Precision Higgs Physics

Getting a Discussion Going

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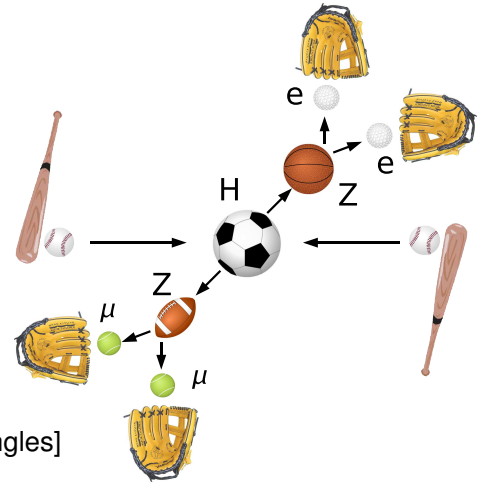
Universität Heidelberg

Aspen, January 2015

In field theory language



1. What are the ‘Higgs’ Operators

- CP-even spin-0 scalar pretty much clear
  spin-1 vector unlikely
  spin-2 graviton unexpected
- ask flavor colleagues [Cabibbo–Maksymowicz–Dell’Aquila–Nelson angles]

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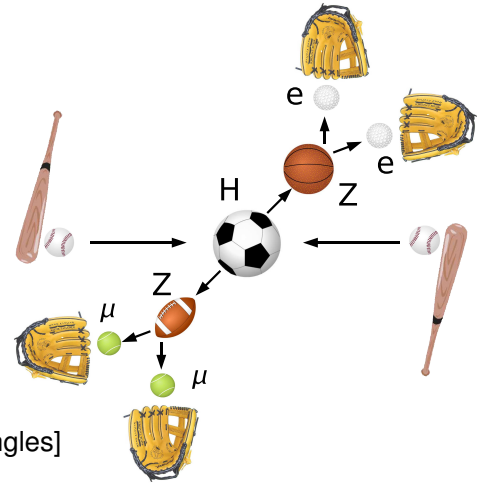

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- only sensible question after fixing operator basis
- Standard Model operators vs anomalous couplings
- effective theory to exploit distributions?

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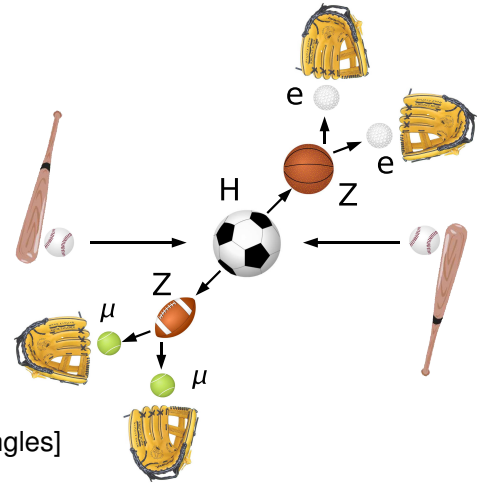

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3. What does all this tell us?

- strongly interacting models?
- weakly interacting two-Higgs-doublet models?
- TeV-scale new physics?
- vacuum stability?

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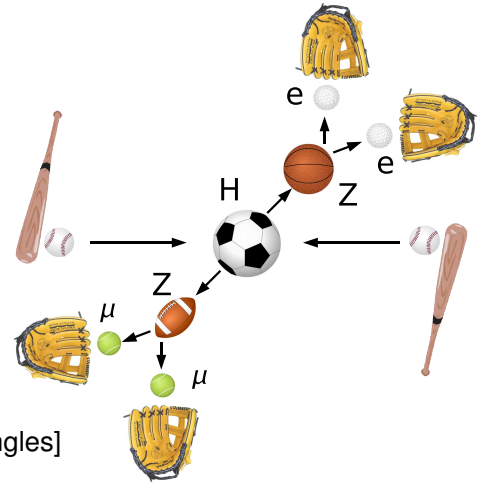

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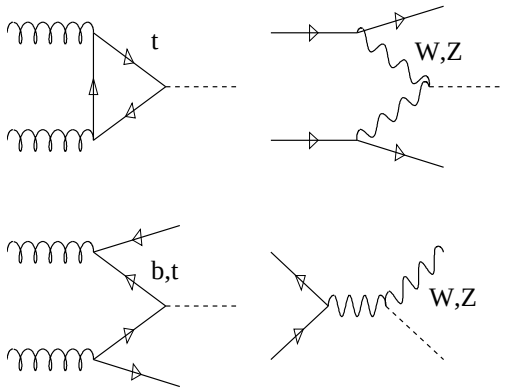
3. Can this contribute to the case for future colliders?

