Higgs self-coupling @ Linear Collider

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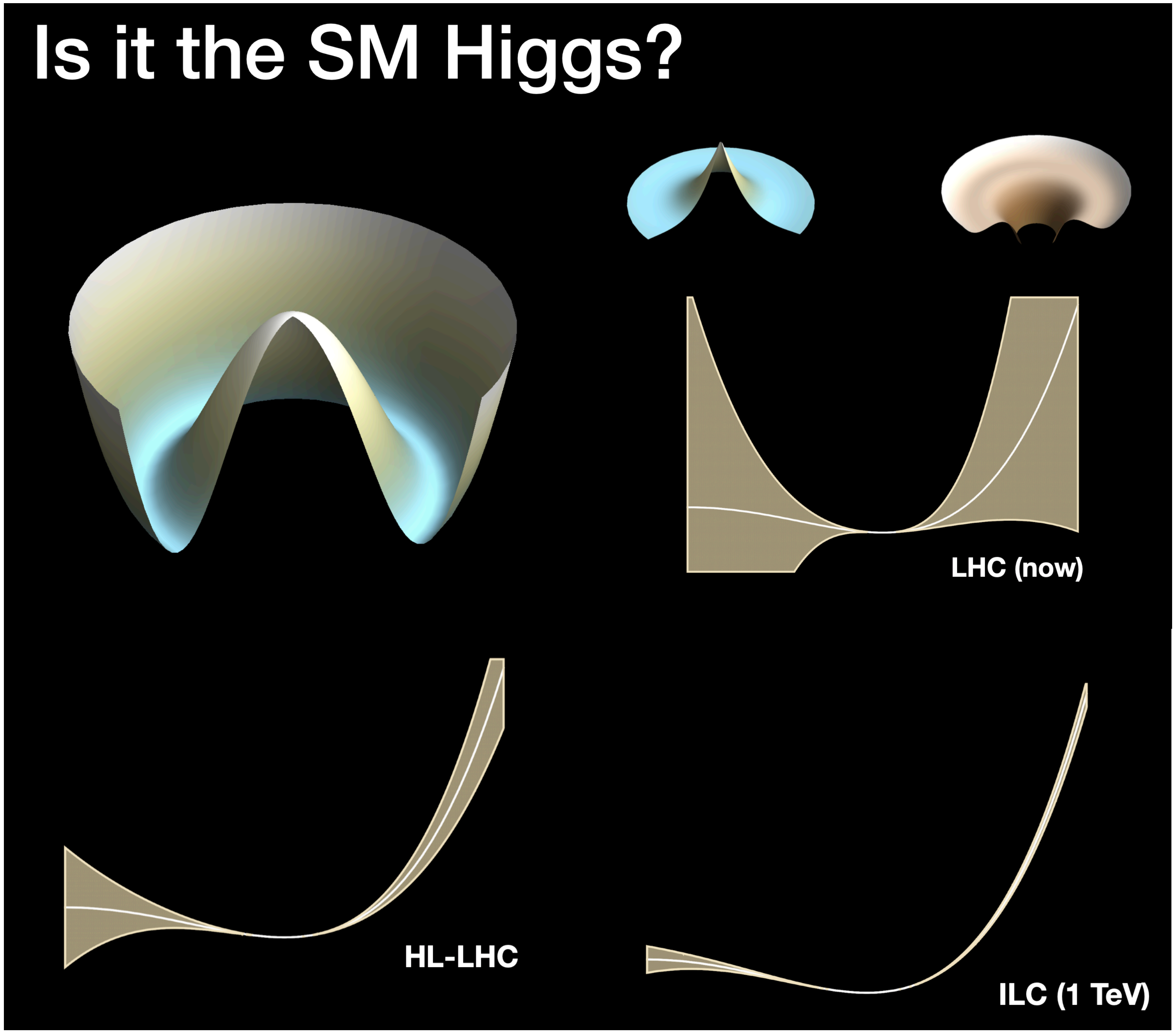


[courtesy: N. Craig @ LCWS 2023]

Junping Tian (U. Tokyo)

Higgs 2024 @ Uppsala U.
Nov. 4-8, 2024

Collaborators:

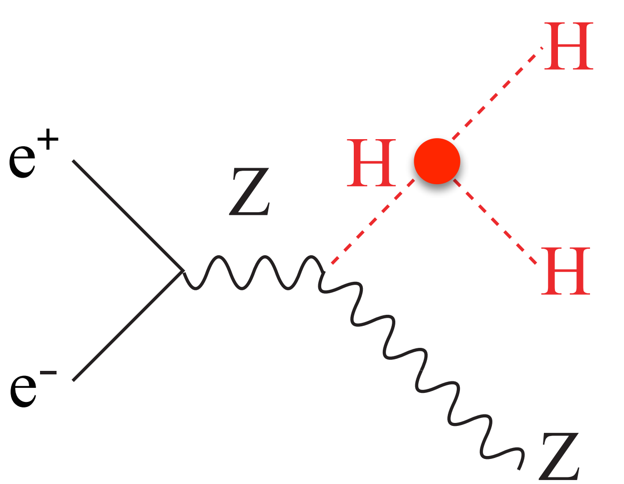
Bryan Bliewert, Jenny List, Julie Torndal (DESY)

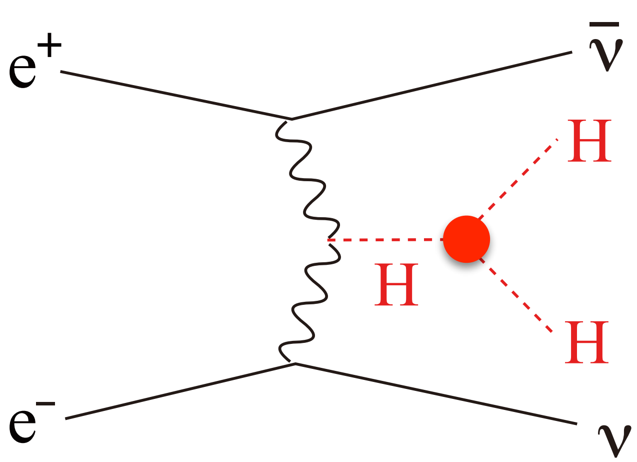
Dimitris Ntounis, Caterina Vernieri (SLAC)

arXiv:2410.15323
arXiv:2411.01507
arXiv:2307.16515

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

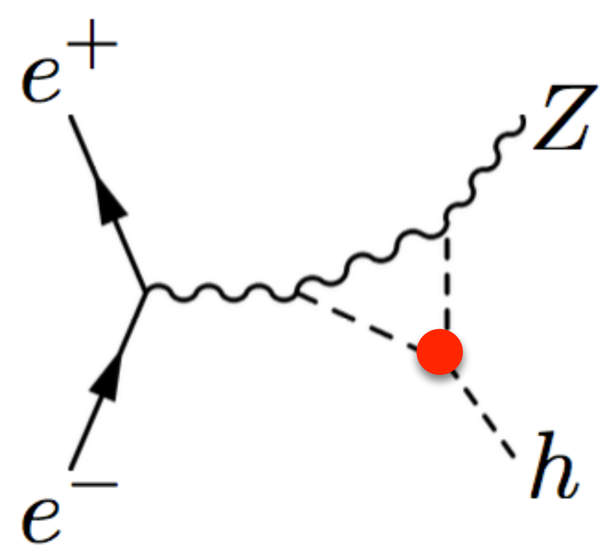
$\sqrt{s} \gtrsim 500$ GeV

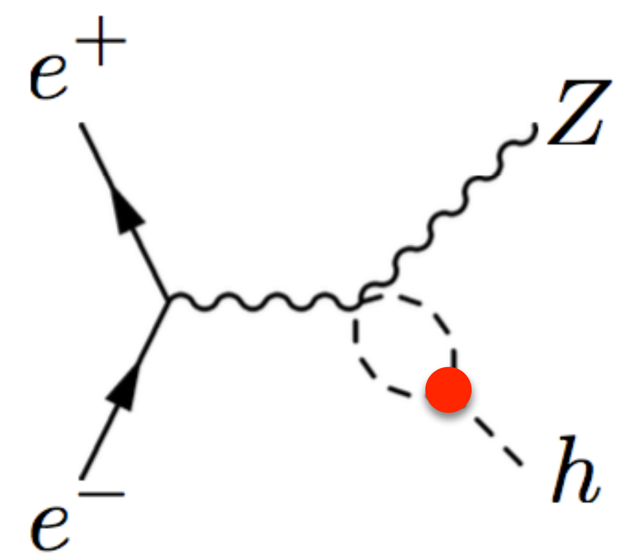




$\sigma_{HH} \sim O(0.1)$ fb

$\sqrt{s} \gtrsim 240\text{–}250$ GeV

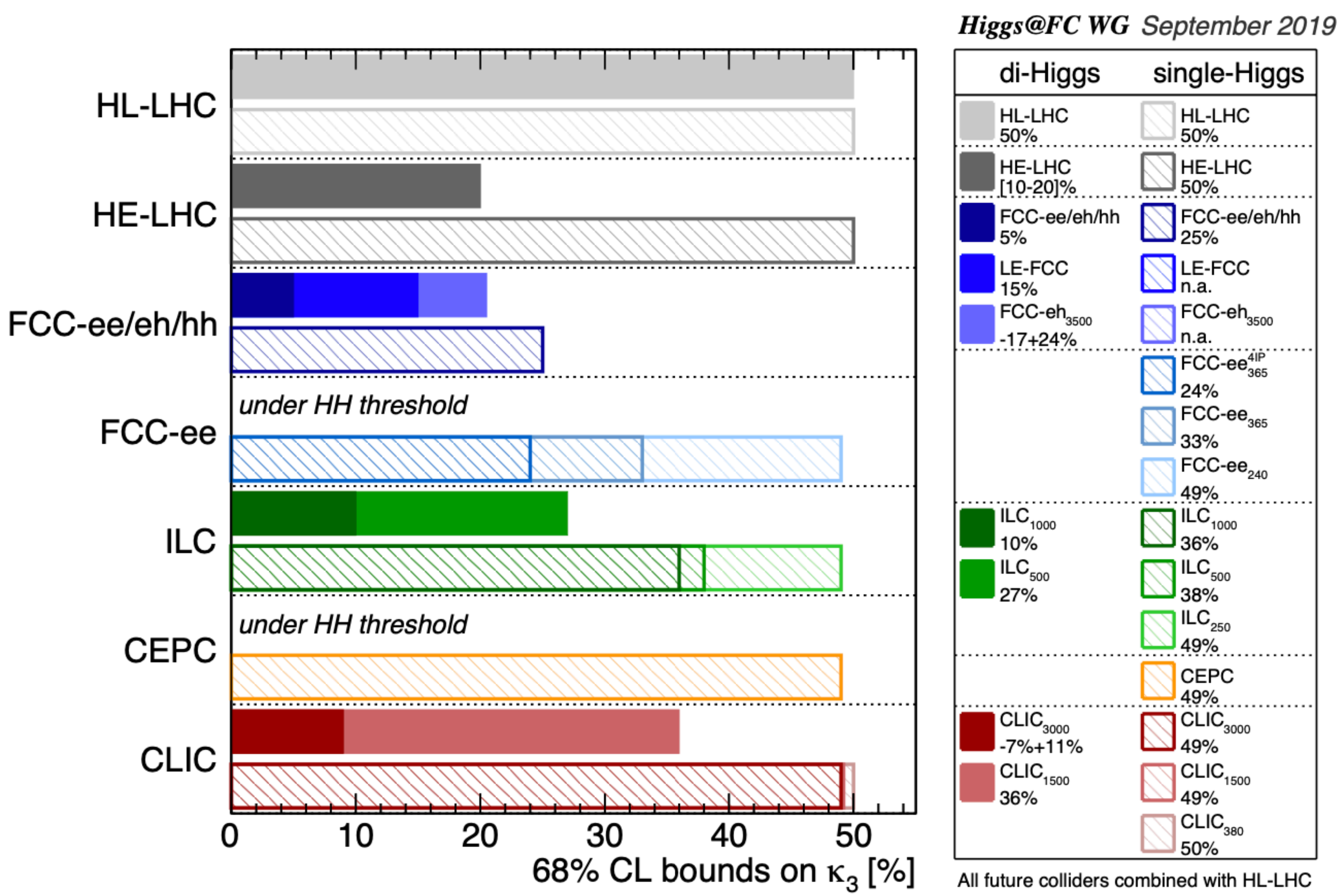




$\delta\sigma_{ZH} \sim O(1\%)$

Goal: update the projections in ESU 2020

[Physics Briefing Book, arXiv:1910.11775]

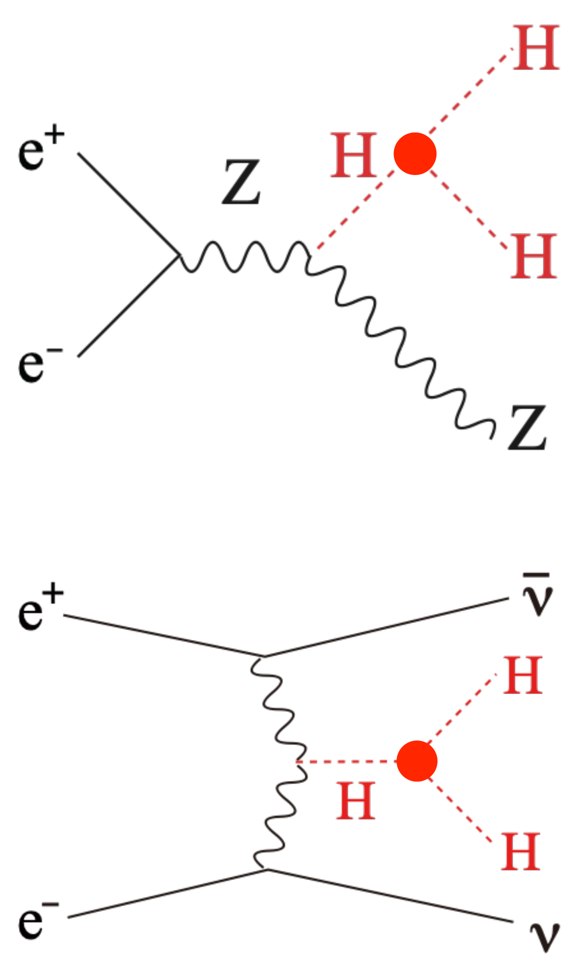


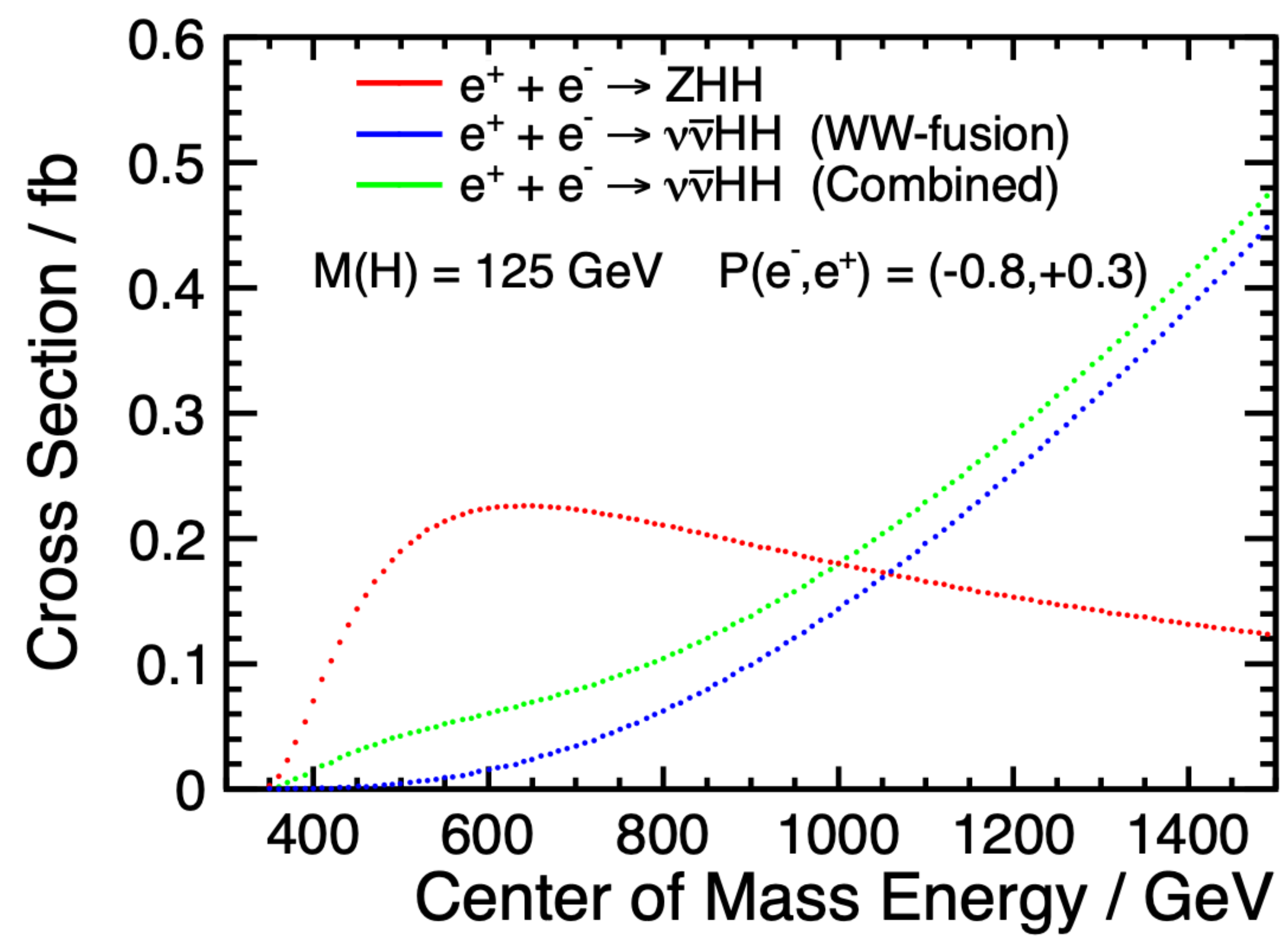
- based on global SMEFT fits
- HL-LHC di-Higgs contribution was always combined

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

Higgs self-coupling studies @ ILC

- $\sqrt{s}$~500 GeV: e+e- —> ZHH
- $\sqrt{s}$~1 TeV: e+e- —> $\nu_e\nu_e$HH





C.Duerig, DESY-Thesis-2016-027 M. Kurata, LC-REP-2014-025 J. Tian, LC-REP-2013-003

full simulation studies @ ILC

- dominant channels covered

<50%

Z decay mode	HH decay mode	BranchingRatio
$Z \to e^+e^-$	$HH \to b\bar{b}b\bar{b}$	1.1%
$Z \to \mu^+\mu^-$	$HH \to b\bar{b}b\bar{b}$	1.1%
$Z \to \nu^+\bar{\nu}$	$HH \to b\bar{b}b\bar{b}$	6.7%
$Z \to b\bar{b}$	$HH \to b\bar{b}b\bar{b}$	5.0%
$Z \to q\bar{q}$	$HH \to b\bar{b}b\bar{b}$	17%
$Z \to b\bar{b}$	$HH \to b\bar{b}WW^*, WW^* \to 4q$	1.7%
$Z \to c\bar{c}$	$HH \to b\bar{b}WW^*, WW^* \to 4q$	1.4%
$Z \to b\bar{b}$	$HH \to b\bar{b}WW^*, WW^* \to l\nu 2q$	1.1%
$Z \to c\bar{c}$	$HH \to b\bar{b}WW^*, WW^* \to l\nu 2q$	0.92%
$Z \to l^+l^-$	$HH \to b\bar{b}WW^*, WW^* \to 4q$	0.76%
$Z \to l^+l^-$	$HH \to b\bar{b}WW^*, WW^* \to l\nu 2q$	0.50%

Table 1: signal channels analysed for $e^+e^- \to ZHH$ at $\sqrt{s} = 500$ GeV.

