The CEPC R&D

Jianchun Wang

(*For the CEPC physics and detector working group*)

The 6th China LHCP Workshop

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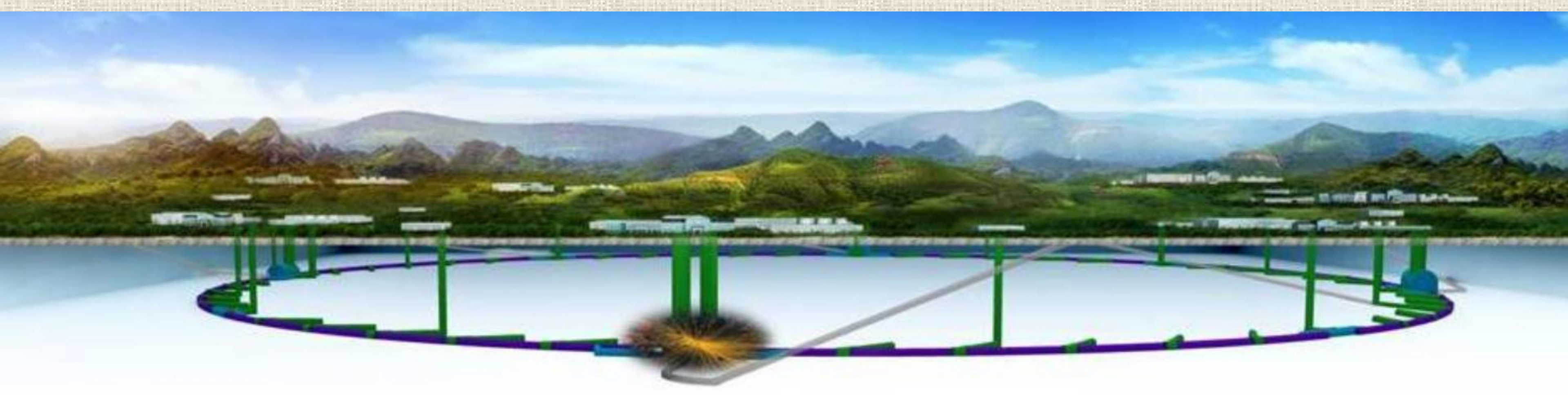
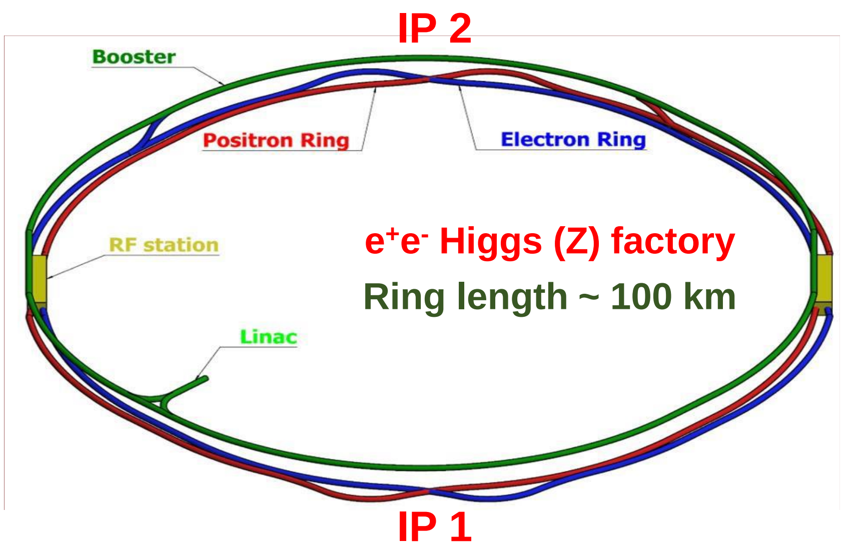
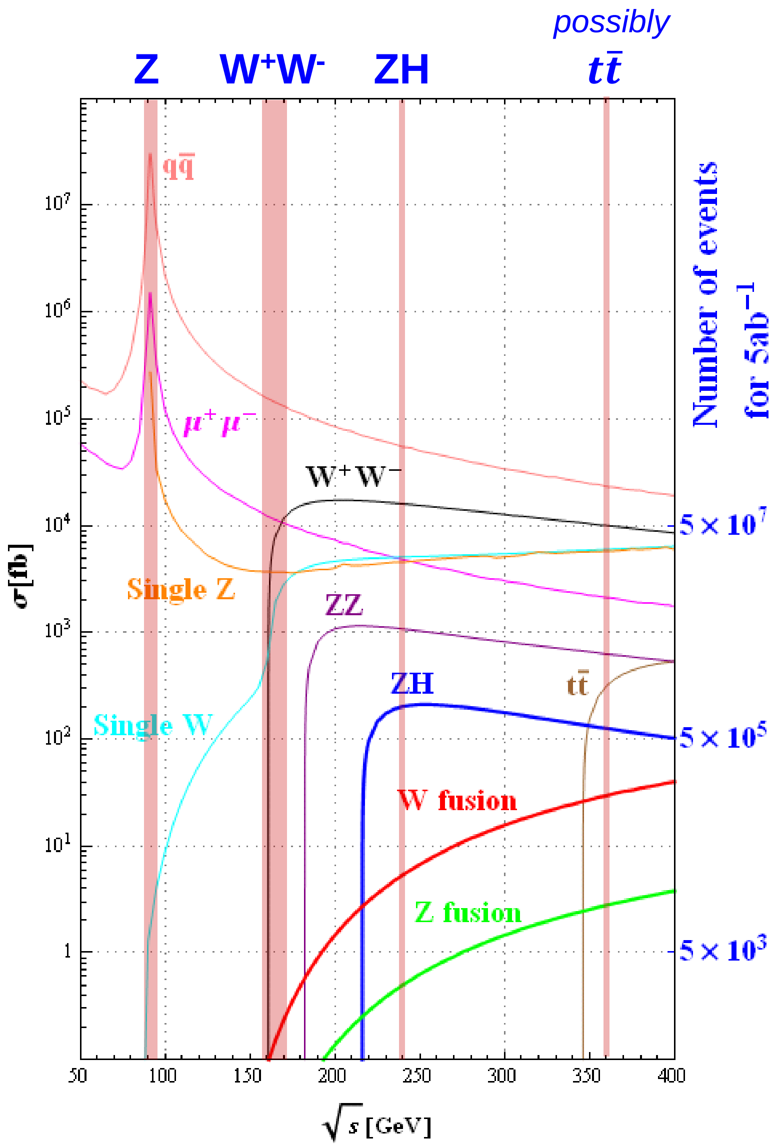


