Measuring the Higgs Self-Couplings

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LPC, Fermilab, March 4, 2014

Outline

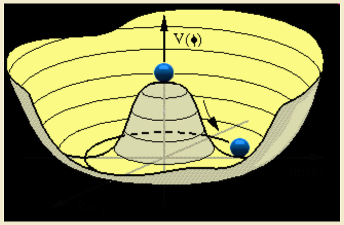
- Why measure the Higgs-self couplings?
- What do we expect?
  – Standard Model
  – Beyond the Standard Model
- Some phenomenology

How far from the SM prediction can the HH rate get?

SM Higgs Mechanism

- Standard Model includes complex Higgs SU(2) doublet

$$\Phi = \frac{1}{\sqrt{2}}\begin{pmatrix}\phi_1 + i\phi_2 \\ \phi_3 + i\phi_4\end{pmatrix} = \begin{pmatrix}\varphi^+ \\ \varphi^0\end{pmatrix}$$



- With SU(2) x U(1) invariant scalar potential

$$V = \mu^2 \Phi^+ \Phi + \lambda (\Phi^+ \Phi)^2$$

- If $\mu^2 < 0$, then spontaneous symmetry breaking
- Minimum of potential at:

$$\langle \Phi \rangle = \frac{1}{\sqrt{2}}\begin{pmatrix}0 \\ v\end{pmatrix} \qquad \Phi \to e^{i\varpi^a \cdot \sigma^a / v}\begin{pmatrix}0 \\ \frac{h+v}{\sqrt{2}}\end{pmatrix}$$

After symmetry breaking

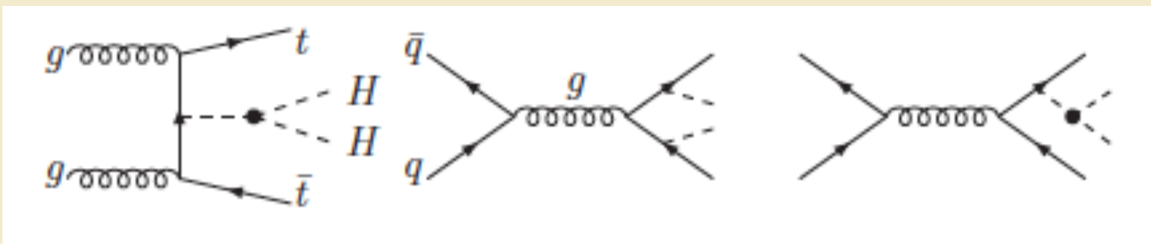
$$V = -\frac{M_H^2}{2}H^2 + \lambda_3 H^3 + \lambda_4 H^4$$

- HHH and HHHH couplings prediction of theory
- They are perturbative $\lambda_3 = \frac{M_H^2}{2v} \sim .13v \qquad \lambda_4 = \frac{M_H^2}{8v^2}$
- Calculations sensible
- In general $V = \Sigma_n \frac{c_n}{\Lambda^{2n}} \left(\Phi^\dagger \Phi - \frac{v^2}{2} \right)^{2+n}$

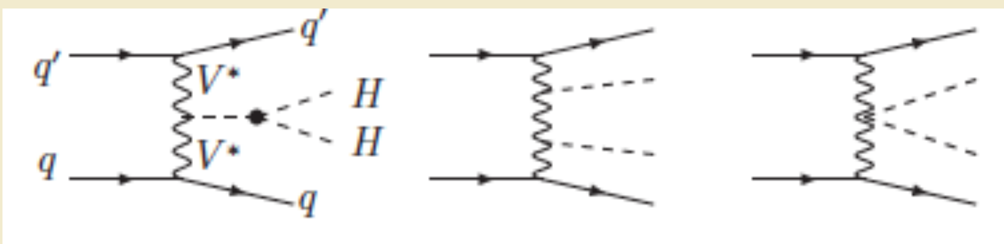
Corrections to relationship between λ_3 and λ_4 of $O(1/\Lambda^2)$

Production of HH

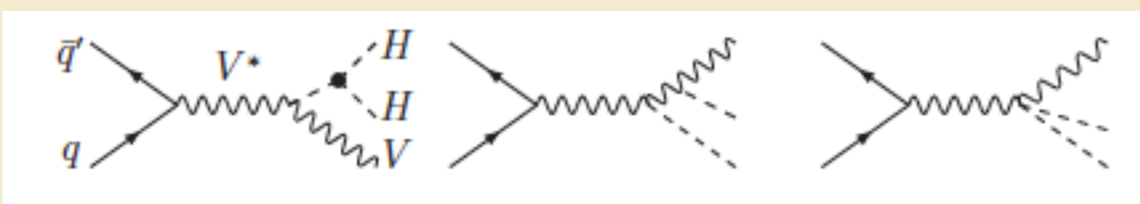
Sensitive to heavy colored particles (eg stops or top partners)



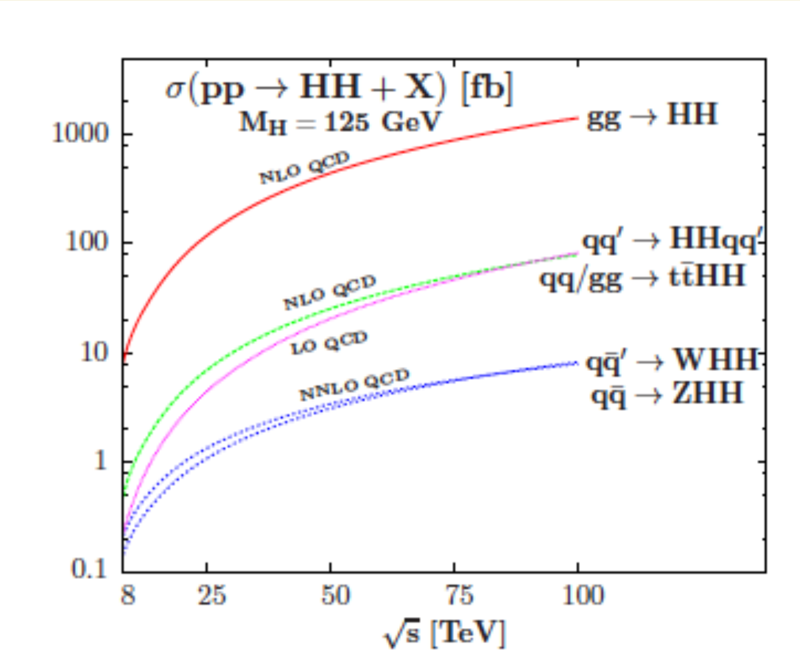
Sensitive to anomalous top-Higgs couplings



Sensitive to anomalous VVHH couplings



Small Rates



gg rate increases by a factor of ~40 when going from 14 TeV to 100 TeV

Gluon fusion is always the largest production channel

K factor ~ 2 for gg→ HH

Baglio et al, arXiv:1215.5581

Theory Uncertainties

- For gg➔H: PDF, α_s, scale uncertainties give ± ~15-20% uncertainties
  - Theory frontier is understanding uncertainties in jet binning
- For gg➔HH at 14 TeV:

$$\sigma_{gg\to HH} = 34\ fb^{+18\%}_{-15\%}{}^{+4\%}_{-4\%}$$

Scale PDF

- Calculation includes QCD in $m_t \to \infty$ limit

Need more theory!

