ILC Physics

1st IUEP mini-workshop
Chonnam National University
Oct. 7, 2018

Hyung Do Kim
(Seoul National University)

on behalf of LCC physics working group:
T.Barklow, R.Contino, K.Fujii, Y.Gao, C.Grojean,
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R.Poeschl, J.Reuter, F.Simon, T.Tanabe, J.Wells, J.Yu

2013

THE INTERNATIONAL LINEAR COLLIDER

Technical Design Report | Volume 2: Physics

June, 2015

Physics Case for the International Linear Collider

LCC Physics Working Group

Keisuke Fujii[1], Christophe Grojean[2,3] Michael E. Peskin[4](conveners);
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James D. Wells[13]; Hitoshi Murayama[14,15,16], Hitoshi Yamamoto[17]

July, 2016

Implications of the 750 GeV $\gamma\gamma$ Resonance as a Case Study for the International Linear Collider

LCC Physics Working Group

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The Potential of the ILC for Discovering New Particles

Document Supporting the ICFA Response Letter to the ILC Advisory Panel

LCC Physics Working Group

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Physics Case for the 250 GeV Stage of the International Linear Collider

LCC Physics Working Group

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The role of positron polarization for the inital 250 GeV stage of the International Linear Collider

LCC Physics Working Group

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Higgs precision

Top quark physics

Higgs self coupling

new particle discovery

Higgs precision

*** Some of the slides are stolen from
Junping Tian, Christophe Grojean, Keisuke Fujii,
Michael Peskin, Shinya Kinemura, etc.

Precision Higgs Measurements @ (I)LC

Junping Tian (U' of Tokyo)

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

(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?

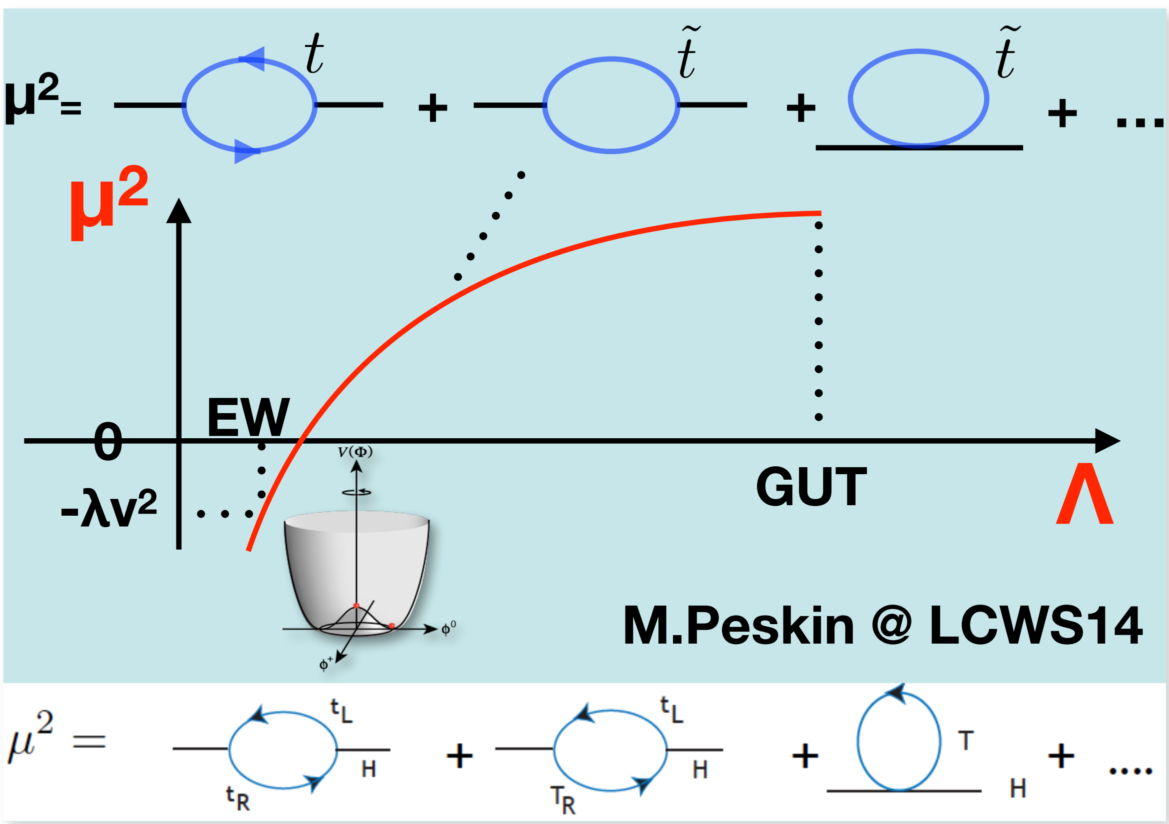
why Higgs physics

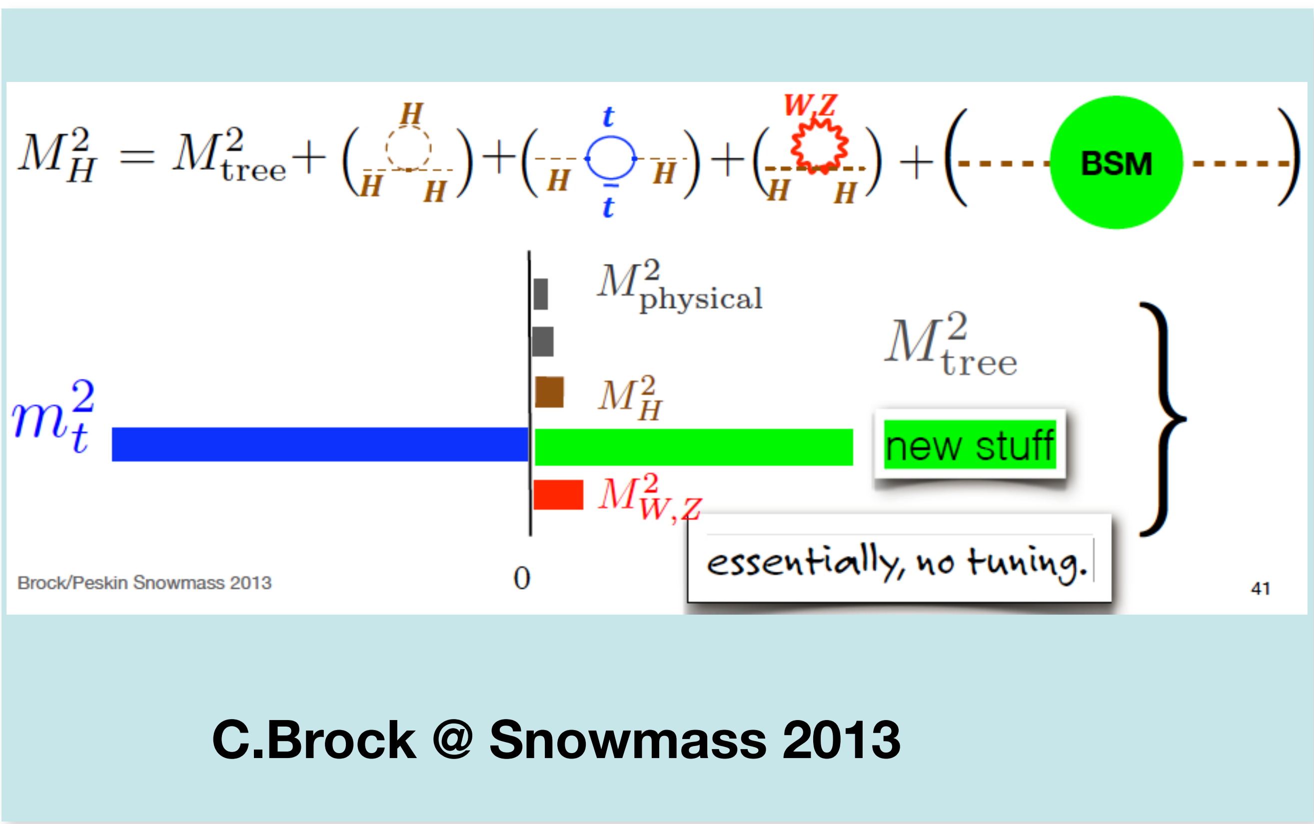
- to reveal the mysteries at electroweak scale
  - Why is $\mu^2 < 0$? what is the dynamics responsible for EWSB?
  - How to explain the naturalness for the light scalar?
  - Any connection to Dark Matter, BAU, inflation?
  - $H(125) = H_{SM}$? any siblings?

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





why precision higgs physics

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

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

challenging at LHC

typical deviation

Mixing with singlet

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

Composite Higgs

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

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

SUSY

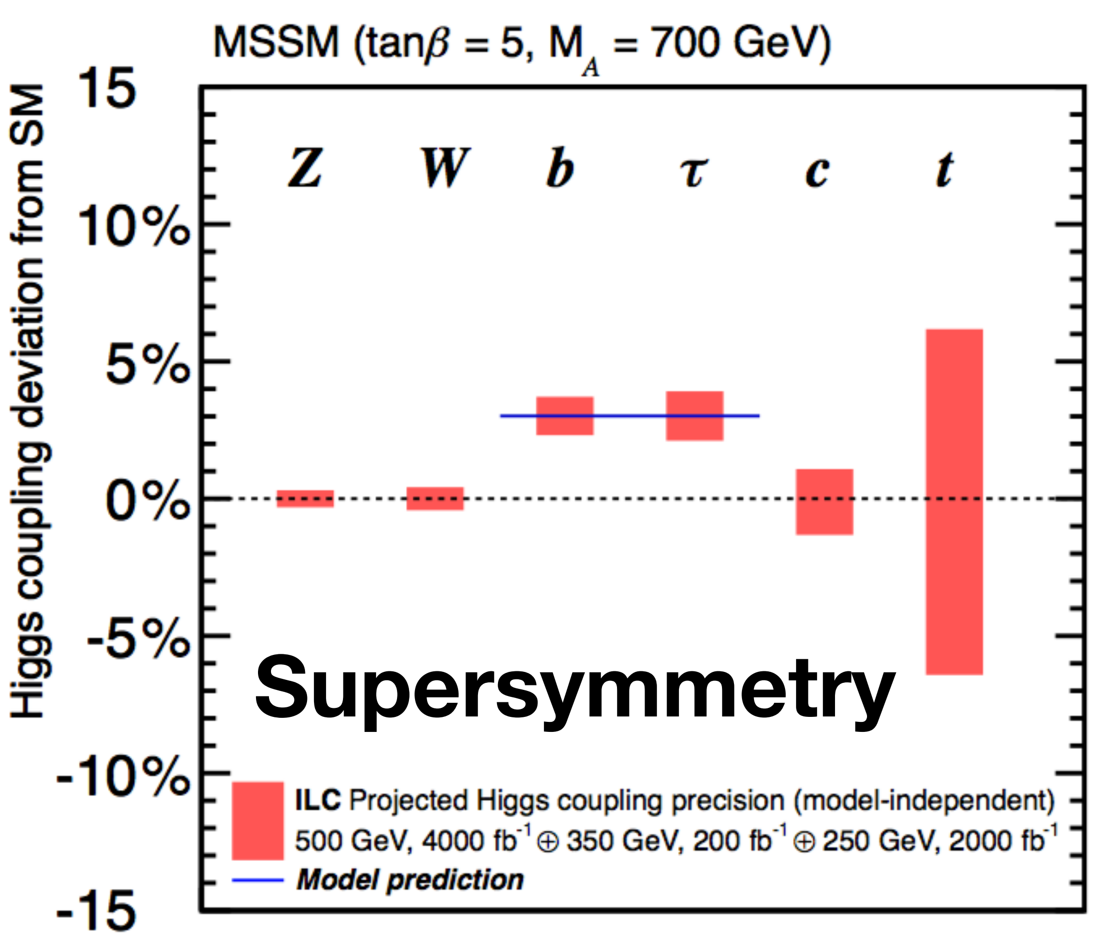
$$\frac{g_{hbb}}{g_{h_{\rm SM}bb}} = \frac{g_{h\tau\tau}}{g_{h_{\rm SM}\tau\tau}} \simeq 1 + 1.7\% \left(\frac{1\ {\rm TeV}}{m_A}\right)^2$$

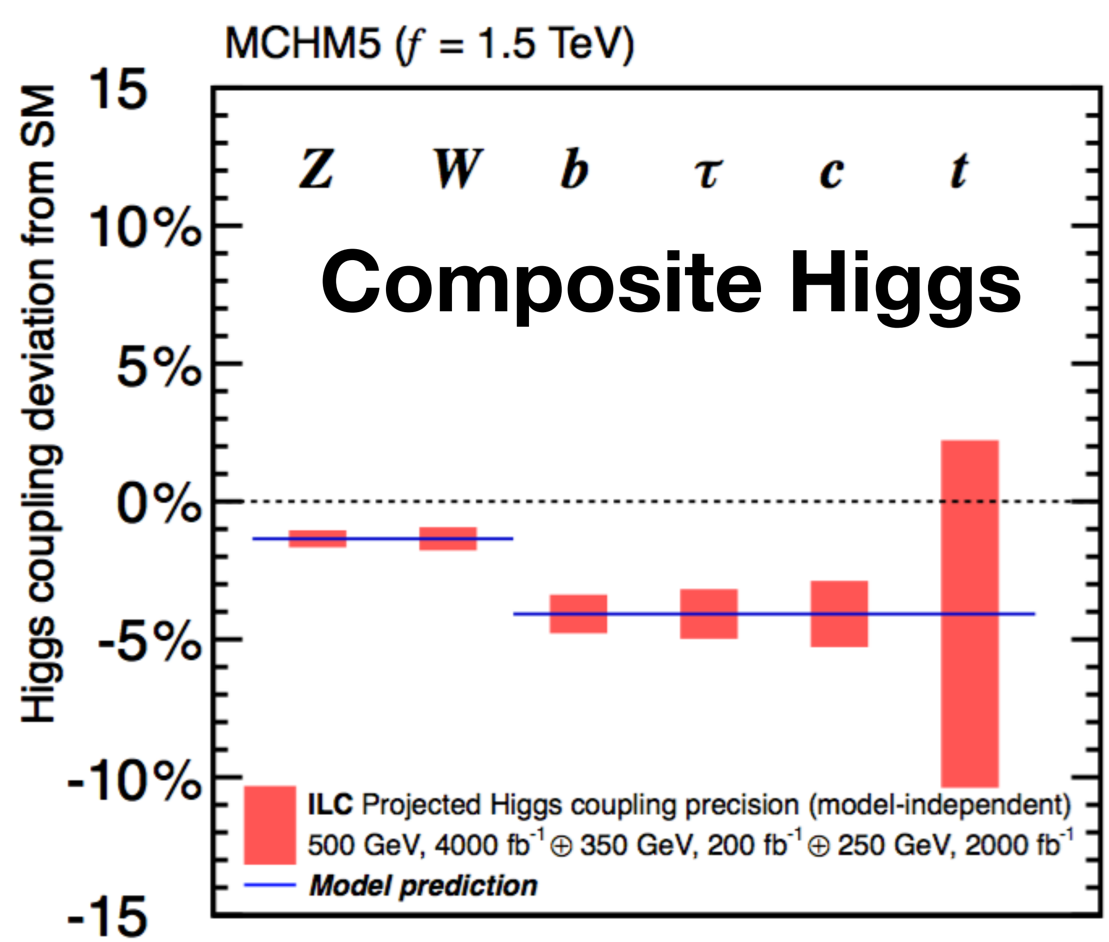
arXiv:1306.6352

why precision higgs physics

- fingerprint BSM by patterns of deviations

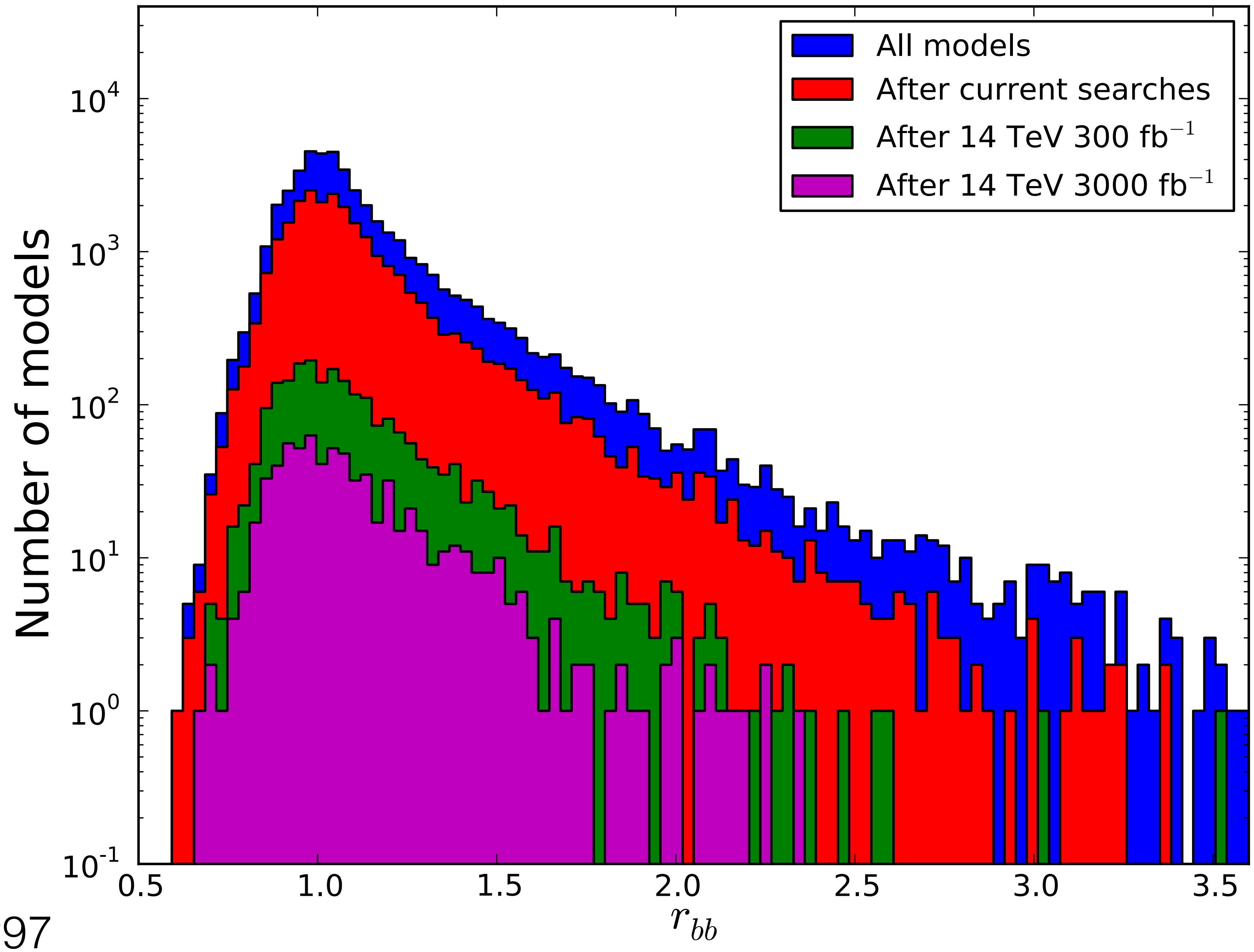
  —> measure as many couplings as possible





arXiv:1506.05992 be careful for the interpretation

discovery opportunities: direct versus indirect



arXiv:1308.0297

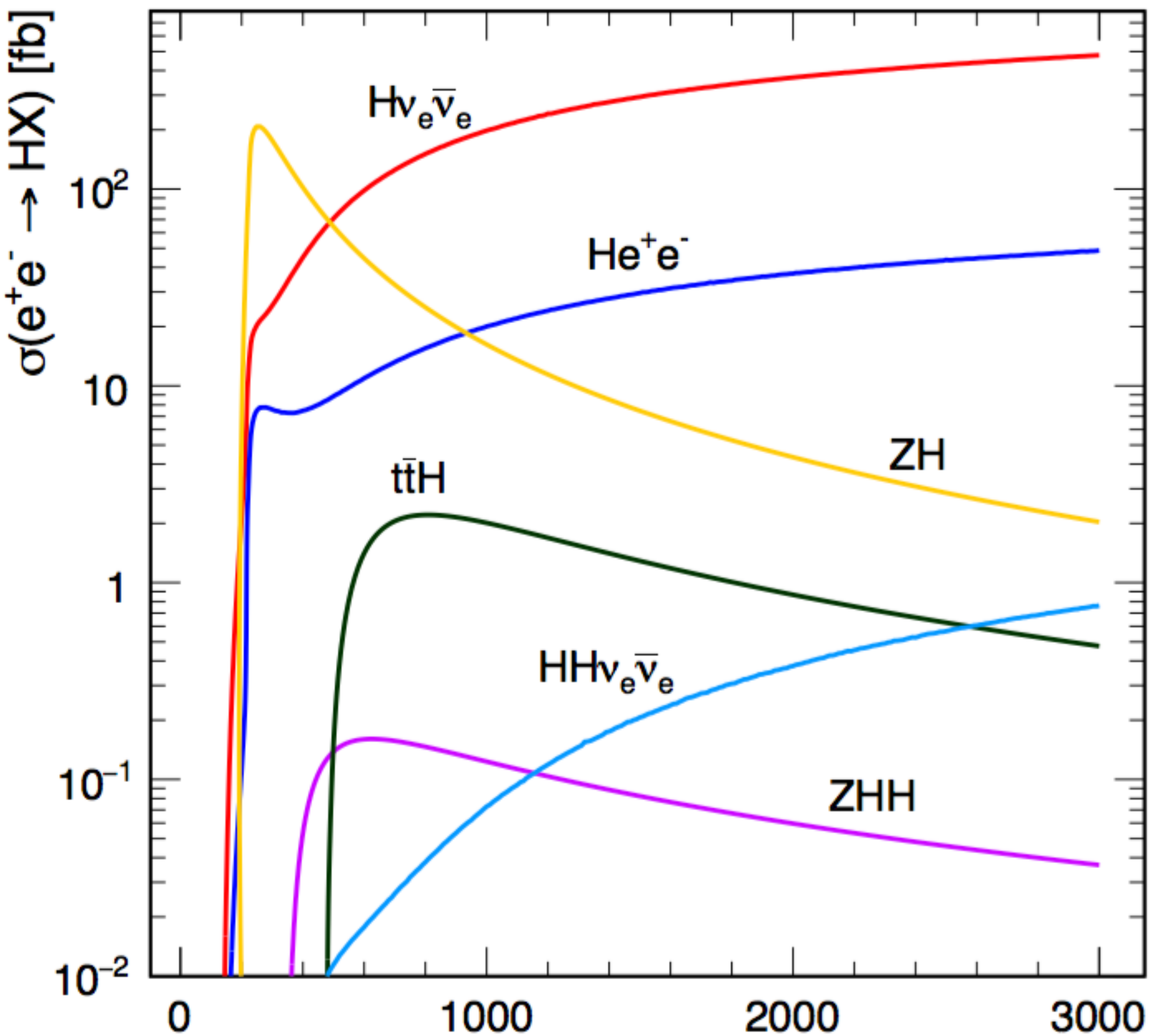
Figure 8: Histograms of the ratio $r_{bb} = \Gamma(h \to \bar{b}b)/\Gamma(h \to \bar{b}b)_{\rm SM}$ within a scan of the approximately 250,000 supersymmetry parameter sets after various stages of the LHC, assuming the LHC does not find direct evidence for supersymmetry. The purple histogram shows parameter 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

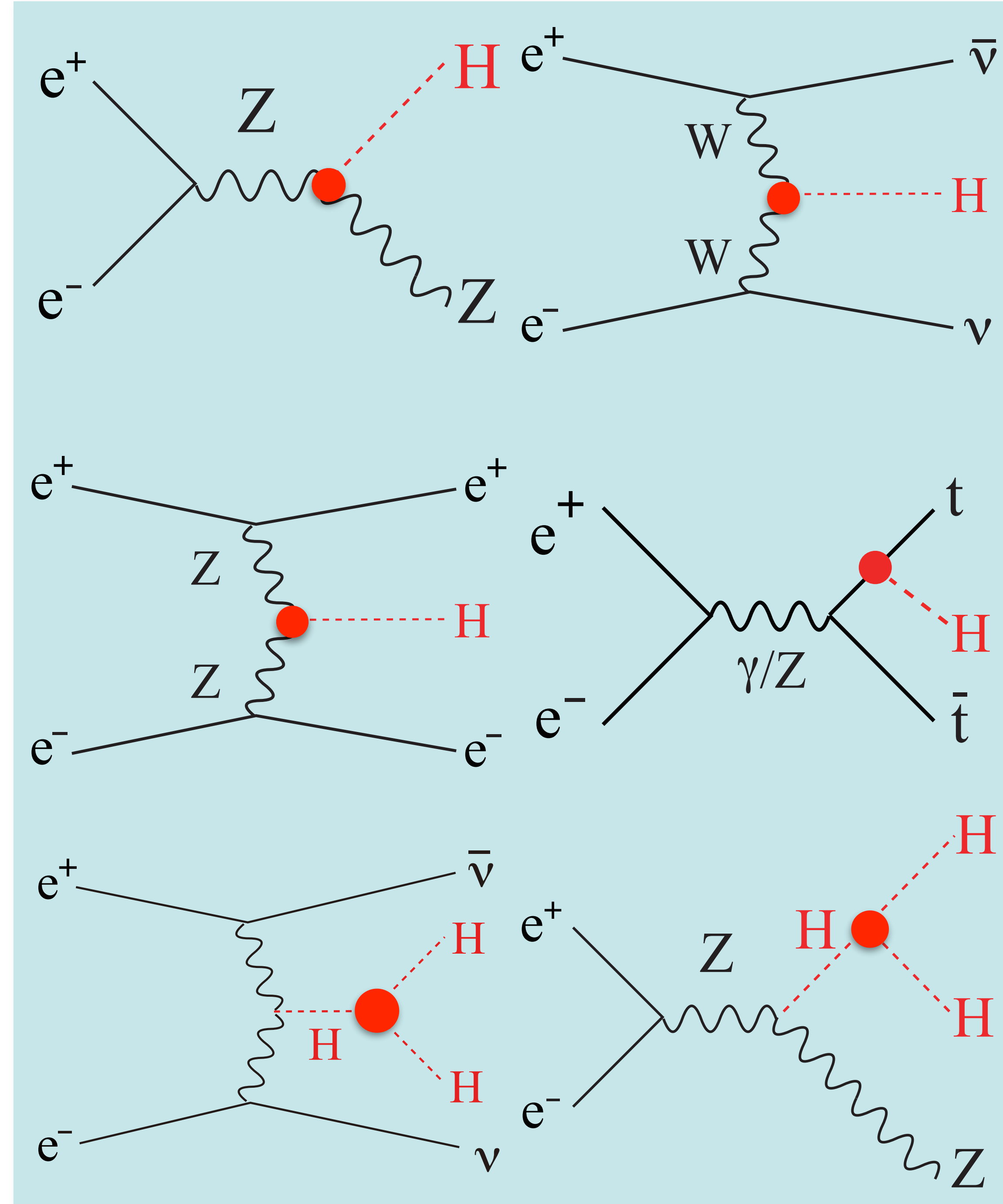
	$\sqrt{s}$	beam polarisation	$\int Ldt$ for Higgs	R&D phase
ILC	0.1 - 1 TeV	e-: 80% e+: 30%	2000 fb^{-1} @ 250 GeV 200 fb^{-1} @ 350 GeV 4000 fb^{-1} @ 500 GeV	TDR completed
CLIC	0.35 - 3 TeV	e-: (80%) e+: 0%	500 fb^{-1} @ 380 GeV 1500 fb^{-1} @ 1.4 TeV 2000 fb^{-1} @ 3 TeV	CDR completed
CEPC	90 - 240 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: √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} $\quad M_h \quad \Gamma_h \quad J^{\mathrm{CP}}$	new CP violating source?
L_{Higgs} $\quad hhh: \ -6i\lambda v = -3i\frac{m_h^2}{v}, \quad hhhh: \ -6i\lambda = -3i\frac{m_h^2}{v^2}$	probe Higgs potential, EWBG?
L_{Gauge} $\quad W^+_\mu W^-_\nu h: \ i\frac{g^2 v}{2}g_{\mu\nu} = 2i\frac{M_W^2}{v}g_{\mu\nu}, \quad W^+_\mu W^-_\nu hh: \ i\frac{g^2}{2}g_{\mu\nu} = 2i\frac{M_W^2}{v^2}g_{\mu\nu},$ $\quad Z_\mu Z_\nu h: \ i\frac{g^2+g'^2 v}{2}g_{\mu\nu} = 2i\frac{M_Z^2}{v}g_{\mu\nu}, \quad Z_\mu Z_\nu hh: \ i\frac{g^2+g'^2}{2}g_{\mu\nu} = 2i\frac{M_Z^2}{v^2}g_{\mu\nu}$	SU(2) nature? m_V from SSB?
L_{Yukawa} $\quad h\bar{f}f: \ -i\frac{y^f}{\sqrt{2}} = -i\frac{m_f}{v}$	m_f from Yukawa coupling? 2HDM?
L_{Loop} $\quad h\gamma\gamma \quad hgg \quad h\gamma Z$	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

$\gamma\gamma$, gg couplings - heavy vectorlike particles

tt coupling - top compositeness

hhh coupling (large deviations) - baryogenesis

what are the direct experimental observables

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

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

$$Y_i' = F_i \cdot \frac{g^2_{HA_iA_i} \cdot g^2_{HB_iB_i}}{\Gamma_0} \qquad (A_i = Z, W, t)$$

$$(B_i = b, c, \tau, \mu, g, \gamma, Z, W : \text{decay})$$

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

From observables to couplings — kappa formalism

(examples)

