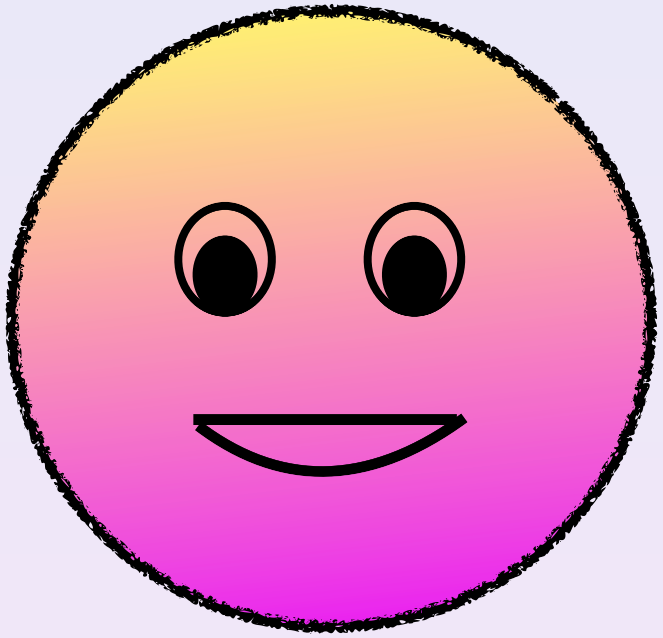
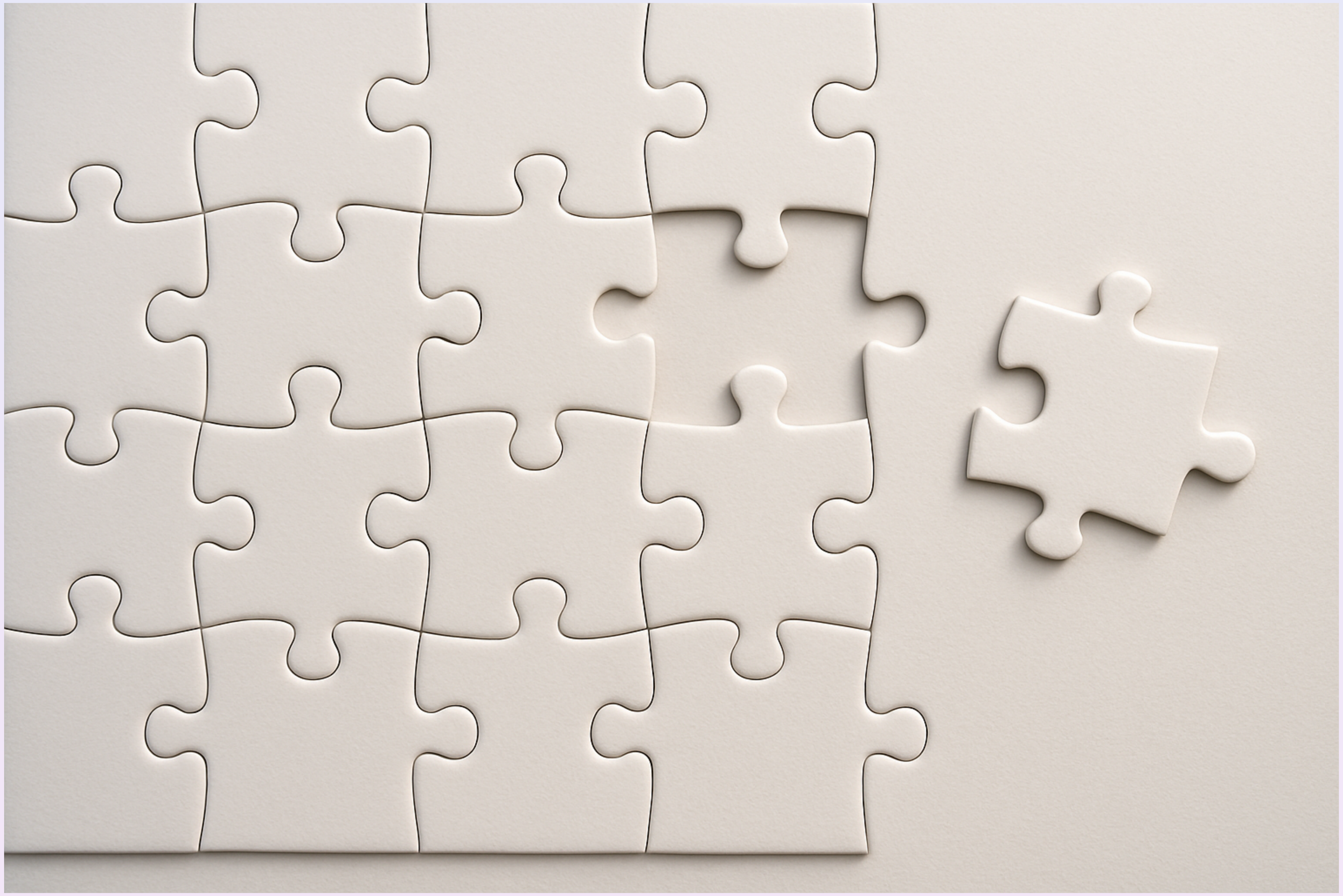


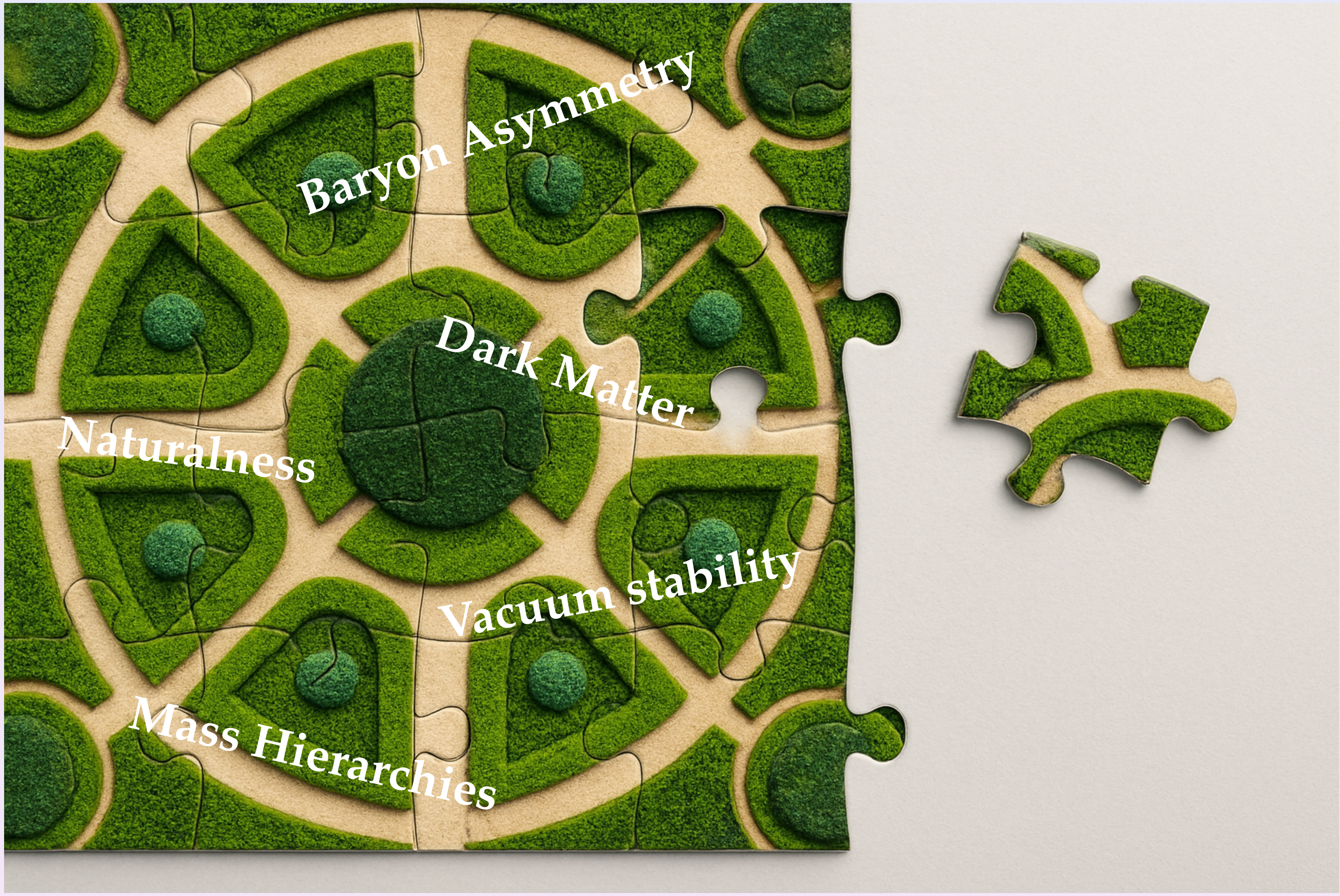
Or maybe it is not all SM-like and helps us in understanding the open puzzles of our universe

Higgs boson is puzzling



....so far the situation is more puzzling than ever.

Higgs boson is puzzling

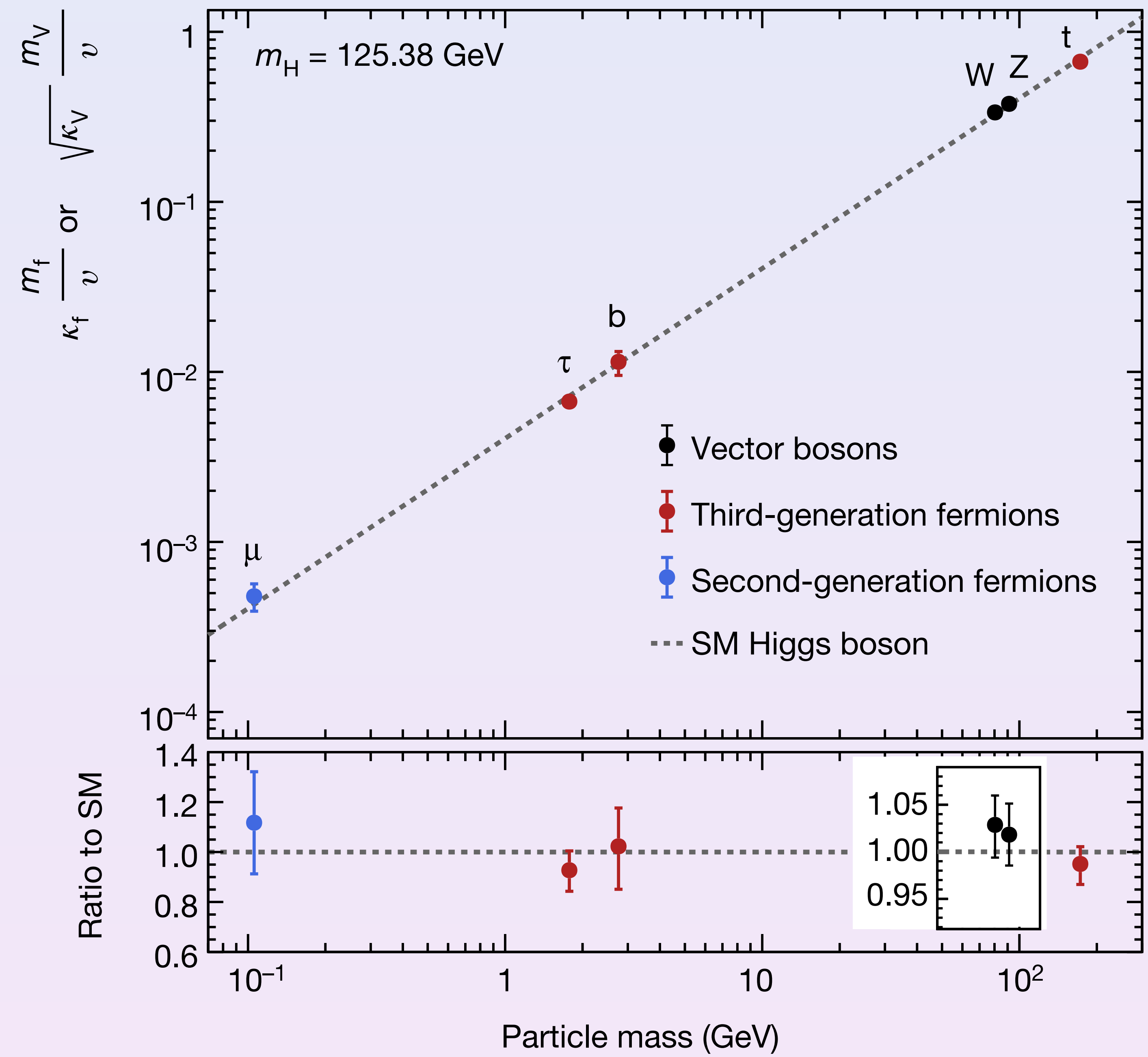


Will the Higgs boson help us to let a clearer picture emerge behind?

Higgs Couplings

- Higgs couplings to massive vector bosons and third generation fermions measured with amazing precision

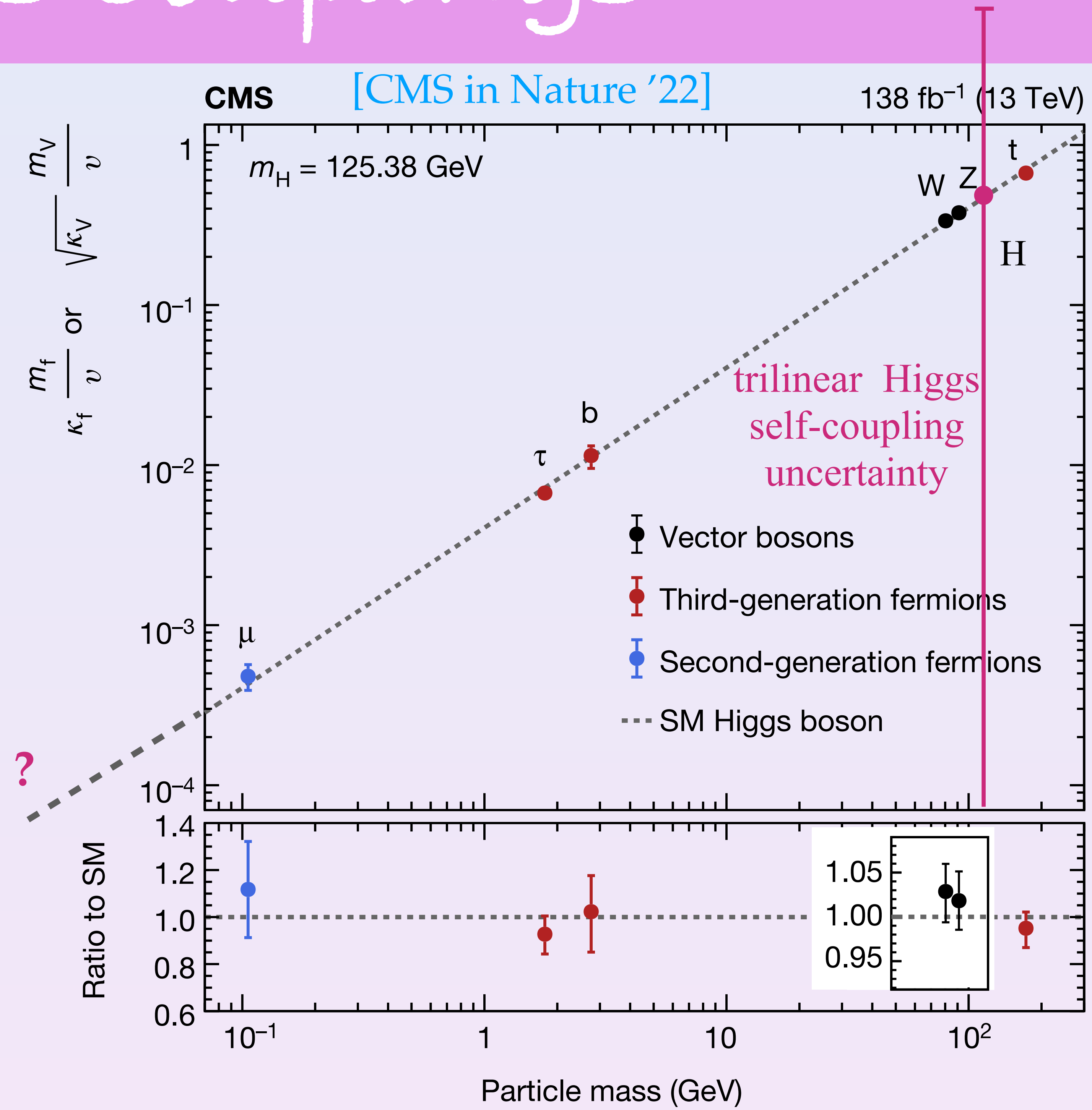
[CMS in Nature '22]



Higgs Couplings

- Higgs couplings to massive vector bosons and third generation fermions measured with amazing precision

- first/(second) generation? Higgs self-couplings?



Current bound on

$|y_e/y_e^{SM}| < 260$ [ATLAS '19]

$|y_c/y_c^{SM}| < 4.5$ [ATLAS '22]

Higgs self-couplings basically unconstrained

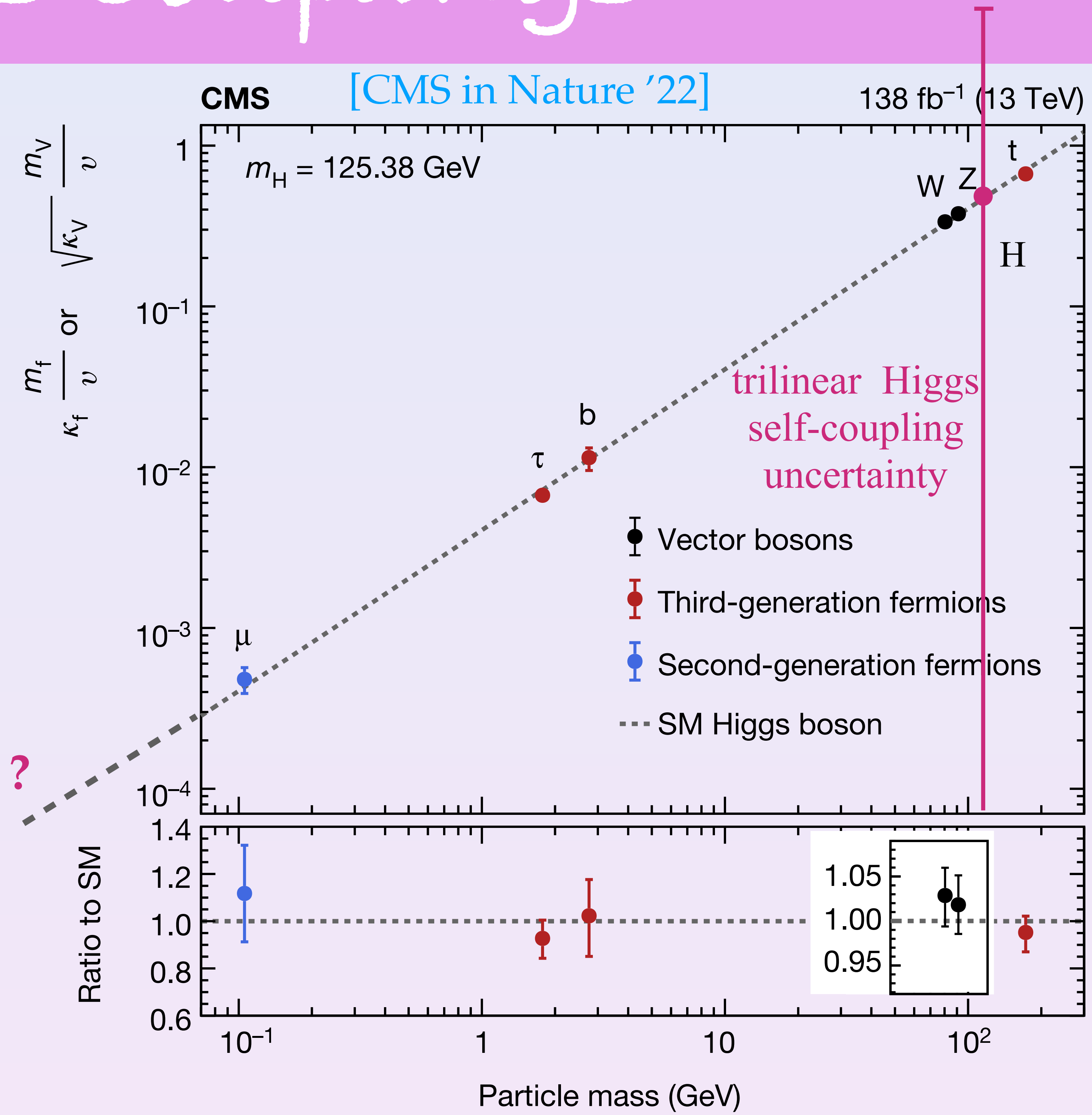
$-0.4 < \lambda_{hhh}/\lambda_{hhh}^{SM} < 6.3$ [ATLAS '22]

Higgs Couplings

- Higgs couplings to massive vector bosons and third generation fermions measured with amazing precision

- first/(second) generation? Higgs self-couplings?

