Experimental Higgs Studies @ FCC-ee

- **Outline**
  - Basics of Higgs studies @ FCC-ee
  - Discussion about performance and systematic uncertainties
  - Projected results and discussion
  - Conclusion and outlook

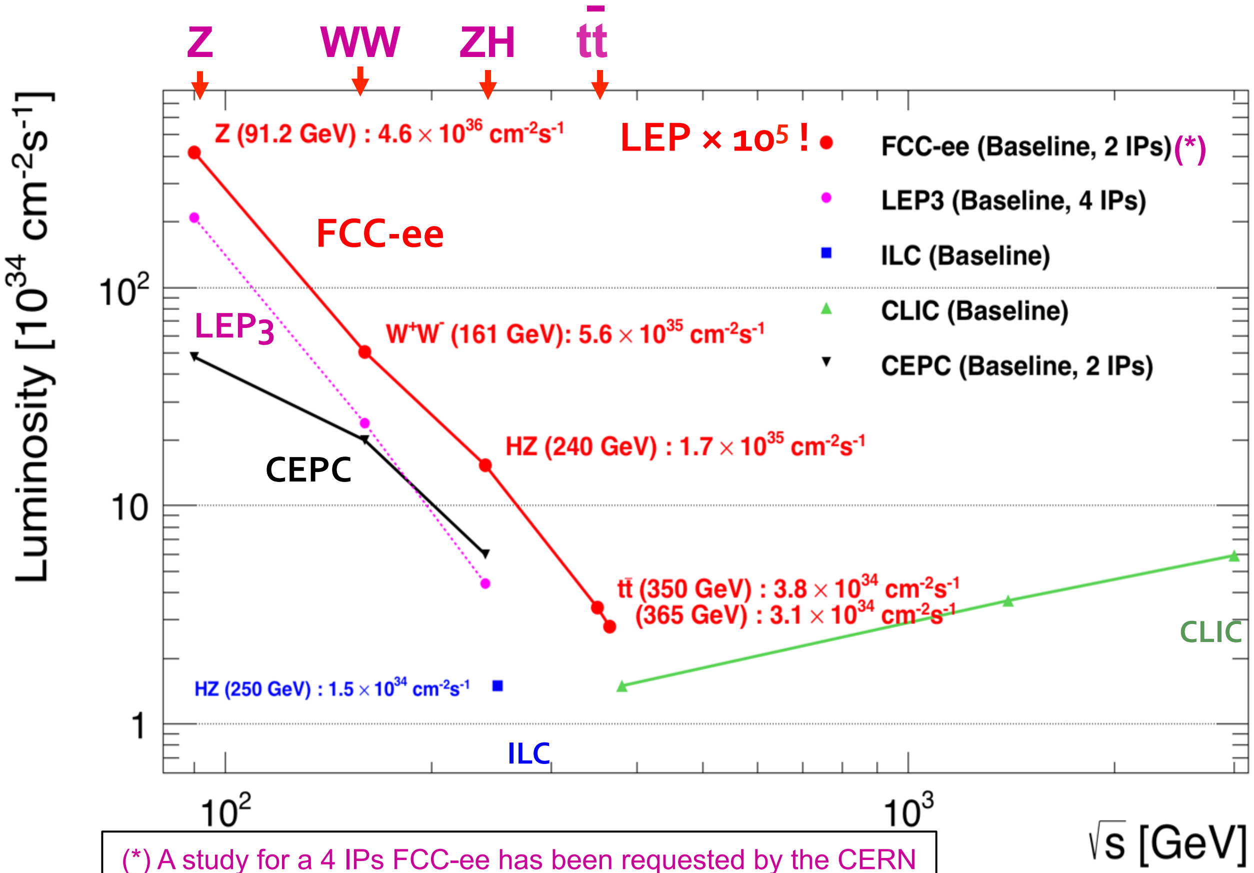
On behalf of the FCC Collaboration

Generic references
- FCC CDR Volume 1, Physics Opportunities, https://fcc-cdr.web.cern.ch/
- FCC CDR Volume 2, The Lepton Collider, https://fcc-cdr.web.cern.ch/
- Physics case of FCC-ee, arxiv:1308.6176 + FCC CDR
- Prospective Studies for LEP3 with the CMS detector, arxiv:1208.1662
- Physics case for the 250 GeV ILC, arxiv:1710.07621, 1708.08912
- Higgs physics at CLIC, arxiv:1608.07538
- Standard Model theory for the FCC-ee, arxiv:1809.01830
- Strategies for Higgs self coupling discovery and measurement, arxiv:1809.10041

Basics of Higgs studies@FCC-ee

Energies and luminosities at the FCC-ee

- The FCC-ee offers the largest luminosities in the 88 → 365 GeV √s range



(*) A study for a 4 IPs FCC-ee has been requested by the CERN management and is foreseen to be conducted this year (2019)

- Ultimate precision:
  - 100 000 Z / second (!)
    - 1 Z / second at LEP
  - 10 000 W / hour
    - 20 000 W at LEP
  - 1 500 Higgs bosons / day
    - 10 times ILC
  - 1 500 top quarks / day
    - in each detector

... in a clean environment:

- No pileup
- Beam backgrounds under control
- E,p constraints

PRECISION and SENSITIVITY to rare or elusive phenomena

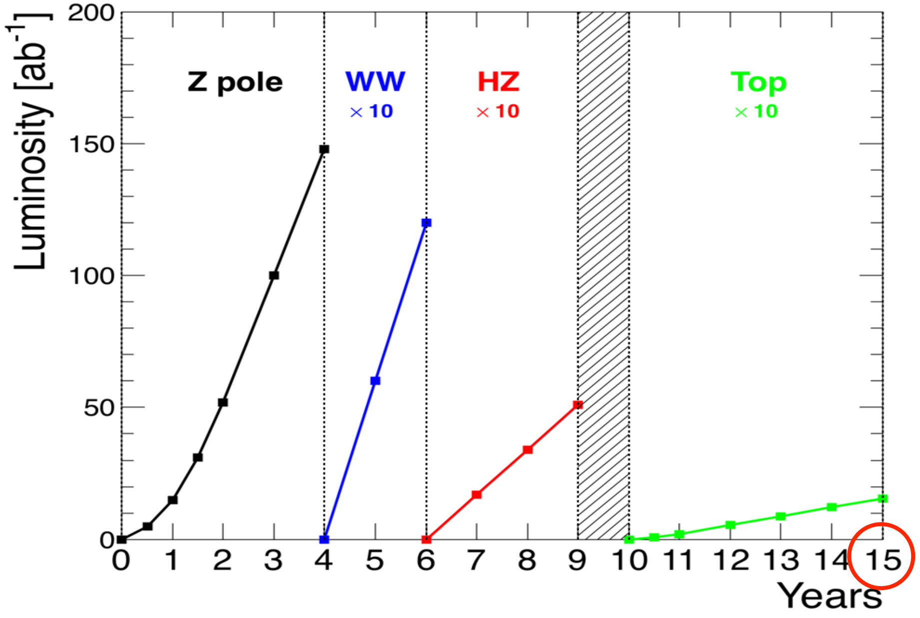
- The FCC-ee precision for the study of the Higgs boson is multiplied by the presence of the four heaviest SM particles (Z, W, H, and top) in its energy range

The FCC-ee operation model and statistics

- 185 physics days / year, 75% efficiency, 10% margin on luminosity

Working point	Z, years 1-2	Z, later	WW	HZ	$t\bar{t}$ threshold…	… and above
√s (GeV)	88, 91, 94		157, 163	240	340 – 350	365
Lumi/IP (10^{34} cm^{-2}s^{-1})	100	200	25	7	0.8	1.4
Lumi/year (2 IP)	24 ab^{-1}	48 ab^{-1}	6 ab^{-1}	1.7 ab^{-1}	0.2 ab^{-1}	0.34 ab^{-1}
Physics goal	150 ab^{-1}		10 ab^{-1}	5 ab^{-1}	0.2 ab^{-1}	1.5 ab^{-1}
Run time (year)	2	2	2	3	1	4

Total : 15 years



Event statistics	√s precision
5×10^{12} $e^+e^- \to Z$	100 keV
10^8 $e^+e^- \to W^+W^-$	300 keV
10^6 $e^+e^- \to HZ$	2 MeV
10^6 $e^+e^- \to t\bar{t}$	5 MeV

