8th International Conference on New Frontiers in Physics (ICNFP 2019)

FCC Physics highlights

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On behalf of the FCC study

Massachusetts Institute of Technology

http://cern.ch/fcc

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24 August 2019

photo: J. Wenninger

Acknowledgements

We should not forget the pioneers of the modern circular Higgs factory idea: **Roy Aleksan, Alain Blondel, John Ellis, Patrick Janot, Frank Zimmermann**, that promoted the idea when it was not fashionable

A. Blondel F. Zimmermann M. Koratzinos J. Ellis P. Janot R. Aleksan

I have taken material liberally from the CDR and from various talks, notably from Patrick Janot

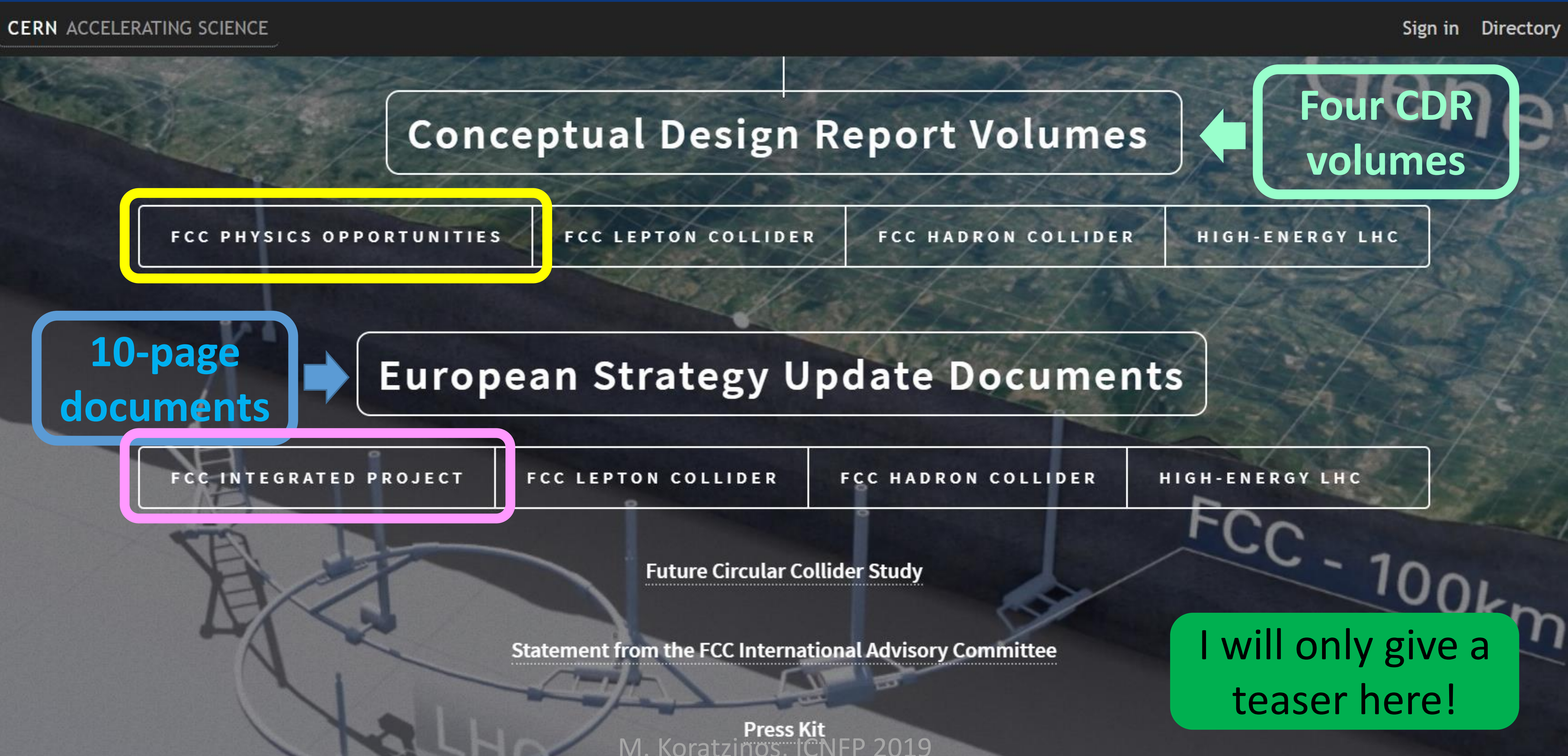
FCC in this conference:

- Katsunobu Oide: FCC status, previous talk
- Mike Koratzinos: FCC-ee physics opportunities

Contents

- FCC aspires to provide physics topics to our community well into the 2080s…
- I will here touch a very selective (and personal) list of physics topics, concentrating on FCC-ee (which comes first)
  - Higgs couplings, higgs self coupling
  - Top mass
  - Electroweak precision observables
  - E_{CM} energy determination
  - Sterile neutrinos
  - (some) comparisons with other projects

FCC study: CDR released on 15 January 2019



Four CDR volumes

10-page documents

I will only give a teaser here!

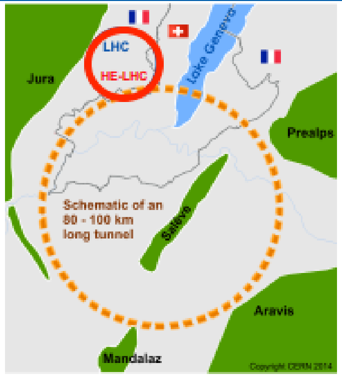
The FCC integrated project

➔ FCC-ee first, followed by FCC-hh

Future Circular Collider (FCC)

Conceptual Design Report released today!

	$\sqrt{s}$	L /IP ($cm^{-2} s^{-1}$)	Int. L /IP(ab^{-1})	Comments
e^+e^- FCC-ee	~90 GeV Z 160 WW 240 H ~365 top	230 x10^{34} 28 8.5 1.5	75 ab^{-1} 5 2.5 0.8	2 experiments Total ~ 15 years of operation
pp FCC-hh	100 TeV	5 x 10^{34} 30	2.5 ab^{-1} 15	2+2 experiments Total ~ 25 years of operation
PbPb FCC-hh	$\sqrt{s_{NN}}$ = 39TeV	3 x 10^{29}	100 nb^{-1}/run	1 run = 1 month operation
ep Fcc-eh	3.5 TeV	1.5 10^{34}	2 ab^{-1}	60 GeV e- from ERL Concurrent operation with pp for ~ 20 years
e-Pb Fcc-eh	$\sqrt{s_{eN}}$ = 2.2 TeV	0.5 10^{34}	1 fb^{-1}	60 GeV e- from ERL Concurrent operation with PbPb



Also studied: HE-LHC: $\sqrt{s}$=27 TeV using FCC-hh 16 T magnets in LHC tunnel; L~1.6x10^{35} → 15 ab^{-1} for 20 years operation

F. Gianotti 15/1/2019

Sequential implementation, FCC-ee followed by FCC-hh, would enable:

- ❑ variety of collisions (ee, pp, PbPb, eh) → impressive breadth of programme, 6++ experiments
- ❑ exploiting synergies by combining complementary physics reach and information of different colliders → maximise indirect and direct discovery potential for new physics
- ❑ starting with technologically ready machine (FCC-ee); developing in parallel best technology (e.g. HTS magnets) for highest pp energy (100++ TeV!)
- ❑ building stepwise at each stage on existing accelerator complex and technical infrastructure

Purely technical schedule, assuming green light to preparation work in 2020.
A 70 years programme

8 years preparation	10 years tunnel and FCC-ee construction	15 years FCC-ee operation	11 years FCC-hh preparation and installation	25 years FCC-hh operation pp/PbPb/eh
2020-2028		2038-2053		2064-2090

The physics landscape

- SM very successful
- We know today that the SM is not the full story and needs to be extended to explain indisputable observations (there are also theoretical issues)
- Theory does not give clear guidance
- The answer might lie in high energy scales or low couplings, beyond the reach of LHC.

➔No easy way forward

➔Our approach: measure, measure, measure

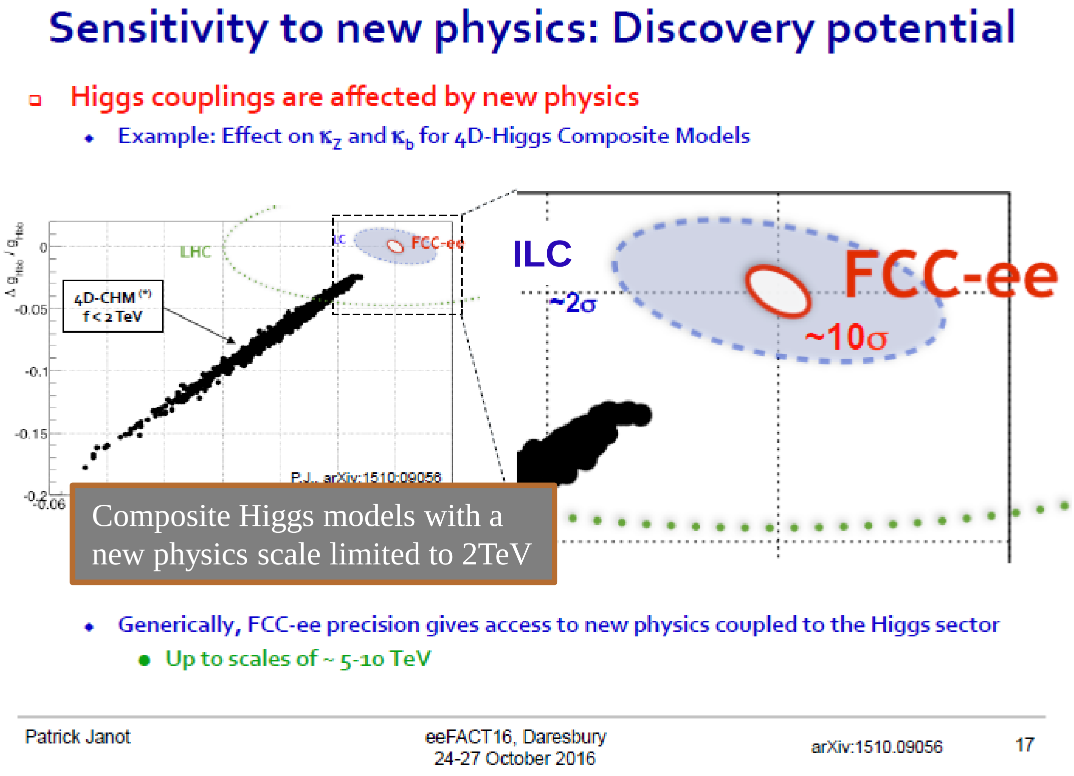
Higgs sector

EW sector

Exotic

A note on precision

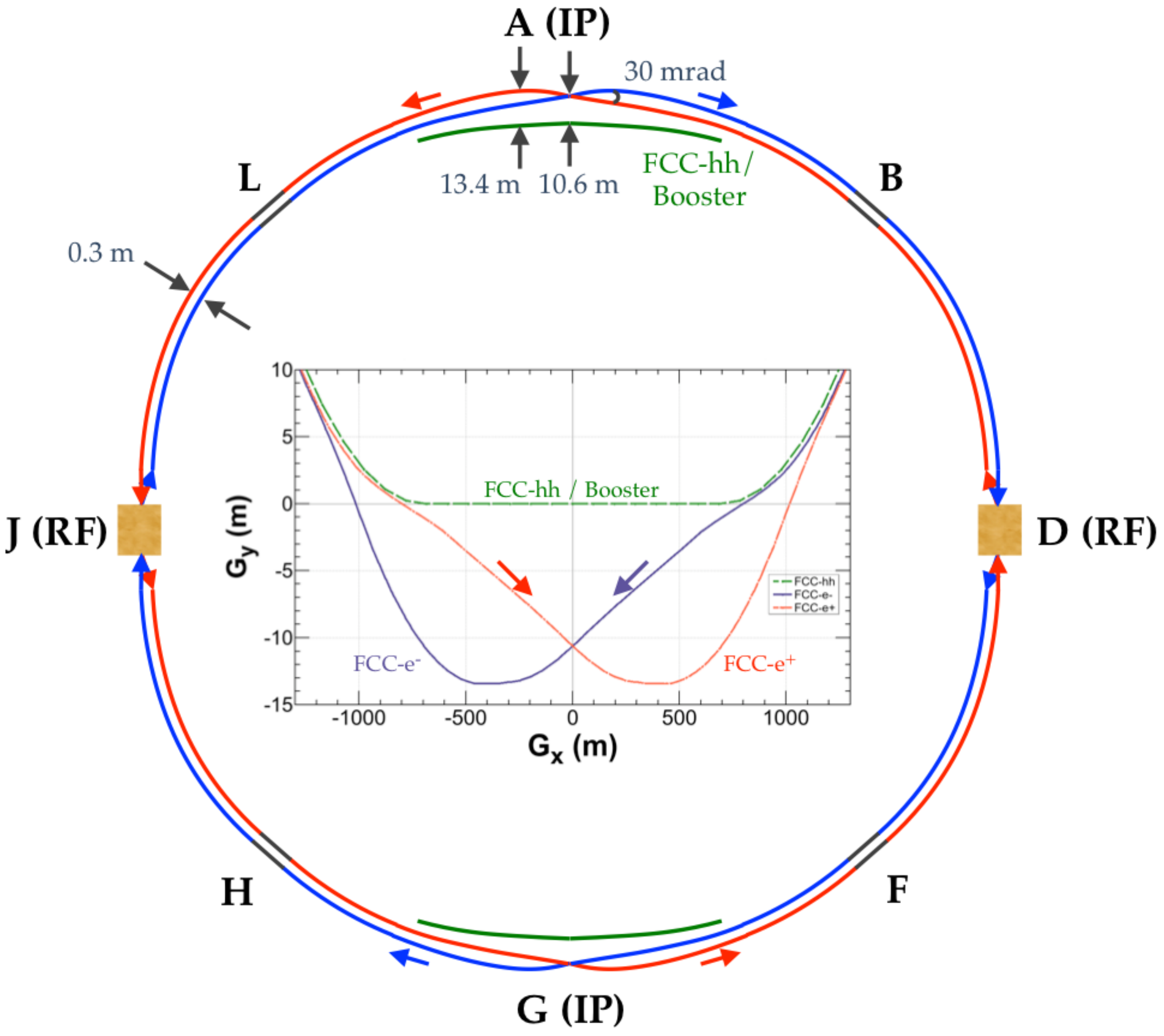
- The strategy behind all (e+e-) future colliders is to measure as many parameters which are sensitive to new physics as possible
- HOWEVER: we need to have a measuring power which is better than the expected signal! For example: Higgs couplings: most extensions to the standard model predict deviations from the standard model of the order of 1%. It is imperative, therefore, to build a machine that can probe these quantities to order ~0.1%



