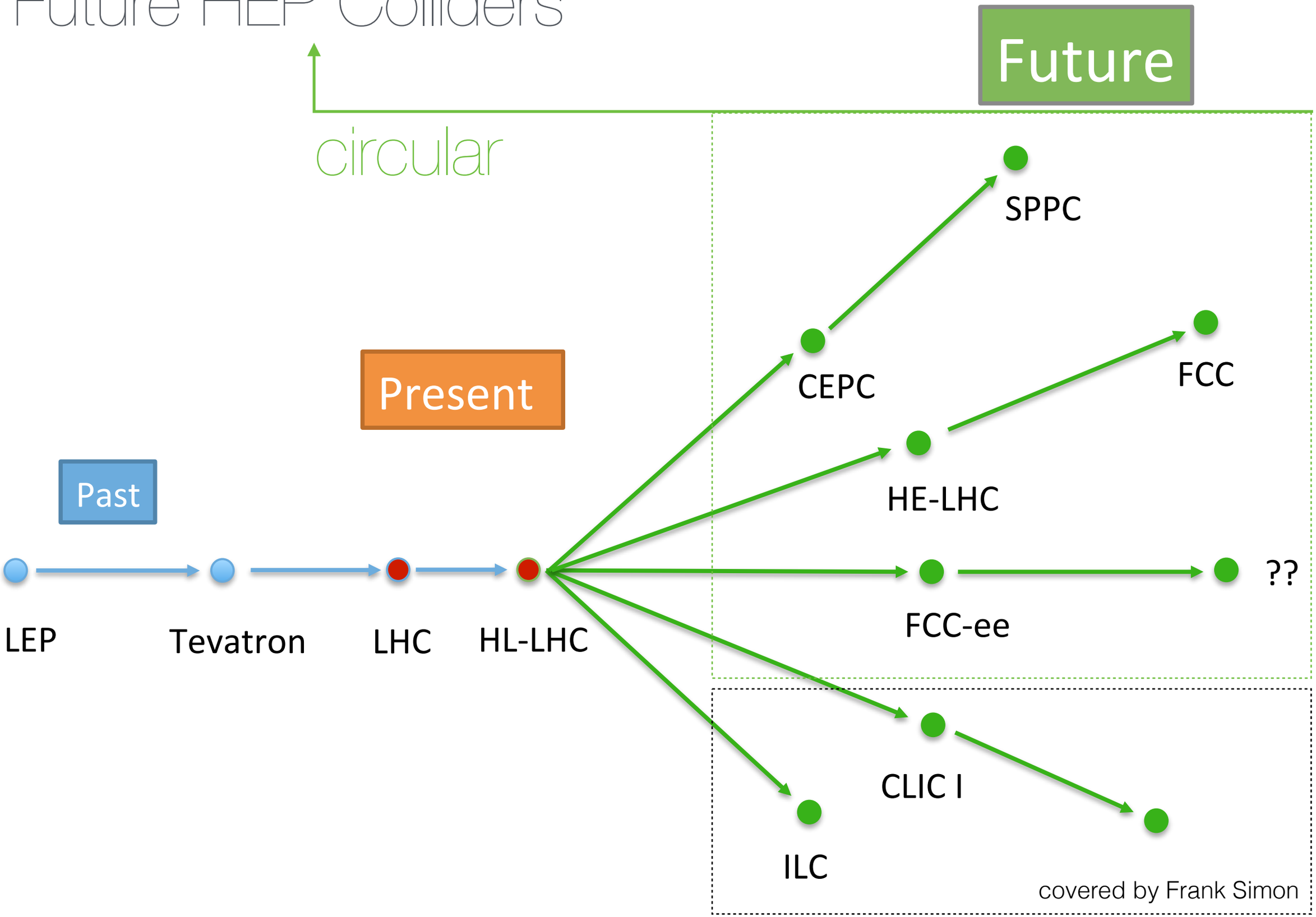
Future collider projects:
technology status, overview, status & timelines

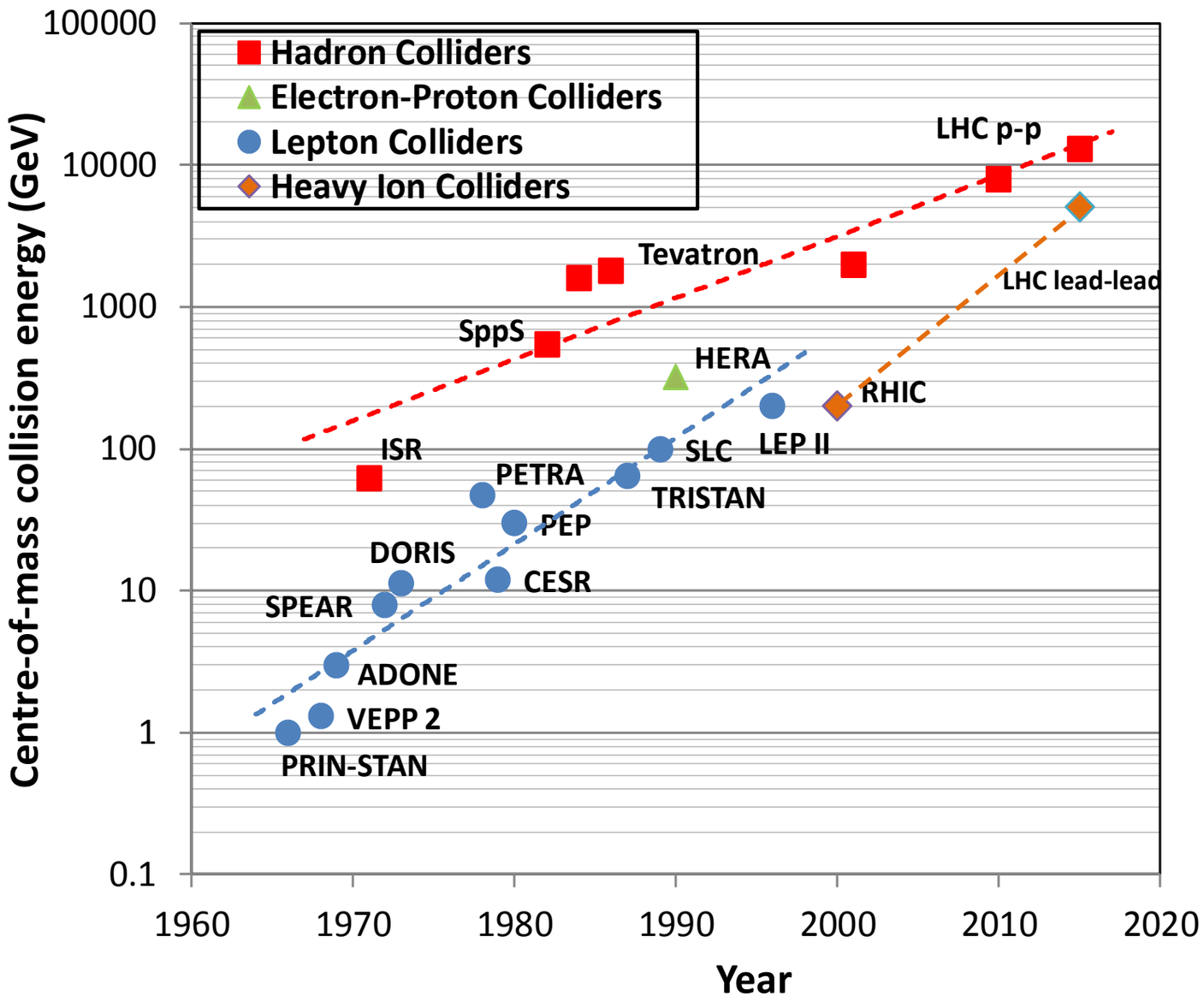
A. Salzburger, F. Hahn (CERN)
with great contribution from M. Benedikt, L. Linssen, J. Osborne, M. Ruan and F. Zimmermann

Future HEP Colliders



Outline

- High-luminosity upgrade of the LHC (HL-LHC)
- e^+e^- and pp colliders
  - challenges and benefits
- (Future) e^+e^- colliders
  - FCC-ee and CepC
  - technologies and physics reach
- (Future) hadron colliders
  - HE-LHC, FCC-hh, SppC
  - technologies and physics reach
- Schedules and summary

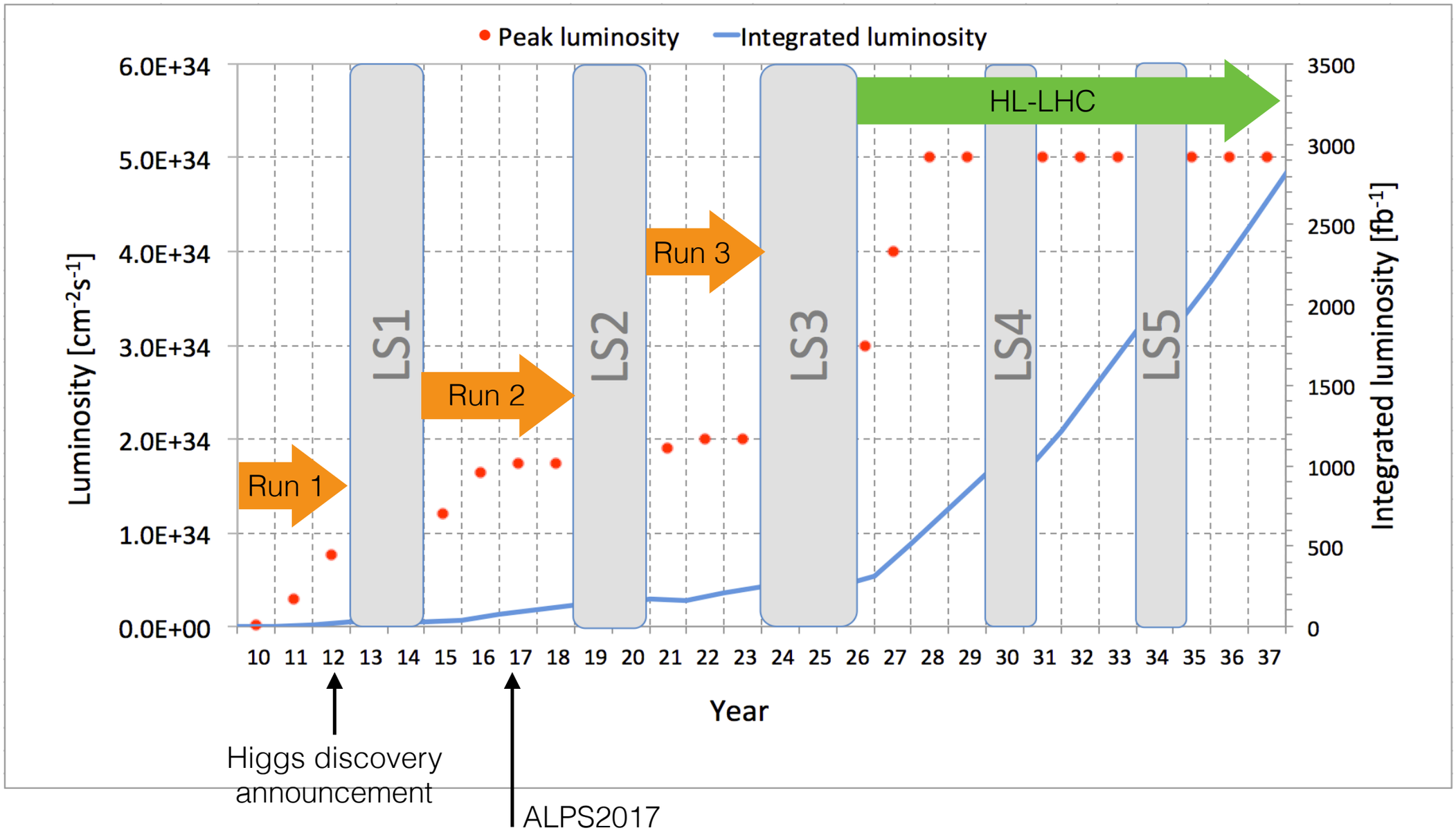


Colliders are powerful instruments in High Energy physics for particle discoveries and precision measurements

HL-LHC Preparations

- Busy planning for HL-LHC upgrade
  - pile-up scenario of <μ> ~ 200

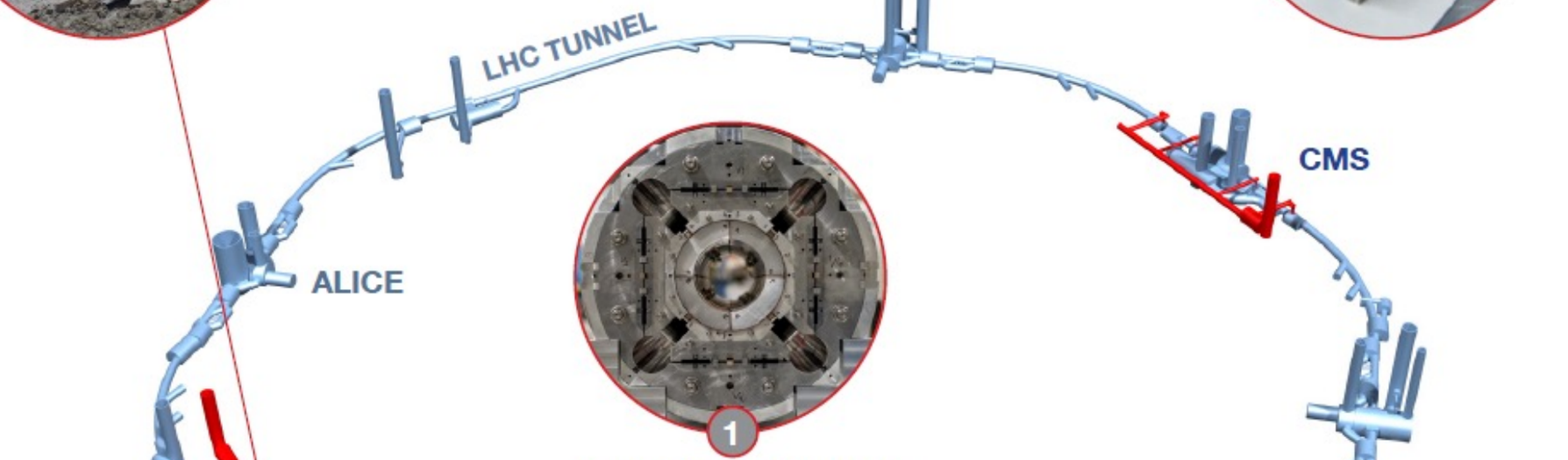
    excellent preparation of the HEP community for future (hadron) colliders



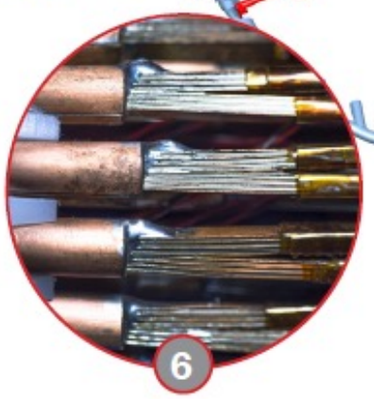
HL-LHC Project Landmarks

2 CIVIL ENGINEERING
2 new 300-metre service tunnels and 2 shafts near to ATLAS and CMS.

"CRAB" CAVITIES
16 superconducting „crab" cavities for each of the ATLAS and CMS experiments to tilt the beams before collisions.

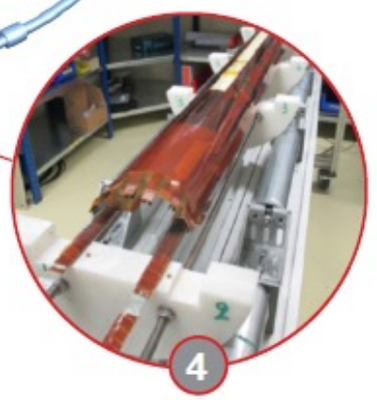


1 FOCUSING MAGNETS
12 more powerful quadrupole magnets for each of the ATLAS and CMS experiments, designed to increase the concentration of the beams before collisions.



6 SUPERCONDUCTING LINKS
Electrical transmission lines based on a high-temperature superconductor to carry current to the magnets from the new service tunnels near ATLAS and CMS.

5 COLLIMATORS
15 to 20 new collimators and 60 replacement collimators to reinforce machine protection.



4 BENDING MAGNETS
4 pairs of shorter and more powerful dipole bending magnets to free up space for the new collimators.

CERN November 2015

HL-LHC preparations by experiments

- ATLAS/CMS are in the phase of submitting TDRs for HL-LHC
  - pile-up scenario of <μ> ~ 200
  - very challenging from experiments
  - will need updates of the detector and (partly of) experimental approaches