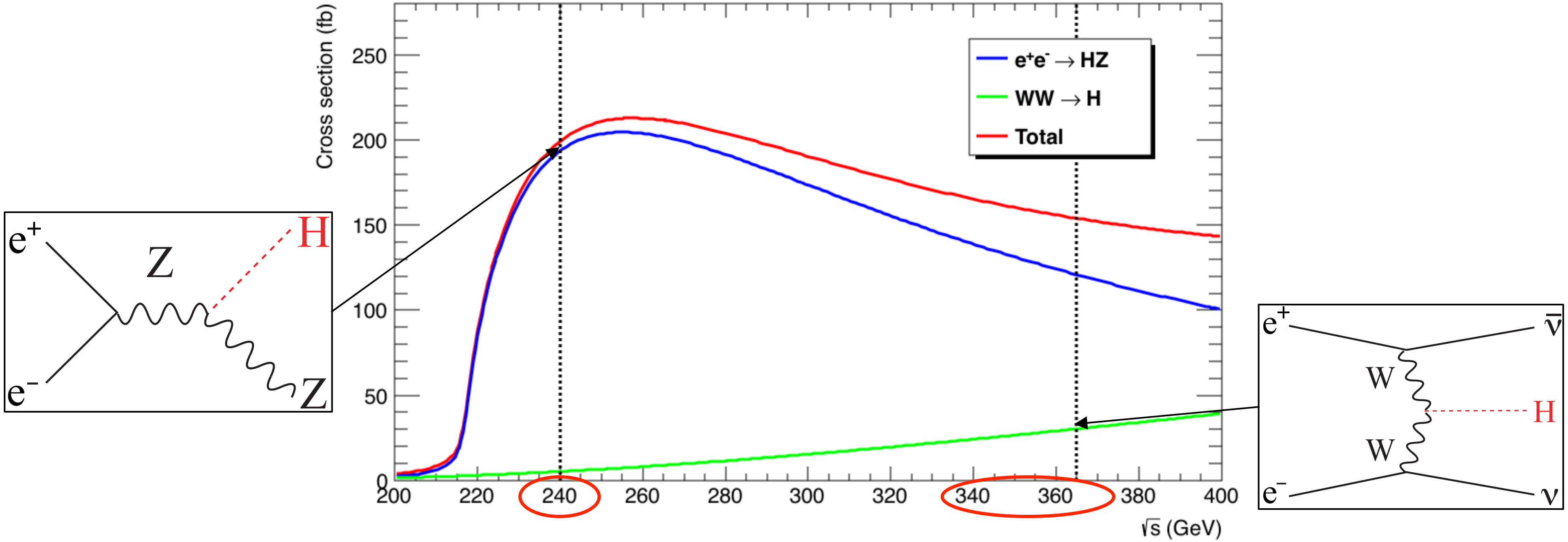
Transverse polarization (E_{beam} calib.),
No longitudinal polarization.

Possible scenario with 4 interaction points…

- Possibly with twice the instantaneous luminosity (to be confirmed)
  - Same statistics at the Z pole, at the WW threshold, and at the tt threshold …
    - … within 3.5 years instead of seven
  - Use the 3.5 saved years at 240 and 365 GeV …
    - … where Higgs (and top) measurements are statistically limted
    - Accumulate 12 ab^{-1} at 240 GeV in 3.5 years
      - ➨ Instead of 5 ab^{-1} in 3 years
    - Accumulate 5.3 ab^{-1} at 365 GeV in 8 years (+0.2 ab^{-1} at 340-350 GeV)
      - ➨ Instead of 1.5 ab^{-1} in 4 years (+0.2 ab^{-1} at 340-350 GeV)
  - Optimized for the first measurement of the Higgs self-coupling @ FCC-ee (see later)
- In this talk, expected precisions are shown in both configurations

The FCC-ee as a Higgs factory

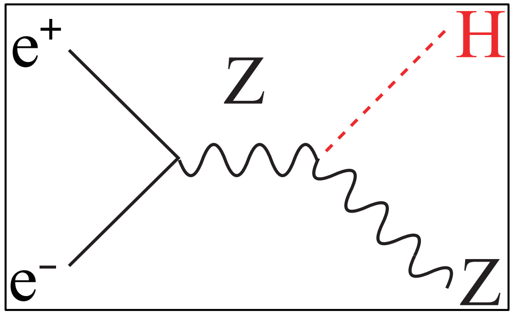
- Higgsstrahlung ($e^+e^- \rightarrow ZH$) event rate largest at $\sqrt{s}$ ~ 240 GeV : σ ~200 fb



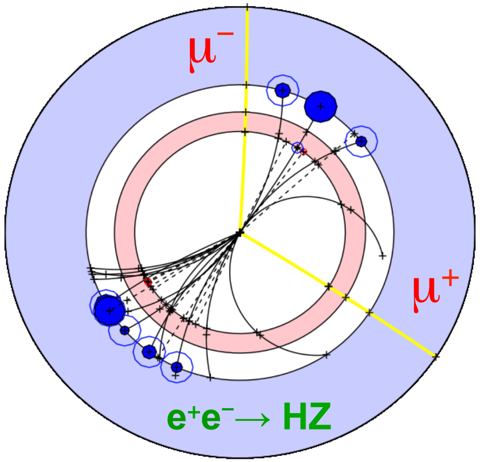
- $(2.4\times)\ 10^6$ $e^+e^- \rightarrow ZH$ events with 5 (12) ab^{-1}
  - Target : (few) per-mil precision, statistics-limited.
  - Complemented with 200k (700k) events at $\sqrt{s}$ = 350 – 365 GeV
    - Of which 30% in the WW fusion channel (useful for the Γ_H precision)

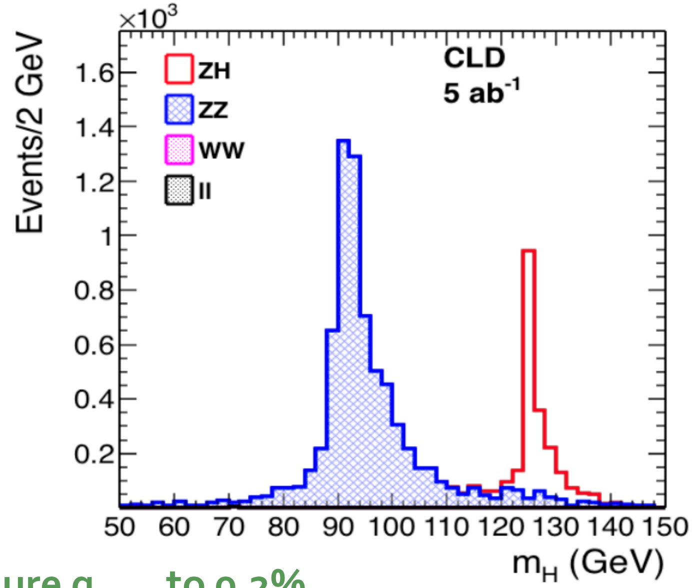
Absolute coupling and width measurement

❑ Higgs tagged by a Z, Higgs mass from Z recoil



$$m_H^2 = s + m_Z^2 - 2\sqrt{s}(E_+ + E_-)$$

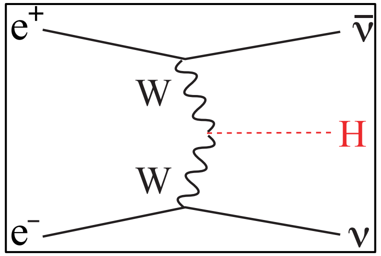




- Total rate ∝ g_{HZZ}^2 → measure g_{HZZ} to 0.2%
- ZH → ZZZ final state, rate ∝ g_{HZZ}^4 / Γ_H → measure Γ_H to a couple %
- ZH → ZXX final state, rate ∝ $g_{HXX}^2 g_{HZZ}^2 / \Gamma_H$ → measure g_{HXX} to a few per-mil / per-cent
- Empty recoil = invisible Higgs width; Funny recoil = exotic Higgs decays

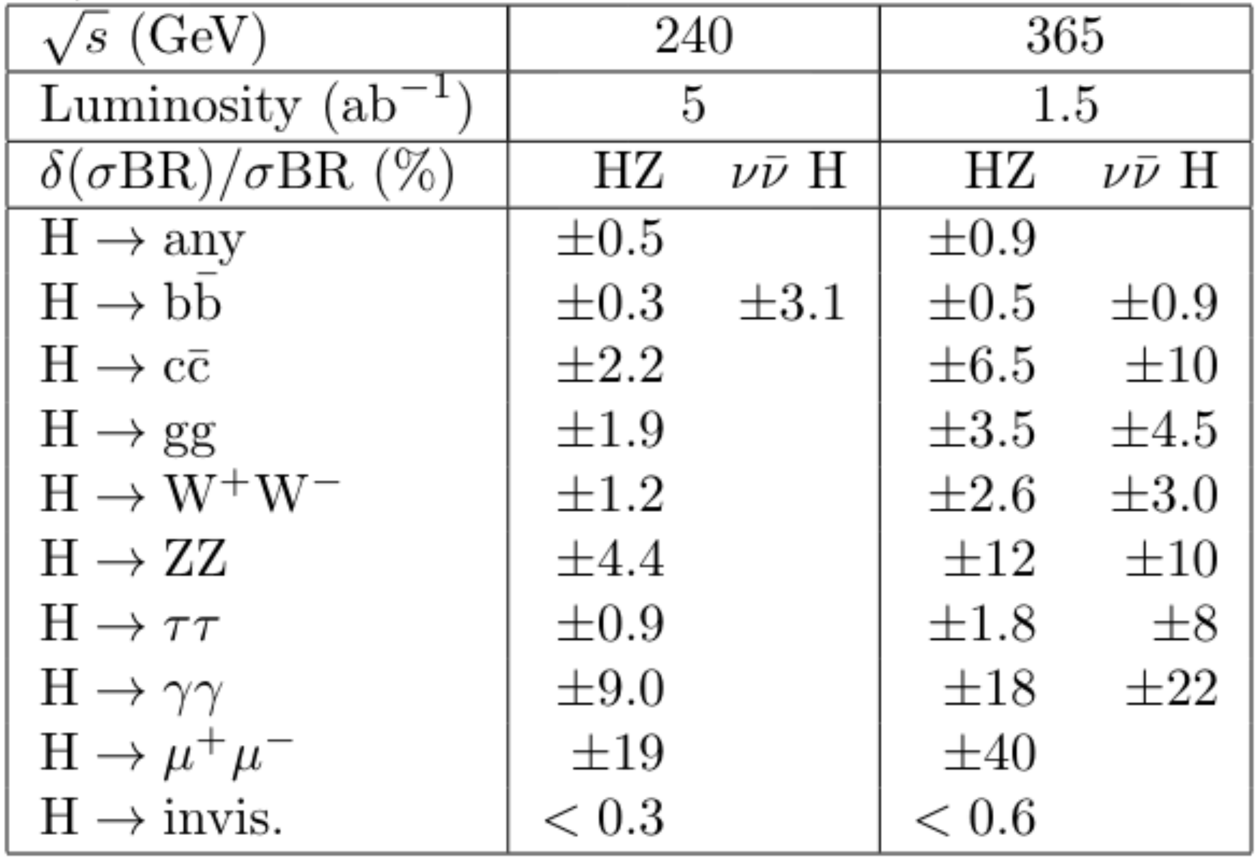
❑ Added value from WW fusion (mostly at 350-365 GeV)

