# Higgs Factory

## – proposals & new ideas

北京大学物理学院
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第十六届粒子物理、核物理和宇宙学交叉学科前沿问题研讨会　2023.6.30-7.4

# Contents

- 10+ years of Higgs
- Higgs factory : proposals
- CEPC status
- Higgs factory : new ideas
- Summary

focus on $e^+e^-$ machines

# Higgs boson and new physics

Nature 607 (2022) 41

**Why is the electroweak interaction so much stronger than gravity?**

- Are there new particles close to the mass of the Higgs boson?
- Is the Higgs boson elementary or made of other particles?
- Are there anomalies in the interactions of the Higgs boson with the $W$ and $Z$ bosons?

**What is dark matter?**

- Can the Higgs boson provide a portal to dark matter or a dark sector?
- Is the Higgs lifetime consistent with the Standard Model?
- Are there new decay modes of the Higgs boson?

**What is the origin of the vast range of quark and lepton masses in the Standard Model?**

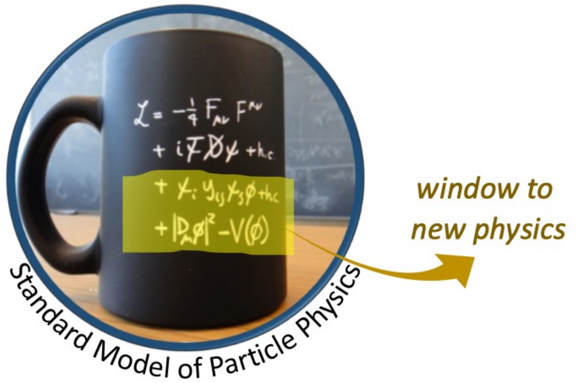
- Are there modified interactions to the Higgs boson and known particles?
- Does the Higgs boson decay into pairs of quarks or leptons with distinct flavours (for example, $H \to \mu^+ \tau^-$)?

**Why is there more matter than antimatter in the Universe?**

- Are there charge-parity violating Higgs decays?
- Are there anomalies in the Higgs self-coupling that would imply a strong first-order early-Universe electroweak phase transition?
- Are there multiple Higgs sectors?

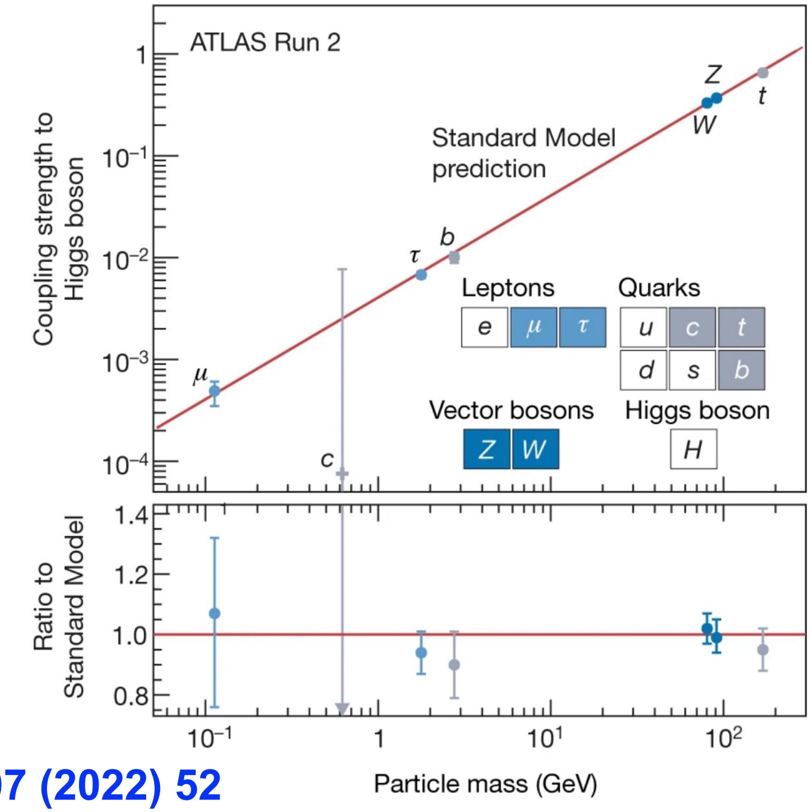
**What is the origin of the early Universe inflation?**

- Any imprint in cosmological observations?



# 10+ years after the discovery

- **All in SM**




**Nature 607 (2022) 52**

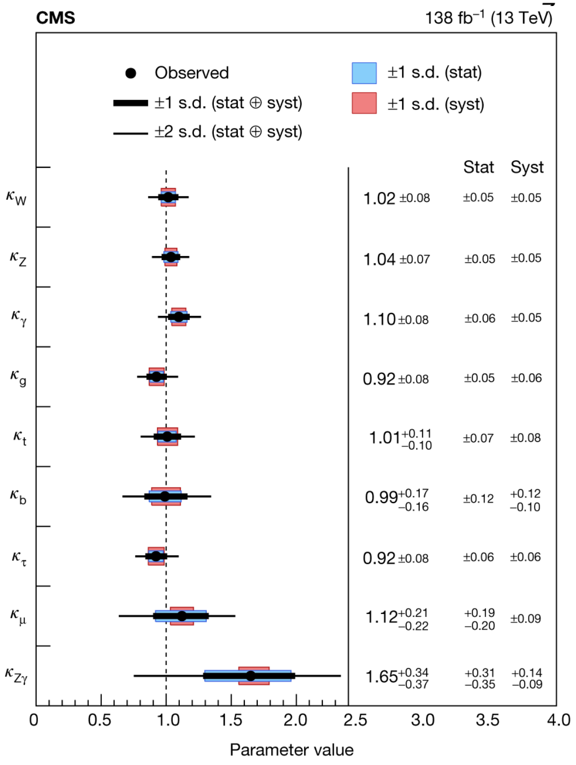
Citation: R.L. Workman *et al.* (Particle Data Group), to be published (2022)

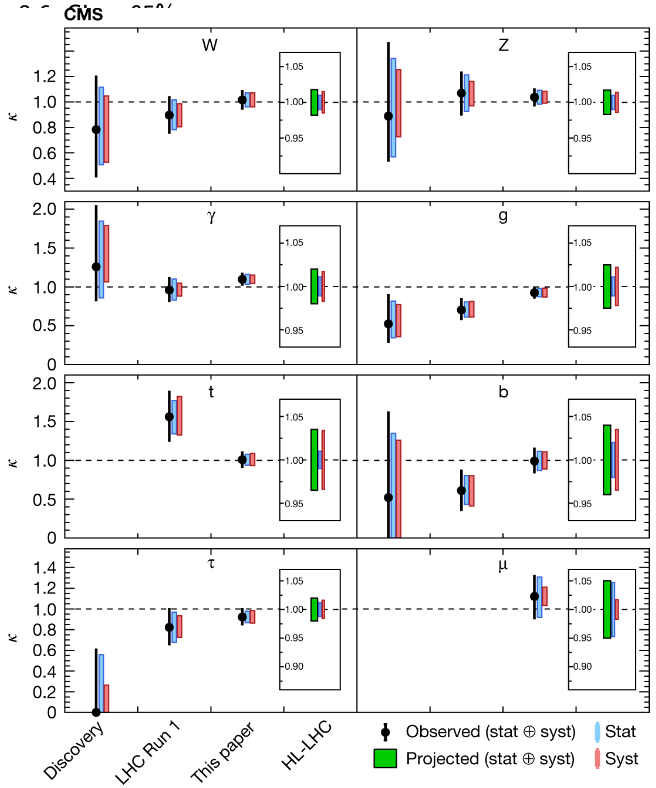
**$H^0$** $J = 0$ **PDG2022**

Mass $m = 125.25 \pm 0.17$ GeV (S = 1.5)
Full width $\Gamma = 3.2^{+2.8}_{-2.2}$ MeV (assumes equal on-shell and off-shell effective couplings)

**$H^0$ Signal Strengths in Different Channels**

Combined Final States = $1.13 \pm 0.06$
$WW^* = 1.19 \pm 0.12$
$ZZ^* = 1.01 \pm 0.07$
$\gamma\gamma = 1.10 \pm 0.07$
$c\bar{c}$ Final State = $37 \pm 20$
$b\bar{b} = 0.98 \pm 0.12$
$\mu^+\mu^- = 1.19 \pm 0.34$
$\tau^+\tau^- = 1.15^{+0.16}_{-0.15}$




**Nature 607 (2022) 1**

# Science Drivers

Report of the Particle Physics Project Prioritization Panel (P5), 2014

- Use the Higgs Boson as a Tool for Discovery
- Pursue the Physics Associated with Neutrino Mass
- Identify the New Physics of Dark Matter
- Understand Cosmic Acceleration: Dark Energy and Inflation
- Explore the Unknown: New Particles, Interactions, and Physical Principles
- Flavor as a Tool for Discovery – Possible New Driver (Snowmass 2022)

# Examples

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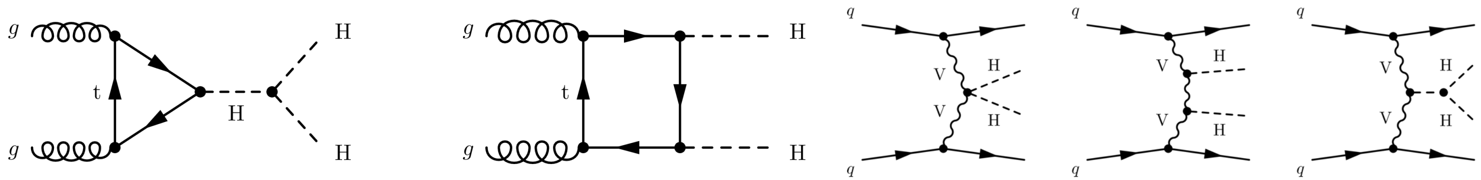
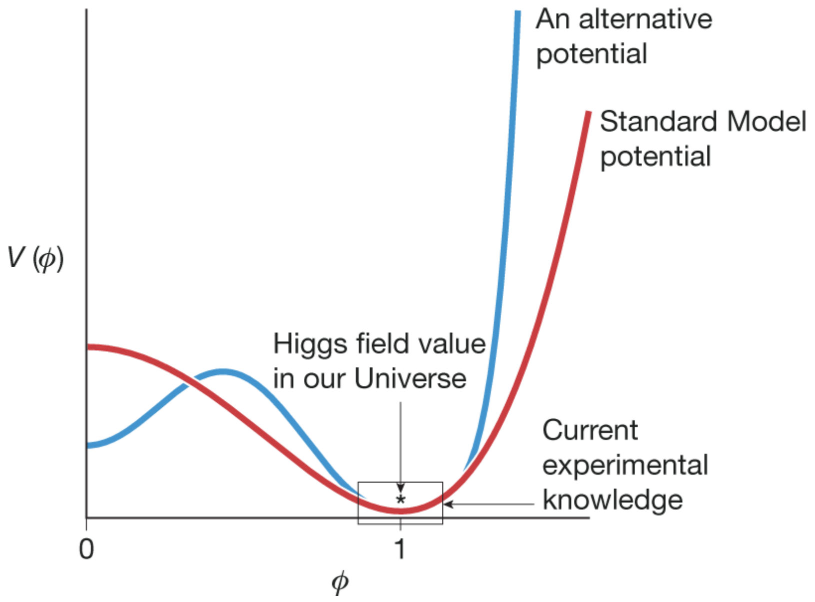
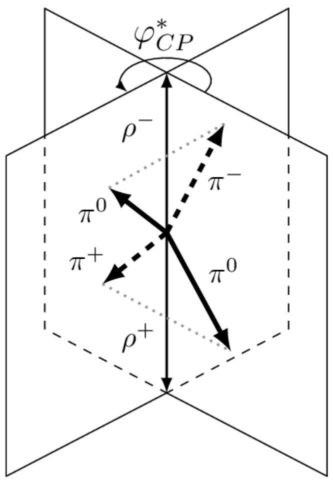
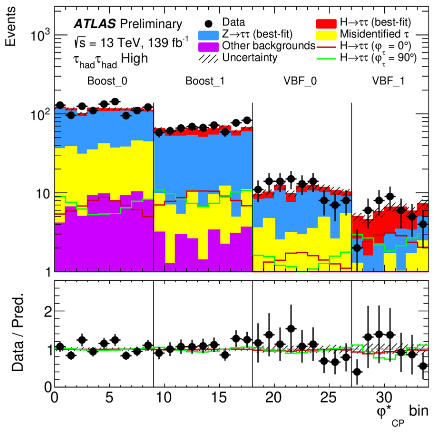
- $V(H) = \frac{1}{2} m_H H^2 + \lambda_3 v H^3 + \frac{1}{4} \lambda_4 H^4 + \cdots$

