Future Circular Colliders

Yifang Wang
Institute of High Energy Physics, Beijing
IPAC'2015, May 8, 2015

Outline

- Ideas
- Strategies
- Science & Machine Requirements
- Machine Design & Status
- Summary

Development of Ideas

- **Initial ideas of e^+e^- circular Higgs factories：**
  - LEP3
  - TLEP
  - Super-TRISTAN
  - Fermilab Site-Filler
- **CHF： pp is added**
  - Circular Higgs factory
    + pp collider
- **FCC： European strategy**
  - FCC-hh, FCC-ee,
    FCC-eh, …

CERN-OPEN-2011-047
20 January 2012
Version 2.9
arXiv:1112.2518v1 [hep-ex]

A High Luminosity e^+e^- Collider in the LHC tunnel to study the Higgs Boson

Alain Blondel[1], Frank Zimmermann[2]
[1]DPNC, University of Geneva, Switzerland; [2]CERN, Geneva, Switzerland

FERMILAB-CONF-13-037-APC
IHEP-AC-2013-001
SLAC-PUB-15370
CERN-ATS-2013-032
arXiv:1302.3318 [physics.acc-ph]

Report of the ICFA Beam Dynamics Workshop

"Accelerators for a Higgs Factory: Linear vs. Circular"

(HF2012)

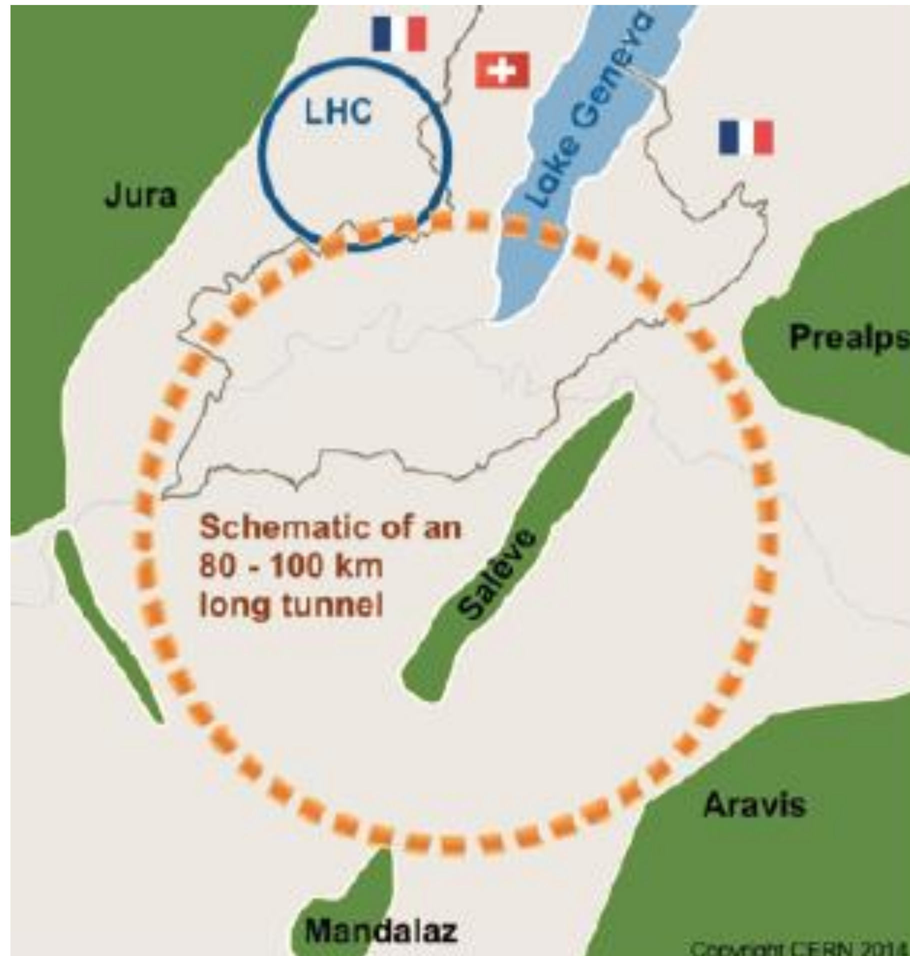
Alain Blondel[1], Alex Chao[2], Weiren Chou[3], Jie Gao[4], Daniel Schulte[5] and Kaoru Yokoya[6]

http://www-bd.fnal.gov/icfabd/HF2012.pdf

Two Major Efforts Developed

IHEP， 50-100 km

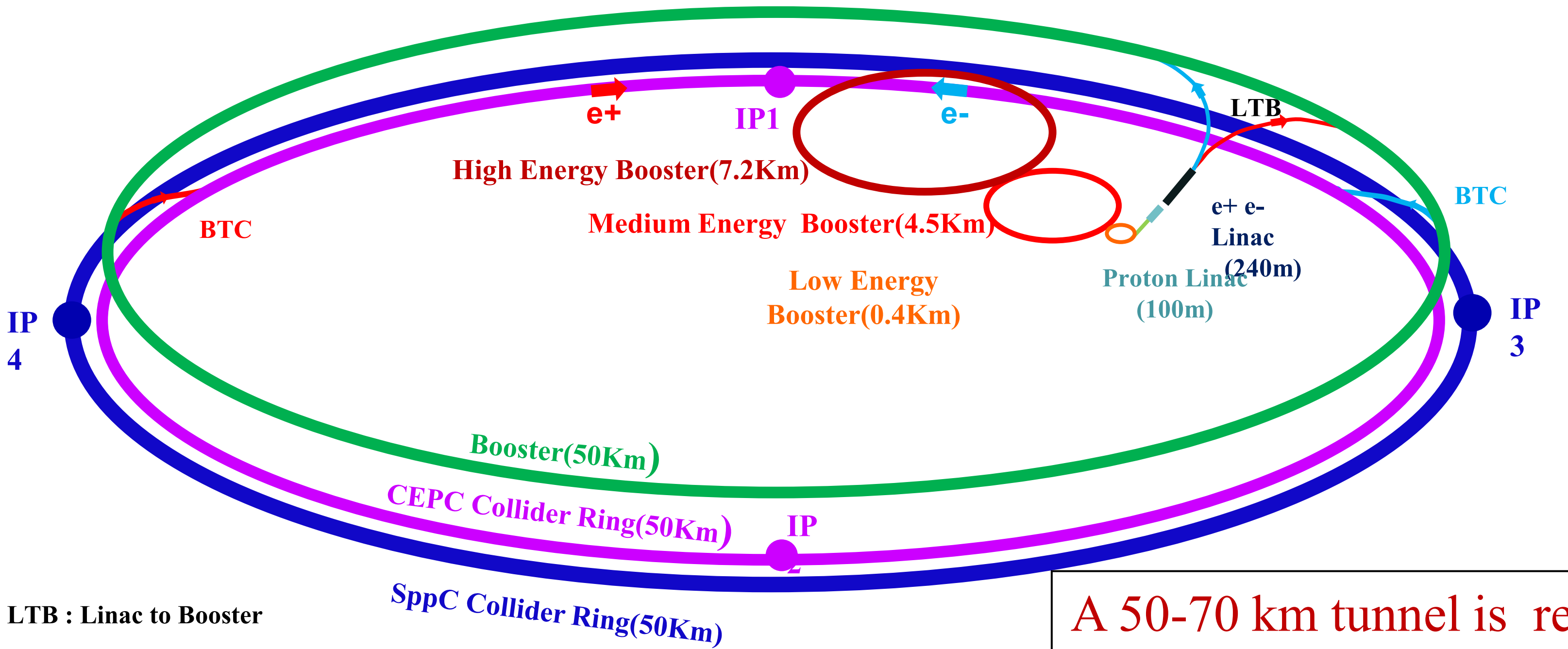
CERN， 80-100 km



Strategy of CEPC+SppC

- Start from an e^+e^- Higgs factory(CEPC), with minimum efforts to run at Z pole(single ring machine). No 350 GeV for htt.
- A continuation of BEPC ➔ BEPCII ➔ CEPC, fit the strategic needs, past experience and available resources

- After the e^+e^- phase, build the pp collider(SppC) in the same tunnel
- Gain sufficient time for magnet R&D and wait for tech. improvement



LTB : Linac to Booster

BTC : Booster to Collider Ring

A 50-70 km tunnel is relatively easier NOW in China

Timeline (dream)

- **CPEC**
  - Pre-study, R&D and preparation work
    - Pre-study: 2013-15
      - **Pre-CDR for R&D funding request**
    - R&D: 2016-2020
    - Engineering Design: 2015-2020
  - Construction: 2021-2027
  - Data taking: 2028-2035
- **SppC**
  - Pre-study, R&D and preparation work
    - Pre-study: 2013-2020
    - R&D: 2020-2030
    - Engineering Design: 2030-2035
  - Construction: 2035-2042
  - Data taking: 2042 -

Strategy of FCC

- **European Strategy for Particle Physics 2013:**

  "…to propose an ambitious post-LHC accelerator project….., CERN should undertake design studies for accelerator projects in a global context,…with emphasis on proton-proton and electron-positron high-energy frontier machines.…."

Goal: **Conceptual Design Report by end of 2018 in time for next European Strategy Update**

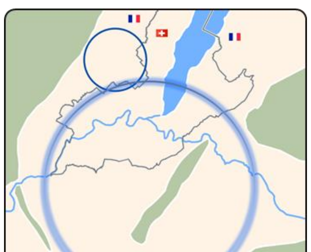
Scope: Accelerator & Infrastructure

Collider Designs

FCC-hh: **100 TeV *pp* collider as long-term goal**
→ defines infrastructure needs
FCC-ee: **e^+e^- collider**, potential intermediate step
FCC-he: **integration aspects** of pe collisions

