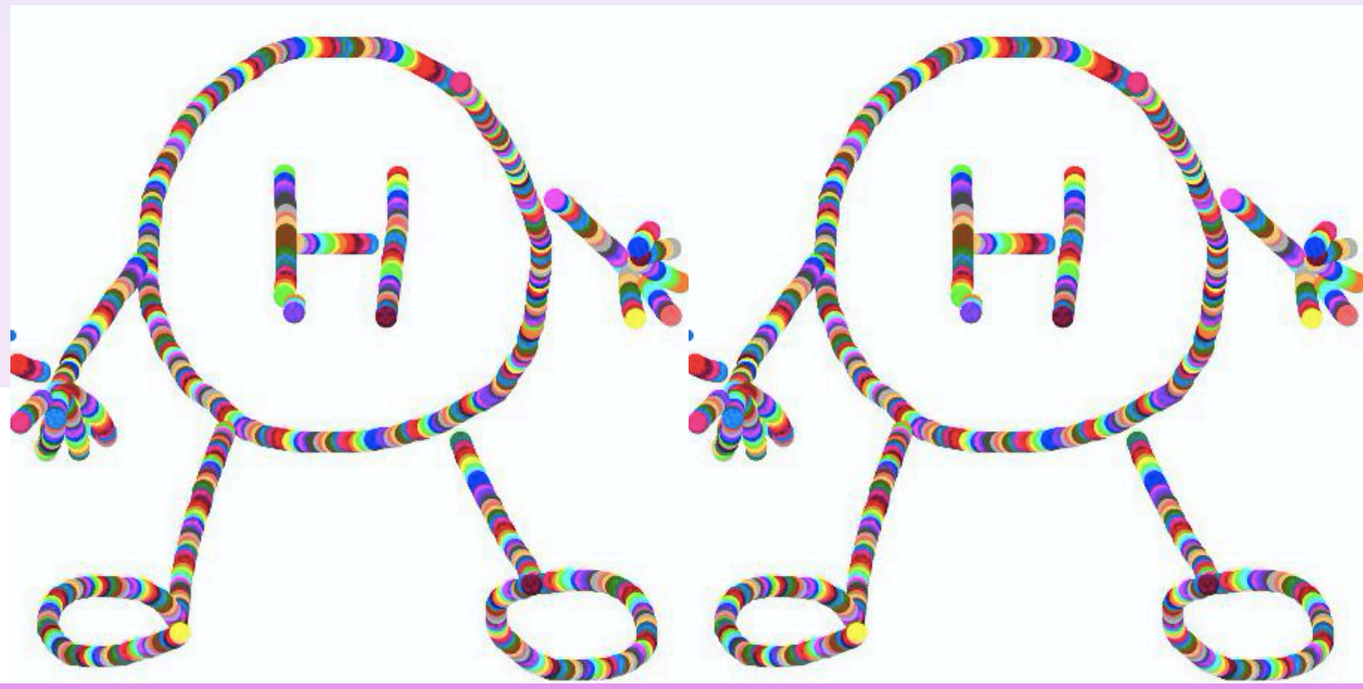
Summary and future plans of the HH cross group

Ramona Gröber

for the HH cross group convenors:

Luca Cadamuro, Arnaud Ferrari, Margarete Mühlleitner and Javier Mazzitelli

11/11/2020



Outline

- Di-Higgs in the Standard Model: Gluon fusion and VBF
- Effective Field Theory description of Di-Higgs
- Resonant Production of a Higgs pair

Gluon fusion

Our prediction based at the moment on NNLO-FTapprox calculation in [Grazzini et al '18]

Update in '20 to allow for variation of κ_λ

$\sigma = 70.3874 - 50.4111*\kappa_\lambda + 11.0595*\kappa_\lambda^2$ in fb.

[LesHouches Procceding, contribution by de Florian, Fabre, Heinrich, Mazzitelli]

13 TeV

κ_λ	-10	-5	-1	0	1	2	2.4	3	5	10
σ [fb]	1680	598.9	131.9	70.38	31.05	13.81	13.10	18.67	94.82	672.2
Scale unc.	$-7.7\%^{+3.0\%}$	$-7.5\%^{+2.7\%}$	$-6.7\%^{+2.5\%}$	$-6.1\%^{+2.4\%}$	$-5.0\%^{+2.2\%}$	$-4.9\%^{+2.1\%}$	$-5.1\%^{+2.3\%}$	$-7.3\%^{+2.7\%}$	$-8.8\%^{+4.9\%}$	$-8.5\%^{+4.2\%}$

New results on N3LO in infinite top mass limit

[Long-Bin Chen, Hai Tao Li, Hua-Sheng Shao, Jian Wang, 19]

$\sqrt{s}$	13 TeV	14 TeV	27 TeV	100 TeV
LO	$13.80^{+31\%}_{-22\%}$	$17.06^{+31\%}_{-22\%}$	$98.22^{+26\%}_{-19\%}$	$2015^{+19\%}_{-15\%}$
NLO	$25.81^{+18\%}_{-15\%}$	$31.89^{+18\%}_{-15\%}$	$183.0^{+16\%}_{-14\%}$	$3724^{+13\%}_{-11\%}$
NNLO	$30.41^{+5.3\%}_{-7.8\%}$	$37.55^{+5.2\%}_{-7.6\%}$	$214.2^{+4.8\%}_{-6.7\%}$	$4322^{+4.2\%}_{-5.3\%}$
N^3LO	$31.31^{+0.66\%}_{-2.8\%}$	$38.65^{+0.65\%}_{-2.7\%}$	$220.2^{+0.53\%}_{-2.4\%}$	$4439^{+0.51\%}_{-1.8\%}$

NNLO results do not include FTapprox,
awaiting their newest results for consistent update of numbers on wiki

mt -scheme uncertainty

How to renormalise the top mass appearing in the diagrams ?

