Physics programme at FCC-ee

LFC15: Linear & Future Colliders after the Higgs discovery

ECT* Trento, 7th–11th Sept. 2015

David d'Enterria

(on behalf of FCC-ee study group)

CERN

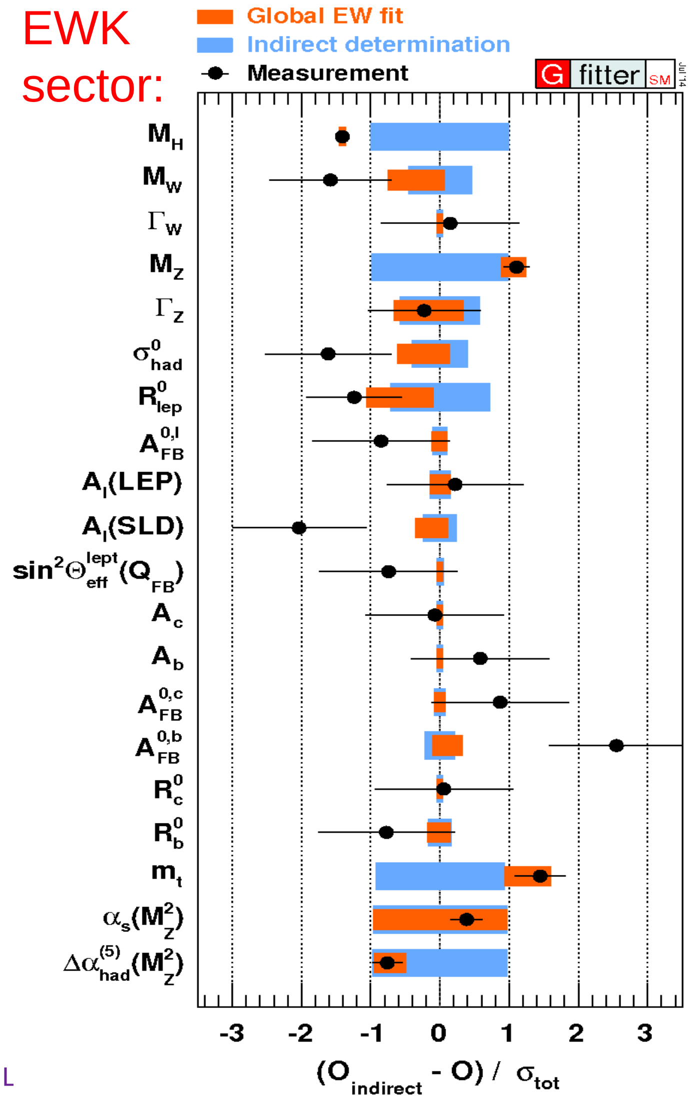
Standard Model of particles & interactions

- Renormalizable QFT of electroweak $SU_L(2)\times U_Y(1)$ & strong $SU_c(3)$ gauge interactions

  O(20) parameters: Couplings, H mass&vev, H-f Yukawa, CKM mix., CP phases.

  Experimentally confirmed to great precision for 40(!) years:

EWK sector:



$$
\begin{aligned}
\mathcal{L} = & -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{8}tr(\mathbf{W}_{\mu\nu}\mathbf{W}^{\mu\nu}) - \frac{1}{2}tr(\mathbf{G}_{\mu\nu}\mathbf{G}^{\mu\nu}) \\
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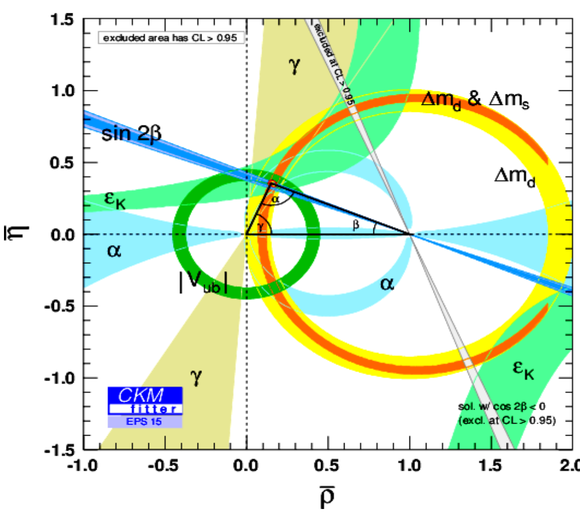
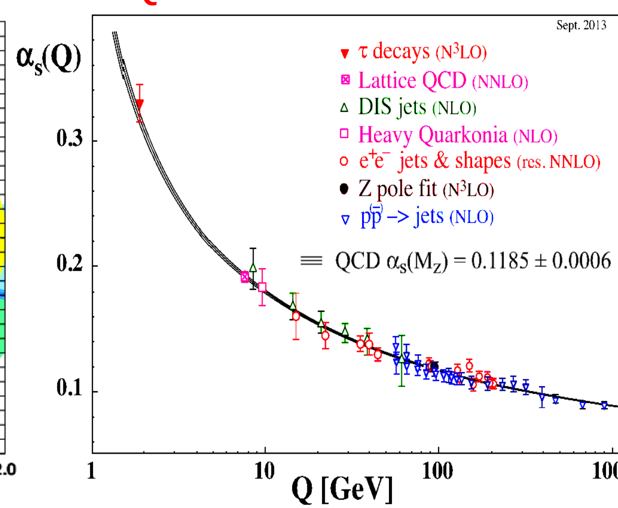
Flavour sector:



QCD sector:



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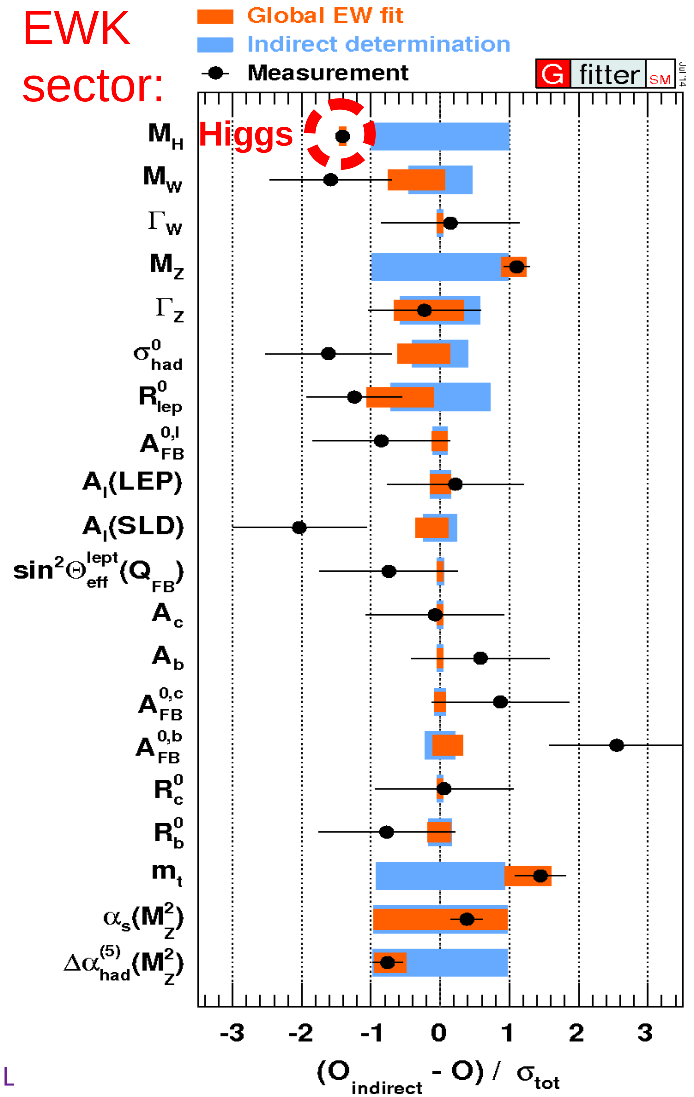

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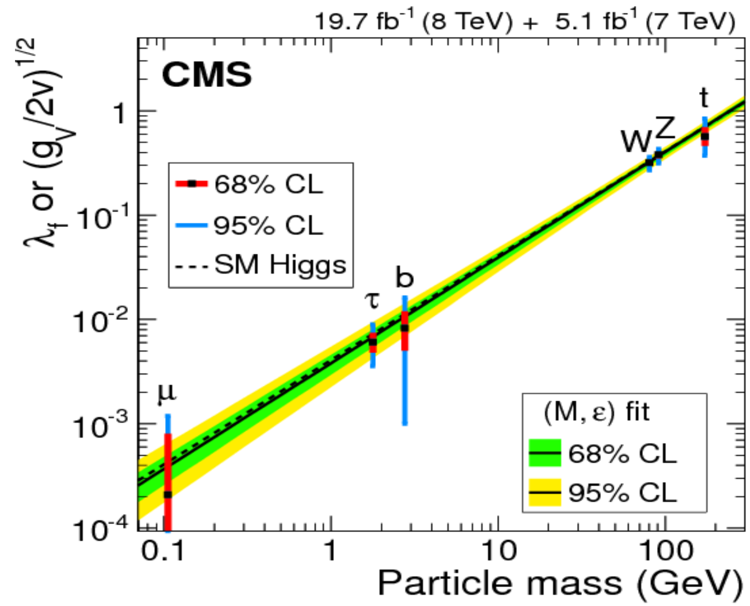

Open questions in the SM (1)

$$\mathcal{L} = -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{8}tr(\mathbf{W}_{\mu\nu}\mathbf{W}^{\mu\nu}) - \frac{1}{2}tr(\mathbf{G}_{\mu\nu}\mathbf{G}^{\mu\nu})$$ [Gauge interactions: $U_Y(1)$, $SU_L(2)$, $SU_c(3)$]

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- ✘ Higgs: Generation of 1st-gen. fermion (and all ν's) masses to be confirmed
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[Lepton dynamics]

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[Lepton masses]

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[Quark dynamics]

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[Lepton dynamics]

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[Quark dynamics]

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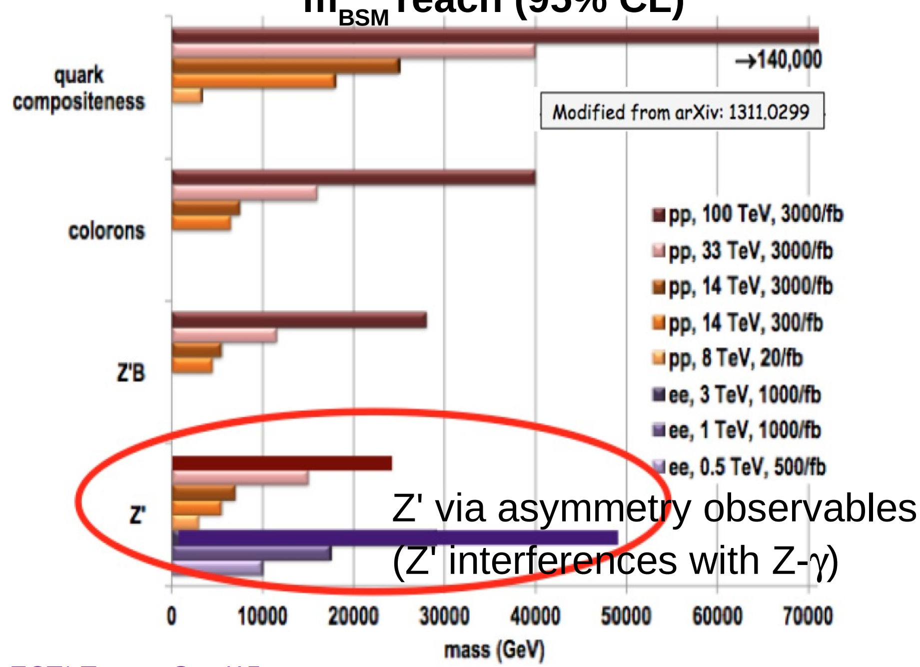
- ✘ Dark matter: SM describes only 4% of Universe (visible fermions+bosons)
- ✘ Others: Quantum gravity, cosmological constant, dark energy, inflation,...

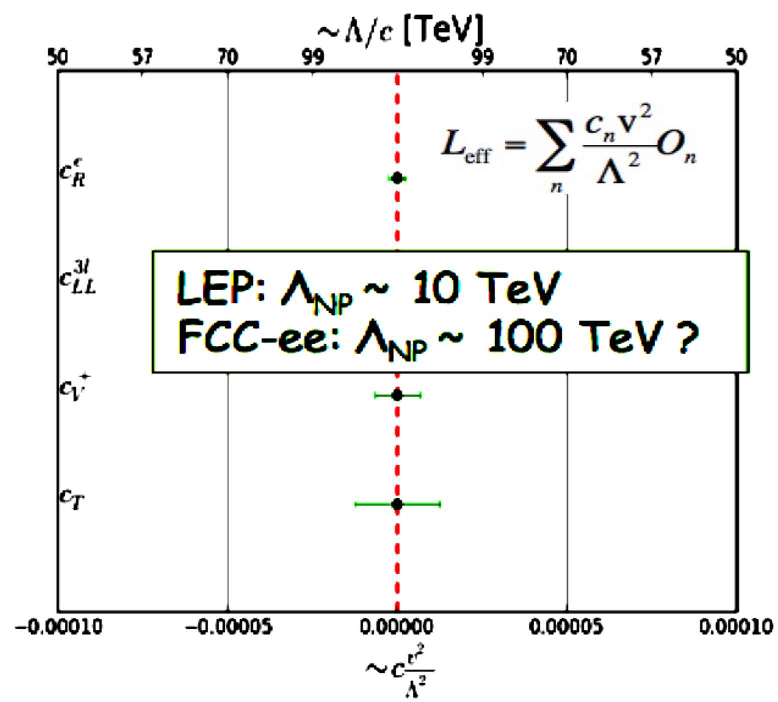
Some/Most(?) of these questions will not be fully answered at the LHC

Why new e^+e^- colliders ?