- More generically: Constrain Effective Lagrangian where several operators modify the Higgs interactions



Plan

SM/SMEFT, and Higgs theory overview

Precision in the SM Higgs sector

Interpreted by me as: Effective Field Theory
and connection to UV models for Higgs couplings

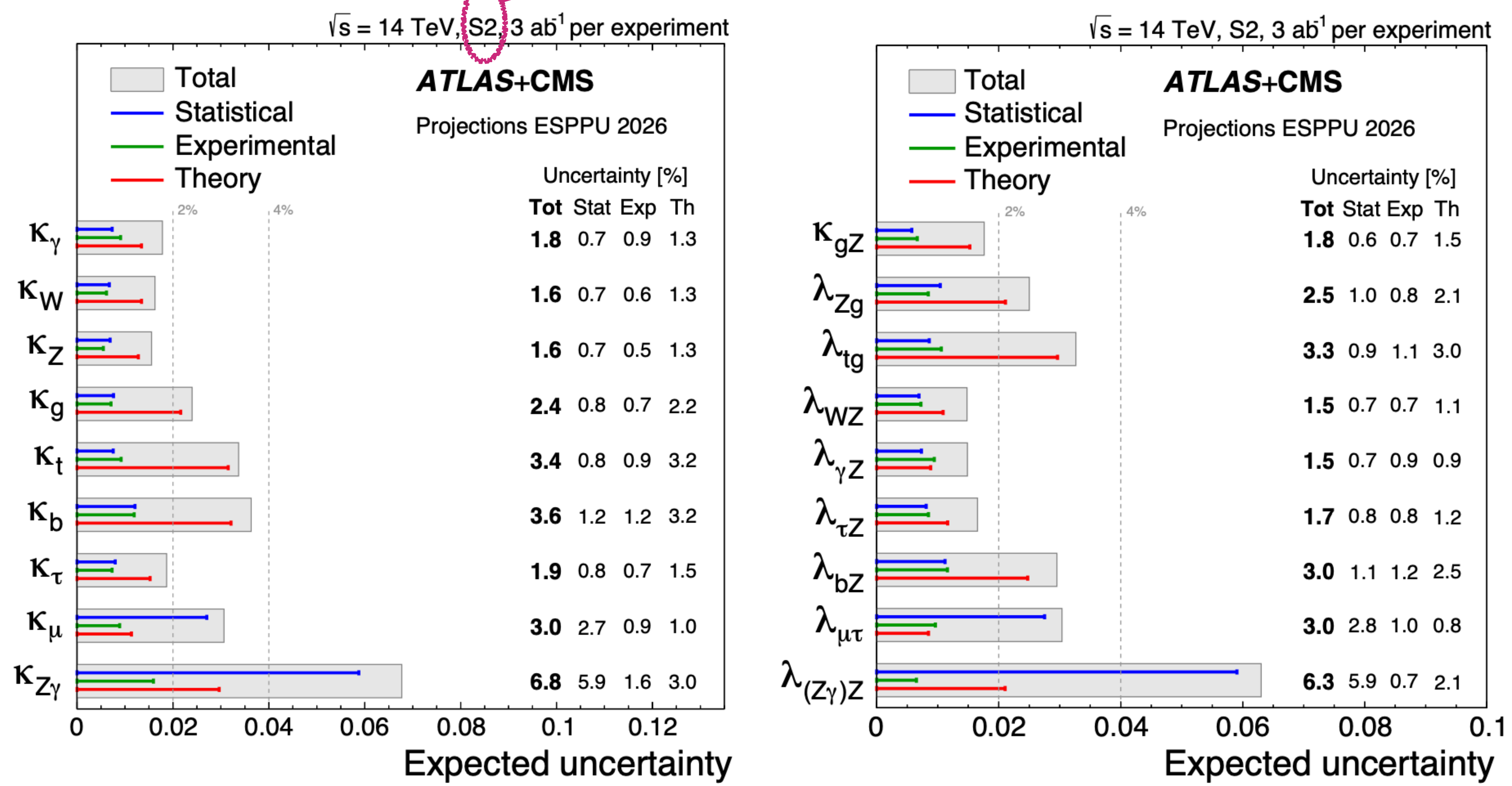
I apologise for being very incomplete and biased

Precision Higgs Boson

Precise Predictions for Higgs physics are needed.
Theory Uncertainty could be bottle neck for HL-LHC programme.

assumes halving of TH uncertainty

$\lambda_{XY} = \kappa_X / \kappa_Y$



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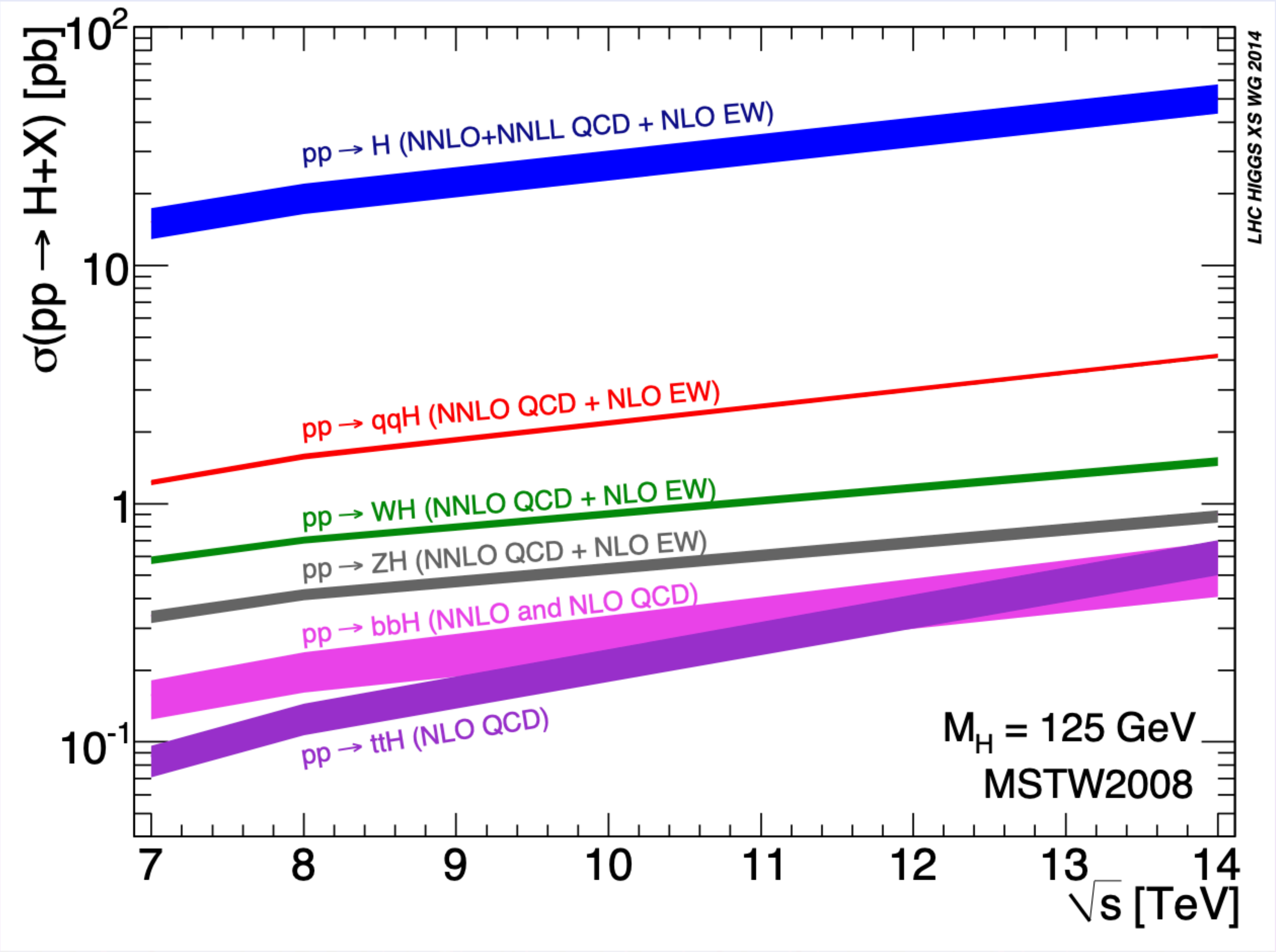
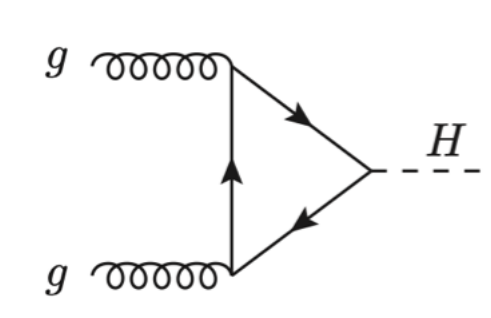


Gluon fusion is dominant



Gluon fusion Cross section prediction as of YR4

$$\sigma = 48.58\,\mathrm{pb}^{+2.22\,\mathrm{pb}\,(+4.56\%)}_{-3.27\,\mathrm{pb}\,(-6.72\%)}\;\textbf{(theory)} \pm 1.56\,\mathrm{pb}\,(3.20\%)\;\textbf{(PDF+}\alpha_s\textbf{)}\,.$$

Incorporate QCD correction in heavy top limit up to N³LO [Anastasiou, Duhr, Dulat, (Furlan) , Gehrmann, Herzog, Mistlberger ’14,’15, ‘15]

Finite quark mass effects at NLO [Graudenz, (Djouadi), Spira, Zerwas ’93 ’95, Aglietti et al. ’07]

$1/m_t^2$ expansion at NNLO [Harlander, Ozeren ’09, Pak, Rogal, Steinhauser ’09]

Electroweak NLO and approximate mixed QCD+EW corrections

[Aglietti et al’04, Actis et al ’08] [Anastasiou et al. ’08]

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Recent Updates

Finite quark mass effects at NNLO and t+b interference [Czakon, (Harlander, Klappert) Niggetiedt ’20, ’21, Czakon et al. ’23]

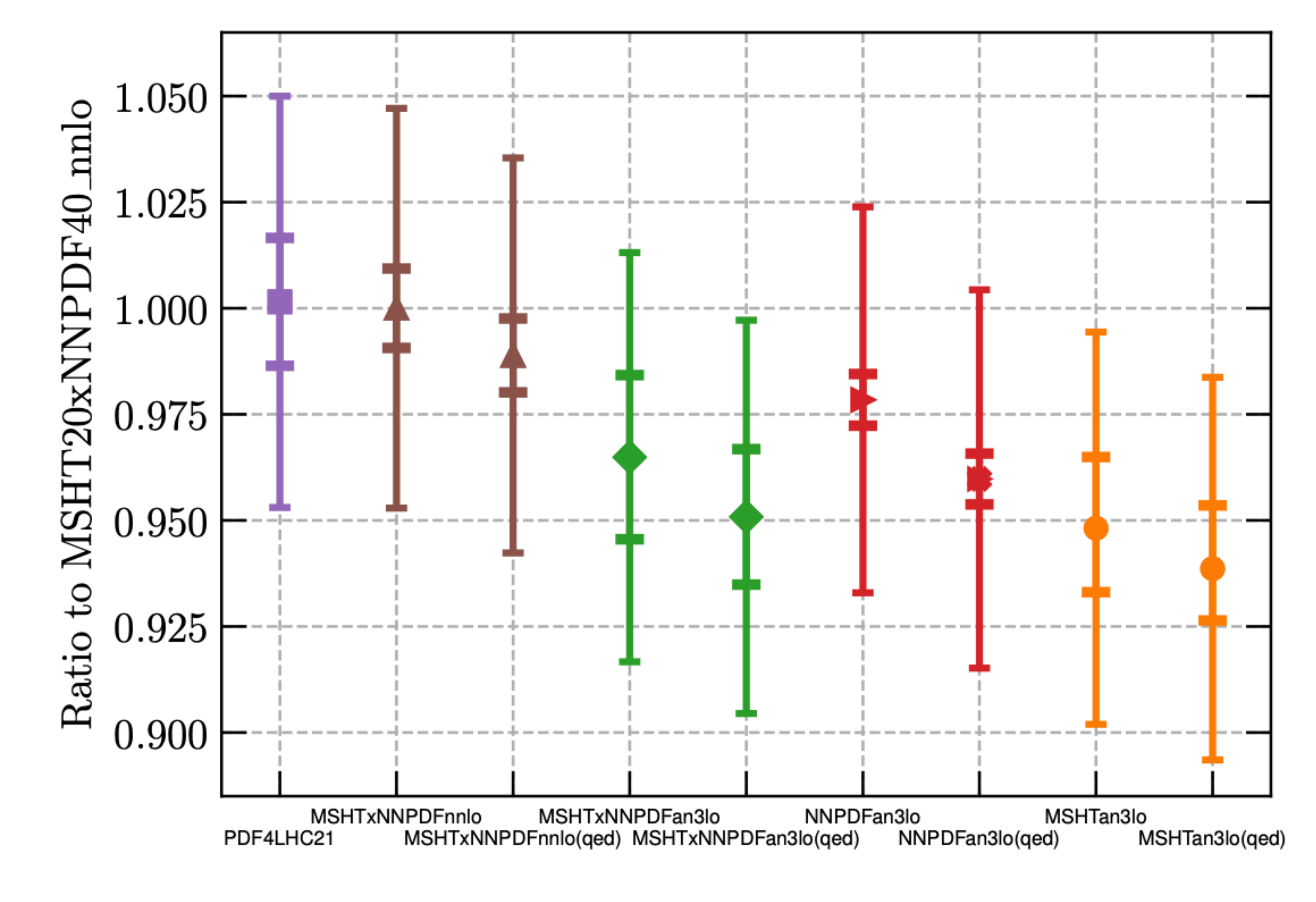
allow to study renormalisation scheme dependence and FS

$$\sigma_{ggH} = 48.81(1)^{+0.65}_{-2.02}(\text{N}^3\text{LO HEFT}) - 0.16^{+0.13}_{-0.03}(\text{NNLO } t) - 1.74(2)^{+0.13}_{-0.03}(\text{NNLO } t \times b)\ \text{pb}.$$

[Czakon, Eschment, Niggetiedt, Poncelet, Schellenberger ’24] approximate N^3LO PDF sets now available [McGowen et al. '22, Ball et al. '24]

Combination between NNPDF and MSHT [Ball et al. '24; ; talk by R. Stegeman]

Higgs production in gluon fusion



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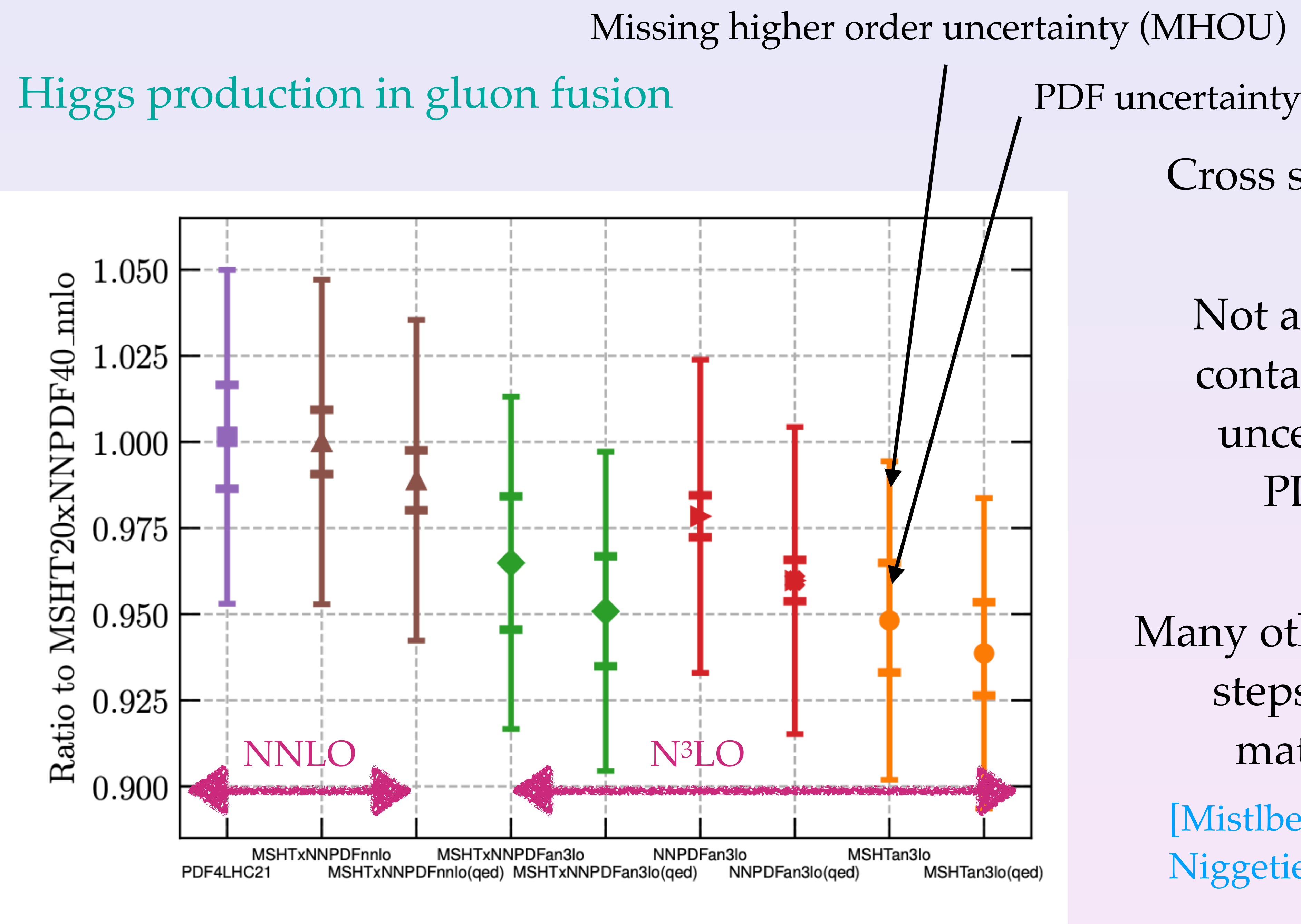


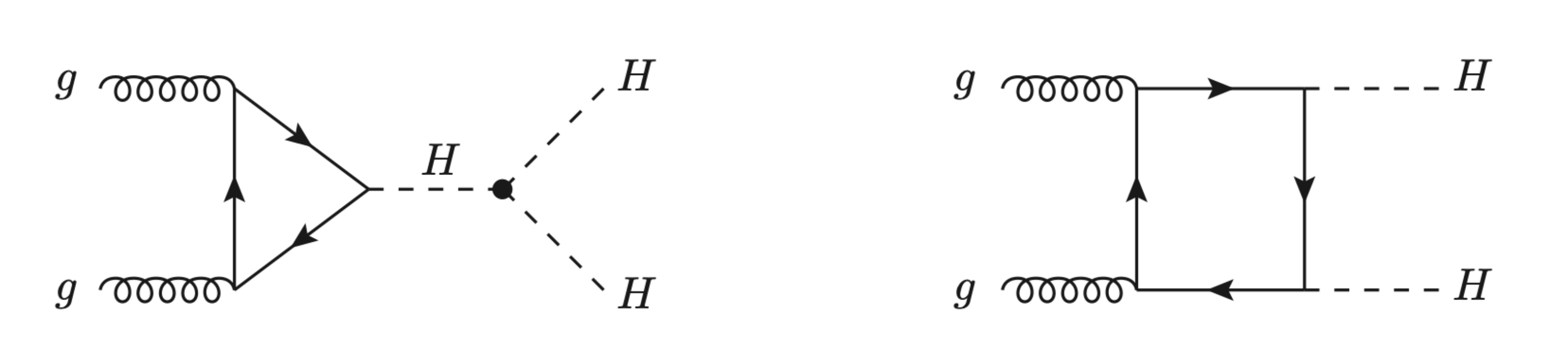
Cross section shrinks

Not all N^{3}LO options contained in the PDF uncertainty (but in PDF+MHOU)

