An Introduction

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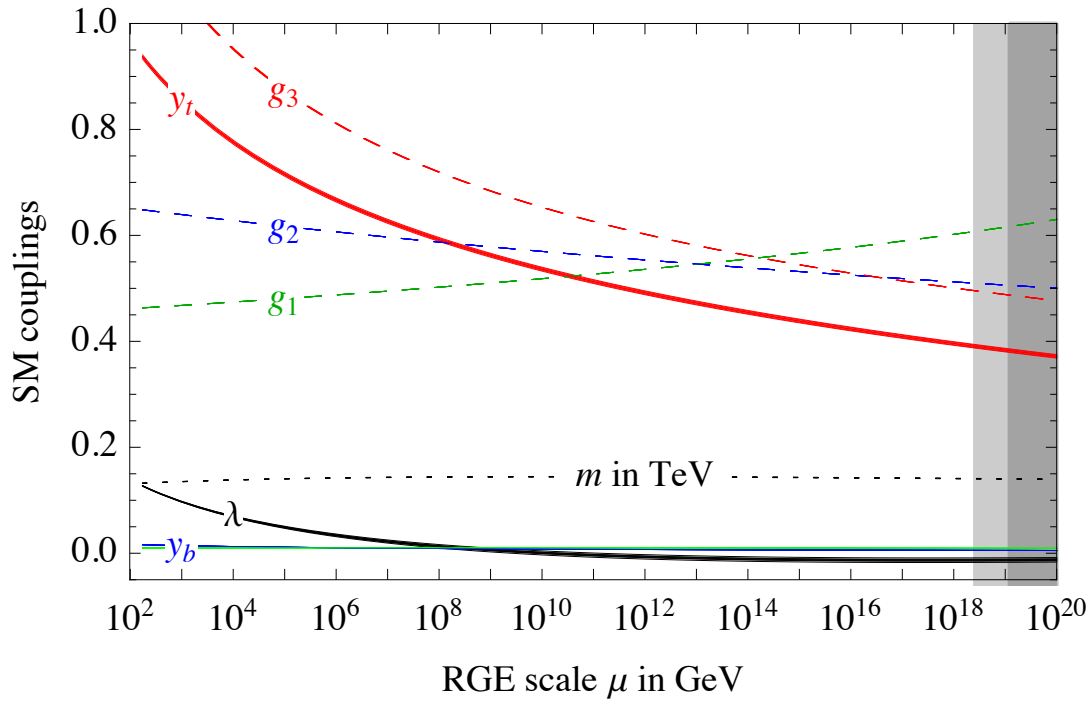
Higgs self coupling

Link to fundamental questions

- Standard Model possibly consistent to Planck scale
- renormalizable theory tool to probe fundamental physics
- vacuum stability one of them
  decision on stability made at TeV scale [Buttazzo et al; Eichorn et al]



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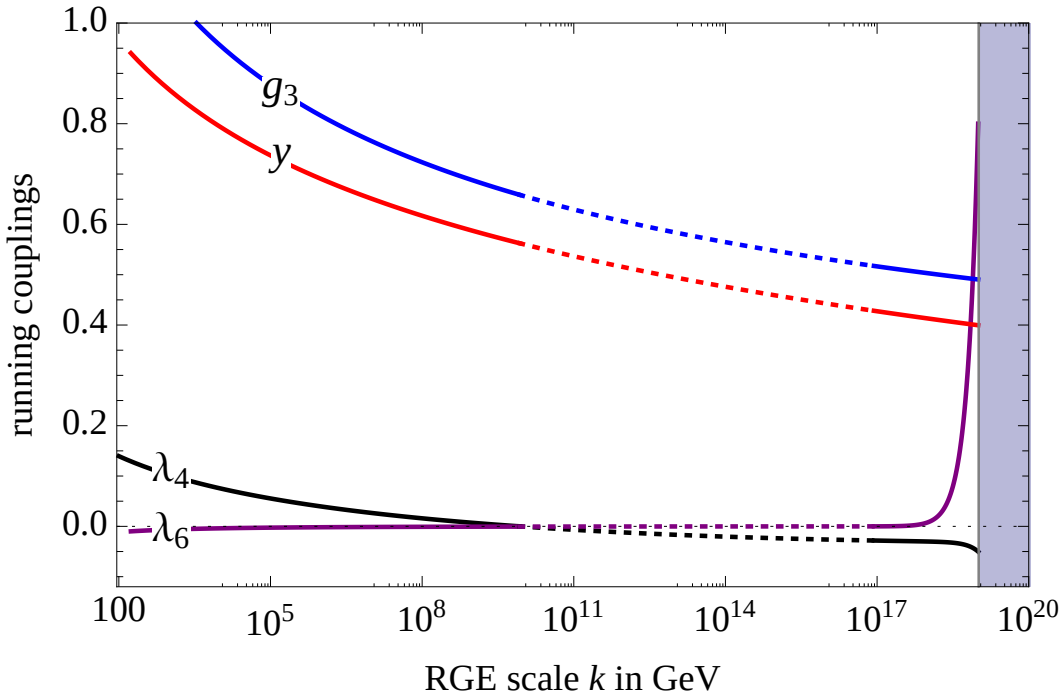

