Some Theory Thoughts

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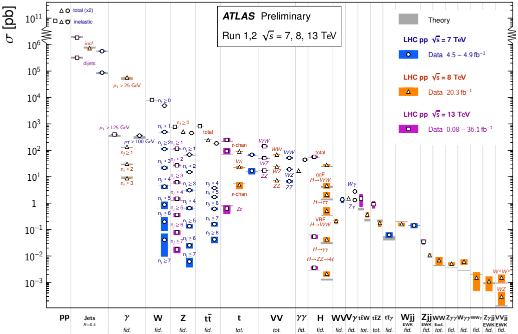
Higgs Hunting, September 2021

Why Higgs physics?

Show-off measurements

- many processes
- vastly different rates
- high precision
- predicted by theory



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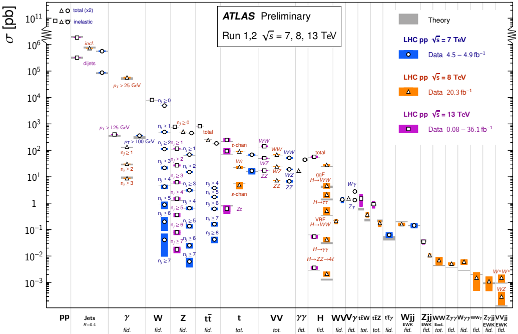
$\Rightarrow$ But completely useless



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Fundamental questions

- particle nature of dark matter?
- origin of the Higgs mechanism?
- matter-antimatter asymmetry?

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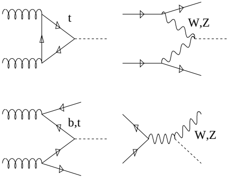
Fundamental questions in Higgs physics

- ~~Higgs couplings?~~
- new particles in Higgs-gauge sector?
- form of Higgs potential?

$\Rightarrow$ Kinematics, not just rates [simulation-based inference]

Higgs couplings



How the LHC became a precision machine

- assume: narrow *CP*-even scalar
  Standard Model operators
- Lagrangian like non-linear symmetry breaking

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \Delta_W \; g m_W H \; W^\mu W_\mu + \Delta_Z \; \frac{g}{2c_w} m_Z H \; Z^\mu Z_\mu - \sum_{\tau,b,t} \Delta_f \; \frac{m_f}{v} H \left(\bar{f}_R f_L + \text{h.c.} \right)$$
$$+ \Delta_g F_G \; \frac{H}{v} \; G_{\mu\nu} G^{\mu\nu} + \Delta_\gamma F_A \; \frac{H}{v} \; A_{\mu\nu} A^{\mu\nu} + \text{invisible} + \text{unobservable}$$

Production		Coupling		Decay
$gg \to H$ $gg \to H+j$ (boosted) $gg \to H^*$ (off-shell) $qq \to qqH$ $gg \to t\bar{t}H$ $qq' \to VH$	$\longleftrightarrow$	$g_{HXX} = g_{HXX}^{\text{SM}} \; (1 + \Delta_X)$	$\longleftrightarrow$	$H \to ZZ$ $H \to WW$ $H \to b\bar{b}$ $H \to \tau^+\tau^-$ $H \to \gamma\gamma$ $H \to$ invisible

$\Rightarrow$ Brilliant Run 1 results, but answering wrong question

Higgs-gauge operators

D6 Lagrangian for Run 2 [SMEFT]

– Higgs operators [renormalizable]

$$\mathcal{O}_{GG} = \phi^\dagger \phi G^a_{\mu\nu} G^{a\mu\nu} \qquad \mathcal{O}_{WW} = \phi^\dagger \hat{W}_{\mu\nu} \hat{W}^{\mu\nu} \phi \qquad \mathcal{O}_{BB} = \cdots$$

$$\mathcal{O}_{BW} = \phi^\dagger \hat{B}_{\mu\nu} \hat{W}^{\mu\nu} \phi \qquad \mathcal{O}_{W} = (D_\mu \phi)^\dagger \hat{W}^{\mu\nu} (D_\nu \phi) \qquad \mathcal{O}_{B} = \cdots$$

$$\mathcal{O}_{\phi,1} = (D_\mu \phi)^\dagger \phi \, \phi^\dagger \, (D^\mu \phi) \qquad \mathcal{O}_{\phi,2} = \frac{1}{2} \partial^\mu \left(\phi^\dagger \phi\right) \partial_\mu \left(\phi^\dagger \phi\right) \qquad \mathcal{O}_{\phi,3} = \frac{1}{3} \left(\phi^\dagger \phi\right)^3$$

