Precision Higgs Measurements @ (I)LC

Junping Tian (U’ of Tokyo)

7th Linear Collider School, May 6-13, 2018 @ Frauenchiemsee

the last HEP school I joined: FAPPS 2009 @ Mt. Fujii

I was a PhD student then, and was told ILC will be approved soon

hope it will not take another 9 years…

outline — Higgs Physics at LC

(i) introduction

(ii) key measurements

Lecture 1

(iii) effective field theory

(iv) some loose ends

Lecture 2 (Wed.)

focus is on experimental part; see theory part in Georg's lecture

(i) introduction

— build up the story

why we are interested in Higgs physics at LC?
what we actually want to determine at LC?
what are the experimental observables at LC?
how we can get the couplings from observables?

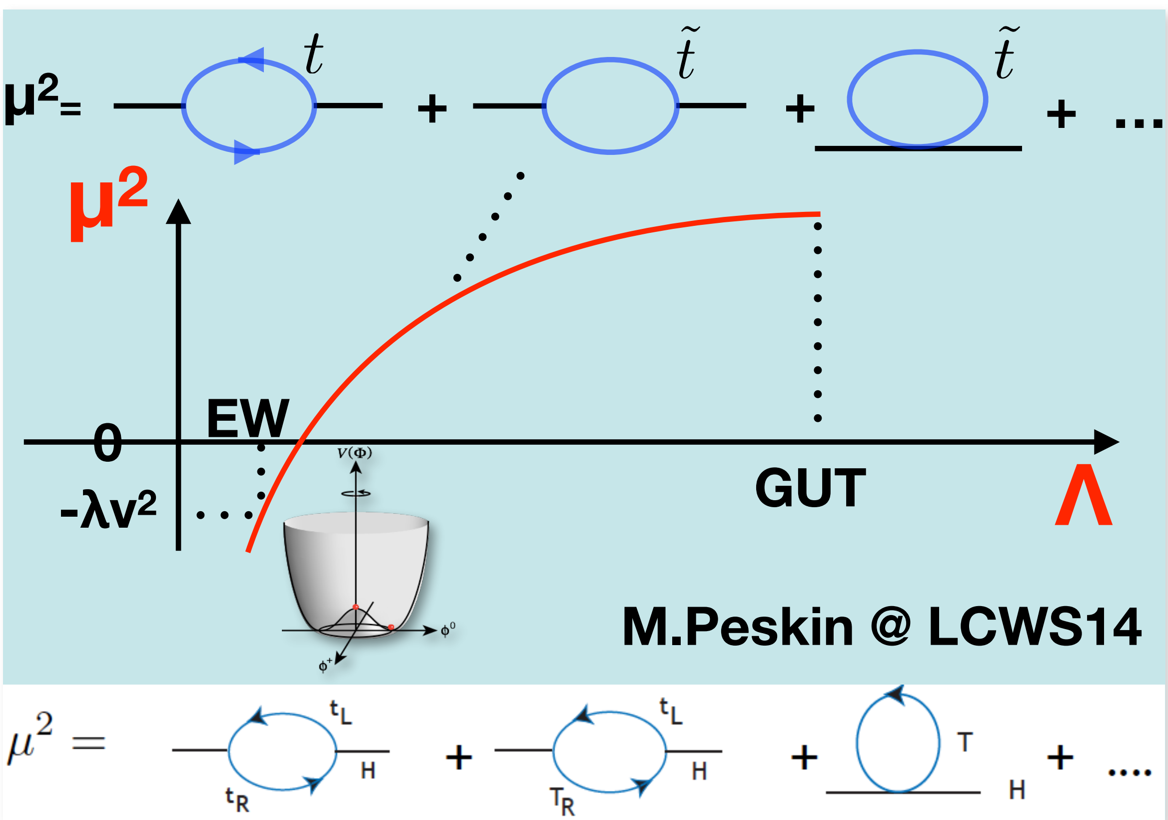
why Higgs physics

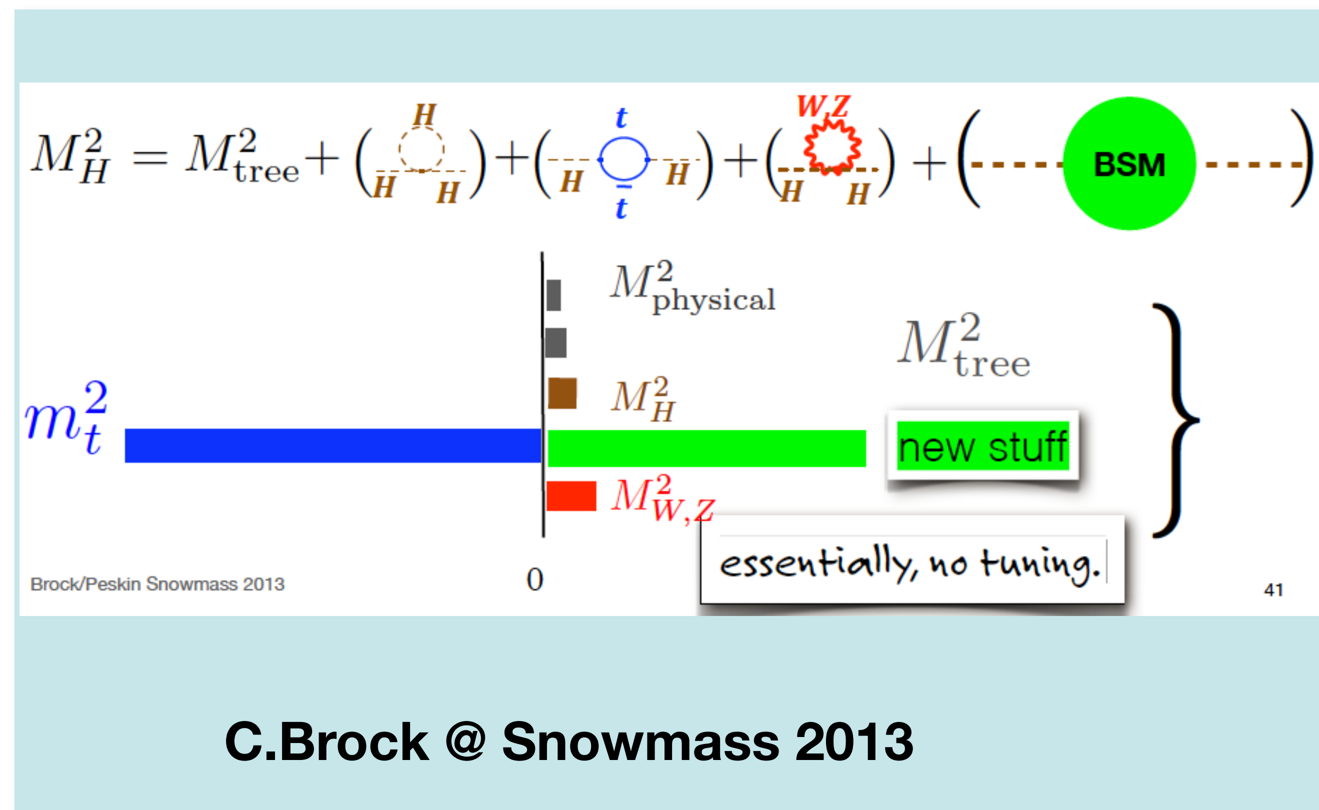
- to reveal the mysteries at electroweak scale
  - Why is $\mu^2 < 0$? what is the dynamics responsible for EWSB?
  - How to explain the naturalness for the light scalar?
  - Any connection to Dark Matter, BAU, inflation?
  - $H(125) = H_{SM}$? any siblings?

Higgs is a window to new physics

why Higgs physics

- there do exist many theories which can answer those questions
- importantly those theories will have imprints in Higgs physics





learn more systematically Higgs theory from tomorrow's lecture by Georg

why precision higgs physics

- Haber's decoupling limit, deviation ~ m_h^2/M^2.

—> $\Delta g/g \sim O(1\%)$ for M ~ 1 TeV

challenging at LHC

Mixing with singlet

$$\frac{g_{hVV}}{g_{h_{\rm SM}VV}} = \frac{g_{hff}}{g_{h_{\rm SM}ff}} = \cos\theta \simeq 1 - \frac{\delta^2}{2}$$

typical deviation

Composite Higgs

$$\frac{g_{hVV}}{g_{h_{\rm SM}VV}} \simeq 1 - 3\%(1\ \mathrm{TeV}/f)^2$$

$$\frac{g_{hff}}{g_{h_{\rm SM}ff}} \simeq \begin{cases} 1 - 3\%(1\ \mathrm{TeV}/f)^2 & (\mathrm{MCHM4}) \\ 1 - 9\%(1\ \mathrm{TeV}/f)^2 & (\mathrm{MCHM5}) \end{cases}$$

SUSY

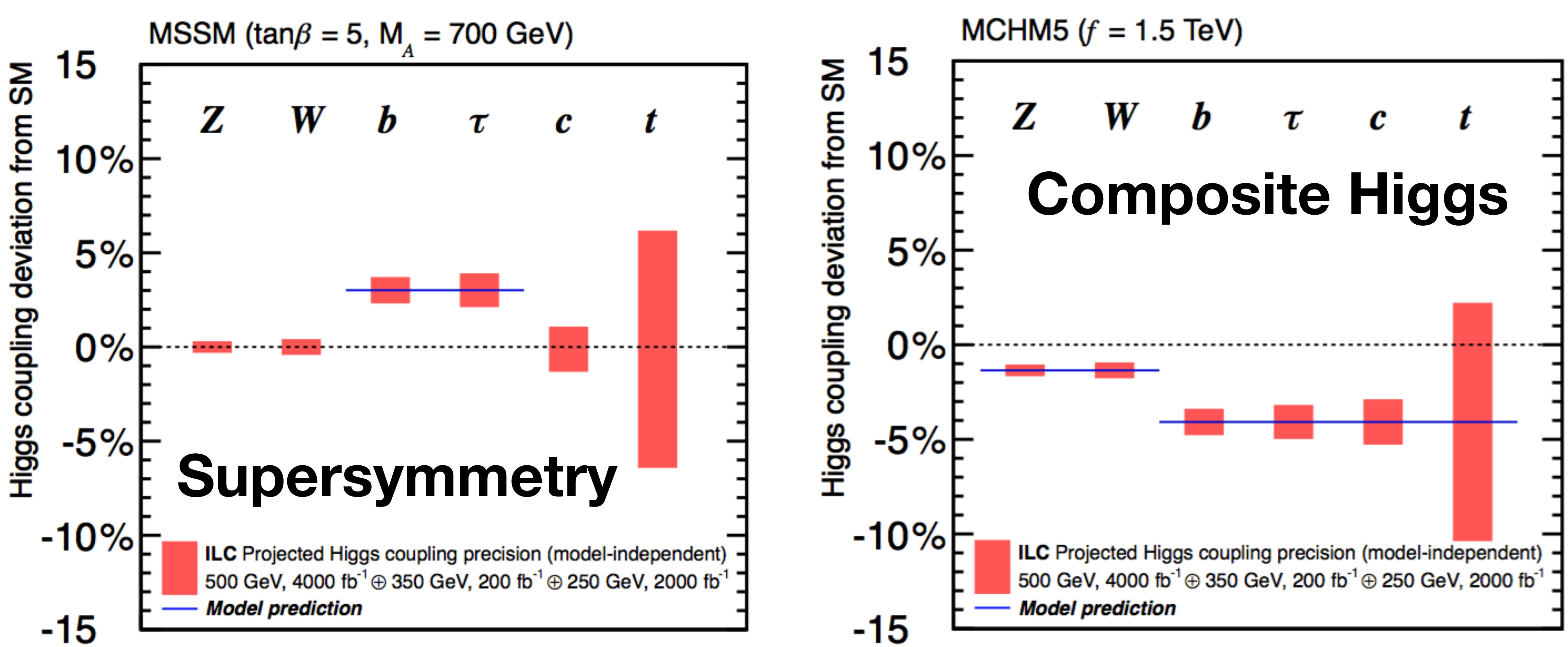
$$\frac{g_{hbb}}{g_{h_{\rm SM}bb}} = \frac{g_{h\tau\tau}}{g_{h_{\rm SM}\tau\tau}} \simeq 1 + 1.7\% \left(\frac{1\ \mathrm{TeV}}{m_A}\right)^2$$

arXiv:1306.6352

why precision higgs physics

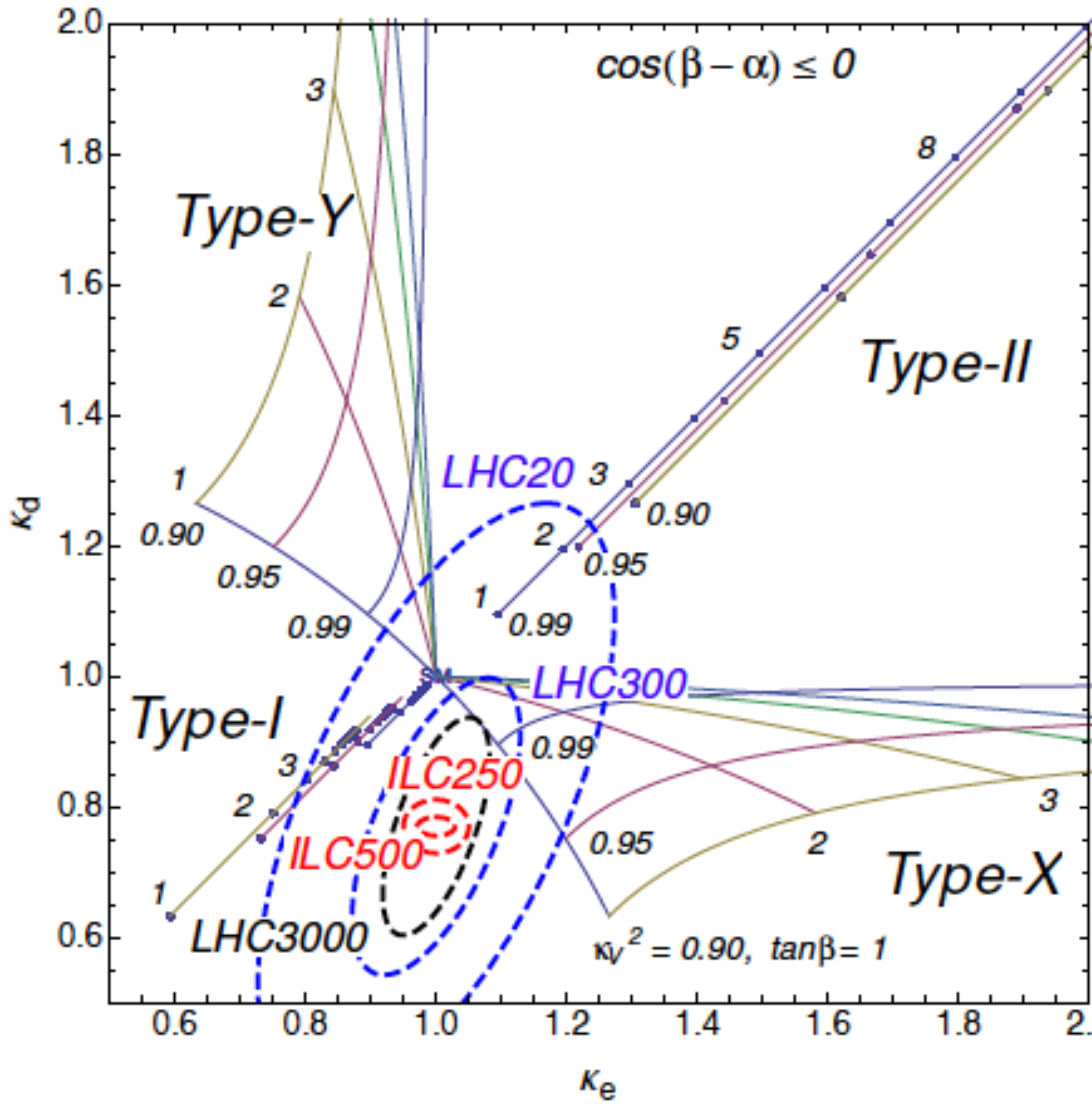
- fingerprint BSM by patterns of deviations

  —> measure as many couplings as possible



arXiv:1506.05992

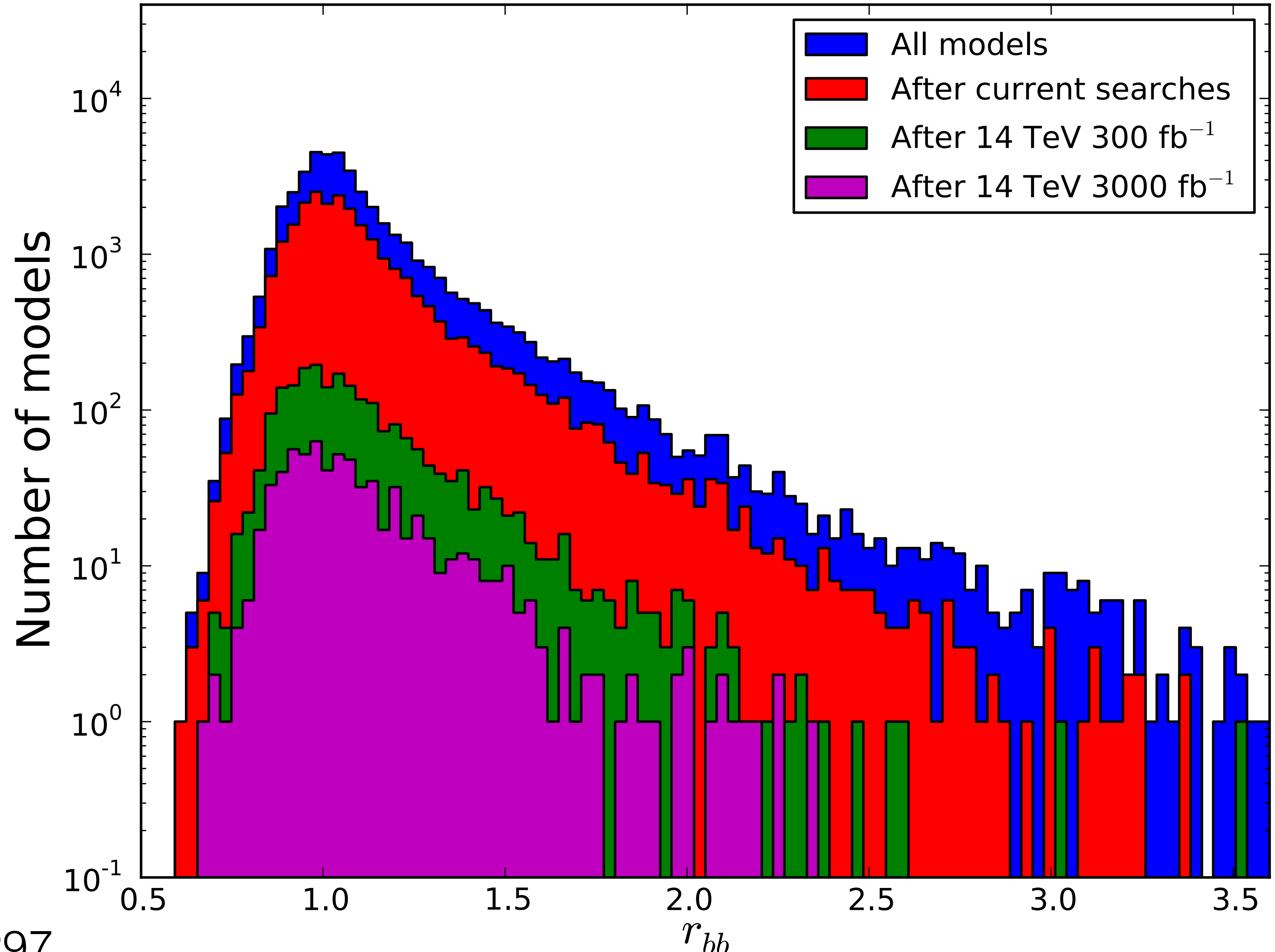
why precision higgs physics



Kanemura et al., arXiv: 1406.3294

fingerprint the 4 types of 2HDM

discovery opportunities: direct versus indirect



arXiv:1308.0297

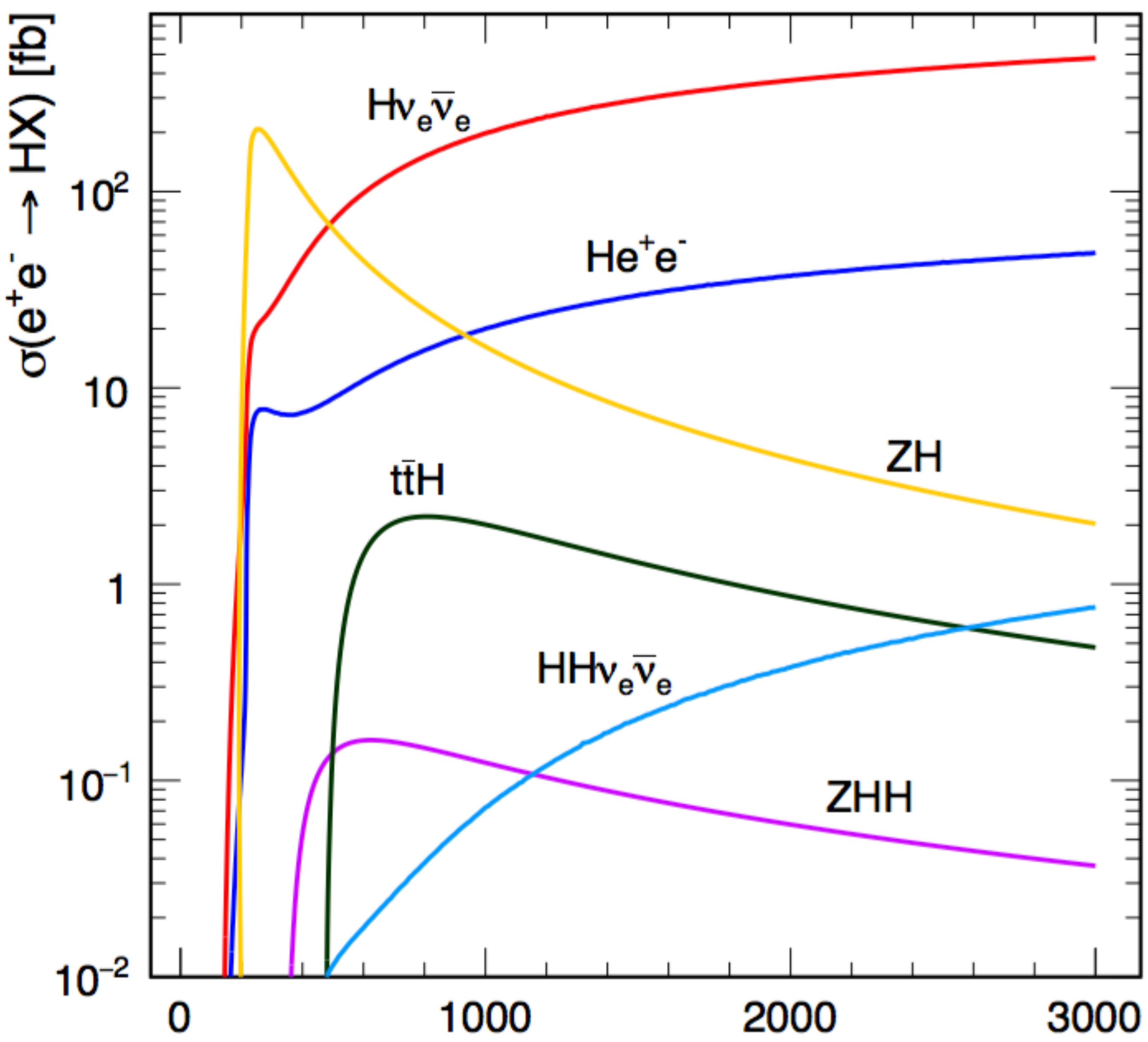
Figure 8: Histograms of the ratio $r_{bb} = \Gamma(h \to \bar{b}b)/\Gamma(h \to \bar{b}b)_{\rm SM}$ within a scan of the approximately 250,000 supersymmetry parameter sets after various stages of the LHC, assuming the LHC does not find direct evidence for supersymmetry. The purple histogram shows parameter points that would not be discovered at future upgrades of the LHC (14 TeV and $3\,{\rm ab}^{-1}$ integrated luminosity). From [38].