Many other updates, i.e. first steps towards N^{4}LO, matching to PS, …

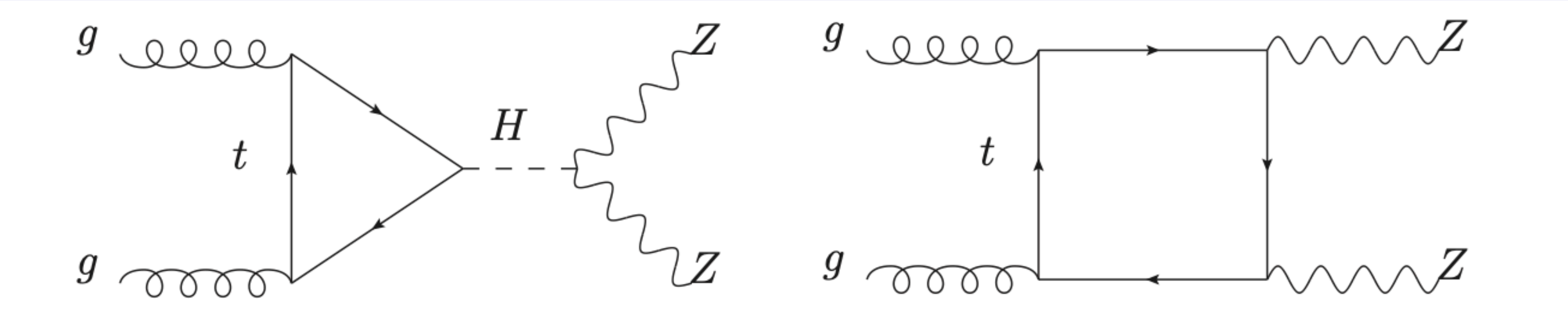
[Mistlberger, Suresh '25; Niggetiedt, Wiesemann '24; …]

Gluon fusion Higgs Production



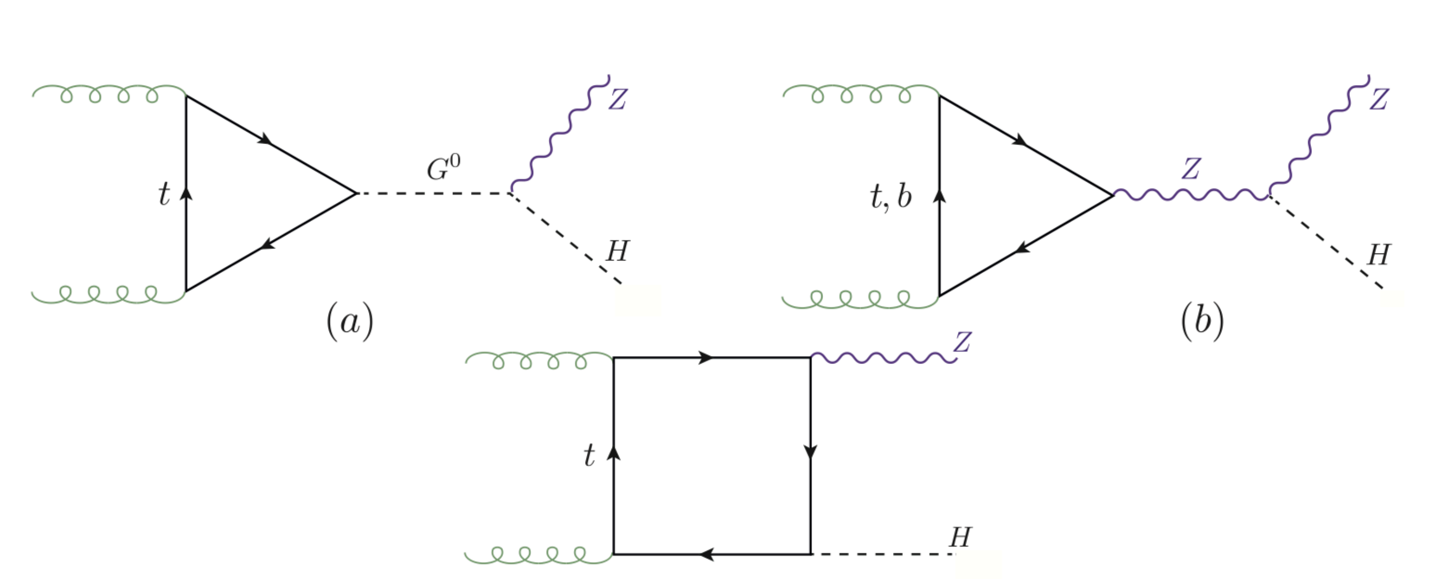
Double Higgs Production

Measurement of triple Higgs coupling



Offshell Higgs Production

Higgs width measurement



VH Production, contribution at NNLO QCD

third largest Higgs production

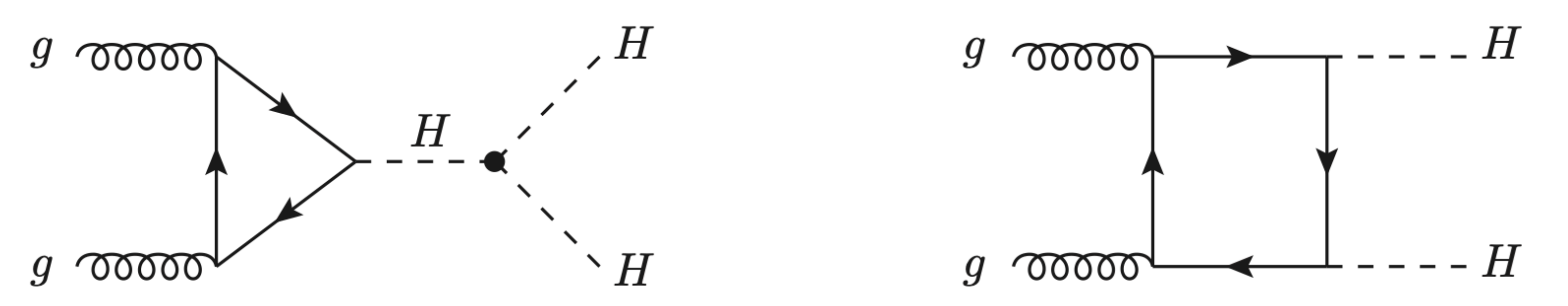
$h \to b\bar{b}$ measurement

Computation at NLO QCD more difficult with respect to single Higgs due to many scales in the problem

Solutions: numerical evaluation or expansions

[numerical: Borowka et al. '16, Chen et al '20]

Gluon fusion Higgs Production



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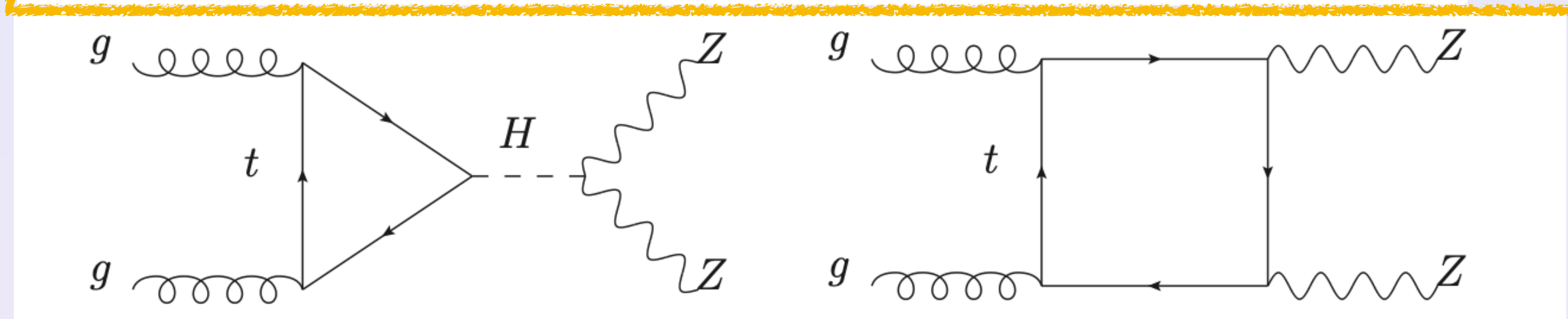

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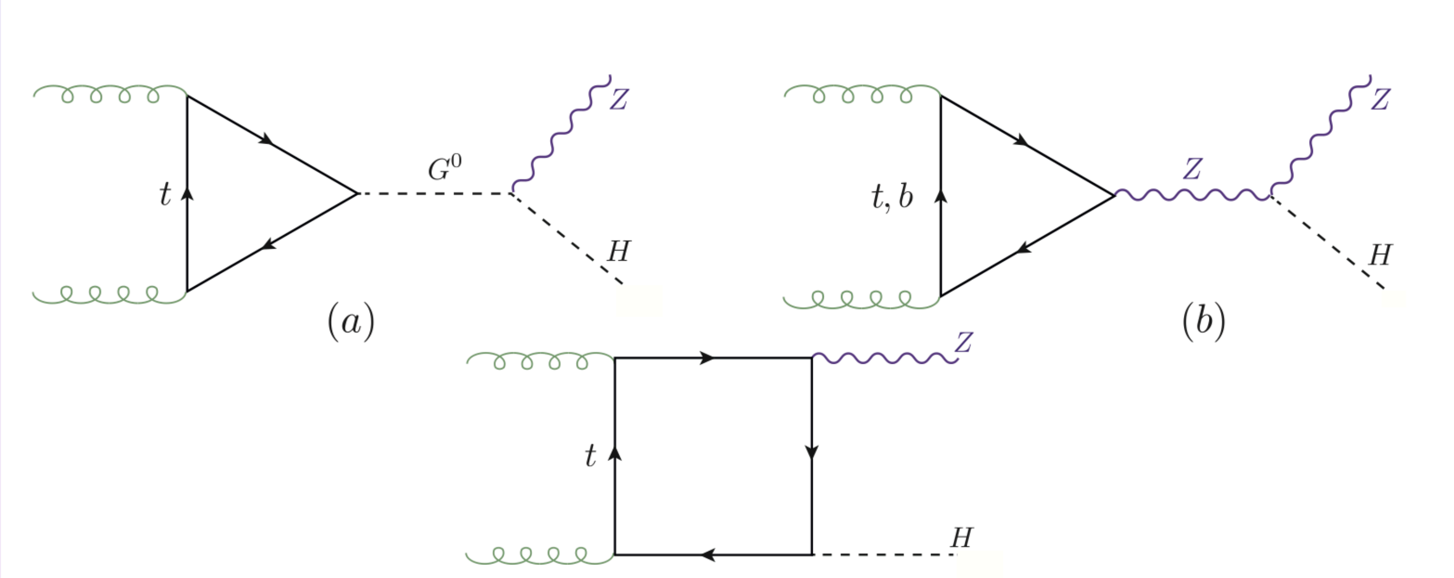

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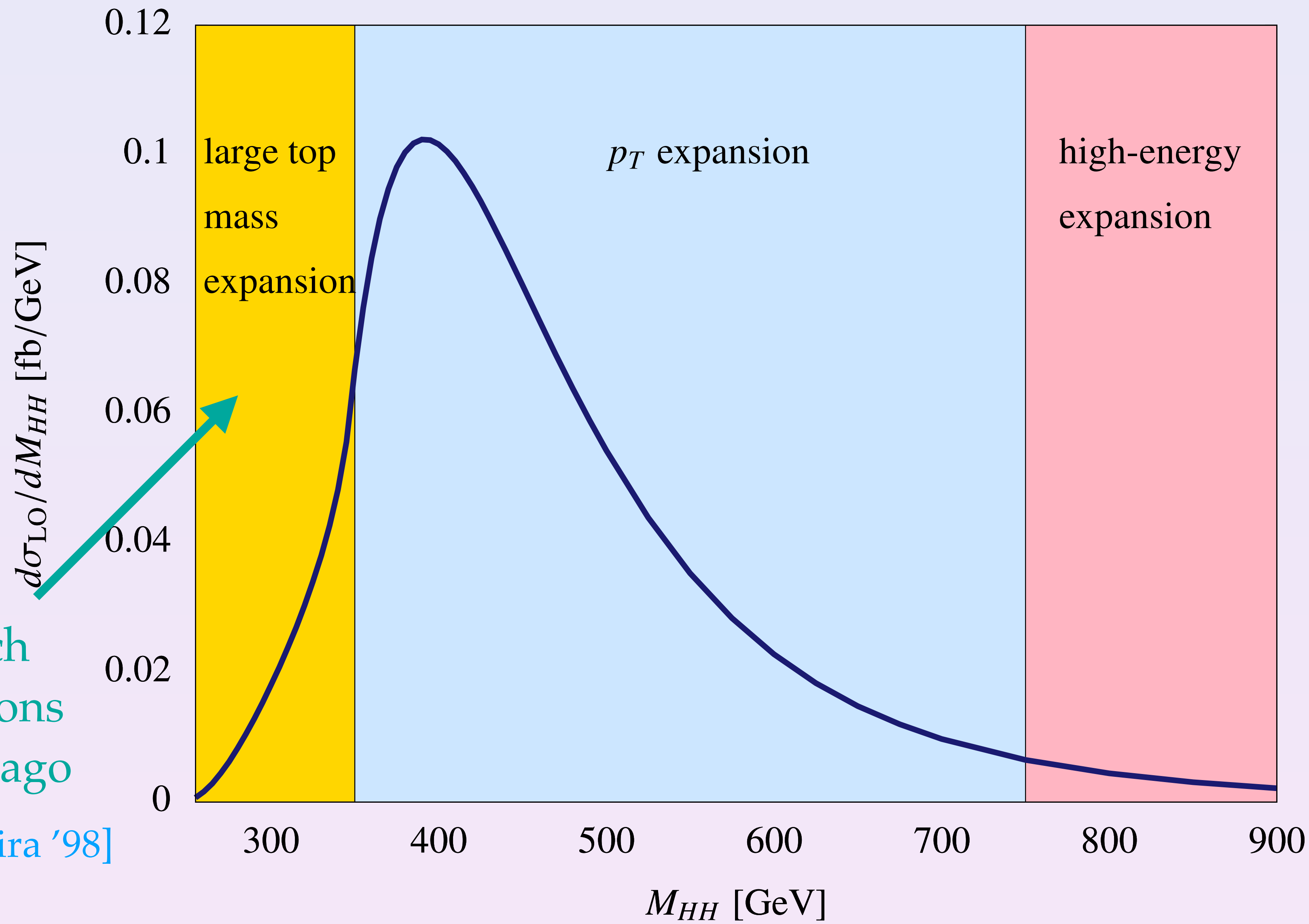
Expansion Method

Method: reduce amount of scales by dividing in small/large

BUT: needs to cover (nearly) whole phase space



standard approach
NLO QCD corrections
computed 25 years ago

[Dawson, Dittmaier, Spira '98]

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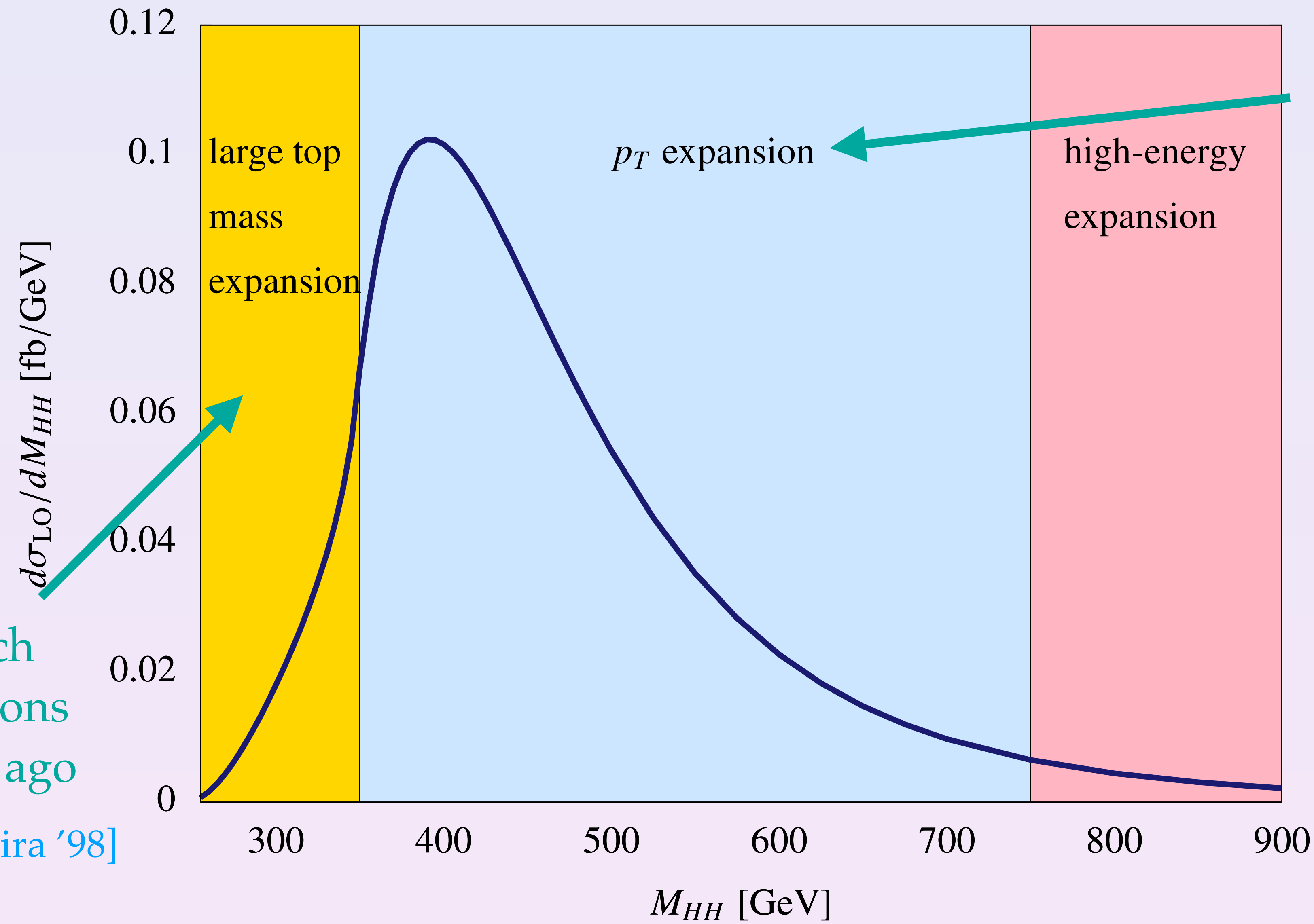

NLO QCD

[Bonciani, Degrassi, Giardino, RG, '18]

partial NNLO QCD

[Davies, Schönwald, Steinhauser, (Vitti) '24 '25, see also M. Vitti's talk]

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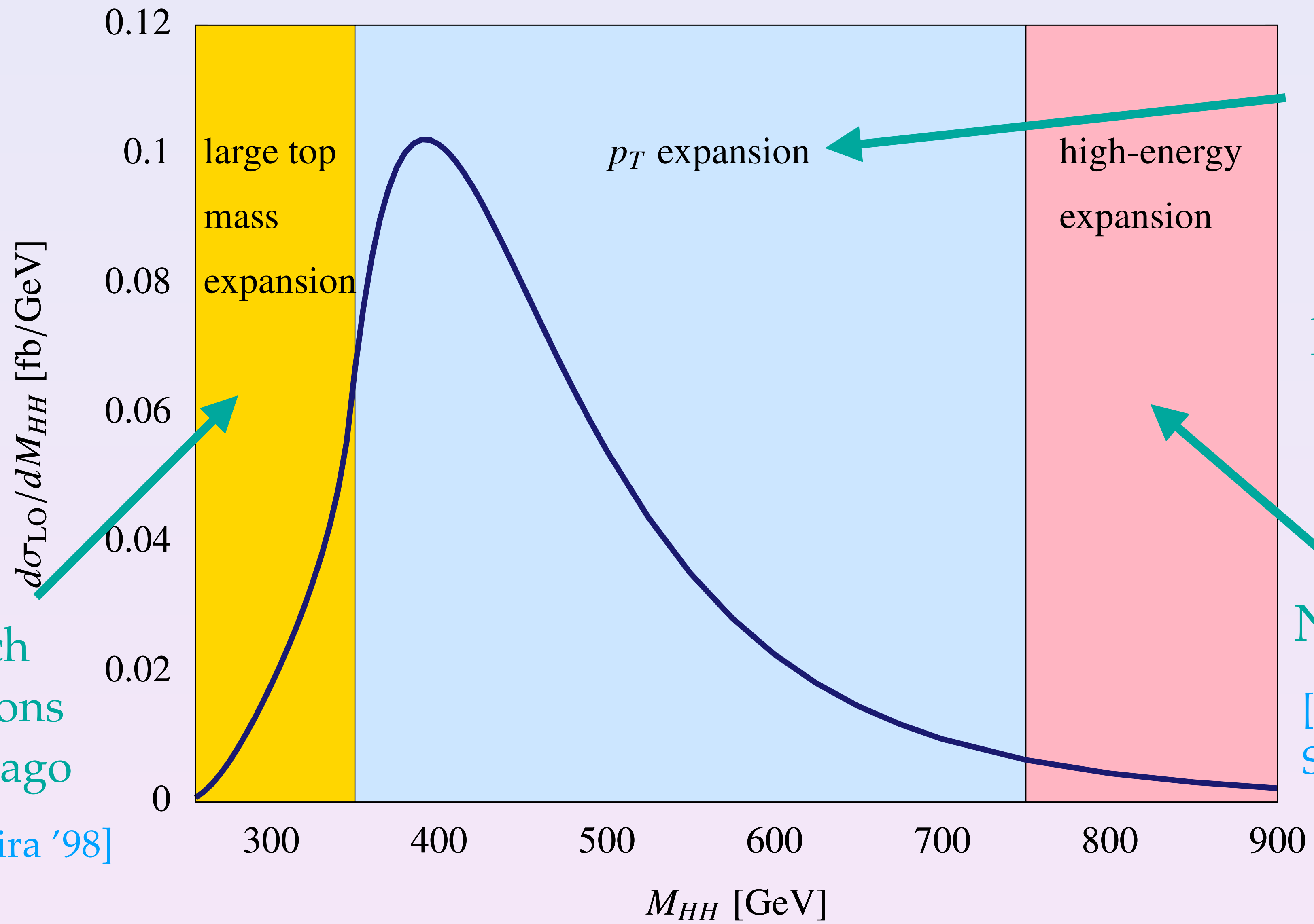