- precision Higgs measurements?
- direct searches for extended Higgs sectors?
- or maybe go for 'dark matter factory'?

Couplings from LHC rates



Standard Model operators [SFitter: Klute, Lafaye, TP, Rauch, Zerwas]

- most inclusive information: signal strengths
- assume: narrow CP-even scalar
  Standard Model operators
- couplings from production & decay rates

$$\boxed{\begin{array}{l} gg \to H \\ qq \to qqH \\ gg \to t\bar{t}H \\ qq' \to VH \end{array}} \quad \longleftrightarrow \quad \boxed{g_{HXX} = g_{HXX}^{\text{SM}} \; (1 + \Delta_X)} \quad \longleftrightarrow \quad \boxed{\begin{array}{l} H \to ZZ \\ H \to WW \\ H \to b\bar{b} \\ H \to \tau^+\tau^- \\ H \to \gamma\gamma \end{array}}$$

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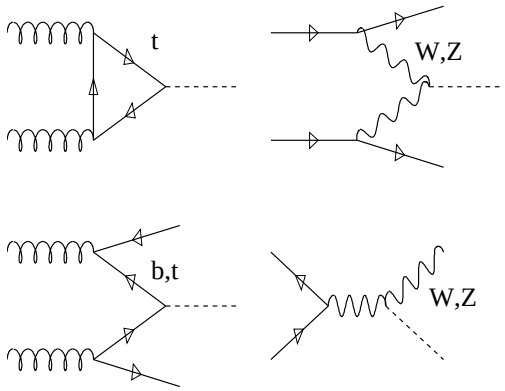

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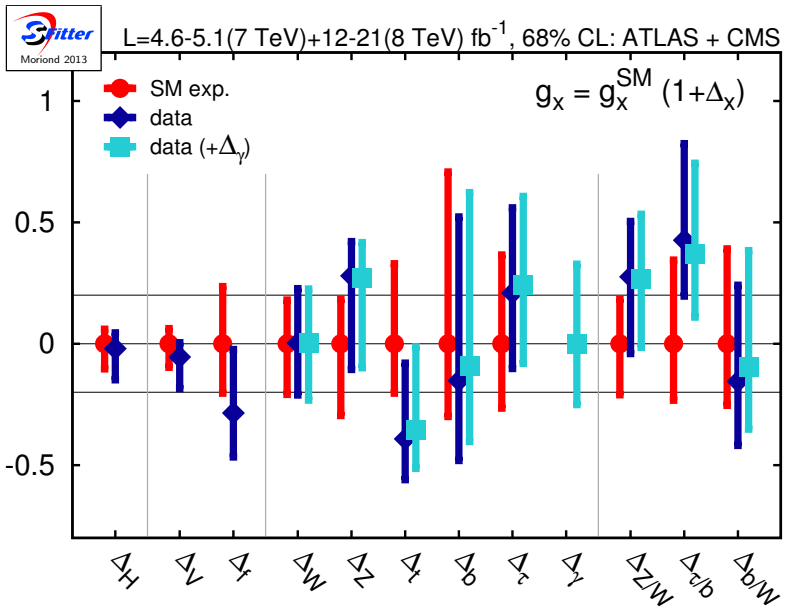
After Run 1 [Lopez-Val, TP, Rauch]

- SFitter: focus on theory uncertainties
  6D, SM-like [secondary solutions possible]
  ratios and correlations fully included