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

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

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

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

$$\Rightarrow$$

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

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

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

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

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

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

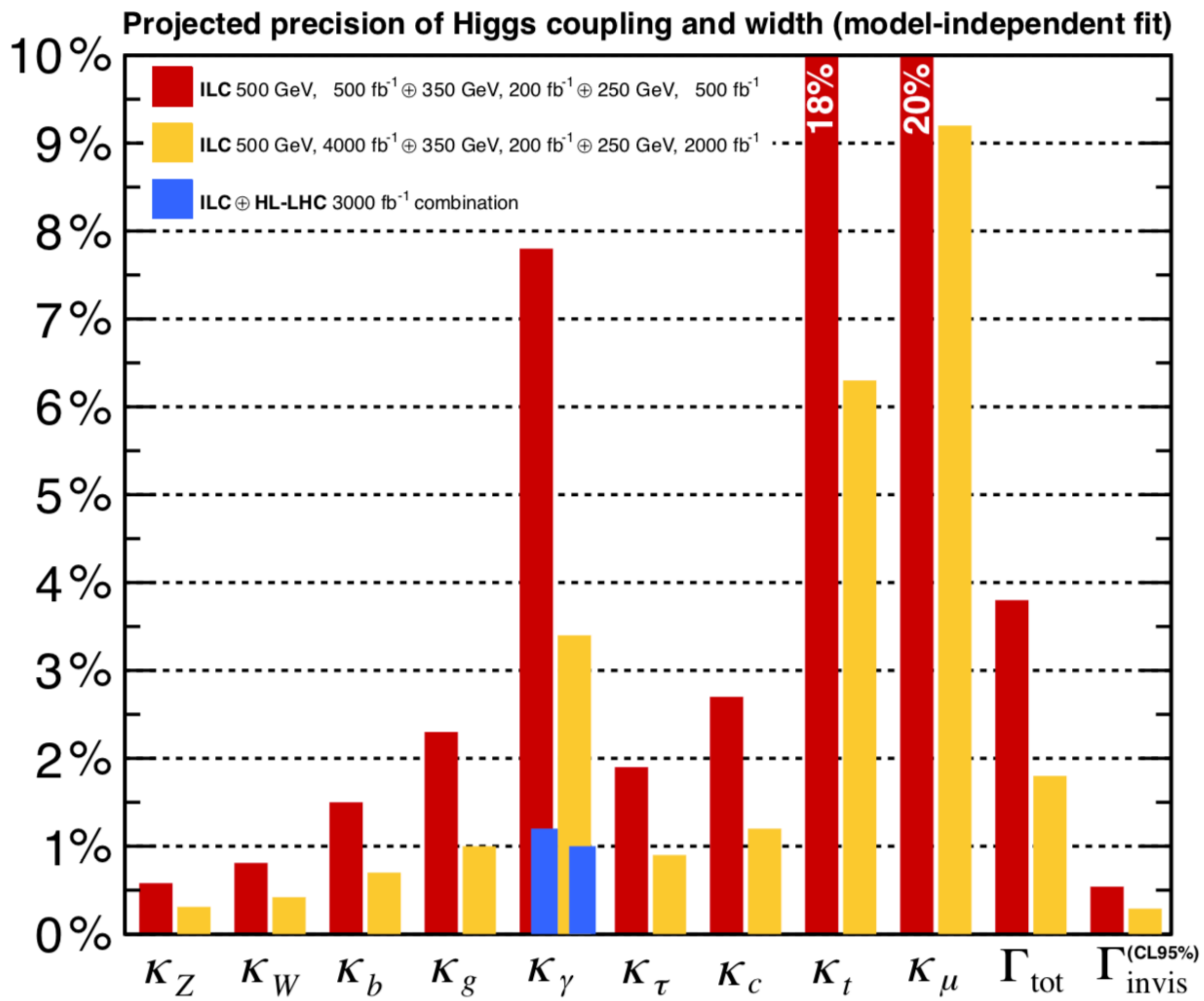
$$\Delta g_{HWW} \sim \frac{1}{2}\Delta Y_1 \oplus \frac{1}{2}\Delta Y_2 \oplus \frac{1}{2}\Delta Y_3$$

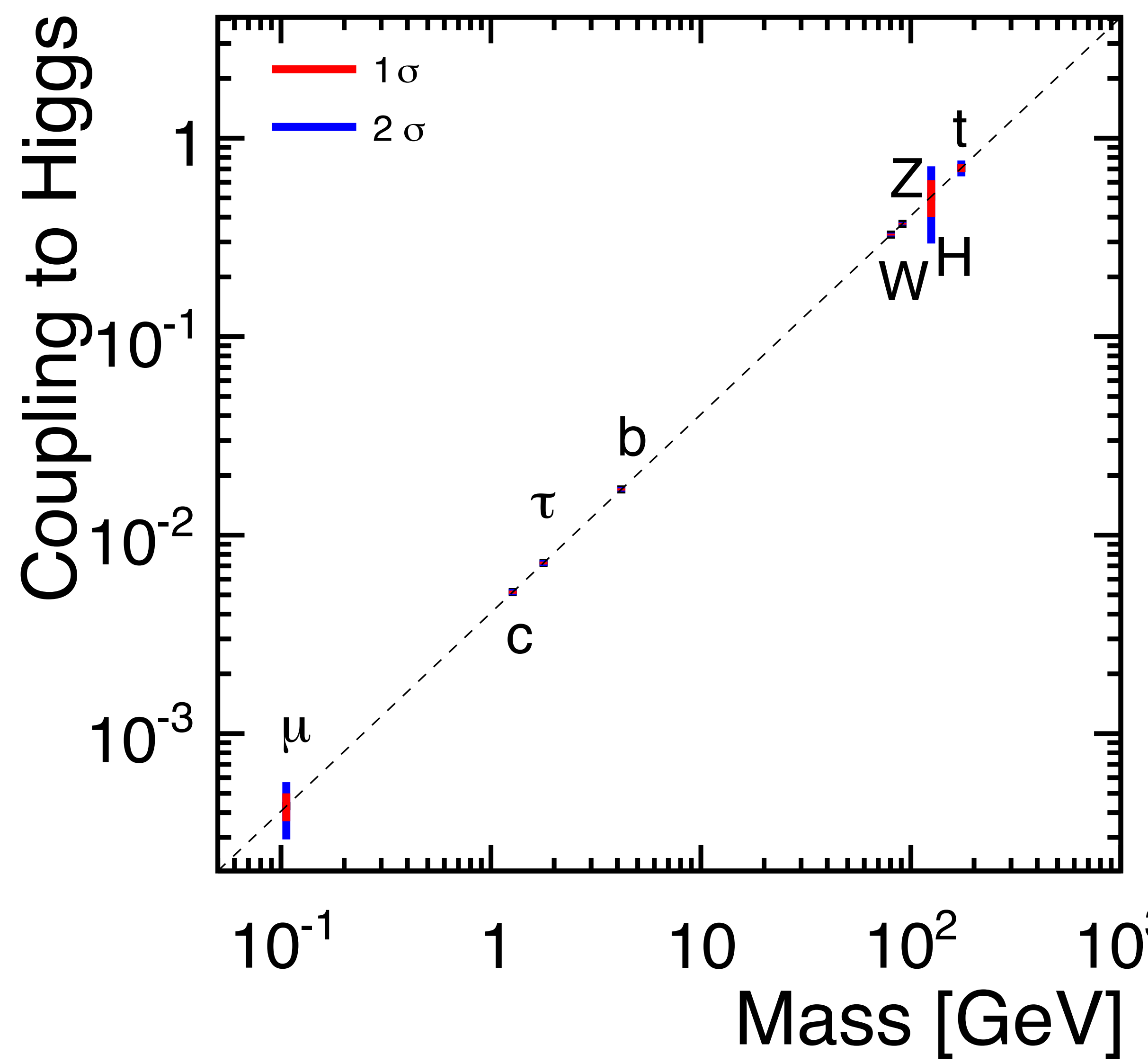
$$\Delta g_{Hbb} \sim \frac{1}{2}\Delta Y_1 \oplus \Delta Y_2 \oplus \frac{1}{2}\Delta Y_3 \oplus \frac{1}{2}\Delta Y_4$$

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

- ☑ both ZH and vvH productions matter
- ☑ every coupling is limited by $\Delta\sigma_{ZH}$
- ☑ every coupling except g_{HZZ} is limited by $\Delta\sigma_{vvH}$
- ☑ 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

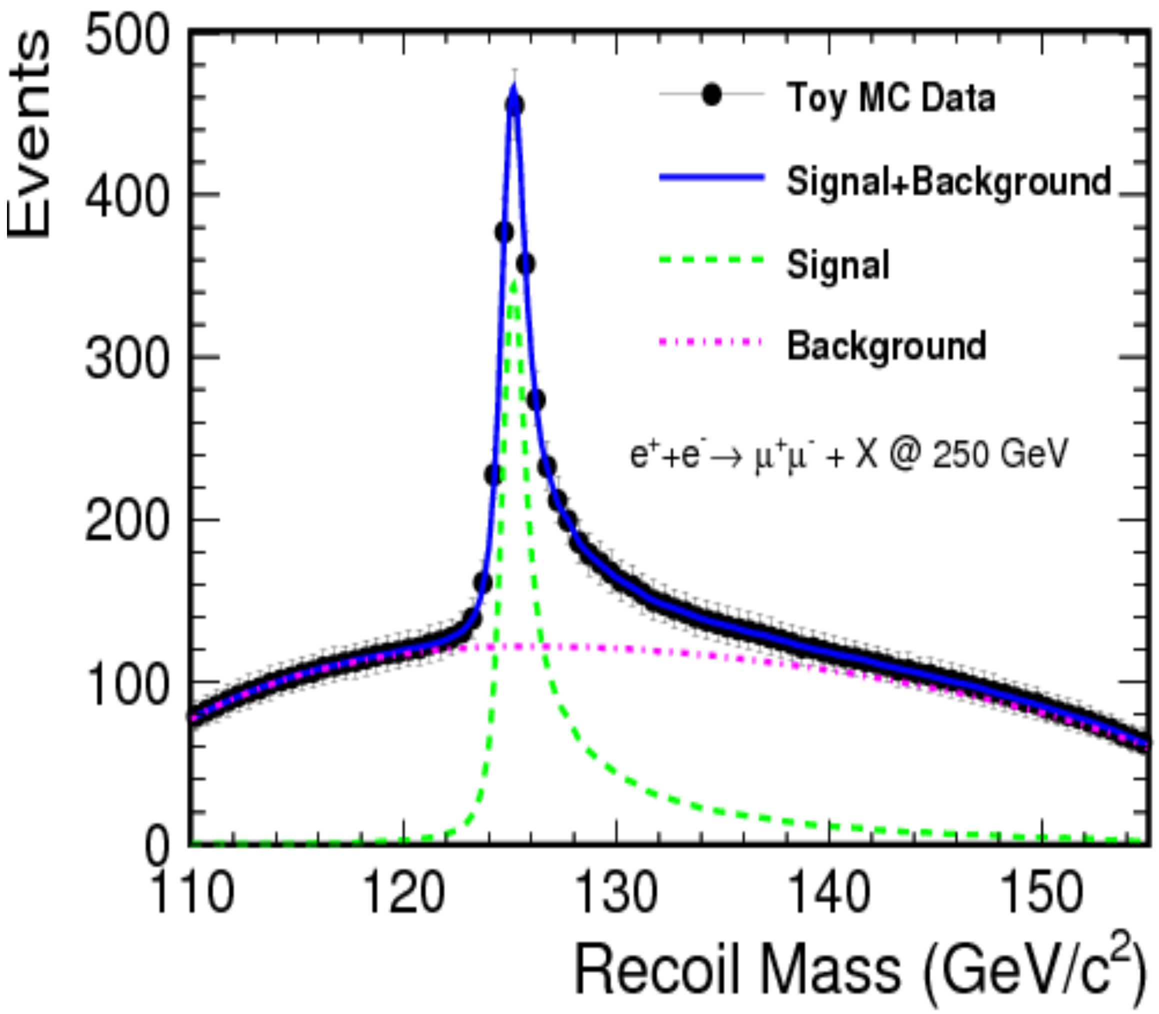
(ii) key measurements

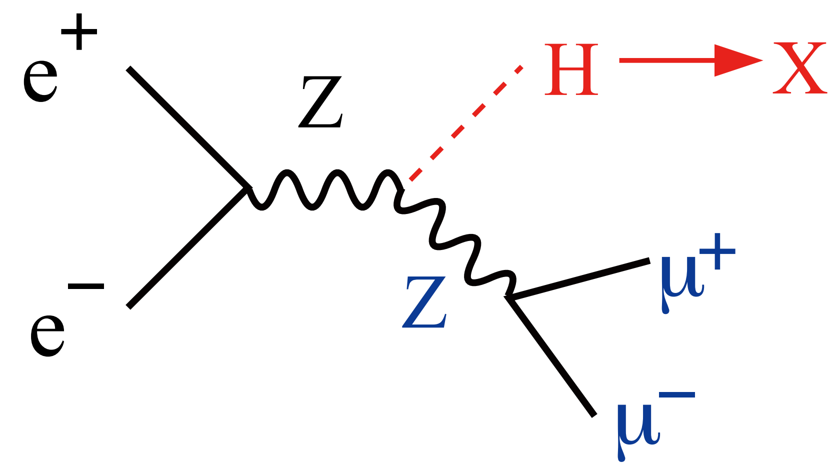
I will explain some details in one/two analyses, talk very briefly in other ones; mainly focus on physics issues instead of analysis techniques, which are important as well though and can be learned from the references.

(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





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

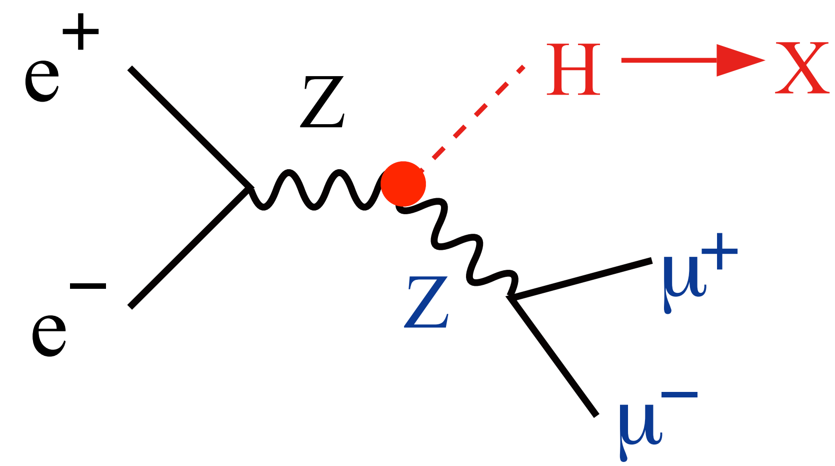
$\Delta m_H = 14\text{MeV}$ $\delta g_{HZZ} \sim 0.38\%$

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

- 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

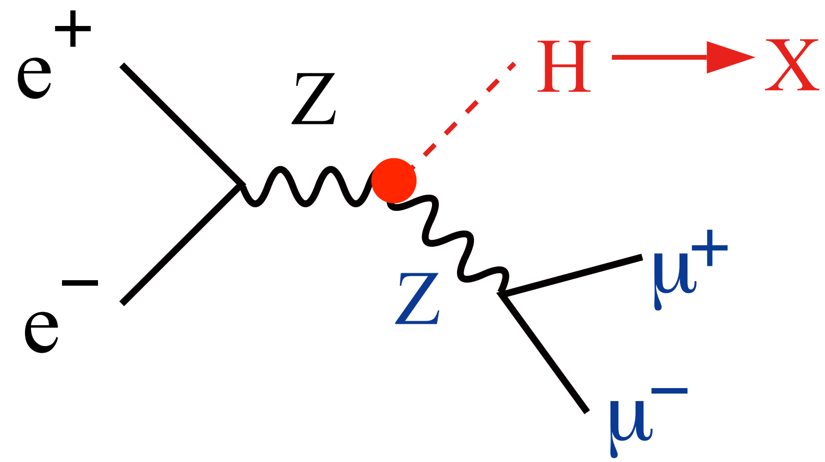
is it really possible?

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

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

Higgs self coupling in the SM

$$V(H) = -\mu^2|H|^2 + \lambda|H|^4$$

$\mu^2 = \lambda v^2$ at the minimum of the potential

$$m_h^2 = 2\lambda v^2$$

All three definitions give the same quartic coupling.

$$\lambda_{\rm eff}^{(2)SM} = \frac{m^2}{2v^2} \longrightarrow \frac{1}{2!}\frac{d^2V}{d\phi^2}\Big|_{\phi=v}\frac{1}{v^2}$$

$$\lambda_{\rm eff}^{(3)SM} = \frac{1}{3!}\frac{d^3V}{d\phi^3}\Big|_{\phi=v}\frac{1}{v}$$

$$\lambda_{\rm eff}^{(4)SM} = \frac{1}{3!}\frac{d^4V}{d\phi^4}\Big|_{\phi=v}$$

Coleman-Weinberg Higgs

D Chway et al, PRL(2014)

$$V(\phi) = m^2\phi^\dagger\phi + \lambda(\phi^\dagger\phi)^2$$

$$m^2 = 0$$

(second derivative of V at the origin)

Spontaneous symmetry breaking can occur
by radiative corrections.

Starting from scale invariant potential

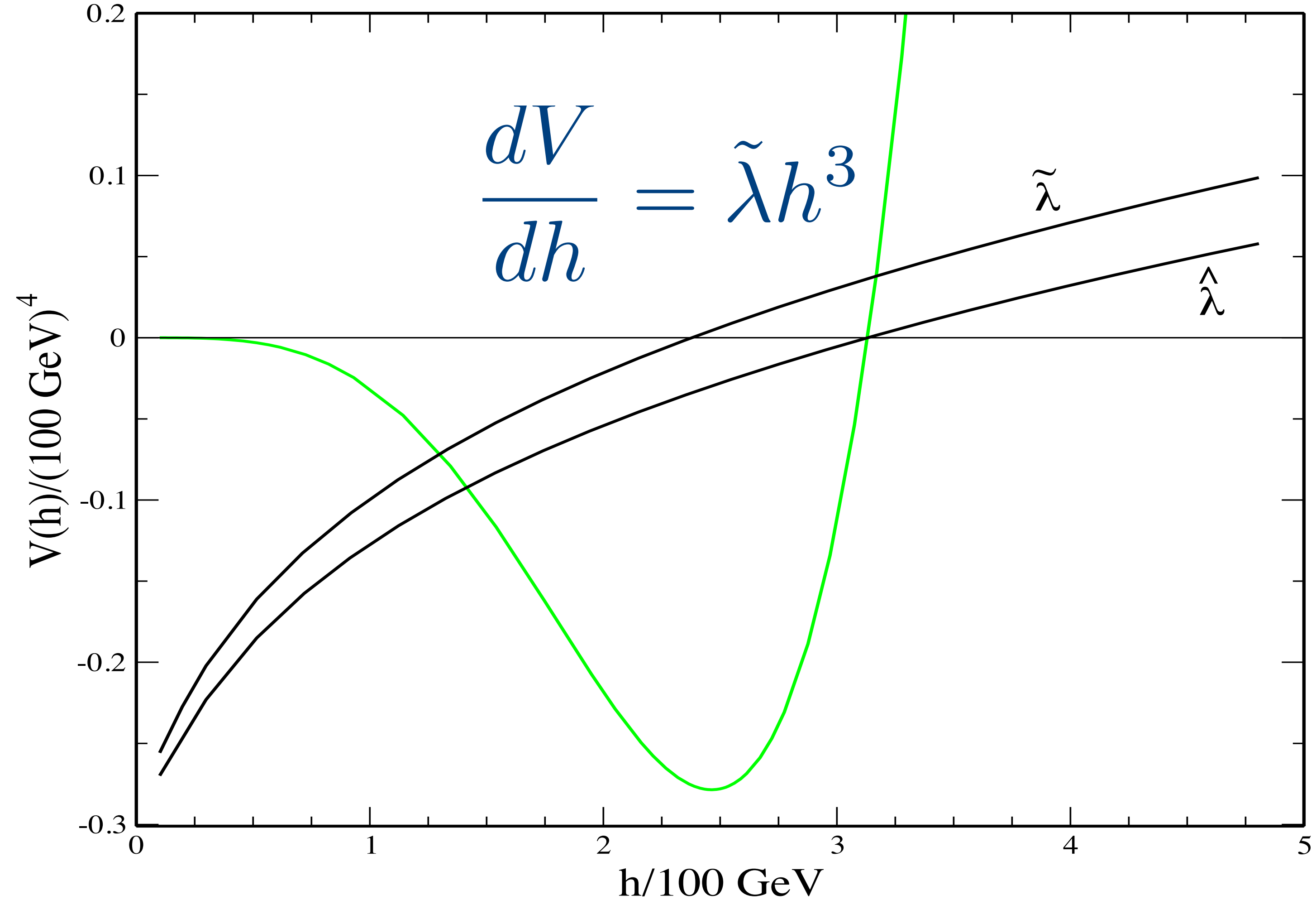
$$V(\phi) = \lambda(\phi^\dagger \phi)^2$$

RG improved effective potential is then

$$V(\phi) = \lambda(\phi)(\phi^\dagger \phi)^2$$

$$V(h) = \frac{\hat{\lambda}}{4} h^4$$

If the quartic changes sign at low energy, nontrivial minimum is developed



Espinosa and Quiros, PRD (2007)

Scalar QED and Standard Model in 1970s

$$\frac{m_h^2}{m_V^2} = \frac{3}{2\pi}\frac{e^2}{4\pi} = \frac{3}{2\pi}\alpha \qquad\qquad m_V^2 = e^2\langle\phi\rangle^2$$

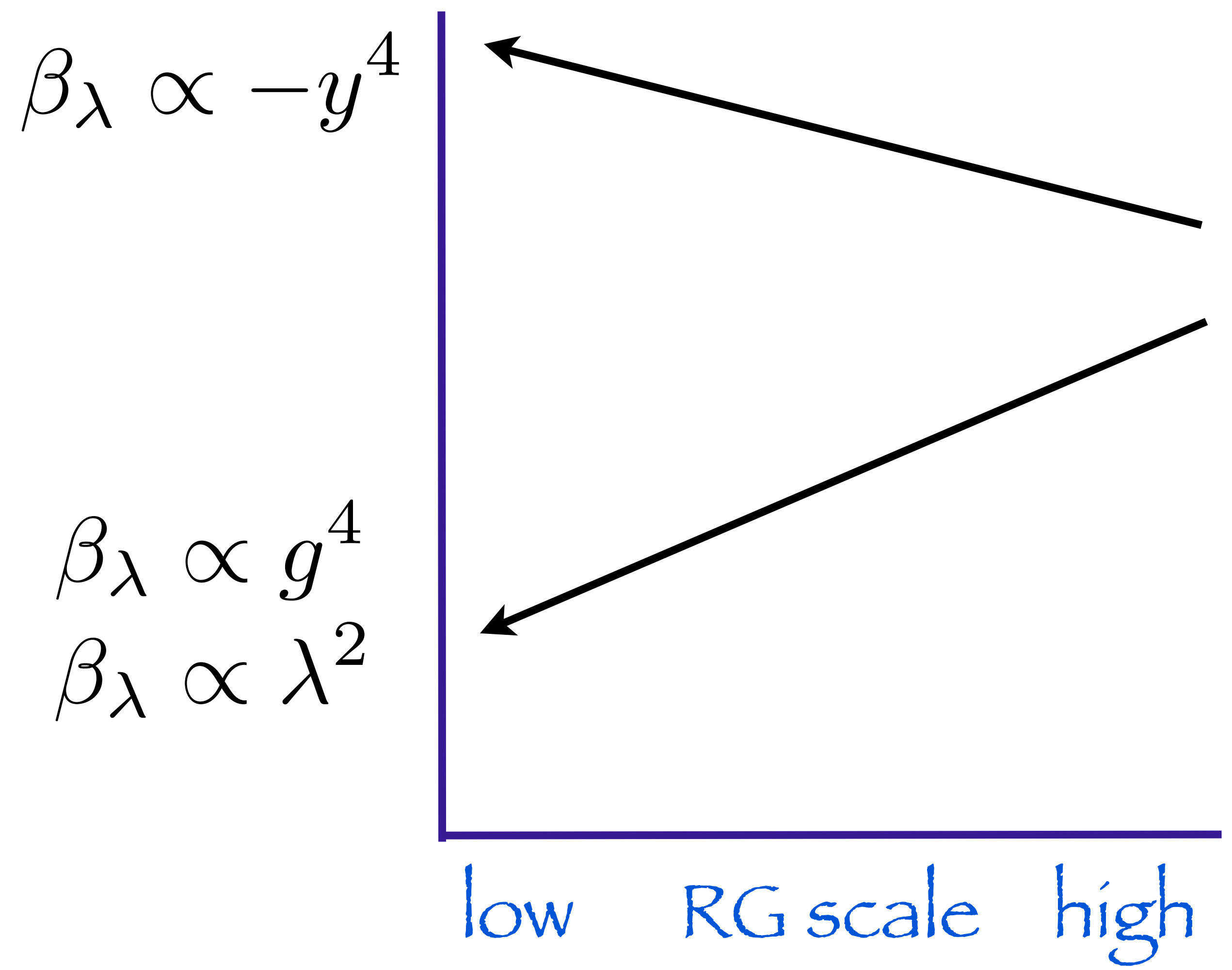
$$m_h^2 = \frac{3}{32\pi^2}\left[2g^2 m_W^2 + (g^2 + g'^2)m_Z^2\right]$$

SM with W and Z (without top) : mh ~ 10 GeV

Radiatively generated Higgs mass is one loop suppressed compared to the vector boson mass

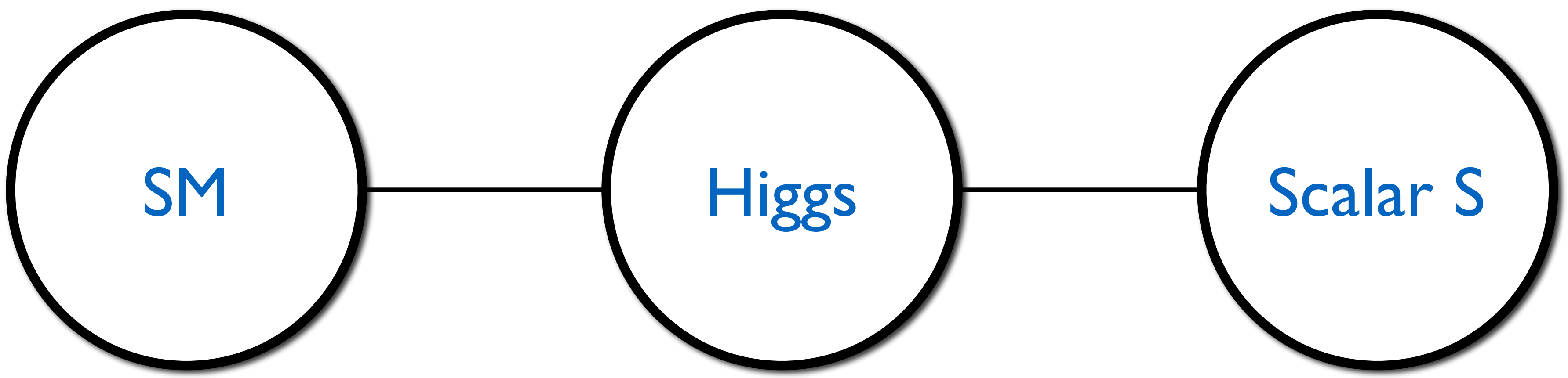
Superconductor :
Coherence length is much longer than London penetration length

Top Yukawa prevents CW mechanism in the SM



Radiative symmetry breaking is possible
with gauge or mixed quartic interactions.

New particles interacting with Higgs



$$V(h) \propto h^4 \log h$$

Coleman-Weinberg Higgs

D Chway et al, PRL(2014)

$$V(\phi) = \frac{\lambda(t)}{4}\phi^4$$

$$t = \log\phi$$

$$\frac{dV}{d\phi} = \frac{dt}{d\phi}\frac{\beta_\lambda}{4}\phi^4 + \frac{\lambda}{4}\cdot 4\phi^3$$

$$= (\lambda + \frac{\beta_\lambda}{4})\phi^3|_{\phi=v} = 0$$

-75% (tree) + 175% (loop)

$$m^2 = \frac{d^2V}{d\phi^2}|_{\phi=v} = (\beta_\lambda + \cancel{\frac{\beta'_\lambda}{4}})v^2$$

$$\lambda_{\text{eff}}^{(2)} = \frac{1}{2}\frac{m^2}{v^2} \sim \frac{1}{8}$$

(precisely = 0.129)

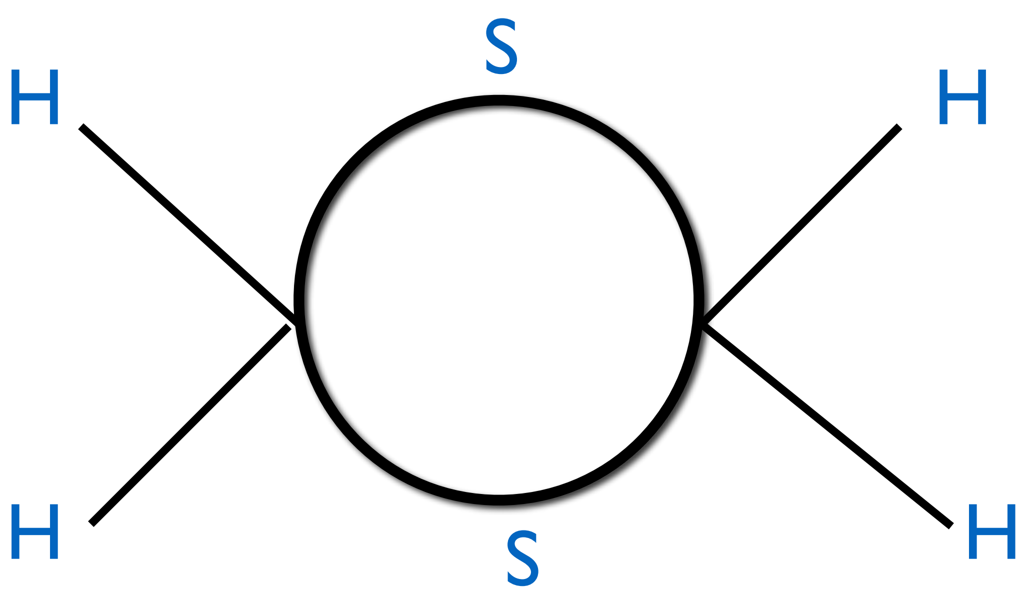
$$\boxed{\beta_\lambda \sim \frac{1}{4}}$$

$$\boxed{\begin{aligned}\lambda_{\text{eff}}^{(3)} &= \frac{5}{3}\lambda_{\text{eff}}^{(2)}, \\ \lambda_{\text{eff}}^{(4)} &= \frac{11}{3}\lambda_{\text{eff}}^{(2)}.\end{aligned}}$$

Scale dependence of the beta function is neglected here.

