Opportunities and challenges of FCC-ee

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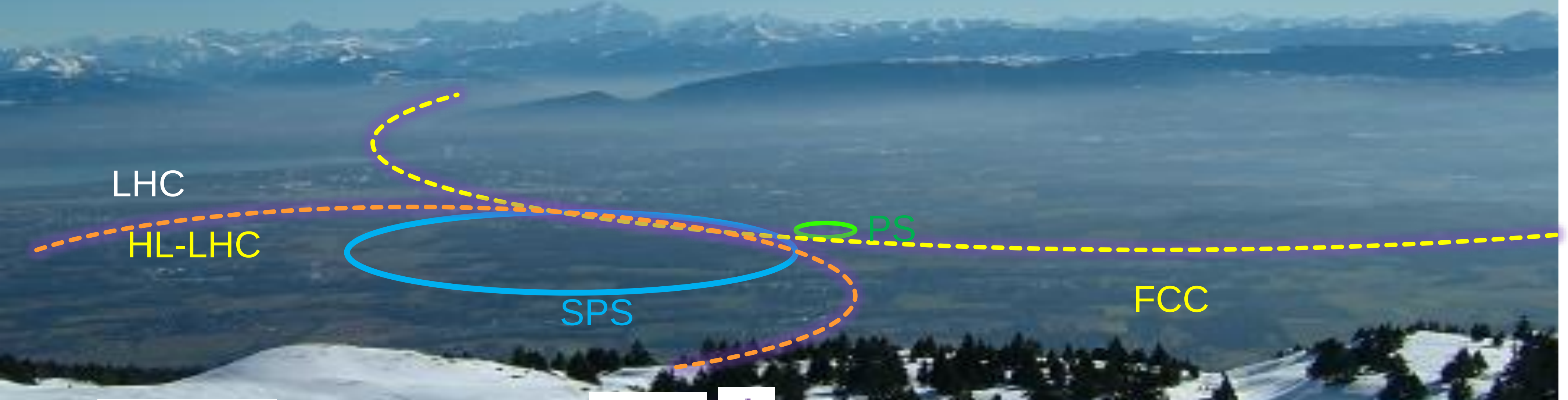
With many thanks to all in the FCC collaboration

Future Circular Collider Feasibility Study



http://cern.ch/fcc

*Work supported by the **European Commission** under the **HORIZON 2020 projects EuroCirCol**, grant agreement 654305; **EASITrain,** grant agreement no. 764879; **ARIES**, grant agreement 730871, and **E-JADE**, contract no. 64547*

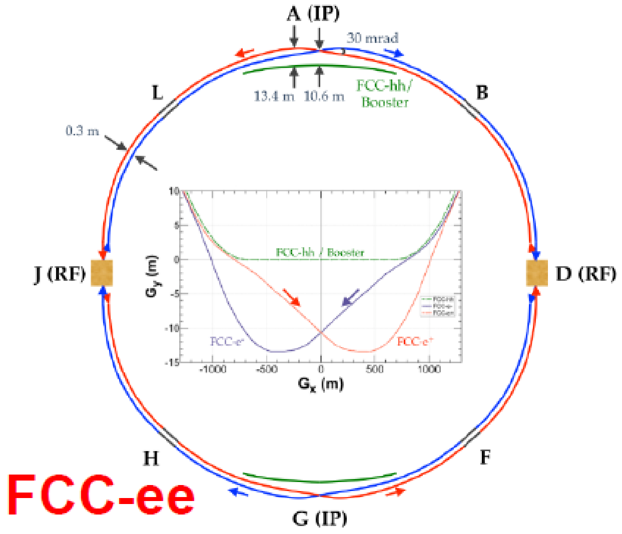
European Commission | Horizon 2020 European Union funding for Research & Innovation

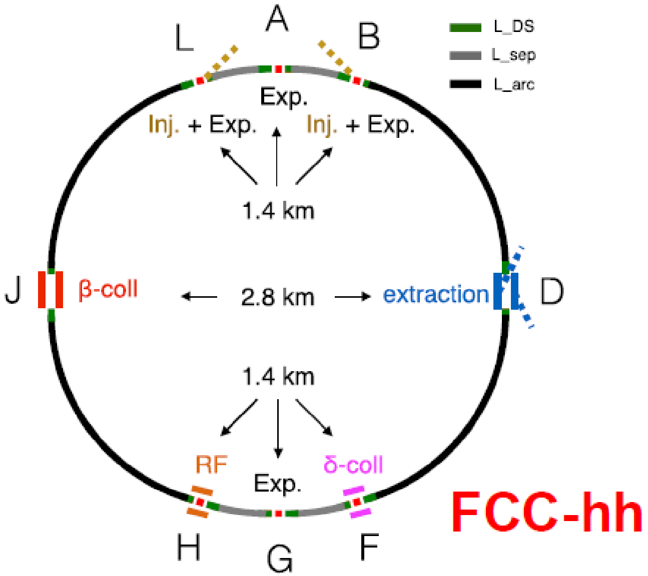
photo: J. Wenninger

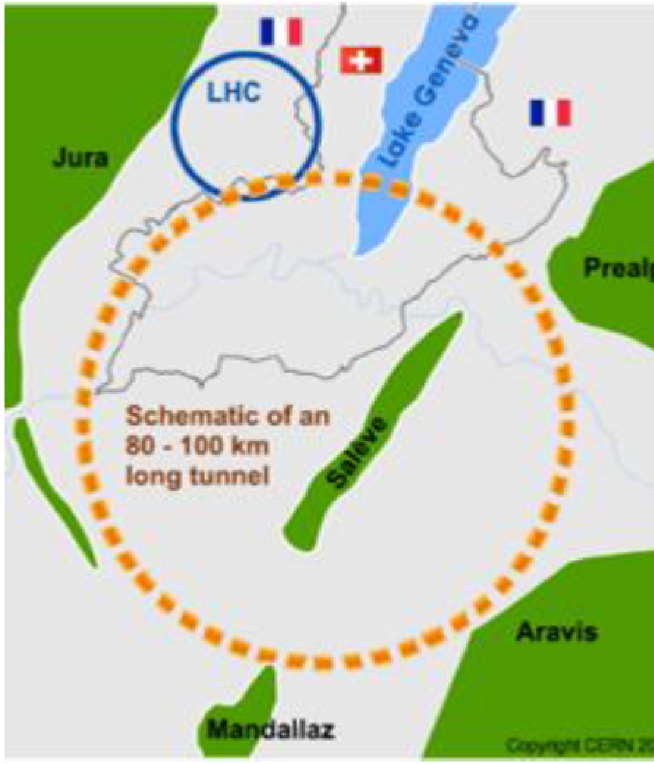
The FCC integrated program inspired by successful LEP – LHC programs at CERN

Comprehensive long-term program, maximizing physics opportunities

- **Stage 1: FCC-ee (Z, W, H, $t\bar{t}$) as Higgs factory, electroweak & and top factory at highest luminosities**
- **Stage 2: FCC-hh (~100 TeV) as natural continuation at energy frontier, with ion and eh options**
- Complementary physics
- Common civil engineering and technical infrastructures
- Building on and reusing CERN's existing infrastructure
- FCC integrated project allows seamless continuation of HEP after HL-LHC







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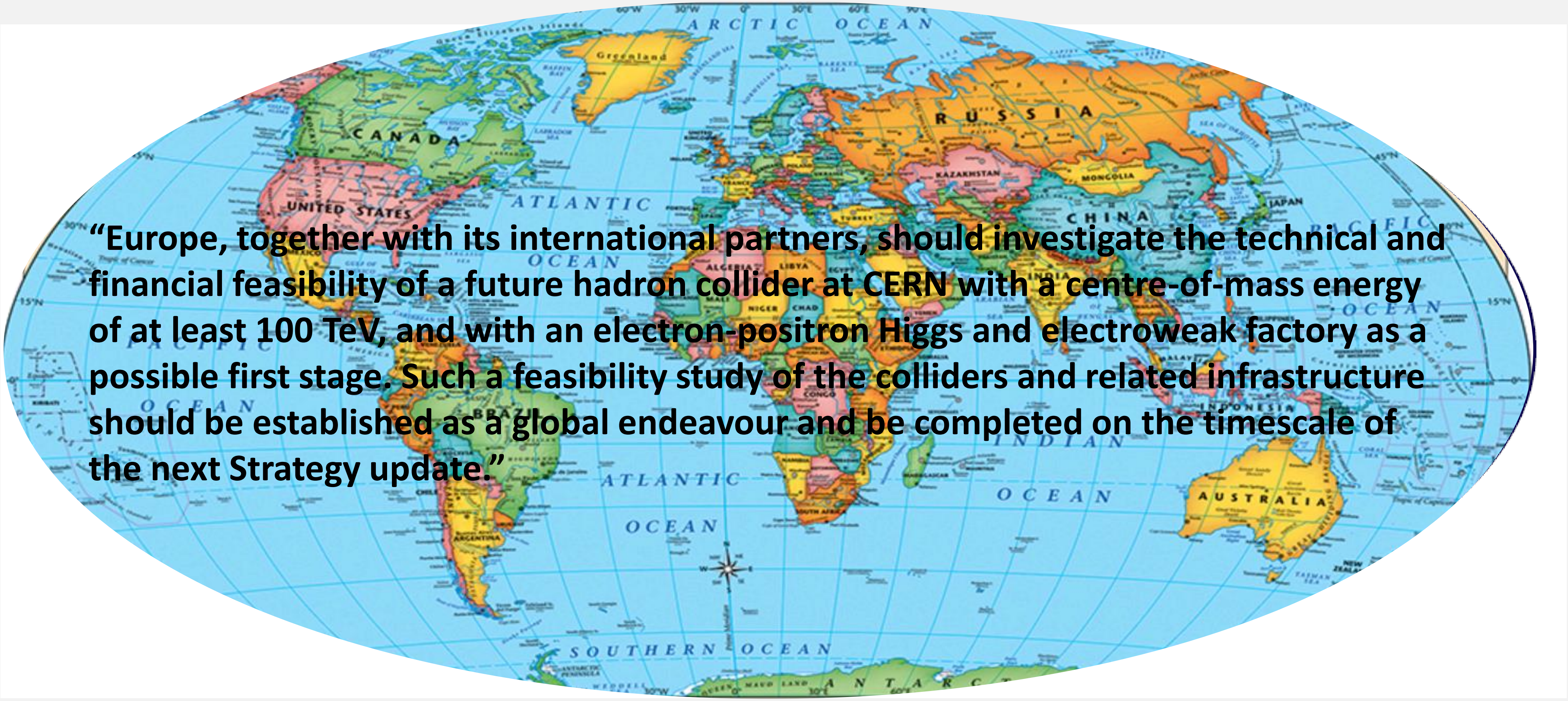
Our marching orders from ESPP 2020:



“Europe, together with its international partners, should investigate the technical and financial feasibility of a future hadron collider at CERN with a centre-of-mass energy of at least 100 TeV, and with an electron-positron Higgs and electroweak factory as a possible first stage. Such a feasibility study of the colliders and related infrastructure should be established as a global endeavour and be completed on the timescale of the next Strategy update.”

Feasibility of the colliders (ee and hh) and related infrastructure.

-- **FCC is the highest priority for Europe and its international partners (Plan A)**

Essential news for FCC

-- June 2021 The FCC Feasibility Study (2021-2025) organization proposed to CERN council and approved unanimously

-- Council documents :

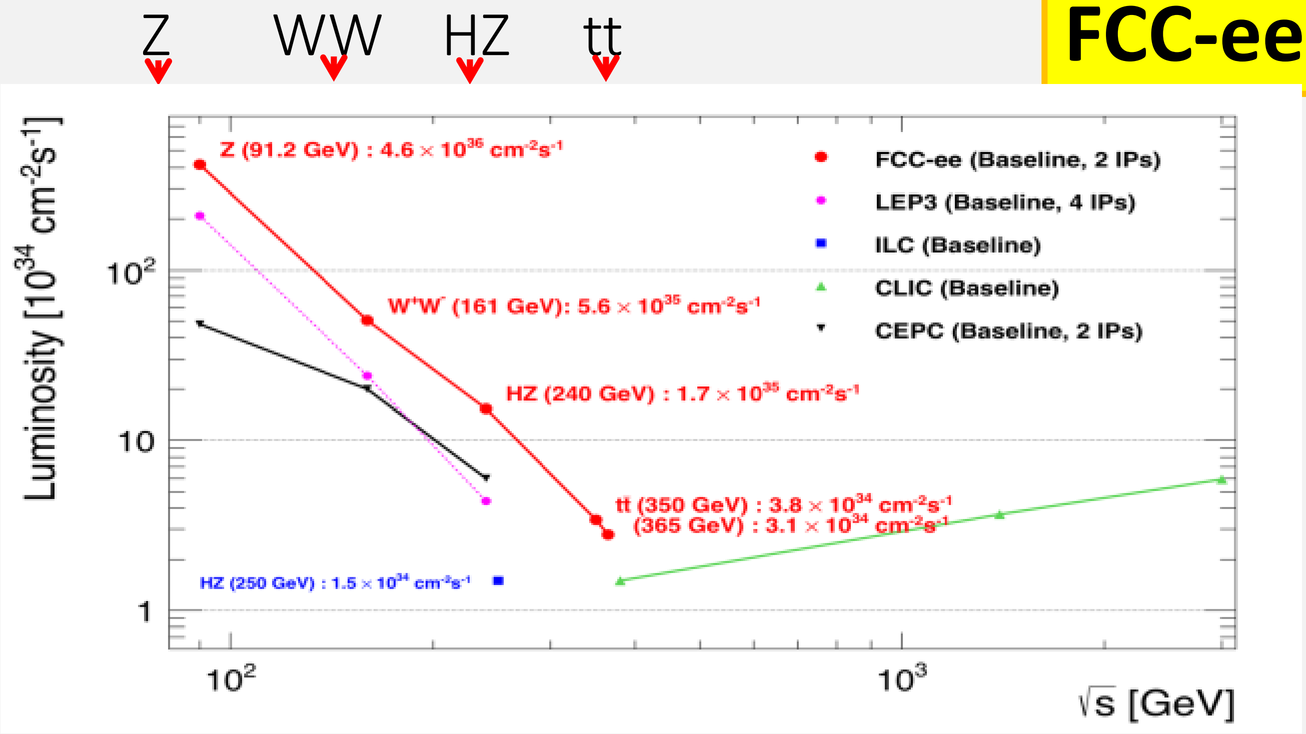
- Organisational structure of the FCC feasibility study
http://cds.cern.ch/record/2774006/files/English.pdf

- Main deliverables and timeline of the FCC feasibility tudy
http://cds.cern.ch/record/2774007/files/English.pdf

-- " The focus will be on the tunnel and the first-stage collider (FCC-ee)"
-- intermediate review mid 2023, delivery of Feasibility Study Report (FSR) end 2025, (first collisions 2040+)
-- Stress the importance of communication towards
scientific community, governments and funding agencies, industries and general public
-- work has started on placement in Geneva area (France and Switzerland)
→ reduce number of surface points to 8
→ layout consistent with later choice of 2 or 4IP for the e+e- collider
-- in parallel, high field magnet R&D for FCC-hh will be carried out with high priority

These events bring FCC-ee and FCC-hh one big step closer to reality

FCC-ee



Event statistics :

					E_{CM} errors:
Z peak	E_{cm} : 91 GeV	$5\ 10^{12}$	e+e- → Z	LEP x 2.10^5	<100 keV
WW threshold+	$E_{cm} \geq 161$ GeV	10^8	e+e- → WW	LEP x 2.10^3	<300 keV
ZH threshold	E_{cm} : 240 GeV	10^6	e+e- → ZH	Never done	2 MeV
$\bar{t}t$ threshold	E_{cm} : 350 GeV	10^6	e+e- → $\bar{t}t$	Never done	5 MeV

Great energy range for the heavy particles of the Standard Model.

FCC challenges: Centre of mass Energy Calibration and Monochromatization

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Context: FCC technical and financial feasibility study approved
as CERN ‘plan A’. First stage: ‘tunnel and e+e- H/ EW factory’.

allow exploring existence of more particles with SM Couplings

Beam Energy measurement by RDP

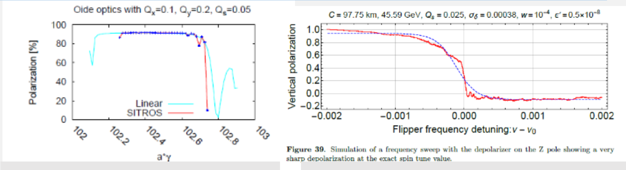
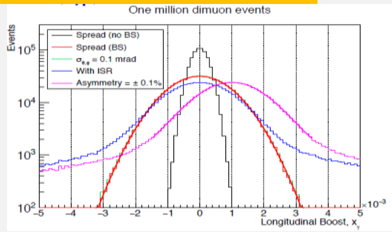


Figure 39. Simulation of a frequency sweep with the depolarizer on the Z pole showing a very sharp depolarization at the exact spin tune value.



Oppo… Reso… mono…

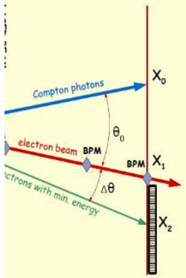
…ed to measure …d

Chal…

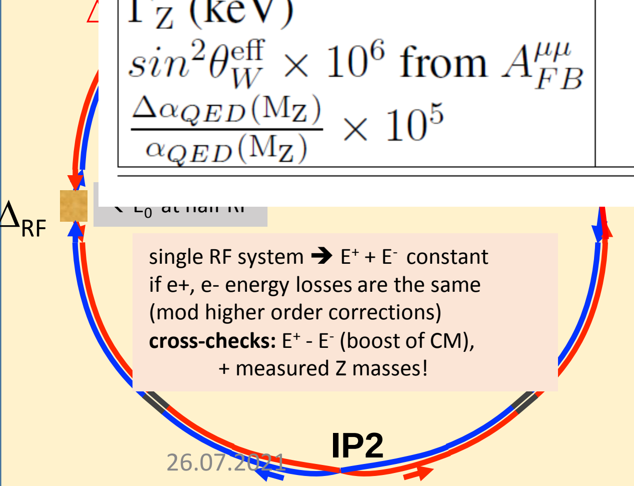
from b… energy…

Table 15: Calculated uncertainties on the quantities most affected by the center-of-mass energy uncertainties, under the final systematic assumptions.

Quantity	statistics	ΔE_{CMabs} 100 keV	$\Delta E_{CMSyst-ptp}$ **40 keV**	calib. stats. 200 keV/$\sqrt{(N^i)}$	σE_{CM} (84) ± **0.05** MeV
m_Z (keV)	4	100	**28**	1	–
Γ_Z (keV)	7	2.5	**22**	1	**10**
$sin^2\theta_W^{eff} \times 10^6$ from $A_{FB}^{\mu\mu}$	2	–	**2.4**	0.1	–
$\frac{\Delta\alpha_{QED}(M_Z)}{\alpha_{QED}(M_Z)} \times 10^5$	3	0.1	**0.9**	–	**0.05**



…eter
& γ
→ $\mathcal{P}_y \mathcal{P}_x$

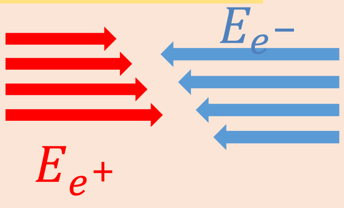


single RF system ➔ $E^+ + E^-$ constant
if e+, e- energy losses are the same
(mod higher order corrections)
cross-checks: $E^+ - E^-$ (boost of CM),
+ measured Z masses!

Δ_{BS} = 0 up to 0.62 MeV
Beamstrahlung E loss compensated by RF.

-- how do we operate it all ?