The LHC cannot distinguish between models, even if it could measure a deviation

The FCC-ee accelerator

- Circular accelerator with the largest reasonable size – **100 kms**. Luminosity is proportional to circumference
- Synchrotron radiation power limited to **100MW at all energies**. Luminosity is proportional to SR power
- **Separate beam-pipes** for electrons and positrons – gives much more flexibility
- **Full size booster** (a third ring) for top-up injection – beam lifetimes are very short
- Collision at an angle ("**crab waist**" scheme) of 30 mrad to minimize beam-beam interaction
- **Asymmetric** "moustache" **IR layout** and optics to limit synchrotron radiation towards the detector
- **The design can be modified to a 4-IP layout** if needed
- **FCC-ee can deliver excellent luminosities at the Z peak (E_{CM} 91 GeV), the WW threshold (160 GeV), the ZH maximum (240 GeV) and the tt threshold (365 GeV)**



Physics goals of FCC

- We start with (FCC-ee)
  - Higgs couplings
  - EW measurements
  - Rare decays
  - Rare processes
- We continue with (FCC-hh)
  - Direct mass reach
  - Measurements that still have insufficient precision with FCC-ee (for instance Higgs self-coupling)

The FCC-ee accelerator – interesting facts

The FCC-ee accelerator is not simply a bigger LEP! It is a modern synchrotron that pushes the design envelope to the maximum.

- The luminosity is so high that the beams burn up very quickly (beam lifetime 12 minutes at the ZH). Mandatory to use a full-size booster – the injector is the same size as the main ring and injects at top energy)
- Full LEP physics dataset every 2 minutes!
- Beam energy will be known to (much) better than 100keV, whereas the (gravitational) effect of the moon passing overhead gives an energy change of 100MeV, one thousand times bigger.
- The performance quoted in the CDR is not a paper exercise, it is fully backed by simulations, leading to stringent requirements: Colliding bunches must have the same charge to within 10%
- Emittance blow up in the region ±2m from the IPs is equal to the emittance of the rest of the 100 kilometers – the area around the IP is very tricky and complex

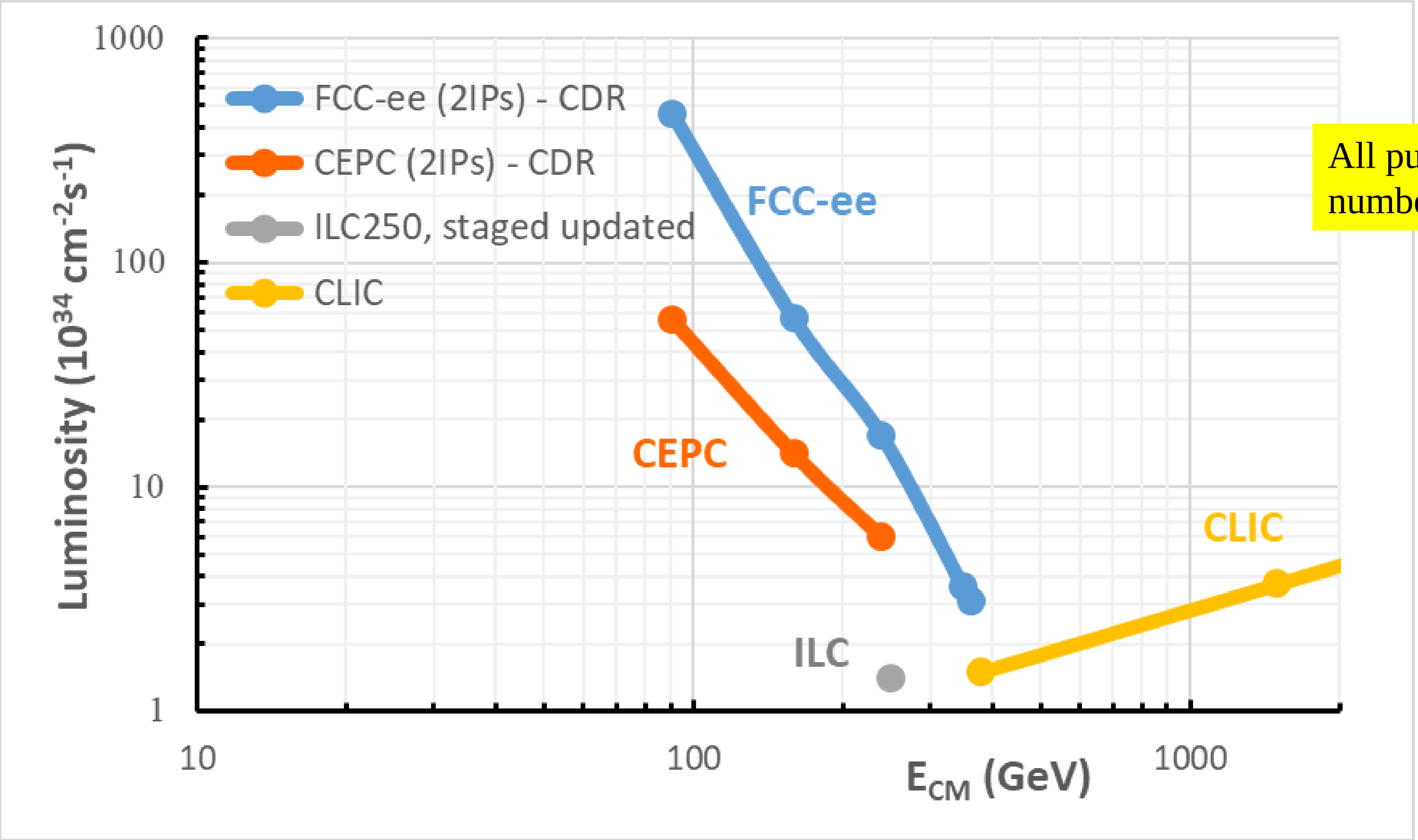
A number of interesting questions:

- Which part of the physics programme of FCC-ee is more important? The Higgs/top running or the Z/W running?
- Is there any reason to repeat the LEP programme every 2 minutes?
- Interplay between FCC-ee and FCC-hh
- What does longitudinal polarization buy us?

FCC-ee collider parameters

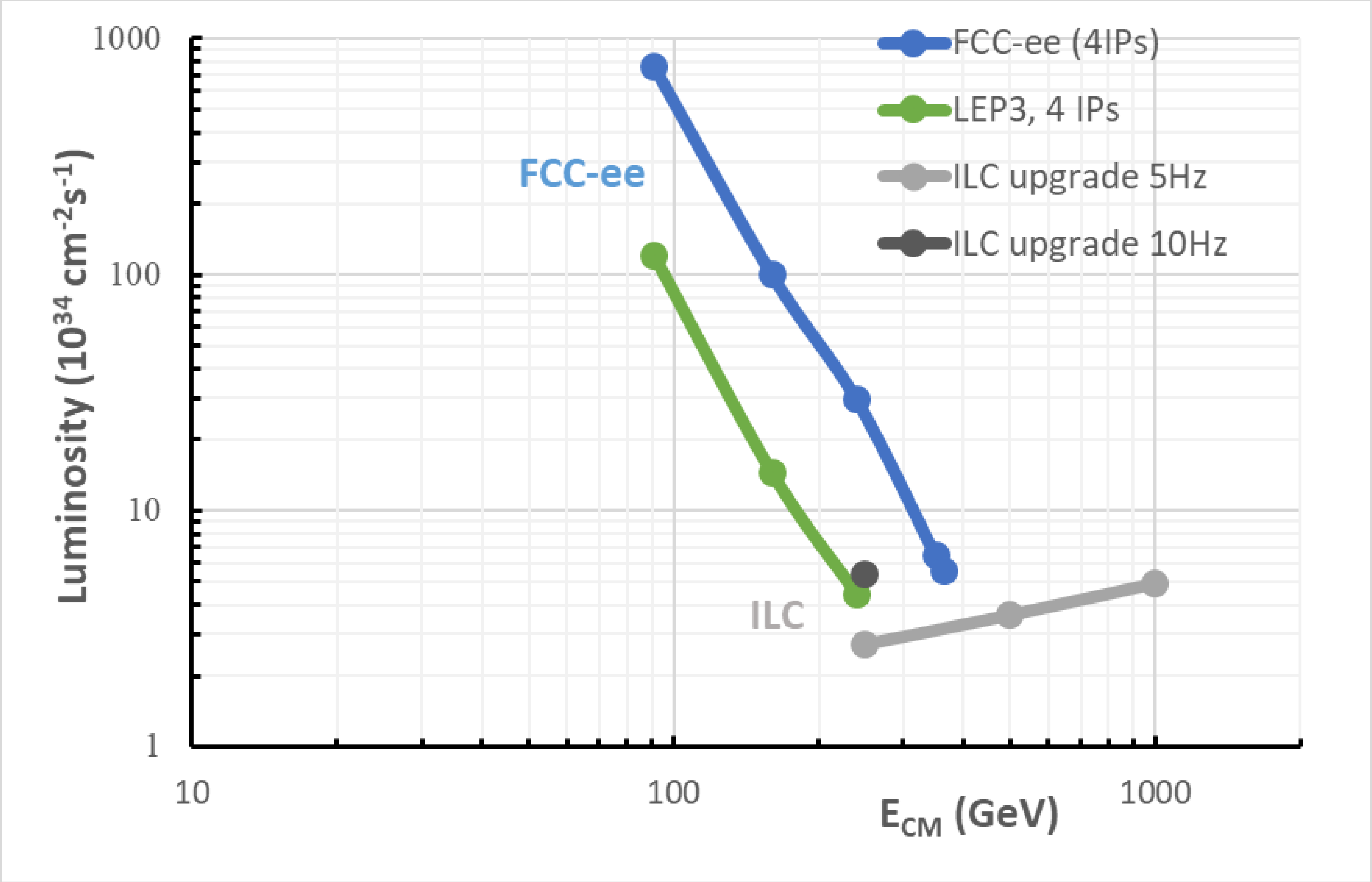
parameter	FCC-ee				LEP2
energy/beam [GeV]	**45**	**80**	**120**	**182.5**	105
bunches/beam	16640	2000	328	48	4
beam current [mA]	1390	147	29	5.4	3
luminosity/IP x 10^{34} $cm^{-2}s^{-1}$	**230**	**28**	**8.5**	**1.5**	0.0012
energy loss/turn [GeV]	0.036	0.34	1.72	9.2	3.34
total synchrotron power [MW]	100				22
RF voltage [GV]	0.1	0.75	2.0	4+6.9	3.5
rms bunch length (SR,+BS) [mm]	3.5, 12	3.0, 6.0	3.2, 5.3	2.0, 2.5	12, 12
rms emittance $e_{x,y}$ [nm, pm]	0.3, 1.0	0.84, 1.7	0.6, 1.3	1.5, 2.9	22, 250
Horiz.,vertical beta* [mm]	150, 0.8	200, 1	300, 1	1000, 1.6	1500,50
longit. damping time [turns]	1273	236	70	20	31
crossing angle [mrad]	30				0
beam lifetime (rad.B+BS) [min]	68	59	12	12	434

Lepton collider luminosities - published



All published numbers

Lepton collider luminosities - upgrades



Notes:

- All these upgrades/downgrades are not in the baseline proposal (yet)
- FCC-ee with 4 IPs is based on full beam-beam simulation
- Luminosity goes up by a factor 1.7
- The ILC upgrades consist of doubling the number of bunches per pulse (third damping ring) and doubling the repetition frequency (more cryogenics)
- LEP3 downgrade numbers are based on simulation results using an FCC-ee lattice and a tunnel length of 27 Kms with 4 IPs

FCC-ee physics opportunities

FCC-ee will create vast physics opportunities due to its huge statistics and the centre-of-mass energy range it can cover (from 88 to 365GeV):

- EW precision observable (EWPO) measurements sensitive to the 10-70TeV scale

20 to 50 times improved precision on ALL electroweak observables
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 …

- Model-independent Higgs coupling measurements

~10 times more precise and model-independent Higgs couplings measurements

- Precise tests of flavour conservation/universality
- Possible direct observation of very weakly coupled particles
- Possible discovery of dark matter in invisible H or Z decays
- …