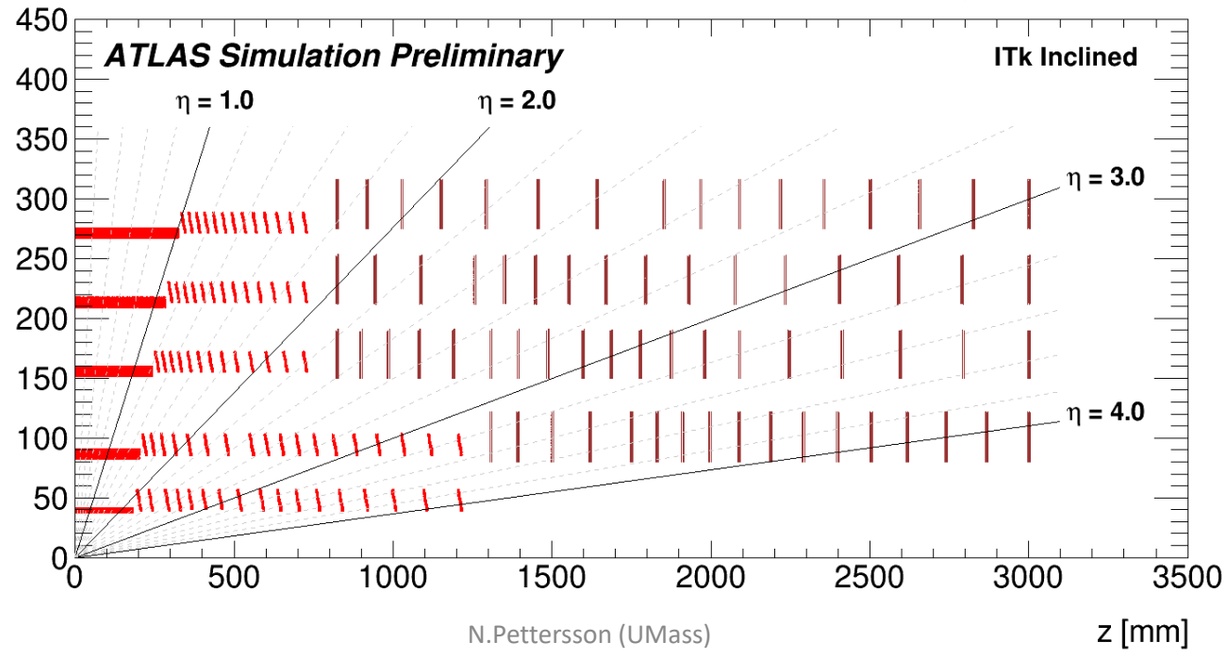
    expanded pseudo rapidity range

    higher granularity detectors

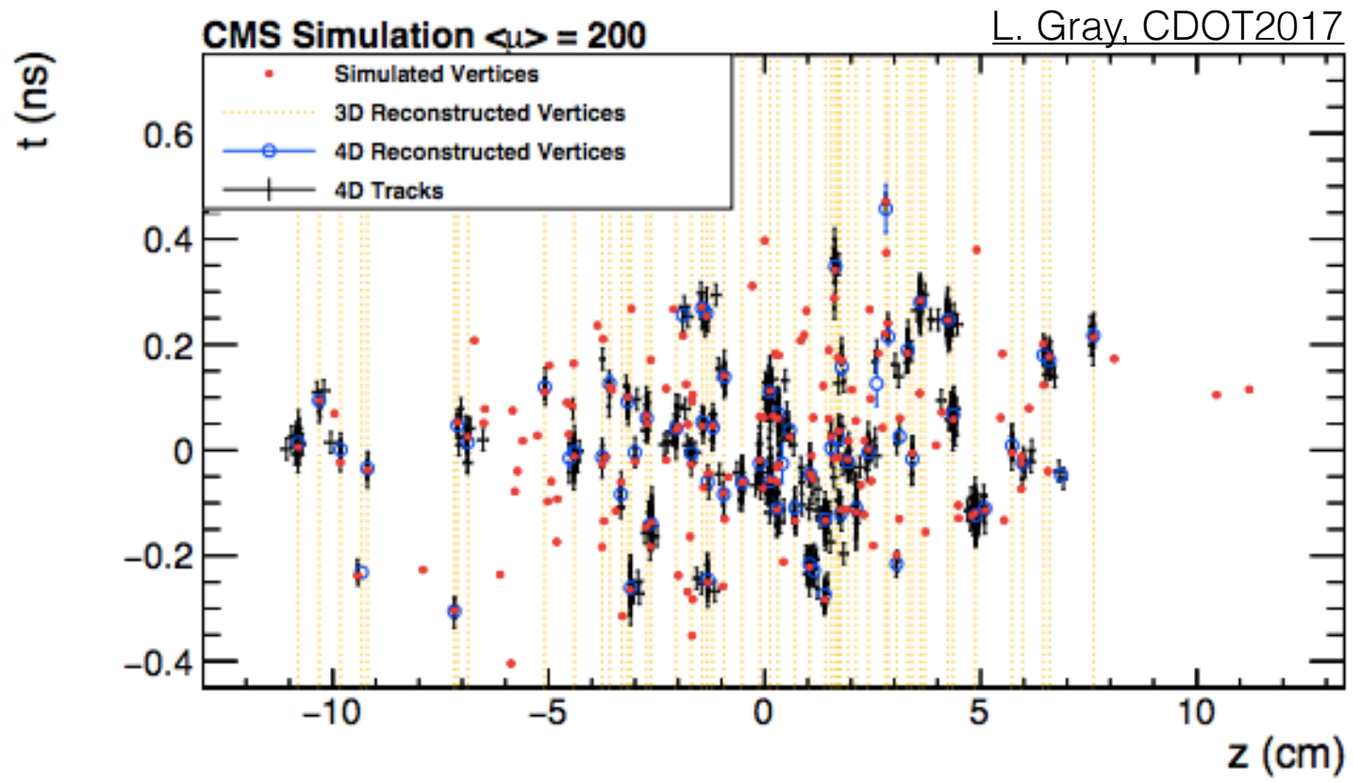
    refined combined reconstruction

- Is an excellent preparation for experiments at future circular colliders

N. Pettersson, CDOT2017



L. Gray, CDOT2017



Studies of High Energy Circular Colliders

FCC

Future Circular Collider

FCC-ee: e^+e^- with $\sqrt{s}$ = 90 - 350 GeV

FCC-hh: pp with $\sqrt{s}$ ~ 100 TeV

Circumference: 80-100 km

CepC

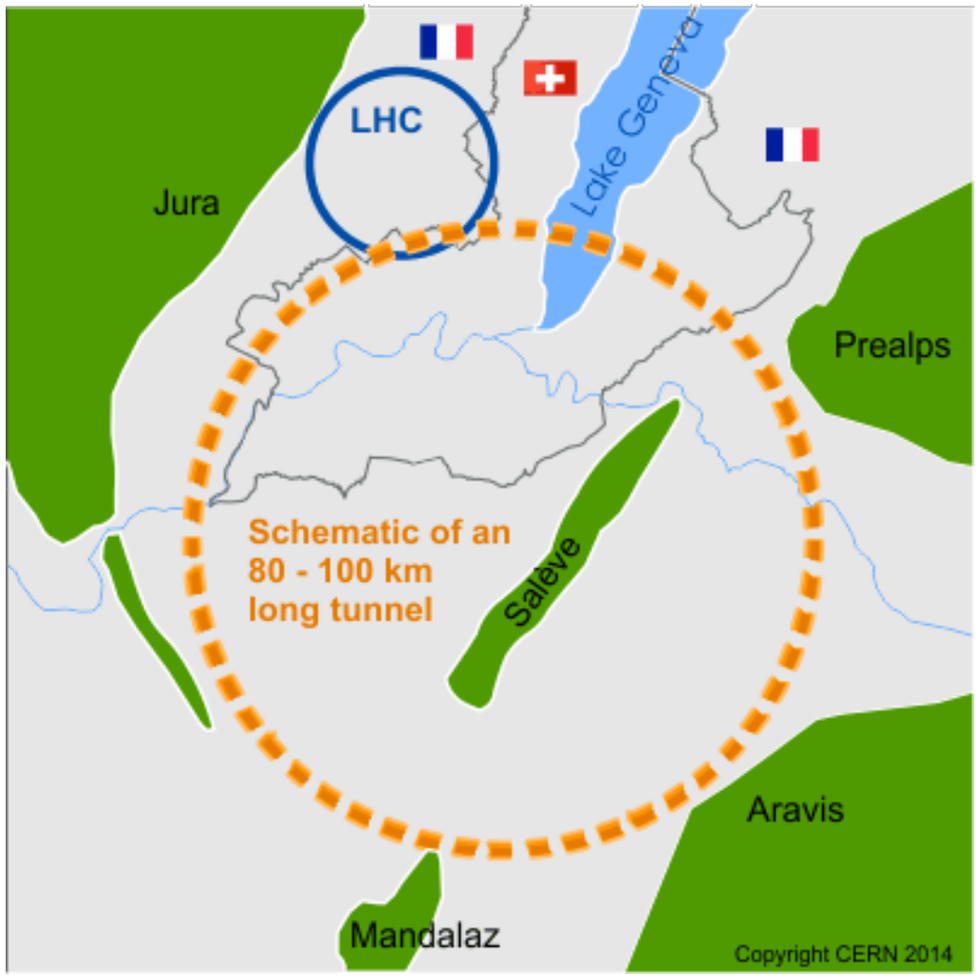
Circular Electron Positron Collider

CepC: e^+e^- with $\sqrt{s}$ = 240 - 250 GeV

SppC: pp with $\sqrt{s}$ = 70 - 100 TeV

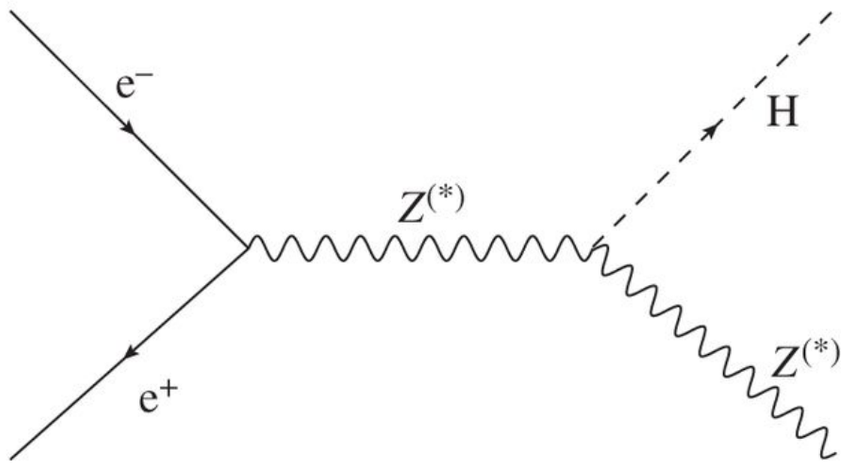
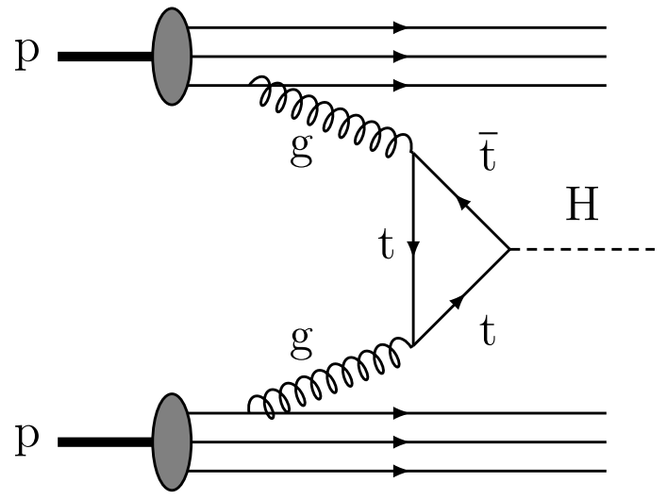
Circumference/Length: 54-100 km

schematic at CERN location



investigated site in China

(Dominant) Higgs production

e^+e^- collider	pp collider
	
e^+/e^- are point-like → Initial state well defined ($\sqrt{s}$ / polarisation) → Best for high-precision measurements	proton is compound object → Initial state not known event-by-event → Limits achievable precision
Cleaner experimental environment → Trigger-less readout → Low radiation levels	High rates of QCD backgrounds (next slide) → Complex triggering schemes → High levels of radiation
Superior sensitivity for electro-weak states	High cross-sections for colored states
High energy limited: Limits discovery of heavy particle → <≈350 GeV e^+e^- for circular colliders → <≈3 TeV e^+e^- for linear colliders	High-energy circular pp colliders feasible → Best for discoveries at high energy frontier

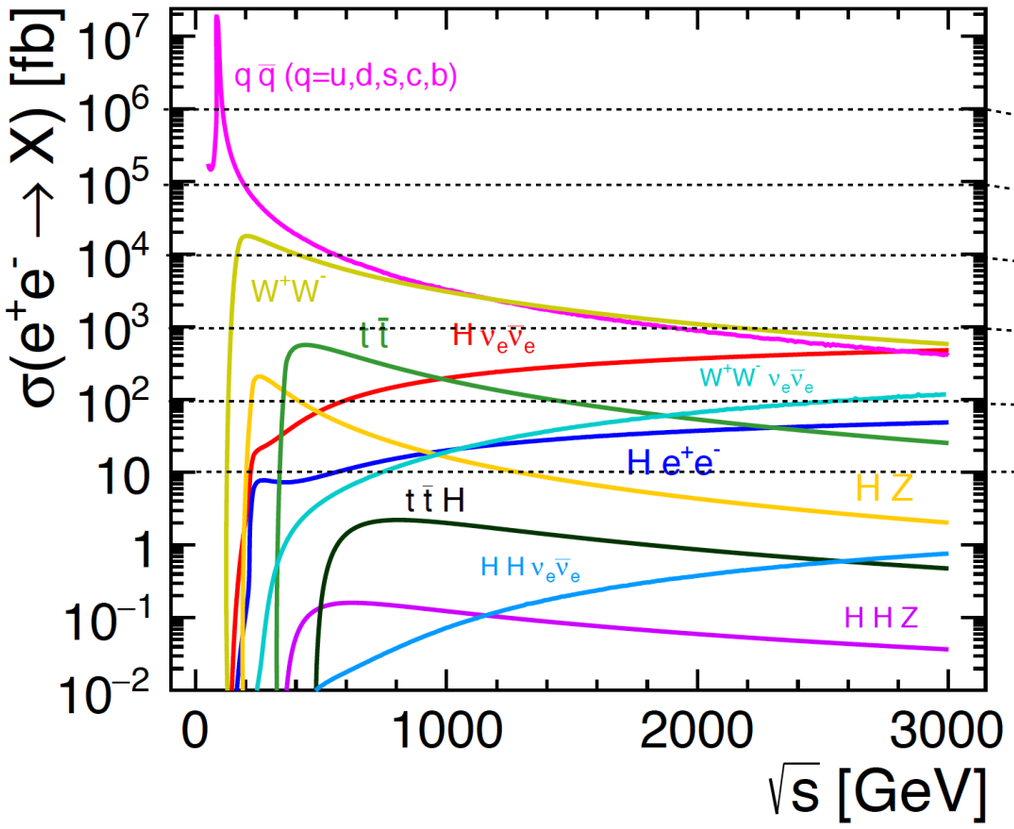
more details, see backup

e^+e^- vs pp collisions

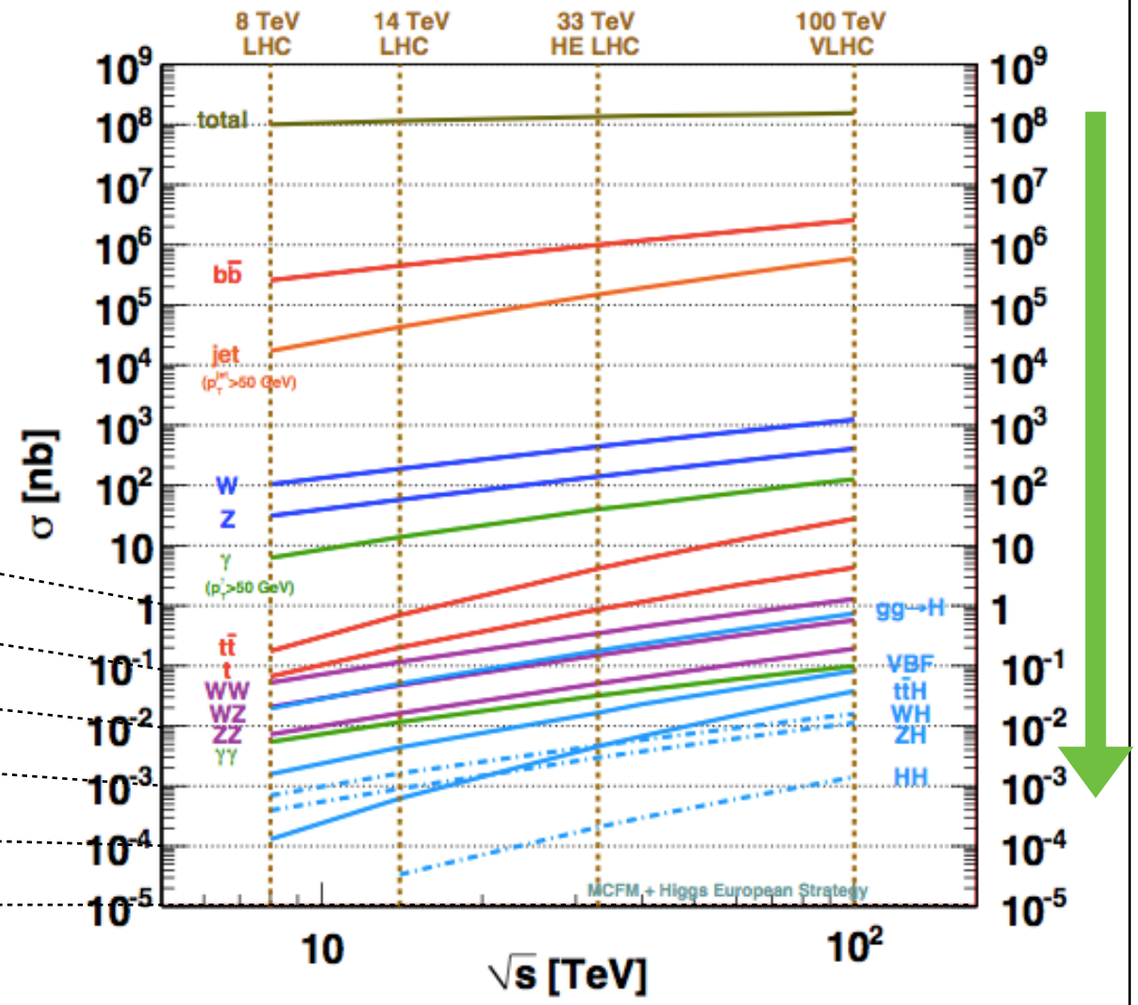
e^+e^- collider

Lower cross-section

Cleaner experimental environment
→ Trigger-less readout
→ Low radiation levels



pp collider

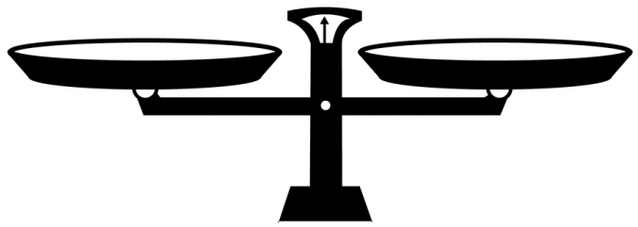


Higher energy reach

High rates of QCD backgrounds
→ Complex triggering schemes
→ High levels of radiation

