Recent status and progress of the CEPC

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for the CEPC study group

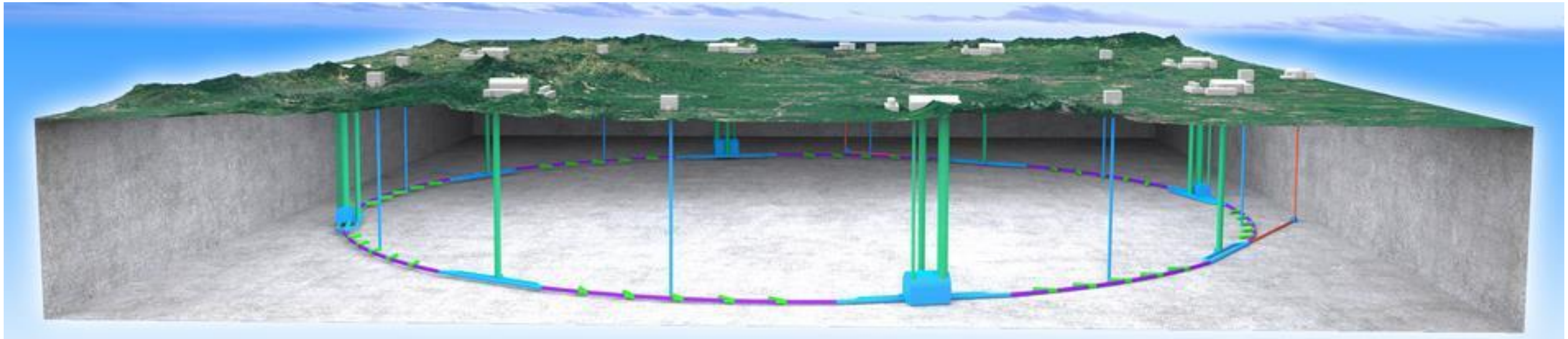
第三届高能物理理论与实验融合发展研讨会, Nov 1 – 4, 2024

Outline

- Introduction to CEPC
  - Goal and major milestones
  - Consensus on e^+e^- Higgs Factory
- CEPC Status and Progress
  - Physics Program
  - Accelerator R&D
  - Detector R&D
- Project Planning and Development
- Summary

Circular Electron Positron Collider (CEPC)

- CEPC is an e^+e^- Higgs factory to deliver H / W / Z bosons and top quarks, aims at discovering new physics beyond the Standard Model
- Proposed in September 2012 right after the Higgs discovery
- Upgradable: Super pp Collider (SppC) of $\sqrt{s}$ ~ 100 TeV in the future.



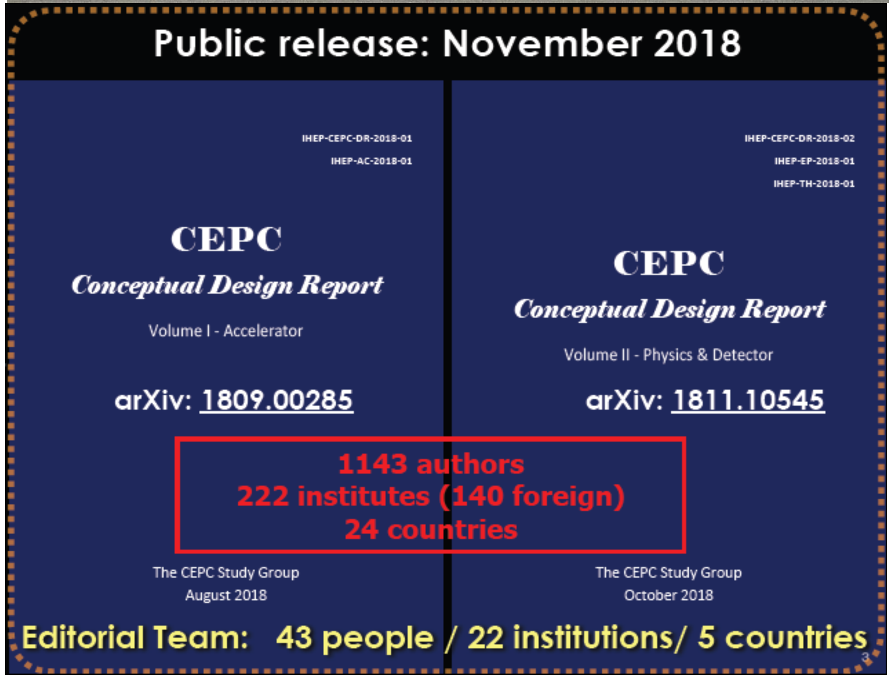
http://cepc.ihep.ac.cn

CEPC Major Milestones

CEPC-SPPC Kickoff (2013.9)

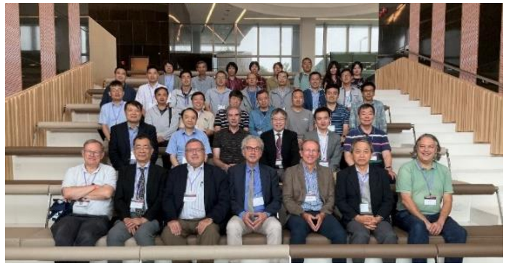
First CEPC IAC Meeting (2015.9)

CEPC CDR Released (2018.11)

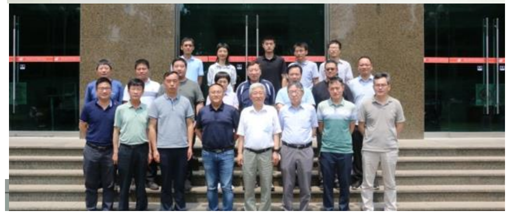


CEPC Major Milestones

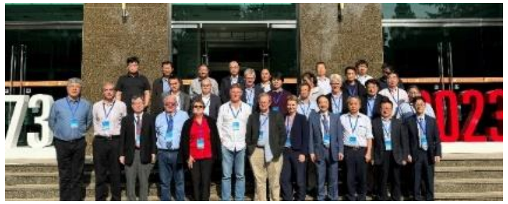
CEPC Accelerator TDR Review
June 12-16, 2023, Hong Kong



CEPC Accelerator TDR Cost Review
Sept. 11-15, 2023, Hong Kong



Domestic Civil Engineering
Cost Review, June 26, 2023, IHEP



9th CEPC IAC 2023 Meeting
Oct. 30-31, 2023, IHEP

CEPC Accelerator TDR released in December, 2023

IHEP-CEPC-DR-2023-01
IHEP-AC-2023-01

CEPC

Technical Design Report

Accelerator

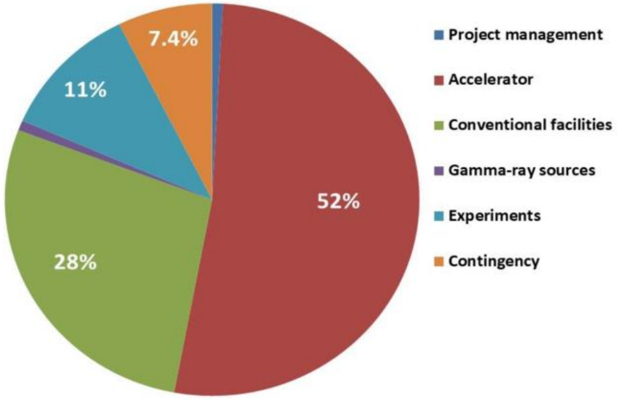
arXiv:2312.14363
1114 authors
278 institutes
(159 foreign institutes)
38 countries

The CEPC Study Group
December 2023

TDR cost of 36.4B RMB (~4.7B Euro)

Table 12.1.2: CEPC project cost breakdown, (Unit: 100,000,000 yuan)

Total	364	100%
Project management	3	0.8%
Accelerator	190	52%
Conventional facilities	101	28%
Gamma-ray beam lines	3	0.8%
Experiments	40	11%
Contingency (8%)	27	7.4%



Global HEP Consensus on Higgs Factories

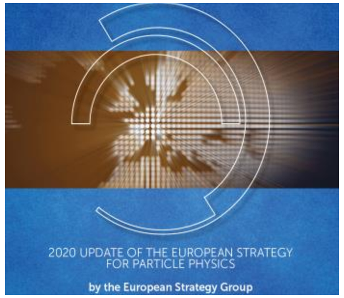
The scientific importance and strategical value of e^+e^- Higgs factories is clearly identified.

China

2013, 2016: China Xiangshan Science Conference concluded that ***CEPC is the best approach*** *and a major historical opportunity for the national development of accelerator-based high-energy physics program.*

JAHEP Japan

2017: *Japan Association of High Energy Physicists (JAHEP) proposes to construct* ***A 250 GeV center of mass ILC promptly as a Higgs factory.***



Europe

2020: *European Strategy for Particle Physics,* ***An electron-positron Higgs factory is the highest priority next collider.*** *For the longer term, the European particle physics community has the ambition to operate a proton-proton collider at the highest achievable energy.*

ICFA

2022, *ICFA "reconfirmed the international consensus on the importance of* ***a Higgs factory as the highest priority for realizing the scientific goals of particle physics****", and expressed support for the above-mentioned Higgs factory proposals*

Exploring the Quantum Universe

Pathways to Innovation and Discovery in Particle Physics

Report of the Particle Physics Project Prioritization Panel 2023

Exploring the Quantum Universe

Recommendation 6

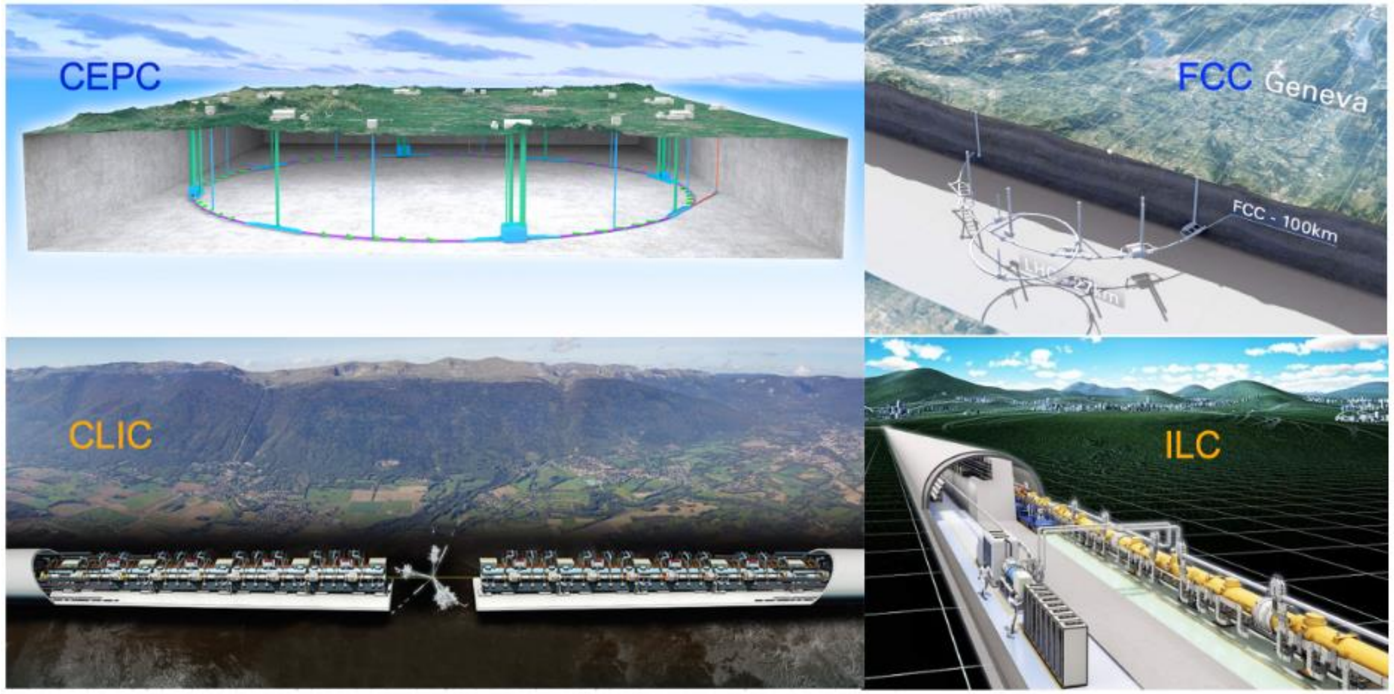
Convene a targeted panel with broad membership across particle physics later this decade that makes decisions on the US accelerator-based program at the time when major decisions concerning an off-shore Higgs factory are expected, and/or significant adjustments within the accelerator-based R&D portfolio are likely to be needed. A plan for the Fermilab accelerator complex consistent with the long-term vision in this report should also be reviewed.