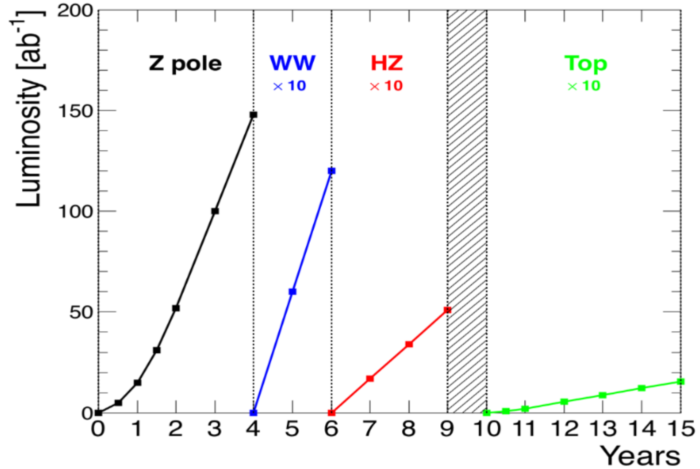
FCC-ee is not only a Higgs factory! It is also a Z, W, and t factory

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
√s precision (MeV)	<0.1		0.3	1	2	
Lumi/IP (10^{34} $cm^{-2}s^{-1}$)	115	230	28	8.5	0.95	1.55
Lumi/year (2 IP, ab^{-1})	24	48	6	1.7	0.2	0.34
Physics goal (ab^{-1})	150 ab-1 (30,90,30 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
Number of events	5×10^{12} Z		10^8 W^+W	10^6 HZ 25k WW→ H	10^6 tt 200k HZ 50k WW→ H	

Total : 15 years



Different projects use different definition for a ‘year’:

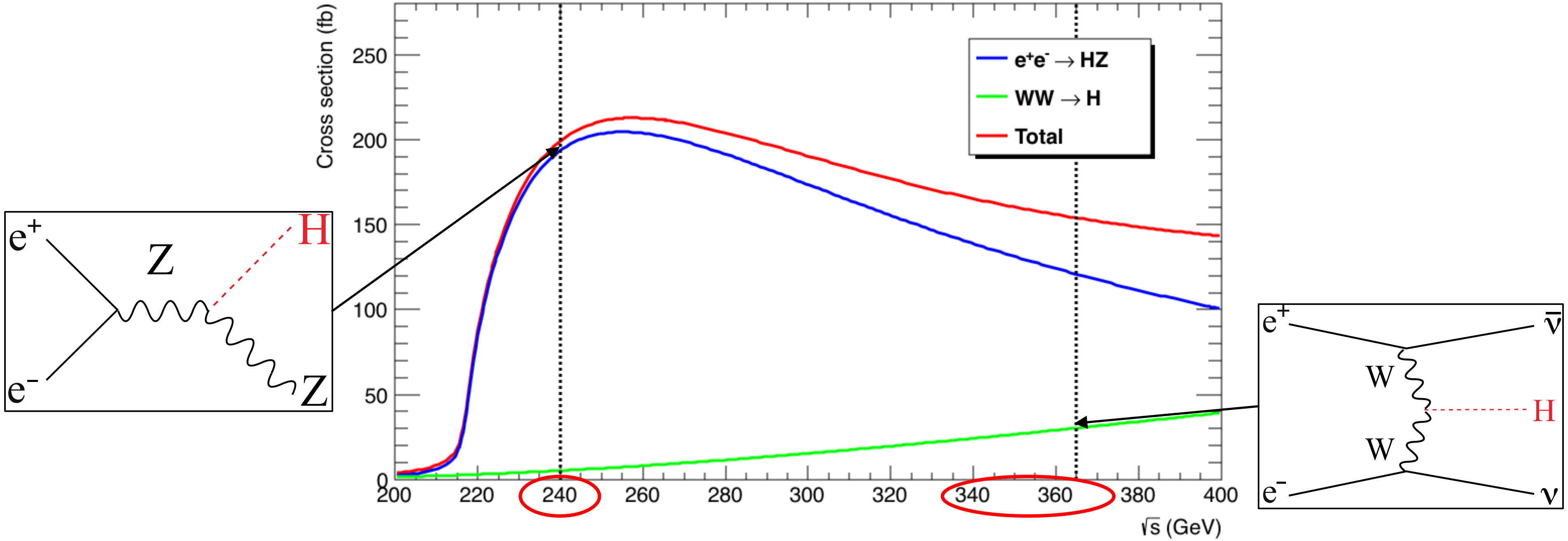
- 1 ILC year = 1.5 FCC years

M. Koratzinos, ICNFP 2019

FCC AS A HIGGS FACTORY

The FCC-ee as a Higgs factory

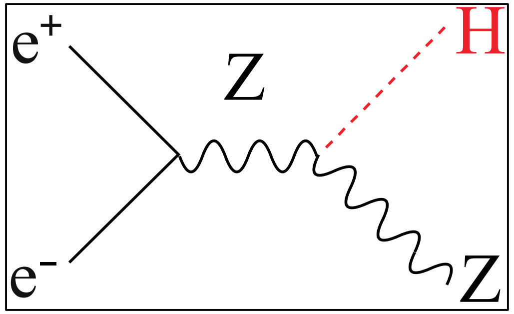
- Higgsstrahlung ($e^+e^- \to ZH$) event rate largest at $\sqrt{s}$ ~ 240 GeV : σ ~200 fb



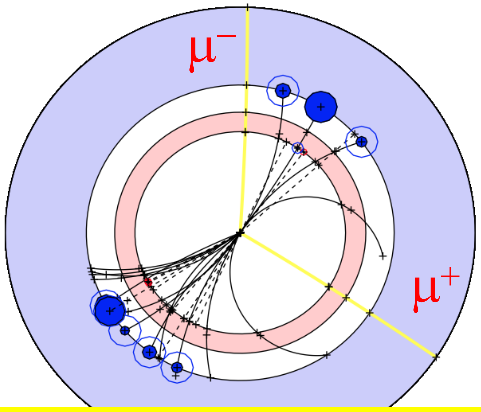
- 10^6 $e^+e^- \to ZH$ events with 5 ab^{-1} – cross section predicted with great accuracy
  - Target : (few) per-mil precision on couplings, statistics-limited.
  - Complemented with 200k events at $\sqrt{s}$ = 365 GeV
    - ➔ Of which 30% in the WW fusion channel (useful for the Γ_H precision)

Absolute coupling and width measurement

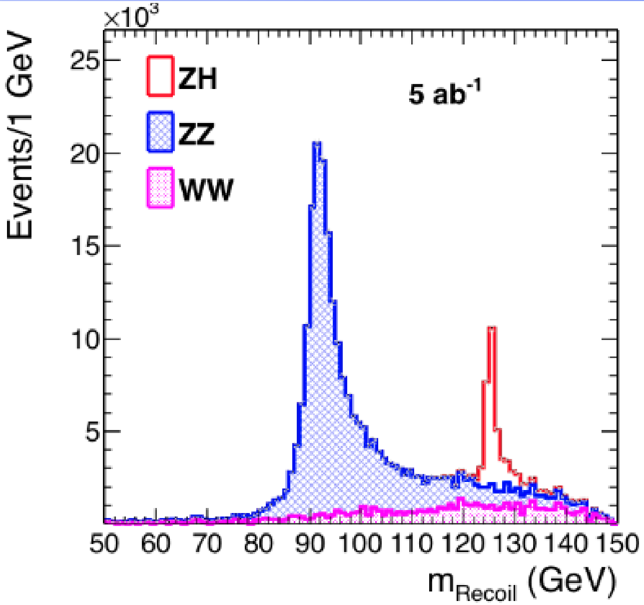
- Higgs tagged by a Z, Higgs mass from Z recoil



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



$e^+e^- \to HZ$; $Z \to \mu\mu$; $H \to$ hadrons



Mass recoiling against a muon pair (determined from energy-momentum conservation)

- Total rate $\propto g_{HZZ}^2$ $\rightarrow$ measure g_{HZZ} to 0.2%
- $ZH \rightarrow ZZZ$ final state $\propto g_{HZZ}^4 / \Gamma_H$ $\rightarrow$ measure Γ_H to a couple %
- $ZH \rightarrow ZXX$ final state $\propto g_{HXX}^2\, g_{HZZ}^2 / \Gamma_H$ $\rightarrow$ 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 …
  - $\sigma_{i\rightarrow f}^{(observed)} \propto \sigma_{prod}\, (g_{Hi})^2\, (g_{Hf})^2 / \Gamma_H$
    - Difficult to extract the couplings from cross sections (observable): σ_{prod} is uncertain and Γ_H is largely unknown
      - ➔ Must do physics with ratios or with additional assumptions.

Result of the "kappa" fit on Higgs couplings

- Same fit applied to all Higgs factories for an unbiased comparison

Collider	HL-LHC	ILC_{250}	CLIC_{380}	$\mathrm{LEP3}_{240}$	CEPC_{250}	$\mathrm{FCC\text{-}ee}_{240+365}$		
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
$\delta g_{HZZ}/g_{HZZ}$ (%)	1.3	0.3	0.60	0.32	0.25	0.2	**0.17**	0.16
$\delta g_{HWW}/g_{HWW}$ (%)	1.4	1.7	1.0	1.7	1.4	1.3	**0.43**	0.40
$\delta g_{Hbb}/g_{Hbb}$ (%)	2.9	1.7	2.1	1.8	1.3	1.3	**0.61**	0.55
$\delta g_{Hcc}/g_{Hcc}$ (%)	SM	2.3	4.4	2.3	2.2	1.7	**1.21**	1.18
$\delta g_{Hgg}/g_{Hgg}$ (%)	1.8	2.2	2.6	2.1	1.5	1.6	**1.01**	0.83
$\delta g_{H\tau\tau}/g_{H\tau\tau}$ (%)	1.8	1.9	3.1	1.9	1.5	1.4	**0.74**	0.64
$\delta g_{H\mu\mu}/g_{H\mu\mu}$ (%)	4.4	14.1	n.a.	12	8.7	10.1	**9.0**	3.9
$\delta g_{H\gamma\gamma}/g_{H\gamma\gamma}$ (%)	1.6	6.4	n.a.	6.1	3.7	4.8	**3.9**	1.1
$\delta g_{Htt}/g_{Htt}$ (%)	2.5	–	–	–	–	–	–	2.4
$\mathrm{BR}_{\mathrm{EXO}}$ (%)	SM	< 1.7	< 2.1	< 1.6	< 1.2	< 1.2	< 1.0	< 1.0

- 68% CL (exotic: 95% CL)
- Model-independent fit
- HL-LHC: out 'best guess' fit
- Results for Γ_H and g_{HWW} are significantly improved by adding the WW fusion process at 365GeV. This in turn improves all coupling estimates

- **The FCC-ee improves precision of 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)**
  - Combination better by a factor 2 (4) than 240 (365) GeV alone

…and for the ultimate FCC-ee performance (4 IPs)

- Same fit applied to all Higgs factories for an unbiased comparison

Collider	HL-LHC	ILC_{250}	$CLIC_{380}$	$LEP3_{240}$	$CEPC_{250}$	$FCC\text{-}ee_{240+365}$	
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**
$\delta g_{HZZ}/g_{HZZ}$ (%)	1.3	0.3	0.60	0.32	0.25	0.13	**0.10**
$\delta g_{HWW}/g_{HWW}$ (%)	1.4	1.7	1.0	1.7	1.4	0.85	**0.24**
$\delta g_{Hbb}/g_{Hbb}$ (%)	2.9	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**
$\delta g_{Hgg}/g_{Hgg}$ (%)	1.8	2.2	2.6	2.1	1.5	1.07	**0.60**
$\delta g_{H\tau\tau}/g_{H\tau\tau}$ (%)	1.8	1.9	3.1	1.9	1.5	0.92	**0.43**
$\delta g_{H\mu\mu}/g_{H\mu\mu}$ (%)	4.4	14.1	n.a.	12	8.7	6.8	**5.5**
$\delta g_{H\gamma\gamma}/g_{H\gamma\gamma}$ (%)	1.6	6.4	n.a.	6.1	3.7	3.0	**2.2**
$\delta g_{Htt}/g_{Htt}$ (%)	2.5	–	–	–	–	–	–
BR_{EXO} (%)	SM	< 1.7	< 2.1	< 1.6	< 1.2	< 0.8	$< \mathbf{0.65}$

- 68% CL (exotic: 95% CL)
- Model-independent fit
- HL-LHC: out 'best guess' fit
- Results for Γ_H and g_{HWW} are significantly improved by adding the WW fusion process at 365GeV. This in turn improves all coupling estimates

