The FCC-ee discovery potential

CDR submitted for publication
10-page documents submitted to ESPP advertizing the FCC integrated programme

Future Circular Collider Study

Volume 2 - The Lepton Collider (FCC-ee)

Conceptual Design Report

P R E P R I N T submitted to Eur. Phys. J. ST

20 December 2018

Volume 1 - Physics Opportunities

Conceptual Design Report

P R E P R I N T submitted to Eur. Phys. J. C

20 December 2018

Future Circular Collider (18 Dec. 2018) The Integrated Programme (FCC-int)

Future Circular Collider
The Integrated Programme (FCC-int)

Contact person: Michael Benedikt (Michael.Benedikt@cern.ch)

Abstract:

The most effective and comprehensive approach to thoroughly explore the open questions in modern particle physics is a staged research programme, integrating in sequence lepton (FCC-ee) and hadron (FCC-hh) collision programmes, to achieve an exhaustive understanding of the Standard Model and of electroweak symmetry breaking, and to maximize the potential for the discovery of phenomena beyond the Standard Model. The project would rely on a shared and cost effective technical and organizational infrastructure, as was the case with LEP followed by LHC. This integrated programme is complementary to other ongoing research activities and leverages cross-disciplinary synergies to expand our understanding of the universe. It cements and enlarges Europe's leadership in particle and high-energy physics for decades to come. This document provides an overview of the physics potential of the integrated FCC programme and outlines its implementation scenario.

The FCC Conceptual Design Report volumes are available for download from 15 January 2019 at **http://fcc-design-report.web.cern.ch**

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Future Circular Collider (18 Dec. 2018) The Lepton Collider (FCC-ee)

Future Circular Collider
The Lepton Collider (FCC-ee)

Contact person: Michael Benedikt (Michael.Benedikt@cern.ch)

Abstract:

This report contains the description of a novel research infrastructure based on a highest-luminosity energy frontier electron-positron collider (FCC-ee) to address the open questions of modern physics. It will be a general precision instrument for the continued in-depth exploration of nature at the smallest scales, optimised to study with high precision the Z, W, Higgs and top particles, with samples of $5 \cdot 10^{12}$ Z bosons, 10^8 W pairs, 10^5 Higgs bosons and 10^6 top quark pairs. FCC-ee offers unprecedented sensitivity to signs of new physics, appearing in the form of small deviations from the Standard Model, of forbidden decay processes or of production of new particles with very small couplings.

This collider will be implemented in stages, successively spanning the entire energy range from the Z pole over the WW threshold and H production peak to the $t\bar{t}$ threshold. Most of the infrastructure (e.g. underground structures, surface sites, electrical distribution, cooling & ventilation, RF systems) can be directly reused for a subsequent energy-frontier hadron collider (FCC-hh, see FCC conceptual design report volume 3), serving the world-wide particle-physics community in a highly synergetic and cost-effective manner throughout the 21st century.

The FCC Conceptual Design Report volumes are available for download from 15 January 2019 at **http://fcc-design-report.web.cern.ch.**

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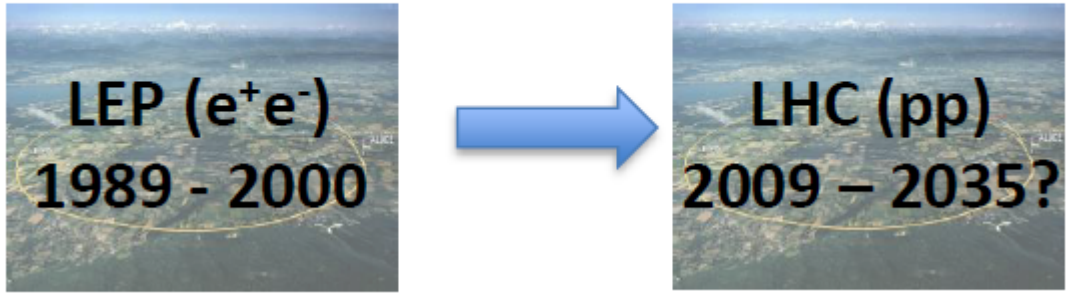
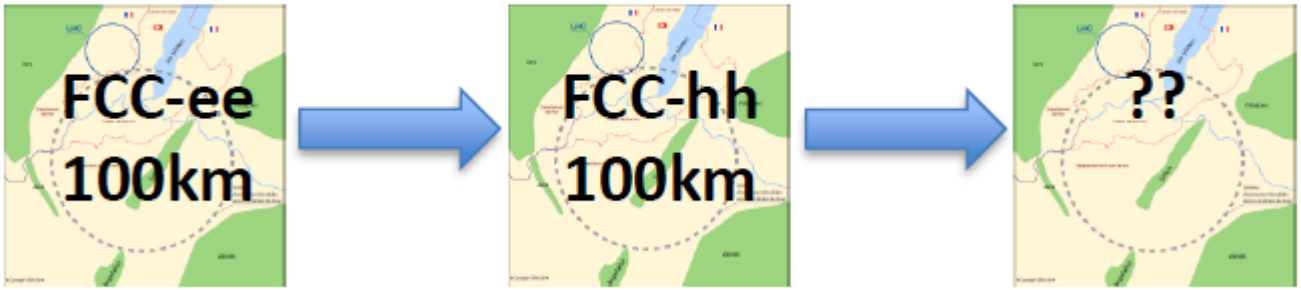
The FCC integrated programme