The panel would consider the following:

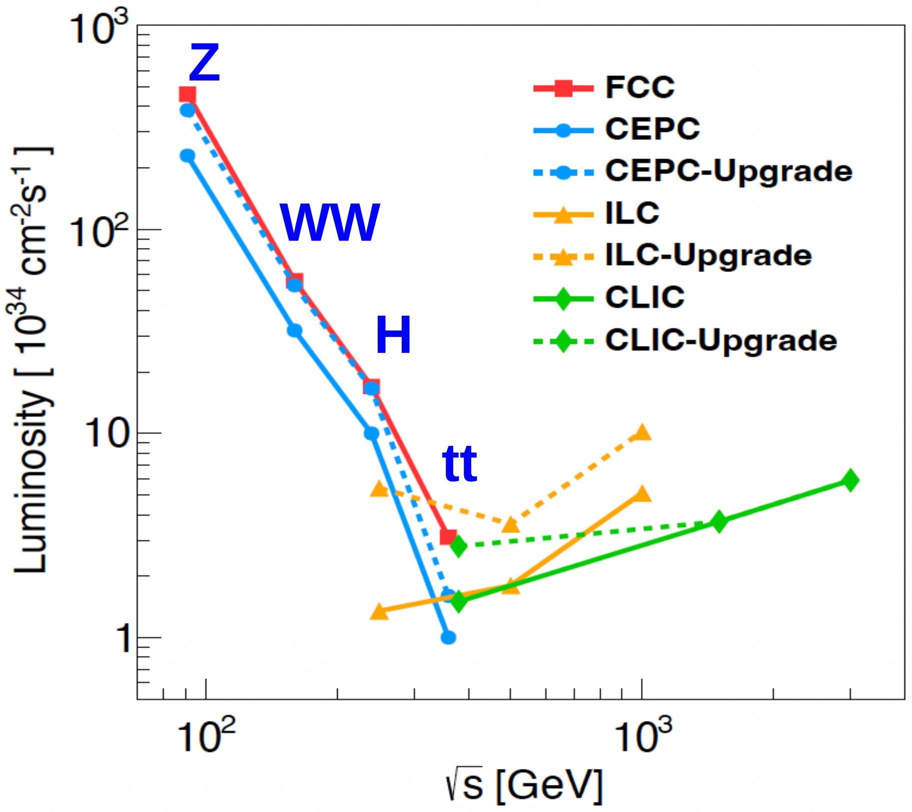
1. The level and nature of US contribution in a specific Higgs factory including an evaluation of the associated schedule, budget, and risks once crucial information becomes available.
2. Mid- and large-scale test and demonstrator facilities in the accelerator and collider R&D portfolios.
3. A plan for the evolution of the Fermilab accelerator complex consistent with the longterm vision in this report, which may commence construction in the event of a more favorable budget situation.

P5 report, USA, 2023

Comparison of Higgs factories: Circular vs Linear



CEPC Accelerator white paper for Snowmass21, arXiv:2203.09451



CEPC has strong advantages among mature e^+e^- Higgs factories (design report delivered)

Versus FCC-ee

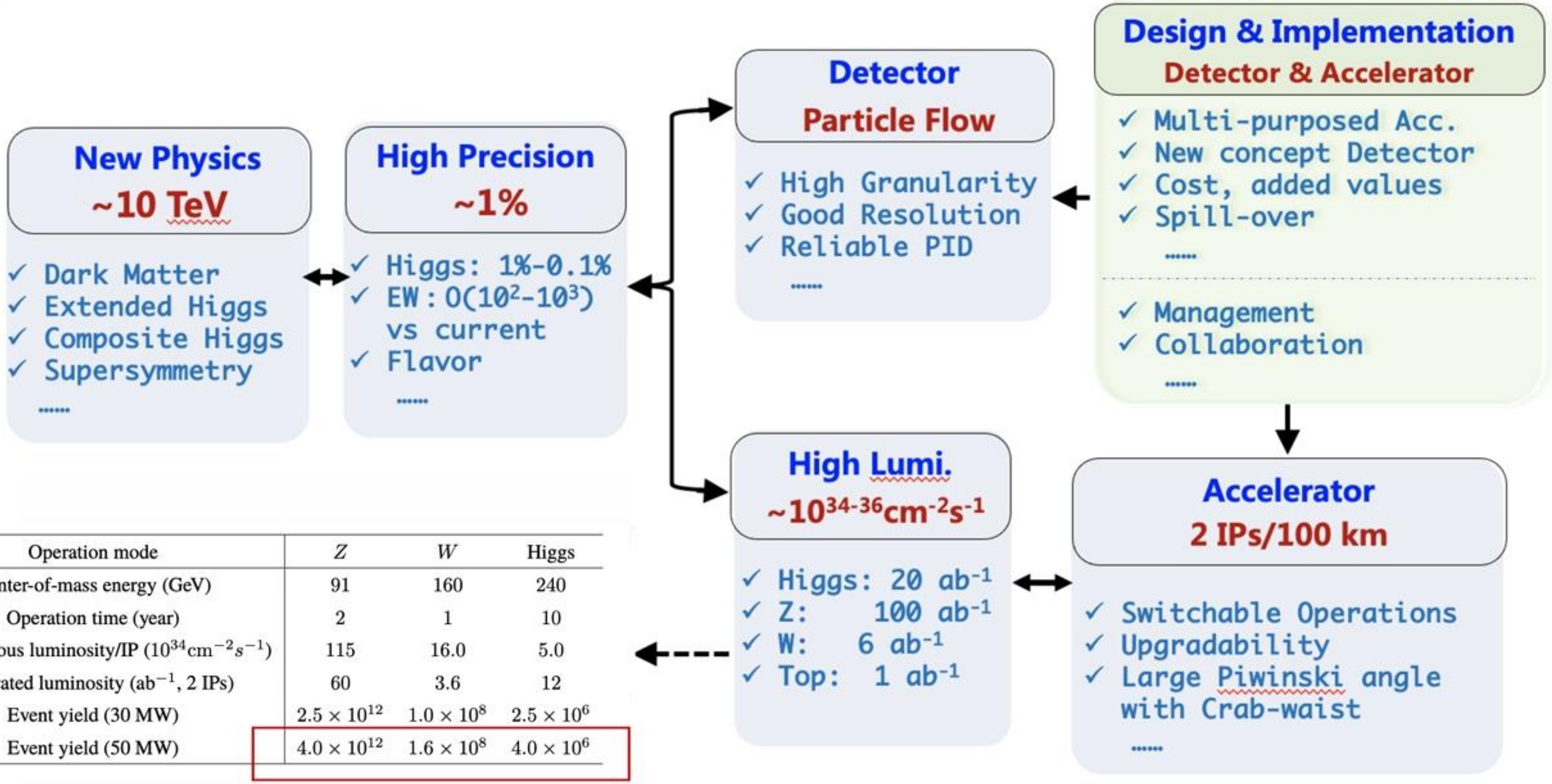
- Earlier data: collisions expected in 2030s (vs. ~ 2040s)
- Large tunnel cross section (ee & pp coexistence)
- Lower construction cost

Versus Linear Colliders

- Higher luminosity / precision for Higgs & Z
- Potential upgrade for pp collider

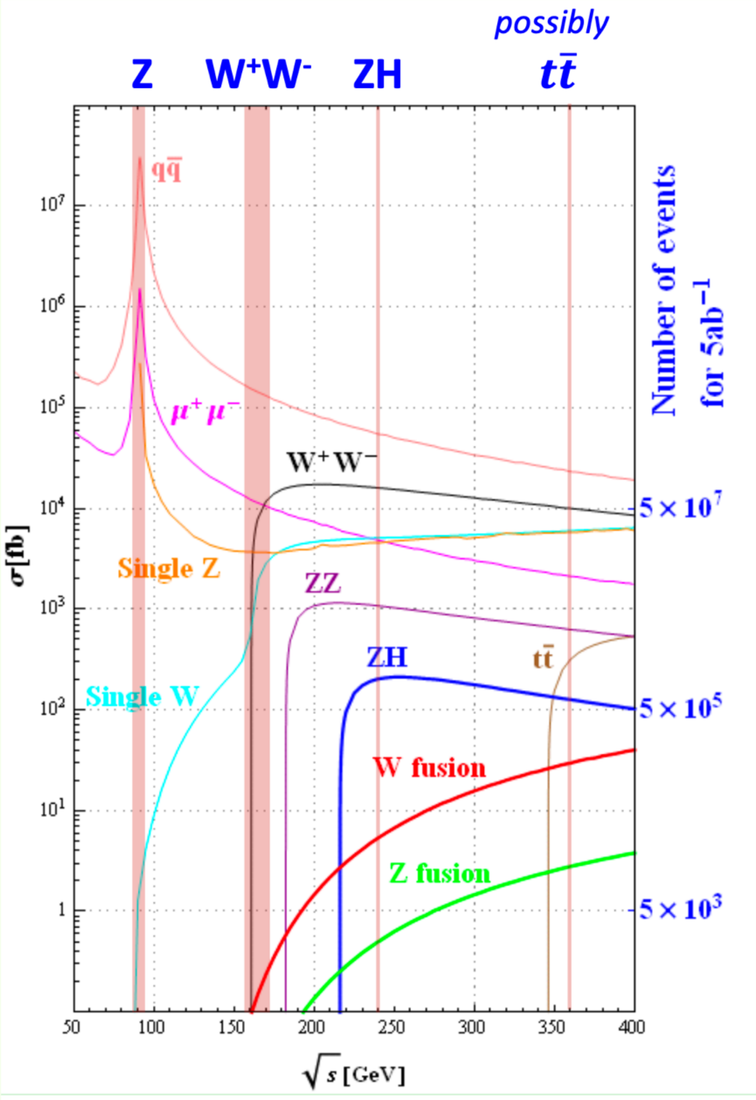
CEPC Concepts

CEPC Key Scientific Issues and Technologies Route



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 Operation Scenario



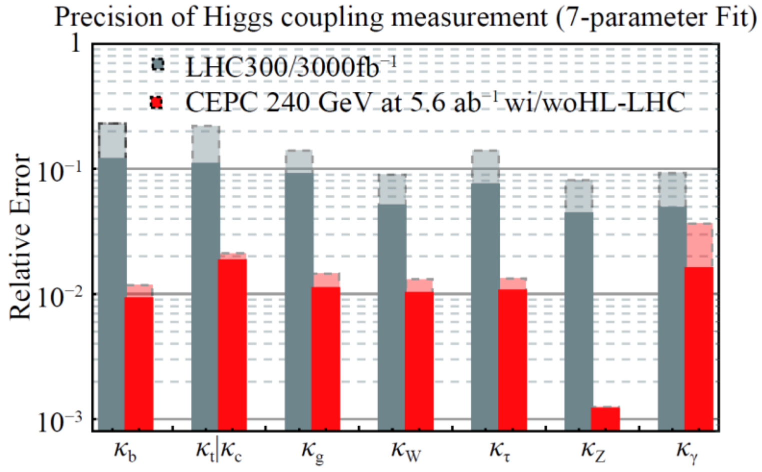
Operation mode		ZH	Z	W^+W^-	$t\bar{t}$
$\sqrt{s}$ [GeV]		~240	~91	~160	~360
Run Time [years]		10	2	1	5
30 MW	L / IP [$\times10^{34}$ cm^{-2}s^{-1}]	**5.0**	**115**	**16**	**0.5**
	$\int L\,dt$ [ab^{-1}, 2 IPs]	13	60	4.2	0.65
	Event yields [2 IPs]	2.6×10^6	2.5×10^{12}	1.3×10^8	4×10^5
50 MW	L / IP [$\times10^{34}$ cm^{-2}s^{-1}]	**8.3**	**192**	**26.7**	**0.8**
	$\int L\,dt$ [ab^{-1}, 2 IPs]	21.6	100	6.9	1
	Event yields [2 IPs]	4.3×10^6	4.1×10^{12}	2.1×10^8	6×10^5

CEPC accelerator TDR (Xiv:2312.14363)

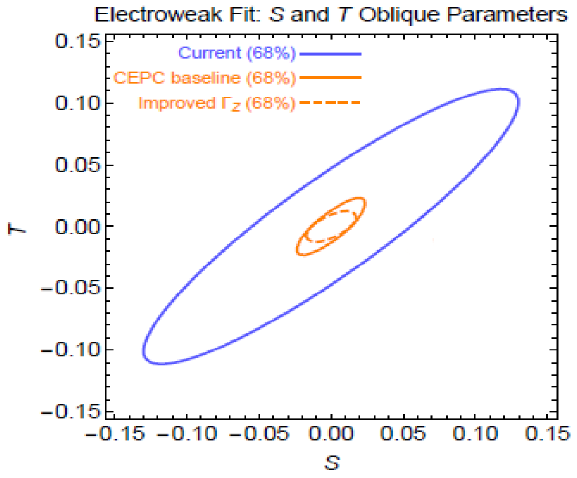
While aiming to have a detector that matches the needs of the whole energy range, we emphasize more on the Higgs operation mode.