Main technical challenges / benefits

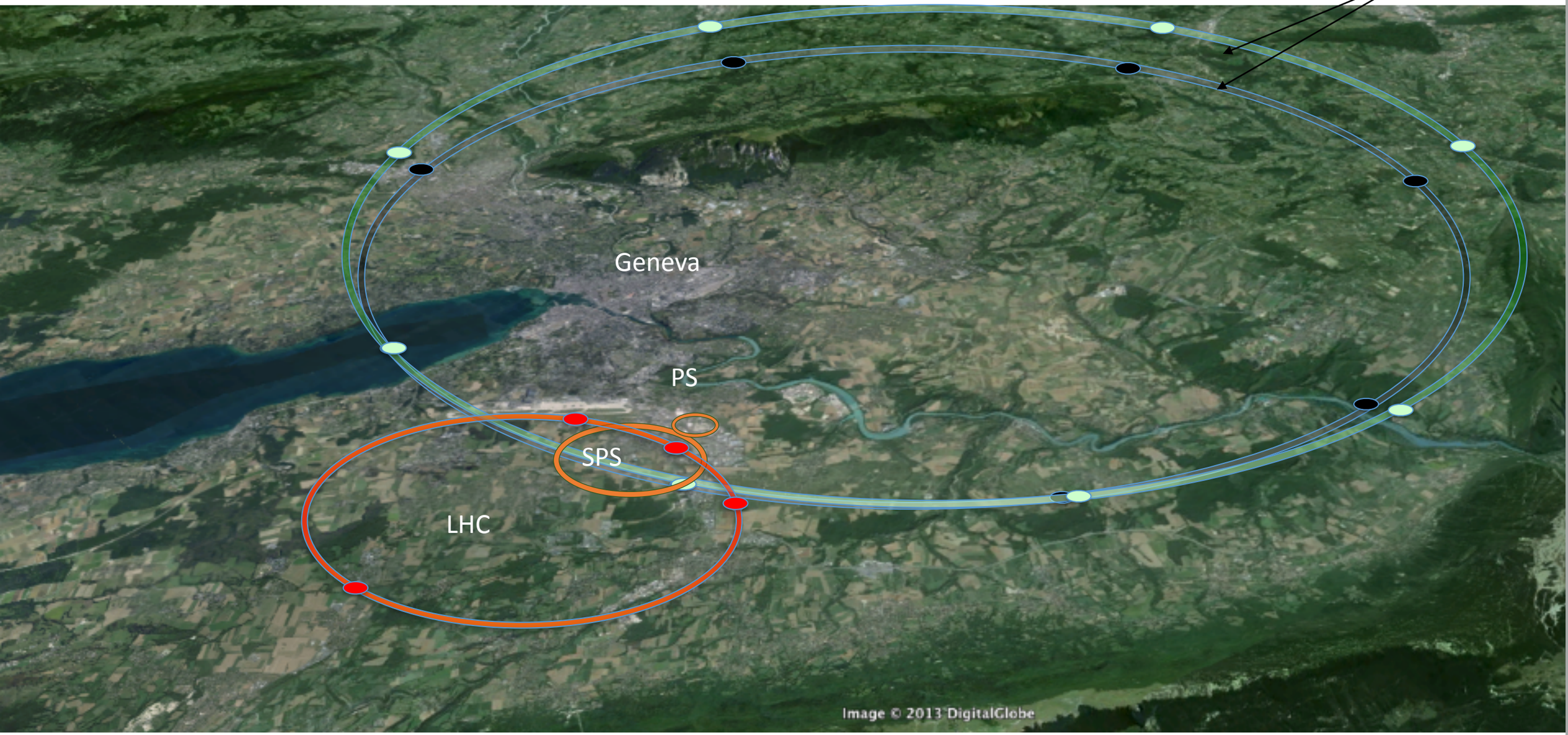
e^+e^- collider	pp collider
Detectors: → **No pile up, max. event rate 20kHz@ Z peak** → **Material budget of inner detector**	Detectors: → Huge pile up (200, 1000) → Radiation hardness required → Complex triggering system (computing) → Huge detectors (containment, bending)
Accelerator: → High accelerating gradient → Power consumption	Accelerator: → High field magnets → Stored energy
Machine Detector Interface: → Booster bypass at IP → Detector L<≈ 2.2 m at each side → Large beam crossing angle 30 mrad	Machine Detector Interface: → IP configuration (see later) → shielding



Future e^+e^- Circular Colliders

FCC-ee

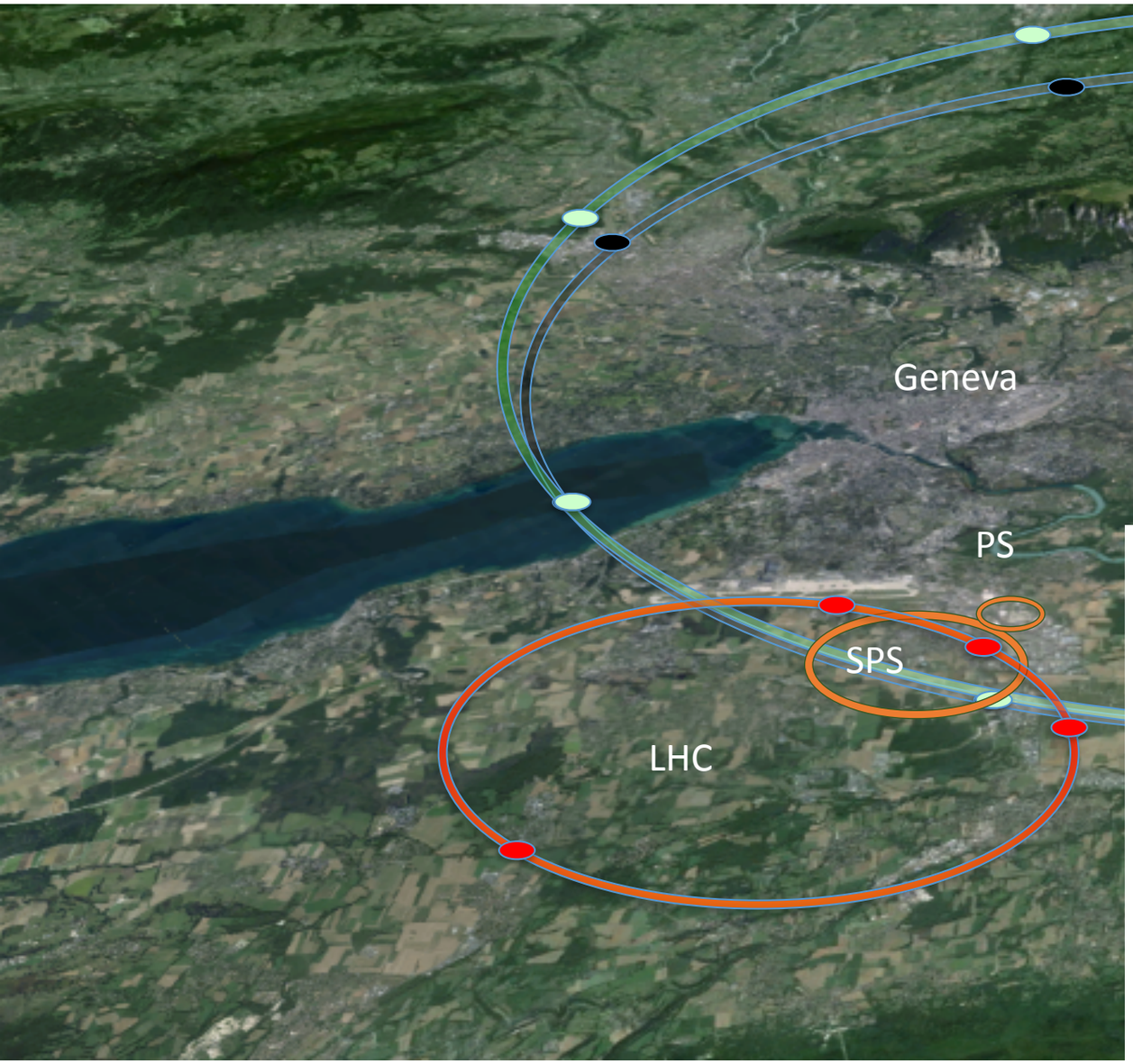
80/100 km FCC ring option



Future e^+e^- Circular Colliders

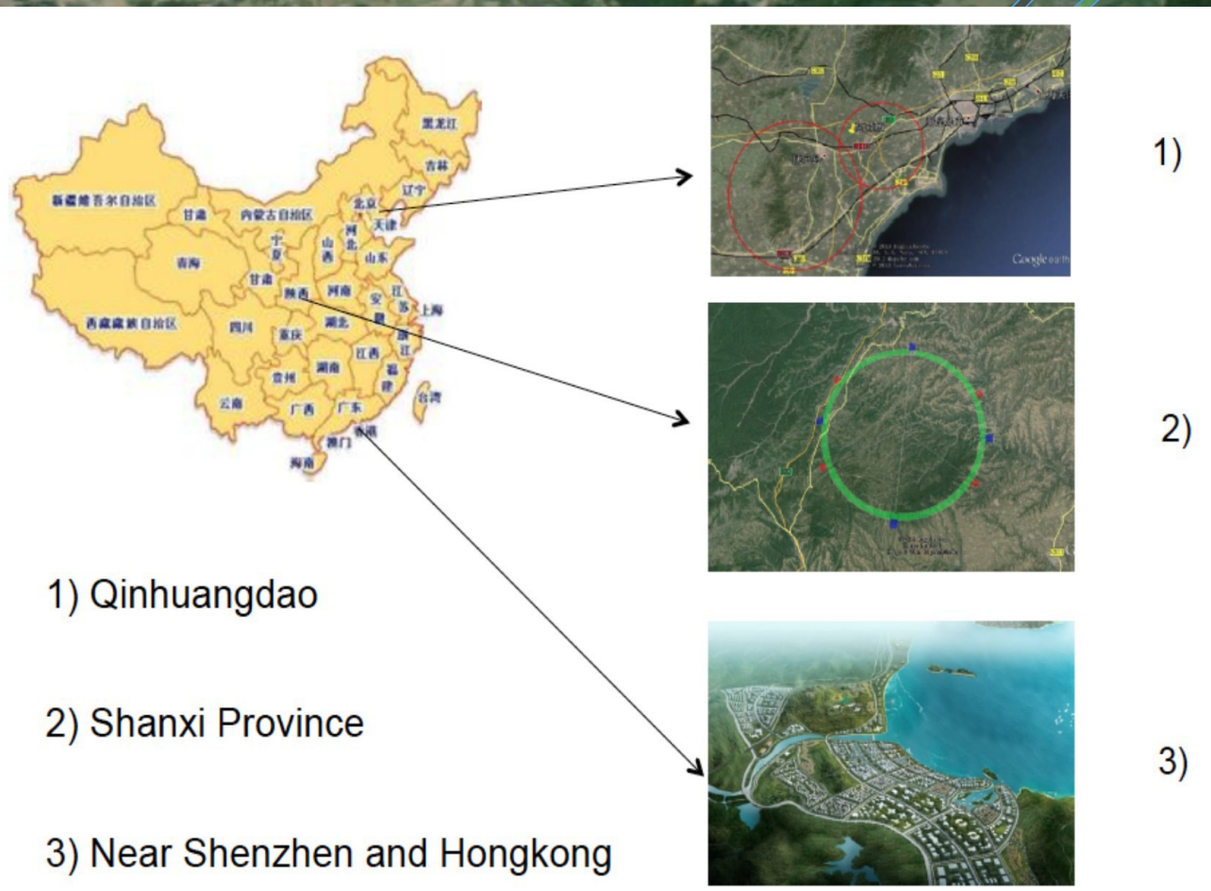
FCC-ee

80/100 km FCC ring option



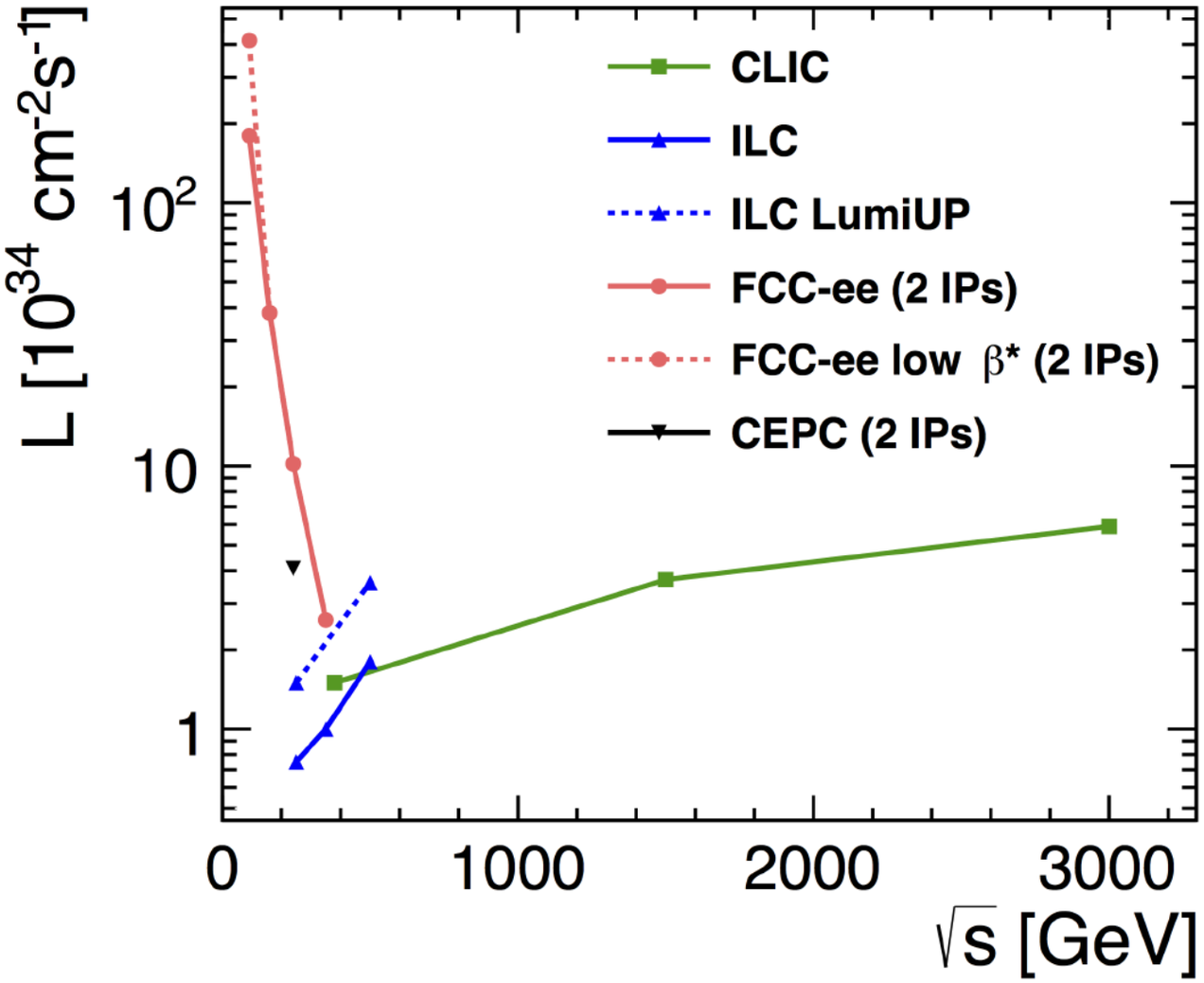
CepC

baseline 45 km (possibility up to 100 km)



Luminosity performance for e^+e^-

- Linear/circular colliders show different luminosity scaling



Circular colliders:
- Large luminosity at lower energies
- Luminosity decreases with energy

Linear colliders:
- Can reach the higher energies
- Luminosity rises with energy
- Beam polarisation at all energies

Note: Peak luminosity at LEP2 (209 GeV) was ~10^{32} $cm^{-2}s^{-1}$

FCC (ee/hh) site investigations

Alignment | Shafts | Query

Choose alignment option

100km quasi-circular

Tunnel elevation at centre:261mASL

Grad. Params

Azimuth (°):	-20
Slope Angle x-x(%):	0.65
Slope Angle y-y(%):	0

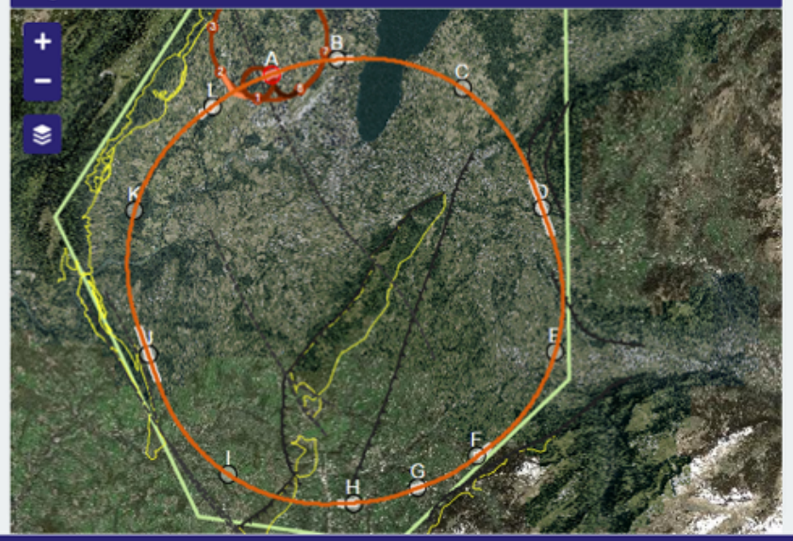
LOAD SAVE CALCULATE

Alignment centre

X: 2499731 Y: 1108403

	CP 1		CP 2	
	Angle	Depth	Angle	Depth
LHC	-64°	220m	64°	172m
SPS		242m		241m
TI2		235m		241m
TI8		242m		170m

