The CEPC Physics and Detector

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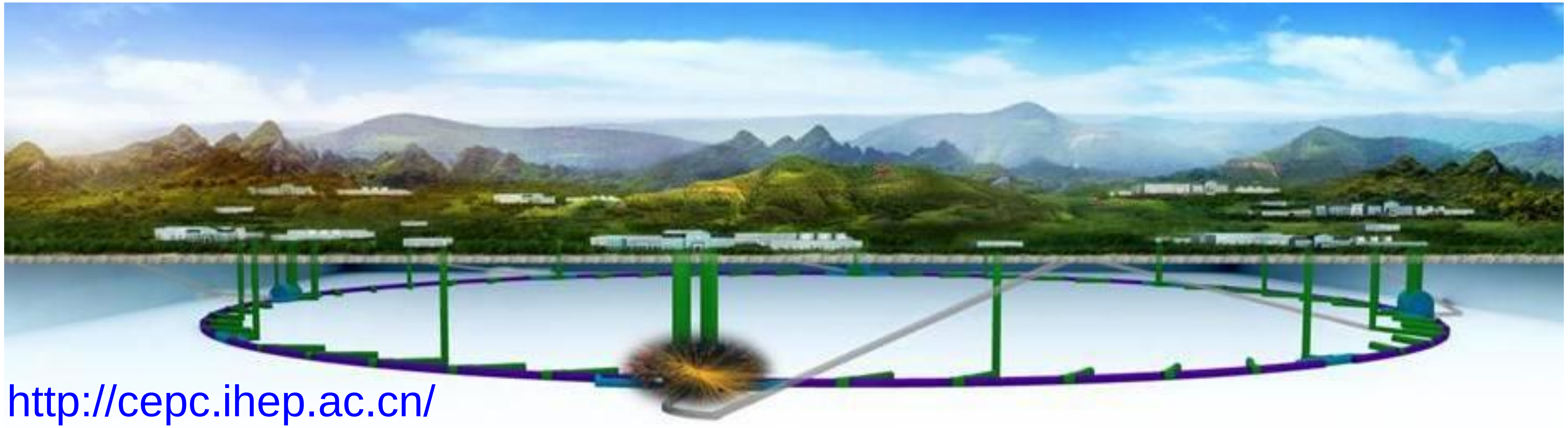
Joint Workshop to Commemorate the MOU Between Korea University (KU) and the Institute of High Energy Physics (IHEP), Oct. 14 – 16, 2024



http://cepc.ihep.ac.cn/

Outline

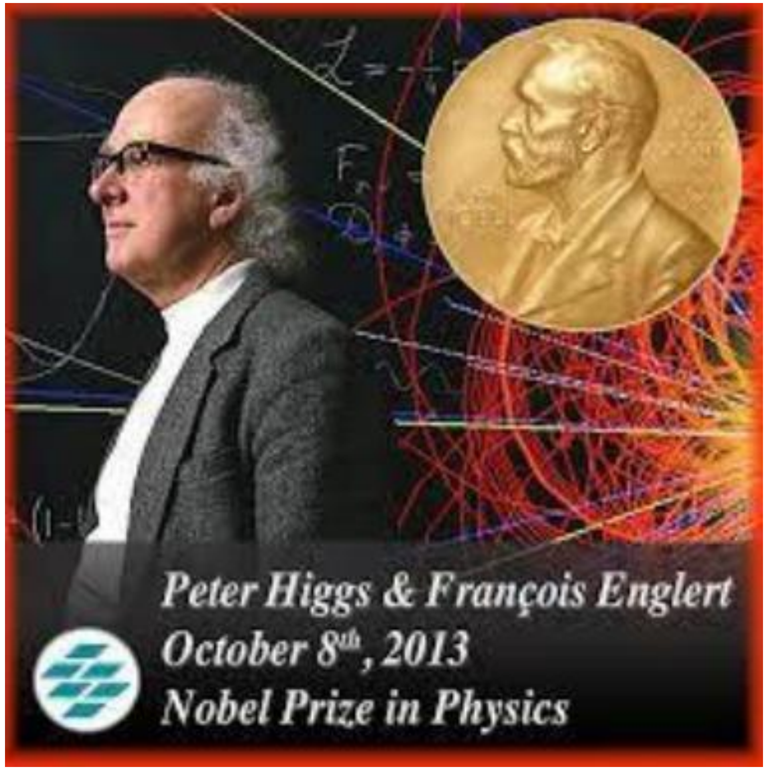
- The CEPC proposal and major milestones have been covered by Prof. Gao
- The CEPC Physics Programs ⇦ I will start from here.
- The CEPC Detector R&Ds
- Summary

The Higgs Particle: Discovery and Measurements

2012 discovery

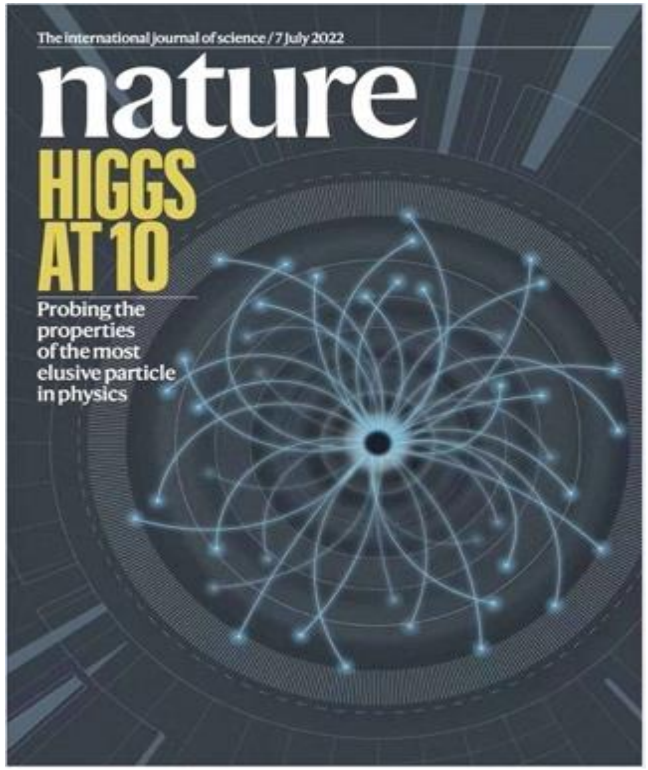
The discovery:
Phys. Lett. B 716(2012) 1-29
Phys. Lett. B 716(2012) 30-61
Science 338 (2012) 1569-1575
Science 338 (2012) 1576-1582

2013 Nobel Prize



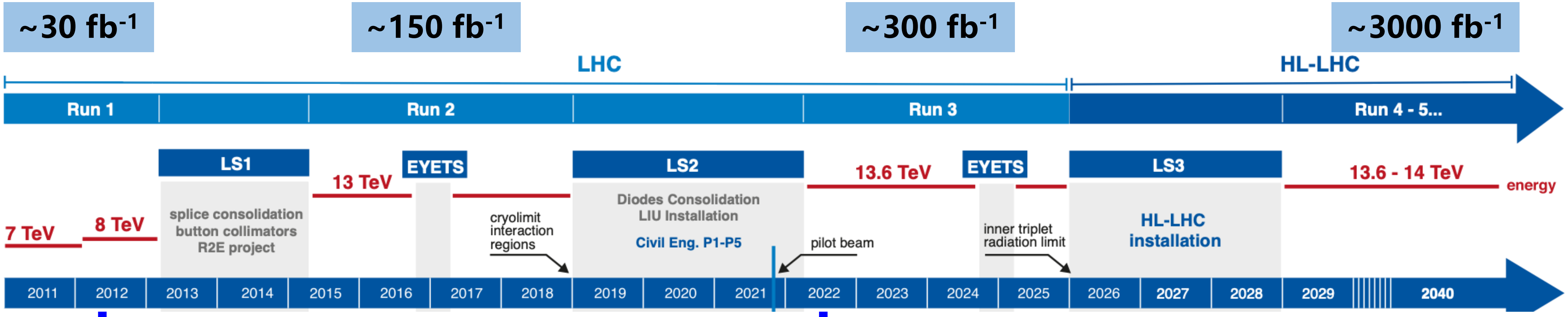
"for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider"

2022 ten yrs measurements



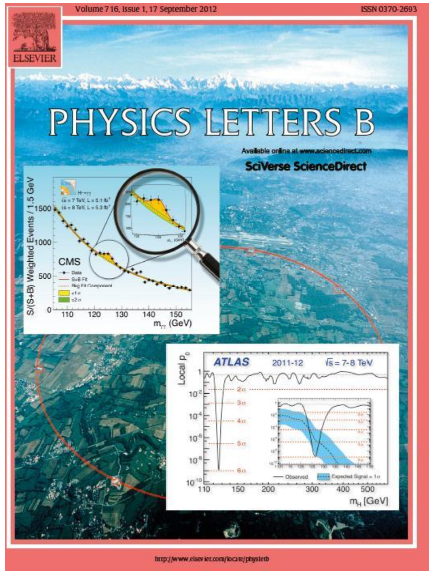
The measurements:
Nature 607, 52-59 (2022)
Nature 607, 60-68 (2022)

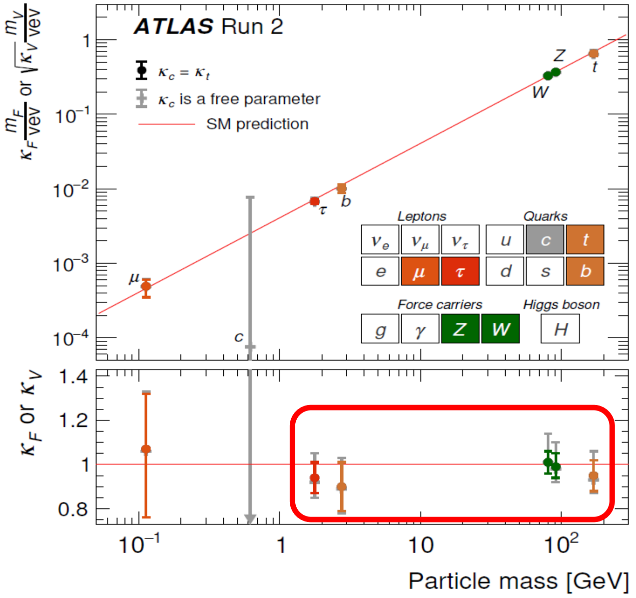
Measurements in ten years



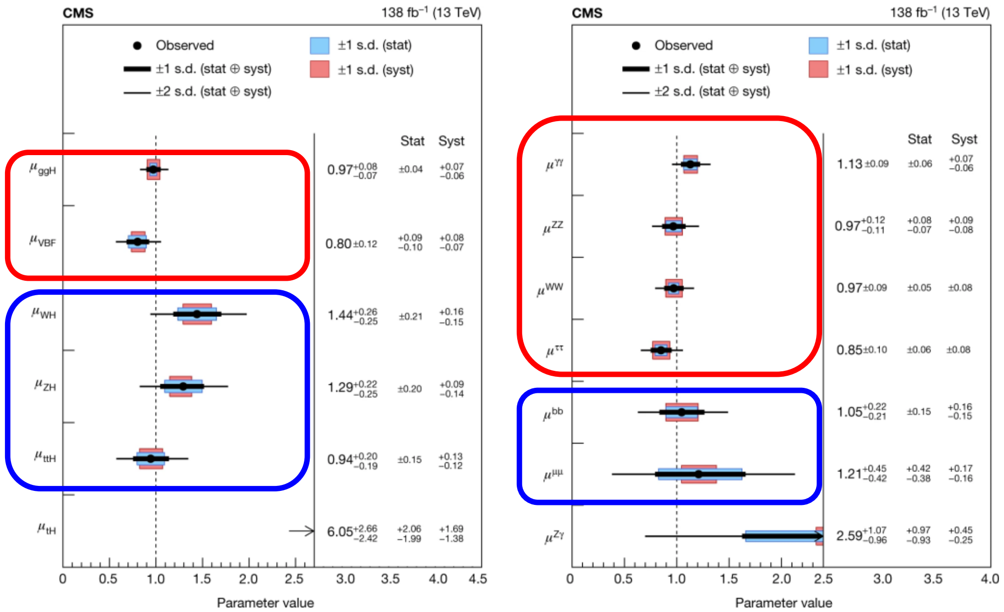
New milestone after 10 years of the Higgs discovery

Higgs Discovery





Nature 607 (2022) 52-59



Nature 607 (2022) 60-68

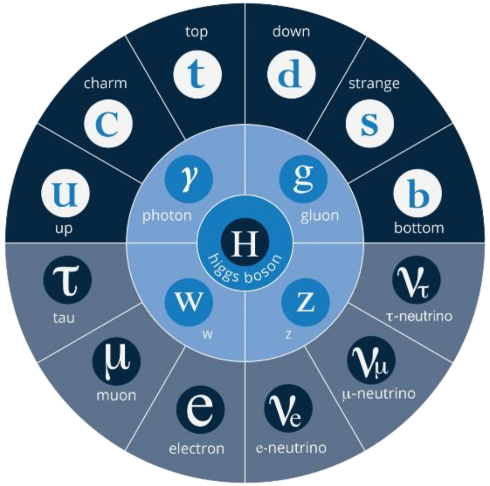
5-10%

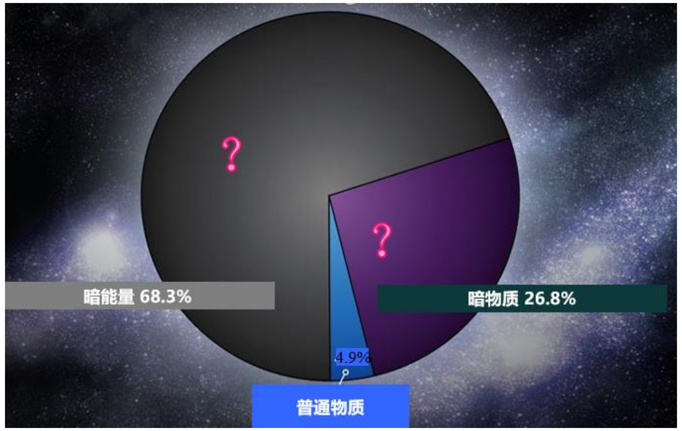
20-40%

Particle Physics after the Higgs Discovery

SM is a complete and self-consistent theory after the Higgs discovery.

But it doesn't accommodate dark matter and dark energy ➔ New physics ?

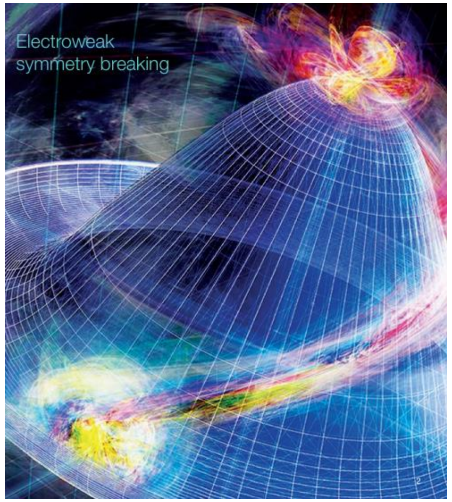


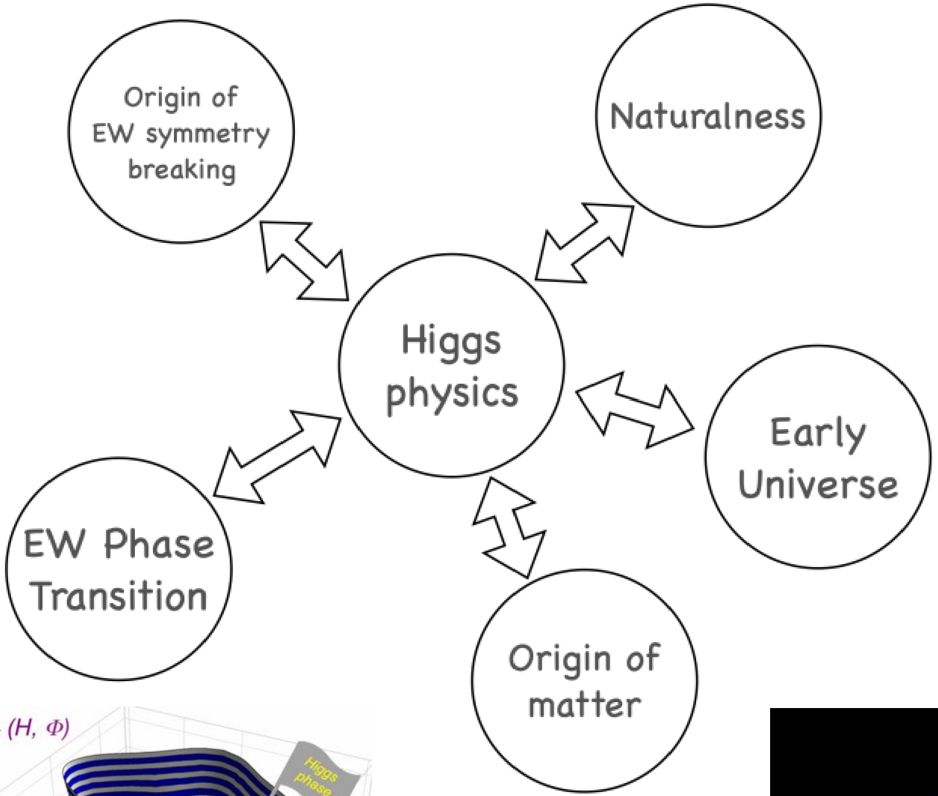


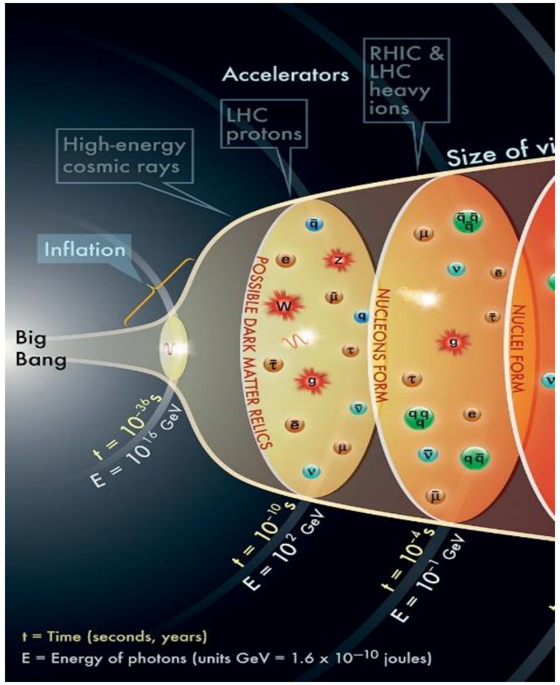
Dark matter and dark energy ~ 95%

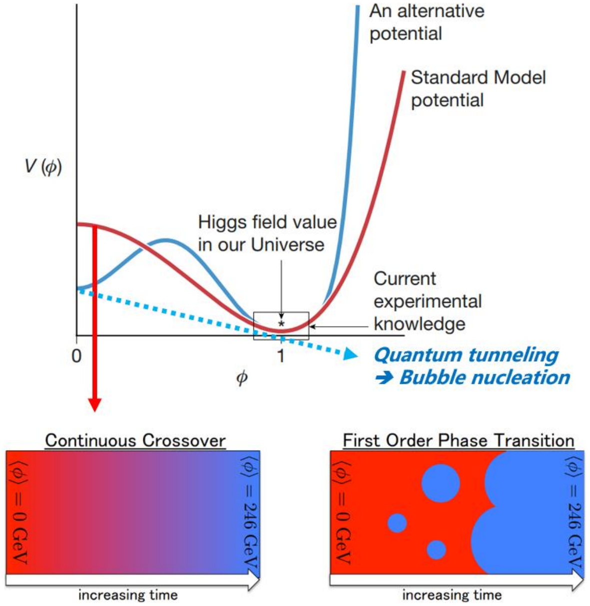
Higgs boson: a probe to new physics

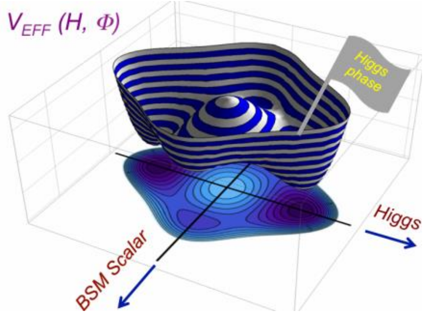
➔ EW symmetry breaking **➔ Naturalness** **➔ Early Universe**

