Physics at FCC-ee

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Outline

1. The Future Circular Collider Study
2. FCC-ee Electroweak Studies at the Z Pole, ZH, W^+W^- and $t\bar{t}$ thresholds
3. QCD Physics at FCC-ee

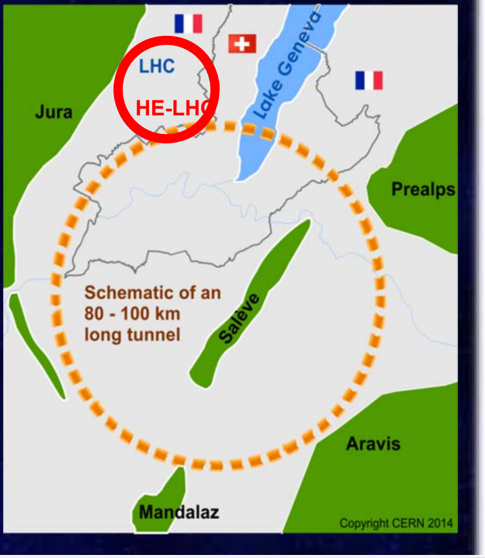
FCC – Future Circular Collider

FCC - international collaboration hosted at CERN, goal: construction of ~100 km circumference tunnel infrastructure in Geveva area

https://fcc.web.cern.ch/

to host:

- ✓ **e^--e^+ collider:** FCC-ee – potential first step, preceding the FCC-pp
- ✓ **p-p collider:** FCC-hh – flagship, 100 TeV p-p, 16T Nb$_3$Sn magnets
- ✓ **e-p collider:** FCC-he – additional option of e-p collisions; e^- from ERL



- **136 institutes**
- **34 countries**
- **32 industrial partners**

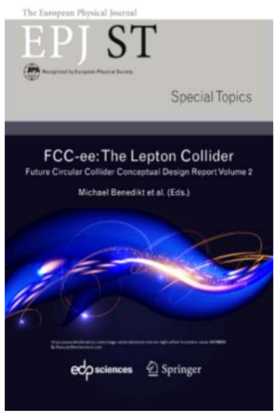
EC
H2020

- **EuroCirCol project**
- **EASITrain ITN**

The Conceptual Design Report issued in January, 2019:
(~1364 contributors, 351 institutes – a truly global collaboration and effort – as suggested by the EPPSU'13): https://fcc-cdr.web.cern.ch/

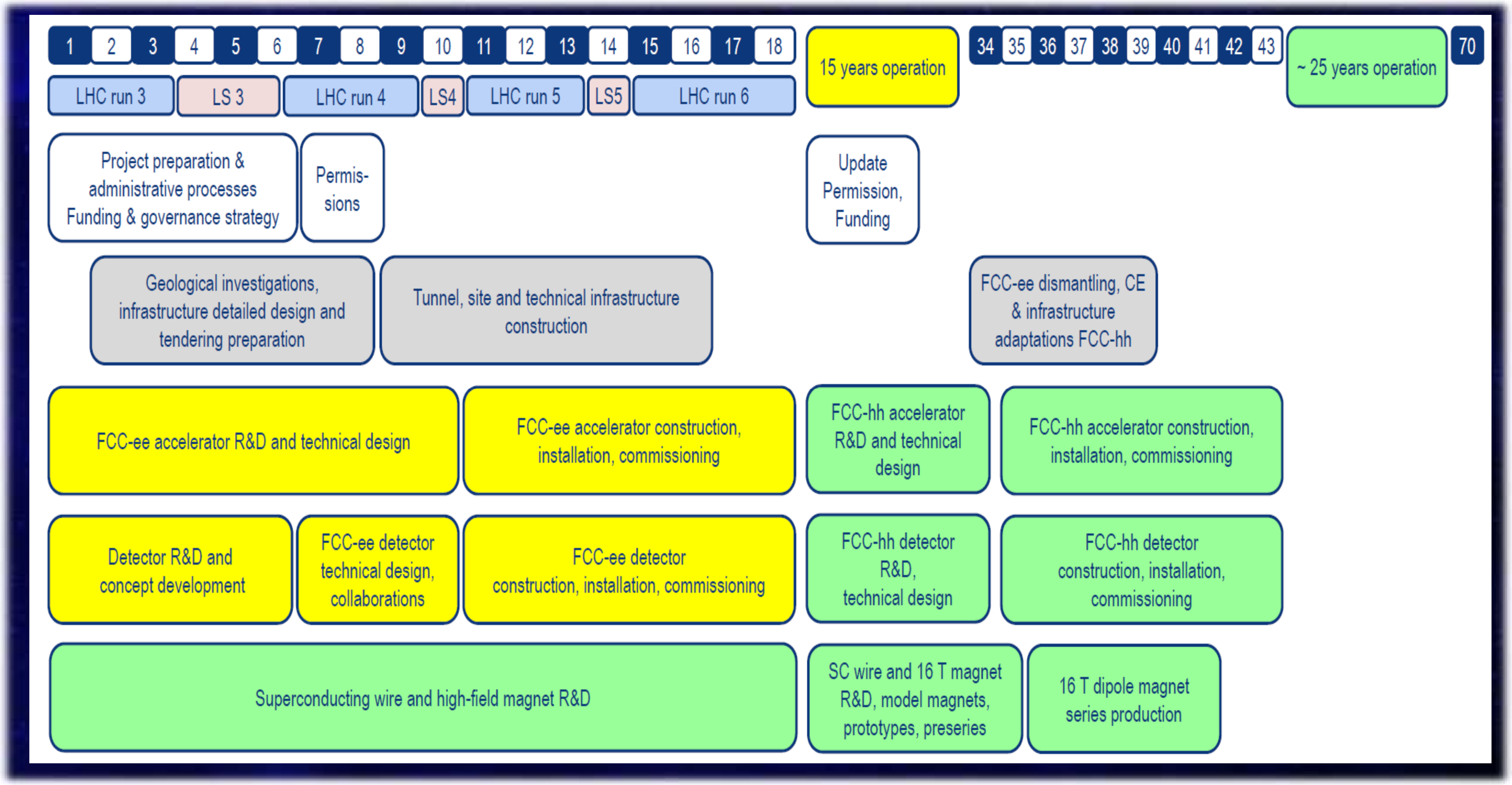
The FCC-ee European Particle Physics Strategy Update (EPPSU) document: https://cds.cern.ch/record/2653669

FCC week 2019, Brussels, 24-28, June http://fccweek2019.web.cern.ch/


The European Physical Journal
EPJ ST
Special Topics
FCC-ee: The Lepton Collider
Future Circular Collider Conceptual Design Report Volume 2
Michael Benedikt et al. (Eds.)
edp sciences
Springer

FCC Integrated Project Technical Schedule

The FCC project plan is fully integrated with HL-LHC exploitation and provides for seamless further continuation of particle physics in Europe



1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18

15 years operation

34 35 36 37 38 39 40 41 42 43

~ 25 years operation

70

LHC run 3

LS 3

LHC run 4

LS4

LHC run 5

LS5

LHC run 6

Project preparation & administrative processes Funding & governance strategy

Permis-sions

Update Permission, Funding

Geological investigations, infrastructure detailed design and tendering preparation

Tunnel, site and technical infrastructure construction

FCC-ee dismantling, CE & infrastructure adaptations FCC-hh

FCC-ee accelerator R&D and technical design

FCC-ee accelerator construction, installation, commissioning

FCC-hh accelerator R&D and technical design

FCC-hh accelerator construction, installation, commissioning

Detector R&D and concept development

FCC-ee detector technical design, collaborations

FCC-ee detector construction, installation, commissioning

FCC-hh detector R&D, technical design

FCC-hh detector construction, installation, commissioning

Superconducting wire and high-field magnet R&D

SC wire and 16 T magnet R&D, model magnets, prototypes, preseries

16 T dipole magnet series production

FCC-ee Operation Model

working point	Design luminosity/IP $[10^{34}\ cm^{-2}s^{-1}]$	total luminosity (2 IPs)/ yr	physics goal	run time [years]
Z **first 2 years**	115 (50% nominal)	24 ab^{-1}/year	**150 ab^{-1}**	**4**
Z **later**	230	48 ab^{-1}/year		
W	28	6 ab^{-1}/year	**10 ab^{-1}**	**2**
H	8.5	1.7 ab^{-1}/year	**5 ab^{-1}**	**3**
machine modification for RF installation & rearrangement: **1 year**				
top 1st year (350 GeV)	0.95 (50% nominal)	0.2 ab^{-1}/year	**0.2 ab^{-1}**	**1**
top later (365 GeV)	1.55	0.34 ab^{-1}/year	**1.5 ab^{-1}**	**4**

total program duration: 15 years (*including machine modifications)*

phase 1 (*Z, W, H*): 9 years,
phase 2 (top): 6 years

(Total luminosity calculation based on 185 physics days per year, 75% efficiency, design luminosities and 10% overall contingency)

FCC-ee Collider Parameters

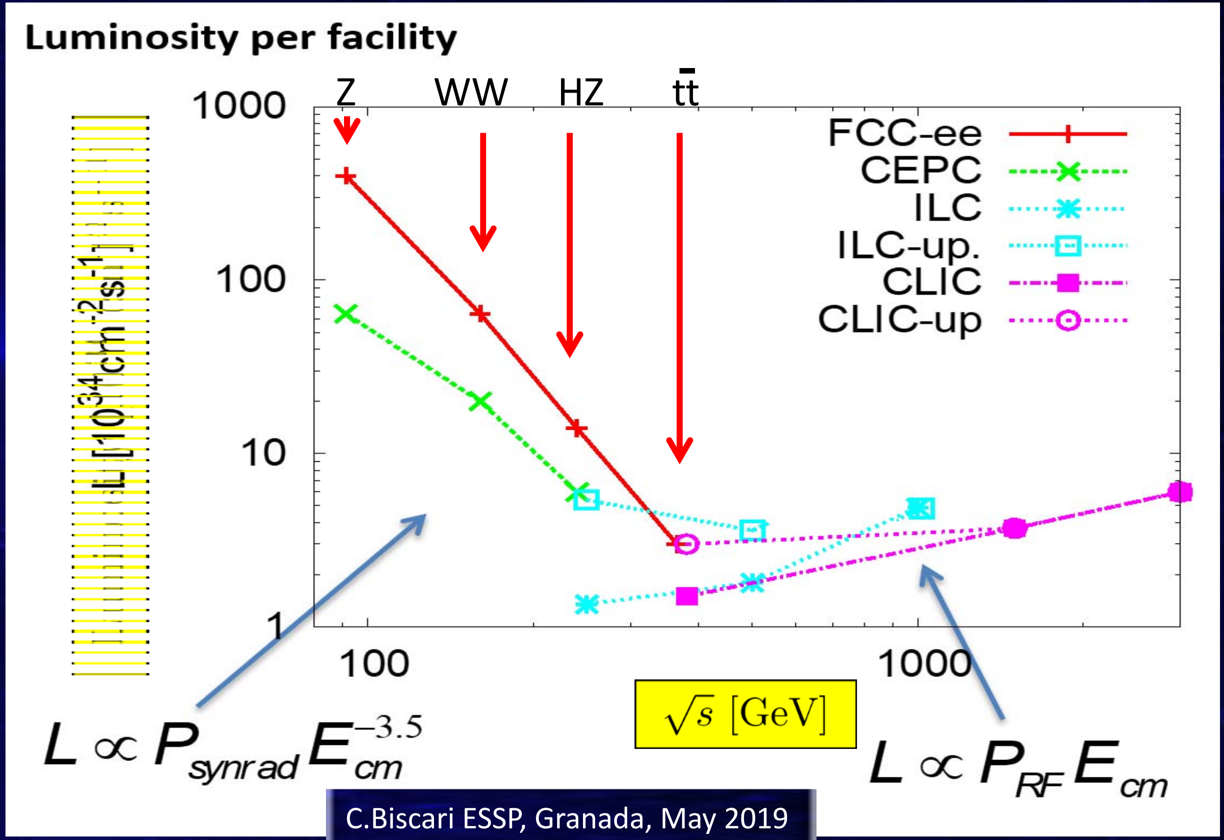
- two rings (separate for e^+ and e^-); two interaction points (3 & 4 IPs under study), flat beams with very strong focusing ($\beta^*_y \approx 1$mm); top-up injection (booster), crab waist crossing optics, non-zero (30 mrad) crossing angle; P_{SR} = 100 MW, four working points:
-

Parameter	$\sqrt{s} = M_Z$	$\sqrt{s} = M(WW)$	$\sqrt{s} = M(ZH)$	$\sqrt{s} = M(t\bar{t})$	LEP2
E_{beam} [GeV]	45.6	80	120	175 - 182.5	104.5
Beam current [mA]	1390	147	29	5.4	4
No. Bunches/beam	16 640	2 000	393	48	4
SR energy loss/turn [GeV]	0.036	0.34	1.72	9.21	3.34
SR power [MW]	100	100	100	100	22
SR energy loss/turn [GeV]	0.036	0.34	1.72	9.21	3,4
RF Voltage [GV]	0.1	0.44	2.0	10.9	3.5
β^*_x [m]	0.15	0.2	0.3	1	1.5
β^*_y [mm]	0.8	1	1	1.6	50
ε_x [nm]	0.27	0.28	0.63	1.46	19.3
ε_y [pm]	1	1.7	1.3	2.9	230
L (10^{34} cm^{-2}s^{-1})/IP	230	28	8.5	1.55	0.012
Statistics (2expts)	5×10^{12} Z / 6yrs	3×10^7 WW/2yr	10^6 ZH/5yrs	10^6 $\bar{t}t$ / 5yrs	

LEP1 : $2.1 \times 10^{31}\ \mathrm{cm^{-2}s^{-1}}$

LEP2 : $3.6 \times 10^{31}\ \mathrm{cm^{-2}s^{-1}}$

FCC-ee Collider Parameters



C.Biscari ESSP, Granada, May 2019

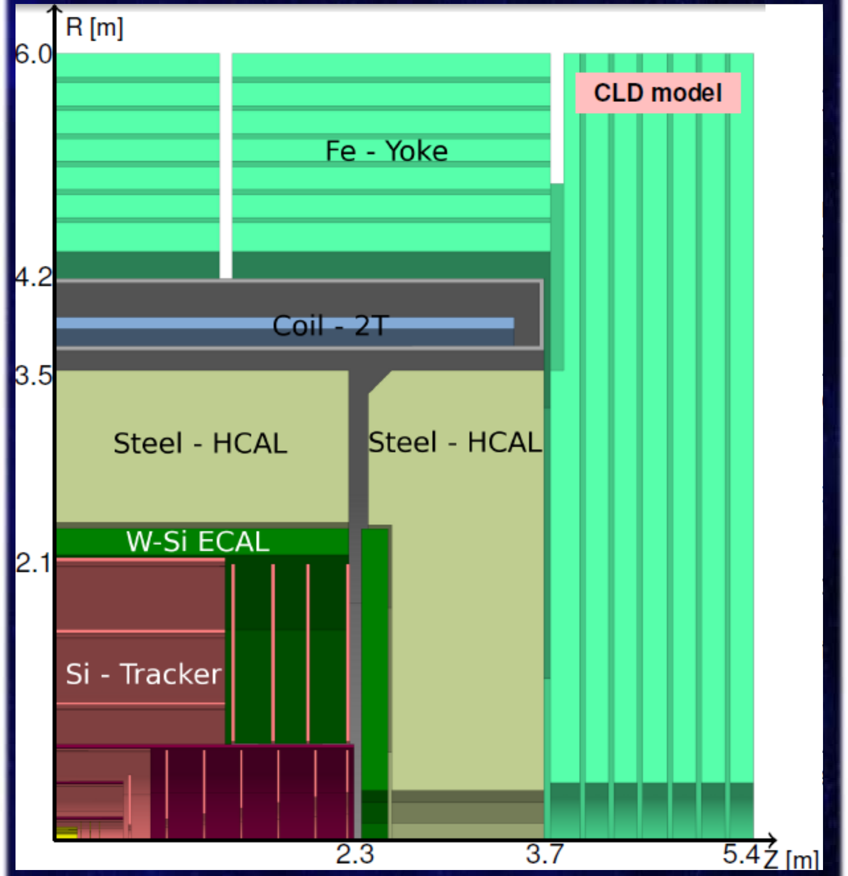
Event statistics:

					E_{CM} errors:
Z peak	E_{cm} : 91 GeV	$5\ 10^{12}$	e+e- → Z	LEP x 10^5	100 keV
WW threshold	E_{cm} : 161 GeV	$3\ 10^{7}$	e+e- → WW	LEP x 10^3	300 keV
ZH threshold	E_{cm} : 240 GeV	10^{6}	e+e- → ZH	Never done	5 MeV
$t\bar{t}$ threshold	E_{cm} : 350 GeV	10^{6}	e+e- → ttbar	Never done	10 MeV

FCC-ee Detectors: CLD

CLD - detector model for FCC-ee derived from CLICdp model and optimized for FCC-ee experimental conditions