Suppression of Higgs couplings to the SM

Expected precision for hZZ
LHC : 2% to 5%
Higgs factory 1% to 0.4%



$$\frac{1}{p^2 - m_h^2 + \Sigma(p^2)}$$
$$\simeq \frac{Z}{p^2 - m_h^2 + (Z^{-1} - 1)(p^2 - m_h^2) + i m_h \Gamma_h}$$
$$= \frac{Z}{p^2 - m_h^2 + i m_h Z \Gamma_h}$$

expansion at the resonance
can not be valid for off-shell

Generate dimension 6 operator

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \frac{c_H}{m_\phi^2}\left(\frac{1}{2}\partial_\mu |H|^2 \partial^\mu |H|^2\right) + \ldots$$

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

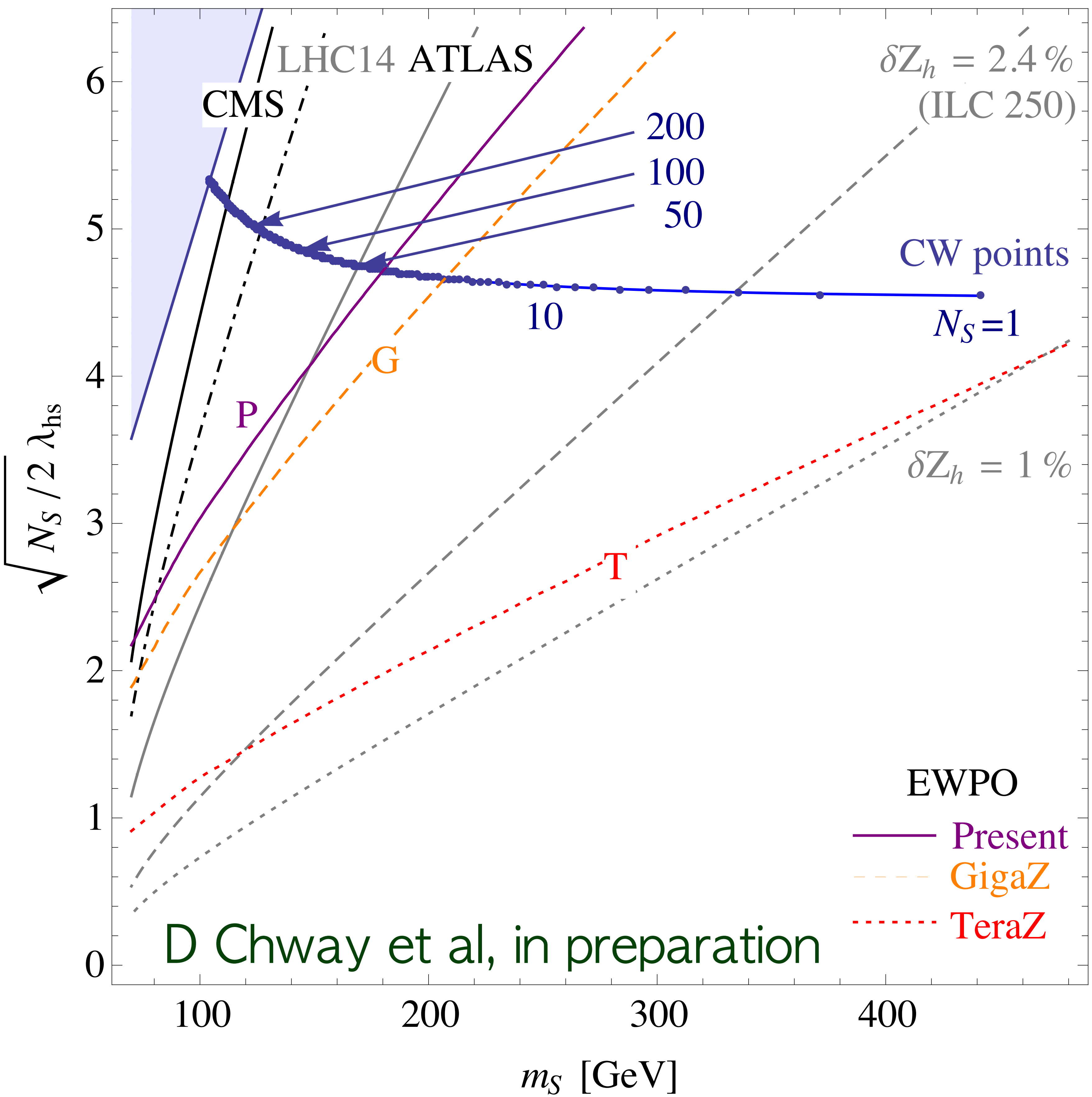
Canonically normalizing $h \to \left(1 - c_H v^2/\Lambda^2\right) h$

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

Coleman-Weinberg Higgs parameter space



D Chway et al, in preparation

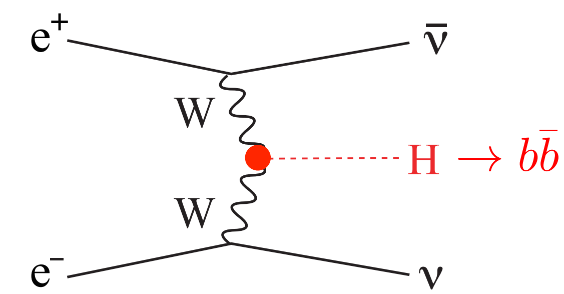
(ii-3) WW-fusion channel & Higgs total width Γ_H

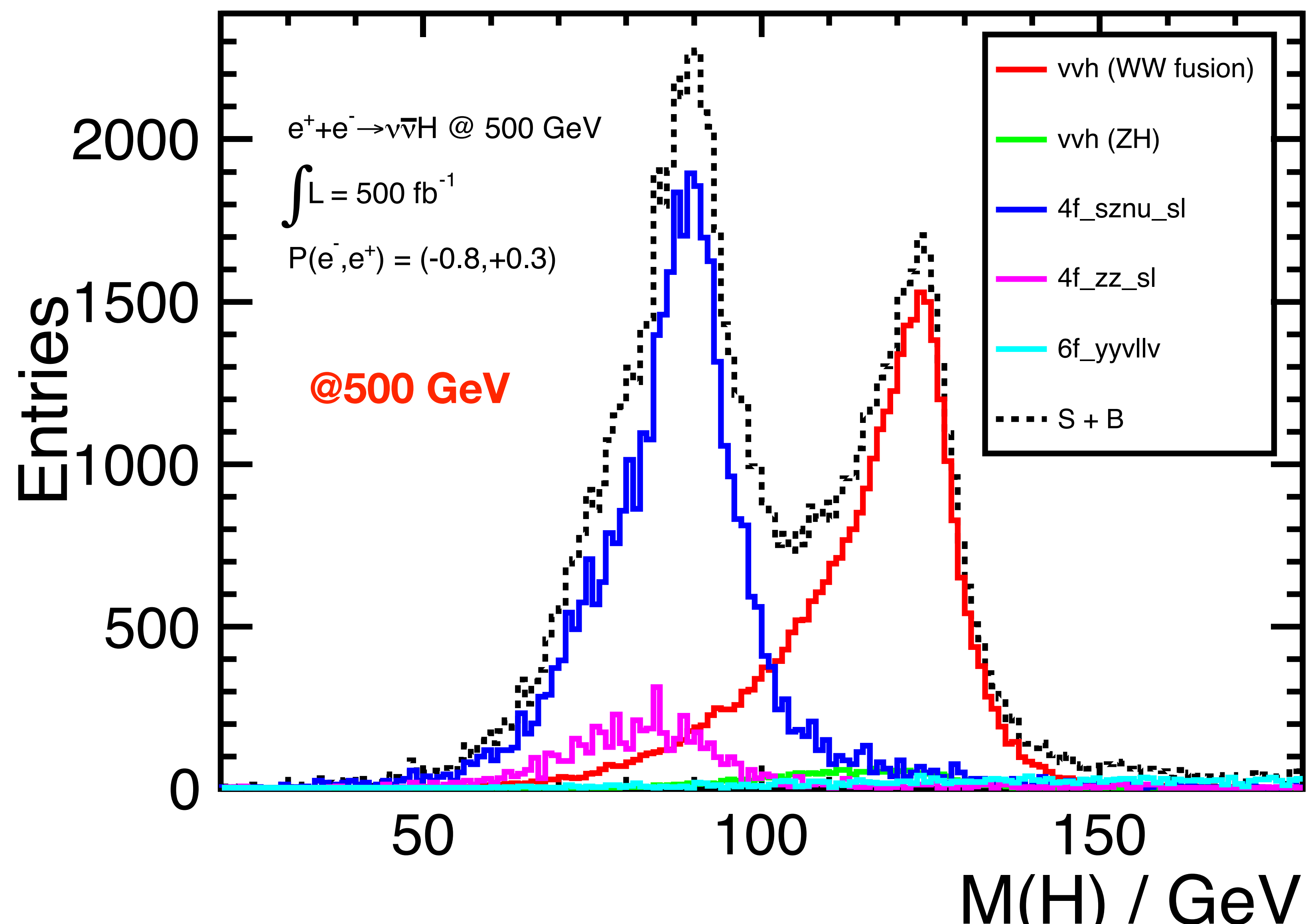
$$\Gamma_H = \frac{\Gamma_{HZZ}}{\mathrm{Br}(H \to ZZ^*)} \propto \frac{g^2_{HZZ}}{\mathrm{Br}(H \to ZZ^*)}$$

—>Br(H->ZZ*) very small

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

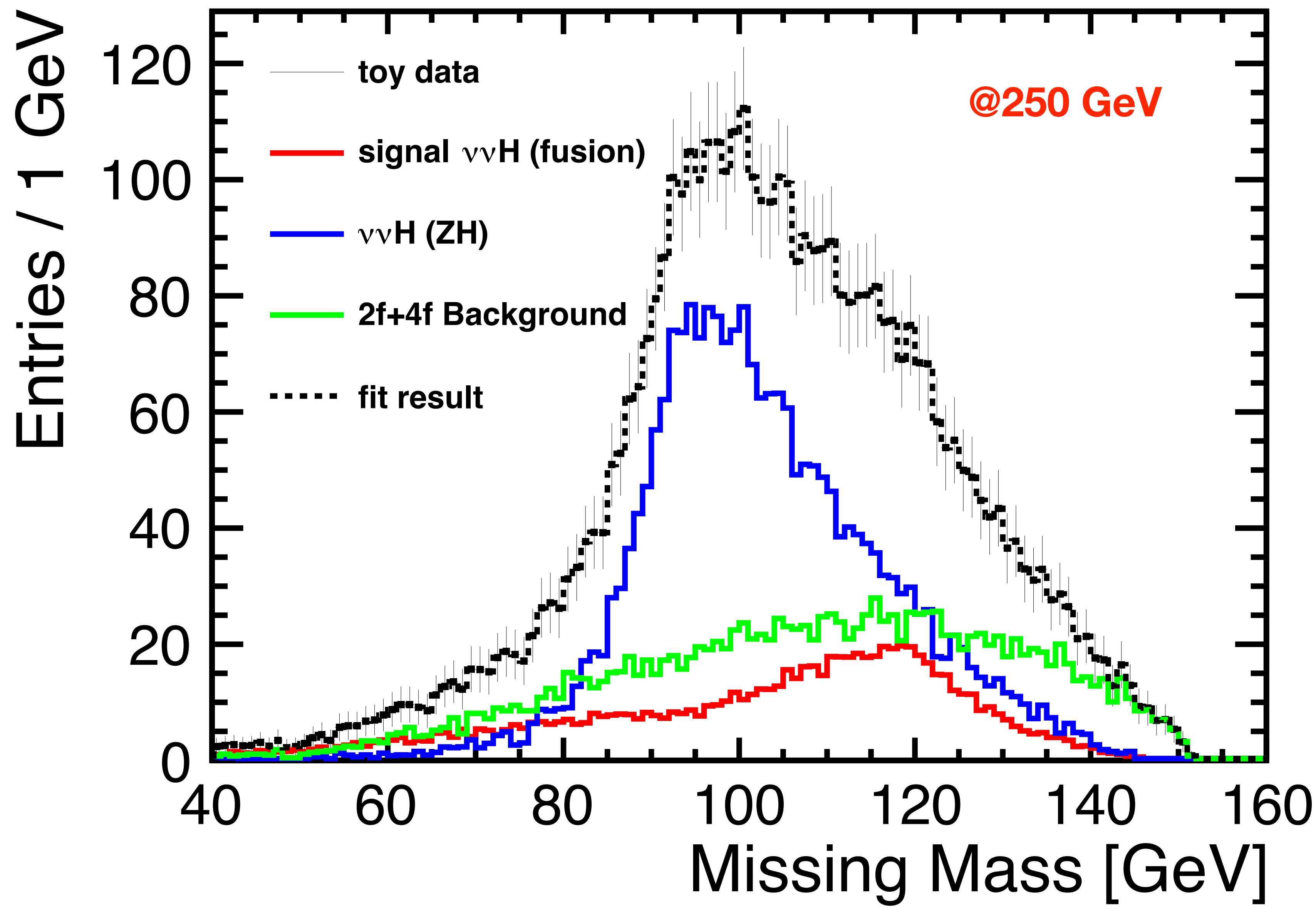
—> better option!

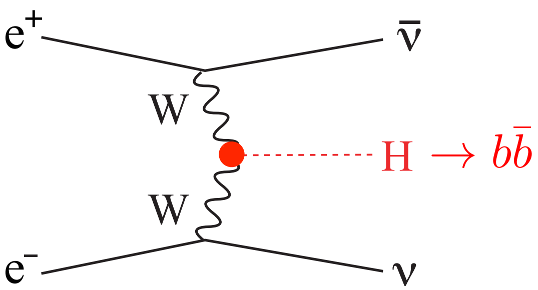




Duerig, et al., arXiv:1403.7734

very different at Ecm=250 GeV





ρ = -34% correlation between

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

(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)

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

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

Jeans et al, 1804.01241

through HZZ/HWW

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

(CP-odd)

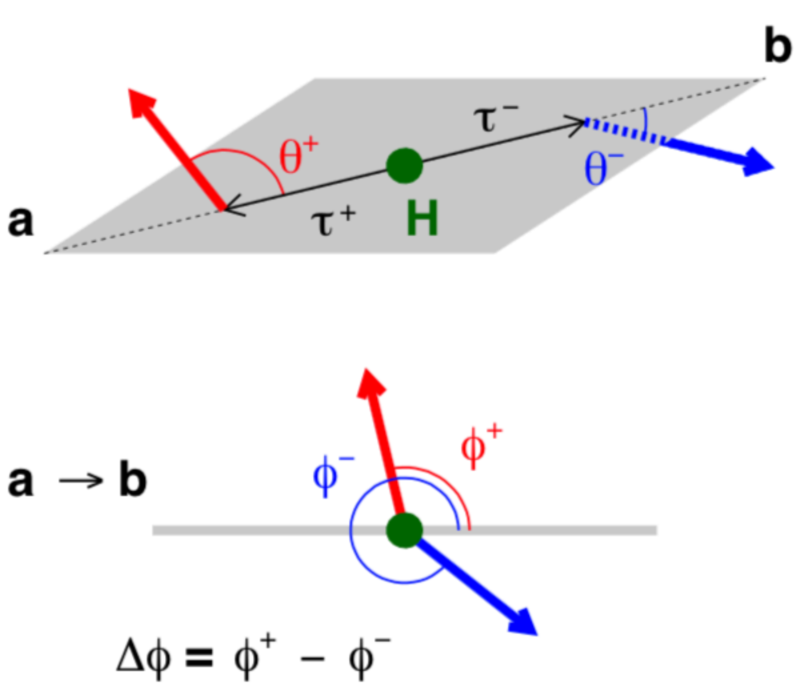
$\Delta\tilde{b} \sim 0.016$ (for Λ=1TeV)

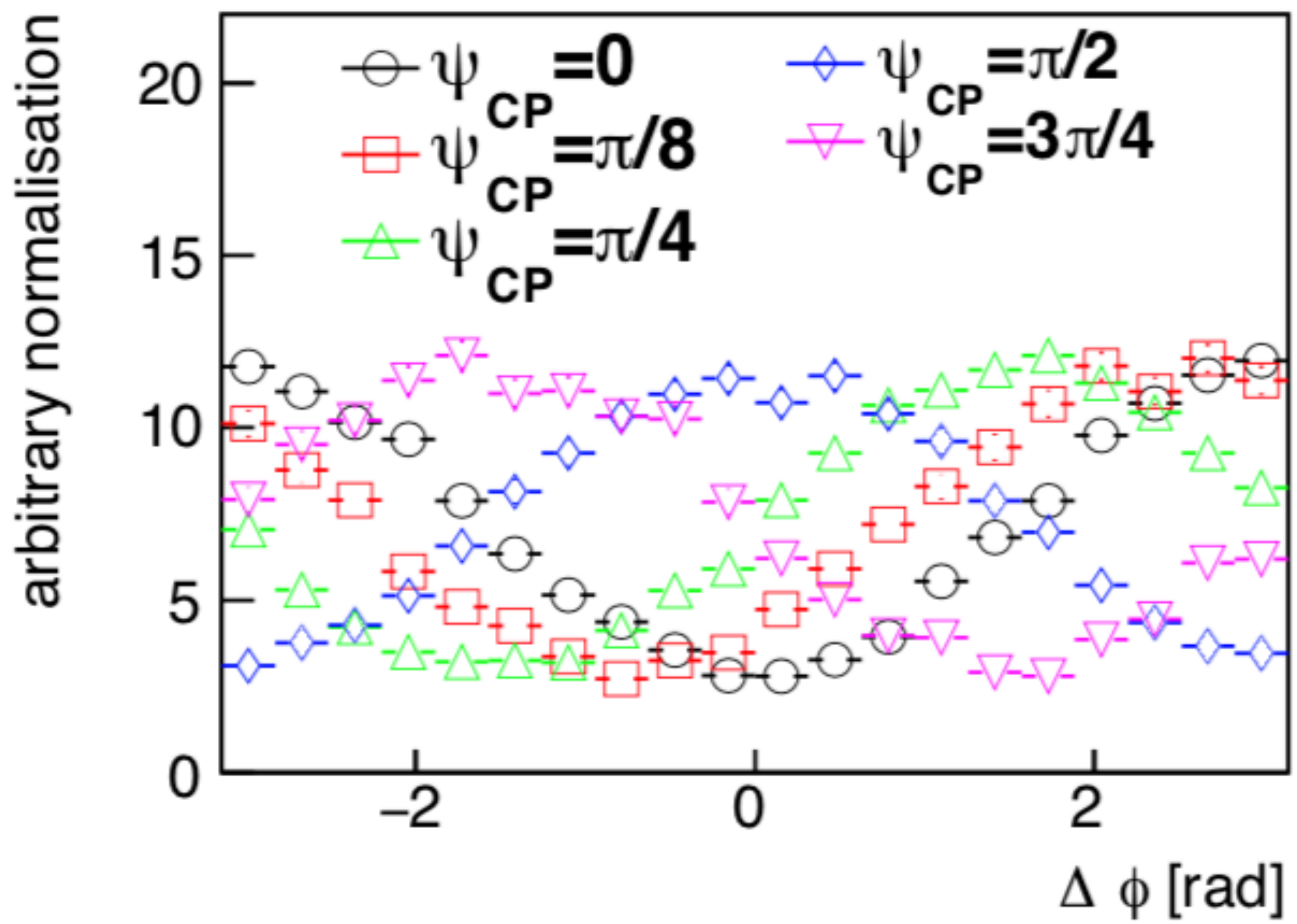
Ogawa, 1712.09772

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

CP sensitive observable in H->τ⁺τ⁻

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



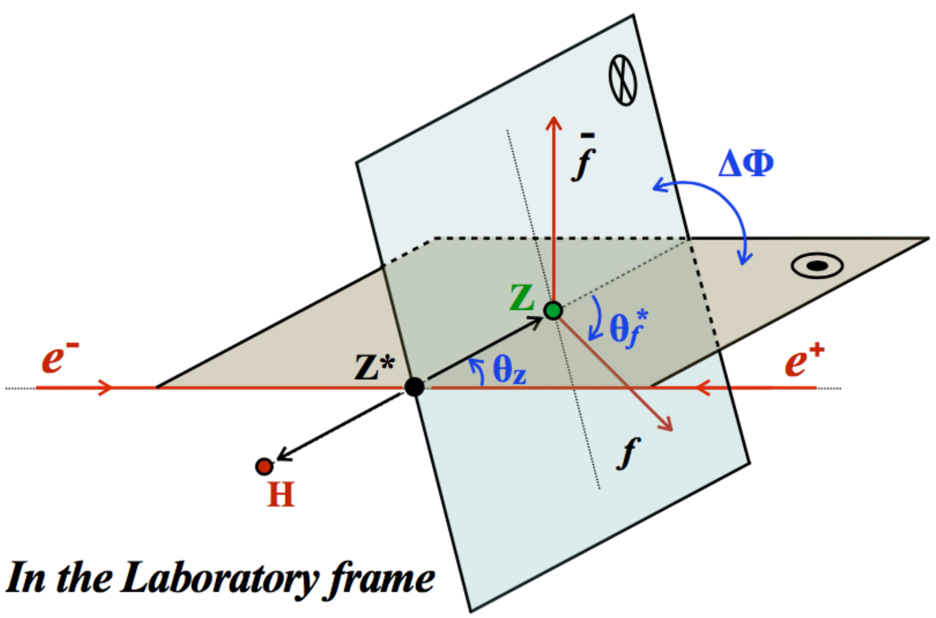


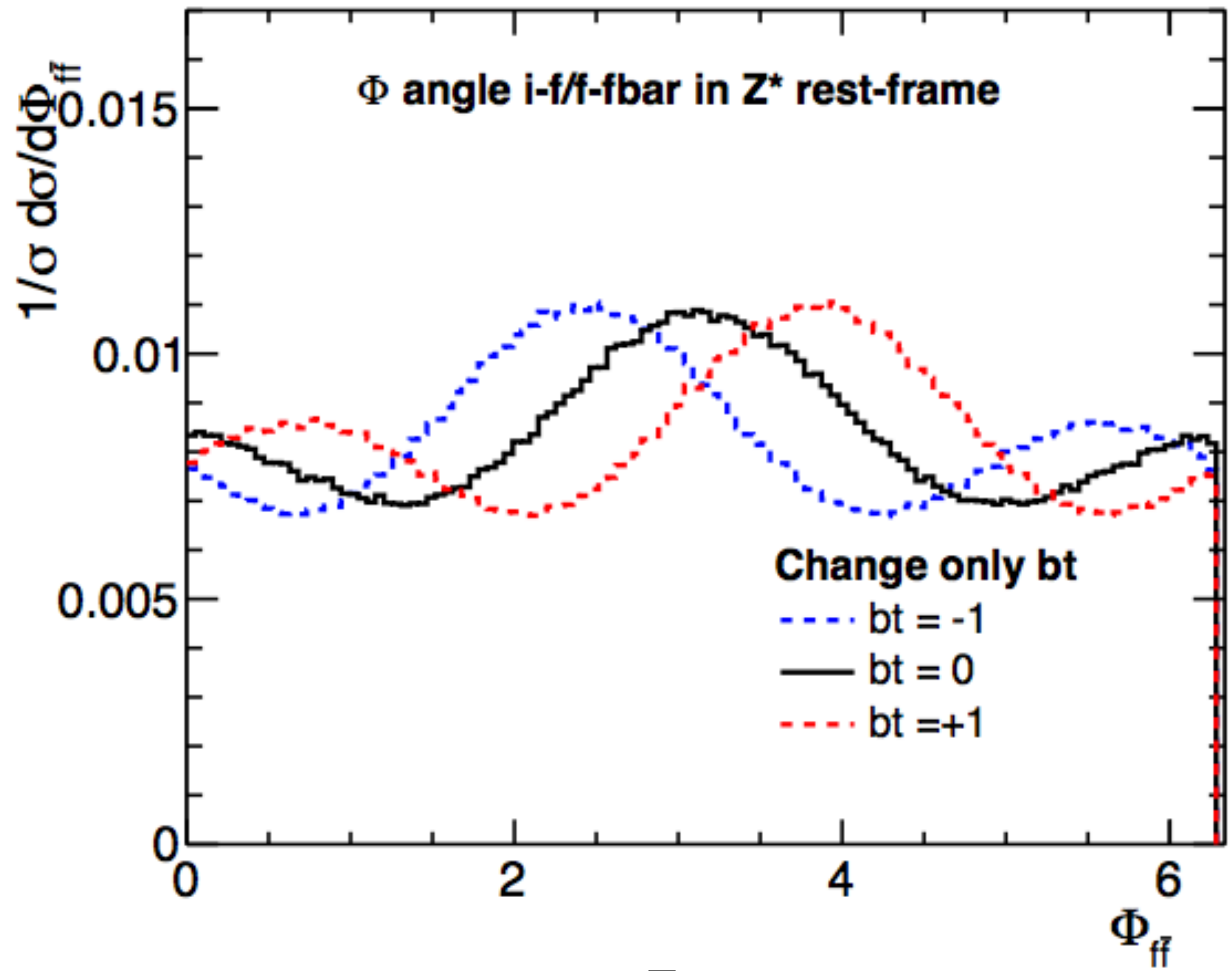
CP sensitive observable in HZZ coupling

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

(CP-odd)

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



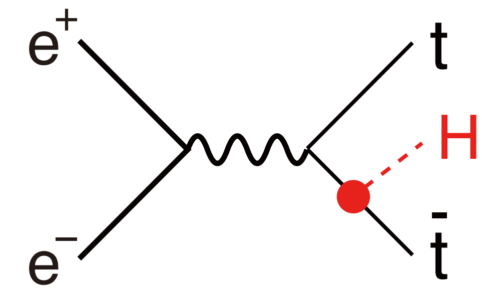


@ $\sqrt{s} = 250\text{GeV}$

Top quark physics

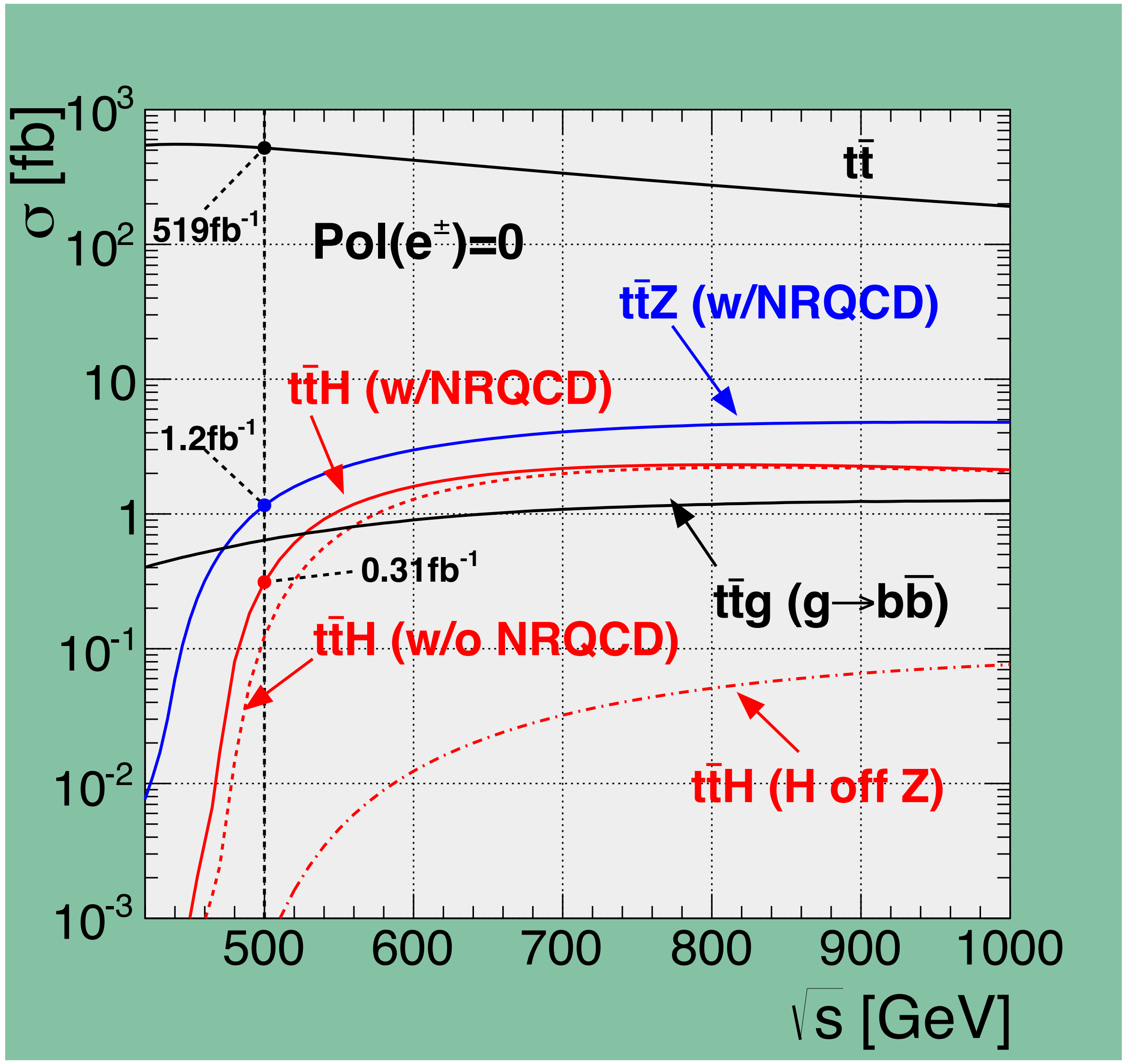
(ii-5) Top-Yukawa coupling

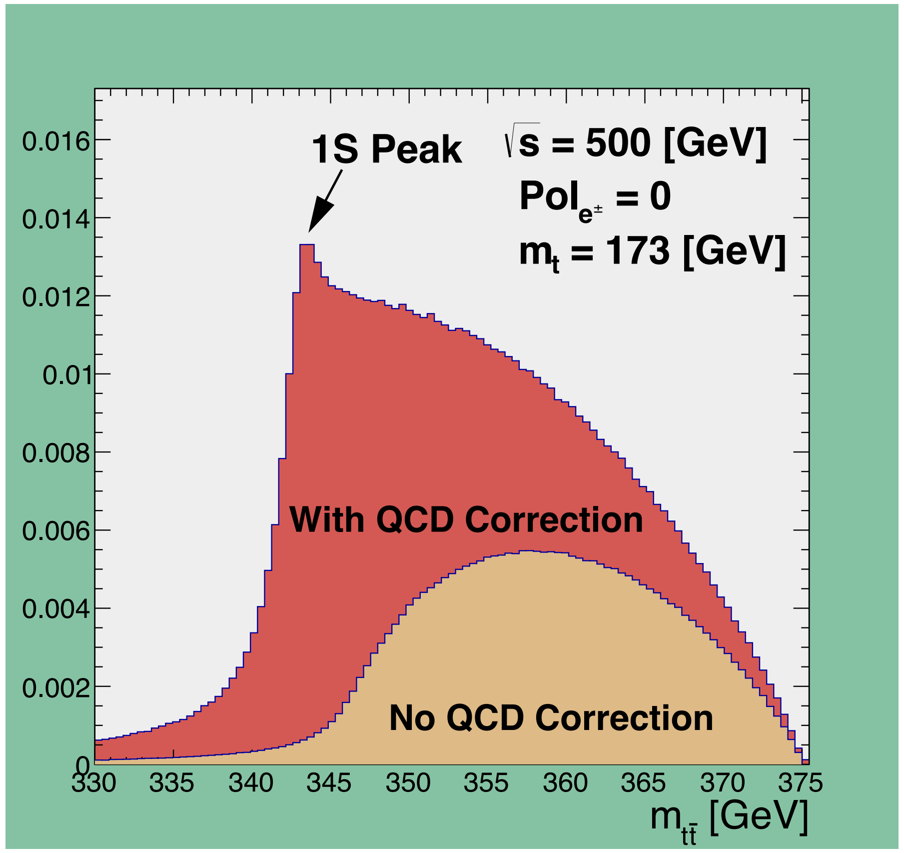
- largest Yukawa coupling; crucial role in theory
- non-relativistic tt-bar bound state correction: enhancement by ~2 at 500 GeV
- Higgs CP measurement