(for e+e- ->vvHH@1TeV: HH->bbbb/bbWW* are covered)

full simulation studies @ ILC

[analysis ~10y ago]

- **generator**: *Whizard* 1.95, *Physsim* (realistic beamsstrahlung, ISR, pile-up)
- **parton shower & hadronization**: *Pythia* 6
- **detector model**: ILD (as realistic as possible material budget, blind areas)
- **simulation & reconstruction**: *Geant* 4, *iLCSoft* (realistic algorithms for tracking, particle flow (*PandoraPFA*), flavor tagging (*LCFI*+), jet-clustering, etc)
- **event selection**: full SM background, realistic cuts, careful categorization, kinematic fitting, multivariate method

full simulation studies @ ILC

[analysis ~10y ago]

- results (example individual channels)

ZHH channel	s $(HH \to bbbb)$	b	σ_e	eff.
$eeHH$	3.9 ± 0.03 (2.6)	7 ± 0.6	1.29σ	59%
$\mu\mu HH$	5.1 ± 0.03 (2.8)	9 ± 0.5	1.48σ	55%
$\nu\nu HH$	5.6 ± 0.04 (5.5)	7 ± 1.0	1.78σ	19%
$bbHH$	8.5 ± 0.10 (8.0)	22 ± 1.3	1.75σ	29%
$qqHH$	12.6 ± 0.1 (10.9)	55 ± 2.0	1.65σ	15%

Table 2: Results of the event selection of ZHH with $HH \to bbbb$ corresponding to an integrated luminosity of $\mathcal{L} = 2$ ab^{-1} and a beam polarisation of $P(e^+e^-) = (0.3, -0.8)$.

major bkg.: tt, ZZ, ZZZ, ZZH

- results (combined)

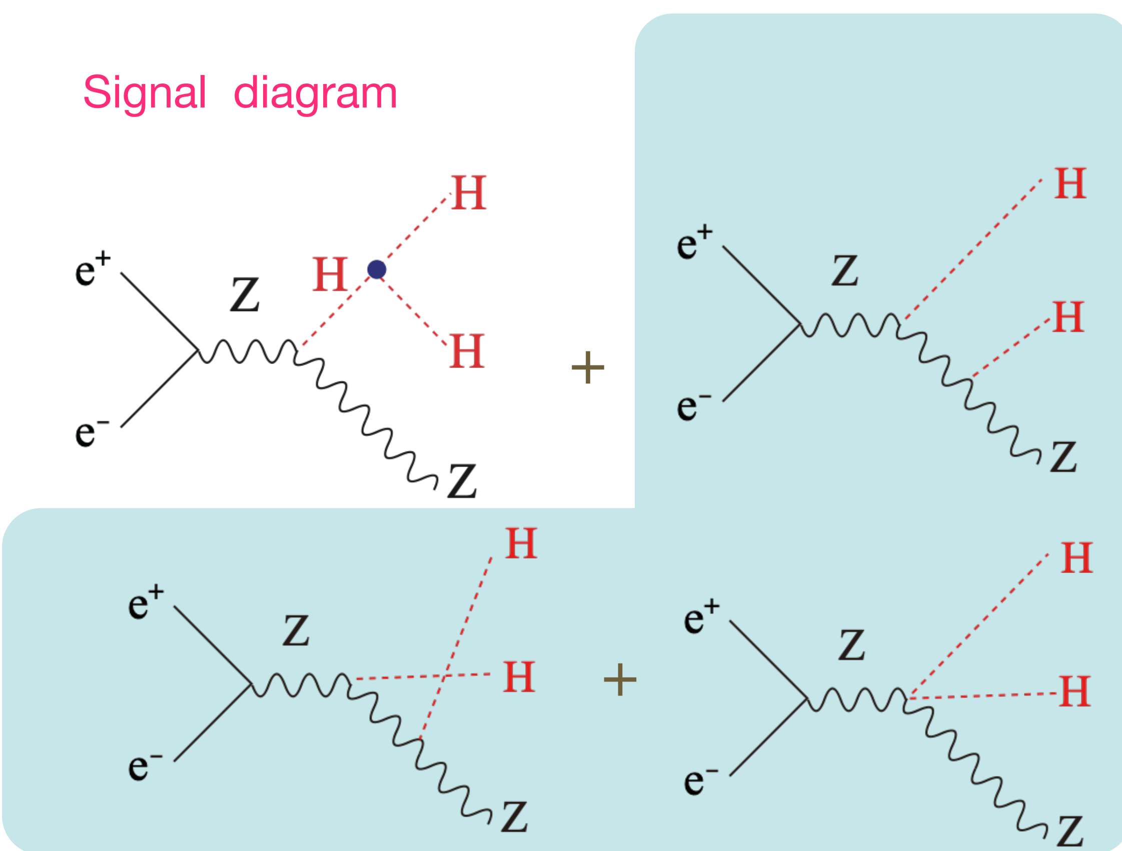
$\sqrt{s}$	$\int Ldt$	$\Delta\sigma/\sigma$	$\Delta\lambda_{HHH}/\lambda_{HHH}$
ZHH @ 500 GeV	4 ab^{-1} (*)	17%	27%
vvHH @ 1 TeV	4 ab^{-1} (**)	15%	10%

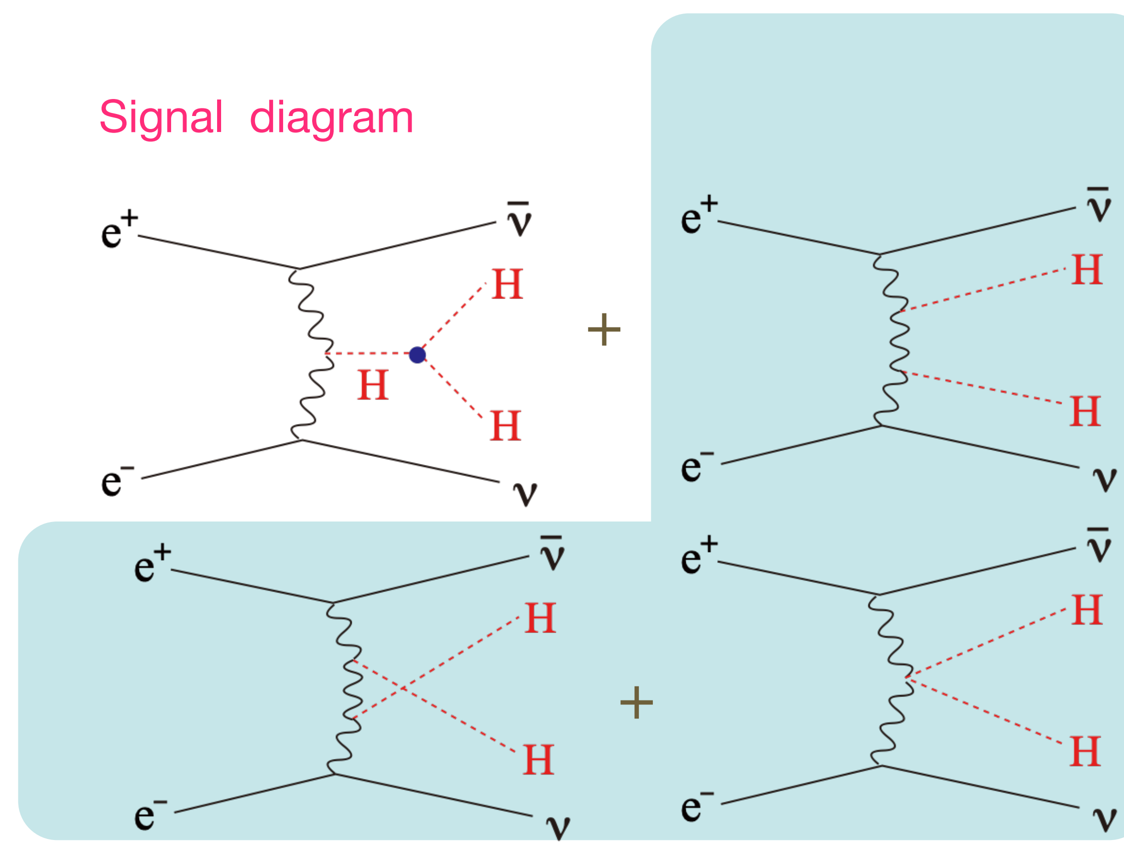
P(e+, e-) = *: equally shared by (-0.8,+0.3) and (+0.8,-0.3); **: (-0.8,+0.2)

from di-Higgs cross section to λ_{HHH}

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

(signal diagram) (interference) (background diagram)



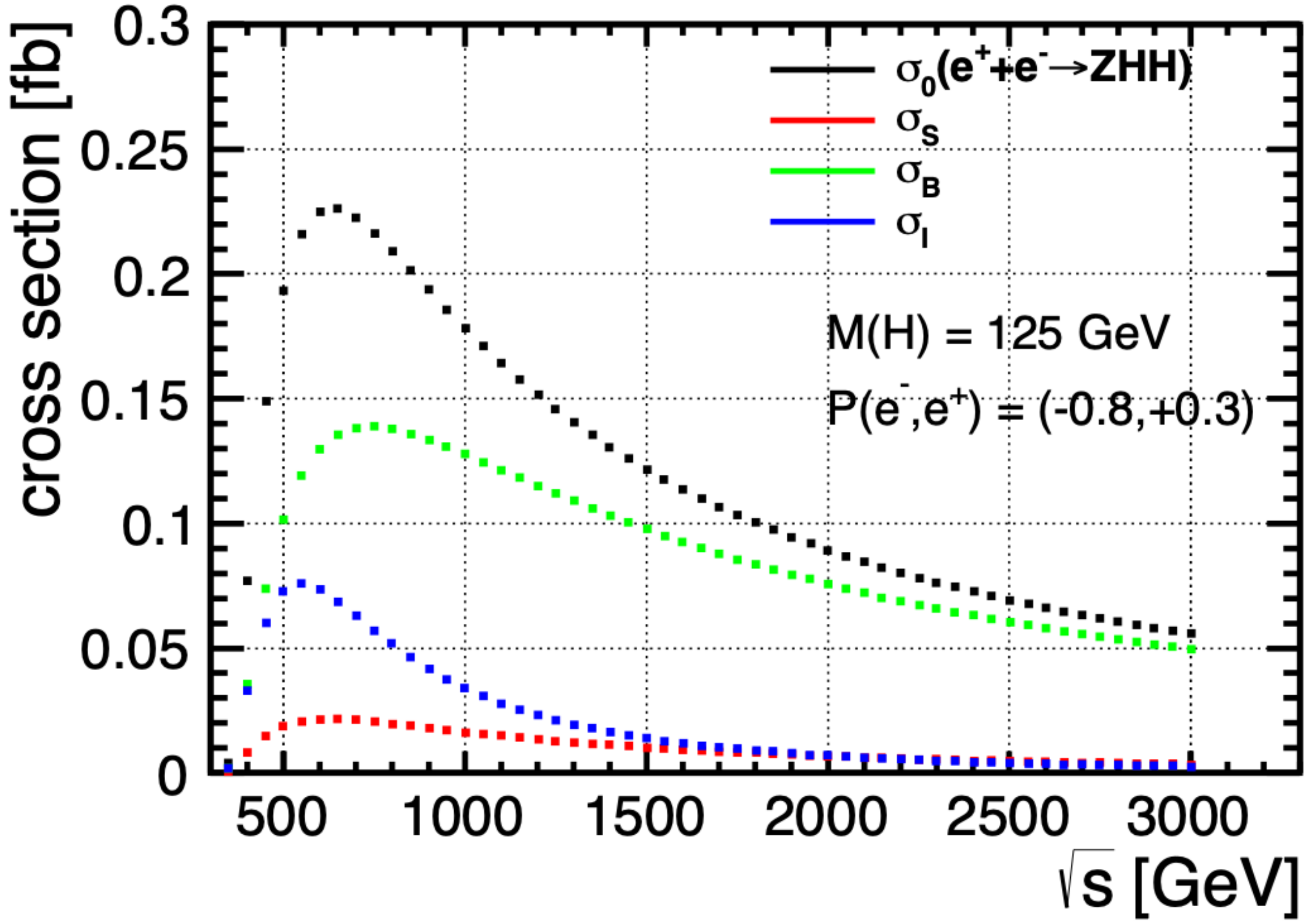


interference: constructive in ZHH, destructive in ννHH

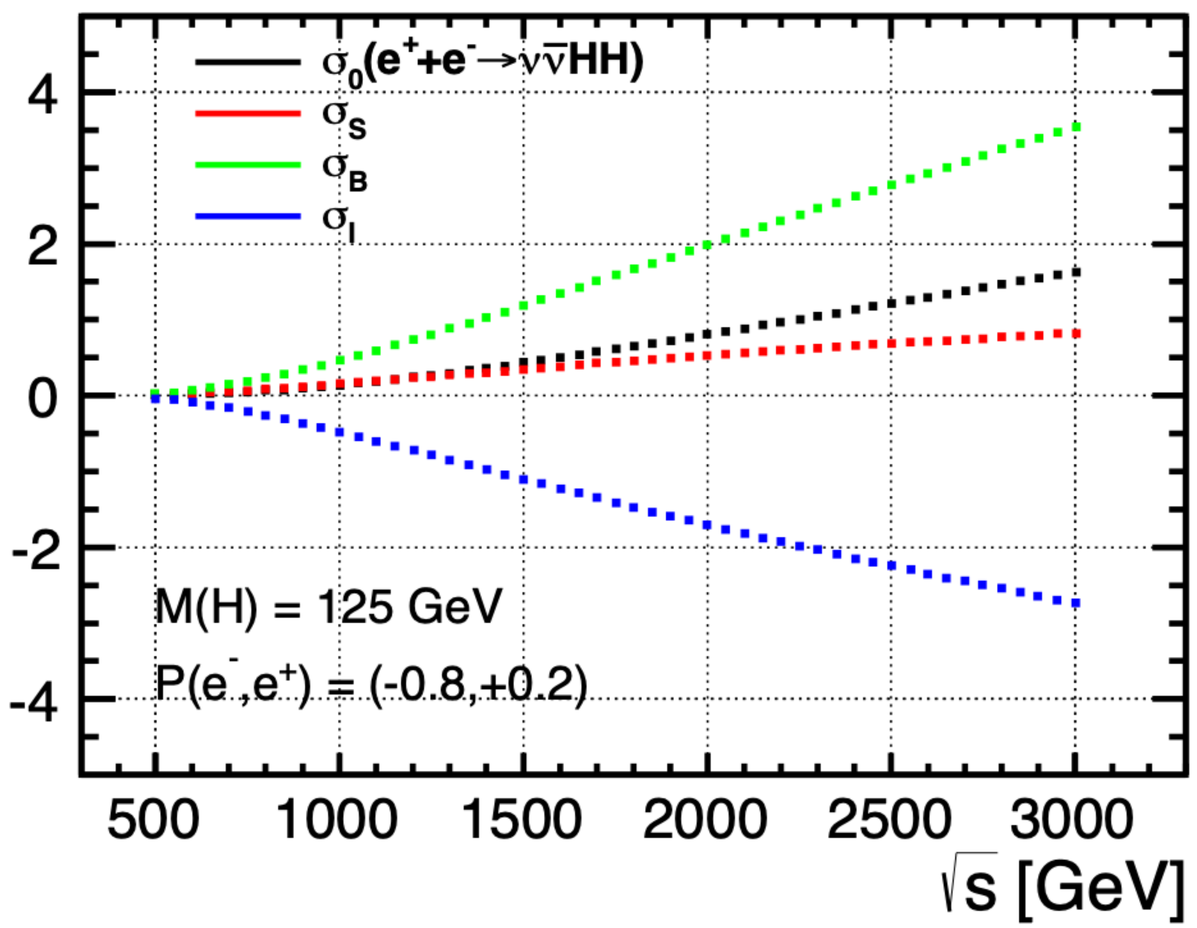
Di-Higgs cross section: break down & impact of √s

