Focus topic: Higgs self-coupling

expert team (3 meetings May 8, Jun. 23, Oct. 6, 23')

Gauthier Durieux (CERN)	Theory
Ricardo Goncalo (Coimbra)	ALTAS / FCC-ee
Sven Heynemeyer (IFT CSIC)	WG1-GLOB / Theory
Michael Peskin (SLAC)	Theory
Philipp Roloff (CERN)	CLIC
Roberto Salerno (LLR/Ecole Polytechnique)	CMS / FCC-ee
Junping Tian (U.Tokyo)	WG1-GLOB / ILC
Jenny List (ex-officio)	

latest meeting on May 15, 24': Mini-workshop on Higgs self-coupling focus topic

3rd ECFA Workshop on Higgs/EW/Top Study
Oct. 9-11, 2024 @ Paris

Preliminary outline of the H-self report

(aligned to Ch3 in current ECFA focus topic document arXiv:2401.07564)

Talks in this WS

1. Introduction

- 1.1 Motivation of measuring λ_{HHH}
- 1.2 Prospects from HL-LHC
- 1.3 Two approaches at future e+e-

[M. Mühlleitner]
[G. Weiglein]

2. Progress in Theory

- 2.1 Higher Order Predictions
- 2.2 Large $\delta\lambda_{HHH}$ in BSM models

[J. Braathen]

3. Progress in Single-Higgs approach

- 3.1 Degeneracies at NLO SMEFT in ZH
- 3.2 Differential σ Measurements
- 3.3 Results from New Global SMEFT Fit

[P. Giardino]
[A. Maria]
[J. Hoeve]
[M. Peskin]

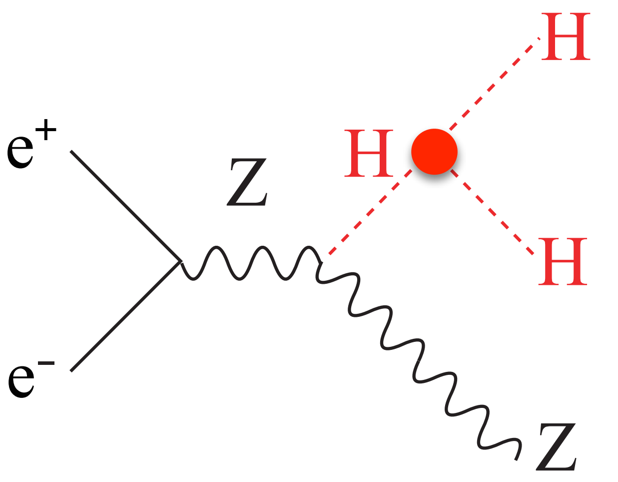
4. Progress in Di-Higgs approach

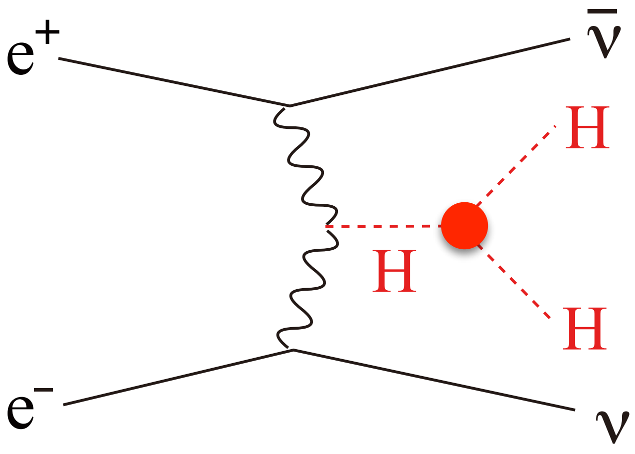
- 4.1 New analysis techniques
- 4.2 Improved ZHH analysis with $\sqrt{s}$ ~ 550 GeV
- 4.3 Prospects for $\lambda_{HHH}/\lambda_{SM} \neq 1$

[B. Bliewert]

λ_{HHH}: di-Higgs & single-Higgs processes

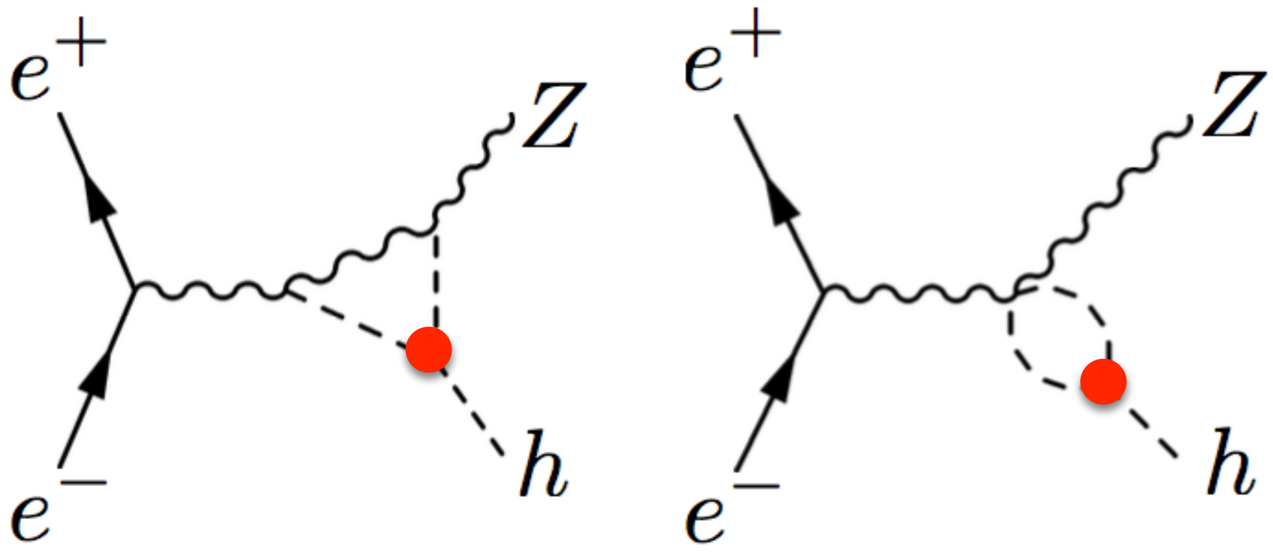
$\sqrt{s} \gtrsim 500$ GeV





$\sigma_{HH} \sim O(0.1)$ fb

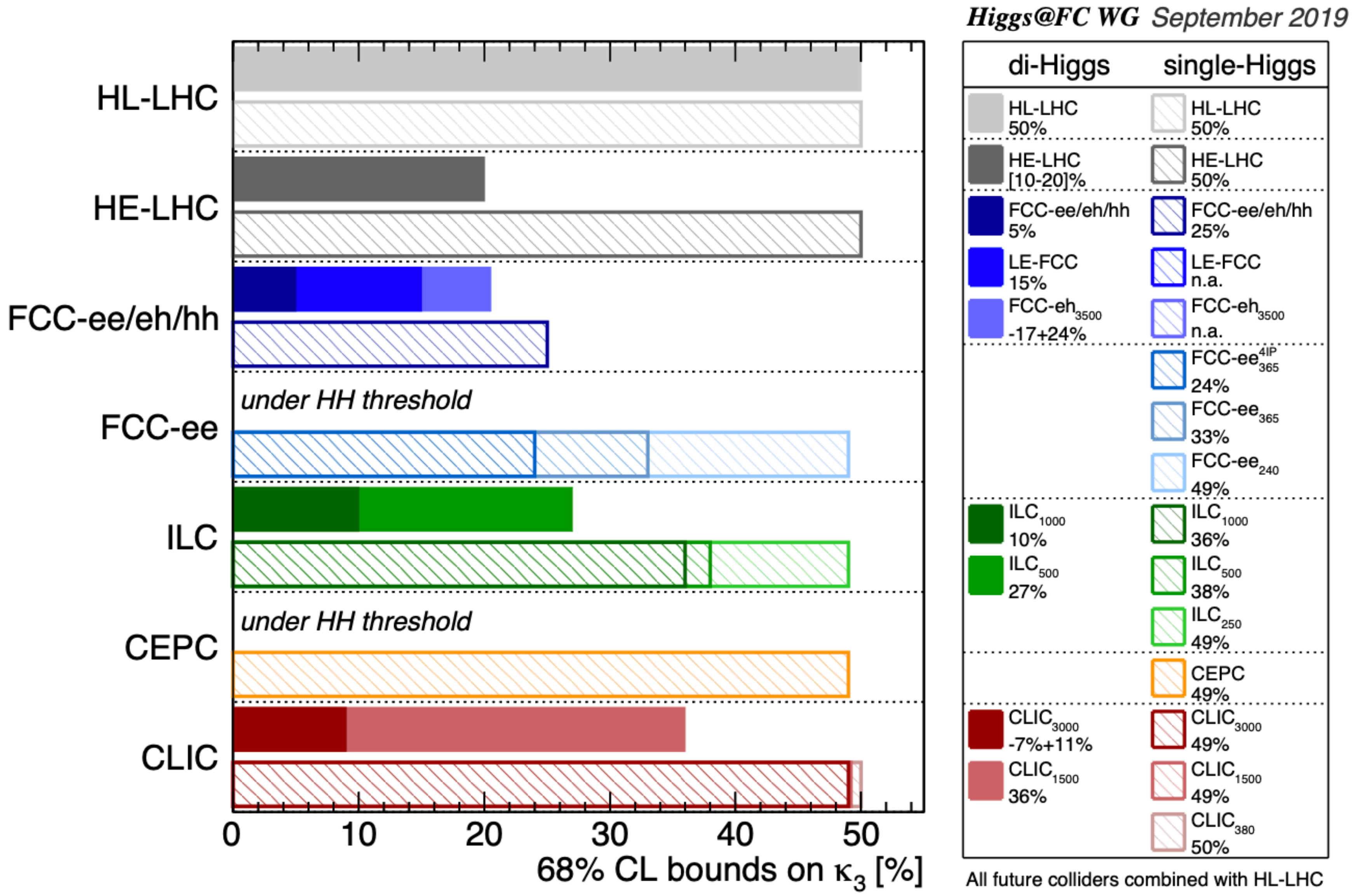
$\sqrt{s} \gtrsim 240$–250 GeV



$\delta\sigma_{ZH} \sim O(1\%)$

Goal: update the projections in ESU 2020

[Physics Briefing Book, arXiv:1910.11775]



- based on global SMEFT fits
- HL-LHC di-Higgs contribution was always combined

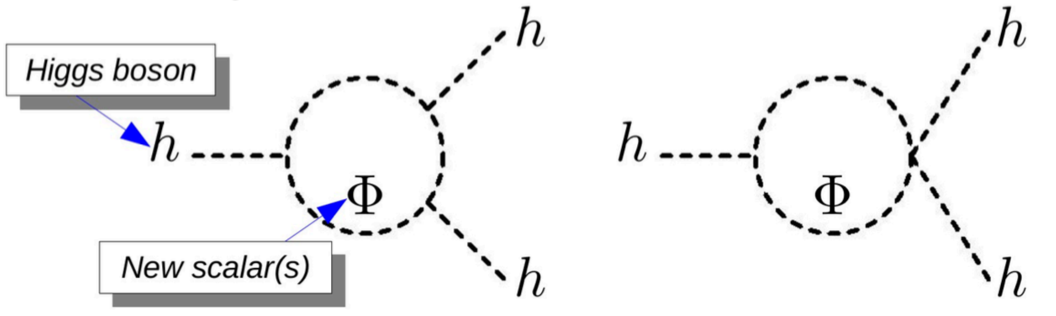
- focus: detailed look in Single-Higgs about other NLO effects; potential improvement in Di-Higgs analyses

(ii) progress in theory

[talk by J. Braathen]

Probing New Physics with the trilinear Higgs coupling

- **Large effects from New Physics possible in λ$_{hhh}$** due to radiative corrections from extra scalars, e.g. at leading order



$$g_{hh\Phi\Phi} = -\frac{2(M^2 - m_\Phi^2)}{v^2}$$

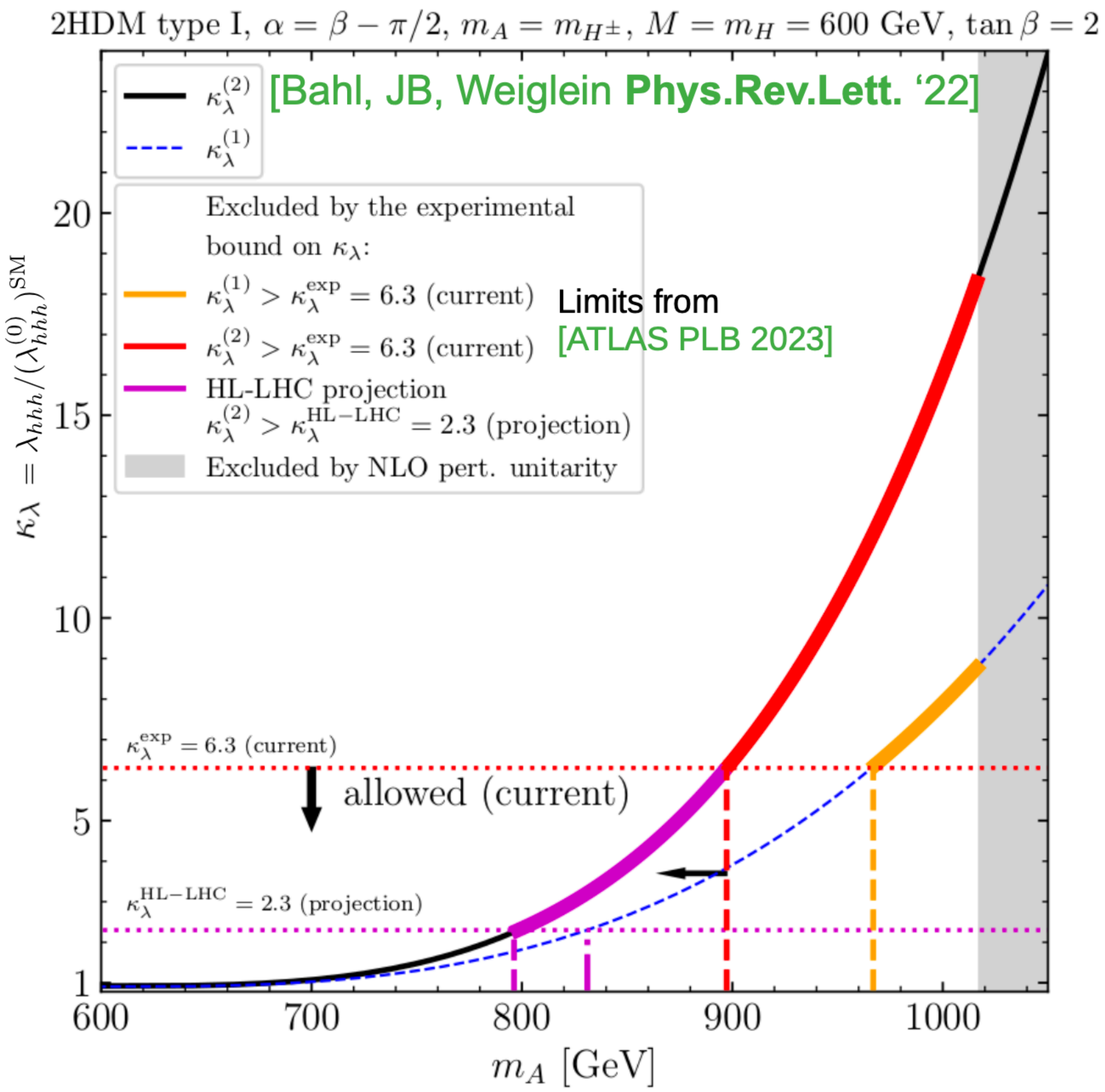
- Comparing latest exp. bounds

$$-1.2 < \kappa_\lambda = \frac{\lambda_{hhh}}{(\lambda_{hhh}^{(0)})^{\mathrm{SM}}} < 7.2$$

[ATLAS 2024]

with precise theory predictions for λ$_{hhh}$ provides a **powerful new tool to constrain BSM models**