Circular Electron Positron Collider

- The CEPC aims for high precision measurements of Higgs, Z & W bosons, and search for new physics, in 2030's.
- Milestones achieved: Kick-off (2013.9), Pre-CDR(2015.3), CDR (2018.8/10).
- The CEPC working groups have very active R&D. Need to form international collaborations and release TDRs in the coming years.
- CEPC will operate at **ZH**, **Z**, **W^+W^-** and possibly $t\bar{t}$ energies. No need of hardware change when switching the beam energy.
- Upgradable to a pp collider (SppC) with $\sqrt{s}$ ~ 50–100 TeV.



Physics Motivation



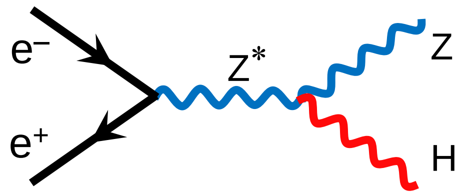
Update since CDR

Operation mode	ZH	Z	W^+W^-
$\sqrt{s}$ (GeV)	~240	~91.2	158-172
L / IP (10^{34} cm^{-2}s^{-1})	**3 (5)**	**32 (102)**	**10**
Run time (years)	7	2	1
$\int L\,dt$ (ab^{-1}, 2 IPs)	5.6	16	2.6
Event yields	**1×10^6**	**7×10^{11}**	**2×10^7**

- ❑ Higgs factory & Z factory: > **10^6** Higgs, **10^{12}** Z, and **10^8** W bosons.
- ❑ High precision Higgs, EW measurements,
- ❑ Study flavor physics (b, c, tau) and QCD,
- ❑ Rare decays,
- ❑ Probe new physics.
- ❑ …

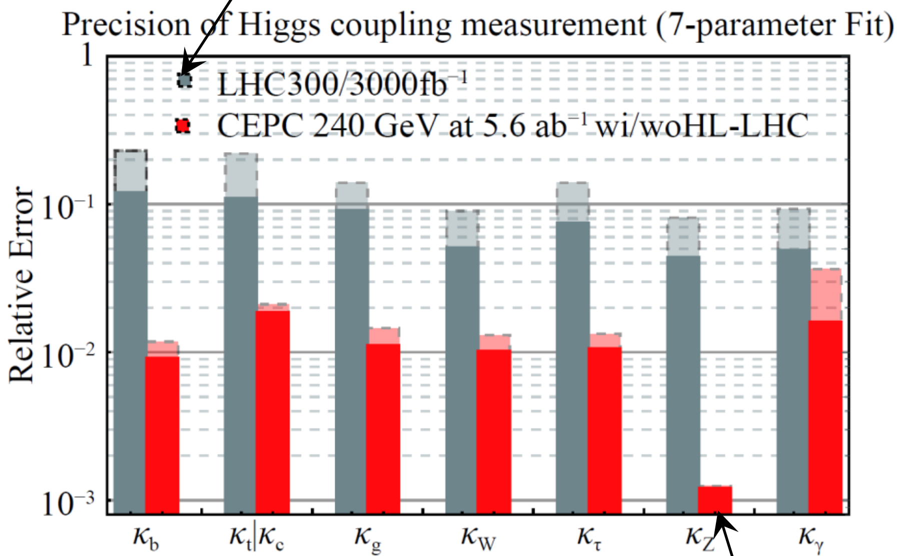
Reference: discussions in the CEPC/FASER session by Yaquan Fang, Lingfeng Li, Jiarong Yuan, & Qi Liu.

Higgs Coupling Measurements



- Higgs boson candidates can be identified through Z recoil mass without tagging its decays
- Model independent measurement of the Higgs boson width.
- Delivers ≤1% precision in some key measurements of Higgs properties, some not accessible @ LHC.
- Sensitive to invisible decay modes of Br ~0.3%, with the recoiling mass technique.
- Sensitive to exotic decay channels.