Onshell/ MSbar? New uncertainty! [see talk by Michael Spira]

Proposal to include scheme uncertainties [Baglio et al. 2008.11626]

- take envelope of prediction with top pole mass and MSbar top mass evaluated at $\mu = m_t$, $\mu = M_{HH}$ and $\mu = M_{HH}/4$

- linear combination with scale uncertainty

- for FTapprox NNLO numbers: combine the NNLO scale uncertainties linearly with NLO scheme uncertainty

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Uncertainty large!!!

$$\begin{aligned}
\sqrt{s} = 13 \text{ TeV}: \quad \sigma_{tot} &= 31.05^{+6\%}_{-23\%} \text{ fb}, \\
\sqrt{s} = 14 \text{ TeV}: \quad \sigma_{tot} &= 36.69^{+6\%}_{-23\%} \text{ fb}, \\
\sqrt{s} = 27 \text{ TeV}: \quad \sigma_{tot} &= 139.9^{+5\%}_{-22\%} \text{ fb}, \\
\sqrt{s} = 100 \text{ TeV}: \quad \sigma_{tot} &= 1224^{+4\%}_{-21\%} \text{ fb}
\end{aligned}$$

mt -scheme uncertainty

Future plans:

Update of the numbers including the m_t scheme dependence

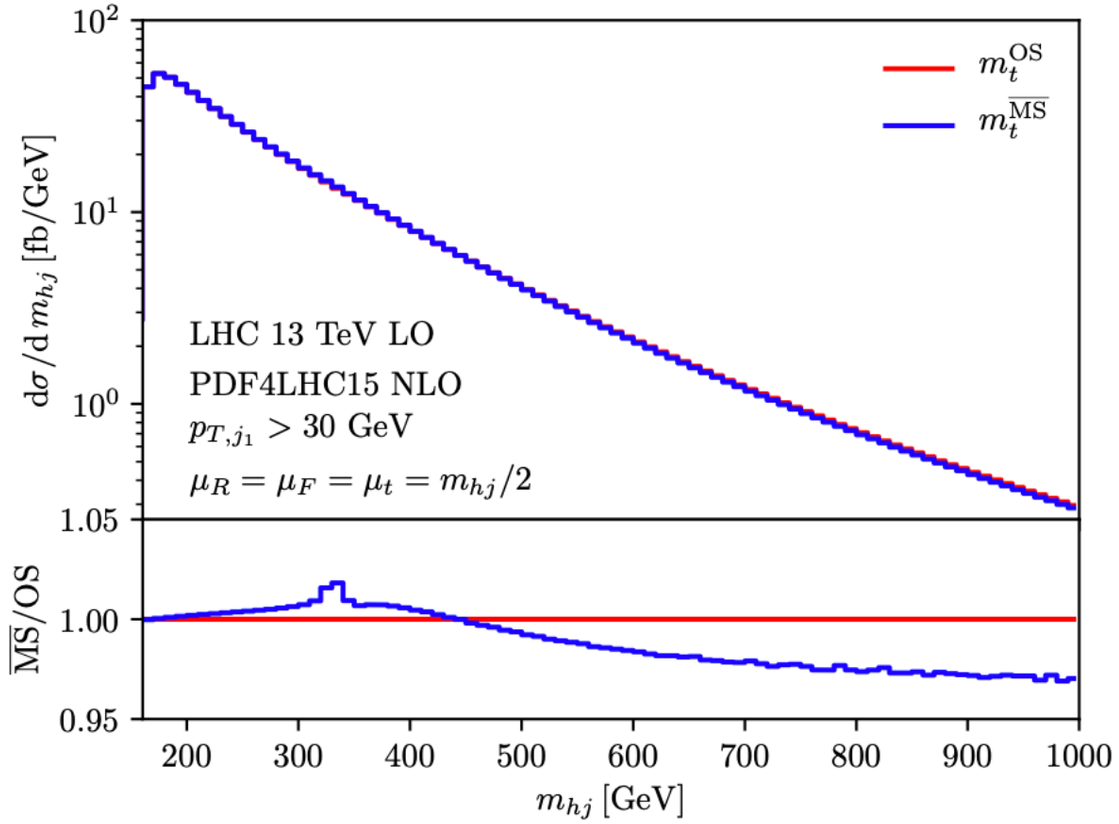
Do other WG's agree with the proposed procedure?

