Trilinear Higgs coupling sensitivity in $e^+e^- \to Zh$ angular measurements – theory considerations

Johannes Braathen (DESY)

ECFA meeting on $e^+e^- \to Zh$ angular measurements |
12 December 2023

Emmy
Noether-
Programm

DFG Deutsche Forschungsgemeinschaft

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

DESY.

Disclaimer

- I was asked to talk about “Zh self-coupling theory” [sic] and pointed to
  - [Beneke, Boito and Wang, JHEP 11 (2014) 028]
  - [Craig, Gu, Liu and Wang, JHEP 03 (2016) 050]
  - [Nakamura and Shivaji, Phys.Lett.B 797 (2019) 134821]

  as references to start with

- I am certainly not an expert on collider physics / angular distributions / etc.

- Apologies if my literature survey missed your own or your favourite work on the topic!

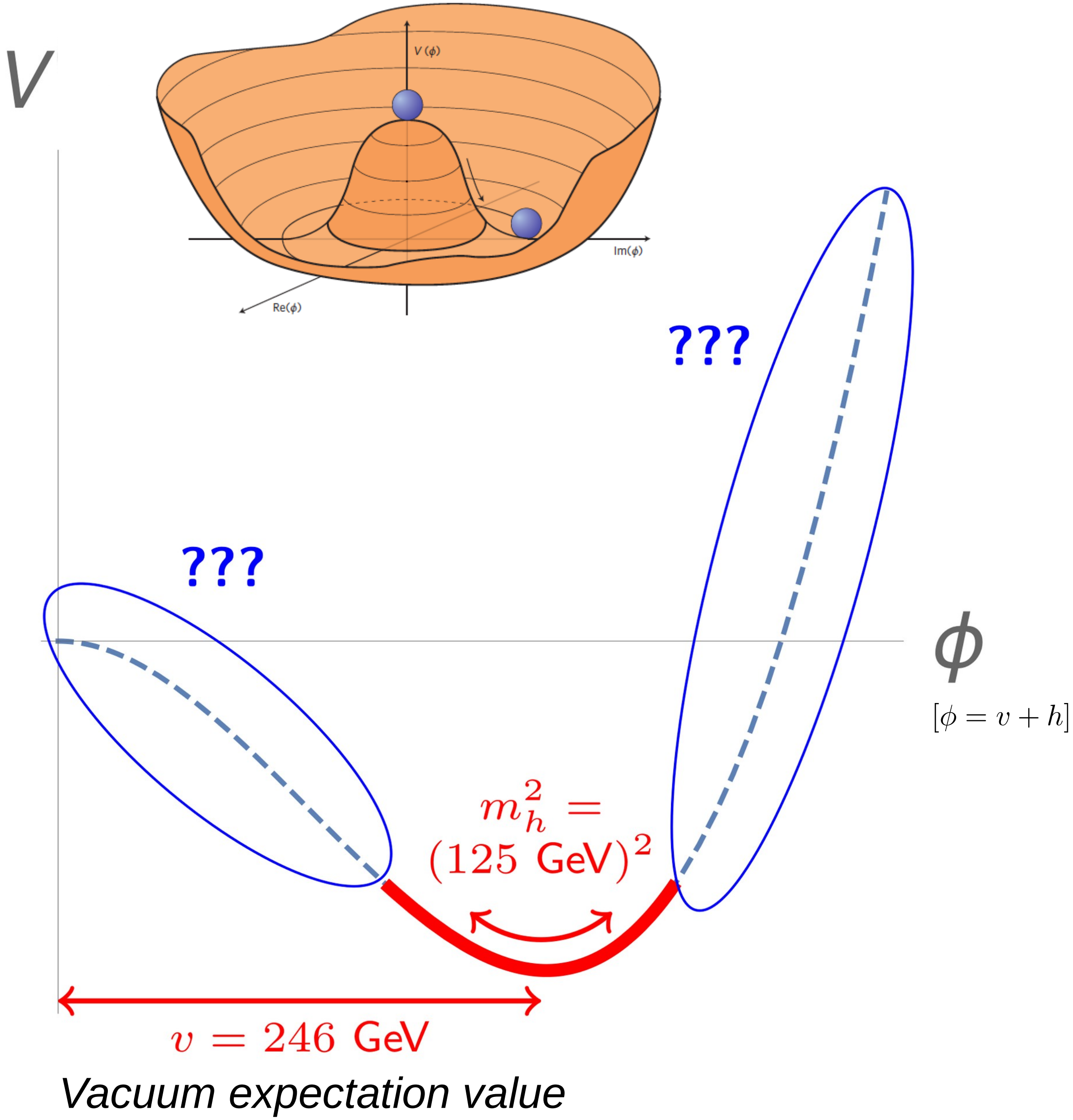
Outline

- Why investigate λ_{hhh} ?
- How is it currently being constrained at the LHC (and prospects at HL-LHC) ?
- A review of “traditional approaches” at e^+e^- colliders
- Can angular distributions help?
- Conclusion and discussion

Why investigate λ_{hhh} ?

Form of the Higgs potential and trilinear Higgs coupling

- Brout-Englert-Higgs mechanism = **origin of electroweak symmetry breaking** ...
  … but very little known about the **Higgs potential** causing the phase transition



Form of the Higgs potential and trilinear Higgs coupling

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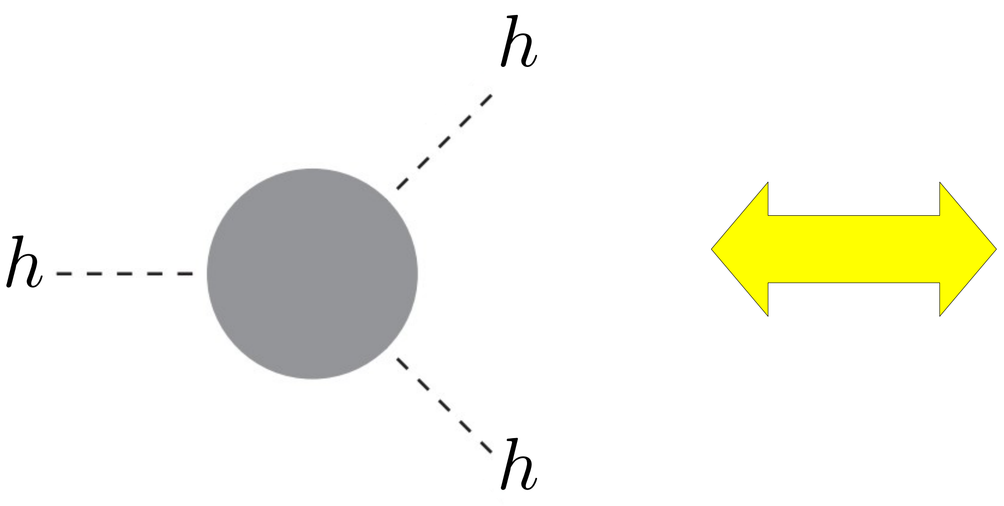
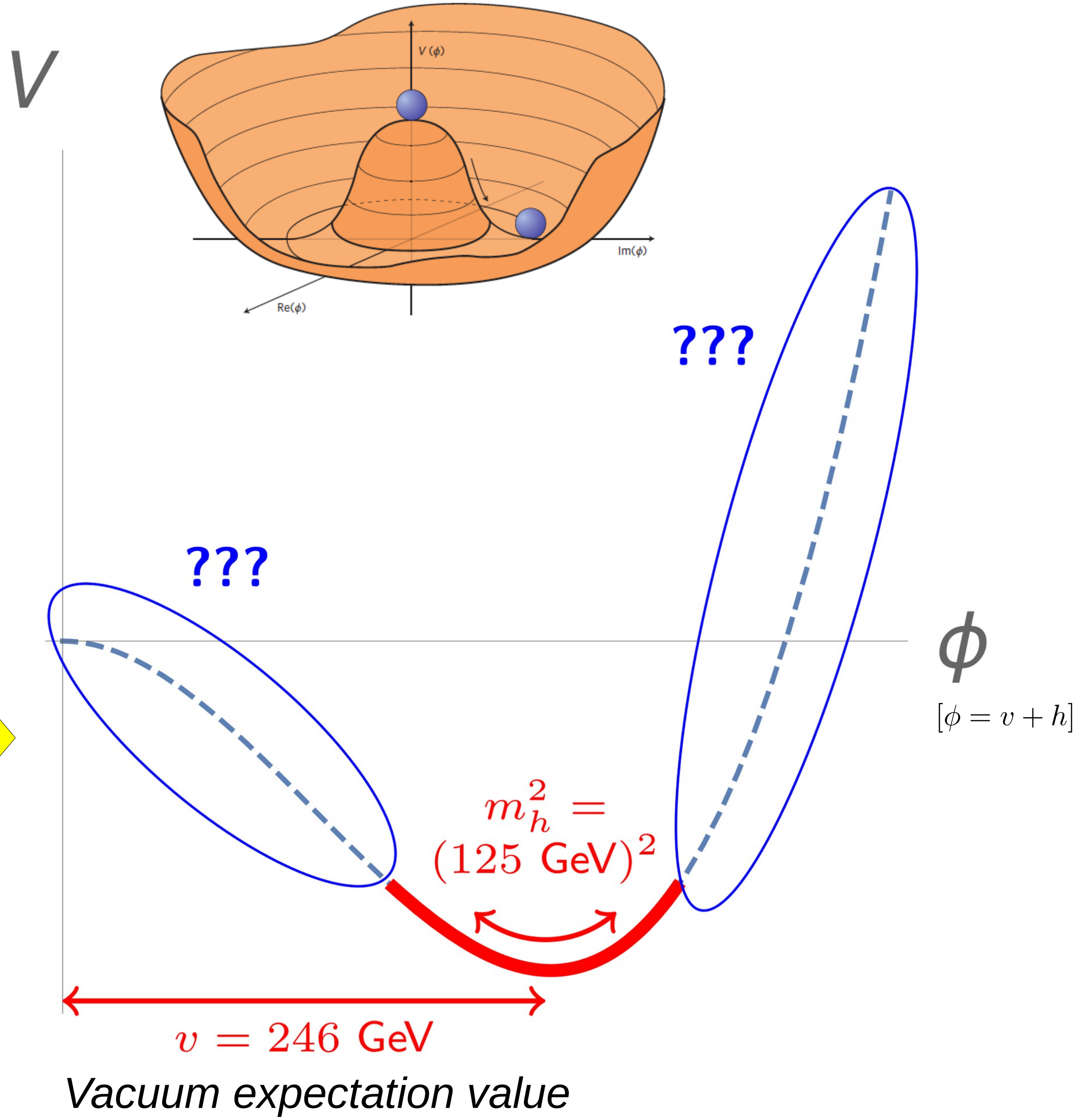
- Shape of the potential determined by **trilinear Higgs coupling λ_{hhh}**



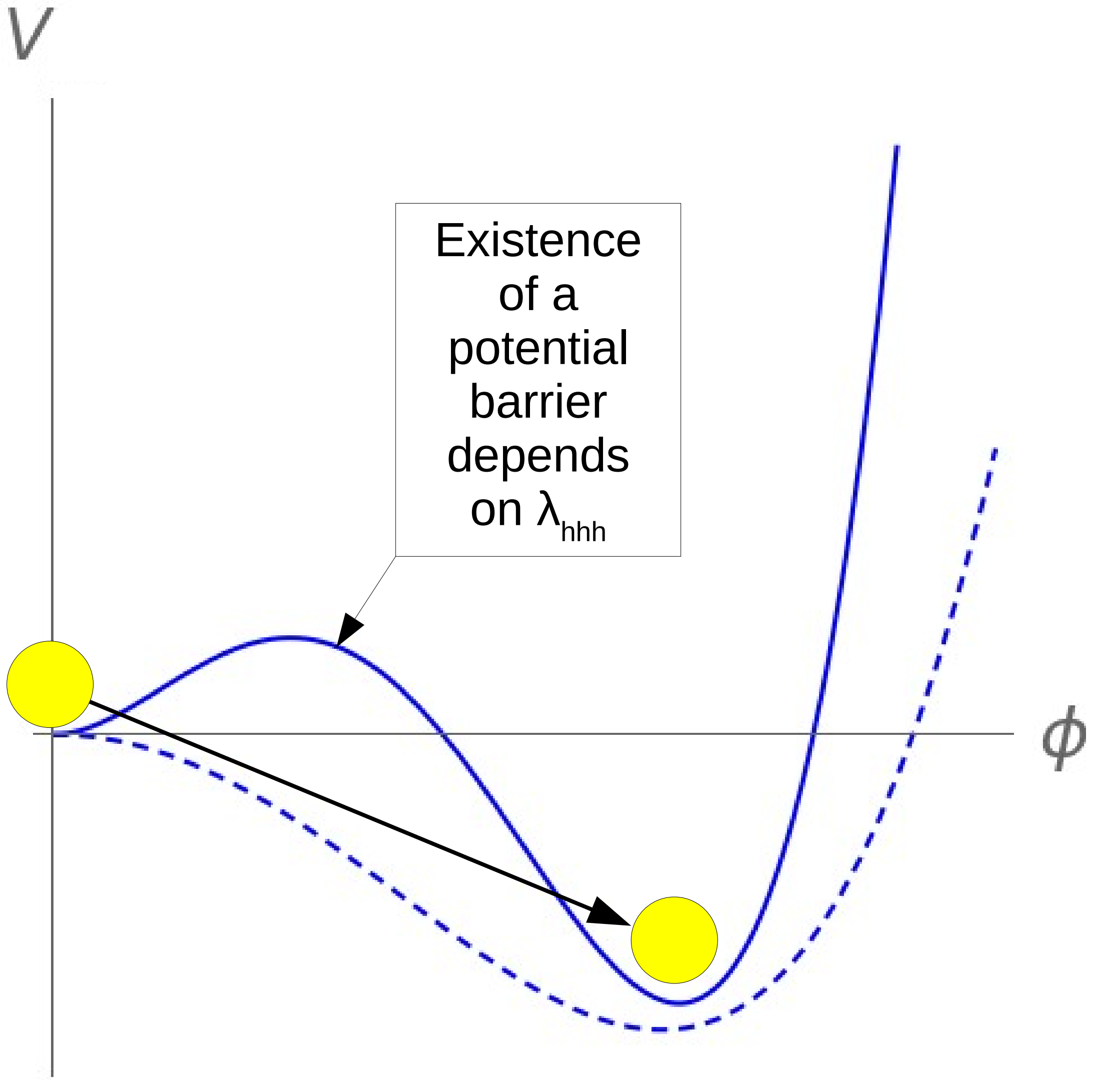


Form of the Higgs potential and baryon asymmetry

- Brout-Englert-Higgs mechanism = **origin of electroweak symmetry breaking** ...
  … but very little known about the **Higgs potential** causing the phase transition