LHC Higgs cross section working group

Two Higgs Production at LHC

- Cross section has spin-0 and spin-2 contributions

$$\frac{d\sigma(gg \to HH)}{dt} = \frac{\alpha_s^2}{32768\pi^3 v^4}\left(\mid F_0 \mid^2 + \mid F_2 \mid^2\right)$$

- $M_t^2 >> s$, p_T^2 (low energy theorem)

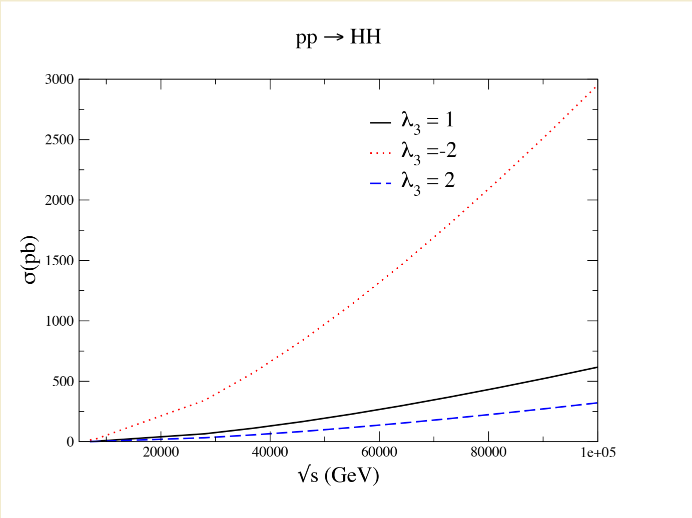
$$F_0 \to -\frac{4}{3} + \frac{4M_H^2}{s - M_H^2}(\lambda_3)$$

$$F_2 \to 0$$

HHH coupling (1 for SM)

- For large s, dependence on λ_3 suppressed
- More sensitivity to negative λ_3
- Exact cancellation at threshold

Small Rates

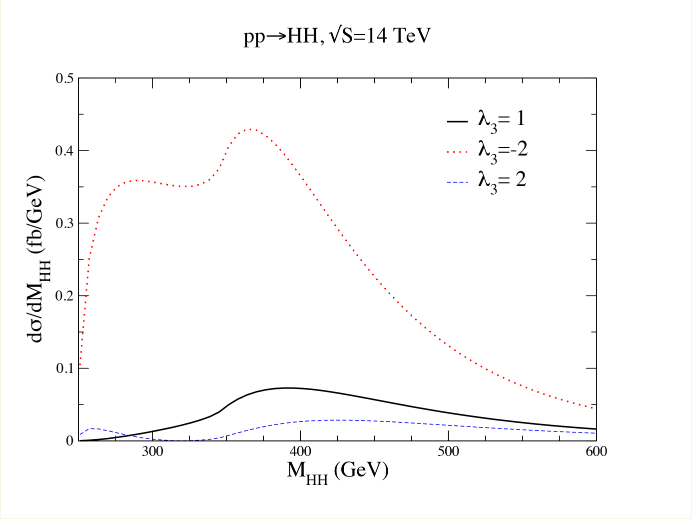


For $\sqrt{S}$=14 TeV,
K ~ 2 in $m_t \to \infty$ limit
(not in plot)

