FCC-ee Status

Mogens Dam
Niels Bohr Institute
Copenhagen University

For the FCC-ee Study Group

IAS Conference on HEP 2019
Hong Kong,
21-24 January, 2019

Picture and slide layout, courtesy Jörg Wenninger

Future Circular Collider Study

International FCC collaboration to study (since 2014)

- **~100 km tunnel infrastructure** in Geneva area, linked to CERN
- **Ultimate goal: ≥ 100 TeV pp-collider (FCC-hh)**

≥16 T magnets

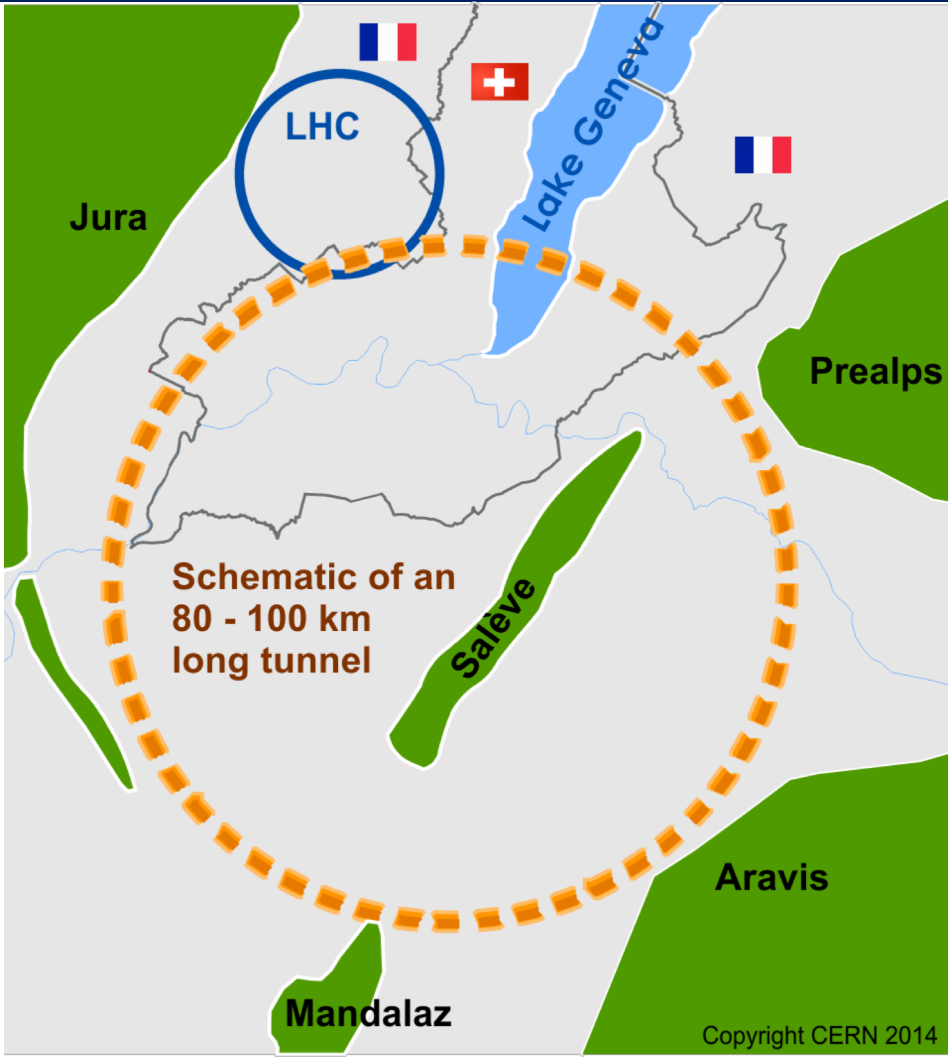
→ defining infrastructure requirements

Two possible first steps:

- ***e^+e^-*** **collider (FCC-ee)**
  High Lumi, E_{CM} = 90-400 GeV
- ***HE-LHC:*** **16 T ⇒ 27 TeV**
  in LEP/LHC tunnel

Possible addition

- **p-e (FCC-he)**

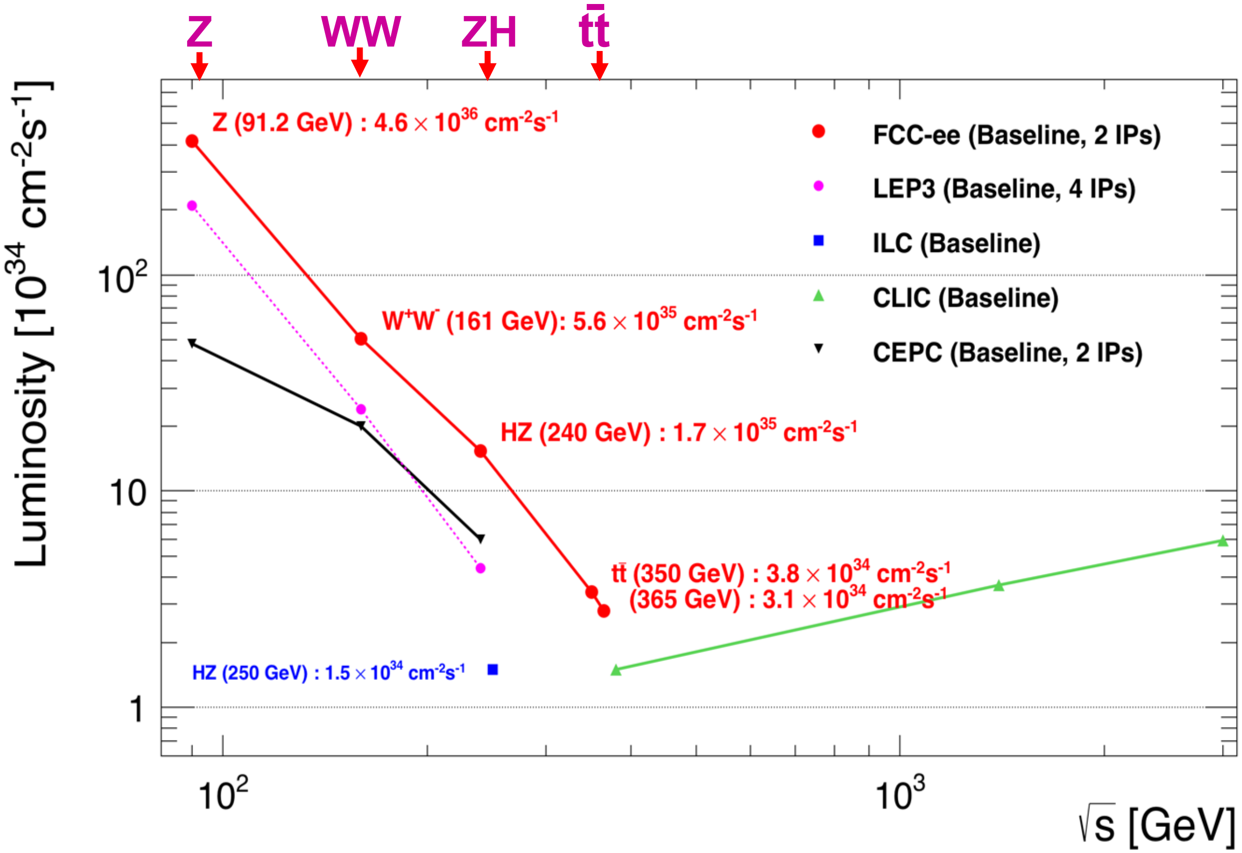


FCC CDRs available at

http://fcc-cdr.web.cern.ch/

EW factories: Energies and luminosities

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



Ultimate statistics/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

PRECISION and SENSITIVITY
to rare or elusive phenomena

Design with 4 IPs to be investigated
- Experience from LEP3 study: Luminosity per IP not much affected
- Approaching a doubling of total luminosity !

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")

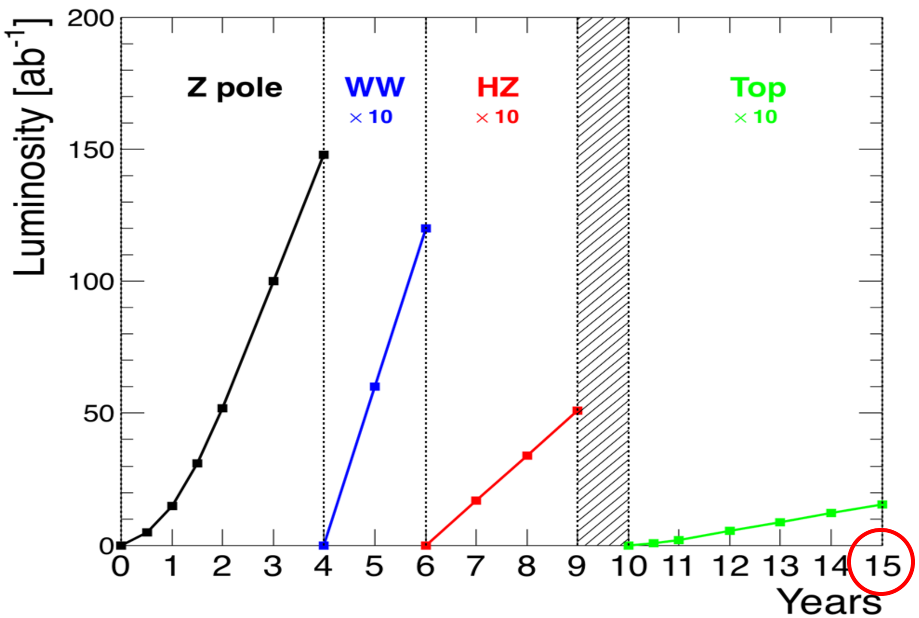
***FCC-ee is not only a Higgs factory*. Z, WW, and $t\bar{t}$ factories are important for discovery potential**