- Hνν → bbνν final state, rate $R_2 \propto g_{HWW}^2 g_{Hbb}^2 / \Gamma_H$
  - bbνν / (Zbb × ZWW) ∝ g_{HZZ}^4 / Γ_H → Γ_H to ~1 %
- Hνν → WWνν final state, rate $R_1 \propto g_{HWW}^4 / \Gamma_H$ → g_{HWW} to a few per mil



Statistical precision with 2 IPs

- **Obtained with 5 ab^{-1} at 240 GeV, and 1.5 ab^{-1} at 365 GeV**



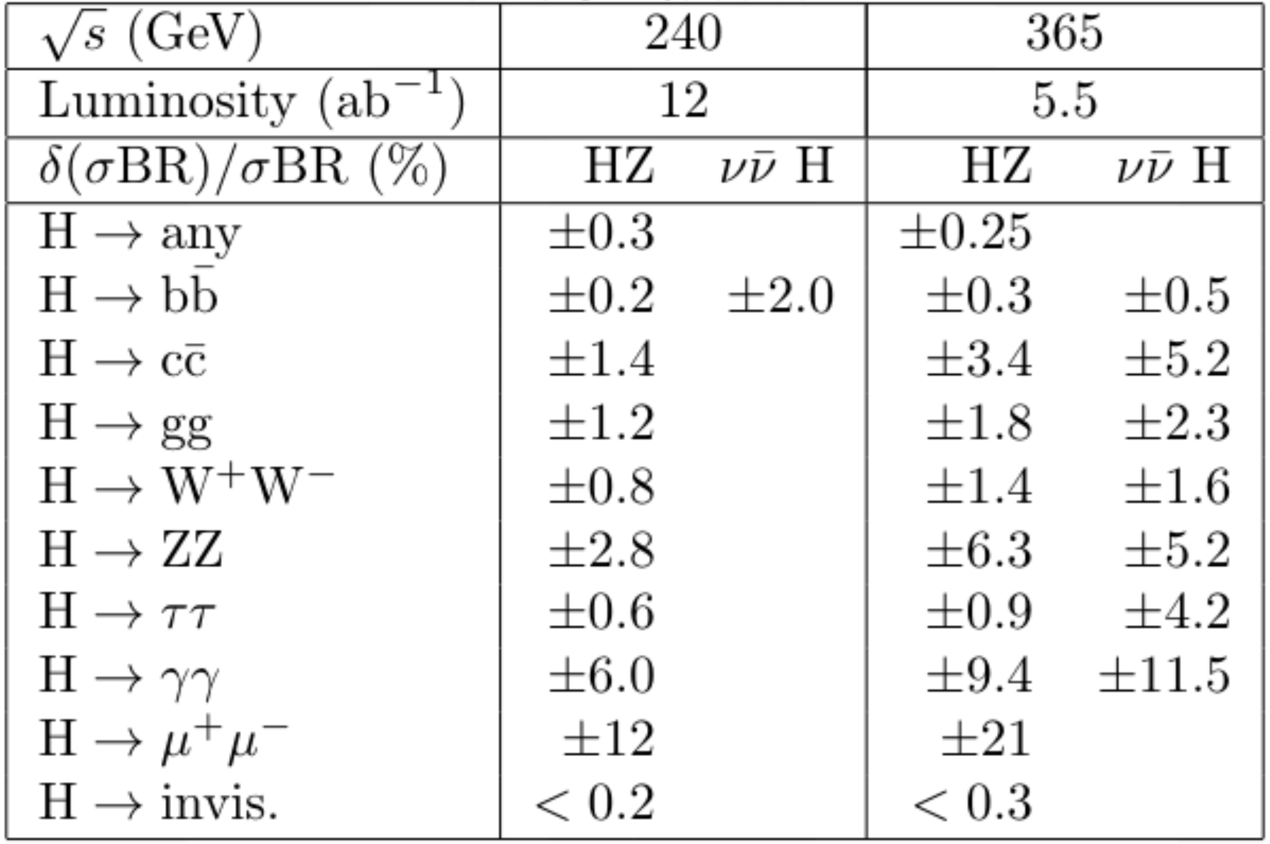
$\sqrt{s}$ (GeV)	240		365	
Luminosity (ab^{-1})	5		1.5	
$\delta(\sigma\mathrm{BR})/\sigma\mathrm{BR}$ (%)	HZ	$\nu\bar{\nu}$ H	HZ	$\nu\bar{\nu}$ H
H → any	±0.5		±0.9	
H → $\mathrm{b\bar{b}}$	±0.3	±3.1	±0.5	±0.9
H → $\mathrm{c\bar{c}}$	±2.2		±6.5	±10
H → gg	±1.9		±3.5	±4.5
H → $\mathrm{W^+W^-}$	±1.2		±2.6	±3.0
H → ZZ	±4.4		±12	±10
H → $\tau\tau$	±0.9		±1.8	±8
H → $\gamma\gamma$	±9.0		±18	±22
H → $\mu^+\mu^-$	±19		±40	
H → invis.	< 0.3		< 0.6	

Note 1 : Small cross-channel correlations not (yet) included in the fits

Note 2 : H → Z γ and Z → H γ still to be analysed (for the HZγ coupling)

Statistical precision with 4 IP scenario

- **Obtained with 12 ab^{-1} at 240 GeV, and 5.5 ab^{-1} at 365 GeV**



$\sqrt{s}$ (GeV)	240		365	
Luminosity (ab^{-1})	12		5.5	
$\delta(\sigma\mathrm{BR})/\sigma\mathrm{BR}$ (%)	HZ	$\nu\bar{\nu}$ H	HZ	$\nu\bar{\nu}$ H
H → any	±0.3		±0.25	
H → $\mathrm{b\bar{b}}$	±0.2	±2.0	±0.3	±0.5
H → $\mathrm{c\bar{c}}$	±1.4		±3.4	±5.2
H → gg	±1.2		±1.8	±2.3
H → $\mathrm{W^+W^-}$	±0.8		±1.4	±1.6
H → ZZ	±2.8		±6.3	±5.2
H → $\tau\tau$	±0.6		±0.9	±4.2
H → $\gamma\gamma$	±6.0		±9.4	±11.5
H → $\mu^+\mu^-$	±12		±21	
H → invis.	< 0.2		< 0.3	

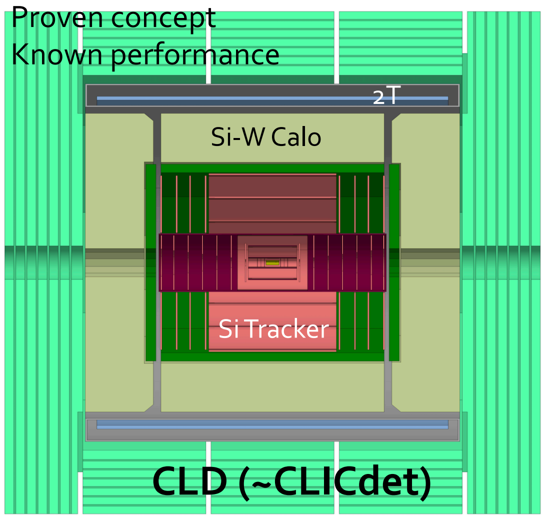
For information only, not in the CDR.

