Future Circular Collider Study

Status and Progress

P. Azzi(INFN Padova)

gratefully acknowledging input from FCC coordination group global design study team and all other contributors

http://cern.ch/fcc

*Work supported by the **European Commission** under the HORIZON 2020 project EuroCirCol, grant agreement 654305*

what after LHC?

- What if no new physics is found at the LHC? Why?
  - because of a higher mass scale?
  - elusive final states for the LHC strategies?

- The two scenarios impact in a different way the future of HEP and the choice of possible future facilities:
- Need to guarantee that both scenarios can be addrressed:

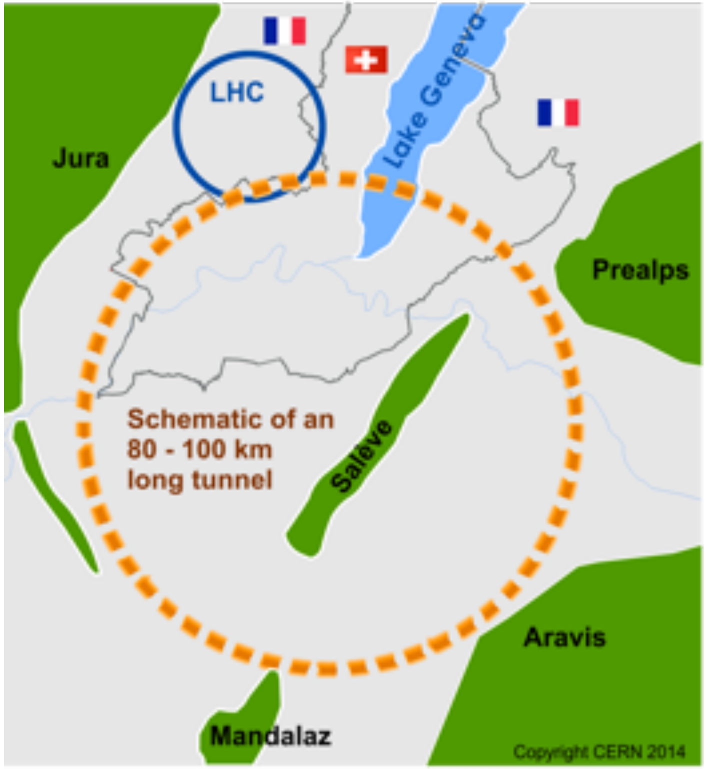
  - **precision**
  - **sensitivity (to difficult signatures)**
  - **extended energy/mass reach (direct/indirect)**

Future Circular Collider Study

- International FCC collaboration (CERN as host lab) to study
  - pp collider , 100 TeV (FCC-hh)
    - Ultimate goal, defining infrastructure requirements

~16 T ⇒ 100 TeV *pp* in 100 km

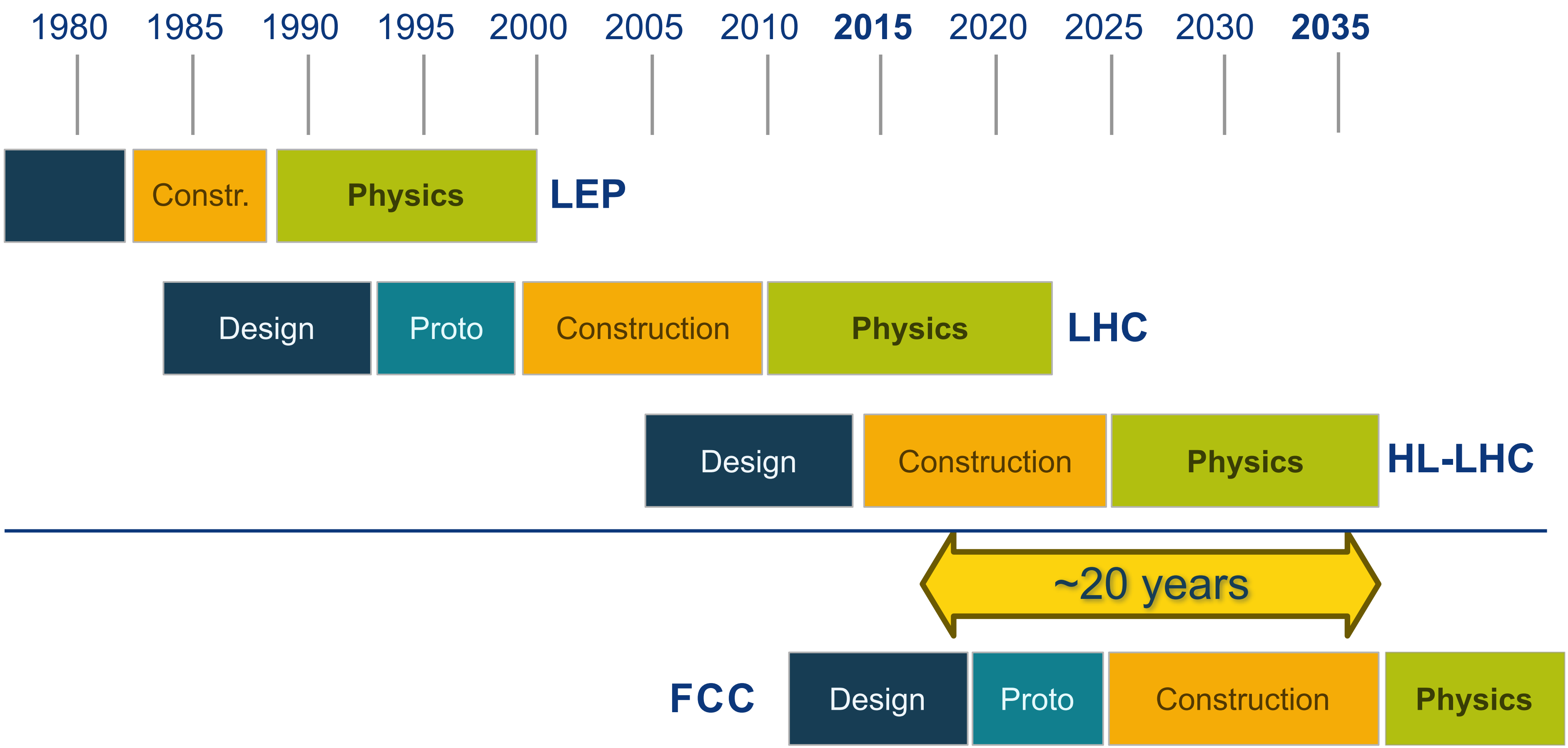
  - 80-100 km tunnel infrastructure in Geneva area
  - e^+e^- collider (FCC-ee) as a possible first step, with $\sqrt{s}$ from ~90 to ~400 GeV
  - p-e collider (FCC-eh) option



- The FCC-ee may serve as a spring board for the 100 TeV pp collider, bringing:
  - A large tunnel, most of the infrastructure, cryogenics, time, ...
  - Additional physics motivations + performance goals for FCC-hh
  - The largest energy upgrade for e^+e^- projects on the market

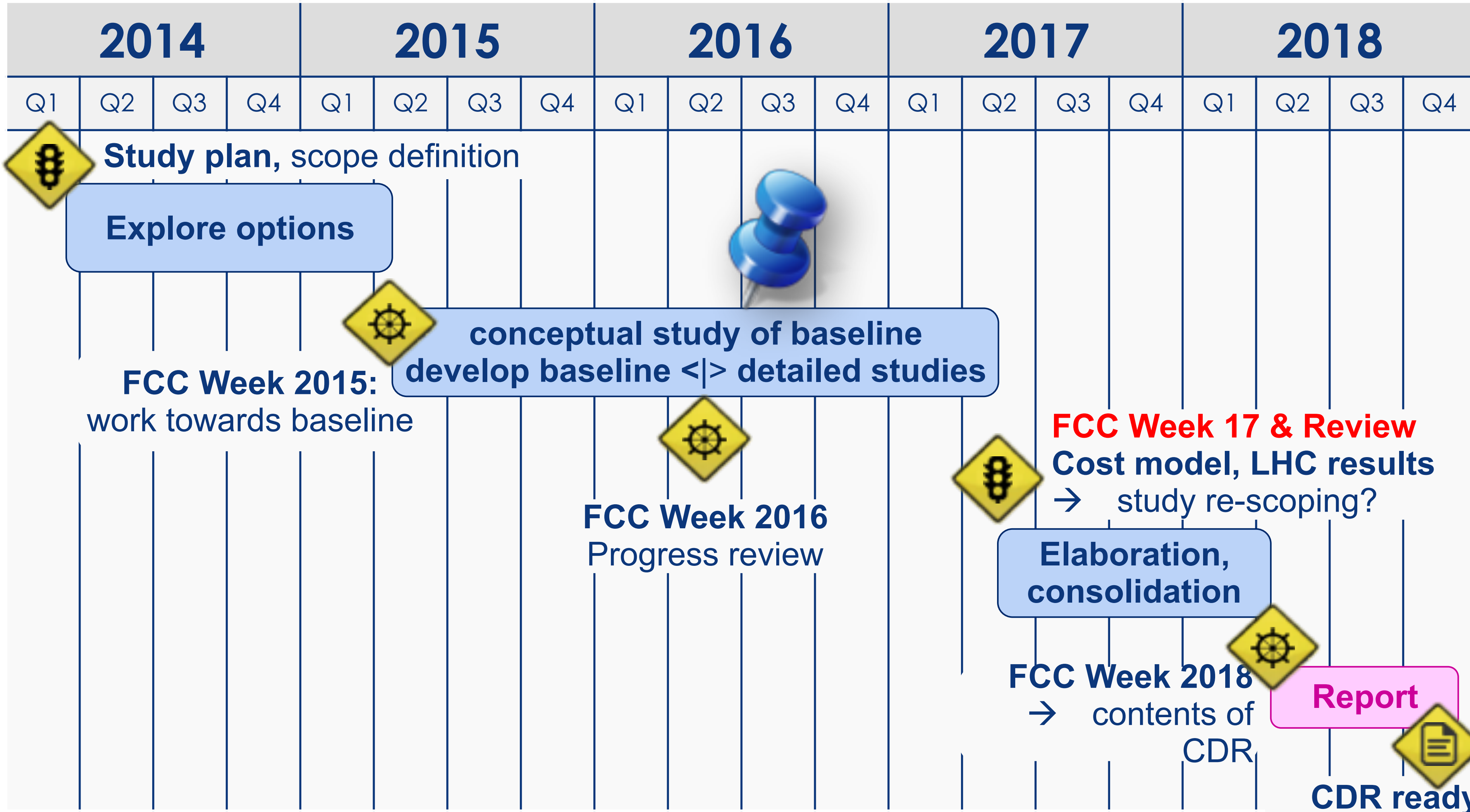
M. Benedikt
F. Zimmermann

CERN Circular Colliders & FCC

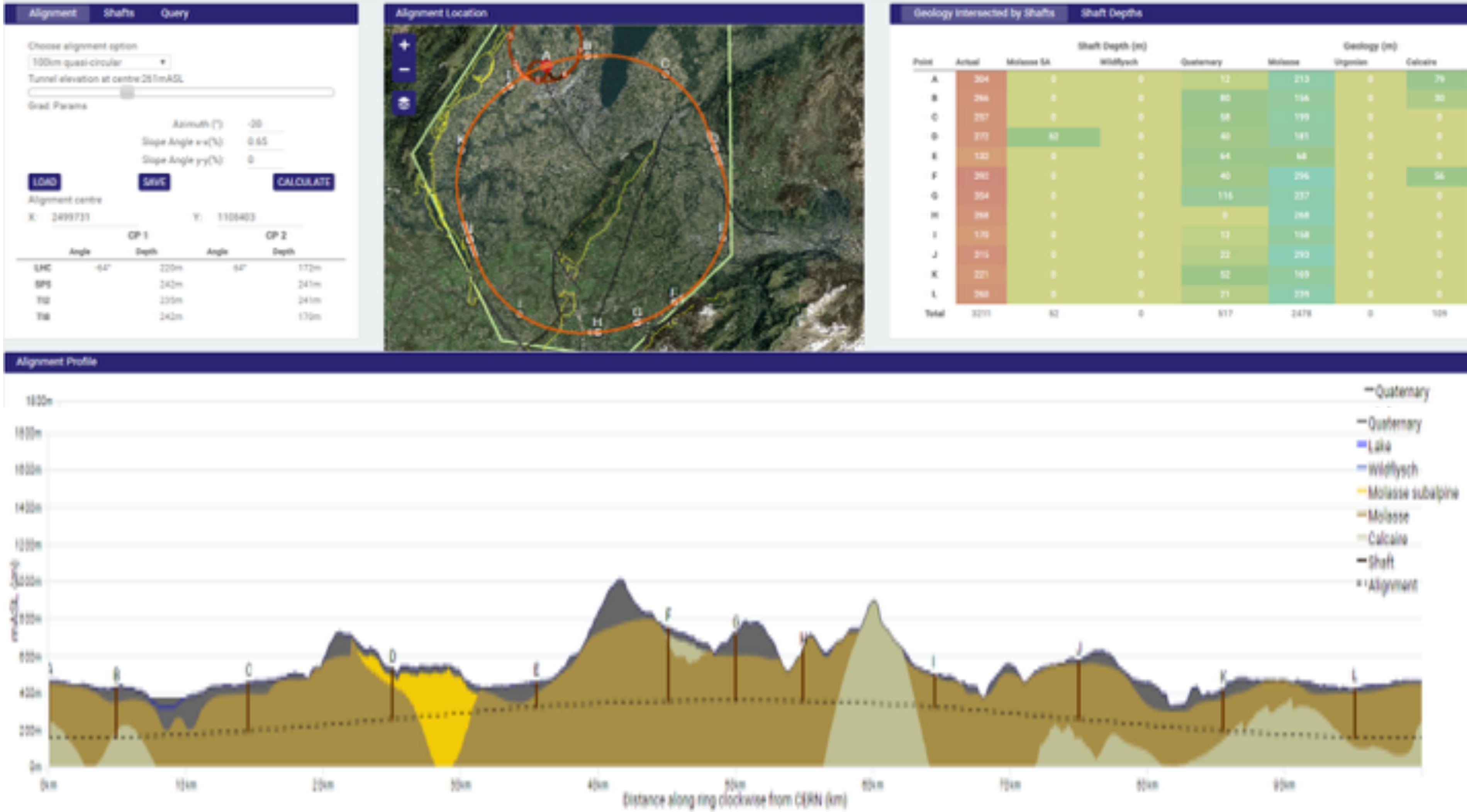


Must advance fast now to be ready for the period 2035 – 2040
Goal of phase 1: CDR by end 2018 for next update of European Strategy