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

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

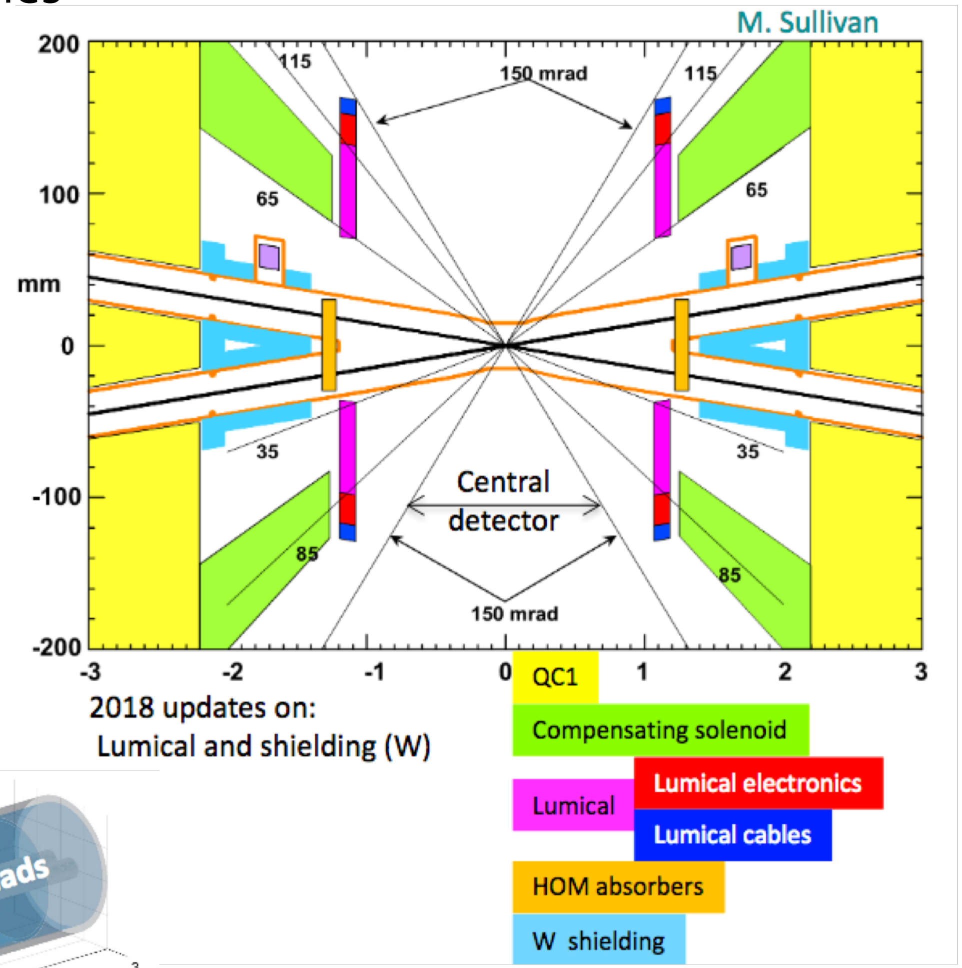
Event statistics	√s precision
5×10^{12} $e^+e^- \rightarrow Z$	100 keV
10^8 $e^+e^- \rightarrow W^+W^-$	300 keV
10^6 $e^+e^- \rightarrow HZ$	1 MeV
10^6 $e^+e^- \rightarrow t\bar{t}$	2 MeV

Important features for precision measurements

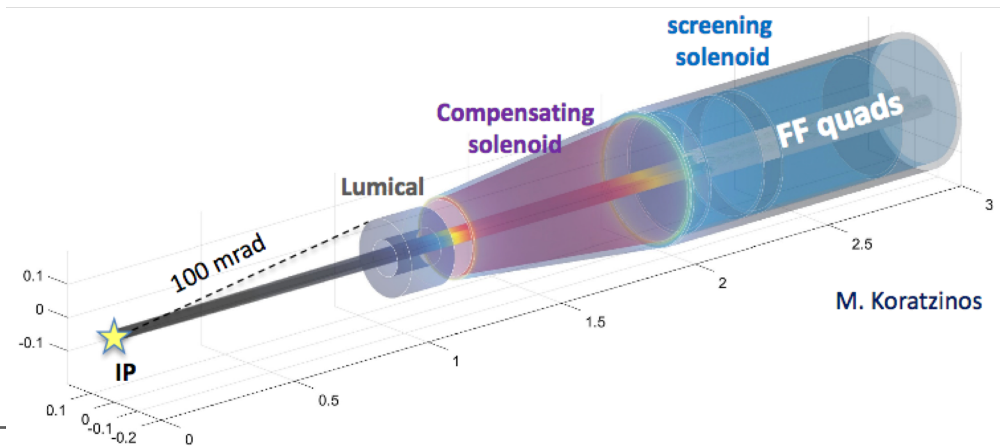
- Statistics
  - Very high statistics at the Z pole (70 kHz of visible Z decays)
  - Beam-induced background are mild compared to linear colliders, but not negligible
    - Readout must be able to cope with both
    - CW running imposes constraints on detector cooling
- Luminosity measurement
  - Aim 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 approach 0.001%
- √s calibration and measurement of √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
  - Small beam pipe radius: Vertex detector 1st layer at 17 mm.
    - Impact parameter resolution: 3-5 μm ($c\tau$ = 89 μm for τ and more for Bs)
    - New CEPC studies claim Purity × Efficiency ~ 97% for H → 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 ⇒ $B_{Detector} \leq 2$T
  - Beam pipe
    - Warm, liquid cooled (~SuperKEKB)
    - Be in central region, then Cu
    - R = 15 mm in central region
      - 1st vertex detector layer 17 mm from IP
    - SR masks, W shielding
  - Mechanical design and assembly concept
    - Under engineering study



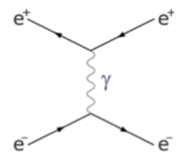
2018 updates on:
Lumical and shielding (W)



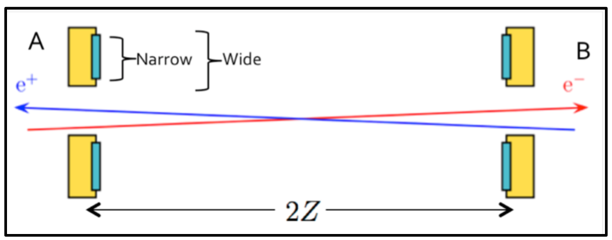
Luminosity Measurement

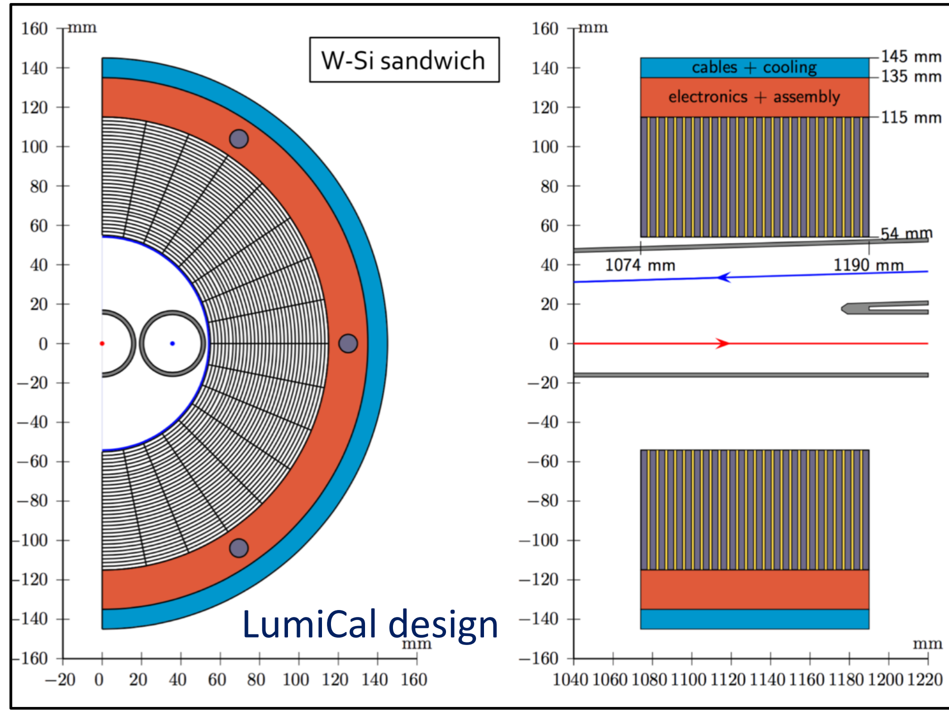
Ambitious goal:
- Absolute to 10^{-4}
- Relative (energy-to-energy point) to 10^{-5}

Small angle Bhabha scattering.
Very strongly forward peaked



Monitors centered around outgoing beam line
-- micron level precision needed

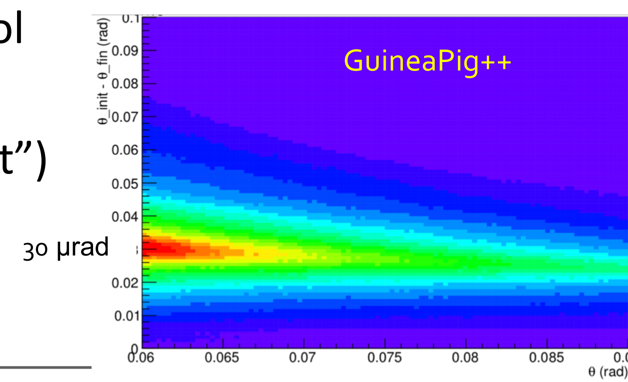




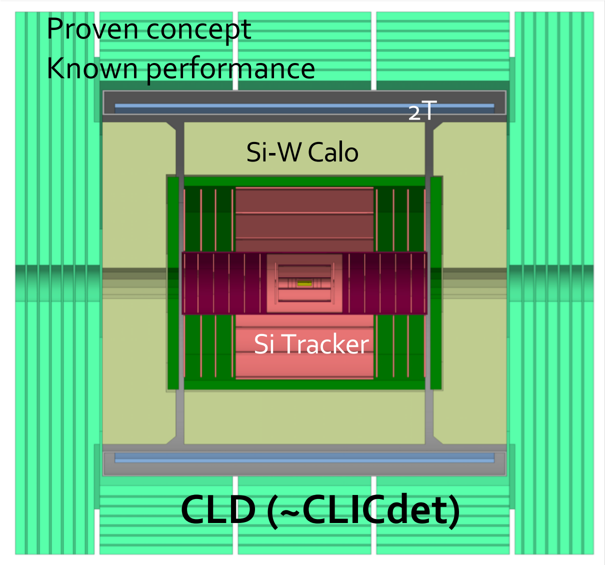
- **Theory:** Now at 3.8×10^{-4}; theory friends foresees that 1×10^{-4} will happen