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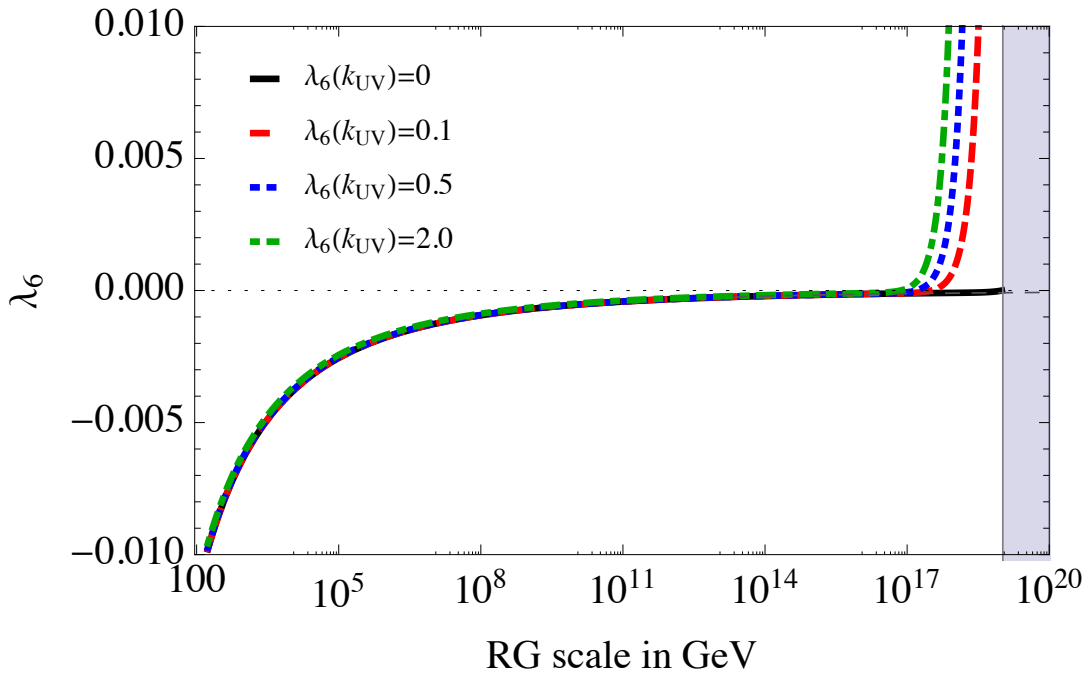

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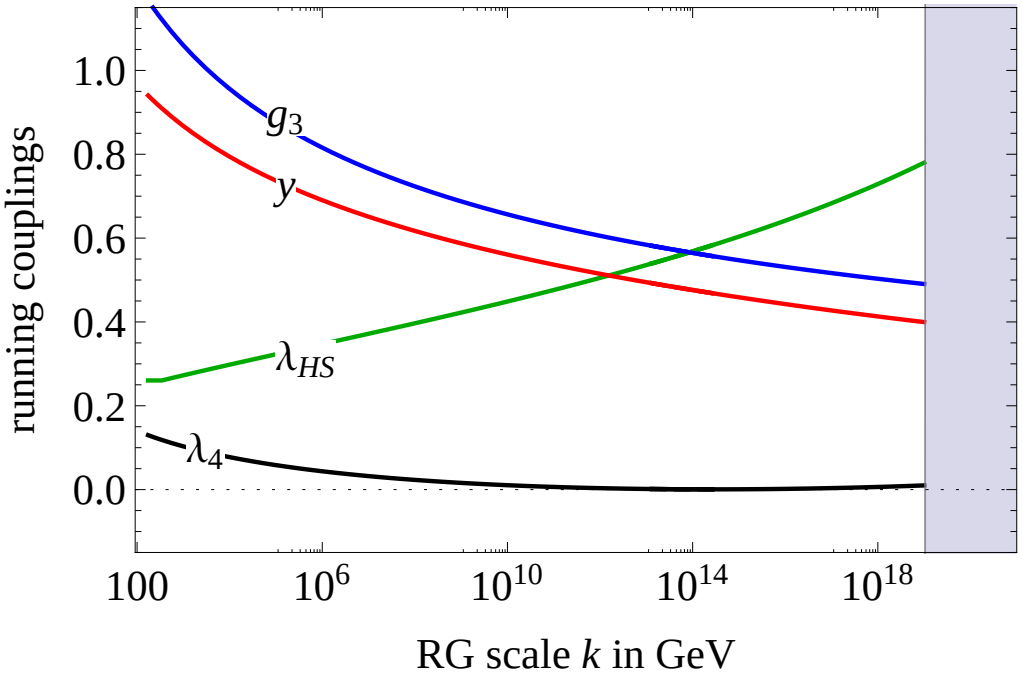