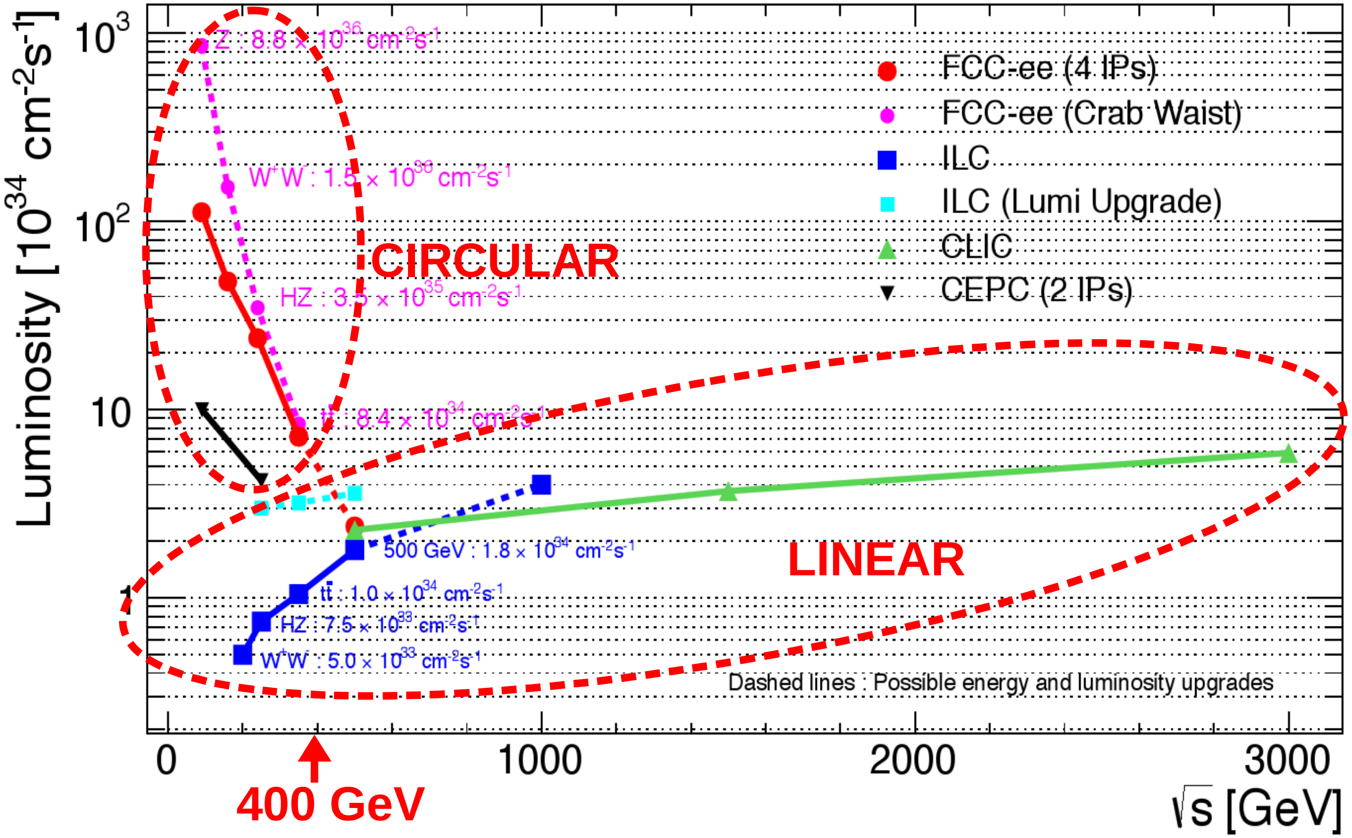
- New physics (NP): Hidding well ? Or beyond present reach ?
  At larger masses? Or at smaller couplings? Or both?
- Electron-positron colliders:
  - ➨ Direct model-indep. discovery of new particles coupling to Z^*/γ^* up to $m \sim \sqrt{s}/2$
  - ➨ Low, very-well understood backgrounds: Fill “blind spots” in p-p searches
  - ➨ Polarised beams: Extra handle to constrain theory underlying any NP
  - ➨ Sensitivity to weakly-interacting (Z,W) physics
  - ➨ Indirect constraints on new physics: Precision ~ $1/\Lambda^2_{NP}$

m_{BSM} reach (95% CL)





Circular or Linear e$^+$e$^-$ colliders ?



- √s limited to ~400 GeV by SR~E^4/R
- Large # of circulating bunches:
  - → Much higher Lumi (better at low √s, lower SR)
  - → Top-up injection ring to compensate L burnoff
- Various Interaction Points possible
- Precise E_{beam} from resonant depolarization

- Larger √s reach (TeV's)
- Low repetition rate
  - → Lumi from nm-size beams
  - → Large bremsstrahlung
  - → Large energy spread
- Longitudinal polarization easier

Why FCC-ee ?

- Indirect searches through loops in high-stat W, Z, H, top precision studies at very high-luminosity e-e colliders with <<1% accuracy
- Indirect constraints on new physics: Precision ~ $1/\Lambda^2_{NP}$
- New scalar-coupled physics:

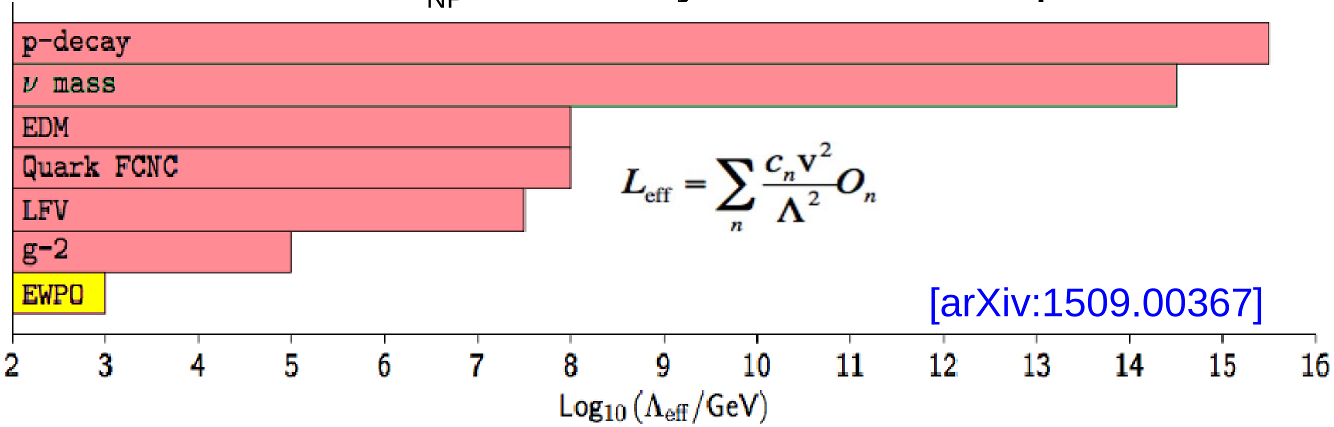
At Λ_{NP} ~1 TeV: ~5% deviations of Higgs couplings wrt. SM:

$$\frac{\delta g_{\rm HXX}}{g^{\rm SM}_{\rm HXX}} \leq 5\% \times \left(\frac{1\,\rm TeV}{\Lambda}\right)^2$$

~10^6 Higgs ⇒ ~0.1% Higgs couplings precision ⇒ Λ>7 TeV

- New weakly-coupled physics:

Excluded below Λ_{NP}~3 TeV by current EWK precision fit.



$$L_{\rm eff} = \sum_n \frac{c_n v^2}{\Lambda^2} O_n$$

[arXiv:1509.00367]

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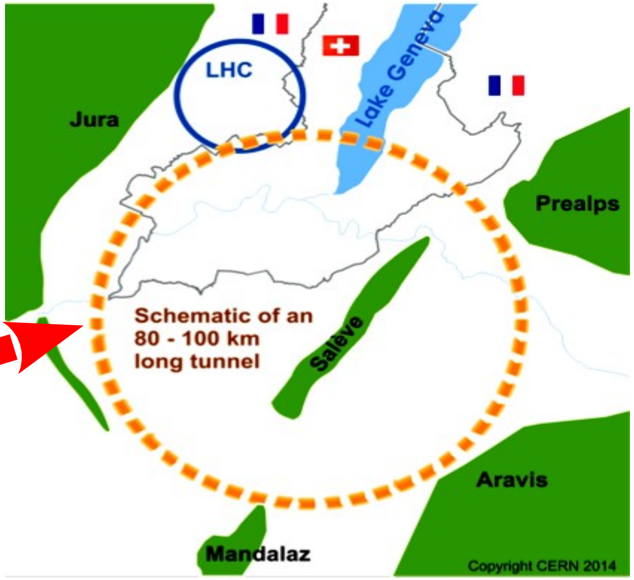
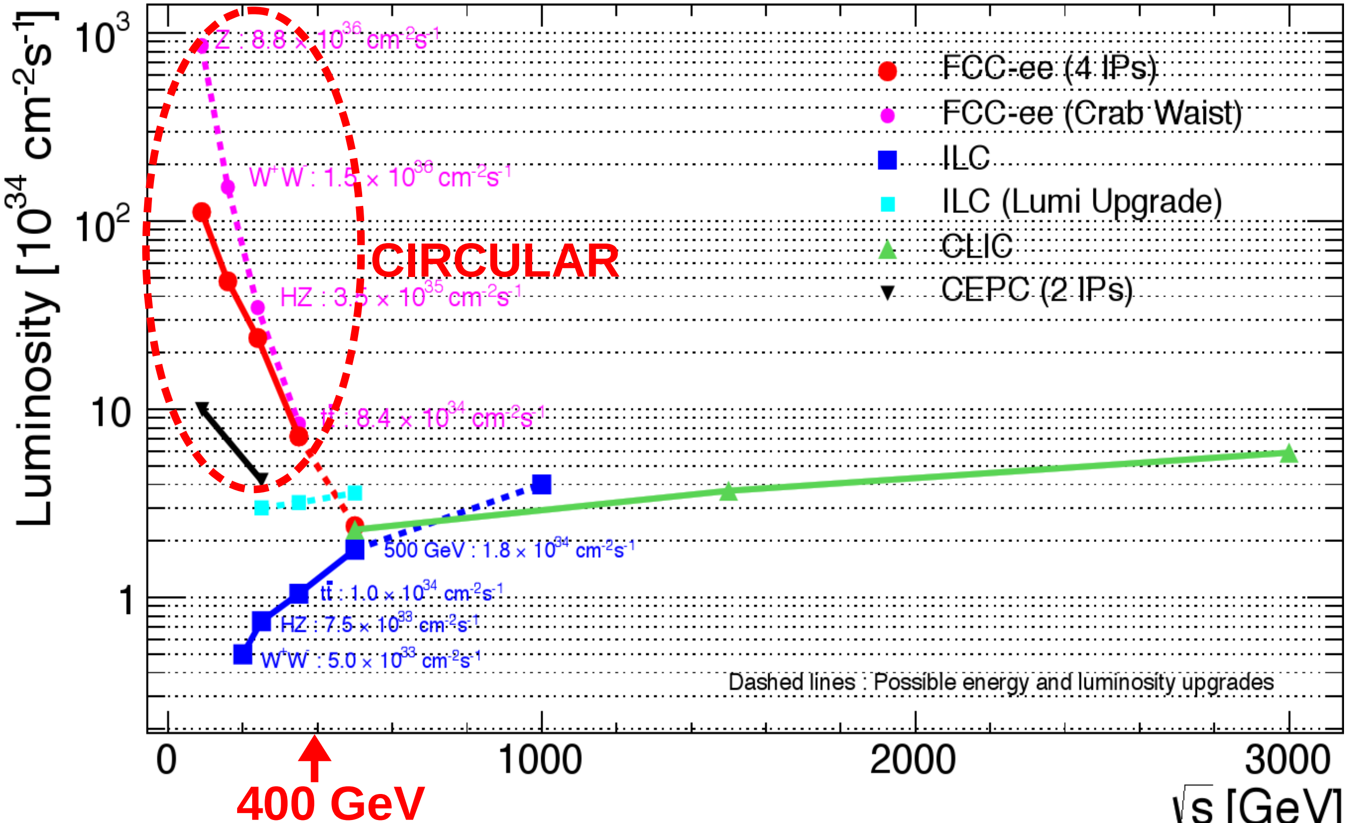
- New weakly-coupled physics:

  Excluded below Λ_{NP}~3 TeV by EWK fit.

  Λ_{NP} ~30 TeV requires: ×10^2 precision w.r.t. LEP (10^4 W's, 10^7 Z's), i.e. ×10^4 more stats. (10^8 W's, 10^{11} Z's) reachable in e^+e^- circular collider with R~80–100 km



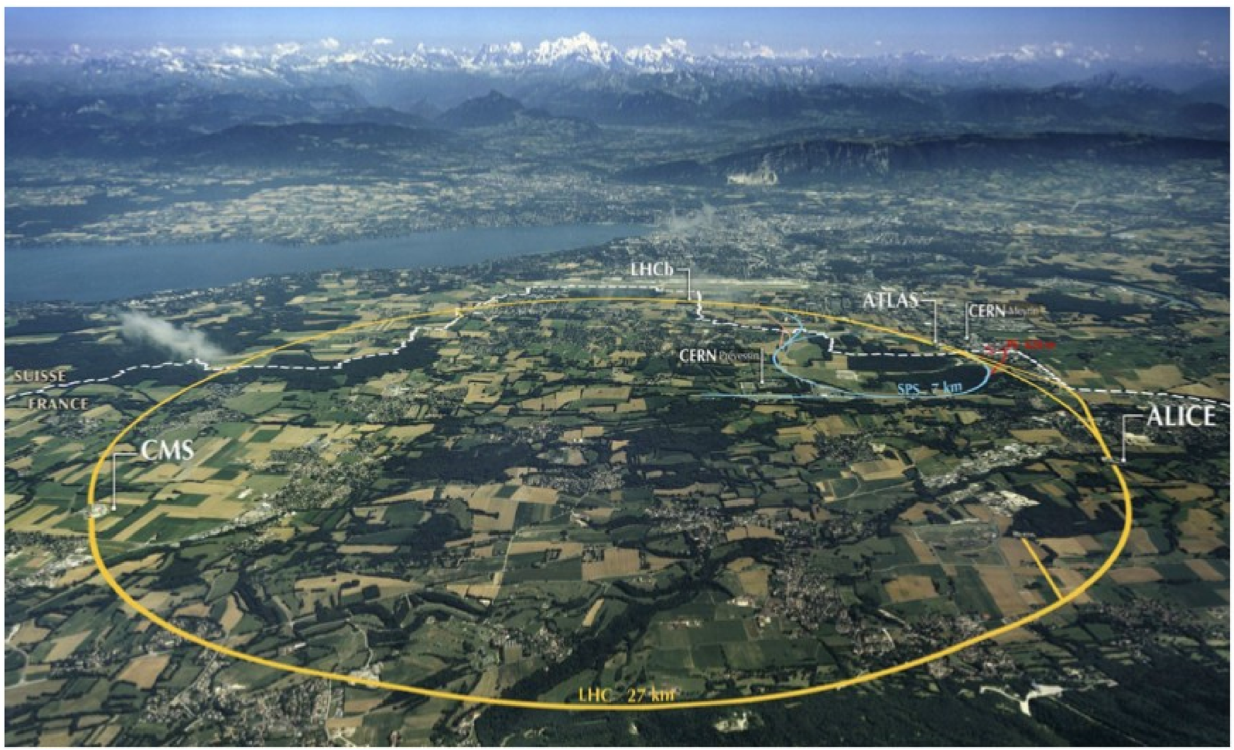
FCC-ee characteristics



- √s limited to ~400 GeV by SR~E^4/R: R~80 km (×3 LEP radius)
- Large # of circulating bunches: ×10^4 LEP bunches +crab-waist collisions
  - → High Lumi (better at low √s): ×10^4–10 more lumi than ILC for √s = 90–400 GeV
  - → Top-up injection ring to compensate L burnoff
- Various Interaction Points possible: 4 expected
- Precise E_{beam} from resonant depolarization: ±0.1 MeV (2 MeV at LEP)

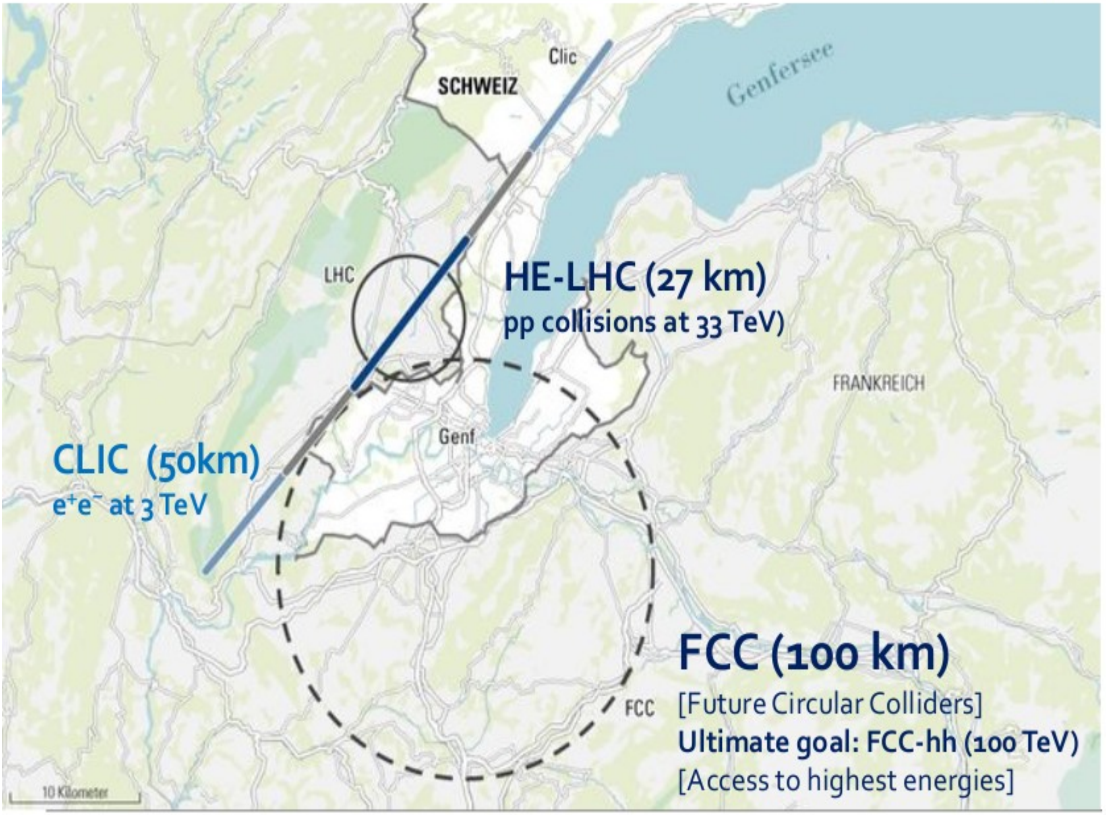
EU HEP short-term perspectives (2020-2030)