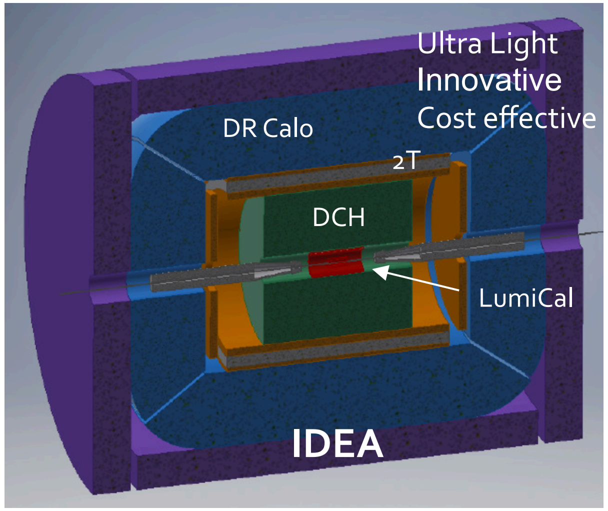
Discussion about performance and systematic uncertainties

Detector performance

- **Two detector concepts studied so far**

Mogens Dam





- **It was demonstrated that detectors satisfying the requirements are feasible**
  - **Physics performance as good as [better than] SiD/ILD or CLICDet (Full Sim)**
    - **e.g., b- and c-tagging due to small beam pipe (15 mm inner radius)**
  - **Beam backgrounds (mild wrt linear colliders) cause negligible detector occupancy**
    - **With careful asymmetric IR layout and masks against synchrotron radiation**
  - **Invasive MDI below 100 mrad causes negligible acceptance loss (Fast Sim)**
    - **Luminosity can still be measured to 0.01% precision**

Analysis performance

- **Full Sim, Fast Sim, Extrapolation**
  - We have developed benchmark analyses with CMS full sim analyses (2012)
    - H → bb, ττ, WW, ZZ, γγ, μμ, …
  - We have checked a few of them with CLICDet full sim (2013)
    - Improves over CMS precisions by 20% (for those channels accessible to CMS)
  - We have developed a fast simulation able to reproduce CMS and CLICDet performance
    - Validated on full simulation
  - We have checked that the fast simulation gives the same results as ILC/CLIC analyses
    - For a number of benchmark analyses
  - For the final FCC-ee numbers, we have conservatively assumed same detector performance as ILC and CLIC detectors in our fast simulation (CLD)
    - We expect better performance
      - Smaller beam pipe – currently checking if 10 mm radius is feasible
      - Ten years to develop innovative detectors at up to 4 IPs
      - Better calibration, new analysis techniques, etc.
  - We have extrapolated statistical precision from ILC (250 GeV) and CLIC (380 GeV)
    - For those channels not fully analysed by the FCC-ee team
      - Note: H → Zγ final state not yet in the tables, but can be included as well.

Experimental uncertainties

- Many sources were examined, and solutions exist for all of them
  - Centre-of-mass energy can be calibrated to ~2-5 MeV with Zγ, WW, and ZZ events
    - From the knowledge of m_Z and m_W to 0.1 and 0.5 MeV
      - ➨ Negligible impact on m_H and on Higgs branching fractions
  - Beam energy spread can be measured continuously (1% / √day) with $\mu^+\mu^-$ events
    - Negligible impact on recoil mass uncertainty and on σ_{HZ}
  - Alignment (absolute and relative) and calibration (calo, b-tag, PID, etc)
    - Can be performed with regular runs at the Z pole
      - ➨ Requires 12 hours for setup, e.g., every month
      - ➨ One hour data taking gives 3.10^8 Z in Higgs mode, and 10^7 Z in top mode

        i.e., about 1000 times the monthly Higgs statistics
    - Fermion pairs at 240 and 365 GeV can also be used as a complement
      - ➨ Cross section 300 times the Higgs cross section (3.10^8 events at 240 GeV)
  - Integrated luminosity can be measured fast with 0.01% precision
    - i.e., 10 times better than the ultimate precision expected from $2.5\ 10^6$ Higgs events
  - Magnetic field will not be uniform
    - Will be measured in the tracker volume before tracker installation
    - Will be followed with $\mu^+\mu^-$ events (Z pole) and with coil current measurements

Experimental uncertainties

- ☐ Many sources were examined, and solutions exist for a
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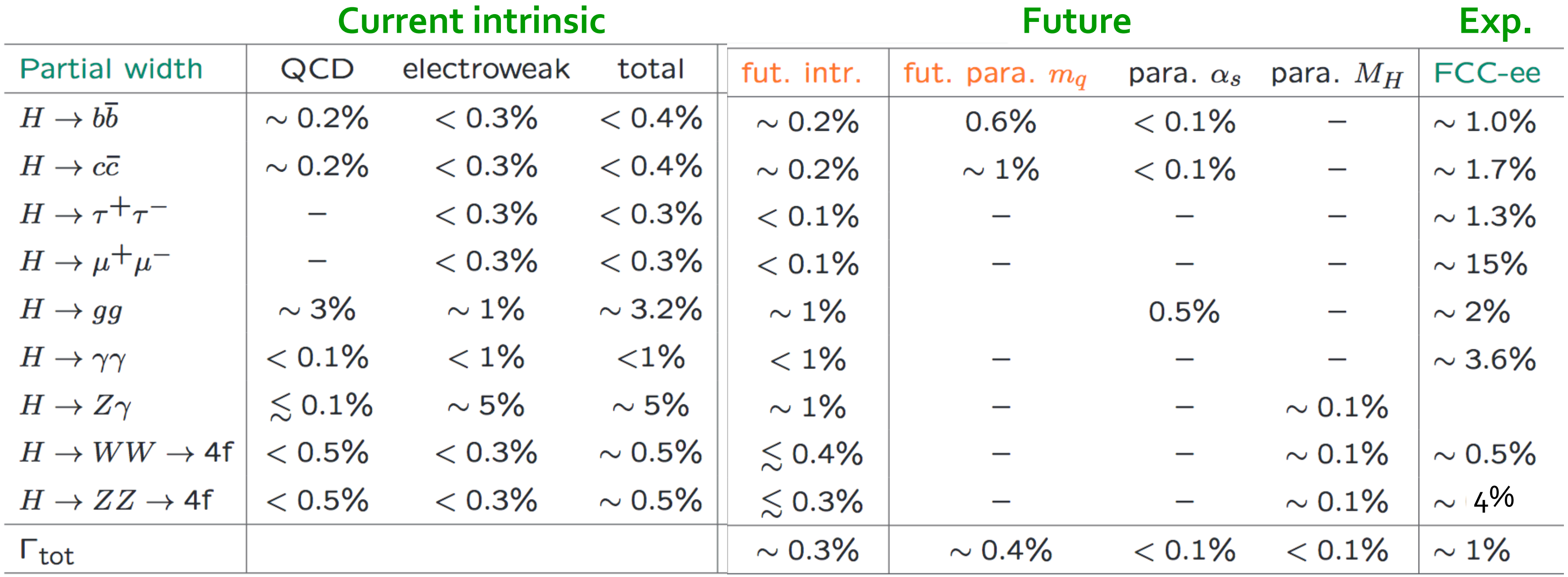
    - ● e followed with $\mu^+\mu^-$ events (Z pole) and with coil current measurements

Experimental uncertainties are not expected to be a concern for Higgs measurements

Theoretical uncertainties

- **(Conservative) evaluation**
  - Intrinsic (missing higher orders) and parametric uncertainties on total and partial widths



	Current intrinsic			Future				Exp.
Partial width	QCD	electroweak	total	fut. intr.	fut. para. m_q	para. α_s	para. M_H	FCC-ee
$H \to b\bar{b}$	$\sim 0.2\%$	$< 0.3\%$	$< 0.4\%$	$\sim 0.2\%$	0.6%	$< 0.1\%$	–	$\sim 1.0\%$
$H \to c\bar{c}$	$\sim 0.2\%$	$< 0.3\%$	$< 0.4\%$	$\sim 0.2\%$	$\sim 1\%$	$< 0.1\%$	–	$\sim 1.7\%$
$H \to \tau^+\tau^-$	–	$< 0.3\%$	$< 0.3\%$	$< 0.1\%$	–	–	–	$\sim 1.3\%$
$H \to \mu^+\mu^-$	–	$< 0.3\%$	$< 0.3\%$	$< 0.1\%$	–	–	–	$\sim 15\%$
$H \to gg$	$\sim 3\%$	$\sim 1\%$	$\sim 3.2\%$	$\sim 1\%$		0.5%	–	$\sim 2\%$
$H \to \gamma\gamma$	$< 0.1\%$	$< 1\%$	$<1\%$	$< 1\%$	–	–	–	$\sim 3.6\%$
$H \to Z\gamma$	$\lesssim 0.1\%$	$\sim 5\%$	$\sim 5\%$	$\sim 1\%$	–	–	$\sim 0.1\%$	
$H \to WW \to 4f$	$< 0.5\%$	$< 0.3\%$	$\sim 0.5\%$	$\lesssim 0.4\%$	–	–	$\sim 0.1\%$	$\sim 0.5\%$
$H \to ZZ \to 4f$	$< 0.5\%$	$< 0.3\%$	$\sim 0.5\%$	$\lesssim 0.3\%$	–	–	$\sim 0.1\%$	$\sim 4\%$
Γ_{tot}				$\sim 0.3\%$	$\sim 0.4\%$	$< 0.1\%$	$< 0.1\%$	$\sim 1\%$

Table from S. Heinemeyer

- All expected to be smaller than statistical uncertainties
  - Uncertainties on HZ and ννH cross sections also expected to be sufficiently small
    - When two-loop contributions are calculated in the SM

- **Effort to improve theoretical calculations has started on all fronts**
  - In order to reach and exceed this conservative estimate by the time FCC-ee starts

Theoretical uncertainties

- (Conservative) evaluation
  - Intrinsic (missing higher orders) and parametric uncertainti [illegible] rtial widths

Current intrinsic | Exp.

