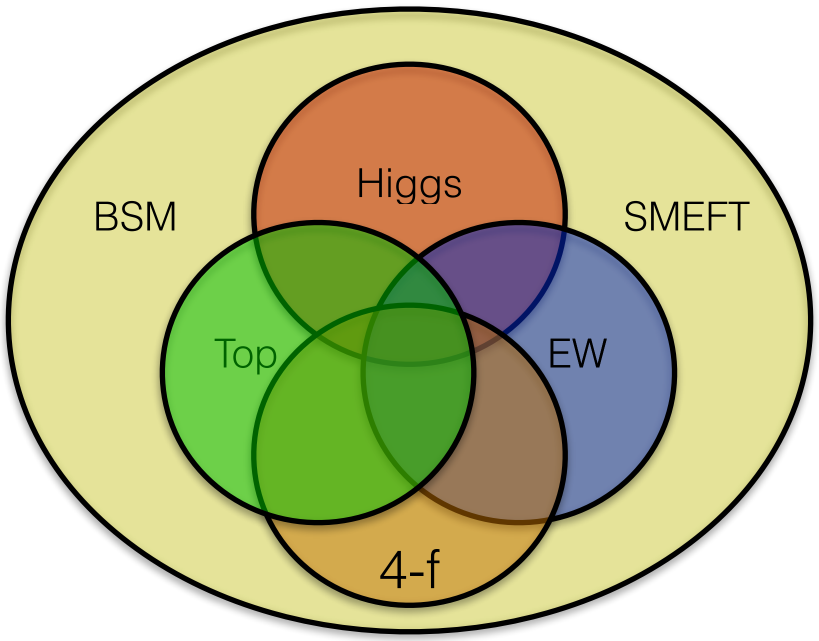
Opportunities & Experimental Challenges at the Higgs-Top interface



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LCWS 2024 @ Tokyo, July 8-11, 2024

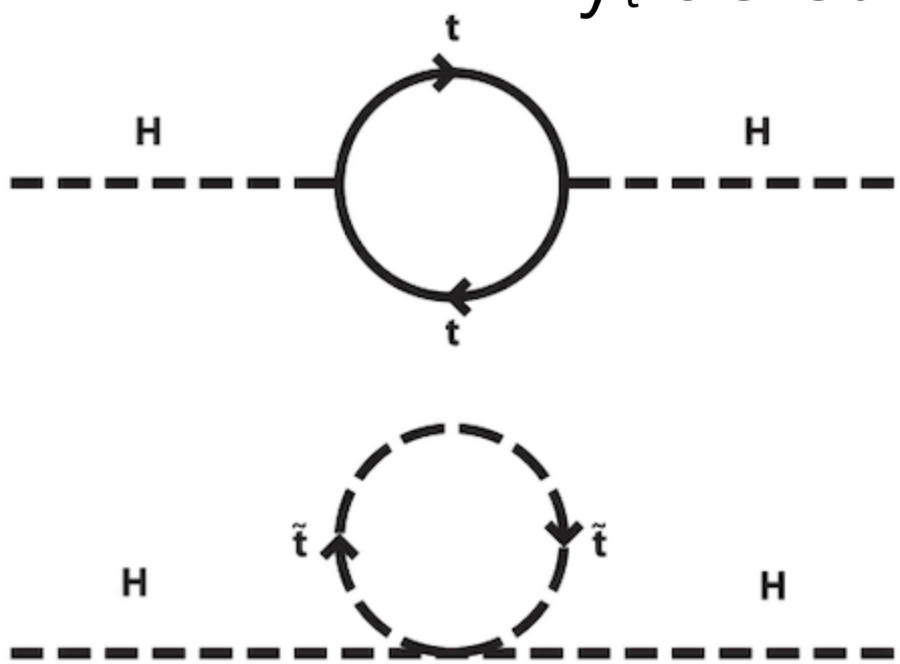
ICEPP
The University of Tokyo

many thanks to M. Vos, J. List, D. Jeans, et al for helpful discussions

(caution: significance bias from my selection)

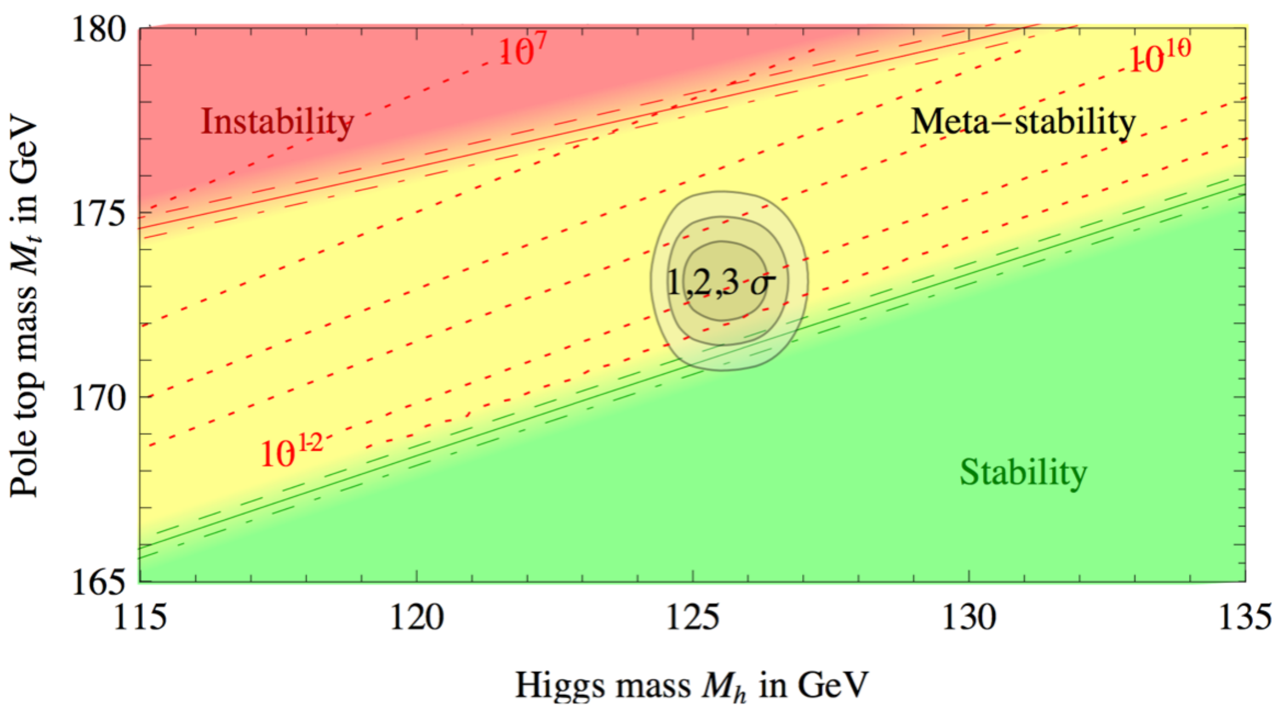
Higgs & Top-quark "naturally" engaged in probing BSM

y_t as strong as α_S



- gauge hierarchy problem

- many models require certain top-quark "partners" to solve the problems

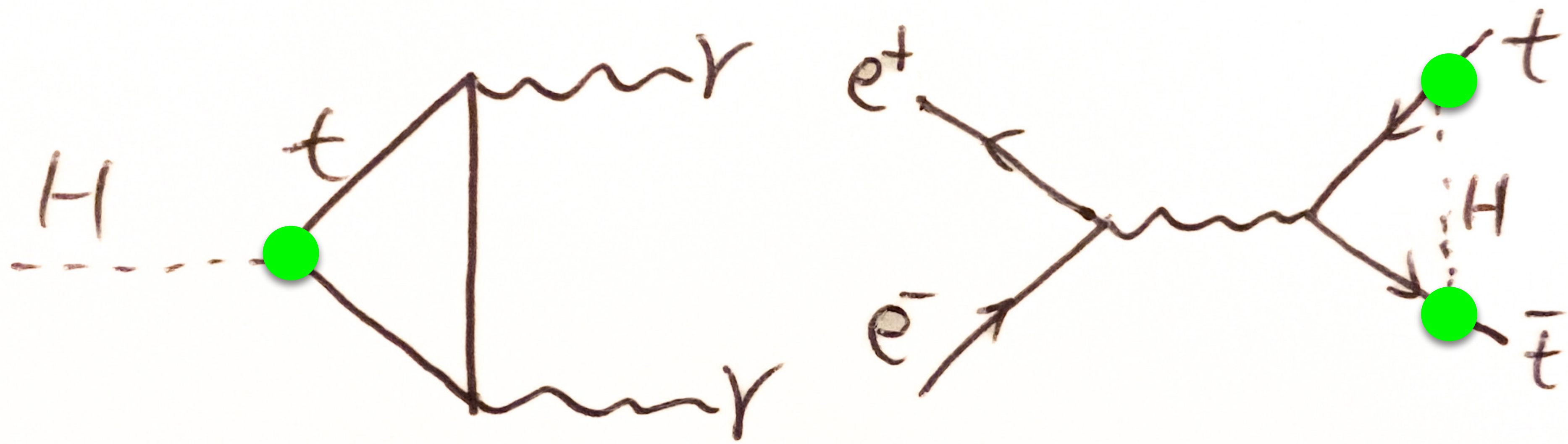


[Degrassi et al, JHEP 1208 (2012) 098]

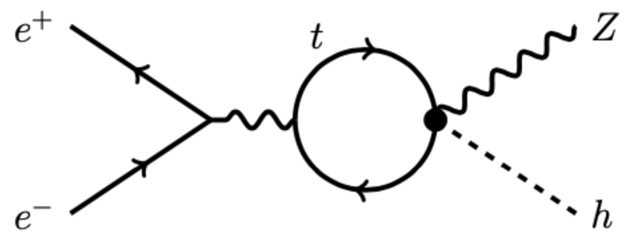
- vacuum stability

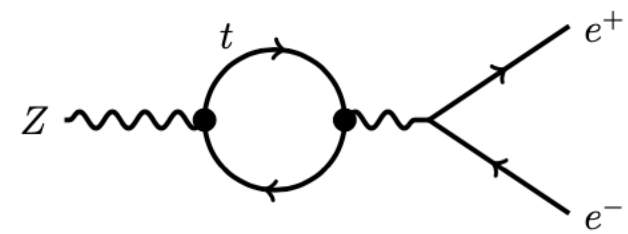
Opportunities from Higgs-Top interplay

- sensitivity to y_t in H—>γγ decay
- sensitivity to y_t in e+e- —> tt threshold scan

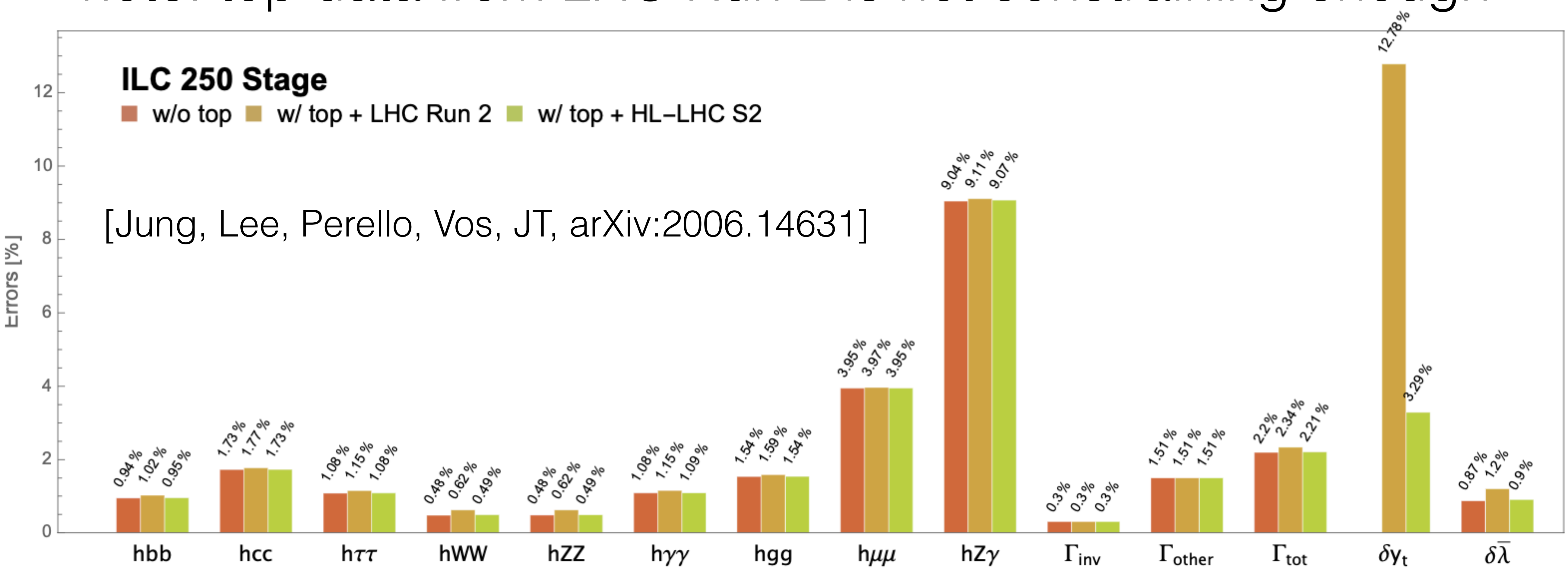


Challenges: large NLO uncertainties induced in precision EW and Higgs measurement



