Rencontres du Vietnam

Future High Energy Physics in China

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IHEP, Beijing

Outline

- Introduction
- Frontiers, Status and Plans
  - Neutrino: JUNO
  - Intensity: BESIII at BEPCII, STCF
  - Energy/Intensity: CEPC
- Summary

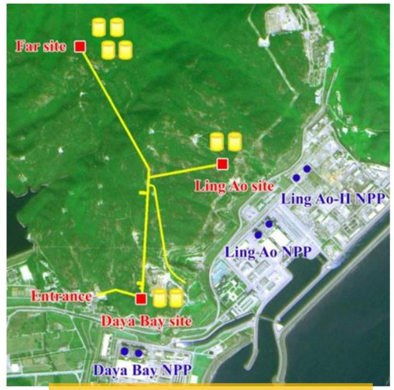
Introduction

Three frontiers

previous/current → **future**

Neutrino

Daya Bay (2011-22)

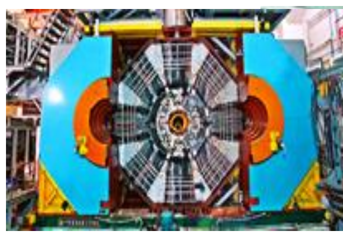


Running: 24 Dec 2011 – 12 Dec 2022

JUNO (2024-)

Intensity

BESIII@BEPCII



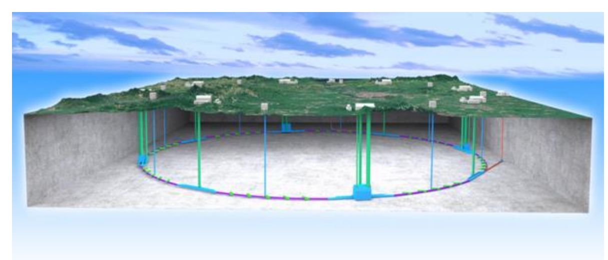
BEPCII-U

STCF (~2030-)

Energy

participation in **ATLAS/CMS**

Participations in the LHC experiments



CEPC (~2036-)

Introduction

Dedicated presentations at this conference (Tuesday)

JUNO

S. KUMARAN

The JUNO Experiment: Current Status and Prospects

BESIII@BEPCII

F. Bianchi

Highlights from BESIII

STCF

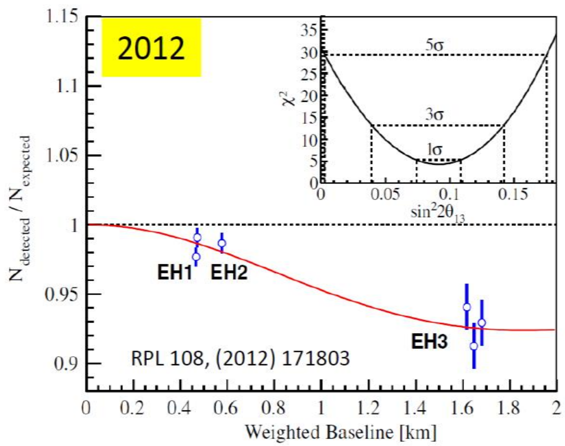
X. R. ZHOU

The Progress of Super Tau-Charm Facility in China

Neutrino frontier – Daya Bay

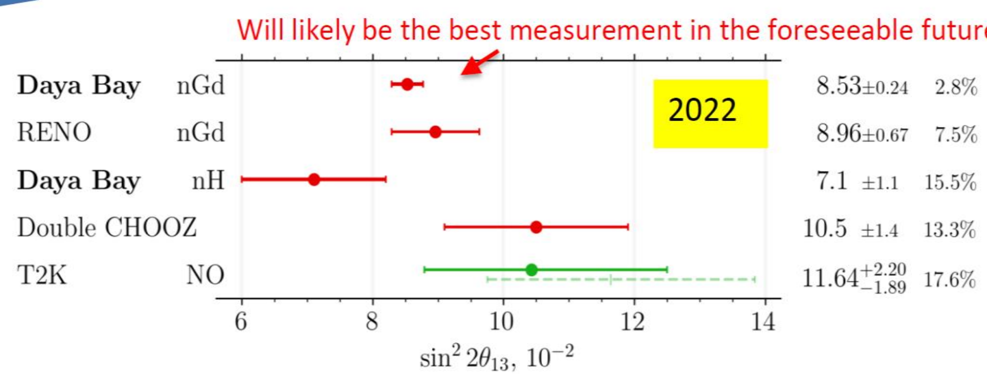
Completed in 2022

Running: 24 Dec 2011 – 12 Dec 2022



- Precision oscillation measurement
  - $\sin^2 2\theta_{13}$ precision : 2.8%
  - Δm^2_{32} precision : 2.3% (under either mass ordering scenario)
- Precise reactor $\bar{\nu}_e$ flux & spectrum meas.
  - "Reactor Anomaly" is likely due to model prediction problems
  - First evidence of reactor $\bar{\nu}_e$ with E>10 MeV
  - Provide model independent $\bar{\nu}_e$ spectrum for other experiments

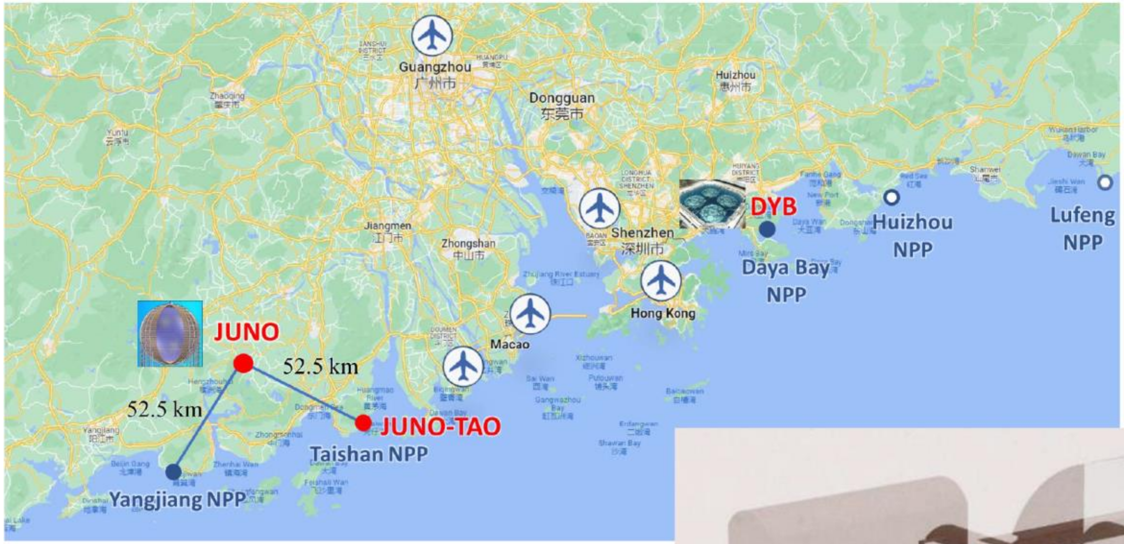
Daya Bay Mission Completion Ceremony (2020.12)

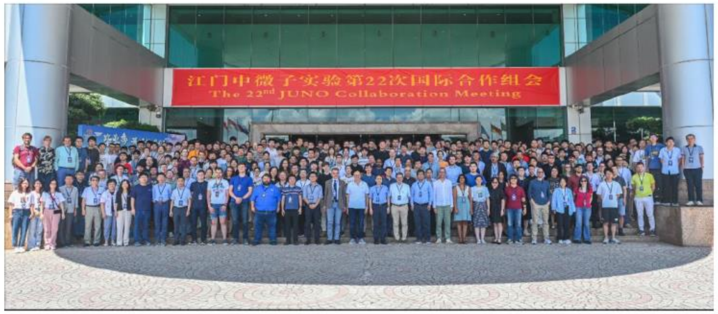


Neutrino frontier - JUNO

Jiangmen Underground Neutrino Observatory

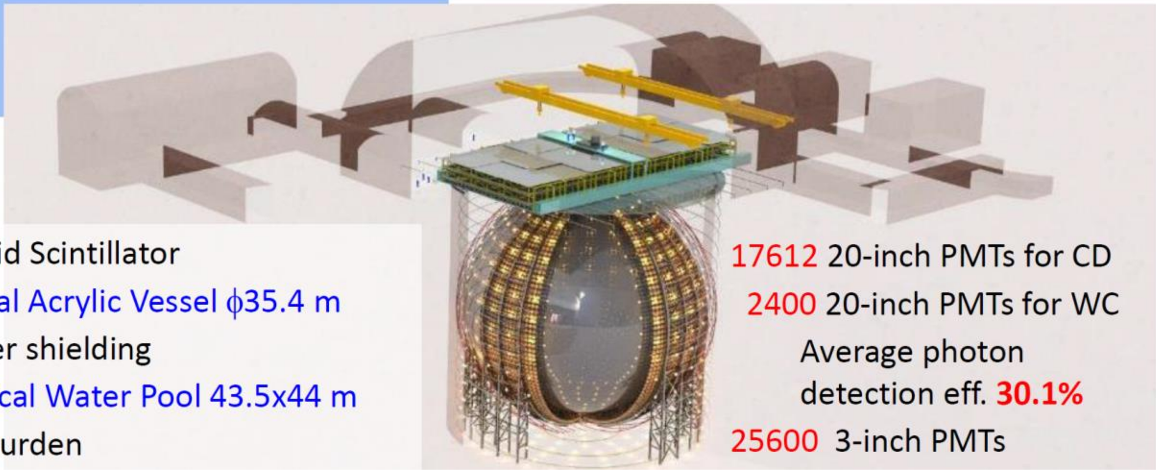
approved in 2013, civil construction began in 2015; data expected in 2024





JUNO collaboration: >700 collaborators,
74 institutions, 17 countries/regions

Yangjiang NPP: 2.9 GW x 6
Taishan NPP: 4.6 GW x 2
Equal baseline: 52.5 km



20 kton Liquid Scintillator

Spherical Acrylic Vessel ϕ35.4 m

35 kton water shielding

Cylindrical Water Pool 43.5x44 m

700 m overburden

17612 20-inch PMTs for CD

2400 20-inch PMTs for WC

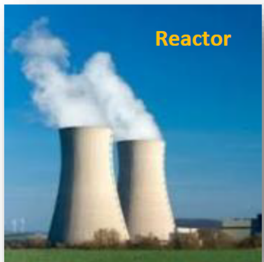
Average photon detection eff. **30.1%**

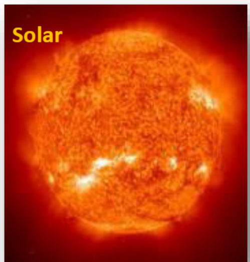
25600 3-inch PMTs

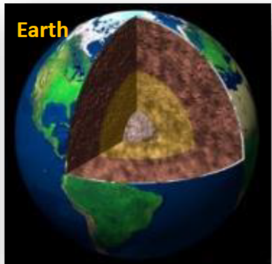
Liangjian Wen

Neutrino frontier - JUNO

Jiangmen Underground Neutrino Observatory
a multiple purpose neutrino observatory







\+ New physics

Prog. Part. Nucl. Phys. 123, 103927 (2022)

~60 IBDs per day | Several per day | Hundreds per day | ~5000 IBDs for CCSN @10 kpc | Several IBDs per day

IBD: inverse beta decay
CCSN: core-collapse supernova
DSNB: Diffused Supernova Neutrino Background