- Shape of the potential determined by **trilinear Higgs coupling λ_{hhh}**

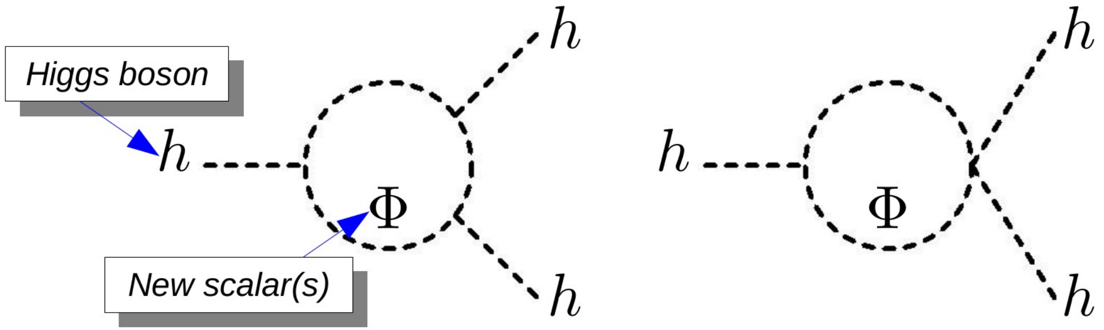
- Among **Sakharov conditions** necessary to explain **baryon asymmetry via electroweak phase transition** (EWPT):
  - ***Strong first-order EWPT***
    → barrier in Higgs potential
    → typically significant deviation in λ_{hhh} from SM



Existence of a potential barrier depends on λ_{hhh}

Probing New Physics with the trilinear Higgs coupling

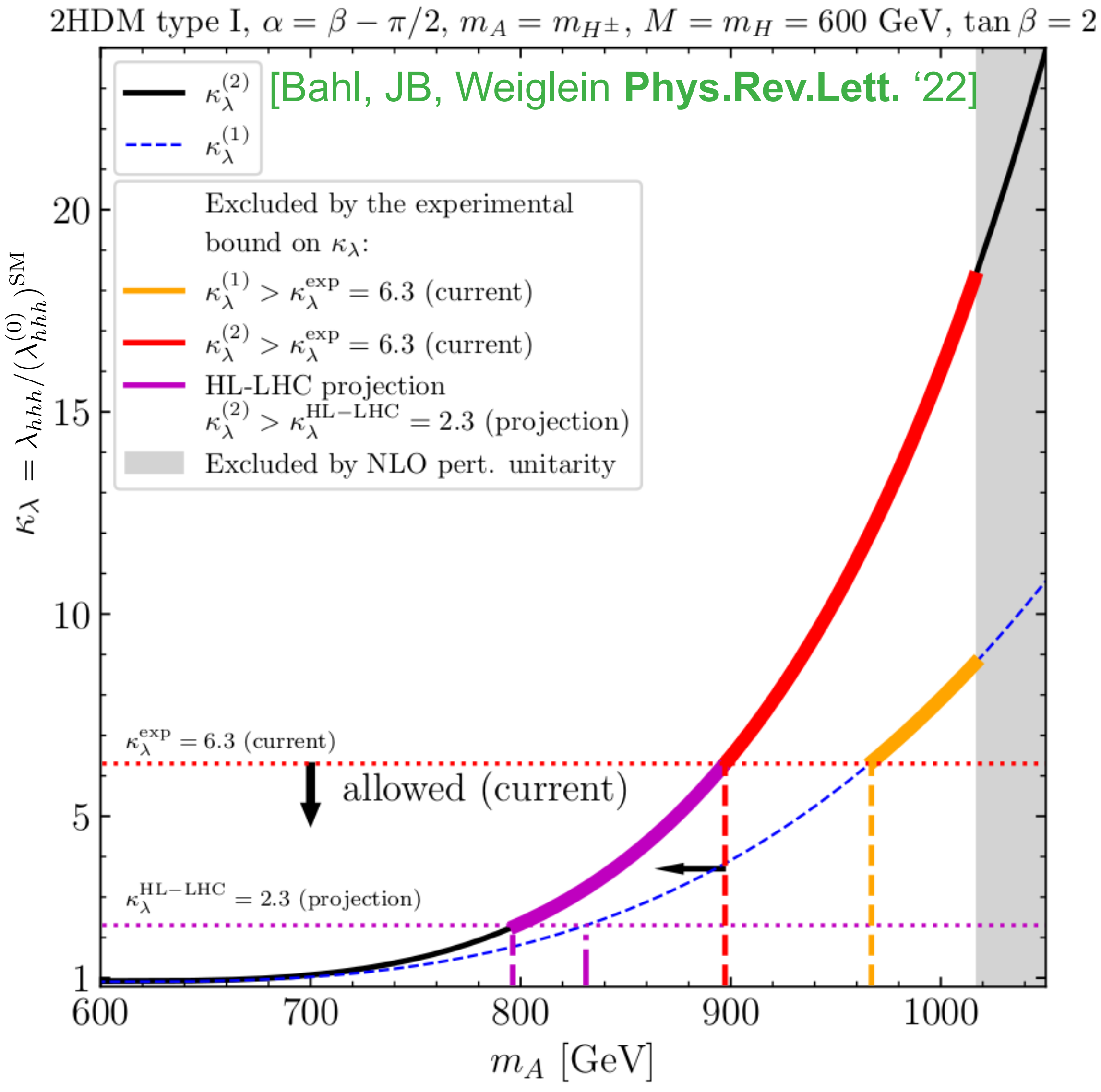
- **Large effects from New Physics possible in λ_{hhh},** due to radiative corrections from extra scalars, e.g. at leading order



- Comparing latest exp. bounds

$$-0.4 < \kappa_\lambda = \frac{\lambda_{hhh}}{(\lambda^{(0)}_{hhh})^{\text{SM}}} < 6.3$$

[ATLAS PLB 2023]
with precise theory predictions for λ_{hhh} provides a **powerful new tool to constrain BSM models**
[Bahl, JB, Weiglein **Phys.Rev.Lett.** '22]



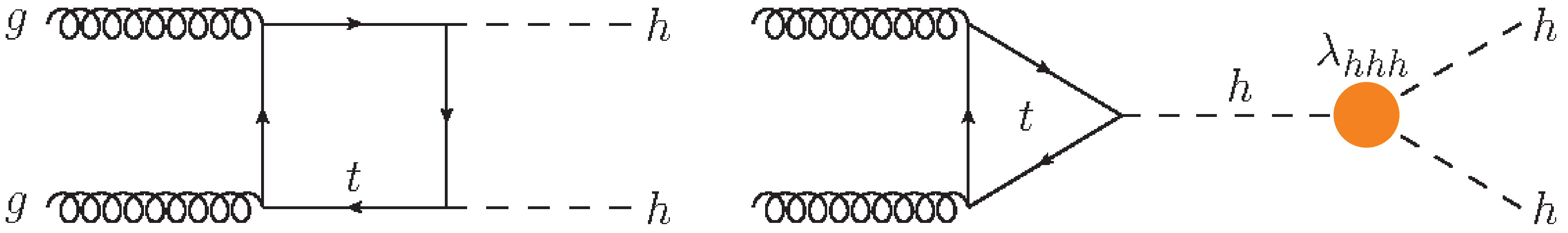
[Bahl, JB, Weiglein **Phys.Rev.Lett.** '22]

Probing λ_{hhh} at the (HL-)LHC

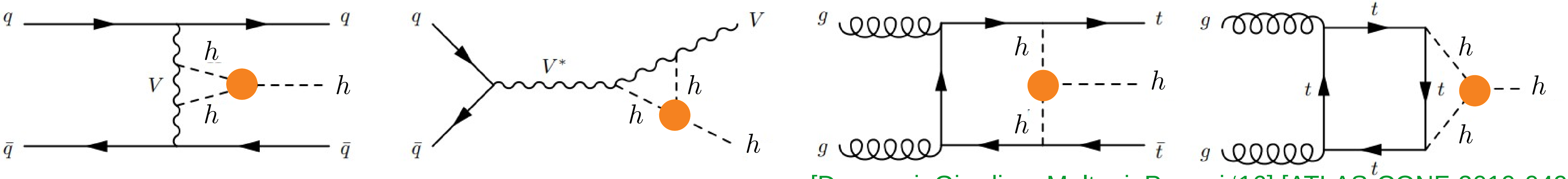
Experimental probes of λ_{hhh}

[NB: triple-Higgs production in a few slides]

- **Double-Higgs production** → λ_{hhh} enters at leading order (LO) → **most direct probe!**

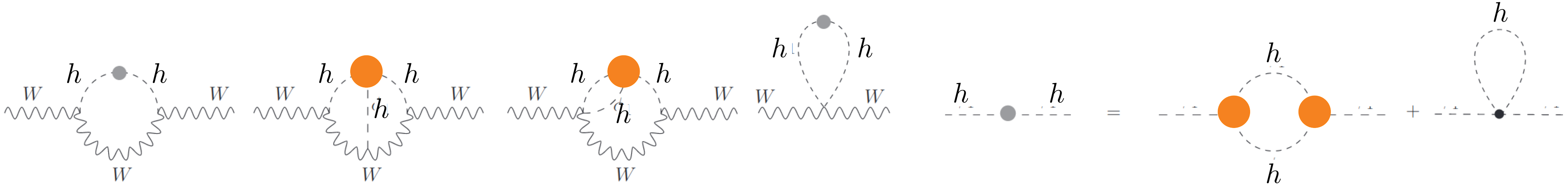


- **Single-Higgs production** → λ_{hhh} enters at NLO (i.e. indirect probe)



[Degrassi, Giardino, Maltoni, Pagani ‘16] [ATLAS-CONF-2019-049]

- **Electroweak Precision Observables** (EWPOs) → λ_{hhh} enters at NNLO (i.e. indirect probe)

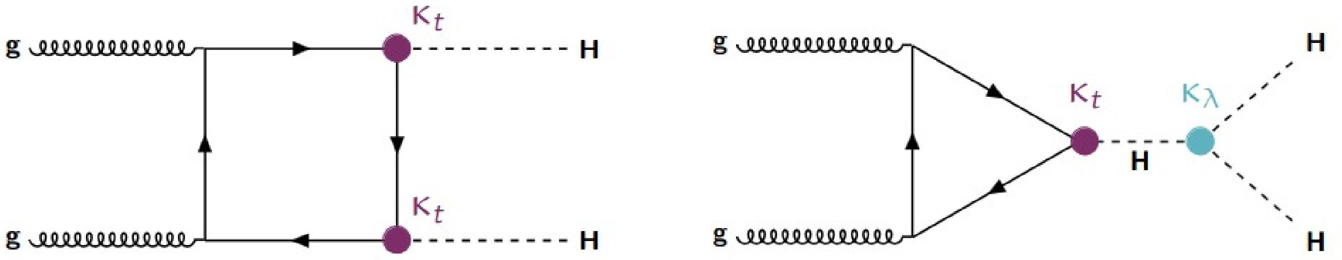


[Degrassi, Fedele, Giardino ‘17]