proposals of future lepton colliders

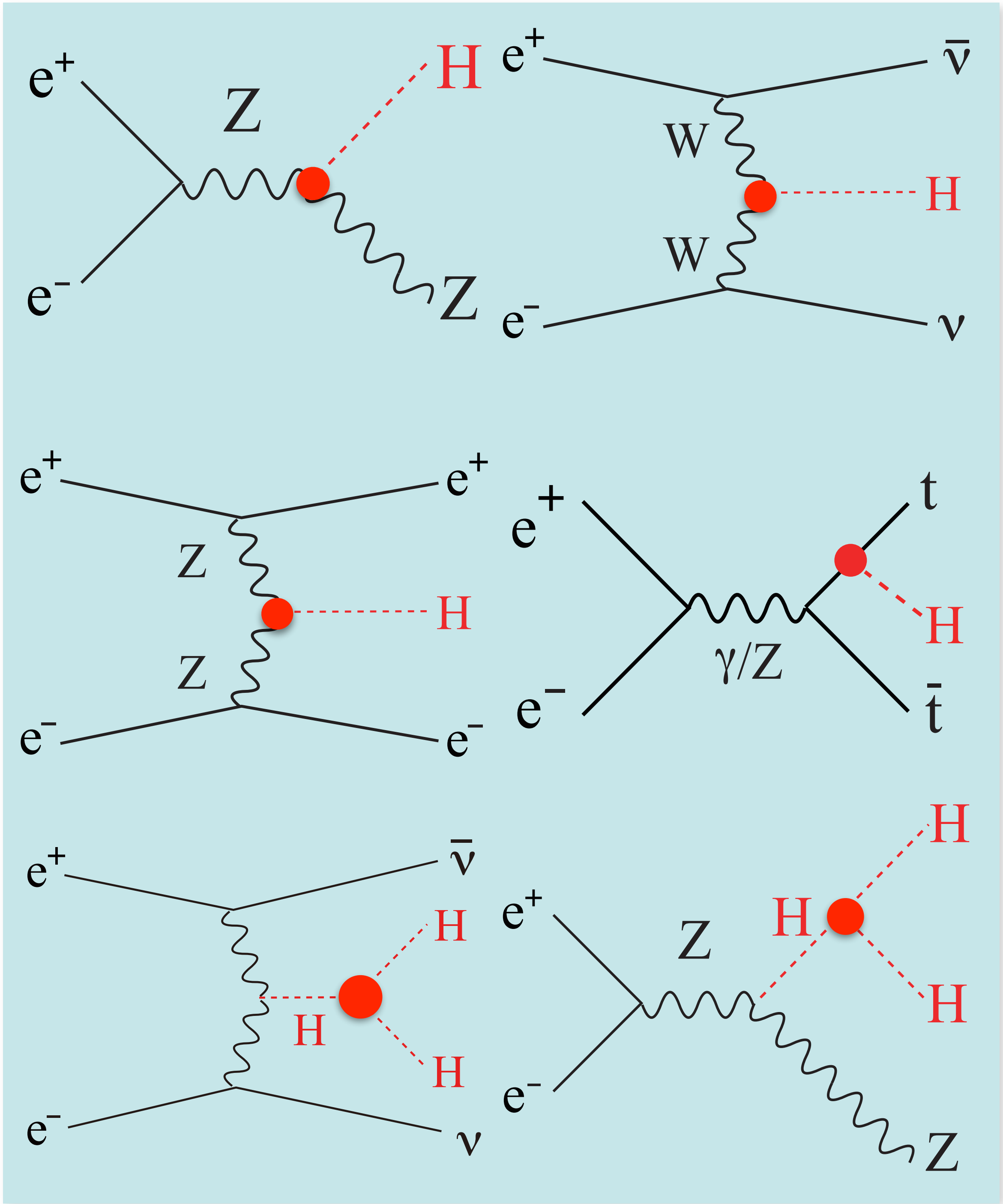
	$\sqrt{s}$	beam polarisation	$\int L dt$ for Higgs	R&D phase
ILC	0.1 - 1 TeV	e-: 80% e+: 30%	2000 fb^{-1} @ 250 GeV 200 fb^{-1} @ 350 GeV 4000 fb^{-1} @ 500 GeV	TDR completed
CLIC	0.35 - 3 TeV	e-: (80%) e+: 0%	500 fb^{-1} @ 380 GeV 1500 fb^{-1} @ 1.4 TeV 2000 fb^{-1} @ 3 TeV	CDR completed
CEPC	90 - 240 GeV	e-: 0% e+: 0%	5000 fb^{-1} @ 250 GeV	preCDR completed
FCC-ee	90 - 350 GeV	e-: 0% e+: 0%	5000 fb^{-1} @ 250 GeV 1500 fb^{-1} @ 350 GeV	towards CDR

common: Higgs factory with $O(10^6)$ Higgs events

Higgs productions at e+e-



(unpolarized case)



- two apparent important thresholds: $\sqrt{s}$ ~ 250 GeV for ZH, ~500 GeV for ZHH and ttH
- + another threshold for t t-bar, important for Higgs sector as well

what are the fundamental quantities to determine

reconstruct the Higgs sector in a bottom-up and model independent way

Mass & J^{CP}	$M_h \quad \Gamma_h \quad J^{\mathrm{CP}}$	new CP violating source?
L_{Higgs}	$hhh: \; -6i\lambda v = -3i\frac{m_h^2}{v}, \quad hhhh: \; -6i\lambda = -3i\frac{m_h^2}{v^2}$	probe Higgs potential, EWBG?
L_{Gauge}	$W_\mu^+ W_\nu^- h: \; i\frac{g^2 v}{2} g_{\mu\nu} = 2i\frac{M_W^2}{v} g_{\mu\nu}, \quad W_\mu^+ W_\nu^- hh: \; i\frac{g^2}{2} g_{\mu\nu} = 2i\frac{M_W^2}{v^2} g_{\mu\nu},$ $Z_\mu Z_\nu h: \; i\frac{g^2 + g'^2 v}{2} g_{\mu\nu} = 2i\frac{M_Z^2}{v} g_{\mu\nu}, \quad Z_\mu Z_\nu hh: \; i\frac{g^2 + g'^2}{2} g_{\mu\nu} = 2i\frac{M_Z^2}{v^2} g_{\mu\nu}$	SU(2) nature? m_V from SSB?
L_{Yukawa}	$h\bar{f}f: \; -i\frac{y^f}{\sqrt{2}} = -i\frac{m_f}{v}$	m_f from Yukawa coupling? 2HDM?
L_{Loop}	$h\gamma\gamma \quad hgg \quad h\gamma Z$	new particles in the loop?

+ possible exotic/anomalous interactions of Higgs, e.g. h—>dark matter

The study of the deviations from these predictions is guided by the idea that each Higgs coupling has its own personality and is guided by different types of new physics. This is something of a caricature, but, still, a useful one.

M. Peskin @ HPNP2015

fermion couplings - multiple Higgs doublets

gauge boson couplings - Higgs singlets, composite Higgs

γγ, gg couplings - heavy vectorlike particles

tt coupling - top compositeness

hhh coupling (large deviations) - baryogenesis

what are the direct experimental observables

- ☑ σ_{ZH}
- ☑ $\sigma_{ZH}\times Br(H \rightarrow bb)$, $\sigma_{\nu\nu H}\times Br(H \rightarrow bb)$
- ☑ $\sigma_{ZH}\times Br(H \rightarrow cc)$, $\sigma_{\nu\nu H}\times Br(H \rightarrow cc)$
- ☑ $\sigma_{ZH}\times Br(H \rightarrow gg)$, $\sigma_{\nu\nu H}\times Br(H \rightarrow gg)$
- ☑ $\sigma_{ZH}\times Br(H \rightarrow WW^*)$, $\sigma_{\nu\nu H}\times Br(H \rightarrow WW^*)$
- ☑ $\sigma_{ZH}\times Br(H \rightarrow ZZ^*)$, $\sigma_{\nu\nu H}\times Br(H \rightarrow ZZ^*)$
- ☑ $\sigma_{ZH}\times Br(H \rightarrow \tau\tau)$, $\sigma_{\nu\nu H}\times Br(H \rightarrow \tau\tau)$
- ☑ $\sigma_{ZH}\times Br(H \rightarrow \gamma\gamma)$, $\sigma_{\nu\nu H}\times Br(H \rightarrow \gamma\gamma)$
- ☑ $\sigma_{ZH}\times Br(H \rightarrow \mu\mu)$, $\sigma_{\nu\nu H}\times Br(H \rightarrow \mu\mu)$
- ☑ $\sigma_{ZH}\times Br(H \rightarrow Invisible)$
- ☑ $\sigma_{ttH}\times Br(H \rightarrow bb)$
- ☑ $\sigma_{ZHH}\times Br^2(H \rightarrow bb)$, $\sigma_{\nu\nu HH}\times Br^2(H \rightarrow bb)$

note the important complementarity with LHC

what are the direct experimental observables

estimates at ILC by simulation

-80% e^-, +30% e^+ polarization:

	250 GeV		350 GeV		500 GeV	
	Zh	$\nu\bar{\nu}h$	Zh	$\nu\bar{\nu}h$	Zh	$\nu\bar{\nu}h$
σ [50–53]	2.0		1.8		4.2	
$h \to invis.$ [54,55]	0.86		1.4		3.4	
$h \to b\bar{b}$ [56–59]	1.3	8.1	1.5	1.8	2.5	0.93
$h \to c\bar{c}$ [56,57]	8.3		11	19	18	8.8
$h \to gg$ [56,57]	7.0		8.4	7.7	15	5.8
$h \to WW$ [59–61]	4.6		5.6 *	5.7 *	7.7	3.4
$h \to \tau\tau$ [63]	3.2		4.0 *	16 *	6.1	9.8
$h \to ZZ$ [2]	18		25 *	20 *	35 *	12 *
$h \to \gamma\gamma$ [64]	34 *		39 *	45 *	47	27
$h \to \mu\mu$ [65,66]	72 *		87 *	160 *	120 *	100 *
a [27]	7.6		2.7 *		4.0	
b	2.7		0.69 *		0.70	
$\rho(a,b)$	-99.17		-95.6 *		-84.8	

(arXiv: 1708.08912; numbers are in %, for nominal $\int Ldt$ = 250 fb^{-1})

see chapter (ii) for details

From observables to couplings — Global Fit

$$\chi^2 = \sum_{i=1}^{n} (\frac{Y_i - Y_i'}{\Delta Y_i})^2$$

Yi: measured values by experiments

Yi': predicted values by underlying theory

ΔYi: measurement uncertainty

n: number of independent observables

- kappa formalism

$$Y_i' = F_i \cdot \frac{g^2_{HA_iA_i} \cdot g^2_{HB_iB_i}}{\Gamma_0} \qquad \begin{array}{l}(A_i = Z, W, t) \\ (B_i = b, c, \tau, \mu, g, \gamma, Z, W \ : \mathrm{decay})\end{array}$$

$$g_{HXX} = \kappa_X \cdot g^{SM}_{HXX}$$

- effective field theory formalism (Lecture 2)

From observables to couplings — Global Fit

in case there are correlated observables

$$\chi^2 = \sum_{i=1}^{n} (\frac{Y_i - Y_i'}{\Delta Y_i})^2 + (Y_j - Y_j')^T C_j^{-1} (Y_j - Y_j')$$

Yj: column vector of correlated observables

Cj: covariance matrix for those observables

see one example in chapter (ii)

From observables to couplings — kappa formalism

(examples)

$$Y_1 = \sigma_{ZH} \propto g^2_{HZZ}$$

$$Y_2 = \sigma_{\nu\bar{\nu}H} \cdot \mathrm{Br}(H \to b\bar{b}) \propto \frac{g^2_{HWW} g^2_{Hbb}}{\Gamma_H}$$

$$Y_3 = \sigma_{ZH} \cdot \mathrm{Br}(H \to b\bar{b}) \propto \frac{g^2_{HZZ} g^2_{Hbb}}{\Gamma_H}$$

$$Y_4 = \sigma_{\nu\bar{\nu}H} \cdot \mathrm{Br}(H \to WW^*) \propto \frac{g^4_{HWW}}{\Gamma_H}$$

$$g_{HZZ} \propto \sqrt{Y_1}$$

$$g_{HWW} \propto \sqrt{\frac{Y_1 Y_2}{Y_3}}$$

$$g_{Hbb} \propto \sqrt{\frac{Y_1 Y_2^2}{Y_3 Y_4}}$$

$$\Gamma_H \propto \frac{Y_1^2 Y_2^2}{Y_3^2 Y_4}$$

From observables to couplings — kappa formalism

$$Y_1 = \sigma_{ZH} \propto g^2_{HZZ}$$

$$Y_2 = \sigma_{\nu\bar{\nu}H} \cdot \mathrm{Br}(H \to b\bar{b}) \propto \frac{g^2_{HWW} g^2_{Hbb}}{\Gamma_H}$$

$$Y_3 = \sigma_{ZH} \cdot \mathrm{Br}(H \to b\bar{b}) \propto \frac{g^2_{HZZ} g^2_{Hbb}}{\Gamma_H}$$

$$Y_4 = \sigma_{\nu\bar{\nu}H} \cdot \mathrm{Br}(H \to WW^*) \propto \frac{g^4_{HWW}}{\Gamma_H}$$

good approximation of uncertainties

$$\Delta g_{HZZ} \sim \frac{1}{2}\Delta Y_1$$

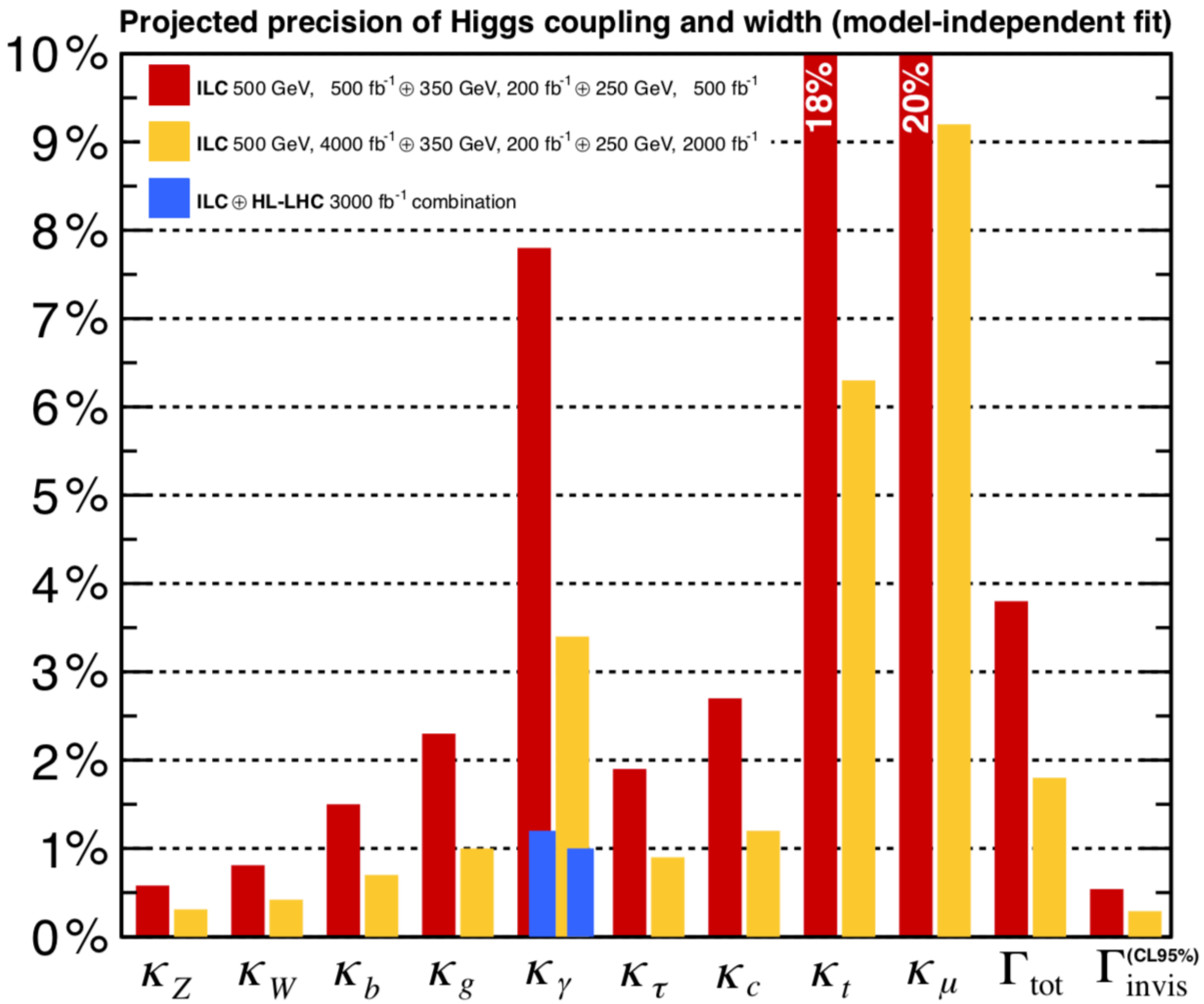
$$\Delta g_{HWW} \sim \frac{1}{2}\Delta Y_1 \oplus \frac{1}{2}\Delta Y_2 \oplus \frac{1}{2}\Delta Y_3$$

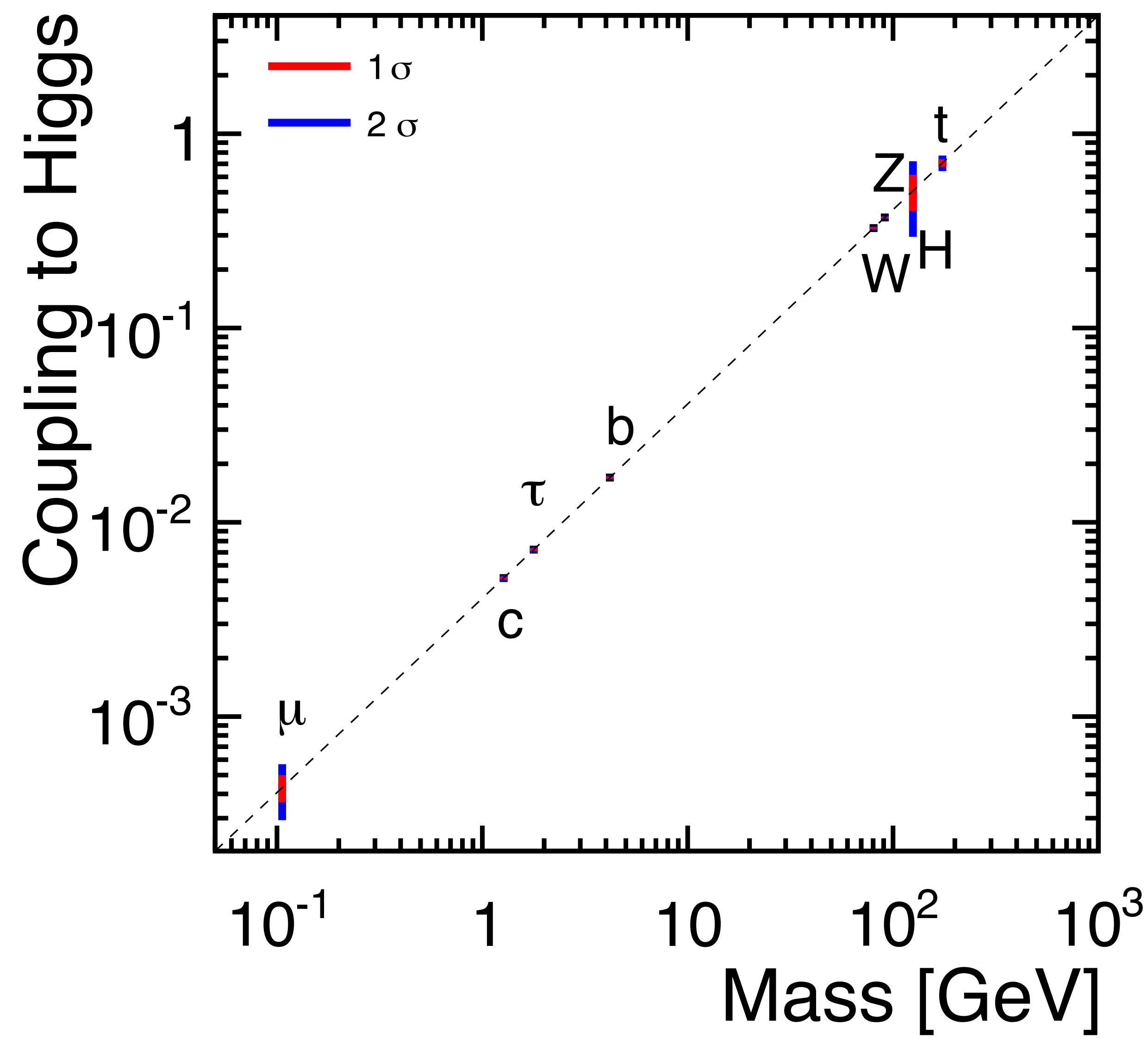
$$\Delta g_{Hbb} \sim \frac{1}{2}\Delta Y_1 \oplus \Delta Y_2 \oplus \frac{1}{2}\Delta Y_3 \oplus \frac{1}{2}\Delta Y_4$$

$$\Delta\Gamma_H \sim 2\Delta Y_1 \oplus 2\Delta Y_2 \oplus 2\Delta Y_3 \oplus \Delta Y_4$$