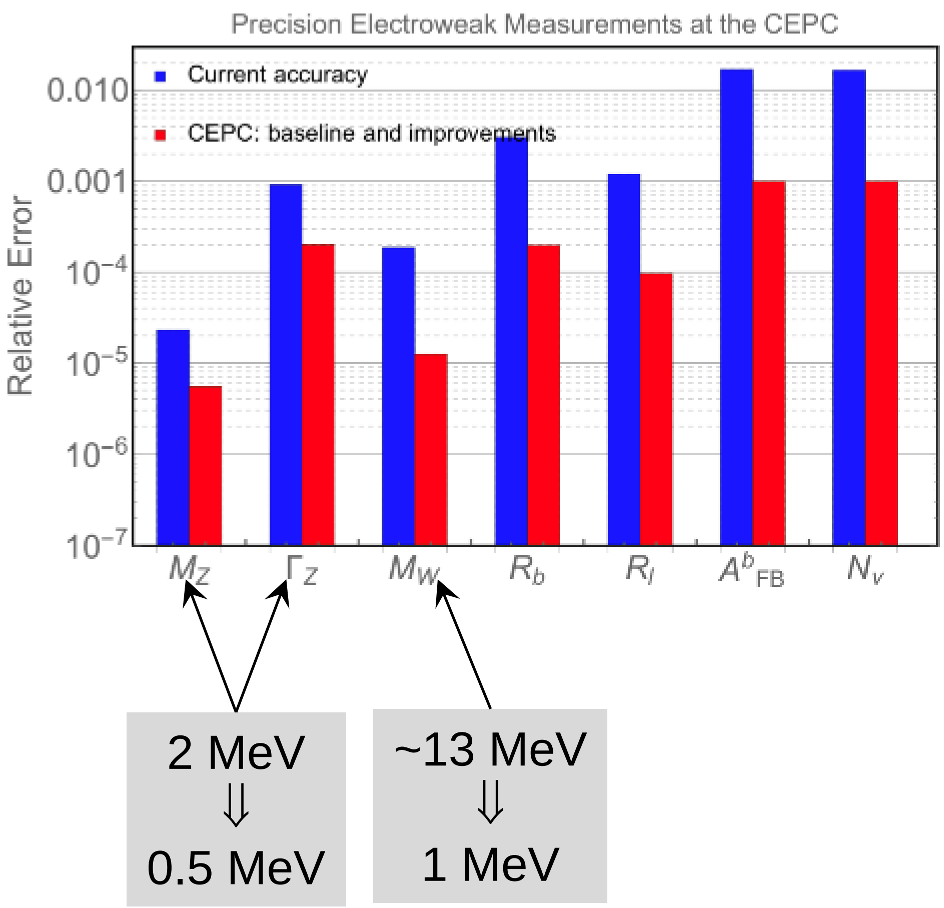
Higgs coupling uncertainty ~ (2-5)% in updated HL-LHC



K_Z uncertainty ~ 0.13%

Most others ~ 1%

Precision of Electroweak Observables



- Two years at the Z pole ($\sqrt{s} = 87.9$, 90.2, 91.2, 92.2, 94.3 GeV). Much more data will be taken on-peak.
- One year at WW threshold ($\sqrt{s} = 157.5$, 161.5, 162.5, 172.0 GeV). Runs @172 GeV mainly for $\alpha_s(m_W^2)$ measurement.
- Beam energy spread ~0.08% @ Z, and ~0.1% @WW.
- Beam energy will be measured by the depolarizing resonance method, which was developed at LEP. For CEPC, δ(Ecm) ~0.5 MeV at WW.
- Relative luminosity measurement uncertainty $\delta L / L \sim 10^{-4}$.

Flavor Physics

- CEPC produces a huge sample of *b, c & τ*, especially at the Z-pole, provides a unique opportunity for the flavor physics, including CP violation, rare decays and probing new physics.

Observable	Current sensitivity	Future sensitivity	Tera-Z sensitivity
$\text{BR}(B_s \to ee)$	2.8×10^{-7} (CDF) [438]	$\sim 7 \times 10^{-10}$ (LHCb) [435]	$\sim$ few $\times 10^{-10}$
$\text{BR}(B_s \to \mu\mu)$	0.7×10^{-9} (LHCb) [437]	$\sim 1.6 \times 10^{-10}$ (LHCb) [435]	$\sim$ few $\times 10^{-10}$
$\text{BR}(B_s \to \tau\tau)$	5.2×10^{-3} (LHCb) [441]	$\sim 5 \times 10^{-4}$ (LHCb) [435]	$\sim 10^{-5}$
R_K, R_{K^*}	$\sim 10\%$ (LHCb) [443, 444]	$\sim$few% (LHCb/Belle II) [435, 442]	$\sim$few %
$\text{BR}(B \to K^*\tau\tau)$	–	$\sim 10^{-5}$ (Belle II) [442]	$\sim 10^{-8}$
$\text{BR}(B \to K^*\nu\nu)$	4.0×10^{-5} (Belle) [449]	$\sim 10^{-6}$ (Belle II) [442]	$\sim 10^{-6}$
$\text{BR}(B_s \to \phi\nu\bar{\nu})$	1.0×10^{-3} (LEP) [452]	–	$\sim 10^{-6}$
$\text{BR}(\Lambda_b \to \Lambda\nu\bar{\nu})$	–	–	$\sim 10^{-6}$
$\text{BR}(\tau \to \mu\gamma)$	4.4×10^{-8} (BaBar) [475]	$\sim 10^{-9}$ (Belle II) [442]	$\sim 10^{-9}$
$\text{BR}(\tau \to 3\mu)$	2.1×10^{-8} (Belle) [476]	$\sim$ few $\times 10^{-10}$ (Belle II) [442]	$\sim$ few $\times 10^{-10}$
$\frac{\text{BR}(\tau \to \mu\nu\bar{\nu})}{\text{BR}(\tau \to e\nu\bar{\nu})}$	3.9×10^{-3} (BaBar) [464]	$\sim 10^{-3}$ (Belle II) [442]	$\sim 10^{-4}$
$\text{BR}(Z \to \mu e)$	7.5×10^{-7} (ATLAS) [471]	$\sim 10^{-8}$ (ATLAS/CMS)	$\sim 10^{-9} - 10^{-11}$
$\text{BR}(Z \to \tau e)$	9.8×10^{-6} (LEP) [469]	$\sim 10^{-6}$ (ATLAS/CMS)	$\sim 10^{-8} - 10^{-11}$
$\text{BR}(Z \to \tau\mu)$	1.2×10^{-5} (LEP) [470]	$\sim 10^{-6}$ (ATLAS/CMS)	$\sim 10^{-8} - 10^{-10}$

