Physics at FCC-ee

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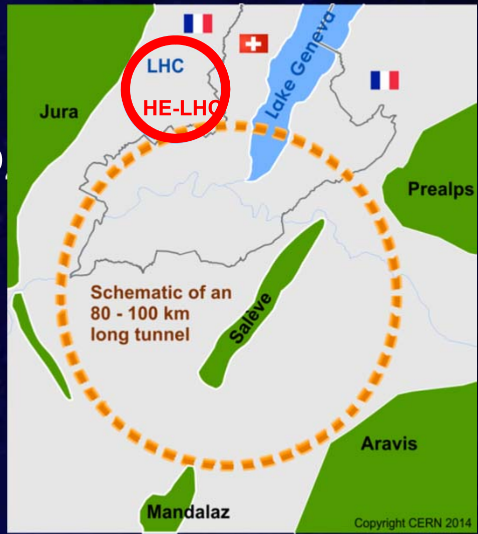
Outline

1. The Future Circular Collider Study
2. FCC-ee Electroweak Studies at the Z Pole, ZH, W+W- and ttbar 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:

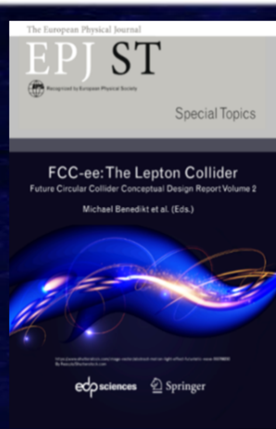
- ✓ **e^--e^+ collider:** FCC-ee – potential first step, preceding the FCC-pp
- ✓ **p-p collider:** FCC-hh – flagship, 100 TeV p-p, 16T Nb_3Sn magnets
- ✓ **e-p collider:** FCC-he – additional option of e-p collisions; e^- from ERL

- **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/

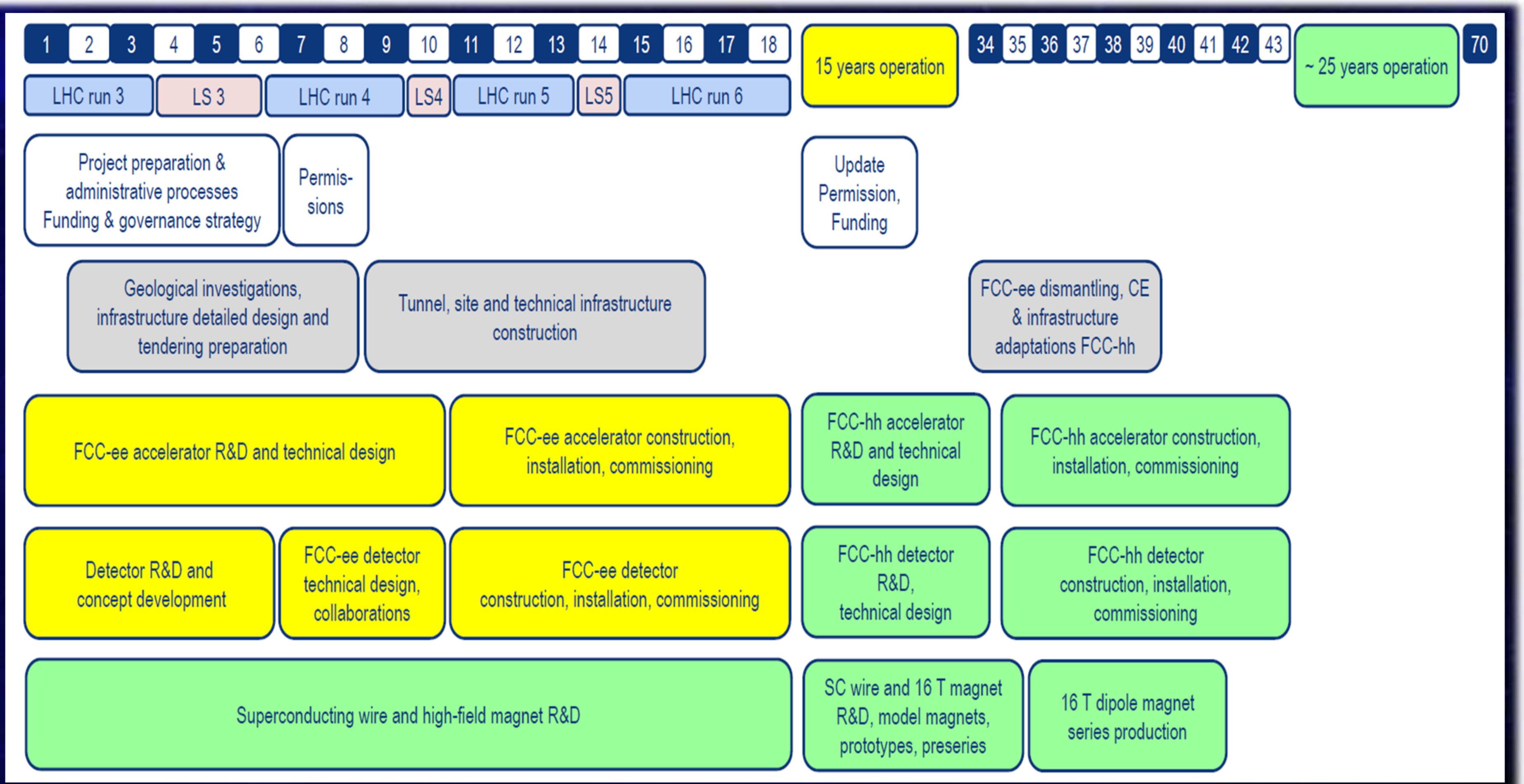


The FCC-ee European Particle Physics Strategy Update (EPPSU) document: https://cds.cern.ch/record/2653669

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

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



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

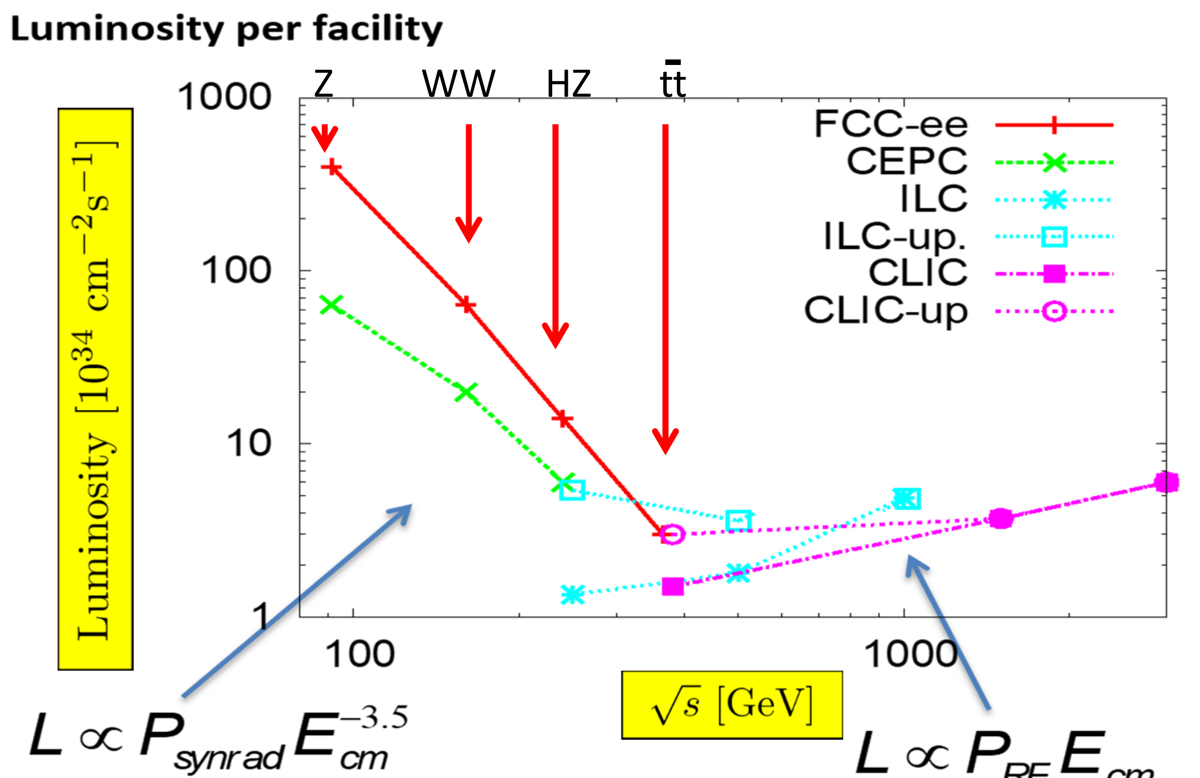
- two rings (separate for e^+ and e^-); two interaction points (3 & 4 IPs under study), flat beams with very strong focusing ($\beta^*_y \approx 1$mm); top-up injection, crab waist crossing optics, non-zero (30 mrad) crossing angle; P_{SR} = 50 MW four working points:

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} $t\bar{t}$ / 5yrs	

LEP1 : 2.1×10^{31} cm^{-2}s^{-1}

LEP2 : 3.6×10^{31} cm^{-2}s^{-1}

FCC-ee Collider Parameters



C.Biscari ESSP, Granada, May 2019

Event statistics :

