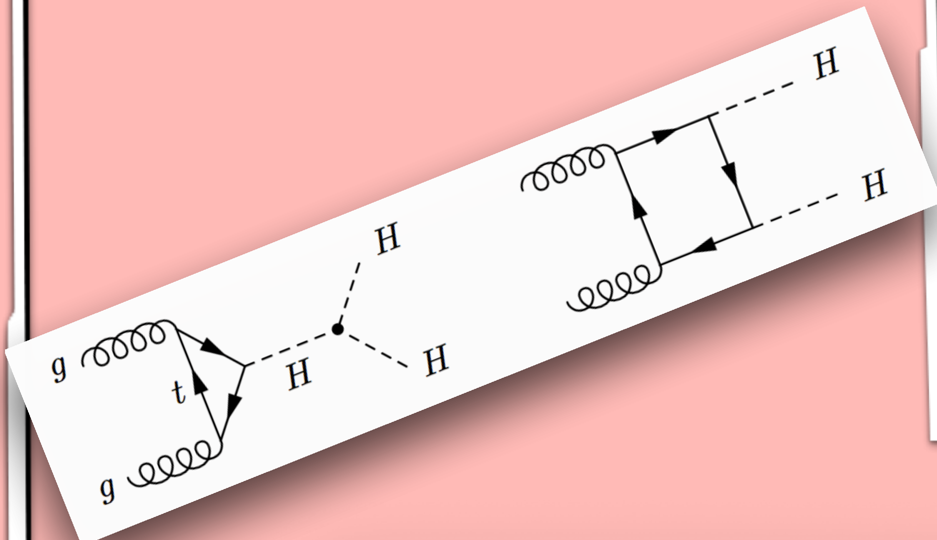
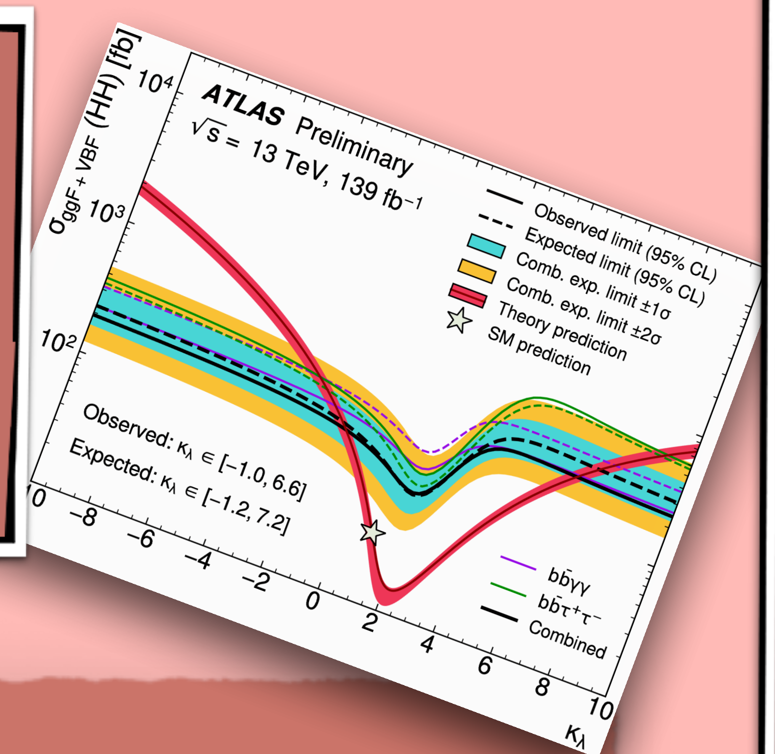
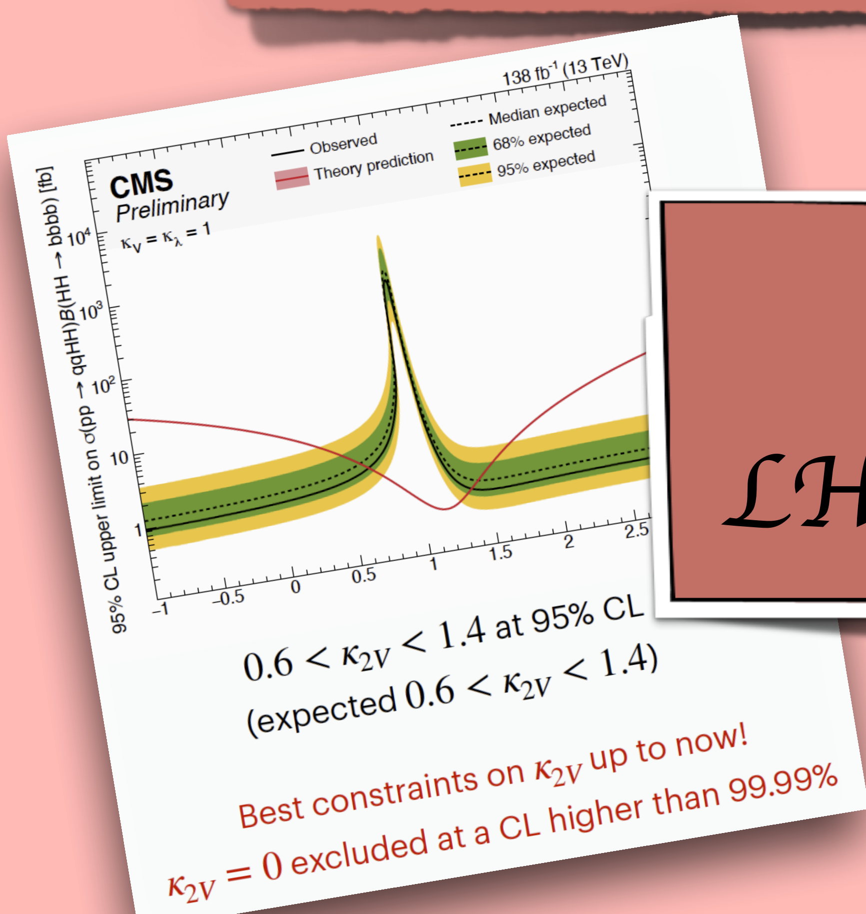
HH Subgroup Summary



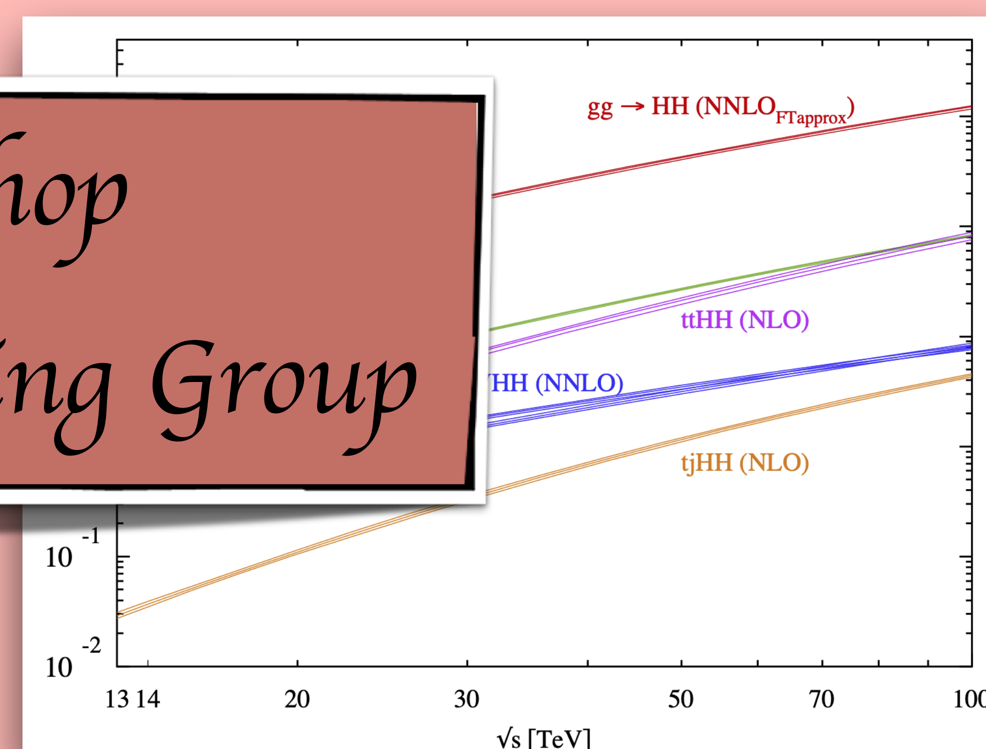


Conveners:

E. Brost, L. Cadamuro, R. Gröber, N. Lu, J. Mazzitelli, M. Mühlleitner



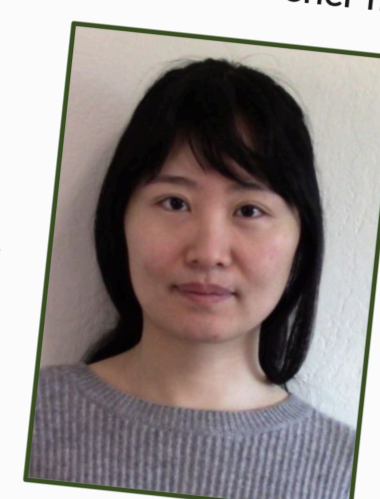
18th Workshop LHC Higgs Working Group



Ongoing work in the HH cross group

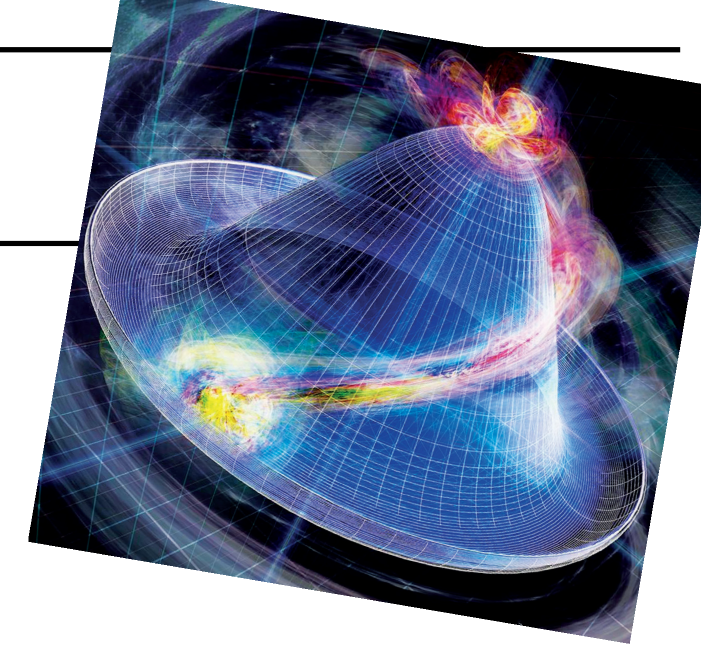
task	status
ggF: top-quark mass renormalization scheme uncertainty	Phys. Rev. D 103, 056002 (2021)
ggF: NLO EFT frameworks and new shape benchmarks, HEFT vs SMEFT	In progress
ggF: combination of H and HH (in connection with WG2 activities)	In progress
ggF: cross section / MC for gg -> H + bb	To be started
ggF/VBF: cross section and MC prediction for various m_H values	To be started
VBF: fiducial cross-sections vs. coupling modifiers	Started
VBF: cross-sections for ggF HH+2j at hard matrix-element	Ongoing. MC studies @ LHC-HH
Resonant: benchmarks for spin-0 HH, SH and SS to be probed with 100-300/fb, including interference with non-resonant HH	Paper in preparation (report today!)
Compositeness models: covered by EFT?	To be started

Nan Lu will take over from Luca Cadamuro as LHC-HH convener from CMS



Welcome, Nan, and thank you Luca for all your work!

Understanding Electroweak Symmetry Breaking



$$V(H) = M_H^2/2\ H^2 + 1/3!\ \lambda_{3H} + 1/4!\ \lambda_{4H}$$

λ_{4H} → triple Higgs production out of reach?

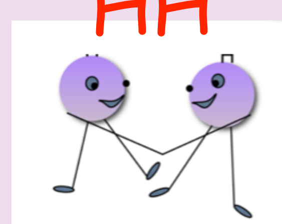
λ_{3H} → Higgs pair production challenging!

LHCHXSWG

√s	7 TeV	8 TeV	13 TeV	14 TeV	27 TeV	100 TeV
$\sigma_{\text{NNLO FTapprox}}$ [fb]	6.572	9.441	31.05	36.69	139.9	1224