- **27 km tunnel**



- **The next step: 100 km tunnel**

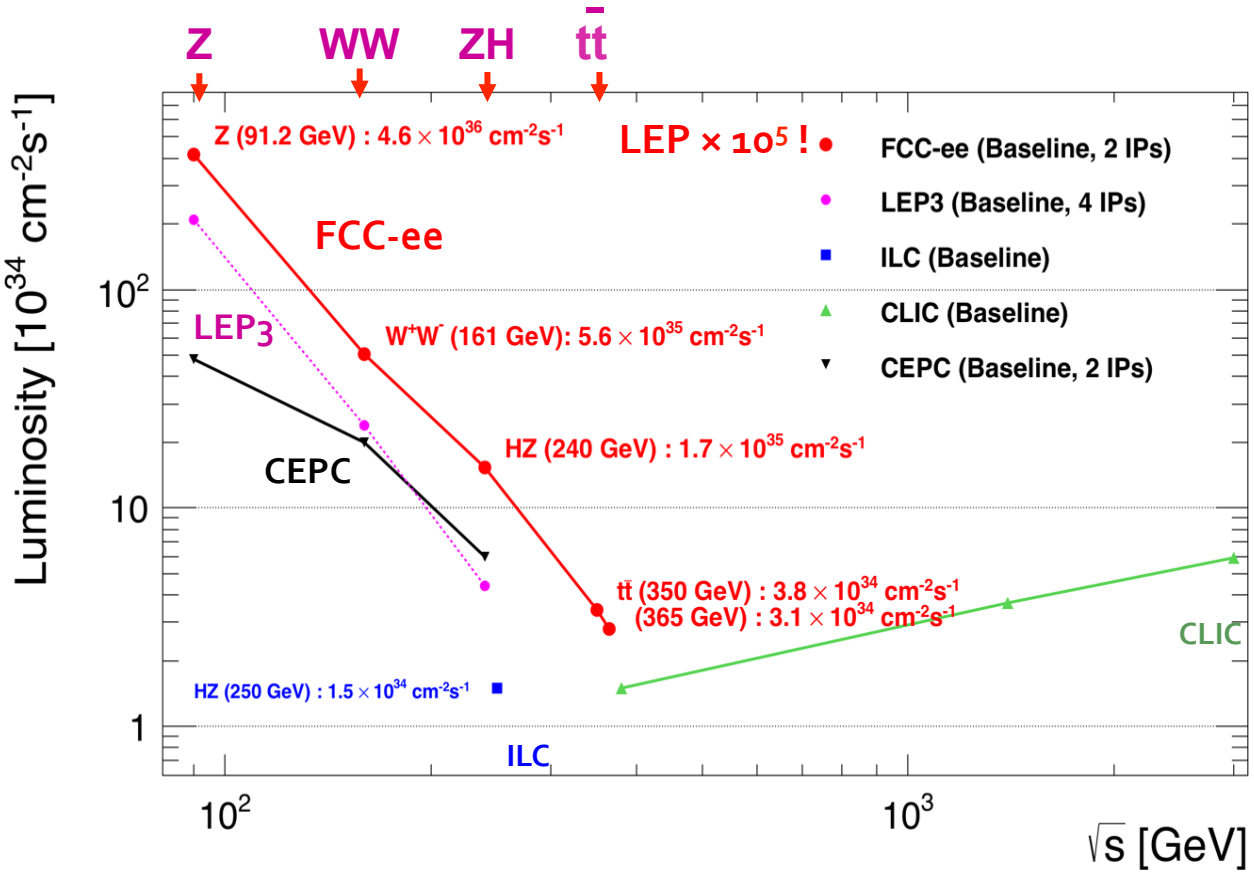
M. Aleksa



- **The FCC-ee can start seamlessly at the end of the HL-LHC**

EW factories : Energies and luminosities

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



- 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

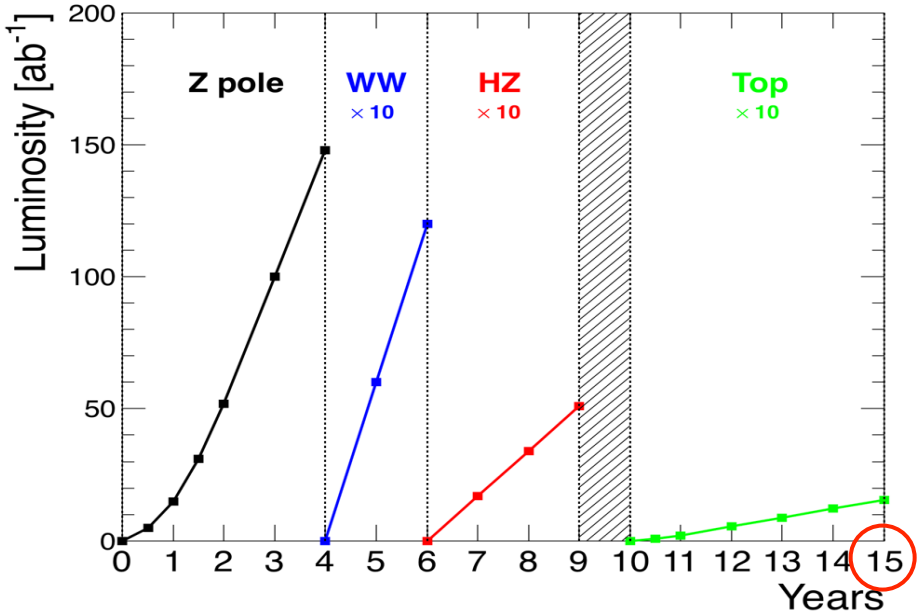
PRECISION and SENSITIVITY to rare or elusive phenomena

- The FCC-ee discovery potential at the precision frontier 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	tt 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} $e^+e^- \rightarrow Z$	100 keV
10^8 $e^+e^- \rightarrow W^+W^-$	300 keV
10^6 $e^+e^- \rightarrow HZ$	1 MeV
10^6 $e^+e^- \rightarrow t\bar{t}$	2 MeV

The FCC-ee discovery potential (excerpt)

- **EXPLORE the 10-100 TeV energy scale**
  - With precision measurements of the properties of the Z, W, Higgs, and top particles
    - Up to 20-50-fold improved precision on ALL electroweak observables (EWPO)
      - ➨ m_Z, m_W, m_{top}, Γ_Z, $\sin^2\theta_w^{eff}$, R_b, $\alpha_{QED}(m_z)$, $\alpha_s(m_z\ m_W\ m_\tau)$, top EW couplings …
    - Up to 10-fold more precise and model-independent Higgs couplings measurements

arXiv:1512.05544
arXiv:1603.06501
arXiv:1503.01325

- **DISCOVER that the Standard Model does not fit**
  - NEW PHYSICS ! Pattern of deviations may point to the source.
- **DISCOVER a violation of flavour conservation / universality**
  - Examples: $Z \to \tau\mu$ in 5×10^{12} Z decays; or $\tau \to \mu\nu$ / $\tau \to e\nu$ in 2×10^{11} τ decays; …
  - Also $B^0 \to K^{*0}\tau^+\tau^-$ or $B_S \to \tau^+\tau^-$ in 10^{12} bb events
- **DISCOVER dark matter as invisible decays of Higgs or Z**
- **DIRECT DISCOVERY of very-weakly-coupled particles**
  - in the 5-100 GeV mass range, such as right-handed neutrinos, dark photons, ALPs, …
    - Motivated by all measurements / searches at colliders (SM and "nothing else")

FCC-ee is not only a Higgs factory. Z, WW, and $t\bar{t}$ factories are important for discovery potential

First look at the physics case of TLEP https://arxiv.org/abs/1308.6176 (Aug. 2013)

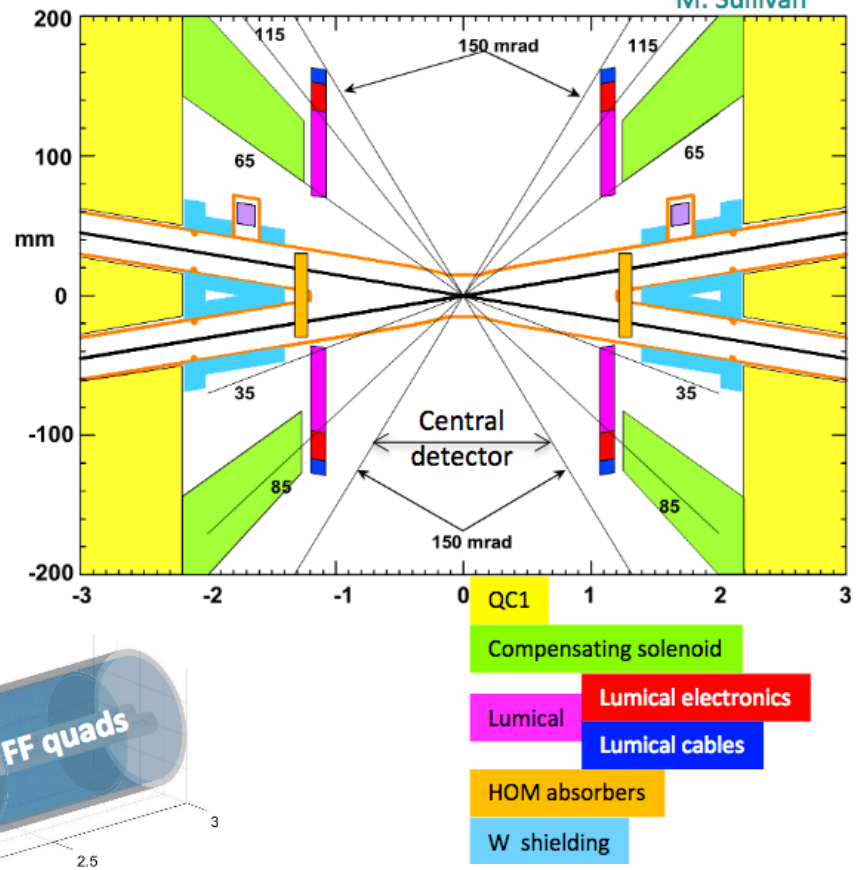
Important features for precision (examples)

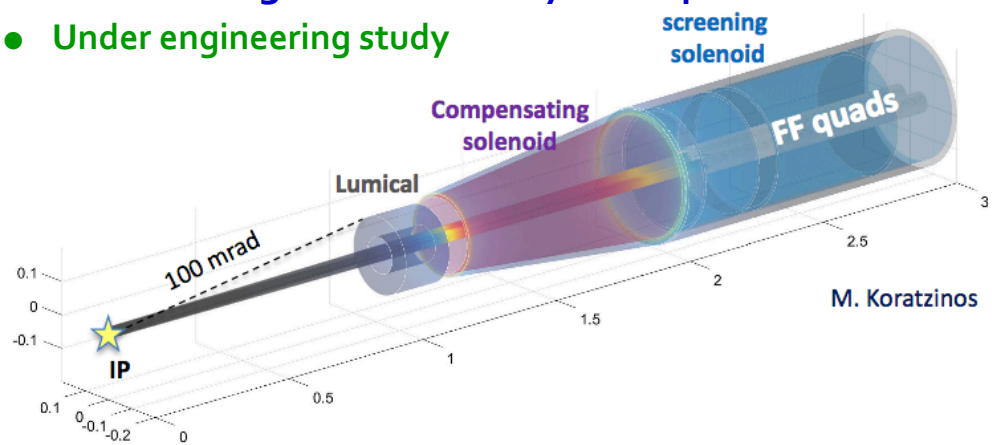
- **Statistics**
  - Very high statistics at the Z pole (70 kHz of visible Z decays)
  - Beam-induced background are mild compared to linear colliders, but not negligible
    - Readout must be able to cope with both
    - CW running imposes constraints on detector cooling
- **Luminosity measurement**
  - Aim at 0.01% from small angle Bhabhas
    - Requires μm precision for LumiCal
    - Requires measurement of outgoing $e^{\pm}$ deflection from the opposite bunch
  - Need to study $e^+e^- \rightarrow \gamma\gamma$ to possibly reach 0.001%
- **$\sqrt{s}$ calibration and measurement of $\sqrt{s}$ spread**
  - 50 keV "continuous" E_{BEAM} measurement with resonant depolarization
  - Powerful cross checks from di-muon acollinearity and polarimeter/spectrometer
    - Requires muon angle measurement to better than 100 μrad
- **Flavour tagging**
  - Beam pipe radius (15 mm) smaller than at linear collider (vertex detector 1st layer)
    - New CEPC studies claim Purity × Efficiency ~ 97% for $H \rightarrow bb$. And at FCC-ee ?