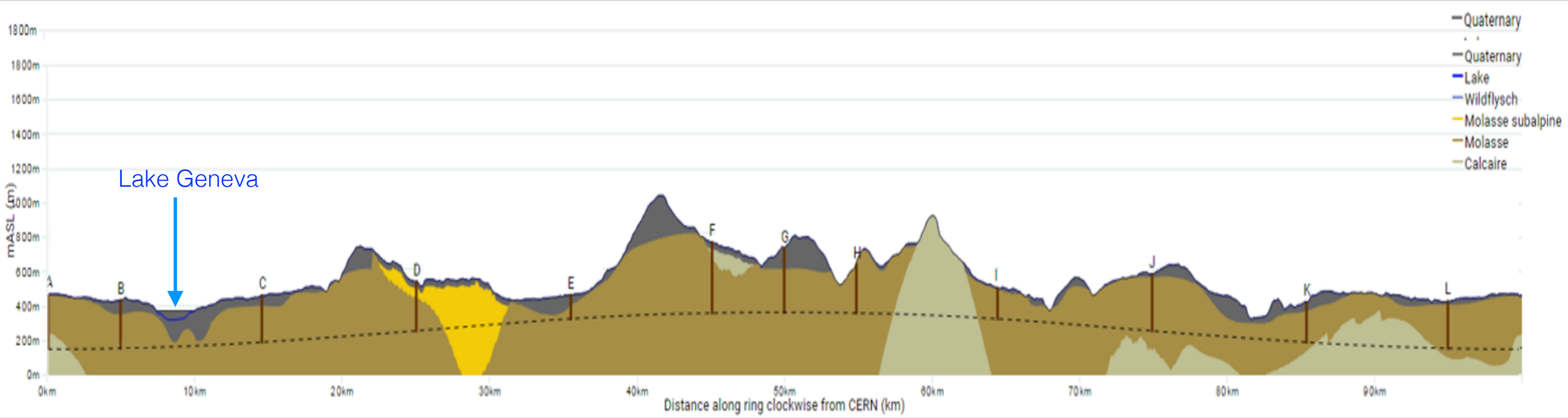
Alignment Location



Geology Intersected by Shafts | Shaft Depths

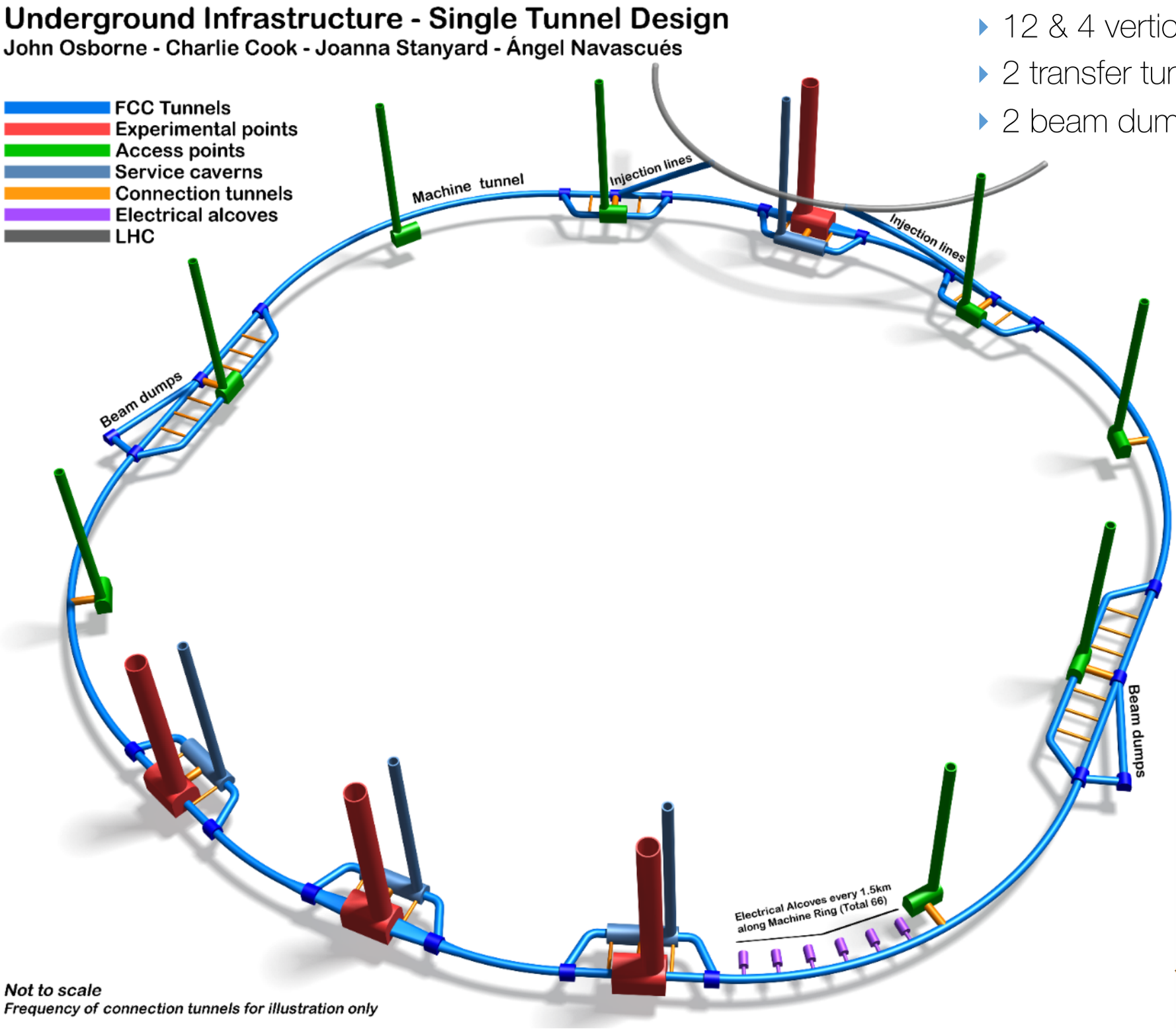
		Shaft Depth (m)			Geology (m)		
Point	Actual	Molasse SA	Wildflysch	Quaternary	Molasse	Urgonian	Calcaire
A	304	0	0	12	213	0	79
B	266	0	0	80	156	0	30
C	257	0	0	58	199	0	0
D	272	52	0	40	181	0	0
E	132	0	0	64	68	0	0
F	392	0	0	40	296	0	56
G	354	0	0	116	237	0	0
H	268	0	0	0	268	0	0
I	170	0	0	12	158	0	0
J	315	0	0	22	293	0	0
K	221	0	0	52	169	0	0
L	260	0	0	21	239	0	0
Total	3211	52	0	517	2478	0	109

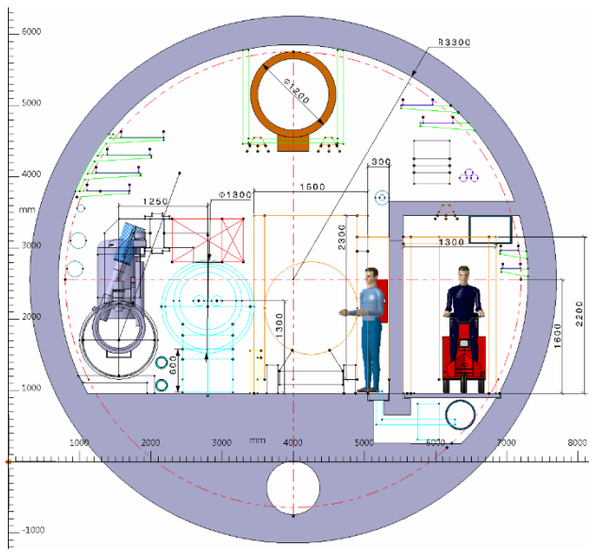
Alignment Profile



FCC baseline layout

- 100 km tunnel 6 m inner diameter
- 4 large experimental caverns
- 8 service caverns for infrastructure
- 12 & 4 vertical shafts (3 km integral)
- 2 transfer tunnels (10 km)
- 2 beam dump tunnels (4 km)





FCC-ee top-up injection & booster ring

- Top-up injection is essential
  - very short luminosity lifetime ($\tau \approx 21$ min @ 140 GeV)

    short lifetime caused by radiative Bhabha scattering cross section
  - needs booster ring of same size (sam tunnel) to provide top-up injection

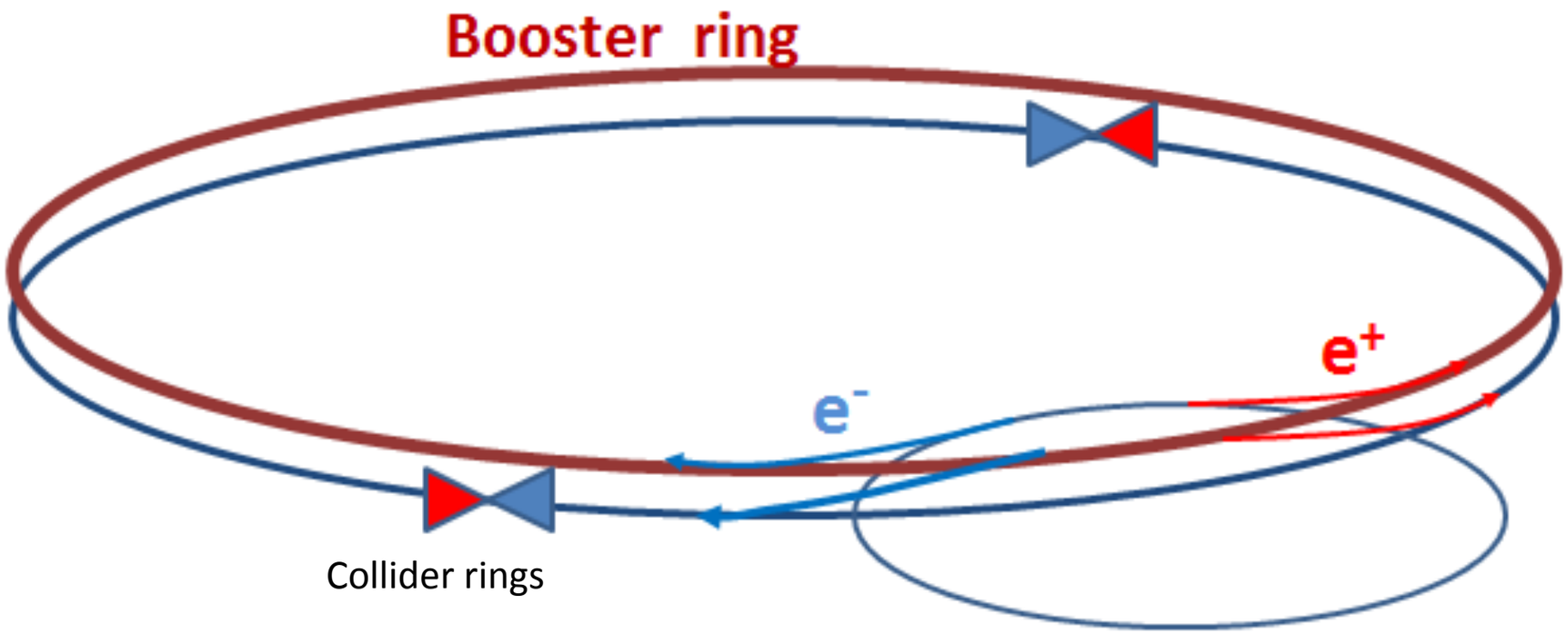
    repetition < 0.1 Hz

    top-up injection frequency of 0.05 Hz (one booster filling two rings)

    booster injection energy ~ 20 GeV

    collider ring injection energy of 45.6 - 175 GeV

    booster by-pass around experiments



FCC-ee parameters

high currents high gradients

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

Limitation: synchrotron radiation - strong dependency on beam energy

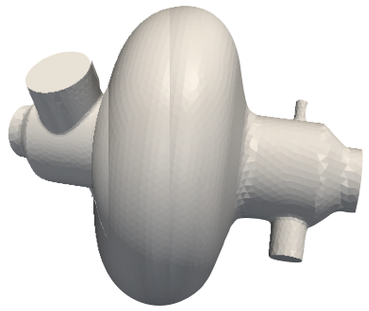
CepC parameters

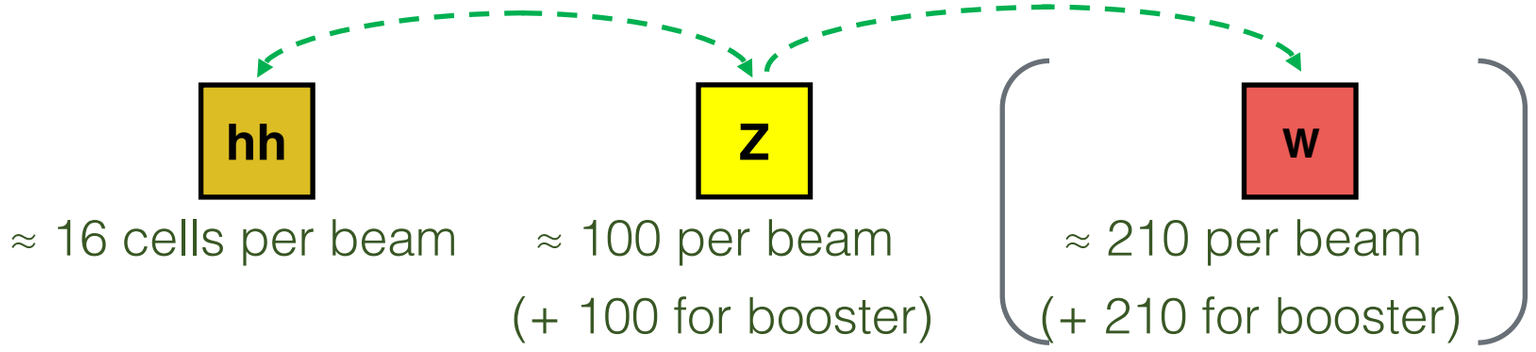
- CepC double-ring option
  - 61 km circumference

	Pre-CDR	H-high lumi.	H-low power	W	Z	Z-5cell
Energy (GeV)	120	120	120	80	45.5	45.5
Circumference (km)	54	61	61	61	61	61
SR loss/turn (GeV)	3.1	2.96	2.96	0.58	0.061	0.061
N_e/bunch (10^{11})	3.79	2.0	1.98	0.85	0.6	0.6
Bunch number	50	107	70	400	1100	700
SR power /beam (MW)	51.7	50	32.5	15.7	3.2	2.0
β_{IP} x/y (m)	0.8/0.0012	0.272/0.0013	0.275 /0.0013	0.16/0.001	0.12/0.001	0.12/0.001
Emittance x/y (nm)	6.12/0.018	2.05/0.0062	2.05 /0.0062	0.93/0.003	0.87/0.0046	0.87/0.0046
ξ_x/IP	0.118	0.041	0.042	0.0145	0.0098	0.0098
ξ_y/IP	0.083	0.11	0.11	0.084	0.073	0.073
V_{RF} (GV)	6.87	**3.48**	**3.51**	**0.7**	**0.12**	**0.12**
f_{RF} (MHz)	650	650	650	650	650	650
Nature σ_z (mm)	2.14	**2.7**	**2.7**	**3.23**	**3.9**	**3.9**
Total σ_z (mm)	2.65	2.95	2.9	3.35	4.0	4.0
HOM power/cavity (kw)	3.6	0.74	0.48	0.47	0.59	0.93
Energy acceptance (%)	2	2	2			
Energy acceptance by RF (%)	6	**2.3**	**2.4**	**1.3**	**1.1**	**1.1**
Life time due to beamstrahlung_cal (minute)	47	37	37			
L_{max}/IP (10^{34}cm^{-2}s^{-1})	2.04	3.1	2.01	3.5	3.44	2.2

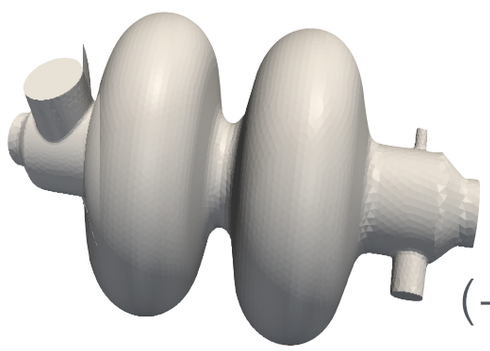
R&D lines for SC RF systems

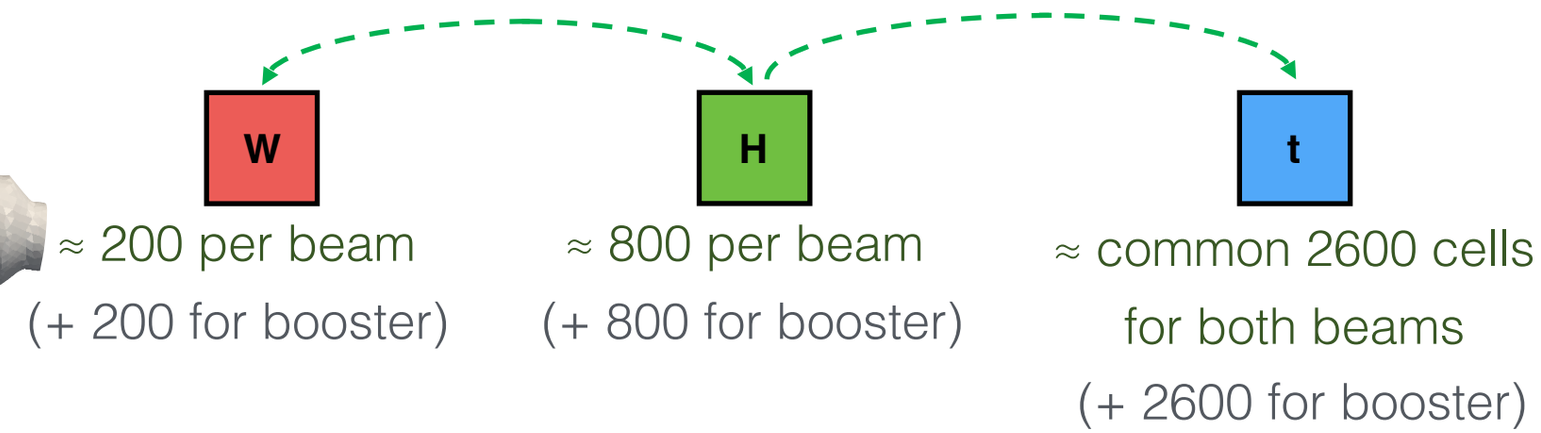
- 400 MHz single-cell cavities preferred for hh machine and ee at Z pole (few MeV/m)
  - Baseline Nb/Cu @4.5 K, development with synergies to HL-LHC, HE-LHC





- 400/800 MHz multi-cell cavities preferred for higher energy e+e- machine
  - Baseline options 400 MHz Nb/Cu @ 4.5 K and 800 MHz Nb system @ 2K
  - Long term R&D: Nb_3Sn like components





RF system requirements

- Very large scale of operation parameters

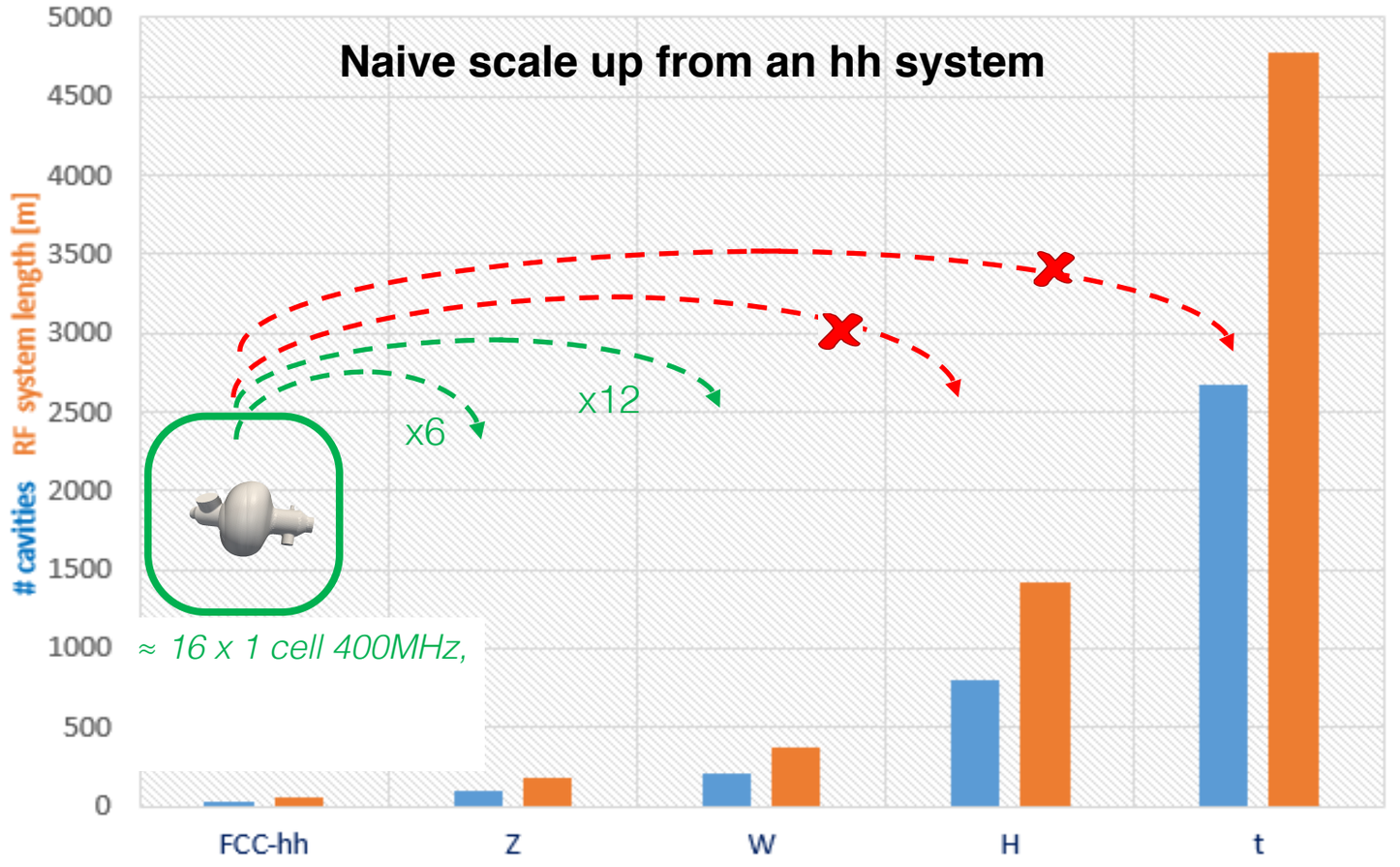
- Voltage and beam current spans over more than a factor 10^2

- Currently no well-adapted single RF system satisfies this requirement

"Ampere-class" machines

"high gradient" machines

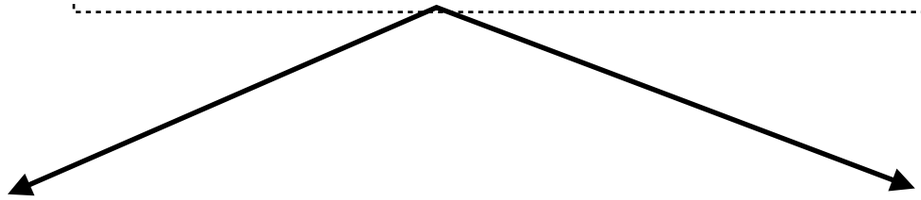
	V_{total} GV	$n_{bunches}$	I_{beam} mA	ΔE/turn GeV
hh	0.032		500	
Z	0.4/0.2	30000/90000	1450	0.034
W	0.8	5162	152	0.33
H	5.5	770	30	1.67
t	10	78	6.6	7.55



Physics reach of e^+e^- colliders

Strategic Decision

see also talk by Frank Simon



- Linear Collider

- precision Higgs (ZH) and top physics (including top threshold scan)

- extendable to higher energies:

  Higgs coupling at higher energies.