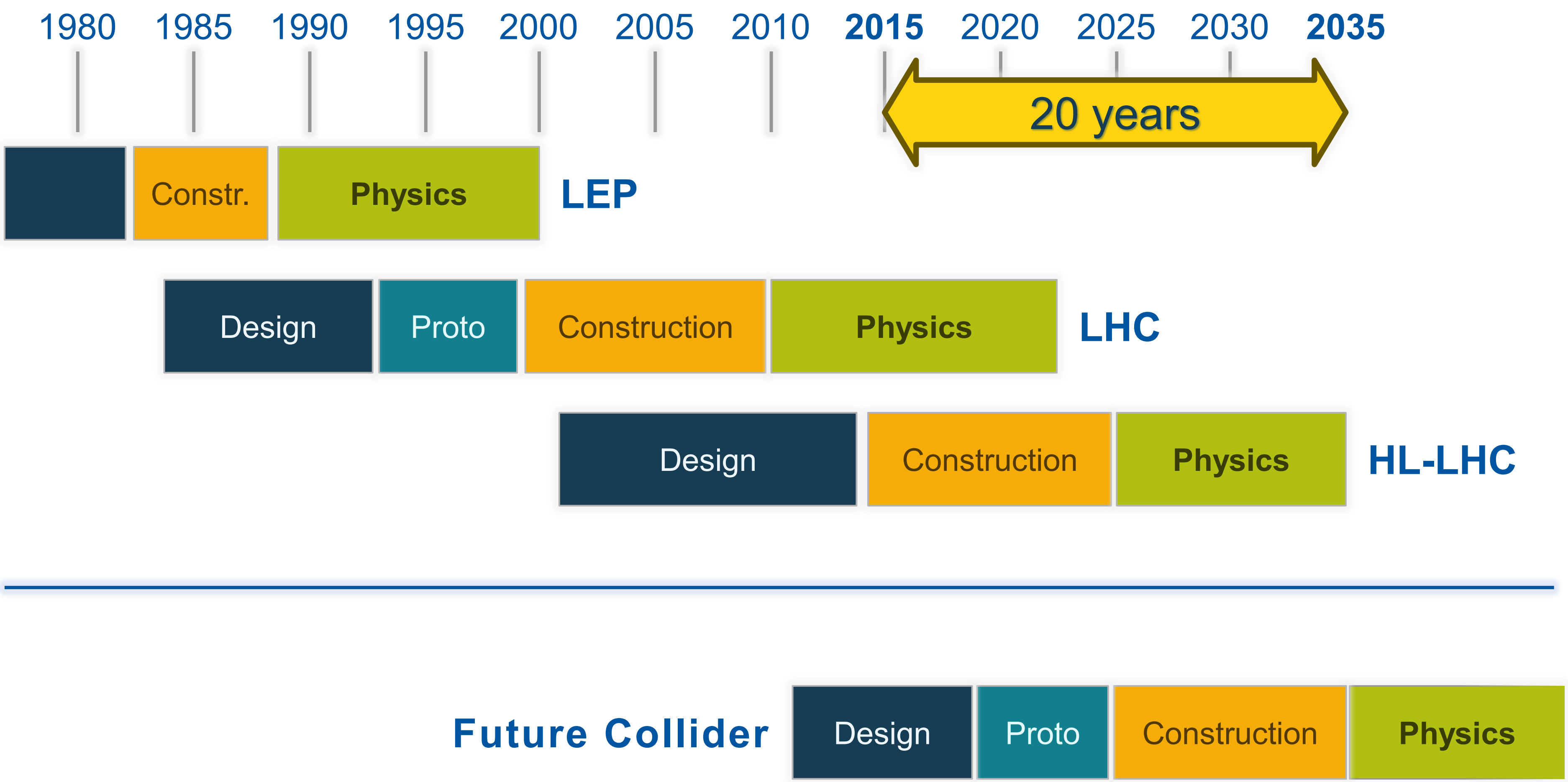

R&D Programs

Push key technologies
in dedicated R&D programmes e.g.
16 Tesla magnets for **100 TeV** pp in **100 km**
SRF technologies and RF power sources


Infrastructures

Tunnel infrastructure in Geneva area, linked to CERN accelerator complex
Site-specific, requested by European strategy

CERN Circular Colliders + FCC



M. Benedikt

- **Why we need it ?**
- **After the Higgs, game is over ?**
- **Is ILC enough ?**
- **Shall we wait for results from LHC, and ILC ?**

- **What can be done exactly at these machines ?**
- **What energy and luminosity ?**

We need to answer these questions based on Science

Reference:

FCC-ee: “First Look at the Physics Case of TLEP”, JHEP 1401 (2014) 164
CEPC/SppC pre-CDR: http://ihep.ac.cn/preCDR/volume.html
Many talks at various conferences, workshops

IHEP-CEPC-DR-2015-01

IHEP-EP-2015-01

IHEP-TH-2015-01

CEPC-SPPC

Preliminary Conceptual Design Report

Volume I - Physics & Detector

The CEPC-SPPC Study Group

March 2015

IHEP-CEPC-DR-2015-01

IHEP-AC-2015-01

CEPC-SPPC

Preliminary Conceptual Design Report

Volume II - Accelerator

The CEPC-SPPC Study Group

March 2015

Revisions after international reviews

Can be downloaded from

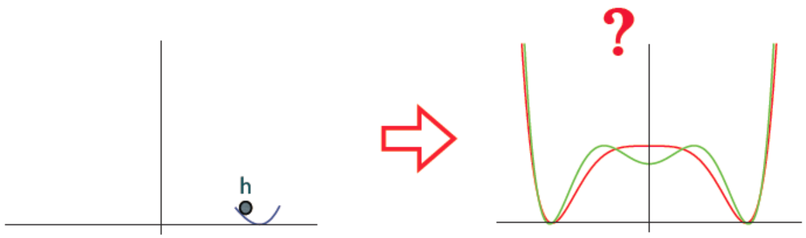
http://cepc.ihep.ac.cn/preCDR/volume.html

0, 2015

New Tasks after the Higgs Discovery

- **Open questions about Higgs**
  - Consistent with SM ?
  - Composite or elementary ?
  - Other Higgs ？
  - New properties ？
  - Responsible for CP violation？
  - What type of potential ?

Never seen point-like scalars !



- **New type of interactions concerning only the Higgs:**
  - Yukawa coupling through Higgs with spin 0:
    - hττ, hbb, htt coupling constant， ~10% after LHC
  - Self-coupling h^3 & h^4:
    - ~ 50% after LHC

Need a factor of ~10 improvement over LHC !

Standard Model is not complete

- From neutrinos to top quark, masses differs by a factor 10^{13}, why ?
- Fine tuning of Higgs mass(naturalness):

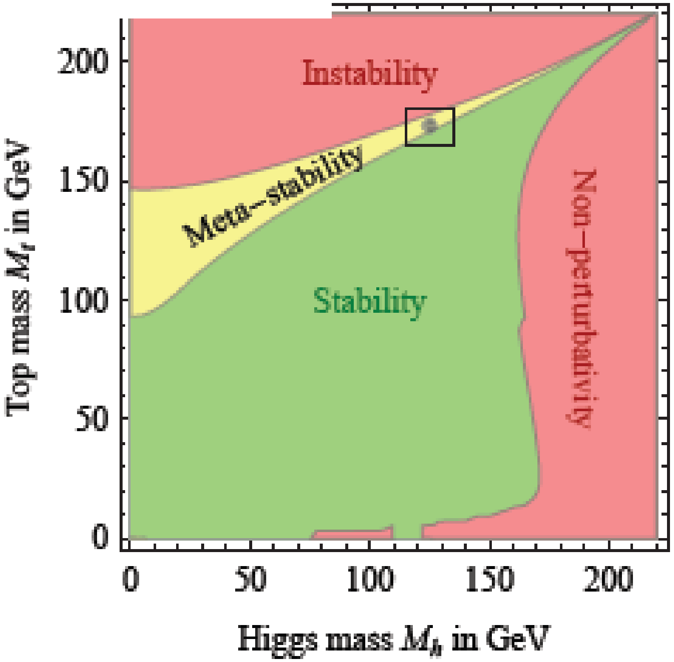
$$m_H^2 - m_{H,0}^2 \sim -\frac{3}{8\pi^2} y_t^2 \Lambda^2$$

A coincidence of 10^{-34} ?
Never before even at 10^{-4}

For Λ(new physics) at the Planck scale ~ 10^{16} TeV:

m_H^2 = 36,127,890,984,789,307,394,520,932,878,928,933,023
−36,127,890,984,789,307,394,520,932,878,928,917,398
= (125 GeV)^2 ! ?

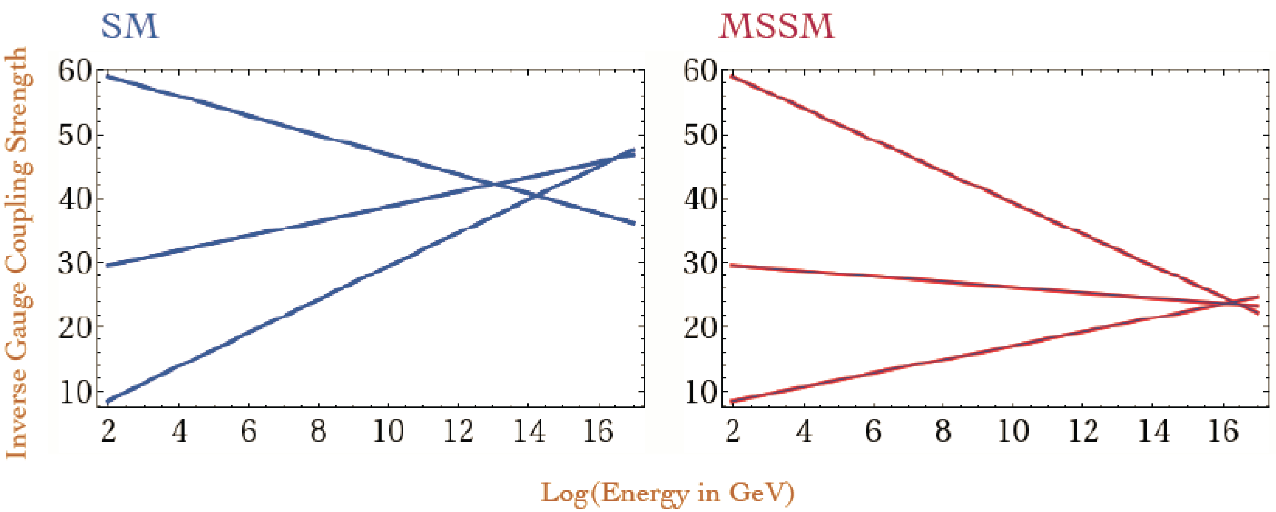
- Masses of Higgs and top quark are in the meta-stable region, why ? Fundamental reason ?
- Many of the free parameters in the SM are related to Higgs. Coincidence ?



Fundamental reason(s) beyond SM ?!

Evidence Beyond the Standard Model

- **Unification at a high energy ?**



- **No dark matter particles in the SM, Needed ? Where ?**
- **No CP in the SM to explain Matter-antimatter asymmetry, why ?**
- **How to describe neutrinos in the SM ?**
- **SUSY can provide solutions to many of these problems, incident ?**

Specific Science Cases

- **Electron-positron collider(90, 250, 350 GeV)**
  - Higgs Factory: Precision study of Higgs(m_H, J^{PC}, couplings)
    - Similar & complementary to ILC
  - Z & W factory: precision test of SM
    - Deviation from SM ? Rare decays ?
  - Flavor factory: b, c, τ and QCD studies
- **Proton-proton collider(~100 TeV)**
  - Directly search for new physics beyond SM
  - Precision test of SM
    - e.g., h^3 & h^4 couplings

Precision measurement + searches:
Complementary with each other !

* Powerful + Complementary probes of Higgs couplings

$[\Lambda^2 \mathcal{L}_6]$: $[\partial h^\dagger h]^2$, $h^\dagger h\, h f f^c$, $h^\dagger h F^2$ ← Higgs Factory

$(h^\dagger h)^3$ ← 100 TeV

Totally Generic

$(h^\dagger D^\mu h)^2$, $h^\dagger W^{\mu\nu} B_{\mu\nu} h$, $h^\dagger \overleftrightarrow{D}_\mu h \bar{f} \bar{\sigma}^\mu f$

↑ • 1 Tera Z

Λ probed to (multi-) TeV scale

N. Arkani-Hamed

- **Every body agrees that a new machine may find solutions to these fundamental questions**
- **But many still feel uncomfortable. They will ask: Is it guaranteed ?**

New Physics for sure ?