- ☑ both ZH and vvH productions matter
- ☑ every coupling is limited by $\Delta\sigma_{ZH}$
- ☑ every coupling except g_{HZZ} is limited by $\Delta\sigma_{\nu\nu H}$
- ☑ total width uncertainty is > x4 worse than g_{HZZ} or g_{HWW}

end of chapter (i)





$$\frac{g(hWW)}{\sqrt{2}m_W^2} = \frac{g(hZZ)}{\sqrt{2}m_Z^2} = \frac{y_c}{m_c} = \frac{y_\tau}{m_\tau} = \frac{y_b}{m_b} = \frac{y_t}{m_t} = \frac{\sqrt{2}\lambda(hhh)}{3m_h^2} = \cdots = \frac{1}{v}$$?

references when omitted

- ILC TDR, 1306.6352
- ILC Higgs White Paper, 1310.0763
- ILC Operation Scenario, 1506.07830
- ILC Physics Case, 1506.05992, 1710.07621
- CLIC Higgs Physics, 1608.07538

disclaimer

- apologies for personal bias that most of the example measurements are taken from ILC studies
- precision is offen illustrated in kappa formalism
- see chapter (iii) EFT for full picture

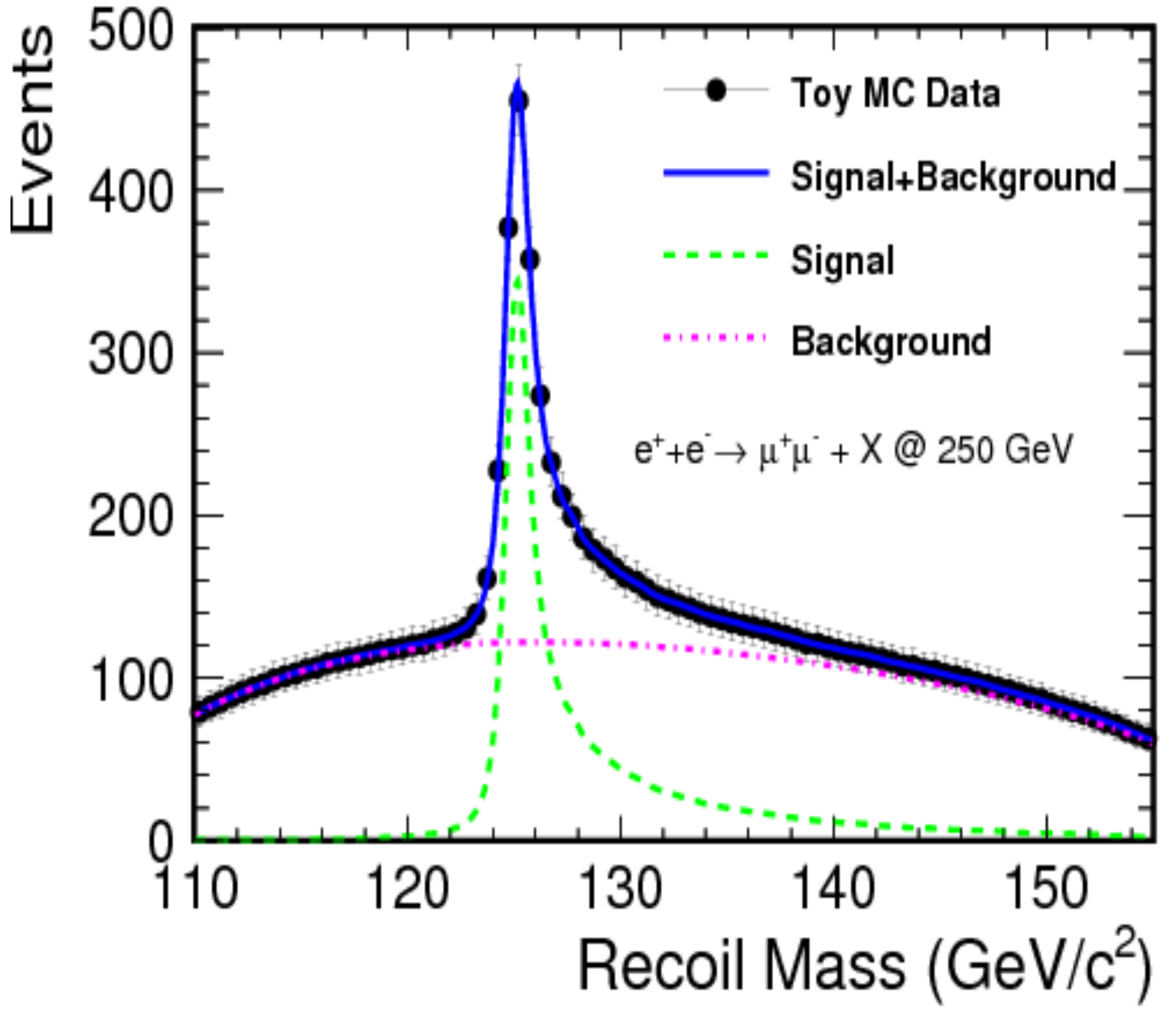
(ii) key measurements

I will explain some details in one/two analyses, talk very briefly in other ones; mainly focus on physics issues instead of analysis techniques, which are important as well though and can be learned from the references.

(1) recoil mass analysis
(2) Higgs self-coupling analysis
(3) Higgs total width
(4) top-Yukawa coupling
(5) Higgs CP
(6) H->bb/cc/gg
(7) …

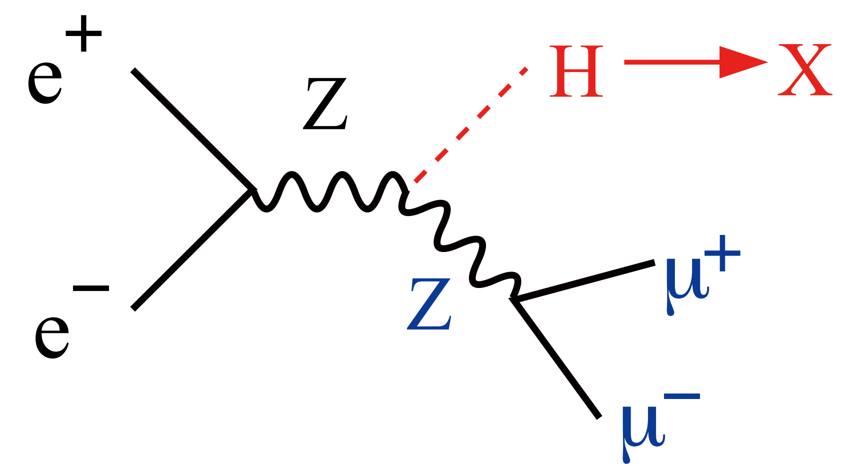
as usual, selection is always biased

(ii-1) inclusive σ_{ZH}: the key of model independence



$$\Delta m_H = 14\text{MeV} \qquad \delta g_{HZZ} \sim 0.38\%$$

$$Y_1 = \sigma_{ZH} \propto g^2_{HZZ}$$

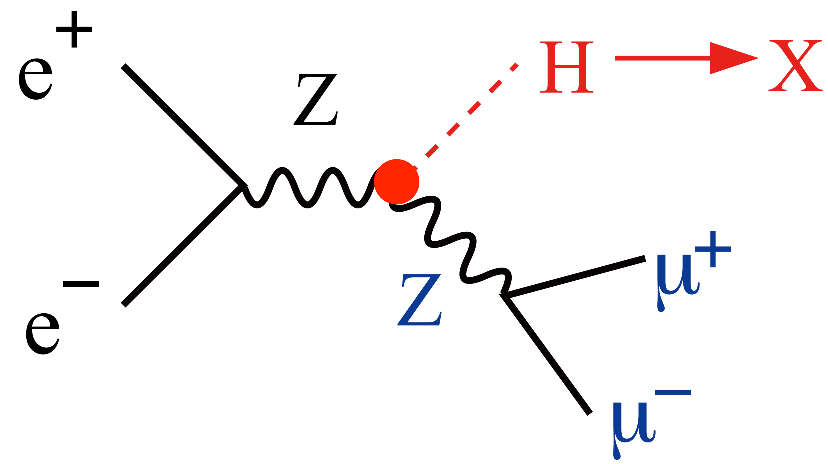


$$M_X^2 = \left(p_{CM} - (p_{\mu^+} + p_{\mu^-})\right)^2$$

- well defined initial states at e+e-
- recoil mass technique —> tag Z only
- Higgs is tagged without looking into H decay
- absolute cross section of e^+e^- —> ZH

for Z->ll (leptonic recoil), Yan et al, arXiv:1604.07524;
for Z->qq (hadronic recoil), Thomson, arXiv:1509.02853

what does model independence mean?



$$M_X^2 = \left(p_{CM} - (p_{\mu^+} + p_{\mu^-})\right)^2$$

- meas. of σ_{ZH} doesn't depend on how Higgs decays
- meas. of σ_{ZH} doesn't depend on underlying HZZ vertex

is it really possible?

independent of H decay modes?

$$e^+ + e^- \to ZH \to l^+l^- / q\bar{q} + X$$

- this question is almost equivalent to whether we can tag the Z decay products unambiguously
- might be easy in Z->ll, certainly not trivial in Z->qq
- even in Z->ll mode, we know there can be isolated leptons from Higgs decay, e.g. H->WW*/τ τ/ZZ, which get mis-identified as leptons from Z decay
- keep in mind we are targeting 0.1-1% precision measurement

efficiencies breakdown (leptonic recoil)

$H \to XX$	bb	cc	gg	$\tau\tau$	WW^*	ZZ^*	$\gamma\gamma$	γZ
BR (SM)	57.8%	2.7%	8.6%	6.4%	21.6%	2.7%	0.23%	0.16%
Lepton Finder	93.70%	93.69%	93.40%	94.02%	94.04%	94.36%	93.75%	94.08%
Lepton ID+Precut	93.68%	93.66%	93.37%	93.93%	93.94%	93.71%	93.63%	93.22%
$M_{l^+l^-} \in [73, 120]$ GeV	89.94%	91.74%	91.40%	91.90%	91.82%	91.81%	91.73%	91.47%
$p_T^{l^+l^-} \in [10, 70]$ GeV	89.94%	90.08%	89.68%	90.18%	90.04%	90.16%	89.99%	89.71%
$\|\cos\theta_{miss}\| < 0.98$	89.94%	90.08%	89.68%	90.16%	90.04%	90.16%	89.91%	89.41%
BDT > - 0.25	88.90%	89.04%	88.63%	89.12%	88.96%	89.11%	88.91%	88.28%
$M_{rec} \in [110, 155]$ GeV	88.25%	88.35%	87.98%	88.43%	88.33%	88.52%	88.21%	87.64%

- every cut is applied very carefully to avoid large bias, still ~1%
- nevertheless, it becomes almost a paradox:
  - no cut, no bias; looser cuts, less bias
  - extremely tighter cuts, less bias;
  - too loose or too tight cuts -> remain too much background or too little signal -> bad precision measurement

efficiencies breakdown (hadronic recoil)

Decay mode	$\varepsilon^{\text{vis.}}_{\mathscr{L}>0.65}$	$\varepsilon^{\text{invis.}}_{\mathscr{L}>0.60}$	$\varepsilon^{\text{vis.}} + \varepsilon^{\text{invis.}}$
$H \to$ invis.	<0.1 %	23.5 %	23.5 %
$H \to q\bar{q}/gg$	22.6 %	<0.1 %	22.6 %
$H \to WW^*$	22.1 %	0.1 %	22.2 %
$H \to ZZ^*$	20.6 %	1.1 %	21.7 %
$H \to \tau^+\tau^-$	25.3 %	0.2 %	25.5 %
$H \to \gamma\gamma$	25.7 %	<0.1 %	25.7 %
$H \to Z\gamma$	18.6 %	0.3 %	18.9 %
$H \to WW^* \to q\bar{q}q\bar{q}$	20.8 %	<0.1 %	20.8 %
$H \to WW^* \to q\bar{q}\ell\nu$	23.3 %	<0.1 %	23.3 %
$H \to WW^* \to q\bar{q}\tau\nu$	23.1 %	<0.1 %	23.1 %
$H \to WW^* \to \ell\nu\ell\nu$	26.5 %	0.1 %	26.5 %
$H \to WW^* \to \ell\nu\tau\nu$	21.1 %	0.5 %	21.6 %
$H \to WW^* \to \tau\nu\tau\nu$	16.3 %	2.3 %	18.7 %

- relative bias can be as large as ~15%

a nice trick: categorization

$$\sigma_{ZH} = \sigma^{cat1} + \sigma^{cat2} + \sigma^{cat3} + \sigma^{cat4} + \cdots$$

- if we have a complete list of categories
- then we only need to keep all selection cuts independent of decay mode in each category;
- selections cuts among categories can be very different

for example

$$\sigma_{ZH} = \sigma^{H\to\mathrm{invisible}} + \sigma^{H\to\mathrm{visible}}$$

a realistic solution: make use of individual BR measurement

$$\sigma_{ZH} = \frac{N_S}{R_f L \bar{\epsilon}} \qquad \bar{\epsilon} \equiv \sum_i B_i \epsilon_i$$

N_S: # of signal
R_f: BR of Z->ff
L: int. luminosity
Bi: BR of H decay mode i
εi: efficiency of mode i

- if every ε_i is same -> $\Sigma B_i = 1$; no need for any knowledge about B_i
- nevertheless, we can measure many of the $\sigma x B_i$; assume i=1..n is known with ΔBi; i=n+1,… is unknown, sum up to Bx;

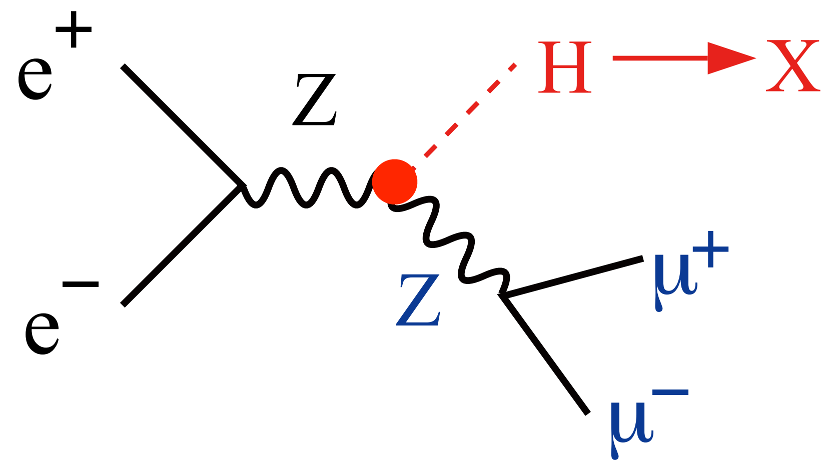
known modes | systematic error to σ_{ZH} | unknown modes

$$\frac{\Delta\sigma_{\rm ZH}}{\sigma_{\rm ZH}} = \frac{\Delta\bar{\varepsilon}}{\bar{\epsilon}} = \sqrt{\sum_{i=1}^{n} \Delta B_i^2 \left(\frac{\varepsilon_i}{\varepsilon_0} - 1\right)^2}.$$

$$\frac{\Delta\sigma_{\rm ZH}}{\sigma_{\rm ZH}} = \frac{\Delta\bar{\varepsilon}}{\bar{\epsilon}} < \sum_{i=n+1} B_i \frac{\delta\varepsilon_{\rm max}}{\varepsilon_0} = B_x \frac{\delta\varepsilon_{\rm max}}{\varepsilon_0}$$

- leptonic recoil, demonstrated possible $\delta\sigma_{ZH}$~0.1% for Bx<10%
- hadronic recoil, still need more work for $\delta\sigma_{ZH}$ <1% for Bx<10%

independent of HZZ vertex?



- different HZZ vertex might change angular distributions of Z
- hence, this question is equivalent to whether the selections cuts are democratic for all production angles of Z
- open question, this is not sufficiently studied yet

importance of absolute coupling determination

- in some BSM, only normalization of Higgs field gets modified
- Higgs BR, and ratio of Higgs couplings could stay unchanged

$$\mathcal{O}_H = \frac{1}{2}\left(\partial_\mu |H|^2\right)^2$$

N. Craig @ LCWS16
arXiv: 1702.06079

Appears in Lagrangian as $\mathcal{L} \supset \frac{c_H}{\Lambda^2}\mathcal{O}_H$ and after EWSB $H \to v + \frac{1}{\sqrt{2}}h$

$$\frac{c_H}{\Lambda^2} \cdot \frac{1}{2}\left(\partial_\mu |H|^2\right)^2 \to \left(\frac{2c_H v^2}{\Lambda^2}\right) \cdot \frac{1}{2}(\partial_\mu h)^2$$

Correction to Higgs wavefunction in broken phase

Canonically normalizing $h \to \left(1 - c_H v^2/\Lambda^2\right) h$

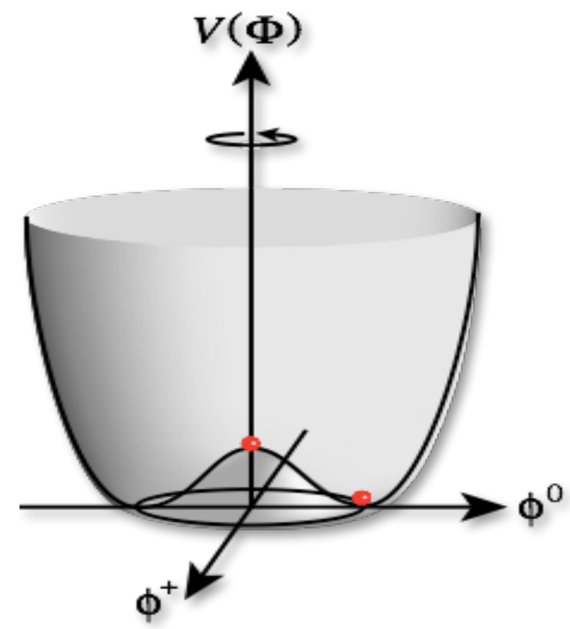
shifts all Higgs couplings uniformly, e.g.

$$\frac{m_Z^2}{v} h Z_\mu Z^\mu \to \frac{m_Z^2}{v}\left(1 - c_H v^2/\Lambda^2\right) h Z_\mu Z^\mu$$

δg_{HZZ} ~ 0.38% —> Λ > 2.8 TeV

(ii-2) Higgs self-coupling

- direct probe of the Higgs potential
- large deviation (> 20%) motivated by electroweak baryongenesis, could be ~100%
- √s>=500 GeV, e+e- —> ZHH
- √s>=1 TeV, e+e- —> vvHH (WW-fusion)

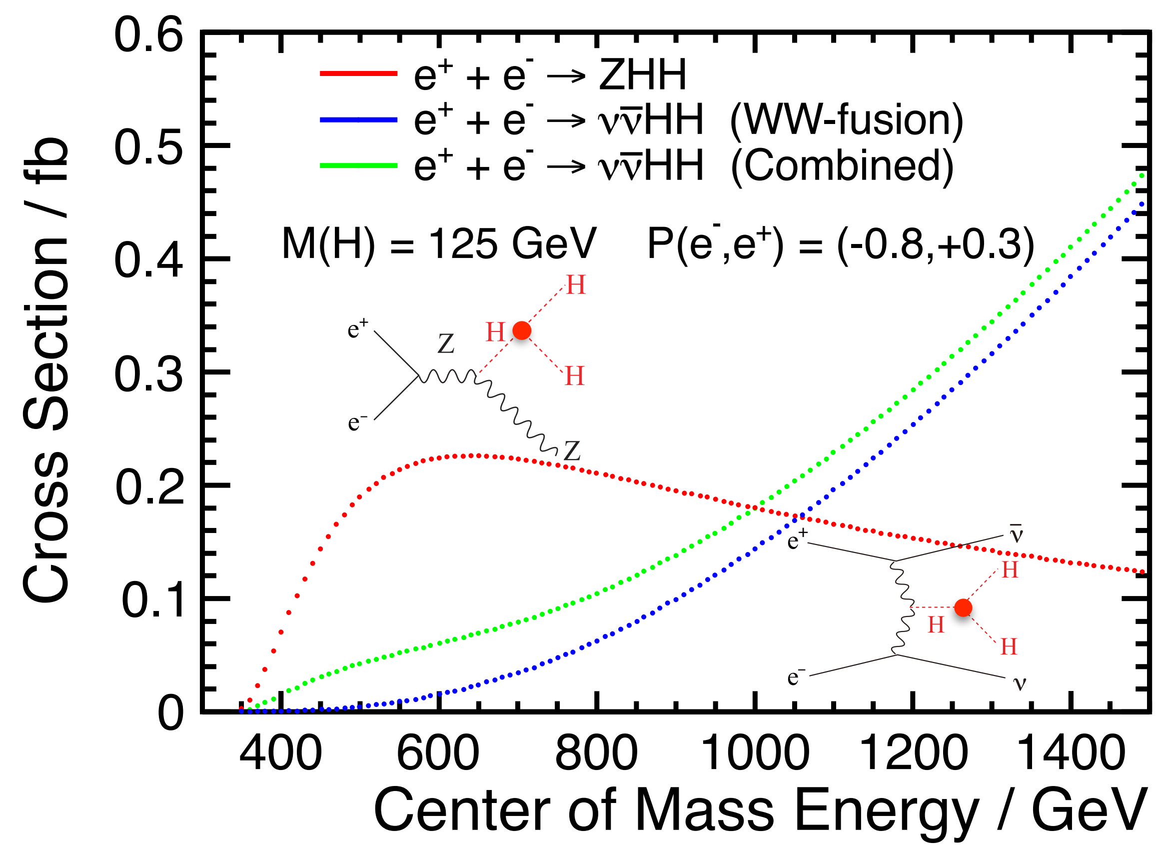


ILC

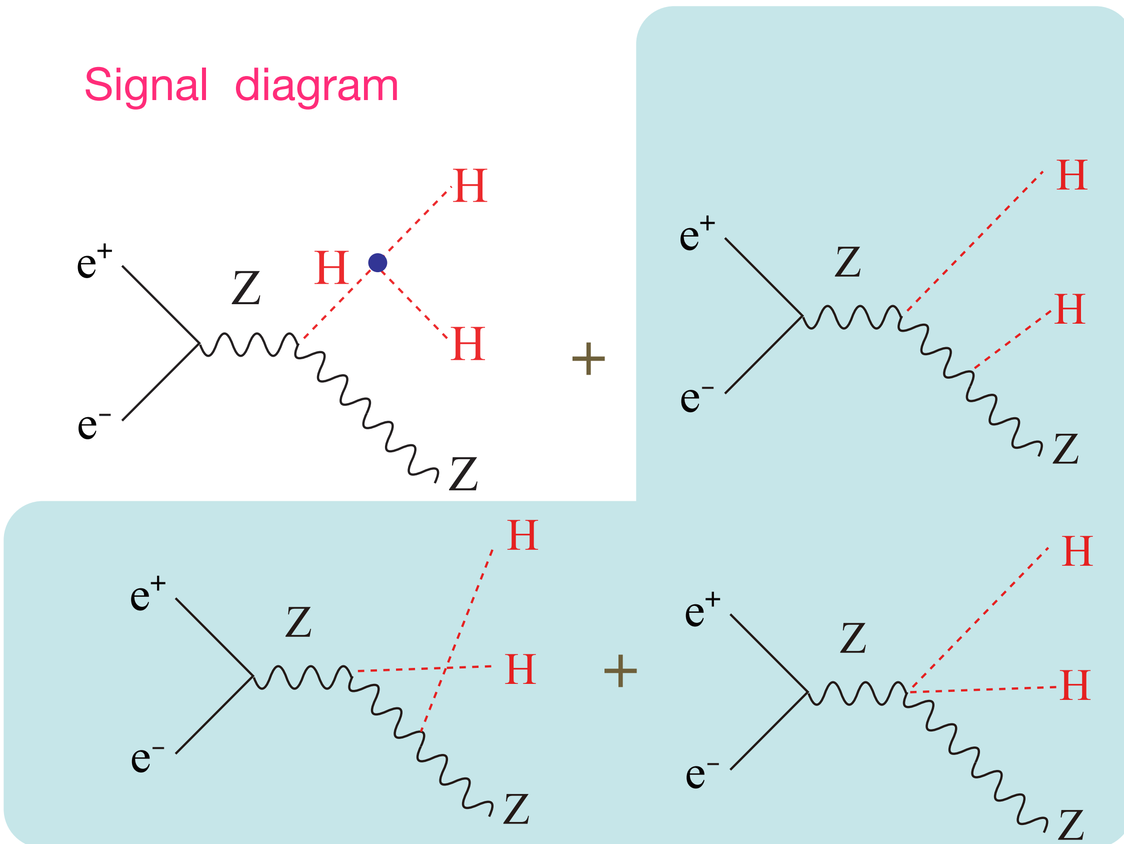
$\Delta\lambda_{HHH}/\lambda_{HHH}$	500 GeV	+ 1 TeV
Snowmass	46%	13%
H20	27%	10%