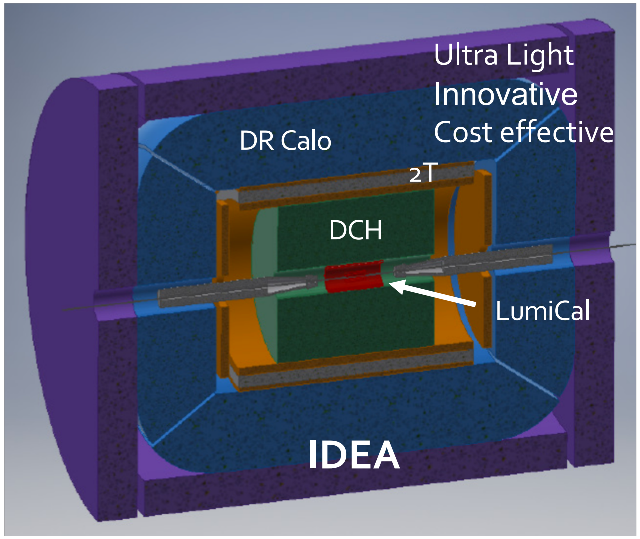
arXiv:1812.01004]

- **Backgrounds:** have been studied and seem to be under control
  - Only "incoherent pair production" starts to pop up at $t\bar{t}$ energies
- **Electromagnetic focussing of Bhabhas** (similar to "pinch effect")
  - average focussing of 30 μrad: 15×10^{-4} effect on acceptance
  - under study…



FCC-ee detector design concepts

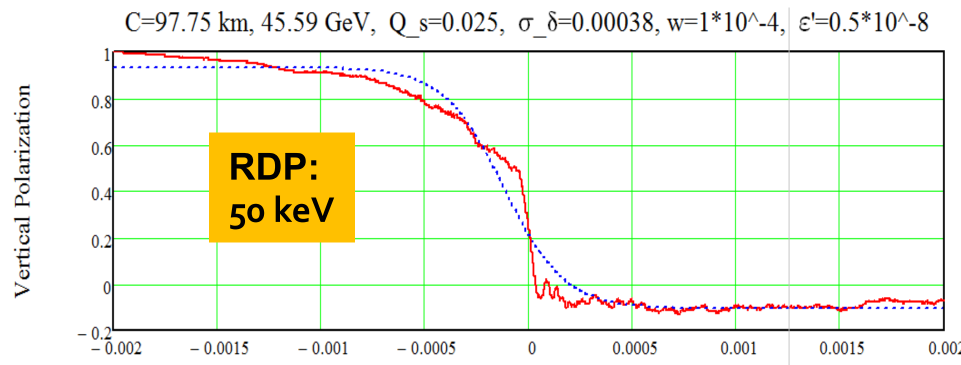




- Two designs studied so far
  - Has been demonstrated that detectors satisfying the requirements are feasible
    - Physics performance, invasive MDI, beam backgrounds
- Next: more complete studies, with full simulation
  - Towards 4++ detector proposals by ~2026
    - Light, granular, fast, b and c tagging, lepton ID and resolutions, hadron ID
    - Cost effective
    - Satisfy constraints from interaction region layout

Beam Polarization and Energy Calibration

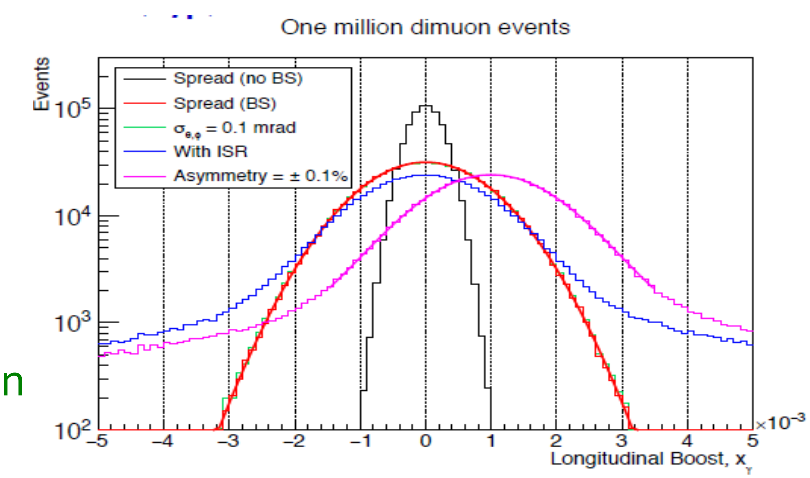
- Simulation show transverse polarization at the Z (wigglers) and WW energies
  - Energy calibration by resonant depolarization every 10 mins on pilot bunches
    - UNIQUE TO CIRCULAR COLLIDERS



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 $\delta\sqrt{s}$
    - Also measures $\Delta E = E^+ - E^-$ to similar precision



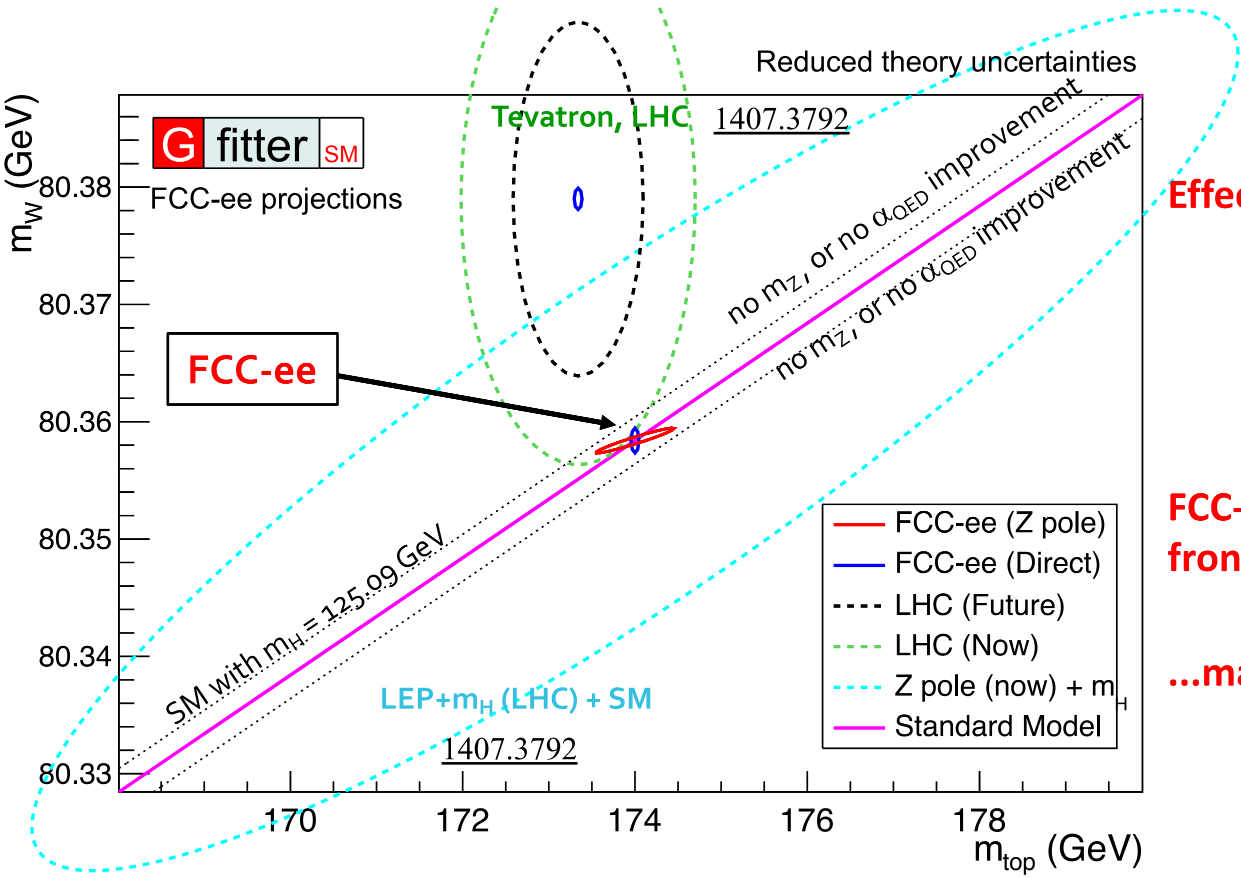
Sample of EW observables, experimental precisions

Z pole | WW thresh. | $t\bar{t}$ thresh.