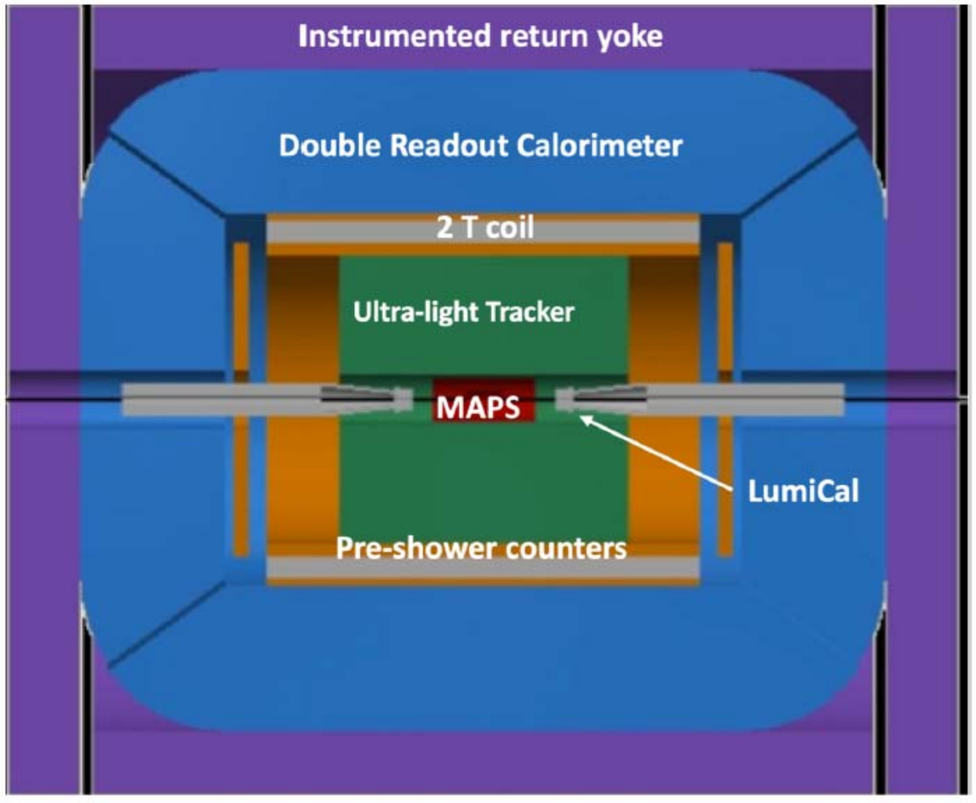
- **Full silicon tracking system** (≥12 hits/track)
- **High granularity calorimeters optimized for particle flow reconstruction**
- **Superconducting coil (2T) located outside the calorimeters**
- **Steel return yoke containing muon chambers**
- **Forward region reserved for Machine-Detector Interface and LumiCal**
- Tracking fully efficient from 700 MeV
- δpT ≈ 4 x 10^{-5} GeV^{-1} (for muons p=100 GeV)
- ΔE/E = (3-5)% (barrel region)
- Efficiency for electrons and gammas > 95%



FCC-ee Detectors: IDEA

IDEA – new, innovative, possibly more cost-effective design

- **Silicon vertex detector**
  (5 layers of pixels (MAPS) 30x30 µm^2, point resolution of 5 µm)
- **Short-drift, ultra light wire chamber** (90%/10% He/iC_4H_{10}, momentum resolution 0.25%, impact parameter resolution 4 µm)
- **Dual-readout calorimeter**
  (scintillating fibers sensitive to all charged particles, clear fibers sensitive only to Cherenkov light; $\frac{\sigma}{E} = \frac{11\%}{\sqrt{E}} + 1\%$)
- **Thin and light solenoid coil inside calorimetric system**
  (2T, stored energy 170 MJ)



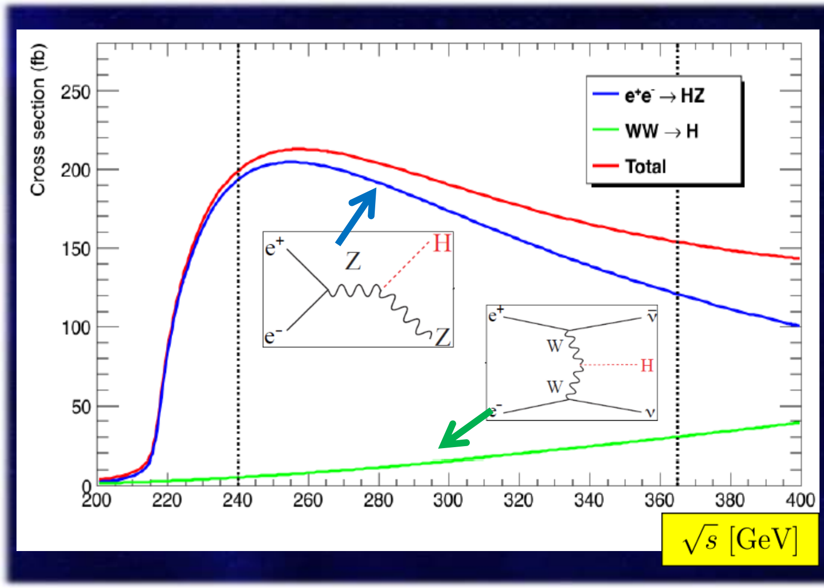
FCC-ee Higgs Physics

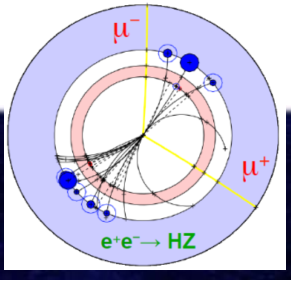
The ZH threshold never studied in e^+e^- **FCC-ee** $N_{ZH} \sim 10^6$

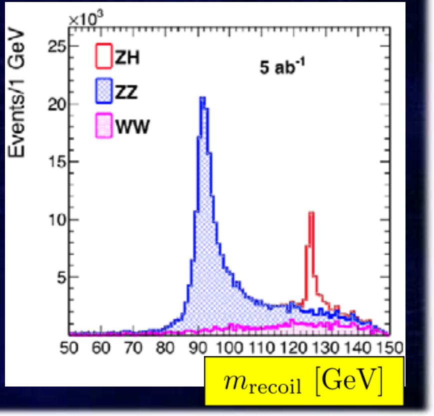
- ✓ The Higgs production measured inclusively from its presence as a recoil to the Z in the process $e^+e^- \rightarrow$ ZH

$$m^2_{recoil} = (\sqrt{s} - E_Z)^2 - p^2_Z$$

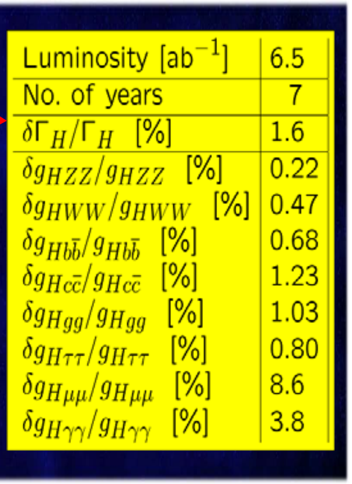
- ✓ $\Delta m_H = 10$ MeV
- ✓ Absolute measurement of the g_{HZZ} ➔ Γ_H ➔ ➔ other couplings g_{ZXX} (X = b, c, τ, μ, W, g, γ,…)







- ✓ The couplings of the 3rd and 2nd generation fermions accessible (most with sub-percent precision)
- ✓ This precision yields the New Physics (NP) sensitivity ~10 TeV
- ✓ A possible pattern of deviations can discriminate between different BSM models
- ✓ See the talks: *Higgs measurements at the FCC-ee* *(abstract 280)*
  Global EFT fits from Higgs at the FCC-ee (abstract 283)

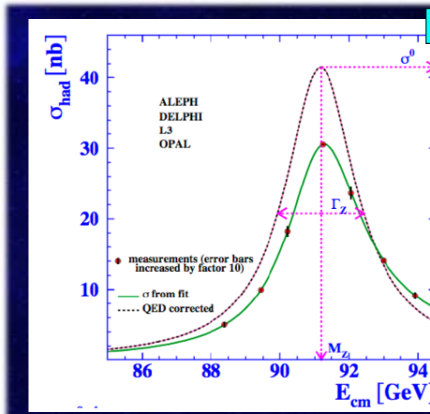


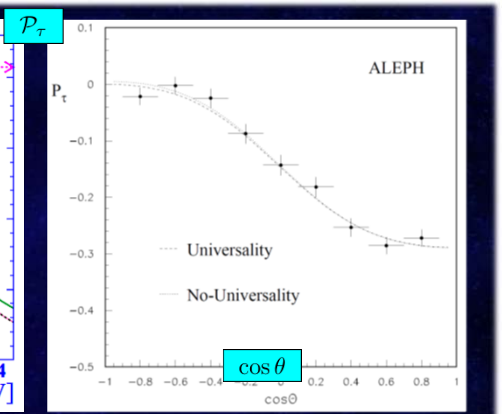
Luminosity [ab^{-1}]	6.5
No. of years	7
$\delta\Gamma_H/\Gamma_H$ [%]	1.6
$\delta g_{HZZ}/g_{HZZ}$ [%]	0.22
$\delta g_{HWW}/g_{HWW}$ [%]	0.47
$\delta g_{Hb\bar{b}}/g_{Hb\bar{b}}$ [%]	0.68
$\delta g_{Hc\bar{c}}/g_{Hc\bar{c}}$ [%]	1.23
$\delta g_{Hgg}/g_{Hgg}$ [%]	1.03
$\delta g_{H\tau\tau}/g_{H\tau\tau}$ [%]	0.80
$\delta g_{H\mu\mu}/g_{H\mu\mu}$ [%]	8.6
$\delta g_{H\gamma\gamma}/g_{H\gamma\gamma}$ [%]	3.8

FCC-ee Electroweak Physics at the Z Pole

LEP $N_Z = 1.7 \times 10^7$ → **FCC-ee** $N_Z \sim 5 \times 10^{12}$ → **Extreme precision of EW observables**

- ✓ Z pole scan:
- ✓ Beam energy calibration is crucial
- ✓ Precision limited by beam energy calibration and theoretical uncertainties





$$\mathcal{P}_\tau(\cos\theta) = \frac{\mathcal{A}_\tau(1+\cos^2\theta) + 2\mathcal{A}_e\cos\theta}{(1+\cos^2\theta) + \mathcal{A}_e\mathcal{A}_\tau\cos\theta}$$

Observable	present value ±error	FCC – ee Stat.	FCC – ee Syst.	Improvement factor
m_Z [keV/c^2]	91186700 ± 2200	5	100	22
Γ_Z [keV]	2495200 ± 2300	8	100	23
R_l^Z [$\times 10^3$]	20767 ± 25	0.06	0.2 – 1	125 – 25
$\alpha_S(m_Z)$ [$\times 10^4$]	1196 ± 30	0.1	0.4 – 1.6	75 – 19
R_b [$\times 10^6$]	216290 ± 660	0.3	< 60	11
N_ν [$\times 10^3$]	2991 ± 7	0.005	1	7
$\sin^2\theta_W^{\mathrm{eff}}$ [$\times 10^6$]	231480 ± 160	3	2 – 5	44 – 28
$1/\alpha_{\mathrm{QED}}(m_Z)$ [$\times 10^3$]	128952 ± 14	4	small	3.5
$A_{\mathrm{FB},0}^b$ [$\times 10^4$]	992 ± 16	0.02	1 – 3	16 – 5
$A_{\mathrm{FB}}^{\mathrm{pol},\tau}$ [$\times 10^4$]	1498 ± 49	0.15	< 2	25

$$\mathrm{R_l} = \frac{\Gamma_{\mathrm{had}}}{\Gamma_{\mathrm{l\bar{l}}}} \quad l = e, \mu, \tau \qquad \mathrm{N}_\nu = \left(\frac{\Gamma_{\mathrm{l}}}{\Gamma_\nu}\right)_{\mathrm{SM}} \cdot \left(\sqrt{\frac{12\pi \mathrm{R_l}}{\mathrm{M_Z^2}\sigma_{\mathrm{had}}^{\mathrm{peak},0}}} - \mathrm{R_l} - 3\right)$$

$$\mathcal{A}_{\mathrm{f}} = \frac{2\mathrm{g_V^f g_A^f}}{(\mathrm{g_V^f})^2 + (\mathrm{g_A^f})^2}$$

$$\mathrm{A_{FB}^f} = \frac{\sigma_{\mathrm{F}} - \sigma_{\mathrm{B}}}{\sigma_{\mathrm{F}} + \sigma_{\mathrm{B}}} = \frac{3}{4}\mathcal{A}_{\mathrm{e}}\mathcal{A}_{\mathrm{f}} \qquad \sin^2\theta_{\mathrm{W}}^{\mathrm{eff}} = \frac{1}{4}\left(1 - \frac{\mathrm{g_V^f}}{\mathrm{g_A^f}}\right)$$

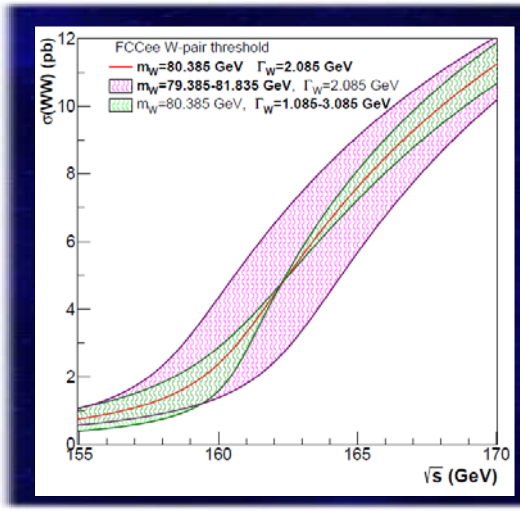
- ✓ The direct measurement of $\alpha_{\mathrm{QED}}(m_Z{}^2)$ from the muon FB asymmetry just below and just above the Z pole (as part of Z resonance scan – no need of extrapolation from $\alpha_{\mathrm{QED}}(0)$)

P.Janot JHEP 02 (2016) 053

- ✓ See the talk *„Electroweak physics at FCC-ee”* *(abstract 281)*

FCC-ee Top and W Physics

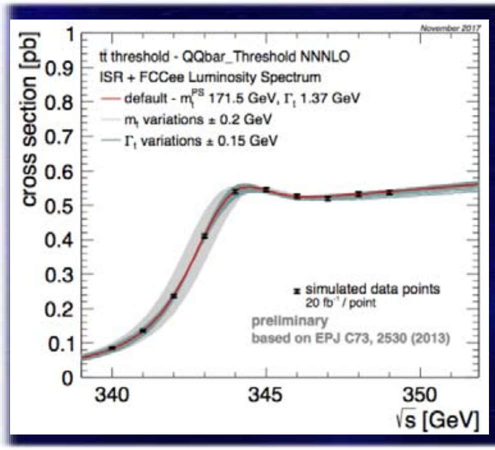
The WW threshold scan **LEP** $N_{WW} = 1.1 \times \times 10^4$ ⇨ **FCC-ee** $N_{WW} \sim 3 \times 10^7$



Observable	present value ±error	FCC – ee Stat.	FCC – ee Syst.	Improvement factor
m_W [MeV/c^2]	80379 ± 12	0.6	0.3	18
Γ_W [MeV]	2085 ± 42	1.5	0.3	27

See the talk *„ Electroweak physics at FCC-ee”* *(abstract 281)*

The t-tbar threshold never studied in e$^+$e$^-$ **FCC-ee** $N_{t\bar{t}} \sim 10^6$

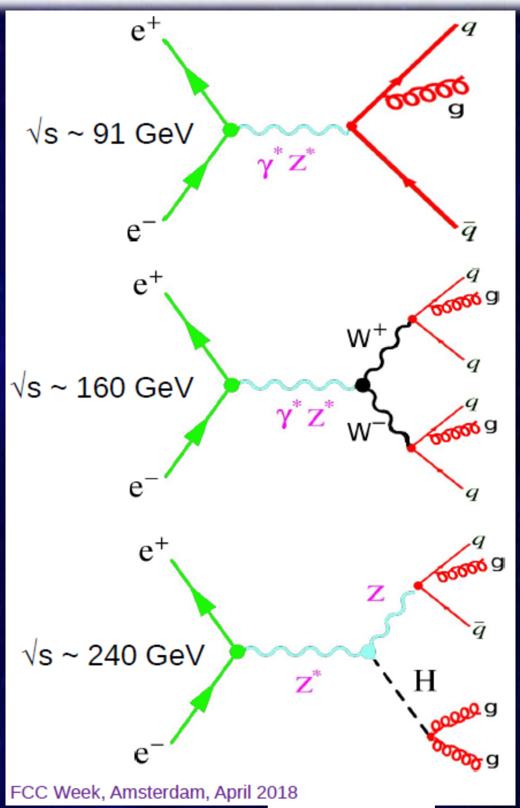


Observable	present value ±error	FCC – ee Stat.	FCC – ee Syst.	Improvement factor
m_t [MeV/c^2]	172900 ± 400	20	small	20
Γ_t [MeV]	1420 ± 190	40	small	5

See the talk *„Top quark physics at the FCC-ee”* *(abstract 284)*

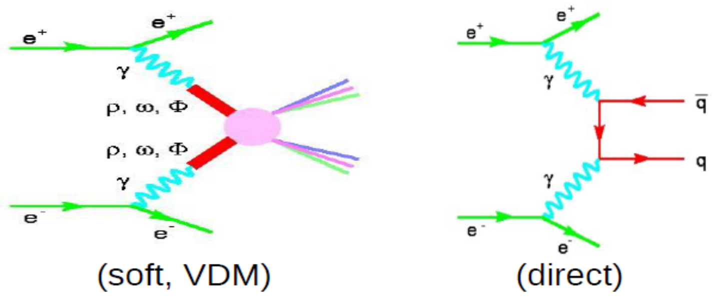
Assets of QCD Studies in e^+e^- Collisions

- ✓ Extremely clean environment
- ✓ Fully controlled QED initial-state with known kinematics
- ✓ Controlled QCD radiation - only from the final state
- ✓ Well defined quark, gluon and heavy-quark jets
- ✓ Relatively small non-perturbative QCD uncertainties (lack of QCD underlying event, no PDFs....)
- ✓ Fragmentation and hadronization - direct and clean
- ✓ Large statistical samples
- ✓ Studies of γ-γ SM and BSM collisions (in Equivalent Photon Approximation (EPA))
- ✓ …



FCC Week, Amsterdam, April 2018

David d'Enterria



(soft, VDM)

(direct)

Reminder: QCD Studies at LEP

- ✓ The successful running of LEP yielded a crucial impact on the understanding of QCD (~240 publications)

- ✓ **The QCD highlights from LEP:**
  - Studies of hadronic event shapes
  - Measurements of α_S
  - Determinations of QCD colour factors and tests of the non-Abelian gauge structure of QCD
  - Studies of differences between quark and gluon jets
  - Tests of Monte Carlo shower and hadronization models
  - Studies of QCD with heavy quarks
  - Advances in two-photon scattering processes
  - …

No. of hadronic events	LEP	FCC-ee
$\sqrt{s} \sim 91$ GeV	10^7	10^{12}
$\sqrt{s} \sim 160$ GeV	10^4	10^7
$\sqrt{s} \sim 240$ GeV	-	10^5

The QCD Objectives of FCC-ee

- ✓ **High precision α_S determination** (with the accuracy at the ‰ level) **from**
  - hadronic τ decays
  - Jet rates, event shapes
  - hadronic Z decays
  - hadronic W decays