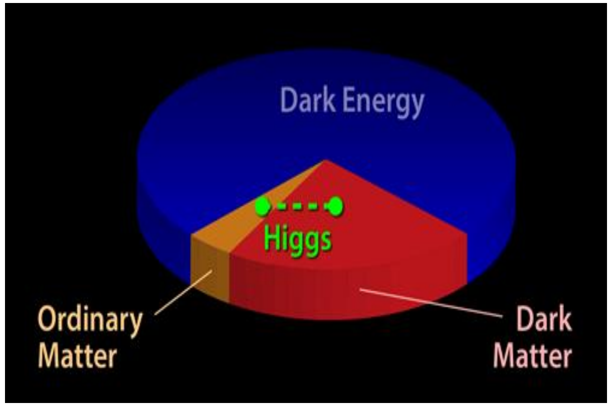












➔ EW Phase Transition

➔ Origin of matter

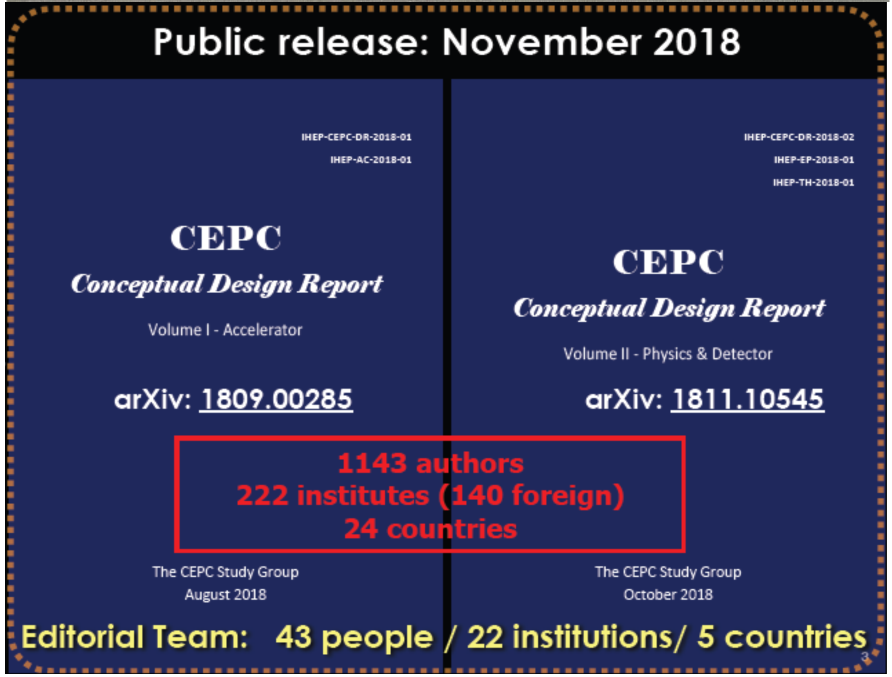
➔ Higgs portal to DM

CEPC Major Milestones

CEPC-SPPC Kickoff (2013.9)

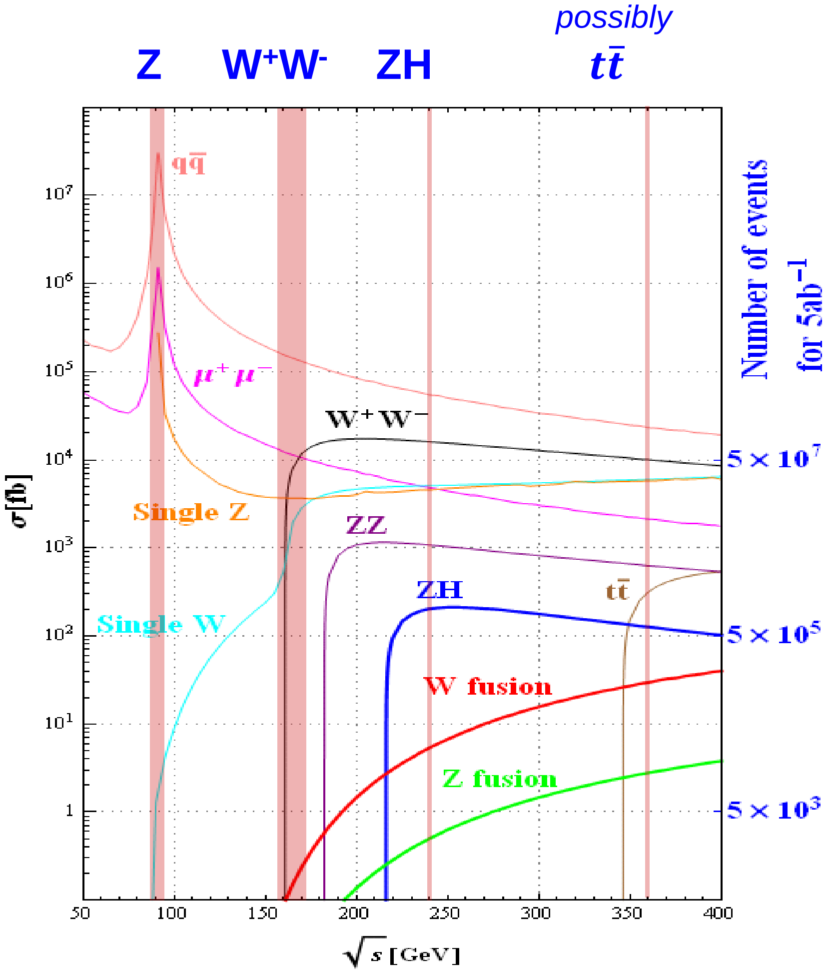
First CEPC IAC Meeting (2015.9)

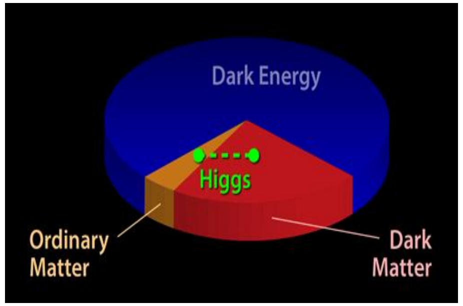
CEPC CDR Released (2018.11)

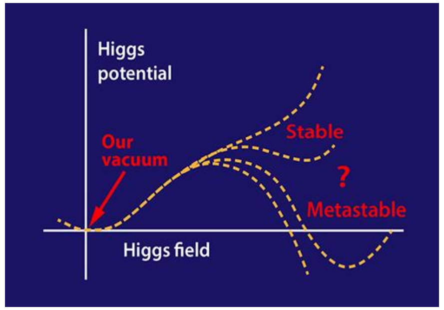


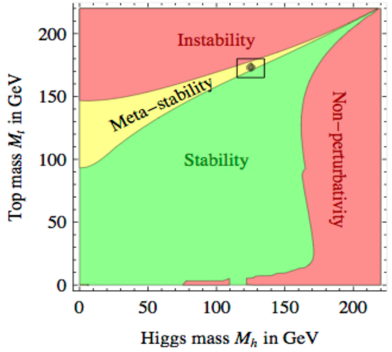
CEPC Physics Program

- **Measurements of Higgs, EW, flavor physics & QCD at unprecedented precision**
- **BSM physics (e.g. dark matter, EWPT, LLP, …) up to ~ 10 TeV scale**







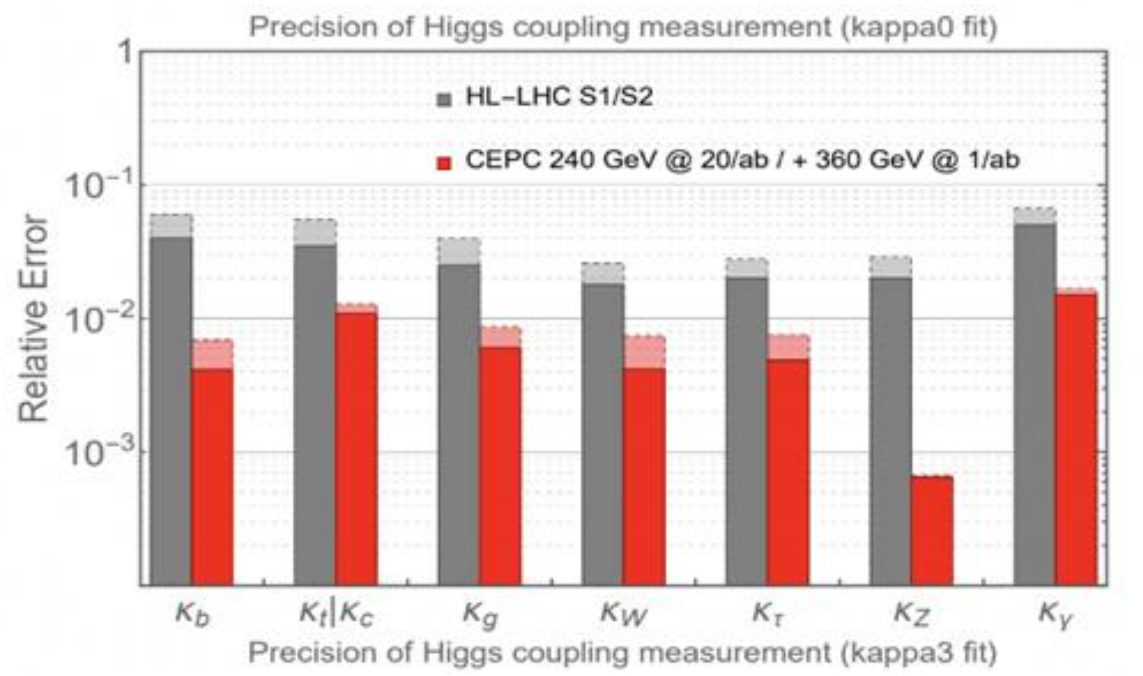


Operation mode		ZH	Z	W+W-	$t\bar{t}$
$\sqrt{s}$ [GeV]		~240	~91	~160	~360
Run Time [years]		10	2	1	~5
30 MW	L / IP [$\times10^{34}$ cm^{-2}s^{-1}]	**5.0**	**115**	**16**	**0.5**
	$\int L\,dt$ [ab^{-1}, 2 IPs]	13	60	4.2	0.6
	Event yields [2 IPs]	2.6×10^6	2.5×10^{12}	1.3×10^8	4×10^5
50 MW	L / IP [$\times10^{34}$ cm^{-2}s^{-1}]	**8.3**	**192**	**26.7**	**0.8**
	$\int L\,dt$ [ab^{-1}, 2 IPs]	22	100	6.9	1
	Event yields [2 IPs]	4.3×10^6	4.1×10^{12}	2.1×10^8	6×10^5

CEPC： Higgs Properties

➢ **CEPC has significantly better precision on Higgs properties than that of HL-LHC**

Higgs		
观测量	HL-LHC 预期精度	CEPC 预期精度
M_H	20 MeV	3 MeV
Γ_H	20%	1.7%
$\sigma(ZH)$	4.2 %	0.26%
$B(H \to bb)$	4.4%	0.14%
$B(H \to cc)$	-	2.0%
$B(H \to gg)$	-	0.81%
$B(H \to WW^*)$	2.8%	0.53%
$B(H \to ZZ^*)$	2.9%	4.2%
$B(H \to \tau^+\tau^-)$	2.9%	0.42%
$B(H \to \gamma\gamma)$	2.6%	3.0%
$B(H \to \mu^+\mu^-)$	8.2%	6.4%
$B(H \to Z\gamma)$	20%	8.5%
$B_{upper}(H \to \text{inv.})$	2.5%	0.07%



《Precision Higgs Physics at CEPC》
Chinese Physics C, 43（2019）043002

CEPC： Electroweak Measurements

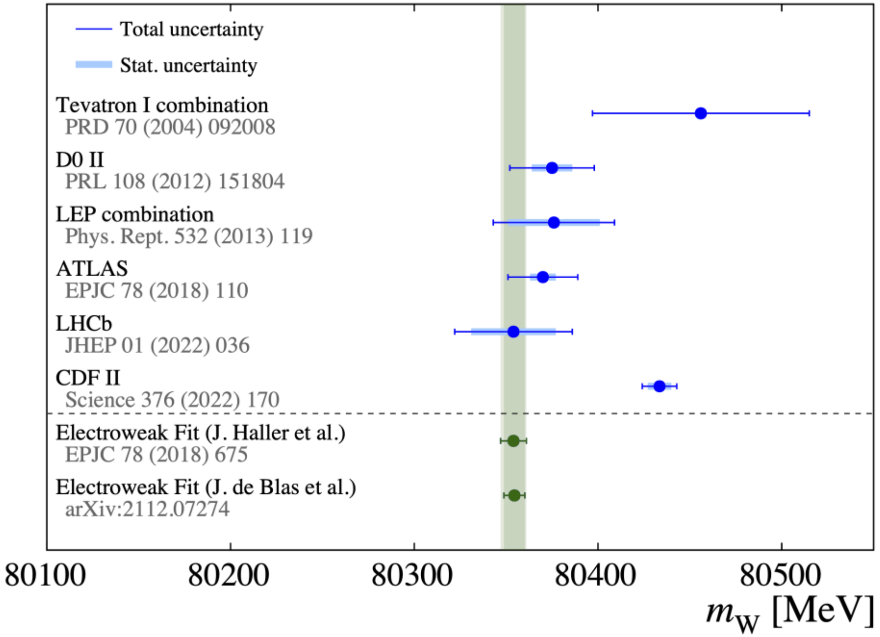
➢ **CEPC has better EW precisions than current value by 1-2 order of magnitude**

W、Z 和 top		
观测量	当前精度	CEPC 预期精度
M_W	9 MeV	0.5 MeV
Γ_W	49 MeV	2 MeV
M_{top}	760 MeV	$\mathcal{O}(10)$ MeV
M_Z	2.1 MeV	0.1 MeV
Γ_Z	2.3 MeV	0.025 MeV
R_b	3×10^{-3}	2×10^{-4}
R_c	1.7×10^{-2}	1×10^{-3}
R_μ	2×10^{-3}	1×10^{-4}
R_τ	1.7×10^{-2}	1×10^{-4}
A_μ	1.5×10^{-2}	3.5×10^{-5}
A_τ	4.3×10^{-3}	7.0×10^{-5}
A_b	2×10^{-2}	2×10^{-4}
N_ν	2.5×10^{-3}	2×10^{-4}