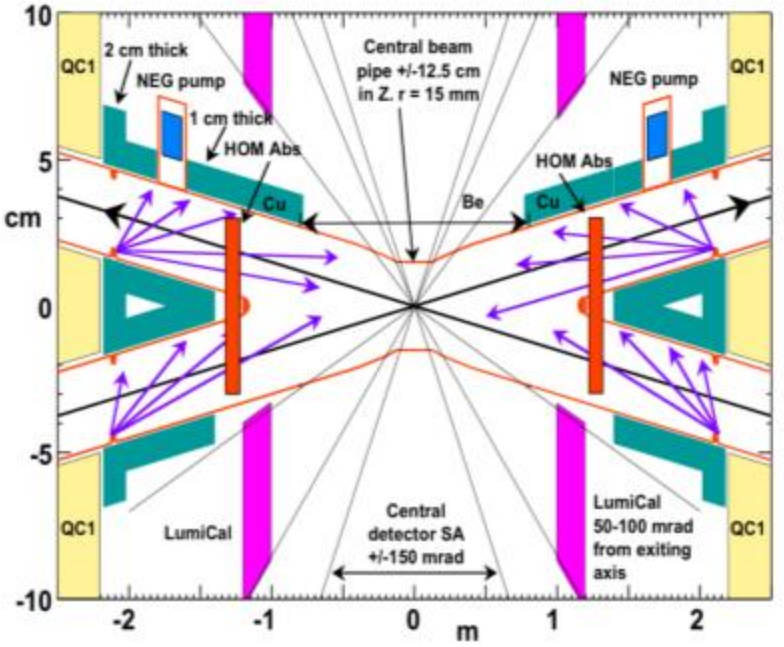
Issue from collision offset x parasitic opposite sign IP dispersion
➔ vernier scans and $D_{x,y}$ measurements
Radiative Bhabha monitor to measure beam-beam kick of colliding particles

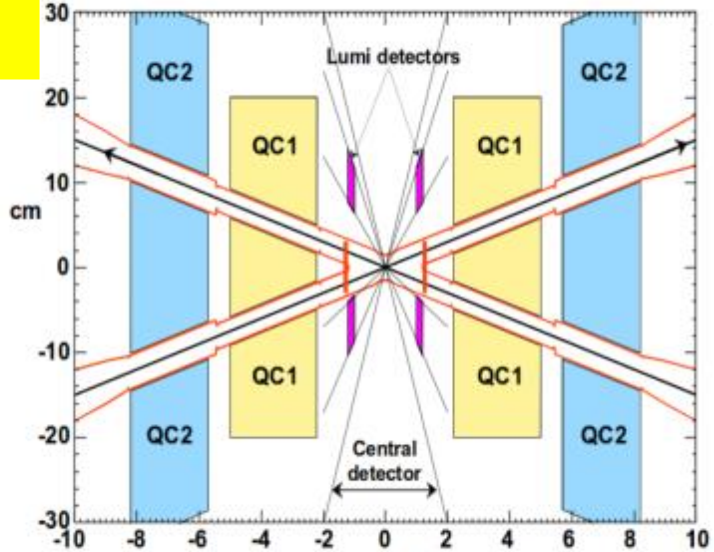


FCC EPOL group:
arxiv 1909.12245
challenges:
AB E.Gianfelice EPJ+

FCC-ee Interaction Region Design

A. Novokhatski, M. Sullivan, E. Belli, M. Gil Costa, and R. Kersevan, *Unavoidable trapped mode in the interaction region of colliding beams*, **Phys. Rev. Accel. Beams 20**, 111005 (2017)





M. Boscolo, H. Burkhardt, and M. Sullivan, *Machine detector interface studies: Layout and synchrotron radiation estimate in the future circular collider interaction region*, **Phys. Rev. Accel. Beams 20**, 011008 (2017)

<u>heat loads:</u> rad Bhabha (kW), beamstrahlung (MW), res. wall (kW), HOMs, quadr. synchrotron rad.

3D sketch of key IR systems over first 3 m from IP

M. Boscolo, N. Bacchetta, A. Bogomyagkov, H. Burkhardt, M. Dam, D. El Khechen, M. Koratzinos, E. Levichev, M. Luckhof, A. Novokhatski, L. Pellegrino, S. Sinyatkin, M. Sullivan, et al.

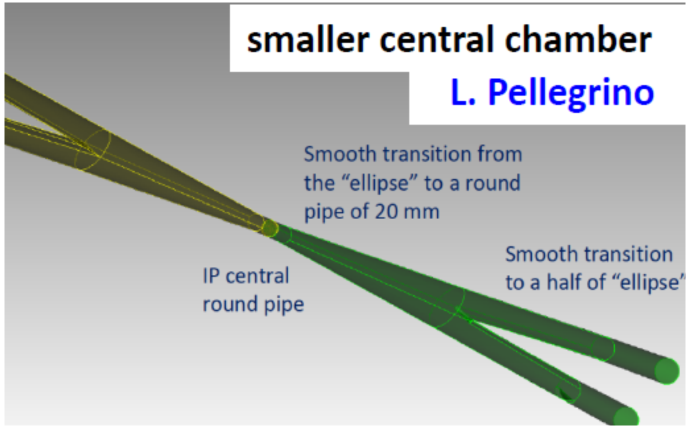
MDI limit: 100mrad

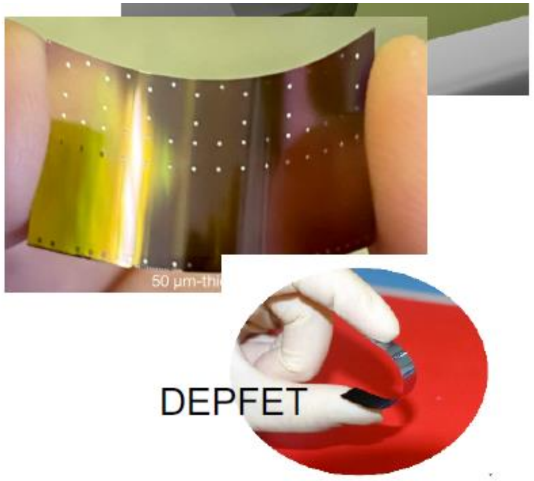
FCC

M. Boscolo et al

A. Jung, M. Mager

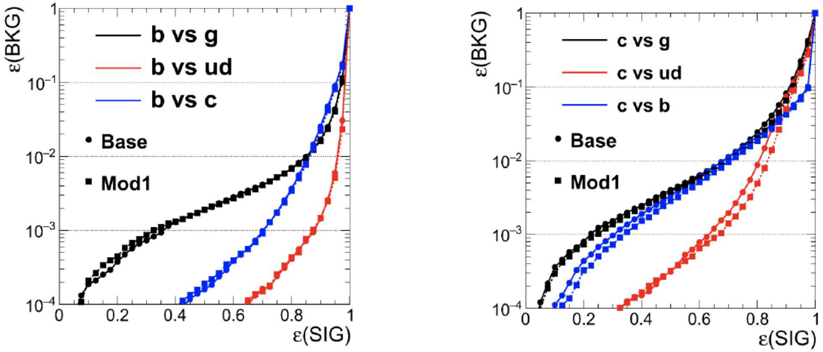
It appears that beam pipe might be smaller than CDR (20mm diameter vs 30)
➔ better b/c tagging eff. (85% for 1% contamination)





Performance (smaller beampipe / closer vtx)

b-tagging	c-tagging



Mod1: additional vertex layer @1 cm

- Effect is small in b-tagging:
  - Effect is significant in c-tagging, as expected
  - Gain ~ 10-30% background rejection (vs. gluon and light)
    - possibly explore thinner beam-pipe (to limit MS)

M. Selvaggi et al

1st layer of tracker inside vacuum? (sketch from ALICE upgrade)

FCC-ee physics programme

M. Dam ECFA R&D road map input
https://indico.cern.ch/event/994685/

"Higgs Factory" Programme

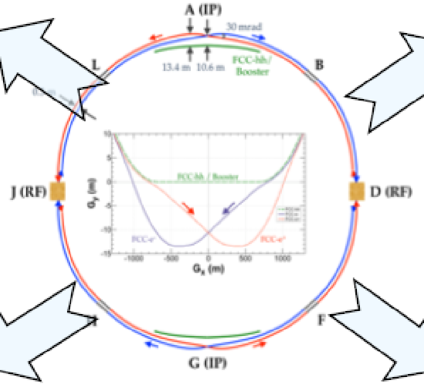
- At two energies, 240 and 365 GeV, collect in total
  - 1.2M HZ events and 75k WW → H events
- Higgs couplings to fermions and bosons
- Higgs self-coupling (2-4 σ) via loop diagrams
- Unique possibility: measure electron coupling in s-channel production $e^+e^- \to H$ @ $\sqrt{s}$ = 125 GeV

Ultra Precise EW Programme & QCD

Measurement of EW parameters with factor ~300 improvement in *statistical* precision wrt current WA

- 5×10^{12} Z and 10^8 WW
  - m_Z, Γ_Z, Γ_{inv}, $\sin^2\theta_W^{eff}$, R^Z_ℓ, R_b, α_s, m_W, Γ_W...
- 10^6 tt
  - m_{top}, Γ_{top}, EW couplings

Indirect sensitivity to new phys. up to Λ=70 TeV scale



Heavy Flavour Programme

- Enormous statistics: 10^{12} bb, cc; 1.7×10^{11} ττ
- Extremely clean environment, favourable kinematic conditions (boost) from Z decays
- CKM matrix, CP measurements, "flavour anomaly" studies, e.g. b → sττ, rare decays, cLFV searches, lepton universality, PNMS matrix unitarity

Feebly Coupled Particles - LLPs

Intensity frontier: Opportunity to directly observe new feebly interacting particles with masses below m_Z:

- Axion-like particles, dark photons, Heavy Neutral Leptons
- Signatures: long lifetimes - LLPs

Detector requirements (present status)

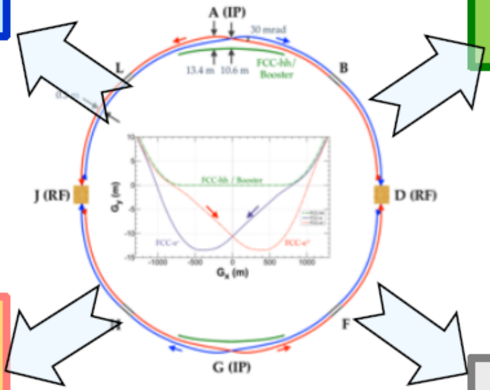
M. Dam ECFA R&D road map input
https://indico.cern.ch/event/994685/

"Higgs Factory" Programme

- Momentum resolution of $\sigma_{p_T}/p_T^2 \simeq 2 \times 10^{-5}\,\mathrm{GeV}^{-1}$ commensurate with $\mathcal{O}(10^{-3})$ beam energy spread
- Jet energy resolution of 30%/√E in multi-jet environment for Z/W separation
- Superior impact parameter resolution for c, b tagging

Ultra Precise EW Programme

- Absolute normalisation (luminosity) to 10^{-4}
- Relative normalisation (e.g. $\Gamma_{had}/\Gamma_{\ell}$) to 10^{-5}
- Momentum resolution "as good as we can get it"
  - Multiple scattering limited
- Track angular resolution < 0.1 mrad (BES from μμ)
- Stability of B-field to 10^{-6} : stability of √s meast.



Heavy Flavour Programme

- Superior impact parameter resolution: secondary vertices, tagging, identification, life-time measts.
- ECAL resolution at the few %/ √E level for inv. mass of final states with π^0s or γs
- Excellent π^0/γ separation and measurement for tau physics
- PID: K/π separation over wide momentum range for b and τ physics

Feebly Coupled Particles - LLPs

Benchmark signature: Z → νN, with N decaying late

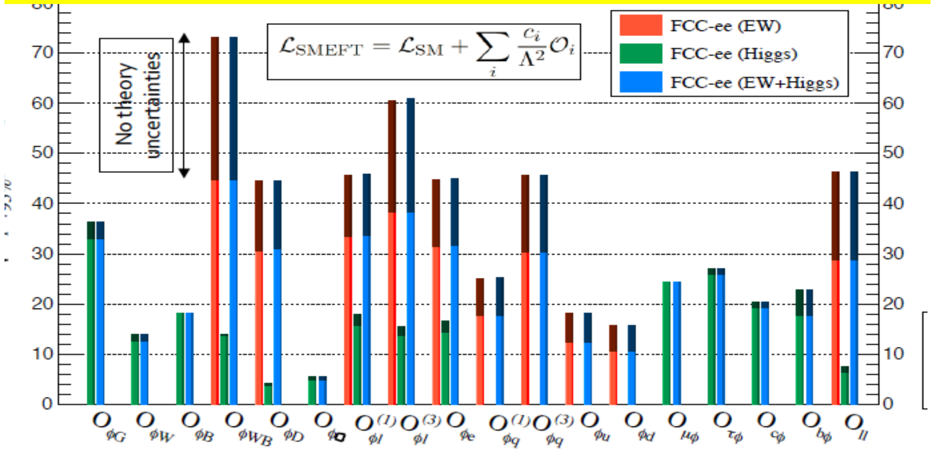
- Sensitivity to far detached vertices (mm → m)
  - Tracking: more layers, continous tracking
  - Calorimetry: granularity, tracking capability
- Large decay lengths ⇒ extended detector volume
- Hermeticity

The Challenge

Precision EW measurements: is the SM complete?

Observable	present value ± error	FCC-ee Stat.	FCC-ee Syst.	Comment and leading exp. error
m_Z (keV)	91186700 ± 2200	**4**	100	From Z line shape scan Beam energy calibration
Γ_Z (keV)	2495200 ± 2300	**4**	25	From Z line shape scan Beam energy calibration
$\sin^2\theta_W^{eff}(\times 10^6)$	231480 ± 160	**2**	2.4	from $A_{FB}^{\mu\mu}$ at Z peak Beam energy calibration
$1/\alpha_{QED}(m_Z^2)(\times 10^3)$	128952 ± 14	**3**	small	from $A_{FB}^{\mu\mu}$ off peak QED&EW errors dominate
R_ℓ^Z $(\times 10^3)$	20767 ± 25	**0.06**	0.2-1	ratio of hadrons to leptons **acceptance for leptons**
$\alpha_s(m_Z^2)$ $(\times 10^4)$	1196 ± 30	**0.1**	0.4-1.6	from R_ℓ^Z above
σ_{had}^0 $(\times 10^3)$ (nb)	41541 ± 37	**0.1**	4	peak hadronic cross section luminosity measurement
$N_\nu(\times 10^3)$	2996 ± 7	**0.005**	1	Z peak cross sections Luminosity measurement
R_b $(\times 10^6)$	216290 ± 660	**0.3**	< 60	ratio of $b\bar{b}$ to hadrons stat. extrapol. from SLD
$A_{FB}^b, 0$ $(\times 10^4)$	992 ± 16	**0.02**	1-3	b-quark asymmetry at Z pole from jet charge
$A_{FB}^{pol,\tau}$ $(\times 10^4)$	1498 ± 49	**0.15**	<2	τ polarization asymmetry τ decay physics
τ lifetime (fs)	290.3 ± 0.5	**0.001**	0.04	radial alignment
τ mass (MeV)	1776.86 ± 0.12	**0.004**	0.04	momentum scale
τ leptonic $(\mu\nu_\mu\nu_\tau)$ B.R. (%)	17.38 ± 0.04	**0.0001**	0.003	e/μ/hadron separation
m_W (MeV)	80350 ± 15	**0.25**	0.3	From WW threshold scan Beam energy calibration
Γ_W (MeV)	2085 ± 42	1.2	0.3	From WW threshold scan Beam energy calibration
$\alpha_s(m_W^2)(\times 10^4)$	1170 ± 420	**3**	small	from R_ℓ^W
$N_\nu(\times 10^3)$	2920 ± 50	**0.8**	small	ratio of invis. to leptonic in radiative Z returns
m_{top} (MeV/c^2)	172740 ± 500	**17**	small	From $t\bar{t}$ threshold scan QCD errors dominate
Γ_{top} (MeV/c^2)	1410 ± 190	45	small	From $t\bar{t}$ threshold scan QCD errors dominate
$\lambda_{top}/\lambda_{top}^{SM}$	1.2 ± 0.3	**0.10**	small	From $t\bar{t}$ threshold scan QCD errors dominate
ttZ coupling	± 30%	0.5 – 1.5%	small	From $\sqrt{s} = 365$ GeV run

2106.13885



-^- EFT D6 operators (some assumptions)

-^- Higgs and EWPOs are complementary

-^- top quark mass and couplings essential!

(the 100km circumference is optimal for this)

<-- systematics are preliminary ‘book keeping’

➔ aim at reducing to same level as stat. errors

<-- more HF observables to be added

<-- complemented by high energy FCC-hh

Theory work is critical and initiated

FCC

	Quantity	Value ± error	Stat.	Syst.	leading exp. error
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arXiv.org > hep-ph > arXiv:1901.02648

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High Energy Physics - Phenomenology

[Submitted on 9 Jan 2019]

Theory Requirements and Possibilities for the FCC-ee and other Future High Energy and Precision Frontier Lepton Colliders

Alain Blondel, Ayres Freitas, Janusz Gluza, Sven Heinemeyer, Stanislaw Jadach, Patrick Janot, Tord Riemann

The future lepton colliders proposed for the High Energy and Precision Frontier set stringent demands on theory. The most ambitious, broad-reaching and demanding project is the FCC-ee. We consider here the present status and requirements on precision calculations, possible ways forward and novel methods, to match the experimental accuracies expected at the FCC-ee. We conclude that the challenge can be tackled by a distributed collaborative effort in academic institutions around the world, provided sufficient support, which is estimated to about 500 man-years over the next 20 years.

Comments: Input to the European Strategy Particle Physics 2018-2020
Subjects: **High Energy Physics - Phenomenology (hep-ph)**; High Energy Physics - Theory (hep-th)
Cite as: arXiv:1901.02648 **[hep-ph]**
(or arXiv:1901.02648v1 **[hep-ph]** for this version)

We conclude that the challenge can be tackled... collaborative effort around the world... about 500 person-years

also arxiv: *1809.01830, 1905.05078 (workshops) 1906.05379*

Conclusions

A. Following ESPP, CERN has now launched the second phase FCC study, the FCC technical and financial feasibility study
B. The first stage of the FCC (FCC-ee) is a machine offering great physics opportunities at Z,W,H, and top, and heavy flavour (esp. b,τ) factory.
C. High luminosity, precise ECM, clean environment and effective MDI (10mm beam pipe)
D. The challenges arise to match systematics to the statistical precisions
E. This will require a systematic 'case studies' of measurements leading to detector (accelerator and theory) requirements
F. a proactive preparation is necessary with everybody together
    - accelerator design and running mode
    - detector concepts (up to four)
    - theoretical calculations
    - analysis tools and methods

G. History has shown that systematic errors are usually statistics limited.

Appendix : documentation

CDR + Documentation

- **FCC-Conceptual Design Reports:**
  - **Vol 1 – Physics**
    Vol 2 – FCC-ee,
    Vol 3 – FCC-hh,
    Vol 4 – HE-LHC
    1338 authors

A public presentation of the CDR was given on 4-5 March 2019 at CERN https://indico.cern.ch/event/789349/
+ FCC Phys. Workshop Jan 20 https://indico.cern.ch/event/838435/
FCC Phys workshop Nov 9-13 2020 https://indico.cern.ch/event/932973/
FCC week 28/06-02/07/2021 https://indico.cern.ch/event/995850/
→ many further details can be found there!

  - Preprints since 15 January 2019 on http://fcc-cdr.web.cern.ch/ and INSPIRE
  - **CDRs published in European Physical Journal C (Vol 1) and ST (Vol 2 – 4)**
  - **ESPP summaries: FCC-integral, FCC-ee, FCC-hh, HE-LHC** http://fcc-cdr.web.cern.ch/
  - FCC-ee «Your questions answered» https://arxiv.org/abs/1906.02693v1
  - "Circular vs linear, another story of complementarity" arXiv:1912.11871v2
  - LOIs to Snowmass, **challenges**: https://indico.cern.ch/event/951830/

A future Higgs and Electroweak Factory; Challenges towards discovery *EPJ+ spec. issue*

[1] A. Blondel and E. Gianfelice, *The challenges of beam polarization and keV-scale center-of-mass energy calibration* in A future Higgs and Electroweak factory (FCC): Challenges towards discovery, EPJ+ special issue, Focus on FCC-ee.

[2] A. Blondel and P. Janot, *FCC-ee overview: new opportunities create new challenges* in A future Higgs and Electroweak factory (FCC): Challenges towards discovery, EPJ+ special issue, Focus on FCC-ee, arXiv:2106.13885 [hep-ex].

[3] P. Azzi, L. Gouskos, M. Selvaggi, and F. Simon, *Higgs and top physics reconstruction challenges and opportunities at FCC-ee* in A future Higgs and Electroweak factory (FCC): Challenges towards discovery, EPJ+ special issue, Focus on FCC-ee, arXiv:2107.05003 [hep-ex].