  BSM physics

- Circular Collider

- precision Higgs (ZH) and top physics (including top threshold scan)

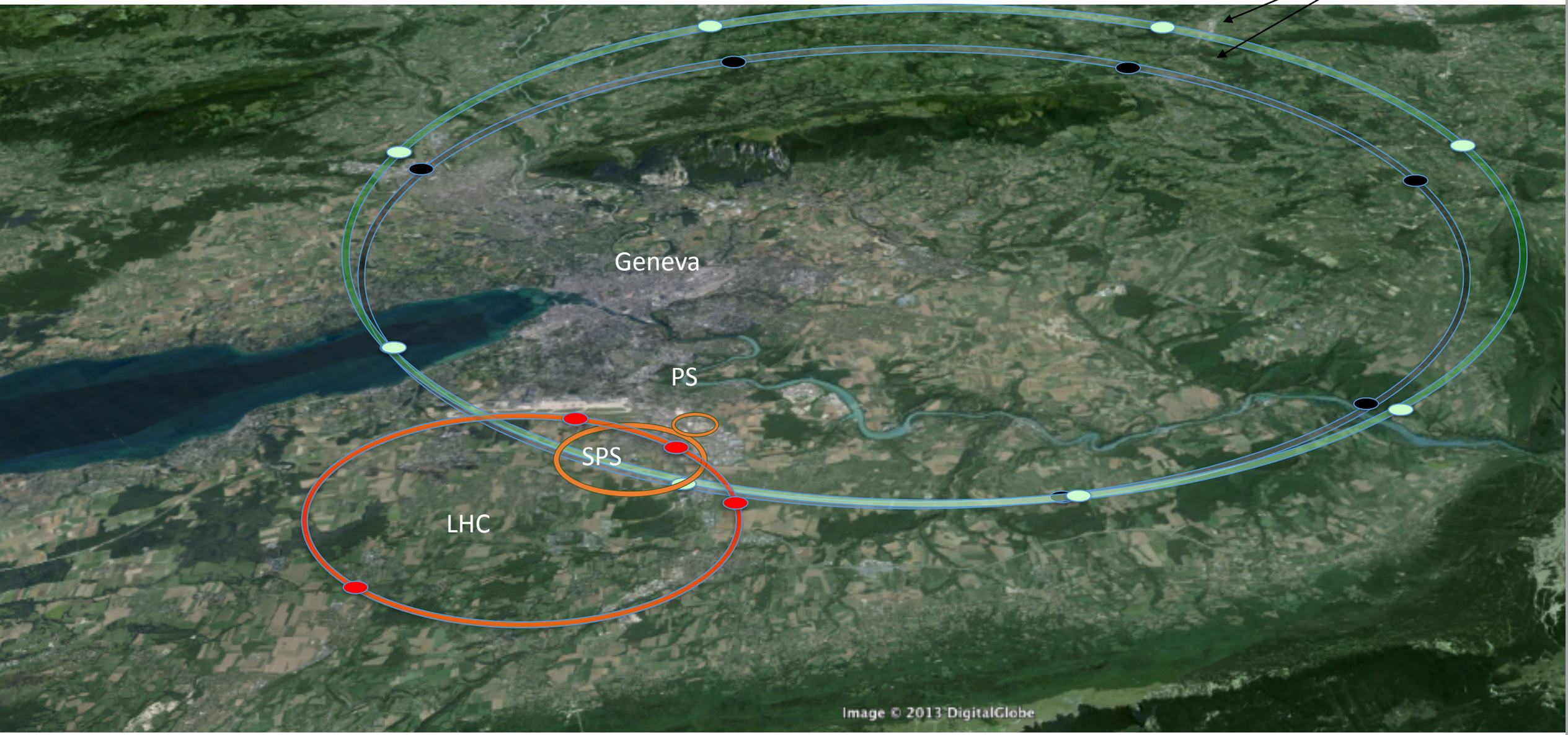
- extendable to lower energies

  Z,W factories possible at very high statistics (discovery potential in there)

Future Hadron Circular Colliders

FCC-hh

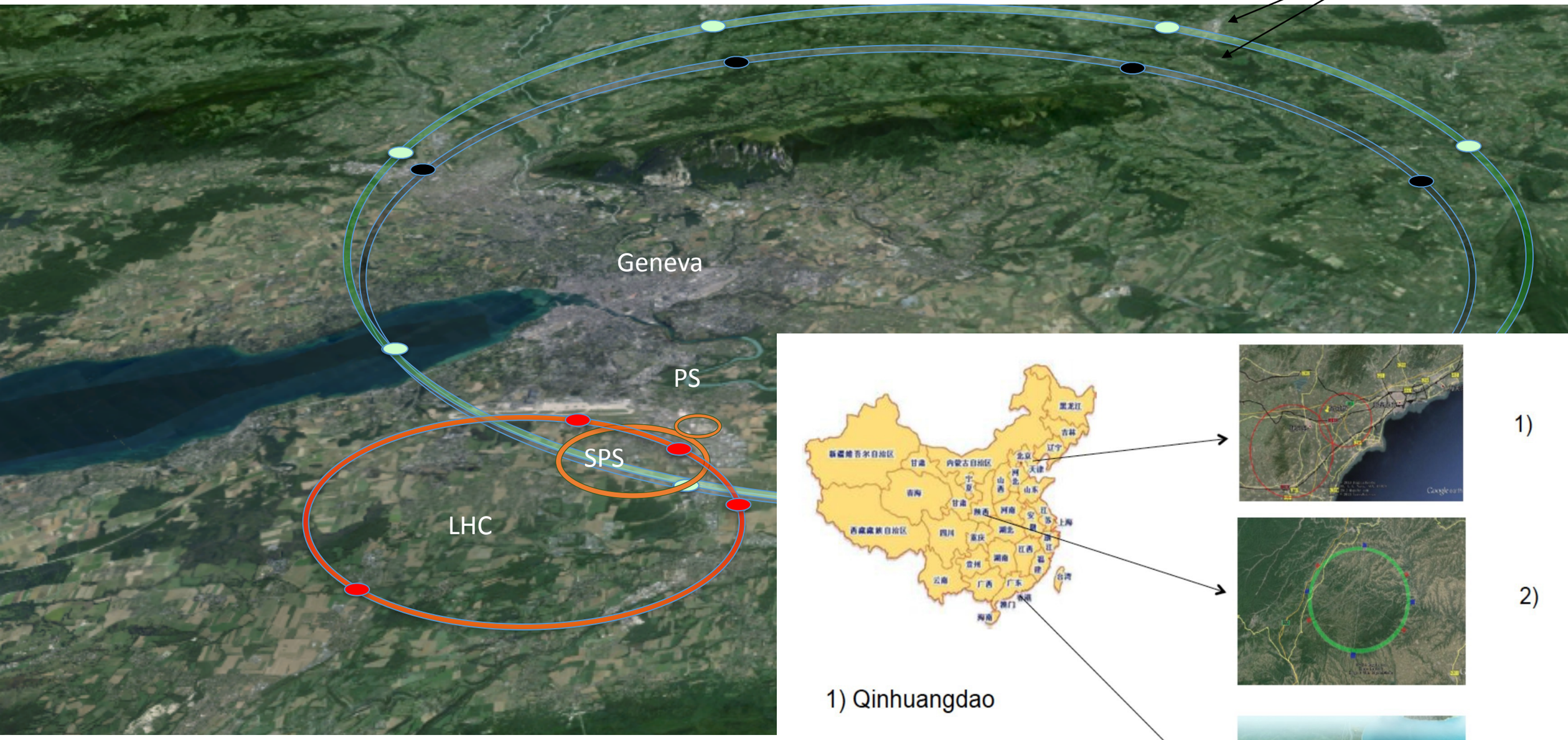
80/100 km FCC ring option



Future Hadron Circular Colliders

FCC-hh

80/100 km FCC ring option



SppC

baseline 45 km (possibility up to 100 km)

Hadron collider magnet technology

- Future pp colliders require development of SC magnet technology beyond state of the art

- Present magnets
  - LHC uses 8 T magnets, HL-LHC new shorter 11 T magnets

- Future magnet needs
  - HE-LHC and FCC-hh are designed for 16 T magnets
  - SppC need 20 T magnets to reach 100 TeV

- Requirements
  - conductor (Nb_3Sn) that can support 16/20 T
  - current density > 1500 kA/mm^2
  - reliable electro-mechanical assembly
  - good field quality

very challenging combination

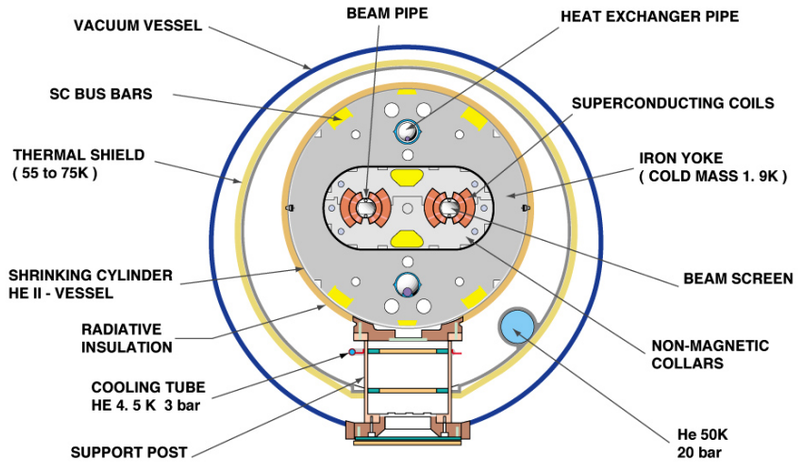
FCC-hh / hadron collider parameters

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

Hadron collider magnet options & requirements

	LHC	HL-LHC	HE-LHC	FCC baseline	FCC (optional)
Circumference	27 km	27 km	27 km	100 km	80 km
B-field	8.33 T	11.25 T	16 T	16 T	20 T
Conductor	1’300 t NbTi	Nb_3Sn	2’500 t Nb_3Sn	10’000 t Nb_3Sn	2000 t HTS 8000 t LTS
Center of mass energy	14 TeV	14 TeV	26 TeV	100 TeV	100 TeV

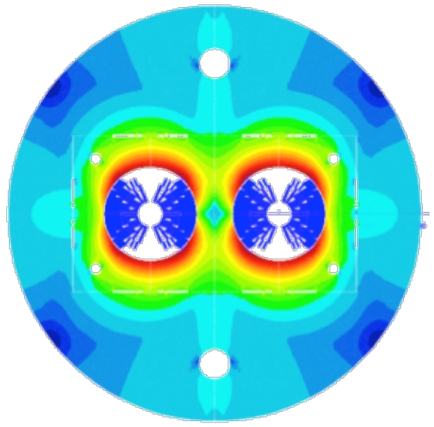
LHC



Dipoles:
1232 units, 14.3 m long, 8.3 T
$\int \mathrm{B}\, d\mathrm{l} = 0.15\ \mathrm{MTm}$

Stored energy: ~ 9 GJ

FCC

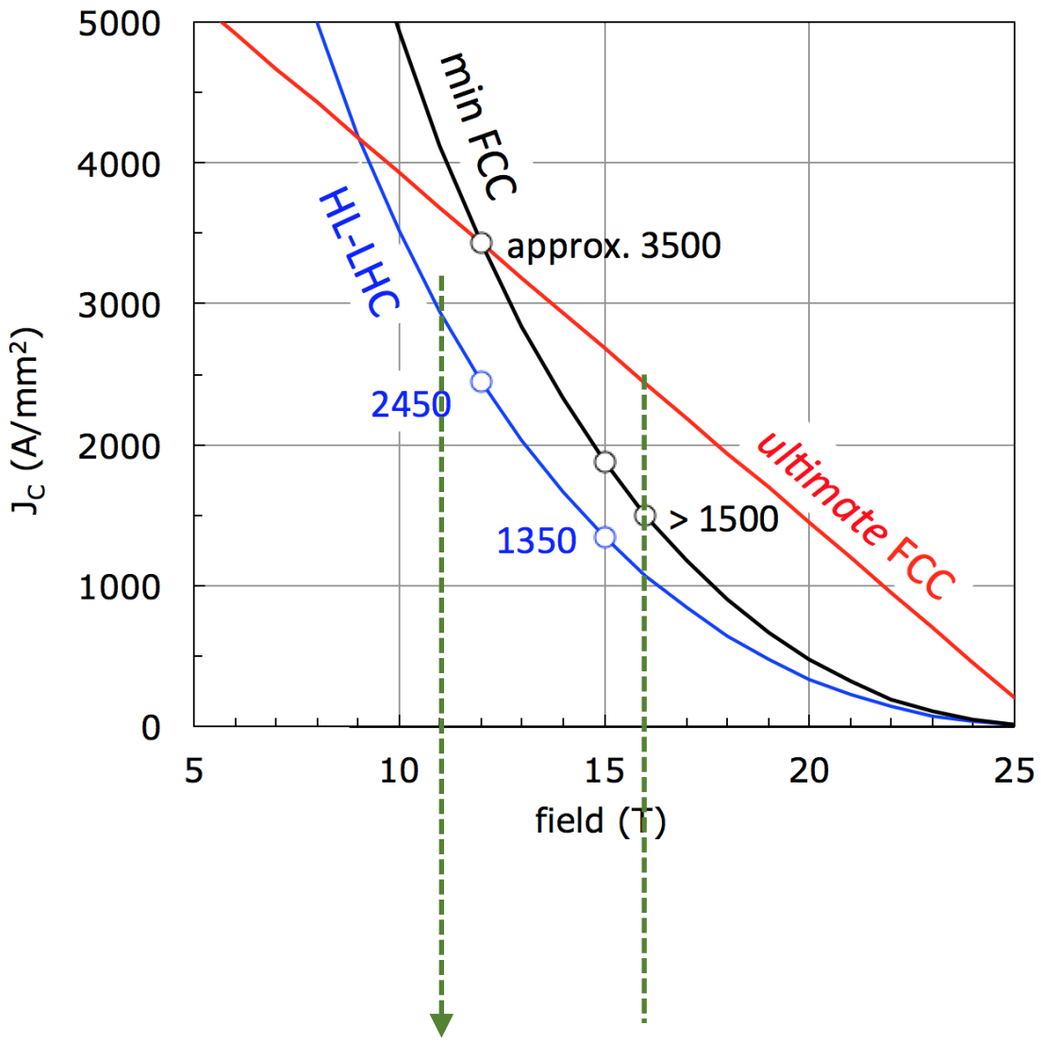


Dipoles:
4578 units, 14.3 m long, 16 T
$\int \mathrm{B}\, d\mathrm{l} = 1\ \mathrm{MT/m}$

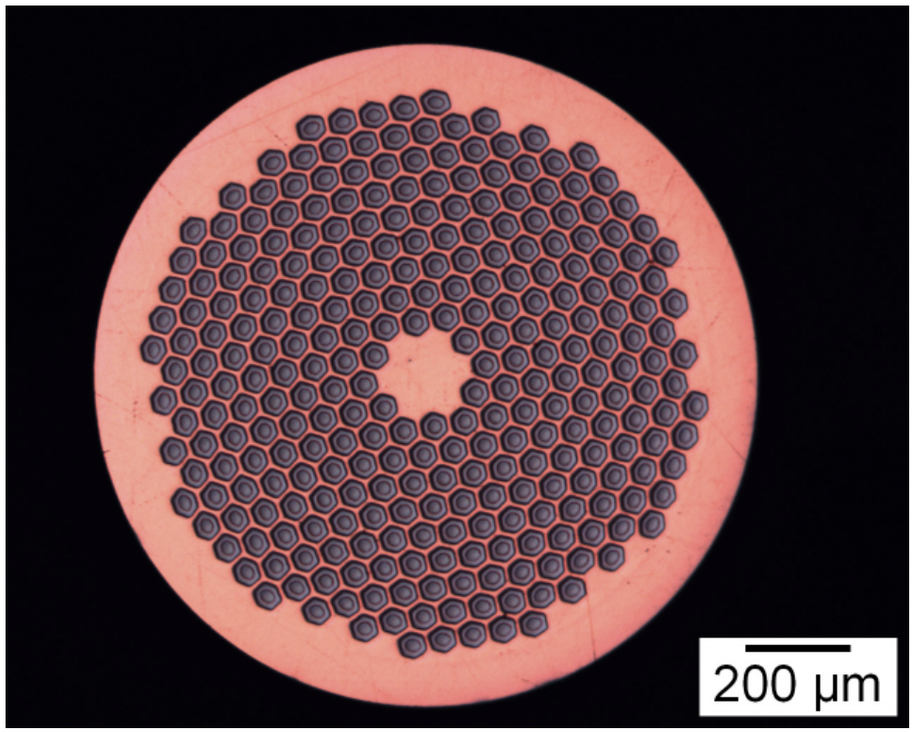
Stored energy: ~ 200 GJ

Nb_3Sn superconductor program

- Nb_3Sn is one of the major cost & performance factors for FCC-hh
  - as such requires highest attention
  - dedicated R&D program



11T 2750A/mm² for HL-LHC



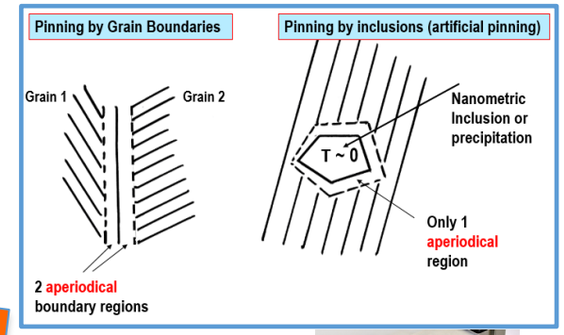
- Main development goals for 2020
  - J_c increase (16T, 4.2K) > 1500 A/mm² i.e. 50% increase wrt HL-LHC wire
  - Reference wire diameter 1 mm
  - Potentials for large scale production and cost reduction

