Future Colliders for High Energy Physics in China (CEPC & STCF)

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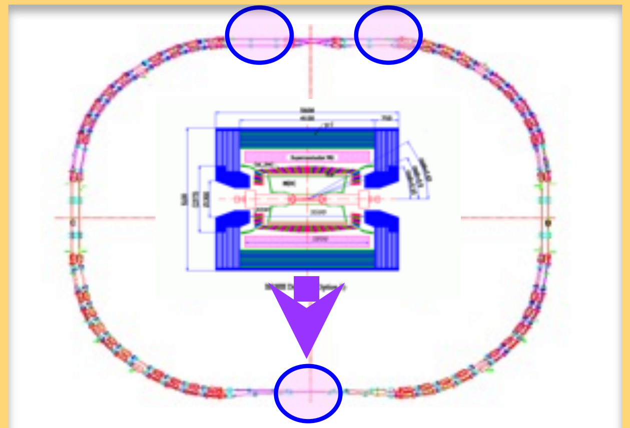
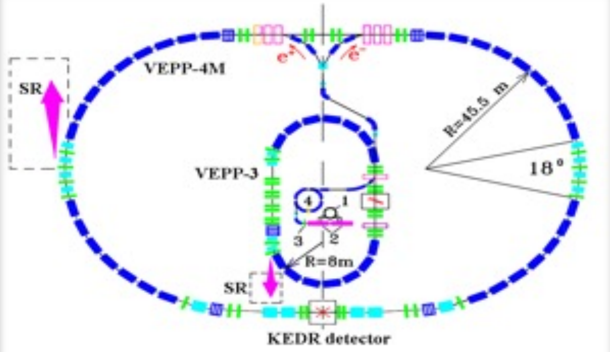
University of Science and Technology of China

The 8th International Conference on Micro-Pattern Gaseous Detectors
University of Science and Technology of China
Hefei, China
October 15, 2024

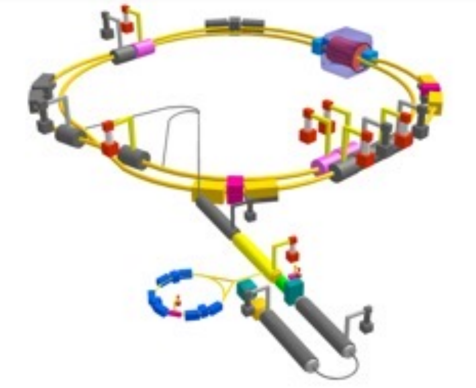
High Energy Physics with Colliders



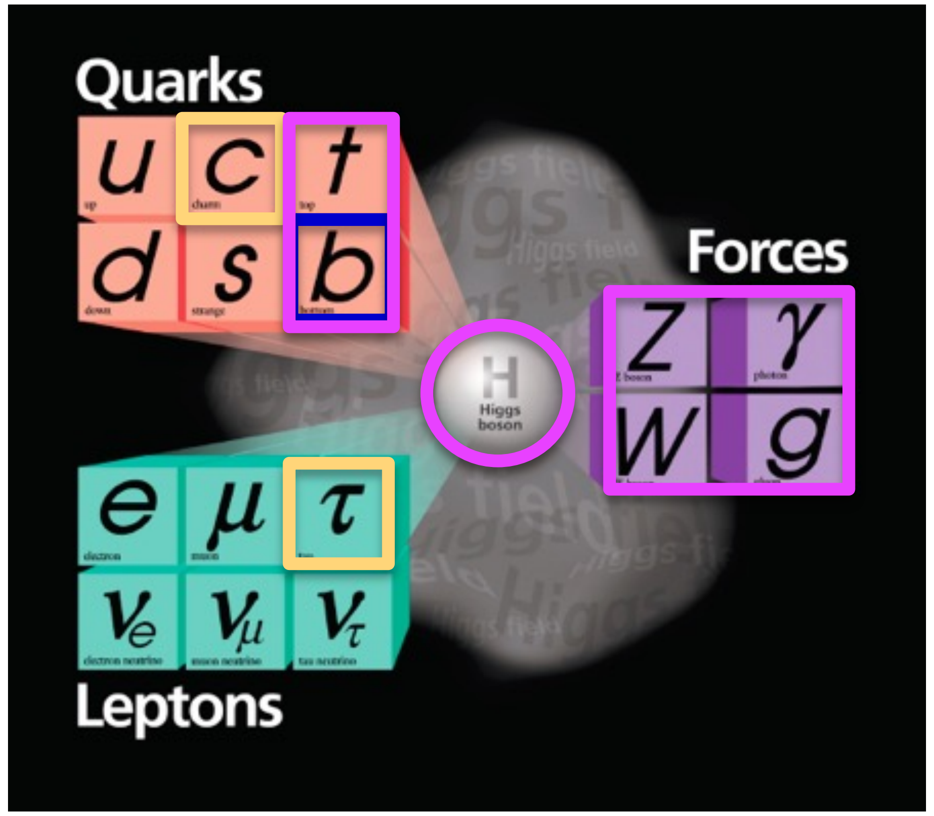
China BEPC II



Russia VEPP-4M



Japan SuperKEKB



Europe LHC

BEPCII, SKEKB

LHC

High Precision Frontier

hadron structure, exotic states, nature of strong interaction, flavor physics & CPV …

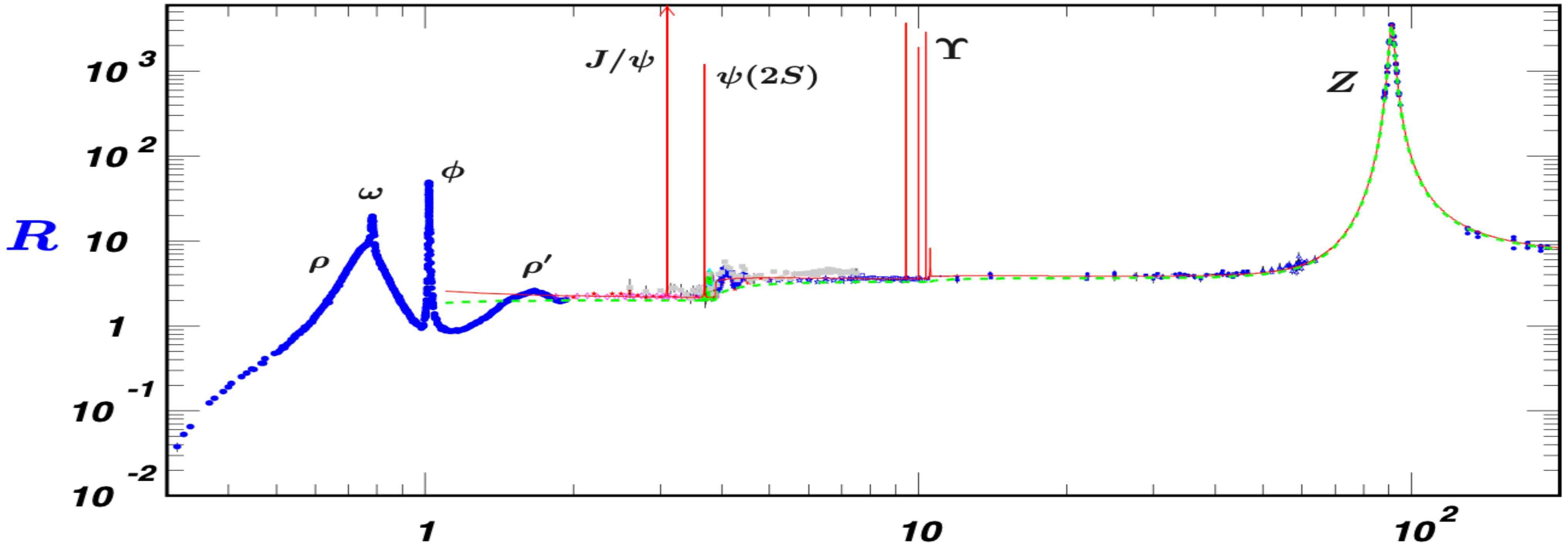
High Energy Frontier

origin of mass, nature of EWSB, new physics with Higgs, SUSY, Dark matter, universe evolution …

In-depth exploration at both precision and energy frontiers is called for more than ever in the post Higgs era

Future HEP Colliders Proposed in China

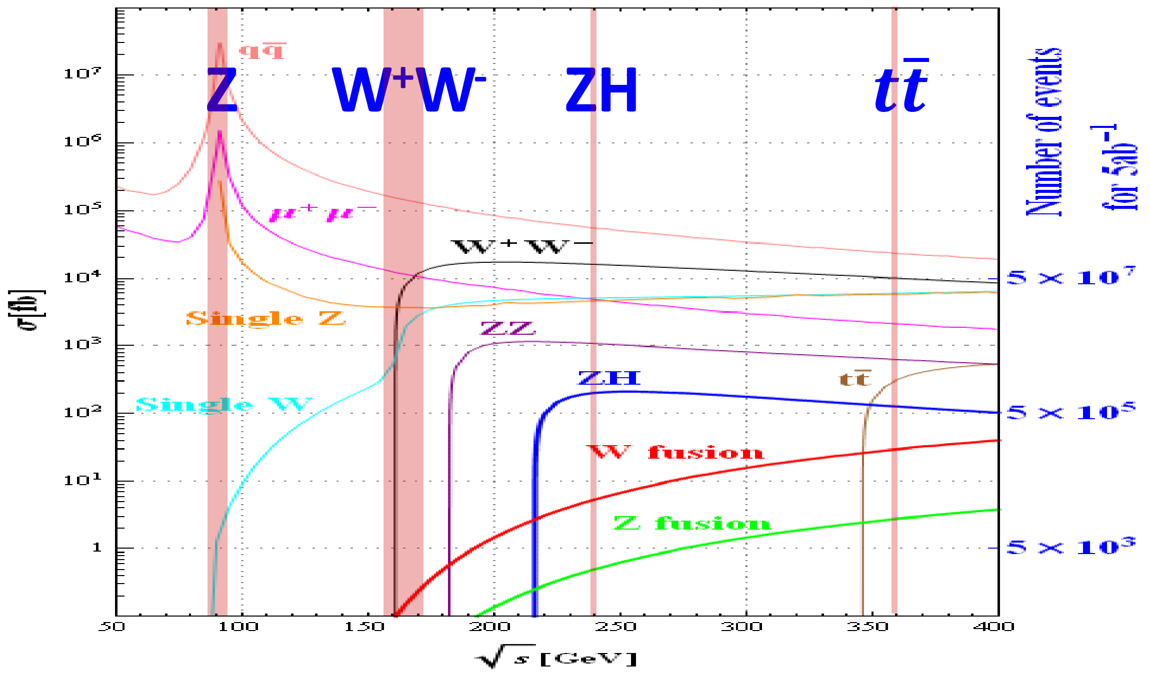
High Precision Frontier



2-7 GeV

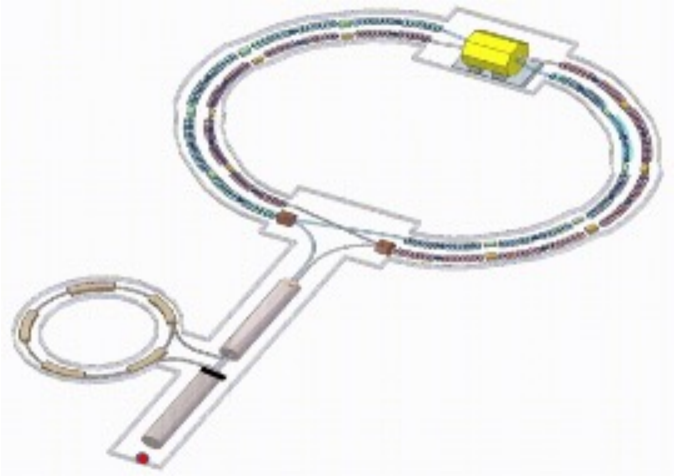
Super Tau-Charm Facility (STCF)

High Energy Frontier

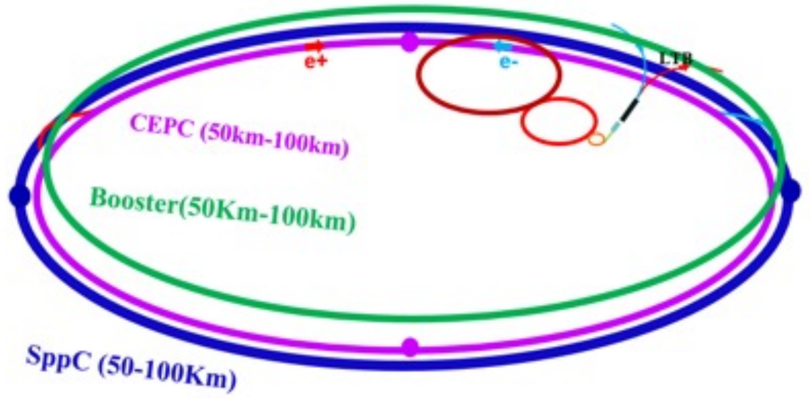


90-360 GeV

Circular Electron Positron Collider (CEPC)



Ring ~1 km
E_{cm}= 2-7 GeV
L>=0.5×10^{35} $cm^{-2}s^{-1}$@4GeV



Ring ~100 km
E_{cm}= 90-360 GeV
L=0.5×10^{35} $cm^{-2}s^{-1}$@240 GeV

Both are an e+e- machine

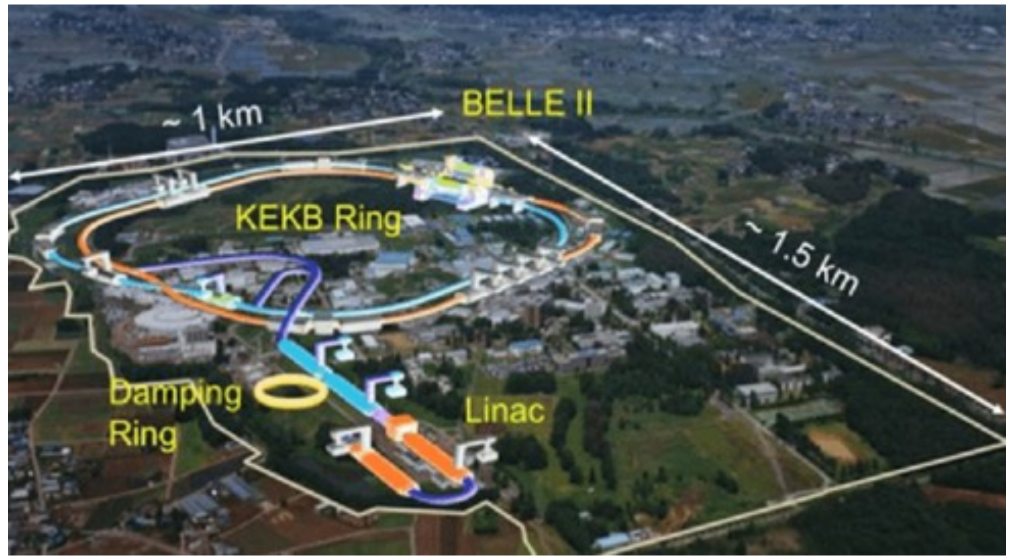
CEPC and STCF in International Context

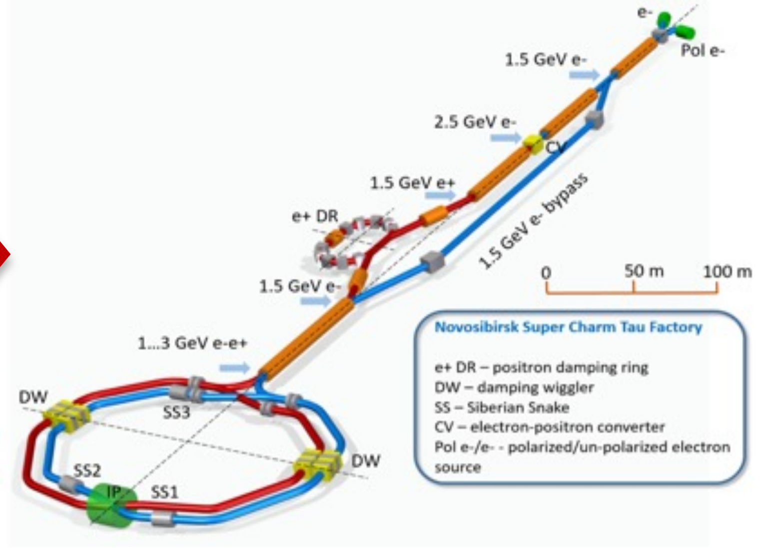
BEPCII
2-5 GeV, 10^{33} cm^{-2}s^{-1}

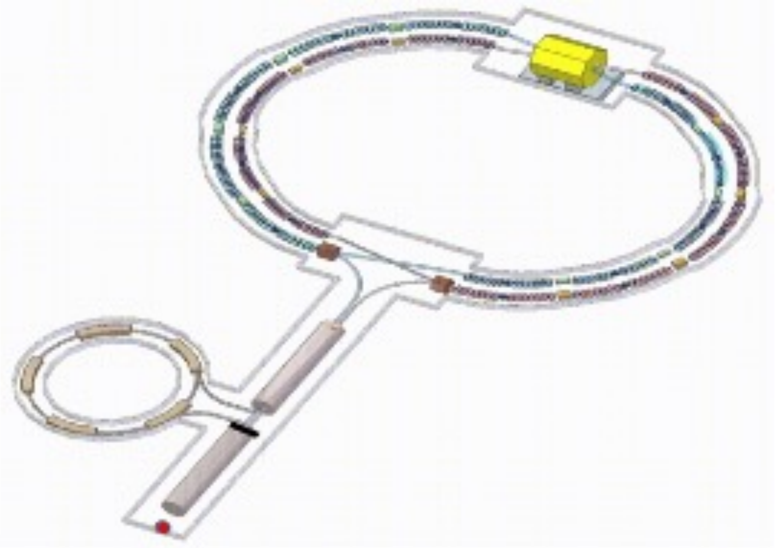
SKEKB
~10 GeV, 8×10^{35} cm^{-2}s^{-1}(target)

SCTF, STCF
2-7 GeV, ~10^{35} cm^{-2}s^{-1}

High Precision Frontier







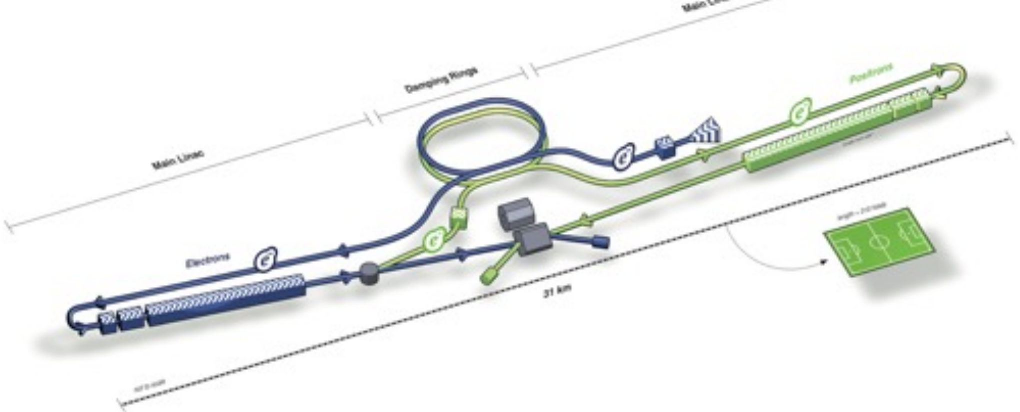
LHC (HL-LHC)
~14 TeV, 10^{34} cm^{-2}s^{-1}(×5-7)

ILC: 0.25-1TeV

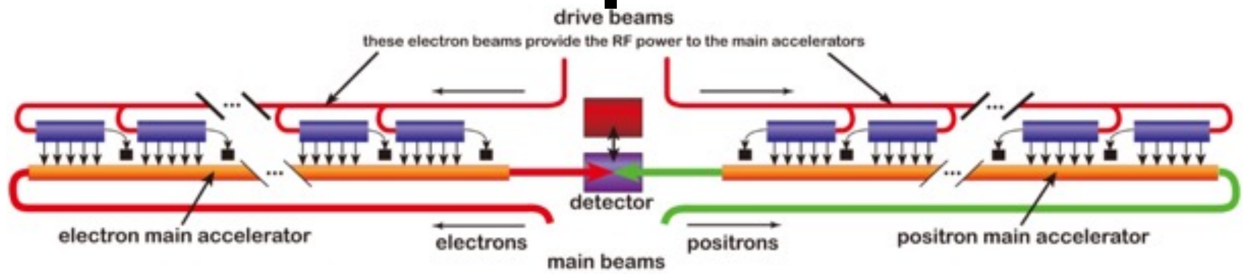
FCC-ee, hh(100TeV)

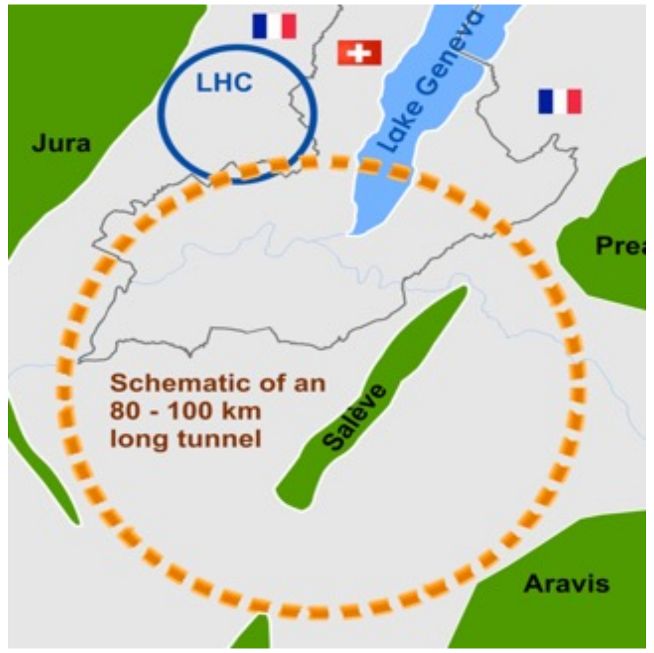
CEPC(90-360GeV)
SPPS(100TeV)

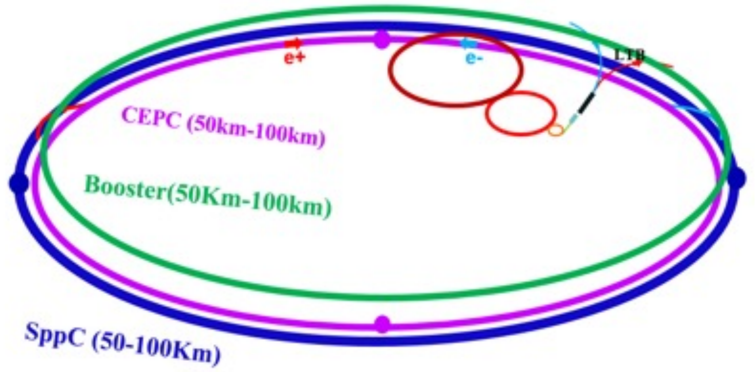
High Energy Frontier



CLIC: up to 3TeV

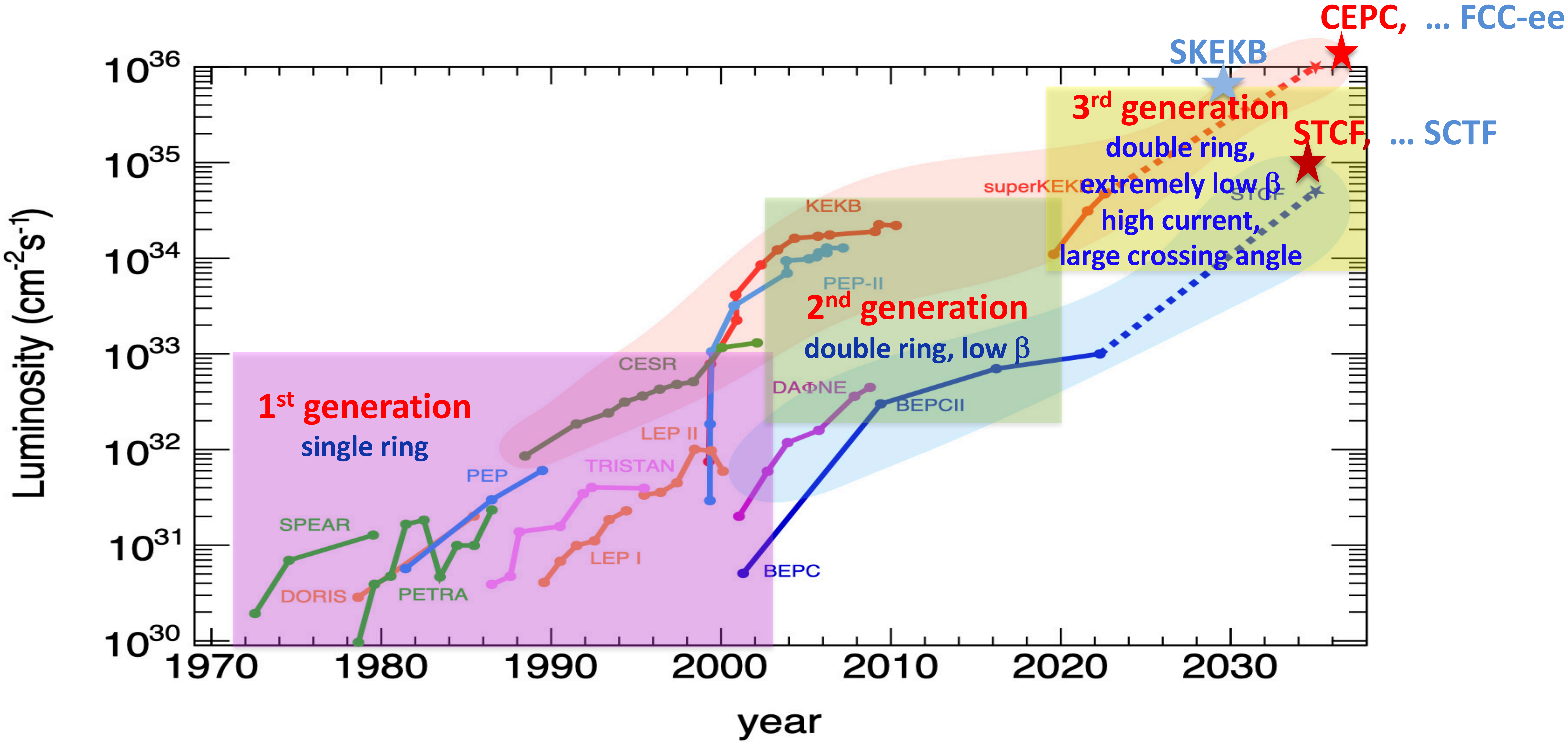






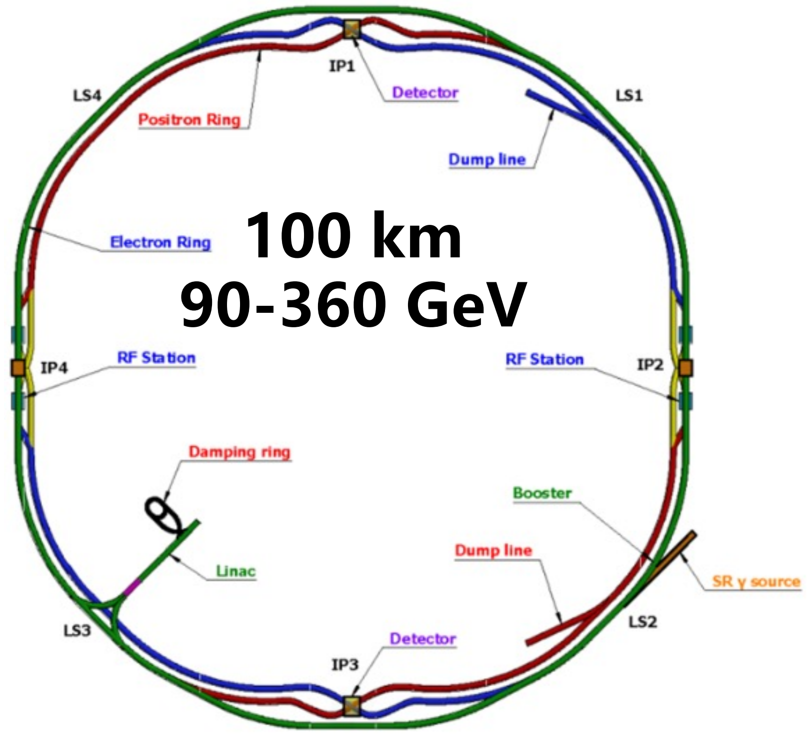
2020 European Strategy Update: An electron-positron Higgs factory is the highest-priority next collider

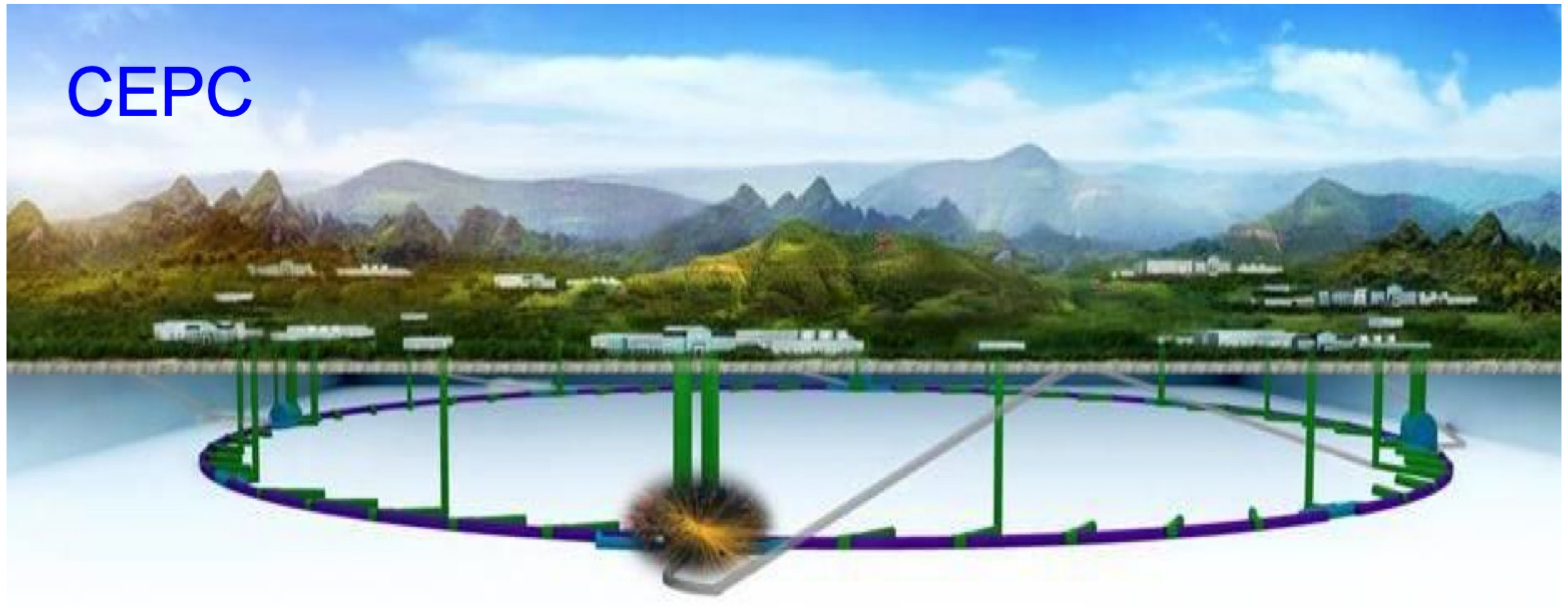
CEPC and STCF in Historical Context

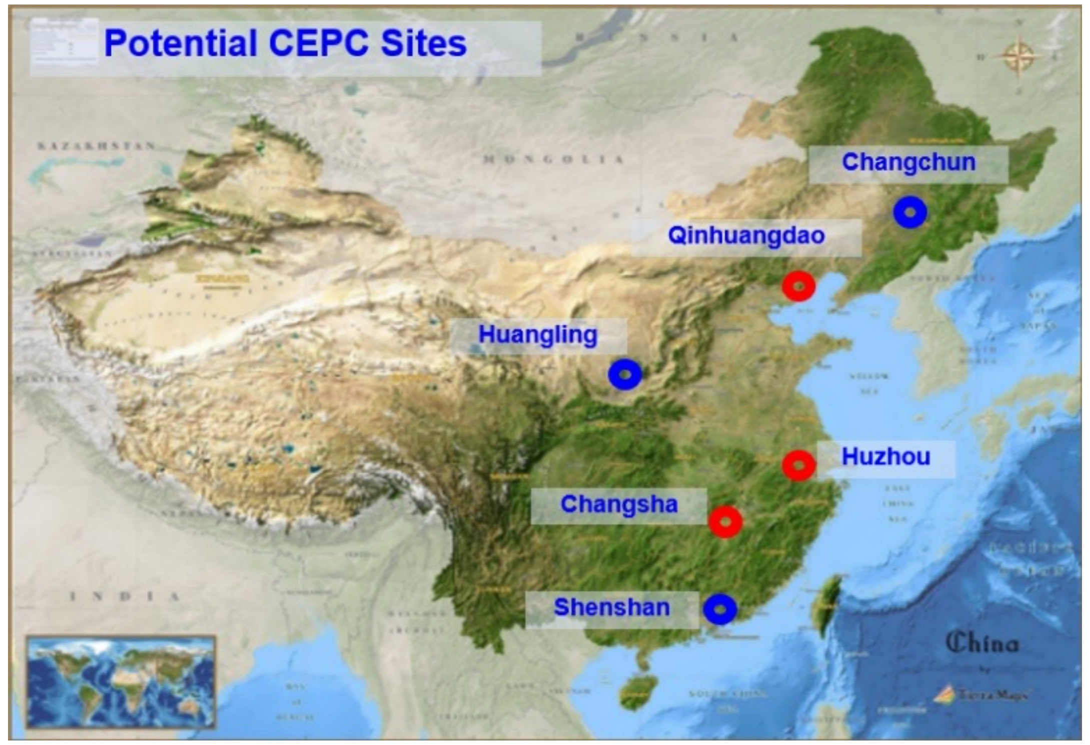


CEPC and STCF：both a 3th generation e+e- collider

CEPC

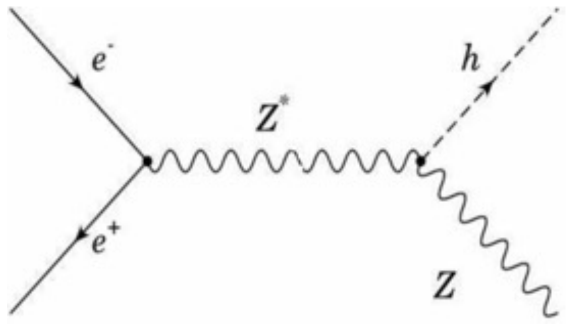


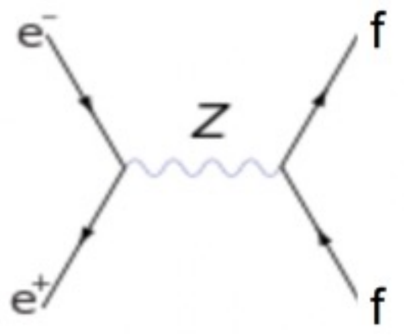


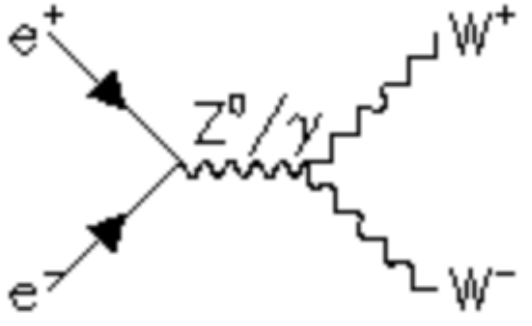


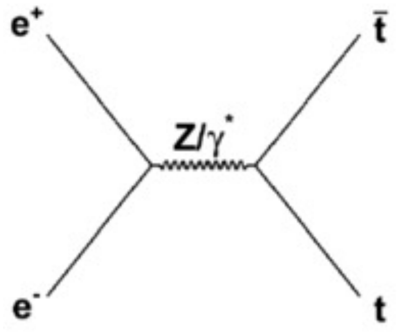
- ❑ **Proposed in 2012 after the Higgs discovery.**
- ❑ **Aiming to start operation in 2030s, as a Higgs / Z / W factory.**
- ❑ **Abundant production of Higgs / W / Z bosons for precision measurements and new physics searches.**
- ❑ **Upgradable for a pp collider (SppC) of ~ 100 TeV in the future.**

CEPC Physics Program

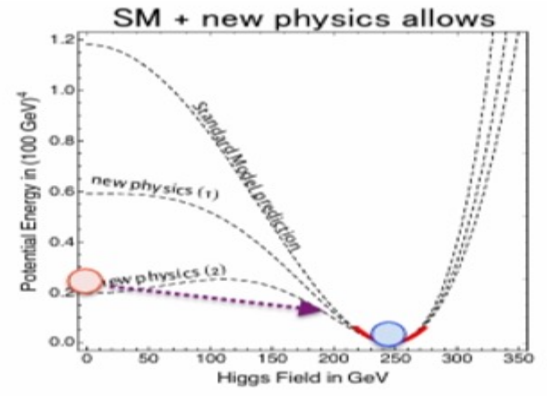








$$h \rightarrow X_{\mathrm{dm}} X_{\mathrm{dm}}$$



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 [$\times 10^{34}$ cm^{-2}s^{-1}]	**5.0**	**115**	**16**	**0.5**
	$\int L\,dt$ [ab^{-1}, 2 IPs]	13	60	4.2	0.6
	Event yields [2 IPs]	2.6×10^6	2.5×10^{12}	1.3×10^8	4×10^5
50 MW	L / IP [$\times 10^{34}$ cm^{-2}s^{-1}]	**8.3**	**192**	**26.7**	**0.8**
	$\int L\,dt$ [ab^{-1}, 2 IPs]	22	100	6.9	1
	Event yields [2 IPs]	4.3×10^6	4.1×10^{12}	2.1×10^8	6×10^5

- **The centerpiece: precise measurement of the Higgs boson properties**
- **Huge measurement potential for precision tests of SM: electroweak physics, flavor physics, QCD**
- **Searching for exotic or rare decays of H, Z, B and τ, and BSM physics (dark matter, EWPT, LLP ...)**
- **Top quark physics**

An extremely versatile machine combining precision and discovery capabilities with a broad spectrum of physics opportunities → Far beyond a Higgs factory

CEPC Physics Studies

2018

IHEP-CEPC-DR-2018-02
IHEP-EP-2018-01
IHEP-TH-2018-01

CEPC
Conceptual Design Report
Volume II - Physics & Detector

The CEPC Study Group
October 2018

2019

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

Precision Higgs physics at the CEPC

Higgs White Paper

2021

The Physics potential of the CEPC

Prepared for the US Snowmass Community Planning Exercise

(Snowmass 2021)

CEPC Physics Study Group

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SNOWMASS White Paper

2023

Contents

Flavor Physics White Paper, More on EWK and NP in preparation

2024

PHYSICAL REVIEW LETTERS 132, 221802 (2024)

Jet-Origin Identification and Its Application at an Electron-Positron Higgs Factory

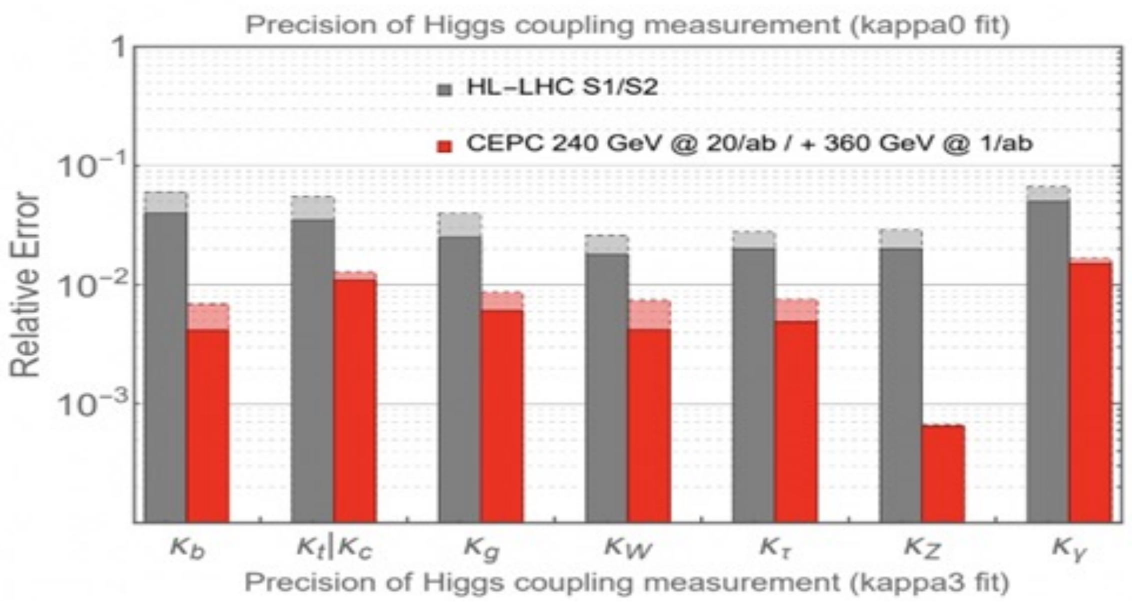
Development and Application of Advanced Analysis Tools

Participation in ECFA physics studies

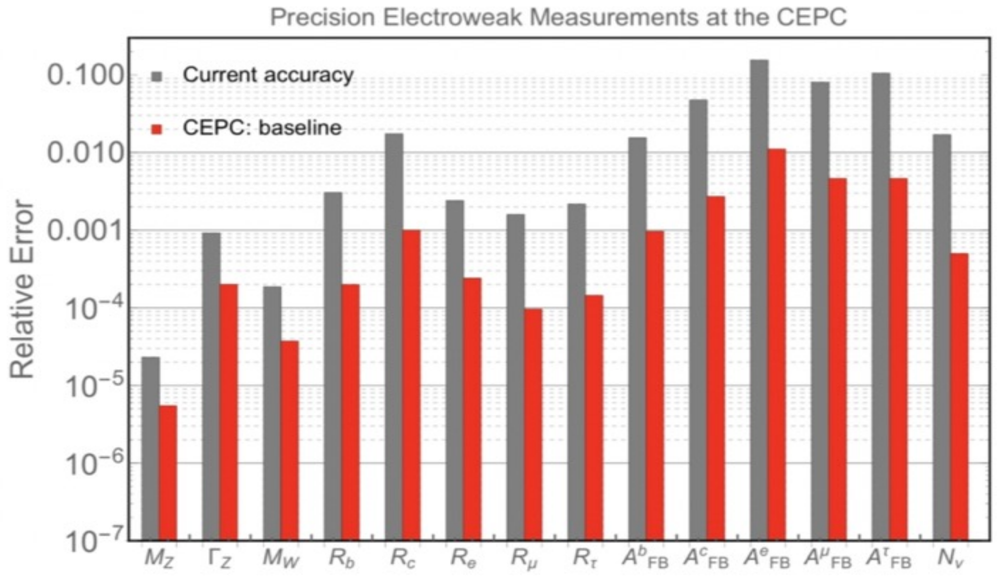
~100 Journal/arXiv papers

Precision and Discovery @ CEPC

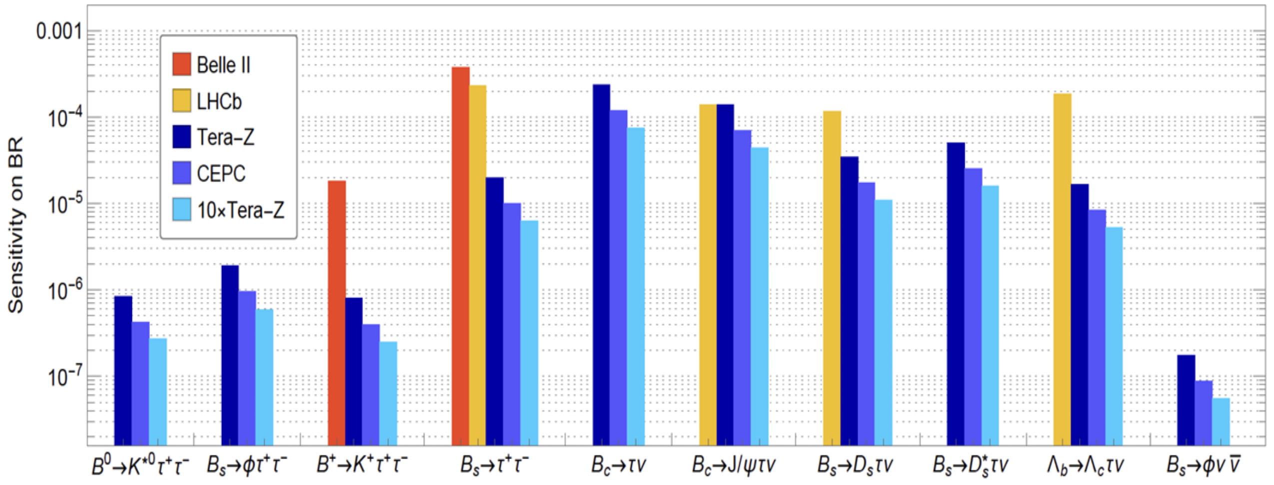
Higgs coupling measurements
(model independent)



EWK measurements

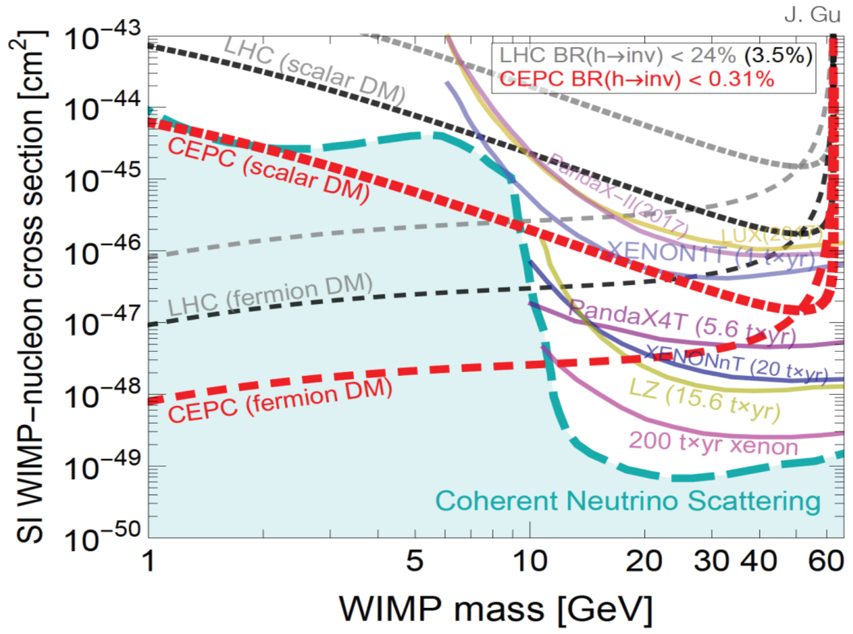


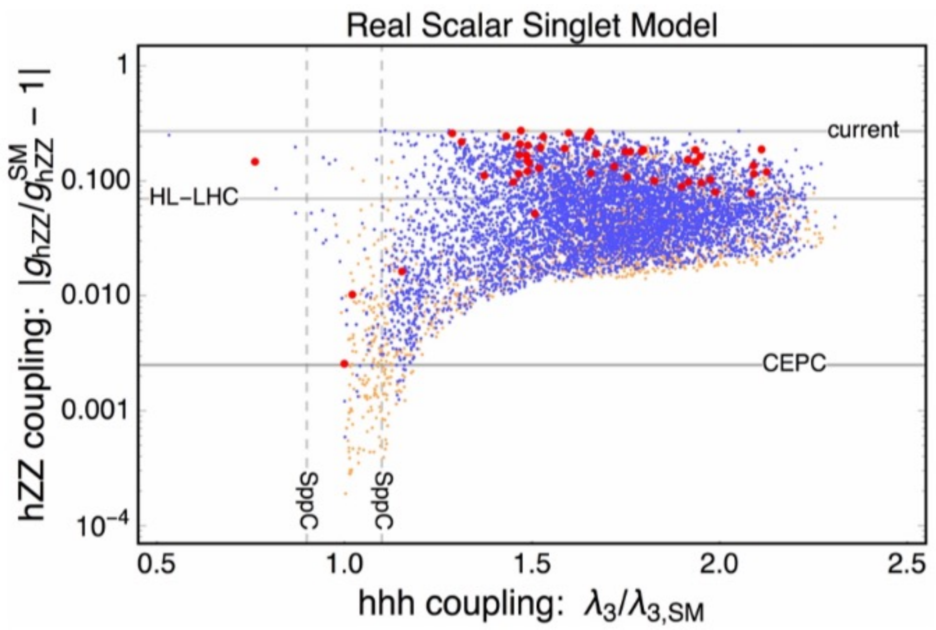
Rare decays



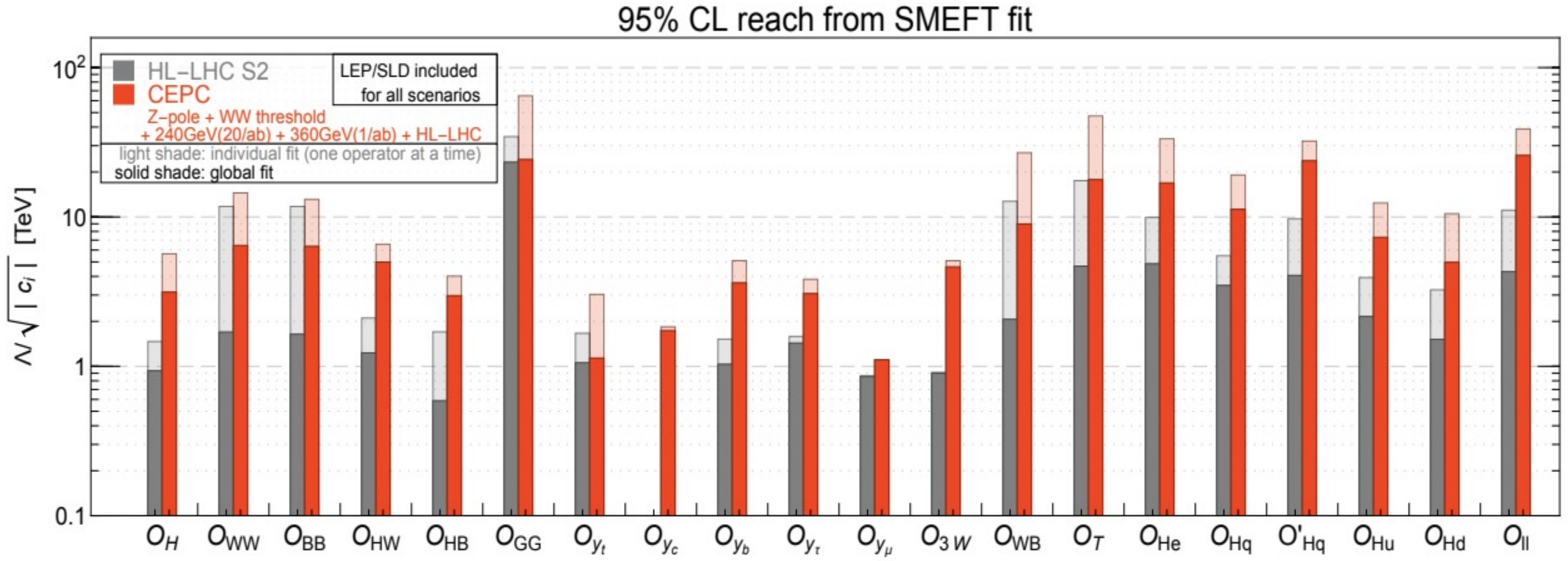
Mode	LEP bound (95% CL)		LHC bound (95% CL)		CEPC/FCC-ee
$BR(Z \to \mu e)$	1.7×10^{-6}	[2]	7.5×10^{-7}	[3]	$10^{-8} - 10^{-10}$
$BR(Z \to \tau e)$	9.8×10^{-6}	[2]	5.0×10^{-6}	[4, 5]	10^{-9}
$BR(Z \to \tau \mu)$	1.2×10^{-5}	[6]	6.5×10^{-6}	[4, 5]	10^{-9}

BSM：dark matter，EWPT etc.