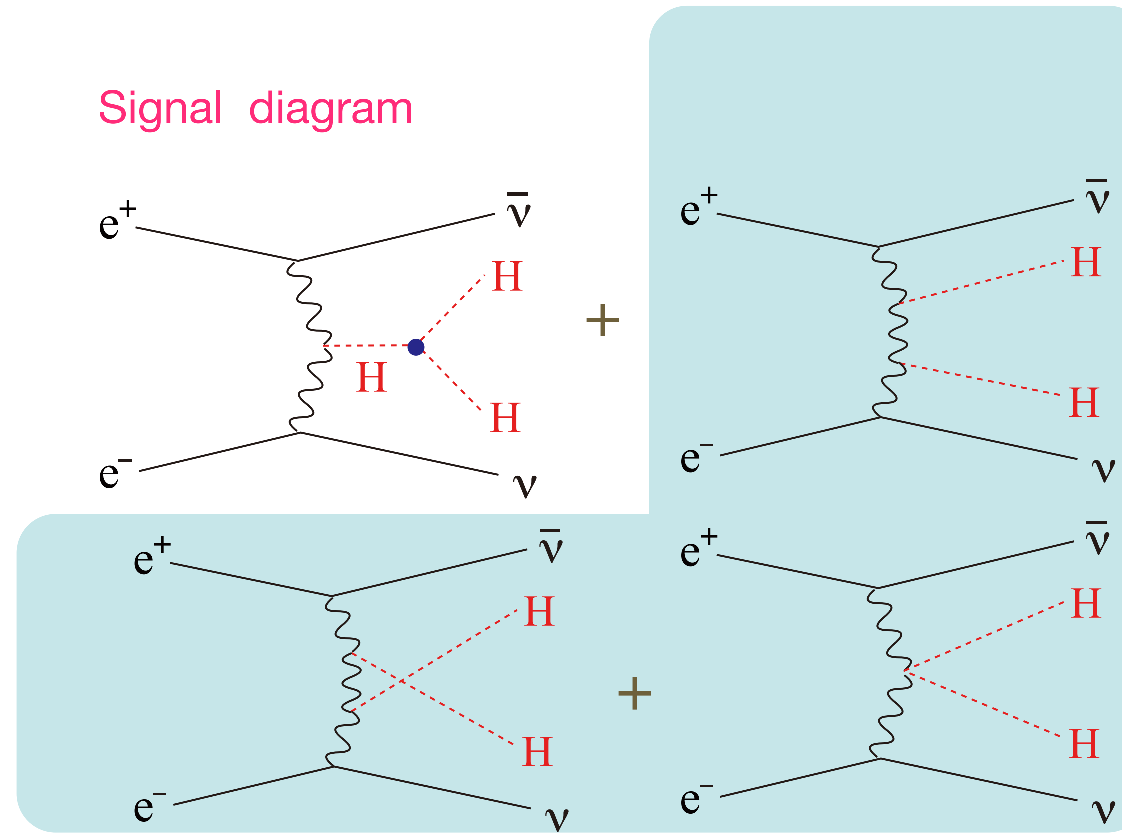
CLIC

1.4 TeV	+3 TeV
24%	11%



physics issues: diagrams for double Higgs production



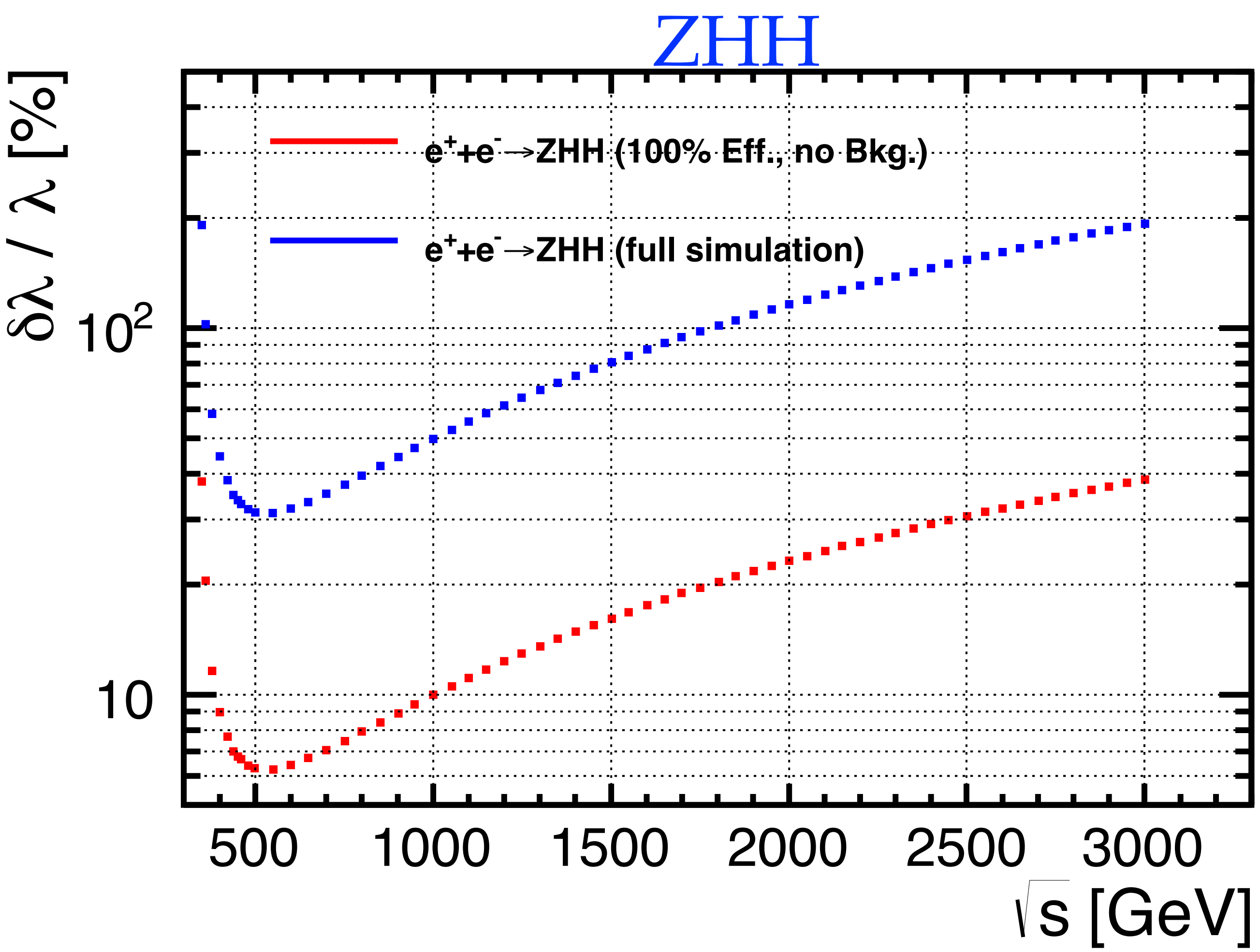


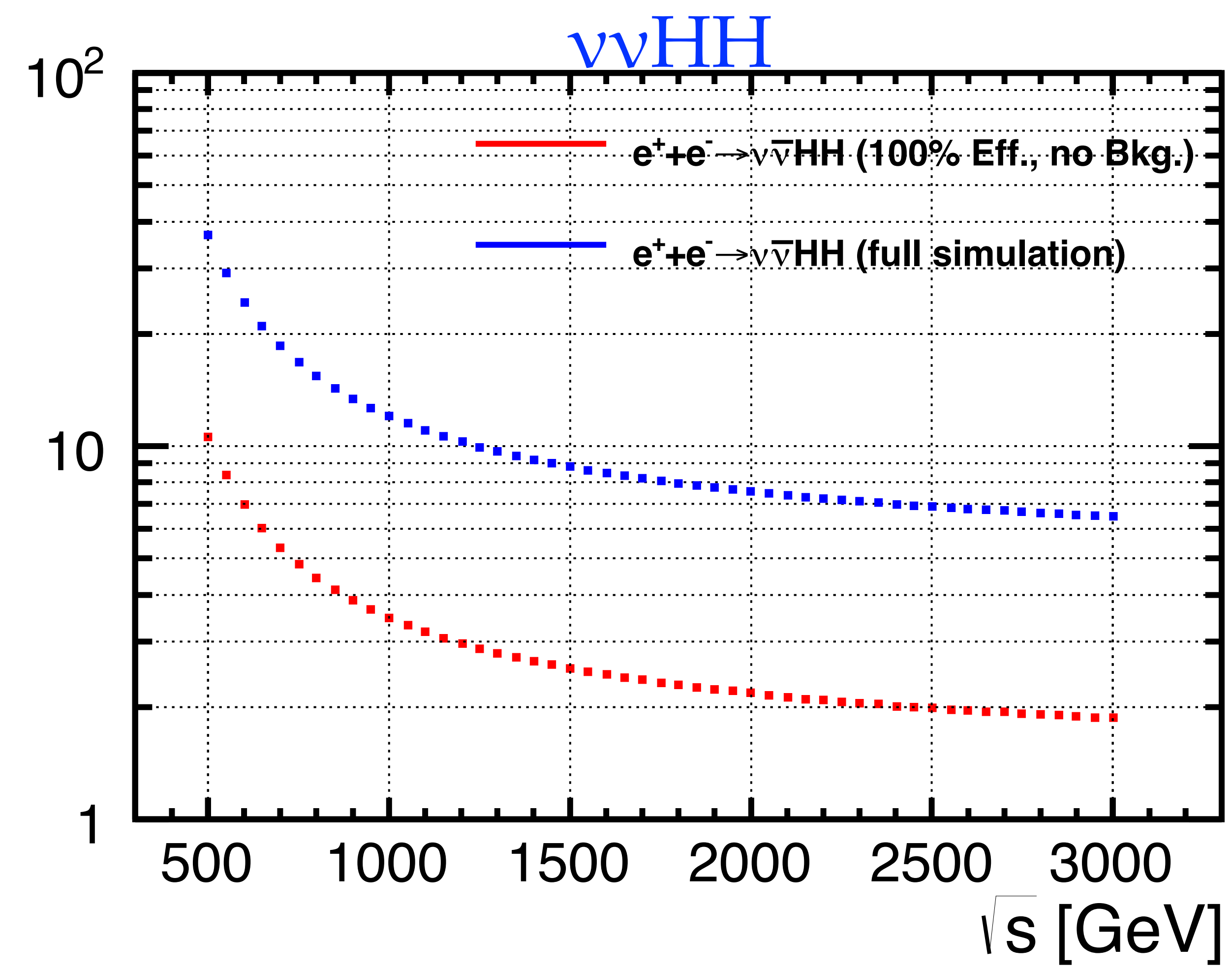
$$\sigma = S\lambda^2 + I\lambda + B$$

(signal diagram) (interference) (background diagram)

- the sensitivity of λ is determined not just by the apparent total cross section, in fact is determined by S and I term;
- if B term dominates, measurement would be very difficult

expected precision of λ: impact of Ecm



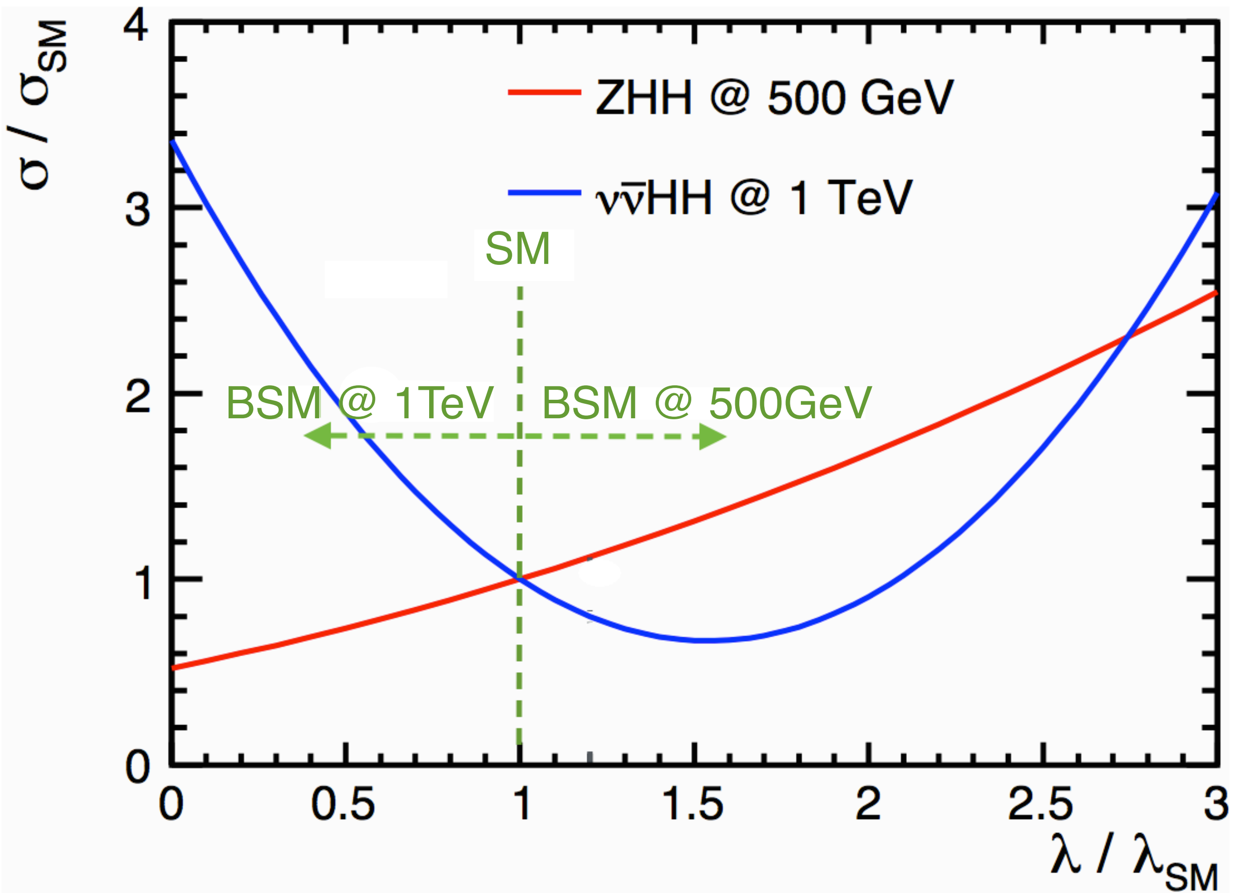


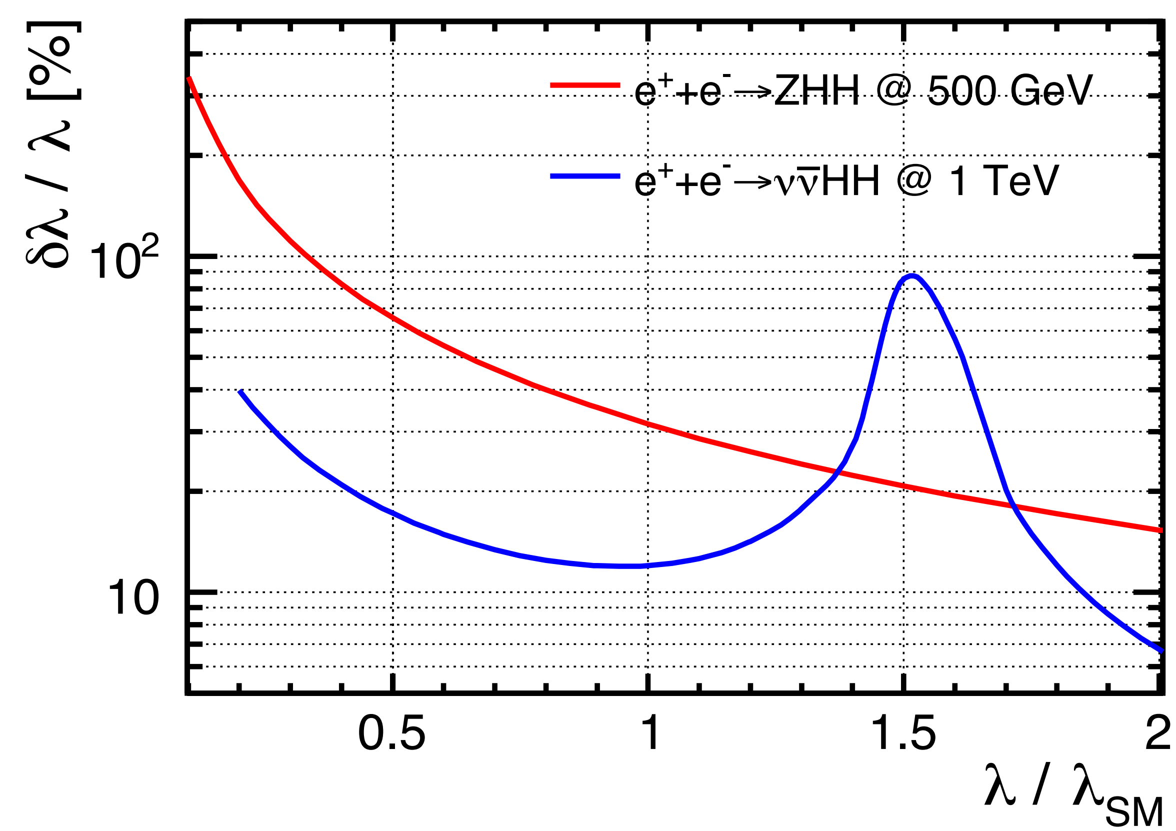
- gap of these two expectations —> room of improvement
- for ZHH: 500 GeV is the optimal energy, $\delta\lambda/\lambda \sim 6\% : 30\%$, but rather mild dependence between around 500-600 GeV, significantly worse if much lower or higher than that
- for ννHH: significantly better going from 500 GeV to 1 TeV, $\delta\lambda/\lambda \sim 10\%$ achievable when ecm >= 1TeV; better precision at higher ecm, but not drastically, from 1 TeV to 3 TeV, improved by 50%

Higgs self-coupling: when $\lambda_{HHH} \neq \lambda_{SM}$?