Probing λ_{hhh} via double-Higgs production

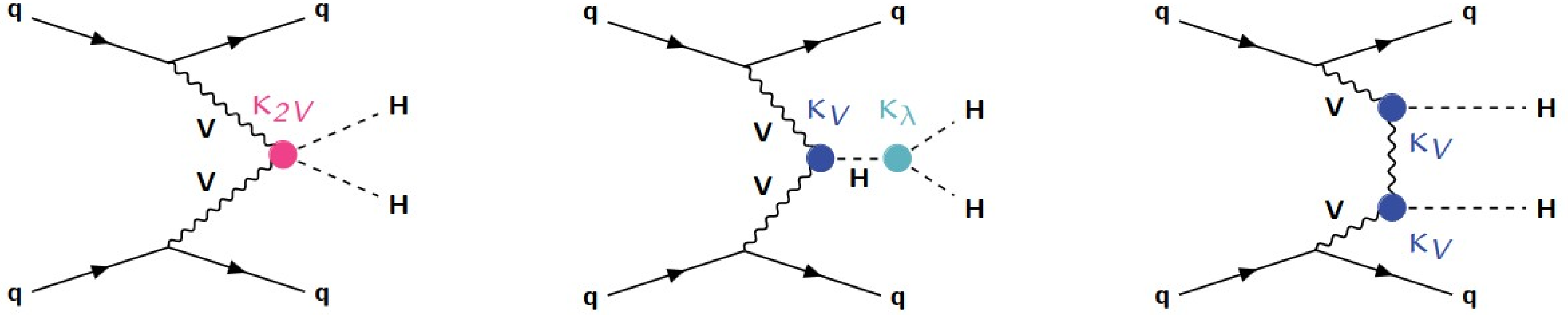
gluon-fusion

$\sigma_{ggF}(pp \rightarrow HH) = 31.05$ fb



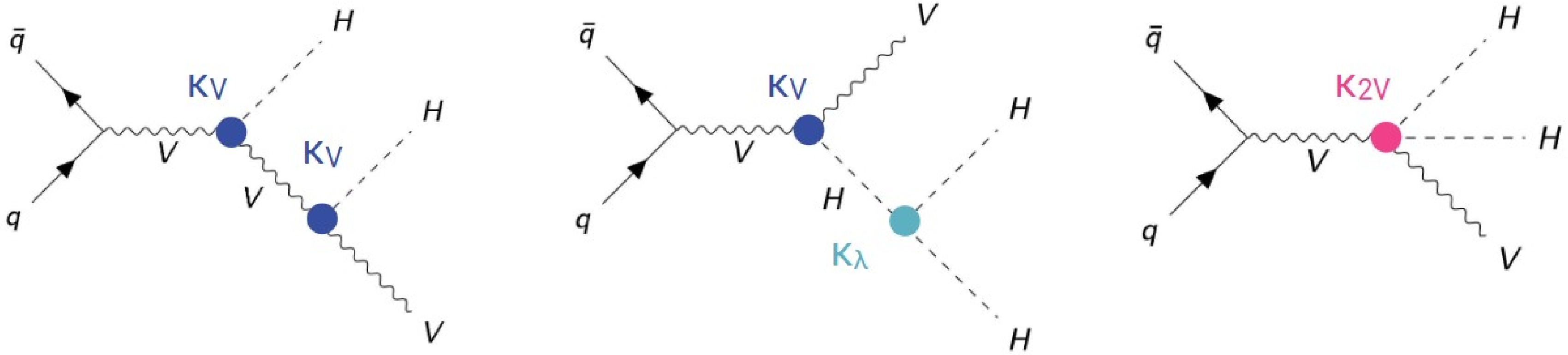
VBF

$\sigma_{VBF}(pp \rightarrow HH) = 1.726$ fb



VHH

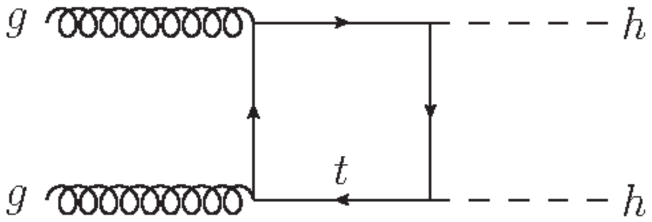
$\sigma_{VHH}(pp \rightarrow HH) = 0.86$ fb

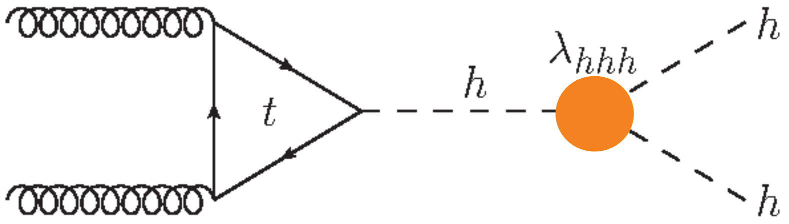


Slide by K. Leney @ HiggsDays 23

Probing λ_{hhh} via double-Higgs production

- **Double-Higgs production** → λ_{hhh} enters at LO → **most direct probe of λ_{hhh}**



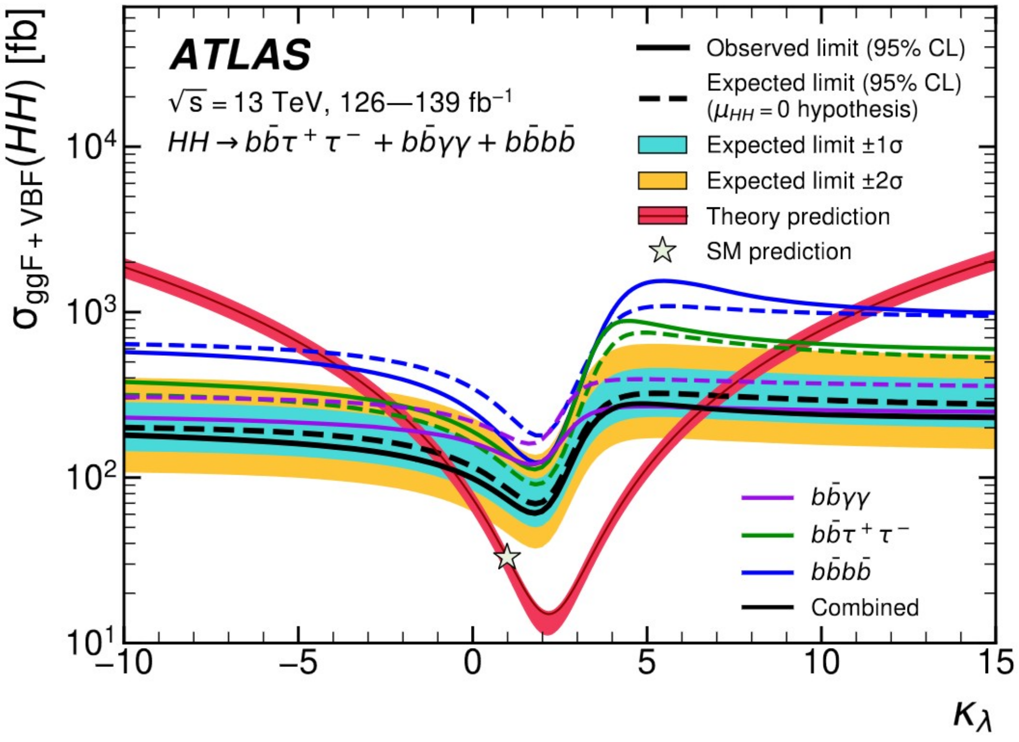


- Box and triangle diagrams **interfere destructively**
→ small prediction in SM

→ BSM deviation in λ_{hhh} can **significantly enhance double-Higgs production!**

- Search limits on double-Higgs production
→ **limits on effective coupling $\kappa_\lambda \equiv \lambda_{hhh}/(\lambda_{hhh}^{(0)})^{SM}$**

- Current best limits: **$-0.4 < \kappa_\lambda < 6.3$** (95% CL) [ATLAS PLB '23]
(including information from single-Higgs production)
$-1.4 < \kappa_\lambda < 6.3$ (95% CL) [ATLAS PLB '23]
(including information from single-Higgs production + κ_t floating)
$-1.2 < \kappa_\lambda < 6.5$ (95% CL) [CMS '22]



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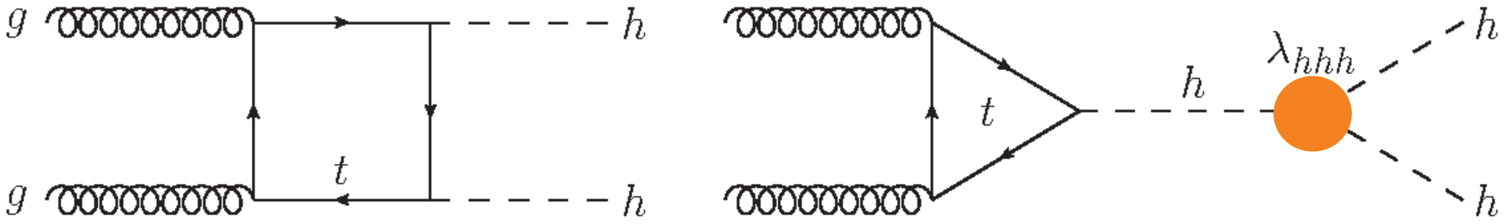

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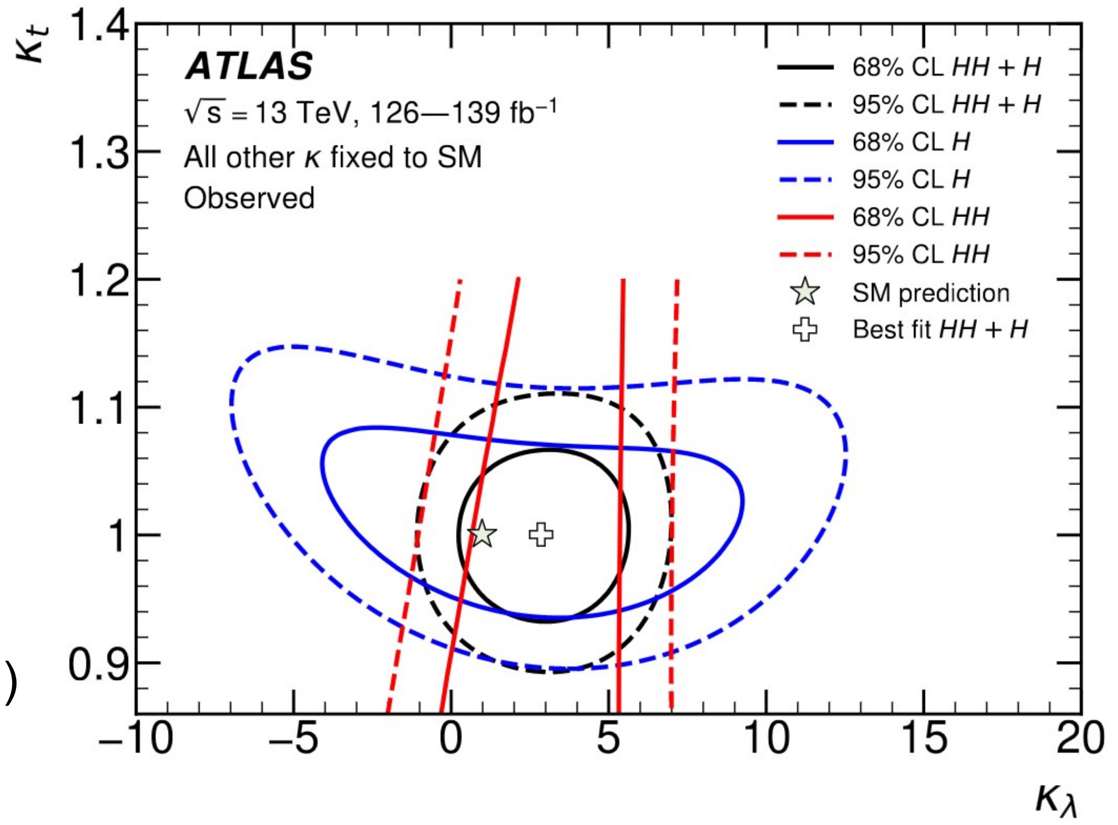

Probing λ_{hhh} via double-Higgs production

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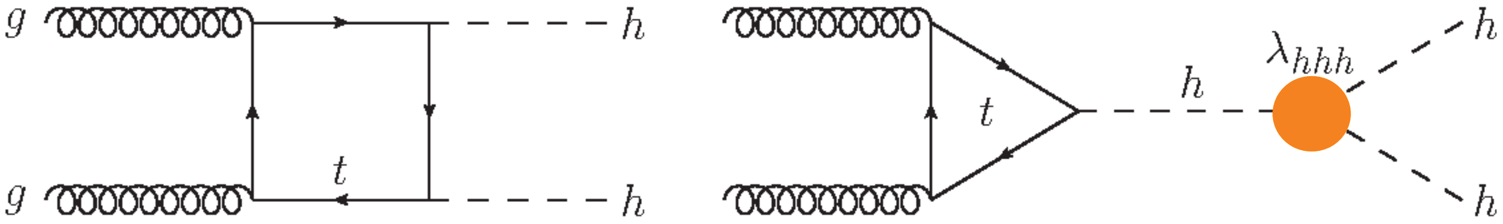