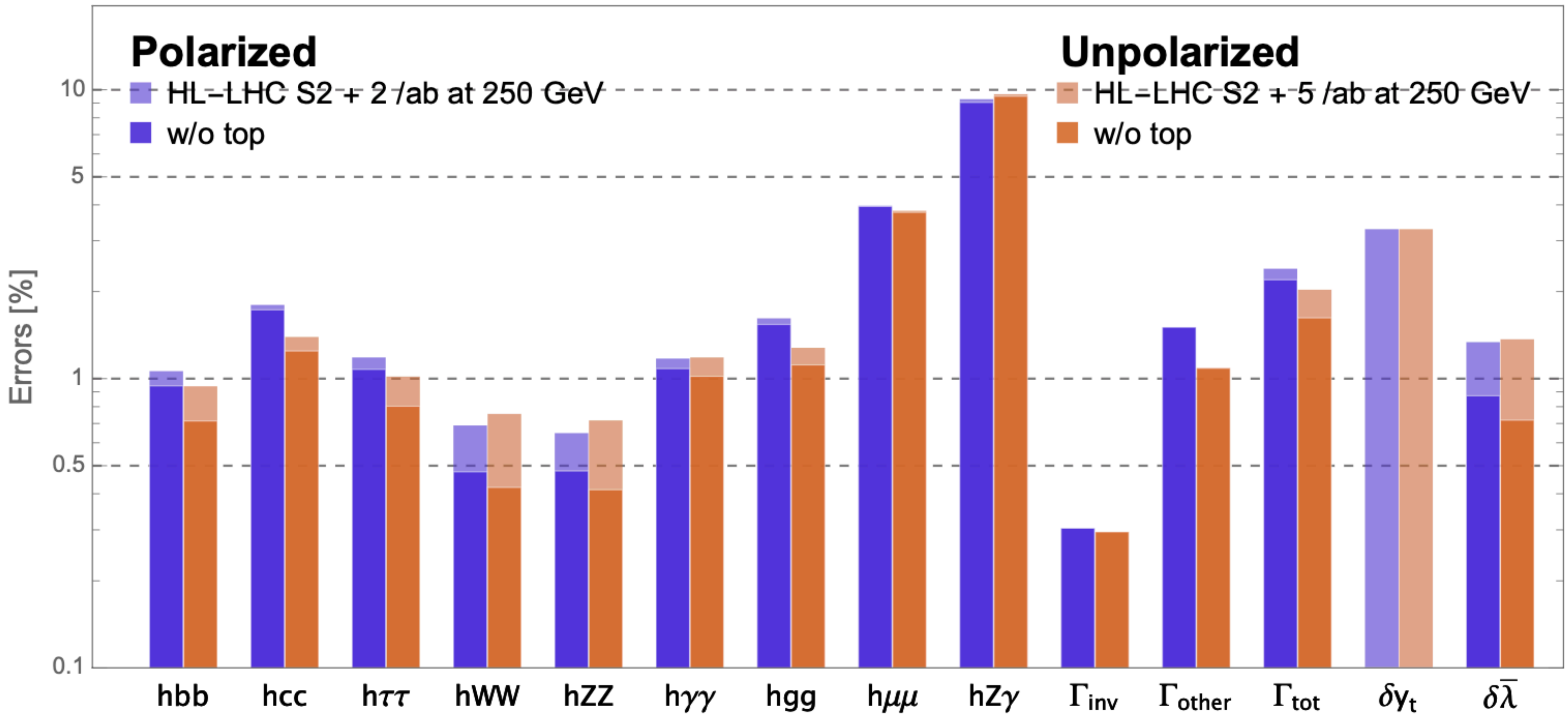


- with the help of LHC top data, Higgs coupling precisions @ ILC250 are almost restored
- note: top data from LHC Run 2 is not constraining enough



Mitigating challenges: beam polarization helps

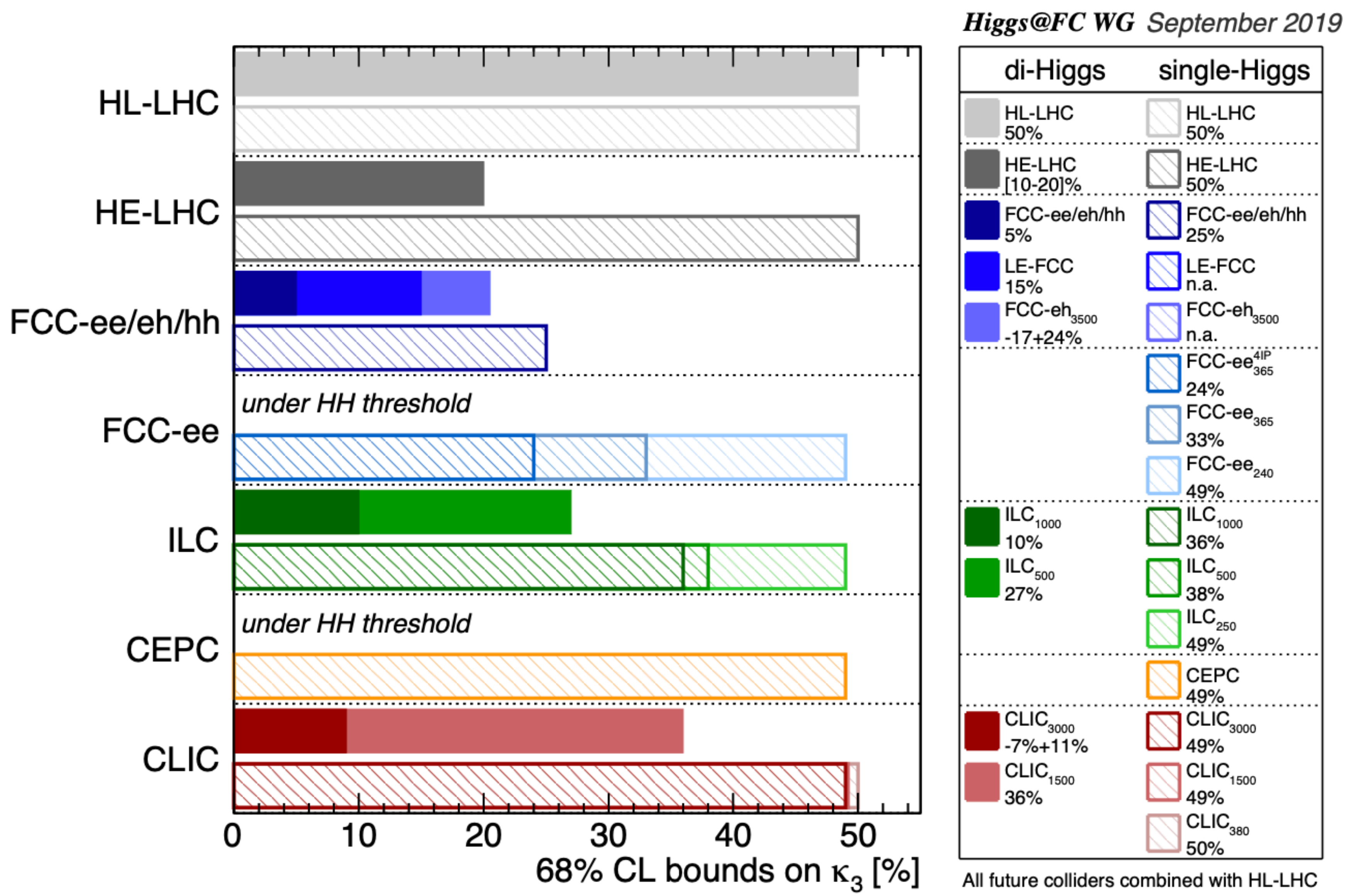
- beam polarizations double independent observables, more robust in resolving various effects from top-EW at NLO



[Jung, Lee, Perello, Vos, JT, arXiv:2006.14631]

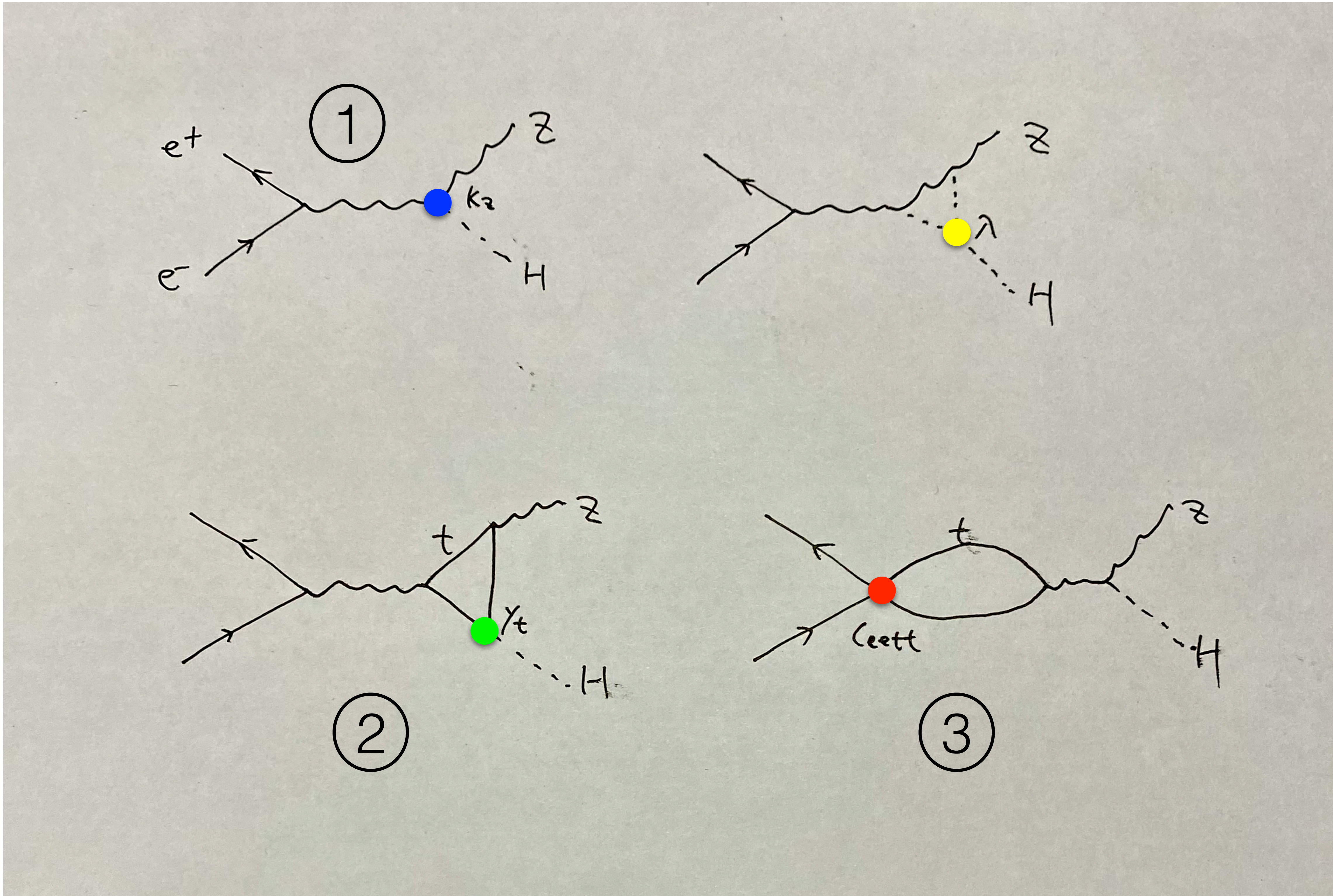
λ_{HHH}: emerging new opportunities from single-Higgs