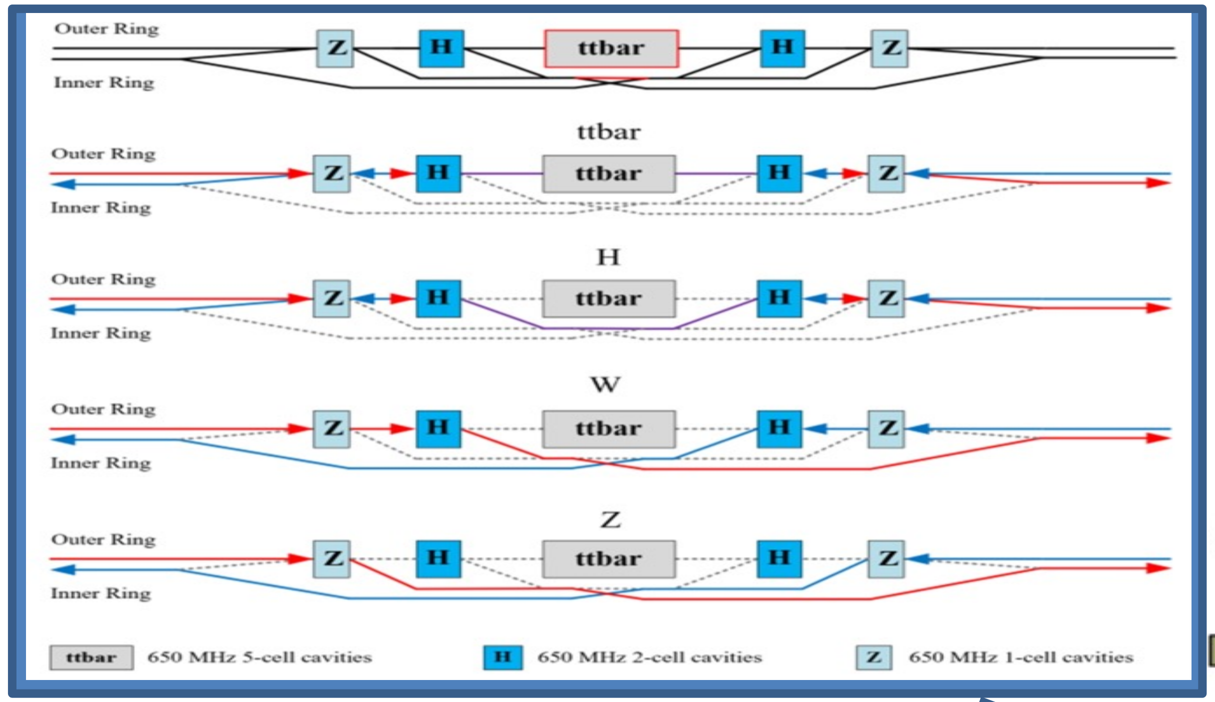


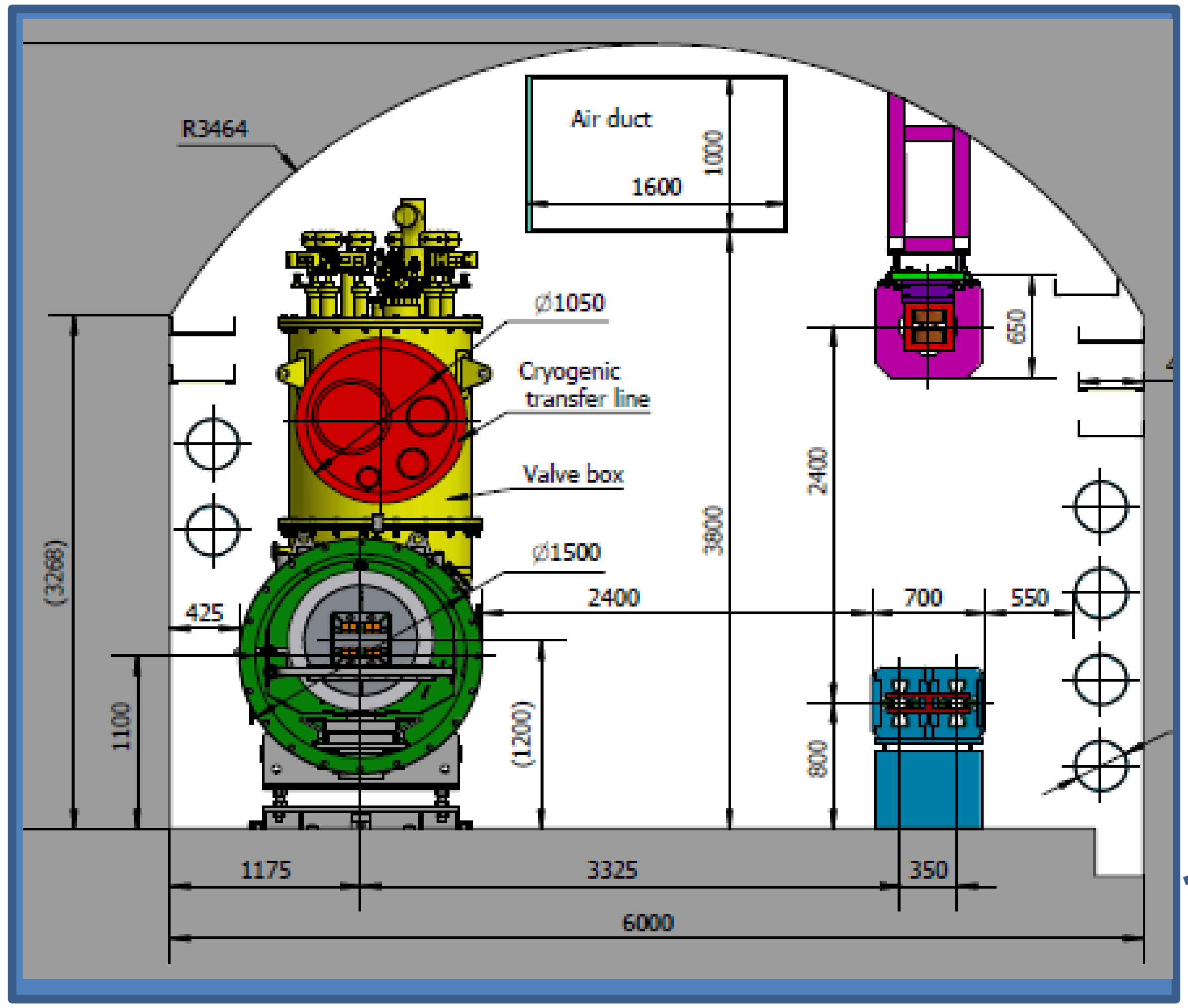
Potential to reveal new physics @10 TeV or higher

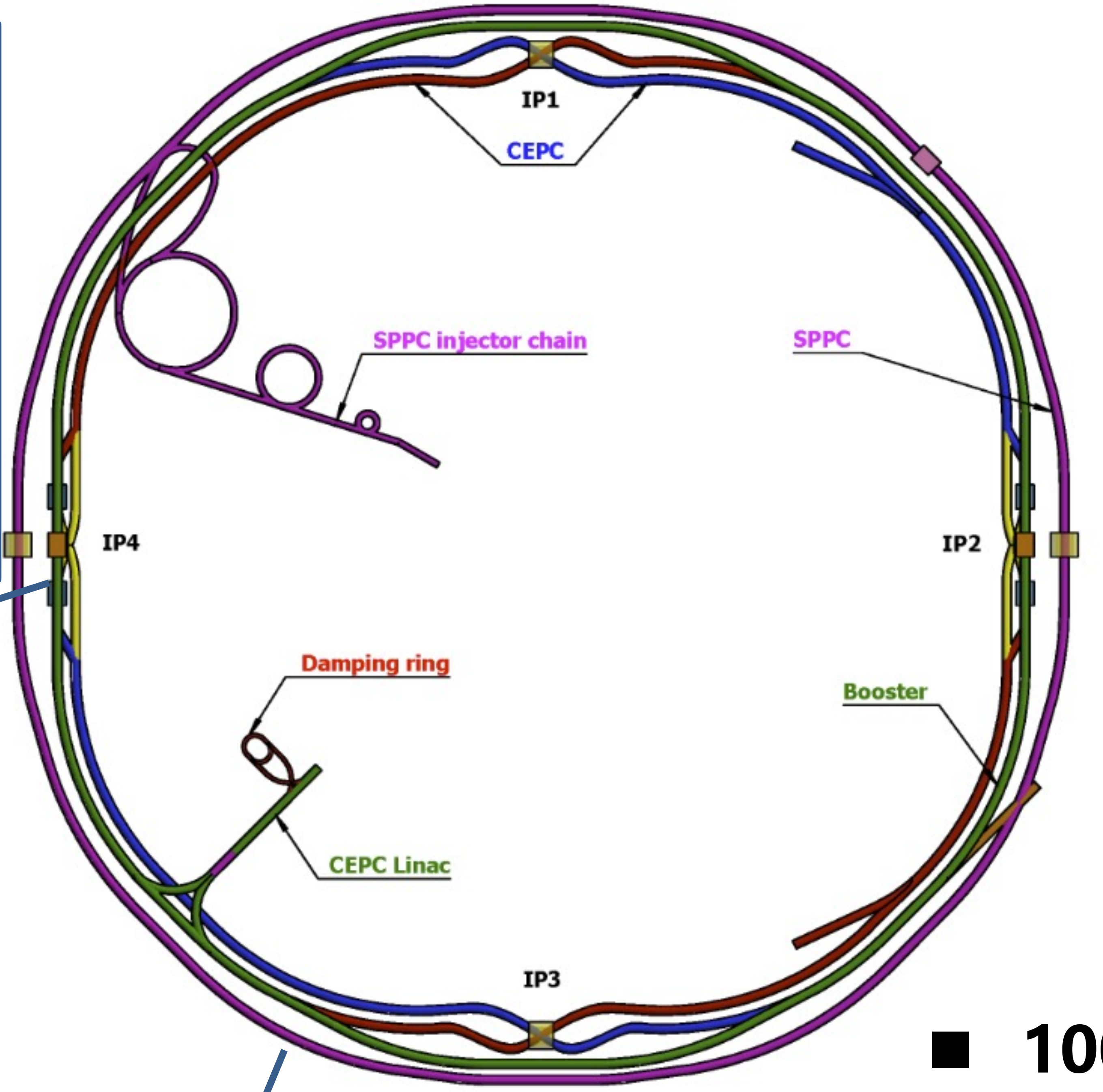


Unprecedented precisions or sensitivities: Orders of magnitude improvement or enhancement

CEPC Accelerator Design





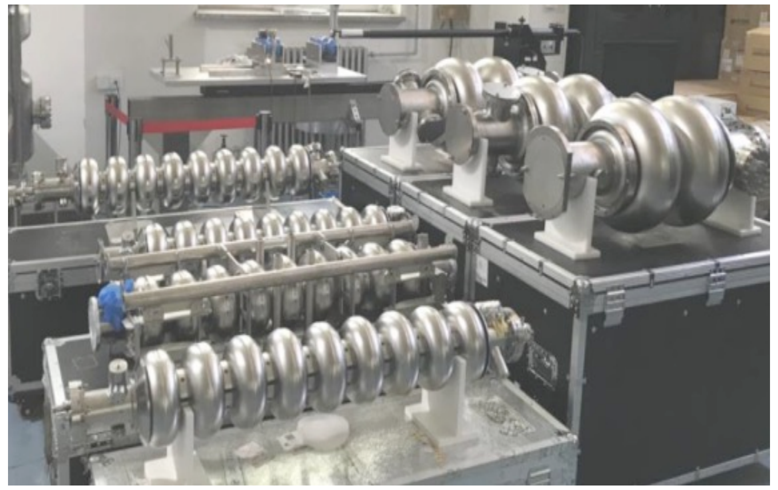


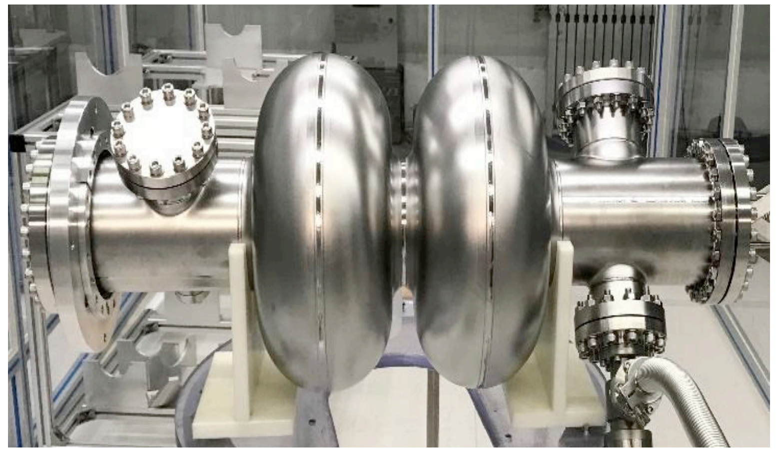
	Higgs	Z	W	$t\bar{t}$
Number of IPs	2			
Circumference (km)	100.0			
SR power per beam (MW)	30			
Energy (GeV)	**120**	**45.5**	**80**	**180**
Bunch number	268	11934	1297	35
Emittance $\varepsilon_x/\varepsilon_y$ (nm/pm)	0.64/1.3	0.27/1.4	0.87/1.7	1.4/4.7
Beam size at IP σ_x/σ_y (um/nm)	14/36	6/35	13/42	39/113
Bunch length (natural/total) (mm)	2.3/4.1	2.5/8.7	2.5/4.9	2.2/2.9
Beam-beam parameters ξ_x/ξ_y	0.015/0.11	0.004/0.127	0.012/0.113	0.071/0.1
RF frequency (MHz)	650			
Luminosity per IP (10^{34} cm^{-2} s^{-1})	**5.0**	**115**	**16**	**0.5**

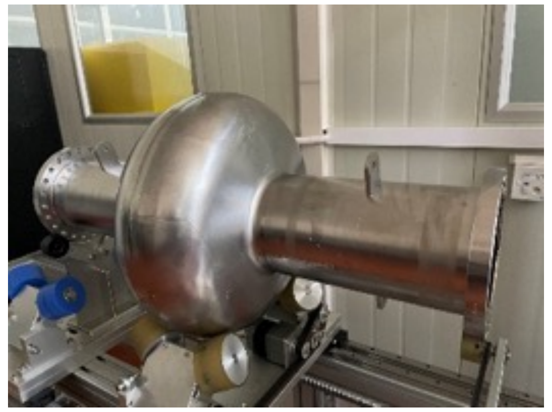
- **100 km double-ring (30 MW SR, upgradable to 50MW and ttbar)**
- **Switchable operation for H, Z, W and ttbar modes (bypass scheme)**
- **Common tunnel for CEPC and SppC**

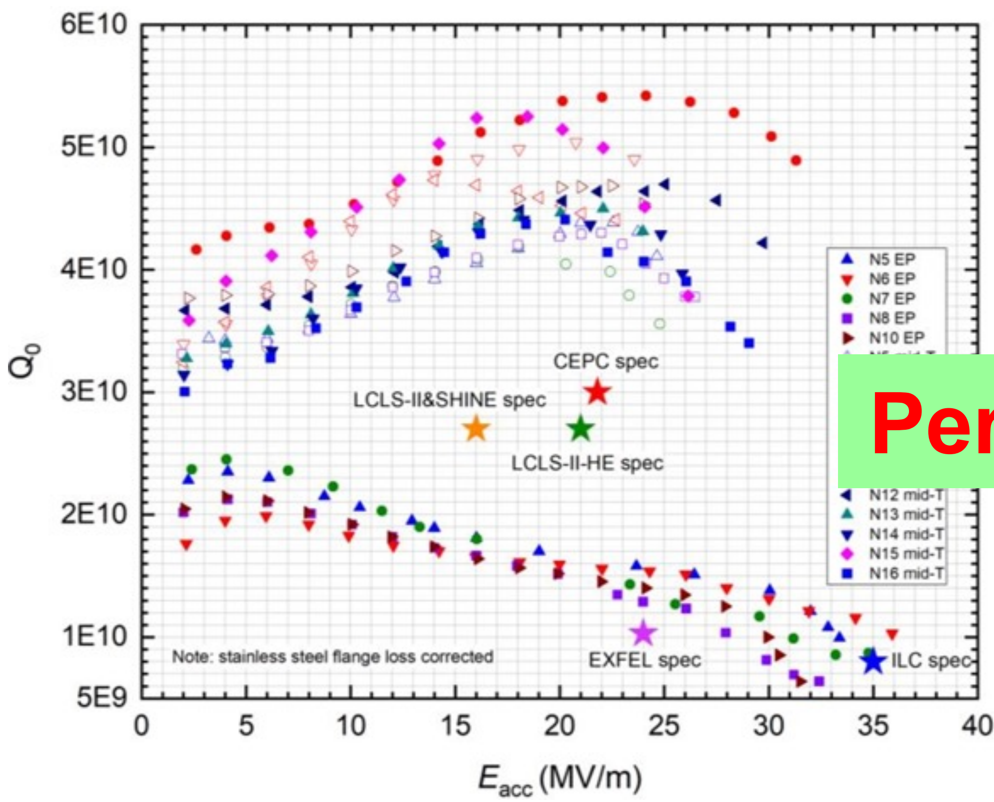
High Q SRF Cavities

- 1.3 GHz 9-cell SRF cavity (booster): Q = 4.9E10 @ 31.0 MV/m
- 650 MHz 2-cell SRF cavity (collider): Q = 6.0E10 @ 22.0 MV/m
- 650 MHz 1-cell SRF cavity (collider): Q = 6.3E10 @ 31.0 MV/m



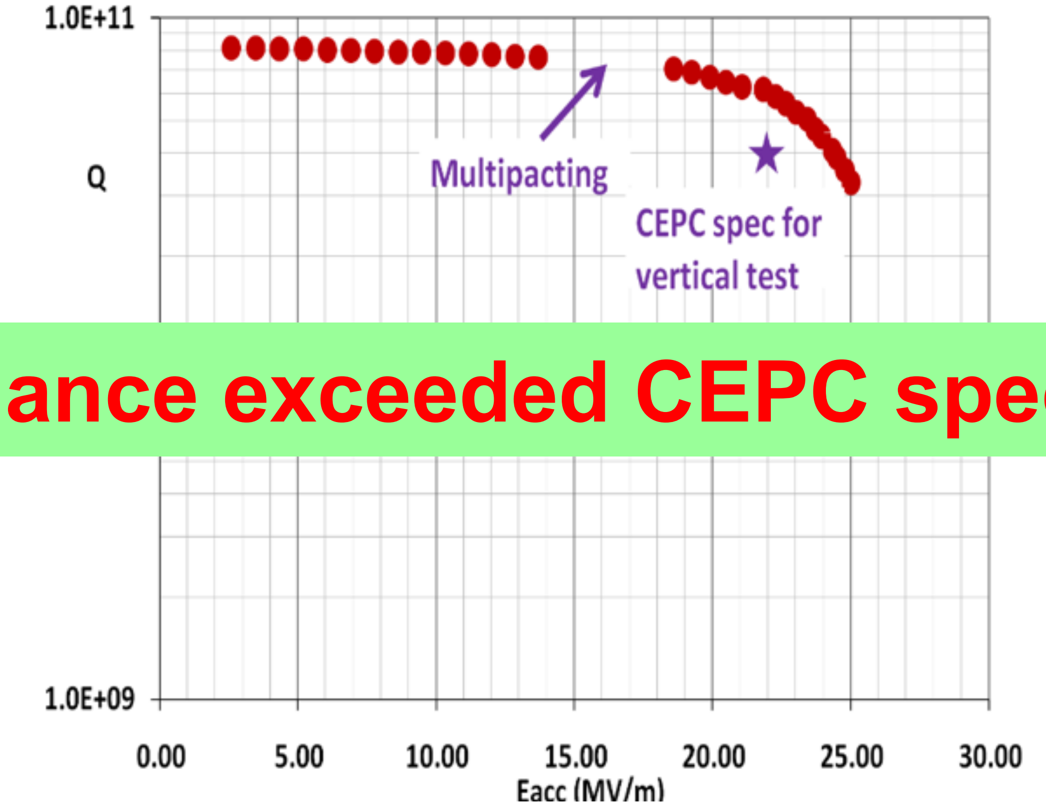






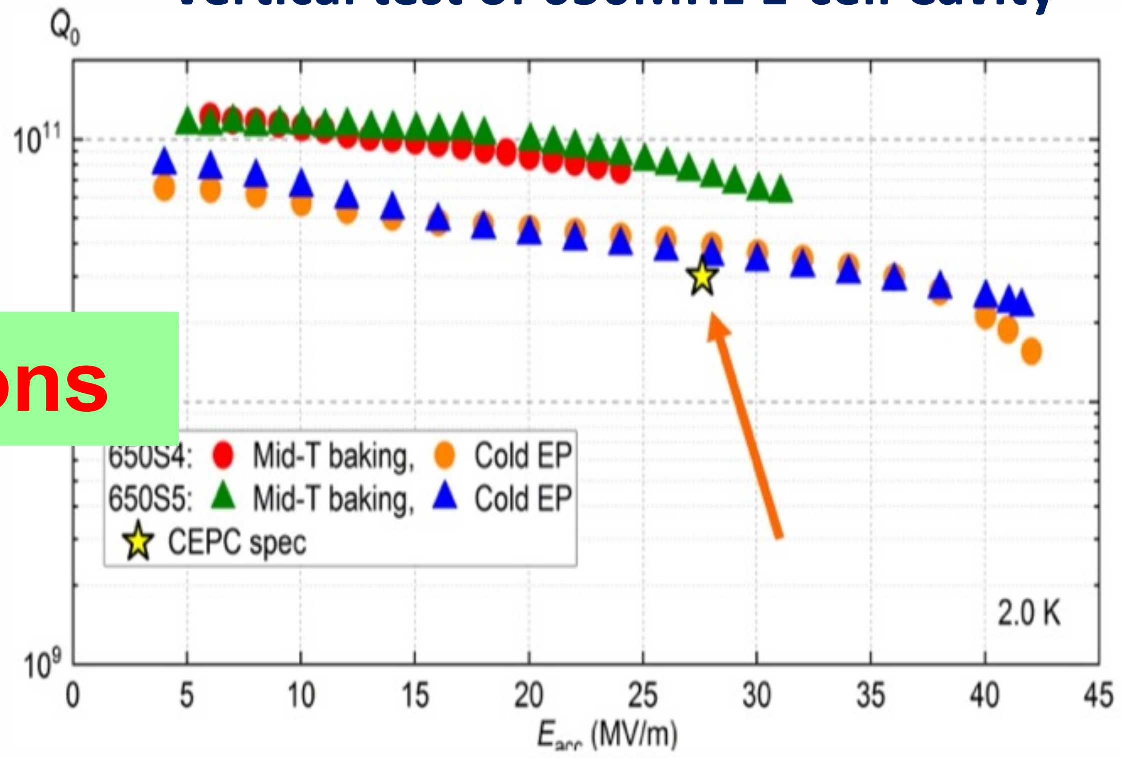
Medium-temperature annealing adopted to reach Q_0 = 4.9E10 @ 31.0 MV/m

Vertical test of 650 MHz 2-cell cavity



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

Vertical test of 650MHz 1-cell Cavity



Cold-EP and Mid-T baking Q_0 = 6.3E10 @ 31 MV/m

Performance exceeded CEPC specifications

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}			

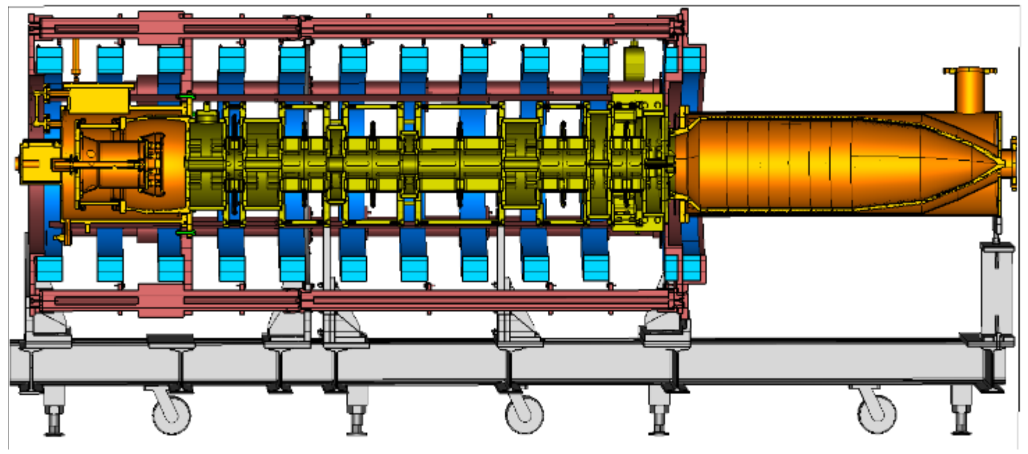
Performance exceeded CEPC specifications

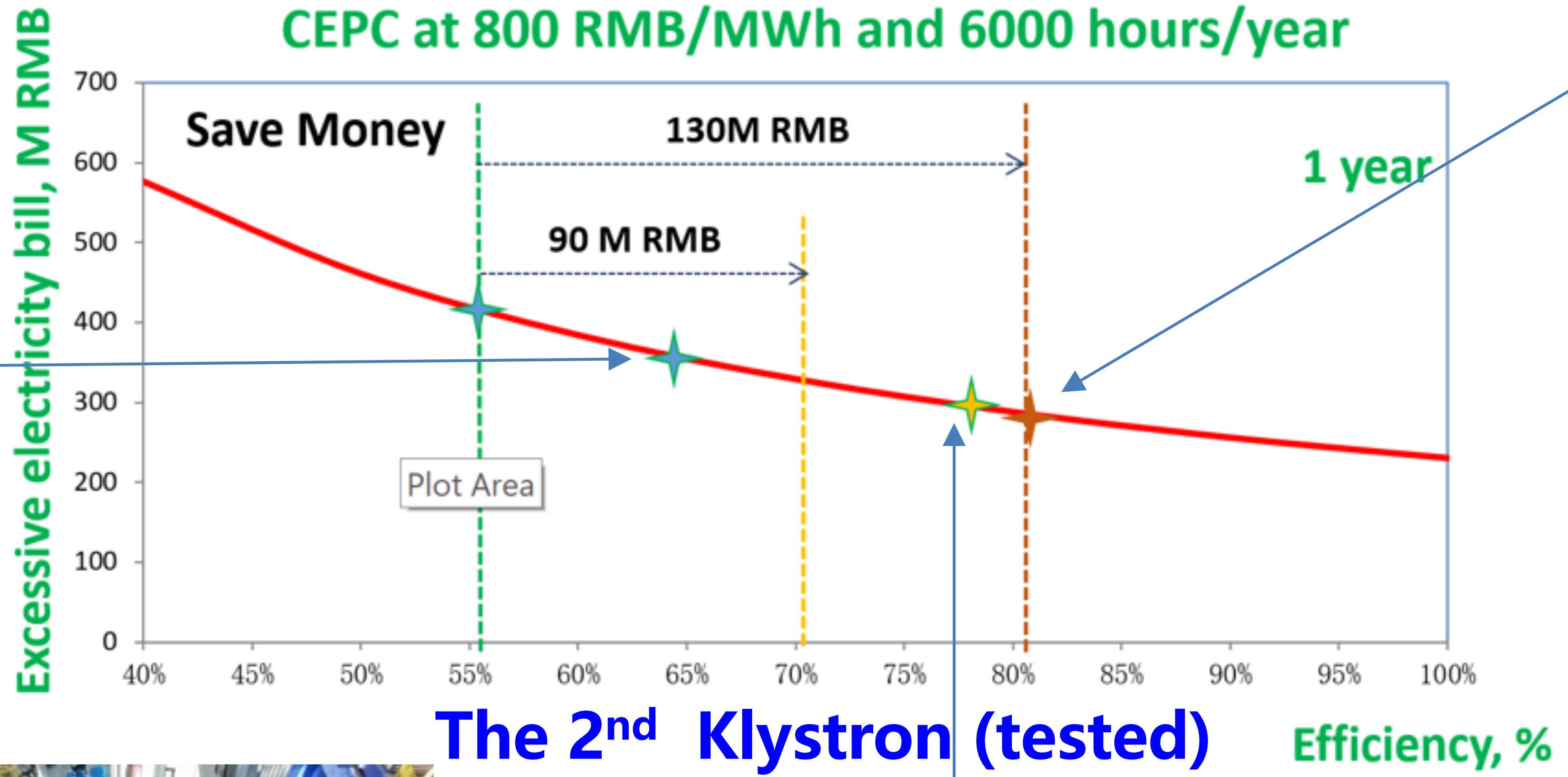
High Efficiency Klystrons

High-efficiency klystrons are key technology critical to saving power

- ❑ 1st Klystron prototype，efficiency tested ~ 62%
- ❑ 2nd Klystron prototype，efficiency tested ~ 77.2%
- ❑ 3rd Klystron prototype (MBK) under fabrication，target ~ 80%

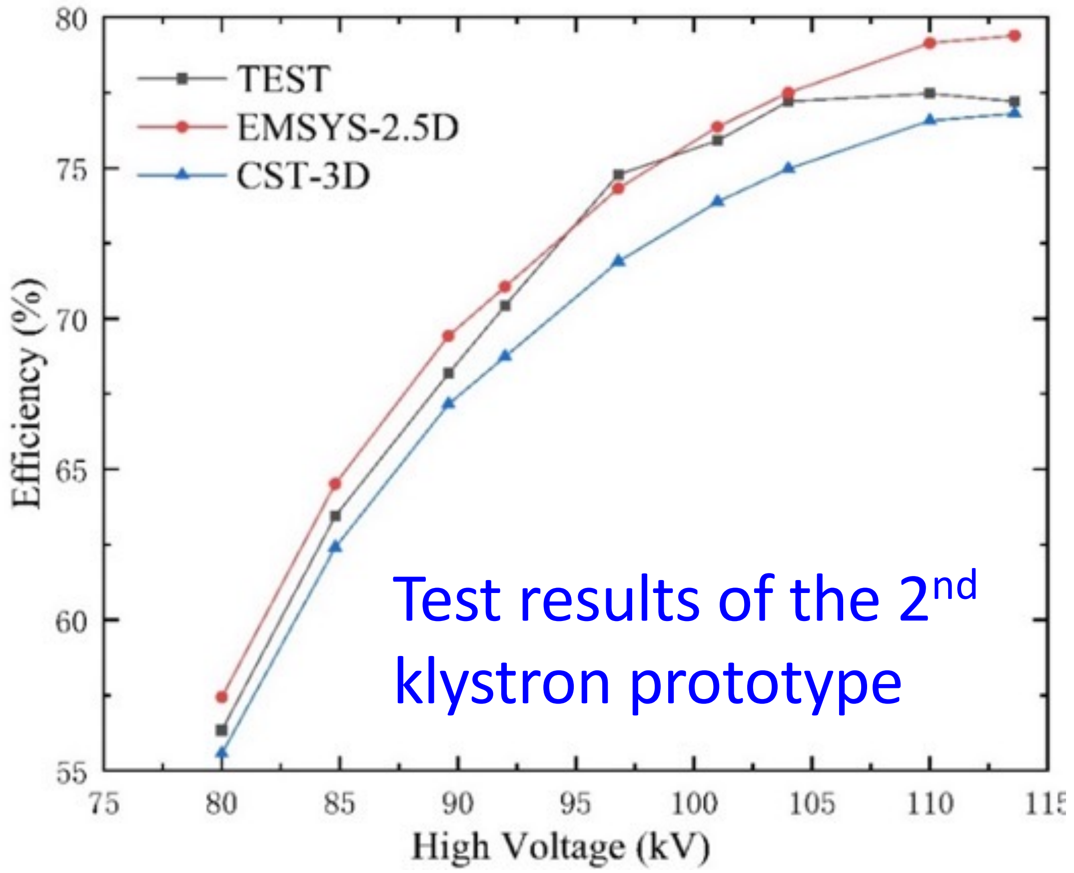
The 3rd multi-beam Klystron (MBK) under fabrication





The 1st Klystron (tested)

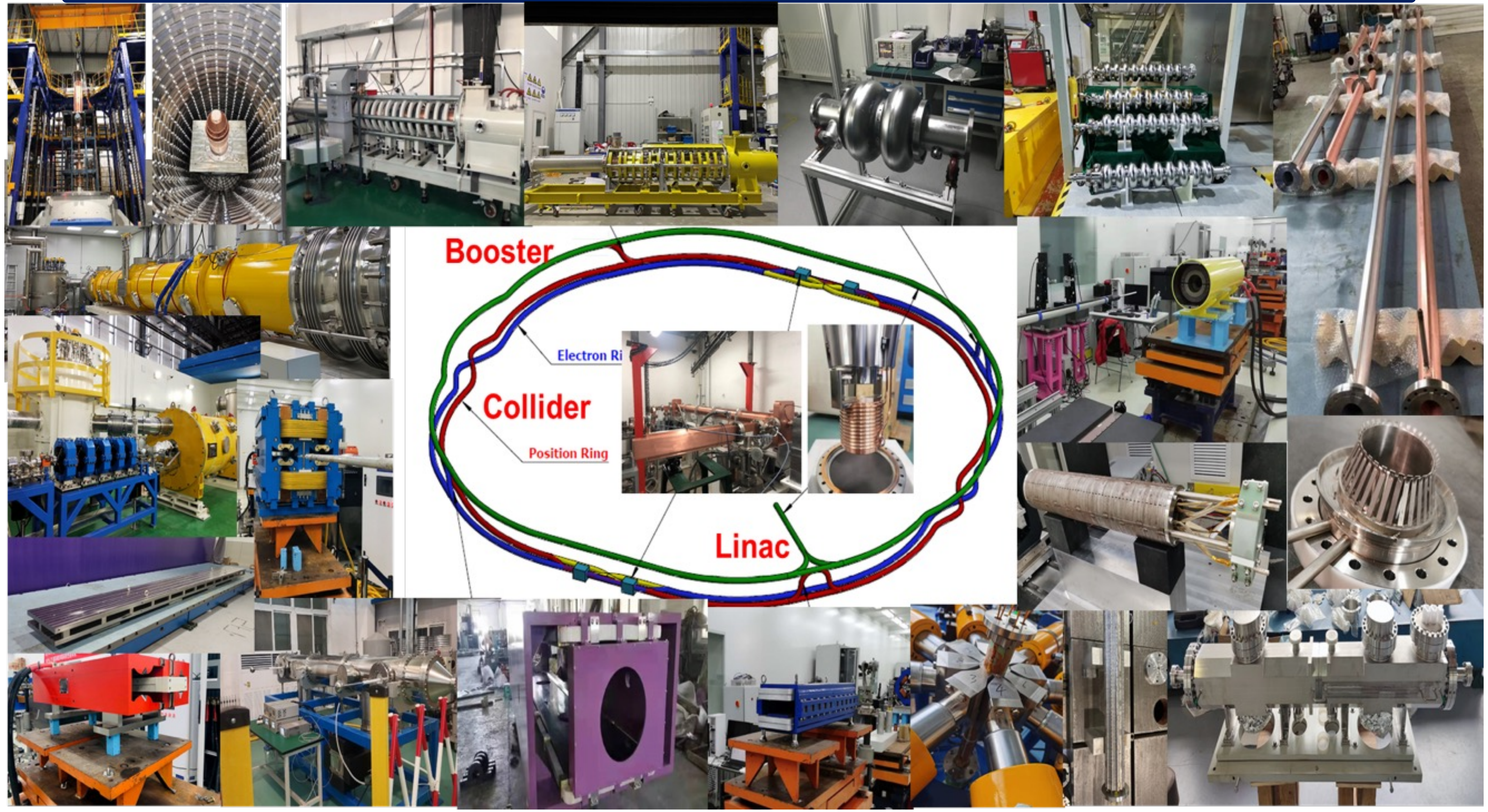
The 2nd Klystron (tested)



Test results of the 2nd klystron prototype

CEPC Accelerator R&D Overall Status

- CEPC accelerator key technologies R&D program has covered all key components listed in the CDR.
- 90% have met specifications. The remaining 10% to be completed by 2026.



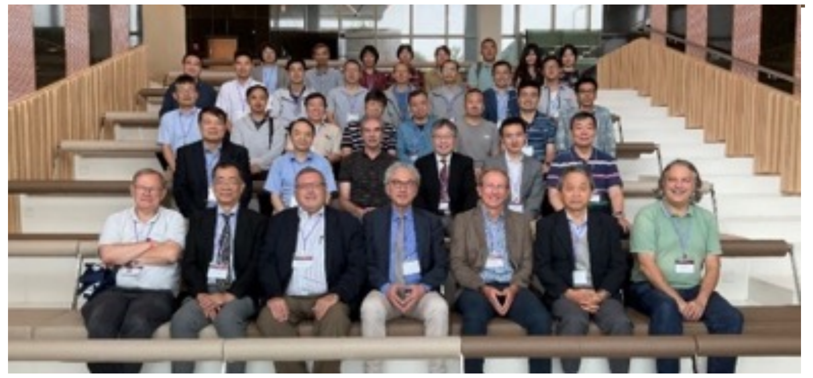
Specification Met

Prototype Manufactured

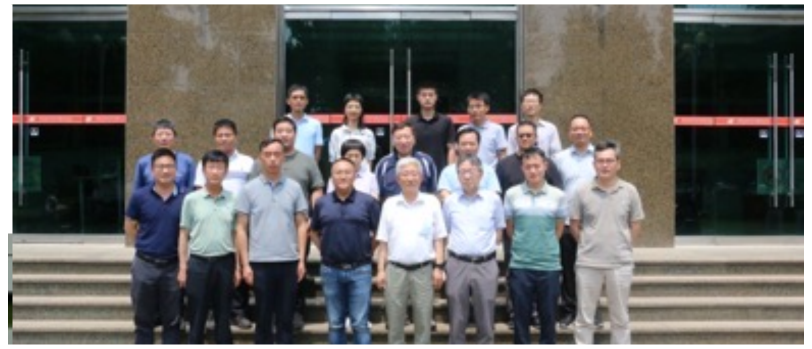
Accelerator	Ratio
Magnets	27.3%
Vacuum	18.3%
RF power source	9.1%
Mechanics	7.6%
Magnet power supplies	7.0%
SC RF	7.1%
Cryogenics	6.5%
Linac and sources	5.5%
Instrumentation	5.3%
Control	2.4%
Survey and alignment	2.4%
Radiation protection	1.0%
SC magnets	0.4%
Damping ring	0.2%

CEPC Accelerator TDR, and EDR Effort

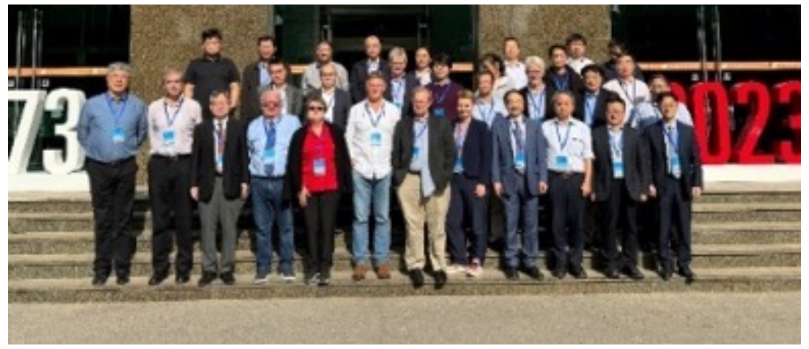
CEPC Accelerator TDR Review
June 12-16, 2023, Hong Kong



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



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



CEPC Accelerator TDR released in December, 2023

IHEP-CEPC-DR-2023-01

IHEP-AC-2023-01

CEPC

Technical Design Report

Accelerator

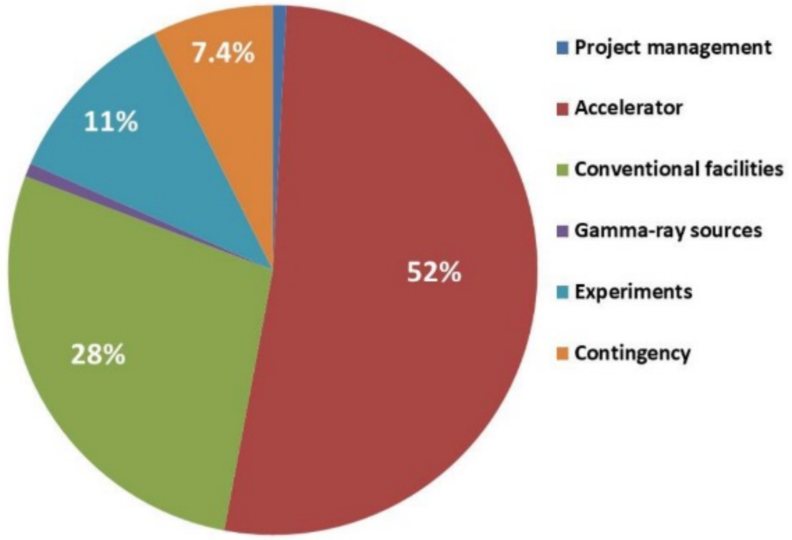
arXiv:2312.14363
1114 authors
278 institutes
(159 foreign institutes)
38 countries

The CEPC Study Group
December 2023

CEPC Project cost
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%

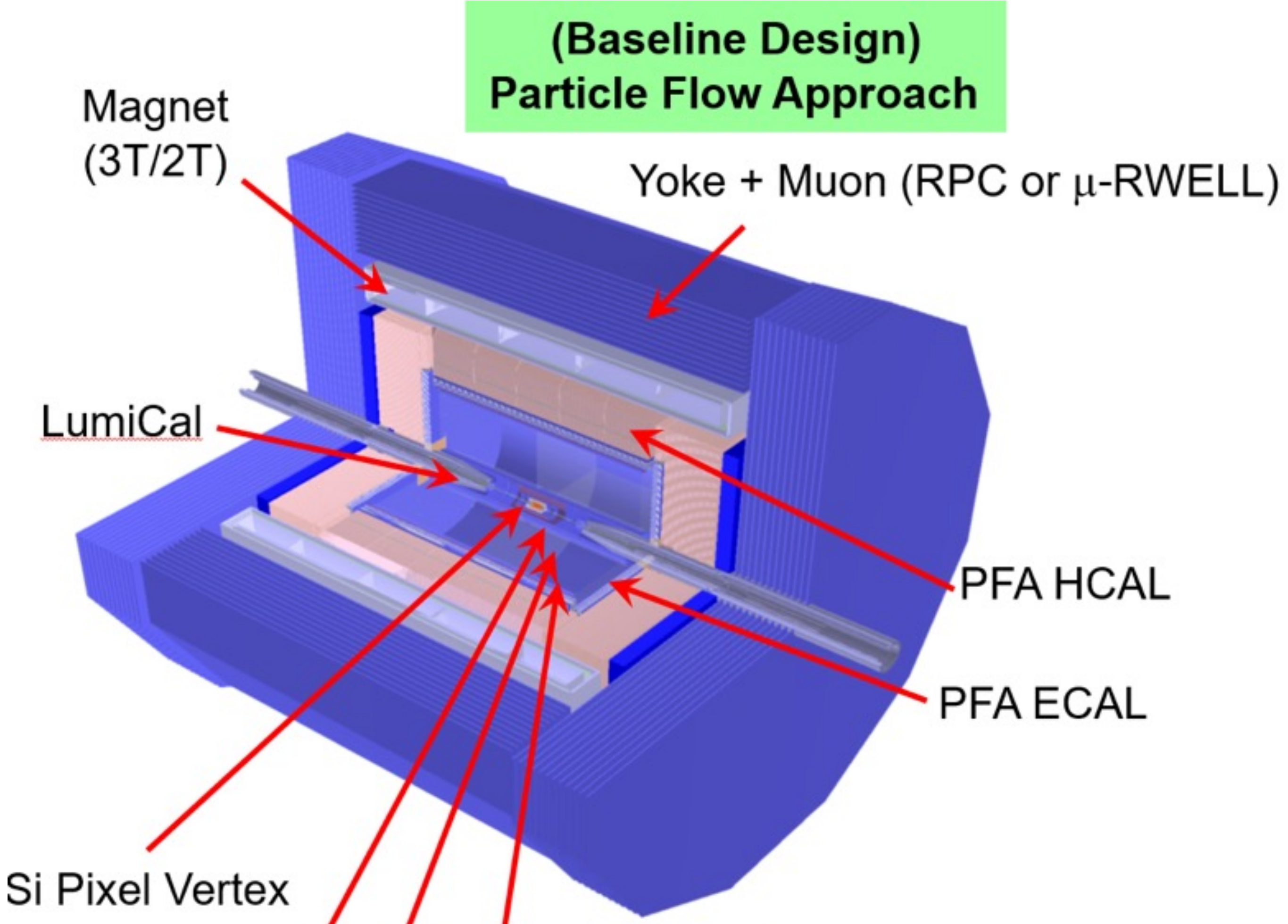


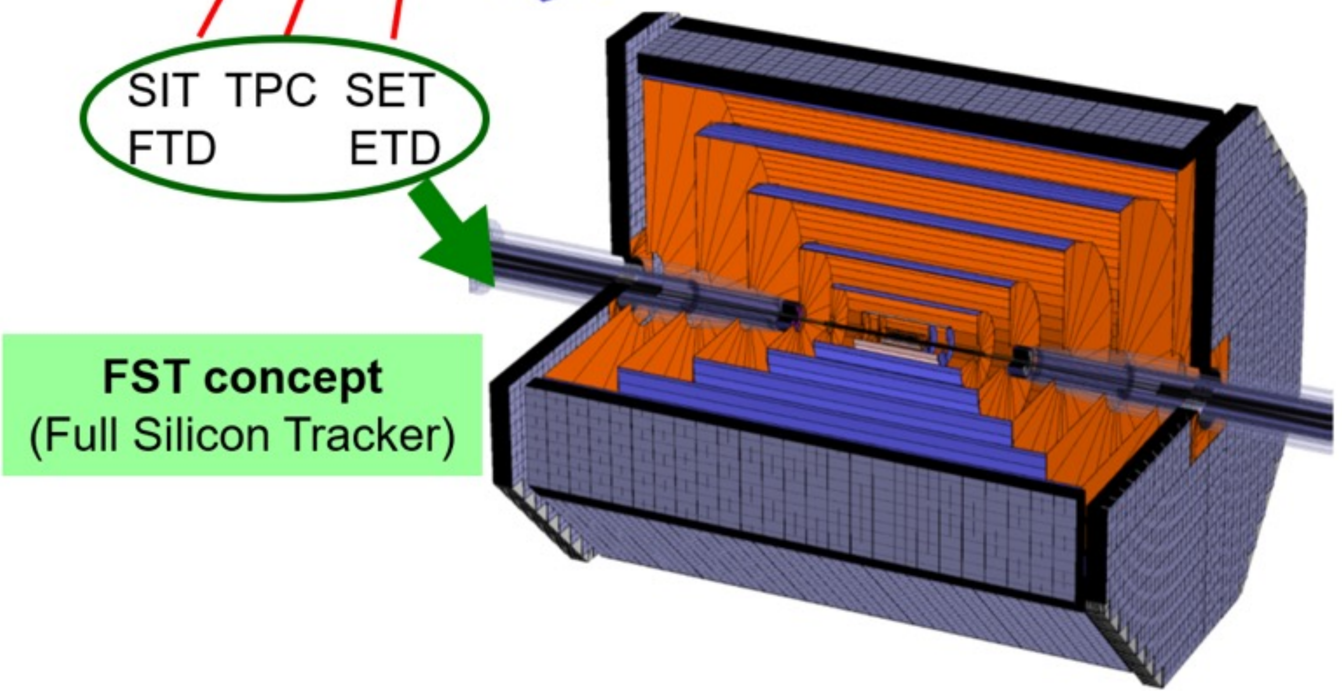
CEPC accelerator EDR effort has started in 2024, including 35 WGs focusing on designs and technologies in engineering aspects of the project construction.