[4] J. A. Maestre, A. Blondel, M. Dam, and P. Janot, *The Z lineshape challenge: ppm and keV measurements* in A future Higgs and Electroweak factory (FCC): Challenges towards discovery, EPJ+ special issue, Focus on FCC-ee, arXiv:2107.00616 [hep-ex].

[5] S. Monteil and G. Wilkinson, *Heavy-quark Challenges at FCC-ee* in A future Higgs and Electroweak factory (FCC): Challenges towards discovery, EPJ+ special issue, Focus on FCC-ee, arXiv:2106.01259 [hep-ex].

[6] M. Dam, *The tau challenges at FCC-ee* in A future Higgs and Electroweak factory (FCC): Challenges towards discovery, EPJ+ special issue, Focus on FCC-ee. https://www.overleaf.com/read/nhcvhcskrydf.

[7] M. Chrzaszcz, R. G. Suarez, and S. Monteil, *Hunt for rare processes and long-lived particles at FCC-ee* in A future Higgs and Electroweak factory (FCC): Challenges towards discovery, EPJ+ special issue, Focus on FCC-ee, arXiv:2106.15459 [hep-ex].

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SPARES

FCC-ee basic design choices

K. Oide et al.

Double ring e^+e^- collider + injector ~100 km

follows footprint of FCC-hh, except around IPs

Asymmetric IR layout & optics to limit synchrotron radiation towards the detector
-- also separates detector from injector

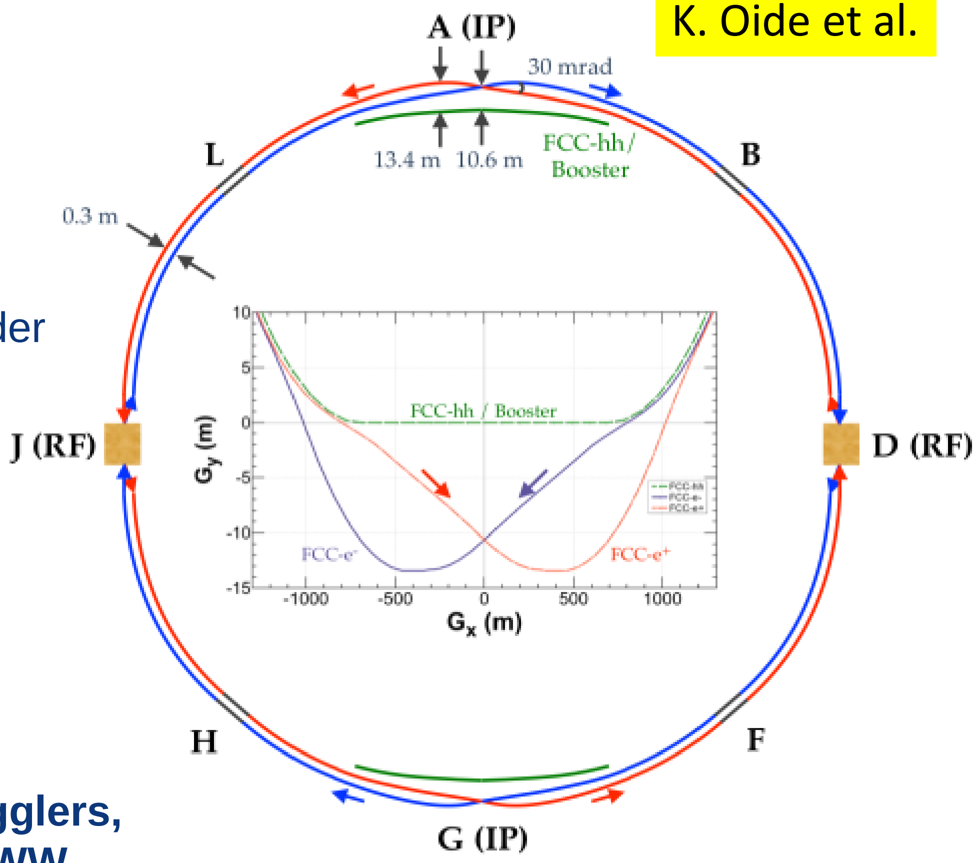
Presently 2 IPs (alternative layout with 4 IPs under study), **large** horizontal x-ing angle **30mrad, crab-waist optics**

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

common RF for $t\bar{t}$ running

top-up injection: **booster in collider tunnel**

Beam Polarization and energy calibration, wigglers, polarimeters, depolarization kicker for Z and WW

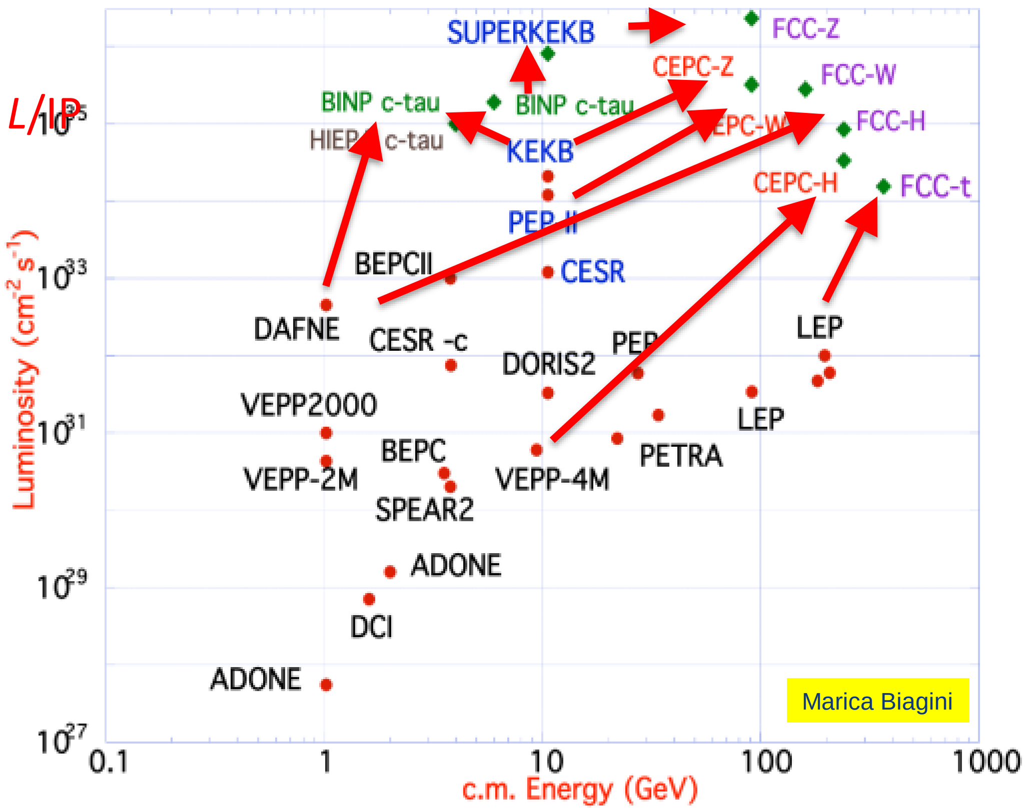


FCC-ee Collider Parameters

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 design

based on lessons and techniques from past colliders



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

DAFNE: crab waist, double ring

SuperB-factories, **S-KEKB: low β_y***

LEP: high energy, SR effects

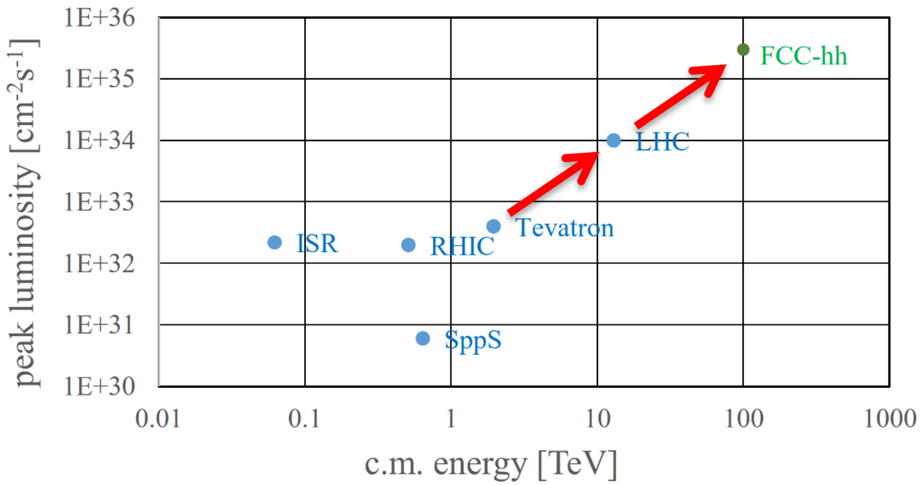
VEPP-4M, LEP: precision E calibration

KEKB: *e^+* source

HERA, LEP, RHIC: spin gymnastics

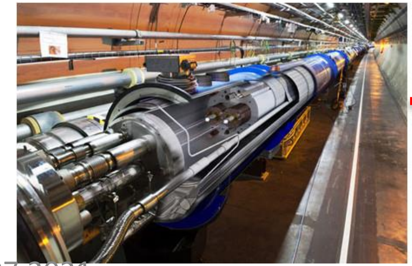
combining successful ingredients of several recent colliders
→ highest luminosities & energies

FCC-hh: highest collision energies

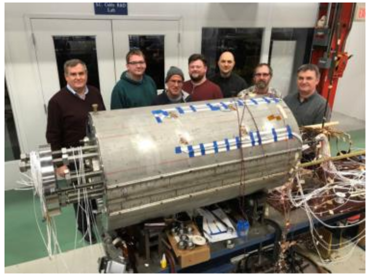


- **order of magnitude performance increase** in both **energy & luminosity**
- **100 TeV cm collision energy** (vs 14 TeV for LHC)
- **20 ab^{-1} per experiment collected over 25 years** of operation (vs 3 ab^{-1} for LHC)
- similar performance increase as from Tevatron to LHC
- **key technology: high-field magnets**

from
LHC technology
8.3 T NbTi dipole

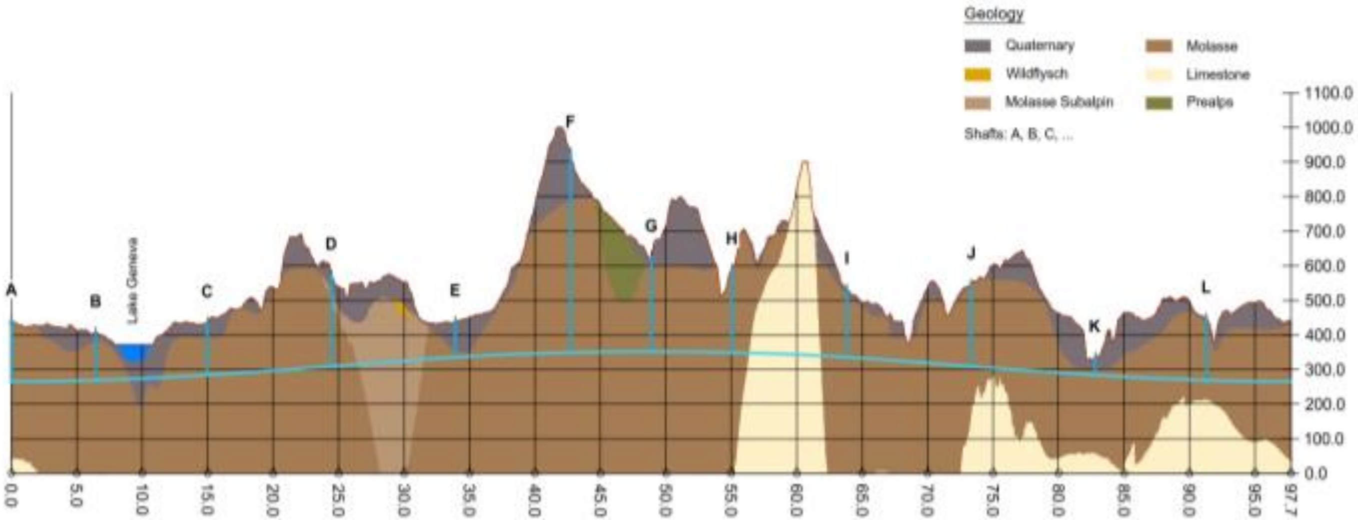


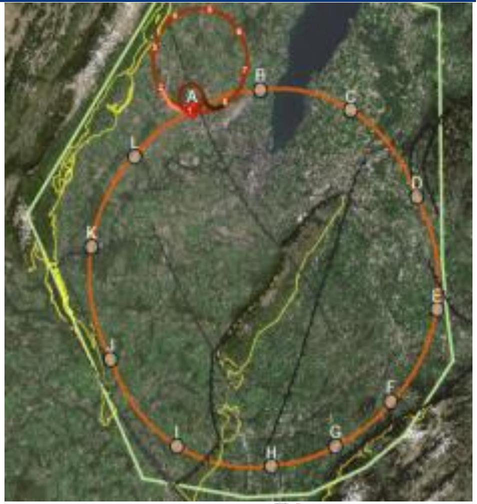
via
HL-LHC technology
12 T Nb_3Sn quadrupole

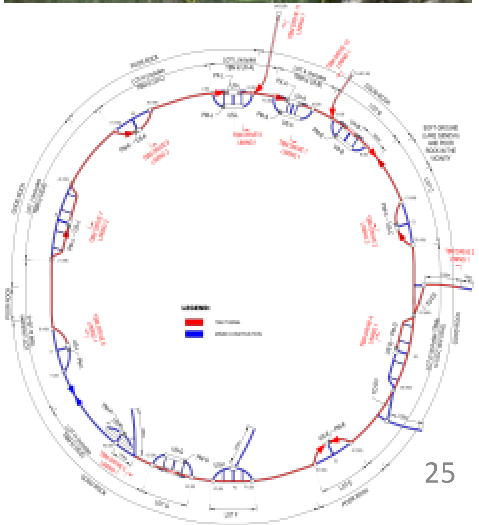


FNAL dipole demonstrator
14.5 T Nb_3Sn

FCC implementation - footprint baseline



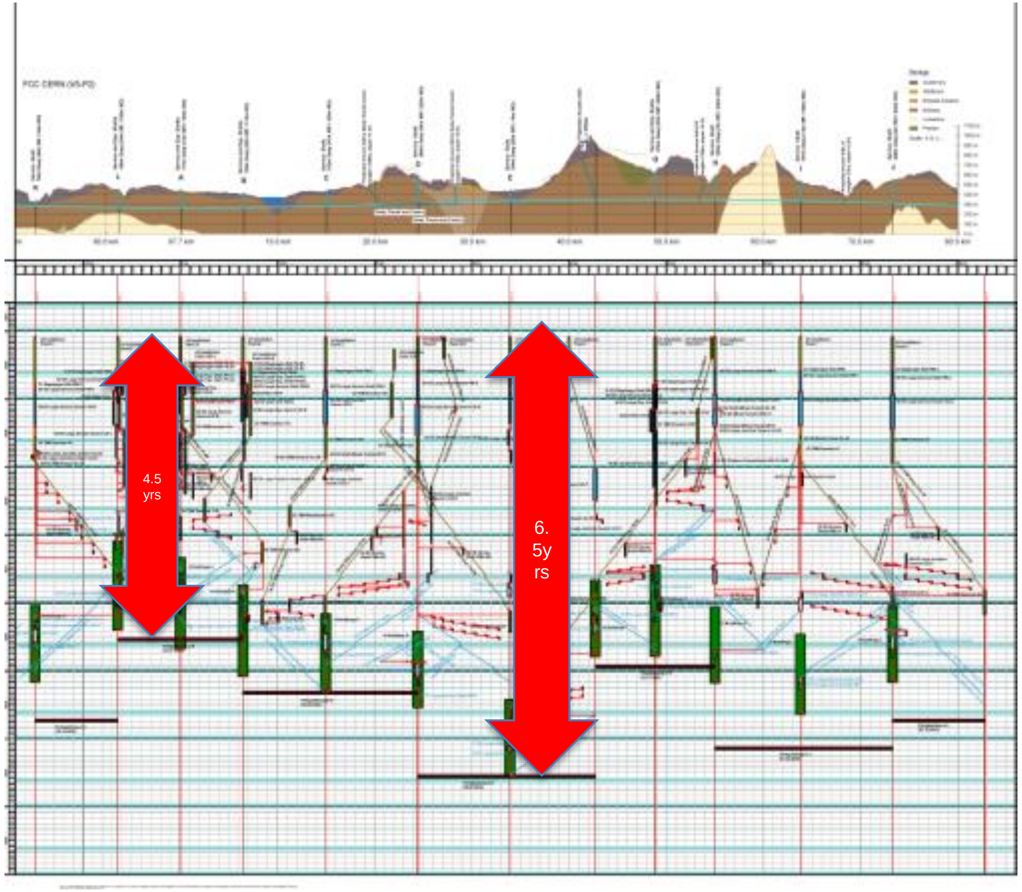


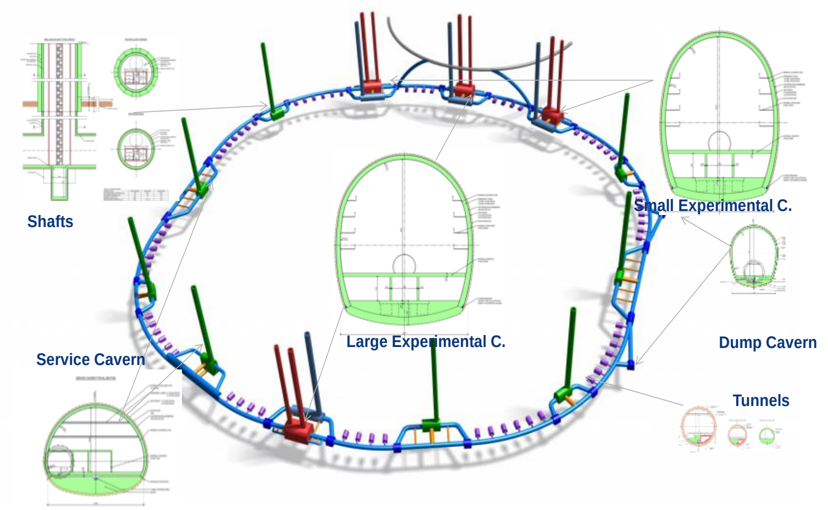


- **Present baseline position was established considering:**
- lowest risk for construction, fastest and cheapest construction
- feasible positions for large span caverns (most challenging structures)

- **More than 75% tunnel in France, 8 (9) / 12 access points in France.**
- **next step review of surface site locations and machine layout**