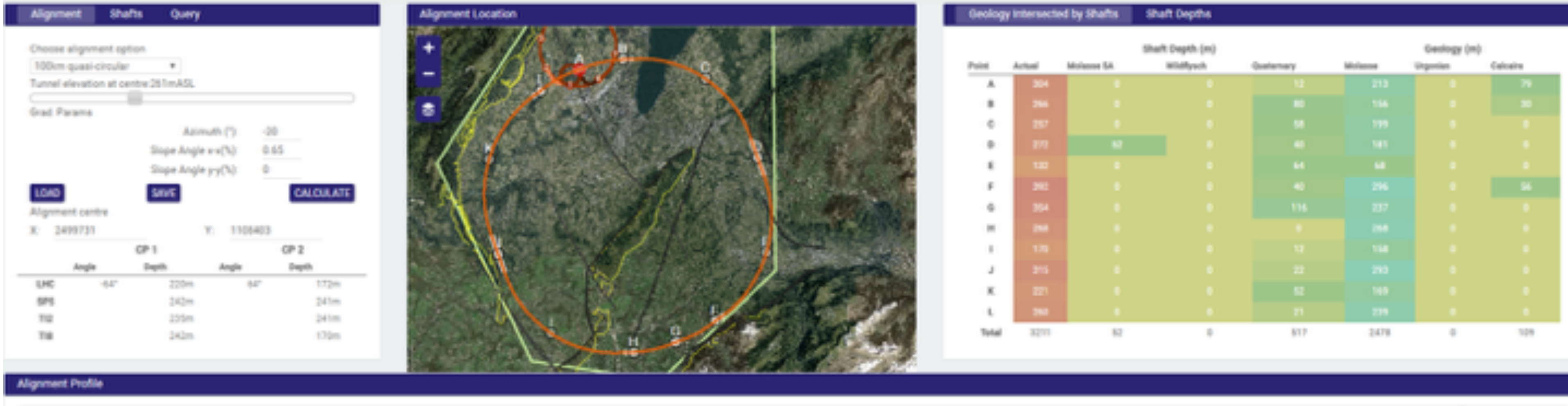
CDR Study Time Line



Progress on site investigations



Progress on site investigations

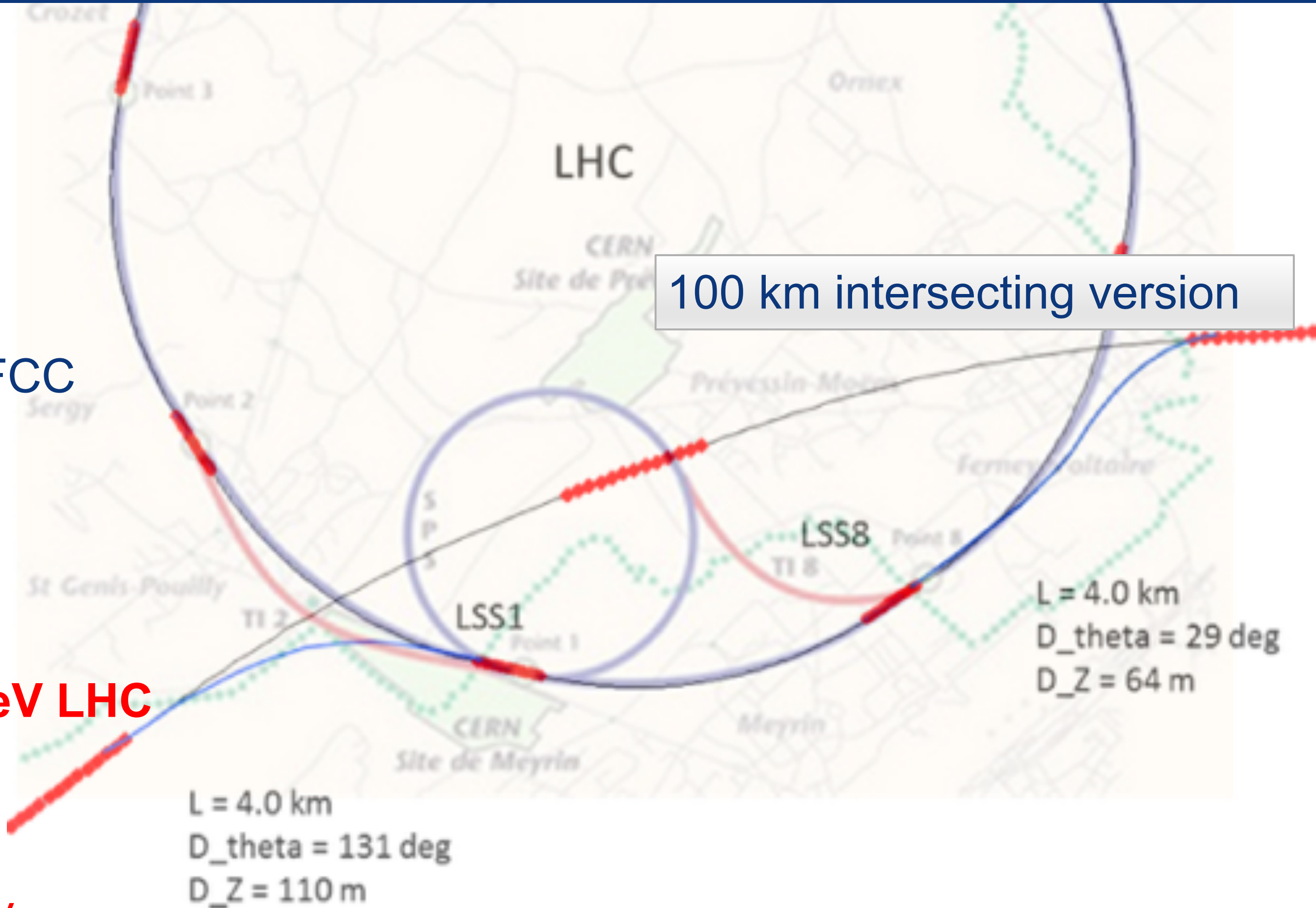


- 90 – 100 km fits geological situation well
- LHC suitable as potential injector
- The 100 km version, intersecting LHC, is now being studied in more detail

FCC-hh injector studies

Injector options:

- **SPS → LHC → FCC**
- SPS/$SPS_{upgrade}$ → FCC
- SPS -> FCC booster → FCC



Current baseline:

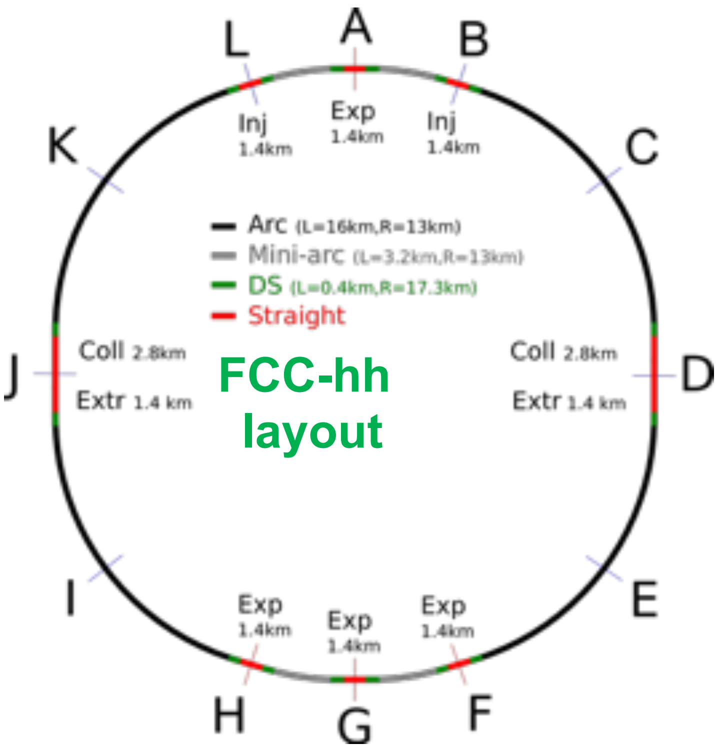
- **injection energy 3.3 TeV LHC**
- confirmed by review

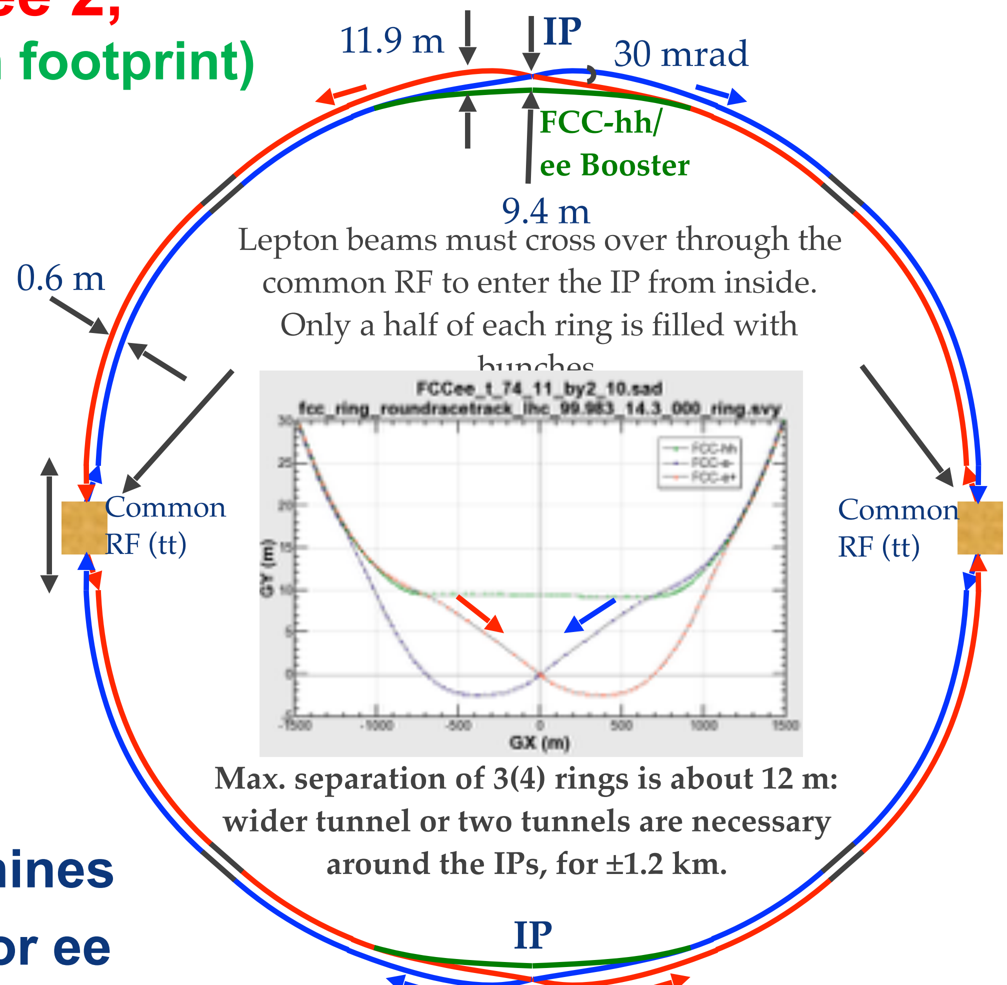
Alternative options:

- Injection around 1.5 TeV
- **compatible with: $SPS_{upgrade}$, LHC, FCC booster**

Common layouts for hh & ee

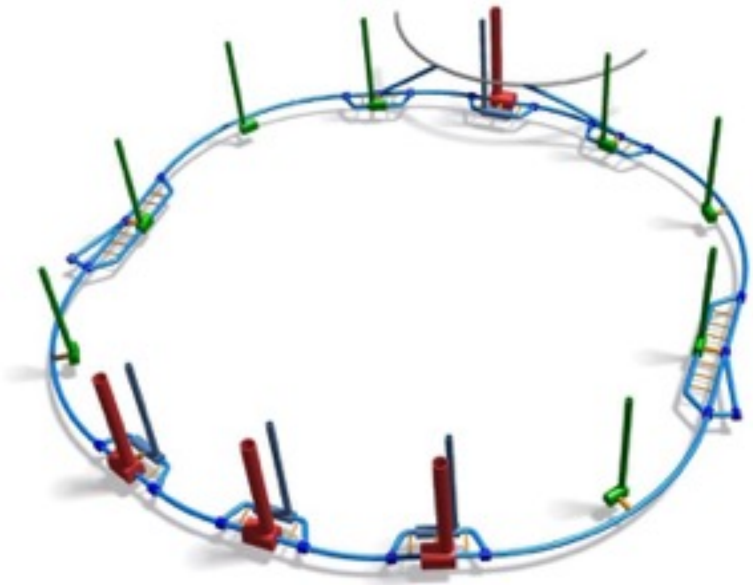
FCC-ee 1, FCC-ee 2, FCC-ee booster (FCC-hh footprint)

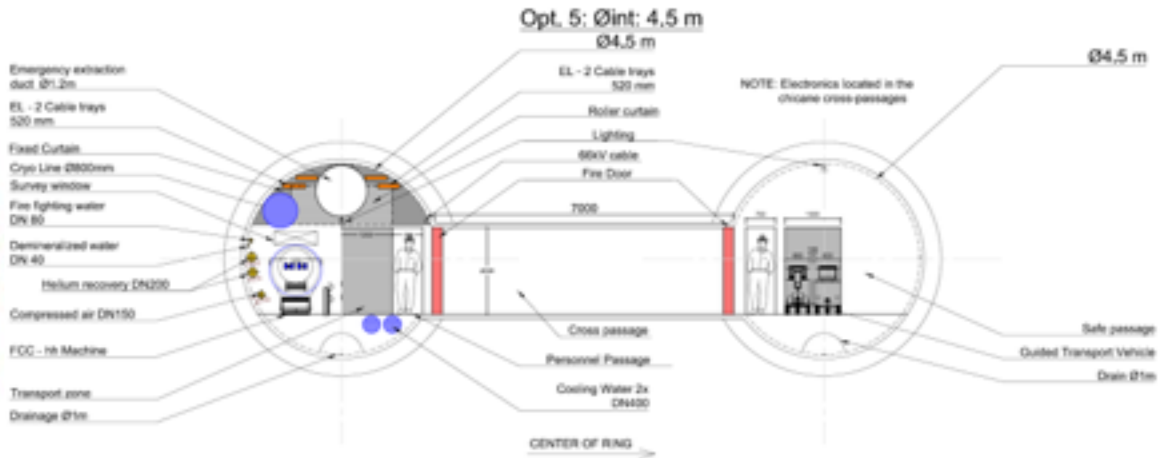




- 2 main IPs in A, G for both machines
- asymmetric IR optic/geometry for ee to limit synchrotron radiation to detector