[ESUPP 2020 arXiv:1910.11775] **[—>talk by Jorge de Blas]**

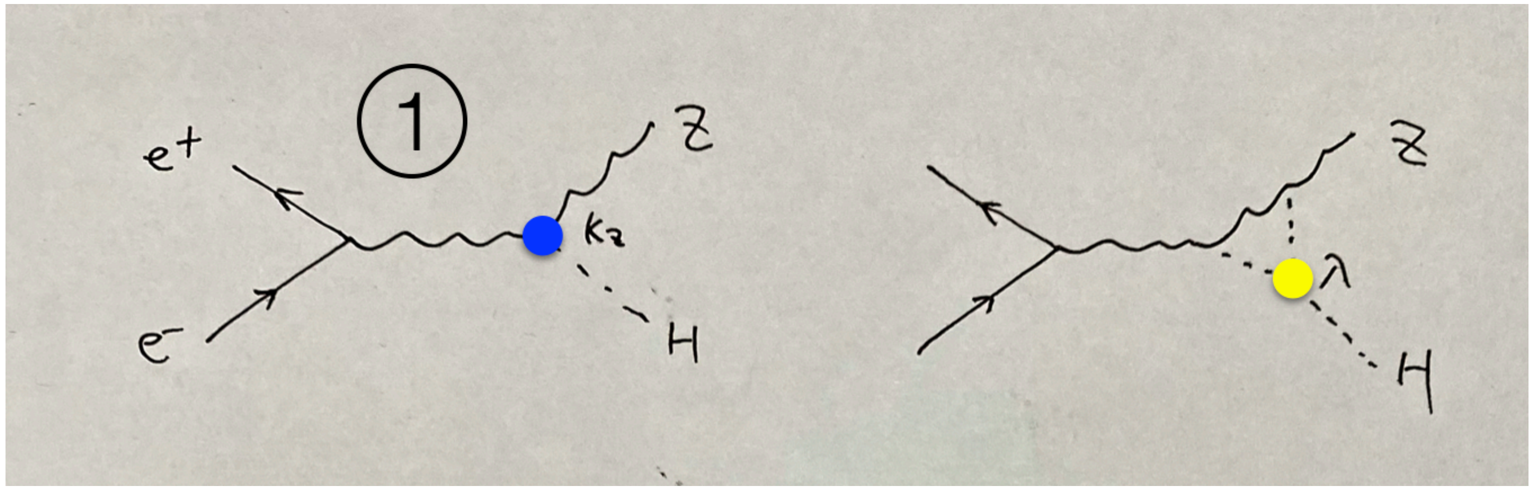


- note: 5σ is potentially reachable at an e+e- < 500 GeV
- Would that be a discovery of Higgs self-coupling?

Challenges: three hurdles to clarify



How to discriminate with HZZ coupling

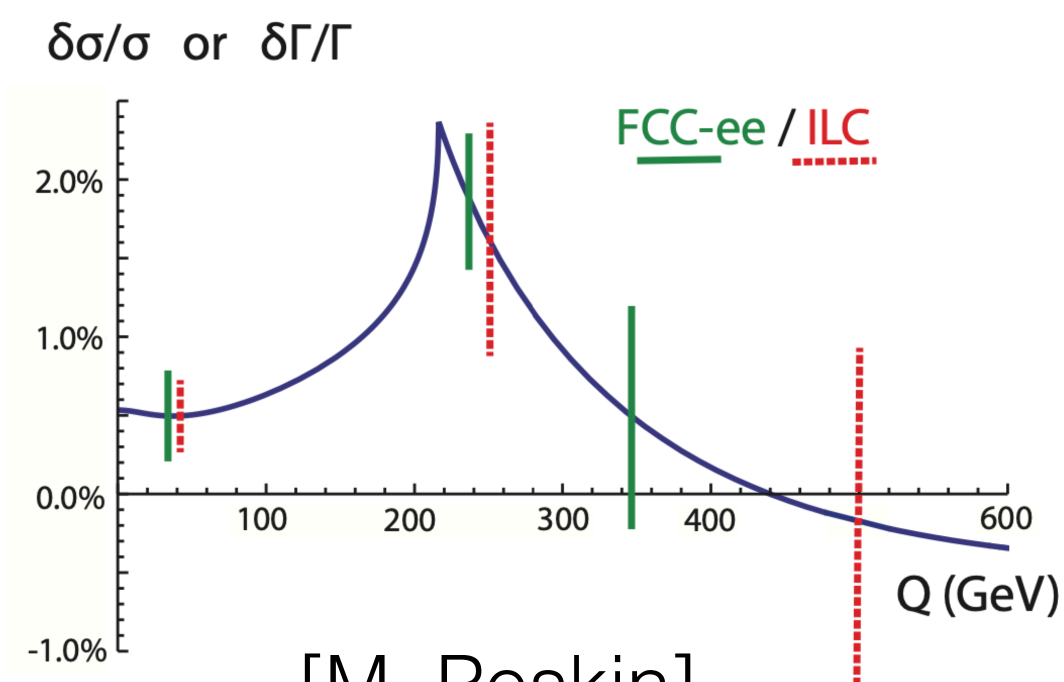


[McCullough, '13]

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

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

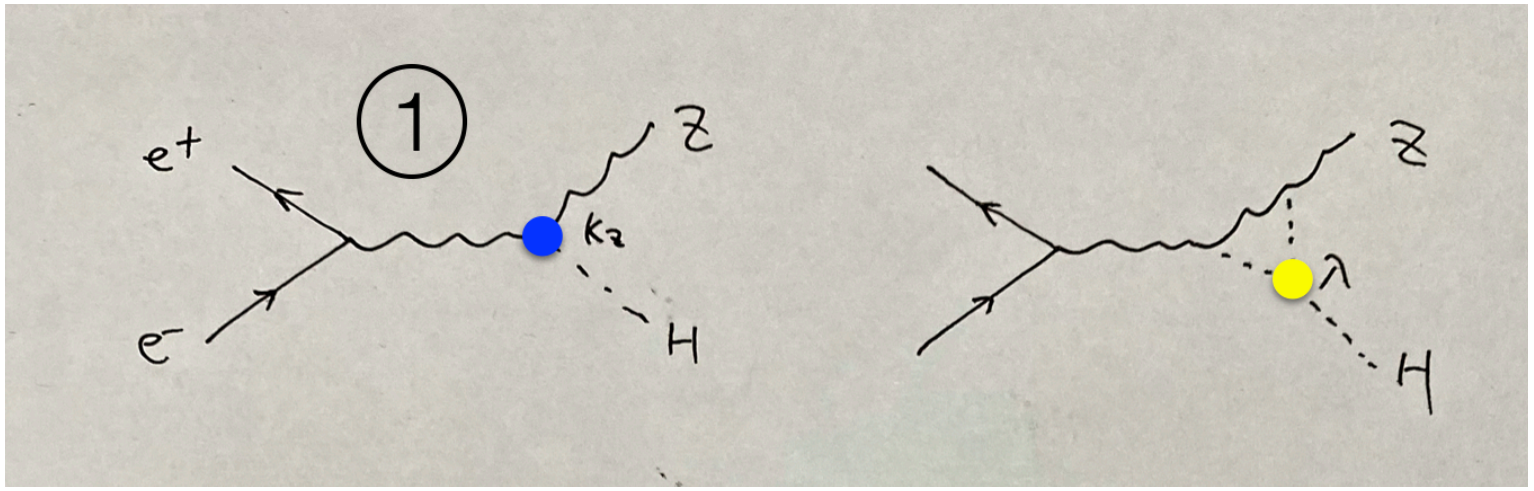
  —> **δh ~ 500%** at 250GeV only; [Gu, et al, arXiv:1711.03978]



[M. Peskin]

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

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**

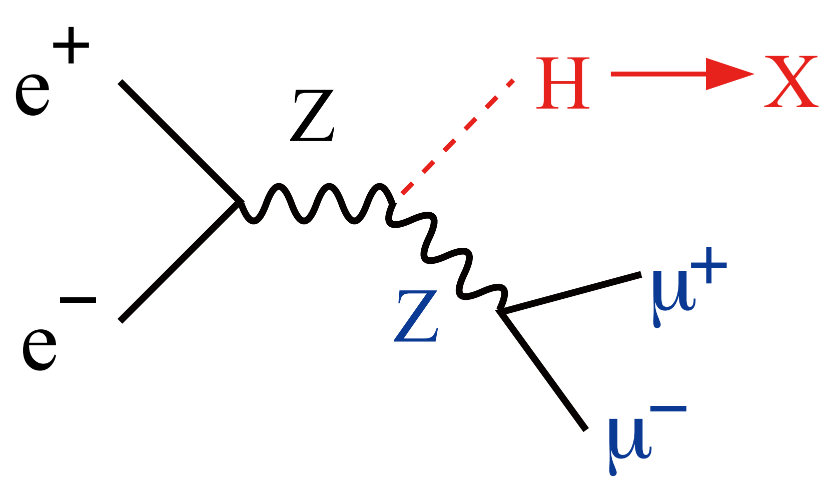
- effect of λ can be absorbed into anomalous HZZ coupling

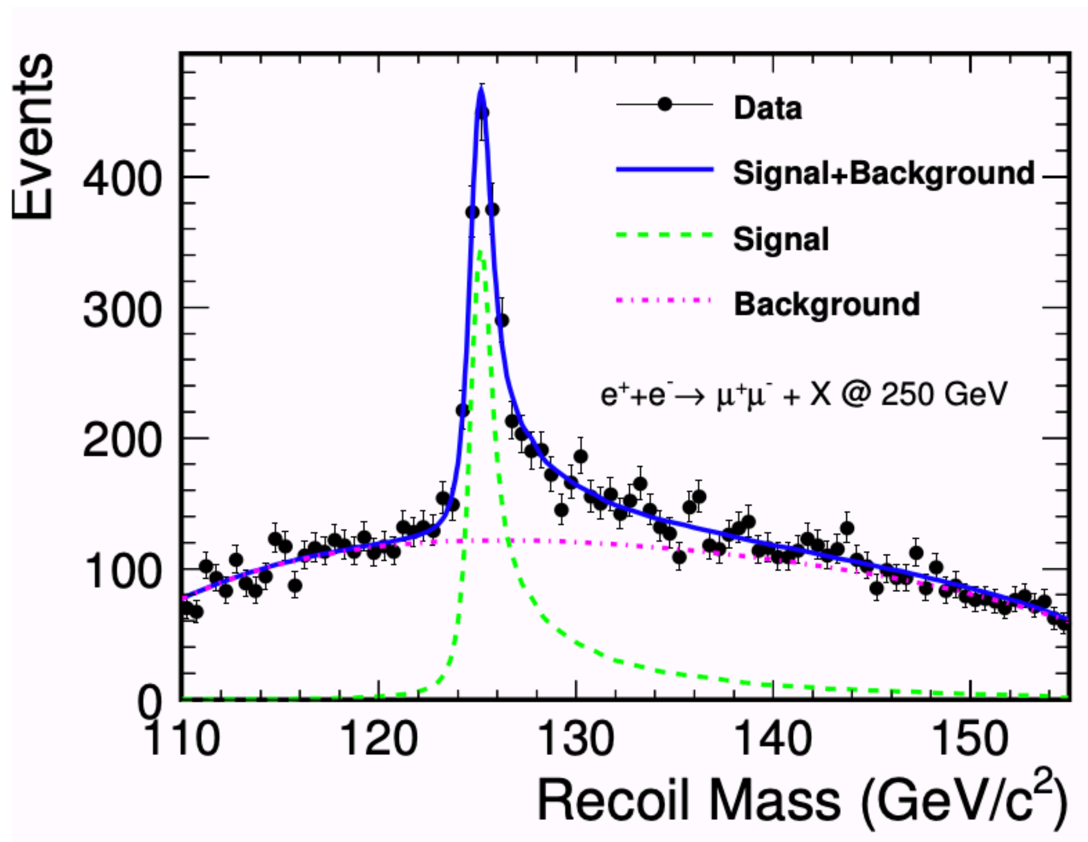
$$\mathscr{L} = m_Z^2(\frac{1}{v} + \frac{a}{\Lambda})HZ^\mu Z_\mu + \frac{b}{2\Lambda}HZ^{\mu\nu}Z_{\mu\nu} + \frac{\tilde{b}}{\Lambda}HZ^{\mu\nu}\tilde{Z}_{\mu\nu}$$