- ✓ **High precision studies of perturbative parton radiation including:**
  - jet rates and event shapes
  - jet substructure,
  - quark/gluon/heavy-quark discrimination
  - g,q,b,c parton-to-hadron fragmentation functions

- ✓ **High precision non-perturbative QCD studies including:**
  - colour reconnection
  - final-state multiparticle correlations

- ✓ **High precision hadronization studies**
  - very rare hadron production and decays

The QCD Coupling Constant α_S at FCC-ee

- ✓ The α_S determines the strength of the strong interaction at a given scale
- ✓ The unique free parameter of QCD in the limit $m_q \rightarrow 0$

- ✓ The α_S is the least precisely measured of all four couplings of fundamental interactions:

$$\Delta\alpha \sim 10^{-10}$$

$$\Delta G_F \sim 10^{-7}$$

$$\Delta G \sim 10^{-5}$$

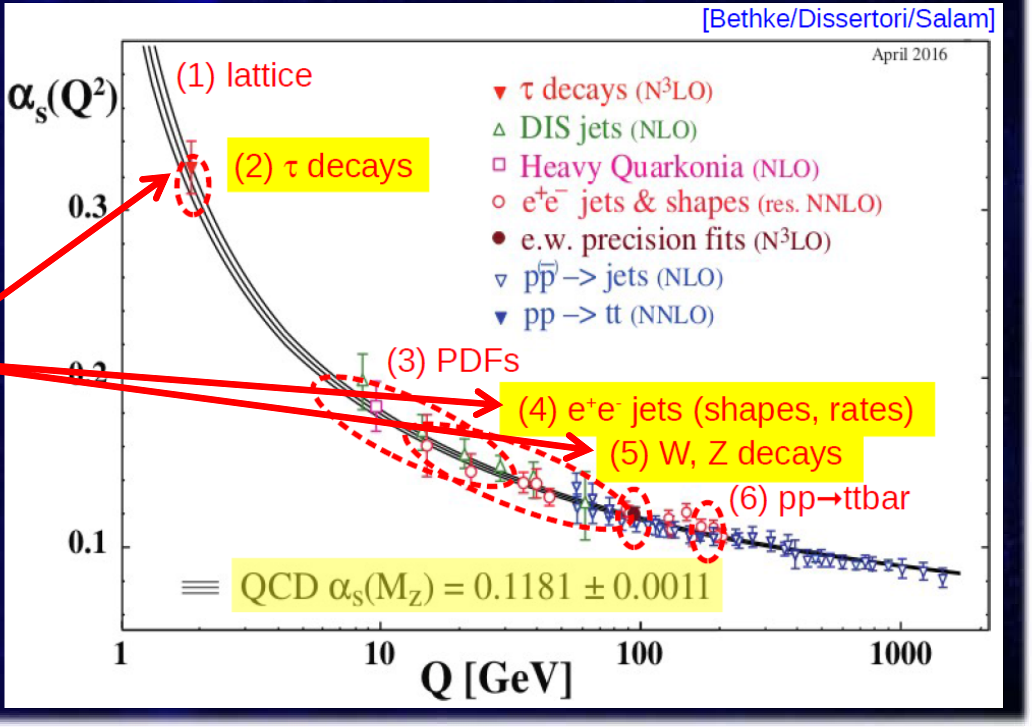
$$\boxed{\Delta\alpha_S \sim 10^{-2}}$$

- ✓ **huge statistics of hadronic τ, W and Z decays**
- ✓ **N^3LO perturbative QCD calculations**

$$\boxed{\Delta\alpha_S \sim 10^{-3}}$$

- ✓ The α_S is determined by comparing now 6 groups of experimental observables to pQCD NNLO and N^3LO predictions

- ✓ The global average is provided at the Z pole



The QCD Coupling Constant α_S at FCC-ee

✓ **τ decays:** The relevant quantity: computable at N^{3}LO:

$$\mathbf{R}_\tau = \frac{\Gamma(\tau^- \to \nu_\tau + \text{hadrons})}{\Gamma(\tau^- \to \nu_\tau \mathbf{e}^- \bar{\nu}_\mathbf{e})}$$

$$\mathbf{R}_\tau = \mathbf{S}_{\mathbf{EW}} \mathbf{N}_\mathbf{C} \left(1 + \sum_{\mathbf{n}=1}^{4} \mathbf{c}_\mathbf{n} \left(\frac{\alpha_\mathbf{S}}{\pi}\right)^\mathbf{n} + \mathcal{O}(\alpha_\mathbf{S}^5) + \delta_{\mathbf{np}} \right)$$

✓The current experimental value: $\mathbf{R}_{\tau,\mathbf{exp}} = \mathbf{3.4697 \pm 0.0080} \quad (\pm \mathbf{0.23\%})$

✓The current determination of the α_S: $\alpha_\mathbf{S}(\mathbf{m_Z}) = \mathbf{0.1192 \pm 0.0018} \quad (\pm \mathbf{1.5\%})$

FCC-ee $N(Z \to \tau^+\tau^-) \sim 10^{11}$ & theoretical progress ➡ $\delta\alpha_\mathbf{S}(\mathbf{m_Z})/\alpha_\mathbf{S}(\mathbf{m_Z}) < \mathbf{1\%}$

✓ **The event shapes**, like e.g. thrust (T) , C-parameter… **and N jet cross sections** are computed at N^{2,3}LO+N^{2}LL accuracy

$$T = \max_{\vec{n}} \left(\sum_{i=1}^{n} |\vec{p}_i \cdot \vec{n}| \right) / \left(\sum_{i=1}^{n} |\vec{p}_i| \right)$$

$$C = \frac{3}{2} \frac{\sum_{i,j=1}^{n} |\vec{p}_i||\vec{p}_j| \sin^2\theta_{ij}}{(\sum_{i=1}^{n} |\vec{p}_i|)^2}$$

✓ The current combination of LEP results yields $\delta\alpha_\mathbf{S}(\mathbf{m_Z})/\alpha_\mathbf{S}(\mathbf{m_Z}) < \mathbf{2.9\%}$

FCC-ee $N(Z \to \text{hadrons}) \sim 10^{12}$ ➡ $\delta\alpha_\mathbf{S}(\mathbf{m_Z})/\alpha_\mathbf{S}(\mathbf{m_Z}) < \mathbf{1\%}$

& theoretical progress

The QCD Coupling Constant α_s at FCC-ee

Hadronic Z decays:

- ✓ at LEP, the α_s was extracted from the fits to the three Z-peak observables

$$\sigma_l^0 = \frac{12\pi}{m_Z}\frac{\Gamma_l^2}{\Gamma_Z^2} \qquad \sigma_{\text{had}}^0 = \frac{12\pi}{m_Z}\frac{\Gamma_e\Gamma_{\text{had}}}{\Gamma_Z^2}$$

$$R_l^0 = \frac{\Gamma(Z \to \text{had})}{\Gamma(Z \to l)} = \frac{\Gamma_{\text{had}}}{\Gamma_l}$$

- ✓ computable at N^{3}LO:

$$R_l^0 = R_Z^{\text{EW}} N_C \left(1 + \sum_{n=1}^{4} c_n \left(\frac{\alpha_S}{\pi}\right)^n + \mathcal{O}(\alpha_S^5) + \delta_{\text{m}} + \delta_{\text{np}}\right)$$

- ✓ The current α_s value:

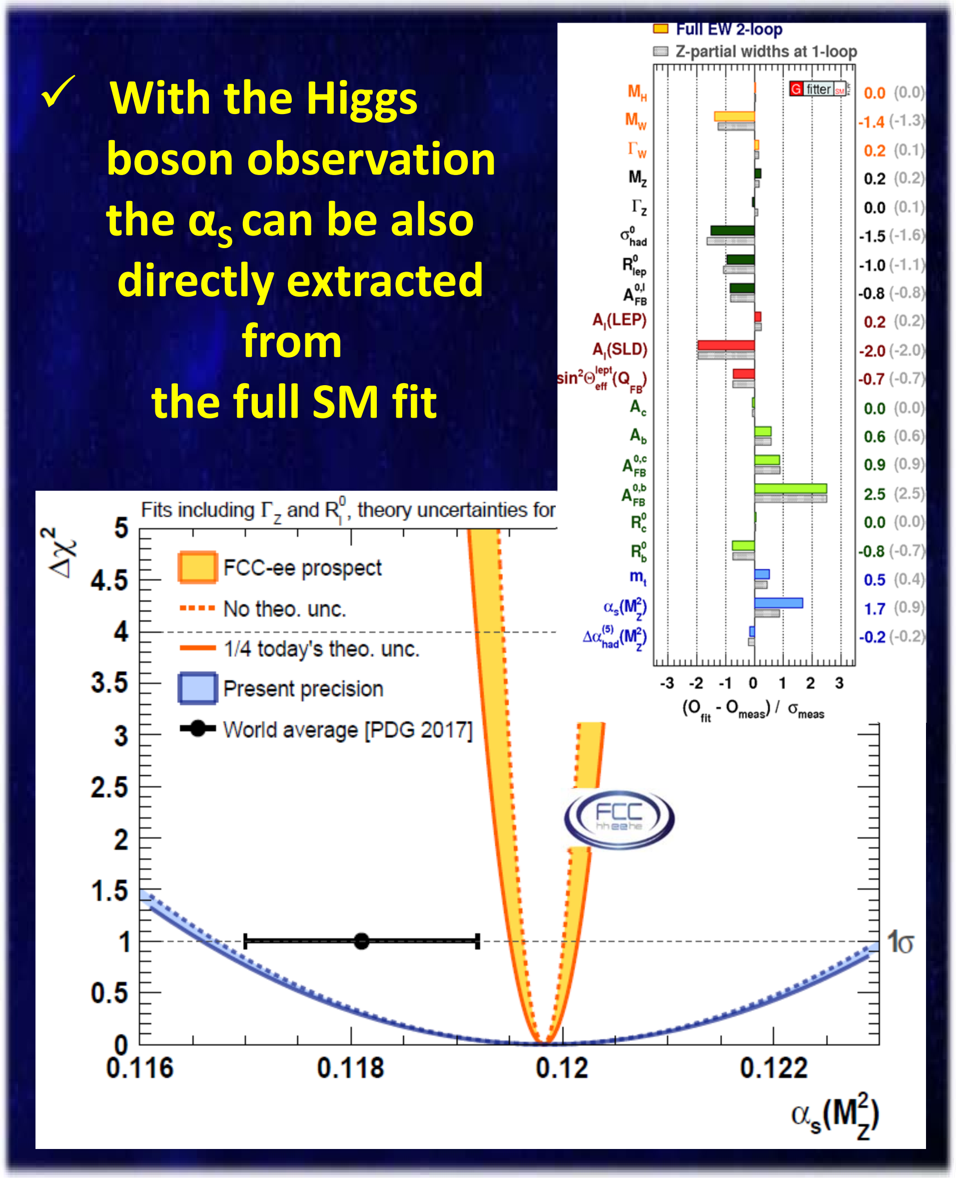
$$\alpha_\mathbf{S}(\mathbf{m_Z}) = \mathbf{0.1196 \pm 0.0030} \quad (\pm \mathbf{2.5\%})$$

FCC-ee $N_Z \sim 5 \times 10^{12}$

and theoretical progress

➡ $$\delta\alpha_\mathbf{S}(\mathbf{m_Z})/\alpha_\mathbf{S}(\mathbf{m_Z}) < \mathbf{0.2\%}$$

- ✓ **With the Higgs boson observation the α_s can be also directly extracted from the full SM fit**



The QCD Coupling Constant α_S at FCC-ee

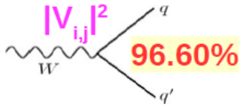
Hadronic W decays:

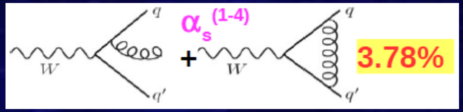
- ✓ The observable: ratio of hadronic to leptonic W decay widths $R_W = \frac{\Gamma^W_{\text{had}}}{\Gamma^W_l}$

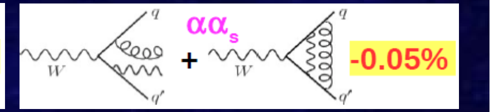
$$\Gamma_{W,\text{had}} = \frac{\sqrt{2}}{4\pi} G_F m_W^3 \sum_{\text{quarks i,j}} |V_{i,j}|^2 \left[1 + \sum_{k=1}^{4} \left(\frac{\alpha_S}{\pi}\right)^k + \delta_{\text{EW}}(\alpha_{\text{QED}}) + \delta_{\text{mixed}}(\alpha_{\text{QED}}\alpha_S) \right]$$

[EWK: -0.35%]

- ✓ computable at N^{2,3}LO:





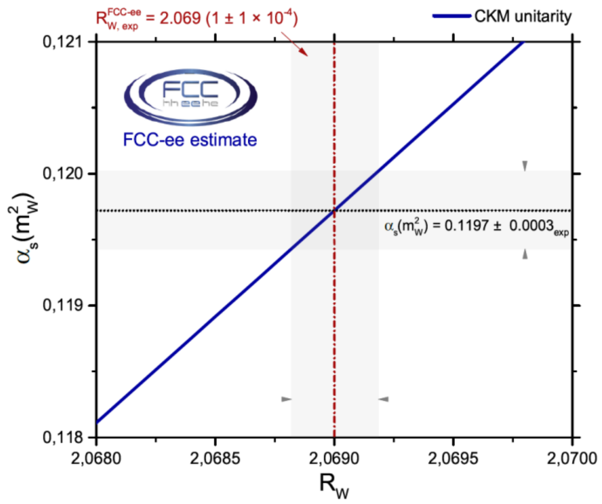


- ✓ The LEP α_S value: $\alpha_S(m_Z) = 0.117 \pm 0.040 \quad (\pm 35\%)$

FCC-ee $N_{WW} \sim 3 \times 10^7$ ⇒ $\delta\alpha_S(m_Z)/\alpha_S(m_Z) < 0.3\%$

and theoretical progress

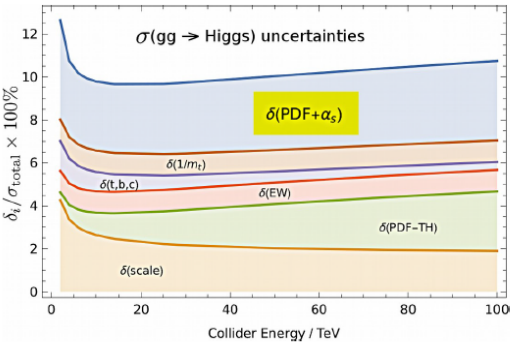
D.d'Enterria, M.Srebre, arXiv:1603.06501



The precision on α_S influences all QCD cross-sections and decays …

Quantity	FCC-ee	future param.unc.	Main source
Γ_Z [MeV]	0.1	0.1	$\delta\alpha_s$
R_b [10^{-5}]	6	< 1	$\delta\alpha_s$
R_ℓ [10^{-3}]	1	1.3	$\delta\alpha_s$

David d'Enterria FCC Phys. Workshop, CERN, Jan 2018



High Precision Studies of Perturbative Parton Radiation – Jet Rates and Event Shapes

- ✓ **Jet rates** are expected to be measured with the accuracy 10^{-6} (at the Z pole), including:

Rate of	up to k_T [GeV]	|ln(y)|
4-jet events	~30	~2
5-jet-events	~20	~3
6-jet events	~12	~4
7-jet events	~7.5	~5

(jet resolution parameter: $\mathrm{y} = \frac{\mathrm{k}_\mathrm{T}^2}{\mathrm{s}}$)

Comparison with theoretical calculations with accuracy beyond the NNLO+NNLL

(→ α_S extraction)

- ✓ Event shapes are affected by logarithmic enhancements (resummed up to N^3LL: pQCD, SCET,…) and hadronization corrections (estimated from MC generators)

- ✓ **The FCC-ee operating at different CM energies will provide much tighter control on resummation and hadronization effects in event shape distributions**

$\sqrt{s} = 91.2\ \mathrm{GeV}$ → **non-perturbative uncertainties reduced from 9% to 2%**

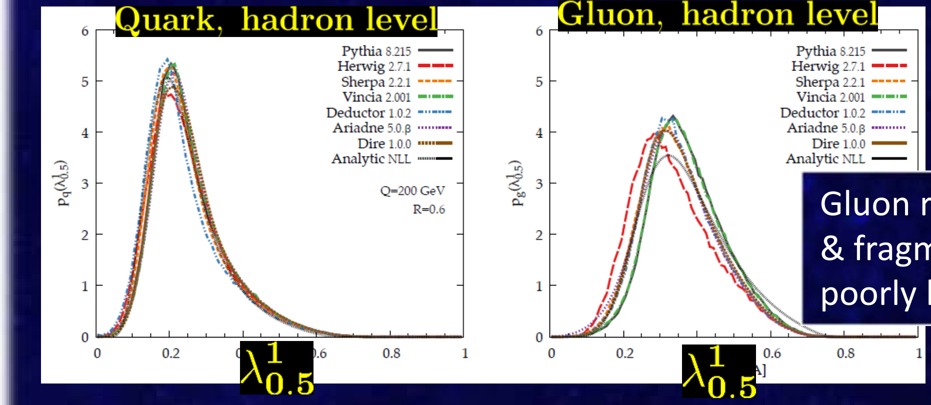
High Precision Studies of Perturbative Parton Radiation – Jet Substructure and Parton Flavour Studies

- ✓ **Goal:** parton flavour discrimination (PFD): quark – gluon; (u,d,s) – c – b
- ✓ Such separation crucial for precision SM measurements and BSM searches
- ✓ The PFD is based on the comparison of jet substructure properties to MC predictions
- ✓ Quark-gluon PFD at LEP: studies of $Z \to b\bar{b}g$ (statistically limited)

✓ **- 10^5 more Zs**

- a unique sample of 10^4 $H \to gg$ events - FCC-ee as a „pure gluon" factory

✓ The current level of discrepacies between MC generators (hadron level distributions):