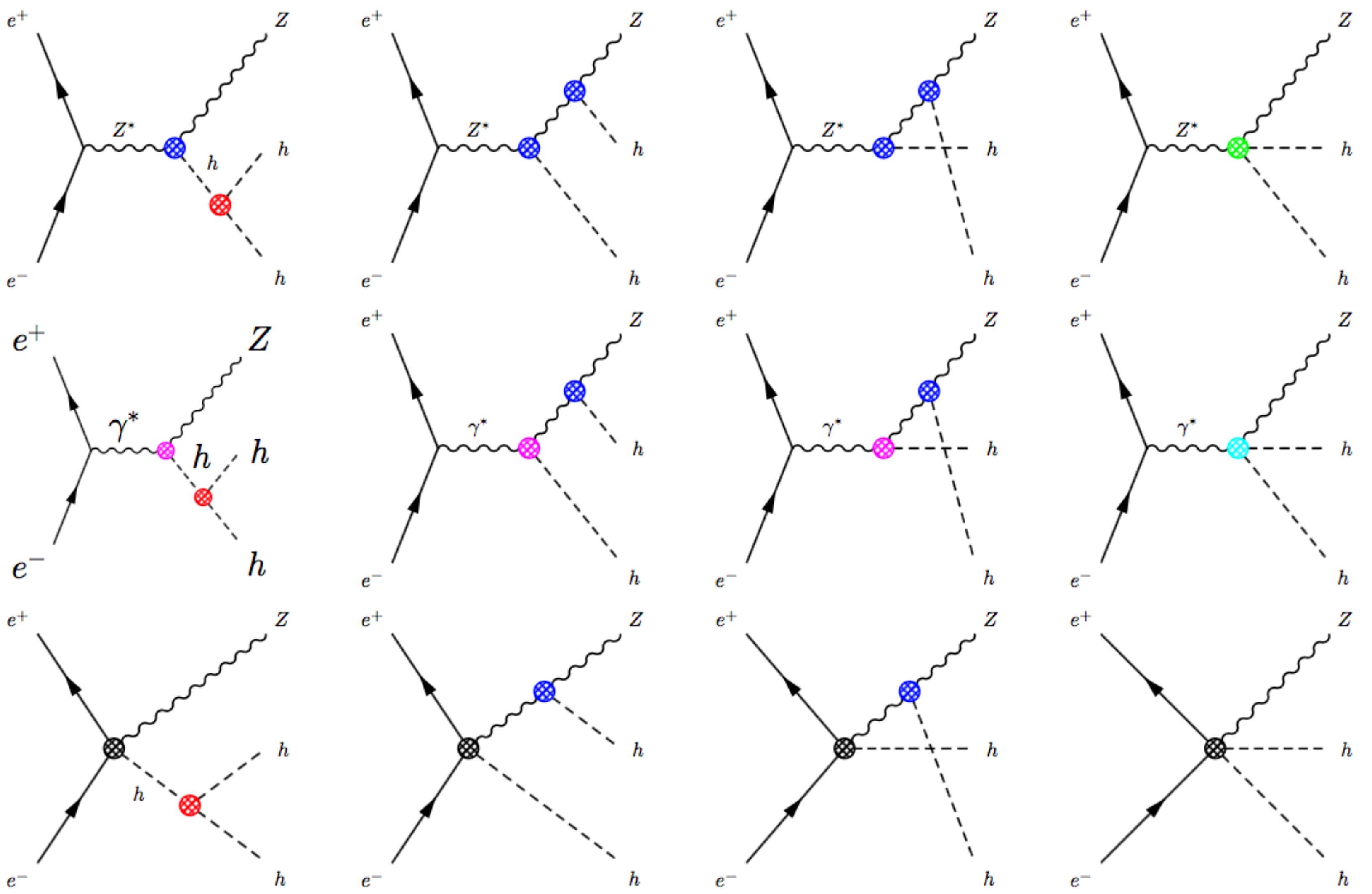
[Bahl, JB, Weiglein **Phys.Rev.Lett.** '22]



[Bahl, JB, Weiglein **Phys.Rev.Lett.** '22]

Limits from [ATLAS PLB 2023]

(iii) progress in double-Higgs approach



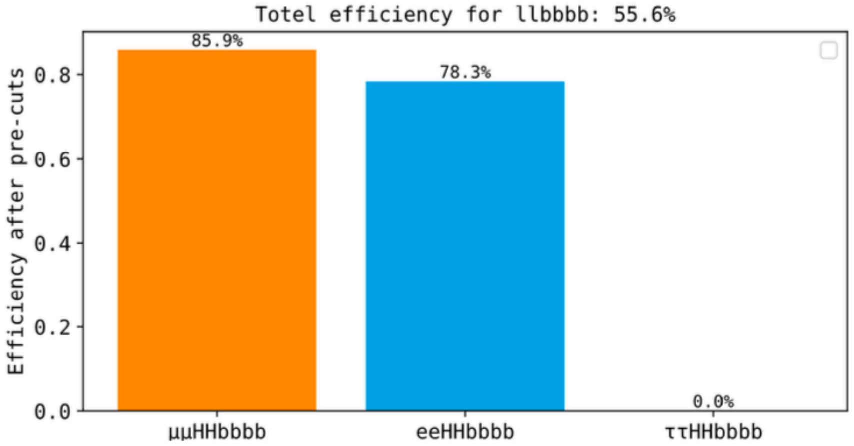
[Barklow, Fujii, Jung, Peskin, JT, '17]

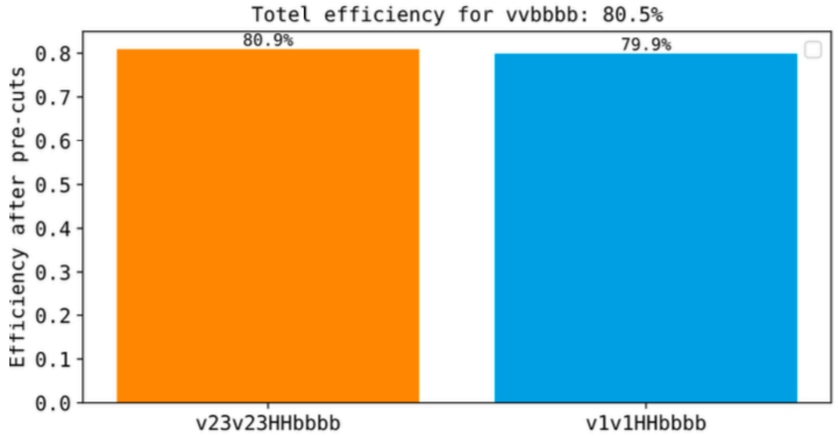
- degeneracies from same-order SMEFT resolved
- Main questions are related to how we can improve experimental analyses

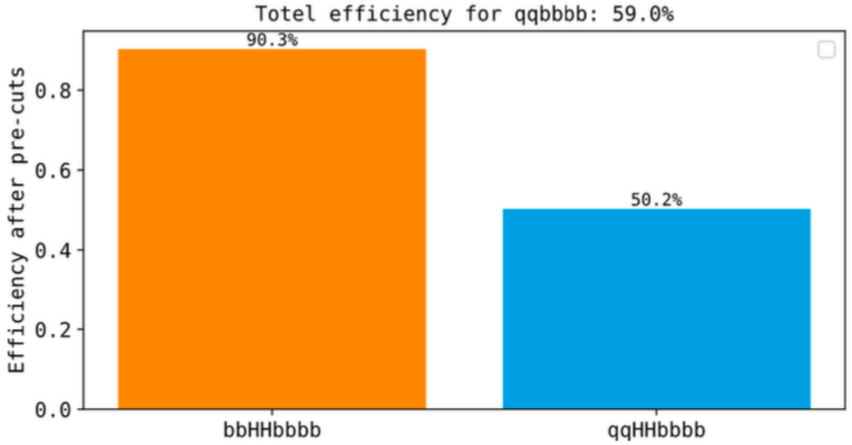
(iii) progress in double-Higgs approach

[talk by B. Bliewert]

	Last	**Now**
llbbbb	**53.8%**	**55.6%**
vvbbbb	**75.4%**	**80.5%**
qqbbbb	**58.8%**	**59.0%**



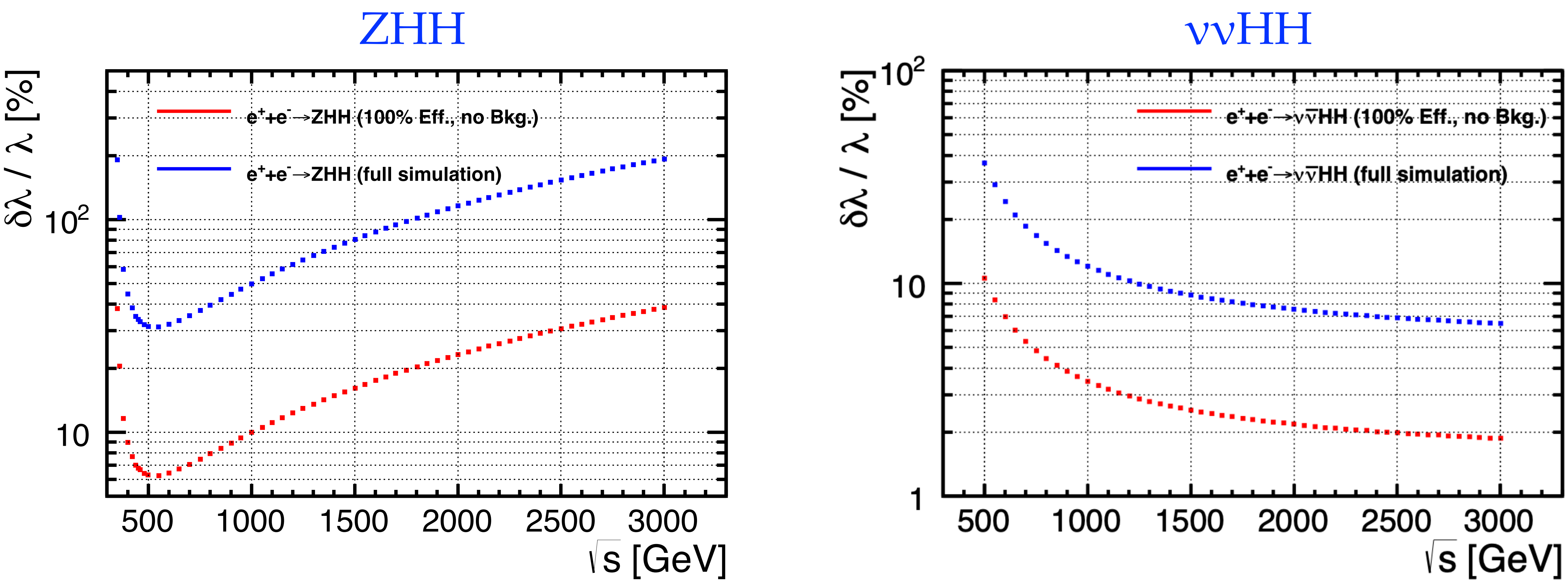




(new flavor tagging not included yet)

- Potential improvements: More Signal channels; Modern analysis techniques, ML for favor-tagging, jet-clustering, etc.
- Updated ZHH analysis ongoing, incorporating some latest algorithms

(iii) di-Higgs: $\Delta\lambda_{HHH}$ a factor of 5 from "perfect"

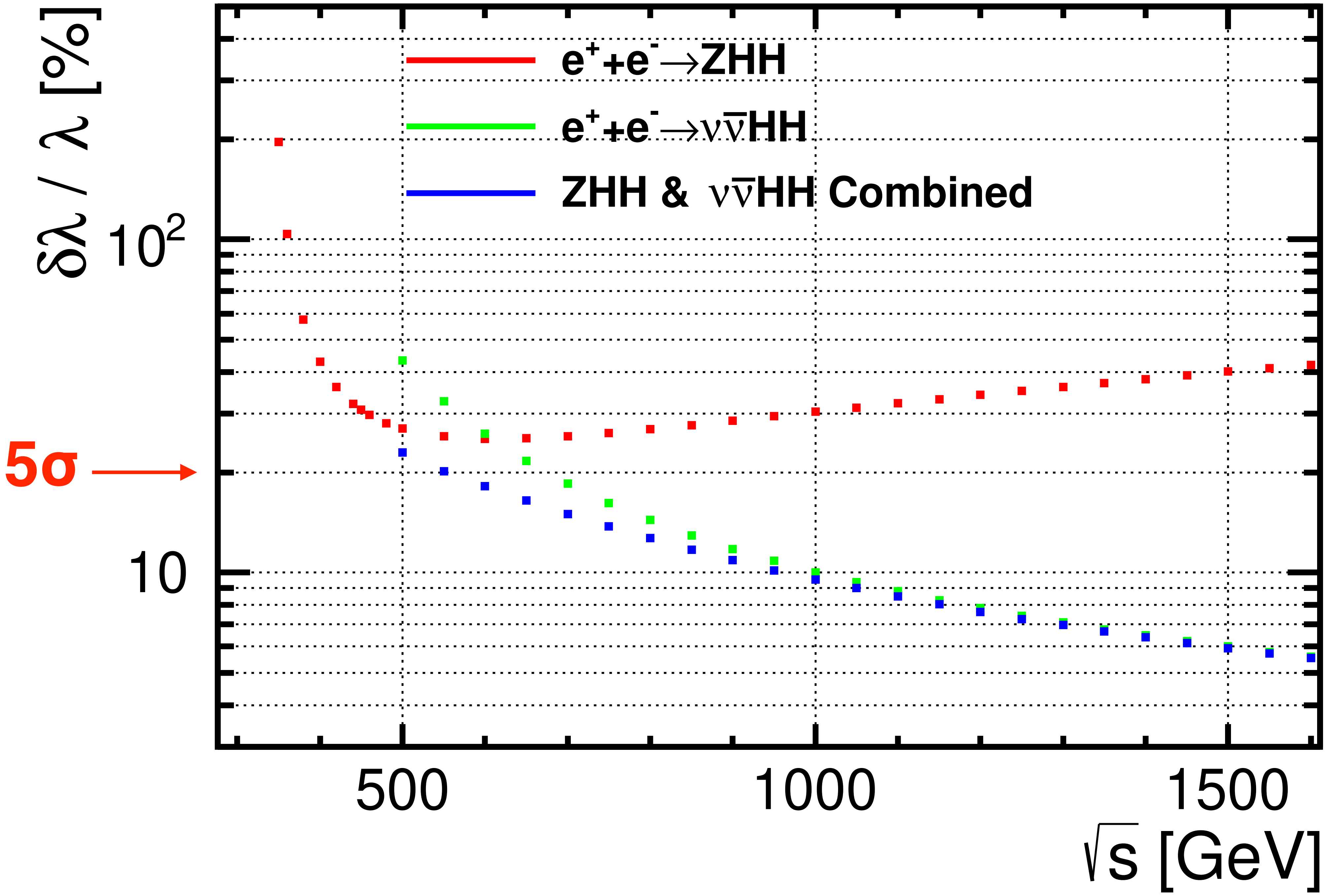


[Duerig, PhD Theis, 2016]

- how far can we go?
- welcome to join the adventure!

