Higgs Pair Production

(and part of a 27 TeV case)

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Universität Heidelberg

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Fundamental Higgs questions

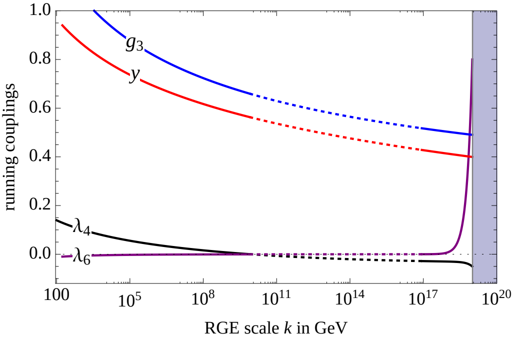
Vacuum stability

– Standard Model possibly consistent to Planck scale

– renormalizable theory tool to probe fundamental physics
usually interpreted as m_H vs m_t
strictly speaking λ_4 vs y_t [otherwise it's SM]

– decision on stability made bottom-up [Buttazzo...]

– vacuum stability determined by λ_4? [Eichorn, TP...]



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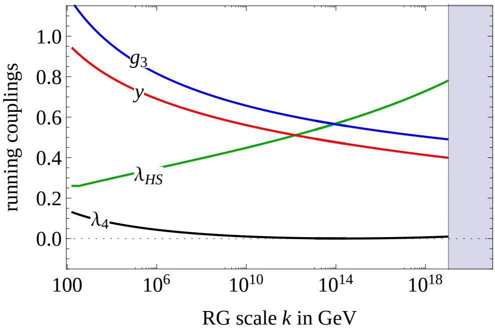

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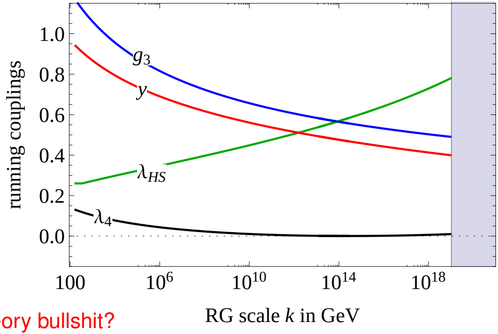


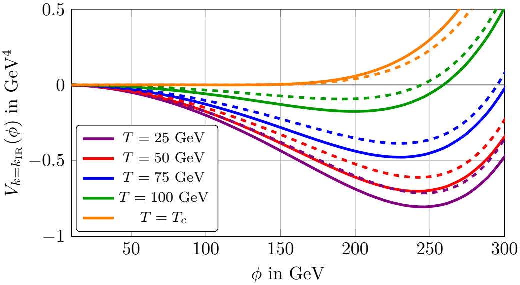
$\Rightarrow$ more than the usual theory bullshit?

Fundamental Higgs questions

More specific: baryogenesis [Eichhorn, TP,...]

– Sakharov conditions

baryon number violation
C and CP violation [Maggie's talk?]
departure from thermal equilibrium $\to$ 1st-order e-w phase transition



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general potential: phase transition vs self-coupling? [technique interesting-tedious]

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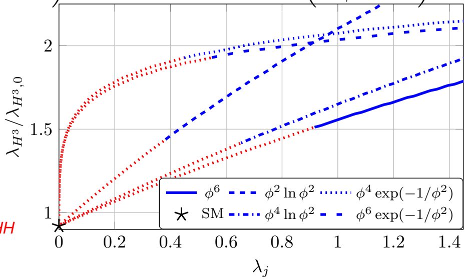
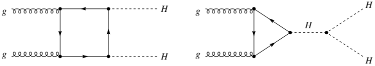


$\Rightarrow$ strong e-w phase transition
requiring 50% enhanced λ_{HHH}

LHC analysis



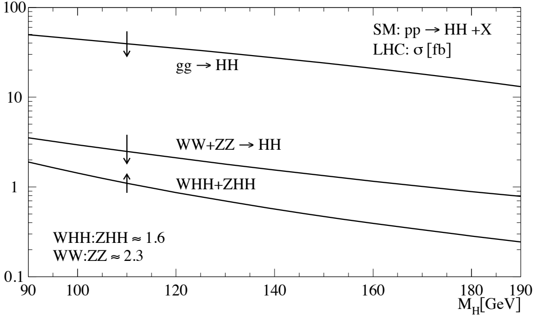
Loop amplitude $gg \to HH$ [Glover & v.d.Bij (1988)]