Interaction Region Layout (MDI)

- **Unique and flexible design at all energies**
  - $L^* = 2.2$ m
    - Acceptance: 100 mrad
  - Solenoid compensation scheme
    - Reduce ε_y blow-up ⇒ $B_{Detector} \leq 2T$
  - Beam pipe
    - Warm, liquid cooled (~SuperKEKB)
    - Be in central region, then Cu
    - R = 15mm in central region
      - ➨ Vertex detector close to the IP
    - SR masks, W shielding
  - Mechanical design and assembly concept
    - Under engineering study

M. Sullivan

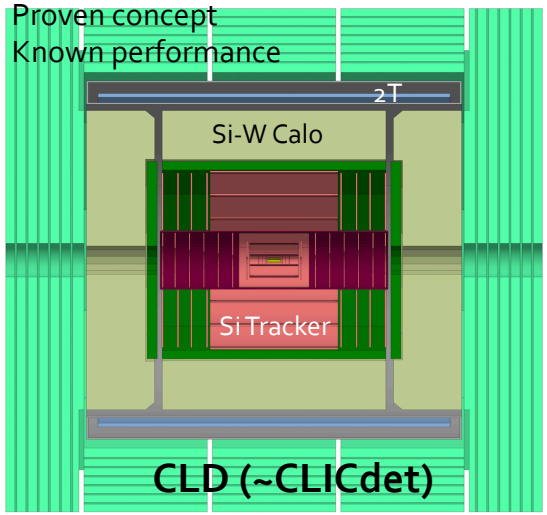


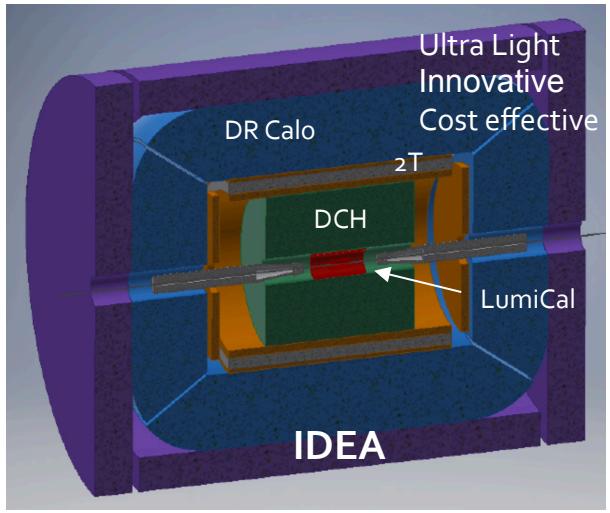


M. Koratzinos

FCC-ee detector design concepts

- **Two designs studied so far**

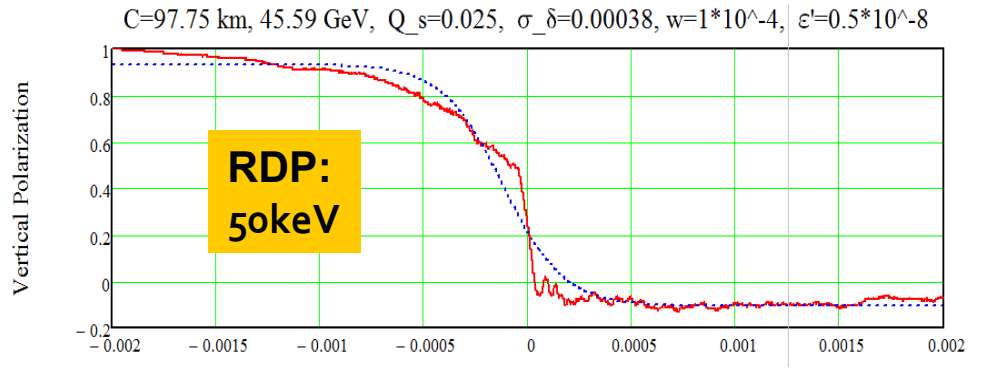




  - It was demonstrated that detectors satisfying the requirements are feasible
    - Physics performance, invasive MDI, beam backgrounds
- **More complete studies, with full simulation, needed**
  - Towards at least four detector proposals to be made by ~2026
    - Light, granular, fast, b and c tagging, lepton ID and resolutions, hadron ID
    - Cost effective
    - Satisfy constraints from interaction region layout

Beam Polarization and Energy Calibration

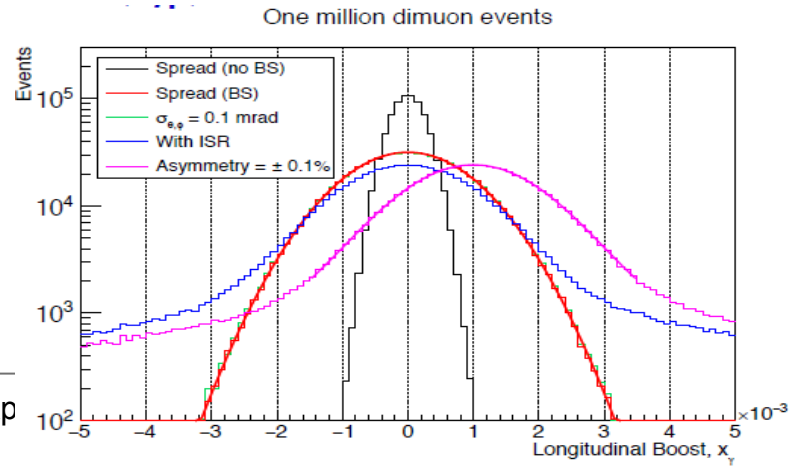
- **Simulation show transverse polarization at the Z and WW energies**
  - Energy calibration by resonant depolarization every 10 mins on pilot bunches
    - UNIQUE TO CIRCULAR COLLIDERS



260 seconds sweep of depolarizer frequency

- Total √s uncertainty of 100 keV @ Z pole, and 300 keV at the WW threshold

- **Energy spread (~100 MeV) will be measured**
  - From $e^+e^- \rightarrow \mu^+\mu^-$ longitudinal boost
    - 10^6 events every 4 mins @ Z pole
      - ➨ Continuous 35 keV precision on δ√s
    - Also measures $\Delta E = E^+ - E^-$ to at both IPs

