Impression from ECFA Higgs/Top/EW Factory WS - WG1

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32nd Future Colliders @ DESY Meeting, 18.10.2024

ECFA Higgs/EW/Top Factory Study

- In 2021, **ECFA** launched a series of workshops on physics studies, experiment design, and detector technologies towards a future electron-positron Higgs/EW/Top factory.
- After the successful meetings at DESY (2022) and Paestum (2023), the **final** workshop was organised in Paris last week.

Structure of the study

3 working groups:

- WG1 – Physics Performance:
  - Global Interpretations
  - Precision
  - Higgs/Top/EW
  - Flavour
  - Searches

  this talk
- WG2 – Physics Analysis Methods
- WG3 – Detector R&D

This talk

"WG1" corresponds to:

- 49 parallel talks (9 sessions),
- 13 plenary talks,
- 3 posters.

* I will also briefly comment on the ECR activities.

Disclaimer

Personal highlights of the highlighted person:

sorry for possible omissions!

HTE: H→ss

Motivations

Measurement of **Higgs couplings** to quarks and gluons at FCC-ee

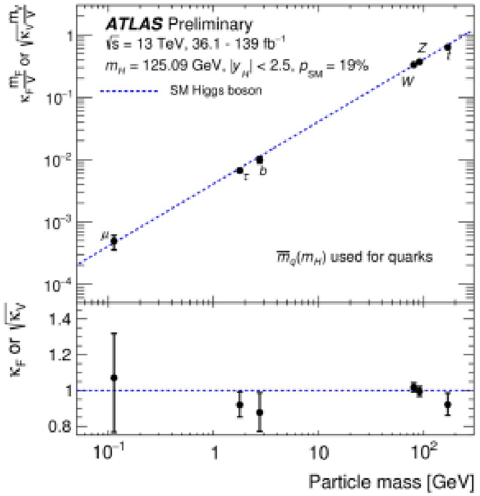
Yukawa coupling

$$m_f = v \frac{y_f}{\sqrt{2}}$$

Coupling-mass relation for fermions in the SM

Deviation from SM → Possible BSM physics

2022 (LHC)



~2040 (HL-LHC)

Coupling	HL-LHC
κ_W [%]	1.5*
κ_Z [%]	1.3*
κ_g [%]	2*
κ_γ [%]	1.6*
$\kappa_{Z\gamma}$ [%]	10*
κ_c [%]	–
κ_t [%]	3.2*
κ_b [%]	2.5*
κ_μ [%]	4.4*
κ_τ [%]	1.6*
BR_{inv} (<%, 95% CL)	1.9*
BR_{unt} (<%, 95% CL)	4*

Fully hadronic represents 80% of the Higgs decays

Higgs decay	H→bb	H→WW/ZZ	H→gg	H→cc	H→ss	(H→ττ)
BR	57.7%	11%	8.6%	2.9%	0.024%	(6.2%)

only one observed to this day

Observable at FCC-ee

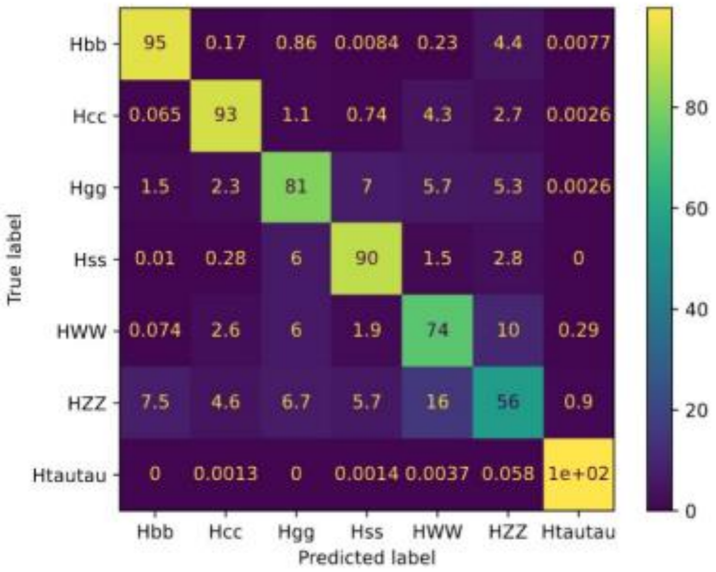
Also possible future observation of **Flavour-violating** decay

talk by A. Maloizel

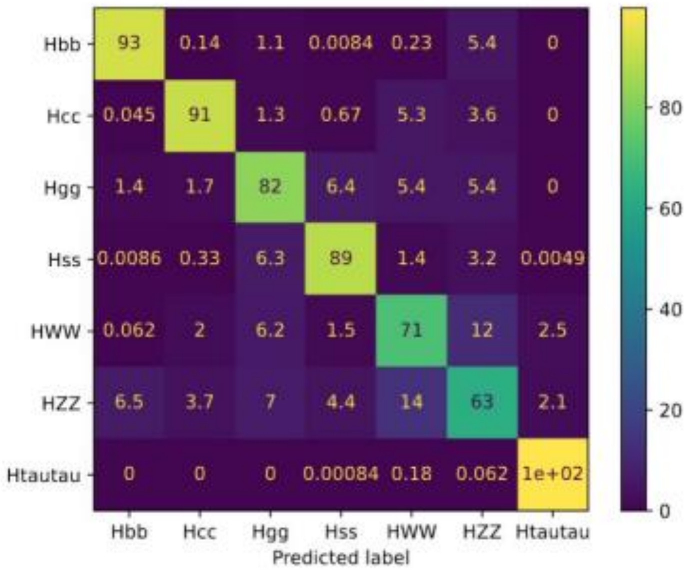
Events categorization - 240 GeV

We train a Neural Network to categorize the events in each signal channels

Z($\nu\nu$) Confusion Matrix



Z(ll) Confusion Matrix

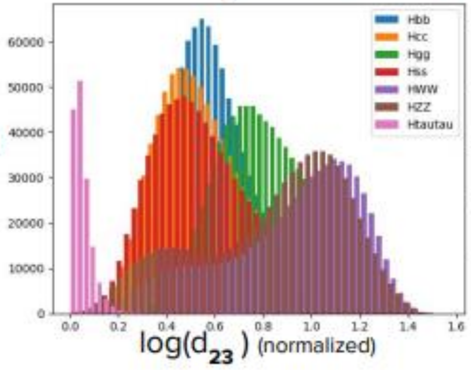


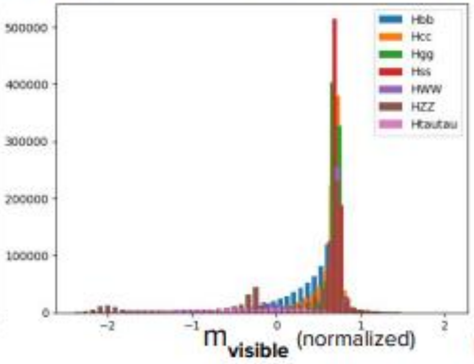
Training variables

```
        "jet1_isB",
        "jet2_isB",
        "jet1_isC",
        "jet2_isC",
        "jet1_isG",
        "jet2_isG",
        "jet1_isU",
        "jet2_isU",
        "jet1_isD",                 'log_d23',
        "jet2_isD",                 'log_d34',
        # "jet1_isTAU",             'm_visible',
        # "jet2_isTAU",
    ]
)
if include_ss:
    varlist.extend(["jet1_isS", "jet2_isS"])
```

angular distance between the 2nd and 3rd jet components

Training variables consist of output scores of a ParticleNet jet tagger which runs after reconstruction + some additional kinematic variables improving sensitivity in some channels





Conclusion & prospects

Promising results at **% level** in some categories

Achieved full combination at **240 GeV**. Combination at **365 GeV** is **WIP**

Need to **disentangle VBF** from **ZH** and extract couplings from the fit

Include **FV-violating** samples and **uu/dd** channels

Expected sensitivity (%) of σ(ZH).BR(H⟶jj) at 68% CL **L = 10.8ab-1**

240 GeV	H⟶bb	H⟶cc	H⟶gg	H⟶ss	H⟶ZZ	H⟶WW	H⟶ττ
Combined (BNL)	0.21	1.66	0.8	104.99	10.07	1.16	3.97
Combined (APC)	0.22	1.65	0.93	121	9.56	1.11	3.79

Full-simulation ILD study expected in a few days...

talk by A. Maloizel

HTE: Higgs self-coupling

λ_{hhh}: very large deviations from the SM value possible!