– heavy-top approximation [TP, Spira, Zerwas (1996)]

$$\mathscr{L}_{ggH} = G^{\mu\nu} G_{\mu\nu} \, \frac{\alpha_s}{\pi} \left(\frac{H}{12v} - \frac{H^2}{24v^2} + \dots \right) = \frac{\alpha_s}{12\pi} \, G^{\mu\nu} G_{\mu\nu} \, \log \left(1 + \frac{H}{v} \right)$$

rule out modified λ_{HHH} from lack of events

[Djouadi, Kilian, Mühlleitner, Zerwas (1999)]



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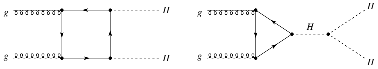

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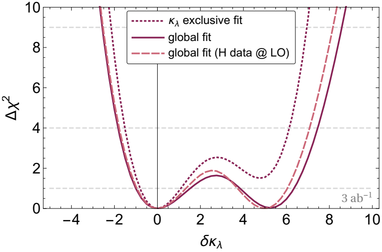

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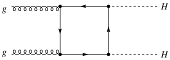

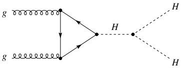

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– $2 \to 2$ process $\to$ one distribution: m_{HH} [Baur, TP, Rainwater (2002)]

1– threshold behavior $m_{HH} \approx 2m_H$

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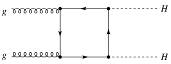

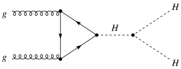

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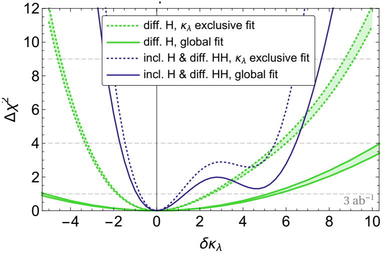

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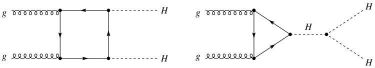

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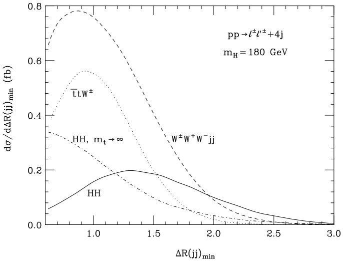
– large-m_t approx useless [Baur...; Heinrich...]

– HH signatures old news

resonance searches $HH \to 4b$
SM-measurement $HH \to bb\gamma\gamma, bb\tau\tau$
dreaming about $HH \to bbWW$

$\Rightarrow$ statistics limitation obvious



MadMax

Understanding modern analyses

– hardly any counting experiments left

– kinematic information central
but more and more x-axes with NN output

$\Rightarrow$ which feature drives analyses?

Differential significance distribution [Brehmer, Kling, TP, Schichtel, Wiegand]

– Neyman–Pearson lemma
log-likelihood ratio the best discriminator

– maximum significance through PS integral [Cranmer & TP]

$$q(r) = -\sigma_{\text{tot},s}\, \mathcal{L} \; + \log\left(1 + \frac{d\sigma_s(r)}{d\sigma_b(r)}\right) \; .$$

– LLR evaluated in parallel to cross sections
translated into significance

– leading detector effects for irreducible processes

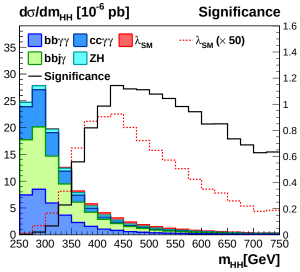
– examples: BSM effect vs SM prediction
SM signal vs SM background
BSM signal vs all SM

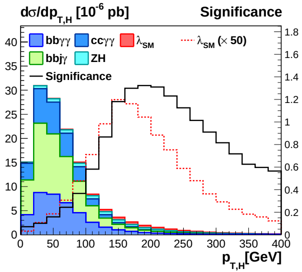
$\Rightarrow$ significance distributed over phase space

MadMax and the future

Application to $HH \to bb\gamma\gamma$ [Goncalves, Han, Kling, TP, Schichtel, Takeuchi]

– SM signal vs continuum backgrounds [rate and significance]