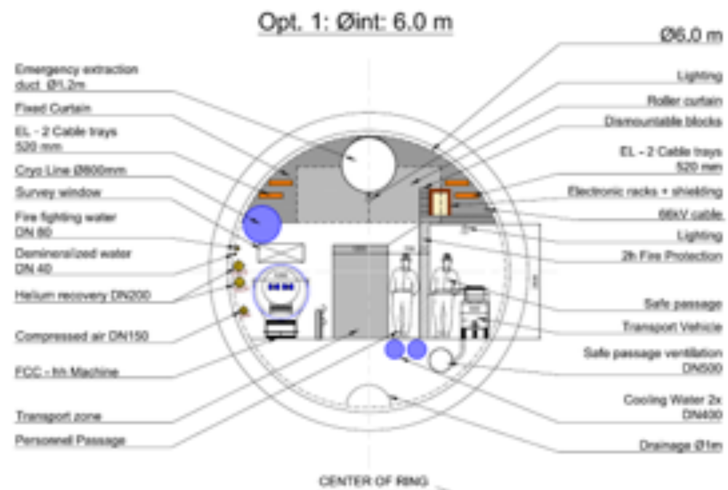
Further CE and TI optimisation





More detailed studies launched on

- CE: single vs. double tunnels
- CE: caverns, shafts, underground layout
- technical infrastructures
- safety, access
- transport, integration, installation
- operation aspects



Hadron collider parameters

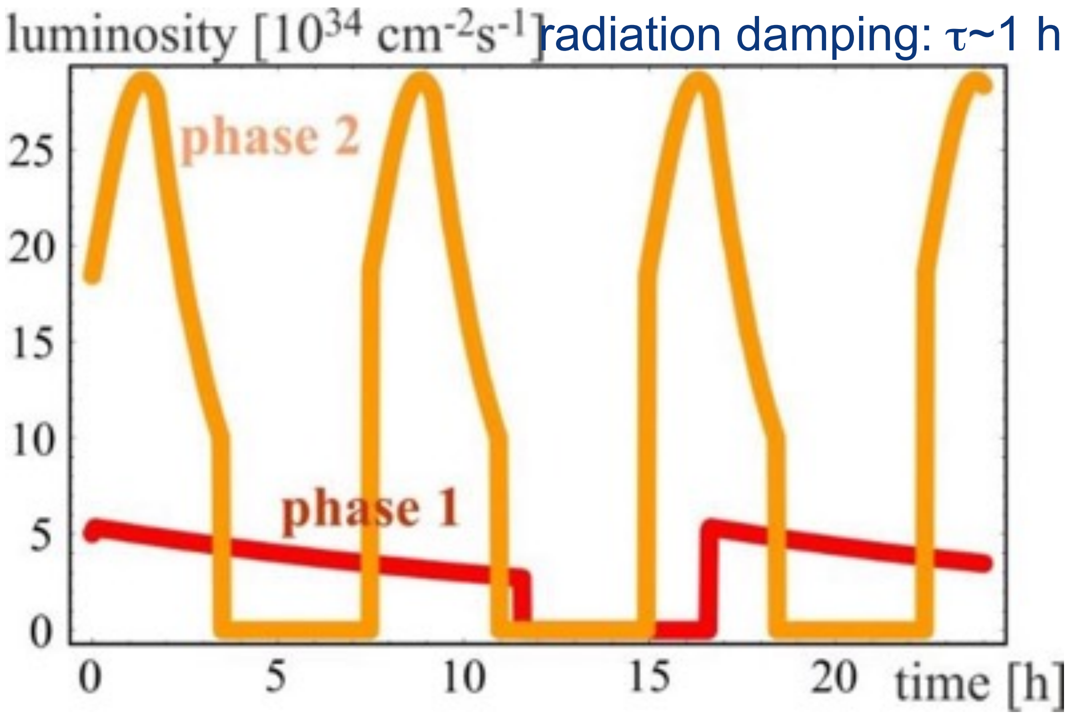
parameter	FCC-hh		SPPC	HE-LHC* (*tentative)	(HL) LHC
collision energy cms [TeV]	100		71.2	>25	14
dipole field [T]	16		20	16	8.3
circumference [km]	100		54	27	27
# IP	2 main & 2		2	2 & 2	2 & 2
beam current [A]	0.5		1.0	1.12	(1.12) 0.58
bunch intensity [10^{11}]	1	1 (0.2)	2	2.2	(2.2) 1.15
bunch spacing [ns]	25	25 (5)	25	25	25
beta* [m]	1.1	0.3	0.75	0.25	(0.15) 0.55
luminosity/IP [10^{34} $cm^{-2}s^{-1}$]	5	20 - 30	12	>25	(5) 1
events/bunch crossing	170	<1020 (204)	400	850	(135) 27
stored energy/beam [GJ]	8.4		6.6	1.2	(0.7) 0.36
synchrotr. rad. [W/m/beam]	30		58	3.6	(0.35) 0.18

FCC-hh luminosity phases

phase 1: β^*=1.1 m, $\Delta Q_{tot}=0.01$, t_{ta}=5 h, 250 fb^{-1} / year

phase 2: β^*=0.3 m, $\Delta Q_{tot}=0.03$, t_{ta}=4 h, 1 ab^{-1} / year

Transition via operational experience, no HW modification



Total integrated luminosity over 25 years operation:

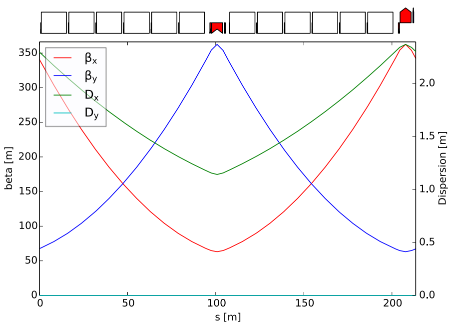
O(20) ab^{-1}/experiment

consistent with physics goals

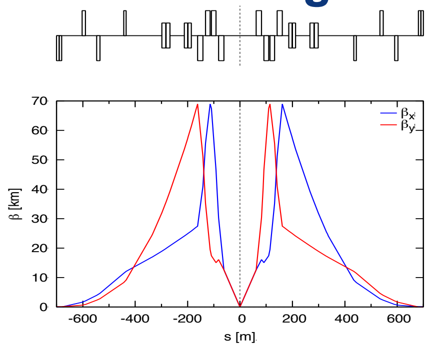
PRST-AB 18, 101002 (2015)

FCC-hh full-ring optics design

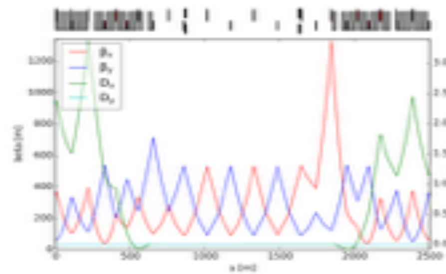
Regular arc cell



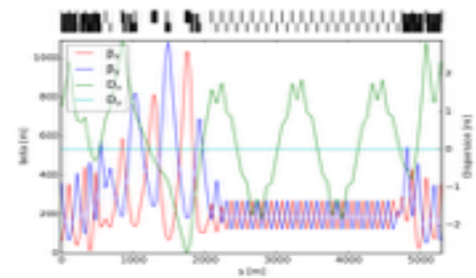
Interaction region

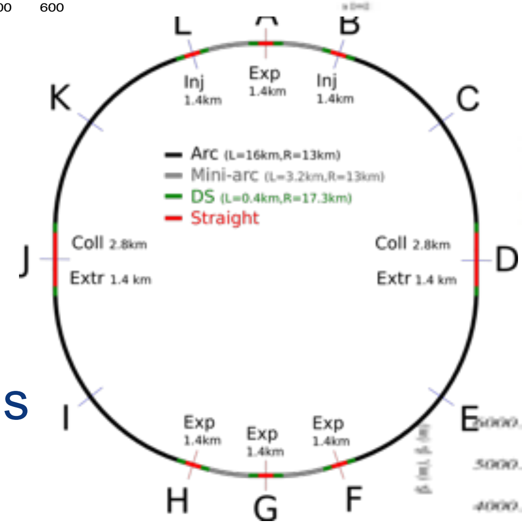


Injection with RF

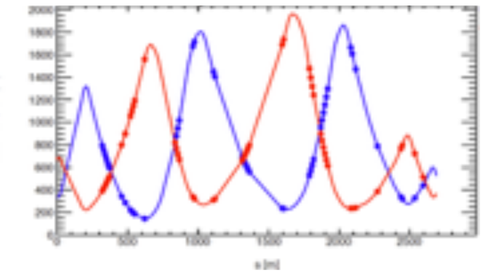


Momentum collim.

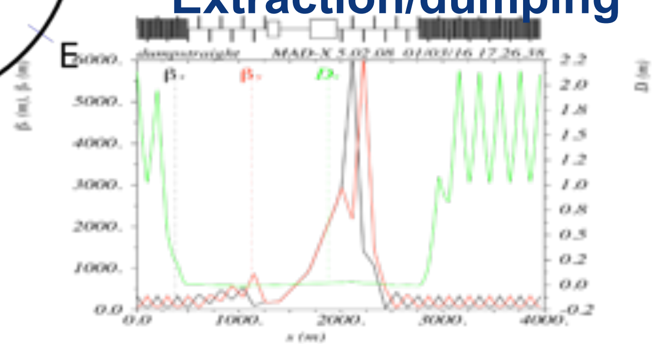




Betatron collimation



Extraction/dumping



Full ring optics design available as basis for:

- beam dynamics studies
- optimisation of each insertion
- definition of system specifications (apertures, etc.)
- improvement of baseline optics and layout

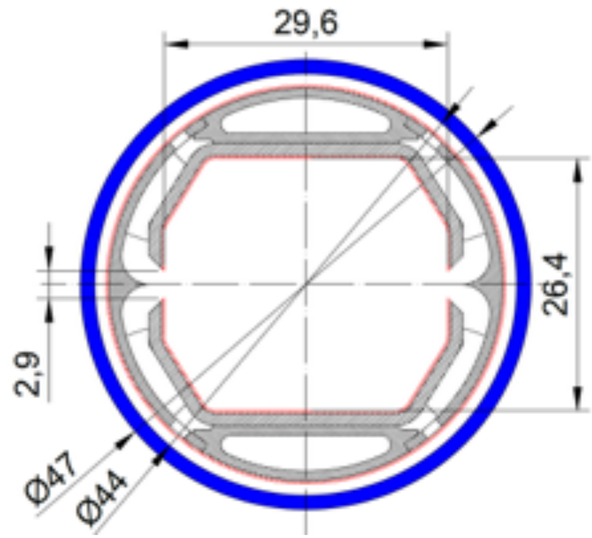
Synchrotron radiation beam screen prototype

High synchrotron radiation load of protons @ 50 TeV:

- **~30 W/m/beam (@16 T)** (LHC <0.2W/m)
- **5 MW total in arcs**

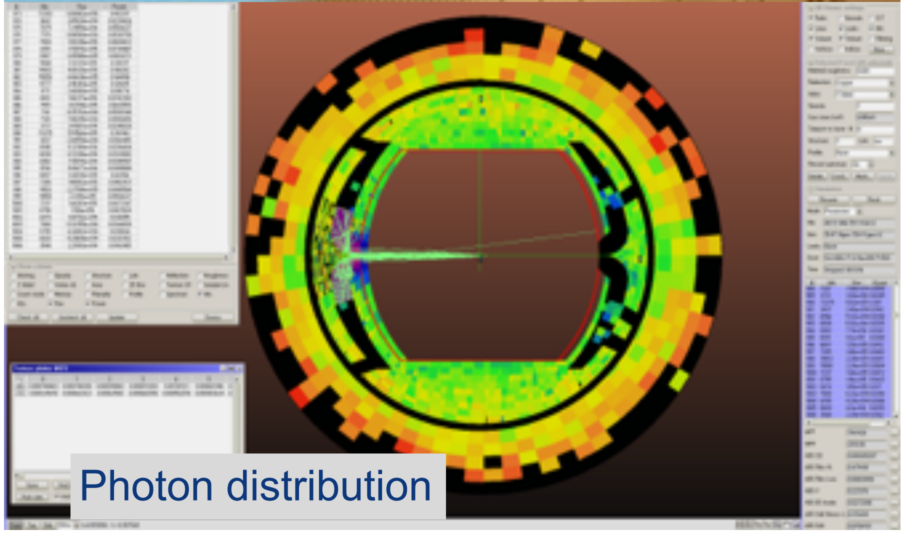
New Beam screen with ante-chamber

- absorption of synchrotron radiation at 50 K to reduce cryogenic power
- avoids photo-electrons, helps vacuum