EFT perspective: *[M. McCullough, ICHEP 2024]*

Self-Coupling Dominance

No obstruction to having Higgs self-coupling modifications a "loop factor" greater than **all** other couplings. Could have

$$\left|\frac{\delta_{h^3}}{\delta_{VV}}\right| \lesssim \min\left[\left(\frac{4\pi v}{m_h}\right)^2, \left(\frac{M}{m_h}\right)^2\right]$$

without fine-tuning any parameters, as big as,

$$(4\pi v/m_h)^2 \approx 600$$

which is significant!

Durieux, MM, Salvioni. 2022

"Higgs self-coupling, … arguably the most important of them all!"

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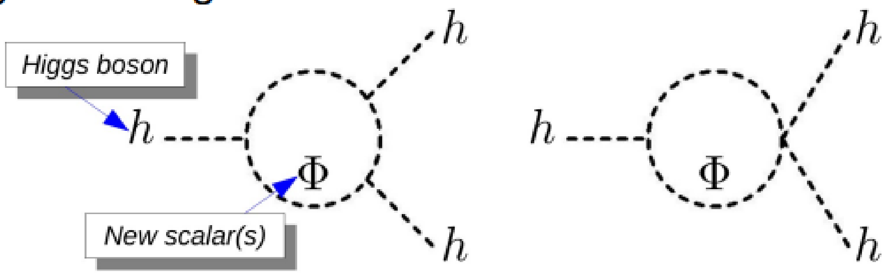
Physics case for an e⁺e⁻ collider at 500 GeV and above, Georg Weiglein, 3rd ECFA Workshop on e+e- Higgs, Electroweak and Top Factories, Paris, 10 / 2024

talk by G. Weiglein

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

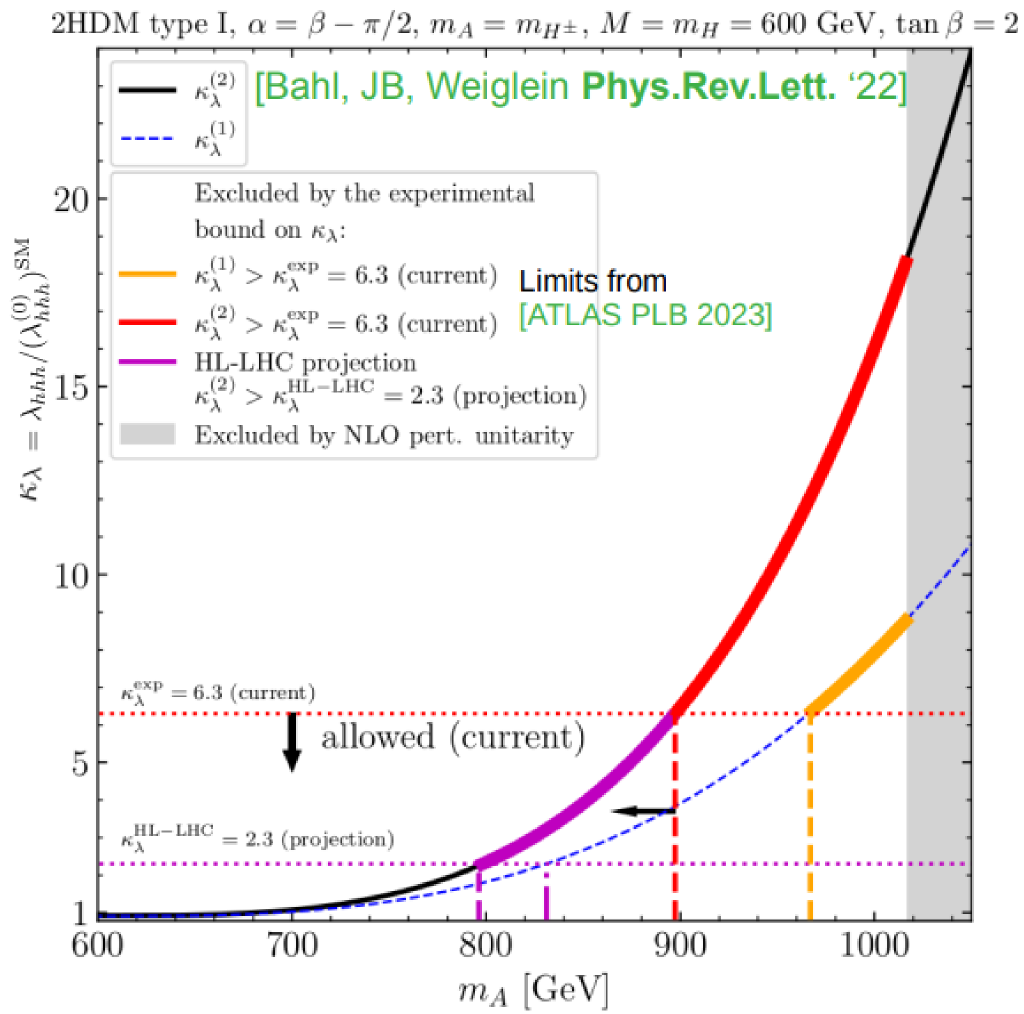


$$g_{hh\Phi\Phi} = -\frac{2(M^2 - m_\Phi^2)}{v^2}$$

- Comparing latest exp. bounds

$$-1.2 < \kappa_\lambda = \frac{\lambda_{hhh}}{(\lambda_{hhh}^{(0)})^{SM}} < 7.2$$ [ATLAS 2024]

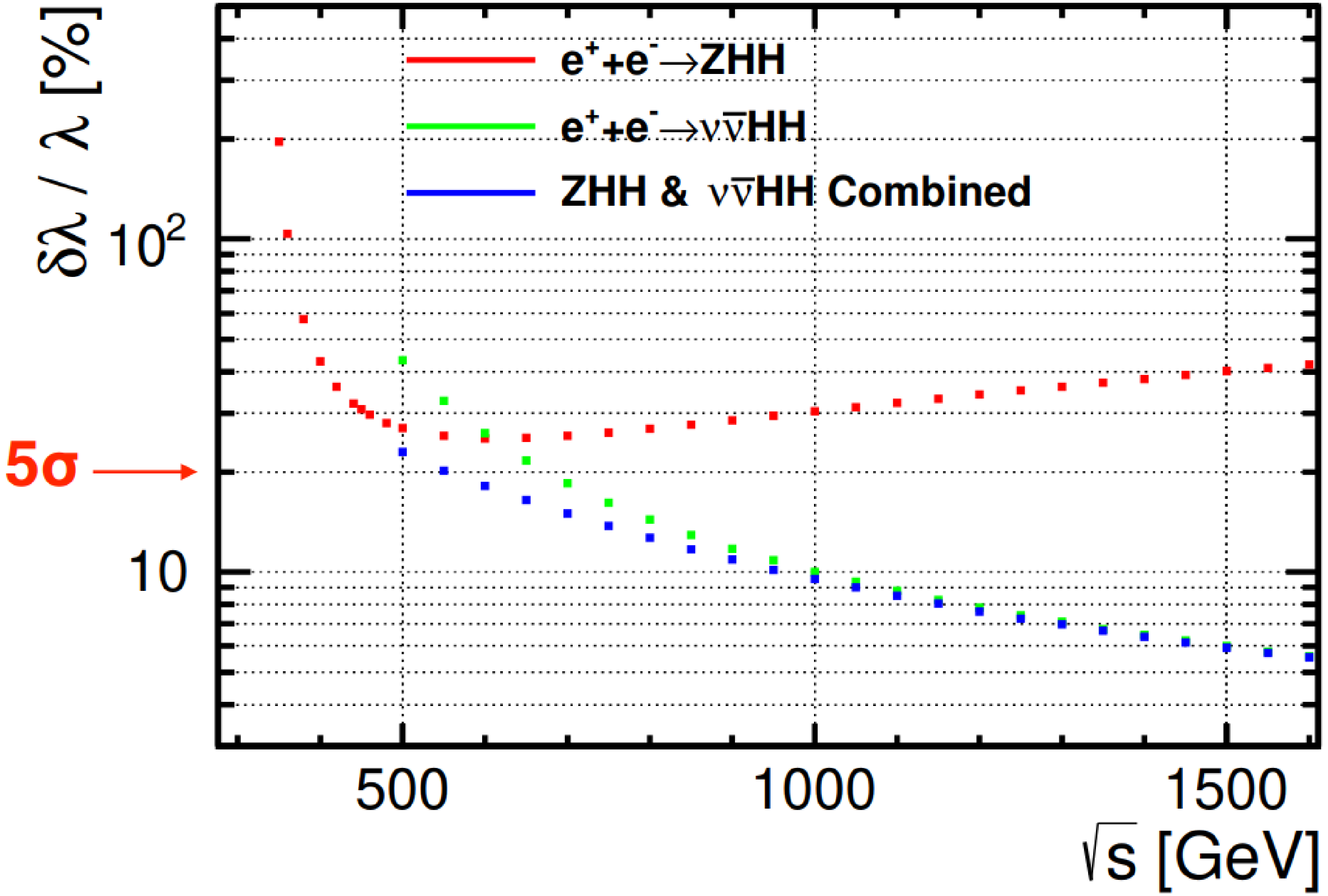
with precise theory predictions for λ_{hhh} provides a **powerful new tool to constrain BSM models** [Bahl, JB, Weiglein **Phys.Rev.Lett.** '22]



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

talk by J. Tian

- 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

Conclusions

The Higgs self-couplings are crucial for gaining experimental access to the Higgs potential!