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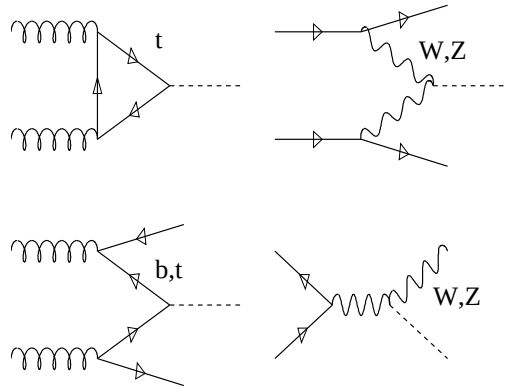

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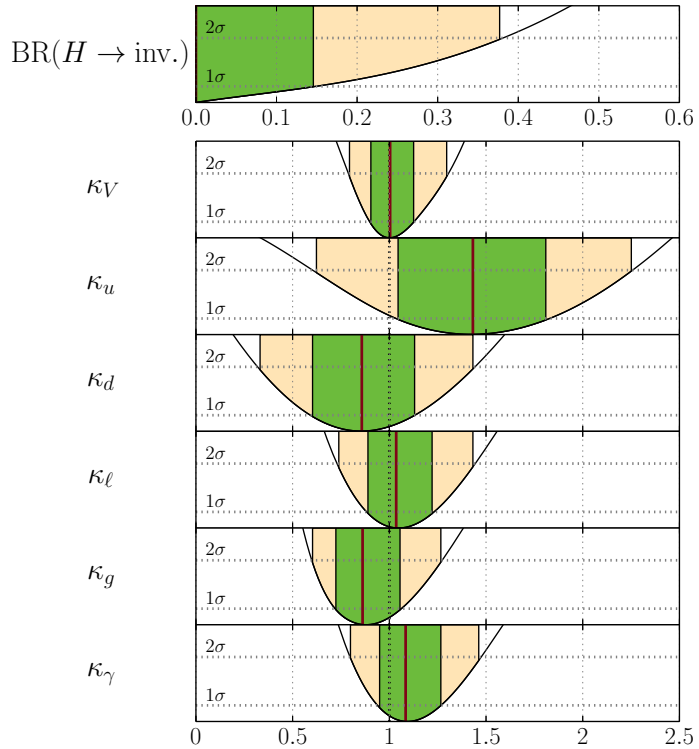
- SFitter: focus on theory uncertainties
  6D, SM-like [secondary solutions possible]
  ratios and correlations fully included
- HiggsSignals: focus on public tool
  7D including invisible decay
- ATLAS and CMS similar

$\Rightarrow$ couplings and ratios very successful



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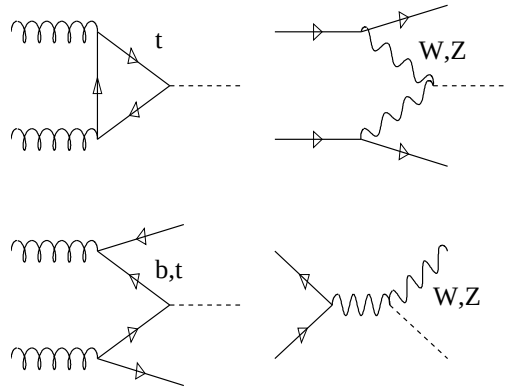

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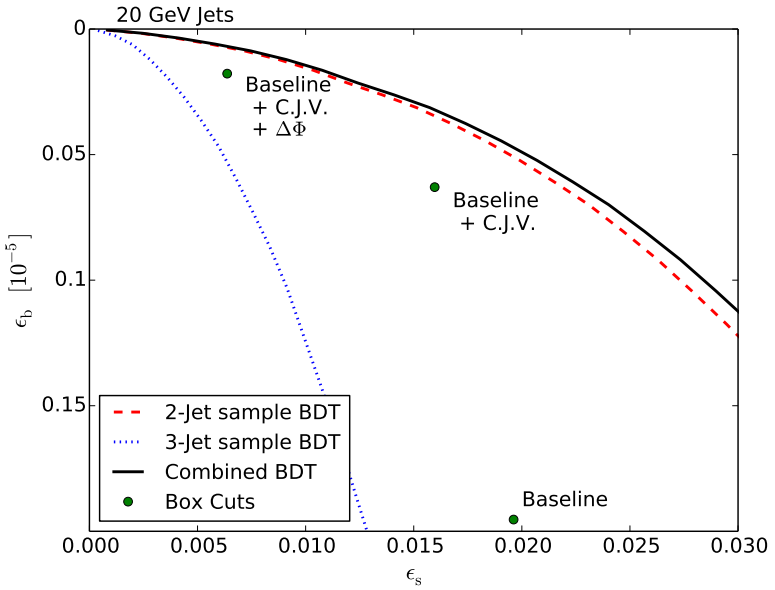
LHC challenges: invivible decays [Bernaciak, TP, Schichtel, Tattersall]