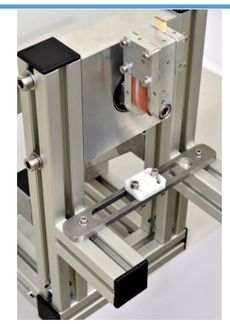
FCC-hh technology program 2016-2020

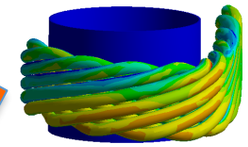
FCC-ST-0001

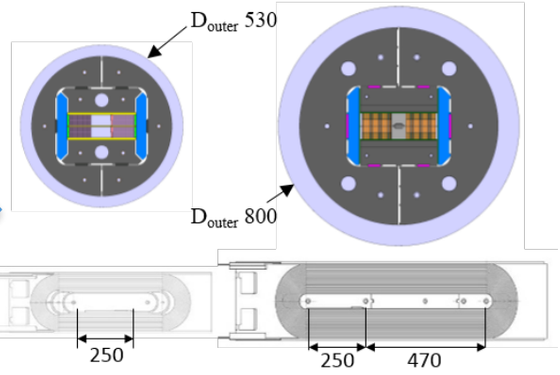
Table of Contents

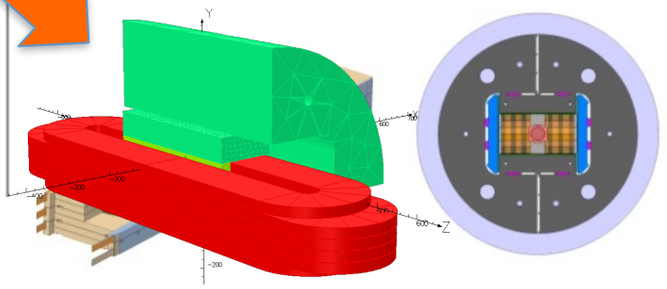
INTRODUCTION 4
ORGANIZATION 4
SUMMARY OF MATERIAL BUDGET 5
1. STRAND DEVELOPMENT & PROCUREMENT 6
1.1 MATERIAL R&D 6
1.2 INDUSTRIAL DEVELOPMENT & PROCUREMENT 7
1.3 CHARACTERIZATION OF ELECTROMECHANICAL PERFORMANCE 8
2. WOUND CONDUCTOR PROGRAM 9
2.1 CHARACTERIZATION OF CABLE WINDABILITY 9
2.2 MECHANICAL CHARACTERIZATION OF A CABLE STACK 10
2.3 CHARACTERIZATION OF COIL DEGRADATION DUE TO ASSEMBLY 11
2.4 STUDY OF PARAMETERS AFFECTING TRAINING PERFORMANCE 12
3. 16T ENHANCED RACETRACK MODEL COIL (ERMC) 13
3.1 DESIGN, MANUFACTURE AND TEST 13
4. 16T RACETRACK 50 MM CAVITY MODEL MAGNET (RMM) 14
4.1 DESIGN, MANUFACTURE AND TEST 14
5. 16T DIPOLE DEMONSTRATORS 15
5.1 COORDINATION 15
5.2 MANUFACTURE AND TEST 16









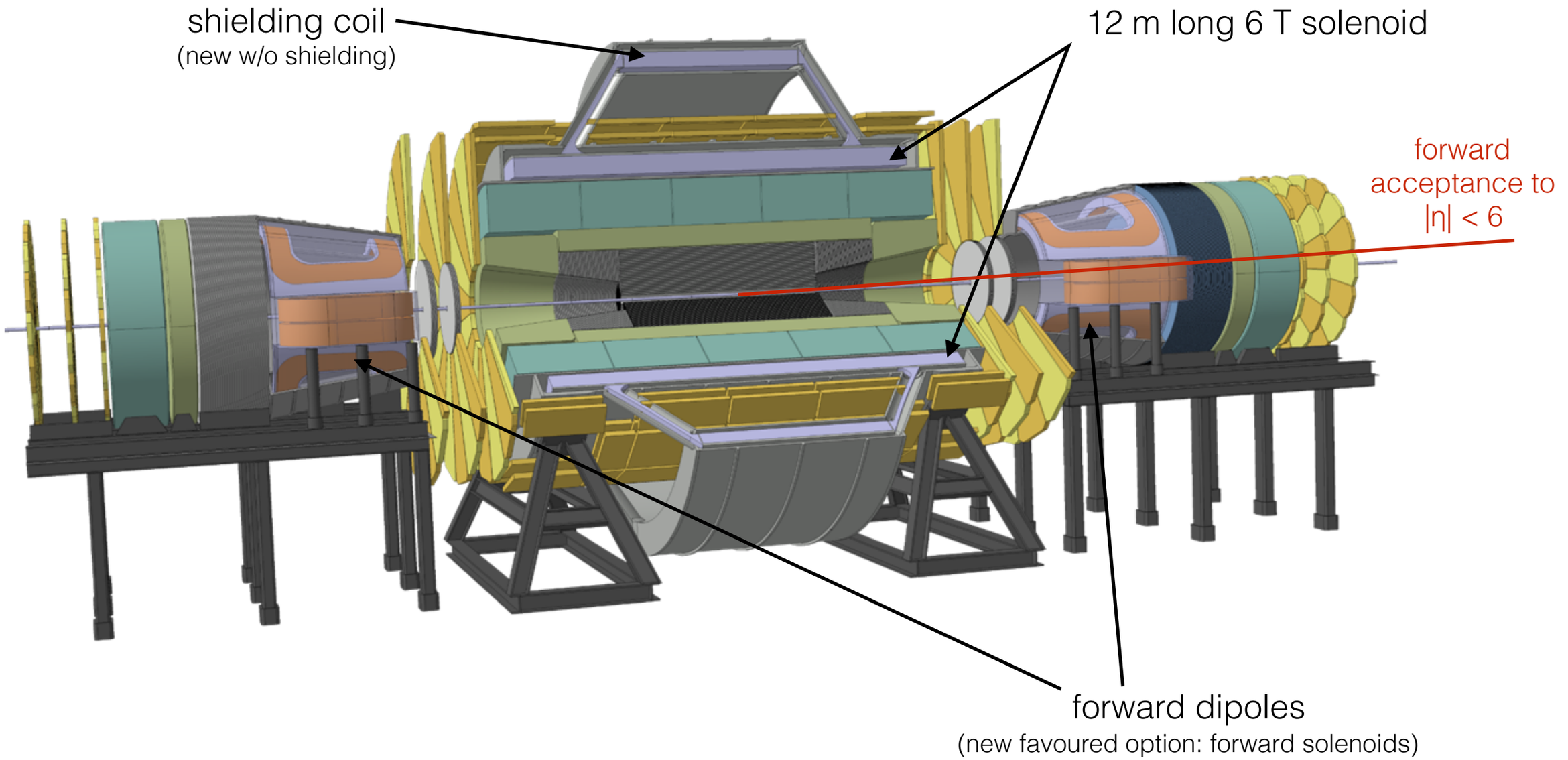


15 MCHF material over 4 years (8 MCHF on conductor R&D)

FCC-hh detector studies

- Very large volume of high magnetic field
  - needed for momentum measurement

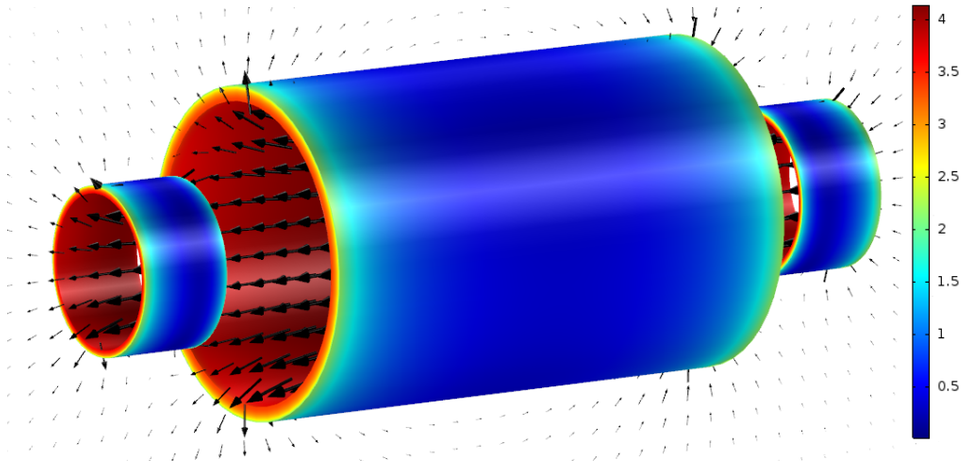
- First baseline design started from LHC detector concepts



Length 64 m, diam. 30 m, magnet 7000 tons, stored energy 50 GJ

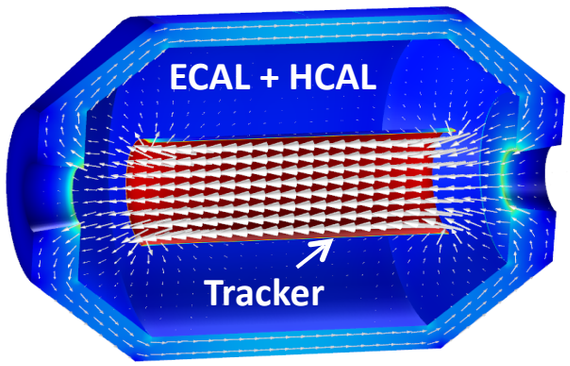
FCC-hh detector baseline

- Detector magnet system



Today's baseline:

4T/10m bore 20m long Main Solenoid 4T Side Solenoids – all unshielded
14 GJ stored energy, 30 kA and 2200 tons system weight



Alternative challenging design:

4T/4m Ultra-thin, high-strength Main Solenoid allowing positioning inside the e-calorimeter,
280 MPa conductor (side solenoids not shown)
0.9 GJ stored energy, elegant, 25 t only,
but needs R&D!

- Detector performance evaluated in first simulation studies
  - fed back into parameterised physics smearing simulation
  - full simulation/reconstruction chain being developed

Physics requirements - inelastic collisions

parameter	FCC-hh	SPPC	HE-LHC*	(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
inelastic cross section (mb)	108	2	2 & 2	80
avg. number of particles per rapidity unit	8	2	2.2	5.4
avg. particles p_T (GeV)	0.8	0.75	0.25	0.6
rel. increase of avg. transverse energy wrt LHC	2	6.6	1.2	-
synchrotr. rad. [W/m/beam]	30	58	3.6	(0.35) 0.18

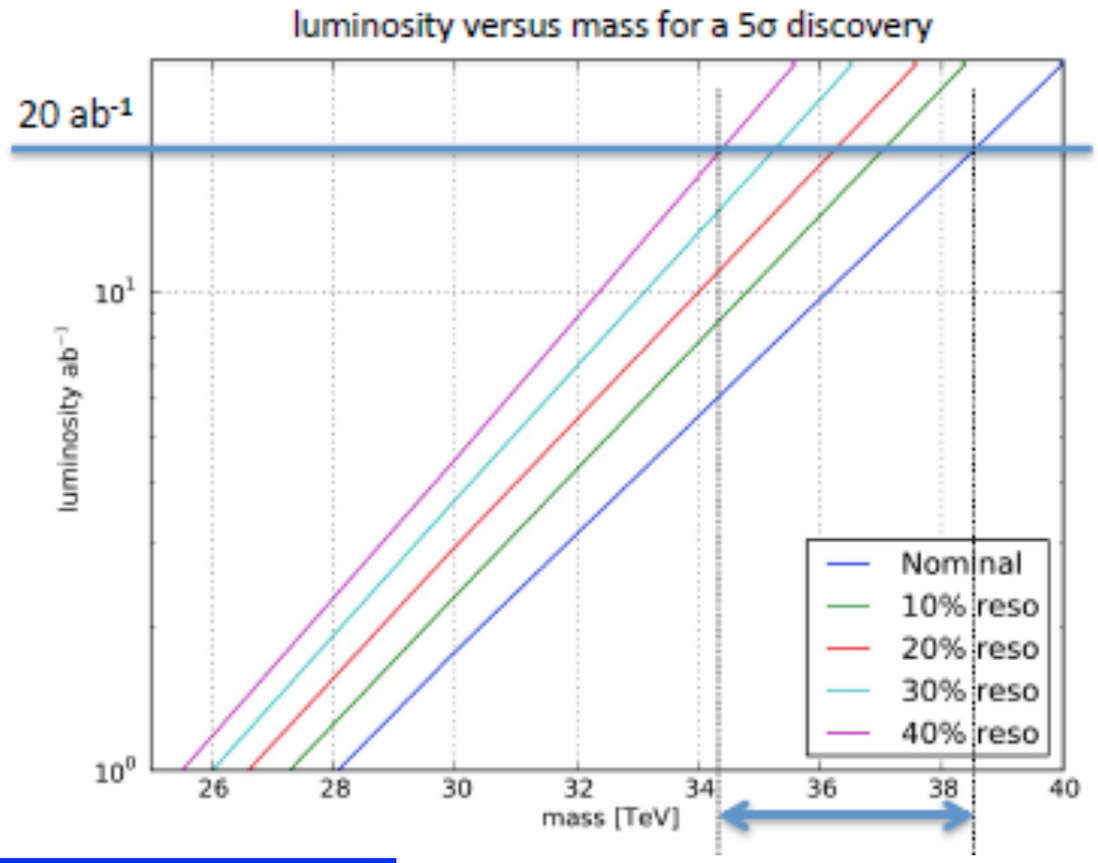
Minimum bias interactions at 100 TeV

- will not be vastly different with respect to 14 TeV
  (and we have a lot of experience how to deal with those in moderate pile-up)
- slightly increased bending power needed for tracker
  (though soft QCD is not the motivation for that, really)
- LHC (HL-LHC) detector concepts are a very good start for FCC-hh development

LHC type detectors

Physics requirements - Searches (exemplary)

parameter	FCC-hh	SPPC	HE-LHC*	(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
15 % p_T resolution reached at	**10 TeV**			**~1.2 TeV**
#IP	2 main & 2	2	2 & 2	2 & 2
beam current [A]	0.5	1.0	1.12	(1.12) 0.58
1	1 (0.2)	2	2.2	(2.2) 1.15
25	25 (5)	25	25	25
1.1	0.3	0.75	0.25	(0.15) 0.55
5	30	10	>25	(5) 1
170	30 (20)	100	50	(10) 27
	8.4	6.6	1.2	(0.7) 0.36
	30	10	3.6	(0.35) 0.18



$Z' \longrightarrow \mu^+\mu^-$

Tracker/Muon System

15% momentum resolution at 10TeV

$$\frac{\Delta p}{p} \propto \frac{p}{BL^2}$$

Calorimeter

Di-jet resonance mass resolution: need few % jet energy resolution at high energies

$$\frac{\Delta E}{E} \propto \frac{1}{\sqrt{E}} \oplus k$$ **(target *k* < 2%)**

high energy resolution

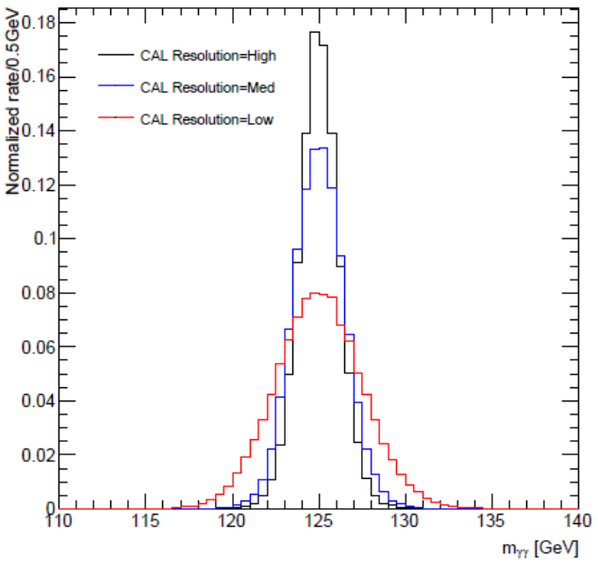
high p_T resolution

LHC like detectors

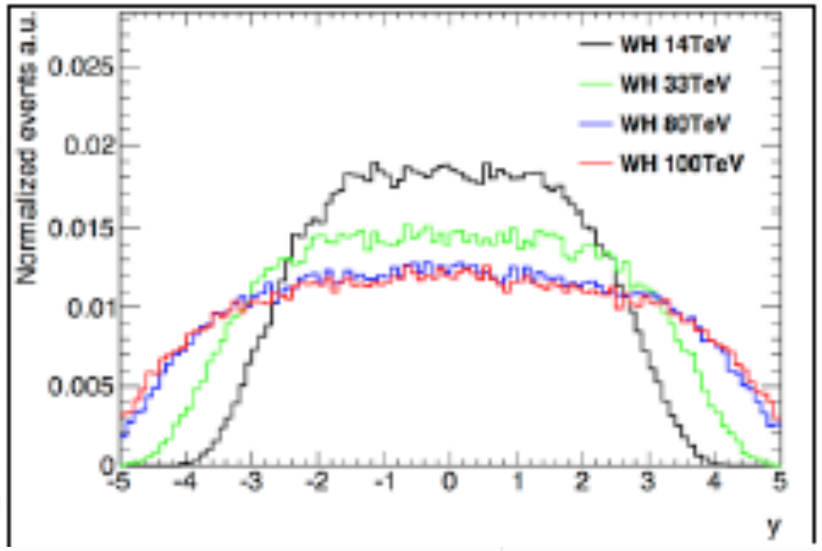
Physics requirements - Higgs physics

parameter	FCC-hh	SPPC	HE-LHC*	(HL) LHC
collision energy cms [TeV]	100	71.2	>25	14
dipole field [T]	16	20	16	8.3
circumference [km]	100	100	27	27
2 main & 2	2	2	2 & 2	2 & 2

$H \longrightarrow \gamma\,\gamma$



*H*iggs production mechanism



	14 TeV		100 TeV	
	2.5	4	2.5	4
ggF	0.74	0.99	**0.56**	0.88
WH	0.66	0.97	**0.45**	0.77
ZH	0.69	0.98	**0.48**	0.80
ttH	0.84	1	**0.56**	0.90
VBF	0.75	0.98	**0.55**	0.87