Gluon radiation & fragmentaion poorly known

The generalized angularities:

$$\lambda^\kappa_\beta = \sum_{i \in jet} Z_i^\kappa \theta_i^\beta$$

Z_i – the momentum fraction of particle i

Θ_i – the angular fraction of part. i w.r.t. the jet radius

Significant variations between generators for gluon distributions

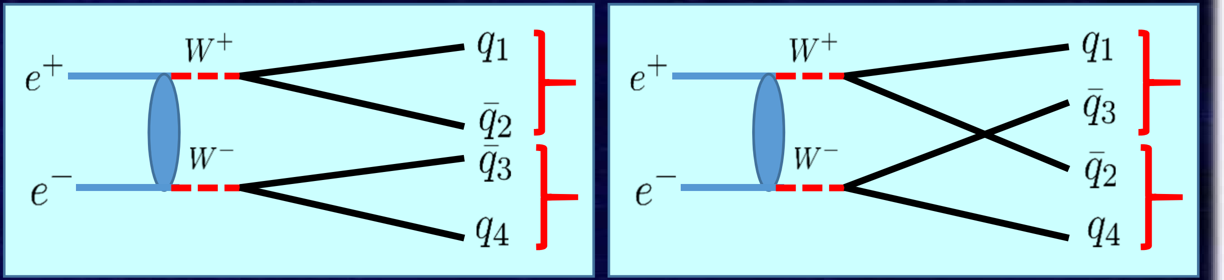
new insight from the FCC-ee

: large samples of top, W, Z, H decays to b and c quarks; important progress in heavy-quark fragmentation and in gluon fragmentation $g \to b\bar{b}\ (c\bar{c})$

High Precision Non-Perturbative QCD – Colour Reconnection

- ✓ The uncertainties due to non-perturbative QCD effects (colour reconnection, hadronization, final state interactions…) impact many high-precision SM studies
- ✓ e^+e^- collisions offer favourable conditions to control them

- ✓ **Colour Reconnection (CR):** strong interaction (colour flow) between colour singlet parton systems of different origin
- ✓ LEP2: exclusion (99.5% CL) of the no-CR null hypothesis but statistics insufficient for more quantitative results



- ✓ **FCC-ee:** $\Delta m_W \sim 1\ \mathrm{MeV}$ (threshold scan) & the $3\mathrm{x}10^3$ gain in the number of WW pairs

- ✓ The shift in the reconstructed m_W expected from different PYTHIA 8 CR models:

	E_{cm} (GeV)	$\langle\delta\overline{m}_{\mathrm{W}}\rangle$ (MeV) I	II	II′	GM-I	GM-II	GM-III	CS
small (S):	170	+18	−14	−6	−41	+49	+2	+7
maximal (L):	240	+95	+29	+25	−74	+400	+104	+9
medium size (M):	350	+72	+18	+16	−50	+369	+60	+4

discrimination between CR models

High Precision Non-Perturbative QCD – Parton Hadronization

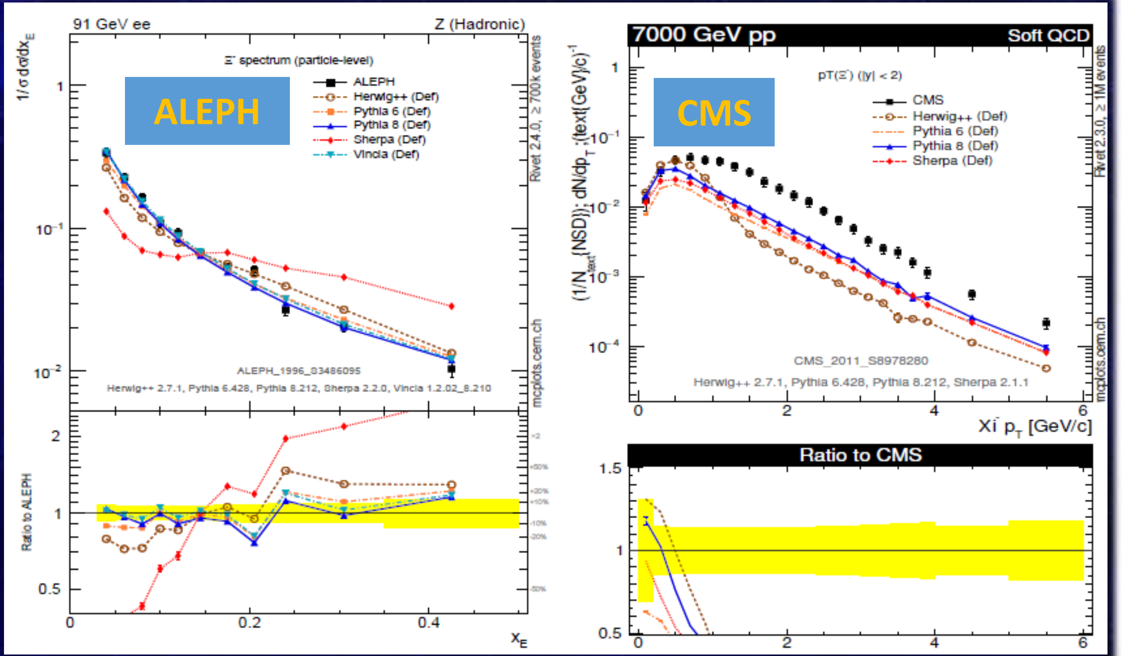
✓ **Parton Hadronization (PH) – phenomenological models – MC generators**

✓ **The understanding of many aspects of PH like**

- baryon production
- strangeness production
- final state correlations
- colour string dynamics
- ….

✓ **can profit significantly from the FCC-ee (hadronic) data samples:**

- large statistics
- excellent tracking and calorimetry
- efficient hadron identification
- …



Ξ- spectra measured by ALEPH and CMS,
compared to the predictions from modern event generators

Summary

- ✓ The FCC-ee project aims at collection of huge data samples at the four relevant working points: Z-pole, ZH, WW and ttbar thresholds
- ✓ The uncertainties of the most important electroweak observables are expected to be improved by a factor of at least 10
- ✓ The QCD program of the FCC-ee encompasses
  - High precision α_S determination
  - High precision studies of perturbative parton radiation
  - High precision non-perturbative QCD studies
  - High precision hadronization studies

BACKUP

FCC hh ee he

EU H2020 Design Study EuroCirCol

EuroCirCol

European Union Horizon 2020 program:

- 3 MEURO co-funding
- Started June 2015, ends in Dec 2019
- 15 European beneficiaries & KEK & associated FNAL, BNL, LBL, NHFML

UNIVERSITY OF TWENTE.

INFN

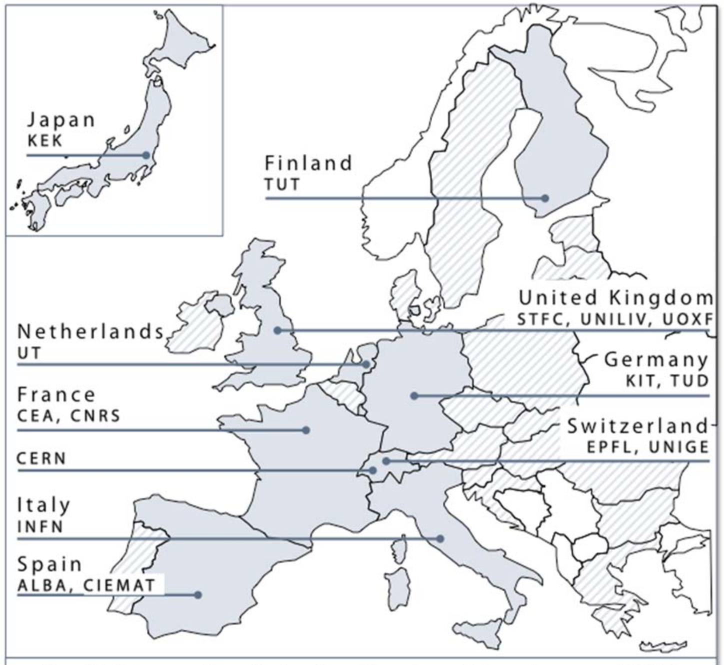
TAMPERE UNIVERSITY OF TECHNOLOGY

cea

cnrs dépasser les frontières

CERN

UNIVERSITY OF OXFORD



EuroCirCol consortium, federating 16 partners, 1 from Japan and 1 IEIO

TECHNISCHE UNIVERSITÄT DARMSTADT

KIT Karlsruher Institut für Technologie

EPFL ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

UNIVERSITY OF LIVERPOOL

UNIVERSITÉ DE GENÈVE

ALBA

Ciemat Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas

MANCHESTER 1824

Covers FCC-hh key work packages:

- Optics design (arc & IR)
- Cryogenic beam vacuum system design including beam tests at ANKA
- 16 T dipole design, construction folder for demonstrator magnets

FCC hh ee he

EU H2020 Marie Curie ITN
EASITrain

EASITrain

European Advanced Superconductivity Innovation and Training Network

Funding 15 Early Stage Researchers over 3 years & training in key areas

- **SC wires at low temperatures for magnets (Nb_3Sn, MgB_2, HTS)**
- **Superconducting thin films for RF and beam screen (Nb_3Sn, Tl)**
- **Electrohydraulic forming for RF structures**
- **Turbocompressor for Nelium refrigeration**
- **Magnet cooling architectures**
- ➢ **started 1 October 2017**

13 Beneficiaries

BRUKER
cea
Columbus Superconductors
HZB Helmholtz Zentrum Berlin
SPIN
Universität Stuttgart
INFN
TECHNISCHE UNIVERSITÄT DRESDEN
TU WIEN TECHNISCHE UNIVERSITÄT WIEN
UNIVERSITÄT SIEGEN
WU
I-CUBE
CERN

12 Partners

Bmax power to shape
ASG Superconductors
BILFINGER Babcock Noell GmbH
CemeCon The Tool Coating
IEEE Advancing Technology for Humanity
Criotec IMPIANTI S.r.l.
MAN Diesel & Turbo
Terra Mater Factual Studios
Red Bull MEDIA HOUSE
research instruments
SIGMAPHI
UNIVERSITÀ DEGLI STUDI DI GENOVA
AIR LIQUIDE

FCC-ee basic design choices

double ring e⁺e⁻ collider ~100 km

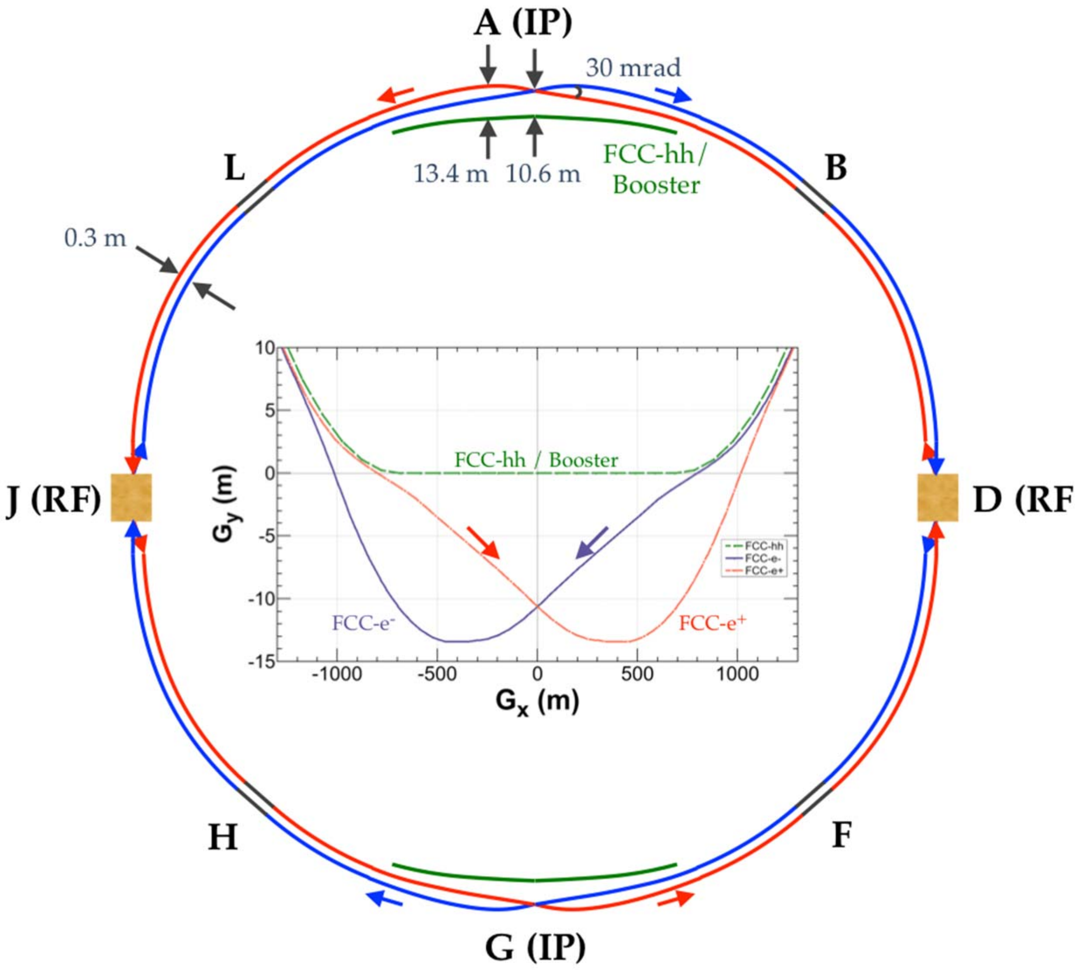
follows footprint of FCC-hh, except around IPs

asymmetric IR layout & optics to limit synchrotron radiation towards the detector

presently 2 IPs (alternative layouts with 3 or 4 IPs under study), **large** horizontal crossing angle **30 mrad, crab-waist optics**

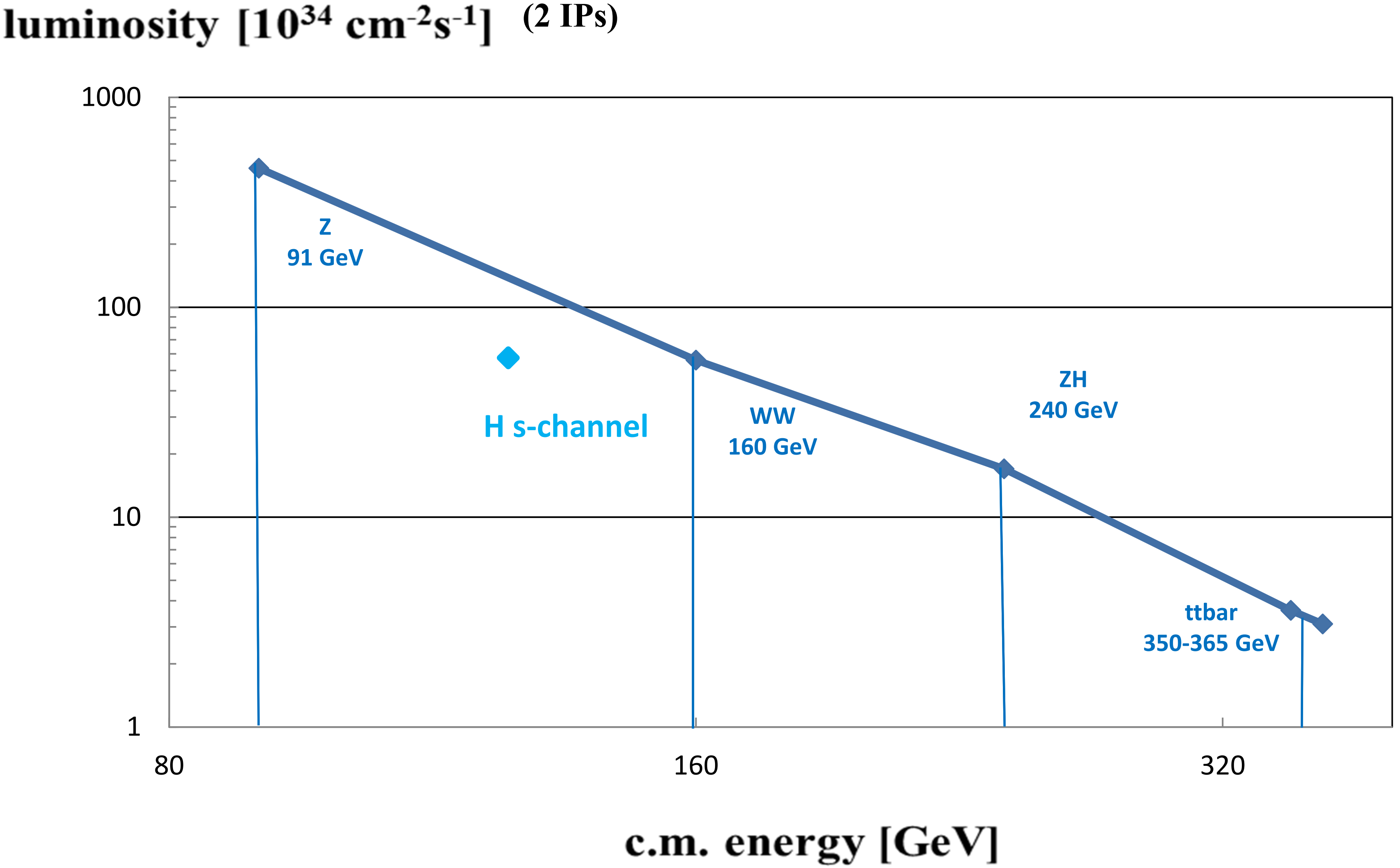
synchrotron radiation power 50 MW/beam at all beam energies; tapering of arc magnet strengths to match local energy