CEPC Physics Program: Precision Measurement

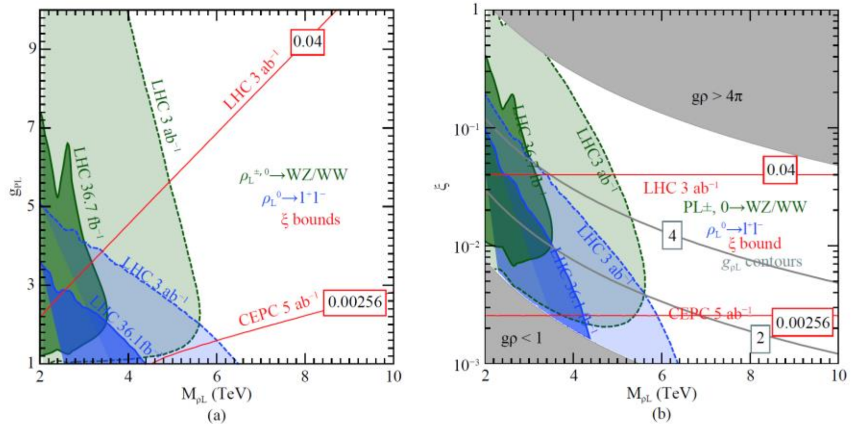
Higgs coupling precision can be improved by an order of magnititude

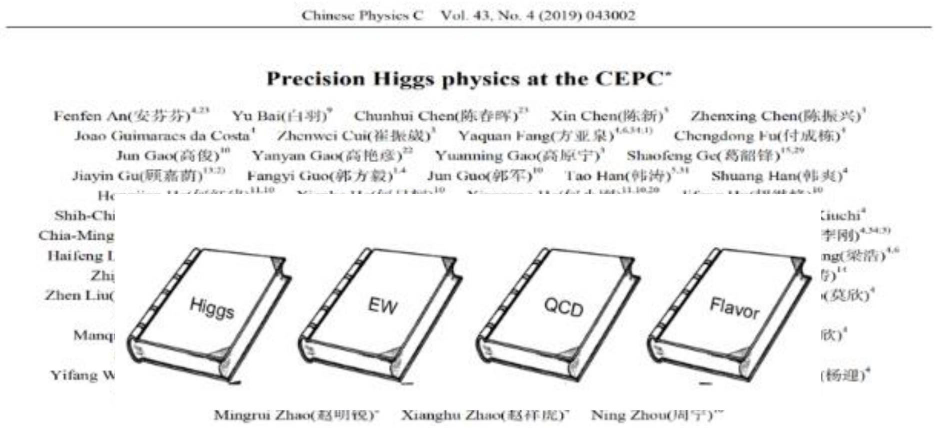


EW measurement can be improved by a large factor



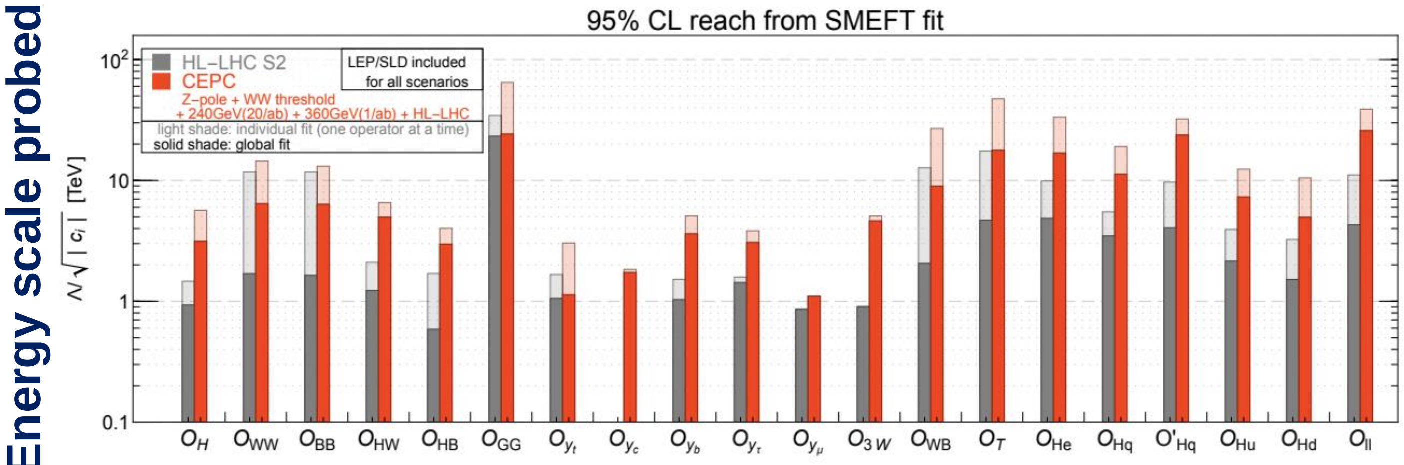
Direct and indirect probe to new physics up to 10 TeV, an order of magntitude higher than the HL-LHC




Chinese Physics C Vol. 43, No. 4 (2019) 043002
Precision Higgs physics at the CEPC*
Higgs
EW
QCD
Flavor

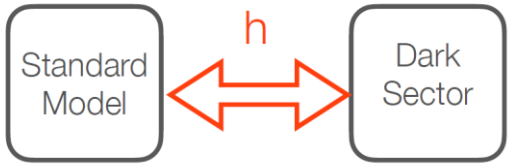
Chinese Physics C Vol. 43, No. 4 (2019) 043002

❖ ~ 300 Journal / arXiv papers

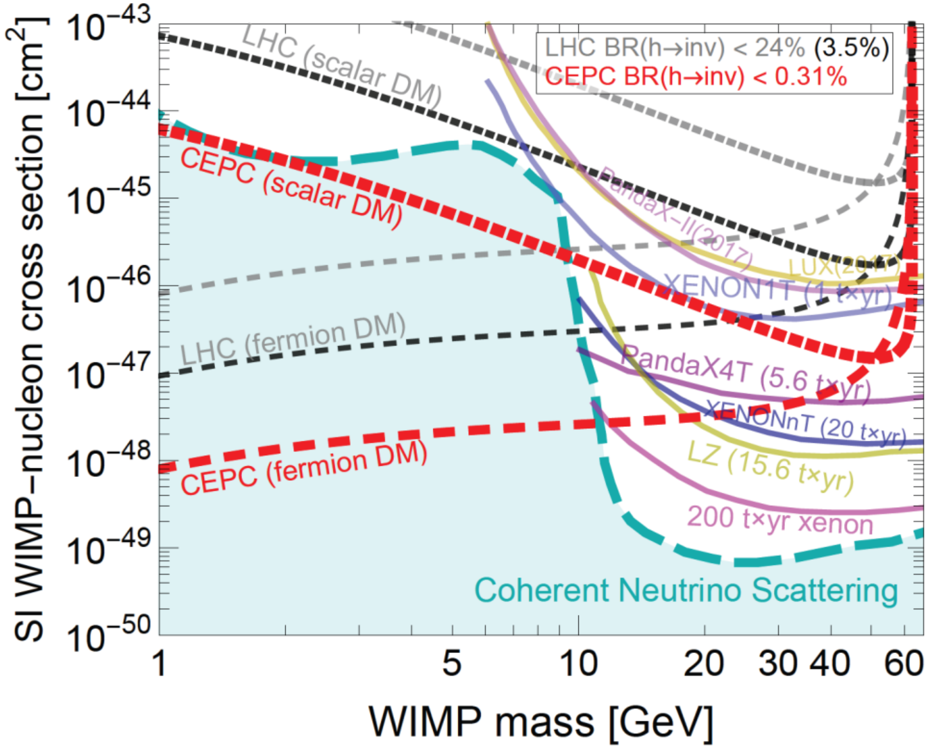


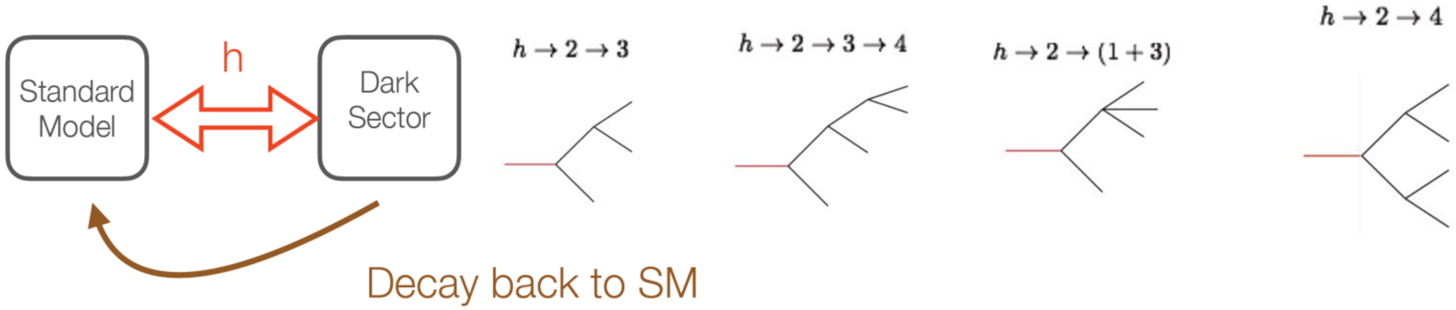
CEPC can reveal new physics at energy ~ 10 TeV or higher

CEPC Physics Program: Discovery Potential

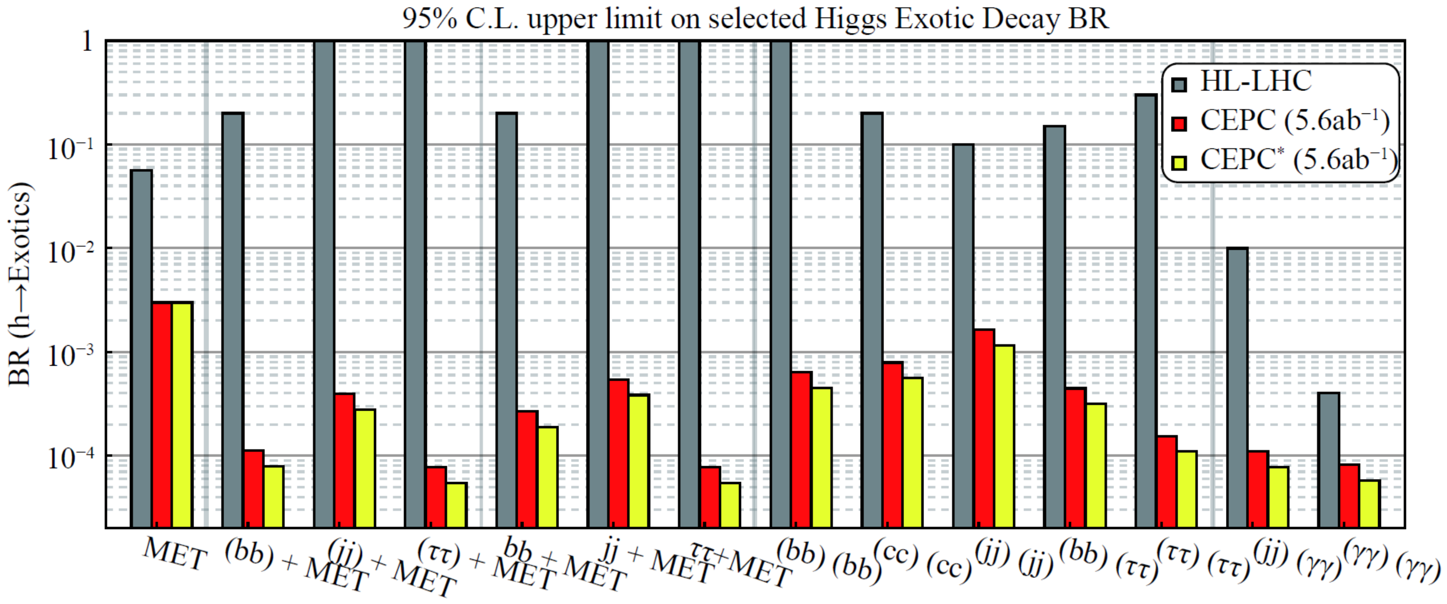


$$h \to X_{dm} X_{dm}$$





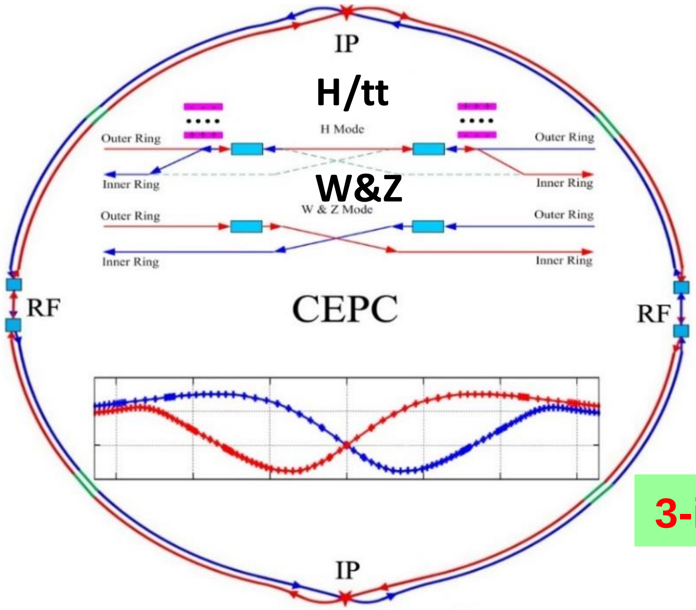
Higgs decays into BSM particles, H→ X_1X_2

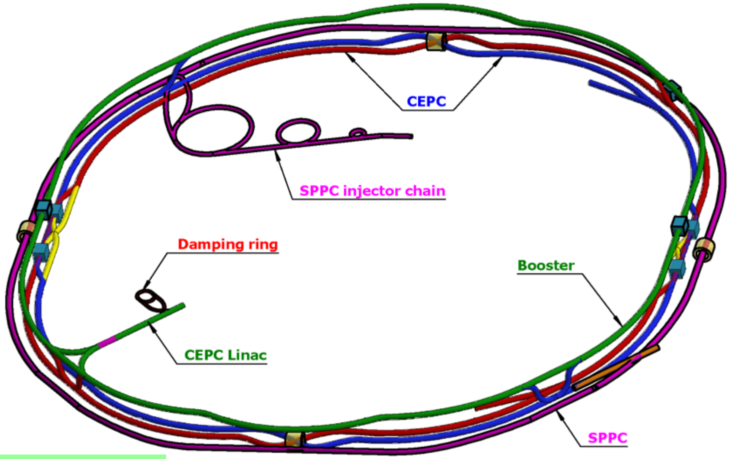


CEPC has significantly better detection sensitivity for dark matter and selected Higgs exotic decays than HL-LHC