Partial width	QCD	electroweak	total	fut. intr.	fut	[illegible]	para. M_H	FCC-ee
$H \to b\bar{b}$	$\sim 0.2\%$	$< 0.3\%$	$< 0.4\%$	$\sim 0.2\%$	[illegible]	[illegible]	–	$\sim 1.0\%$
$H \to c\bar{c}$	$\sim 0.2\%$	$< 0.3\%$	$< 0.4\%$	[illegible]	[illegible]	$< 0.1\%$	–	$\sim 1.7\%$
$H \to \tau^+\tau^-$	–	$< 0.3\%$	$< 0.3\%$	[illegible]	[illegible]	–	–	$\sim 1.3\%$
$H \to \mu^+\mu^-$	–	$< 0.3\%$	$< 0.3\%$	[illegible]	[illegible]	–	–	$\sim 15\%$
$H \to gg$	$\sim 3\%$	$\sim 1\%$	[illegible]	[illegible]	[illegible]	0.5%	–	$\sim 2\%$
$H \to \gamma\gamma$	$< 0.1\%$	$< 1\%$	[illegible]	[illegible]	–	–	–	$\sim 3.6\%$
$H \to Z\gamma$	$\lesssim 0.1\%$	$\sim 5\%$	[illegible]	[illegible]	–	–	$\sim 0.1\%$	
$H \to WW \to$ 4f	$< 0.5\%$	[illegible]	[illegible]	0.4%	–	–	$\sim 0.1\%$	$\sim 0.5\%$
$H \to ZZ \to$ 4f	$< 0.5\%$	[illegible]	[illegible]	$\lesssim 0.3\%$	–	–	$\sim 0.1\%$	$\sim 4\%$
Γ_{tot}	[illegible]	[illegible]	[illegible]	$\sim 0.3\%$	$\sim 0.4\%$	$< 0.1\%$	$< 0.1\%$	$\sim 1\%$

Table from S. Heinemeyer

- All [illegible] aller than statistical uncertainties
  - Un [illegible] d ννH cross sections also expected to be sufficiently small
    - [illegible] p contributions are calculated in the SM
- Effort t [illegible] ove theoretical calculations has started on all fronts
  - In orde [illegible] to reach and exceed this conservative estimate by the time FCC-ee starts

Theoretical uncertainties are not expected to be a concern for Higgs measurements

Summary about systematic uncertainties

- The floor is statistics
  - Nobody wants to be the dominant source of uncertainty
    - Especially if it reduces the discovery potential

  - For most problems, hard work will lead to an uncertainty ~ o(statistical error)

  - Reduction of experimental errors goes through collecting independent information
    - Calibration runs at the Z help tremendously (not possible at linear colliders)
    - Statistics at $\sqrt{s}$ = 240 or 365 GeV helps too (much larger than at linear colliders)
    - The FCC-ee luminosities and new ideas have been found to solve all our problems
      - ➨ (so far)

  - Reduction of theoretical errors goes through new tools and more computing power
    - It is a great challenge, but has discovery potential
    - It is therefore recognized as strategic in the FCC CDR
    - Two workshops already organized (January 2018 and January 2019)
    - Requires ~500 person.year (50 MCHF) over the next 20 years

Summary about systematic uncerta s

- **The floor is statistics**
  - Nobody wants to be the dominant source of uncertainty
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Higgs coupling fits are done with statistical uncertainties when it comes to FCC-ee projections

Projected results and discussion

Two different sorts of Higgs fits

- **The “kappa” fits**
  - Assume the Standard model structure (no new coupling, no new processes)
    - The SM couplings are g_{HXX} allowed to scale by a factor κ_x
  - Nine free parameters : κ_W , κ_Z , κ_t , κ_b , κ_t , κ_g , κ_γ , Γ_{tot} , BR_{EXO}
    - Or more: κ_c , κ_μ , $\kappa_{\gamma Z}$, κ_λ , …
    - Or less: $\kappa_W = \kappa_Z$, universal κ_f, $\Gamma_{tot} = \Gamma_{SM}$
  - Simple parameterization, transparent interpretation, free from theoretical bias
    - But violates gauge invariance …

Results in this presentation

- **The “EFT” fits**
  - Expand Standard Model in gauge and Lorentz invariant dim. 6 operators (up to 2500!)
    - Only valid for new physics scale much larger than m_H or $\sqrt{s}$
  - Consistent theoretical description, but still involves theoretical assumptions
    - New operators modify Higgs kinematics, add energy dependence
    - Includes correlation with Electroweak Precision Observables
      - ➨ FCC-ee runs at the Z pole, WW and tt thresholds play an important role

See Jorge de Blas’ presentation

Result of the “kappa” fit

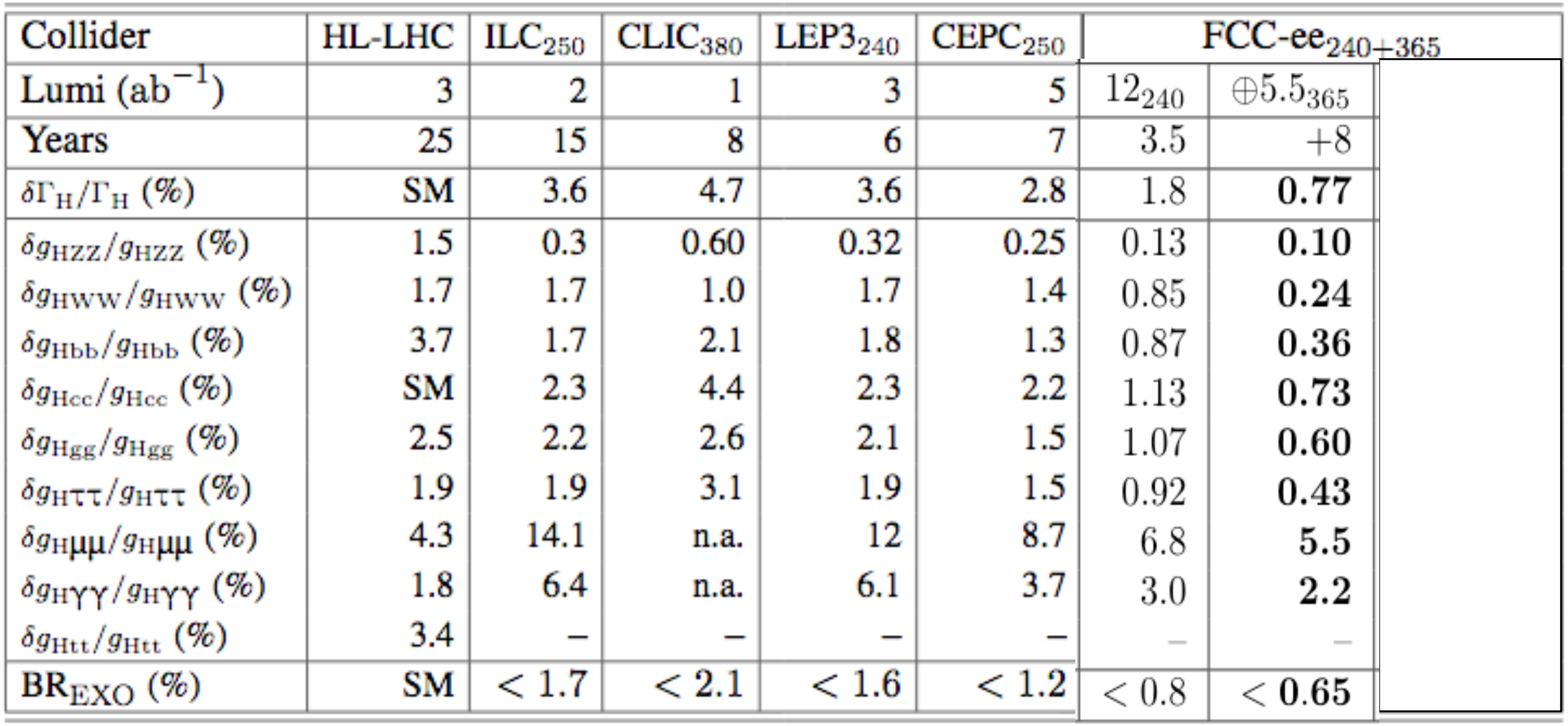
- Same fit applied to all Higgs factories inputs (for unbiased comparison)

Collider	HL-LHC	ILC_{250}	CLIC_{380}	LEP3_{240}	CEPC_{250}	$\text{FCC-ee}_{240+365}$		
Lumi (ab^{-1})	3	2	1	3	5	5_{240}	$+1.5_{365}$	+ HL-LHC
Years	25	15	8	6	7	3	+4	
$\delta\Gamma_H/\Gamma_H$ (%)	SM	3.6	4.7	3.6	2.8	2.7	**1.3**	1.1
$\delta g_{HZZ}/g_{HZZ}$ (%)	1.5	0.3	0.60	0.32	0.25	0.2	**0.17**	0.16
$\delta g_{HWW}/g_{HWW}$ (%)	1.7	1.7	1.0	1.7	1.4	1.3	**0.43**	0.40
$\delta g_{Hbb}/g_{Hbb}$ (%)	3.7	1.7	2.1	1.8	1.3	1.3	**0.61**	0.56
$\delta g_{Hcc}/g_{Hcc}$ (%)	SM	2.3	4.4	2.3	2.2	1.7	**1.21**	1.18
$\delta g_{Hgg}/g_{Hgg}$ (%)	2.5	2.2	2.6	2.1	1.5	1.6	**1.01**	0.90
$\delta g_{H\tau\tau}/g_{H\tau\tau}$ (%)	1.9	1.9	3.1	1.9	1.5	1.4	**0.74**	0.67
$\delta g_{H\mu\mu}/g_{H\mu\mu}$ (%)	4.3	14.1	n.a.	12	8.7	10.1	**9.0**	3.8
$\delta g_{H\gamma\gamma}/g_{H\gamma\gamma}$ (%)	1.8	6.4	n.a.	6.1	3.7	4.8	**3.9**	1.3
$\delta g_{Htt}/g_{Htt}$ (%)	3.4	–	–	–	–	–	–	3.1
BR_{EXO} (%)	SM	< 1.7	< 2.1	< 1.6	< 1.2	< 1.2	< 1.0	< 1.0