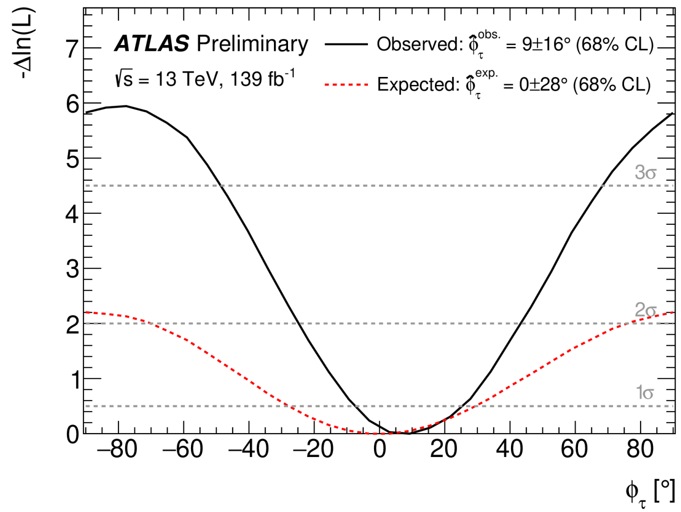





- $\mathcal{L}_{H\tau\tau} \sim (\cos\phi_\tau \bar{\tau}\tau + \sin\phi_\tau \bar{\tau} i \gamma_5 \tau) H$





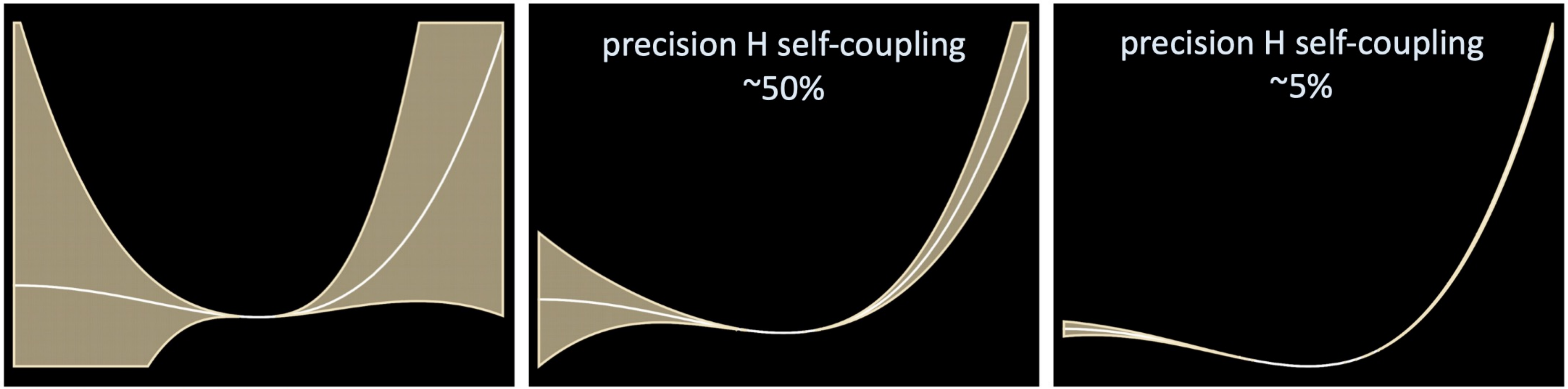




ATLAS-CONF-2022-032

# (long) way to the precision

ee @ 240 GeV
pp @ 100 TeV
ep @ 3.5 TeV

NOW HL-LHC

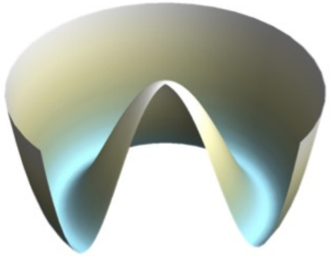


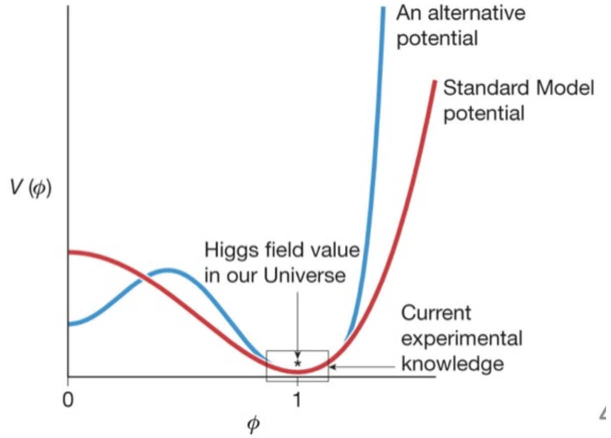

Adapted from Nathanial Craig

Is the H-field indeed represented by the standard model H-potential?