– basis after equation of motion, field re-definition, integration by parts

$$\mathcal{L}_{\text{D6}} = -\frac{\alpha_s v}{8\pi} \frac{f_g}{\Lambda^2} \mathcal{O}_{GG} + \frac{f_{BB}}{\Lambda^2} \mathcal{O}_{BB} + \frac{f_{WW}}{\Lambda^2} \mathcal{O}_{WW} + \frac{f_B}{\Lambda^2} \mathcal{O}_{B} + \frac{f_W}{\Lambda^2} \mathcal{O}_{W} + \frac{f_{\phi,2}}{\Lambda^2} \mathcal{O}_{\phi,2}$$

– Higgs couplings [derivatives = momentum]

$$\begin{aligned} \mathcal{L}_{\text{D6}} = \; & g_g \; H G^a_{\mu\nu} G^{a\mu\nu} + g_\gamma \; H A_{\mu\nu} A^{\mu\nu} \\ & + g^{(1)}_Z \; Z_{\mu\nu} Z^\mu \partial^\nu H + g^{(2)}_Z \; H Z_{\mu\nu} Z^{\mu\nu} + g^{(3)}_Z \; H Z_\mu Z^\mu \\ & + g^{(1)}_W \; \left(W^+_{\mu\nu} W^{-\,\mu} \partial^\nu H + \text{h.c.} \right) + g^{(2)}_W \; H W^+_{\mu\nu} W^{-\,\mu\nu} + g^{(3)}_W \; H W^+_\mu W^{-\,\mu} + \cdots \end{aligned}$$

plus Yukawa structure $f_{\tau,b,t}$

– one more operator for TGV

$$\mathcal{O}_{WWW} = \text{Tr} \left(\hat{W}_{\mu\nu} \hat{W}^{\nu\rho} \hat{W}^\mu_\rho \right)$$

⇒ Bosonic electroweak sector: 10 operators

Fermionic operators

Enlarging operator basis [Biekötter, Corbett, TP; Zhang; Baglio, Dawson, Lewis; Alves etal]

– gauge-fermion operators visible [$qqVH$ vertex]

$$\mathcal{O}^{(1)}_{\phi L} = \phi^\dagger \overleftrightarrow{D}_\mu \phi (\bar{L}_i \gamma^\mu L_i) \qquad \mathcal{O}^{(1)}_{\phi e} = \phi^\dagger \overleftrightarrow{D}_\mu \phi (\bar{e}_{R,i} \gamma^\mu e_{R,i}) \qquad \mathcal{O}^{(3)}_{\phi L} = \phi^\dagger \overleftrightarrow{D}^a_\mu \phi (\bar{L}_i \gamma^\mu \sigma_a L_i)$$

$$\mathcal{O}^{(1)}_{\phi Q} = \cdots \qquad \mathcal{O}^{(1)}_{\phi d} = \cdots \qquad \mathcal{O}^{(3)}_{\phi Q} = \cdots$$

$$\mathcal{O}^{(1)}_{\phi ud} = \tilde{\phi}^\dagger \overleftrightarrow{D}_\mu \phi (\bar{u}_{R,i} \gamma^\mu d_{R,i}) \qquad \mathcal{O}^{(1)}_{\phi u} = \cdots \qquad \mathcal{O}_{LLLL} = (\bar{L}_1 \gamma_\mu L_2)\,(\bar{L}_2 \gamma^\mu L_1)$$

– bosonic operators bounded by EWPD

$$\mathcal{O}_{\phi,1} = (D_\mu \phi)^\dagger \; \phi \phi^\dagger \; (D^\mu \phi) \qquad \mathcal{O}_{BW} = \phi^\dagger \hat{B}_{\mu\nu} \hat{W}^{\mu\nu} \phi$$