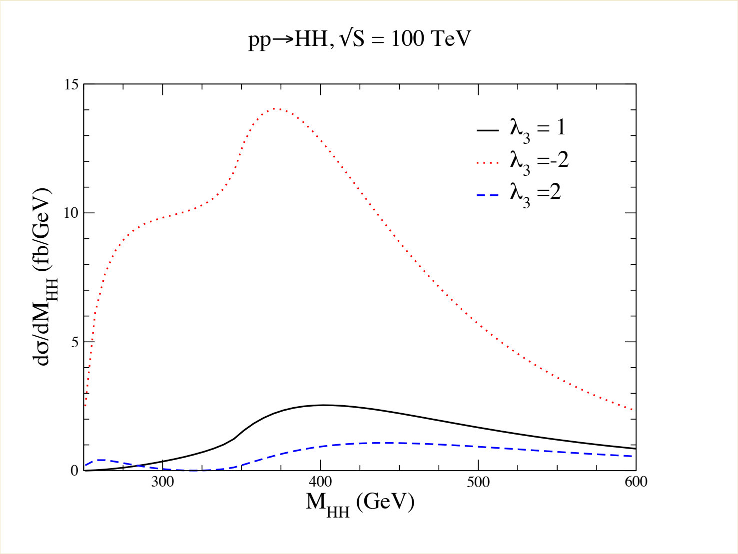
Sensitivity to HHH coupling

* Exact calculation, not low energy theorem

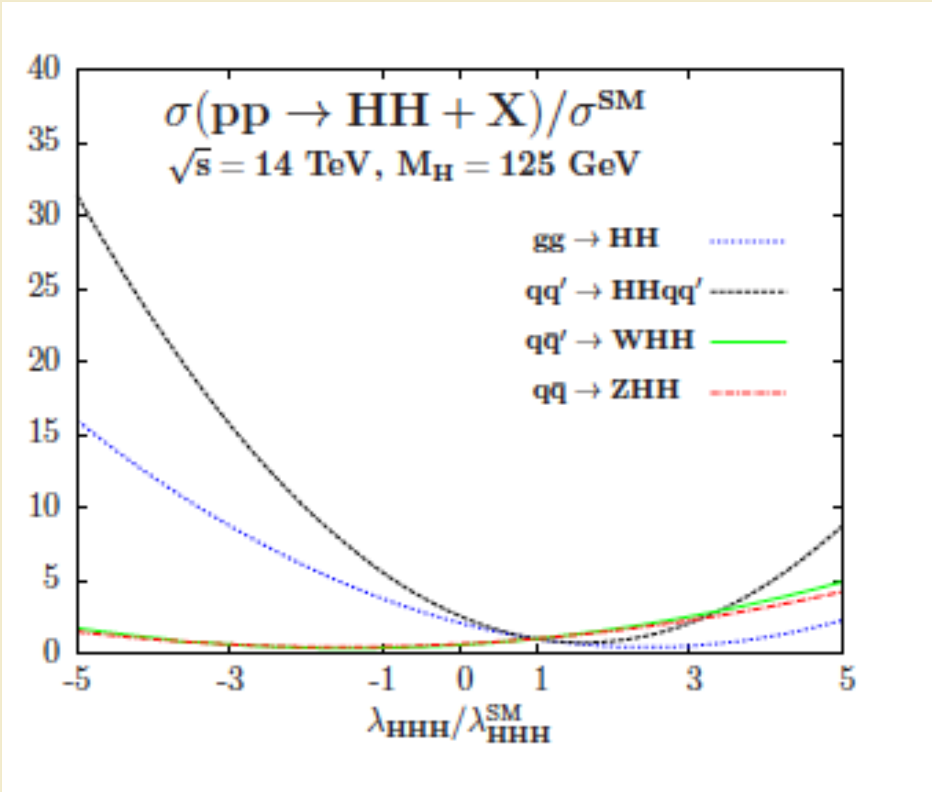
Distributions sensitive to λ_3



Gluon fusion



VBF is most sensitive channel to λ_3



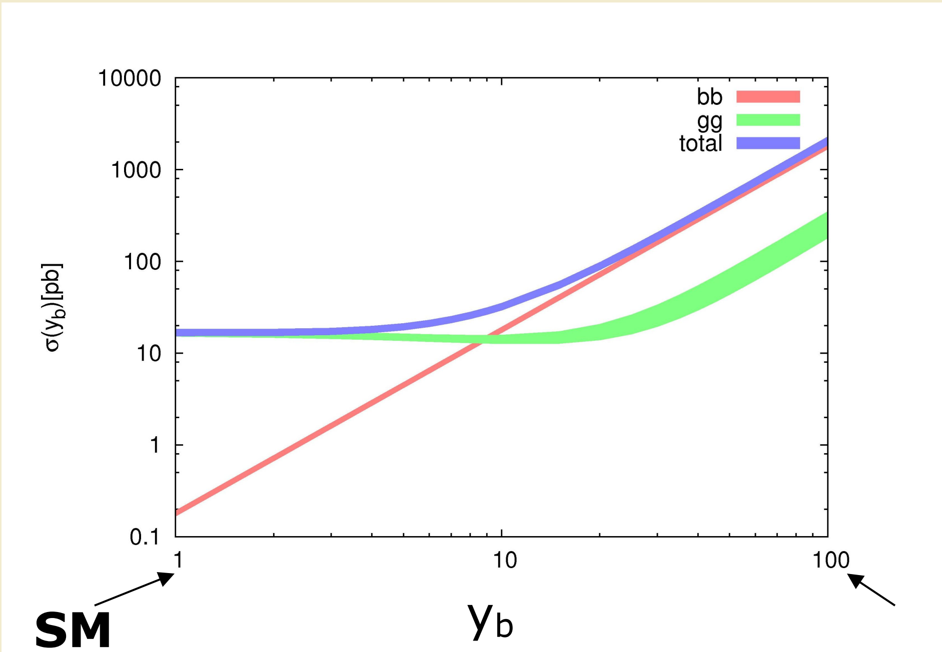
Fit σ/σ_{sm} as a function of λ/λ_{sm} to extract measurement of λ

Baglio et al

The Role of b-loops in Single Higgs

K factor for b loops smaller than for top loops

b loops are 2-5% of SM gg→H



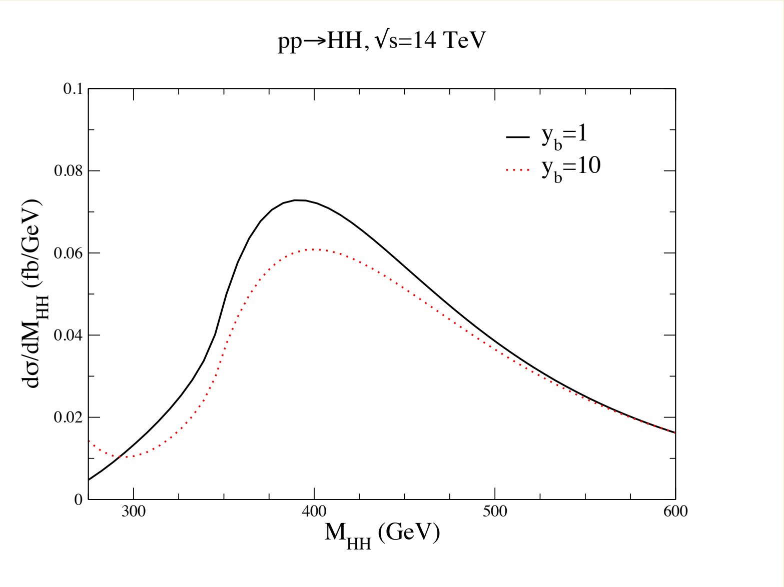
$$L \sim \frac{m_b}{v} y_b \bar{b} h H$$