$$V_{higgs} = -\frac{1}{2} m^2 |\varphi|^2 + \frac{\lambda}{4} |\varphi|^4$$

$m_H$ *H self-coupling*

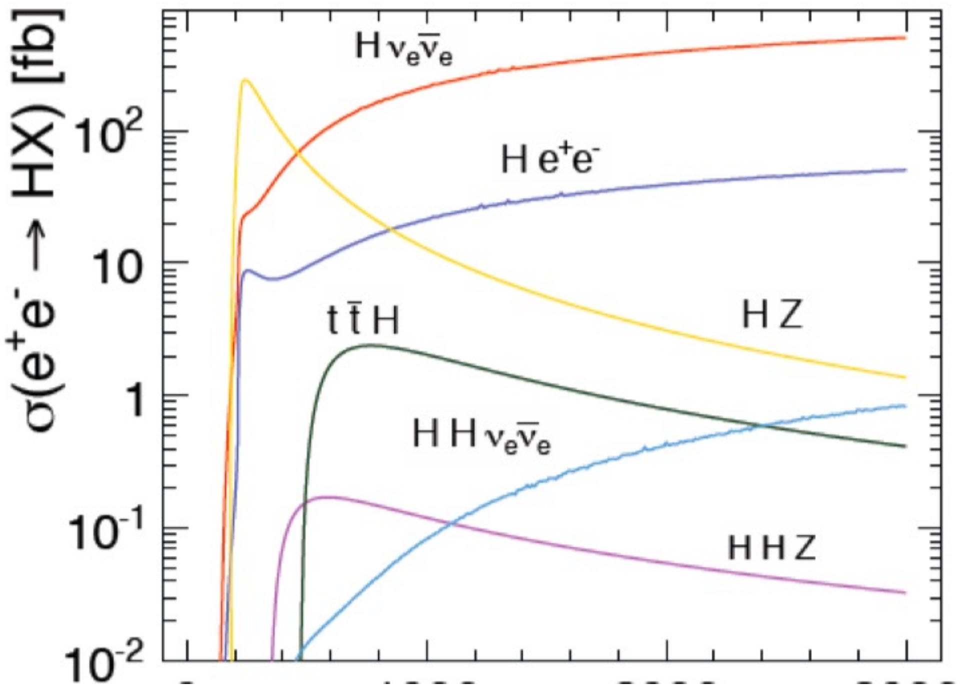




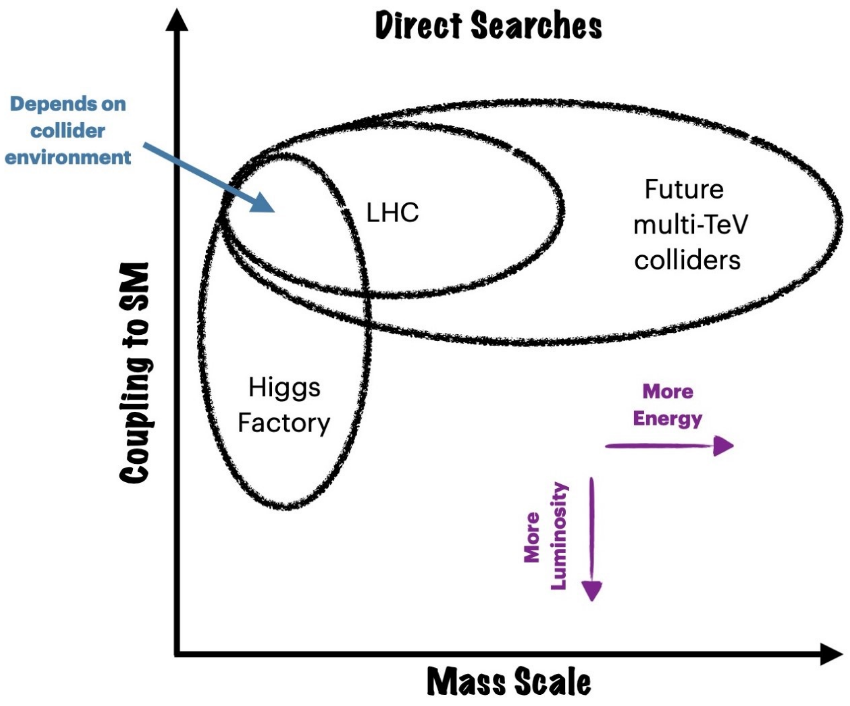
# A $e^+e^-$ Higgs factory

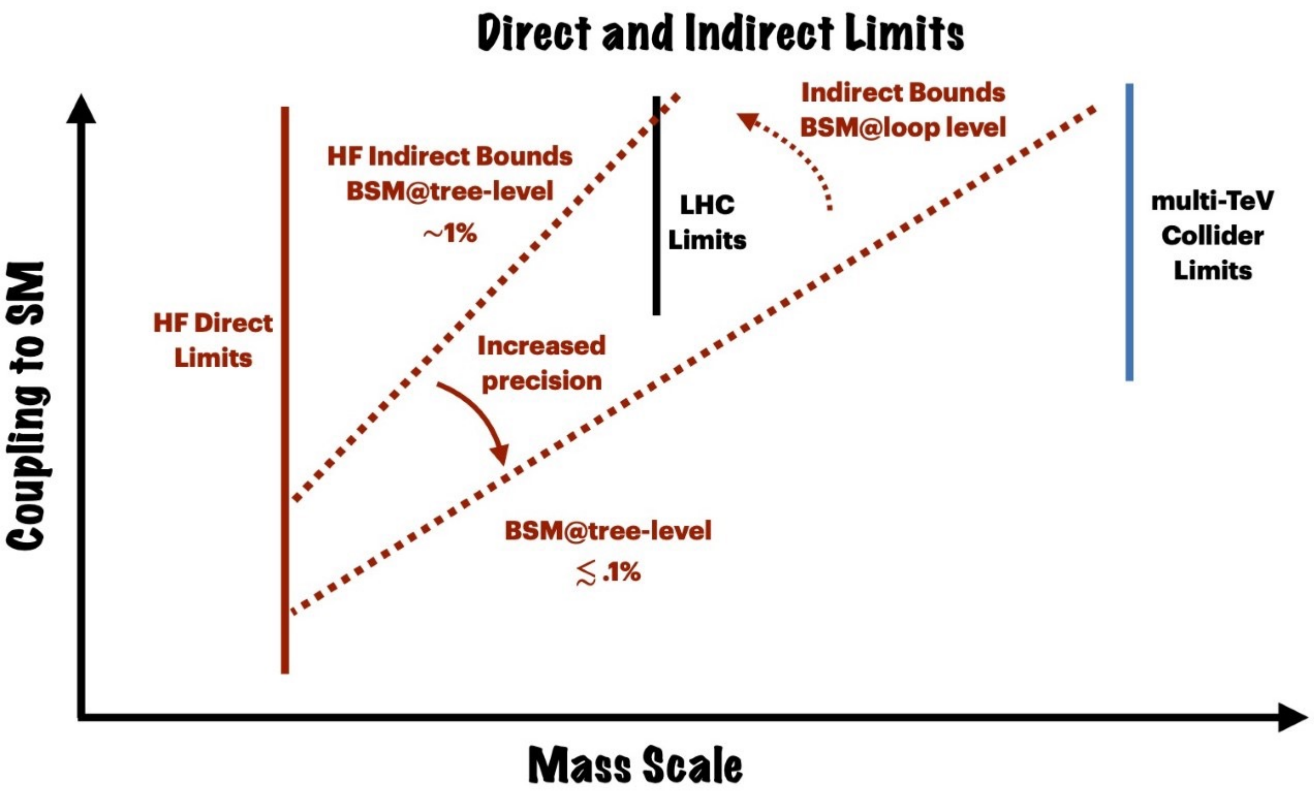
~$10^6$ ZH events @ ~240 GeV

+ Z pole @ 91.2 GeV
+ WW @ ~160 GeV
+ tt @ 360 GeV
+ ttH @550 GeV
+ … …

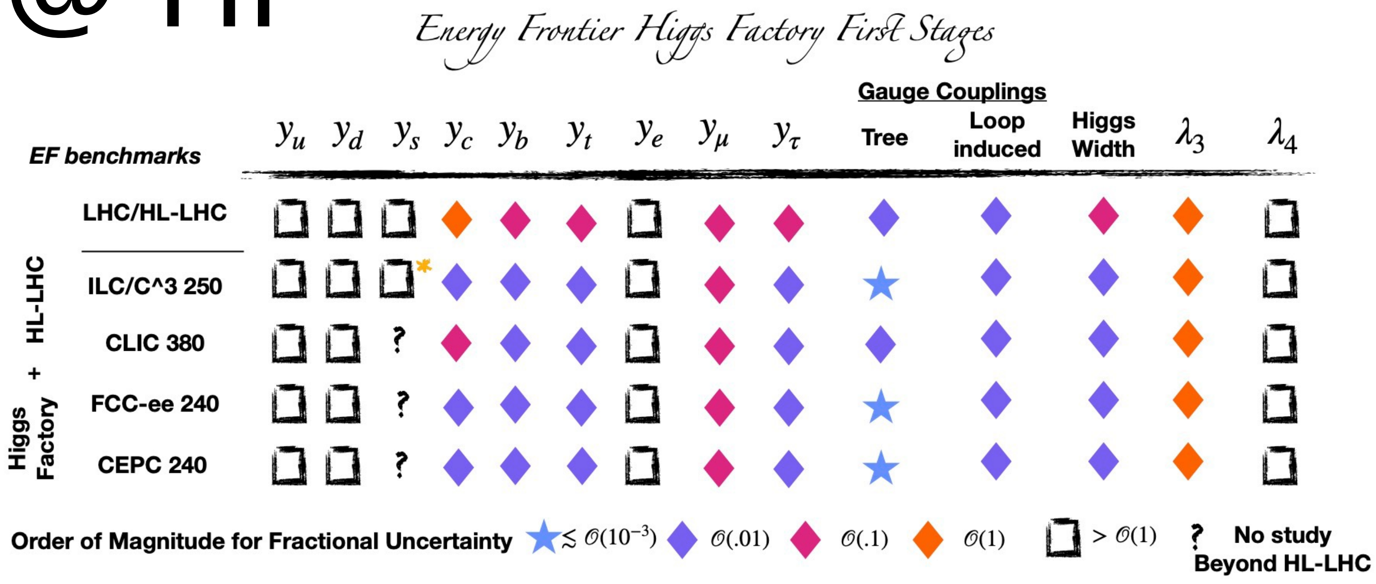


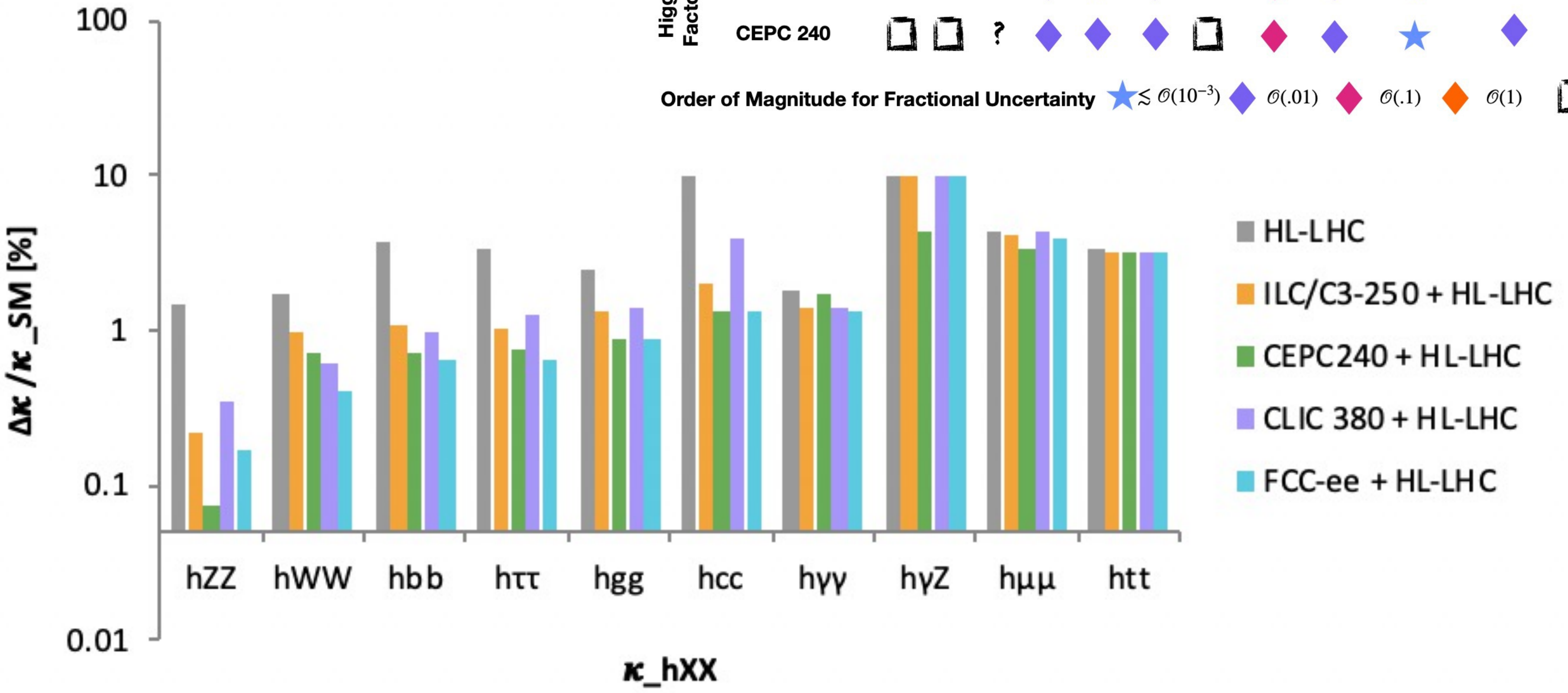
# Higgs factory and energy frontier



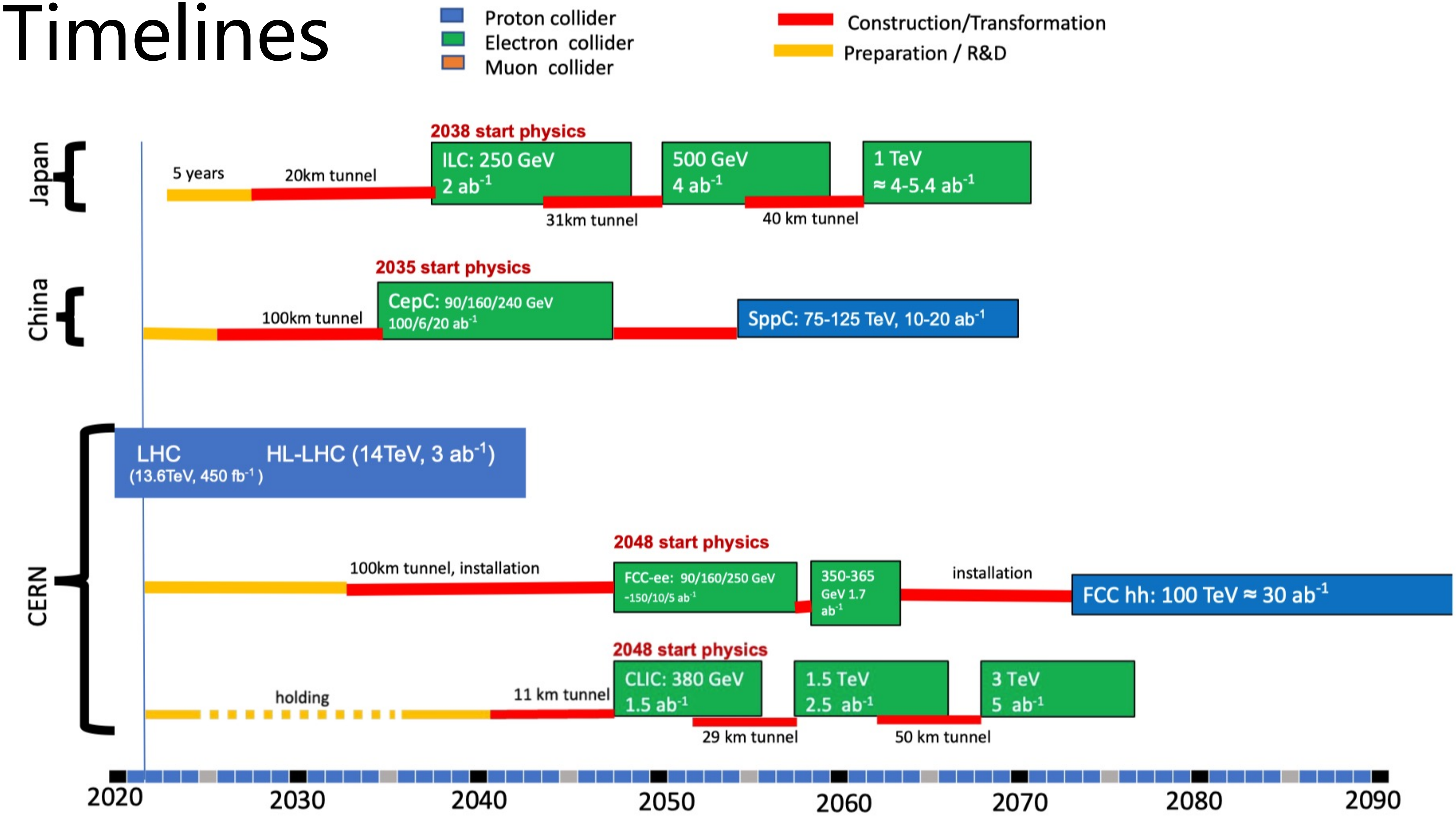



# Higgs couplings @ HF



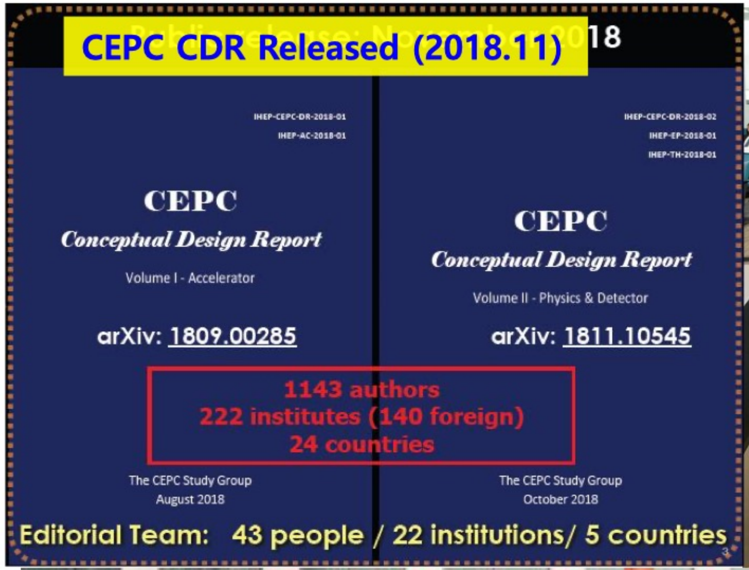



# Timelines



Proton collider
Electron collider
Muon collider
Construction/Transformation
Preparation / R&D
Japan
2038 start physics
5 years
20km tunnel
ILC: 250 GeV
2 ab-1
500 GeV
4 ab-1
1 TeV
≈ 4-5.4 ab-1
31km tunnel
40 km tunnel
China
2035 start physics
100km tunnel
CepC: 90/160/240 GeV
100/6/20 ab-1
SppC: 75-125 TeV, 10-20 ab-1
CERN
LHC
(13.6TeV, 450 fb-1 )
HL-LHC (14TeV, 3 ab-1)
2048 start physics
100km tunnel, installation
FCC-ee: 90/160/250 GeV
-150/10/5 ab-1
350-365
GeV 1.7
ab-1
installation
FCC hh: 100 TeV ≈ 30 ab-1
2048 start physics
holding
11 km tunnel
CLIC: 380 GeV
1.5 ab-1
1.5 TeV
2.5 ab-1
3 TeV
5 ab-1
29 km tunnel
50 km tunnel
2020
2030
2040
2050
2060
2070
2080
2090

# CEPC status






**The committee believes that the CDR has already reached a sufficient level of maturity to allow approval to proceed to a Technical Design Report……**

# CEPC Accelerator TDR International Review

Jun 12 – 16, 2023
IAS, HKUST
Asia/Hong_Kong timezone

Ent

- Overview
- Timetable
- Charge
- Participation Guide
- Accommodation
- Transportation

**Contact person**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Meeting URL 会议链接:: https://us06web.zoom.us/j/88529293870?pwd=ME01WGpxbzVzcDAzd01hQlFuY0RLZz09

Meeting ID 会议号: 88529293870

Password 会议密码: 335616

For the venue wireless connection, delegates might use "eduroam" with
details will also be posted in the meeting venue.

- SSID： eduroam
- Login ID: iasprogwifi
- Password: HKUST20#3Guest

**Starts** Jun 12, 2023, 9:00 AM
**Ends** Jun 16, 2023, 6:00 PM
Asia/Hong_Kong

IAS, HKUST

charge-cepc-T

Phase 1 Review of the CEPC Technical Design Report
June 12-16, 2023, HKUST, Hong Kong

## Charge

The CEPC Study Group, hosted by the Institute of High Energy Physics (IHEP), has been working on the design and development of a forefront $e^+e^-$ collider as a Higgs factory that can extend to energies corresponding to the Z, WW and the top quark pairs, with the upgrade potential to a high energy pp collider. The CEPC represents a grand plan proposed, studied, and to be constructed by Chinese scientists in close collaboration with international partners. Since the release of the CEPC Conceptual Design Report in 2018, the CEPC Study Group has devoted significant effort to the design optimization, the R&D of key technologies and the study of the technical systems of the CEPC.