– bigger and better basis

$$\begin{aligned}\mathcal{L}_\text{eff} = & -\frac{\alpha_s v}{8\pi} \frac{f_g}{\Lambda^2} \mathcal{O}_{GG} + \frac{f_{BB}}{\Lambda^2} \mathcal{O}_{BB} + \frac{f_{WW}}{\Lambda^2} \mathcal{O}_{WW} + \frac{f_B}{\Lambda^2} \mathcal{O}_B + \frac{f_W}{\Lambda^2} \mathcal{O}_W + \frac{f_{WWW}}{\Lambda^2} \mathcal{O}_{WWW} \\ & + \frac{f_{\phi,2}}{\Lambda^2} \mathcal{O}_{\phi,2} + \sum_{\tau bt} \frac{m_f}{v} \frac{f_f}{\Lambda^2} \mathcal{O}_f + \frac{f_{\phi,1}}{\Lambda^2} \mathcal{O}_{\phi 1} + \frac{f_{BW}}{\Lambda^2} \mathcal{O}_{BW} + \frac{f_{LLLL}}{\Lambda^2} \mathcal{O}_{LLLL} \\ & + \frac{f^{(1)}_{\phi Q}}{\Lambda^2} \mathcal{O}^{(1)}_{\phi Q} + \frac{f^{(1)}_{\phi d}}{\Lambda^2} \mathcal{O}^{(1)}_{\phi d} + \frac{f^{(1)}_{\phi u}}{\Lambda^2} \mathcal{O}^{(1)}_{\phi u} + \frac{f^{(1)}_{\phi e}}{\Lambda^2} \mathcal{O}^{(1)}_{\phi e} + \frac{f^{(3)}_{\phi Q}}{\Lambda^2} \mathcal{O}^{(3)}_{\phi Q}\end{aligned}$$

$\Rightarrow$ Physics: rates vs kinematics vs EWPD

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$\Rightarrow$ Physics: rates vs kinematics vs EWPD

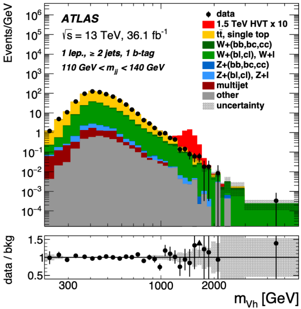
Higgs constraints from no-Higgs measurements

– m_{VH} perfect SMEFT kinematics

Search for heavy resonances decaying into a W or Z boson and a Higgs boson in final states with leptons and b-jets in 36 fb^{-1} of $\sqrt{s}$ = 13 TeV pp collisions with the ATLAS detector

The ATLAS Collaboration

A search is conducted for new resonances decaying into a W or Z boson and a 125 GeV Higgs boson in the $\nu\bar{\nu}b\bar{b}$, $\ell^\pm\nu b\bar{b}$, and $\ell^+\ell^-b\bar{b}$ final states, where $\ell^\pm = e^\pm$ or $\mu^\pm$, in pp collisions at $\sqrt{s}$ = 13 TeV. The data used correspond to a total integrated luminosity of 36.1 fb^{-1} collected with the ATLAS detector at the Large Hadron Collider during the 2015 and 2016 data-taking periods. The search is conducted by examining the reconstructed invariant or transverse mass distributions of Wh and Zh candidates for evidence of a localised excess in the mass range of 220 GeV up to 5 TeV. No significant excess is observed and the results are interpreted in terms of constraints on the production cross-section times branching fraction of heavy W' and Z' resonances in heavy-vector-triplet models and the CP-odd scalar boson A in two-Higgs-doublet models. Upper limits are placed at the 95% confidence level and range between 9.0×10^{-4} pb and 8.1×10^{-1} pb depending on the model and mass of the resonance.