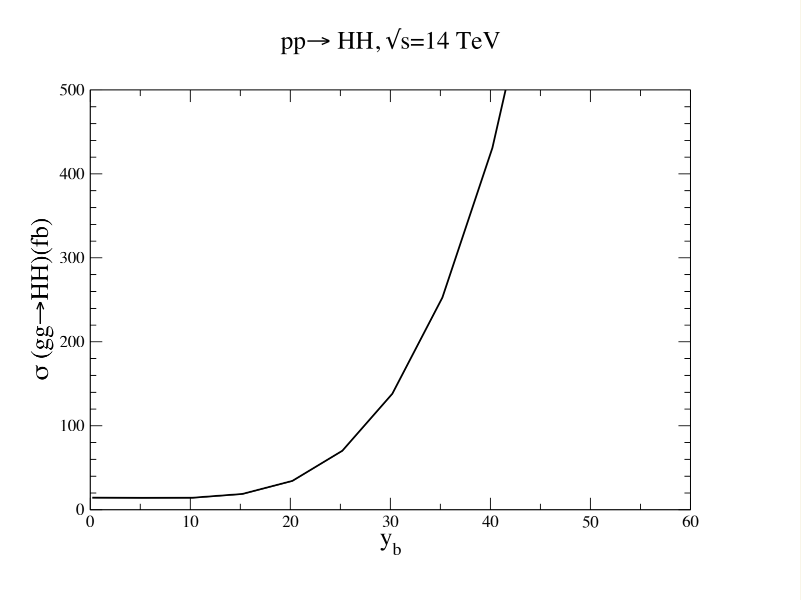
gg "only" NLO

[Anastasiou, Buehler, Herzog, Lazopoulos]

Sensitivity to y_b

- Y_b comes in twice in box diagrams





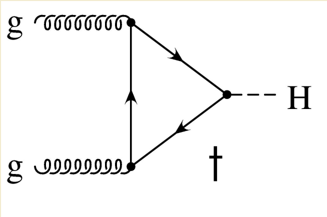
But we already know $y_b < 4$ from single Higgs production

Adding heavy fermions

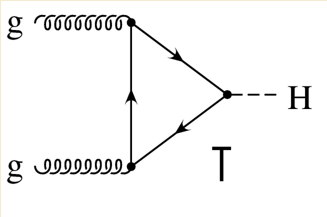
- Can't add new chiral generation:

$$\sigma(gg \to H) \to \sigma_{SM}(1 + N_F)^2$$

- Add vector fermions:
  - Left and right-handed fermions transform the same way under SU(2): T_L and T_R



~cos$^2\theta$

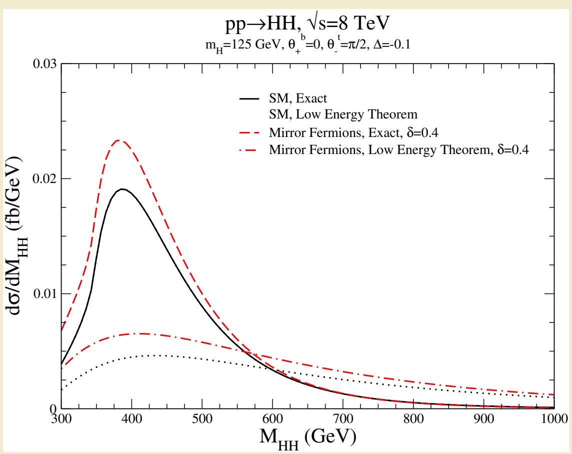


~sin$^2\theta$

⇨ Generically, hard to get far from Standard Model result

Double Higgs Rate: How big can it be?

- Toy model with top partners
  - Many restrictions on parameters from precision EW
  - Single Higgs rate always suppressed in these models
- gg➔H rate assumed to be 90% of SM
- gg➔HH rate can be increased by < 20% relative to SM



Optimal choice of parameters

Fairly general result: leading contributions to H and HH production in top partner models are similar to SM

Dawson, Furlan, Lewis

Double Higgs in Composite Models

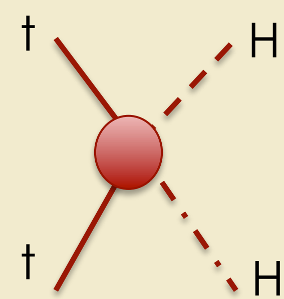
- MCHM5 model:
  - Top partners couple to Higgs
  - SM-like particles don't couple directly to Higgs
  - Higgs couplings scaled by parameter ζ
- Single Higgs production suppressed

$$R = \frac{\sigma(pp \to H)}{\sigma(pp \to H)\mid_{SM}} \sim (1 - 3\zeta)$$

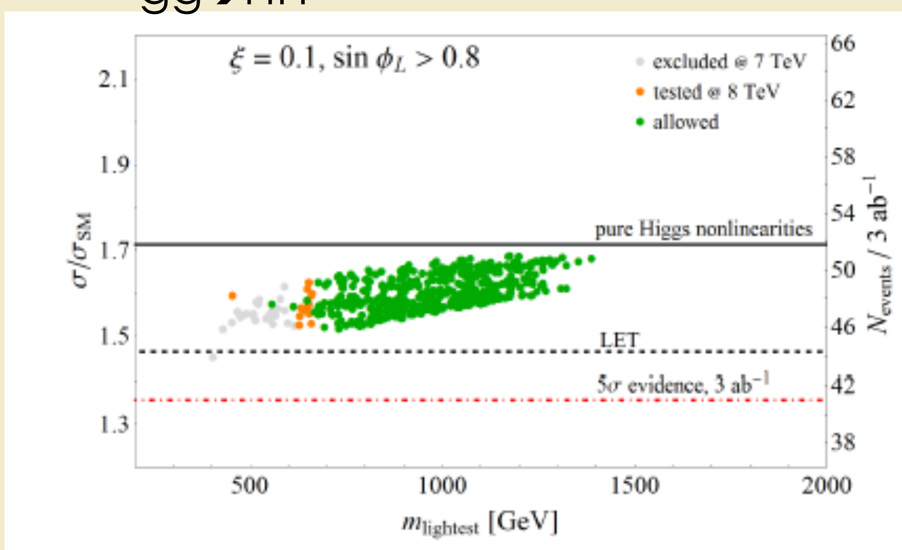
- Suppose $R_{experimental} > 0.8$
  - $\zeta < .07$

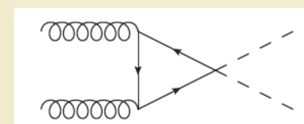
HH in Composite Models

- HH production enhanced
  - Enhancement grows with ξ
- New effect: ttHH vertex
  - Can have O(1) effects



gg→HH





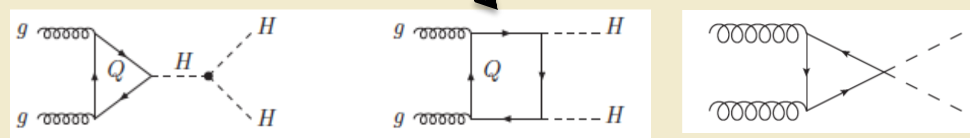
Number of bbγγ events (1 tagged b jet)