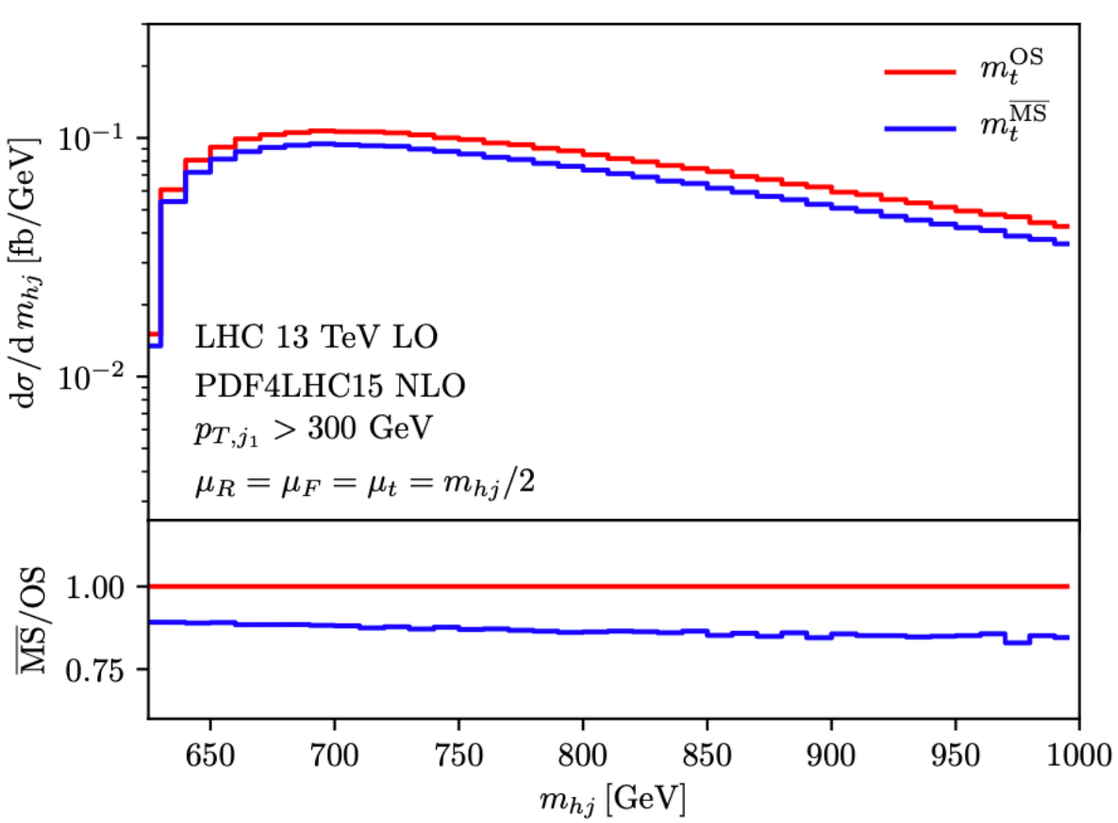
same issue for other processes!

$gg \to ZZ, gg \to Hj, gg \to HZ$

$gg \to \Phi$ for a heavy Higgs boson

$pp \to H + j$ [S. Jones and M. Spira in Les Houches] $pp \to H + j$





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Can we understand more looking at other processes?

How do we expect the uncertainty to look like at NNLO?
What is the best way to combine with NNLO?

Cross check with analytical results [Bonciani, Degrassi, Giardino, Gröber '18, Gröber, Maier, Rauh '17]

VBF

Recommendations at NNNLO QCD

[Dreyer, Karlberg '18]

m_H (GeV)	$\sqrt{s}$ = 13 TeV	$\sqrt{s}$ = 14 TeV	$\sqrt{s}$ = 27 TeV	$\sqrt{s}$ = 100 TeV
124.5	$1.739\ ^{+0.03\%}_{-0.04\%}$ ±2.1%	$2.071\ ^{+0.03\%}_{-0.04\%}$ ±2.1%	$8.459\ ^{+0.11\%}_{-0.04\%}$ ±2.0%	$83.25\ ^{+0.15\%}_{-0.05\%}$ ±2.1%
125	$1.726\ ^{+0.03\%}_{-0.04\%}$ ±2.1%	$2.055\ ^{+0.03\%}_{-0.04\%}$ ±2.1%	$8.404\ ^{+0.11\%}_{-0.04\%}$ ±2.0%	$82.84\ ^{+0.13\%}_{-0.04\%}$ ±2.1%
125.09	$1.723\ ^{+0.03\%}_{-0.04\%}$ ±2.1%	$2.052\ ^{+0.03\%}_{-0.04\%}$ ±2.1%	$8.394\ ^{+0.11\%}_{-0.04\%}$ ±2.0%	$82.77\ ^{+0.11\%}_{-0.04\%}$ ±2.1%
125.5	$1.711\ ^{+0.03\%}_{-0.04\%}$ ±2.1%	$2.038\ ^{+0.03\%}_{-0.04\%}$ ±2.1%	$8.349\ ^{+0.11\%}_{-0.04\%}$ ±2.0%	$82.44\ ^{+0.14\%}_{-0.05\%}$ ±2.1%

to be updated to include NLO EW corrections and non-factorisable corrections

[Dreyer, Karlberg, Lang, Pellen '20]