- A few key features @ CEPC: clean event environment, high energy to access B_c and b-baryons, efficient $e/\gamma/\pi^0$ reconstruction.
- Extra requirements on detector design:
  powerful PID for π/K separation, good vertex, and efficient ECal.

Recent Physics Benchmark Analyses

- Higgs: H→ττ, et.al...
- Flavor:
  - $B_c \to \tau\nu$;
  - $B_s \to \Phi + \nu\nu$;
  - $B_s \to J/psi + \Phi$;
  - $b \to s\tau\tau$
  - ...

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THE EUROPEAN PHYSICAL JOURNAL C

Check for updates

Regular Article - Experimental Physics

The measurement of the $H \to \tau\tau$ signal strength in the future e^+e^- Higgs factories

Dan Yu[1], Manqi Ruan[1,a], Vincent Boudry[2], Henri Videau[2], Jean-Claude Brient[2], Zhigang Wu[1], Qun Ouyang[1], Yue Xu[3], Xin Chen[3]

[1] IHEP, Beijing, China
[2] LLR, Ecole Polytechnique, Palaiseau, France
[3] Tsinghua University, Beijing, China

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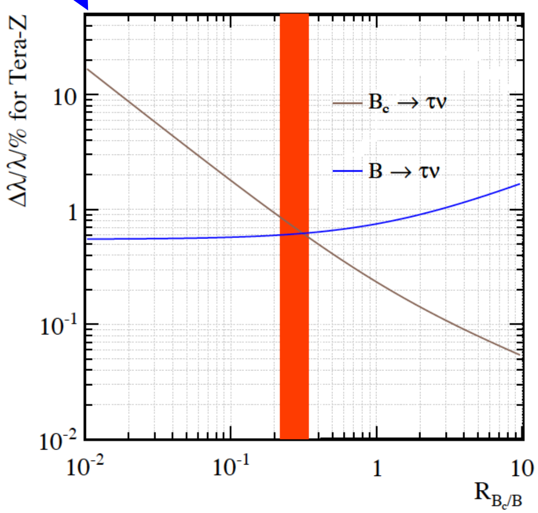
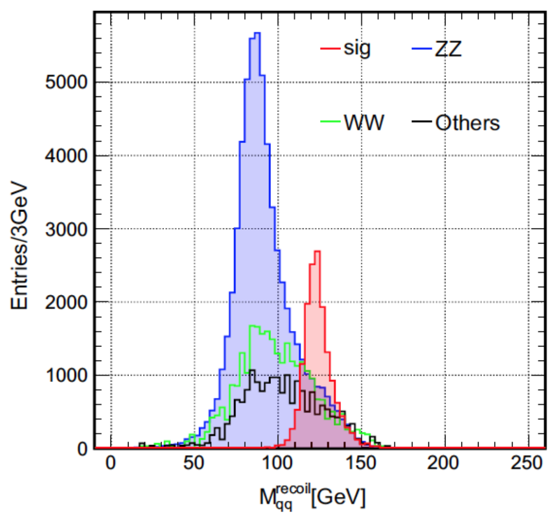
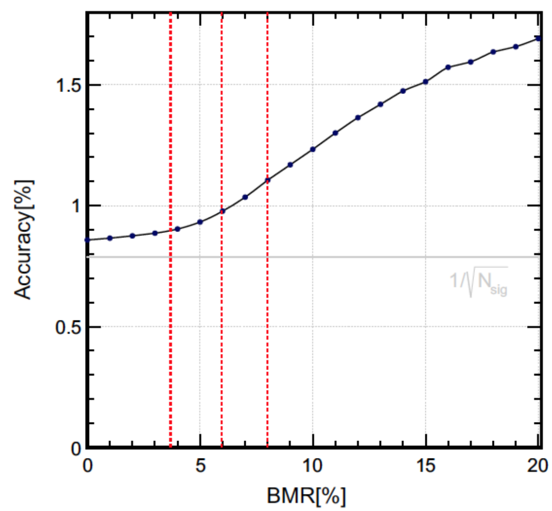
Table 9 Extrapolated accuracy $\delta(\sigma \times BR)/(\sigma \times BR)$ in the ILC 250 GeV (2000 fb^{-1})

	CEPC	ILC(L)	ILC(R)
Luminosity (ab^{-1})	5.6	2	2
Polarization (e^-, e^+)	–	(0.8, −0.3)	(−0.8, 0.3)
Total Higgs	1.18 M	0.60 M	0.40 M
Accuracy (%)	0.8	1.09	1.21







Key Requirements on Detector

New interesting physics topics & more simulation studies provide valuable inputs to the detector design.