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- Search limits on double-Higgs production
  → **limits on effective coupling $\kappa_\lambda \equiv \lambda_{hhh} / (\lambda_{hhh}^{(0)})^{SM}$**

- Prospects at HL-LHC: **$0.1 < \kappa_\lambda < 2.3$** (95% CL) with ATLAS+CMS

  [Cepeda et al. '19]

  $0.0 < \kappa_\lambda < 2.7$ (95% CL) with ATLAS alone

  [ATL-PHYS-PUB-2022-053]

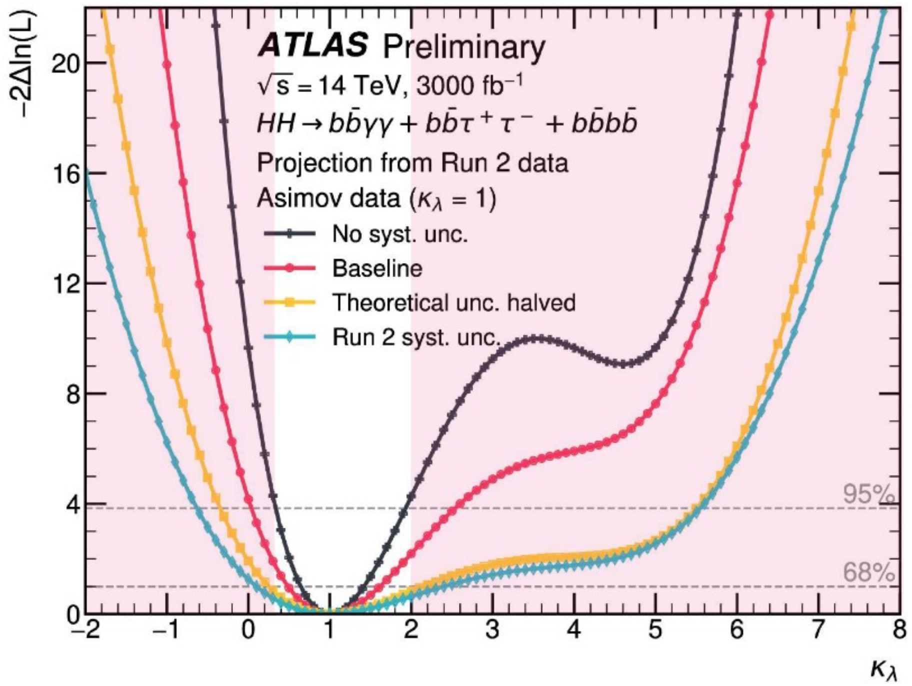


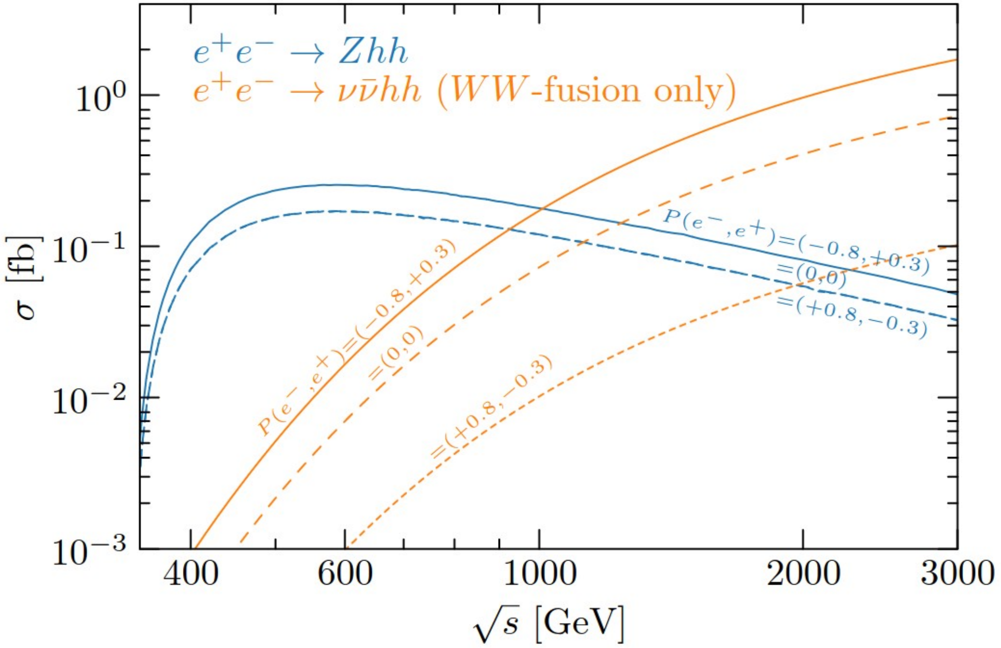
Figure adapted from [ATL-PHYS-PUB-2022-053]

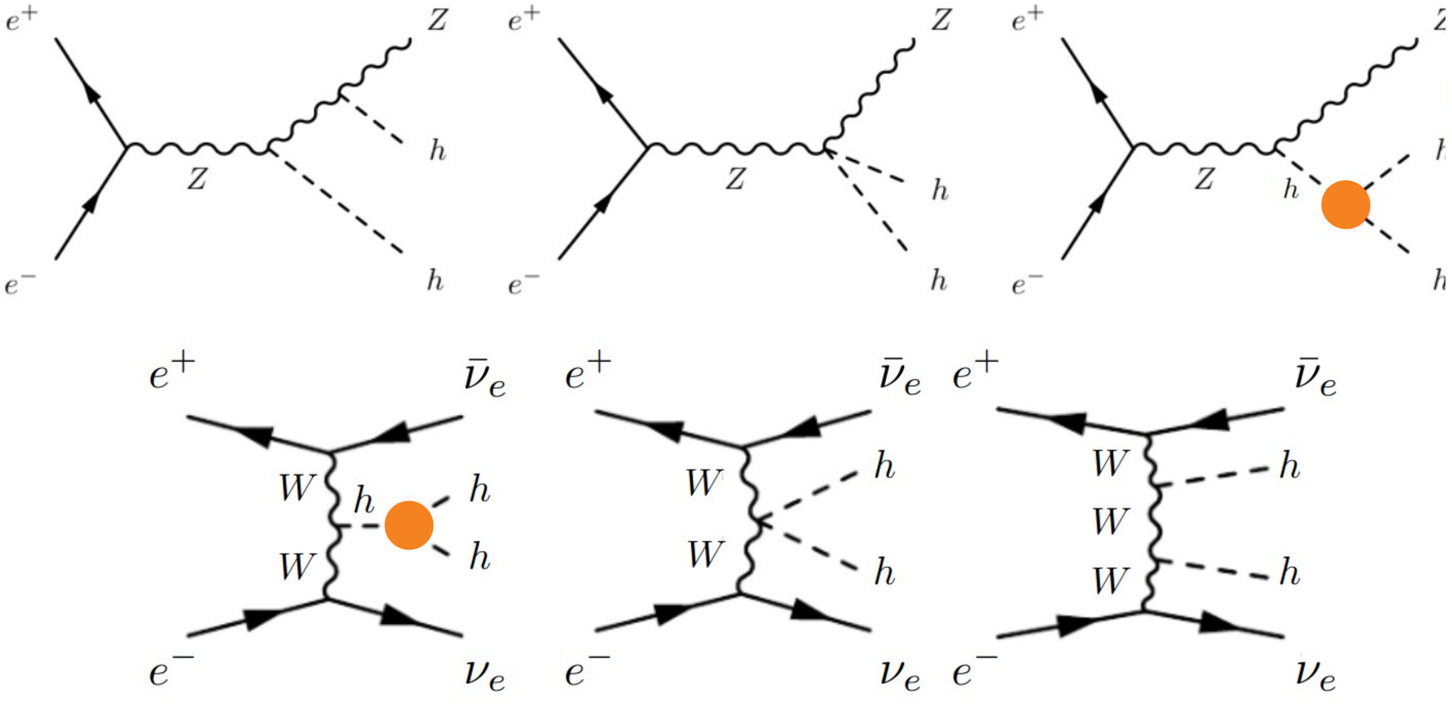
Standard probes of λ_{hhh} at e^+e^- colliders

Direct probes of λ_{hhh} at e^+e^- colliders

- **Double-Higgs production, either in $e^+e^- \to Zhh$ or $e^+e^- \to \nu\bar{\nu}hh$**
- Relies however on being above the Zhh threshold!

Figure from [De Blas et al. `1812.02093`]





- $e^+e^- \to Zhh$ better at $\sqrt{s}$~500 GeV
- $e^+e^- \to \nu\bar{\nu}hh$ better for larger $\sqrt{s}$

Figure from [De Blas et al. `1905.03764`]

Indirect probes of λ_{hhh} at e^+e^- colliders

- Below the Zhh threshold, λ_{hhh} can still be investigated through its (indirect) effect in quantum corrections to single-Higgs production

- In particular, λ_{hhh} enters NLO corrections to $e^+e^- \to Zh$
  First pointed out in [McCullough ‘13], numerous works since (also with global analyses in EFT setting)

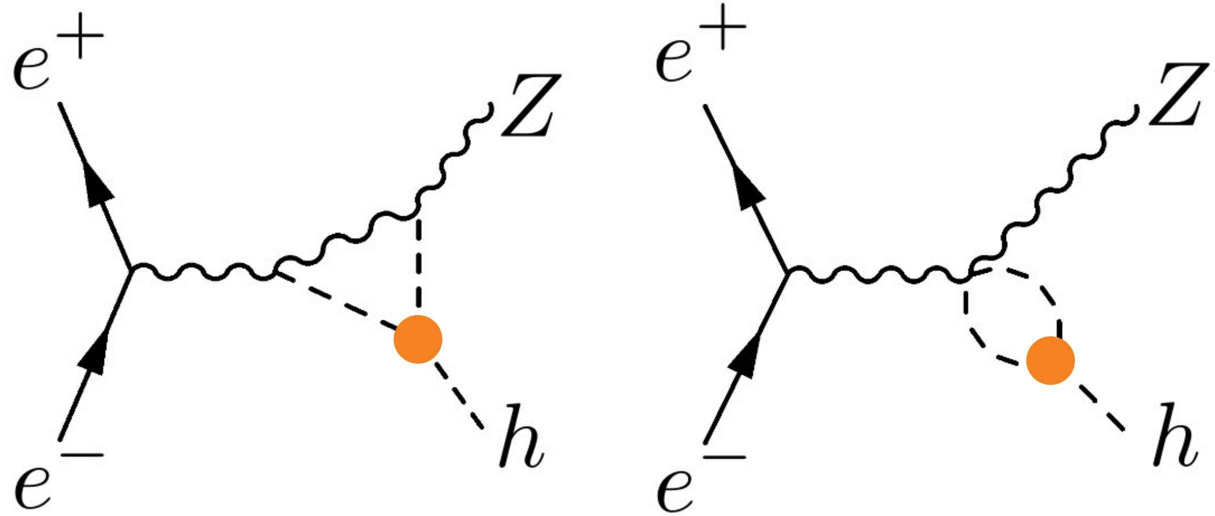


Figure adapted from [McCullough 1312.3322]