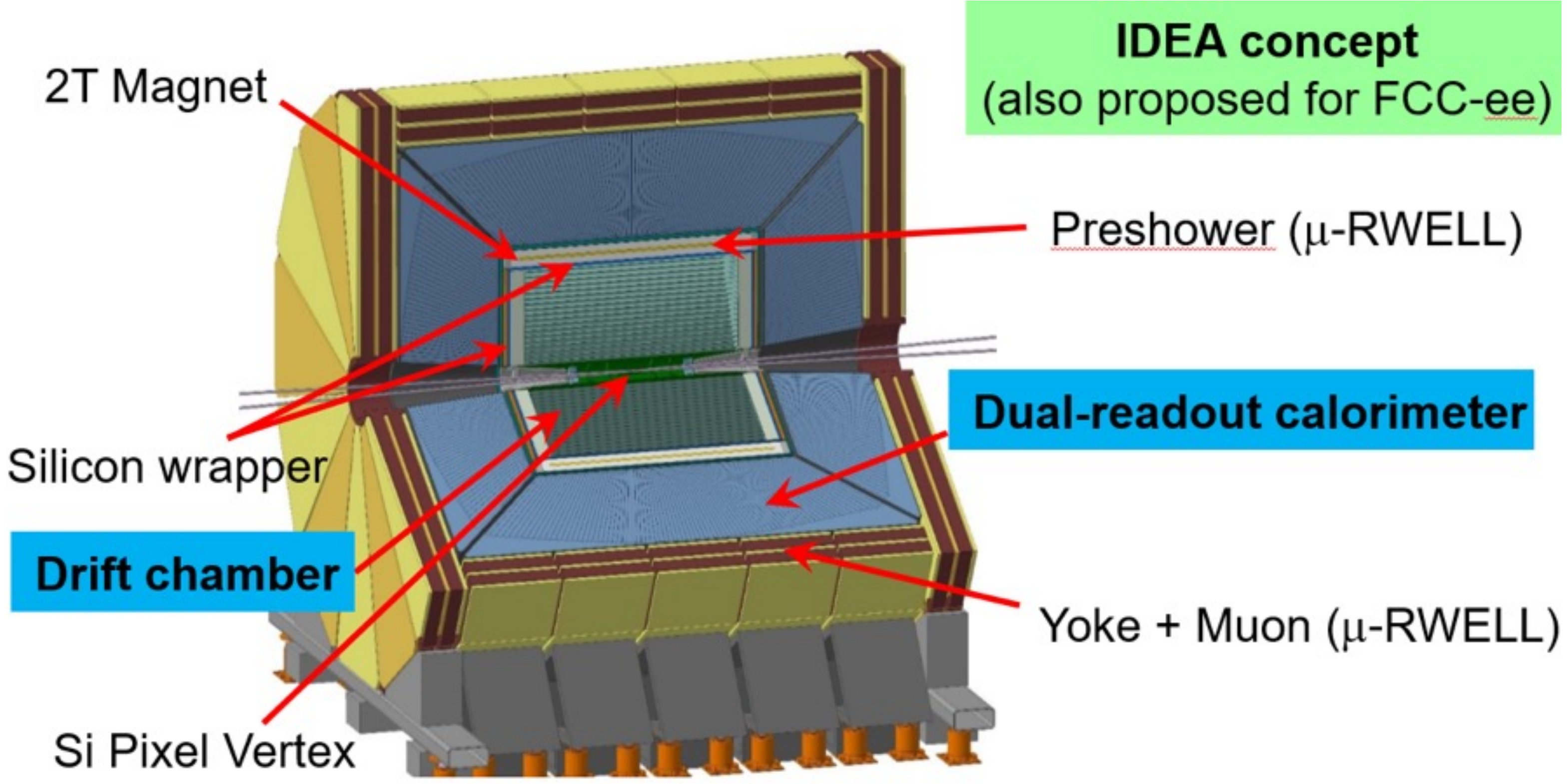
CEPC Detector: CDR → New Concept

CDR detector requirements completely driven by Higgs physics

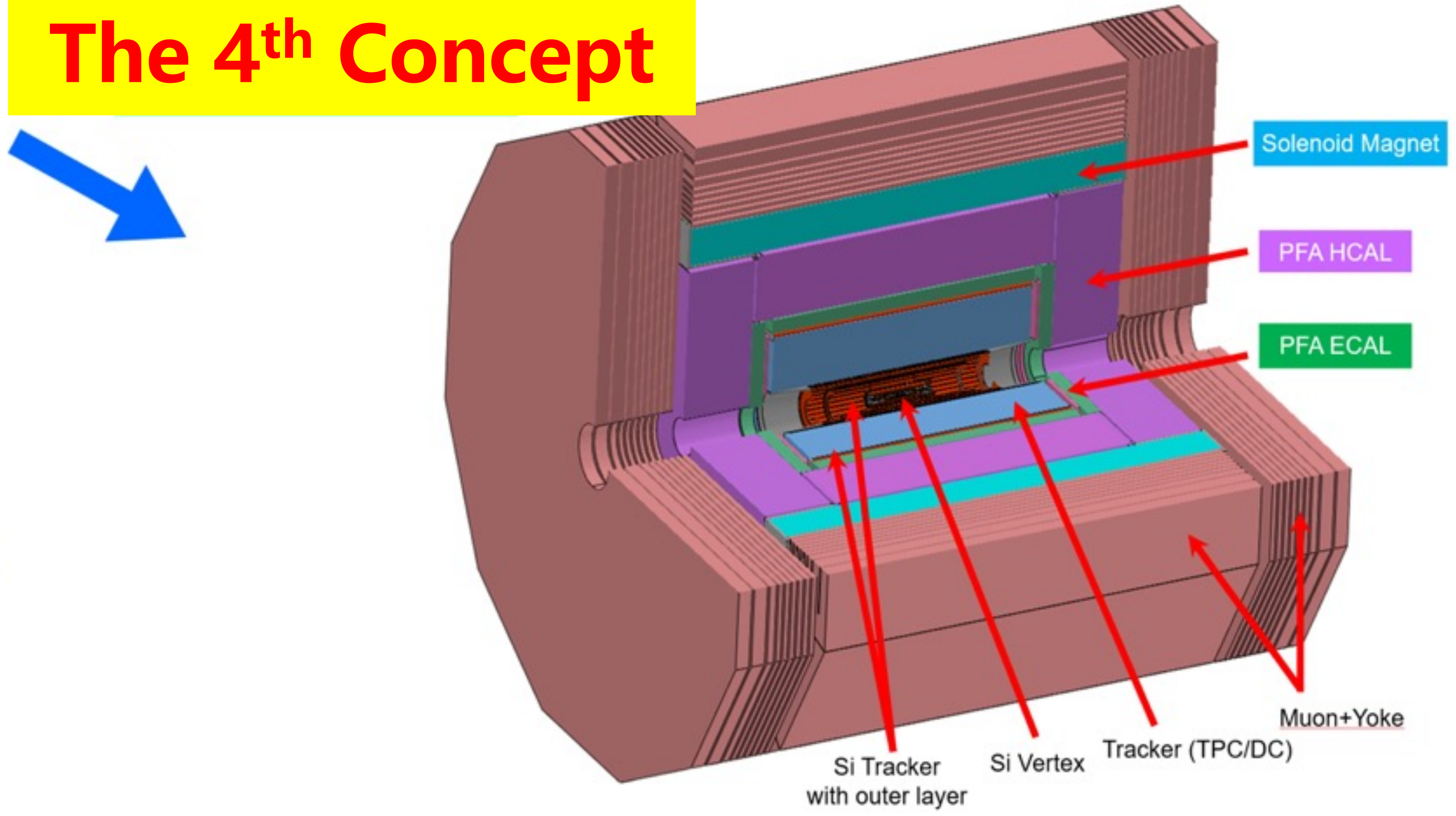
Physics process	Detector subsystem	Performance requirement
$ZH, Z \to e^+e^-, \mu^+\mu^-$ $H \to \mu^+\mu^-$	Tracker	$\Delta(1/p_T) = 2 \times 10^{-5} \oplus \frac{0.001}{p(\mathrm{GeV}) \sin^{3/2}\theta}$
$H \to b\bar{b}/c\bar{c}/gg$	Vertex	$\sigma_{r\phi} = 5 \oplus \frac{10}{p(\mathrm{GeV}) \times \sin^{3/2}\theta} (\mu\mathrm{m})$
$H \to q\bar{q}, WW^*, ZZ^*$	ECAL HCAL	$\sigma_E^{\mathrm{jet}}/E = 3 \sim 4\%$ at 100 GeV
$H \to \gamma\gamma$	ECAL	$\Delta E/E = \frac{0.20}{\sqrt{E(\mathrm{GeV})}} \oplus 0.01$





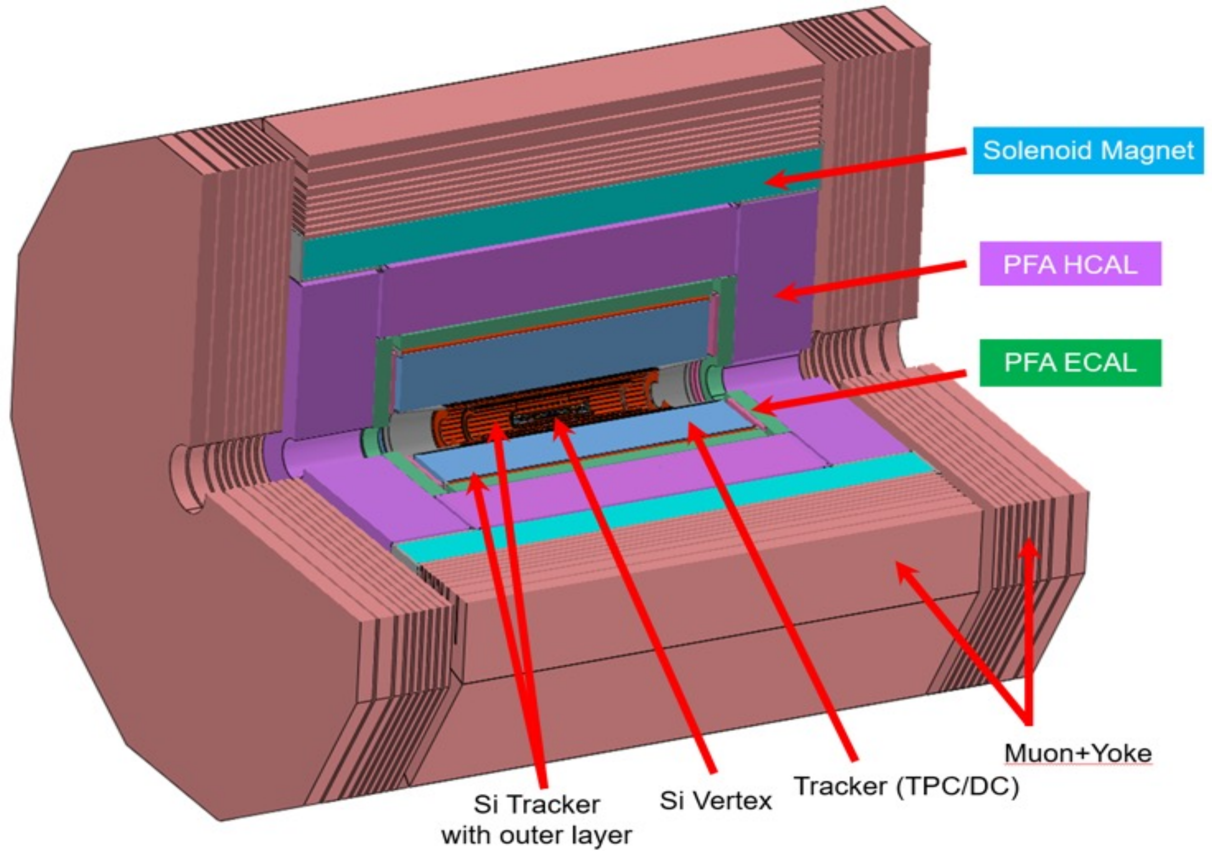


The 4th Concept



The 4th Concept Detector

CDR detector (focusing on Higgs) → The 4th concept (versatile)

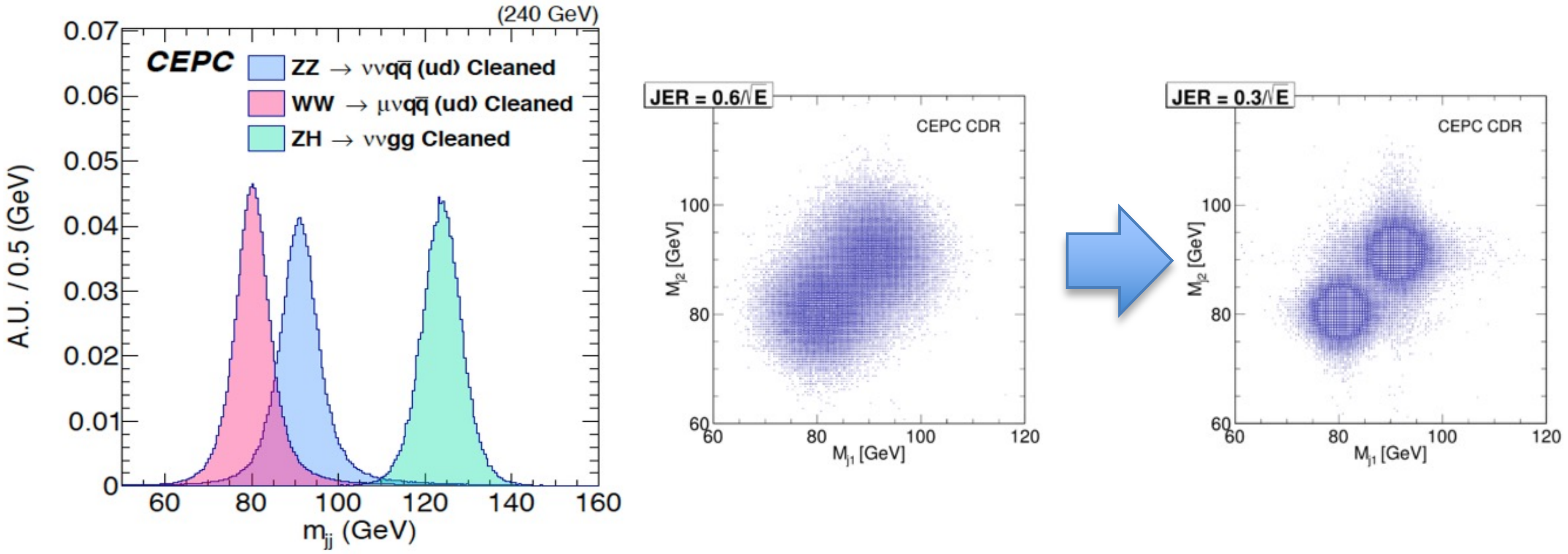


To fully meet the broad spectrum of physics demands from CEPC and fully explore the CEPC physics potential

- Boson mass resolution 4% → 3%
- EM energy resolution 15% → 3%
- Hadron PID 3σ up to 20 GeV/c

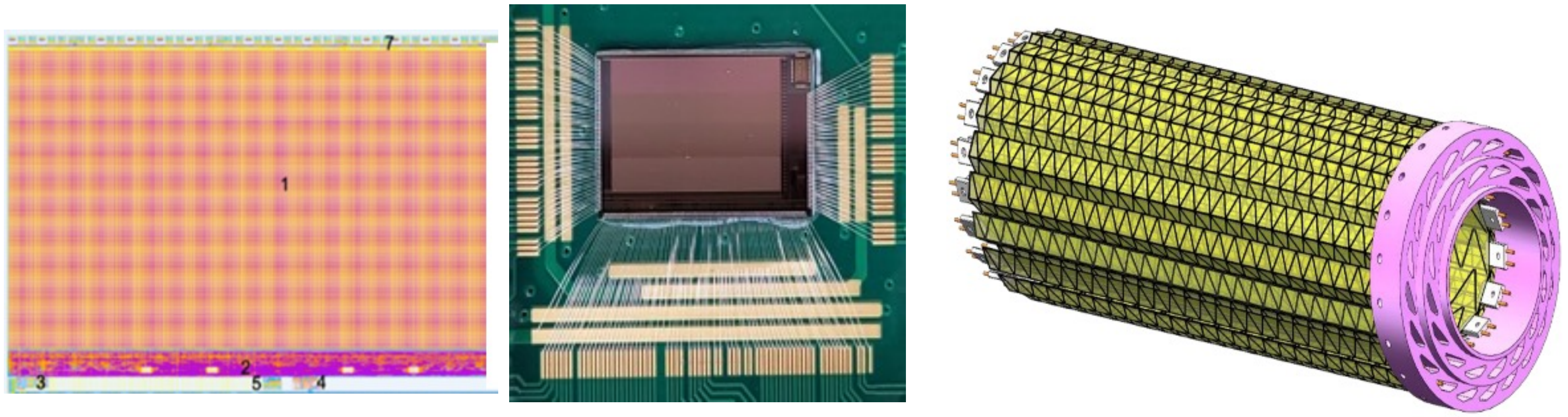
Detector	World-class level	4th concept
PFA ECAL	~ 15-20% / √E	~ 3% / √E
PFA HCAL	~ 50-60% / √E	~ 40% / √E

- Silicon trackers (outer timing layer) combined with TPC/DC
  Better tracking & PID
- Highly-granular crystal ECAL
  PFA & high EM resolution
- Scintillating glass sampling HCAL
  Better hadron energy resolution

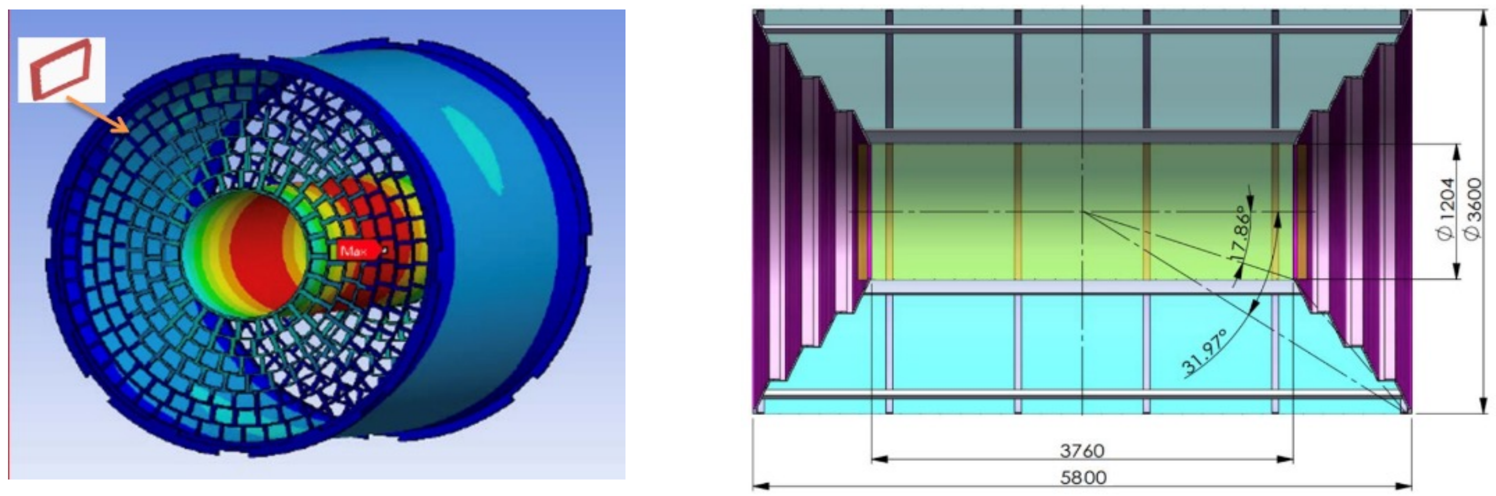


Technologies and Requirements

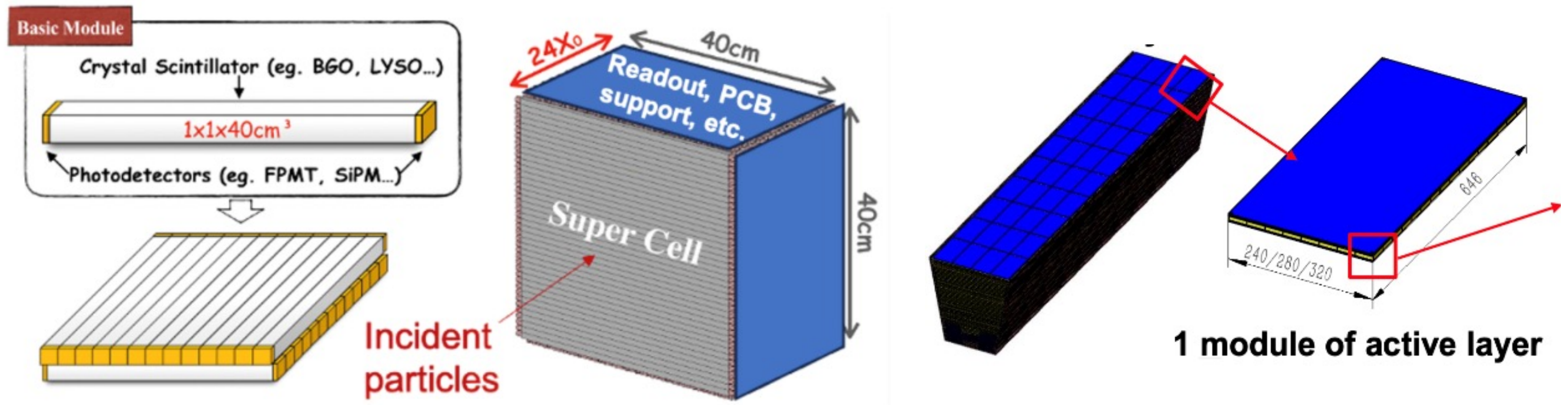
Detector	Technology	Performance Requirements
Silicon vertex detector	MAPS chip Low-mass structure	Position resolution ~ 3 um Material budget $< 0.15\%\ X_0$/layer
Silicon tracker	Large area silicon tracker	Momentum resolution $\sigma(\frac{1}{p_T}) \sim 2 \times 10^{-5} \oplus \frac{1 \times 10^{-3}}{p \sin^{3/2} \vartheta} (\mathrm{GeV}^{-1})$
Gaseous tracker	High precision dE/dx (dN/dx) measurement	$\sim 2\%$
TOF detector	Silicon timing detector	Time resolution ~ 30 ps
ECAL	4D crystal ECAL	EM energy resolution $\sim 3\%/\sqrt{E(\mathrm{GeV})}$ Granularity $2\mathrm{cm} \times 2\mathrm{cm} \times 2\mathrm{cm}$
Magnet	Low mass HTS magnet	B field 2-3 T Thickness < 150 mm Material budget $< 1.5\ X_0$
HCAL	Scintillator glass HCAL with high granularity	Hadron energy res $\sim 40\%/\sqrt{E(\mathrm{GeV})}$ Jet energy resolution $\sim 30\%/\sqrt{E(\mathrm{GeV})}$



MAPS and low-mass system



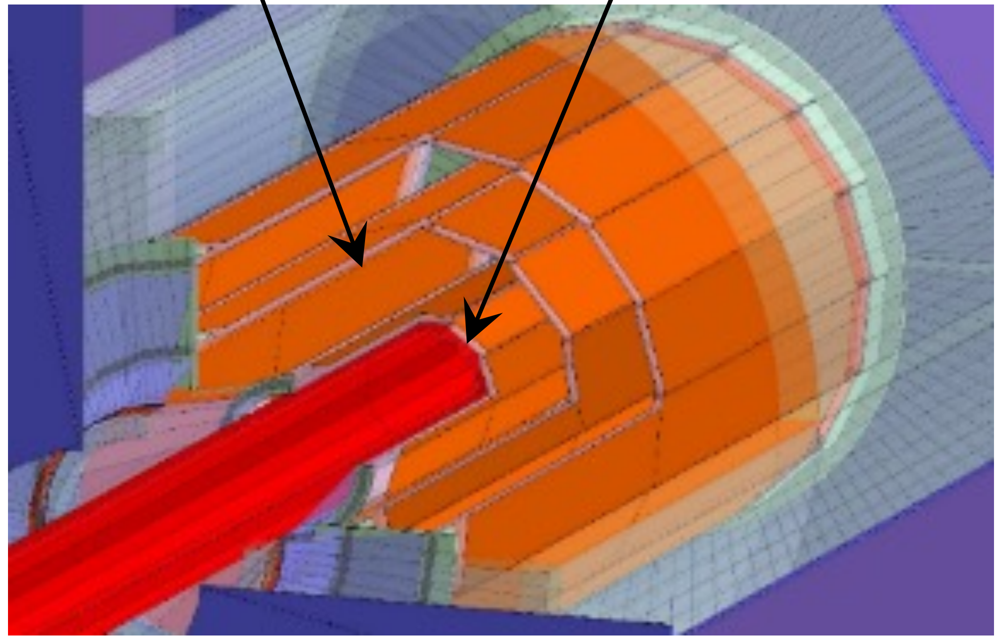
Large volume TPC or drift chamber



4D Crystal ECAL & Glass HCAL

MAPS and Detector Prototype

2 layers / ladder **R_{in}~16 mm**



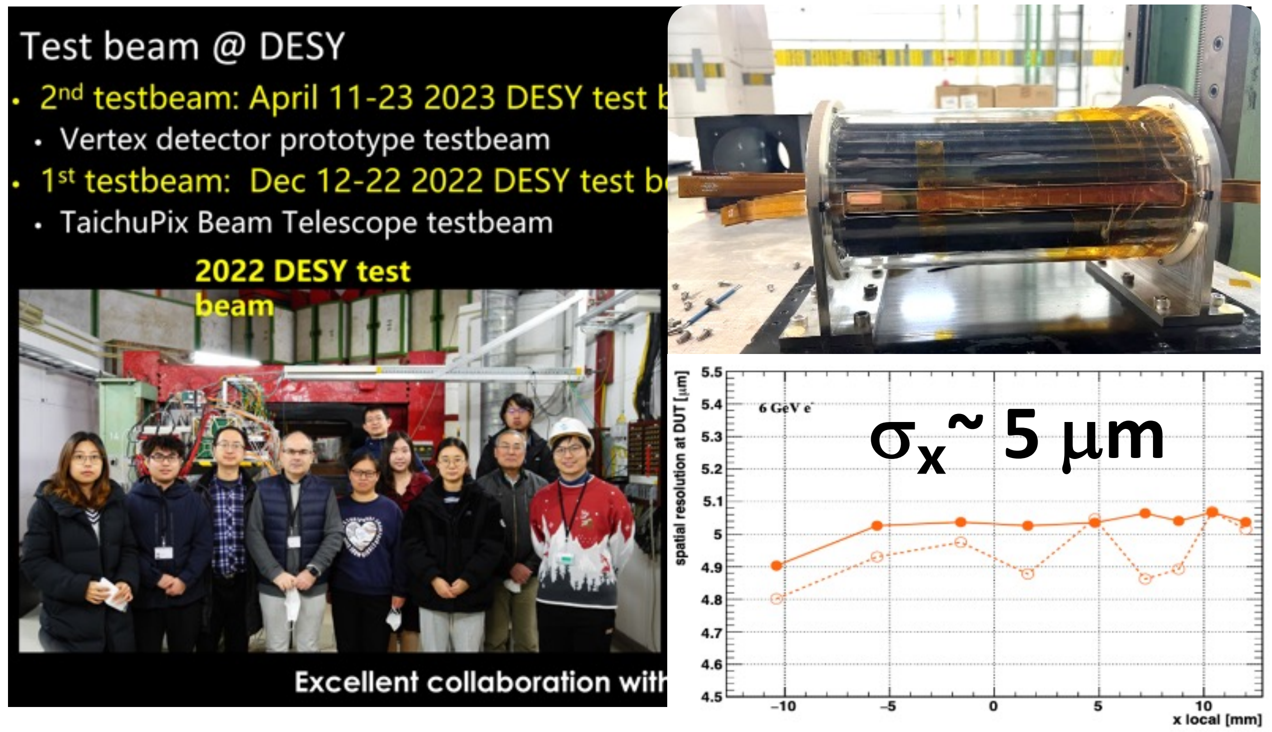
Goal: σ(IP) ~ 5 μm for high P tracks

CDR design specifications

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

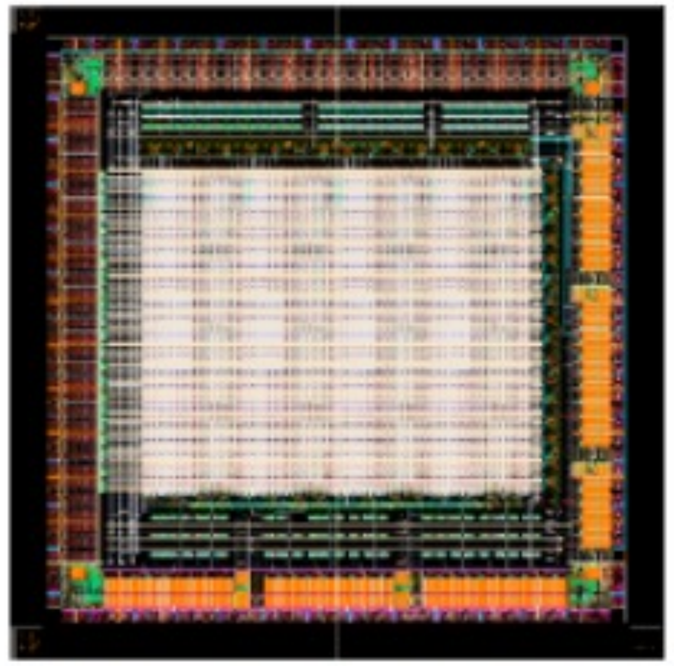
Silicon pixel sensors developed in 5 series: JadePix, CPV, TaichuPix, Arcadia, COFFEE

Vertex detector prototype with Taichu chips and its beam test

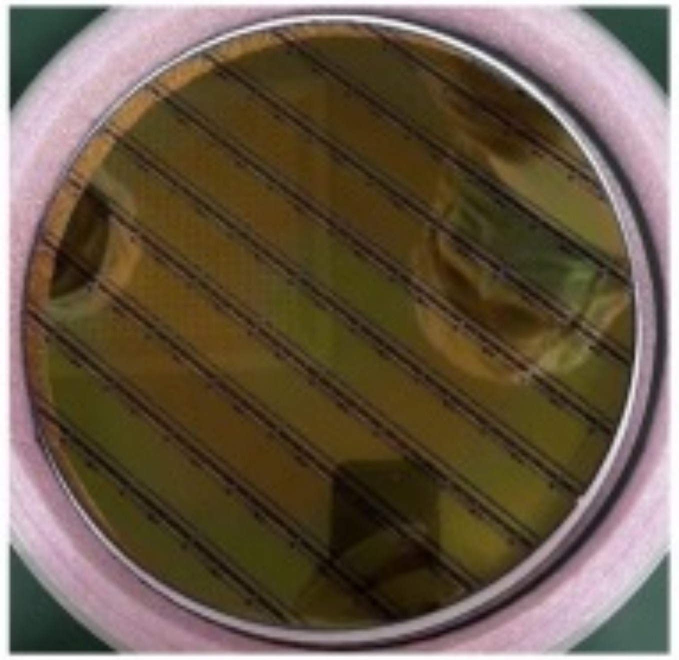


JadePix-3 pixel size ~16×23 um², Tower-Jazz 180nm CiS process, σ_x~5 μm, 53mW/cm²

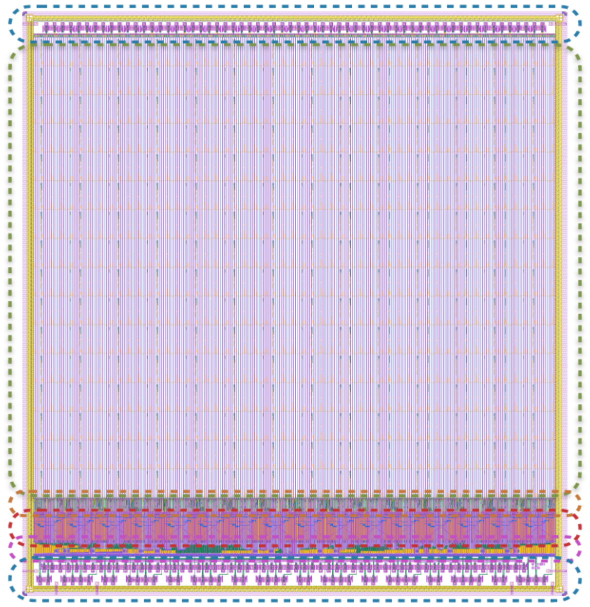
CPV4 (SOI-3D), 64×64 array ~21×17 μm² pixel size



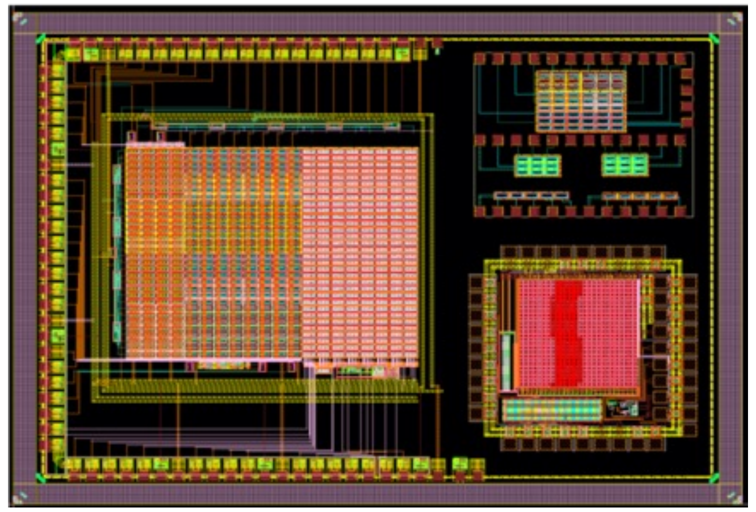
TaichuPix-3, FS 2.5x1.5 cm² 25×25 μm² pixel size



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

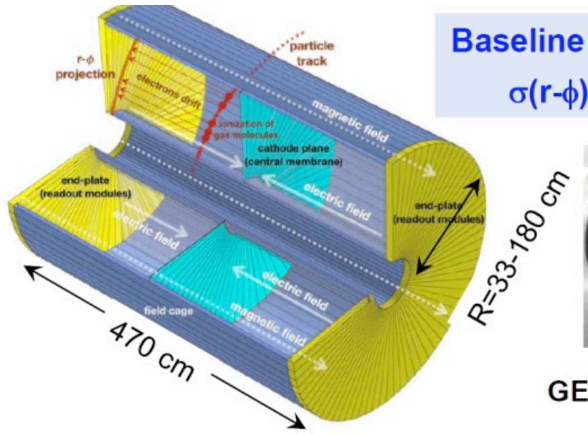


COFFEE for a CEPC tracker using SMIC 55nm HV-CMOS process

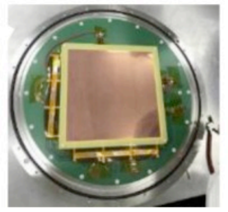


TPC, DC, PFA Calorimeters

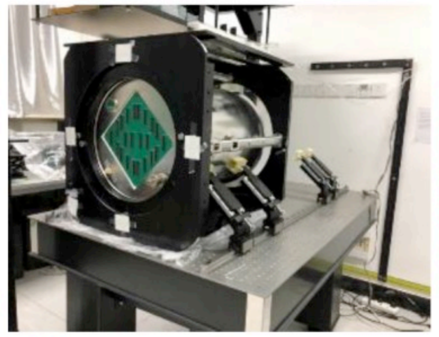
TPC R&D



Baseline main tracker
σ(r-ϕ) ~100 μm



GEM-MM cathode

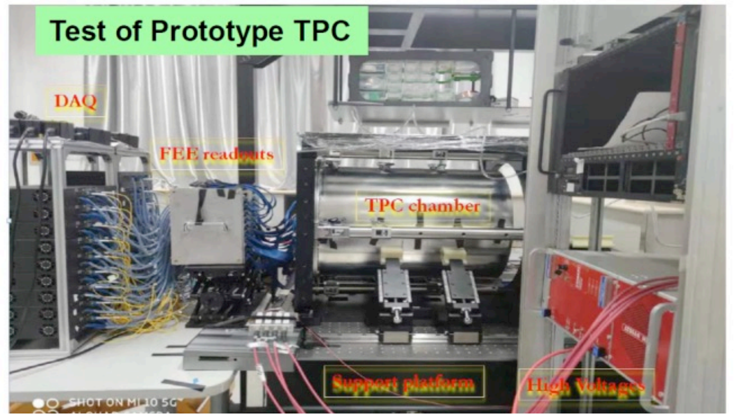


TPC Prototype + UV laser beams

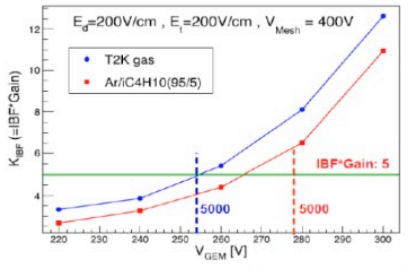
MOST 1 (IHEP+THU)

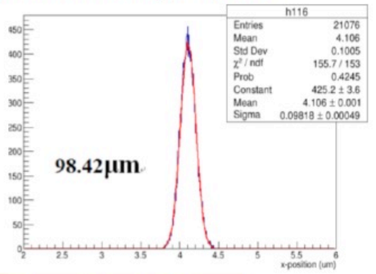
Low power FEE ASIC

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.

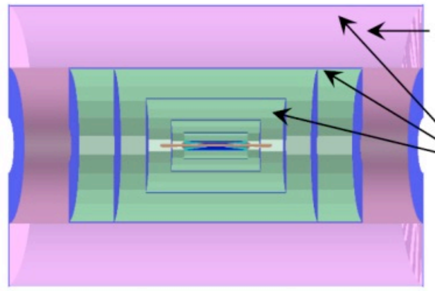


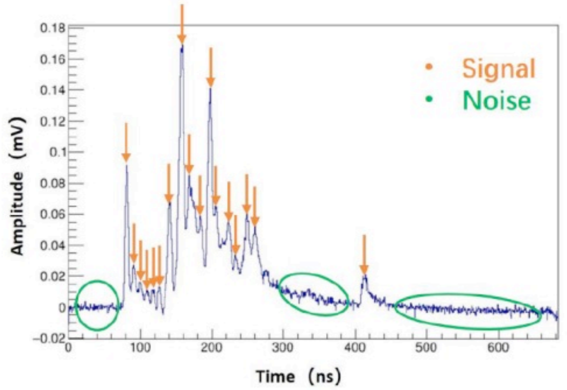


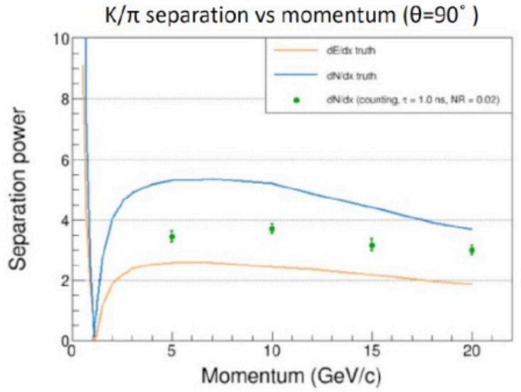
σ_x < 100 μm for drift length of 27cm

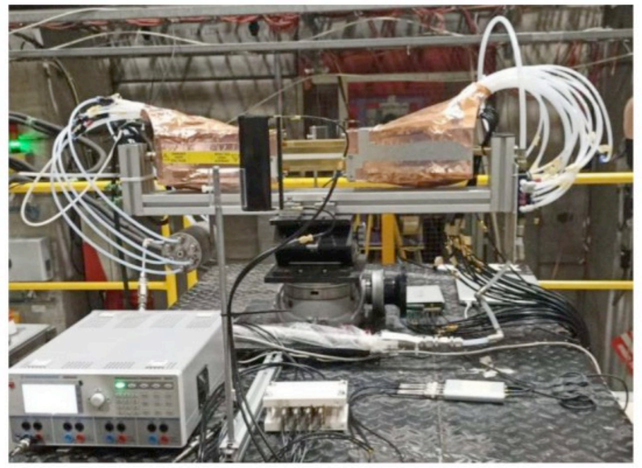
Drift Chamber R&D

- **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.