- constructive interference in ZHH, while destructive in vvHH (& LHC) —> complementarity between ILC & LHC, between √s ~500 GeV and >1TeV
- if $\lambda_{HHH} / \lambda_{SM} = 2$, Higgs self-coupling can be measured to ~15% using ZHH at 500 GeV e+e-

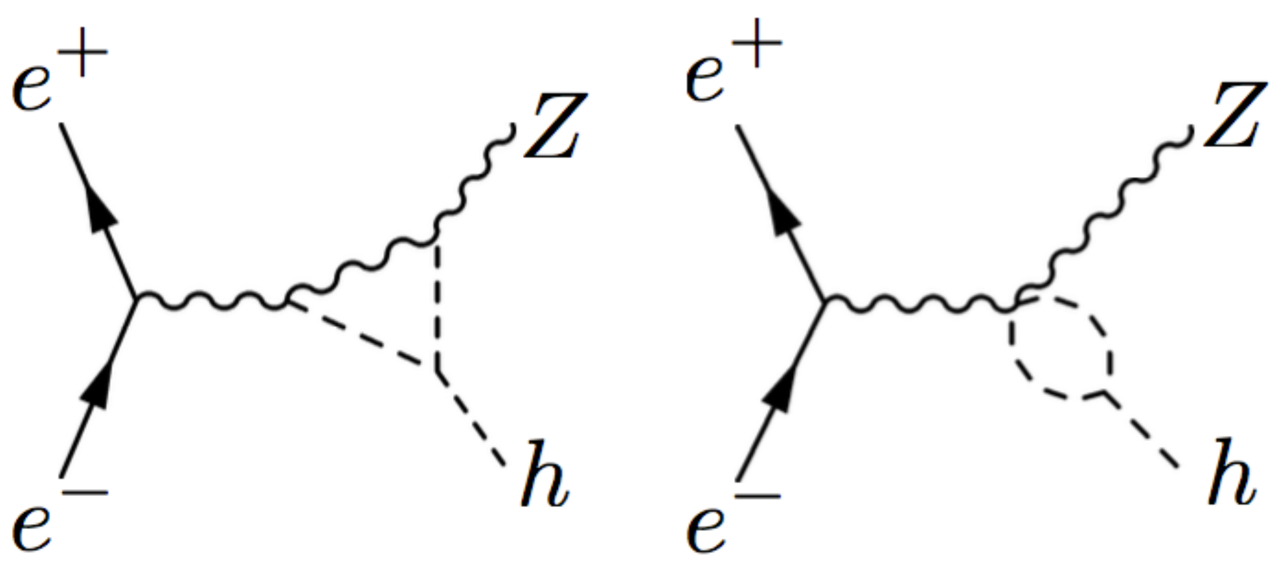
Duerig, Tian, et al, paper in preparation





references for large deviations e.g. Grojean, et al., PRD71, 036001; Kanemura, et al., 1508.03245; Kaori, Senaha, PHLTA,B747,152; Perelstein, et al., JHEP 1407, 108

Higgs self-coupling: indirect determination



McCullough, 1312.3322

$$\delta_\sigma^{240} = 100\,(2\delta_Z + 0.014\delta_h)\,\%$$

- if only δh is deviated —> δh ~ 28%
- if both δz and δh deviated —> δh ~ 90%
- δσ could receive contributions from many other sources
- open question: what happens after taking into account all possible modifications (see chapter (iii))

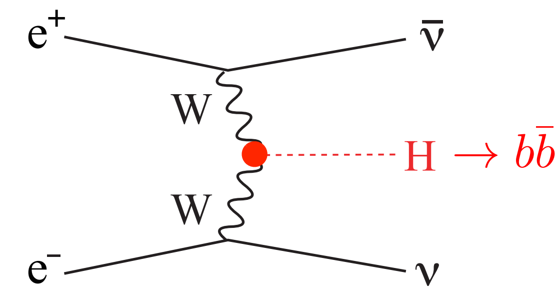
(ii-3) WW-fusion channel & Higgs total width Γ_H

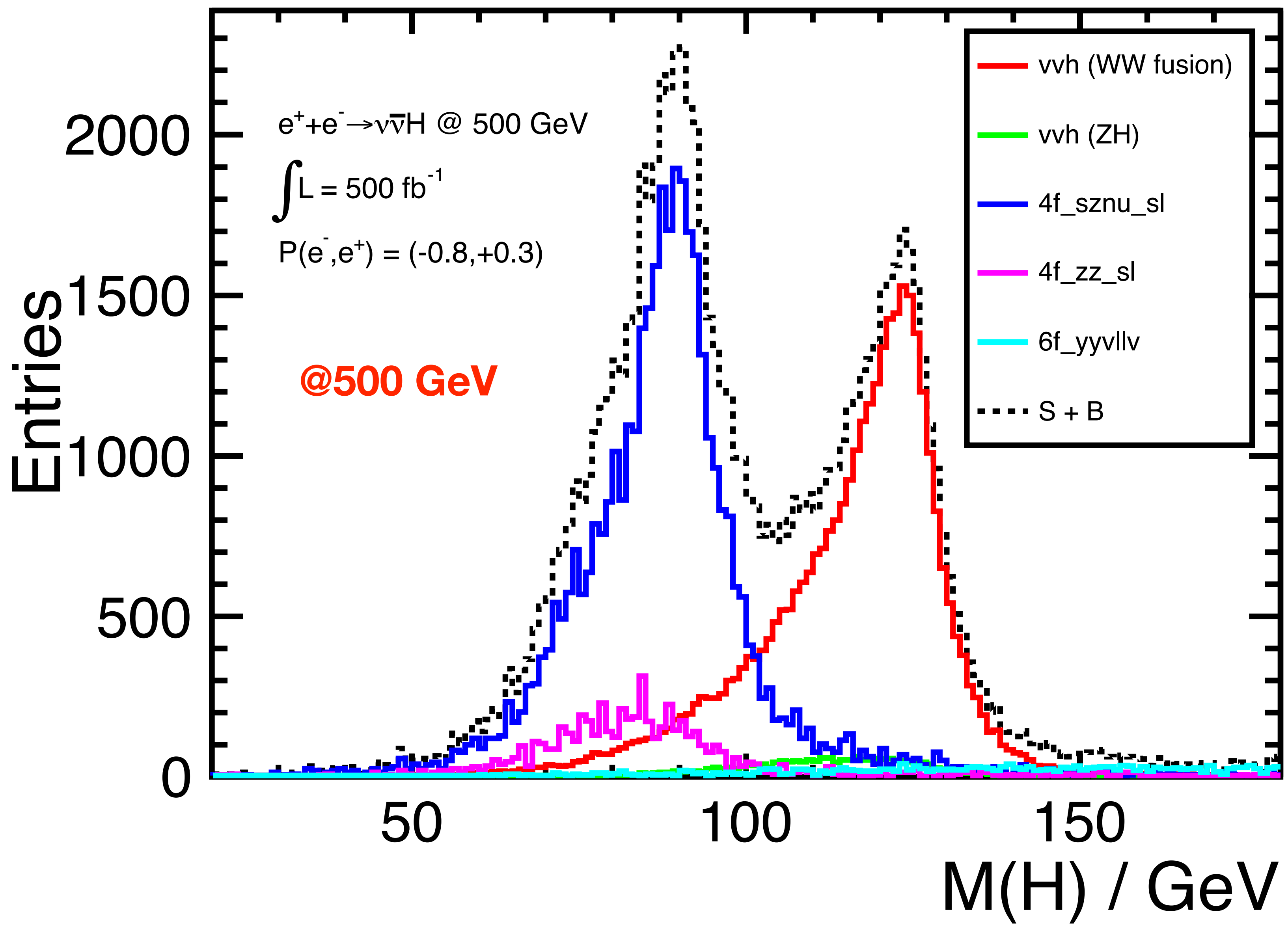
$$\Gamma_H = \frac{\Gamma_{HZZ}}{\mathrm{Br}(H \to ZZ^*)} \propto \frac{g^2_{HZZ}}{\mathrm{Br}(H \to ZZ^*)}$$

—>Br(H->ZZ*) very small

★ $$\Gamma_H = \frac{\Gamma_{HWW}}{\mathrm{Br}(H \to WW^*)} \propto \frac{g^2_{HWW}}{\mathrm{Br}(H \to WW^*)}$$

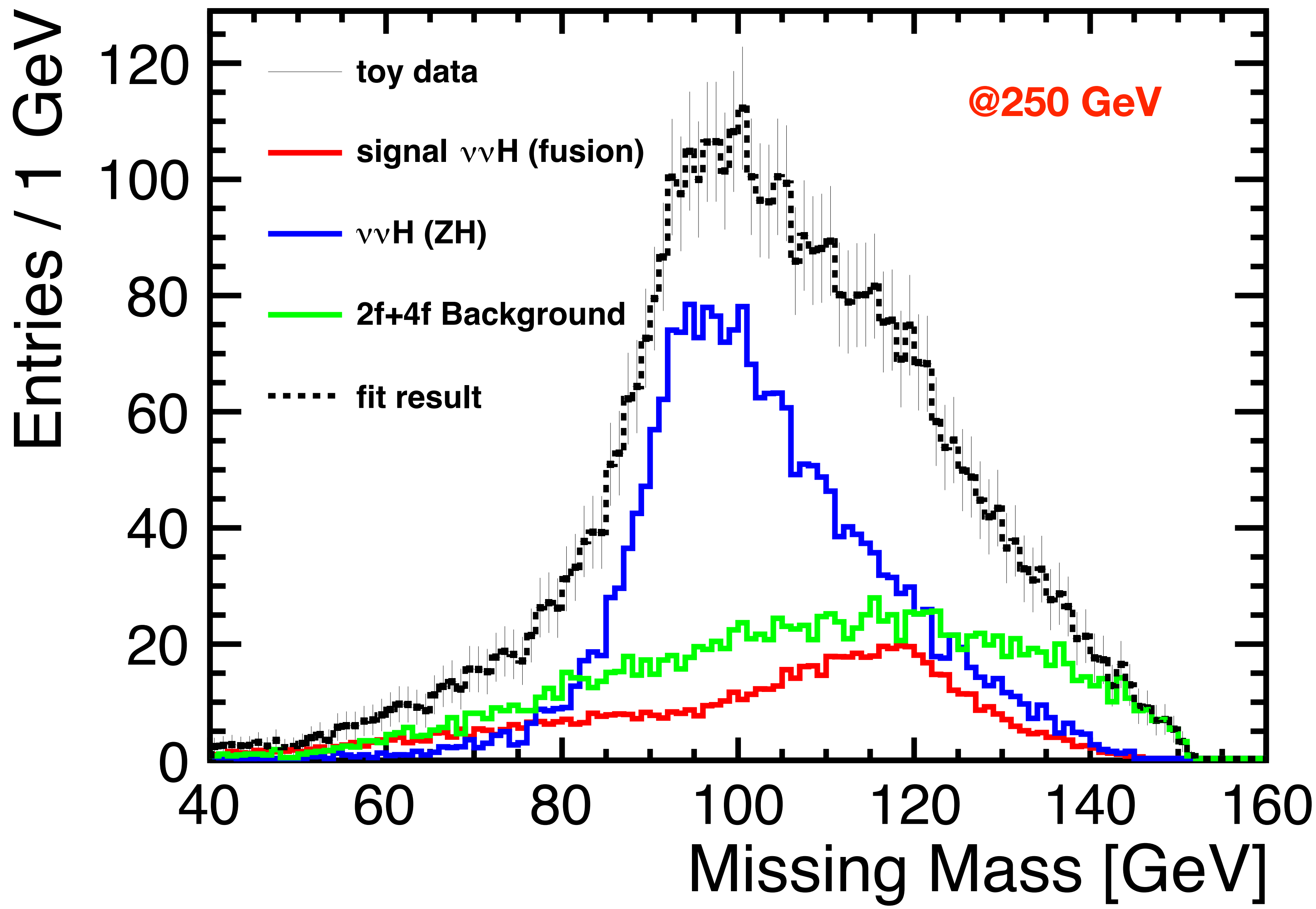
—> better option!

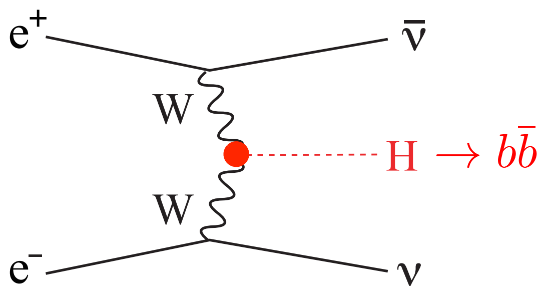




Duerig, et al., arXiv:1403.7734

very different at Ecm=250 GeV





ρ = -34% correlation between

$Y_2 = \sigma_{\nu\nu H}$xBR(H->bb) and $Y_3 = \sigma_{ZH}$xBR(H->bb)

(ii-4) determine Higgs CP (admixture)

- find CP-violating source in Higgs sector —> EW baryongenesis
- essential to understand structures of all Higgs couplings

through H—>$\tau^+\tau^-$

(or ttH)

$$L_{Hff} = -\frac{m_f}{v} H \bar{f} (\cos\Phi_{CP} + i\gamma^5 \sin\Phi_{CP}) f$$

$$\Delta\Phi_{CP} \sim 4.3^\circ$$

Jeans et al, 1804.01241

through HZZ/HWW

$$L_{HVV} = 2C_V M_V^2 \left(\frac{1}{v} + \frac{a}{\Lambda}\right) H V_\mu V^\mu + C_V \frac{b}{\Lambda} H V_{\mu\nu} V^{\mu\nu} + C_V \frac{\tilde{b}}{\Lambda} H V_{\mu\nu} \tilde{V}_{\mu\nu}$$

(CP-odd)

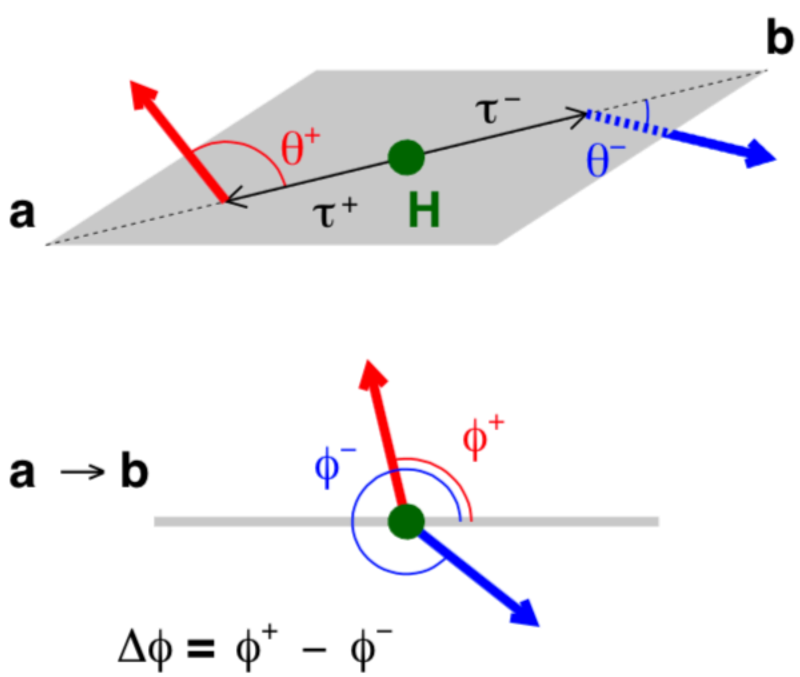
$\Delta\tilde{b} \sim 0.016$ (for Λ=1TeV)

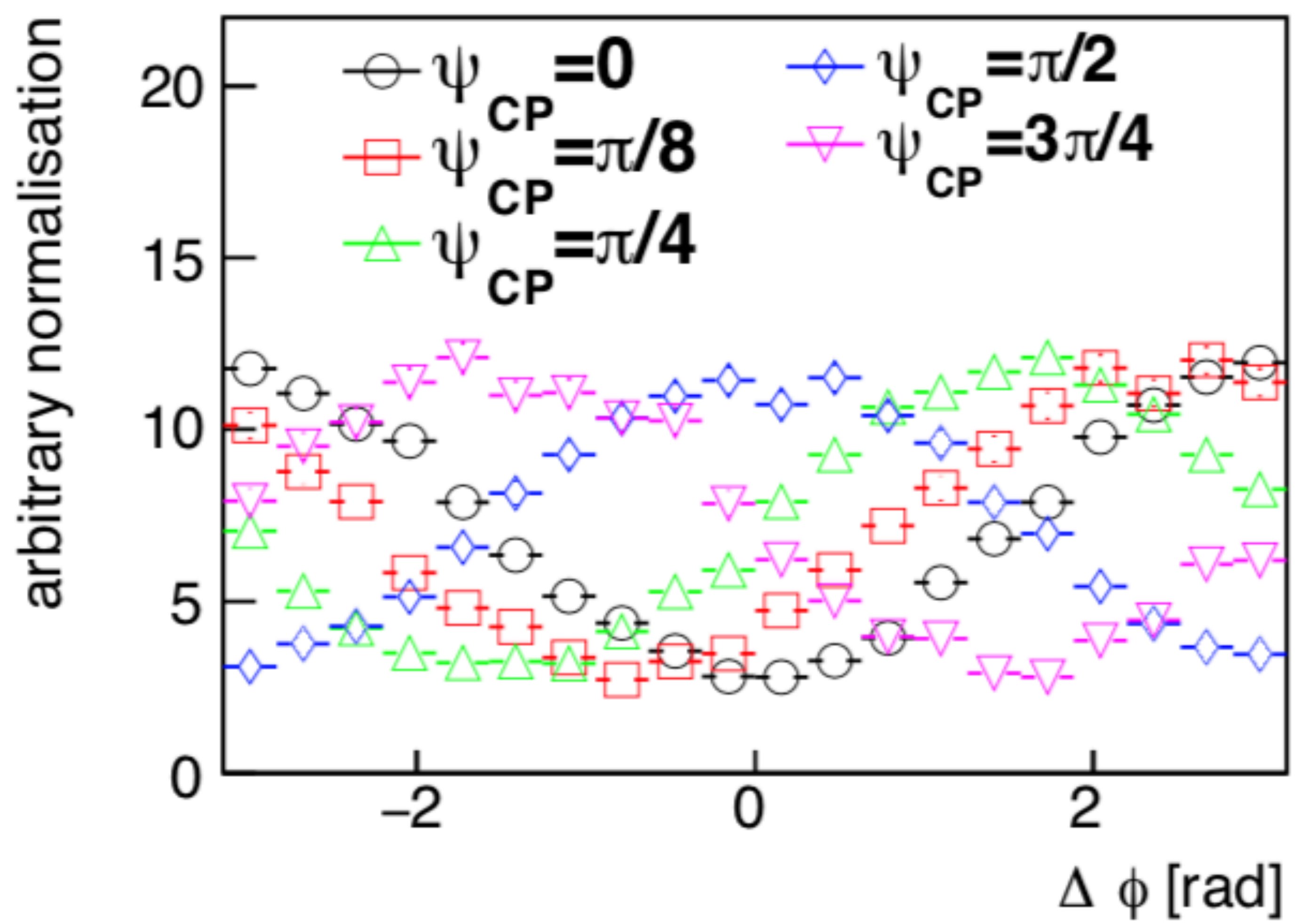
Ogawa, 1712.09772

for BR(H—>τ+τ-): Kawada, et. al, Eur.Phys.J. C75 (2015), 617

CP sensitive observable in $H \to \tau^+\tau^-$

$$L_{Hff} = -\frac{m_f}{v} H \bar{f} (\cos \Phi_{CP} + i\gamma^5 \sin \Phi_{CP}) f$$



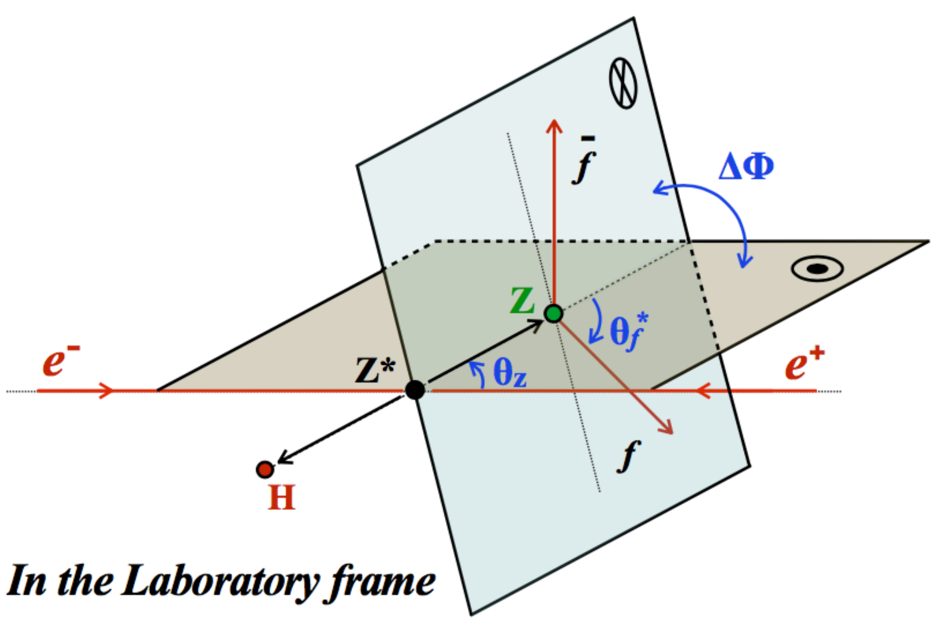


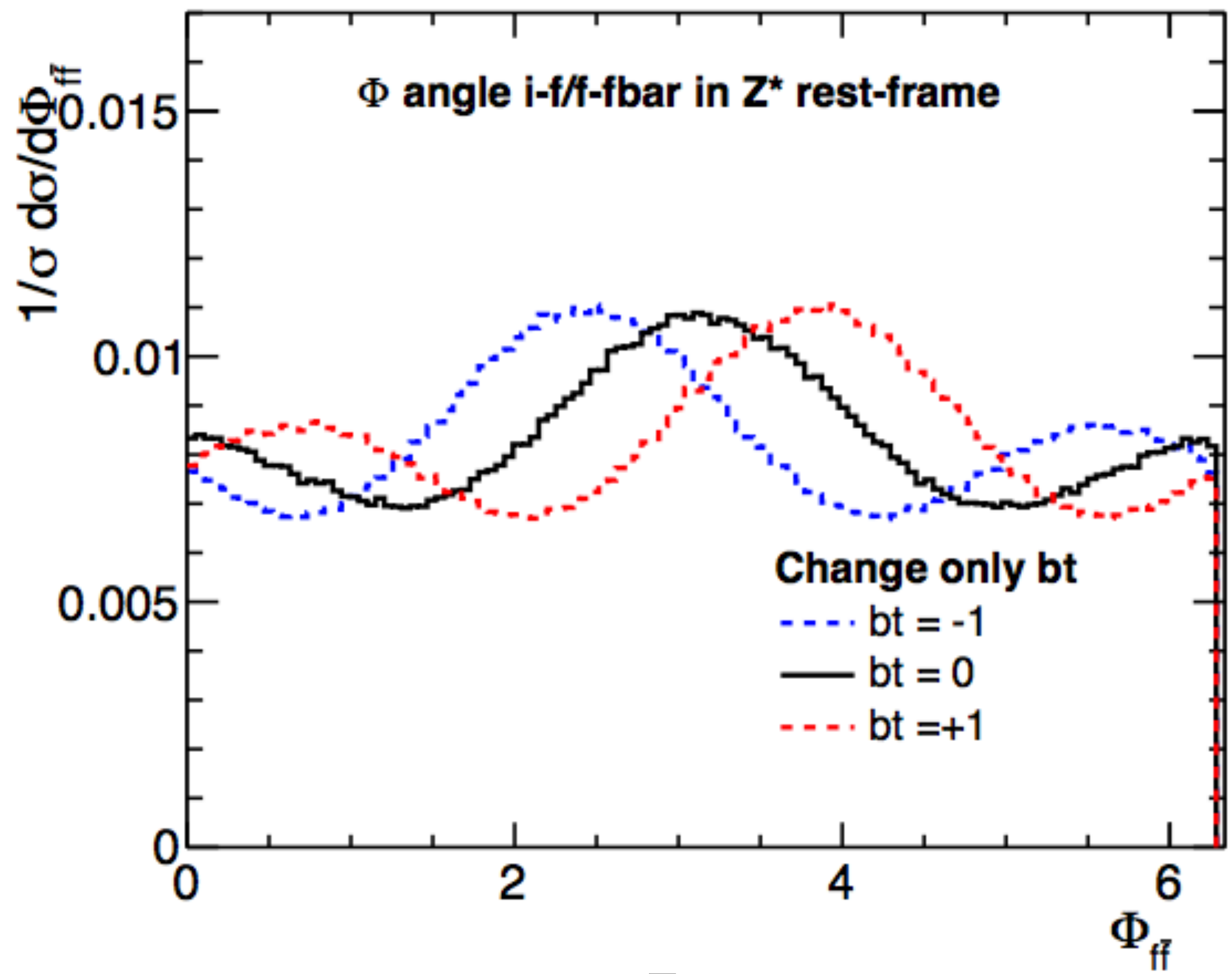
CP sensitive observable in HZZ coupling

$$L_{hZZ} = M_Z^2\left(\frac{1}{v} + \frac{a}{\Lambda}\right)hZ_\mu Z^\mu + \frac{b}{2\Lambda}hZ_{\mu\nu}Z^{\mu\nu} + \underline{\frac{\tilde{b}}{2\Lambda}hZ_{\mu\nu}\tilde{Z}_{\mu\nu}}$$