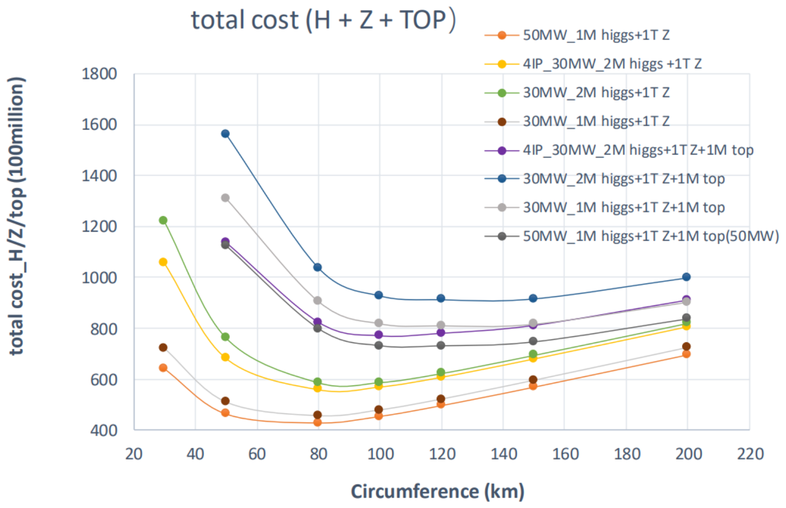
CEPC Accelerator Design and Layout

- 100 km double ring design (30 MW SR, upgradable to 50MW, ttbar)
- Switchable operation for H, Z, W and top modes
- Shared tunnel: compatible design for booster, CEPC and SppC





3-in-1 tunnel

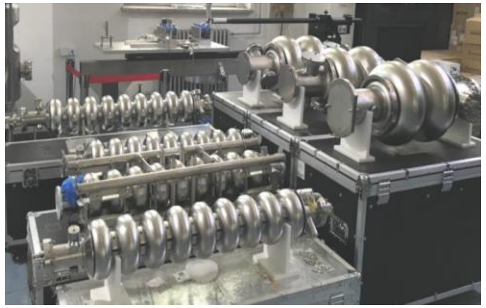


Cost optimization

JINST 17 P10018 (2022)

CEPC R&D: High Q SRF Cavities

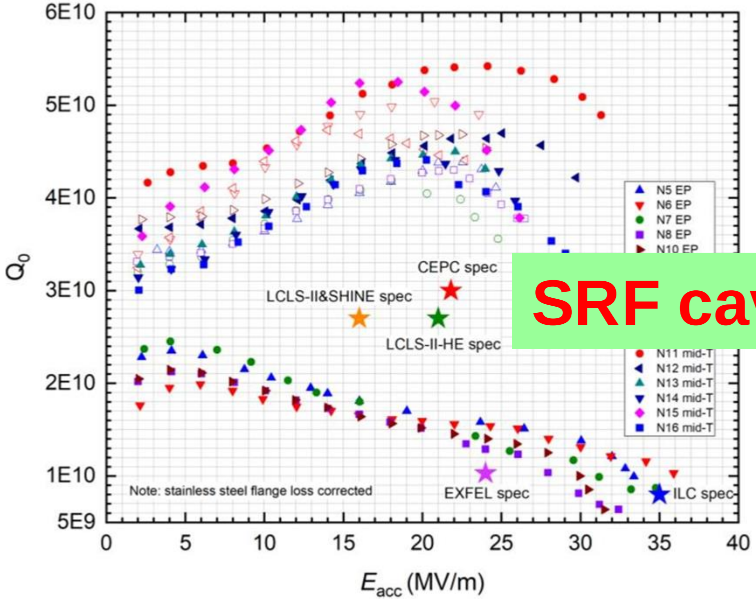
- 1.3 GHz 9-cell SRF cavity for booster: Q_0 = 3.4E10 @ 26.5 MV/m
- 650 MHz 2-cell SRF cavity for collider ring: Q_0 = 6.0E10 @ 22.0 MV/m
- 650 MHz 1-cell SRF cavity for collider ring: Q_0 = 6.0E10 @ 31.0 MV/m



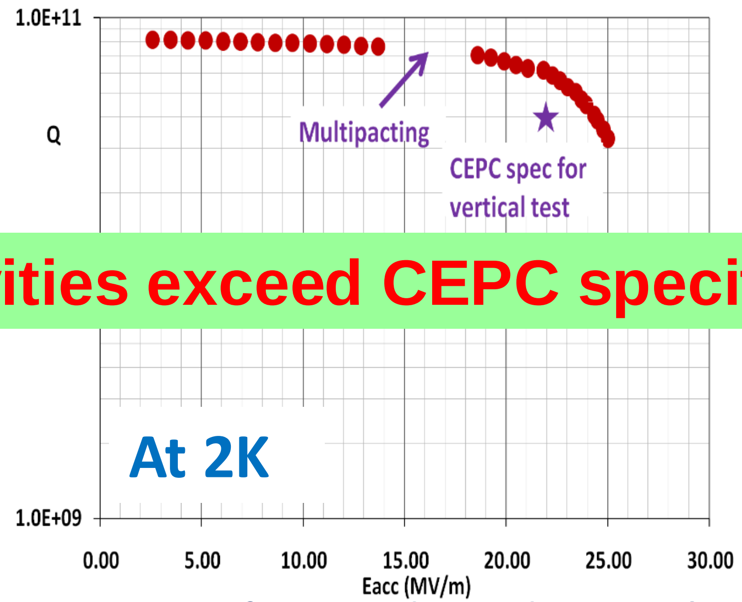
Vertical test of 650 MHz 2-cell cavity

Vertical test of 650MHz 1-cell Cavity

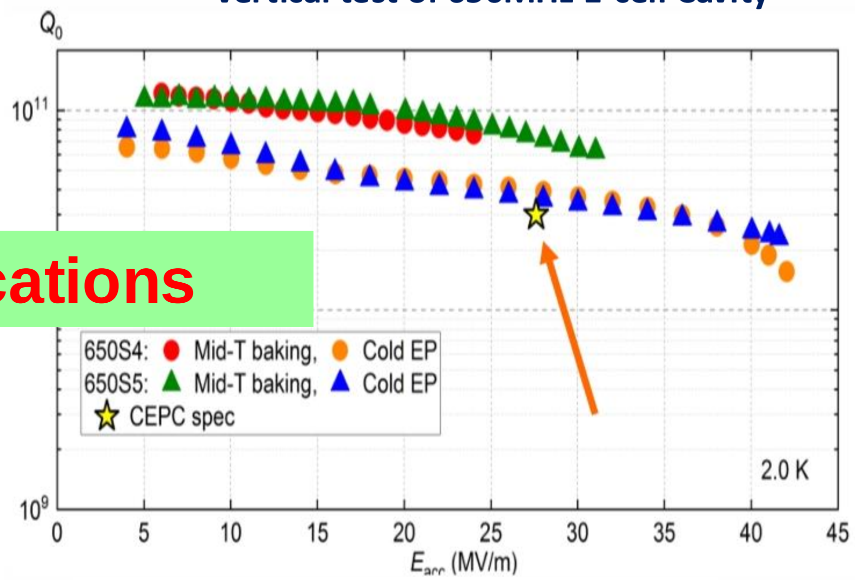
SRF cavities exceed CEPC specifications



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



Cold-EP and Mid-T baking Q_0 = 6.0E10 @ 31 MV/m

CEPC R&D: 8 × 9-cell High Q Cryomodule

CEPC Booster 1.3 GHz SRF R&D and industrialization in synergy with CW FEL projects

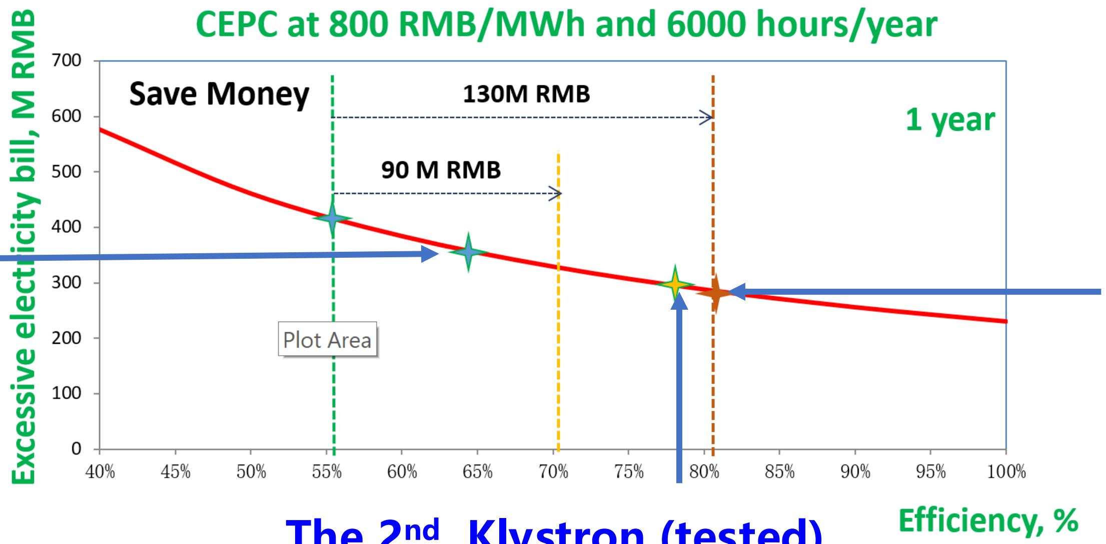
Parameters	Horizontal test results	CEPC Booster Higgs Spec	LCLS-II, SHINE Spec	LCLS-II-HE Spec
Average usable CW E_{acc} (MV/m)	23.1	3.0×10^{10} @ 21.8 MV/m	2.7×10^{10} @ 16 MV/m	2.7×10^{10} @ 20.8 MV/m
Average Q_0 @ 21.8 MV/m	3.4×10^{10}			

SRF cavities exceed CEPC specifications

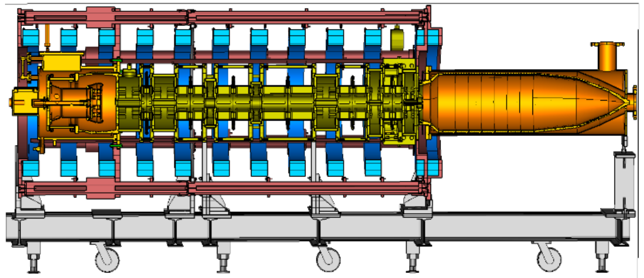
CEPC R&D: High Efficiency Klystrons

- The 1st Klystron prototype, achieved efficiency ~ 62%
- The 2nd Klystron prototype was tested in Feb. 2024, achieved efficiency ~ 77.2%
- The 3rd Klystron prototype with manufacture underway, design efficiency is ~ 80%
- High efficiency Klystron helps to reduce electricity consumption

The 1st Klystron (tested)



The 3rd multi-beam Klystron (MBK) under fabrication



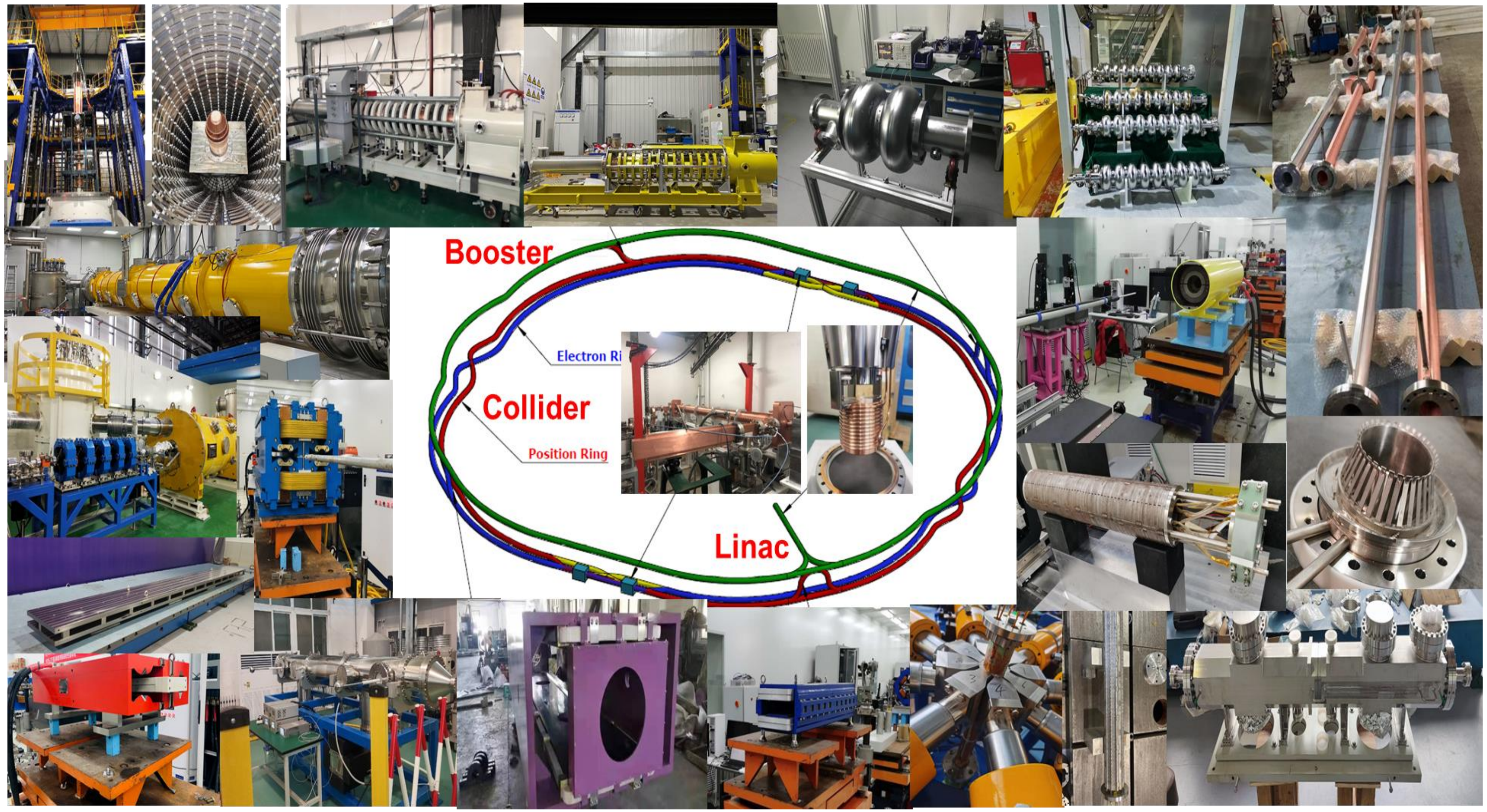
The 2nd Klystron (tested)

CEPC R&D: Accelerator Key Technologies

- CEPC accelerator key technologies R&D in TDR covers all component listed in the CDR.
- About 10% remaining (e.g. RF power source, machine integration, control, alignment) to be completed by 2026.