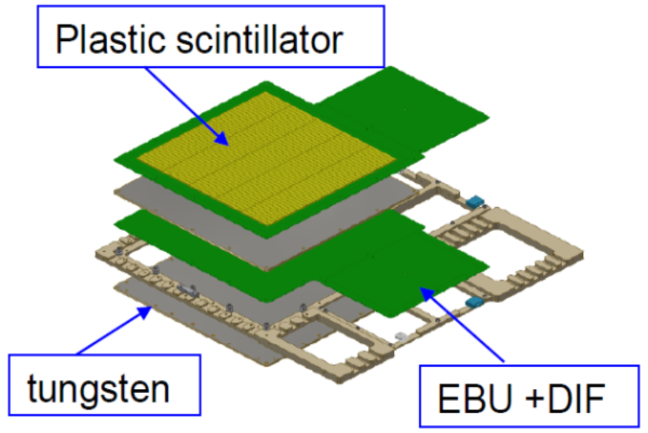


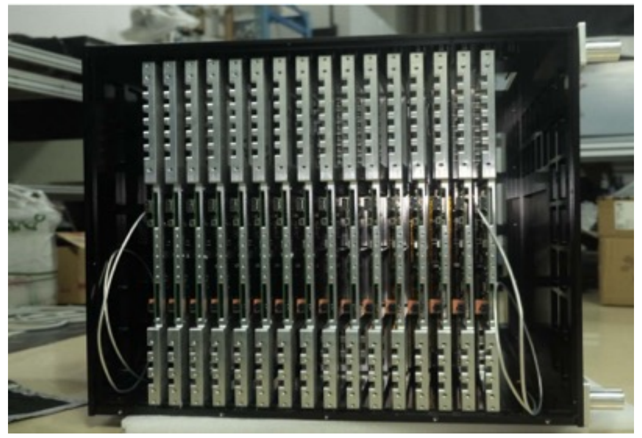


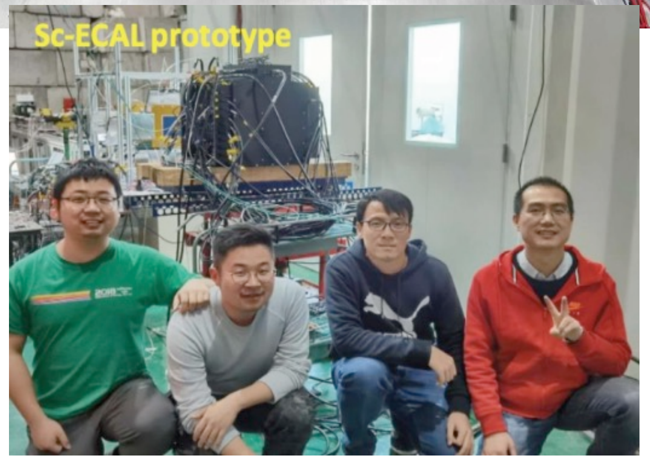


IHEP and Italian INFN groups have close collaboration and regular meetings.
IHEP joined the TB (led by INFN group) in 2021 and 2022

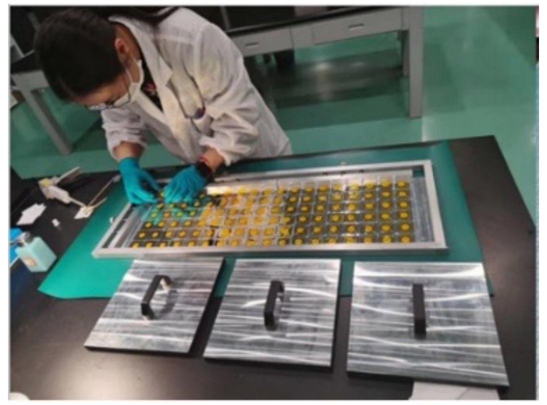
Sci-W ECAL Prototype (32-layer, 6720 chs)

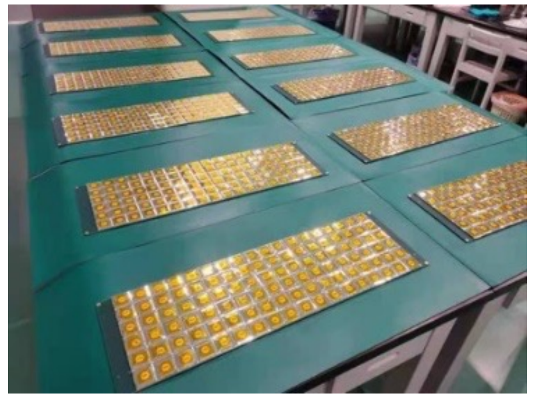


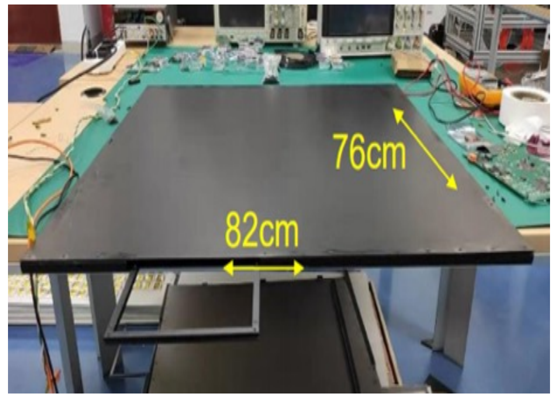


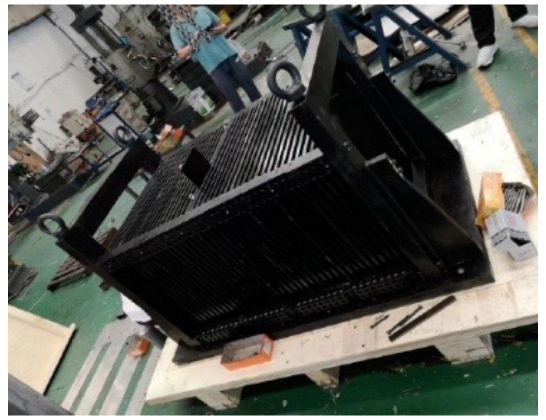


Sci-Fe AHCAL Prototype (40-layer, 12960 chs)



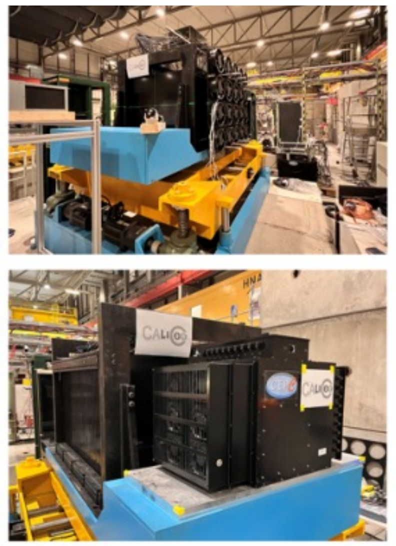


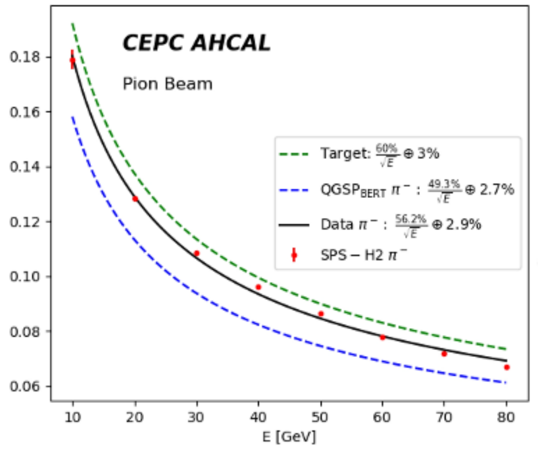


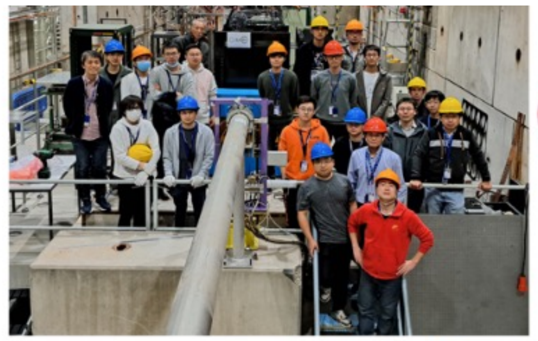


More on Calorimeters

Beam tests of Sci-W ECAL and Sci-Fe AHCAL Prototypes at CERN in 2022 & 2023

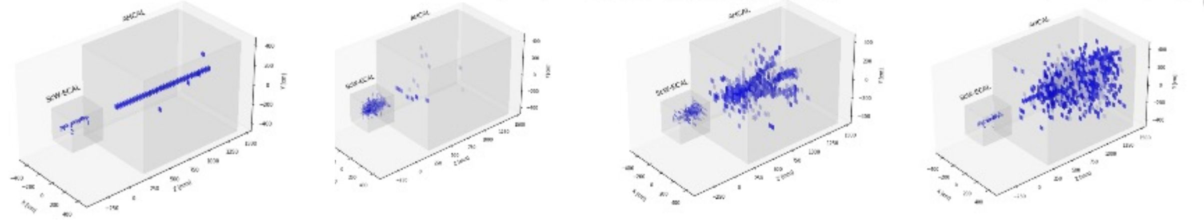


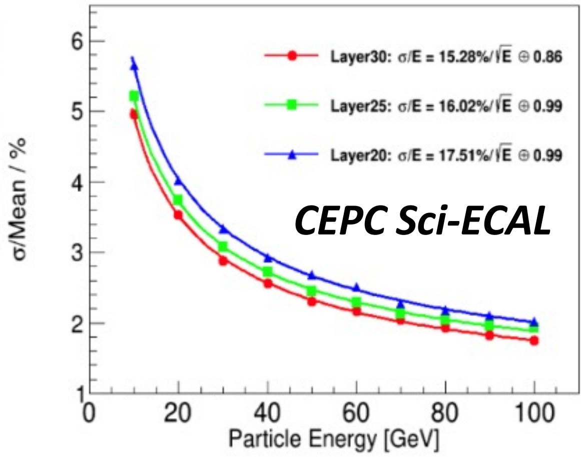




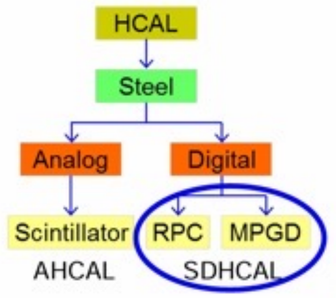
Oct 19 - Nov 2, 2022 — SPS H8 beamline
Apr 26 - May 10, 2023 — SPS H2 beamline
May 17 - 31, 2023 — PS T9 beamline

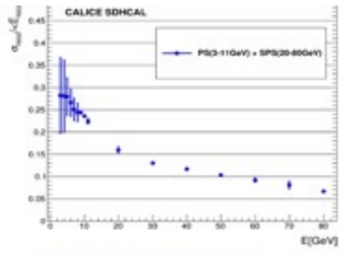
100 GeV mu- | 60 GeV electron (SPS) | 60 GeV negative pion (SPS) | 350 GeV negative pion (SPS)

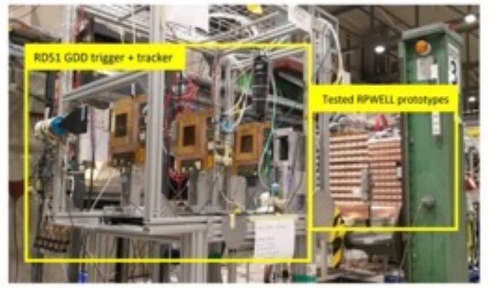




PFA DHCAL R&D







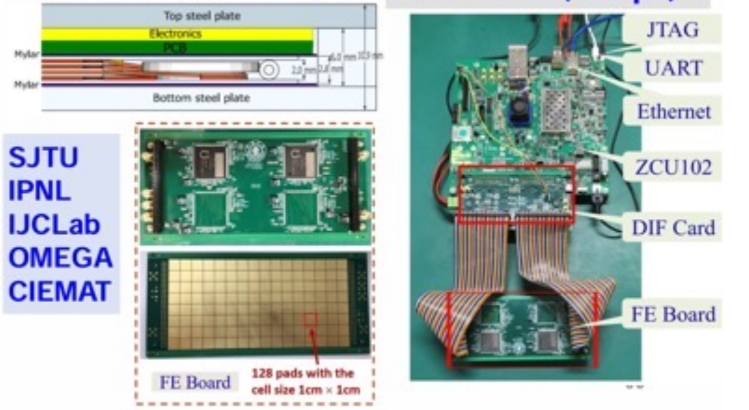
SDHCAL-GRPC (1.3 m³, IPNL) — JINST 15, P10009 (2020); JINST 17, P07017 (2022) — RPWELL (50x50cm², WIS+IIT, Israel)

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

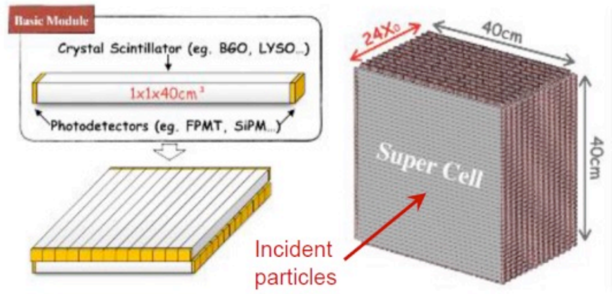
GRPC 1m x 1m (SJTU) — JINST 16, P12022 (2021)
RWELL 0.5m x 1m (USTC+IHEP)

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

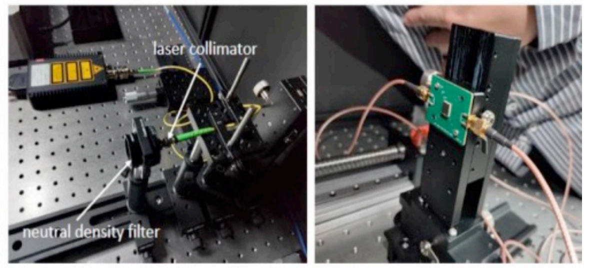
SJTU
IPNL
IJCLab
OMEGA
CIEMAT



PFA crystal ECAL designs and simulation



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

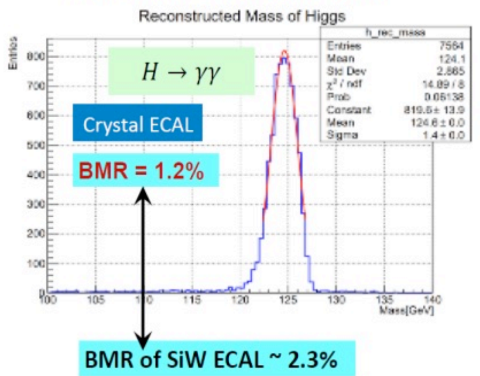


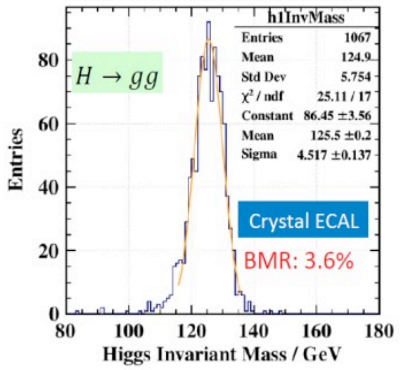
Bench Test

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

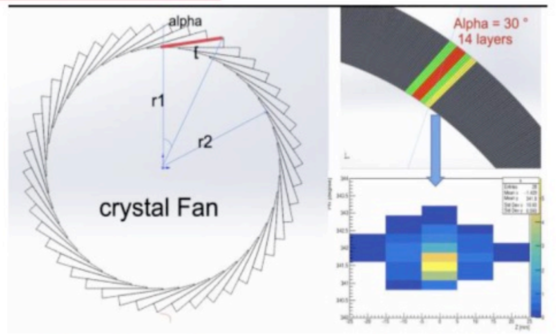
Full Simulation Studies + Optimizing PFA for crystals

Performance with photons | Performance with jets



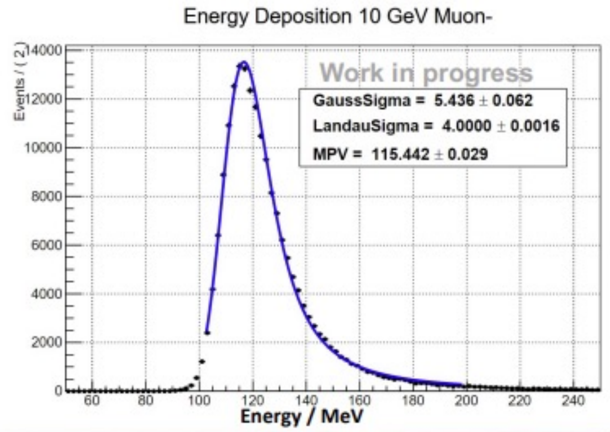


Crystal Fan Design Fine segmentation in Z, ϕ, r

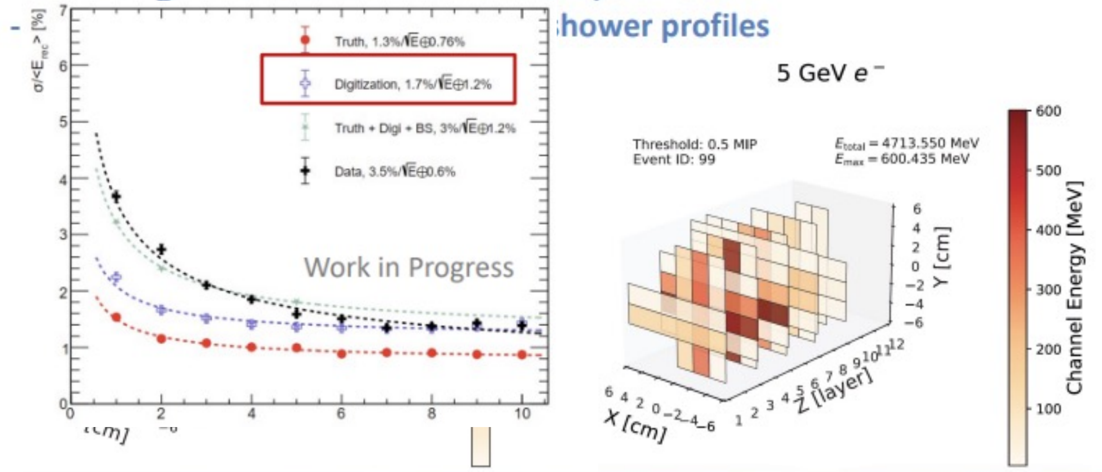


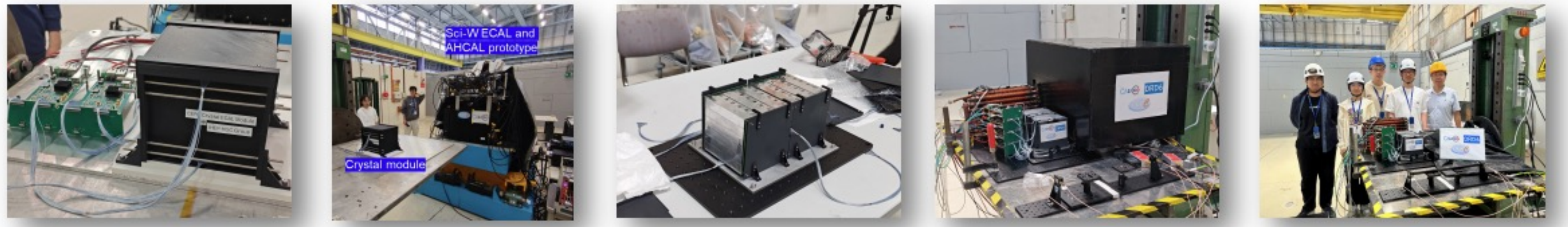
Crystal ECAL R&D

2023 CERN beam test at PS-T9
- Successful system commissioning
- Clear MIP signals for all channels



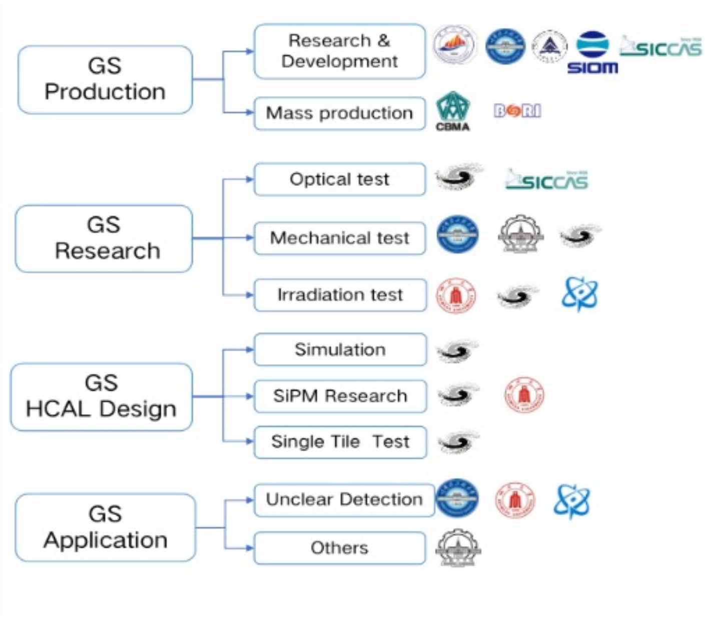
2024 CERN beam test at PS-T9 (June 24 – July 10)
- Promising EM resolution with 1-10 GeV/c e^- beam
- ... shower profiles



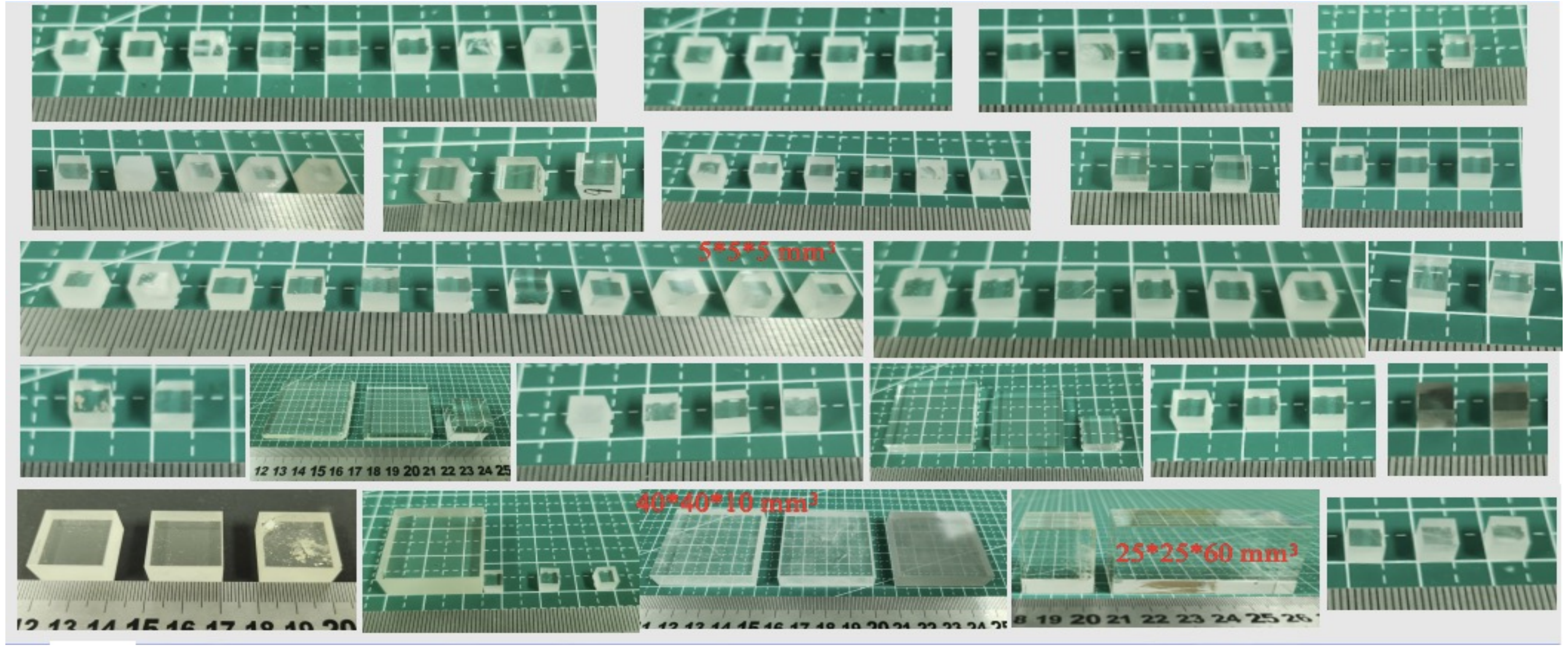


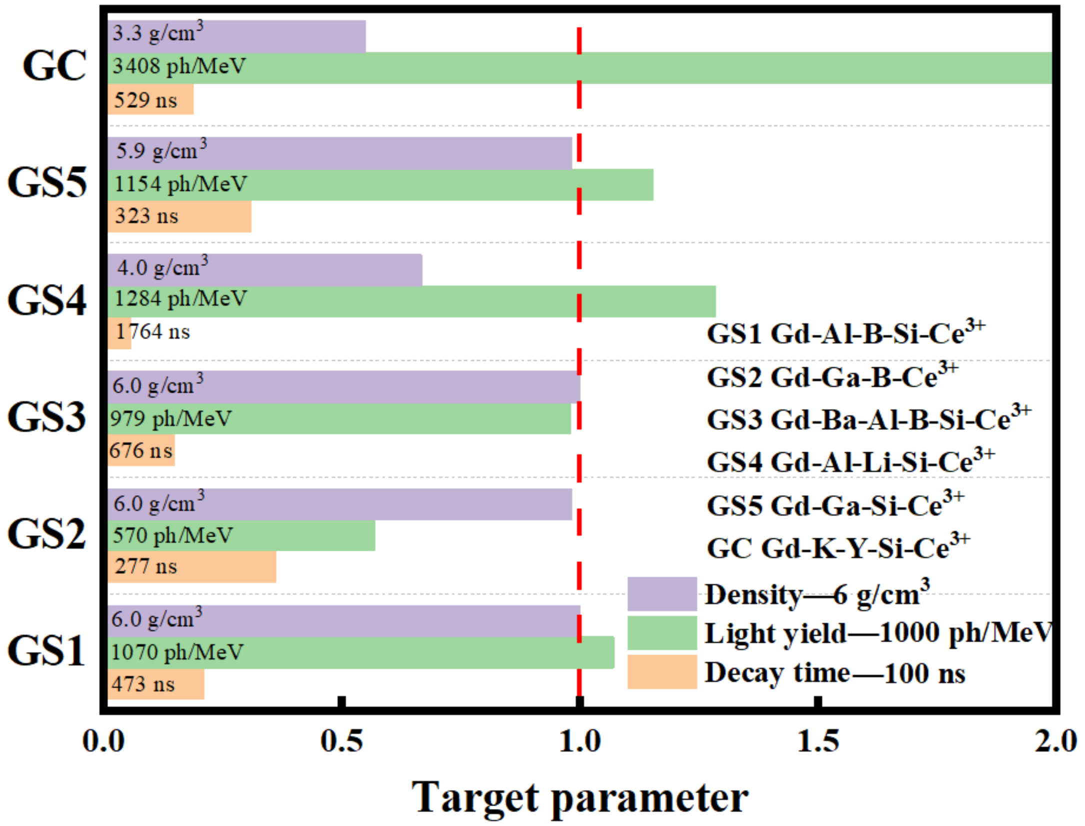
Glass Scintillator R&D

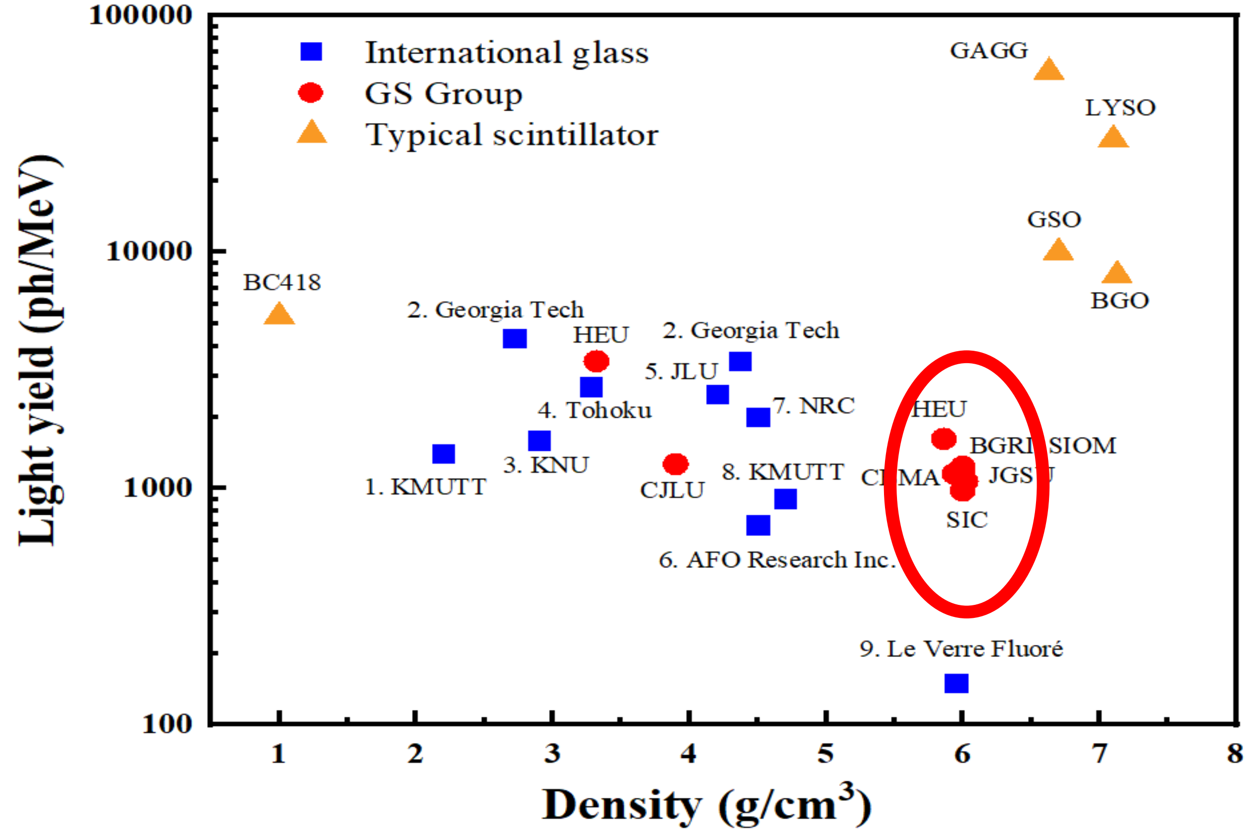
- A collaboration with 11 institutes has been formed
- R&D targets: ~6g/cm³ , ~1000ph/MeV, ~100ns



- Institute of High Energy Physics，CAS 中国科学院高能物理研究所
- Jinggangshan University 井冈山大学
- Beijing Glass Research Institute 北京玻璃研究院
- China Building Materials Academy 中国建筑材料研究院
- China Jiliang University 中国计量大学
- Harbin Engineering University 哈尔滨工程大学
- Harbin Institute of Technology 哈尔滨工业大学
- Sichuan University 四川大学
- Shanghai Institute of Ceramics，CAS 中国科学院上海硅酸盐研究所
- Shanghai Institute of Optics and Fine Mechanics，中国科学院上海光学精密机械研究所
- CNNC Beijing Unclear Instrument Factory 中核（北京）核仪器有限责任公司





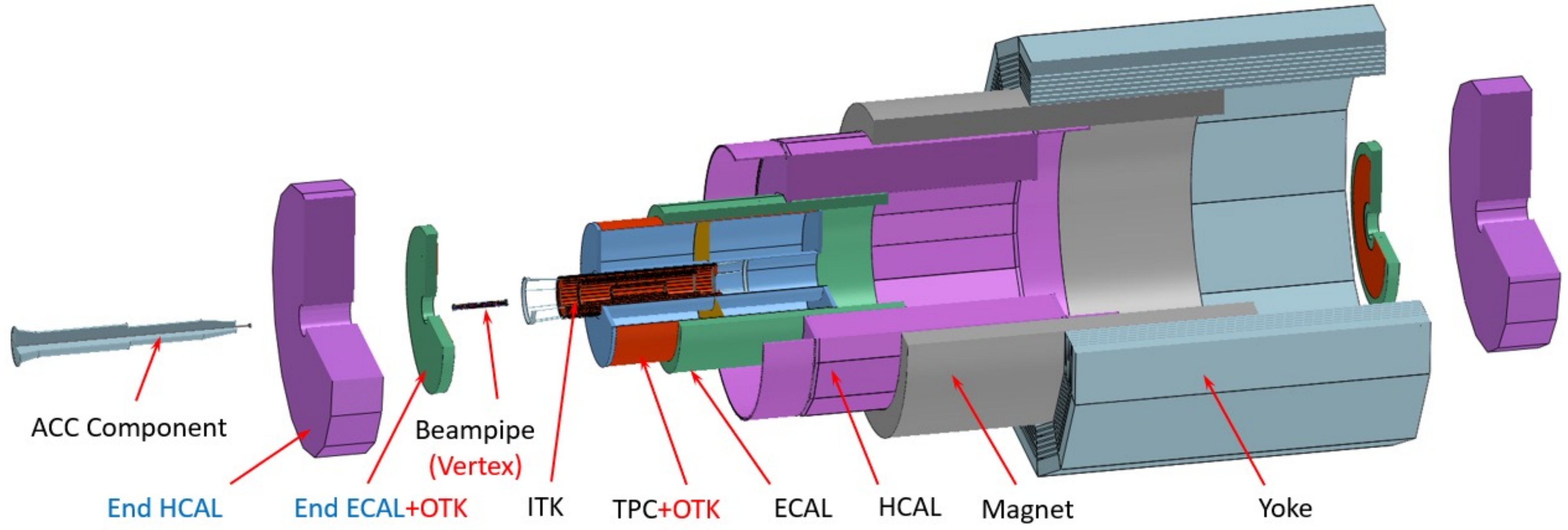


An important direction in future calorimeter development

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		

- **A large number of detector technology options and R&D activities at different levels of maturity.**
- **Need to converge on a set of options to produce a CEPC reference detector TDR (Ref-TDR)**
  - **Ref-TDR effort started in Jan. 2024**
  - **Ref-TDR draft expected in Dec. 2024**
  - **Official release of Ref-TDR in Jun. 2025**

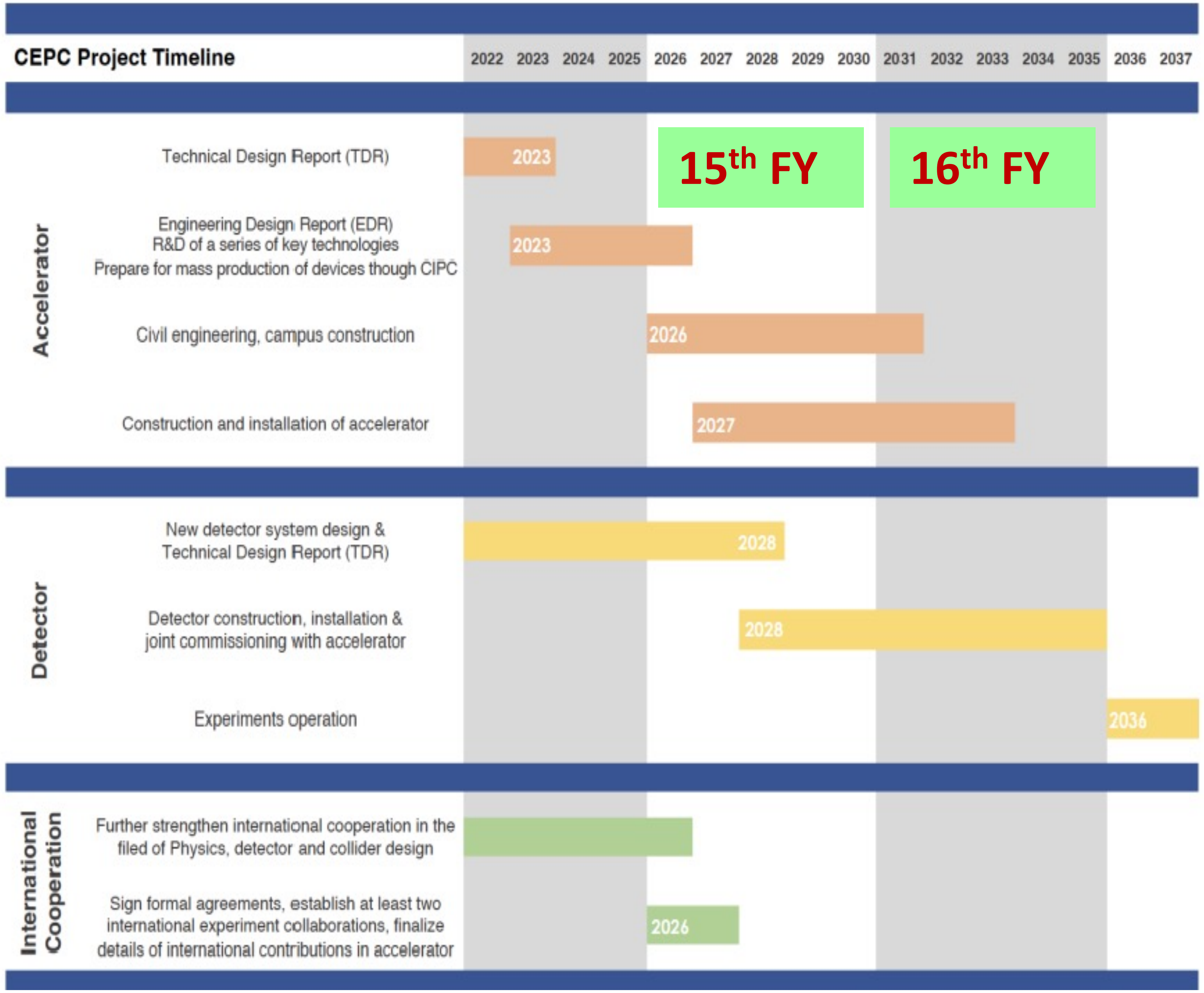


CEPC Project Planning and Schedule

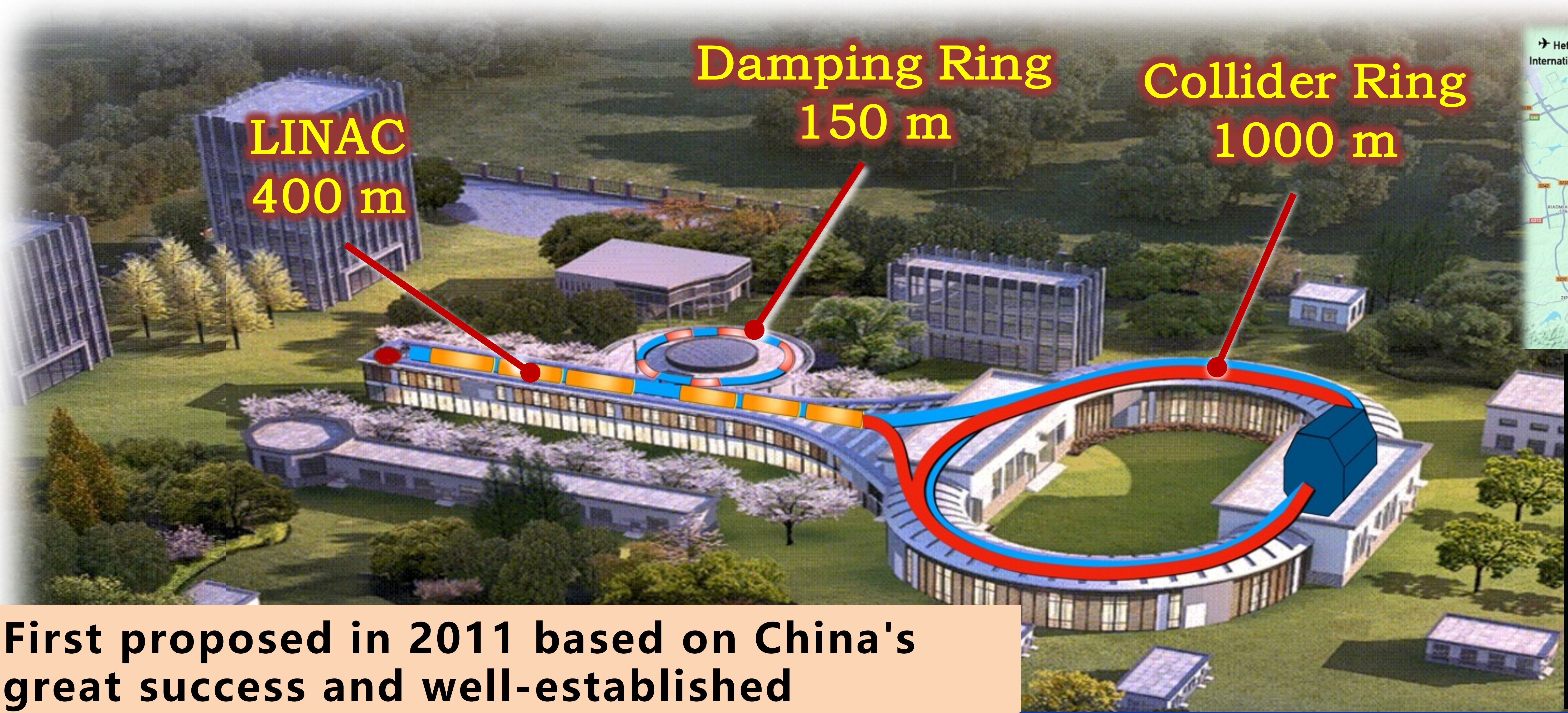
2012.9	2015.3	2018.11	2023.12	2025.6	2027	15th five year plan (2026-2030)
proposed	Pre-CDR	CDR	Acc. TDR	Det. TDR	EDR	Start of construction

CEPC EDR Phase: 2024-2027

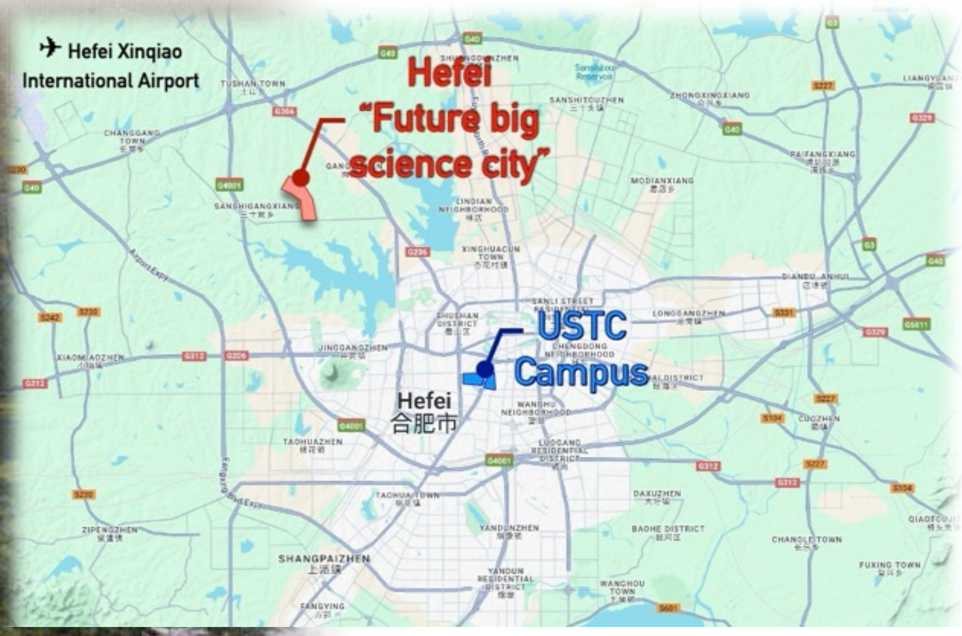
- **CEPC Accelerator EDR** started with 35 WGs in 2024, to be completed in **2027**
- **CEPC Reference Detector TDR** will be released by June, **2025**
- **CEPC proposal** will be submitted to the national government for approval in **2025**
- **Upon approval**, establish at least two international experiment collaborations
- **CEPC construction starts** during the 15th five year plan (2026-2030, e.g. **2027**)
- **CEPC construction completes** around **2035**, at the end of the 16th five year plan

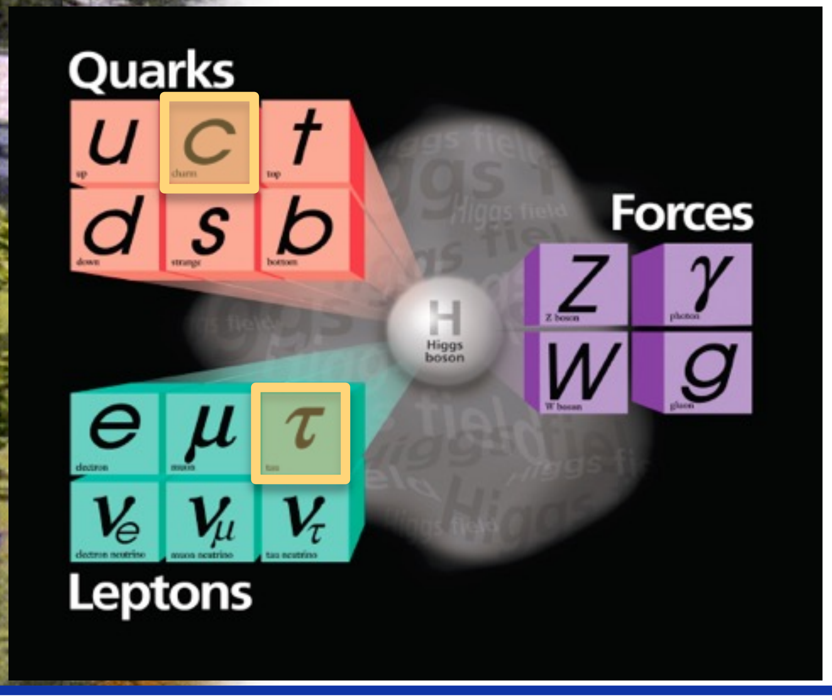


STCF



Candidate Site

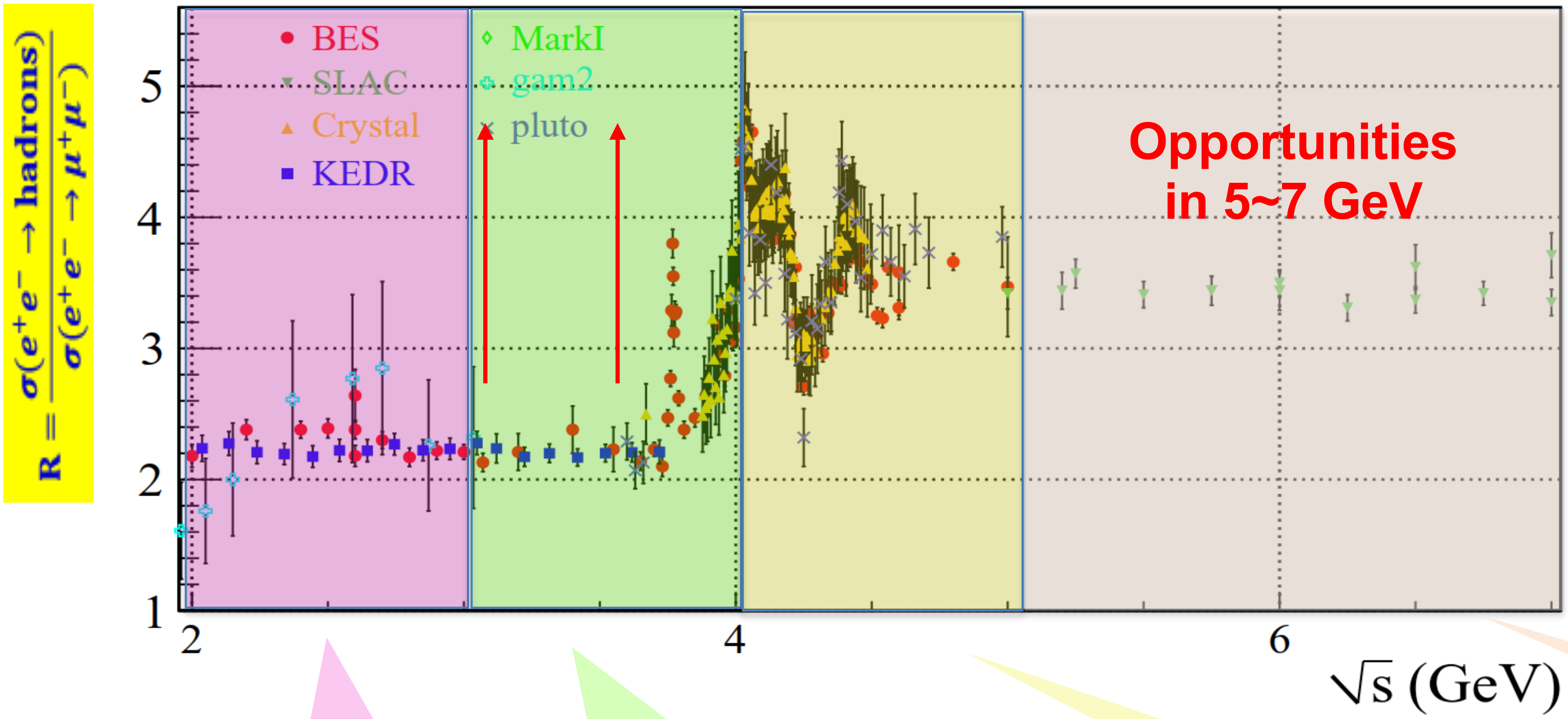




- First proposed in 2011 based on China's great success and well-established international position in tau-charm physics (Beijing Electron-Positron Collider / BEPC)
- Energy: 2-7GeV, peak L>= $0.5\times10^{35}cm^{-2}s^{-1}$
- Potential for luminosity upgrade and beam polarization

STCF can produce an enormous amount of "clean" tau leptons and charm hadrons, allowing full exploration of the unique physics potential in the tau-charm energy region: QCD, exotic hadrons, flavor physics and CPV, new physics...