(CP-odd)

$$e^+ + e^- \to Zh \to f\bar{f}h$$

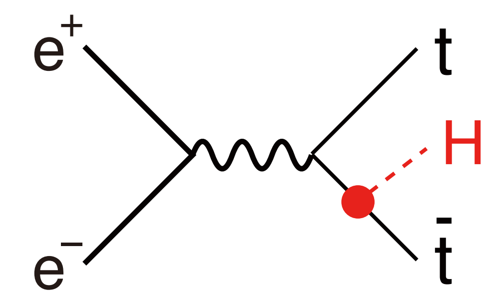




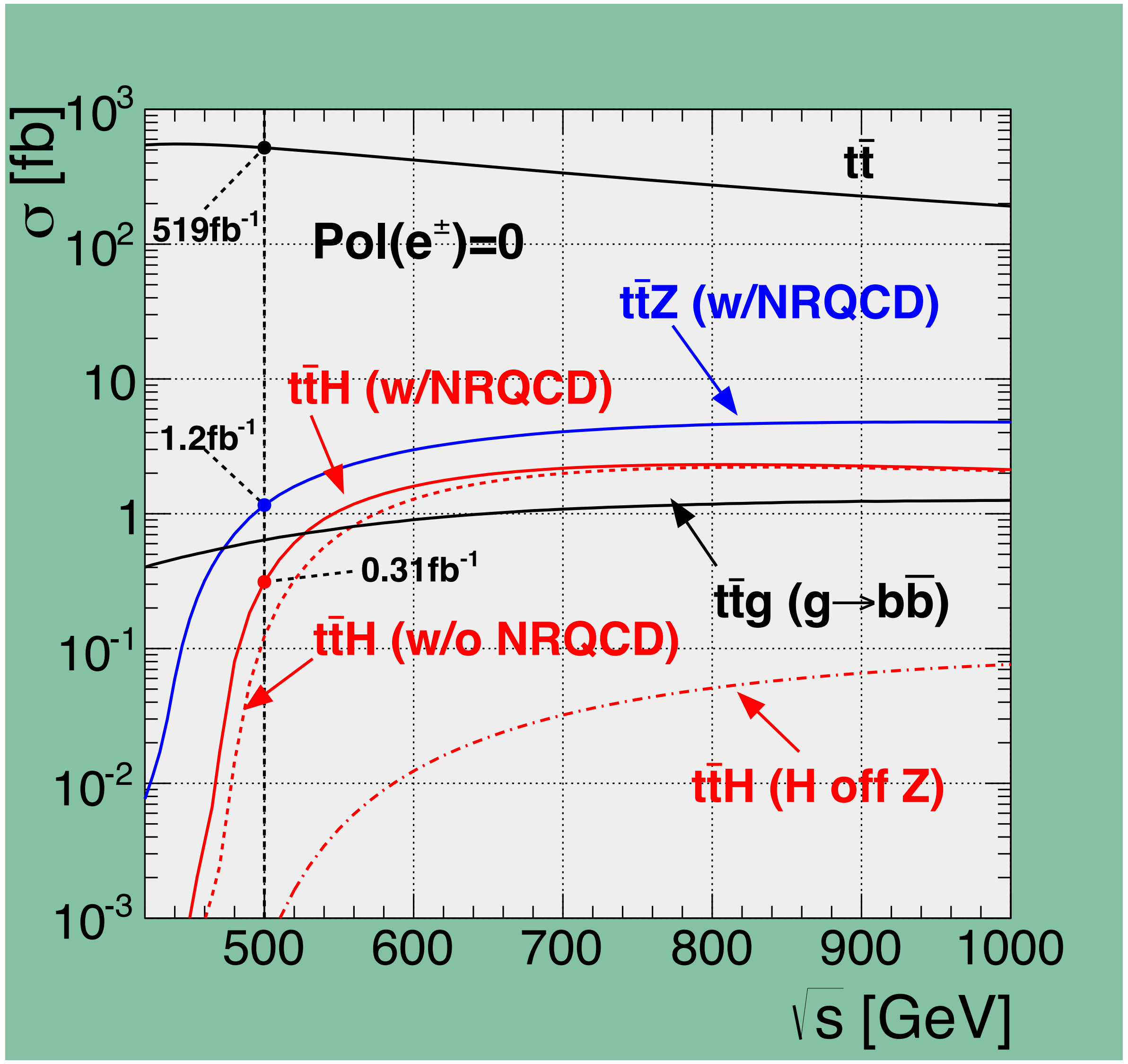
$@\ \sqrt{s} = 250\text{GeV}$

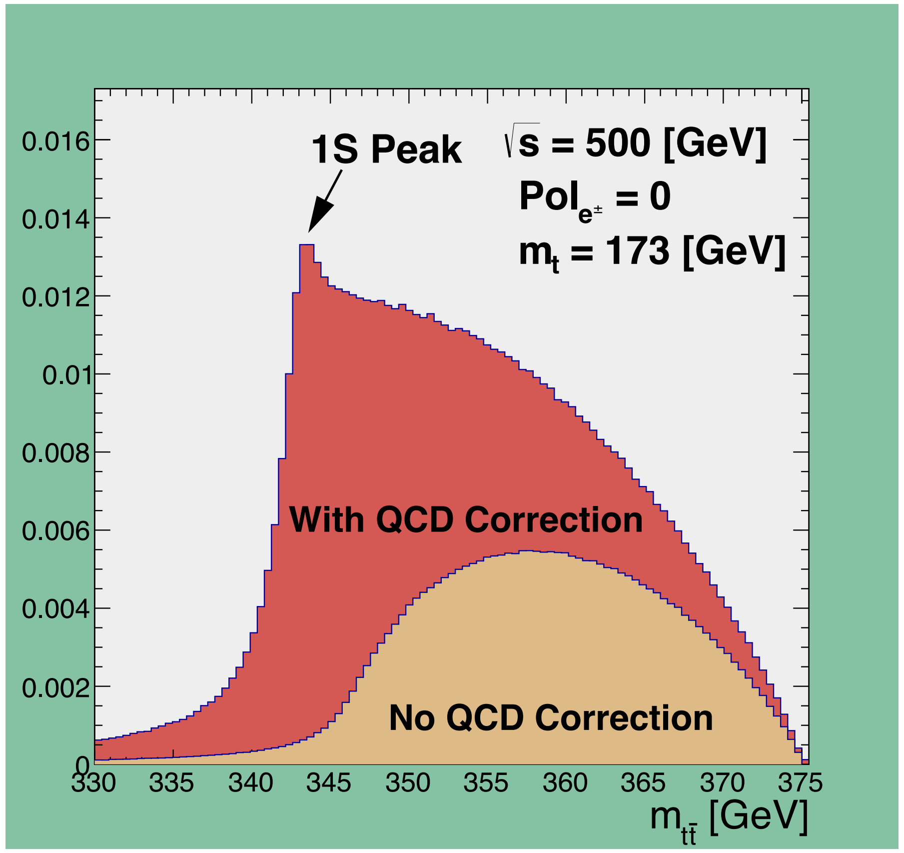
(ii-5) Top-Yukawa coupling

- largest Yukawa coupling; crucial role in theory
- non-relativistic tt-bar bound state correction: enhancement by ~2 at 500 GeV
- Higgs CP measurement



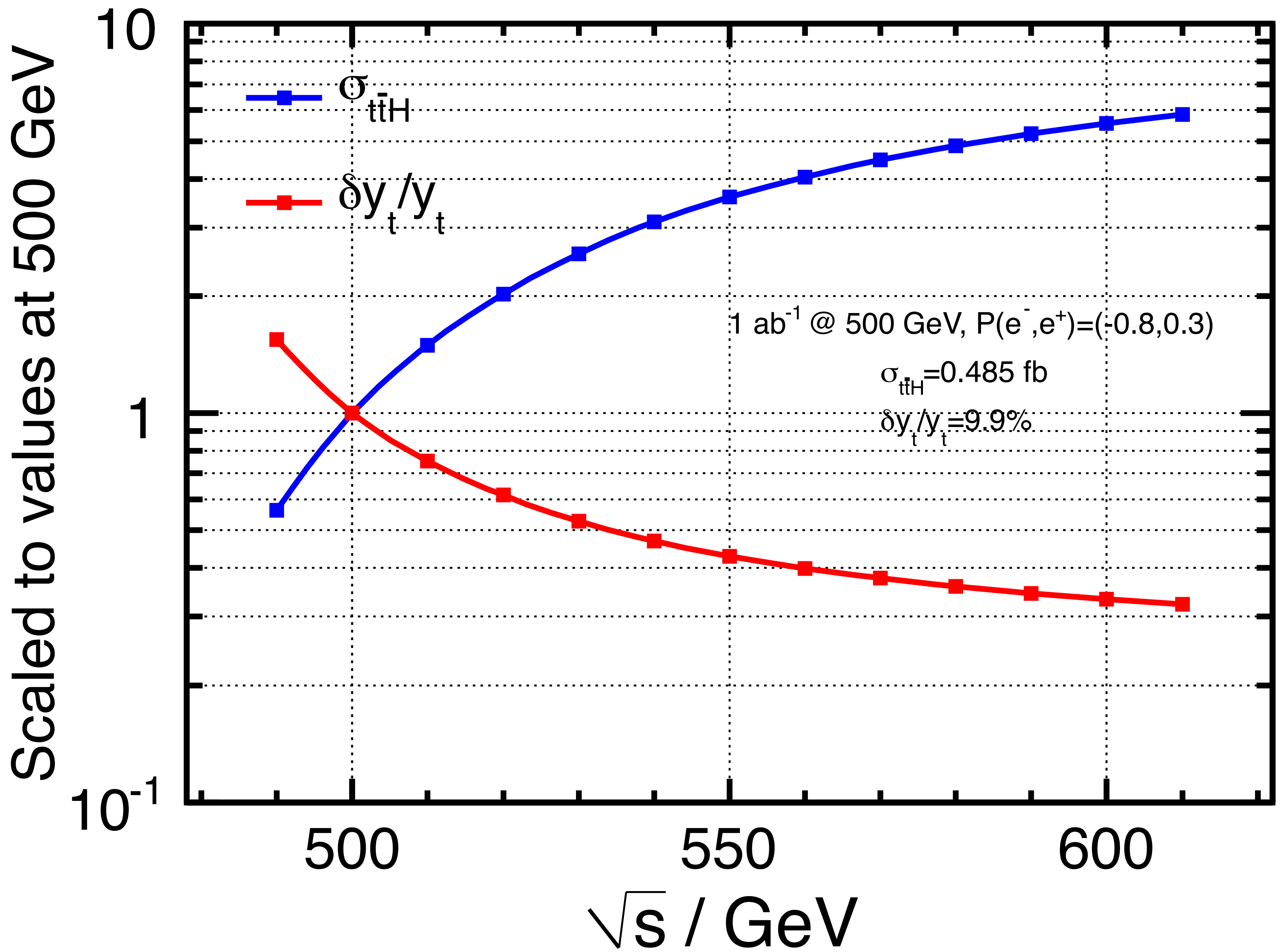
$\Delta g_{ttH}/g_{ttH}$	500 GeV	+ 1 TeV
Snowmass	7.8%	2.0%
H20	6.3%	1.5%





Yonamine, et al., PRD84, 014033;
Price, et al., Eur. Phys. J. C75 (2015) 309

Top-Yukawa coupling

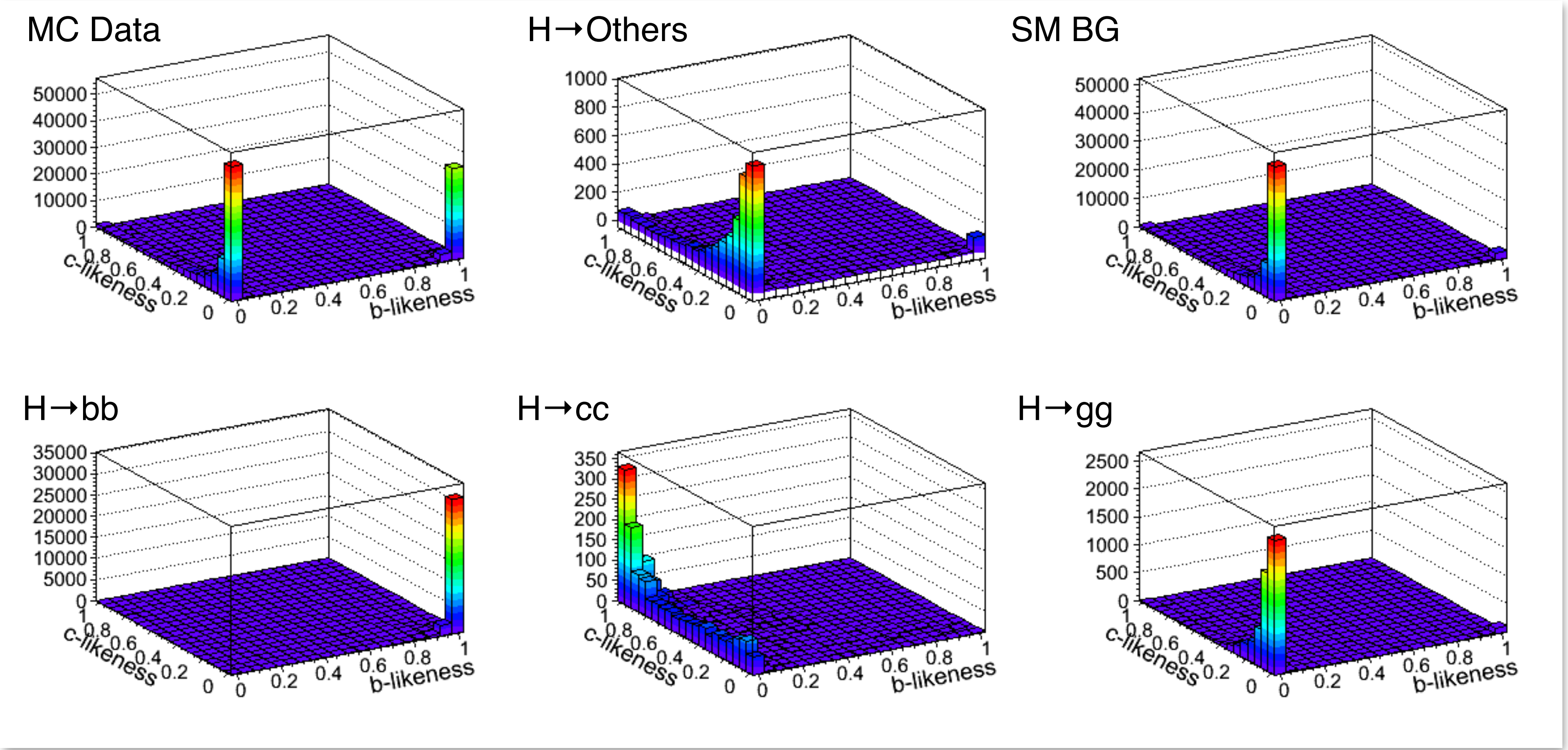


Y. Sudo

(ii-6) Higgs direct couplings to bb, cc and gg

- clean environment at e+e-; excellent b- and c-tagging performance
- bb/cc/gg modes can be separated simultaneously by template fitting

e+e- —> ZH —> ff(jj): b-likeness .vs. c-likeness



directly measured →

$$\sigma_{ZH} \cdot \mathrm{Br}(H \to b\bar{b}) \propto g^2_{HZZ} g^2_{Hbb} / \Gamma_H$$
$$\sigma_{ZH} \cdot \mathrm{Br}(H \to c\bar{c}) \propto g^2_{HZZ} g^2_{Hcc} / \Gamma_H$$
$$\sigma_{ZH} \cdot \mathrm{Br}(H \to gg) \propto g^2_{HZZ} g^2_{Hgg} / \Gamma_H$$

with Γ_H →

δg_{Hbb}=2.0%
δg_{Hcc}=2.5%
δg_{Hgg}=2.4%

Ono, et. al, Euro. Phys. J. C73, 2343; F.Mueller, PhD thesis (DESY)