Direct measurements with the best possible precision are needed!
CEPC and FCC-ee will not be able to tell us much about the Higgs potential beyond what we will know from the LHC

An e^+e^- Linear Collider with c.m. energy of at least 500 GeV can directly measure λ_{hhh} in the Zhh production processs: qualitative game-changer compared to capabilities of lower-energy Higgs factories

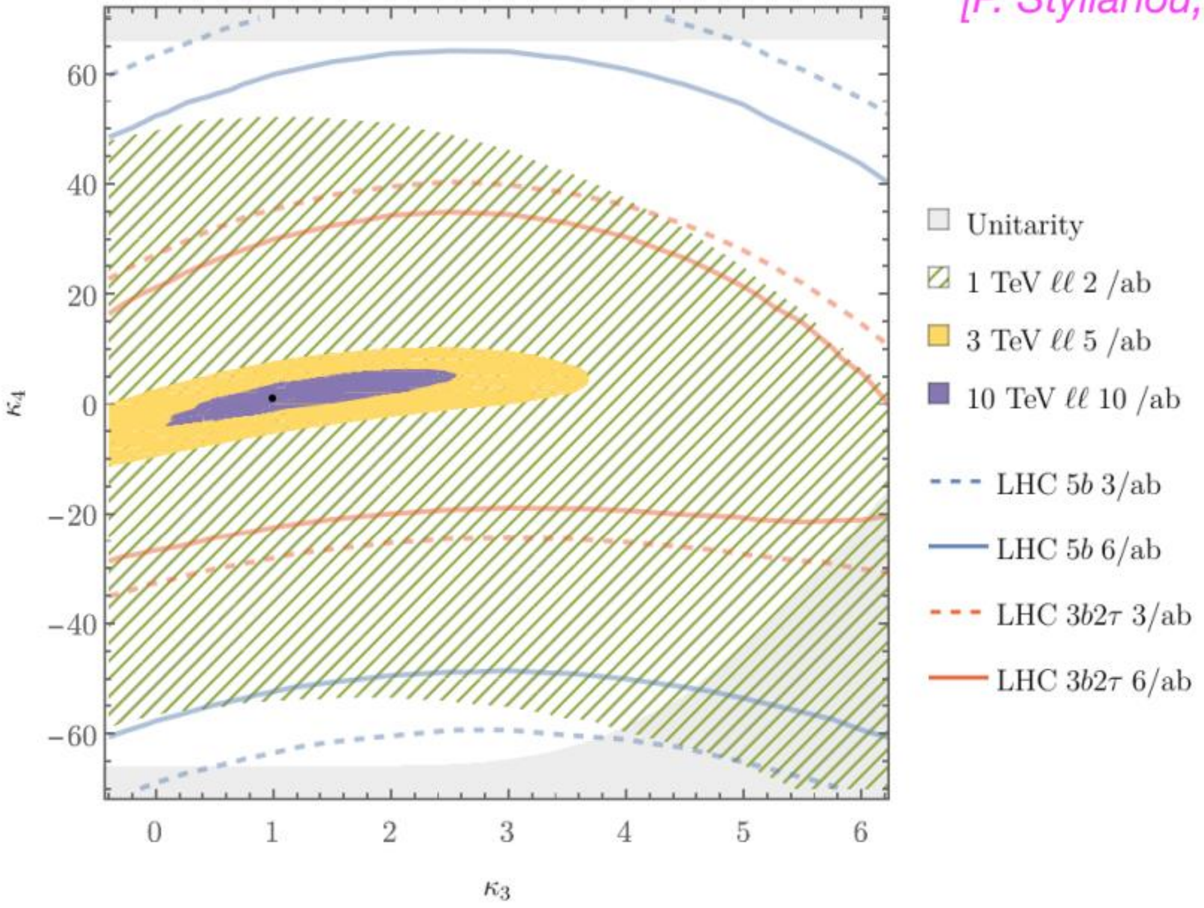
This, in combination with the significantly extended reach for BSM searches, is a strong motivation for designing a future e^+e^- Higgs factory such that an upgrade to at least 500 GeV is possible

The highest-energetic lepton colliders provide sensitivity for constraining the quartic Higgs self-coupling

talk by G. Weiglein

Triple Higgs production: HL-LHC vs. lepton colliders

[P. Stylianou, G. W. '24]



HL-LHC is competitive to 1 TeV lepton collider; higher-energetic lepton colliders have better sensitivity

talk by G. Weiglein

Precision: 2 fermions

SUMMARY

- **The FCC-ee will (also) be a tau factory**
- Very rich program! Exploit the **huge sample (10^{11}) of $e^+e^- \to Z \to \tau^+\tau^-$ decays** to measure the properties of the tau lepton, and derive **stringent tests of the SM**
  - Precise measurements of lifetime, mass and leptonic decays
  - Search for rare and LFV decays
  - Study of Tau Polarization
- Beyond tau properties, taus are a important part of the **Higgs and BSM searches** program: precise measurement of tau coupling, CP studies, dedicated searches
- Tau measurements pose **demanding detector requirements** on momentum resolution, on the knowledge of the vertex detector dimensions, on e/μ/π separation over the whole momentum range, and require fine granularity and high efficiency in the tracker and electromagnetic calorimeter
- Implementations of **tau reconstruction using full simulation** (traditional and ML-based) coming together for detailed systematic studies for detector optimization

talk by M. Cepeda

Krzysztof Mękała

separating u- and d-type jet events
based on Final State Radiation

Γ_{had} scales as:

$$\Gamma_{had} \sim (3c_d + 2c_u)$$

and $\Gamma_{had+\gamma}$ as:

$$\Gamma_{had+\gamma} \sim \frac{\alpha}{2\pi} f(y_{cut}) \left(3q_d^2 c_d + 2q_u^2 c_u\right)$$

The correction factor $f(y_{cut})$ to be determined for a given value of the resolution parameter y_{cut}.

We want to consider:

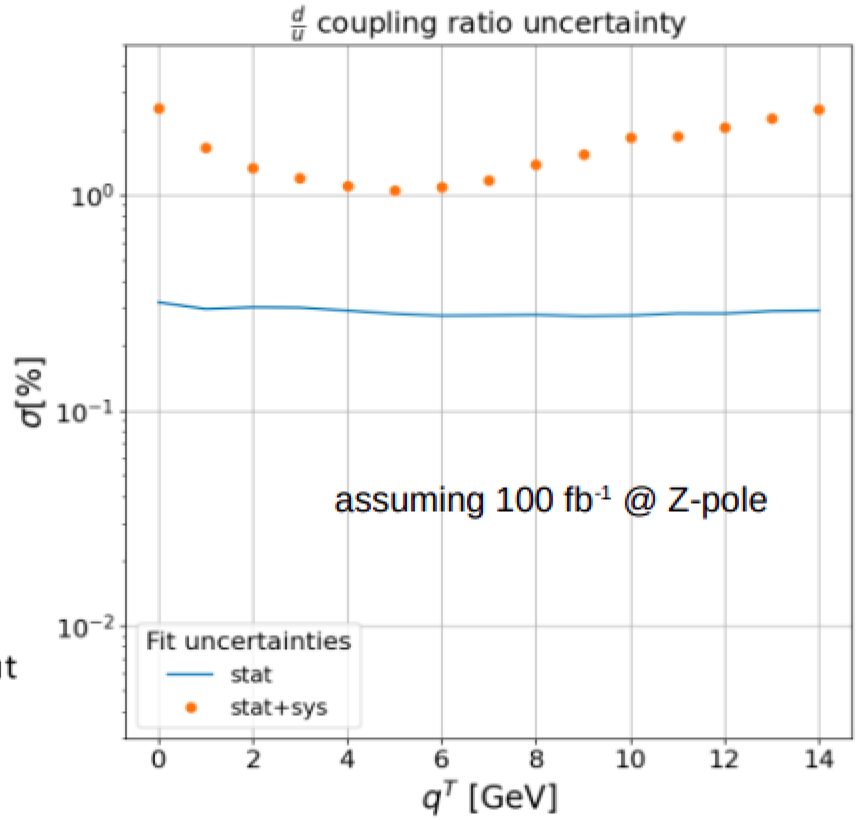
$$e^+e^- \to q\bar{q}(\gamma)$$

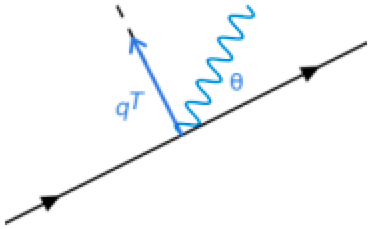
Experimentally measured photons can originate not only from the Final State Radiation but also from the Initial State Radiation, hadronisation and decays...