Civil Engineering studies



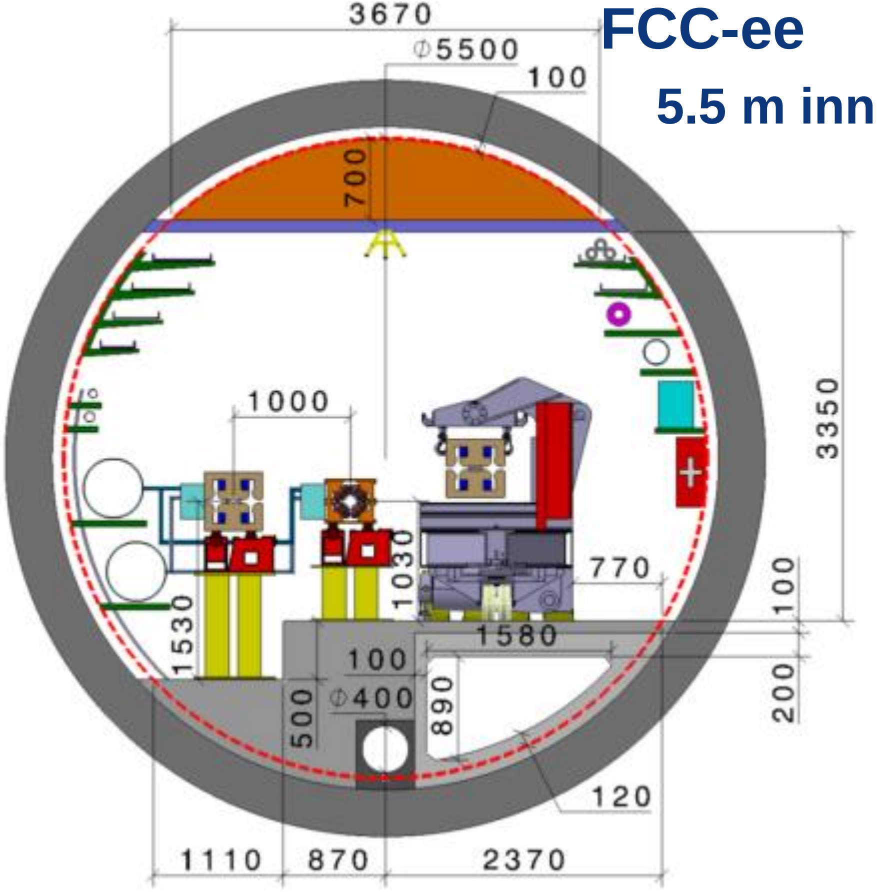


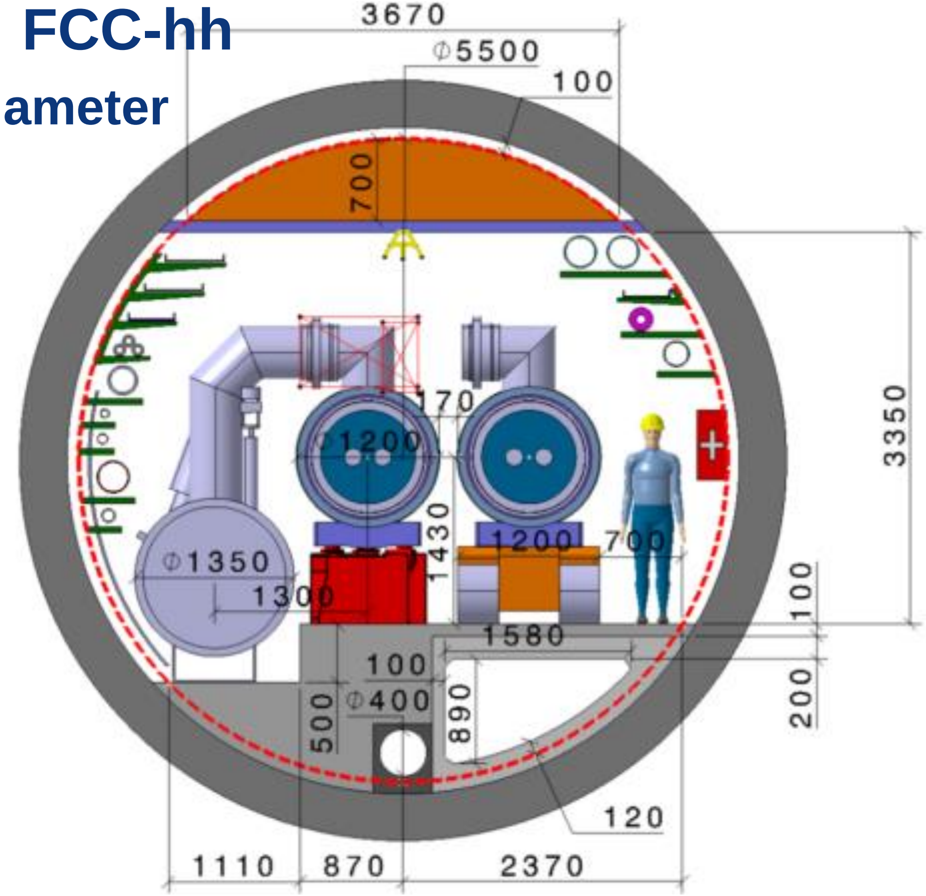
- **Total construction duration 7 years**
- **First sectors ready after 4.5 years**

FCC-tunnel integration in arcs

FCC-ee **FCC-hh**

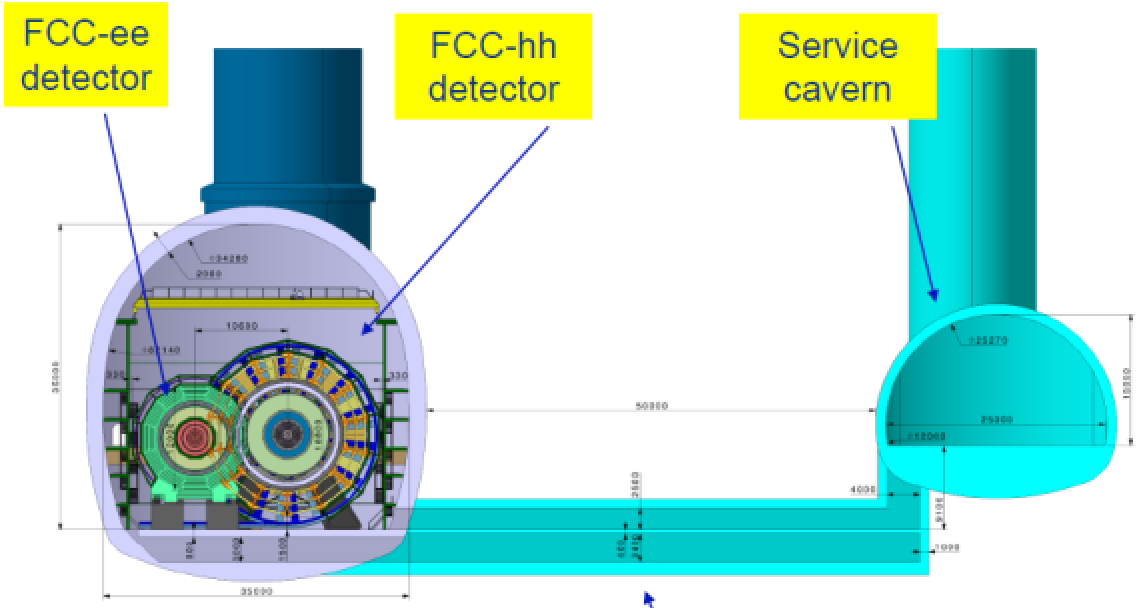
5.5 m inner diameter

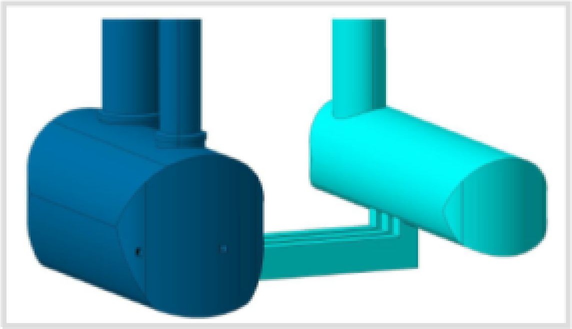




Common experimental points (A, G)

Distance between detector cavern and service cavern 50 m.
Strayfield of unshielded detector solenoid < 5mT.





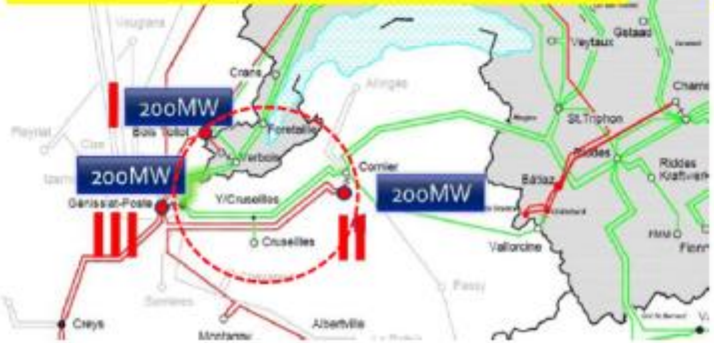
Preliminary design of access and cable paths

FCC-ee el. power consumption [MW]

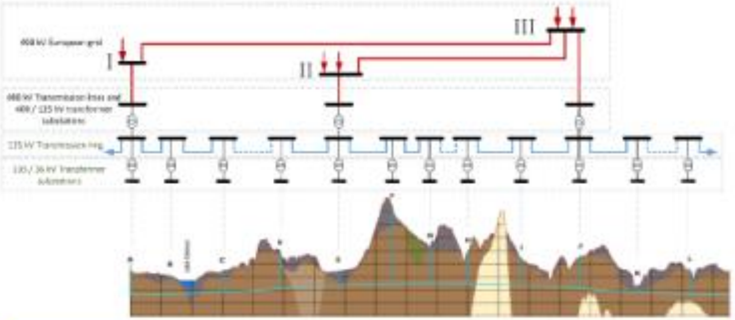
Beam energy (GeV)	45.6 Z	80 W	120 ZH	182.5 ttbar
RF (SR = 100)	163	163	145	145
Collider cryo	1	9	14	46
Collider magnets	4	12	26	60
Booster RF & cryo	3	4	6	8
Booster magnets	0	1	2	5
Pre injector	10	10	10	10
Physics detector	8	8	8	8
Data center	4	4	4	4
Cooling & ventilation	30	31	31	37
General services	36	36	36	36
Total	259	278	282	359

Supply and distribution of electrical energy

Additional 200 MW available for FCC at each of the three 400 kV sources.

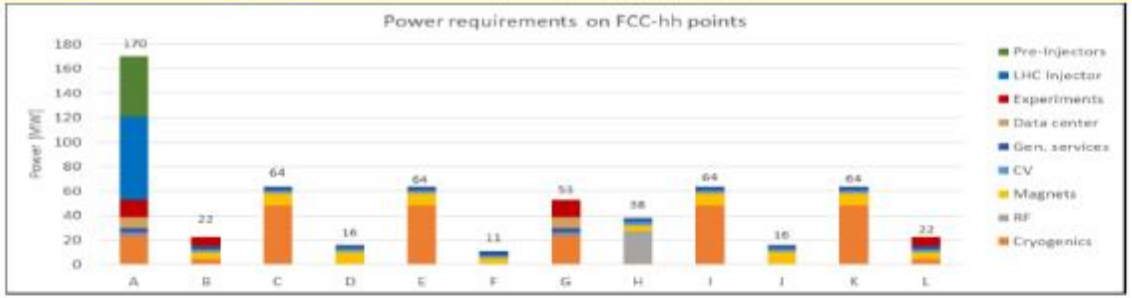


---- 400 kV ---- 230 kV

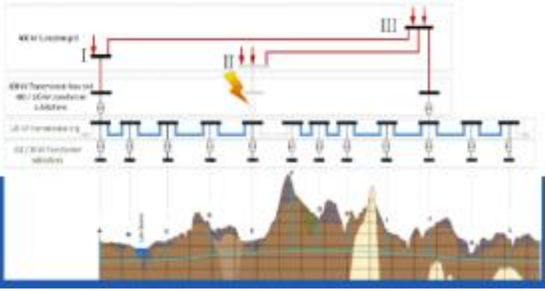


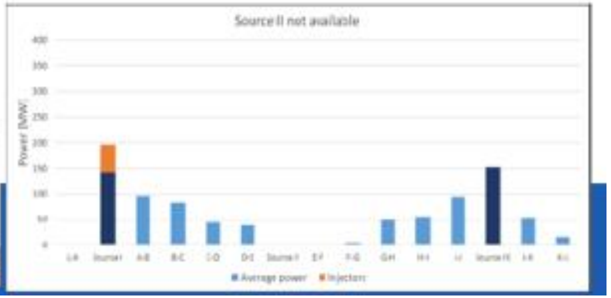
3 x 400 kV connections
+ 135 kV underground power distribution (NC)

Per-point power requirements as input for infrastructure-optimized conceptual design. (Peak FCC-ee 260 - 340 MW, total FCC-hh 550 MW)



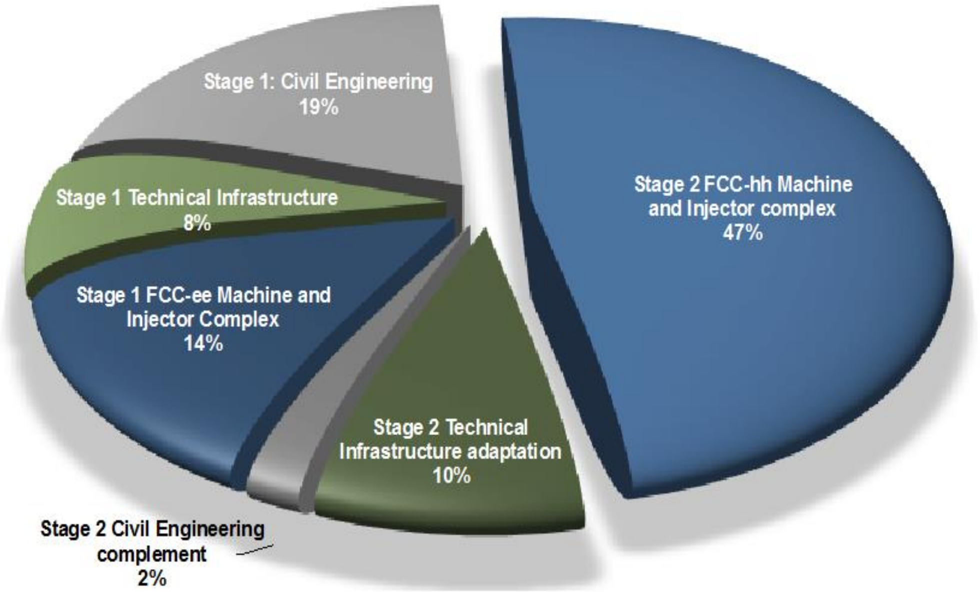
If one power source goes down fall back to „degraded mode": FCC remains cold, vacuum preserved, controls on, RF off, no beam ("standby"). All FCC points supplied from 2 other 400 kV points, through the power transmission line.





FCC-integrated cost estimate

Domain	Cost in MCHF
Stage 1 - Civil Engineering	5,400
Stage 1 - Technical Infrastructure	2,200
Stage 1 - FCC-ee Machine and Injector Complex	4,000
Stage 2 - Civil Engineering complement	600
Stage 2 - Technical Infrastructure adaptation	2,800
Stage 2 - FCC-hh Machine and Injector complex	13,600
TOTAL construction cost for integral FCC project	**28,600**



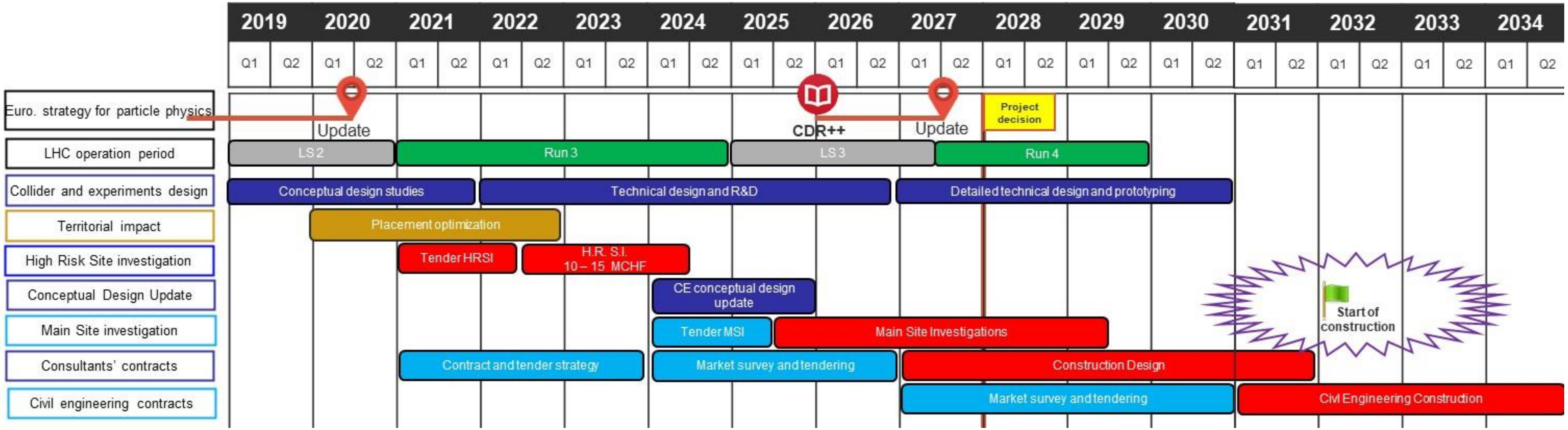
Total construction cost FCC-ee (Z, W, H) amounts to 10,500 MCHF & 1,100 MCHF (tt).

- Associated to a total project duration of ~20 years (2025 – 2045)

Total construction cost for subsequent FCC-hh amounts to 17,000 MCHF.

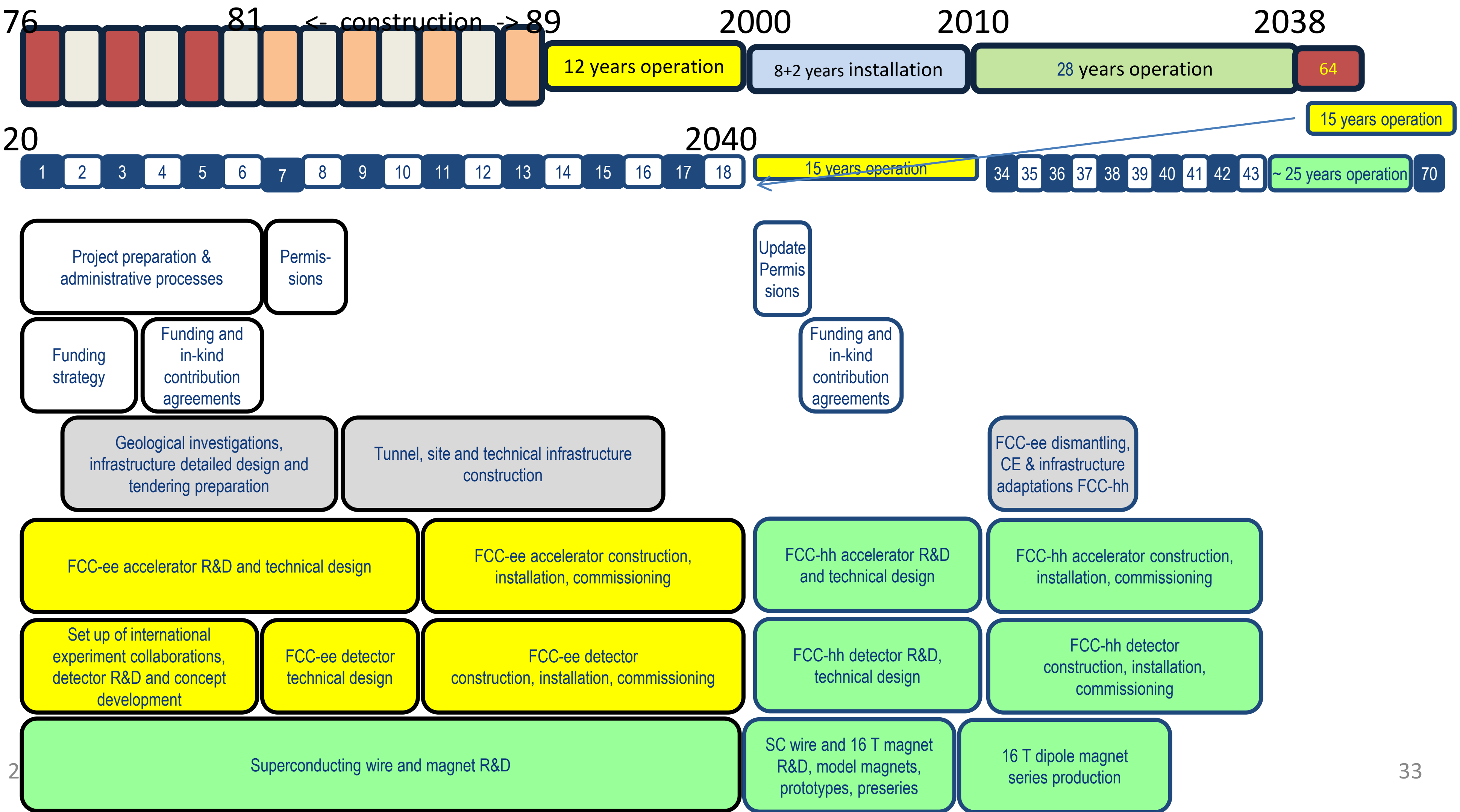
- Associated to a total project duration of ~25 years (2035 – 2060) (FCC-hh stand alone 25 BCHF)

Civil Engeneering preparatory activities 2020 - 2030



- **Technical schedule of main processes leading to start of construction begin 2030ies**
- **For proof of principle feasibility: High risk area site investigations, 2022 – 2024**
- **Followed by update of civil engineering conceptual design and CE cost estimate 2025**

FCC-INT timeline, compared with LEP/LHC



CHALLENGE 1 : why do we need a new accelerator after the LHC?