Observable	Measurement	Current precision	FCC-ee **stat.**	FCC-ee **syst.**	Dominant exp. error
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**	$g \rightarrow bb$
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
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 ($\times 10^3$)	$e^+e^- \rightarrow \gamma Z$, $Z \rightarrow \nu\nu$, 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
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 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

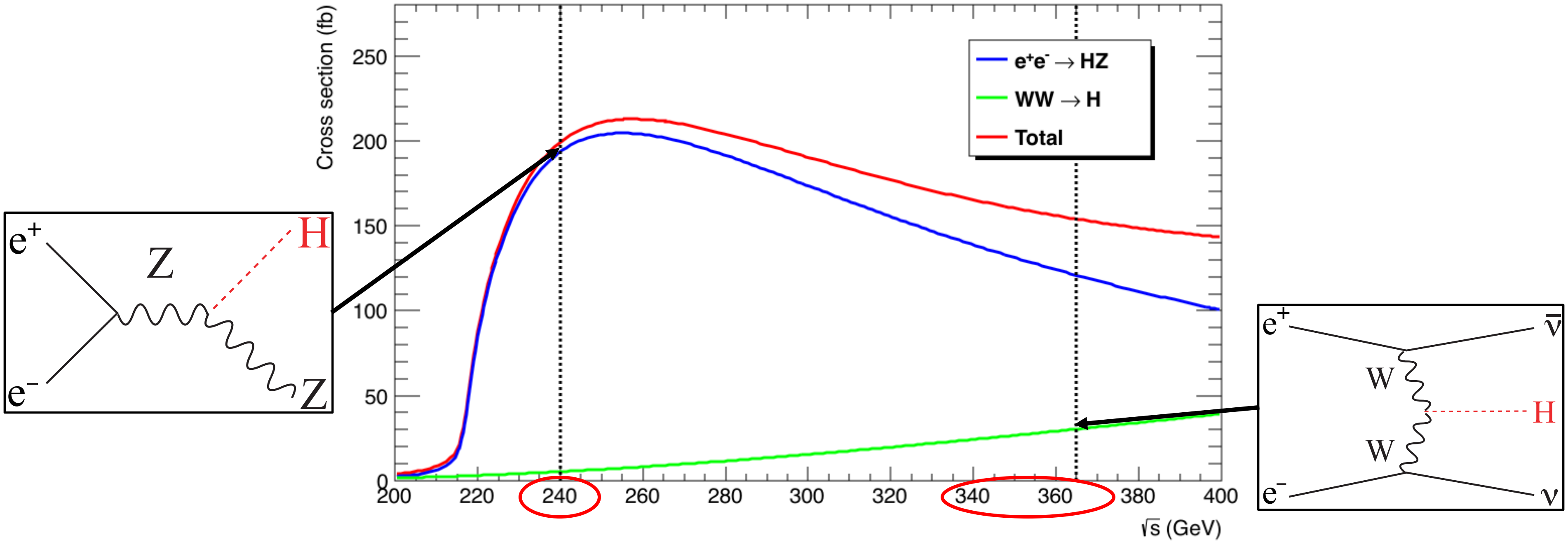
FCC-ee provides improvement from all fronts…

e.g. m_Z, α_{QED}, m_{top}, …

…maximizing sensitivity to BSM physics

- Precision of theory predictions needs to improve for full sensitivity to new physics
  - higher order calculations needed

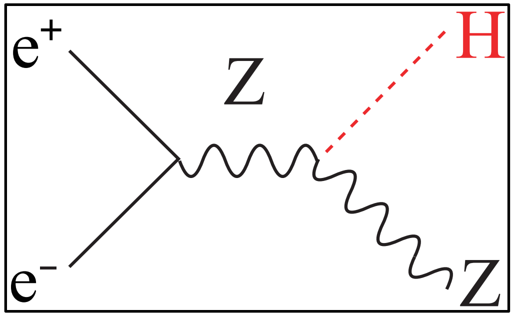
FCC-ee as a Higgs factory



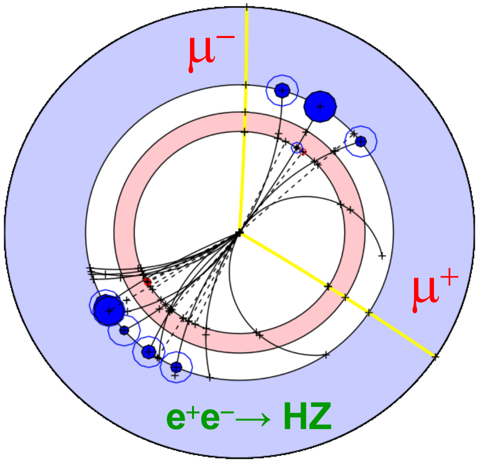
- Higgsstrahlung ($e^+e^- \rightarrow ZH$) event rate largest at $\sqrt{s}$ ~ 240 GeV : σ ~ 200 fb
  - 10^6 $e^+e^- \rightarrow ZH$ events with 5 ab^{-1} – cross section predicted with great accuracy
    - Target : (few) per-mil precision, statistics-limited
    - Complemented with 200k events at $\sqrt{s}$ = 350 – 365 GeV
      - Of which 30% in the WW fusion channel (important for the Γ_H precision)

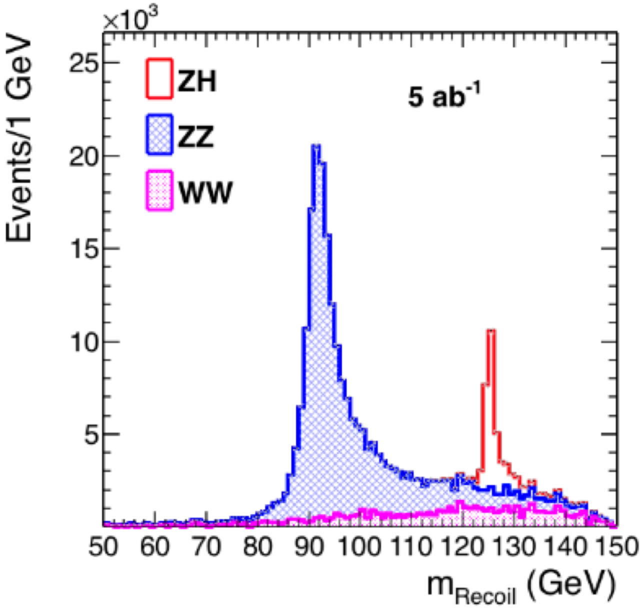
Higgs: Absolute couplings and width

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



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





- Total rate $\propto g_{HZZ}^2$ → measure g_{HZZ} to 0.2%
- ZH → ZZZ final state $\propto g_{HZZ}^4 / \Gamma_H$ → measure Γ_H to a couple %
- ZH → ZXX final state $\propto g_{HXX}^2\, g_{HZZ}^2 / \Gamma_H$ → 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

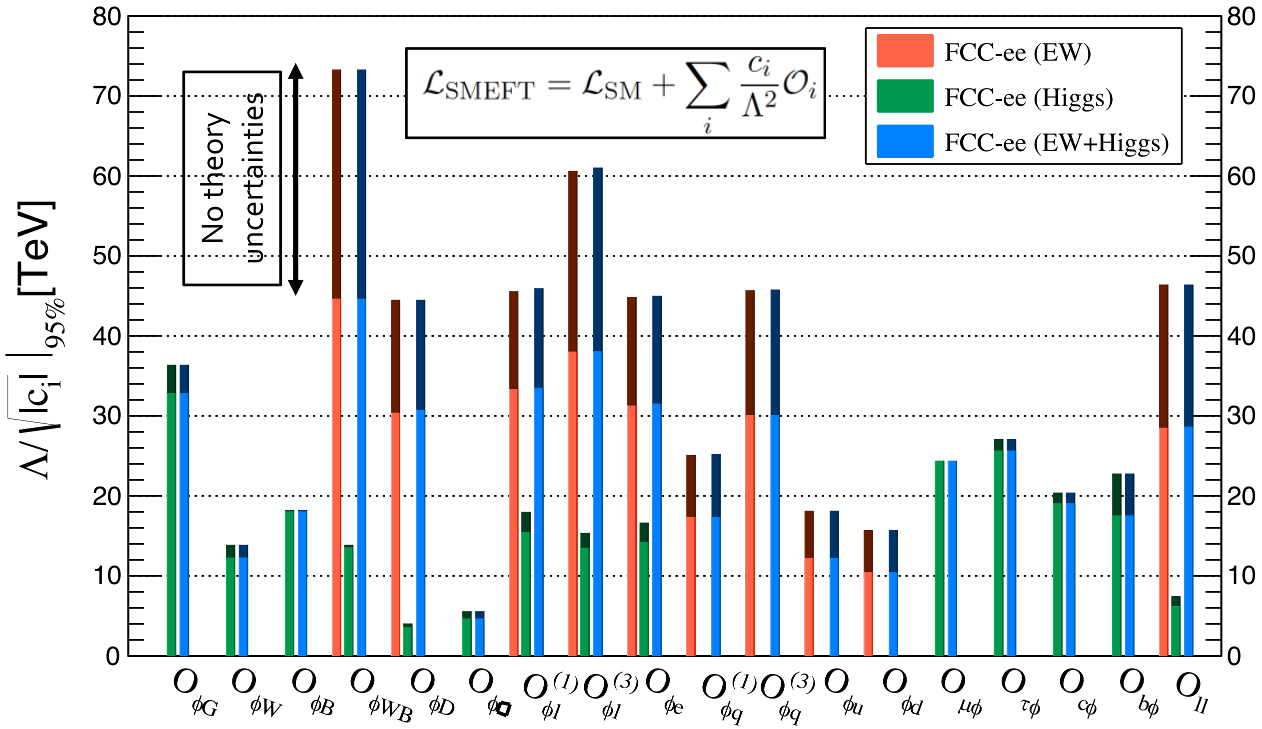
Collider	HL-LHC	FCC-ee		
Luminosity (ab^{-1})	3	5 @ 240GeV	+1.5 @ 365GeV	+HL-LHC
Years	25	3	**+4**	-
$\delta\Gamma_H/\Gamma_H$ (%)	SM	2.7	**1.3**	1.1
$\delta g_{HZZ}/g_{HZZ}$ (%)	1.3	0.2	**0.17**	0.16
$\delta g_{HWW}/g_{HWW}$ (%)	1.4	1.3	**0.43**	0.40
$\delta g_{Hbb}/g_{Hbb}$ (%)	2.9	1.3	**0.61**	0.55
$\delta g_{Hcc}/g_{Hcc}$ (%)	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

- 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)
  - 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 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 over the next 20 years

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

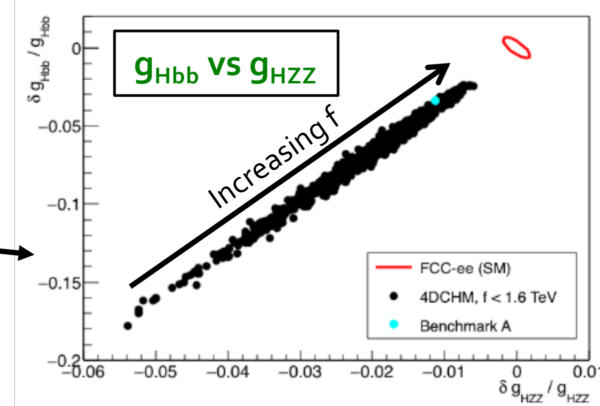
- Workshop series continued in January 2019
  - Topics cover the whole FCC-ee programme, 106 registered participants
    - Z, W, Higgs, top, b, c, QED, Monte Carlo, software, and detector technologies