Synchrotr. rad. [W/m/beam] 30 58 3.6 (0.35) 0.18

Extended pseudo-rapidity coverage

- already in discussion/planning for LHC detector upgrades (both CMS and ATLAS plan to $|\eta| < 4$)
- plan for FCC-hh to $|\eta| < 6$
- b-tagging, c-tagging required to high pseudo rapidity for e.g. VBF Higgs
- still maintaining low p_T trigger thresholds

low p_T trigger threshold

large eta coverage

high energy resolution

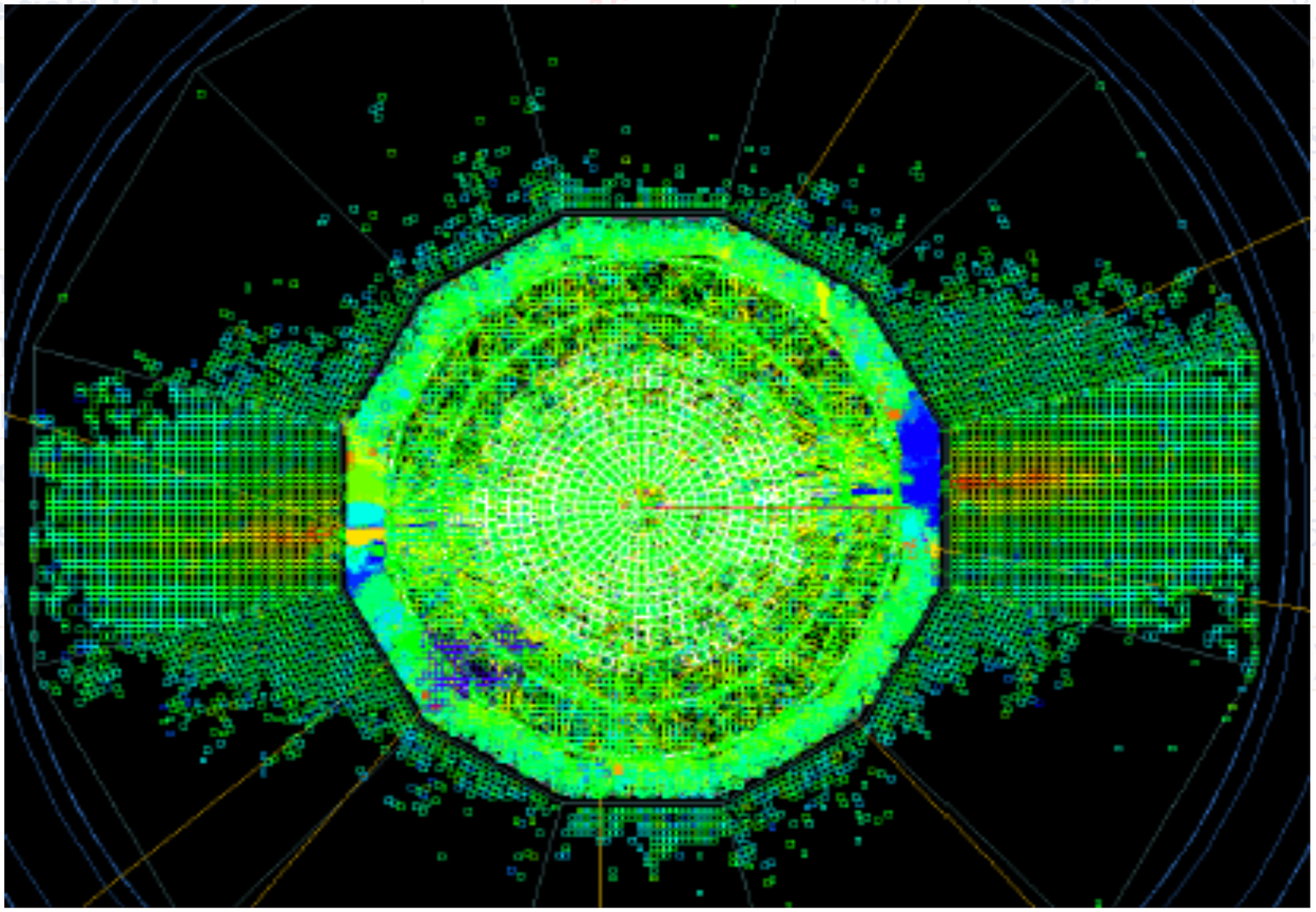
high p_T resolution

LHC like detectors

Physics requirements - Boosted objects

parameter	FCC-hh	SPPC	HE-LHC*	(HL) LHC
collision energy cms [TeV]	100	71.2	>25	14

Z'(40TeV)→*qq*



boosted object rec.

low p_T trigger threshold

large eta coverage

high energy resolution

high pT resolution

LHC like detectors

Energy increase leads to high-energetic, boosted objects

- calorimetry: shower containment requires *thick* calorimeter (HCAL will require 12 Λ_0 for shower contamination)
- tracking:double-track resolution, track reconstruction in dense jets (including b-tagging)

Physics requirements - environment

parameter	FCC-hh		SPPC	HE-LHC*	(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

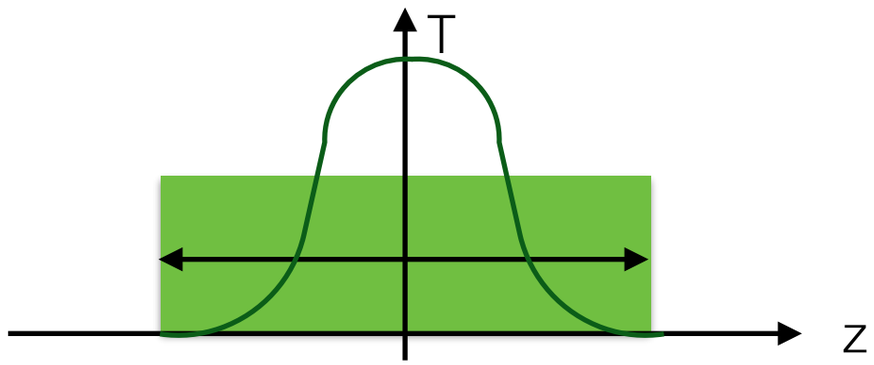
- pile-up robustness
- radiation hardness
- boosted object rec.
- low p_T trigger threshold
- large eta coverage
- high energy resolution
- high p_T resolution
- LHC like detectors

Radiation and pile-up environment

- up to a factor 5 increase in pile-up
  (not only an experimental challenge, but also computational)
- up to a factor 50 increase in radiation at 20 ab^{-1}
  (technological challenge)

FCC-hh luminous region

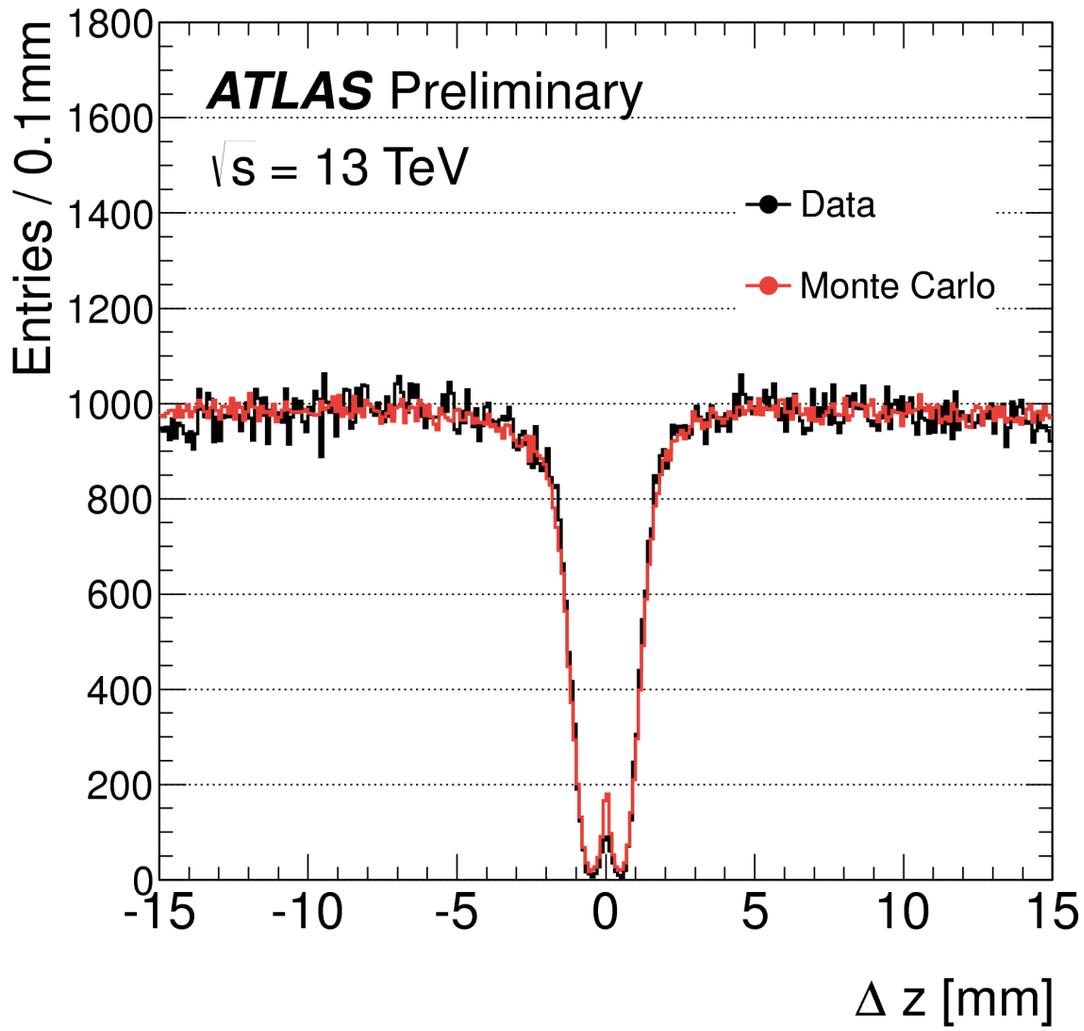
- RMS of luminous region around 80 mm (LHC ~ 50 mm)
  - let's assume the optimal beam profile, i.e. totally flat beam & bunch structure



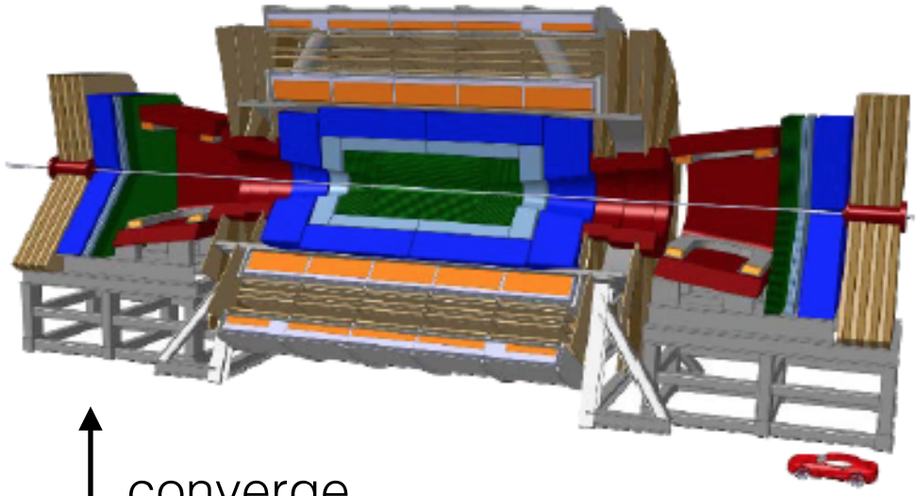
277 mm /√12 ~ 80 mm

	FCC-hh Baseline	FCC-hh Ultimate
IP beta-function β [m]	1.1	0.3
IP beam size σ [μm]	6.8 (3)	3.5 (1.6)
RMS bunch length σ_z [cm]	8	

- average vertex separation: 277m/1000 ~ 270 um
- is resolvable for high multiplicity vertices
- timing detectors will help here !!



From physics to detector requirements



converge

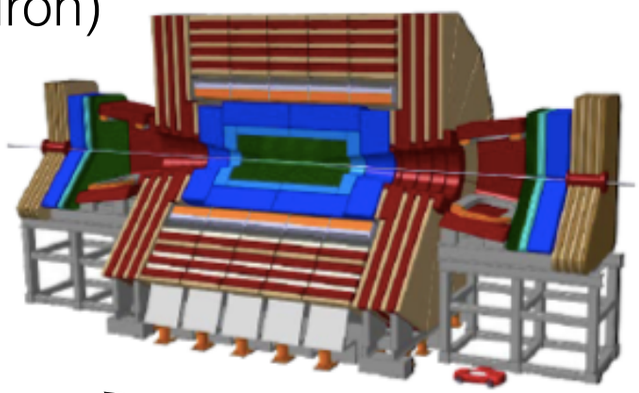
converge

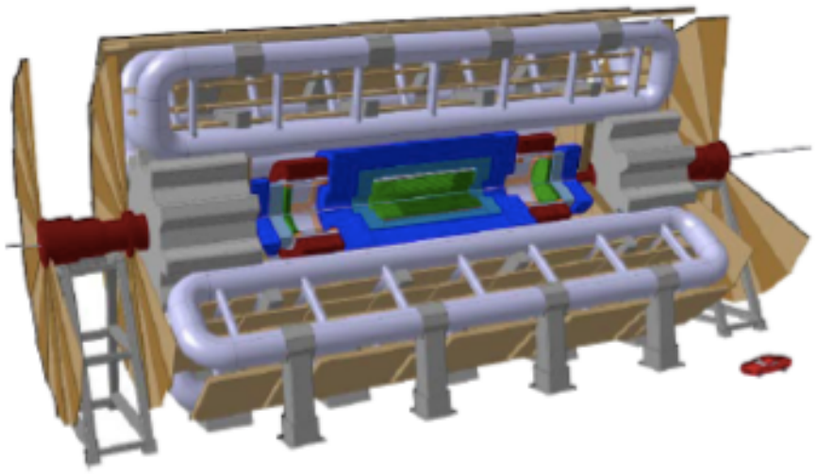
ATLAS stand-alone Muon System

- precision tracker within toroidal field
- motivated by worries that precision Tracking in the Inner Tracker would not work with high pile-up
- we know better now :-)

CMS scaled-up version

- large coil with yoke that returns all the flux (a lot of expensive iron)





pile-up robustness

radiation hardness

boosted object rec.

low p_T trigger threshold

large eta coverage

high energy resolution

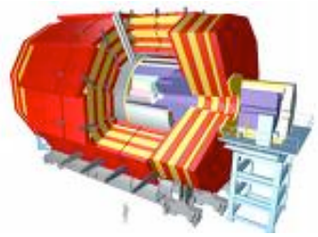
high p_T resolution

LHC like detectors

refine

extend

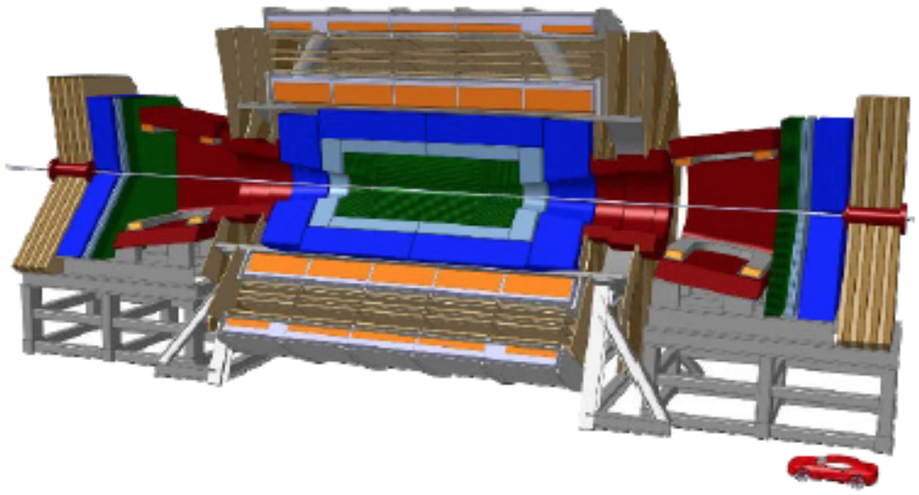
scale



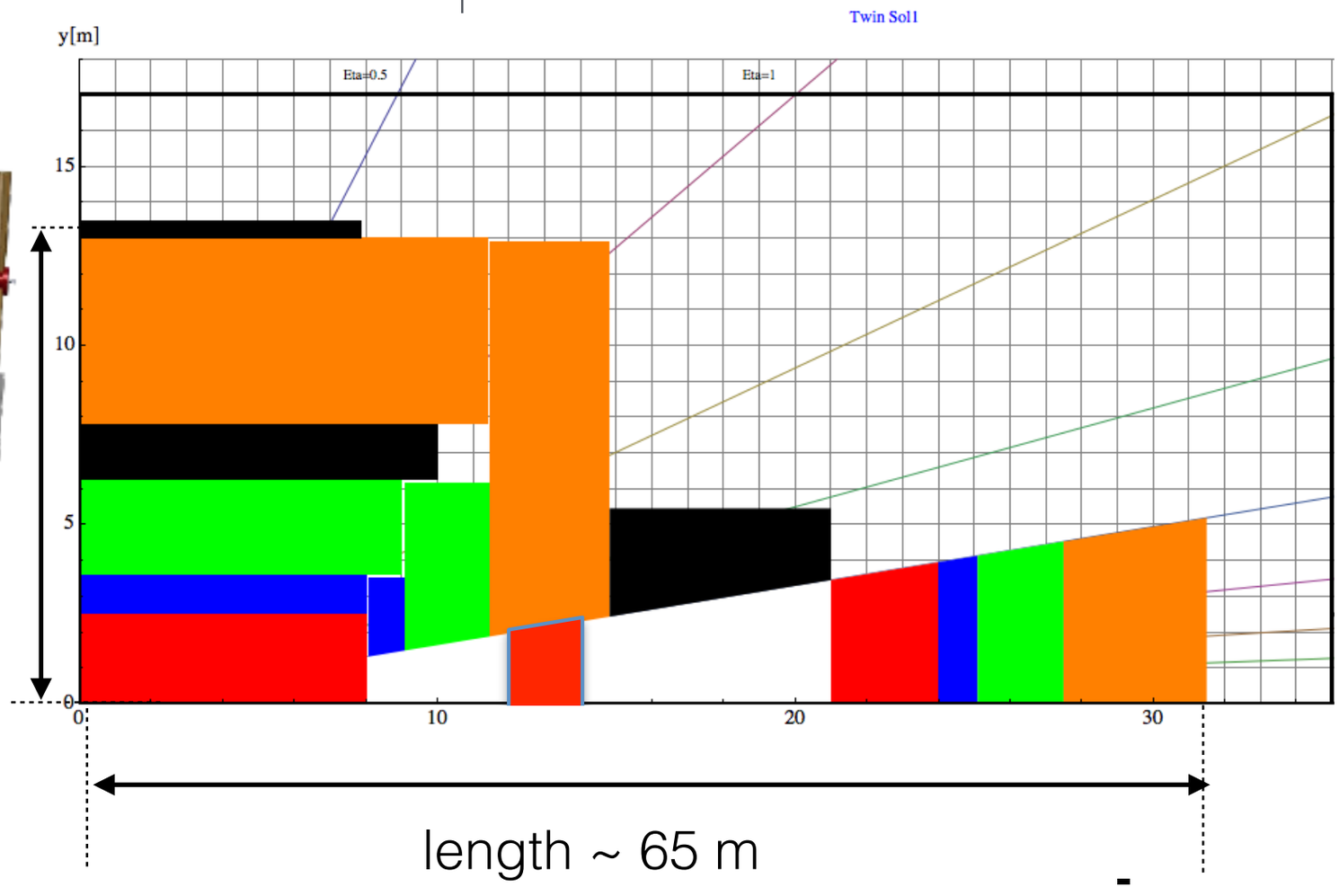
CMS

ATLAS

From physics to detector requirements



radius ~ 13 m
(~ ATLAS)