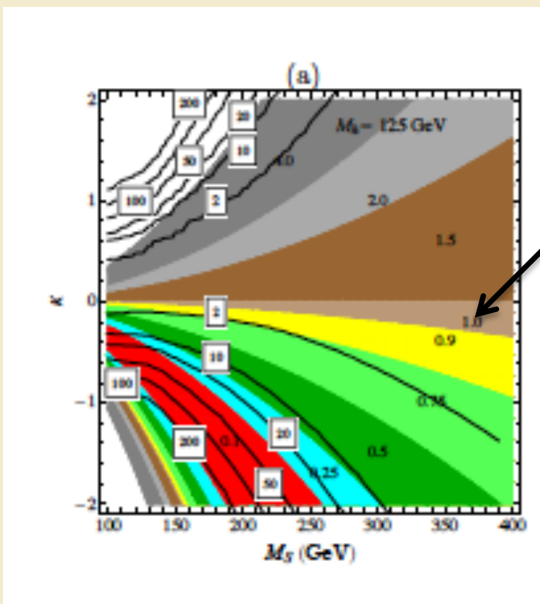
Gillioz et al, 1206.7120

One more model

- Add colored octet scalars with mixing to SM H: $\kappa\phi\phi H^2$
- Motivatlon:
  - large coupling to gluons
  - $\phi\phi$HH vertex

New scalars





Single H/single H SM less than #

Boxes #: ratio of HH to HH(SM)

Same story…. Knowing single Higgs production rate restricts double Higgs possibilities

Kribs and Martin, ArXiv1207.4496

Double Higgs Production

- If fermion masses arise from electroweak symmetry breaking, they have the form

$$O_{LE} = \frac{\alpha_s}{24\pi} G^A_{\mu\nu} G^{A,\mu\nu} \log\left(\frac{H^+ H}{v^2}\right) = \frac{\alpha_s}{12\pi} G^A_{\mu\nu} G^{A,\mu\nu} \left(\frac{H}{v} - \frac{H^2}{2v^2}\right)$$

- A general expansion could also generate

$$O_{eff} = \frac{\alpha_s}{4\pi} C_1 G^A_{\mu\nu} G^{A,\mu\nu} \left|\frac{H^+ H}{v^2}\right|^2 = \frac{\alpha_s}{4\pi} C_1 G^A_{\mu\nu} G^{A,\mu\nu} \left(\frac{H}{v} + \frac{H^2}{2v^2}\right)$$

- Measuring single and double Higgs production is window into source of EWSB, but probe the same operators

The Bottom Line

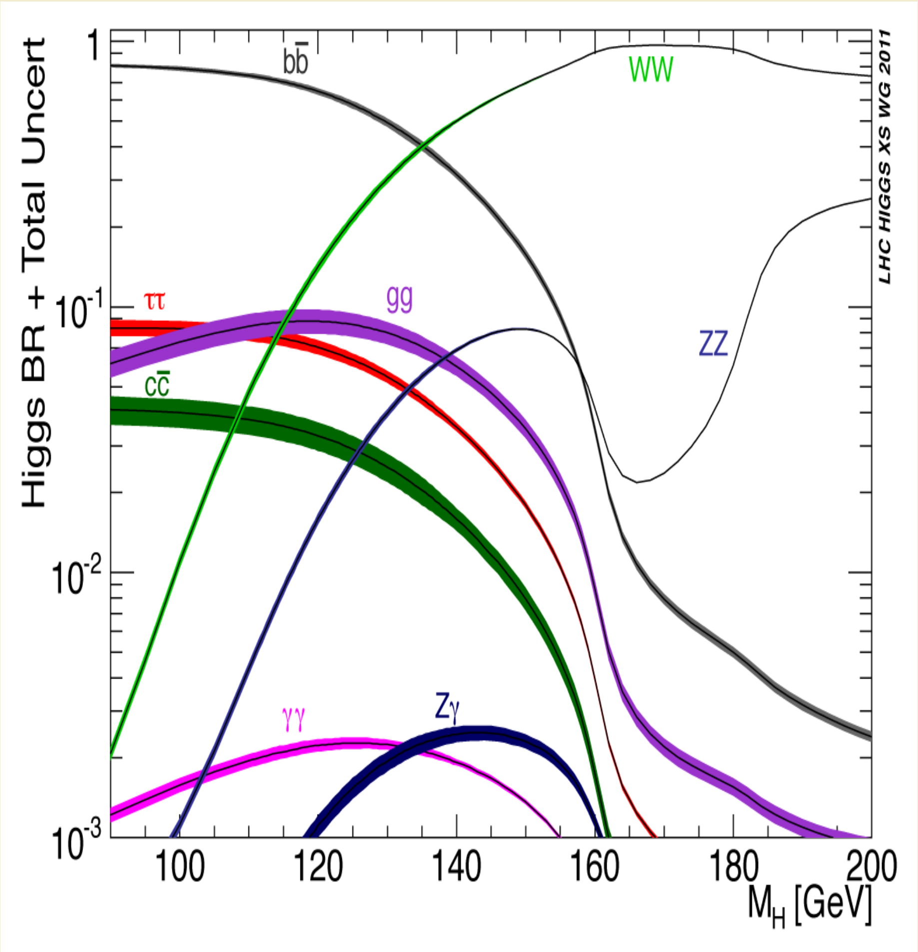
- Since single Higgs production rate is ~SM
- Hard to get double Higgs production much more than ~2Xs SM in models with only one Higgs

- No general theorem….it's proof by exhaustion

Models with multiple Higgs can get enhancements from resonance production, gg➔H➔hh