The CEPC Study Group has produced a draft Technical Design Report (TDR). The International Review Committee, chaired by Dr. Frank Zimmermann (CERN) is asked to conduct the first phase review# of this TDR draft. This first phase review shall cover all but the cost and site aspects of the CEPC. The Committee is specifically asked to review and comment on the following aspects:

1. Are the accelerator system design goals well defined? Have the goals been reached in the TDR?
2. Are the accelerator physics issues adequately addressed?
3. Are the accelerator complex design, the key technologies adopted, and the conventional facilities effective for achieving the performance goals?
4. Are the CEPC operation modes and upgrade plans well defined?
5. Is the CEPC design compatible with the future upgrade to the SppC?
6. Regarding the key technology research and development, are critical technologies and components of the CEPC accelerator ready or will they be ready before 2026, through the R&D program being carried out, or achieved with the Light Source project undertaken by IHEP, for the eventual realization of the CEPC?
7. What are the primary technical risks and their potential impacts on the CEPC? What are the mitigation measures that should be taken?
8. Will the CEPC accelerator be ready for construction, after the completion of the outlined R&D program, and industrial and engineering preparation, as well as issues identified in item 7 above be properly addressed in due time?
9. Any other issues you notice or any improvements you may suggest.

# Progress towards TDR

New SC Lab Design (4500m²)

SC New Lab (PAPS) has been put to operation in June 2021

Crygenic system hall

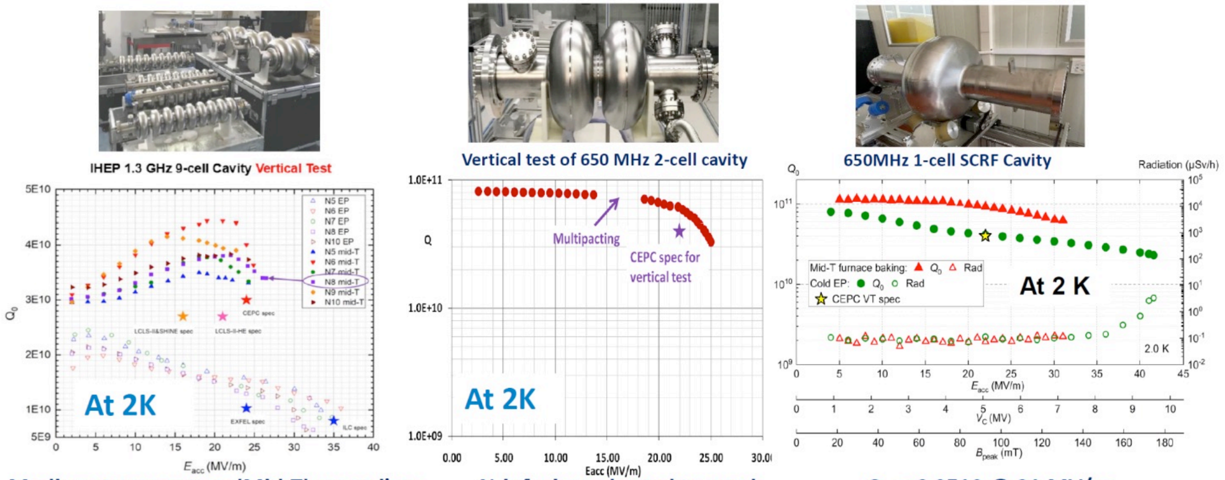


2023/7/1

Higgs factory - p

- 1.3 GHz 9-cell SCRF cavity for booster: $Q_0$ = 3.4E10 @ 26.5 MV/m
- 650 MHz 2-cell SCRF cavity for collider ring: $Q_0$ = 6.0E10 @ 22.0 MV/m
- 650 MHz 1-cell SCRF cavity for collider ring: $Q_0$ = 6.0E10 @ 31.0 MV/m

**All SCRF satisfied CEPC design specifications !**




Medium-temperature (Mid-T) annealing adopted to reach $Q_0$ = 3.4E10 @ 26.5 MV/m

N-infusion adopted to reach $Q_0$ = 6.0E10 @ 22.0 MV/m

$Q_0$ = 6.0E10 @ 31 MV/m
$Q_0$ = 2.1E10 @ 42 MV/m

**X.C Lou**

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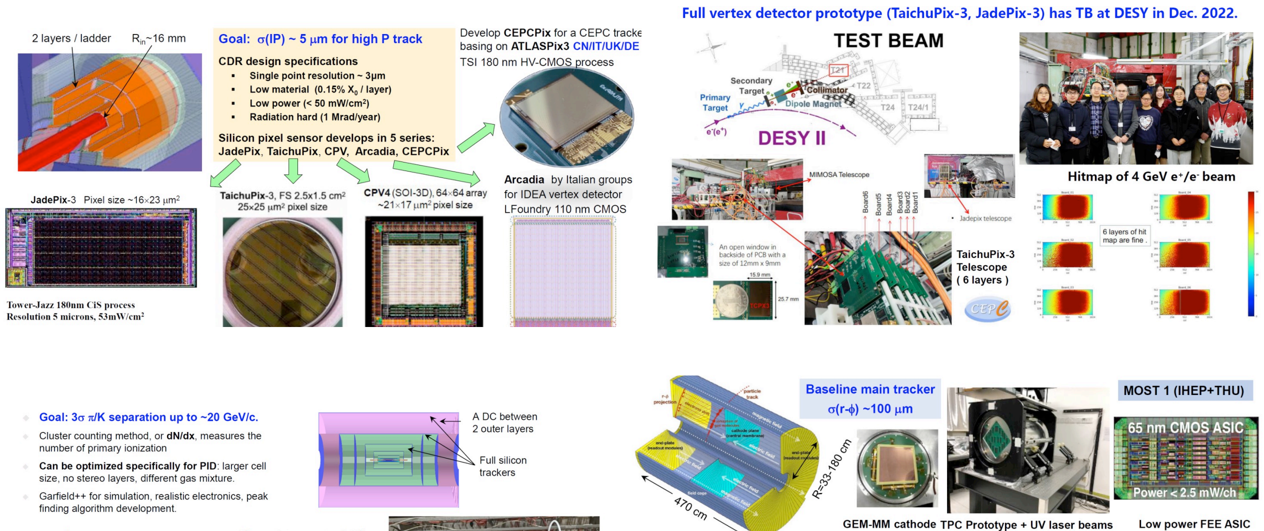