- WBF best channel at LHC [Eboli & Zeppenfeld]
- baseline cuts: jet veto plus $\Delta\phi_{jj}$
  multivariate: 2-jet, 3-jet sample
- reach $\text{BR}_{\text{inv}} \sim 7\%$ for 3000 fb^{-1}
- further improvement to 3%
  from QCD jets to 10 GeV...

$\Rightarrow$ QCD the limiting factor



Couplings from LHC distributions 1

Top–Higgs–gluon Lagrangian [Ellis, Hinchliffe, Soldate, v d Bij; Baur & Glover]

- test ggH vertex structure [to keep production rate]

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \left(\Delta_t g_{ggH} + \Delta_g \frac{\alpha_s}{12\pi} \right) \frac{H}{v} G_{\mu\nu} G^{\mu\nu}$$

- high-p_T logarithms [Banfi etal; Azatov etal; Grojean etal; Buschmann etal]

$$|\mathcal{M}_{Hj(j)}|^2 \sim \frac{m_t^4}{p_T^4} \log^4 \frac{p_T^2}{m_t^2}$$

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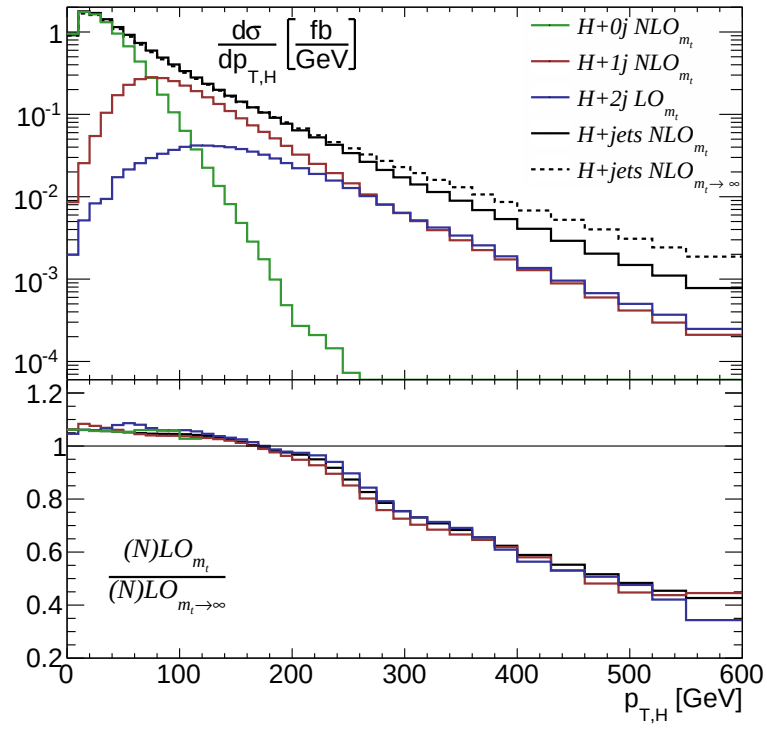