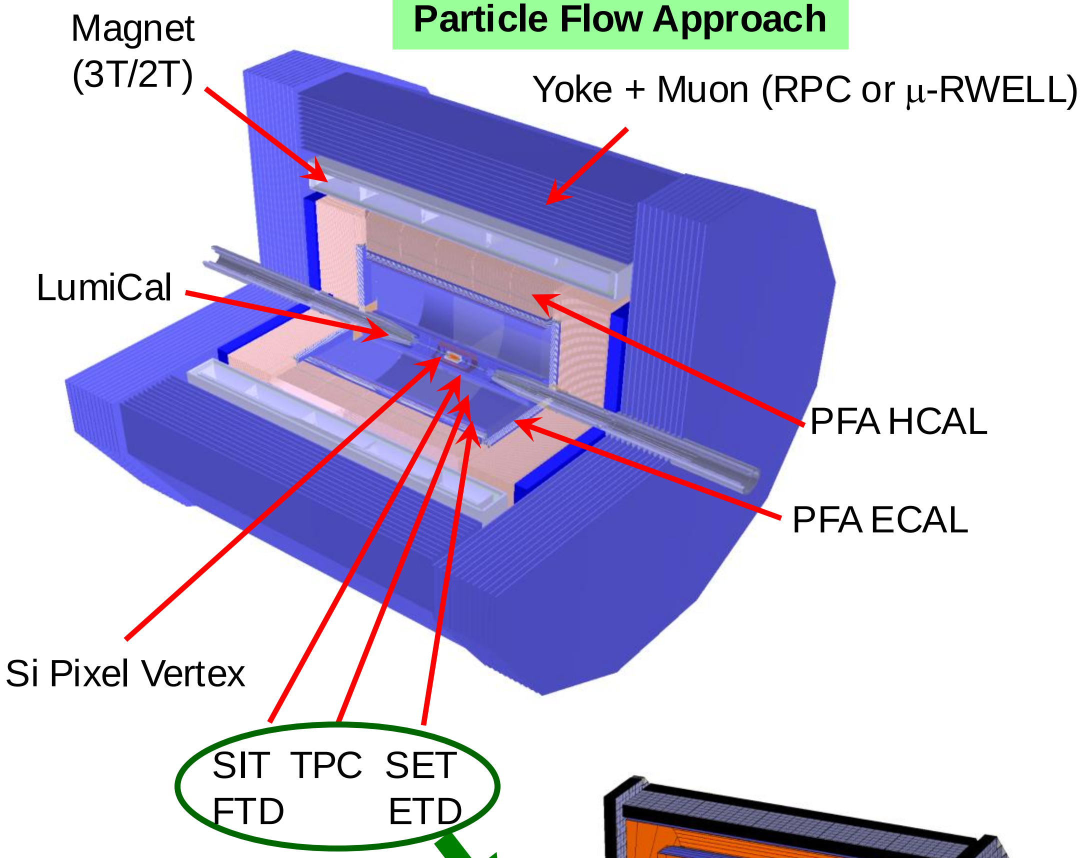
Specification Met   Prototype Manufactured

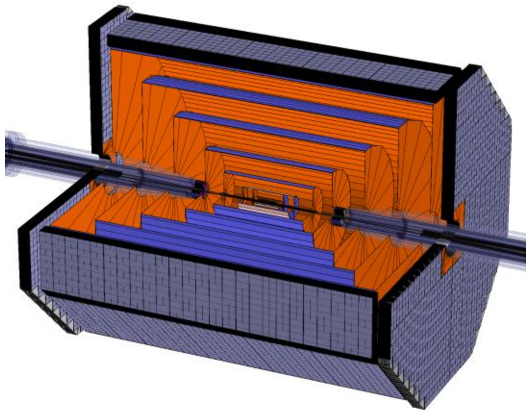
Accelerator	Ratio
Magnets	27.3%
Vacuum	18.3%
RF power source	9.1%
Mechanics	7.6%
Magnet power supplies	7.0%
SC RF	7.1%
Cryogenics	6.5%
Linac and sources	5.5%
Instrumentation	5.3%
Control	2.4%
Survey and alignment	2.4%
Radiation protection	1.0%
SC magnets	0.4%
Damping ring	0.2%



CEPC Conceptual Detector Designs

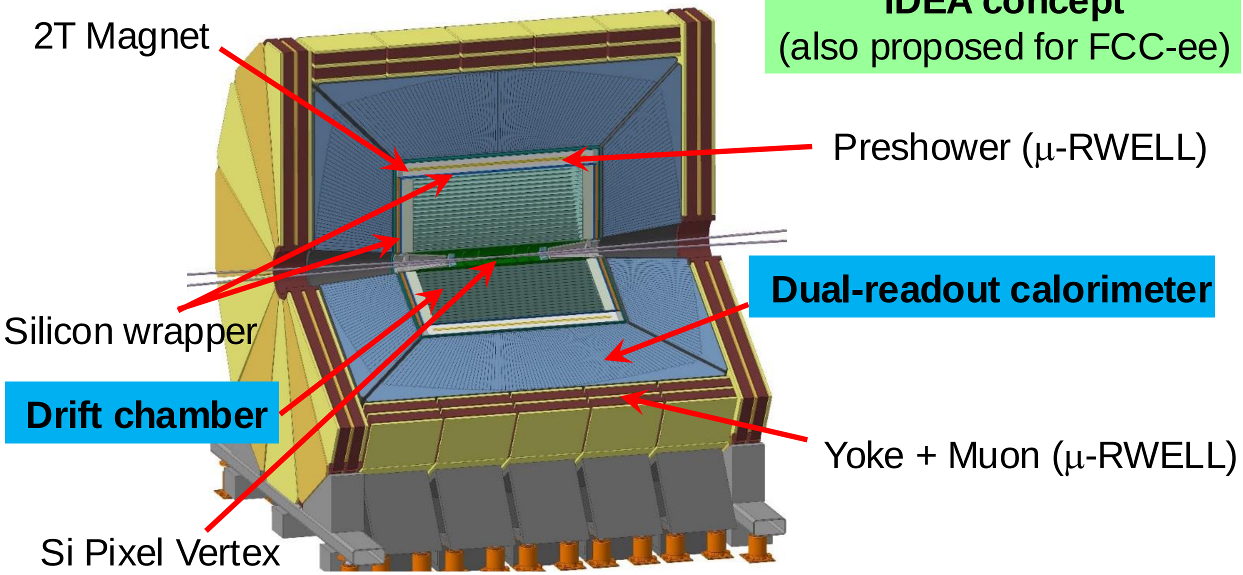
(Baseline Design)
Particle Flow Approach



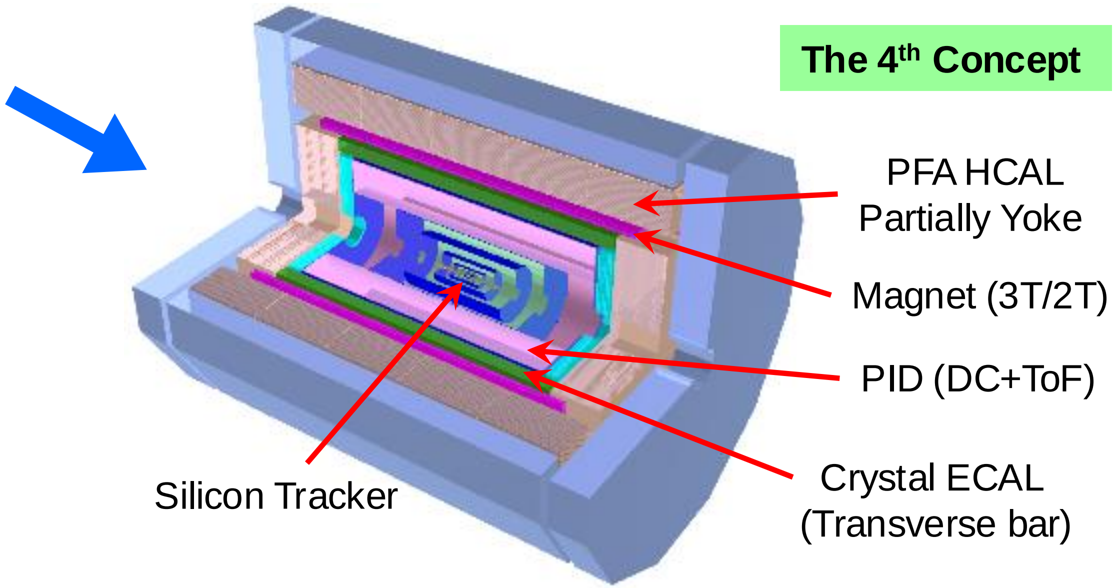


FST concept
(Full Silicon Tracker)

IDEA concept
(also proposed for FCC-ee)



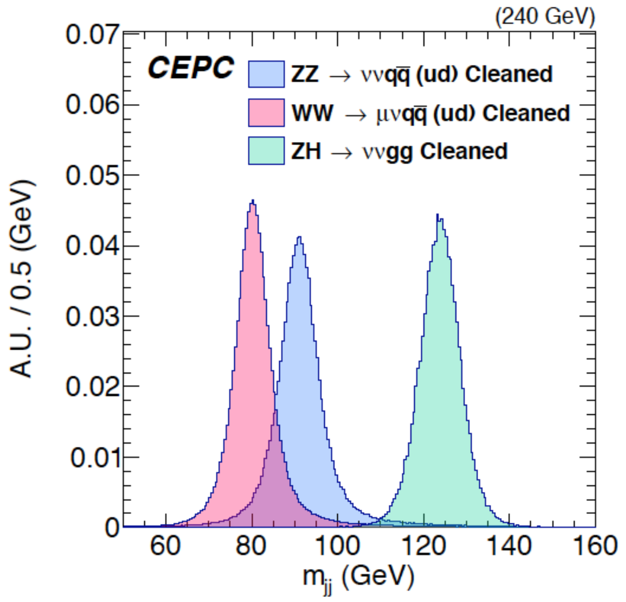
The 4th Concept

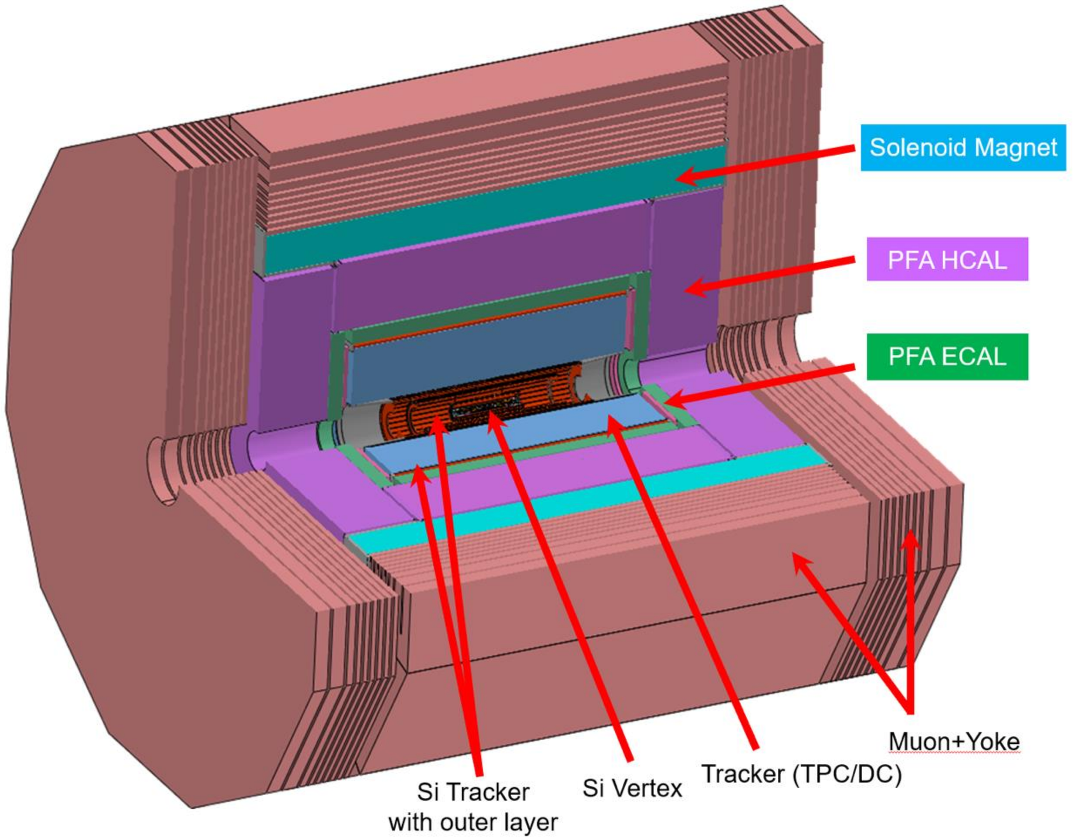


Idea of the "4th Concept"