- In May 2013, European Strategy said (very similar statements from US)
  - Exploit the full potential of the LHC until ~2030 as the highest priority
    - Get 75-100 fb^{-1} at 13-14 TeV by 2018 (LHC Run2: running)
    - Get ~300 fb^{-1} at 14 TeV by 2022 (LHC Run3: approved)
    - Upgrade machine and detectors to get 3 ab^{-1} at 14 TeV by 2035 (HL-LHC: project)
      - ➨ A first step towards both energy and precision frontier



EU HEP long-term perspectives (2040-2060)

- In May 2013, European Strategy said (very similar statements from US)
  - Perform R&D and design studies for high-energy frontier machines at CERN
    - HE-LHC, a programme for an energy increase to 33 TeV in the LHC tunnel
    - FCC, a 100-km circular ring with a pp collider long-term project at $\sqrt{s}$ = 100 TeV
    - CLIC, an e^+e^- collider project with $\sqrt{s}$ from 0.3 to 3 TeV



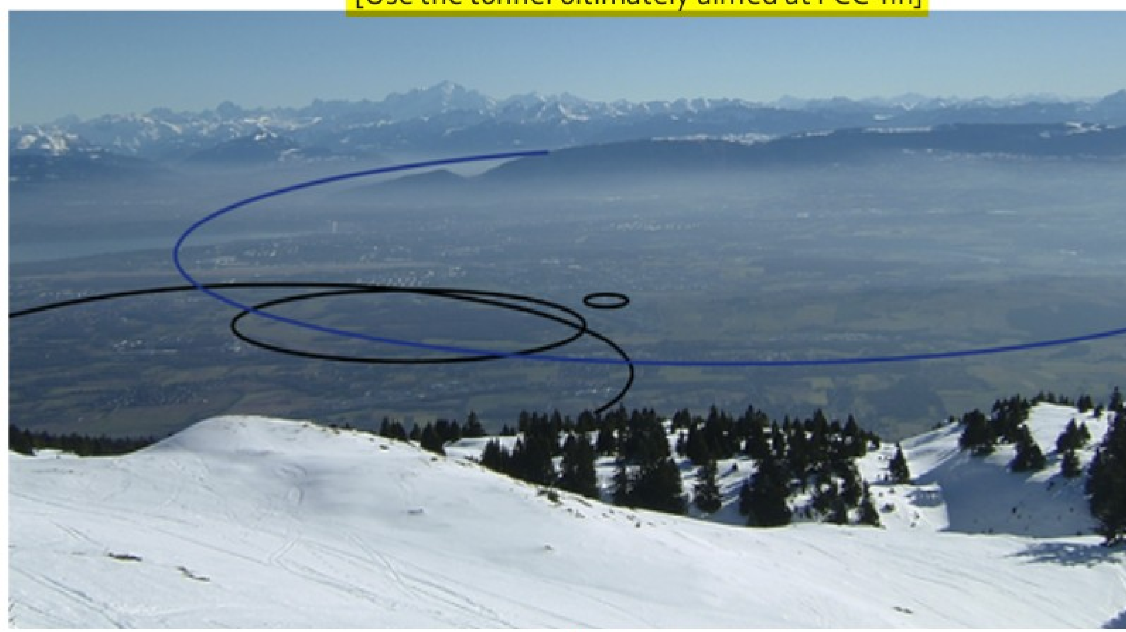
Similar circular projects (50 or 70km) in China
pp collisions at $\sqrt{s}$ ~ 50 or 70 TeV

EU HEP mid-term perspectives (2030-2040)

- In May 2013, European Strategy said (very similar statements from US)
  - Acknowledge the strong physics case of e^+e^- colliders with intermediate $\sqrt{s}$
    - Participate in ILC if Japan government moves forward with the project
    - In the context of the FCC, perform accelerator R&D and design studies
      - ➡ In view of a high-luminosity, high-energy, circular e^+e^- collider as a first step

FCC (100 km)

First step: FCC-ee (91-400GeV)
[Use the tunnel ultimately aimed at FCC-hh]



Note: CLIC can also run at $\sqrt{s}$ ~ 350 GeV in ~2035-2040

FCC-ee is an ongoing CERN study project

- **Lepton studies – Coordinators A. Blondel, P. Janot (EXP) + J.Ellis, C.Grojean (TH)**
  - Study the properties of the Higgs and other particles with unprecedented precision

EW Physics (Z pole)
R. Tenchini F. Piccinini
S. Heinemeyer

Diboson physics, m_W
R. Tenchini F. Piccinini
S. Heinemeyer

H(125) Properties
M. Klute
K. Peters

Top Quark Physics
P. Azzi

QCD and $\gamma\gamma$ Physics
D. d'Enterria
P. Skands

Flavour Physics
S. Monteil
J. Kamenik

New Physics
M. Pierini C. Rogan
A. Weiler

- Develop the necessary tools — Understand the experimental conditions

Physics Software
C. Bernet
B. Hegner

Common with FCC-hh/eh,
Synergies with LHC, LC

Online & Trigger
E. Perez
C. Leonidopoulos

Exp'tal Environment
N. Bacchetta

Synergy with FCC-hh
and Linear Colliders

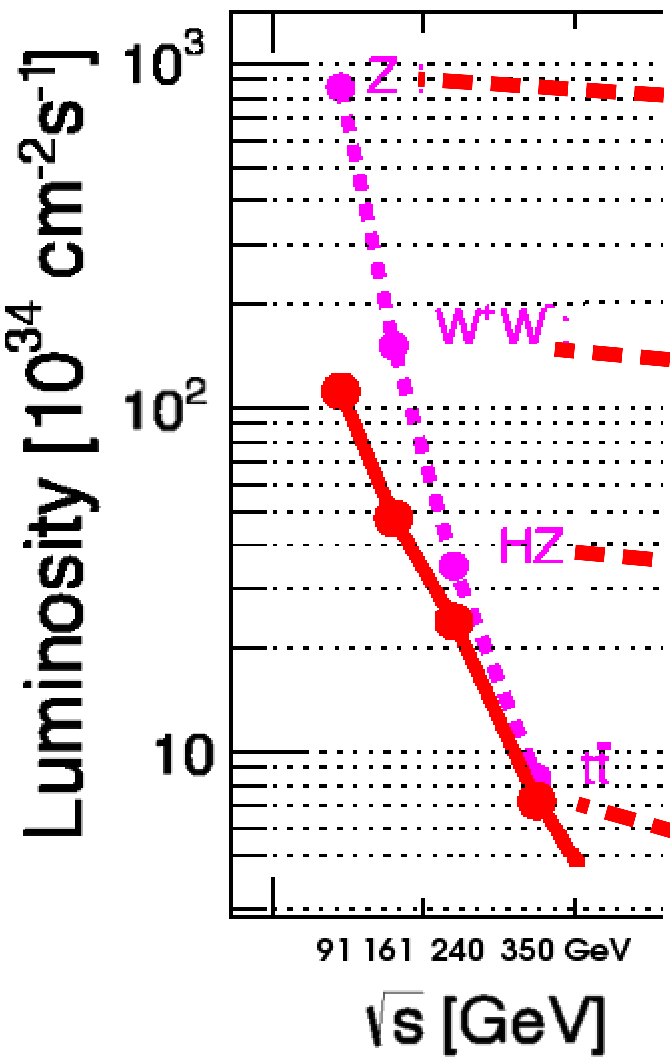
- Set constraints on the possible detector designs to match statistical precision

Detector Designs
A. Cattai
G. Rolandi

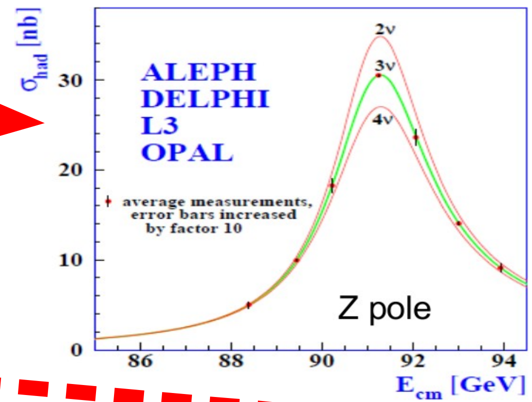
Synergy with Linear Collider
detectors and others

FCC-ee physics programme in a nutshell

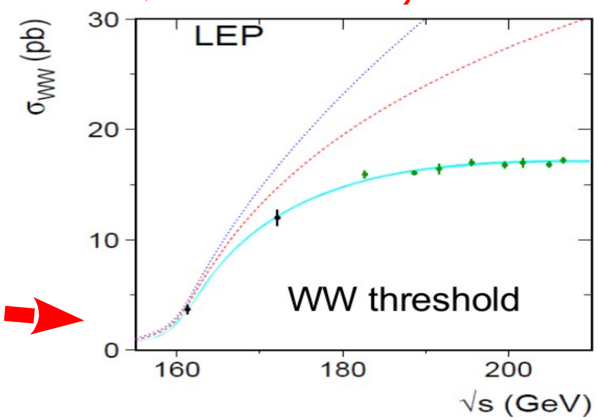
[arXiv:1308.6176]



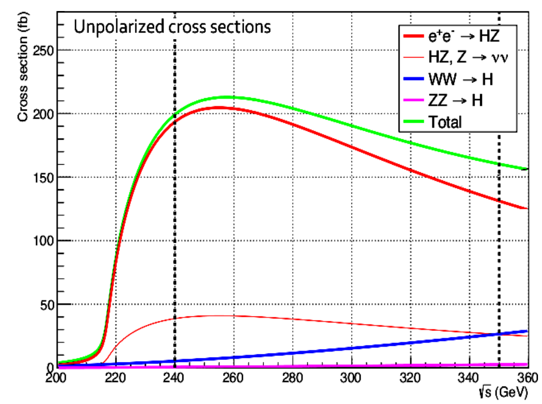
√s=91 GeV, 10^{12} Z's



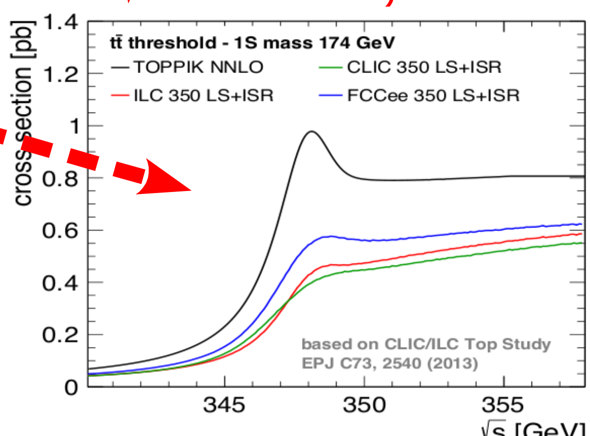
√s~161 GeV, 10^8 W's



√s~240 GeV, 10^6 H's



√s~350 GeV, 10^{5-6} t's



FCC-ee physics programme: Duration

- 4 IP's and in the crab-waist optics scheme :

$\sqrt{s}$ (GeV)	90 (Z)	160 (WW)	240 (HZ)	350 (tt)	350 (WW→H)
Lumi (ab^{-1}/yr)	86.0	15.2	3.5	1.0	1.0
Events/year	3.7×10^{12}	6.1×10^{7}	7.0×10^{5}	4.2×10^{5}	2.5×10^{4}
# years	(0.3) 2.5	1	3	0.5	3
Events@LC (*)	3×10^{9}	2×10^{6}	1.4×10^{5}	10^{5}	3.5×10^{4}
LC @ FCC-ee	1 day	1 week	2 months	3 months	1.5 year

See e.g., arXiV:1506.07830
"ILC Operating Scenarios"

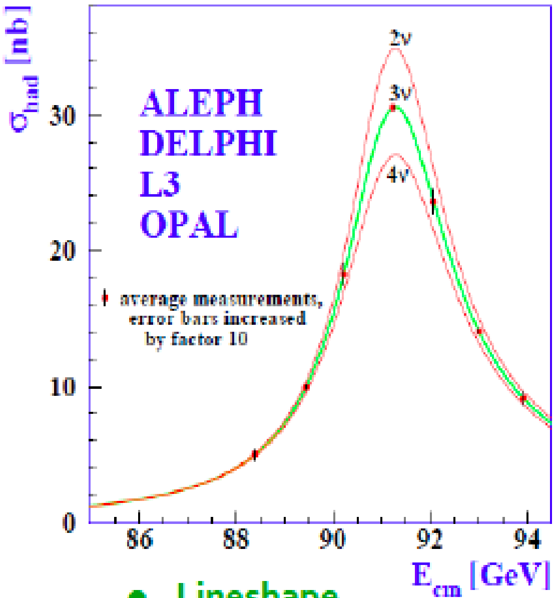
(*) LC = 500 fb^{-1} @ 500 GeV (6 y), 200 fb^{-1} @ 350 GeV (2 y), 500 fb^{-1} @ 250 GeV (5 y)
100 fb^{-1} @ 90 GeV (>3 y), 500 fb^{-1} @ 160 GeV (>5 y)
with ±80% / ±30% polarization for e^-/e^+ beams

>21 years
(1 y = 10^7 s)