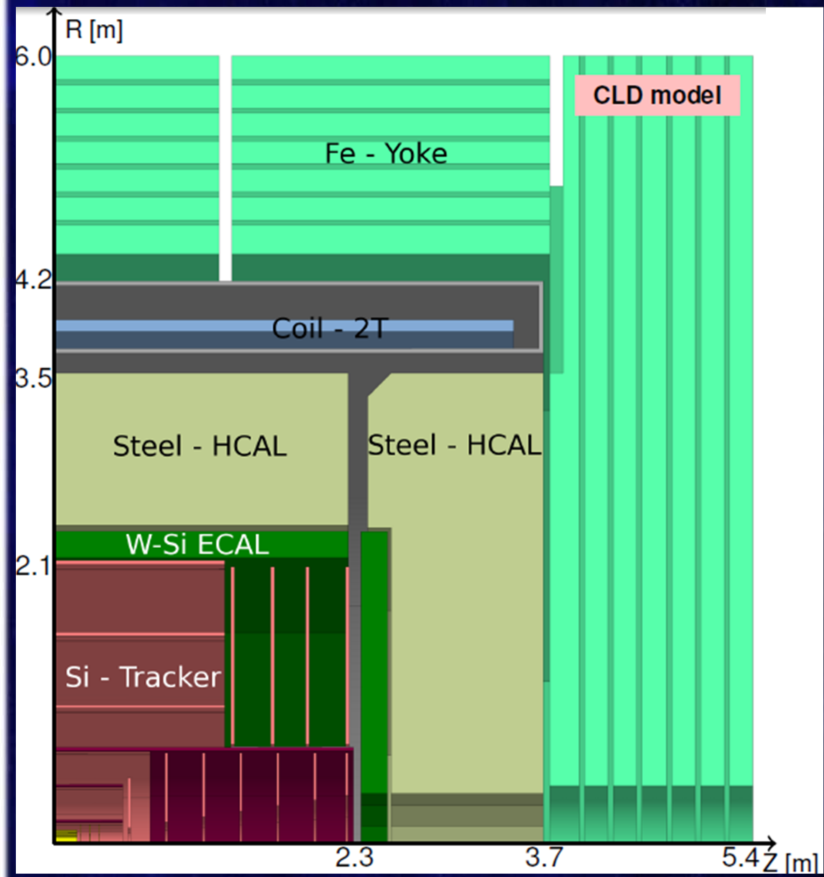
E_{CM} errors:

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- → $t\bar{t}$**	**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
- $\delta p_T \approx 4 \times 10^{-5}$ GeV^{-1} (for muons p=100 GeV)
- $\Delta E/E = (3\text{-}5)\%$ (barrel region)
- Efficiency for electrons and gammas > 95%



FCC-ee Detectors: IDEA

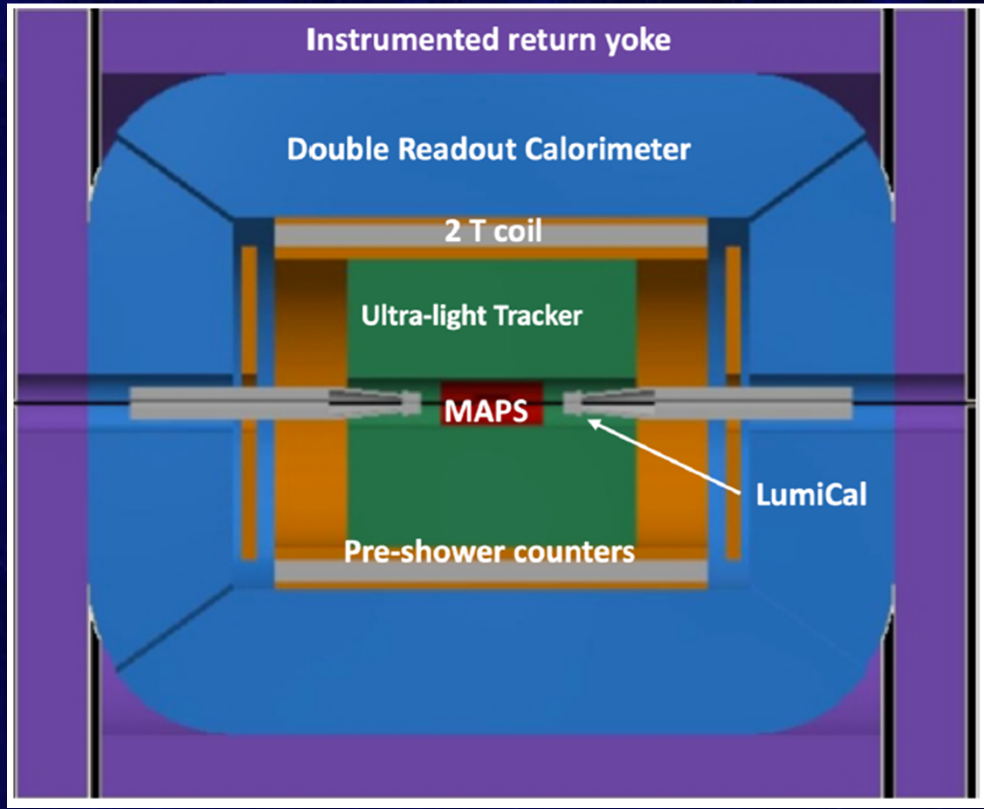
IDEA – new, innovative, possibly more cost-effective design

- **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)

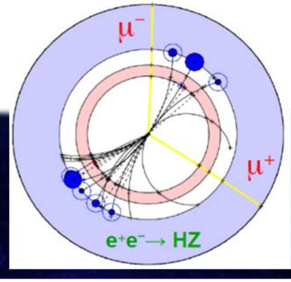
- **Dual-readout calorimeter**
  (scintillating fibers sensitive to all charged particles, clear fibers sensitive only to Cherenkov light; $\frac{\sigma}{E} = \frac{11\%}{\sqrt{E}} + 1\%$)

- **Thin and light solenoid coil inside calorimetric system**
  (2T, stored energy 170 MJ)



FCC-ee Higgs Physics

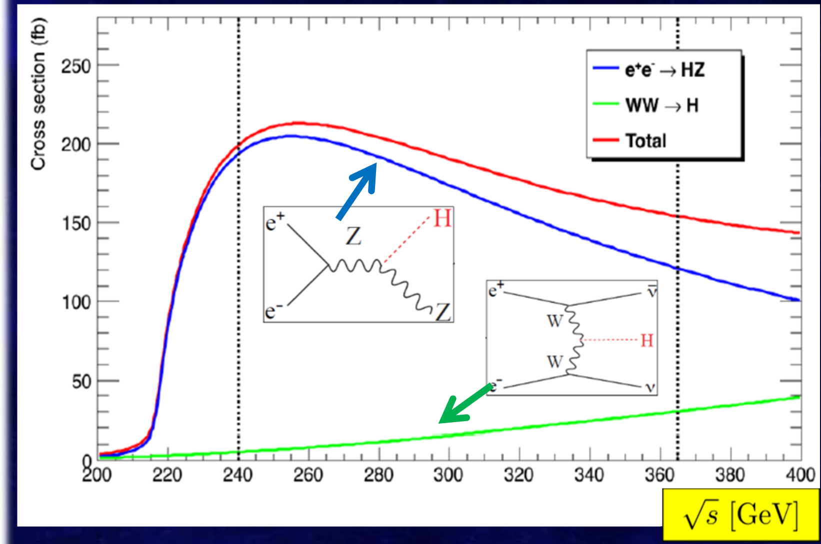
The ZH threshold never studied in e^+e^- | **FCC-ee** | $N_{ZH} \sim 10^6$

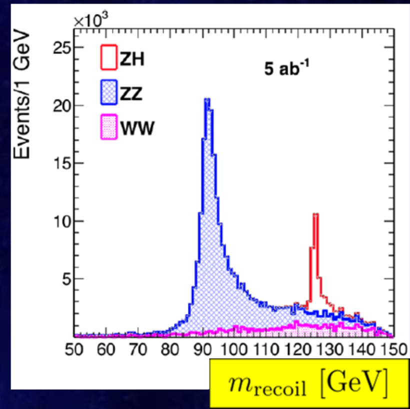


- ✓ The Higgs production measured inclusively from its presence as a recoil to the Z in the process $e^+e^- \rightarrow ZH$

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

- ✓ Absolute measurement of the g_{HZZ} ➔ Γ_H ➔
  ➔ other couplings g_{ZXX}
  (X = b, c, τ, μ, g, γ,…)





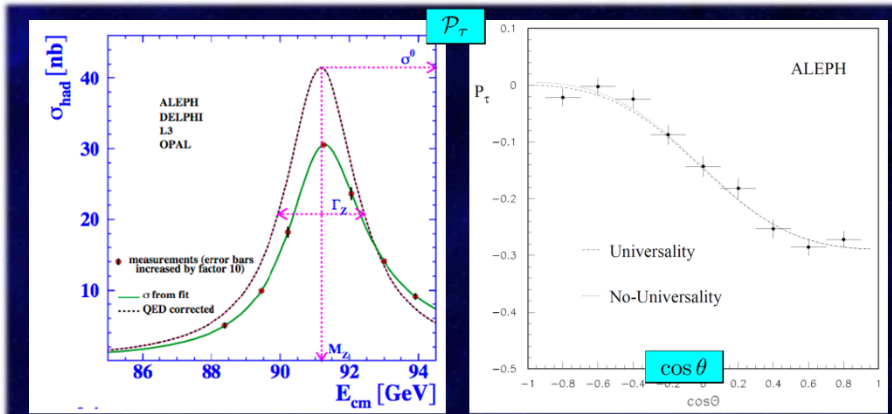
- ✓ The couplings of the 3rd and 2nd generation fermions accessible (most with sub-percent precision)
- ✓ This precision yields the New Physics (NP) sensitivity ~10 TeV
- ✓ A possible pattern of deviations can discriminate between different BSM models
- ✓ See the talks: *Higgs measurements at the FCC-ee* *(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
$\sin^2\theta_W^{\rm eff}$ [$\times 10^6$]	231480 ± 160	3	2 – 5	44 – 28
$1/\alpha_{\rm QED}(m_Z)$ [$\times 10^3$]	128952 ± 14	4	small	3.5
$A_{FB,0}^b$ [$\times 10^4$]	992 ± 16	0.02	1 – 3	16 – 5
$A_{FB}^{{\rm pol},\tau}$ [$\times 10^4$]	1498 ± 49	0.15	< 2	25