Novel detector design based on PFA calorimeter. Aim at improving BMR from 4% to 3%

Detector	World-class level	4th concept
PFA based (ECAL)	～ 20% / √E	< 3% / √E
PFA based (HCAL)	～ 50% / √E	～ 40% / √E

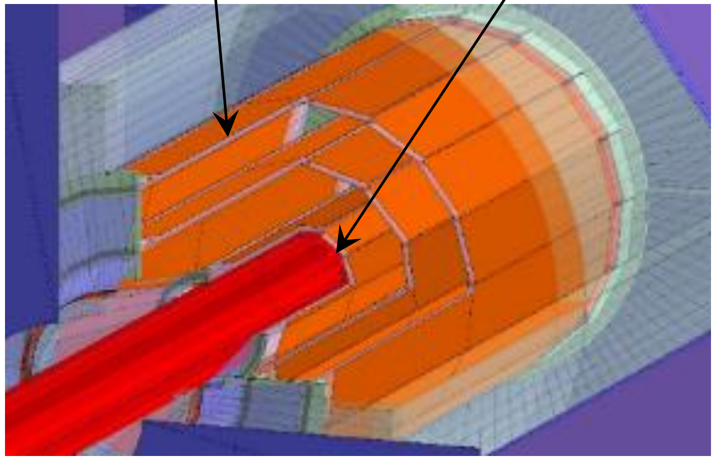




- Silicon combined with TPC or DC for **better tracking & PID**
- Crystal ECAL with timing for **PFA and better EM resolution**
- Scintillating glass HCAL for **better sampling and resolution**

CEPC R&D: Silicon Pixel Chips

2 layers / ladder R_{in}~16 mm



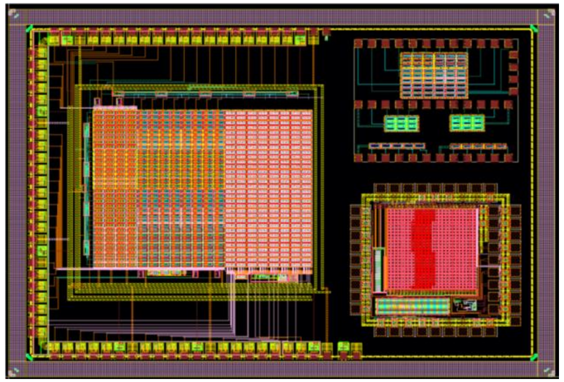
Goal: σ(IP) ~ 5 μm for high P track

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**, **COFFEE**

Develop **COFFEE** for a CEPC tracker using SMIC 55nm HV-CMOS process

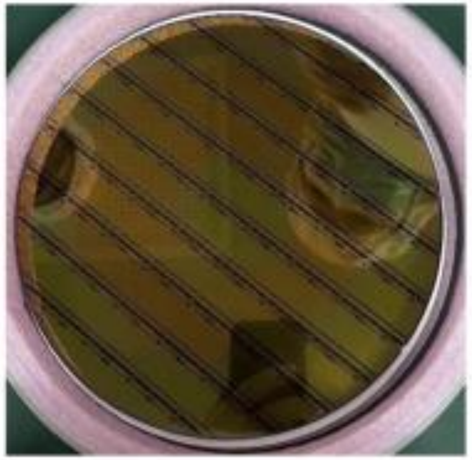


JadePix-3 Pixel size ~16×23 μm²

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

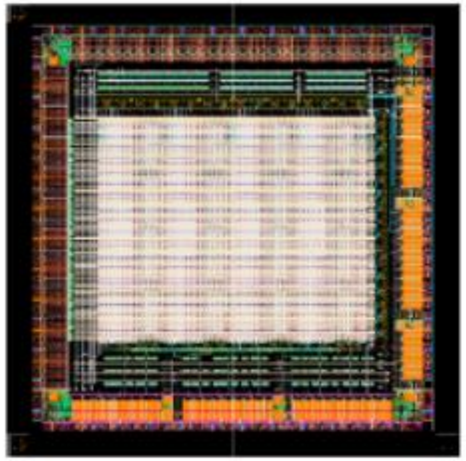
MOST 1

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

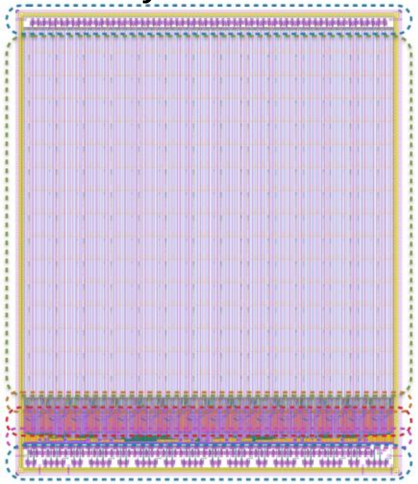


MOST 2

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



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



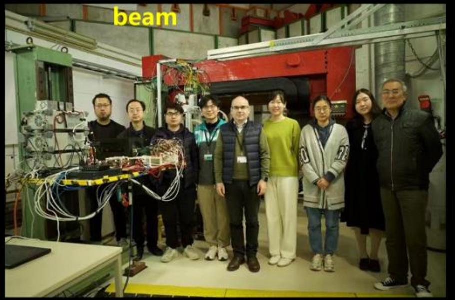
CEPC Detector R&D: Silicon, TPC, DC Prototypes

Test beam @ DESY

- 2^{nd} testbeam: April 11-23 2023 DESY test beam in Germany (4-6 GeV electron)
  - Vertex detector prototype testbeam
- 1^{st} testbeam: Dec 12-22 2022 DESY test beam in Germany (4-6 GeV electron)
  - TaichuPix Beam Telescope testbeam

2022 DESY test beam

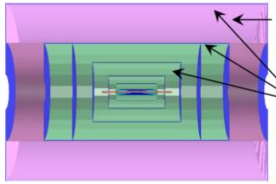
2023 DESY test beam

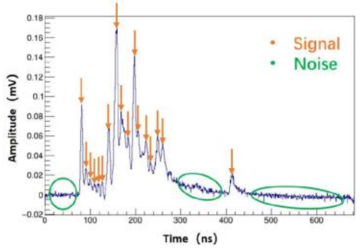


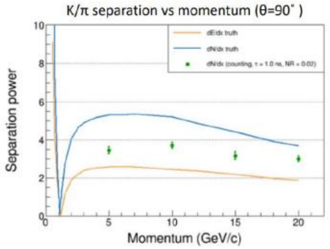
Excellent collaboration with DESY testbeam team

13

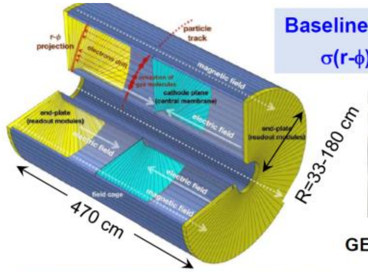
- **Goal: 3σ π/K separation up to ~20 GeV/c.**
- Cluster counting method, or **dN/dx**, measures the number of primary ionization
- **Can be optimized specifically for PID**: larger cell size, no stereo layers, different gas mixture.
- Garfield++ for simulation, realistic electronics, peak finding algorithm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



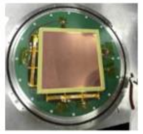


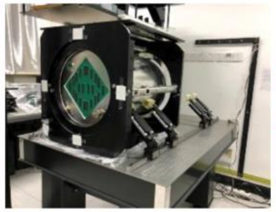


IHEP and Italian INFN groups have close collaboration and regular meetings.
IHEP joined the TB (led by INFN group) in 2021 and 2022

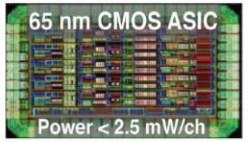


Baseline main tracker
σ(r-ϕ) ~100 μm



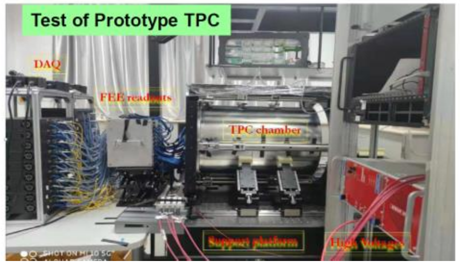


MOST 1 (IHEP+THU)

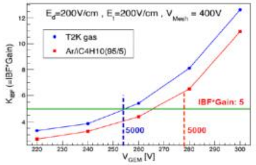


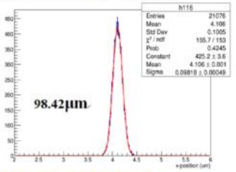
GEM-MM cathode TPC Prototype + UV laser beams Low power FEE ASIC

Test of Prototype TPC

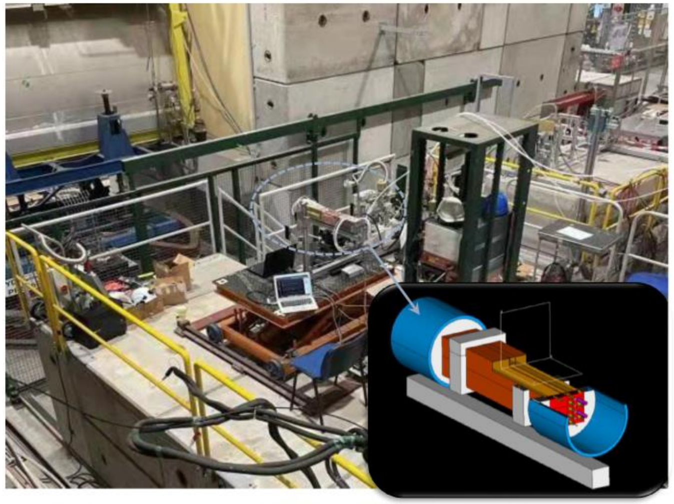


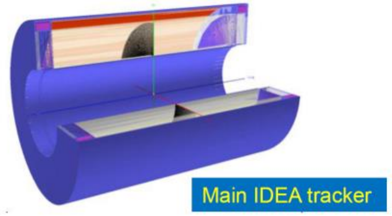
- Challenge: Ion backflow (IBF) affects the resolution. It can be corrected by a laser calibration at low luminosity, but difficult at high luminosity Z-pole.



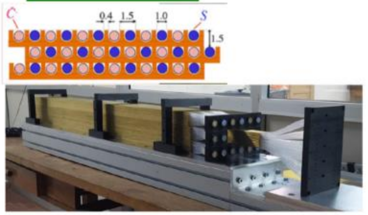


σ_x < 100 μm for drift length of 27cm





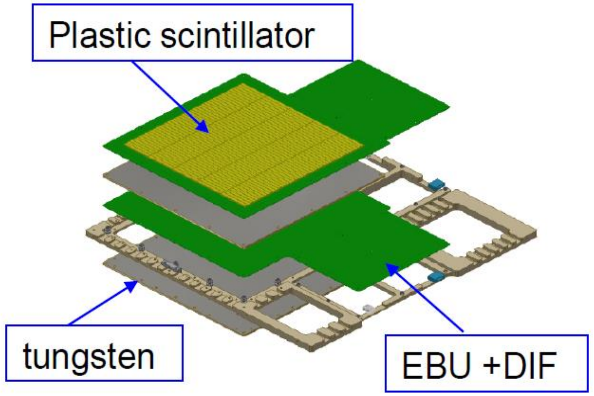
Dual Readout CAL

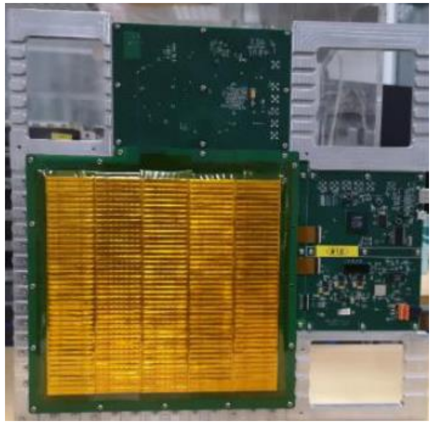


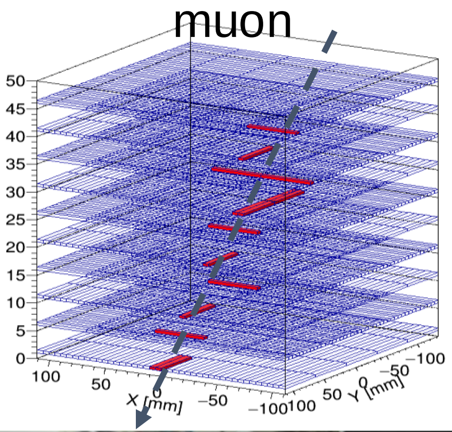
Italian groups and IHEP colleagues participated the test beam at CERN.