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

ZHH

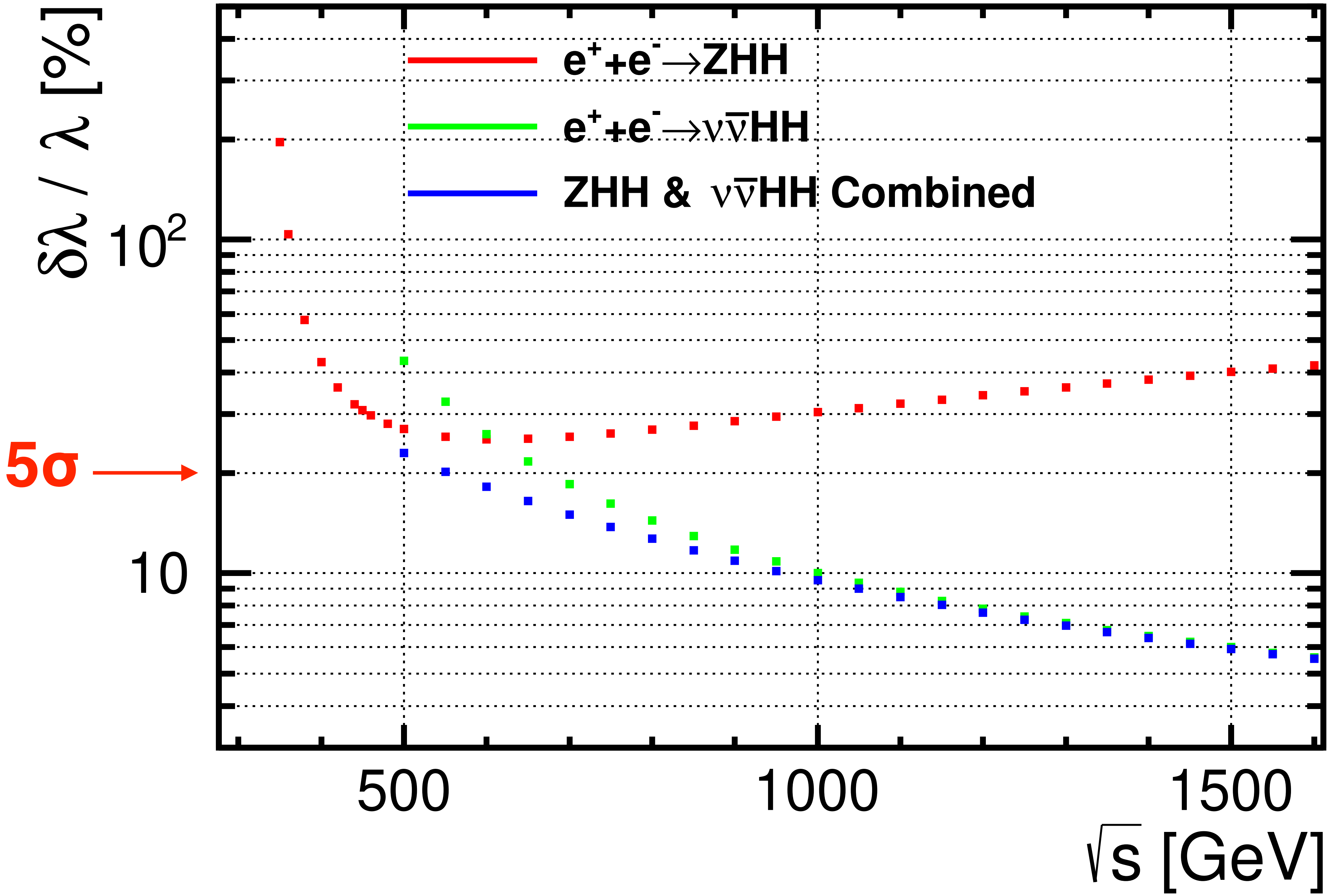


ννHH



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%

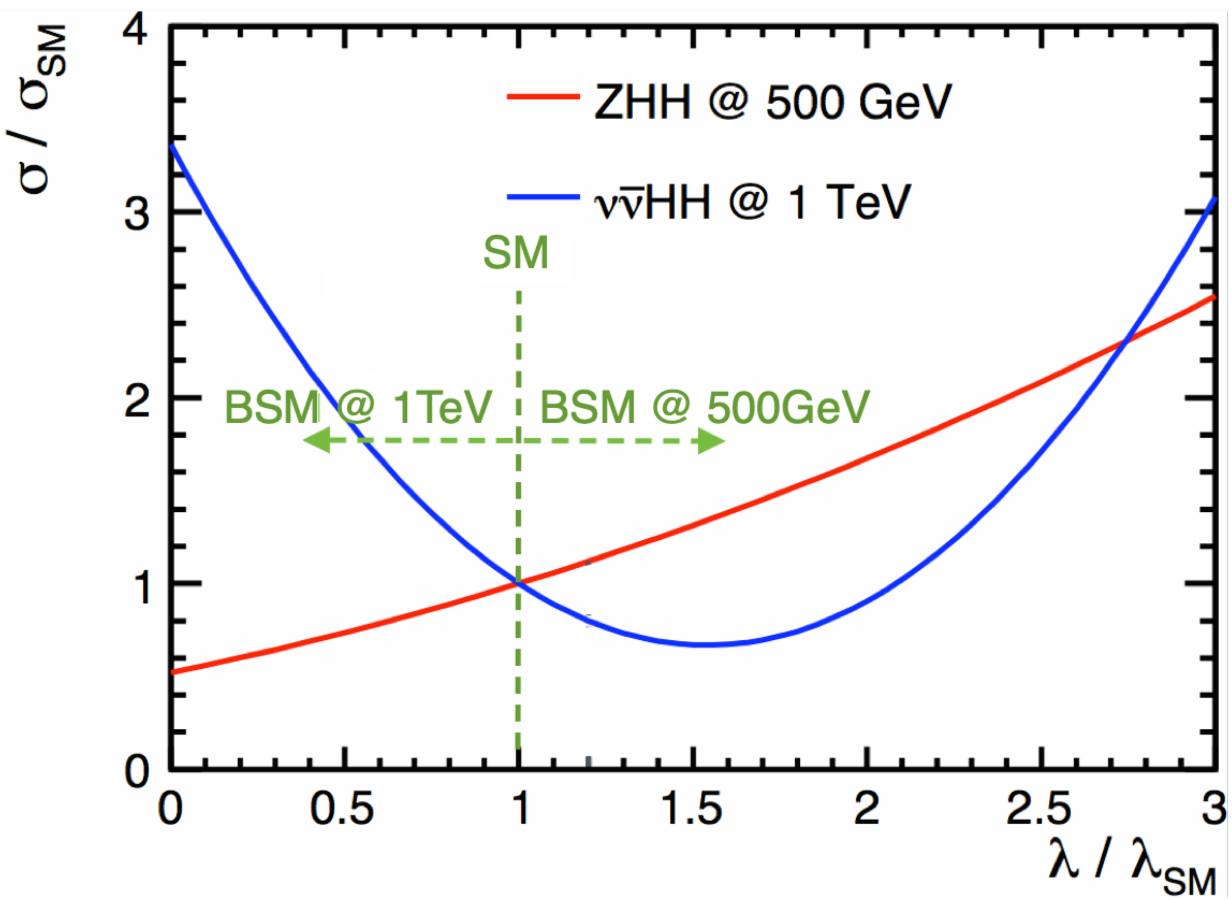
ILC550: 20%

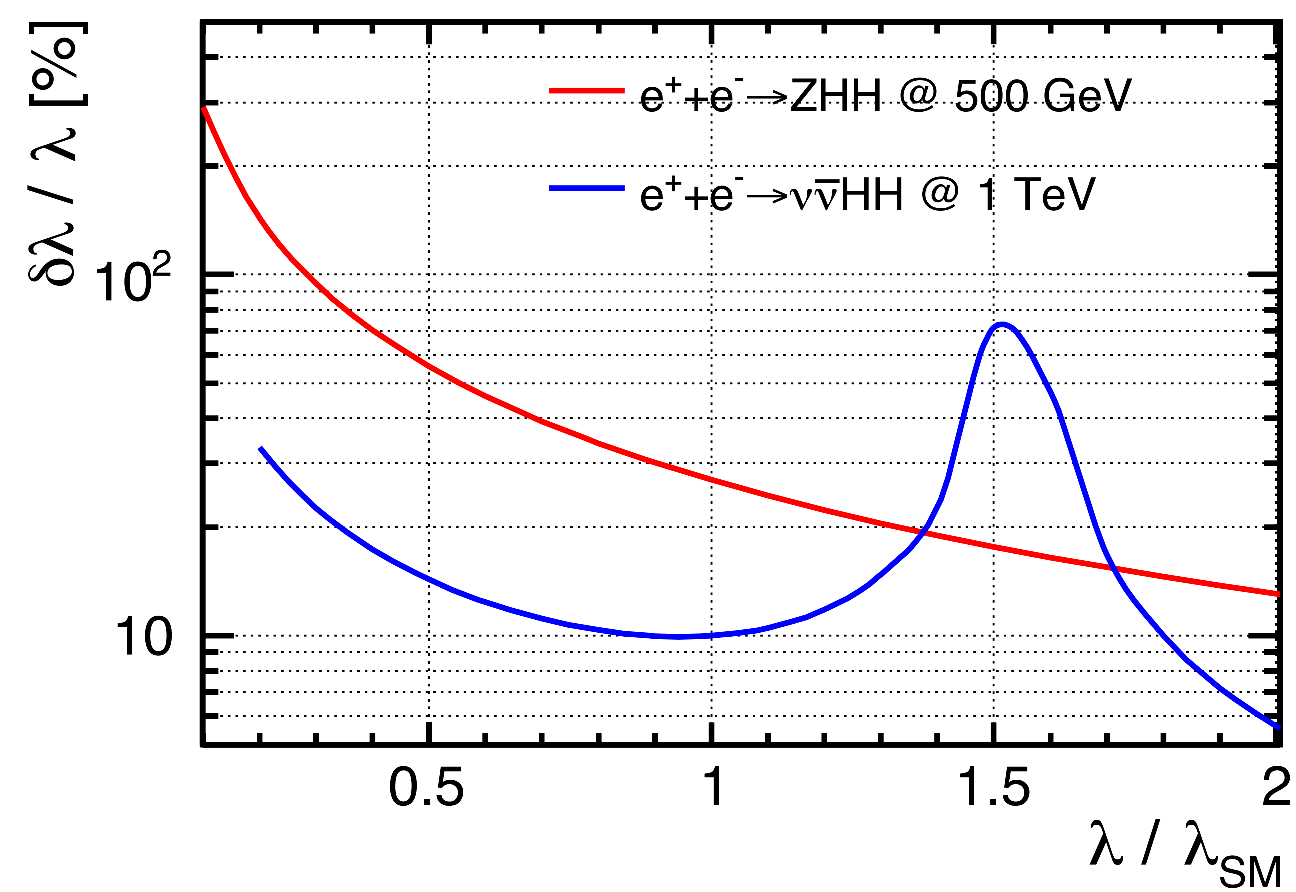
ILC600: 18%

note: this is still based on old ILD DBD analysis

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

- λ_{HHH} can be enhanced significantly O(1) in BSM → [J. Braathen @ ECFA'24]
- complementarity between ZHH & ννHH (& LHC): interference nature
- if $\lambda_{HHH} / \lambda_{SM} = 2$, λ_{HHH} be measured to ~10% using ZHH @ ILC550 GeV





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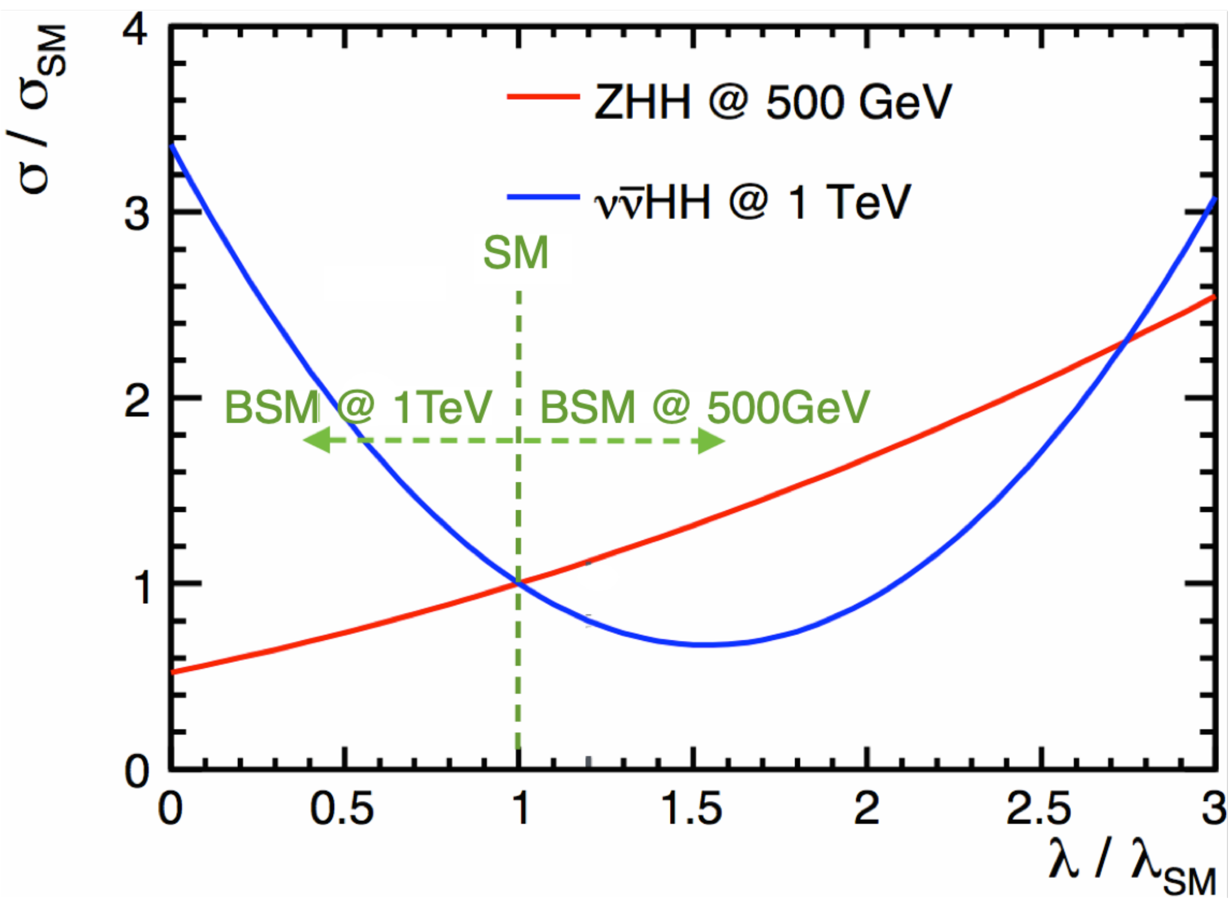
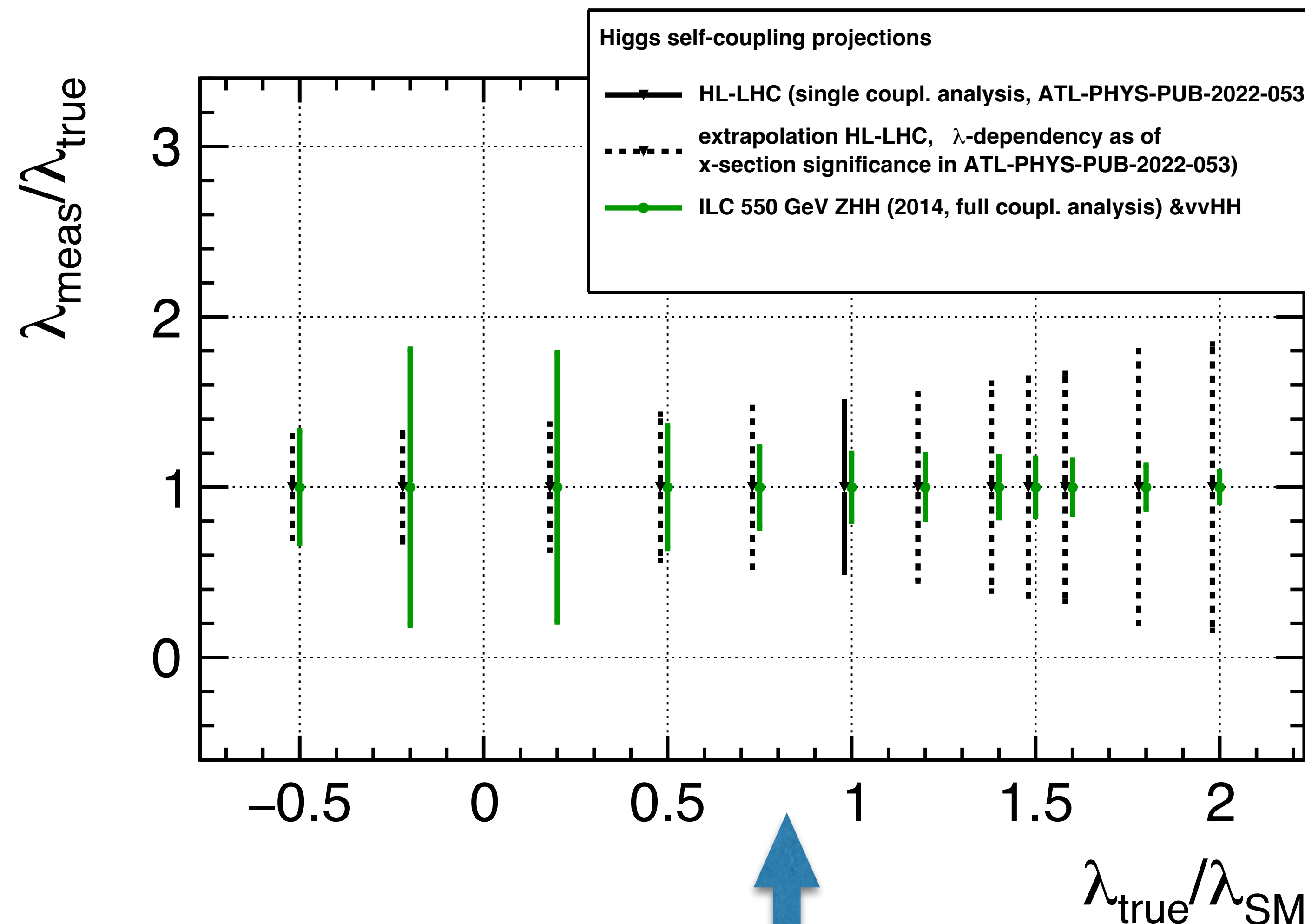
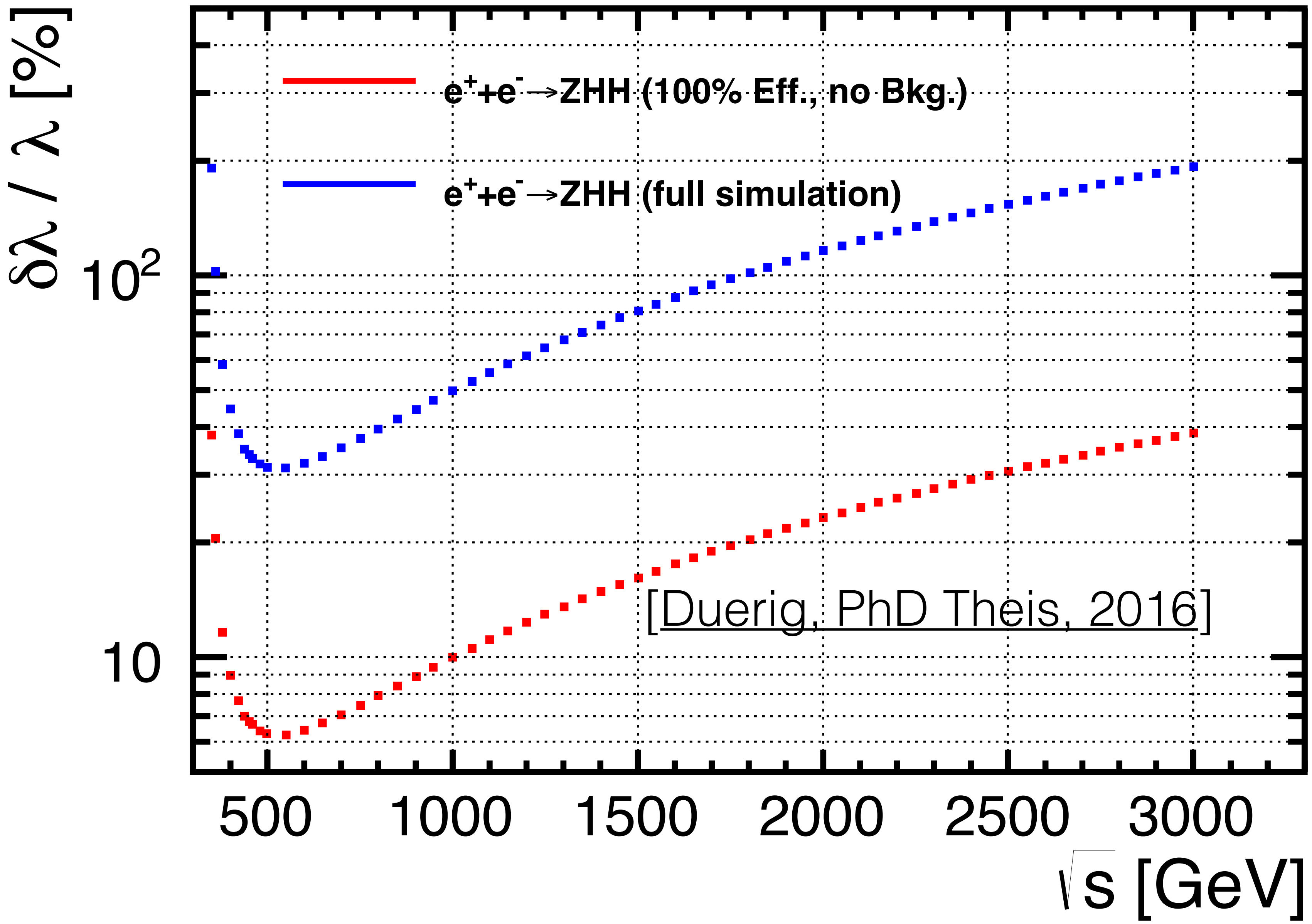