(iii) di-Higgs: updated projection $\Delta\lambda_{HHH}$

- two production channels **combined** at all √s: WW-fusion channel rapidly becomes useful just a little above 500 GeV
- luminosity now also scaled **proportionally** to √s



Discovery can be guaranteed

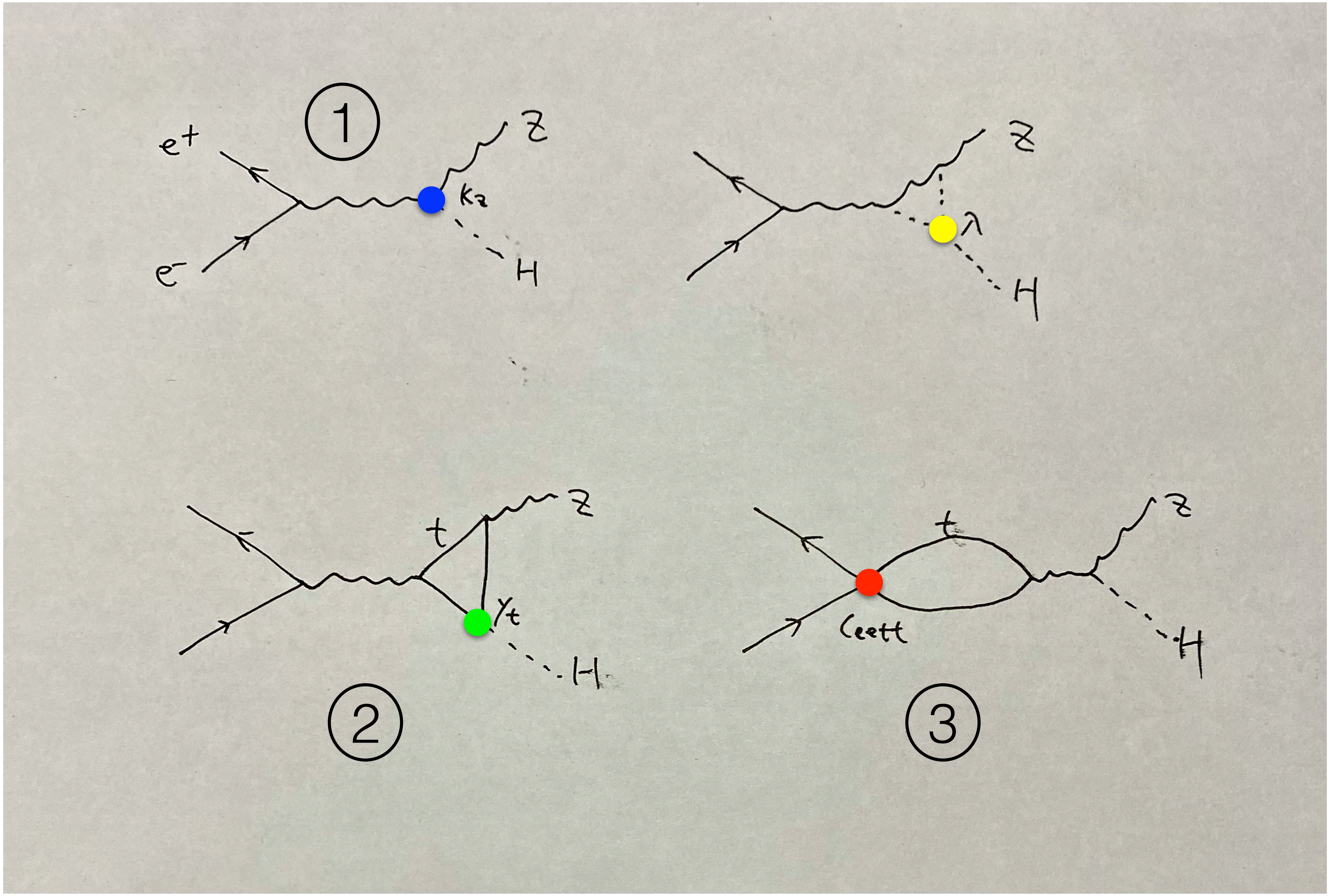
ILC500: 23%

ILC550: 20%

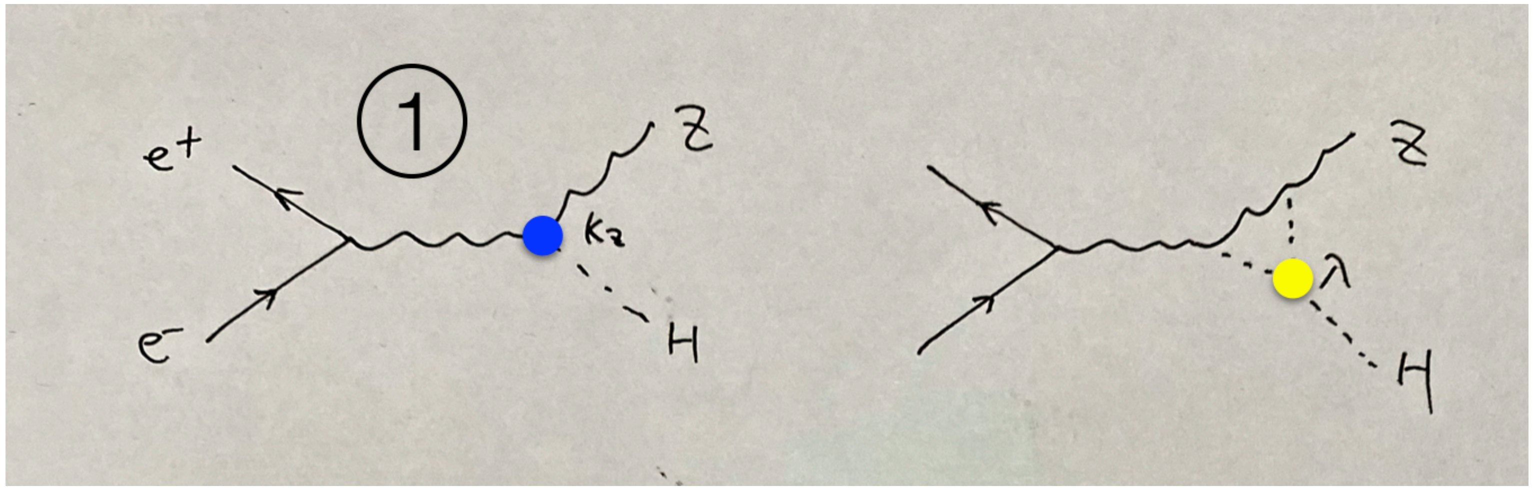
ILC600: 18%

note: this is still based on old ILD DBD analysis

(iv) progress in Single-Higgs: same-order (higher) effects



(iv) How to discriminate with HZZ coupling

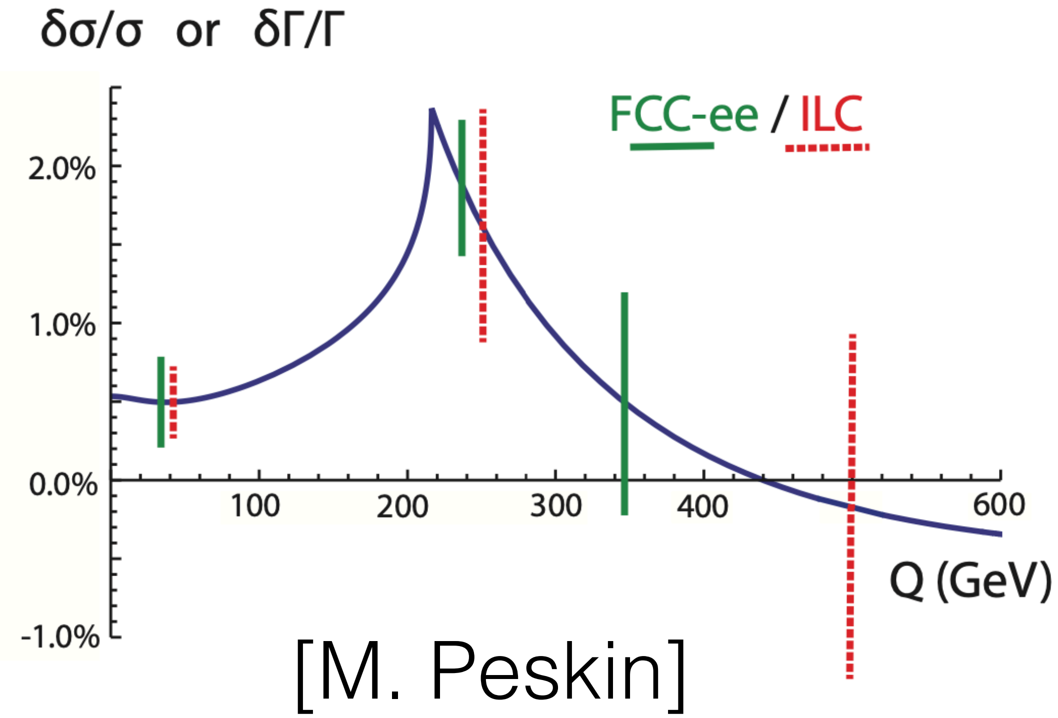


[McCullough, ’13]

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

- **$\delta\sigma_{ZH} < 1\%$** is a necessity; but not sufficient
- δσ could receive contributions from many other sources

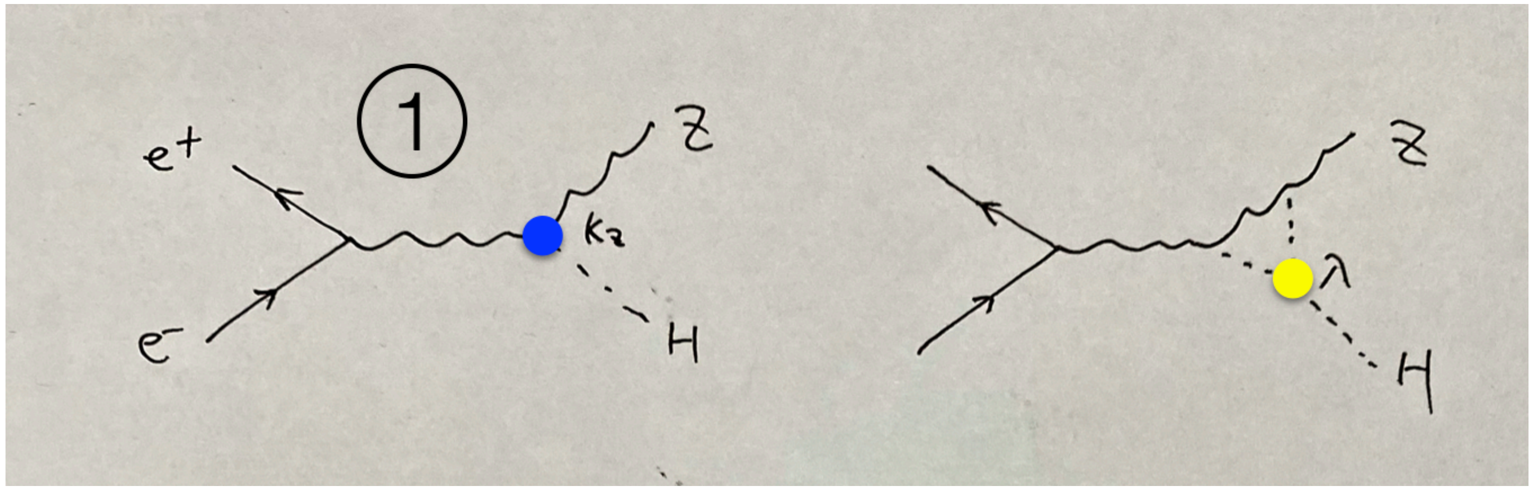
  —> **δh ~ O(500)%** at 250GeV only; [Gu, et al, arXiv:1711.03978]



[M. Peskin]

- **“easy” solution: lift degeneracy by multiple √s**

(iv) How to discriminate with HZZ coupling



[McCullough, '13]

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

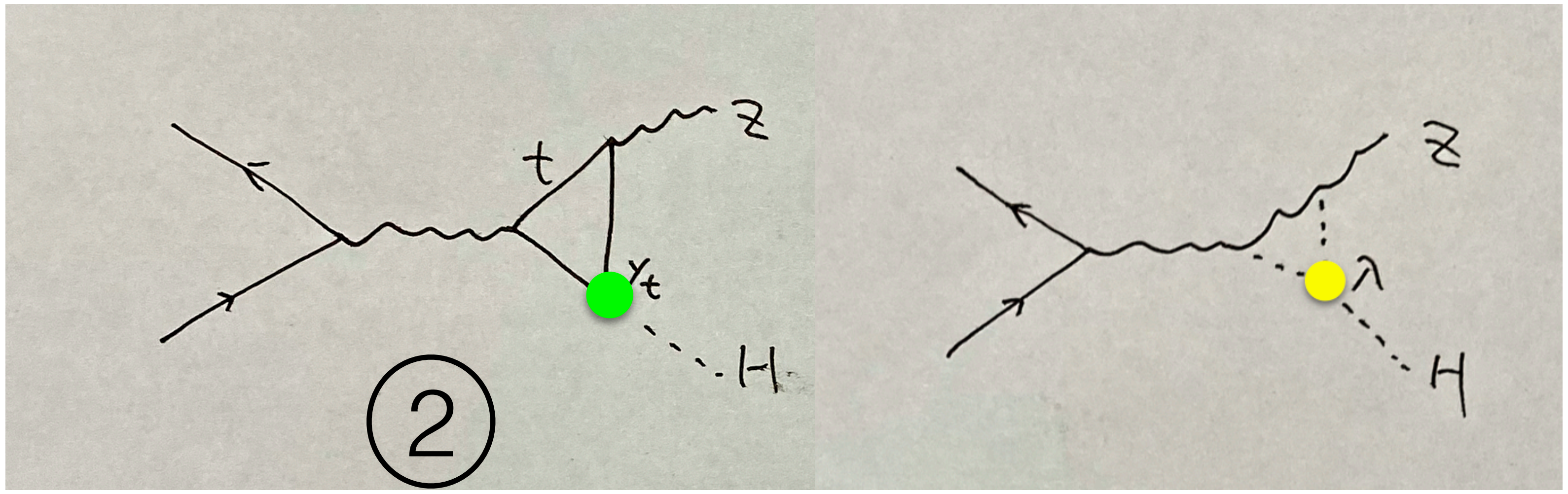
- **difficult solution: using differential cross section**

- effect of λ can be probed with anomalous HZZ coupling

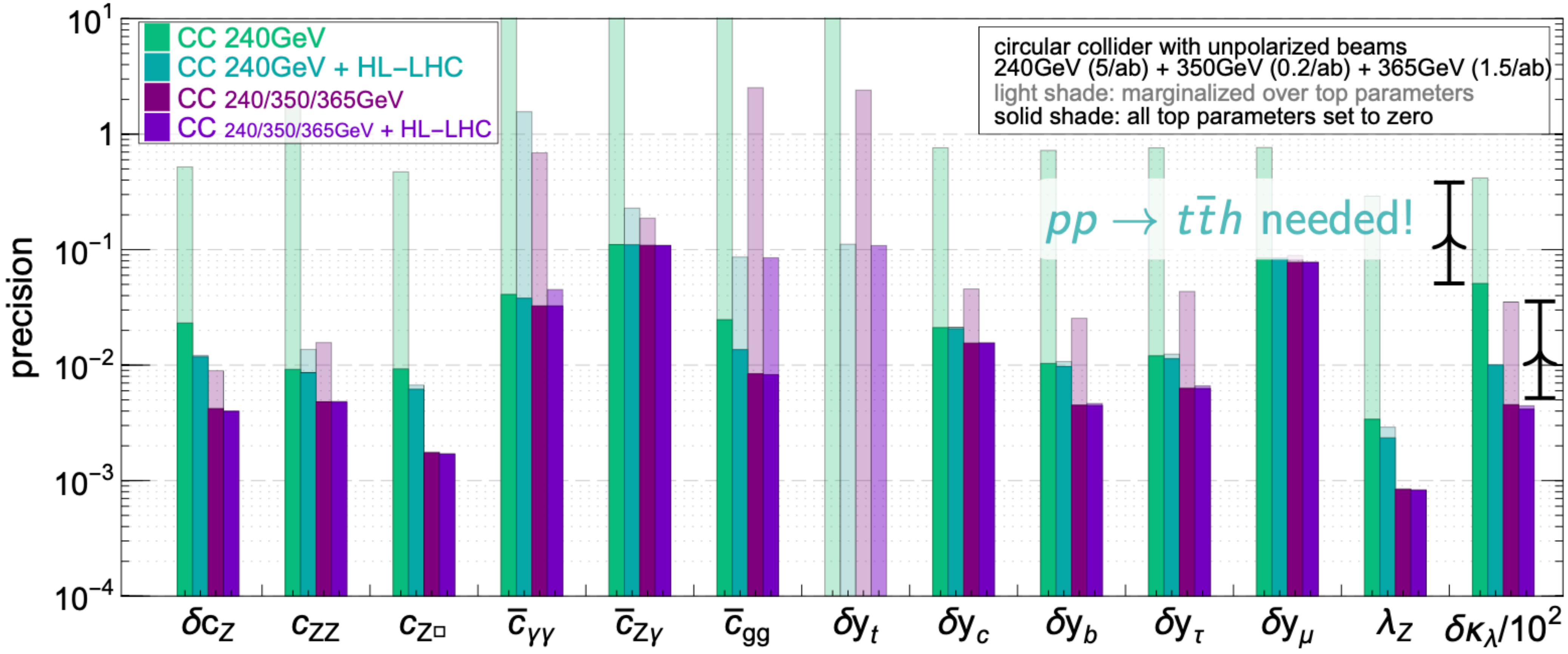
$$\mathscr{L} = m_Z^2(\frac{1}{v} + \frac{a}{\Lambda})HZ^\mu Z_\mu + \frac{b}{2\Lambda}HZ^{\mu\nu}Z_{\mu\nu} + \frac{\tilde{b}}{\Lambda}HZ^{\mu\nu}\tilde{Z}_{\mu\nu}$$