H-> bb

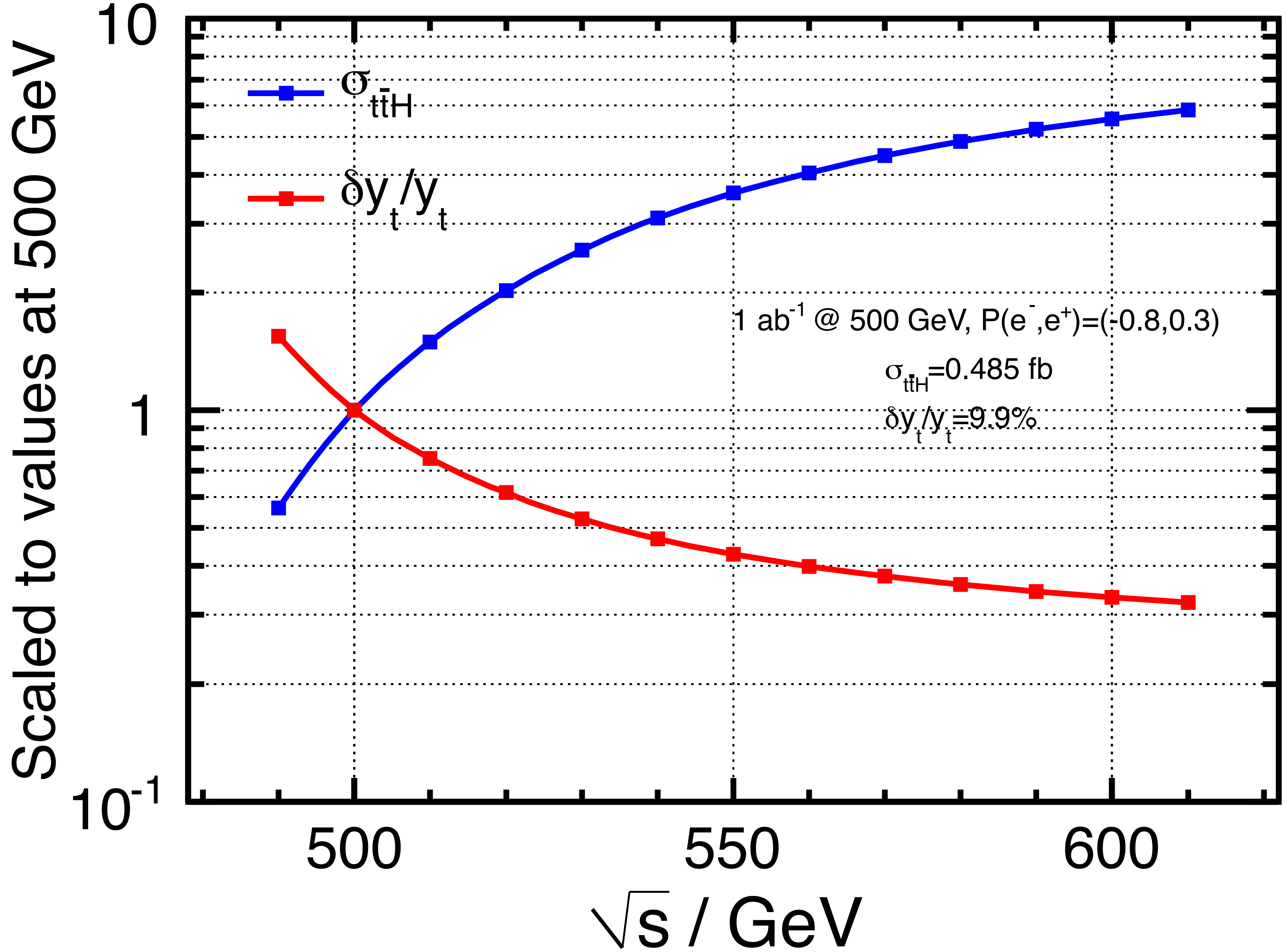
$\Delta g_{ttH}/g_{ttH}$	500 GeV	+ 1 TeV
Snowmass	7.8%	2.0%
H20	6.3%	1.5%





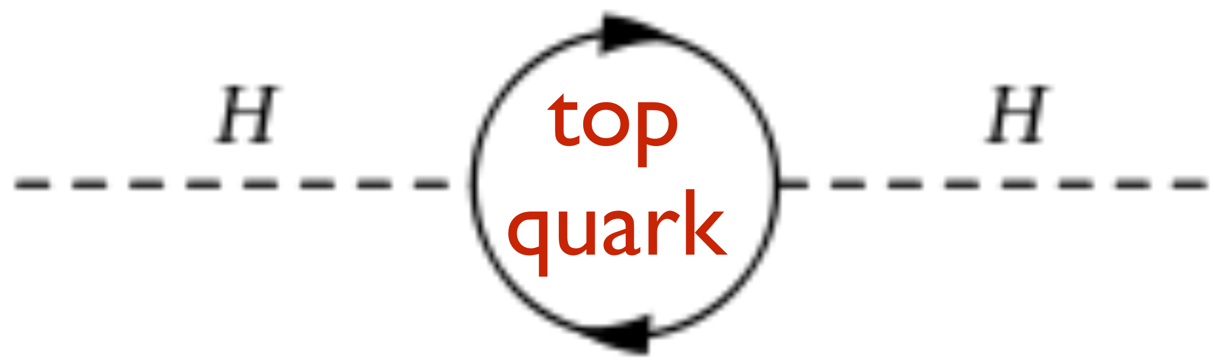
Yonamine, et al., PRD84, 014033;
Price, et al., Eur. Phys. J. C75 (2015) 309

Top-Yukawa coupling



Y. Sudo

Natural(motivated) BSM(Beyond the Standard Model)



should be light

& modifies
Higgs couplings

relevant operator

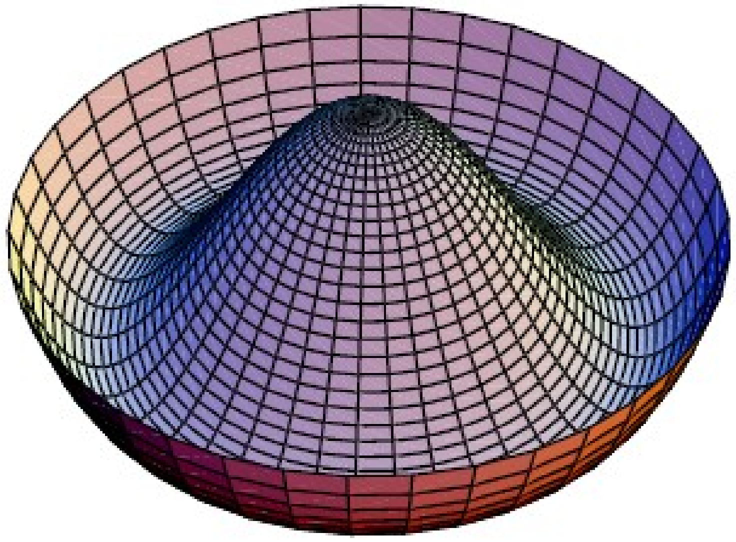
$m^2 H^\dagger H$

Higgs portal

$S^\dagger S H^\dagger H$

difficult to measure
(hardly known)

Fate of the SM



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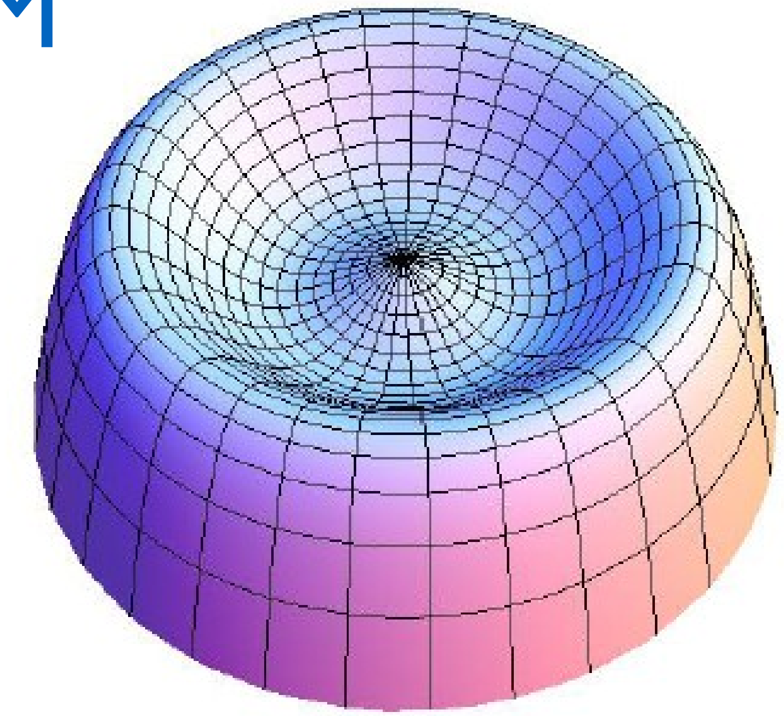
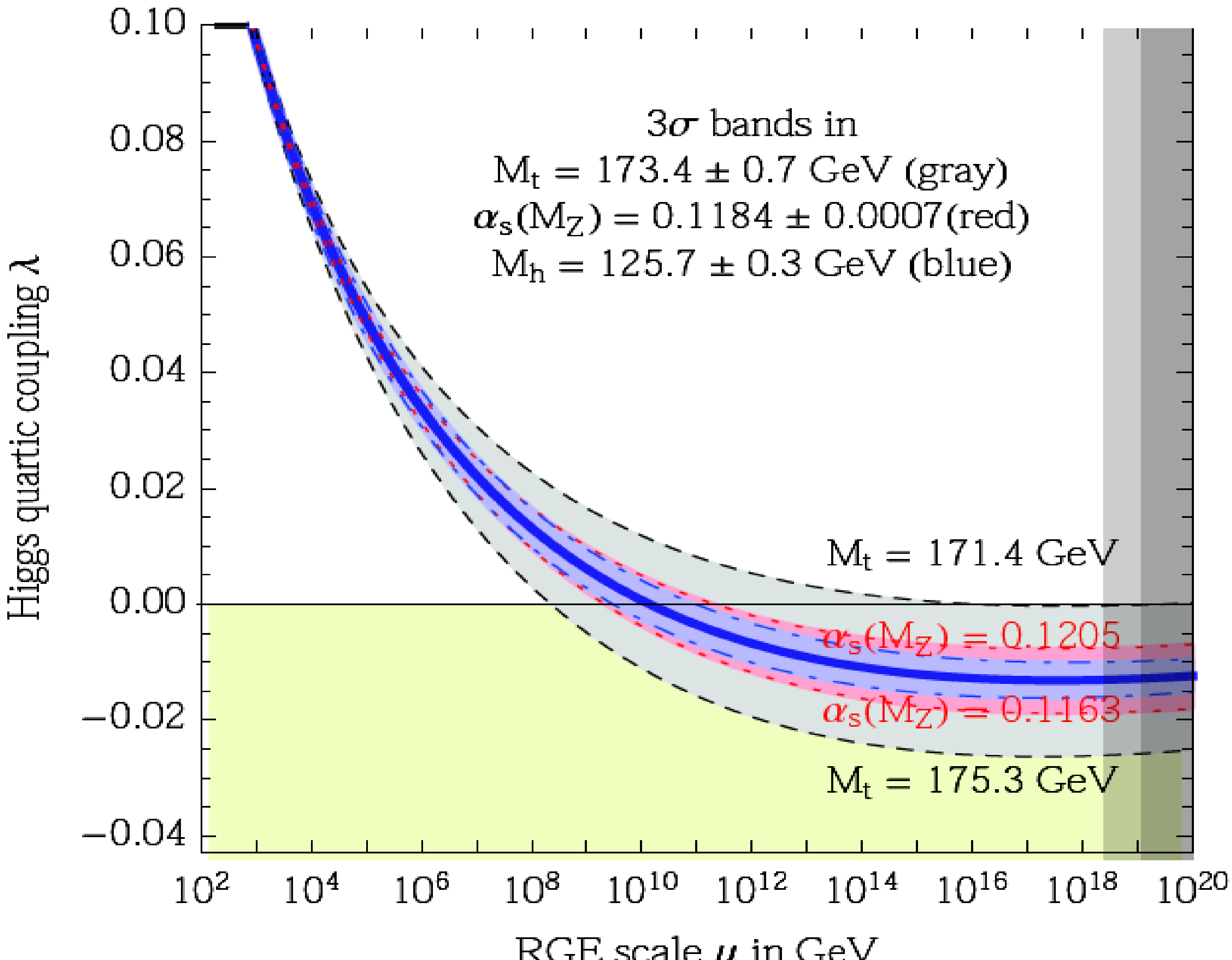
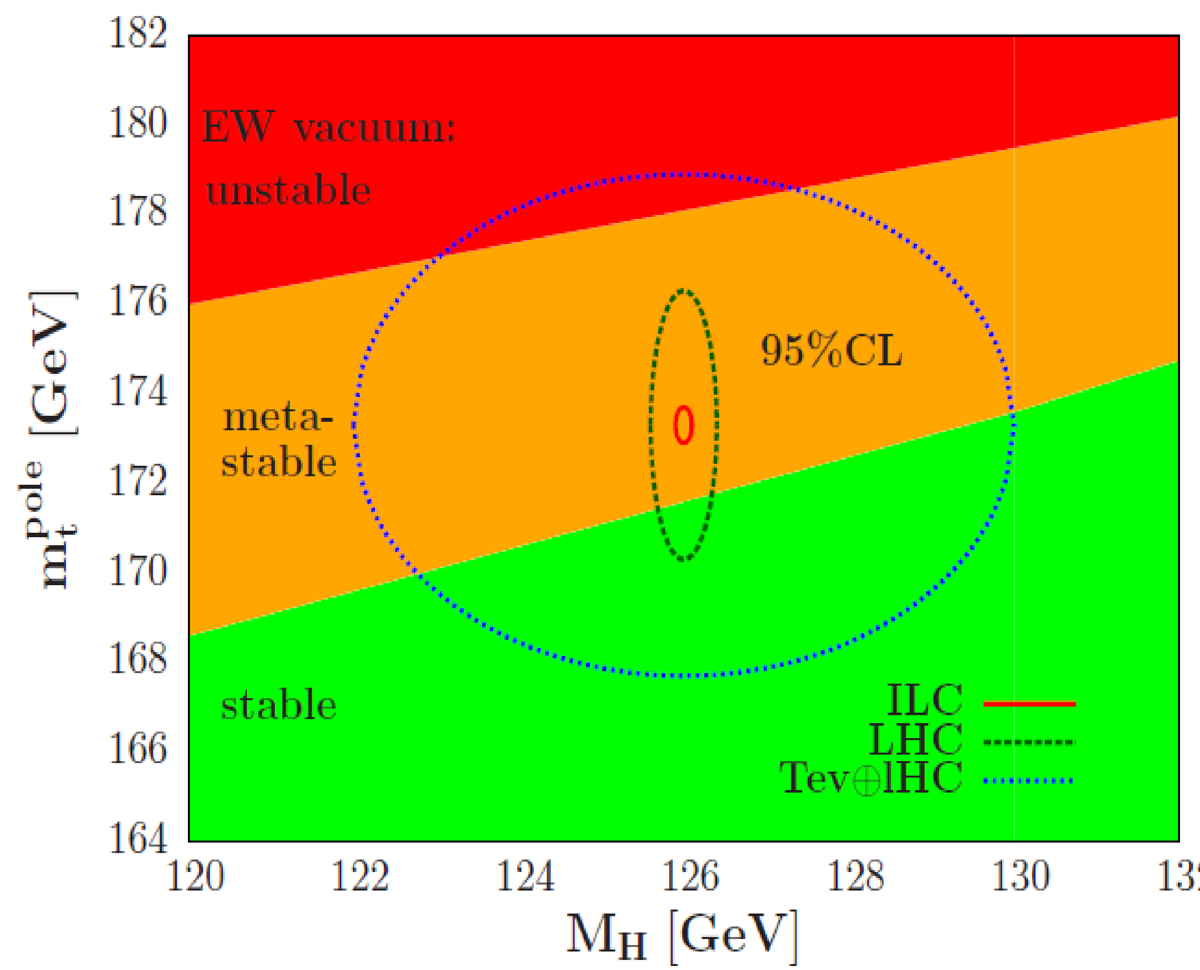


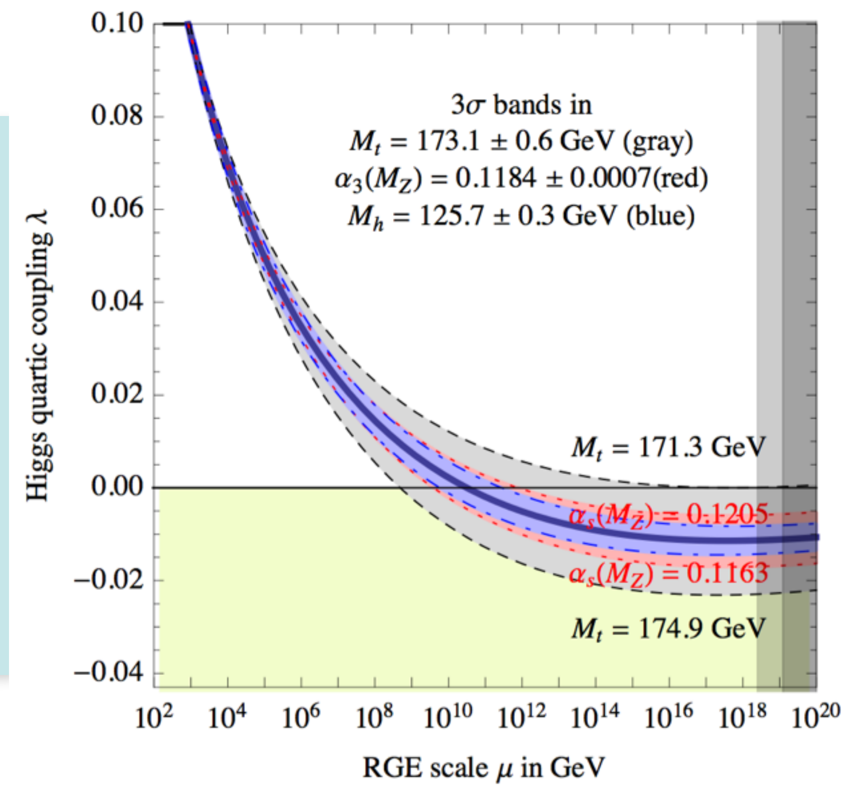


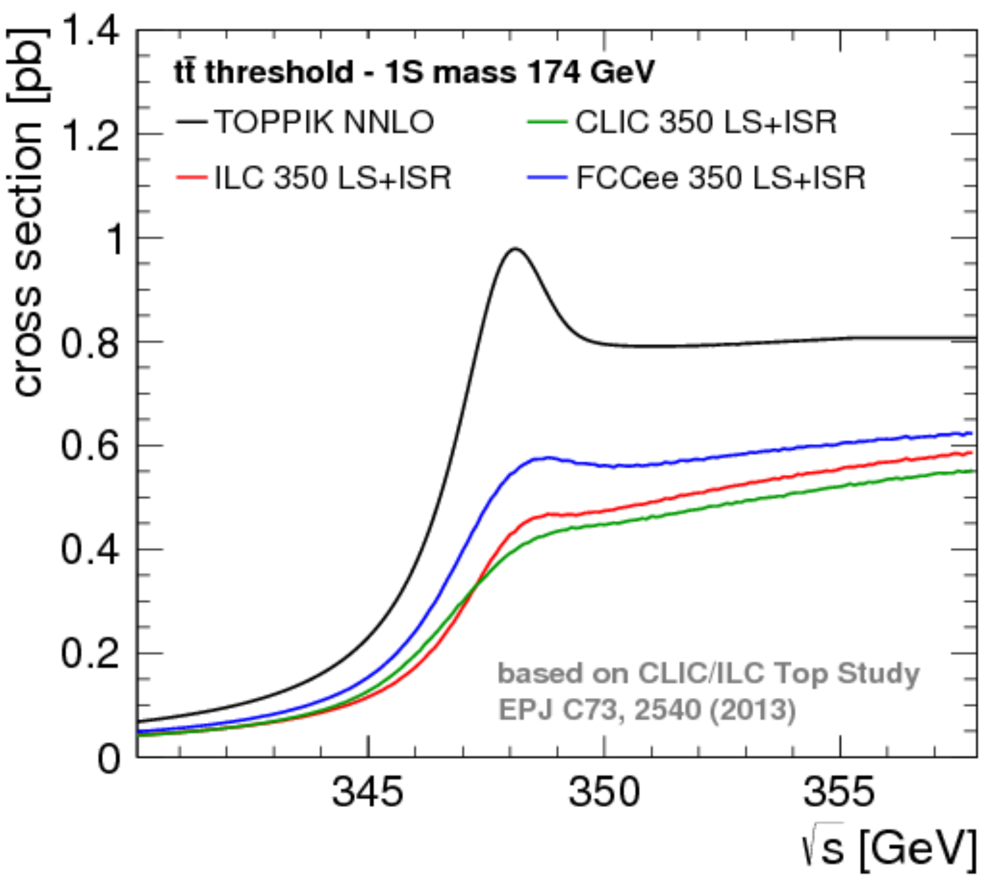


Degrassi

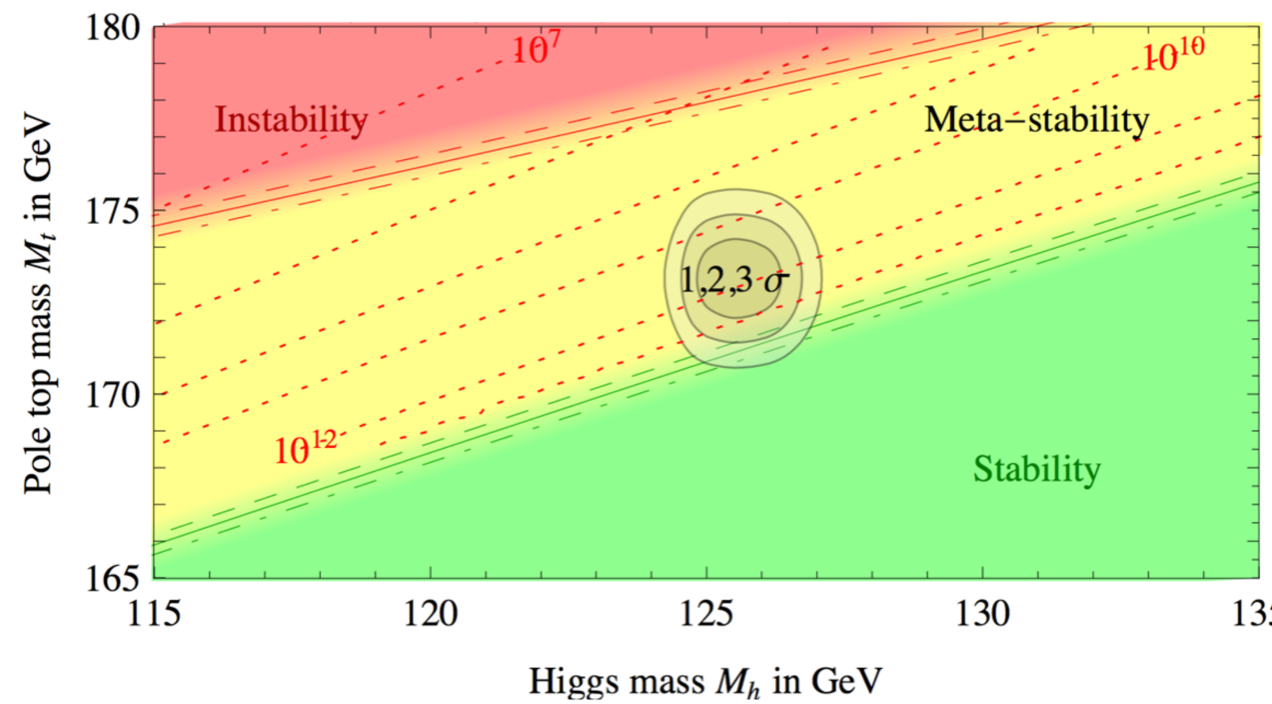
vacuum stability

- 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)

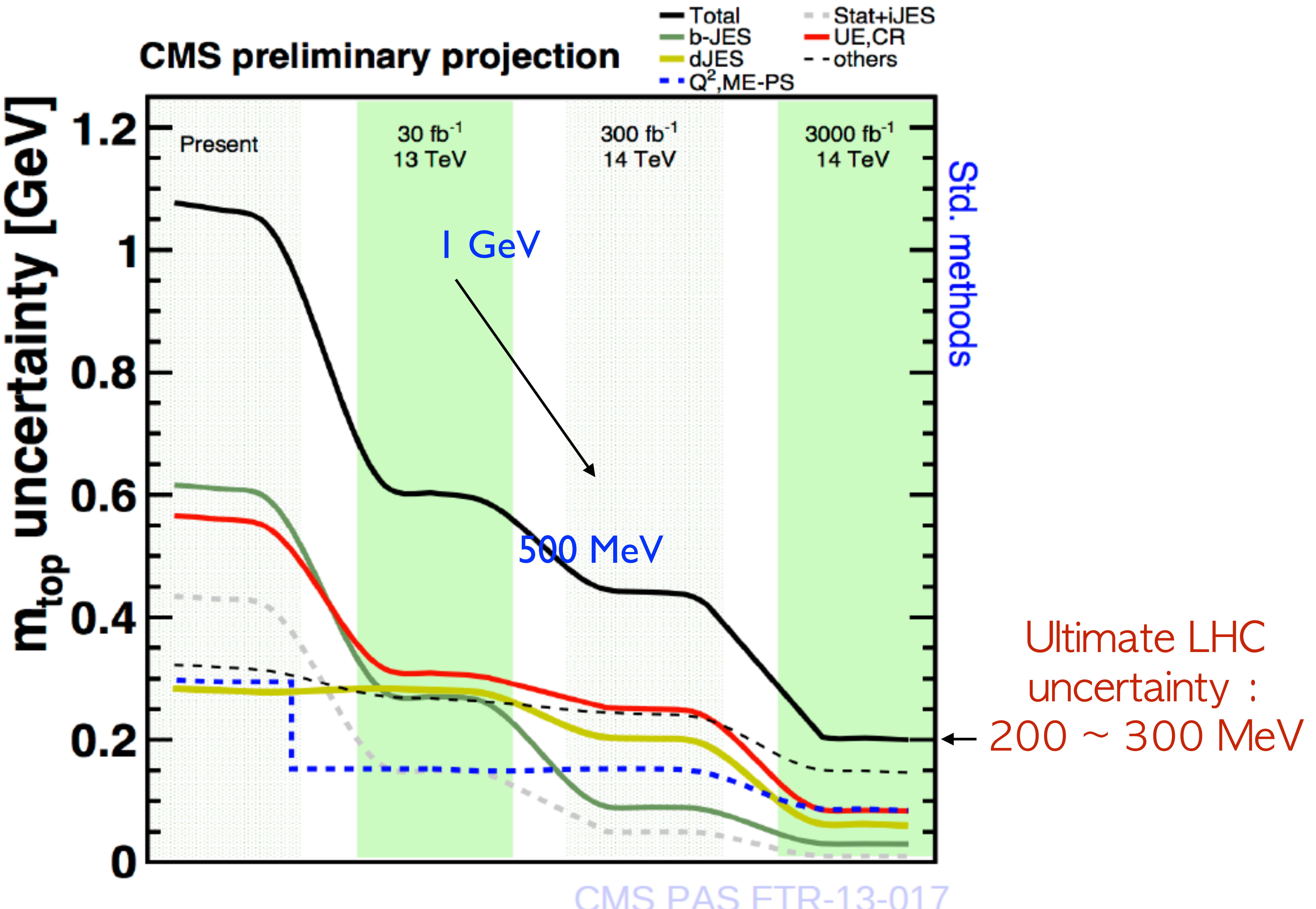




Degrassi et al, JHEP 1208 (2012) 098



CMS top mass uncertainty projection



Combinations of ATLAS & CMS Results

Updated since Moriond 2015!