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NLO QCD

[Davies, Mishima, Steinhauser, Wellmann '18]

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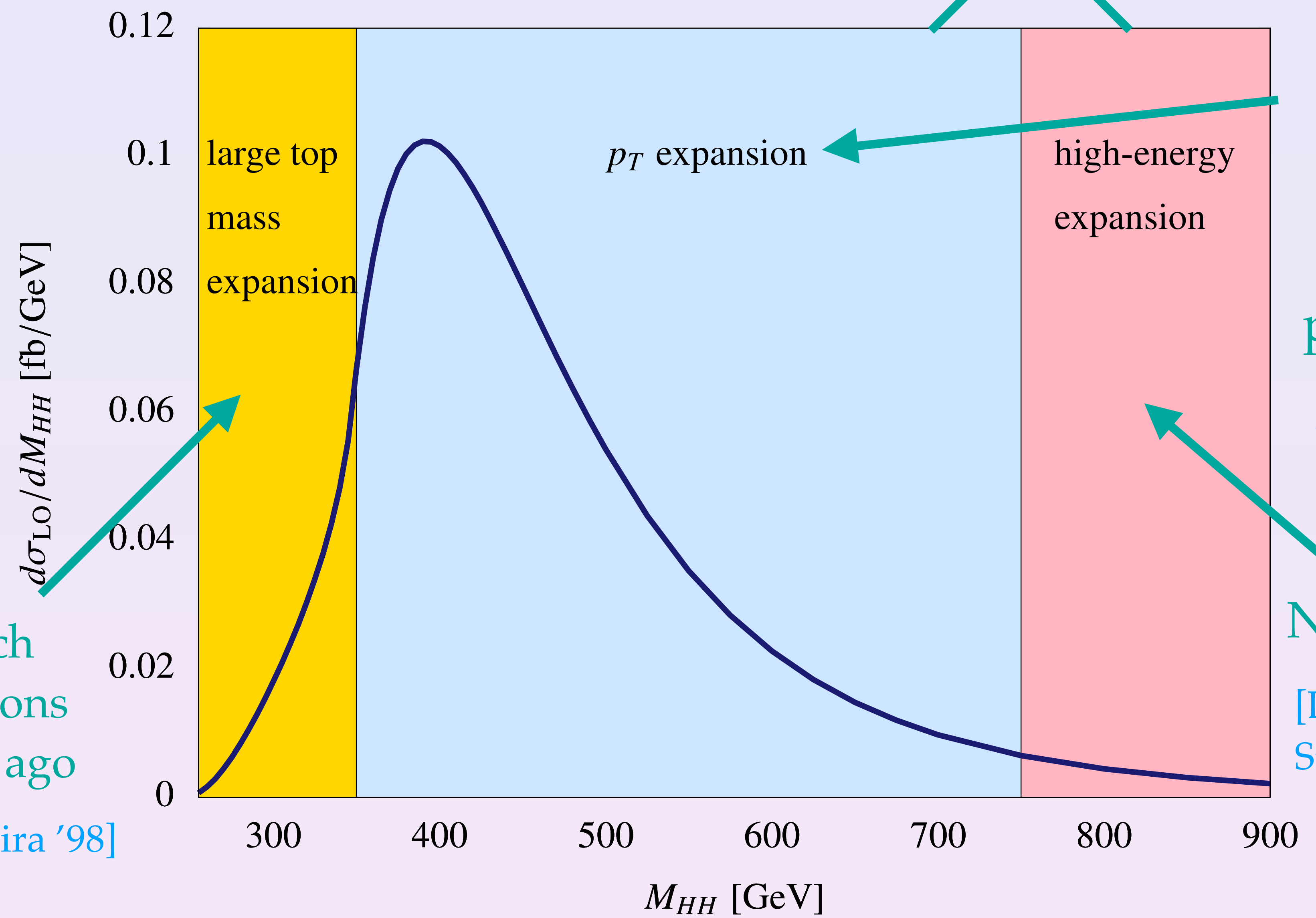
Can be combined

[Bellafronte, Degrassi, Giardino, RG, Vitti '22]



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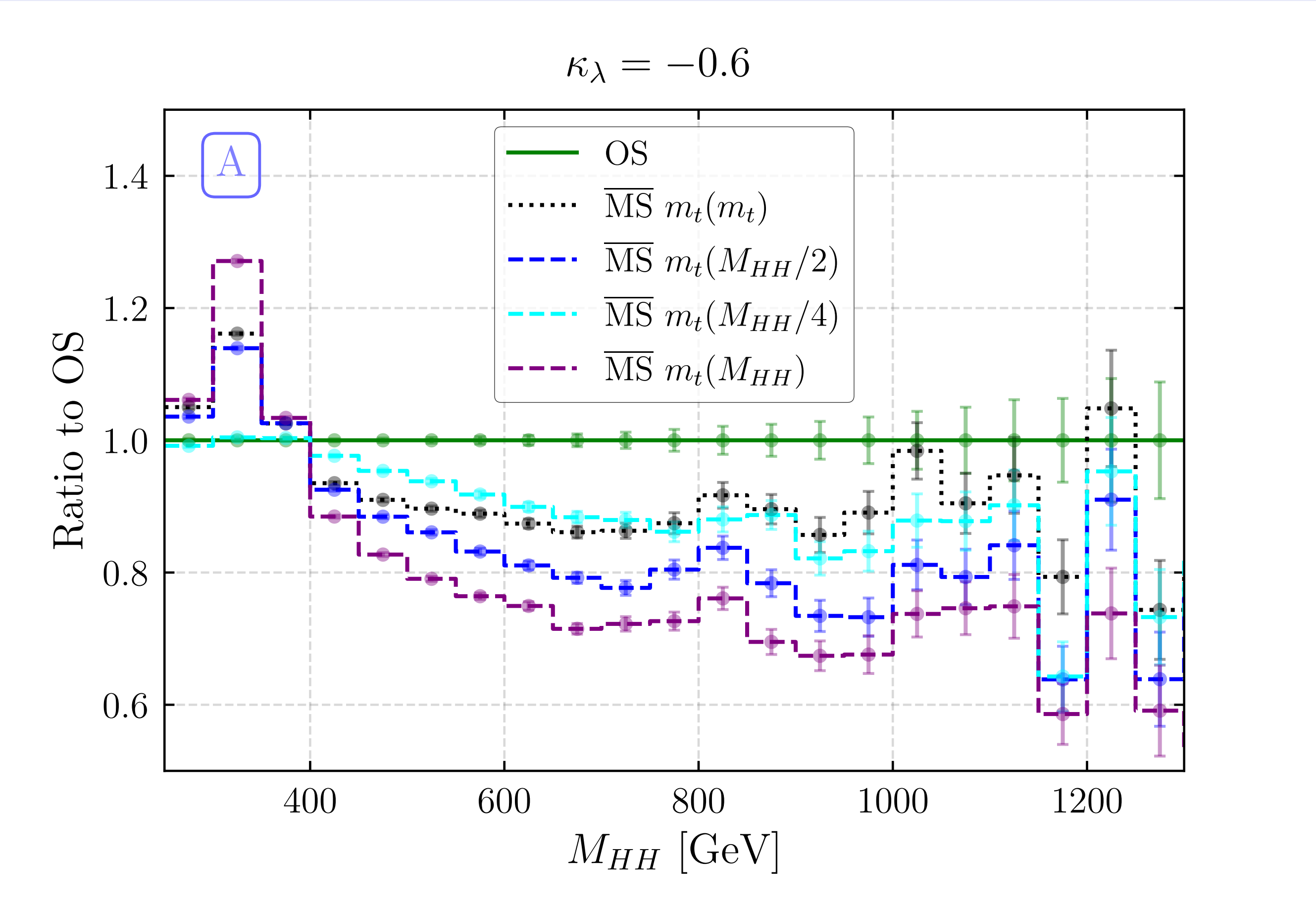
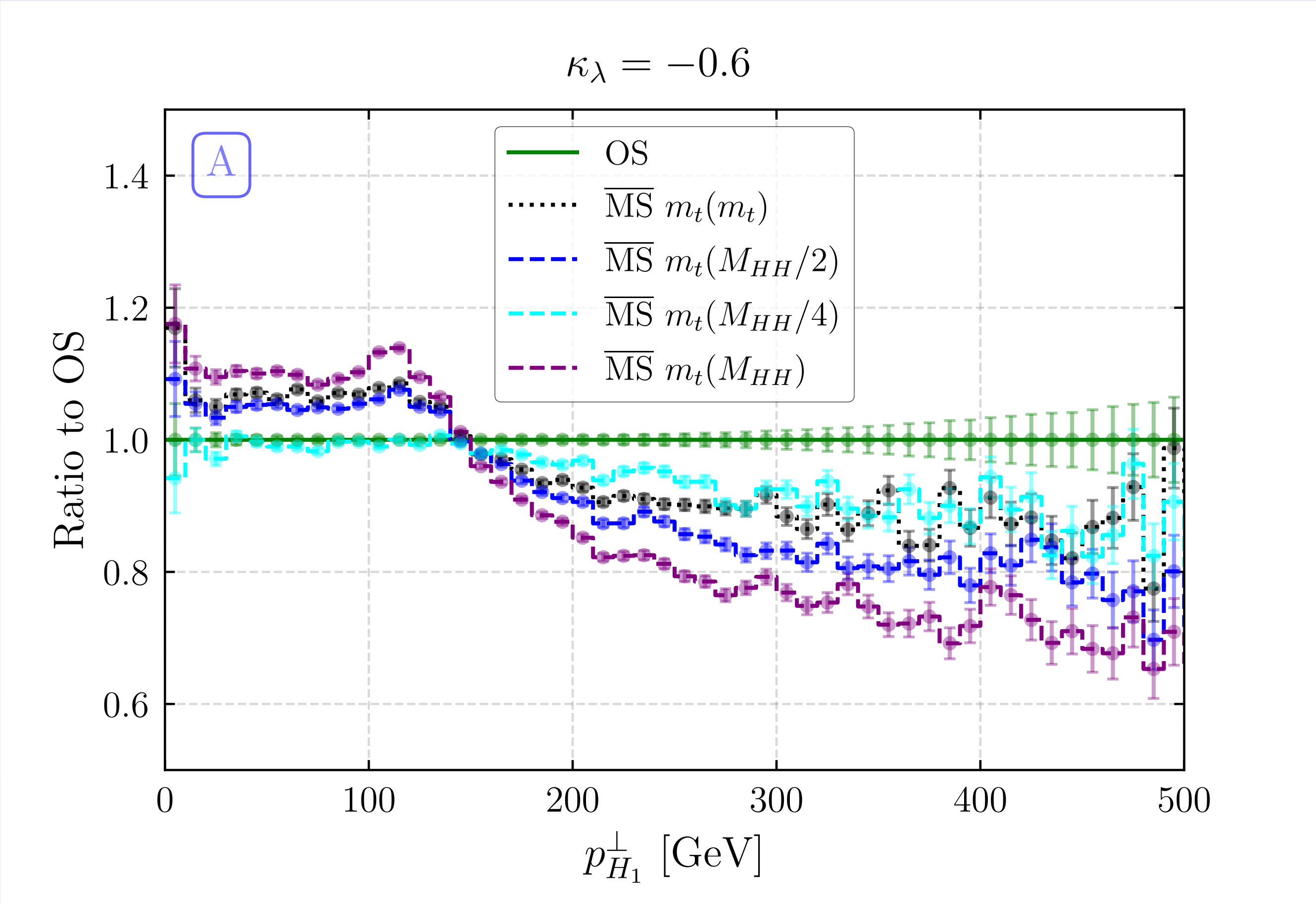
Numerical evaluation in Monte Carlo very fast and flexible, see POWHEG implementation

[HH: Bagnaschi, Degrassi, RG '23; ZH: Campillo, RG, Heinrich, Jones, Kerner, Vitti 'in prep.; also ggXY D. Stremmer's talk]

Top mass uncertainty

[Bagnaschi, Degrassi, RG '23]

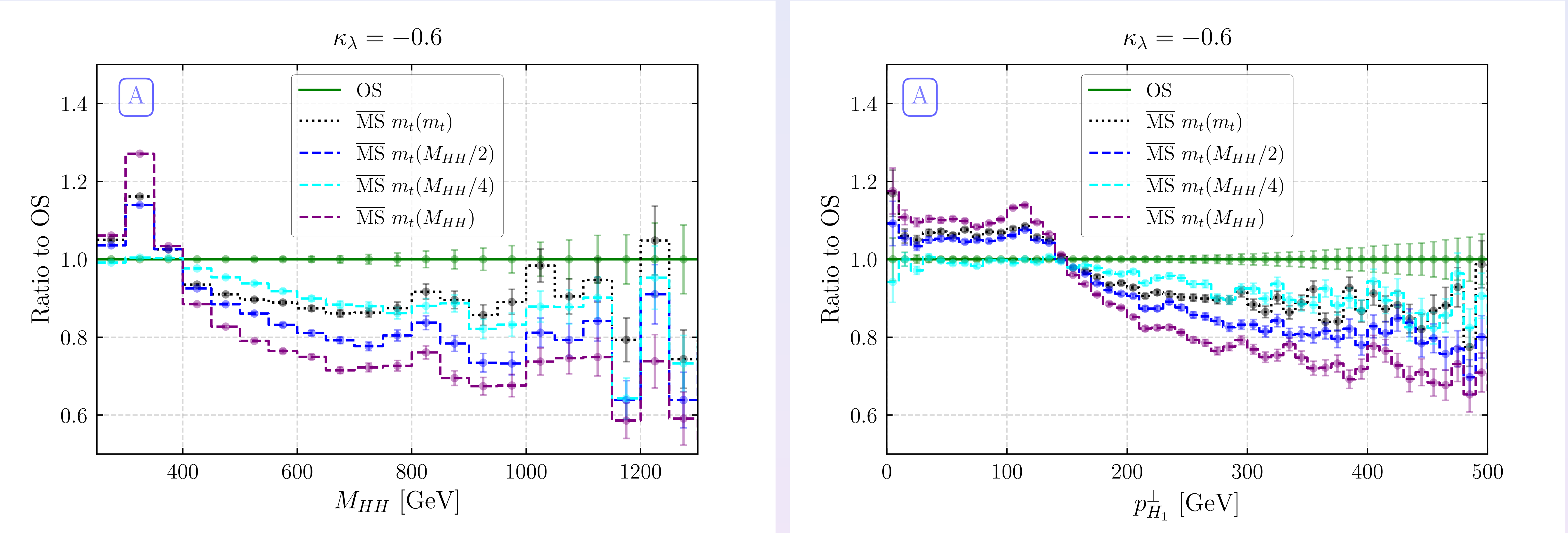




Large Uncertainty due to choice of renormalisation scheme of top quark mass

Top mass uncertainty

[Bagnaschi, Degrassi, RG '23]



Large Uncertainty due to choice of renormalisation scheme of top quark mass

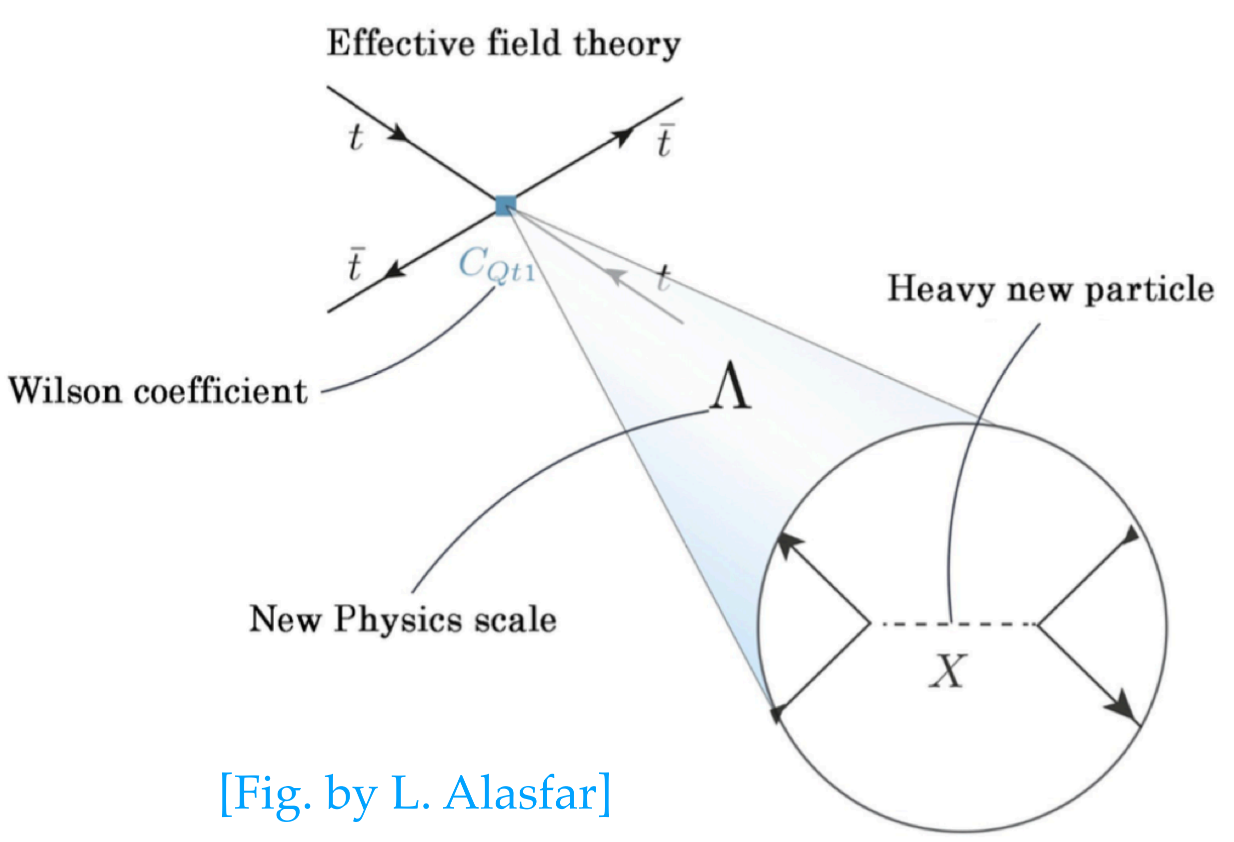
Uncertainty addressed in [Jaskiewicz, Jones, Szafron, Ulrich '25]

in high-energy limit can be understood in SCET ⟶

include tower of higher log's in OS definition in HE range to reduce uncertainty

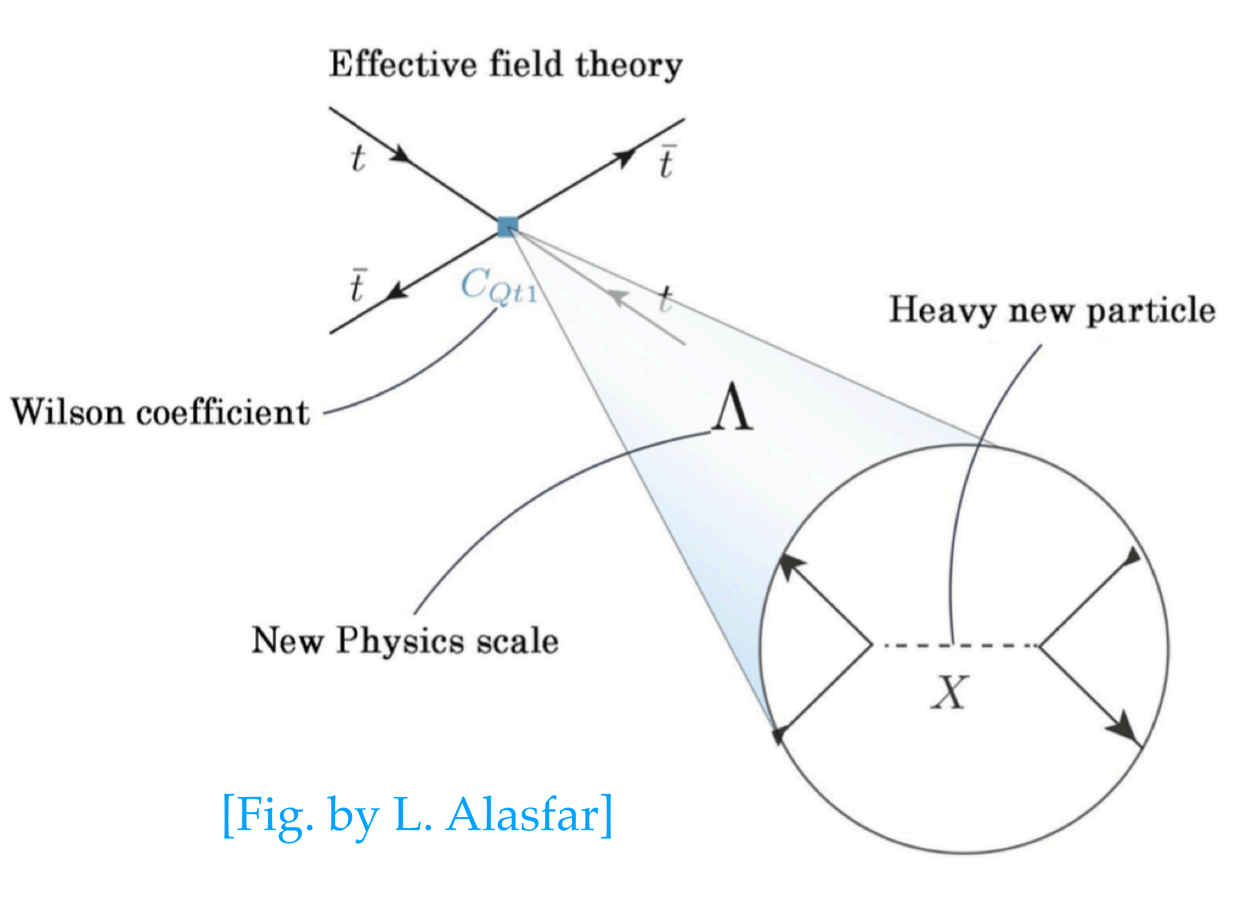
SMEFT and HEFT in Higgs pair production

Effective Field Theory



[Fig. by L. Alasfar]