top-up injection scheme; requires **booster synchrotron in collider tunnel**

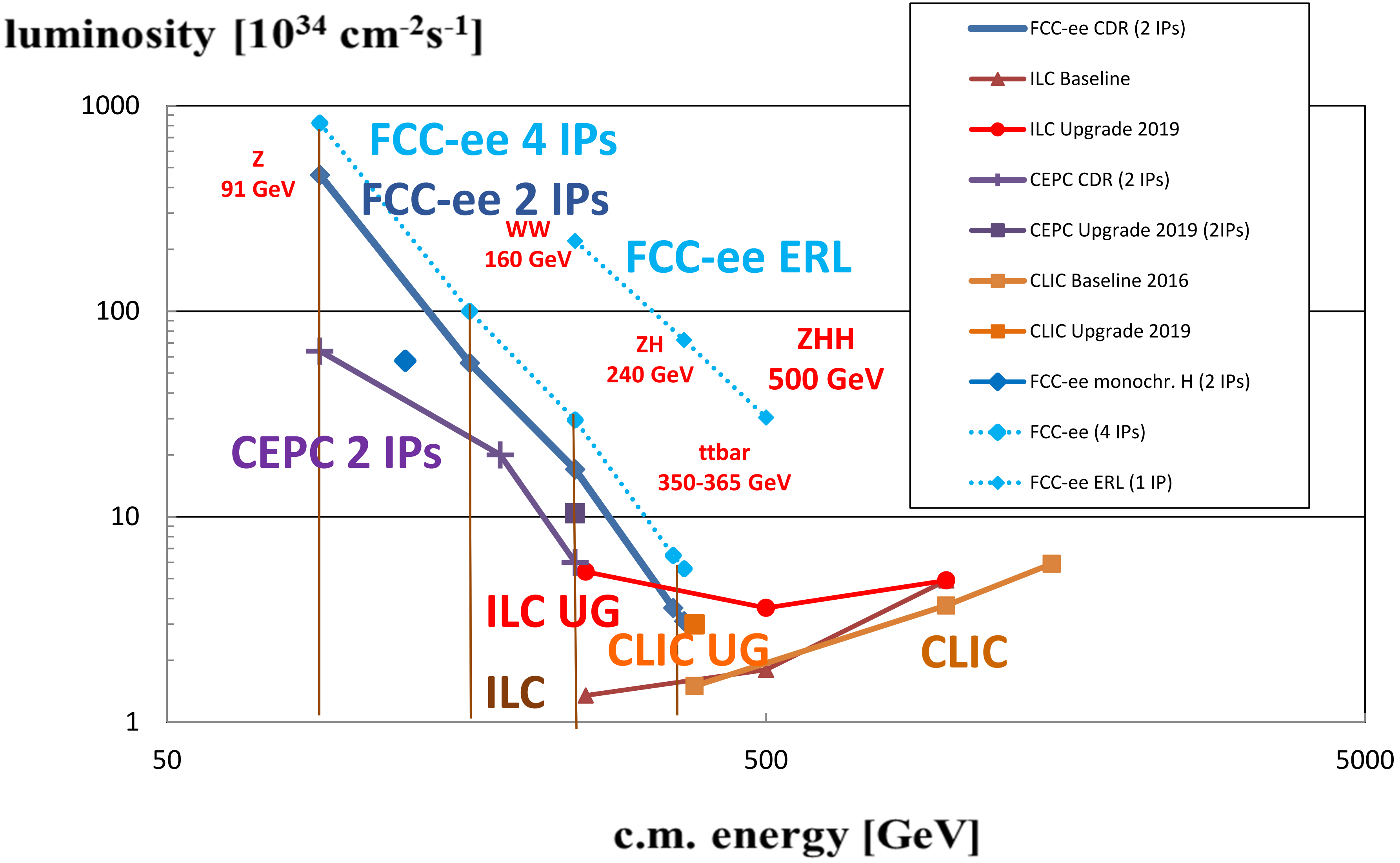


K. Oide et al.

FCC-ee luminosity versus energy

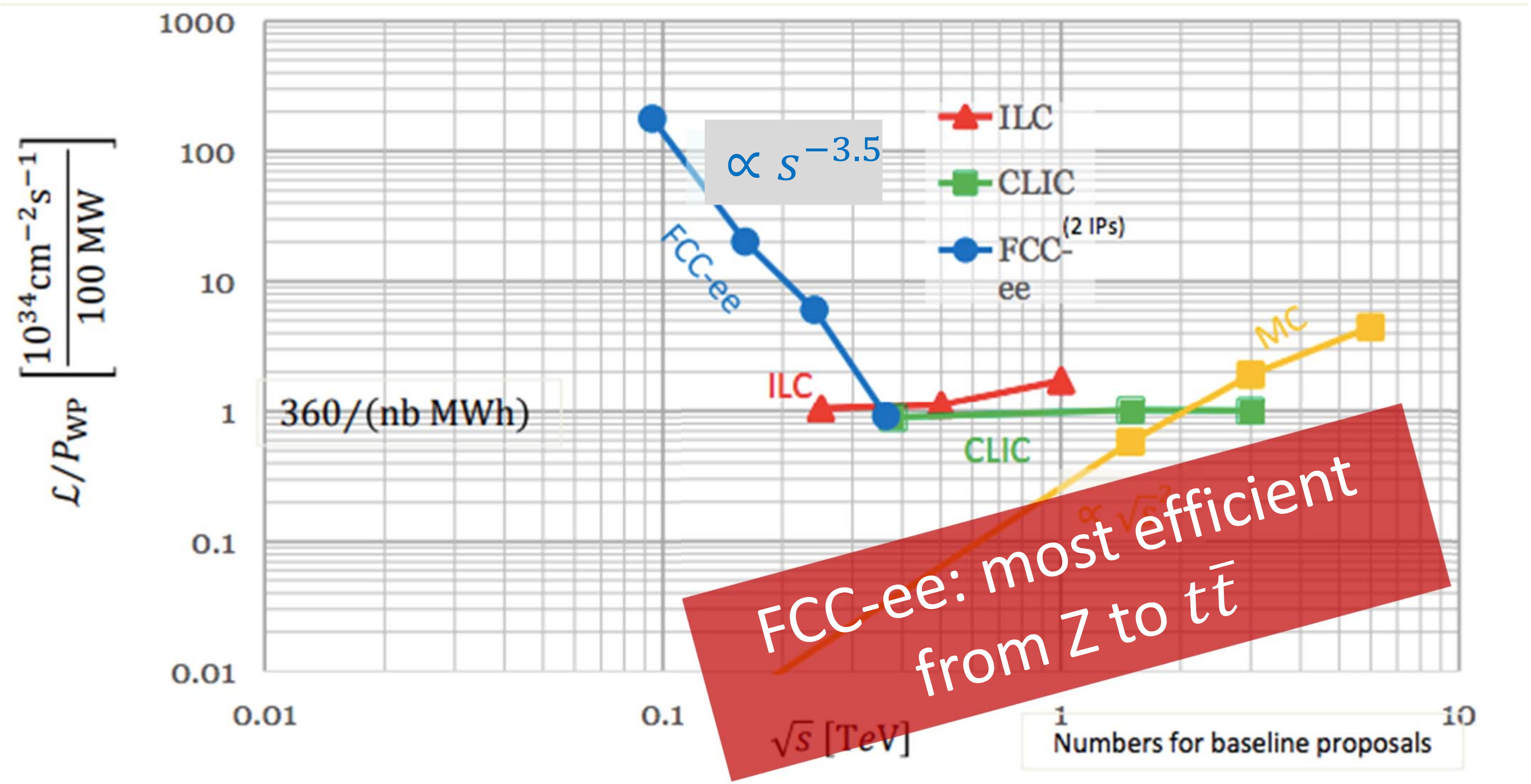


FCC-ee luminosity in perspective



Benno List, Daniel Schulte, Dmitry Shatilov, Cheng Hui Yu, Vladimir Litvinenko, Thomas Roser

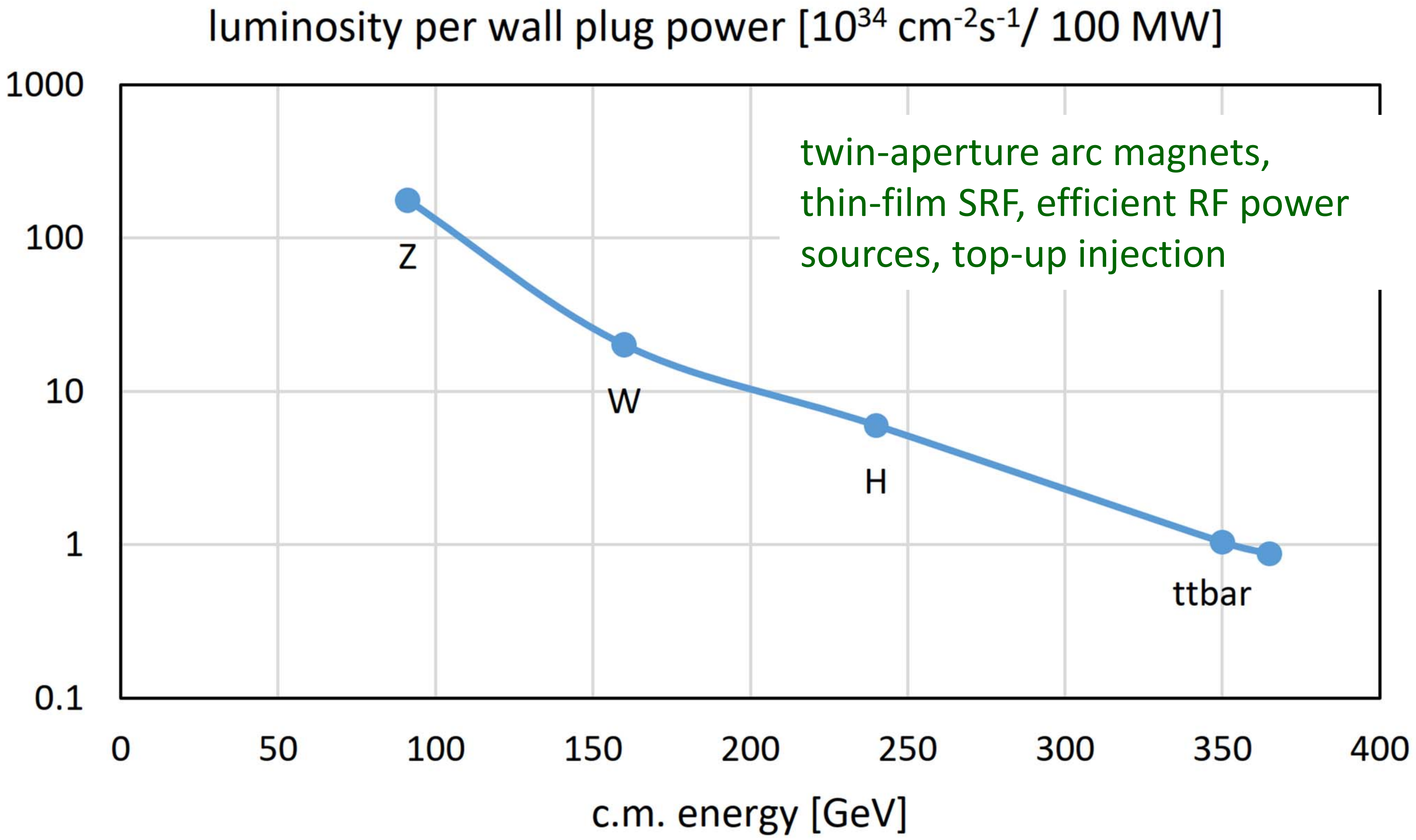
figure of merit for lepton colliders



FCC-ee: most efficient from Z to $t\bar{t}$

E. Jensen, EPPSU symposium, Granada

FCC-ee: a sustainable accelerator



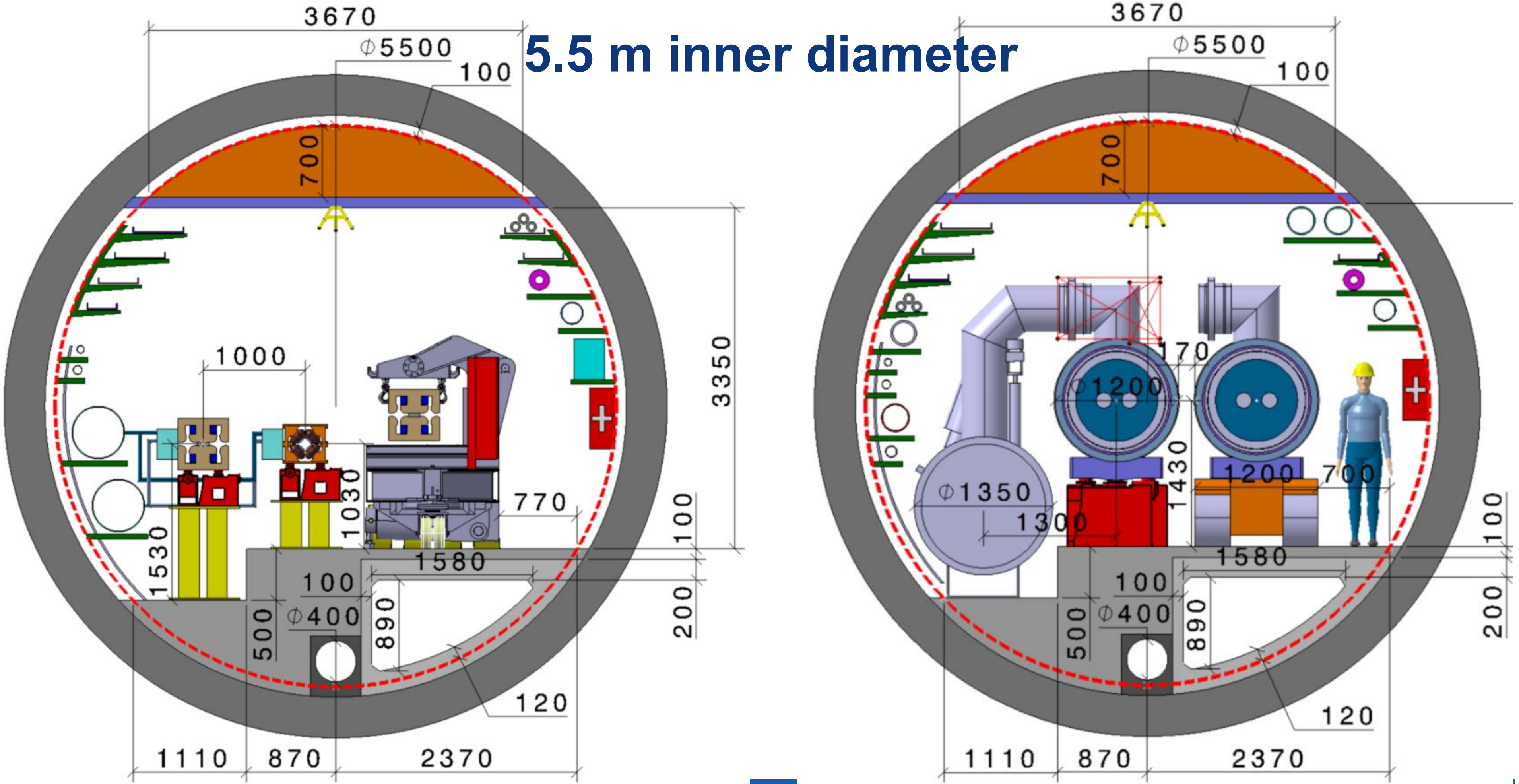
twin-aperture arc magnets, thin-film SRF, efficient RF power sources, top-up injection

electricity cost ~200 euro per Higgs boson

Tunnel integration in arcs

FCC-ee FCC-hh

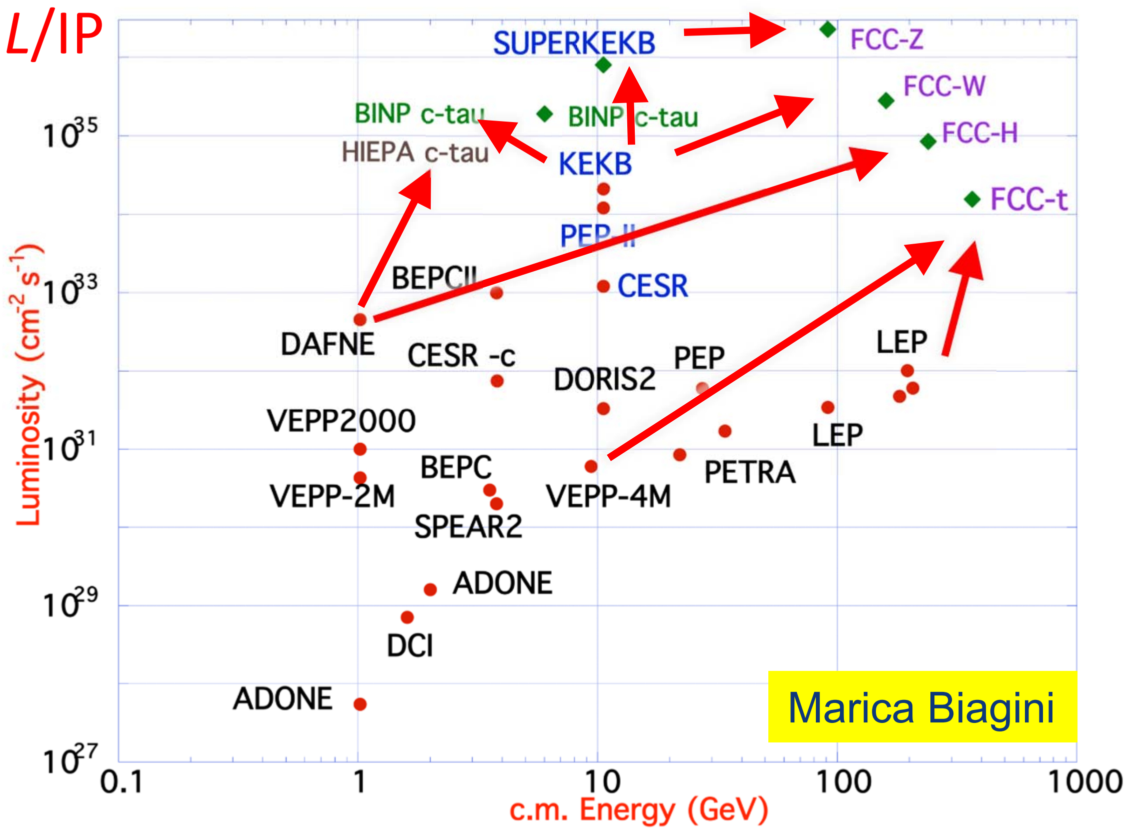
5.5 m inner diameter



FCC-ee – EW factory: performance

FCC-ee reaches highest luminosities & energies

by combining ingredients and well-proven concepts of several recent colliders:



B-factories: **KEKB & PEP-II:**
double-ring lepton colliders,
high beam currents,
top-up injection

DAFNE: crab waist, double ring

Super B-fact., **S-KEKB: low β_y***

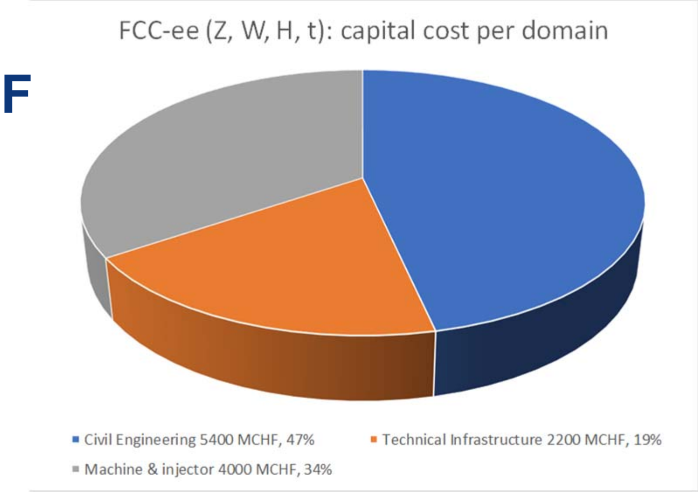
LEP high energy, SR effects

VEPP-4M, LEP:
precision E calibration

KEKB: *e*$^+$ source

HERA, LEP, RHIC: spin gymnastics

FCC integrated project cost estimate



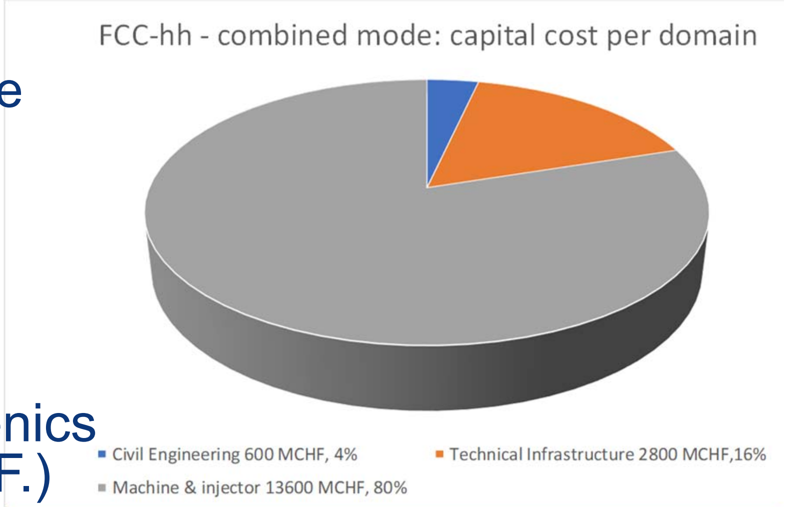
Construction cost phase1 (FCC-ee) is 11,6 BCHF

- 5,4 BCHF for civil engineering (47%)
- 2,2 BCHF for technical infrastructure (19%)
- 4,0 BCHF accelerator and injector (34%)

Construction cost phase 2 (FCC-hh) is 17,0 BCHF.