- FCC-ee core physics programme can be completed in 8–10 years

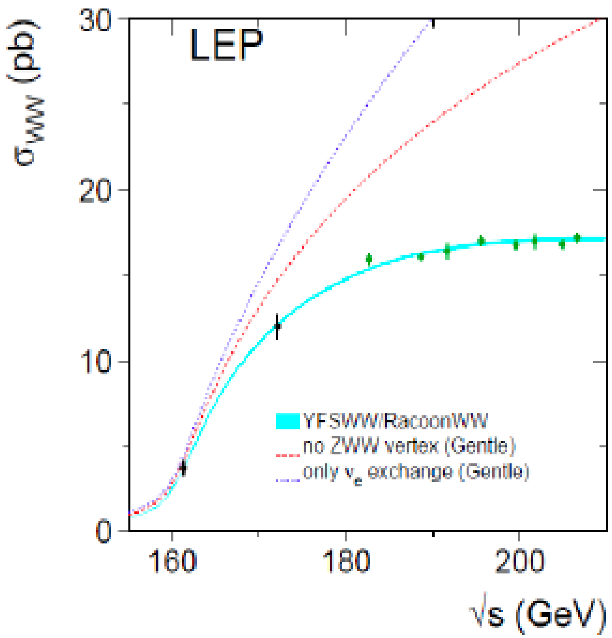
FCC-ee physics: High-precision W,Z,top

Z resonance: TeraZ



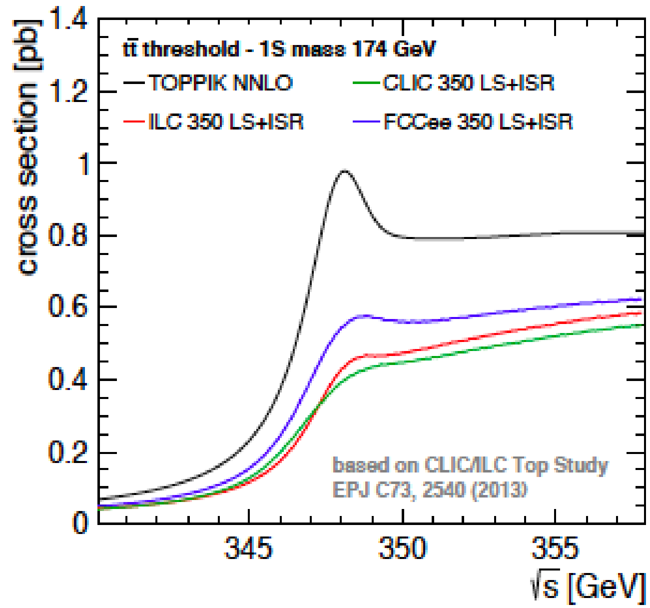
- Lineshape
  - ➨ Exquisite E_{beam} (unique!)
  - ➨ m_Z, Γ_Z to 10 keV
- Asymmetries
  - ➨ $\sin^2\theta_W$ to 2×10^{-6}
- Branching ratios, R_l, R_b
  - ➨ $\alpha_s(m_Z)$ to 0.0002
- Predict m_{top}, m_W in SM

WW threshold scan: OkuW



- Threshold scan
  - ➨ m_W to 500 keV
- Branching ratios R_l, R_{had}
  - ➨ $\alpha_s(m_W)$ to 0.0002
- Radiative returns $e^+e^-\to\gamma Z$ ($Z\to\nu\nu$, $\mu^+\mu^-$)
  - ➨ N_ν to 0.0004

tt threshold scan: MegaTops



- Threshold scan + 4D fit
  - ➨ m_{top} to 10 MeV
  - ➨ λ_{top} to 13%
  - ➧ EWK couplings to 1–10%

■ Mostly thanks to: (i) huge stats, (ii) threshold scans with E_{beam}~0.1 MeV

High-precision W,Z,top: FCC-ee uncertainties

- Experimental uncertainties mostly of systematic origin
  - So far, mostly conservatively estimated based on LEP experience
  - Work ahead to establish more solid numbers

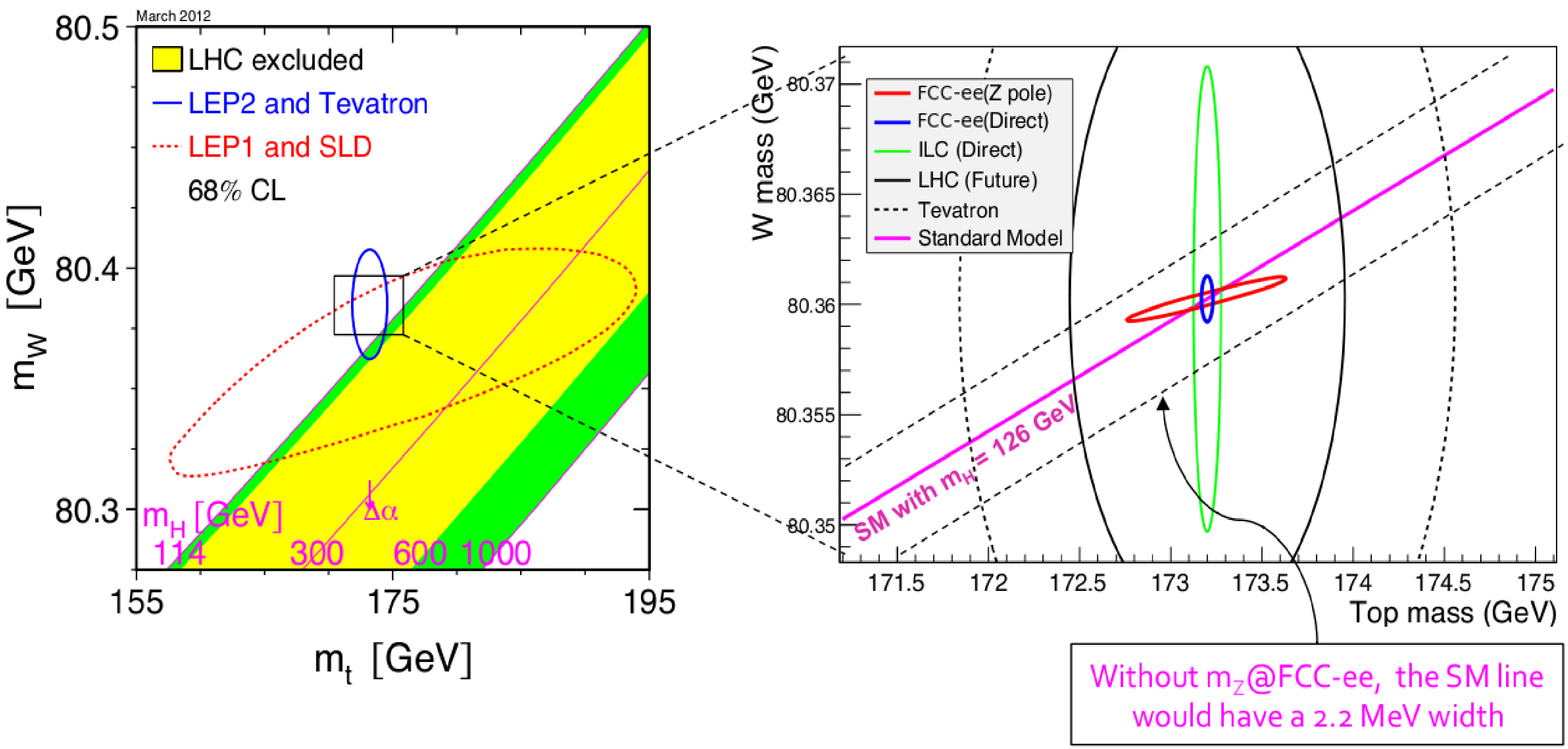
Observable	Measurement	Current precision	FCC-ee stat.	Possible syst.	Challenge
m_Z (MeV)	Lineshape	91187.5 ± 2.1	0.005	< 0.1	QED corr.
Γ_Z (MeV)	Lineshape	2495.2 ± 2.3	0.008	< 0.1	QED corr.
R_l	Peak	20.767 ± 0.025	0.0001	< 0.001	Statistics
R_b	Peak	0.21629 ± 0.00066	0.000003	< 0.00006	g -> bb
N_ν	Peak	2.984 ± 0.008	0.00004	0.004	Lumi meast.
$A_{FB}^{\mu\mu}$	Peak	0.0171 ± 0.0010	0.000004	<0.00001	E_{beam} meast.
$\alpha_s(m_Z)$	R_l	0.1190 ± 0.0025	0.000001	0.00015	New Physics
m_W (MeV)	Threshold scan	80385 ± 15	0.3	< 1	QED corr.
N_ν	Radiative return e^+e^- -> γZ(inv)	2.92 ± 0.05 2.984 ± 0.008	0.0008	< 0.001	?
$\alpha_s(m_W)$	$B_{had} = (\Gamma_{had}/\Gamma_{tot})_W$	B_{had} = 67.41 ± 0.27	0.00018	0.00015	CKM Matrix
m_{top} (MeV)	Threshold scan	173200 ± 900	10	10	QCD (~40 MeV)

Generally better by factor ≥ 25

- Theoretical developments needed to match expected experimental uncertainties

High-precision W,Z,top: BSM constraints

- **Combination of all precision electroweak measurements (Z, W, top)**
  - In absence of new physics, the (m_{top}, m_W) plot would look like this



- Indirect constraints on new weakly-coupled physics:
  Precision ~ $1/\Lambda^2_{NP}$, i.e. Λ^2_{NP} ~ O(30 TeV)

High-precision W,Z,top: Weakly-coupled BSM

- Higher-dimensional operators as relic of new physics
  - Possible corrections to the Standard Model Lagrangian

Dim-6 operators
Pomarol & Riva basis
1308.1426

$$L_{\rm eff} = \sum_n \frac{c_n v^2}{2} O_n$$

$$\mathcal{O}_R^e = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{e}_R \gamma^\mu e_R)$$

$$\mathcal{O}_{LL}^{(3)\,l} = (\bar{L}_L \sigma^a \gamma^\mu L_L)\,(\bar{L}_L \sigma^a \gamma_\mu L_L)$$

$$\mathcal{O}_W = \frac{ig}{2}\left(H^\dagger \sigma^a \overleftrightarrow{D^\mu} H\right) D^\nu W^a_{\mu\nu}$$

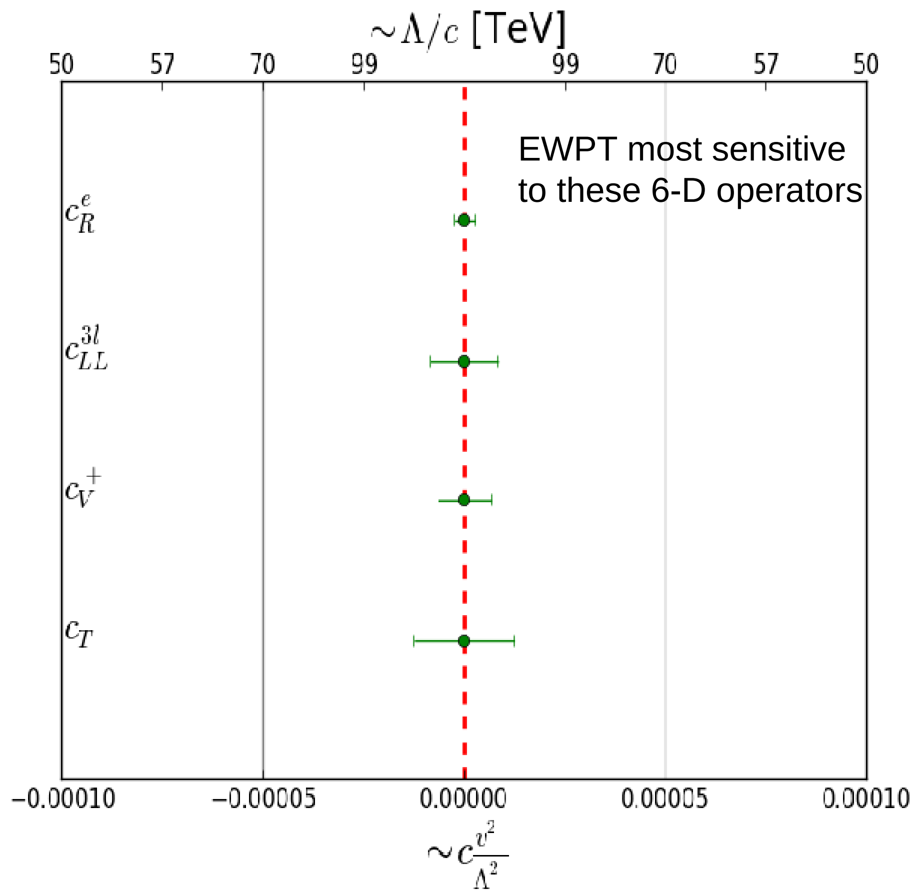
$$\mathcal{O}_B = \frac{ig'}{2}\left(H^\dagger \overleftrightarrow{D^\mu} H\right) \partial^\nu B_{\mu\nu}$$

$$\mathcal{O}_T = \frac{1}{2}\left(H^\dagger \overleftrightarrow{D}_\mu H\right)^2$$

LEP constraints: Λ_{NP} >3-10 TeV

After FCC-ee: Λ_{NP} > 30-100 TeV

Sensitivity to Weakly-coupled NP



J. Ellis, T. You, see e.g. 8th FCC-ee Workshop, Paris, Oct. 2014

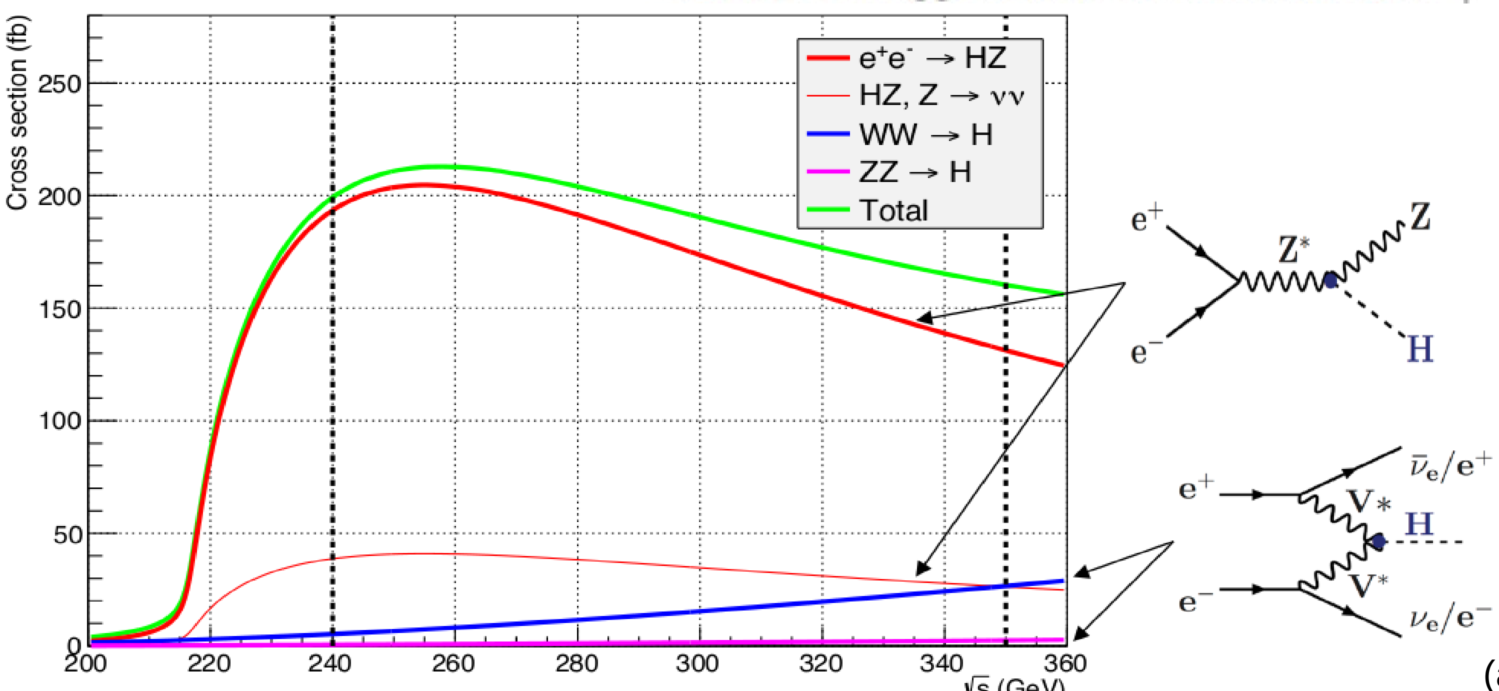
Higgs physics at FCC-ee

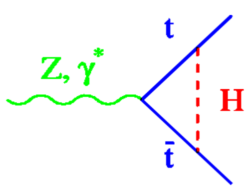
- Precision (<1%) Higgs couplings studies, plus total width.
- Higgs self-coupling constrain through loop corrections.
- 1st (uds, e±) and 2nd fermion generation Yukawa couplings.
- Rare and exotic decays, in particular DM decays.