Neutrino oscillation & properties

Neutrinos as a probe

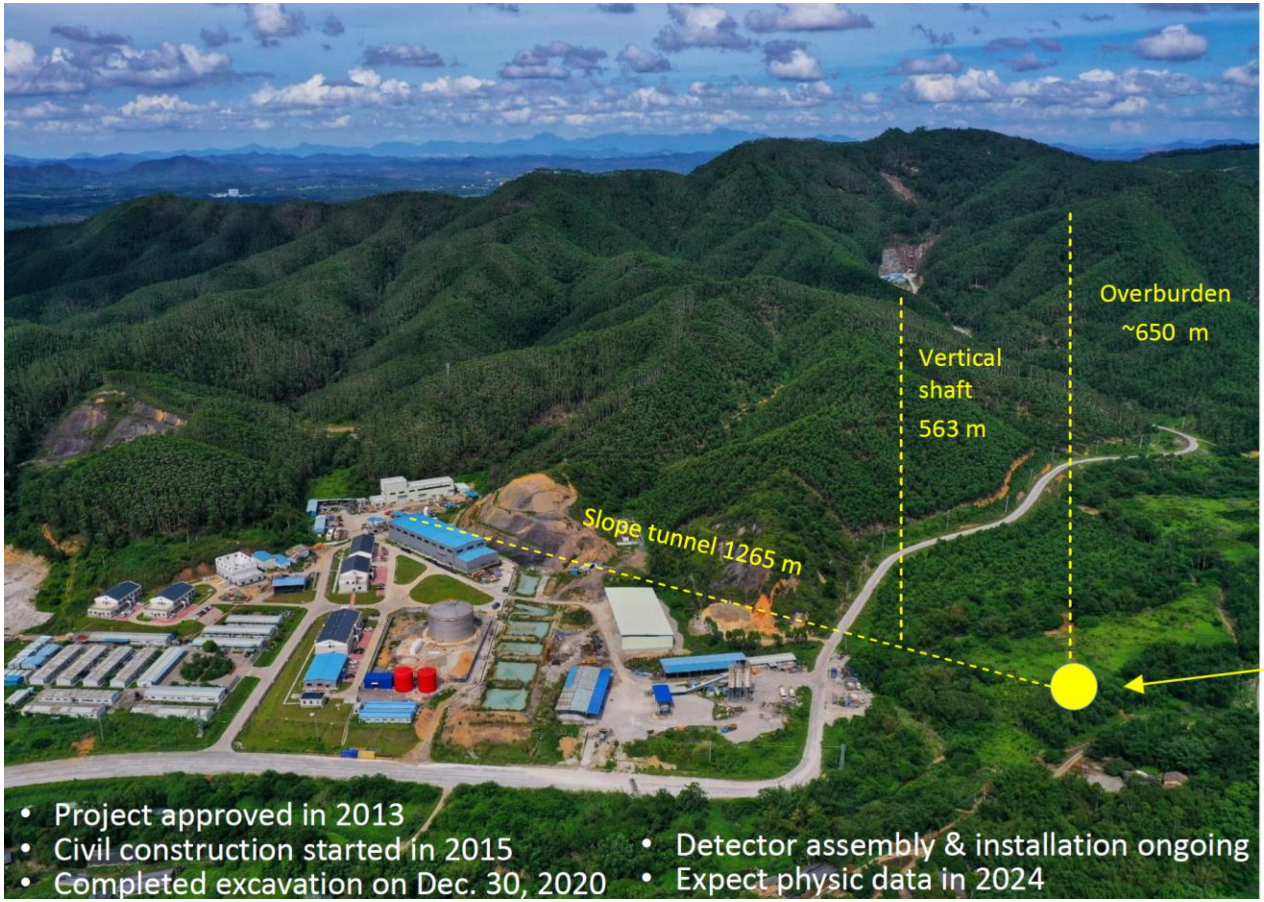
- Energy resolution **2.95%** @ 1MeV w/ full simulation
- **ν mass ordering: 3σ (reactor only)** @ ~6 yrs (Neutrino 2022), atmospheric ν oscillation being improved
- **ν oscillation parameters:** precision of $\sin^2\theta_{12}$, Δm^2_{21}, $|\Delta m^2_{31}|$ **< 0.5%** in 6 yrs (2204.13249)

- **Supernova** ν: ~7300 of all-flavor neutrinos @ 10 kpc
- **DSNB**: **3σ** in 3 yrs (2205.08830)
- **Solar** ν:
  - ^{7}Be, pep, CNO (2303.03910)
  - ^{8}B flux (2210.08437)
- **Geo** ν: ~400 per year, 8% measurement in 10 yrs

- **Nucleon Decays**: $p \rightarrow \bar{\nu} K^+$ 9.6×10^{33} yrs (90% C.L.) in 10 yrs (2212.08502), neutron invisible decay (ongoing)
- **Indirect DM search:** ~good sensitivity in 15-100 MeV region (2306.09567)
- **Future upgrade (2030s) : searching for 0νββ**

Neutrino frontier - JUNO

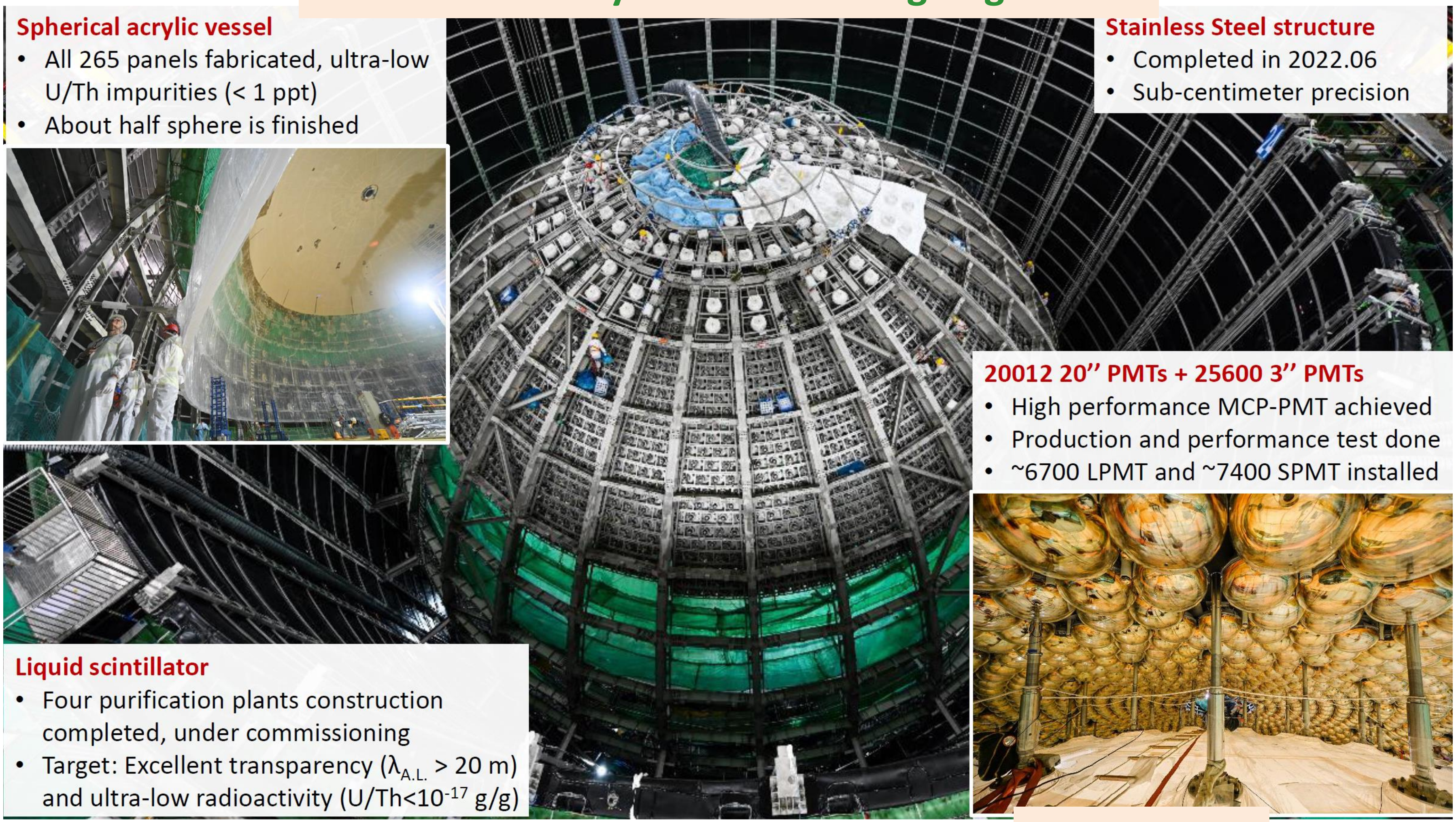
Jiangmen Underground Neutrino Observatory
approved in 2013, civil construction began in 2015; data expected in 2024



Liangjian Wen

Neutrino frontier - JUNO

Jiangmen Underground Neutrino Observatory
assembly and test are ongoing



Spherical acrylic vessel
- All 265 panels fabricated, ultra-low U/Th impurities (< 1 ppt)
- About half sphere is finished

Stainless Steel structure
- Completed in 2022.06
- Sub-centimeter precision

20012 20'' PMTs + 25600 3'' PMTs
- High performance MCP-PMT achieved
- Production and performance test done
- ~6700 LPMT and ~7400 SPMT installed

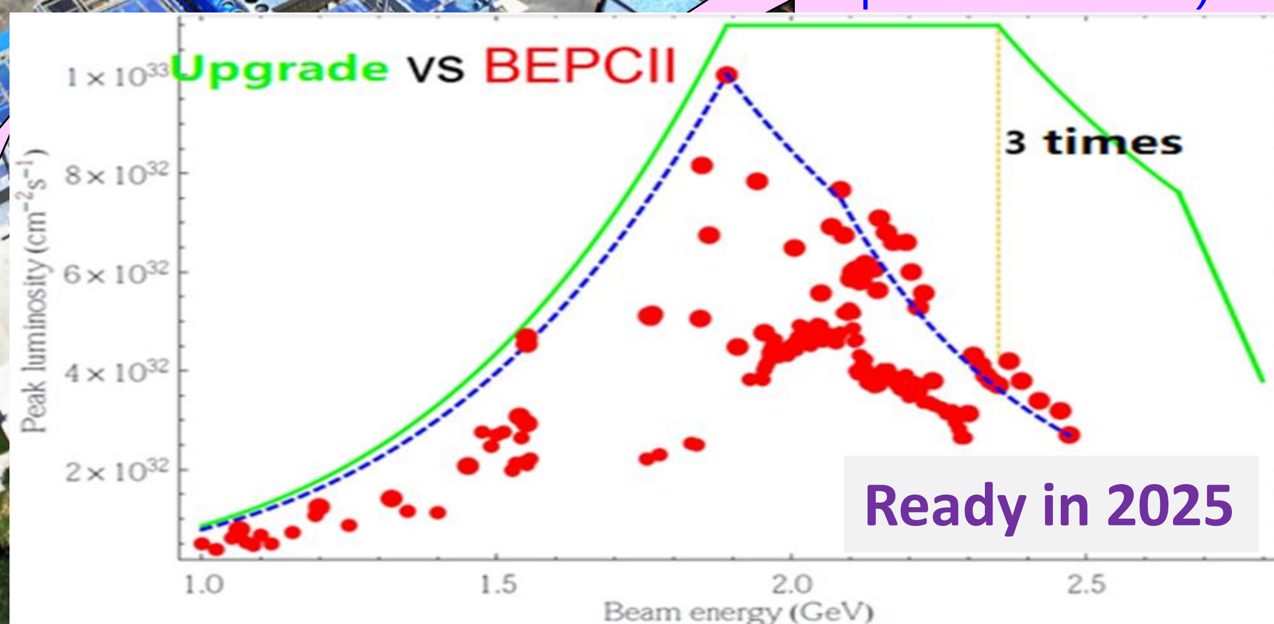
Liquid scintillator
- Four purification plants construction completed, under commissioning
- Target: Excellent transparency ($\lambda_{A.L.} > 20$ m) and ultra-low radioactivity (U/Th<10^{-17} g/g)

Intensity frontier - BEPCII & upgrade

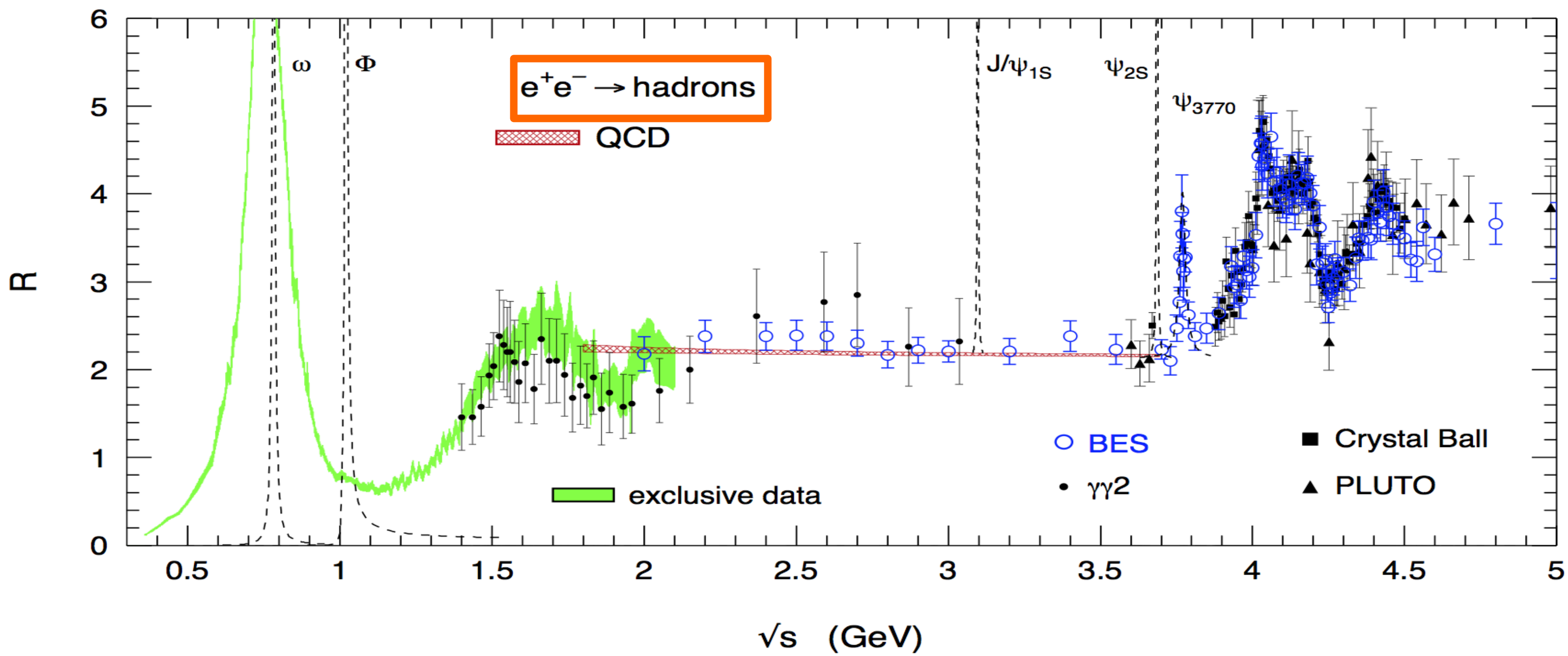
Center-of-mass energy
2.0 - 4.6 GeV

1989 - 2005 (BEPC):
$L_{peak}=1.0\times10^{31}$ /cm^{2}s

2008 - (BEPCII):
$L_{peak}=1.0\times10^{33}$/cm^{2}s
(Apr. 5, 2016)