- angular meas. may help **[connection with ZHang]**

(iv) How to discriminate with top-Yukawa coupling



- **mitigated by LHC top-Yukawa measurement**

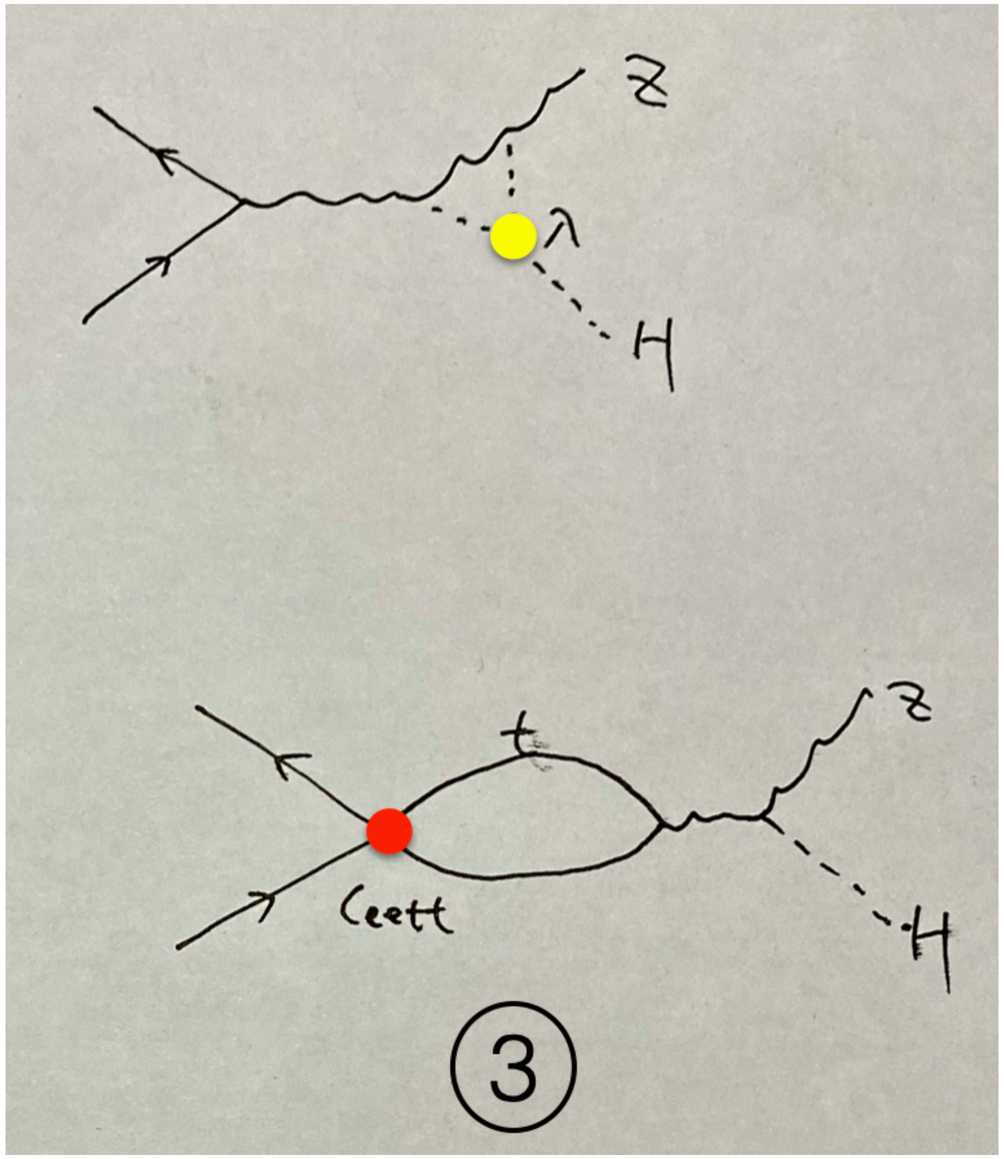


Top-quark uncertainties can impede Higgs precision!

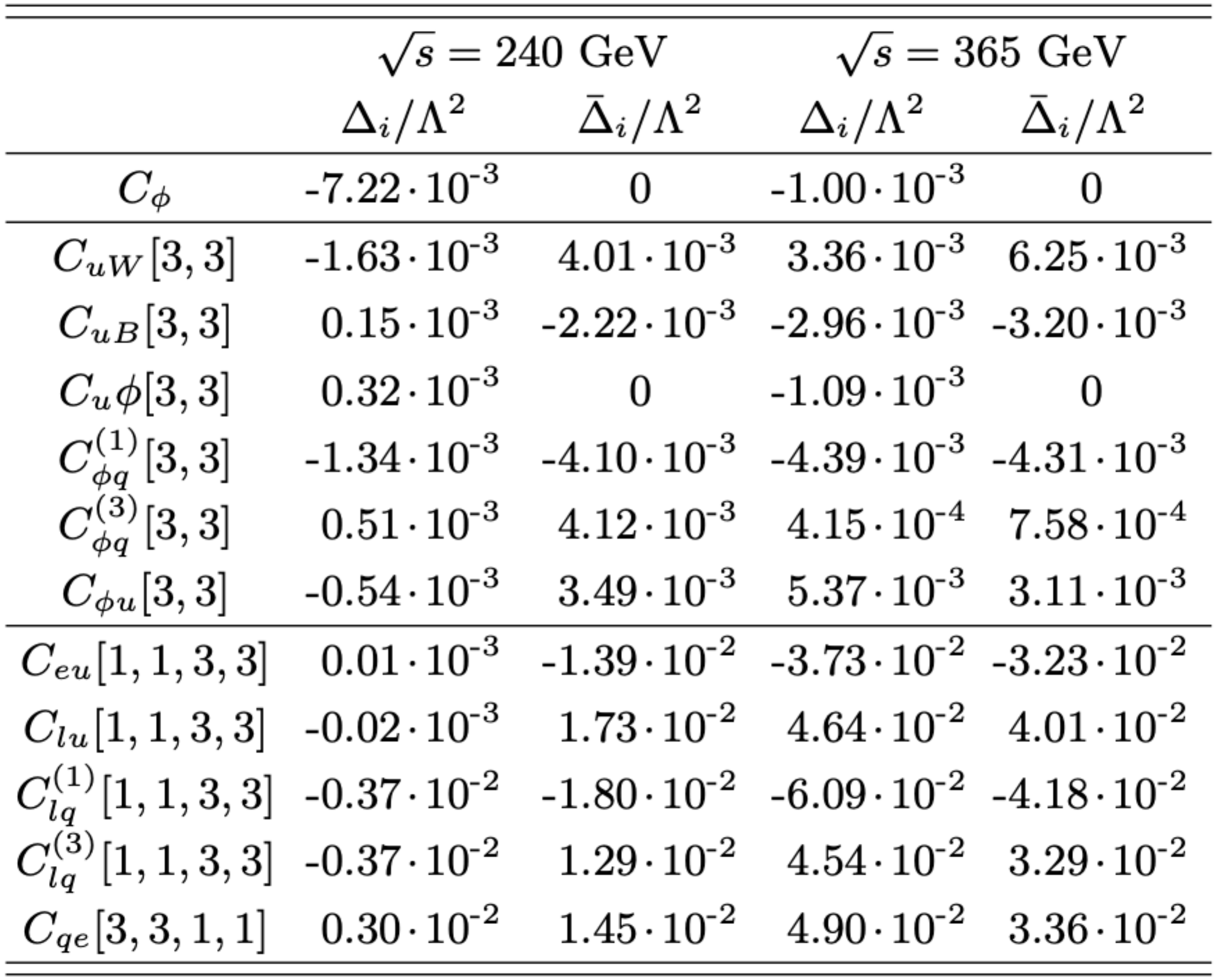
[Durieux, Gu, Vyronidou, Zhang, '18]

(iv) How to discriminate with 4-fermion interaction

[talk by P. Giardino]



- the effects from (many) eett operators have just been calculated! [Asteriadis, Dawson, Giardino, Szafron, arXiv:2406.03257]

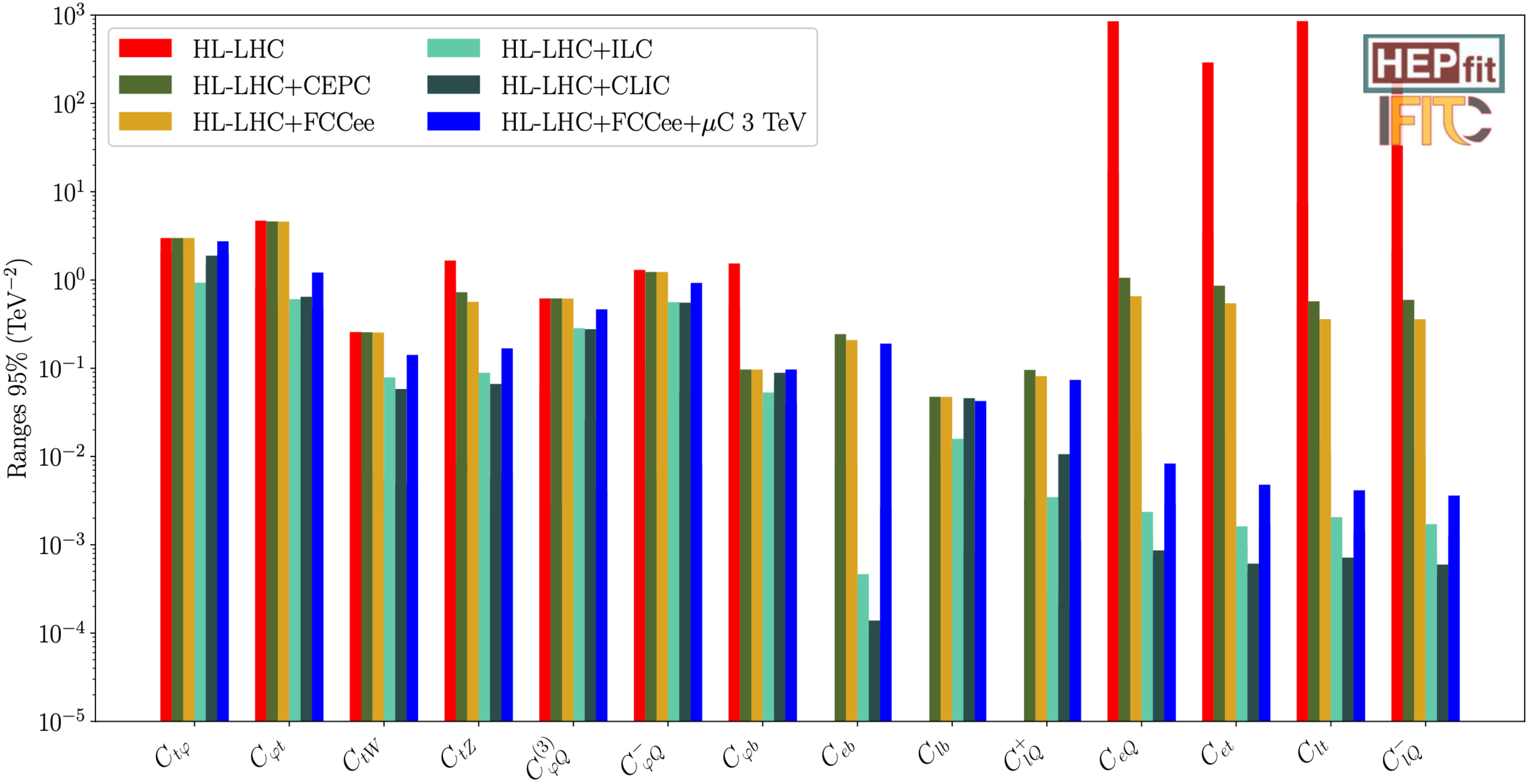


	$\sqrt{s} = 240$ GeV		$\sqrt{s} = 365$ GeV	
	Δ_i/Λ^2	$\bar{\Delta}_i/\Lambda^2$	Δ_i/Λ^2	$\bar{\Delta}_i/\Lambda^2$
C_ϕ	$-7.22\cdot10^{-3}$	0	$-1.00\cdot10^{-3}$	0
$C_{uW}[3,3]$	$-1.63\cdot10^{-3}$	$4.01\cdot10^{-3}$	$3.36\cdot10^{-3}$	$6.25\cdot10^{-3}$
$C_{uB}[3,3]$	$0.15\cdot10^{-3}$	$-2.22\cdot10^{-3}$	$-2.96\cdot10^{-3}$	$-3.20\cdot10^{-3}$
$C_{u\phi}[3,3]$	$0.32\cdot10^{-3}$	0	$-1.09\cdot10^{-3}$	0
$C_{\phi q}^{(1)}[3,3]$	$-1.34\cdot10^{-3}$	$-4.10\cdot10^{-3}$	$-4.39\cdot10^{-3}$	$-4.31\cdot10^{-3}$
$C_{\phi q}^{(3)}[3,3]$	$0.51\cdot10^{-3}$	$4.12\cdot10^{-3}$	$4.15\cdot10^{-4}$	$7.58\cdot10^{-4}$
$C_{\phi u}[3,3]$	$-0.54\cdot10^{-3}$	$3.49\cdot10^{-3}$	$5.37\cdot10^{-3}$	$3.11\cdot10^{-3}$
$C_{eu}[1,1,3,3]$	$0.01\cdot10^{-3}$	$-1.39\cdot10^{-2}$	$-3.73\cdot10^{-2}$	$-3.23\cdot10^{-2}$
$C_{lu}[1,1,3,3]$	$-0.02\cdot10^{-3}$	$1.73\cdot10^{-2}$	$4.64\cdot10^{-2}$	$4.01\cdot10^{-2}$
$C_{lq}^{(1)}[1,1,3,3]$	$-0.37\cdot10^{-2}$	$-1.80\cdot10^{-2}$	$-6.09\cdot10^{-2}$	$-4.18\cdot10^{-2}$
$C_{lq}^{(3)}[1,1,3,3]$	$-0.37\cdot10^{-2}$	$1.29\cdot10^{-2}$	$4.54\cdot10^{-2}$	$3.29\cdot10^{-2}$
$C_{qe}[3,3,1,1]$	$0.30\cdot10^{-2}$	$1.45\cdot10^{-2}$	$4.90\cdot10^{-2}$	$3.36\cdot10^{-2}$

(iv) How to discriminate with 4-fermion interaction

[talk by M. Vos]

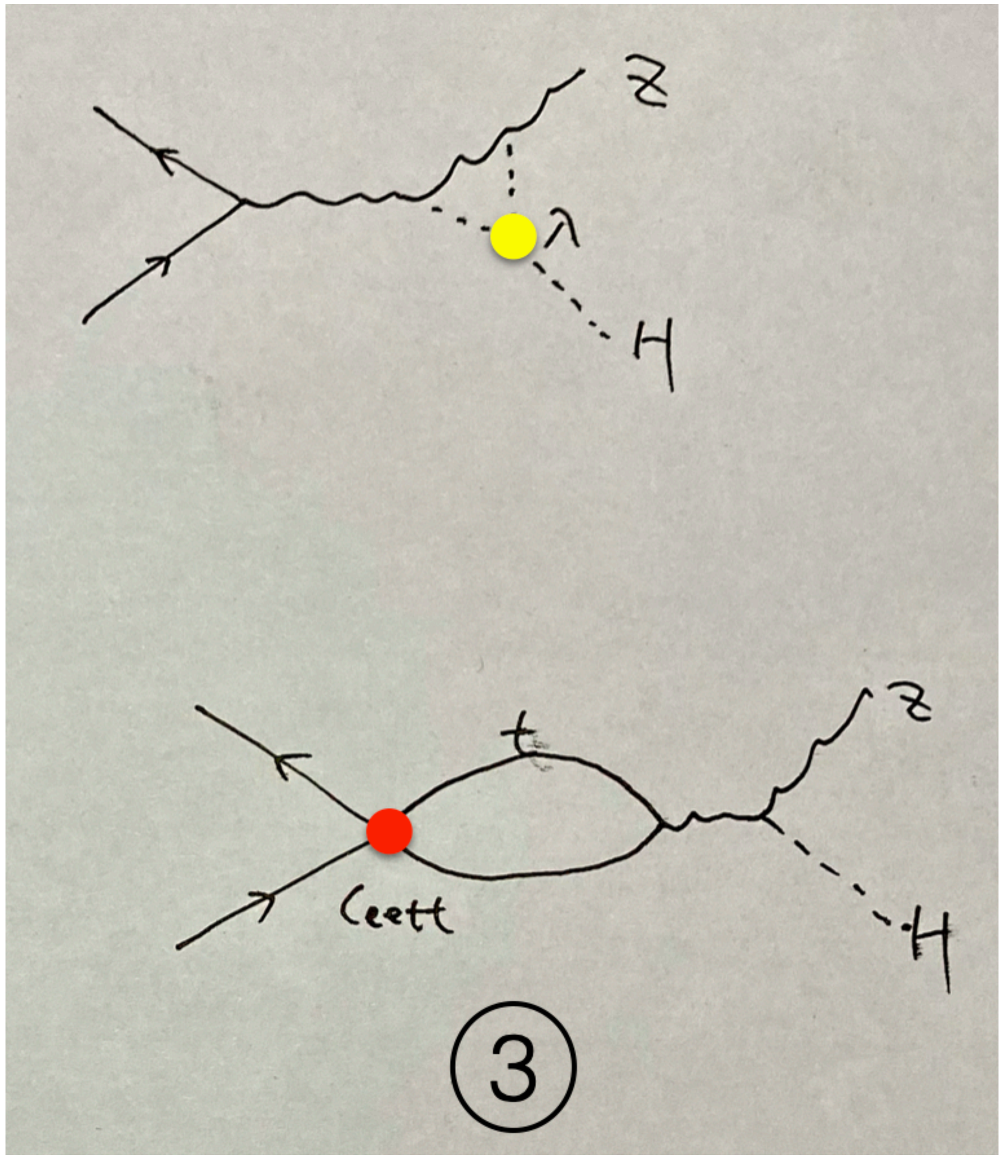
- need projection for eett at HL-LHC & e+e-