Unique Tau-Charm Energy Region



- **Transition** region between perturbative and non-perturbative QCD
- **Pair production** of hadrons and τ leptons **at threshold**
- **Abundant resonances**
- **Large production X-sec for charmonium(-like) states and exotic states**

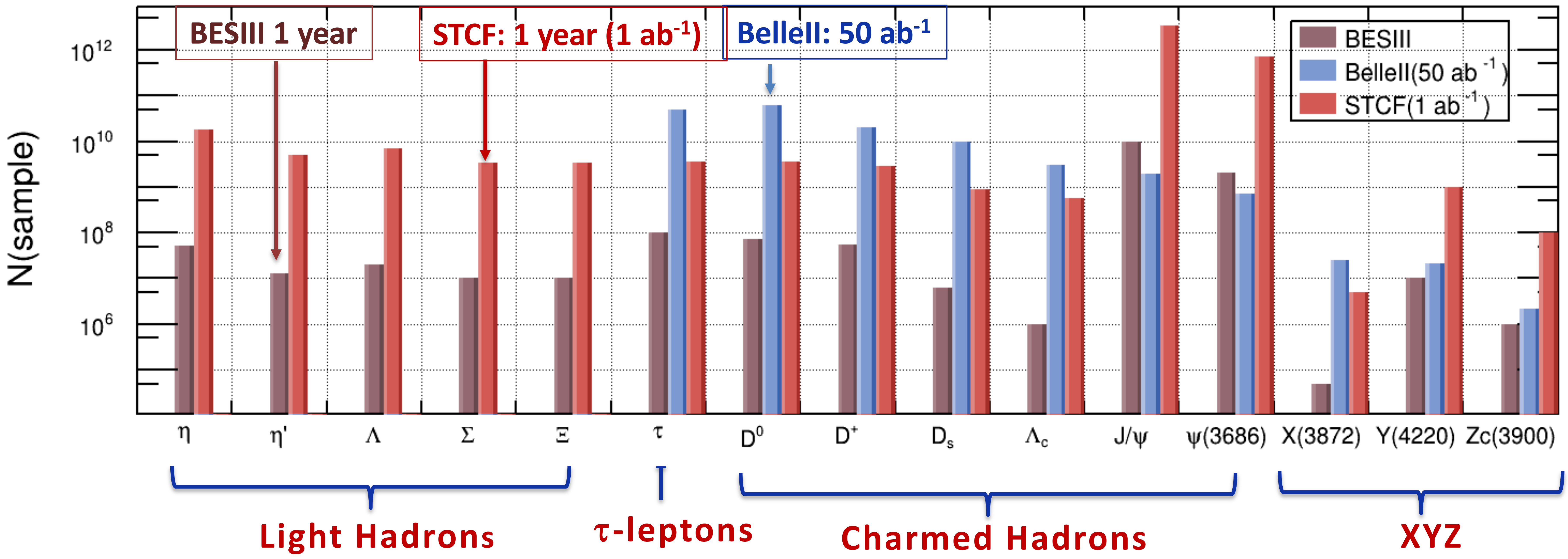
- Hadron form factors
- $Y(2170)$ resonance
- Mutltiquark states with s quark
- R value / g-2 related

- Light hadron spectroscopy
- Gluonic and exotic states
- Processes of LFV and CPV
- Rare and forbidden decays
- Physics with τ lepton

- XYZ particles
- Physics with D mesons
- f_D and f_{D_s}
- $D^0 - \bar{D}^0$ mixing
- Charm baryons

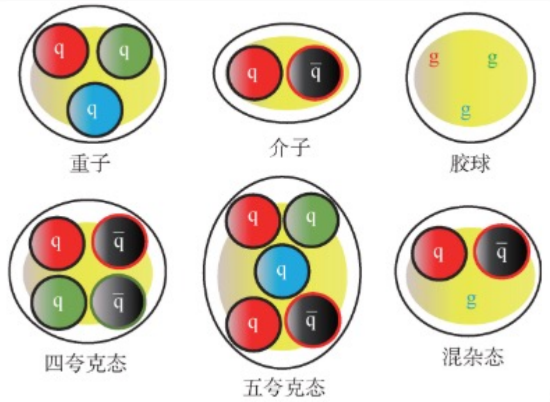
- Complete XYZ family
- Hidden-charm pentaquarks
- Search for di-charmonium states
- More charmed baryons
- Hadron fragmentation

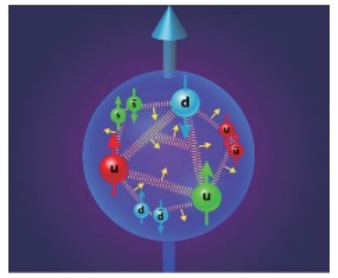
STCF: A Super Factory of Various Particles



- **STCF is not only a super τ-charm factory, but also a super factory of XYZ, hyperons and light hadrons to unravel the mystery of how quarks form matter and the symmetries of fundamental interactions**

STCF Physics Program

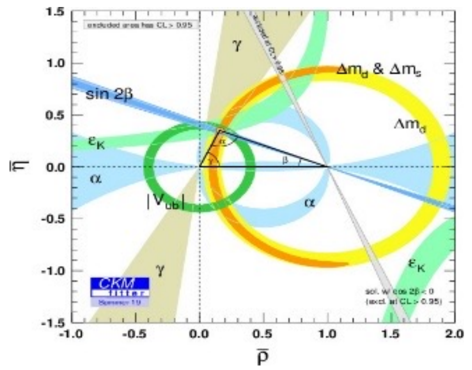


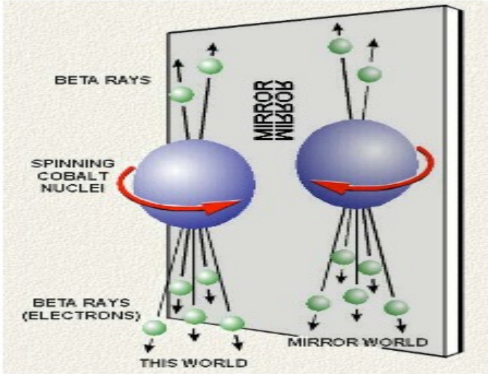


Physics at STCF

QCD and hadronic physics

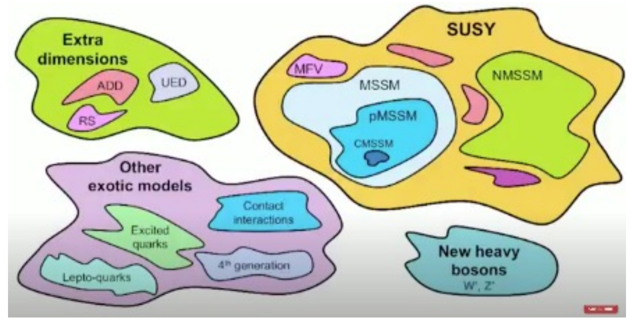
- **XYZ Properties:** e+e-→Y→γX,ηX,φX; e+e-→Y→πZc, KZcs
- **Hadron Spectroscopy:** Excited ccbar and their transition, Charmed hadron spectroscopy, Light hadron spectroscopy
- **R value:** e+e-→inclusive; τ mass: e+e-→τ+τ-
- **Nucleon Form Factors:** e+e-→BBbar from threshold
- **Pentaquarks:** e+e-→J/ψppbar, Λc Dbar pbar, Σc Dbar pbar
  Di-charmonium: e+e-→J/ψηc, J/ψhc
- **Muon g-2:** e+e-→π+ π-, π+ π- π0, 4π, K+ K-, γγ→π0, η(′),π+ π-
- **Fragmentation functions:** e+e-→(π,K,p,Λ,D)+X, e+e-→(ππ,KK,πK)+X





Flavor Physics and CP Violation

- **CKM matrix (Vcd, Vcs):** D_(s)+→l+v, D→P l+ v
- **Charm hadron decay:** Λc+, Σc, Ξc, Ωc decay
- **CPV in Hyperons:** J/ψ→ΛΛbar, ΣΣbar, Ξ- Ξ+bar, Ξ0 Ξ0bar
- **D0-D0bar mixing:** ψ(3770)→(D0 D0bar)(CP=-), ψ(4140)→π0 (D0 D0bar)(CP=-) or γ(D0 D0bar)(CP=+)
- **CPV in τ:** τ→Ks πv, EDM of τ, τ→π/K π0 v for polarized e- beam
- **CPV in Charm:** D0→K+K-/π+π-, Λc→pK-π+π0/Λπ+π+π-/pKs π+π-
- **γ/φ3 measurement:** D0→K(s/L) π+ π-, K(s/L) K+ K-,K3π, 4π
- **γ polarization:** D0→K1 e+ v_e



Forbidden/Rare decay and New Particle

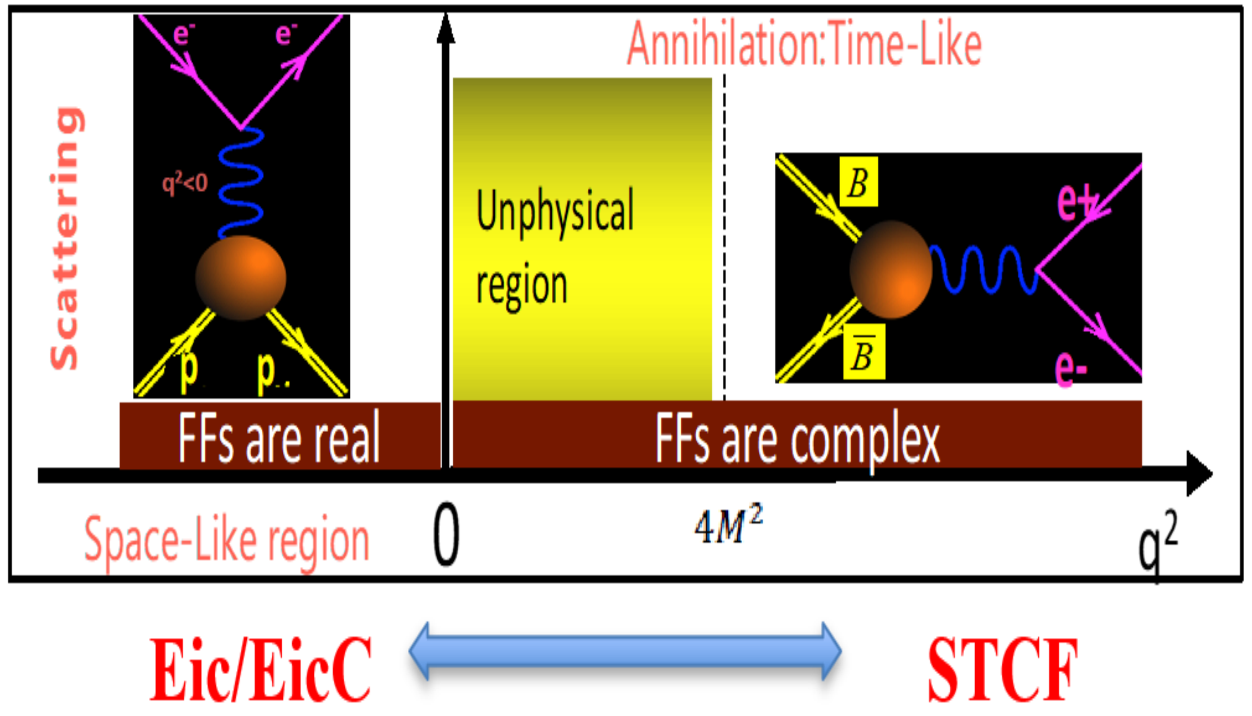
- **LNV, BNV:** D(s)+→l+ l+ X-, J/ψ→Λc e-, B→Bbar…
- **Symmetry violation:** η(′)→llπ0, η′→ηll…
- **FLV decays:** τ→γl, lll,l P1 P2 , J/ψ→ll′, D0→ll′ (l′≠l)…
- **FCNC:** D→γV, D0→l+ l-, e+e-→D*, Σ+→pl+ l-…
- **Dark photon:** e+e-→γA′(→l+ l-), J/ψ→e+e-A′…
  Millicharged: e+e-→χχ̄ γ…

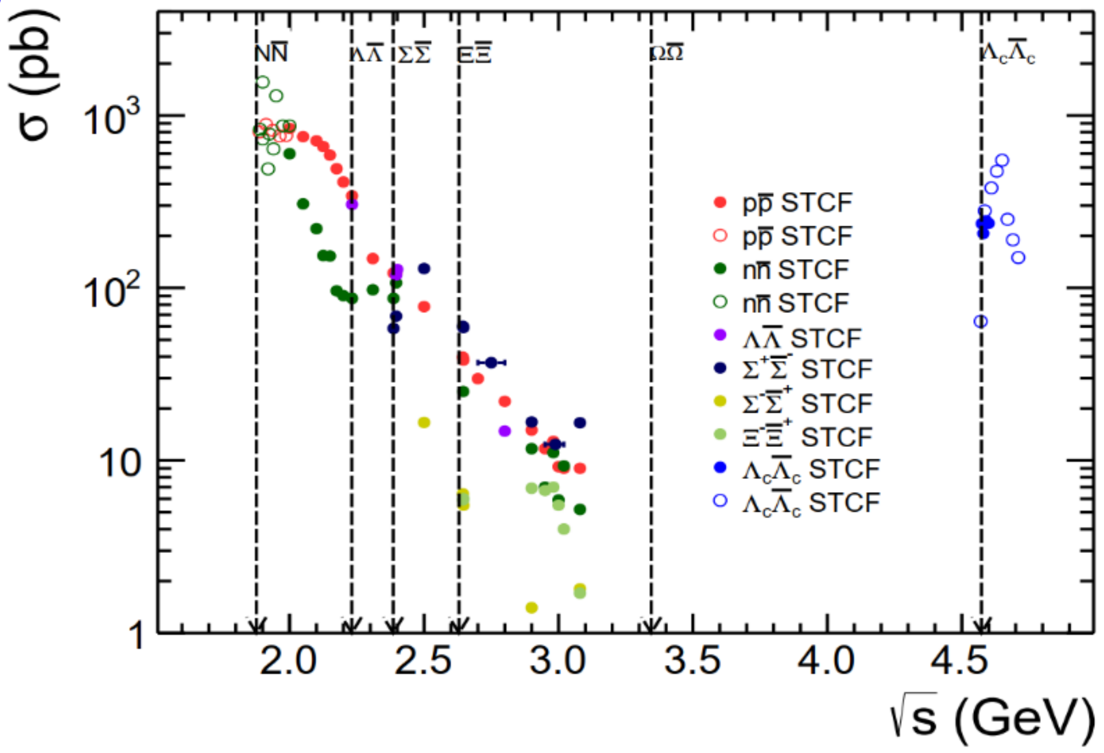
- **Leading role**
- Competing with Belle II/LHCb
- **Complementary to BelleII/LHCb/Eic/EicC**

Hadron Production

Hadron production at STCF is a key avenue to study the strong interaction

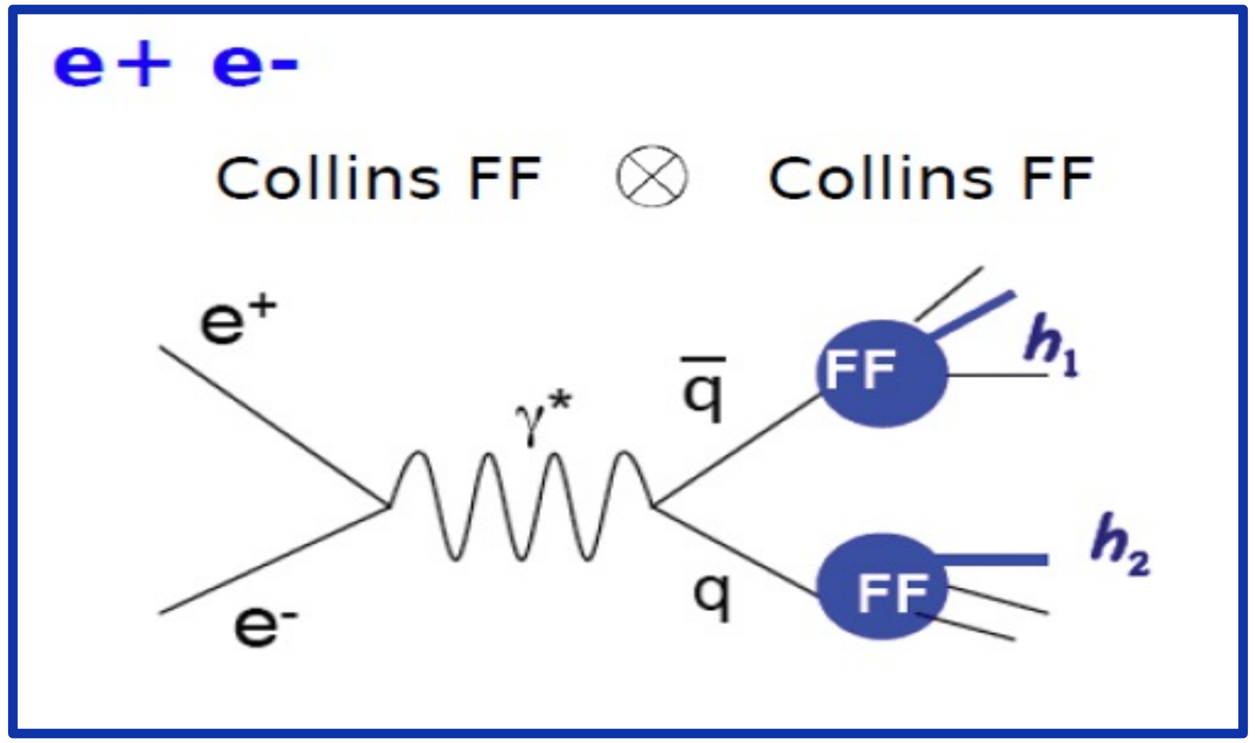
Nucleons/Baryons EM form factors

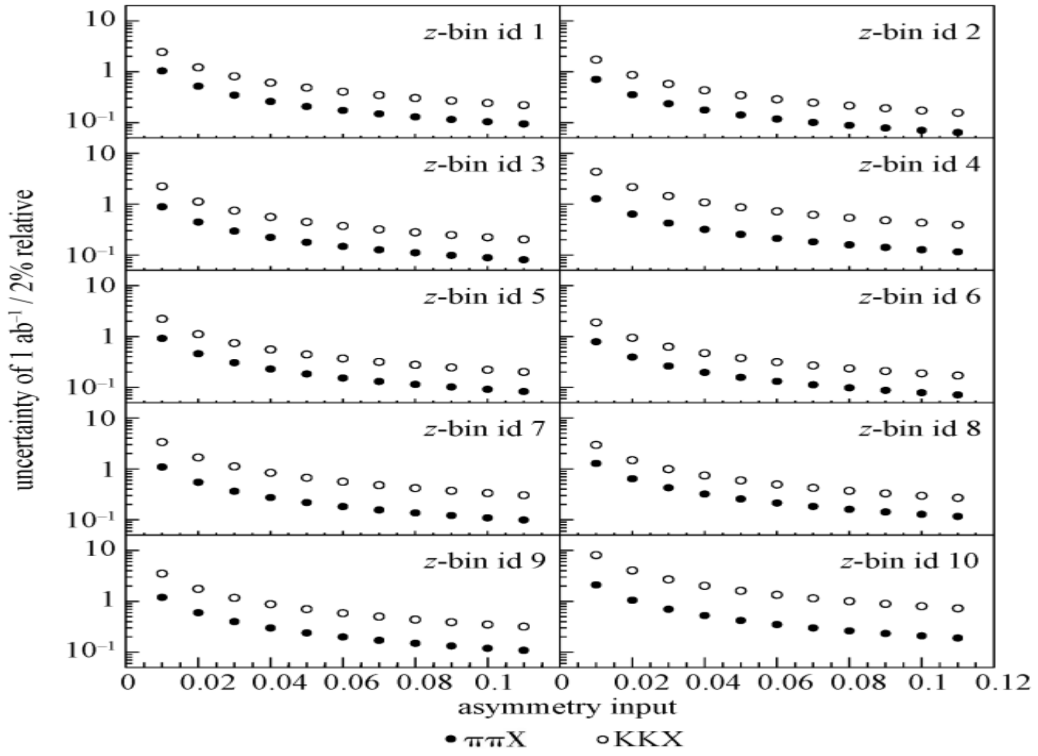




STCF will improve the measurement precision by 2 orders of magnitude, revealing the near-threshold cross section singularity and mystery of G_E and G_M

Fragmentation Functions

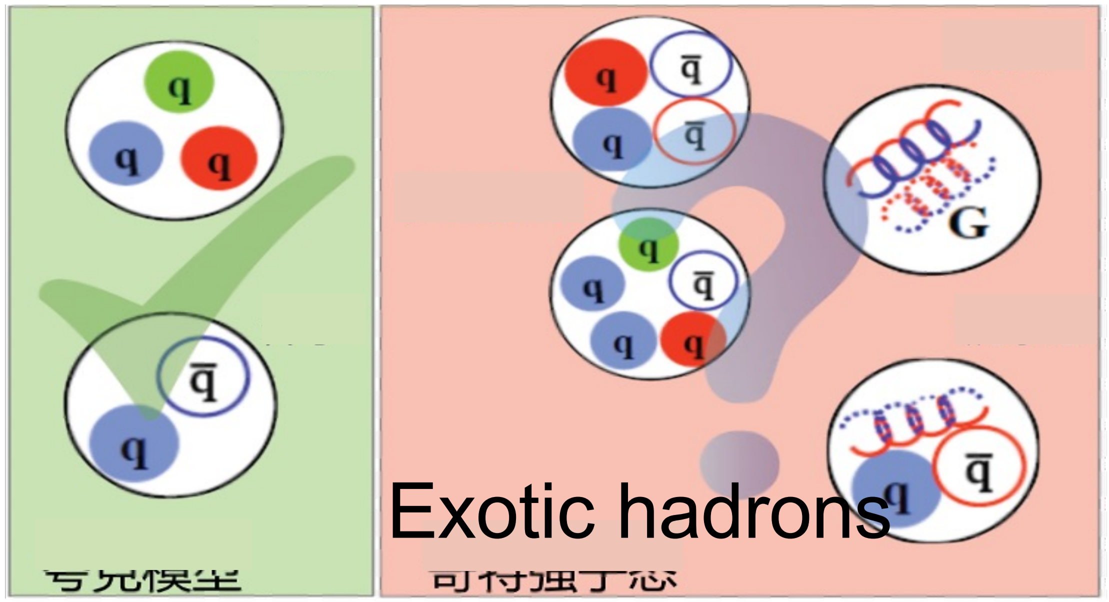


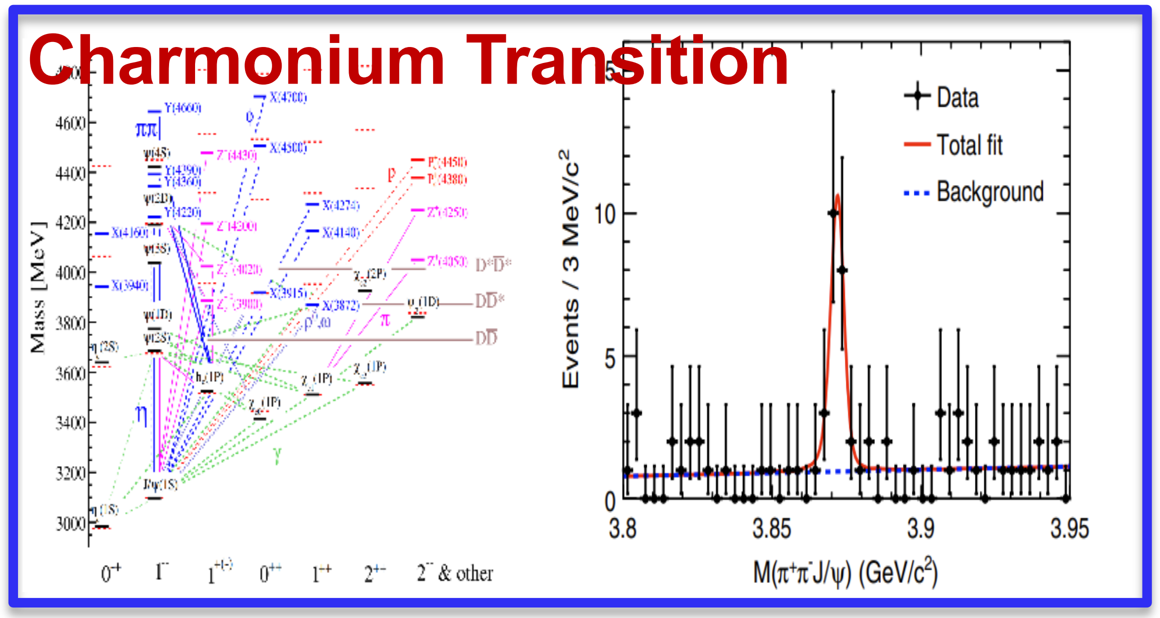


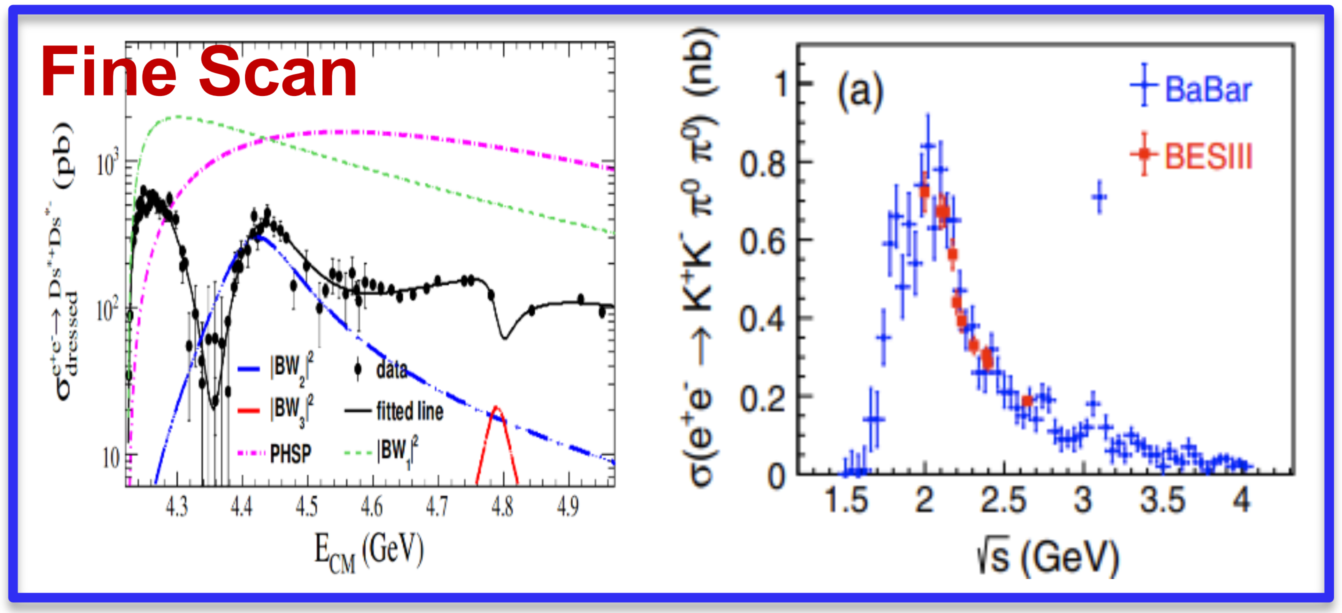
STCF will provide precise Collins FF input for TMD extraction at EIC/EicC

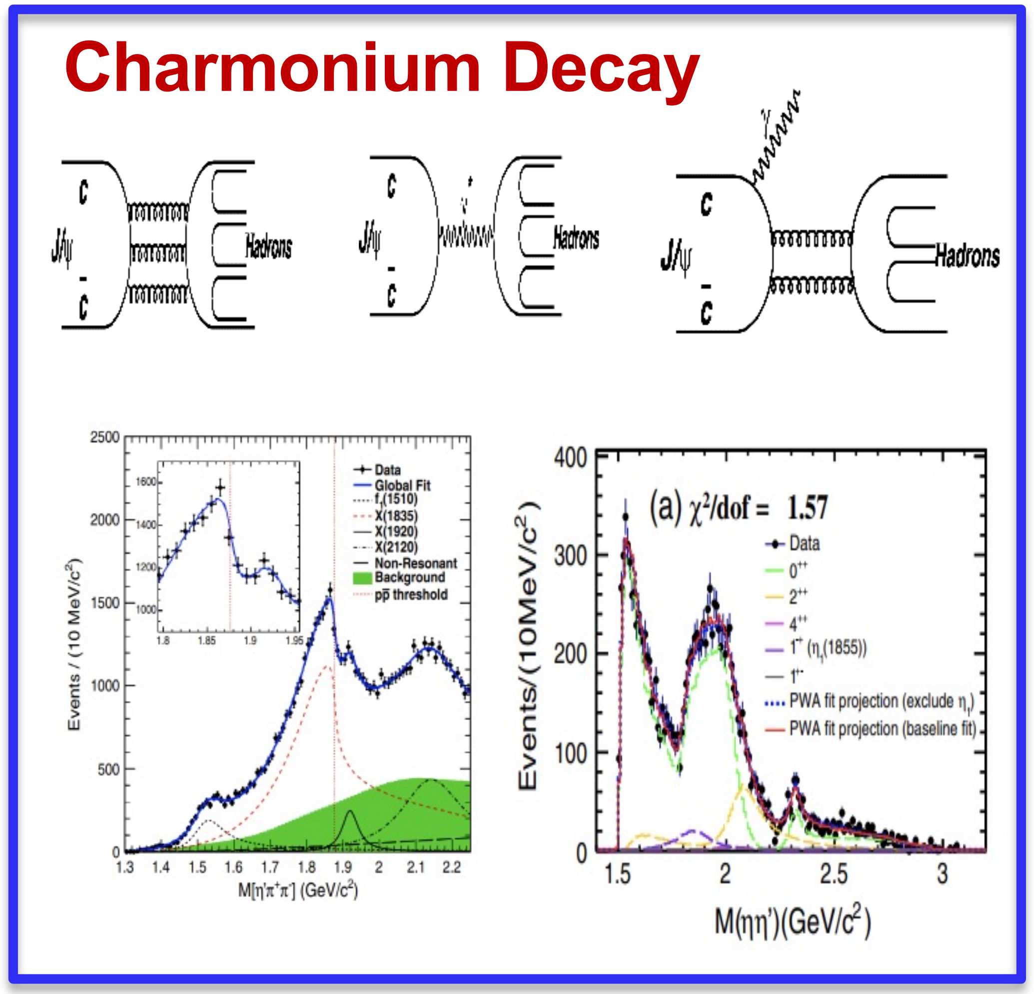
Hadron Spectroscopy and Exotic States

A unique territory for the QCD confinement









A Charmonium(-like) factory (per year):

- 3T J/ψ, 0.6T $\psi(3686)$, 1B Y(4230), 100M $Z_c(3900)$ and 5M X(3872)

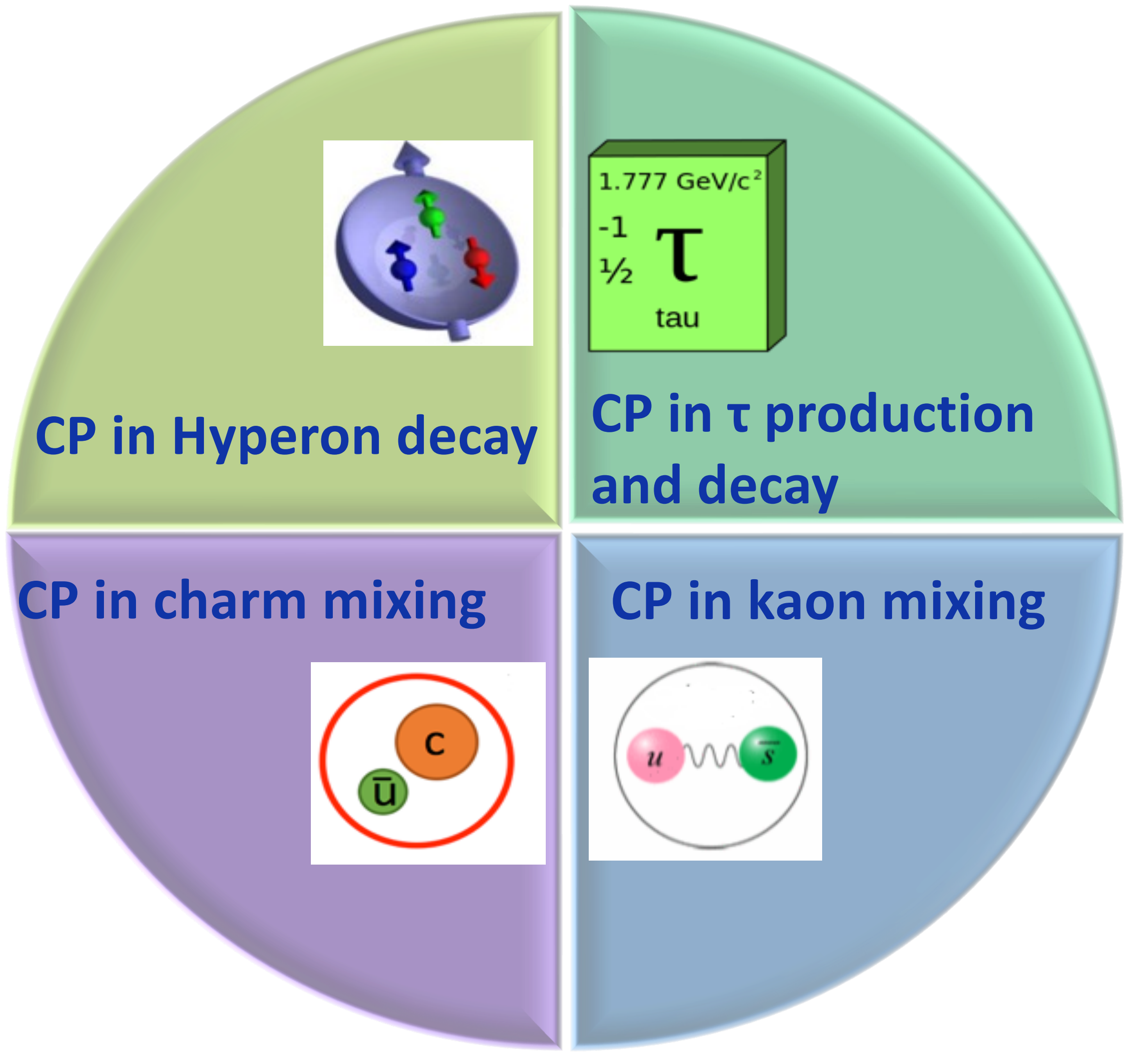
Physics opportunities :

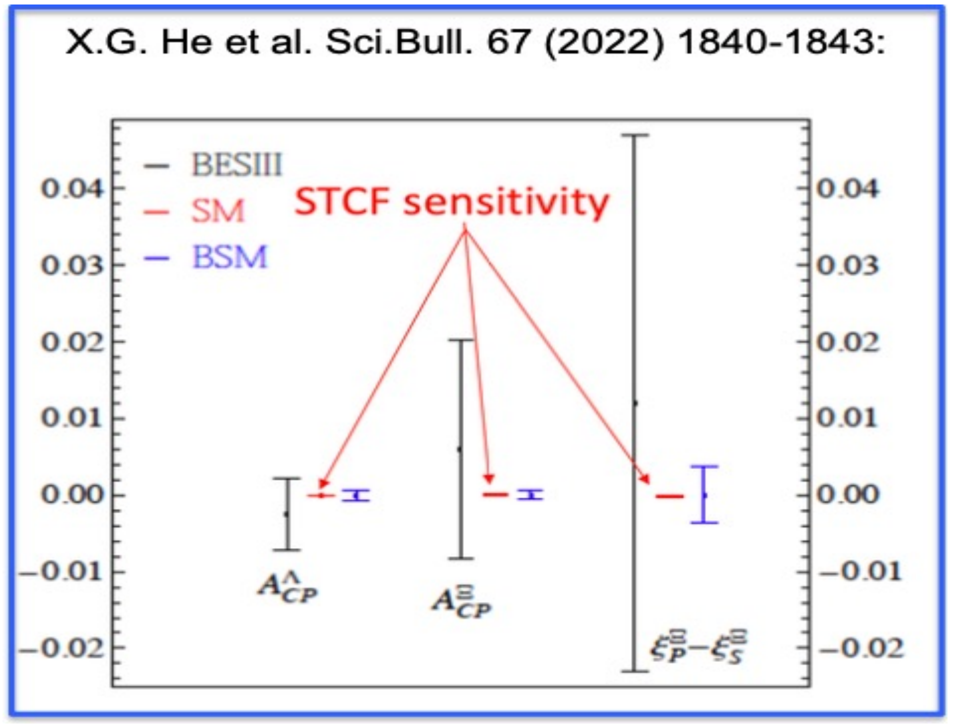
- Energy dependent structures of $Z_{c(s)}$
- More XYZ states → spectroscopy
- Missing charmonium states and their transitions
- Traces of glueballs and hybrid states

STCF has an absolute advantage in studying hadron spectroscopy and exotic states, and is expected to make significant breakthroughs

CPV

- CPV observed in K, B, D mesons, all consistent with CKM theory in SM
- Baryon asymmetry of the universe indicates the existence of non-SM CPV sources
- STCF is capable of searching for **CPV in hyperon and τ lepton**, as well as **CPT violation in Kaon** with high sensitivity
- **Unique advantages at STCF:** Quantum correlated, large statistics, clear environment





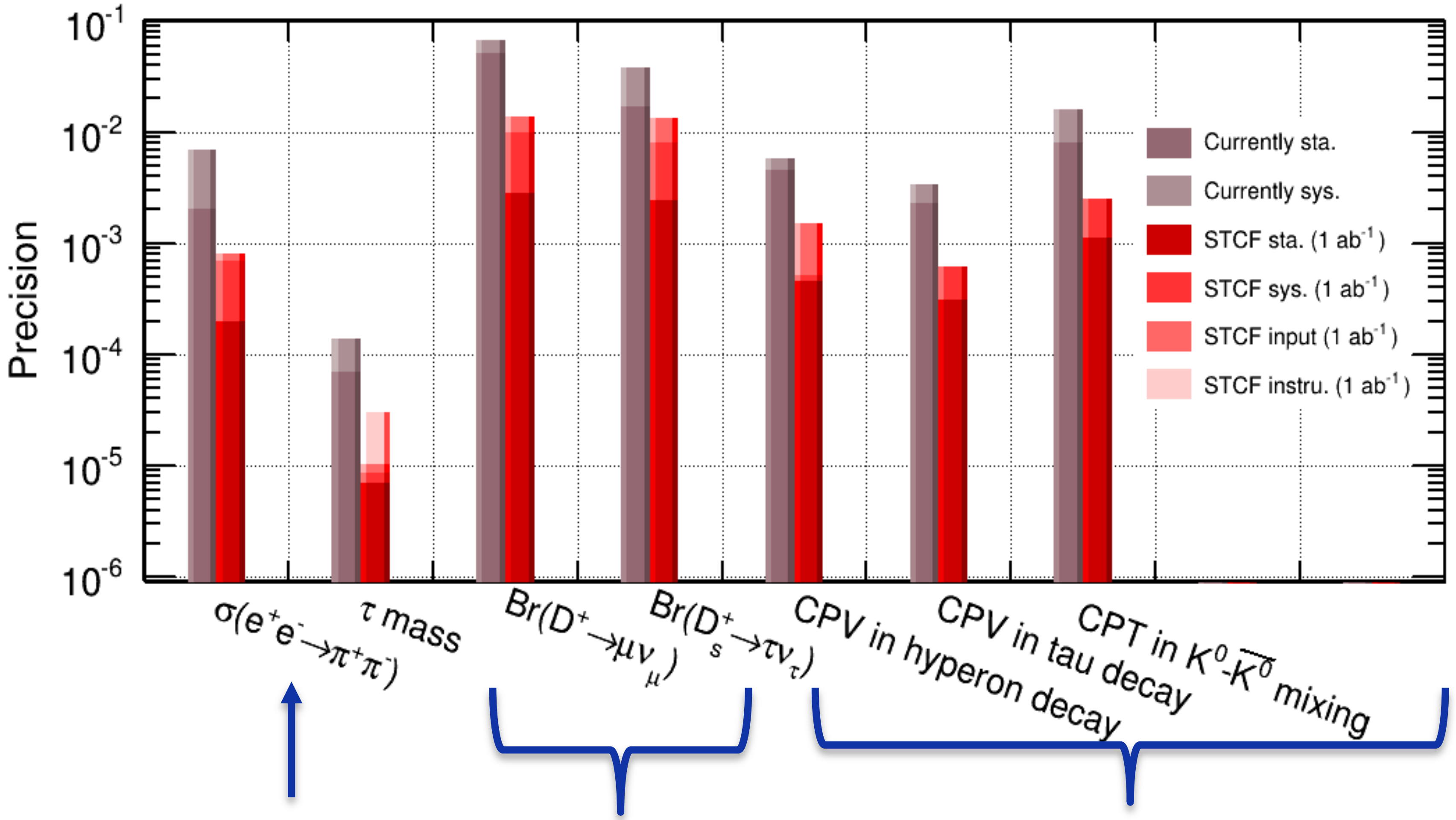
$$\sigma_{A_{CP}} \approx \sqrt{\frac{3}{2}} \frac{1}{\alpha_1 \sqrt{N_{sig}} \sqrt{\langle P_B^2 \rangle}}.$$

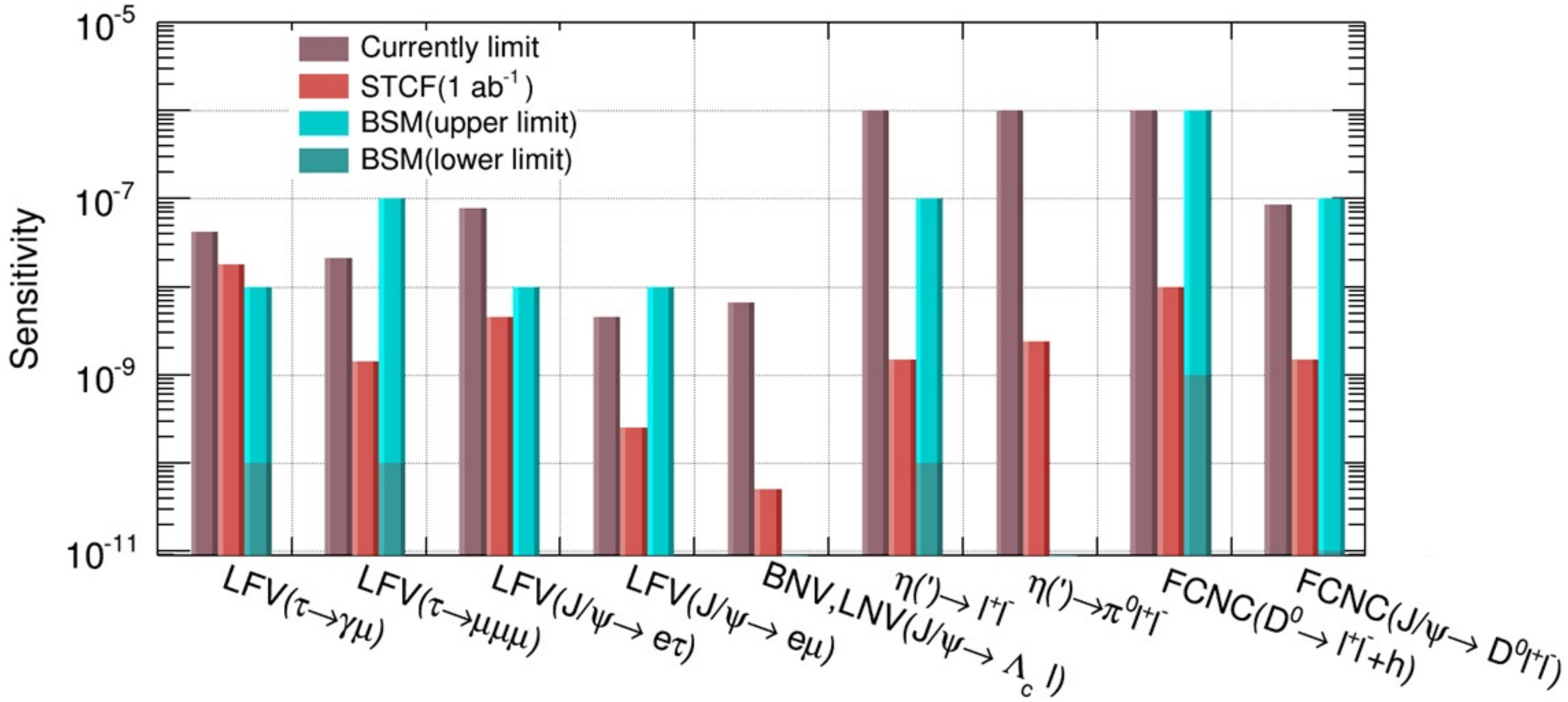
$$\xrightarrow{1\times10^9\ \Lambda\bar{\Lambda},\quad \langle P_B^2\rangle=0.1} \sigma_{A_{CP}} \sim 1.4\times10^{-4}$$

$$\xrightarrow{1\times10^9\ \Lambda\bar{\Lambda},\quad \langle P_B^2\rangle=0.8} \sigma_{A_{CP}} \sim 5\times10^{-5}$$

Precision Measurements and Rare Decays

- **STCF is expected to improve the current precisions of many important measurements by ~1 order of magnitude and enhance sensitivities to various rare or forbidden decays by ~2 orders of magnitude**
- **Great potential to reveal new physics**





LFV, BNV, FCNC to probe BSM

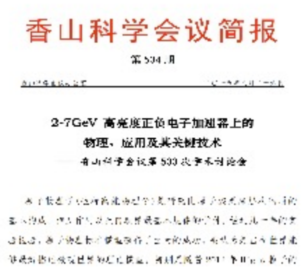
STCF Project Development

2011

Super Charm-tau Factory

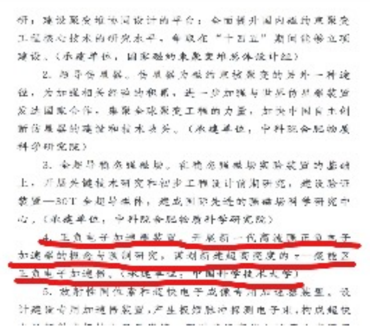
Proposed at “Workshop for acc. based high energy physics development strategy”

2015



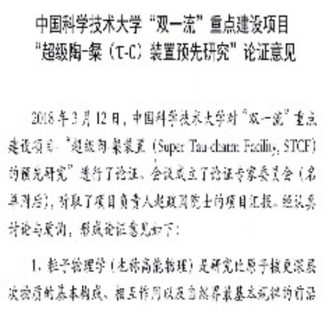
Fragrant Hills Science Forum
Demonstrated its importance and necessity, urging to lauch fesibility study and R&D