# The Evolution: from CDR to TDR

Yuhui Li

**Main Parameters (30MW)**

**CDR（2018）**

| | *Higgs* | *W* | *Z（3T）* | *Z（2T）* |
|---|---|---|---|---|
| Number of IPs | 2 | | | |
| Circumference (km) | 100 | | | |
| Bunch number | 242 | 1524 | 12000 | |
| β function at IP $\beta_x$* / $\beta_y$* (m/mm) | 0.36/1.5 | 0.36/1.5 | 0.2/1.5 | 0.2/1.0 |
| Emittance $e_x/e_y$ (nm/pm) | 1.21/3.1 | 0.54/1.6 | 0.18/4.0 | 0.18/1.6 |
| Energy acceptance (%) | 1.35 | 0.4 | 0.23 | |
| **Luminosity per IP ($10^{34}cm^{-2}s^{-1}$)** | **2.93** | **10.1** | **16.6** | **32.1** |

**TDR（2023）**

| | *Higgs* | *W* | *Z (2T)* | *ttbar* |
|---|---|---|---|---|
| Number of IPs | 2 | | | |
| Circumference (km) | 100.0 | | | |
| Bunch number | 268 | 1297 | 11934 | 35 |
| Beta functions at IP $\beta_x^*/\beta_y^*$ (m/mm) | 0.3/1 | 0.21/1 | 0.13/0.9 | 1.04/2.7 |
| Emittance $\varepsilon_x/\varepsilon_y$ (nm/pm) | 0.64/1.3 | 0.87/1.7 | 0.27/1.4 | 1.4/4.7 |
| Energy acceptance (%) | 1.6 | 1.0 | 1.0 | 2.0 |
| **Luminosity per IP ($10^{34}cm^{-2}s^{-1}$)** | **5.0** | **16** | **115** | **0.5** |

**Key technology R&D**

- **RF power supply and high efficiency klystron**
- **SRF cavities & modules (1.3G & 650MHz)**
- **Key components of the positron source**
- **High performance accelerator (S&C-band)**
- **Novel magnets: Weak field dipole, dual aperture magnets**
- **Injection/extraction**
- **Electrostatic deflector**
- **Vacuum chamber with NEG coating**
- **Instrumentation, Feedback system**
- **Cryogenic system**
- **Magnet power supply**

# Operational plan

Yuhui Li

| Particle | $E_{c.m.}$ (GeV) | Years | SR Power (MW) | Lumi. per IP ($10^{34}cm^{-2}s^{-1}$) | Integrated Lumi. per year ($ab^{-1}$, 2 IPs) | Total Integrated L ($ab^{-1}$, 2 IPs) | Total no. of events |
|---|---|---|---|---|---|---|---|
| H* | 240 | 10 | 50 | 8.3 | 2.2 | 21.6 | $4.3 \times 10^{6}$ |
| | | | 30 | 5 | 1.3 | 13 | $2.6 \times 10^{6}$ |
| Z | 91 | 2 | 50 | 192** | 50 | 100 | $4.1 \times 10^{12}$ |
| | | | 30 | 115** | 30 | 60 | $2.5 \times 10^{12}$ |
| W | 160 | 1 | 50 | 26.7 | 6.9 | 6.9 | $2.1 \times 10^{8}$ |
| | | | 30 | 16 | 4.2 | 4.2 | $1.3 \times 10^{8}$ |
| $t\bar{t}$ | 360 | 5 | 50 | 0.8 | 0.2 | 1.0 | $0.6 \times 10^{6}$ |
| | | | 30 | 0.5 | 0.13 | 0.65 | $0.4 \times 10^{6}$ |

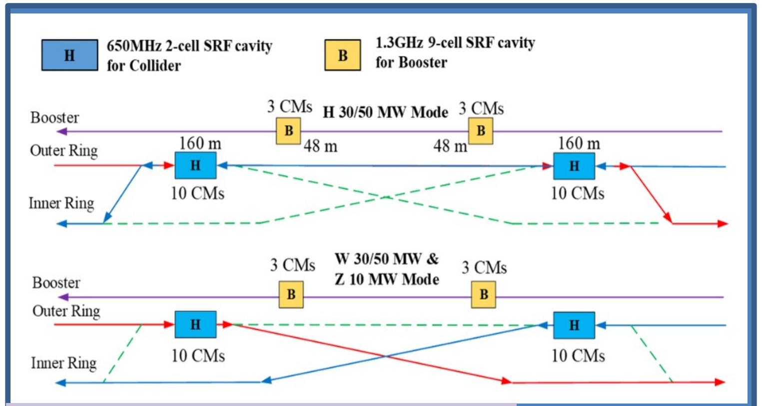
* Higgs is the top priority. The CEPC will commence its operation with a focus on Higgs.

** Detector solenoid field is 2 Tesla during Z operation, 3Tesla for all other energies.

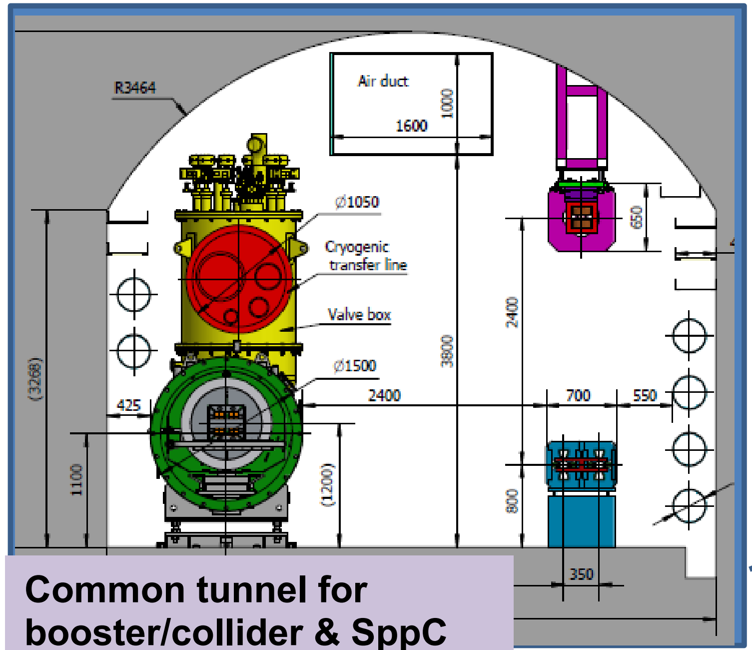
*** Calculated using 3,600 hours per year for data collection.

# CEPC layout and design essentials

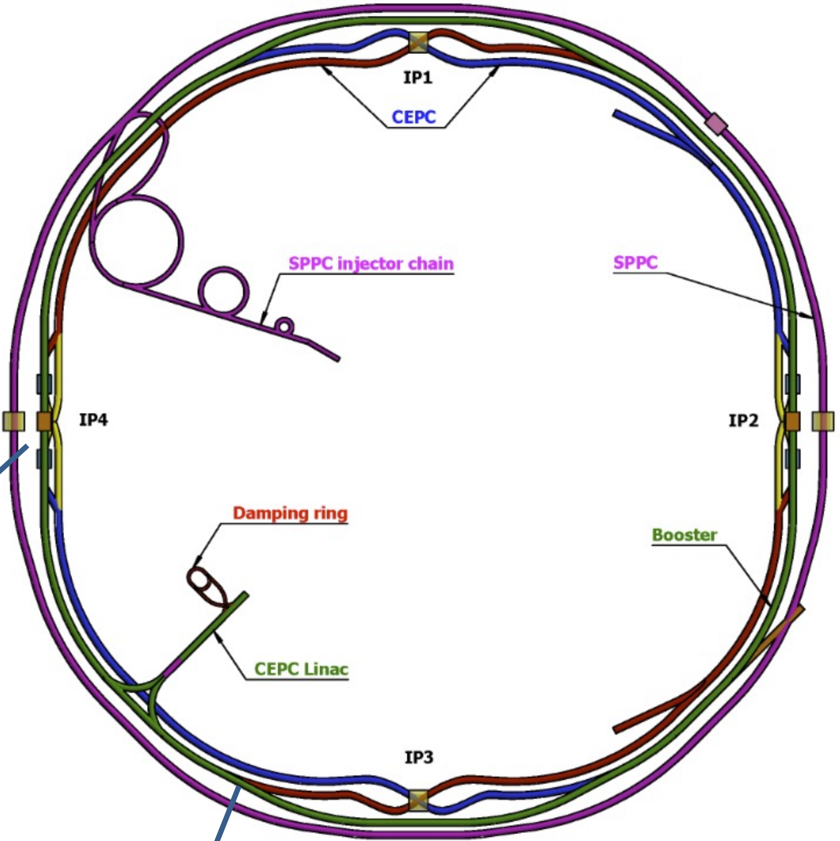
Yuhui Li



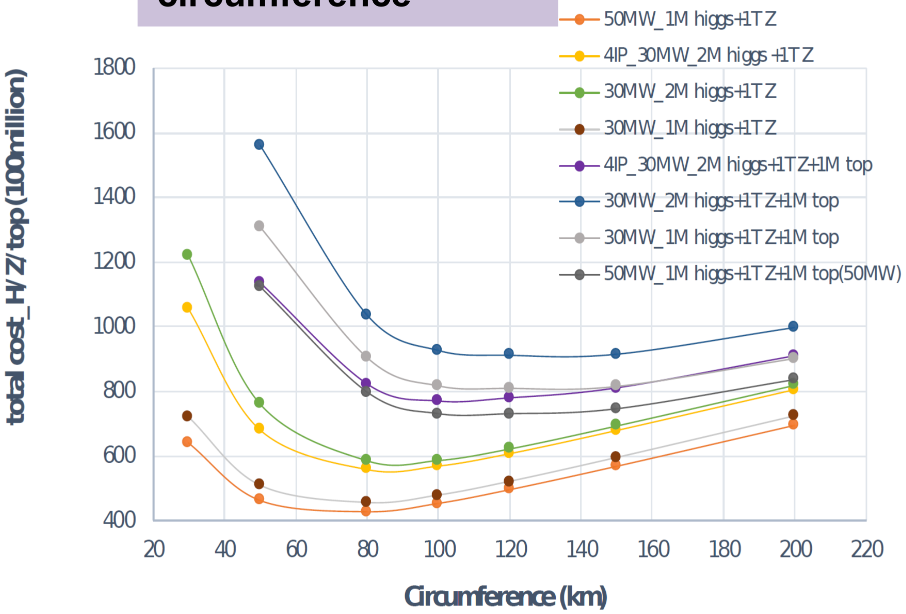

Switchable operation for Higgs W and Z




Common tunnel for booster/collider & SppC




Cost optimization v.s. circumference




D. Wang *et al* 2022 *JINST* **17** P10018

- **Circular collider**: Higher luminosity than a linear collider
- **100km circumference**: Optimum total cost
- **Shared tunnel**: Compatible design for CEPC and SppC
- **Switchable operation**: Higgs, W/Z, top