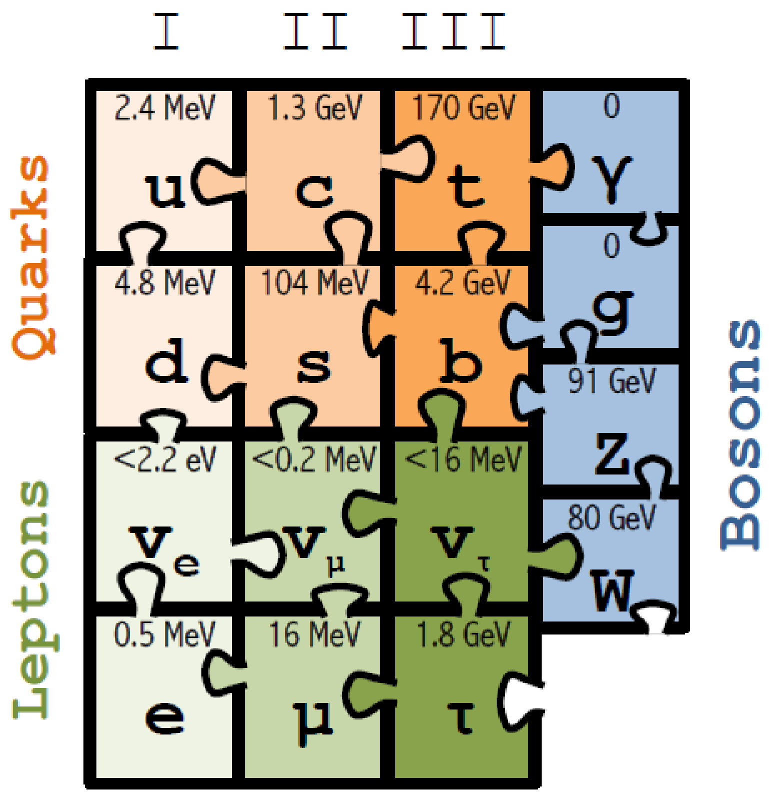
Particle physics has arrived at an important moment of its history

The expression 'Standard Model' appeared in 1976 after the discoveries of

-- neutrino Neutral currents (Z boson exchange) in 1973 and
-- Charmed particles (BNL, SLAC) in 1974-76

since then we have been discovering all the particles that have
electric charge or **QCD** **charge**, or **weak isospin** (SM couplings)
by increasing accelerator energies.

1989-1999: top mass predicted (LEP, mostly Z mass&width)
top quark discovered (Tevatron)
t'Hooft and Veltman get Nobel Prize 1999

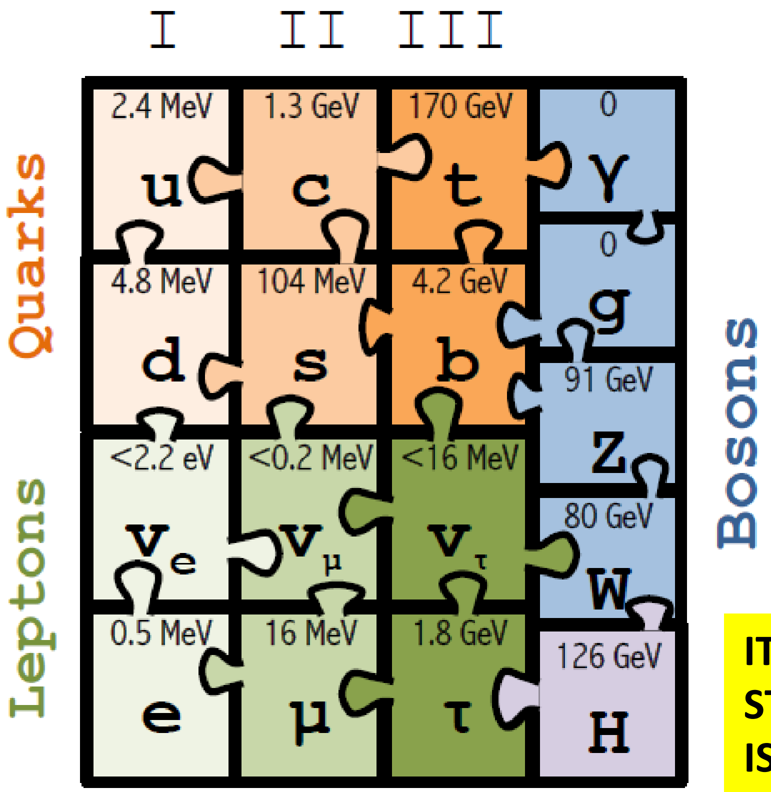


(c) Sfyrla

1997-2013 Higgs boson mass cornered (LEP H, M_Z etc +Tevatron m_t , M_W)

Higgs Boson discovered (LHC)

Englert and Higgs get Nobel Prize 2013

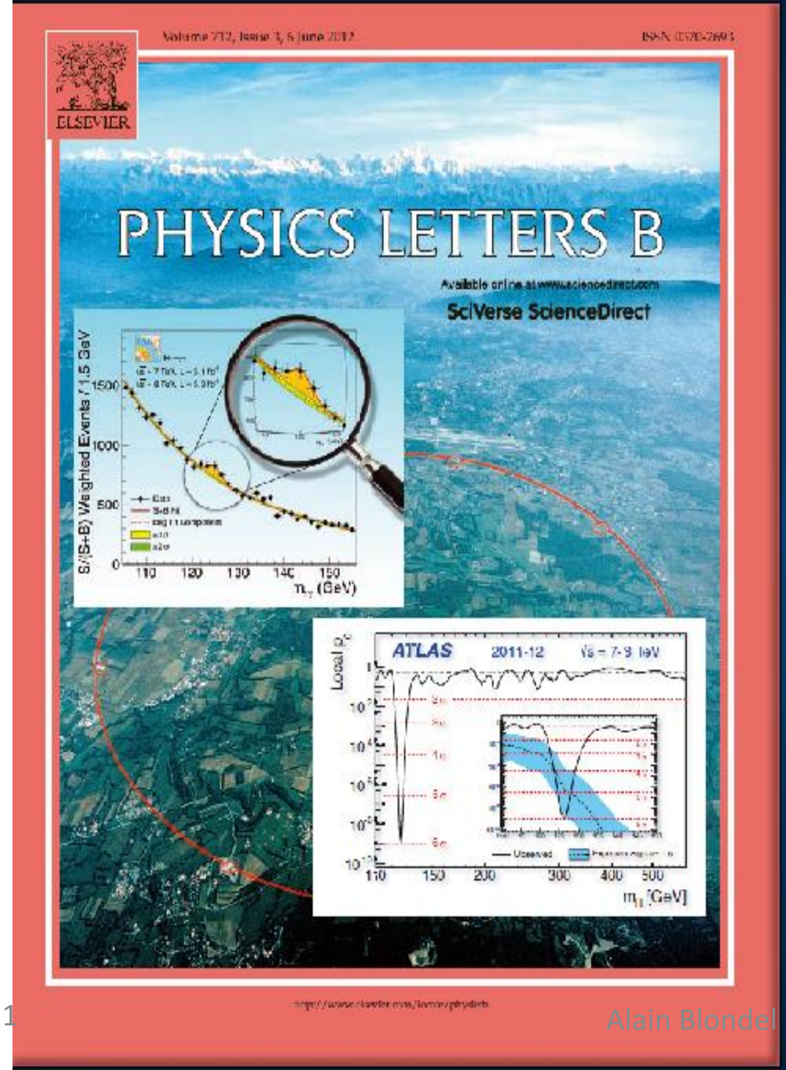


NB in fact we know from oscillations and cosmology that all 3 neutrino masses are less than ~0.1 eV

IT LOOKS LIKE THE STANDARD MODEL IS COMPLETE.....

(c) Sfyrla

EIGHT YEARS AGO ALREADY



The Standard Model is a very consistent and complete theory.

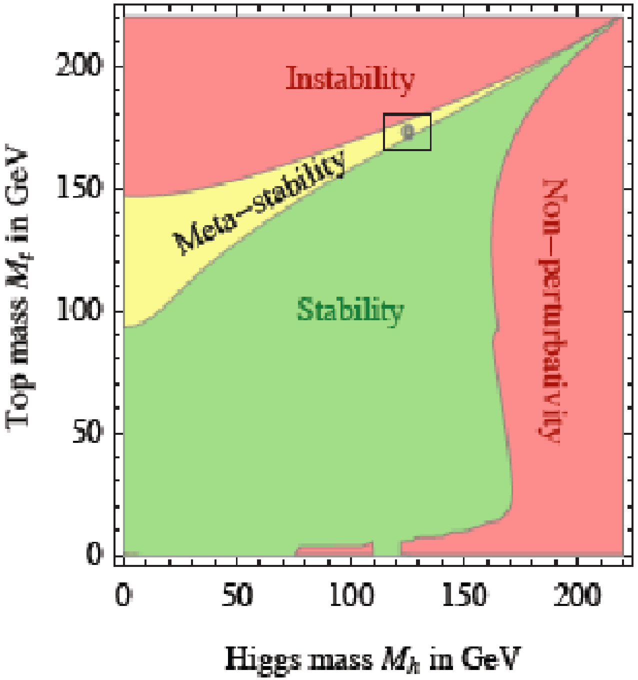
It explains all known collider phenomena and almost all particle physics (except ν's)

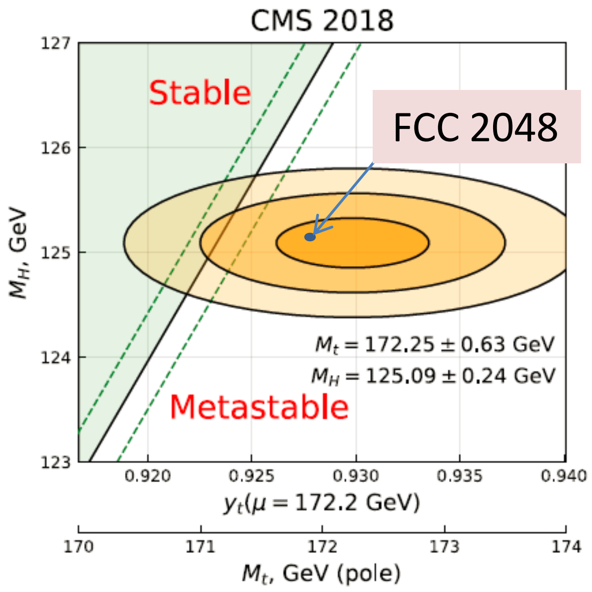
– this was beautifully verified at LEP, SLC, Tevatron and the LHC.

-- the EWPO radiative corrections predicted top and Higgs masses

assuming SM *and nothing else*

we can even extrapolate the Standard Model all the way to the the Plank scale :





FCC

arXiv:0912.0208v2 [hep-th] 12 Jan 2010

Asymptotic safety of gravity and the Higgs boson mass

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12 January 2010

Abstract

There are indications that gravity is asymptotically safe. The Standard Model (SM) plus gravity could be valid up to arbitrarily high energies. Supposing that this is indeed the case and assuming that there are no intermediate energy scales between the Fermi and Planck scales we address the question of whether the mass of the Higgs boson m_H can be predicted. For a positive gravity induced anomalous dimension $A_\lambda > 0$ the running of the quartic scalar self interaction λ at scales beyond the Planck mass is determined by a fixed point at zero. This results in $m_H = m_{\min} = 126$ GeV, with only a few GeV uncertainty. This prediction is independent of the details of the short distance running and holds for a wide class of extensions of the SM as well. For $A_\lambda < 0$ one finds m_H in the interval $m_{\min} < m_H < m_{\max} \simeq 174$ GeV, now sensitive to A_λ and other properties of the short distance running. The case $A_\lambda > 0$ is favored by explicit computations existing in the literature.

Key words:
Asymptotic s…
PACS: 04.60.…

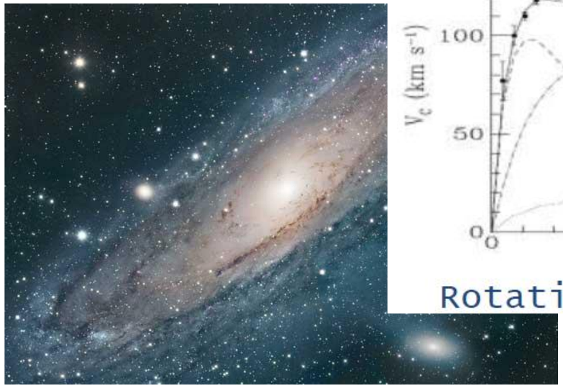
Detecting the Higgs scalar with mass around 126 GeV at the LHC could give a strong hint for the absence of new physics influencing the running of the SM couplings between the Fermi and Planck/unification scales.

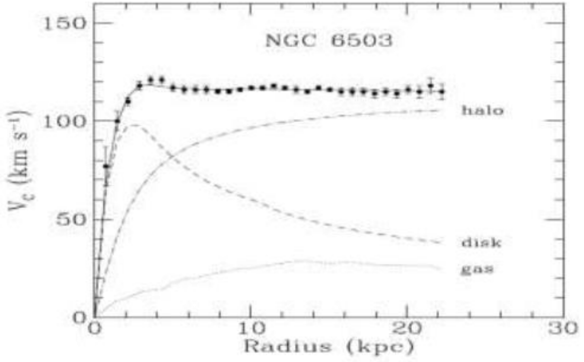
Is it the end?

We cannot explain:

Dark matter

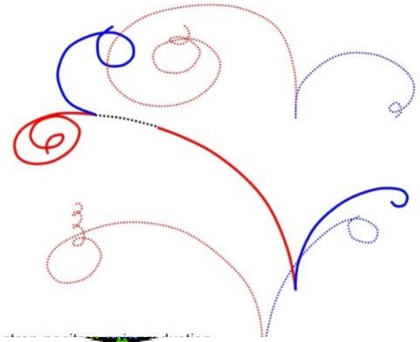
Standard Model particles constitute only 5% of the energy in the Universe





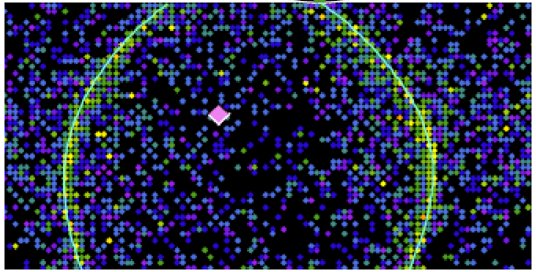
Rotation curve for Galaxy

Were is antimatter gone?



What makes neutrino masses?

Not a unique solution in the SM --
Dirac masses (why so small?)
Majorana masses (why not Dirac?)
Both (the preferred scenarios, see-saw...) ?
➔ heavy right handed neutrinos?



Is it the end?

Certainly not!

-- Dark matter

-- Baryon Asymmetry in Universe

-- Neutrino masses

these facts require particle physics explanations.

To which, one can add many theoretical questions on the SM

are experimental proofs that there is more to understand.

We must continue our quest, but HOW?

Direct observation of new particles (but not only!)

New phenomena (ex: Neutral currents, neutrino oscillations, CP violation..)

Deviations from precise predictions

(ref. Uranus to Neptune, Mercury's perihelion,
top and Higgs predictions from LEP/SLC/Tevatron/B factories, g-2, etc…)

The Physics Landscape

We are in a fascinating situation: where to look and what will we find?

For the first time since Fermi theory, <u>WE HAVE NO SCALE</u>

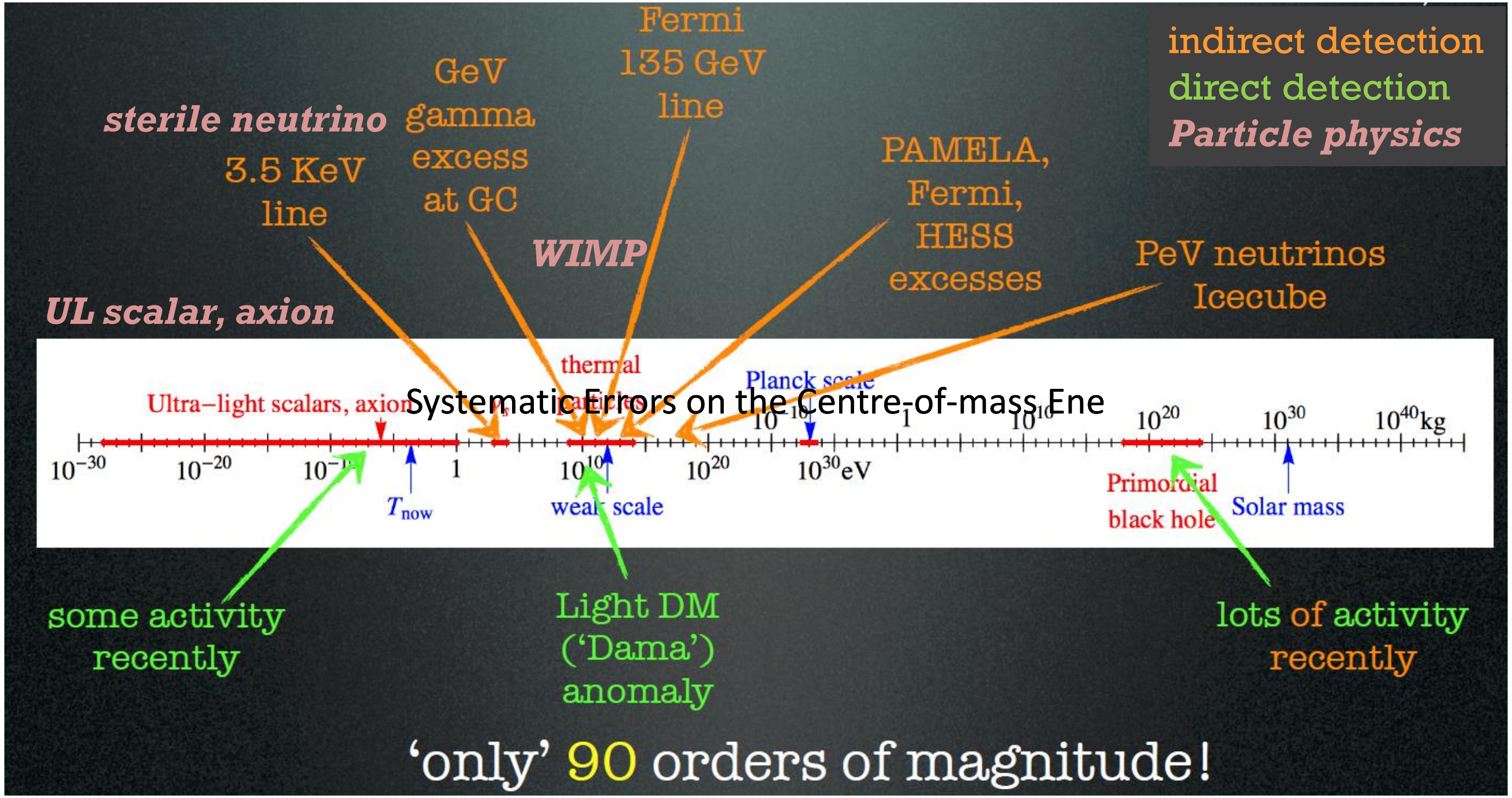
The next facility must be versatile with as broad and powerful reach as possible, as there is no precise target

<u>→ more Sensitivity, more Precision, more Energy</u>

FCC , thanks to synergies and complementarities, offers
the most versatile and adapted response to today's physics landscape,

Dark Matter exists. It is made of very long lived neutral particle(s).