One may encounter the following issues:

- **Matrix Element** calculations – divergent or very slow for low photon-emission angles;
- **ISR structure functions** – good for small angles, a proper matching procedure needed;
- **FSR showers** – important for QCD emissions, may cause double-counting;
- **hadron decays** – photons to be included properly.

dedicated photon matching procedure essential !





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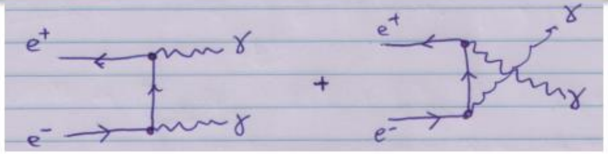
Precision: luminosity measurement

Transition from Bhabha to di-photon events

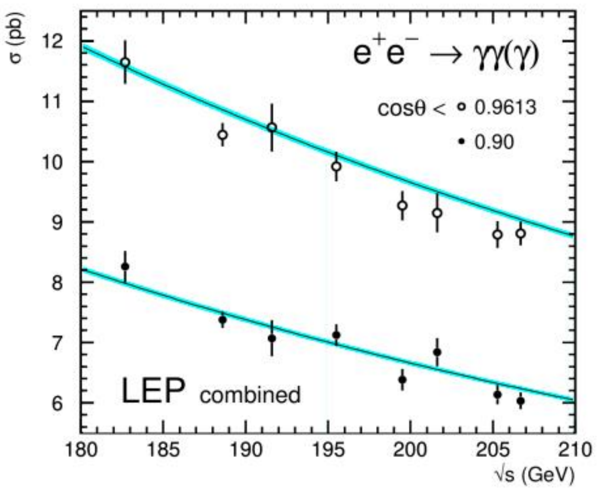
Di-Photon Basics



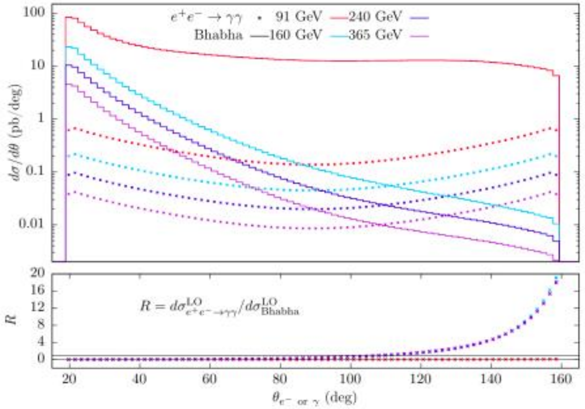
$$\frac{d\sigma^U_{\text{Born}}}{d|\cos\theta|} \approx \frac{2\pi\alpha^2}{s}\left(\frac{1+\cos^2\theta}{\sin^2\theta}\right)$$

Not so large. 40 pb at the Z (for 20°).

1302.3415



Here $\theta_\gamma > 16^\circ$ or $\theta_\gamma > 26^\circ$



$\sqrt{s}$ (GeV)	LO (pb)	NLO (pb)	w h.o. (pb)	Bhabha LO (pb)
91	39.821	41.043 [+3.07%]	40.870(4) [−0.43%]	2625.9
160	12.881	13.291 [+3.18%]	13.228(1) [−0.49%]	259.98
240	5.7250	5.9120 [+3.27%]	5.8812(6) [−0.54%]	115.77
365	2.4752	2.5581 [+3.35%]	2.5438(3) [−0.58%]	50.373

$20^\circ < \theta_\gamma < 160^\circ$, $x_2 > 0.5$ from 1906.08056

Why is $e^+e^- \to \gamma\gamma$ so attractive?

Focus here on experimental things. The hope and expectation is that theory will be able to keep up.

- Bhabhas look very **problematic** for high-precision absolute lumi. It was even not under control experimentally at LEP1. Beam-induced **EM deflections** affected the luminosity acceptance at the 0.1% level (see 1908.01704).
- Di-photon process should not be much affected.
- Di-photons much less sensitive to **polar angle metrology** than Bhabhas.
- Di-photons less sensitive to FSR than Bhabhas.
- More feasible now with modern calorimeters to do a **particle-by-particle reconstruction**. Likely easier with di-photons (no B-field effect).
- Current detector designs are arguably **over-designed for Bhabhas** with some compromises for overall performance especially for high energy photons in azimuthal and energy reconstruction, and perhaps for hermeticity.
- Di-photons at very low angle is **challenging!** - but gives significant added value to the assumed clean measurements in the tracker acceptance.

So let's design precision forward calorimetry for electrons AND photons inspired by various ideas (and avoiding some of the compromises) of related designs, CALICE, ILD, SiD, CMS-HGCAL, ALICE-FoCal, Fermi-LAT.

talk by G. Wilson

What about NP?

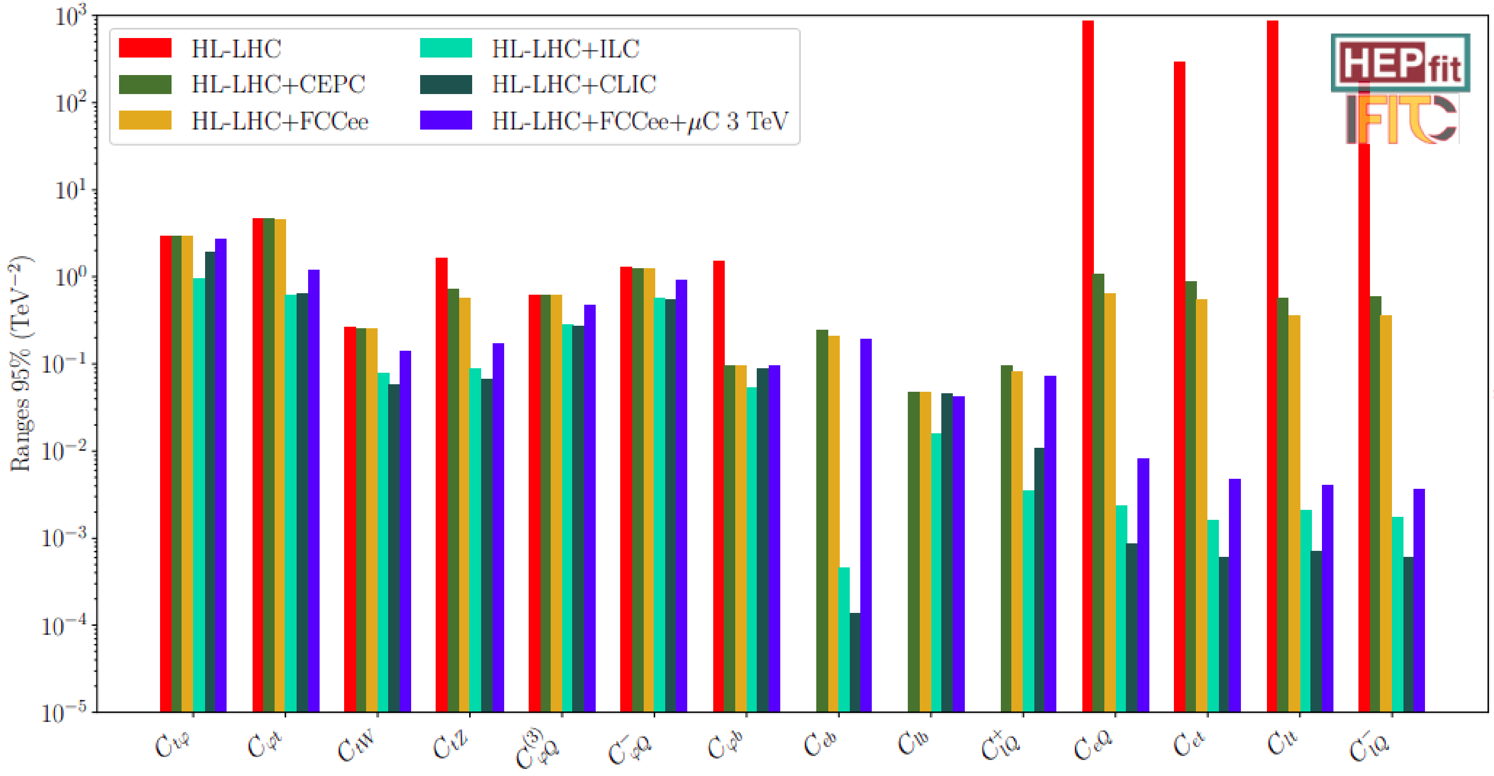
New physics already excluded?