Thanks to huge, clean datasets:

	FCC-ee
Total Integrated Luminosity (ab^{-1})	10
Number of Higgs bosons from $e^+e^- \to HZ$	2,000,000
Number of Higgs bosons from boson fusion	50,000

Unpolarized cross sections



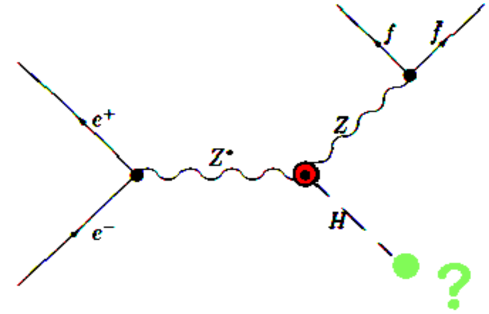


(also sensitivity to y_t)

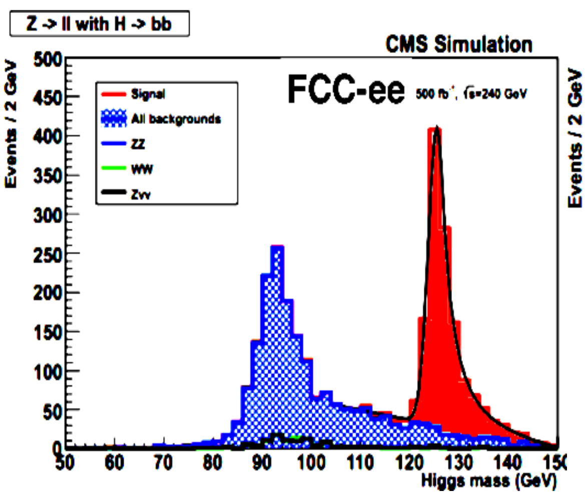
Precision Higgs couplings & total width

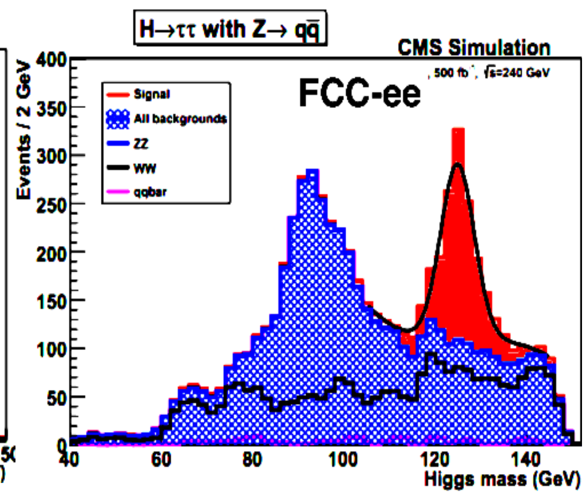
- Recoil method in H-Z is unique to lepton collider, allows to tag Higgs event independent of its decay mode.

  Provides high-precision (0.05%) measurement of $\sigma(ee \to ZH) \propto g_{HZ}^2$



$$m^2_{\rm recoil} = (\sqrt{s} - E_{\ell\ell})^2 - |\vec{p}_{\ell\ell}|^2$$





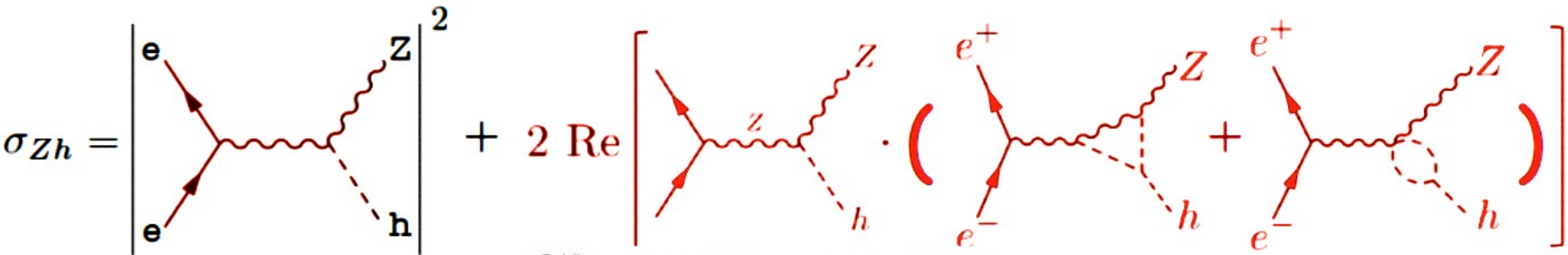
	Model-independent fit		
	FCC-ee -240	FCC-ee	
g_{HZZ}	0.16%	**0.15%**	(0.18%)
g_{HWW}	0.85%	**0.19%**	(0.23%)
g_{Hbb}	0.88%	**0.42%**	(0.52%)
g_{Hcc}	1.0%	**0.71%**	(0.87%)
g_{Hgg}	1.1%	**0.80%**	(0.98%)
$g_{H\tau\tau}$	0.94%	**0.54%**	(0.66%)
$g_{H\mu\mu}$	6.4%	**6.2%**	(7.6%)
$g_{H\gamma\gamma}$	1.7%	**1.5%**	(1.8%)
BR_{exo}	0.48%	**0.45%**	(0.55%)

stat. uncertainties

- Total width (Γ_H) with <1% precision from combination of measurements:
  $\sigma(ee \to ZH(\to X)) \propto \Gamma_{H\to X}$, plus known BR ($H \to X$): Obtain Γ_H
- Branching fraction to invisible tested directly to 0.2% @ 95% CL

Higgs physics at FCC-ee(240): Self-coupling

- Higgs self-coupling through loop corrections to σ(H+Z):



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

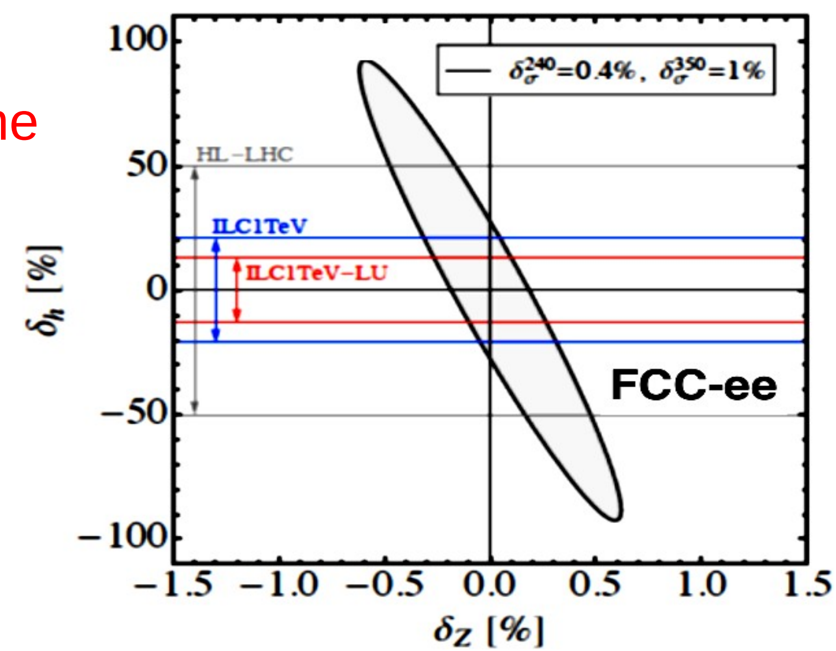
Self-coupling correction δ_h: energy-dependent

δ_Z: energy-independent (distinguishable).

[M. McCullough, 2014]

- Tiny effect but visible thanks to extreme precision on g_{ZH} (0.05%) coupling reachable at FCC-ee.

- Indirect and model-dependent limits on trilinear Higgs coupling can be set (~70% level) comparable to HL-LHC

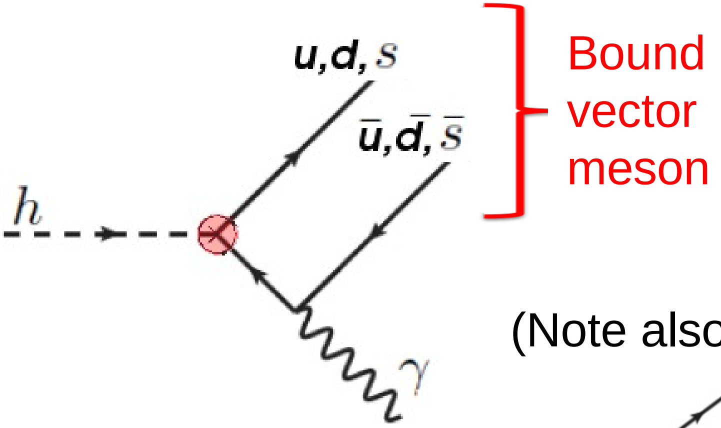


Higgs physics at FCC-ee: 1st-gen. Yukawa

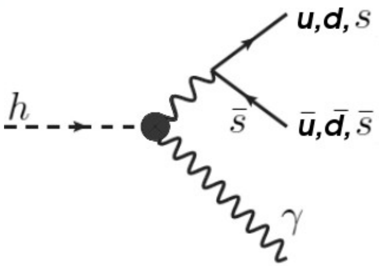
- First and second generation couplings accessible
  - Study of **ργ channel** most promising; expect ~50 evts.
  - Sensitivity to u/d quark Yukawa coupling
  - Sensitivity due to interference

$$\frac{\mathrm{BR}_{h\to\rho\gamma}}{\mathrm{BR}_{h\to b\bar{b}}} = \frac{\kappa_\gamma\left[(1.9\pm0.15)\kappa_\gamma - 0.24\bar{\kappa}_u - 0.12\bar{\kappa}_d\right]}{0.57\bar{\kappa}_b^2}\times 10^{-5}$$

- Alternative H→MV decays should be studied (V= γ, W, and Z)



(Note also):



$H \to \rho\,\gamma$
$H \to \omega\,\gamma$ ➡ y_u, y_d

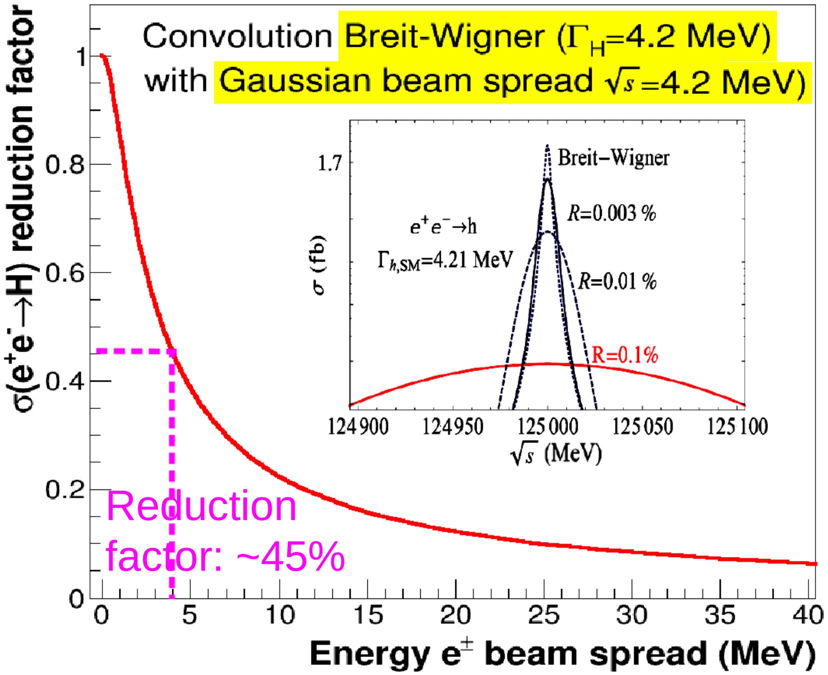
$H \to \phi\,\gamma$ ➡ y_s

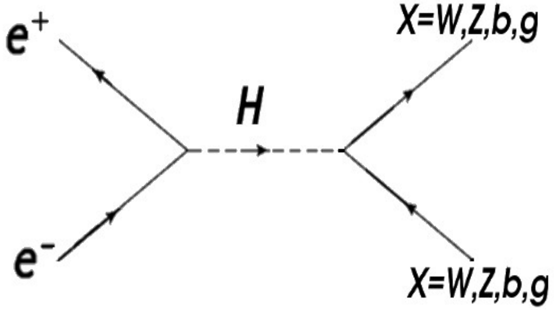
$H \to J/\Psi\,\gamma$ ➡ y_c

Higgs physics at FCC-ee(125): e± Yukawa

- Higgs-e± Yukawa g_{Hee} unobservable via decay: BR($H \to e^+e^-$)~$5.3 \cdot 10^{-9}$
- Resonant s-channel production considered so far only for μμ collider ($\sigma_{\mu\mu\to H}$ ~ 70 pb). $\frac{g_{H\mu\mu}}{g_{Hee}} \propto \frac{m_\mu^2}{m_e^2} = 4.28 \times 10^4$ ⇒ Tiny σ(ee→H)

$$\sigma(e^+ e^- \to H) = \frac{4\pi\Gamma_H^2 Br(H \to e^+e^-)}{(\hat{s} - M_H^2)^2 + \Gamma_H^2 M_H^2} = 1.6 \text{ fb}$$





Including ISR + $\sqrt{\sigma_{spread}} \sim \Gamma_H$ = 4.2 MeV:

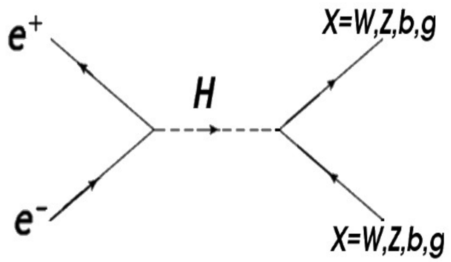
σ(ee→H) = 280 ab

- Is the measurement of Higgs to electron coupling completely hopeless ?