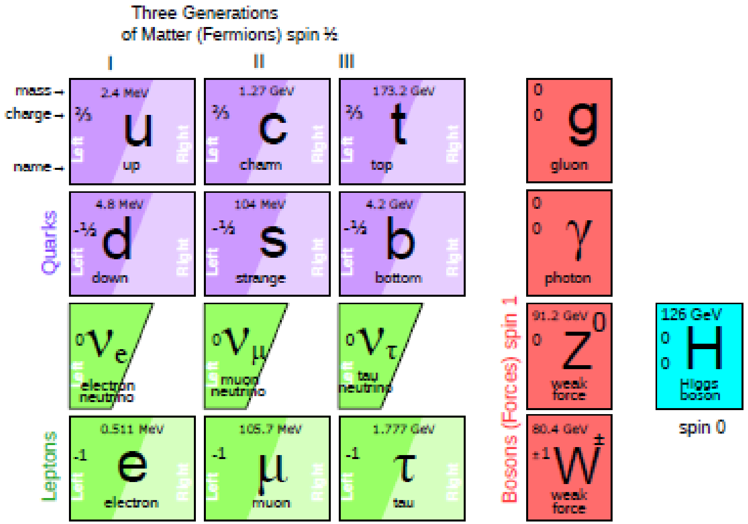
Plausible candidates:

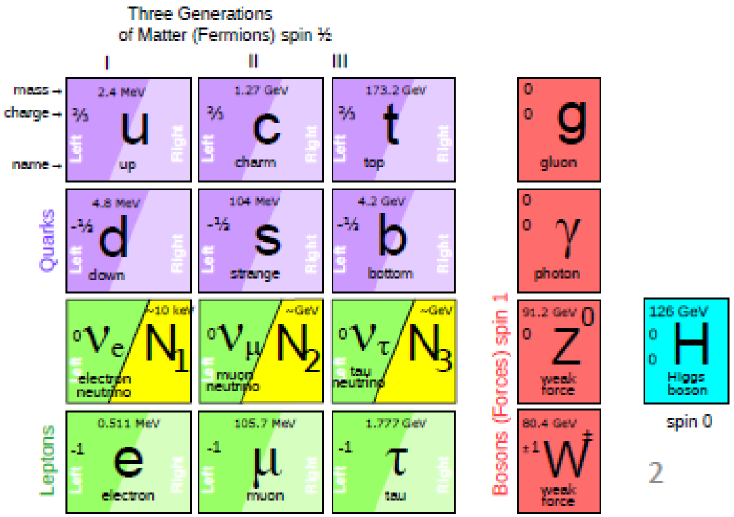


Systematic Errors on the Centre-of-mass Ene

Cirelli

at least 3 pieces are still missing





Since 1998 it is established that neutrinos have mass (oscillations) and this very probably implies new degrees of freedom

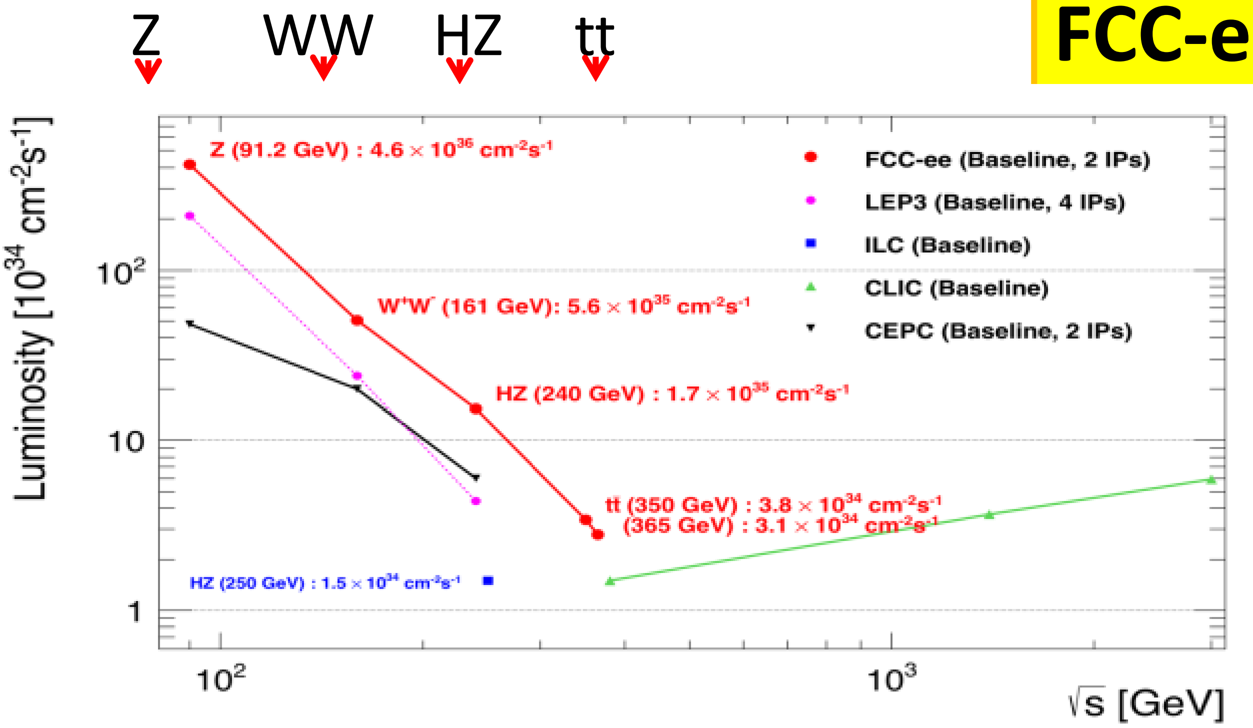
➔ «sterile», very small coupling to known particles

completely unknown masses (eV to ZeV), nearly impossile to find.

.... but could perhaps explain all: DM, BAU,ν-masses

FCC

FCC-ee



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	10^8 e+e- → WW	LEP x 2.10^3	<300 keV
ZH threshold	E_{cm} : 240 GeV	10^6 e+e- → ZH	Never done	2 MeV
$t\bar{t}$ threshold	E_{cm} : 350 GeV	10^6 e+e- → $t\bar{t}$	Never done	5 MeV

Great energy range for the heavy particles of the Standard Model.

FCC-ee run plan

Table 2.1: Run plan for FCC-ee in its baseline configuration with two experiments. The number of WW events is given for the entirety of the FCC-ee running at and above the WW threshold.

from the CDR

Phase	Run duration (years)	Center-of-mass Energies (GeV)	Integrated Luminosity (ab^{-1})	Event Statistics
FCC-ee-Z	4	88-95	150	3×10^{12} visible Z decays
FCC-ee-W	2	158-162	12	10^8 WW events
FCC-ee-H	3	240	5	10^6 ZH events
FCC-ee-tt	5	345-365	1.5	10^6 $t\bar{t}$ events

1. Obviously this is a working assumption; order of Z,W and H points can be changed, this will all be decided close to turn on.

2. e+e- → H (ECM = m_H) unique, not in the schedule so far.

3. Transerse polarization → precision beam energy.
   Longitudinal possible (for both beams) but not in CDR by choice

Physics at FCC-ee

1. HIGGS FACTORY

Higgs provides a very good reason why we need e+e- (or $\mu\mu$) collider

2. ELECTROWEAK PRECISION (10^{-3} today → 10^{-5})

Z + WW + top required!

This is a test of the completeness of the SM

existence of weakly interacting new particles

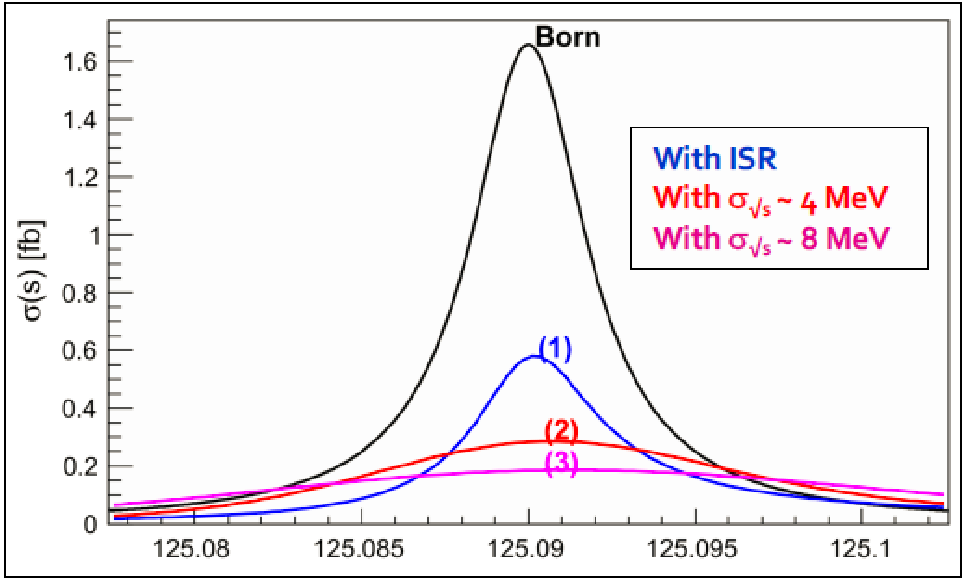
3. Z FACTORY (5 10^{12} Z)

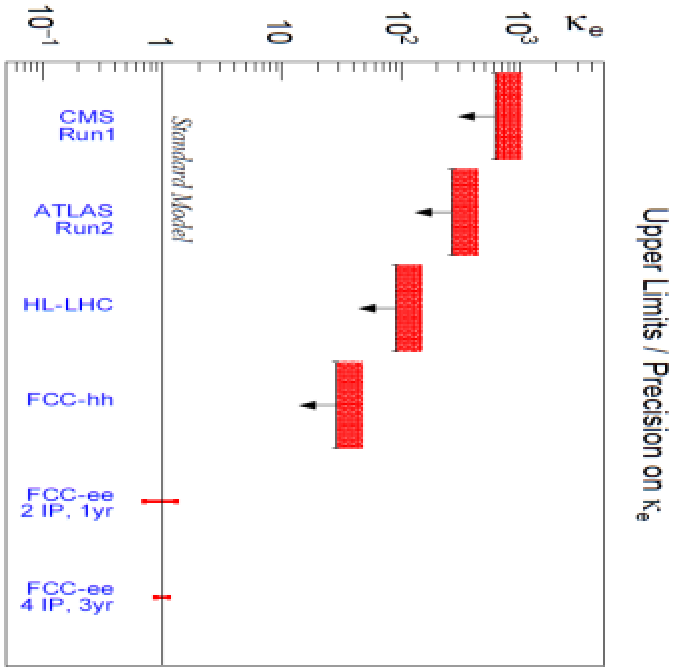
High statistics for Heavy Flavours and Search for Feebly Coupled Particles

The place for 'direct discovery'

+ comments on the synergy and complementarity of FCC-ee hh and eh

Something unique!





HUGE CHALLENGE

e+e- → H @ 125.xxx GeV requires

-- Higgs mass to be known to <5 MeV from 240 GeV run (CEPC group almost there)

-- **Huge luminosity**

-- **monochromatization** (opposite sign dispersion using magnetic lattice) to reduce σ_{ECM}

-- **continuous monitoring and adjustment of E_{CM}** to MeV precision (transv. Polar.)

-- an extremely sensitive event selection against backgrounds

-- a generous lab director to spend 3 years doing this and neutrino counting

FCC-ee Detectors

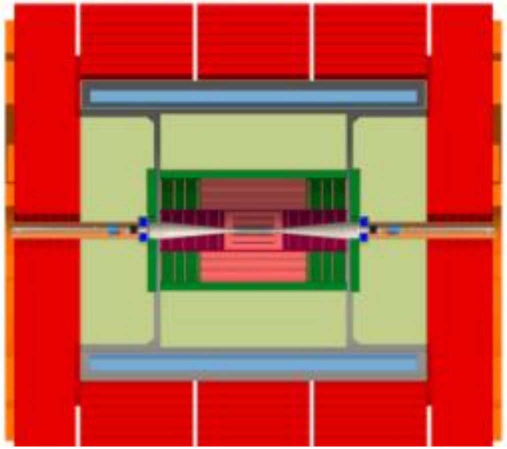
Detectors can be done and work for the FCC-ee but physics optimization remains to be done.

Two integration, performance and cost estimates:

-- Linear Collider Detector group at CERN has undertaken the adaption of CLIC-SID detector for FCC-ee

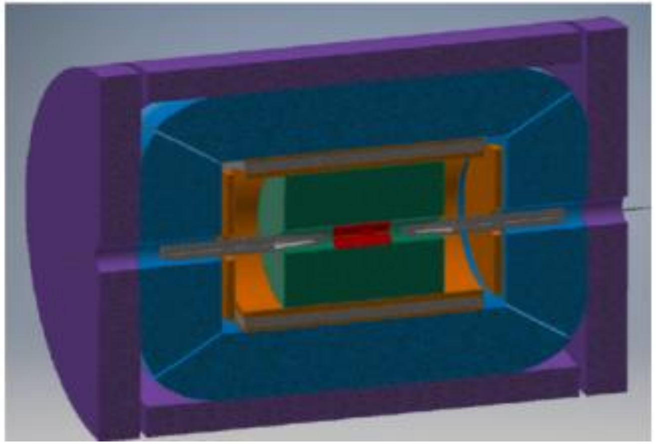
-- IDEA, detector specifically designed for FCC-ee (and CEPC)

"CLIC-detector revisited"



SiD at ILC, CLD at FCC-ee

"IDEA"



IDEA at FCC-ee & CEPC

- Vertex detector: ALICE MAPS
- Tracking: MEG2
- Si Preshower
- Ultra-thin solenoid (2T)
- Calorimeter: DREAM
- Equipped return yoke

Many challenges to come mainly because of the Z run.

The Z peak

Is the most unique, most challenging and (once you get used to it) the most promising part of the program!

Trivia:

L = 230 /cm^2 /s and 35 nb of Z cross section corresponds to 80 kHZ of events with typ. 20 charged and 20 neutral particles
(all to be preciously and fully recorded, stored, reconstructed)

3 years at 10^7 s /year = 2.4 10^{12} evts per exp.

Processing time 1ms/evt → 240 years of processing…. + Monte Carlo.

FCC-ee discovery potential and Highlights

Today we do not know how nature will surprise us. A few things that FCC-ee could discover :

EXPLORE 10-100 TeV energy scale (and beyond) with Precision Measurements

-- ~20-100 fold improved precision on many EW quantities (equiv. to factor 5-10 in mass)

m_Z, m_W, m_{top} , $\sin^2\theta_w^{eff}$, R_b , $\alpha_{QED}(m_z)$ $\alpha_s(m_z\, m_W\, m_\tau)$, Higgs and top quark couplings

model independent «fixed candle» for Higgs measurements, ee-H coupling.

DISCOVER a violation of flavour conservation or universality and unitarity of PMNS @10^{-5}

-- ex FCNC (Z --> $\mu\tau$, $e\tau$) in 5 10^{12} Z decays and τ BR in 2 10^{11} Z→ $\tau\tau$

+ flavour physics (10^{12} bb events) (B→s $\tau\tau$ etc..)

DISCOVER dark matter as «invisible decay» of H or Z (or in LHC loopholes)

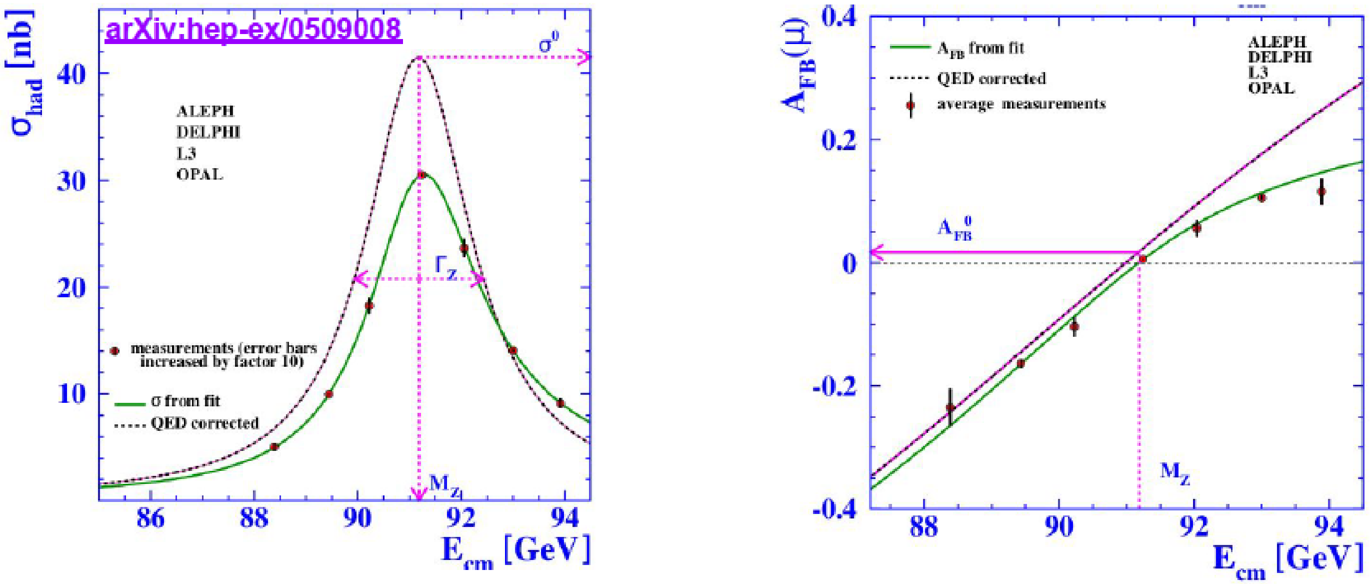
DISCOVER very weakly coupled particle in 5-100 GeV energy scale

such as: Right-Handed neutrinos, Dark Photons, ALPS, etc…

+ and many opportunities in – e.g. QCD (α_s @ 10^{-4}, fragementations, H→ gg) etc….