- **For FCC: Λ scales of ≈ 1.7 TeV already excluded by other experiments?**
  - Not by LEP2 (Λ > 0.7 TeV ⇒ $\Delta\sigma_{NP} / \sigma_{SM}$ < 4 x 10^{-4})
    - But no problem if we wnt a luminosity precision ≳ 4 x 10^{-4} ...
  - qq→$\gamma\gamma$ excluded for Λ ≲7 TeV scales (reinterpreting a limit of M_S ≳ 10 TeV on GRW large extra-dimensions)
    - but this can only be strictly translated to the ee case assuming universal new physics effects (for instance, we could still have excited electrons at lower scales)
  - ee→$\gamma\gamma$ or $\gamma\gamma$→ee with high Q^2 at LHC ?
    - Not enough precision from ee initiated states, PDF uncertainties dominate ee high mass final states, elastic scattering in pp→ee affected by "proton dissociation" events, ...
- **Anyway, running first at the HZ threshold, for instance, would be an easy way to constrain any new QED physics at the Z pole**

talk by J. Alcaraz

Global: SMEFT

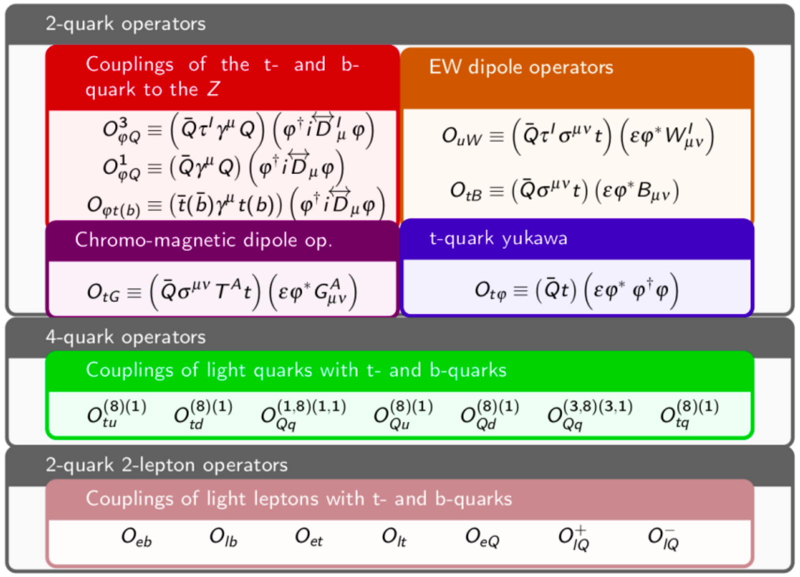
SMEFT fit for different colliders



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

ECFA Higgs/top/EW factory studies '24 24 marcel.vos@ific.uv.es

EFT basis for the top sector



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Studies in top sector

[talk by M. Vos]

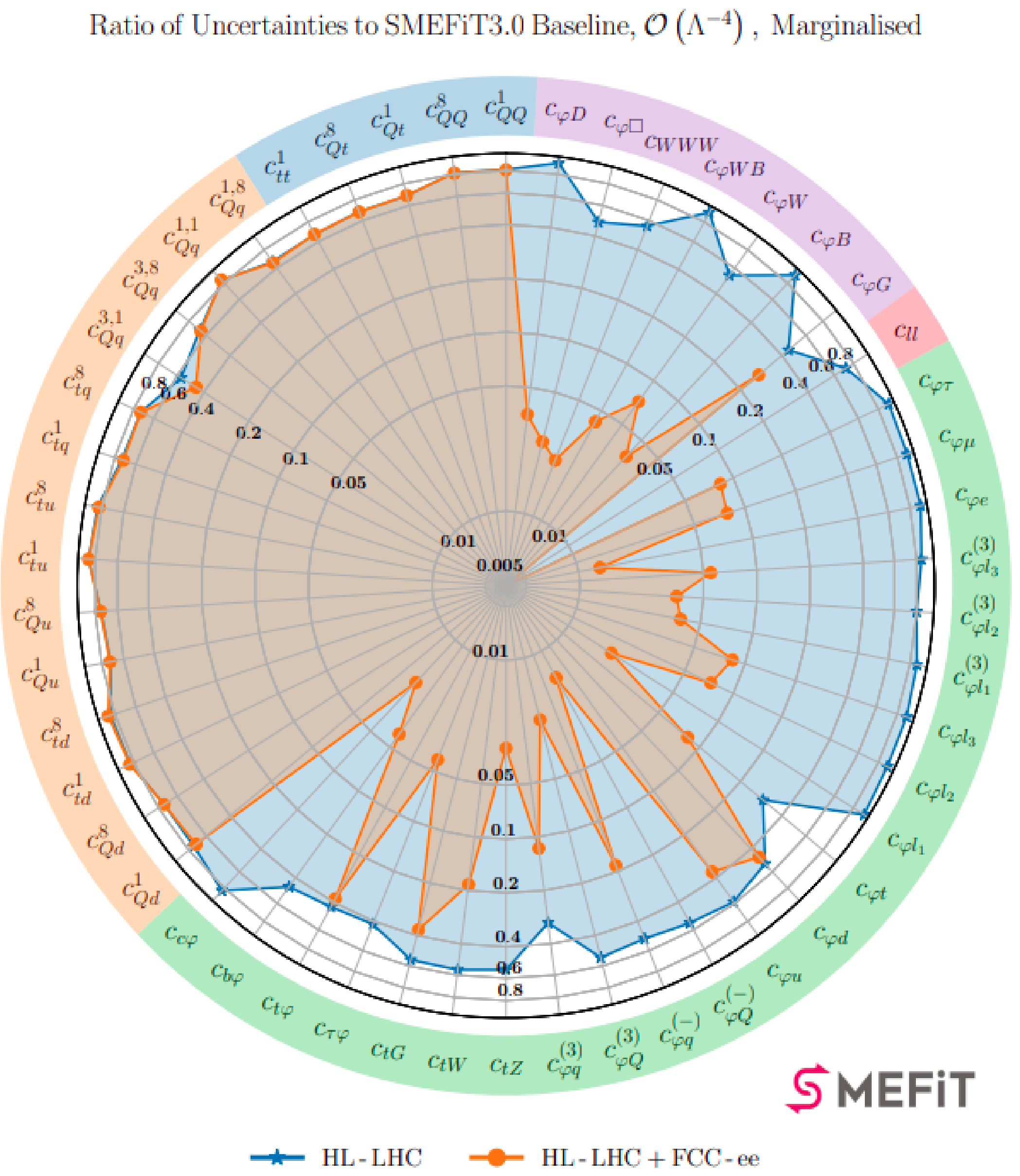
talk by J. ter Hoeve

Result: FCC-ee

Dataset input

- EWPOs at the Z-pole
- Light fermion pair prediction
- Higgstrahlung and VBF
- Gauge boson pair production
- Top-quark pair production
- Optimal Observables

Energy ($\sqrt{s}$)	$\mathcal{L}_{\text{int}}$ (Run time)	
	FCC-ee	CEPC
91 GeV (Z-pole)	300 ab^{-1} (4 years)	100 ab^{-1} (2 years)
161 GeV ($2\,m_W$)	20 ab^{-1} (2 years)	6 ab^{-1} (1 year)
240 GeV	10 ab^{-1} (3 years)	20 ab^{-1} (10 years)
350 GeV	0.4 ab^{-1} (1 years)	-
365 GeV ($2\,m_t$)	3 ab^{-1} (4 years)	1 ab^{-1} (5 years)



talk by M. Peskin

An observable that is very sensitive to ζ_Z is the beam polarization asymmetry in e+e- -> ZH.