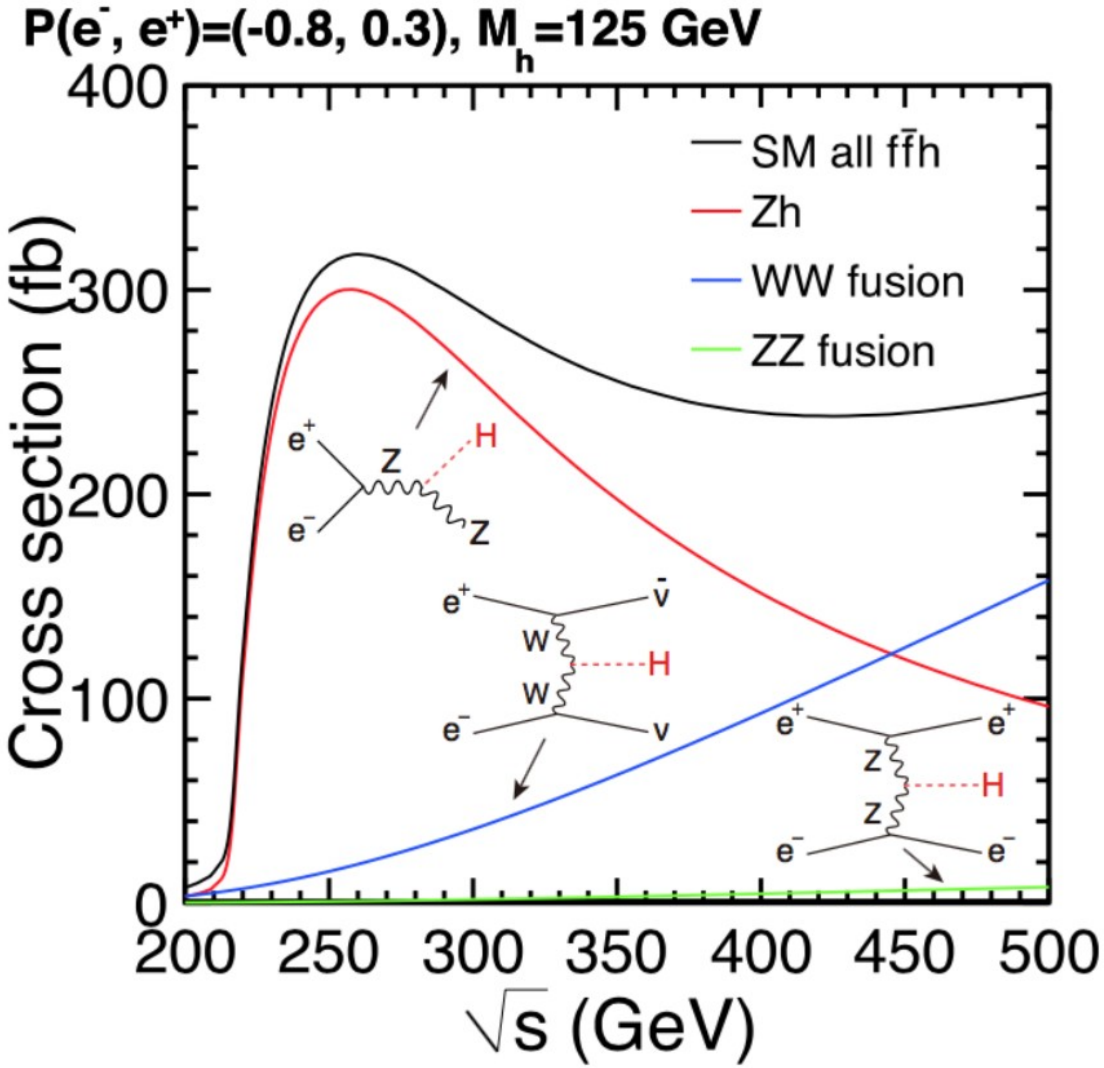
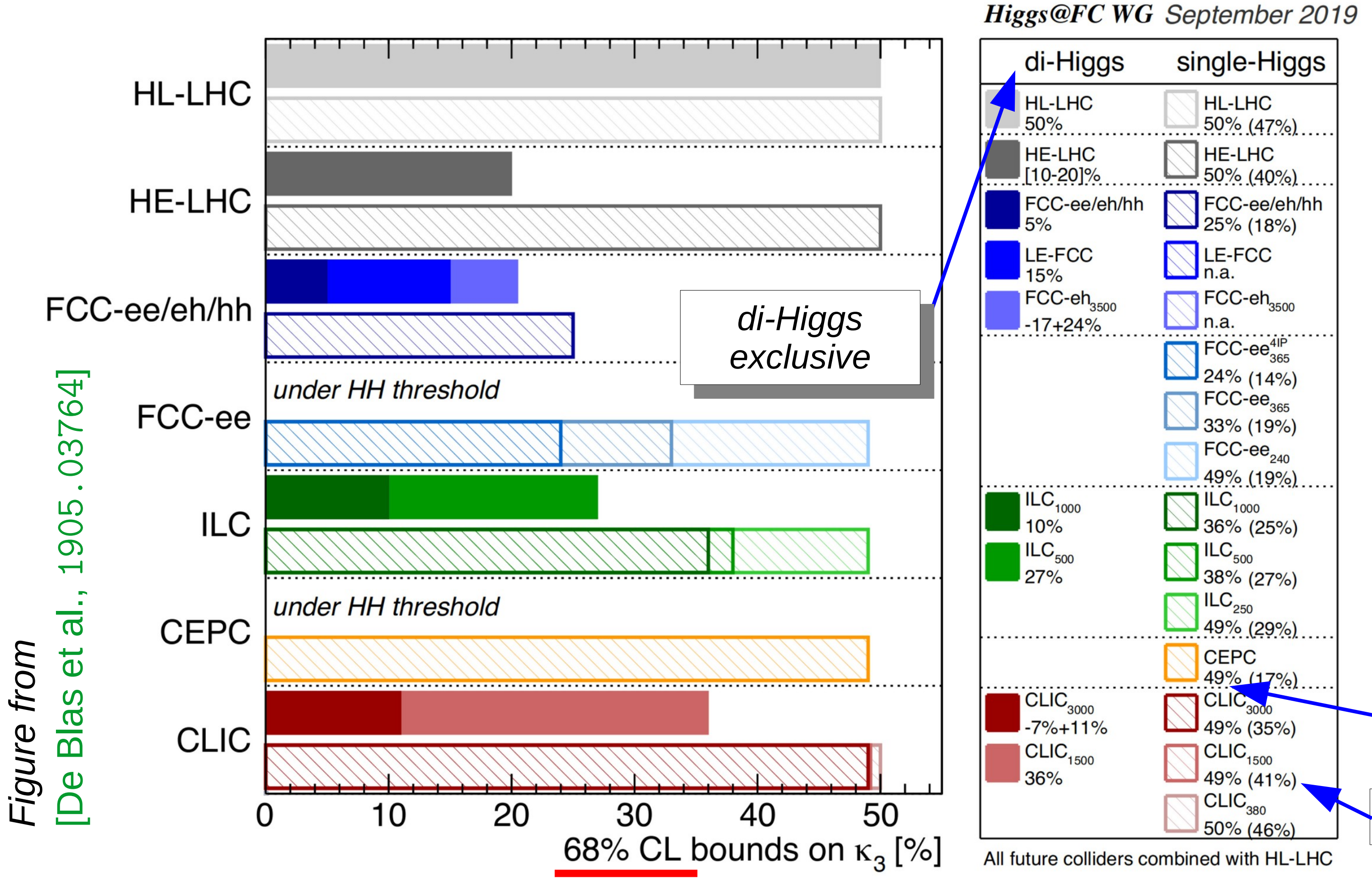


Figure from [Fujii et al. 1710.07621]

Future determination of λ_{hhh}

Expected sensitivities in literature, assuming $\lambda_{hhh} = (\lambda_{hhh})^{SM}$



di-Higgs exclusive

single-Higgs exclusive

single-Higgs global

Figure from [De Blas et al., 1905.03764]

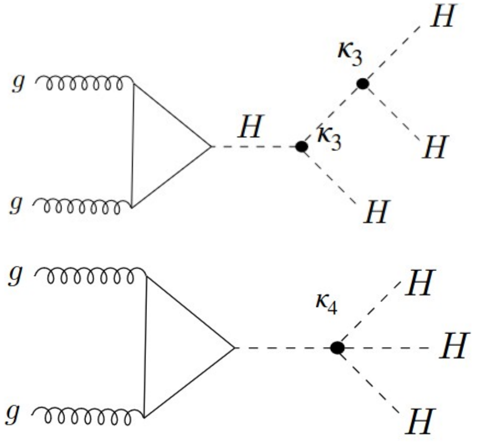
- HL-LHC limits will likely outperform 2019 prospects (even with global analyses)
- Single-Higgs results at lepton colliders always include information from HL-LHC, and don't improve much (if at all)
- Significant improvements only with double-Higgs production at (high-energy) lepton colliders or FCC-hh

see also [Cepeda et al., 1902.00134], [Di Vita et al.1711.03978], [Fujii et al. 1506.05992, 1710.07621, 1908.11299], [Roloff et al., 1901.05897], [Chang et al. 1804.07130,1908.00753], *etc.*

New investigations via triple-Higgs production

Constraining the trilinear and quartic Higgs couplings at the same time

Hadron collider



$\kappa_3 = \kappa_\lambda$: trilinear coupling modifier
κ_4 : quartic coupling modifier

Lepton collider

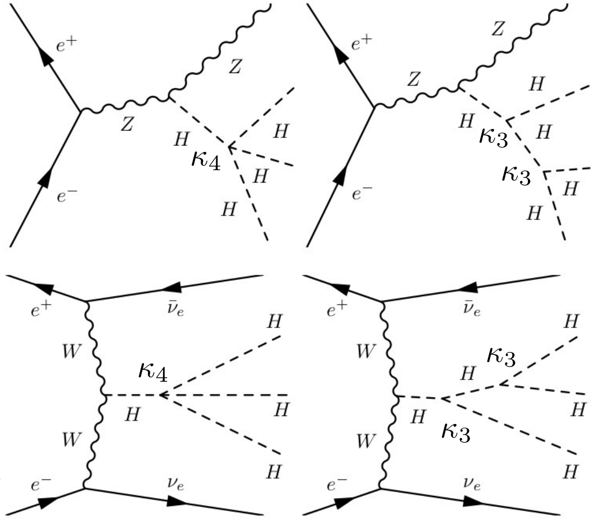
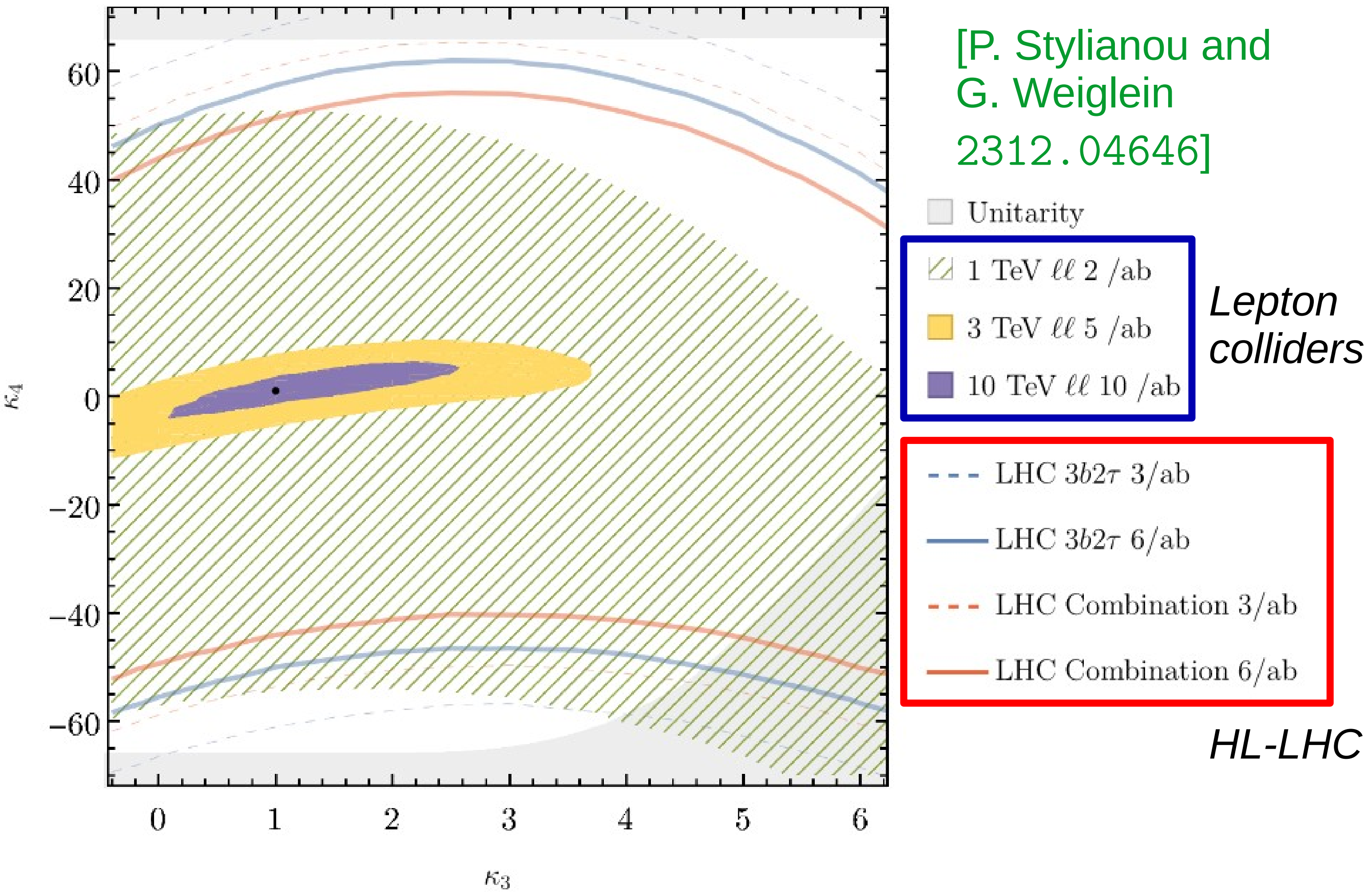