Effective Field Theory



[Fig. by L. Alasfar]

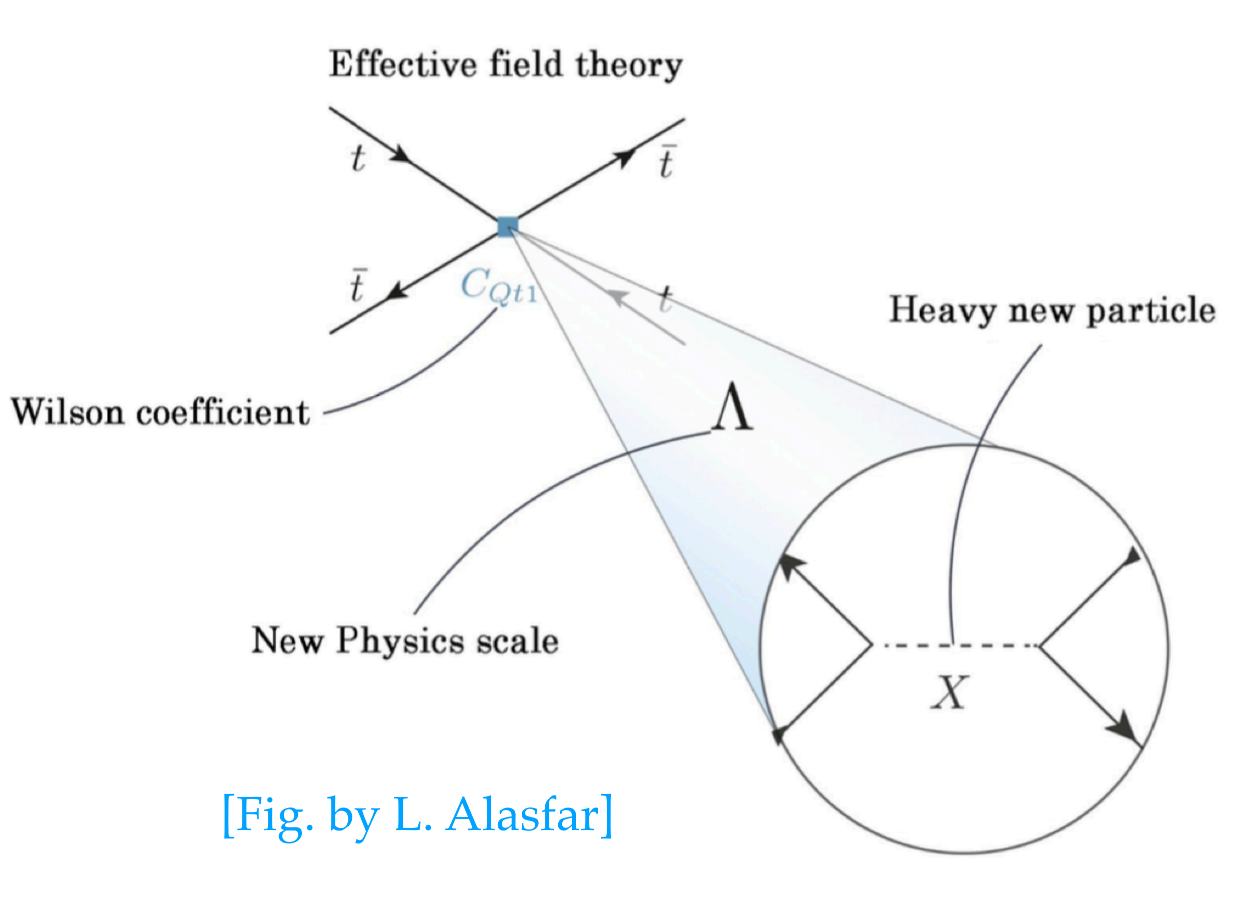
Standard Model Effective Field Theory

$$\mathscr{L} = \mathscr{L}_{SM} + \sum_i \frac{c_{\mathcal{O}}}{\Lambda^i}\mathcal{O}_i$$

for Higgs physics
$i \geq 2$

respects the SM gauge symmetries, all fields transform as in SM

Effective Field Theory



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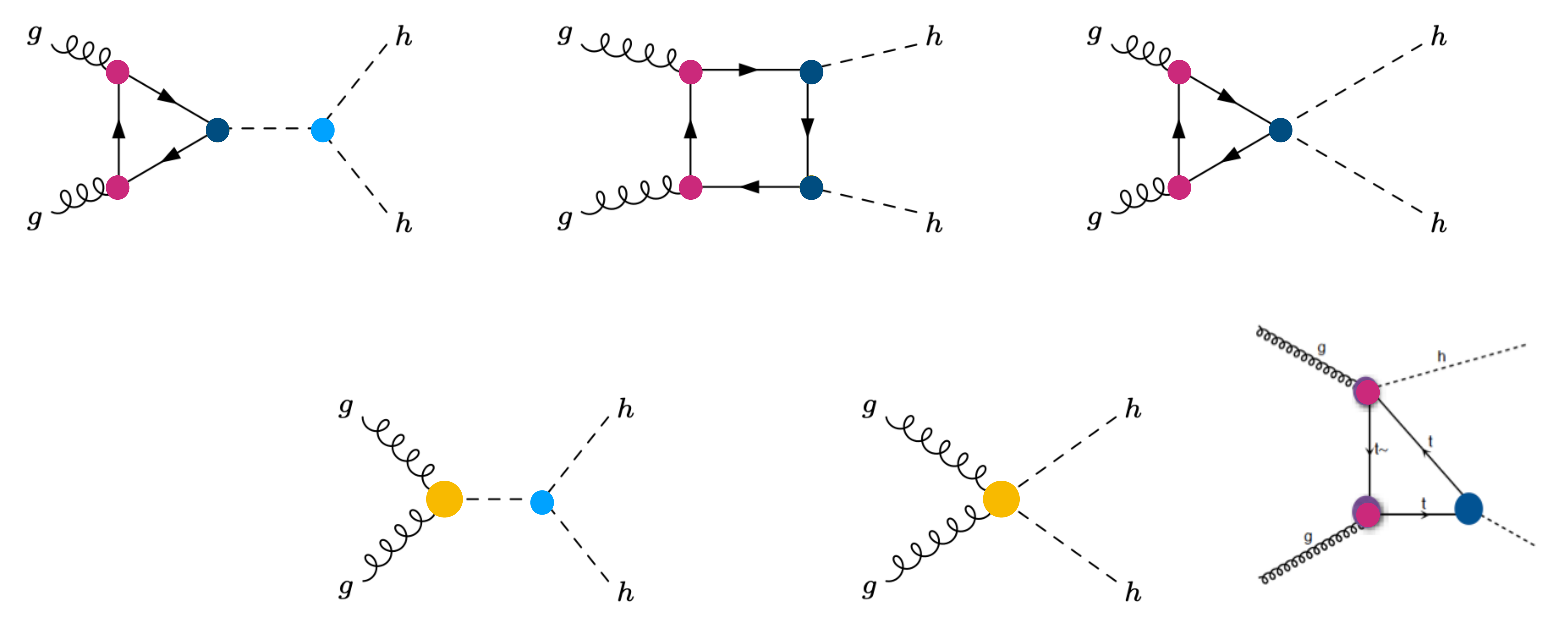
Higgs Effective Field Theory

Goldstone matrix

$$\mathscr{L} = \mathscr{L}_{kin,SM} + V(h) - \frac{v^2}{2} Tr(V_\mu V^\mu) F(h) - \frac{v}{\sqrt{2}} (\bar{F}_L U Y_F(h) F_R + h.c.)$$

polynomial in the physical Higgs field, i.e. $F(h) = a\frac{h}{v} + b\frac{h^2}{v^2} + ..$

SMEFT in HH



SMEFT:

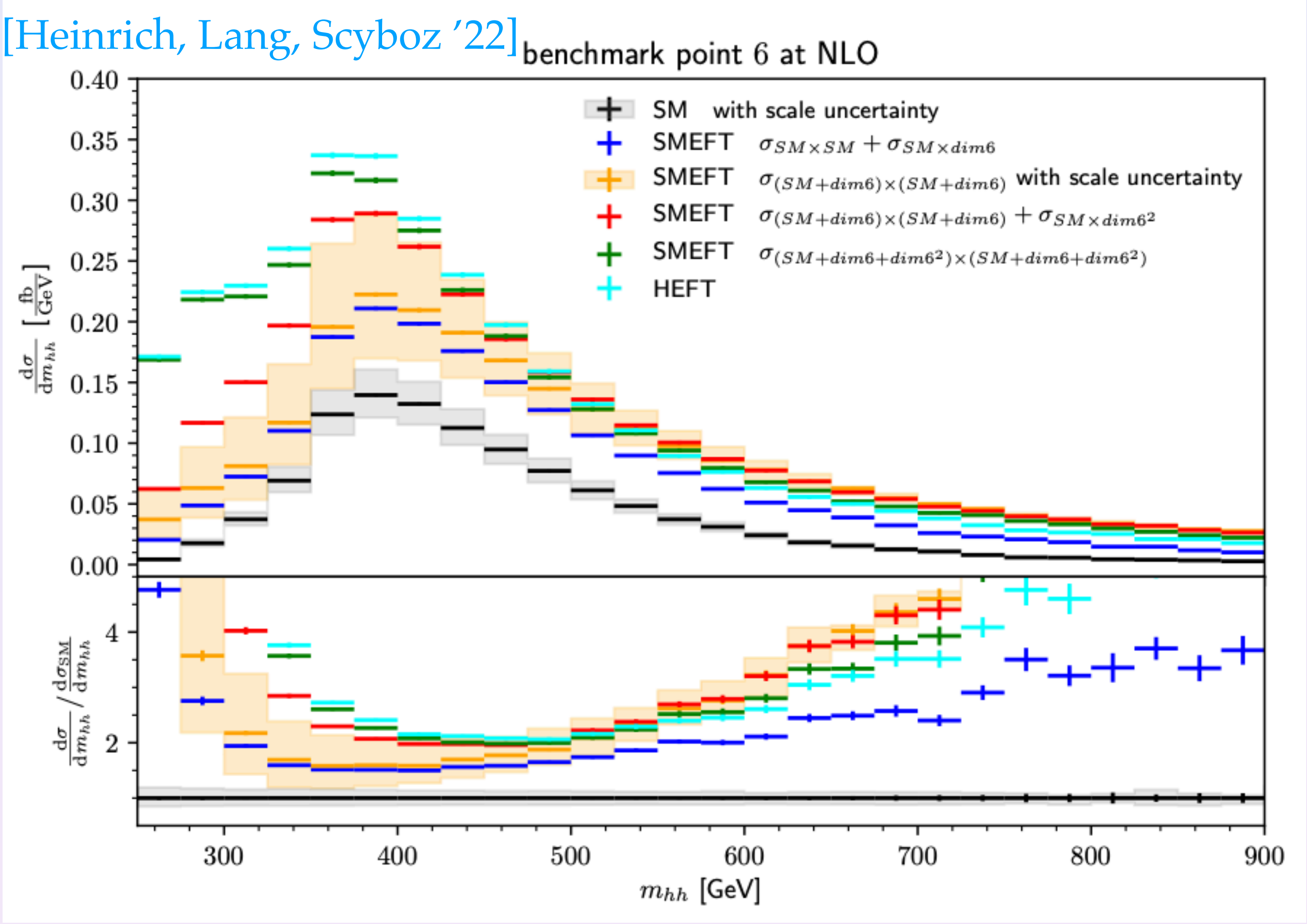
$$\mathscr{L} = C_{H,\Box}(H^\dagger H)\Box(H^\dagger H) + C_{HD}D_\mu(H^\dagger H)D^\mu(H^\dagger H)^* + C_H|H|^6 +$$
$$C_{HG}|H|^2 G_{\mu\nu}G^{\mu\nu} + C_{uH}\bar{Q}_L\tilde{H}t_R|H|^2 + h.c. + C_{uG}\bar{Q}_L\sigma_{\mu\nu}T^a\tilde{H}t_R G^a_{\mu\nu} + h.c.$$

Warsaw basis

coefficients of $\mathcal{O}(1/\Lambda^2)$

SMEFT @ NLO QCD implemented into POWHEG [Heinrich, Lang, Scyboz '22]

[Heinrich, Lang, Scyboz '22]



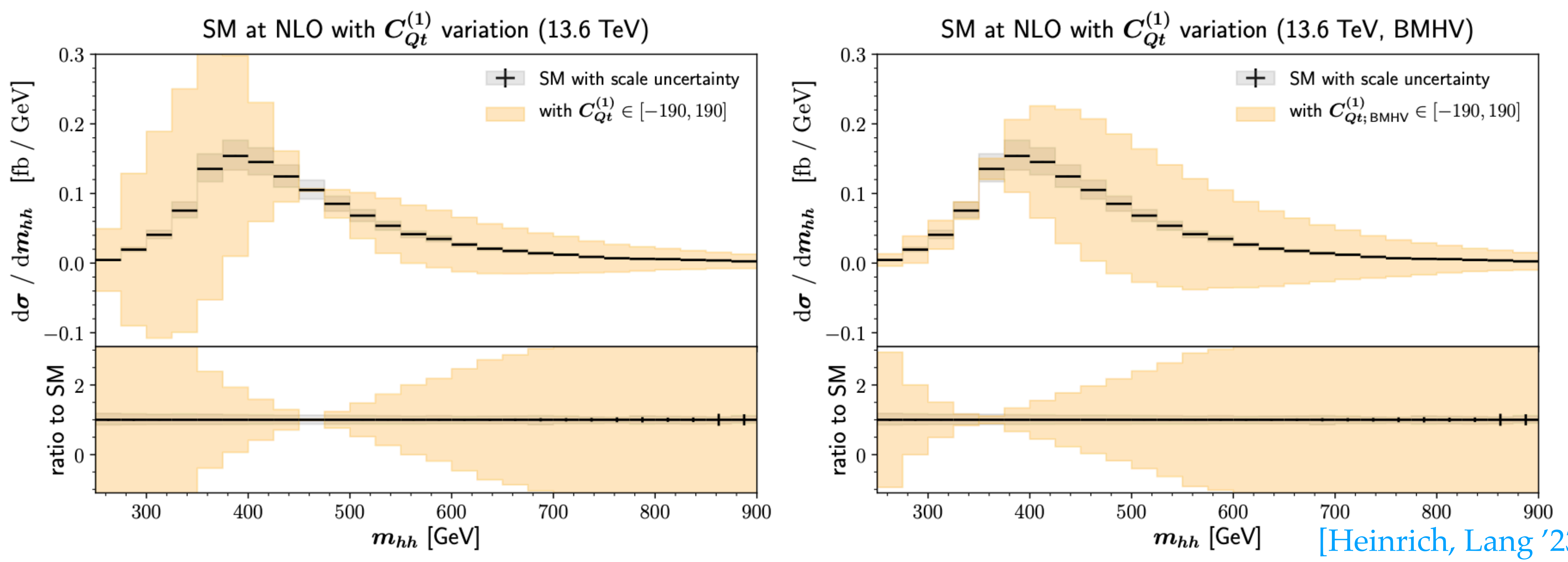
Uncertainty on EFT truncation

[Alasfar, Cadamuro, Dimitriati, Ferrari, RG et al. '23
see also:
Heinrich, Lang, Scyboz '22]

SMEFT in HH

SMEFT @ NLO QCD implemented into POWHEG [Heinrich, Lang, Scyboz '22]

Inclusion of chromomagnetic operator and four-fermion operators in weakly-interacting loop counting [Heinrich, Lang '23] [Buchalla, Heinrich, Müller-Salditt, Prandler '22]



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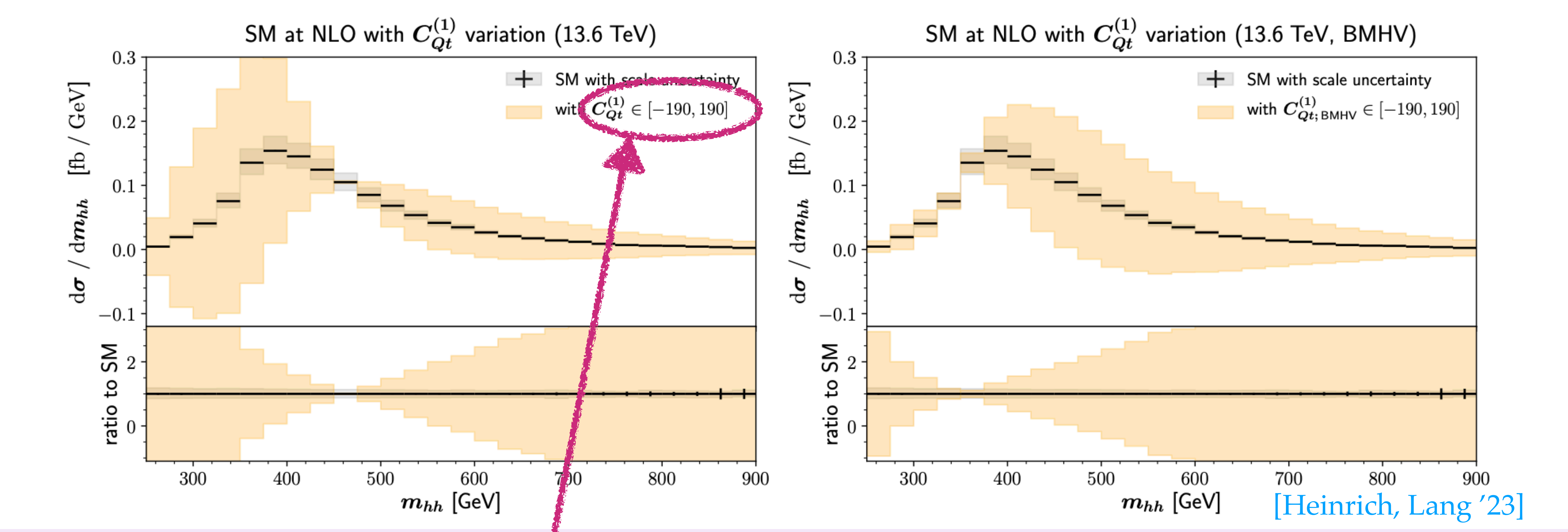