ATLAS/CMS m_{top} Combinations

Link to ATLAS Top Quark Public Results
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/TopPublicResults

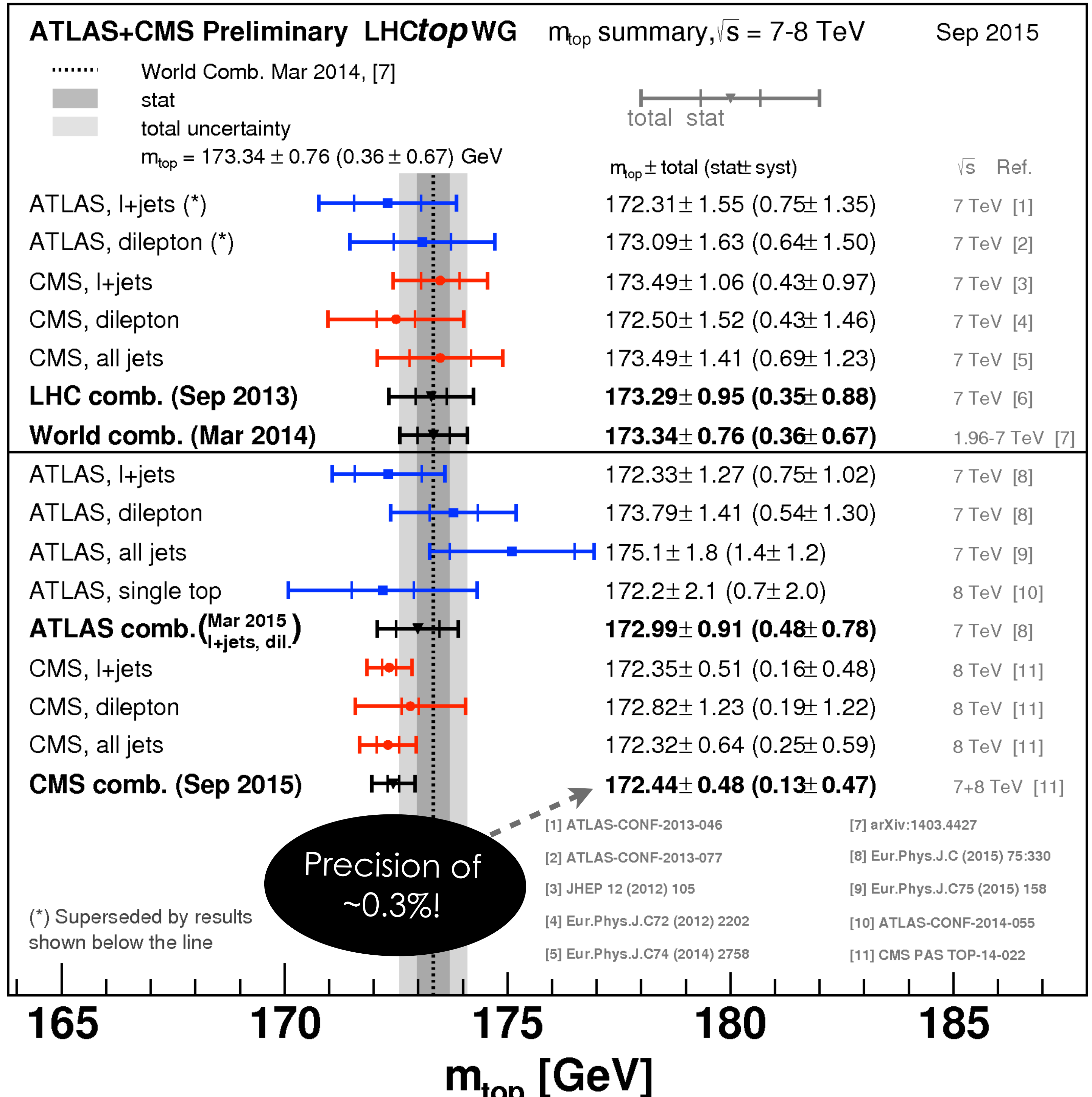
Link to CMS Top Quark Public Results
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsTOP

LHC Combination *($\sqrt{s}$ = 7 TeV)*

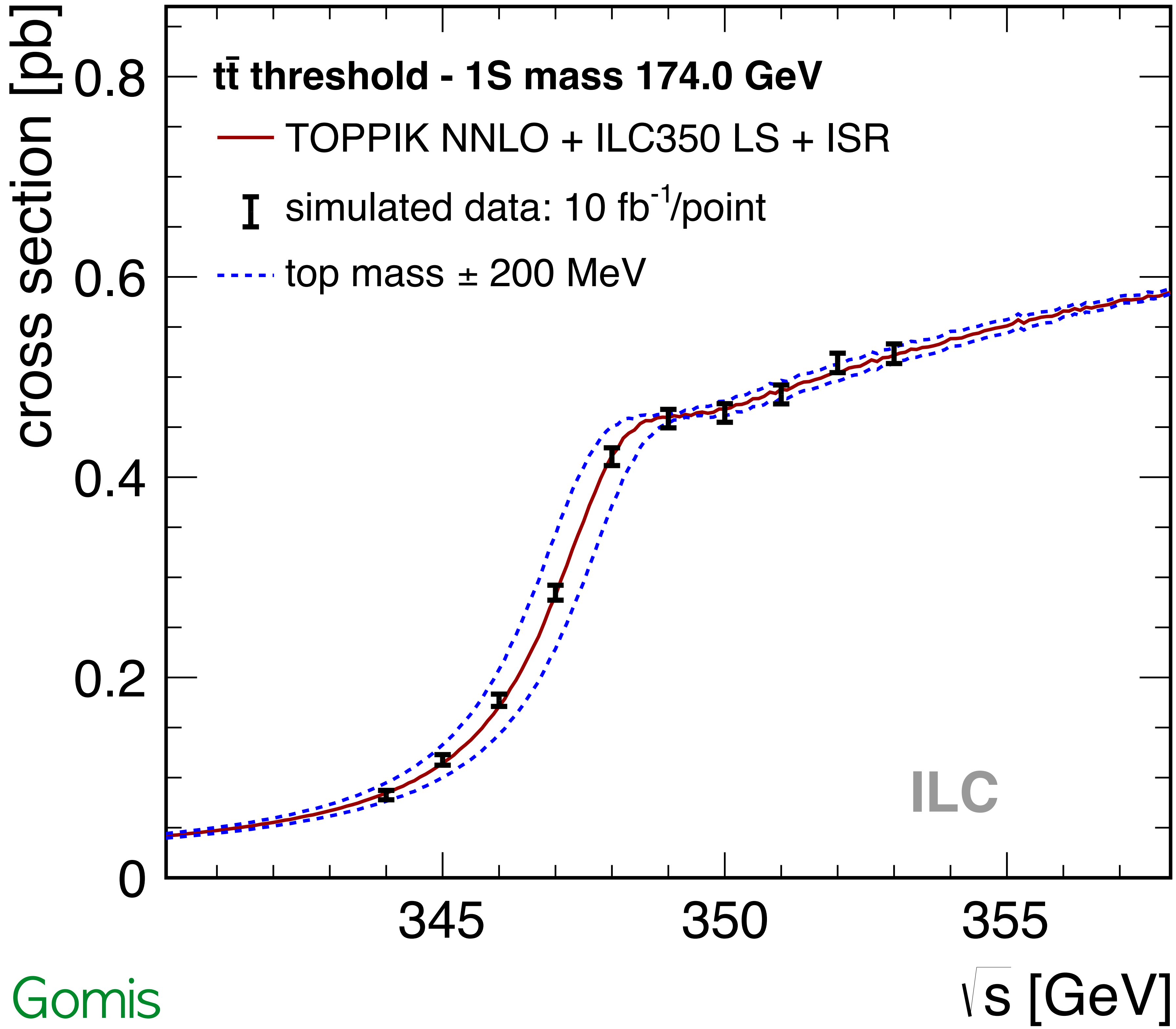
CMS-PAS-TOP-13-005
ATLAS-CONF-2013-102

LHC / Tevatron (World) Combination

CMS-PAS-TOP-13-014
ATLAS-CONF-2014-008
CDF Note 11071
D0 Note 6416



ILC : top mass precision ~ 20 MeV



Talk by P. Gomis

ISR/FSR from the continuum can measure the top mass with 100 MeV to 60 MeV precision

X750

Generic predictions of natural(motivated) models

S couples to top at tree level (order one coupling)
S couples to Higgs at tree level (order one coupling)

$$\mathrm{Br}(S \to \gamma\gamma) \sim (\frac{\alpha}{4\pi})^2 \sim 10^{-6}$$

Note that $\Gamma(S \to gg) \lesssim 1 \text{ GeV}$

Then the cross section to diphoton is too small

$$\sigma(pp \to S \to \gamma\gamma) \lesssim 5 \text{ ab}$$
$$\sigma(pp \to S)\mathrm{Br}(S \to \gamma\gamma)$$

All the examples in the natural(motivated) models have a tuning to cancel order one coupling at tree level

W. D. Goldberger et al for dilaton (RS radion) 0708.1463

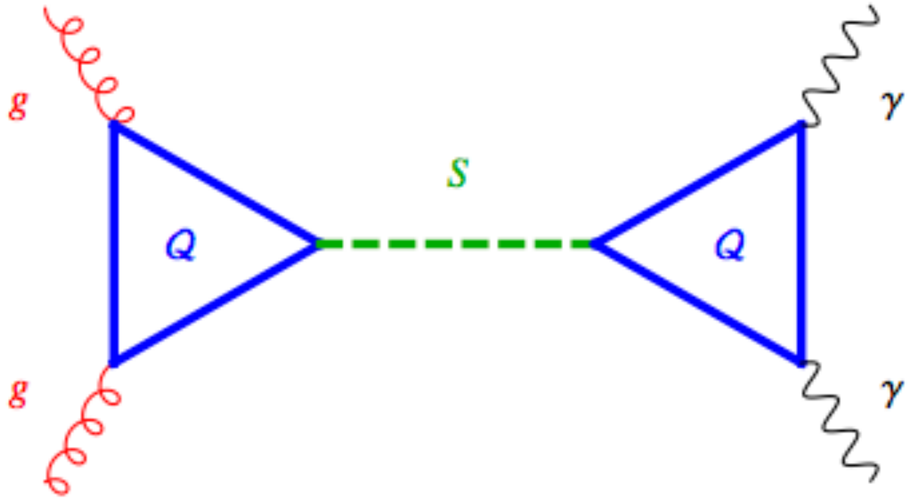
$$\mathcal{L}_{\chi,SM} = \left(\frac{2\bar{\chi}}{f} + \frac{\bar{\chi}^2}{f^2}\right)\left[m_W^2 W_\mu^+ W^{-\mu} + \frac{1}{2} m_Z^2 Z_\mu Z^\mu\right] + \frac{\bar{\chi}}{f}\sum_\psi m_\psi \bar{\psi}\psi, \quad (10)$$

$$\left(\frac{X}{f} + c_i \frac{m_X^2}{f^2}\right) m_i \bar{\psi}_i \psi_i \qquad \left(\frac{2X}{f} + d_i \frac{m_X^2}{f^2}\right) m_i^2 \phi^\dagger \phi$$

explicit breaking of dilatation symmetry

Large correction of the order $\frac{m_X^2}{\Lambda^2}$ is expected for top, Higgs, W and Z with arbitrary order one coefficients c_t, d_h, d_w and d_z.

X750(or S) from extended Higgs sector



S can mix with Higgs $\sin^2\theta_m < 0.12$

ILC precision < 0.01

DM (300 GeV < M < 450 GeV) not possible to discover at the LHC
but possible at the ILC

If two resonances are with a few tens of GeV, PLC would resolve precisely

S as a heavy Higgs in the NMSSM with S to (2 gamma)+(2 gamma) :

Pros and Cons : Is X750 a Signal of New Physics?

Pro

: Diphoton channel is very clean
: Repetition of Higgs discovery
: Both in ATLAS and CMS

If real, X750 would be a tip of the iceberg

Con

: Excess is close to the event tail
: Not in ttbar, jj, ll
: So many 2 sigma bumps in CMS
: Strong coupling is necessary
(cross section*Br is too big)
: No motivated BSM can explain it

We have to wait till summer or the end of the year

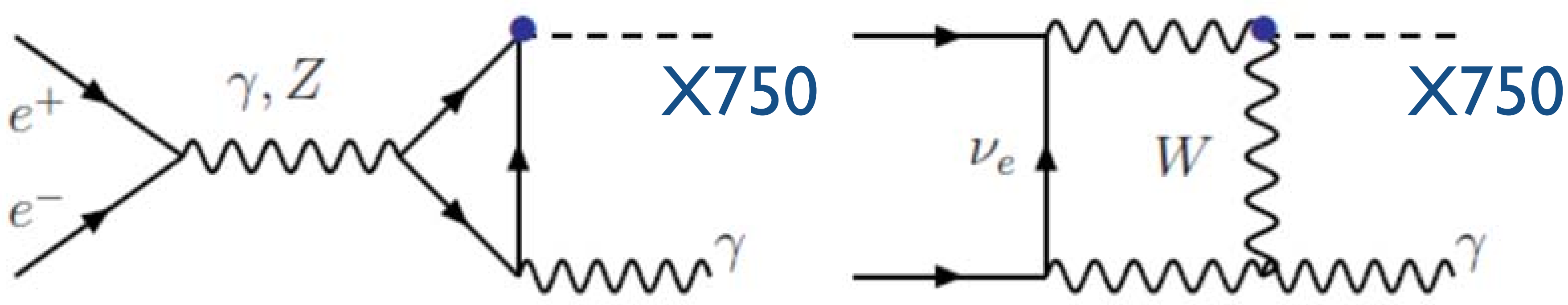
Physics of ambulance chasing

One success in 2012 Dec.
: precursor of Higgs discovery

Many other failures
: Many B physics anomalies
Tevatron W+dijet,
dimuon charge asymmetry,
top A_FB,
DAMA/LIBRA,
CoGeNT,
PAMELA,
140 GeV Higgs (WW*)
BICEP2

1 TeV ILC (optional)

S (X750) production at 1 TeV ILC



Talk by F. Richard

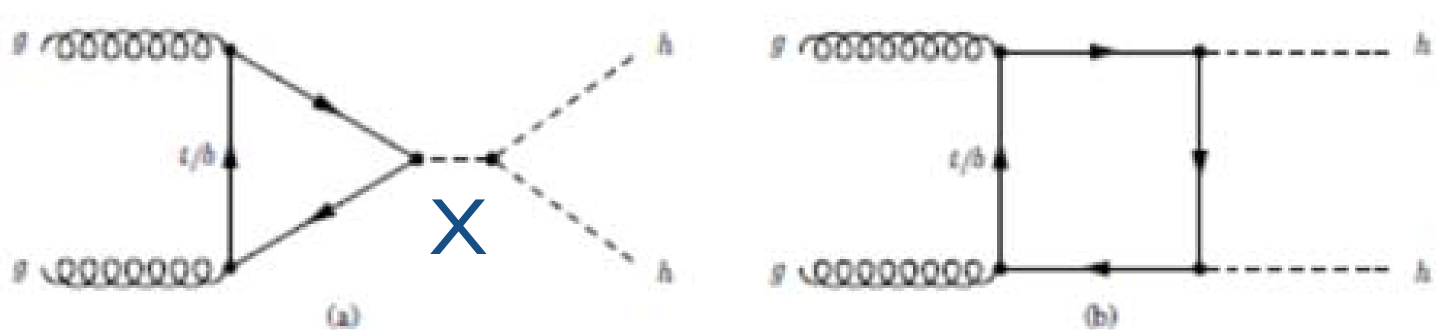
Associated production : e+e- to Z*/gamma* to S Z/gamma ~100 ab
(monochromatic Z and/or gamma)

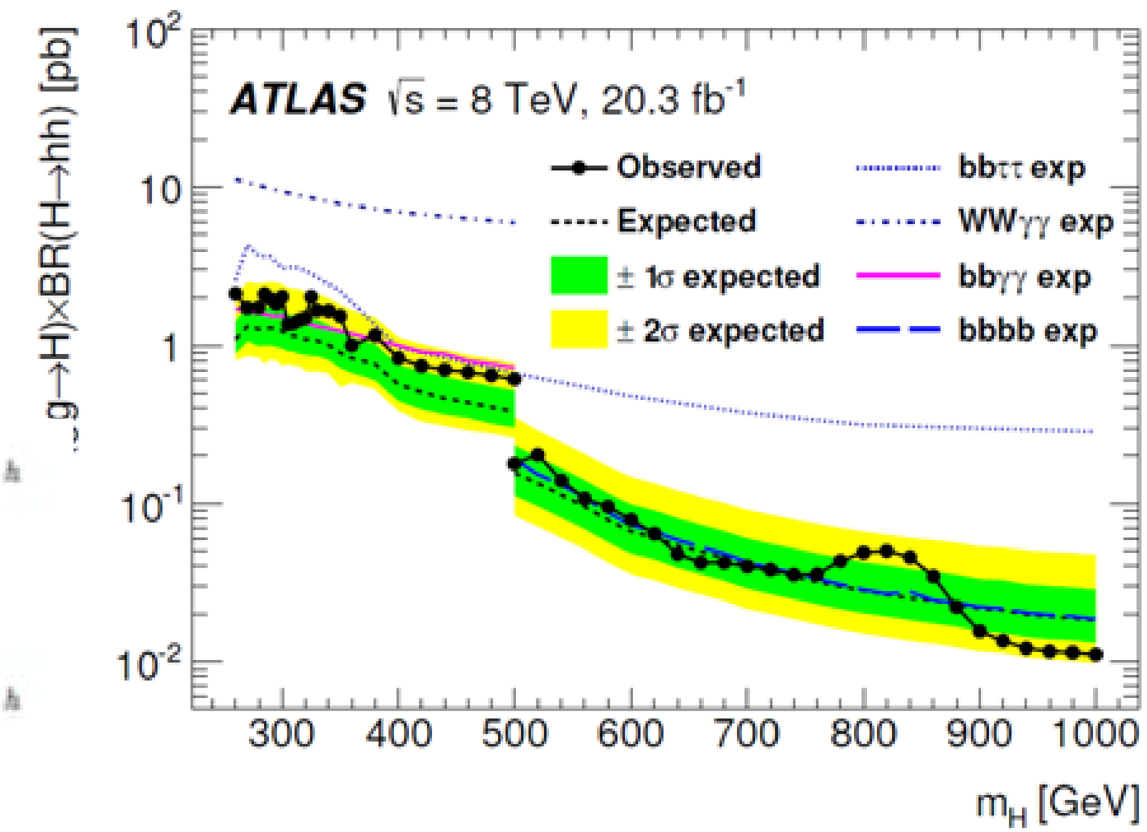
Vector boson fusion : e+e- to ee S or nunu S ~100 ab
(P_T~mW, forward e+,e-) (forward e : 10 ~ 1ab)

X750 to jj, tt, WW, ZZ (iceberg)

X750 to hh (iceberg)

many new particles (iceberg)

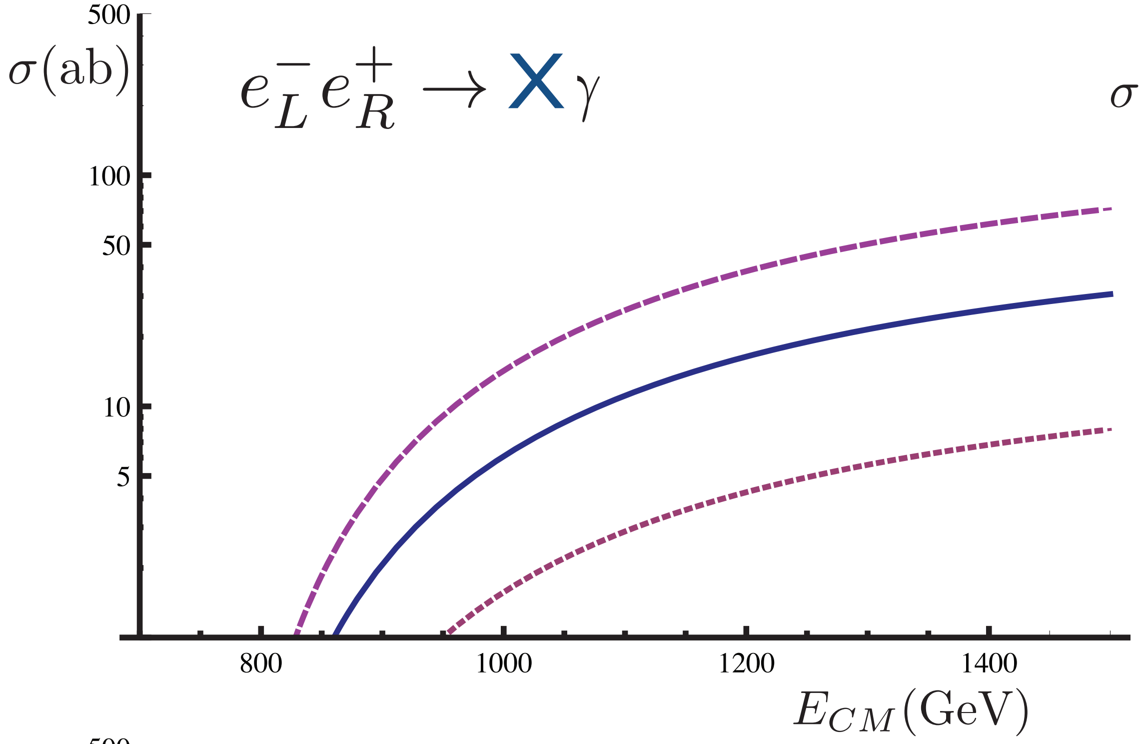


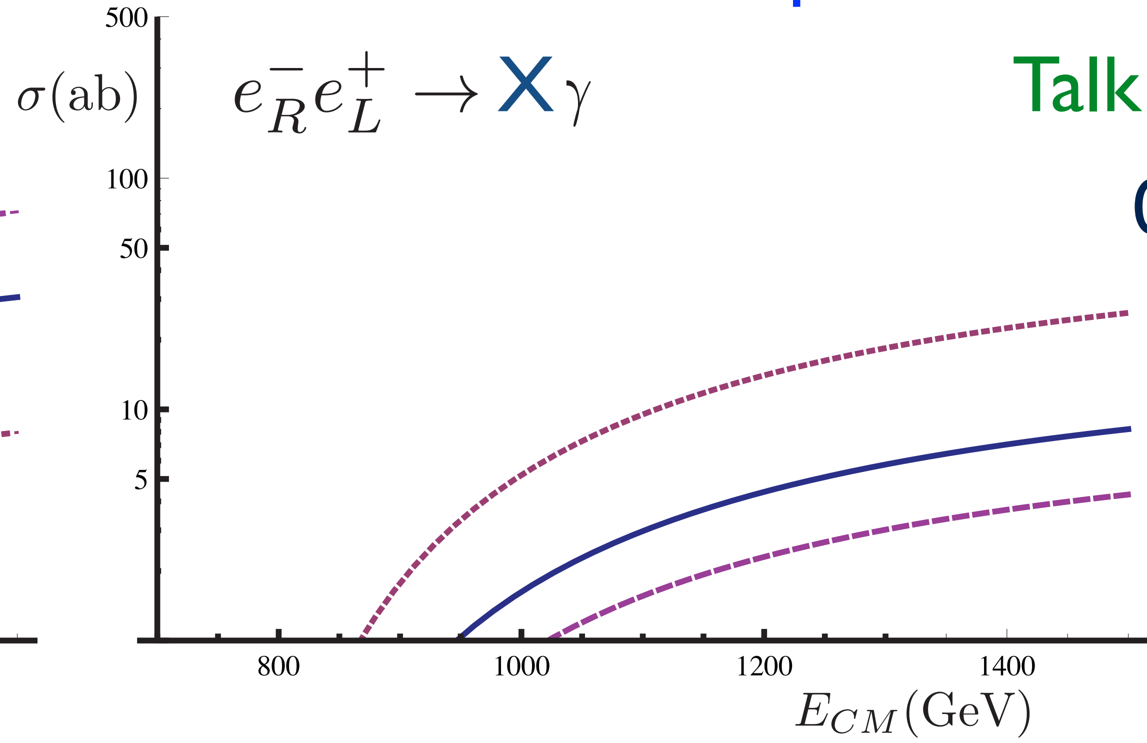


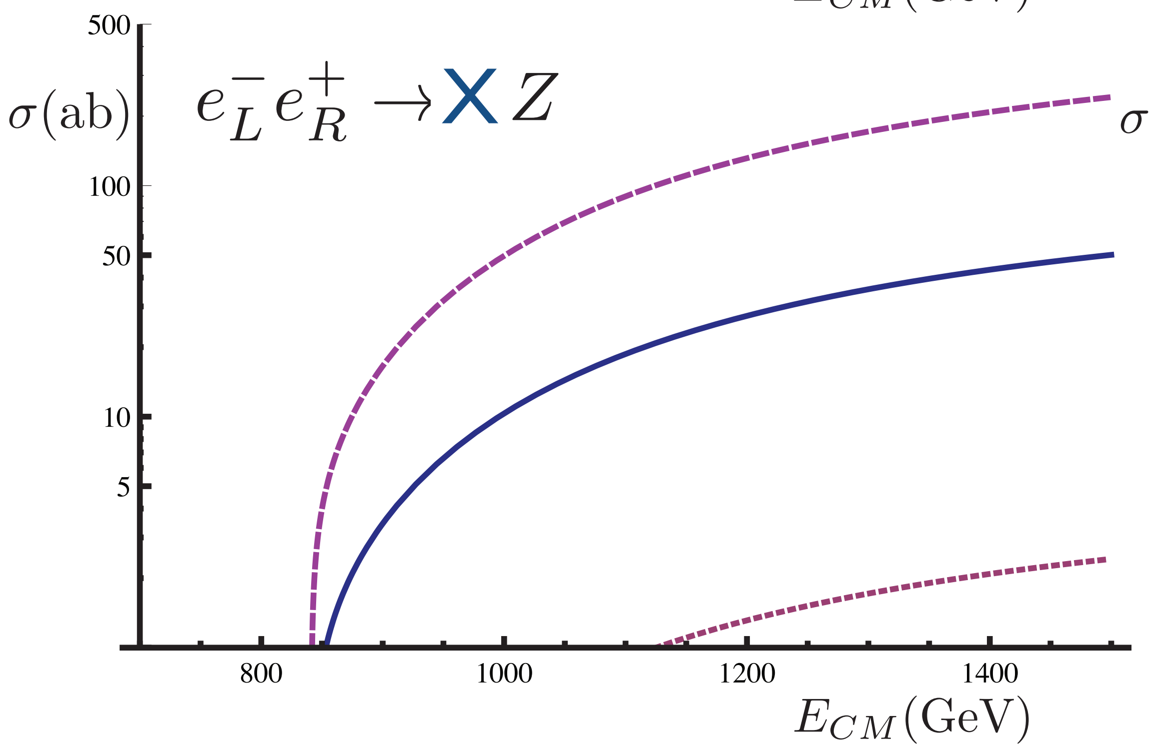
S production at 1 TeV ILC

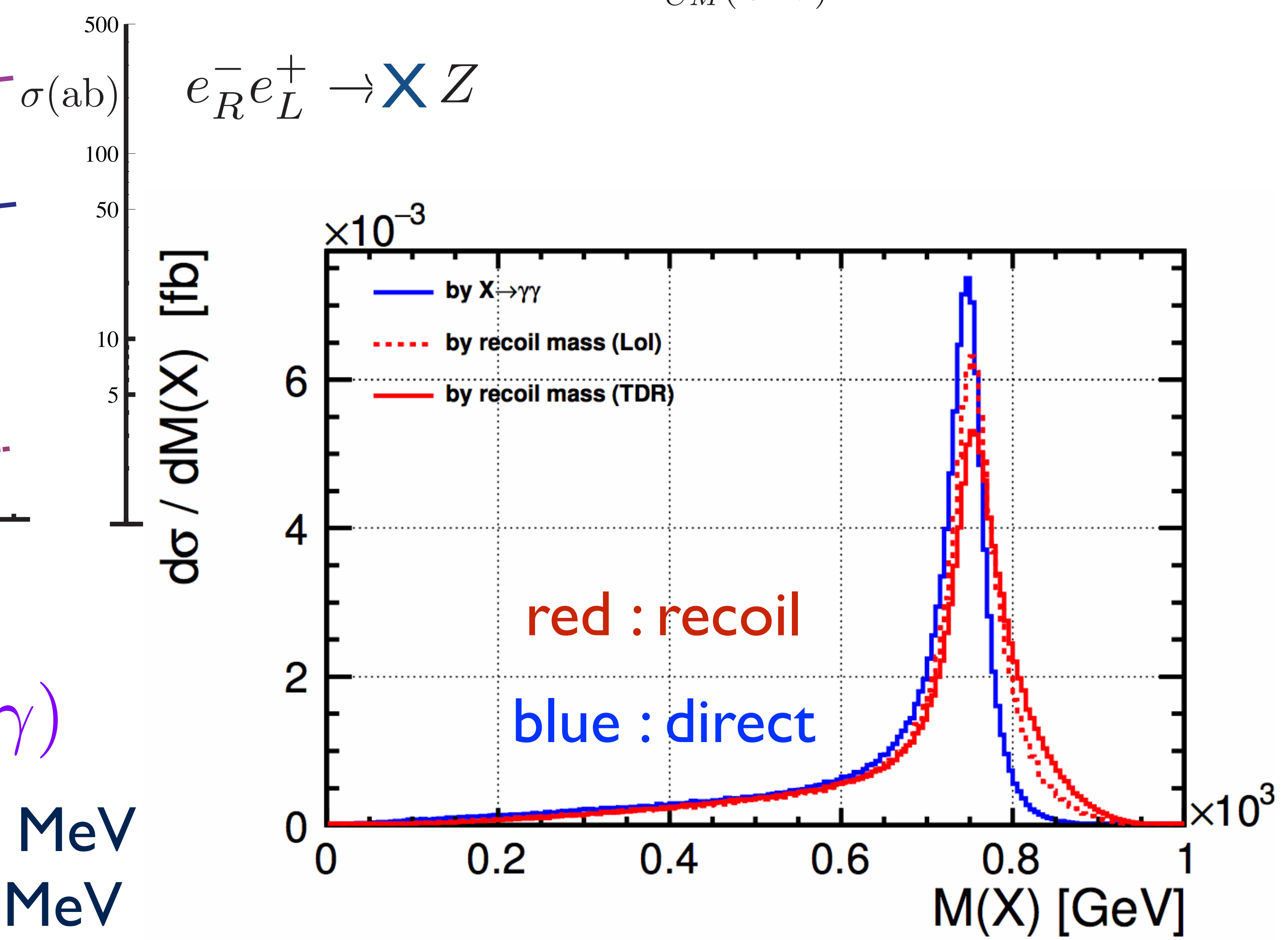
Talk by F. Richard

0.1 fb or less









Talk by J.Tian

$\Gamma(X \to \gamma\gamma)$

discover : 25 MeV

2 sigma : 10 MeV

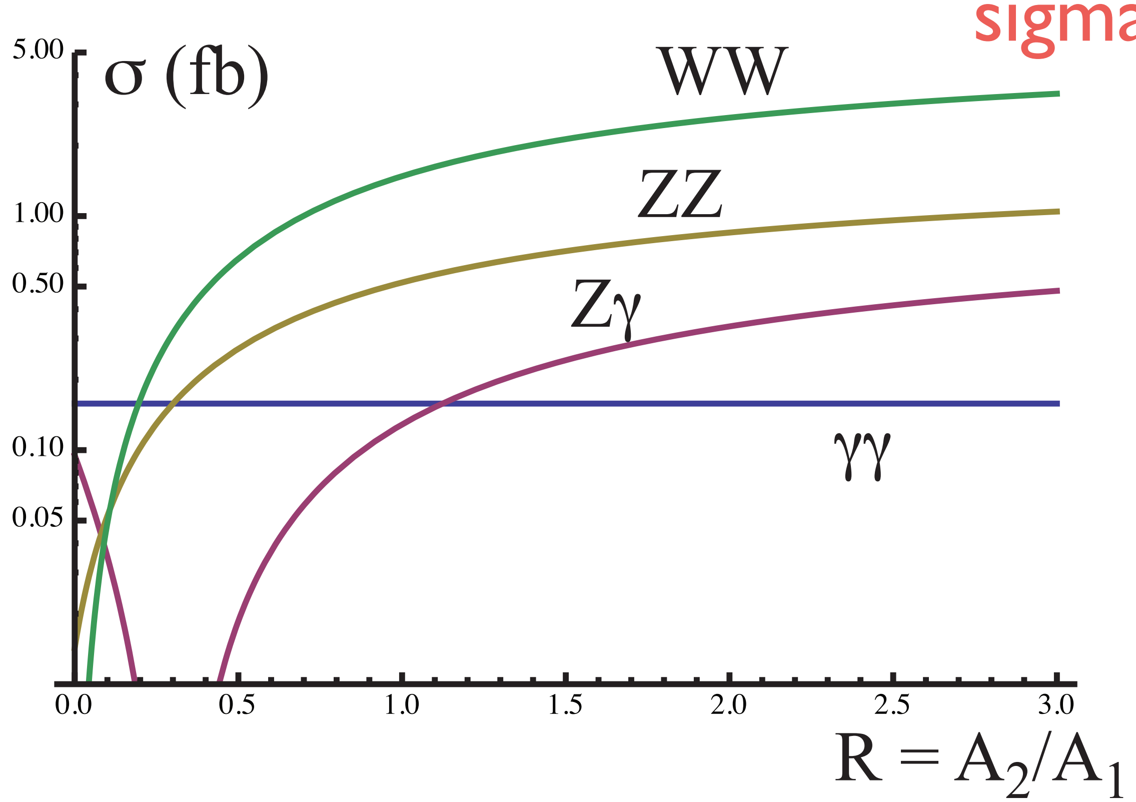
S production at 1 TeV photon linear collider

gamma gamma to S

Talk by F. Richard

Compton backscattering of laser beams from the electron beams

sigma_eff (S to gg) ~16 fb



beam crossing angle (ILC TDR) : 14 mrad

25 mrad needed for Compton backscattering and beam dump

can be done during energy upgrade

or can start from 20 mrad from the beginning

Talk by F. Richard

	$qq+gg$	bb	tt	$\tau\tau$	$ee+\mu\mu$	$\gamma\gamma$	$Z\gamma$	ZZ	hh	WW	Zh
σ (fb)	9	0.3	100	34	6	0.5	5	12	1	700	0.03
$BR\ 5\sigma$	2%	0.3%	6%	3%	1%	0.4%	1%	2%	0.6%	15%	0.1%

Table 3: Standard Model background cross sections for the observation of Φ decays at a PLC. The second line gives the braching ratio, relative to $BR(\Phi \to gg)$, for a 5 σ observation with a 3 ab^{-1} data set.

Mass of S from recoil of gamma and Z
and also directly from gamma gamma and glue glue

Spin, CP of S from angular distribution of S production and decay

Total decay rate from S to VV and Br(S to VV)

Conclusion

Who ordered X750?

If it is real, huge structure related to EW symmetry breaking will follow.

500 GeV ILC would be complementary to discriminate
various models explaining the structure discovered at the LHC.

Dark matter, vector-like fermions can be directly probed at the ILC.

Currently X750 does not play a role connected to EWSB.

We expect new particles (top friends) at around 750 GeV.

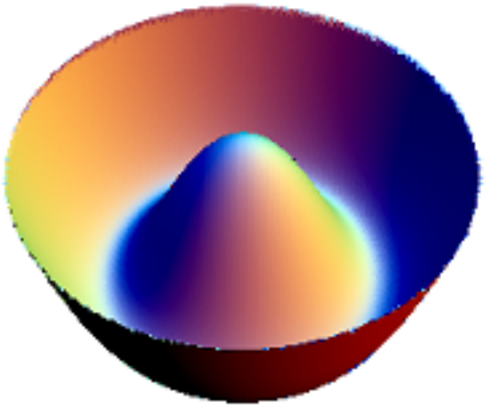
Upgrade of the ILC(expandable) to 1 TeV would be an interesting opportunity.