CDF (2022) : 80433 ± 9 MeV

ATLAS (2023) : 80360 ± 16 MeV

SM Prediction : 80354 ± 7 MeV



➢ **CEPC: expected W mass resolution < 1MeV**

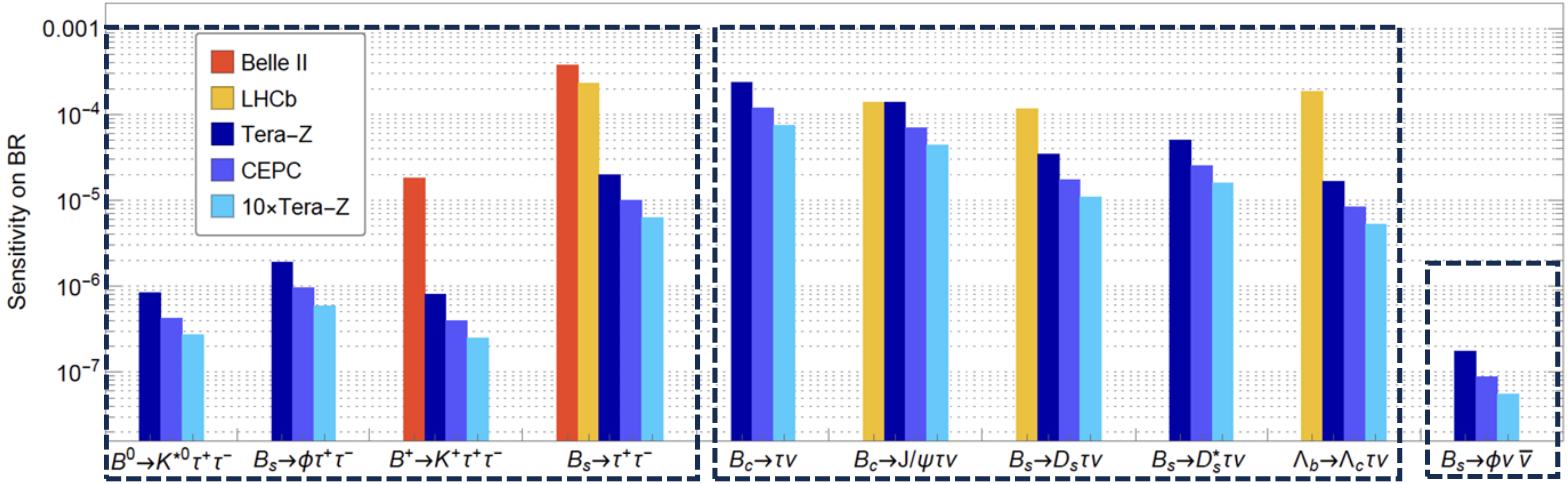
CEPC: Flavor Physics

Tera-Z → B factory

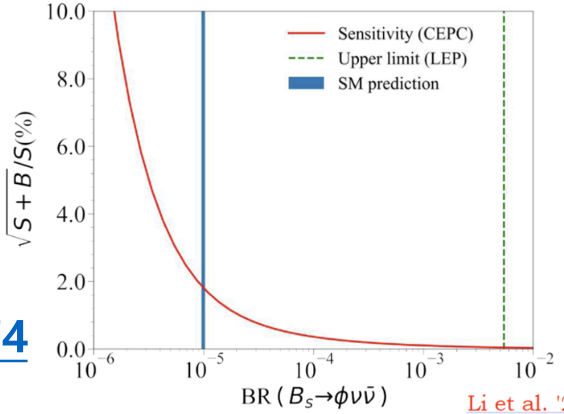
b-hadrons	Belle II (50+5 ab^{-1})	LHCb (300 fb^{-1})	Tera-Z
B^0, $\bar{B}^0$	5.4×10^{10} (50 ab^{-1} on $\Upsilon(4S)$)	3×10^{13}	1.2×10^{11}
$B^\pm$	5.7×10^{10} (50 ab^{-1} on $\Upsilon(4S)$)	3×10^{13}	1.2×10^{11}
B_s^0, $\bar{B}_s^0$	6.0×10^{8} (5 ab^{-1} on $\Upsilon(5S)$)	1×10^{13}	3.1×10^{10}
$B_c^\pm$	-	1×10^{11}	1.8×10^{8}
Λ_b^0, $\bar{\Lambda}_b^0$	-	2×10^{13}	2.5×10^{10}
$c(\bar{c})$	2.6×10^{11}	$\gtrsim 10^{14}$	2.4×10^{11}
$\tau^\pm$	9×10^{10}	-	7.4×10^{10}

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}

Lepton Flavor Violation (FLV)



BR ($B_s\to\phi\nu\nu$) precision is ~2% in SM, it can make indirect constraint on B anomaly !



Li et al. '22

Lepton Flavor Universality (B → s ττ)

Lepton Flavor Universality (B_c → τν)

2201.07374

CEPC： BSM Physics

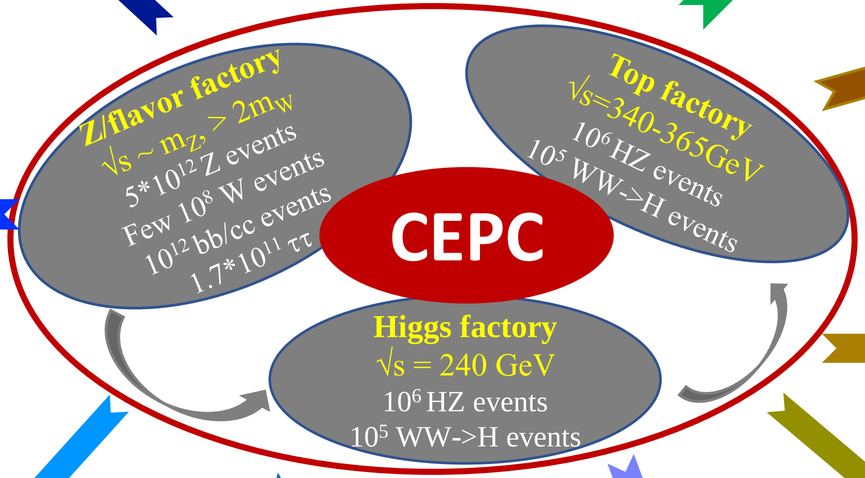
1: Exotics of Higgs, W, Z, top
- Higgs exotic decay (SUSY, LLP, DS, invisible)
- Light higgs
- Z exotic decay
- Top exotic decay

10. Indirect searches from SM precision measurements

9: Global fits
- Global fit of SUSY
- 2HDM global fit
- SMEFT global fit

8: More exotics
- Axion-like particles
- Lepton form factors
- Emergent Hadron Mass
- Exotic lepton mass
- ……

2: Dark Matter & Dark Sector
- SUSY DM
- Higgs portal DM
- Vector boson portal DM
- Fermion portal DM
- EFT
- ……



7: Neutrino
- Heavy neutrinos
- Active-sterile neutrino
- Non-standard ν interactions

3: LLP
- At CEPC and FAR detector
- H/Z decay
- SUSY LLP
- VLL, ALP, …

4: SUSY
- Light EWKinos
- Light sleptons
- Heavy selectrons
- ……

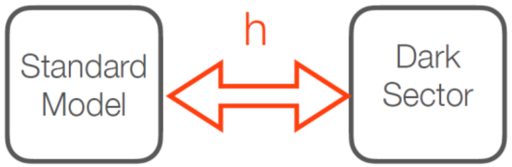
5: Flavor portal NP
- cLFV processes
- Decays of b and c hadrons
- ……

6: EWPT & GW
- Probe nature EWPT
- Higgs precision
- Higgs exotic decay

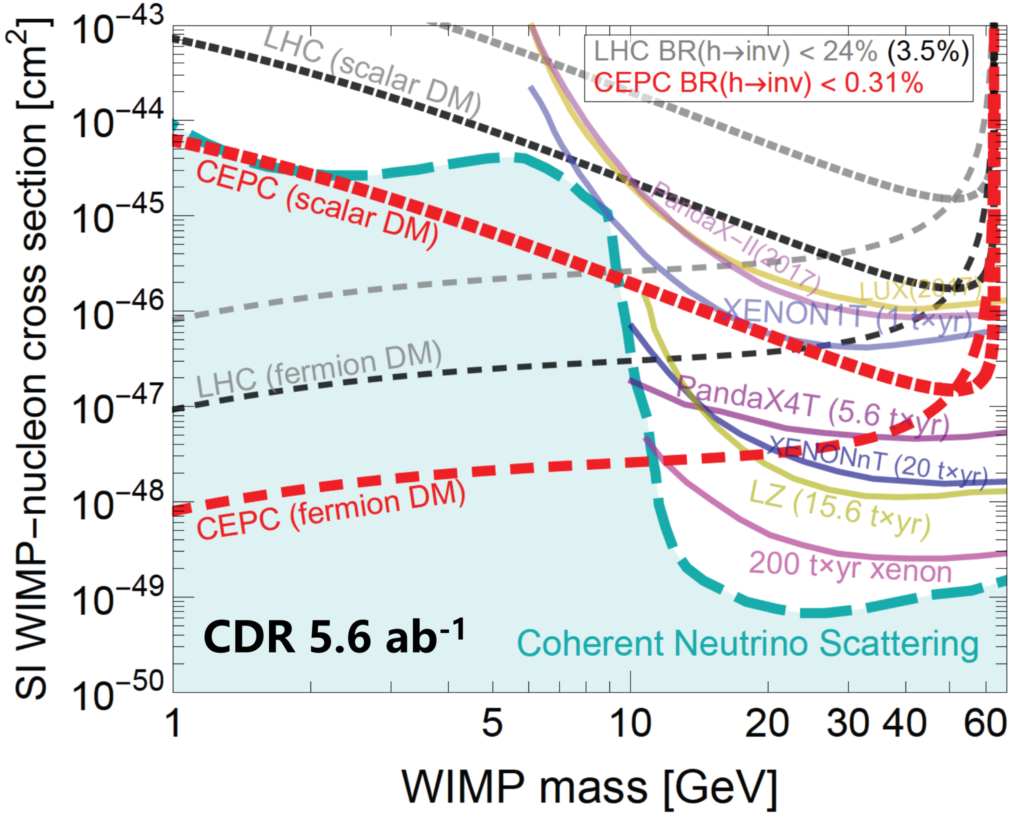
2205.08553

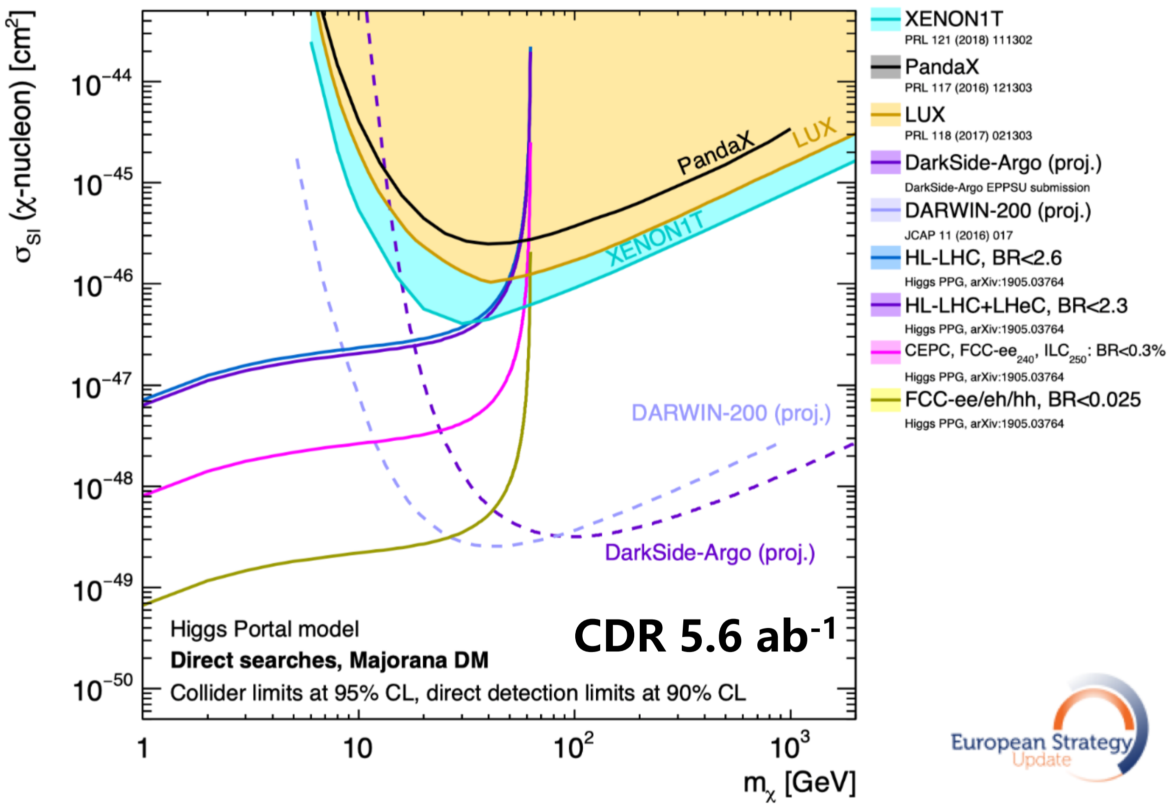
Higgs： Dark Matter Portal

Higgs-portal DM



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



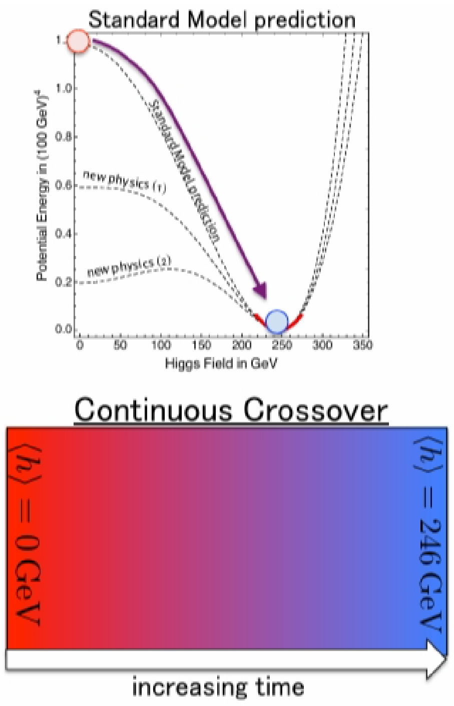


➔ **CEPC has significantly better detection sensitivity for DM than HL-LHC**

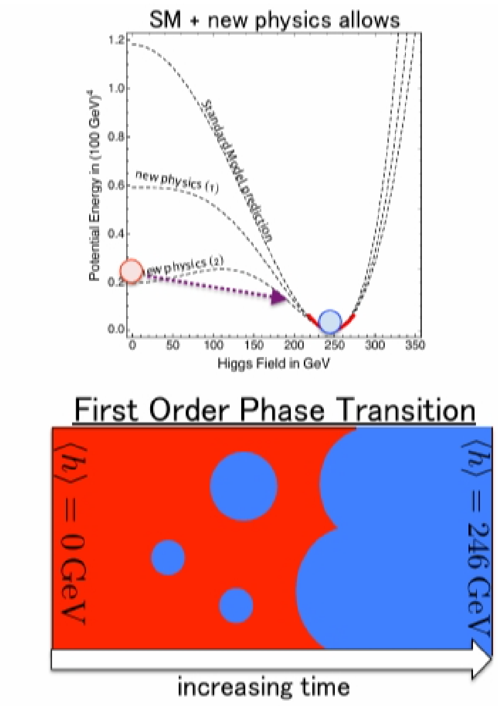
➔ **Complementary to direct DM search experiments for mass below 10 GeV**

Higgs： EW Phase Transition

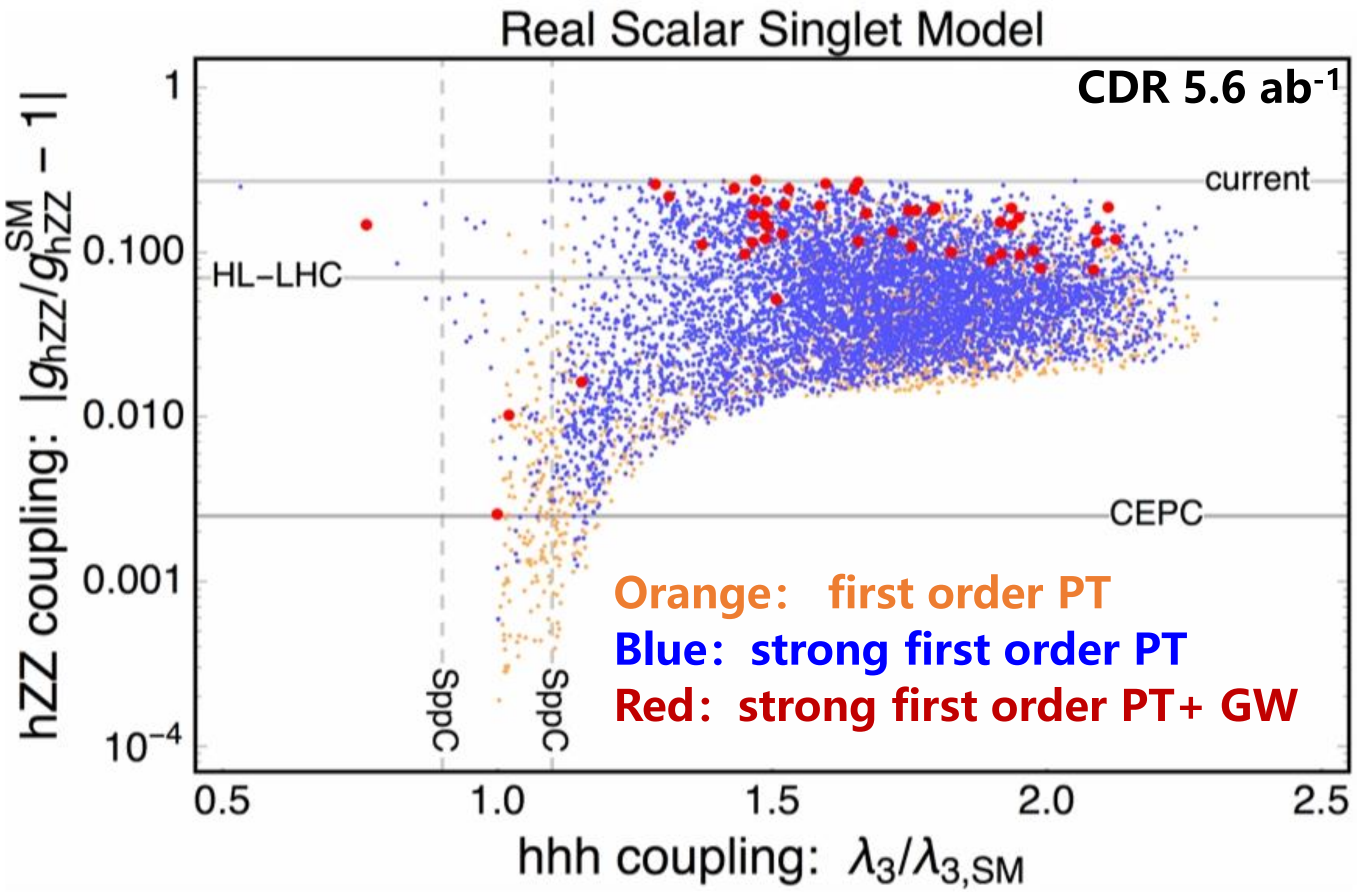
➔ **CEPC can study EWPT via hZZ coupling measurement which may help to understand the matter-antimatter asymmetry, its detection sensitivity is about one order of magnitude better than that of the HL-LHC.**