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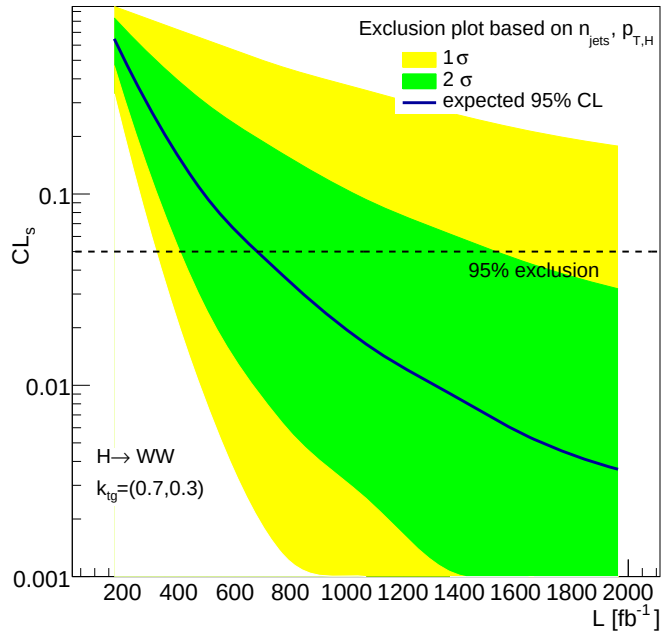
$\Rightarrow$ $\Delta_t = -0.3$ to 95% CL with 700 fb^{-1}



Couplings from LHC distributions 2

Not-model-independent width measurements [Kauer & Passarino; Caola & Melnikov; Ellis & Williams]

- peak cross section vs off-shell interference in $H \to ZZ$

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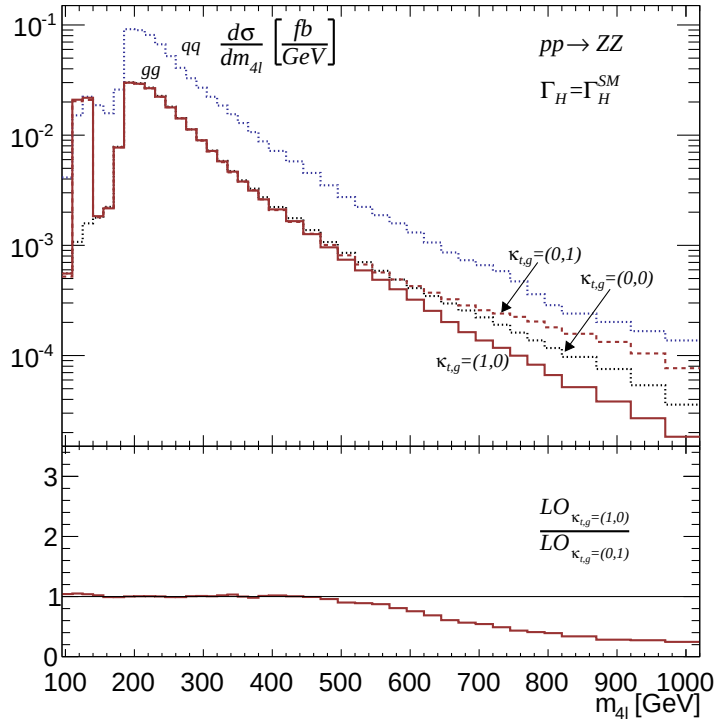

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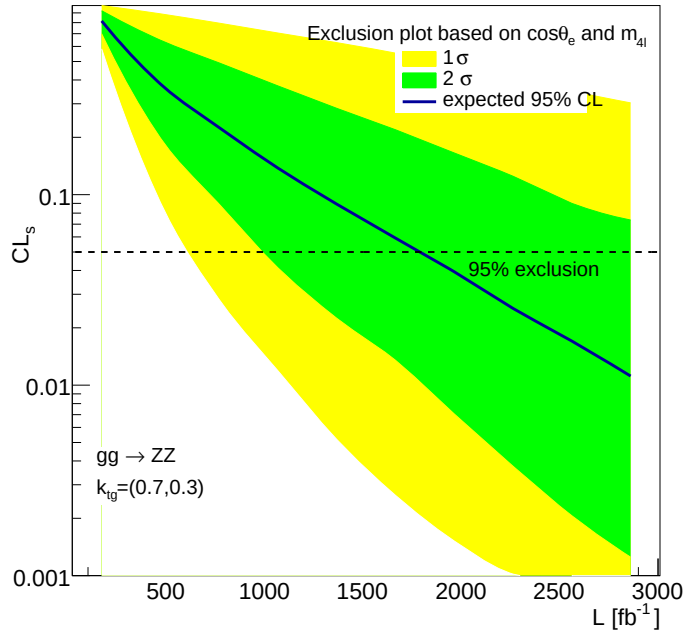