- **The FCC-ee improves precision of HL-LHC by large factors (copious modes)**
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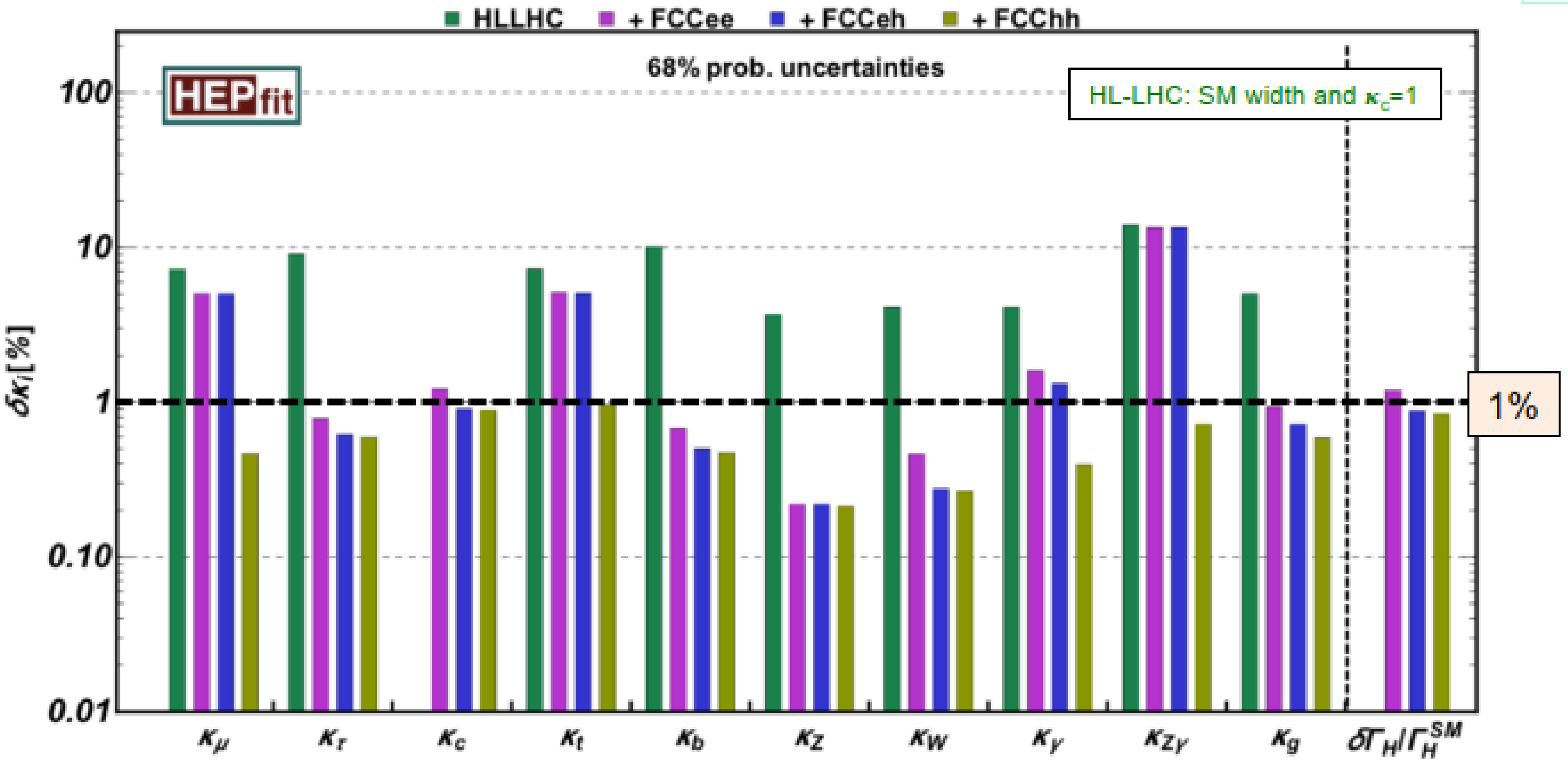
FCC-ee, FCC-ep, FCC-pp together

"Ultimate" precision on the Higgs coupling measurements by combining the results from HL-LHC and each FCC collider sequentially.

Number of Higgs bosons produced:
FCC-ee: 10^6
FCC-eh: 2. 10^6
FCC-hh: 10^{10}



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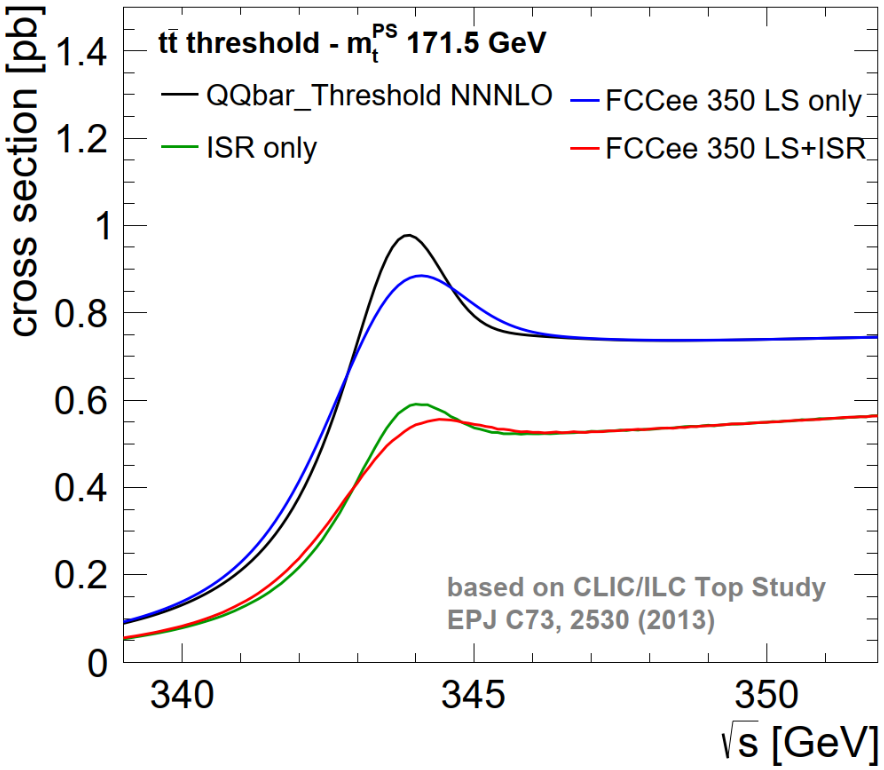
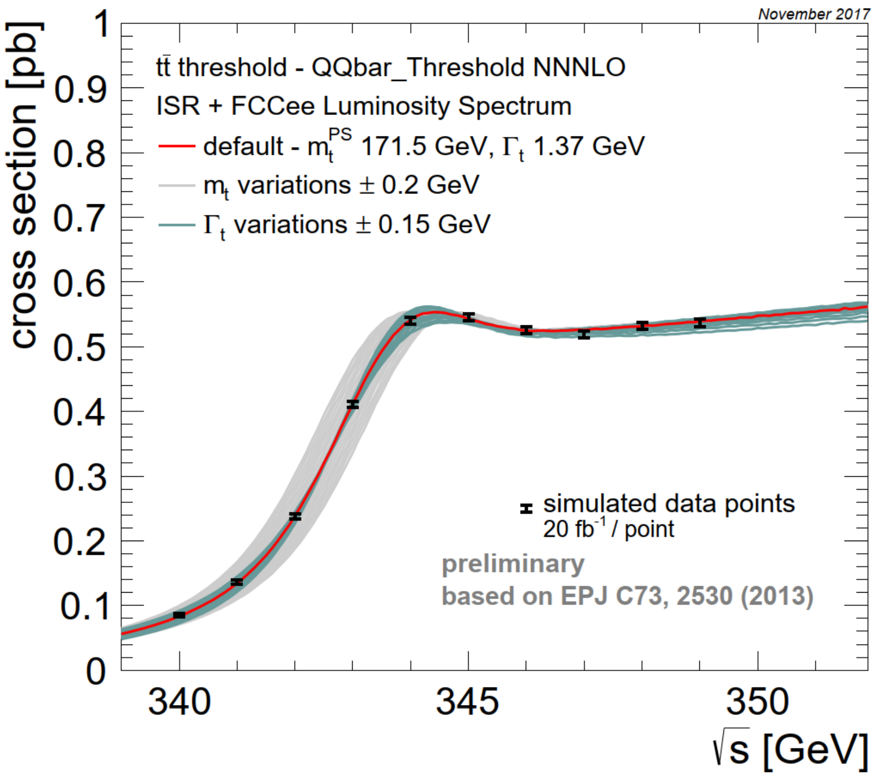
One-sigma precision reach at the FCC on the different Higgs coupling scaling factors within the κ-framework

Note: input from FCC-ee (e.g. HZZ coupling) removes model-dependence of several couplings that are best measured at FCC-HH (e.g. ttH, H→μμ, H → Zγ)

FCC AT THE TOP THRESHOLD

Physics goals at the top threshold





- **Measurement of the top quark mass** is a major goal of the FCC-ee physics programme
- An **energy scan** around the top pair production threshold provides the highest accuracy

- The tt production cross-section shape depends strongly on $\mathbf{m_{top}}$ but also on $\mathbf{\Gamma_{top}}$, $\boldsymbol{\alpha_s}$ and the top Yukawa coupling $\mathbf{y_{top}}$
- The resulting statistical uncertainty on m_{top} (Γ_{top}) is 17 MeV (45 MeV)
- The systematic error due to the knowledge of the E_{CM} energy (10 MeV) is 3 MeV
- The systematic error due to the uncertainty in α_s (measured at low energies to 2×10^4) is 5MeV
- The current status of the theory uncertainty from NNNLO calculations is of O(40 MeV) for the mass and the width. This is the dominant systematic error
- The top Yukawa coupling could be extracted indirectly with a 10% uncertainty

FCC FOR ELECTROWEAK PRECISION OBSERVABLES

FCC-ee for EW precision observables

- The low energy runs of FCC-ee (around the Z peak and WW threshold) give **immense statistics**
- This, coupled to **excellent E_{CM} knowledge**, **excellent energy spread measurements** and **very good luminosity determination** give unprecedented accuracy on EW precision observables.
- **Z run:** statistics at the peak 91.2GeV, plus a scan at 87.7 and 93.9 (slightly different than LEP energies, dictated by the alpha_QED measurement)
- **WW run:** 157.3 and 162.6 GeV, 12 ab-1
- **tt run:** top threshold scan, 340 to 350 GeV, ~10 points

Selected EW observables, experimental precision

	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
	G_Z (MeV)	Z Lineshape	2495200 ± 2300	8	< 100	Beam energy
	R_l (×10^3)	Z Peak (G_{had}/G_{lep})	20767 ± 25	0.06	0.2 – 1	Detector acceptance
	R_b (×10^6)	Z Peak (G_{bb}/G_{had})	216290 ± 660	0.3	< 60	g → bb
	N_v (×10^3)	Z Peak (s_{had})	2984 ± 8	0.005	1	Lumi measurement
	$\sin^2\theta_W^{eff}$ (×10^6)	A_{FB}^{mm} (peak)	231480 ± 160	3	2 – 5	Beam energy
	$1/\alpha_{QED}(m_Z)$ (×10^3)	A_{FB}^{mm} (off-peak)	128952 ± 14	4	< 1	Beam energy
	$\alpha_s(m_Z)$ (×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_v (×10^3)	$e^+e^- \rightarrow$ gZ, Z → nn, ll	2920 ± 50	0.8	small	?
	$\alpha_s(m_W)$ (×10^4)	$B_l = (G_{had}/G_{lep})_W$	1170 ± 420	2	small	CKM Matrix
tt thresh.	m_{top} (MeV)	Top Threshold scan	173340 ± 760 ± 500	17	< 40	QCD corr.
	Γ_{top} (MeV)	Top Threshold scan	?	45	< 40	QCD corr.
	$\lambda_{top}/\lambda_{top}^{SM}$	Top Threshold scan	1.3 ± 0.3	0.08	< 0.05	QCD corr.
	ttZ couplings	√s = 365 GeV	± 30%	0.5 – 1.5%	< 2%	QCD corr

Important features for precision – EWPO regime

- **Statistics**
  - Very high statistics at the Z pole (70 kHz of visible Z decays) – we are systematics dominated at the Z!
  - Beam-induced backgrounds are mild compared to linear colliders, but not negligible
    - Detector readout must be able to cope with both
- **Luminosity measurement**
  - Aim at 0.01% from small angle Bhabhas
    - Requires μm precision for LumiCal
    - Requires calculation/measurement of outgoing $e^{\pm}$ deflection from the opposite bunch
  - Need to study $e^+e^- \to \gamma\gamma$ 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). 10 mm radius is currently investigated!
    - New CEPC studies claim Purity × Efficiency ~ 97% for $H \to bb$. And at FCC-ee ?

Energy measurement using the resonant depolarization method

Unique to circular colliders

Energy, E of an electron in a synchrotron, is proportional to spin tune, ν (number of times the average spin vector precesses in one revolution in a synchrotron), the electron rest mass and the ratio of anomalous to normal parts of the gyromagnetic ratio:

$$E = \nu \frac{mc^2}{q'/q_0} \,.$$

The ratio of anomalous and normal parts of gyromagnetic ratio is $q'/q_0 = 1.15965218091 \cdot 10^{-3} \pm 0.26 \cdot 10^{-12}$, the electron rest mass is $mc^2 = 0.5109989461 \pm 0.31 \cdot 10^{-8}$ MeV [57]. Hence, beam energy is given by

$$E[MeV] = 440.64846 \cdot \nu \,, \tag{52}$$

with an accuracy of

$$\frac{\Delta E}{E} = \sqrt{\left(\frac{\Delta(mc^2)}{mc^2}\right)^2 + \left(\frac{\Delta(q'/q_0)}{q'/q_0}\right)^2} \simeq \frac{\Delta(mc^2)}{mc^2} = 7.8 \cdot 10^{-8} \,.$$

Uncertainty dominated by the knowledge of the electron mass, corresponding to 7keV on the Z mass…

The resonant depolarization method – instantaneous accuracy

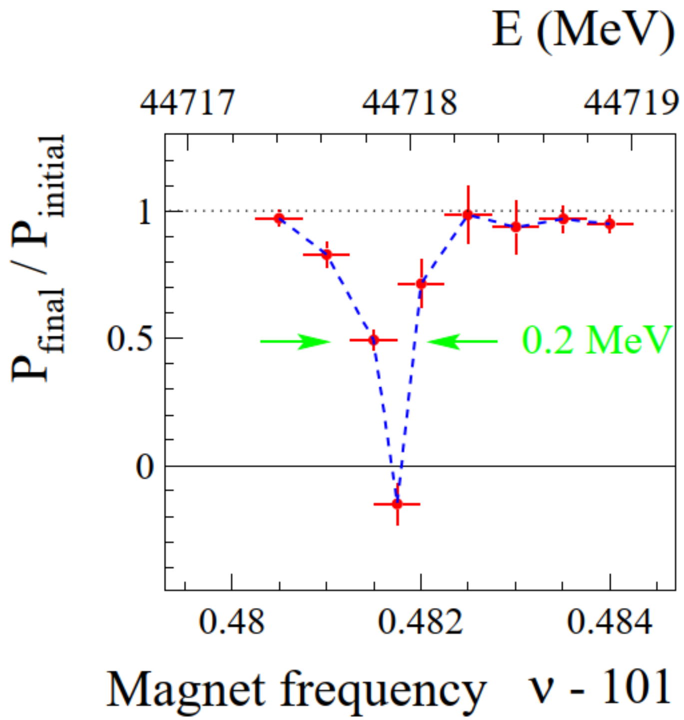
- In an accelerator, we need to deal with bunches of electrons, so their collective spin tune relates to the average energy of the whole bunch.
- By depolarizing a previously polarized bunch (using a resonance) we can measure the (non-integer) part of the spin tune
- Instantaneous accuracy is exquisite: 200keV

Measurement over many turns, over the ensemble of particles

The problem:
- natural polarization timescale is huge: 15 hours for 5% polarization

➔ The polarized bunches are non-colliding bunches!