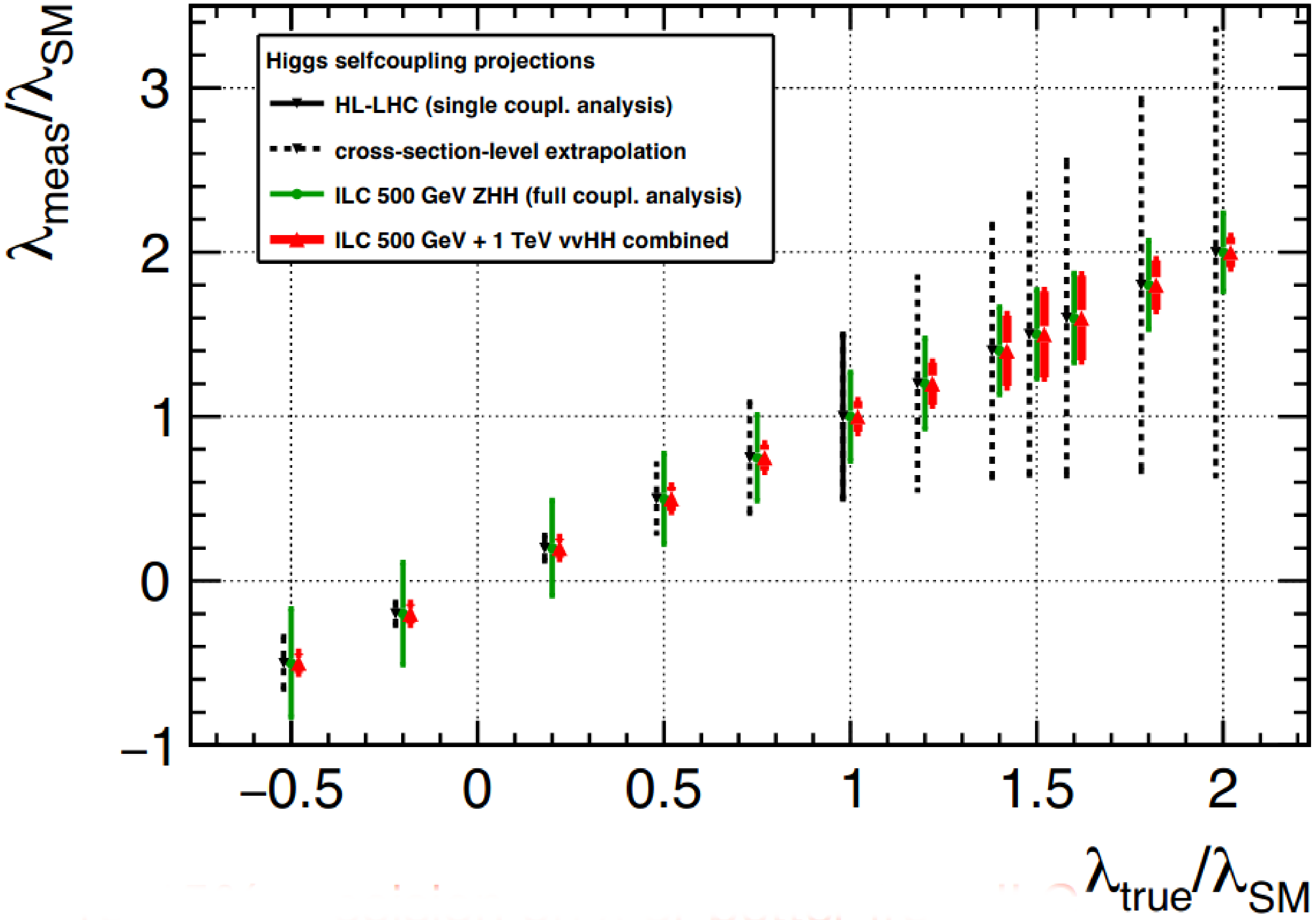
Figure adapted from
[Maltoni, Pagani, Zhao
1802.07616]



[P. Stylianou and
G. Weiglein
`2312.04646`]

Future determination of λ_{hhh}

Achieved accuracy actually depends on the value of λ_{hhh}



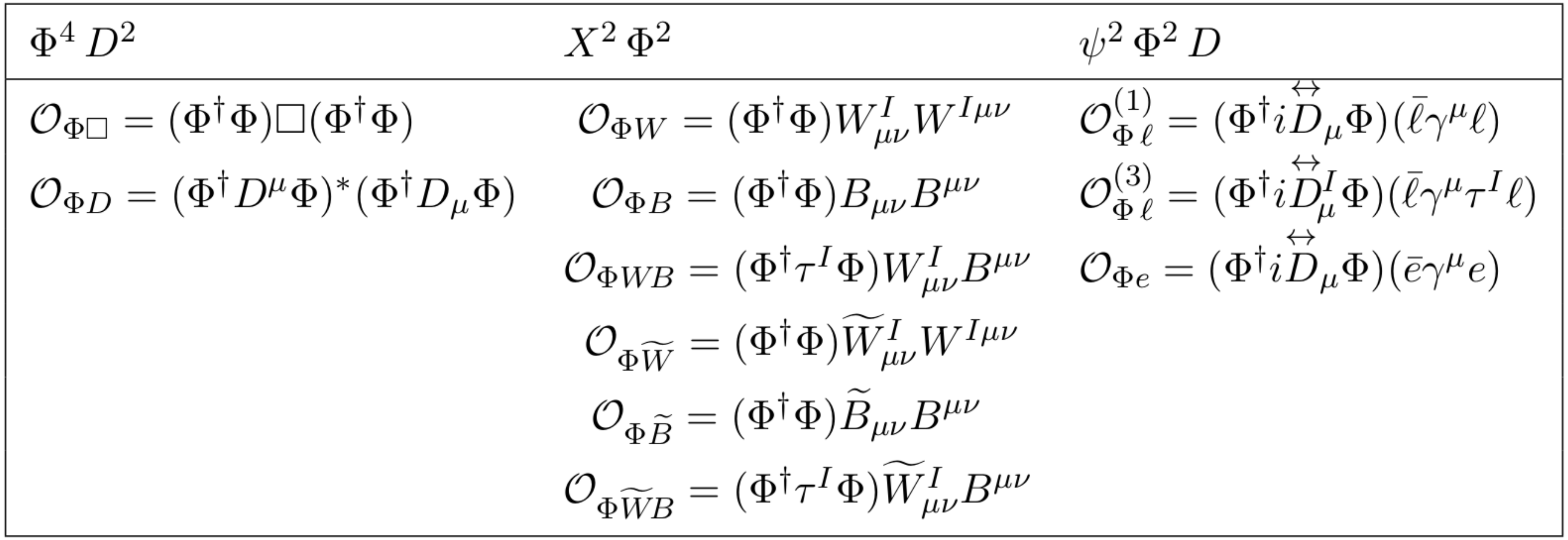
[J. List et al. ‘21]

See also [Dürig, DESY-THESIS-2016-027]

λ_{hhh} with angular distributions in $e^+e^- \rightarrow Zh$

Anomalous Higgs couplings in angular asymmetries

h→Z l^+l^- and e^+e^- → Zh



$\Phi^4 D^2$	$X^2 \Phi^2$	$\psi^2 \Phi^2 D$
$\mathcal{O}_{\Phi\Box} = (\Phi^\dagger\Phi)\Box(\Phi^\dagger\Phi)$	$\mathcal{O}_{\Phi W} = (\Phi^\dagger\Phi)W^I_{\mu\nu}W^{I\mu\nu}$	$\mathcal{O}^{(1)}_{\Phi\,\ell} = (\Phi^\dagger i\overleftrightarrow{D}_\mu\Phi)(\bar\ell\gamma^\mu\ell)$
$\mathcal{O}_{\Phi D} = (\Phi^\dagger D^\mu\Phi)^*(\Phi^\dagger D_\mu\Phi)$	$\mathcal{O}_{\Phi B} = (\Phi^\dagger\Phi)B_{\mu\nu}B^{\mu\nu}$	$\mathcal{O}^{(3)}_{\Phi\,\ell} = (\Phi^\dagger i\overleftrightarrow{D}^I_\mu\Phi)(\bar\ell\gamma^\mu\tau^I\ell)$
	$\mathcal{O}_{\Phi WB} = (\Phi^\dagger\tau^I\Phi)W^I_{\mu\nu}B^{\mu\nu}$	$\mathcal{O}_{\Phi e} = (\Phi^\dagger i\overleftrightarrow{D}_\mu\Phi)(\bar e\gamma^\mu e)$
	$\mathcal{O}_{\Phi\widetilde{W}} = (\Phi^\dagger\Phi)\widetilde{W}^I_{\mu\nu}W^{I\mu\nu}$	
	$\mathcal{O}_{\Phi\widetilde{B}} = (\Phi^\dagger\Phi)\widetilde{B}_{\mu\nu}B^{\mu\nu}$	
	$\mathcal{O}_{\Phi\widetilde{W}B} = (\Phi^\dagger\tau^I\Phi)\widetilde{W}^I_{\mu\nu}B^{\mu\nu}$	

Table 1. The subset of $d = 6$ operators that contribute to $H \to Z\ell^+\ell^-$ and $e^+e^- \to HZ$

Table from [Beneke, Boito, Wang '14],
same as in [Craig, Gu, Liu, K. Wang '18]

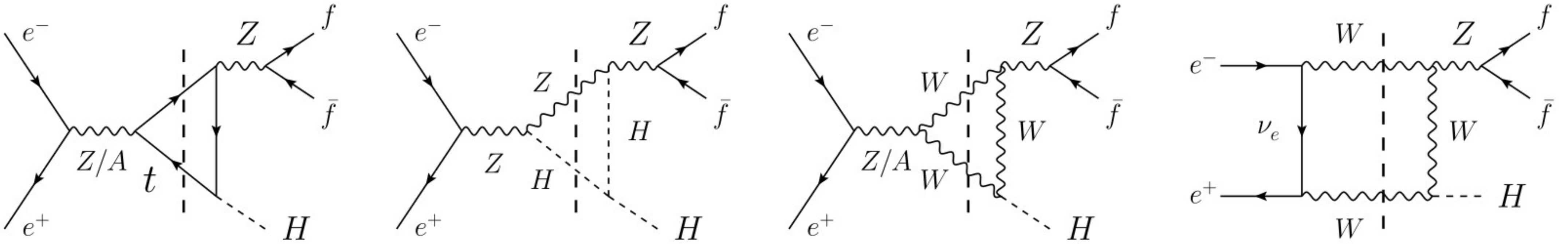
- [Beneke, Boito, Wang '14], [Craig, Gu, Liu, K. Wang '18] → investigate modified Higgs couplings in context of SMEFT → see also earlier talk by J. Gu
- No operator $\mathcal{O}_\Phi \propto (\Phi^\dagger\Phi)^3$ modifying λ_{hhh} directly appearing in these analyses!
  ($O_{\Phi\Box}$ and $O_{\Phi D}$ only impact λ_{hhh} indirectly, via external-leg corrections)
- SMEFT is not built to capture mass-splitting effects that drive large corrections to λ_{hhh} – would require an infinite tower of operators of the form $(\Phi^\dagger\Phi)^n$ (or an appropriate reparametrisation)

λ_{hhh} in $e^+e^-\to Zh$ via a T-odd observable

[Nakamura, Shivaji PLB '19]

Construct a T-odd asymmetry involving imaginary part of loop corrections to $e^+e^-\to Zh$

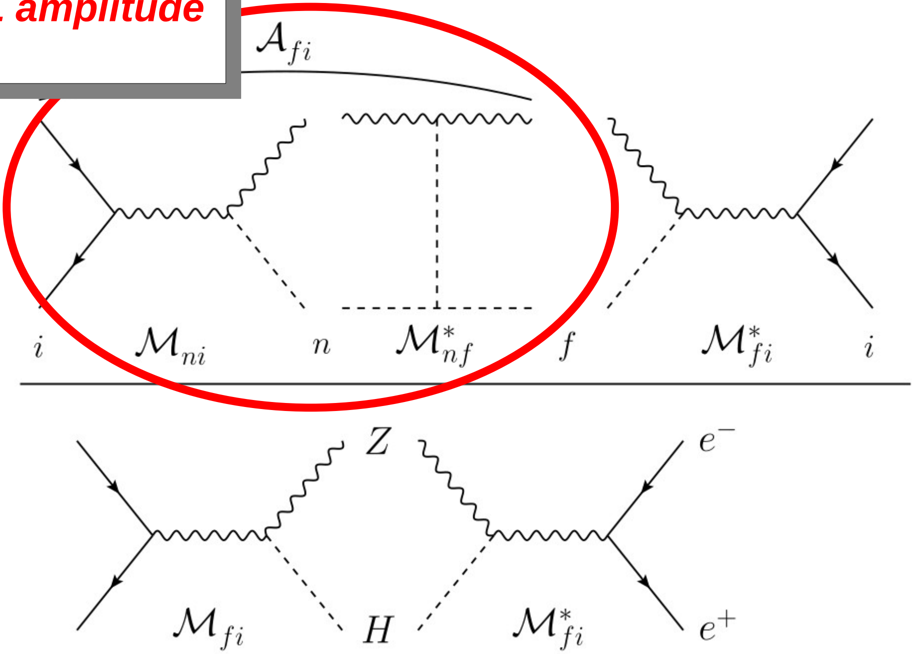
One-loop (NLO) corrections to $e^+e^- \to Zh$