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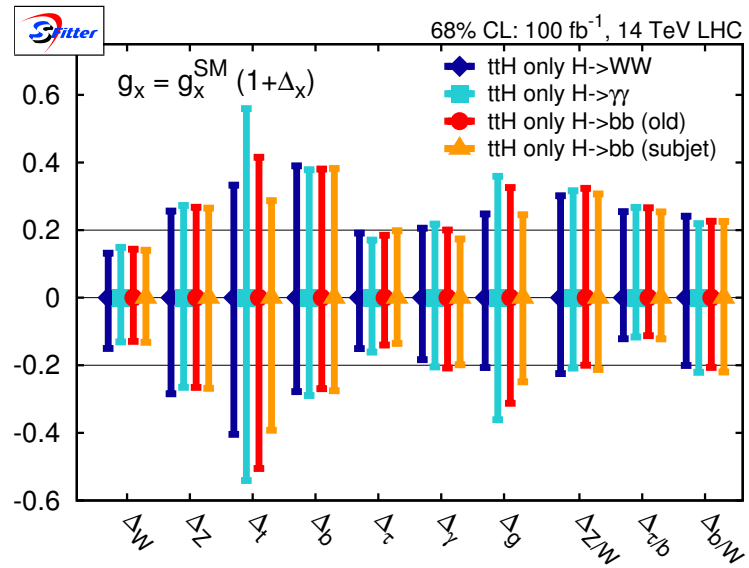
$\Rightarrow$ probably statistics limited
not great compared to SFitter extrapolation...



Couplings from e^+e^- rates

Obviously Higgs precision machine

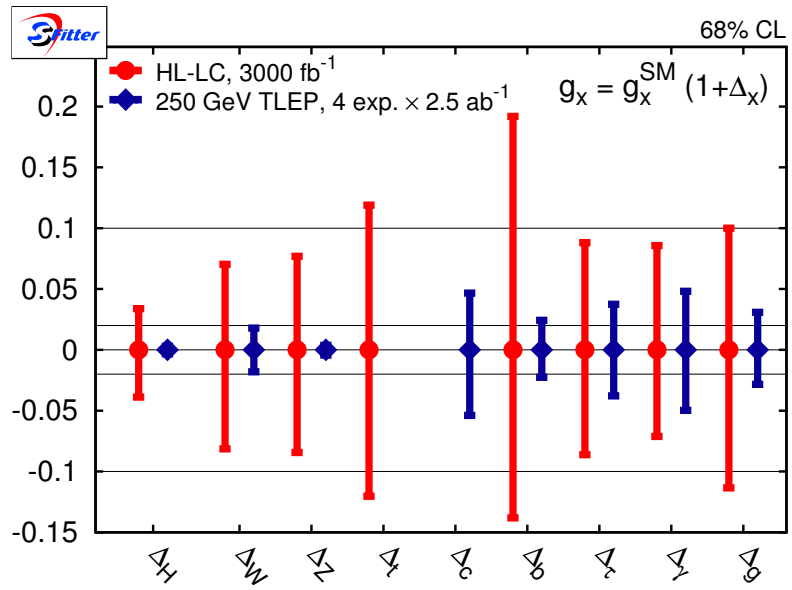
- *ZH* production requiring 250 GeV
  recoil measurement better than direct Higgs production
- clean detector environment
- $\alpha \ll \alpha_s$ and few nasty logs

$\Rightarrow$ sub-percent precision realistic

Precision rate measurements [Klute, Lafaye, TP, Rauch, Zerwas]

- again assume SM-like Higgs
- recoil measurement of σ_{ZH} to check
- theory uncertainties on BRs critical
- Δ_c possible
  Δ_t challenging
  Δ_g and Δ_γ mostly from LHC

$\Rightarrow$ e^+e^- Higgs factory a clear Euro-case



Effective theory

Beyond modified coupings

- Higgs couplings Lagrangian not complete

  $HA_{\mu\nu}A^{\mu\nu}$ included
  $HZ_{\mu\nu}Z^{\mu\nu}$ not included [numerically relevant?]
- consistent basis from EFT [all D6 operators, Buchmüller & Wyler, Hagiwara & Zeppenfeld]
- added benefit from ∂/Λ terms [p_T shape in VH production]
- consistency check from convergence [Azatov, Grojean, Paul, Salvioni; Dawson, Lewis, Zeng]
- trustworthy range of distributions key issue...