- 13,6 BCHF accelerator and injector (57%)
  - Major part for4,700 Nb_3Sn 16 T main dipole magnets, totalling 9,4 BCHF, targeting 2 MCHF/magnet.
- CE and TI from FCC-ee re-used, 0,6 BCHF for adaptation
- 2,8 BCHF for additional TI, driven by cryogenics

(Cost FCC-hh stand alone would be 24,0 BCHF.)

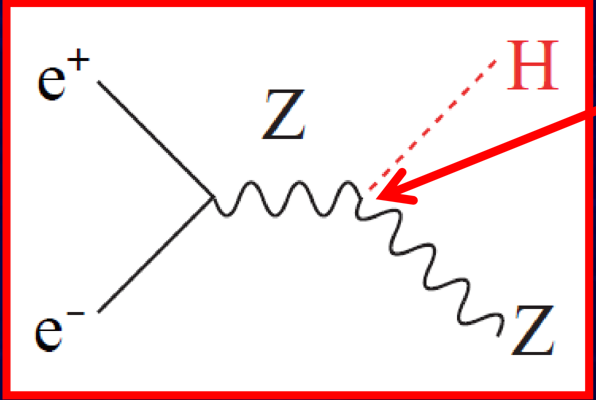


Higgs Mass and H-Z-Z Coupling

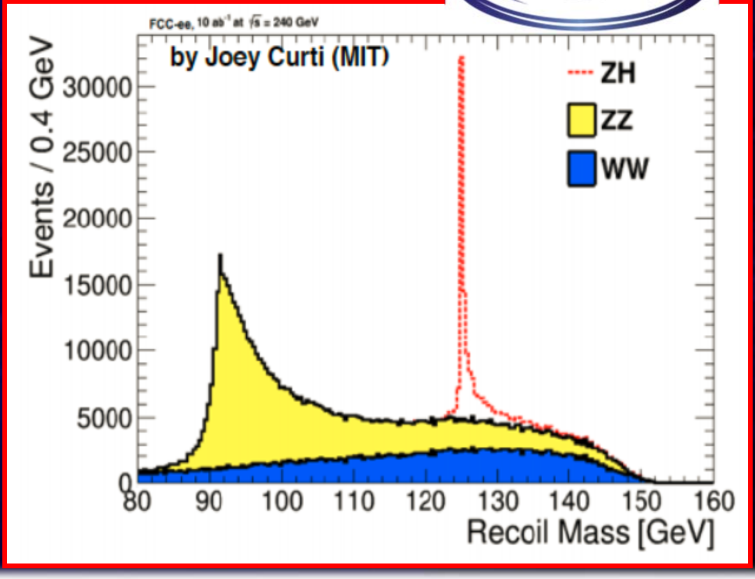
- **The recoil technique in $e^+e^- \rightarrow ZH$ - unique for lepton colliders :**
- Look just at the Z and reconstruct its decay products
- ZH events are tagged independently of Higgs decay mode (include invisible decay modes)
- Very clean Higgs mass determination: $\mathbf{m^2_{recoil} = (\sqrt{s} - E_{ll})^2 - |\tilde{p}_{ll}|^2}$

$$\Delta m_H \sim 10 \text{ MeV}$$

- Precise determination of the ZH cross-section $\Delta\sigma(ZH)/\sigma(ZH) \sim 0.5\%$
- Precise measurement of the H-Z-Z coupling (g_{HZZ}):



$$\sigma(HZ) \propto g^2_{HZZ}$$



Higgs Total Width and HWW Coupling

➢ Determination of the H-W-W coupling (g_{HWW}):

- Measure the rate of WW Fusion to HZ processes – preferably at 350 GeV, using Higgs decays to the given final state e.g.

$$\frac{\sigma(e^+e^- \to H\nu_e\bar{\nu}_e) \times BR(H \to b\bar{b})}{\sigma(e^+e^- \to HZ) \times BR(H \to b\bar{b})} \propto \frac{g^2_{HWW}}{g^2_{HZZ}}$$

g_{HWW} measured

➢ Determination of the Higgs total width (Γ_H):

1. Use the HZ proces and H→Z Z*

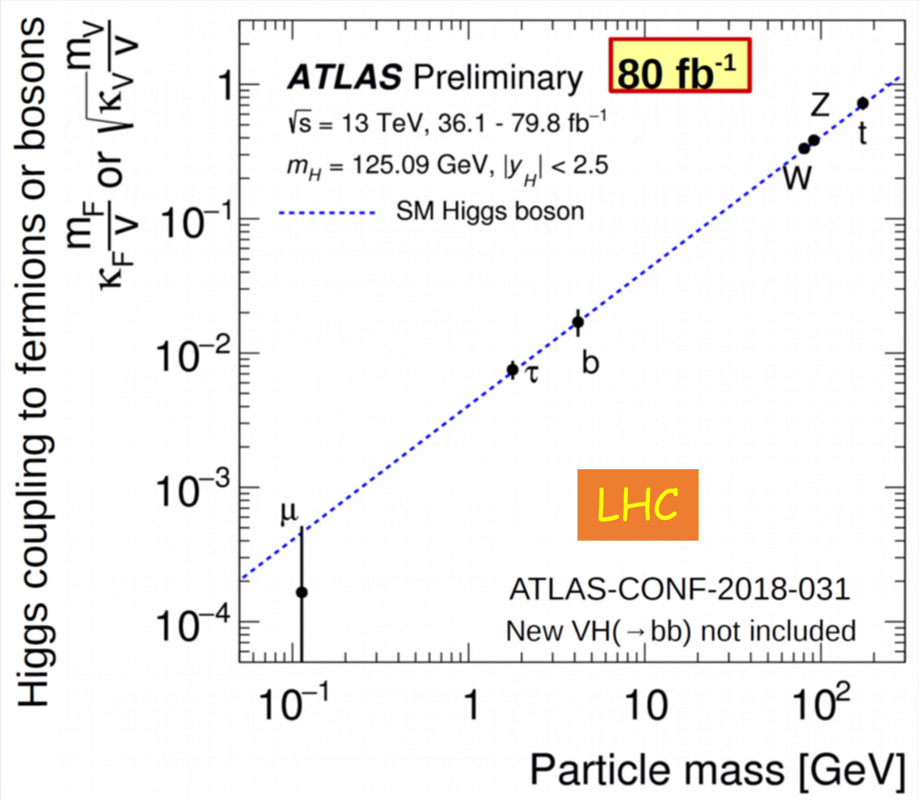
$$\sigma(e^+e^- \to HZ) \times BR(H \to ZZ^*) \propto \frac{g^4_{HZZ}}{\Gamma_H}$$

2. Use the WW Fusion proces and H→ WW*:

$$\sigma(e^+e^- \to H\nu_e\bar{\nu}_e) \times BR(H \to WW^*) \propto \frac{g^4_{HWW}}{\Gamma_H}$$

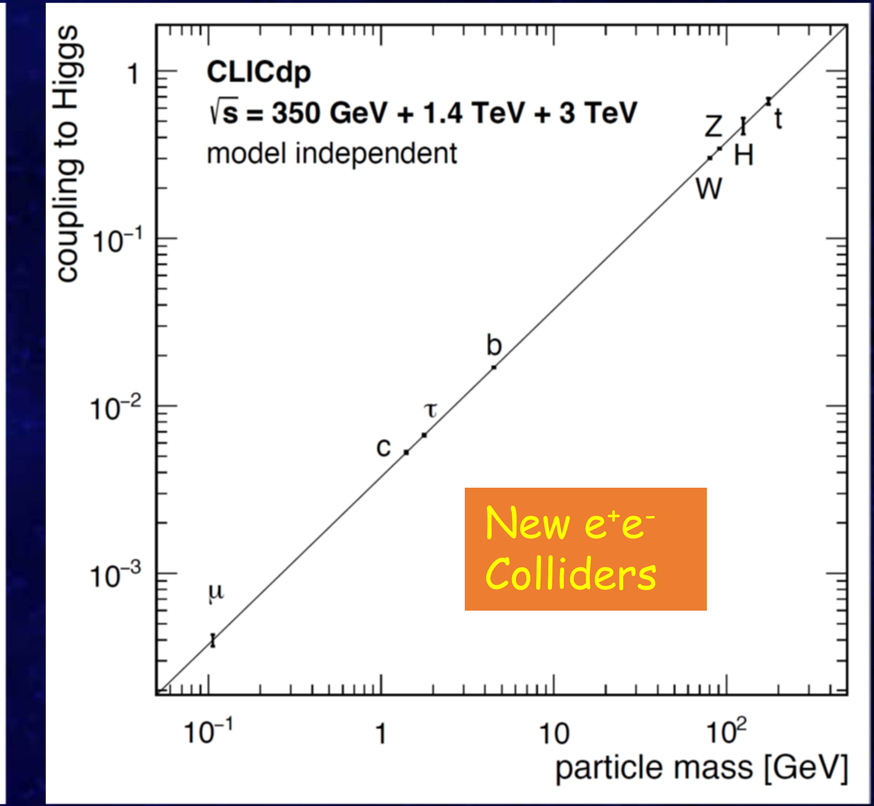
Γ_H measured

Higgs Couplings: Post Factum



80 fb^{-1}

LHC



New e$^+$e$^-$ Colliders

$\Delta k_f \sim 15\%$ → $\Delta k_f \sim 1\%$

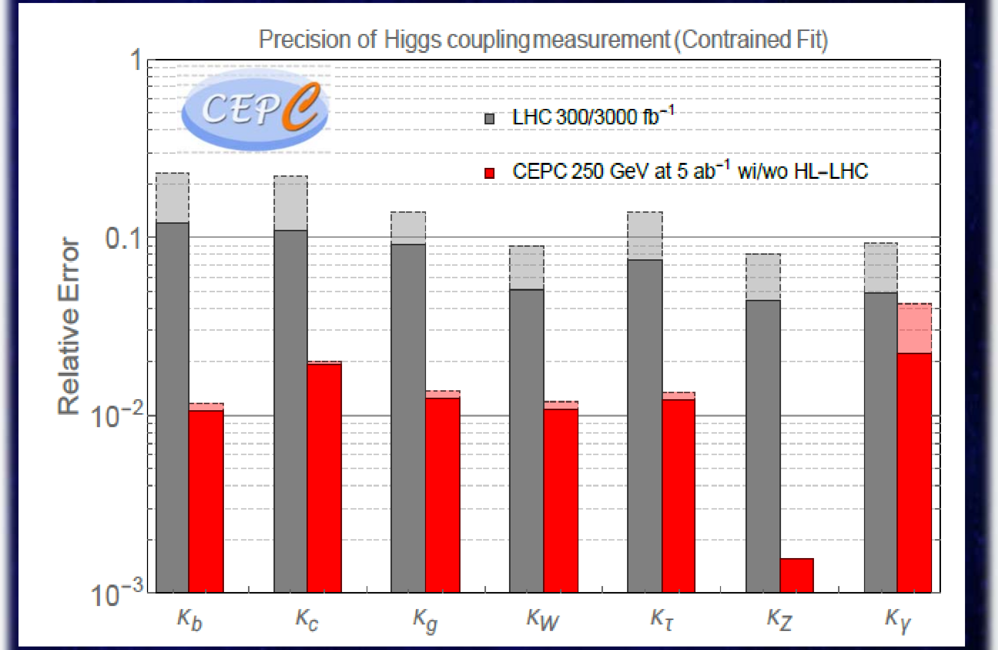
3rd generation only
(qualitative precision level)
→
3rd AND 2nd generations accessible

Normalized Higgs Couplings

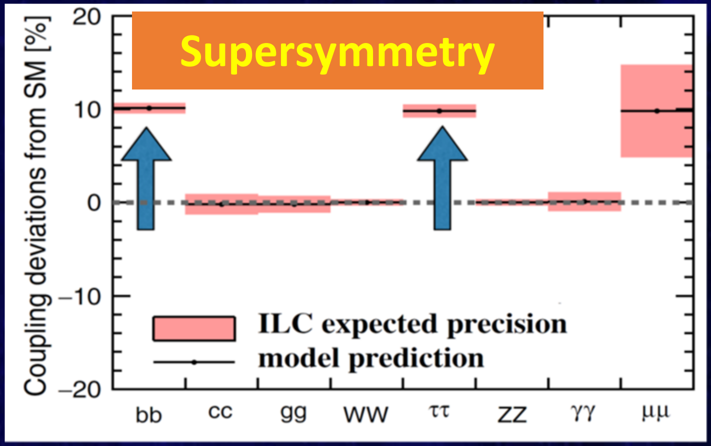
- **Higgs couplings normalized to the Standard Model predictions:**

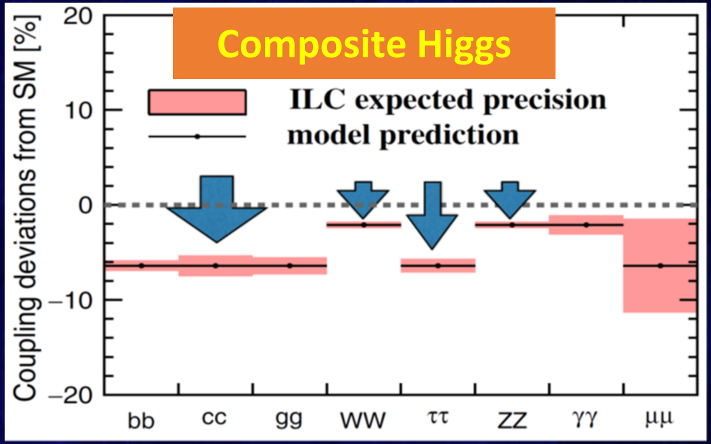
$$k_f = \frac{g_{Hff}}{g^{SM}_{Hff}}, \quad f = b, c, \tau$$

$$k_V = \frac{g_{HVV}}{g^{SM}_{HVV}}, \quad V = W, Z, \gamma, g$$



- **Fingerprinting NP:** different BSM models predict different pattern of deviations from the SM:

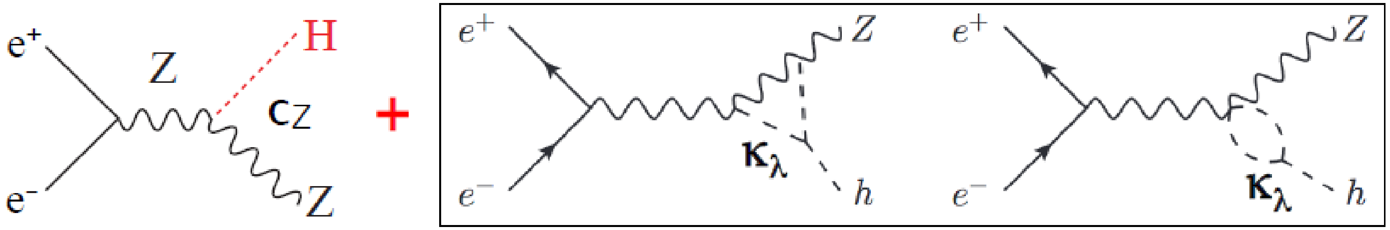




Phys Rev. D 97, 053003 (2018)