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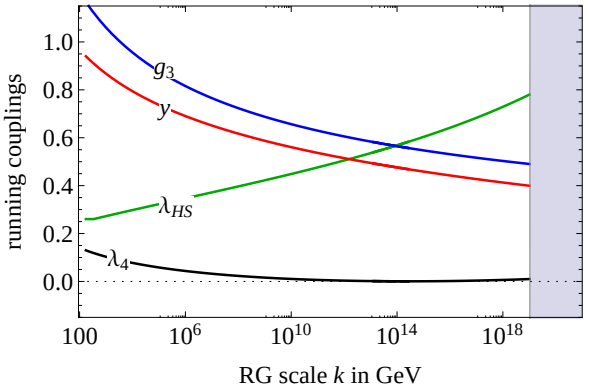
  only consistency condition on Standard Model
- strictly speaking λ vs y_t
  seriously hard at colliders [case for 100 TeV?]



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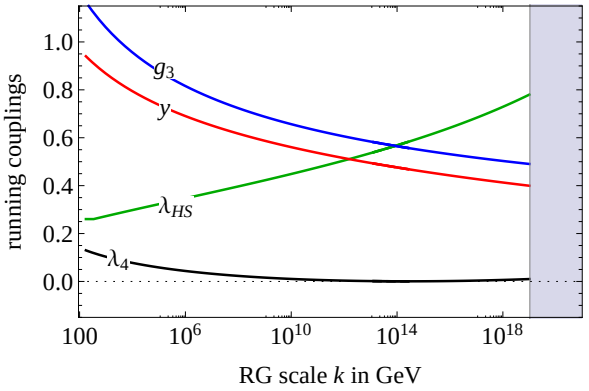
  seriously hard at colliders [case for 100 TeV?]
- Higgs portal for dark matter, baryogenesis,...

  [many papers: Pospelov; Ramsey-Musolf; Lebedev, Englert]
- smoking gun for strongly interacting Higgs

  [Contino... ; Grojean...; Gröber, Mühlleitner]

$\Rightarrow$ we are in HEP for fundamental questions!



Missing piece

Less visionary — missing piece in Standard Model

- LHC measurements of g_{HXX} on the way [rate-based and EFT]
- Higgs potential $V = \mu^2(\Phi^\dagger\Phi) + \lambda(\Phi^\dagger\Phi)^2 \quad \Rightarrow \quad \lambda = \frac{m_H^2}{2v^2}$

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- including D6 operators [Goertz, Papaefstathiou, Yang, Zurita; ...]

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

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

- modified self couplings

$$\mathscr{L}_{\text{self}} = -\frac{m_H^2}{2v}\left[\left(1 - \frac{f_1 v^2}{2\Lambda^2} + \frac{2f_2 v^4}{3\Lambda^2 m_H^2}\right)H^3 - \frac{2f_1 v^2}{\Lambda^2 m_H^2}\,H\,\partial_\mu H\,\partial^\mu H\right]$$

$$-\frac{m_H^2}{8v^2}\left[\left(1 - \frac{f_1 v^2}{\Lambda^2} + \frac{4f_2 v^4}{\Lambda^2 m_H^2}\right)H^4 - \frac{4f_1 v^2}{\Lambda^2 m_H^2}H^2\,\partial_\mu H\partial^\mu H\right]$$

Feynman rule $$-i\frac{3m_H^2}{v}\left[1 - \frac{f_1 v^2}{2\Lambda^2} + \frac{2f_2 v^4}{3\Lambda^2 m_H^2} + \frac{2f_1 v^2}{3\Lambda^2 m_H^2}\sum_{j<k}^{3}(p_j p_k)\right]$$