SM expects Higgs potential has smooth crossover



New Physics
Quantum tunneling
First order phase transition

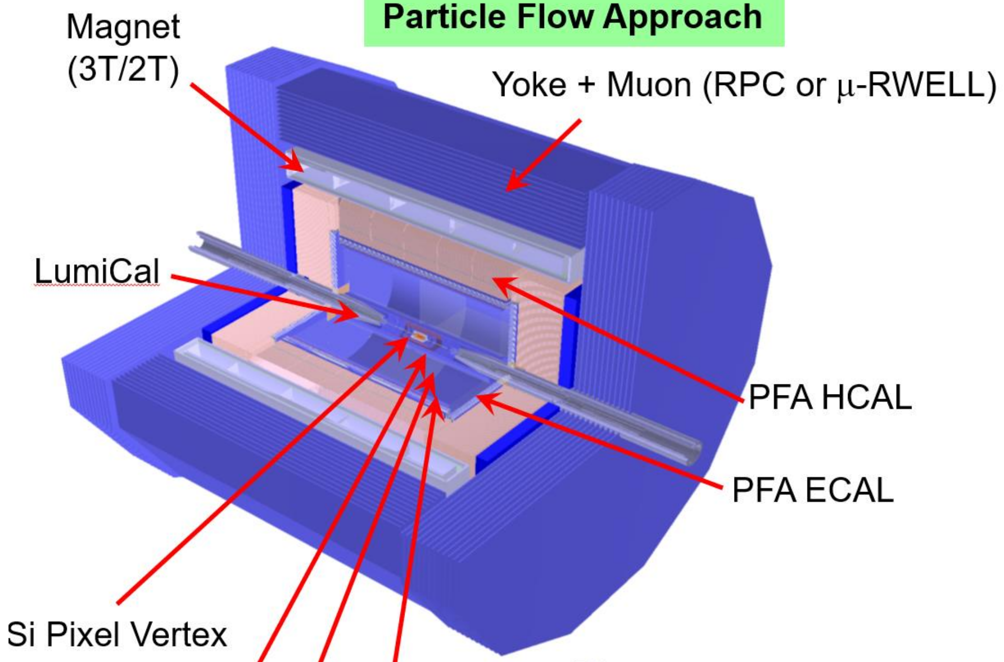


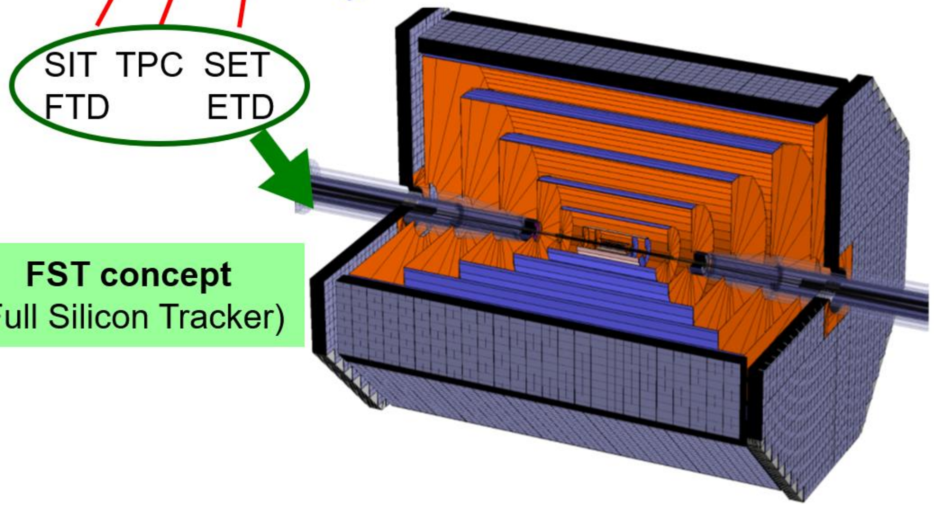
Outline

- The CEPC proposal and major milestones have been covered by Dr. Gao
- The CEPC Physics Programs
- **The CEPC Detector R&Ds** ⇦ Let me switch gears to
- Summary and Prospect

CEPC Detector Concepts ➔ New Design

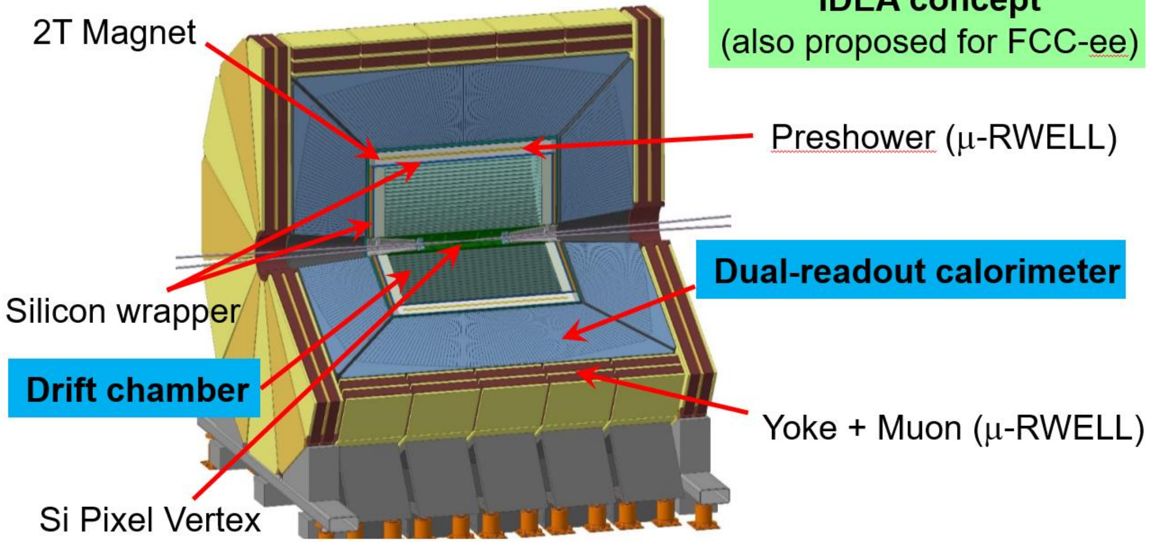
(Baseline Design)
Particle Flow Approach



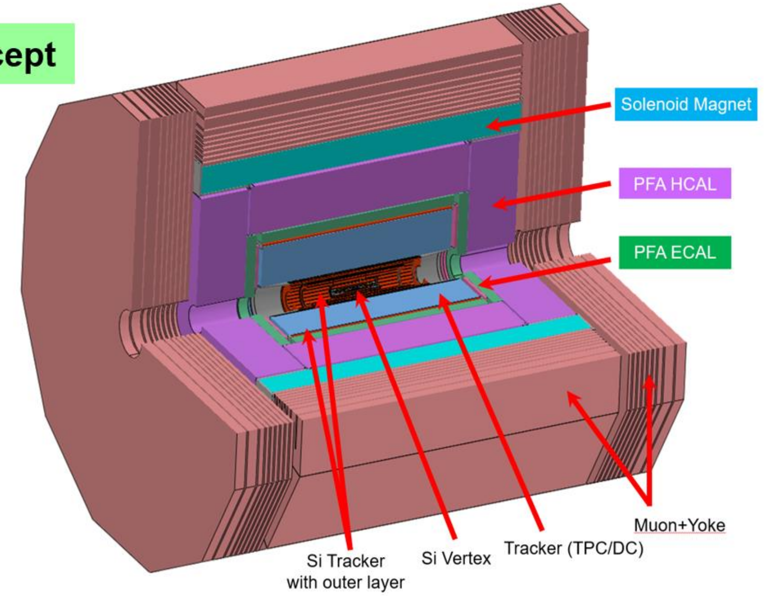


FST concept
(Full Silicon Tracker)

IDEA concept
(also proposed for FCC-ee)



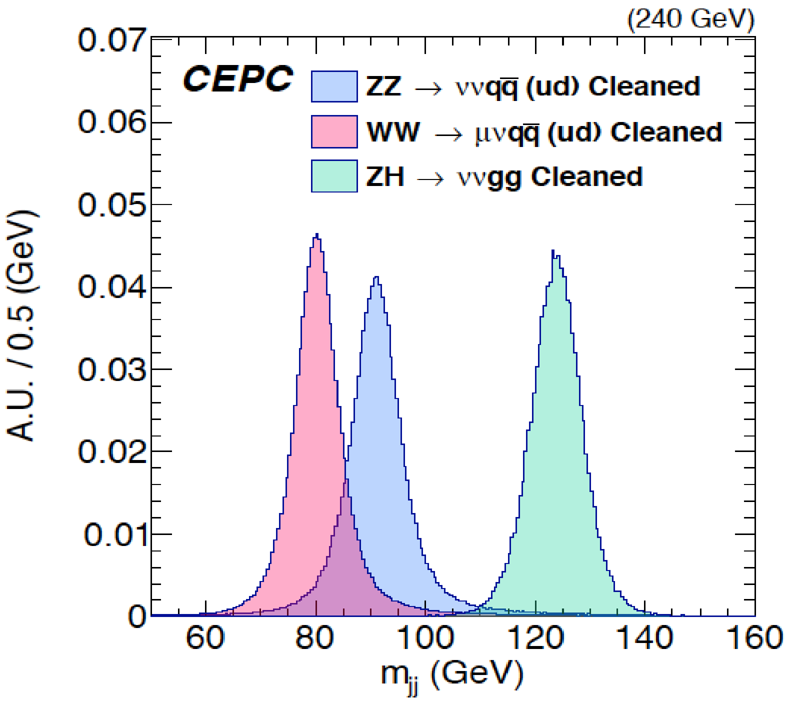
The 4th Concept

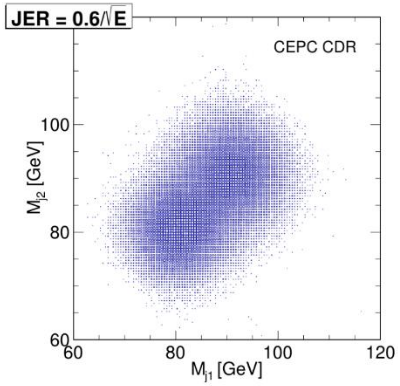


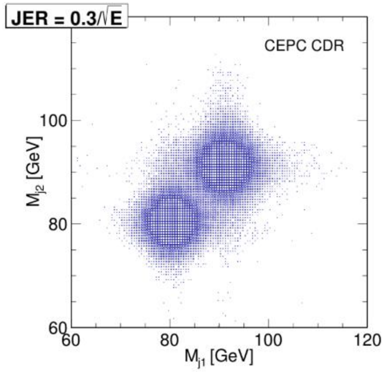
CEPC New Detector Design

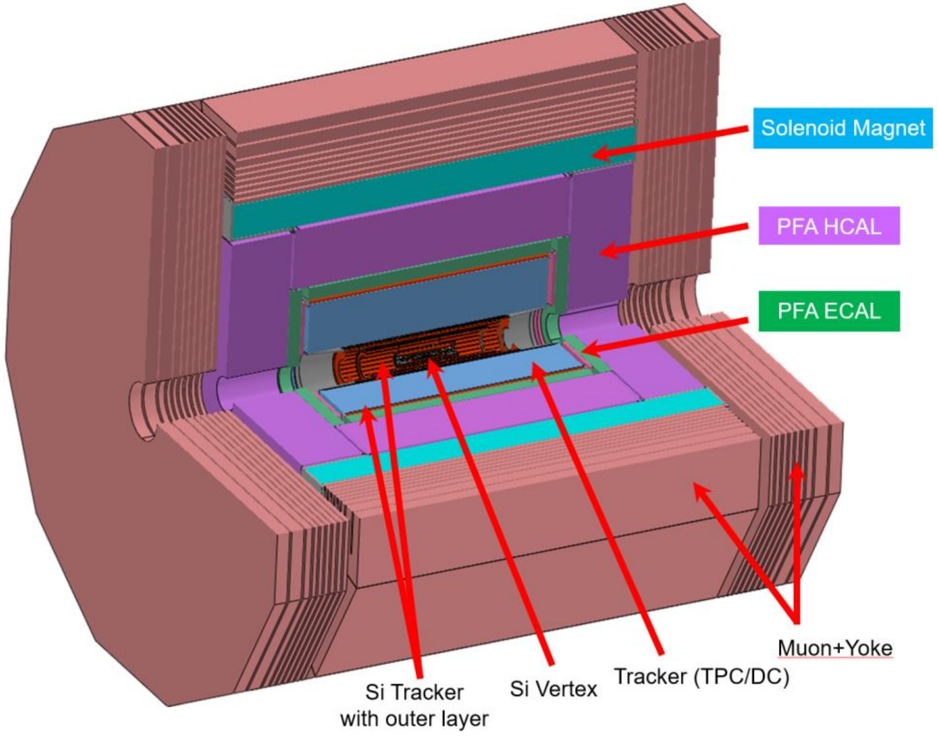
Goal: with PFA calorimeters to improve boson mass resolution (BMR) from 4% ➔ 3%。

Calorimeter	World-class	New design
PFA ECAL	～ 15-20% / √E	～ 3% / √E
PFA HCAL	～ 50-60% / √E	～ 40% / √E





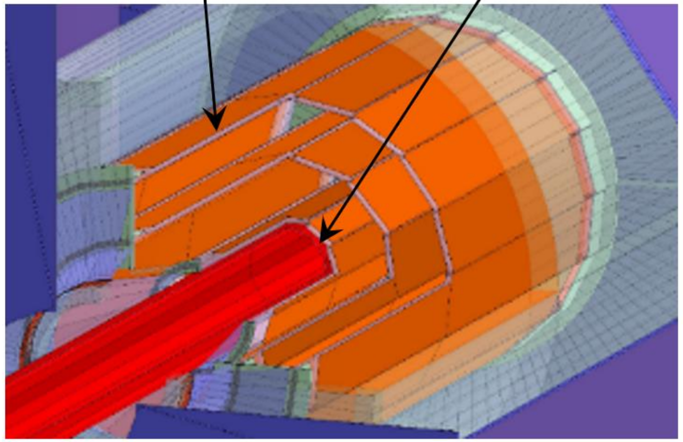




- **Silicon tracker with TPC / DC:**
  to improve track reconstruction & PID
- **PFA ECAL with crystal:**
  to improve π^0, γ energy resolution
- **PFA HCAL with scintillating glass:**
  to improve hadron energy resolution

CEPC Detector R&D: Silicon Detectors

2 layers / ladder R_{in}~16 mm



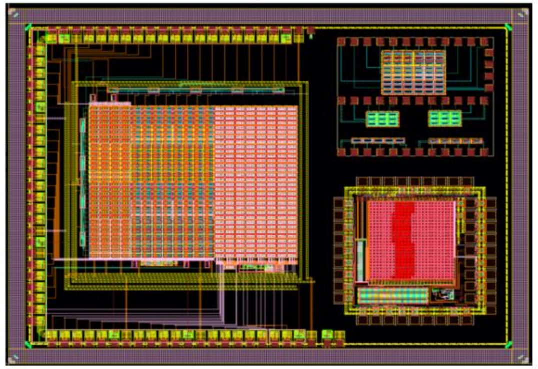
Goal: σ(IP) ~ 5 μm for high P track

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

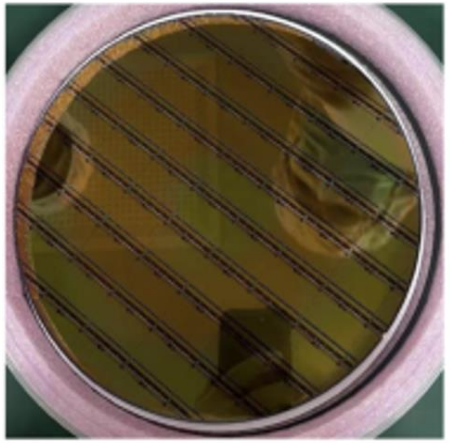
Develop **COFFEE** for a CEPC tracker using SMIC 55nm HV-CMOS process



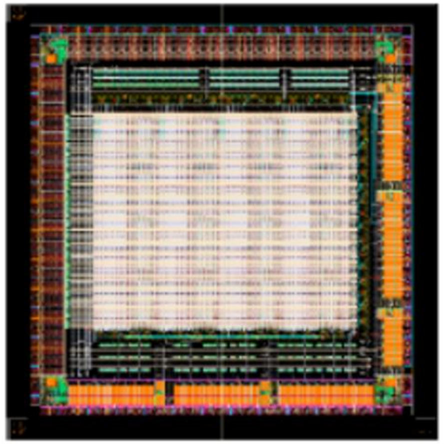
JadePix-3 Pixel size ~16×23 μm^2

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

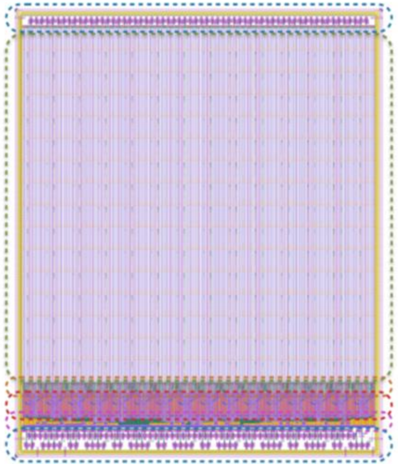
TaichuPix-3, FS 2.5x1.5 cm²
25×25 μm^2 pixel size



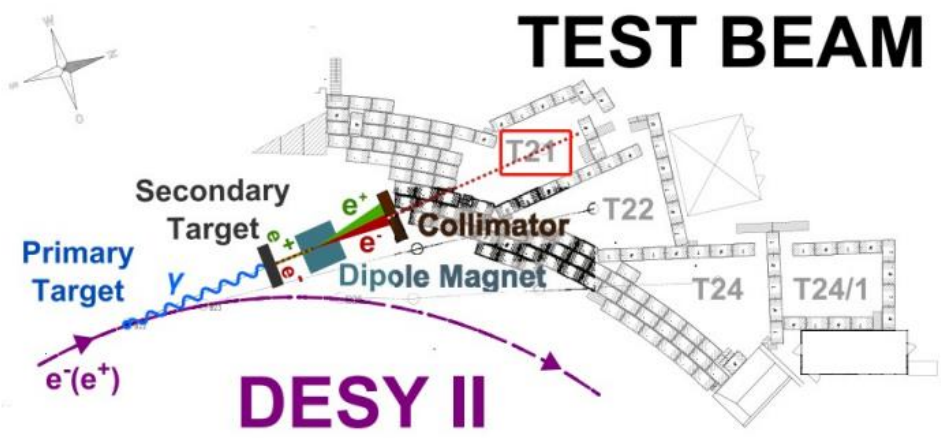
CPV4 (SOI-3D), 64×64 array
~21×17 μm^2 pixel size



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



CEPC Detector R&D: Beamtest on the Vertex Det.