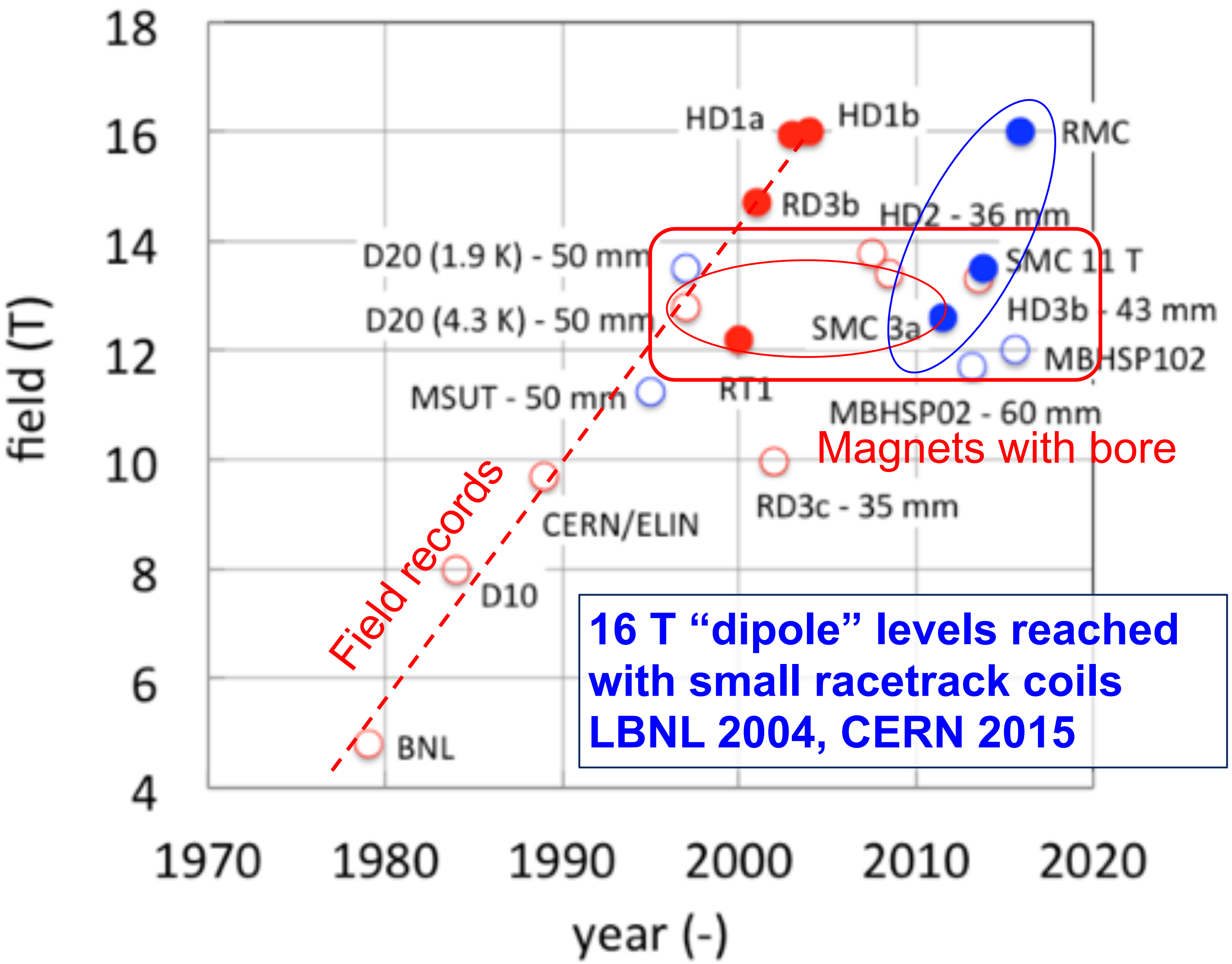
First FCC-hh beam screen prototype

Testing 2017 in ANKA within EuroCirCol



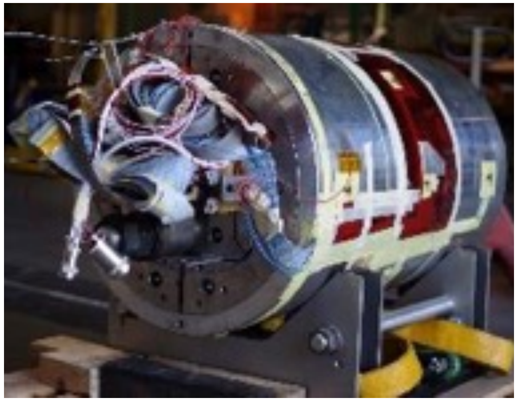
Photon distribution

Towards 16T magnets



16 T "dipole" levels reached with small racetrack coils LBNL 2004, CERN 2015

LBNL HD1



CERN RMC

Nb_3Sn conductor program

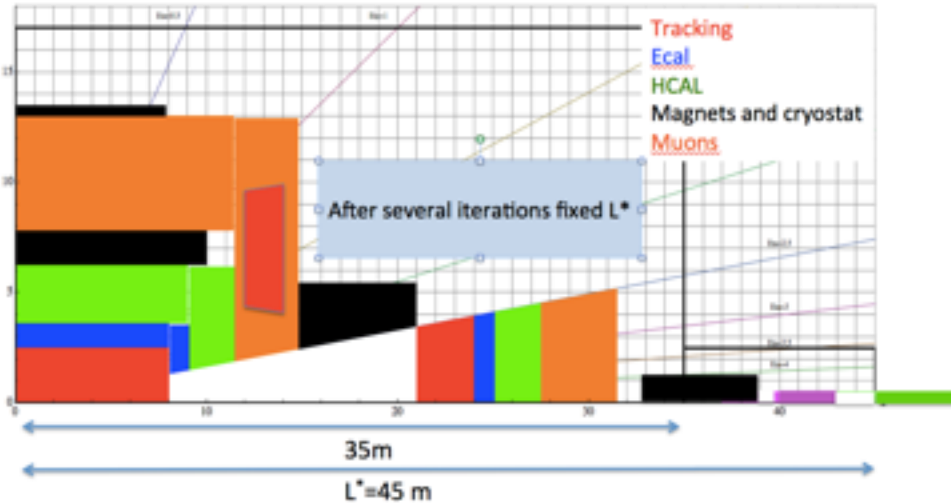
Nb_3Sn conductor is one of the major cost and performance factors for FCC-hh and must be given highest attention

- **Goals: J_c increase (16 T, 4.2 K) > 1500 A/mm^2, significant cost reduction**
- **Actions ongoing and planned (in addition to activities at CERN):**
  - Purchase of wires in Europe, US
  - Industrial R&D in Europe
  - Collaboration agreements with KEK, Russia, Korea to stipulate conductor development with regional industry
  - Collaborations with several European Universities and Research Centres on conductor development and characterisation
  - Discussions with US DOE towards a strong US industrial R&D program

FCC-hh MDI status

Design of interaction region

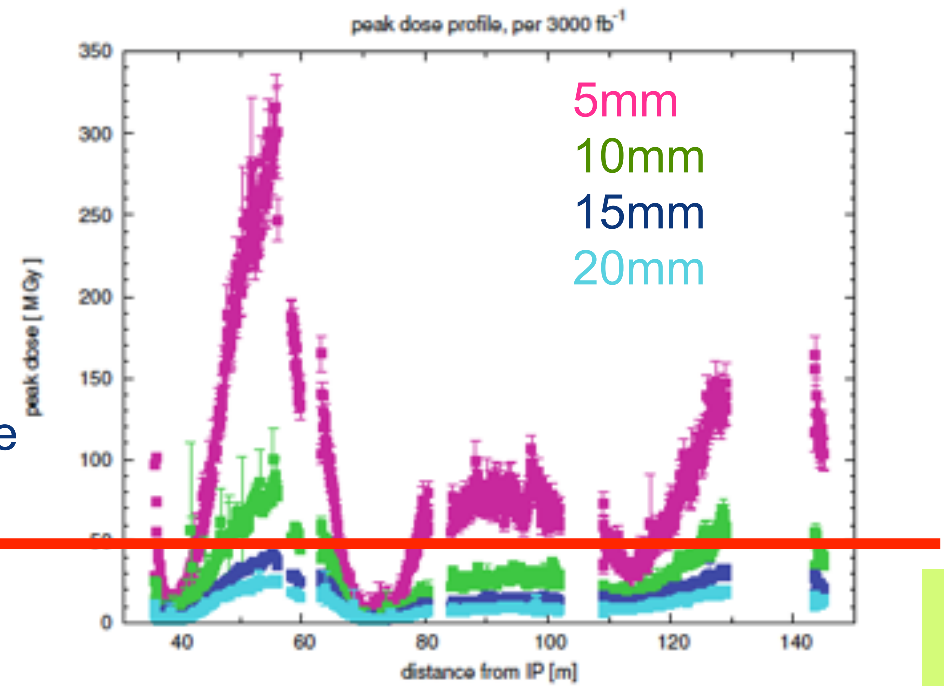
- consistent for machine and detector
  - $L^*=45$ m
  - integrated spectrometer and compensation dipoles
- new optics design with longer triplet with large aperture
  - should help for collision debris
  - more beam stay clear



Radiation dose for final quadrupoles

dose at 3000 fb^{-1}

30 MGy present limit: acceptable with 20mm shielding

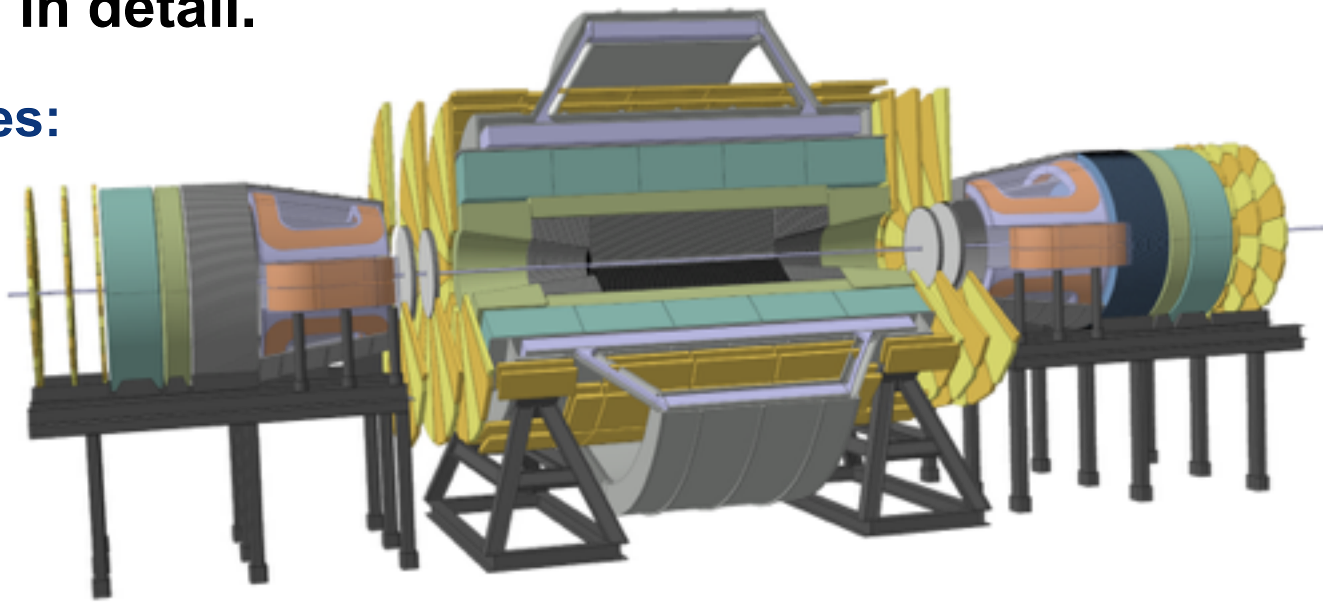


Detector Concepts for 100 TeV pp

B=6 T, 12 m bore, solenoid with shielding coil and 2 dipoles 10 Tm has been engineered in detail.

Some design challenges:

- large η acceptance
- radiation levels of >50 x LHC Phase II
- pileup of ~1000



Preliminary estimate of the cost ~ 2-3 BCHF.

For instance scaling down magnet system to 10m, 4T for the solenoid and 4T/m for the dipoles ➨ Reduces the cost by a factor 2.

R&D for FCC detectors is continuation of LHC Phase II upgrade

FCC-hh: life at $\sqrt{s}$=100TeV

- Numerology for 10ab^{-1} @100TeV
- **10^{10} Higgs bosons** => 10^4x today
- **10^{12} top quarks** => 5 10^4 x today
  - =>10^{12} W bosons from top decays
  - =>10^{12} b hadrons from top decays
  - =>10^{11} t->W->taus
  - few 10^{11} t->W charm hadrons

➡precision measurements
➡rare decays
➡FCNC probes: H->eμ

➡precision measurements
➡rare decays
➡FCNC probes: t->cV (V=Z,g,γ), t->cH
➡CP violation
➡BSM decays ???

➡rare decays τ->3μ, μγ, CPV

➡rare decays D->$\mu^+\mu^-$,… CPV

Amazing potential, extreme detector and reconstruction challenges

Physics prospects

Physics at the FCC-hh

https://twiki.cern.ch/twiki/bin/view/LHCPhysics/FutureHadroncollider

- **Volume 1: SM processes** (238 pages)
- **Volume 2: Higgs and EW symmetry breaking studies** (175 pages)
- **Volume 3: beyond the Standard Model phenomena** (189 pages)
- **Volume 4: physics with heavy ions** (56 pages)
- **Volume 5: physics opportunities with the FCC-hh injectors** (14 pages)

- **Being published as CERN yellow report**

FCC–ee physics requirements

A. Blondel, J. Ellis, C. Grojean, P. Janot

- **physics programs / energies:**

  ***Z* (45.5 GeV) *Z* pole,** *'TeraZ' and high precision* M_Z & Γ_Z

  ***W* (80 GeV) *W* pair production** *threshold, high precision* M_W

  ***H* (120 GeV) *ZH* production** *(maximum rate of H's)*

  ***t* (175 GeV): $t\bar{t}$ threshold**, *H studies*

- **beam energy range from 35 GeV to ≈200 GeV**
- **highest possible luminosities** *at all working points*
- possibly ***H* (63 GeV) direct *s*-channel** production with **monochromatization** (**c.m. energy spread <6 MeV**, presentation at IPAC'16)
- **beam polarization up to ≥80 GeV** for beam energy calibration

Lepton collider parameters

J.Wenninger et al.
FCC-ACC-SPC-003

parameter	FCC-ee (400 MHz)					CEPC	LEP2
Physics working point	**Z**		**WW**	**ZH**	**tt_{bar}**	H	
energy/beam [GeV]	**45.6**		**80**	**120**	**175**	120	105
bunches/beam	30180	**91500**	**5260**	**780**	**81**	50	4
bunch spacing [ns]	7.5	**2.5**	**50**	**400**	**4000**	3600	22000
bunch population [10^{11}]	1.0	**0.33**	**0.6**	**0.8**	**1.7**	3.8	4.2
beam current [mA]	1450	**1450**	**152**	**30**	**6.6**	16.6	3
luminosity/IP x $10^{34}cm^{-2}s^{-1}$	210	**90**	**19**	**5.1**	**1.3**	2.0	0.0012
energy loss/turn [GeV]	0.03	**0.03**	**0.33**	**1.67**	**7.55**	3.1	3.34
synchrotron power [MW]	**100**					103	22
RF voltage [GV]	0.4	**0.2**	**0.8**	**3.0**	**10**	6.9	3.5