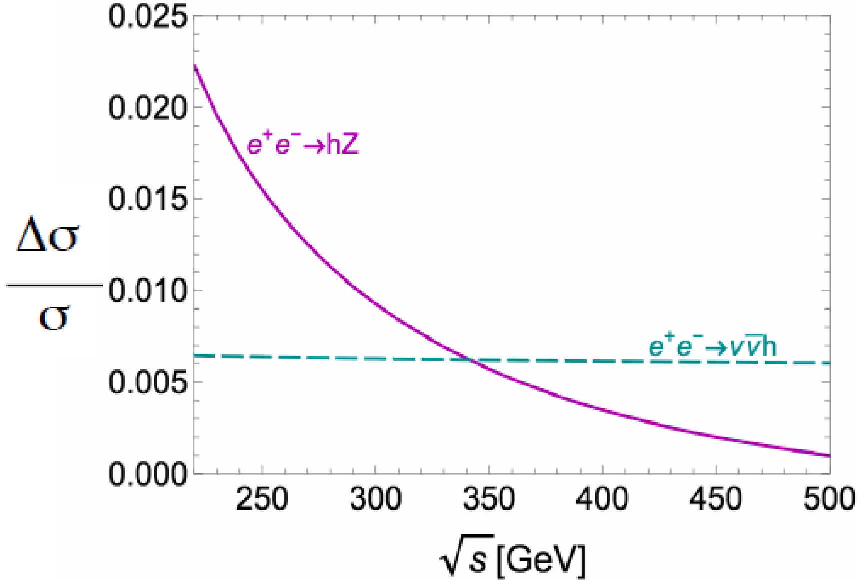
Measurements of the Higgs self-coupling

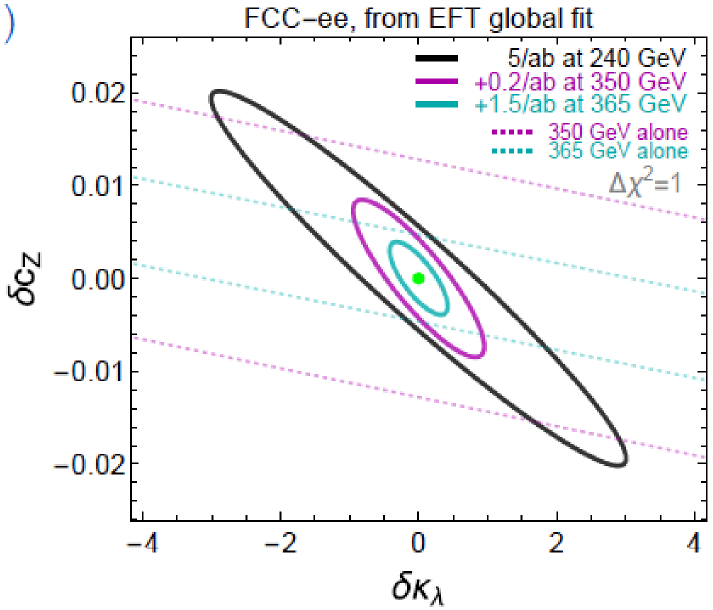
σ_{HZ}



M. McCullough
arXiv:1312.3322

- assuming all other couplings at MS, $\Delta\kappa_\lambda/\kappa_\lambda \sim 12\%$ (9% 4 I.P.)
- maximum sensitivity at the threshold production

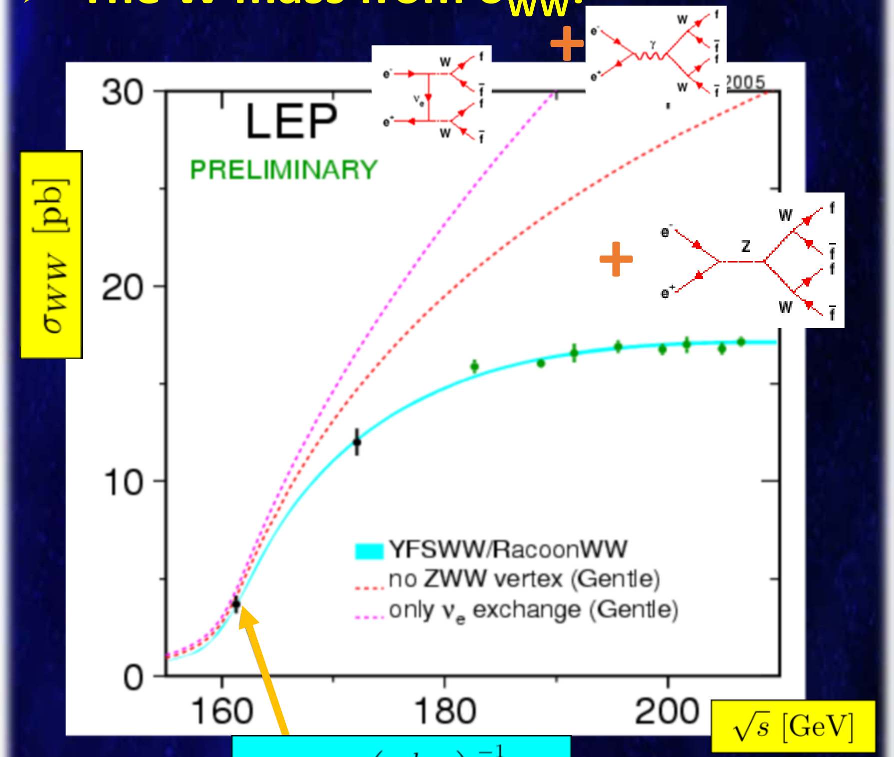




- from a global EFT fit $\Delta\kappa_\lambda/\kappa_\lambda \sim 25\%$ (4 IPs)
- changing CMS energy helps in reducing correlations

WW Threshold Scan: the W Mass and Width

➢ The W mass from σ_{WW}:

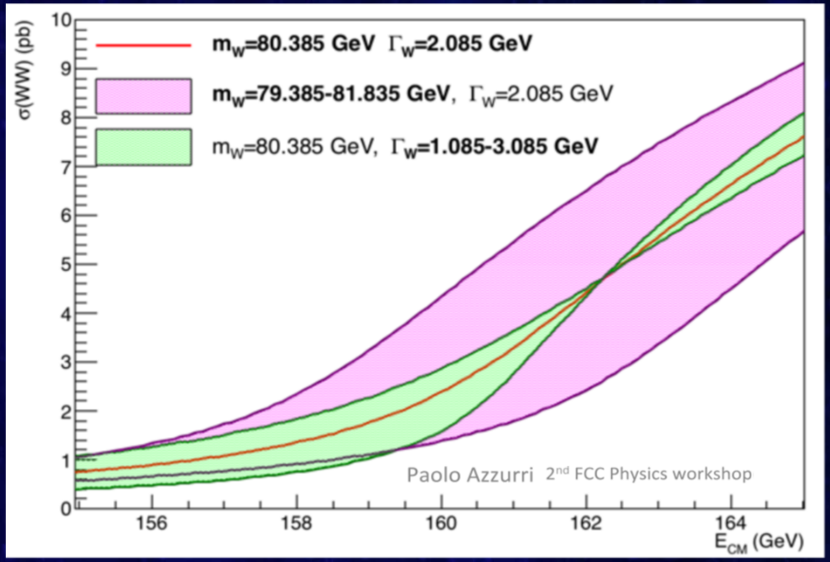


$$\Delta m_W = \left(\frac{d\sigma}{dm_W}\right)^{-1} \Delta\sigma$$

	LEP2 Stat./Prec.	FCC – ee stat (syst)
N_{WW}	4×10^4	3×10^7
M_W [MeV]	$80376 \pm 33 \pm 4$	$0.3\ (< \pm 1)$

$$\Delta m_W = 1\ \text{MeV}$$

➢ The W width from σ_{WW}:



- Measure σ_{WW} in two energy points E_1 and E_2, with the fractions of luminosity f and (1-f) ➔ evaluation of both m_W and Γ_W
- Choose the parameters E_1, E_2 and f in order to minimize the errors: $\Delta\Gamma_W$ an Δm_W:

$E_1 = 157.1\ \text{GeV}$ $E_1 = 162.3\ \text{GeV}$ $f = 0.4$

➡ $\Delta\Gamma_W = 1.5\ \text{MeV}$ $\Delta m_W^{\text{stat}} = 0.6\ \text{MeV}$

W Physics: Branching Ratios, TGCs…

➢ WW samples (FCC-ee)

$\sqrt{s}$ [GeV]	161	240	350
$N_{WW}[\times 10^6]$	30	80	15

➢ W Branching ratios (%)

LEP2

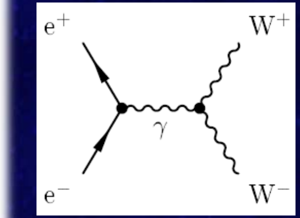
$\mathrm{BR}(W \to e\nu)$	10.65 ± 0.17
$\mathrm{BR}(W \to \mu\nu)$	10.59 ± 0.15
$\mathrm{BR}(W \to \tau\nu)$	11.44 ± 0.22
$\mathrm{BR}(W \to l\nu)$	10.84 ± 0.09
$\mathrm{BR}(W \to \text{hadrons})$	67.48 ± 0.28

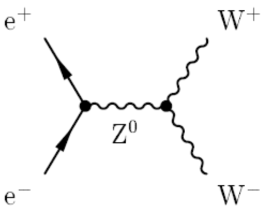
- Lepton universality tested at 2% level (2.7σ discrepancy between τand μ/e)
- Quark-lepton universality tested at 0.6%

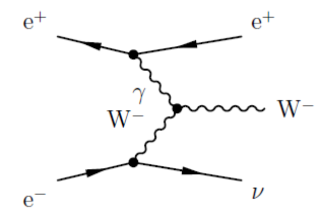
FCC-ee

•Lepton universality test at 0.04% level
•Quark-lepton universality test at 0.01%
•Flavour tagging → V_{cs} V_{cb}…

➢ Triple Gauge Couplings







- Selected LEP limits (95% C.L.)

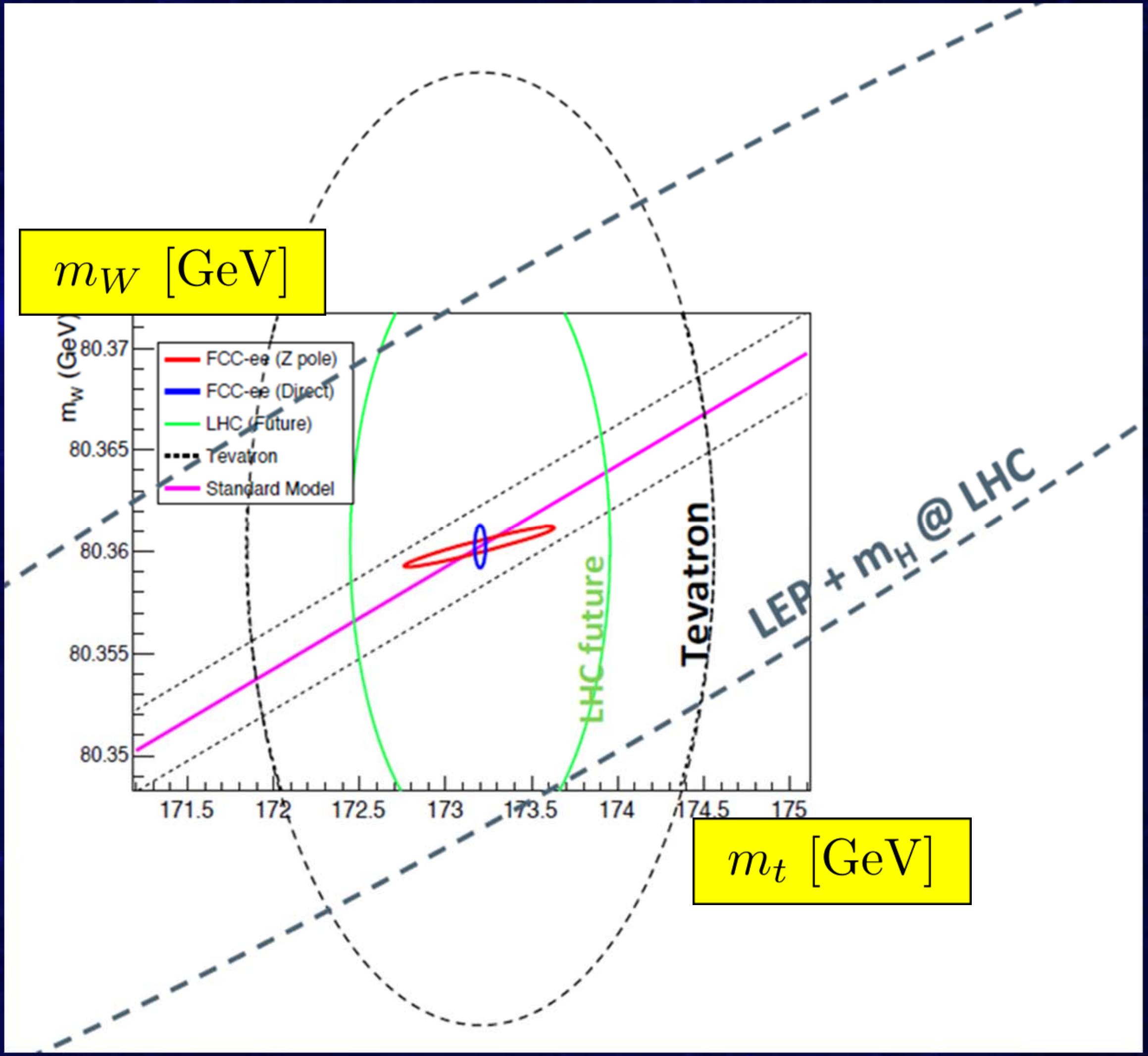
Δk_γ	$[-9.9, 6.6] \times 10^{-2}$
λ_γ	$[-5.9, 1.7] \times 10^{-2}$
Δk_Z	$[-7.4, 5.1] \times 10^{-2}$
λ_z	$[-5.9, 1.7] \times 10^{-2}$
Δg_1^Z	$[-5.4, 2.1] \times 10^{-2}$

- FCC-ee: overall improvements by a factor of 50 to compare with LEP

➢ The strong coupling constant:

- FCC-ee: $\Delta_{\mathrm{rel}}\alpha_S(m_W^2) = 3 \times 10^{-3}$
  from hadronic W decays (Γ_W and $\mathrm{BR}_{W,\mathrm{had}}$)
- LEP2 precision: 37%

m_W vs m_t


m_W [GeV]
m_W (GeV)
80.37
80.365
80.36
80.355
80.35
FCC-ee (Z pole)
FCC-ee (Direct)
LHC (Future)
Tevatron
Standard Model
LHC future
Tevatron
LEP + m_H @ LHC
171.5
172
172.5
173
173.5
174
174.5
175
m_t [GeV]

Electroweak Physics at the Z pole

LEP $N_Z = 1.7 \times 10^7$ → **FCC-ee** $N_Z \sim 5 \times 10^{12}$ → **Extreme precision of EW observables**

➢ Z mass and width (from Z pole scan):

The crucial factor: continuous E_{CM} calibration (resonant depolarization)

$$\Delta E_{\rm CM} \approx (10\ ({\rm stat}) + 100\ ({\rm syst}))\ {\rm keV}$$

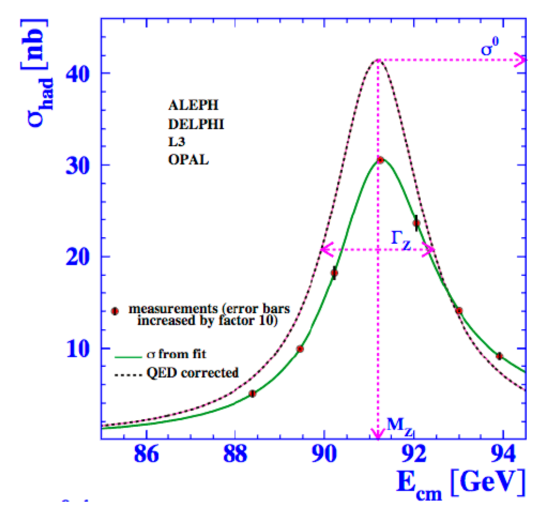
	Δ_{rel} (LEP)	Improvement factor
Z mass	1×10^{-6}	20
Z width	5×10^{-5}	20

$(\sim 300\ ({\rm stat}) \oplus\ \sim 10\ ({\rm syst}))$

→

$2.1\ {\rm MeV} \rightarrow 100\ {\rm keV}$

$2.3\ {\rm MeV} \rightarrow 100\ {\rm keV}$



➢ Normalized partial widths:

$$R_l = \frac{\Gamma_{\rm had}}{\Gamma_{l\bar{l}}},\ l = e, \mu, \tau$$

$$R_q = \frac{\Gamma_{q\bar{q}}}{\Gamma_{\rm had}},\ q = b, c$$

$$\Gamma_{f\bar{f}} \propto (g_V^f)^2 + (g_A^f)^2$$

$$f = l,\ q$$

	PDG (LEP) value	PDG (LEP) rel. precision	FCC – ee Improvement factor
R_e	20.804 ± 0.050	2.4×10^{-3}	20
R_μ	20.785 ± 0.033	1.6×10^{-3}	20
R_τ	20.764 ± 0.045	2.2×10^{-3}	20
R_b	0.21629 ± 0.00066	3.1×10^{-3}	10
R_c	0.1721 ± 0.0030	1.7×10^{-2}	10

necessary input for a precise measurement of EW couplings (next slide)

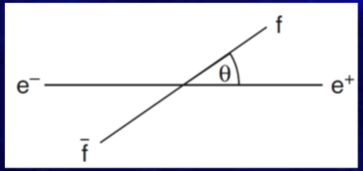
and $\alpha_S(m_Z^2)$ (from hadronic Z decays). FCC-ee precision: $\Delta_{\rm rel}\alpha_S(m_Z^2) = 2 \times 10^{-3}$ LEP: 2.5%

Electroweak Physics at the Z pole

- **Z asymmetries:**

$$\frac{d\sigma_{f\bar{f}}}{d\cos\theta} = \frac{3}{8}\sigma_{f\bar{f}}^{tot}\left[(1-\mathcal{P}_e\mathcal{A}_e)(1+\cos^2\theta)+2(\mathcal{A}_e-\mathcal{P}_e)\mathcal{A}_f\cos\theta\right]$$

$\mathcal{P}_e$ - polarization of the initial state e$^-$



The forward-backward asymmetry: $A_{FB}^f = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B} = \frac{3}{4}\mathcal{A}_e\mathcal{A}_f$

The left-right asymmetry: $A_{LR}^f = \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R} = \mathcal{A}_e$

$$\mathcal{A}_f = \frac{2g_V^f g_A^f}{(g_V^f)^2 + (g_A^f)^2}$$

LEP & SLC: longstanding discrepancies between different asymmetry measurements; uncertainties dominated by statistics