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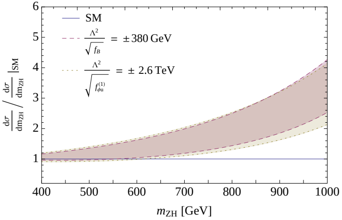
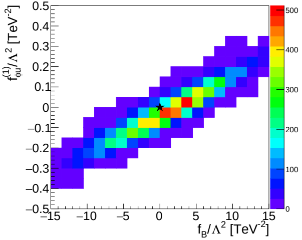
– hierarchy $\mathcal{O}^{(1)}_{\phi u} \to g_{qqZH}$ vs $\mathcal{O}_W \to g_{ZZH}$





All combined

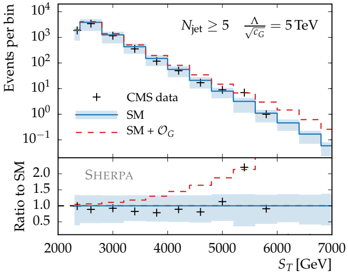
Ubiquitous QCD operator [Simmons etal; Dixon etal; TP, Krauss, Kuttimalai]

– anomalous gluon coupling

$$\mathcal{O}_G = g_s\, f_{abc} G^{\rho}_{a\nu} G^{\nu}_{b\lambda} G^{\lambda}_{c\rho}$$

– multi-jet production [black hole search]

4-fermion operator for $N_{\text{jets}} = 2, 3$
gluon operator for $N_{\text{jets}} \geq 5$



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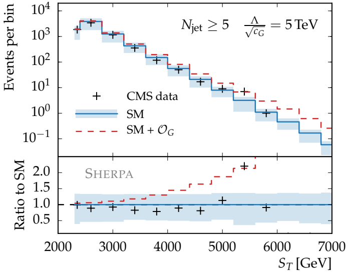


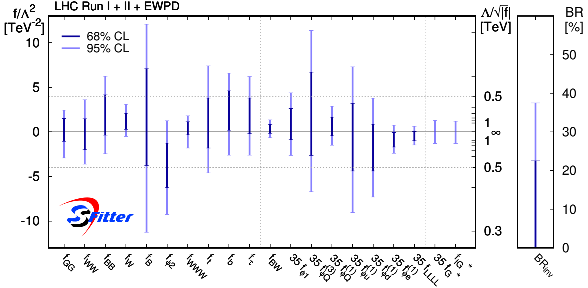
Run II Higgs-gauge analysis [Biekötter, Corbett, TP]

– quote f_{tG} [Sanz etal: not good assumption]

– quote multi-jet

– hierarchical limits

$\Rightarrow$ No anomalies

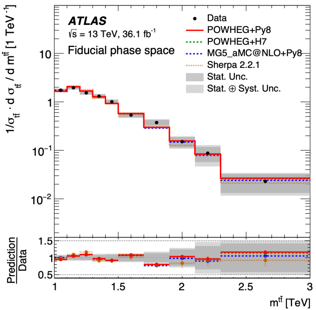


Higgs-gauge-top legacy

Top sector, executive summary [Brivio, Bruggisser, Maltoni, Moutafis, TP, Vryonidou, Westhoff, Zhang]

– production channels $t\bar{t}$, $t\bar{t}V$, tj, tV, plus top decays
– NLO predictions, theory uncertainties not only from scales
– m_{tt}, $p_{T,t}$ distributions unfolded
– highly correlated 4-fermion sector
– flat directions circular

$\Rightarrow$ Still no anomalies



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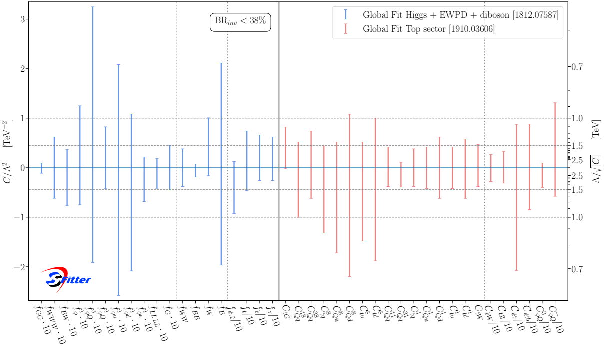
⇒ Still no anomalies

Combined Run II analysis — our future? [Sanz etal, Maltoni etal]



Back to actual models

SMEFT vs full model analyses [Brivio, Bruggisser, Geoffray, Kilian, Krämer, Luchmann, TP, Summ]

– usual vector triplet benchmark

$$\mathcal{L} = \mathcal{L}_{\text{SM}} - \frac{1}{4}\tilde{V}^{\mu\nu A}\tilde{V}^{A}_{\mu\nu} - \frac{\tilde{g}_M}{2}\,\tilde{V}^{\mu\nu A}\tilde{W}^{A}_{\mu\nu} + \frac{\tilde{m}_V^2}{2}\tilde{V}^{\mu A}\tilde{V}^{A}_{\mu}$$
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1- effect of one-loop matching?