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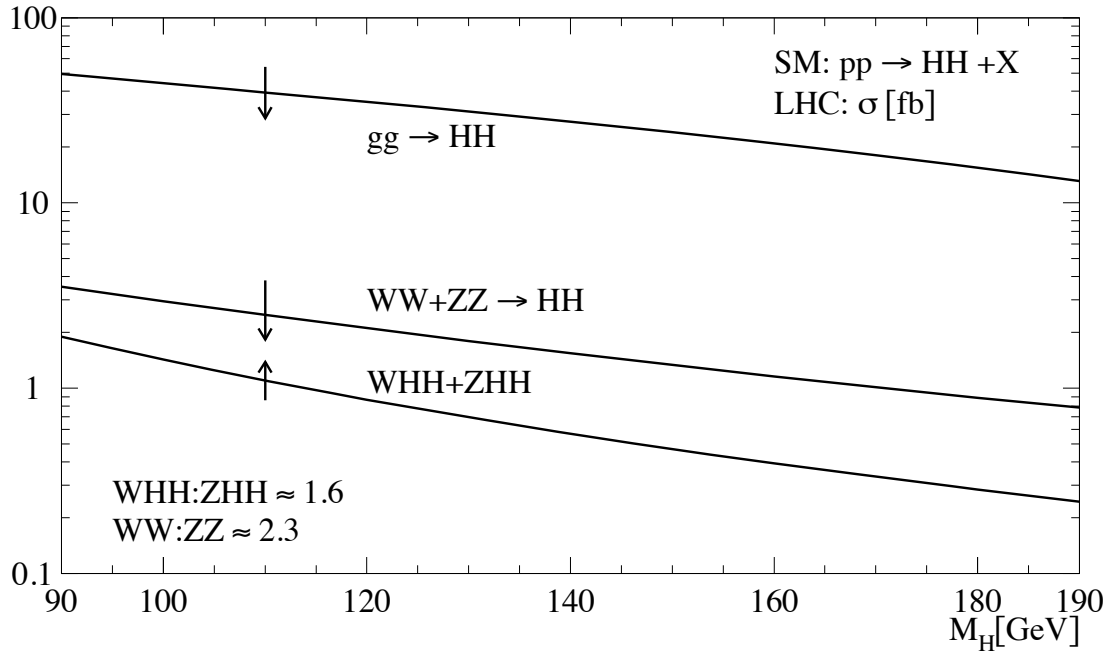
$\Rightarrow$ Higgs pair production

[Djouadi, Kilian, Mühlleitner, Zerwas]



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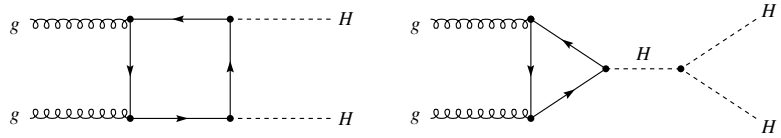

One-loop amplitude $gg \to HH$

- destructive interference
- convenient effective theory [links $ggHH$ vertex to gluon self energy for $m_H \ll m_t$]

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

- threshold behavior

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

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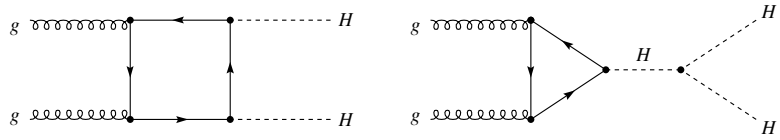

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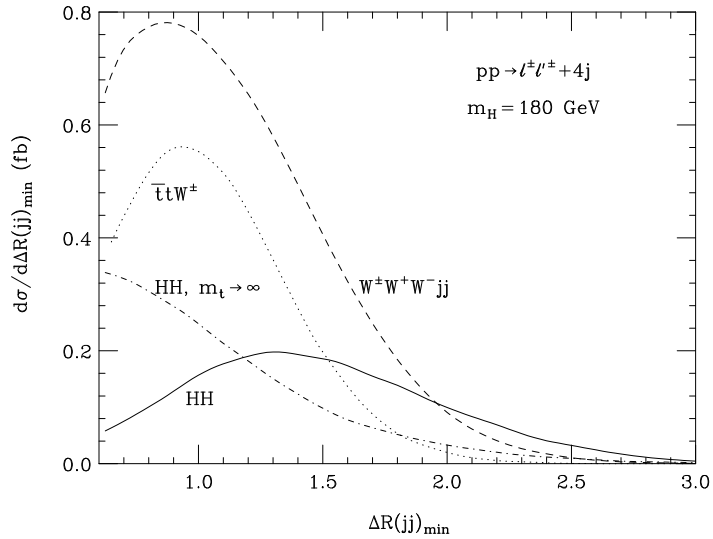

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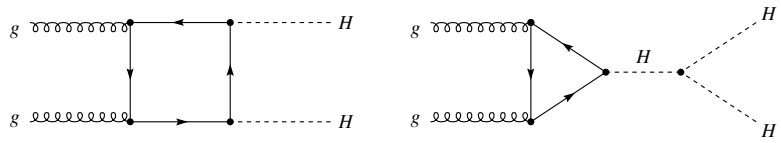