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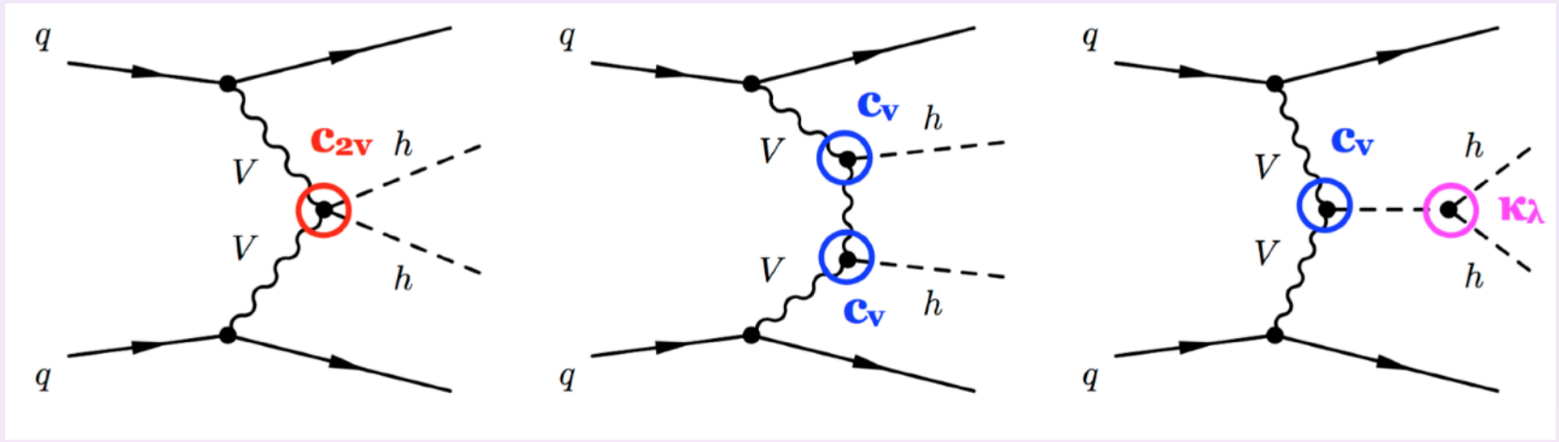

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[Dreyer, Karlberg, Lang, Pellen '20]

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EFT predictions in VBF:

So far: EFT prediction obtained by

$$\sigma^{EFT}_{N^3LO} = \sigma^{EFT}_{LO} \frac{\sigma^{SM}_{N^3LO}}{\sigma^{SM}_{LO}}$$

exact in structure function approach (which is exact up to NLO)

VBF

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$\lambda = M_V$	σ_{TT}	σ_{BB}	σ_{TB}	Σ
Born	10.393 fb	14.172 fb	−23.904 fb	0.662 fb
1-loop NF	0.339%	0.518%	0.399%	2.03%
2-loop NF	−0.667%	−0.658%	−0.666%	−0.50%
Full NF	−0.327%	−0.139%	−0.267%	1.52%

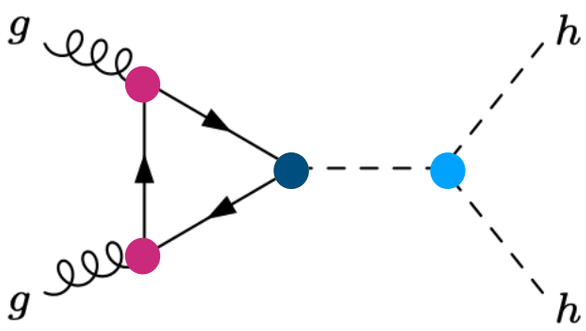
Effect O(1-2%) but bigger with VBF cuts and for distributions

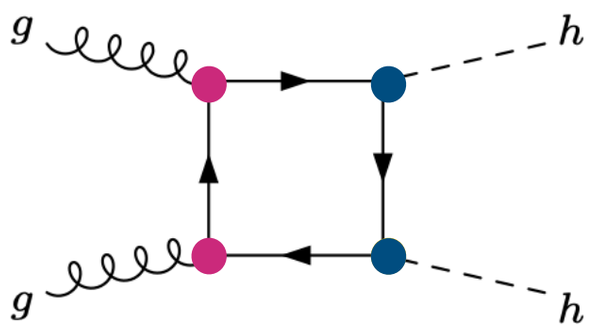
Effect on EFT predictions to be checked!