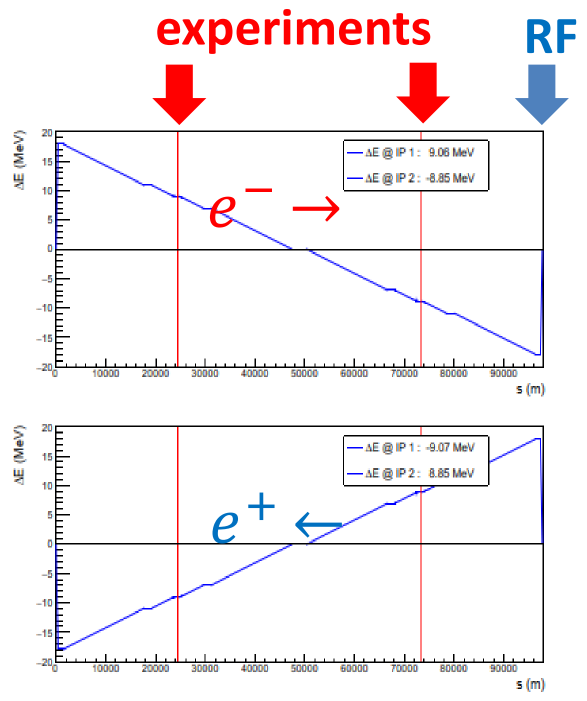
➔ We need to extrapolate from an excellent instantaneous average energy determination of a non-colliding buch to the E_{CM} at the experiments

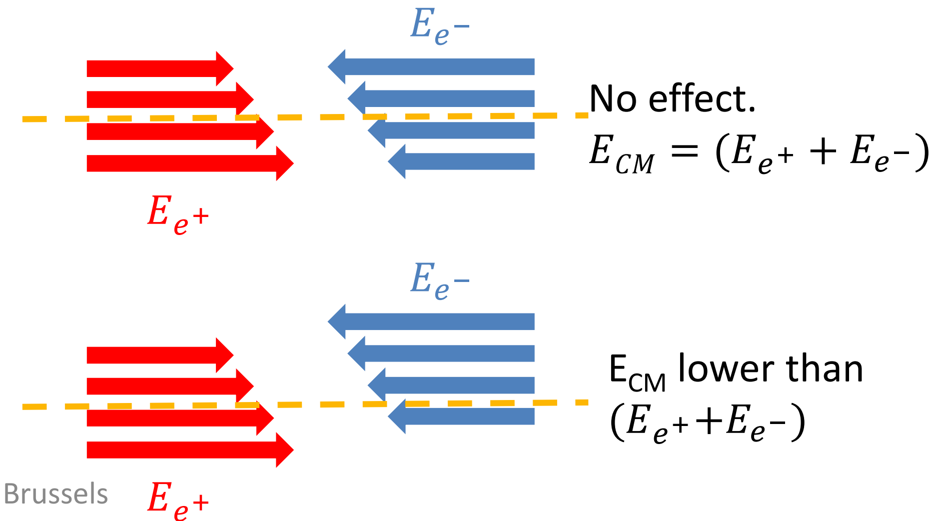


From the LEP campaign: 200 keV instantaneous accuracy

Energy determination strategy

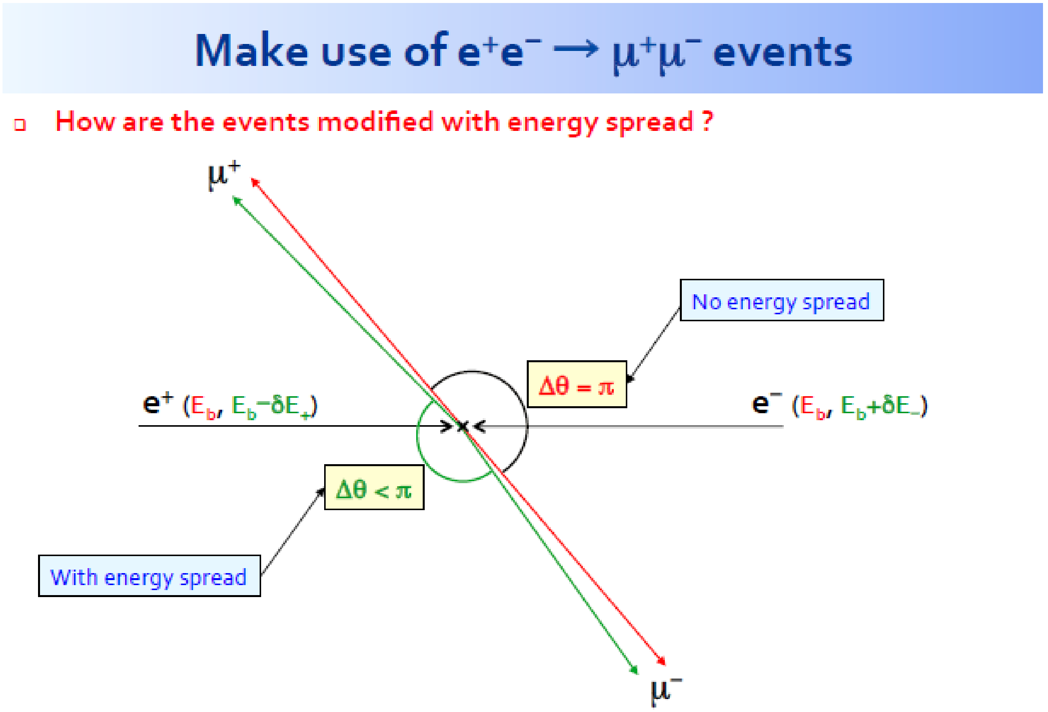
- A resonant depolarization measurement every 15 minutes for electrons and positrons (non-colliding bunches). This measures very precisely the average energy of the bunch over the whole ring. 10,000 measurements per year, 200keV error per measurement
- Tides alone change the bunch energy by 100MeV
- Extrapolate to the energy at each IP (RF model, impedance model)
- From beam energy to ECM energy: dispersion
- Energy spread: di-muon events

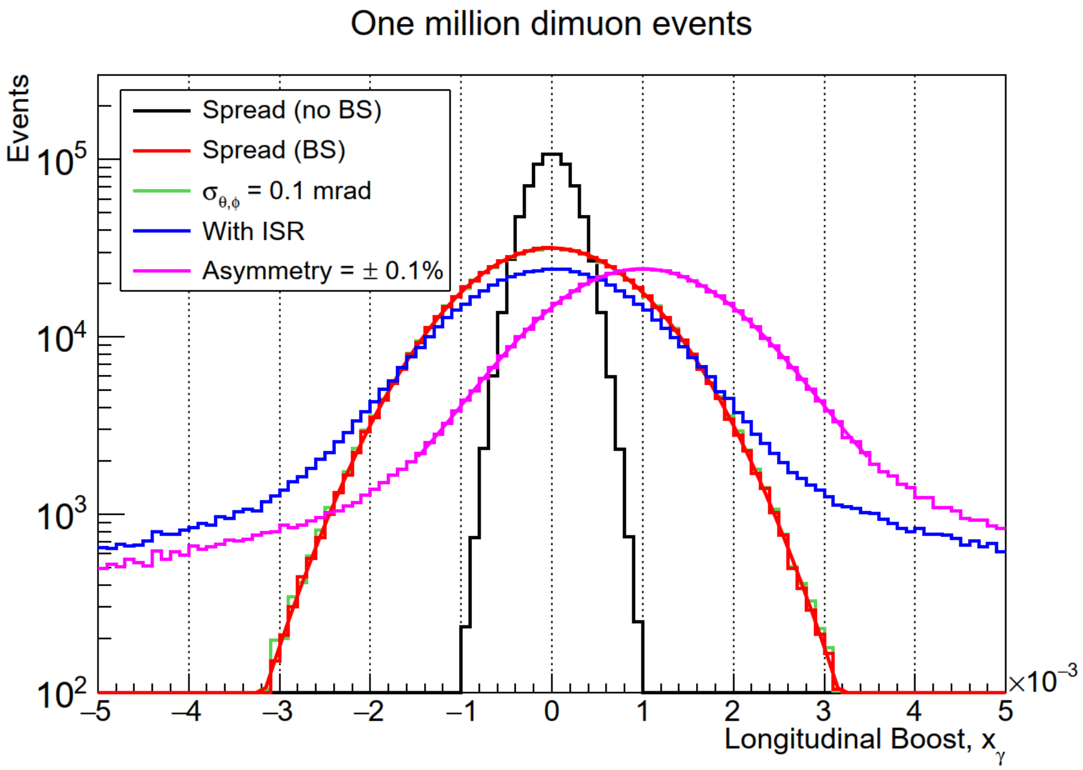




Energy spread determination

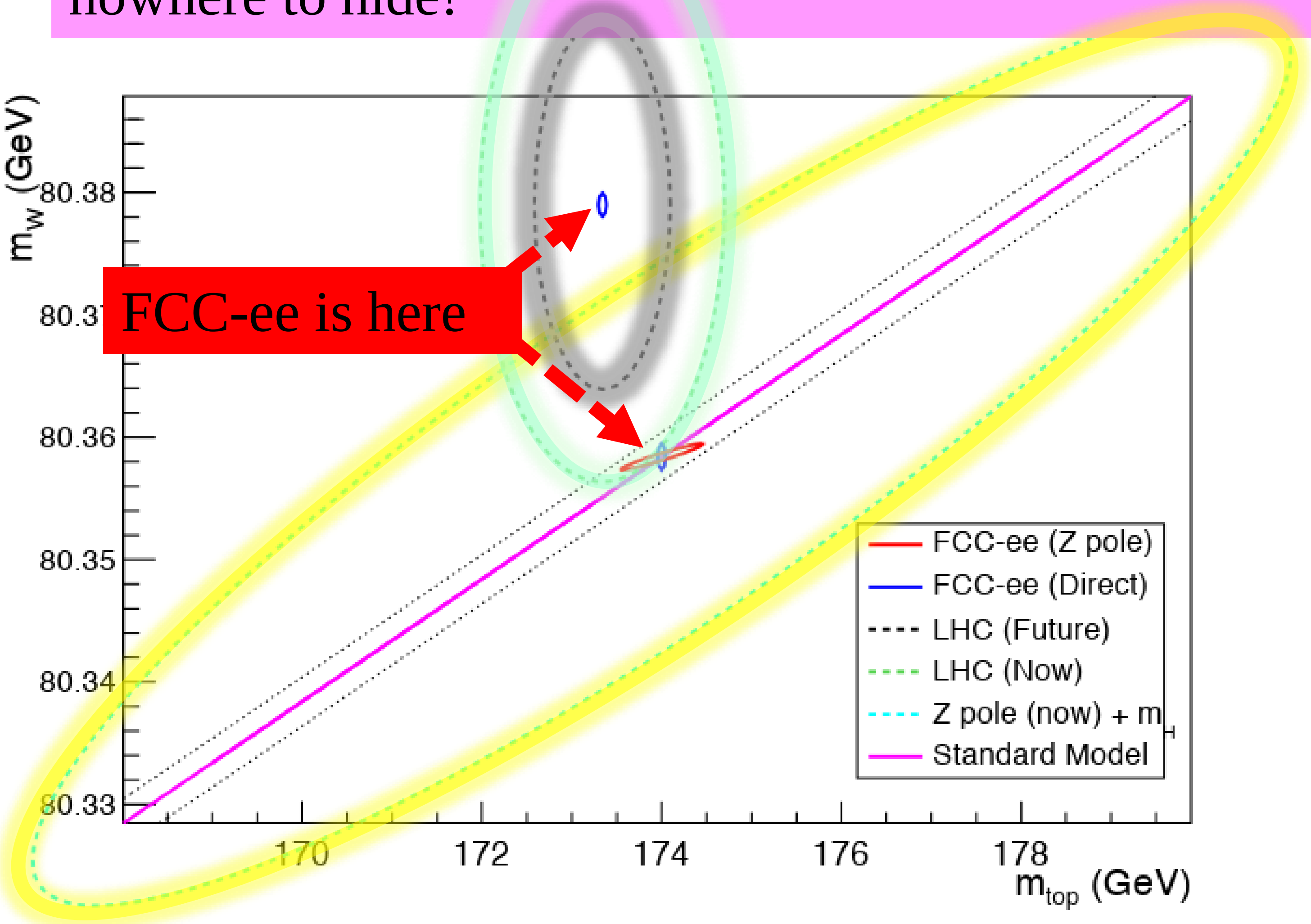
- Use di-muon events: 1M events every 4 minutes at the Z
- Can determine the energy spread plus any electron-positron energy asymmetry from the longitudinal boost
- Continuous 35keV precision on energy spread





Combination of all EW measurements

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



Effect of BSM physics is to modify EW observables through quantum effects (cf top & H @ LEP)

LEP + M_H @LHC

LHC (now)

LHC (future)

Standard model

FCC-ee direct

FCC-ee Z-pole

A note on attainable precision

Example: the W mass

Prediction:

before FCC | After FCC

$$m_W = 80.3593 \pm \boxed{0.0001}(m_{top}) \pm \boxed{0.0001}(m_Z) \pm \boxed{0.0003}(\alpha_{QED})$$
$$\pm \boxed{0.0002}(\alpha_S) \pm \boxed{0.0000}(m_H) \pm 0.0040\,(\text{theo.})$$

direct measurement:

$$m_W = 80.385 \pm \boxed{0.0005}$$

If only one ingredient is missing, the sensitivity to new physics may entirely vanish

Essential to reduce theory error: necessitates calculation up to 3-4 loops. Effort has already started. 2 loop calculations finished – 3 loops started. There is good hope that the theory error can be reduced so that it does not dominate the calculations

Comment about longitudinal polarization

- The FCC-ee e^+ and e^- beams will not be longitudinally polarized
  - Unlike at linear colliders where 80% polarized e^- can be injected and accelerated
    - And, with some 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
  - 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
- At the FCC-ee, longitudinal 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 $\sqrt{s}$

J. De Blas

Comment about longitudinal polarization

- The FCC-ee e^+ and e^- beams won't be longitudinally polarized
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Beam polarization brings no information
that cannot be obtained otherwise.
There is no obvious need for it.