Intensity - BEPCII & upgrade



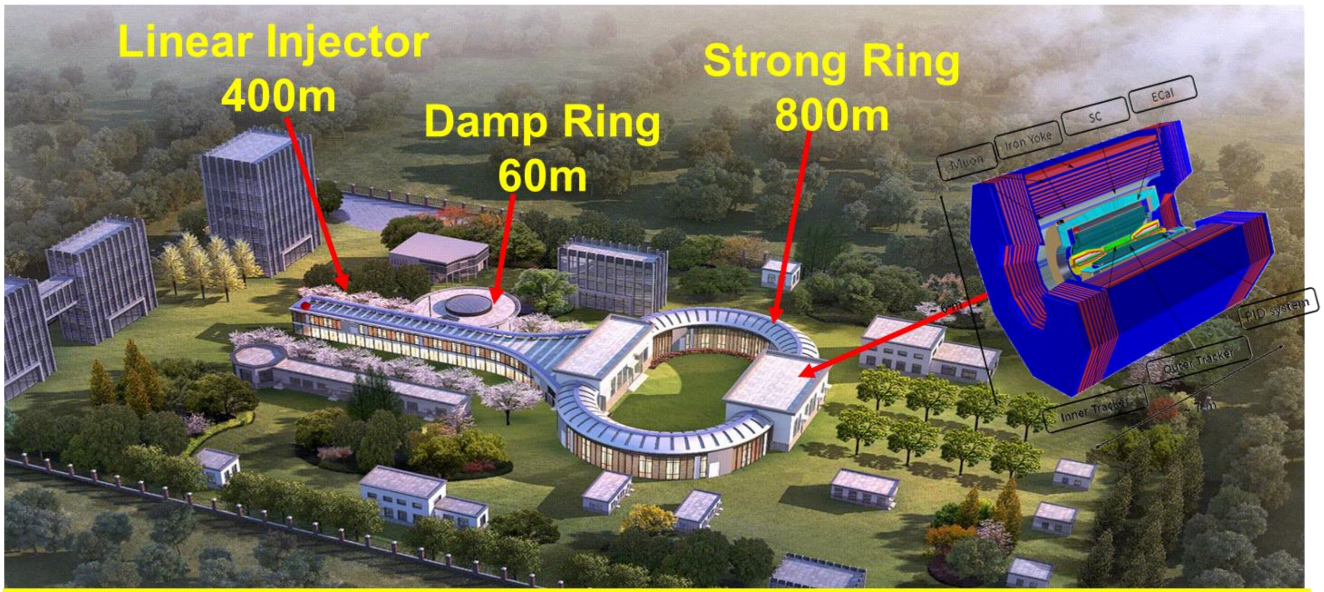
experimental opportunities with QCD, hadron physics, charm, tau lepton, ….

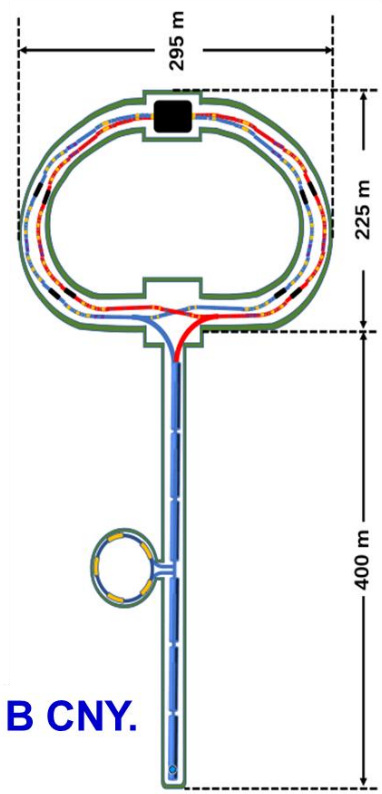
BESIII white paper: **Future Physics Programme**

arXiv:1912.05983 : Chin.Phys. C44 (2020) no.4, 040001

Intensity frontier - STCF

Super Tau-Charm Facility planned and under development





- E_{cm}=2-7GeV, peaking Luminosity =5×10^{34} cm^{-2} s^{-1} @ 4GeV
- Potential for upgrade to increase L and realize polarized beam

- 14th 5-year plan (2021-2025): Key technology R&D, funded with 0.42 B CNY.
- 15th 5-year plan (2026-2030): Construction, 6 years, 4.5 B CNY.
- Operating for 10 years, upgrade for 3 years, operating for another 7 years.

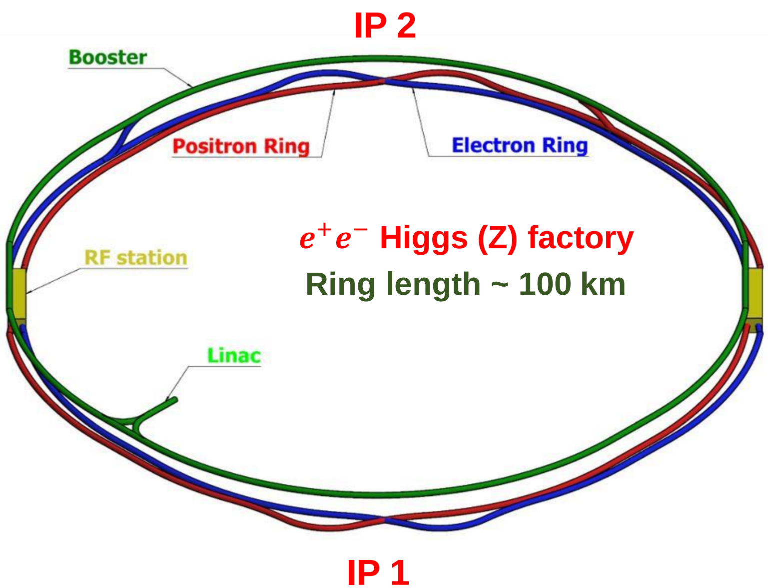
Xiaorong Zhou

Energy Frontier: CEPC

Circular Electron Positron Collider planned and under development

The idea of CEPC followed by a possible Super proton-proton collider(SPPC) was proposed in Sep. 2012, and quickly gained the momentum in IHEP and in the world.

- Looking for Hints@e+e-Collider ➔ If yes, direct search@PP collider
- The tunnel can be re-used for pp, AA, ep colliders up to ~ 100 TeV

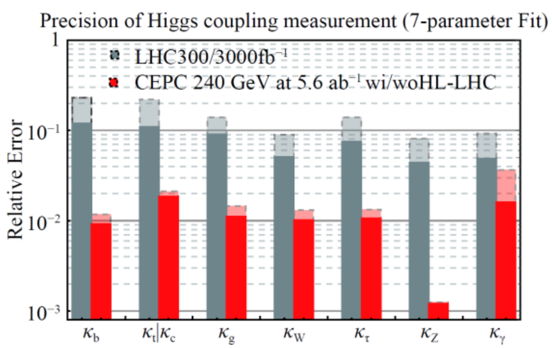


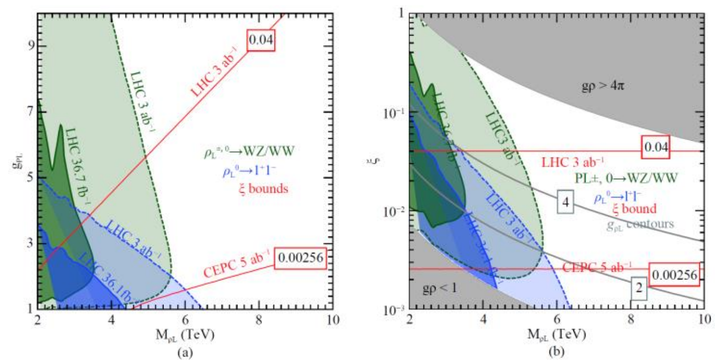
Scientific Obj.: “Discovery + precision measurement”

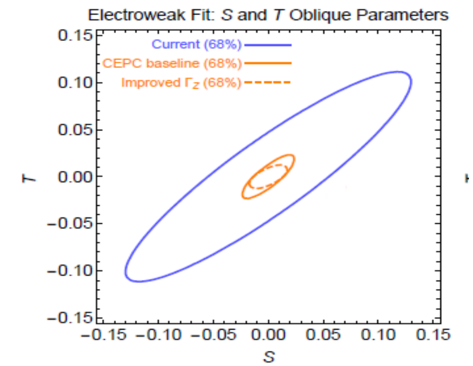
Higgs coupling measurement can be improved by orders magnititude

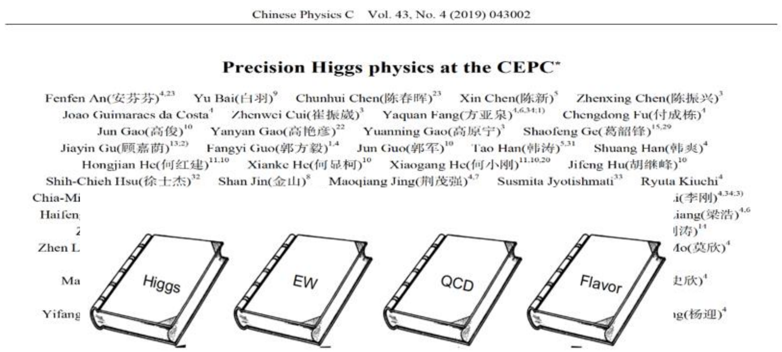
Direct and indirect proble to new physics up to 10 TeV, an order of magntitude higher then HL-LHC

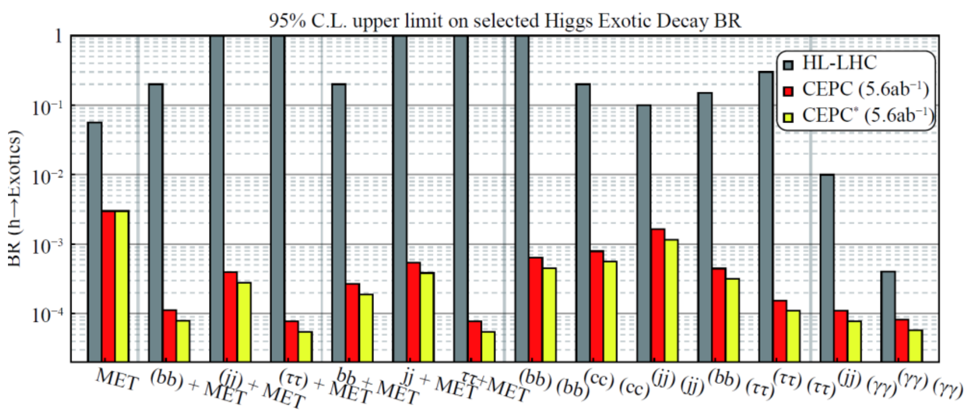
Electroweak measurement can be improved by a large factor











Physics white papers published and to be published

CEPC Concepts

New Physics
~10 TeV

- ✓ Dark Matter
- ✓ Extended Higgs
- ✓ Composite Higgs
- ✓ Supersymmetry
- ……

High Precision
~1%

- ✓ Higgs: 1%-0.1%
- ✓ EW : O(10^2-10^3) vs current
- ✓ Flavor
- ……

Detector
Particle Flow

- ✓ High Granularity
- ✓ Good Resolution
- ✓ Reliable PID
- ……

Design & Implementation
Detector & Accelerator

- ✓ Multi-purposed Acc.
- ✓ New concept Detector
- ✓ Cost, added values
- ✓ Spill-over
- ……