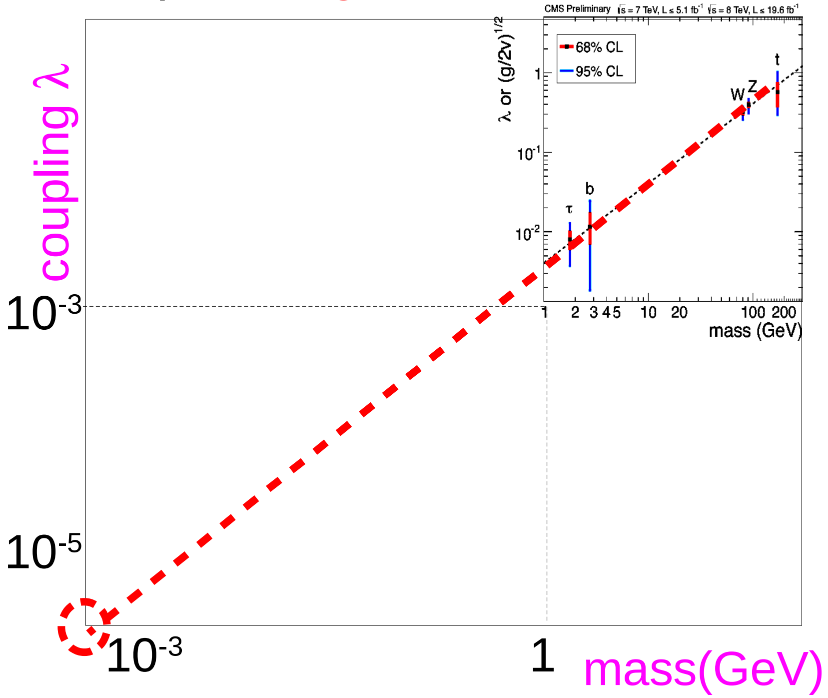
Higgs physics at FCC-ee(125): e± Yukawa

- Higgs-e± Yukawa g_{Hee} unobservable via decay: BR($H \to e^+e^-$)~$5.3 \cdot 10^{-9}$
- Resonant s-channel production considered so far only for μμ collider ($\sigma_{\mu\mu\to H}$ ~ 70 pb). $\frac{g_{H\mu\mu}}{g_{Hee}} \propto \frac{m_\mu^2}{m_e^2} = 4.28 \times 10^4$ $\Rightarrow$ Tiny σ(ee→H)

$$\sigma(e^+ e^- \to H) = \frac{4\pi\Gamma_H^2 Br(H \to e^+ e^-)}{(\hat{s} - M_H^2)^2 + \Gamma_H^2 M_H^2} = 280 \text{ ab} \qquad (\text{ISR} + \sqrt{\sigma_{spread}} = \Gamma_H)$$



- Exploit huge luminosities available at FCC-ee:



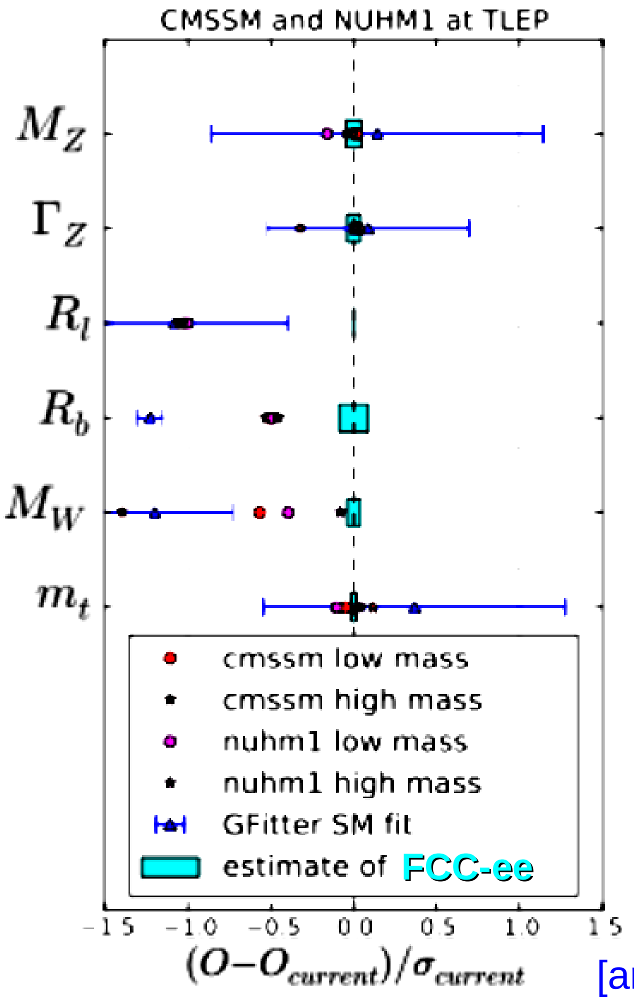
→ $\sqrt{s}_{spread}$ reduceable with mono-chromators (but <20 MeV challenging).

→ Analysis of 7 Higgs decay channels:
L_{int} = 10 ab^{-1}, S=0.65:
BR(Hee) < 4.6×BR_{SM} (3σ)
g_{hee} < 2.2 × $g_{Hee,SM}$ (3σ)

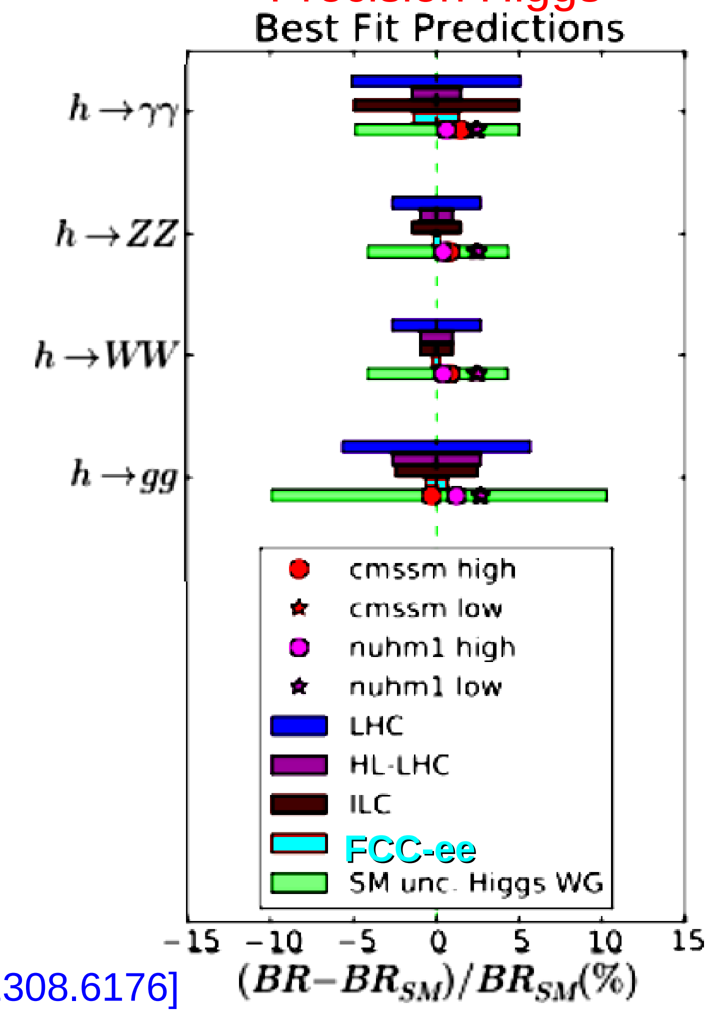
New physics constraints (1): SUSY

- FCC-ee measurements significantly improve limits in benchmark SUSY models (CMSSM, NUHM1):

Precision Electroweak



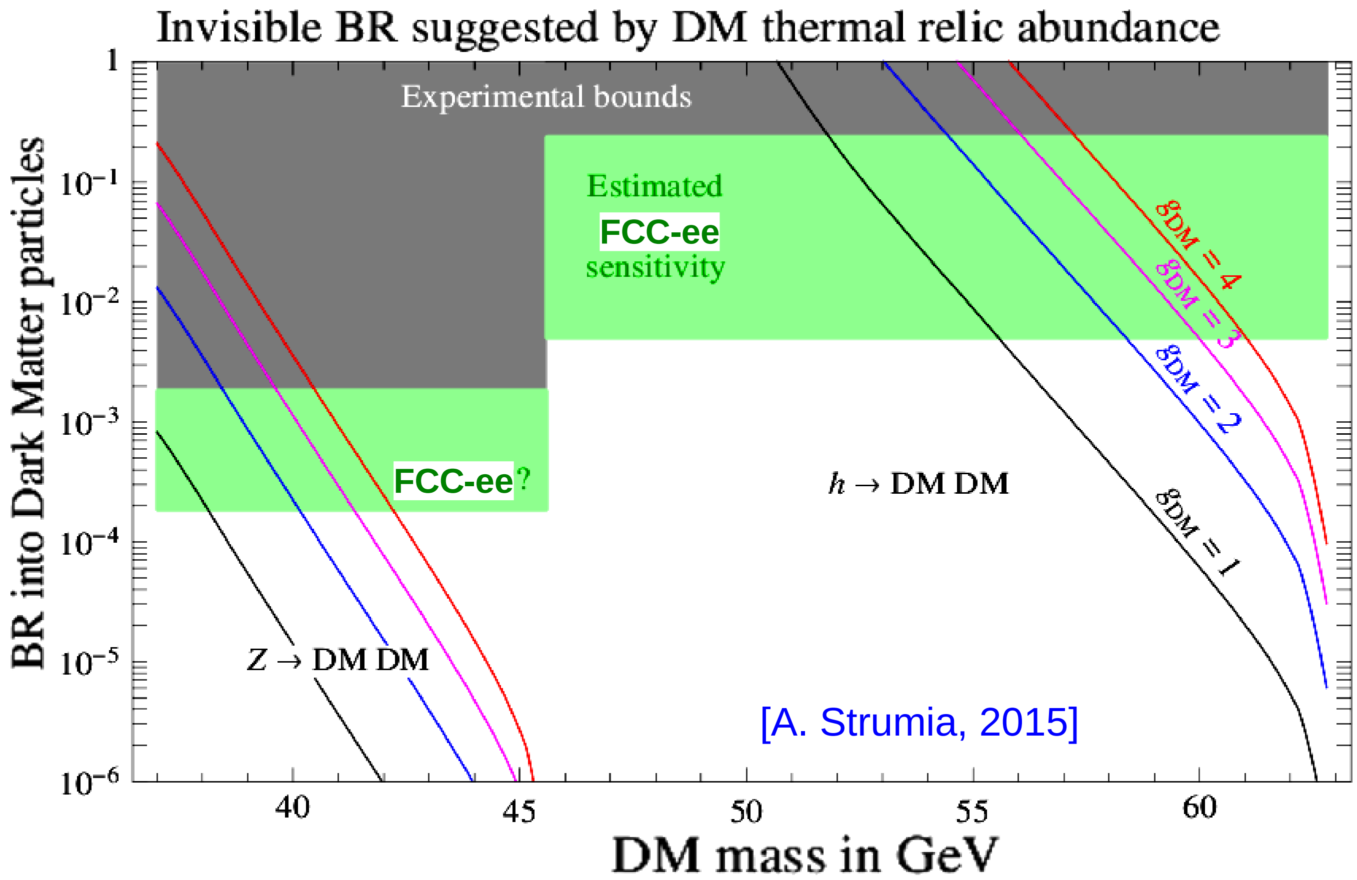
Precision Higgs



[arXiv:1308.6176]

New physics constraints (2): Dark Matter

- DM freeze-out fixes $\sigma v \approx 3\ 10^{-26} cm^3/s$. If m_{DM} is just below $m_{Z,H}/2$, DM freeze-out dominated by resonant Z,H exchange, fixing $\Gamma_{Z,H}$.



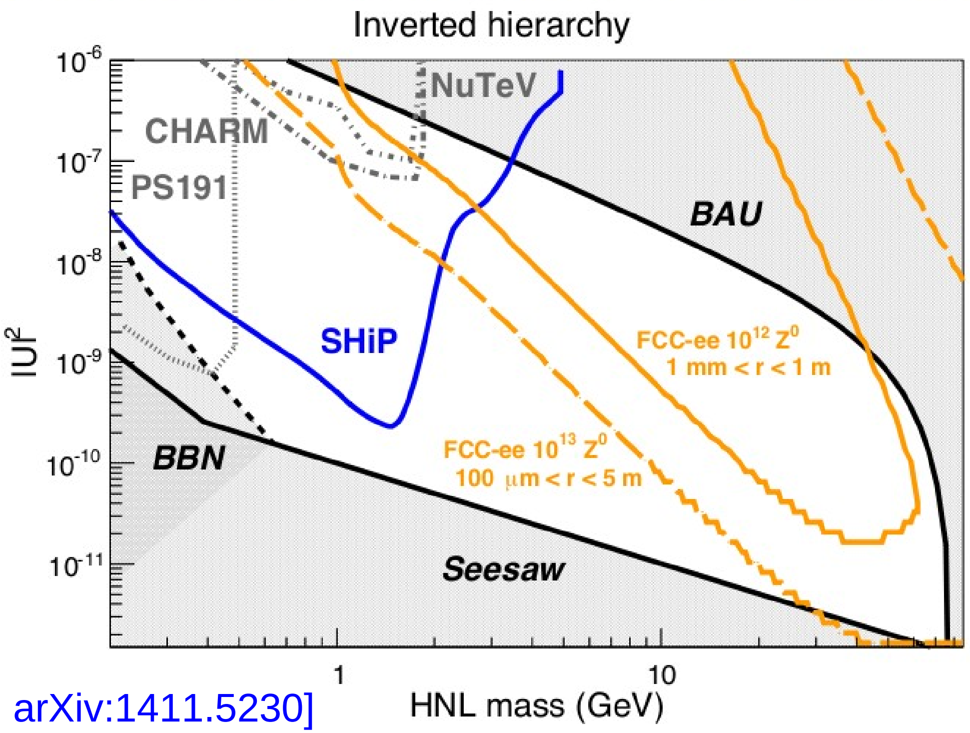
- $<10^{-3}$ and $<10^{-1}$ precision measurements of invisible Z & H widths are best collider option to test any $m_{DM}<m_{Z,H}/2$ that couples via SM mediators.

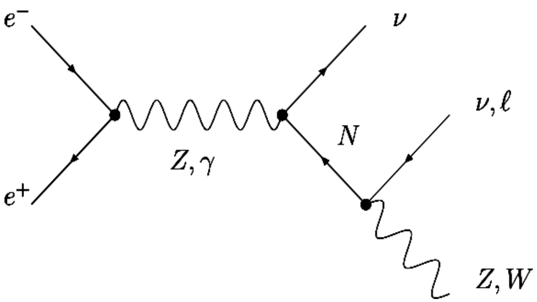
New physics constraints (3): RH neutrinos

- Opportunities for direct searches for new physics through rare decays
  - 10^{12} (10^{13}) Z, 10^{11} b, c or τ : A fantastic potential that remains to be explored.
  - E.g, search for right-handed neutrino in Z decays

$$Z \rightarrow N\nu_i, \text{ with } N \rightarrow W^* l \text{ or } Z^* \nu_j$$

- Number of events depend on mixing between N and ν, and on m_N



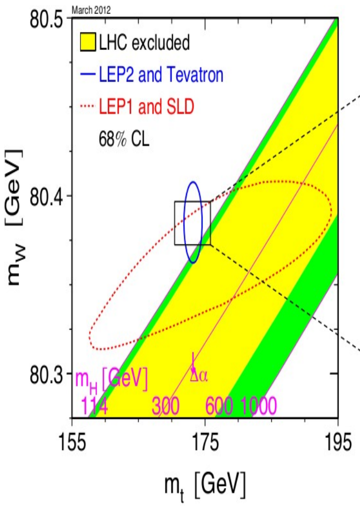


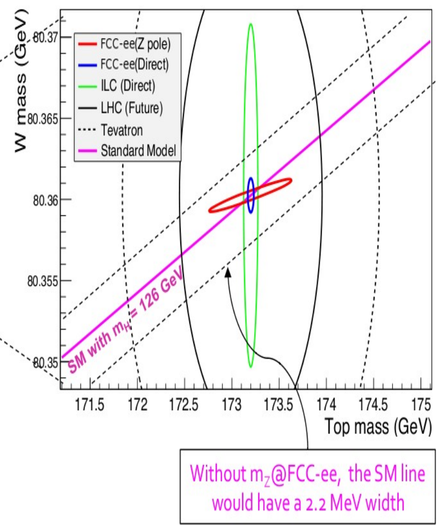
(Also through H decays)

[A. Blondel et al. arXiv:1411.5230]

Summary

- FCC-ee circular (R~100 km) collider provides unparalleled luminosities O(1-100 ab^{-1}) at $\sqrt{s}$ = 90–350 GeV for high-precision W,Z,H,t studies (<<1% uncert.) setting unique new physics constraints up to O(30 TeV):