- The FCC-ee precision better than HL-LHC by large factors (for the copious modes)
  - The FCC-ee is best on the e^+e^- Higgs factory market
- It is important to have two energy points (240 and 365 GeV), as at the FCC-ee
  - Combination better by a factor up to 2 (4) than 240/250 (365/380) GeV alone

Result of the “kappa” fit in 4 IP scenario

- Same fit applied to all Higgs factories inputs (for unbiased comparison)



Collider	HL-LHC	ILC$_{250}$	CLIC$_{380}$	LEP3$_{240}$	CEPC$_{250}$	FCC-ee$_{240+365}$	
Lumi (ab^{-1})	3	2	1	3	5	12$_{240}$	$\oplus$5.5$_{365}$
Years	25	15	8	6	7	3.5	+8
$\delta\Gamma_H/\Gamma_H$ (%)	SM	3.6	4.7	3.6	2.8	1.8	**0.77**
$\delta g_{HZZ}/g_{HZZ}$ (%)	1.5	0.3	0.60	0.32	0.25	0.13	**0.10**
$\delta g_{HWW}/g_{HWW}$ (%)	1.7	1.7	1.0	1.7	1.4	0.85	**0.24**
$\delta g_{Hbb}/g_{Hbb}$ (%)	3.7	1.7	2.1	1.8	1.3	0.87	**0.36**
$\delta g_{Hcc}/g_{Hcc}$ (%)	SM	2.3	4.4	2.3	2.2	1.13	**0.73**
$\delta g_{Hgg}/g_{Hgg}$ (%)	2.5	2.2	2.6	2.1	1.5	1.07	**0.60**
$\delta g_{H\tau\tau}/g_{H\tau\tau}$ (%)	1.9	1.9	3.1	1.9	1.5	0.92	**0.43**
$\delta g_{H\mu\mu}/g_{H\mu\mu}$ (%)	4.3	14.1	n.a.	12	8.7	6.8	**5.5**
$\delta g_{H\gamma\gamma}/g_{H\gamma\gamma}$ (%)	1.8	6.4	n.a.	6.1	3.7	3.0	**2.2**
$\delta g_{Htt}/g_{Htt}$ (%)	3.4	–	–	–	–	–	–
BR$_{EXO}$ (%)	SM	< 1.7	< 2.1	< 1.6	< 1.2	< 0.8	$< \mathbf{0.65}$

- The FCC-ee precision better than HL-LHC by large factors (for the copious modes)
    - The FCC-ee is best on the e^+e^- Higgs factory market
- It is important to have two energy points (240 and 365 GeV), as at the FCC-ee
    - Combination better by a factor up to 2 (4) than 240/250 (365/380) GeV alone

Comment about longitudinal polarization

- **The FCC-ee e^+ and e^- beams won't be longitudinally polarized**
  - Unlike at linear colliders where 80% polarized e^- can be injected and accelerated
    - And, with more difficulty and money, may get 30% polarized e^+ as well.
- **Effect of longitudinal polarization at 240/250 GeV for Higgs couplings**
  - Polarization causes σ_{HZ} to increase by 1.4 (1.08) in $e^-_L e^+_R$ ($e^-_R e^+_L$) configuration
    - Similar increase for the backgrounds (except for WW : 2.34 and 0.14)
      - ➨ Precision better by 20% with the same luminosity in the κ fits (slide 21)
  - EFT fits benefit from different polarization states to constrain additional operators
    - At circular colliders, constraints come from EW precision measurements
      - ➨ Precision still better by ~20% or less with the same luminosity in the EFT fits
      - ➨ The only coupling for which polarization brings significant gain is $g_{HZ\gamma}$

        Much better measured at hadron collider (e.g., FCC-hh) anyway

J. De Blas

- **At the FCC-ee, long. polarization is not worth the induced luminosity loss**
  - NB. Without polarization, one year at the FCC-ee with 2 (4) IPs at $\sqrt{s}$ = 240 GeV offers the same Higgs coupling precision as 8 (16) years with ILC polarized e^+ and e^+
    - Similar remark holds for EWPO or top EW couplings measurements at other $\sqrt{s}$

Comment about longitudinal polarization

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    - At circular colliders precision measurements
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    - Similar rk holds for EWPO or top EW couplings measurements at other $\sqrt{s}$

J. De Blas

Beam polarization brings no information that cannot be obtained otherwise.

There is no obvious need for it.

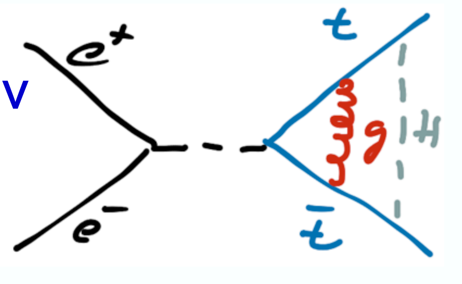
Synergies with HL-LHC and FCC-hh

- The HL-LHC is a great Higgs factory (10^9 Higgs produced) but …
    - $\sigma_{i\to f}^{(\text{observed})} \propto \sigma_{\text{prod}}\,(g_{Hi})^2\,(g_{Hf})^2 / \Gamma_H$
        - σ_{prod} is uncertain and Γ_H is largely unknown
            - ➨ Difficult to extract absolute couplings from the κ fit
        - Must do physics with ratios or with additional assumptions.
            - ➨ e.g., Γ_{tot} and g_{Hcc} fixed to their SM values
            - ➨ And no exotic decays

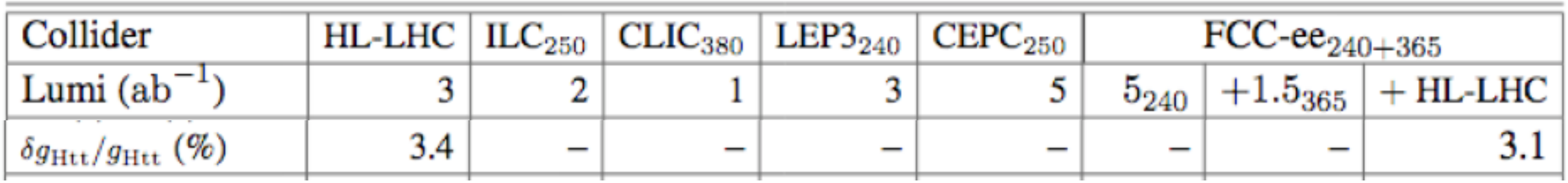
- The FCC-ee absolute measurements of g_{HZZ} and Γ_H break this model dependence
    - Rare decay modes allow the absolute determination of $g_{H\mu\mu}$, $g_{H\gamma\gamma}$, $g_{HZ\gamma}$, …
        - Only in combination with the FCC-ee

- Even more true with FCC-hh
    - See Michele Selvaggi's presentation

The top Yukawa coupling



- The FCC-ee will have some standalone sensitivity (~10%)
  - Through vertex correction with a top-pair threshold scan @ 350 GeV
    - See Patrizia Azzi's presentation
- Much better prior measurement at HL-LHC
  - Already observed with a 5σ significance in ATLAS and CMS
  - Precision of 3.4% , obtained with usual assumptions (BR_{BSM} = 0, Γ_{tot} = BR_{cc} = SM)
- Again, the FCC-ee breaks the model dependence
  - With absolute coupling and width measurements
    - Absolute precision of 3.1 % after 7 years of FCC-ee as a Higgs factory



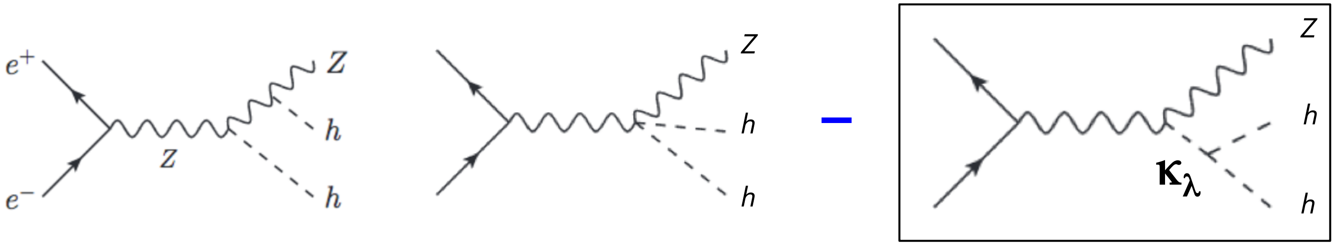
Collider	HL-LHC	ILC_{250}	CLIC_{380}	LEP3_{240}	CEPC_{250}	$\text{FCC-ee}_{240+365}$		
Lumi (ab^{-1})	3	2	1	3	5	5_{240}	$+1.5_{365}$	+ HL-LHC
$\delta g_{\text{Htt}}/g_{\text{Htt}}$ (%)	3.4	–	–	–	–	–	–	3.1

- Conclusion: There is no need for an e^+e^- collider run at $\sqrt{s}$ = 500-550 GeV

The trilinear Higgs self-coupling κ_λ [1]

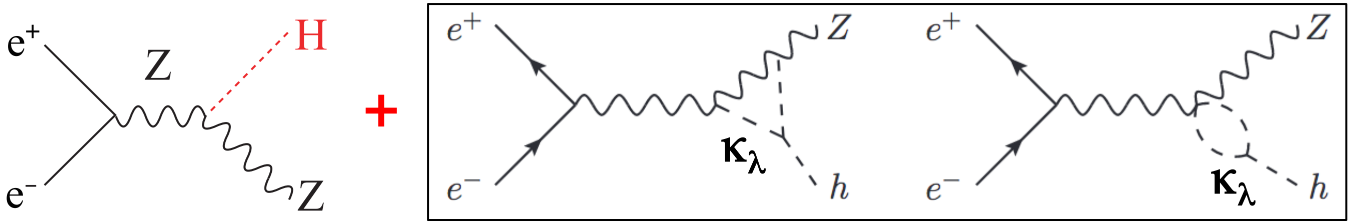
- Traditionally κ_λ is measured with a c.o.m. energy of at least 500 GeV.