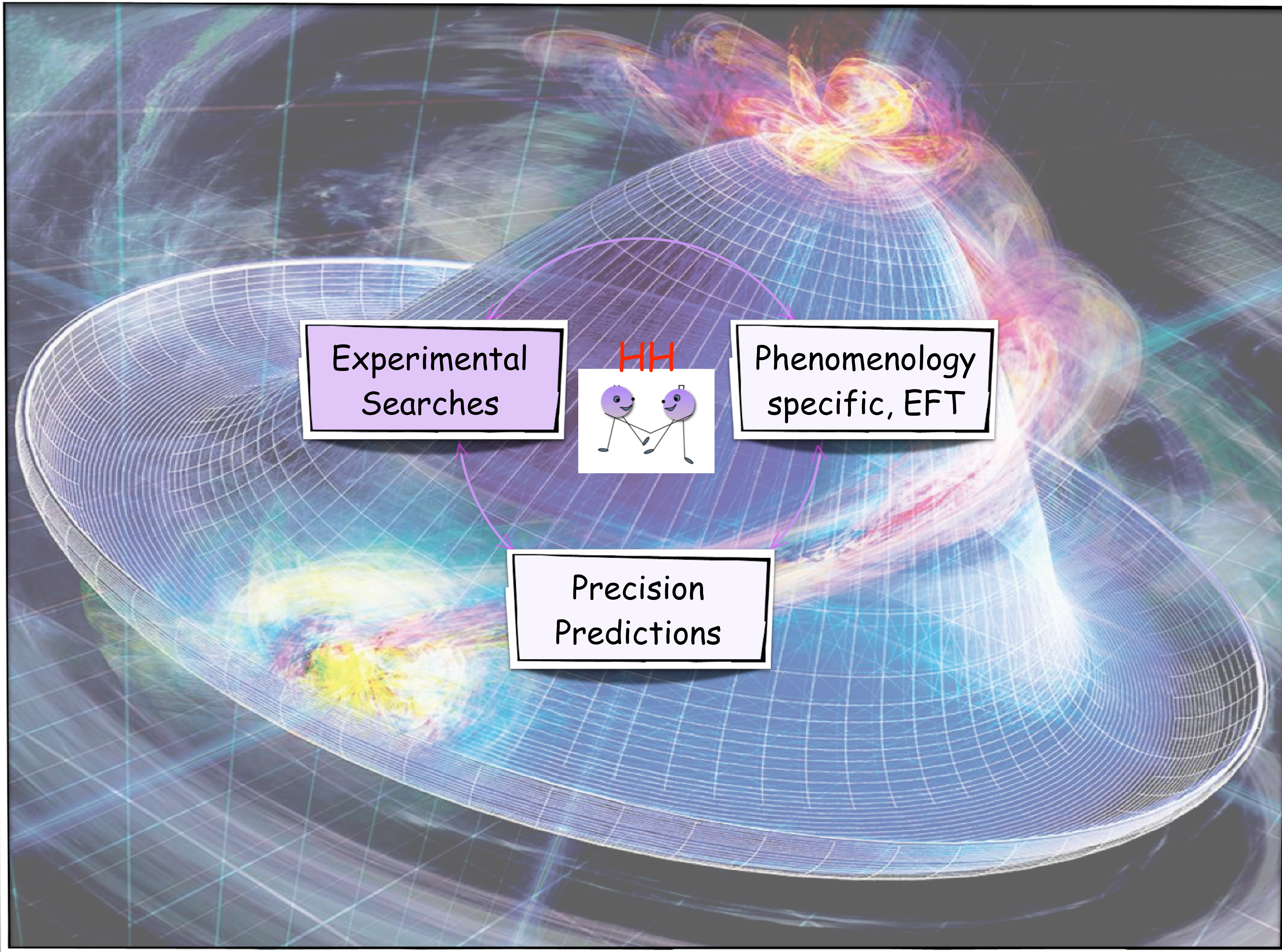
Experimental Searches

HH



Precision Predictions

Phenomenology specific, EFT

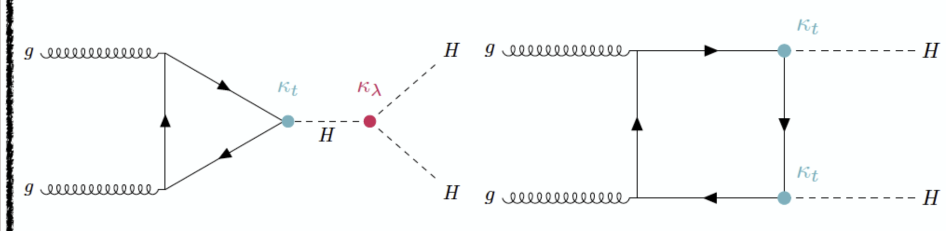

HH
Experimental Searches
Phenomenology specific, EFT
Precision Predictions

Overview of recent di-Higgs ATLAS and CMS results

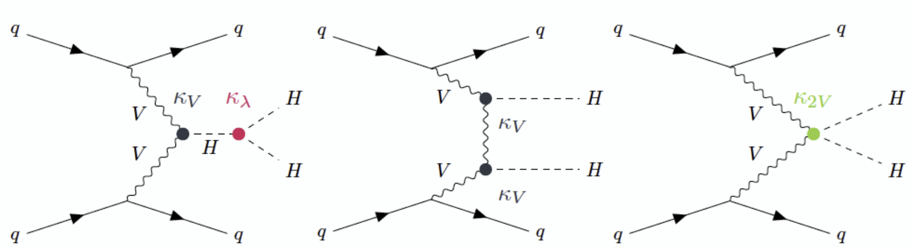
Alessandra Betti on behalf of ATLAS and CMS

Non-resonant HH production

gluon-gluon Fusion (ggF): $\sigma^{SM}_{ggF} = 31.05$ fb

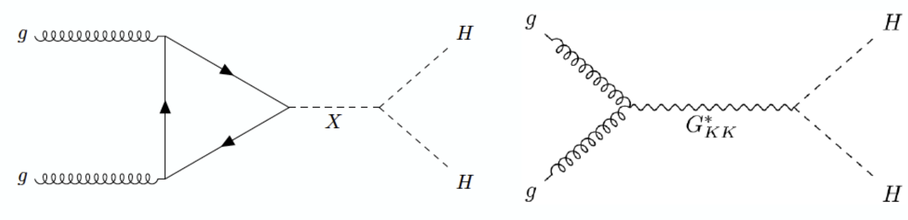


vector-boson-fusion (VBF): $\sigma^{SM}_{VBF} = 1.73$ fb

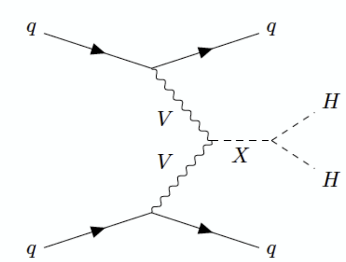


Resonant HH production

Spin-0 and spin-2 resonances ggF X->HH



Spin-0 resonances VBF X->HH



Non-resonant searches with full Run 2 data

ATLAS:

VBF HH->4b (resolved)
HH->bbll (resolved)
HH->bbττ (resolved)
HH->bbγγ (resolved)

CMS:

HH->4b (resolved)
VBF HH-> 4b (boosted)
HH->bbZZ(4l) (resolved)
HH->bbγγ (resolved)

Resonant searches with full Run 2 data

ATLAS:

VBF HH->4b (resolved)
HH->4b (resolved and boosted)
HH->bbττ (resolved)
HH->bbττ (boosted)
HH->bbγγ (resolved)

CMS:

HH->4b (boosted)
HH->bb1l/2l (boosted)

results from full run 2 dataset

searches performed in many different final states

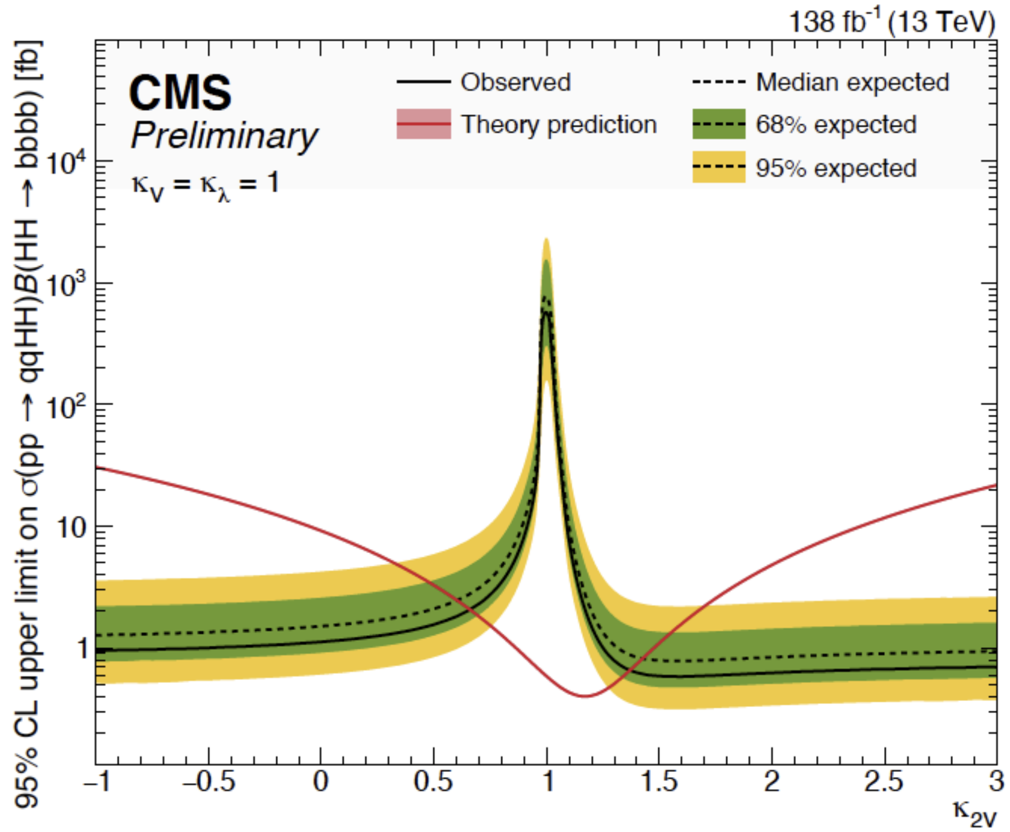
at least one Higgs decay into bb because of large branching ratio

Overview of recent di-Higgs ATLAS and CMS results

Alessandra Betti on behalf of ATLAS and CMS

Highlights

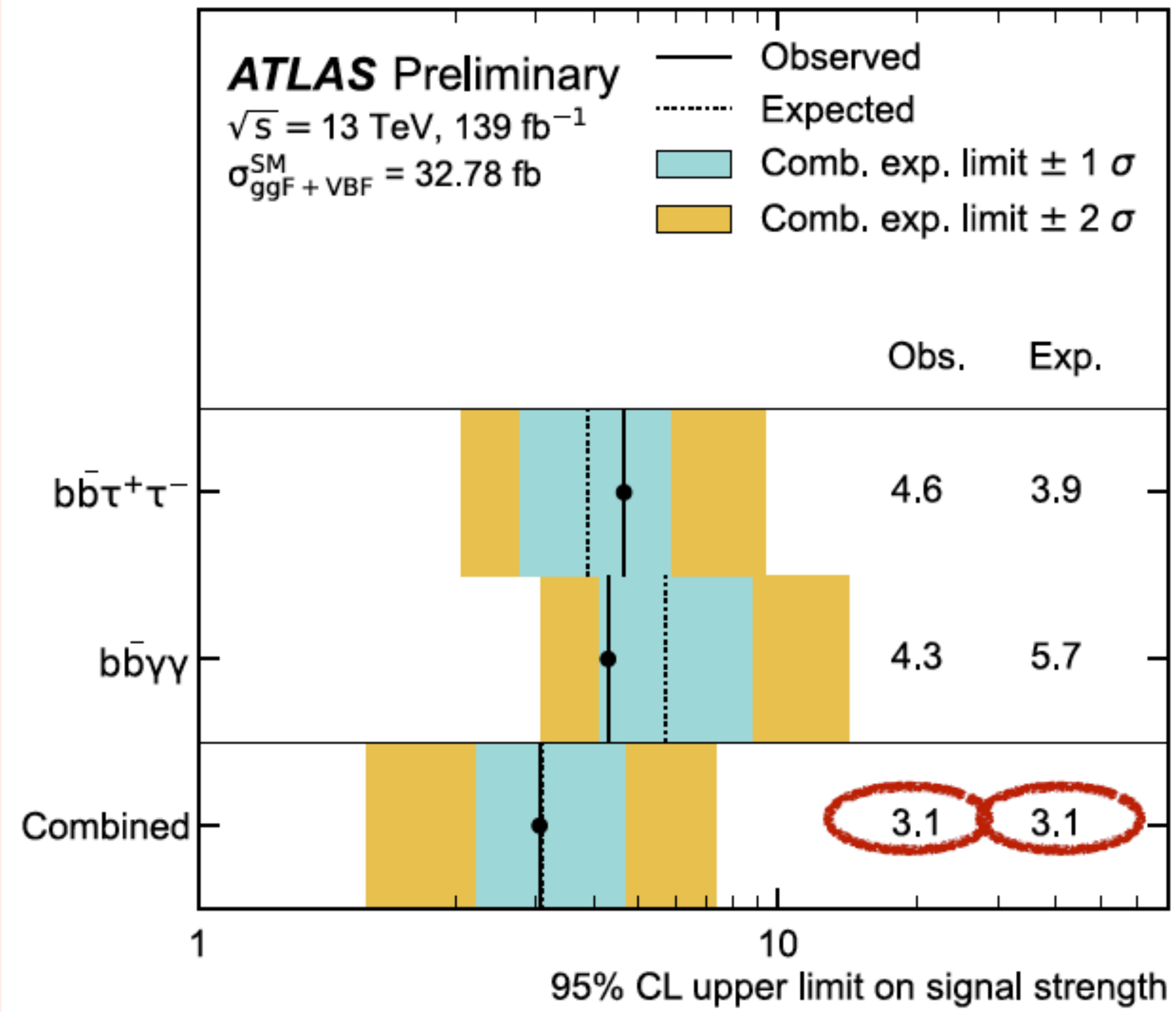
CMS non-resonant VBF HH->4b boosted
CMS-PAS B2G-21-001



$0.6 < \kappa_{2V} < 1.4$ at 95% CL
(expected $0.6 < \kappa_{2V} < 1.4$)

Best constraints on κ_{2V} up to now!
$\kappa_{2V} = 0$ excluded at a CL higher than 99.99%

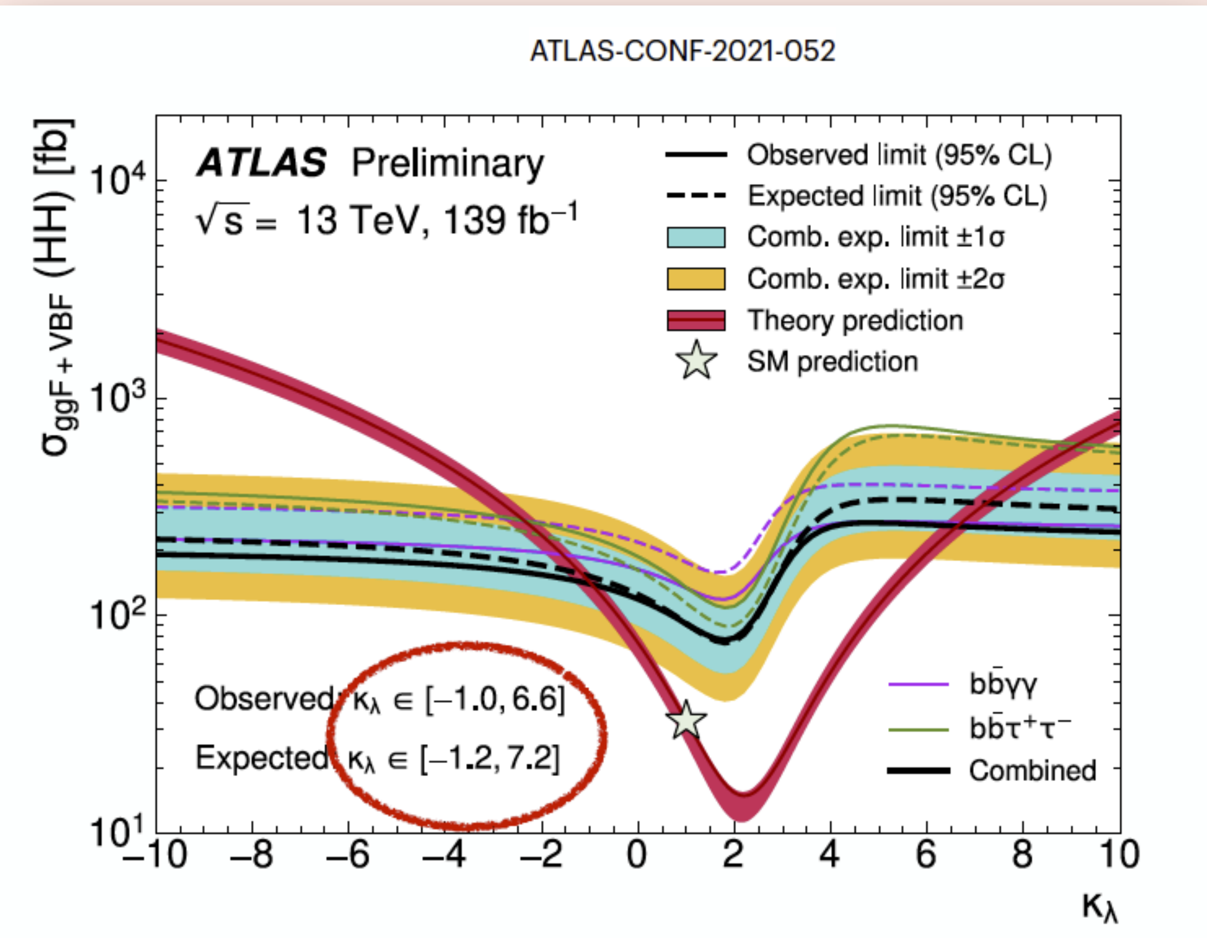
ATLAS-CONF-2021-052
non-resonant HH production