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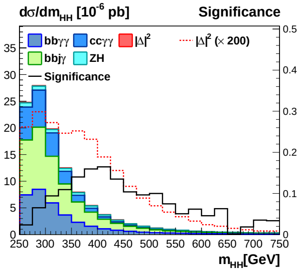

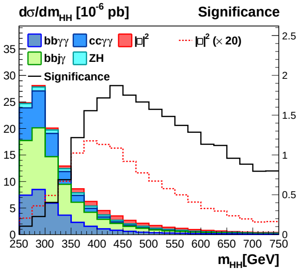

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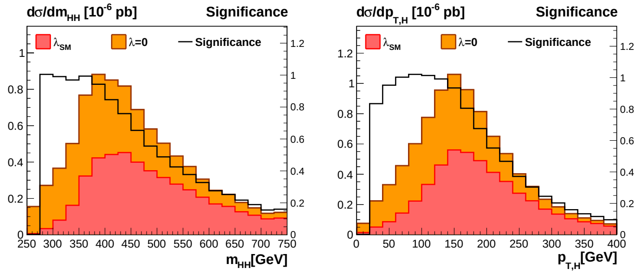

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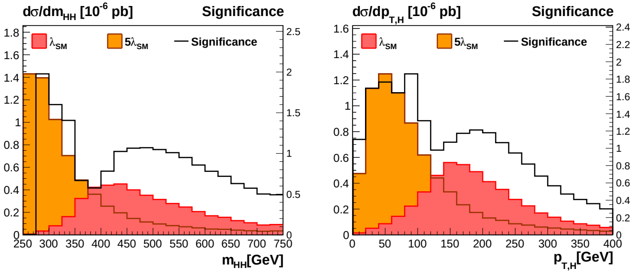

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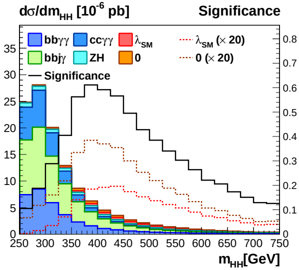

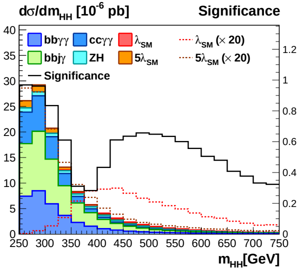

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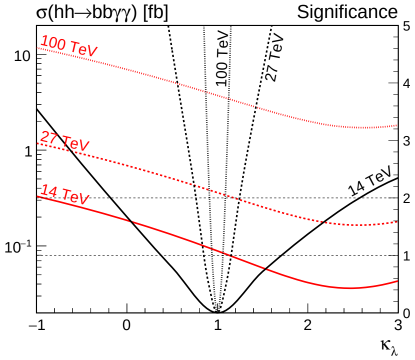
$\Rightarrow$ maximum reach at 27 TeV great [κ_λ varied only]



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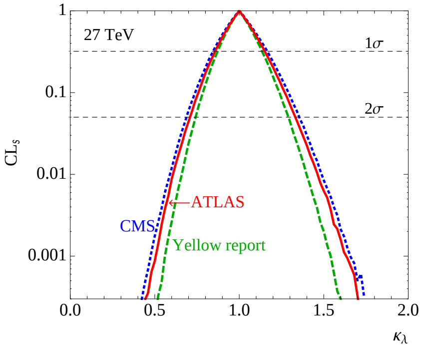
$\Rightarrow$ analysis including extra jet and m_{HH} stable



Precision predictions [Gudrun Heinrich]