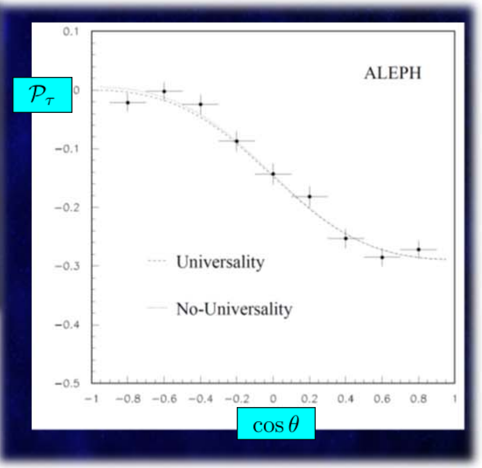
tau lepton case:
the final state helicity can be measured

$$\mathcal{P}_\tau(\cos\theta) = \frac{d(\sigma_r - \sigma_l)}{d\cos\theta}\cdot\left(\frac{d(\sigma_r + \sigma_l)}{d\cos\theta}\right)^{-1}$$

$$\mathcal{P}_\tau(\cos\theta) = \frac{\mathcal{A}_\tau(1+\cos^2\theta)+2\mathcal{A}_e\cos\theta}{(1+\cos^2\theta)+\mathcal{A}_e\mathcal{A}_\tau\cos\theta}$$

$$A_{FB}^\tau = \frac{(\sigma_r-\sigma_l)_F - (\sigma_r-\sigma_l)_B}{(\sigma_r+\sigma_l)_F + (\sigma_r+\sigma_l)_B}$$

Experimentally accessible observables: $\langle\mathcal{P}_\tau\rangle = -\mathcal{A}_\tau$ $A_{FB}^\tau = -\frac{3}{4}\mathcal{A}_e$



$\mathcal{A}_f$ measured (f = e, μ, τ, b, c) → $g_V^f\ g_A^f$ extracted → $\sin^2\theta_{W,\text{eff}}^f = \frac{1}{4}\left(1 - \frac{g_V^f}{g_A^f}\right)$

	Δ_{rel}^{stat} (FCC – ee)	Δ_{rel}^{syst} (FCC – ee)	Improvement factor w.r.t. LEP
$\mathcal{A}_e$	5.0×10^{-5}	1.0×10^{-4}	50
$\mathcal{A}_\mu$	2.5×10^{-5}	1.5×10^{-4}	30
$\mathcal{A}_\tau$	4.0×10^{-5}	3.0×10^{-4}	15
$\mathcal{A}_b$	2.0×10^{-4}	3.0×10^{-3}	5
$\mathcal{A}_c$	3.0×10^{-4}	8.0×10^{-3}	4

Systematic uncertainties dominate

→ **Precision on vector and axial couplings from R_f and A_f :**

Improvement w.r.t. LEP: 10-100

fermion	Δg_V	Δg_A
e	2.5×10^{-4}	1.5×10^{-4}
μ	2.0×10^{-4}	2.5×10^{-5}
τ	3.5×10^{-4}	0.5×10^{-4}
b	1.0×10^{-2}	1.5×10^{-3}
c	1.0×10^{-2}	2.0×10^{-3}

Electroweak Physics at the Z pole

$\sin^2\theta_{\mathrm{W,eff}}$ (absolute) uncertainties:

	stat	syst	Improvement w.r.t. LEP
from muon FB	10^{-7}	5.0×10^{-6}	100
from tau pol	10^{-7}	6.6×10^{-6}	75

- **Measurement of $\alpha_{QED}(m_Z^2)$ - better precision necessary for future precision SM tests !**
  - **Current uncertainty:** $\Delta\alpha_{\mathrm{QED}}(m_Z^2) = 10^{-4}$ from running coupling constant formula: $\alpha_{\mathrm{QED}}(m_Z^2) = \frac{\alpha_{\mathrm{QED}}(0)}{1 - \Delta\alpha_l(m_Z^2) - \Delta\alpha^{(5)}_{\mathrm{had}}(m_Z^2)}$

    dominated by the experimental determination of the hadronic vacuum polarization, obtained from dispersion integral with expt. input from low energies (KLOE, Belle, BaBar, CLEO, BES CMD-2…)

- **Alternative: the direct measurement of $\alpha_{QED}(m_Z^2)$ from the muon FB asymmetry just below and just above the Z pole (as part of Z resonance scan) – no need of extrapolation from $\alpha_{\mathrm{QED}}(0)$**
  - **The $A_{FB}^{\mu\mu}$ - self normalized quantity** $A^{\mu\mu}_{FB} = \frac{\sigma^F_{\mu\mu} - \sigma^B_{\mu\mu}}{\sigma^F_{\mu\mu} + \sigma^B_{\mu\mu}}$

    (no need for measurement of L_{int};
    most uncertainties (sel. efficiency, det. accceptance) cancel in the ratio

$$\frac{\Delta\alpha_{\mathrm{QED}}}{\alpha_{\mathrm{QED}}} \simeq \frac{\Delta A^{\mu\mu}_{\mathrm{FB}}}{A^{\mu\mu}_{\mathrm{FB}}} \times \frac{\mathcal{Z}+\mathcal{G}}{\mathcal{Z}-\mathcal{G}}$$

2x 6 months of FCC-ee running:

$\mathcal{Z}(\mathcal{G})$ - Z(photon)–exchange terms

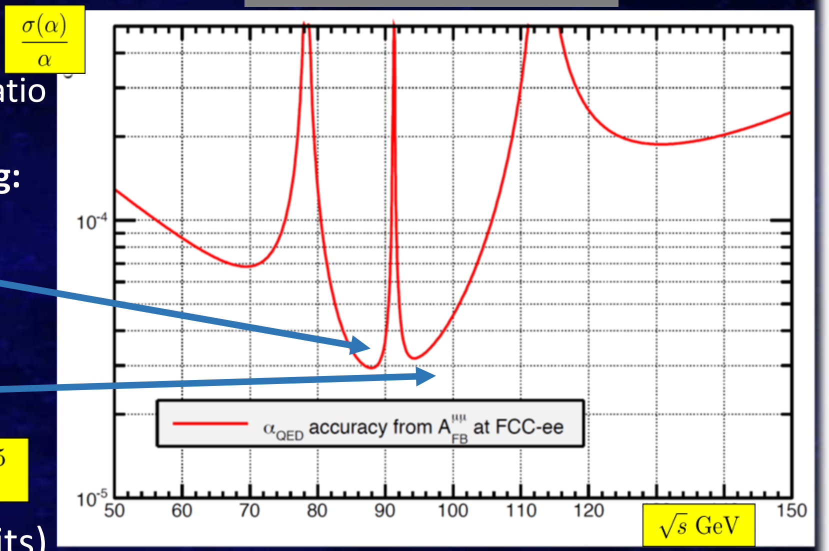
Optimal CMS energies: $\sqrt{s_-} = 87.9\ \mathrm{GeV}$ $\sqrt{s_+} = 94.3\ \mathrm{GeV}$

$$\frac{1}{\alpha_{\mathrm{QED}}(m_Z^2)} = \frac{1}{\alpha_\pm} + \beta_{\mathrm{QED}} \log\frac{s_\pm}{m_Z^2}$$

$\Delta\alpha_{\mathrm{QED}}(m_Z^2) = 3 \times 10^{-5}$

(adequate for future precision EW fits)

P.Janot JHEP 02 (2016 053



The Z Invisible Width – Number of Light Neutrino Species

1) N_ν determined at LEP1 from the Z line-shape scan:

$$\boxed{N_\nu = 2.991 \pm 0.007}$$

$$N_\nu \cdot \Gamma_\nu = \Gamma_Z - \Gamma_h - 3\Gamma_l$$

$$N_\nu = \left(\frac{\Gamma_l}{\Gamma_\nu}\right)_{\mathrm{SM}} \cdot \left(\sqrt{\frac{12\pi R_l}{M_Z^2 \sigma_{\mathrm{had}}^{\mathrm{peak},0}}} - R_l - 3\right)$$

theory

all measured at the peak

Only small room for improvements:
precision limited mainly by the theoretical uncertainty on luminosity determination
i.e. on small angle Bhabha cross section
(LEP1: ΔL/L = 0.00061, $\Delta N_\nu^{\mathrm{lumi}}$ = 0.0046 ➔ $\Delta N_\nu^{\mathrm{lumi}}$ = 0.0001 @FCC-ee).

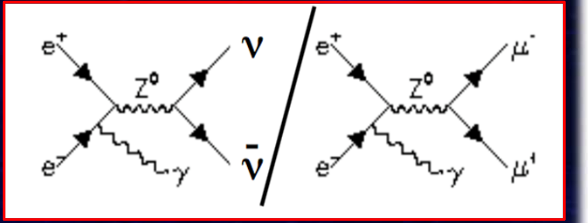
$$\Delta N_\nu^{\mathrm{FCC-ee}} = 0.00008(\mathrm{stat}) \pm 0.0001(\mathrm{syst})$$

2) N_ν from the radiative return process $e^+e^- \to Z\gamma,\quad Z \to \nu\bar{\nu}$

from the higher masses than the Z resonance

Monophoton events (normalized to photon-lepton-lepton events):

$$N_\nu = \left(\frac{e^+e^- \to \gamma Z_{\mathrm{inv}}}{e^+e^- \to \gamma Z_{\mathrm{lept}}}\right)^{\mathrm{meas}} \Big/ \left(\frac{\Gamma_{\nu\bar{\nu}}}{\Gamma_{\mathrm{lept}}}\right)^{\mathrm{SM}}$$



- LEP1: $N_\nu = 2.92 \pm 0.05$ (statistics too scarce).

- Photon selection common for both final states ➔ cancellations of systematics.
- N_ν can be measured vs sqrt(s) ➔ sensitivity to NP at high energy scales.
- FCC-ee sensitivity:

$\sqrt{s}$ [GeV]	years of running	ΔN_ν (stat)
161	1	0.0011
240 & 340	5	0.0008
125	1	0.0004

$3 \times 10^7 \gamma Z(\mathrm{inv})$ ev.

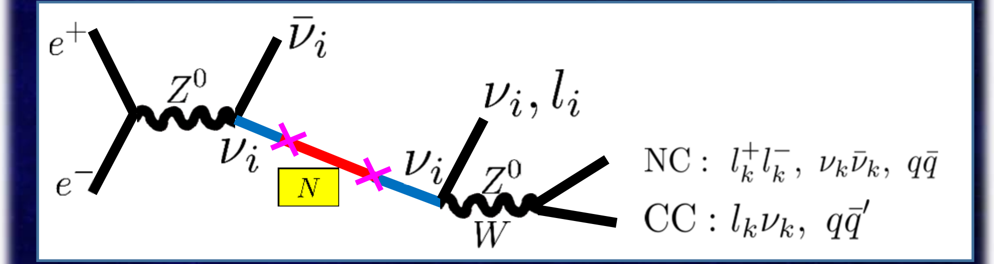
(running parasitically)

$$\Delta N_\nu \leq 4 \times 10^{-4}$$

Heavy Neutral Leptons (HNL) Searches

- Sterile, right-handed neutrinos (N) are common in extensions of the SM; they couple to Higss and SM ν
- Substantial part of them are HNLs: very massive and characterised by macroscopic decay length

- The HNL production and decay at the $\sqrt{s} = M_Z$

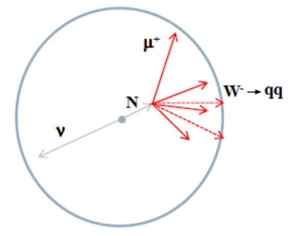


$\nu_L = \nu \cos\theta + N \sin\theta$ $\theta \approx m_\nu / m_N$

- Experimental signatures

NC: 2 leptons/jets + E_{miss}

CC: 2 jets + lepton/E_{miss}



Search for (highly) displaced vertices;

very clean events

- FCC-ee sensitivity

to HNLs up to 10^{-11}

A.Blondel et al., arXiv: 1411.5230 [hep-ex]

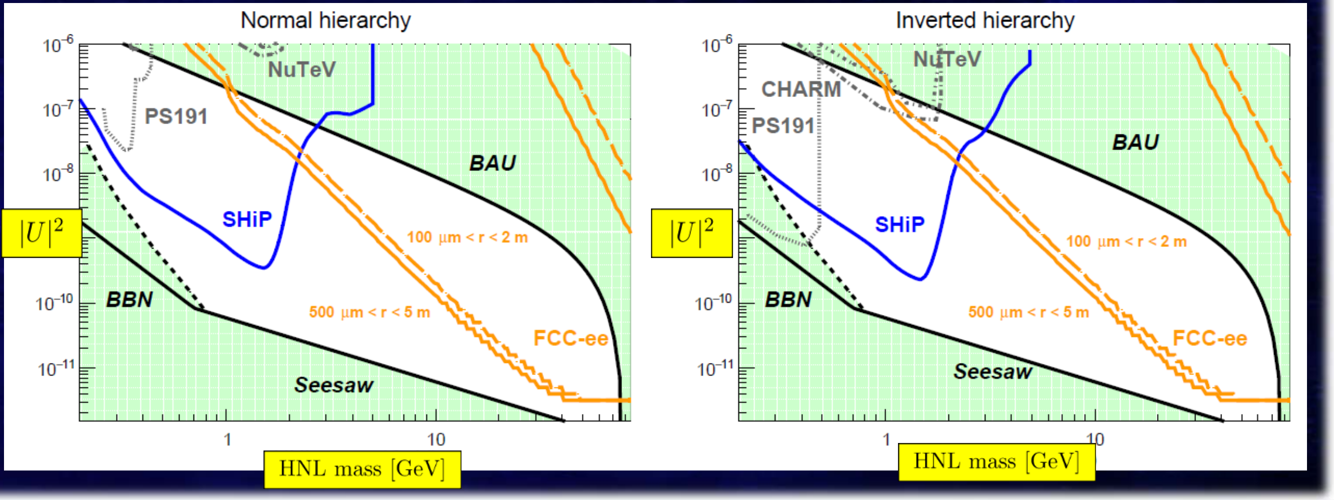
- Complementary to

beam dump facilities

- The upper limits of LEP

searches: 10^{-4}

$|U|^2 = |U_e|^2 + |U_\mu|^2 + |U_\tau|^2 \; (N - \nu \text{ couplings})$ $|U|^2 \propto \theta^2$



Flavour Physics

➢ The sheer power of statistics:

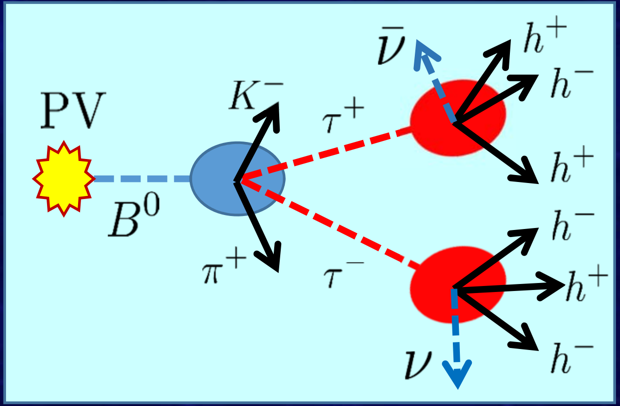
Particles	B^0/B^+	B^0_s	Λ_b	B_c	$Z \to \tau^+\tau^-$
Yields (FCC-ee 150 ab^{-1})	10^{12}	$2.5\ 10^{11}$	$2.5\ 10^{11}$	$2.5\ 10^{9}$	$5.\ 10^{11}$
Yields (Belle II 50 ab^{-1})	10^{11}	10^{7-8}	–	–	$5.\ 10^{10}$

LEP : $\sim 6 \times 10^6$

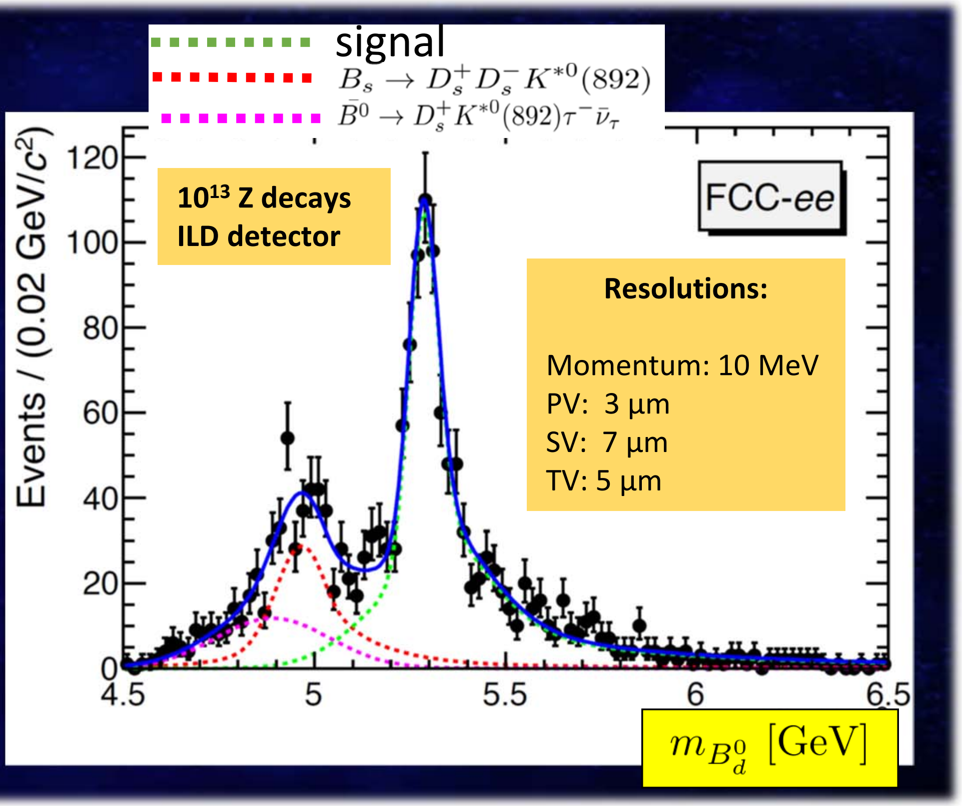
S.Monteil 2nd FCC Physics workshop

➢ Example: B→K*(892)$\tau^+\tau^-$ decay

- Excellent vtx reconstruction (τ → 3 prongs)



- FCC-ee: 1000 signal events expected, Belle2: 10 events expected
- The amplitude analysis feasible



10^{13} Z decays
ILD detector

Resolutions:

Momentum: 10 MeV
PV: 3 μm
SV: 7 μm
TV: 5 μm