# Key technology R&D

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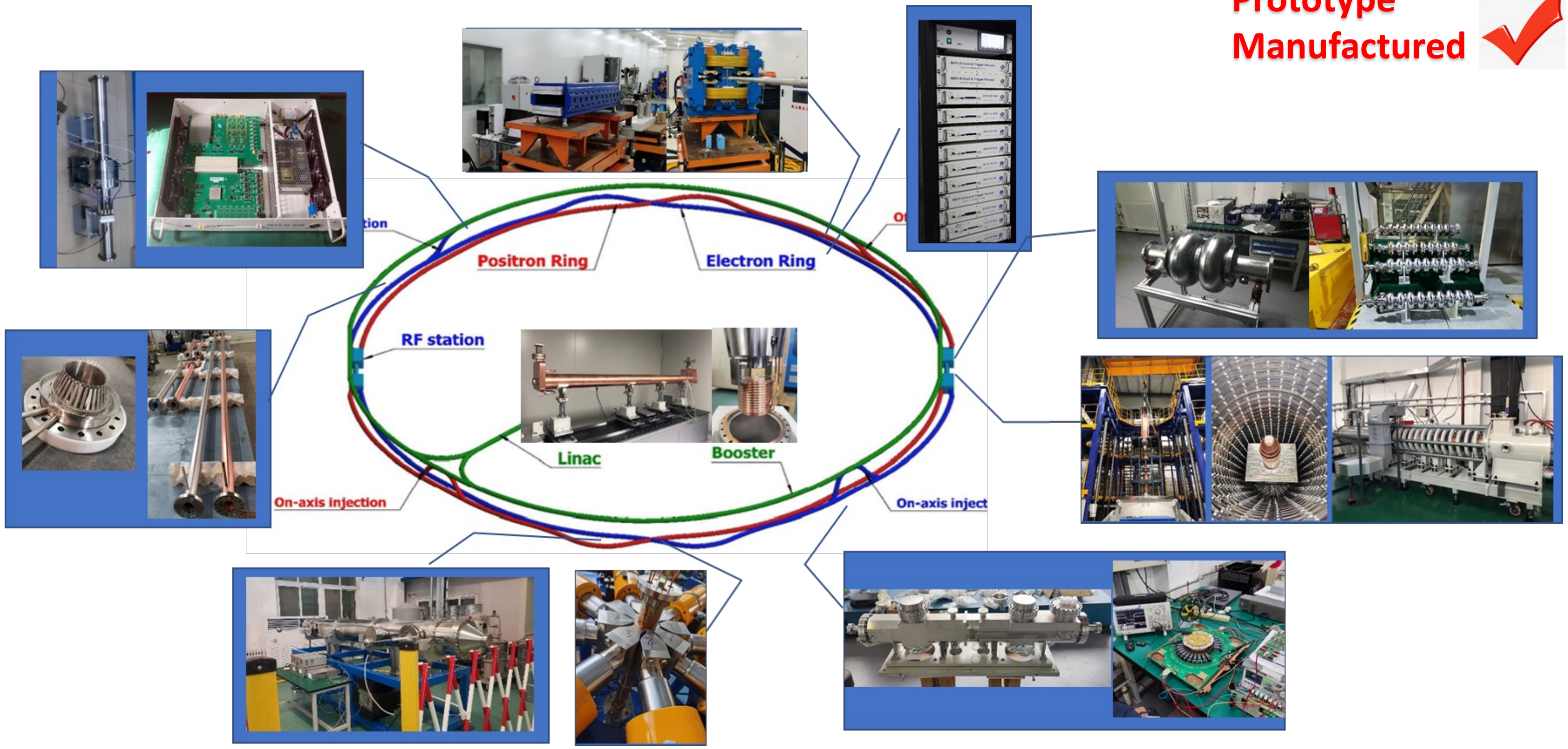
**Represented Key Technologies for the CEPC**




Specification Met ✓ (green)

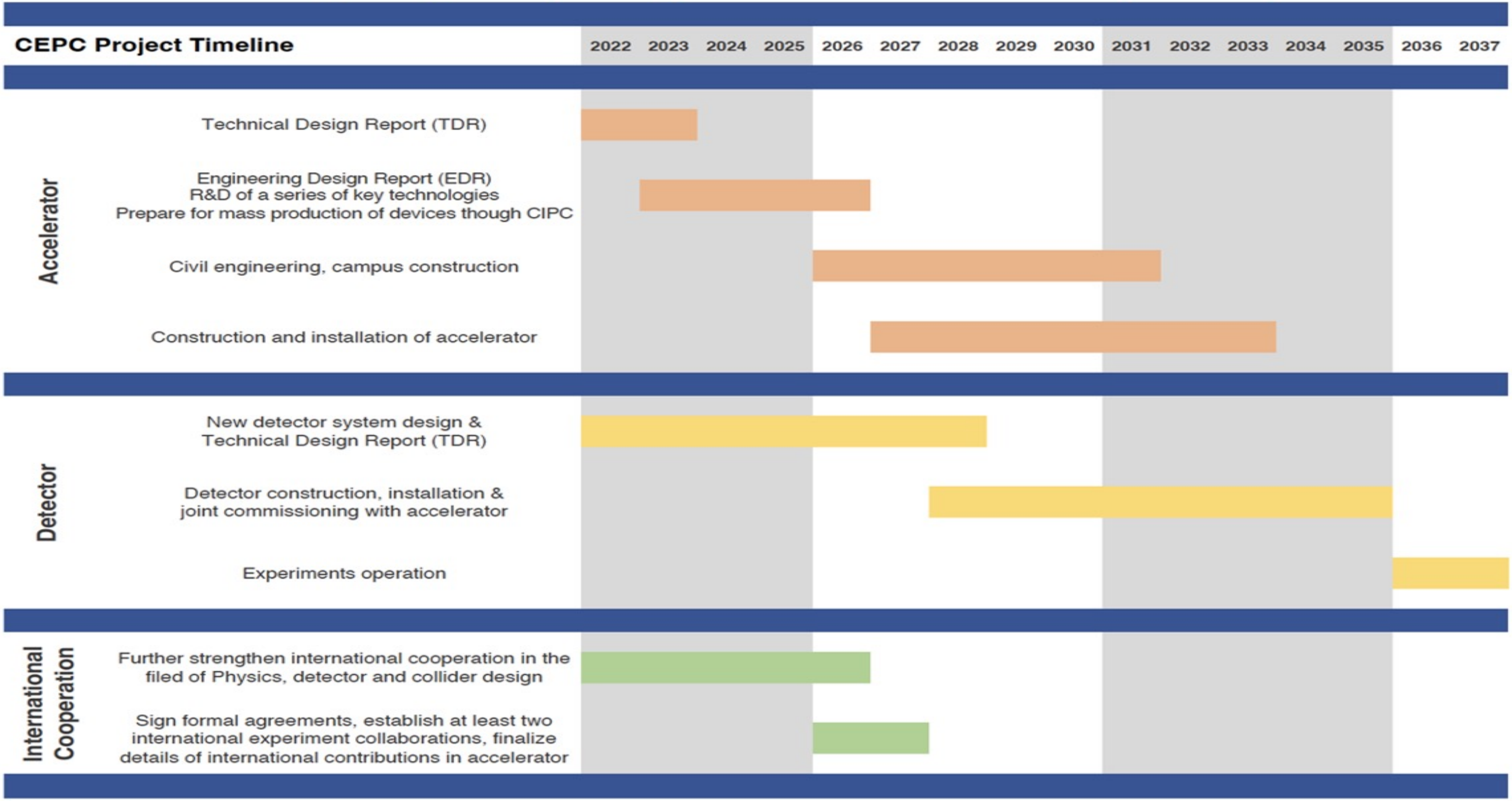
Prototype Manufactured ✓ (red)

| Accelerator | Fraction |
|---|---|
| ✓ Magnets | 27.3% |
| ✓ Vacuum | 18.3% |
| ✓ (red) RF power source | 9.1% |
| ✓ Mechanics | 7.6% |
| ✓ Magnet power supplies | 7.0% |
| ✓ SC RF | 7.1% |
| ✓ Cryogenics | 6.5% |
| ✓ Linac and sources | 5.5% |
| ✓ Instrumentation | 5.3% |
| ✓ (red) Control | 2.4% |
| ✓ (red) Survey and alignment | 2.4% |
| ✓ Radiation protection | 1.0% |
| ✓ (red) SC magnets | 0.4% |
| ✓ Damping ring | 0.2% |