Double Higgs production



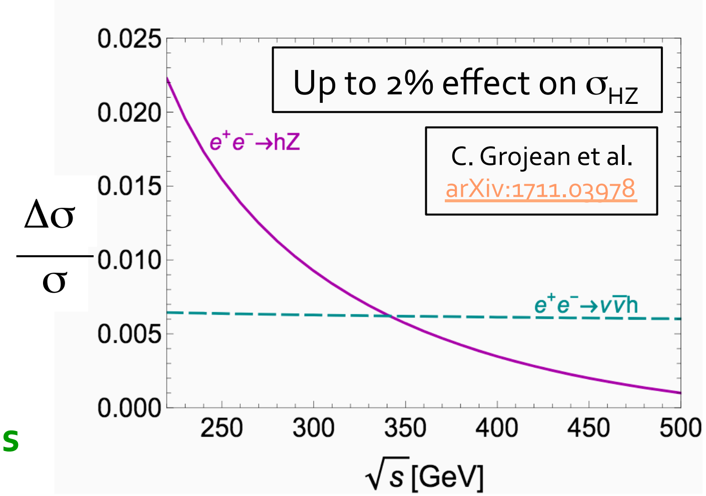
  - At the FCC-ee, a different method can be used with single Higgs production

σ_{HZ}



M. McCullough
arXiv:1312.3322

- Effect on σ_{HZ} is large at the FCC-ee
  - With respect to exp'tal precision on σ_{HZ}
- ~12% exclusive precision on κ_λ with 2 IPs
  - Reduced to 9% with a 4 IP scenario
    - If all other couplings are fixed to their SM values

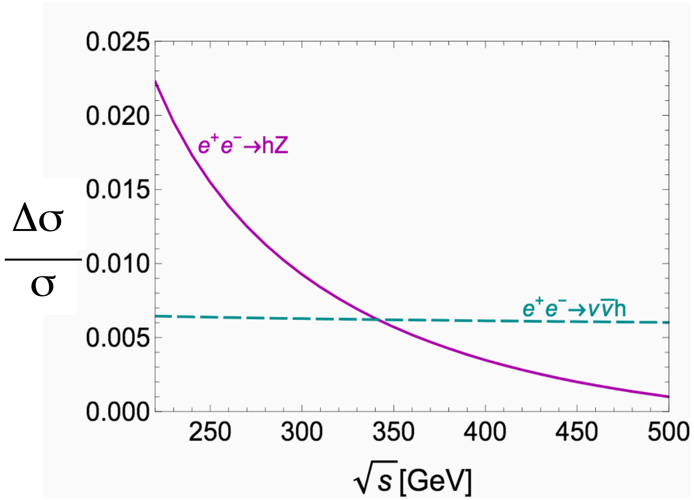


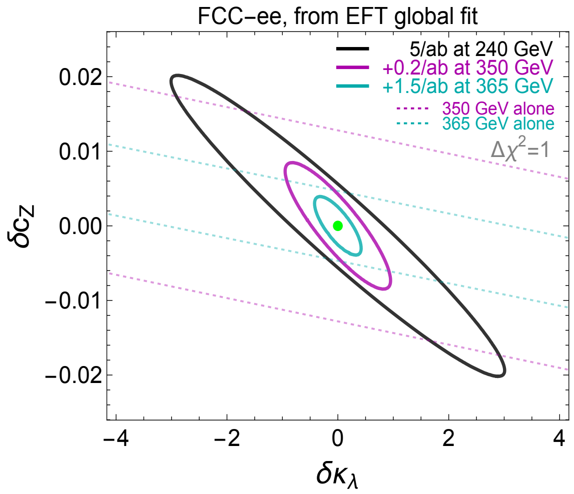
Up to 2% effect on σ_{HZ}

C. Grojean et al.
arXiv:1711.03978

The trilinear Higgs self-coupling κ_λ [2]

- The cross section depends on other couplings (HZZ, HHZZ, at least)
  - … and of the overall model structure, which might differ from SM structure
    - e.g., additional eeZH coupling, or $e^+e^- \to A \to HZ$ graphs
- Two energy points lift off the degeneracy between HZZ and HHH





C. Grojean et al.
arXiv:1711.03978

- Additional couplings addressed by a global EFT fit **(J. De Blas' presentation)**
  - All FCC-ee Higgs measurements are important in this fit
  - Most FCC-ee EW precision measurements are equally important **(R. Tenchini's talk)**
    - To fix extra parameters that would otherwise enter the fit and open flat directions

The trilinear Higgs self-coupling κ_λ [3]

- Precision on κ_λ expected at the FCC-ee from the global EFT fit
  - With the baseline design: 2 IPs and 15 years (91+160+240+350+365 GeV)
    - FCC-ee standalone: $\Delta\kappa_\lambda/\kappa_\lambda \sim \pm 42\%$
    - Combined with HL-LHC: $\Delta\kappa_\lambda/\kappa_\lambda \sim \pm 34\%$
      - ➨ 3σ sensitivity (~$\mathrm{ILC}_{250+500}$ after 30 years)
  - Statistics are of essence for this measurement
    - As for all other Higgs measurements
  - With a 4 IP scenario (and still 15 years at 91+160+240+350+365 GeV)
    - FCC-ee standalone: $\Delta\kappa_\lambda/\kappa_\lambda \sim \pm 25\%$
    - Combined with HL-LHC: $\Delta\kappa_\lambda/\kappa_\lambda \sim \pm 21\%$ (better than $\mathrm{CLIC}_{0.38+1.4}$ after 15 years)
      - ➨ 5σ sensitivity for first discovery of the Higgs self-coupling in 2050

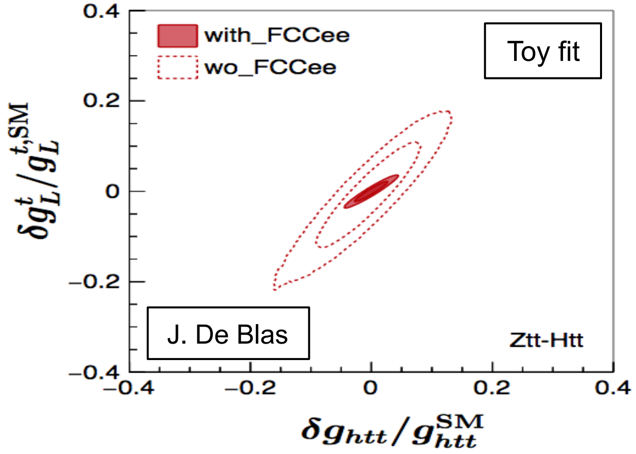
Note: the combination with HL-LHC was done before the latest numbers on double Higgs production had been made available. A slight improvement in the combination is therefore to be expected.

- And of course, the FCC-hh will bring this precision to the few % level
  - Together with synergetic constraints from the FCC-ee (next slide)

κ_t and κ_λ : FCC-ee & FCC-hh synergies

- ❑ **Top Yukawa coupling @ FCC-hh**
  - ◆ Measure σ(ttH) / σ(ttZ) at FCC-hh
    - ● Similar production mechanism
    - ● Most theory uncertainties cancel
      - ➨ <1% precision possible