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

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

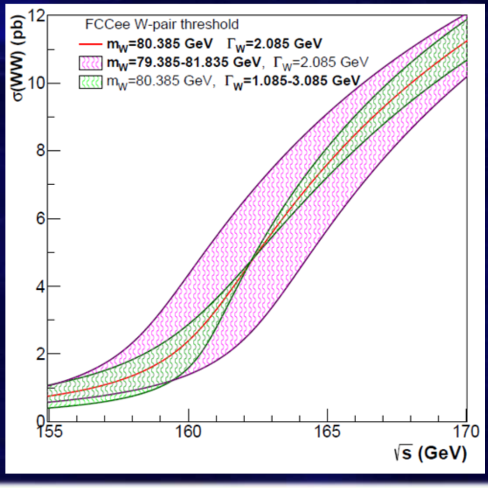
$$A_{FB}^f = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B} = \frac{3}{4}\mathcal{A}_e\mathcal{A}_f \qquad \sin^2\theta_W^{\rm eff} = \frac{1}{4}\left(1 - \frac{g_V^f}{g_A^f}\right)$$

- ✓ 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 $\alpha_{QED}(0)$)
- ✓ 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 $N_{WW} \sim 3 \times 10^7$

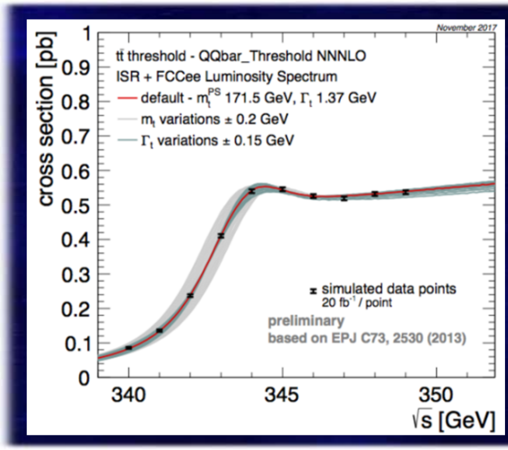


Observable	present value ±error	FCC – ee Stat.	FCC – ee Syst.	Improvement factor
m_W [MeV/c^2]	80379 ± 12	0.6	0.3	18
Γ_W [MeV]	2085 ± 42	1.5	0.3	27

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

The t-tbar threshold never studied in e^+e^-

FCC-ee $N_{t\bar{t}} \sim 10^6$

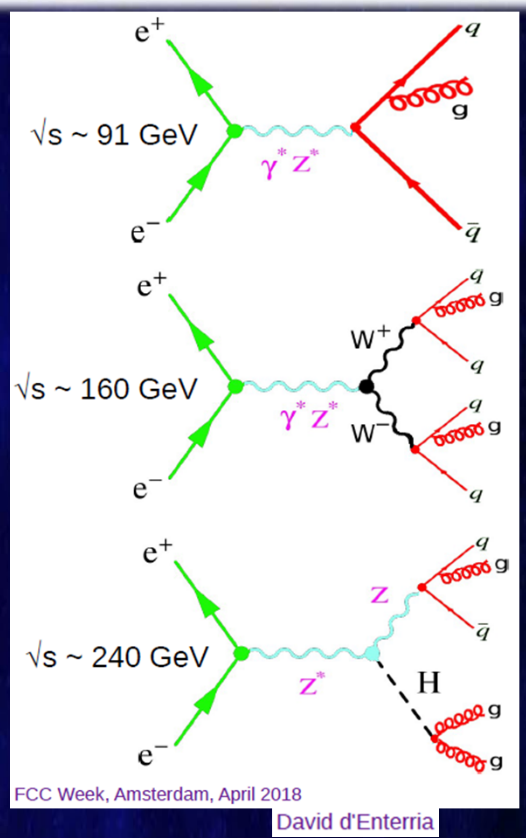


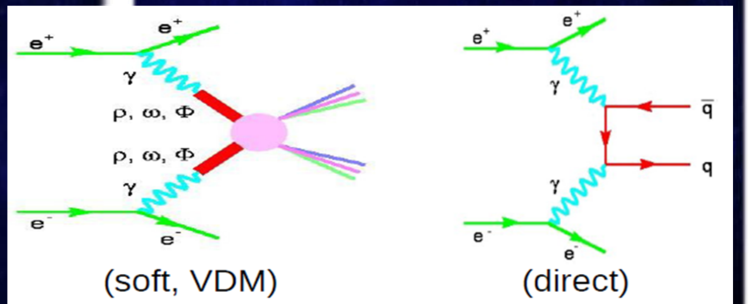
Observable	present value ±error	FCC – ee Stat.	FCC – ee Syst.	Improvement factor
m_t [MeV/c^2]	172900 ± 400	20	small	20
Γ_t [MeV]	1420 ± 190	40	small	5

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))
- ✓ …





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
  - q,g,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:

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

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

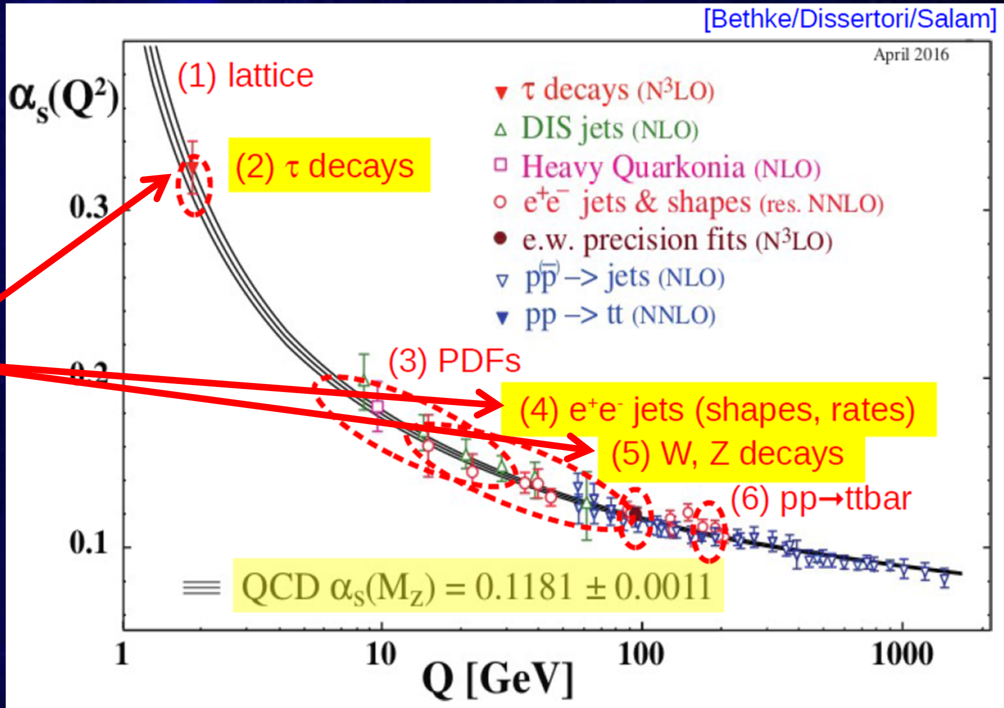
$$\Delta G \sim 10^{-5}$$

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

- ✓ huge statistics of hadronic τ, W and Z decays
- ✓ N³LO perturbative QCD calculations

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

- ✓ The α_S is determined by comparing now 6 groups of experimental observables to pQCD NNLO and N³LO predictions
- ✓ The global average is provided at the Z pole



The QCD Coupling Constant α_S at FCC-ee

✓ **τ decays:** The relevant quantity:

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

computable at N^3LO:

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

✓The current experimental value:

$$\mathbf{R}_{\tau,\mathbf{exp}} = \mathbf{3.4697} \pm \mathbf{0.0080} \quad (\pm \mathbf{0.23}\%)$$

✓The current determination of the α_S:

$$\alpha_\mathbf{S}(\mathbf{m_Z}) = \mathbf{0.1192} \pm \mathbf{0.0018} \quad (\pm \mathbf{1.5}\%)$$

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 $N^{2,3}LO+N^2LL$ 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 $N(Z \to \text{hadrons}) \sim 10^{12}$ & theoretical progress ➡ $\delta\alpha_\mathbf{S}(\mathbf{m_Z})/\alpha_\mathbf{S}(\mathbf{m_Z}) < \mathbf{1}\%$

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

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

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

- ✓ computable at N^3LO:

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

- ✓ The current α_S value:

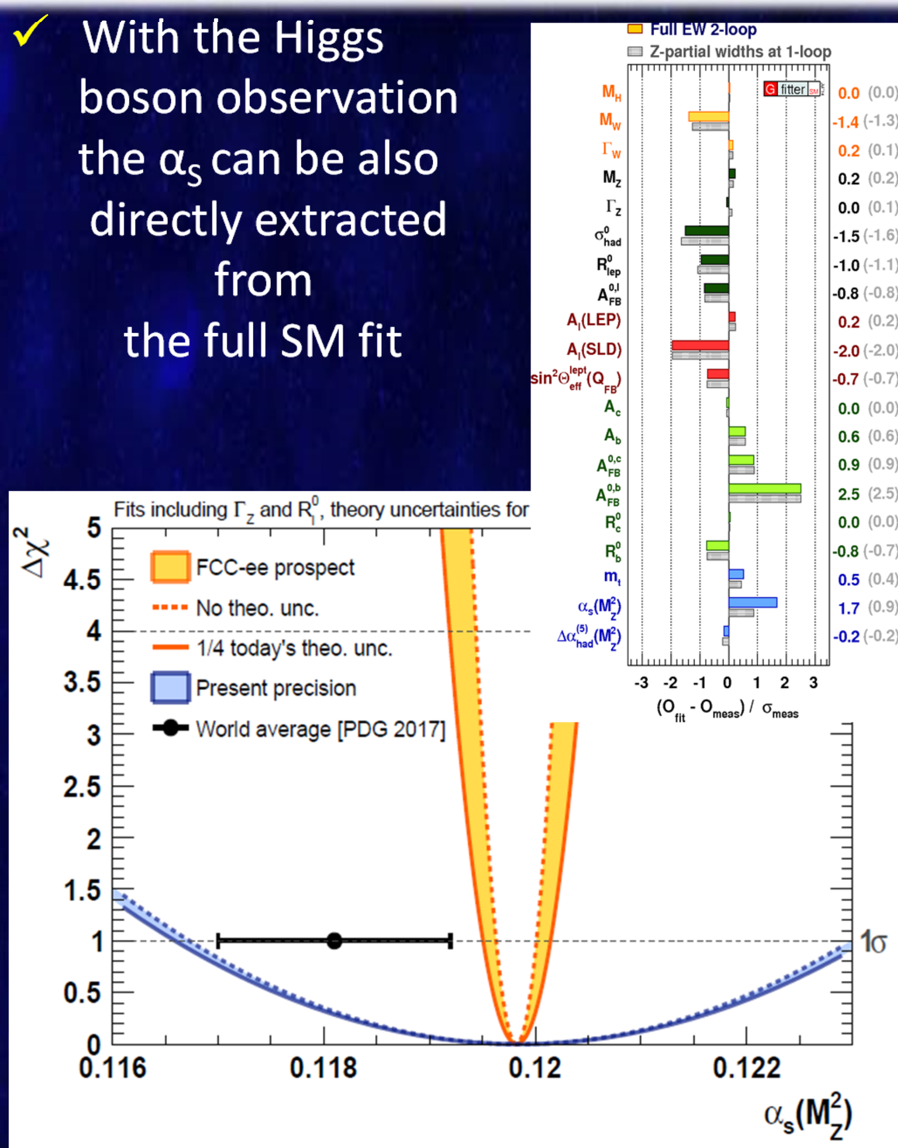
$$\alpha_{\rm S}(\rm m_Z) = 0.1196 \pm 0.0030 \quad (\pm 2.5\%)$$

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

and theoretical progress

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

- ✓ 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

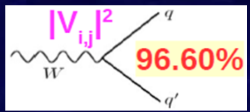
Hadronic W decays:

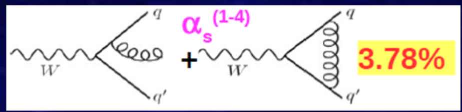
✓ The observable: ratio of hadronic to leptonic W decay widths $R_W = \frac{\Gamma^W_{\rm had}}{\Gamma^W_l}$

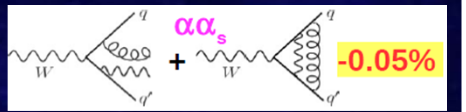
$$\Gamma_{W,\rm had} = \frac{\sqrt{2}}{4\pi} G_F m_W^3 \sum_{\rm quarks\ i,j} |V_{i,j}|^2 \left[1 + \sum_{k=1}^{4} \left(\frac{\alpha_S}{\pi}\right)^k + \delta_{\rm EW}(\alpha_{\rm QED}) + \delta_{\rm mixed}(\alpha_{\rm QED}\alpha_S) \right]$$

[EWK: -0.35%]

✓ computable at N^{2,3}LO:





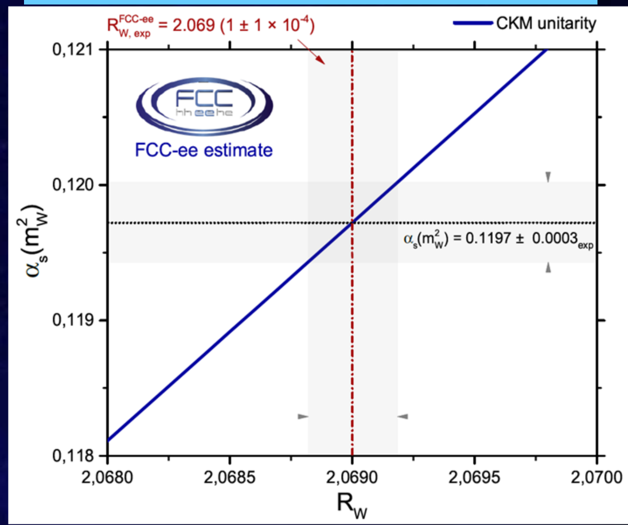


✓ The LEP α_S value: $\alpha_S(m_Z) = 0.117 \pm 0.040 \quad (\pm 35\%)$

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

and theoretical progress

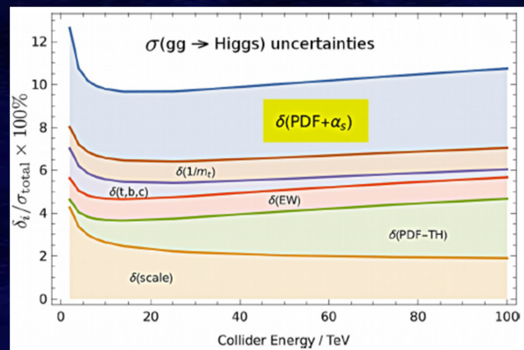
D.d'Enterria, M.Srebre, arXiV1603.06501



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: $y = \frac{k_T^2}{s}$

→ 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%**

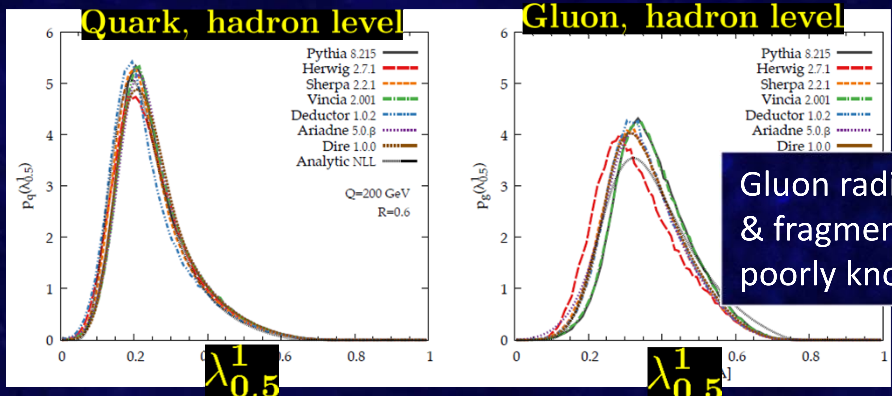
High Precision Studies of Perturbative Parton Radiation – Jet Substructure and Parton Flavour Studies

- ✓ **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 $\mathbf{Z} \to \mathrm{b\bar{b}q}$ (statistically limited)

- ✓ **FCC-ee: - 10^5 more Zs**
  - a unique sample of 10^4 $\mathrm{H} \to \mathrm{gg}$ 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:

$$\lambda_\beta^\kappa = \sum_{\mathrm{i} \in \mathrm{jet}} \mathrm{Z}_\mathrm{i}^\kappa \theta_\mathrm{i}^\beta$$

$\mathbf{Z_i}$ – the momentum fraction of particle i

$\mathbf{\Theta_i}$ – the angular fraction of particle i w.r.t. the jet radius

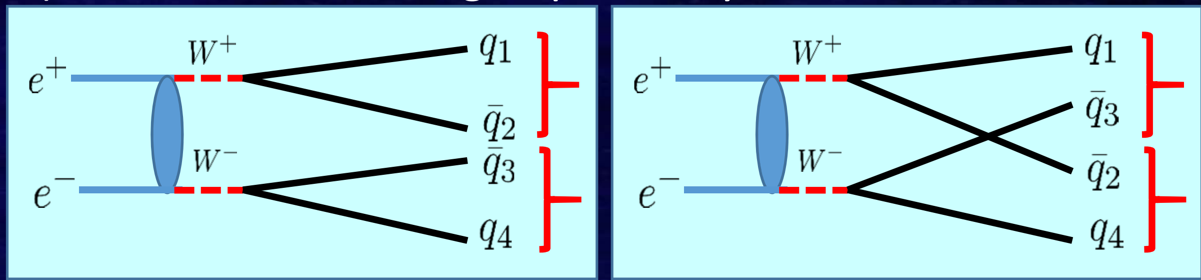
Significant variations between generators for gluon distributions

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

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



- ✓ FCC-ee: $\Delta m_W \sim 1\ \mathrm{MeV}$ (threshold scan) & the 3x10^3 gain in the number of WW pairs

- ✓ The shift in the reconstructed m(W) expected from different PYTHIA 8 CR models:

	E_{cm} (GeV)	$\langle\delta\overline{m}_W\rangle$ (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