- ✓ Management
- ✓ Collaboration
- ……

High Lumi.
~10^{34-36}cm^{-2}s^{-1}

- ✓ Higgs: 20 ab^{-1}
- ✓ Z: 100 ab^{-1}
- ✓ W: 6 ab^{-1}
- ✓ Top: 1 ab^{-1}

Accelerator
2 IPs/100 km

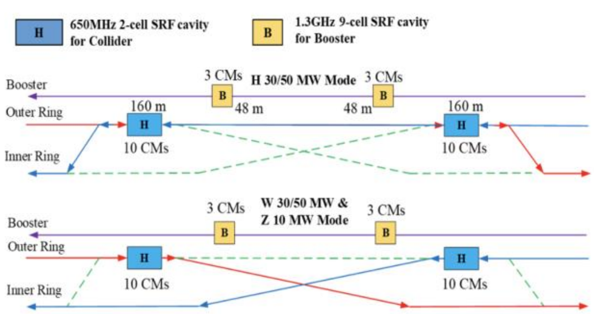
- ✓ Switchable Operations
- ✓ Upgradability
- ✓ Large Piwinski angle with Crab-waist
- ……

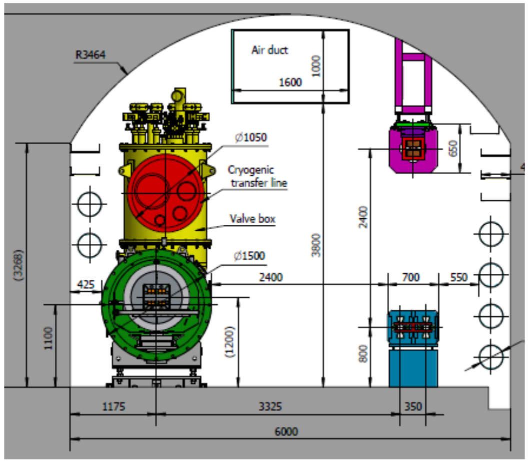
Operation mode	Z	W	Higgs
Center-of-mass energy (GeV)	91	160	240
Operation time (year)	2	1	10
Instantaneous luminosity/IP (10^{34}cm$^{-2}s^{-1}$)	115	16.0	5.0
Integrated luminosity (ab^{-1}, 2 IPs)	60	3.6	12
Event yield (30 MW)	2.5×10^{12}	1.0×10^{8}	2.5×10^{6}
Event yield (50 MW)	4.0×10^{12}	1.6×10^{8}	4.0×10^{6}

CEPC Layout and Design Essentials

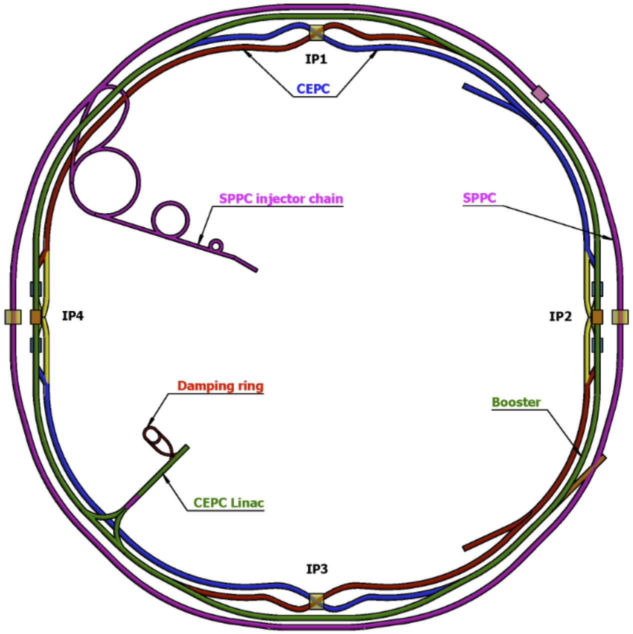
- **Circular collider**: Higher luminosity than a linear collider
- **100km circumference**: Optimal total cost
- **Shared tunnel**: Compatible design for CEPC and SppC
- **Switchable operation**: Higgs, W/Z, top
- Accelerator complex comprised of a Linac, a 100 km booster and a collider ring

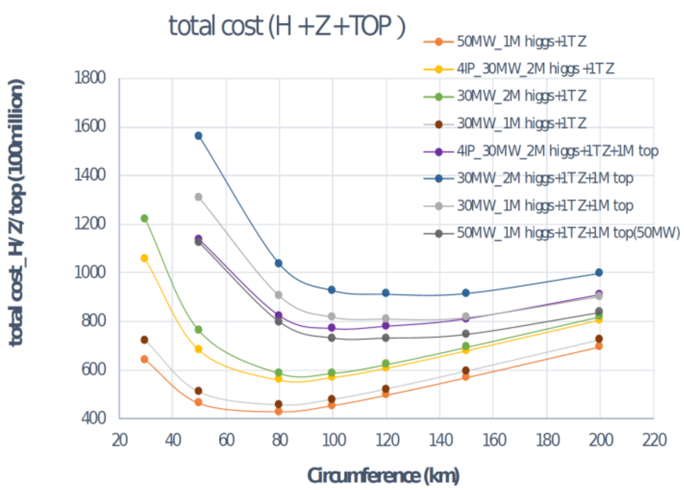
Switchable operation for Higgs W and Z





Common tunnel for booster/collider & SppC





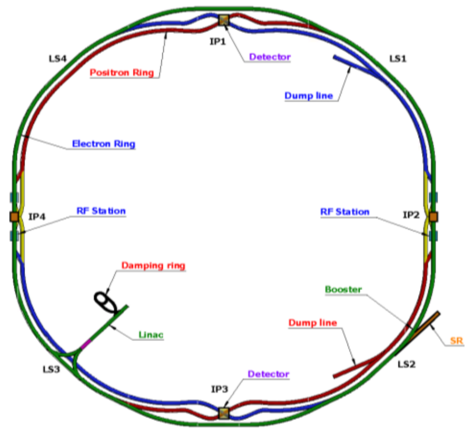
Baseline: 100 km, 30 MW; Upgradable to 50 MW, High Lumi Z, ttbar

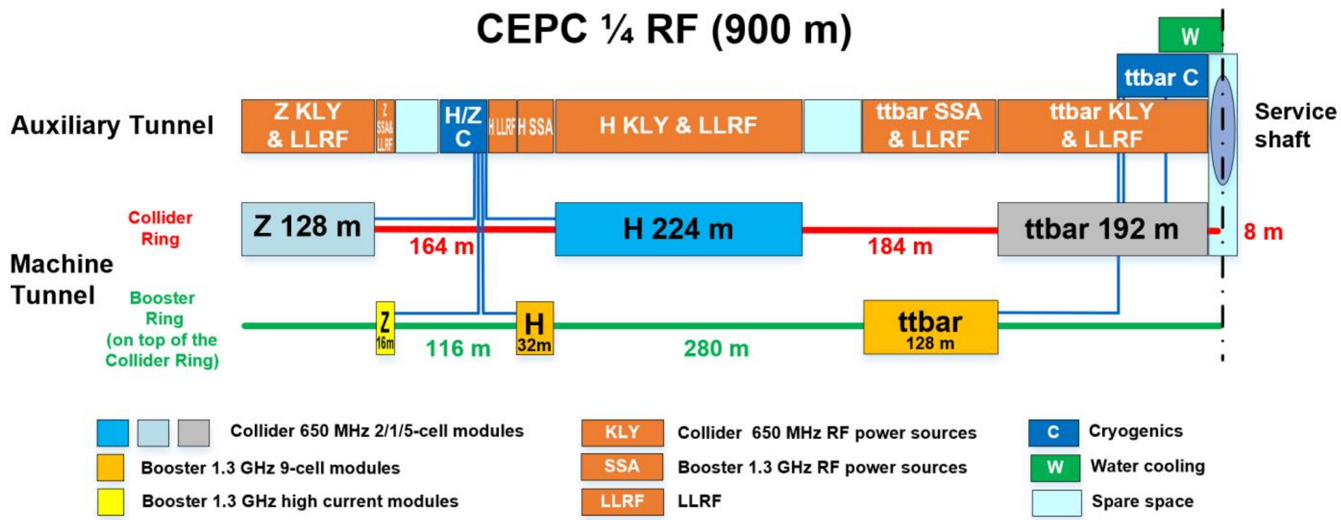
CEPC Operation Plan

Particle	$E_{c.m.}$ (GeV)	Years	SR Power (MW)	Lumi. /IP ($10^{34}cm^{-2}s^{-1}$)	Integrated Lumi. /yr (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	4.3×10^6
			30	5	1.3	13	2.6×10^6
Z	91	2	50	192**	50	100	4.1×10^{12}
			30	115**	30	60	2.5×10^{12}
W	160	1	50	26.7	6.9	6.9	2.1×10^8
			30	16	4.2	4.2	1.3×10^8
$t\bar{t}$	360	5	50	0.8	0.2	1.0	0.6×10^6
			30	0.5	0.13	0.65	0.4×10^6

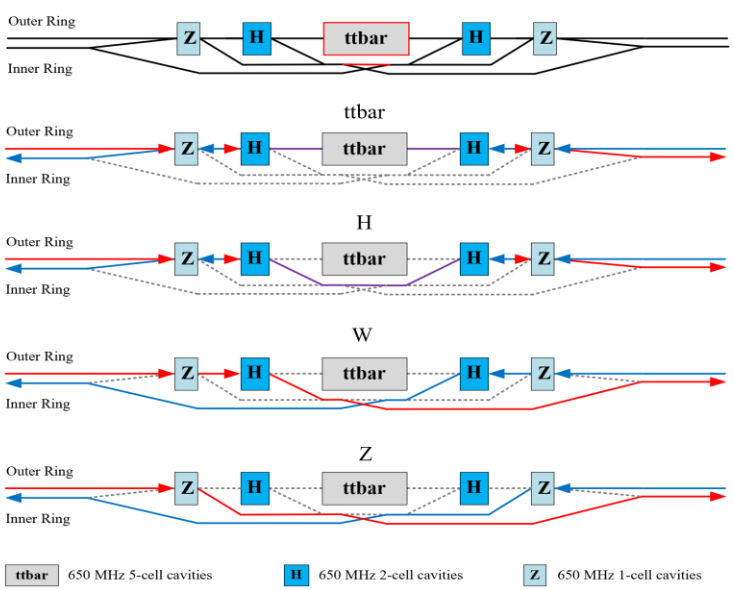
* Higgs is the top priority. The CEPC will commence its operation with a focus on Higgs.
** Detector solenoid field is 2 Tesla during Z operation, 3Tesla for all other energies.
*** Calculated using 3,600 hours per year for data collection.

SRF System Design and Upgrade Plan





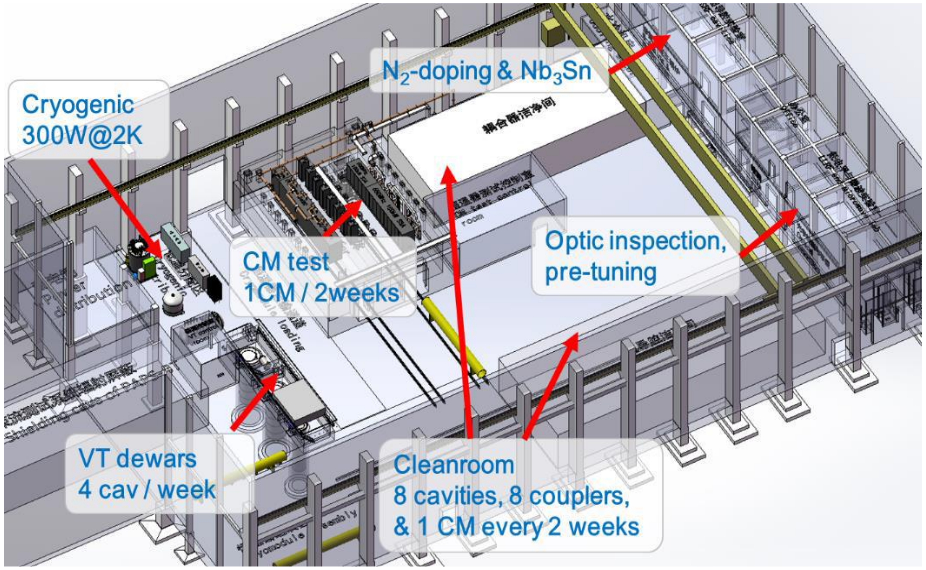
H/W/Z/ttbar bypass scheme



- SRF layout and parameters are designed to meet physics requirements;
- Starting from Higgs, H/W/Z/ttbar can be switchable
- RF system design optimized for Higgs 30/50 MW. Power and energy can be upgraded by adding cavities, RF power sources, cryogenic plants and other systems
- Use dedicated high current 1-cell cavity for 10-50 MW Z. Solve the FM & HOM CBI problems.