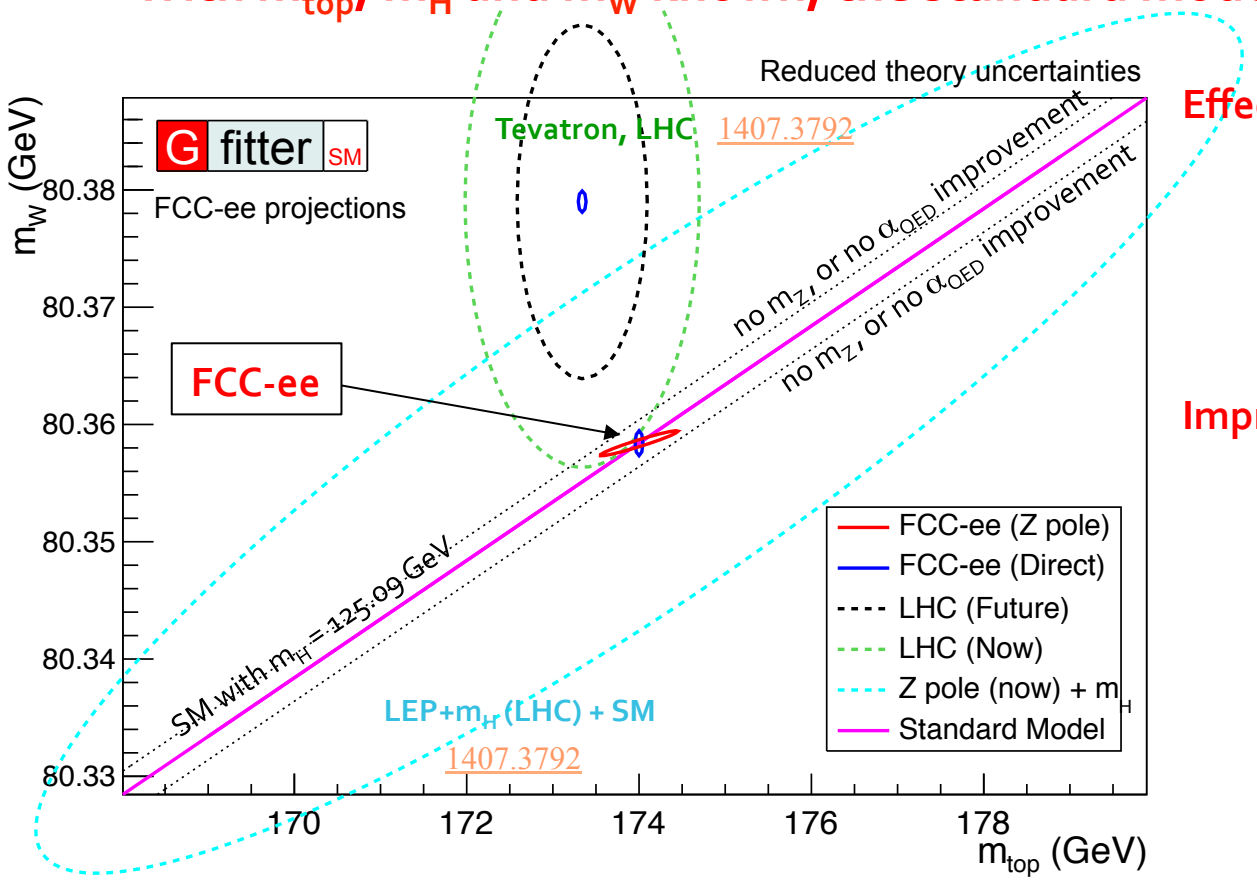


Sample of EW observables, exp'tal precisions

	Observable	Measurement	Current precision	FCC-ee stat.	FCC-ee syst.	Dominant exp. error
Z pole	m_Z (keV)	Z Lineshape	91187500 ± 2100	5	< 100	Beam energy
	Γ_Z (MeV)	Z Lineshape	2495200 ± 2300	8	< 100	Beam energy
	R_l ($\times 10^3$)	Z Peak ($\Gamma_{had}/\Gamma_{lep}$)	20767 ± 25	0.06	0.2 – 1	Detector acceptance
	R_b ($\times 10^6$)	Z Peak (Γ_{bb}/Γ_{had})	216290 ± 660	0.3	< 60	$g \to bb$
	N_ν ($\times 10^3$)	Z Peak (σ_{had})	2984 ± 8	0.005	1	Lumi measurement
	$\sin^2\theta_W^{eff}$ ($\times 10^6$)	$A_{FB}^{\mu\mu}$ (peak)	231480 ± 160	3	2 – 5	Beam energy
	$1/\alpha_{QED}(m_Z)$ ($\times 10^3$)	$A_{FB}^{\mu\mu}$ (off-peak)	128952 ± 14	4	< 1	Beam energy
	$\alpha_s(m_Z)$ ($\times 10^4$)	R_l	1196 ± 30	0.1	0.4 – 1.6	Same as R_l
WW thresh.	m_w (MeV)	WW Threshold scan	80385 ± 15	0.6	0.3	Beam energy
	Γ_W (MeV)	WW Threshold scan	2085 ± 42	1.5	0.3	Beam energy
	N_ν ($\times 10^3$)	$e^+e^- \to \gamma Z$, $Z \to \nu\nu$, ll	2920 ± 50	0.8	small	?
	$\alpha_s(m_W)$ ($\times 10^4$)	$B_l = (\Gamma_{had}/\Gamma_{lep})_W$	1170 ± 420	2	small	CKM Matrix
$t\bar{t}$ thresh.	m_{top} (MeV)	Top Threshold scan	173340 ± 760 ± 500	17	< 40	QCD corr.
	Γ_{top} (MeV)	Top Threshold scan	?	45	< 40	QCD corr.
	λ_{top}	Top Threshold scan	μ = 1.28 ± 0.25	0.10	< 0.05	QCD corr.
	ttZ couplings	$\sqrt{s}$ = 365 GeV	± 30%	0.5 – 1.5%	< 2%	QCD corr

Combination of all EW measurements

- With m_{top}, m_H and m_W known, the standard model has nowhere to go



Effect of BSM physics

- Modify EW observables through quantum effects (*cf* top & H @ LEP)
  - Blue (direct) & red (Z pole) ellipses may not overlap
  - Standard Model may not fit

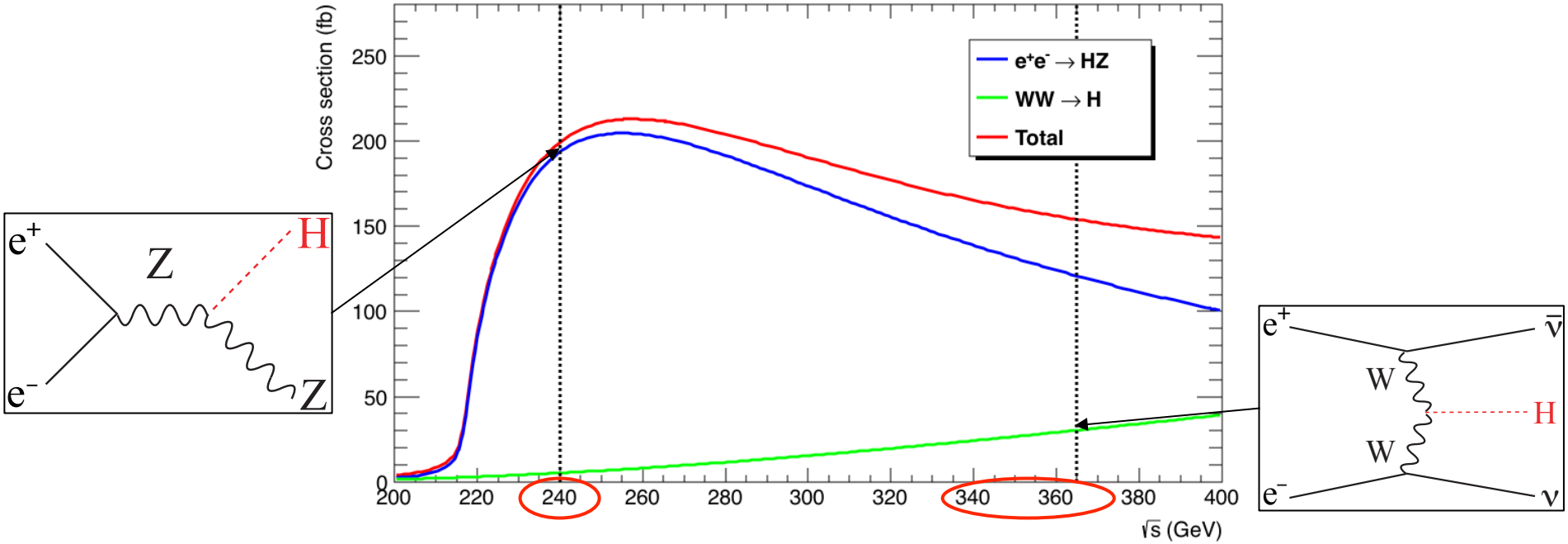
Improvement from all fronts

- Missing ingredients would spoil sensitivity to BSM physics
  - e.g. m_Z, α_{QED}, m_{top}, …
- FCC-ee experimental programme well justified and unique
  - From Z pole to top threshold with the highest luminosities

- Precision of theory predictions may also spoil sensitivity to new physics
  - Theoretical calculations need to be brought to higher orders (more later)

The FCC-ee as a Higgs factory

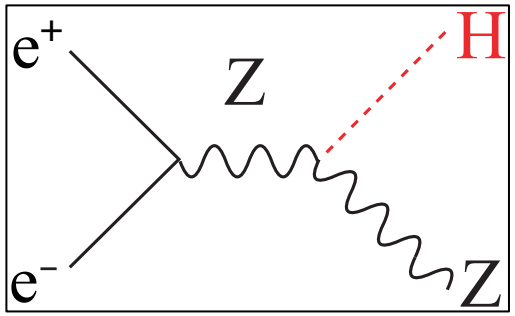
- Higgsstrahlung ($e^+e^- \rightarrow ZH$) event rate largest at $\sqrt{s}$ ~ 240 GeV : σ ~200 fb



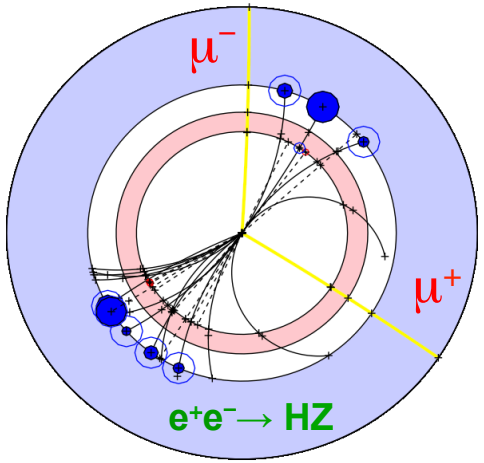
- 10^6 $e^+e^- \rightarrow ZH$ events with 5 ab^{-1} – cross section predicted with great accuracy
  - Target : (few) per-mil precision, statistics-limited.
  - Complemented with 200k events at $\sqrt{s}$ = 350 – 365 GeV
    - Of which 30% in the WW fusion channel (useful for the Γ_H precision)