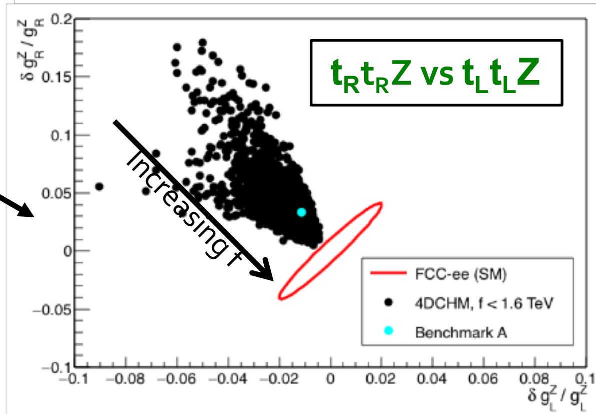
Pattern of deviations

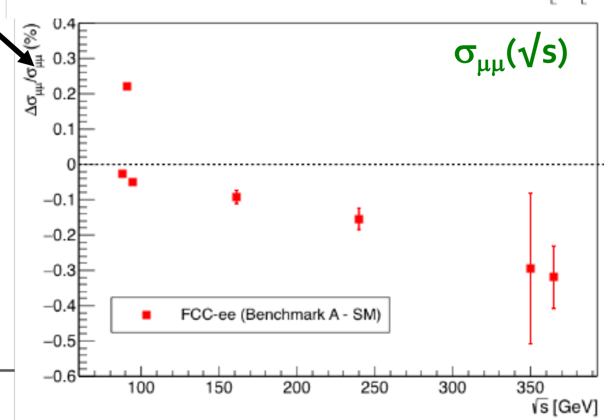
- May point to specific BSM physics
  - E.g, 4D Composite Higgs Model
    - Deviations in Higgs couplings
      - √s = 240, 350, 365 GeV
    - Deviations in EW top couplings
      - √s = 365 GeV optimal
    - Deviations in EW lepton couplings
      - All energies

S. de Curtis et al.
arXiv:1110.1613

P. Janot
arXiv:1503.01325



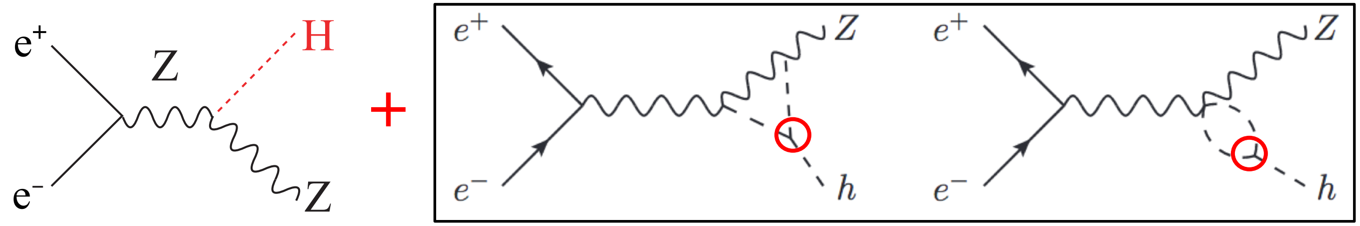




- Pattern of deviations may become significant
  - Correlations between observations
    - Allow first characterization of the model
  - For example, gauge sector parameters in benchmark A
    - f = 1.6 TeV, g*=1.78, $m_{Z'}$ ~ 3 TeV, $\Gamma_{Z'}$ ~ 600 GeV
    - With the FCC-ee precision
      - Z'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

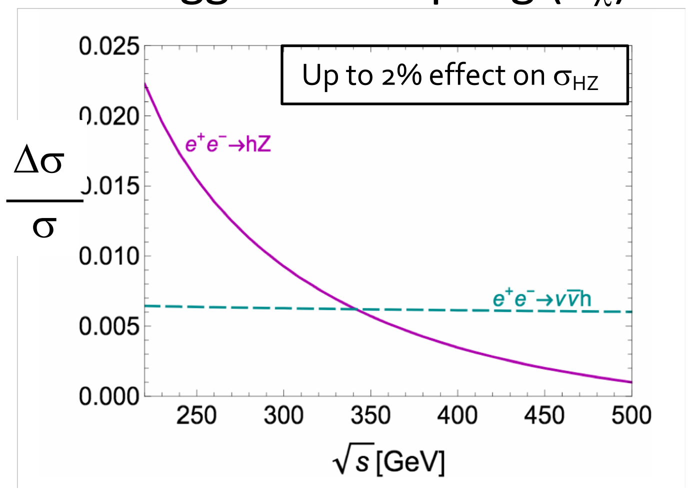
Higgs self-coupling at FCC-ee

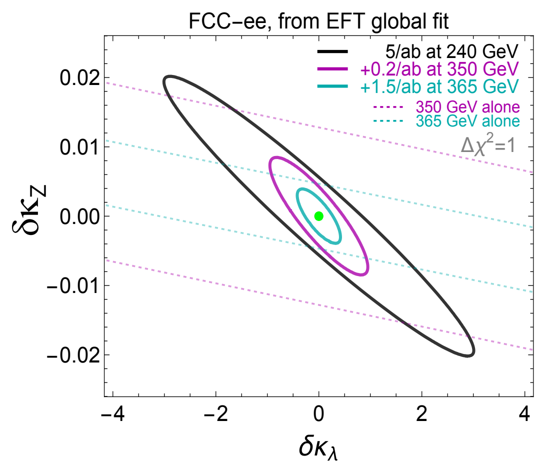
- FCC-ee does not produce Higgs pairs, from which self coupling can be extracted
- But, loops including Higgs self coupling contribute to Higgs production



M. McCullough
arXiv:1312.3322

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





C. Grojean et al.
arXiv:1711.03978

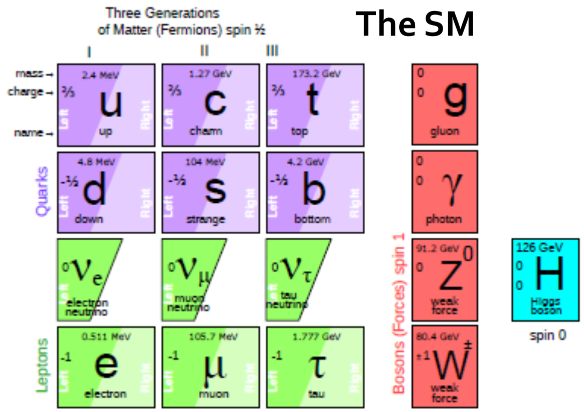
- Two energy points (240 and 365 GeV) lift off the degeneracy between $\delta\kappa_Z$ and $\delta\kappa_\lambda$
  - Precision on κ_λ with 2 IPs at the end of the FCC-ee (91+160+240+365 GeV)
    - Global EFT fit (model-independent) : ±34% **(3σ)** ; in the SM : ±12%
  - Precision on κ_λ with 4 IPs :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

A. Blondel, P. Janot
arXiv:1809.10041

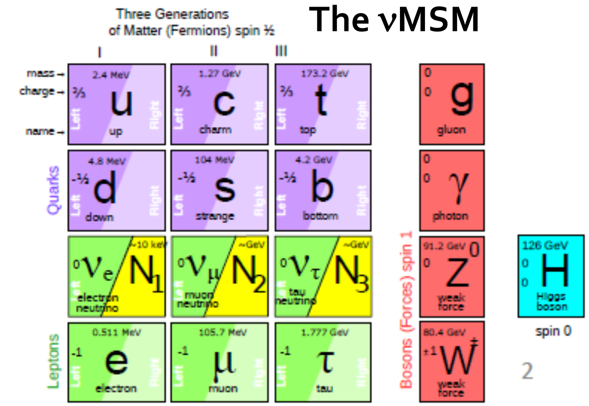
Direct discoveries

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

The SM

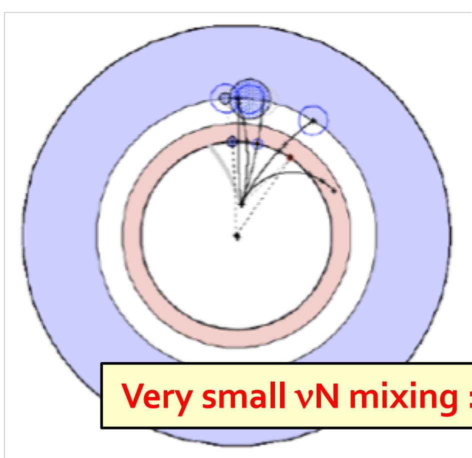


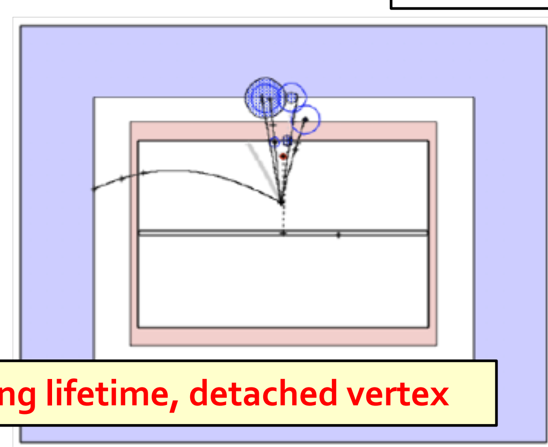
The νMSM



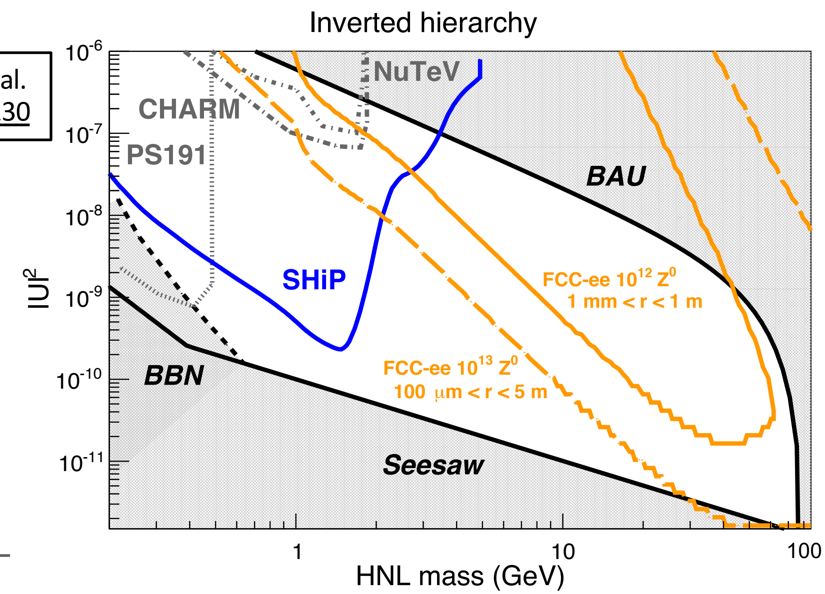
- Could explain everything: Dark matter (N_1), Baryon asymmetry, Neutrino masses
  - Searched for in very rare $Z \to nN_{2,3}$ decays
  - Followed by $N_{2,3} \to W^* \ell$ or $Z^* n$