High Precision Non-Perturbative QCD – Parton Hadronization

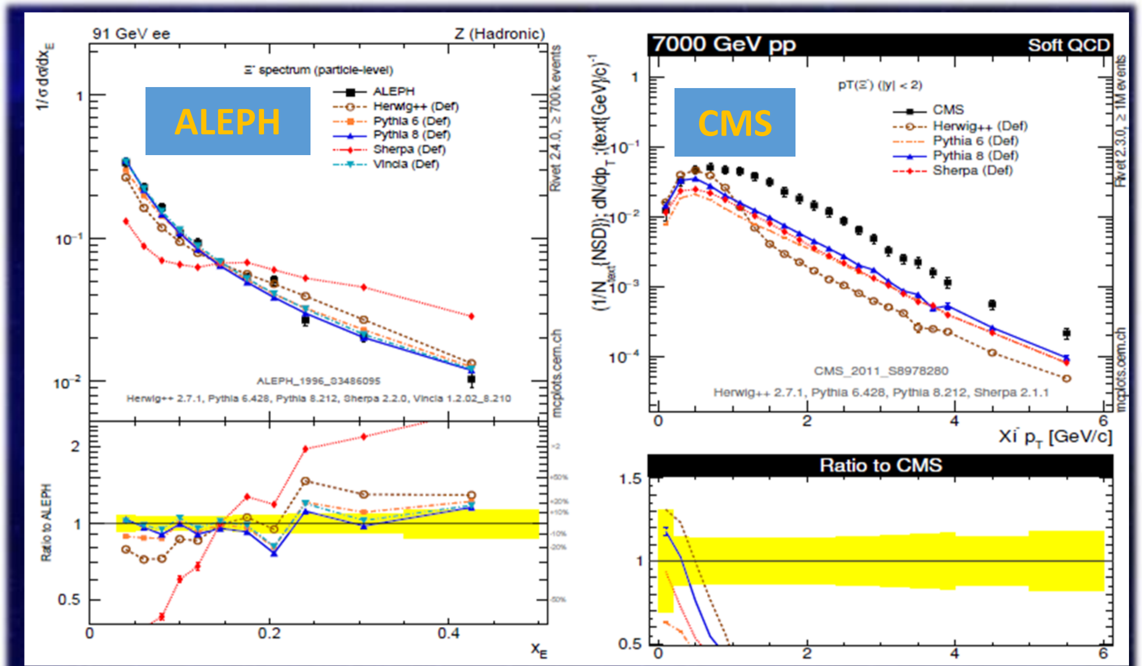
✓ **Parton Hadronization (PH) – phenomenological models – MC generators**

✓ **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

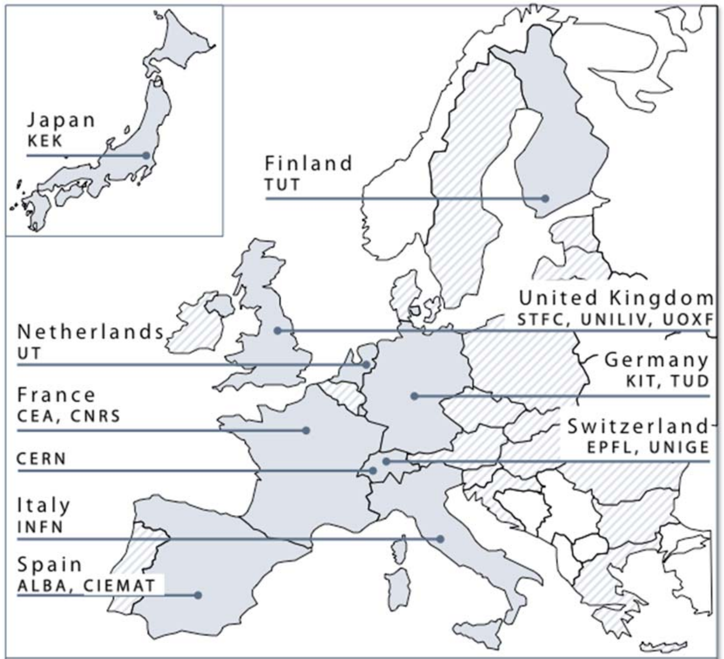
BACKUP

EU H2020 Design Study 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



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

cea

cnrs dépasser les frontières

CERN

UNIVERSITY OF OXFORD

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

EU H2020 Marie Curie ITN 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

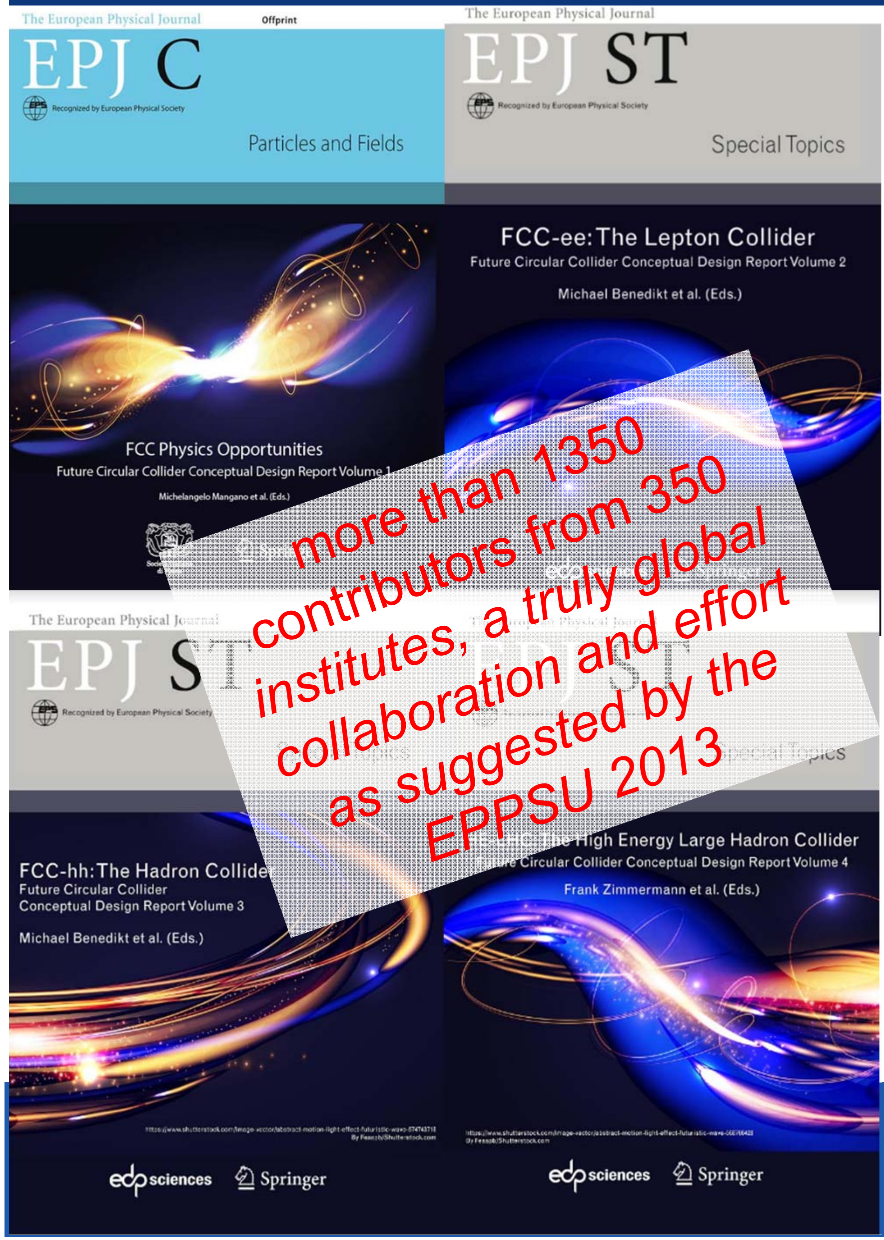
13 Beneficiaries

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, 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

Results of FCC Conceptual Design Study



Study Documentation:

4 CDR volumes submitted to EPJ in December 2018.

- FCC Physics Opportunities
- FCC-ee
- FCC-hh
- HE-LHC
- Preprints available since 15 January 2019 http://fcc-cdr.web.cern.ch/

CDR presentation during welcome event this evening.

Paper copies can be requested at

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

FCC Study input for EPPSU

4 ten-page strategy documents + addenda submitted to ESG in December 2018.

- The FCC integrated program
- Individual documents for FCC-ee and FC C-hh and HE-LHC

- Preprints available since 15 January 2019 on
- http://fcc-cdr.web.cern.ch/

FCC-ee basic design choices

double ring e$^+$e$^-$ collider ~100 km

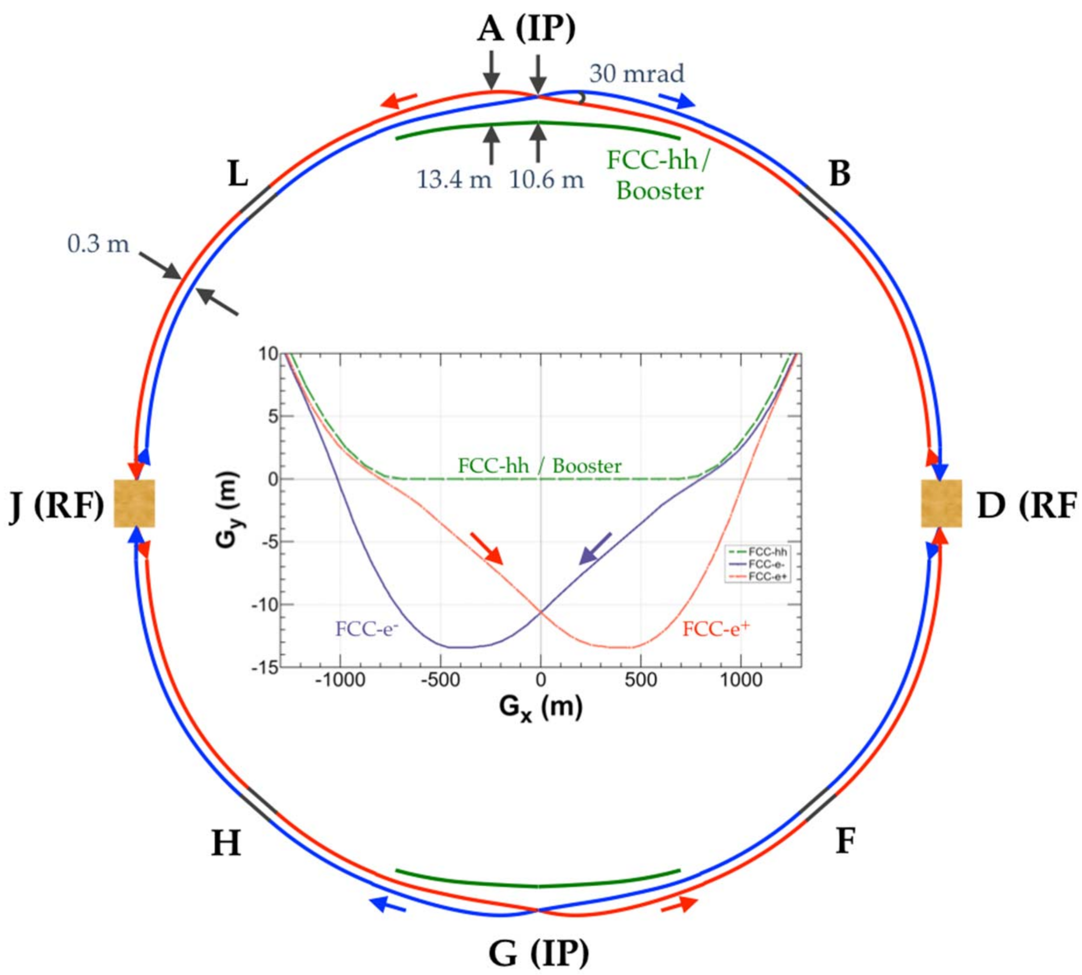
follows footprint of FCC-hh, except around IPs