If not, precision Higgs/top physics will guide us as usual.

The ILC will be complementary to the LHC.

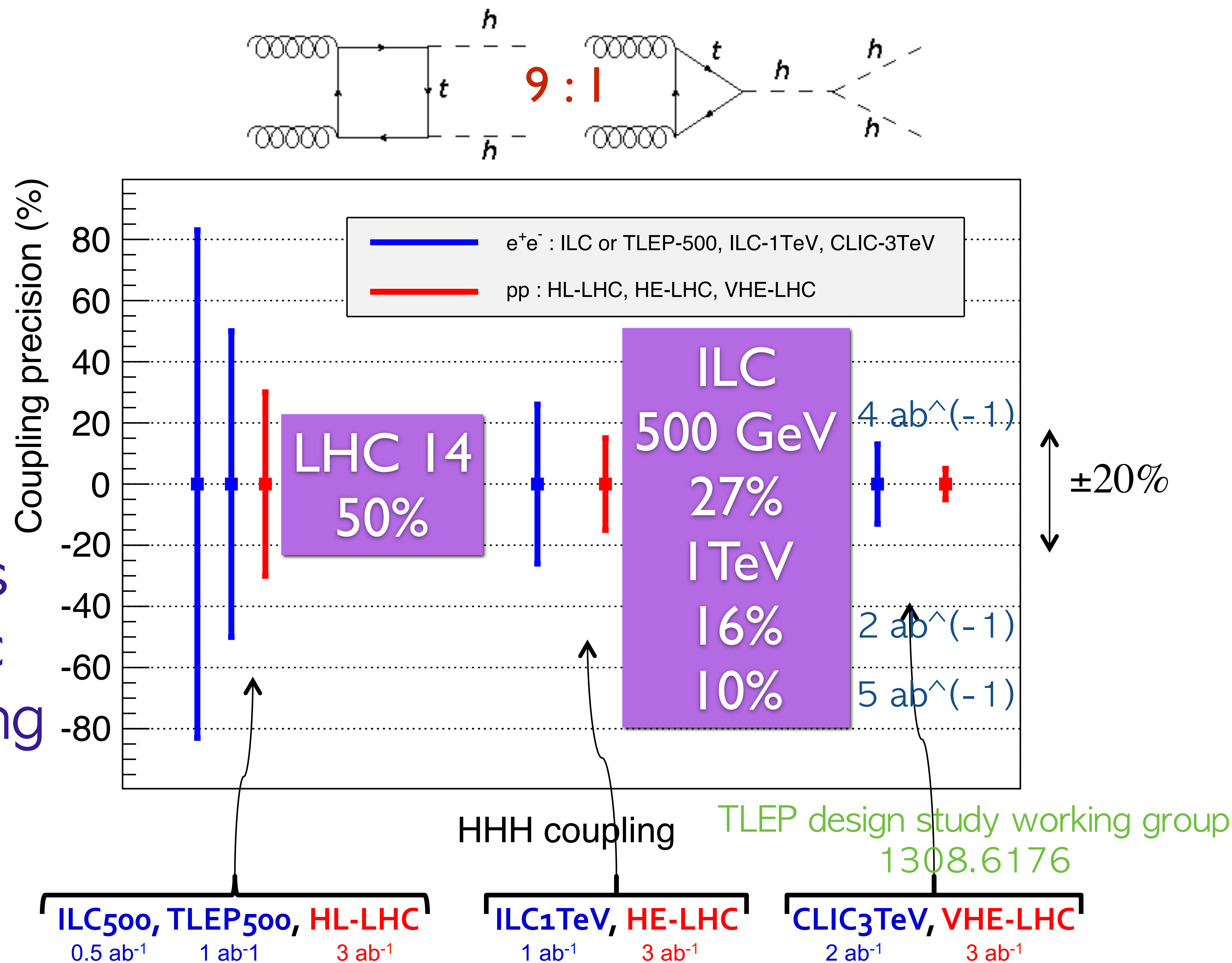
Stay tuned.

Measuring the Higgs potential



Higgs self coupling

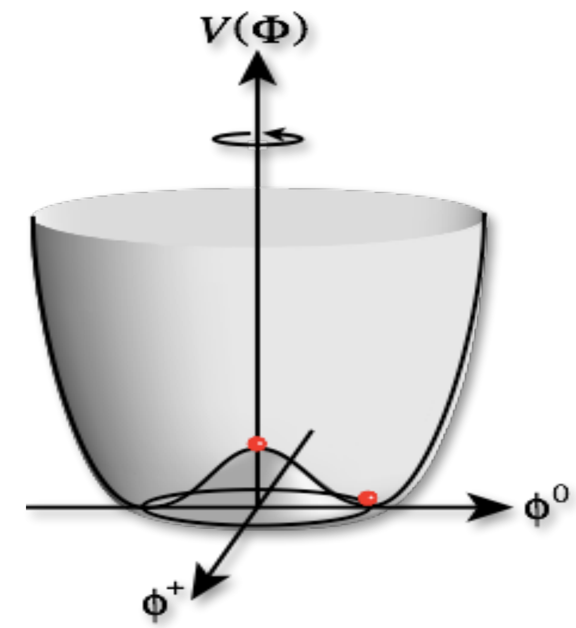
irreducible background in hadron colliders



Higgs cubic coupling

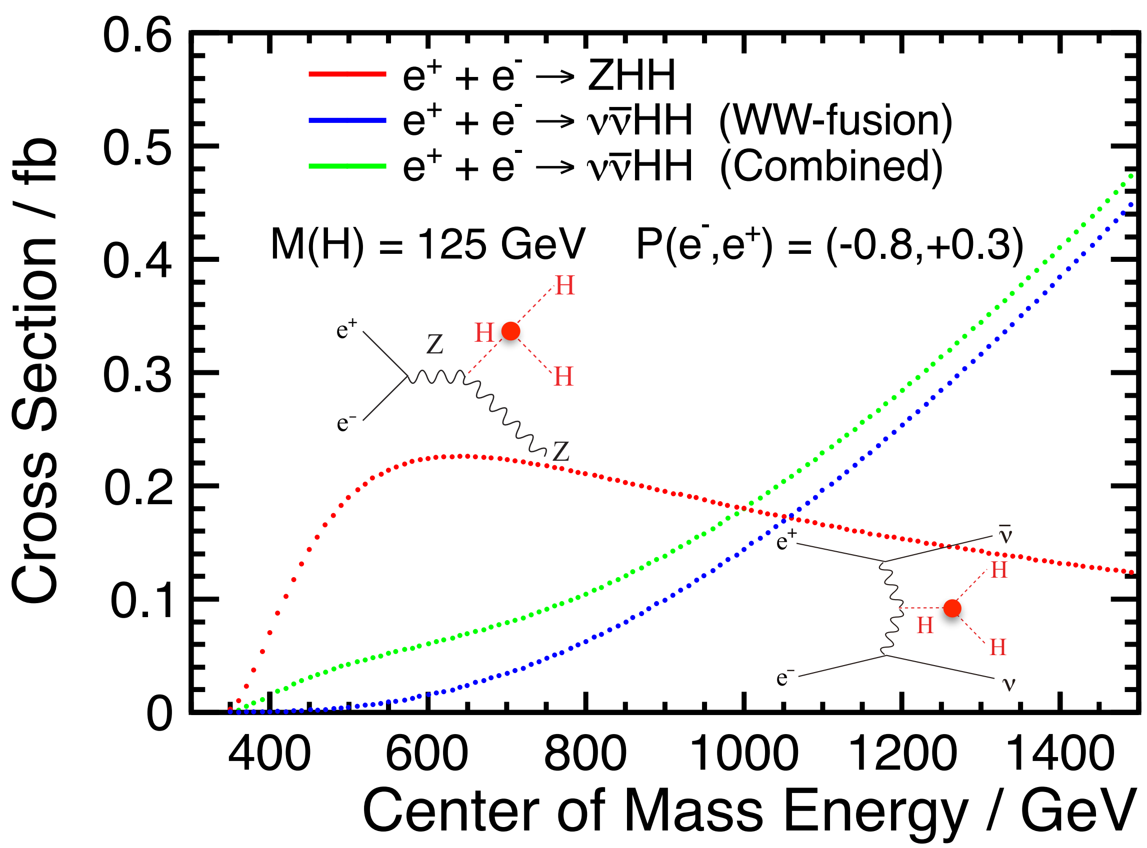
(ii-2) Higgs self-coupling

- 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)

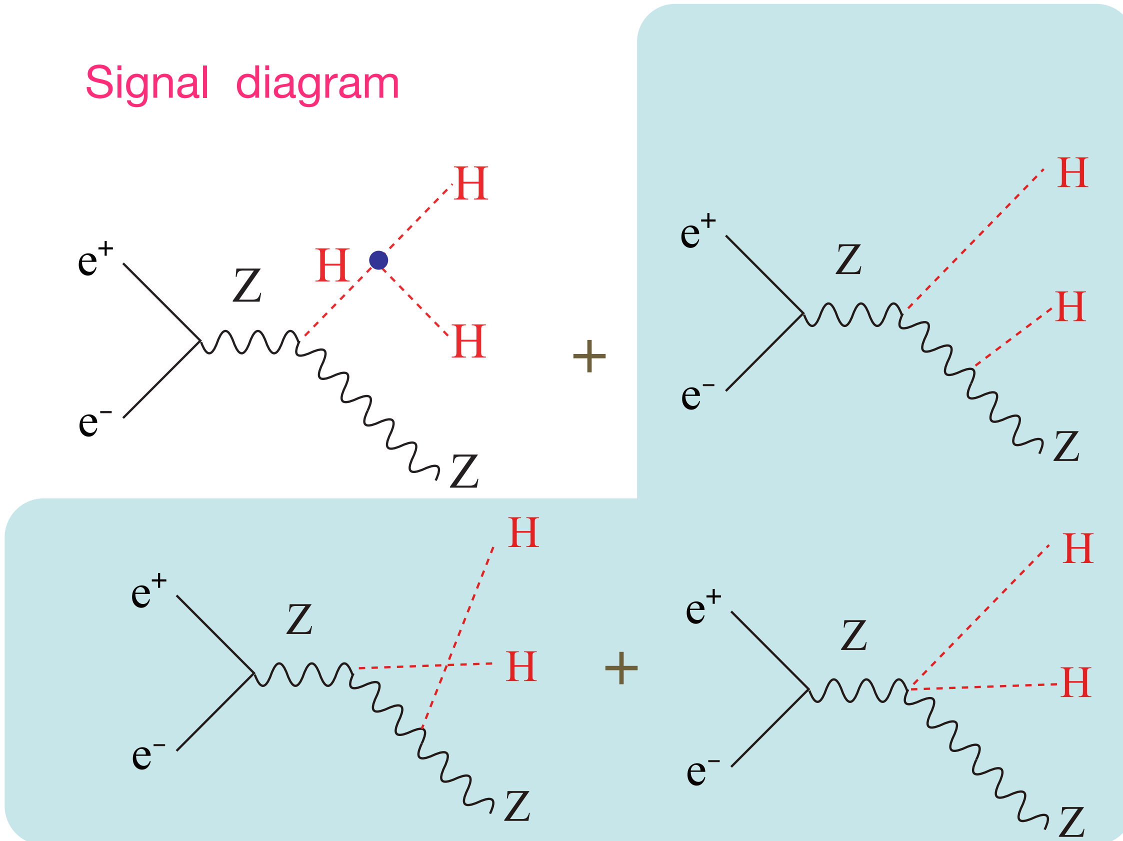


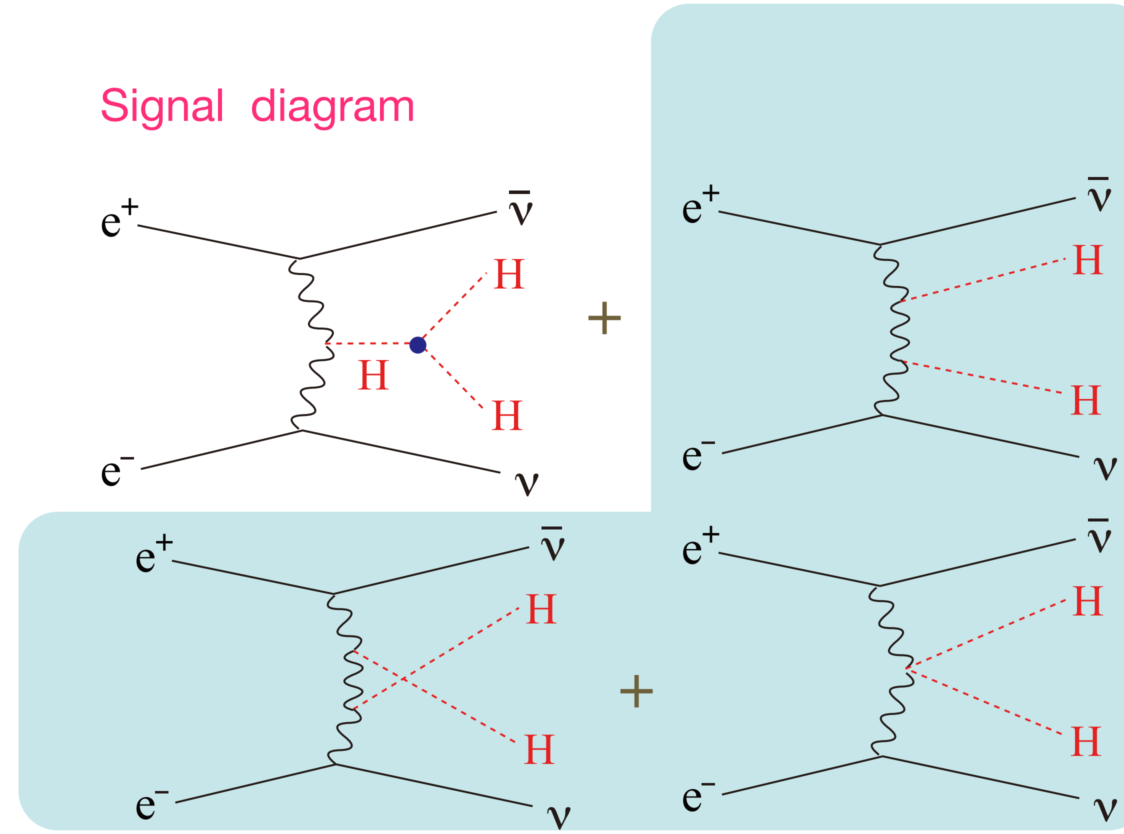
	$\Delta\lambda_{HHH}/\lambda_{HHH}$	500 GeV	+ 1 TeV
ILC	Snowmass	46%	13%
	H20	27%	10%

	1.4 TeV	+3 TeV
CLIC	24%	11%



physics issues: diagrams for double Higgs production



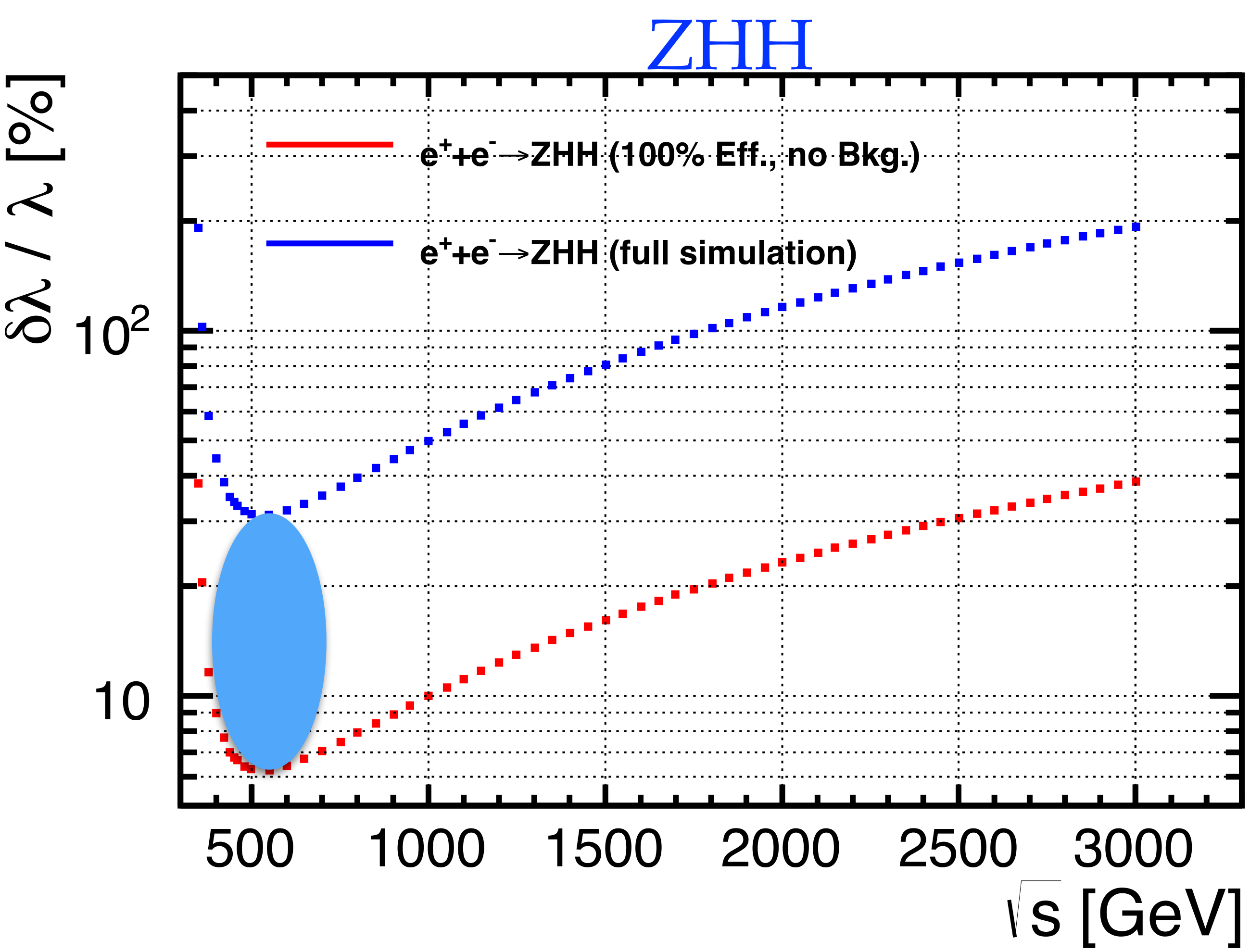


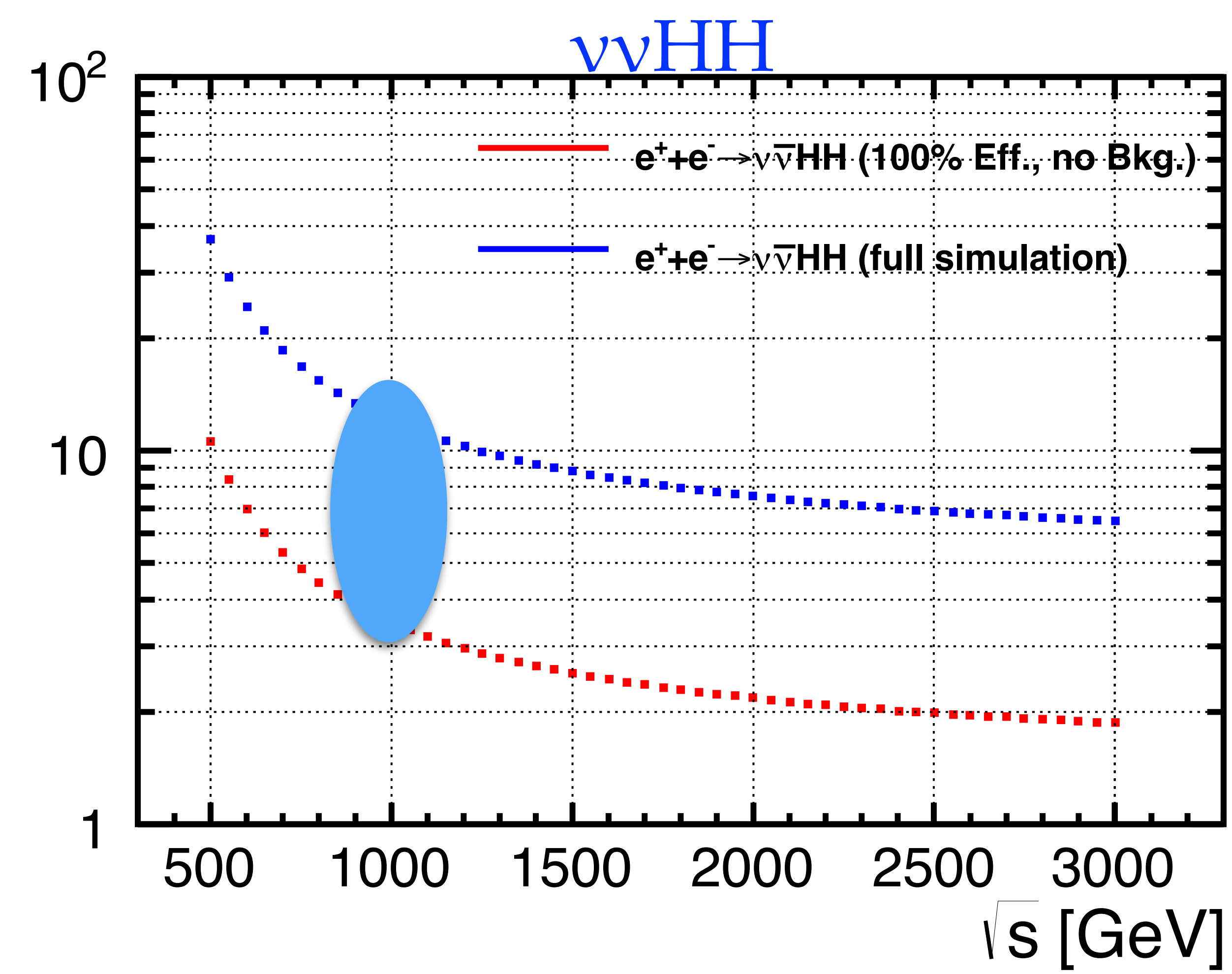
$$\sigma = S\lambda^2 + I\lambda + B$$

(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



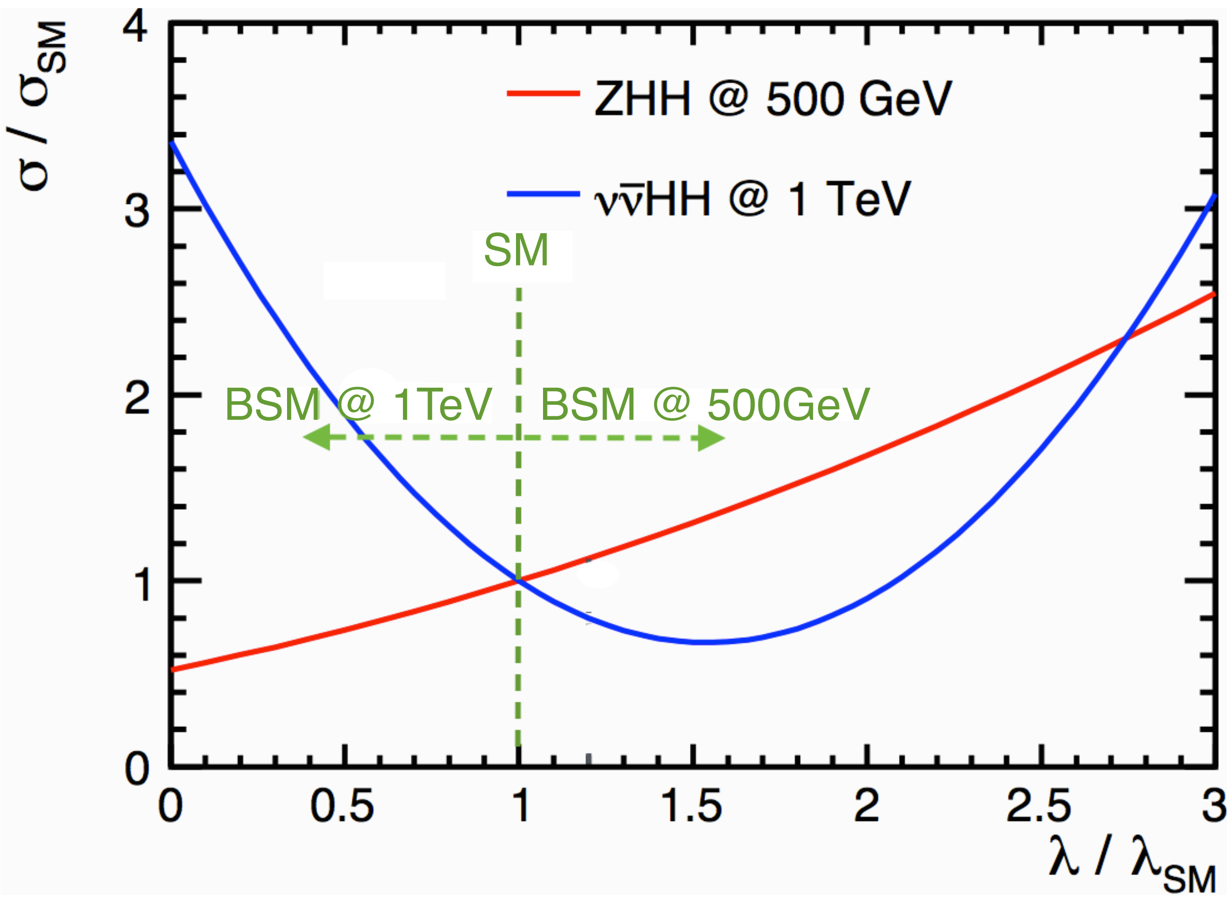


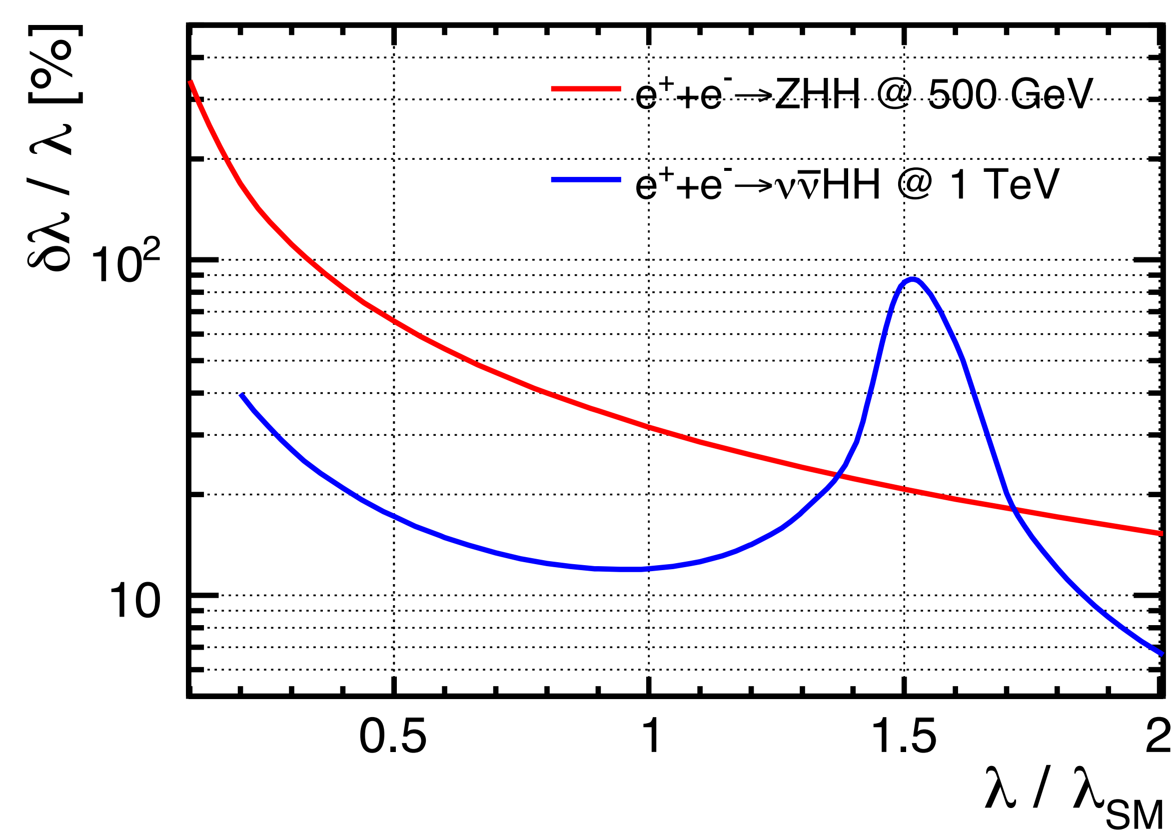
- gap of these two expectations —> room of improvement
- for ZHH: 500 GeV is the optimal energy, $\delta\lambda/\lambda$ ~ 6% : 30%, but rather mild dependence between around 500-600 GeV, significantly worse if much lower or higher than that
- for ννHH: significantly better going from 500 GeV to 1 TeV, $\delta\lambda/\lambda$~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



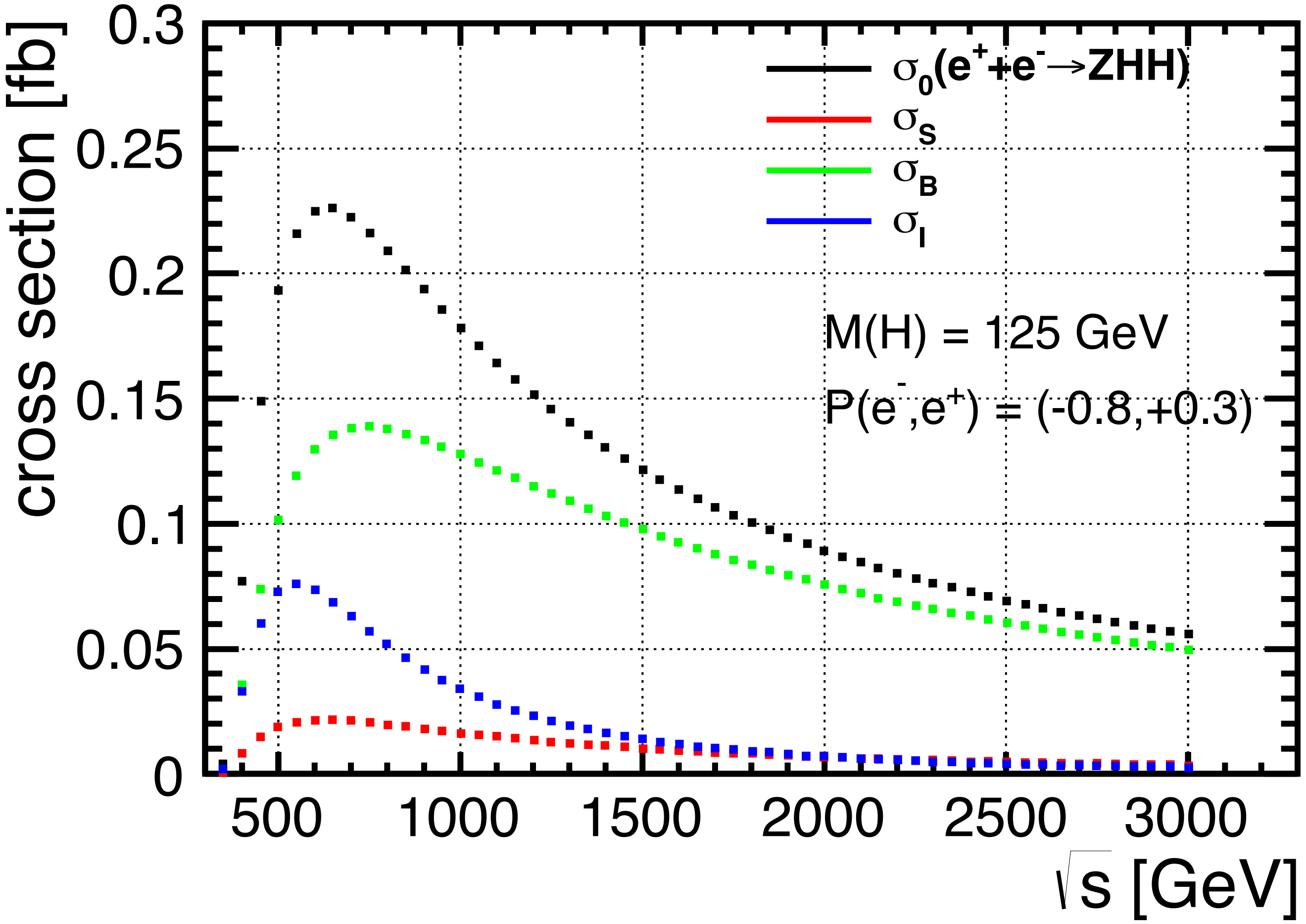


references for large deviations e.g. Grojean, et al., PRD71, 036001; Kanemura, et al., 1508.03245; Kaori, Senaha, PHLTA,B747,152; Perelstein, et al., JHEP 1407, 108