2- theory uncertainty from matching scale Q?

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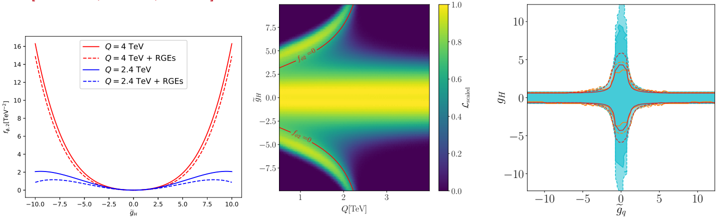
Impact [cf Dawson, Giardino, Homiller]



⇒ EFT uncertainty part of matching

⇒ by the way, SMEFT limits significantly weaker than full model, whenever applicable...

Information in kinematics

Information geometry for LHC [Brehmer, Cranmer, Kling]

- remember Neyman-Pearson lemma:
  how well can a data set compare two hypotheses?
- modern LHC physics:
  how much would a data set tell me about a continuous measurement?

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– wanted: covariance matrix [measurement error in model space **g**]

$$C_{ij}(\mathbf{g}) \equiv E\left[(\hat{g}_i - \bar{g}_i)(\hat{g}_j - \bar{g}_j)\middle|\mathbf{g}\right]$$

– computable: Fisher information [sensitivity in model space]

$$I_{ij}(\mathbf{g}) \equiv -E\left[\frac{\partial^2 \log f(\mathbf{x}|\mathbf{g})}{\partial g_i\, \partial g_j}\middle|\mathbf{g}\right]$$

over phase space [phase space **x**, additive]

$$I_{ij} = \frac{L}{\sigma}\,\frac{\partial\sigma}{\partial g_i}\,\frac{\partial\sigma}{\partial g_j} - L\,\sigma\;E\left[\frac{\partial^2 \log f^{(1)}(\mathbf{x}|\mathbf{g})}{\partial g_i\, \partial g_j}\right]$$

– Cramèr-Rao bound defining best measurement [lowest possible covariance]

$$C_{ij}(\mathbf{g}) \geq (I^{-1})_{ij}(\mathbf{g})$$

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– compute information over phase space regions

D6 operators [Brehmer, Cranmer, Kling, TP]
CP-violation at D6 [Brehmer, Kling, TP, Tait] ...

Information at detector level

Accounting for lost information [MadMiner: Brehmer, Kling, Espejo, Cranmer]

– problem:
  $Z \to \nu\nu$ keeping only missing transverse momentum
  $H \to bb$ spreading out momentum measurement
  backgrounds with different final state

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– needed likelihood ratio at detector level

$$\log \frac{p(x_d|\vec{g}_s)}{p(x_d|\vec{g}_b)} = \log \frac{\int dx_p \, p(x_d|x_p) \; p(x_p|\vec{g}_s)}{\int dx_p \, p(x_d|x_p) \; p(x_p|\vec{g}_b)}$$

– minimization problem for

$$F(x_d) = \int dx_p \; |g(x_d, x_p) - \hat{g}(x_d)|^2 \; p(x_d|x_p) \; p(x_p|\vec{g})$$

smart choice

$$g(x_d, x_p) = \frac{p(x_p|\vec{g}_s)}{p(x_p|\vec{g}_b)} \qquad \Rightarrow \qquad \hat{g}_*(x_d) = \frac{p(x_d|\vec{g}_s)}{p(x_d|\vec{g}_b)}$$

– likelihood ratio at detector level [matrix element method]

⇒ Minimization means ML-era

Analysis benchmarking

Information geometry for benchmarking [Brehmer, Dawson, Homiller, Kling, TP]