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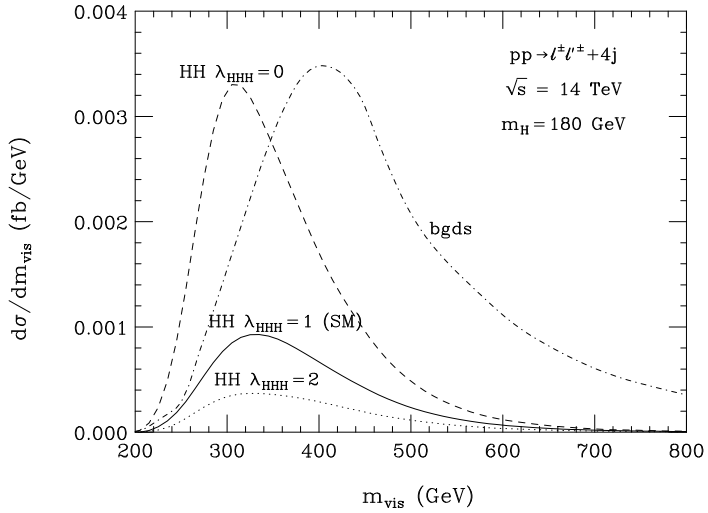

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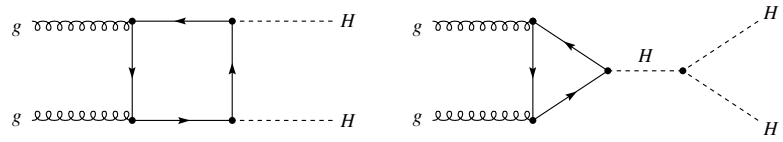

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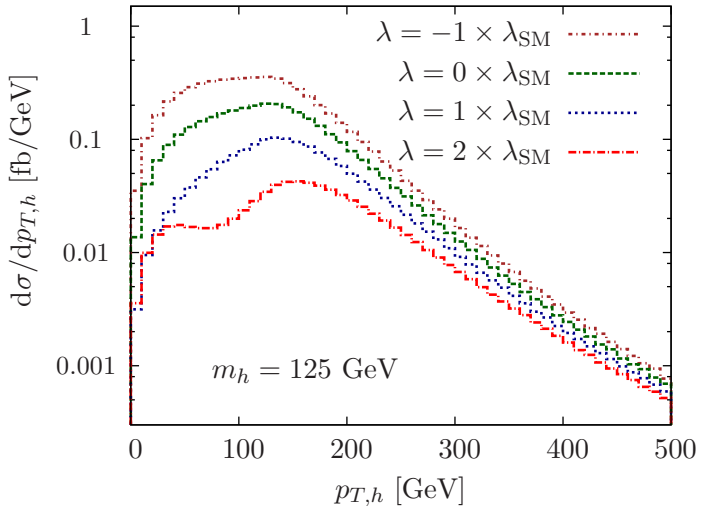

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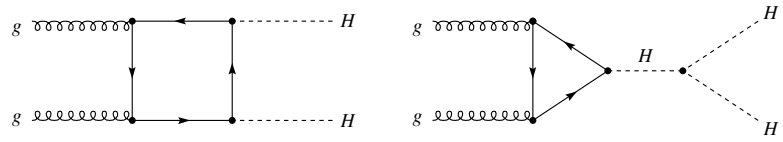

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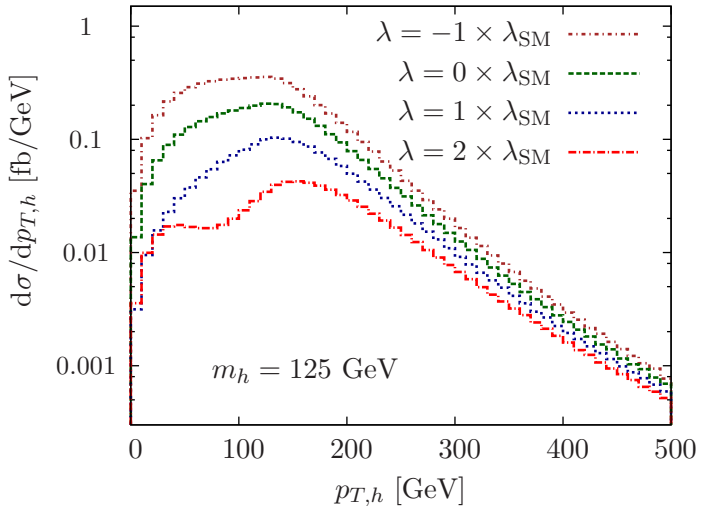
$\Rightarrow$ shape analysis necessary and possible