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**

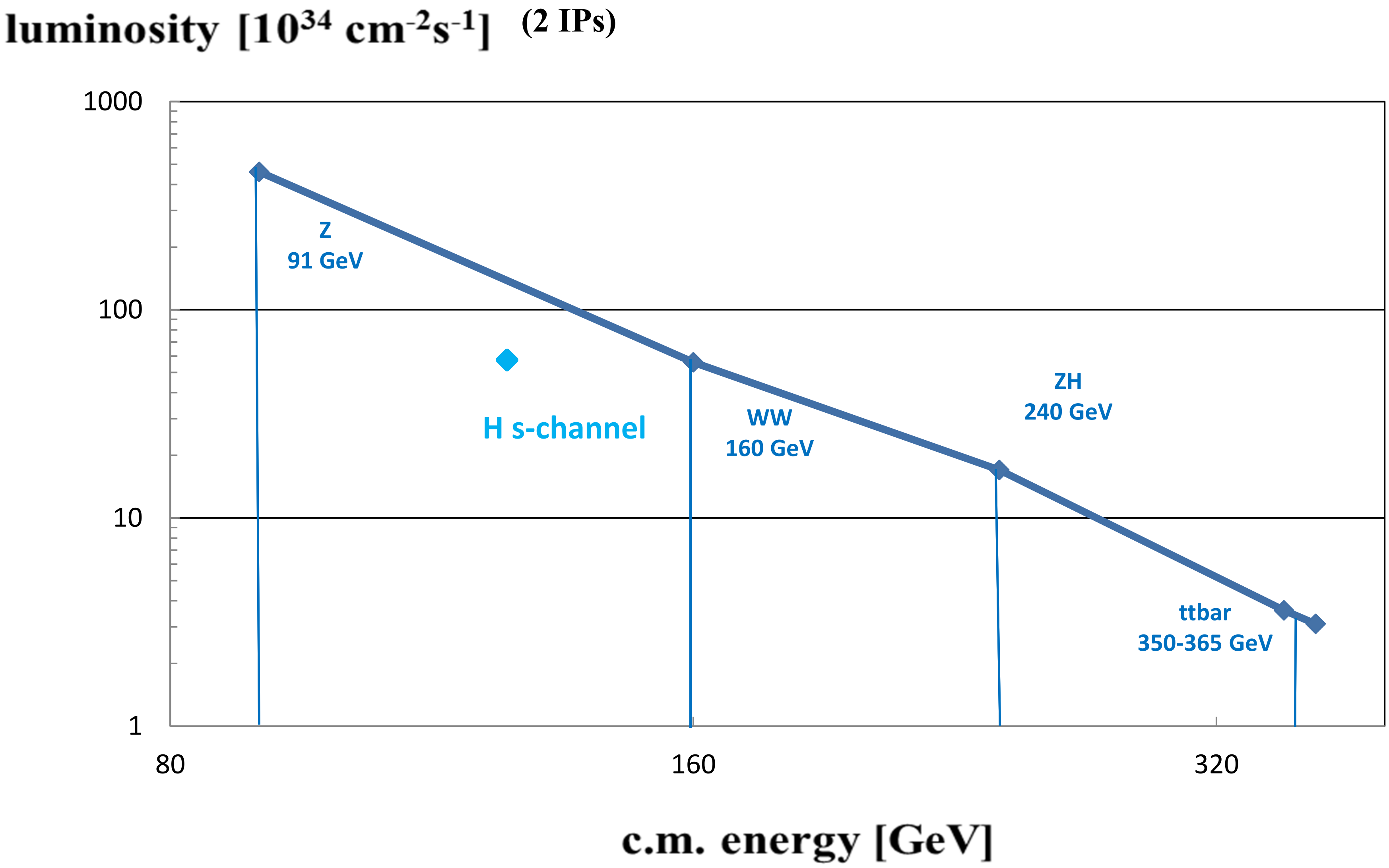


K. Oide et al.

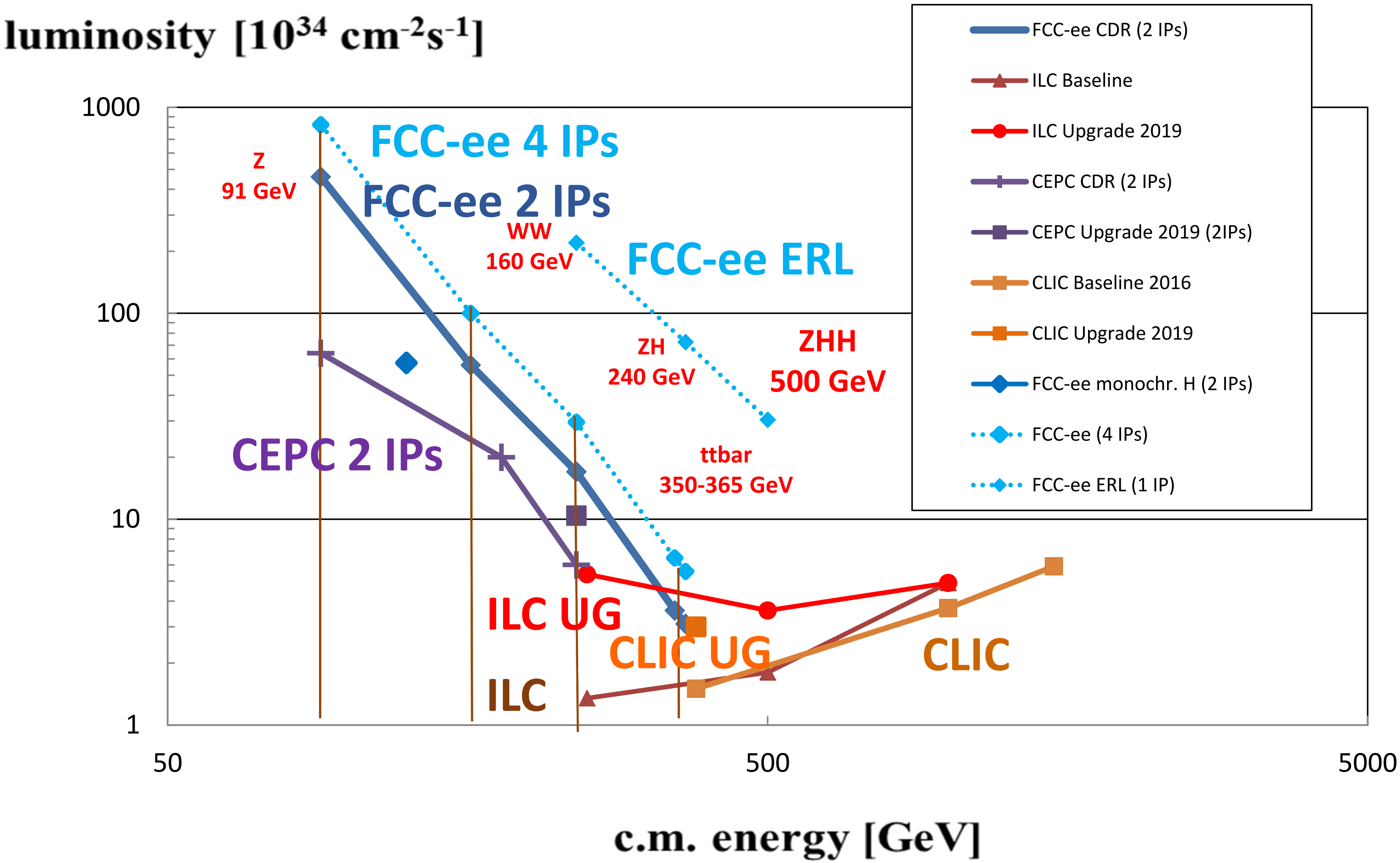
FCC-ee collider parameters

parameter	Z	WW	H (ZH)	ttbar
beam energy [GeV]	45	80	120	182.5
beam current [mA]	1390	147	29	5.4
no. bunches/beam	16640	2000	393	48
bunch intensity [10^{11}]	1.7	1.5	1.5	2.3
SR energy loss / turn [GeV]	0.036	0.34	1.72	9.21
total RF voltage [GV]	0.1	0.44	2.0	10.9
long. damping time [turns]	1281	235	70	20
horizontal beta* [m]	0.15	0.2	0.3	1
vertical beta* [mm]	0.8	1	1	1.6
horiz. geometric emittance [nm]	0.27	0.28	0.63	1.46
vert. geom. emittance [pm]	1.0	1.7	1.3	2.9
bunch length with SR / BS [mm]	3.5 / 12.1	3.0 / 6.0	3.3 / 5.3	2.0 / 2.5
luminosity per IP [10^{34} cm^{-2}s^{-1}]	230	28	8.5	1.55
beam lifetime rad Bhabha / BS [min]	68 / >200	49 / >1000	38 / 18	40 / 18