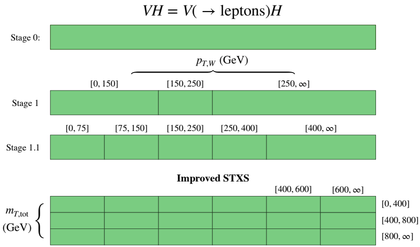
– find best analysis for VH [wf vs vertex structure vs 4-point]

$$\widetilde{\mathcal{O}}_{HD} = (\phi^\dagger \phi)\Box(\phi^\dagger \phi) - \frac{1}{4}(\phi^\dagger D^\mu \phi)^* (\phi^\dagger D_\mu \phi)$$

$$\mathcal{O}_{HW} = \phi^\dagger \phi W^a_{\mu\nu} W^{\mu\nu a} \qquad \mathcal{O}^{(3)}_{Hq} = (\phi^\dagger i\overleftrightarrow{D}^a_\mu \phi)(\overline{Q}_L \sigma^a \gamma^\mu Q_L)$$

– including detector and backgrounds

– favorite 2D-observables $p_{T,W} - m_{T,\text{tot}}$ vs STXSs vs full kinematics



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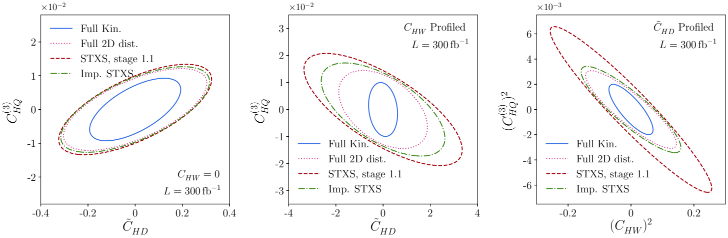

⇒ Kinematics means modern simulation tools

Higgs self-coupling

Higgs self-coupling and baryogenesis

– Sakharov conditions

baryon number violation
C and CP violation
departure from thermal equilibrium $\to$ 1st-order e-w phase transition

– D6-Higgs potential [Grojean, Servant, Wells]
general potential [Reichert, Eichhorn, Gies, Pawlowski, TP, Scherer]

$$\Delta V_6 = \lambda_6 \frac{\phi^6}{\Lambda^2}$$

$$\Delta V_{\ln,2} = -\lambda_{\ln,2} \frac{\phi^2 \Lambda^2}{100} \ln \frac{\phi^2}{2\Lambda^2} \qquad \Delta V_{\ln,4} = \lambda_{\ln,4} \frac{\phi^4}{10} \ln \frac{\phi^2}{2\Lambda^2}$$

$$\Delta V_{\exp,4} = \lambda_{\exp,4} \phi^4 \exp\left(-\frac{2\Lambda^2}{\phi^2} + 23\right) \qquad \Delta V_{\exp,6} = \lambda_{\exp,6} \frac{\phi^6}{\Lambda^2} \exp\left(-\frac{2\Lambda^2}{\phi^2} + 26\right)$$

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baryon number violation
C and CP violation
departure from thermal equilibrium → 1st-order e-w phase transition

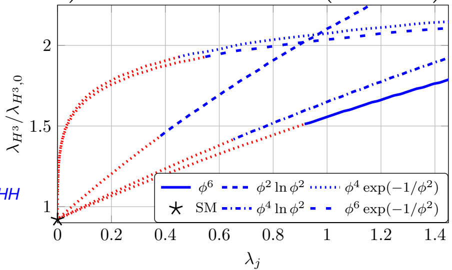
– D6-Higgs potential [Grojean, Servant, Wells]
general potential [Reichert, Eichhorn, Gies, Pawlowski, TP, Scherer]

$$\Delta V_6 = \lambda_6 \frac{\phi^6}{\Lambda^2}$$

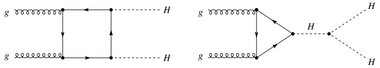
$$\Delta V_{\ln,2} = -\lambda_{\ln,2} \frac{\phi^2 \Lambda^2}{100} \ln \frac{\phi^2}{2\Lambda^2} \qquad \Delta V_{\ln,4} = \lambda_{\ln,4} \frac{\phi^4}{10} \ln \frac{\phi^2}{2\Lambda^2}$$

$$\Delta V_{\exp,4} = \lambda_{\exp,4} \phi^4 \exp\left(-\frac{2\Lambda^2}{\phi^2} + 23\right) \qquad \Delta V_{\exp,6} = \lambda_{\exp,6} \frac{\phi^6}{\Lambda^2} \exp\left(-\frac{2\Lambda^2}{\phi^2} + 26\right)$$