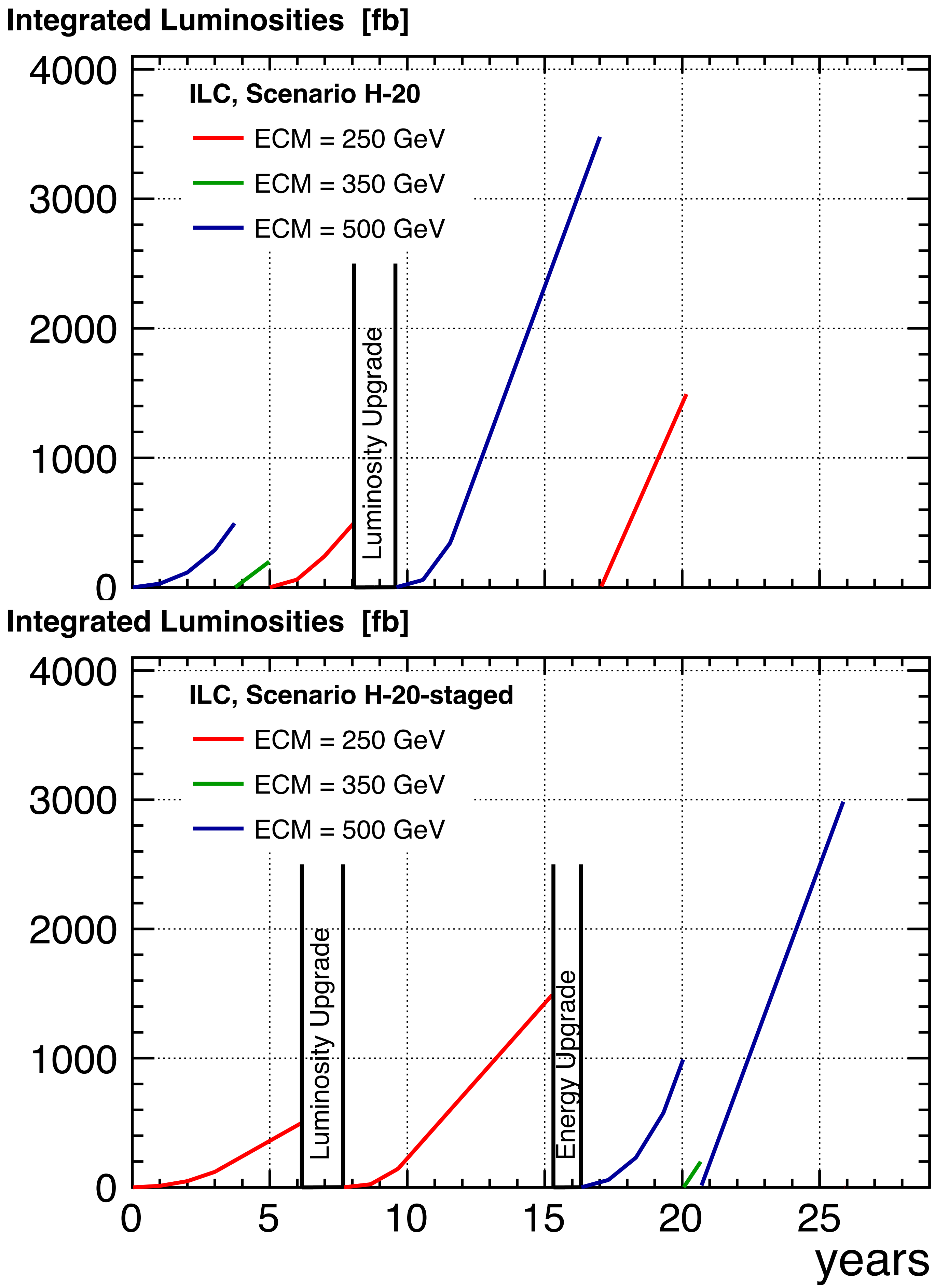
(iii) effective field theory

more

— model independent determination of Higgs (self-)couplings

backup

scenario:
example

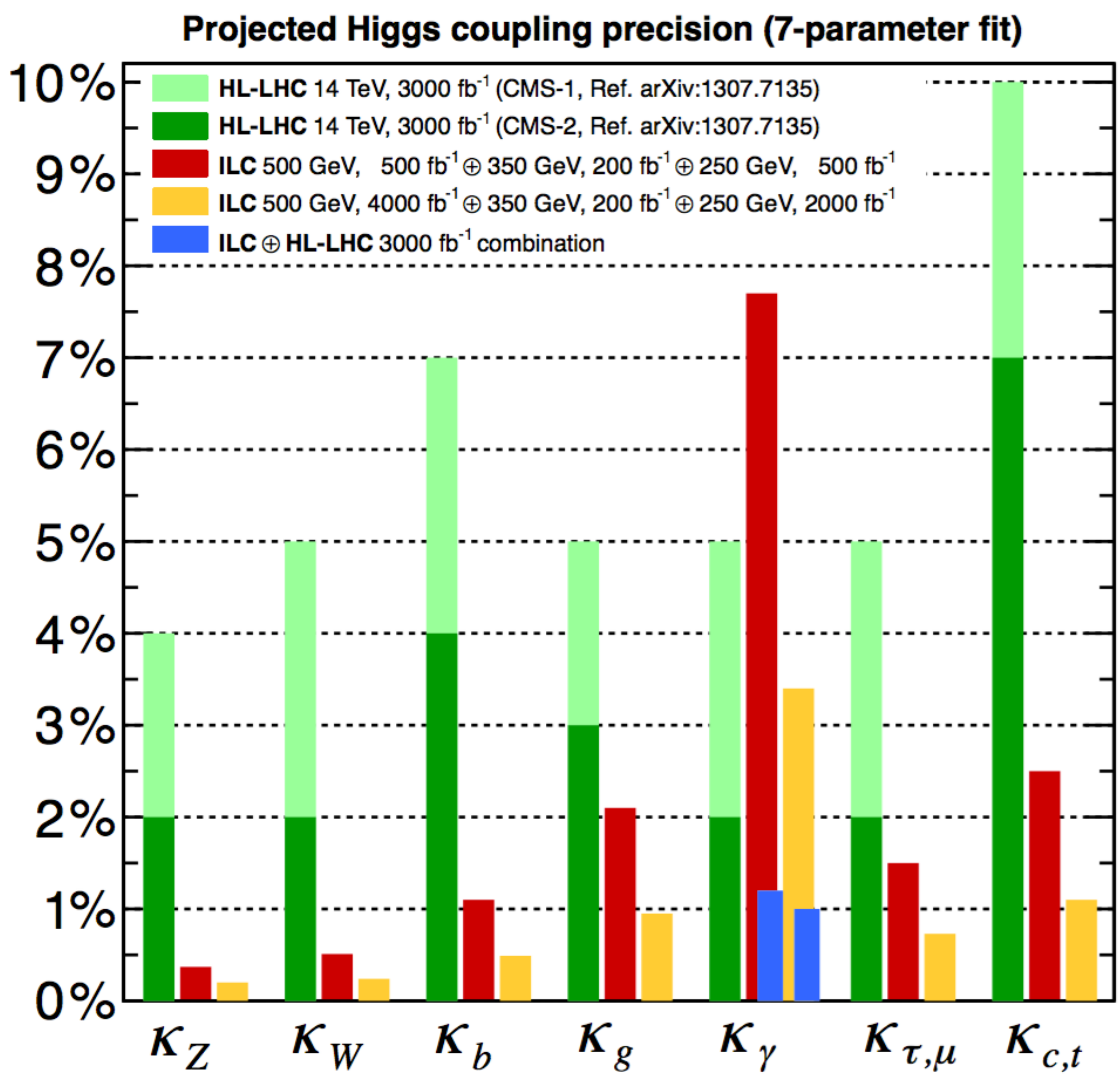


ILC500
H20

ILC250
H20 staged

top physics starts
after > 16y
in total ~ 6y longer

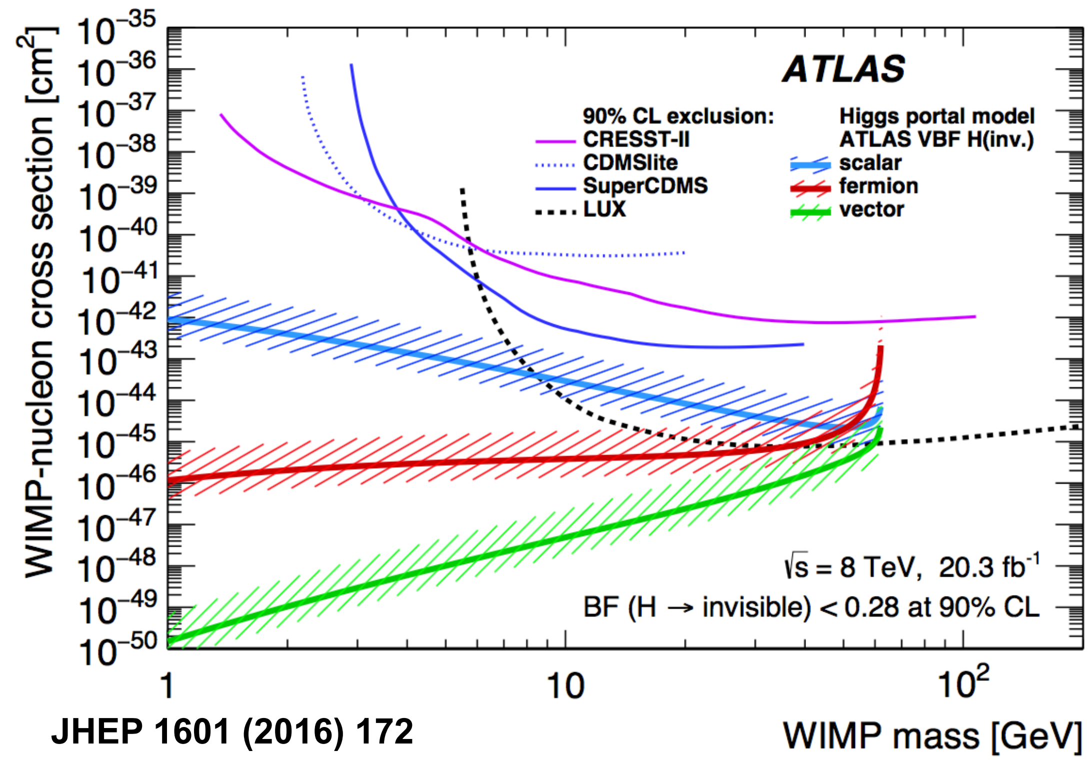
expected precisions of Higgs couplings

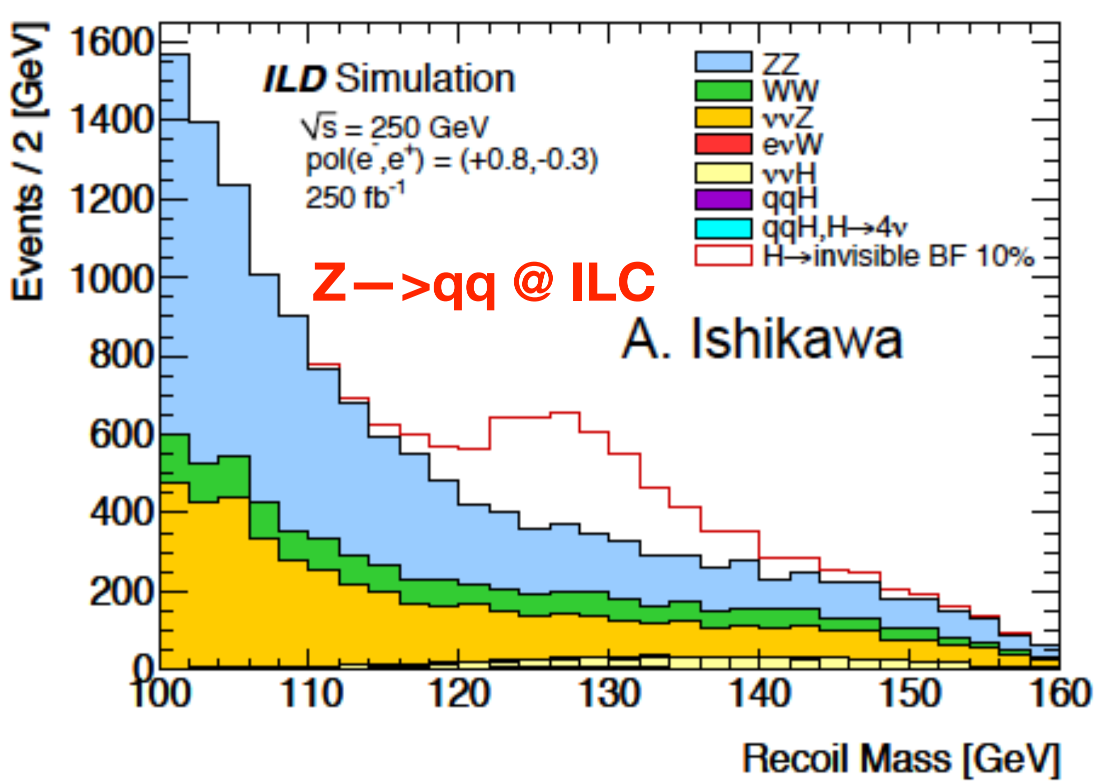


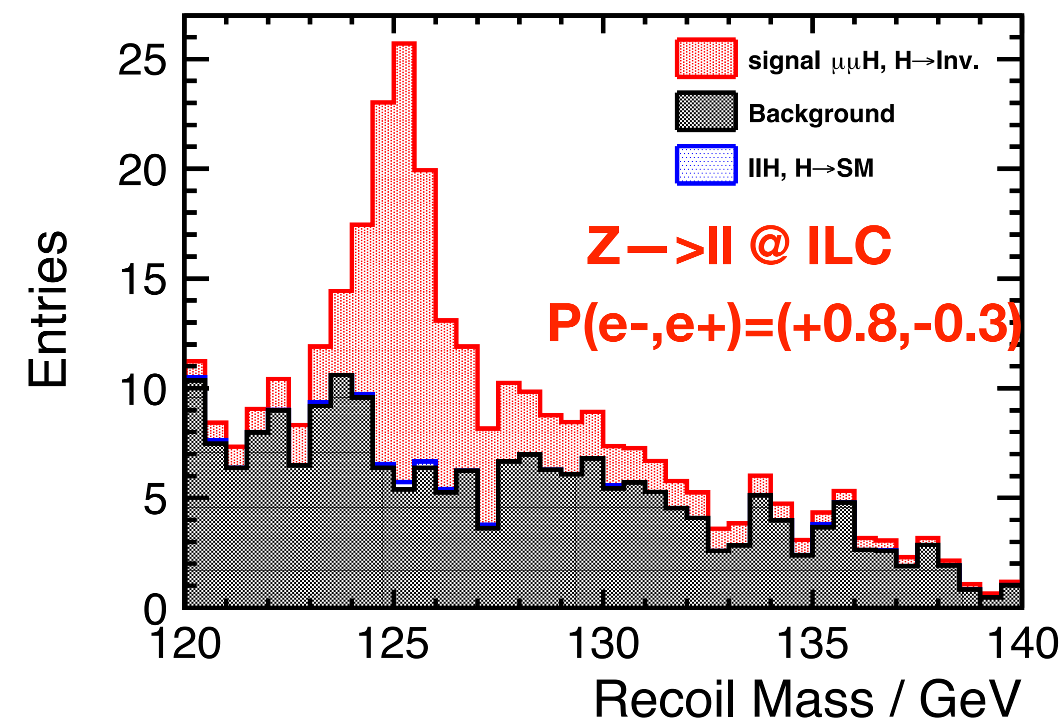
exotic decay: search of Higgs to invisible

$$e^+ + e^- \to ZH \to l^+l^-/q\bar{q} + \text{Missing}$$

- BR(H—>inv.) < 0.3% (CL95%)
- a sensitive test for Higgs portal dark mater model —> complementary for low mass
- right-handed beam polarisation: much lower background

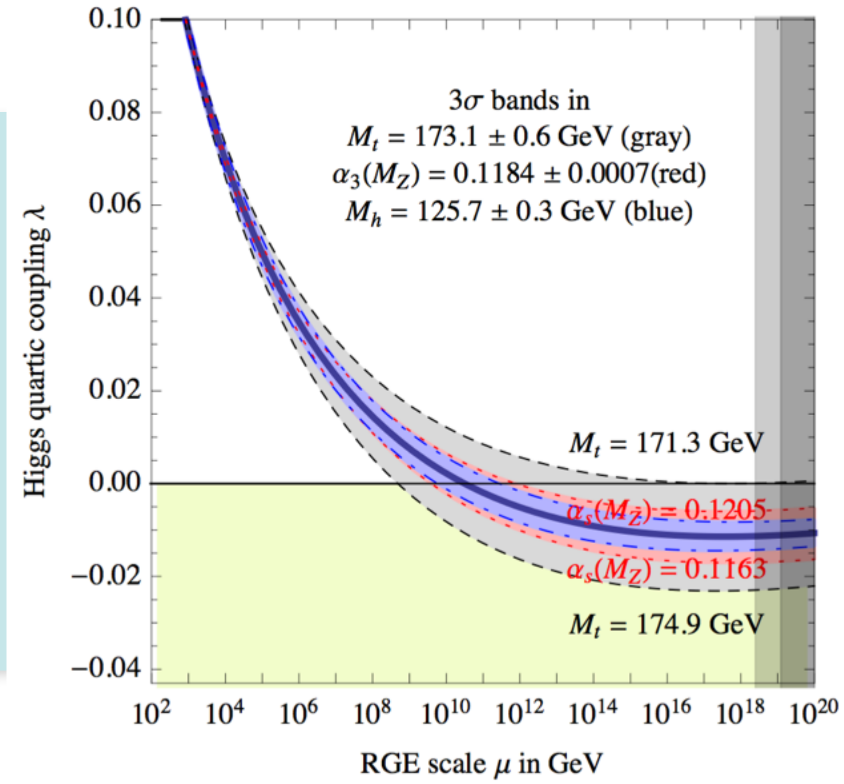


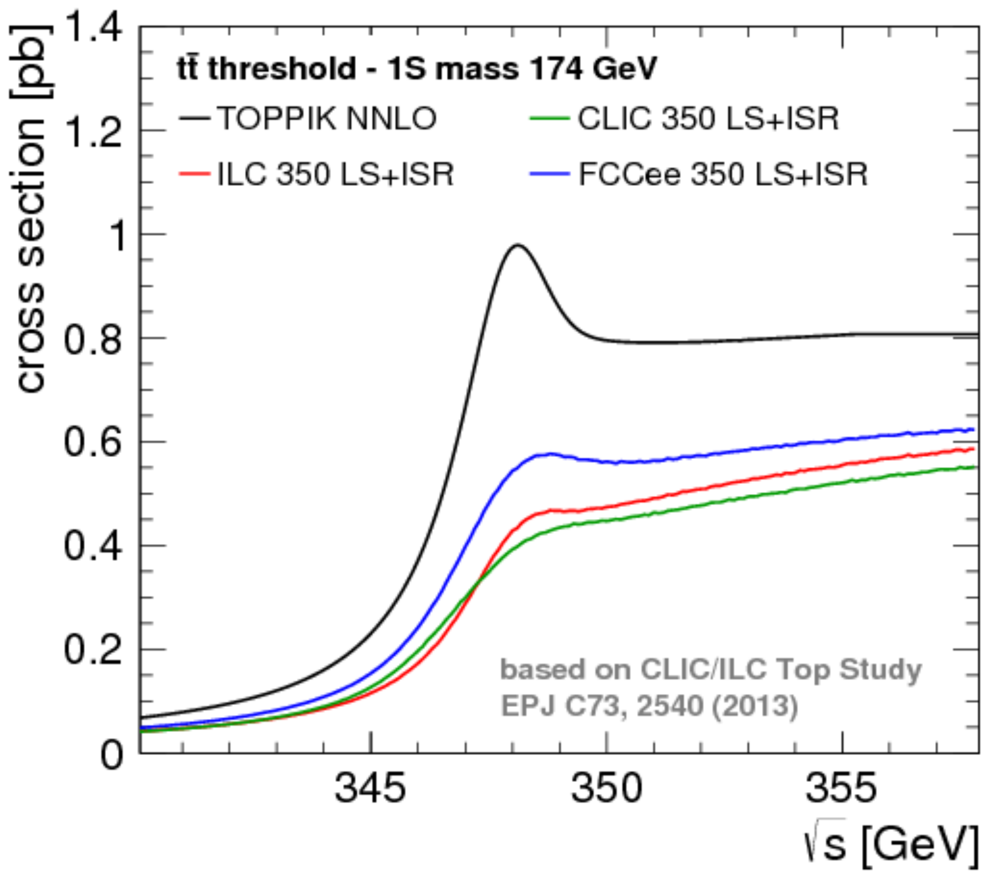




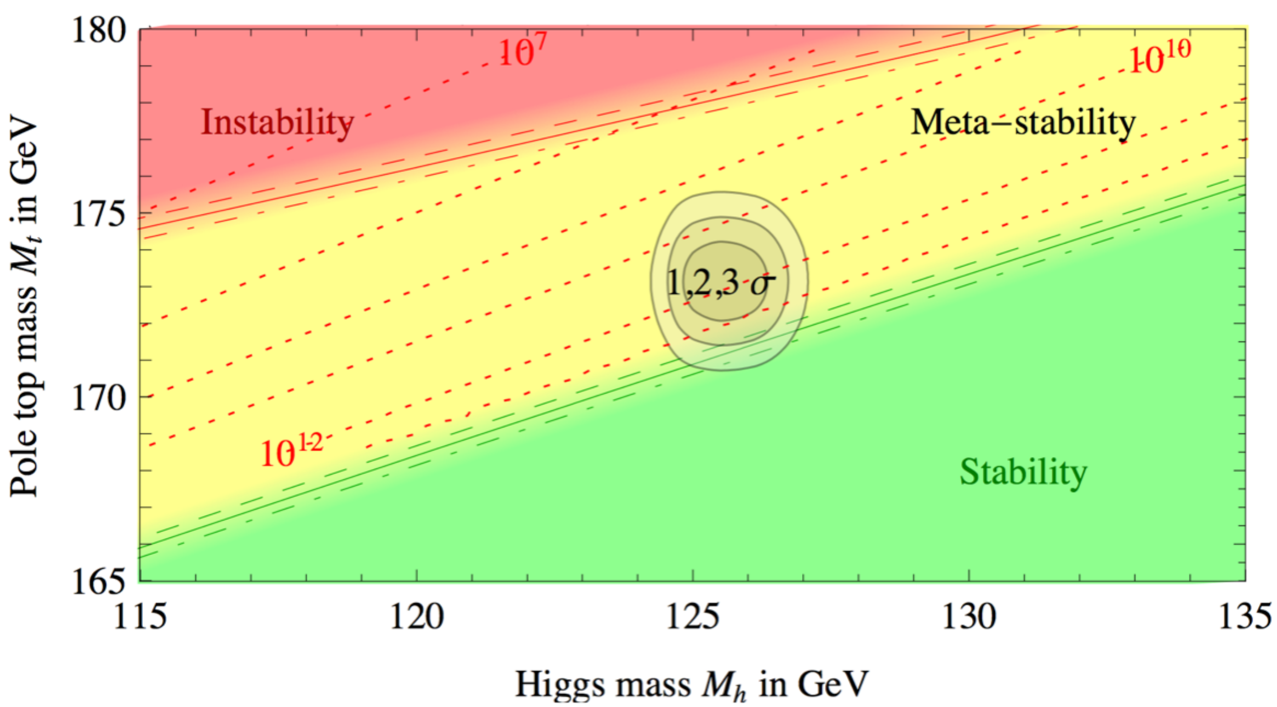
vacuum stability

- λ runs < 0? top mass precision crucial for vacuum stability
- at e+e-: top-pair threshold scan, much lower theory error
- Δm_t(MS-bar) ~ 50 MeV (Δm_H=14MeV)