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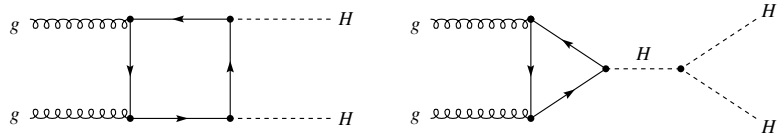

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Analysis strategy [Baur etal]

- search for HH production [like ATLAS paper]
  SM: no 5σ signal
- g_{ttH} from Higgs couplings analysis [similarly EFT]
- limits on 'anomalous' Higgs self coupling
  exclude $\lambda < 0$ with enhanced rate
  exclude $\lambda \gg 1$ from p_T

$\Rightarrow$ which signatures?

Signatures

Old channels: $HH \to 4W, b\bar{b}\gamma\gamma$ [Baur etal (2002-2003)]

- $4W$: visible mass against backgrounds and to probe threshold $[\Sigma_{j,\ell}\, p^\mu)^2]$
  (1) small for 2 particle final state (signal)
  (2) large for many backgrounds
- known problem: $t\bar{t}j$ background [matrix element versus shower?]
- only working for heavier Higgs?

m_h [GeV]	signal	$N^{2\times 300}$	$WWWjj$	$t\bar{t}W$	$t\bar{t}Z$	$t\bar{t}j$	$WZ4j$	$WW4j$	$t\bar{t}t\bar{t}$
150	0.074	44	0.361	0.222	0.054	0.082	0.148	0.0052	0.0018
160	0.194	116	0.486						
180	0.177	106	0.404						
200	0.083	50	0.292						

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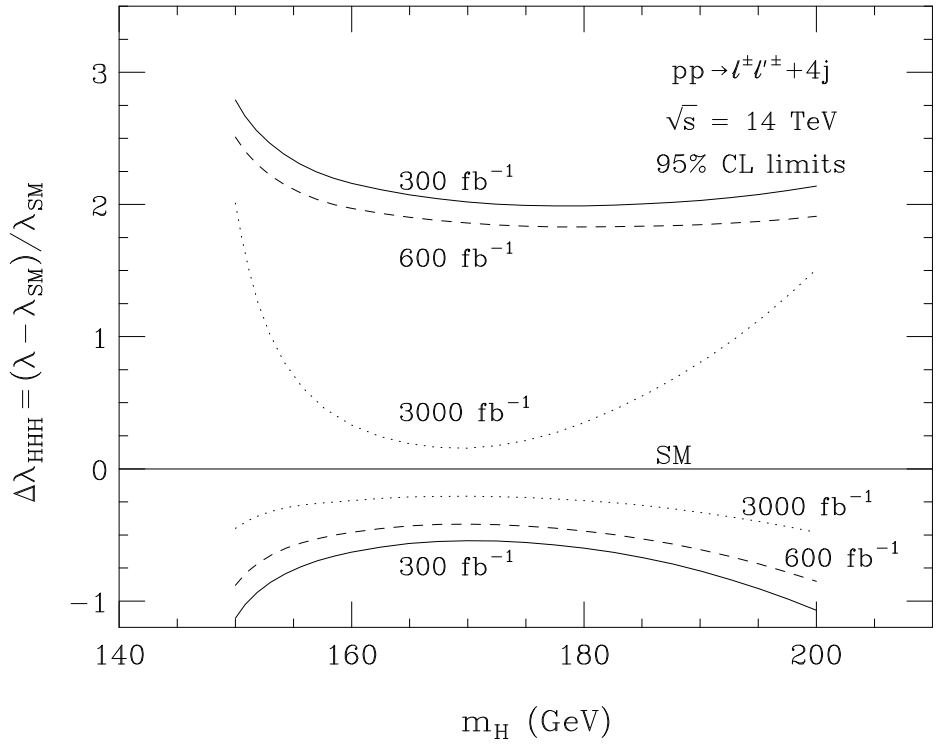