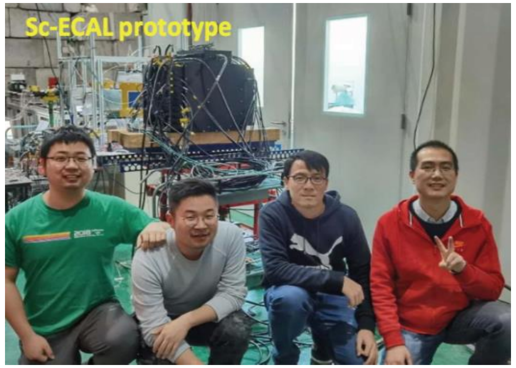
CEPC R&D: PFA Calorimeter Prototypes

ScW ECAL Prototype (32-layer, 6720-ch)

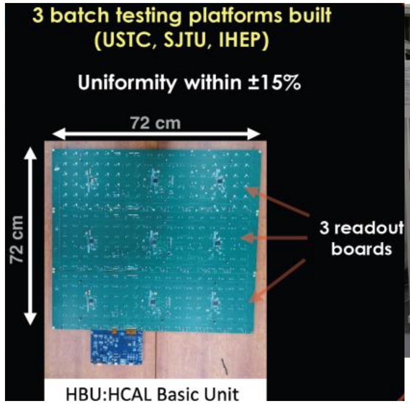


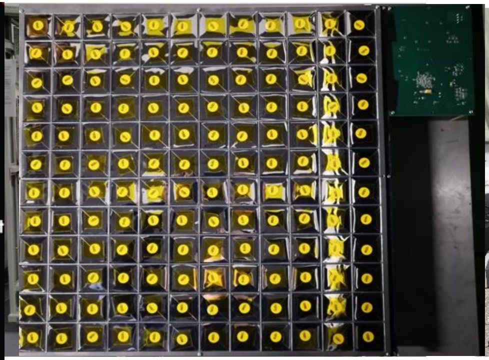






Scintillator + SiPM AHCAL Prototype (40-layer, 12960-ch)

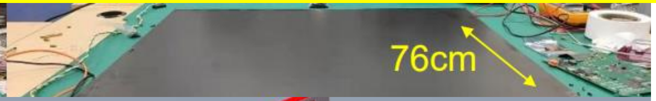


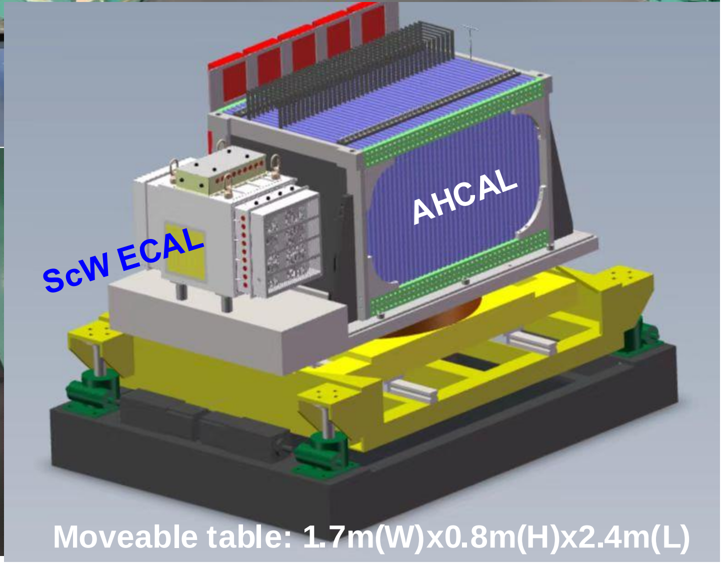


SJTU

IHEP

Combined: ScW-ECAL + AHCAL

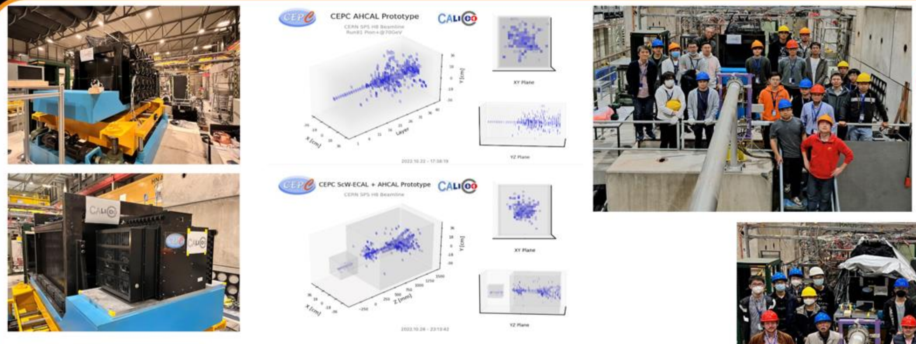




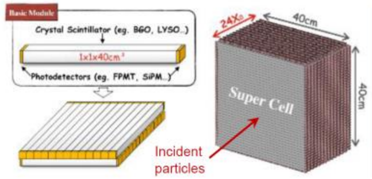
➔ Testbeam at CERN for two prototypes in 2022 and 2023

CEPC Detector R&D: Calorimeter Prototypes

CEPC calorimeter prototypes: beamtest in 2022



- Successful beamtest at CERN SPS H8: **Oct-Nov, 2022**
  - High energy particle beams: muons, positrons and hadrons (10 - 160 GeV)
  - Suffered from beam purity issue in pion and positron beams

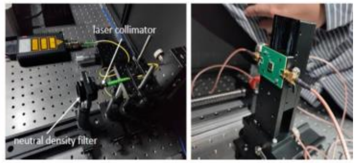


- Long bars: 1 x 40 cm, super-cell: 40x40 cm^2
- Timing at both ends for positioning along bar.
- Significant reduction of number of channels.

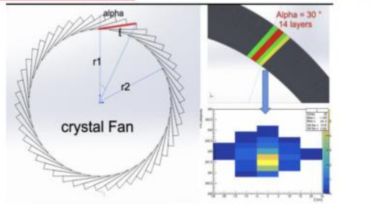
Goal

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

Bench Test

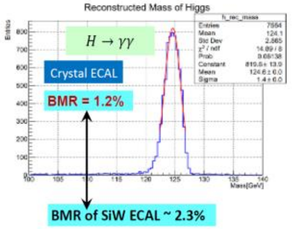


Crystal Fan Design Fine segmentation in Z, ϕ, r

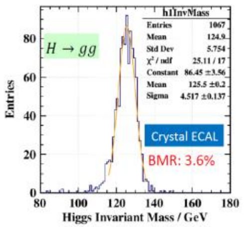


Full Simulation Studies + Optimizing PFA for crystals

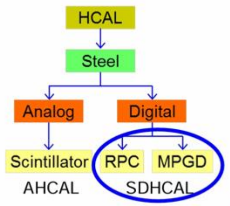
Performance with photons

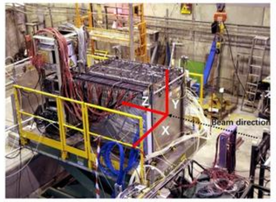


Performance with jets

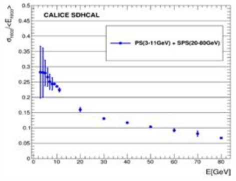


Dual readout crystal calorimeter also being considered by USA and Italian colleagues

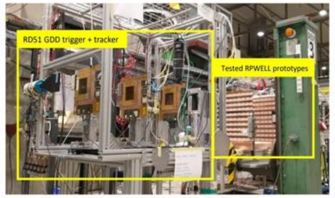




SDHCAL-GRPC (1.3 m^3, IPNL)



JINST 15, P10009 (2020)
JINST 17, P07017 (2022)



RPWELL (50x50cm^2, WIS+IIT, Israel)

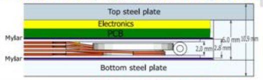
MOST 1: RPC and MPGD (RWELL) R&D，MIP Eff > 95%

GRPC 1m x 1m (SJTU)

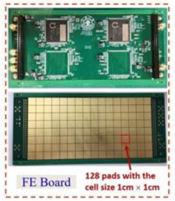
JINST 16, P12022 (2021)

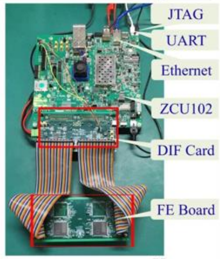
RWELL 0.5m x 1m (USTC+IHEP)

R&D Plan: 5-D SDHCAL (X, Y, Z, E, Time)
- MRPC + fast timing PETIROC ASIC (~40 ps)



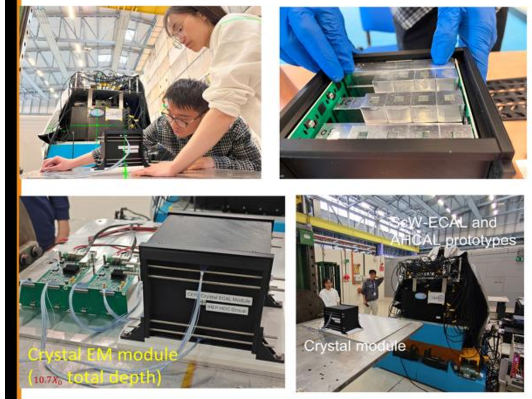
SJTU
IPNL
IJCLab
OMEGA
CIEMAT

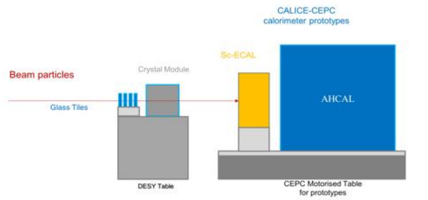




Crystal modules: beamtest at CERN in 2023

- Successful CERN beamtest: parasitic runs at PS-T9 (May 16-23, 2023)





- Achieved major goals
  - Commissioning of the first crystal module
  - Validation of simulation and digitization

CEPC Reference Detector TDR

Det	Technology	Det	Technology
Pixel Vertex	JadePix	Calorimeter	Crystal ECAL
	TaichuPix		Stereo Crystal ECAL
	CPV(SOI)		Scint+W ECAL
	Stitching		Si+W ECAL
	Arcadia		Scint+Fe AHCAL
Tracker & PID	CEPCPix		ScintGlass AHCAL
	Silicon Strip		RPC SDHCAL
	TPC		MPGD SDHCAL
	Drift chamber		DR Calorimeter
	PID drift chamber	Muon	Scintillation Bar
	LGAD ToF		RPC
Lumi	SiTrk+Crystal ECAL		μ-Rwell
	SiTrk+SiW ECAL		HTS / LTS Magnet
	CEPC SW		MDI & Integration
	TDAQ		

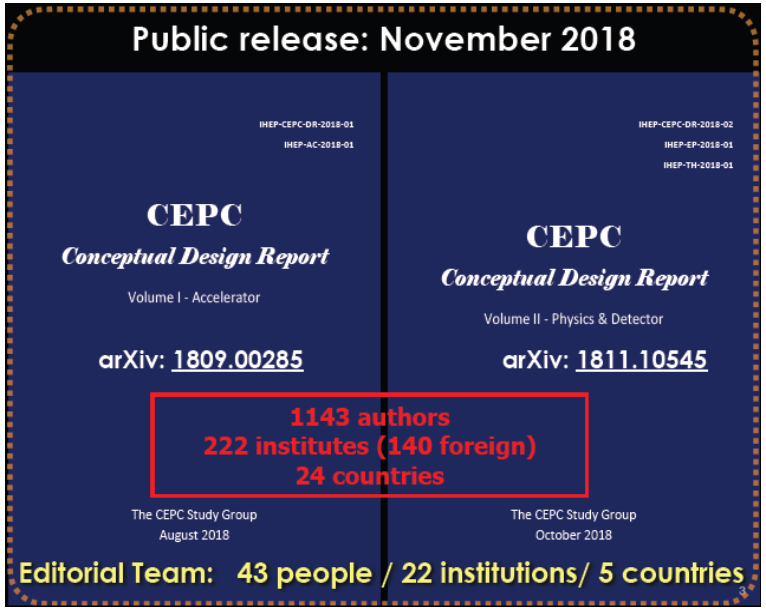
- **Large number of detector technology options and R&D projects on-going, they are not at similar level of maturity.**
- **Need to converge technology options towards a CEPC reference detector TDR**
  - Start preparation in Jan. 2024
  - A draft version of TDR in Dec. 2024
  - **Official release of TDR in Jun. 2025**

CEPC International Collaboration

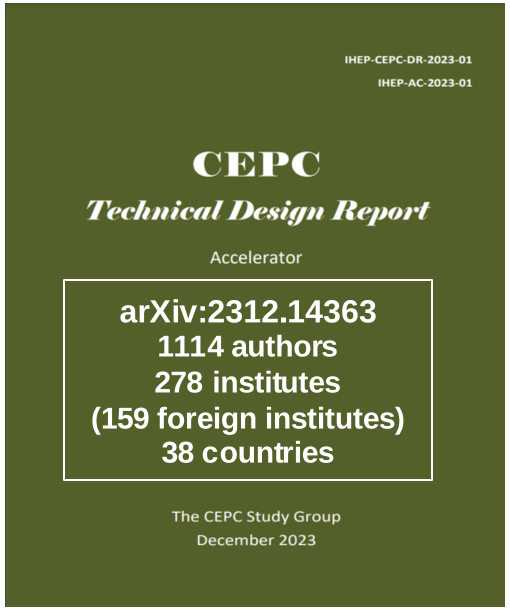
CEPC attracts significant International participation