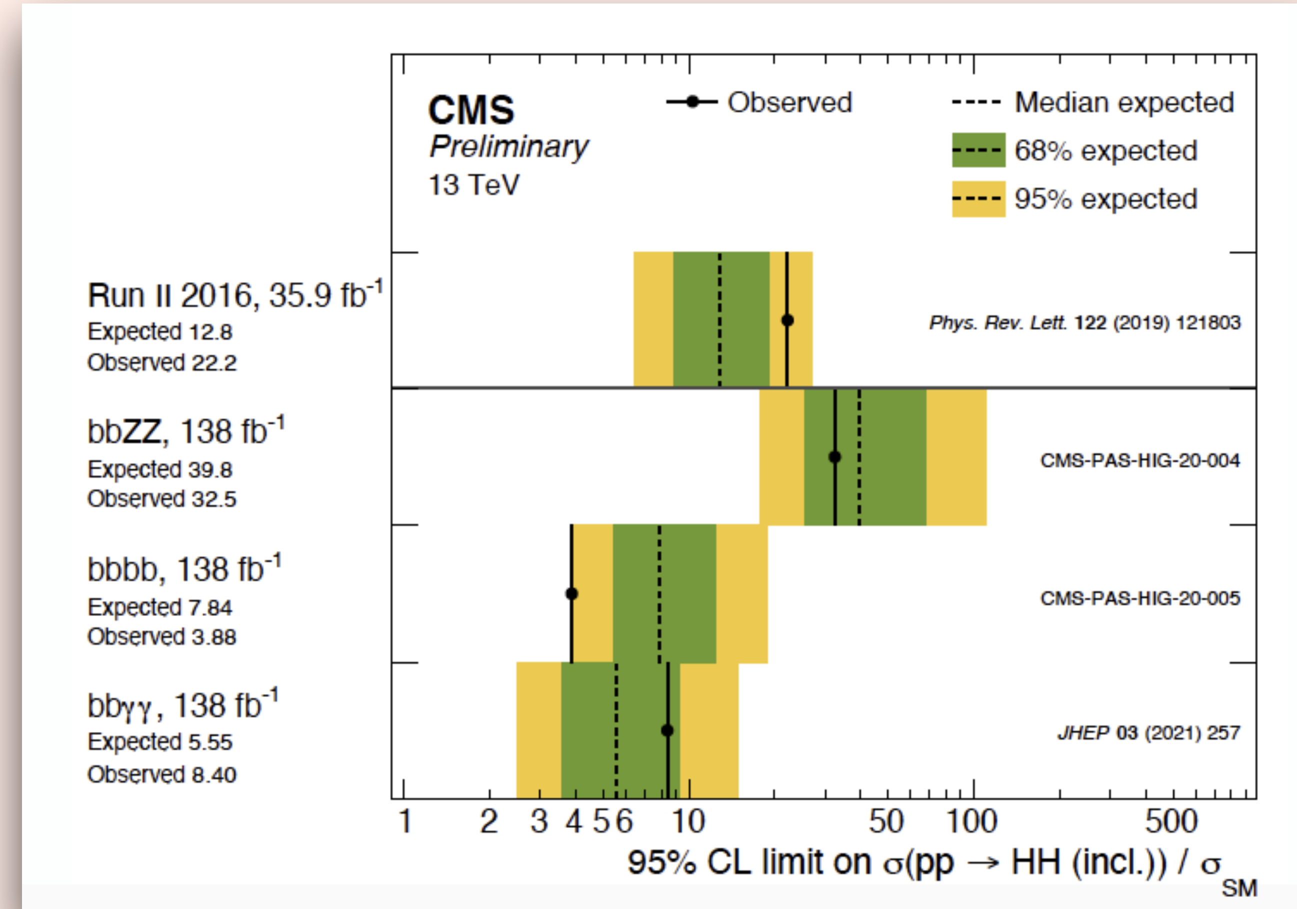


Best upper limit on non-resonant HH production
and κ_λ (next slide) up to now

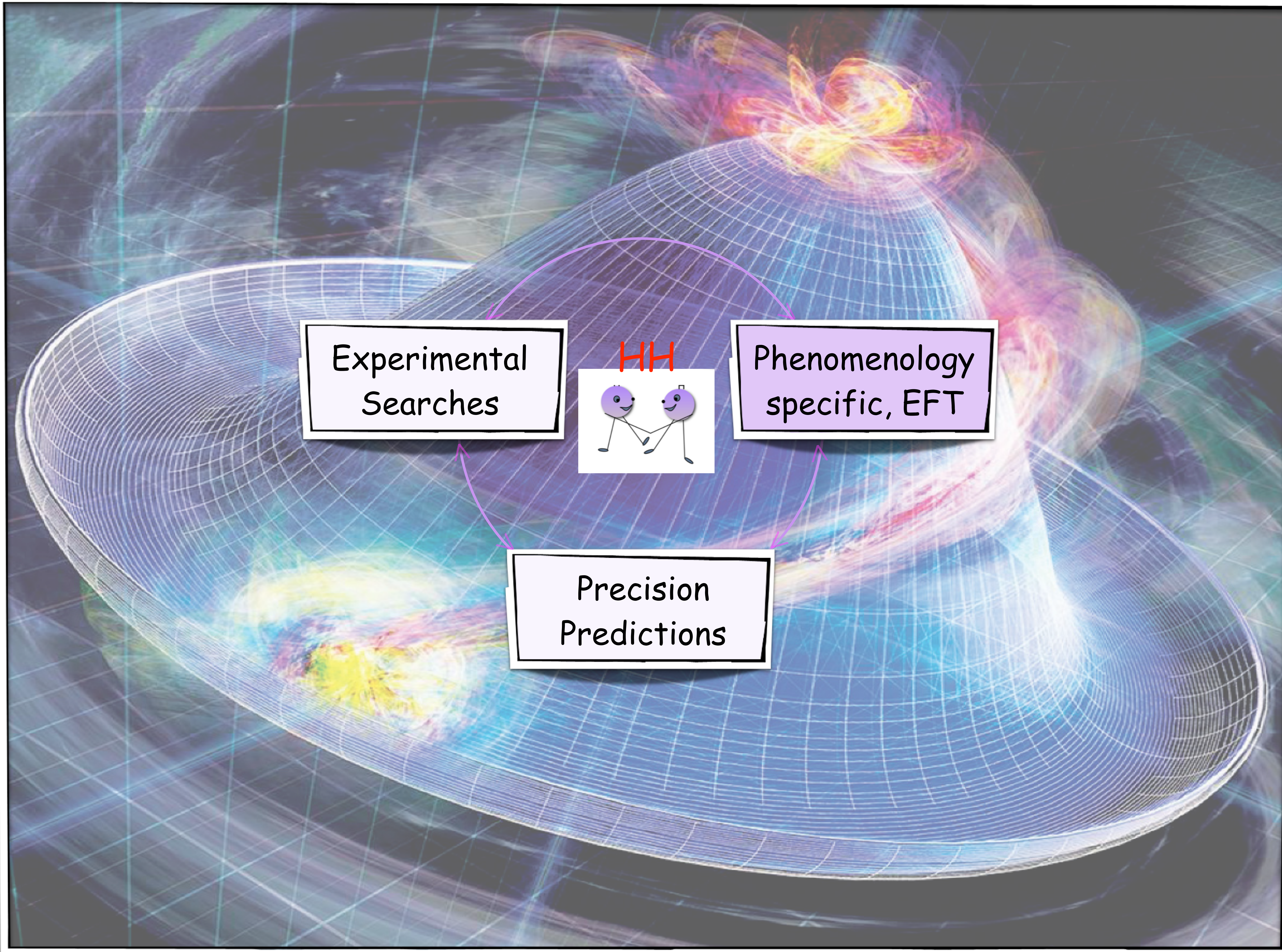
Overview of recent di-Higgs ATLAS and CMS results

Alessandra Betti on behalf of ATLAS and CMS



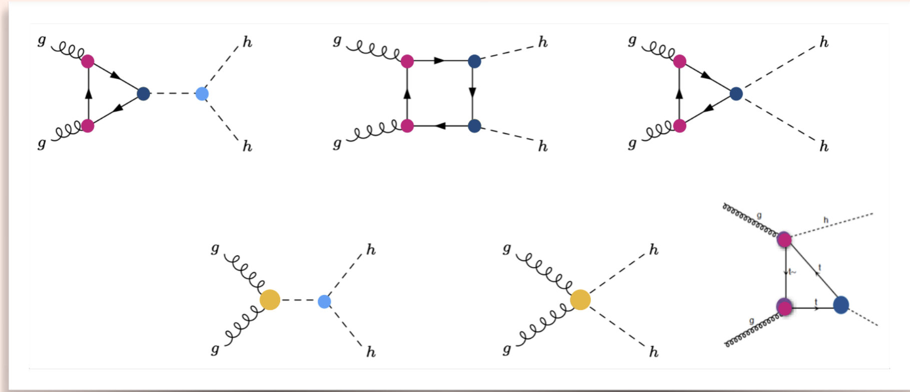


- results significantly improved compared to partial run 2 results
- beyond luminosity increase: improved objects reconstruction and analysis techniques
- constraints on κ_λ and κ_{2V}
- more analyses ongoing, covering more decay channels and more interpretations


Experimental Searches
HH
Phenomenology specific, EFT
Precision Predictions

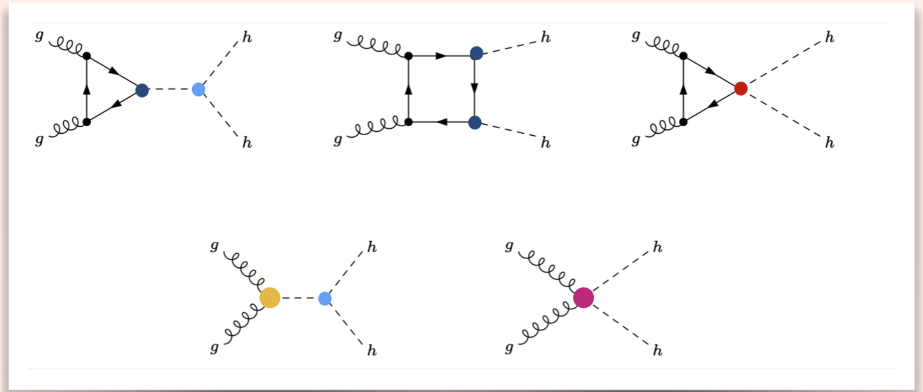
EFT for Higgs Pair Production

Ramona Gröber (Univ. Padua, INFN Padua)



SMEFT ($1/\Lambda^n$ expansion)
combination w/ single Higgs
fit simpler

or

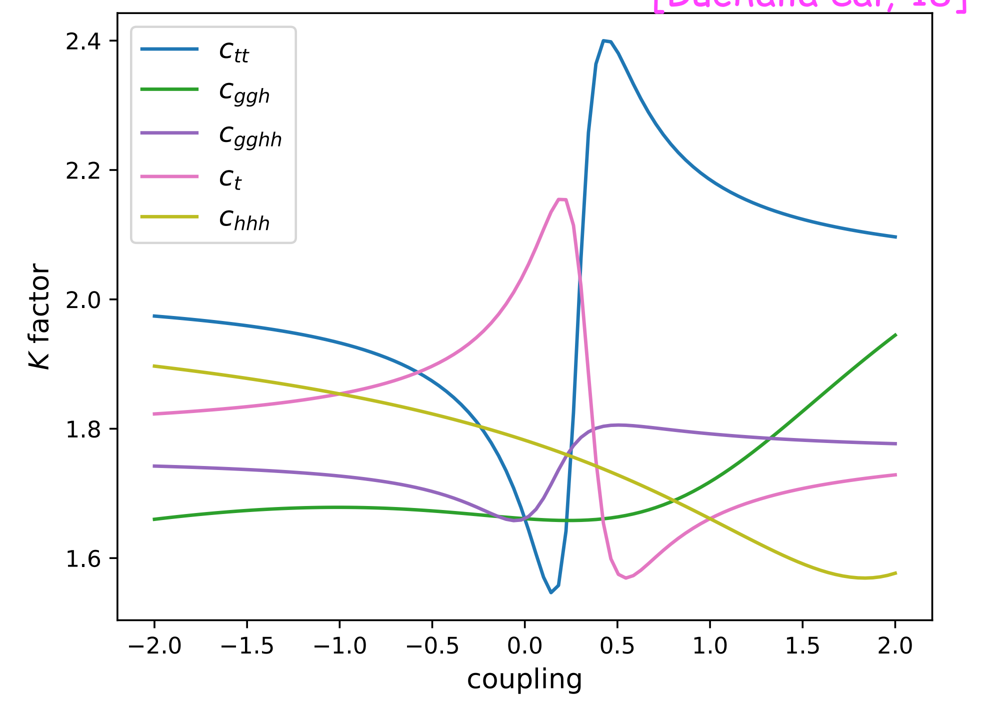


HEFT (chiral dimension expansion)
di-Higgs: probe differences in 1- and 2-Higgs couplings
NLO w/ full mass dependence available
[Buchalla eal,'18; Heinrich eal,'20]

Higher-Order Corrections

POWHEG implementation of HEFT at NLO QCD ['20]