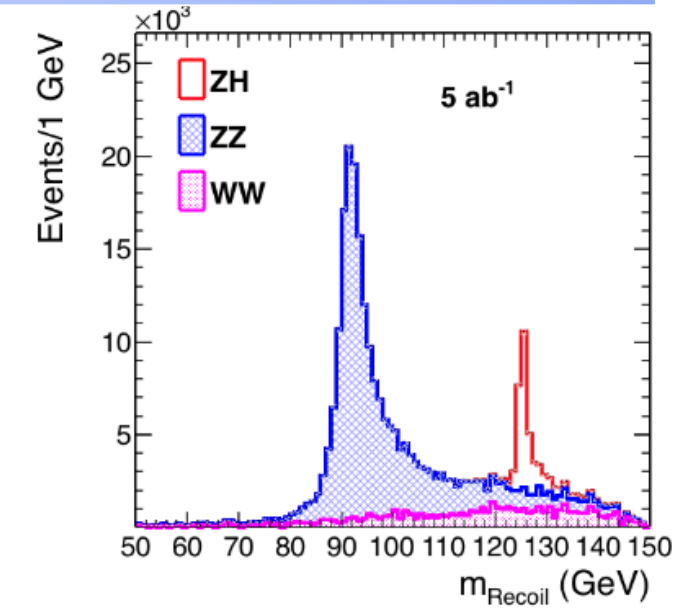
Absolute coupling and width measurement

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

- **Note: The HL-LHC is a great Higgs factory (10^9 Higgs produced) but …**
  - $\sigma_{i\to f}^{(observed)} \propto \sigma_{prod}\, (g_{Hi})^2\, (g_{Hf})^2 / \Gamma_H$
    - Difficult to extract the couplings : σ_{prod} is uncertain and Γ_H is largely unknown
      - ➨ Must do physics with ratios or with additional assumptions.

Result of the "kappa" fit

- **Relative precisions for HL-LHC * and the FCC-ee**

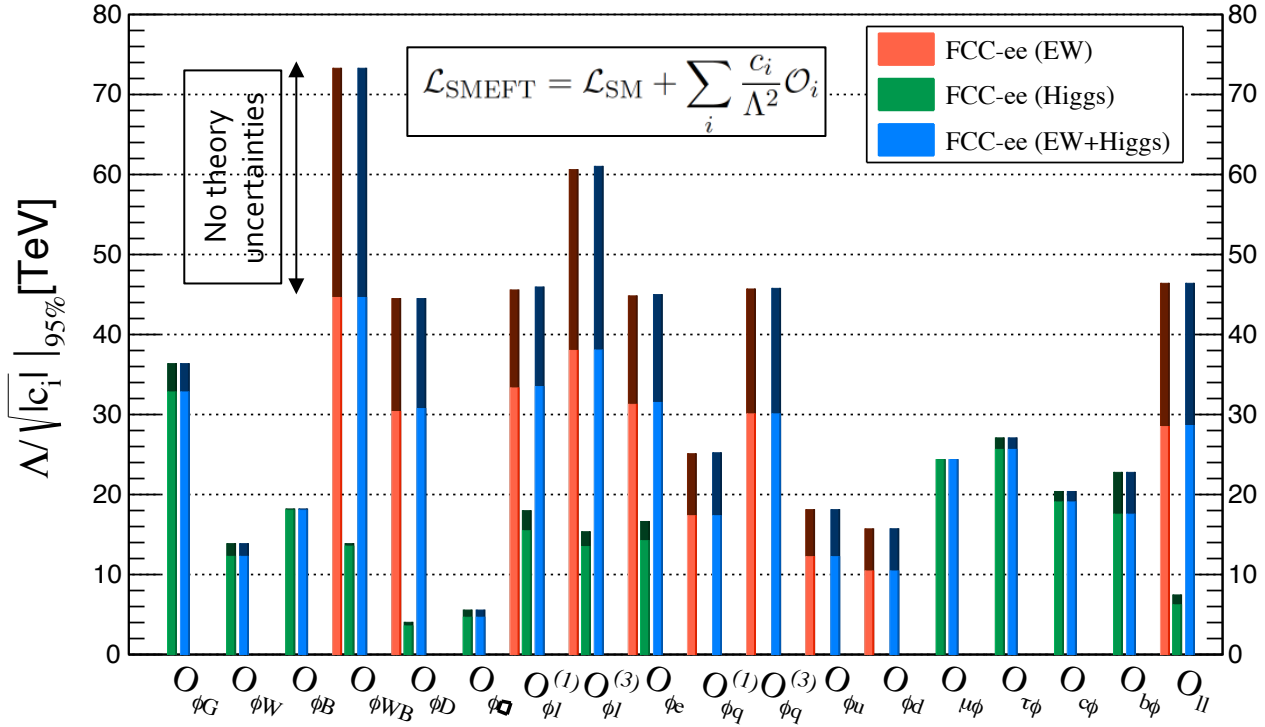
Collider	HL-LHC	FCC-ee		
Luminosity (ab^{-1})	3	5 @ 240GeV	+1.5 @ 365GeV	+HL-LHC
Years	25	3	**+4**	-
$\delta\Gamma_H/\Gamma_H$ (%)	SM	2.7	**1.3**	1.1
$\delta g_{HZZ}/g_{HZZ}$ (%)	1.3	0.2	**0.17**	0.16
$\delta g_{HWW}/g_{HWW}$ (%)	1.4	1.3	**0.43**	0.40
$\delta g_{Hbb}/g_{Hbb}$ (%)	2.9	1.3	**0.61**	0.55
$\delta g_{Hcc}/g_{Hcc}$ (%)	SM	1.7	**1.21**	1.18
$\delta g_{Hgg}/g_{Hgg}$ (%)	1.8	1.6	**1.01**	0.83
$\delta g_{H\tau\tau}/g_{H\tau\tau}$ (%)	1.7	1.4	**0.74**	0.64
$\delta g_{H\mu\mu}/g_{H\mu\mu}$ (%)	4.4	10.1	**9.0**	3.9
$\delta g_{H\gamma\gamma}/g_{H\gamma\gamma}$ (%)	1.6	4.8	**3.9**	1.1
$\delta g_{Htt}/g_{Htt}$ (%)	2.5	–	**–**	2.4
BR_{EXO} (%)	SM (0.0)	<1.2	**<1.0**	<1.0

Model-independent

- The FCC-ee precision better than HL-LHC by large factors (copious modes)
  - With no need for additional assumptions – best on the e^+e^- collider market
- It is important to have two energy points (240 and 365 GeV), as at the FCC-ee
  - Combination better by a factor 2 (4) than 240 (365) GeV alone
- (HL-)LHC measures the σ_{ttH} , but requires assumptions for the g_{Htt}
  - Absolute g_{Htt} measurement in a combination with the FCC-ee (precision: 2.4%)

Precision ⟺ Discovery

- **Combining precision Higgs and EW measurements in SMEFT**



Deviating operators may point to the new physics to be looked for at the FCC-hh

- Higgs and EWPO measurements are well complementary (b,c,τ PO to be added)
- EWPO are more sensitive to heavy new physics (up to 50-70 TeV)
  - Sensitivity was at the level of up to ~5 TeV at LEP
- Larger statistics pays off for Higgs measurements (4 IPs ?)
- ***Further improvement in theory predictions pays off for EWPO measurements***

Precision of theory predictions

- **Improving the precision of EW and QCD calculations for the FCC**
  - Is a great challenge (exponentially growing number of diagrams with # loops)
  - Has discovery potential (see previous slide)
  - Is therefore recognized as strategic
    - *Included in the FCC-ee CDR volume as a target for "Strategic R&D"*

- **First workshop on "Methods and tools" in January 2018**
  - 33 participants
  - Produced a 250+ pages proceedings !
  - Conclusion of the workshop
    - We cannot promise, but yes, we can do it !
    - Requires ~500 person-year (50 MCHF) over the next 20 years

Standard Model theory for the FCC-ee (2018)
J. Gluza et al., https://arxiv.org/abs/1809.01830

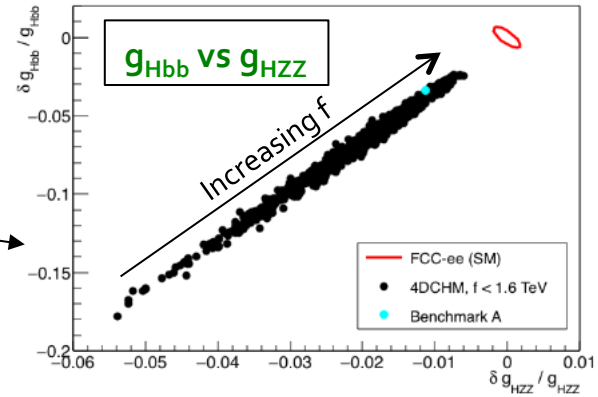
- **Workshop series is being continued**
  - This workshop in January 2019: https://indico.cern.ch/event/766859/
  - Topics cover the whole FCC-ee programme, 106 registered participants !
    - Z, W, Higgs, top, b, c, QED, Monte Carlo, software, and detector technologies