⇒ requiring 50% enhanced λ_{HHH}



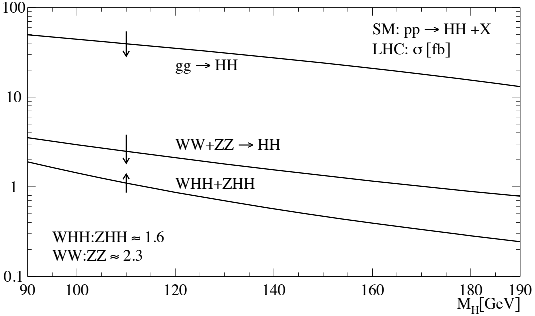
LHC kinematics



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

– rule out modified λ_{HHH} from lack of events [TP, Spira, Zerwas (1996)]

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



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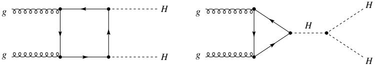

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- mostly m_{HH} distribution [Baur, TP, Rainwater (2002)]

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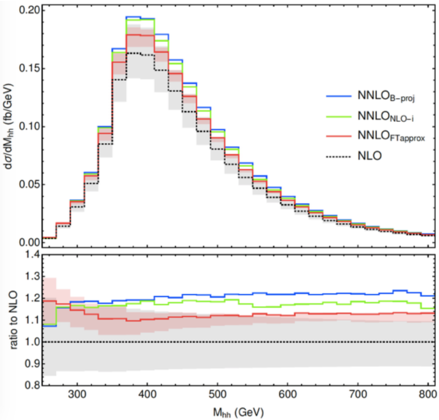
$$\left[3m_H^2 \, \frac{g_{ggH}}{s - m_H^2} + g_{ggHH} \right]^2 \sim g_{ggH} \, \left[3m_H^2 \, \frac{1}{3m_H^2} - 1 \right]^2 \to 0$$

  absorptive kink $m_{HH} \approx 2m_t$

  triangle suppression $m_{HH} \gg m_H, m_t$
- large-m_t approx bad [Baur...; Heinrich...]



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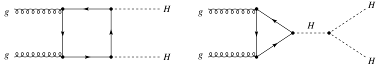

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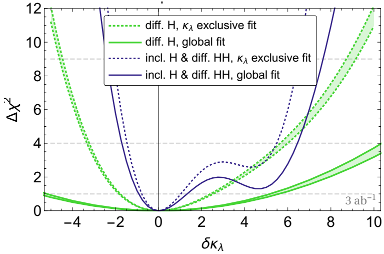
$\Rightarrow$ Calling for global EFT/model analysis

[Di Vita, Grojean, Panico, Riembau, Vantalon]



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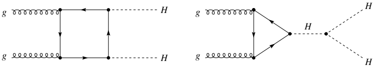

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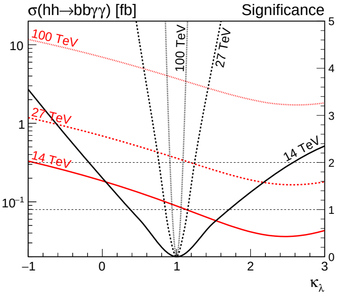


CP-violating (N)MSSM

Constructing actual baryogenesis model [Basler, Muhlleitner, Müller]

– NMSSM Higgs Sector: 2 doublets, 1 complex singlet

$$H_d \sim \begin{pmatrix} v_d + h_d + ia_d \\ h_d^- \end{pmatrix} \qquad H_u \sim e^{i\varphi_u} \begin{pmatrix} h_u^+ \\ v_u + h_u + ia_u \end{pmatrix} \qquad S = e^{i\varphi_s}(v_s + h_s + ia_s)$$