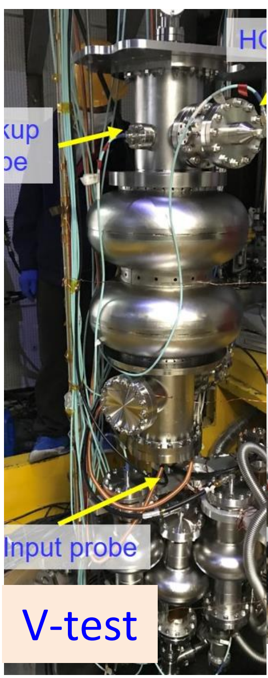
A New Lab at IHEP for SRF system(PAPS)

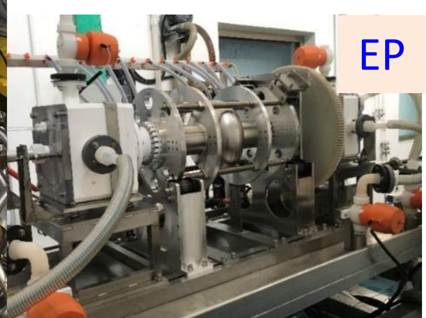
- A gift by the city of Beijing, next to HEPS
- A cryogenic system with 2.5KW@4.5K or 300W@2K
- Ovens and clean rooms for cavity production
- 2 horizontal and 3 vertical SRF test stand
- ~200 SRF cavities/year
- Testing of klystrons, electron guns, magnets, etc., and NEG coating of vacuum pipes
- ATF in the future



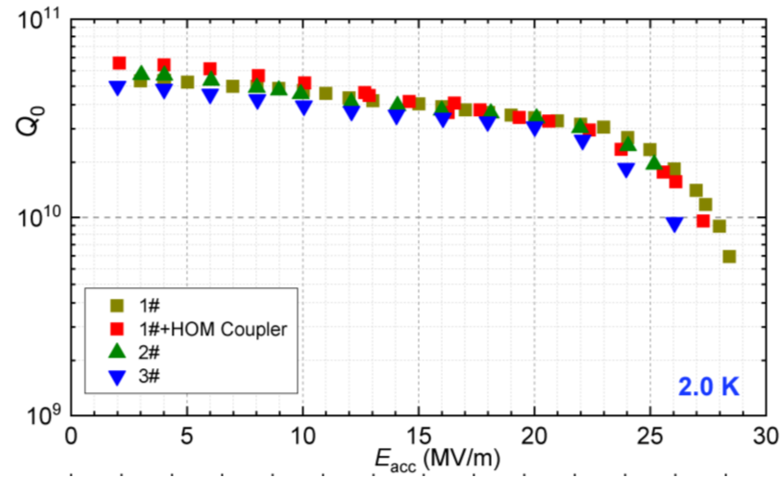
CEPC R&D: 650 MHz SRF Cavities

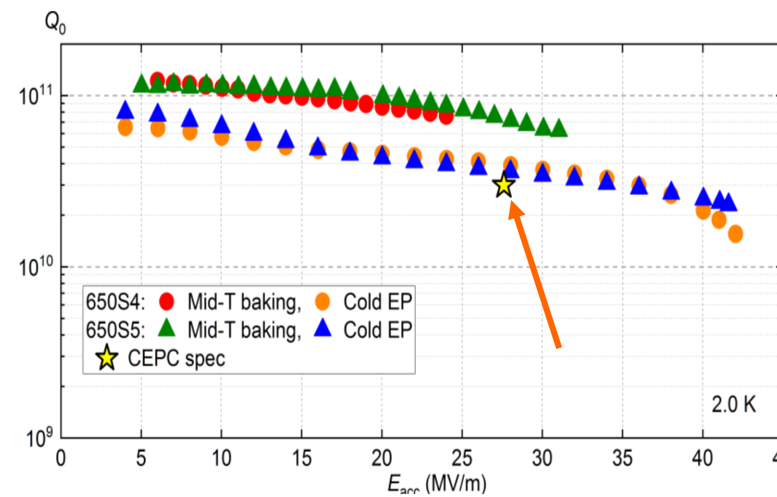
- First three 2-cell cavities based mainly on BCP shows reasonable performance
- Recent 1-cell cavity based on cold-EP and Mid-temperature baking achieved the world best results, exceeding CEPC spec.
- Continue to develop multi-cell cavities





Vertical test of 650 MHz 2-cell cavity

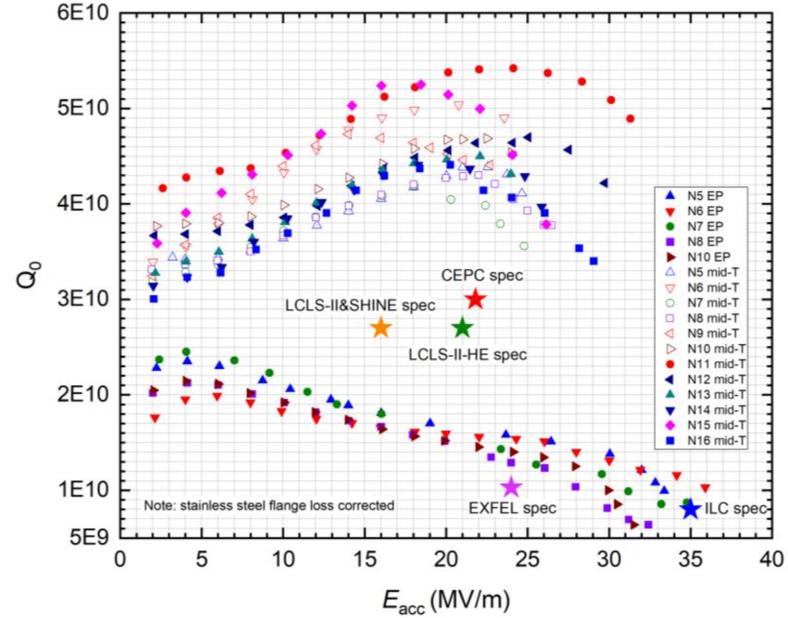


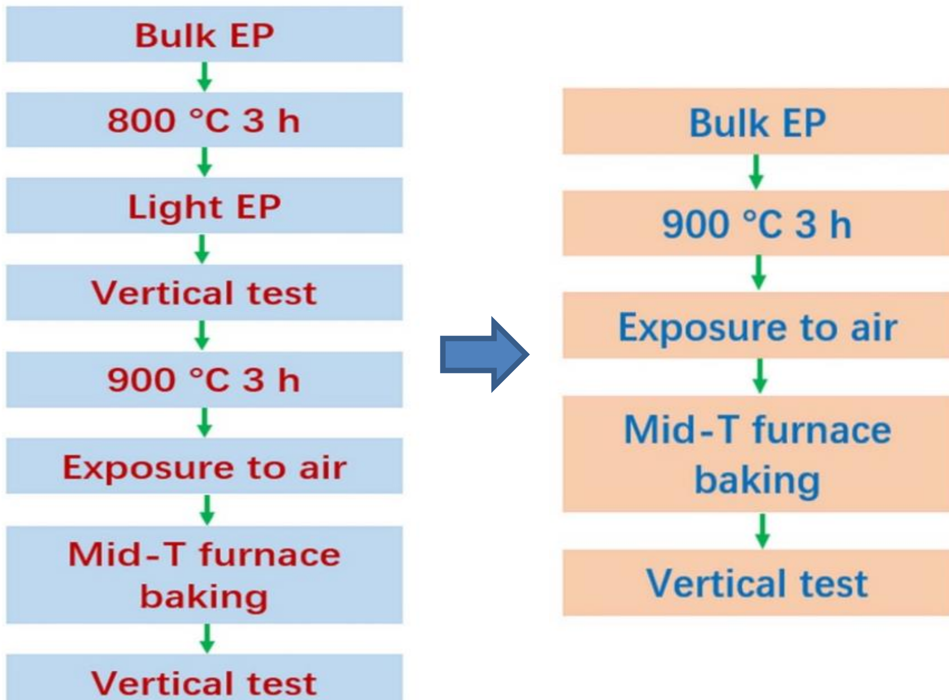


Vertical test of 650 MHz 1-cell cavity

CEPC R&D: 1.3 GHz SRF Cavities

- Mid-T baking (O-doping) VS N-doping: higher E_{acc} & Q, simple process, less EP.
- Excellent results obtained, exceeding requirements by CEPC, SHINE, LCLS-II, etc.
- ILC type of cavity with higher E_{acc} is also under development





CEPC R&D: SRF Modules

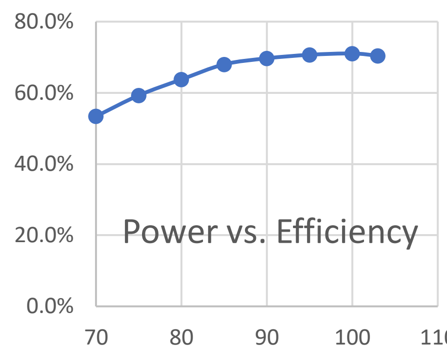
- 650 MHz test cryomodules including cavities, couplers, HOM absorbers, tuners..., was built and tested OK
- A full eight 1.3 GHz 9-cell cavities with input couplers, tuners, SC magnet, BPM, cryostat, module cart, feed/end-cap, volve-box … was built and tested OK

Parameters	Horizontal test results	CEPC Booster Higgs	LCLS-II, SHINE	LCLS-II-HE
Average Q_0 @ 21.8 MV/m	3.4×10^{10}	3.0×10^{10} @ 21.8 MV/m	2.7×10^{10} @ 16 MV/m	2.7×10^{10} @ 20.8 MV/m
Average CW E_{acc} (MV/m)	23.1			

CEPC R&D: High Eff. Klystrons

- 1st prototype: normal eff.
    - Single-beam with 70 kV
    - output power reached design value of 800 kW
    - efficiency ~ 62%
- 2nd prototype: High eff.
    - Single-beam with 110 kV
    - Designed eff. ~77%, test result 70%
    - Issues understood, to be re-tested soon
- 3rd prototype: High eff.
    - Multi-beam Klystron(MBK) with a designed eff. of 80%
    - Manufacture underway



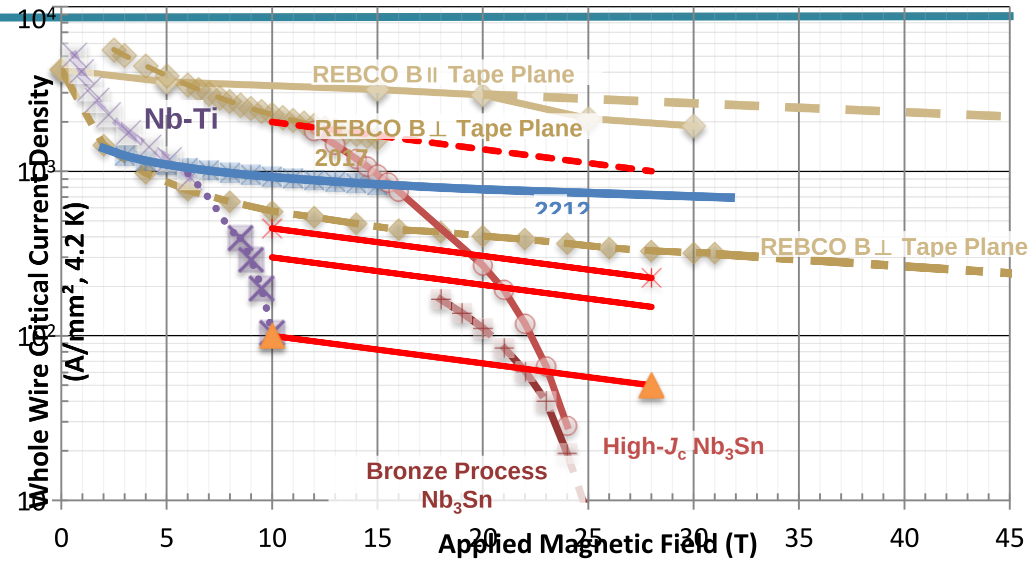


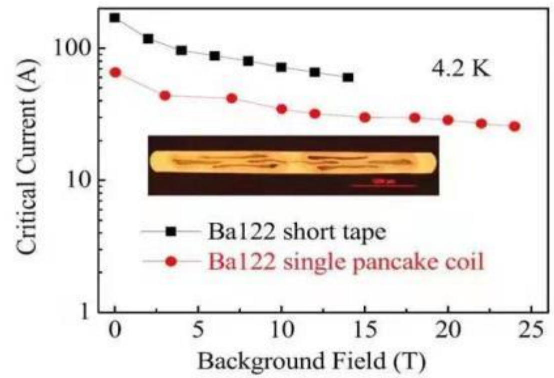


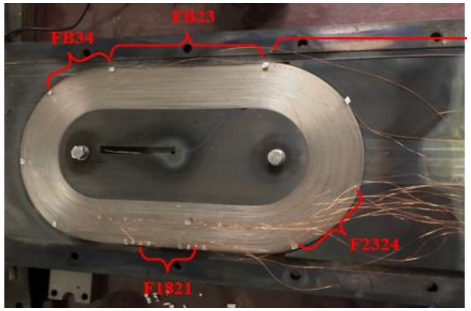
Window processing

CEPC High Tc superconductor for SPPC

- Iron-based superconducting materials are very promising for high-field magnets
  - Isotropic
  - May go to very high field
  - Raw materials are cheap
  - Metal, easy for production
- Technology spin-off can be enormous
- Major R&D goals
  - High Jc: > 1000A/mm^2@4.2K
  - Long cable: > 1000 m
  - Low cost: < 5$/kA·m
- A collaboration formed in 2016 by IHEP, IOP, IOEE, SJTU, etc., and supported by CAS
- World first: 1000m IBS cable, IBS coil, ➔ magnet