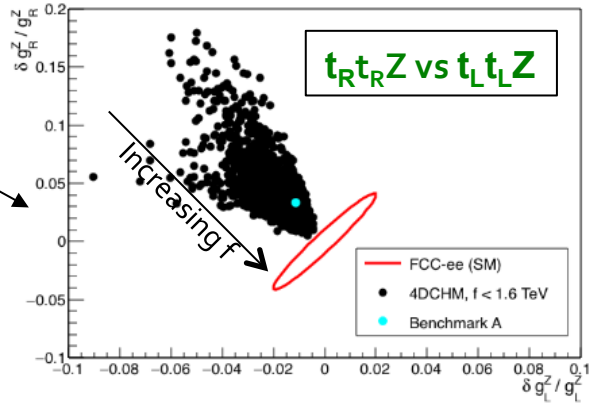
Pattern of deviations

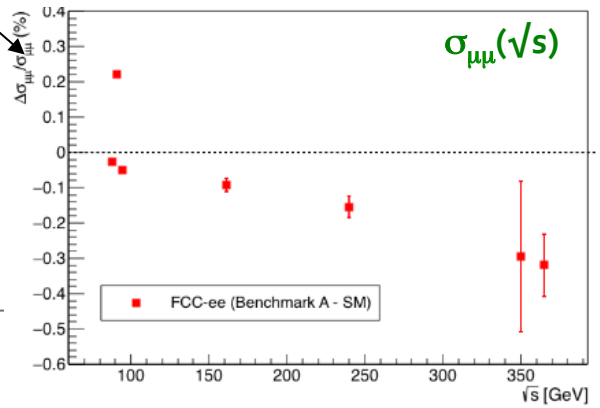
- **May point to specific BSM physics**
  - E.g, 4D Composite Higgs Model
    - Deviations in Higgs couplings
      - ➨ $\sqrt{s}$ = 240, 350, 365 GeV
    - Deviations in EW top couplings
      - ➨ $\sqrt{s}$ = 365 GeV optimal
      - No need for beam polarization
    - Deviations in EW lepton couplings
      - ➨ All energies
- **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, $m_{Z'}$ ~ 3 TeV, $\Gamma_{Z'}$ ~ 600 GeV
    - With the FCC-ee precision
      - ➨ Z' mass predicted wth 2% precision
      - ➨ Scale f, coupling g* predicted with 8% precision

S. de Curtis et al. arXiv:1110.1613

P. J. arXiv:1503.01325

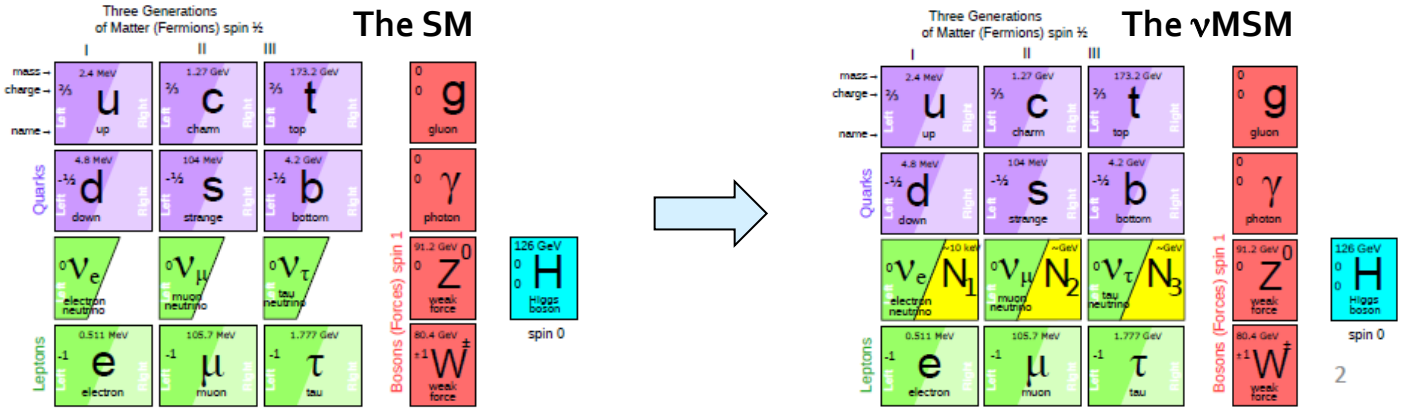






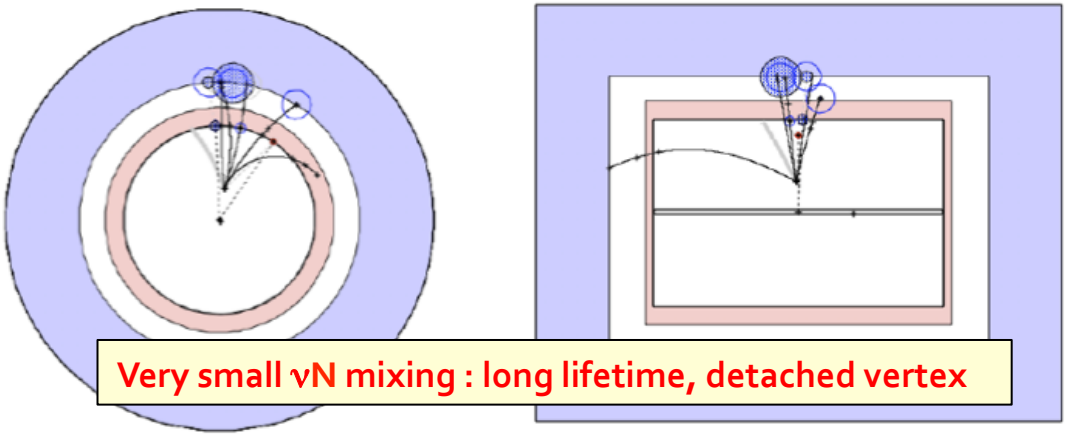
Direct discoveries

- **Discover right-handed neutrinos**
  - **νMSM : Complete particle spectrum with the missing three right-handed neutrinos**

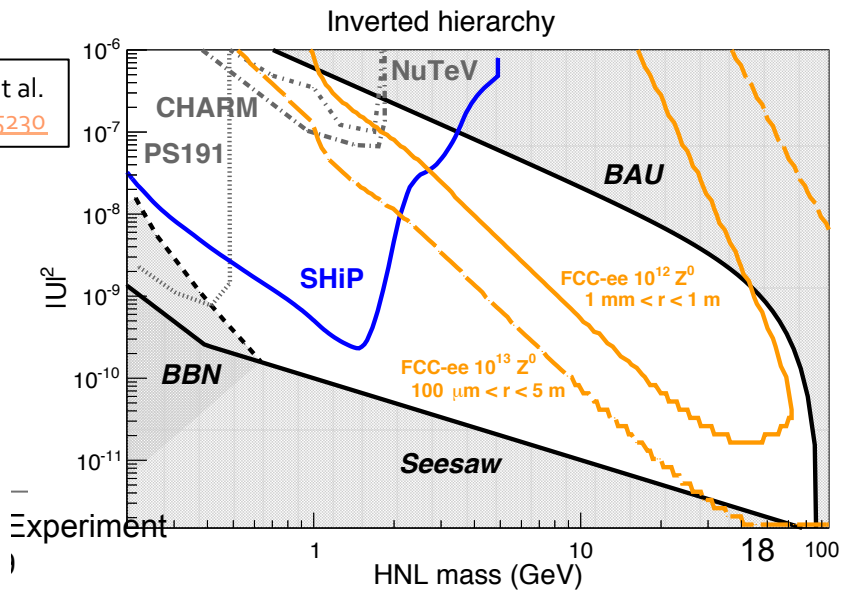


    - **Could explain everything: Dark matter (N_1), Baryon asymmetry, Neutrino masses**
  - **Searched for in very rare $Z \to \nu N_{2,3}$ decays**
    - **Followed by $N_{2,3} \to W^{*}\ell$ or $Z^{*}\nu$**