FCC-ee luminosity versus energy

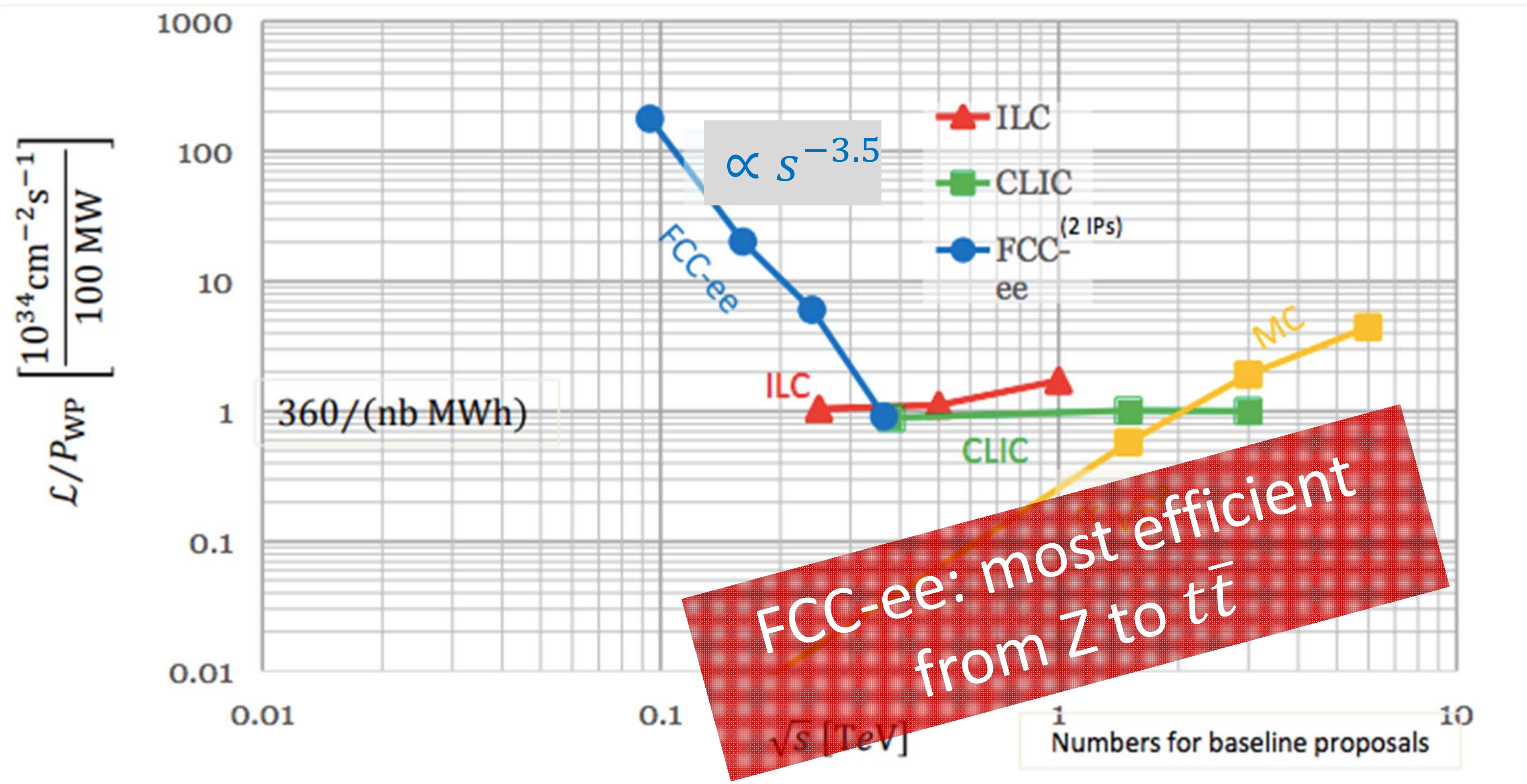


FCC-ee luminosity in perspective



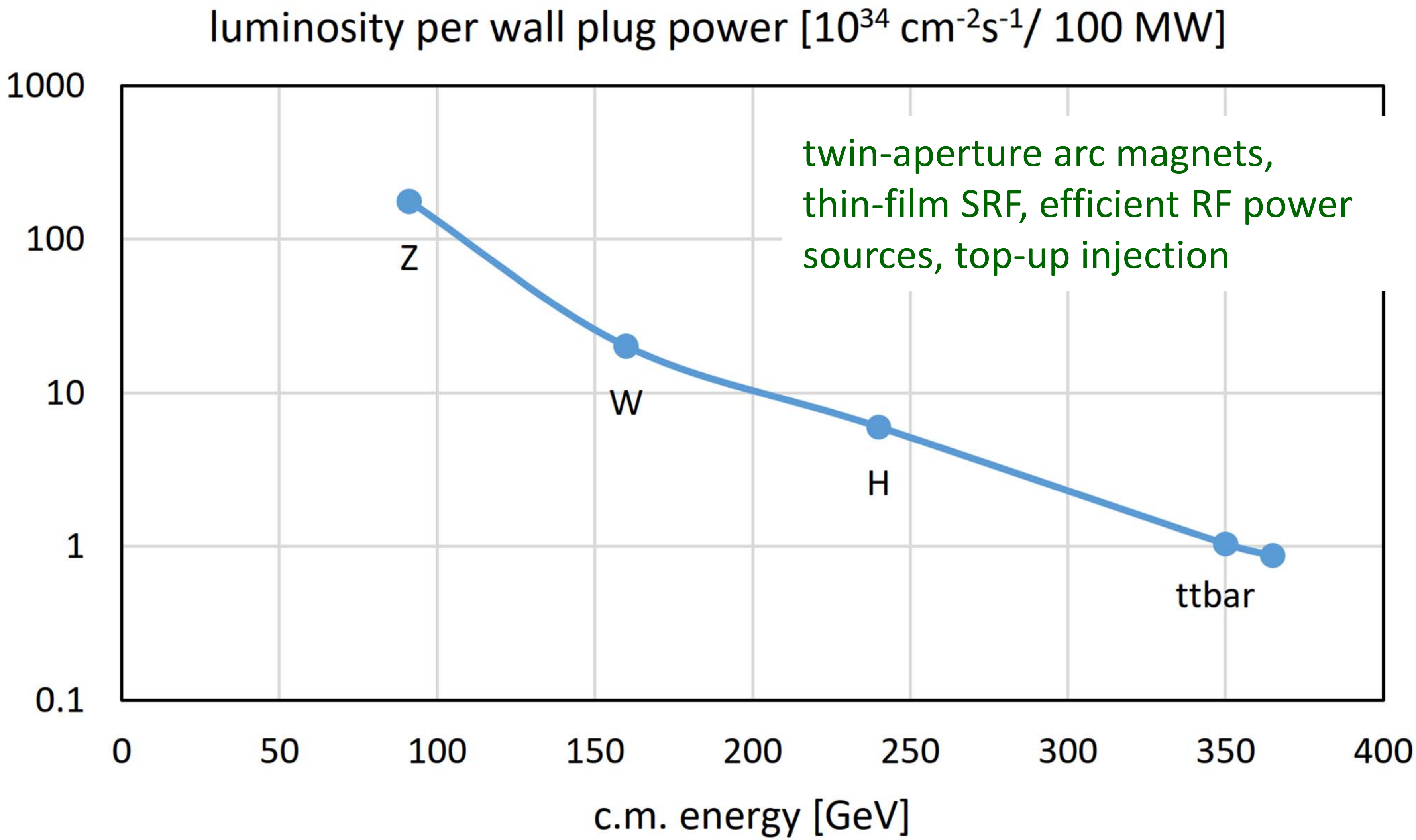
Benno List, Daniel Schulte, Dmitry Shatilov, Cheng Hui Yu, Vladimir Litvinenko, Thomas Roser