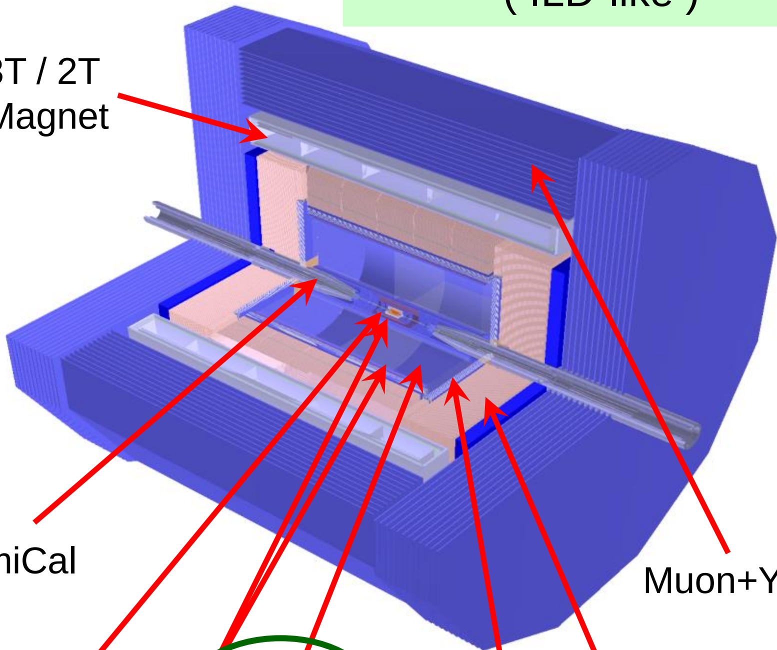
Physics process	Measurands	Detector subsystem	Performance requirement
$ZH, Z \to e^+e^-, \mu^+\mu^-$ $H \to \mu^+\mu^-$	$m_H, \sigma(ZH)$ $\mathrm{BR}(H \to \mu^+\mu^-)$	Tracker	$\Delta(1/p_T) = 2 \times 10^{-5} \oplus \frac{0.001}{p(\mathrm{GeV}) \sin^{3/2}\theta}$
$H \to b\bar{b}/c\bar{c}/gg$	$\mathrm{BR}(H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

All requirements need to further evaluation

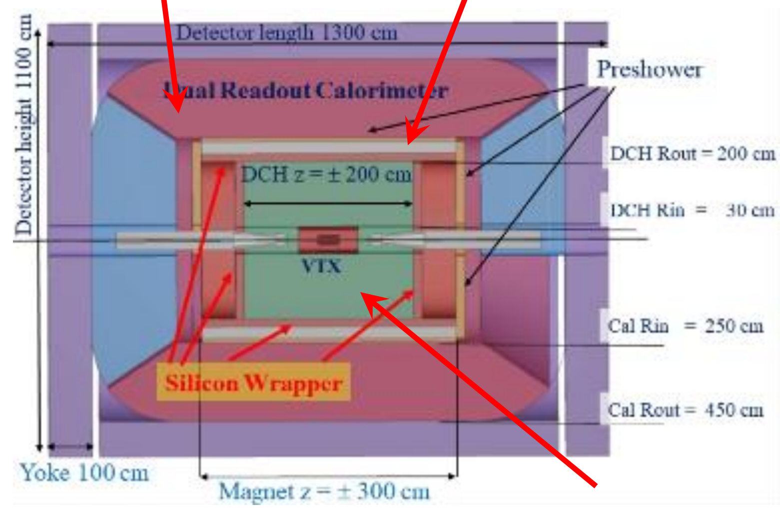
- Flavor physics $\Rightarrow$ Excellent PID, for π/K separation up to ~20 GeV.
- EW measurements $\Rightarrow$ High precision luminosity measurement, $\delta L / L \sim 10^{-4}$.

Conceptual Detector Designs

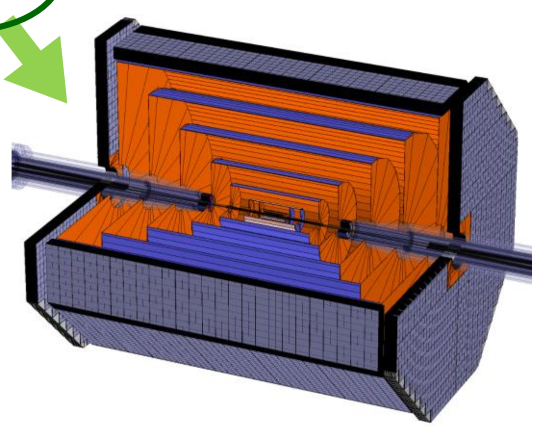
Particle Flow Approach
(ILD-like)



IDEA concept
(also proposed for FCC-ee)