All e+e- colliders improve the bounds on the top sector dramatically
High-energy operation is important to provide the strongest global bounds

(iv) first look at the global fit with NLO eett for $\Delta\lambda_{HHH}$

[ongoing work by: Yong Du, Jiayin Gu, JT]



- based on a fitting program for last ESU: 23 (Higgs + WW + EWPO) + 5 (eett) operators
- take directly covariance matrix as eett bounds (from Victor Miralles)
- reproduced (almost) the NLO calculation about eett in ZH

extra uncertainty induced by eett on σ_{ZH}

$\delta\sigma_{ZH}$ ~ 0.3% (1.5%) for 240 (365) GeV

a test fit for 5000 fb^{-1} (240) + 1500 fb^{-1} (365)

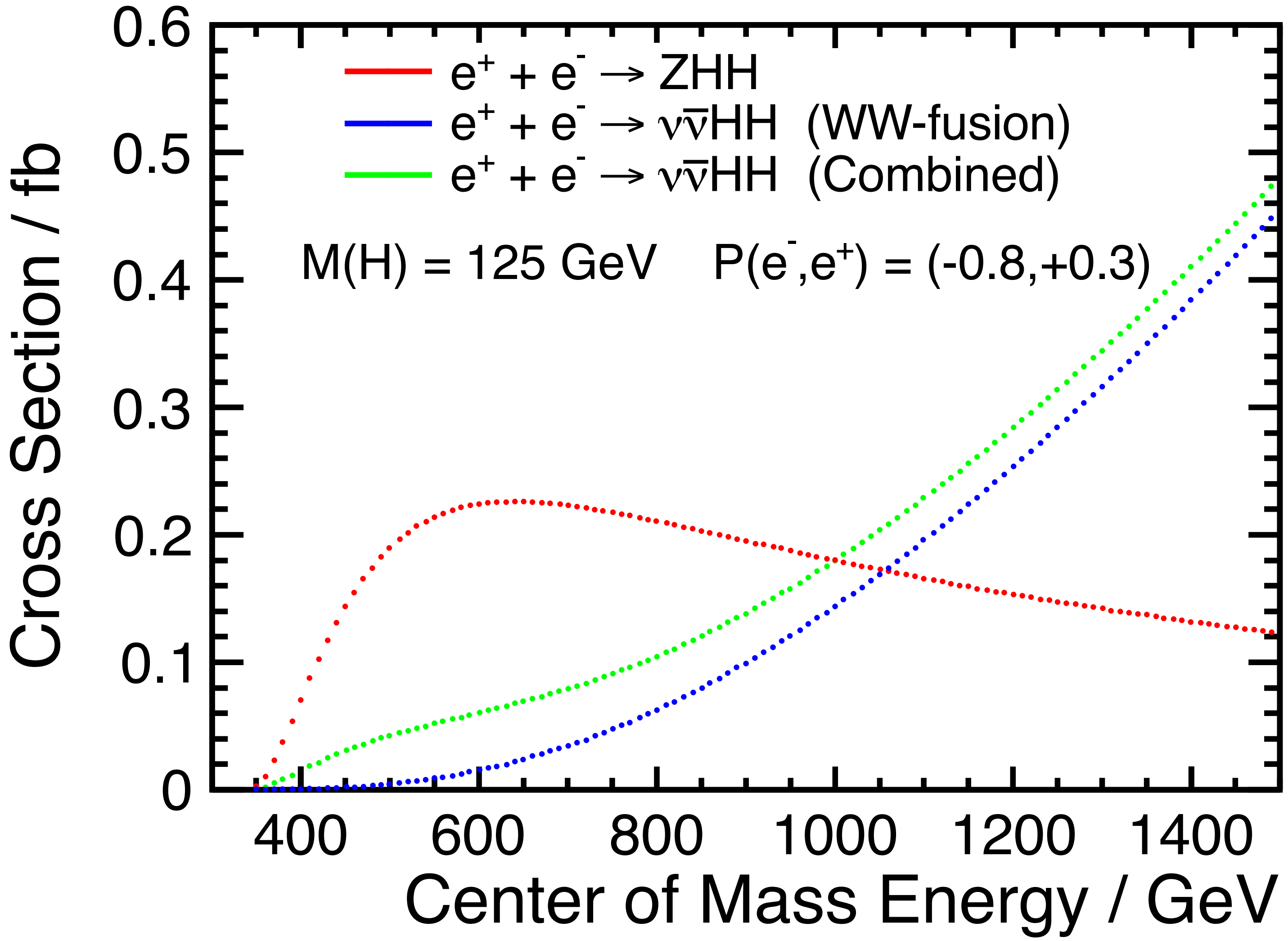
$\delta\lambda_{HHH}$ mildly degraded from 57% to 77%

[warning: this is very preliminary, many things to be done, e.g. include NLO eett in other observables as well.]

summary

- Many progresses on theory, di-Higgs & single-Higgs approaches
- Large corrections to λ_{HHH} in BSM models
- Ongoing di-Higgs analysis to update λ_{HHH} projection
- A new global SMEFT fit is being worked out to address the opportunity / challenges in probing λ_{HHH} using single-Higgs

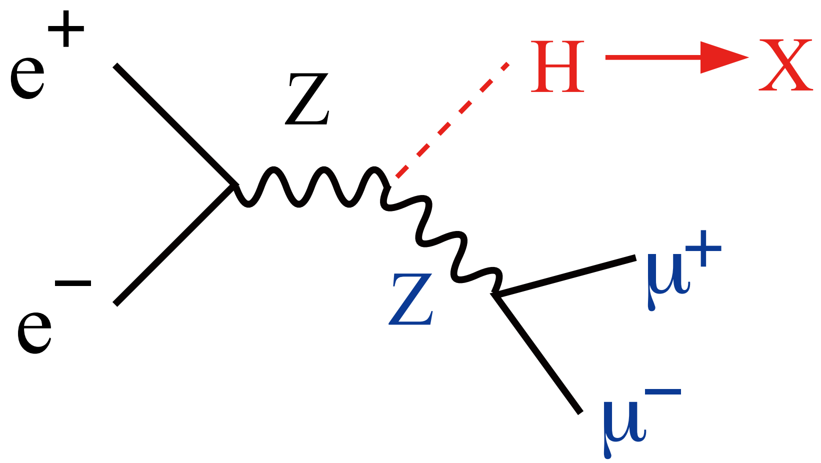
backup

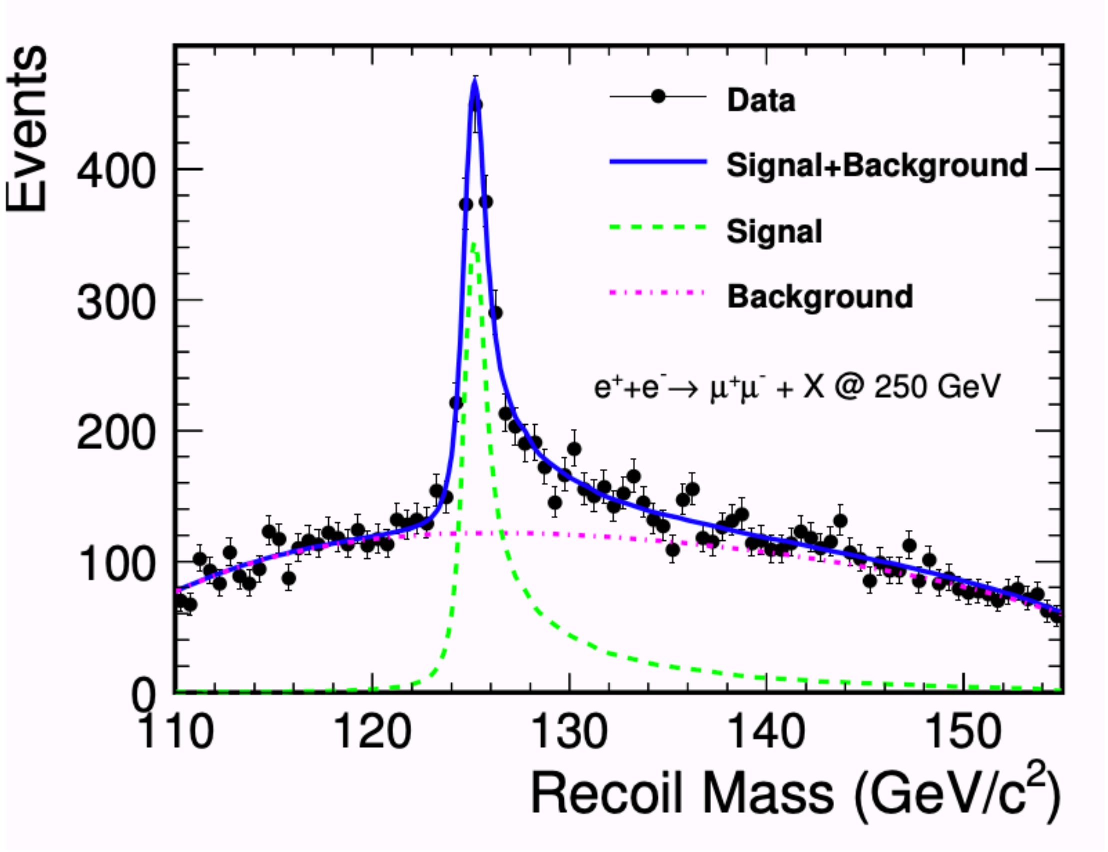


Cross Section / fb
0.6
0.5
0.4
0.3
0.2
0.1
0
400
600
800
1000
1200
1400
Center of Mass Energy / GeV
$e^+ + e^- \rightarrow ZHH$
$e^+ + e^- \rightarrow \nu\bar{\nu}HH$ (WW-fusion)
$e^+ + e^- \rightarrow \nu\bar{\nu}HH$ (Combined)
M(H) = 125 GeV
$P(e^-,e^+) = (-0.8,+0.3)$

Challenges: $\delta\sigma_{ZH}$ << 1%?

- **A: yes!** Just give me **1 million** recoil Higgs events —>0.1%
- **B: likely!** Assume only **1/4** of the 1M events useful —> 0.2%
- **C: let's look at some systematics first**





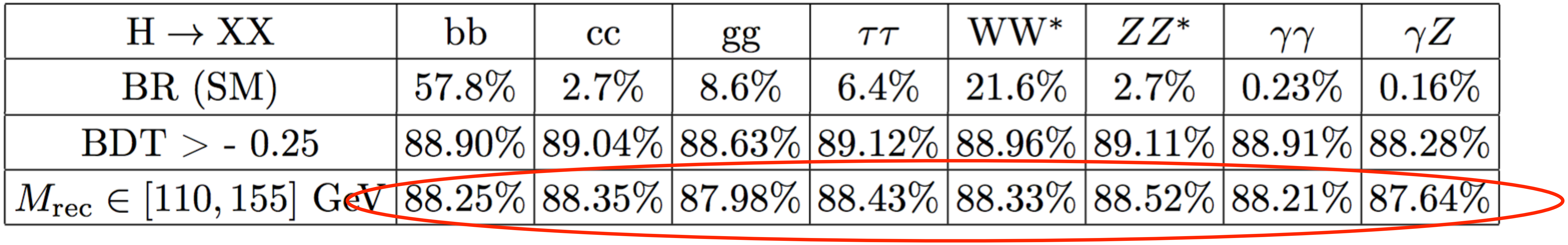
[Yan et al, arXiv:1604.07524]

▶ a crucial requirement for measuring σ_{ZH} using recoil mass technique: **independent of how Higgs decay —> who not just test it!**

Challenges: $\delta\sigma_{ZH}$ << 1%?

- Z—>μμ: δEfficiency ~ 1%

[Yan et al, arXiv:1604.07524]

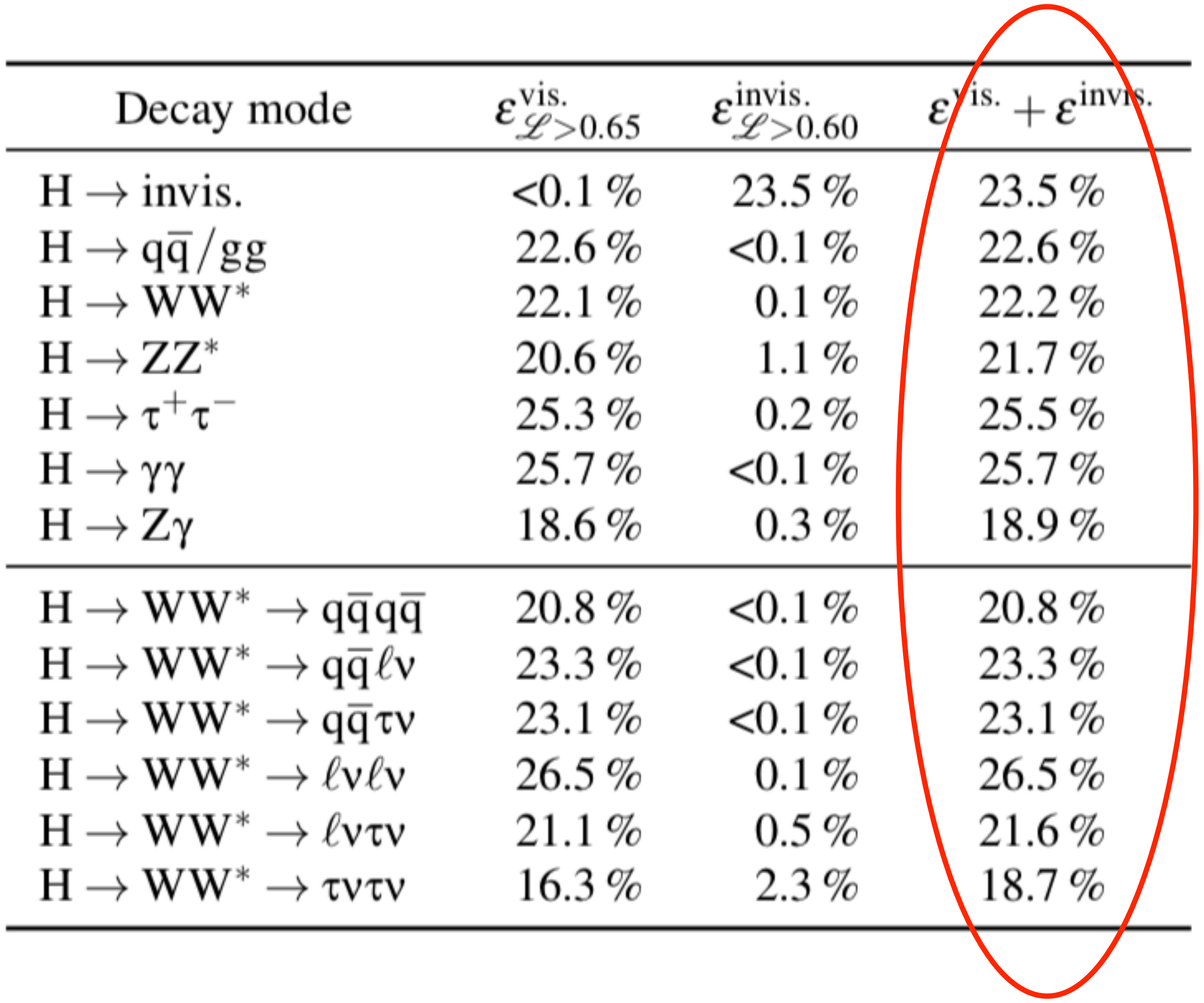


$H \to XX$	bb	cc	gg	$\tau\tau$	WW*	ZZ^*	$\gamma\gamma$	γZ
BR (SM)	57.8%	2.7%	8.6%	6.4%	21.6%	2.7%	0.23%	0.16%
BDT > - 0.25	88.90%	89.04%	88.63%	89.12%	88.96%	89.11%	88.91%	88.28%
$M_{\text{rec}} \in [110, 155]$ GeV	88.25%	88.35%	87.98%	88.43%	88.33%	88.52%	88.21%	87.64%