2017



Hefei Comprehensive National Science and Technology center,
STCF listed as a big science facility to be promoted

2018



USTC “double first-class” key project
Launched the conceptual design study and feasibility study

2021

Conceptual Design report
Released the CDR for the physics and Detector, and the pre-CDR for accelerator

2022.4

Governments of Anhui Province and Hefei City
Endorsed the STCF Key Technology R&D project

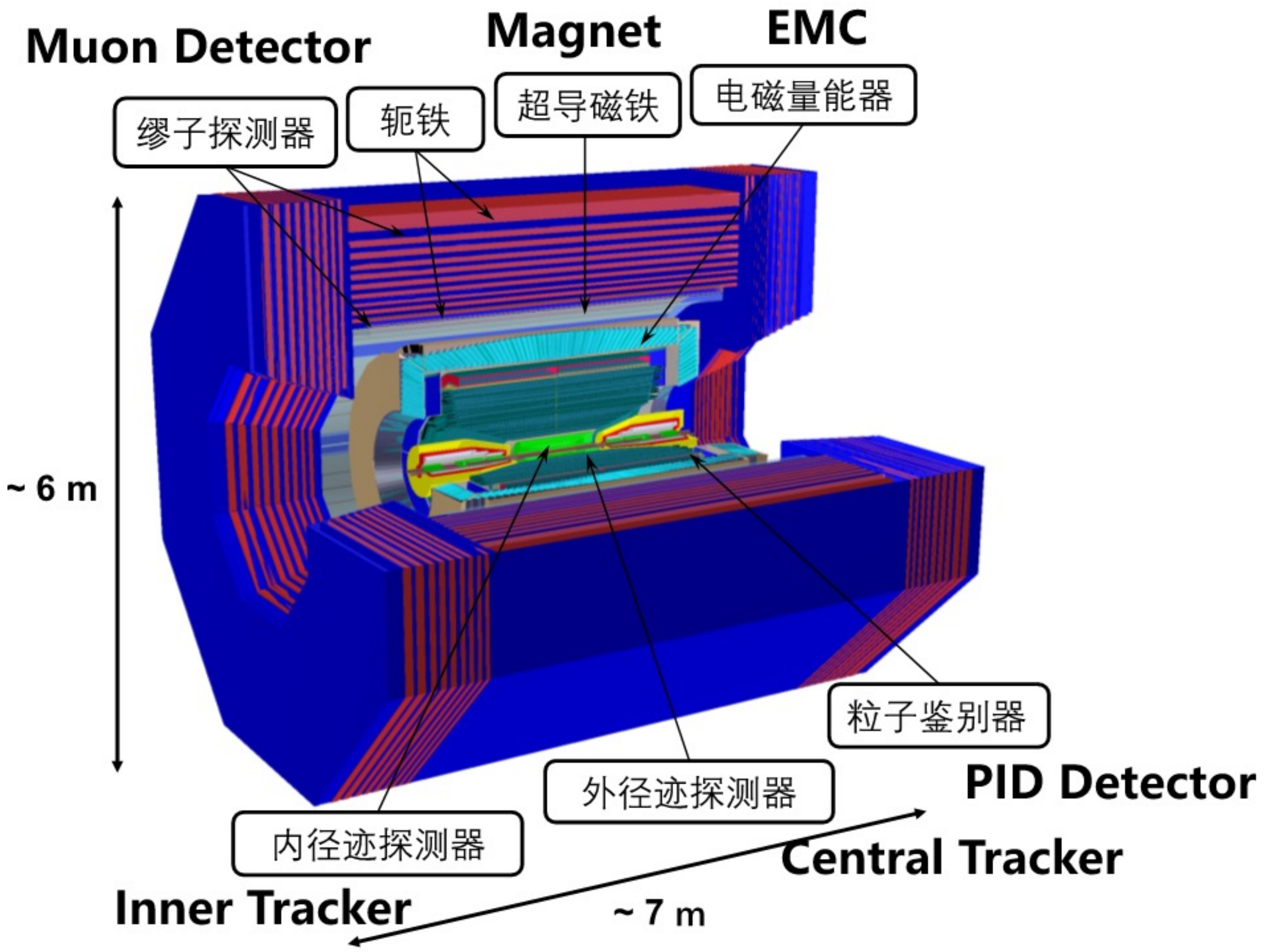
STCF Conceptual Design Studies

Physics & Detector CDR

FRONTIERS OF PHYSICS
REPORT
Volume 19 / Issue 1 / 14701 / 2024

STCF conceptual design report (Volume 1): Physics & detector

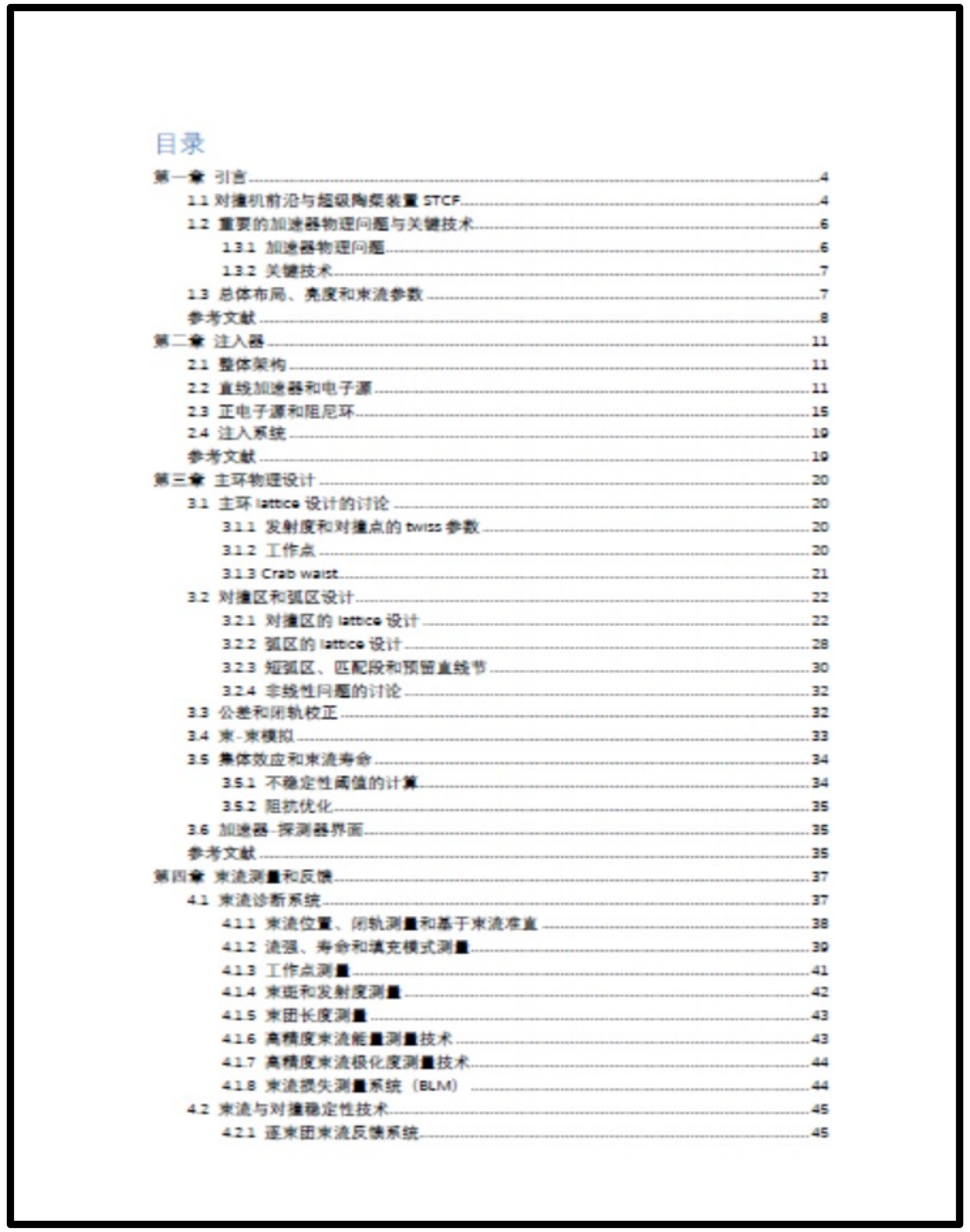
M. Achasov[3], X. C. Ai[82], R. Aliberti[38], Q. An[63,72], X. Z. Bai[63,72], Y. Bai[62], O. Bakina[39], A. Barnyakov[3,50], V. Blinov[3,50,51], V. Bobrovnikov[3,51], D. Bodrov[23,60], A. Bogomyagkov[3], A. Bondar[3], I. Boyko[39], Z. H. Bu[73], F. M. Cai[20], H. Cai[77], J. J. Cao[20], Q. H. Cao[54], X. Cao[33], Z. Cao[63,72], Q. Chang[20], K. T. Chao[54], D. Y. Chen[62], H. Chen[81], H. X. Chen[62], J. F. Chen[58], K. Chen[6], L. L. Chen[20], P. Chen[78], S. L. Chen[6], S. M. Chen[66], S. Chen[69], S. P. Chen[69], W. Chen[64], X. Chen[74], X. F. Chen[58], X. R. Chen[33], Y. Chen[32], Y. Q. Chen[36], H. Y. Cheng[34], J. Cheng[48], S. Cheng[28], T. G. Cheng



82 institutions, 453 authors

arXiv:2303.15790

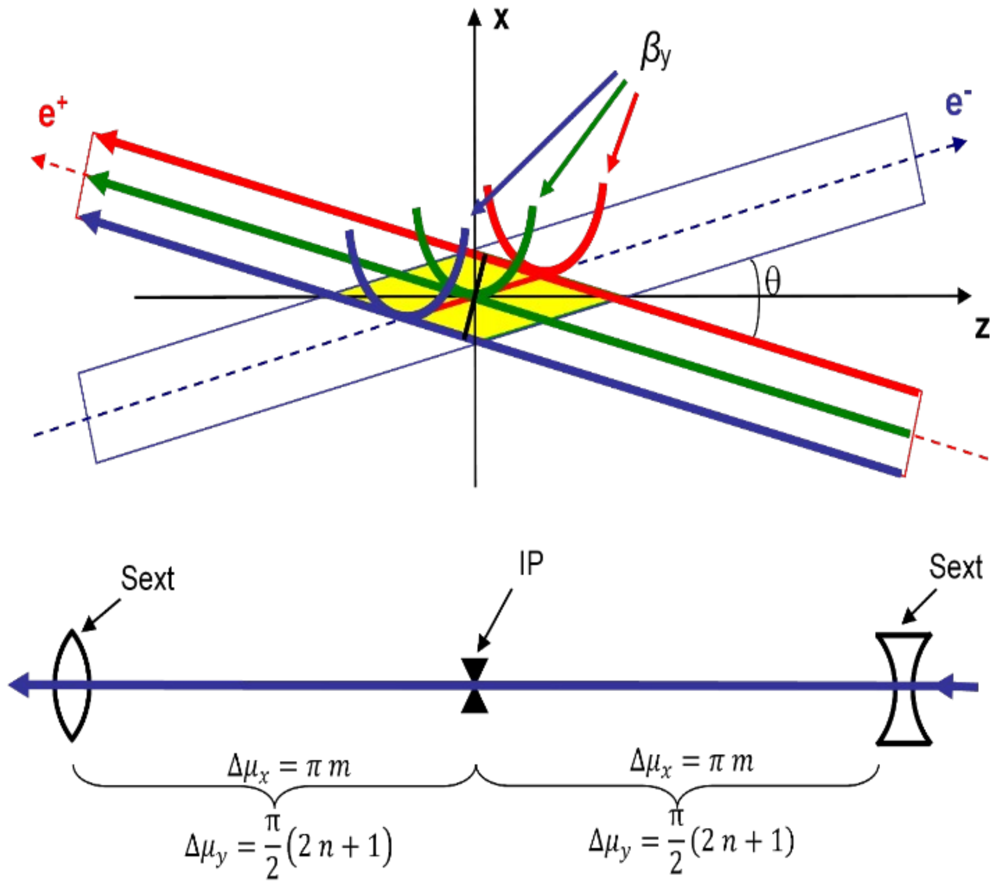
Accelerator Pre-CDR



目录

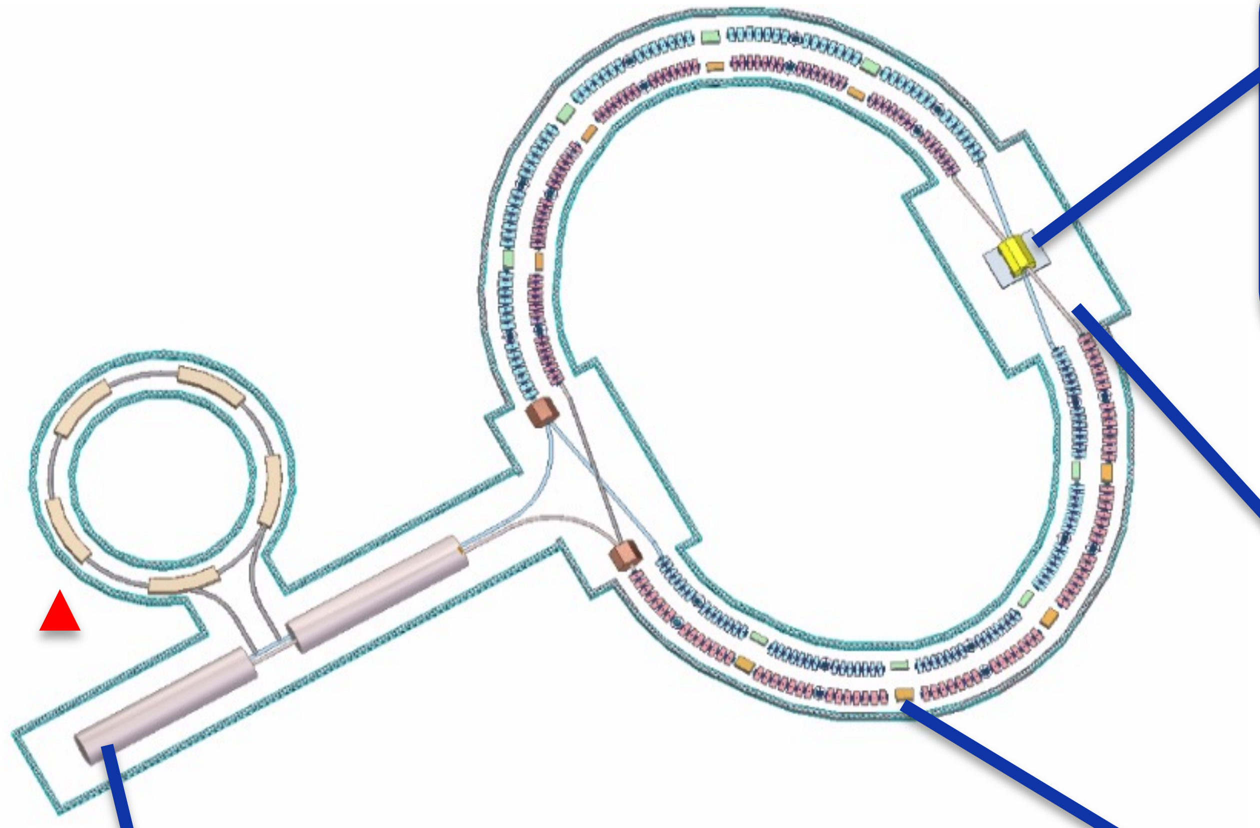
Challenges of STCF Accelerator

- **Ultra-high luminosity in the tau charm energy region, high-quality beam, stable operation**
- **Characterized by extremely small bunch size, high beam current, strong nonlinearity and collective effects**



$$L = \frac{\gamma n_b I_b}{2 e r_e \beta_y^*} \xi_y H$$

Large Piwinski angle + Crab Waist



Collider Ring and IR Physics Design
IP beam size (Y) nm scale, Crab-Waist, nonlinear compensation extremely difficult

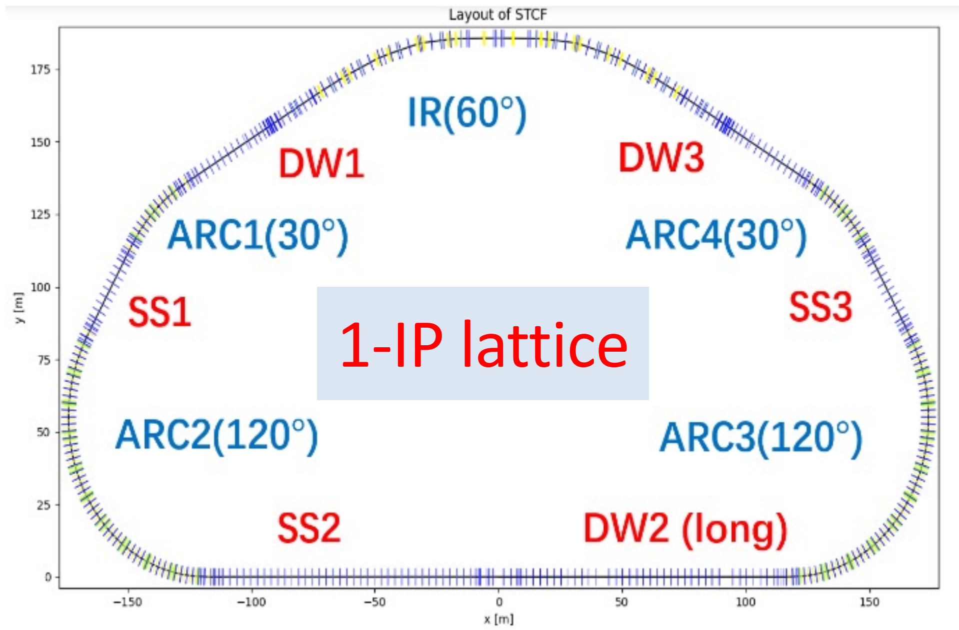
IR Technologies
SC magnets, MDI

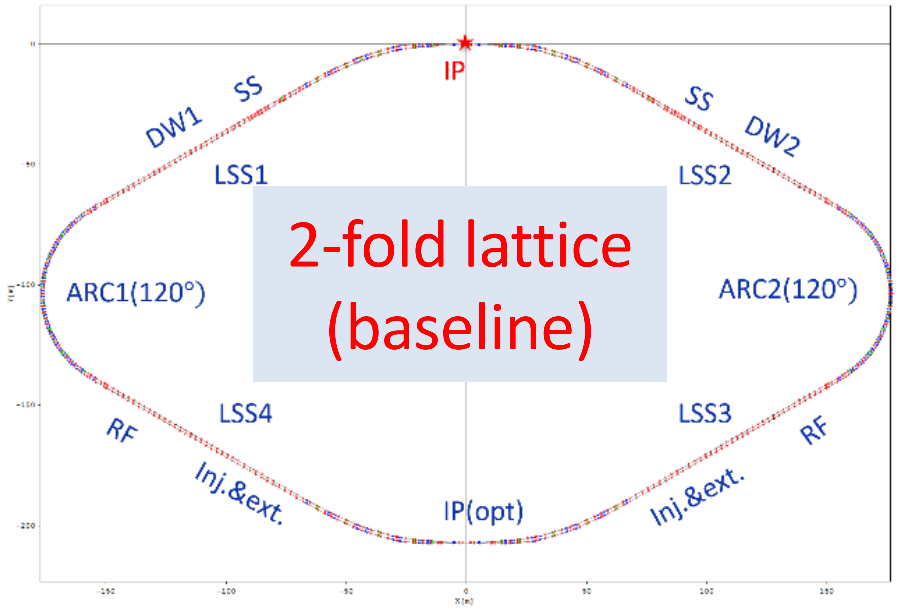
Injection into CR (small DA)
high I_b and low ε e+/e- sources

Other key technologies
Ring RF, beam instrumentation and control, beam injection…

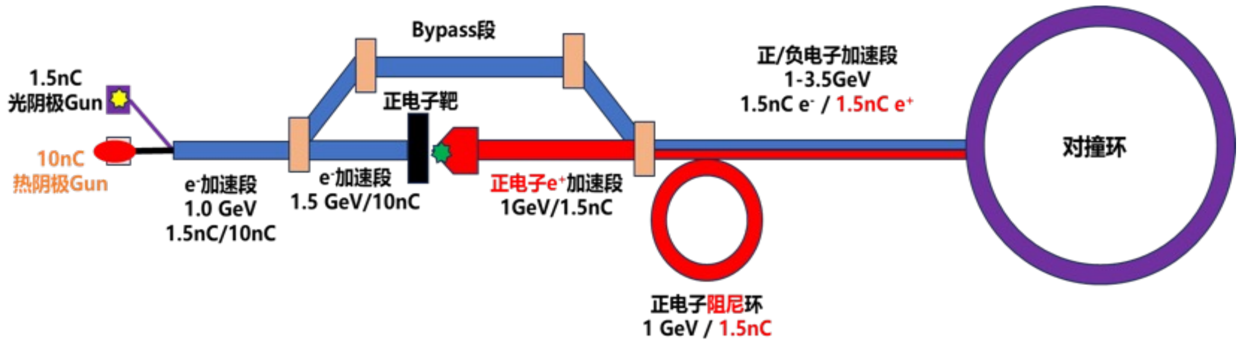
STCF Accelerator Conceptual Design

- **Two Lattice designs, optimal beam energy: 2 GeV**
- **Injection energy: 1-3.5 GeV**
- **Two injection schemes: off-axis, swap-out (baseline)**
  - ✓ **Variable energy: 1-3.5 GeV**
  - ✓ **Damping ring (off-axis) or accumulator ring (swap-out) for positrons @1 GeV**
  - ✓ **Total length: ~400 m (+100 m beam transp.)**

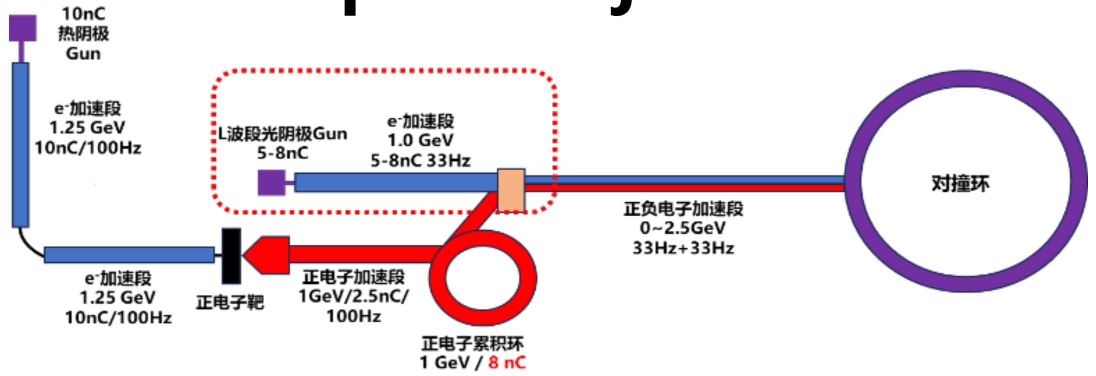




Off-axis injection



Swap-out injection

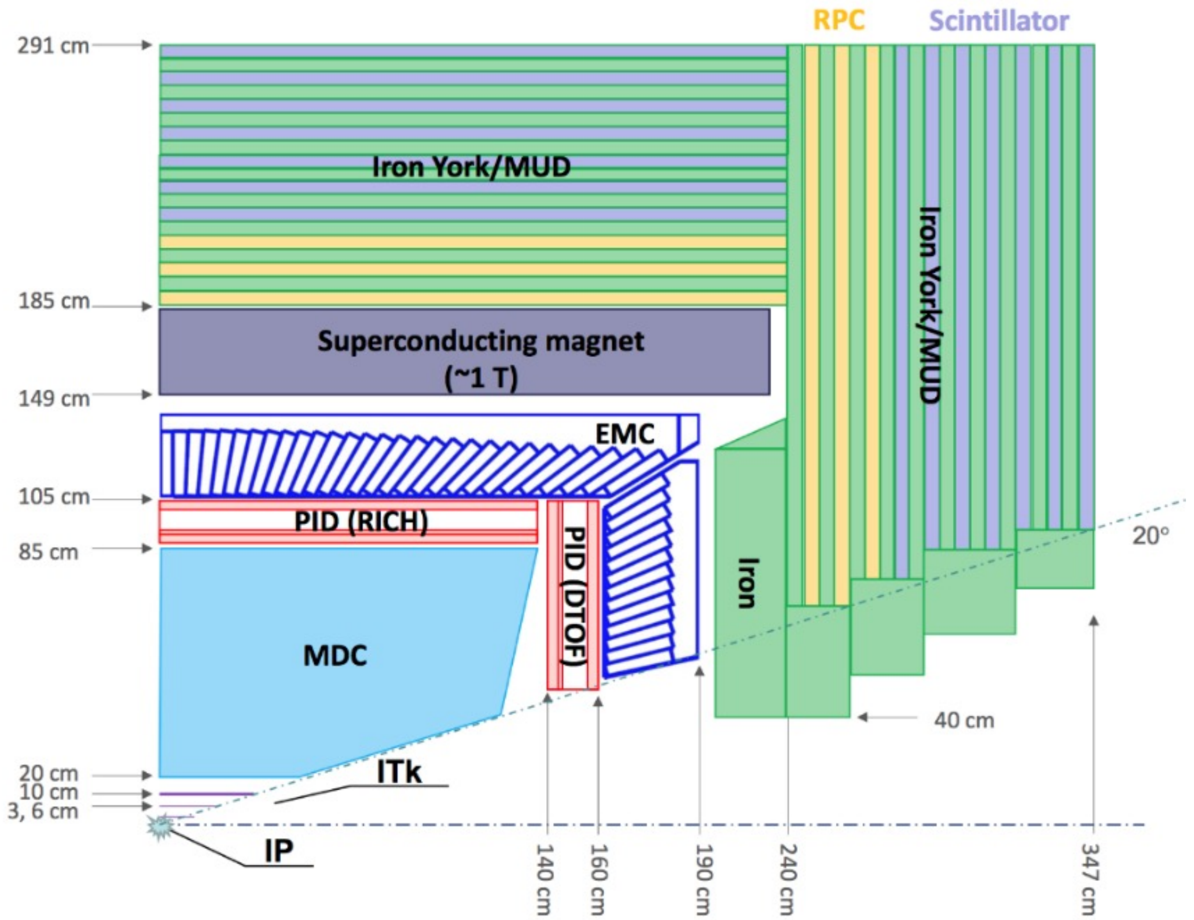


Parameters	Units	STCF
Optimal beam energy, E	GeV	2
Circumference, C	m	871.76
Crossing angle, 2θ	mrad	60
Revolution period, T	μs	2.908
Horizontal emittance, $\varepsilon_x/\varepsilon_y$	nm	6.857/0.034
Coupling, k		0.50%
Beta functions at IP, β_x/β_y	mm	40/0.6
Beam size at IP, σ_x/σ_y	μm	16.56/0.143
Betatron tune, ν_x/ν_y		32.55/29.57
Momentum compaction factor, α_p	10^{-4}	12.322
Energy spread, σ_e	10^{-4}	8.986
Beam current, I	A	2
Number of bunches, n_b		726
Particles per bunch, N_b	10^{10}	5.00
Single-bunch charge	nC	8.01
Energy loss per turn, U_0	keV	406.8
Damping time, $\tau_x/\tau_y/\tau_z$	ms	28.4/28.6/14.4
RF frequency, f_{RF}	MHz	499.333
Harmonic number, h		1452
RF voltage, V_{RF}	MV	1.8
Synchrotron tune, ν_z		0.0158
Bunch length, σ_z	mm	9.72
RF bucket height, δ_{RF}	%	1.47
Piwinski angle, ϕ_{pwi}	rad	17.61
Beam-beam parameter, ξ_x/ξ_y		0.0027/0.082
Hour-glass factor, F_h		0.87
Luminosity, L	$cm^{-2}s^{-1}$	1.0×10^{35}

STCF Detector Conceptual Design

Detector Requirements from Physics

Process	Physics Interest	Optimized Subdetector	Requirements
$\tau \to K_s \pi \nu_\tau$, $J/\psi \to \Lambda\bar{\Lambda}$, $D_{(s)}$ tag	CPV in the τ sector, CPV in the hyperon sector, Charm physics	ITK+MDC	acceptance: 93% of 4π; trk. effi.: $> 99\%$ at $p_T > 0.3$ GeV/c; $> 90\%$ at $p_T = 0.1$ GeV/c $\sigma_p/p = 0.5\%$, $\sigma_{\gamma\phi} = 130\ \mu$m at 1 GeV/c
$e^+e^- \to KK + X$, $D_{(s)}$ decays	Fragmentation function, CKM matrix, LQCD etc.	PID	π/K and K/π misidentification rate $< 2\%$ PID efficiency of hadrons $> 97\%$ at $p < 2$ GeV/c
$\tau \to \mu\mu\mu$, $\tau \to \gamma\mu$, $D_s \to \mu\nu$	cLFV decay of τ, CKM matrix, LQCD etc.	PID+MUD	μ/π suppression power over 30 at $p < 2$ GeV/c, μ efficiency over 95% at $p = 1$ GeV/c
$\tau \to \gamma\mu$, $\psi(3686) \to \gamma\eta(2S)$	cLFV decay of τ, Charmonium transition	EMC	$\sigma_E/E \approx 2.5\%$ at $E = 1$ GeV $\sigma_{pos} \approx 5$ mm at $E = 1$ GeV
$e^+e^- \to n\bar{n}$, $D_0 \to K_L\pi^+\pi^-$	Nucleon structure Unity of CKM triangle	EMC+MUD	$\sigma_T = \frac{300}{\sqrt{p^3(\mathrm{GeV}^3)}}$ ps



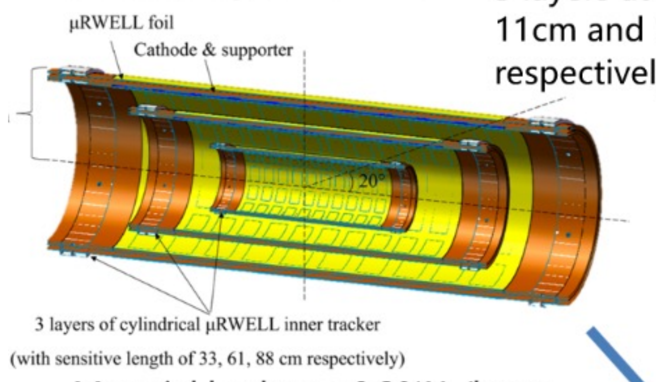
Solid Angle Coverage : 94%•4π (θ~20⁰)

- ❖ **Inner tracker** (**ITK**, two options)
  - MPGD: cylindrical MPGD
  - Silicon: CMOS MAPS
- ❖ **Central tracker (MDC)**
  - Main drift chamber
- ❖ **PID**
  - Barrel: **RICH** with CsI-MPGD
  - Endcaps: DIRC-like TOF (**DTOF**)
- ❖ **EMC**
  - pure CsI + APD
- ❖ **Muon detector (MUD)**
  - RPC + scintillator strips
- ❖ **Magnet**
  - Super-conducting solenoid, 1 T

STCF Detector Conceptual Design

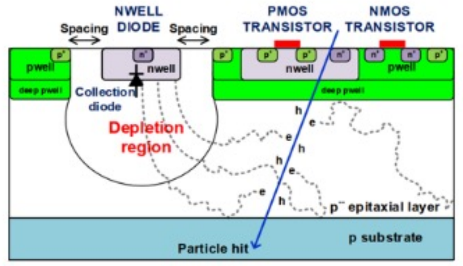
Gaseous option: MPGD

3 layers at 6cm, 11cm and 16 cm, respectively.

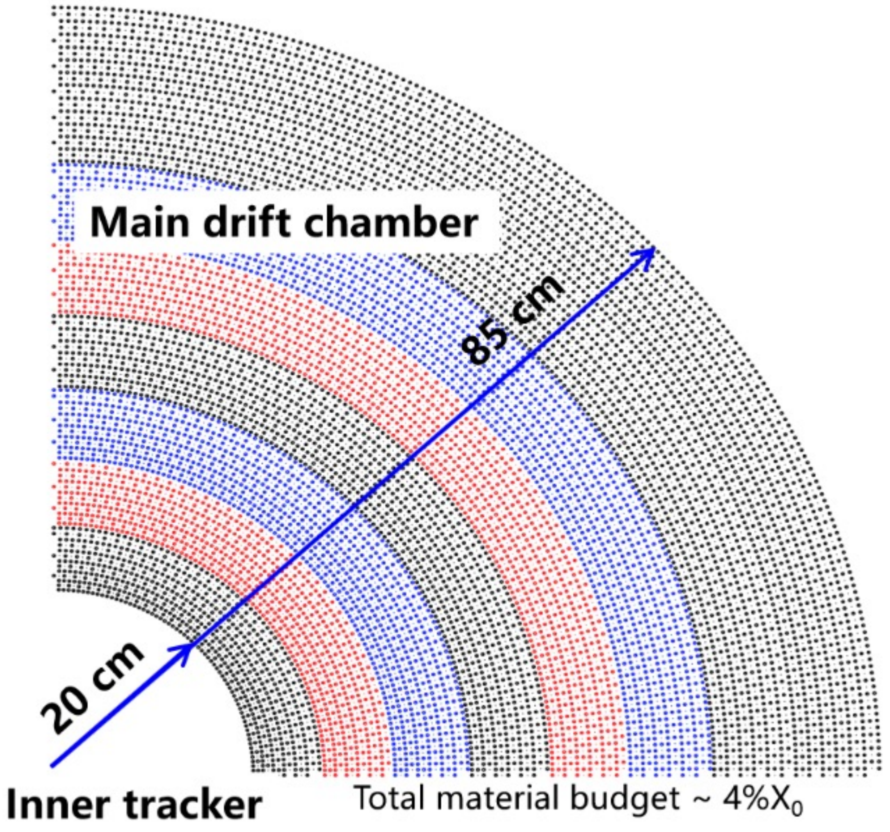


Material budget <0.3%X_0/layer

Silicon option: CMOS MAPS

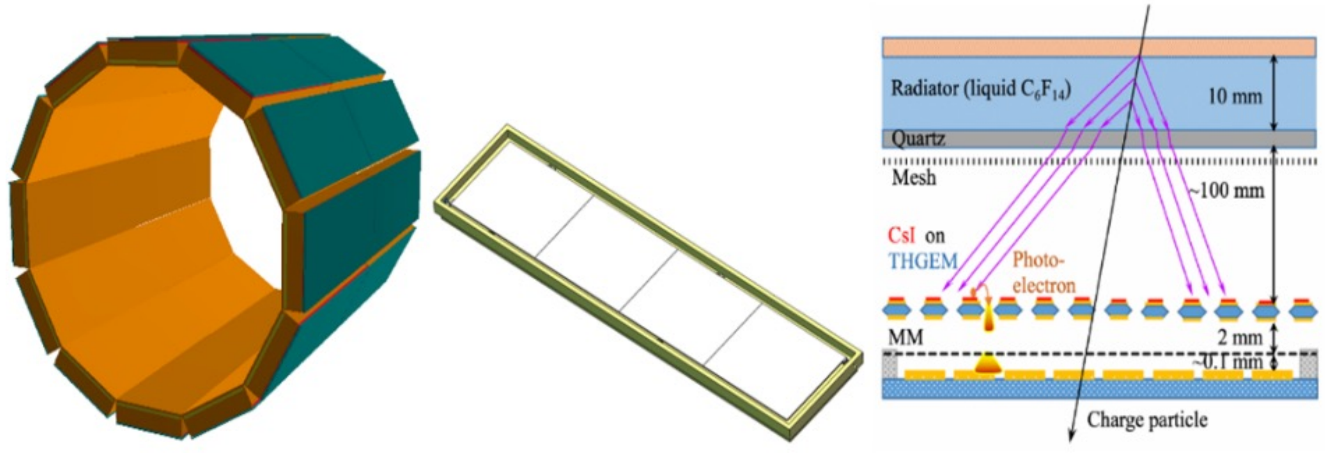


3 layers at 3.6cm, 9.8cm and 16 cm, respectively.



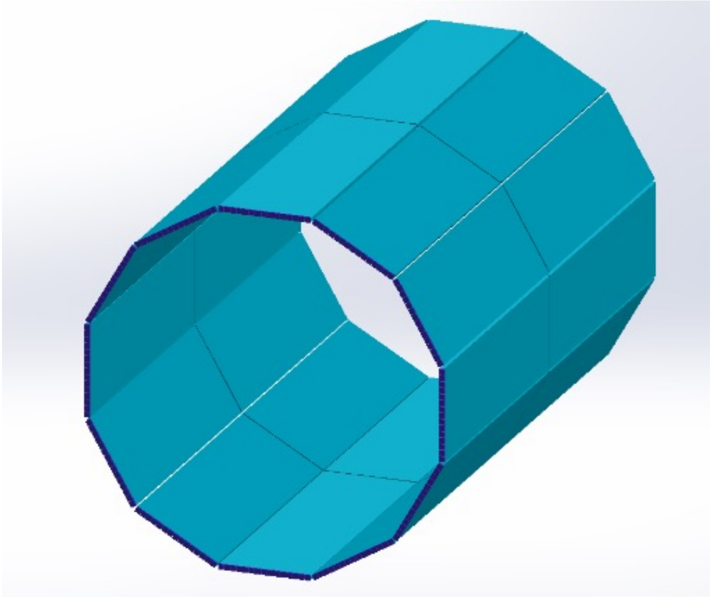
Total material budget ~ 4%X_0

- **Barrel PID: A RICH detector using MPGD (THGEM with CsI + MM) for photon detection**

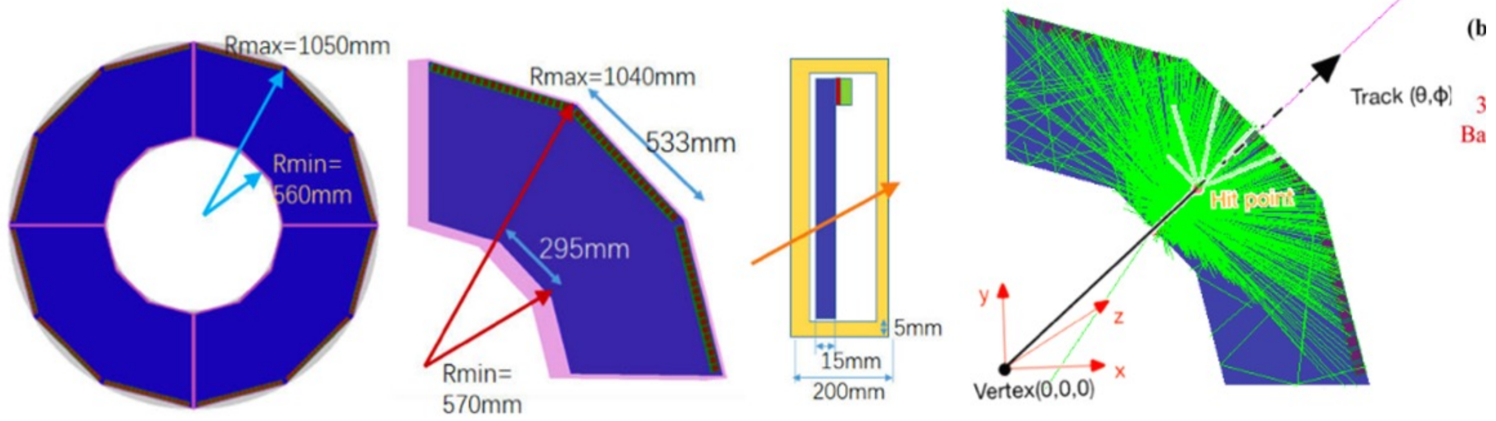


Material budget < 0.3X_0

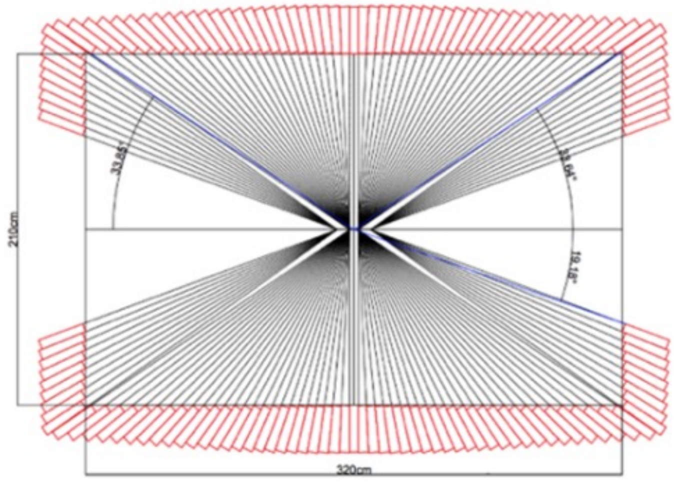
- **Alternative: the same technology as the endcap PID (DTOF)**



- **Endcap PID: A DIRC-like high-resolution TOF detector (DTOF ~ 30ps), quartz plate + MCP-maPMT**

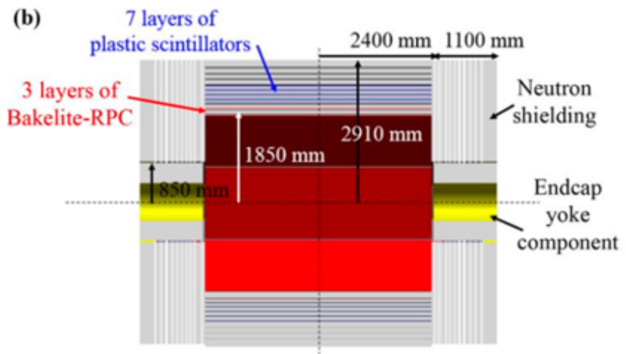


EMC: A pure-CsI crystal calorimeter to tackle a high level of background (~1MHz/ch)



- **Crystal size 28cm (15X0) 5×5cm²**
- **~ 8670 crystals**
- **4 large area APDs (1×1cm²) to enhance light yield**

- **MUD: A RPC-scintillator hybrid detector to optimize muon and neutral hadron ID**



Parameter	Baseline design
R_{in} [cm]	185
R_{out} [cm]	291
R_e [cm]	85
L_{Barrel} [cm]	480
T_{Endcap} [cm]	107
Segmentation in ϕ	8
Number of detector layers	10
Iron yoke thickness [cm] (λ=16.77 cm)	4/4/4.5/4.5/6/6/6/8/8 cm Total: 51 cm, 3.04λ
Solid angle	79.2%×4π in barrel 14.8%×4π in endcap 94%×4π in total
Total area [m^2]	Barrel ~717 Endcap ~520 Total ~1237

R&D Project Review and Kick-Off Meetings

Kick-off Meeting, Aug. 2023, USTC

More than 30 academicians of CAS, as well as government officials of Anhui province and Hefei city, along with representatives from various domestic research institutions, totaling 170 attendees.

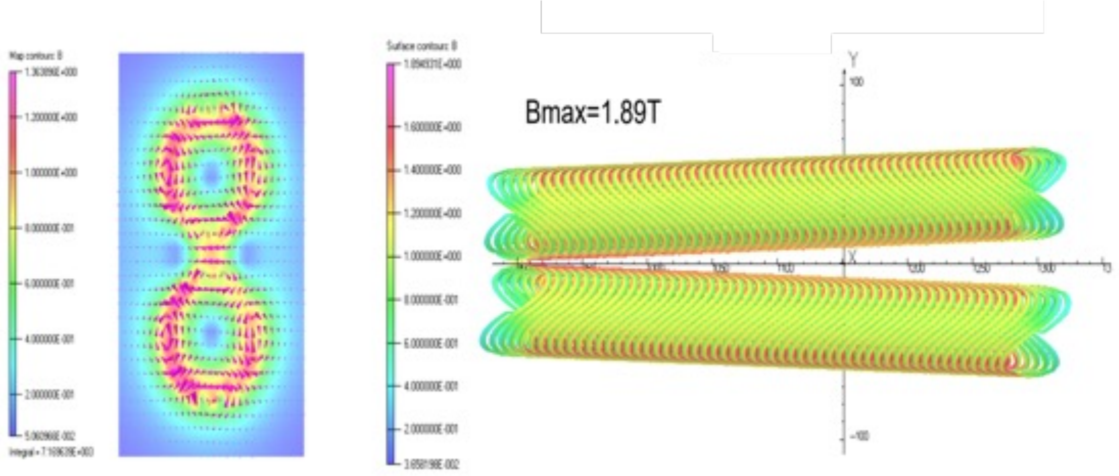
R&D Project Review, Dec. 2023, USTC

Organized by Development and Reform Commissions of Anhui province and Hefei city. The R&D project was approved for a total budget of 364 M RMB and is jointly funded by Anhui, Hefei and USTC.