	Model-independent fit	
	FCC-ee-240	FCC-ee
g_{HZZ}	0.16%	**0.15%** (0.18%)
g_{HWW}	0.85%	**0.19%** (0.23%)
g_{Hbb}	0.88%	**0.42%** (0.52%)
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$g_{H\mu\mu}$	6.4%	**6.2%** (7.6%)
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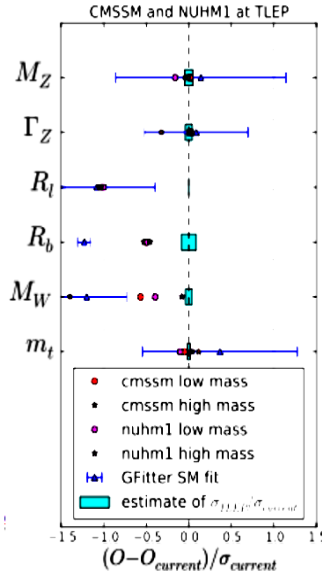
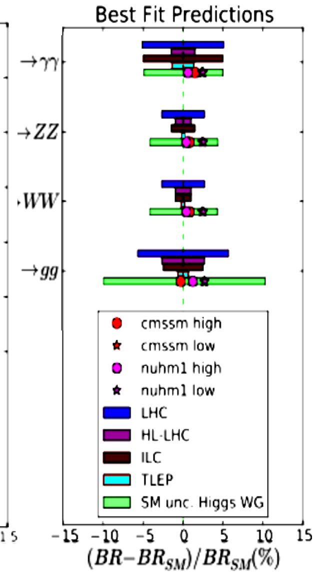
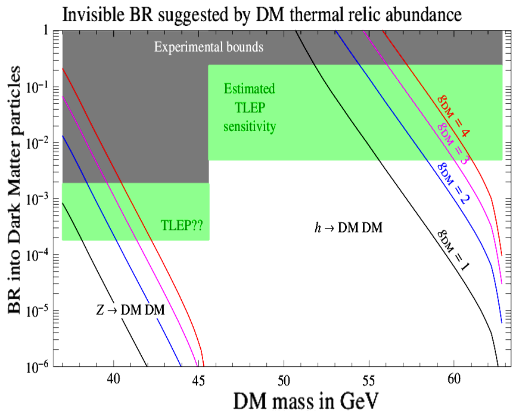
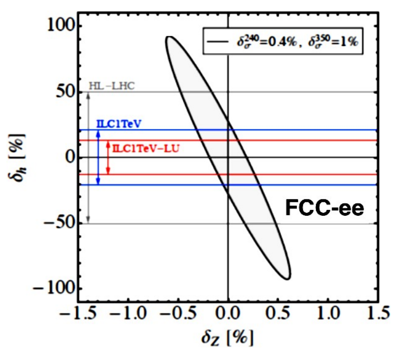
BR_{exo}	0.48%	**0.45%** (0.55%)

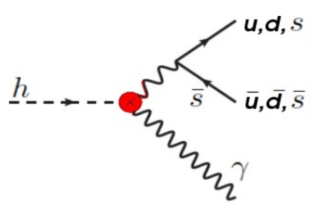
stat. uncertainties

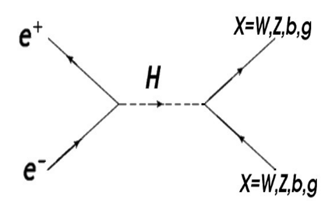


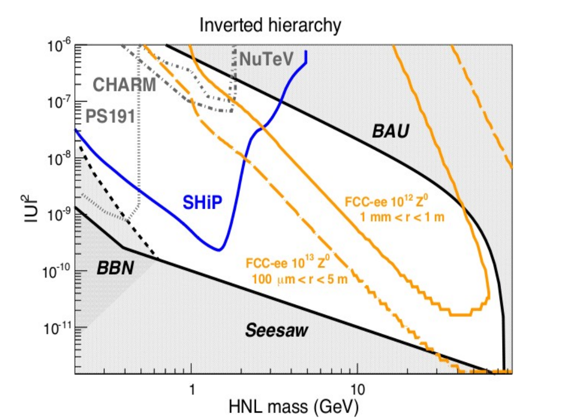










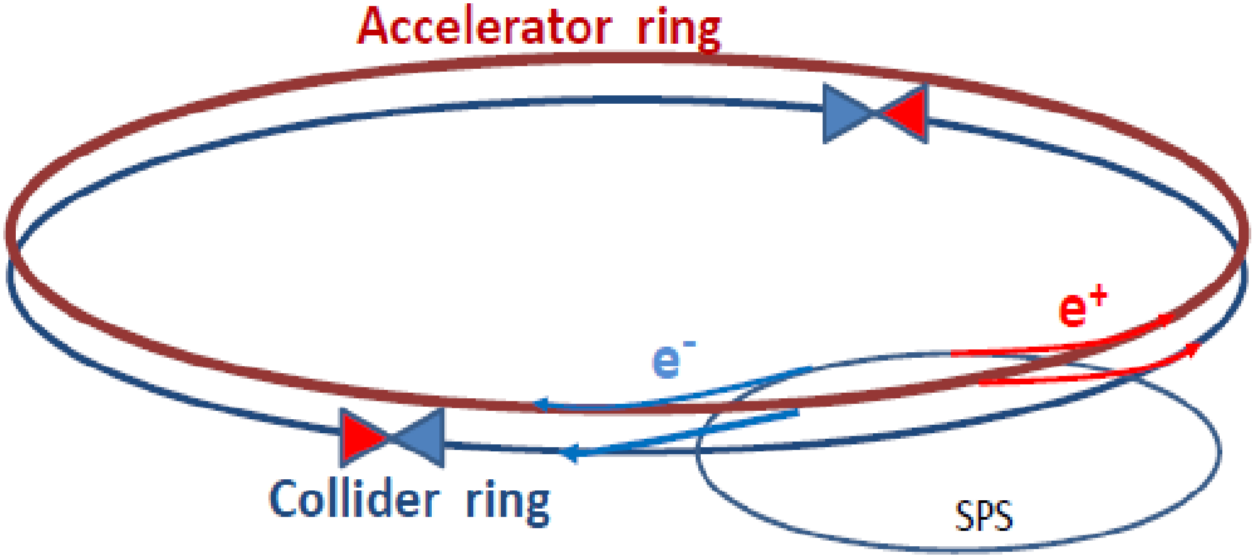


Backup slides

Luminosity gain: FCC-ee vs. LEP

Employ B-factory design to gain factor ~500 w.r.t. LEP:
Low vertical emittance combined small value of β^*_y (very strong focussing in vertical plane):

- Electrons and positrons have a much higher chance of interacting
- ➢ Very short beam lifetimes (few minutes)
- ➢ Top-up injection: feed beam continuously with an ancillary accelerator



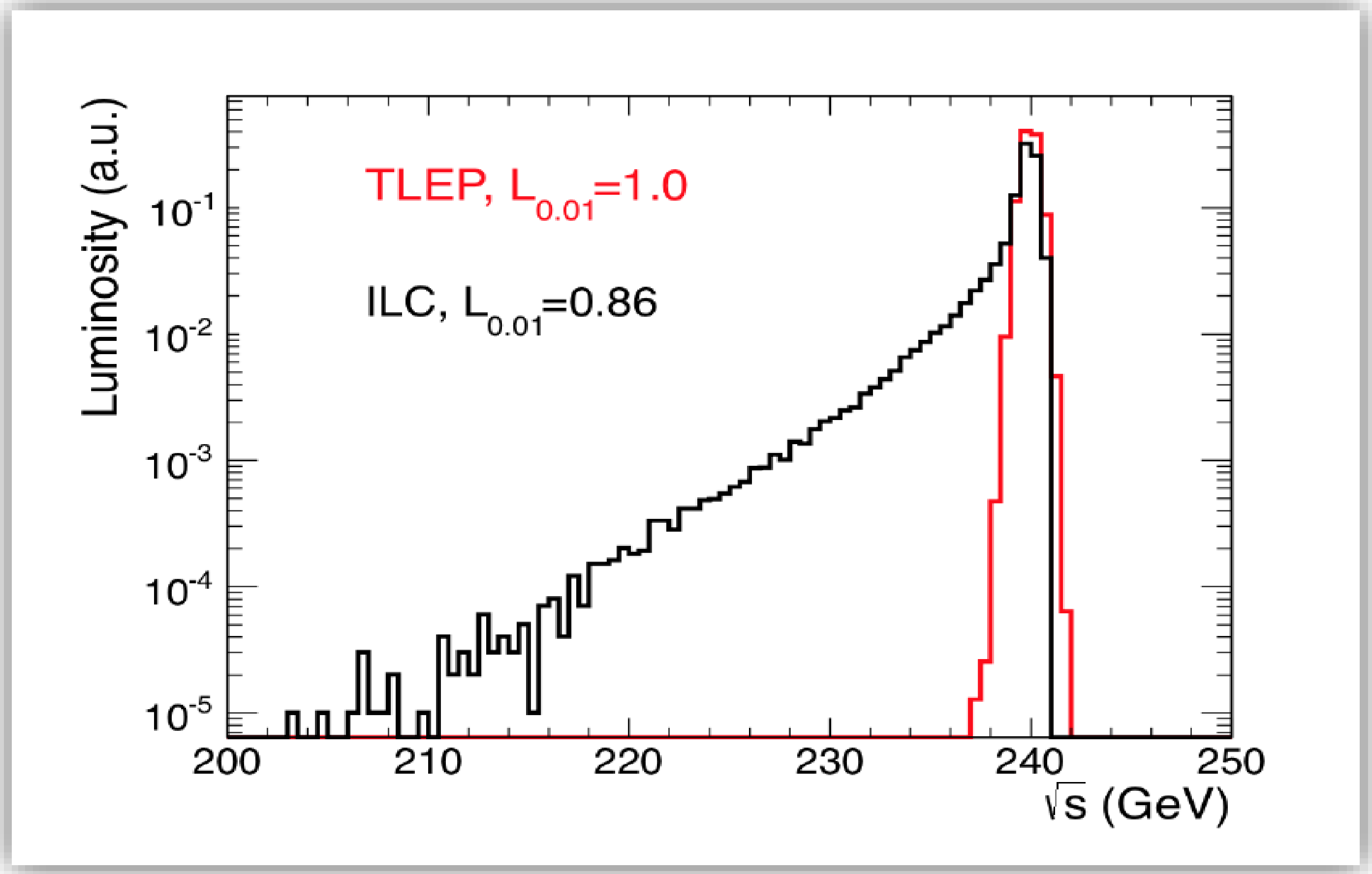
Two separate beam pipes for e^+ and e^- to avoid collisions away from IPs

Hence, a total of three beam pipes

e+e- colliders: FCC-ee vs. LEP, CepC

parameter	LEP2	FCC-ee					CepC
		Z	Z (c.w.)	W	H	t	H
E_{beam} [GeV]	104	45	45	80	120	175	120
circumference [km]	26.7	100	100	100	100	100	54
current [mA]	3.0	1450	1431	152	30	6.6	16.6
$P_{SR,tot}$ [MW]	22	100	100	100	100	100	100
no. bunches	4	16700	29791	4490	1360	98	50
N_b [10^{11}]	4.2	1.8	1.0	0.7	0.46	1.4	3.7
ε_x [nm]	22	29	0.14	3.3	0.94	2	6.8
ε_y [pm]	250	60	1	1	2	2	20
β^*_x [m]	1.2	0.5	0.5	0.5	0.5	1.0	0.8
β^*_y [mm]	50	1	1	1	1	1	1.2
σ^*_y [nm]	3500	250	32	130	44	45	160
$\sigma_{z,SR}$ [mm]	11.5	1.64	2.7	1.01	0.81	1.16	2.3
$\sigma_{z,tot}$ [mm] (w beamstr.)	11.5	2.56	5.9	1.49	1.17	1.49	2.7
hourglass factor F_{hg}	0.99	0.64	0.94	0.79	0.80	0.73	0.61
L/IP [10^{34} cm^{-2}s^{-1}]	0.01	28	212	12	6	1.7	1.8
τ_{beam} [min]	300	287	39	72	30	23	40

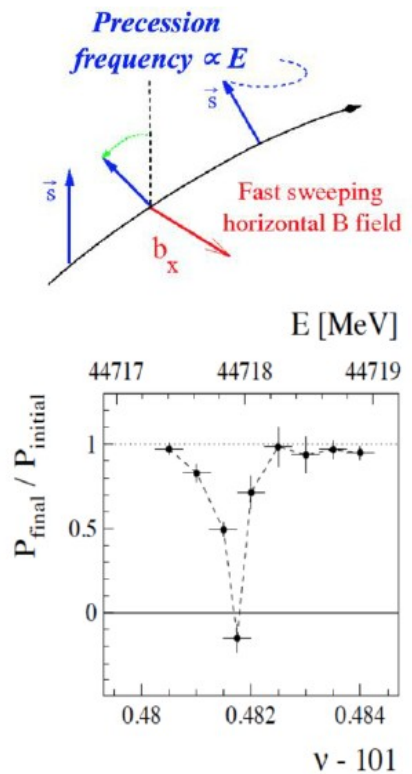
FCC-ee beam energy spread



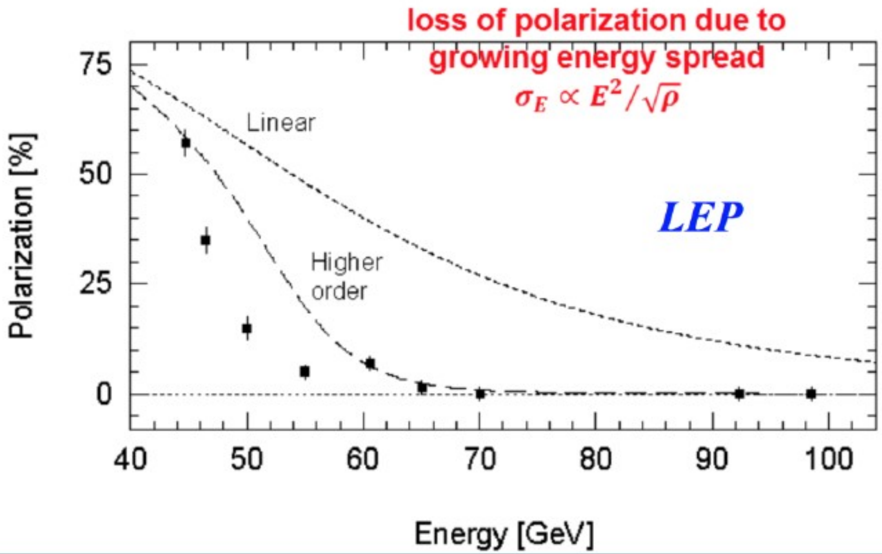
Non-destructive focusing and collision of beams:
- Center-of-mass energy spread by construction modest

Beam energy spread via resonant depolarization

Resonant depolarization
- use naturally occuring transverse beam polarization
- add fast oscillating horizontal B field to depolarize at Thomas precession frequency