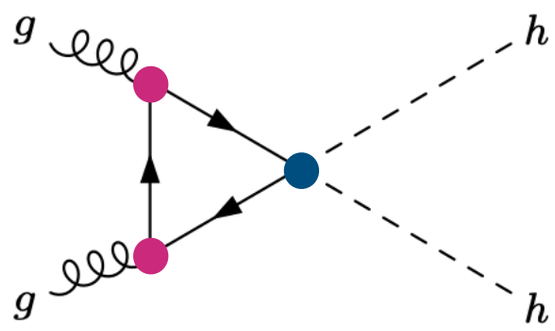
Effective Theory for HH

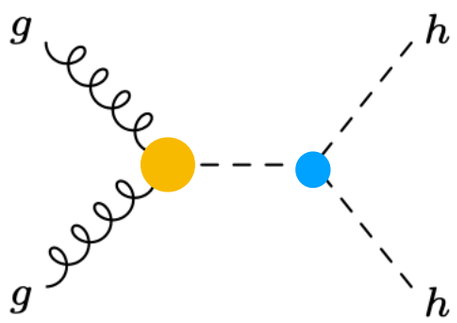
Status:

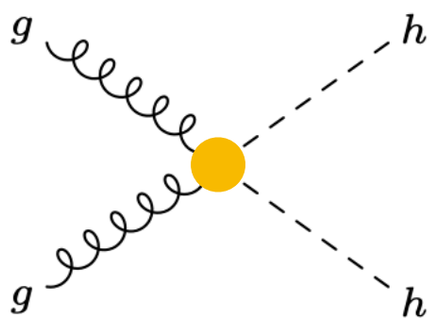
Predictions given only for variation of κ_λ

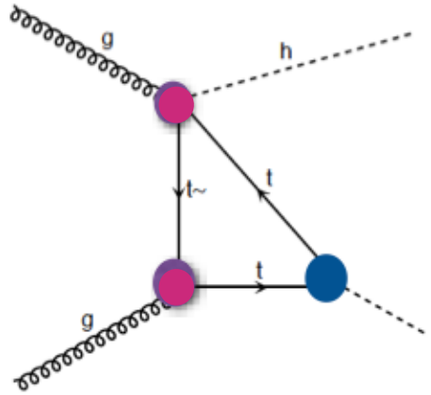












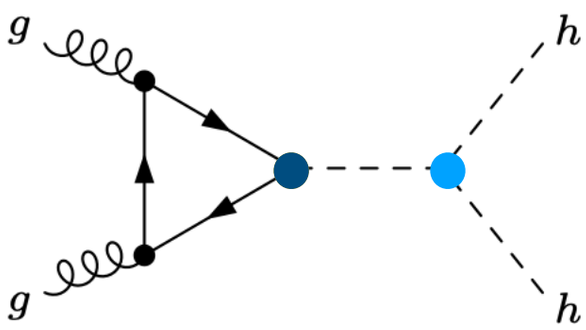
SMEFT:

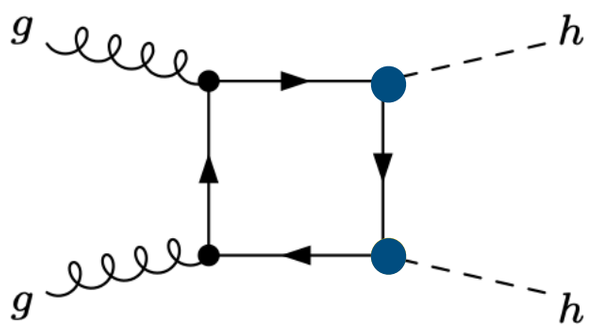
$$\mathscr{L} = \frac{c_H}{\Lambda^2}(H^\dagger \partial_\mu H)^2 + \frac{c_6}{\Lambda^2}|H|^6 + \frac{c_g}{\Lambda^2}|H|^2 G_{\mu\nu}G^{\mu\nu} + \frac{y_t c_y}{\Lambda^2}\bar{Q}_L \tilde{H} t_R |H|^2 + h.c. + \frac{c_{tG}}{\Lambda^2}\bar{Q}_L \sigma_{\mu\nu} T^a \tilde{H} t_R G^a_{\mu\nu} + h.c.$$

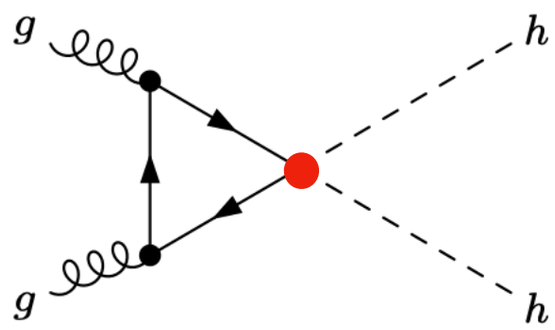
Effective Theory for HH

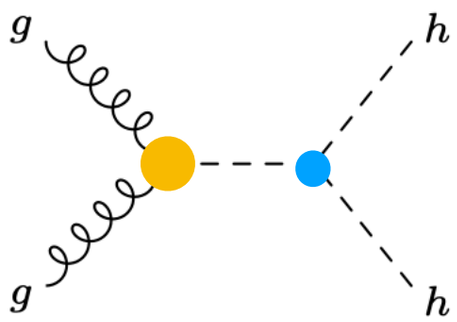
Status:

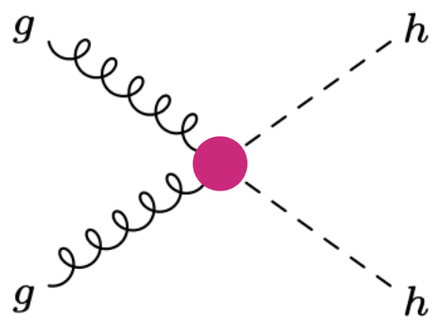
Predictions given only for variation of κ_λ