- angular meas. may help **[—> poster by Andrea Maria]**

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%
$M_{\rm rec} \in [110, 155]$ GeV	88.25%	88.35%	87.98%	88.43%	88.33%	88.52%	88.21%	87.64%

- Z—>qq: δEfficiency ~ 15%

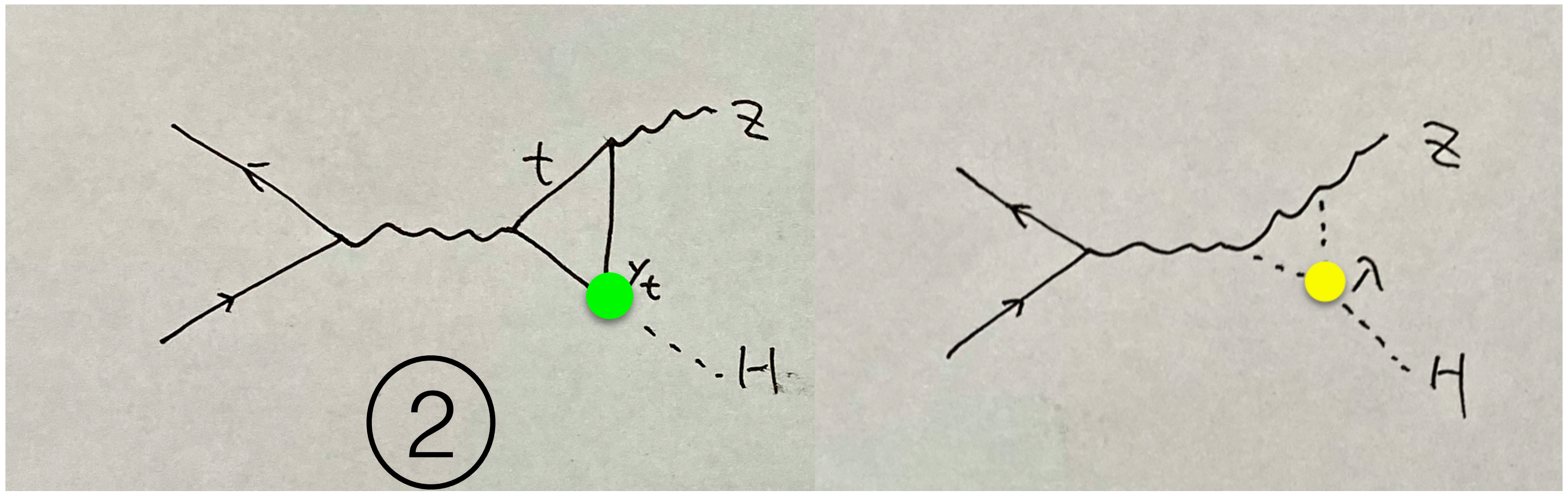
[Thomson, arXiv:1509.02853]

[Tomita 2015; Miyamoto, arXiv:1311.2248]

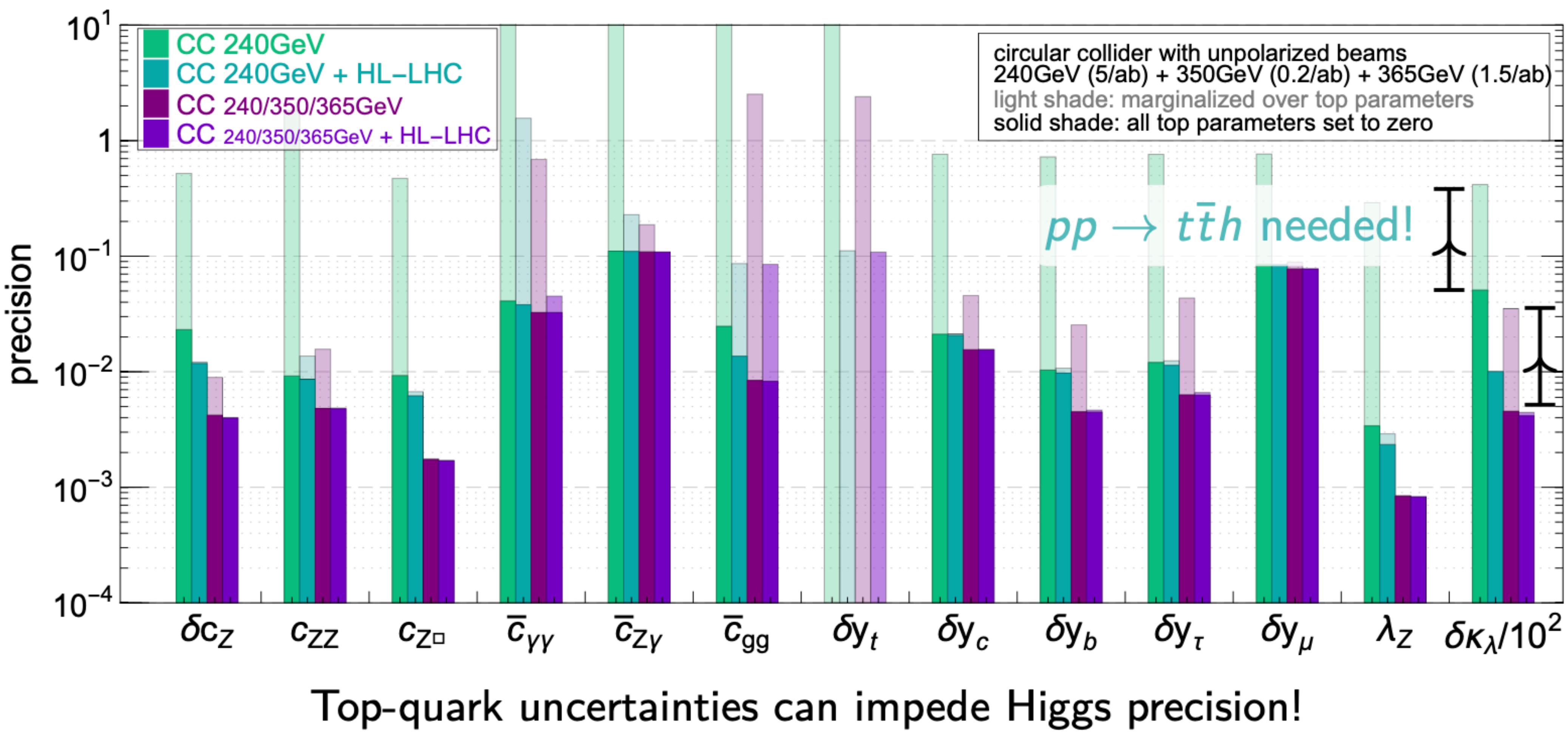
Decay mode	$\varepsilon^{\rm vis.}_{\mathscr{L}>0.65}$	$\varepsilon^{\rm invis.}_{\mathscr{L}>0.60}$	$\varepsilon^{\rm vis.} + \varepsilon^{\rm invis.}$
$H \to$ invis.	<0.1 %	23.5 %	23.5 %
$H \to q\bar{q}/gg$	22.6 %	<0.1 %	22.6 %
$H \to WW^*$	22.1 %	0.1 %	22.2 %
$H \to ZZ^*$	20.6 %	1.1 %	21.7 %
$H \to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