complementarity with LHC

prospect: $\Delta\lambda_{HHH}$ a factor of 5 from "perfect"

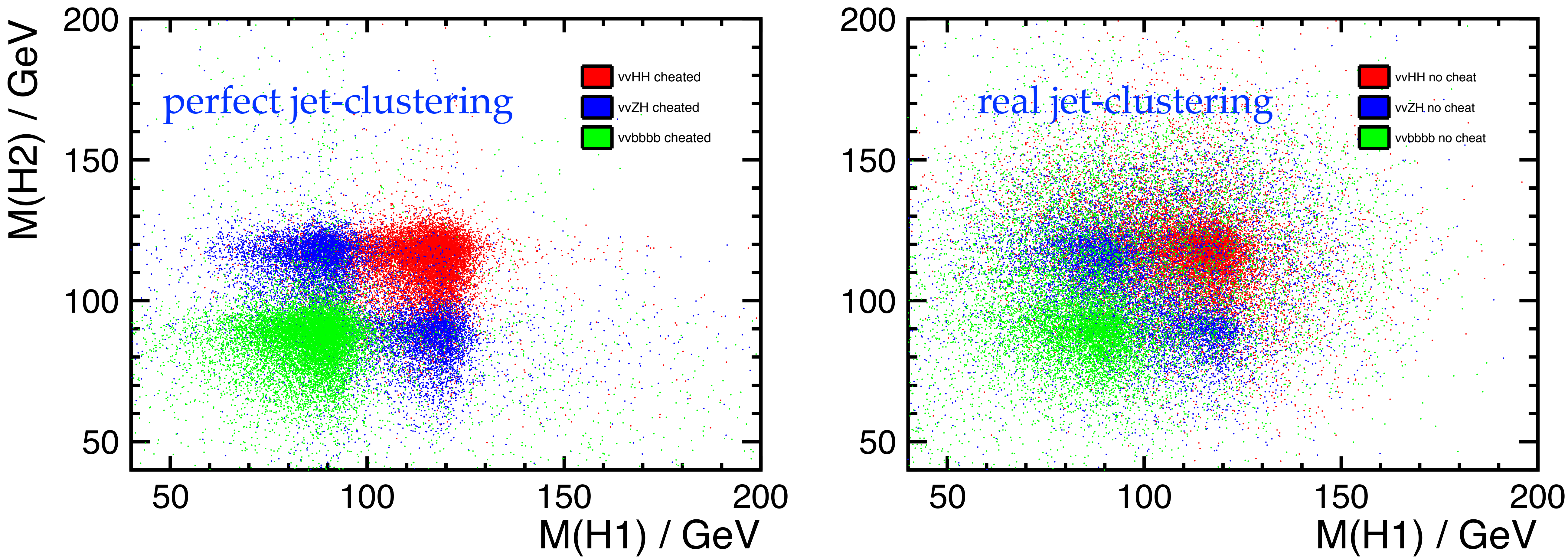


- how far can we go?

limiting factor: new jet-clustering algorithm?

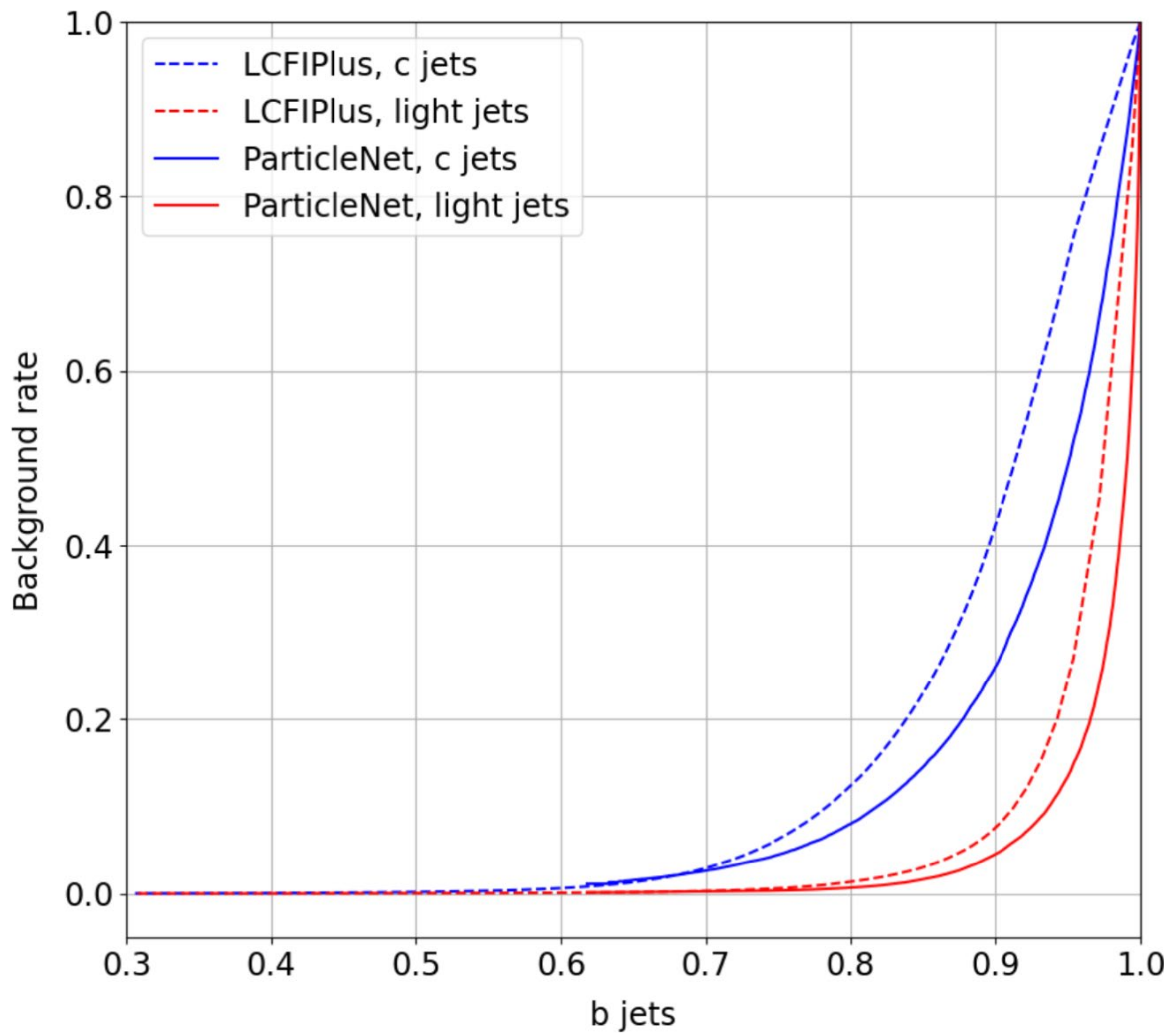
ZHH->ννbbbb (BG: ZZH and ZZZ)

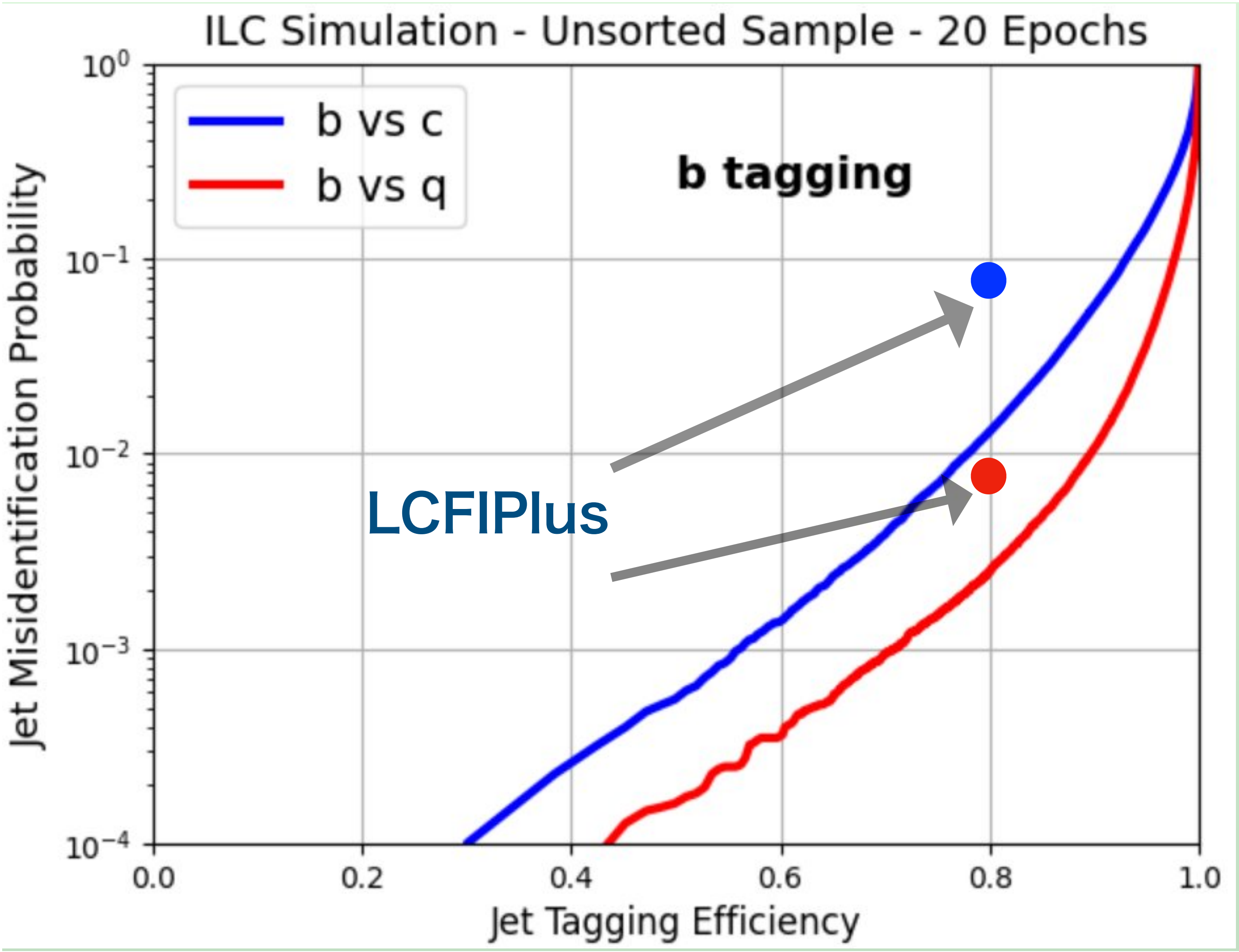
scatter plot of two Higgs masses



- 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%

new development on flavor tagging by ML





ParticleNet

ParticleTransformer

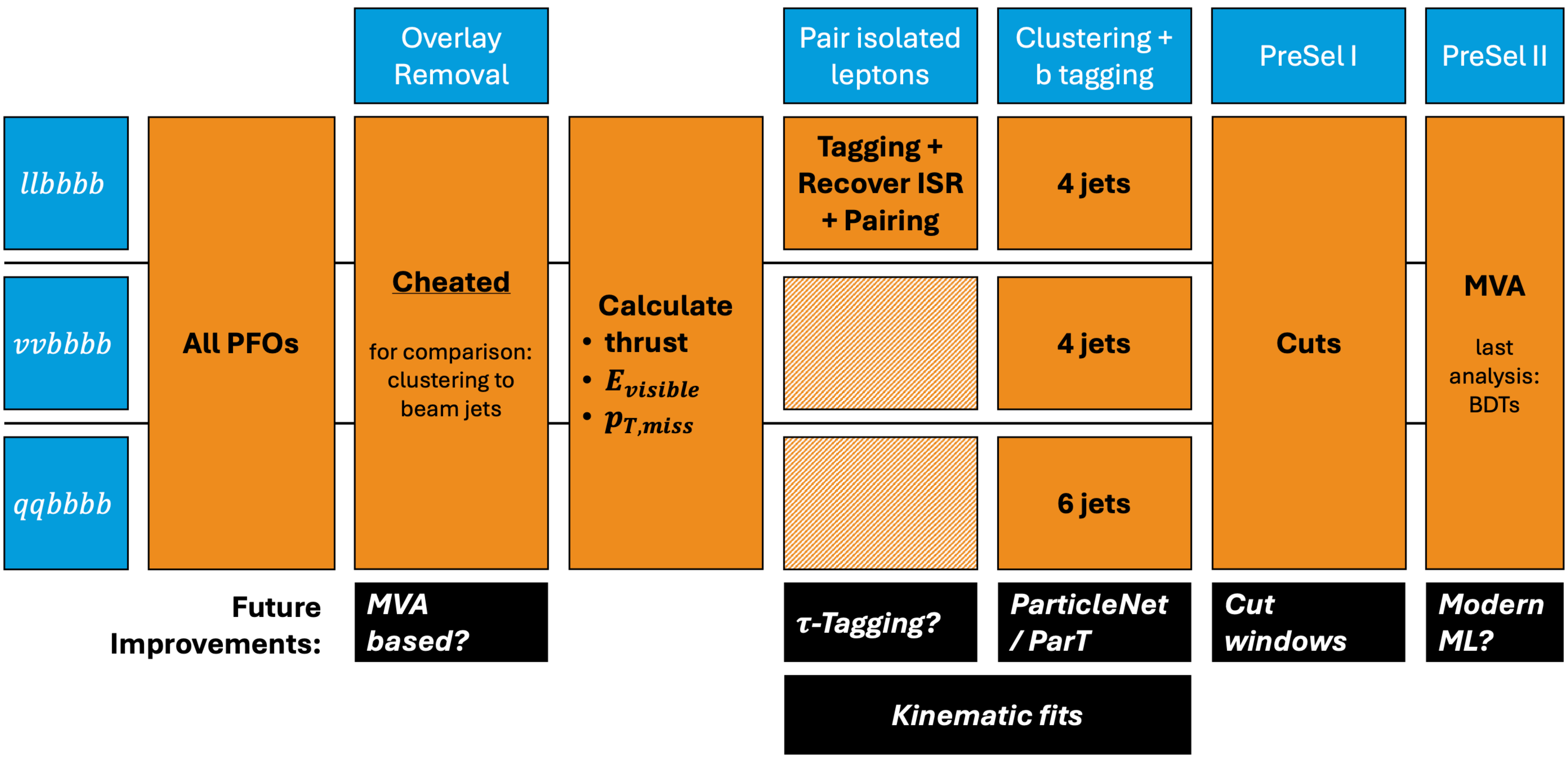
[M. Meyer @ ECFA '23]