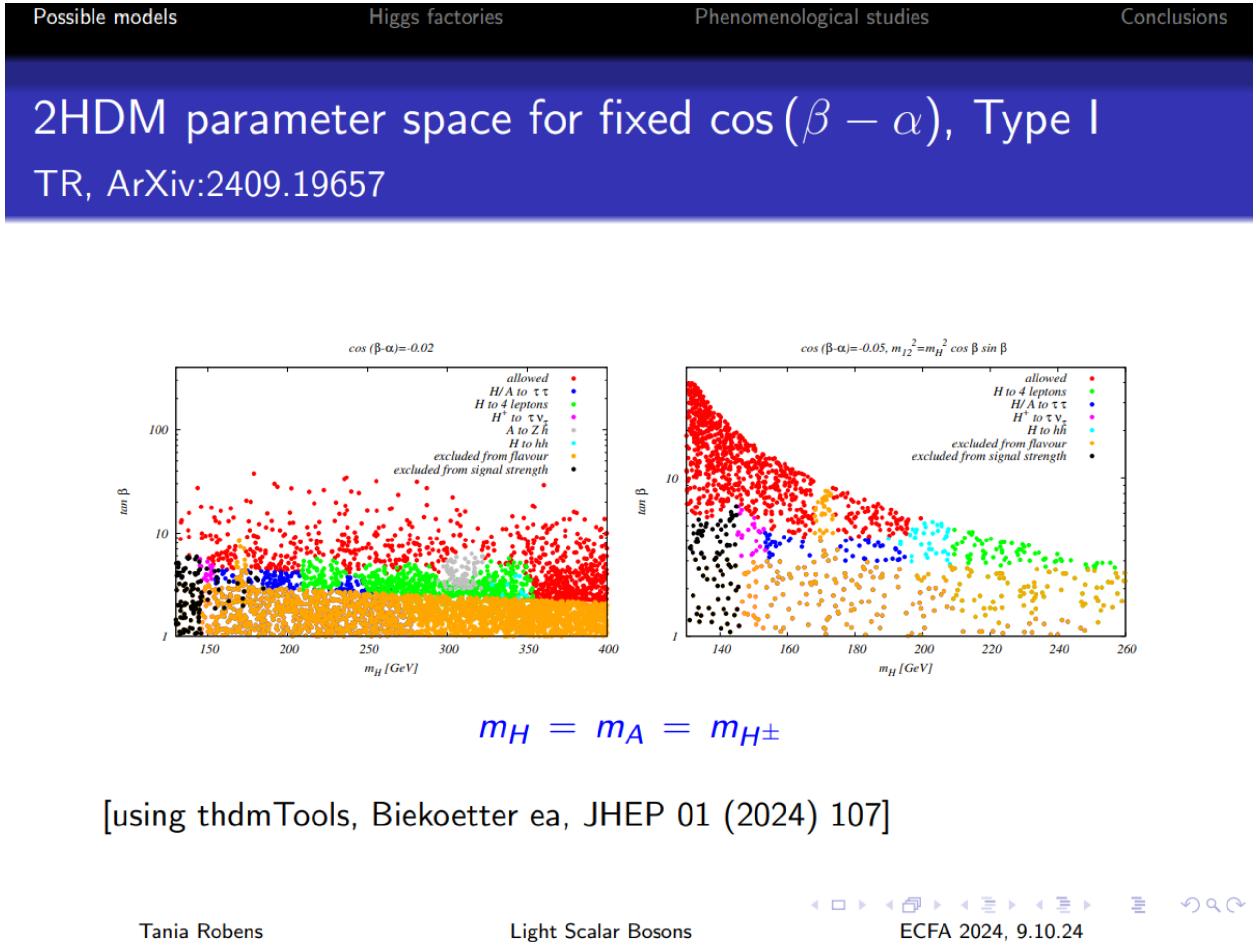
In general, SMEFT operators are chiral and so corrections due to these operators are sensitive to beam polarization. Then this can potentially be used as a handle to improve the determination of SMEFT parameters. This is true in the determination of the Higgs couplings, and also in the determination of the VWW triple gauge couplings.

In both analyses, high e- beam polarization compensates about a factor 2.5 in luminosity.

In the κ method, projections are independent of beam polarization. This already indicates that this method is not general or model-independent.

Searches: exotic scalars

- The scalar sector can be extended in many ways: singlets, doublets, triplets...
- Several constraints coming from theory (e.g. vacuum stability) and experiment (e.g. properties of the 125-GeV state)



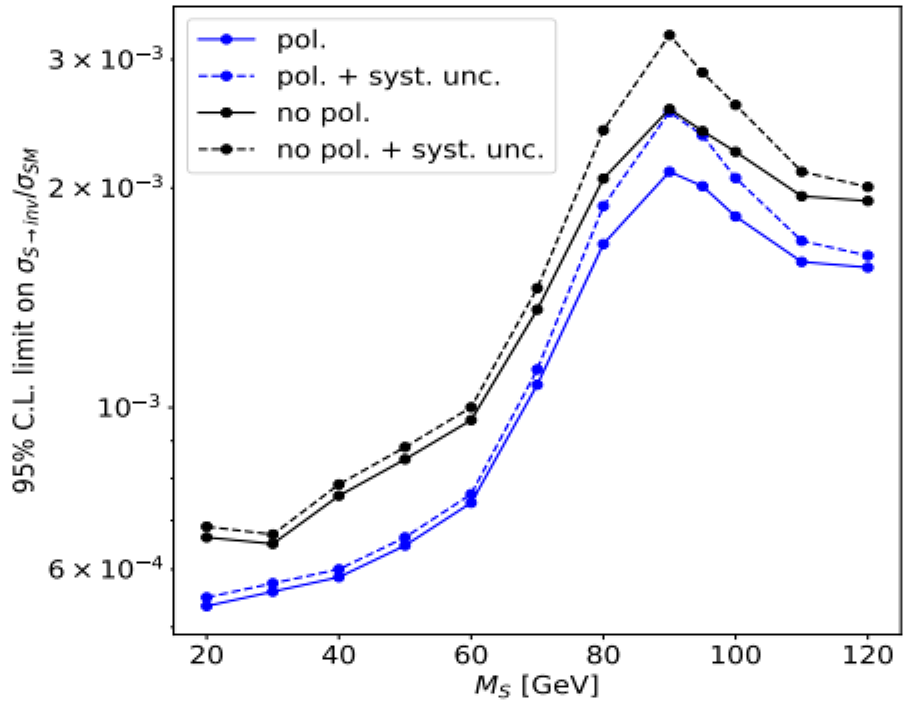
talk by T. Robens

$S \to$ invisible

Results

Kamil Zembaczyński (University of Warsaw)

Cross section limits for $\sigma(e^+e^- \to Z\,S) \cdot BR(S \to \mathrm{inv})$
for H-20 scenario and unpolarized running with the same luminosity



Visible impact of systematic uncertainties

theory predictions: 0.2% for e^+e^-
1% for $\gamma e^\pm$ and $\gamma\gamma$

sample normalization: 0.2% for LR and RL
0.5% for LL and RR

Significant impact for $M_S \sim M_Z$

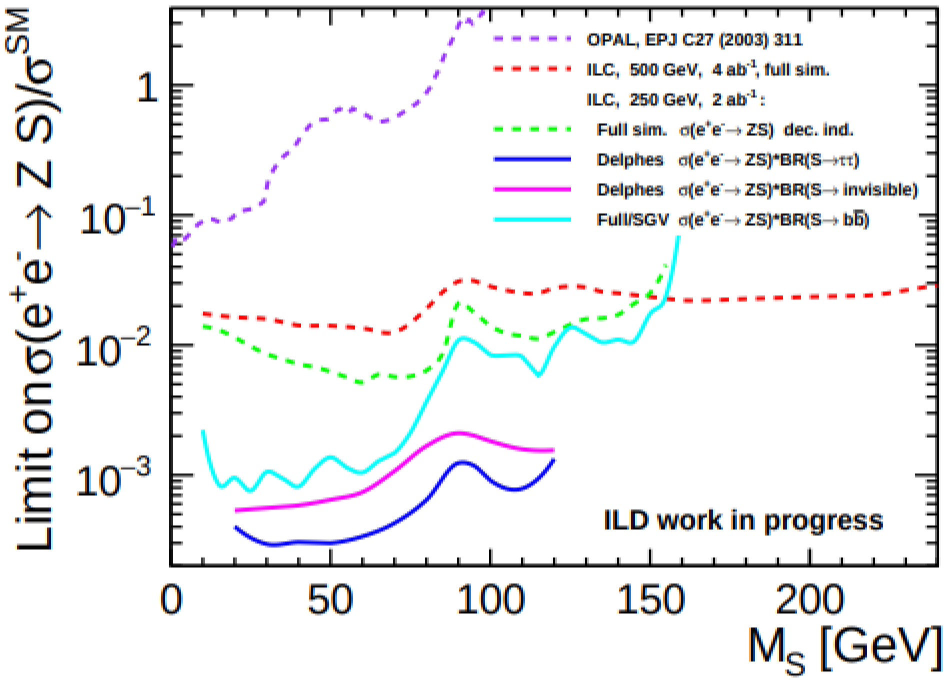
talk by A.F. Żarnecki

$S \to b\bar{b}$

Results

Bartłomiej Brudnowski (University of Warsaw)
supervised by María Teresa Núñez Pardo de Vera (DESY)