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Light Higgs as a Goldstone boson [Contino, Giudice, Grojean, Pomarol, Rattazzi, Galloway,...]

- light state ad-hoc-protected by Goldstone's theorem [Georgi & Kaplan]
- interesting if $v \ll f < 4\pi f \sim m_\rho$ [little Higgs $v \sim g^2 f/(2\pi)$]

$$d\sigma \left(1 + \frac{g^2 v^2}{f^2}\right) \sim d\sigma \left(1 + \frac{16\pi^2 g^2 v^2}{m_\rho^2}\right) \stackrel{?}{\sim} d\sigma\,(1 \pm 10\%)$$

- specific D6 operator basis
- phenomenology dominated by $(\phi^\dagger \phi)$

$\Rightarrow$ EFT useful for strong interactions

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Anomalous Higgs couplings [Corbett, Eboli, Gonzales-Fraile, Gonzales-Garcia]

- complete gauge-invariant Lagrangian with Higgs doublet
- additional higher-dimensional couplings

$$\begin{aligned}\mathcal{L}_{\text{eff}} = &-\frac{\alpha_s v}{8\pi}\frac{f_g}{\Lambda^2}(\phi^\dagger\phi)G_{\mu\nu}G^{\mu\nu} + \frac{f_{WW}}{\Lambda^2}\phi^\dagger W_{\mu\nu}W^{\mu\nu}\phi \\ &+ \frac{f_W}{\Lambda^2}(D_\mu\phi)^\dagger W^{\mu\nu}(D_\nu\phi) + \frac{f_B}{\Lambda^2}(D_\mu\phi)^\dagger B^{\mu\nu}(D_\nu\phi) + \frac{f_{WWW}}{\Lambda^2}\text{Tr}(W_{\mu\nu}W^{\nu\rho}W^\mu_\rho) \\ &+ \frac{f_b}{\Lambda^2}(\phi^\dagger\phi)(\overline{Q}_3\phi d_{R,3}) + \frac{f_\tau}{\Lambda^2}(\phi^\dagger\phi)(\overline{L}_3\phi e_{R,3})\end{aligned}$$

$\Rightarrow$ analyses only just starting

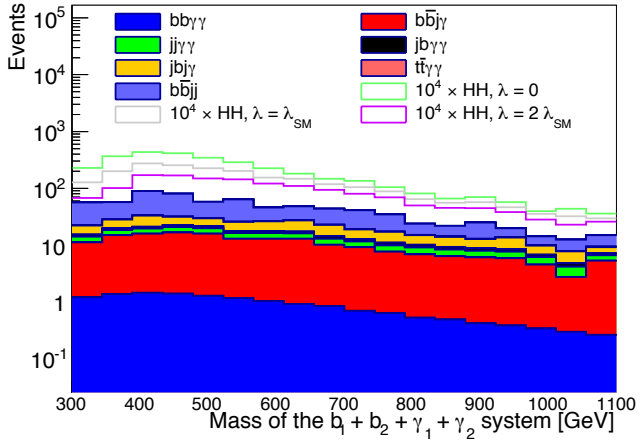
Left for the pp Nimatron

Notorious: Higgs self-coupling

- call it Higgs pair production: strong interactions and resonances [Grober, Muhlleitner]
- marginal reach at HL-LHC [experimental simulations missing]
- equally hard at e^+e^- machines

Better at 100 TeV? [Barr, Dolan, Englert, Ferreira, Spannowky]

- easy channel $HH \to (b\bar{b})(\gamma\gamma)$ [Baur, Rainwater, TP]
- useful distributions m_{HH} and $p_{T,H}$ [not used]
- 95% CL reach $\lambda = \lambda_{\text{SM}} \pm 40\%$