Full Silicon Tracker (FST) concept



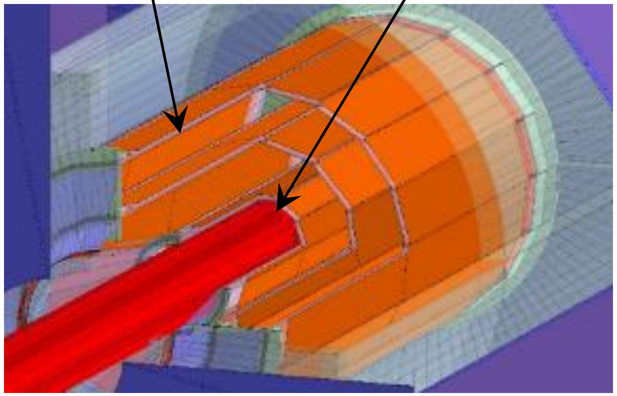
- Official international collaborations are to be formed, and to decide the detector design.
- The working group is doing R&D of all sub-systems in the CDR design, and exploring various other technologies.
- The final two detectors likely are mixtures of different options.

Silicon Vertex Detector

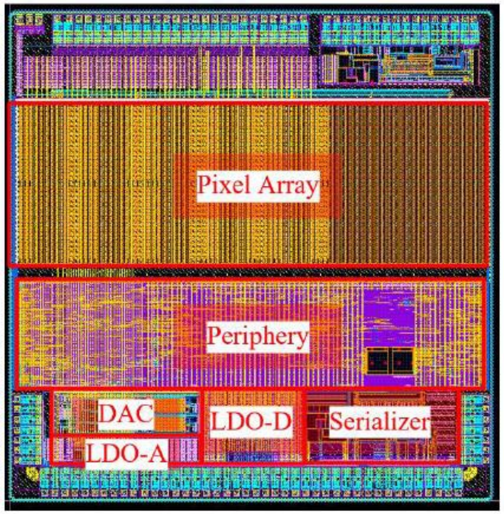
R&D supported by IHEP, MOST 1 & 2 funding, close domestic and international collaborations

- Goal: σ(IP) ~ 5 μm for high P track.
- CDR design spec:
  - 6-layer silicon pixel CMOS detector, single point resolution ~ 3µm.
  - Low material (0.15% X_0 / layer), low power (< 50 mW/cm^2), rad-hard (1 Mrad/year)
- Developing 2 lines of ASICs:
  - JadePix-3: (& MIC4) low power, rolling shutter readout.
  - TaichuPix-2: close to full functionality, rad-hard, under test. In rev-1 time resolution ~75-150 ns, power ~ 100-200 mW/cm^2.

2 layers / ladder R_{in}~16 mm



TaichuPix-2, 64×192 array
25×24 μm^2 pixel size



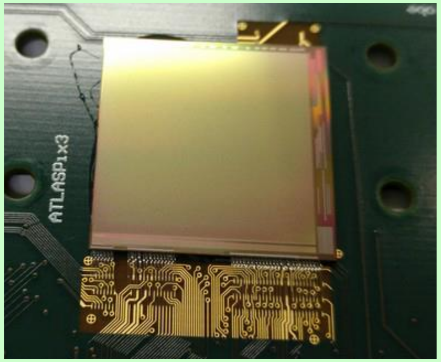
JadePix-3   Pixel size ~16×23 μm^2

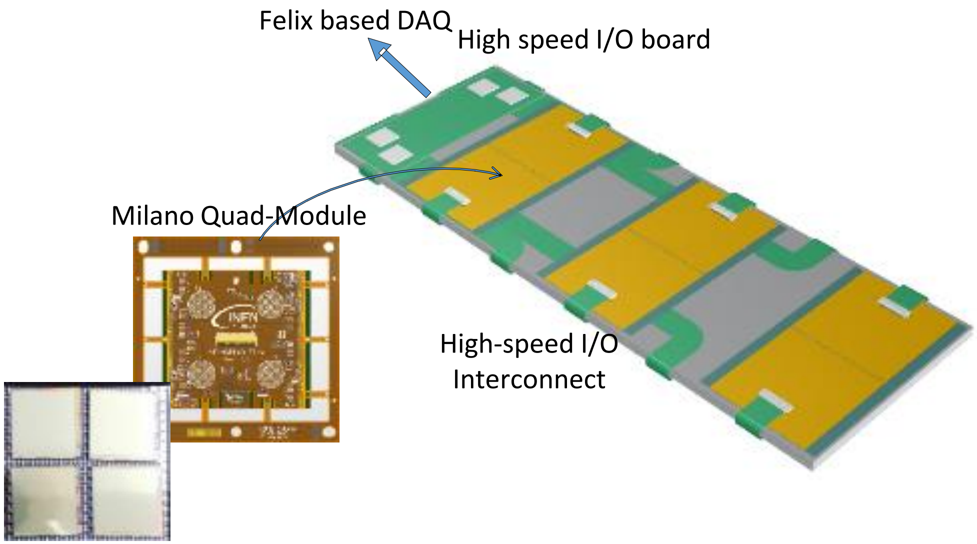
To build a full size prototype ladder

Silicon Tracker

- The silicon tracker has very large area, ~70 m^2 in SiTrk + TPC, or ~140 m^2 in Full SiTrk plans. R&D focuses on cost effective and high performance.
- The tracking group is investigating a HV-CMOS solution based on the ATLASPix3 designed by KIT.
- Test boards are produced and wire-bonded at Liverpool & IHEP. They are distributed to European & Chinese collaborators.
- A short stave demonstrator will be built using the ATLASPix3. More prototyping are in planning.