HEFT:

$$\mathscr{L} = -m_t \bar{t} t \left(c_t \frac{h}{v} + c_{tt} \frac{h^2}{v^2} \right) + \frac{\alpha_s}{8\pi} \left(c_g \frac{h}{v} + c_{gg} \frac{h^2}{v^2} \right) G^{\mu\nu} G_{\mu\nu} + c_{hhh} \frac{m_h^2}{2v} h^3$$

Effective Theory for HH

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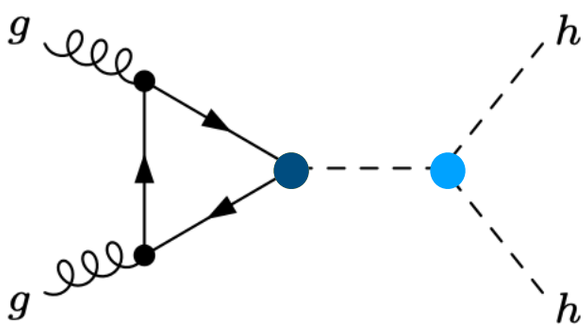
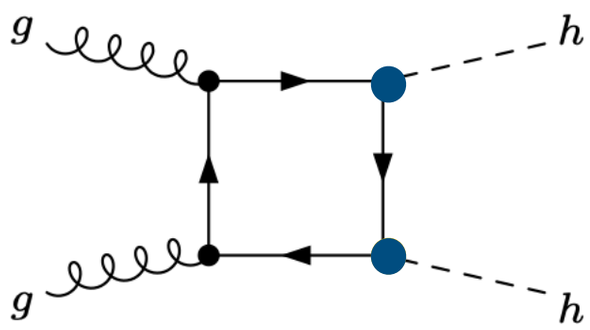
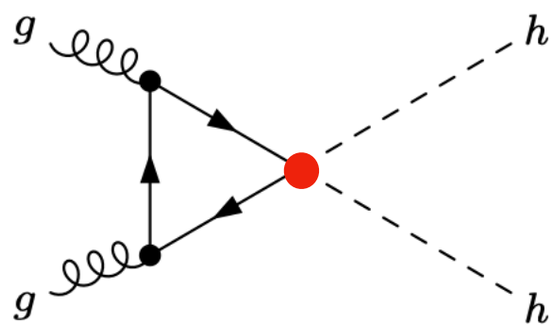
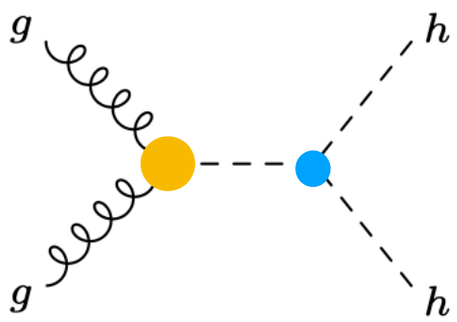
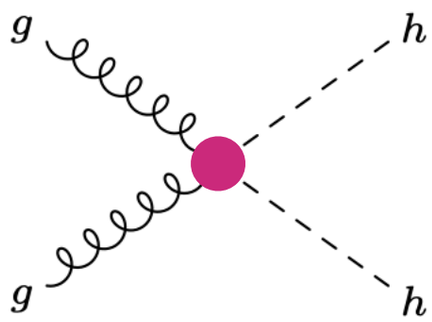
Predictions given only for variation of κ_λ











HEFT: two Higgs couplings only to be probed in HH

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Effective Theory for HH

What to recommend? HEFT/SMEFT?

based on discussion among the HH/WG2 convenors on 2nd Nov

HEFT

⊕ NLO results available

[Buchalla et al '18; Heinrich et al '20]

⊕ di-Higgs is THE place to probe differences in one or two Higgs couplings

⊖ many more couplings only in HH: degeneracies?

⊖ UV models that don't linearise?

SMEFT

⊕ contains dipole operator (which by power counting is expected to be of higher order though)

⊕ Combination with single Higgs fits simpler (take bounds on single Higgs operators from there and determine trilinear from that)

Next steps: understand constraining power of HEFT

Resonant production

[talk by Maggie]