Three pillars of future circular colliders

EW phase transition

Dark Matter

Naturalness

New Physics ≠ New Particles

New Physics = New Phenomena

New Physics = New Principles

$$m_H^2 - m_{H,0}^2 \sim -\frac{3}{8\pi^2} y_t^2 \Lambda^2$$

For Λ(new physics) at the Planck scale ~ 10^{16} TeV:

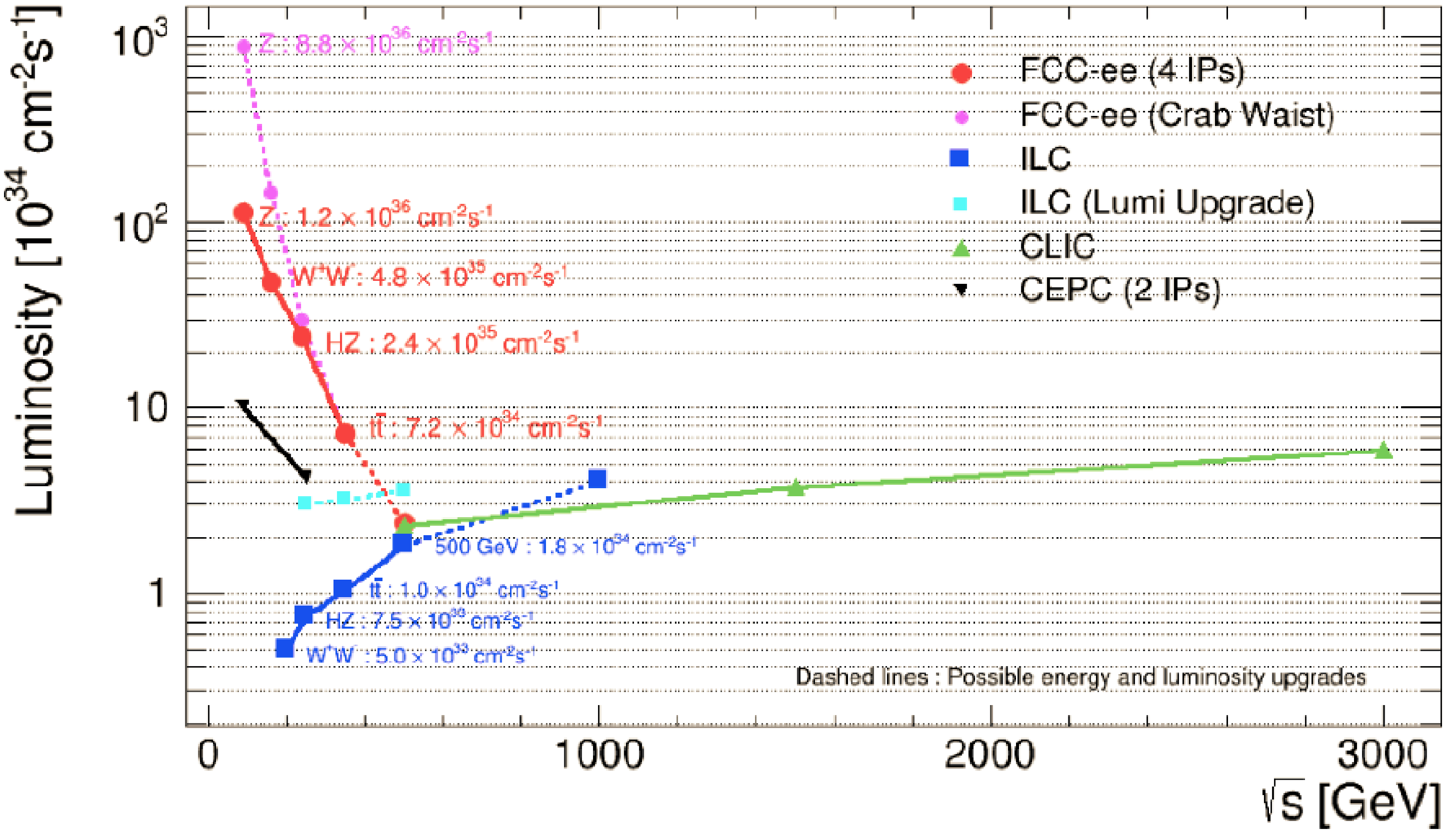
m_H^2 = 36,127,890,984,789,307,394,520,932,878,928,933,023
−36,127,890,984,789,307,394,520,932,878,928,917,398
= $(125\ \text{GeV})^2$! ?

- **If no new physics at LHC**
  - Λ~ 1 TeV ➔ 10^{-2} fine tuning
- **If no new physics at 100 TeV**
  - Λ~ 10 TeV ➔ 10^{-4} fine tuning
  - Never before

If naturalness does not work, then ?

Design Goal of CEPC/FCC-ee

- Limit SR power to 50 MW per beam
- CEPC: single ring, head-on collision, up to 250 GeV
- FCC-ee: double ring, large crossing angle, up to 350 GeV



CEPC:
- 10^6 Higgs
- 10^{10} Z

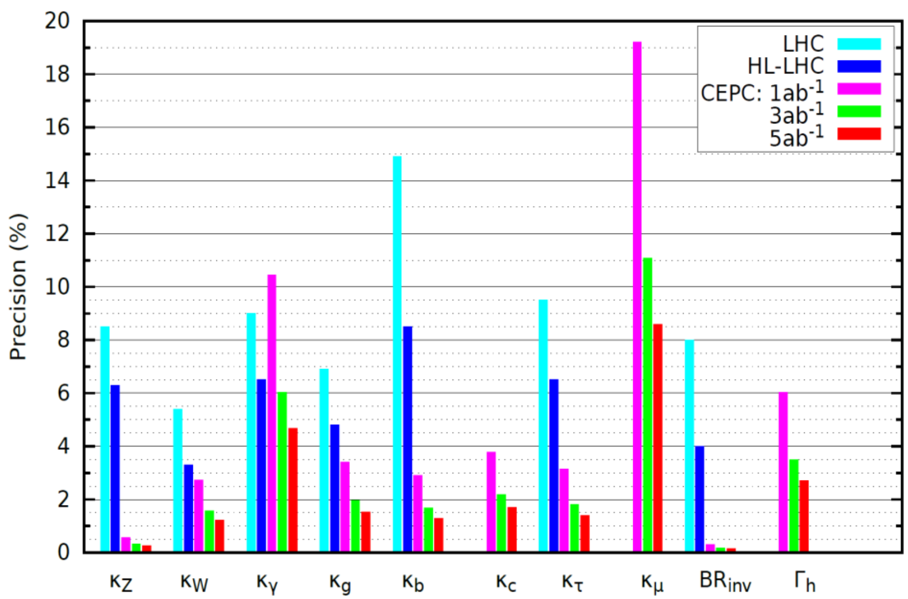
FCC-ee:
- 10^7 Higgs
- $10^{12\text{-}13}$ Z

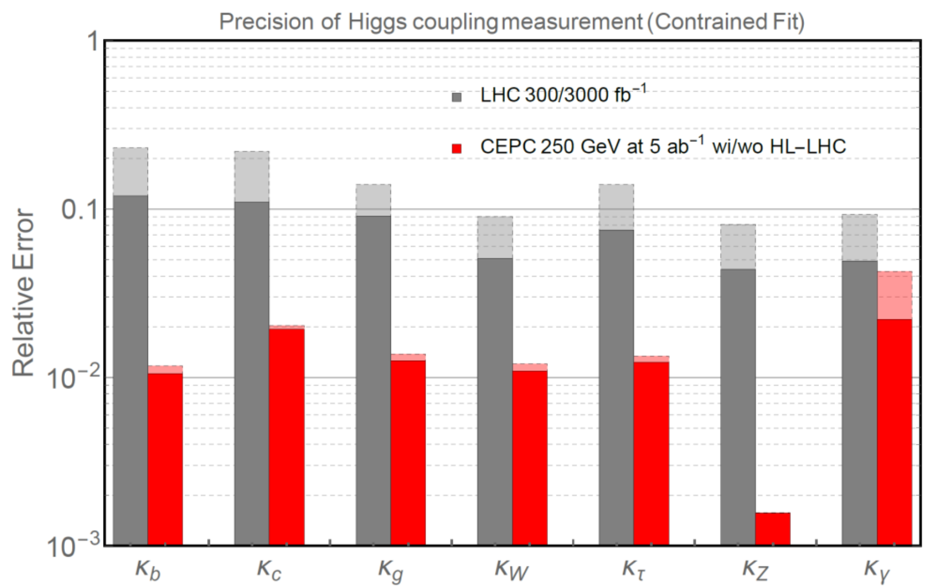
Precision Higgs Physics by CEPC/FCC-ee

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_i \frac{c_i}{M^2} \mathcal{O}_{6,i} \qquad \delta \sim c_i \frac{v^2}{M^2}$$

% precision → M ~ 1 TeV

CEPC/FCC-ee to new physics → ~ × 10 over LHC





CEPC preCDR Volume 1 (p.9)

Search for Deviations from SM

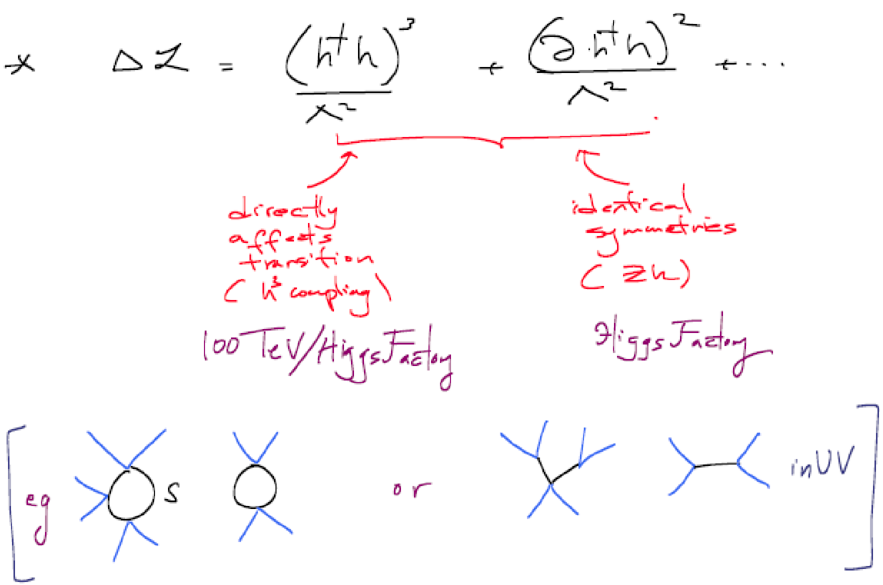
Experiment	κ_Z (68%)	f (GeV)	κ_g (68%)	$m_{\tilde{t}_L}$ (GeV)
HL-LHC	3%	1.0 TeV	4%	430 GeV
ILC500	0.3%	3.1 TeV	1.6%	690 GeV
ILC500-up	0.2%	3.9 TeV	0.9%	910 GeV
CEPC	0.2%	3.9 TeV	0.9%	910 GeV
TLEP	0.1%	5.5 TeV	0.6%	1.1 GeV