[Heinrich, Lang '23]

Updated fit [Di Noi, El Faham, RG, Vitti, Vryonidou '25] allows smaller range due to better 4top production limits and inclusion of EWPOs [Dawson, Giardino '19, '22; Haisch, Schnell '24; Biekötter, Pecjak '22]

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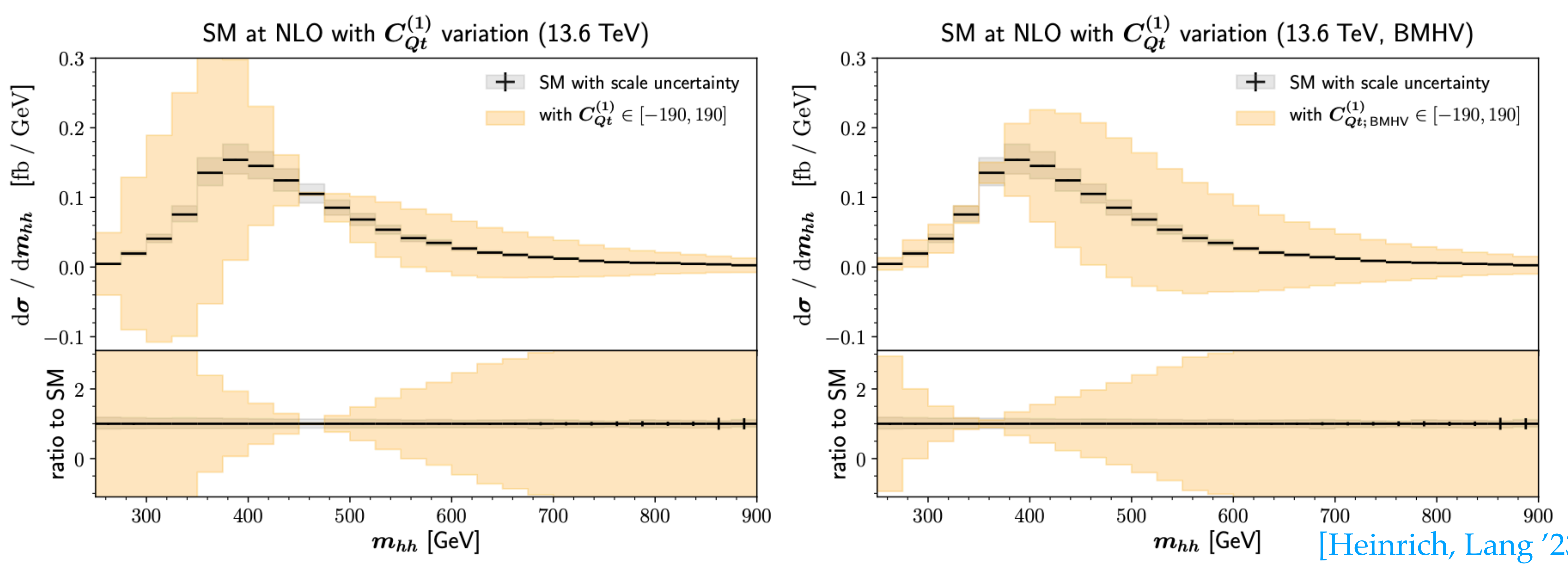


[Heinrich, Lang '23]

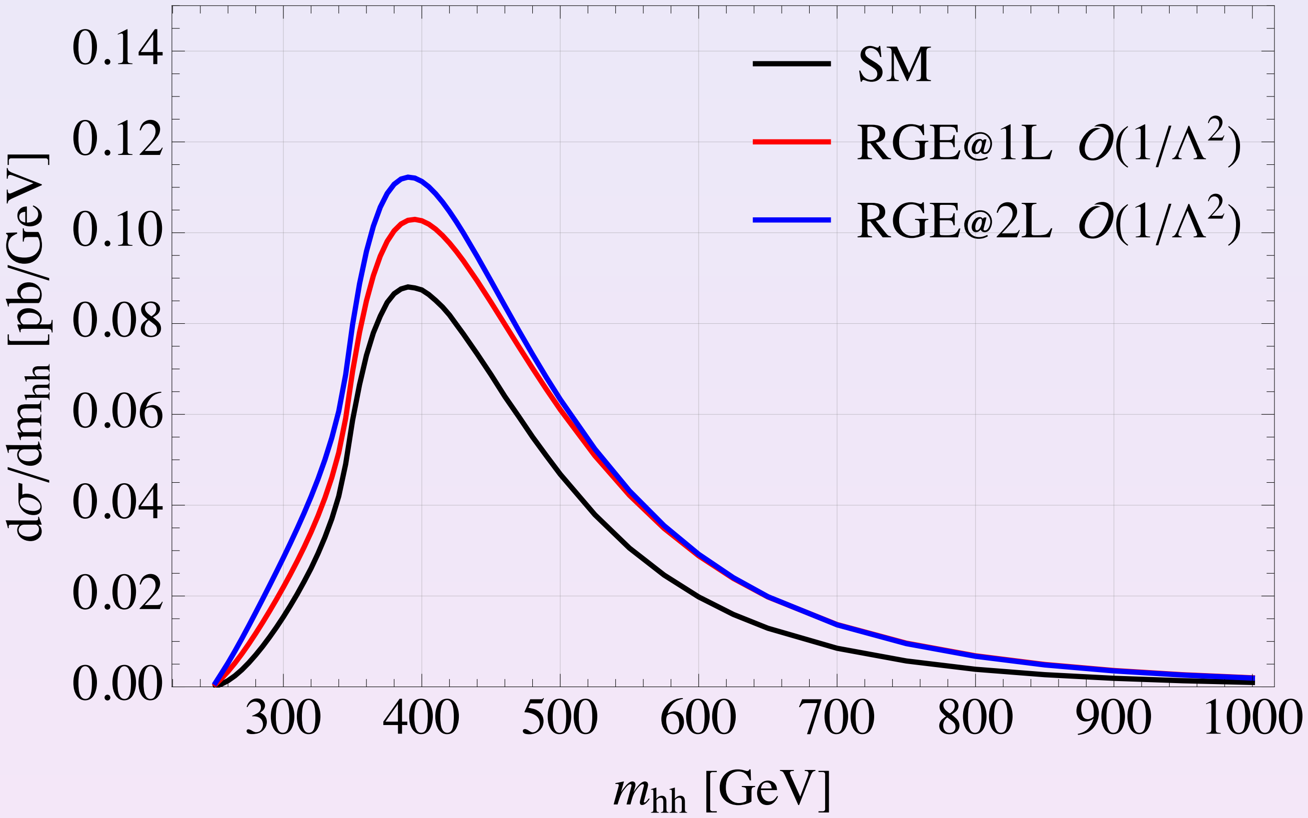
→ Sizeable effect on m_{hh} distribution
dependence on γ_5 continuation scheme can be translated in chiral SMEFT

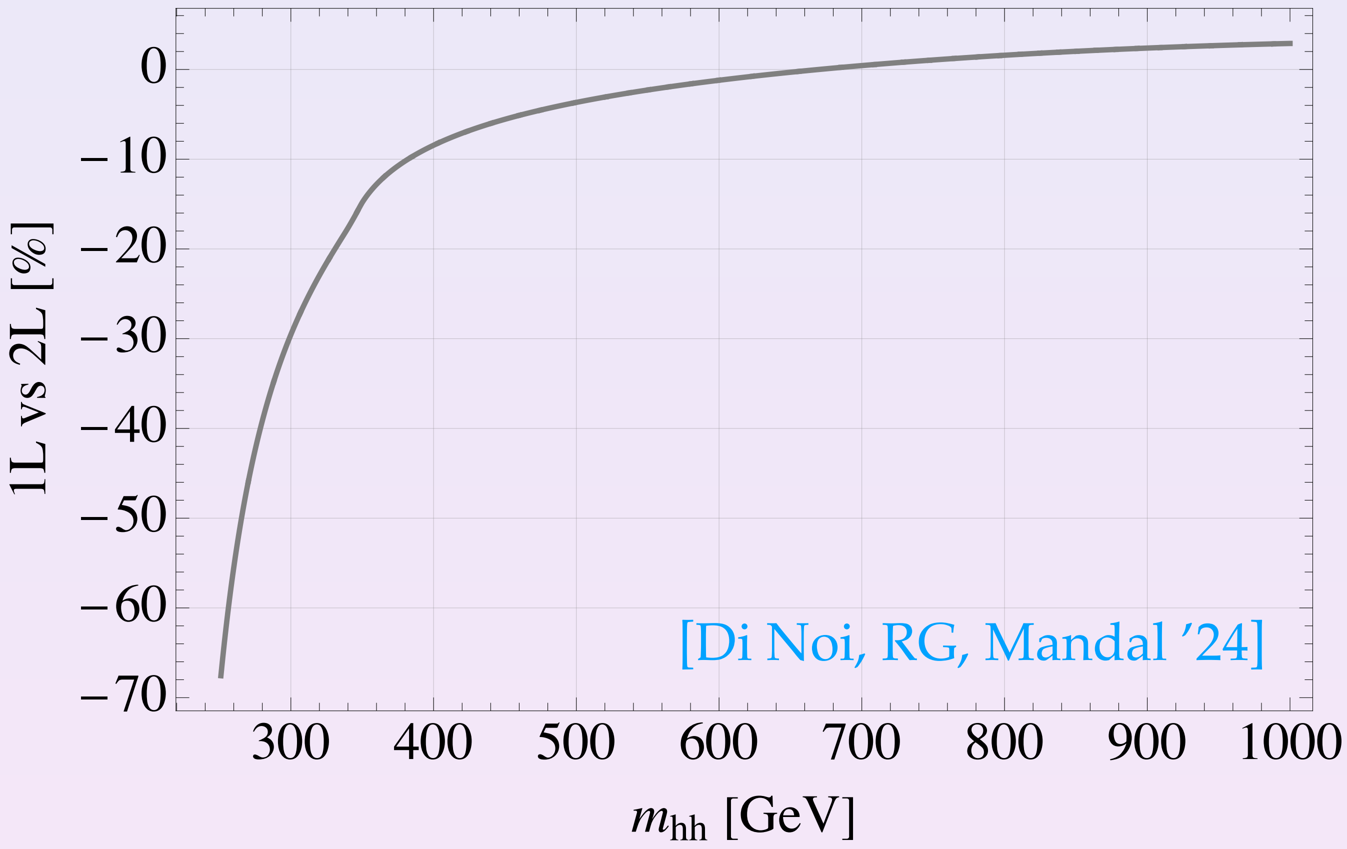
[See also: Di Noi, RG, Heinrich, Lang, Vitti '23]

[Di Noi, RG, Olgoso '25]

for processes with dynamical scale choice the running effects in the Wilson coefficients can sizeably affect the cross section [Maltoni, Ventura, Vryonidou '24; Heinrich, Lang '24]

Consistent loop counting: include the two-loop running effects in the Higgs-gluon coupling from potentially tree-level generated operators

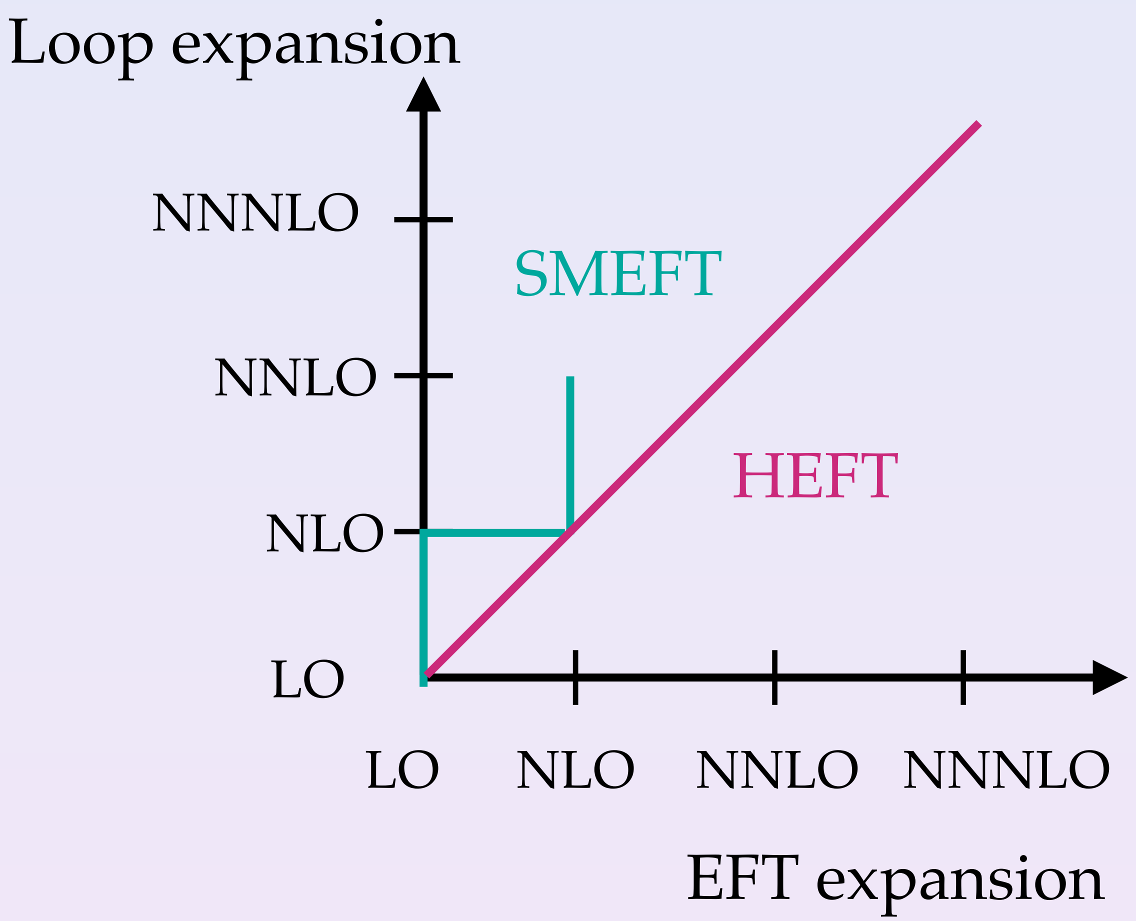




$$\text{S1}: \quad \mathcal{C}_{tH}(\Lambda) = 1,\ \mathcal{C}_{HG}(\Lambda) = \frac{1}{16\pi^2},\ \mathcal{C}_{tG}(\Lambda) = -\frac{1}{16\pi^2},\ \mathcal{C}_{Qt(1,8)}(\Lambda) = -10,\ \mathcal{C}_H(\Lambda) = 0.$$

Powercounting

[Brivio, RG, Schmid ’in preparation]



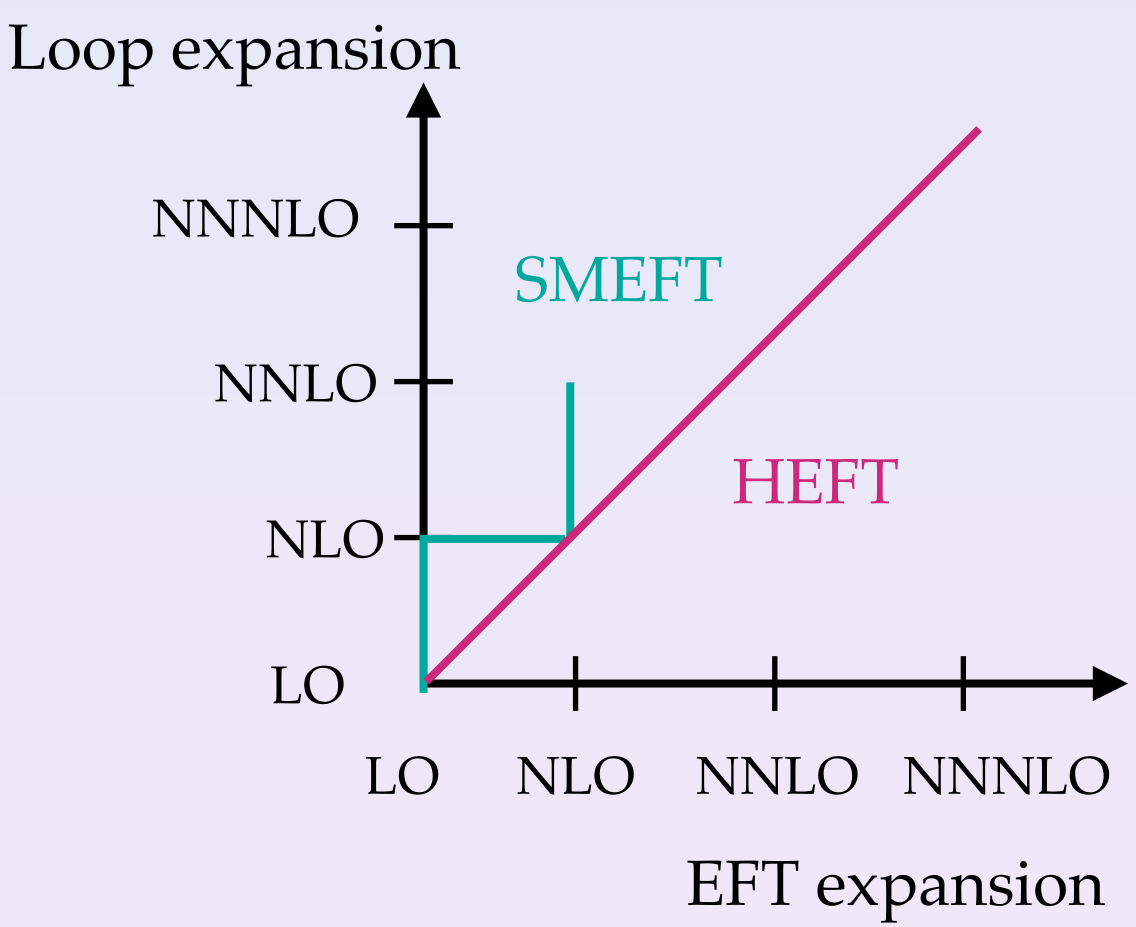
SMEFT power counting keeps EFT expansion independent of loop expansion

HEFT power counting counts loops, so one is constrained on the diagonal

HEFT in HH

Powercounting

[Brivio, RG, Schmid 'in preparation]



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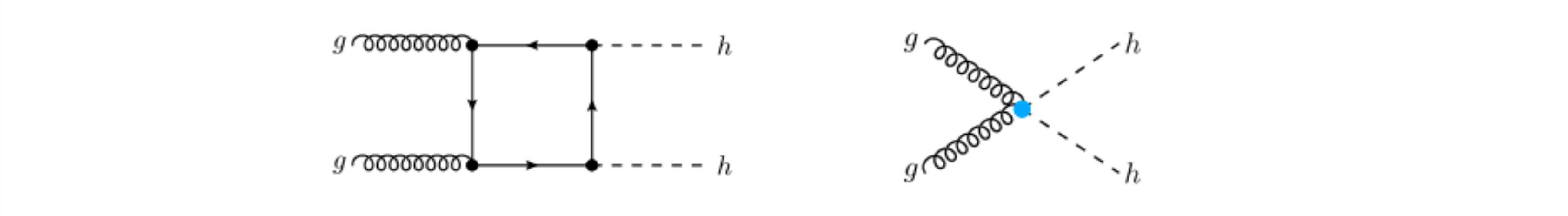