A. Blondel et al.
arXiv:1411.5230

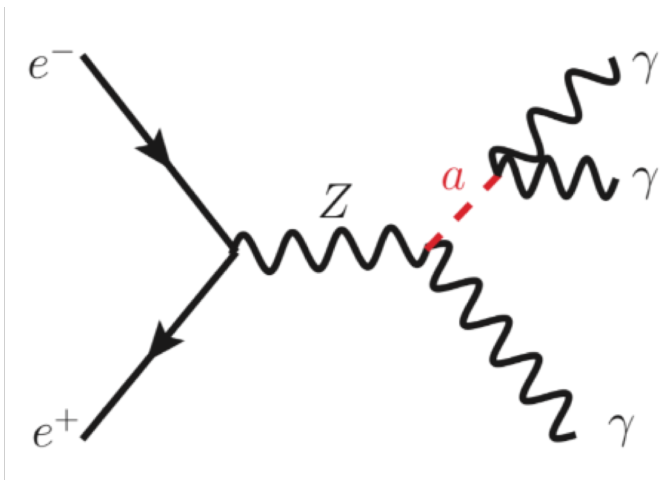




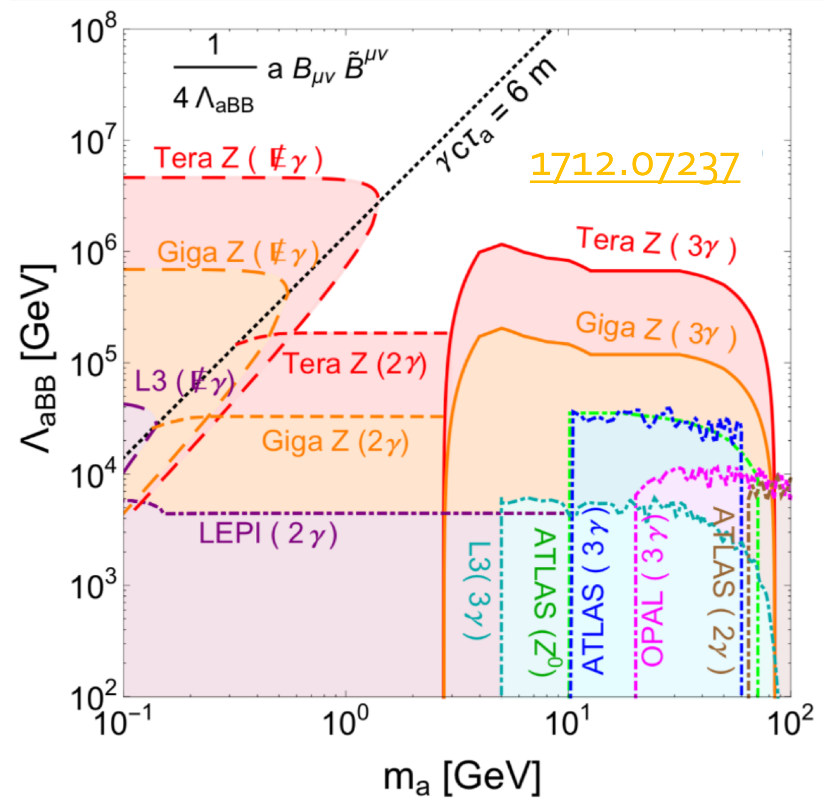
Very small νN mixing : long lifetime, detached vertex



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



- $\gamma\gamma$ for light a
- $\gamma\gamma\gamma$ for heavier a



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

Heavy flavour

- Z run ➪ 10^{12} bb events 1.7×10^{11} $\tau^+\tau^-$ events (significantly more than BelleII)
  - Higher energy, higher boost ➪ better $e/\mu/\pi$ separation
  - lifetime, branching fractions, rare decays, test of Universality

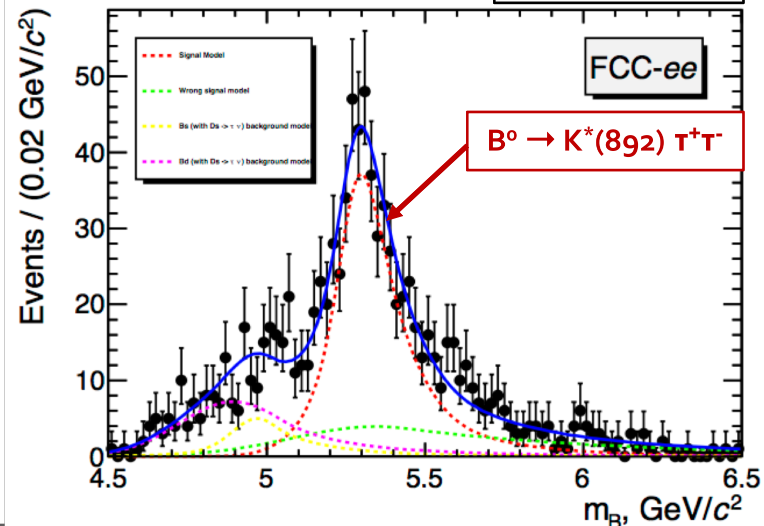
Table 7.1: Expected production yields of heavy-flavoured particles at Belle II (50 ab^{-1}) and FCC-ee.

Particle production (10^9)	B^0 / $\overline{B}^0$	B^+ / B^-	B^0_s / $\overline{B}^0_s$	Λ_b / $\overline{\Lambda}_b$	$c\overline{c}$	$\tau^+\tau^-$
Belle II	27.5	27.5	n/a	n/a	65	45
FCC-*ee*	1000	1000	250	250	550	170

- Study of B decays and test of flavour universality

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)

J.F. Kamenik et al.
arXiv:1705.11106



τ physics

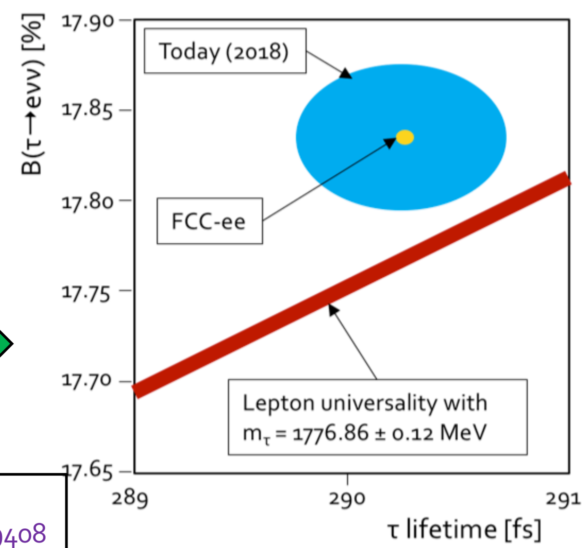
τ properties and Universality

- τ branching fractions and lifetime provide strong test of Universality of the α - ν_α CC coupling, α = e, μ, τ
  - Sensitive to light-heavy neutrino mixing
  - Need also (more) precise mass measurement

Visible Z decays	3×10^{12}
$Z \rightarrow \tau^+\tau^-$	1.3×10^{11}
1 vs. 3 prongs	3.2×10^{10}
3 vs. 3 prong	2.8×10^{9}
1 vs. 5 prong	2.1×10^{8}
1 vs. 7 prong	< 67,000
1 vs 9 prong	?

Observable	Current precision	FCC-ee **stat.**	**Possible syst.**
m_τ [MeV]	1776.86 **± 0.12**	**0.004**	**0.1**
τ_τ [fs]	290.3 **± 0.5 fs**	**0.001**	**0.04**
B($\tau \rightarrow e\nu\nu$) [%]	17.82 **± 0.05**	**0.0001**	**0.003**
B($\tau \rightarrow \mu\nu\nu$) [%]	17.39 **± 0.05**		

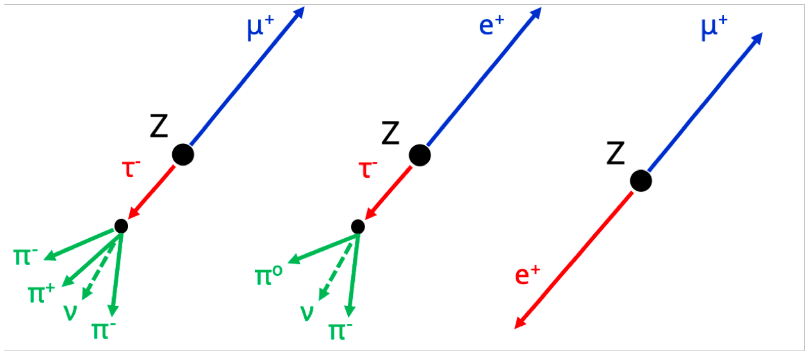
Quantity	Measurement	Current precision	FCC-ee precision
$\lvert g_\mu/g_e \rvert$	$\Gamma_{\tau\rightarrow\mu} / \Gamma_{\tau\rightarrow e}$	1.0018 **± 0.0014**	**Improvement by a factor 10 or more**
$\lvert g_\tau/g_\mu \rvert$	$\Gamma_{\tau\rightarrow e} / \Gamma_{\mu\rightarrow e}$	1.0030 **± 0.0015**	