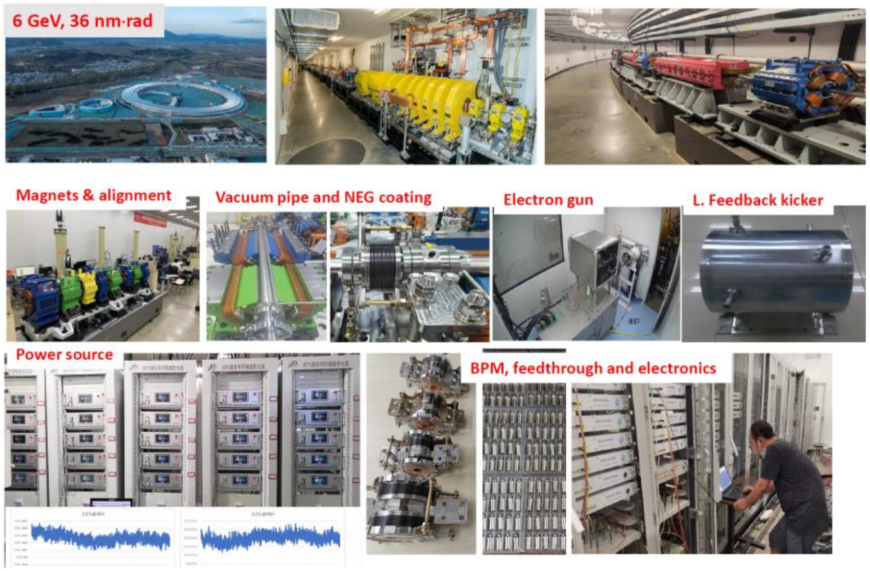


1st Iron-based Superconducting solenoid Coil at 24T

CEPC R&D and Prototypes

R&D: Other Prototypes

Experience at HEPS & BEPCII



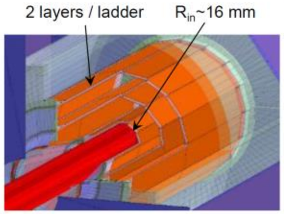
Summary of Key Technology R&D

- CEPC received ~ 260 Million CNY from MOST, CAS, NSFC for key technology R&D
- Large amount of key technology validated in other project by IHEP: BEPCII, HEPS, …

CEPC R&D **~ 40% cost of acc. components**	➢ High efficiency klystron ➢ SRF cavities ➢ Positron source ➢ High performance accelerator	➢ Novel magnets: Weak field dipole, dual aperture magnets ➢ Extremely fast injection/extraction ➢ Electrostatic deflector ➢ MDI
BEPCII / HEPS **~ 50% cost of acc. components**	➢ High precision magnet ➢ Stable magnet power source ➢ Vacuum chamber with NEG coating ➢ Instrumentation, Feedback	➢ Survey & Alignment ➢ Ultra stable mechanics ➢ Radiation protection ➢ Cryogenic system ➢ MDI

- **~10% remaining (the machine integration, commissioning etc.) to be completed by 2026.**
- **International contribution/collaboration important**

CEPC Detector R&D



Goal: σ(IP) ~ 5 μm for high P track

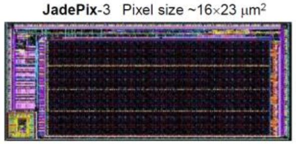
CDR design specifications

- Single point resolution ~ 3μm
- Low material (0.15% X_0 / layer)
- Low power (< 50 mW/cm²)
- Radiation hard (1 Mrad/year)

Silicon pixel sensor develops in 5 series: JadePix, TaichuPix, CPV, Arcadia, CEPCPix

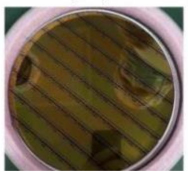
Develop **CEPCPix** for a CEPC tracke basing on **ATLASPix3** CN/IT/UK/DE TSI 180 nm HV-CMOS process

JadePix-3 Pixel size ~16×23 μm²

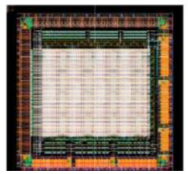


Tower-Jazz 180nm CiS process
Resolution 5 microns, 53mW/cm²

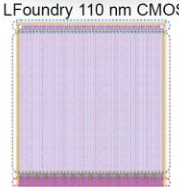
TaichuPix-3, FS 2.5x1.5 cm², 25×25 μm² pixel size



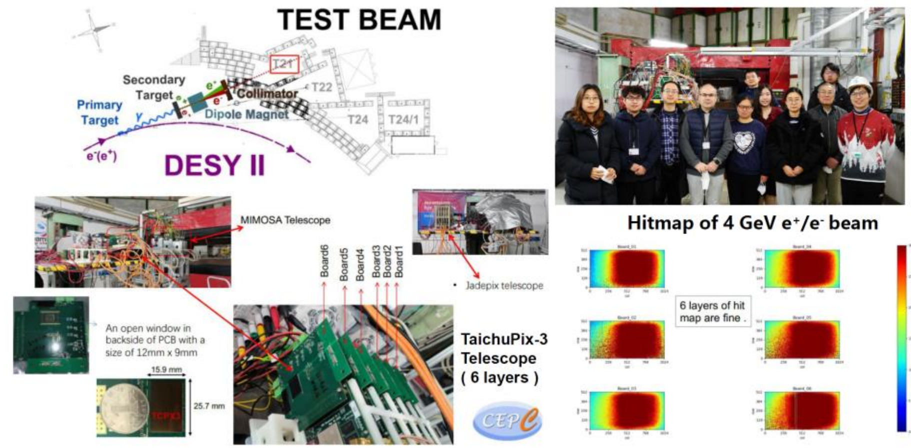
CPV4 (SOI-3D), 64×64 array ~21×17 μm² pixel size



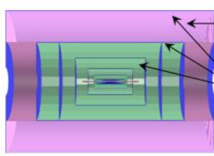
Arcadia by Italian groups for IDEA vertex detector LFoundry 110 nm CMOS

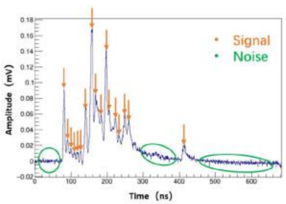


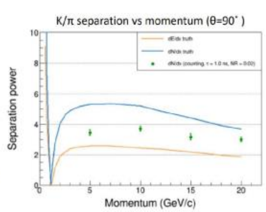
Full vertex detector prototype (TaichuPix-3, JadePix-3) has TB at DESY in Dec. 2022.



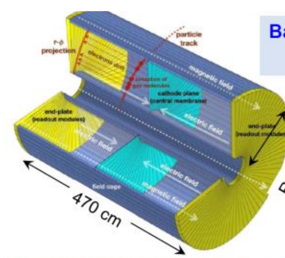
- **Goal: 3σ π/K separation up to ~20 GeV/c.**
- Cluster counting method, or **dN/dx**, measures the number of primary ionization
- **Can be optimized specifically for PID**: larger cell size, no stereo layers, different gas mixture.
- Garfield++ for simulation, realistic electronics, peak finding algorithm development.



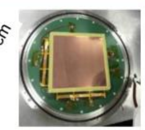




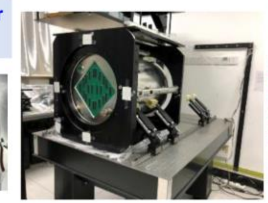
IHEP and Italian INFN groups have close collaboration and regular meetings.
IHEP joined the TB (led by INFN group) in 2021 and 2022



Baseline main tracker
σ(r-ϕ) ~100 μm



GEM-MM cathode

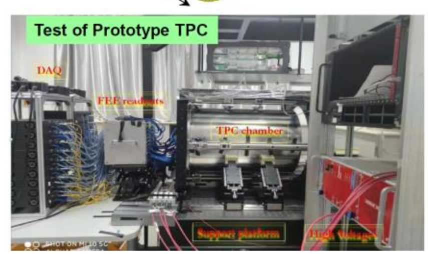


TPC Prototype + UV laser beams

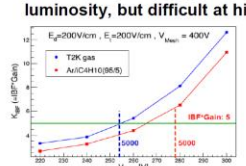
MOST 1 (IHEP+THU)

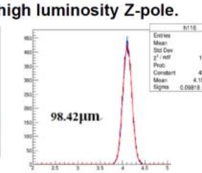
Low power FEE ASIC

Test of Prototype TPC



- **Challenge: Ion backflow (IBF) affects the resolution. It can be corrected by a laser calibration at low luminosity, but difficult at high luminosity Z-pole.**

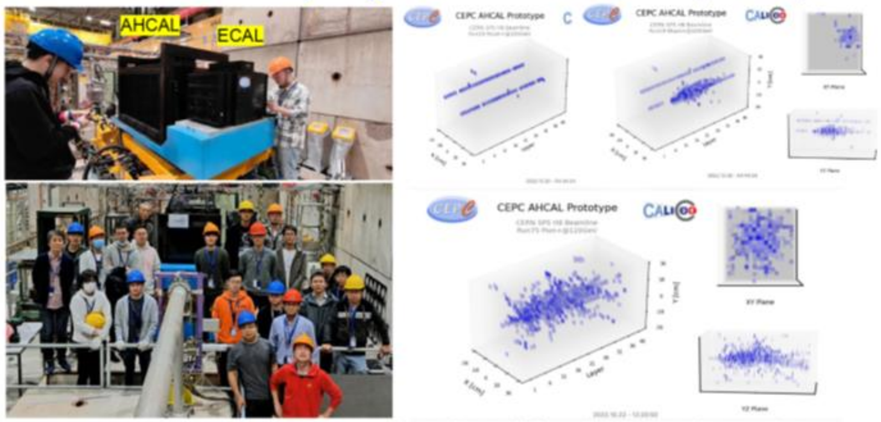




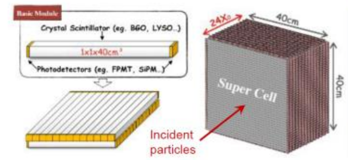
σ_x < 100 μm for drift length of 27cm

CEPC Detector R&D

➢ PFA ScW-ECAL & AHCAL prototypes: Test Beam at CERN SPS H8 (Oct. 2022)

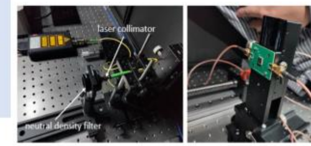


USTC, IHEP, SJTU, Japanese & Israel groups have close collaboration and regular meetings



Goal

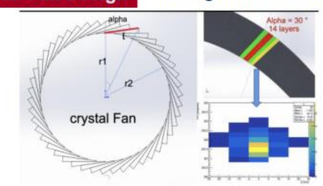
- Boson Mass Resolution < 4%
- Better BMR than ScW-ECAL
- Much better sensitivity to γ/e, especially at low energy.



Bench Test

- Long bars: 1 x 40 cm, super-cell: 40x40 cm²
- Timing at both ends for positioning along bar.
- Significant reduction of number of channels.

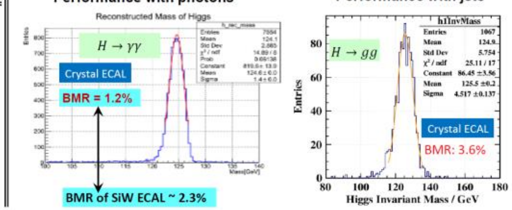
Crystal Fan Design Fine segmentation in Z, ϕ, r



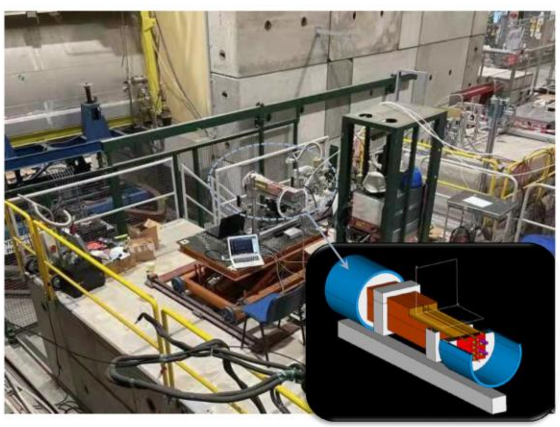
Full Simulation Studies + Optimizing PFA for crystals

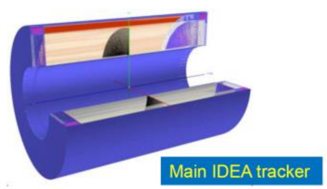
Performance with photons

Performance with jets



Dual readout crystal calorimeter also being considered by USA and Italian colleagues





Italian groups and IHEP colleagues participated the test beam at CERN.