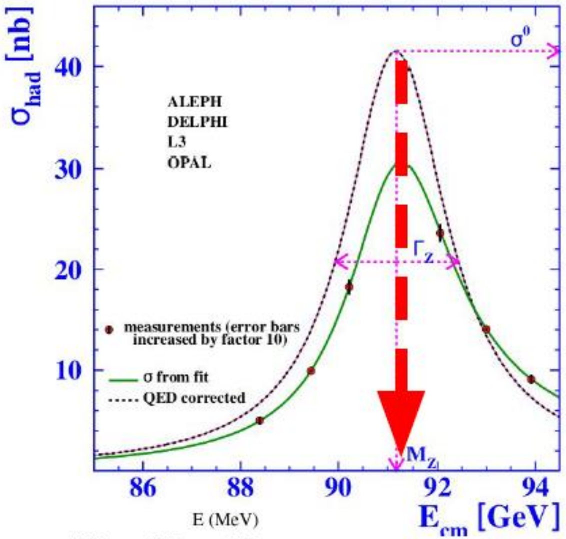
NB Not only a «Higgs Factory»! «Z factory» and «top» are important for 'discovery potential'

Z lineshape measurements

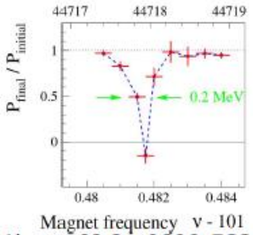


- Expected precisions in a nutshell:
  - ≈ 10^{-4} on cross sections (aimed luminosity uncertainty); possibility to reduce it by an order of magnitude using the measured $\sigma(ee\to\gamma\gamma)$ as reference
  - ≈ 10^{-6} statistical uncertainties (≈ 1/ √N) on relative measurements like forward-backward charge asymmetries
  - Ultimate uncertainties typically dominated by systematics; precious value of “Tera” Z samples to study / constrain many of those uncertainties

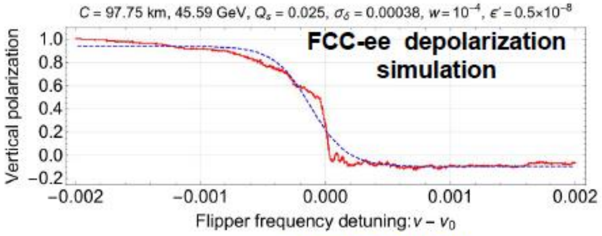
Z lineshape: mass



- m_Z: position of Z peak
- Beam energy measured with extraordinary precision ($\Delta\sqrt{s}\approx100$ keV) using resonant depolarization of transversely polarized beams (method already used at LEP, much better prepared now, calibrations in situ with pilot bunches, no energy extrapolations, …)
- Beam width/asymmetries studied analyzing the longitudinal boost distribution of the $\mu\mu$ system



Resonant depolarization at LEP

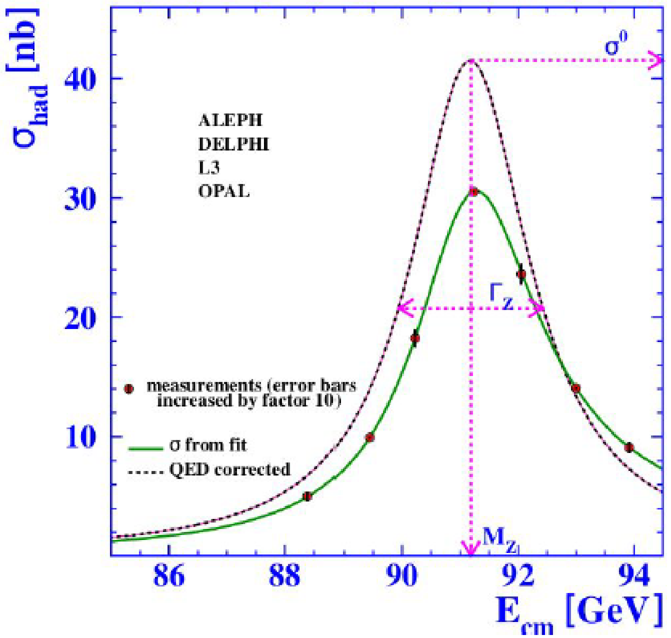


arXiv:1909.12245

J. Alcaraz, 23 Oct 2020, FCC-ee Z lineshape and EW HF

5

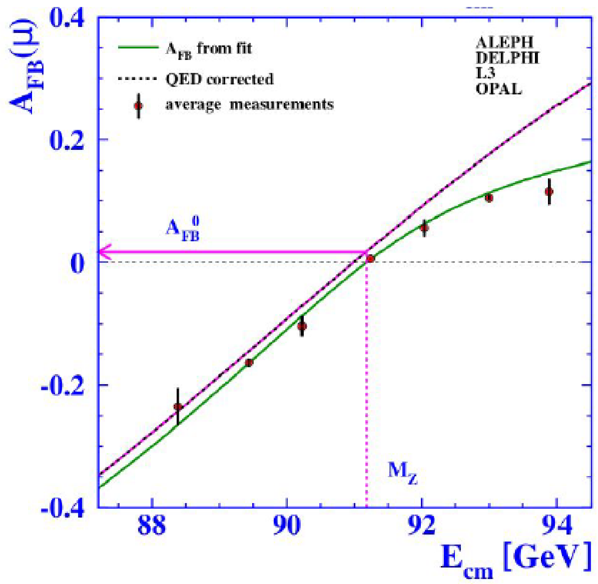
$R_l = \Gamma_{had} / \Gamma_l$



- Relative measurement, independent of luminosity: aiming for a 10^{-5} precision
- Extremely sensitive to new physics deviations (ϱ,T parameters: deviations of custodial symmetry)
- $\alpha_s(m^2_Z)$ modifies the hadronic partial width → R_l provides an ultra-precise measurement
- **Studies to define detector requirements to ensure negligible systematic uncertainties on acceptance (a priori more critical on leptons)**

J. Alcaraz, 23 Oct 2020, FCC-ee Z lineshape and EW HF 7

$\sin^2\theta_W^{eff}$ and $\alpha_{QED}(m^2_Z)$



- $\sin^2\theta_W$ effective: g_V/g_A coupling ratio → forward-backward charge asymmetries (most precise in $\mu\mu$ in final state)
- $\alpha_{QED}(m^2_Z)$: off-peak/peak evolution of the asymmetry (due to interference with γ^* exchange)
- Measurement approaching the ultimate statistical sensitivity: 3 x 10^{-6}
- 3 energy points (≈88, 91.2, 94 GeV)

- **Studies to establish the experimental/theoretical needs (energy resolutions, exact angular description at this level of precision, …)**

J. Alcaraz, 23 Oct 2020, FCC-ee Z lineshape and EW HF 8

M. Boscolo

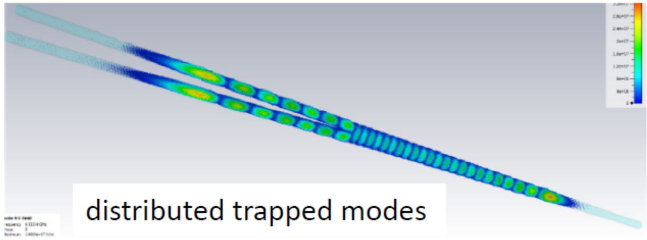
A. Jung, M. Mager

A new low impedance FCC-ee IR beam pipe

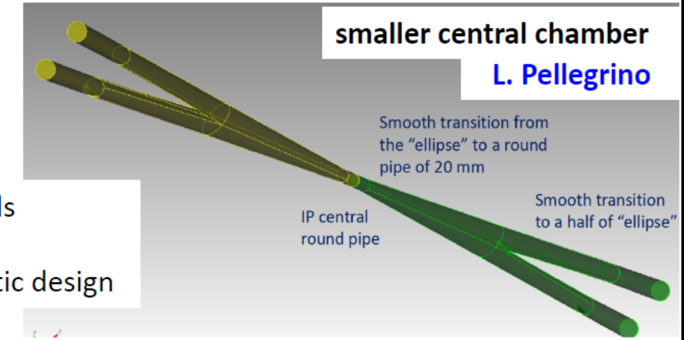
A. Novokhatski

Impact on heat load, wake fields, trapped modes has been evaluated with a new smaller central pipe and smooth geometry

We need only cooling of the beam pipe and no HOM absorber

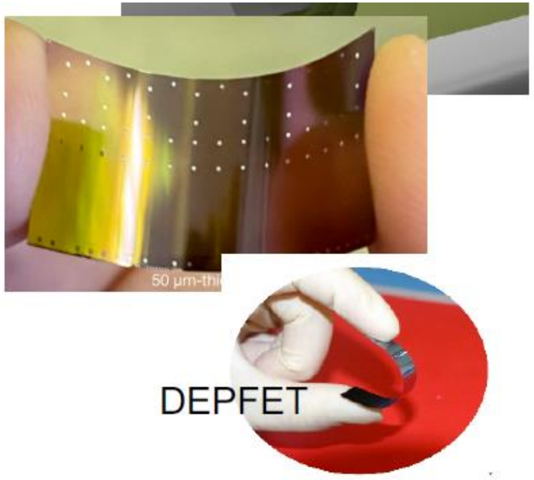


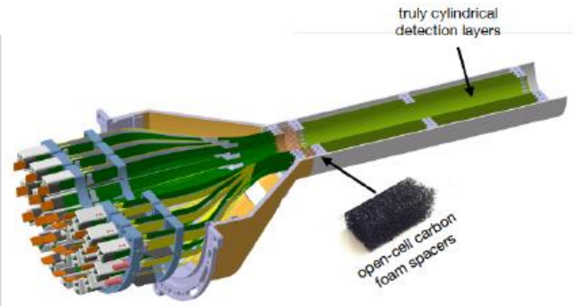
- A small loss factor and small heating power is found
- Double effect of smoothing the geometry with a smaller central pipe produced almost 10 times smaller heating power
- Heating power is **260 W** (two beams), main part will go away from IP
- Distributed trapped modes produce less than **200 W** (two beams)



This is the CAD design used for wake fields calculations,
Work has started for a feasible and realistic design

M.Boscolo, 13/11/2020





between vertex detector and beam pipe desing much progress in sight!

Systematic errors

-- a common mistake that was often made in ‘studies’ in the past is to underestimate the creativity of a 100% dedicated team to deconstruct a delicate systematic errors problem .
➔ systematic uncertainties were grossly overestimated

example: in the 1986 LEP yellow report Z mass (width) errors were given as 50(20) MeV
In reality the total final errors were 2 (2) MeV. (i.e. close to the statistical ones)
As a consequence we argued in the 1988 yellow report (polarization at LEP) that we should have longitudinal polarization to measure ALR (and $\sin^2\theta^{eff}_W$ *to +- 0.00035) (spin rotators etc..) because we could not measure* $\sin^2\theta^{eff}_W$ *better than +- 0.0008 (syst) otherwise.*
(final LEP: +-0.00016 without longitudinal polarization) (CERN 86-02, 88-06)
In the end LEP measured the Z mass 800 times better than the W.A. of 1986!

- This conservative behaviour can have considerable consequences on detector design or on the running plan e.g. (to scan or not to scan, longitudinal polarization or not…etc.)

Unless otherwise specified we would advocate the use of statistical errors (with appropriate selection efficiencies and background subtractions) as the best way to assess the physics potential of a facility.

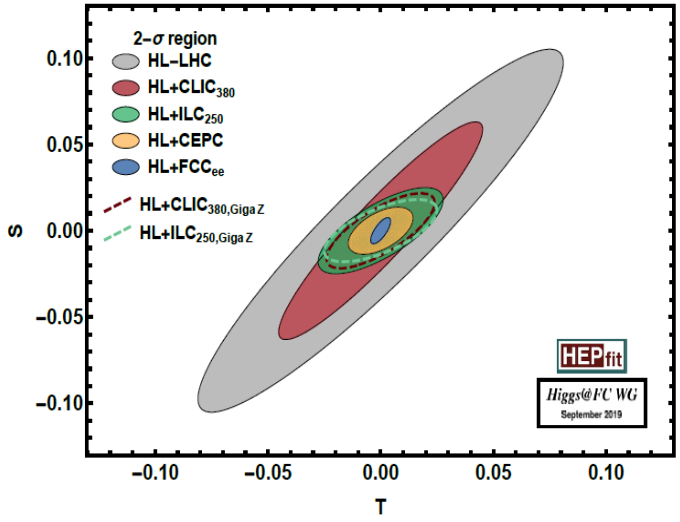
It is however important to concentrate on finding the potential ‘show stoppers’ or ‘stumbling blocks’, to guide the detector R&D and detector requirements , and Strong support for theoretical calculations will be needed if the program is to be successful

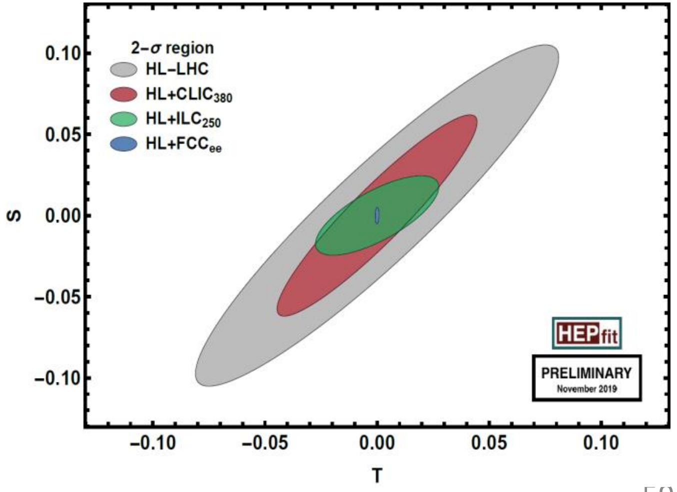
Electroweak Physics

Low Energy: the realm of FCC-ee

Highest luminosities at 91, 160 and 350 GeV
Transverse pol. at 91 and 160 GeV→Ecm calibration
m_Z (100 keV) Γ_Z (25 keV), m_W (<500 keV), $\alpha_{QED}(m_Z)$ (3.10^{-5})
and $\sin^2\theta_w$ at 310^{-6}

Complete set of EW observables can be measured
Precision unique to FCC-ee + new physics sensitivity
→ a lot more potential to exploit
with good detector design than present treatment suggests





The reach for new physics depends on which new physics:
-- $1/\Lambda^2$ new physics → 30-70 TeV
-- Heavy Neutrino → 500-1000 TeV
-- new non-degenerate doublet etc....
Challenge is to test specific models
and include all information including flavour

Tau physics at FCC-ee

Snowmass2021 - Letter of Interest

Tau lepton properties and lepton universality measurements at the FCC-ee

Thematic Areas:
- EF04: EW Physics: EW Precision Physics and constraining new physics
- EF03: EW Physics: Heavy flavor and top quark physics

Contact Information:
Mogens Dam (Niels Bohr Institute, Copenhagen University) [dam@nbi.dk]

Authors:
Alain Blondel[1], Mogens Dam[2], Patrick Janot[3]

LoI #252

Abstract:
The FCC-ee is a frontier Higgs, Top, Electroweak, and Flavour factory. It will be operated in a 100-km circular tunnel built in the CERN area, and will serve as the first step of the FCC integrated programme towards $\geq$ 100-TeV proton-proton collisions in the same infrastructure [1]. With its huge luminosity at Z-pole energies, unrivalled samples of 5×10^{12} Z decays will be produced at multiple interaction points. The five orders of magnitude larger statistics than at LEP opens the possibility of much improved measurements of τ-lepton properties—lifetime, (leptonic) branching fractions, and mass—in $\tau^+\tau^-$ final states. Such measurements provides interesting tests of lepton universality, in effect probing whether the Fermi coupling constant is the same in τ decays as in μ decays. The ultimate goal, that experimental errors match the statistical accuracy, leads to highly demanding requirements on detector design. This Letter of Interest describes some of the many challenges presented by this benchmark measurement.

Snowmass2021 - Letter of Interest

Tau exclusive branching fractions and tau polarisation observables at the FCC-ee

Thematic Areas:
- EF04: EW Physics: EW Precision Physics and constraining new physics
- EF05: QCD and strong interactions:Precision QCD

Contact Information:
Mogens Dam (Niels Bohr Institute, Copenhagen University) [dam@nbi.dk]

Authors:
Alain Blondel[1], Mogens Dam[2], Clement Helsens[3], Patrick Janot[3]

LoI #255

Abstract:
The FCC-ee is a frontier Higgs, Top, Electroweak, and Flavour factory. It will be operated in a 100-km circular tunnel built in the CERN area, and will serve as the first step of the FCC integrated programme towards $\geq$ 100 TeV proton-proton collisions in the same infrastructure [1]. With its huge luminosity at Z-pole energies, unrivalled samples of 5×10^{12} Z-decays will be produced at multiple interaction points. This opens the possibility for very precise measurements of τ leptons including their exclusive branching fractions and their polarisation in Z decays, one of the most precise electroweak observables. This letter of interest concentrates on some of the main experimental challenges in τ-lepton measurements, namely the inter-channel separation and the precise measurement of the final state kinematics. This relies critically on the precise measurement of photons and π^0s (and other neutral particles) in the calorimeter system, on the precise tracking of high-multiplicity collimated topologies, and—at least for the exclusive branching fractions—on the ability to separate pions from kaons over the full momentum range.

τ-lepton properties and Lepton Universality

Snowmass2021 - Letter of Interest

Tau lepton properties and lepton universality measurements at the FCC-ee

Thematic Areas:
■ EF04: EW Physics: EW Precision Physics and constraining new physics
■ EF03: EW Physics: Heavy flavor and top quark physics

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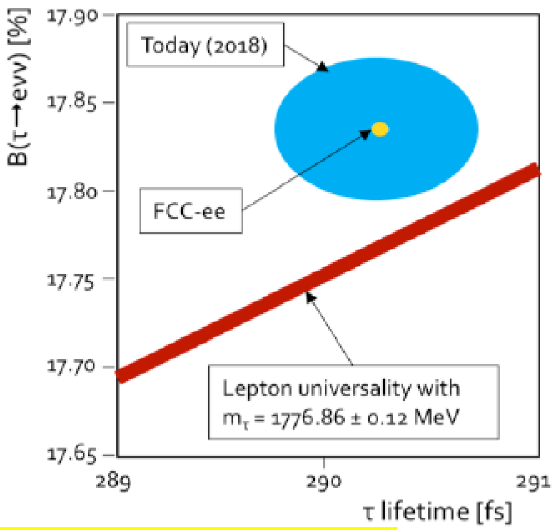
a) Mass
b) Lifetime
c) Leptonic branching fractions



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This measurement is sensitive to heavy neutrino mixing with the ν_τ

Tau Mass (i)

- **Current world average:** $m_\tau = 1776.86 \pm 0.12$ MeV
- Best in world: BES3 (threshold scan) $m_\tau = 1776.91 \pm 0.12$ (stat.) $^{+0.10}_{-0.13}$ (syst.) MeV
- Best at LEP: OPAL $m_\tau = 1775.1 \pm 1.6$ (stat.) $\pm$ 1.0 (syst.) MeV

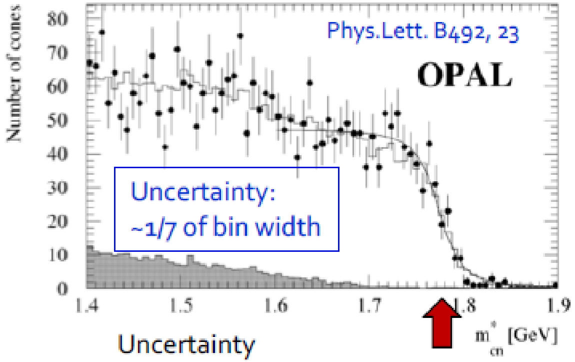
- Prospects for FCC-ee:
  - 3 prong, 5 prongs, (perhaps even 7 prongs?)
  - Statistics 10^5 times OPAL: $\delta_{stat} = 0.004$ MeV
  - Systematics:
    - At FCC-ee, E_{BEAM} determined to better than 0.1 MeV (~ 1 ppm) from resonant spin depolarisation
      - Negligible effect on m_τ
    - Control of mass scale
      - Suggest to exploit 10^9 J/ψ → μμ from Z decays as reference, with m(J/ψ) known to 0.006 MeV (2 ppm) from KEDR
    - Reduce uncertainty from parametrisation of spectrum edge by use of theoretical spectrum checked against high statistics data
    - Cross checks using 5-prongs
  - Overall systematics:
    - Study to be performed to shed more light on this. Improvement with respect to current measurements seems possible. Sugg…

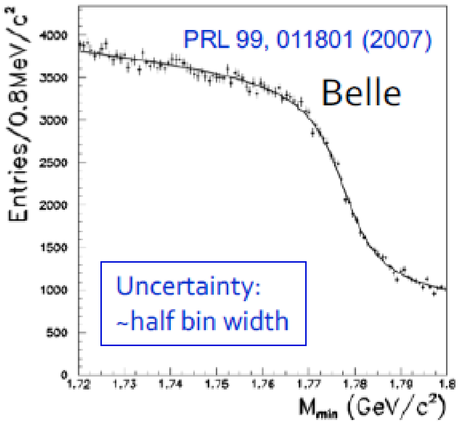
      $\delta_{syst} \lesssim 0.04$ MeV

Don't be shy! 0.004

⇒ **Key:** precise control of momentum scale also in dense, multi-prong topologies

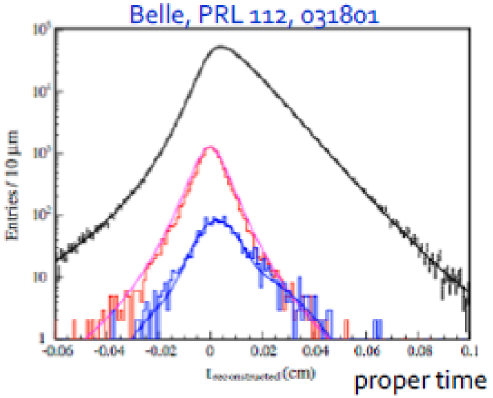
Pseudo-mass: $M_{min} = \sqrt{M_{3\pi}^2 + 2(E_{beam} - E_{3\pi})(E_{3\pi} - P_{3\pi})}$





Tau Lifetime (i)

- **Current world average:** $\tau_\tau = 290.3 \pm 0.5$ fs
- **Best in world** (Belle): $\tau_\tau = 290.17 \pm 0.53_{\text{stat}} \pm 0.22_{\text{syst}}$ fs
    - Large statistics: 711 fb^{-1} @ Υ(4s): 6.3×10^8 $\tau^+\tau^-$ events



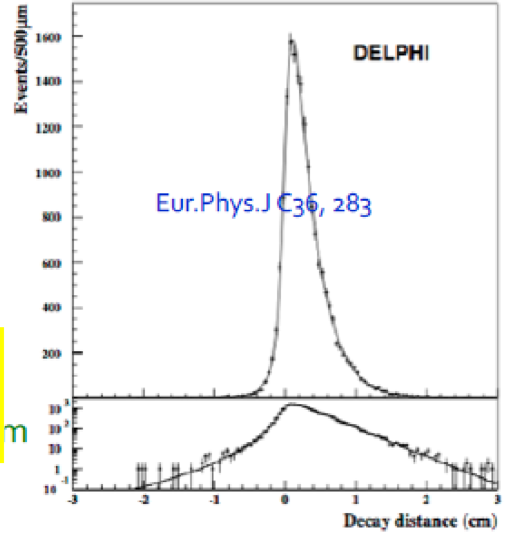
- Prospects at FCC-ee
    - Small beam-pipe radius (15 mm): Vertex detector with 3 μm space points at 18, 38, 58 mm [DELPHI: 7.5 μm @63, 90, 109 mm]
    - Impact parametre resolution ~5 times better than at LEP for relevant momenta
        - DELPHI: a = 20 μm, b = 65 μm
        - Belle: a = 19 μm, b = 50 μm
        - FCC-ee: a = 3 μm, b = 15 μm

$$\sigma(d_0) = \sqrt{a^2 + b^2 \cdot GeV^2/(p^2 \sin^3(\theta))}.$$

- Assume same alignment uncertainty as Belle:
    - 0.25 μm, i.e. factor 30 improvement wrt DELPHI.
    - Possible systematics on flight distance method: 1.3/30 fs

$\delta_{\text{syst}} = 0.04$ fs ; $\delta_{\text{stat}} = 0.001$ fs

Don't be shy! 0.001



- Further prospects: lifetime can be measured with different systematics in many modes
    - 1v1: impact parameter difference, miss distance
    - 1v3: flight distance
    - 3v3 (4×10^9 events): flight distance sum

This corresponds to knowing the radius of the vtx det to ± 5nm

⇒ **Key:** Careful design and precise control of vertex detector

More on TeraZ

The Flavour Factory

Progress in flavour physics wrt SuperKEKb/BELLEII requires > 10^{11} b pair events,
FCC-ee(Z): will provide ~10^{12} b pairs. "**Want at least 5 10^{12} Z…"**

-- precision of CKM matrix elements
-- Push forward searches for FCNC, CP violation and mixing
-- Study rare penguin EW transitions such as $b \rightarrow s\, \tau^+ \tau^-$, spectroscopy (produce b-baryons, B_s …)
-- Test lepton universality with 10^{11} τ decays (with τ lifetime, mass, BRs) at 10^{-5} level, LFV to 10^{-10}
-- all very important to constrain / (provide hints of) new BSM physics.

need special detectors (PID); a story to be written!