- Z—>qq: δEfficiency ~ 15%

[Thomson, arXiv:1509.02853]

[Tomita 2015; Miyamoto, arXiv:1311.2248]

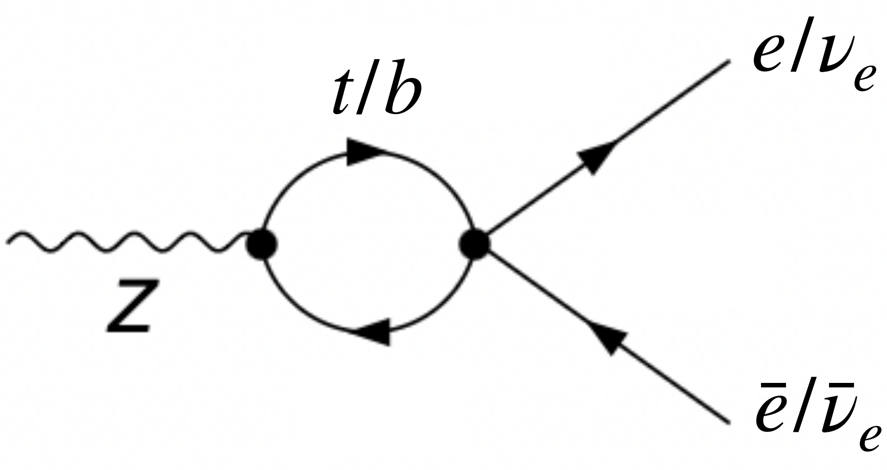


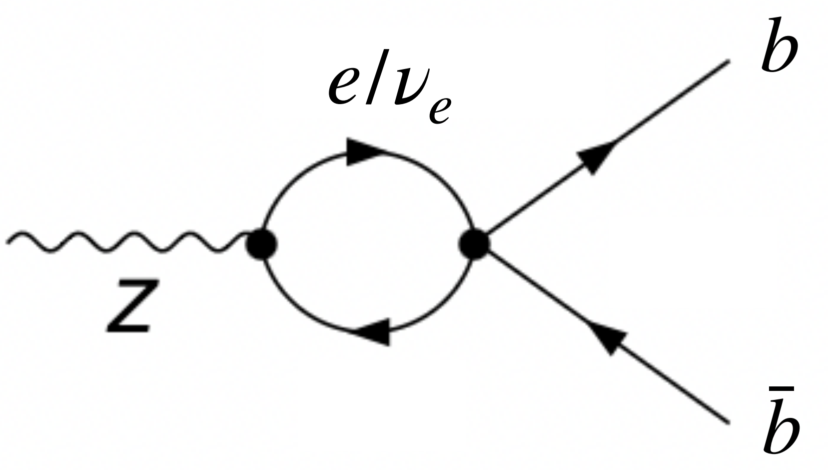
Decay mode	$\varepsilon^{\text{vis.}}_{\mathscr{L}>0.65}$	$\varepsilon^{\text{invis.}}_{\mathscr{L}>0.60}$	$\varepsilon^{\text{vis.}} + \varepsilon^{\text{invis.}}$
$H \to$ invis.	<0.1 %	23.5 %	23.5 %
$H \to q\bar{q}/gg$	22.6 %	<0.1 %	22.6 %
$H \to WW^*$	22.1 %	0.1 %	22.2 %
$H \to ZZ^*$	20.6 %	1.1 %	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 %

- trash **99%** of those 1M events unless one can improve the bias

NLO SMEFT Global Fit: Z pole

Z pole observables: only affects $\Gamma_{Z\to\nu_e\bar{\nu}_e}$, $\Gamma_{Z\to ee}$, $\Gamma_{Z\to bb}$





$\Gamma_{Z\to\nu_e\bar{\nu}_e}$: t loop sensitive to $c_{lq}^{(1)}+c_{lq}^{(3)}$, b loop instead to $c_{lq}^{(1)}-c_{lq}^{(3)}$

$\Gamma_{Z\to ee}$: t loop sensitive to $c_{lq}^{(1)}-c_{lq}^{(3)}$, b loop instead to $c_{lq}^{(1)}+c_{lq}^{(3)}$

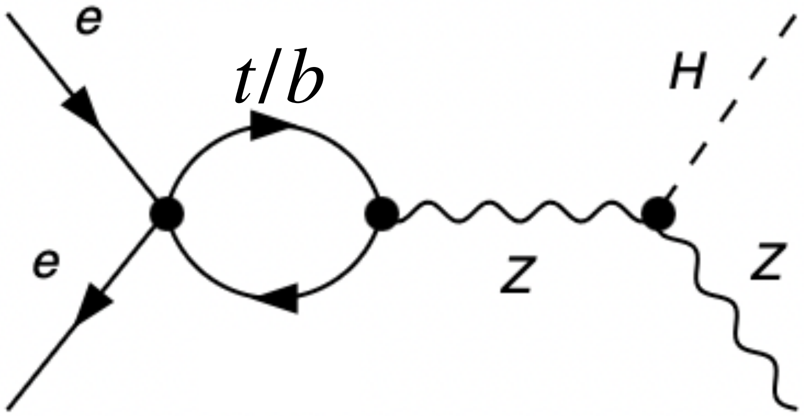
$\Gamma_{Z\to bb}$: sensitive to both $c_{lq}^{(1)}-c_{lq}^{(3)}$ and $c_{lq}^{(1)}+c_{lq}^{(3)}$

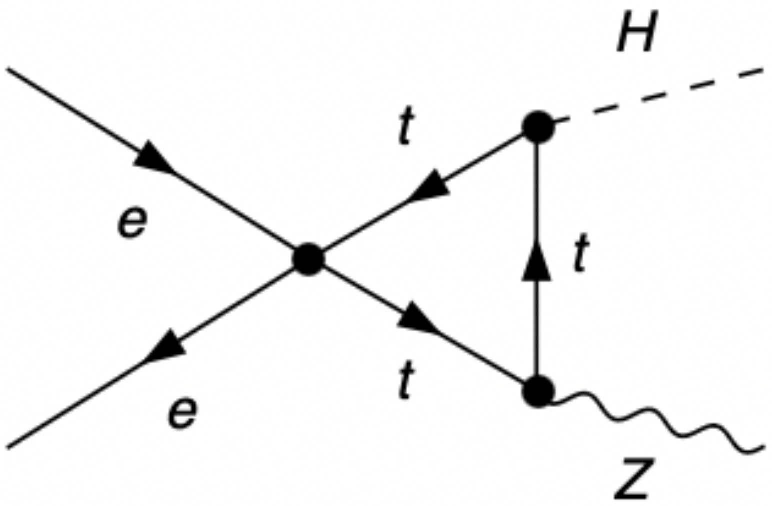
	Yong	Jorge
ceu	-0.00349183	0.00326031
clq1	-0.00445899	0.00353399
clq3	0.00321914	-0.00293391
clu	0.00398355	-0.00415644
ceq	0.00390859	-0.00277206

Generation indices ignored for all WCs;
$\overline{\text{MS}}$ subtraction scheme is used;
Renorm. scale fixed at $\mu=\Lambda=1\,\text{TeV}$
The Higgs basis is used to compare with Jorge

NLO SMEFT Global Fit: $e^+e^- \to Zh$

Corrections from $\mathcal{Q}_{eett}$ to Zh production at one loop





Results

$$\left(\begin{array}{c}\text{ceu}\\ \text{clu}\\ \text{clq1}\\ \text{clq3}\\ \text{ceq}\end{array}\right), \left(\begin{array}{cc|cc} \multicolumn{2}{c|}{\sqrt{s}=240\,\mathrm{GeV}} & \multicolumn{2}{c}{\sqrt{s}=365\,\mathrm{GeV}} \\ -0.0723259 & -1.44436 & -4.40175 & -3.36686 \\ 0.0825107 & 1.64775 & 5.0216 & 3.84097 \\ -0.275528 & -1.72153 & -5.31298 & -4.01294 \\ -0.168964 & 1.45483 & 4.27685 & 3.39127 \\ 0.241518 & 1.50903 & 4.65717 & 3.5176 \end{array}\right)\times 10^{-2}$$

Renorm. scale dependent part

(The Warsaw basis is used to compare with Sally)

Observation

Each corresponds to a gauge-invariant subset of diagrams.

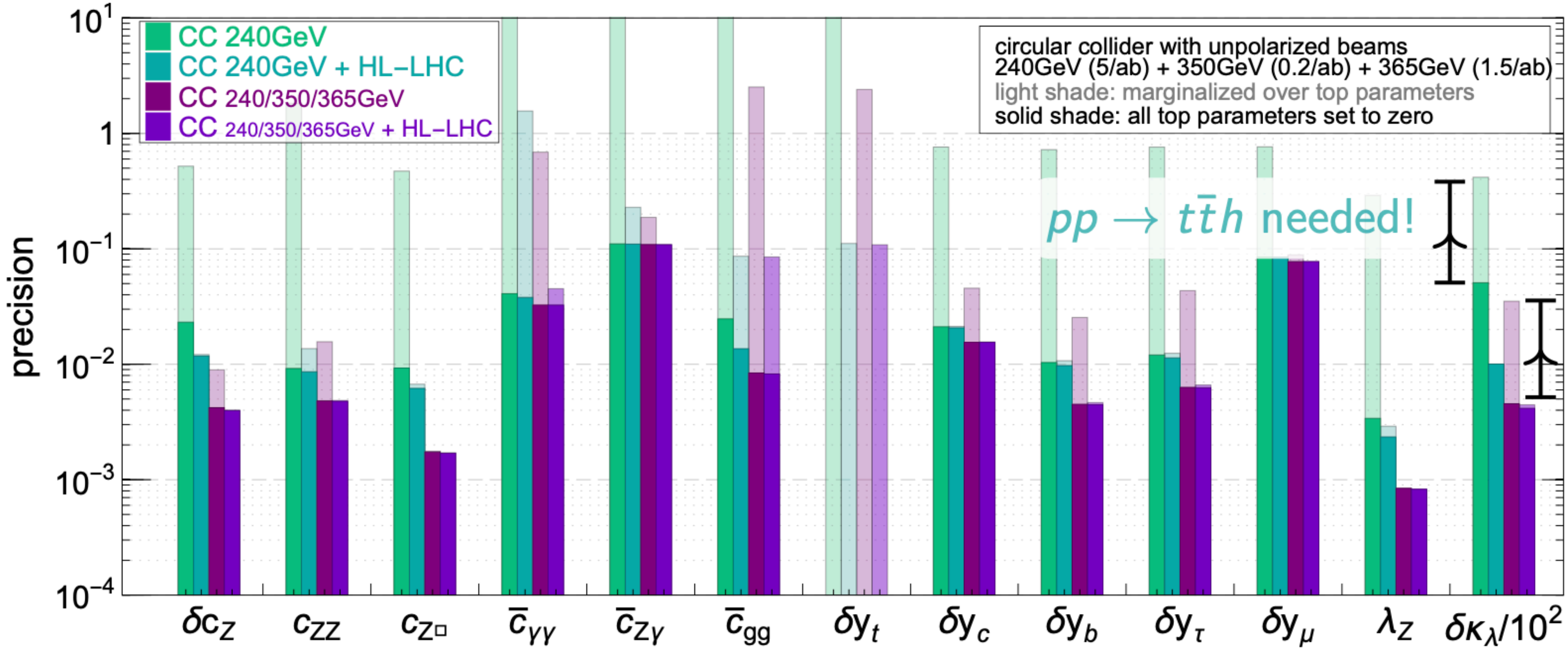
The triangle is of the same order as the self-energy loops (either t or b loop) on the left-hand side. There exists accidental cancellation between them.

y_b suppressed triangle diagrams are ignored; Goldstone self-energy diagrams are suppressed by m_e

Top and trilinear

[GD, Gu, Vryonidou, Zhang '18]
[see also Jung, Lee, Perelló, Tian, Vos '20]

light shades: 12 Higgs op. floated + 6 top op. floated
dark shades: 12 Higgs op. floated + 6 top op. $\to 0$



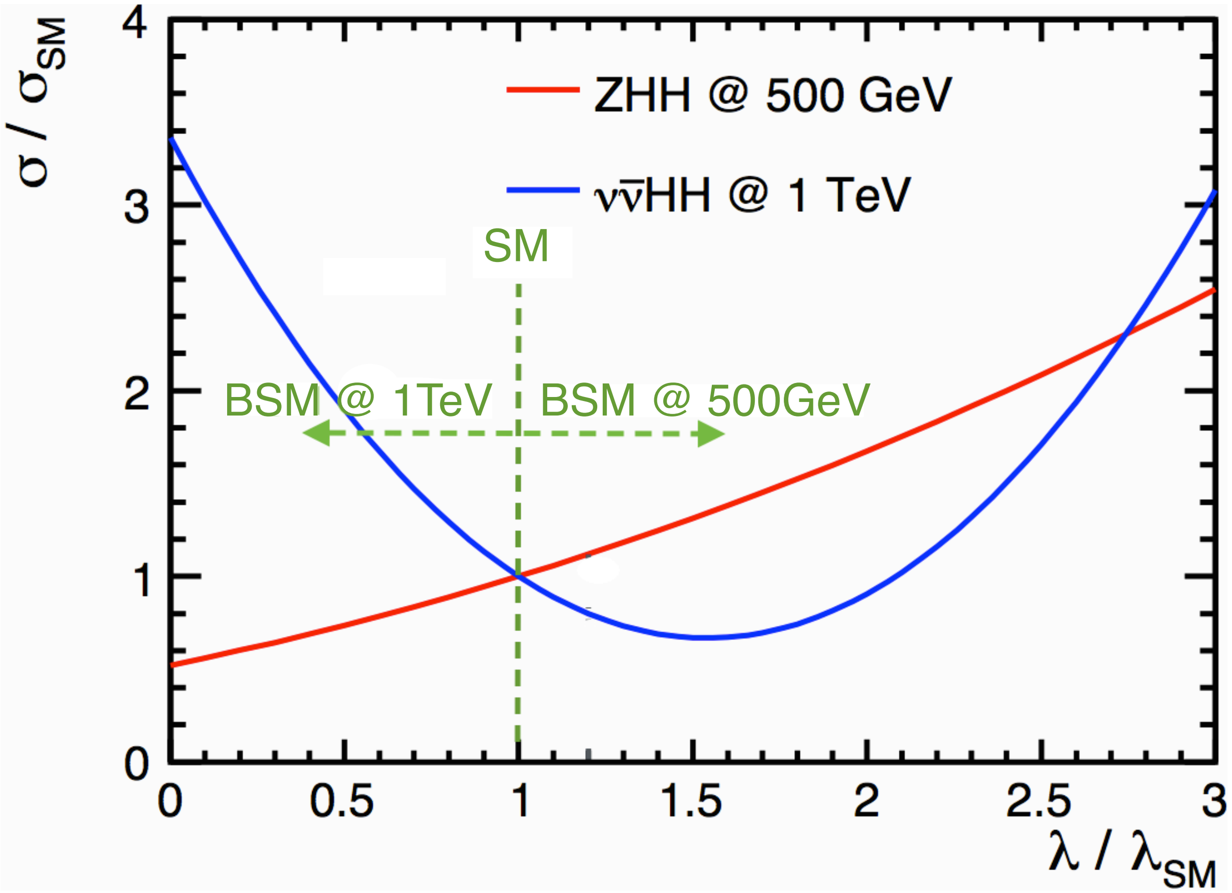
Uncertainties on the top have a big effect on the Higgs