How to discriminate with top-Yukawa coupling

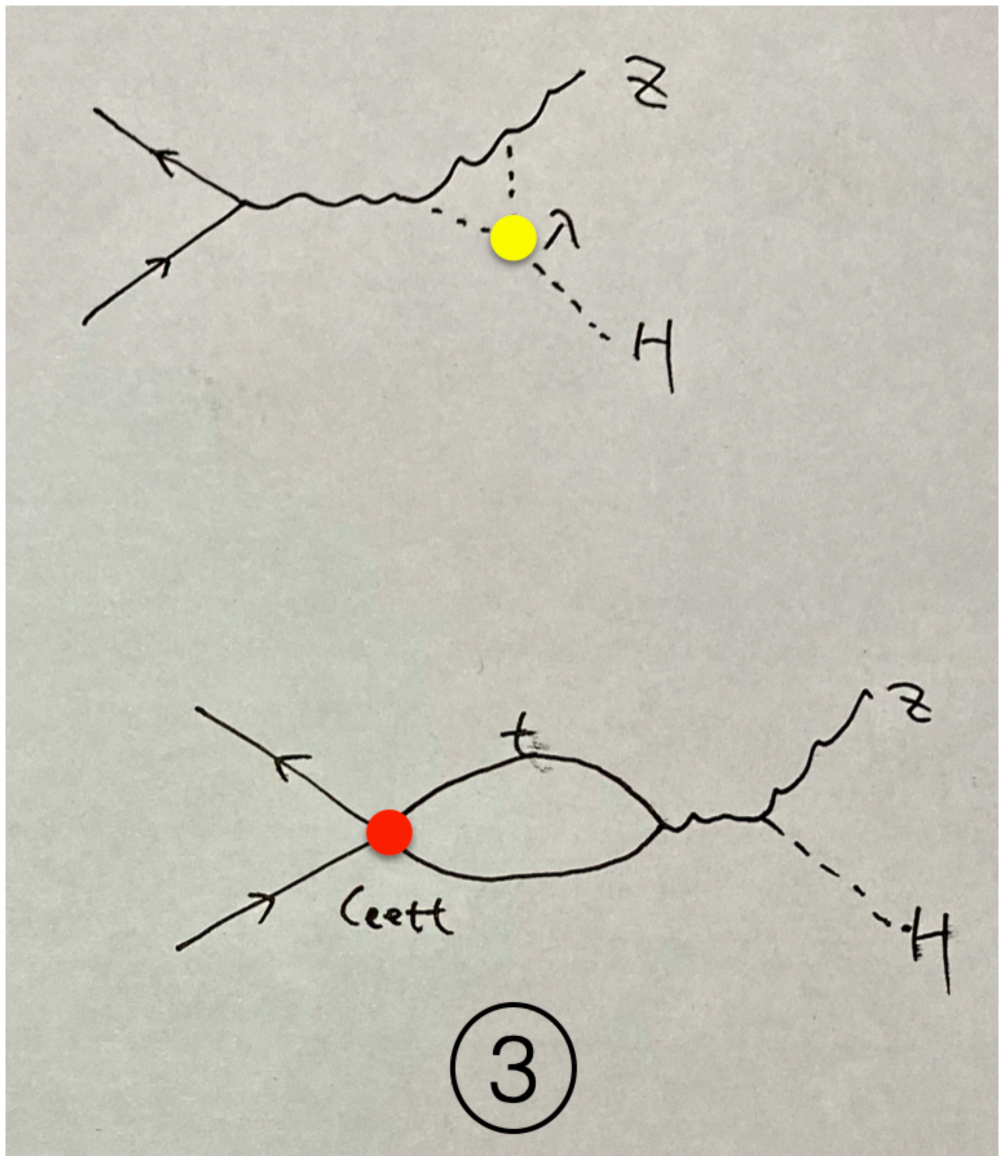


- **mitigated by LHC top-Yukawa measurement**



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

How to discriminate with 4-fermion interaction

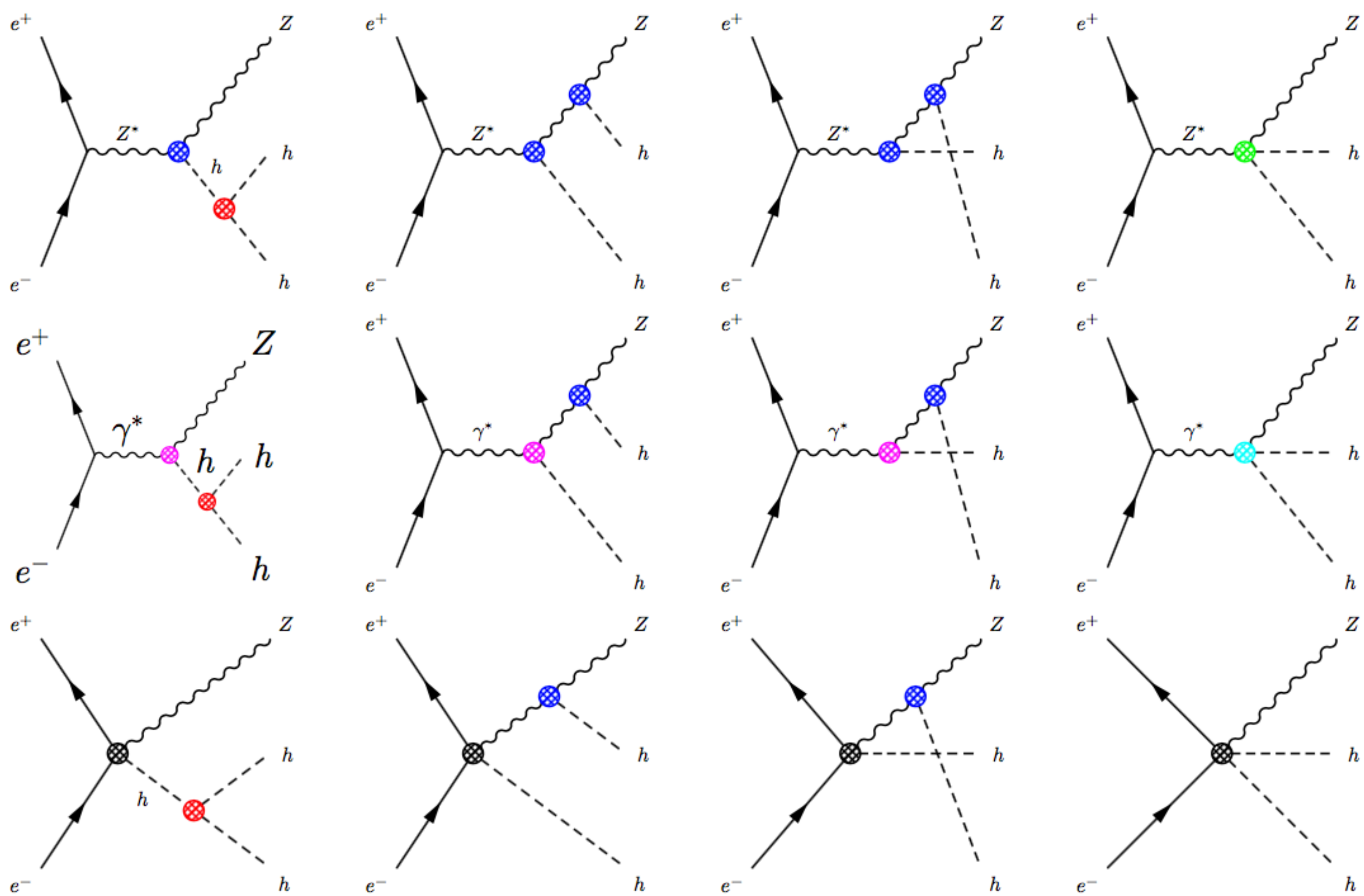


probably the most pressing

- the effects from (many) eett operators have just been calculated! [Dawson et al, arXiv:2406.03257]
- need to facilitate both theory & experimental studies towards a new global SMEFT fit
- need HL-LHC projection for eett; need projections at e+e-, probably at multiple √s ~350/365/500 —> **[talk by Marcel Vos]**

- the new fit should include Higgs+EWPOs+WW+top-EW+4-fermion, include NLO SMEFT contributions in ZH / EWPOs; volunteers?

λ_{HHH}: THE opportunity that we are almost sure

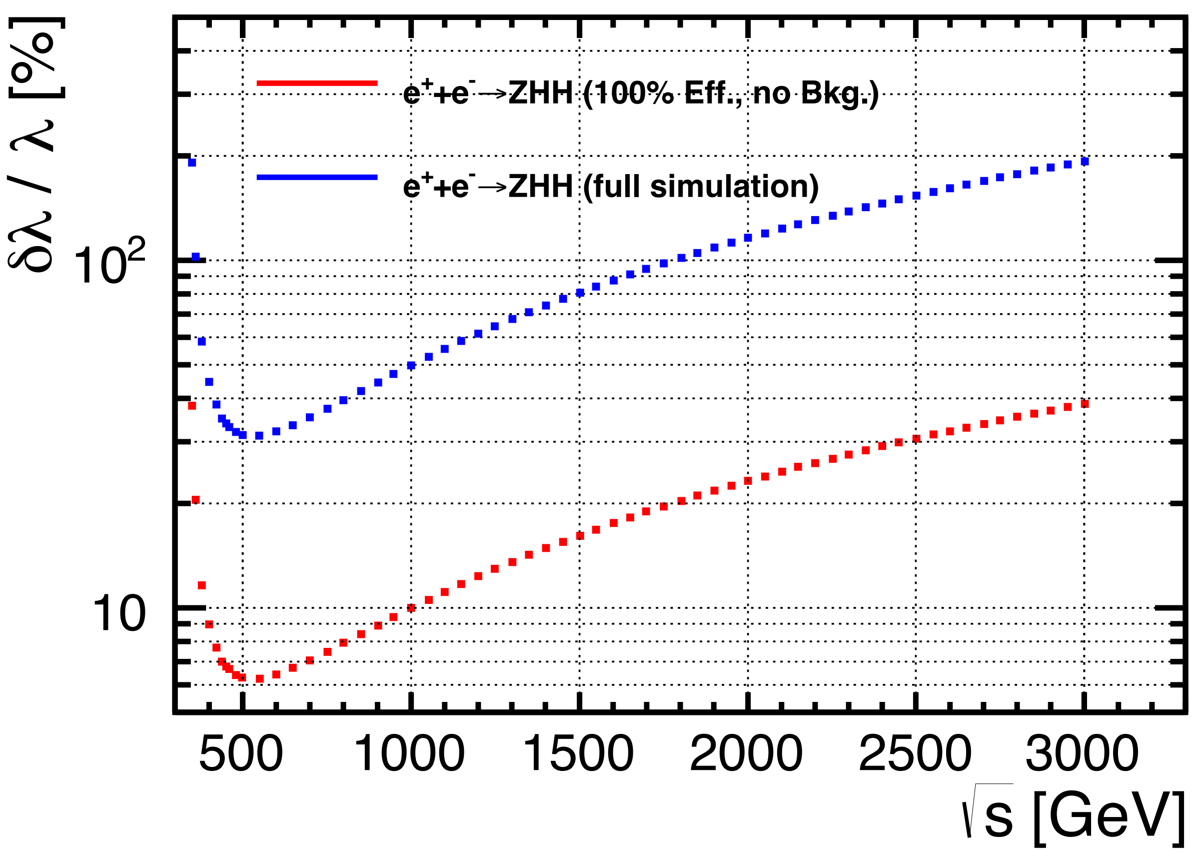


[Barklow, Fujii, Jung, Peskin, JT, '17]

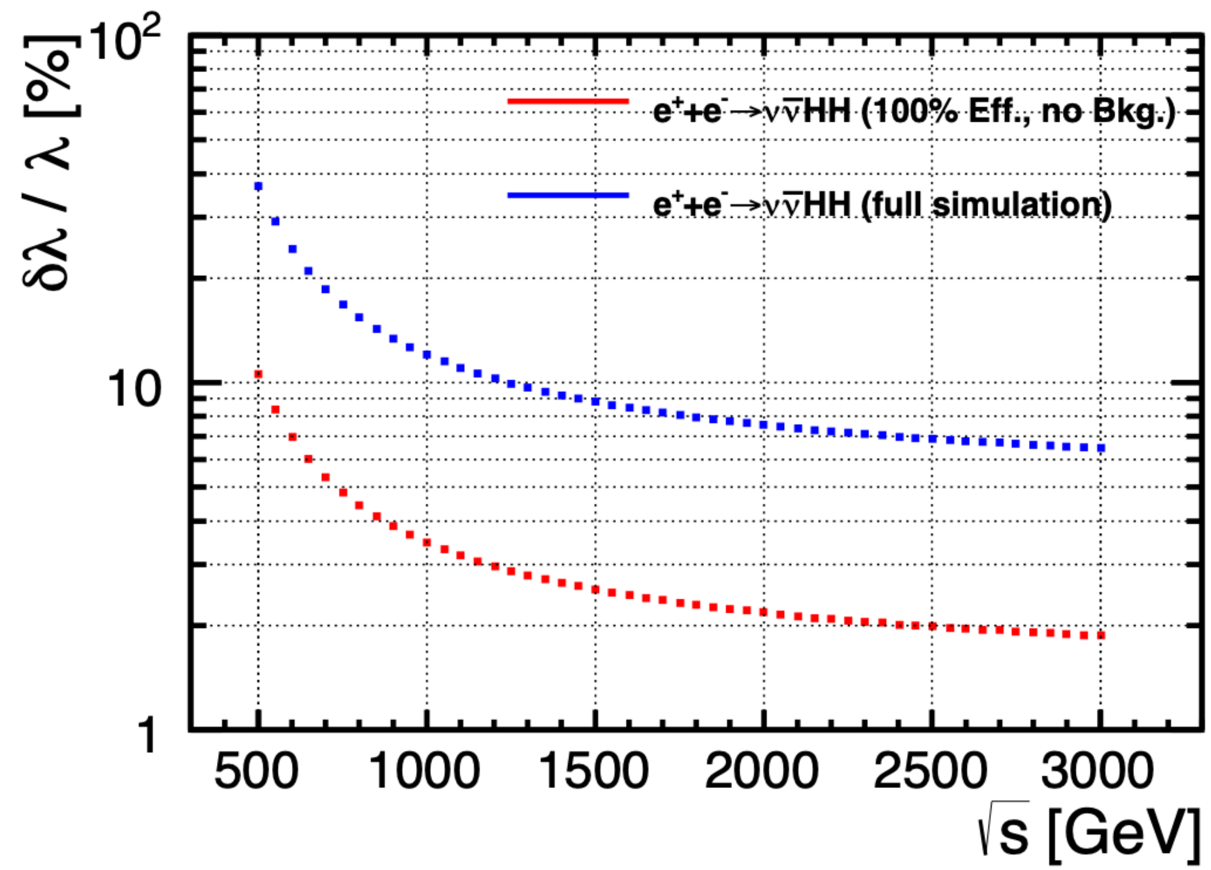
- Much less challenge from degeneracies
- Main challenges are related to how we can improve experimental analyses

di-Higgs: can we improve $\Delta\lambda_{HHH}$ by a factor of 5?