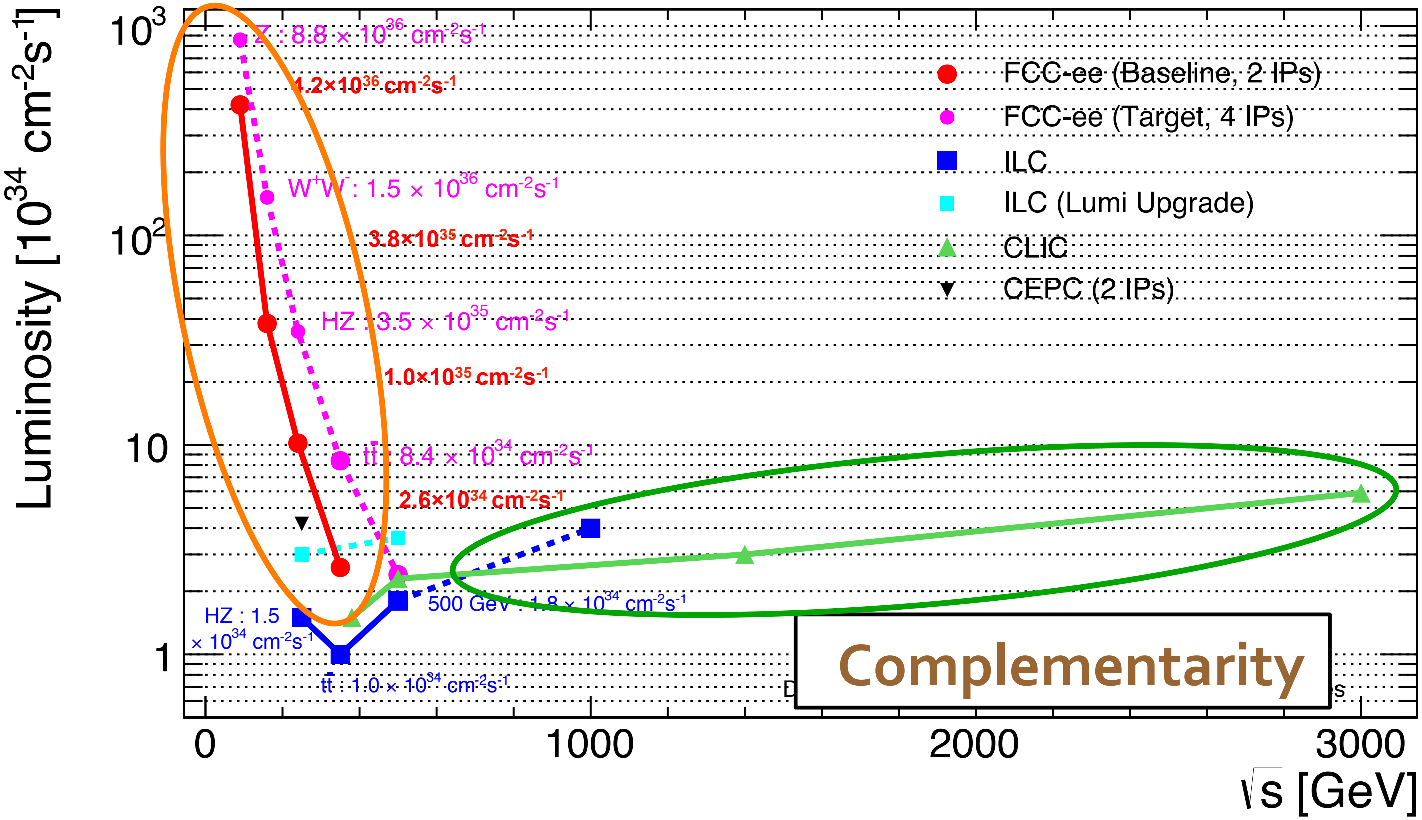
FCC-ee: 2 separate rings   CEPC, LEP: single beam pipe

FCC-ee Challenges

- The FCC-ee is designed to be the ultimate Z, W, H, and top factories
  - It is a project in its infancy: less than three years old
    - Lots of progress were made in the past two years
      - ➨ Technology is ready – on paper
  - This machine has still many technological challenges to solve
    - A high-power (200 MW), high-gradient (10 MV/m), 2 km-long, RF system
    - Loads of synchrotron radiation (100 MW) to deal with
    - A booster (for top up injection), and a double ring for e^+ and e^-
    - An optics with very low β^*, and large momentum acceptance
    - An intense positron source
    - Transverse polarization for beam energy measurement
    - Up to four experiments to serve
    - … and much more
  - It is supported by 50 years of experience and progress with e^+e^- circular machines
    - Most of the above challenges are being addressed at SuperKEKB (starting 2015)
      - ➨ FCC-ee will have to build on this experience

Extremely high luminosities

- In the energy range from the Z pole to the top-pair threshold
  - (So-far) conservative baseline, with functioning optics and 2 IPs
    - Room for improvement with smaller β^* and 4 IPs



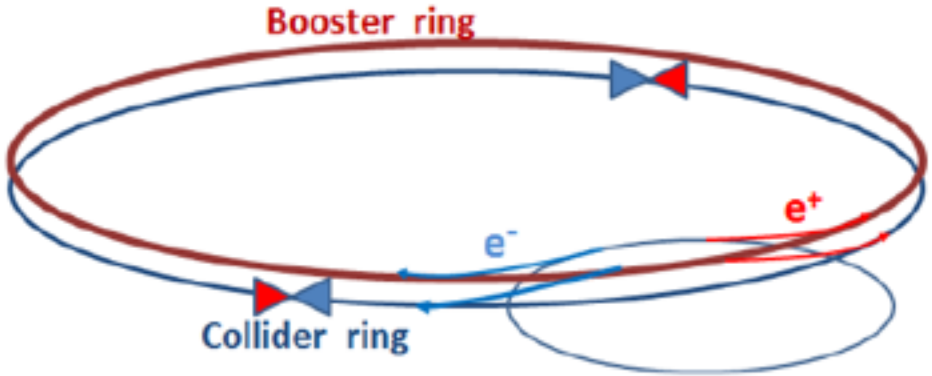
Beam lifetime & Top-up injection

Bhabha scattering cross section (σ~0.215 barn) implies a burn-off lifetime of ~20 min at 1e34 cm^{-2}Hz

Reminder, SuperKEKB is a demonstrator: τ~6min!

beside the collider ring(s), a booster of the same size (same tunnel) must provide beams for top-up injection to sustain the extremely high luminosity

- same size of RF system, but low power (~ MW)
- top up frequency ≈0.1 Hz
- booster injection energy ≈5-20 GeV
- bypass around the experiments

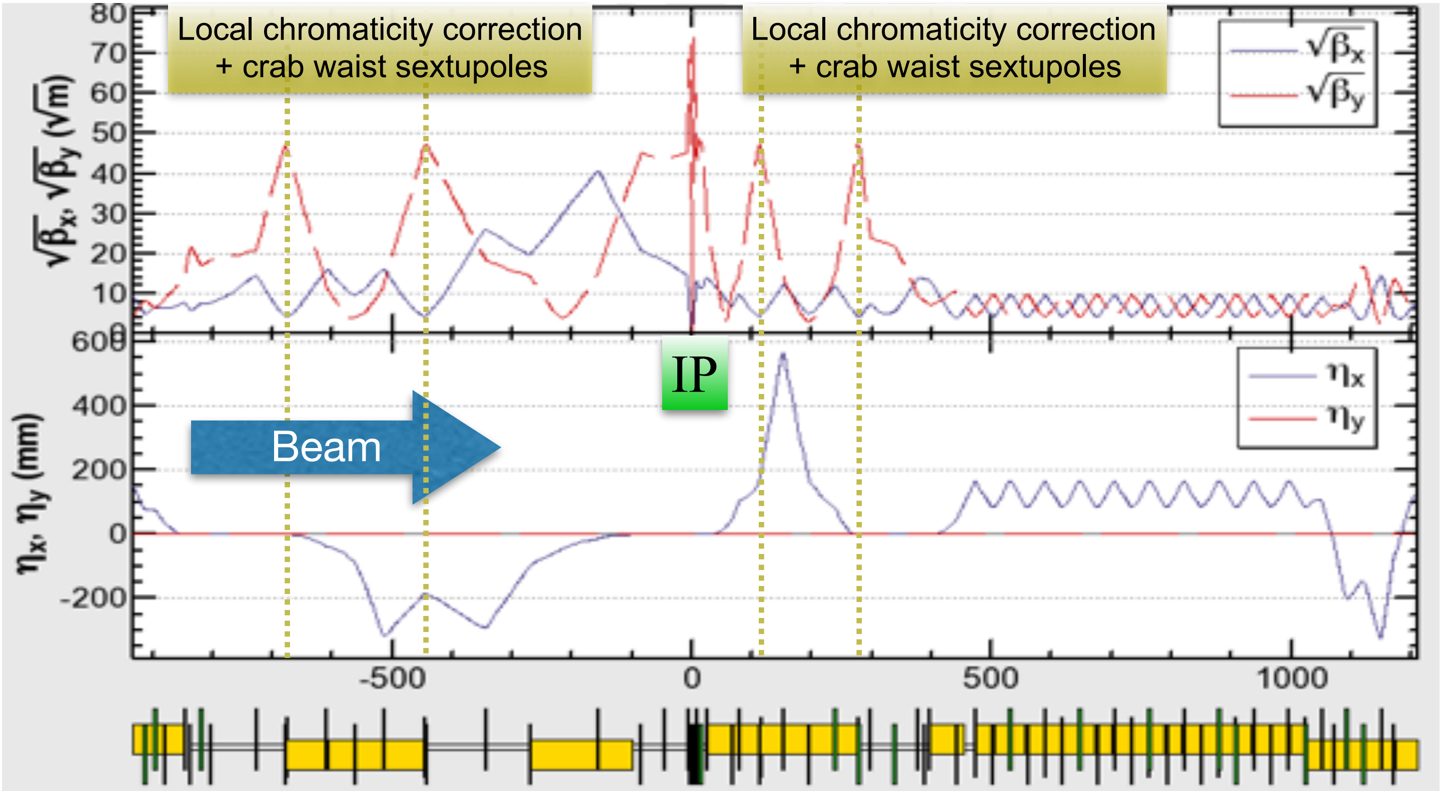


FCC-ee optics design

Optics design for all working points achieving baseline performance

Interaction region: asymmetric optics design

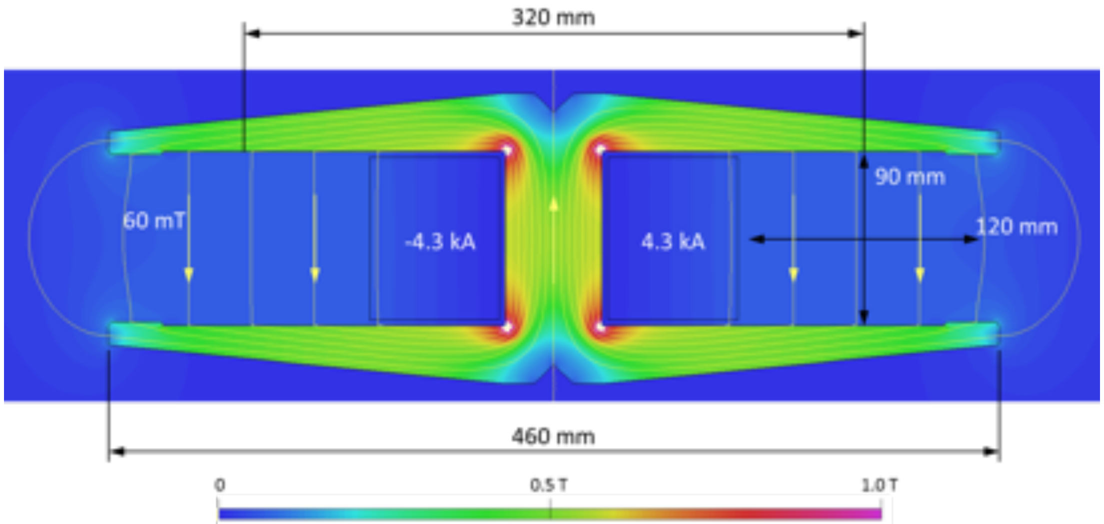
- Synchrotron radiation from upstream dipoles <100 keV up to 450 m from IP
- Dynamic aperture & momentum acceptance requirements fulfilled at all WPs



K. Oide

Efficient 2-in-1 FCC-ee arc magnets

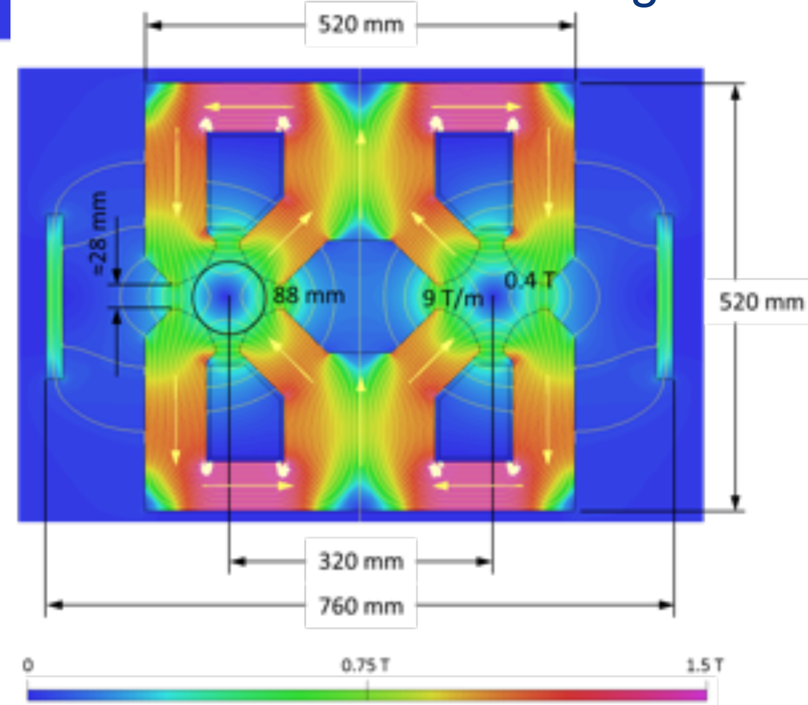
A. Milanese



Dipole:
twin aperture yoke
single busbars as coils

Quadrupole:
twin 2-in-1 design

midplane shield
for stray field



- **Novel arrangements allow for considerable savings in Ampere-turns and power consumption**
- **Less units to manufacture, transport, install, align, remove,…**