$\sqrt{s}$	13 TeV	14 TeV	27 TeV	100 TeV
NLO [fb]	$27.78^{+13.8\%}_{-12.8\%}$	$32.88^{+13.5\%}_{-12.5\%}$	$127.7^{+11.5\%}_{-10.4\%}$	$1147^{+10.7\%}_{-9.9\%}$
$\mathrm{NLO}_{\mathrm{FTapprox}}$ [fb]	$28.91^{+15.0\%}_{-13.4\%}$	$34.25^{+14.7\%}_{-13.2\%}$	$134.1^{+12.7\%}_{-11.1\%}$	$1220^{+11.9\%}_{-10.6\%}$
$\mathrm{NNLO}_{\mathrm{NLO-i}}$ [fb]	$32.69^{+5.3\%}_{-7.7\%}$	$38.66^{+5.3\%}_{-7.7\%}$	$149.3^{+4.8\%}_{-6.7\%}$	$1337^{+4.1\%}_{-5.4\%}$
$\mathrm{NNLO}_{\mathrm{B-proj}}$ [fb]	$33.42^{+1.5\%}_{-4.8\%}$	$39.58^{+1.4\%}_{-4.7\%}$	$154.2^{+0.7\%}_{-3.8\%}$	$1406^{+0.5\%}_{-2.8\%}$
$\mathrm{NNLO}_{\mathrm{FTapprox}}$ [fb]	$31.05^{+2.2\%}_{-5.0\%}$	$36.69^{+2.1\%}_{-4.9\%}$	$139.9^{+1.3\%}_{-3.9\%}$	$1224^{+0.9\%}_{-3.2\%}$
M_t unc. $\mathrm{NNLO}_{\mathrm{FTapprox}}$	$\pm 2.6\%$	$\pm 2.7\%$	$\pm 3.4\%$	$\pm 4.6\%$
$\mathrm{NNLO}_{\mathrm{FTapprox}}/\mathrm{NLO}$	1.118	1.116	1.096	1.067

considerable reduction of scale uncertainties

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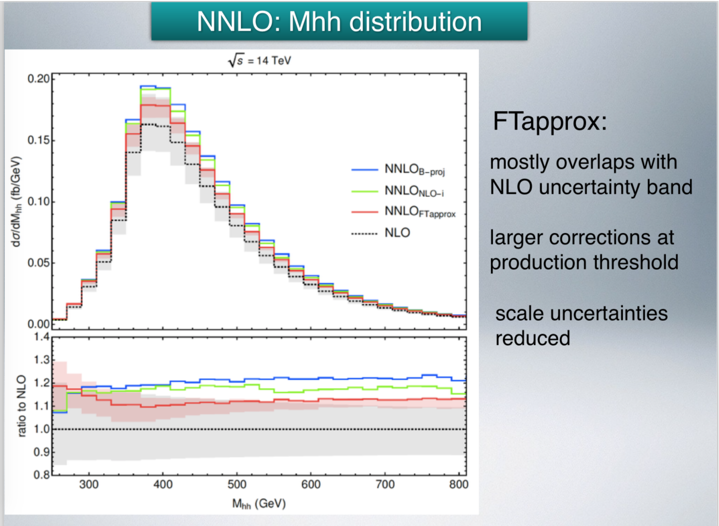

Standard Model EFT

Higgs sector including dimension-6 operators

$$\mathcal{L}_{D6} = \sum_{i=1}^{2} \frac{f_i}{\Lambda^2} \mathcal{O}_i \quad \text{with} \quad \mathcal{O}_{\phi,2} = \frac{1}{2} \partial_\mu (\phi^\dagger \phi) \, \partial^\mu (\phi^\dagger \phi) \; , \quad \mathcal{O}_{\phi,3} = -\frac{1}{3} (\phi^\dagger \phi)^3$$

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first operator, wave function renormalization

$$\mathcal{O}_{\phi,2} = \frac{1}{2} \partial_\mu (\phi^\dagger \phi) \, \partial^\mu (\phi^\dagger \phi) = \frac{1}{2} \, (\tilde{H} + v)^2 \, \partial_\mu \tilde{H} \, \partial^\mu \tilde{H}$$

proper normalization of combined kinetic term [LSZ]

$$\mathcal{L}_{\text{kin}} = \frac{1}{2} \partial_\mu \tilde{H} \, \partial^\mu \tilde{H} \left(1 + \frac{f_{\phi,2} v^2}{\Lambda^2} \right) \stackrel{!}{=} \frac{1}{2} \partial_\mu H \, \partial^\mu H \quad \Leftrightarrow \quad H = \tilde{H} \sqrt{1 + \frac{f_{\phi,2} v^2}{\Lambda^2}}$$

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second operator, minimum condition giving v

$$v^2 = -\frac{\mu^2}{\lambda} - \frac{f_{\phi,3} \mu^4}{4 \lambda^3 \Lambda^2}$$

both operators contributing to Higgs mass

$$\mathcal{L}_{\text{mass}} = -\frac{\mu^2}{2} \tilde{H}^2 - \frac{3}{2} \lambda v^2 \tilde{H}^2 - \frac{f_{\phi,3}}{\Lambda^2} \frac{15}{24} v^4 \tilde{H}^2 \stackrel{!}{=} -\frac{m_H^2}{2} H^2$$

$$\Leftrightarrow \qquad m_H^2 = 2 \lambda v^2 \left(1 - \frac{f_{\phi,2} v^2}{\Lambda^2} + \frac{f_{\phi,3} v^2}{2 \Lambda^2 \lambda} \right)$$