Key4hep: an international collaboration with CEPC participation
CEPCSW: a first application of Kep4hep – Tracking software
CEPCSW is already included in Key4hep software stack

https://github.com/cepc/CEPCSW

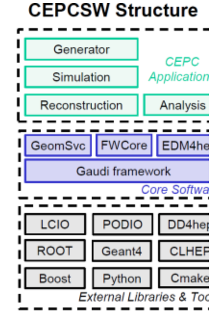
Architecture of CEPCSW

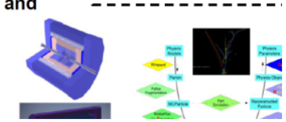
- External libraries
- Core software
- CEPC applications for simulation, reconstruction and analysis

Core Software

- Gaudi framework: defines interfaces of all software components and controls the event loop
- EDM4hep: generic event data model
- FWCore: manages the event data
- GeomSvc: DD4hep-based geometry management service

CEPCSW Structure

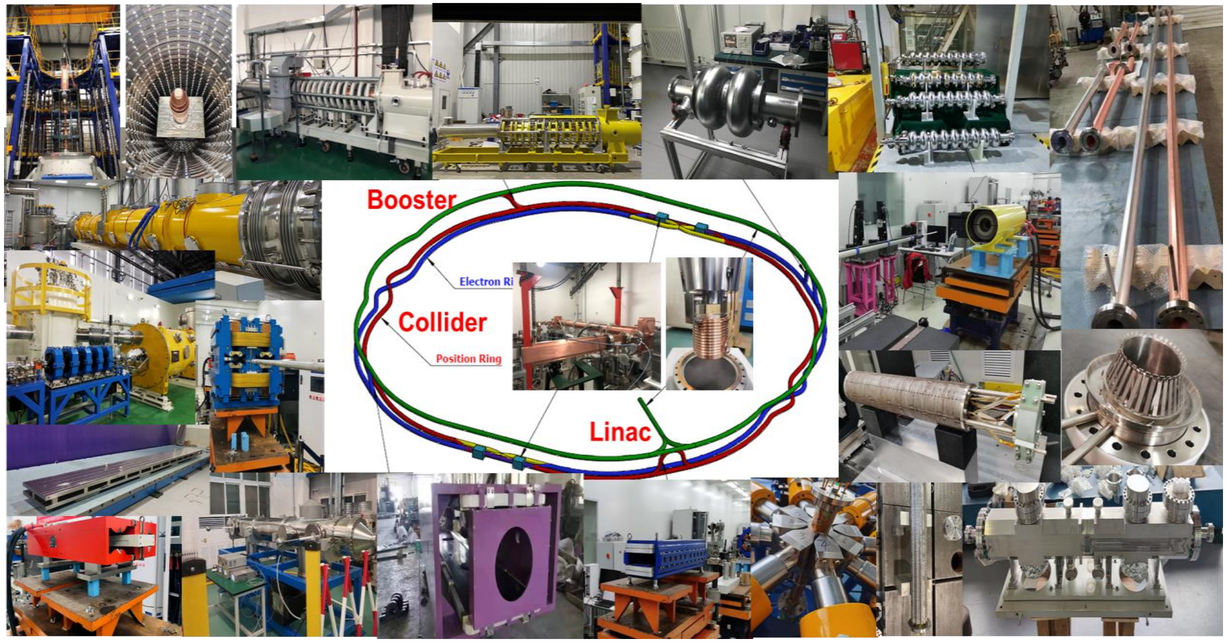




Key Technology Readiness

Represented Key Technologies for the CEPC

Specification Met ✓   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%

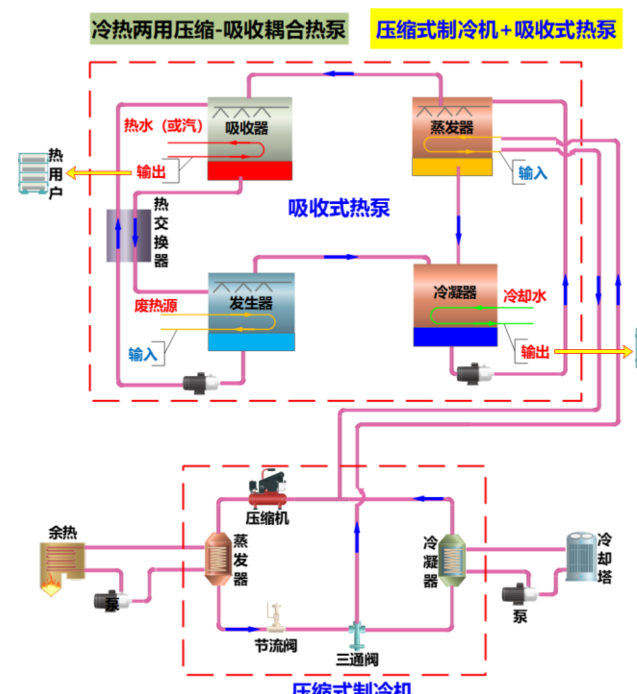
Key technology R&D spans all component list for CEPC

Will be ready for construction by 2026

Efforts Towards a Green Accelerator

- Experience at HEPS
  - Solar panel: 10 MW ➔ 10% saving
  - Permanent magnet: 5.6 GWh saving/yr
  - Hot water(13 MW@42ºC) for heating: more than what HEPS needs
- R&D for CEPC
  - High eff. Klystron, energy recovery Klystron, ...
  - Design and R&D of a "cooling-compressor + heating-pump system" to recover hot water in winter and cooling water in summer for use at HEPS
  - Continue to investigate power generator using low-T hot water

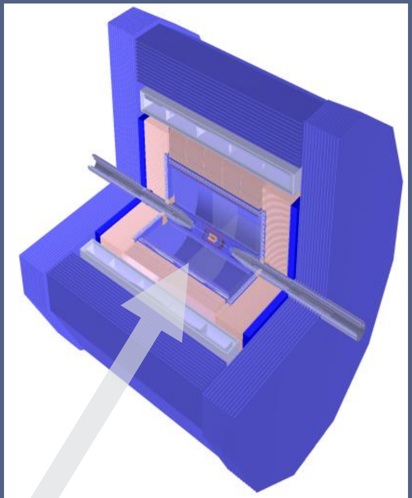
Solar panel on the roof of HEPS

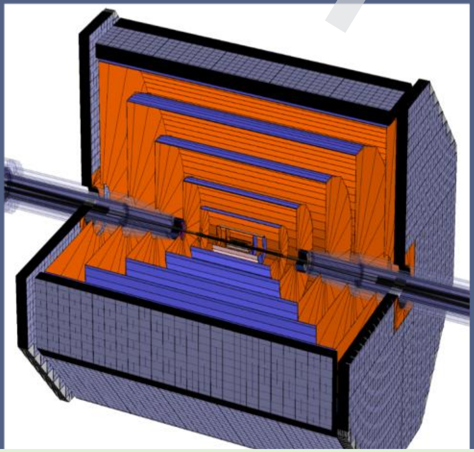


Detector Concepts Studied

Particle Flow Approach

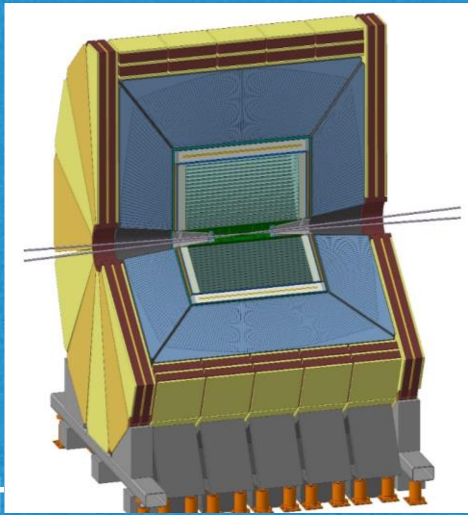
High magnetic field concept (3 Tesla)





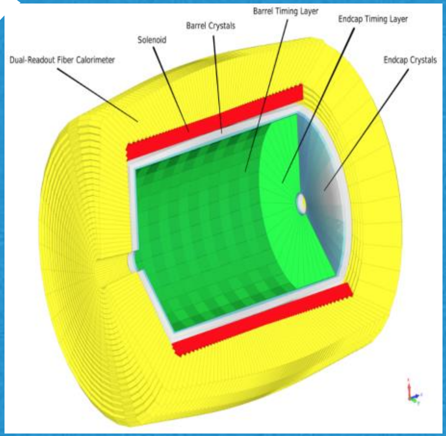
Full silicon tracker concept

Low magnetic field concept (2 Tesla)



IDEA Concept

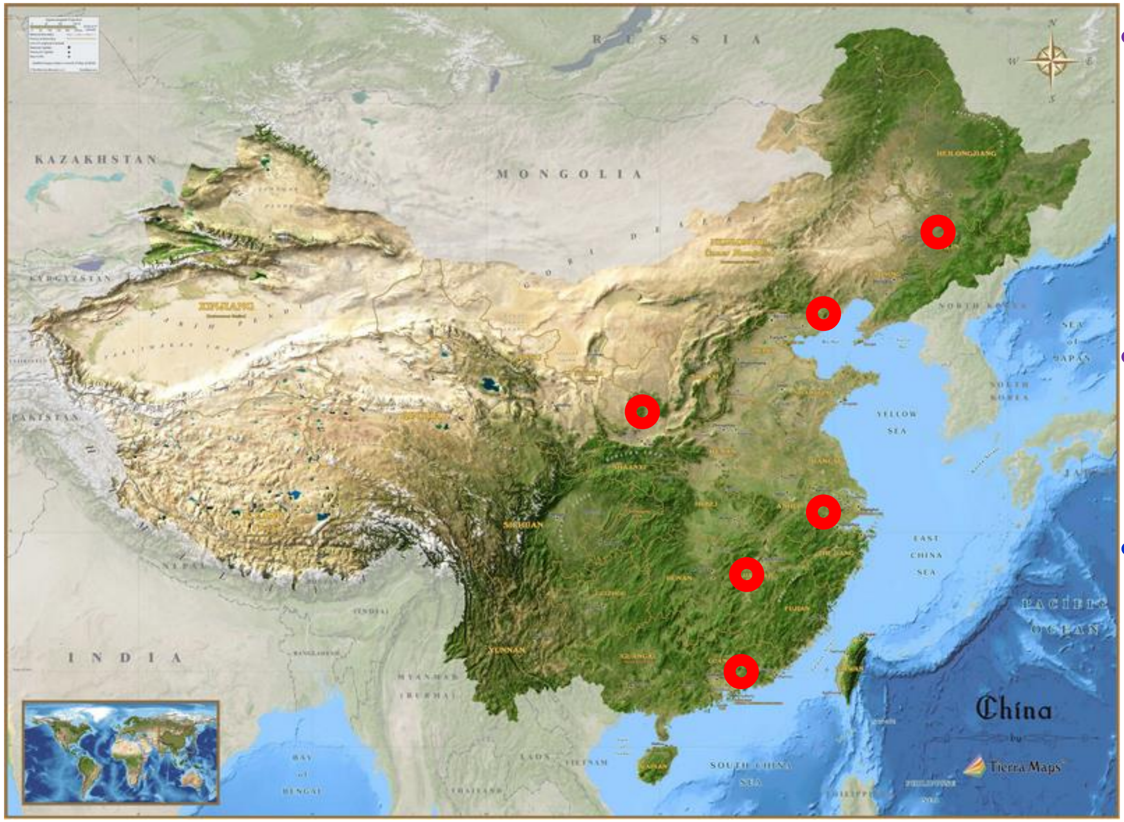
also proposed for FCC-ee



“Fourth concept”: Crystal Calorimeter based detector (2-3 Tesla)