RF System

- Very broad range of operation parameters
  - ΔE_{SR} from 34 MeV to 7.55 GeV
  - Accelerating gradient from 0.2 to 10 GV
  - Total current from 6.6 mA to 1.45 A

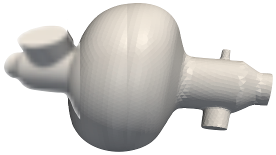
"Ampere-class" machines

	V_{total} GV	$n_{bunches}$	I_{beam} mA	ΔE/turn GeV
FCC-hh	0.032		500	
Z	0.4/0.2	30000/90000	1450	0.034
W	0.8	5162	152	0.33
H	5.5	770	30	1.67
t	10	78	6.6	7.55

"high gradient" machines

O. Brunner, A. Butterworth, R. Calaga

- No well-adapted single RF system solution
  - Start with 400 MHz single-cell Nb/Cu cavities @ 4.5K for Z and WW

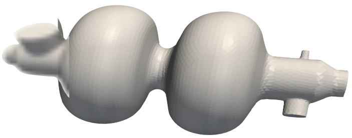


hh ≈ 16 cells per beam

Z ≈ 100 per beam (+ 100 for booster ring)

W ≈ 210 per beam (+ 210 for booster ring)

  - Add 800 MHz multi-cell bulk Nb cavities @ 2K for the higher energies



W ≈ 200 per beam (+ 200 for booster)

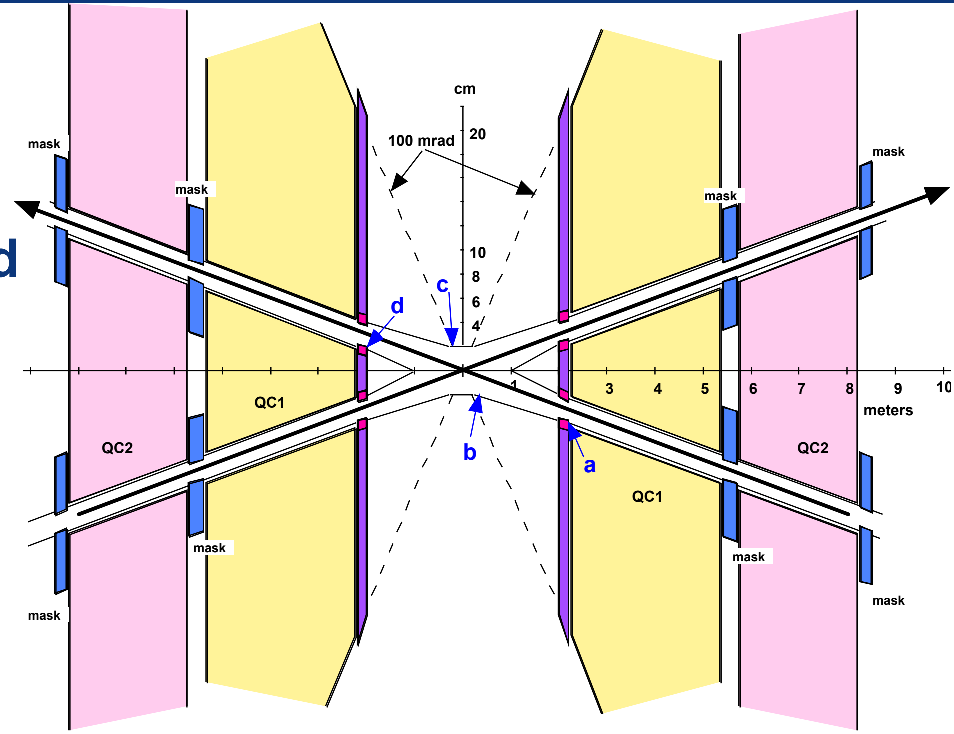
H ≈ 800 per beam (+ 800 for booster)

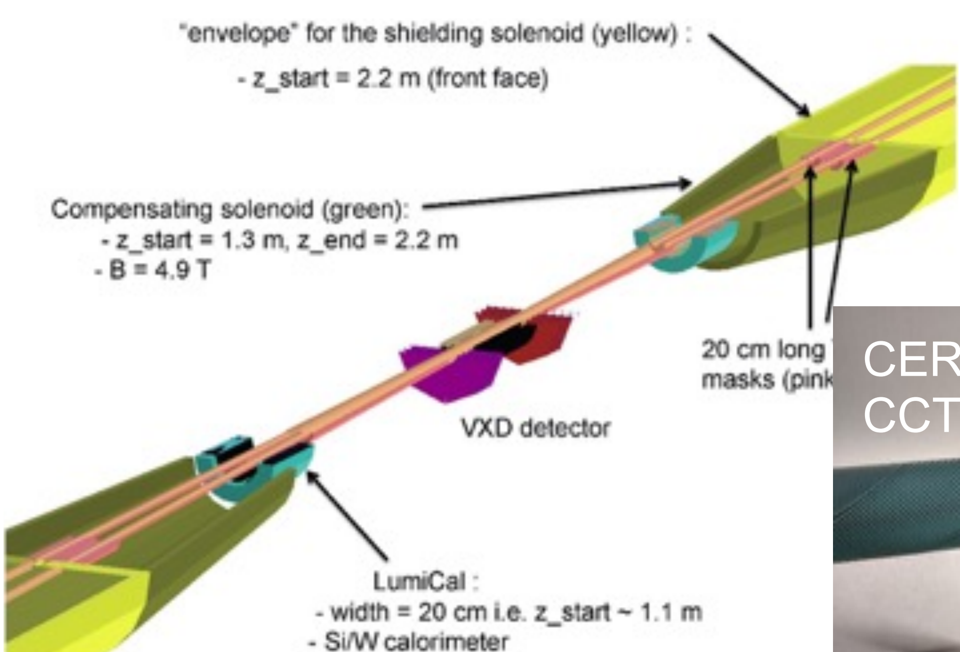
t ≈ 2600 cells for both beams (+ 2600 for booster)

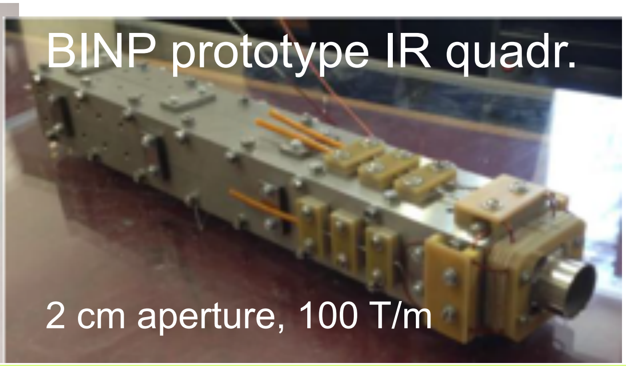
FCC-ee MDI optimisation

MDI work started with optimization of

- *l**, IR quadrupole design
- compensation & shielding solenoid
- SR masking and chamber layout

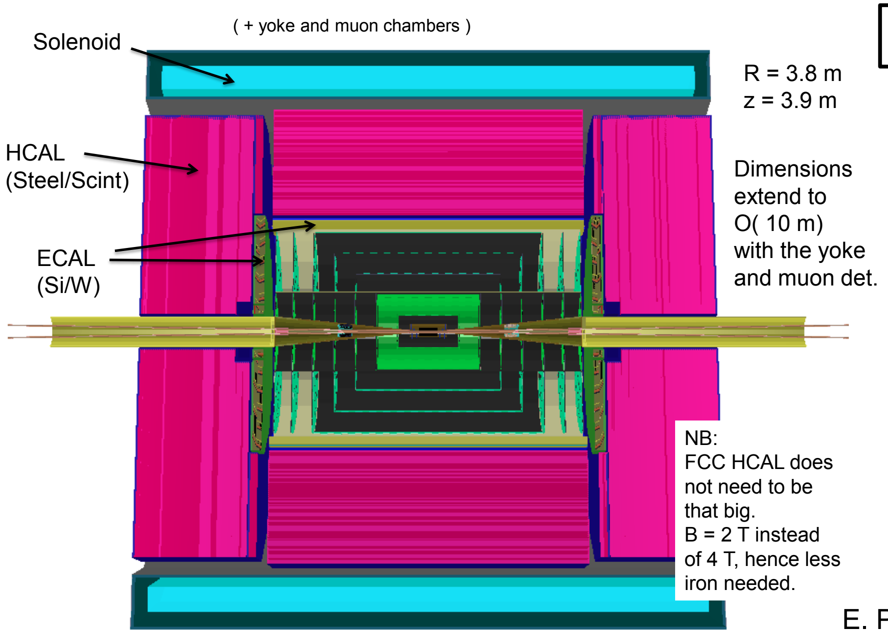




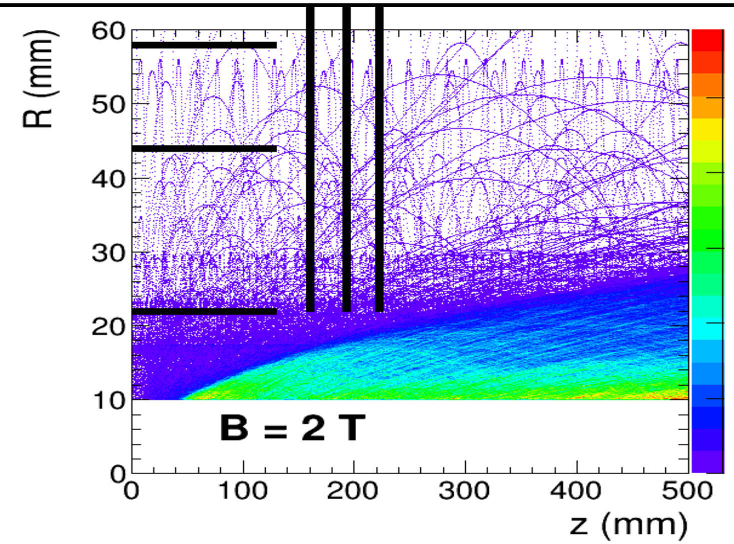


Detector Design

- "To study properties with unprecedented precision"
  - Challenging, but ILC and CLIC detector characteristics are adequate
    - The control of systematic uncertainties will be of paramount importance
      - Possible at the FCC-ee with regular high-statistics runs at the Z pole
- Started to adapt CLIC detector design to FCC-ee



Beamstrahlung simulation: VTX can live at ~2cm from IP



Synchrotron radiation effects being studied

  - Started to work also on specific FCC-ee detector design: first conclusions within a year

Lumi/year & typical running scenario

- **Assumptions**
  - 160 days of physics / year (LEP, LHC)
  - Beam availability 65% with top-up injection (PEP2, KEKB)
  - Conservative baseline with 2 experiments / Target with 4 experiments
- **Integrated luminosities and number of events**

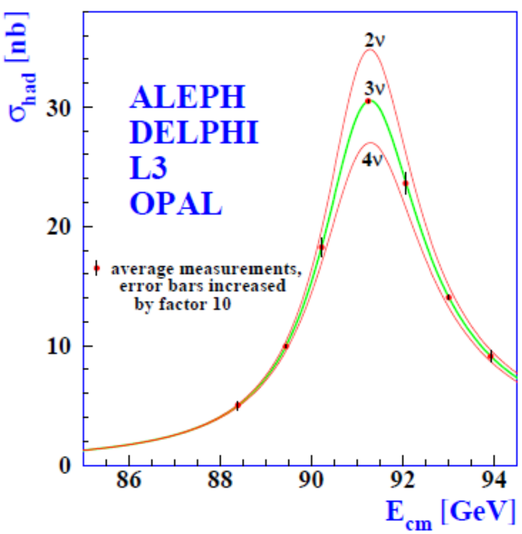
Mode	Lumi / year	# years	# events	Remark
Z (88-94)	40-80 ab^{-1}	3-5	Up to 10^{13} Z	>10^5 LEP
WW (161)	4-15 ab^{-1}	1-2	Up to 10^8 WW	~10^4 LEP
HZ (240)	1-3.5 ab^{-1}	3-5	1-2 × 10^6 HZ	~10 ILC
$t\bar{t}$ (350-370)	0.25-1 ab^{-1}	3-5	1-2 × 10^6 $t\bar{t}$	~ ILC / CLIC
H (125)	2 ab^{-1}	?	500 H / year	Preliminary (*)

(*) Work in progress, needs monochromatization, $\sqrt{s}$ spread ~ 6 MeV possible

- Predicting accuracies with 300 times smaller statistical precision than at LEP is difficult
  - Conservatively used LEP experience for systematic uncertainties

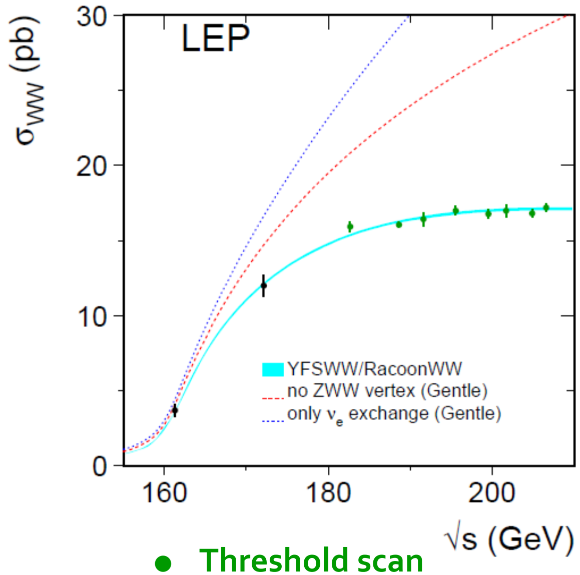
Precision EWK Physics

Z resonance: TeraZ

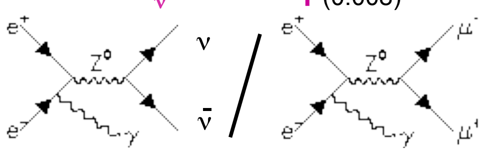


- Lineshape
  - Exquisite E_{beam} (unique!)
  - m_Z, Γ_Z to < 100 keV (2.2 MeV)
- Asymmetries
  - $\sin^2\theta_W$ to 6×10^{-6} (1.6×10^{-4})
  - $\alpha_{QED}(m_Z)$ to 3×10^{-5} (1.5×10^{-4})
- Branching ratios, R_l, R_b
  - $\alpha_S(m_Z)$ to 0.0002 (0.002)