ZHH



ννHH



[Duerig, PhD Theis, 2016]

a lot of room for improvement by advanced analysis technique:
flavor tagging, jet-clustering, kinematic fitting, matrix element method, machine learning, etc

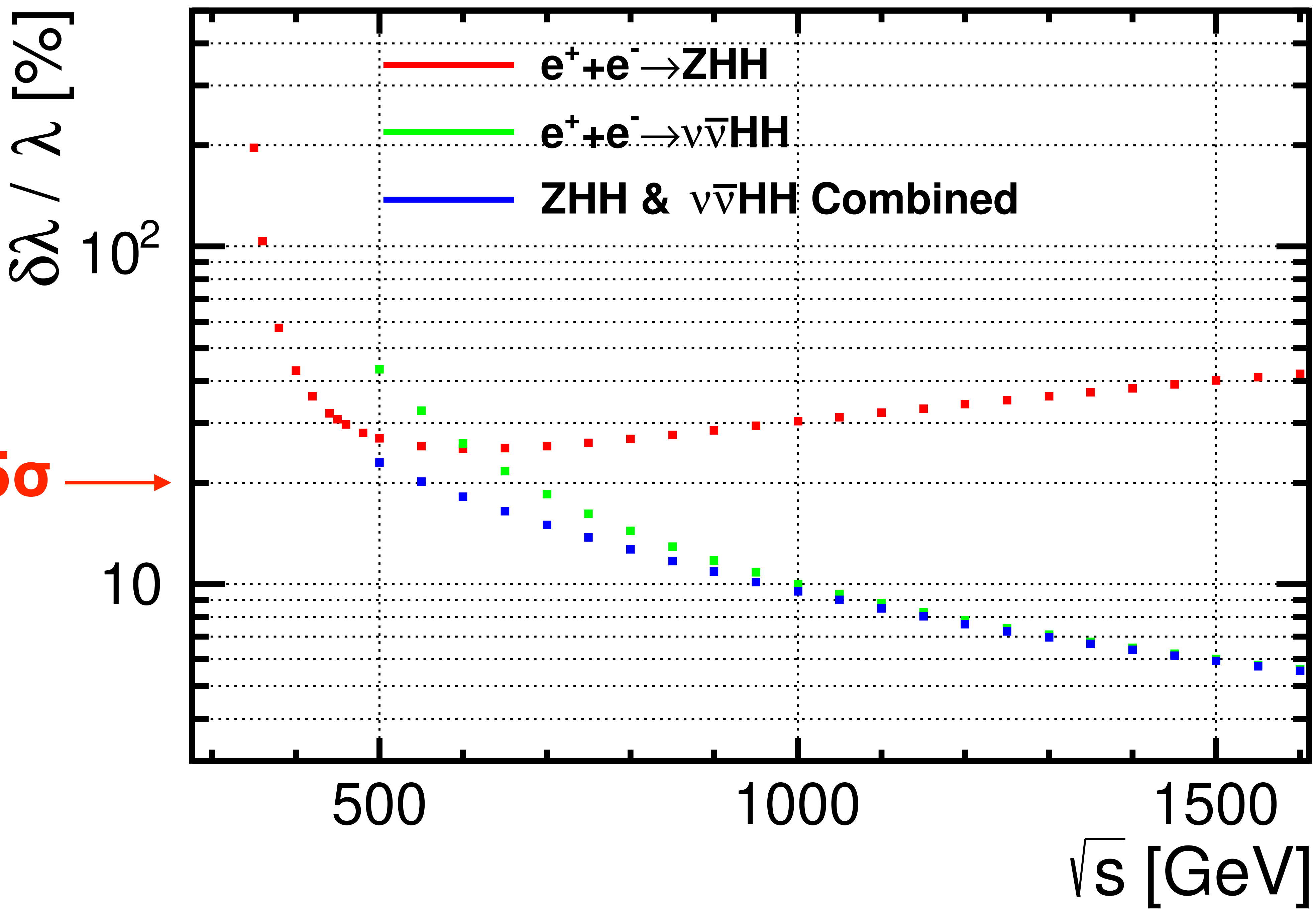
[talk by R.Tagami]

[talk by B.Bliewert]

λ_{HHH}: updated projection

- 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

5σ →



Discovery can be guaranteed

ILC500: 23%

ILC550: 20%

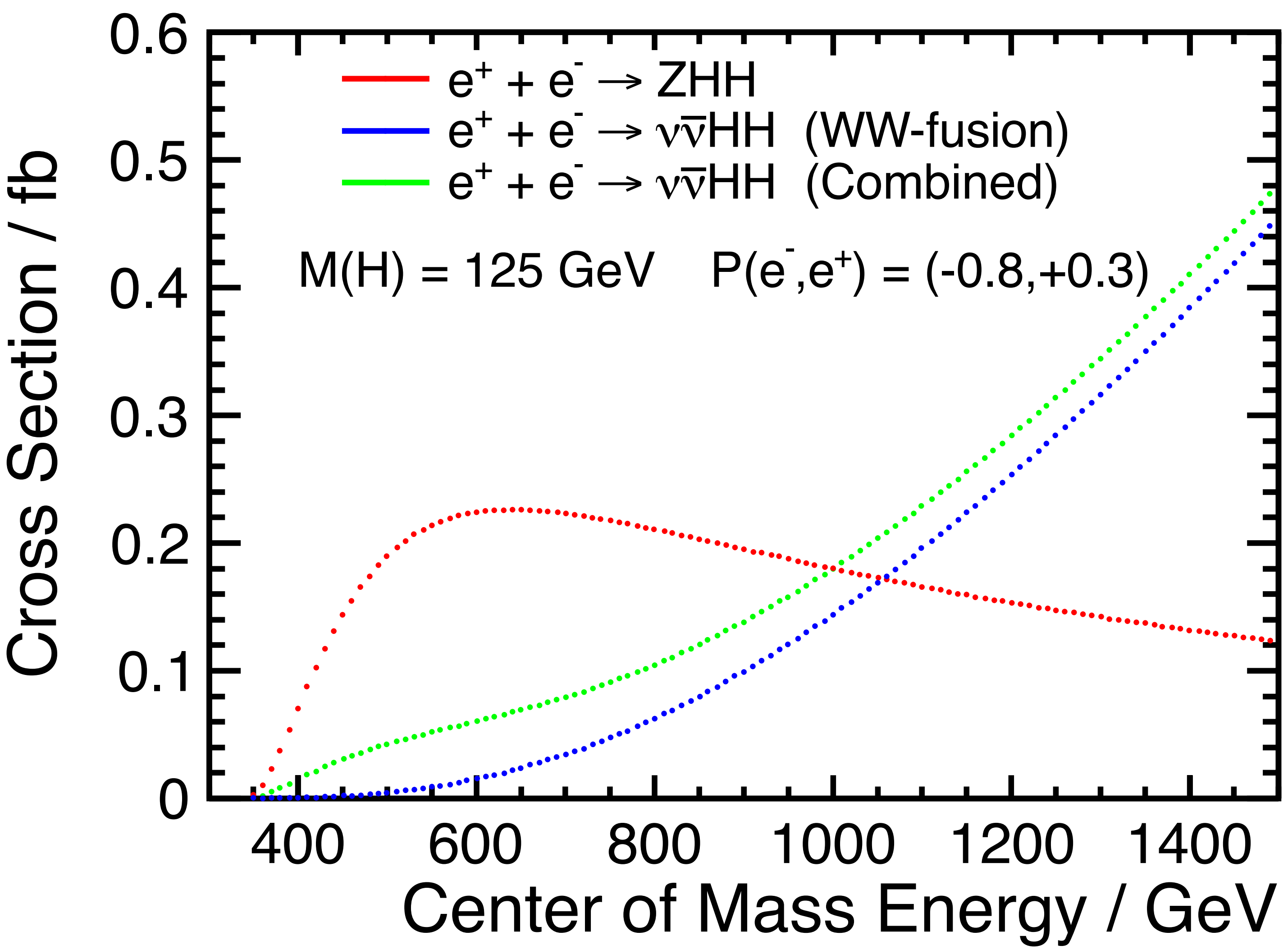
ILC600: 18%

note: this is based on old DBD analysis; large room from new analysis

summary

- Higgs & top are intimately engaged; many opportunities to learn Higgs physics from top-quark events, vise visa
- NLO effects from top-quark play very important role in the precision Higgs/EW measurements; (HL-)LHC input are very important for future Higgs factories
- A new global SMEFT fit is needed urgently to address the opportunity / challenges in probing λ_{HHH} using single-Higgs
- Updated λ_{HHH} projection using di-Higgs suggests discovery potential just a little above 500 GeV

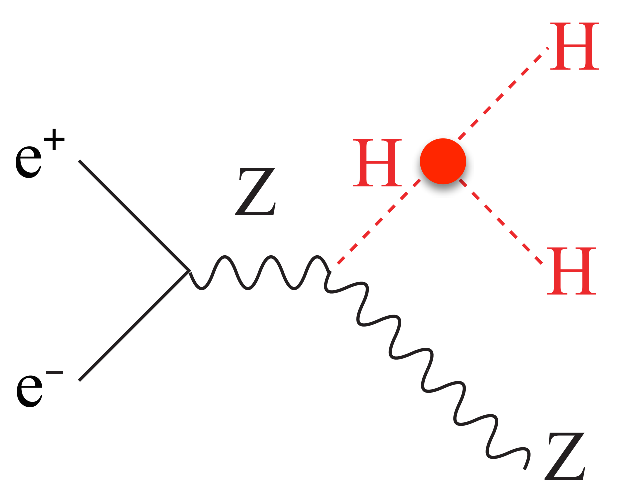
backup

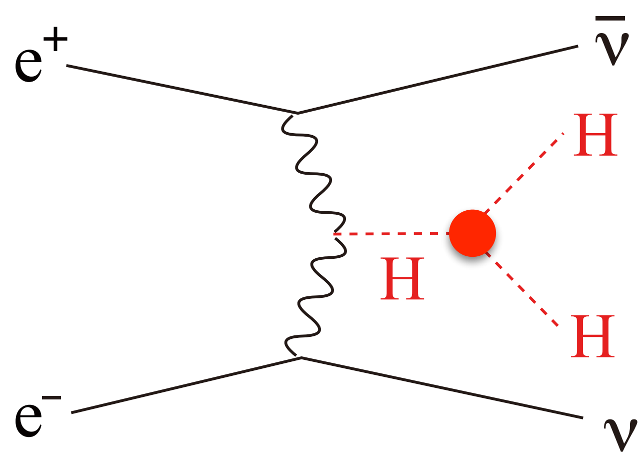


0.6
0.5
0.4
0.3
0.2
0.1
0
Cross Section / fb
e+ + e- → ZHH
e+ + e- → νν̄HH (WW-fusion)
e+ + e- → νν̄HH (Combined)
M(H) = 125 GeV P(e-,e+) = (-0.8,+0.3)
400
600
800
1000
1200
1400
Center of Mass Energy / GeV