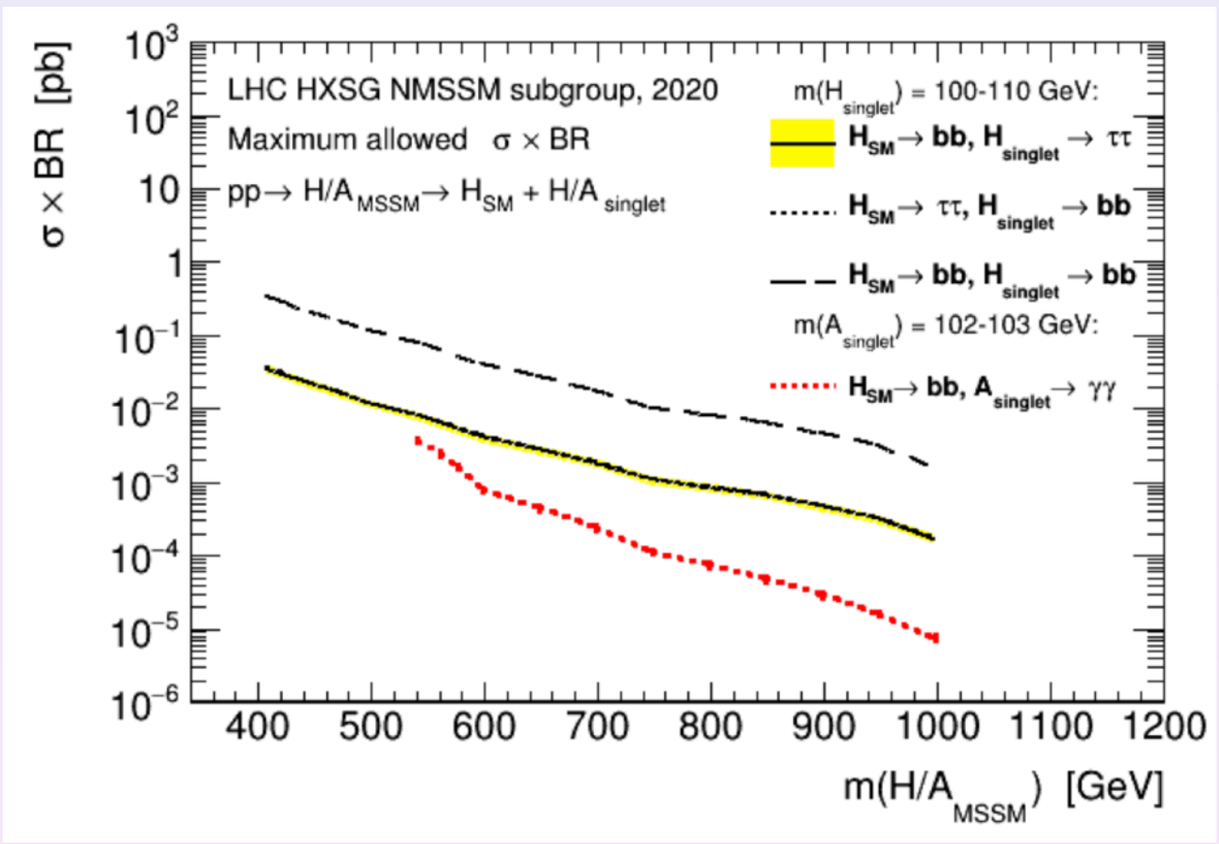
Plan: New and updated benchmarks for di-Higgs including asymmetric final states

$$pp \to H \to hh \qquad\qquad pp \to S \to Hh$$

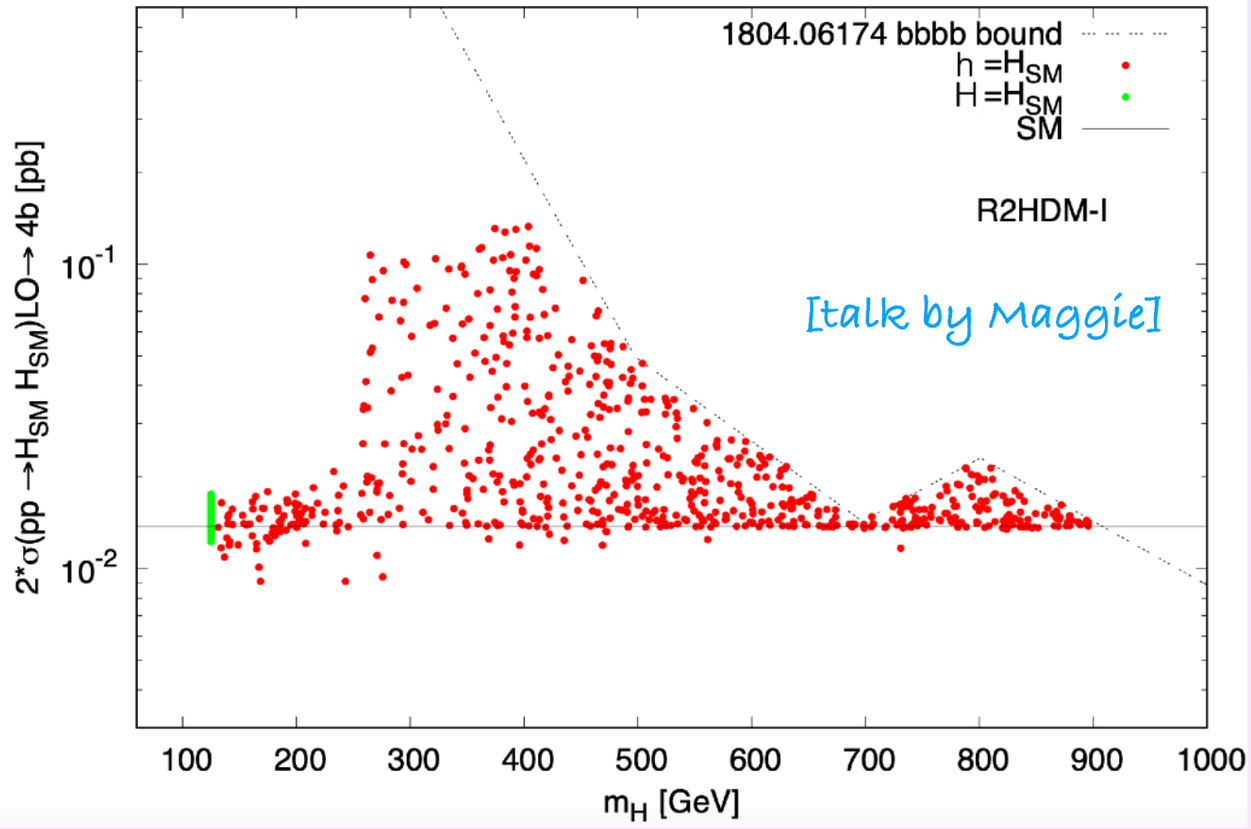
received some benchmark scenarios in 2019/2020, NMSSM subgroup