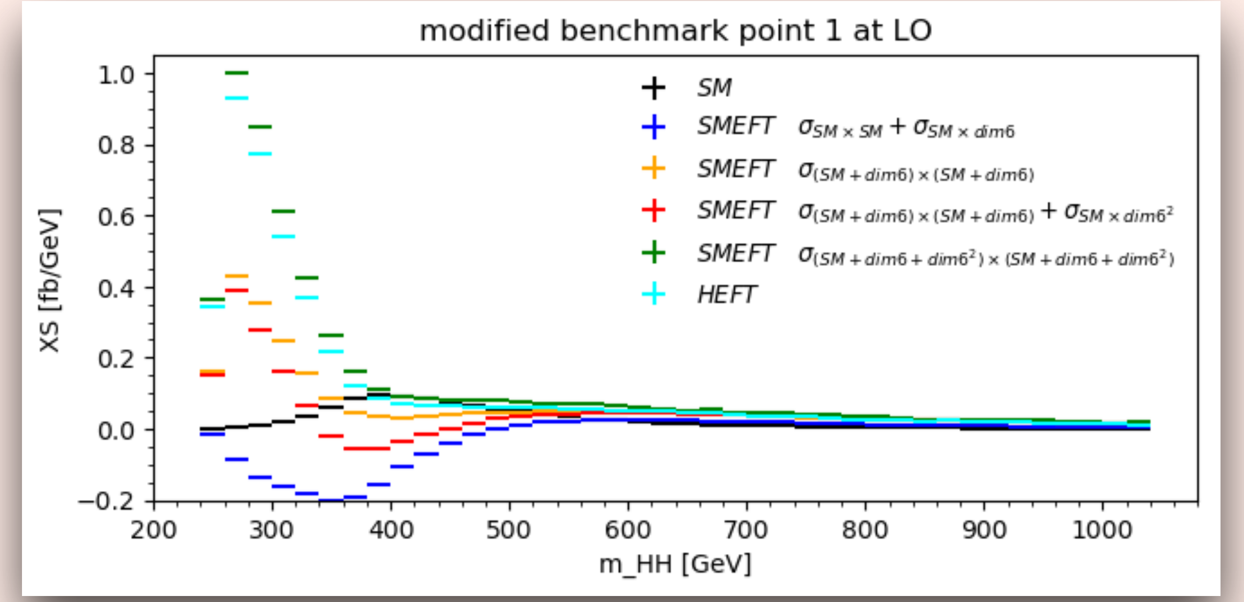
[Buchalla eal,'18]



Translation HEFT/SMEFT

non-trivial on level of matrix element squared

[fig. by Jannis Lang]

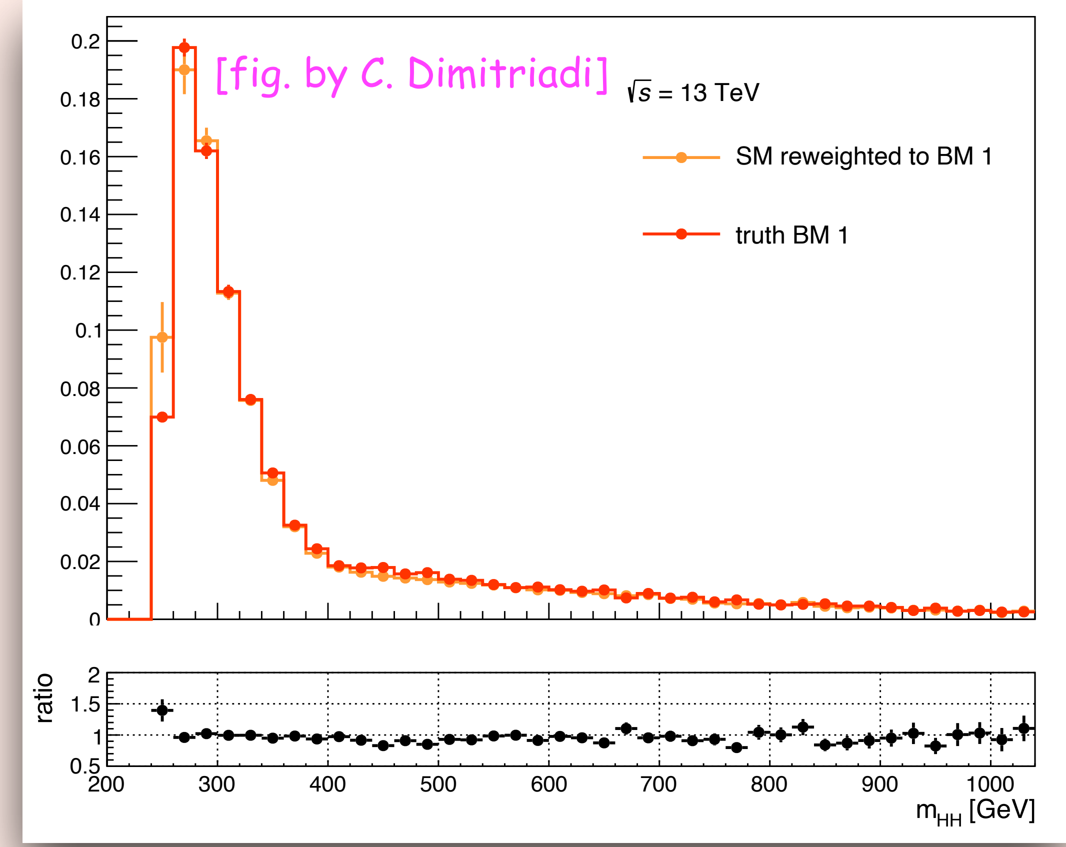


EFT for Higgs Pair Production

Ramona Gröber (Univ. Padua, INFN Padua)

Open questions

- SM large uncertainties from top quark mass renormalization scheme [Baglio et al,'19,'20]
- What are the errors on the EFT distributions that are different from SM ones?



Scans in EFT space w/ new Monte Carlo events too computing time intensive => Reweighting

[Buchalla eal,'18] provide weights

$$Poly(c_i) = \frac{\sigma_{HEFT}(c_i)}{\sigma_{SM}}$$

$$Poly(c_i, m_{hh}) = \frac{\sigma_{HEFT}(c_i, m_{hh})}{\sigma_{SM}(m_{hh})}$$

How do the reweighting in practice?

$$w'(c_i) = \frac{Poly(c_i, m_{hh})}{Poly(c_i)}$$

or normalise reweighed distribution?

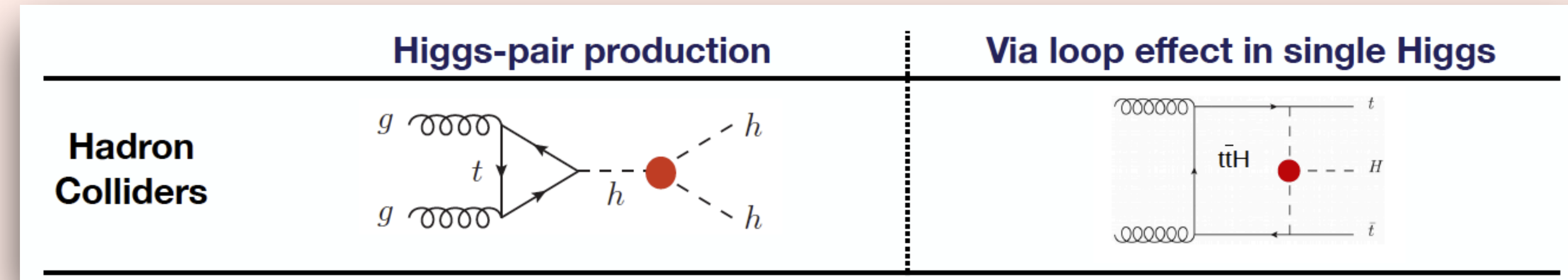
Discussion towards recommendations underway

[Alasfar,Cadamuro,Dimitriadi,Ferrari,Gröber,Heinrich,Lang,Ördek,Pereira Sanchez,Scyboz]

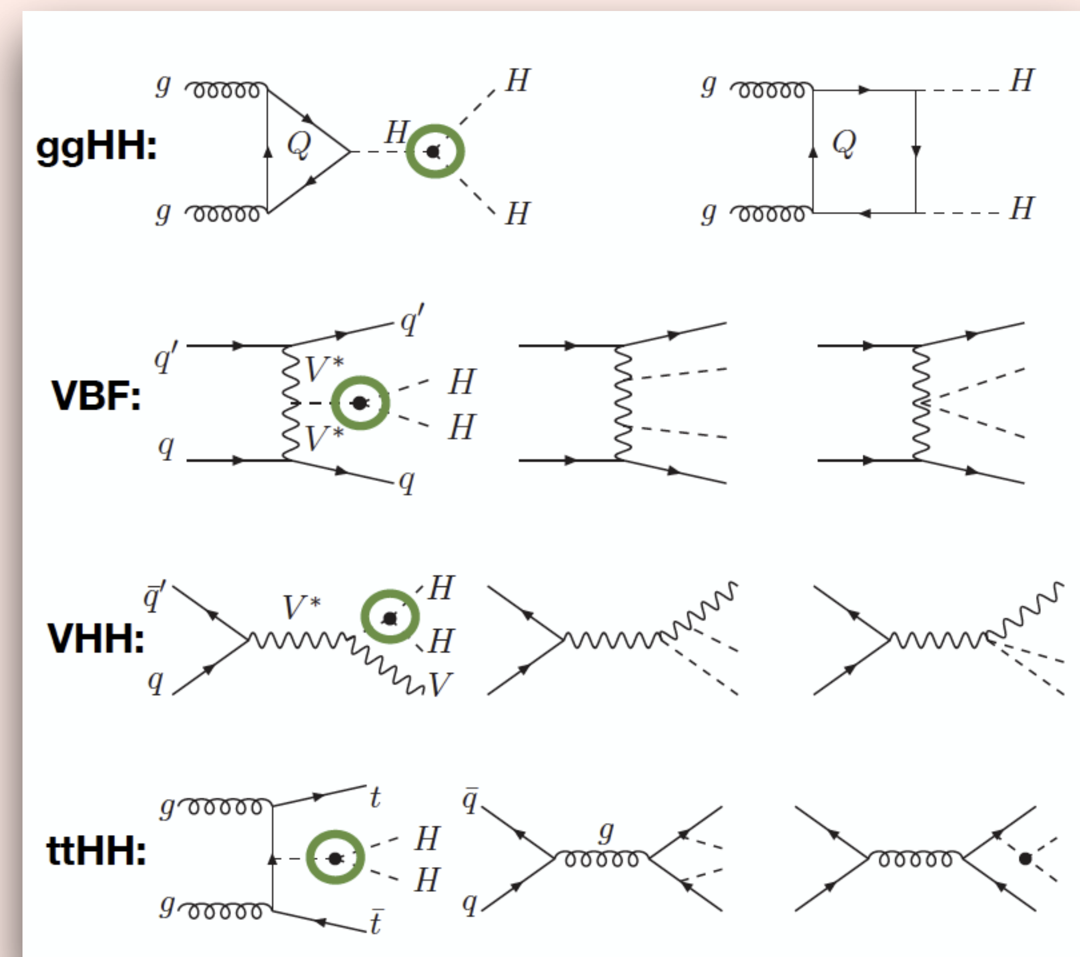
Single and Double Higgs processes: Interpretation in the k_lambda and EFT frameworks

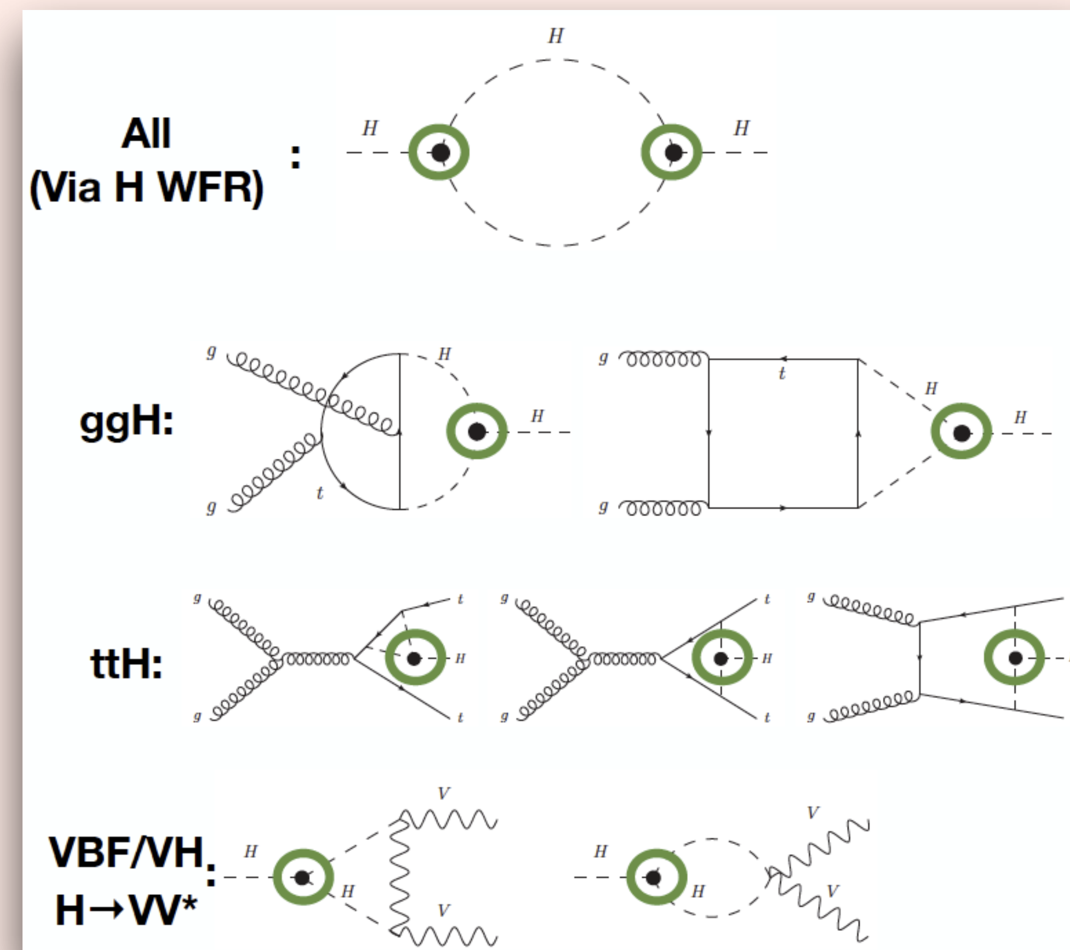
Jorge de Blas (Univ. De Granada)