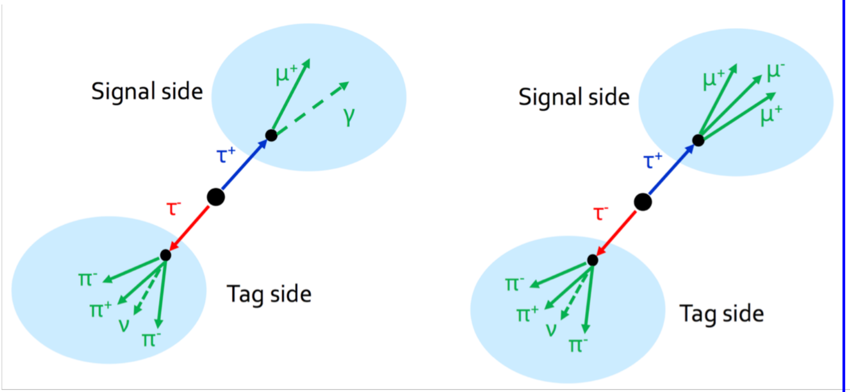
M.Dam
arXiv:1811.09408

τ physics

- Improve sensitivity of lepton flavour violation Z decays by 4 orders of magnitude



- Improve sensitivity of lepton flavour violation τ decays by 1-2 orders of magnitude



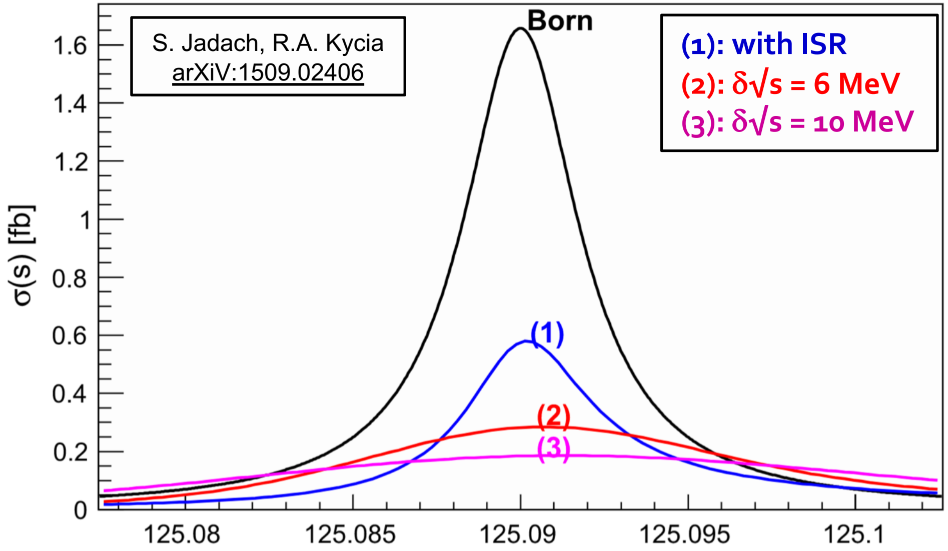
Decay	Present bound	FCC-ee sensitivity
$Z \to \mu e$	0.75×10^{-6}	10^{-10}–10^{-8}
$Z \to \tau\mu$	12×10^{-6}	10^{-9}
$Z \to \tau e$	9.8×10^{-6}	10^{-9}
$\tau \to \mu\gamma$	4.4×10^{-8}	2×10^{-9}
$\tau \to 3\mu$	2.1×10^{-8}	10^{-10}

M.Dam
arXiv:1811.09408

***FCC-ee is not only a Z, WW, Higgs and tt factory*. But also a factory of heavy flavour: b, τ,…**

And if there is time …

- Spend few years at $\sqrt{s}$ = 125.09 GeV with high luminosity
  - For s-channel production $e^+e^- \to H$ (a la muon collider, with 10^4 higher lumi)



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

- Expected signal significance of ~0.4σ / $\sqrt{\text{year}}$ 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

Summary: FCC-ee physics 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: $Z \rightarrow \tau\mu$ in 5×10^{12} Z decays; or $\tau \rightarrow \mu\nu$ / $\tau \rightarrow e\nu$ in 2×10^{11} τ decays; …
  - Also $B^0 \rightarrow K^{*0}\tau^+\tau^-$ or $B_s \rightarrow \tau^+\tau^-$ in 10^{12} bb events
- DISCOVER dark matter as invisible decays of Higgs or Z
  - Precise invisible width measurements
- 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")

All 4 phases of the FCC-ee programme, Z, WW, H, and $t\bar{t}$, are important for the physics potential

Conclusions

The FCC CDR, released on 15/01/2019, demonstrates that:

- The FCC-ee design is robust and mature
  - accelerator with record luminosity performance at all four energy points (Z, WW, H, $t\bar{t}$) and with moderate background levels
  - MDI including luminosity monitors
  - two detector designs (to be extended to four)
- With its 4 energy points, FCC-ee has an outstanding physics reach
  - as summarized on the previous slide
- FCC-ee and FCC-hh are highly synenergetic and complementary
  - The sequential implementation : FCC-ee → FCC-hh maximises the physics reach
  - FCC can serve High-Energy Physics in a cost effective manner throughout this century

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

The FCC integrated programme

Base the next generation of colliders on a proven model

- 27 km tunnel

- The next step: 100 km tunnel

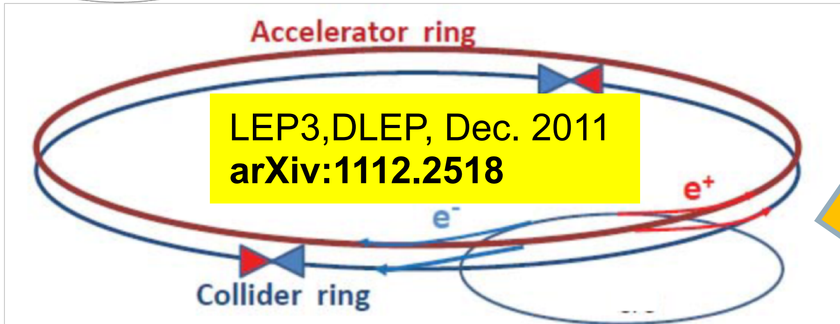
Thank you for you attention !

Acknowledgements:

- I would like to thank all of my FCC-ee colleagues who have contributed material to the CDR and to this talk
- Especially Patrick Janot and Alain Blondel from whom slides have been ruthlessly ”stolen”

Extra Slides

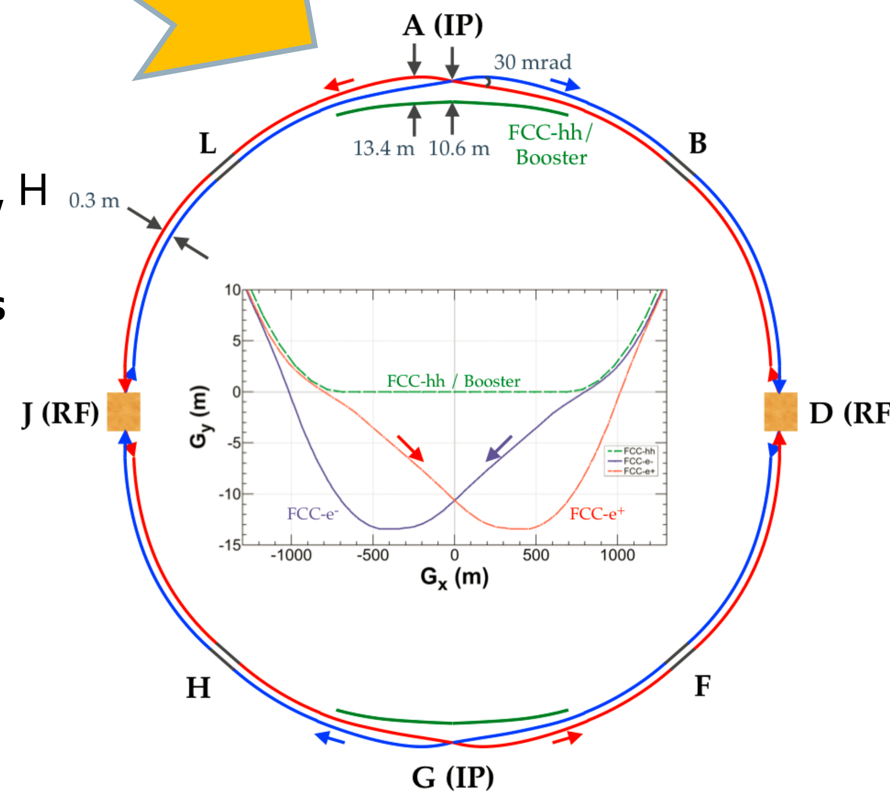
FCC-ee baseline design choices



Design Study

TLEP: arXiv:1208.0504
TLEP physics case: arXiv:1308.6176

- **Follows footprint of FCC-hh, except around IPs**
- **~100 km to reach $t\bar{t}$ production**
- **Double ring (e+, e-) collider, multi-bunch**
- **Top-up injection for high efficiency**
  → high-energy injector in collider tunnel
- **Crab-waist optics** to maximize luminosity @Z, W, H
  30 mrad crossing angle
- **Asymmetric interaction region layout and optics**
  Limit synchrotron radiation in the detector
- **Two interaction points (IP) in A and G**
  4 IPs to be studied -- significant layout changes
- **50 MW/beam Synchrotron Radiation power:**
  at all energies
- **Continuous E_{CM} calibration at Z and W (100 keV)**
  based on resonant transverse depolarization
  polarimeter, wigglers, RF kicker



The FCC CDR

First ideas in 2010-11. Study kicked off in 2014

CDR published on 15/01/2019 at http://fcc-cdr.web.cern.ch/ (>1000 authors)

- Vol.1 : Physics Opportunities
- Vol.2 : The lepton collider (FCC-ee)
- Vol.3 : The hadron collider (FCC-hh) (includes e-h option)
- Vol.4: HE-LHC

Common ~100 km infrastructure @ CERN

- Civil engineering, electricity, cooling, ventilation, cryogenics
- R&D for SC magnets (up to highest affordable field)