ATLASPix3
132×372 pixels
150×50 μm^2 pixel size.
Time resolution: O(10ns)





NEXT:

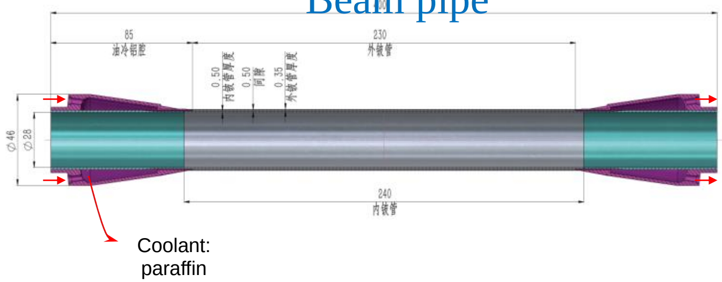
A design optimized for CEPC, basing on ATLASPix3.

Look into domestic production.

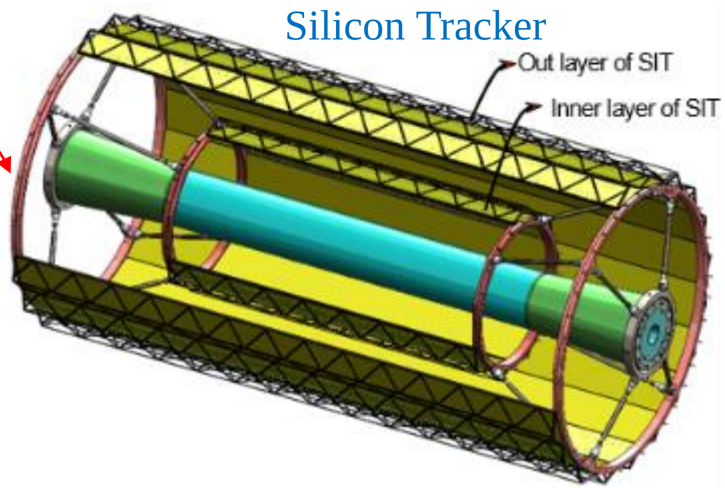
Interaction Region Design

- **Completed:** Synchrotron radiation & high order mode heat load calculation → beam pipe thermal analysis → detector radiation backgrounds evaluation
- **On-going:** Assess physics gains, design risks and difficulties to shrink the central Be beam pipe: **ϕ28mm → ϕ20mm**, wall thickness: **0.5+0.35 mm → 0.2+0.15 mm**.
- **On-going:** Engineering design of sub-detectors including interfacing, integration installation scheme (focused but not limited to the interaction region).

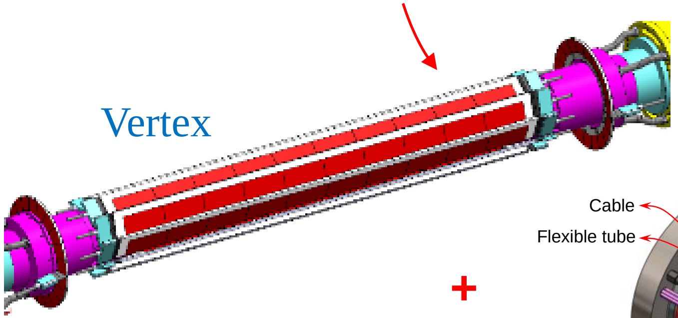
Beam pipe



Silicon Tracker



Vertex



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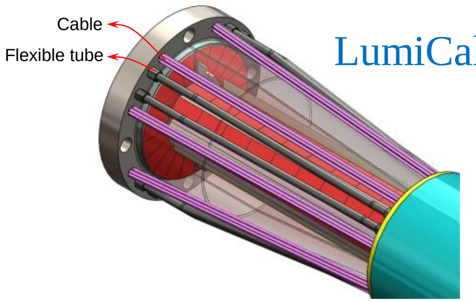
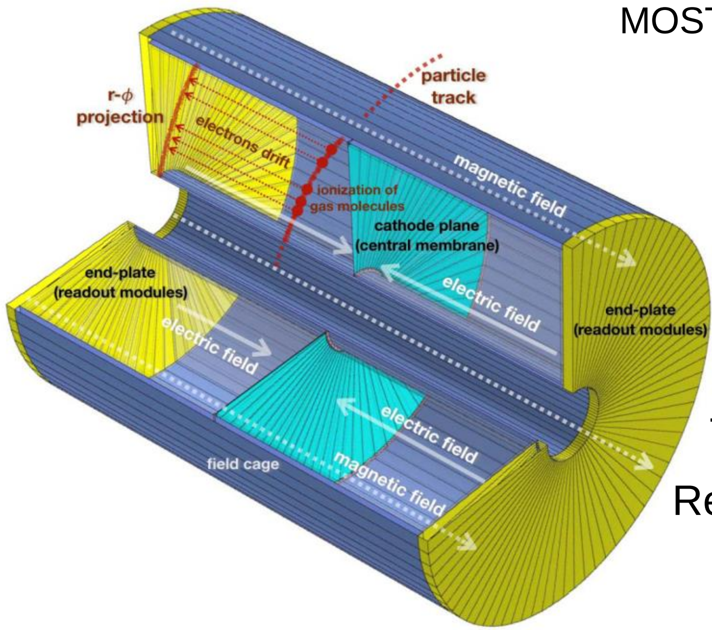