A. Blondel et al.
arXiv:1411.5230

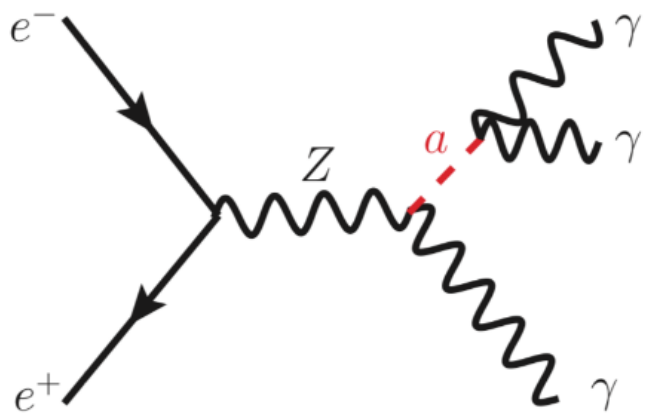


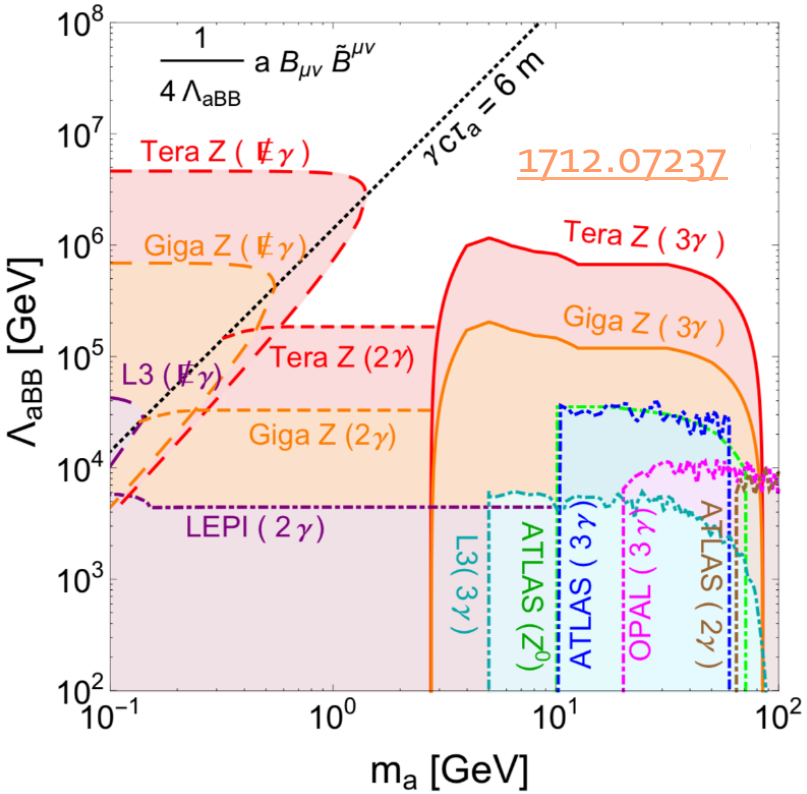
Very small νN mixing : long lifetime, detached vertex



Direct discoveries (cont'd)

- **Discover the dark sector**
  - A very-weakly-coupled window to the dark sector is through light "Axion-Like Particles" (ALPs)





- ➨ $\gamma + E_{MISS}$ for very light a
- ➨ $\gamma\gamma$ for light a
- ➨ $\gamma\gamma\gamma$ for heavier a

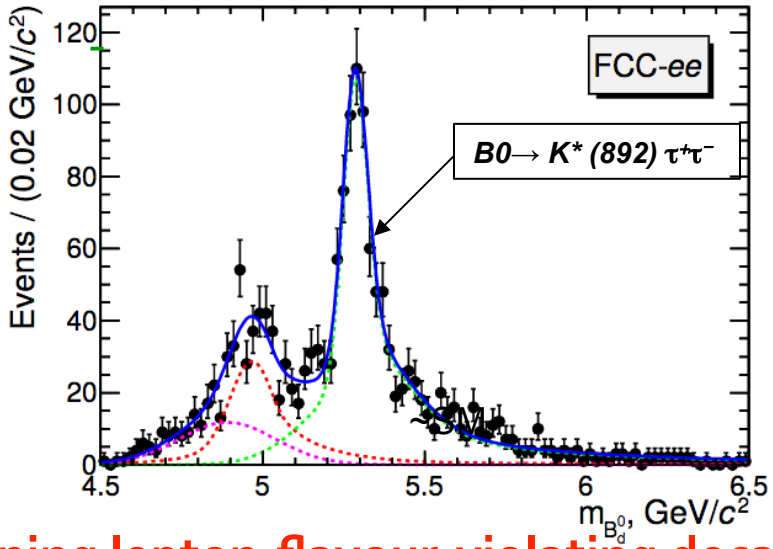
- Orders of magnitude of parameter space accessible at FCC-ee

Flavours : B anomalies, τ physics, …

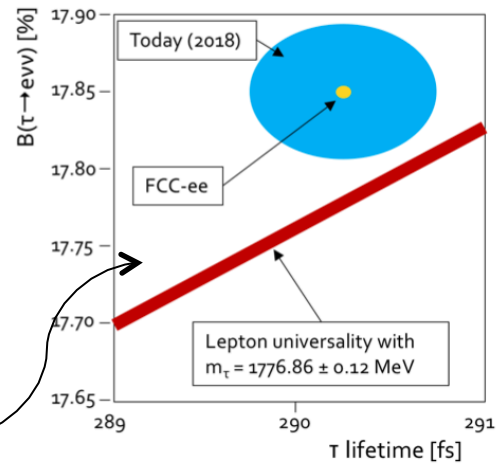
- **Lepton flavour universality is challenged in b → s $\ell^+\ell^-$ transitions @ LHCb**
  - This effect, if real, could be enhanced for $\ell = \tau$, in $B \to K^{(*)} \tau^+\tau^-$
    - Extremely challenging in hadron colliders
    - With 10^{12} Z → bb, FCC-ee is beyond any foreseeable competition
      - ➨ Decay can be fully reconstructed; full angular analysis possible

Talk from A. Bondar

J.F. Kamenik et al.
arXiv:1705.11106



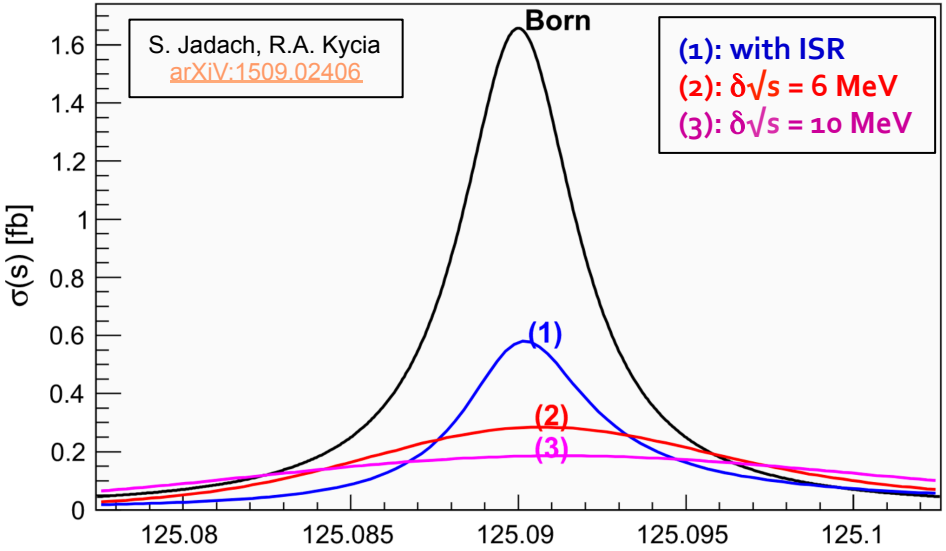
Also 100,000 $B_S \to \tau^+\tau^-$ @ FCC-ee
Reconstruction efficiency under study



- **Not mentioning lepton-flavour-violating decays**
  - BR(Z → eτ, μτ) down to 10^{-9} (improved by 10^4)
  - BR(τ → μγ, μμμ) down to a few 10^{-10}
  - τ lifetime vs BR(τ → $e\nu_e\nu_\tau$,$\mu\nu_\mu\nu_\tau$) : lepton universality tests

And if there is time …

- **Spend few years at $\sqrt{s}$ = 125.09 GeV with high luminosity**
  - For s-channel production $e^+e^- \rightarrow H$ (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
    - $\sigma(e^+e^- \rightarrow H) \sim 100$ ab
  - Option 2: $\delta\sqrt{s}$ = 6 MeV, 2 ab^{-1} / year
    - $\sigma(e^+e^- \rightarrow H) \sim 250$ ab
  - Backgrounds much larger than signal
    - $e^+e^- \rightarrow q\bar{q}, \tau\tau, WW^*, ZZ^*, \gamma\gamma, \ldots$

  - Expected signal significance of ~0.4σ / $\sqrt{\text{year}}$ in both option 1 and option 2
    - Set a electron Yukawa coupling upper limit : $\kappa_e < 2.5$ @ 95% C.L.
    - Reaches SM sensitivity after five years (or 2.5 years with 4 IPs)

D. d'Enterria
arXiV:1701.02663

  - Unique opportunity to constrain first generation Yukawa's

Is a √s = 500 GeV upgrade required/useful ?

- **From European Strategy Update in 2013:**

> There is a strong scientific case for an electron-positron collider, complementary to the LHC, that can study the properties of the Higgs boson and other particles with unprecedented precision and whose energy can be upgraded.

ESPP Update 2013, CERN Council

Is a √s = 500 GeV upgrade required/useful ?