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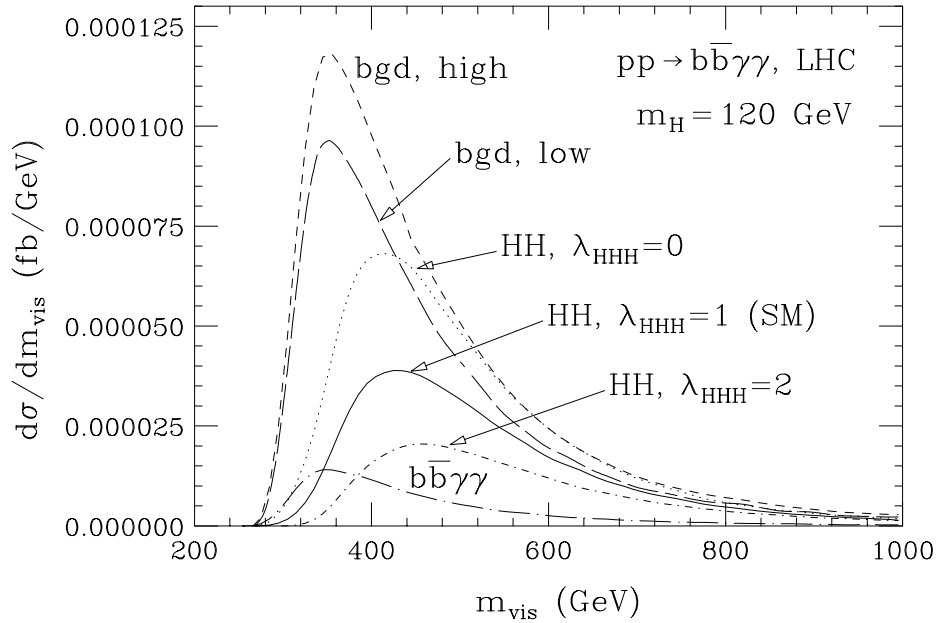

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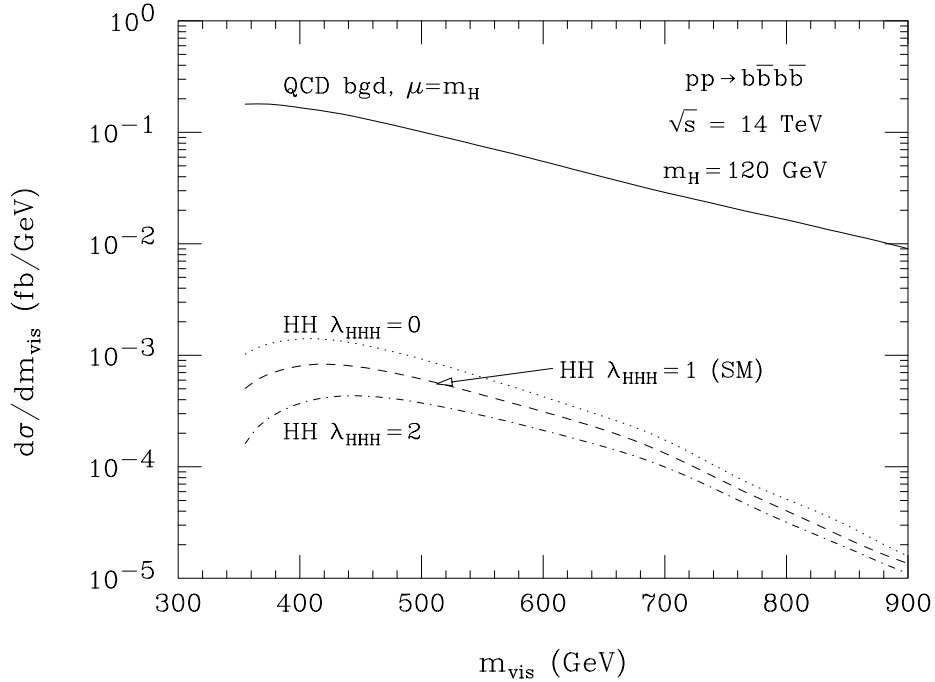

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- $b\bar{b}\tau^+\tau^-$: not very promising with usual analysis [Baur etal (2003)]
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	$\xi = 0$	$\xi = 1$	$\xi = 2$	$b\bar{b}\tau\tau$	$b\bar{b}\tau\tau$ [ew]	$b\bar{b}W^+W^-$	ratio to $\xi = 1$
before cuts	59.48	28.34	13.36	67.48	8.73	873000	$3.2 \cdot 10^{-5}$
reconstructed $m_{\tau\tau}$	4.05	1.94	0.91	2.51	1.10	1507.99	$1.9 \cdot 10^{-3}$
fatjet cuts	2.27	1.09	0.65	1.29	0.84	223.21	$4.8 \cdot 10^{-3}$
reconstructed $m_{b\bar{b}}$	0.41	0.26	0.15	0.104	0.047	9.50	$2.3 \cdot 10^{-2}$
double b-tag	0.148	0.095	0.053	0.028	0.020	0.15	0.48

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- further improved S/B with add'l jet?
- $b\bar{b}W^+W^-$: not very promising [Dolan etal]
  maybe possible [Papaefstathiou etal]
- $t\bar{t}$ background a big challenge