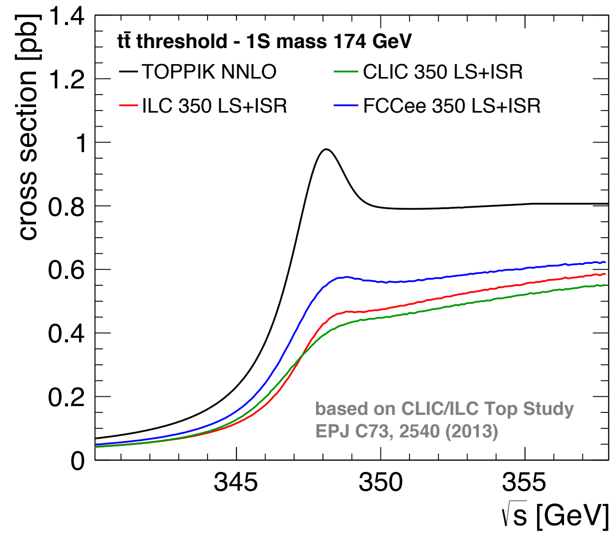
WW threshold scan: OkuW



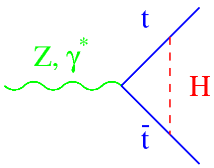
- Threshold scan
  - m_W to 500 keV (15 MeV)
- Branching ratios R_l, R_{had}
  - $\alpha_S(m_W)$ to 0.0002
- Radiative returns $e^+e^-\to\gamma Z$
  - N_ν to 0.0004 (0.008)



tt threshold scan: MegaTops



- Threshold scan
  - m_{top} to 10 MeV (500 MeV)
  - λ_{top} to 13%
  - Top EW couplings to 1%



Precision Higgs Physics

- **From M. Klute, LCWS'15**

Uncertainties	HL-LHC*	μ-	CLIC	ILC**	CEPC	FCC-ee
m_H [MeV]	40	0.06	40	30	5.5	8
Γ_H [MeV]	-	0.17	0.16	0.16	0.12	0.04
g_{HZZ} [%]	2.0	-	1.0	0.6	0.25	0.15
g_{HWW} [%]	2.0	2.2	1.0	0.8	1.2	0.2
g_{Hbb} [%]	4.0	2.3	1.0	1.5	1.3	0.4
$g_{H\tau\tau}$ [%]	2.0	5	2.0	1.9	1.4	0.5
$g_{H\gamma\gamma}$ [%]	2.0	10	6.0	7.8	4.7	1.5
g_{Hcc} [%]	-	-	2.0	2.7	1.7	0.7
g_{Hgg} [%]	3.0	-	2.0	2.3	1.5	0.8
g_{Htt} [%]	4.0	-	4.5	18	-	13 ***
$g_{H\mu\mu}$ [%]	4.0	2.1	8.0	20	8.6	6.2
g_{HHH} [%]	30	-	24	-	-	80 ***

= best potential

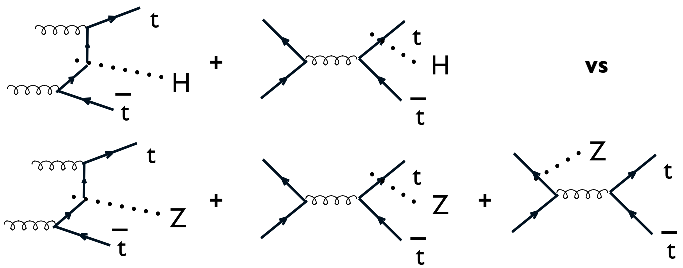
Synergy with FCC-hh

* Estimate for two HL-LHC experiments
** ILC lumi upgrade improves precision by factor 2
*** Indirect

For ~10y operation. Lots of "!,*,?"
Every number comes with her own story.

Synergy with FCC-hh

- **With 30 ab^{-1} at FCC-hh**
  - 10^9 gg → ttH events, 5×10^7 gg → HH events, 5×10^8 gg → H → μμ
    - Statistical precision won't be much of a problem, even after selection
    - Systematic uncertainties will dominate, but can be drastically reduced with ratios
      - Normalize to the precise measurements made at the FCC-ee
  - Example: Infer Htt coupling from the measurement of σ(ttH) / σ(ttZ)
    - Very similar production, gg dominant
    - Most theory uncertainty cancel
    - 1% precision possible on σ(ttH) / σ(ttZ)
    - σ(ttZ) and Higgs BR's from FCC-ee



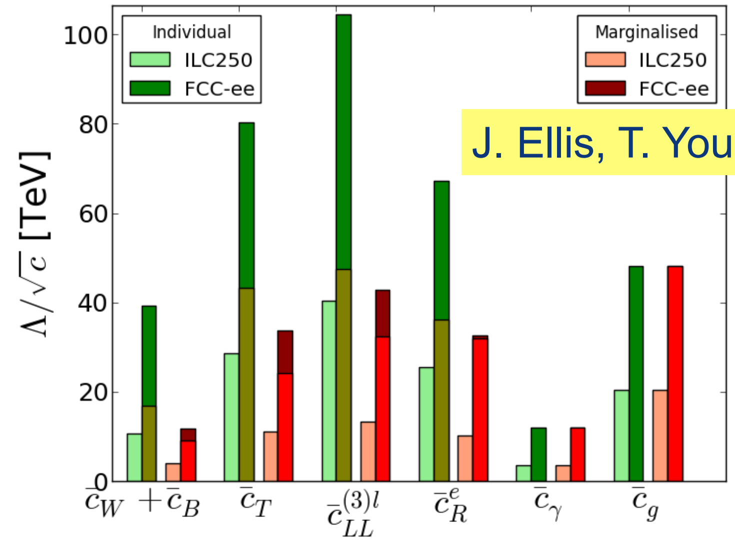
- **Achievable precisions**

Collider	HL-LHC	LC 500 GeV	LC 1-3TeV	FCC-ee+hh
g_{Htt}	4%	7-14%	2-4%	**<1%**
g_{HHH}	50%	30-80%	10-15%	**<5%**
$g_{H\mu\mu}$	4%	10-20%	8%	**<1%**

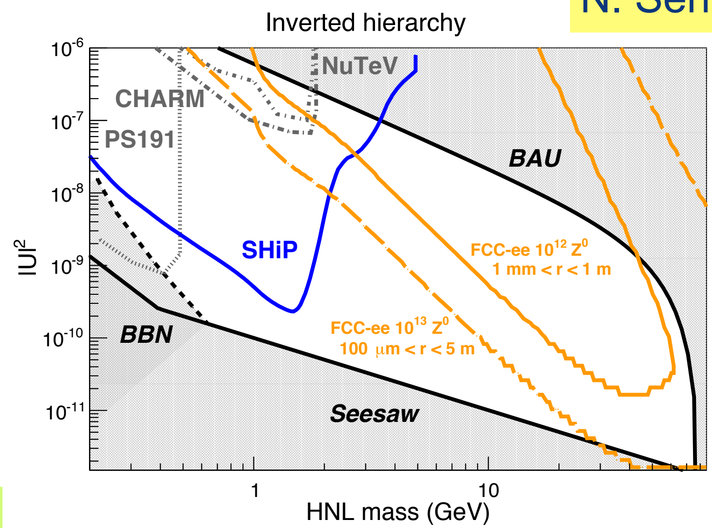
  - The combination of FCC-ee and FCC-hh will be "invincible"

FCC-ee Discovery potential

- **EXPLORE** the 10-100 TeV energy scale with precision measurements
- **DISCOVER** that the Standard Model does NOT fit
  - extra weakly-coupled particle must exist
  - understand the underlying physics through loop effects
- **DISCOVER** a violation of flavour conservation
  - Example: Z->τμ in 1013 Z decays; FCNC in top at 240 or 350 GeV
  - also lots of flavour physics in 1012 bb events…
- **DISCOVER** Dark Matter as invisible decays of Higgs or Z
- **DISCOVER** very weakly coupled particles in the 5-10GeV mass range
  - i.e. right-handed neutrinos, dark photons…



N. Serra



Summary on FCC-ee

F. Zimmermann

- FCC-ee combines several new concepts invented and successfully demonstrated during the last 20 years
- FCC-ee offers extremely high luminosities in the energy range from *Z* to ttbar; combined w. precise energy calibration at *Z* & *W*
- FCC-ee may serve as spring board for the FCC-hh 100 TeV pp collider, bringing a large tunnel, infastructure, cryogenics, time, addt'l physics motivations + performance goals for FCC-hh
- FCC-ee technology is ready; ongoing R&D aims at further increasing efficiency, making FCC-ee a truly „green accelerator"
- optics fulfils all requirements, matched to FCC-hh footprint, baseline luminosity performance is predicted with confidence
- FCC-ee would provide superb discovery potential & a great first step towards 100 TeV; FCC-ee/hh = powerful combination at EF

Summary FCC study status

- Consolidated parameter sets for FCC-hh and FCC-ee machines
- Complete optics baselines for FCC-hh and FCC-ee, beam dynamics compatible with parameter requirements
- Common footprint for both accelerator options
- First round of geology and implementation CE and TI studies completed
- 6 reviews to confirm implementation, layout, optics, hh-injection & rf work
- Convergence on main MDI parameters and detector studies ongoing
- Framework available for physics and detector simulations
- FCC-hh physics report published
- Technologies:
  - SC magnets, cryogenic beam vacuum and cryogenics programs well under way
  - RF, materials, protection, beam transfer, beam diagnostics moving into focus
- *Next milestone is a study review at FCC Week 2017, to confirm baseline and define contents of the Conceptual Design Report.*

FCC International Collaboration

- **75 institutes**
- **26 countries + EC**

Status: April, 2016

FCC Collaboration Status

75 collaboration members & CERN as host institute, April 2016

ALBA/CELLS, Spain
Ankara U., Turkey
U Belgrade, Serbia
U Bern, Switzerland
BINP, Russia
CASE (SUNY/BNL), USA
CBPF, Brazil
CEA Grenoble, France
CEA Saclay, France
CIEMAT, Spain
Cinvestav, Mexico
CNRS, France
CNR-SPIN, Italy
Cockcroft Institute, UK
U Colima, Mexico
UCPH Copenhagen, Denmark
CSIC/IFIC, Spain
TU Darmstadt, Germany
TU Delft, Netherlands
DESY, Germany
DOE, Washington, USA
ESS, Lund, Sweden
TU Dresden, Germany
Duke U, USA
EPFL, Switzerland

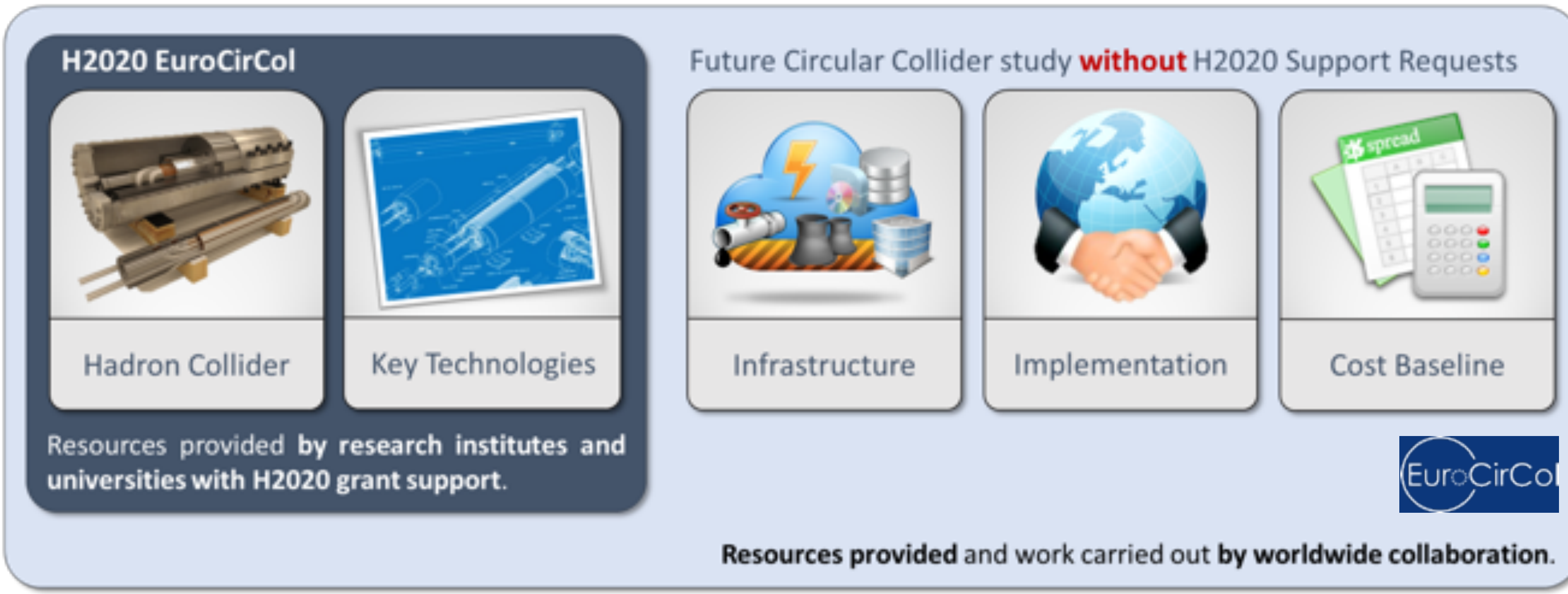
UT Enschede, Netherlands
U Geneva, Switzerland
Goethe U Frankfurt, Germany
GSI, Germany
GWNU, Korea
U. Guanajuato, Mexico
Hellenic Open U, Greece
HEPHY, Austria
U Houston, USA
IIT Kanpur, India
IFJ PAN Krakow, Poland
INFN, Italy
INP Minsk, Belarus
U Iowa, USA
IPM, Iran
UC Irvine, USA
Istanbul Aydin U., Turkey
JAI, UK
JINR Dubna, Russia
Jefferson LAB, USA
FZ Jülich, Germany
KAIST, Korea
KEK, Japan
KIAS, Korea
King's College London, UK