(a) $L = 1$, $N_\chi = 0$ insertions (b) $L = 0$, $N_\chi = 2$ insertion

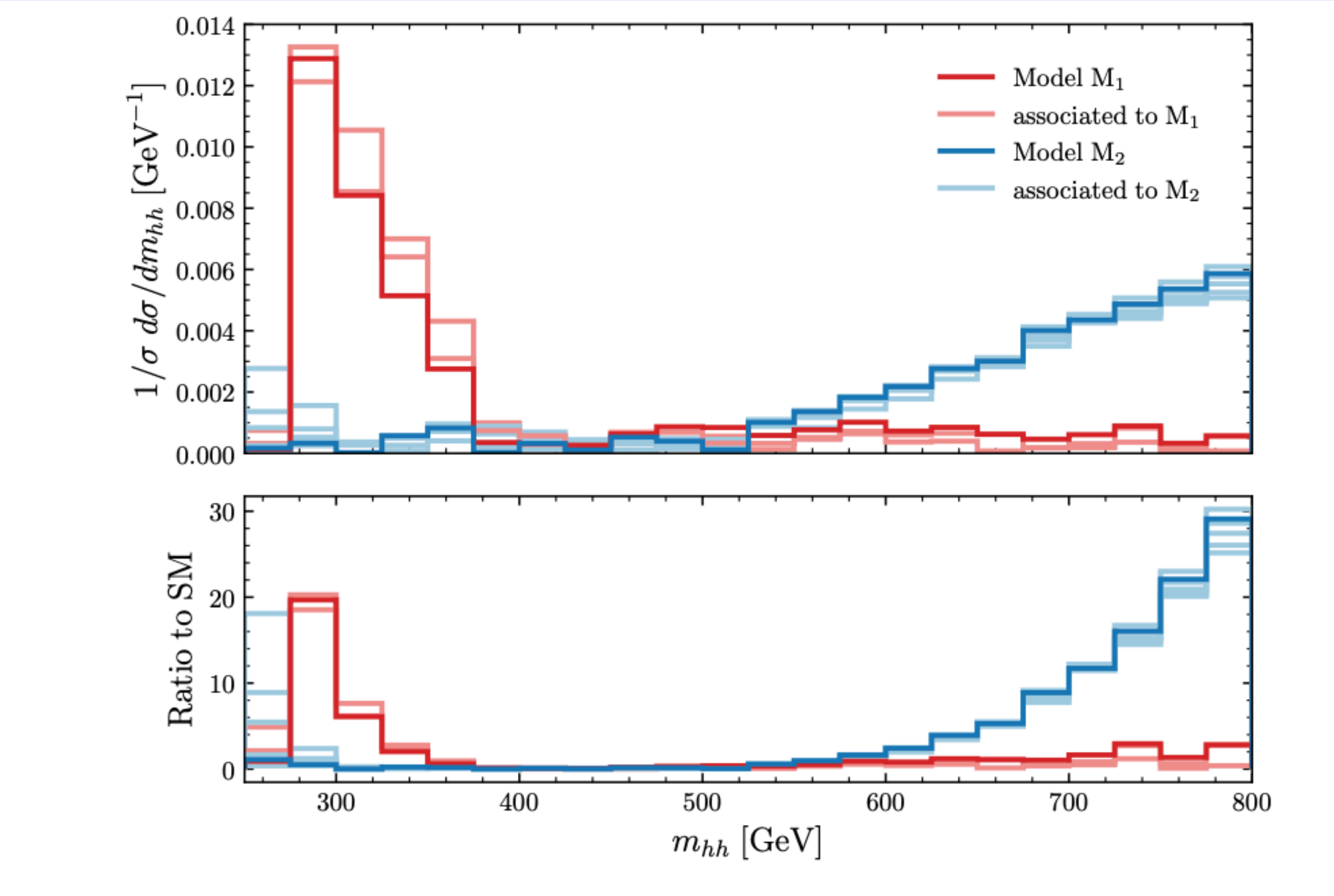
(c) $L = 1$, $N_\chi = 2$ insertion (d) $L = 0$, $N_\chi = 4$ insertion (e) $L = 0$, two $N_\chi = 2$ insertions

NLO and NNLO operators

[Brivio, RG, Schmid 'in preparation]

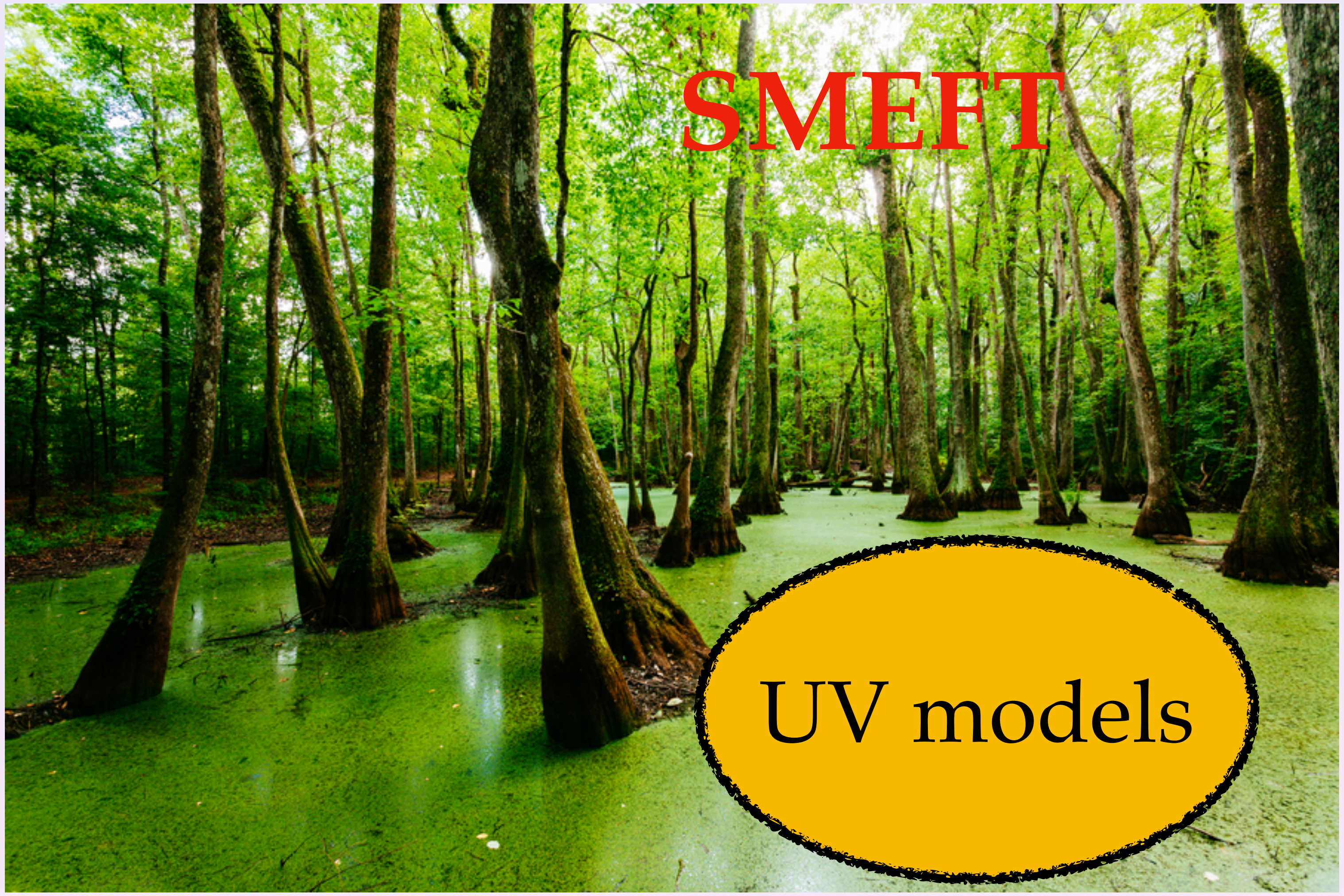
$$\delta\mathcal{L} = \frac{y_t b_D}{4\pi\Lambda}\frac{1}{v^2}(\partial_\mu h)^2\bar{t}t + \frac{g_s y_t}{4\pi\Lambda}\left(\bar{t}_L\sigma^{\mu\nu}G^a_{\mu\nu}T^a t_R + \text{h.c.}\right)\left(d_c + a_c\frac{h}{v} + b_c\frac{h^2}{v^2}\right)$$
$$+ \frac{g_s^2 b_g^{(1)}}{16\pi^2\Lambda^2}\frac{h^2}{v^2}(D^\mu G^{a\nu\lambda})(D_\mu G^a_{\nu\lambda}) + \frac{g_s^2 b_g^{(2)}}{16\pi^2\Lambda^2}\frac{h}{v}G^{a\lambda\nu}G^{a\mu}_{\lambda}\frac{1}{v}(\partial_\mu\partial_\nu h).$$

New kinematic benchmarks with respect to the ones of [Carvalho et al. '16; Capozi, Heinrich '19]



BSM vs. SMEFT

A word of caution



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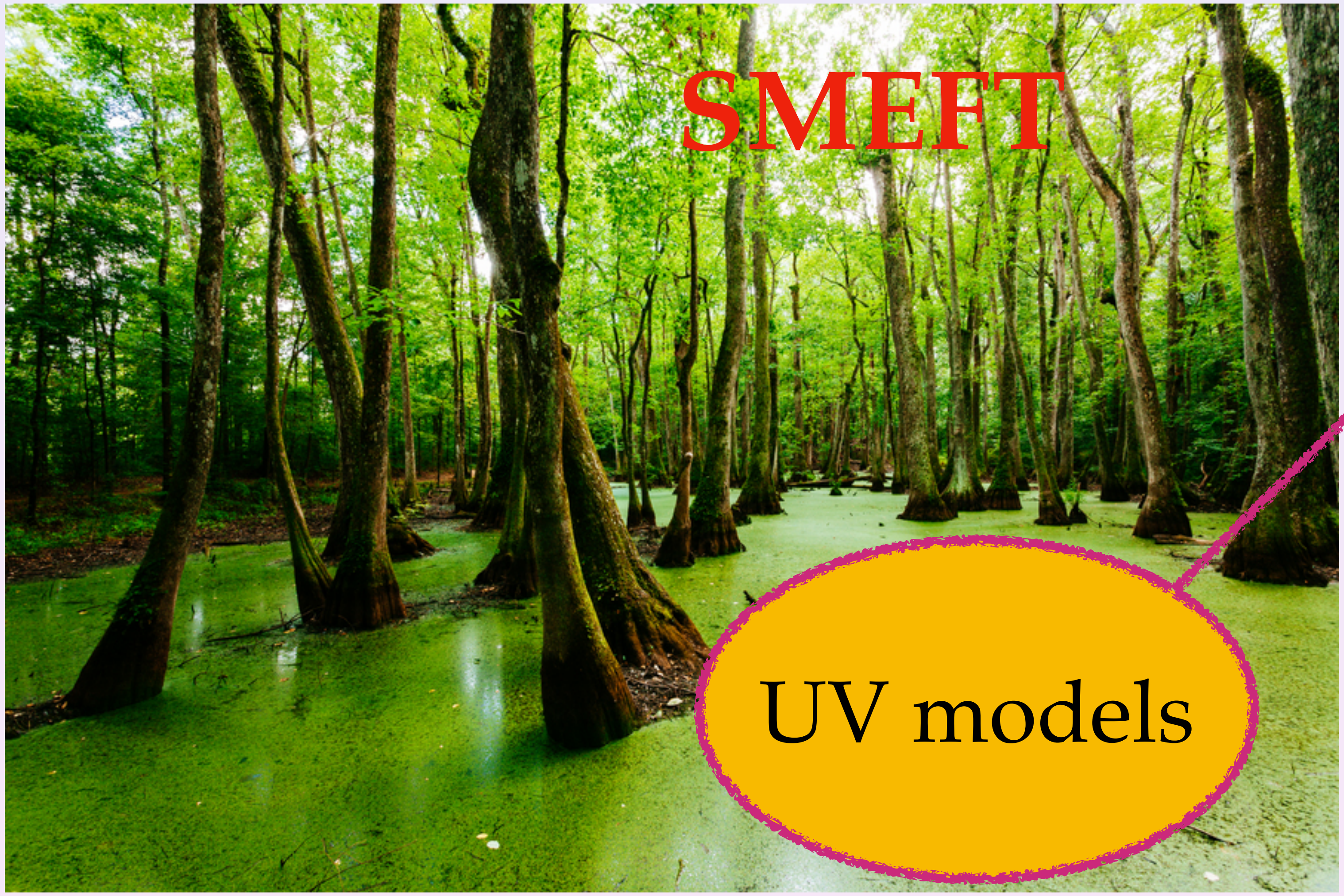


To be kept in mind when thinking about future strategies

Light fermion Higgs couplings

Charm quark:
can be tagged

$pp \to V(h \to c\bar{c})$: ATLAS: $|\kappa_c| < 4.2 @ 95\,\%$ CL [arXiv: 2410.19611]

CMS: $|\kappa_c| < 5.5 @ 95\,\%$ CL [arXiv: 2205.05550]

Further proposals for light quark Yukawa couplings:

$\kappa_f = g_{hff}/g_{hff}^{SM}$

- Higgs p_T spectrum [Bishara, Haisch, Monni, Re '16, Soreq, Zhu, Zupan '16]
- $W^{\pm}h$ charge asymmetry [Yu '16]
- Global fits to Higgs data [De Blas et al '19]
- Higgs pair production [Alasfar, Corral Lopez, RG '19, Alasfar, RG, Grojean, Paul, Qian '22]
- Higgs + photon [Aquilar-Saavedra, Cano, No '20]
- Tri-boson production [Falkowski et al '20]
- Higgs off-shell production [Balzani, RG, Vitti '23]

$|\kappa_c| < 1.2$
$|\kappa_s| < 13$
$|\kappa_d| < 156$
$|\kappa_u| < 260$
@ HL-LHC

Electron Yukawa coupling:

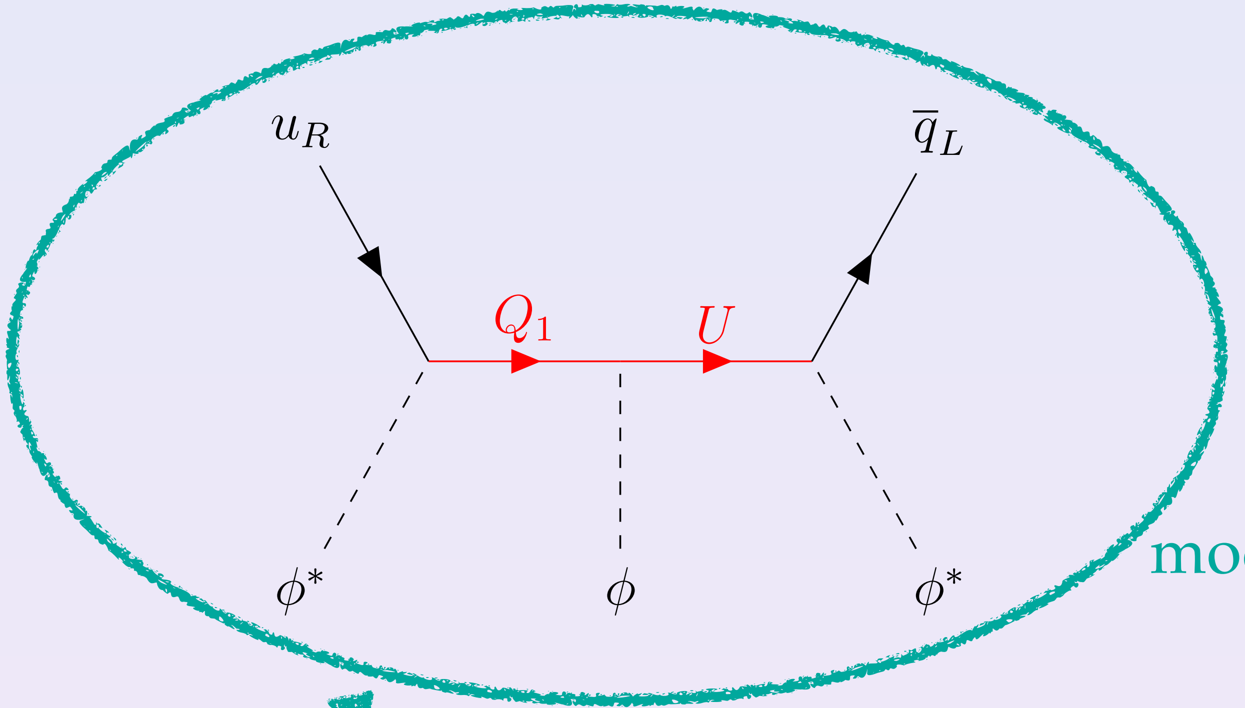
- Higgs decays to electrons ATLAS: $|\kappa_e| < 260$ [PLB 801 (2020) 135148]

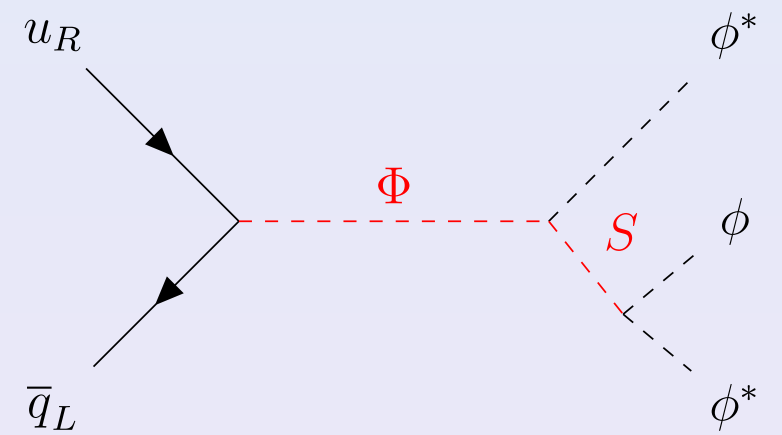
$|\kappa_e| < 120$
@ HL-LHC

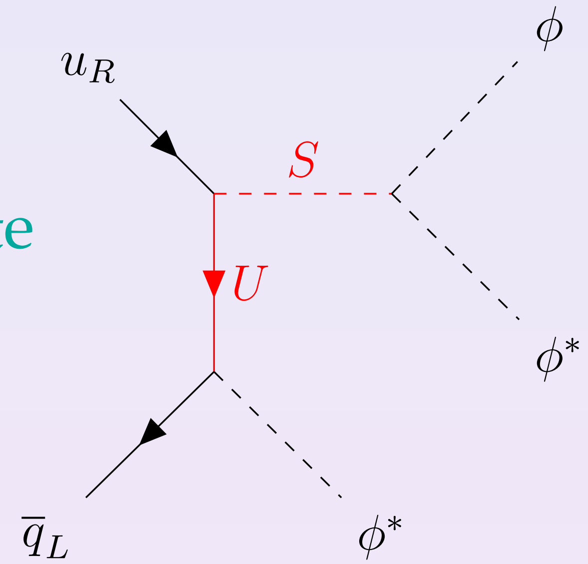
[Cepeda et al. '19]

UV models

[Bar-Shalom, Soni '18;
for charm: Nir, Udhayashankar '24]







models that generate
$\bar{q}_L \tilde{\phi} u_R \phi^\dagger \phi$

two VLQ representations
no s channel resonance
decaying to dijets

$$-\mathcal{L}_1^{\text{int}} = \lambda_U \overline{U}_R \tilde{\phi}^\dagger q_L + \lambda^u_{Q_1} \overline{Q}_{1L} \tilde{\phi}\, u_R + \lambda_{UQ_1} \overline{U} \tilde{\phi}^\dagger\, Q_1 + \text{h.c.}$$