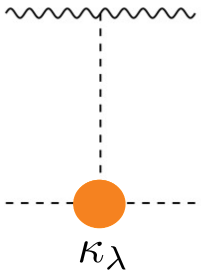
Imaginary part of 1L amplitude (w. Cutkosky cut)

Asymmetry observable

$A \sim$



$\sim$

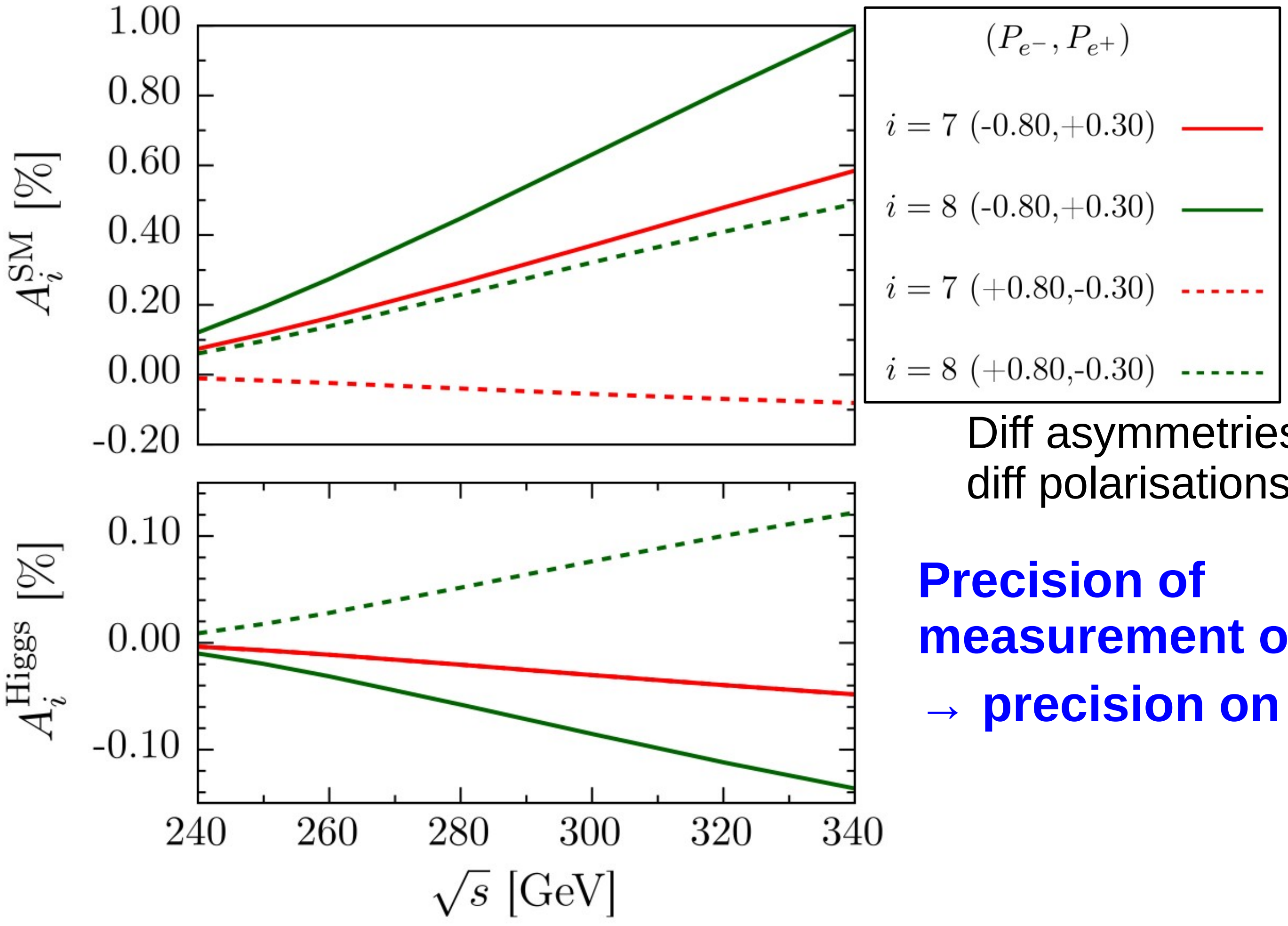


Like if one had direct access to Zh → Zh scattering process!

But does this offer sensitivity to κ_λ?

λ_{hhh} in $e^+e^- \to Zh$ via a T-odd observable: actual sensitivity

[Nakamura, Shivaji PLB ‘19]



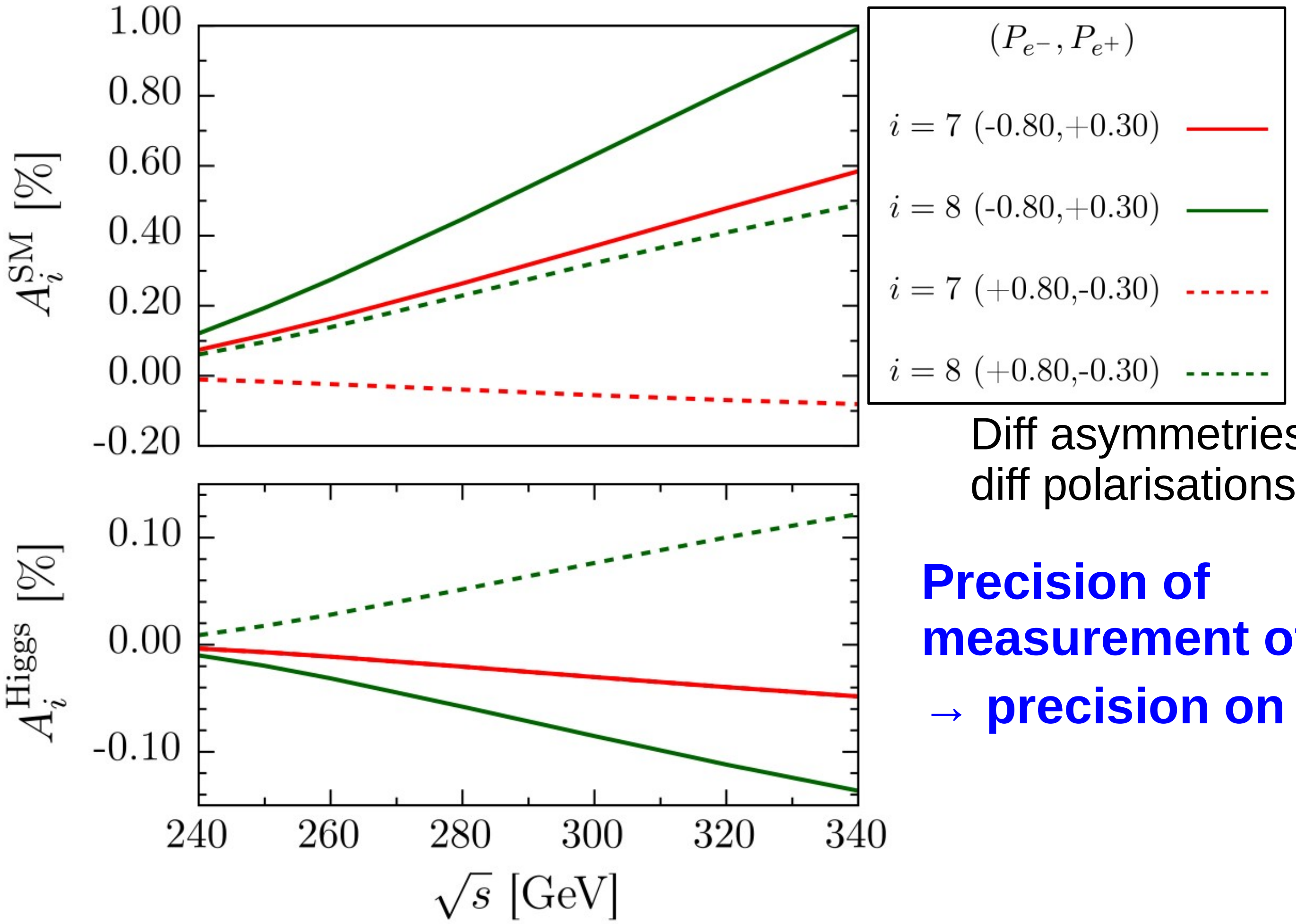
Diff asymmetries,
diff polarisations

Precision of measurement of $A_i^{\rm Higgs}$ → precision on κ_λ

$$A_i^{\rm SM} = A_i^{\rm Higgs} + A_i^{\rm gauge}$$

λ_{hhh} in e⁺e⁻→Zh via a T-odd observable: actual sensitivity

[Nakamura, Shivaji PLB ‘19]

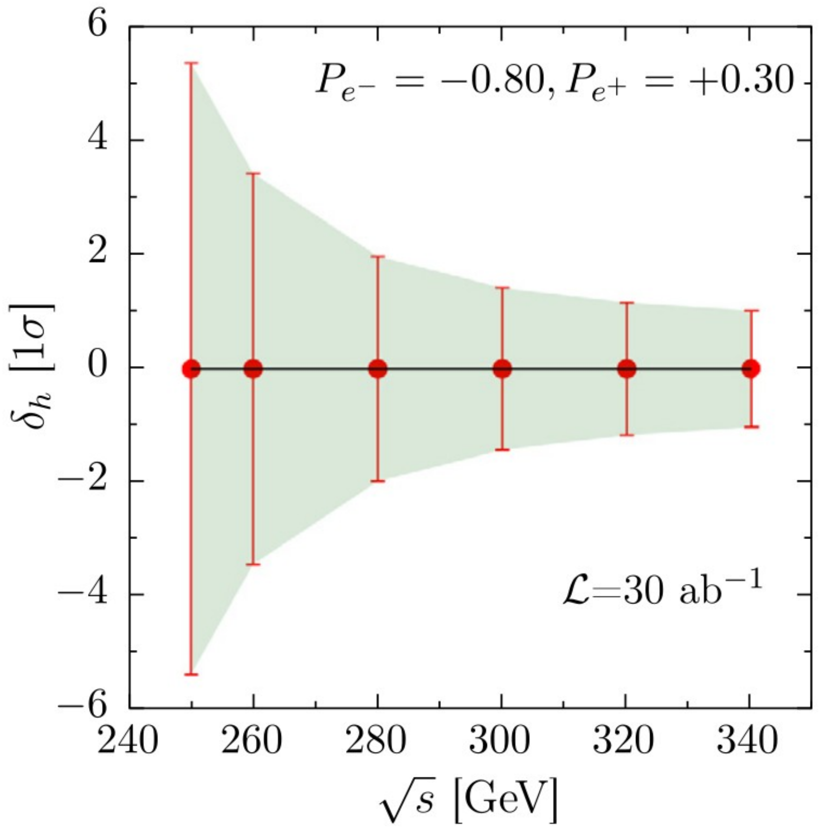


Diff asymmetries, diff polarisations

$$A_i^{SM} = A_i^{Higgs} + A_i^{gauge}$$

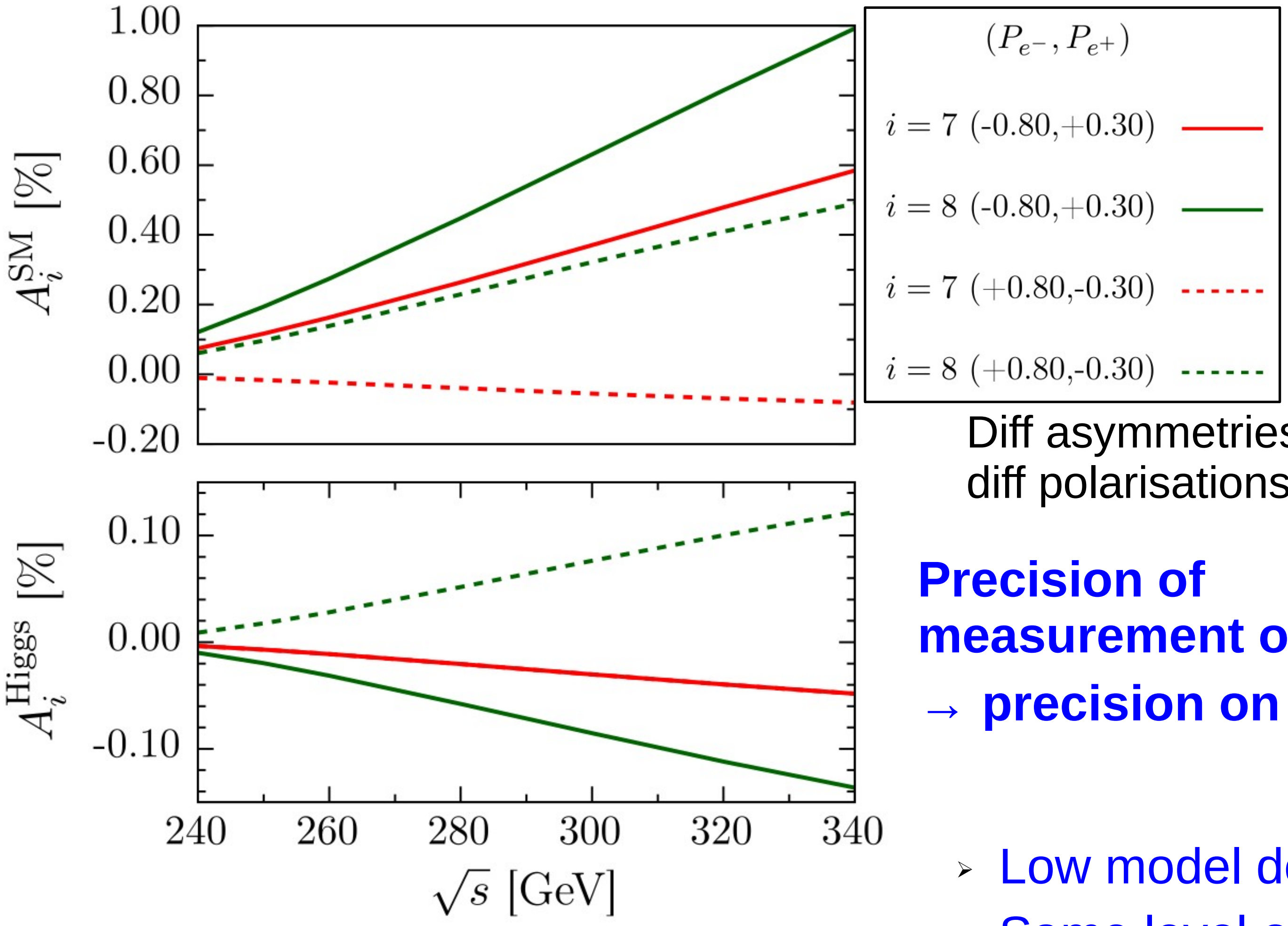
Precision of measurement of A_i^{Higgs} → precision on κ_λ