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

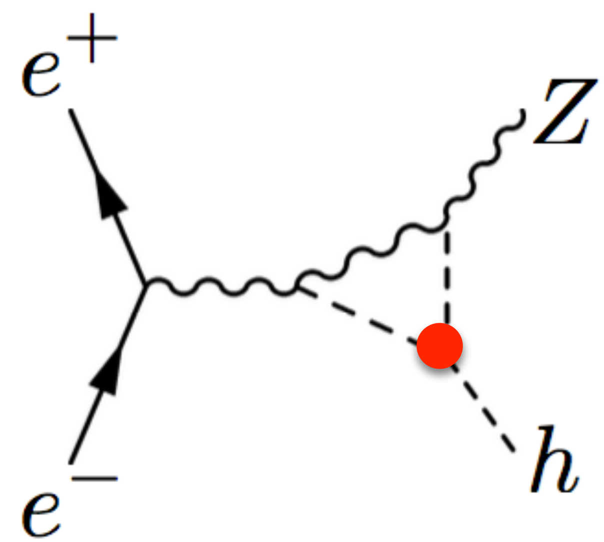
$\sqrt{s} \gtrsim 500$ GeV

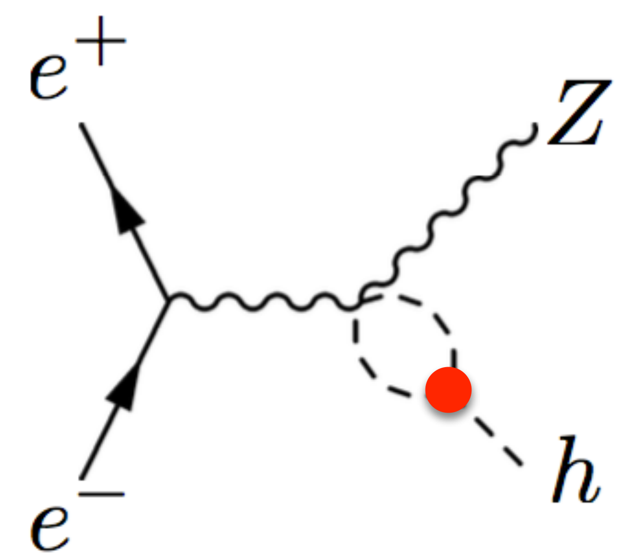




$\sigma_{HH} \sim O(0.1)$ fb

$\sqrt{s} \gtrsim 240\text{–}250$ GeV

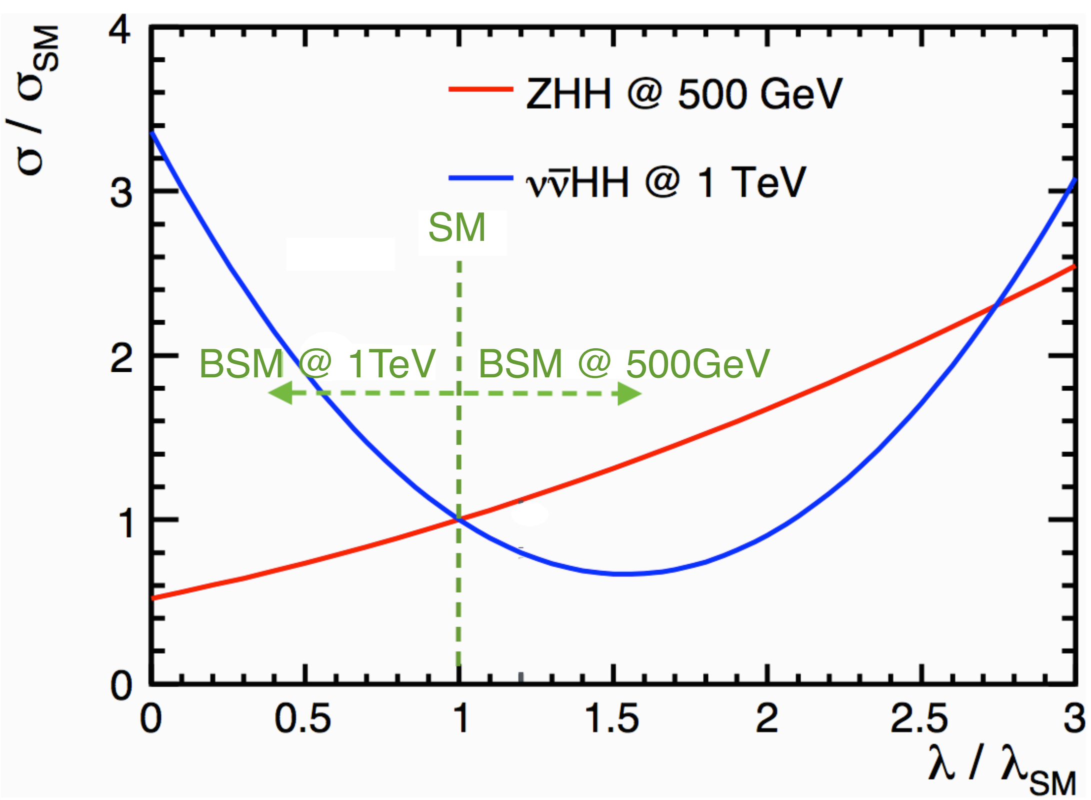


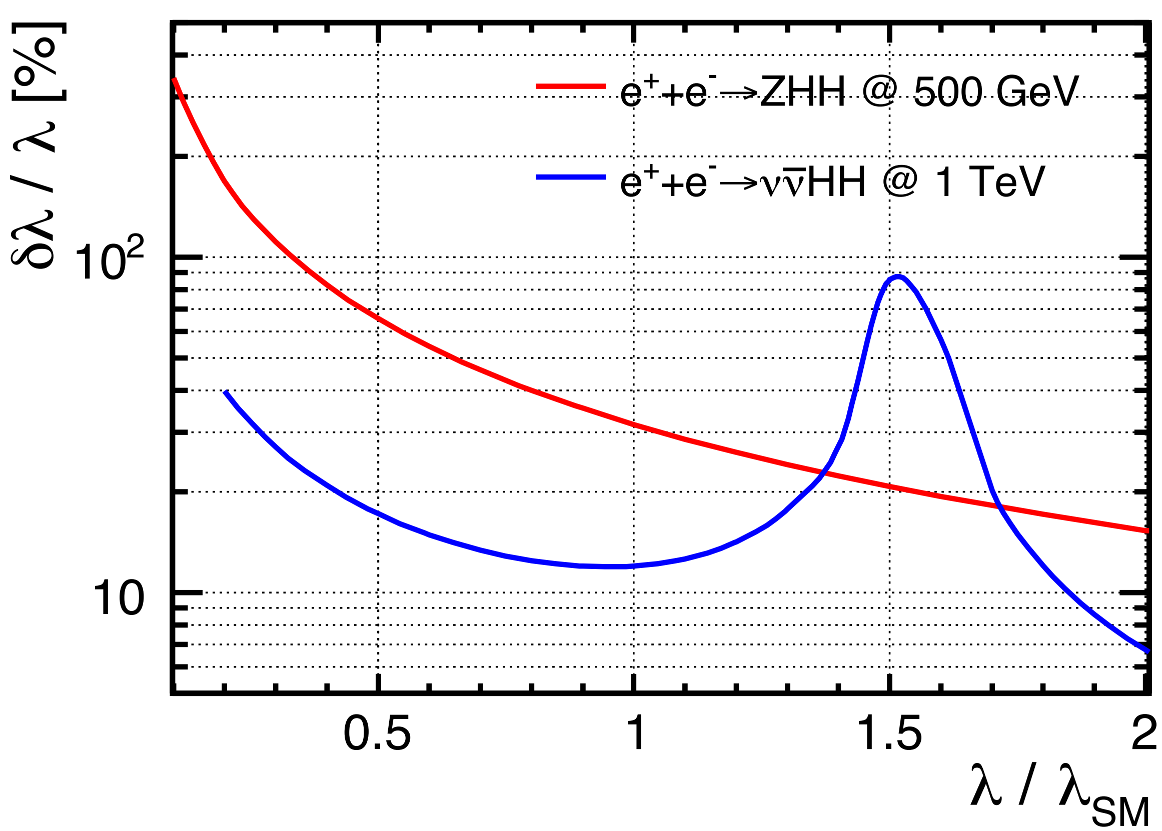


$\delta\sigma_{ZH} \sim O(1\%)$

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

- 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-

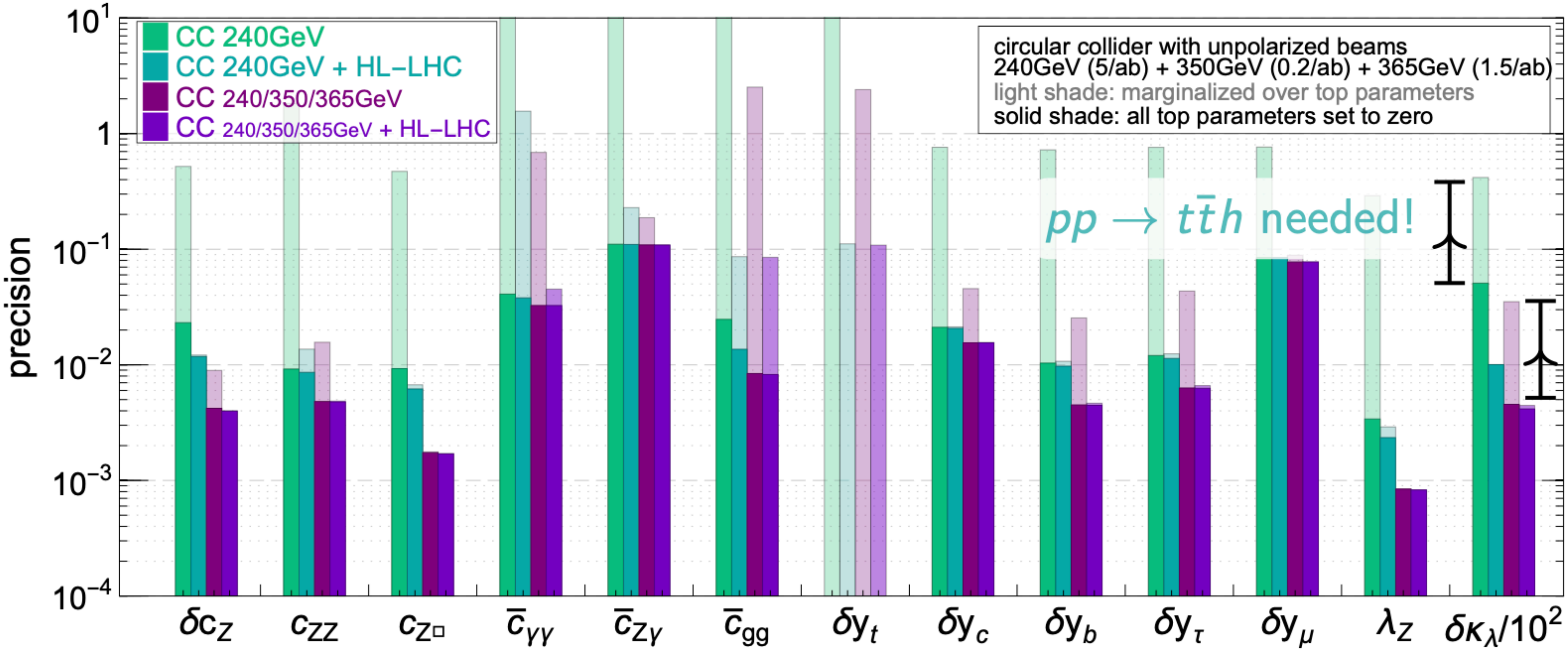




Top and trilinear

[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



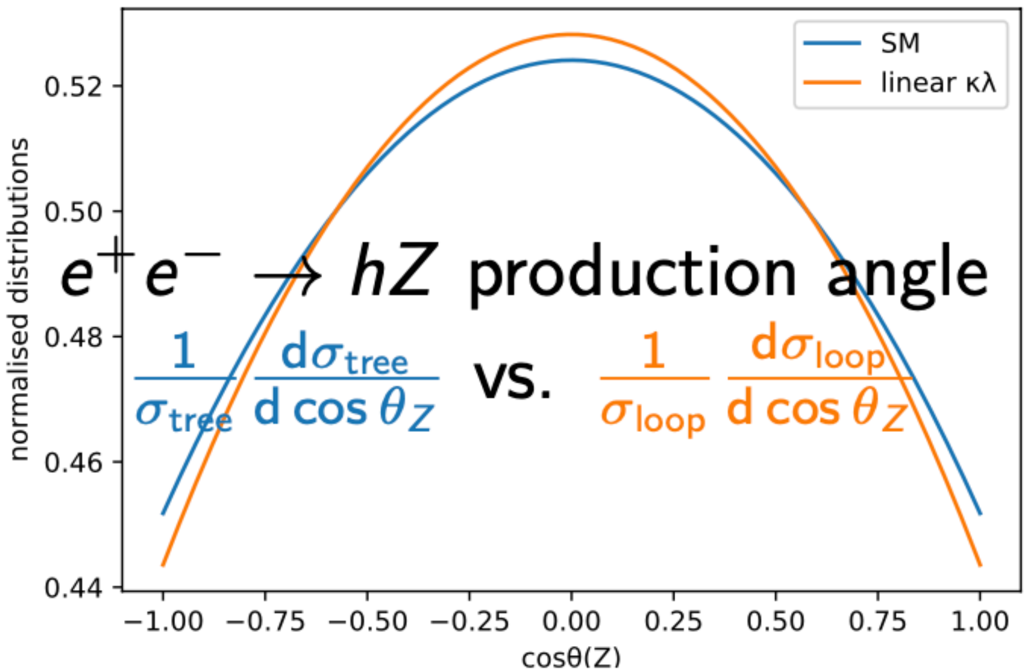
Uncertainties on the top have a big effect on the Higgs

- 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

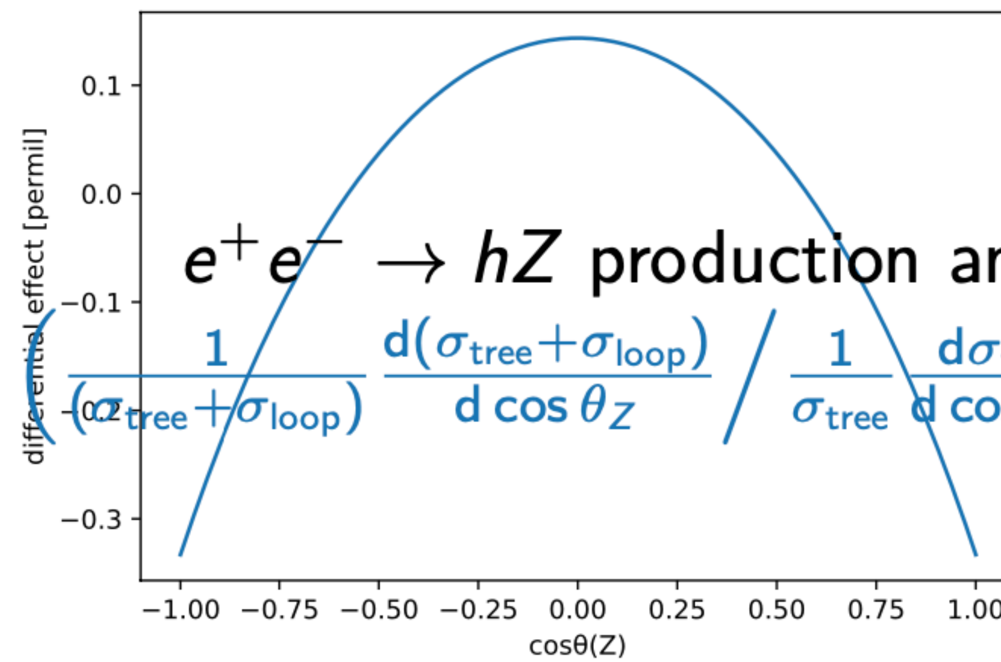
[Back-of-the-envelope calculations!!]
and discussions with Fabio Maltoni
& Xiaoran Zhao