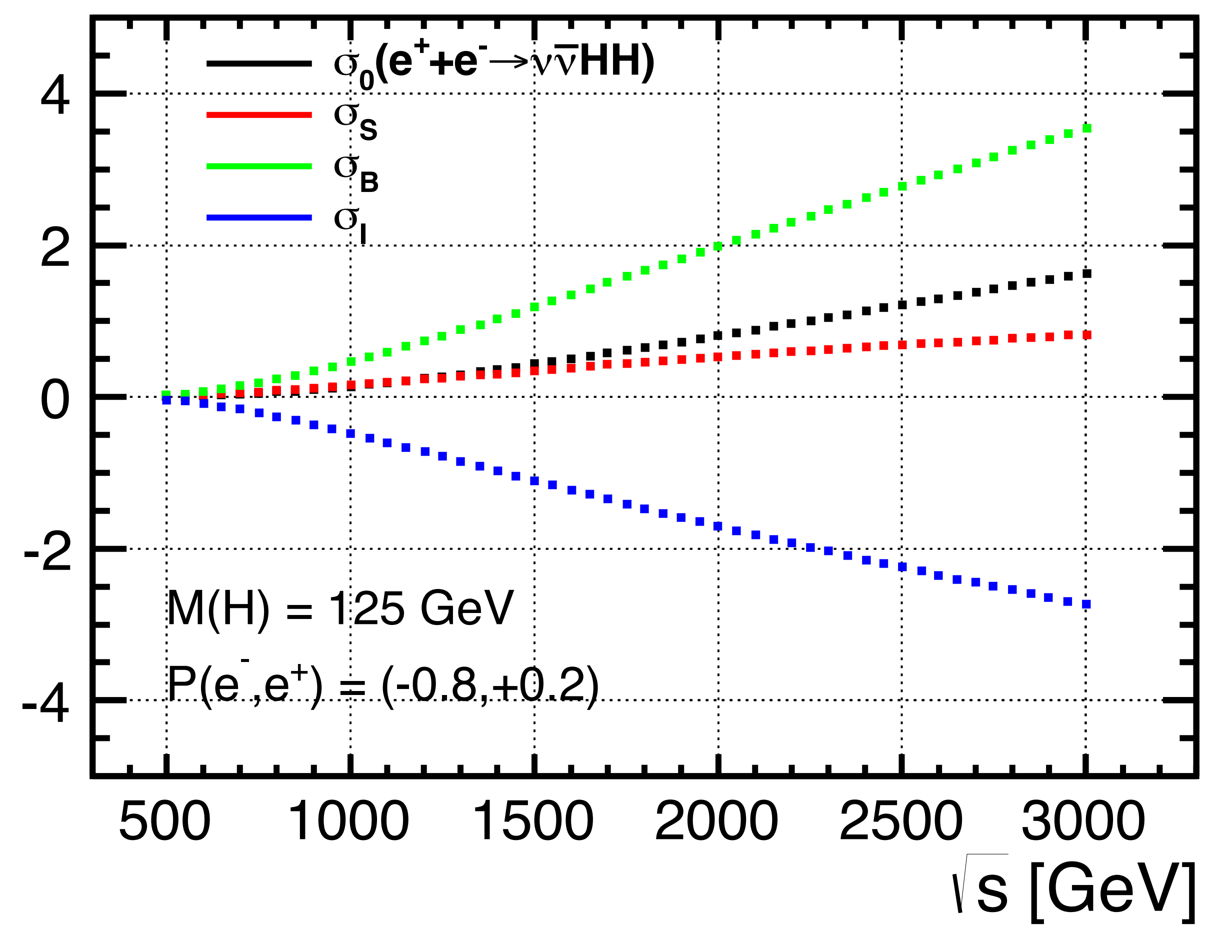
breakdown of σ to *S*, *I* and *B* terms

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

ZHH



ννHH



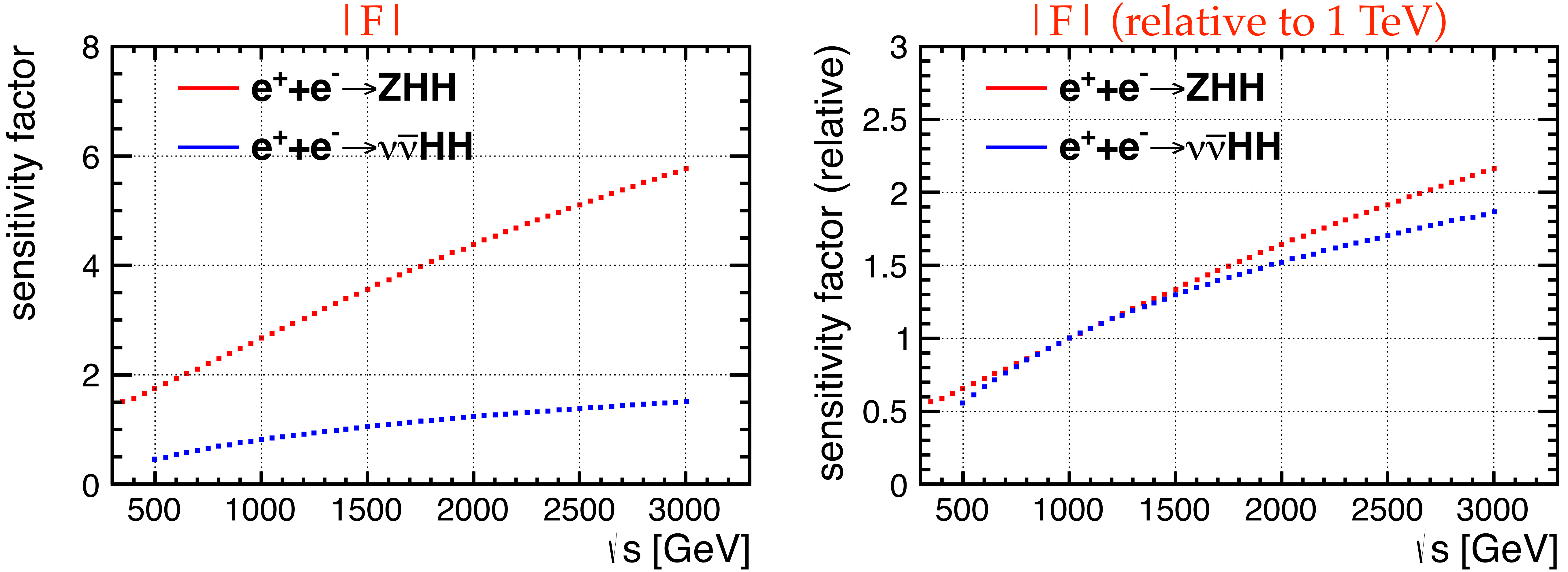
- B term (green) >> S term (red) —> more difficult than expected
- interference I term (blue) plays an crucial role in both cases; larger I term for ννHH indicates potential better sensitivity in ννHH than ZHH
- For ZHH: clearly ~500-600 GeV is preferred; peak positions of I or S term are smaller than 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

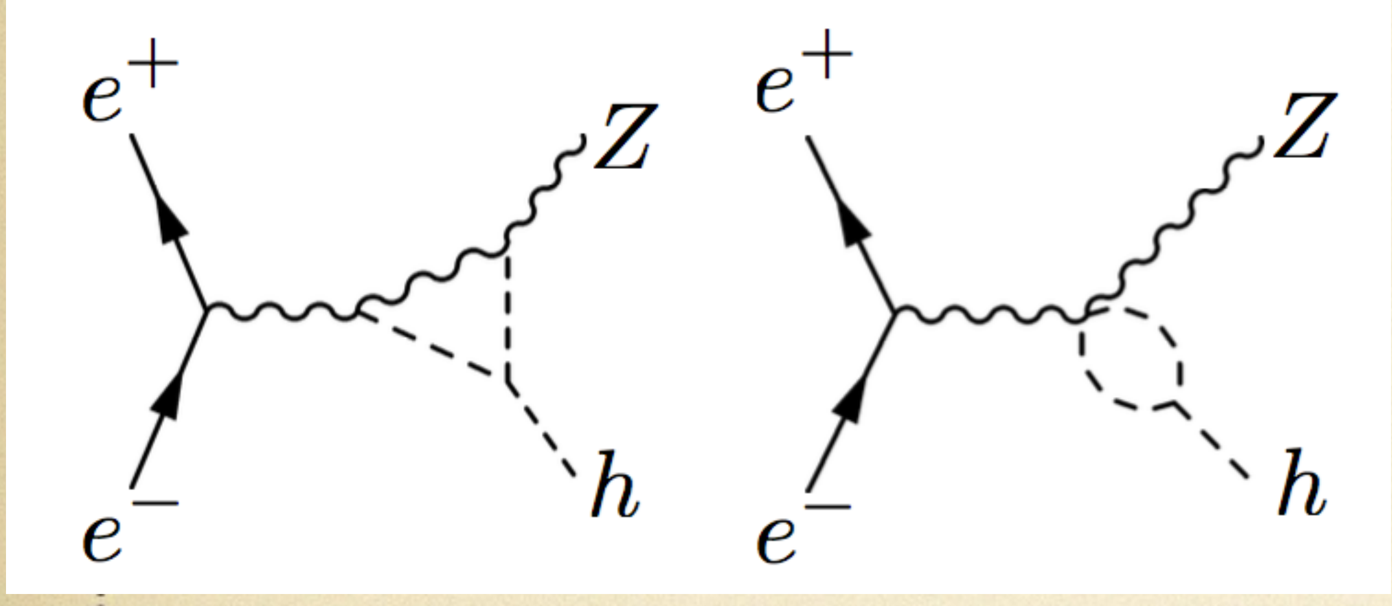
$$\frac{\delta\lambda}{\lambda} = F \cdot \frac{\delta\sigma}{\sigma} \qquad F = \frac{\sigma}{2S\lambda^2 + I\lambda}$$

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



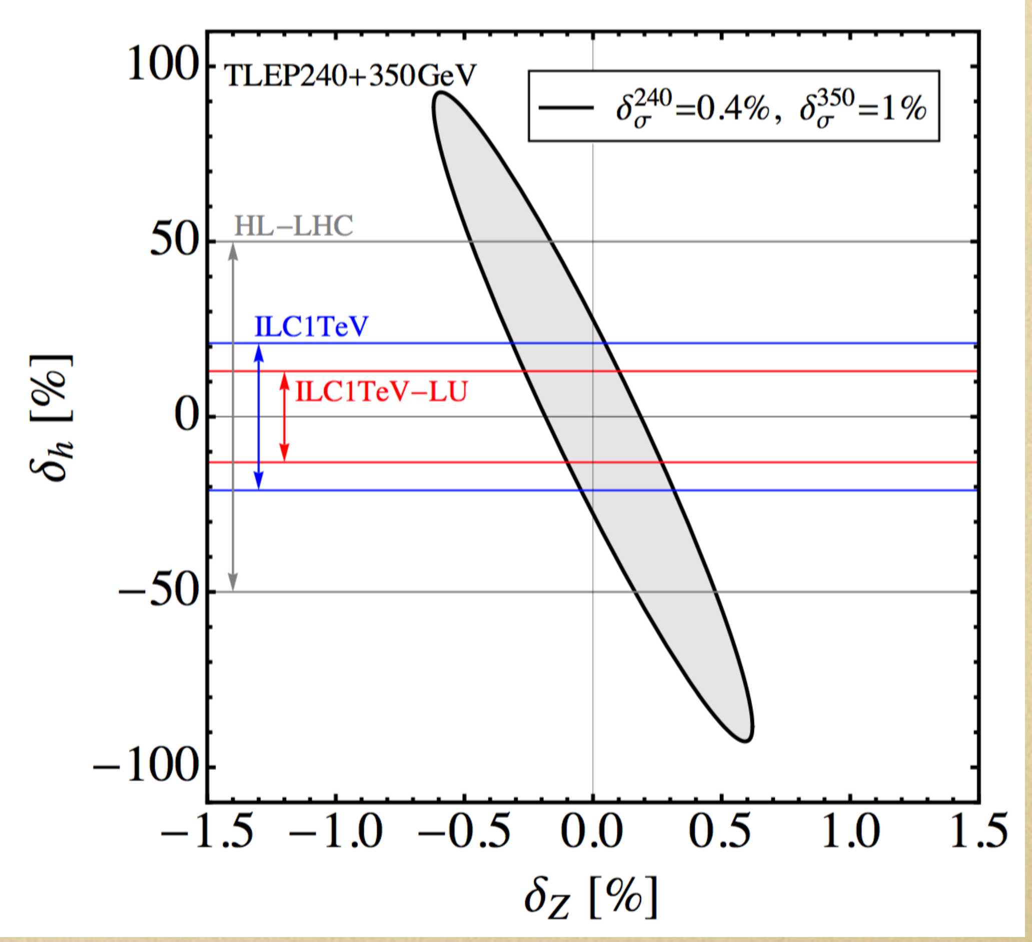
indirect model dependent probe of λ_{HHH}: $\sqrt{s}$ ~ 250 GeV



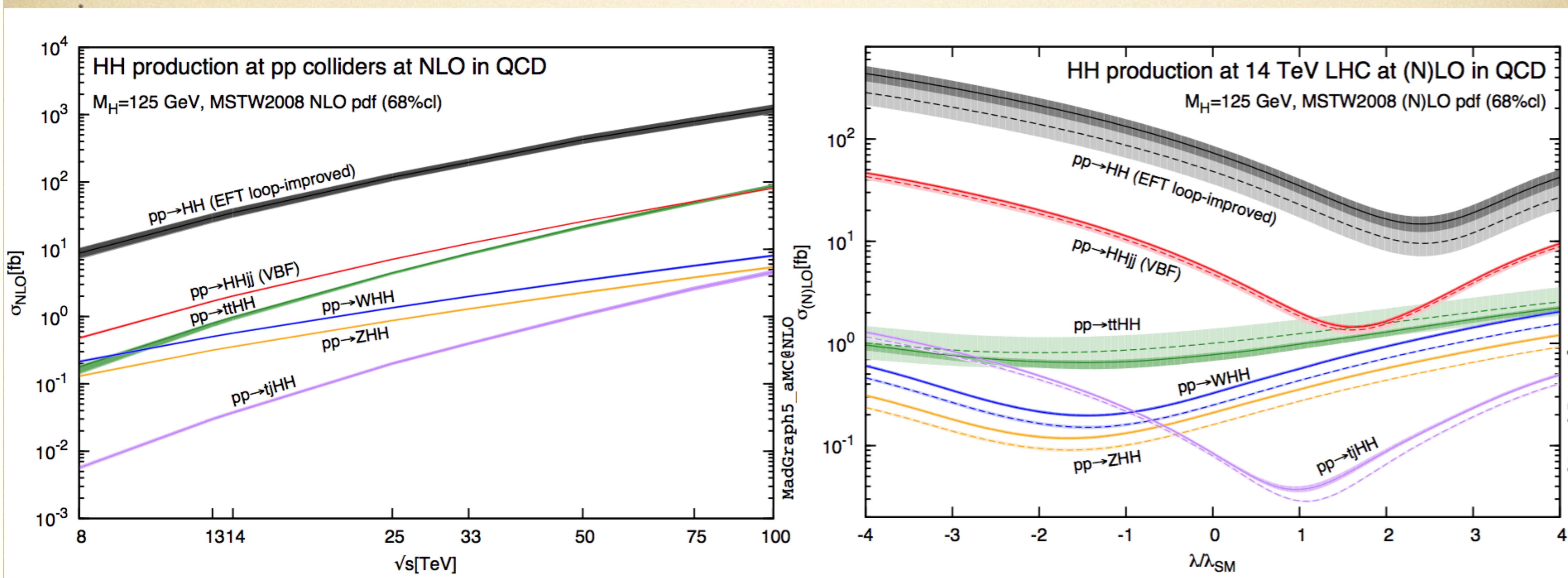
McCullough, 1312.3322

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

- 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



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



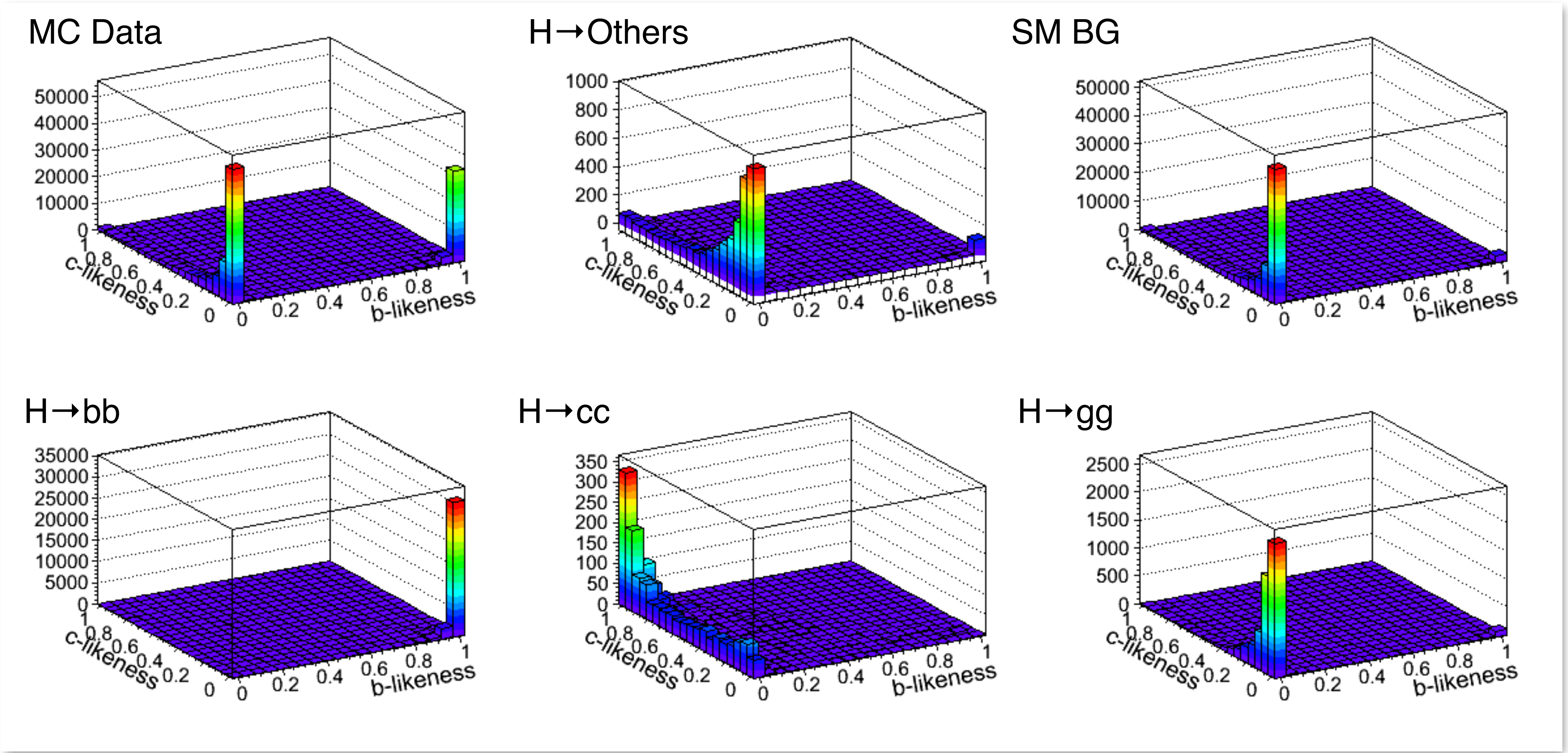
arXiv:1401.7304

- 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)

(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 →

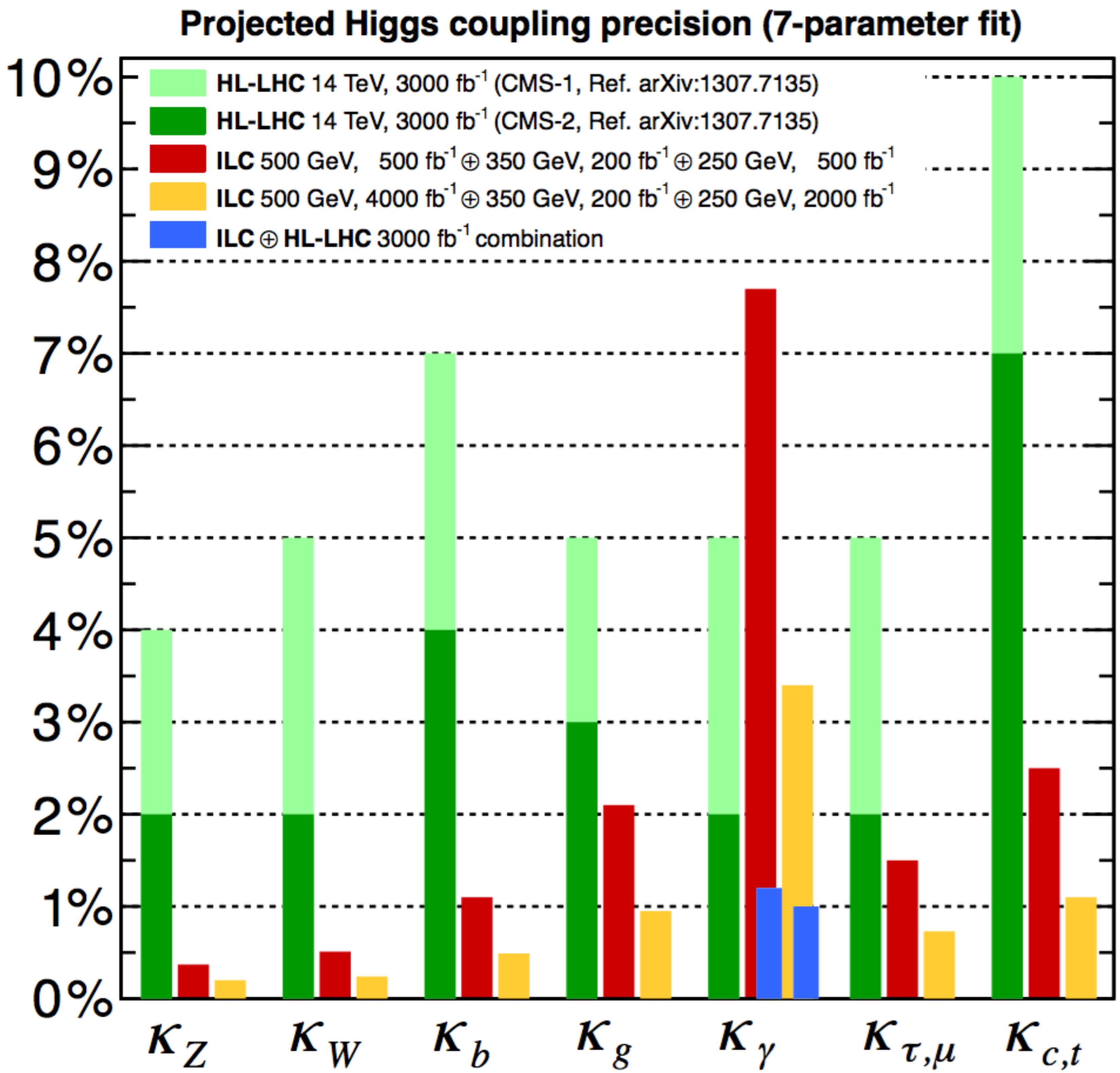
$$\sigma_{ZH} \cdot \mathrm{Br}(H \to b\bar{b}) \propto g^2_{HZZ} g^2_{Hbb} / \Gamma_H$$
$$\sigma_{ZH} \cdot \mathrm{Br}(H \to c\bar{c}) \propto g^2_{HZZ} g^2_{Hcc} / \Gamma_H$$
$$\sigma_{ZH} \cdot \mathrm{Br}(H \to gg) \propto g^2_{HZZ} g^2_{Hgg} / \Gamma_H$$

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)

expected precisions of Higgs couplings

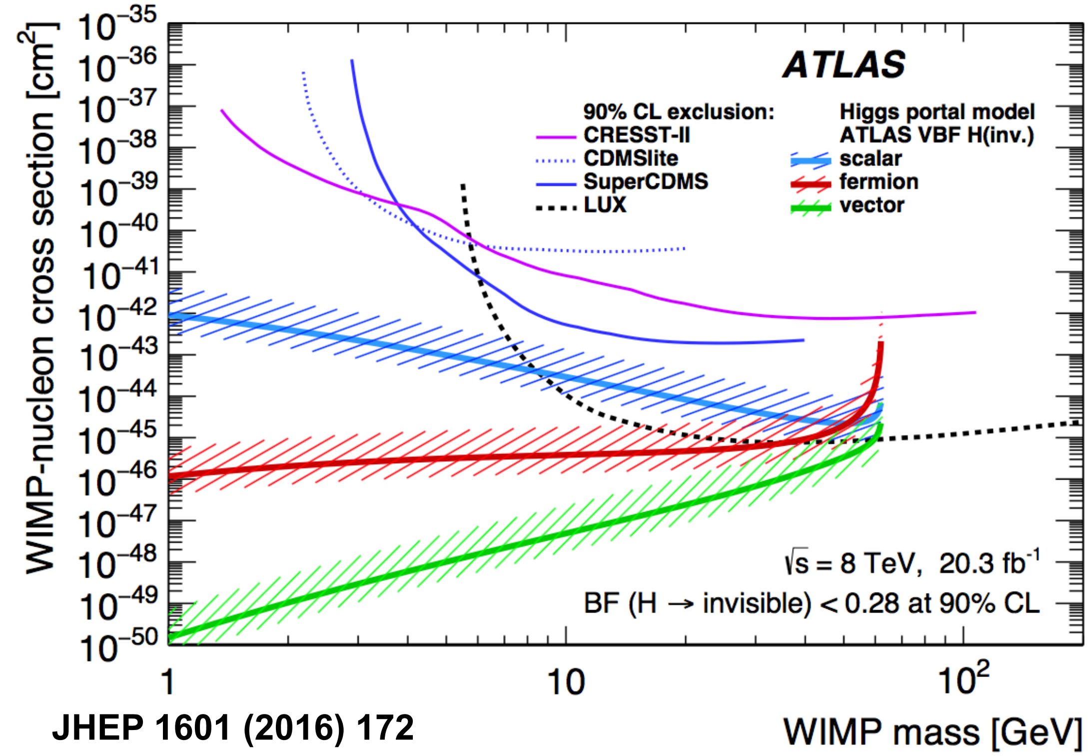


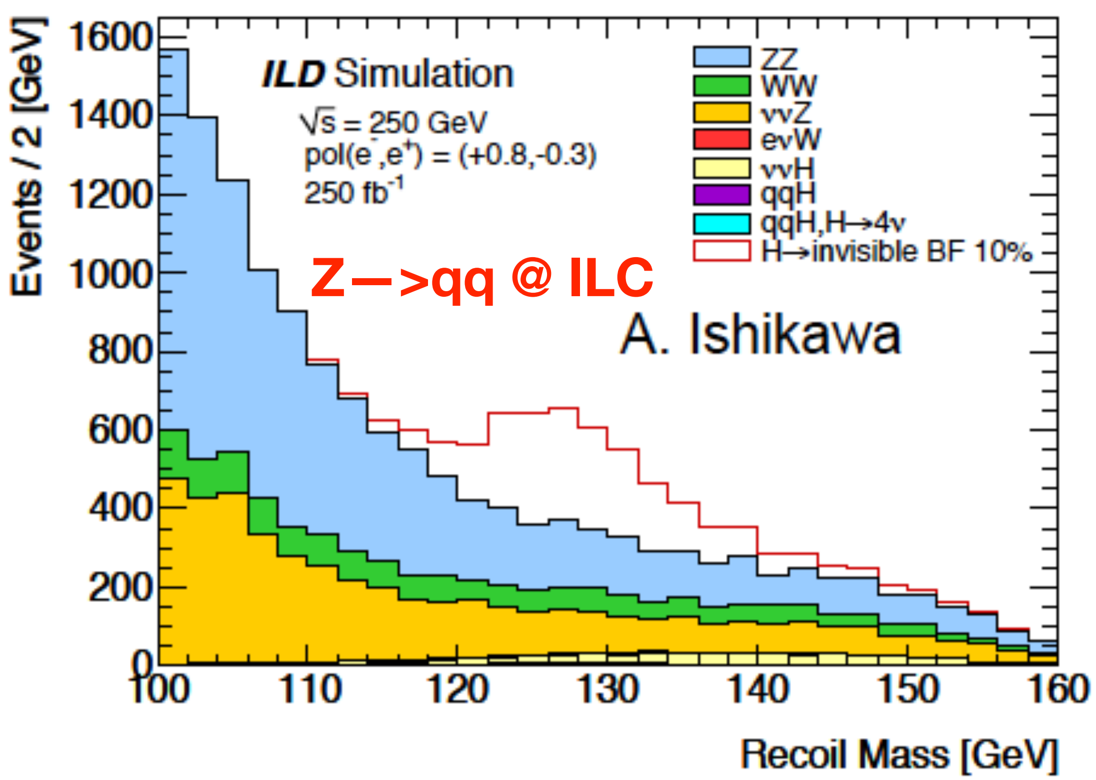
New particle discovery

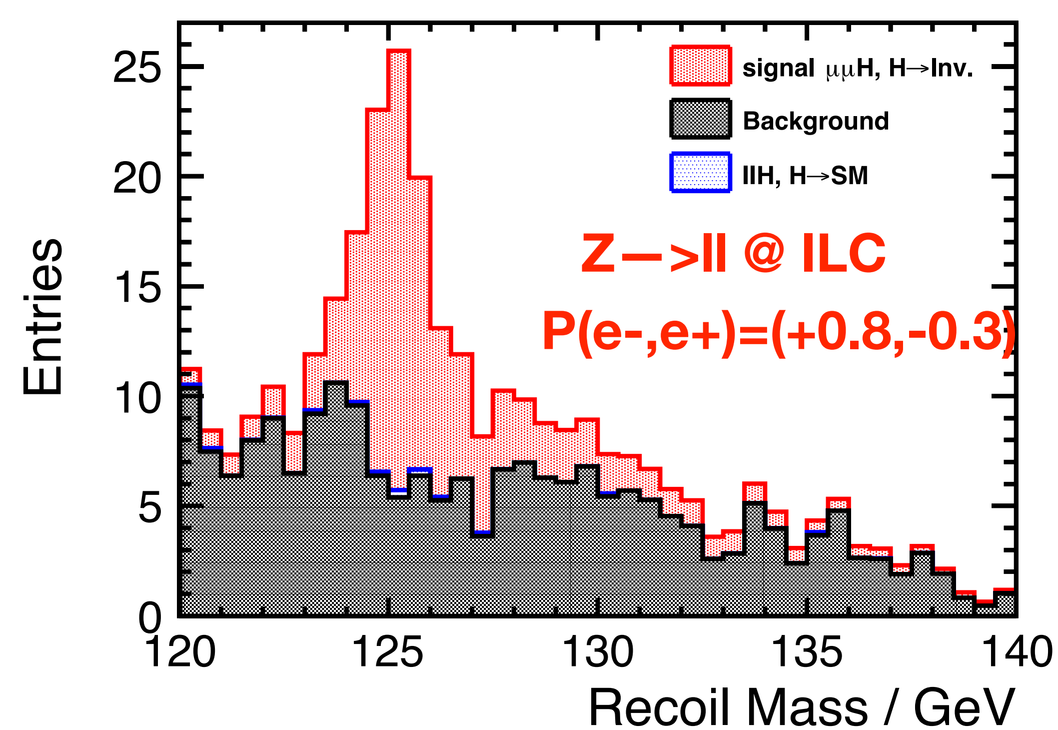
exotic decay: search of Higgs to invisible

$$e^+ + e^- \rightarrow ZH \rightarrow l^+l^-/q\bar{q} + \mathrm{Missing}$$

- BR(H—>inv.) < 0.3% ($CL^{95\%}$)
- a sensitive test for Higgs portal dark mater model —> complementary for low mass
- right-handed beam polarisation: much lower background