STCF Accelerator R&D

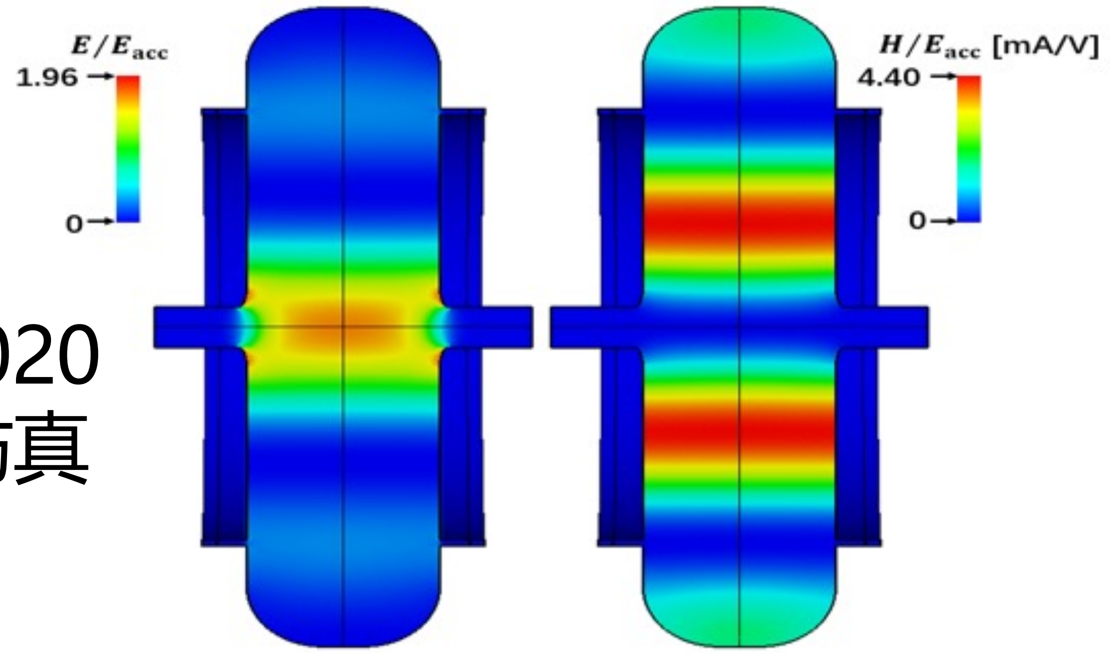
IR SC Magnets

Very constrained Space，50T/m, CCT technology

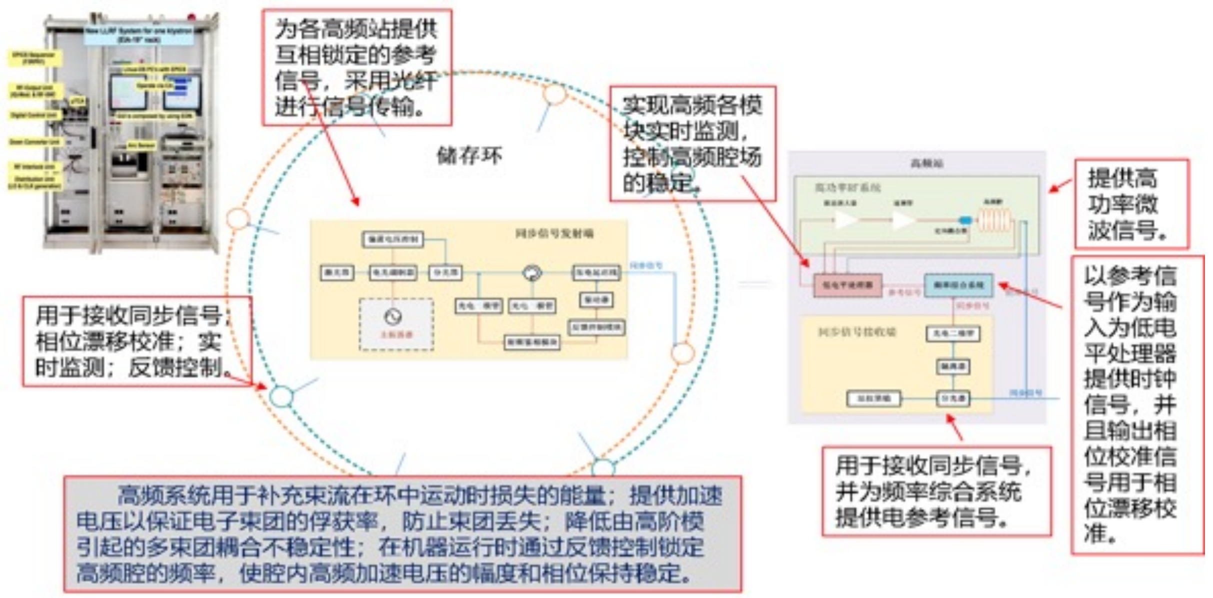


Room-temperature RF cavity

TM020
腔仿真



Low-level RF control system



Bunch by bunch 3D beam position measurement

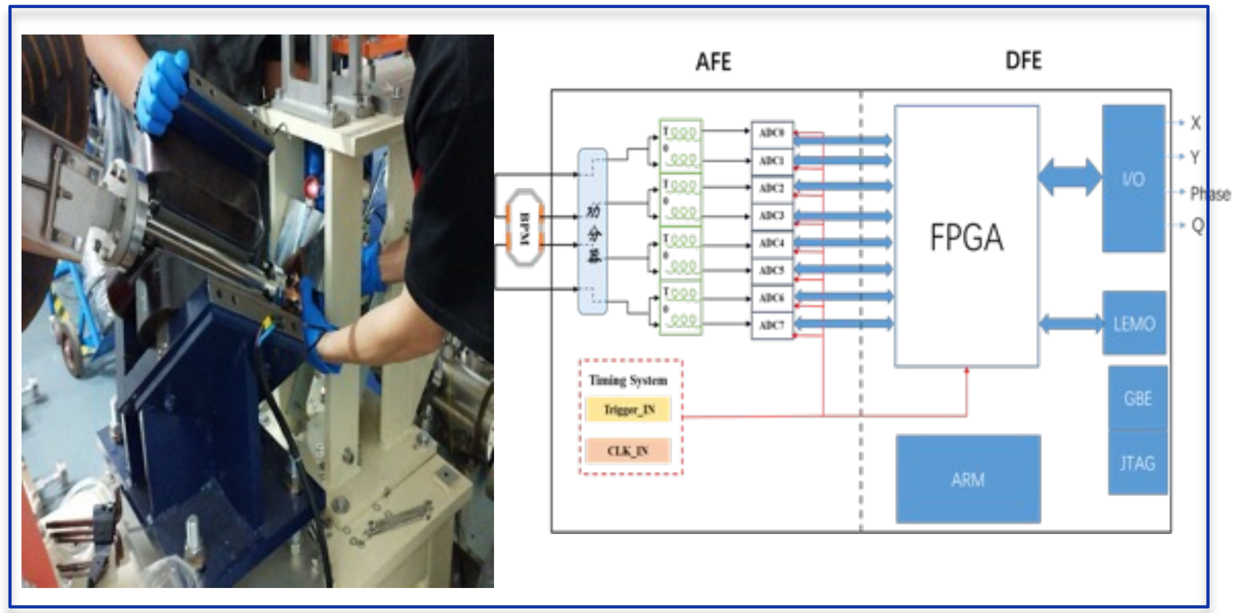
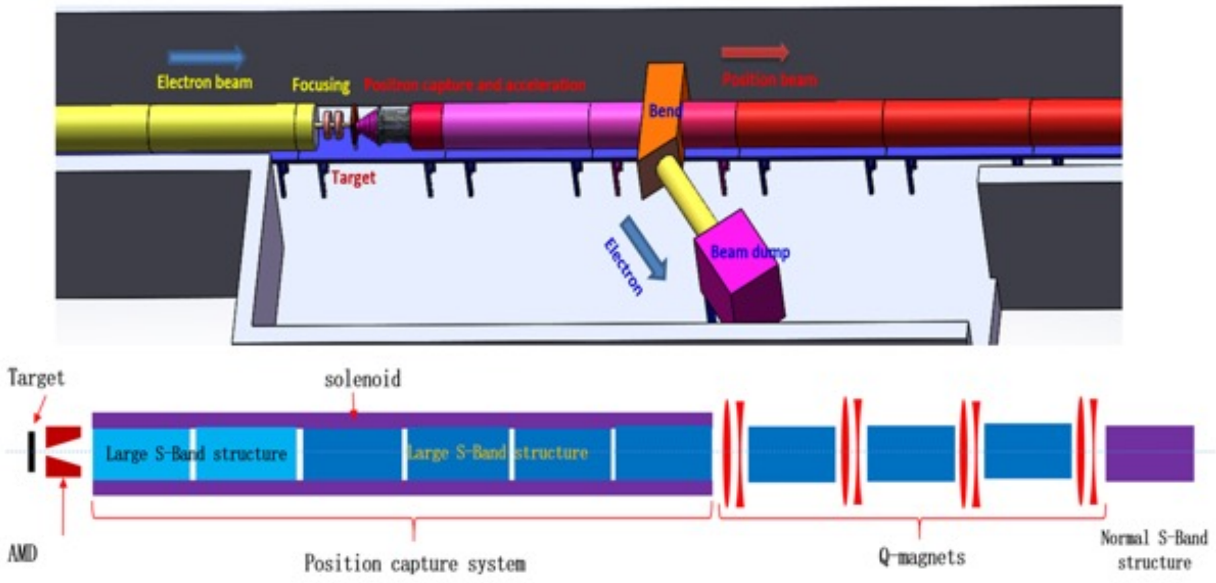


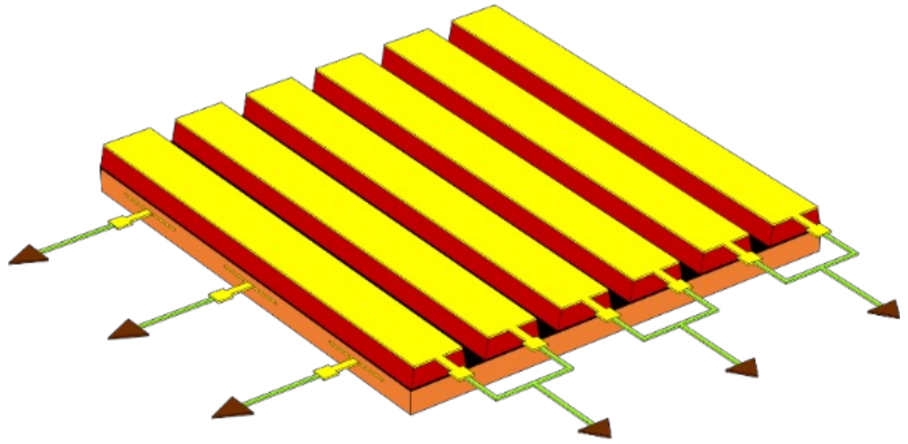
Photo-cathode electron gun

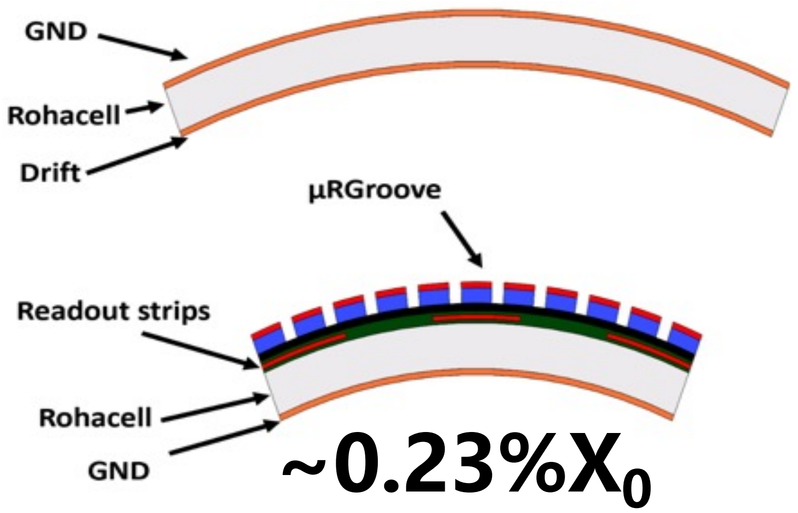
Positron source



ITK-MPGD: µRGroove

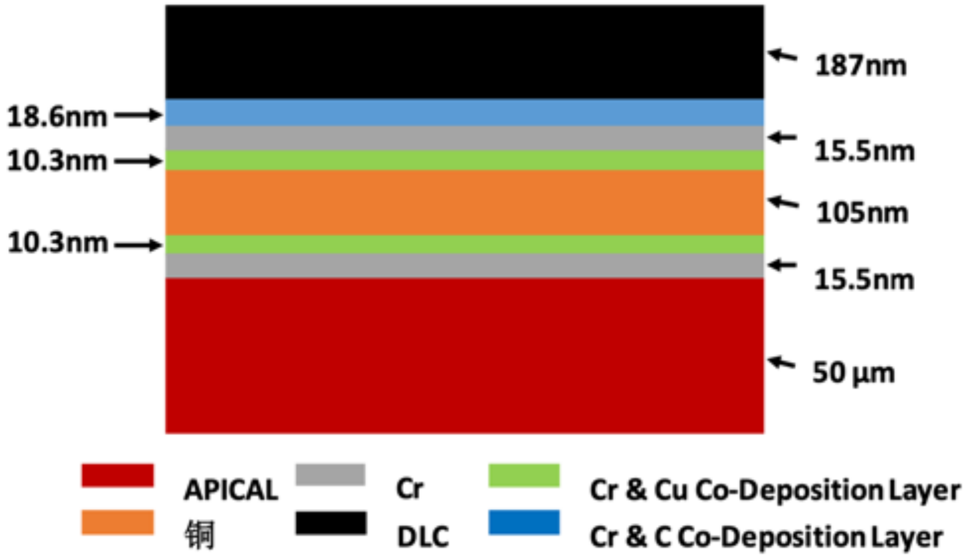
- **µRGroove : A single-stage MPGD involving no stretching or tensioning, 2D strip readout without charge sharing (large S/N), high rate with fast grounding, easy to make a cylinder, low mass, low production cost.**



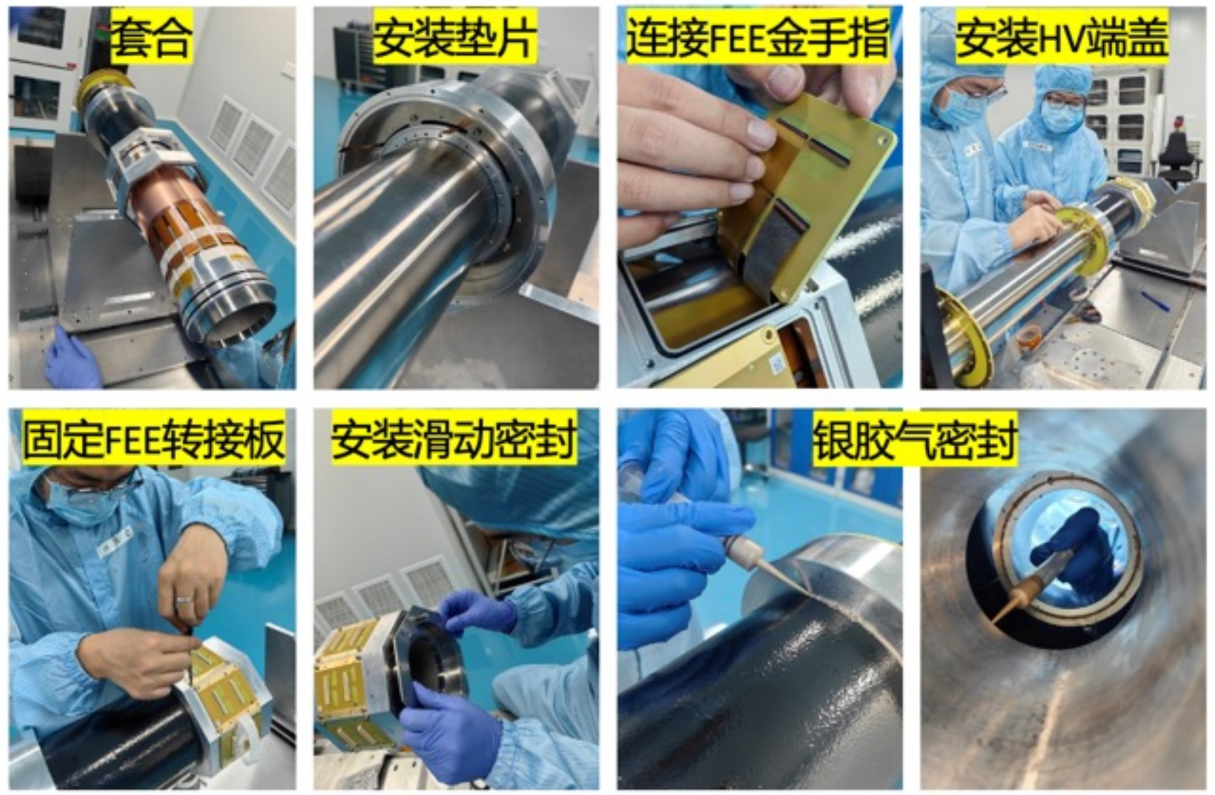


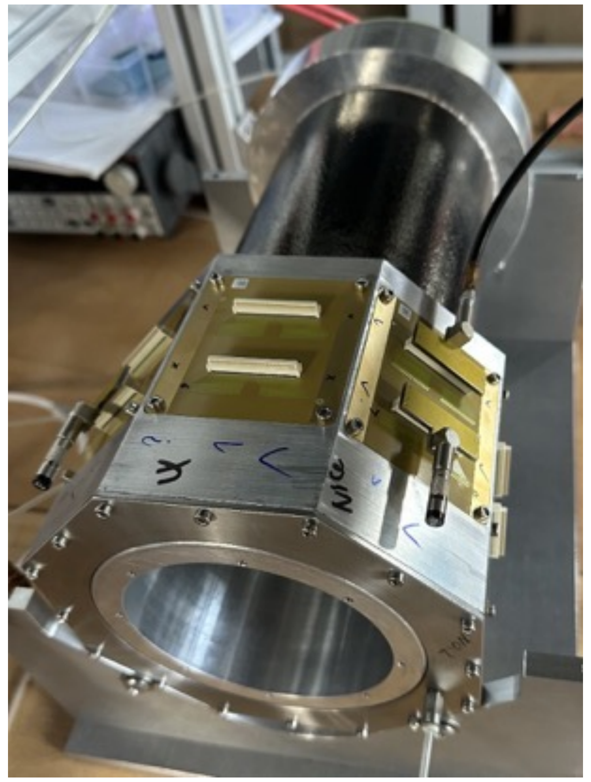
$\sim 0.23\%X_0$

Development of low mass electrodes



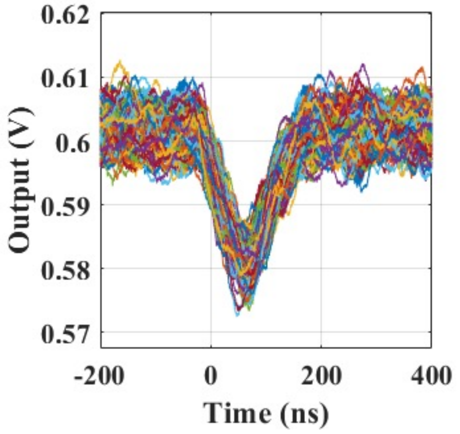
Fabricating cylindrical structure

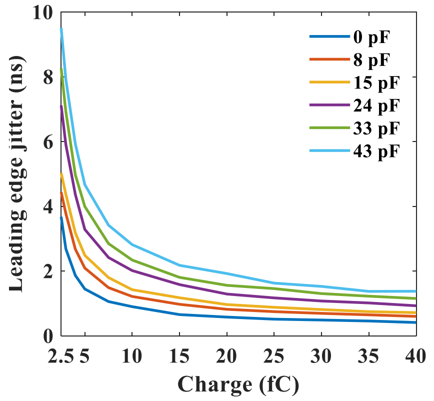


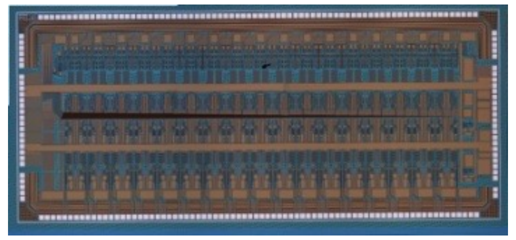


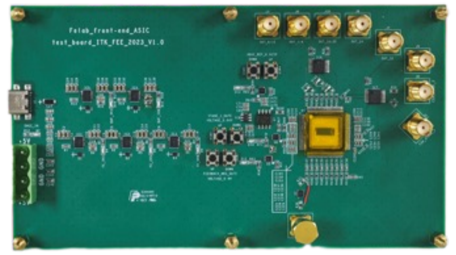
ASIC development

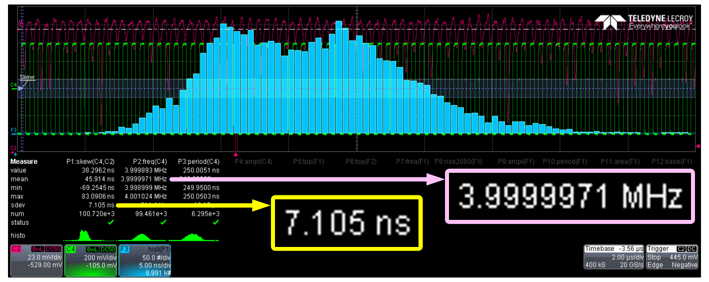
ASIC Specs	Demands
Charge Range	40 fC
Charge precision	～ 1 fC RMS
Time precision	< 10 ns RMS
Max. event rate	4 MHz





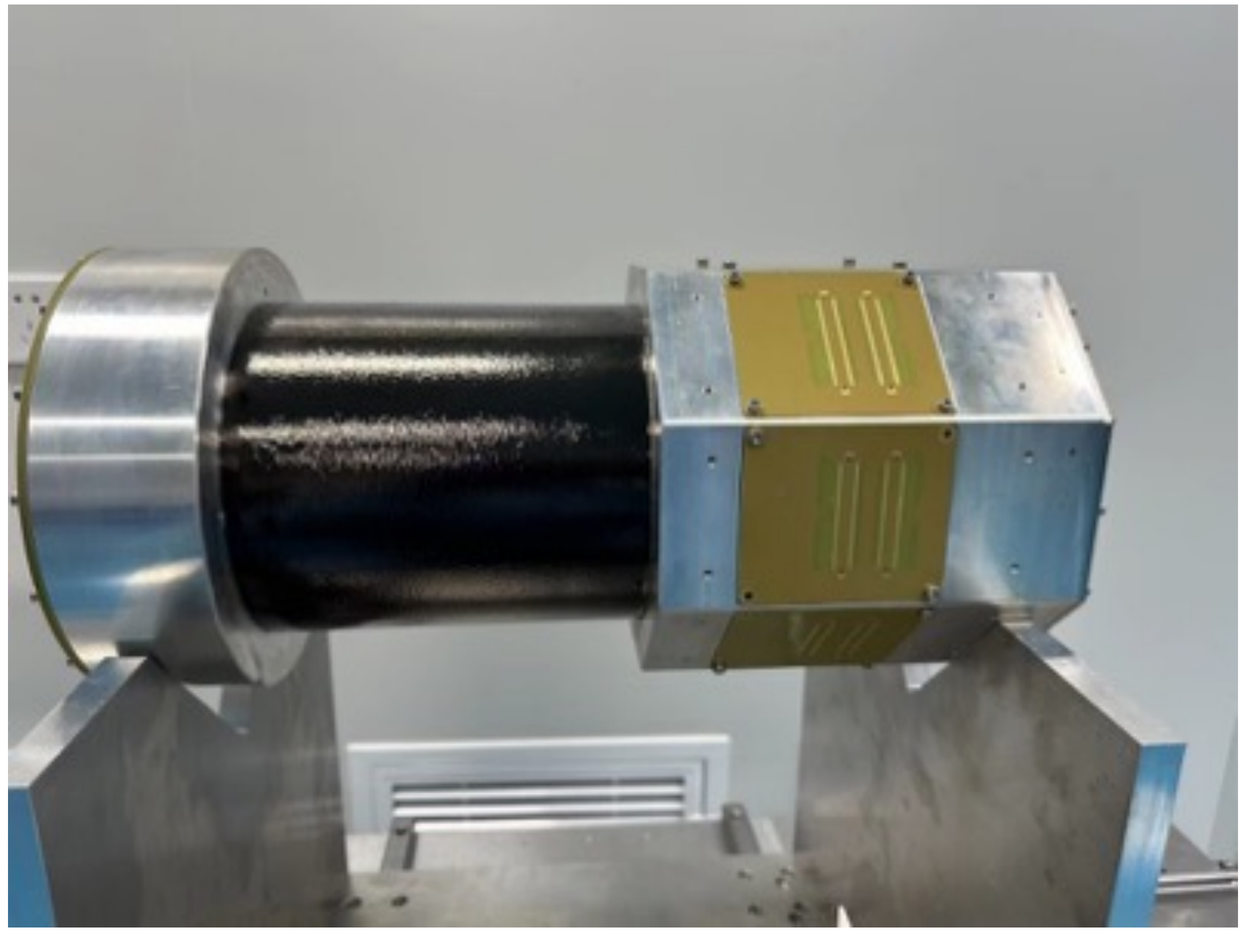


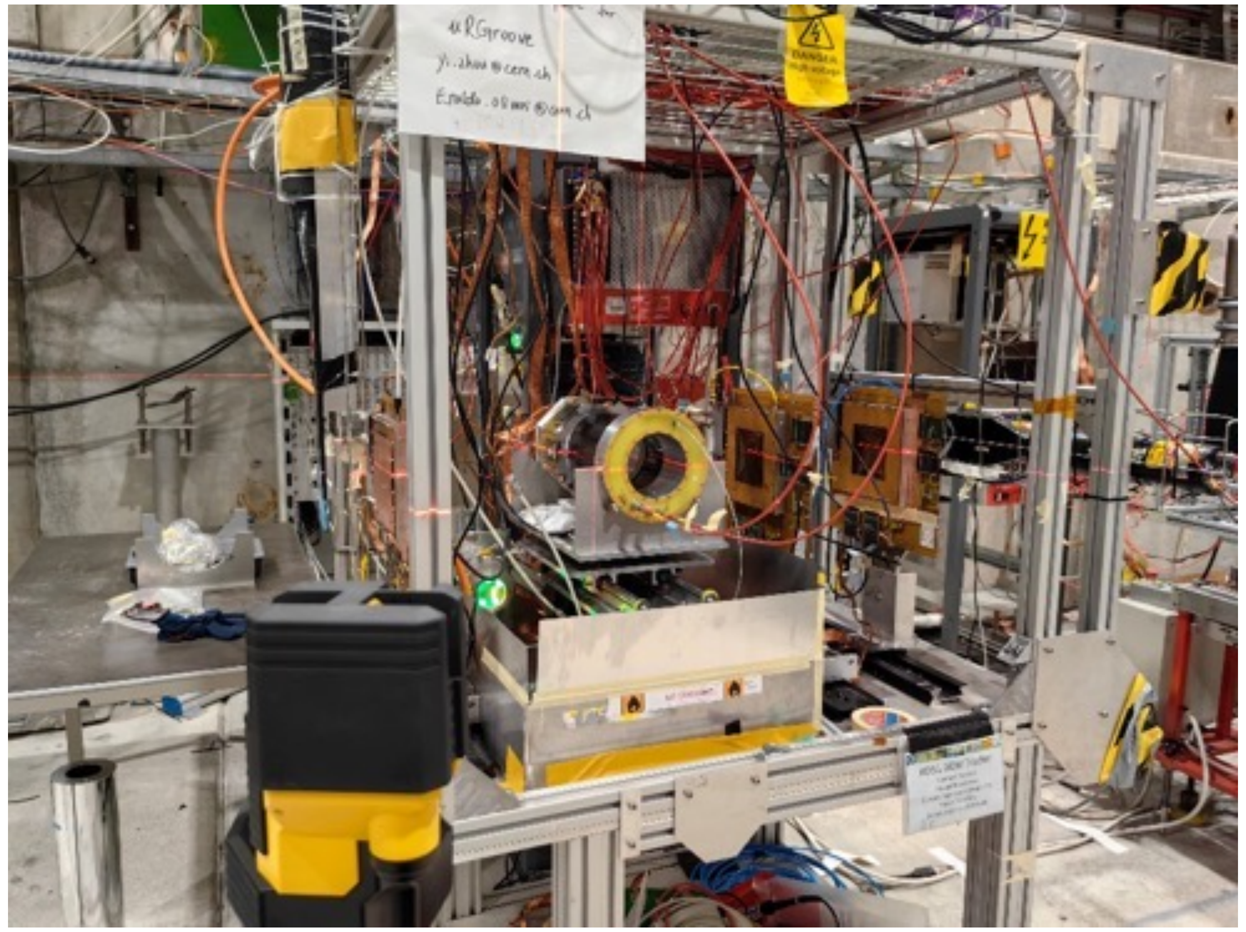


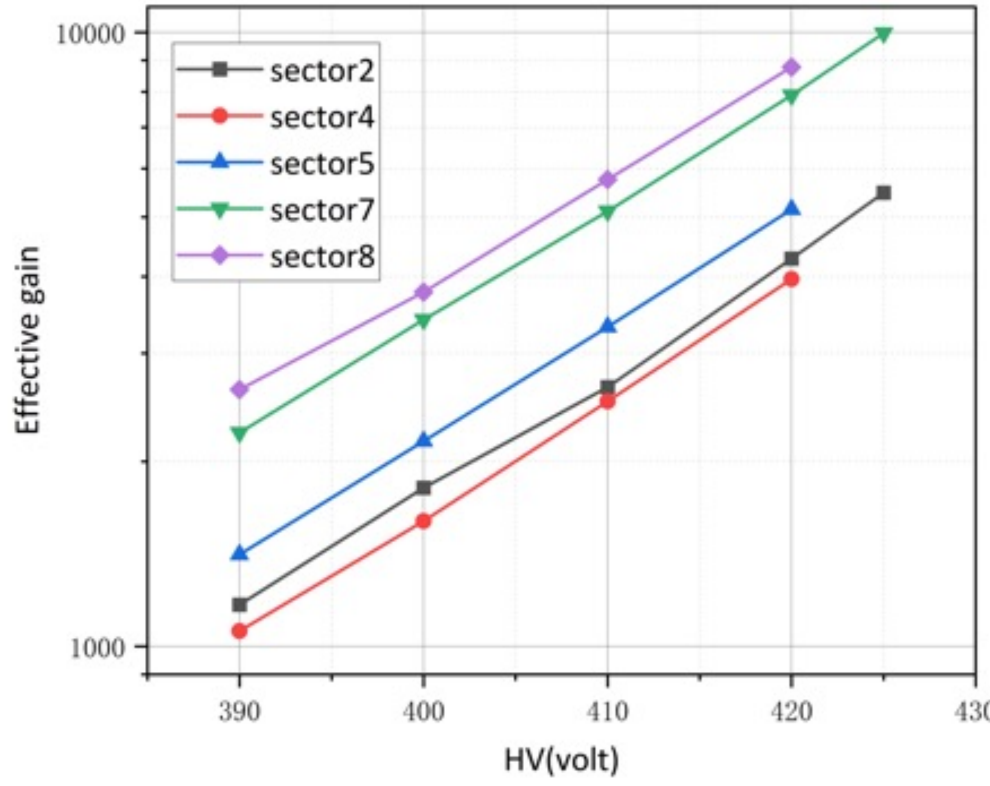


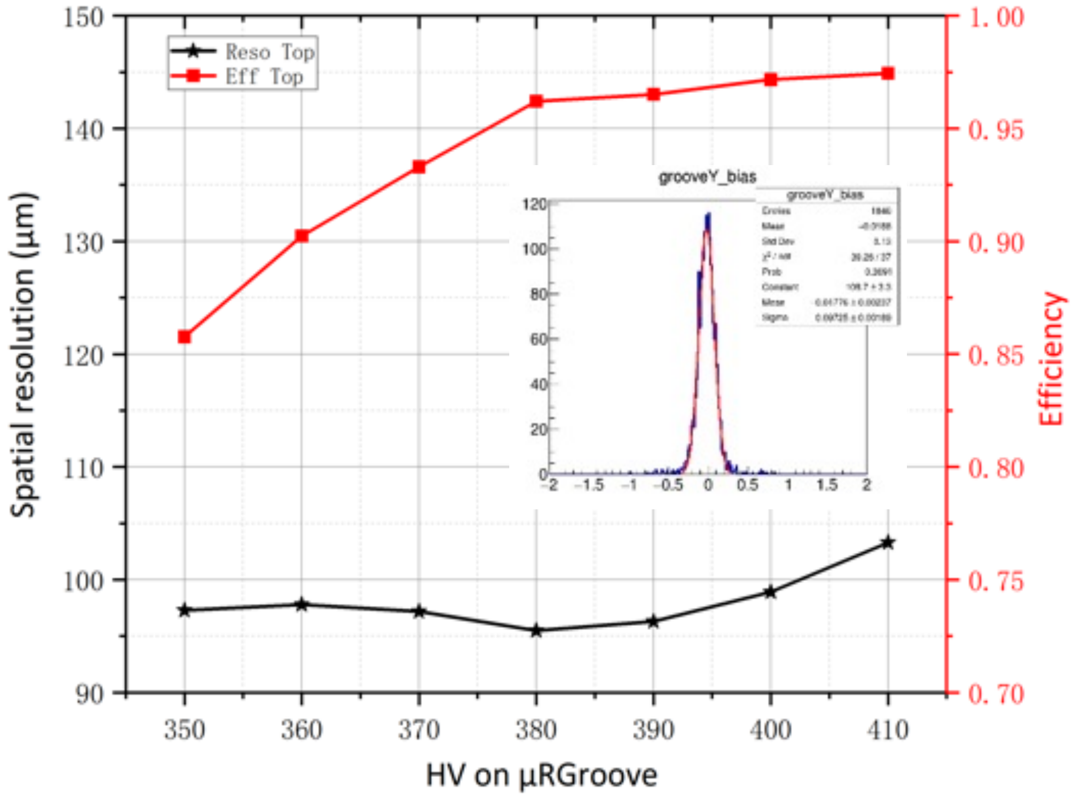
Cylindrical µRGroove Prototype

- Built a cylindrical µRGroove prototype for the ITK inner most layer
- Tested the prototype with ^{55}Fe source in lab and SPS muon beam at CERN
- Effective gain~5000-10000 for most sectors
- Spatial resolution<100 um and efficiency > 95%
- The detector design and fabrication will be optimized in many aspects based on the prototyping experience







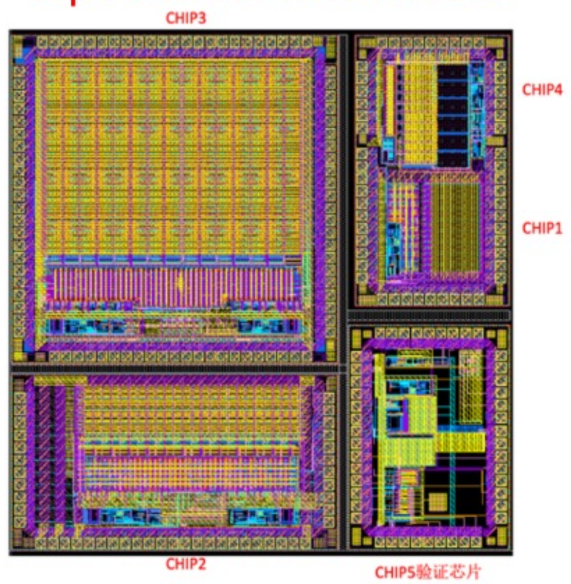


ITK-MAPS: Sensor Design

- **Aiming for a low-power MAPS chip design (required for a low-mass system) with timing and charge measurement capability: position, time and charge (TOT)**
- **Low mass outweighs position resolution: exploring large pixel size to reduce power density**

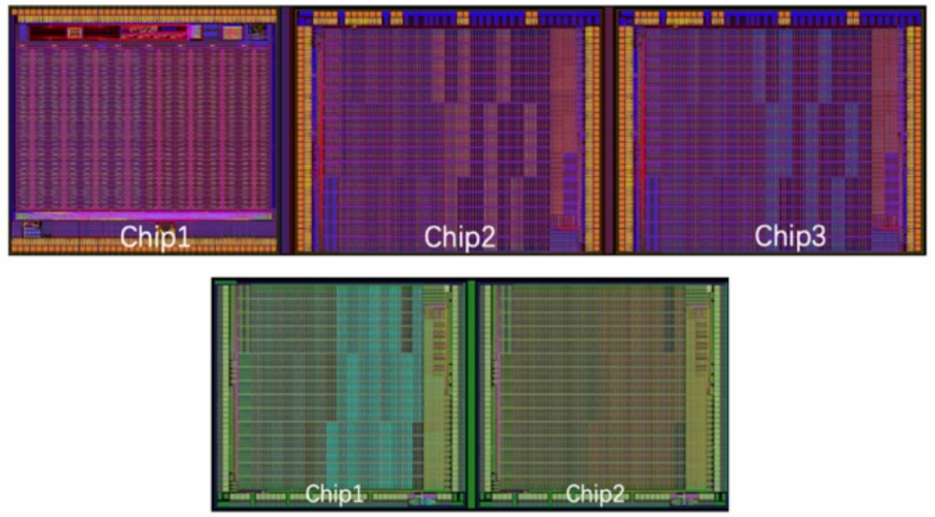
TowerJazz 180nm

Taped out in March 2024



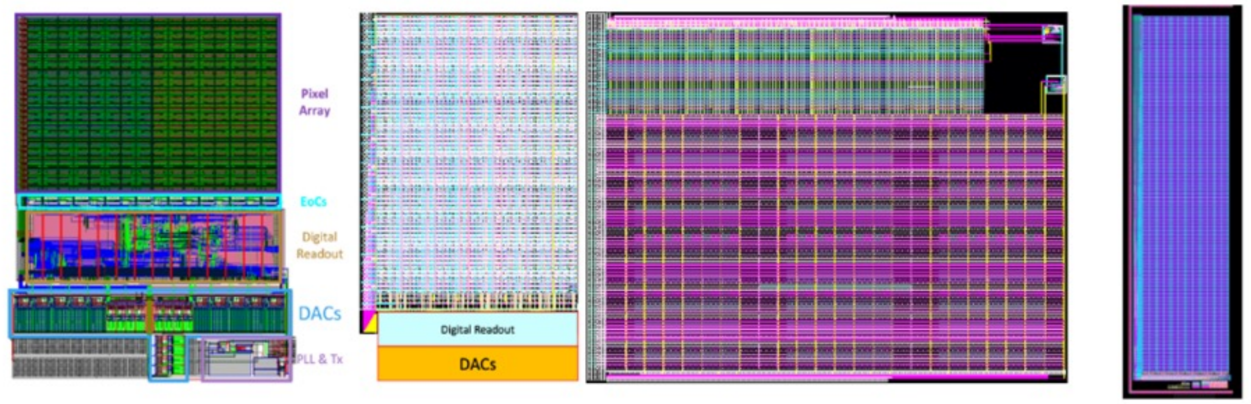
NexChip FCIS/BCIS 90nm

Taped out in May 2024



GSMC 130nm

Taped out in July 2024



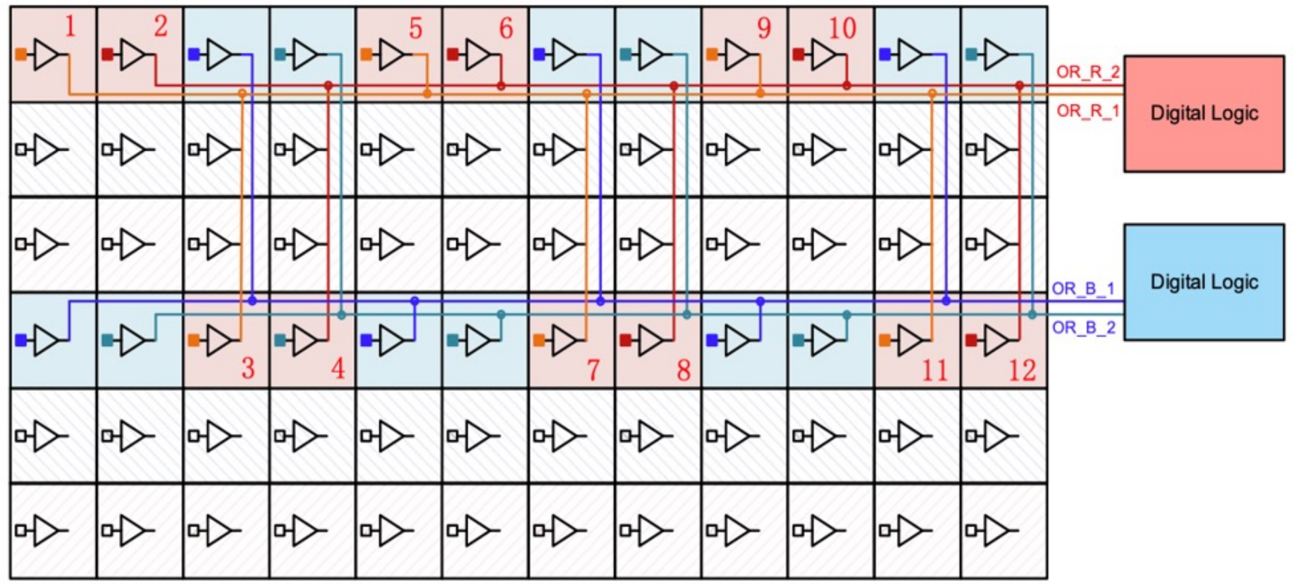
Simulated performance

	TJ-MAPS	GSMC-MAPS
Current	**800 nA/pix**	**120*6 nA/pix**
Supply Voltage	1.8 V	1.2 V
Threshold	309.0 e⁻	153.8 e⁻
ENC	11.4 e⁻	5.1 e⁻
Mismatch	5.7 e⁻	5.8 e⁻
t_r @400 e⁻	**200 ns**	**81 ns**

Items	Power consumption	Notes
Analog in pixel matrix	~26 mW/cm²	Strip-based
	~15 mW/cm²	Pixel-based
Timestamp clock distribution	12.2 mW/cm²	
Dynamic power consumption of the pixel matrix	2.4 mW/cm²	with a data rate of 8.7 MHz/cm²
Periphery	23.5 mW	32MHz event rate
PLL, serializer, LVDS	39 mW	x 2 data/clock output
Analog configuration	20 mW	
Total	222.6 mW	Strip-based
	184.6 mW	Pixel-based

- Strip-based：55.7 mW/cm2
- Pixel-based：46.2 mW/cm2

Super Pixel Design

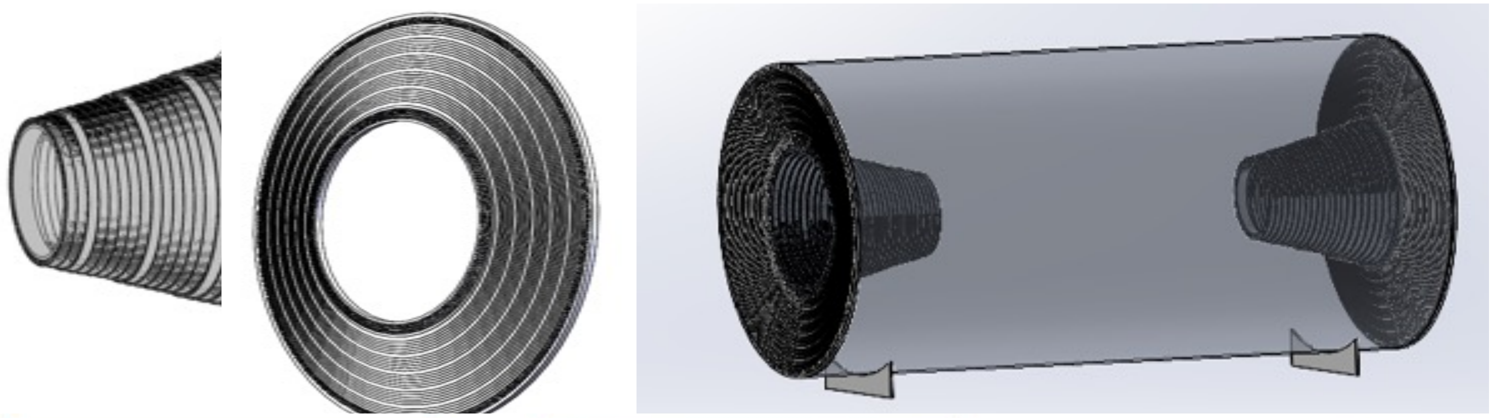


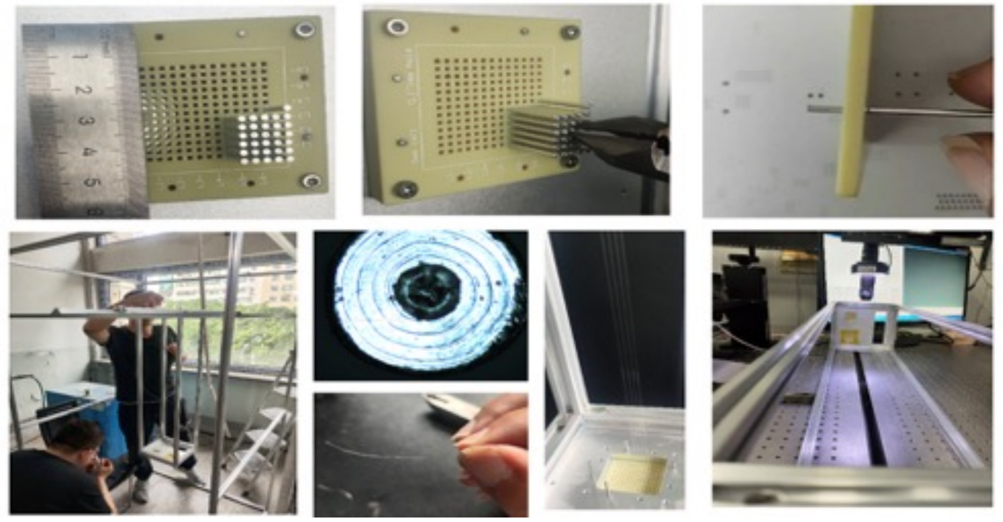
Providing both high position and high time resolutions for low power consumption

MDC, EMC

Main Drift Chamber

low mass(helium-based gas, aluminum wires), super-small cell (5mm×5mm), high rate (~100kHz/cell), spatial resolution <130μm