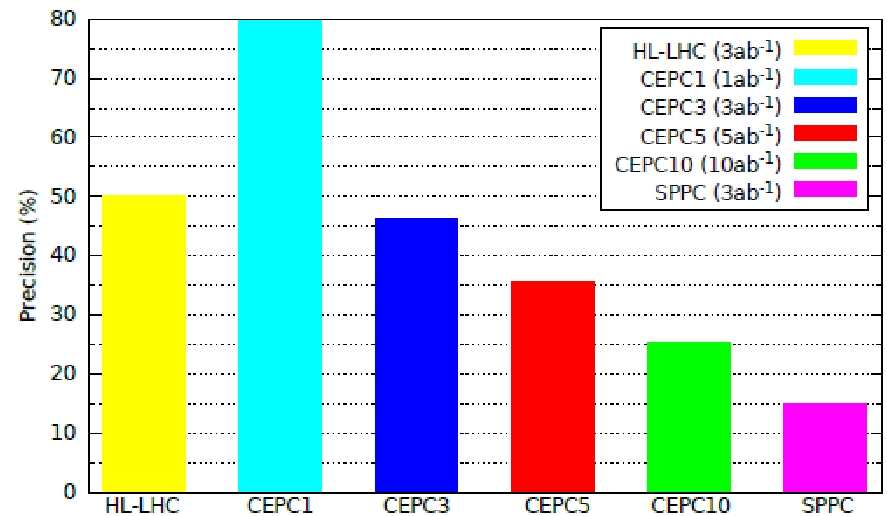
Experiment	S (68%)	f (GeV)	T (68%)	$m_{\tilde{t}_L}$ (GeV)
ILC	0.012	1.1 TeV	0.015	890 GeV
CEPC (opt.)	0.02	880 GeV	0.016	870 GeV
CEPC (imp.)	0.014	1.0 TeV	0.011	1.1 GeV
TLEP-Z	0.013	1.1 TeV	0.012	1.0 TeV
TLEP-t	0.009	1.3 TeV	0.006	1.5 TeV

CEPC preCDR Volume 1 (p.10)

Higgs Self-Couplings & EWSB

- Critical for the EWSB ➔ 1st or 2nd order
- O(1) deviations if 1st order
- Can be directly measured at pp, LHC & SPPC/FCC-hh
- Indirectly(model dependent) at e+e- through 1-loop process of hZZ [M. McCullough, PRD 90(2014)015001]



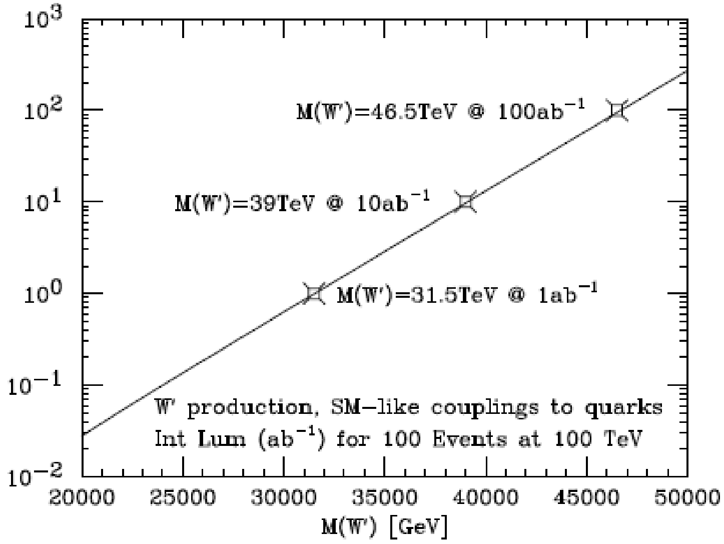


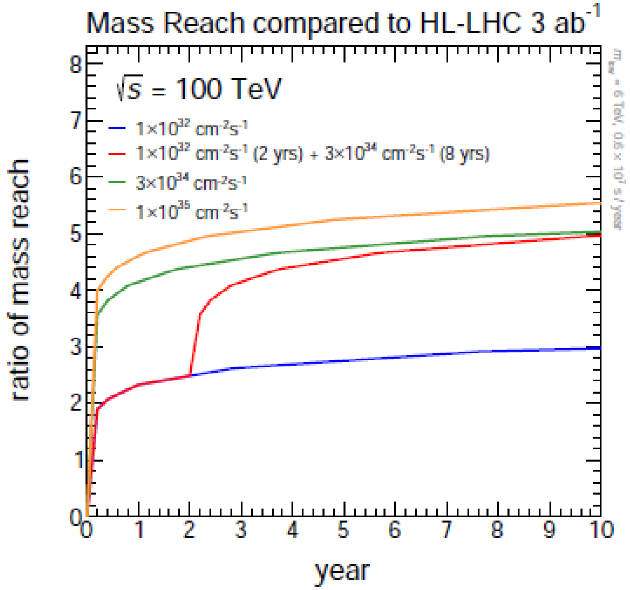
Design Goal of SPPC/FCC-pp

- Technology to bend the proton beam is limited by the field strength of the dipole magnet. Currently we can only imagine up to 20 T.
- Hence, ~ 100 km ring and ~ 100 TeV is a generic desire
- What luminosity ?

Luminosity Scaling Law ?

- **Discovery potential follows L ∝ s** **[B. Richter, arXiv:1409.1196]**
  - $L_{100} > (100/14)^2 L_{LHC}$?
- **Discovery potential dominated by the beam energy:** **[I. Hinchliffe, A. Kotwal, M. Mangano, C. Quigg and L.T. Wang, arXiv:1504.06108]**

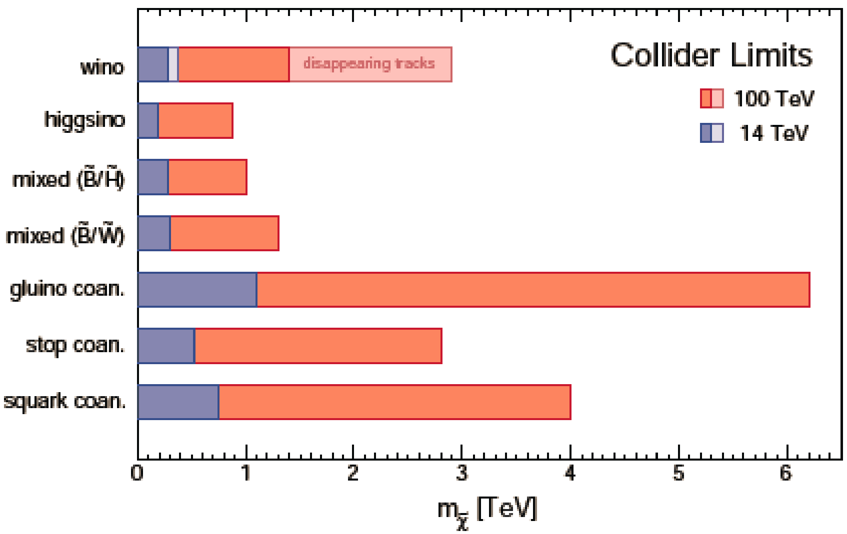




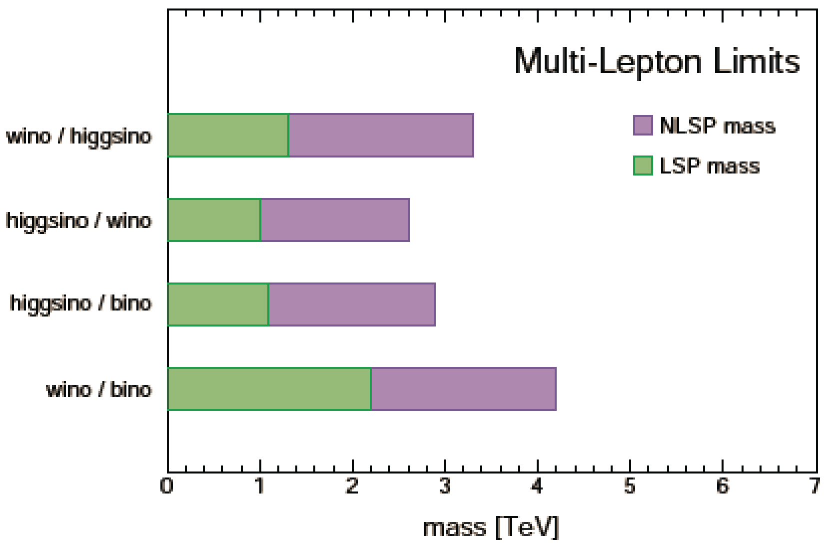
- An integrated Luminosity of 10-20 ab^{-1} per experiment, corresponding to $2*10^{35}$ cm^{-2}s^{-1} well match to our current perspective.
- Even 10^{32} cm^{-2}s^{-1} could be acceptable as a compromise

Dark Matter Searches

- Great improvement over LHC
- ~ TeV region is much more interesting and most probable for simplest possibilities



M. Low et al., JHEP1408(2014)161



S. Gori et al., JHEP1412(2014)108

Shall We Wait for Results from LHC ?

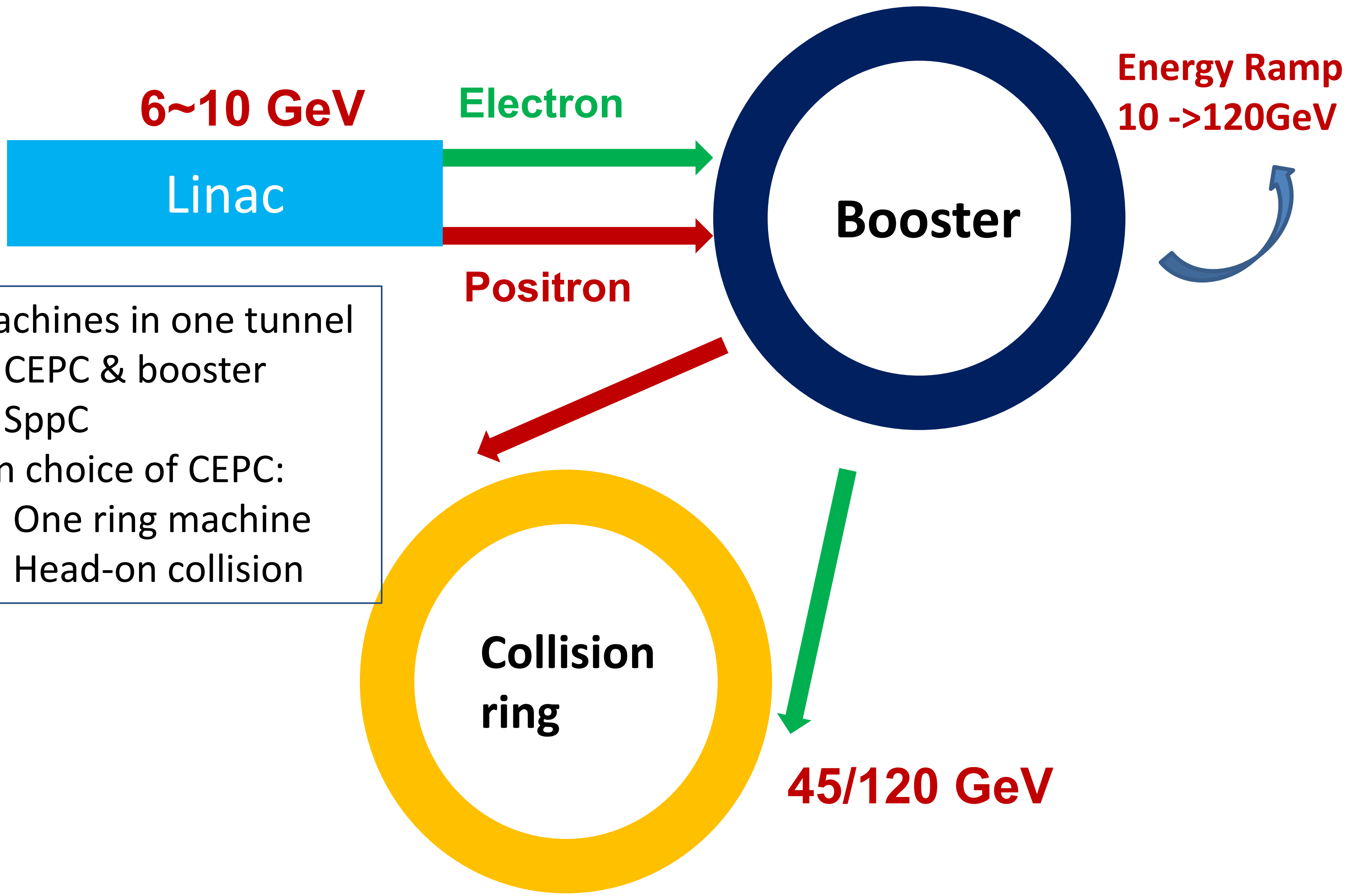
- If LHC finds nothing, we should go to higher energies
  - An e+e- Higgs factory can give us a first indication
  - go directly to 100 TeV pp collider is also a viable option
- If LHC finds something, it is a new era
  - Beyond SM ➔ new energy scale, new spectrum, LHC can not complete it
  - A higher energy pp collider is needed immediately
    - To access the spectra of higher masses
    - To have more statistics since Event No. $\propto E^{\sim 5}_{CM}$
  - An e+e- Higgs factory can give us time to develop technologies for 16-20 T magnet and SC cables