LHC probes of trilinear Higgs coupling



[McCullough,'13; Gorbahn eal,'16; Degrassi eal,'16; Bizon eal,'16; DiVita eal,'17; Maltoni eal,'17; Gorbahn eal,'19; Anisha eal,'21; Haisch eal,'21]





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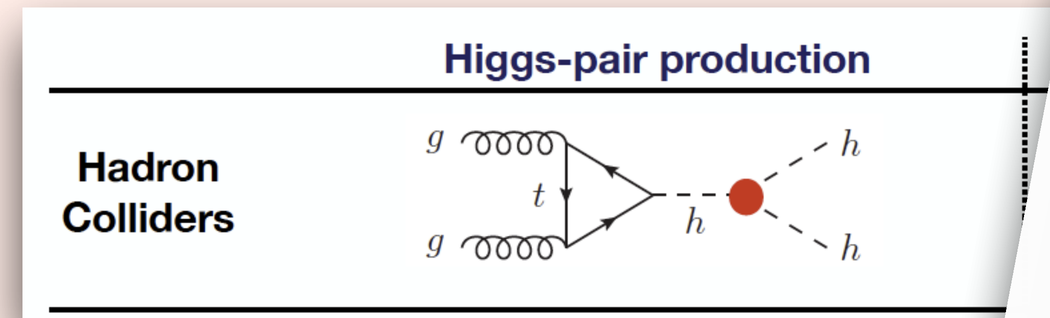
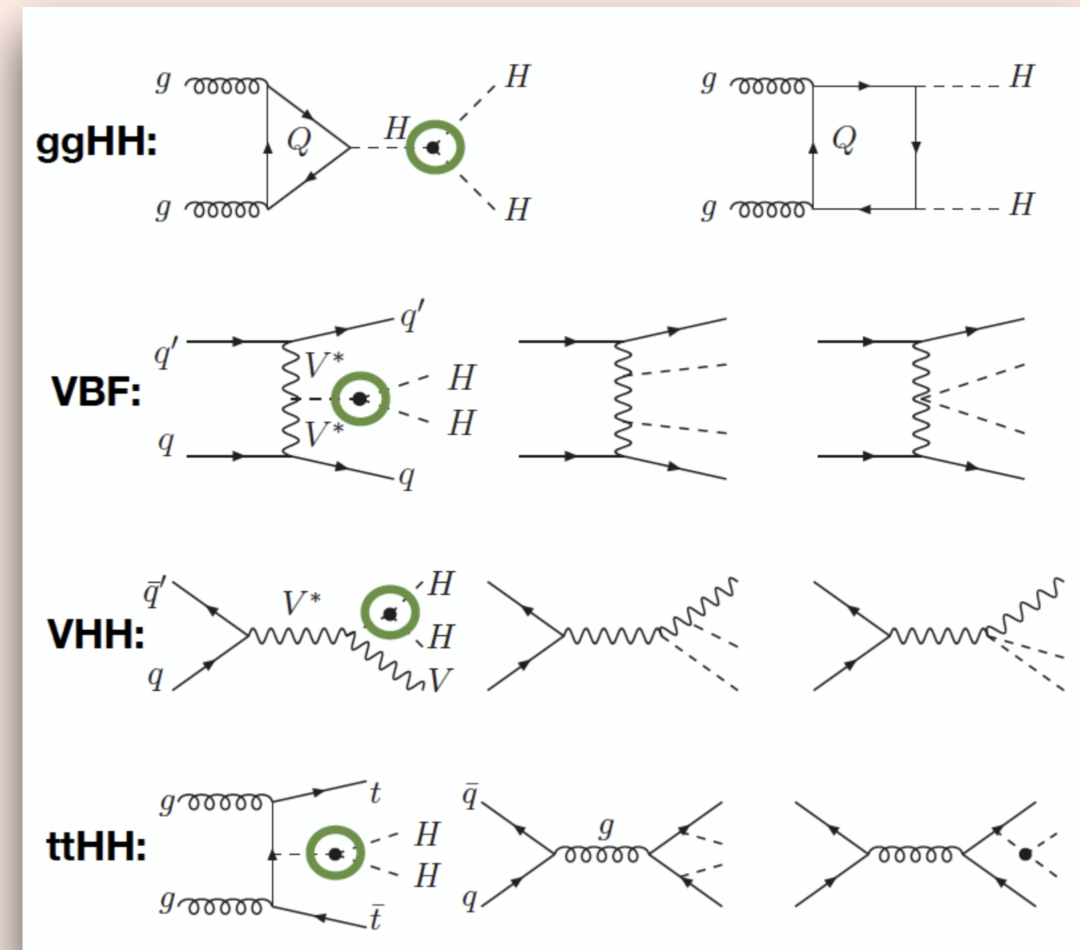
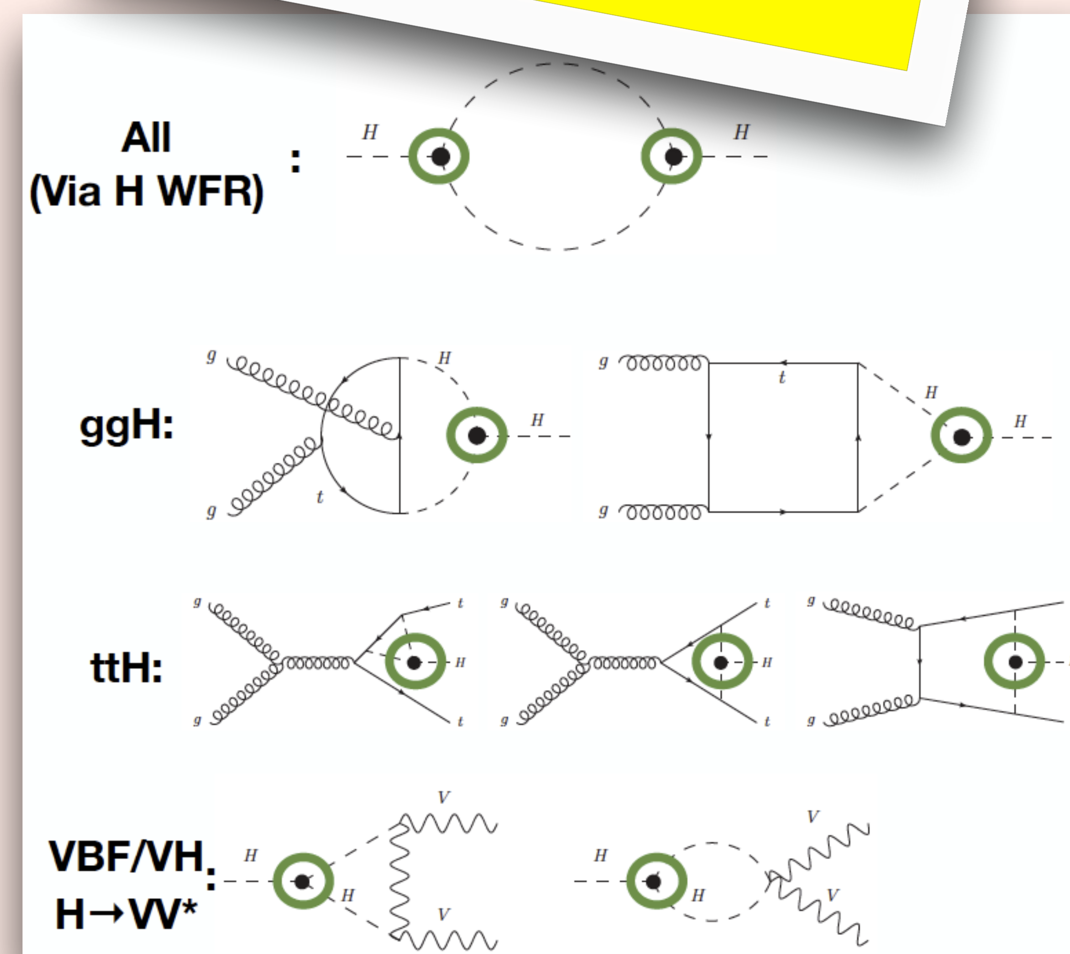


see talk by S.Manzoni (WG2)
common κ_λ parametrisation
for self-coupling from
single H measurements

[McCullough,'13;
...rbahn eal,'16;
...assi eal,'16;
...n eal,'16;
...ta eal,'17;
...toni eal,'17;
...rbahn eal,'19;
...isha eal,'21;
...aisch eal,'21]

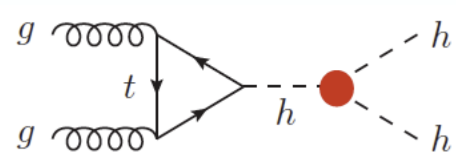
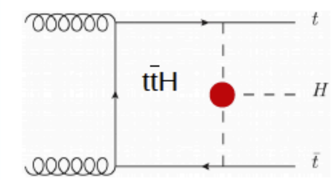




Single and Double Higgs processes: Interpretation in the k_lambda and EFT frameworks

Jorge de Blas (Univ. De Granada)

How interpret these measurements/determinations?

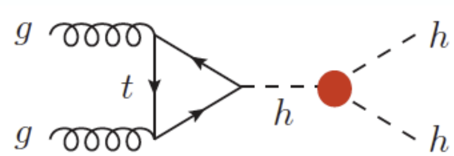
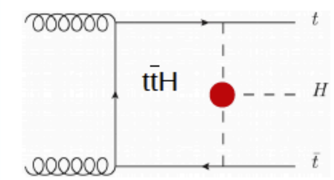
	Higgs-pair production	Via loop effect in single Higgs
Hadron Colliders		

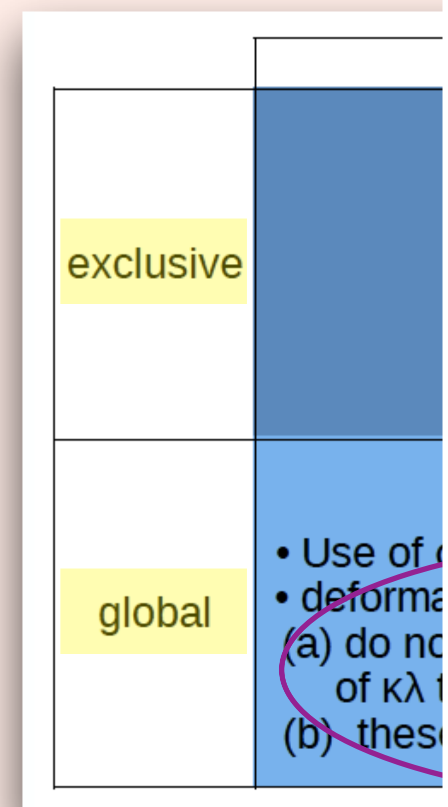
	di-Higgs	single-H
exclusive	**1. di-H, excl.** • Use of σ(HH) • only deformation of κλ	**3. single-H, excl.** • single Higgs processes at higher order • only deformation of κλ
global	**2. di-H, glob.** • Use of σ(HH) • deformation of κλ + of the single-H couplings (a) do not consider the effects at higher order of κλ to single H production and decays (b) these higher order effects are included	**4. single-H, glob.** • single Higgs processes at higher order • deformation of κλ + of the single Higgs couplings

Single and Double Higgs processes: Interpretation in the k_lambda and EFT frameworks

Jorge de Blas (Univ. De Granada)

How interpret these measurements/determinations?

	Higgs-pair production	Via loop effect in single Higgs
Hadron Colliders		



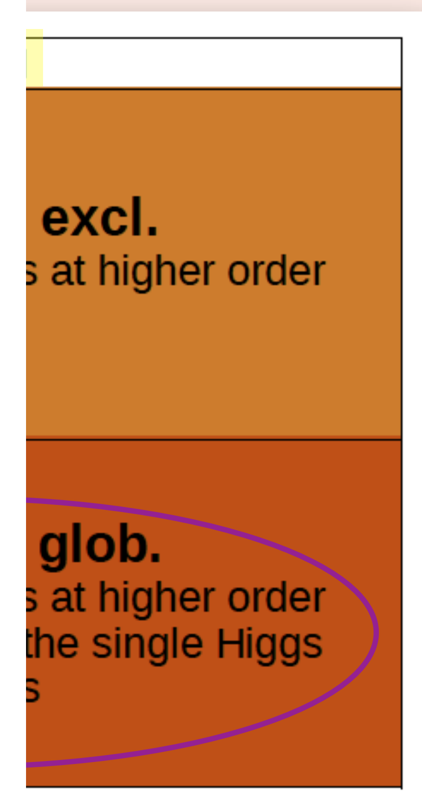
Depends on what you want to learn!

⇒

Sets interpretational framework

⇑

assumptions



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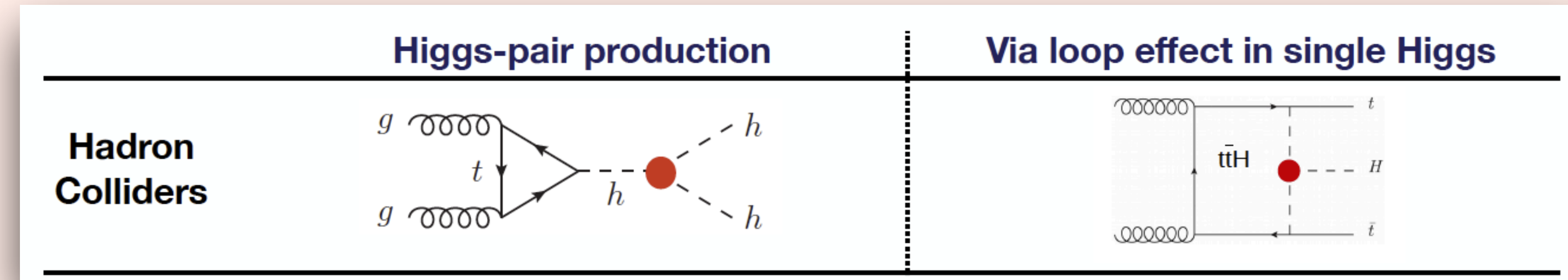
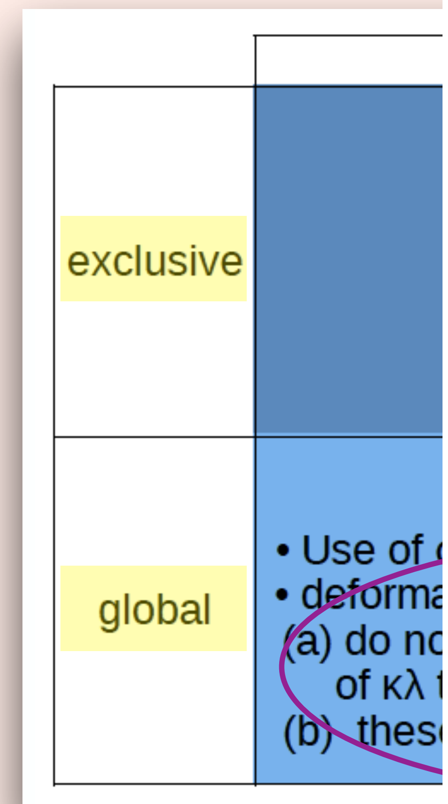
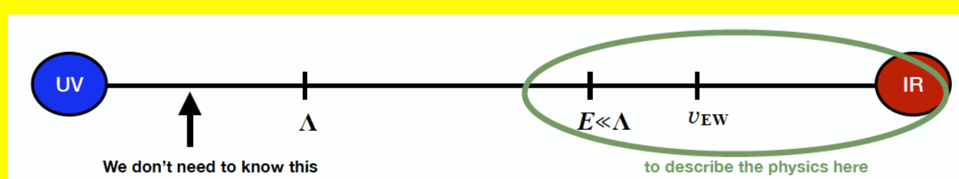
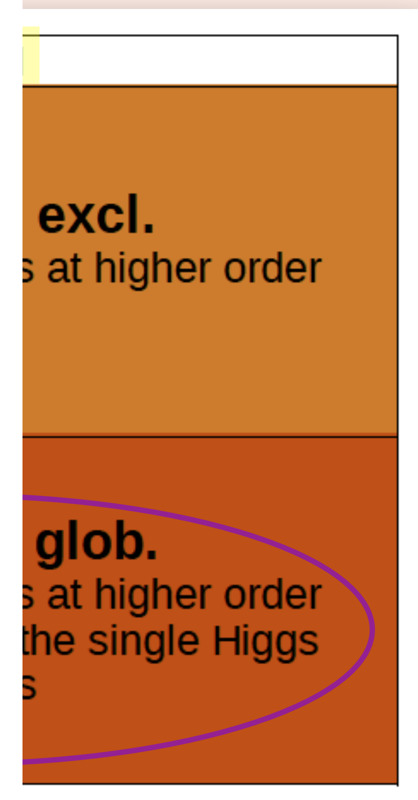
How interpret these measurements/determinations?