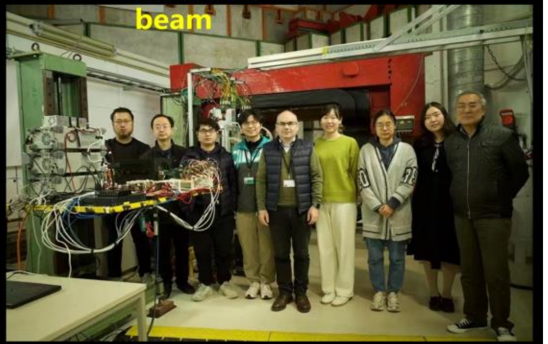


Test beam @ DESY

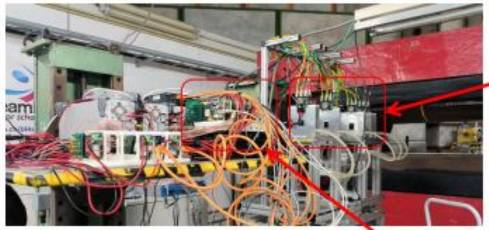
- 2nd testbeam: April 11-23 2023 DESY test beam in Germany (4-6 GeV electron)
  - Vertex detector prototype testbeam
- 1st testbeam: Dec 12-22 2022 DESY test beam in Germany (4-6 GeV electron)
  - TaichuPix Beam Telescope testbeam

2022 DESY test beam

2023 DESY test beam

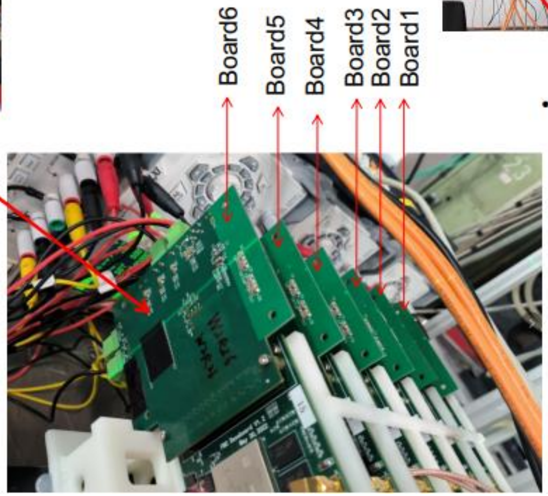


Excellent collaboration with DESY testbeam team

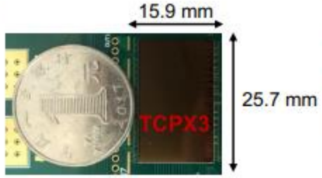


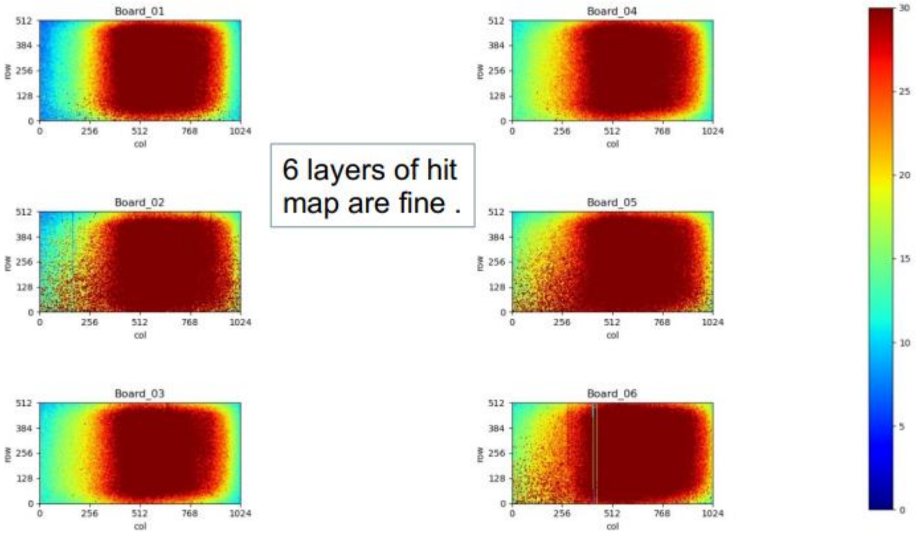
MIMOSA Telescope

Jadepix telescope

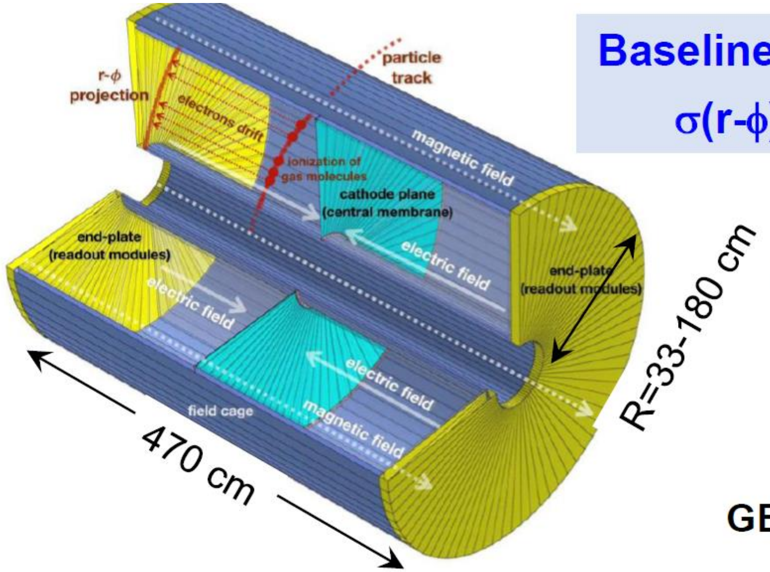


An open window in backside of PCB with a size of 12mm x 9mm

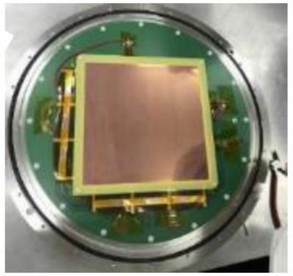




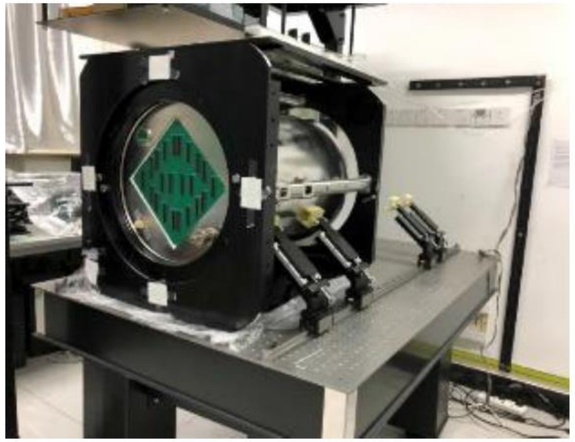
CEPC Detector R&D: TPC and DC Prototypes



Baseline main tracker
$\sigma(r\text{-}\phi)$ ~100 μm



GEM-MM cathode

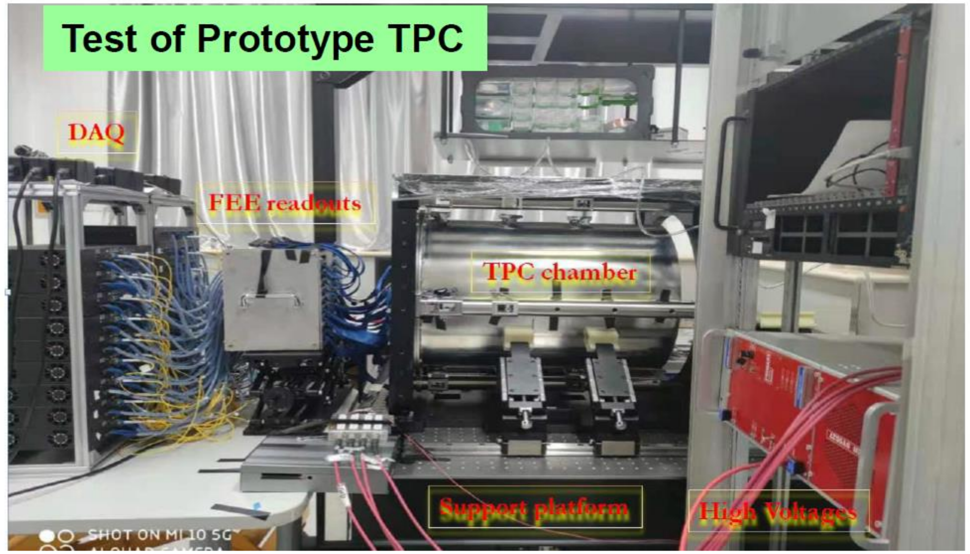


TPC Prototype + UV laser beams

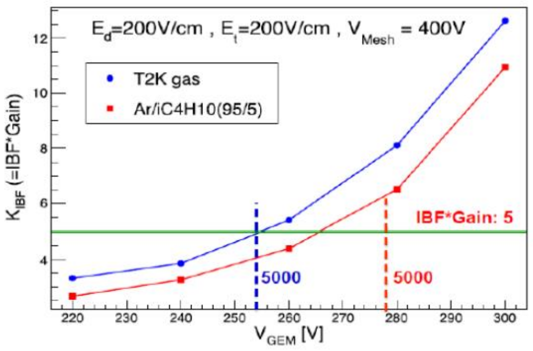
MOST 1 (IHEP+THU)

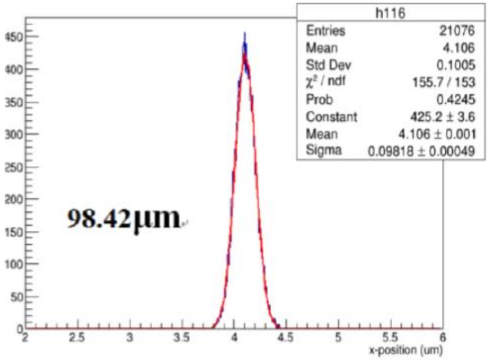
Low power FEE ASIC

Test of Prototype TPC



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

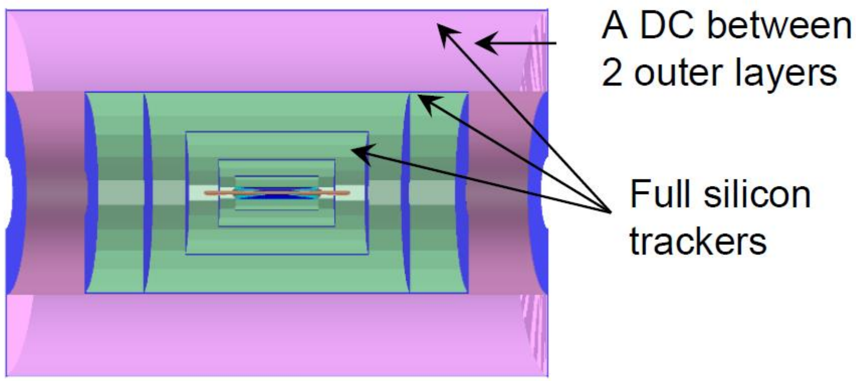


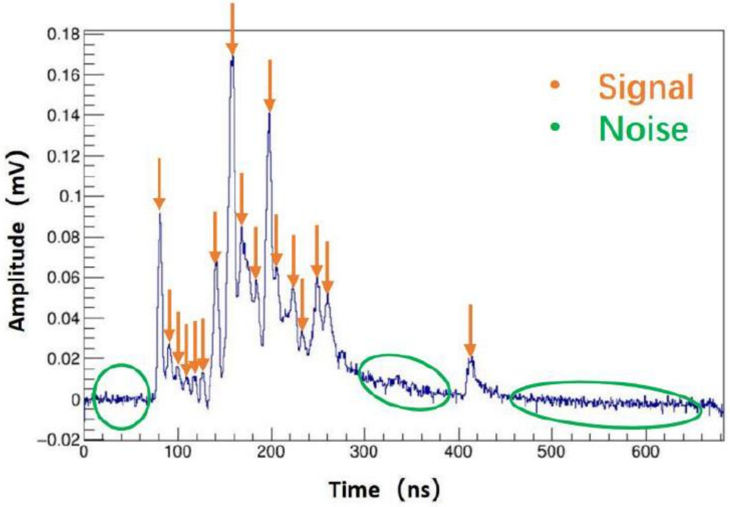


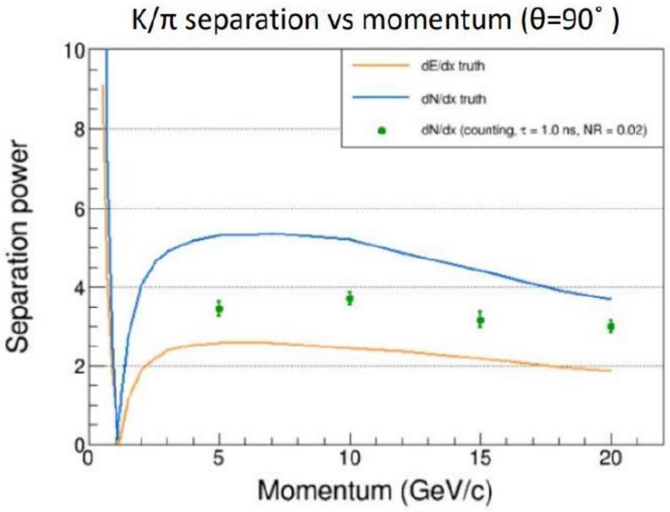
σ_x < 100 μm for drift length of 27cm

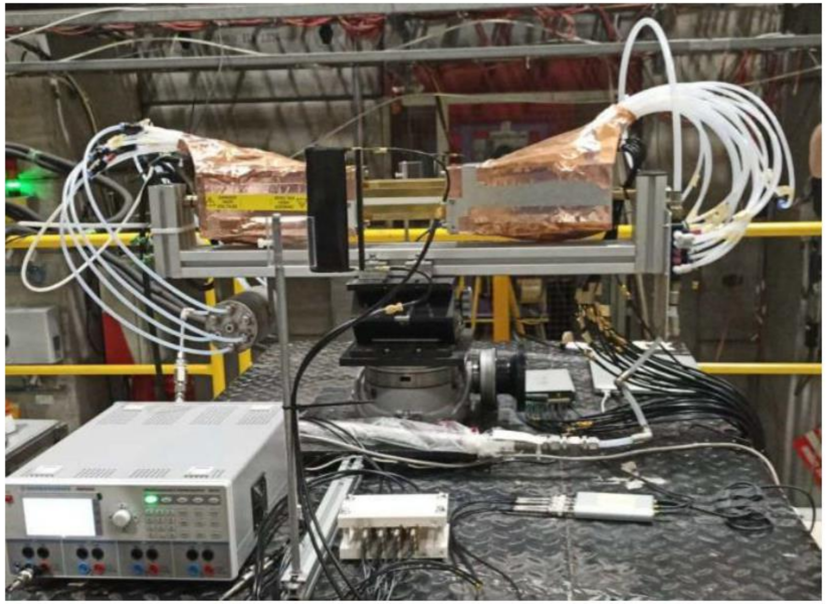
CEPC Detector R&D: TPC and DC Prototypes

- **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.









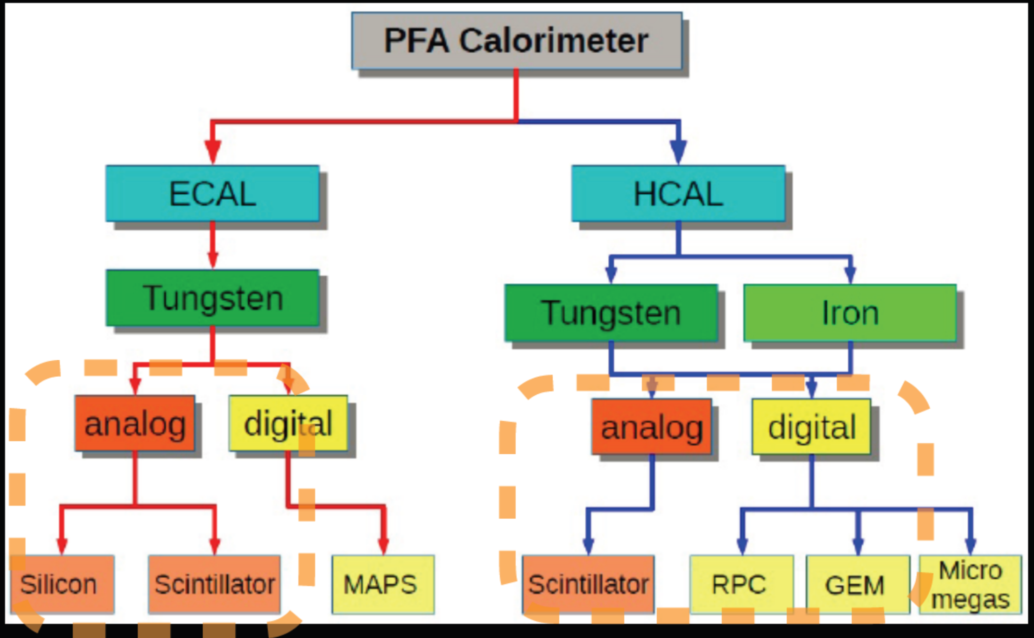
IHEP and Italian INFN groups have close collaboration and regular meetings.
IHEP joined the TB (led by INFN group) in 2021 and 2022

CEPC Detector R&Ds on PFA Calorimeters

Calorimeter options

Chinese institutions have been focusing on Particle Flow calorimeters

R&D supported by MOST, NSFC and IHEP seed funding



High Granularity	Electromagnetic	ECAL with Silicon and Tungsten (LLR, France) ECAL with Scintillator+SiPM and Tungsten (IHEP + USTC)
	Hadronic	SDHCAL with RPC and Stainless Steel (SJTU + IPNL, France) SDHCAL with ThGEM/GEM and Stainless Steel (IHEP + UCAS + USTC) HCAL with Scintillator+SiPM and Stainless Steel (IHEP + USTC + SJTU)
Newer Options	Some longitudinal granularity	Crystal Calorimeter (LYSO:Ce + PbWO) Dual readout calorimeters (INFN, Italy + Iowa, USA) — RD52