Staged approach for collider and physics

- **1st step:** high-luminosity and precision e+e- collider **(FCC-ee)**
  - Phase A: 88 → 240 GeV (Z, W, Higgs)
  - Phase B: 345 → 365 GeV (Higgs, top) (significant RF upgrade)
- **2nd step:** high-energy pp collider (**FCC-hh**, 100-150 TeV?) e-p option (FCC-eh)

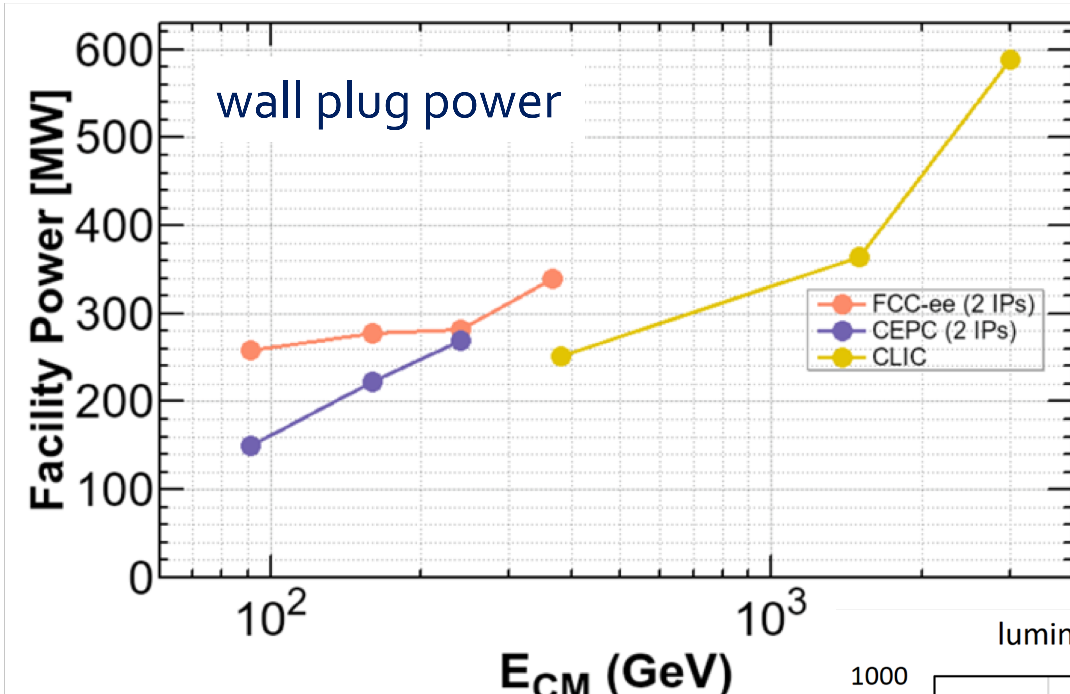
At least 60 years of the most sensitive and versatile search for solutions to the mysteries of Universe (BAU, Dark matter, Neutrino masses, Flavour etc.)

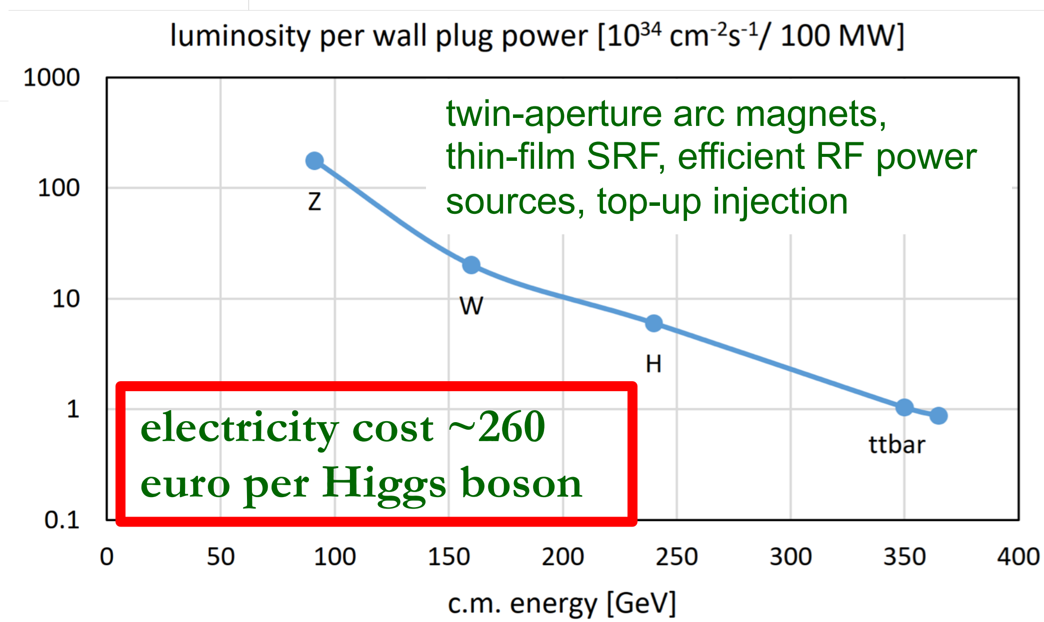
Baseline parameters

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 $\varepsilon_{x,y}$ [nm, pm]	0.3, 1.0	0.8, 1.7	0.6, 1.3	1.5, 2.9	22, 250
longit. damping time [turns]	1273	236	70	20	31
crossing angle [mrad]	30				0
beam lifetime (rad.B+BS) [min]	68	48	12	12	434

FCC-ee: 2 separate rings LEP: Single beam pipe

Power consumption





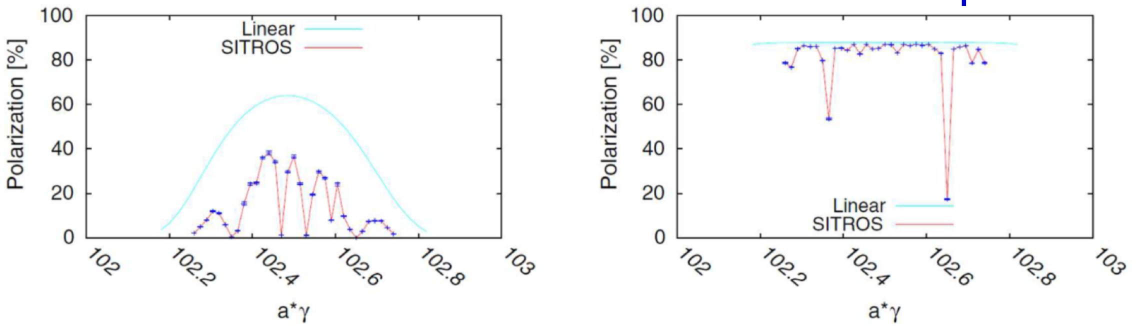
"green accelerator":
Very high luminosity per
input power unit

Polarisation and energy calibration

Z pole with polarisation wigglers

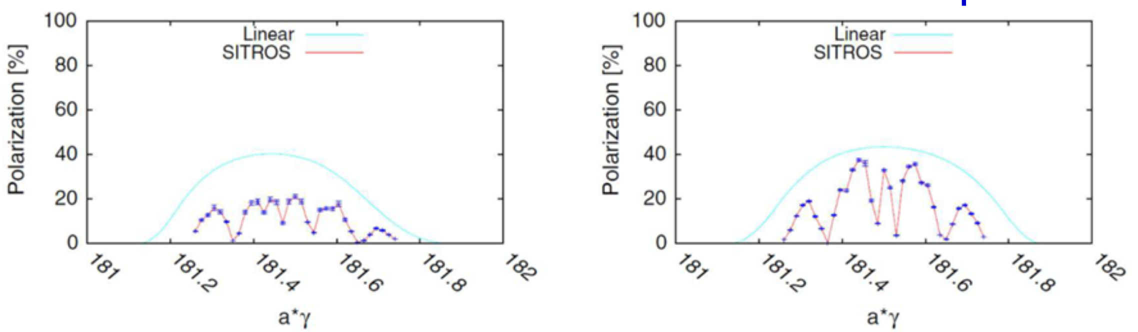
E. Gianfelice-Wendt

orbit correction | + harmonic bumps



WW threshold

orbit correction | + harmonic bumps

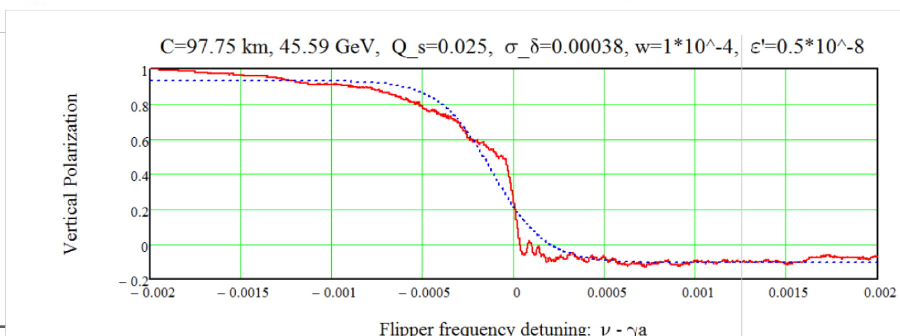


luminosity-averaged centre-of-mass uncertainties:

~100 keV around the Z pole

~300 keV at the W pair threshold

simulated frequency sweep with depolariser



technique used at LEP

Efficient masking against synchrotron radiation

	Energy (GeV)	Critical energy (keV)	number of bunches	Current (mA)	Incident γ/xing (500μm from tip)	Incoming on central pipe/xing	γ rate on central pipe (Hz)
tt+	**182.5**	113.4	33	5.41	3.32E+09	1195	1.18E+08
tt	**175**	100	40	6.4	3.06E+09	1040	1.25E+08
h	**125**	36.4	328	29	1.05E+09	10.3	1.01E+07
W	**80**	9.56	1300	147	6.11E+08	0.18	7.02E+05
Z	**45.6**	1.77	16640	1390	9.62E+07	1.92E-04	9.58E+03

rate of photons that strike the central pipe that come from the mask tip

- No SR from dipoles or from quads hits directly the central beam pipe (cylinder +/- 12.5 cm long, 1.5 cm radius)
- Non-Gaussian beam tails, considered out to +/-20 σ_x and +/-60σ_y
- On-axis beam
- Quadrupole radiation that may strike mask surfaces included