Is ILC enough ?

- **Why two e+e- colliders ? One is enough ?**
  - Two very different technology. Very different possibility for future.
  - Cross check： 2 accelerators + 2 detectors are better than 1 (ILC) + 2 detectors
- **Energy：**
  - CEPC for Z and Higgs(up to 250 GeV)
  - ILC can go to 500 GeV for all couplings(Htt etc)
- **Polarization:**
  - CEPC/FCC-ee: partial transverse polarization for energy measurement
  - ILC: both longitudinal & transverse polarization for physics
- **Detector：**
  - ILC & CEPC/FCC-ee: cross check
  - ILC can give up Push-Pull option
- **Technology:**
  - ILC can go to higher energy ➔ Application: FEL
  - CEPC can go to higher Luminosity ➔ Application: synchrotron
- **Timeline:**
  - ILC starts from 2020 ?
  - CEPC/FCC-ee starts from 2022/2025 ?

Machine Design: CEPC/SppC

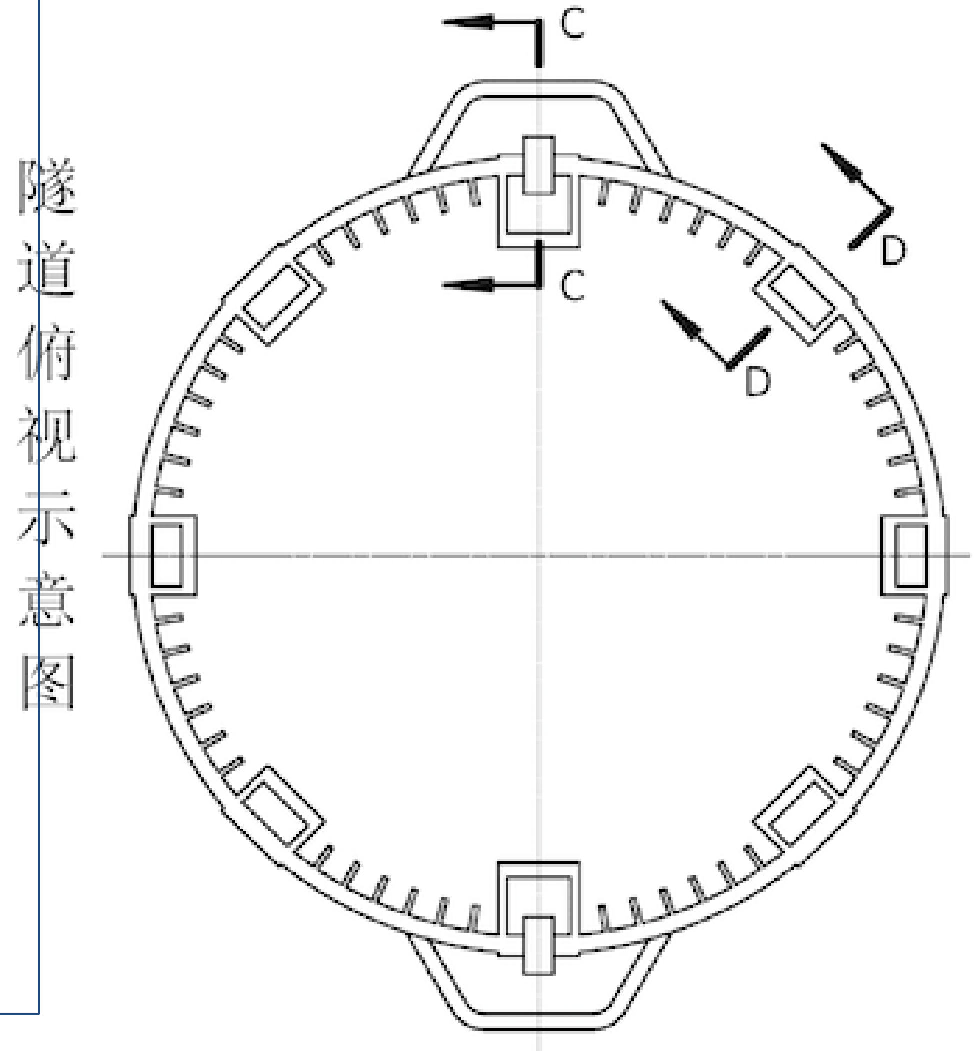
CEPC Accelerator Design



- 3 machines in one tunnel
  - CEPC & booster
  - SppC
- Main choice of CEPC:
  - One ring machine
  - Head-on collision

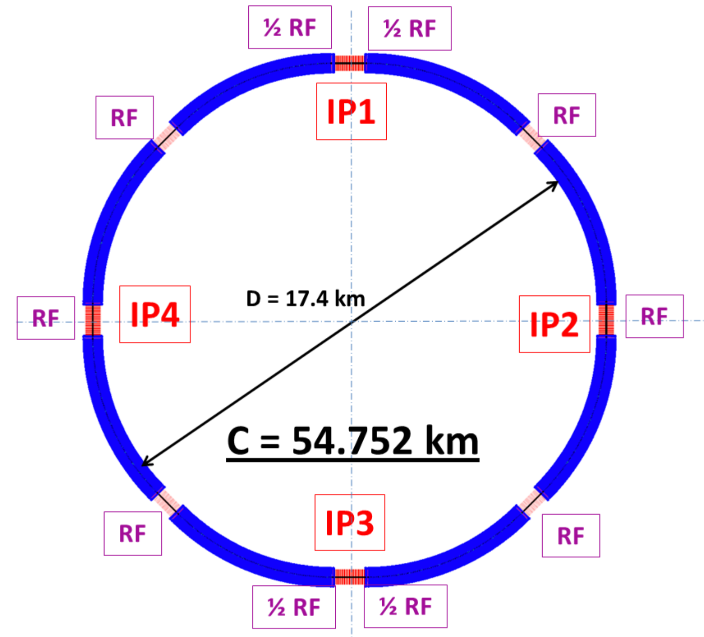
Compatibility: a main Issue

- CEPC & SppC Injectors
- Beam pipe detour for detectors
  - CEPC booster avoid storage ring
  - CEPC avoid SPPC detectors
  - SPPC avoid CEPC detectors
- SR beamlines
- Predict what SPPC needs
  - Collimators
  - Straight sections
  - Tunnel dimensions
  - Access tunnel
  - ....
- To be fully understood in the next 5 years



Main info of CEPC

- Critical parameters:
  - SR power: 51.7 MW/beam
  - 8*arcs, 2*IPs
  - 8 RF cavity sections (distributed)
  - RF Frequency: 650 MHz
  - Filling factor of the ring: ~70%



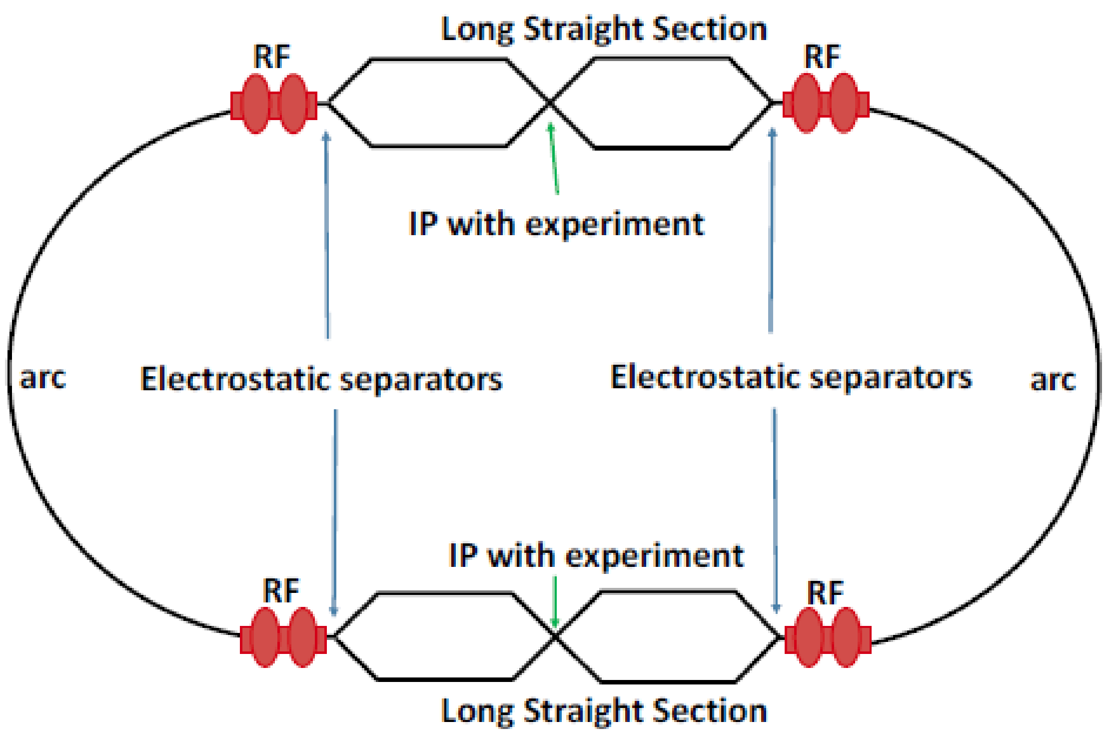
Parameter	Unit	Value	Parameter	Unit	Value
Beam energy [E]	GeV	120	**Circumference [C]**	m	54752
Number of IP[N_{IP}]		2	**SR loss/turn [U_0]**	GeV	3.11
Bunch number/beam[n_B]		50	**Energy acceptance RF [h]**	%	5.99
SR power/beam [P]	MW	51.7	**Beam current [I]**	mA	16.6
emittance (x/y)	nm	6.12/0.018	**β_{IP}(x/y)**	mm	800/1.2
Transverse size (x/y)	μm	69.97/0.15	**Luminosity /IP[L]**	$cm^{-2}s^{-1}$	2.04E+34

Challenges

- Beam physics: dynamic aperture, momentum acceptance, electron cloud, pretzel scheme, …
- Superconducting cavity: HOM dumping, mass production, power consumption,…
- Total power consumption: ~ 500 MW ! ➔ need a green machine
  - Reuse the thermal power, ~ 200 MW
    - Heating of houses ➔ close to a big city, summer ?
    - Gasifying liquified natural gas ➔ close to a harbour
    - Argricultural greenhouse ➔ summer ?
  - Increase the efficiency of the RF power supply to more than 70%, even 80%
  - Partial double-ring machine to increase the luminosity, reduce the power consumption and cost ?