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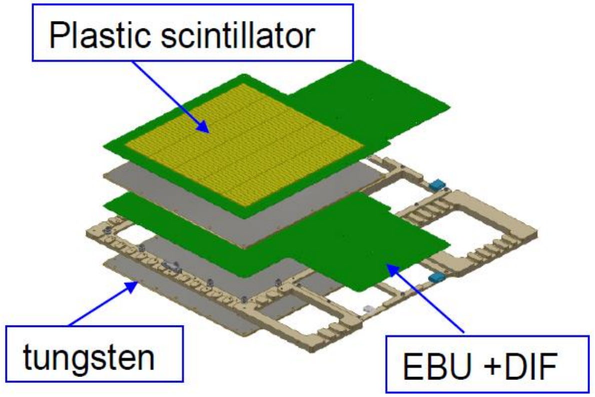
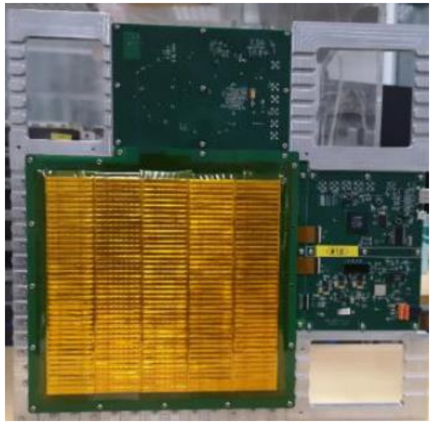
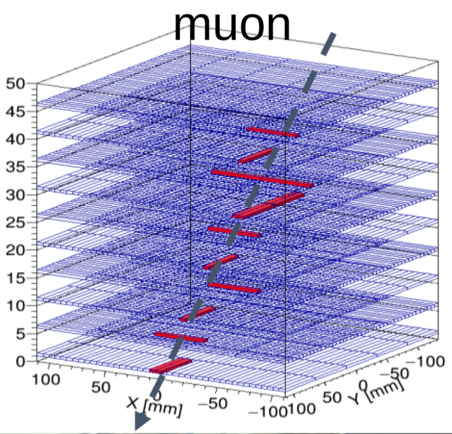
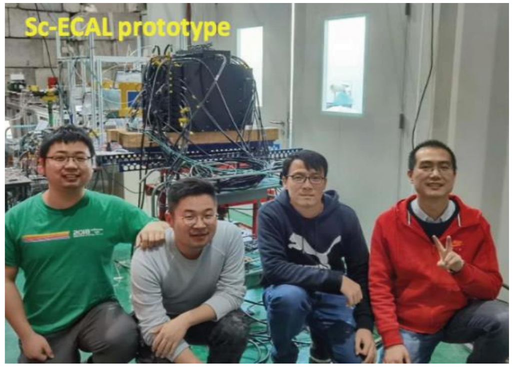
PFA Calorimeter Prototypes

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

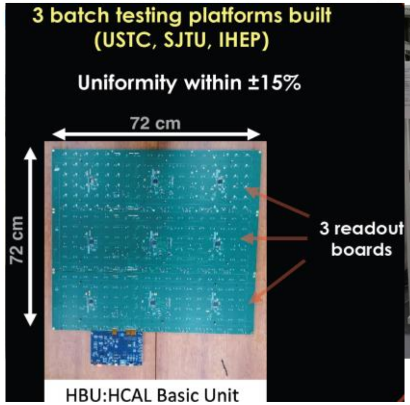


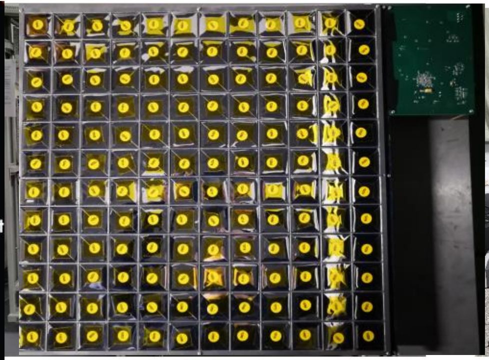






Sct + SiPM AHCAL Prototype (40-layer, 12960-ch)

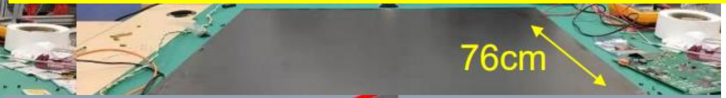


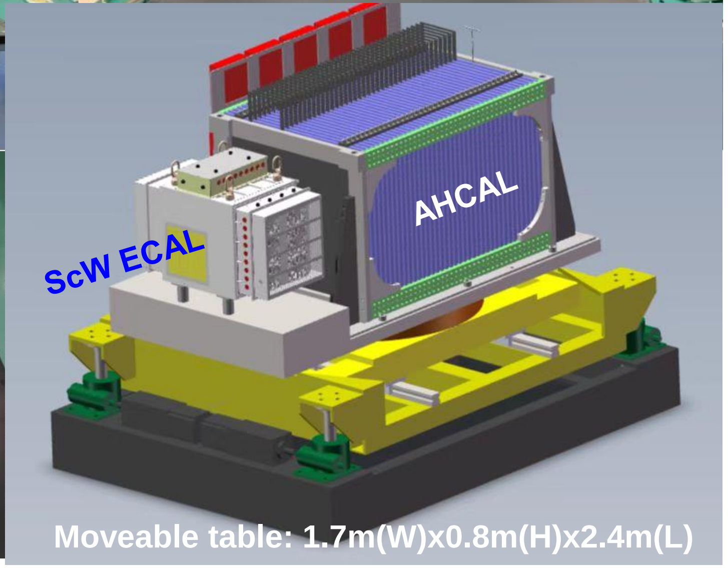


SJTU

IHEP

Combined: ScW-ECAL + AHCAL

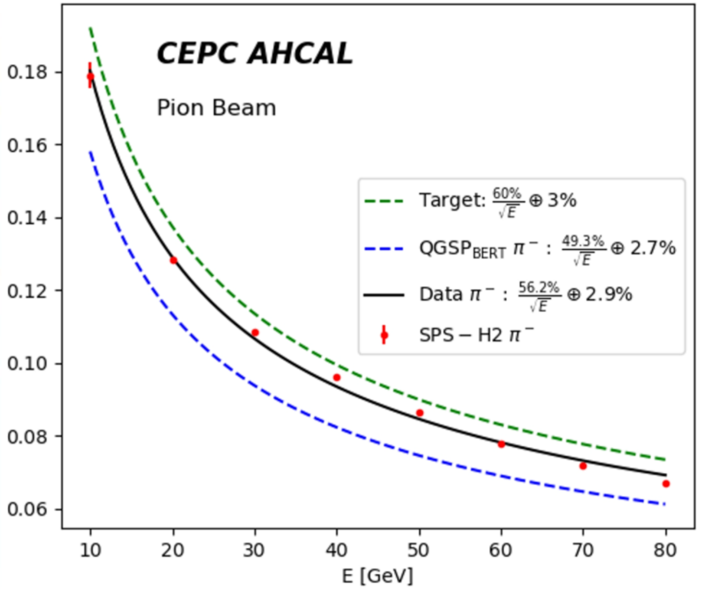


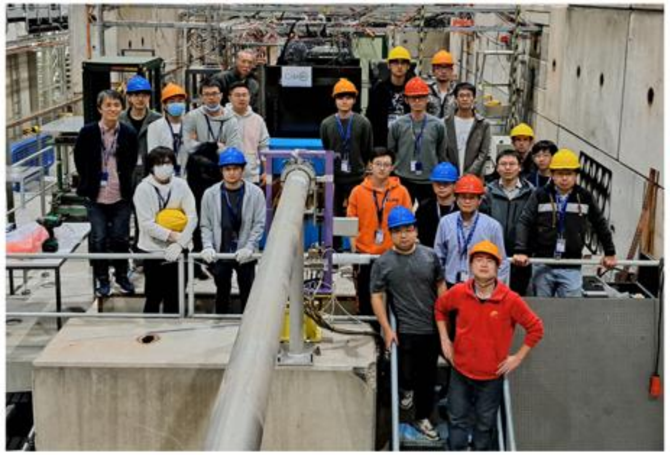


➔ Beam-test at CERN SPS for two prototypes in Oct. 2022

PFA Calorimeter Prototypes

CEPC Calorimeter Prototypes: beam test at CERN in 2022 & 2023



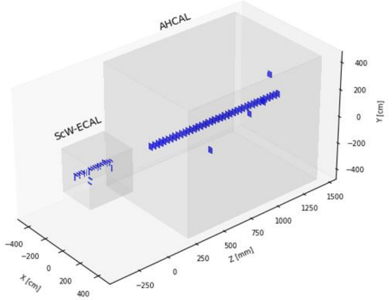


Oct 19 - Nov 2, 2022 — SPS H8 beamline

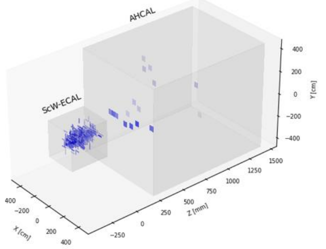
Apr 26 - May 10, 2023 — SPS H2 beamline

May 17 - 31, 2023 — PS T9 beamline

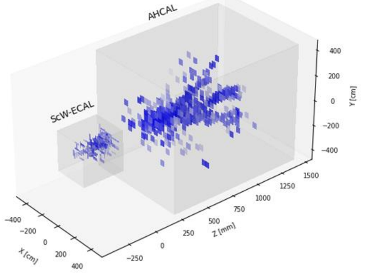
100 GeV mu-



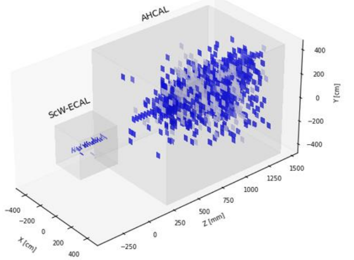
60 GeV electron (SPS)



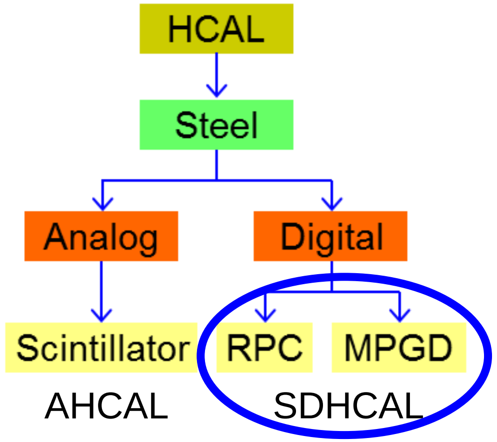
60 GeV negative pion (SPS)

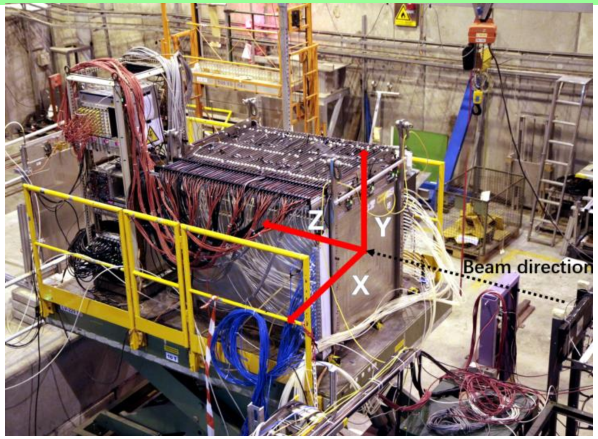


350 GeV negative pion (SPS)

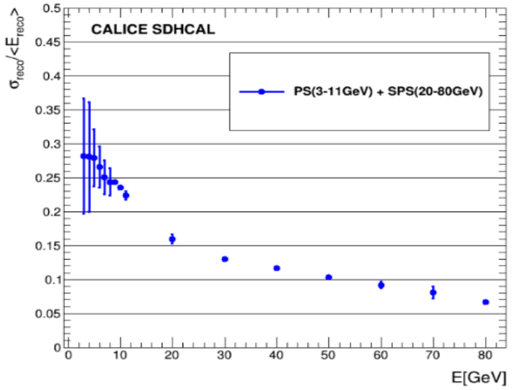


R&Ds on SDHCAL



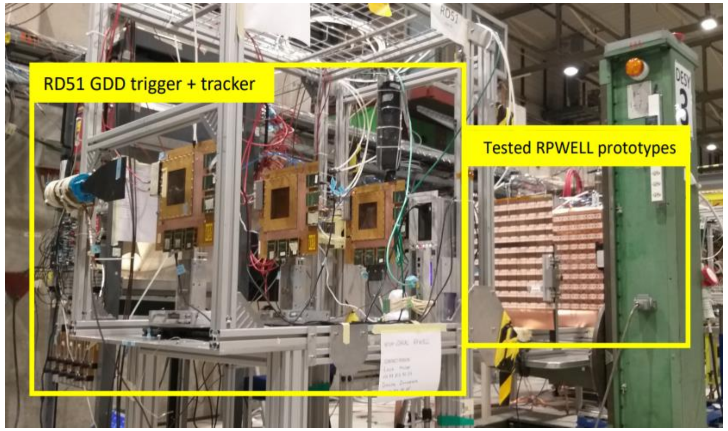


SDHCAL-GRPC (1.3 m^3, IPNL)



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%

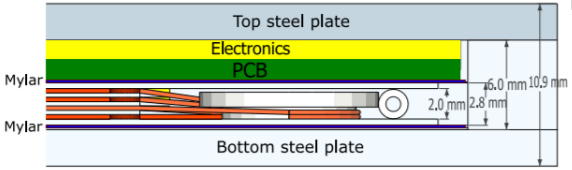
GRPC 1m x 1m (SJTU)

JINST 16, P12022 (2021)

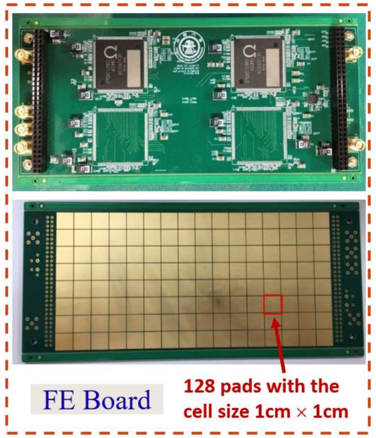
RWELL 0.5m x 1m (USTC+IHEP)

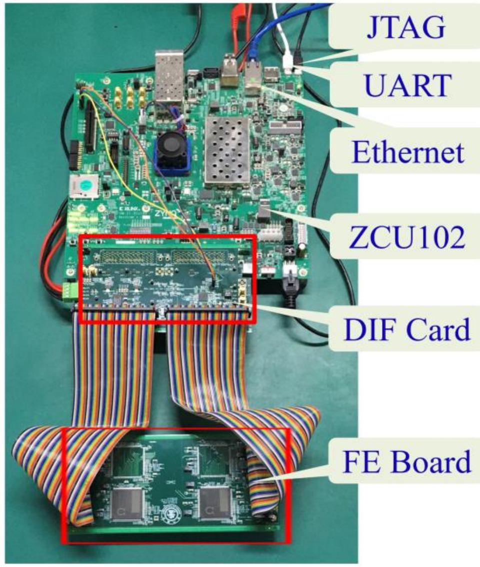
R&D Plan: 5-D SDHCAL (X, Y, Z, E, Time)

- MRPC + fast timing PETIROC ASIC (~40 ps)