Higgs portal model (tuned) can get ~ Xs 20% enhancement of hh rate

HH decays



Channels studied:

$$HH \to b\bar{b}\gamma\gamma$$

$$HH \to b\bar{b}\tau^+\tau^-$$

$$HH \to b\bar{b}W^+W^-$$

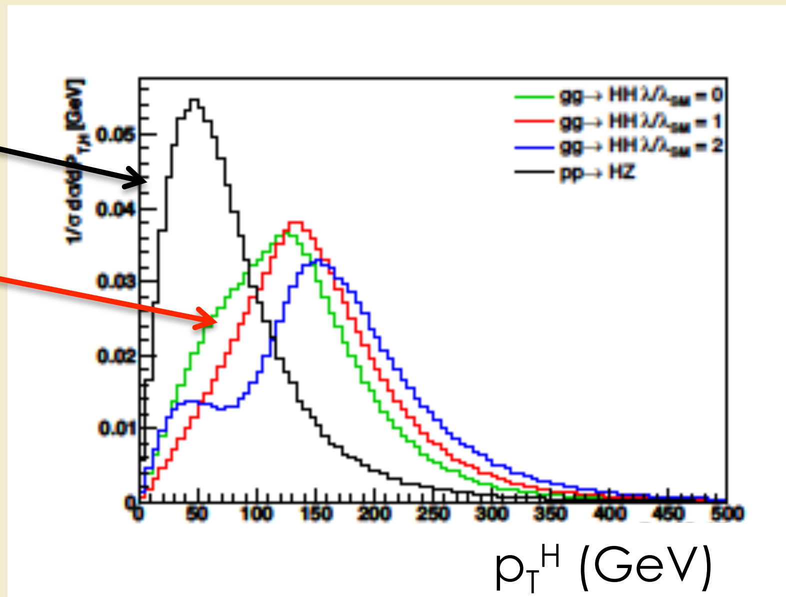
Measuring HH Production

- Higgs are boosted

gg➔HH

Background from ZH

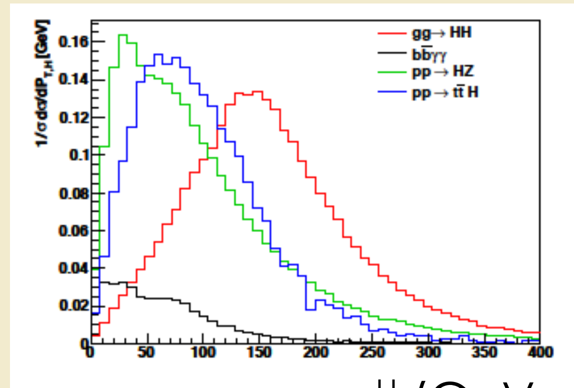
SM



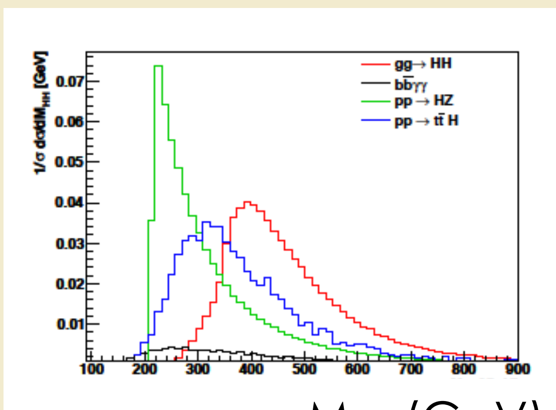
In boosted regime, less sensitivity to λ_3

14 TeV: HH→ bbγγ

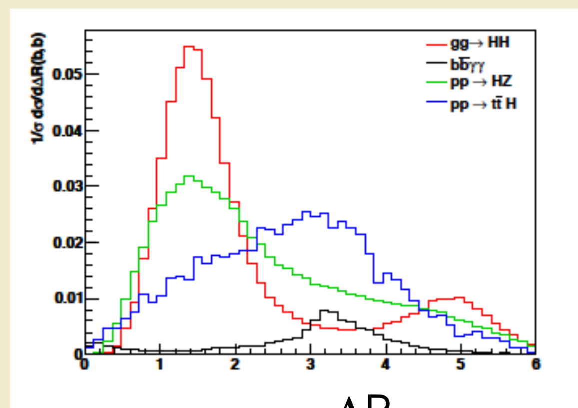
- Cut based analysis
- s/√B~16 with 51 signal events in 3 ab^{-1}



p_T^H (GeV



M_{HH} (GeV)

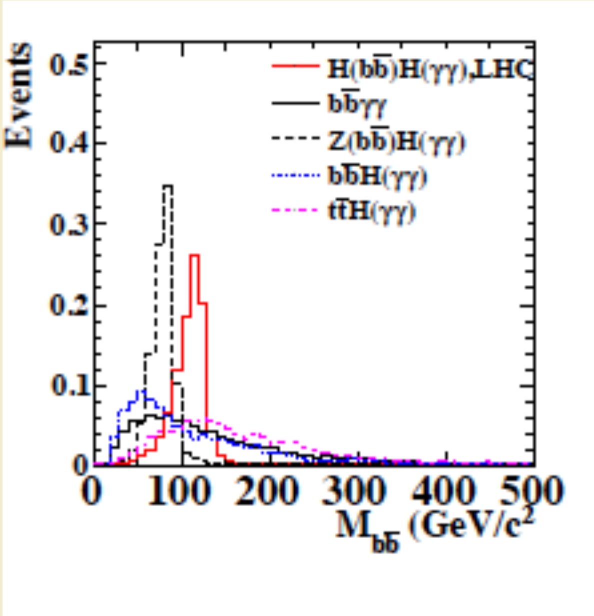


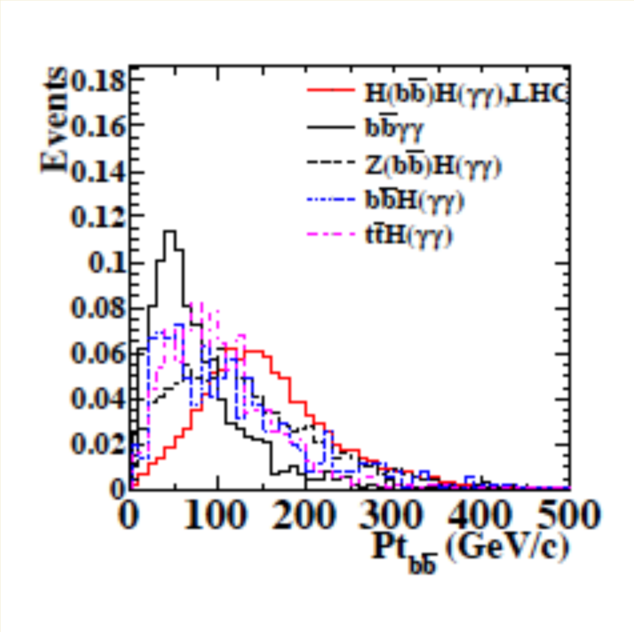
ΔR_{bb}

Baglio et al

Snowmass Simulation: 14/33/100 TeV: HH→ bbγγ

- Delphes simulation framework





Yao, ArXiv:1308.6302

Snowmass Simultation: HH→ bbγγ

- Before cuts:

Samples	Gen. cuts	HL-LHC		TeV33		TeV100	
		$\sigma\cdot B$ (fb)	Eevent	$\sigma\cdot B$ (fb)	Events	$\sigma\cdot B$ (fb)	Events
$H(b\bar{b})H(\gamma\gamma)$		0.0892	80000	0.545	80000	3.73	80000
$b\bar{b}\gamma\gamma$	$Et_{j,b,\gamma} > 20, 20, 25$	294	1033875	1085	952811	5037	763962
$Z(b\bar{b})H(\gamma\gamma)$	$Et_{j,b,\gamma} > 20, 0, 20$	0.109	97168	0.278	82088	0.876	68585
$b\bar{b}H(\gamma\gamma)$	$Et_{j,b,\gamma} > 20, 0, 20$	2.23	120617	9.843	110663	50.49	99611
$t\bar{t}H(\gamma\gamma)$	$Et_{j,b,\gamma} > 20, 0, 20$	0.68	83491	4.76	71790	37.26	63904

- After cuts:

Samples	HL-LHC (3 ab^{-1})			TeV33 (3 ab^{-1})			TeV100 (3 ab^{-1})		
	$\sigma\cdot Br$ (fb)	Acc. (%)	Expect Evnts	$\sigma\cdot Br$ (fb)	Acc. (%)	Expect Evnts	$\sigma\cdot Br$ (fb)	Acc. (%)	Expect Evnts
HH($b\bar{b}\gamma\gamma$)	0.089	6.2	16.6	0.545	5.04	82.4	3.73	3.61	403.9
$b\bar{b}\gamma\gamma$	294	0.0045	40.1	1085	0.0039	126.4	5037	0.00275	415.4
$z(b\bar{b})h(\gamma\gamma)$	0.109	1.48	4.86	0.278	1.41	11.8	0.875	1.57	41.2
$b\bar{b}h(\gamma\gamma)$	2.23	0.072	4.82	9.84	0.084	24.8	50.5	0.099	150.5
$t\bar{t}h(\gamma\gamma)$	0.676	0.178	3.62	4.76	0.12	16.5	37.3	0.11	124.2
Total B	-	-	53.4	-	-	179.5	-	-	731.3
S/$\sqrt{B}$	-	-	2.3	-	-	6.2	-	-	15.0

$$\frac{d(\sigma/\sigma_{SM})}{d(\lambda_3/\lambda_{3,SM})} \sim -.8$$

- Statistical accuracy on λ_3: 50% (8%) at 14 (100) TeV with 3000 fb^{-1}

14 TeV: $HH \rightarrow b\bar{b}W^+W^-$

- Small signal: $W \rightarrow l\nu$, $W \rightarrow$ Jets
  - No cuts: $\sigma \sim 30$ fb
  - 1 isolated lepton: → 4 fb
  - MET+Jet cuts: → .9 fb
  - Hadronic W reconstruction: → .3 fb
  - Kinematic Higgs reconstruction: → .017 fb

- Huge background from bbWW: $S/\sqrt{B}$~.001

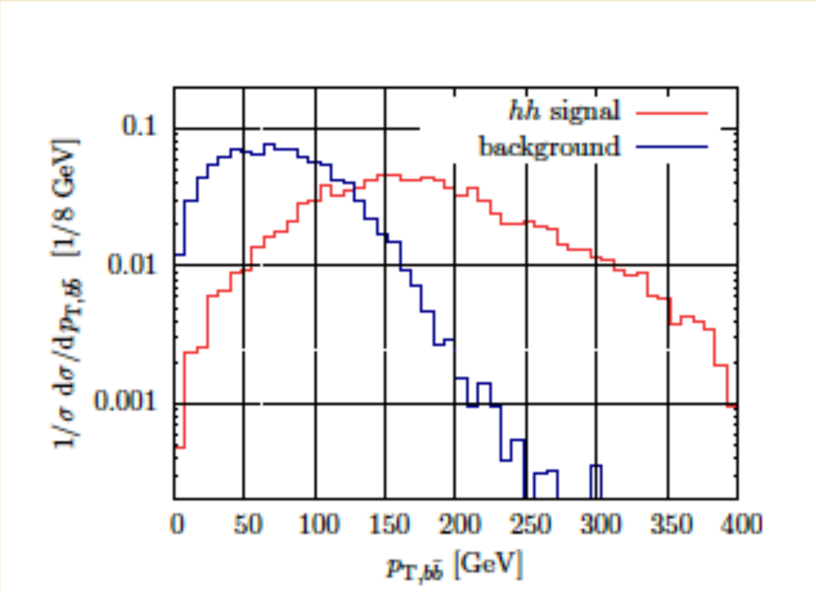
⇨ This channel not seriously considered

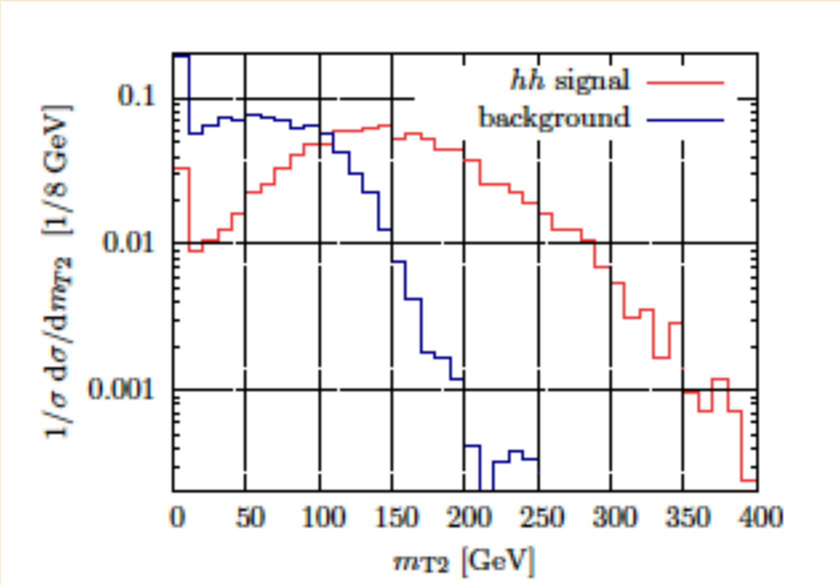
Dolan et al, arXiv:1206.5002

14 TeV: HH → bbττ

- Signal: $hh \to b\bar{b}\tau^+\tau^- + X$
- Largest background: $t\bar{t} \to (bW^+)(\bar{b}W^-) + X$