Does polarization buy a factor 2.5 in luminosity?

A: No

- In several public presentations recently the claim was repeated that [longitudinal] beam polarization is equivalent to a factor of 2.5 in effective luminosity.
- This is very relevant to the comparison of linear and circular colliders, since (e-) polarization comes for free in linear colliders but is very expensive in circular machines
- Comparison is a bit tricky as projects use different analyses and the combination with HL-LHC distorts the picture.
- A recent analysis comparing like for like is available: P. Bambade et al., The International Linear Collider: A Global Project, 1903.01629, compilation of tables 18 and 19

$\sqrt{s}$ (GeV)	250	250 + 350
Lumi (ab^{-1})	2	5 + 1.5
Polarization	Yes	No
g_{HZZ} (%)	0.57	0.34
g_{HWW} (%)	0.55	0.35
g_{Hbb} (%)	1.0	0.62
$g_{H\tau\tau}$ (%)	1.2	0.71
g_{Hcc} (%)	1.8	1.1
g_{Hgg} (%)	1.6	0.96
$g_{H\mu\mu}$ (%)	4.0	3.7
$g_{H\gamma\gamma}$ (%)	1.1	1.0
$g_{HZ\gamma}$ (%)	9.1	8.1
Γ_H (%)	2.4	1.4

Ratios as expected from the luminosity ratio

Combination with HL-LHC, saturated

There is no benefit of polarization, as long as FCC-ee adds the run at 350-365 GeV. Without this run, there is a benefit of 25-60% to weak gauge bosons and 20% to fermions (b,c, τ) and gluons.

Is a $\sqrt{s}$ = 500 GeV upgrade required/useful ?

According to the white book of ESU 2013 :

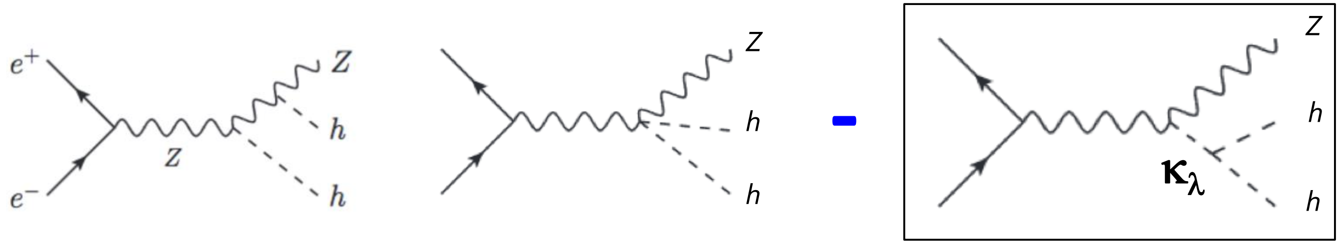
https://cds.cern.ch/record/1567295/

> 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 $\sqrt{s}$ = 500 GeV ?**
  - **For the total width and the coupling to the top quark : the answer is NO (slides 19 and 22) – there is a much better prior measurement (HL-LHC) which becomes model-independent after 7 yers of FCC-ee higgs physics**
  - **For the Higgs self-coupling (κ_λ):**

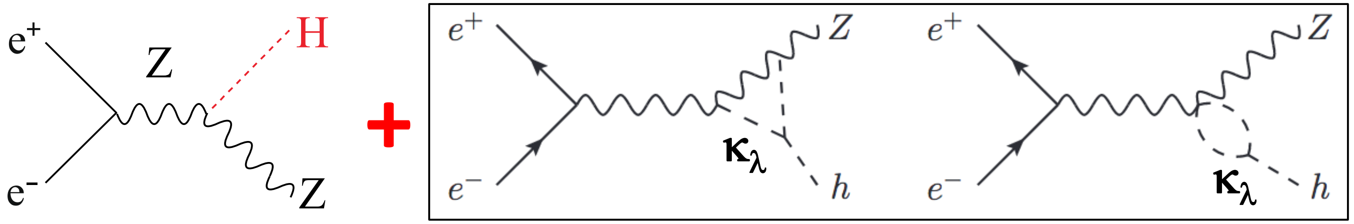
At $\sqrt{s}$ = 500 GeV

Di-Higgs production



At FCC-ee

σ_{HZ}

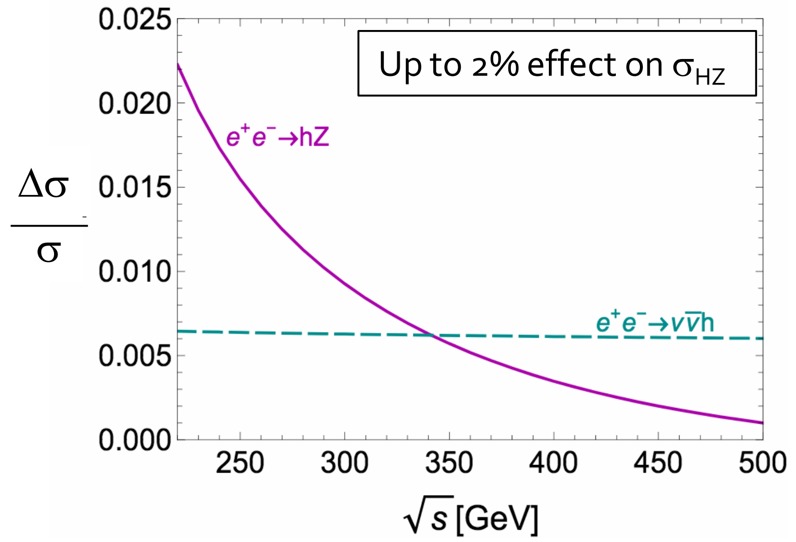


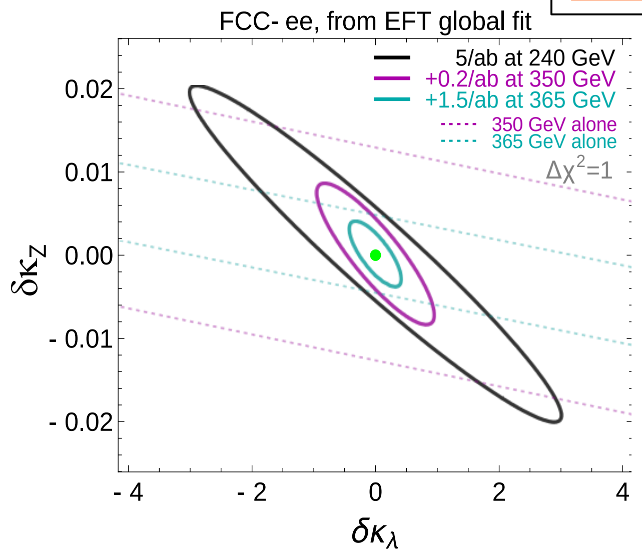
M. McCullough
arXiv:1312.3322

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 $\delta\kappa_\lambda$
  - 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%, respectively.

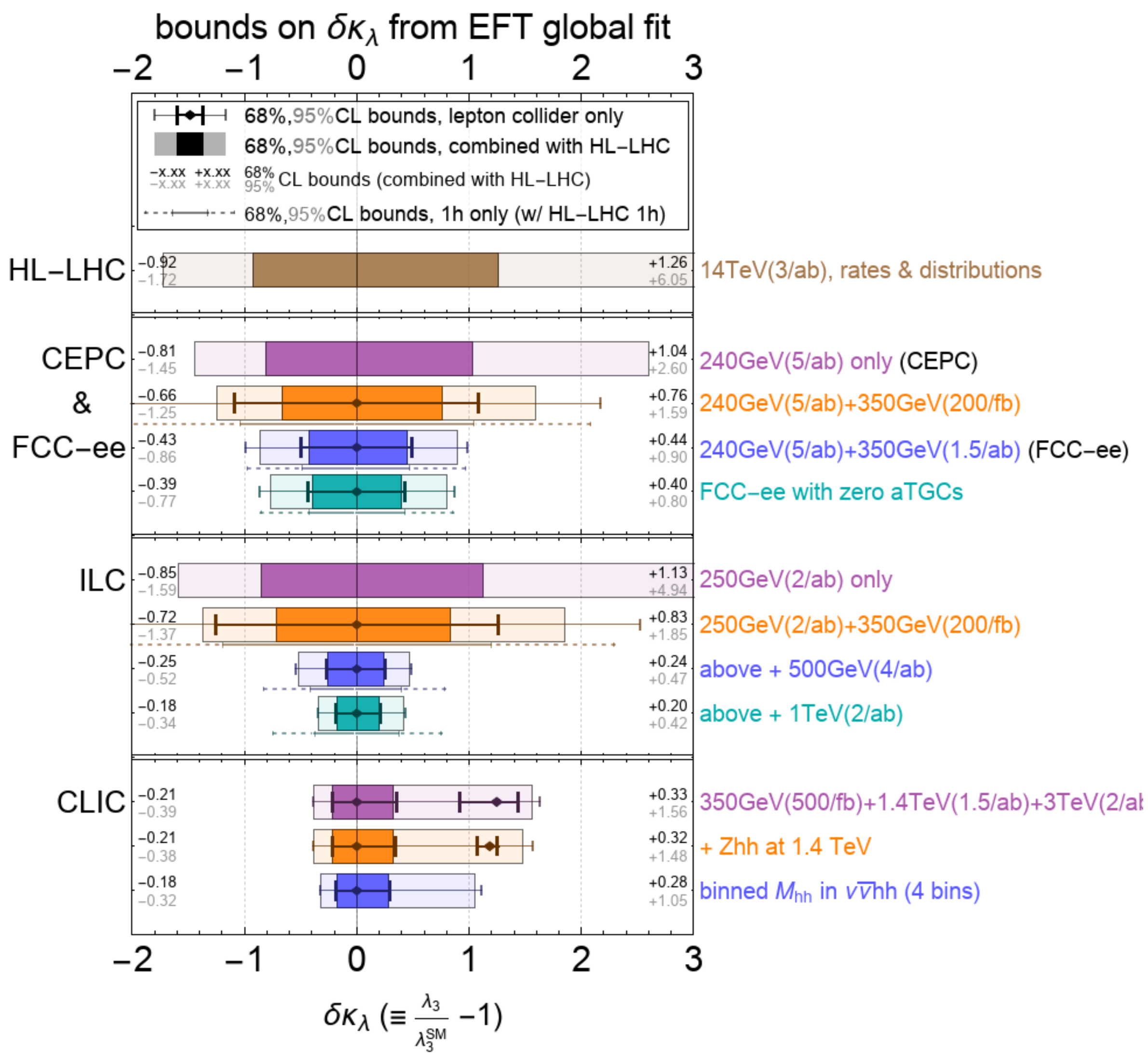
Higgs self coupling – the holy grail

A summary of the bounds on $\delta\kappa_\lambda$ from global fits for various future collider scenarios.