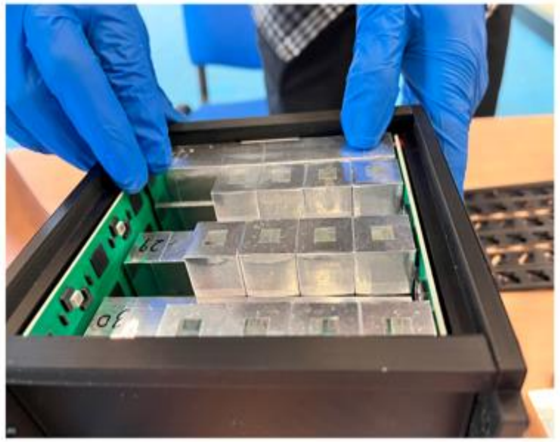
SJTU
IPNL
IJCLab
OMEGA
CIEMAT

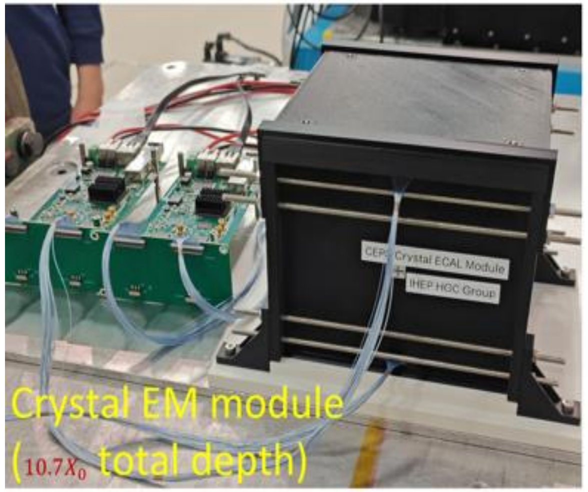


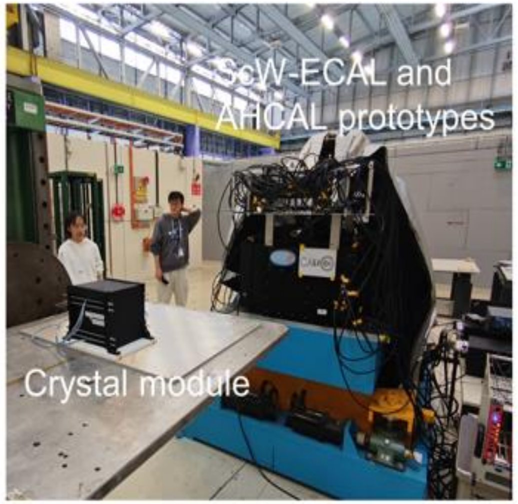


CEPC Detector R&D: Calorimeter Prototypes

Crystal Modules: beam test at CERN and DESY in 2023 & 2024

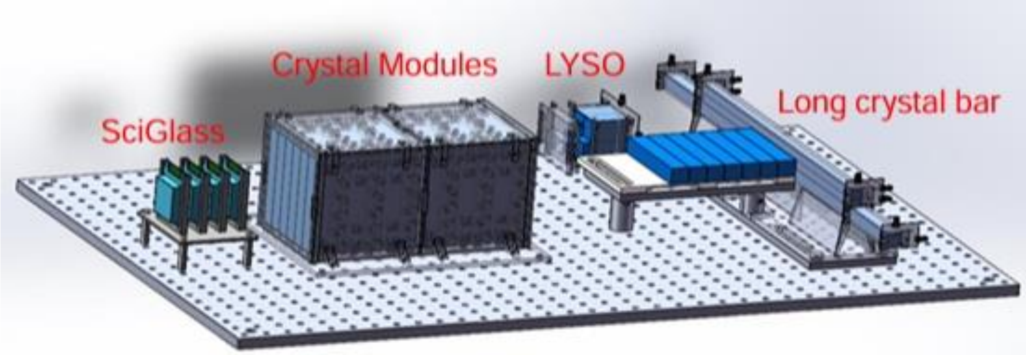


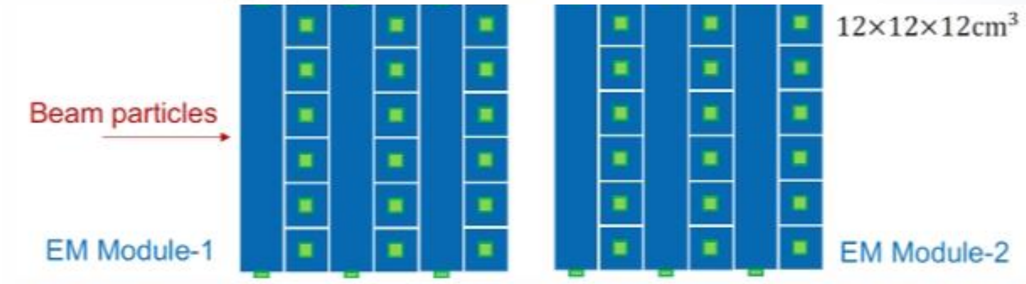


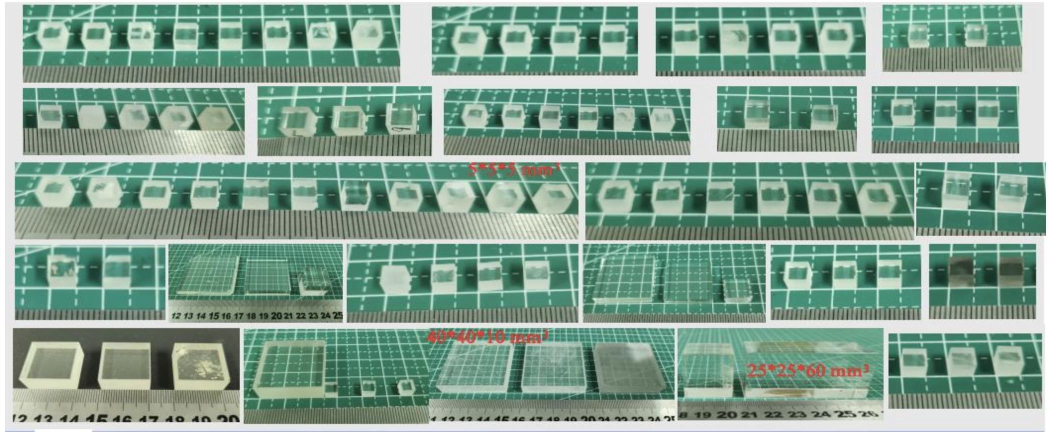


⇑ BGO Crystal

Scintillating Glass ⇒



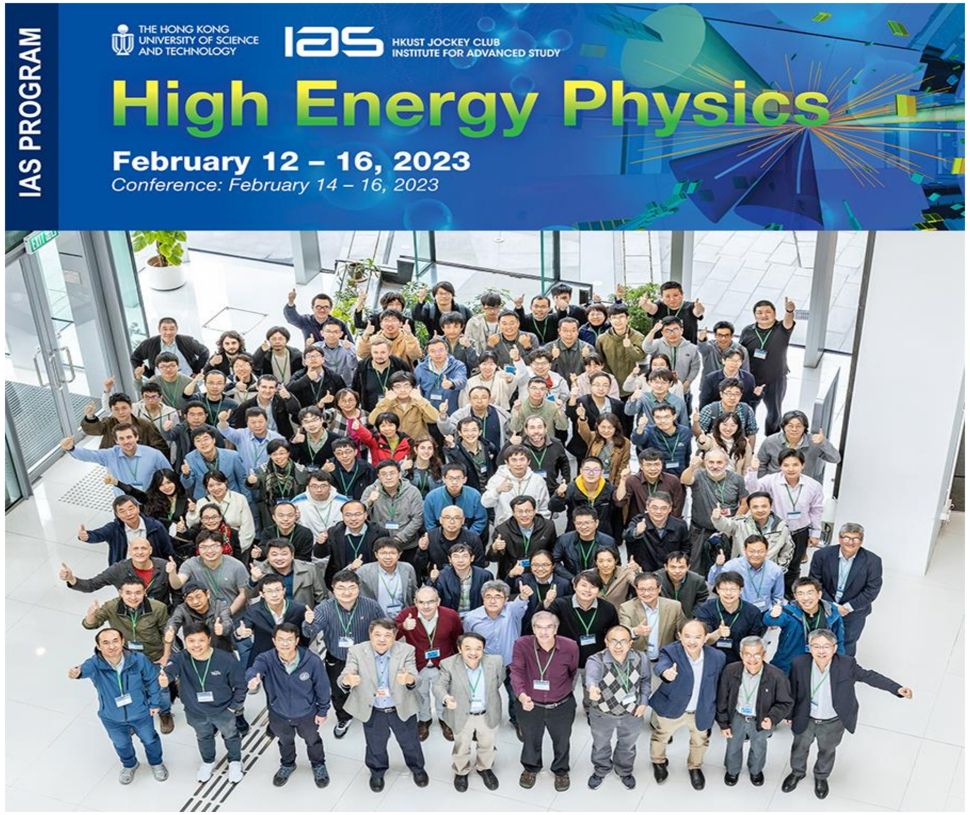




CEPC International Collaboration

CEPC attracts significant International participation

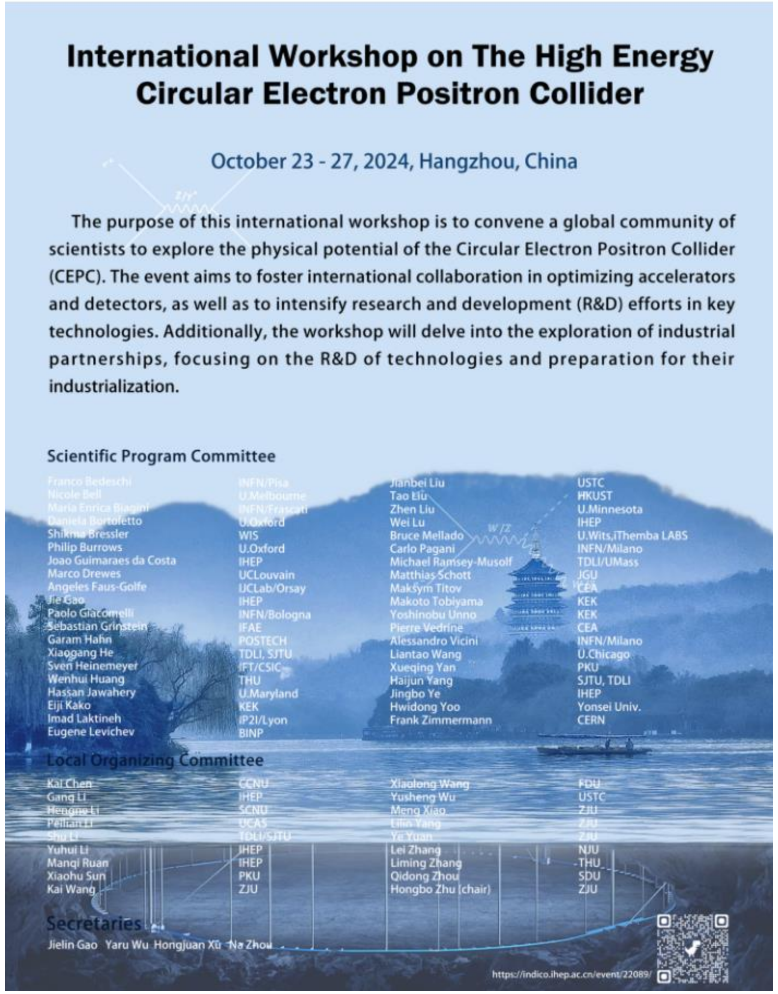
- Both CDR and TDR have significant intl. contributions
- 20+ MoUs signed with Intl. institutions and universities
- Intl. collaborative efforts: DRD & HL-LHC detector R&D
- CEPC International Workshop since 2014
- Annual working month at HKUST-IAS since 2015
- EU-US versions of CEPC Workshop since 2018



Next CEPC Workshop

CEPC International Workshop at Hangzhou, Zhejiang U., Oct. 23-27, 2024

China announced 144-hour visa-free transit policy for 54 selected countries



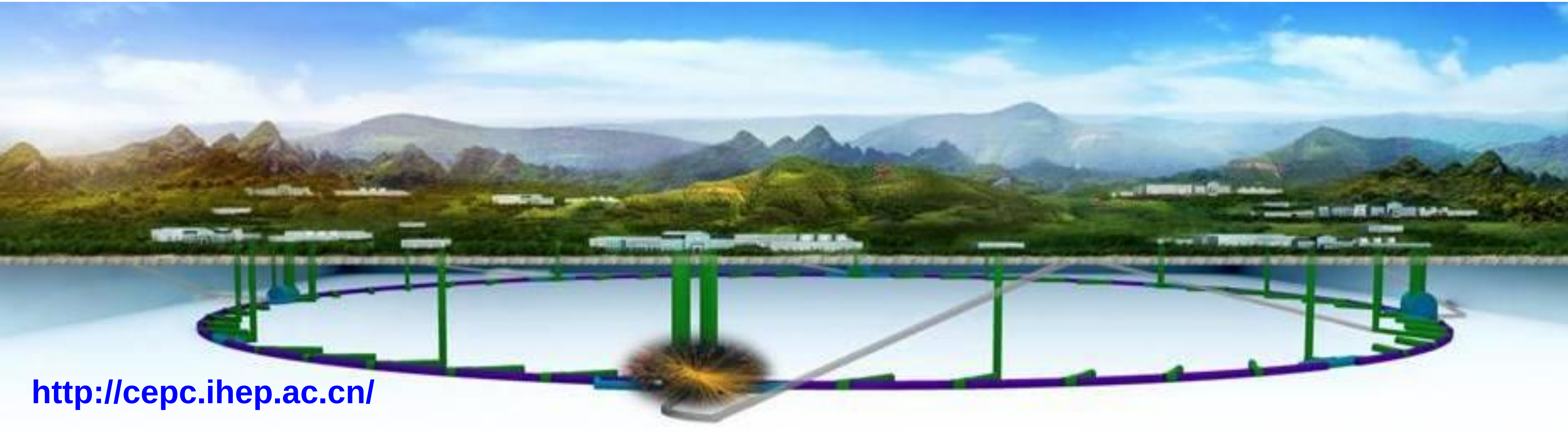
Summary

- **CEPC addresses many most pressing and critical science problems in particle physics.**
- **Detector R&Ds are very active and the efforts lead to the Reference detector TDR, which is to be completed by the mid-2025 for the proposal of China's 15th 5-year plan.**
- **Contributions from international colleagues for both accelerator EDR and reference detector TDR are warmly welcome and highly appreciated.**
- **CEPC schedule will follow the 15th 5-year plan, call for international collaborations and proposals once CEPC is approved.**
- **CEPC will offer the worldwide HEP community an early Higgs factory.**

Acknowledgement

Thanks to CEPC team for enormous efforts and achievements
Special thanks to CEPC IAC, IARC and TDR review committee

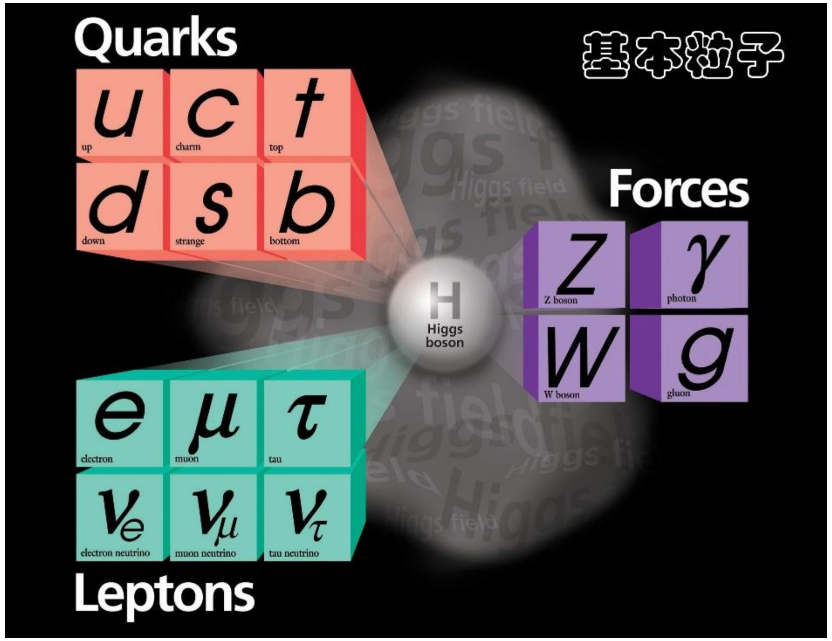
My special gratitude to Prof. Haijun Yang from Tsung-Dao Lee Institute for allowing me to use many of his slides.

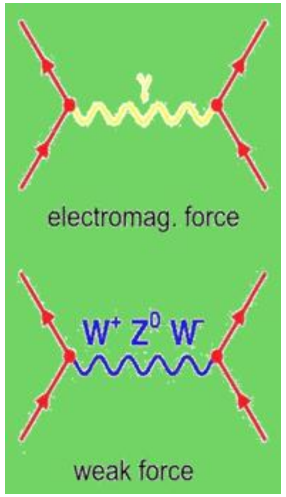


http://cepc.ihep.ac.cn/

Backup Slides

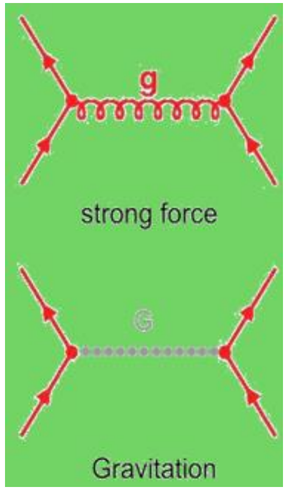
Higgs boson: a new force carrier





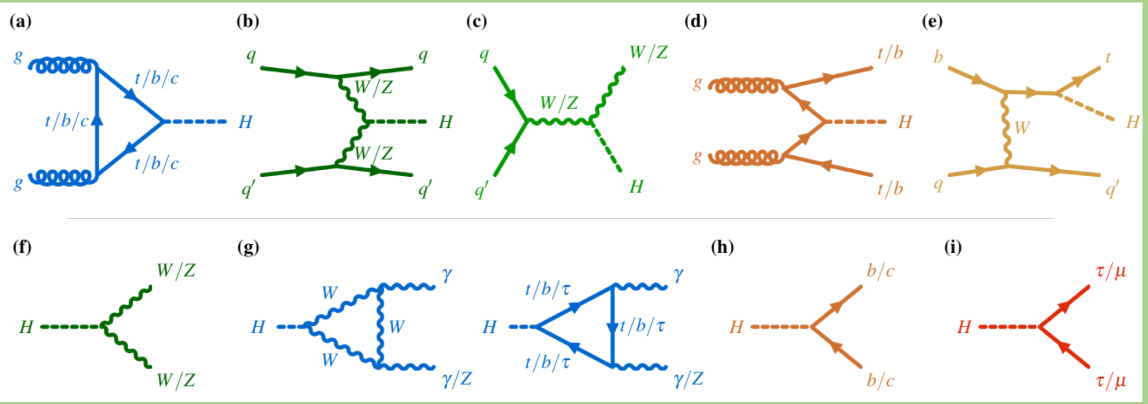
EM force:
Photon spin=1

Weak force:
W/Z spin=1



Strong force:
Gluon spin=1

Gravity:
Graviton spin=2

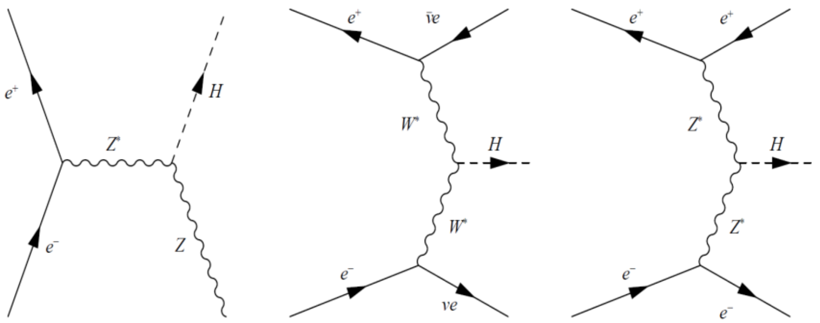


Higgs boson:

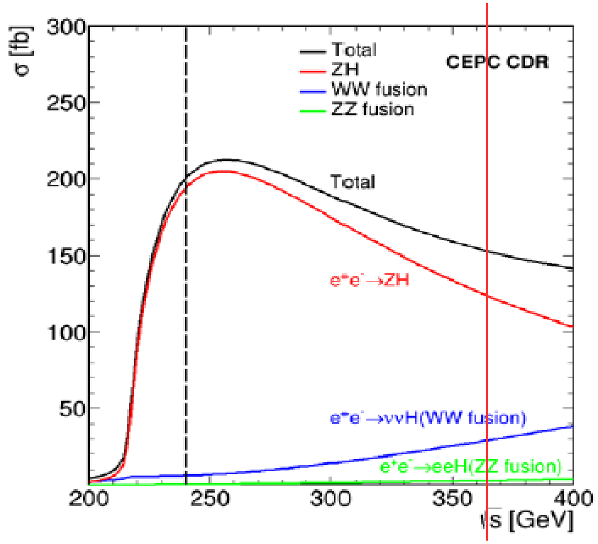
- ➢ Explains mass origin
- ➢ Only SM particle with spin 0
- ➢ A new force carrier