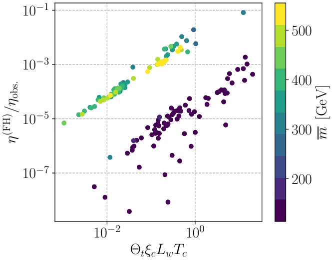
– complex Higgs Potential [neglecting D-terms]

$$\begin{aligned} V_H =& (|\lambda S|^2 + m_{H_d}^2) H_d^\dagger H_d + (|\lambda S|^2 + m_{H_u}^2) H_u^\dagger H_u + m_S^2 |S|^2 \\ &+ \left| \kappa S^2 - \lambda H_d \cdot H_u \right|^2 + \left(\frac{1}{3} \kappa A_\kappa S^3 - \lambda A_\lambda S H_d \cdot H_u + \text{h.c.} \right) \end{aligned}$$

– Higgs interaction states mix, breaking CP [complex top mass]

– compute baryon asymmetry from $\xi_c = v_c / T_c$ [L_w wall thickness]

⇒ Baryogenesis fundamental and calculable



2HDM for baryogenesis

Alternative model for baryogenesis [Hou, Modak, TP]

– complex 2HDM

$$V(\Phi,\Phi') = \mu_{11}^2|\Phi|^2 + \mu_{22}^2|\Phi'|^2 - \left(\mu_{12}^2\Phi^\dagger\Phi' + \text{h.c.}\right) + \frac{\eta_1}{2}|\Phi|^4 + \frac{\eta_2}{2}|\Phi'|^4 + \eta_3|\Phi|^2|\Phi'|^2$$
$$+ \eta_4|\Phi^\dagger\Phi'|^2 + \left[\frac{\eta_5}{2}(\Phi^\dagger\Phi')^2 + \left(\eta_6|\Phi|^2 + \eta_7|\Phi'|^2\right)\Phi^\dagger\Phi' + \text{h.c.}\right] .$$

– complex Yukawa sector $\overline{F}_i(-\lambda_{ij}s_\gamma + \rho_{ij}c_\gamma)hF_i + \cdots$
rotated to $\lambda_{ij} = \sqrt{2}\, m_i/v\delta_{ij} \in \mathbb{R}$ while $\rho_{ij} \in \mathbb{C}$

– allowed $m_{A,H,H^+} \sim 300 ... 600$ GeV, $|\rho_{tc}| \sim 0.5$

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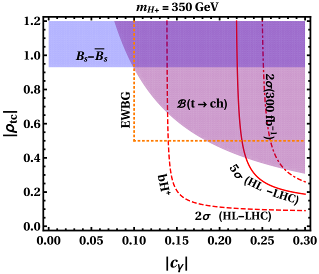
Find the necessary states

– ρ_{tc} from anomalous $t \to ch$ decays

– heavy Higgs produced through $|\rho_{tc}|$

– charged Higgs decaying through c_γ

$$cg \to bH^+ \to b\,(W_\ell^+ h) \to b\;W_\ell^+ W_\ell^+ W_\ell^-$$



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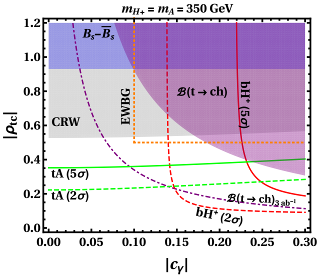
$$cg \to bH^+ \to b\,(W_\ell^+ h) \to b\; W_\ell^+ W_\ell^+ W_\ell^-$$

– neutral Higgs decaying through ρ_{tc}

$$cg \to tH/tA \to t\;(t\bar{c})$$

probed by recycled $4t$ search



⇒ Missing: CP-measurement [Brehmer, Kling, TP, Tait]

Outlook

LHC the best data set for decades

- steps in modern data analysis overdue
- rate measurements fairly uninteresting
- measurements of fundamental parameters much better
- measurements with BSM impact even better
- BSM discoveries what we really want

Future Higgs physics

- link Higgs to dark matter
- link Higgs to baryogenesis
- search for extended Higgs sectors
- search for symmetries: $Z_2, CP, \ldots$