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$$\mathcal{O}_{\phi,2} = \frac{1}{2} \partial_\mu (\phi^\dagger \phi) \, \partial^\mu (\phi^\dagger \phi) = \frac{1}{2} \, (\tilde{H} + v)^2 \, \partial_\mu \tilde{H} \, \partial^\mu \tilde{H}$$

proper normalization of combined kinetic term [LSZ]

$$\mathcal{L}_{\text{kin}} = \frac{1}{2} \partial_\mu \tilde{H} \, \partial^\mu \tilde{H} \left(1 + \frac{f_{\phi,2} v^2}{\Lambda^2} \right) \stackrel{!}{=} \frac{1}{2} \partial_\mu H \, \partial^\mu H \quad \Leftrightarrow \quad H = \tilde{H} \sqrt{1 + \frac{f_{\phi,2} v^2}{\Lambda^2}}$$

Higgs self couplings momentum dependent

$$\begin{aligned} \mathcal{L}_{\text{self}} = &- \frac{m_H^2}{2v} \left[\left(1 - \frac{f_{\phi,2} v^2}{2\Lambda^2} + \frac{2 f_{\phi,3} v^4}{3\Lambda^2 m_H^2} \right) H^3 - \frac{2 f_{\phi,2} v^2}{\Lambda^2 m_H^2} H \, \partial_\mu H \, \partial^\mu H \right] \\ &- \frac{m_H^2}{8v^2} \left[\left(1 - \frac{f_{\phi,2} v^2}{\Lambda^2} + \frac{4 f_{\phi,3} v^4}{\Lambda^2 m_H^2} \right) H^4 - \frac{4 f_{\phi,2} v^2}{\Lambda^2 m_H^2} H^2 \, \partial_\mu \, H \partial^\mu H \right] \end{aligned}$$

alternatively, strong multi-Higgs interactions [Maggie, again]

$$H = \left(1 + \frac{f_{\phi,2} v^2}{2\Lambda^2} \right) \tilde{H} + \frac{f_{\phi,2} v}{2\Lambda^2} \tilde{H}^2 + \frac{f_{\phi,2}}{6\Lambda^2} \tilde{H}^3 + \mathcal{O}(\tilde{H}^4)$$

Standard Model EFT

Self-coupling in a global analysis: 27 TeV [Biekötter, TP, Rauch w/ Goncalves, Takeuchi]

– including relevant D6 operators [Goertz, Papaefstathiou, Yang, Zurita...]

$$\mathcal{O}_H = \partial_\mu(\phi^\dagger\phi)\,\partial^\mu(\phi^\dagger\phi) \qquad \mathcal{O}_6 = -\frac{1}{3}(\phi^\dagger\phi)^3$$

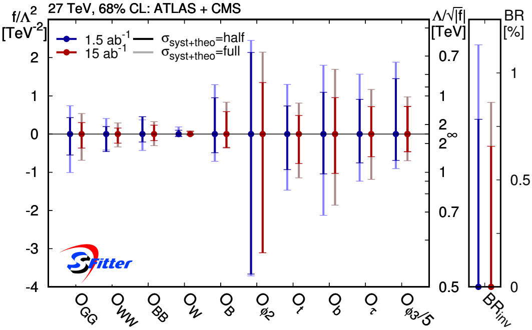
$$\mathcal{O}_G = (\phi^\dagger\phi)\,G_{\mu\nu}G^{\mu\nu} \qquad \mathcal{O}_f = y_f(\phi^\dagger\phi)\bar{Q}_L\phi r_R$$

– including known correlation with top Yukawa

– omitting triple gluon coupling [Krauss, Kuttimalai, TP]

– omitting anomalous top couplings [Buckley, Englert,...]

⇒ reasonably, but worse than general D6 effects



Outlook

30 years of Higgs pairs@LHC [okay, 20 years]

– way too many pheno papers about *HH* decays
– few theory papers on why we should care

– simple 2 $\to$ 2 signal process
– single Higgs does not help
– kinematic distributions helpful

– heavy-top approximation poor
– precision predictions making serious progress

$\Rightarrow$ the one channel where 27 TeV makes all the difference