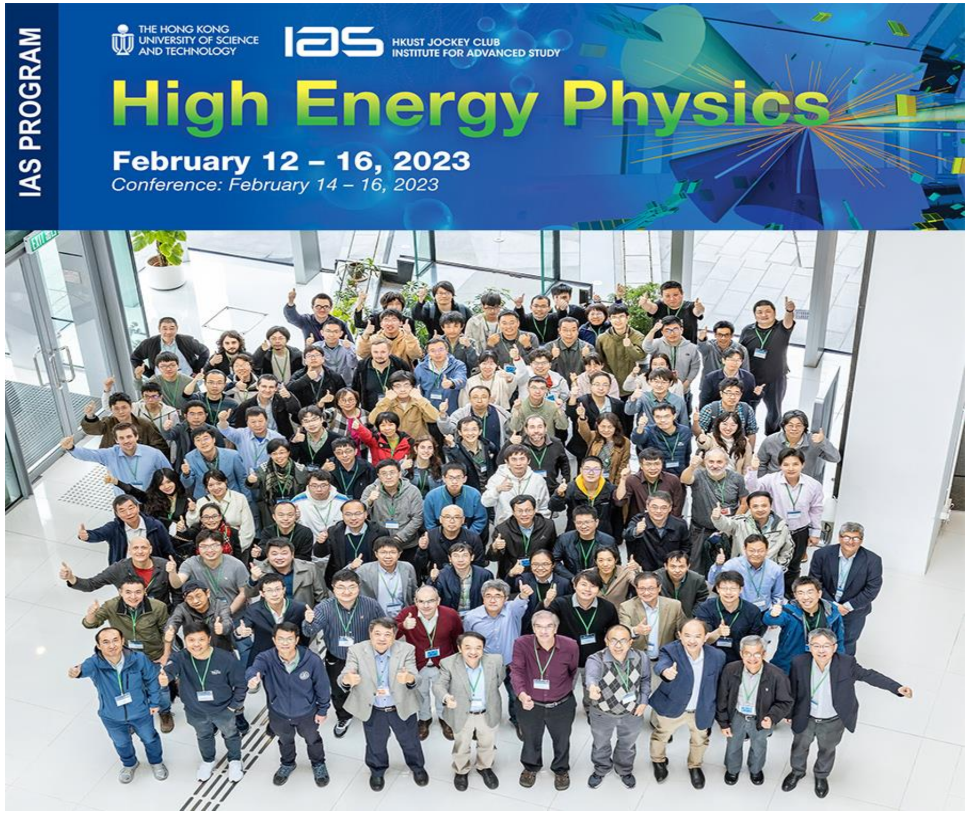
- Both CDR and TDR have significant intl. contributions
- 20+ MoUs signed with Intl. institutions and universities
- CEPC International Workshop since 2014
- EU-US versions of CEPC Workshop since 2018
- Annual working month at HKUST-IAS since 2015

CEPC CDR released (2018)

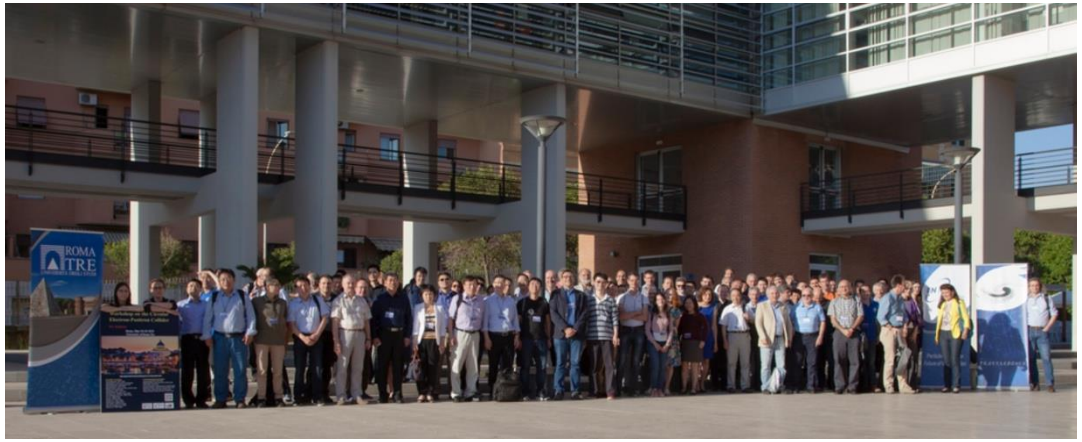


CEPC TDR released (2023)





CEPC International Collaboration



CEPC @ Rome, Italy, May 2018

CEPC @ Oxford, UK, April 2019

CEPC @ Edinburgh, UK, July 2023

CEPC @ U. Chicago, USA, Sept. 2019
CEPC @ Washington DC, USA, April 2020

Industrial Partners and Suppliers Worldwide

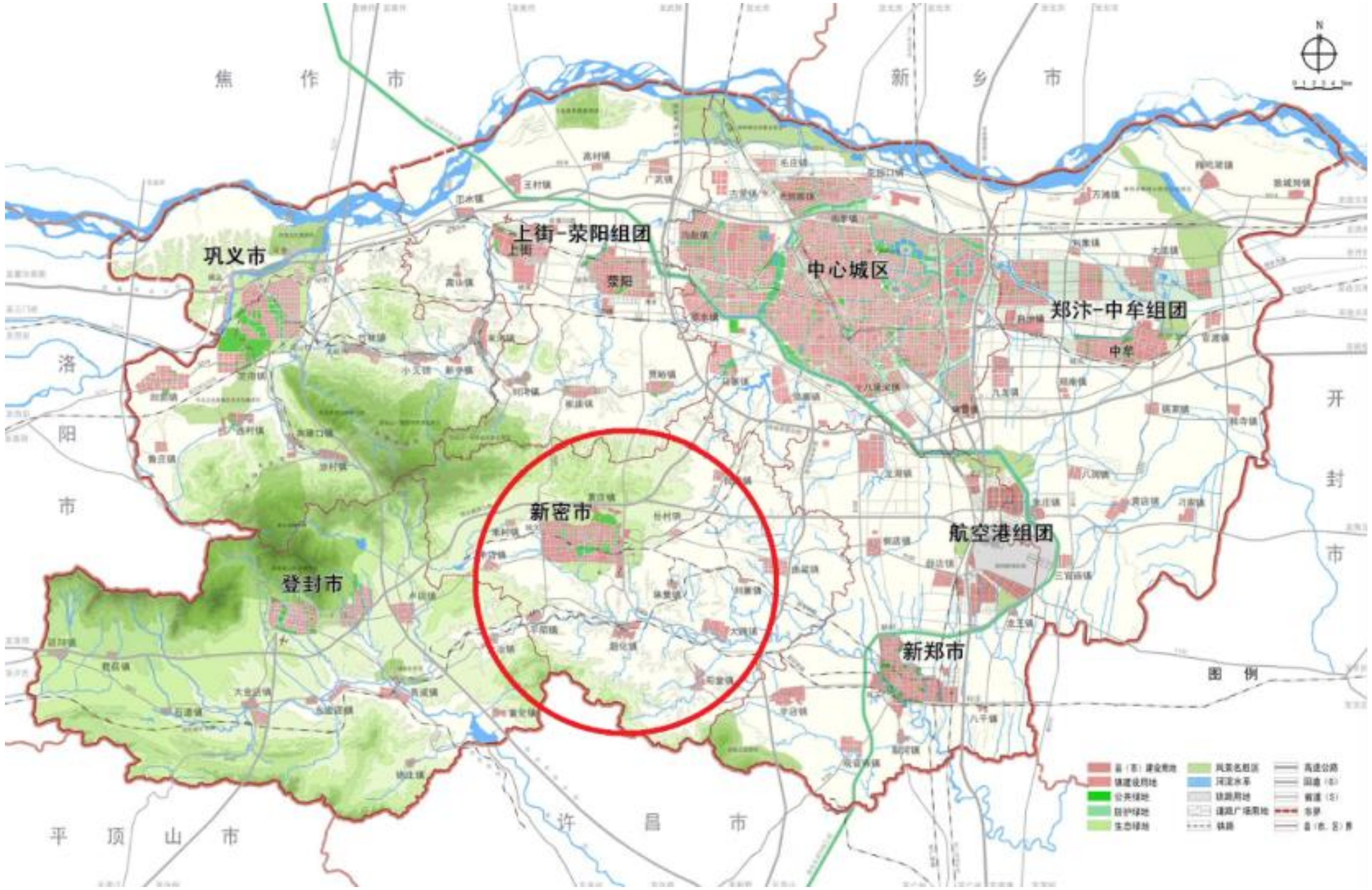
	System
1	Magnet
2	Power supplier
3	Vacuum
4	Mechanics
5	RF Power
6	SRF / RF
7	Cryogenics
8	Instrumentation
9	Control
10	Survey and alignment
11	Radiation protection
12	e^-e^+Sources

CEPC Industrial Promotion Consortium (CIPC, established in Nov. 2017)

Potential international collaborating suppliers and partners worldwide

CEPC选址河南

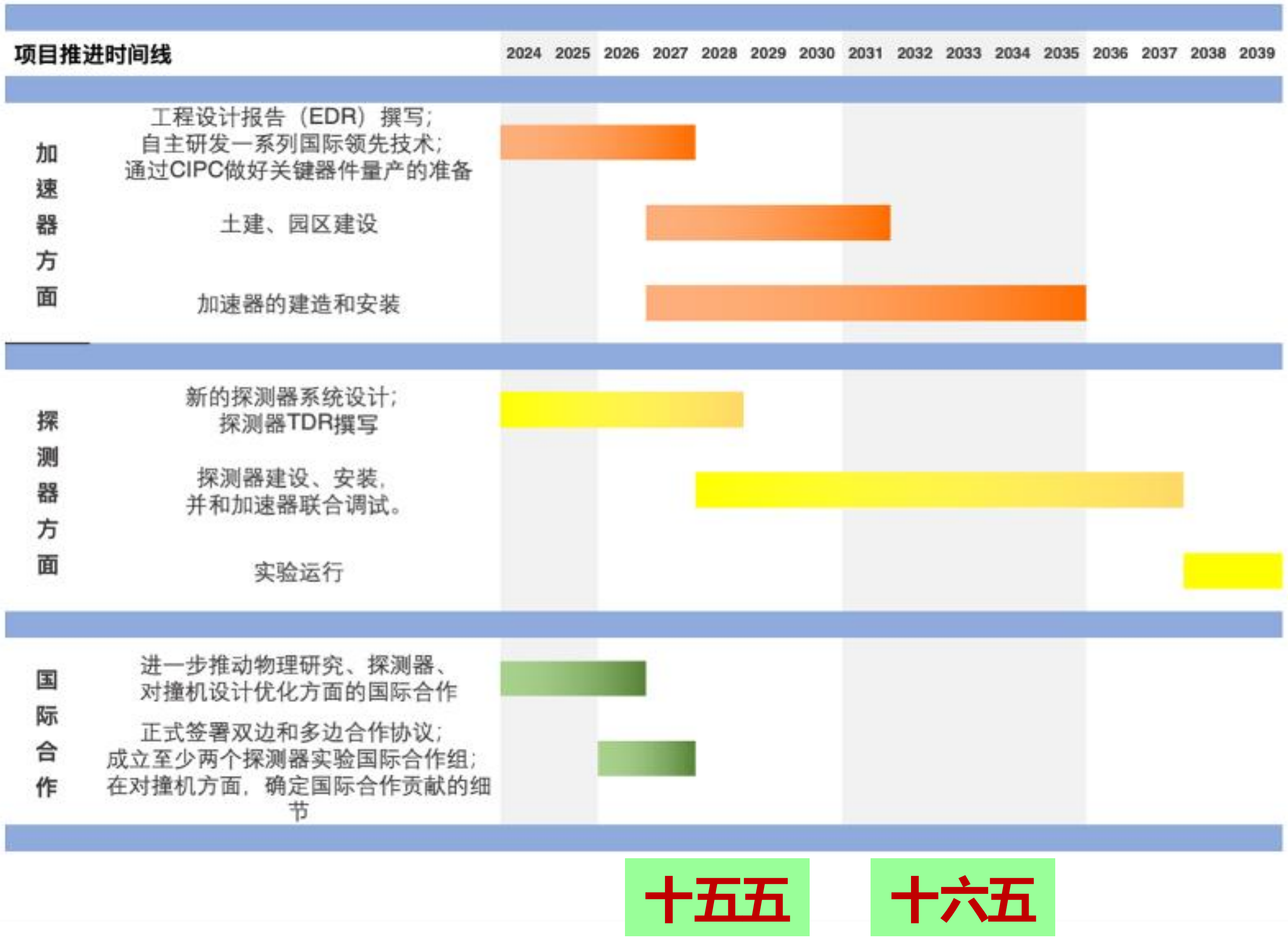
- 河南省委、省政府、省科创委认识到CEPC对地方的引领带动作用，正式决议支持项目落地河南
  - 已决定投入建设“高能物理研究中心”，开展选址与相关预研
    - CT检测中心,正电子源平台，等离子体加速，科教融合，CEPC，…
- 河南省委省政府将选址建设国际科学城，以CEPC为牵引，吸引国内外科教、人才和高新企业资源，建设国际科技高地



项目建设周期（4.1）

2012.9	2015.3	2018.11	2023.12	2025.6	2027	十五五规划
项目提出	初步概念设计报告	概念设计报告	加速器技术设计报告	探测器技术设计报告	加速器工程设计报告	获批准后开始建造

- 2025：完成探测器技术设计报告
- 2025：提交 CEPC 项目建议书
- 批准后成立两个国际合作实验组
- 2027：完成加速器工程设计报告并开始CEPC项目施工
- 2035：完成CEPC项目建设
- 2037：完成加速器和探测器联调



总结

- 将探索粒子物理领域最重要、最紧迫和具有共识的科学问题，科学突破潜力和意义重大。
- 过去多年的持续设计和研发，技术和实施方案均国际领先，相比欧洲FCC优势明显。
- 依托CEPC，围绕粒子物理、技术研发和多学科开展独一无二的研究和创新工作。
- 加速器方案明确可行，设计、技术和工艺成熟；完成《技术设计报告》，通过了国际评审。
- 相比国外FCC等项目，我们具有技术和时间等优势；CEPC希格斯工厂将引领我国粒子物理进入领域的主流前沿。
- 提议在“十五五”期间开建、于“十六五”期间建成并开始运行。

"The greater danger for most of us lies not in setting our aim too high and falling short; but in setting our aim too low, and achieving our mark" *(Michelangelo)*

Aim high or we will not realize the potential of our field, discovery will be stalled and we betray ourselves and the next generation.

"取法于上，仅得为中，取法于中，故为其下"——李世民《帝范》

Photo credit: Michael Hoch/CERN