Effective Field Theories
as a rather
model-independent
approach





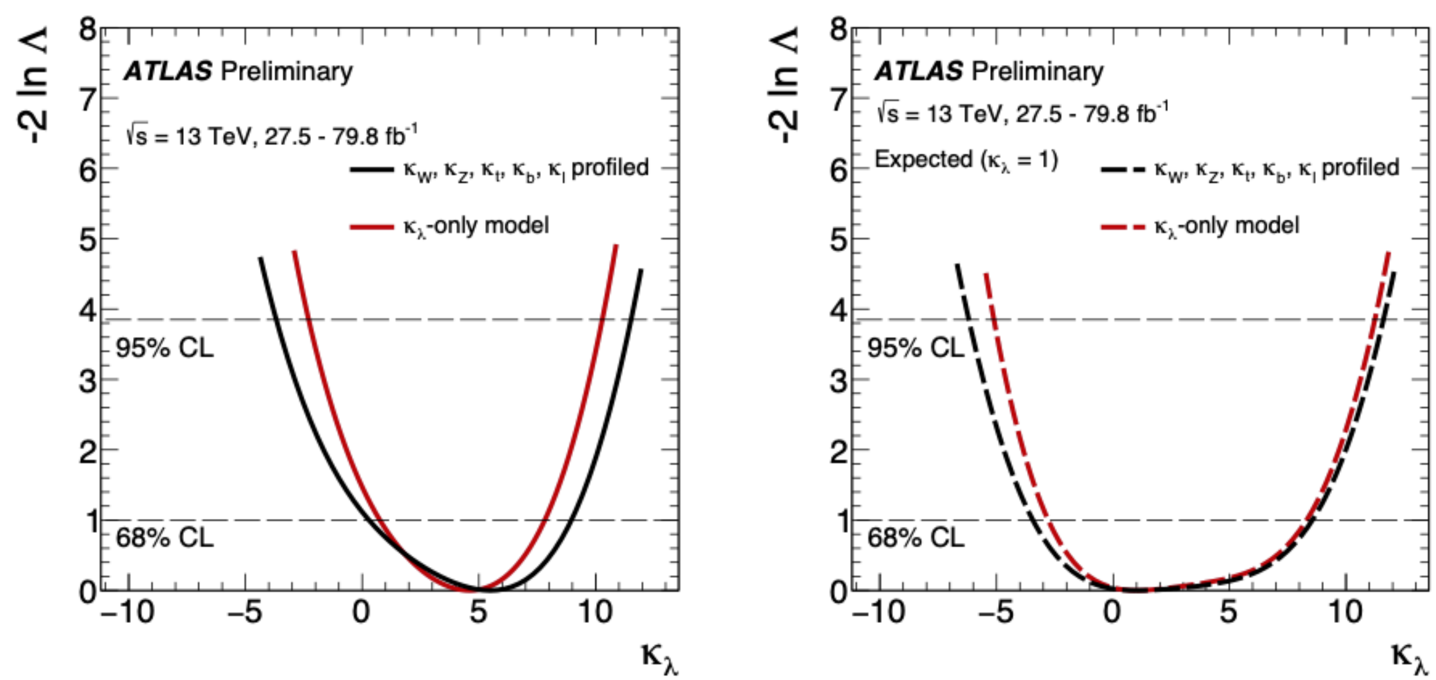
Self-coupling from single Higgs measurements: towards a common κ_λ parametrization

S. Manzoni (CERN)

Experimental Results: Generic Model

ATLAS-CONF-2019-049

- Fit simultaneously several coupling modifiers: κ_λ, κ_W, κ_Z, κ_ℓ, κ_b, κ_t
- Test of BSM models that can modify at the same time κ_λ and other H couplings.



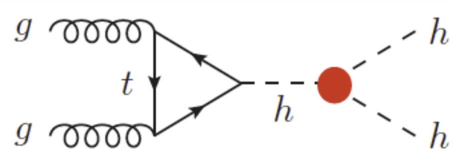
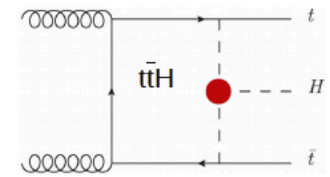
Model	$\kappa_W{}^{+1\sigma}_{-1\sigma}$	$\kappa_Z{}^{+1\sigma}_{-1\sigma}$	$\kappa_t{}^{+1\sigma}_{-1\sigma}$	$\kappa_b{}^{+1\sigma}_{-1\sigma}$	$\kappa_\ell{}^{+1\sigma}_{-1\sigma}$	$\kappa_\lambda{}^{+1\sigma}_{-1\sigma}$	κ_λ [95% CL]	
κ_λ-only	1	1	1	1	1	$4.6^{+3.2}_{-3.8}$	[−2.3, 10.3]	obs.
				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

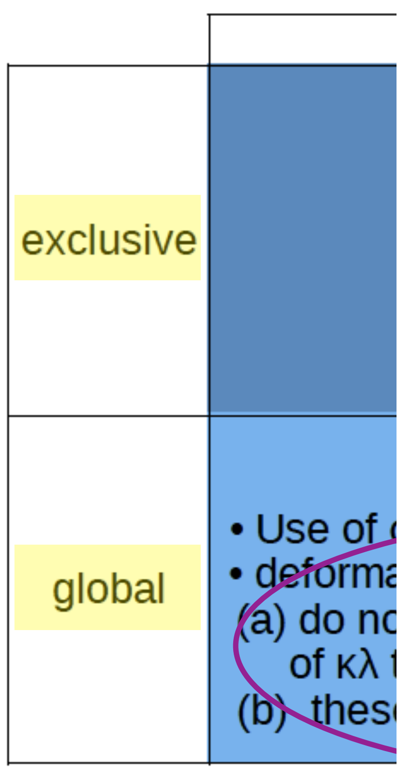
- Substantial constraints on κ_λ even in this more generic model.

Single and Double Higgs processes: Interpretation in the k_lambda and EFT frameworks

Jorge de Blas (Univ. De Granada)

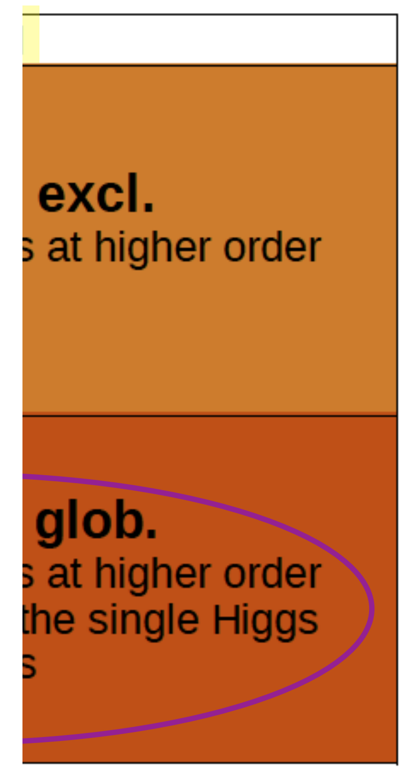
How interpret these measurements/determinations?

	Higgs-pair production	Via loop effect in single Higgs
Hadron Colliders		



Conclusions:

- global analysis: learn more about BSM
- EFTs: model-independent, allow for proper h & hh combination
- SMEFT ⊂ HEFT => HEFT proj on SMEFT
- But SMEFT: correlations between processes facilitate analysis
- exclusive κ_λ approx seems ok in SMEFT
- hh typically outperforms h(<- model-indep.?!)



Di-Higgs Production in Extended Higgs Sectors

Duarte Azevedo (KIT)

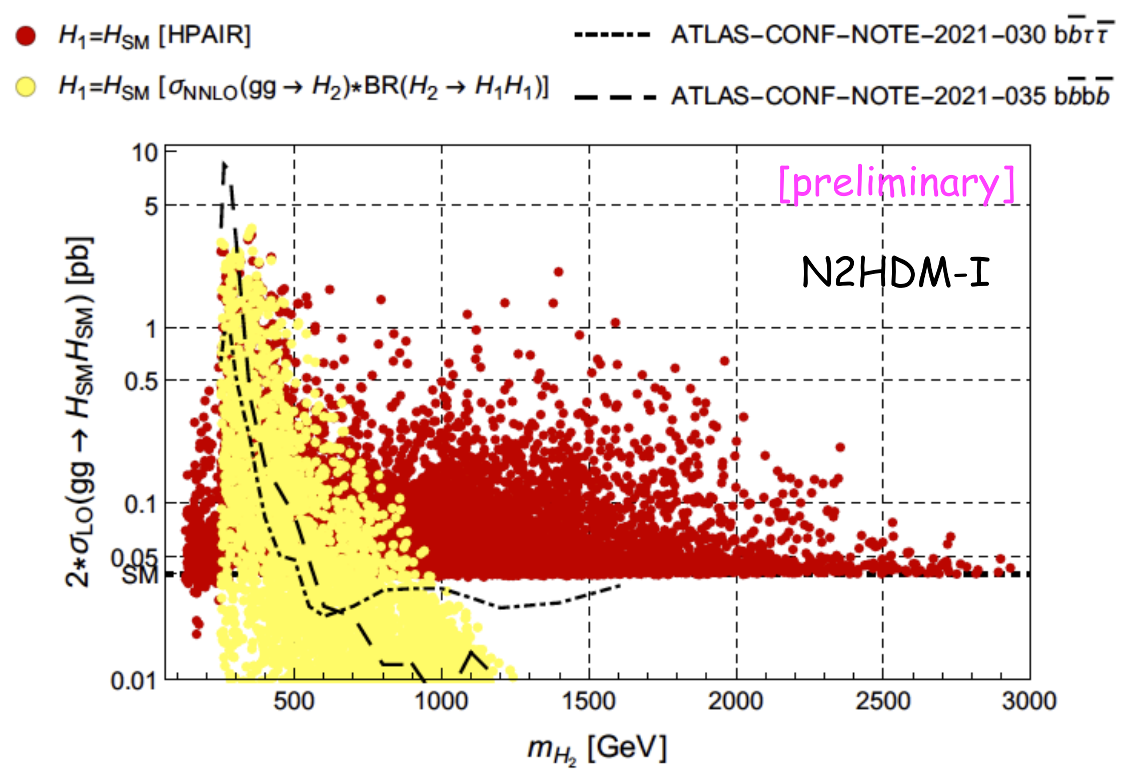
in collaboration w/ H. Abouabid, A. Arhrib, J. El Falaki, P. Ferreira, MM, R. Santos

The models:

- R2HDM - CP-conserving - $(h,\ H,\ A\ ,\ H^{\pm})$
- C2HDM - CP-violation - $(H_1,\ H_2,\ H_3,\ H^{\pm})$
- N2HDM - Singlet admixture - $(H_1,\ H_2,\ H_3,\ A,\ H^{\pm})$
- NMSSM - SUSY - $(H_1,\ H_2,\ H_3,\ A_1,\ A_2,\ H^{\pm})^3$

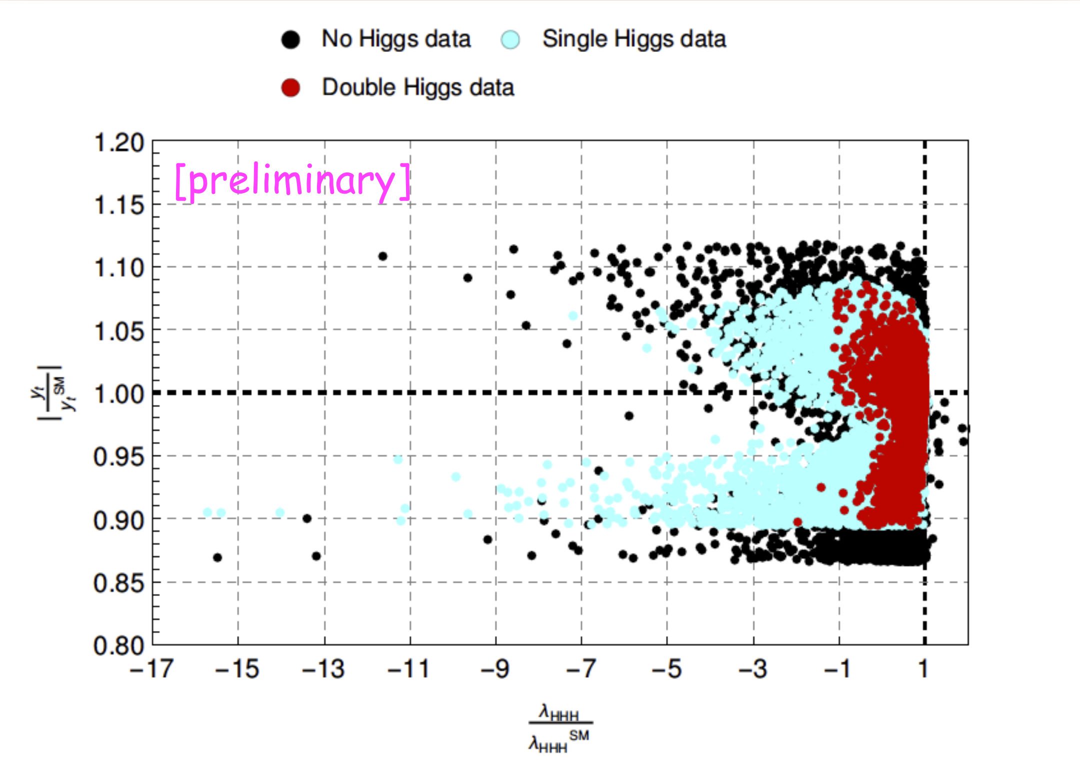
enhancement compared to SM:
- Yukawa and trilinear Higgs couplings different
- Resonant enhancement due to heavy Higgs production
- New particles in the loop (SUSY)

resonant di-Higgs searches cut on parameter spaces of the models; non-resonant ones on N2HDM-I



single Higgs constrains y_t

resonant+non-resonant searches required to constrain λ_{3H}



Di-Higgs Production in Extended Higgs Sectors

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To be published soon:
Benchmarks delivered for
SM-like HH (res, non-res ones),
SM-like H + Φ_i,
$\Phi_i\Phi_j$ final states

criteria for benchmarks:
- large cxns
- di-Higgs beats single Higgs
- Higgs cascades
- relation to EFT