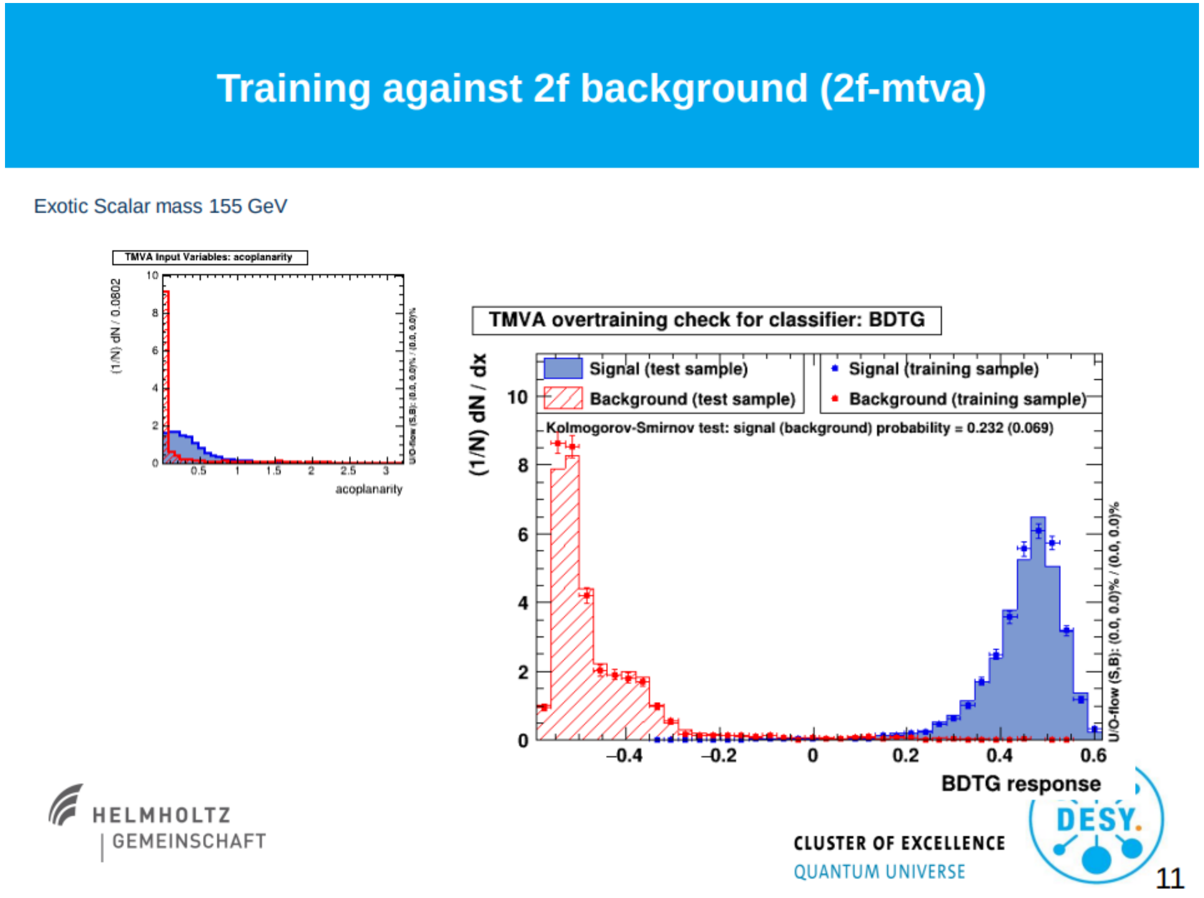
Cross section limits for $\sigma(e^+e^- \to Z\,S) \cdot BR(S \to b\bar{b})$
compared with previously presented results

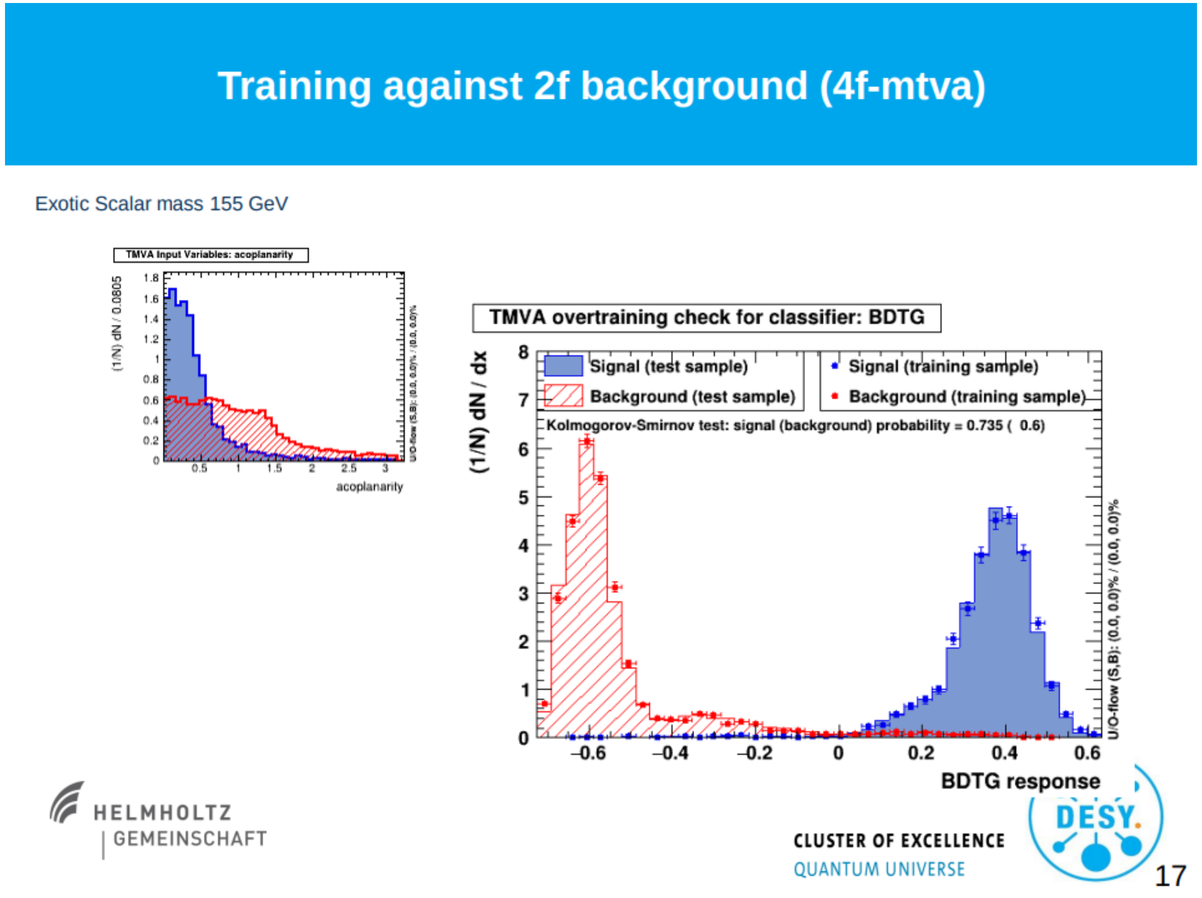


Order of magnitude improvement in the low mass domain, compared to decay independent search.

Limited by statistics of leptonic Z decays...

talk by A.F. Żarnecki





Full simulation search in di-muon final state at ILD

talk by T. Núñez

Searches: heavy neutral leptons

An interesting option providing a DM candidate, baryon asymmetry, neutrino masses... (depending on the model)

HNL: Dirac vs. Majorana and pseudo-Dirac properties

Symmetry-protected benchmark models (BMs) contain pseudo-Dirac HNLs

With care some properties can be correctly approximated by simpler BMs

Dirac BM

- ✓ Correct production cross section
- ✓ Correct decay width
- ϟ No LNV — $R_{ll} = 0$
- ϟ Massless SM neutrinos

Majorana BM

- ✓ Correct production cross section
- ϟ Wrong decay width
- ✓ Lepton number violation (LNV)
- ϟ Generically too much LNV — $R_{ll} = 1$
- ϟ Generically too heavy SM neutrinos

Displaced vertex searches for Dirac HNLs

Generically correct

Prompt searches for LNV with Majorana HNLs

- Generically the bounds are too strong
- In many cases no bounds can be extracted
- Can be correct for some parameter points

→ Model depended reinterpretation necessary

Detectable pseudo-Dirac HNL

- Finite LNV — $0 < R_{ll} < 1$
- Tiny mass splitting — $\mathcal{O}(\text{meV})$
- Heavy neutrino-antineutrino oscillations ($N\bar{N}$Os)
- Damped oscillations due to decoherence