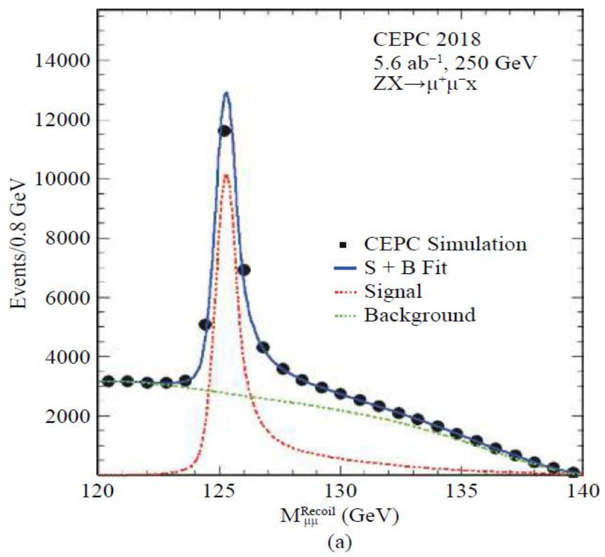
Physics Programs (in CDR)

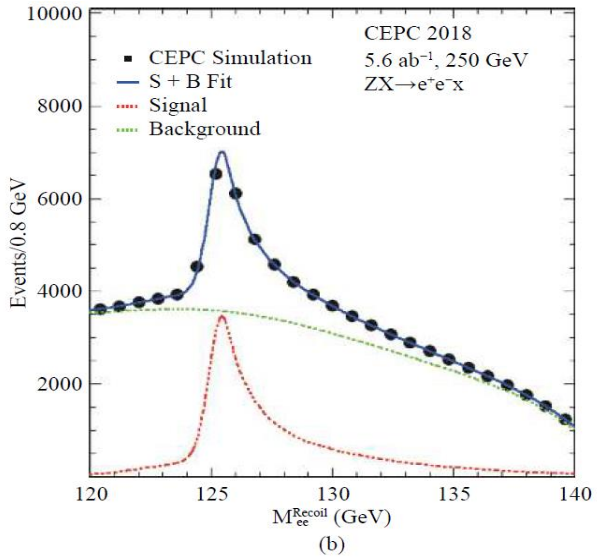
e+e- annihilations at the CEPC

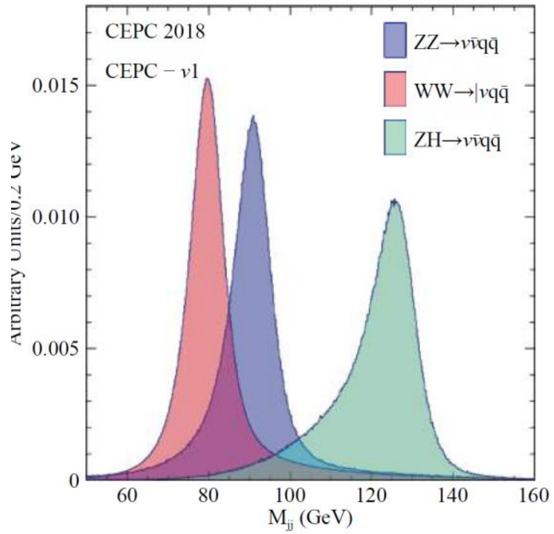


- Will perform detailed studies of various physics processes
- Higgs bosons will be detected via recoil mass of the reconstructed Z, allowing for model independent & full investigation of the Higgs and any new physics that Higgs may reveal
- Jets and events with missing neutrinos will be well reconstructed and identified









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❖ O(100) Journal / arXiv papers

Physics Programs (thrgh workshops + white papers)

Physics similar to FCC-ee, ILC, CLIC

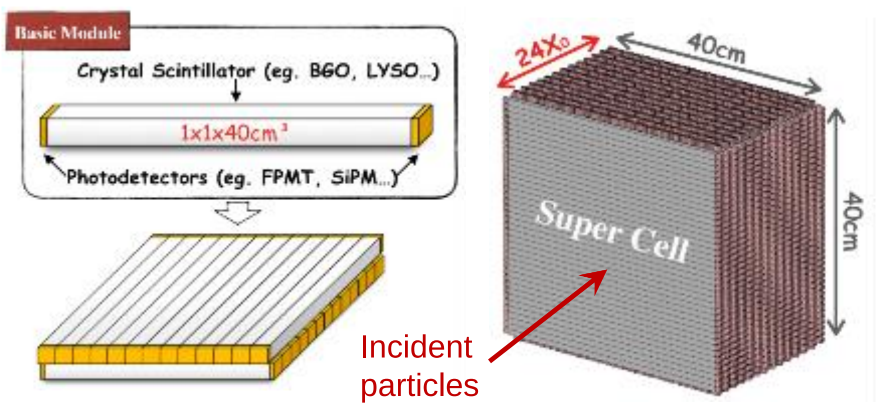
- 2019.3 **Higgs** White Paper published *(CPC V43, No. 4 (2019) 043002)*
- 2019.7 Workshop@PKU: **EW, Flavor, QCD** working groups formed
- 2020.1 Workshop@HKUST-IAS: Review progress, EW draft ready
- 2021.4 Workshop@Yangzhou: **BSM** working group formed
- **2022.5 Workshop of CEPC physics, software and detector**
- **2022 Input for Snowmass study** **arXiv:2205.08553**

CEPC Operation mode		ZH	Z	W^+W^-	ttbar
$\sqrt{s}$ [GeV]		~ 240	~ 91.2	~ 160	~ 360
Run time [years]		7	2	1	-
CDR (30MW)	L / IP [$\times10^{34}$ cm^{-2}s^{-1}]	3	32	10	-
	$\int L\,dt$ [ab^{-1}, 2 IPs]	5.6	16	2.6	-
	Event yields [2 IPs]	1×10^6	7×10^{11}	2×10^7	-
Run time [years]		10	2	1	5
TDR (50MW) (latest)	L / IP [$\times10^{34}$ cm^{-2}s^{-1}]	8.3	191.7	26.6	0.8
	$\int L\,dt$ [ab^{-1}, 2 IPs]	20	96	7	1
	Event yields [2 IPs]	4×10^6	4×10^{12}	5×10^7	5×10^5

Peking U. (2019)

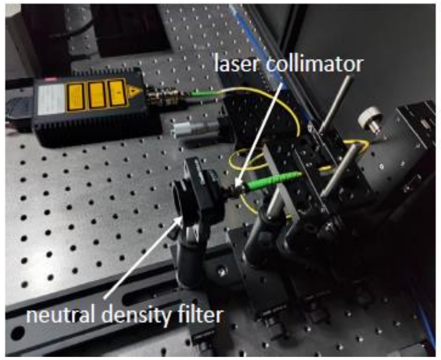
Yangzhou (2021)

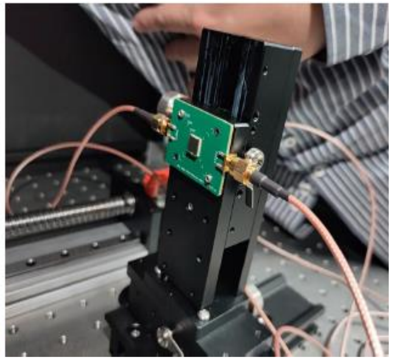
R&Ds on High Granularity Crystal ECAL



Goal

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





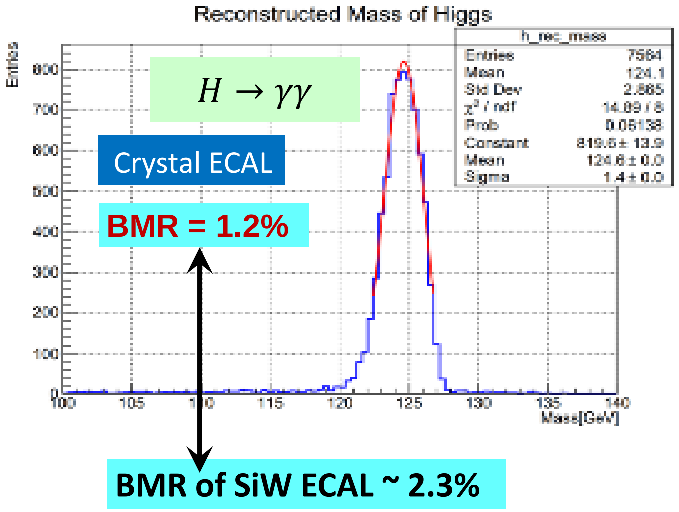
Bench Test

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

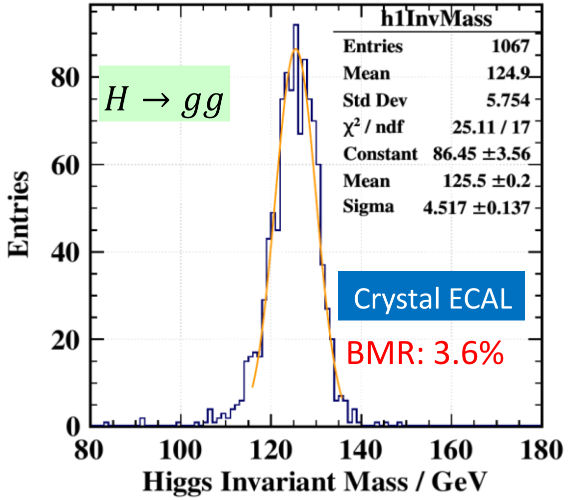
Full Simulation Studies

+ Optimizing PFA for crystals

Performance with photons

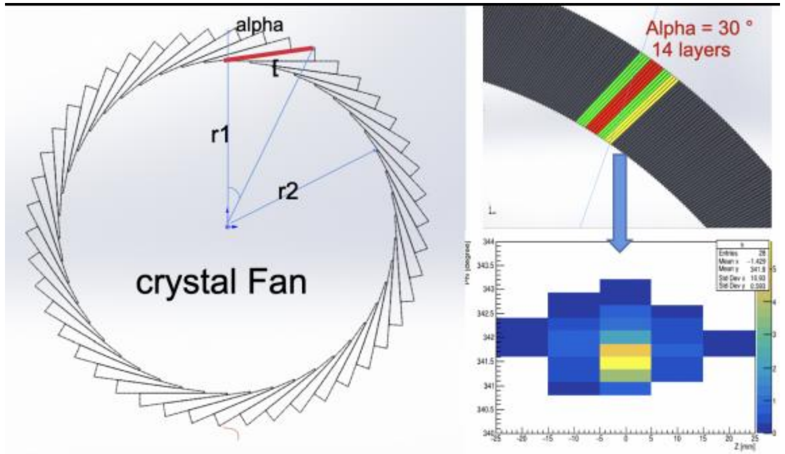


Performance with jets



Crystal Fan Design

Fine segmentation in Z, ϕ, r



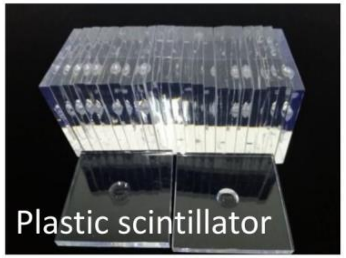
Dual readout crystal calorimeter also being considered by USA and Italian colleagues

R&Ds on New HCAL with Scintillating Glass Tiles

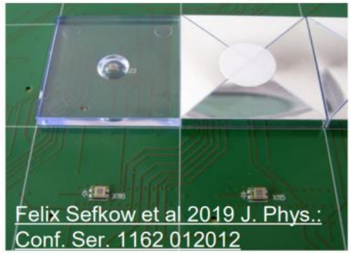
Goal
- **Better hadronic energy resolution**
- **To further improve BMR**

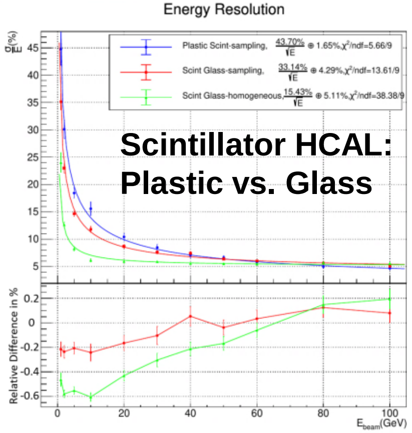
Full simulation studies

Tiles for AHCAL (30x30x3mm)

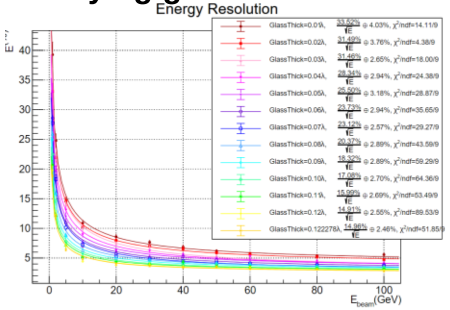


'SiPM-on-Tile" design for HCAL

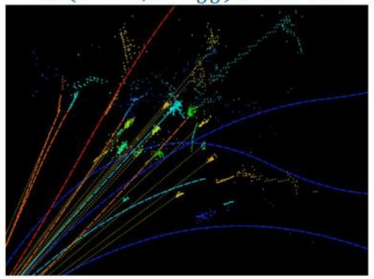




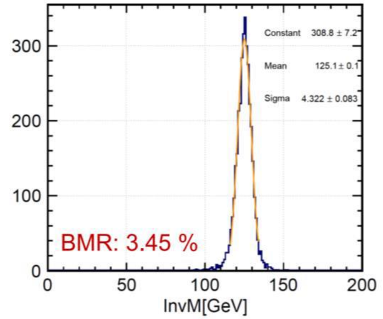
Varying glass thickness



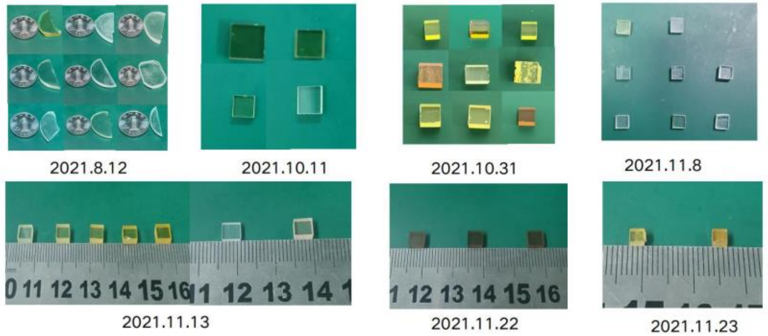
$ZH(Z \to \nu\nu, H \to gg)$ at 240 GeV

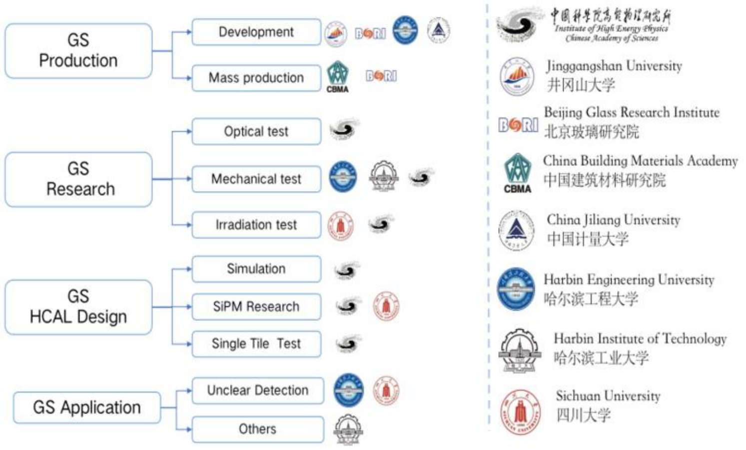


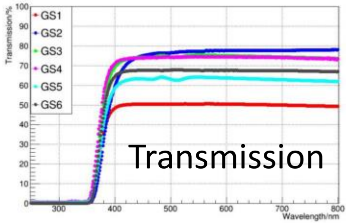
Performance study with jets

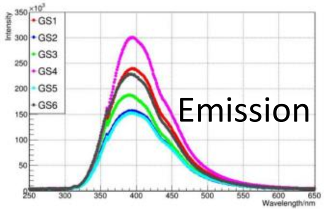


Scintillating Glass R&D

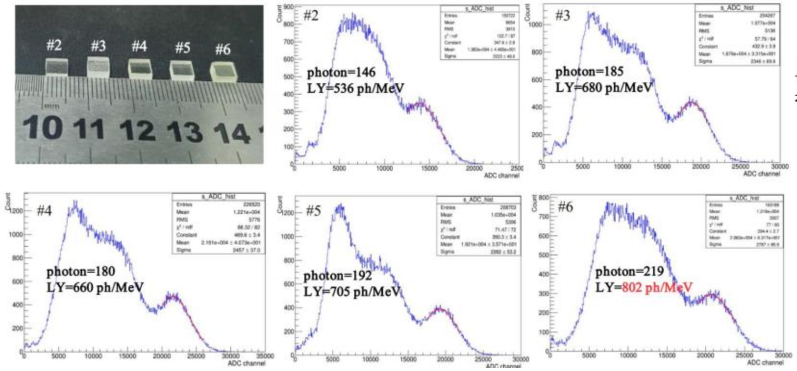


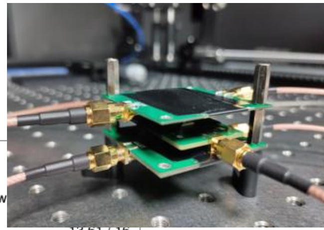


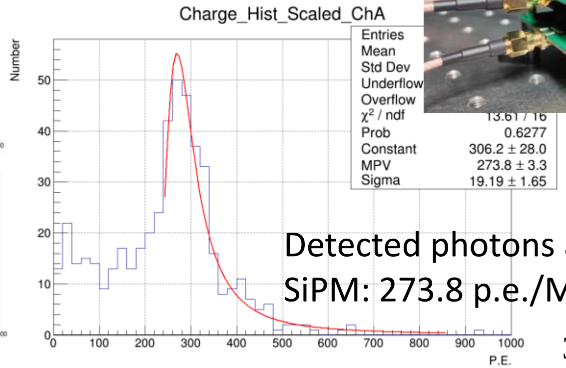




Testing Scintillating Glass Samples







Detected photons at SiPM: 273.8 p.e./MIP