Example: resonant SM-like HH production

Benchmark for resonant production N2HDM-I

→ **Input values:**

m_{H_1} [GeV]	m_{H_2} [GeV]	m_{H_3} [GeV]	m_A [GeV]	$m_{H^\pm}$ [GeV]	$\tan\beta$
125.09	277.06	298.08	257.65	272.55	3.725

α_1	α_2	α_3	v_s [GeV]	Re(m_{12}^2) [GeV^2]	
1.297	0.293	-0.111	2448	18000	

→ **Branching ratios:**

$$\begin{aligned} &\mathrm{BR}(H_2 \to H_1H_1) = 0.342, \quad \mathrm{BR}(H_2 \to WW) = 0.424, \quad \mathrm{BR}(H_2 \to ZZ) = 0.185 \\ &\mathrm{BR}(H_3 \to H_1H_1) = 0.299, \quad \mathrm{BR}(H_3 \to WW) = 0.485, \quad \mathrm{BR}(H_3 \to ZZ) = 0.215 \\ &\mathrm{BR}(A \to bb) = 0.278, \quad \mathrm{BR}(A \to ZH_1) = 0.0927, \quad \mathrm{BR}(H^\pm \to tb) = 0.998 \end{aligned} \quad (1)$$

→ **Production rates:**

$$\begin{aligned} \sigma(H_2) \times \mathrm{BR}(H_2 \to H_1H_1) = 1.046\ \mathrm{pb} \times 0.342 = 357\ \mathrm{fb} \\ \sigma(H_3) \times \mathrm{BR}(H_3 \to H_1H_1) = 0.650\ \mathrm{pb} \times 0.299 = 194\ \mathrm{fb} \end{aligned} \quad (2)$$

$2 * \sigma^{LO}_{H_1H_1}$ [pb]	$\Gamma^{tot}_{H_1}$ [GeV]	$\Gamma^{tot}_{H_2}$ [GeV]	$\Gamma^{tot}_{H_3}$ [GeV]	Γ^{tot}_{A} [GeV]	$\Gamma^{tot}_{H^\pm}$ [GeV]	$\lambda_{3H_1}/\lambda^{SM}_{3H}$
533.4	3.717 10^{-3}	0.018	0.931	0.001	0.491	0.878

input welcome:
- specific benchmark requests
- how present benchmarks
- large data set: benchmarks can be provided on request

Multiscalar Final States in the TRSM

Gilberto Tetlalmatzi-Xolocotzi (Siegen Univ.)

in collaboration w/ A. Papaefstathiou, T. Robens

- Triple Higgs production in SM is tiny: 0.1 fb at NNLO for c.m. energy 14 TeV [De Florian,Fabre,Mazzitelli,'19]

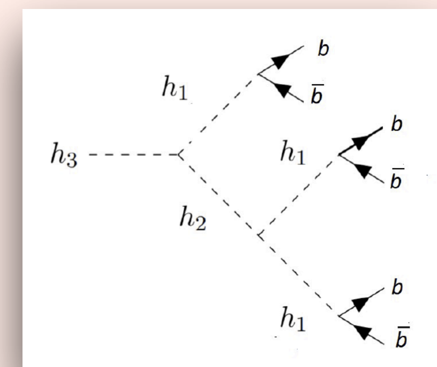
- Enhancement possible in extended scalar sectors

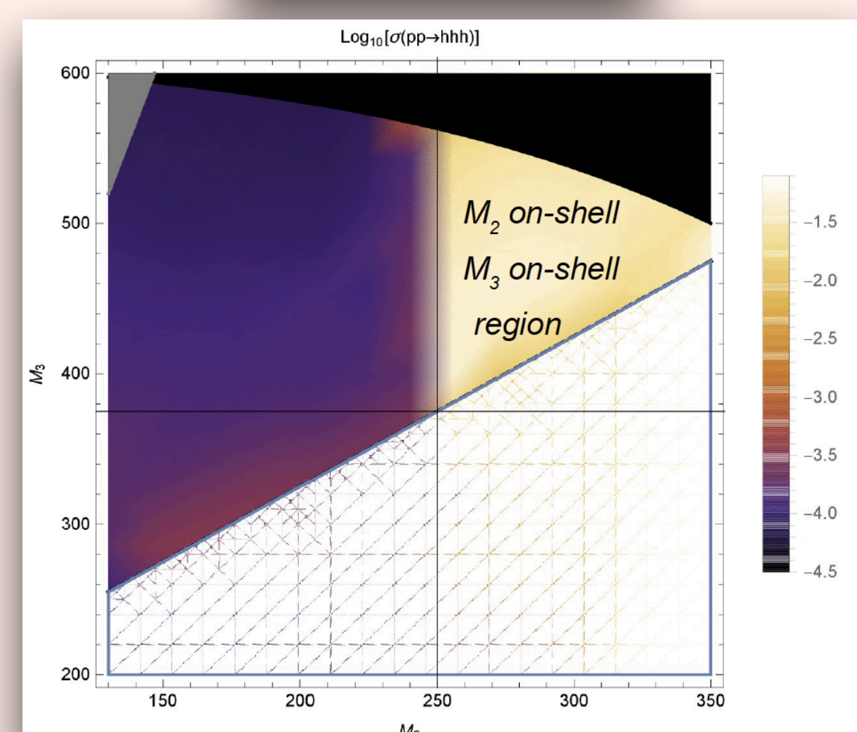
- e.g. Two Real Singlet Extension of the SM (TRSM)

$$V(\Phi, X, S) = \mu_\Phi^2 \Phi^\dagger \Phi + \lambda_\Phi (\Phi^\dagger \Phi)^2 + \mu_S^2 S^2 + \lambda_S S^4 + \mu_X^2 X^2 + \lambda_X X^4 + \lambda_{\Phi S} \Phi^\dagger \Phi X^2 + \lambda_{SX} S^2 X^2$$

$$S = (\phi_S + v_S)/\sqrt{2} \qquad X = (\phi_X + v_X)/\sqrt{2}$$

- Benchmark point w/ sigma(h1h1h1) = up to 50 fb





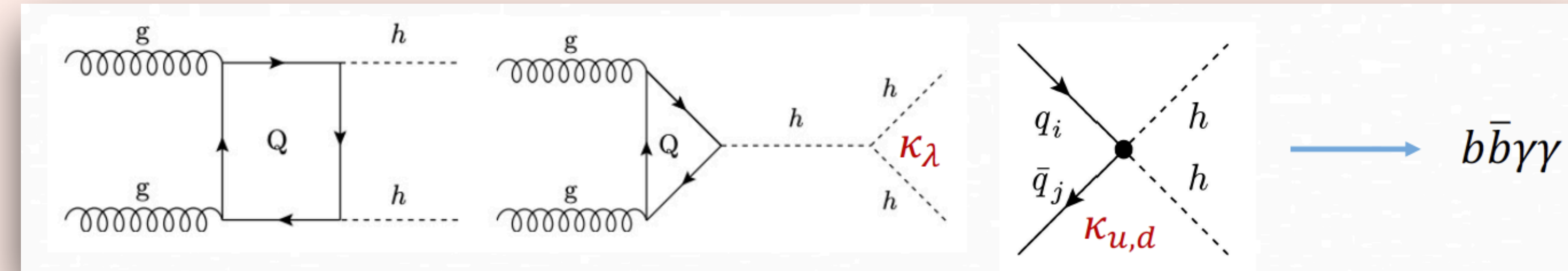
Analysis for 6b final state
(MadGraph5_aMC@NLO, Herwig7, HwSim)

Label	(M_2, M_3) [GeV]	$\varepsilon_{\text{Sig.}}$	$S\vert_{300\text{fb}^{-1}}$	$\varepsilon_{\text{Bkg.}}$	$B\vert_{300\text{fb}^{-1}}$	$\text{sig}\vert_{300\text{fb}^{-1}}$	$\text{sig}\vert_{3000\text{fb}^{-1}}$
A	(255, 504)	0.025	14.12	8.50×10^{-4}	19.16	2.92	9.23
B	(263, 455)	0.019	17.03	3.60×10^{-5}	8.11	4.78	15.11
C	(287, 502)	0.030	20.71	9.13×10^{-5}	20.60	4.01	12.68
D	(290, 454)	0.044	37.32	1.96×10^{-4}	44.19	5.02	15.86
E	(320, 503)	0.051	32.54	2.73×10^{-4}	61.55	3.76	11.88
F	(264, 504)	0.028	18.18	9.13×10^{-5}	20.60	3.56	11.27
G	(280, 455)	0.044	38.70	1.96×10^{-4}	44.19	5.18	16.39
H	(300, 475)	0.054	41.27	2.95×10^{-4}	66.46	4.64	14.68
I	(310, 500)	0.063	41.42	3.97×10^{-4}	89.59	4.09	12.94
J	(280, 500)	0.029	20.67	9.14×10^{-5}	20.60	4.00	12.65

Machine learning augmented problem of light-quark Yukawa and trilinear couplings from Higgs pair production

Ayan Paul (DESY, Humboldt Univ. Berlin)

HH at LHC and FCC-hh:



Machine Learning

Good for probing higher order correlations but can be black boxes

+

Interpretability

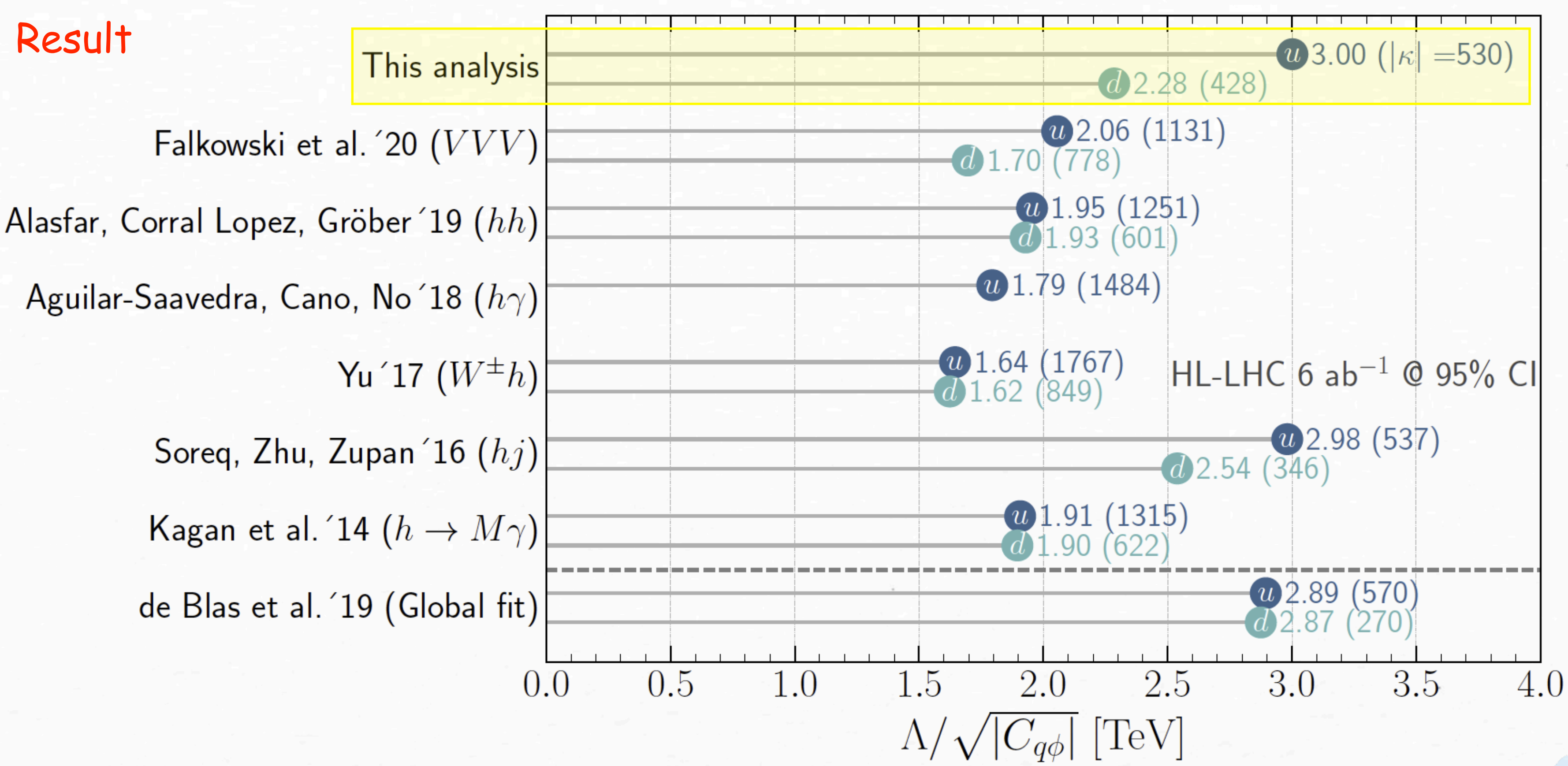
Making black boxes interpretable provides insight into the underlying dynamics