Final two detectors WILL be a mixture of different options

CEPC Site Selection

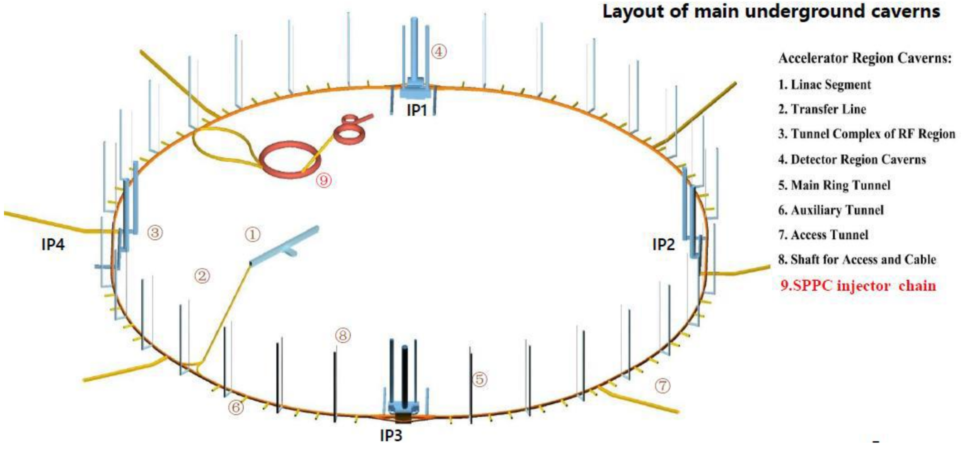


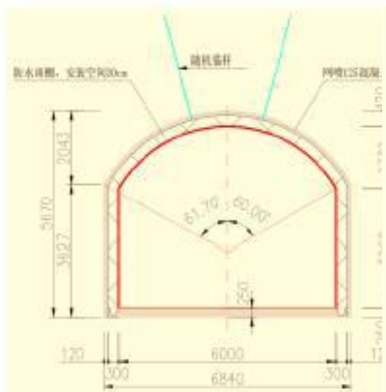
- Site selection based on geology, electricity supply, transportation, environment for foreigners, local support & economy,…
- North are better for running cost; south are better economic support
- Decision shall come from negotiations between central and local government

- 4/6 sites are investigated in detail: Qing-Huang-Dao, Chang-Sha, Chang-Chun, Hu-Zhou
- Geology are all good, with reasonable condition of transportation and local support

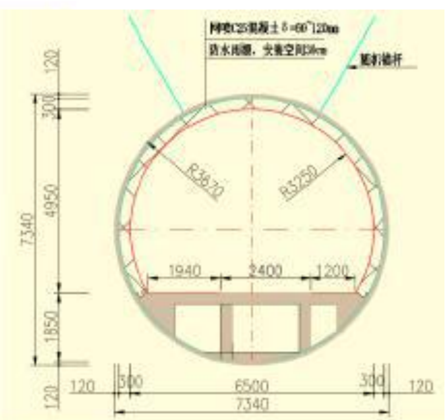
Civil Design and Planning

- 3 companies working on the design, one for each site. Review in progress
- Most of the tunnel(75-95%) in granite, greatly impact the cost
- Construction method yet to be determined
- Time for construction is ~5 yrs

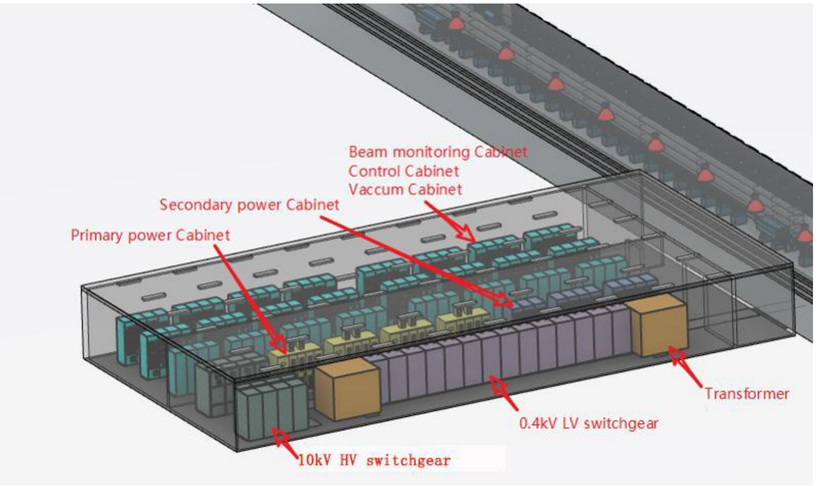


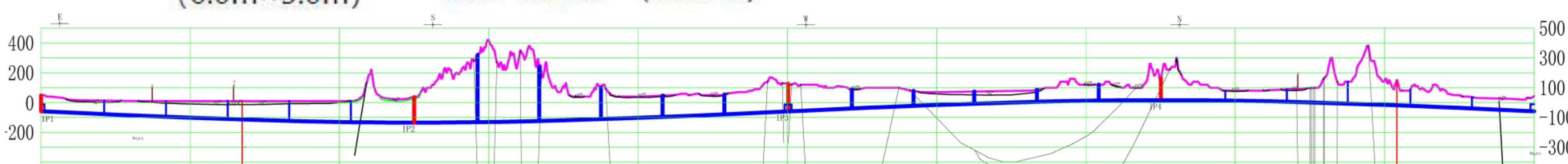


Drill-blast tunnel (6.0m×5.0m)



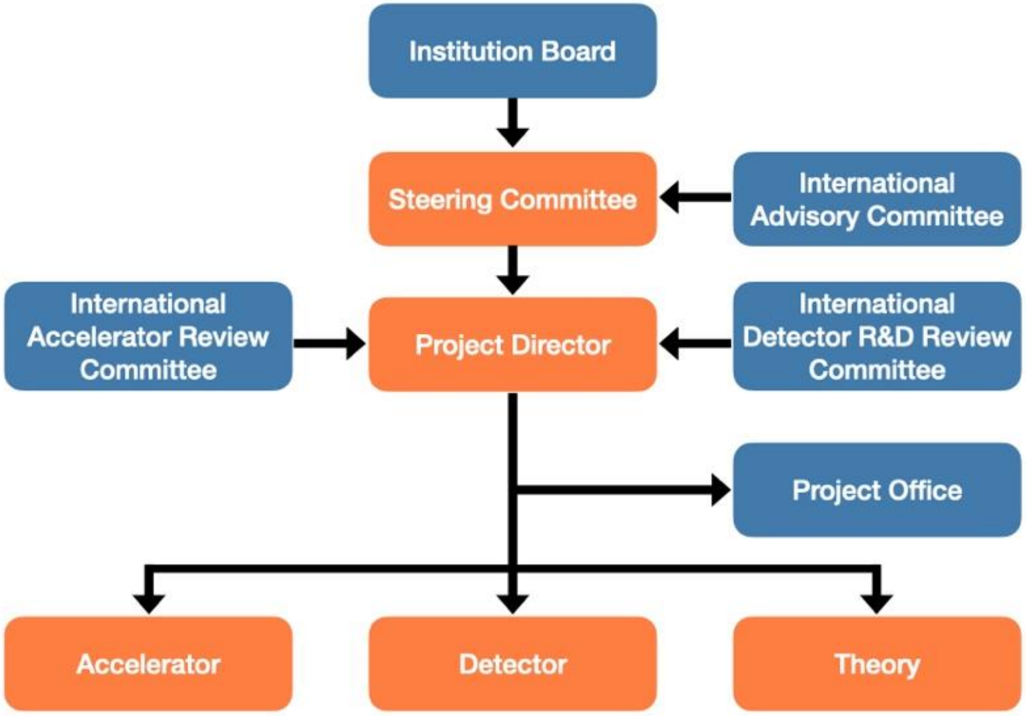
TBM tunnel (D6.5m)





Team and Organization

- Currently, the core team consists of ~ 400 people mainly from China; ~ 400 more from BEPC/JUNO/HEPS will come once CEPC is approved
- IHEP is currently the host lab with experience managing international collaborations such as BESIII/Daya Bay/JUNO, and projects such as BEPCII/CSNS/HEPS
- The temporary management structure is endorsed by the international advisory committee.
- Once approved, Funding agencies will be added at the top



International Collaboration

- Great international participation to CDR, expect similar for TDR
- Many MoUs signed and executed
- substantial collaboration on Physics studies and detector R&D, fewer on accelerator
- Substantial International advice through many committees and conferences, particular to accelerator
- Joined CALICE, ILD TPC, and RD collab.s, in addition to LHC exp. and many others
- Actively involved in the European Strategy update and the Snowmass process
- Annual CEPC International Workshop in China and EU/US-edition since 2014
- Annual working month at HKIAS (since 2015), resumed this year


CEPC workshop in Chicago, 2019

Project Status

- TDR is completed, reviewed by an international committee, to be released soon
- CAS is planning for the 15th 5-years plan for large science projects, and a steering committee has been established, chaired by the president of CAS
- High energy physics, as one of the 8 groups, has been working on this for a year:
  - Setting up rules and the standard(based on scientific and technological merits, strategic value and feasibility, R&D status, team and capabilities, etc.), established domestic and international advisory committees
  - Collected 15 proposals and selected 9, based on the above-mentioned standard
  - Evaluations and ranking by committees after oral presentations by each project
- **CEPC is ranked No. 1, by every committee**
- A final report will be submitted to CAS for consideration

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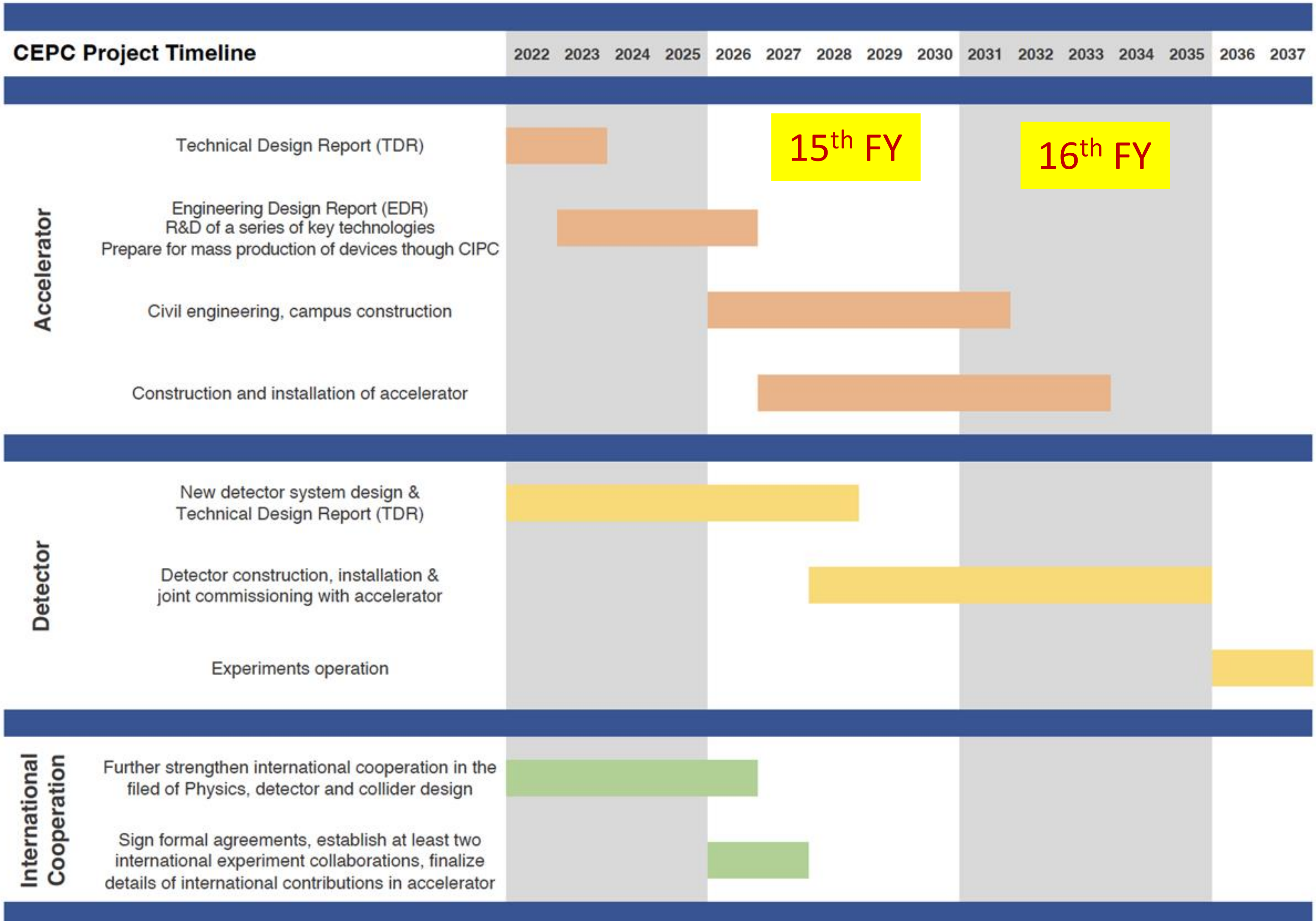
Planning & Schedule

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



Summary

- JUNO will begin operation soon and will provide excellent opportunity for decades.
- BESIII @ BEPCII important (BEPCII upgrade, STCF)
  study of QCD, hadrons, charm, …
  great experience gaining & training for future projects
- Both JUNO and BESIII@BEPCII experiments are sizable international collaborations – very unique in China;
- CEPC is completing the TDR for the e^+e^- accelerator as a boson–top factory (H, Z, W, top) and will enter the EDR phase.
- CEPC schedule follows China's 5-year planning; expects to complete the R&D and the preparation to build the facility and carry out the science program
- CEPC will offer the HEP community an early Higgs factory