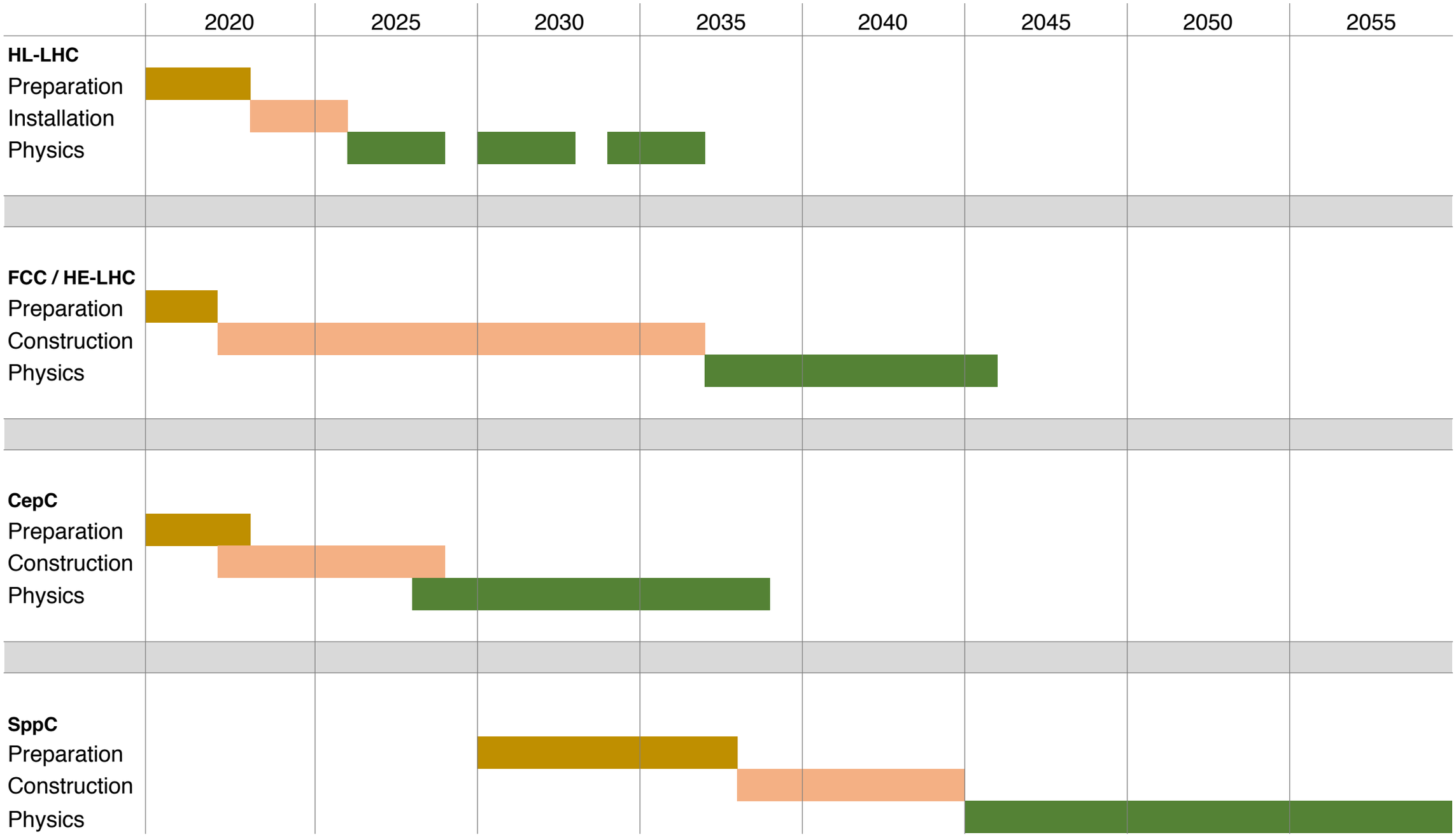


- pile-up robustness
- radiation hardness
- boosted object rec.
- low p_T trigger threshold
- large eta coverage
- high energy resolution
- high p_T resolution
- LHC like detectors

Combining best of both worlds

- huge primary solenoid (6 m, ~6 T)
- air-filled muon system (chamber system like ATLAS)
- active shielding : twin solenoid (TS) solution
- extension to pseudo-rapidity up to 6 for all detector components (needs forward magnet system)
- the obvious ones: hermeticity, …

Proposed schedules



Conclusion | Final Remarks

- HL-LHC is the first step towards future circular colliders

- Superconductivity is the key technology for future colliders in many areas

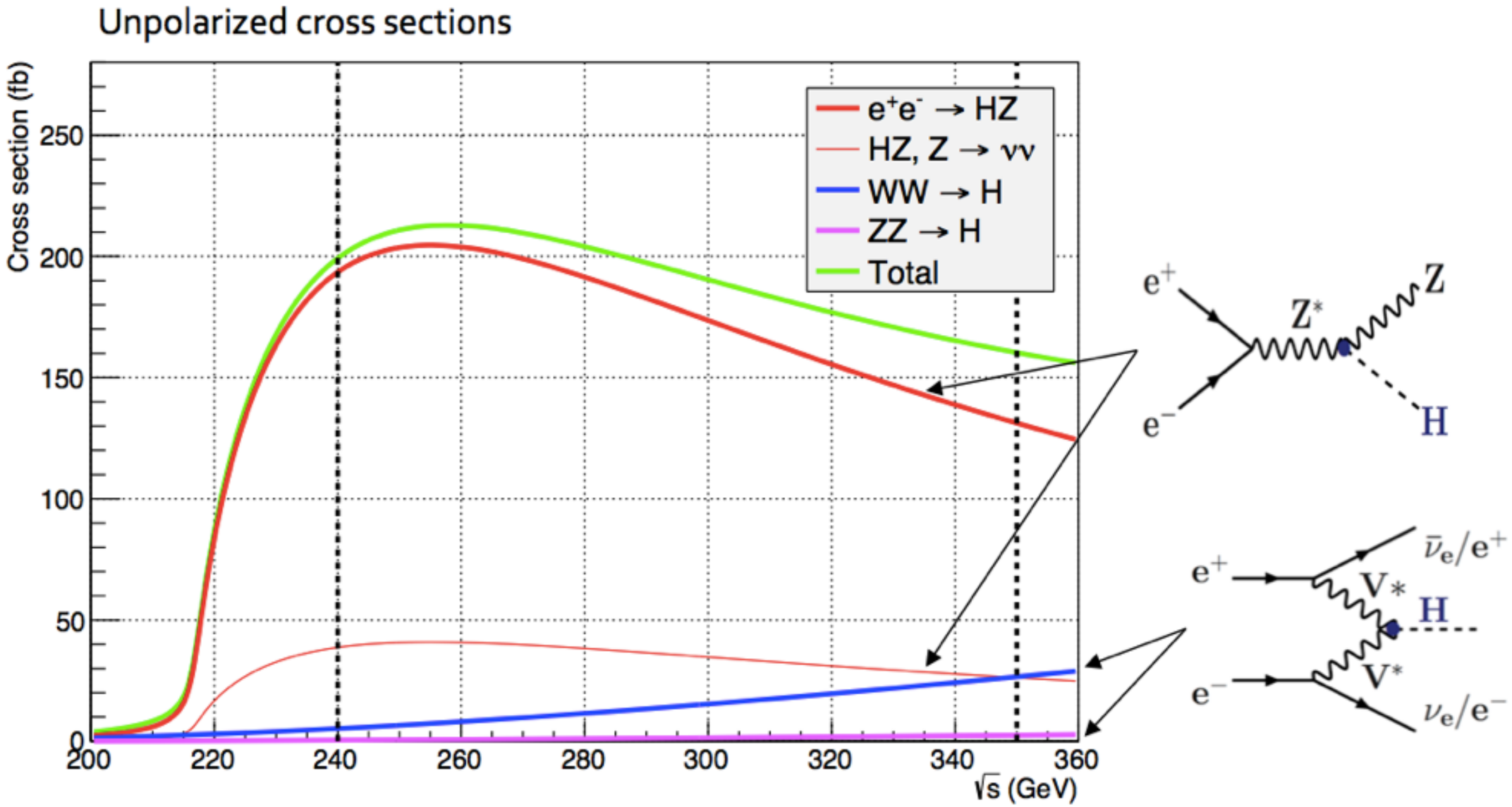
- If the choice of an e^+e^- machine is made:
  - strategic decision: circular / linear
  - both are compatible as Higgs factories, but differ for higher/lower energies

- If the choice of hadron machine is made:
  - HE-LHC could serve as an intermediate step and test case for future FCC
  - the Nb_3Sn program towards building 16 T model magnetics will be crucial

    prime importance for this direction

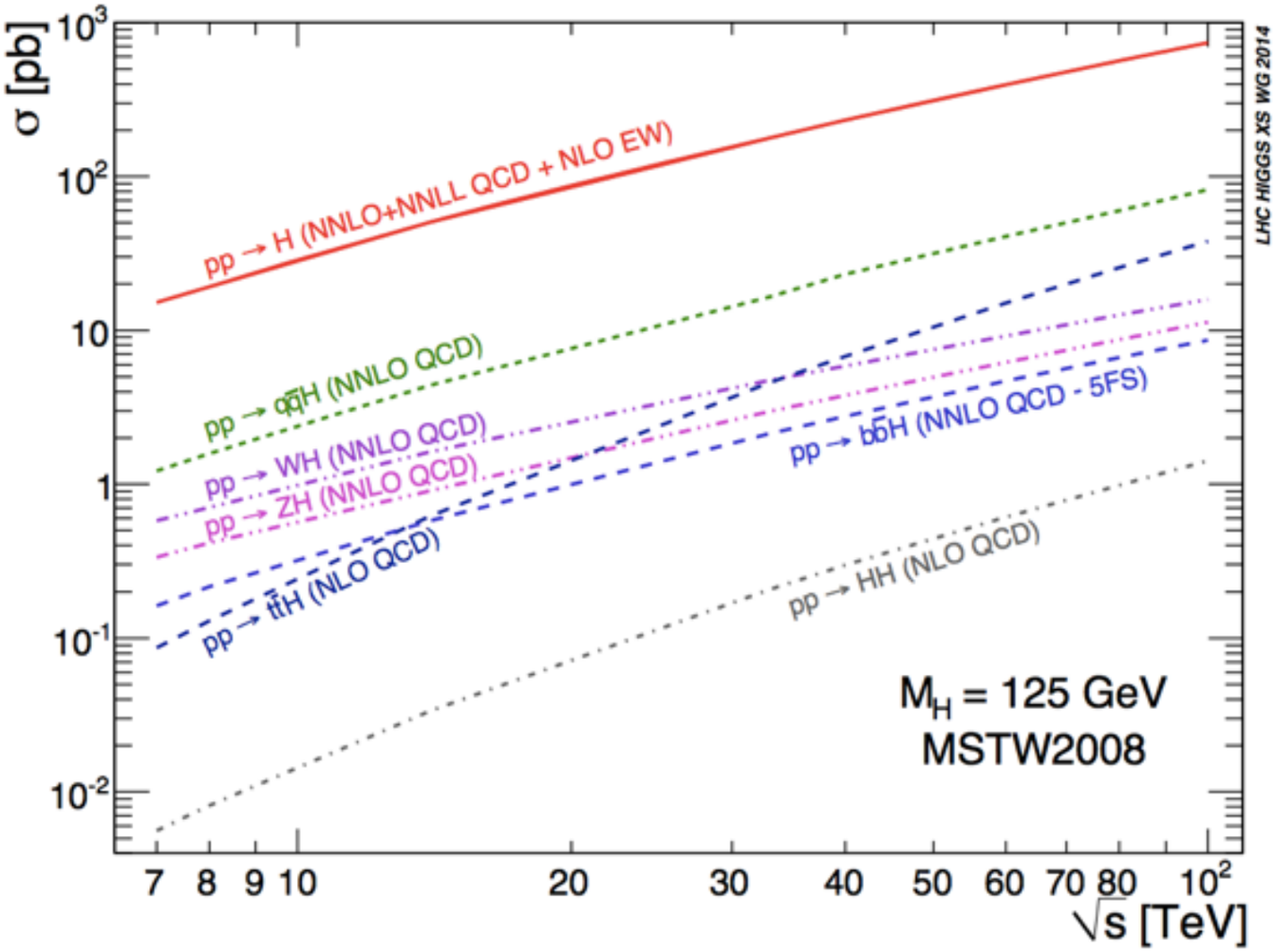
Backup

Backup - Higgs production e+e-



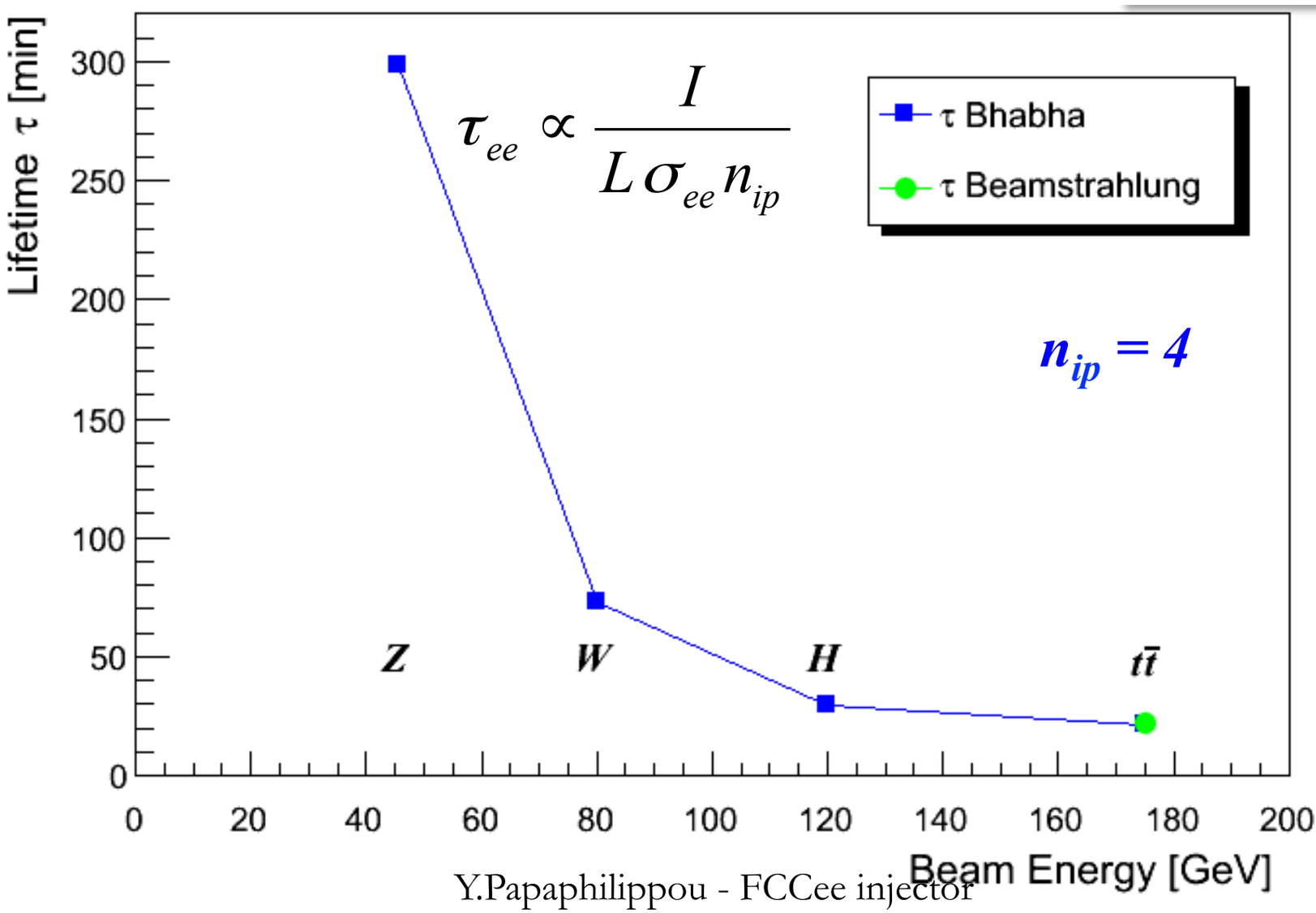
Backup - Higgs production in pp

Process	8 TeV	14 TeV	100 TeV
gF	19.3 pb	50.35 pb	740.3 pb
VBF	1.58 pb	4.40 pb	82.0 pb
WH	0.70 pb	1.63 pb	15.9 pb
ZH	0.42 pb	0.90 pb	11.3 pb
ttH	0.13 pb	0.62 pb	37.9 pb
bbH	0.20 pb	0.58 pb	8.64 pb
gF to HH	8.15 fb	33.8 fb	1.42 fb



Backup - FCC-ee beam lifetime

- Need for a top-up booster



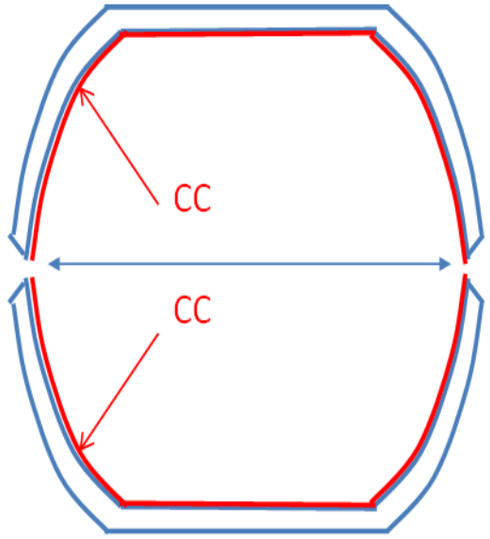
J. Wenninger

High temperature SC coating for beam screens

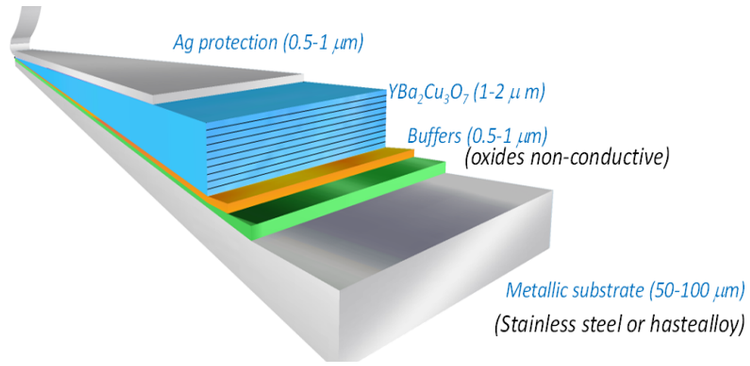
- Synchrotron radiation of proton beam @ 50 TeV
  - about 30 W/m per beam (around 5 MW total in arcs)
  - needs to be kept at 1.9 K

- goal of lowering FCC-hh beam impedance for stability, allowing higher beam-screen temperature for efficiency

HTS can have surface resistance lower than Cu at T< 77 K and f < 10 GHz



CC: coated conductor



Candidate materials:

TI-1223

(promising performance, opens up >100 K temperature window, scalable coating, R&D with CNR-SPIN and TU-Vienna)

YBCO

(proven performance, requires forming technology, R&D with ICMAB-ALBA-IFAE)