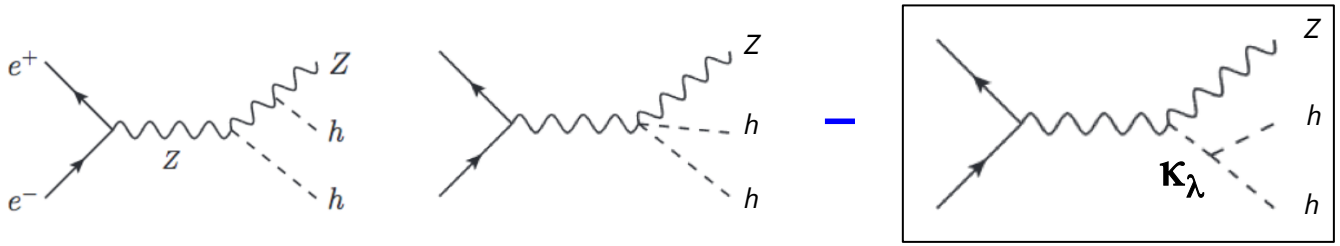
- **According to the white book of ESU 2013 :** https://cds.cern.ch/record/1567295/

At energies of 500 GeV or higher, such a machine could explore the Higgs properties further, for example **the coupling to the top quark, the self-coupling, and the total width.**

- **The same arguments are used by some documents submitted to ESU 2020!**
- **So, should we foresee an upgrade of FCC-ee at √s = 500 GeV ?**
  - **For the total width and the coupling to the top quark : the answer is NO (slide 14)**
  - **For the Higgs self-coupling (κ_λ):**

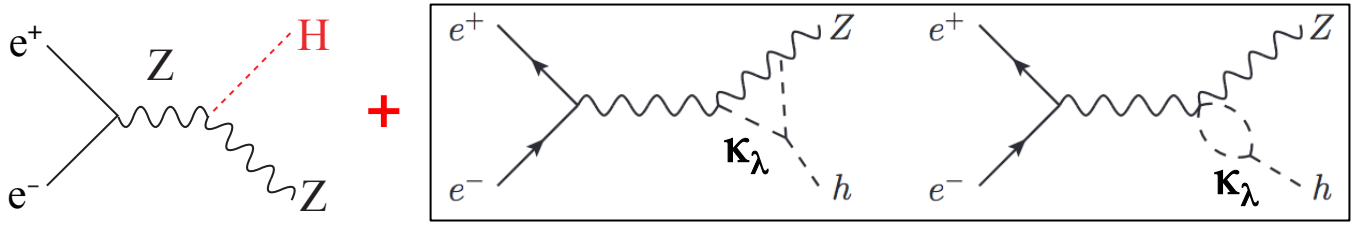
At √s = 500 GeV

Di-Higgs production



At FCC-ee

σ_{HZ}

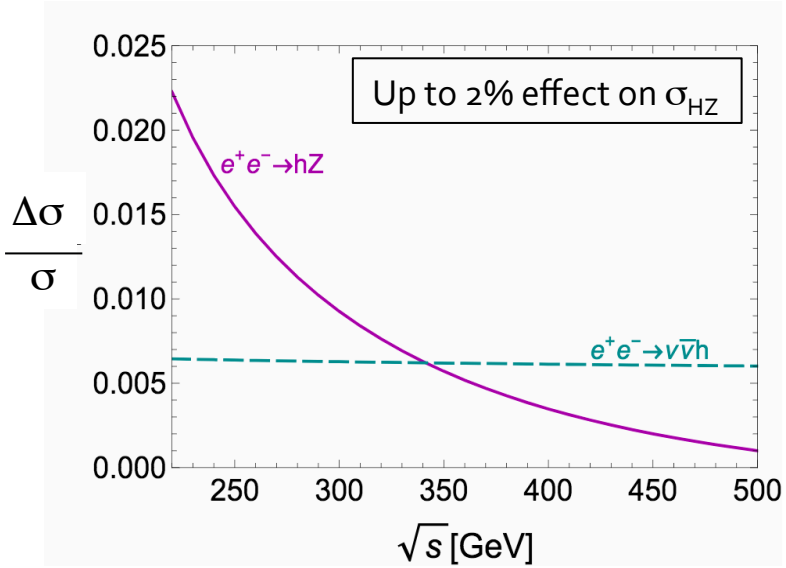


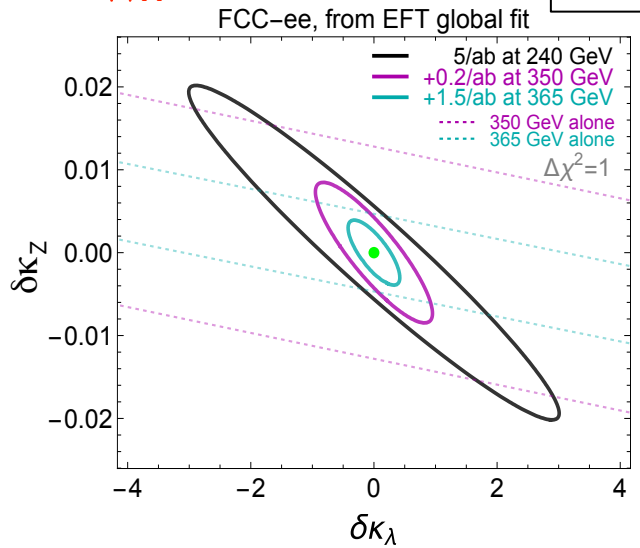
M. McCullough
arXiv:1312.3322

Higgs self-coupling at the FCC-ee

- **Effect of Higgs self coupling (κ_λ) on σ_{ZH} and $\sigma_{\nu\nu H}$ depends on $\sqrt{s}$**

C. Grojean et al.
arXiv:1711.03978





- Two energy points lift off the degeneracy between $\delta\kappa_Z$ and $\delta\kappa_H$
  - Precision on κ_λ with 2 IPs at the end of the FCC-ee (91+160+240+365 GeV)
    - ➨ Global EFT fit (model-independent) : ±34% (3σ) ; in the SM : ±12%
  - Precision on κ_λ with 4 IPs : ±21% (EFT fit) (5σ) ; ±9% (SM fit)
    - ➨ 5σ discovery with 4 IPs instead of 2 – much less costly than 500 GeV upgrade (in time and funds, in view of FCC-hh)

A. Blondel, P. J.
arXiv:1809.10041

- **And, most importantly**
  - Only FCC-hh, in combination with FCC-ee, can measure κ_{top} and κ_λ to 1% and 5%, resp.

See M. Aleksa's talk

Synergies and complementarities with 100 TeV pp collider

- **Higgs physics**
  - ee breaks model dependence (Γ_H, g_{HZZ}) – and measures precisely top EW couplings
    - Turns σ(ttH) measurement @ HL-LHC to an absolute ttH coupling precision of 3%
    - First 3-4σ observation or 5σ discovery of the Higgs self coupling, without a 500 GeV upgrade
  - pp measures ratios-of-BR and gives huge statistics of ttZ, ttH, and HH events
    - Bring top Yukawa and Higgs self coupling precisions to the per-cent level, in particular
- **Search for heavy physics (with at least weak couplings)**
  - ee gives precision measurements sensitive to heavy physics up to 50 TeV and more
    - Patterns of deviations may points to specific BSM
  - pp gives access to direct observation at unprecedented masses and p_T's
    - Also huge samples of Z, W, Higgs, top
- **Right-handed neutrinos (and all very weakly-coupled particles)**
  - ee: powerful and clean, but flavour blind: $Z \to \nu N$, all ν flavours together
  - hh: more difficult, but charge- and flavour-sensitive: $W \to l_1\ (Q_1)\ N$, $N \to l_2\ (Q_2)\ W^*$

5×10^{12} Z

5×10^{13} W

- **Flavour "anomalies" (if they persist – rich flavour physics programme otherwise)**
  - ee beyond any foreseeable competition with in $B \to K^{(*)}\tau^+\tau^-$ and $B_S \to \tau^+\tau^-$
  - hh gives direct access to Z' gauge bosons and leptoquarks
- **QCD**
  - ee gives α_S to ±0.0002 or better (R_l for Z and W), but also 100k $H \to gg$ (gluon fragmentation!)
  - Improves signal and background predictions for new physics discovery at pp

Conclusions

- **The FCC design study is establishing the feasibility of an ambitious set of colliders after LEP/LHC, at the cutting edge of knowledge and technology**
  - The FCC CDR is on the verge of being publicly released and published

- **Both FCC-ee and FCC-hh have outstanding physics cases**
  - Each in their own right (Electroweak Factory and Energy Frontier)
  - The sequential implementation : FCC-ee → FCC-hh maximises the physics reach
    - Taking full advantage of multiple synergies and complementarities
  - Can serve High-Energy Physics in a cost effective manner throughout the 21st century

- **The FCC-ee design is now robust and mature**

FCC-ee can start physics seamlessly at the end of HL-LHC

  - We must get ready to move to the next step – ***many routes are barely touched***
    - Prepare MDI mechanical infrastructure
    - Work on several (at least four) detector proposals
      - ➨ Requires full simulation / reconstruction within user-friendly FCC software
    - Bring theory precision on par with experimental sensitiviy