WIMP Dark Matter Search @ ILC

Weakly Interacting Massive Particle 探索

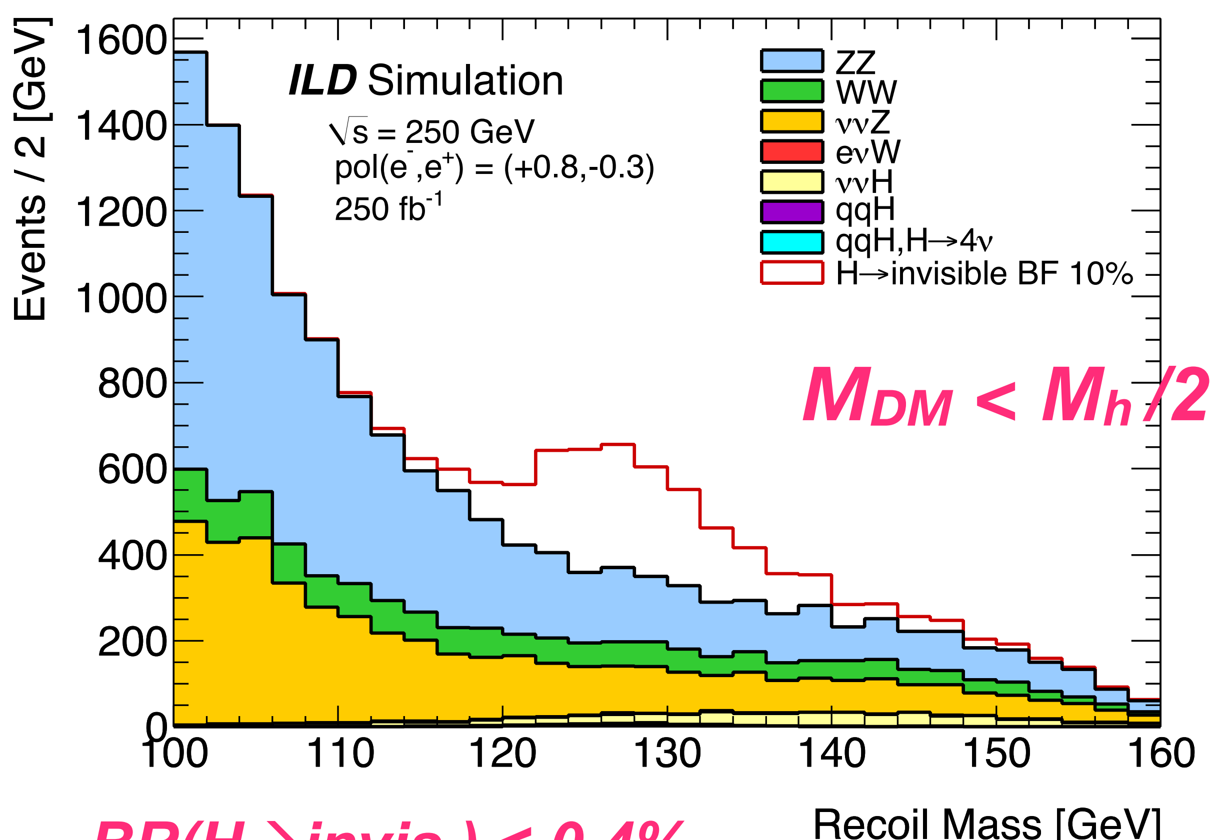
Decay of a new particle to Dark Matter (DM)

DM has a charged partner in many new physics models.

SUSY: The Lightest SUSY Particle (LSP) = DM → Its partner decays to a DM.

- Events with missing Pt (example: light chargino: see the previous page)

Higgs Invisible Decay



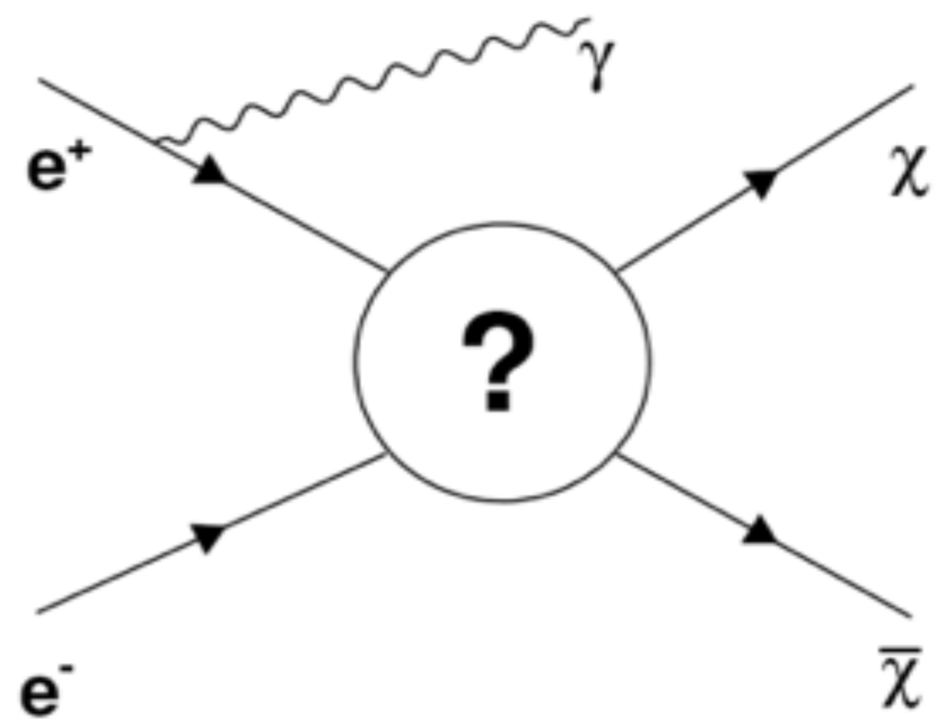
$M_{DM} < M_h/2$

BR(H→invis.) < 0.4%

at 250 GeV, 1150 fb^{-1}

Possible to access BR_{inv} to 0.4%!

Mono-photon Search

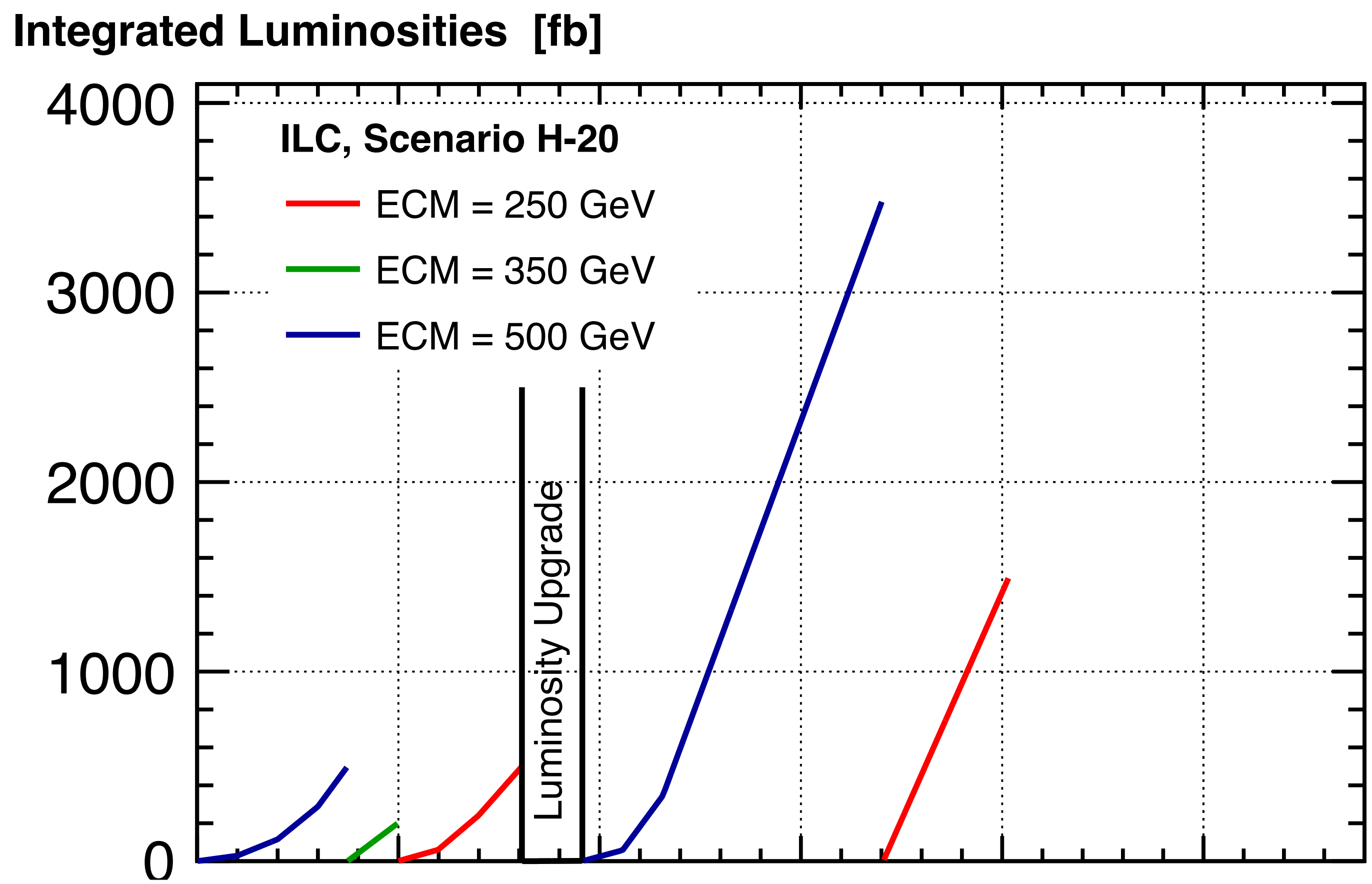


→ ***M_{DM} reach ~ $E_{cm}/2$***

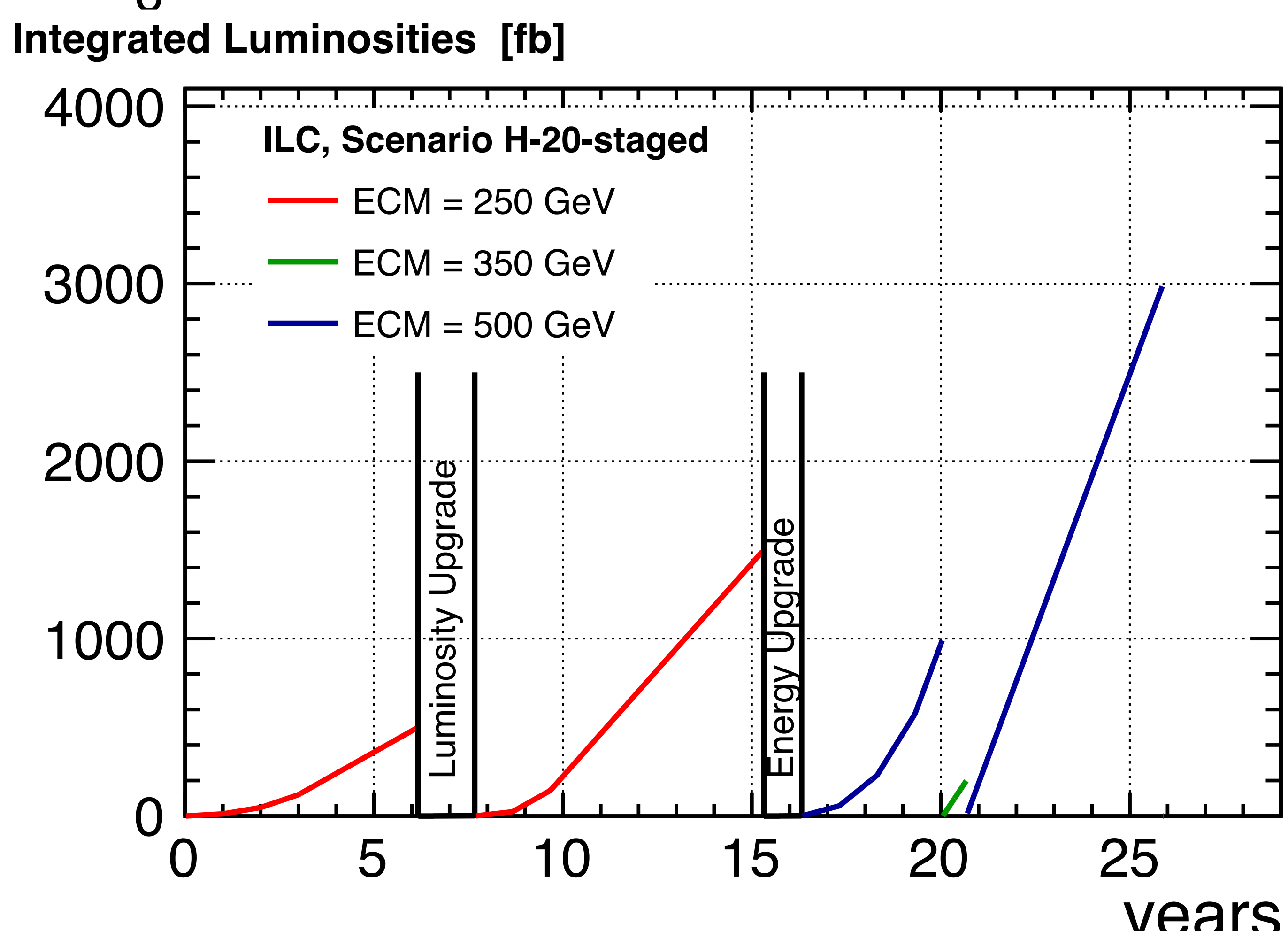
Possible to access DM to ~$E_{cm}/2$!

ILC at 250 GeV

scenario:
example



ILC500
H20



ILC250
H20 staged

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

ILC250 as a Higgs factory

top quark physics

Higgs self coupling

new particle discovery

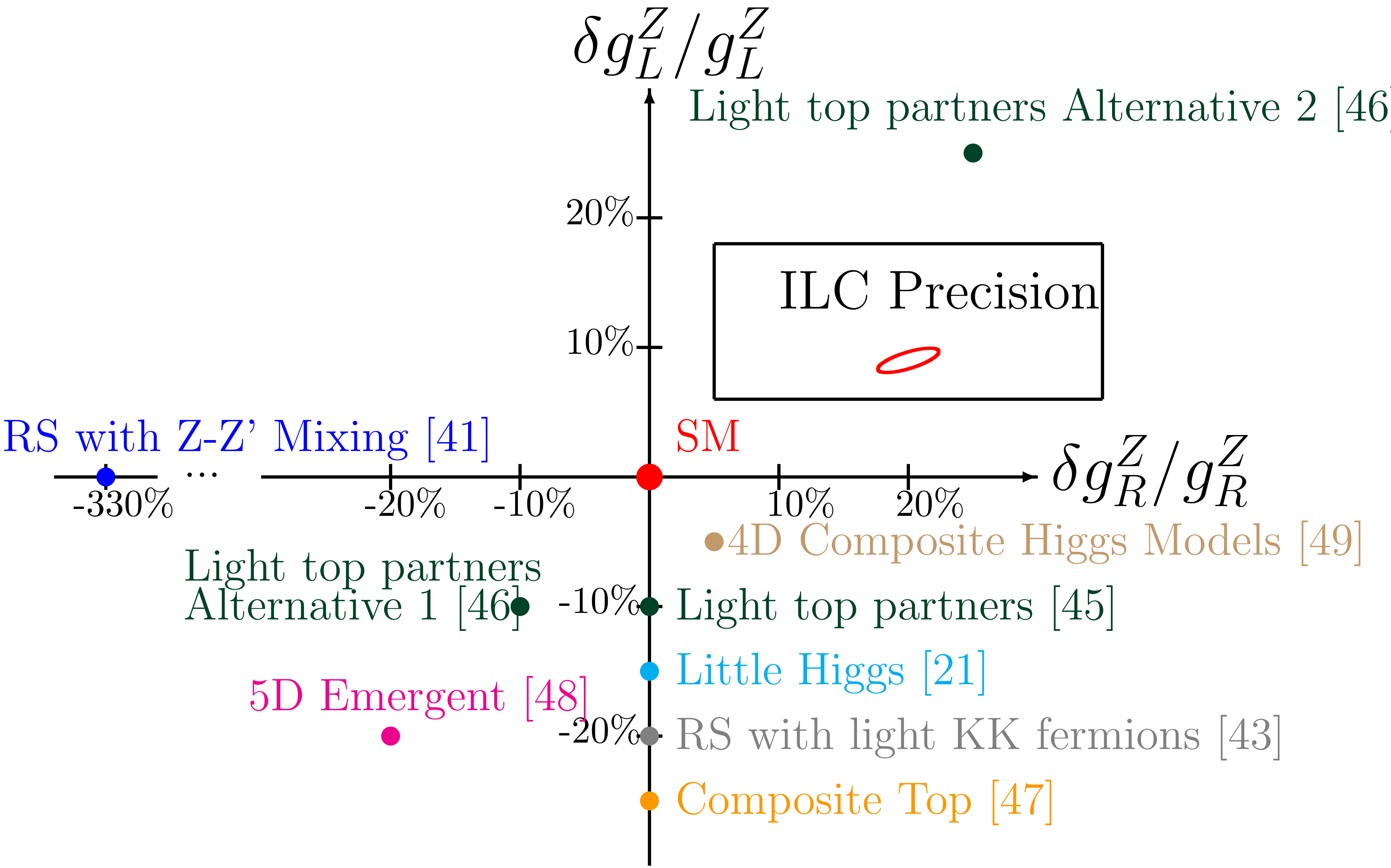
direct search limit

ILC250 = 0.5*ILC500

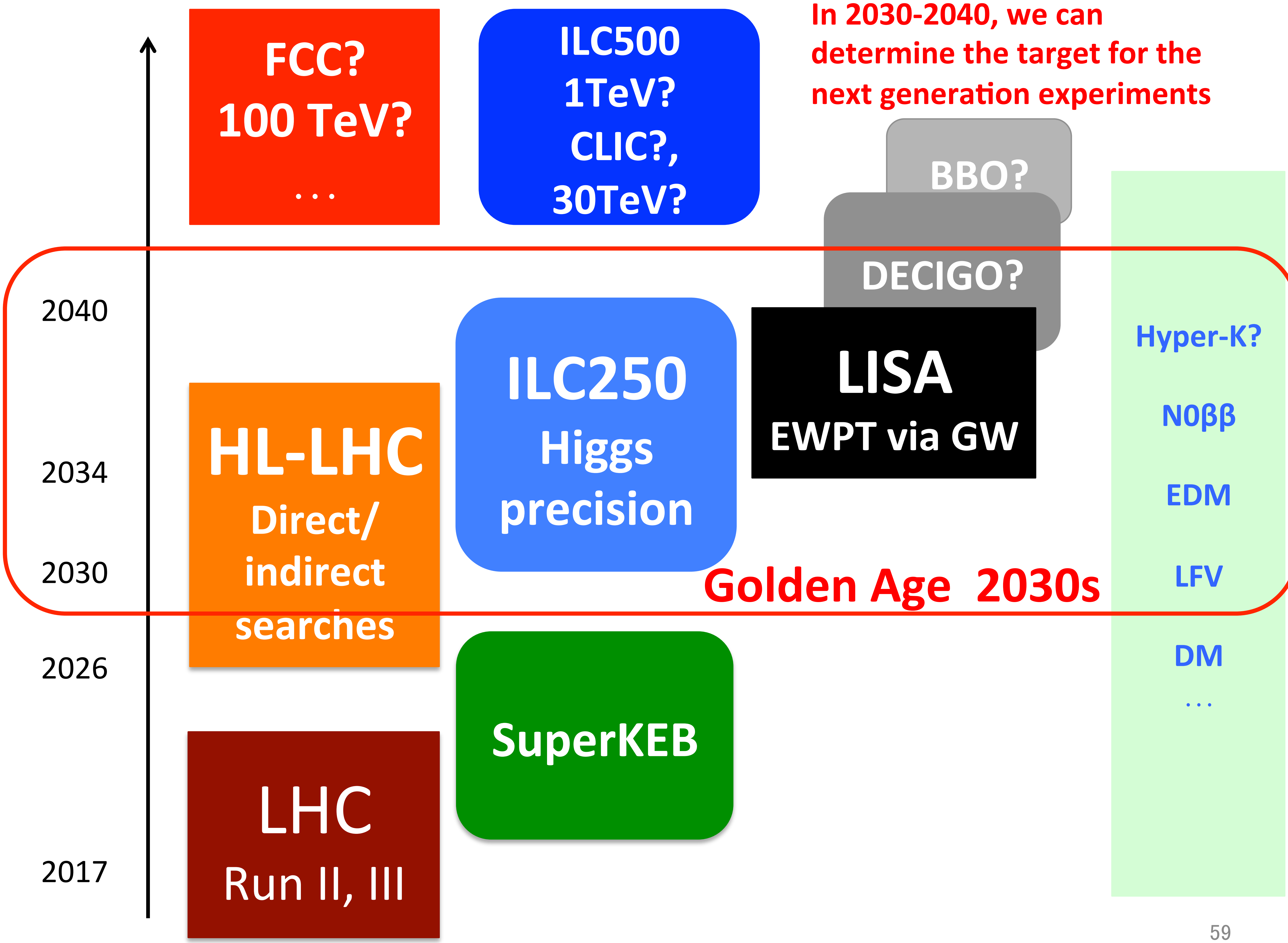
electron positron polarization physics

CepC cannot do polarization physics

ILC : precision measurement of tL and tR to Z (BSM discrimination)



ILC is expandable


In 2030-2040, we can determine the target for the next generation experiments
FCC? 100 TeV? . . .
ILC500 1TeV? CLIC?, 30TeV?
BBO?
DECIGO?
LISA
EWPT via GW
ILC250
Higgs precision
HL-LHC
Direct/ indirect searches
SuperKEB
LHC
Run II, III
Golden Age 2030s
2040
2034
2030
2026
2017
Hyper-K?
N0ββ
EDM
LFV
DM
. . .

Backup

one example for illustrating the physics effect

$$\boxed{\frac{c_H}{2v^2}\partial^\mu(\Phi^\dagger\Phi)\partial_\mu(\Phi^\dagger\Phi)}$$

after EWSB:

(1) $\frac{c_H}{2}\partial^\mu h\partial_\mu h$ $\longrightarrow$ renormalize kinetic term of SM Higgs field $\frac{1}{2}\partial^\mu h\partial_\mu h$

h $\longrightarrow$ $(1-c_H/2)h$

$\longrightarrow$ shift all SM Higgs couplings by $-c_H/2$

(2) $\frac{c_H}{v}h\partial^\mu h\partial_\mu h$ $\longrightarrow$ anomalous triple Higgs coupling

(3) $\frac{c_H}{2v^2}hh\partial^\mu h\partial_\mu h$ $\longrightarrow$ anomalous quartic Higgs coupling

full formalism
23 parameters

SM Effective Field Theory

$$\Delta\mathcal{L} = \frac{c_H}{2v^2}\partial^\mu(\Phi^\dagger\Phi)\partial_\mu(\Phi^\dagger\Phi) + \frac{c_T}{2v^2}(\Phi^\dagger \overleftrightarrow{D}^\mu \Phi)(\Phi^\dagger \overleftrightarrow{D}_\mu \Phi) - \frac{c_6\lambda}{v^2}(\Phi^\dagger\Phi)^3$$
$$+\frac{g^2 c_{WW}}{m_W^2}\Phi^\dagger\Phi W^a_{\mu\nu}W^{a\mu\nu} + \frac{4gg' c_{WB}}{m_W^2}\Phi^\dagger t^a \Phi W^a_{\mu\nu}B^{\mu\nu}$$
$$+\frac{g'^2 c_{BB}}{m_W^2}\Phi^\dagger\Phi B_{\mu\nu}B^{\mu\nu} + \frac{g^3 c_{3W}}{m_W^2}\epsilon_{abc}W^a_{\mu\nu}W^{b\nu}{}_\rho W^{c\rho\mu}$$
$$+i\frac{c_{HL}}{v^2}(\Phi^\dagger \overleftrightarrow{D}^\mu \Phi)(\overline{L}\gamma_\mu L) + 4i\frac{c'_{HL}}{v^2}(\Phi^\dagger t^a \overleftrightarrow{D}^\mu \Phi)(\overline{L}\gamma_\mu t^a L)$$
$$+i\frac{c_{HE}}{v^2}(\Phi^\dagger \overleftrightarrow{D}^\mu \Phi)(\overline{e}\gamma_\mu e)\ .$$

10 operators (h,W,Z,γ): c_H, c_T, c_6, c_{WW}, c_{WB}, c_{BB}, c_{3W}, c_{HL}, c'_{HL}, c_{HE}

+ 4 SM parameters: g, g’, v, λ

+ 5 operators modifying h couplings to b, c, τ, μ, g

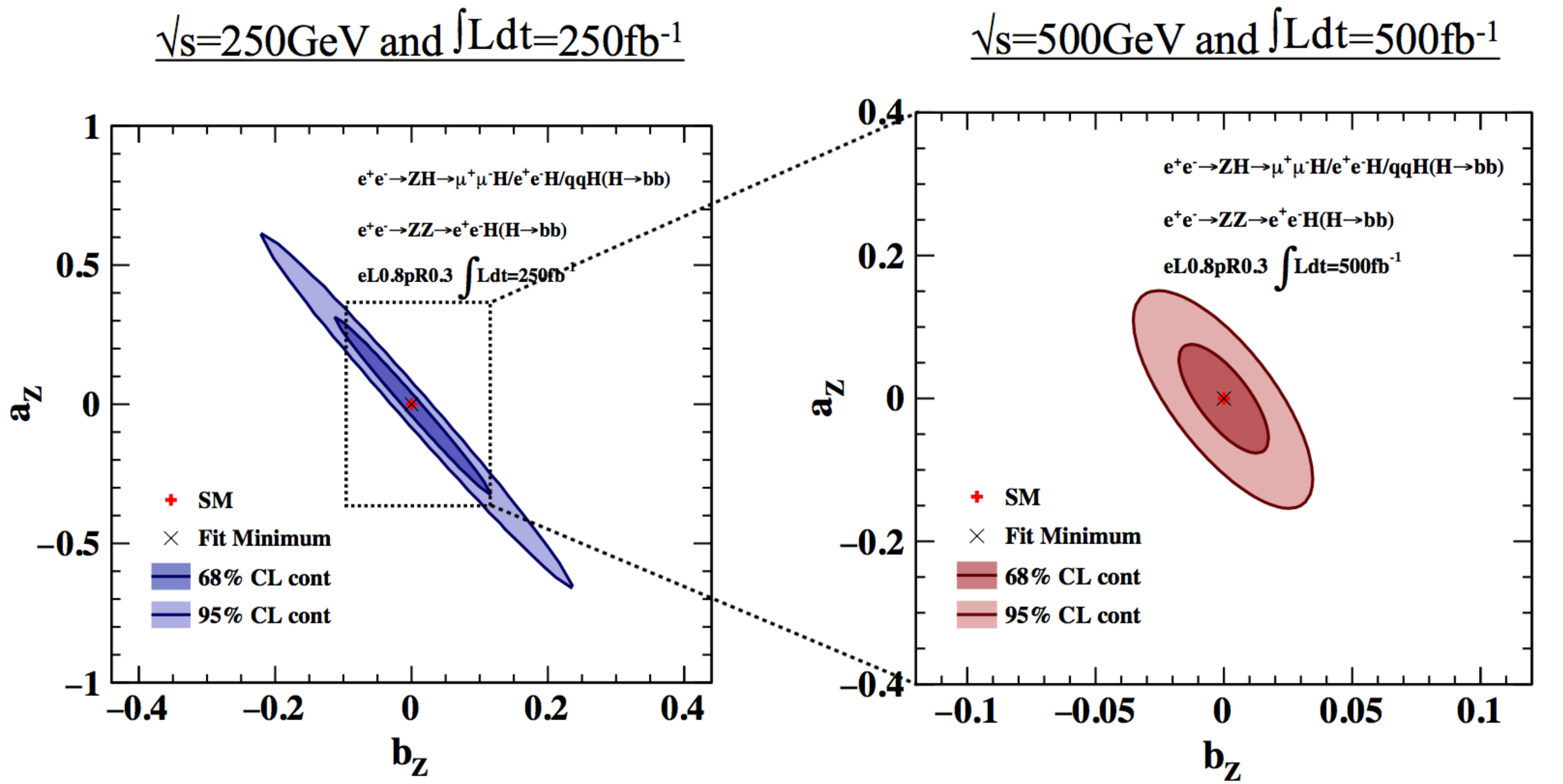
+ 2 parameters for h->invisible and exotic

+ 2 for contact interaction with quarks

determine tensor structure of hVV couplings (full simulation)

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

$$\Lambda = 1\ \mathrm{TeV}$$



for 2 ab-1 @ 250 GeV —> κZ (a) ~ 3% >> 0.38%