Partial Double-Ring Machine ?

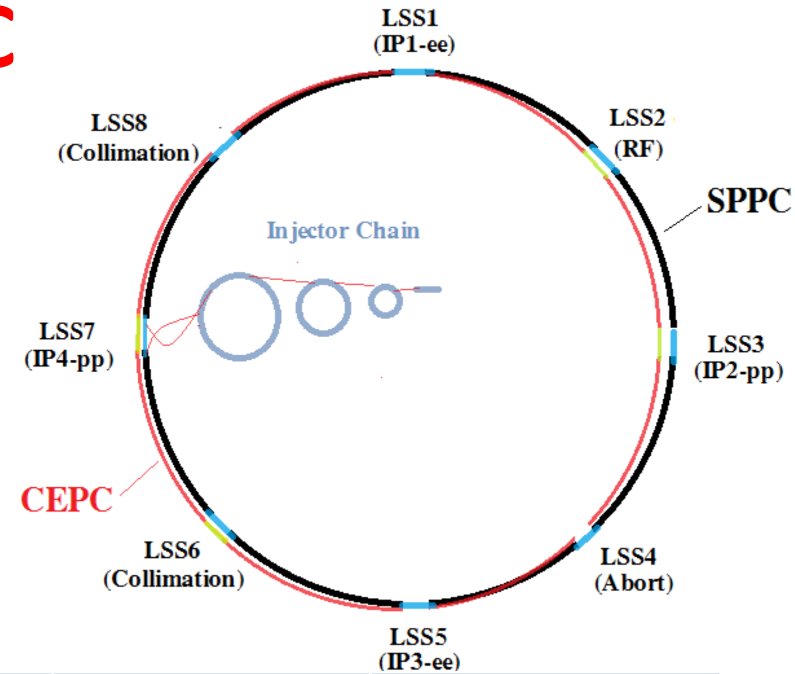
- ~ 10% double-ring
- Large crossing angle & Crab waist & small β_y
- O(1000) bunches
- Luminosity close to double-ring machine ?
- Issues
  - Electrostatic separators
  - RF systems
  - Electron Cloud Issues



M. Koratzinos, talk given at HF2014, Beijing
M. Koratzinos & F. Zimmermann, this Conf.
J. Gao, IHEP-AC-LC-Note2013-012

Conceptual design of SppC

- 8 arcs (5.9 km) and long straight sections (850m*4+1038.4m*4)
- 2 IPs for pp
- 2 IRs for collimation
- 2 IRs for RF and beam abort

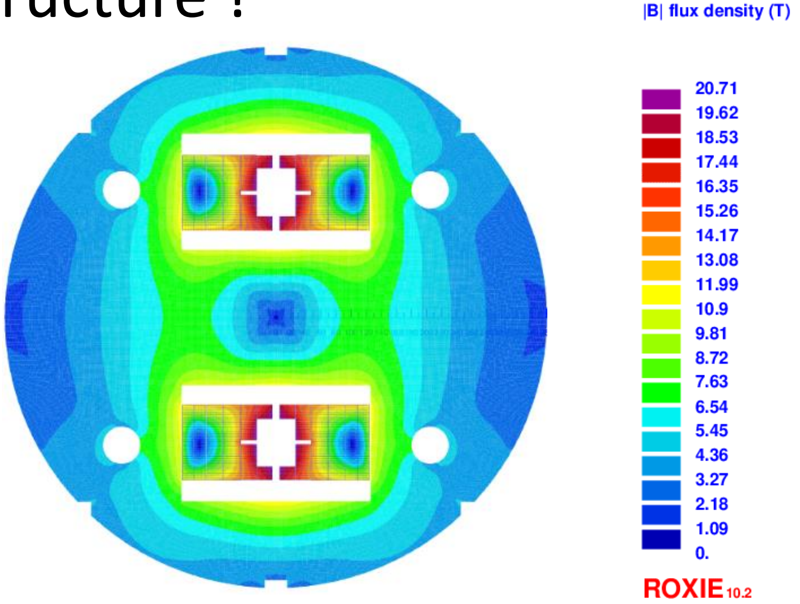


Parameter	Value	Unit
Circumference	54.36	km
Beam energy	35.3	TeV
Dipole field	20	T
Injection energy	2.1	TeV
Peak luminosity per IP	1.2E+35	$cm^{-2}s^{-1}$
Beta function at collision	0.75	m
Circulating beam current	1.0	A
Max beam-beam tune shift per IP	0.006	
Bunch separation	25	ns
SR heat load @arc dipole (per aperture)	56.9	W/m

Challenges

- High field magnets: both dipoles (20 T) and quadrupoles (pole tip field: 14-20 T).
- Beam screen and vacuum: very high synchrotron radiation power inside the cold vacuum:
- Collimation system: high efficiency collimators in cold sections: new method and structure ?
- ……

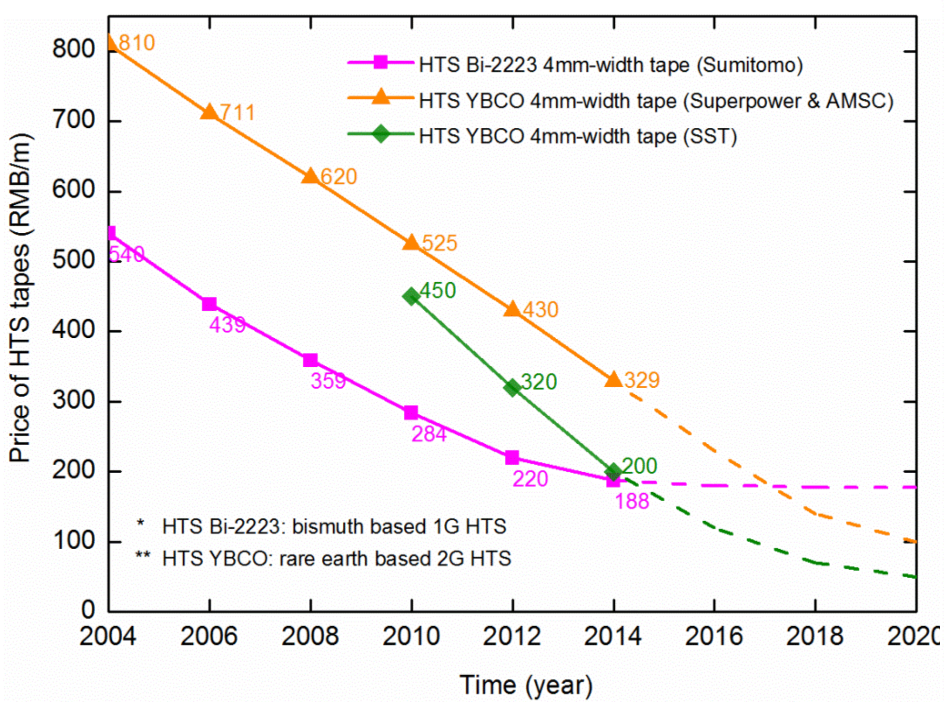
A R&D plan is developed.
Main focus is the magnet

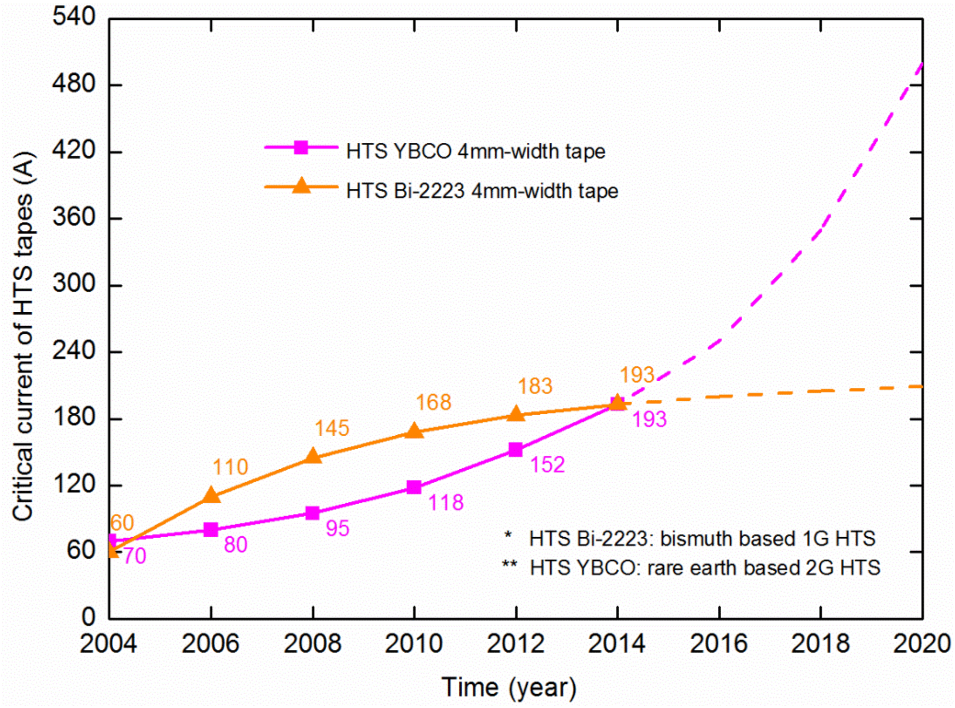


A Conceptual design of *20-T Nb_3Sn + HTS common coil dipole magnet* from IHEP

Future of HTS Superconducting cables

- Cost per meter decreased by ~ 2.5 times per 10 years
- Current limit per unit area increased by ~3 times per 10 years
- Unit price per (A•meter) can improve by ~50 times over 20 years, if past data can be used for prediction !
- 20T Full HTS magnet ???