$$\to (b\tau^+\nu)(\bar{b}\tau^-\overline{\nu}) + X$$

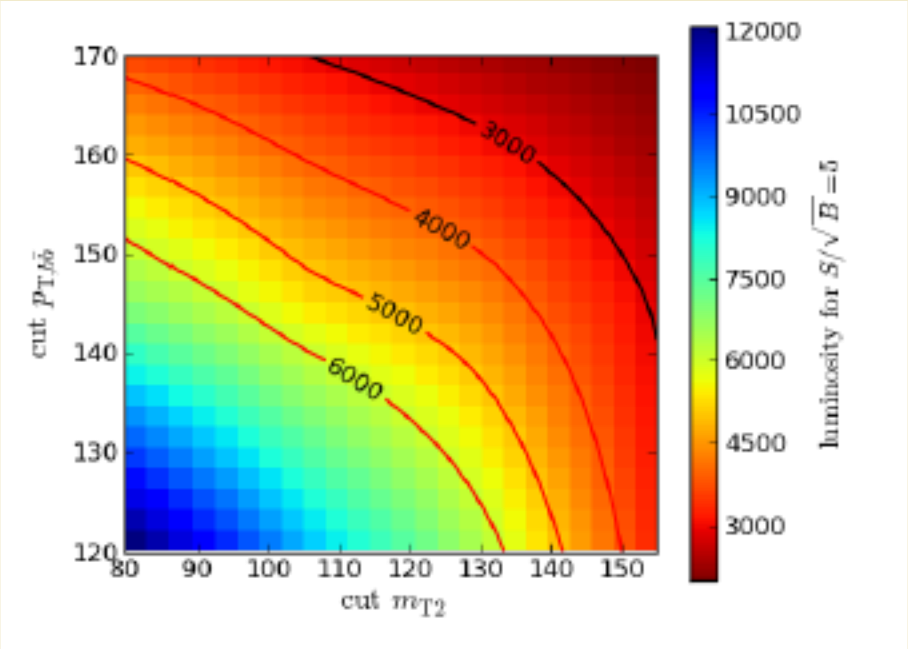




Dolan ArXiv:1206.5001

14 TeV: HH → bbττ

- Luminosity for 5σ measurement of λ_3 with p_{Tbb} and m_{T2} cuts



Comparisons

	HL-LHC	HE-LHC	VLHC
$\sqrt{s}$ (TeV)	14	33	100
$\int \mathcal{L}dt$ (fb^{-1})	3000	3000	3000
$\sigma \cdot \text{BR}(pp \to HH \to bb\gamma\gamma)$ (fb)	0.089	0.545	3.73
$S/\sqrt{B}$	2.3	6.2	15.0
λ (stat)	50%	20%	8%

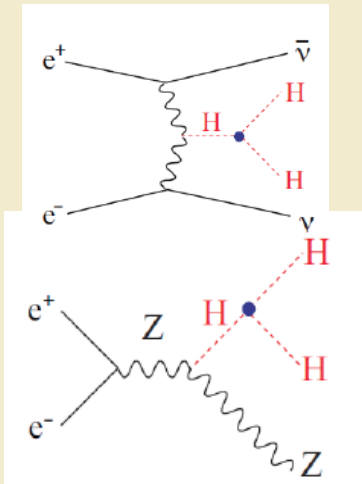
	ILC500	ILC500-up	ILC1000	ILC1000-up	CLIC1400	CLIC3000
$\sqrt{s}$ (GeV)	500	500	500/1000	500/1000	1400	3000
$\int \mathcal{L}dt$ (fb^{-1})	500	$1600^{\ddagger}$	500+1000	$1600+2500^{\ddagger}$	1500	+2000
$P(e^-, e^+)$	$(-0.8, 0.3)$	$(-0.8, 0.3)$	$(-0.8, 0.3/0.2)$	$(-0.8, 0.3/0.2)$	$(0,0)/(-0.8,0)$	$(0,0)/(-0.8,0)$
$\sigma\,(ZHH)$	42.7%		42.7%	23.7%	–	–
$\sigma\,(\nu\bar{\nu}HH)$	–	–	26.3%	16.7%		
λ	83%	46%	21%	13%	28/21%	16/10%

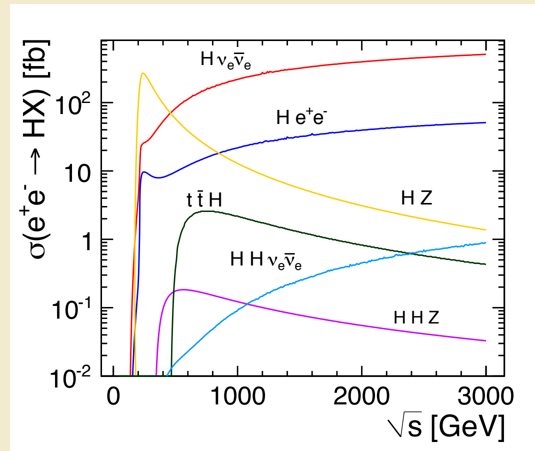
- 5σ deviation requires 4% measurement
- Exclusion of 20% deviation at 95% CL requires 10% measurement

Conclusions

- Measuring HH production required to understand Higgs potential
- Hard to make HH rate much different from SM rate because of constraints from single Higgs production and electroweak measurements
- Small rates….serious study of experimental possibilities just beginning

e^+e^- machines have low rates for HH





	ILC500	ILC500-up	ILC1000	ILC1000-up	CLIC1400	CLIC3000
$\sqrt{s}$ (GeV)	500	500	500/1000	500/1000	1400	3000
$\int \mathcal{L}dt$ (fb^{-1})	500	$1600^{\ddagger}$	500+1000	$1600+2500^{\ddagger}$	1500	+2000
$P(e^-, e^+)$	$(-0.8, 0.3)$	$(-0.8, 0.3)$	$(-0.8, 0.3/0.2)$	$(-0.8, 0.3/0.2)$	$(0,0)/(-0.8,0)$	$(0,0)/(-0.8,0)$
$\sigma\,(ZHH)$	42.7%		42.7%	23.7%	–	–
$\sigma\,(\nu\bar{\nu}HH)$	–	–	26.3%	16.7%		
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