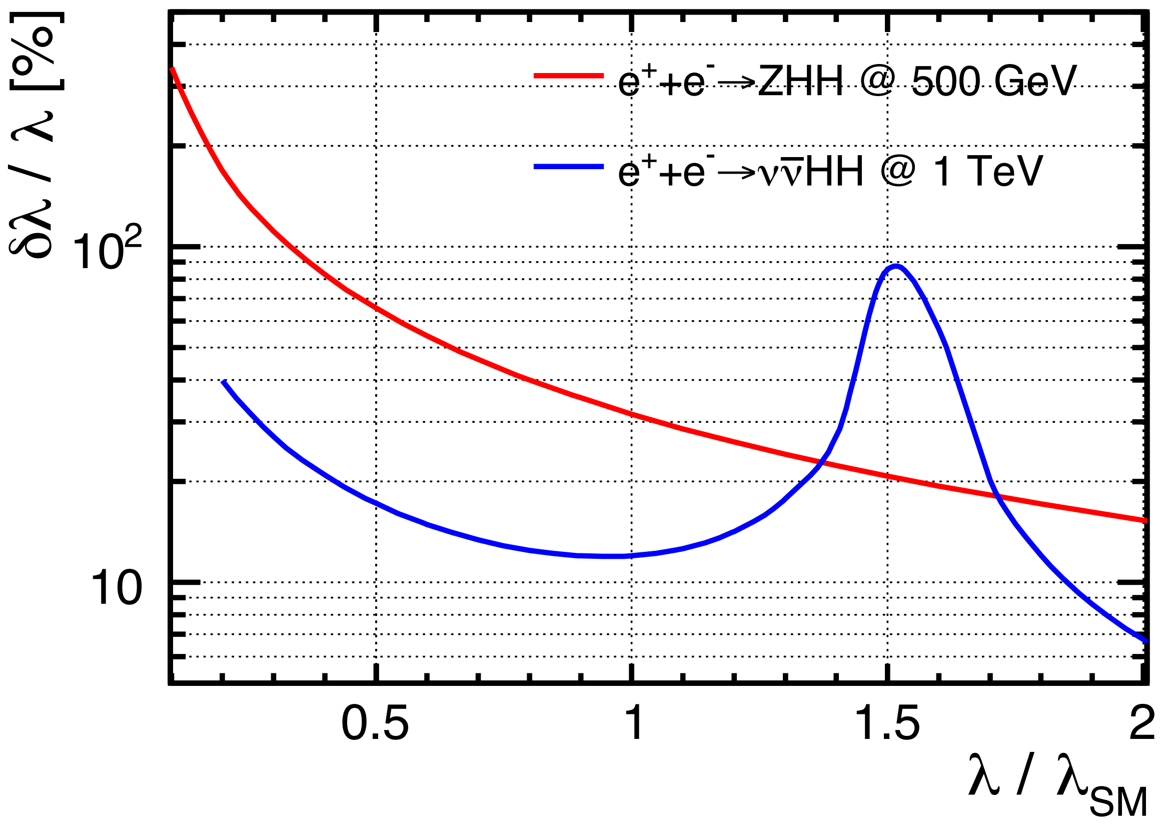
- Higgsstr. run: insufficient
- Higgsstr. run $\oplus$ top@HL-LHC: large top contaminations in $\bar{c}_{\gamma\gamma,gg,Z\gamma,ZZ}$
- Higgsstr. run $\oplus$ $e^+e^- \to t\bar{t}$: large y_t contaminations in various coefficients
- Higgsstr. run $\oplus$ $e^+e^- \to t\bar{t}$ $\oplus$ top@HL-LHC: top contam. in $\bar{c}_{gg}$ only

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

- λ_{HHH} can be enhanced significantly in BSM
- complementarity between ZHH & vvHH (& LHC): interferences different
- if $\lambda_{HHH} / \lambda_{SM} = 2$, λ_{HHH} be measured to ~15% using ZHH at 500 GeV e+e-

Duerig, JT, et al, paper in preparation





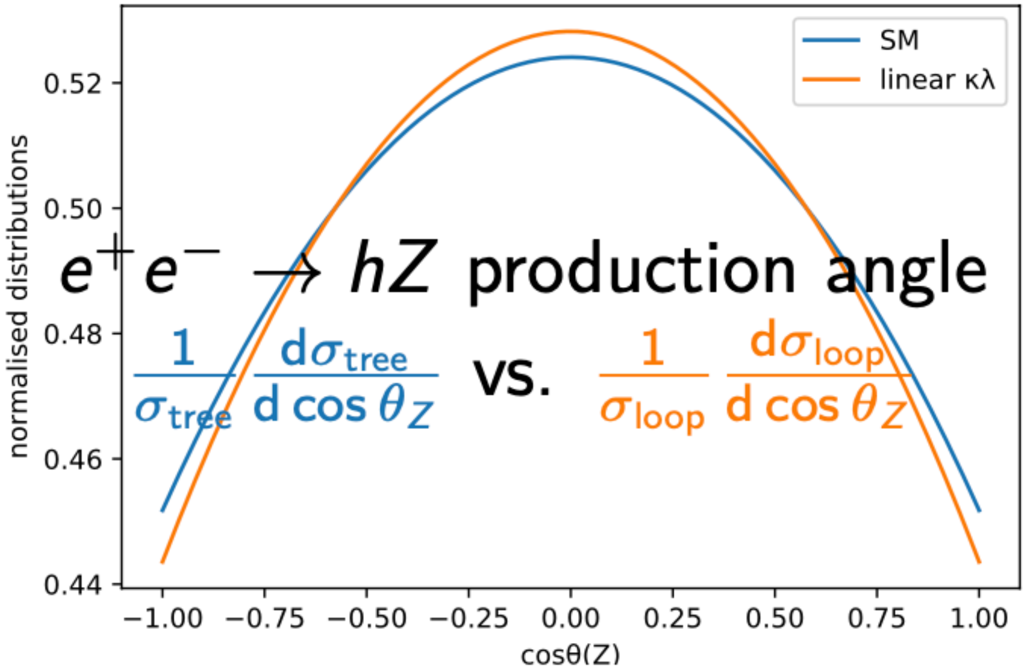
references for large deviations e.g. Grojean, et al., PRD71, 036001; Kanemura, et al., 1508.03245; Kaori, Senaha, PHLTA,B747,152; Perelstein, et al., JHEP 1407, 108

Differential hZ information

[Back-of-the-envelope calculations!!]
and discussions with Fabio Maltoni
& Xiaoran Zhao

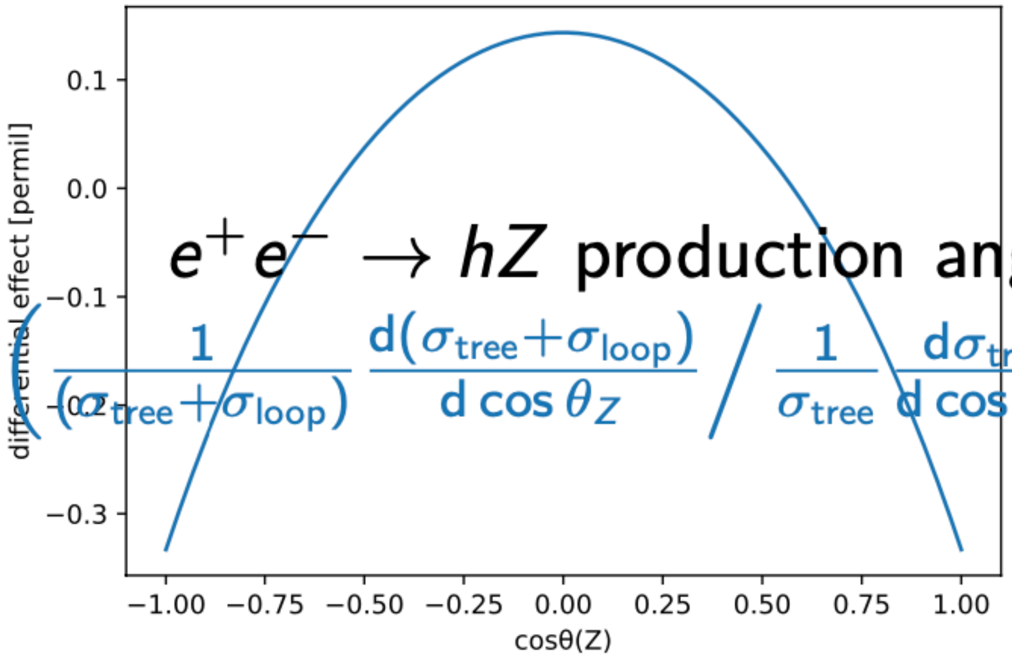
ZZh loop κ_λ vertex: $F_a(p_i^2)\;(\epsilon_1\cdot\epsilon_2)+F_b(p_i^2)\;(p_1\cdot\epsilon_2)(p_2\cdot\epsilon_1)$

with $F_b/F_a\sim 10^{-2}$ so only $\lesssim 10^{-4}$ differential effect



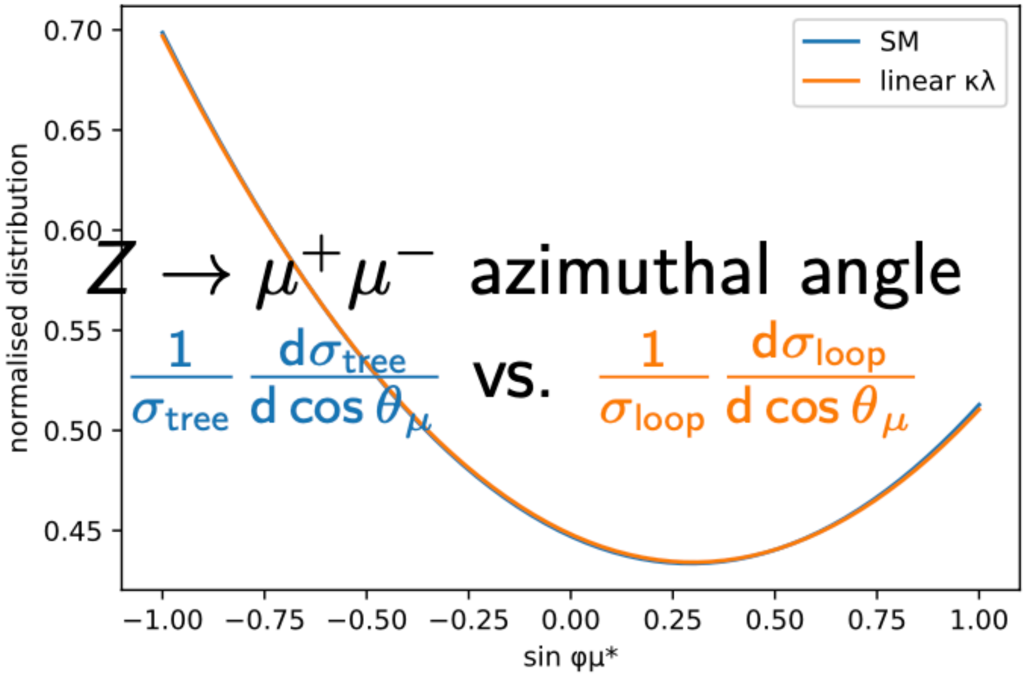
$e^+e^-\to hZ$ production angle

$\frac{1}{\sigma_{\text{tree}}}\frac{d\sigma_{\text{tree}}}{d\cos\theta_Z}$ vs. $\frac{1}{\sigma_{\text{loop}}}\frac{d\sigma_{\text{loop}}}{d\cos\theta_Z}$



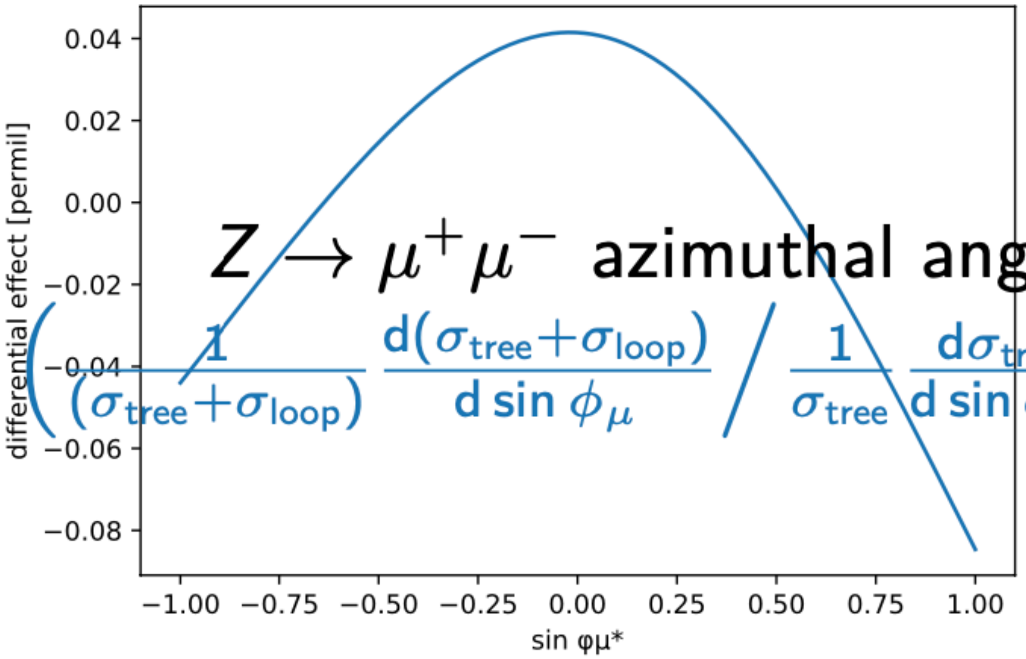
$e^+e^-\to hZ$ production angle

$$\left(\frac{1}{(\sigma_{\text{tree}}+\sigma_{\text{loop}})}\frac{d(\sigma_{\text{tree}}+\sigma_{\text{loop}})}{d\cos\theta_Z}\Big/\frac{1}{\sigma_{\text{tree}}}\frac{d\sigma_{\text{tree}}}{d\cos\theta_Z}\right)-1$$



$Z\to\mu^+\mu^-$ azimuthal angle

$\frac{1}{\sigma_{\text{tree}}}\frac{d\sigma_{\text{tree}}}{d\cos\theta_\mu}$ vs. $\frac{1}{\sigma_{\text{loop}}}\frac{d\sigma_{\text{loop}}}{d\cos\theta_\mu}$