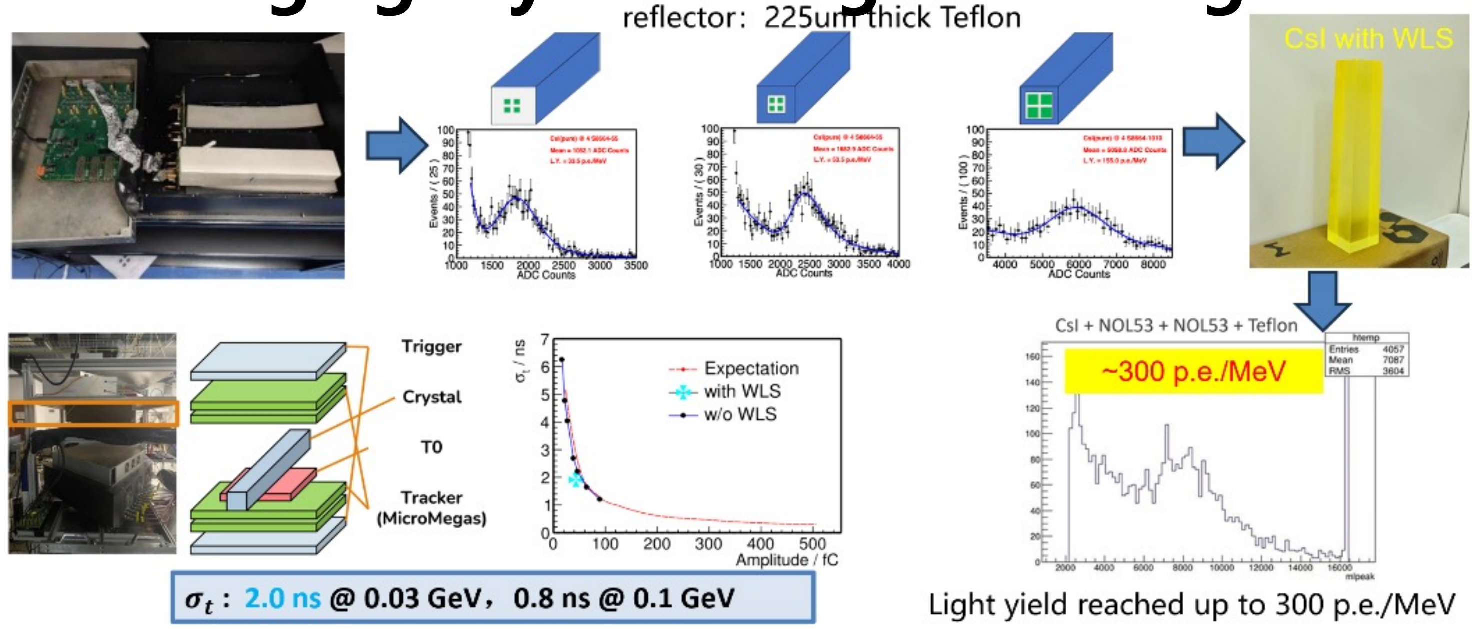




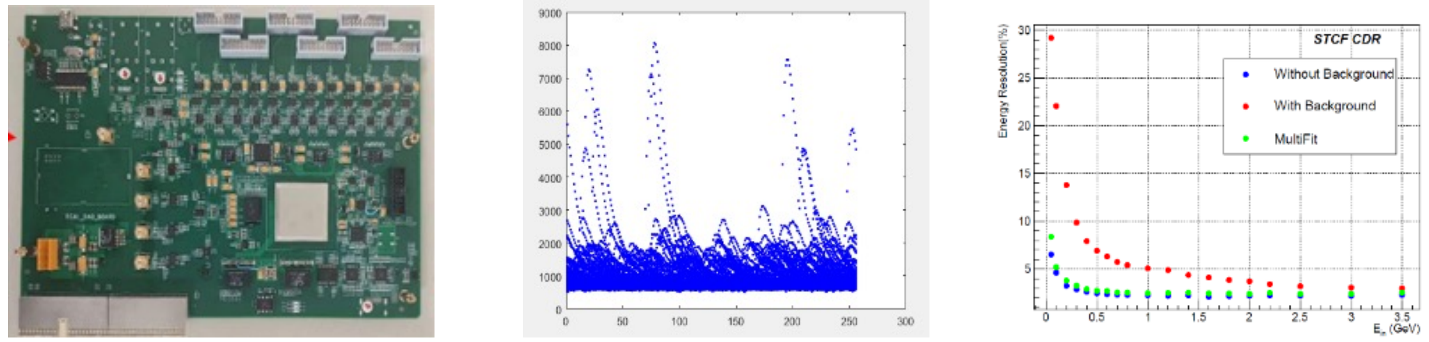
Readout electronics development

Electro-Magnetic Calorimeter

Enhancing light yield using wave length shifter



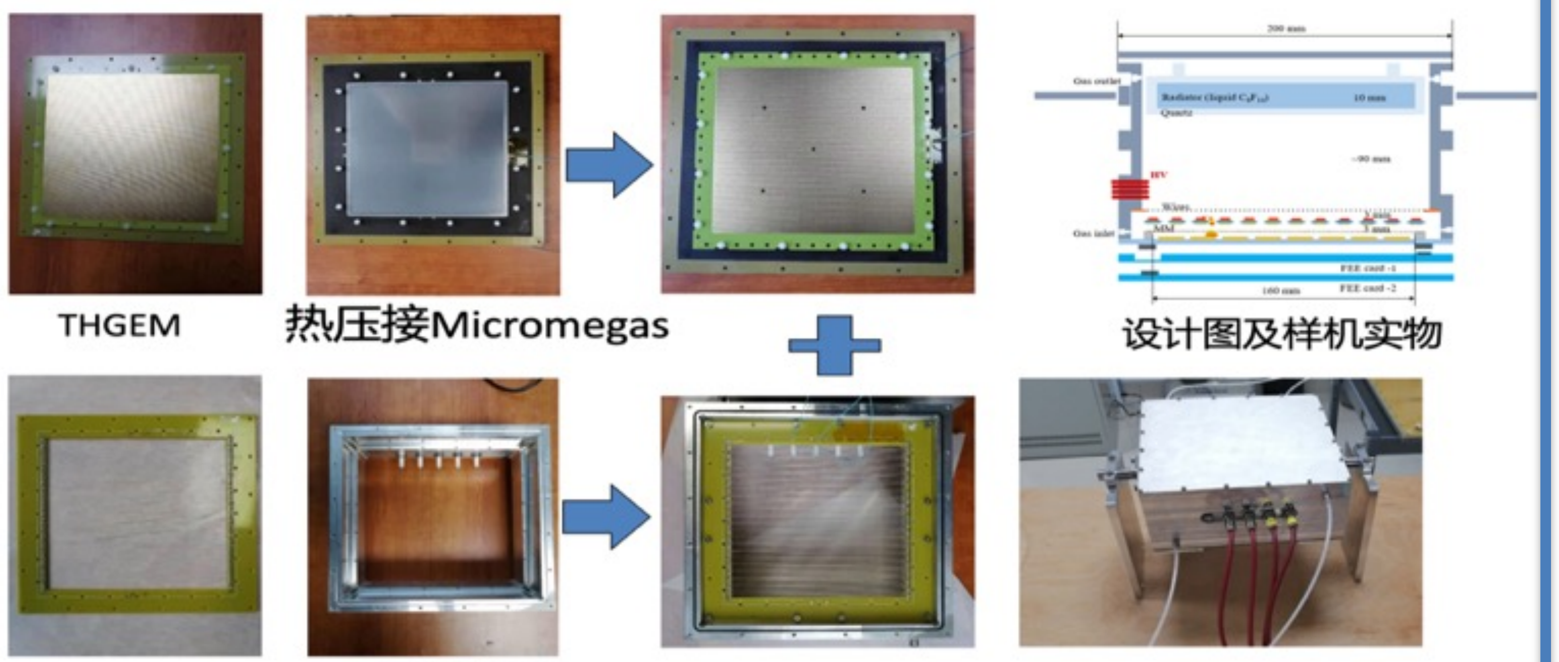
Pileup removal (~1 MHz/channel)
waveform digitization + waveform fitting



5×5 ECAL protype

PID

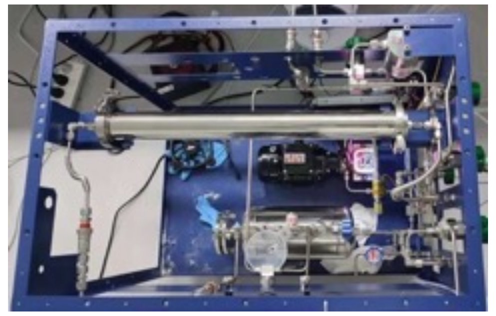
Barrel PID: RICH

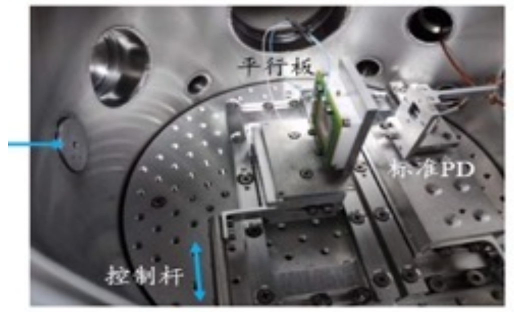


N_{ph} too low (under investigation)

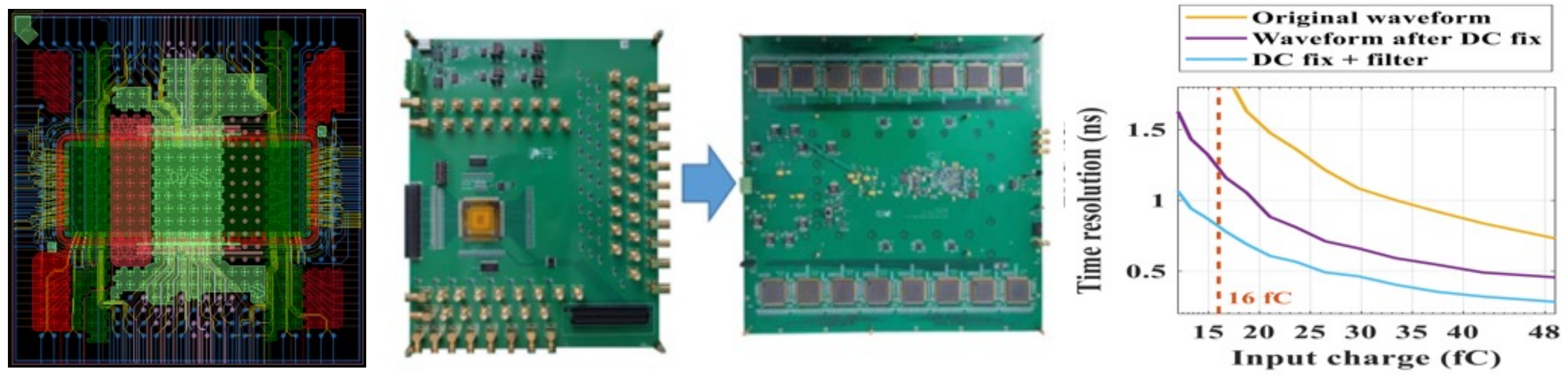
Radiator Purification

CsI Coating



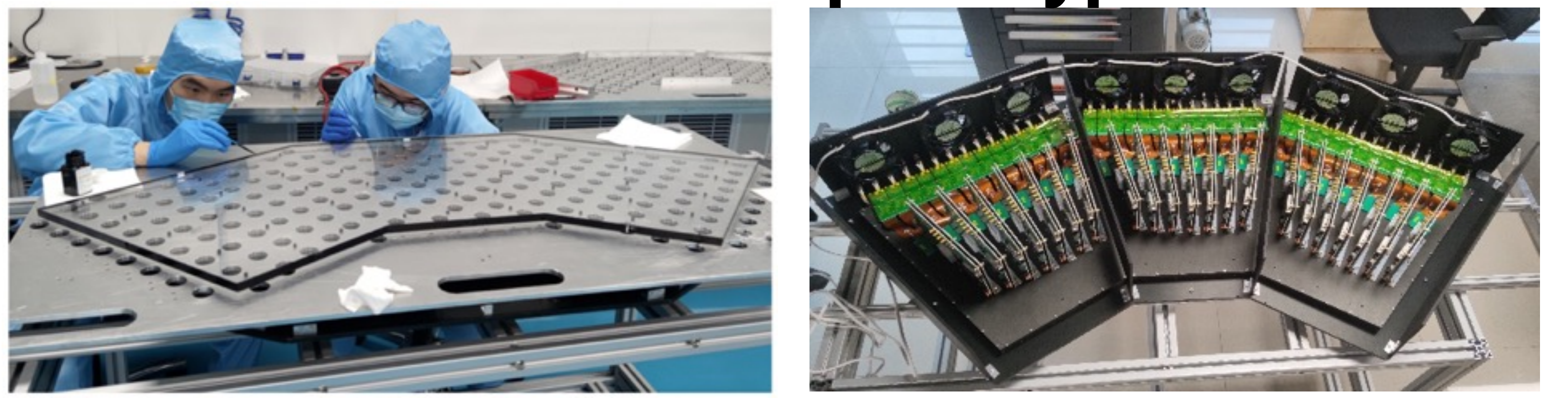


Readout ASIC Development

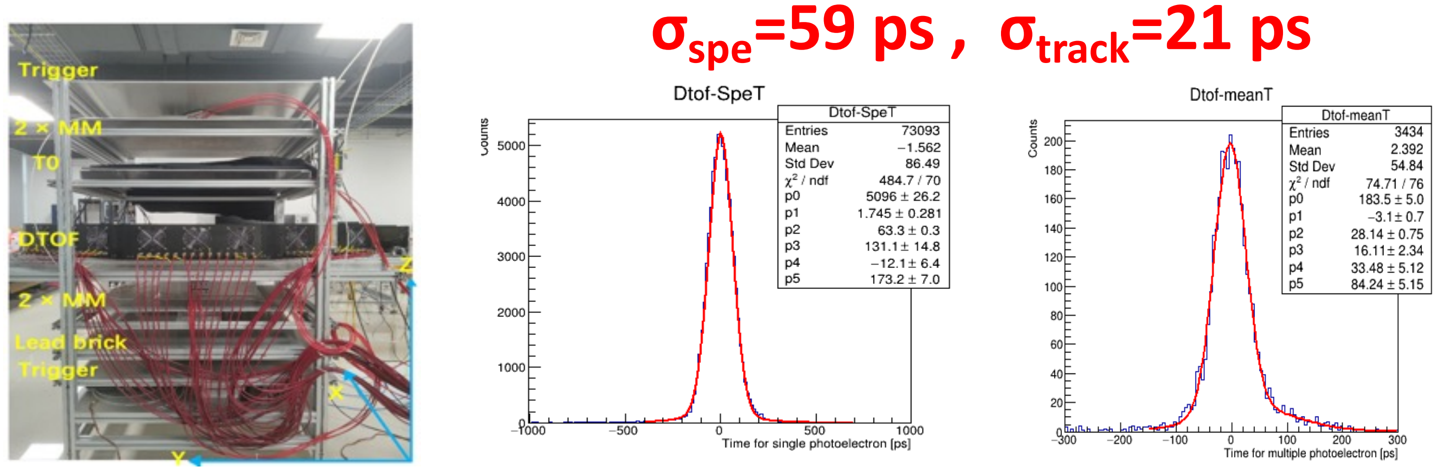


Endcap PID: DTOF

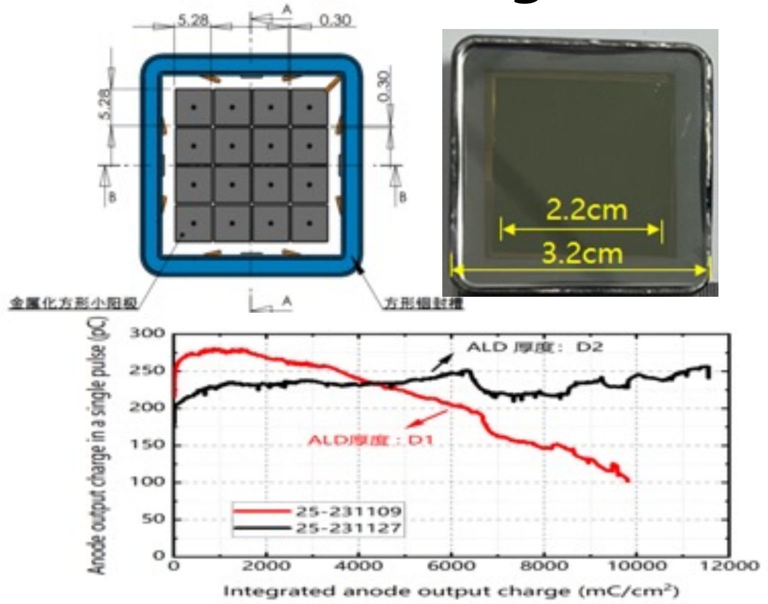
Full-sized prototype



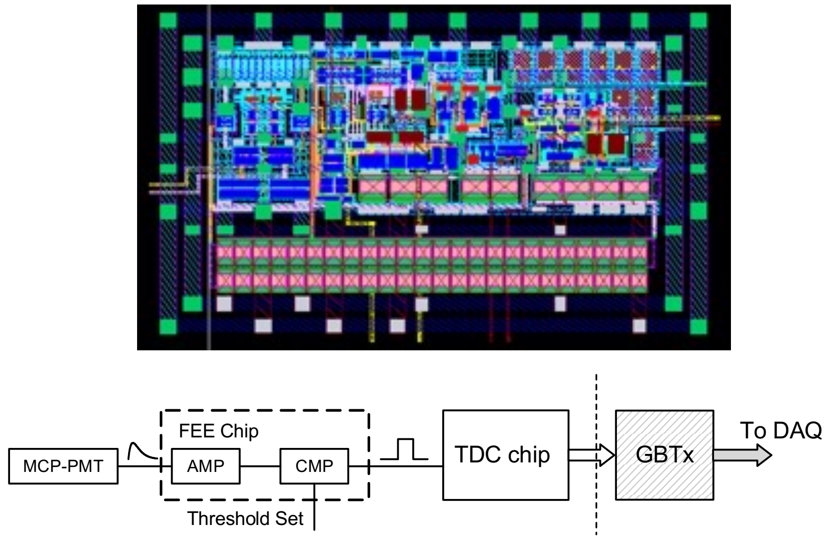
σ_{spe}=59 ps， σ_{track}=21 ps



Development of fast MCP-maPMT with long life time



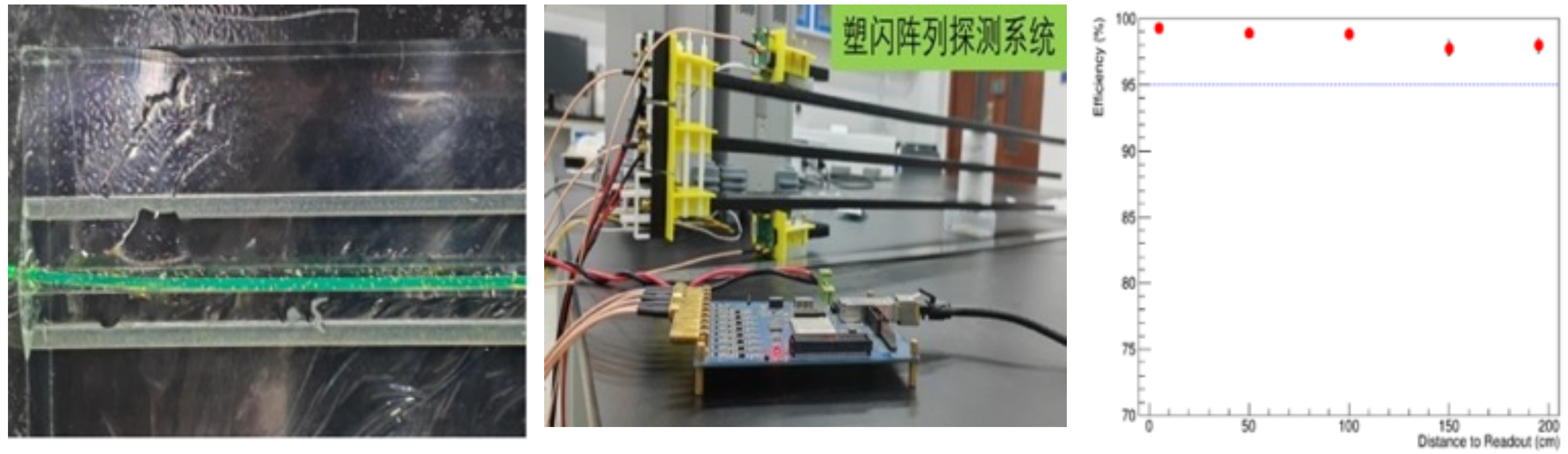
ASIC development



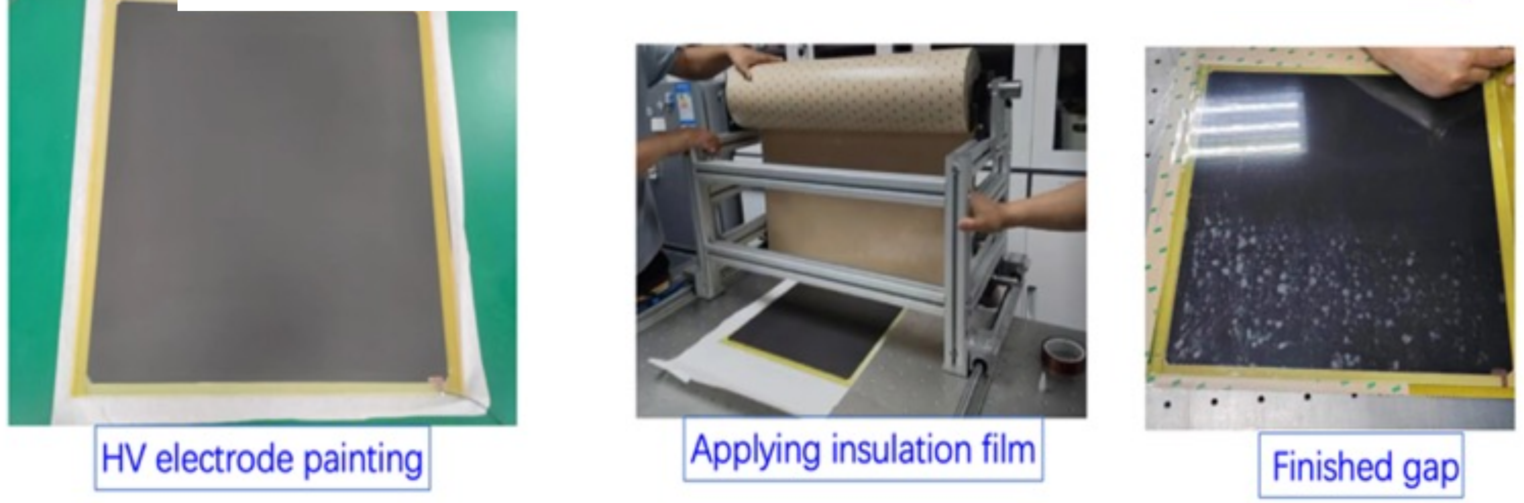
MUD, Trigger, DAQ, Clock, Data Link

Muon Detector

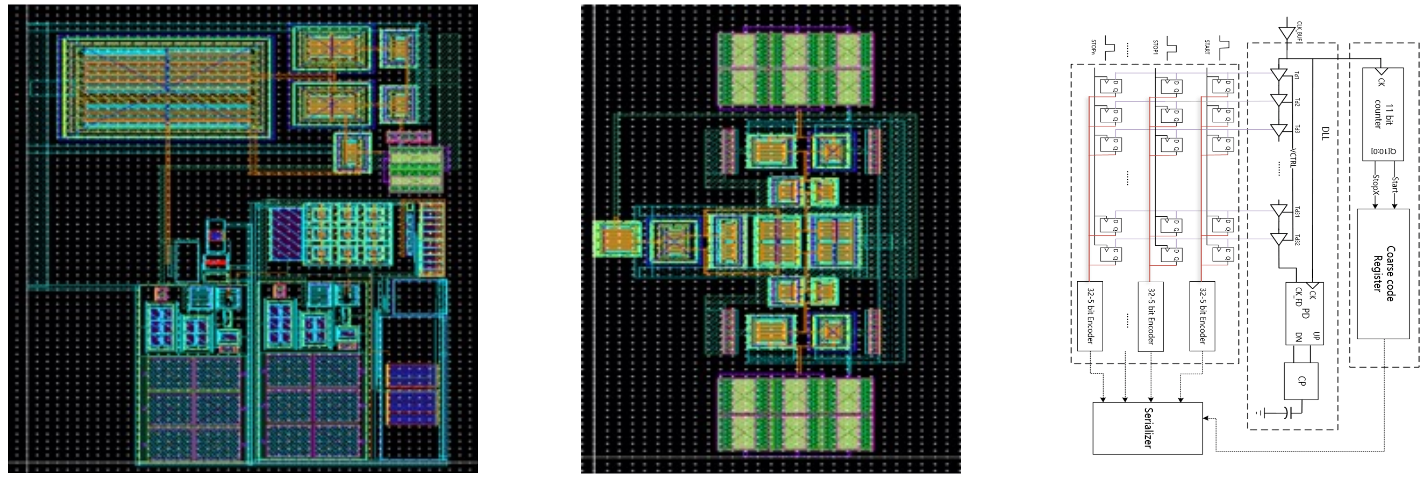
R&D of scintillator strips



R&D of large area high-rate glass-RPC

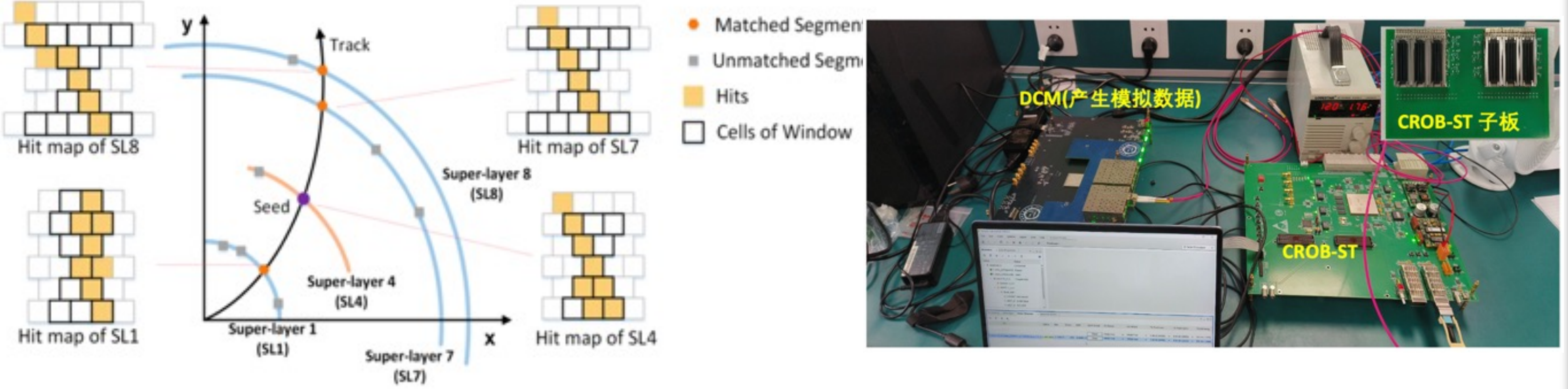


Readout ASIC

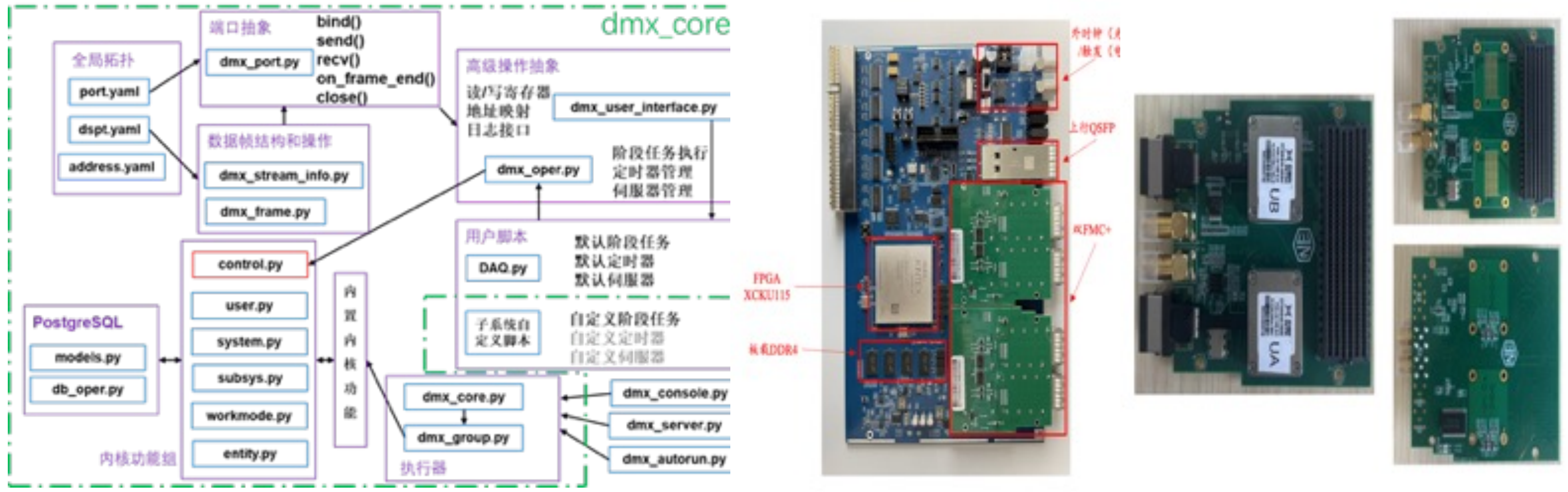


Trigger, DAQ, Clock, Data link

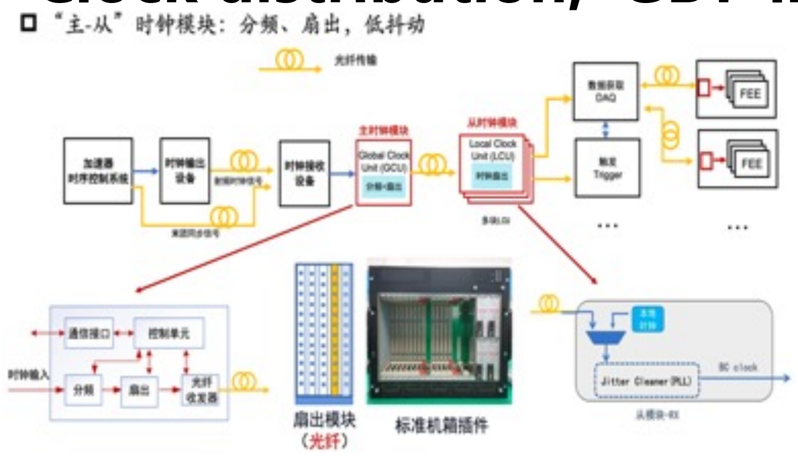
Trigger algorithms and electronics

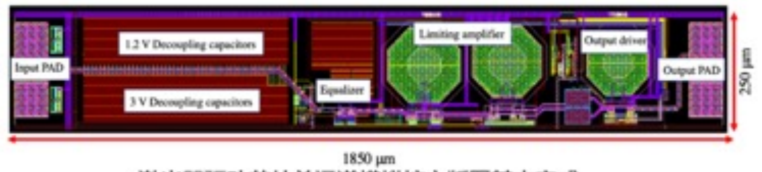


DAQ software design and electronics

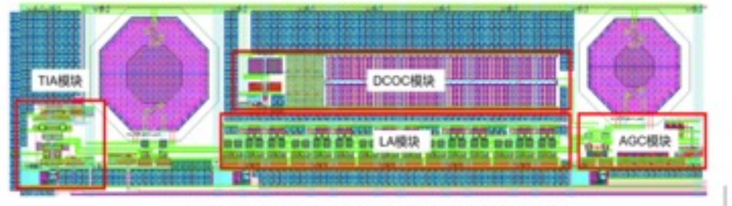


Clock distribution, GBT-like ASIC, Opto-driver ASIC





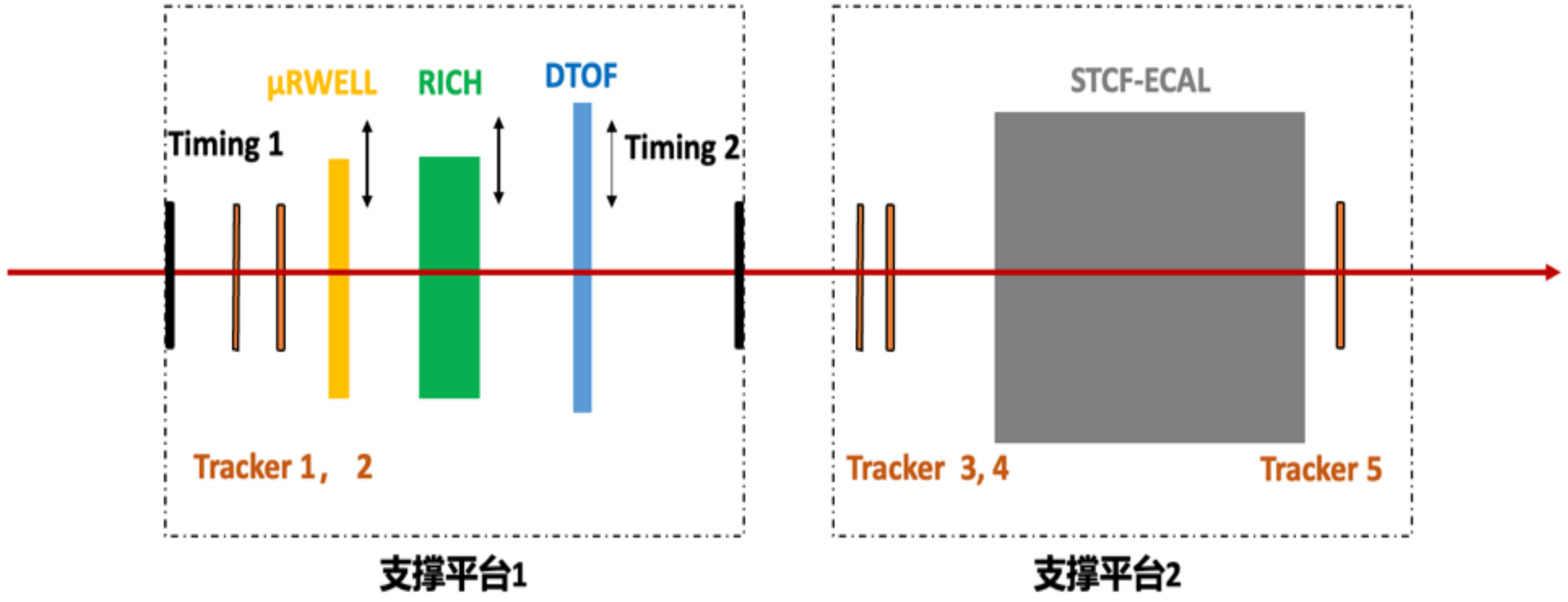
激光器驱动芯片单通道模拟核心版图基本完成



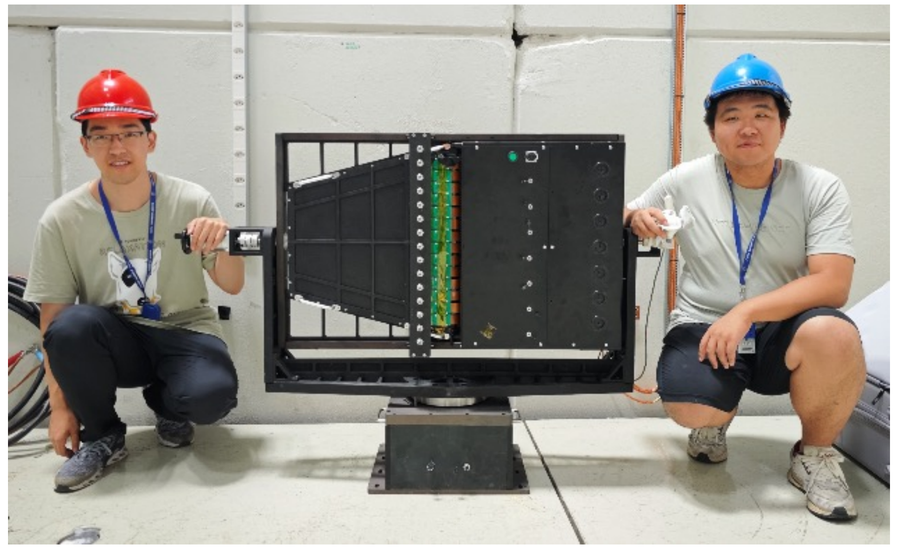
TIA跨导接收芯片单通道模拟核心基本完成

Combined Beam Test

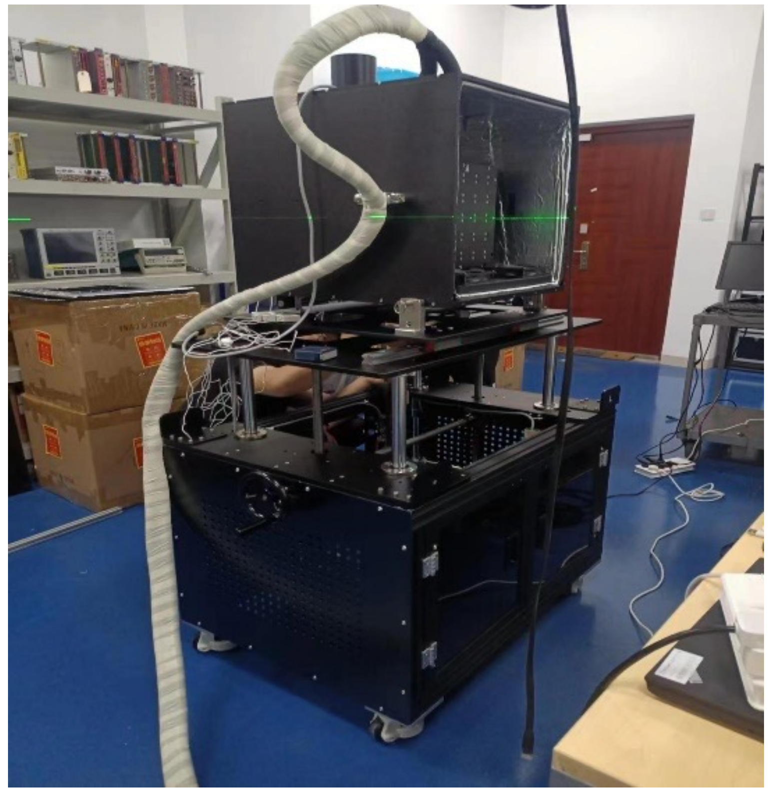
A test beam campaign for a combined system (DTOF, EMC, DAQ)



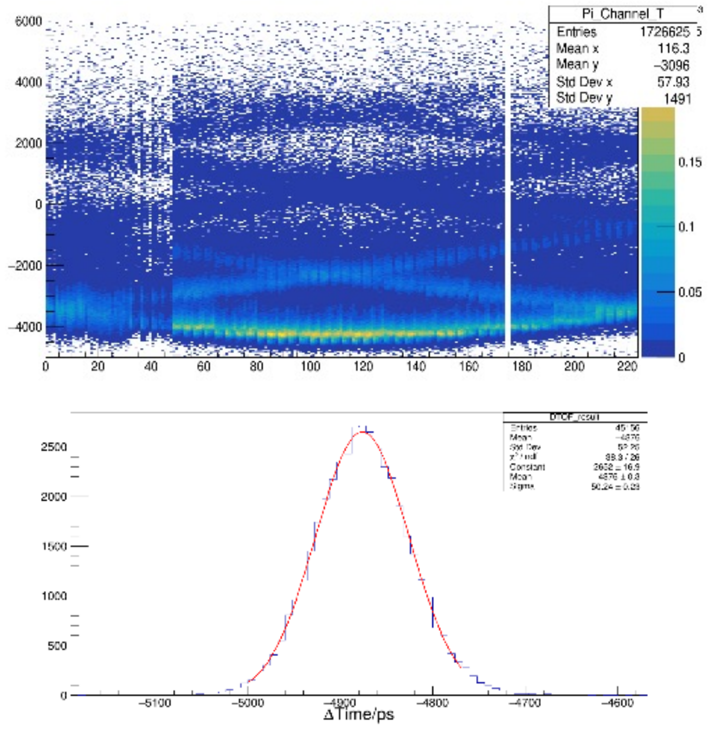
DTOF Prototype



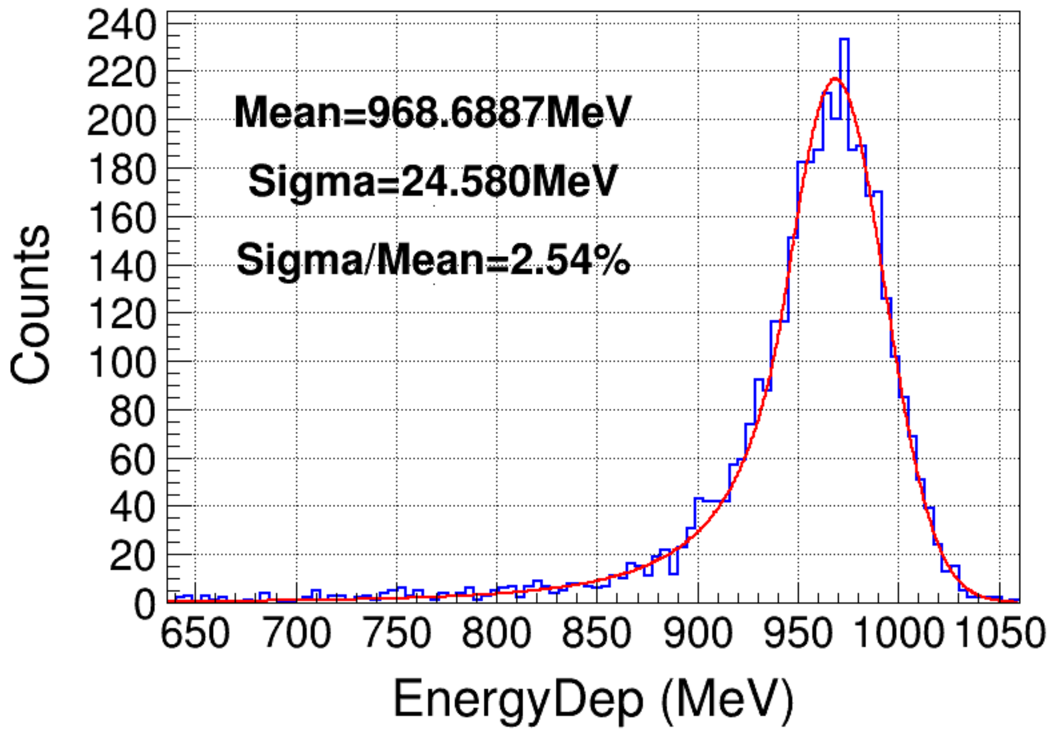
EMC Prototype



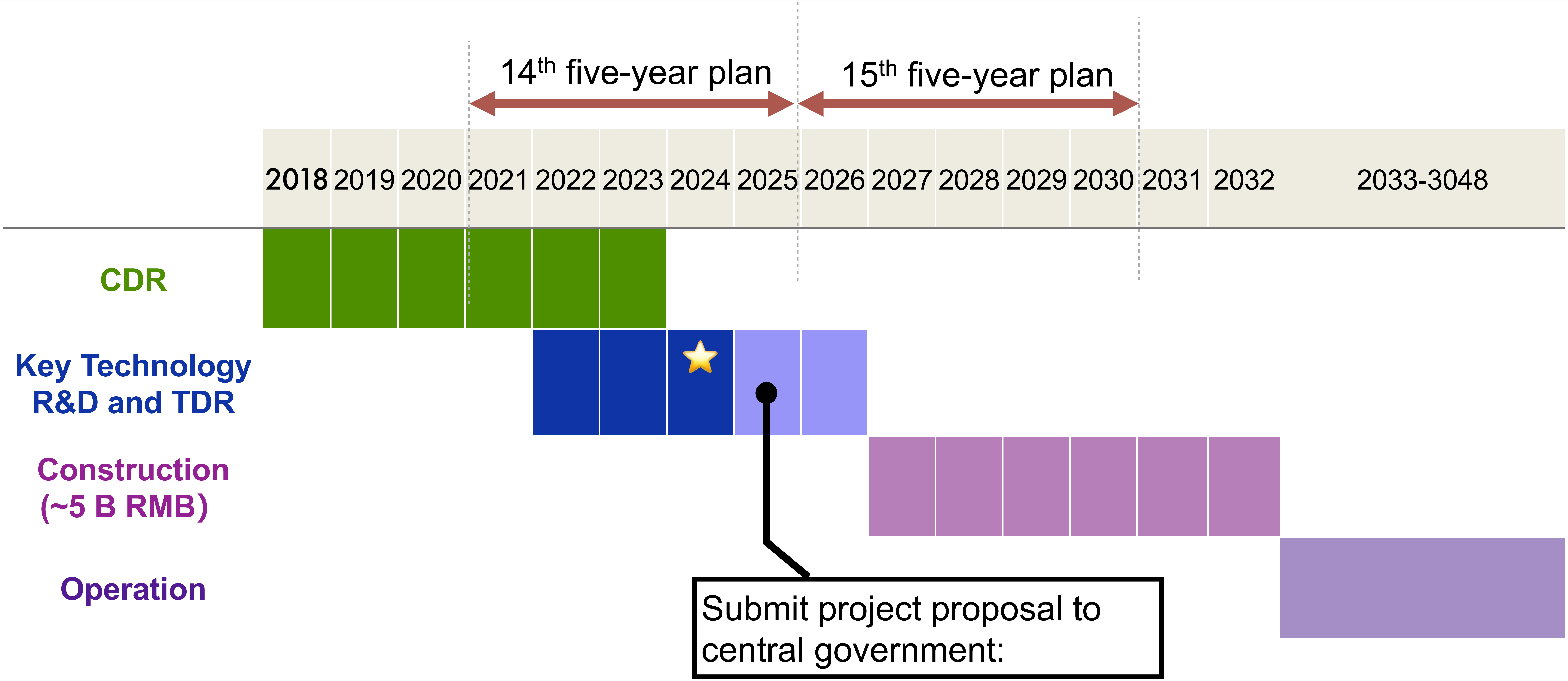
DTOF: σ_t~25 ps



EMC: σ_E/E ~2.5%



STCF Project Schedule

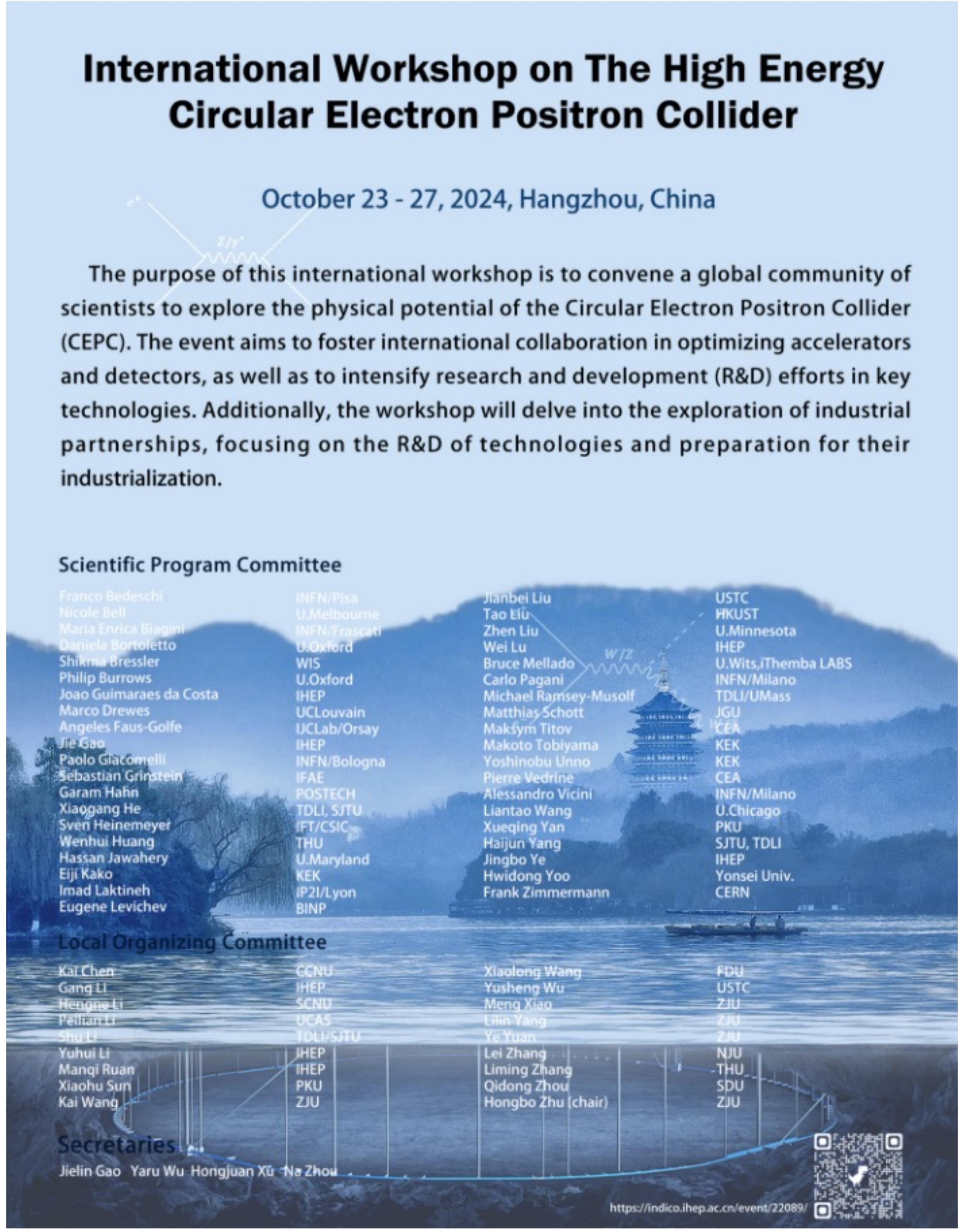


Final Remarks

- **SM has been "standard physics" for too long, and we know it's far from being the end of particle physics. We are desperate for new paradigms in our field and to break through the "standard", particularly in the post-Higgs era.**
- **Colliders have been and will continue to be one of the most powerful tools to explore particle physics and fundamental laws of nature. With no more definite guidance from theory, we need colliders at complementary frontiers for particle physics more than ever.**
- **CEPC and STCF are excellent examples of this complementarity, although they are at very much different scales in many ways.**
- **Tremendous progress has been made and many milestones have been achieved in both projects, demonstrating the passion, aspiration, strength and potential of Chinese HEP community. China should and could play a more important role in the course to HEP future.**
- **International collaboration is always essential or indispensable**
- **We should work together to ensure our future colliders be realized wherever the colliders will be in the world.**

The 2024 International Workshop on CEPC

Oct. 23-27, 2024, Hangzhou, China



https://indico.ihep.ac.cn/event/22089/

The 6th International Workshop on Future Tau Charm Facilities

The 6th International Workshop on Future Tau Charm Facilities (FTCF 2024)

Dates: Nov. 17-21, 2024

Place: Sun Yat-sen University, Guangzhou

https://indico.pnp.ustc.edu.cn/event/1948