Viable alternatives

- Enhanced production e.g. W'-models
- Fine tuning

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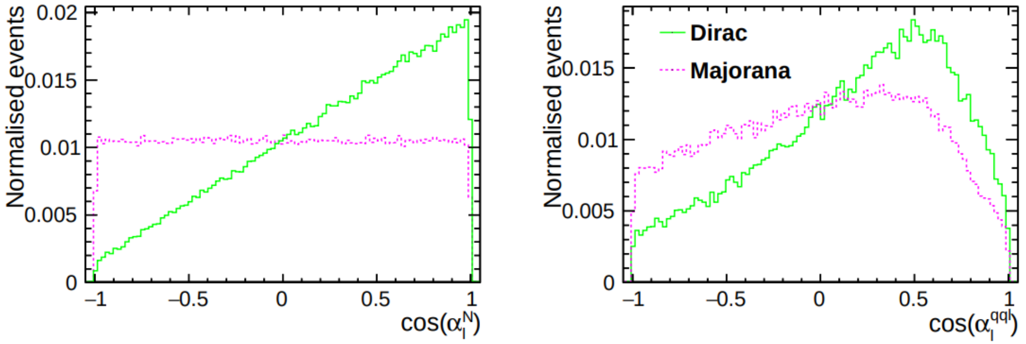
talk by J. Hajer

Angular distributions used for model discrimination

Are there any discriminant variables?

Lepton emission angle in the N rest frame:



generator vs. detector

CLIC 3 TeV

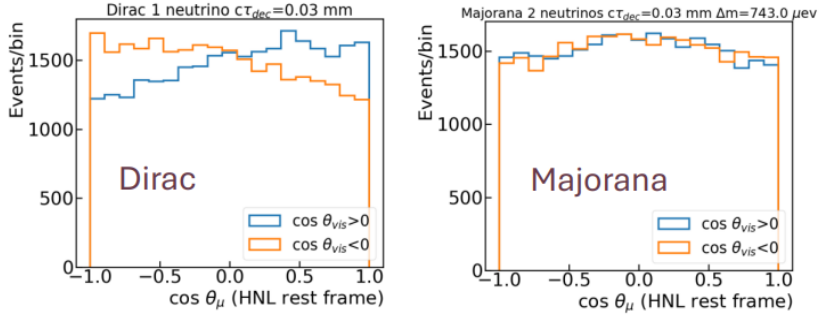
LC talk by K. Mękała

The analysis – Dirac/Majorana limits

1) Toy models used to define variables separating Dirac/Majorana:
- Pure Dirac model
- Majorana model: two Majorana neutrinos with Δm mass split

2) Once the variables are definded: arXiv 2408.01389
- study distributions of discriminant variables for SPSS model in parameter space defined by $(\Gamma, \Delta m)$

$\cos(\theta_\mu)$
(HNL rest frame)



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FCC talk by N. Valle

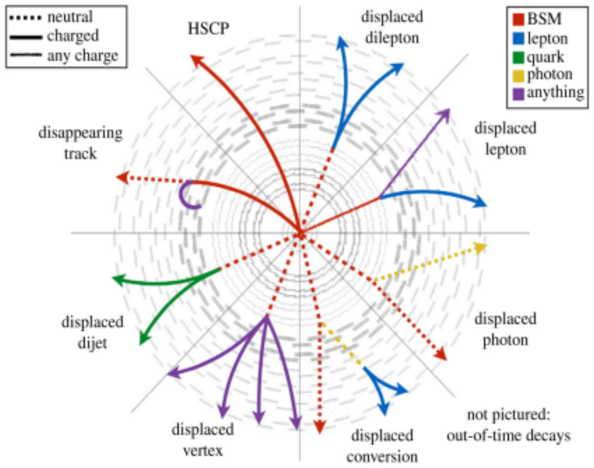
Searches: long-lived particles

Motivation

Particles with macroscopic lifetimes naturally appear in numerous BSM models

Three main mechanisms are responsible for that...

	1810.12602	Small coupling	Small phase space	Scale suppression
SUSY	GMSB			✓
	AMSB		✓	
	Split-SUSY			✓
	RPV	✓		
NN	Twin Higgs	✓		
	Quirky Little Higgs	✓		
	Folded SUSY		✓	
DM	Freeze-in	✓		
	Asymmetric			✓
	Co-annihilation		✓	
Portals	Singlet Scalars	✓		
	ALPs			✓
	Dark Photons	✓		
	Heavy Neutrinos			✓



https://doi.org/10.1098/rsta.2019.0047

Multiple LLP searches at the LHC, sensitive to high masses and couplings

- **complementary region** could be probed at e^+e^- **colliders** (**small masses, couplings, mass splittings**)
- typical properties of feebly interacting massive particles (FIMPs) → challenging for hadron colliders

talk by J. Klamka

detector-oriented study vs. "proof of concept"

Strategy

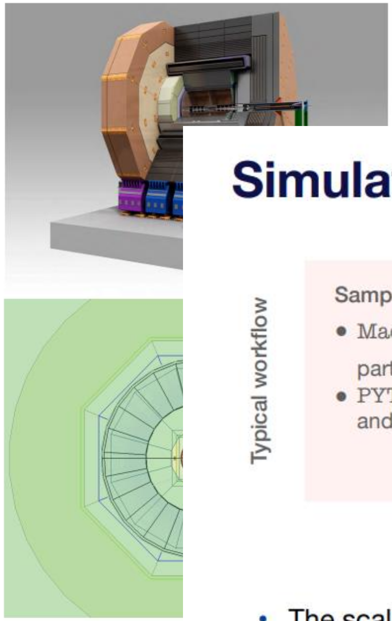
ILD especially promising with a TPC as the main tracker

→ we want to investigate experimental aspects

→ study based on full simulation

- Study such challenging signatures from the **experimental perspective**

  → experimental/kinematic properties, not points in a model parameter space
- Focus on a generic (and most challenging) case – two tracks from a displaced vertex
- No other assumptions about the final state, approach **as general as possible**



[ILC talk by J. Klamka]

[FCC talk by M. Vande Voorde]

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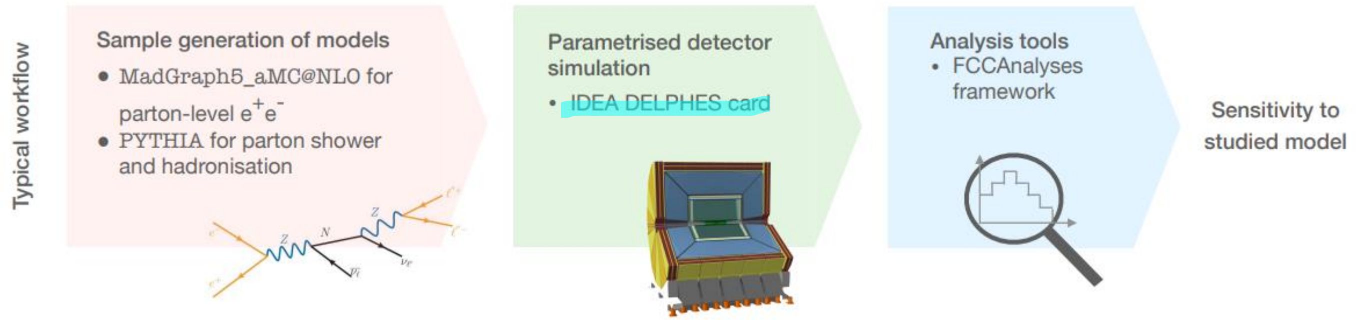
Simulation and analysis of long-lived scalars @ FCC-ee



- The scalars can be simulated with the MadGraph5 HAHM model (arXiv:1312.4992, arXiv:1412.0018)
- Simulation of background processes
  - SM processes in the Winter2023 campaign
    - Centrally produced samples within the FCCAnalyses framework
  - Sample generation with Pythia8 or Pythia6 + Wizard
  - $37 \cdot 10^7$ raw WW events, $56 \cdot 10^6$ raw ZZ events and $32 \cdot 10^6$ raw ZH events (all with inclusive decays)

ECR activities

- "By the time a future collider is built, today’s ECRs will be the ones leading it."
- 2 sessions (a lunch break + just before dinner)
- an introductory talk and a lot of discussion mostly by young people

(but some senior scientists really want to be included...)

- follow-up: ECFA Plenary Meeting in November

ECR attitude

We want *a** collider *soon***.

* – if it's a *very bad* proposal, some people might leave the field

** – to be defined

not to be forgotten: stable funding, career planning, sustainability

Summary

- Productive event with a lot of inputs and discussions
- Higgs boson, top quark, EFT, BSM...
- Tense atmosphere (FCC vs. ILC)
- ECRs want to be included in the process!
- Final report to be submitted by March 31st (talk by A. Robson)