applied to

Higgs Pair Production

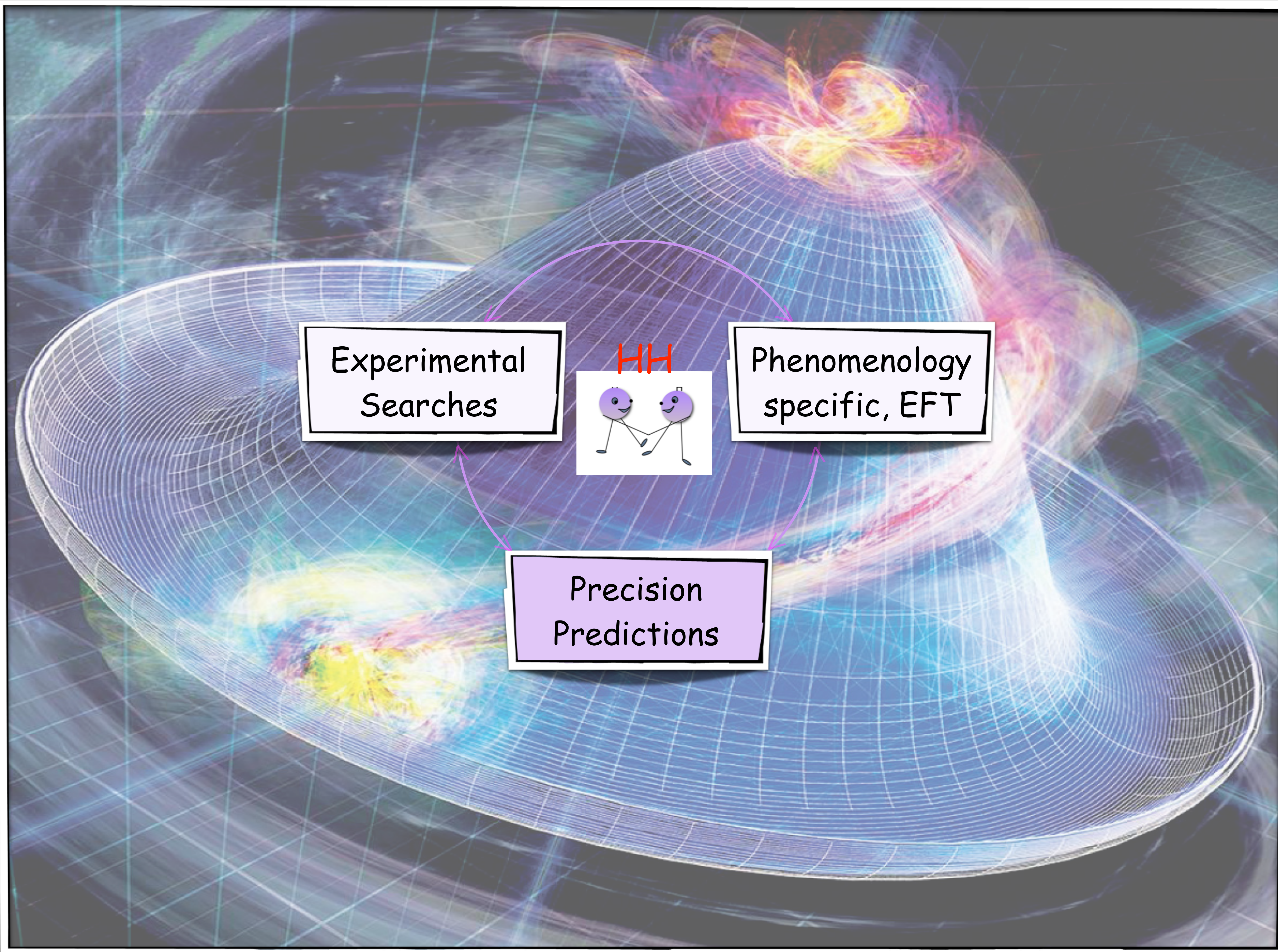
Nice place to look for deformation of Higgs self coupling and light Yukawa couplings

Result



The Future

Putting all three together gives some pretty convincing directions for future measurements


Experimental Searches
HH
Phenomenology specific, EFT
Precision Predictions

Higgs Boson Pair Production at NNLO in the Large-M_t Expansion

Florian Herren

in collaboration w/ J. Davies, G. Mishima, M. Steinhauser, '19,'21

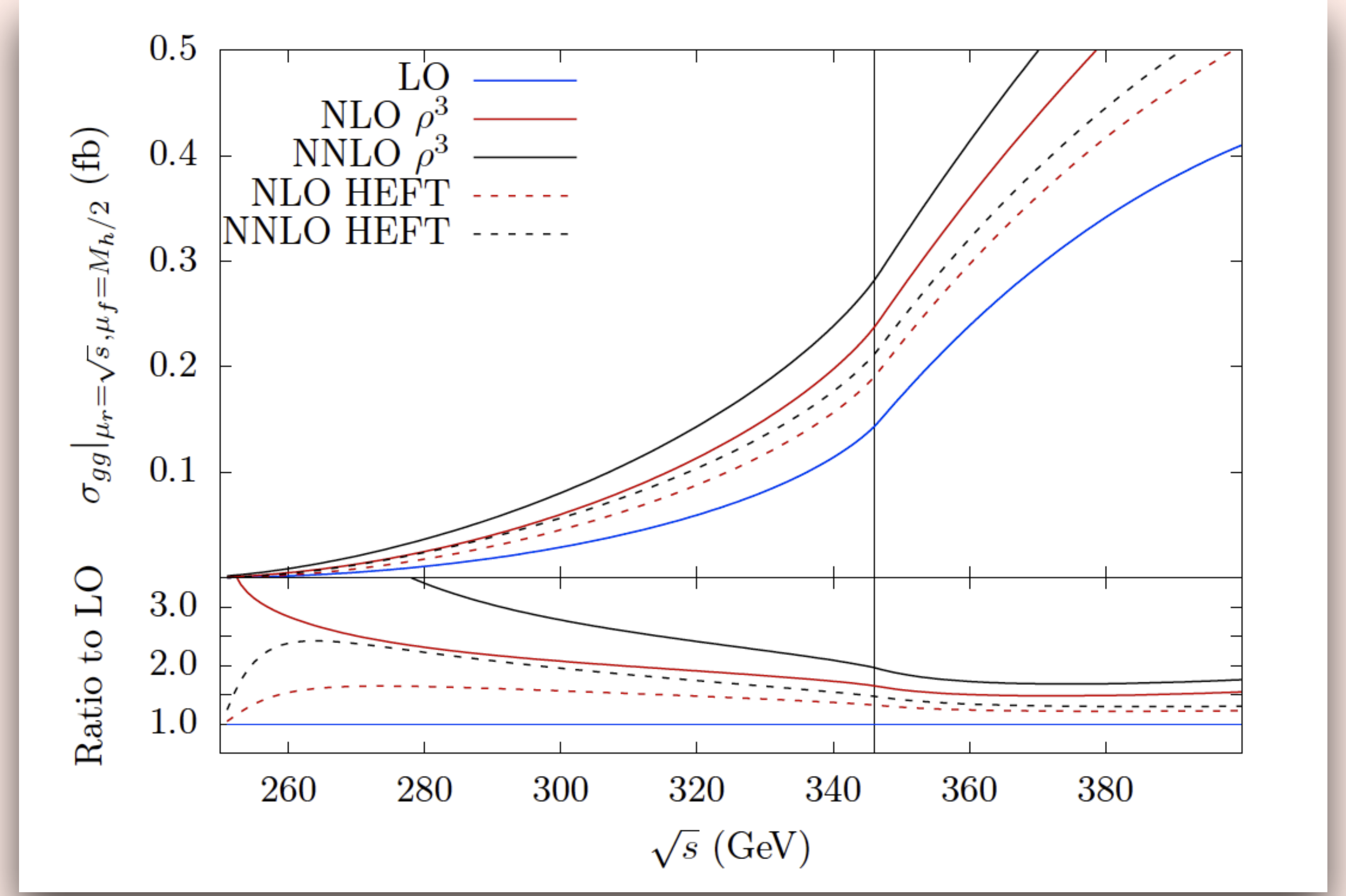
Status higher-order corrections: exact at NLO [Borowka real,'16; Baglio real,'18]

at NNLO based on HEFT or LME:

- HEFT [de Florian,Mazzitelli,'13; Grigo,Melnikov,Steinhauser,'14]
  1/mt^2 corrections for virtual parts [Grigo,Hoff,Steinhauser,'14; Davies,Steinhauser,'19]
- HEFT for virtual parts combined w/ available exact real radiation [Grazzini eal,'18]

LME expansion w/ 4 expansion terms

mass corrections are sizeable



results usable as input for Padé approximant based methods

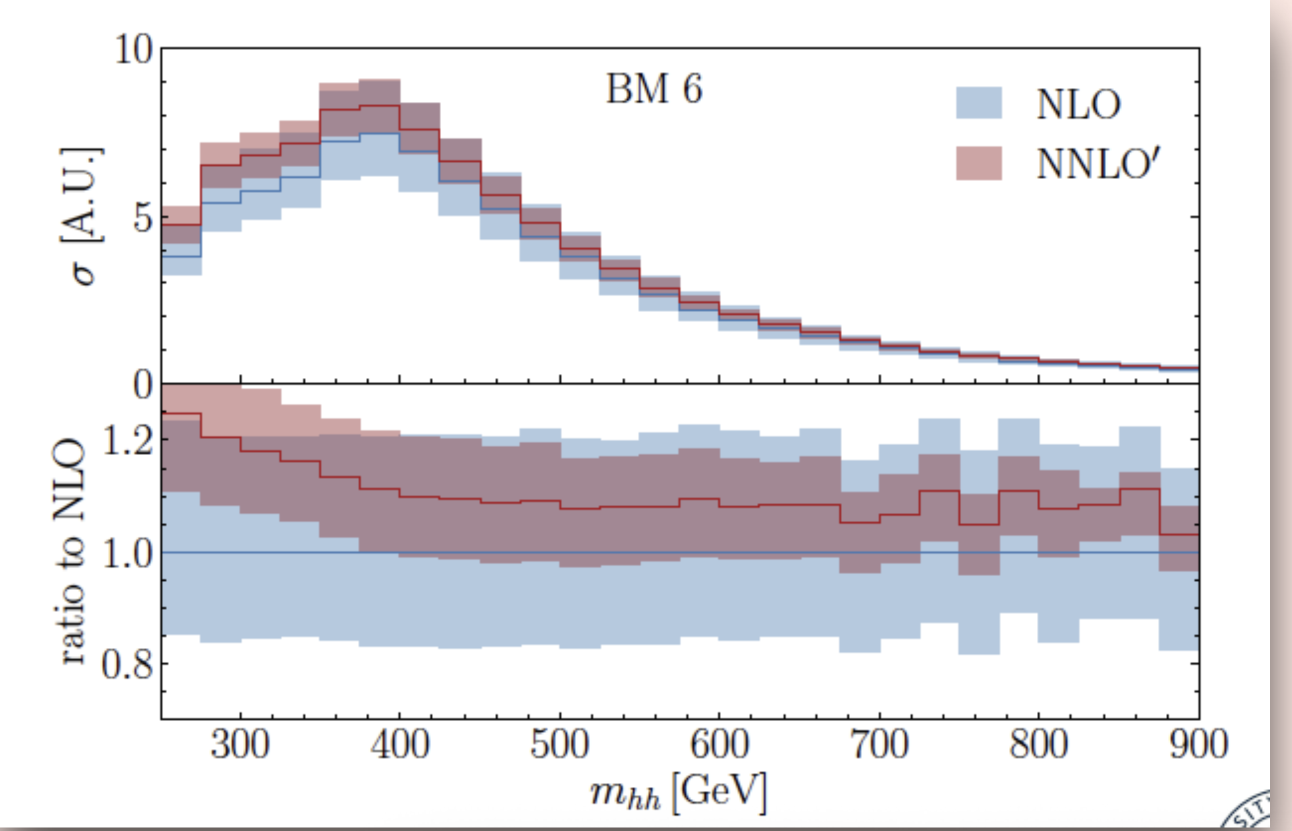
Higgs Pair Production at Approximate NNLO QCD with Anomalous Couplings

Ludovic Scyboz (Oxford University)

in collaboration w/ D. de Florian, I. Fabre, G. Heinrich, J. Mazzitelli

HH at NNLO' in HEFT: Combine

NLO exact m_t	NNLO (B.-i.) HTL
Buchalla, Capozi, Celis, Heinrich, LS '18	de Florian, Fabre, Mazzitelli '16



Provided

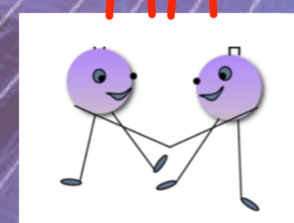
- invariant mass distributions for benchmark points
- set of fitted coefficients $a_1 \ldots a_{25}$ of NNLO' cross section at c.m. energy 14 TeV

$$
\begin{aligned}
\sigma_{\rm BSM}/\sigma_{\rm SM} = {} & a_1\, c_t^4 + a_2\, c_{tt}^2 + a_3\, c_t^2 c_{hhh}^2 + a_4\, c_{ggh}^2 c_{hhh}^2 + a_5\, c_{gghh}^2 + a_6\, c_{tt} c_t^2 + a_7\, c_t^3 c_{hhh} \\
& + a_8\, c_{tt} c_t\, c_{hhh} + a_9\, c_{tt} c_{ggh} c_{hhh} + a_{10}\, c_{tt} c_{gghh} + a_{11}\, c_t^2 c_{ggh} c_{hhh} + a_{12}\, c_t^2 c_{gghh} \\
& + a_{13}\, c_t c_{hhh}^2 c_{ggh} + a_{14}\, c_t c_{hhh} c_{gghh} + a_{15}\, c_{ggh} c_{hhh} c_{gghh} + a_{16}\, c_t^3 c_{ggh} \\
& + a_{17}\, c_t c_{tt} c_{ggh} + a_{18}\, c_t c_{ggh}^2 c_{hhh} + a_{19}\, c_t c_{ggh} c_{gghh} + a_{20}\, c_t^2 c_{ggh}^2 \\
& + a_{21}\, c_{tt} c_{ggh}^2 + a_{22}\, c_{ggh}^3 c_{hhh} + a_{23}\, c_{ggh}^2 c_{gghh} + a_{24}\, c_{ggh}^4 + a_{25}\, c_{ggh}^3 c_t
\end{aligned}
$$

Analyses, calculations, investigations, discussions are ongoing
Stay tuned!

Experimental Searches

HH



Phenomenology specific, EFT

Precision Predictions

Thank you for your attention!

Reminder: Higgs Pairs 2022 workshop

Postponed to May 30th - June 3rd, 2022 in Dubrovnik, Croatia

- We hope to be able to see you all there, in person!