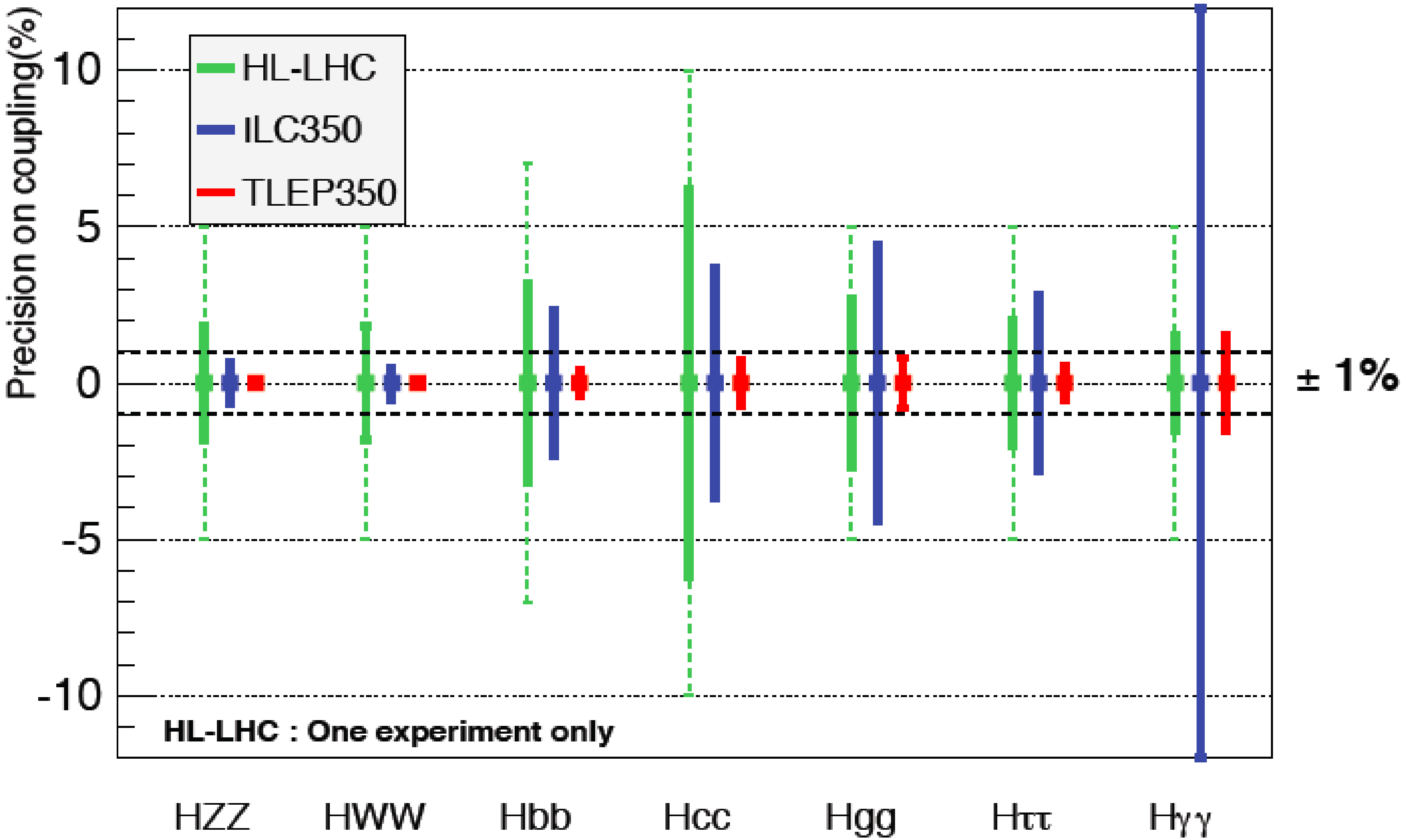
Experience from LEP: Depolarization resonance very narrow: ~100 keV precision for each measurement
- However, final systematic uncertainty was 1.5 MeV due to transport from dedicated polarization runs
- At FCC-ee, continuous calibration with dedicated bunches: no transport uncertainty



Scaling from LEP experience:
- Polarization expected up to the WW threshold

< 100 keV beam energy calibration at Z peak and at WW threshold

Higgs couplings: FCC-ee uncertainties



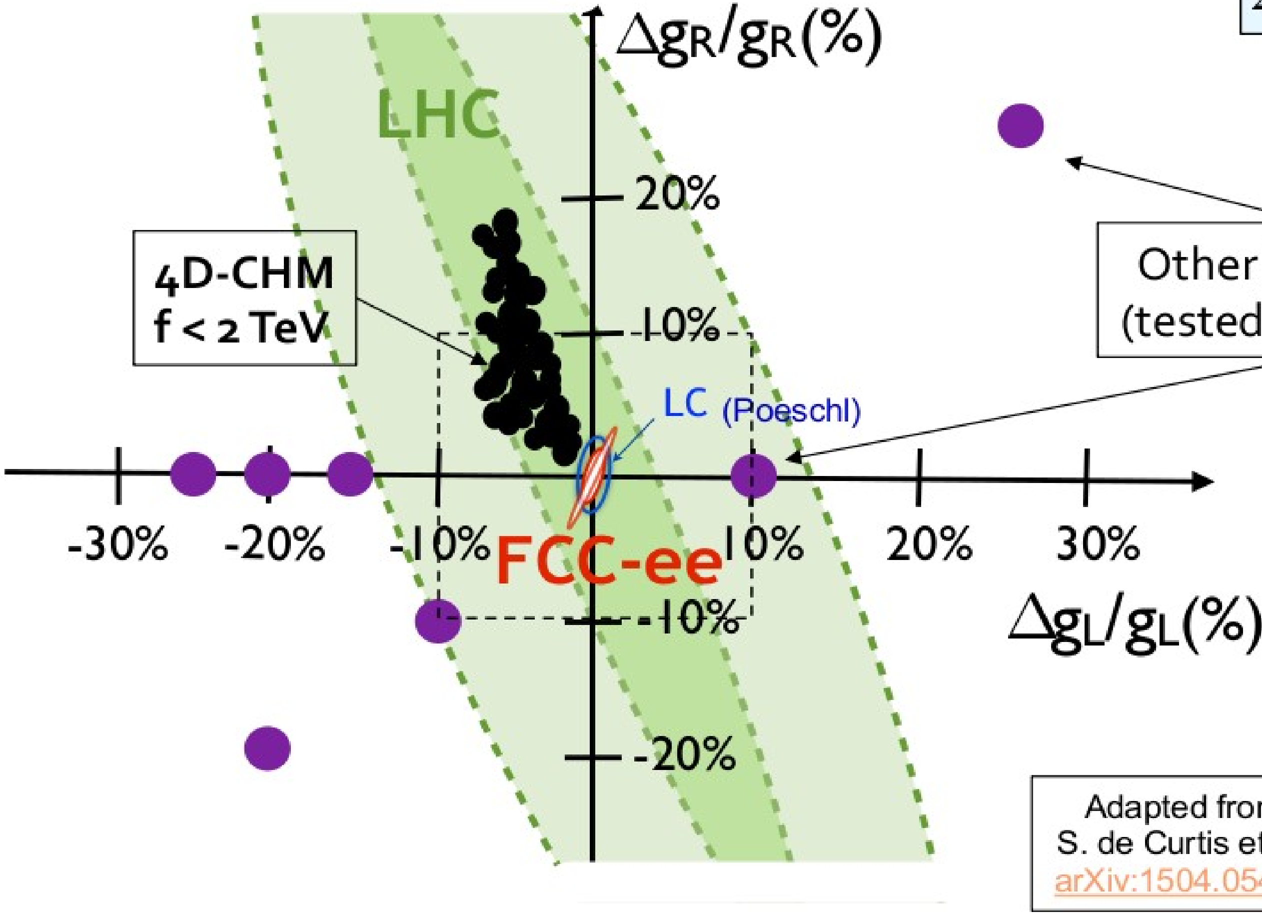
Higgs couplings: FCC-ee uncertainties

Facility		ILC		ILC(LumiUp)	TLEP (4 IP)			CLIC	
$\sqrt{s}$ (GeV)	250	500	1000	250/500/1000	240	350	350	1400	3000
$\int \mathcal{L}dt$ (fb^{-1})	250	+500	+1000	1150+1600+2500‡	10000	+2600	500	+1500	+2000
$P(e^-, e^+)$	$(-0.8, +0.3)$	$(-0.8, +0.3)$	$(-0.8, +0.2)$	(same)	$(0, 0)$	$(0, 0)$	$(-0.8, 0)$	$(-0.8, 0)$	$(-0.8, 0)$
Γ_H	12%	5.0%	4.6%	2.5%	1.9%	1.0%	9.2%	8.5%	8.4%
κ_γ	18%	8.4%	4.0%	2.4%	1.7%	1.5%	–	5.9%	<5.9%
κ_g	6.4%	2.3%	1.6%	0.9%	1.1%	0.8%	4.1%	2.3%	2.2%
κ_W	4.9%	1.2%	1.2%	0.6%	0.85%	0.19%	2.6%	2.1%	2.1%
κ_Z	1.3%	1.0%	1.0%	0.5%	0.16%	0.15%	2.1%	2.1%	2.1%
κ_μ	91%	91%	16%	10%	6.4%	6.2%	–	11%	5.6%
κ_τ	5.8%	2.4%	1.8%	1.0%	0.94%	0.54%	4.0%	2.5%	<2.5%
κ_c	6.8%	2.8%	1.8%	1.1%	1.0%	0.71%	3.8%	2.4%	2.2%
κ_b	5.3%	1.7%	1.3%	0.8%	0.88%	0.42%	2.8%	2.2%	2.1%
κ_t	–	14%	3.2%	2.0%	–	13%	–	4.5%	<4.5%
BR_{inv}	0.9%	$< 0.9\%$	$< 0.9\%$	0.4%	0.19%	$< 0.19\%$			

FCC-ee sensitivity to new physics: Composite Higgs

- Example: $t_L t_L Z$ and $t_R t_R Z$ couplings, g_L and g_R
  - Couplings most sensitive to composite Higgs models

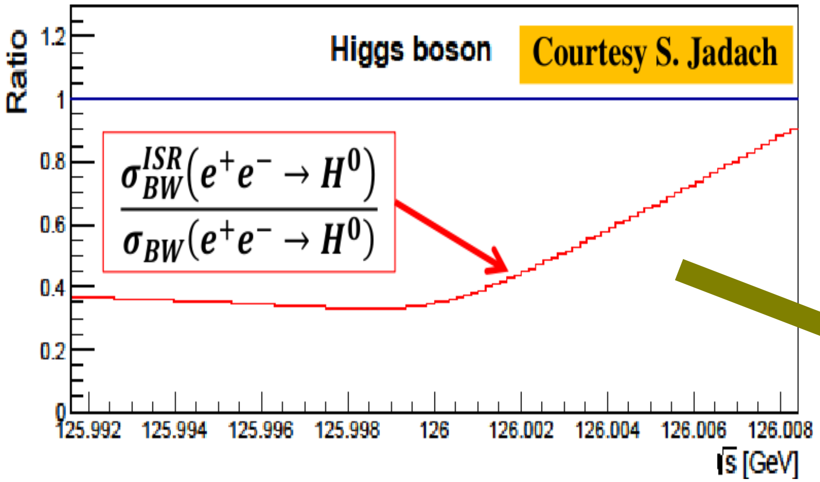
$$2eF_{1V}^Z = g_R + g_L$$
$$2eF_{1A}^Z = g_R - g_L$$

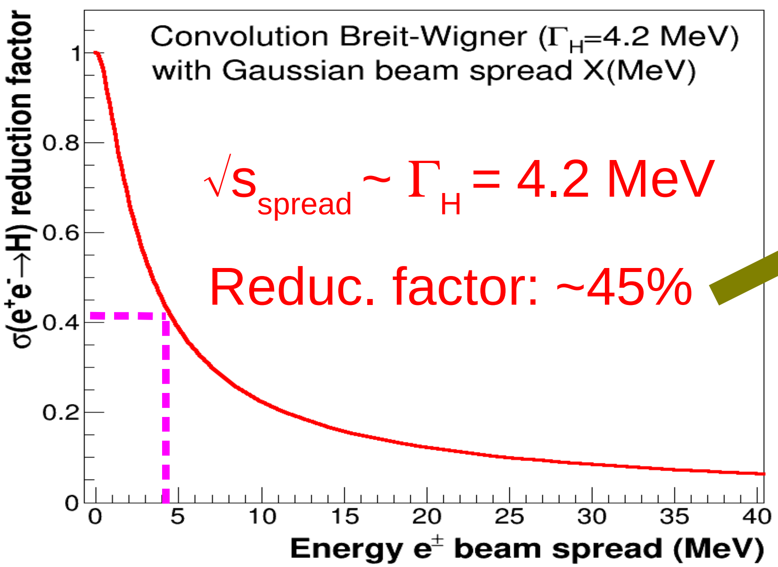


Adapted from
S. de Curtis et al.
arXiv:1504.05407

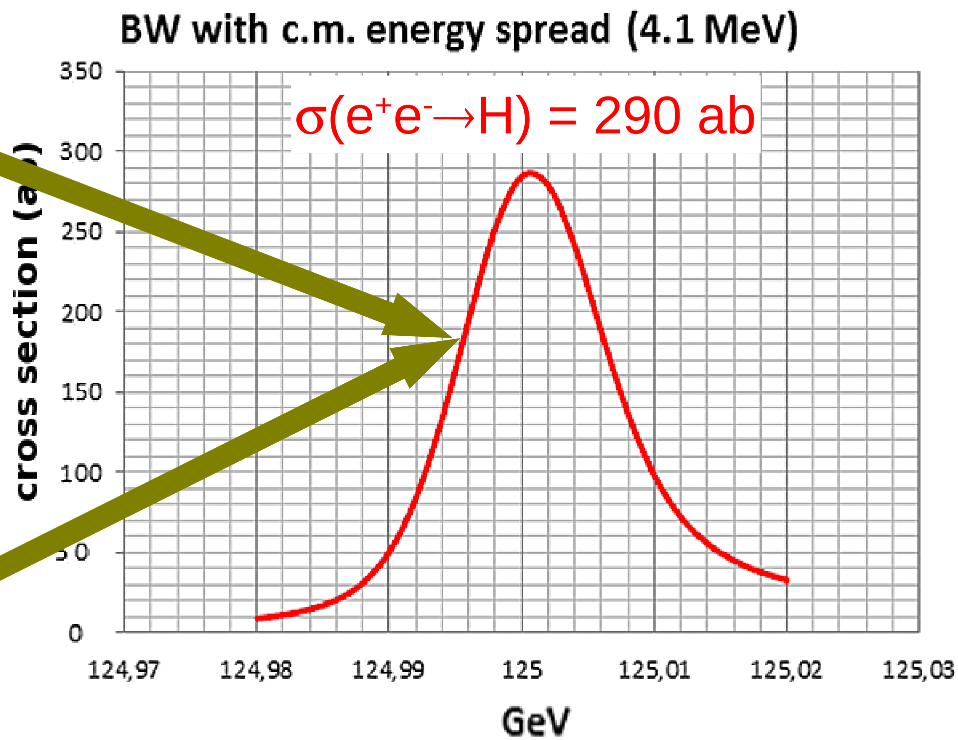
$\sigma(e^+e^- \to H)$ reduction: Beam energy spread + ISR

- Extra ~40% reduction also due to initial state radiation:





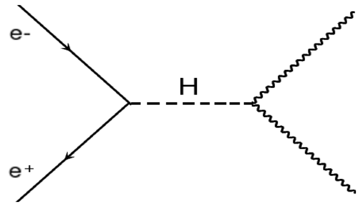
- Combined reduction factors:



$\sigma_{beam\text{-}spread+ISR}(e^+e^- \to H) = 0.17 \times \sigma(e^+e^- \to H)$

Higgs physics at FCC-ee(125): H-e Yukawa

- Resonant s-channel Higgs production at FCC-ee ($\sqrt{s}$ = 125 GeV):



$\sigma(e^+e^-\to H)_{B\text{-}W} \sim 1.64$ fb

$\sigma(e^+e^-\to H)_{visible} \sim 280$ ab (ISR + $E_{beam\text{-}spread} \sim \Gamma_H = 4.2$ MeV)

- Signal + backgrounds study for 7 decay channels:
  WW*(2j,lν) (σ = 28 ab), WW*(2l2ν) (σ = 6.7 ab),
  WW*(4j) (σ = 29.5 ab), ZZ*(2j2ν) (σ = 2.3 ab), ZZ*(2l2j) (σ = 1.14 ab),
  bb (2j) (σ = 156 ab), gg (2j) (σ = 24 ab)

- Preliminary analysis:
  $L_{int} = 10$ ab^{-1}, S=0.65: BR(Hee) < 4.63×BR_{SM} (3σ), $g_{hee} < 2.15 \times g_{Hee,SM}$ (3σ)
  Evidence (observation?) will require further improvements in large-BR (huge background) jet channels: H→ bb, H → WW → 4j

- Challenging accelerator conditions: mono-chromatization, huge lumi

- Fundamental & unique physics accessible if measurement feasible:
  → Electron Yukawa coupling
  → Higgs width measurable ("natural" threshold scan)