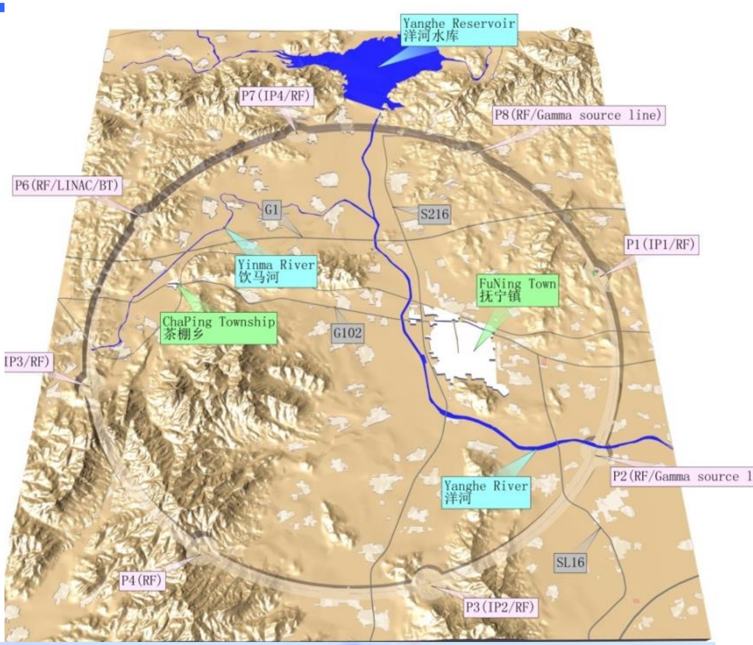


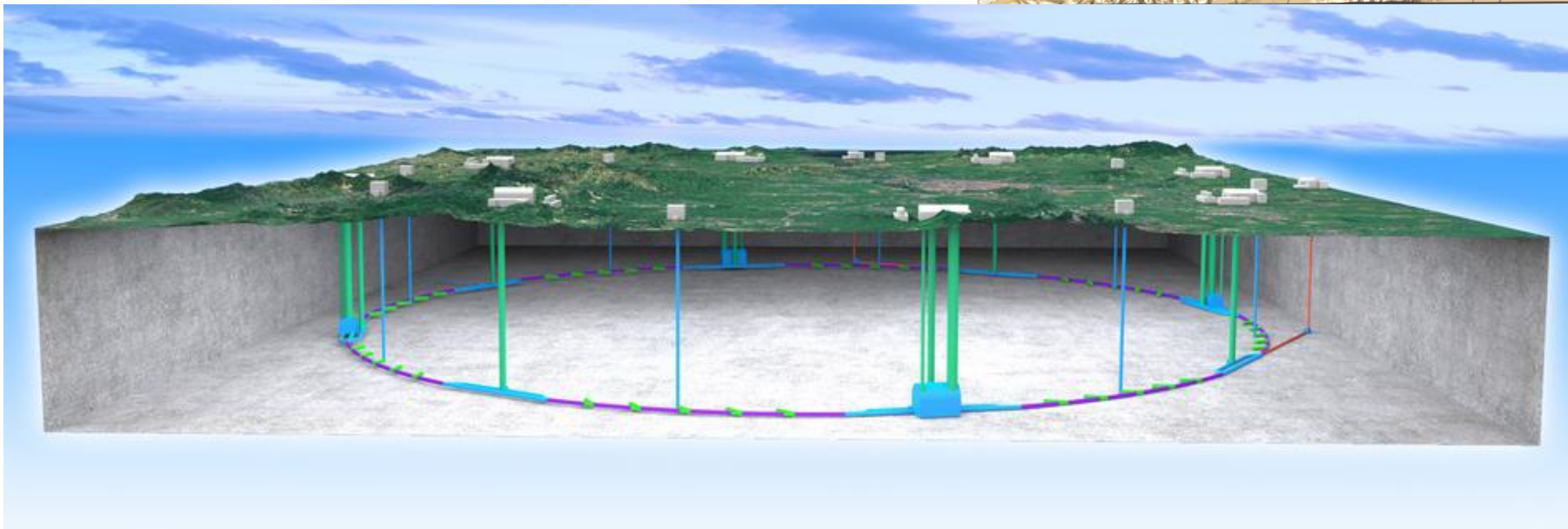


PLEASE KEEP OPTIMISTIC !!!

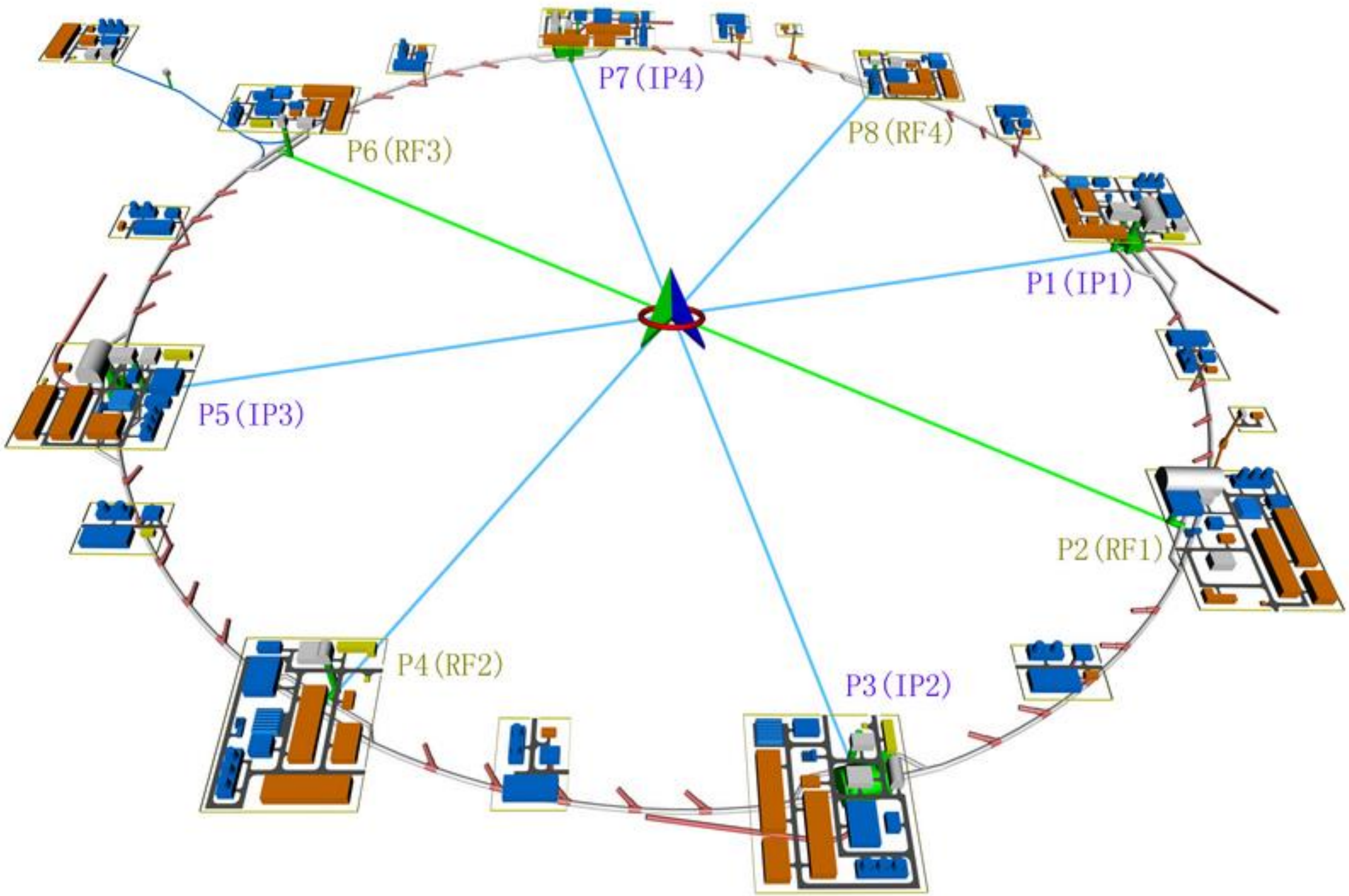
Civil Construction

- A floor plan exists for surface and underground facilities
- Geological survey and preliminary site selection done
- A pre-conceptual design with utilities, power consumption and cost estimate is completed





Surface and Underground Construction



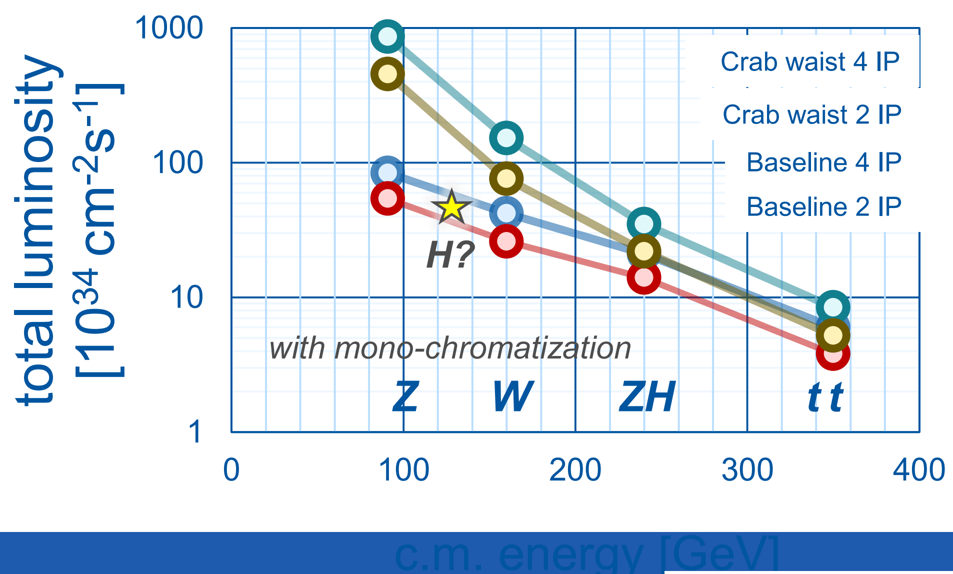
Machine Design: FCC-ee & FCC-hh

M. Benedikt et al, "Combined operation and staging for the FCC-ee collider", "FCC-hh Hadron collider-parameter Scenarios and staging options", this conf.