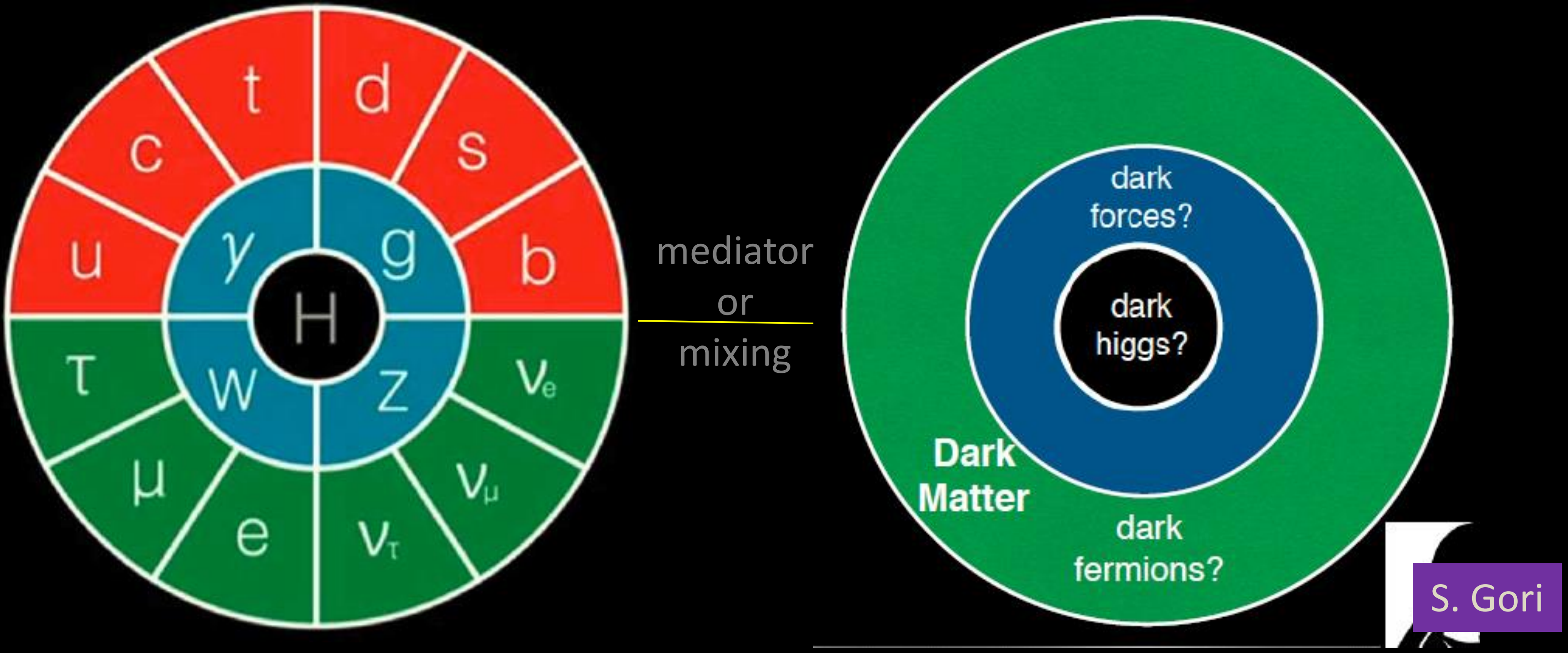
The 3.5 × 10^{12} hadronic Z decay also provide precious input for QCD studies

High-precision measurement of $\alpha_s(m_Z)$ with R_ℓ in Z and W decay, jet rates, τ decays, etc. : $10^{-3} \rightarrow 10^{-4}$
huge $\sqrt{s}$ lever-arm between 30 GeV and 1 TeV (FCC vs ILC), fragmentation, baryon production ….

Testing running of α_s to excellent precision

Dark Sector at Z factory

With the Higgs discovery SM works perfectly, yet we need new physics to explain the baryon asymmetry of the Universe, the dark matter etc… without interfering with SM rad. corr.

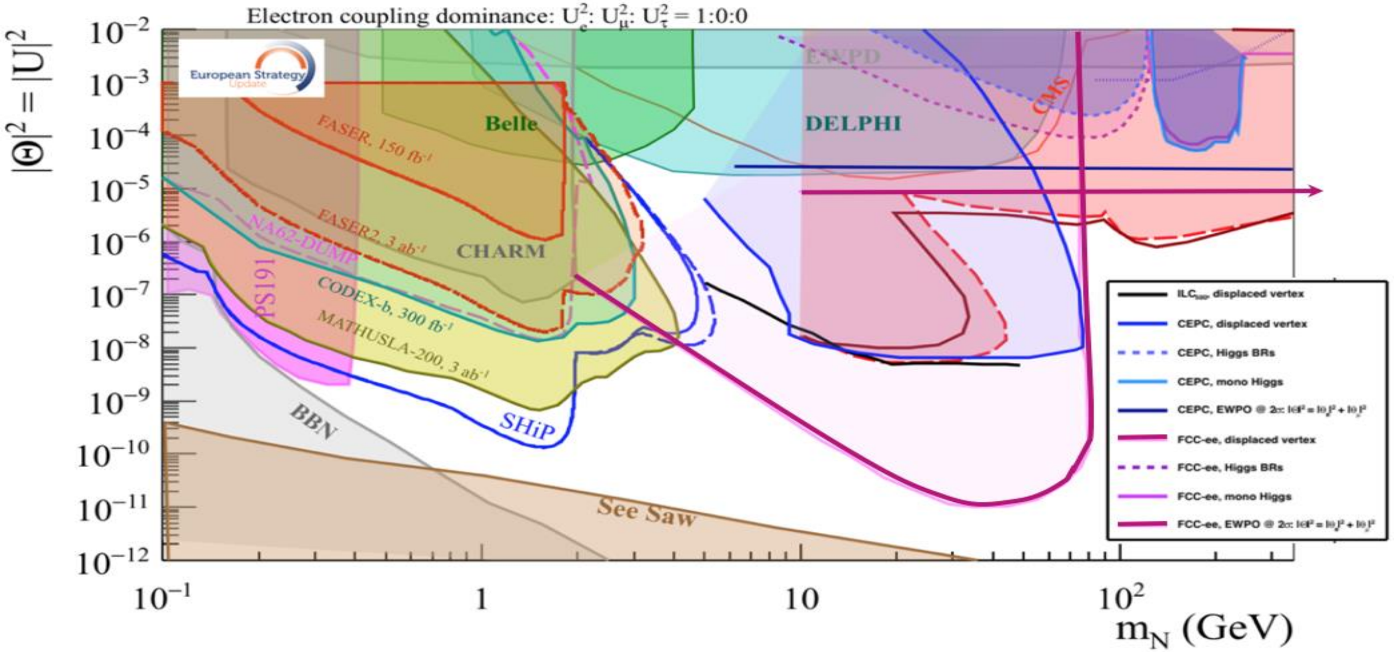


Dark photons, axion like particles, sterile neutrinos, all *feebly coupled* to SM particles

This picture is relevant to Neutrino, Dark sectors and High Energy Frontiers.

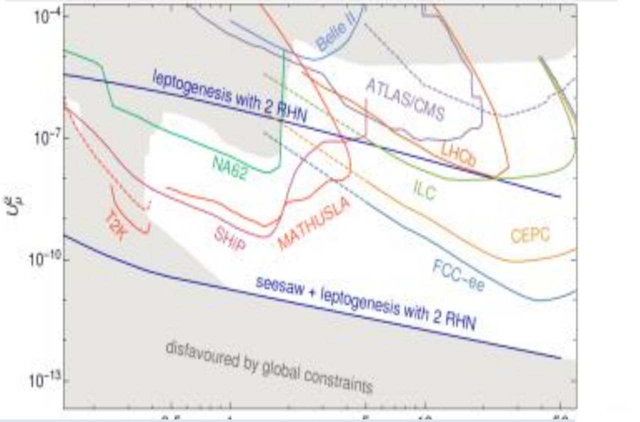
FCC-ee (Z) compared to the other machines for right-handed (sterile) neutrinos

How close can we get to the 'see-saw limit'? can we improve acceptance and reach?



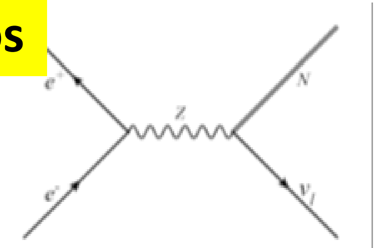
-- the purple line shows the reach for observing **heavy neutrino decays** (here for 10^{12} Z)

-- the horizontal line represents the sensitivity to **mixing of neutrinos** to the dark sector, using EWPOs (G_F vs $\sin^2\theta_W^{eff}$ and m_Z, m_W, tau decays) which extends sensitivity to 10^{-5} mixing all the way to very high energies (500-1000 TeV at least). arxiv:2011.04725



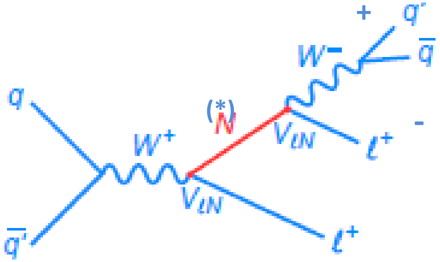
Heavy neutrinos

FCC-ee Z



or $l^{\pm}\nu$

FCC-hh



tau life-time and branching ratios

FCC-ee

-- EWPO, G_F, τ , N_ν: sensitivity 10^{-5} up to v. high Masses

-- high sensitivity to single N(→ $l_2^{\pm}$W) in Z decay

FCC-hh

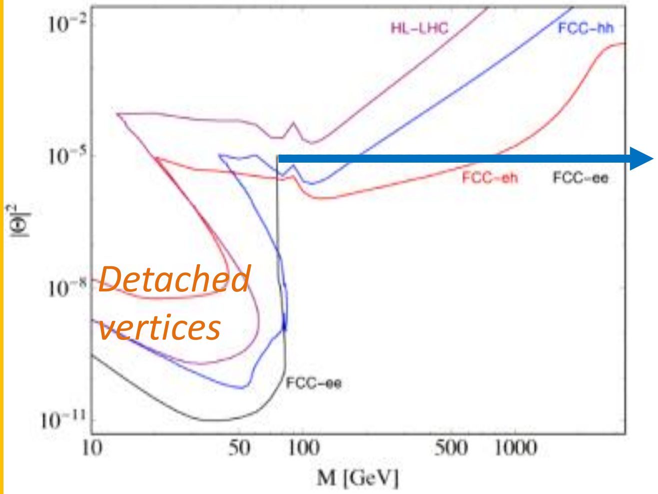
-- production in W-> $l_1^{\pm}$ + N(→ $l_2^{\pm}$W) (LNV+LFV) with initial and final lepton charge and flavour

FCC e-p

-- production in CC $e^{\pm}$ p → X N(→ $l^{\pm}$W) high mass

ee-hh/ep complementarity:

indirect/direct discovery + studies of FNV and LFV!

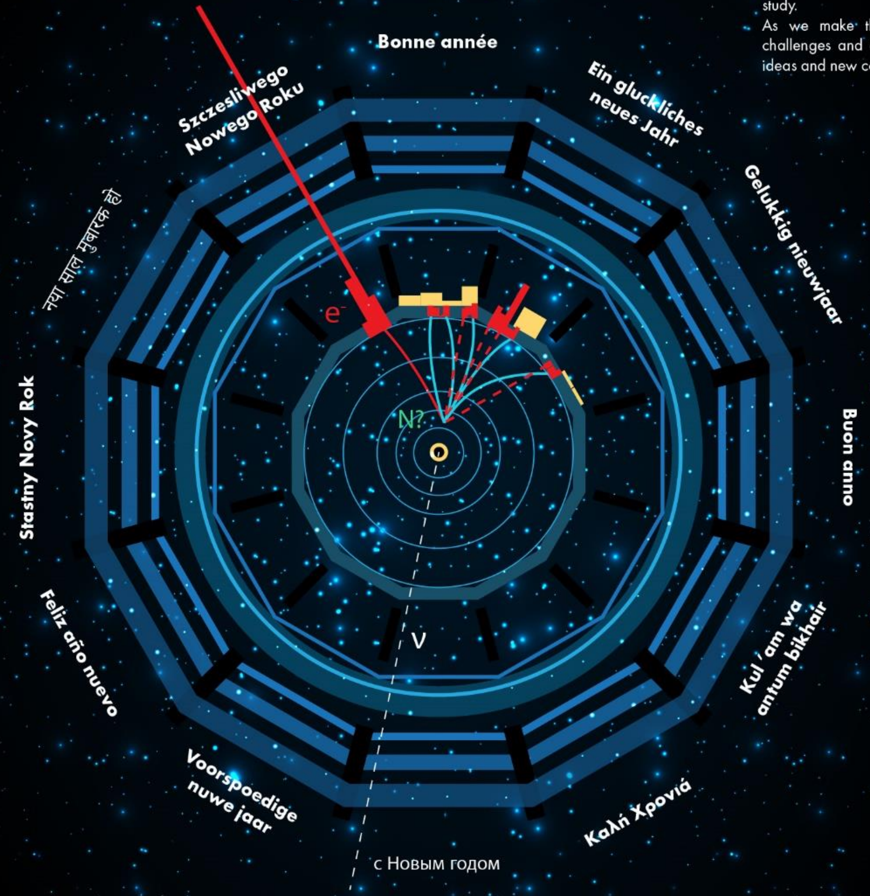


Massive neutrino mechanisms for generating the matter-antimatter asymmetry in the Universe should be a central consideration in the selection and design of future colliders. (neutrino town meeting report to ESPP)

FUTURE
CIRCULAR
COLLIDER

After years of pioneering and enthralling work, the FCC collaboration was rewarded in 2020 with a positive recommendation by the European Strategy of Particle Physics to continue with the preparation of a technical & financial feasibility study.

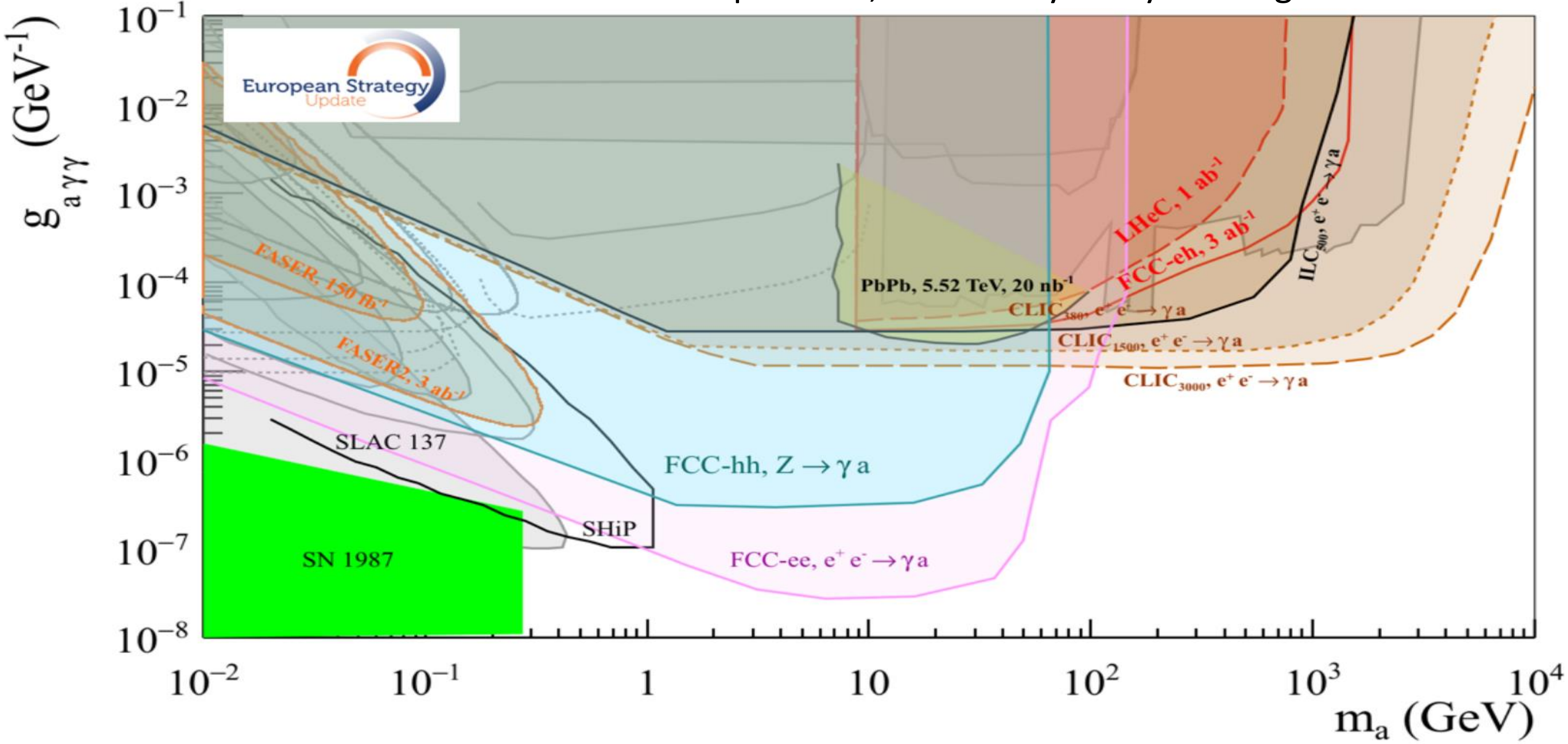
As we make this bold step, we face new challenges and opportunities, calling for fresh ideas and new collaborations.



Happy New Year and Best Wishes for 2041 !

Glimpse of Future discovery? Artistic rendering of the production and decay of a long-lived Heavy Neutral Lepton at FCC-ee.

Similar situation for Axion-like-particles; Luminosity is key to the game



Complementarity with High energy lepton collider,

Much more left to explore at FCC-ee-Z and FCC-hh!