[T. Suehara @ LCWS '24]

ongoing full ZHH analysis for next ESU

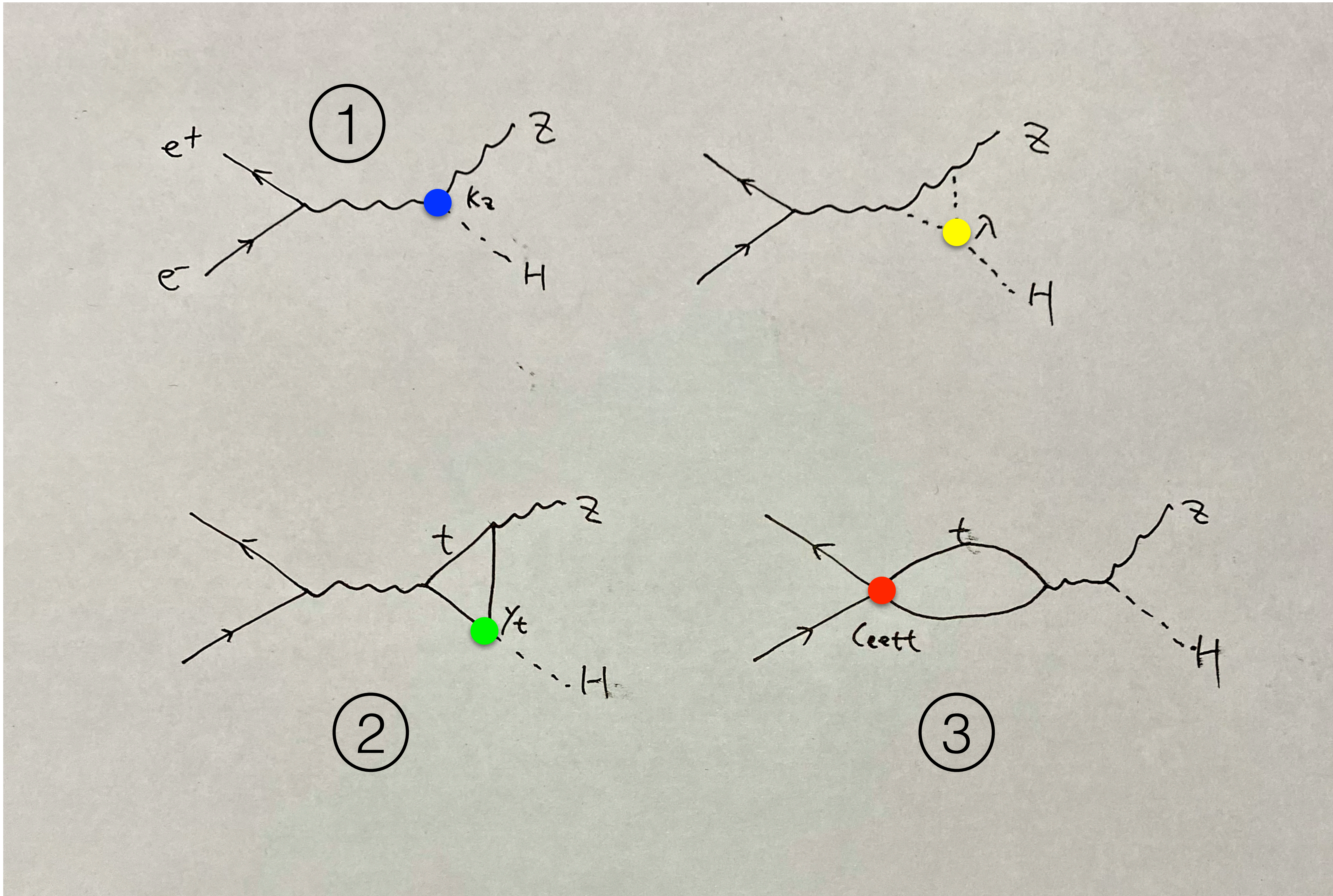
common ILC & C^3

Analysis Flow



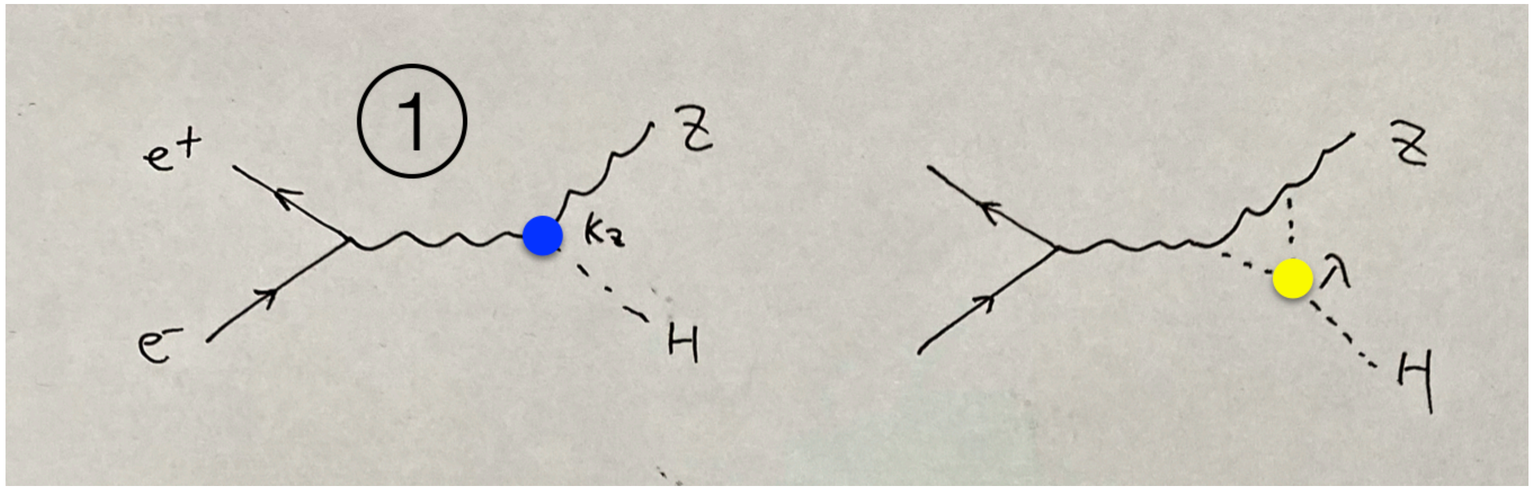
[B. Bliewert @ ECFA '24]

(ii) λ_{HHH} from Single-Higgs



+ many more operators in the same NLO order → [K. Asteriadis @ Higgs'24]

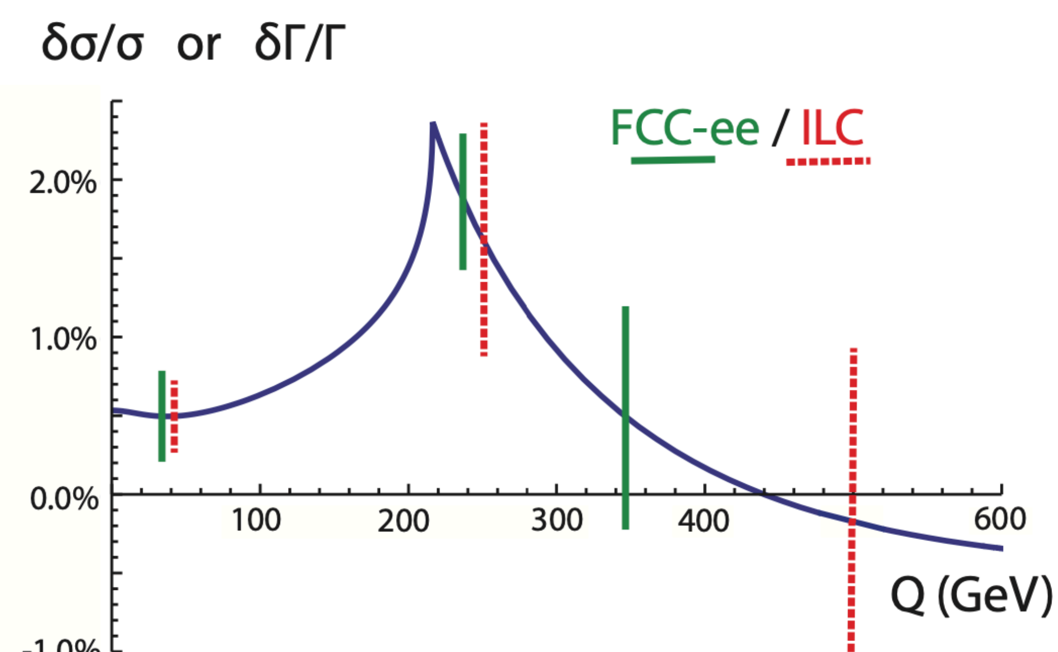
How to discriminate with HZZ coupling



[McCullough, '13]

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

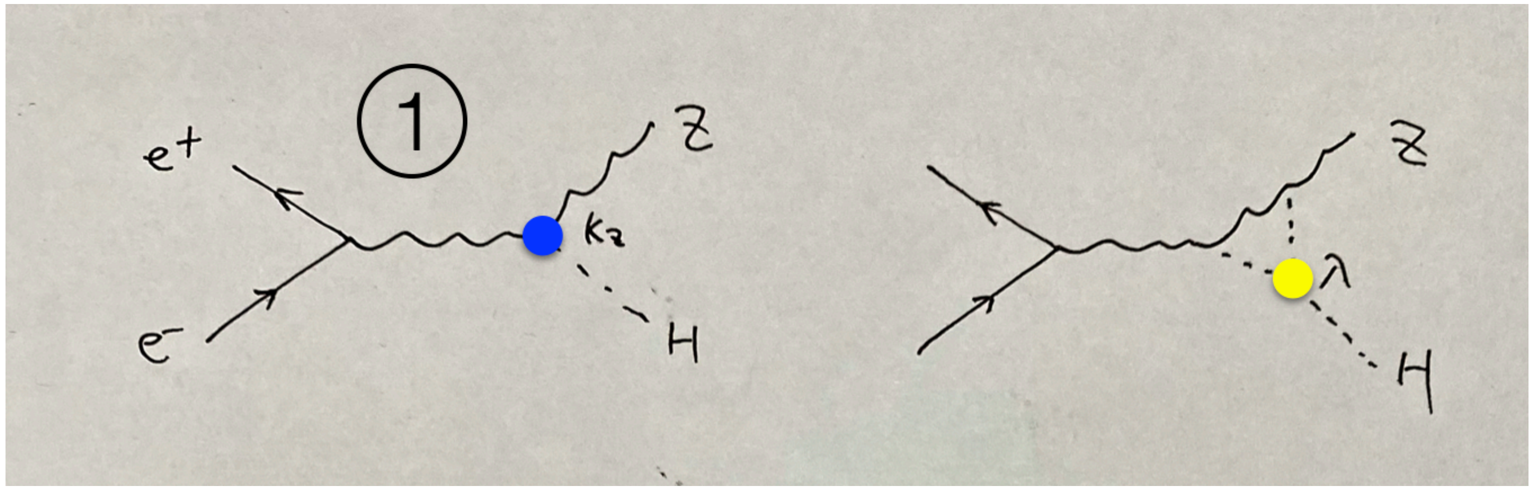
- **$\delta\sigma_{ZH}$ < 1%** is a necessity; but not sufficient
- δσ could receive contributions from many other sources
  —> **δh ~ O(500)%** at 250GeV only; [Gu, et al, arXiv:1711.03978]



[M. Peskin]

- **"easy" solution: lift degeneracy by multiple √s**

(iv) How to discriminate with HZZ coupling



[McCullough, '13]

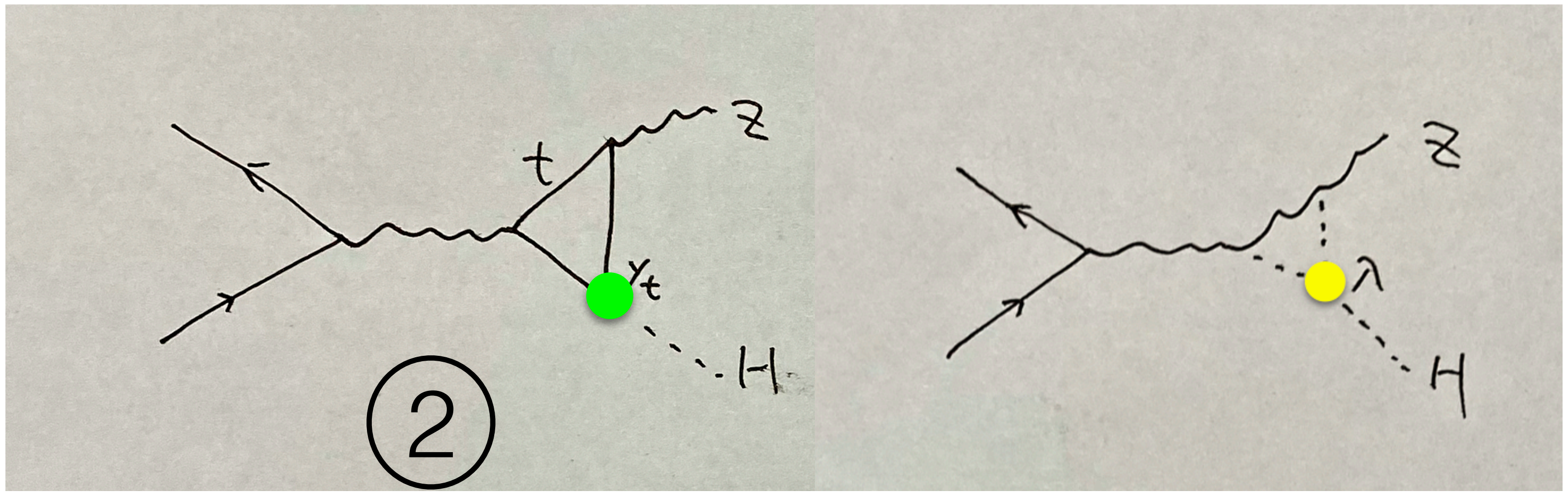
$$\delta_\sigma^{240} = 100\,(2\delta_Z + 0.014\delta_h)\,\%$$

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

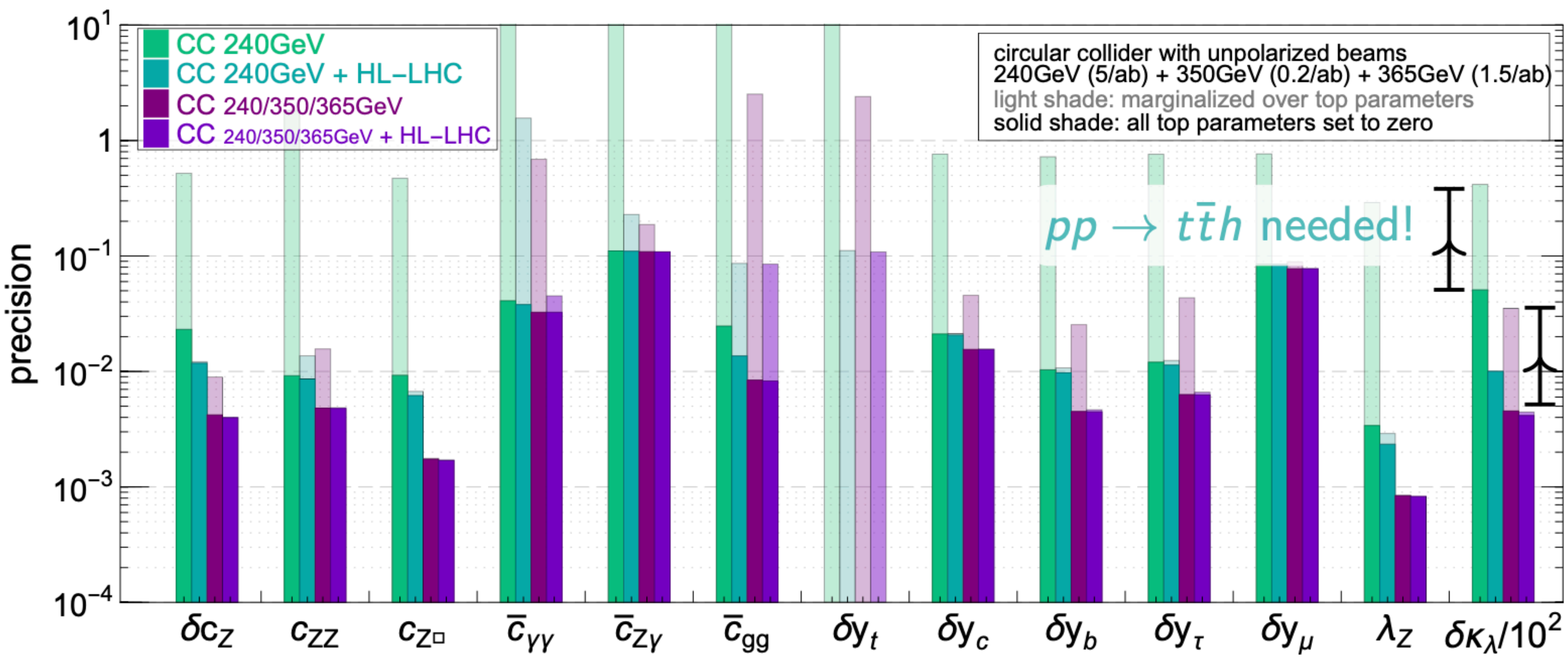
- angular meas.; radiative return → [G. Durieux @ ECFA mini-WS '23]
- effect of λ may connect to anomalous HZZ coupling