$$\delta_h \equiv \kappa_\lambda - 1$$



λ_{hhh} in $e^+e^-\to Zh$ via a T-odd observable: actual sensitivity

[Nakamura, Shivaji PLB '19]



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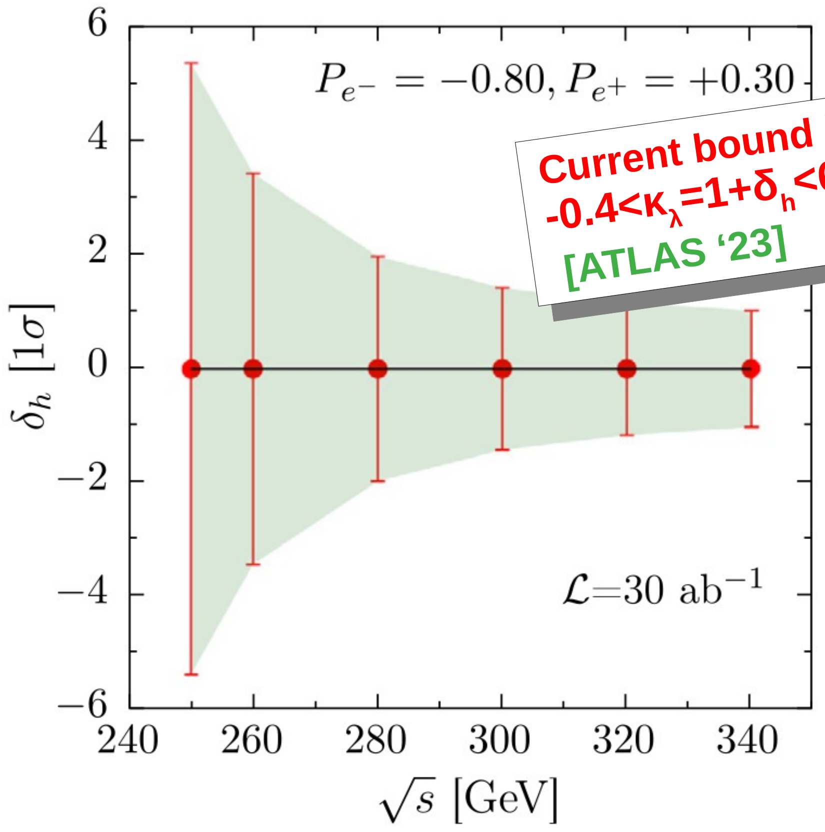

Current bound is $-0.4<\kappa_\lambda=1+\delta_h<6.3$
[ATLAS '23]

Precision of measurement of $A_i^{\rm Higgs}$ → precision on κ_λ

- Low model dependence on κ_t or hZZ coupling
- Same level of accuracy, no matter the value of κ_λ
- But low sensitivity on κ_λ, even with 30 ab^{-1} of data...

Summary

- λ_{hhh} plays a crucial role to understand the **shape of the Higgs potential**, and **probe indirect signs of New Physics**

- Currently, direct probe of λ_{hhh} via double-Higgs production at LHC provides the most stringent constraints on this coupling

- At future e+e- colliders, only direct probes – via Zhh or vvhh – offer additional information on κ_λ beyond what would be obtained at HL-LHC → motivates a collider with $\sqrt{s} > 500$ GeV

- While interesting from the point-of-view of **model independence**, Zh angular measurements do not seem to provide competitive constraints on κ_λ, even with full data set of future e^+e^- collider ($30ab^{-1}$)

Thank you very much for your attention!

Contact

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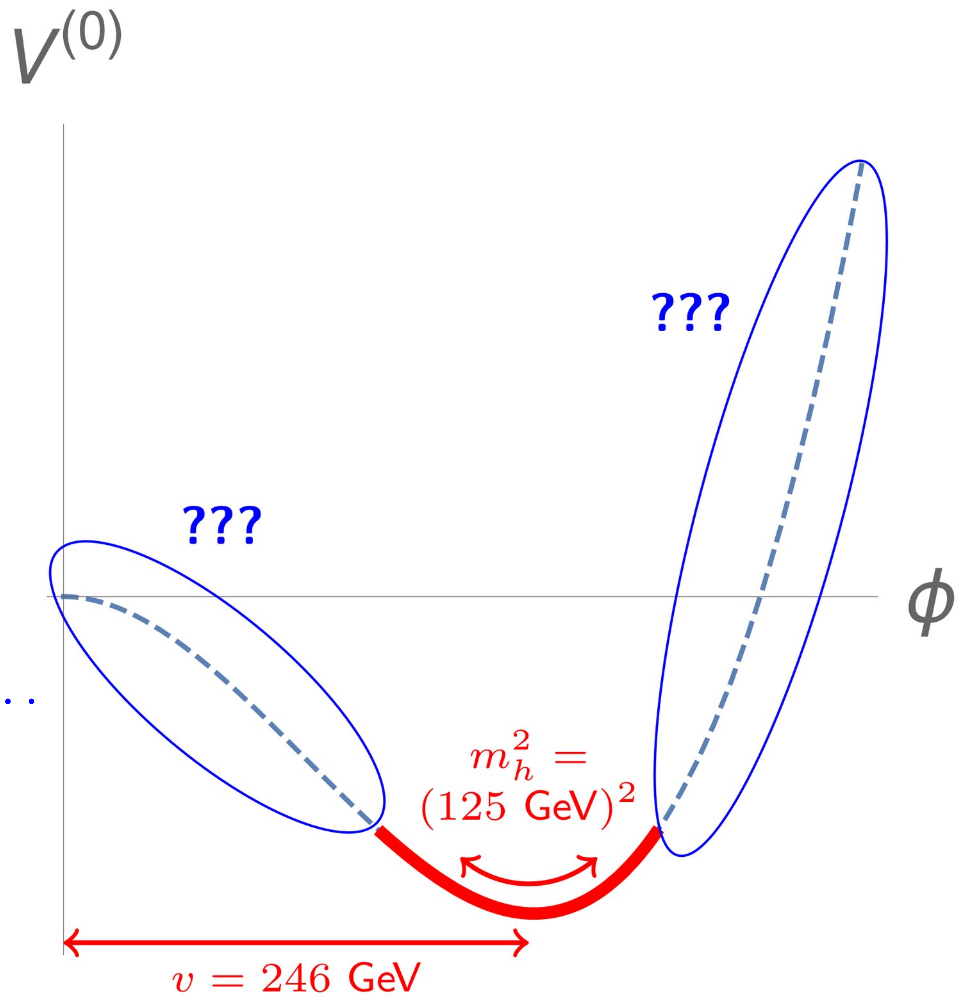
Backup

Probing the shape of the Higgs potential

- Since the Higgs discovery, the existence of the Higgs potential is confirmed, but at the moment we only know:
  → the location of the EW minimum:
  v = 246 GeV
  → the curvature of the potential around the EW minimum:
  M_h = 125 GeV
  However we still don't know the **shape** of the potential, away from EW minimum → **depends on λ_{hhh}**



- In the SM: $V^{(0)}_{\text{SM}} = \frac{1}{2}m_h^2h^2 + \frac{1}{3!}\underbrace{\left(\frac{3m_h^2}{v}\right)}_{\equiv(\lambda^{(0)}_{hhh})^{\text{SM}}}h^3 + \frac{1}{4!}\left(\frac{3m_h^2}{v^2}\right)h^4 + \cdots$

- In general:

$$V^{(0)} = \frac{1}{2}m_h^2h^2 + \frac{1}{3!}\overbrace{\kappa_\lambda\left(\frac{3m_h^2}{v}\right)}^{\equiv\lambda_{hhh}}h^3 + \frac{1}{4!}\kappa_{\lambda_4}\left(\frac{3m_h^2}{v^2}\right)h^4 + \cdots$$

with $\kappa_\lambda \equiv \lambda_{hhh}/(\lambda^{(0)}_{hhh})^{\text{SM}}$

Future determination of λ_{hhh}

Higgs production cross-sections (here double Higgs production) depend on λ_{hhh}

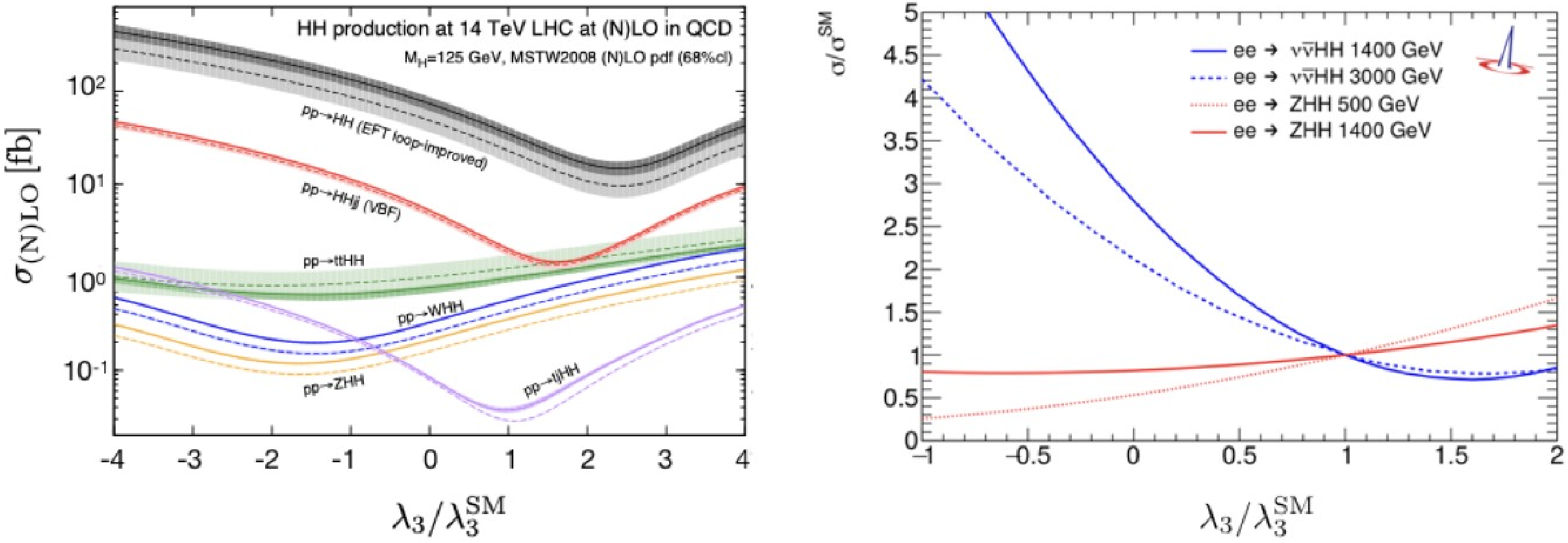


Figure 10. Double Higgs production at hadron (left) [65] and lepton (right) [66] colliders as a function of the modified Higgs cubic self-coupling. See Table 18 for the SM rates. At lepton colliders, the production cross sections do depend on the polarisation but this dependence drops out in the ratios to the SM rates (beam spectrum and QED ISR effects have been included).

[Frederix et al., 1401.7340]

Plots taken from
[de Blas et al., 1905.03764]