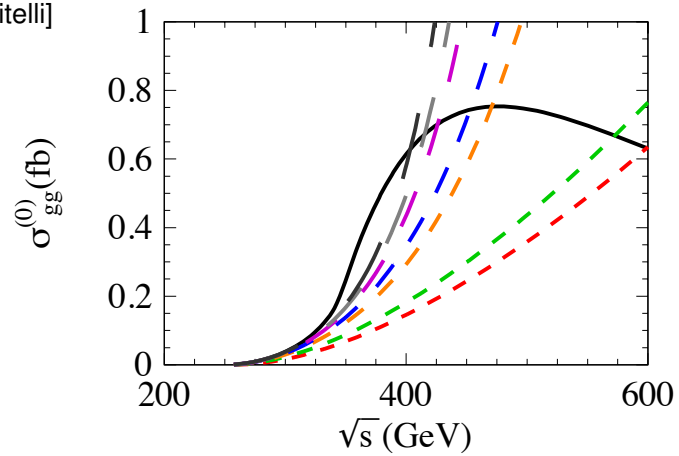
$\Rightarrow$ where are the experimental studies?

Tools

Precision predictions

- LO loop amplitudes in many MC codes
- approximate NLO available [Dawson, Dittmaier, Spira]
- NLO with top mass [Grigo, Hoff, Melnikov, Steinhauser]
- NNLO predictions on the way [de Florian, Mazzitelli]

$\Rightarrow$ remember the distributions!

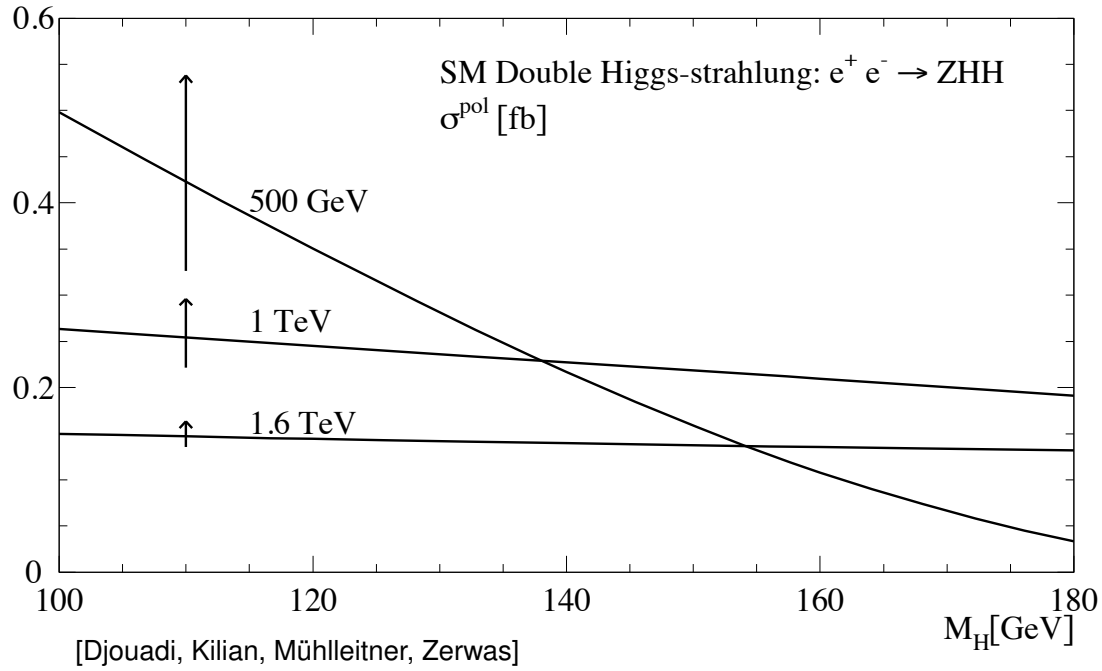


Linear collider

Rate at linear collider: $e^+e^- \to ZHH$

- very limited number of events
- low Higgs mass, decays $H \to b\bar{b}$
- measurement of λ through total rate ($m_h = 120$ GeV)

$\Rightarrow$ hard measurement everywhere



[Djouadi, Kilian, Mühlleitner, Zerwas]

HL-LHC and Nimatron

Make use of 100 TeV and/or 30ab^{-1}

- where do we benefit?
- what is new?
  $pp \to HH \to (b\bar{b})$+weakly interacting [Papaefstathiou]
- combined with top Yukawa measurement?

$\Rightarrow$ what is the progress since 2003?

$\Rightarrow$ where are the experimental studies?

$\Rightarrow$ why Higgs pairs and not cheaper channels?

$\Rightarrow$ why billions of dollars?

That looks really hard!