Key technology R&D spans all component lists in CEPC CDR

# TDR (2023), EDR(2026), start of construction (2027-8)

X.C Lou

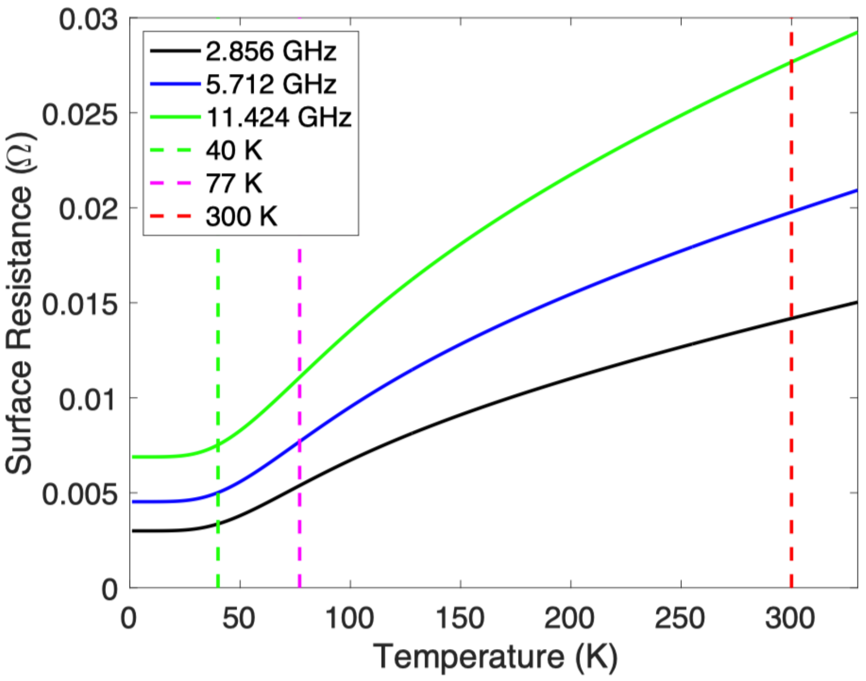


# $C^3$ – Cool Copper Collider


NLC / TESLA → ILC

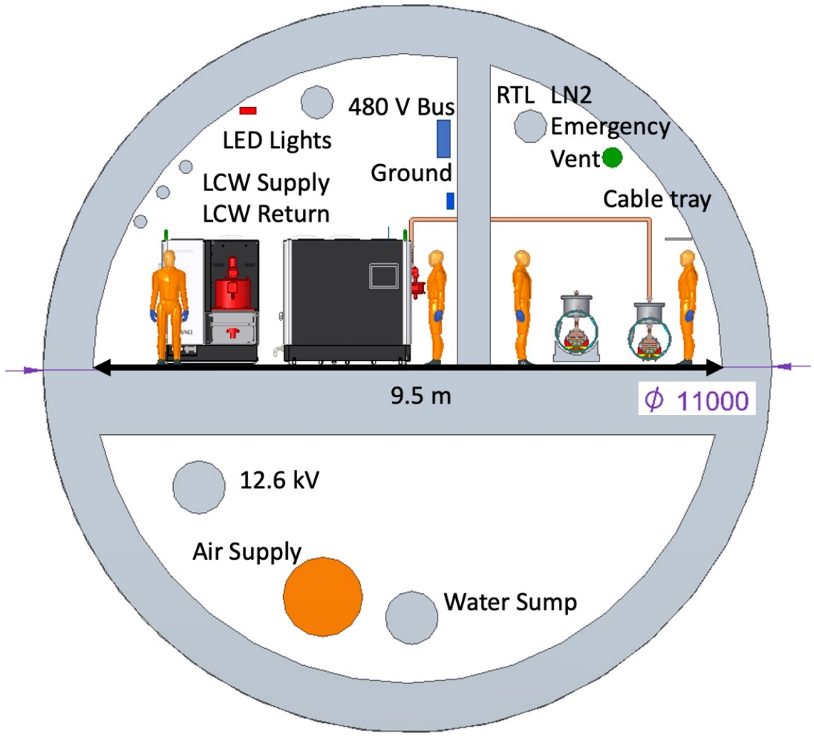
↓

$C^3$ (NLC in 77K)

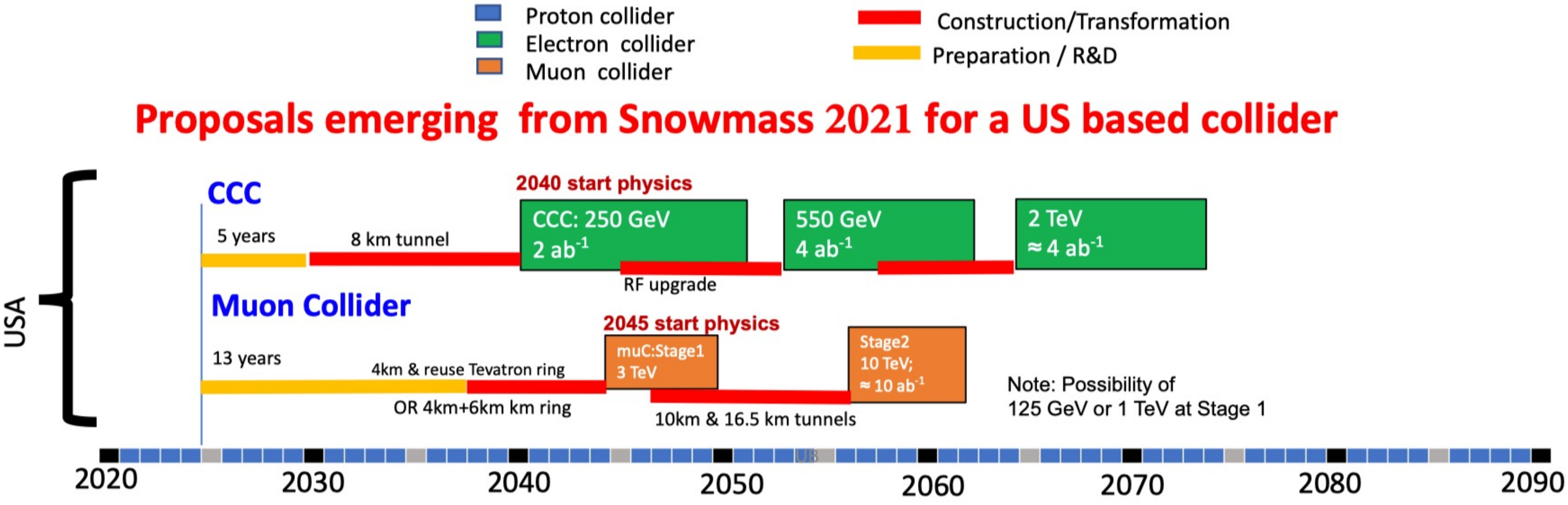


# C³ as next linear collider

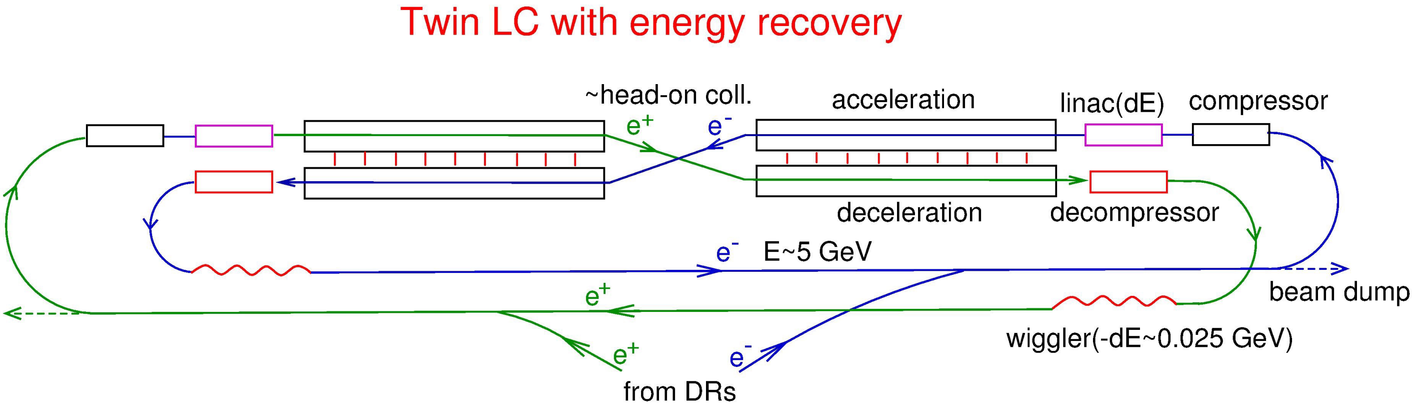
| Collider | NLC[28] | CLIC[29] | ILC[5] | $C^3$ | $C^3$ |
|---|---|---|---|---|---|
| CM Energy [GeV] | 500 | 380 | 250 (500) | 250 | 550 |
| $\sigma_z$ [$\mu$m] | 150 | 70 | 300 | 100 | 100 |
| $\beta_x$ [mm] | 10 | 8.0 | 8.0 | 12 | 12 |
| $\beta_y$ [mm] | 0.2 | 0.1 | 0.41 | 0.12 | 0.12 |
| $\epsilon_x$ [nm-rad] | 4000 | 900 | 500 | 900 | 900 |
| $\epsilon_y$ [nm-rad] | 110 | 20 | 35 | 20 | 20 |
| Num. Bunches per Train | 90 | 352 | 1312 | 133 | 75 |
| Train Rep. Rate [Hz] | 180 | 50 | 5 | 120 | 120 |
| Bunch Spacing [ns] | 1.4 | 0.5 | 369 | 5.26 | 3.5 |
| Bunch Charge [nC] | 1.36 | 0.83 | 3.2 | 1 | 1 |
| Beam Power [MW] | 5.5 | 2.8 | 2.63 | 2 | 2.45 |
| Crossing Angle [rad] | 0.020 | 0.0165 | 0.014 | 0.014 | 0.014 |
| Crab Angle | 0.020/2 | 0.0165/2 | 0.014/2 | 0.014/2 | 0.014/2 |
| Luminosity [x$10^{34}$] | 0.6 (w/ IP dil.) | 1.5 (max is 4) | 1.35 | 1.3 | 2.4 |
| Gradient [MeV/m] | 37 | 72 | 31.5 | 70 | 120 |
| Effective Gradient [MeV/m] | 29 | 57 | 21 | 63 | 108 |
| Shunt Impedance [MΩ/m] | 98 | 95 | | 300 | 300 |
| Effective Shunt Impedance [MΩ/m] | 50 | 39 | | 300 | 300 |
| Site Power [MW] | 121 | 168 | 125 | ~150 | ~175 |
| Length [km] | 23.8 | 11.4 | 20.5 (31) | 8 | 8 |
| L* [m] | 2 | 6 | 4.1 | 4.3 | 4.3 |