KIT Karlsruhe, Germany
KU, Seoul, Korea
Korea U Sejong, Korea
U. Liverpool, UK
U. Lund, Sweden
MAX IV, Lund, Sweden
MEPhI, Russia
UNIMI, Milan, Italy
MIT, USA
Northern Illinois U, USA
NC PHEP Minsk, Belarus
U Oxford, UK
PSI, Switzerland
U. Rostock, Germany
RTU, Riga, Latvia
UC Santa Barbara, USA
Sapienza/Roma, Italy
U Siegen, Germany
U Silesia, Poland
TU Tampere, Finland
TOBB, Turkey
U Twente, Netherlands
TU Vienna, Austria
Wigner RCP, Budapest, Hungary
Wroclaw UT, Poland

EuroCirCol EU Horizon 2020 Grant

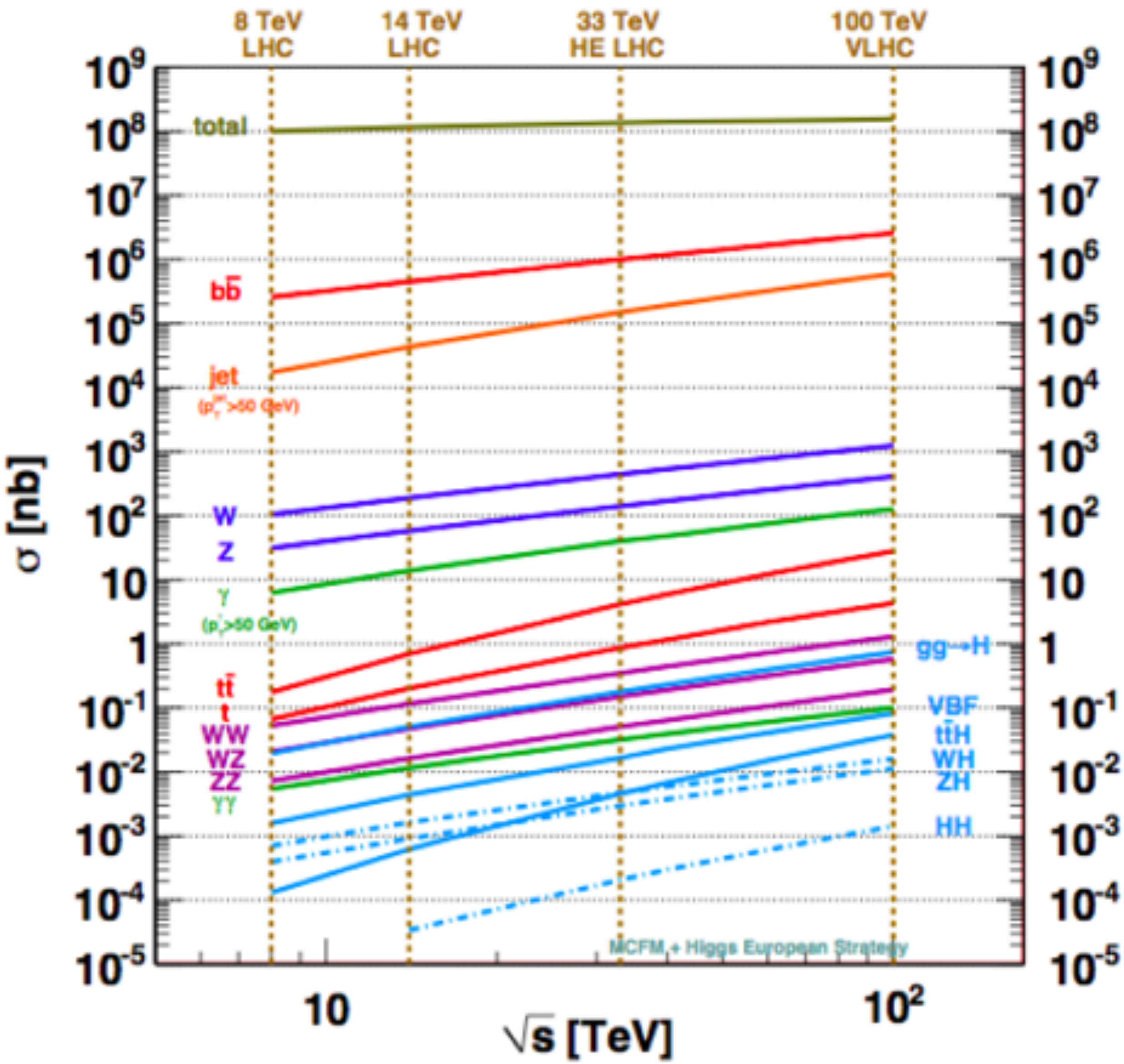
EC contributes with funding to FCC-hh study

- **EuroCirCol H2020 Design Study**, launched in June 2016, is in full swing now and makes essential contributions to the FCC-hh work packages:
- **Arc & IR optics, 16 T dipole design, cryogenic beam vacuum system**




FCC PHYSICS WEEK
16-20 January 2017
@CERN
EuroCirCol
FCC Week 2017
29 May – 2 June 2017
Berlin, Germany

BACKUP

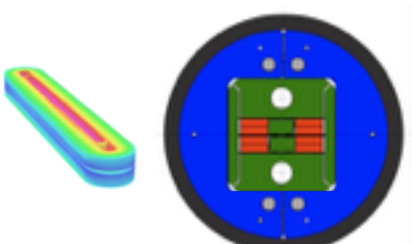


final state	$N_{ev}/10ab^{-1}$
W	10^{13}
t tbar	3×10^{11}
H	10^{10}
HH	10^{6}
jets (p_T>5 TeV)	10^{6}
jets (p_T>10 TeV)	10^{4}

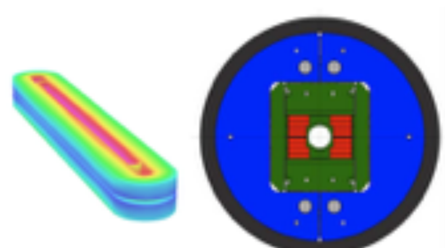
CERN & EuroCirCol 16T programs

Main Stages of the FCC Magnet Program 2015 - 2021

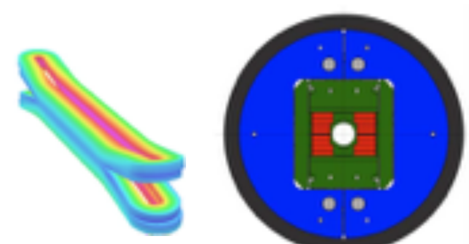
Stages	Description	15	2016	2017	2018	2019	2020	21
S0	High J_c wire development with industry	■	■■	■■	■■	■■	■■	■
S1	Supporting wound conductor test program	■	■■	■■	■■	■■	■■	■
S2	Design, manufacture, test 16T ERMC with existing wire	■	■■	■■	■			
S3	Design, manufacture, test 16 T RMM with existing wire		■■	■■	■■	■		
S5	Procurement of enhanced high J_c wire			■■	■■	■		
S6	EuroCirCol design 16T accelerator quality model	■	■■	■■	■■	■		
S7	Manufacture and test of the 16 T EuroCirCol model					■■	■■	■



ERMC (16 T mid-plane field)
tests from mid 2017



RMM (16 T in 50 mm cavity)
tests from mid 2018



Model magnet (16 T, 50 mm gap)
tests from end 2020

High-Energy LHC

FCC study continues effort on **high-field collider in LHC tunnel**

2010 EuCARD Workshop Malta;
Yellow Report CERN-2011-1

EuCARD-AccNet-EuroLumi Workshop: The High-Energy Large Hadron Collider - HE-LHC10, E. Todesco and F. Zimmermann (eds.), EuCARD-CON-2011-001; arXiv: 1111.7188; CERN-2011-003 (2011)

- based on 16-T dipoles developed for FCC-hh
- extrapolation from (HL-)LHC and from FCC developments
- **Present focus: optics scaling, infrastructure requirements & integration**

Rate comparisons at 8, 14, 100 TeV

	N_{100}	N_{100}/N_8	N_{100}/N_{14}
gg→H	16 G	4.2×10^4	110
VBF	1.6 G	5.1×10^4	120
WH	320 M	2.3×10^4	66
ZH	220 M	2.8×10^4	84
ttH	760 M	29×10^4	420
gg→HH	28 M		280

$N_{100} = \sigma_{100\,TeV} \times 20\ ab^{-1}$

$N_8 = \sigma_{8\,TeV} \times 20\ fb^{-1}$

$N_{14} = \sigma_{14\,TeV} \times 3\ ab^{-1}$

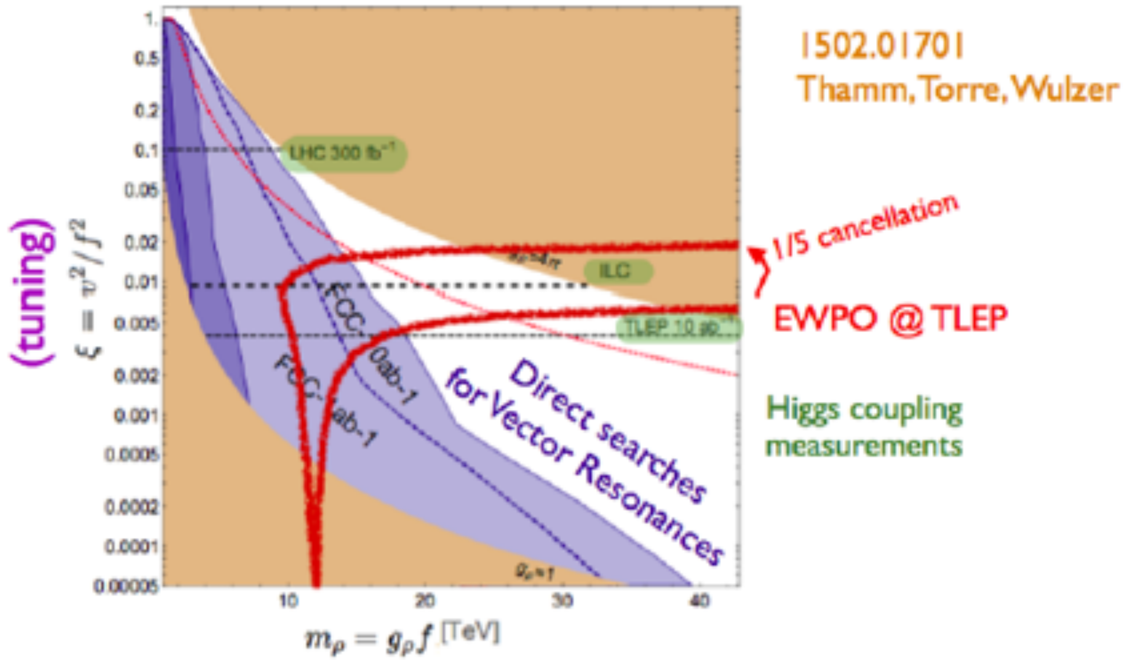
Statistical precision:

- O(100 - 500) better w.r.t Run 1
- O(10 - 20) better w.r.t HL-LHC

Composite Higgs Models

Want Lepton colliders to probe Higgs coupling deviations & EWPO

Want 100 TeV to produce vector resonances of strongly coupled sector
(as well as top partners)



Interplay of EW precision tests (Tera-Z@FCC-ee), Higgs BR measurements (H@FCC-ee) and direct resonance searches (10-30 TeV, @ FCC-hh)

FCC-hh as A-A collider

	Pb-Pb	Pb-p
beam energy [TeV]	4100	50
c.m. energy/nucleon pair [TeV]	39.4	62.8
no. bunches / beam	2072	2072
IP beta function [m]	1.1	1.1
long. emit. rad. damping time [h]	**0.24**	0.5
init. luminosity [10^{27} $cm^{-2}s^{-1}$]	24.5	2052
peak luminosity [10^{27} $cm^{-2}s^{-1}$]	**57.8**	**9918**

based on existing LHC complex; fast radiation damping; secondary beams from IP require dedicated collimators,…

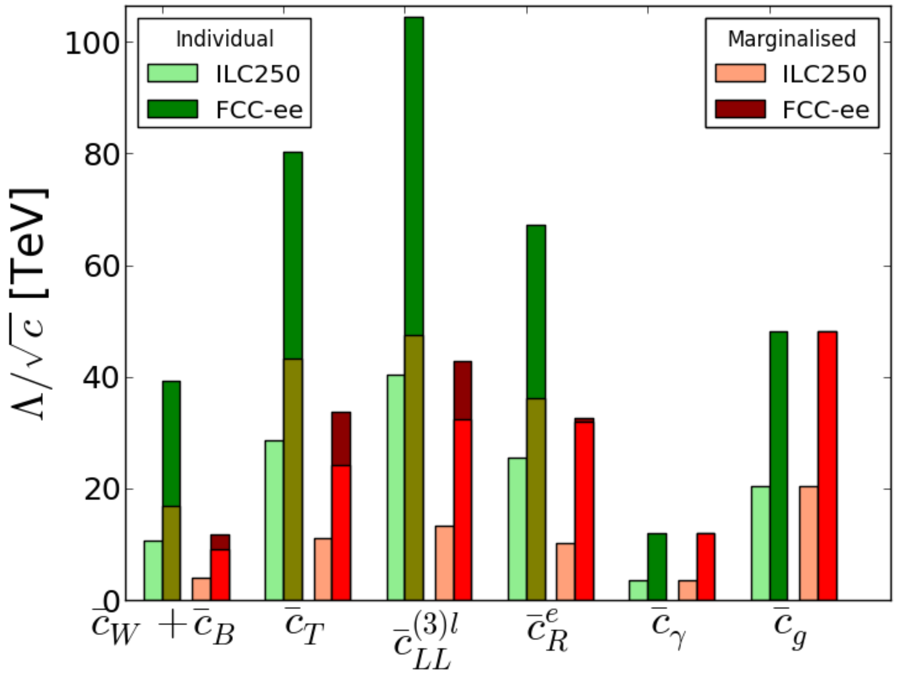
J. Jowett, M. Schaumann

M. Schaumann, "Potential performance for Pb-Pb, p-Pb, and p-p collisions in a future circular collider, Phys. Rev. ST Accel. Beams 18, 091002 (2015).
A. Dainese et al., "Heavy ions at the Future Circular Collider," contribution to forthcoming CERN Report on Physics at FCC-hh, http://arxiv.org/abs/1605.01389 .

❑ Higher-dimensional operators as relic of new physics ?

◆ **Possible corrections to the standard model**

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{c_i}{\Lambda^2} \mathcal{O}_i$$



In green: one operator at a time

In red: all operators together

ILC sensitivity vanishes w/o Z and WW runs

J. Ellis, T. You, arXiv:1510:04561

After FCC-ee: Λ_{NP} > 100 TeV ?