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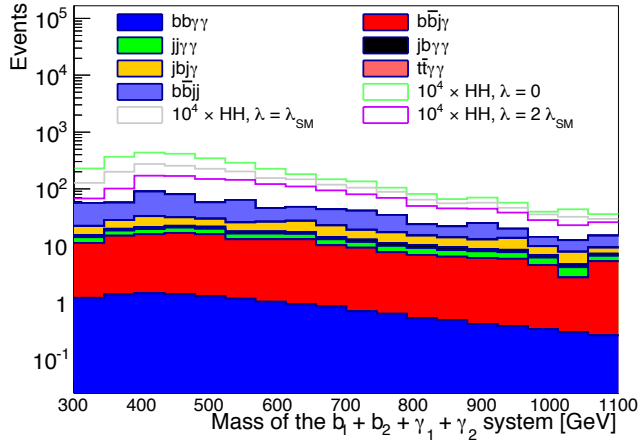
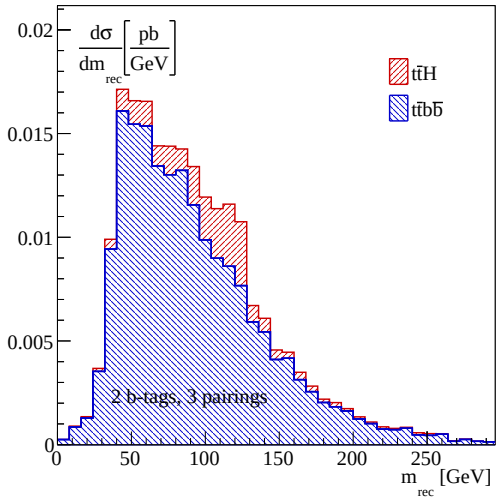


Top Yukawa at 100 TeV? [TP, Schell; update of TP, Salam, Spannowsky]

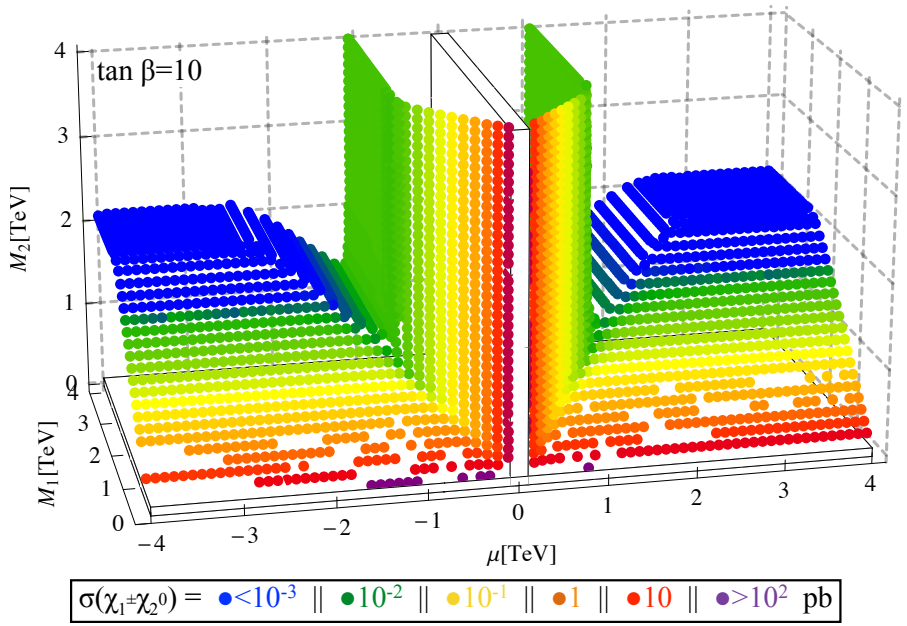
- difficult analysis at LHC
- boosted tops/Higgs to solve combinatorics
- background from side band
- statistically $\Delta\sigma_{ttH}/\sigma_{ttH} \sim 2\%$



Higgs precision goals

Challenges

- hadron colliders systematics/theory limited
- e^+e^- Higgs factory justifiable
- 100 TeV not really Higgs-motivated...
  ...but maybe helpful for λ_H and y_t
- no colorful Higgs advertizing figures, sorry...



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