Key Parameters FCC-ee

Parameter	FCC-ee			LEP2
Energy/beam [GeV]	45	120	175	105
Bunches/beam	13000- 60000	500- 1400	51- 98	4
Beam current [mA]	1450	30	6.6	3
Luminosity/IPx$10^{34}cm^{-2}s^{-1}$	**21 - 280**	**5 - 11**	**1.5 - 2.6**	0.0012
Energy loss/turn [GeV]	0.03	1.67	7.55	3.34
Synchrotron Power [MW]	100			22
RF Voltage [GV]	0.2-2.5	3.6-5.5	11	3.5

Dependency: crab-waist vs. baseline optics and 2 vs. 4 IPs



M. Benedikt

FCC-hh Luminosity Goals

- **Two parameter sets for two operation phases:**

  - **phase 1 (baseline): 5 x 10^{34} $cm^{-2}s^{-1}$ (peak),**
    250 fb^{-1}/year (averaged)
  - **phase 2 (ultimate): ~2.5 x 10^{35} $cm^{-2}s^{-1}$ (peak),**
    1000 fb^{-1}/year (averaged)

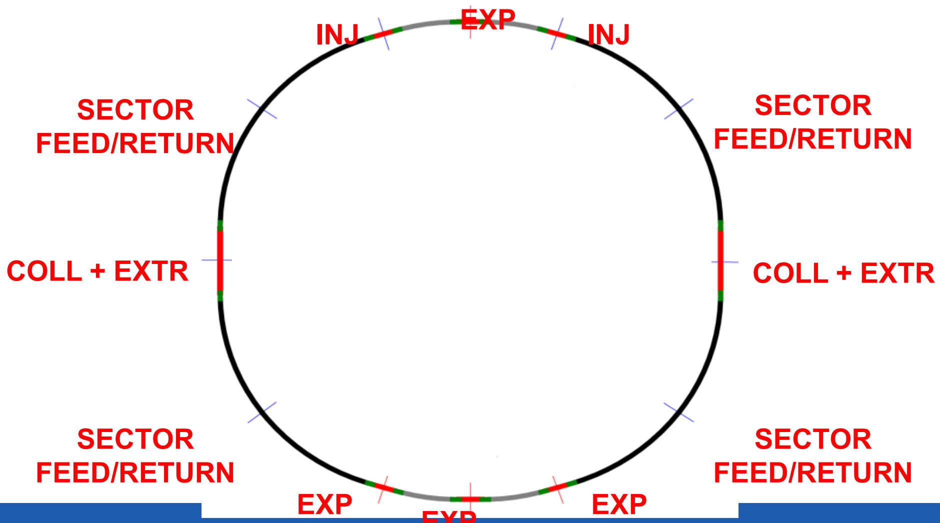
➔ total luminosity a few 10's of ab^{-1} over ~25 years of operation

OK for physics

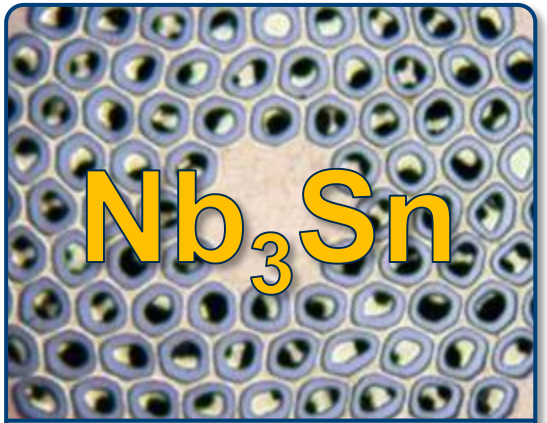
Key Parameters of FCC-hh

Parameter	FCC-hh	LHC
Energy [TeV]	100 c.m.	14 c.m.
Dipole field [T]	16	8.33
# IP	2 main, +2	4
Luminosity/IP$_{main}$ [cm^{-2}s^{-1}]	5 - 25 x 10^{34}	1 x 10^{34}
Stored energy/beam [GJ]	8.4	0.39
Synchrotron rad. [W/m/aperture]	28.4	0.17
Bunch spacing [ns]	25 (5)	25

Allocation of Sectors for FCC-hh



Key Technology R&D - HFM



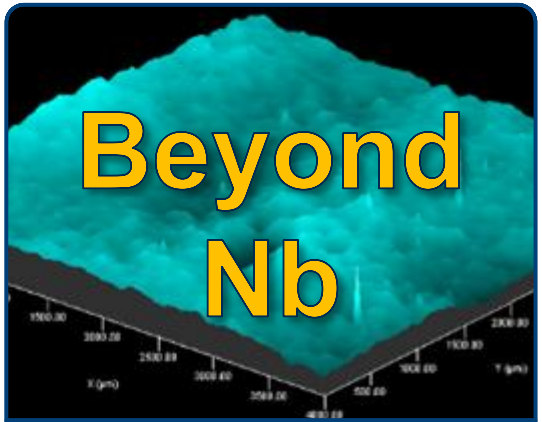
Conductor R&D

- Increase critical current density
- Obtain high quantities at required quality
- Material Processing
- Reduce cost

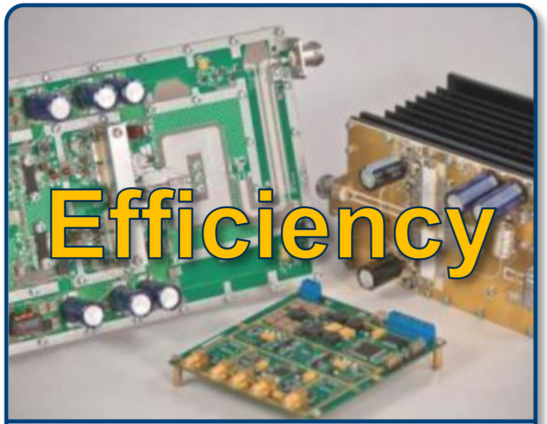
Magnet Design

- Develop 16T short models
- Field quality and aperture
- Optimum coil geometry
- Manufacturing aspects
- Cost optimisation
- First demonstrator in 2016?

Key Technology R&D - RF



Superconducting RF



Power Conversion

- Cavity R&D for large Q_0, high gradient, acceptable cryo power
- Multilayer additive manufacturing combining Cu and LTS materials
- High quality over large surfaces

- Push Klystrons far beyond 70% efficiency
- Increase power range of solid-state amplifiers
- High reliability for high multiplicity

Geology Studies – Example 93 km

Alignment | **Shaft Tools**

Choose alignment option

93km quasi-circular ▾

Tunnel depth at centre: 299mASL

Gradient Parameters

Azimuth (°): -15

Slope Angle x-x(%): .5

Slope Angle y-y(%): 0

CALCULATE

Alignment centre

X: 2499812 Y: 1106889

LHC Intersection	CP 1	CP 2
Angle		
Depth	589m	589m

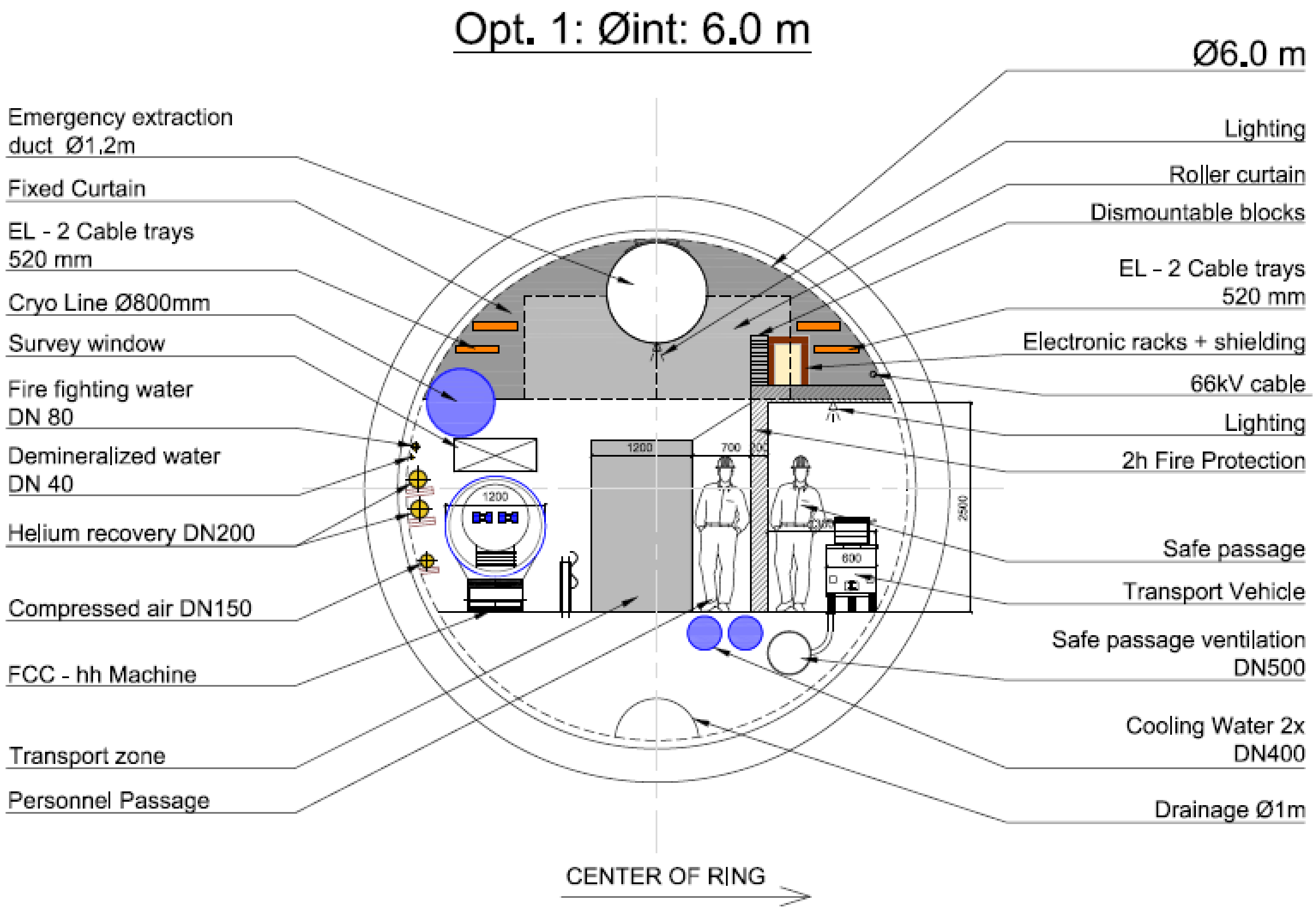
Geology Intersected by Shafts | **Shaft Depths**

	Shaft Depth (m)				Geology (m)			
Point	Actual	Min	Mean	Max	Quaternary	Molasse	Urgonian	Calcaire
A	203	200	204	212	93	111	0	0
B	227	219	226	231	41	185	0	0
C	218	208	217	225	75	143	0	0
D	153	150	154	158	19	134	0	0
E	247	233	249	261	24	223	0	0
F	262	251	269	304	32	230	0	0
G	396	392	393	396	177	220	0	0
H	266	231	274	322	0	325	0	0
I	146	141	144	149	26	120	0	0
J	248	247	251	258	6	242	0	0
K	163	153	159	164	76	87	0	0
L	182	182	184	187	17	165	0	0
Total	2711	2607	2724	2867	585	2185	0	0

- 90 – 100 km fits geological situation well, better than a smaller ring size

- LHC suitable as potential injector

FCC-hh arcs Single tunnel, longitudinal ventilation



Current Status

CEPC-SppC

- Pre-CDR completed after the international review
- R&D issues identified
- A proposal for R&D submitted
- Seed money from IHEP for R&D available
- International advisory committee to be established soon
- A model of international collaboration to be invented

FCC

- Organization established with international participation: 51 institutes and 19 countries
- Funding from CERN is available
- Annual meetings all over the world with very enthusiastic participations
- A lot of technical advances, CDR by 2018

Summary

- Tremendous efforts up to now
- Real progress in all fronts
- A promising future: please be optimistic !
- Let's work together to make it happen

Thanks to N. Arkani-Hamed, M. Benedikt, Jie Gao, Xinchou Lou, M. Mangano, Qin Qing, Liantao Wang, and many other who provided materials for this talk.

Thanks to a lot of people all over the world who did extraordinary works for this study

Thanks
谢谢