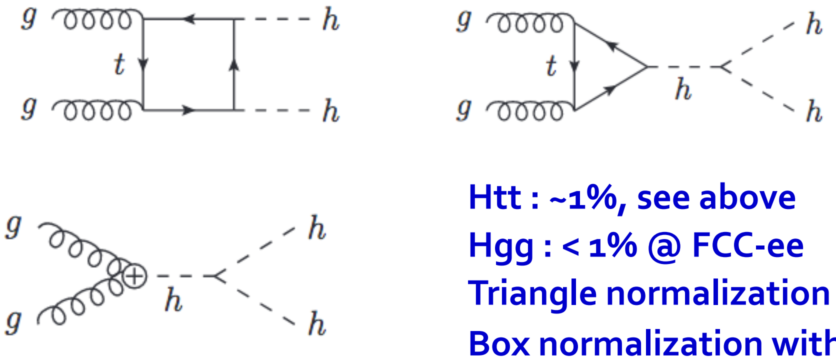
M. Selvaggi



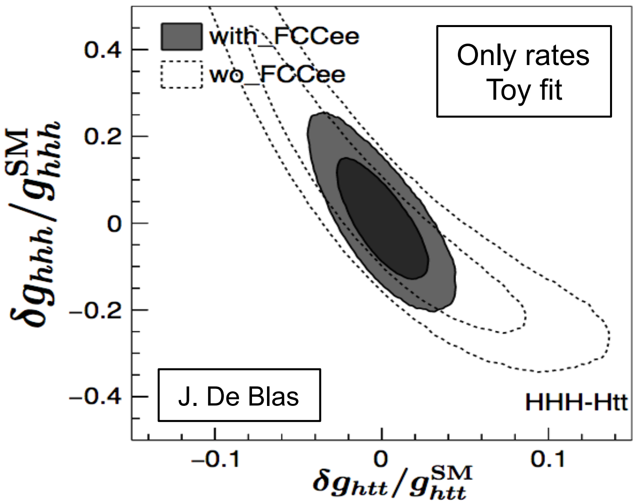
  - ◆ Information needed from FCC-ee to get g_{Htt} to ~1%
    - ● Measure t_Lt_LZ couplings to fix the denominator (precision ~0.5%)
    - ● Measure Higgs branching ratios to fix the numerator (precision ~0.5%)

P. Azzi

- ❑ **Triple Higgs coupling @ FCC-hh**

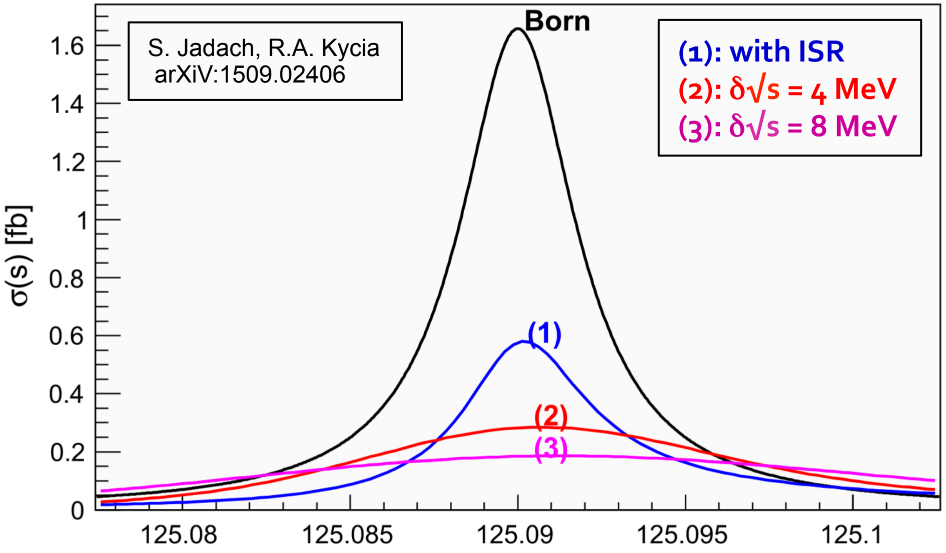


Htt : ~1%, see above
Hgg : < 1% @ FCC-ee
Triangle normalization with H→ZZ
Box normalization with m_{HH} spectrum ?



Unique at FCC-ee : First generation couplings

- If schedule allows or calls for a prolongation of FCC-ee
  - Few years at $\sqrt{s}$ = 125.09 GeV with high luminosity is an interesting addition
    - For s-channel production $e^+e^- \to H$ (a la muon collider, with 10^4 higher lumi)



- FCC-ee monochromatization setups
  - Default: $\delta\sqrt{s}$ = 100 MeV, 25 ab^{-1} / year
    - No visible resonance
  - Option 1: $\delta\sqrt{s}$ = 10 MeV, 7 ab^{-1} / year
    - $\sigma(e^+e^- \to H) \sim 100$ ab
  - Option 2: $\delta\sqrt{s}$ = 6 MeV, 2 ab^{-1} / year
    - $\sigma(e^+e^- \to H) \sim 250$ ab
  - Backgrounds much larger than signal
    - $e^+e^- \to q\bar{q}, \tau\tau, WW^*, ZZ^*, \gamma\gamma, \ldots$

- Expected signal significance of ~0.4σ / √year in both option 1 and option 2
  - Set a electron Yukawa coupling upper limit : $\kappa_e < 2.5$ @ 95% C.L.
    - ➨ Constrain CP violating Higgs-top couplings from EDM measurements
  - Reaches SM sensitivity after five years
- FCC-ee unique opportunity to constrain first generation Yukawa's

Composite Higgs ?

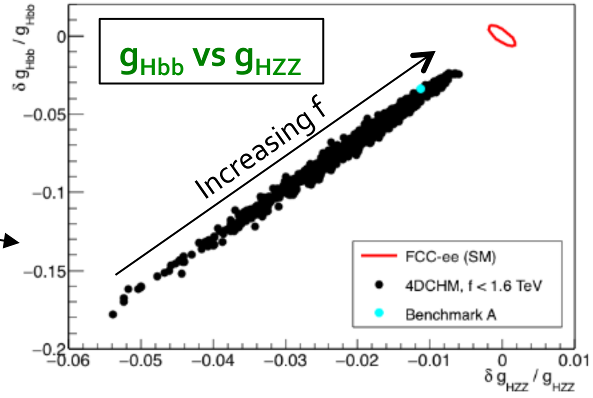
- ❑ **Deviations may point to specific BSM physics**
  - ◆ E.g, 4D Composite Higgs Model
    - ● Deviations in Higgs couplings
      - ➨ $\sqrt{s}$ = 240, 350, 365 GeV
    - ● Deviations in EW top couplings
      - ➨ $\sqrt{s}$ = 365 GeV optimal

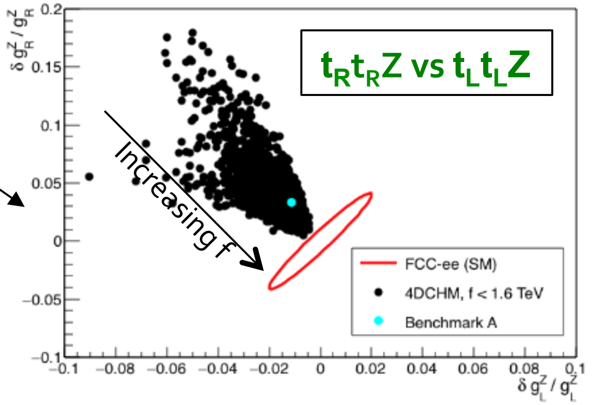
        No need for beam polarization
    - ● Deviations in EW lepton couplings
      - ➨ At all energies

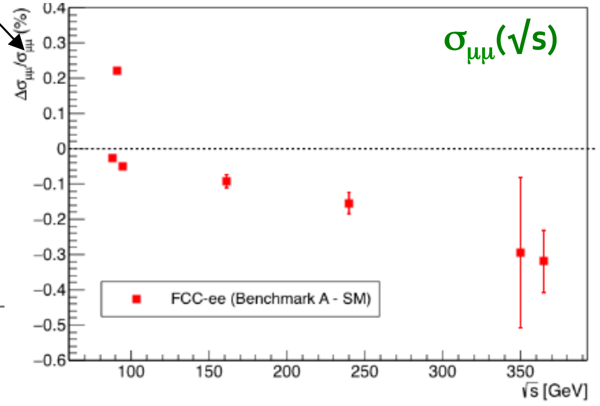
S. de Curtis et al.
arXiv:1110.1613

P. Azzi's presentation
P. J. arXiv:1503.01325

- ❑ **Pattern of deviations may become significant**
  - ◆ Correlations between observations
    - ● Allow first characterization of the model
  - ◆ For example, gauge sector parameters in benchmark A
    - ● f = 1.6 TeV, g*=1.78, $m_{Z'} \sim$ 3 TeV, $\Gamma_{Z'} \sim$ 600 GeV
    - ● With the FCC-ee precision
      - ➨ Z' mass predicted wth 2% precision
      - ➨ Scale f, coupling g* predicted with 8% precision







Conclusion and outlook

- The FCC-ee Higgs factory offers an unique dataset from 240 to 365 GeV)
  - Delivers precise and model-independent measurements of all Higgs properties
    - Couplings (including self-coupling), mass, CP, …
- Higgs studies at the FCC-ee provide solid discovery potential
  - Explore the 10 TeV energy scale (for generic Higgs-coupled new physics) J. De Blas
    - With up to 10-fold more precise and absolute Higgs coupling measurements
  - May discover that the Standard Model does not fit
    - NEW Physics ! Pattern of deviations may point to the source.
  - May directly discover dark matter as invisible Higgs decays
    - Or other new physics from more exotic decays F. Moortgat
- The FCC-ee is much more than a Higgs factory
  - Z, WW, and tt factories are equally important for the (Higgs) discovery potential
    - Precision programme for theoretical / parametric uncertainties is essential
- The FCC-ee provides the precise and necessary "fixed candle"
  - For model-independent measurements at the FCC-hh (eh) M. Selvaggi
    - The FCC-ee therefore maximizes the overall FCC physics reach

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J. De Blas

F. Moortgat

M. Selvaggi

We have just started to scratch the surface.

Many routes are barely touched.

(physics opportunities, analysis techniques, detector concepts and simulation, MDI studies, …)