figure of merit for lepton colliders



E. Jensen, EPPSU symposium, Granada

FCC-ee: a sustainable accelerator

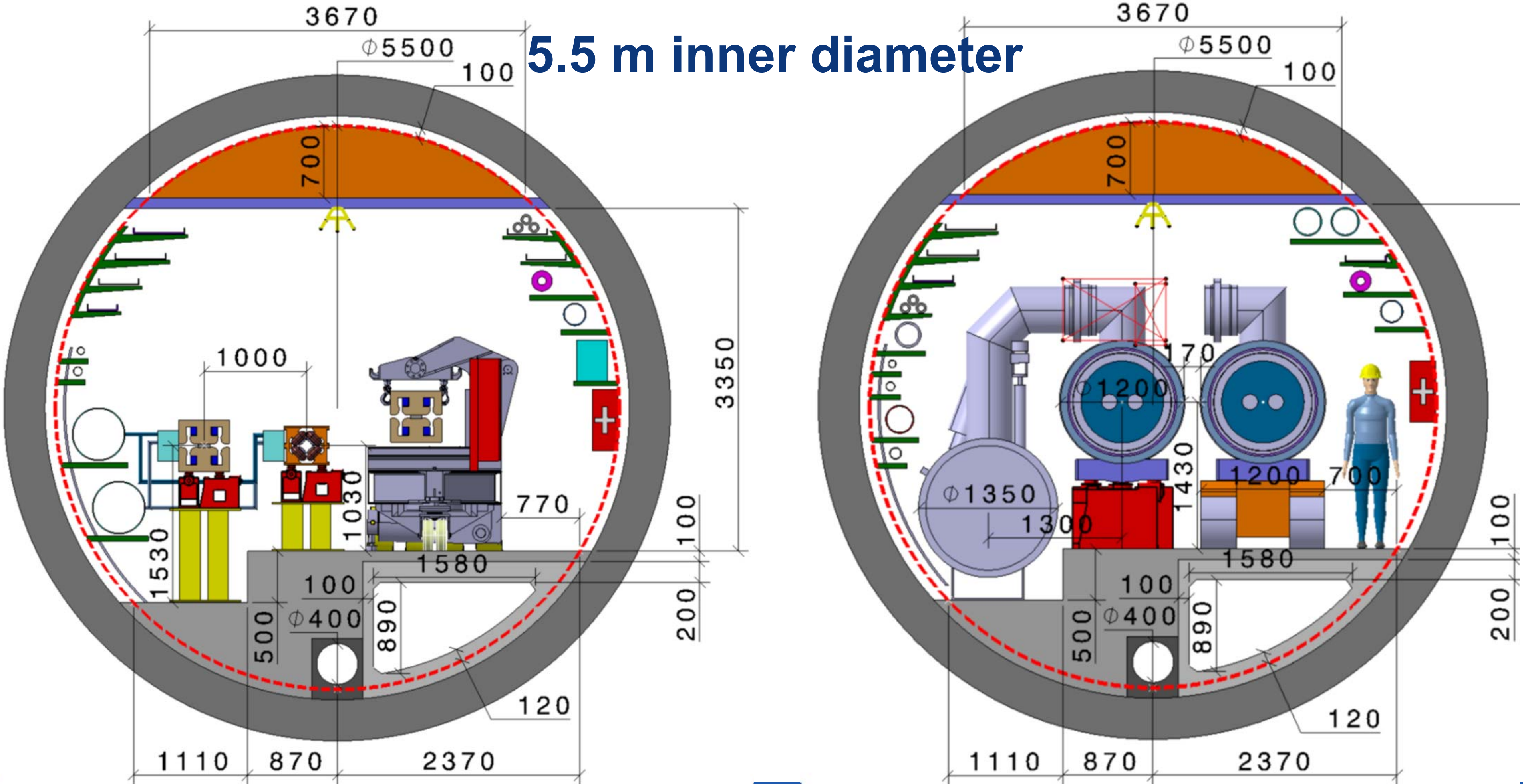


electricity cost ~200 euro per Higgs boson

Tunnel integration in arcs

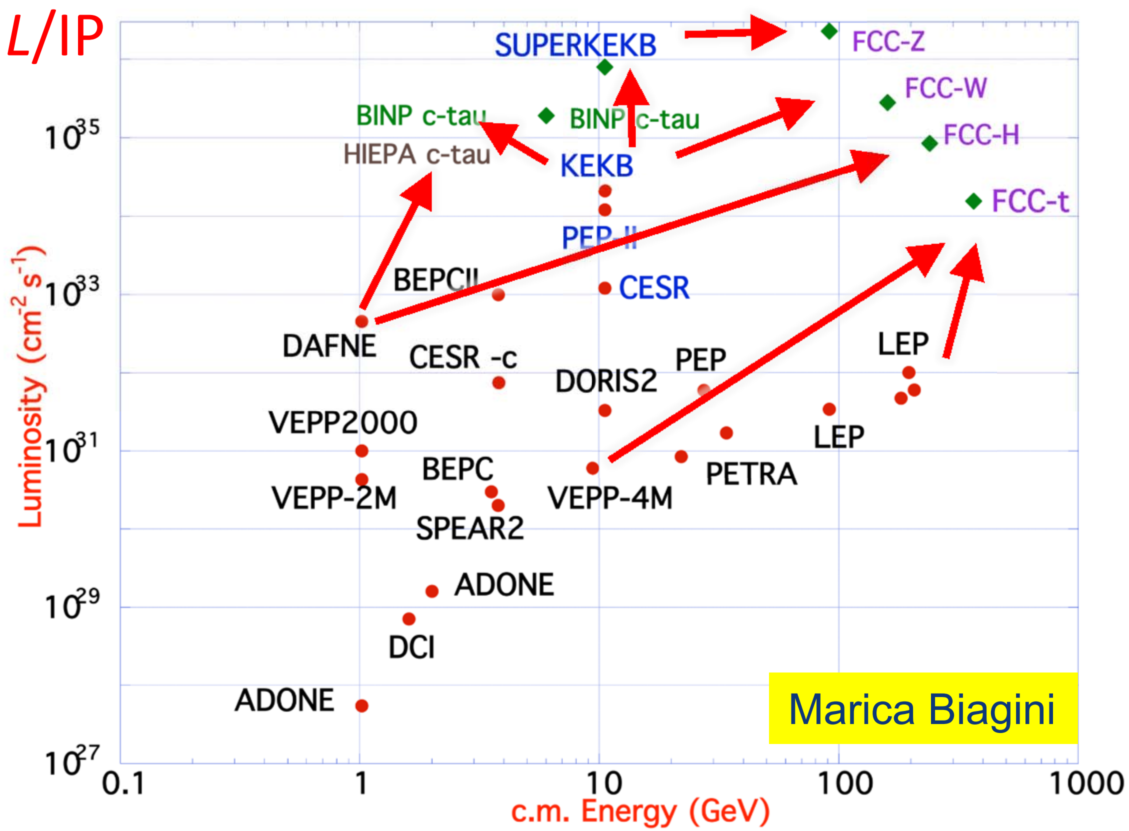
FCC-ee FCC-hh

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***

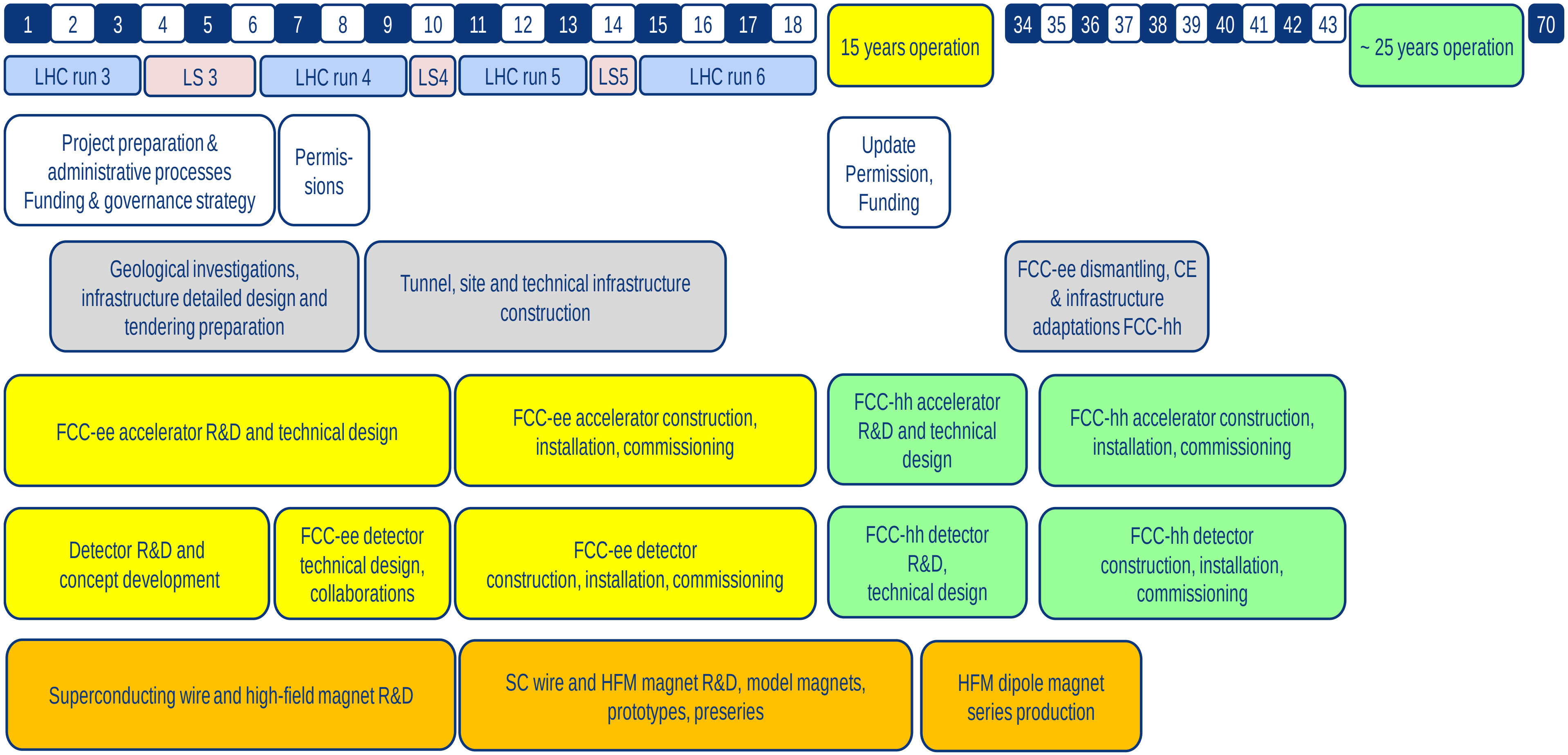
LEP high energy, SR effects

VEPP-4M, LEP: precision E calibration

KEKB: *e^+* source

HERA, LEP, RHIC: spin gymnastics

FCC integrated project technical schedule



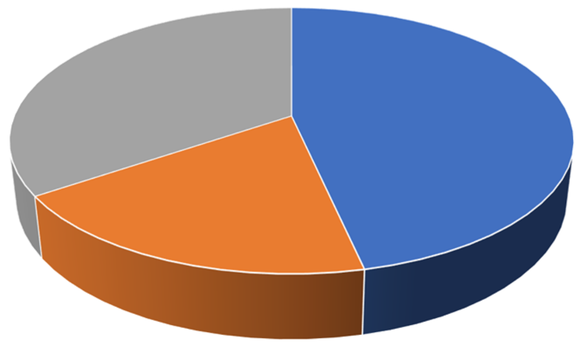
- **FCC integrated project plan is fully integrated with HL-LHC exploitation**
- **provides for seamless further continuation of HEP in Europe.**

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%)

FCC-ee (Z, W, H, t): capital cost per domain



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.)

FCC-hh - combined mode: capital cost per domain