Linear colliders do a better job, but

- FCC data is collected in 7 years
- ILC data in 20 ILC years (H20 scenario)

All is surpassed by FCC-hh that can measure κ_λ to 5%



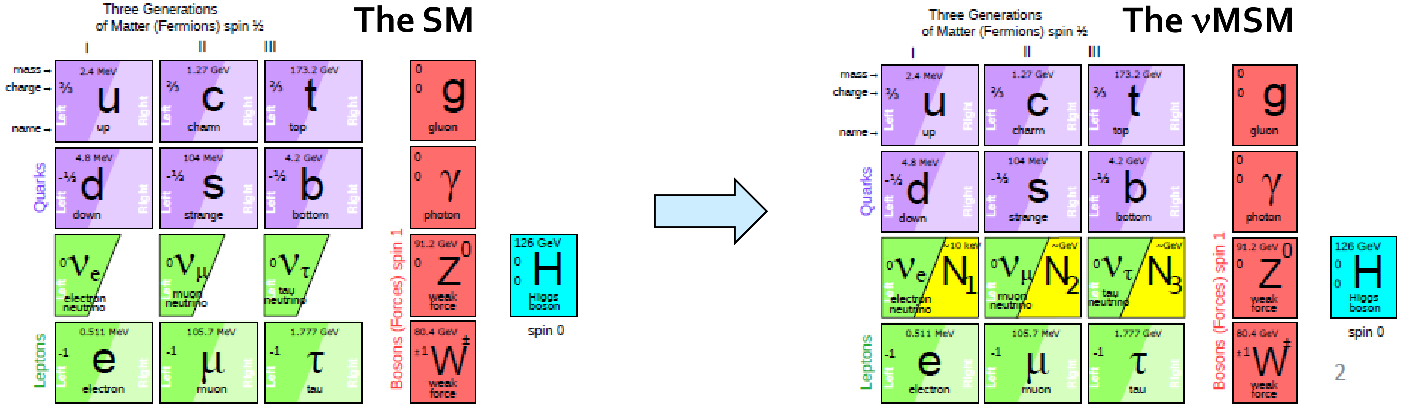
Stefano Di Vita et al, "A global view on the Higgs self-coupling at lepton colliders" arXiv:1711.03978v1 [hep-ph] 10 Nov 2017

Direct discoveries – right-handed neutrinos

- **Right-handed neutrinos**

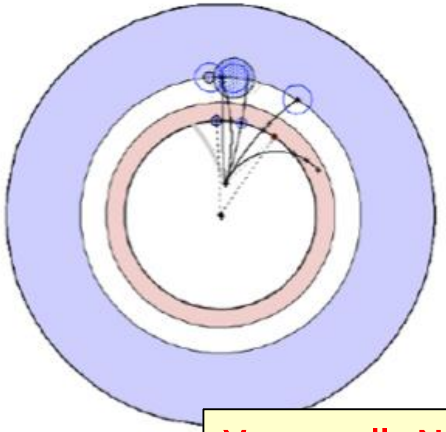
A. Blondel et al. arXiv:1411.5230

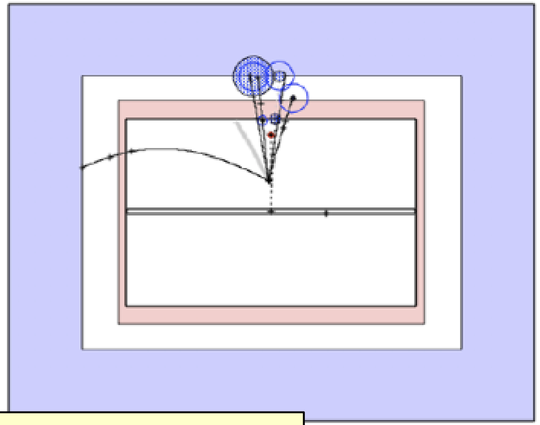
- νMSM : Complete particle spectrum with the missing three right-handed neutrinos



- Could explain everything: Dark matter (N_1), Baryon asymmetry, Neutrino masses

- Search for in very rare $Z \rightarrow \nu N_{2,3}$ decays
  - Followed by $N_{2,3} \rightarrow W^*\ell$ or $Z^*\nu$
  - **Very clean signture**

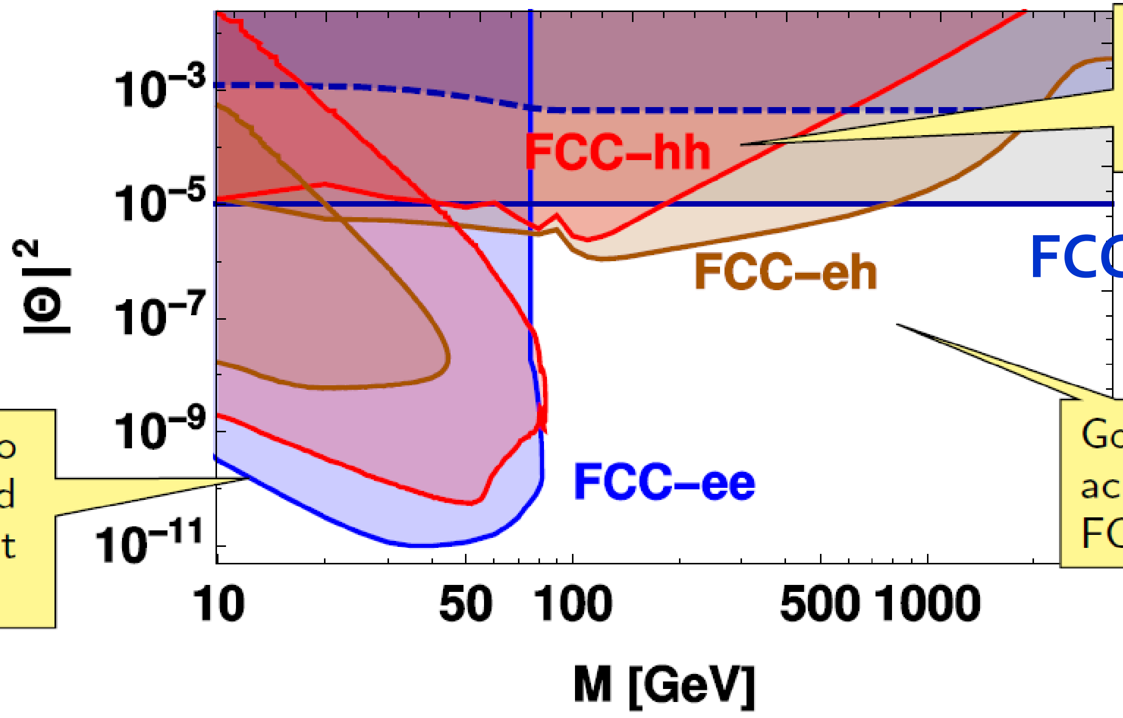




Very small νN mixing : long lifetime, detached vertex

Sterile neutrino sensitivity

- Systematic assessment of heavy neutrino signatures at colliders.
- First looks at FCC-hh and FCC-eh sensitivities.
- Golden channels:
  - **FCC-hh:** LFV signatures and displaced vertex search
  - **FCC-eh:** LFV signatures and displaced vertex search
  - **FCC-ee:** Indirect search via EWPO and displaced vertex search



FCC-hh able to test all flavour combinations.

High mass region: different FCC-ee limits for N3 (dashed) and N1+N2 (solid)

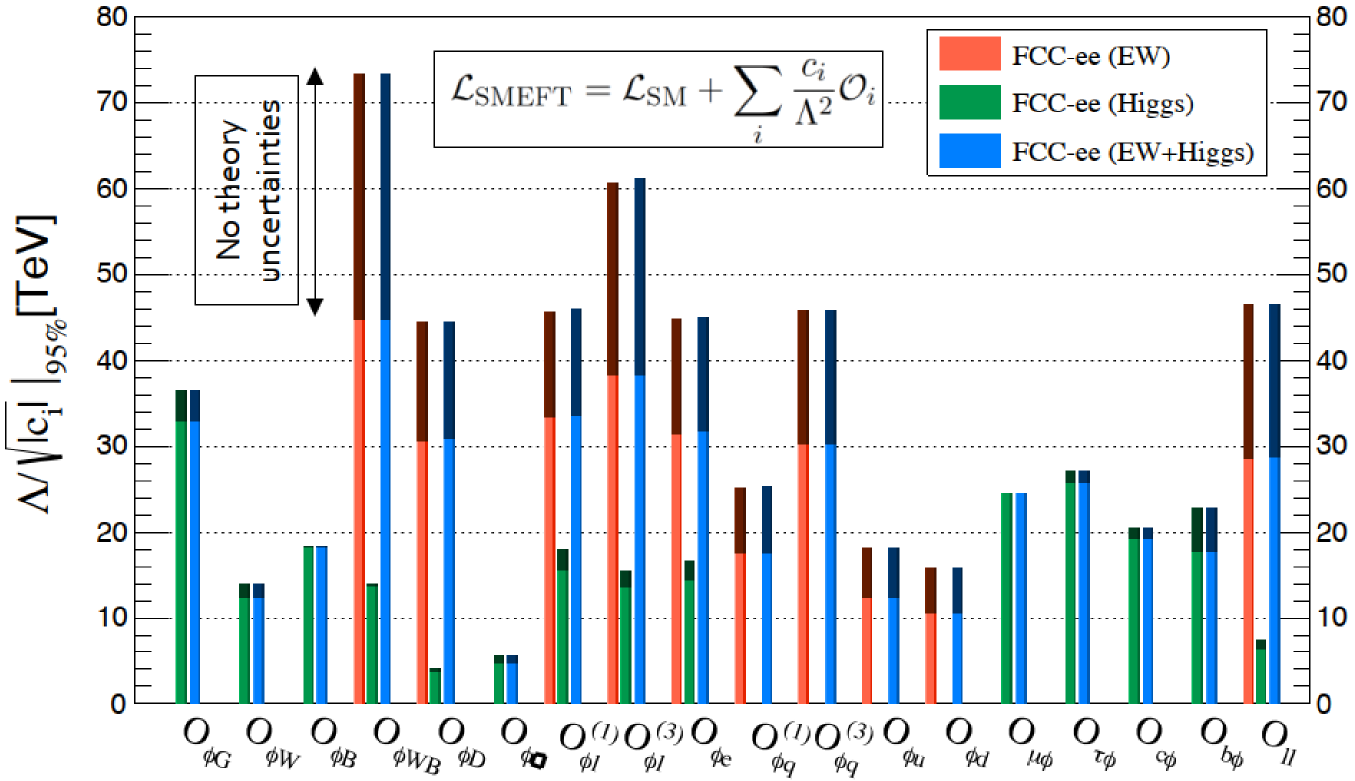
Good sensitivity reach from FCC-hh & FCC-eh.

Best sensitivity to $|\theta|^2$ from displaced vertex searches at the FCC-ee.

Patrick Janot

Precision ⟺ Discovery

Sensitivity to new physics: Combining precision Higgs and EW measurements in SMEFT*



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

FCC-ee reach for new physics: from typically 20TeV all the way to 70TeV

Dark bars: neglecting theory uncertainties

- Higgs and EWPO measurements are well complementary
- EWPO are more sensitive to heavy new physics (up to 50-70 TeV)
- Larger statistics pays off for Higgs measurements – we are statistics limited at ZH (4 IPs ?)
- Further improvement in theory predictions pays off for EWPO measurements

(*)SMEFT The Standard Model effective field theory is a model-independent framework for parameterising deviations from the Standard Model in the absence of light states.

Flavour physics : B anomalies, τ physics, …

- **Lepton flavour universality is challenged in $b \to s\,\ell^+\ell^-$ 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} $Z \to bb$, FCC-ee is beyond any foreseeable competition
      - ➔ Decay can be fully reconstructed; full angular analysis possible

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

J.F. Kamenik et al.
arXiv:1705.11106

Invariant mass reconstruction of $B^0 \to K^{*0}\tau\tau$ with decay vertices reconstructed. Dominant backgrounds are also shown

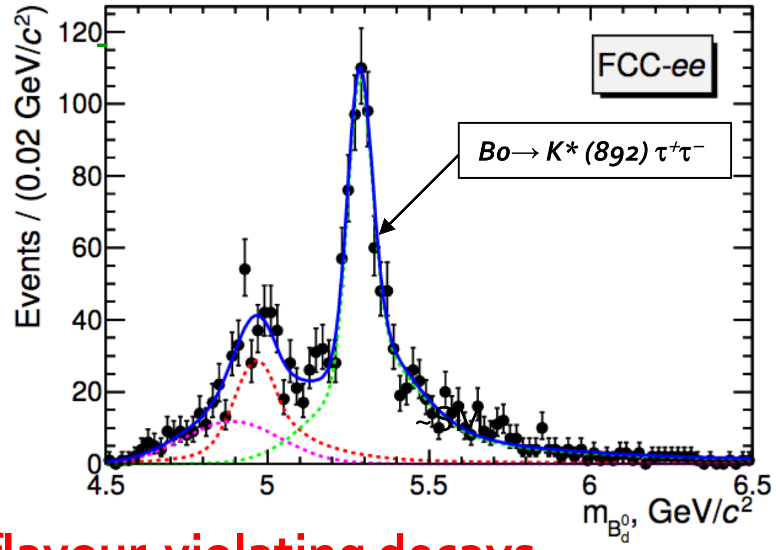
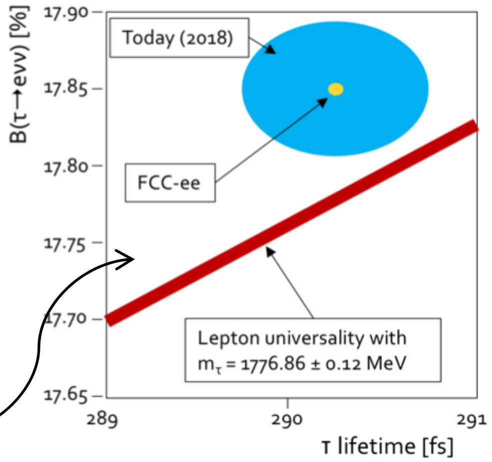


Table 7.2: Comparison of orders of magnitude for expected reconstructed yields of a selection of electroweak penguin and pure dileptonic decay modes in Belle II, LHCb upgrade and FCC-ee experiments. Standard model branching fractions are assumed. The yields for the electroweak penguin decay $B^0 \to K^{*0}(892)e^+e^-$ are given in the low q^2 region.