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



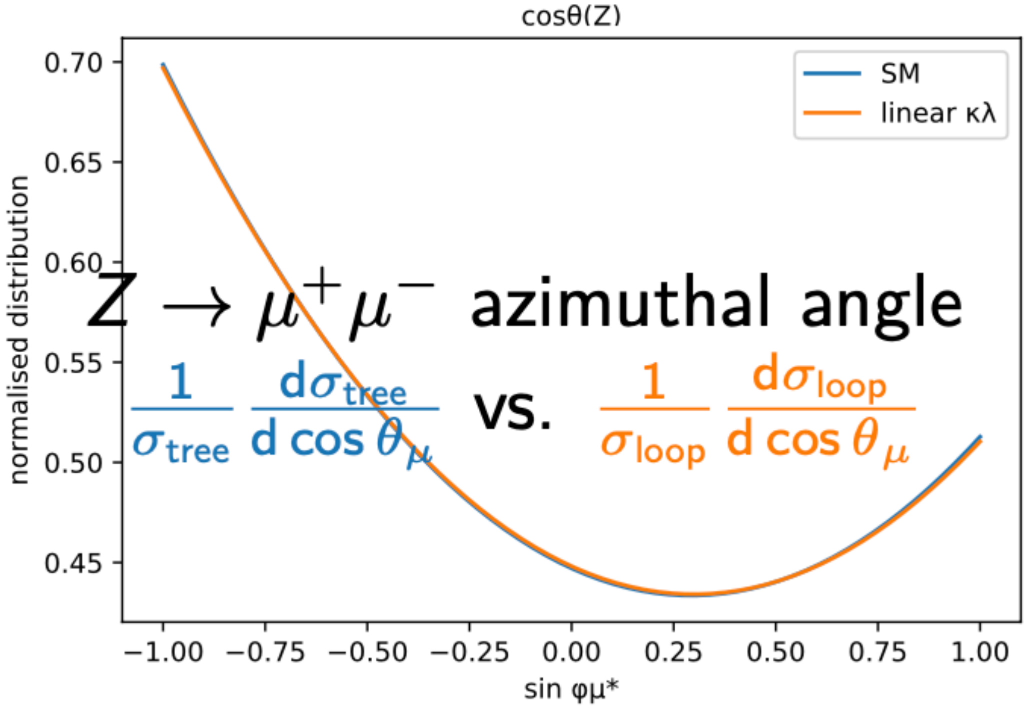
$e^+e^- \to hZ$ production angle

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



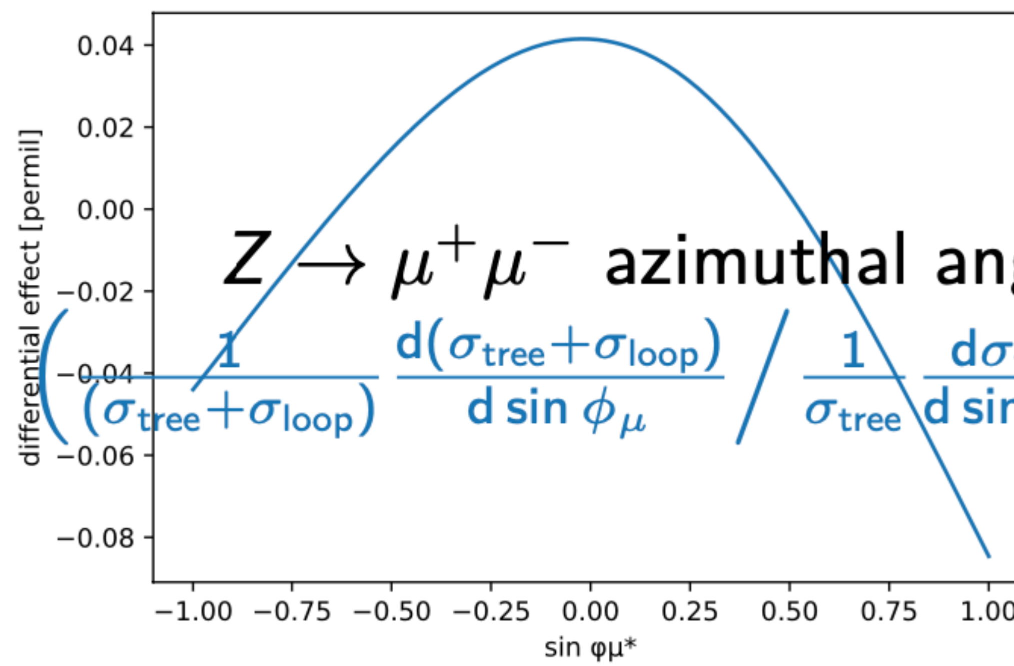
$e^+e^- \to hZ$ production angle

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



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

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



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

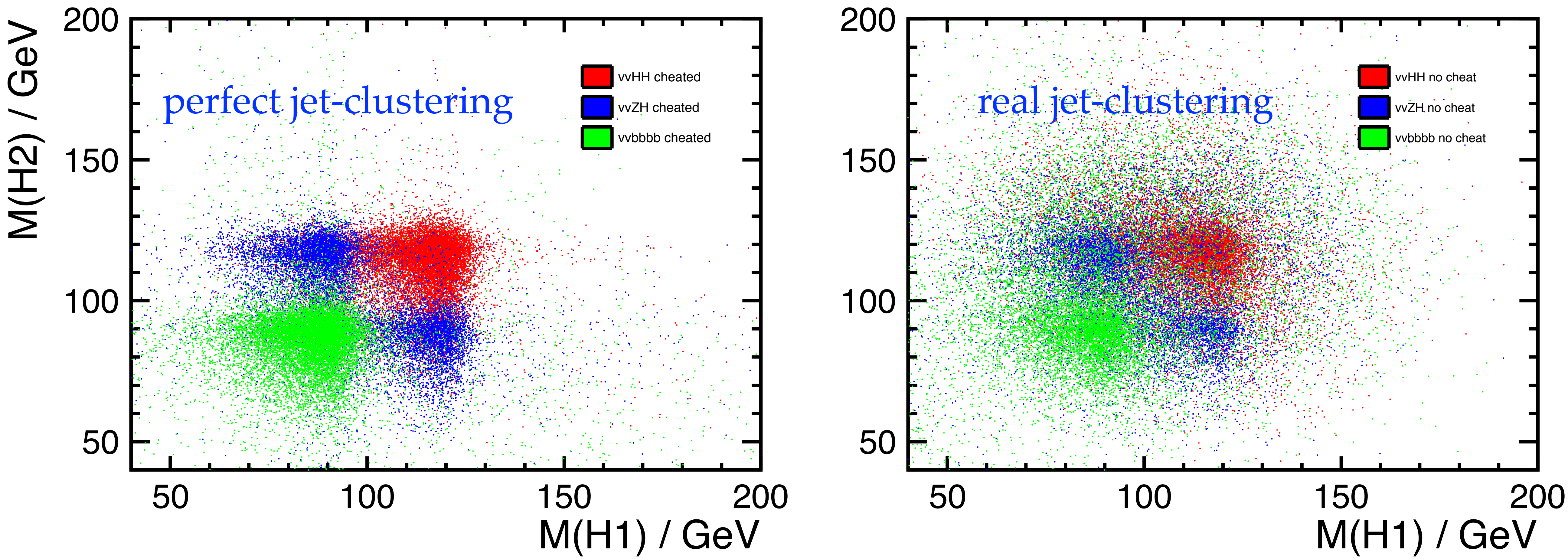
$$\left(\frac{1}{(\sigma_{tree}+\sigma_{loop})}\frac{d(\sigma_{tree}+\sigma_{loop})}{d\sin\phi_\mu} \Big/ \frac{1}{\sigma_{tree}}\frac{d\sigma_{tree}}{d\sin\phi_\mu}\right) - 1$$

¿exploitable with an optimal discriminant?

(iii) improving jet-clustering algorithm?

ZHH->ννbbbb (BG: ZZH and ZZZ)

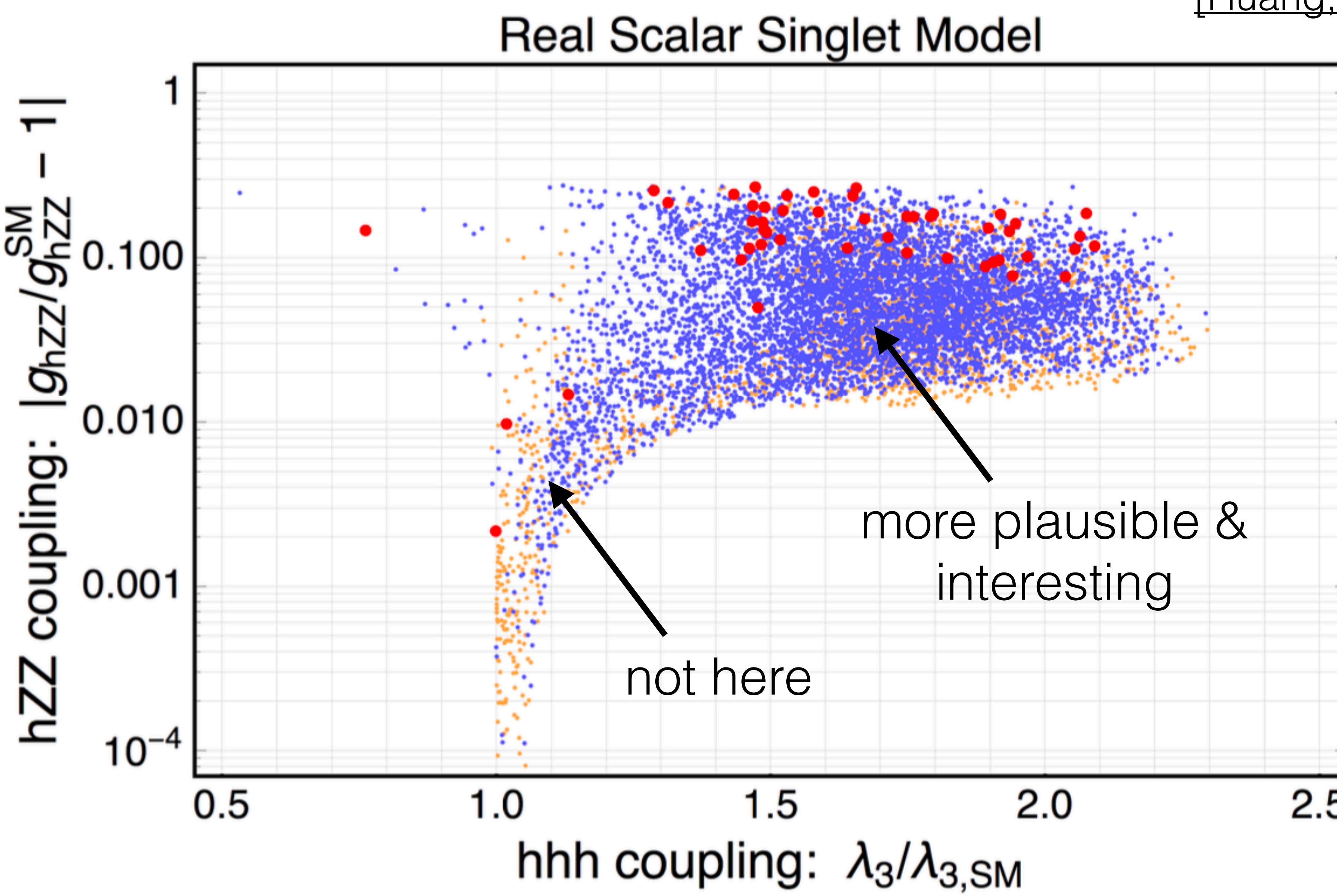
scatter plot of two Higgs masses



- 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]



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]