[Robens, et al.; Basler, Dawson, Englert, Mühlleitner; Baum, Shah]

NMSSM



2HDM



Resonant production

We have a lot of input, now it is time to decide which benchmarks to recommend!

How to choose?

- for different combinations of final state Higgs pairs and different decay signatures

that allow to

- exclude/test models
- identifying for smoking gun/exotic signatures
- complement for standard non-SM Higgs searches
- complement single Higgs results

- VBF resonances? [talk by Rahool]

Summary

Activities di-Higgs cross group

- update SM predictions to newest developments (ggF at N^{3}LO, VBF EW and non-factorisable corrections), mt scheme choice uncertainty

- point 1 left out: modelling of HH+2j but see [talk by Rachel, Siewyan]

- EFT: ongoing discussion with WG2, goal: give EFT recommendations

- BSM HH production: select new/updated benchmarks

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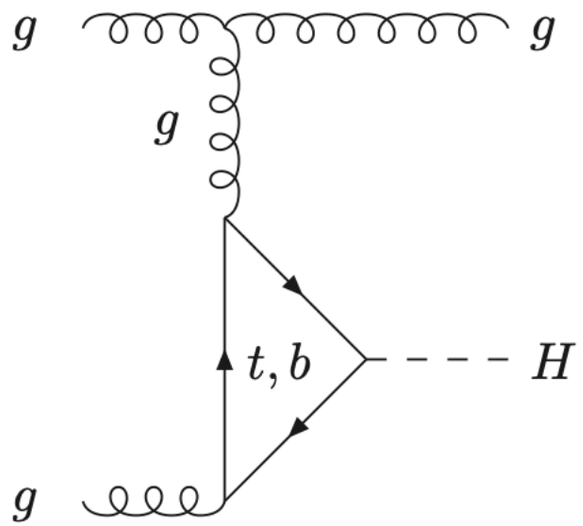
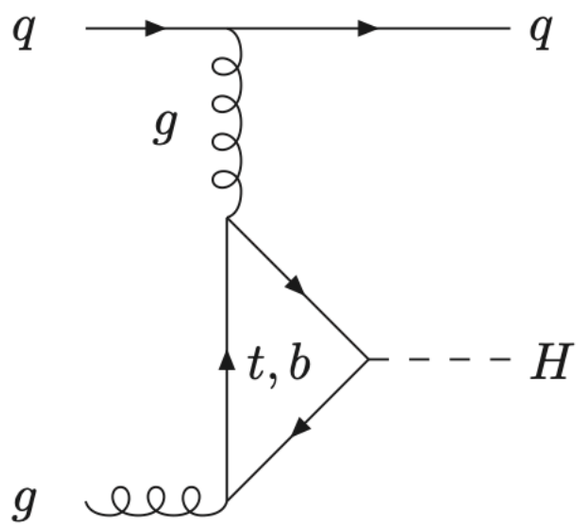
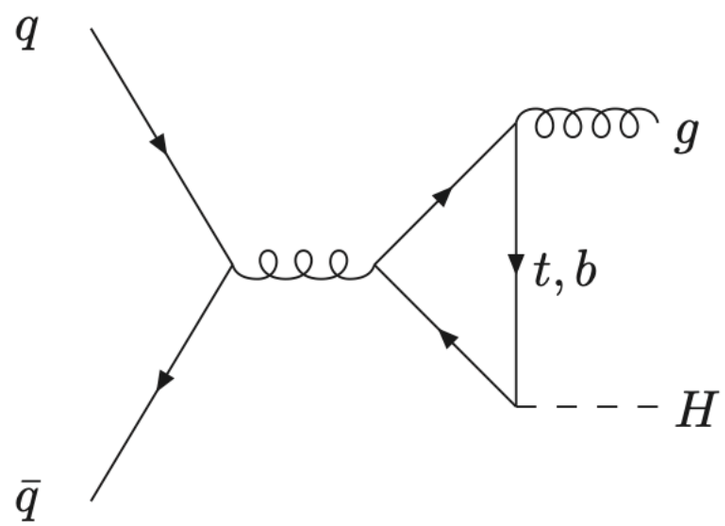
Discussion meeting ID:
893 6843 4922

Thanks for your attention!

mt -scheme uncertainty Hj







Small P_T cut: dominance of t/u channel exchange gluon diagrams