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

How to discriminate with top-Yukawa coupling



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

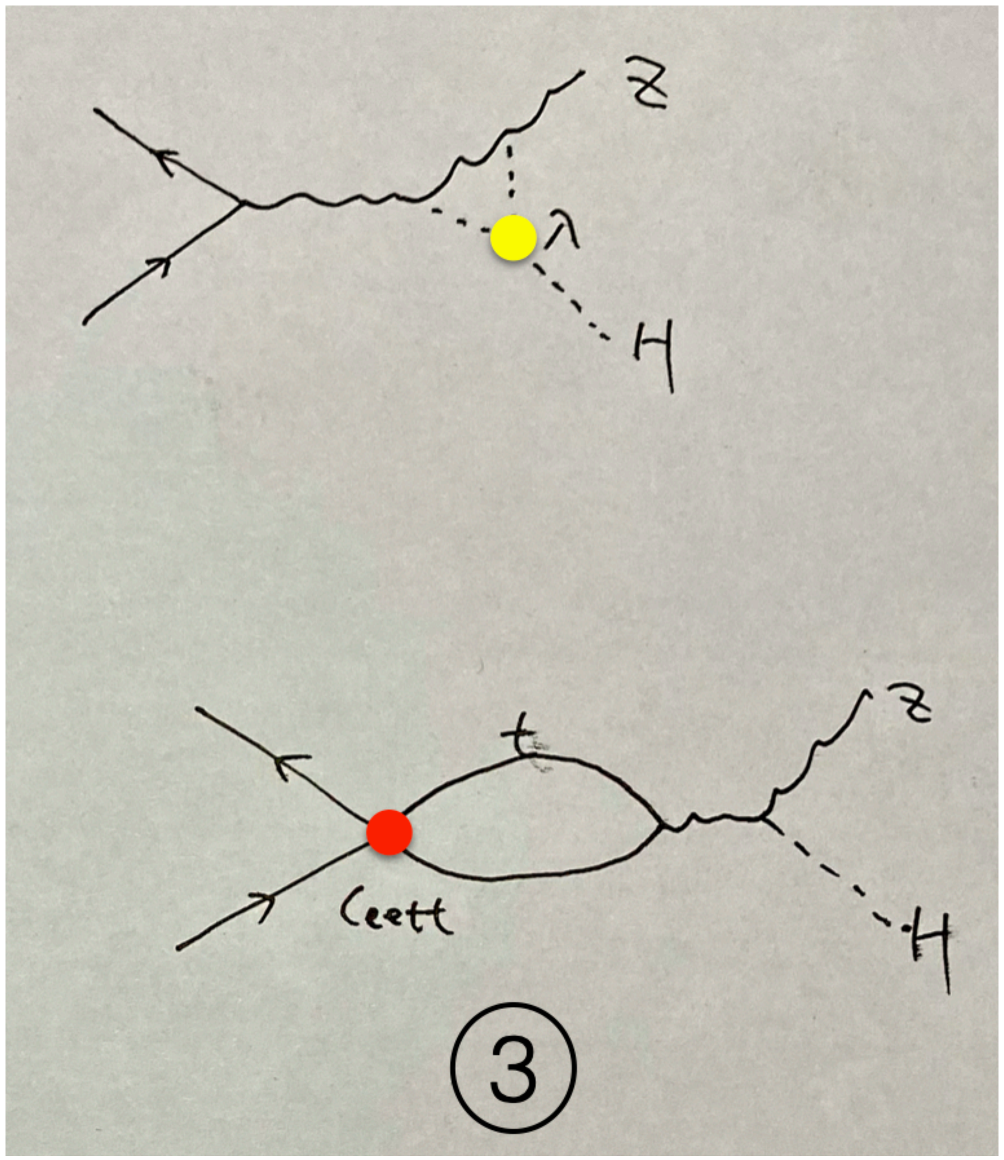


Top-quark uncertainties can impede Higgs precision!

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

How to discriminate with 4-fermion interaction

might be most pressing



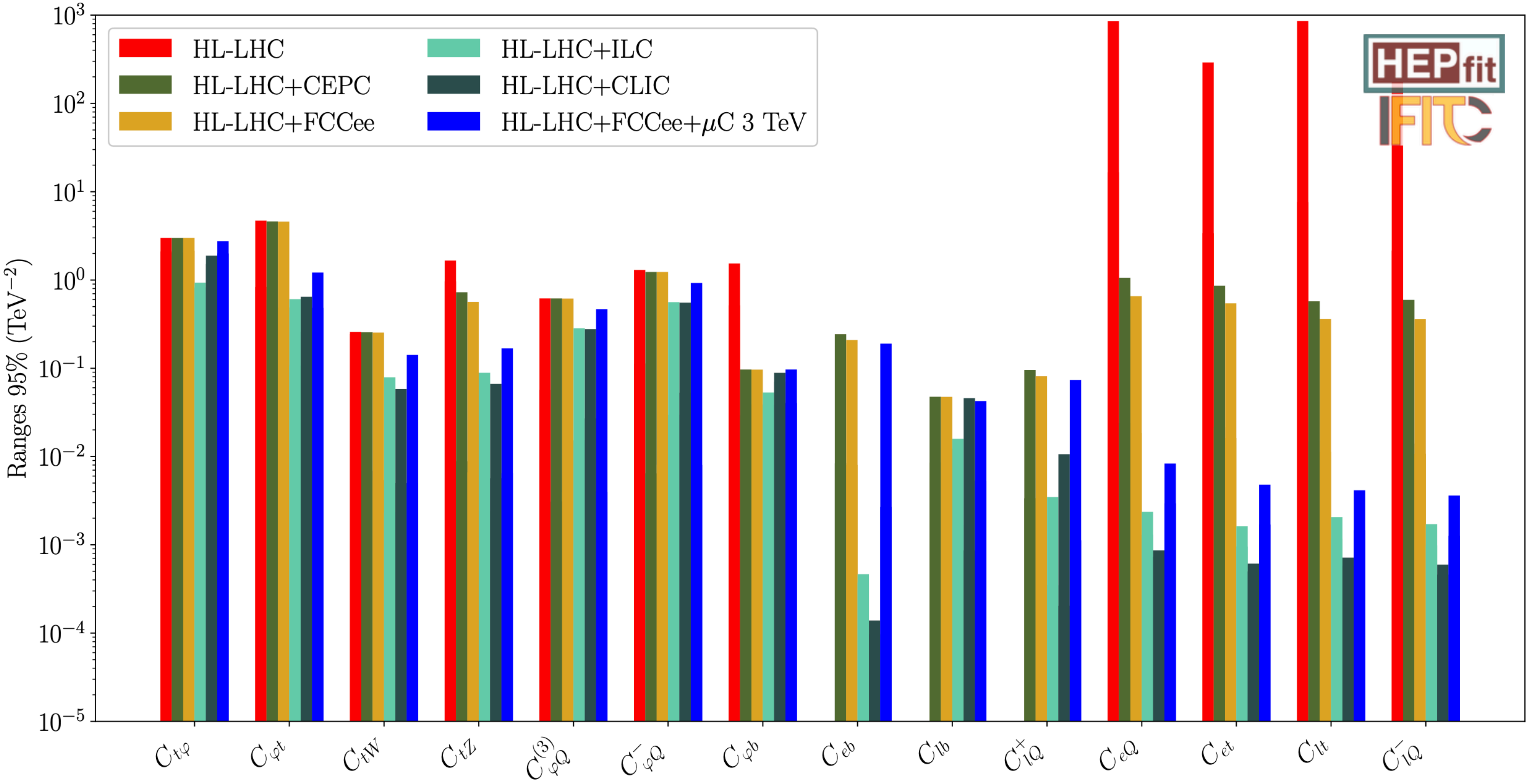
- the effects from (many) eett operators have just been calculated! [Asteriadis, Dawson, Giardino, Szafron, arXiv:2406.03257]

	$\sqrt{s} = 240$ 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
$C_{\phi q}^{(1)}[3,3]$	$-1.34\cdot10^{-3}$	$-4.10\cdot10^{-3}$	$-4.39\cdot10^{-3}$	$-4.31\cdot10^{-3}$
$C_{\phi q}^{(3)}[3,3]$	$0.51\cdot10^{-3}$	$4.12\cdot10^{-3}$	$4.15\cdot10^{-4}$	$7.58\cdot10^{-4}$
$C_{\phi u}[3,3]$	$-0.54\cdot10^{-3}$	$3.49\cdot10^{-3}$	$5.37\cdot10^{-3}$	$3.11\cdot10^{-3}$
$C_{eu}[1,1,3,3]$	$0.01\cdot10^{-3}$	$-1.39\cdot10^{-2}$	$-3.73\cdot10^{-2}$	$-3.23\cdot10^{-2}$
$C_{lu}[1,1,3,3]$	$-0.02\cdot10^{-3}$	$1.73\cdot10^{-2}$	$4.64\cdot10^{-2}$	$4.01\cdot10^{-2}$
$C_{lq}^{(1)}[1,1,3,3]$	$-0.37\cdot10^{-2}$	$-1.80\cdot10^{-2}$	$-6.09\cdot10^{-2}$	$-4.18\cdot10^{-2}$
$C_{lq}^{(3)}[1,1,3,3]$	$-0.37\cdot10^{-2}$	$1.29\cdot10^{-2}$	$4.54\cdot10^{-2}$	$3.29\cdot10^{-2}$
$C_{qe}[3,3,1,1]$	$0.30\cdot10^{-2}$	$1.45\cdot10^{-2}$	$4.90\cdot10^{-2}$	$3.36\cdot10^{-2}$

How to discriminate with 4-fermion interaction

[M. Vos @ ECFA '24]

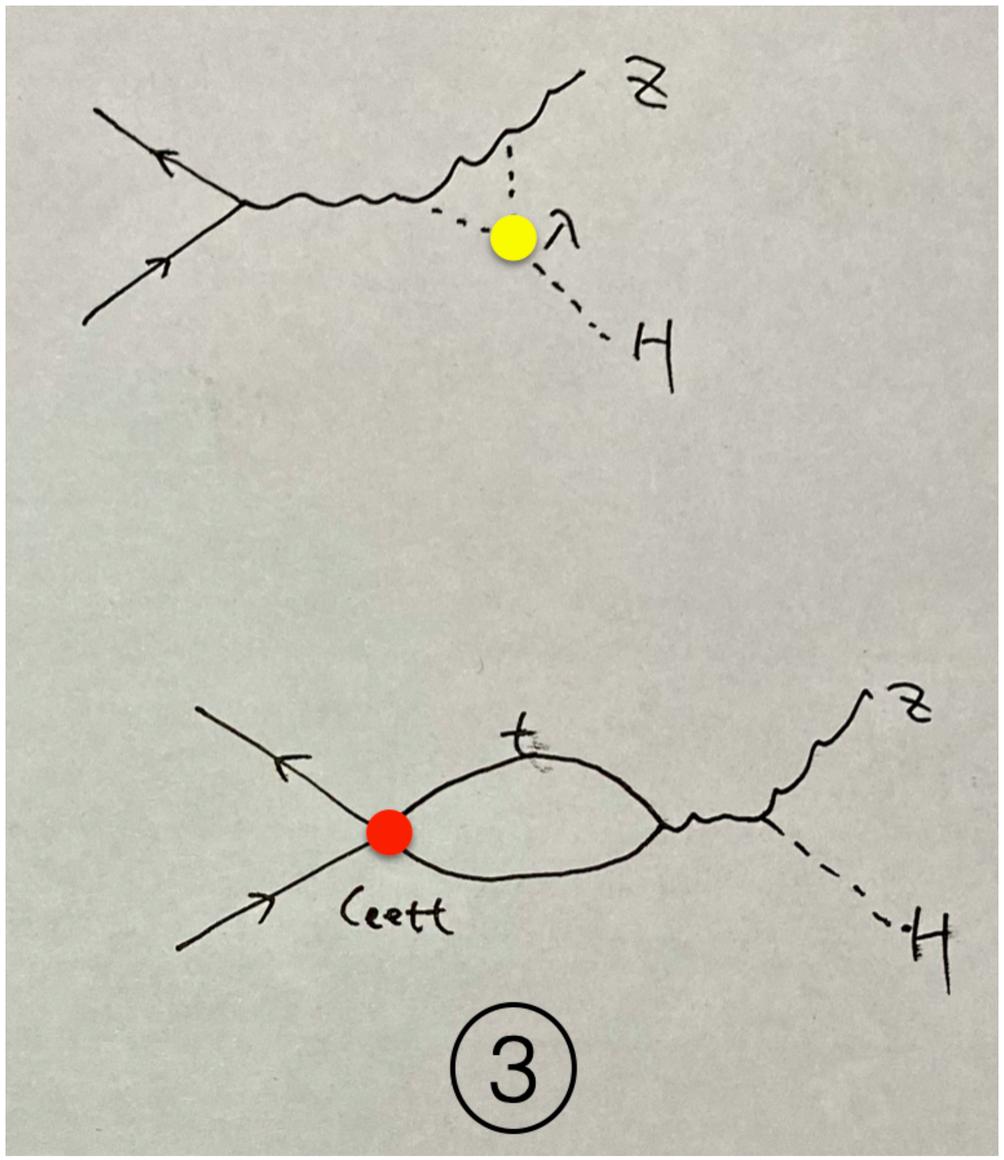
- need projection for eett at HL-LHC & e+e-



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

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

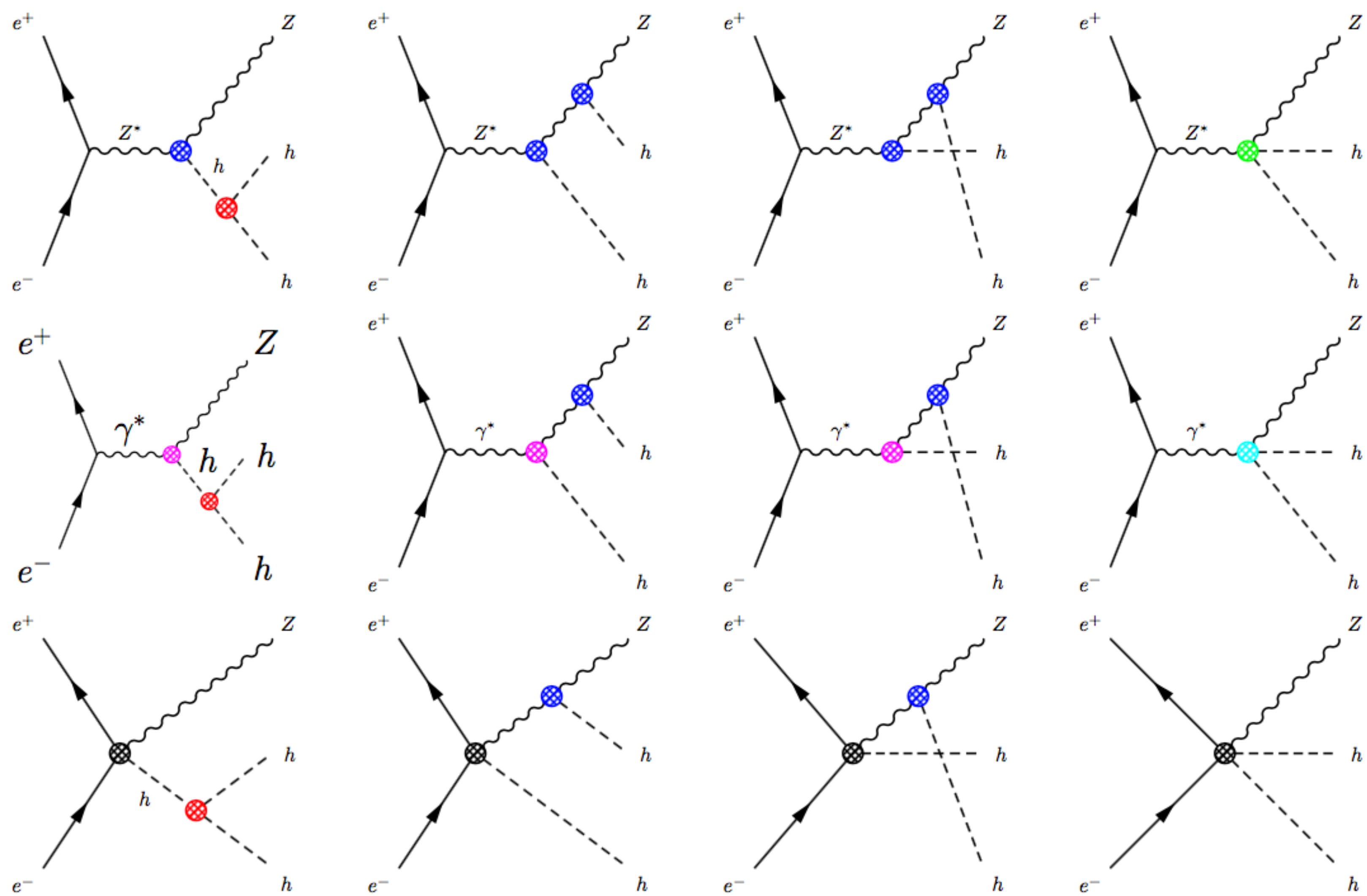
a test fit for 5000 fb^{-1} (240) + 1500 fb^{-1} (365)

$\delta\lambda_{HHH}$ 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.]

similar issue in double-Higgs approach

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



- degeneracies from same-order SMEFT resolved

summary

- Challenging task to measure Higgs self-coupling at future colliders
- Many progresses on theory, di-Higgs & single-Higgs approaches
- Ongoing di-Higgs analysis to update λ_{HHH} projection: huge room existing by new advanced analysis tools
- A new global SMEFT fit is being worked out to address the opportunity / challenges in probing λ_{HHH} using single-Higgs

    - welcome to join the adventure!