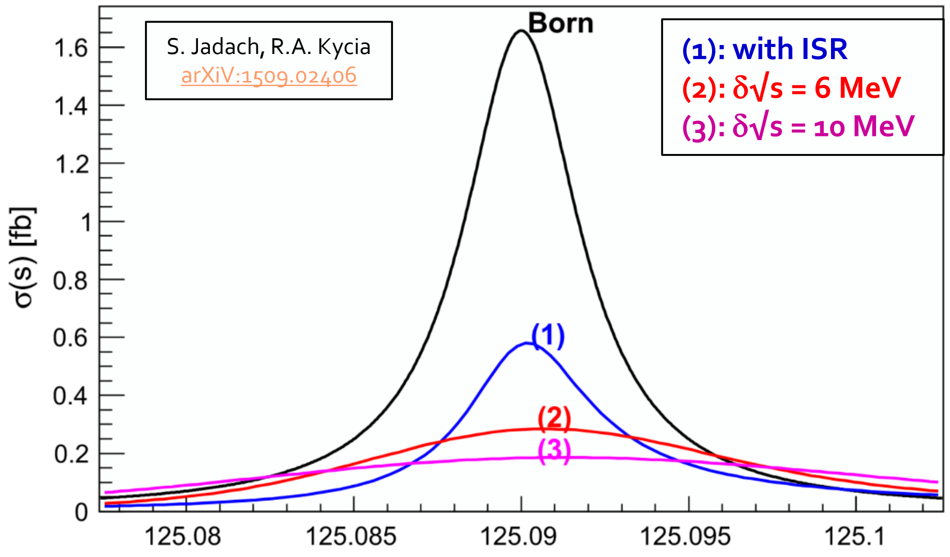
Decay mode	$B^0 \to K^*(892)e^+e^-$	$B^0 \to K^*(892)\tau^+\tau^-$	$B_s(B^0) \to \mu^+\mu^-$
Belle II	~ 2 000	~ 10	n/a (5)
LHCb Run I	150	-	~ 15 (–)
LHCb Upgrade	~ 5000	-	~ 500 (50)
FCC-ee	~ 200000	~ 1000	~1000 (100)



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

Unique at FCC-ee : First generation couplings

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



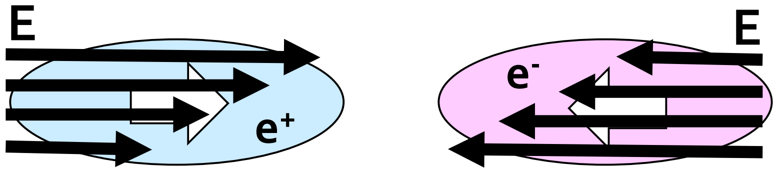
- FCC-ee monochromatization setups
  - Default: $\delta\sqrt{s}$ = 100 MeV, 25 ab^{-1} / year
    - No visible resonance
  - Option 1: $\delta\sqrt{s}$ = 10 MeV, 7 ab^{-1} / year
    - $\sigma(e^+e^- \to H)$ ~ 100 ab
  - Option 2: $\delta\sqrt{s}$ = 6 MeV, 2 ab^{-1} / year
    - $\sigma(e^+e^- \to H)$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

- Expected signal significance of ~0.4σ / √year in both option 1 and option 2
  - Set a electron Yukawa coupling upper limit : κ_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

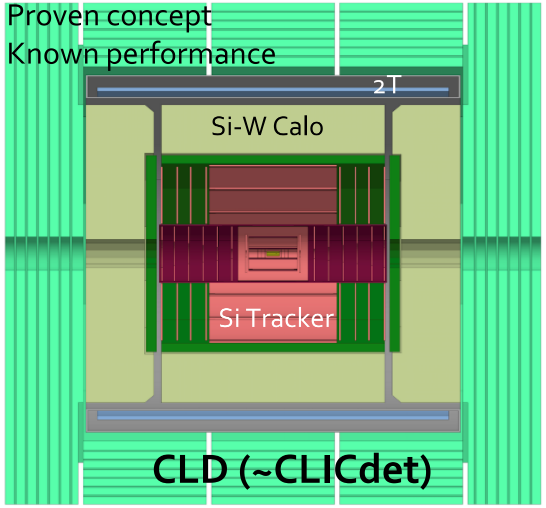
- Unique opportunity to constrain first generation Yukawa's

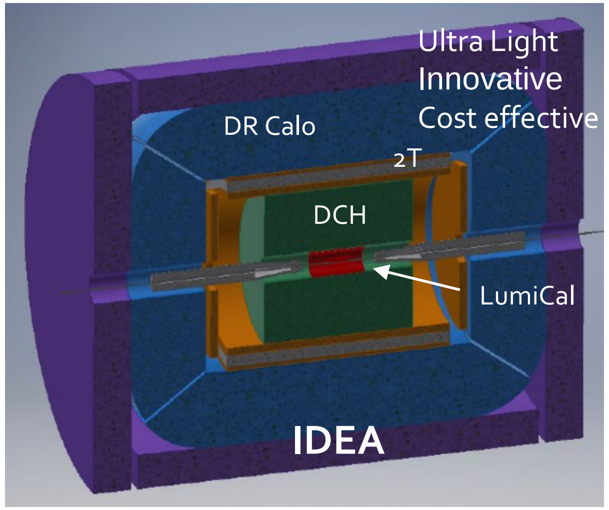
Monochromatization:



FCC-ee detector design concepts

- Two designs studied so far





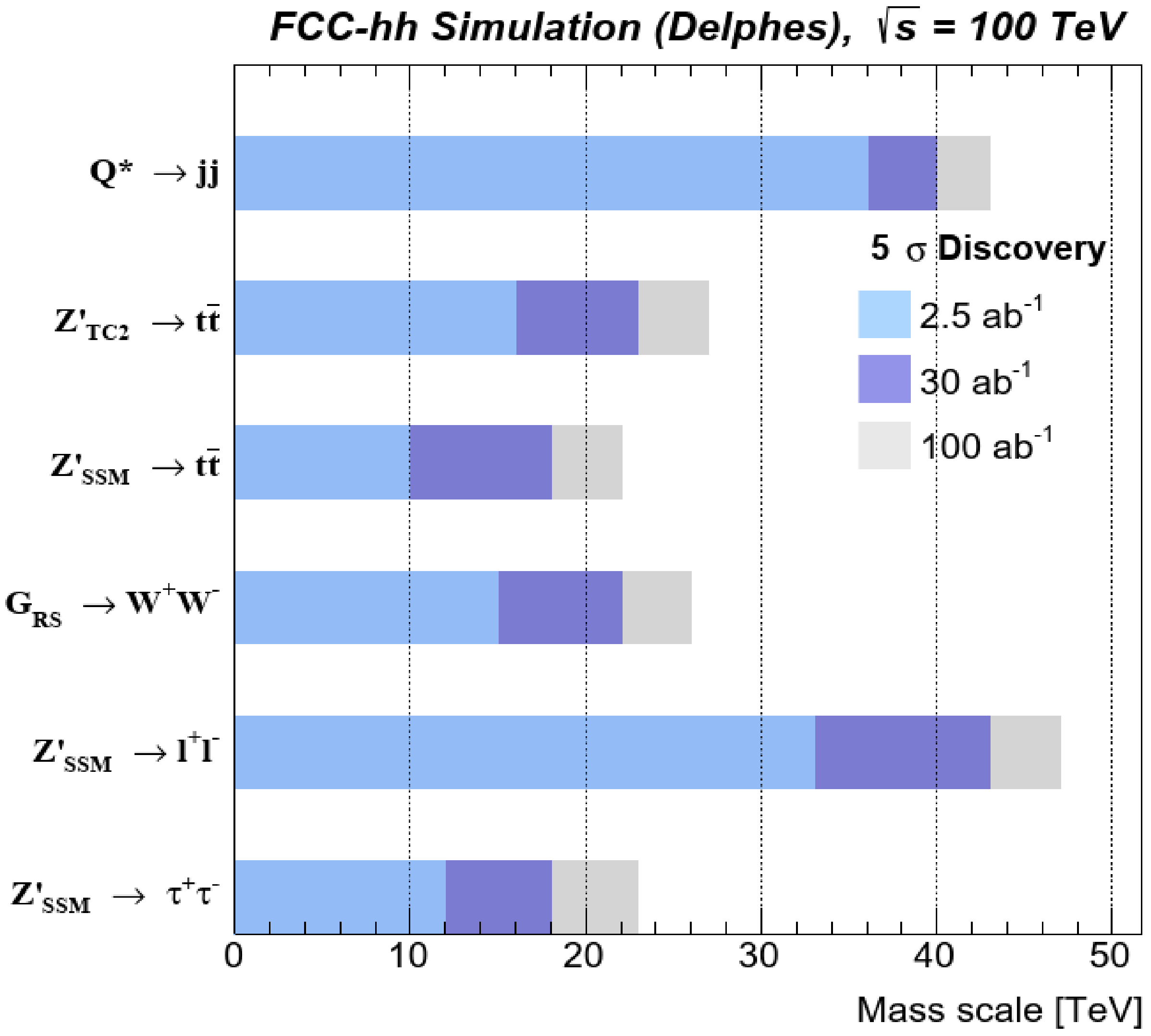
Two different concepts have been demonstrated to work, one a proven concept and the other with a thin solenoid and simple calorimeter (and a factor 2 cheaper)

  - 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

We are now open to detector collaborations!

And then comes FCC-hh

Z' gauge bosons, excited quarks Q*, massive gravitons G_{RS}



FCC-hh mass reach for different s-channel resonances

- Direct exploration of the 10-50TeV energy scale for E_{CM} of 100TeV
- Searches for (higgsino and wino-like) WIMP dark matter up to mass upper limits of 1-3TeV
- Measurement of the Higgs self coupling to 5%
- 100TeV for 16T magnets. For 24T magnets energy would be 150TeV
- Of course formidable technical challenges (very high field magnets, stored energy, cryogenics, pile-up, energy consumption, cost…)

reading

arXiv:1906.02693v1 [hep-ph] 6 Jun 2019

FCC-ee: Your Questions

Contribution to the European Particle Physics S

(See next page for the list of

Abstract

This document answers in simple terms many FAC with other colliders. It complements the FCC-ee CD addressing many questions from non-experts and cla Strategy symposium in Granada, with a view to inf now and the final endorsement by the CERN Counc recommendations. This document will be regularly information becomes available.

Figure 1: Baseline FCC tunnel layo Geneva basin, showing the main topog

[1]Send your questions to patrick.jan

1

Contents

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too afraid
sk...

ttps://arxiv.org/abs/1906.02693

Conclusions

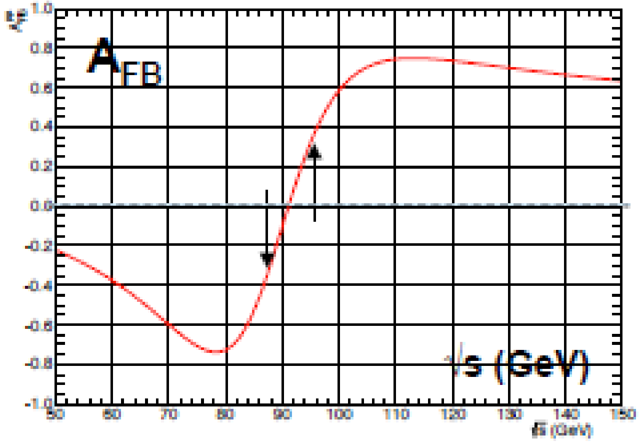
- FCC-ee has tremendous physics potential due to its
  - Huge statistics
  - Great precision
- It can improve EWPO by factors of ~20 to 50 compared to the situation today
- It can measure Higgs couplings to sub-percent precision
- It is sensitive to energy scales for new physics of 20-70TeV
- It has excellent upgrade potential: the FCC-hh, an 100TeV-plus hadron collider

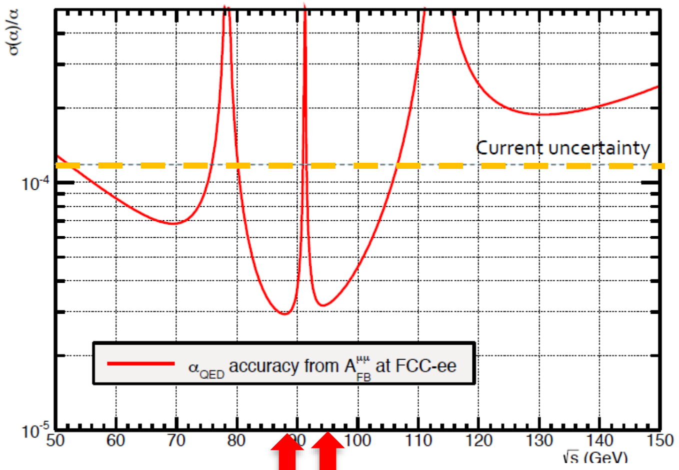
Come and join the adventure!

Extra slides

Statistics needed at/around the Z pole

- Many measurements dominated by systematic uncertainties with 10^{12} Z
  - Baseline FCC-ee parameters give 40 ab^{-1} / year, i.e. 2×10^{12} Z / year at the Z pole
    - Aren't the 0.6 ab^{-1} and 3×10^{10} Z / year at CEPC more than enough ?
- Some crucial measurements / discovery channels need more
  - Example: measurement of $\alpha_{QED}(m_Z)$ from A_{FB} ($\mu\mu$) through γ/Z interference





- With 40 ab^{-1} at 87.9 GeV and 40 ab^{-1} at 94.3 GeV (two years in total)
  - $\Delta\alpha/\alpha$ ~3×10^{-5} (stat) ; Most syst. exp. uncertainties cancel in the combination

    Beam energy calibrat

    A knowledge of the b

This is statistical uncertainty – systematic uncertainty cancels when we measure 2 points

- Similar statistics needed for most asymmetries at / around the Z pole

P.Janot, eeFACT2016, Daresbury