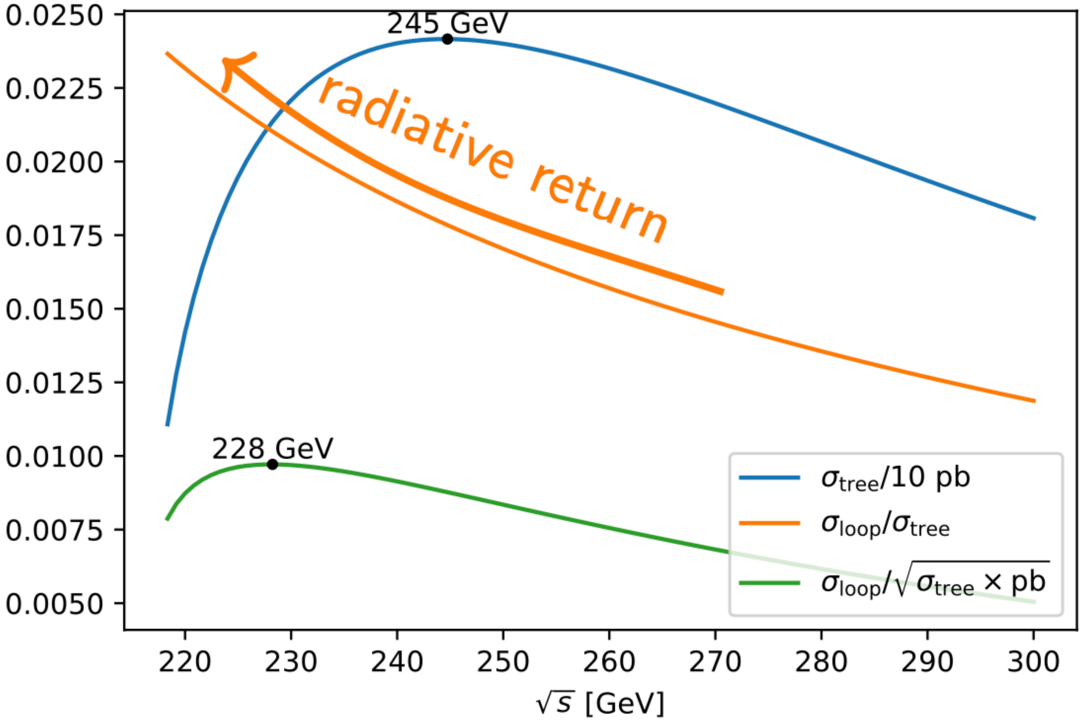
$Z\to\mu^+\mu^-$ azimuthal angle

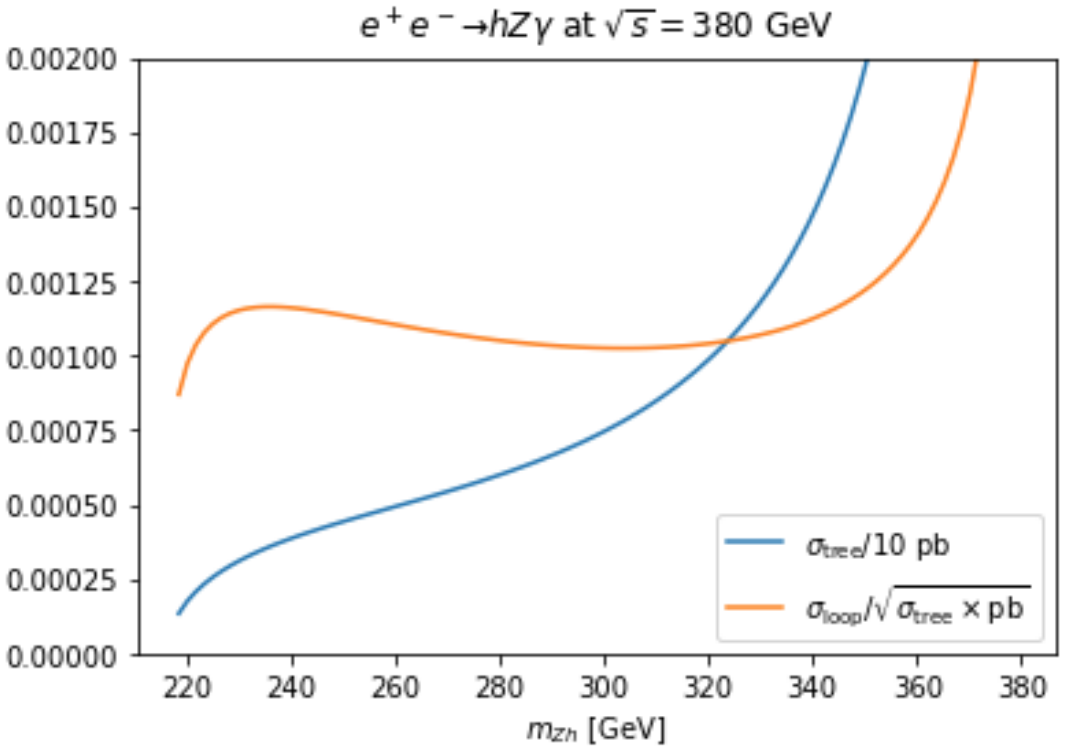
$$\left(\frac{1}{(\sigma_{\text{tree}}+\sigma_{\text{loop}})}\frac{d(\sigma_{\text{tree}}+\sigma_{\text{loop}})}{d\sin\phi_\mu}\Big/\frac{1}{\sigma_{\text{tree}}}\frac{d\sigma_{\text{tree}}}{d\sin\phi_\mu}\right)-1$$

¿exploitable with an optimal discriminant?

(ii) single-Higgs: lift degeneracies

- **can energy scan around 240-250 help? or using radiative return from 365/380 GeV?**



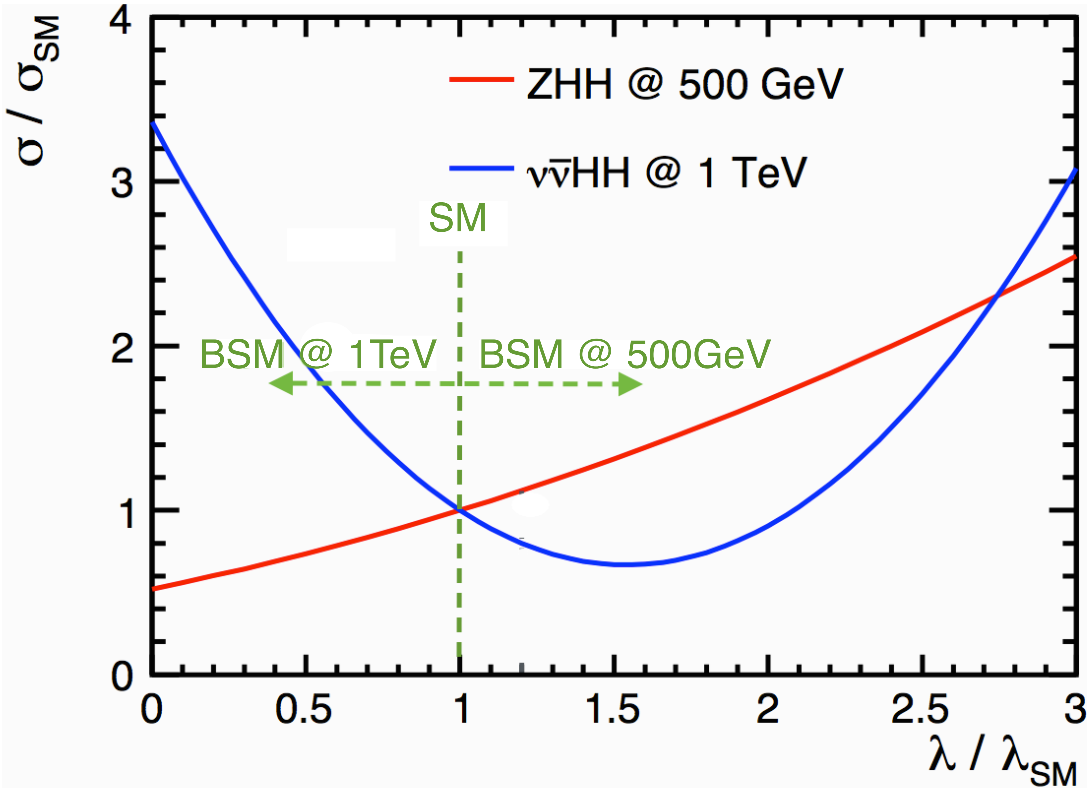


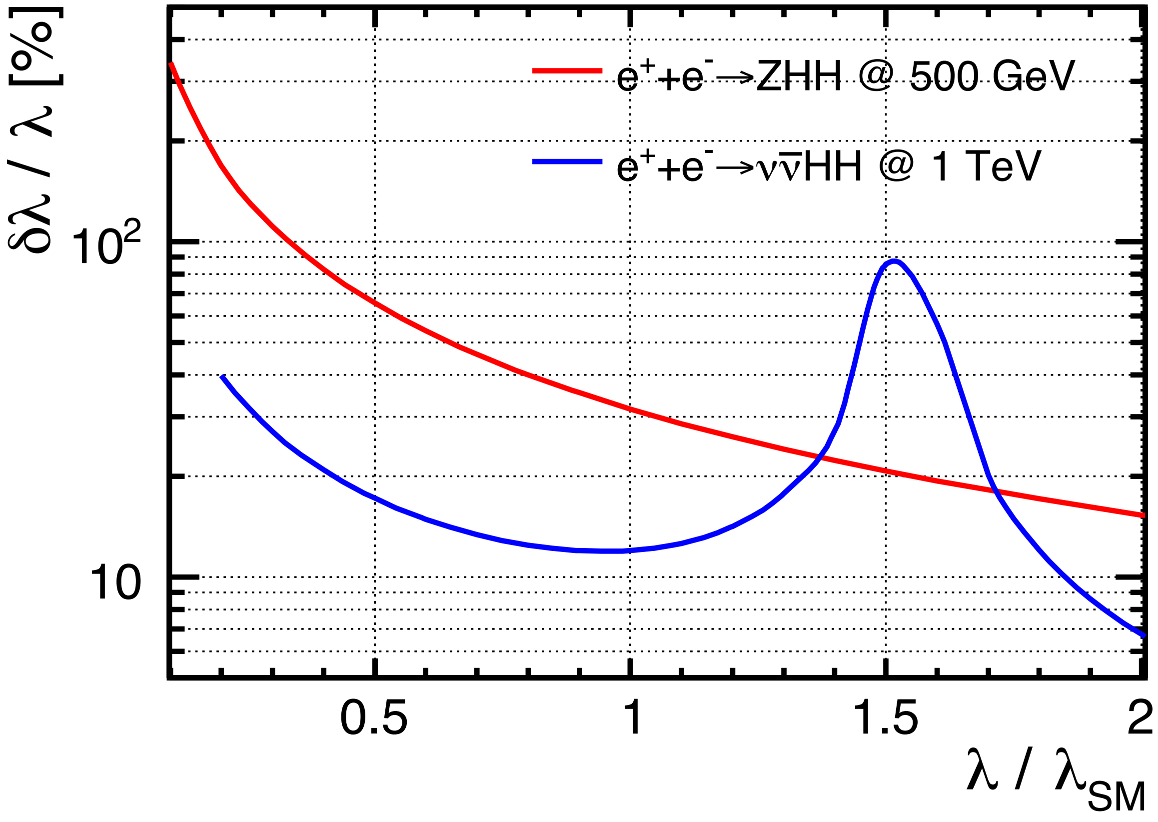
[Durieux, et al, preliminary]

(i) beyond SMEFT: large $\delta\lambda_{hhh}$; light scalars

(examples)

- profound effect on di-Higgs processes
- complementarity between ZHH & vvHH (& LHC): different interference
- if $\lambda_{HHH} / \lambda_{SM} = 2$, λ_{HHH} be *discovered* (~13%) using ZHH at 500 GeV e+e-

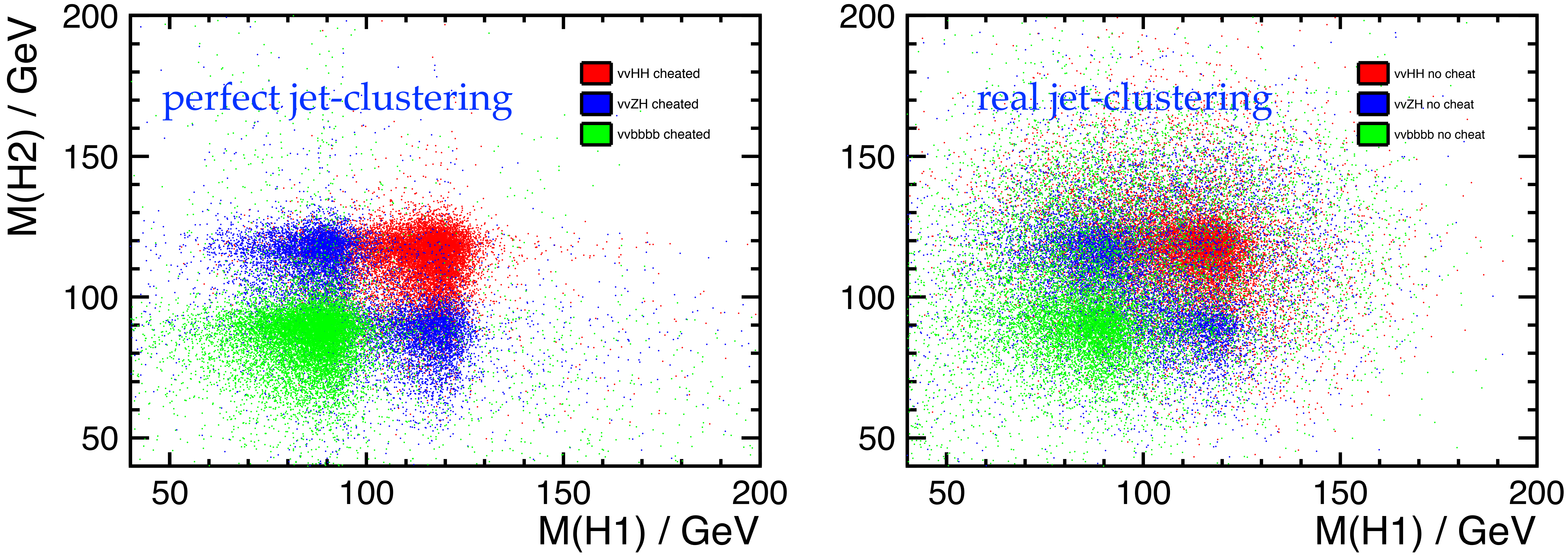




(iii) improving jet-clustering algorithm?

ZHH->ννbbbb (BG: ZZH and ZZZ)

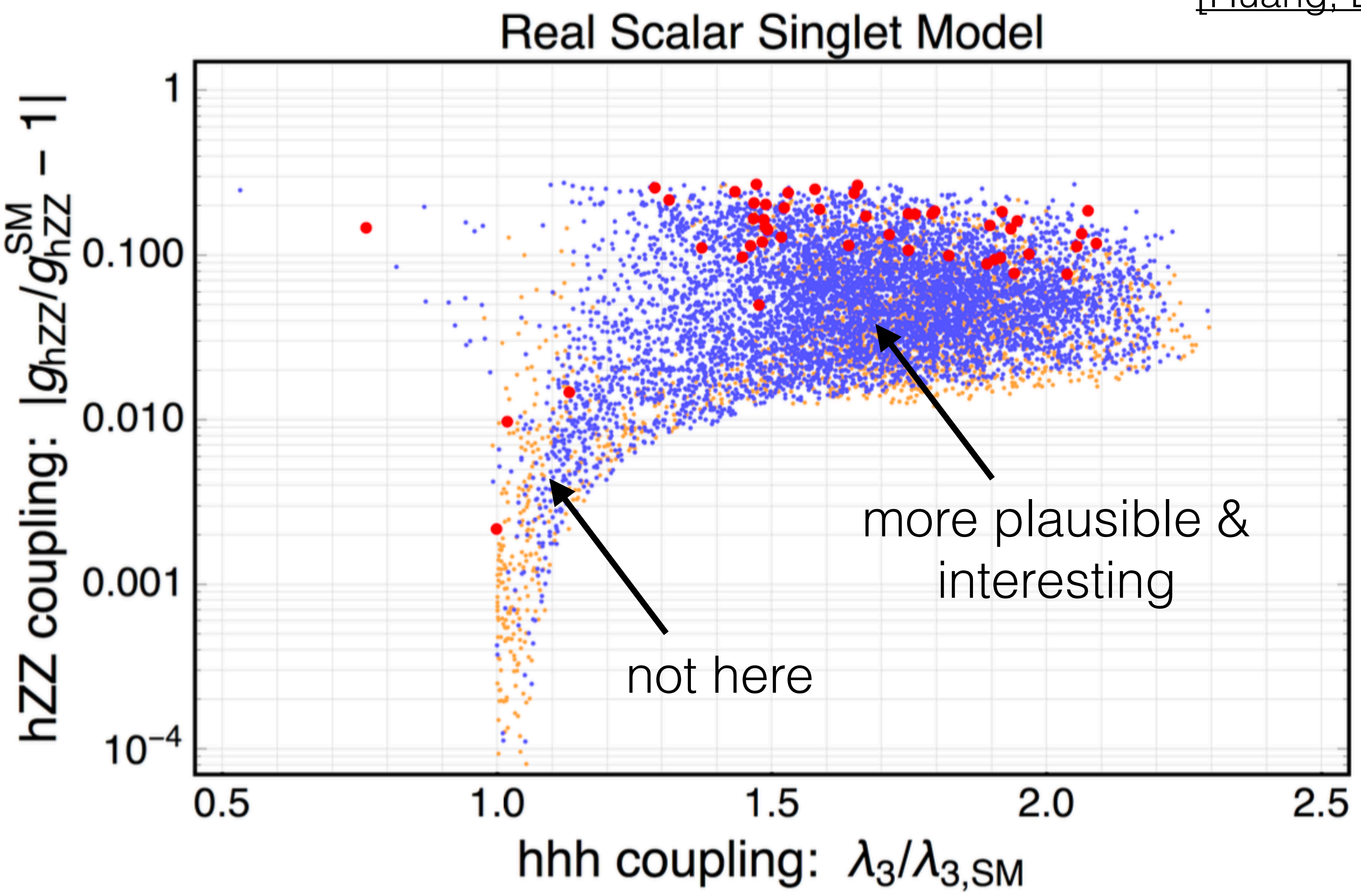
scatter plot of two Higgs masses



- the mis-clustering of particles degrades significantly the separation between signal and BG.
- it is studied that using perfect color-singlet-jet-clustering can improve $\delta\lambda/\lambda$ by 40%

(i) beyond SMEFT: large $\delta\lambda_{hhh}$; light scalars

[Huang, Long, Wang, '16]


Real Scalar Singlet Model

more plausible & interesting

not here

orange: first-order phase transition

blue: strongly first-order phase transition ($v/T > 1.3$)

red: very strongly first-order phase transition (GW @ eLISA)

[recent models with even larger hierarchy δ_{hhh} / δ_{hVV}: Durieux, McCullough, Salvioni, '22]