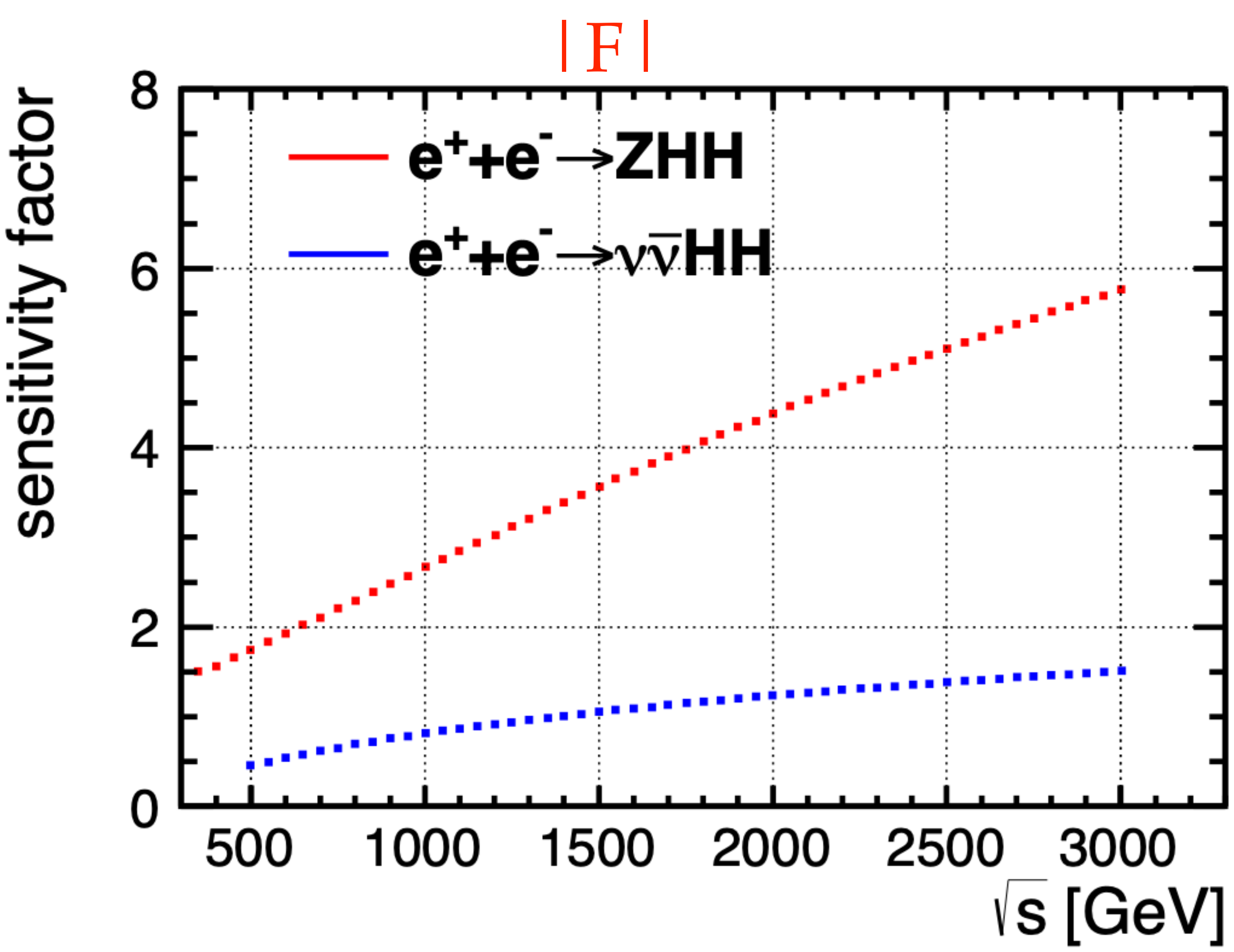
backup

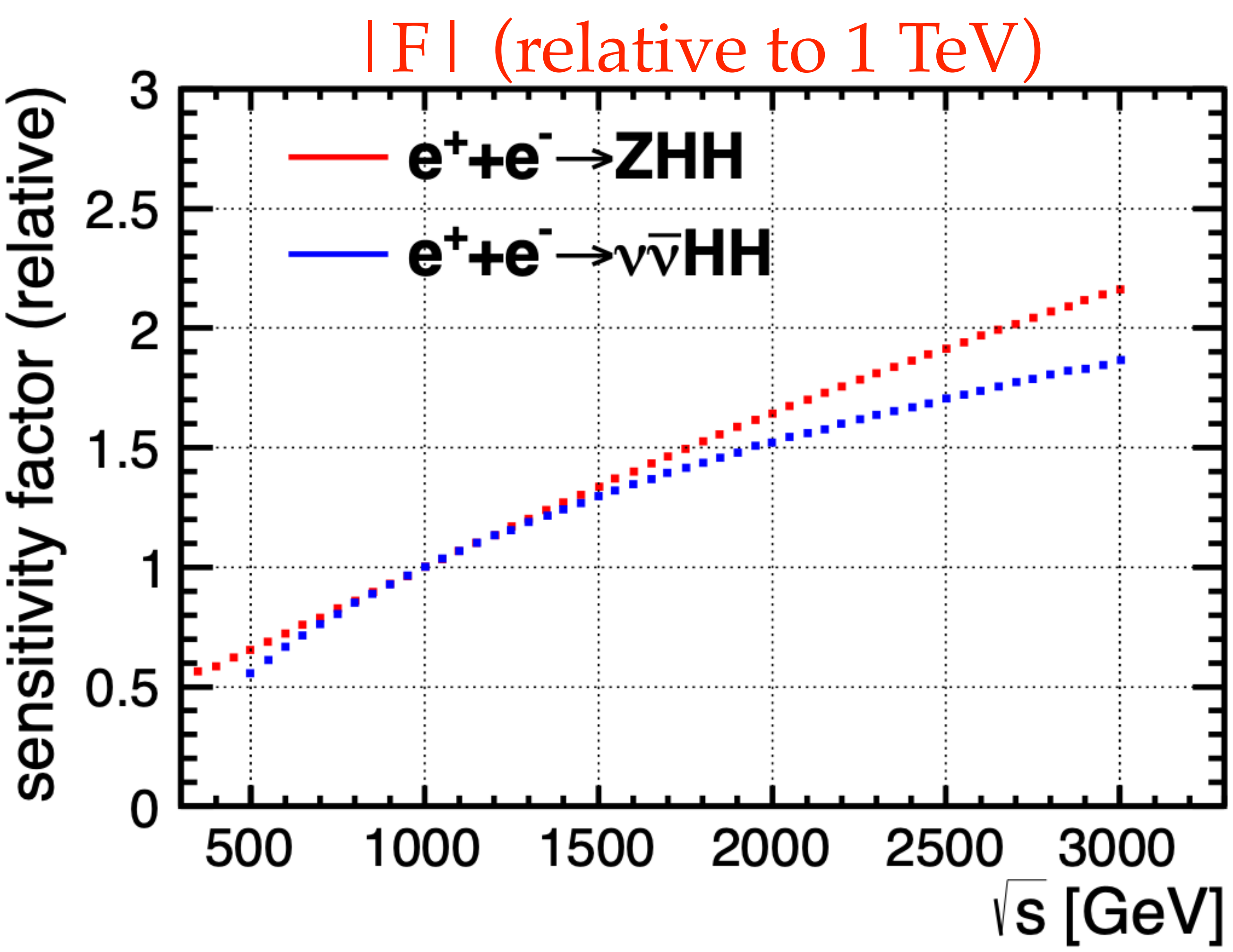
Higgs self-coupling: impact of ECM

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

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

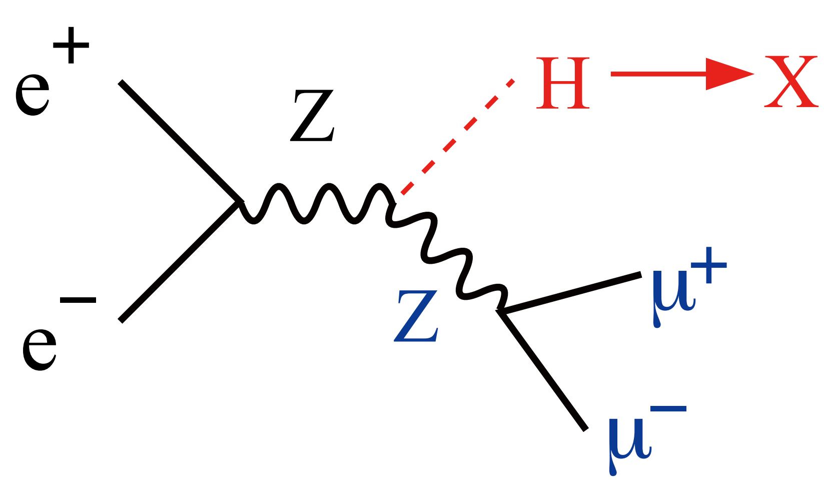
sensitivity factor

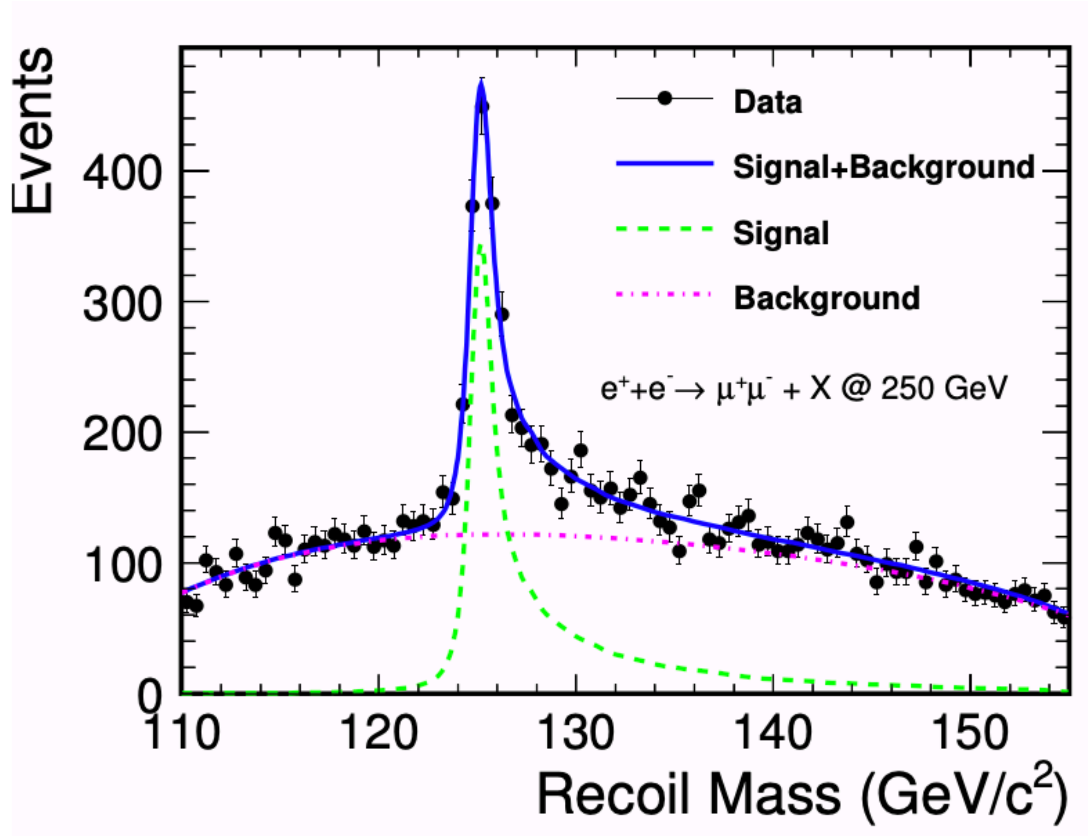




Challenges: $\delta\sigma_{ZH}$ << 1%?

- **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 → 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%
$M_{rec} \in [110, 155]$ 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]

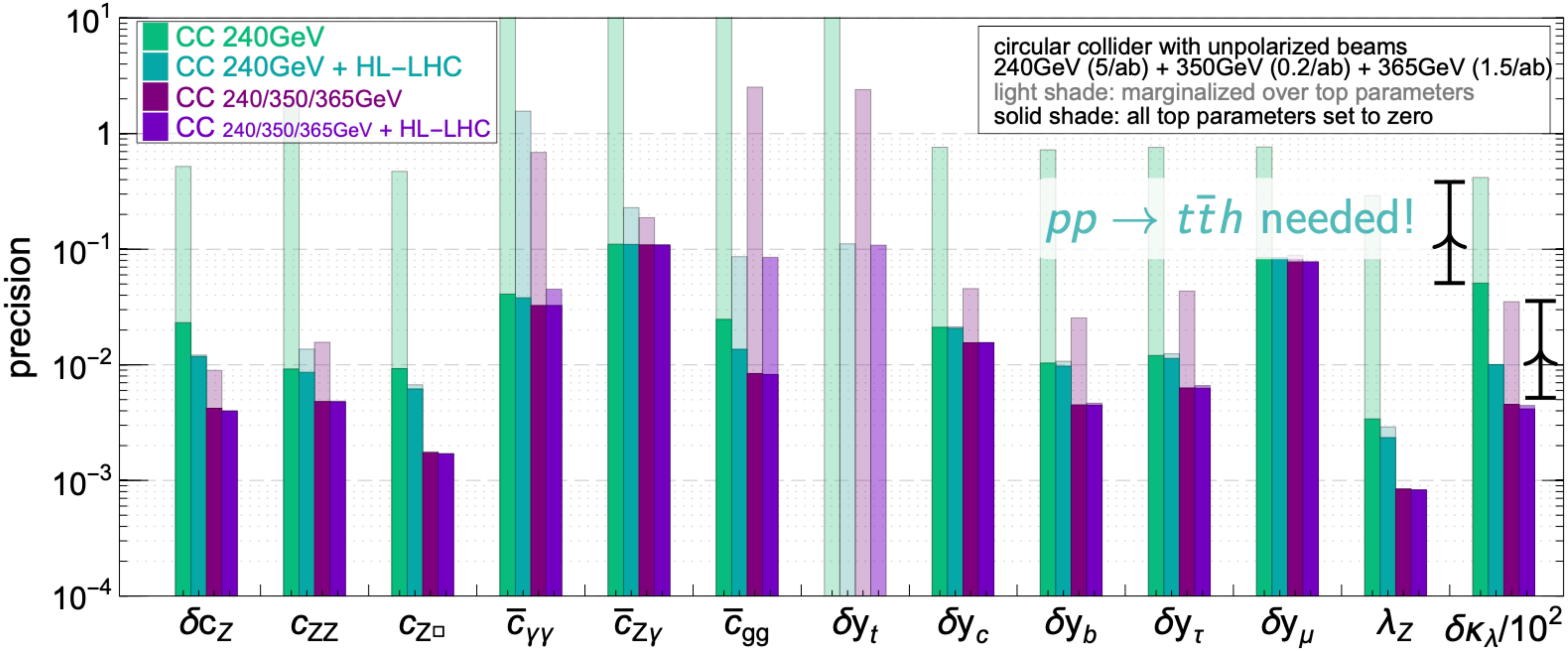
Decay mode	$\varepsilon^{vis.}_{\mathscr{L}>0.65}$	$\varepsilon^{invis.}_{\mathscr{L}>0.60}$	$\varepsilon^{vis.} + \varepsilon^{invis.}$
H → invis.	<0.1 %	23.5 %	23.5 %
$H \to q\bar{q}/gg$	22.6 %	<0.1 %	22.6 %
$H \to WW^*$	22.1 %	0.1 %	22.2 %
$H \to ZZ^*$	20.6 %	1.1 %	21.7 %
$H \to \tau^+\tau^-$	25.3 %	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