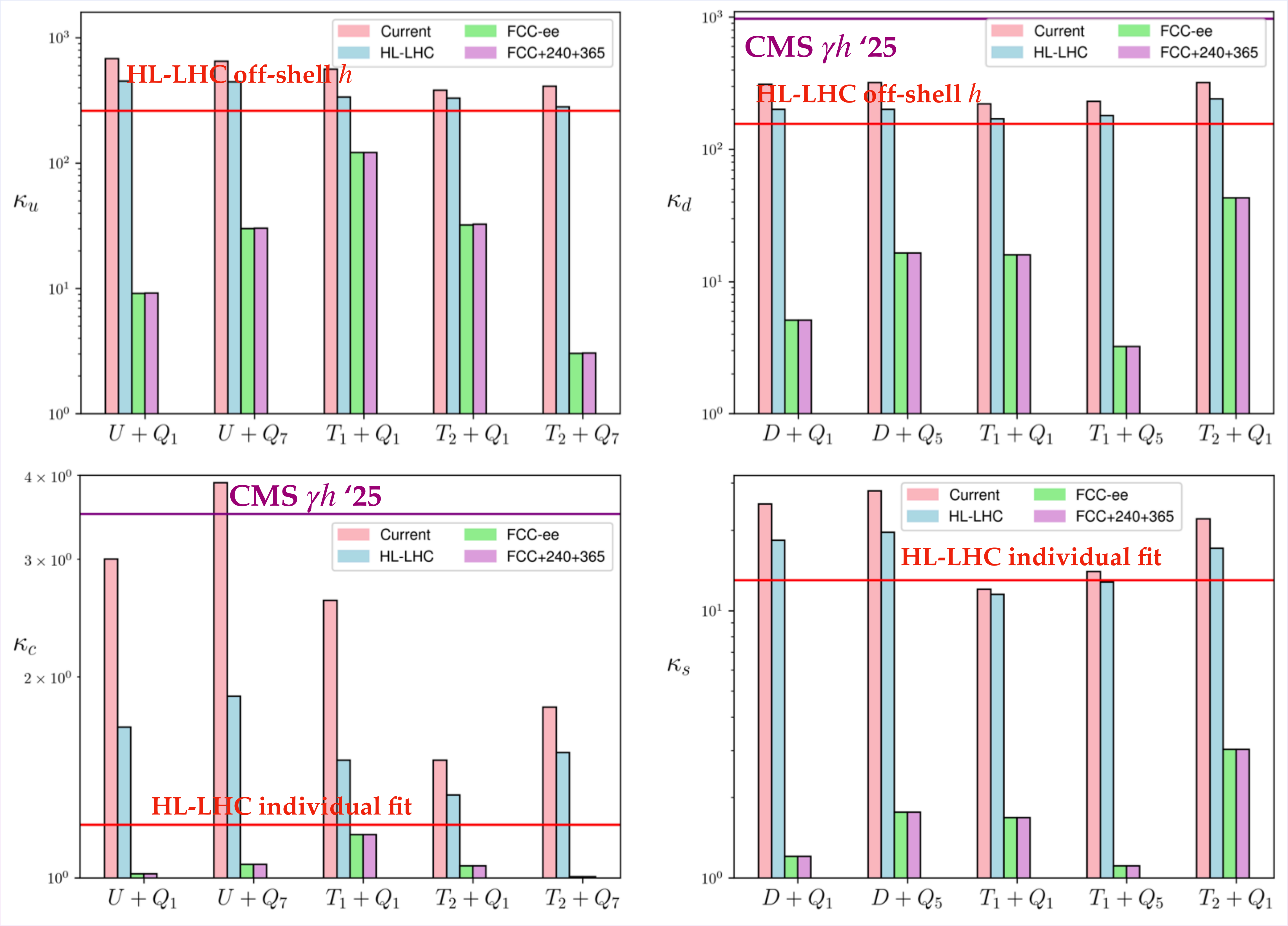
schematically
$$\frac{y_q}{y_q^{SM}} = \kappa_q = 1 + \frac{v^2 \lambda^u_{Q_1} \lambda_U \lambda_{UQ_1}}{M_Q M_U}$$

study case of two VLQs

for electron Yukawa see backup [Erdelyi, RG, Selimović '25]

for 2HDM see [Ginnakopoulou, Meade, Valli '24]

Light quark Yukawa couplings



[Erdelyi, RG, Selimović '24]

Conclusion

- Need for precision to understand Higgs sector better
- Theory uncertainties in SM shrinking due to many advances
- In SMEFT many subtleties and additional uncertainties: truncation uncertainties, RGE running, renormalisation/continuation schemes to be considered
- HEFT can bring changes in kinematic distributions so far not considered
- Case of enhancements in light fermion coupling also motivated by UV model point of view

Conclusion

- Need for precision to understand Higgs sector better
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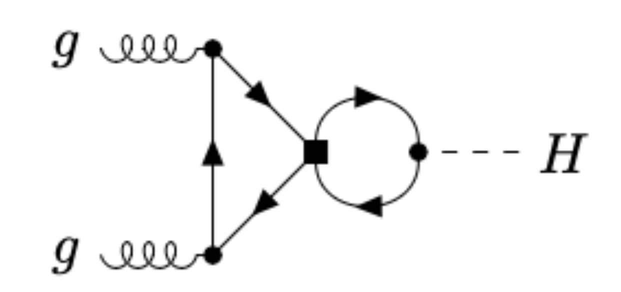
Thanks for you attention !

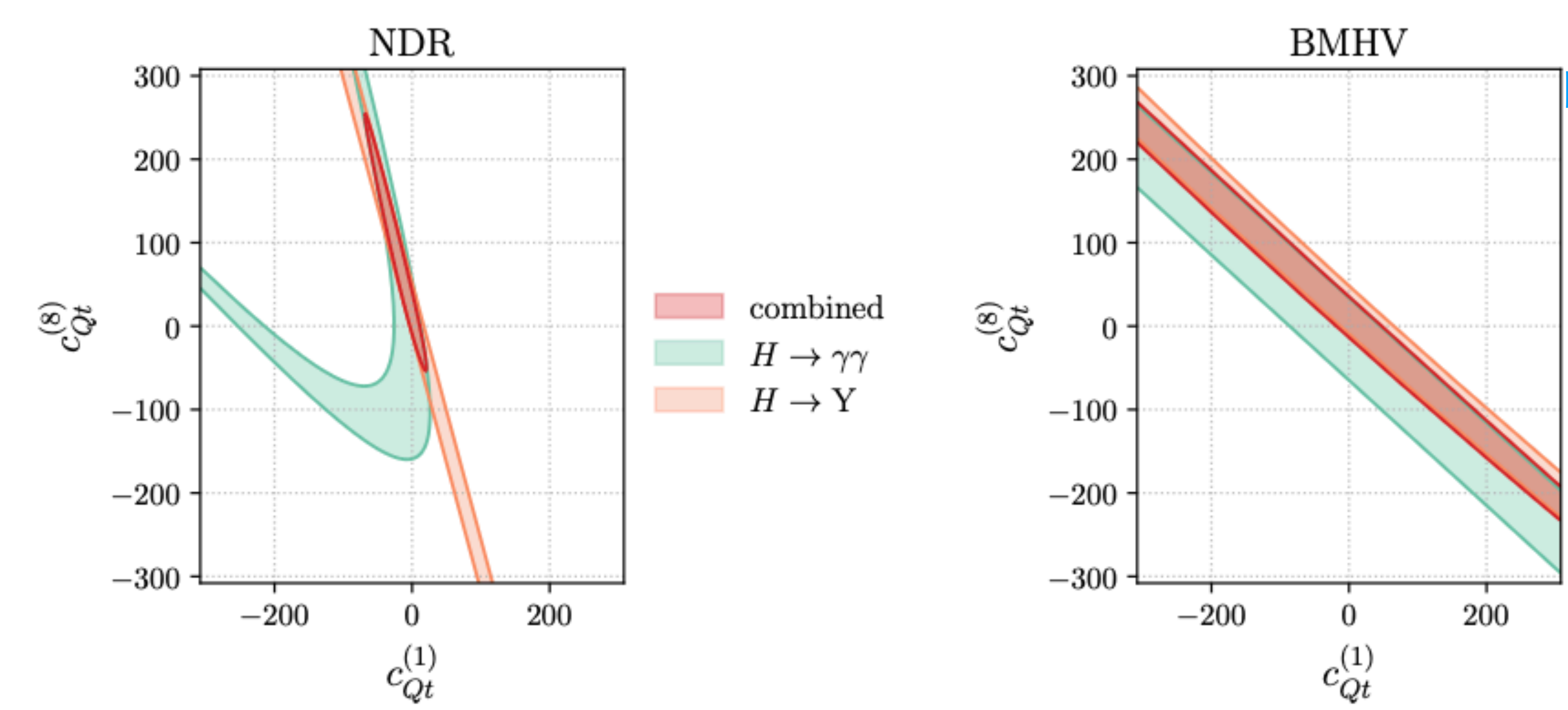
Continuation scheme dependence

γ_5 treatment in d dimensions can lead to different results in bottom up SMEFT approach

Example: 4top operators in Higgs production



$$\mathcal{O}_{Qt}^{(1)} = (\bar{Q}_L \gamma_\mu Q_L)(\bar{t}_R \gamma^\mu t_R) \qquad \mathcal{O}_{Qt}^{(8)} = (\bar{Q}_L \gamma_\mu T^A Q_L)(\bar{t}_R \gamma^\mu T^A t_R)$$

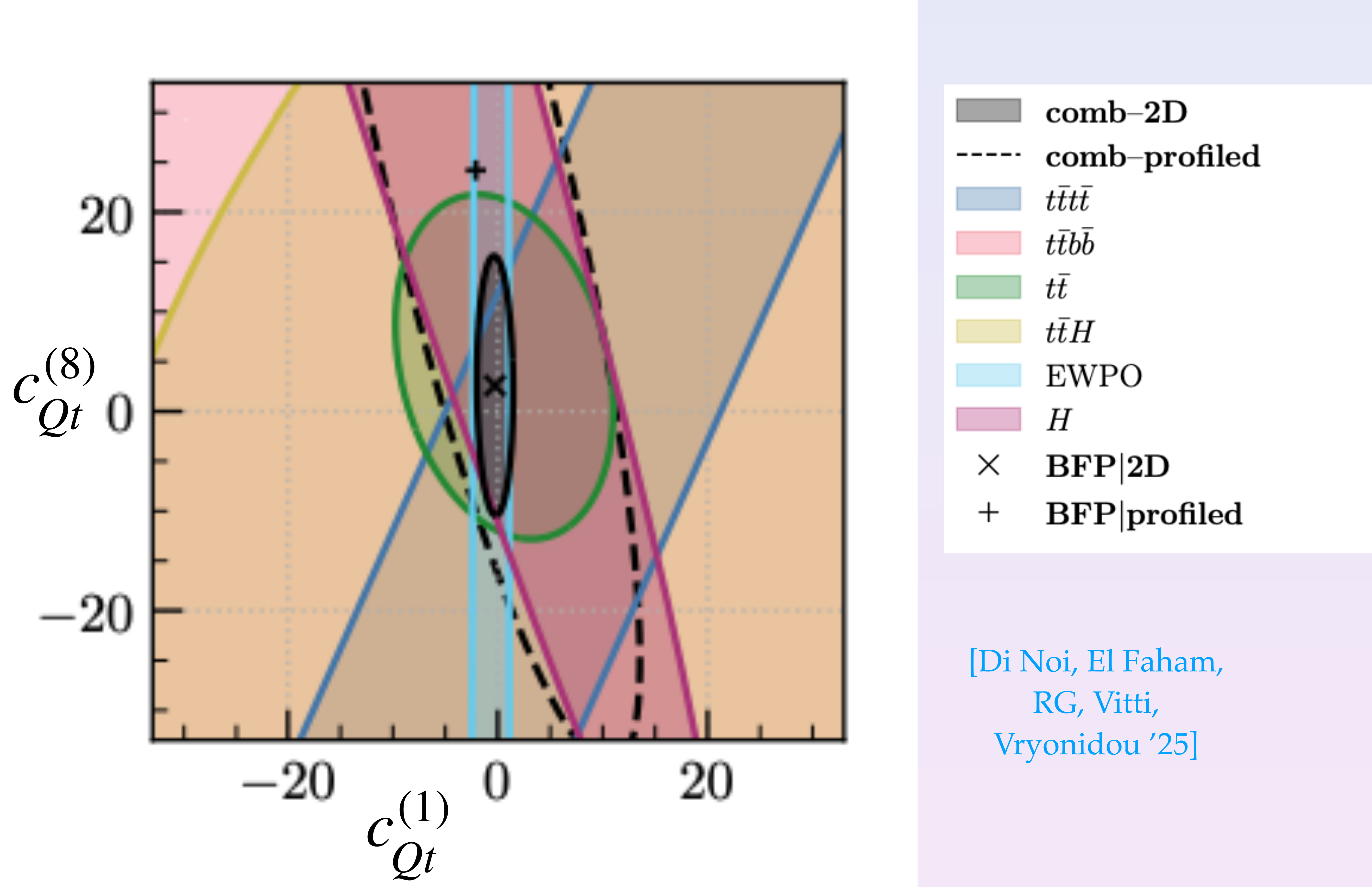


[Di Noi, El Faham, RG, Vitti, Vryonidou '25]

dependence can drop upon matching or can be attributed to different renormalisation schemes

[Di Noi, RG, Olgoso '25]
[Di Noi, RG, Heinrich, Lang, Vitti '23]

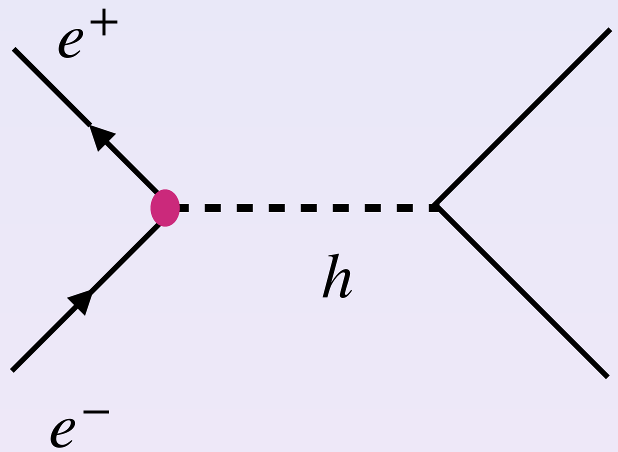
Bound on 4top operators



[Di Noi, El Faham, RG, Vitti, Vryonidou '25]

Electron Yukawa couplings

FCC-ee can directly measure the electron Yukawa coupling by dedicated run at Higgs pole mass



probes $\kappa_e < 1.6$

[d'Enterria, Poldaru, Wojcik '21]

requires monocromatised e^+e^- beam,
precise knowledge of Higgs boson mass,
extended timeline

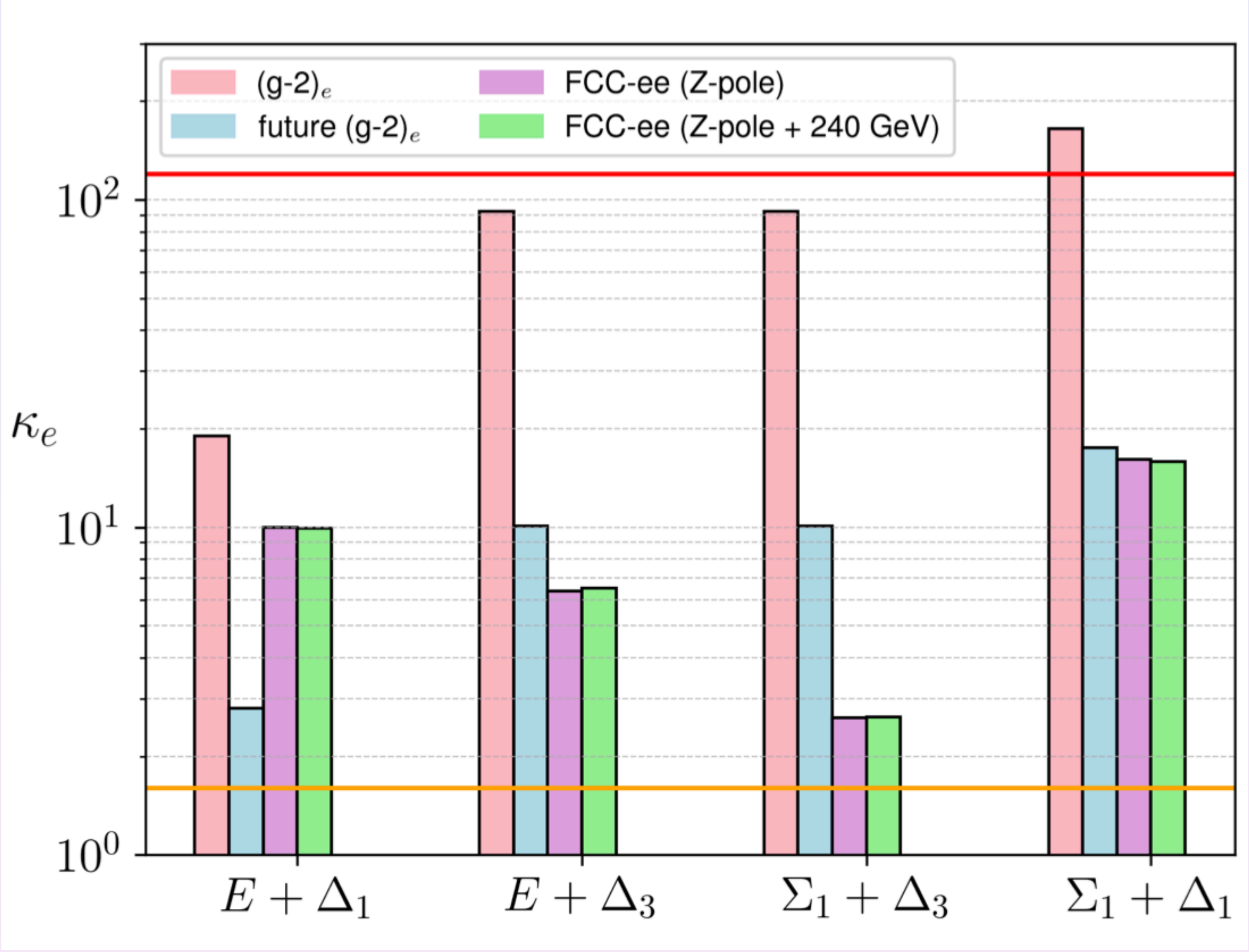
And which models are probed?

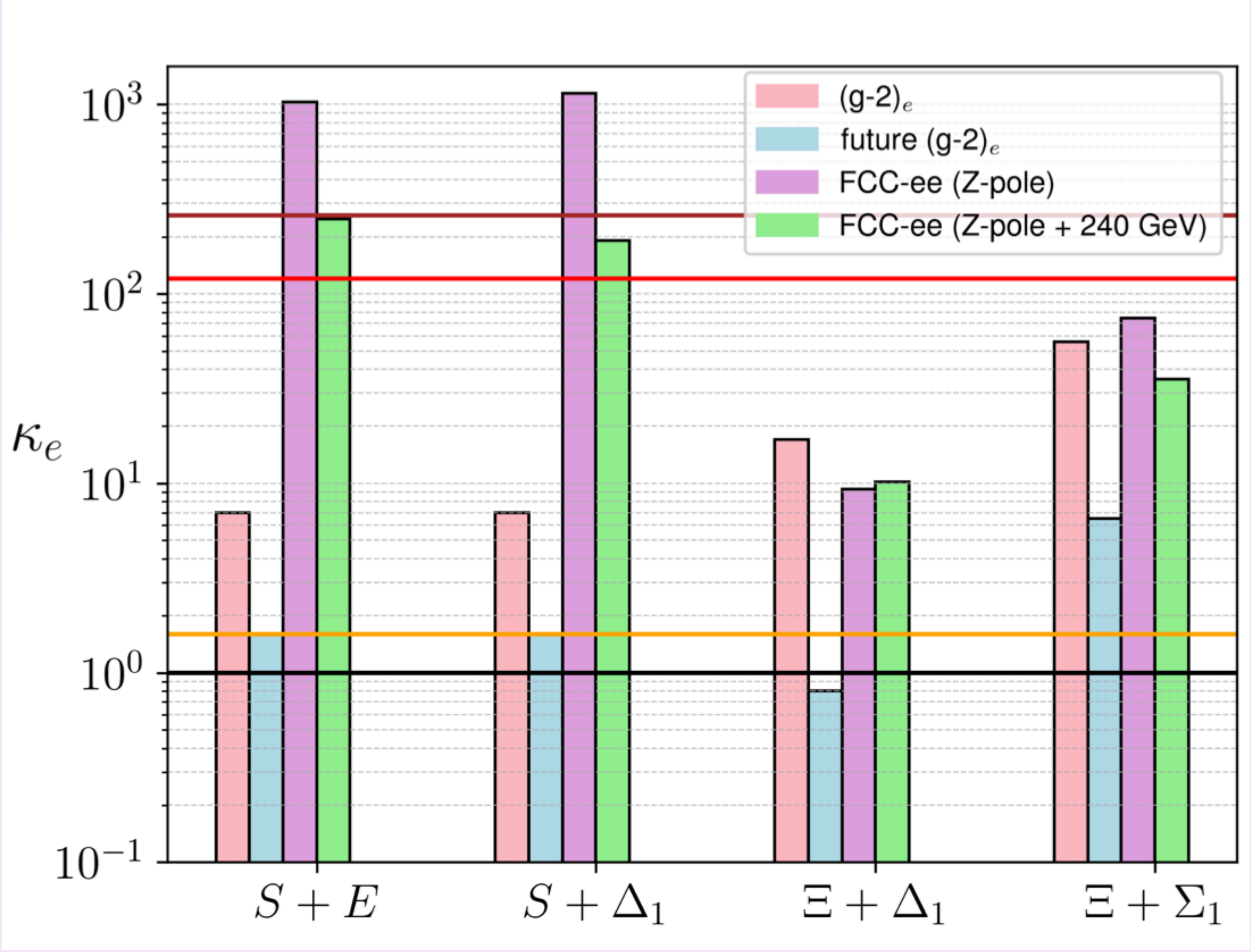
Electron Yukawa couplings

Two Vector-like Lepton representations

Vector-like Lepton + Scalar

[Erdelyi, RG, Selimović '25]





$E=(1,1)_{-1}$ $\Delta_3=(1,2)_{-3/2}$ $\Sigma_1=(1,3)_{-1}$ $S=(1,1)_0$ $\Xi=(1,3)_0$

$\Delta_1=(1,2)_{-1/2}$

a dedicated run for the electron Yukawa coupling at the FCC-ee can probe existing models