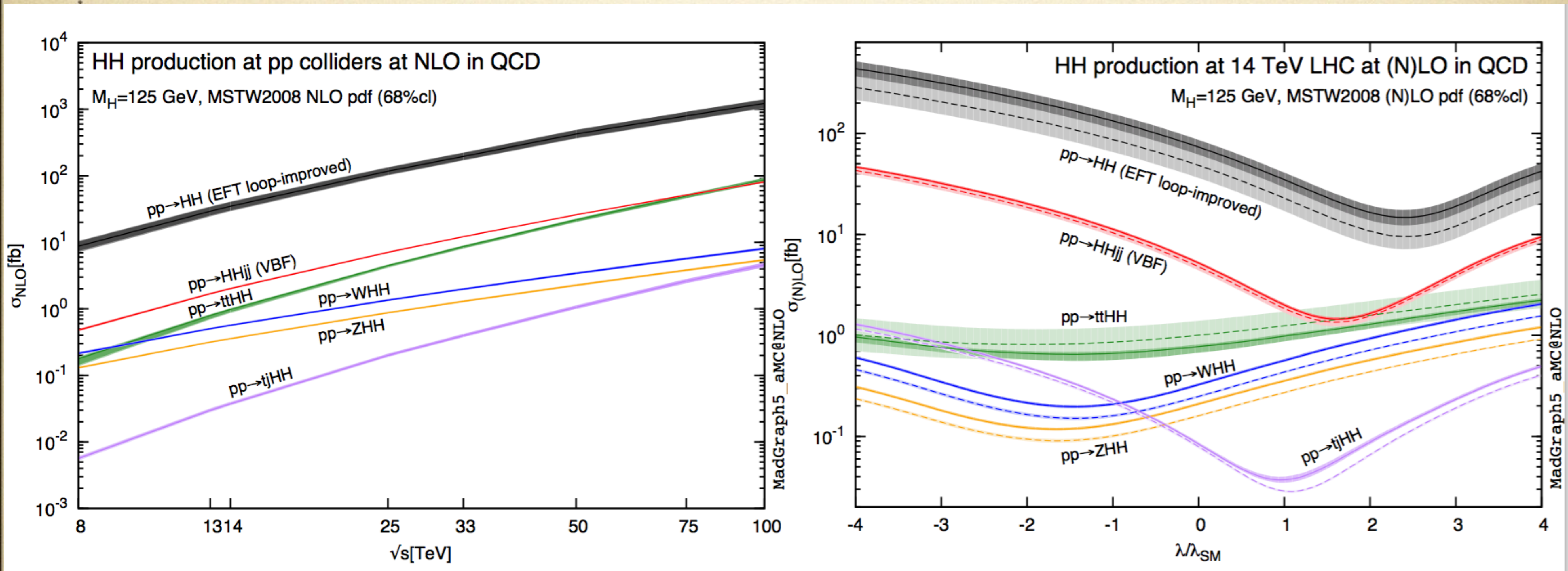




Degrassi et al, JHEP 1208 (2012) 098



what's the expectation if $\lambda \neq \lambda_{SM}$? @ LHC

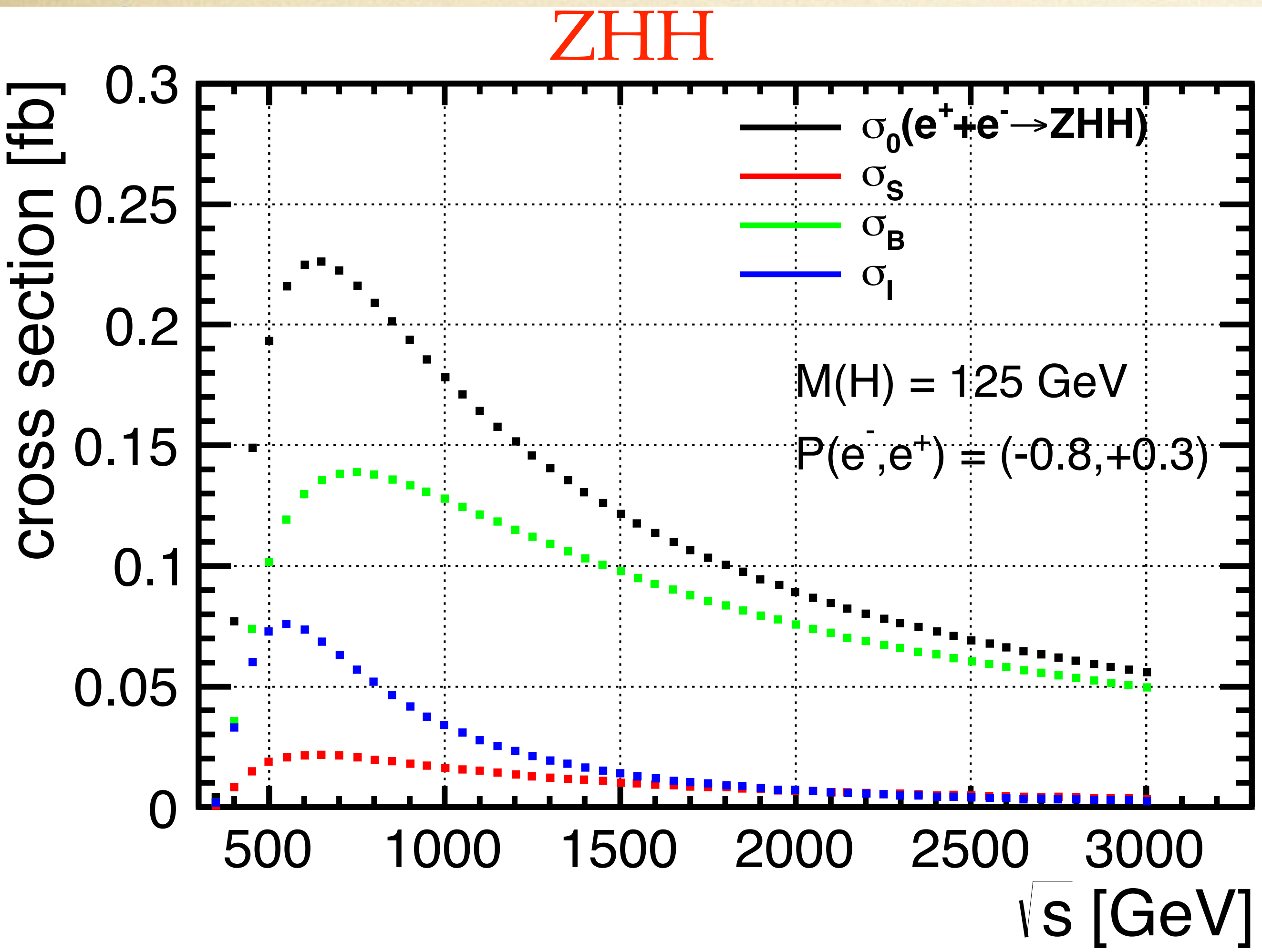


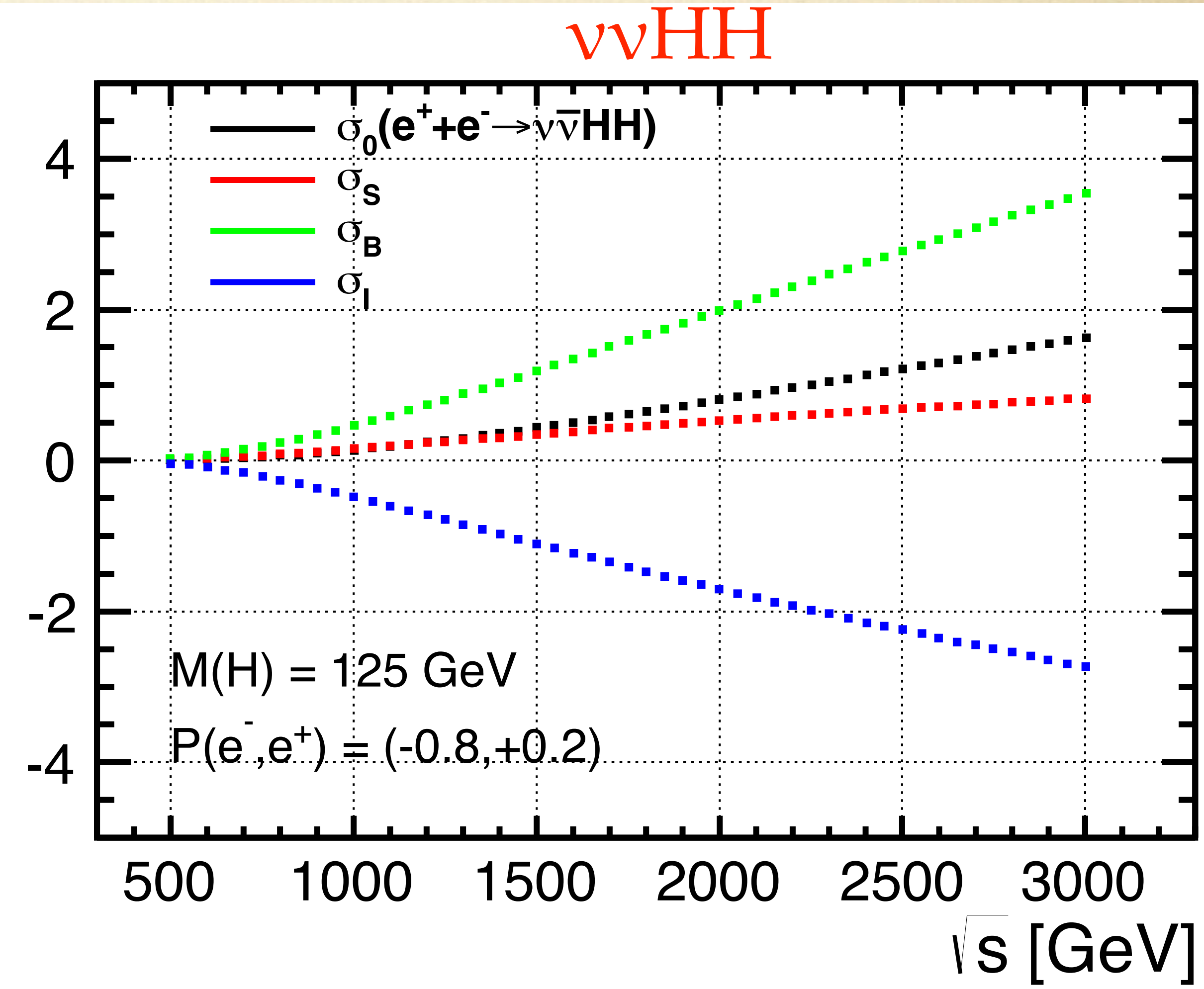
arXiv:1401.7304

- interference is destructive, σ minimum at $\lambda \sim 2.5\lambda_{SM}$; if λ is enhanced, it's going to be very difficult (from snowmass study by 3000 fb-1 @ 14 TeV, significance of double Higgs production is only ~ 2σ, if cross section deceases by a fact of 2~3, very challenging to observe pp—>HH)

breakdown of σ to *S*, *I* and *B* terms

$$\sigma = S\lambda^2 + I\lambda + B$$





- B term (green) >> S term (red) —> more difficult than expected
- interference I term (blue) plays an crucial role in both cases; larger I term for ννHH indicates potential better sensitivity in ννHH than ZHH
- For ZHH: clearly ~500-600 GeV is preferred; peak positions of I or S term are smaller than that of B term and the apparent total σ (black)
- For ννHH: dependence on ecm, S term < apparent σ < B term ≈ I term

sensitivity of λ to the directly measured σ

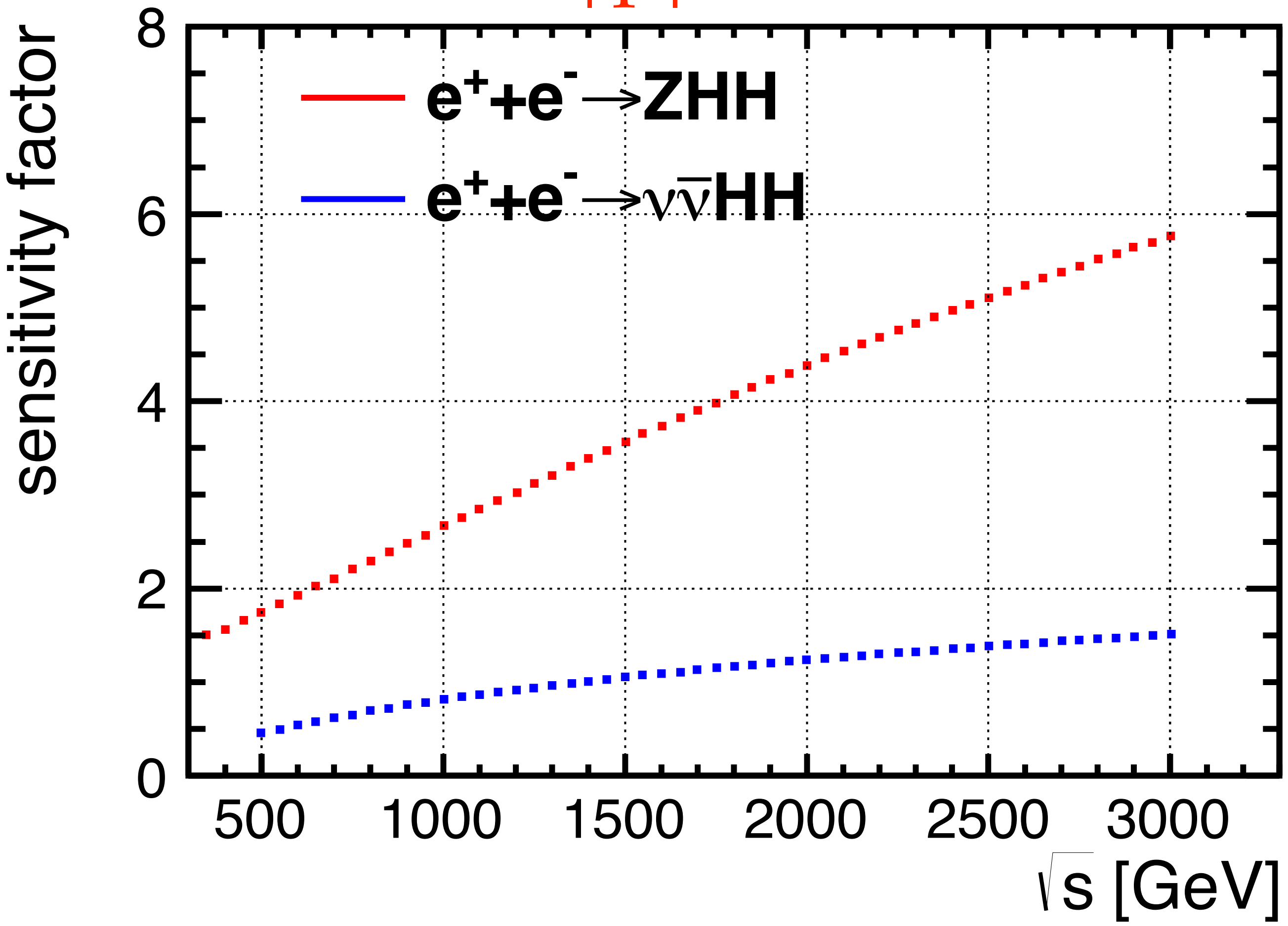
$$\frac{\delta\lambda}{\lambda} = F \cdot \frac{\delta\sigma}{\sigma}$$

$$F = \frac{\sigma}{2S\lambda^2 + I\lambda}$$

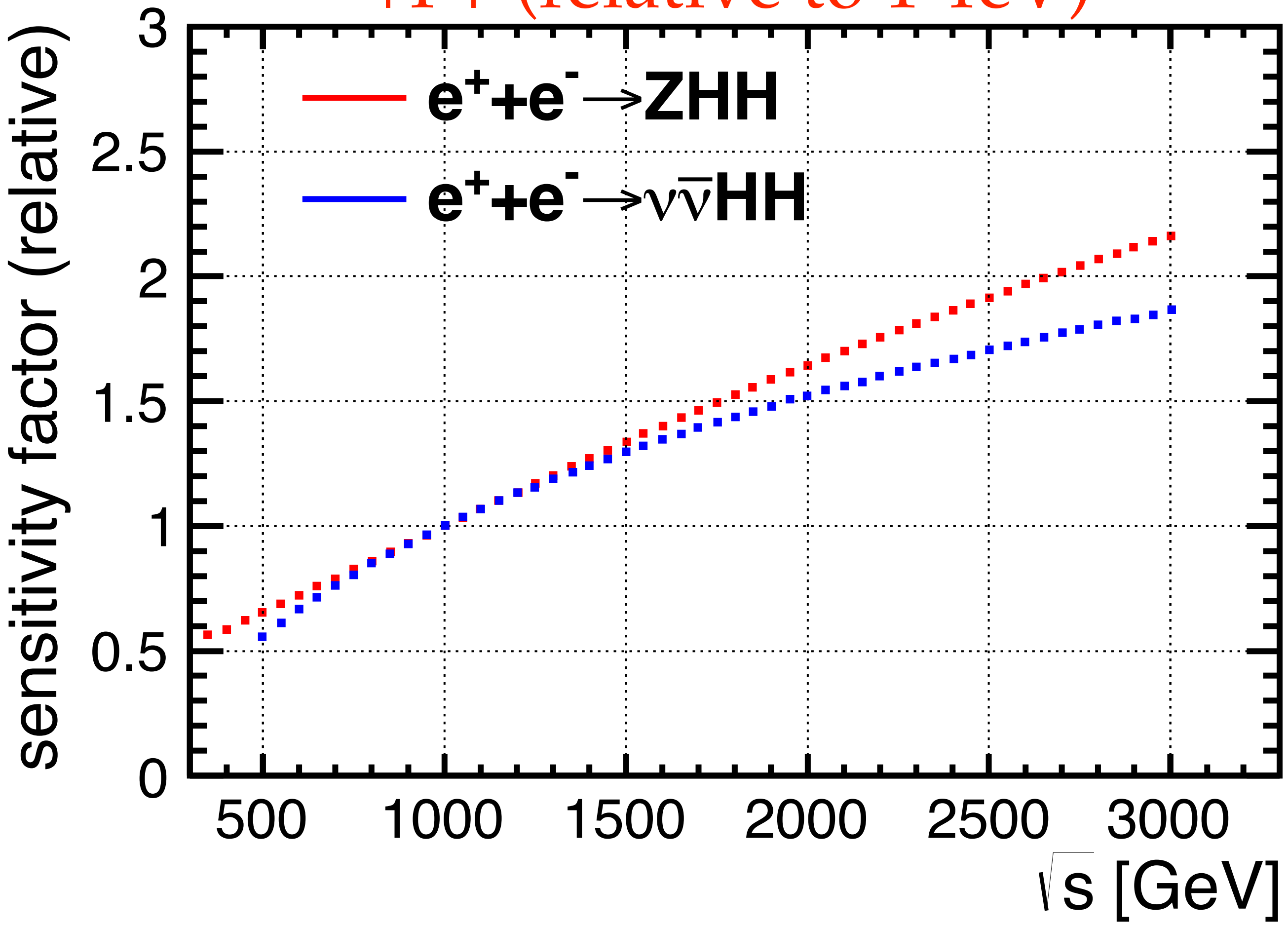
sensitivity factor

- smaller F means better sensitivity; if only signal diagram, F=0.5
- F in ZHH indeed much worse than F in ννHH
- in both cases F increases significantly when ecm increases

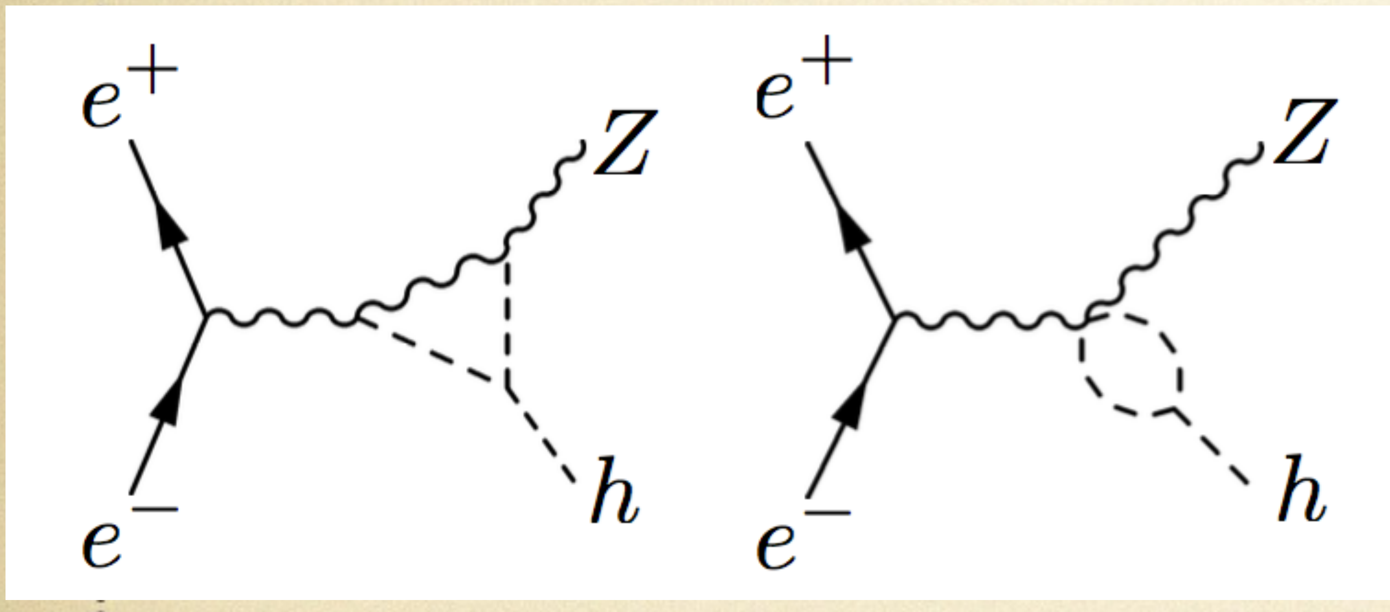
|F|



|F| (relative to 1 TeV)



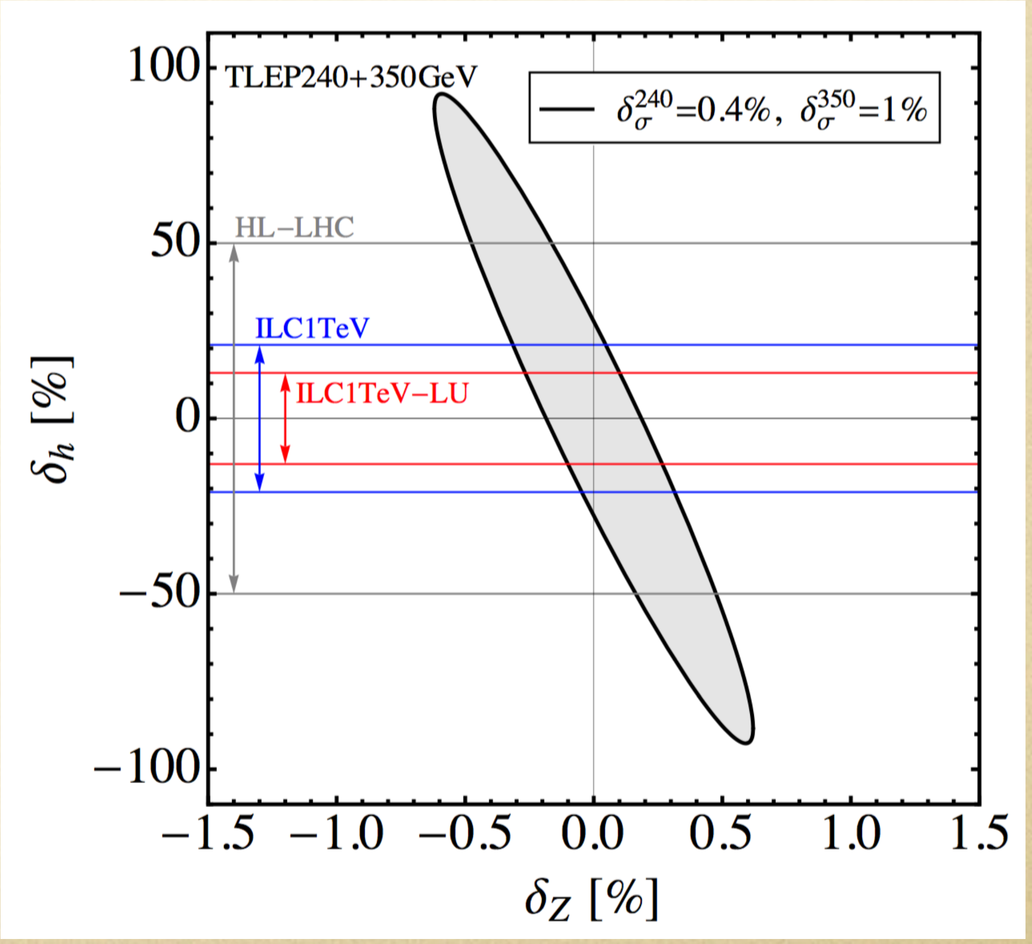
indirect model dependent probe of λ_{HHH}: $\sqrt{s}$ ~ 250 GeV



McCullough, 1312.3322

$$\delta_\sigma^{240} = 100\,(2\delta_Z + 0.014\delta_h)\,\%$$

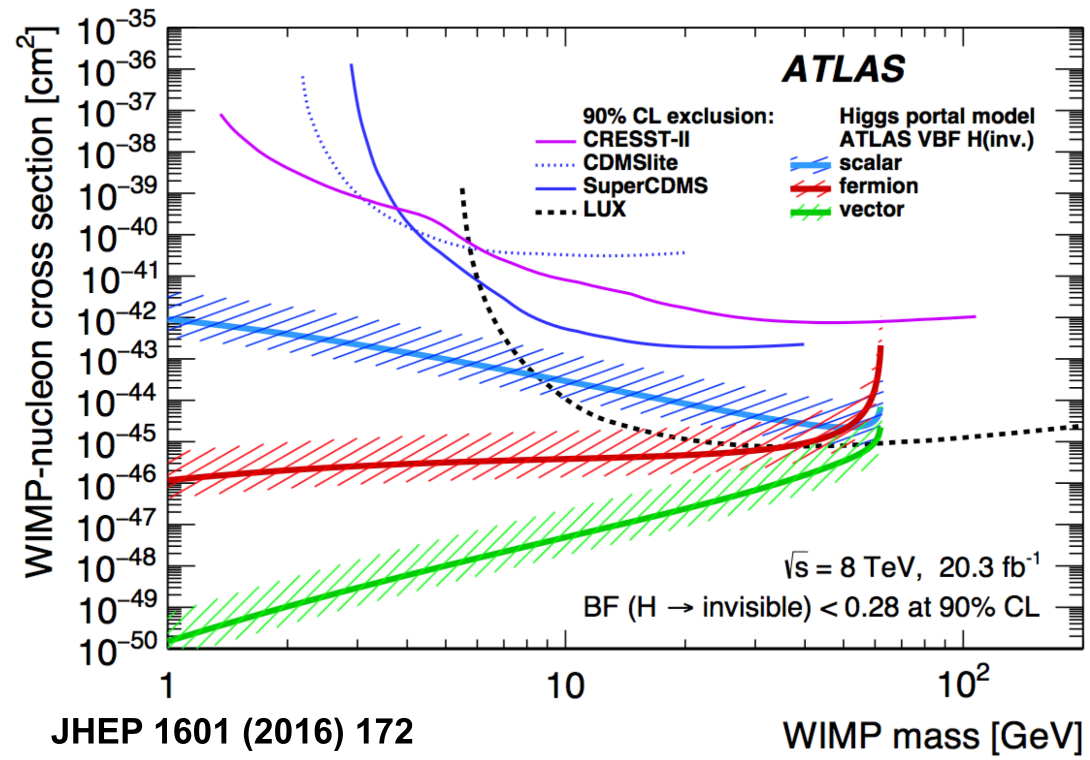
- if only δ_h is deviated —> δ_h ~ 28%
- if both δ_z and δ_h deviated —> δh ~ 90%
- δ_σ could receive contributions from many other sources
- can be considered as a useful consistency test of SM



exotic decay: search of Higgs to invisible

$$e^+ + e^- \to ZH \to l^+l^-/q\bar{q} + \text{Missing}$$

- BR(H—>inv.) < 0.3% (CL95%)
- a sensitive test for Higgs portal dark mater model —> complementary for low mass
- beam polarisation does help



JHEP 1601 (2016) 172