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

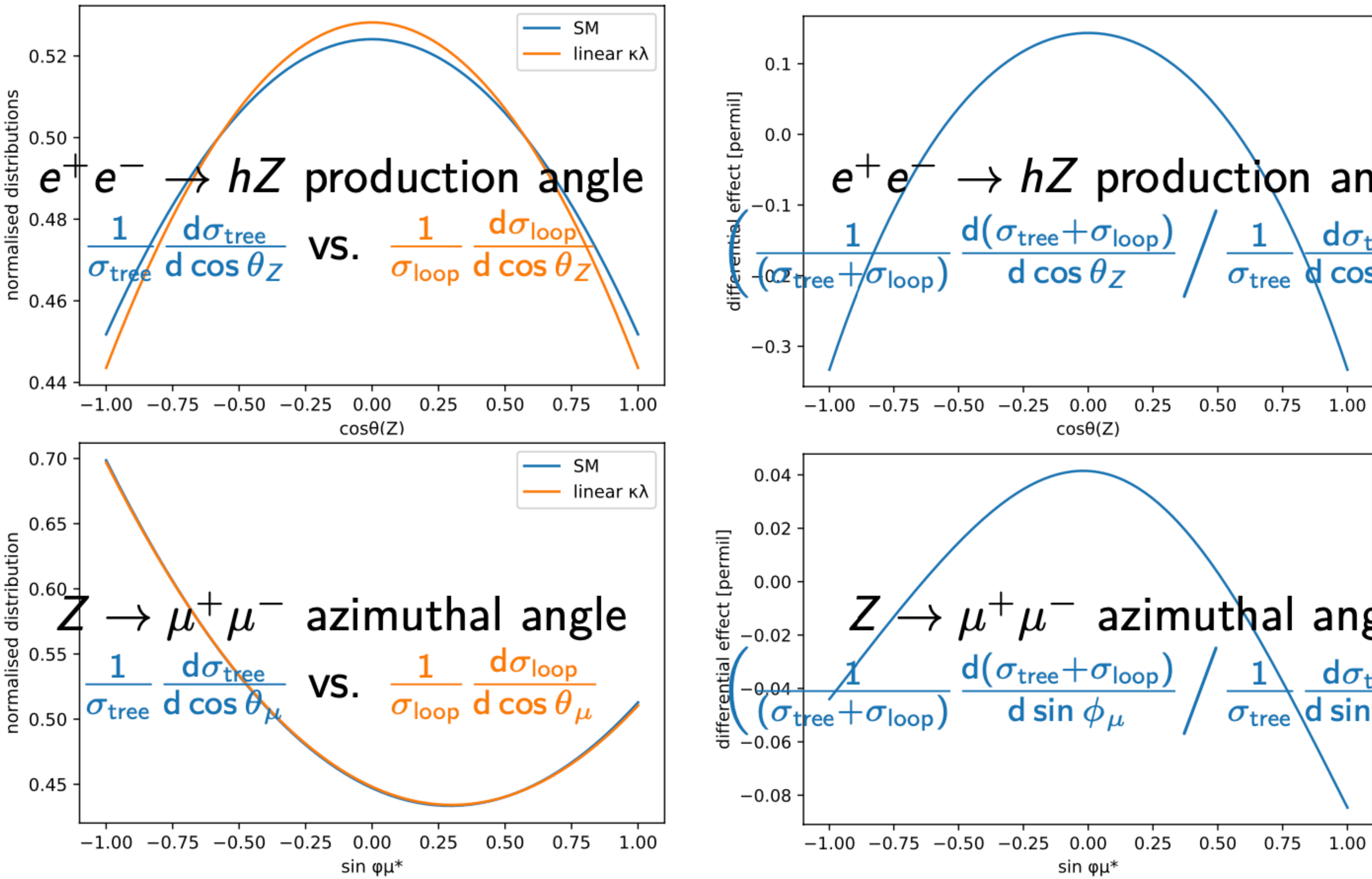
- Higgsstr. run: insufficient
- Higgsstr. run $\oplus$ top@HL-LHC: large top contaminations in $\bar{c}_{\gamma\gamma,gg,Z\gamma,ZZ}$
- Higgsstr. run $\oplus$ $e^+e^- \to t\bar{t}$: large y_t contaminations in various coefficients
- Higgsstr. run $\oplus$ $e^+e^- \to t\bar{t}$ $\oplus$ top@HL-LHC: top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

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

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

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

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

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

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

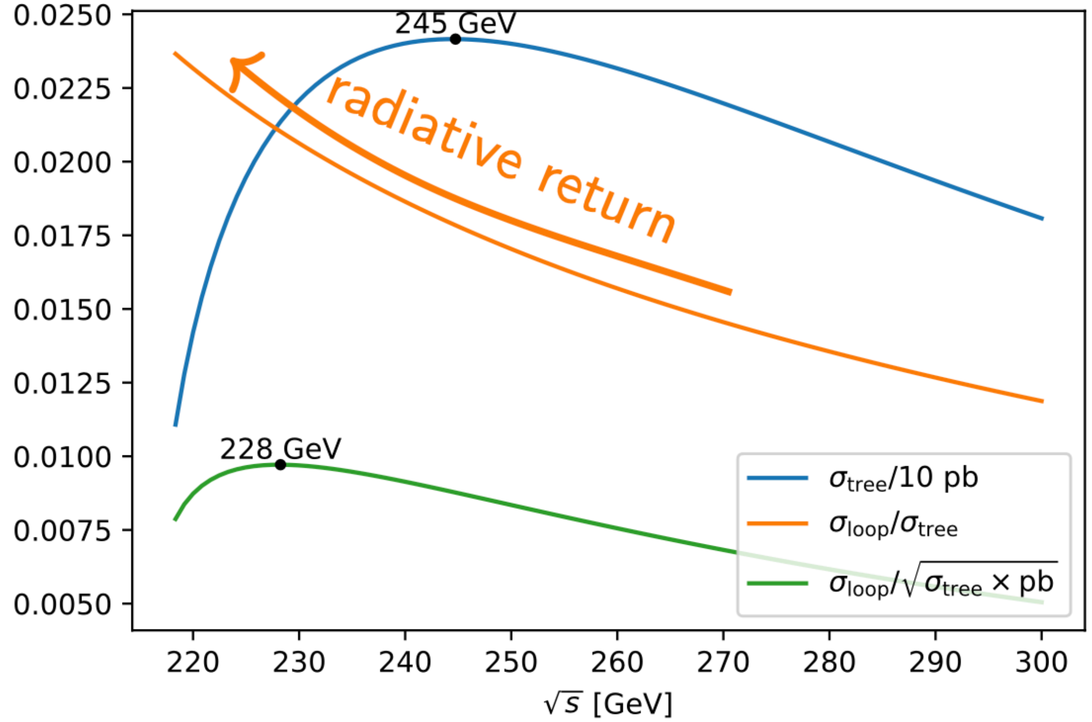
$Z \to \mu^+\mu^-$ azimuthal angle

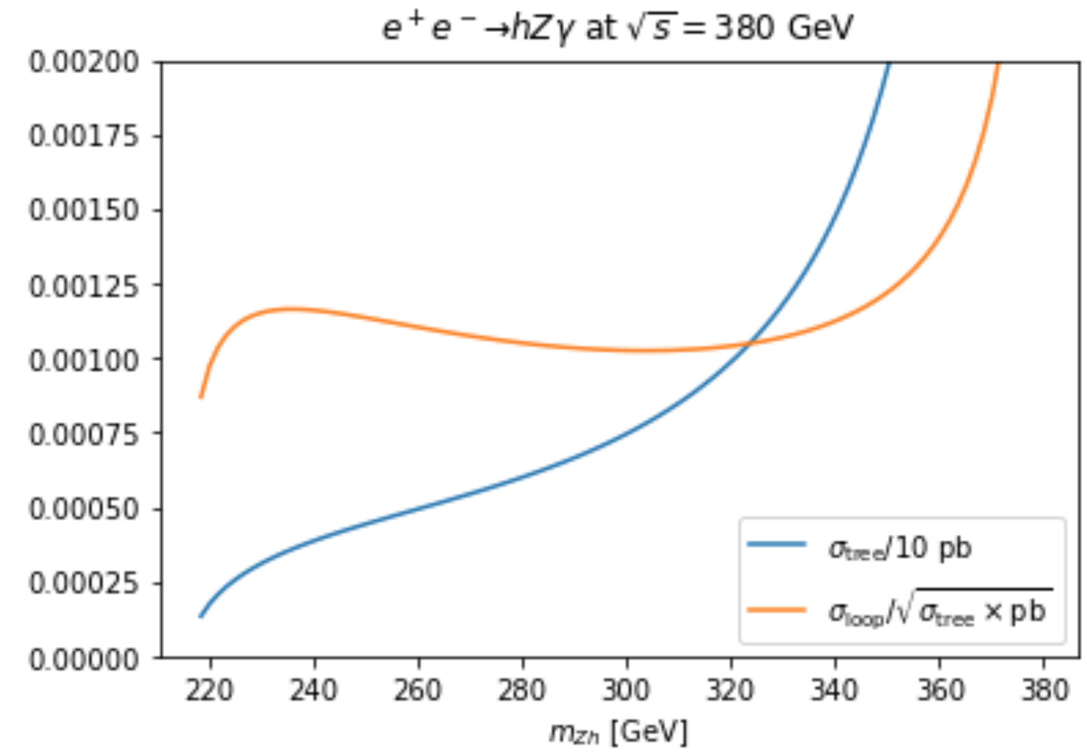
$$\left(\frac{1}{(\sigma_{\rm tree}+\sigma_{\rm loop})}\frac{d(\sigma_{\rm tree}+\sigma_{\rm loop})}{d\sin\phi_\mu} \Big/ \frac{1}{\sigma_{\rm tree}}\frac{d\sigma_{\rm tree}}{d\sin\phi_\mu}\right) - 1$$

¿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?**



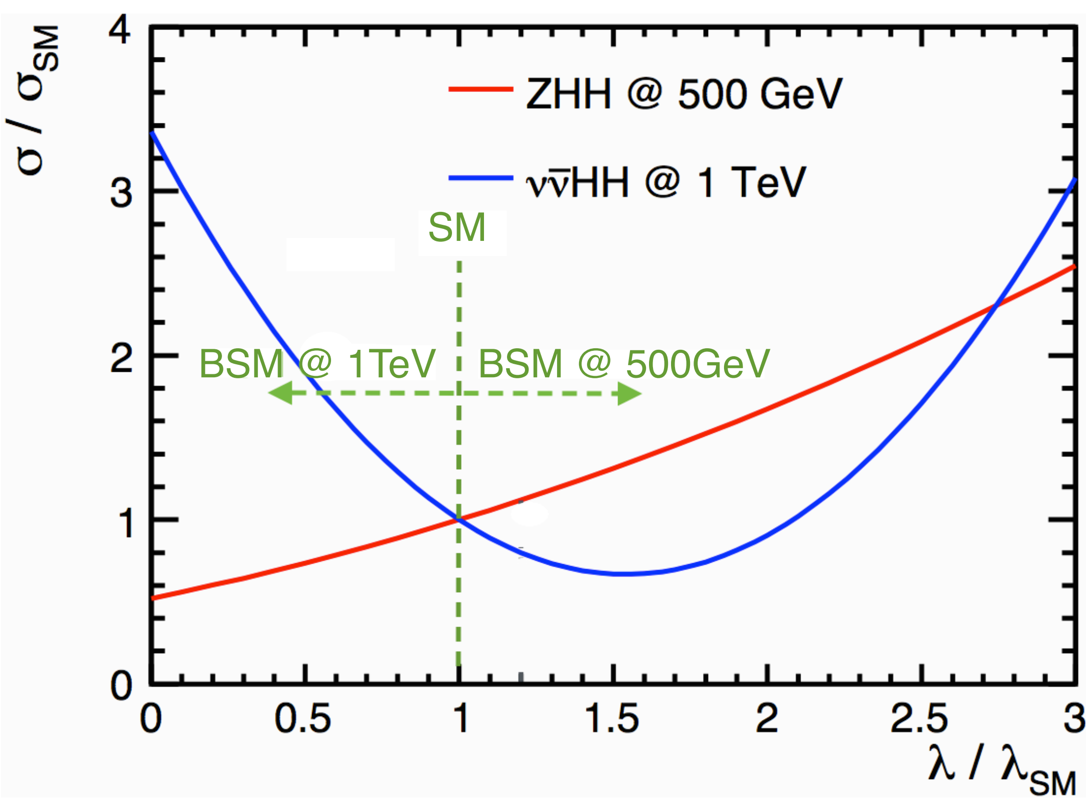


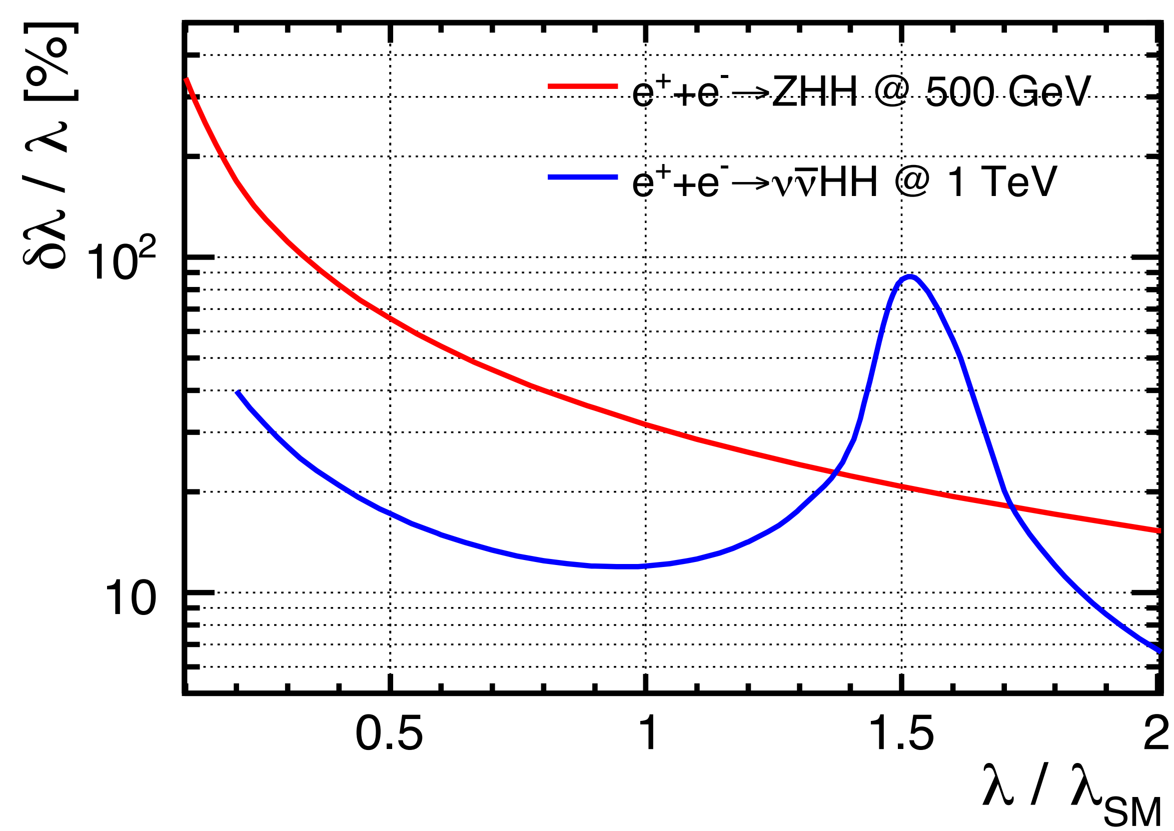
[Durieux, et al, preliminary]

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

(examples)

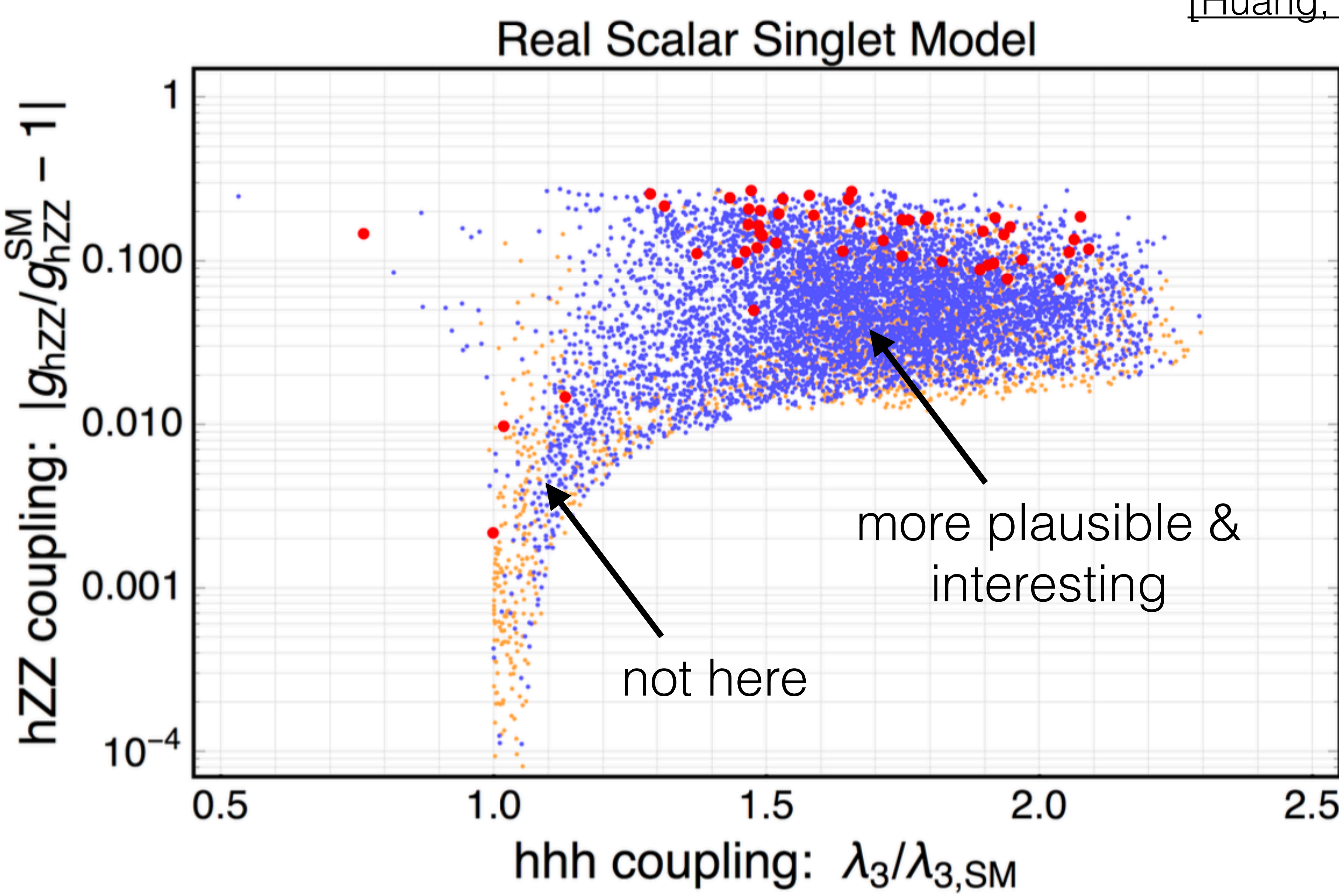
- profound effect on di-Higgs processes
- complementarity between ZHH & ννHH (& LHC): different interference
- if $\lambda_{HHH} / \lambda_{SM} = 2$, λ_{HHH} be *discovered* (~13%) using ZHH at 500 GeV e+e-





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

[Huang, Long, Wang, '16]



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]