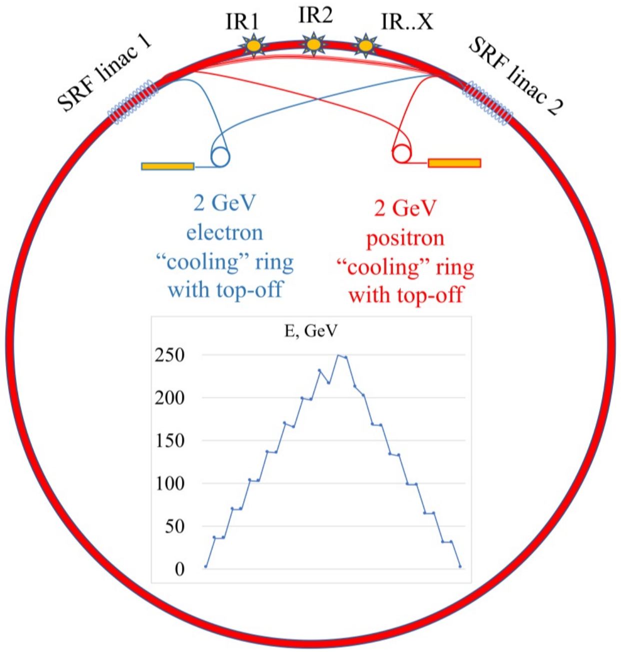


# A collider in US?



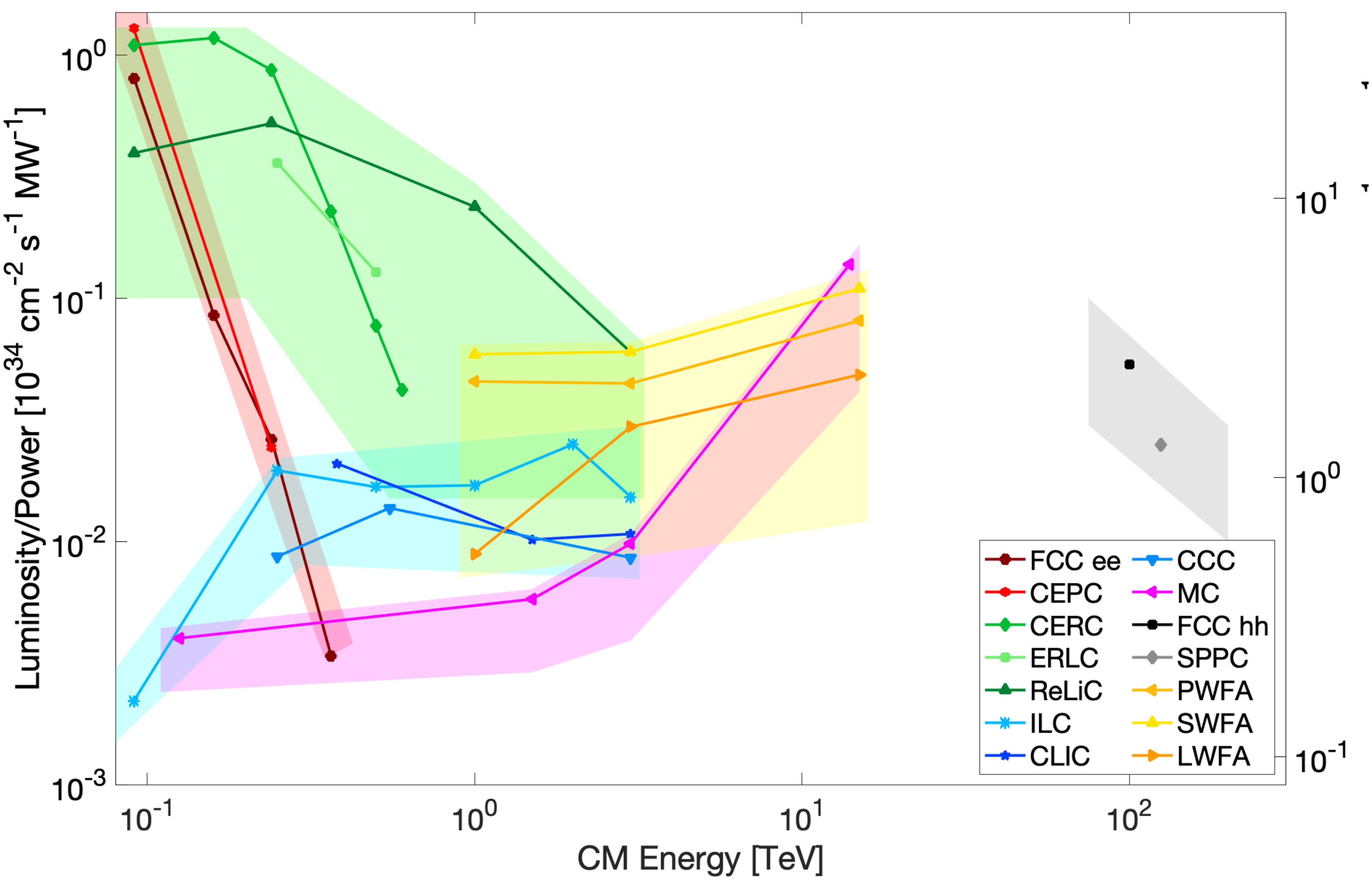
# Energy recovery




LHC: 120 MW
ALL: 230 MW

| Proposal Name | Power Consumption | Size |
|---|---|---|
| FCC-ee (0.24 TeV) | 290 | 91 km |
| CEPC (0.24 TeV) | 340 | 100 km |
| ILC (0.25 TeV) | 140 | 20.5 km |
| CLIC (0.38 TeV) | 110 | 11.4 km |
| CCC (0.25 TeV) | 150 | 3.7 km |
| CERC (0.24 TeV) | 90 | 91 km |
| ReLiC (0.24 TeV) | 315 | 20 km |
| ERLC (0.24 TeV) | 250 | 30 km |
| XCC (0.125 TeV) | 90 | 1.4 km |
| MC (0.13 TeV) | 200 | 0.3 km |
| ILC (3 TeV) | ~400 | 59 km |
| CLIC (3 TeV) | ~550 | 50.2 km |
| CCC (3 TeV) | ~700 | 26.8 km |
| ReLiC (3 TeV) | ~780 | 360 km |
| MC (3 TeV) | ~230 | 10-20 km |
| LWFA (3 TeV) | ~340 | 1.3 km (linac) |
| PWFA (3 TeV) | ~230 | 14 km |
| SWFA (3 TeV) | ~170 | 18 km |
| MC (14 TeV) | ~300 | 27 km |
| LWFA (15 TeV) | ~1030 | 6.6 km |
| PWFA (15 TeV) | ~620 | 14 km |
| SWFA (15 TeV) | ~450 | 90 km |
| FCC-hh (100 TeV) | ~560 | 91 km |
| SPPC (125 TeV) | ~400 | 100 km |



Luminosity/Power [$10^{34}$ cm$^{-2}$ s$^{-1}$ MW$^{-1}$]
$10^{0}$
$10^{-1}$
$10^{-2}$
$10^{-3}$
$10^{1}$
$10^{0}$
$10^{-1}$
$10^{-1}$
$10^{0}$
$10^{1}$
$10^{2}$
CM Energy [TeV]
FCC ee
CEPC
CERC
ERLC
ReLiC
ILC
CLIC
CCC
MC
FCC hh
SPPC
PWFA
SWFA
LWFA

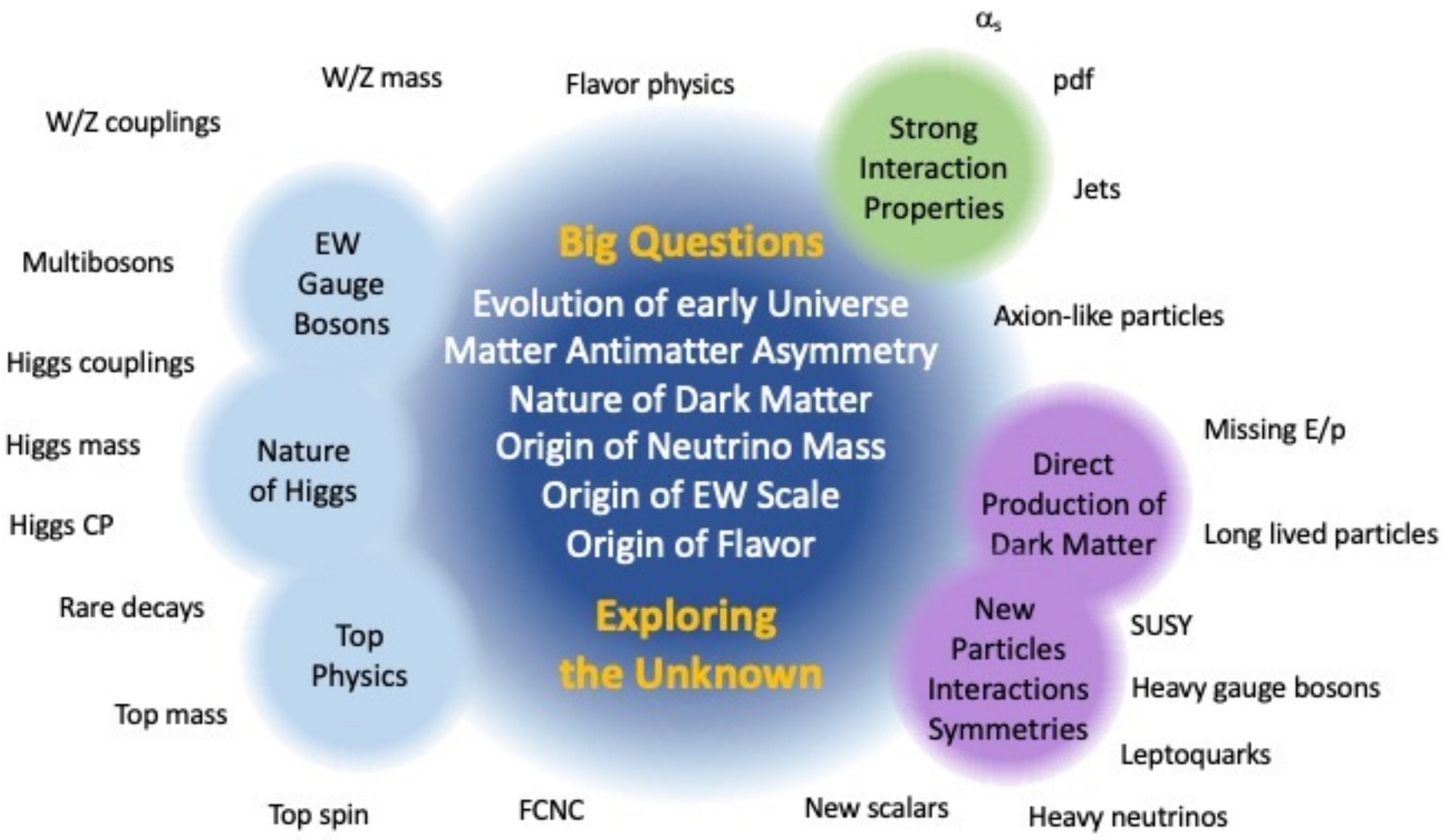
# The future of particle physics is bright !

暗物质，暗能量...

标准模型

Higgs factory
pp collider
ep collider
...

凝聚态，生物...


αs
W/Z mass
Flavor physics
pdf
W/Z couplings
Strong Interaction Properties
Jets
EW Gauge Bosons
Big Questions
Multibosons
Evolution of early Universe
Matter Antimatter Asymmetry
Nature of Dark Matter
Origin of Neutrino Mass
Origin of EW Scale
Origin of Flavor
Axion-like particles
Higgs couplings
Nature of Higgs
Higgs mass
Missing E/p
Direct Production of Dark Matter
Higgs CP
Long lived particles
Rare decays
Top Physics
Exploring the Unknown
New Particles Interactions Symmetries
SUSY
Heavy gauge bosons
Top mass
Leptoquarks
Top spin
FCNC
New scalars
Heavy neutrinos

A single Interaction Point: In addition to a reduced cost with only one detector, this has several accelerator physics advantages which include:

20 – a larger bending radius ρ in the arc cells

– total beam-beam effects (tune shift, beamsstrahlung, Bhabha scattering) are minimized;

– the IR chromaticity is reduced, which will increase the momentum acceptance and consequently the beam lifetime.

• Very small vertical beam size at the IP (0.2 μ m).

• Large number of particles distributed into two bunches for maximizing the luminosity. The single bunch intensity must respect limits set by the Transverse Mode Coupling Instability (TMCI) and by the allowable beam-beam tune shift.

• Head-on collisions for operational simplicity and cost reduction.

# An e + e − circular collider at Fermilab

| | Higgs Factory | Z factory |
|---|---|---|
| Circumference [km] | 16 | 16 |
| Beam energy [GeV] | 120 | 45.6 |
| Total synchrot… | | |
| Beam current … | | |
| $N$ $[10^{11}]$ | | |
| Number of bu… | | |
| $\beta_x^*$ [m] / $\beta_y^*$ | | |
| $\epsilon_x$ / $\epsilon_y$ [nm] | | |
| $\sigma_z$ [mm] | | |
| beam-beam tu… | | |
| RF frequency … | | |
| RF voltage [G… | | |
| Momentum ac… | | |
| $\tau_{bs}$ [min] | | |
| $\tau_{Bhabha}$ [min] | | |
| $\mathcal{L}$ per IP $[10^{34}$… | | |
| Production cr… | | |
| Particle produ… | | |

Table 1: Par…