LumiCal Tracker

Time Projection Chamber

MOST1 & NSFC funding

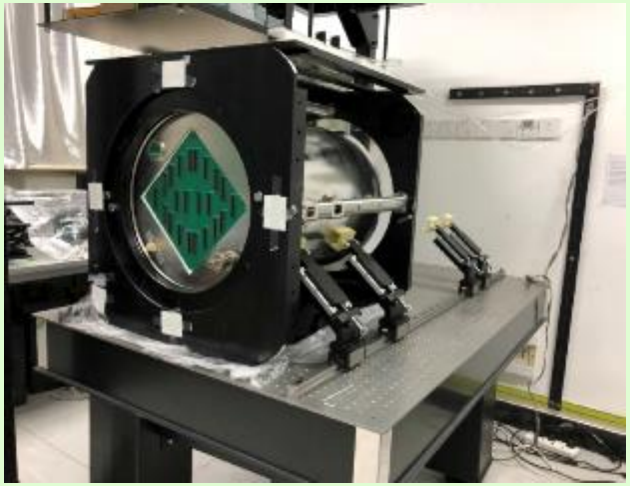


The main tracker

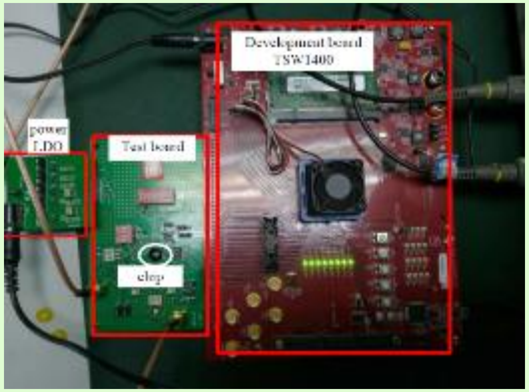
Resol in r-Φ~100 μm

- Challenge: Ion backflow (IBF) affects the resolution. It can be corrected by laser calibration at low lumin, difficult @ Z-pole.
- Potential solutions to suppress IBF, e.g. Pixel TPC with double meshes, or micromegas.
- When Gain×IBF=1, distortion <16 μm @ L 32 $\times 10^{34}$ $cm^{-2}s^{-1}$, <49 μm @10^{36} $cm^{-2}s^{-1}$.

Completed



TPC Prototype + UV laser beams

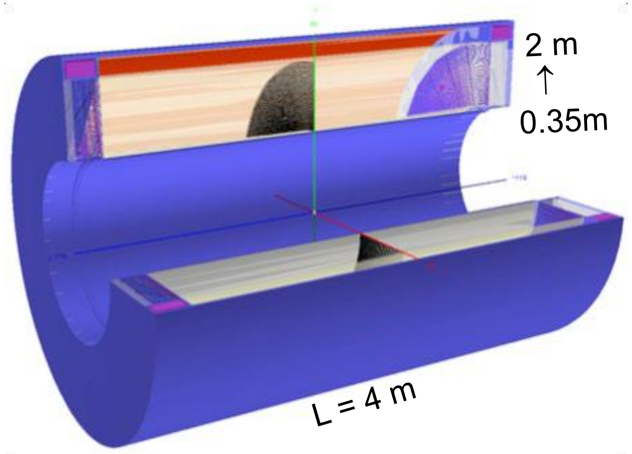


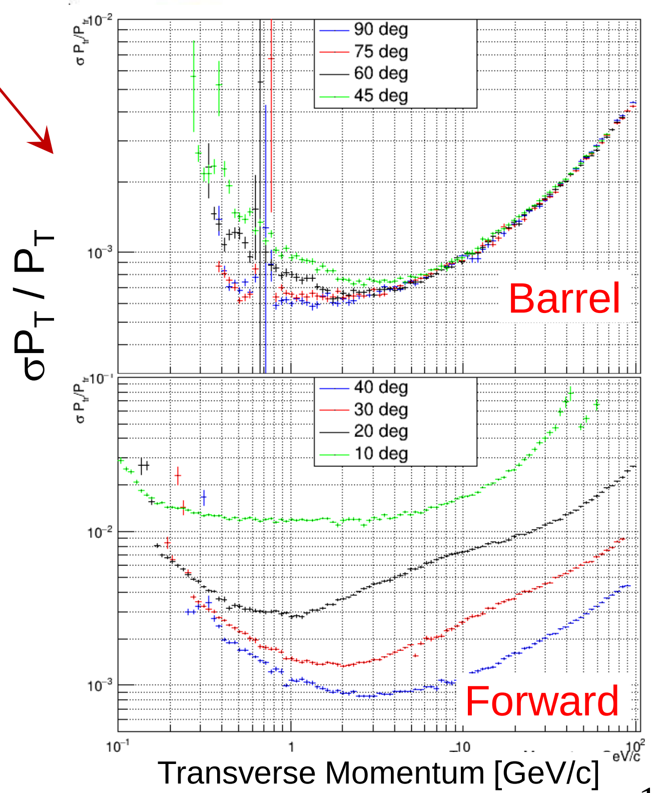
FEE ASIC (65nm CMOS)

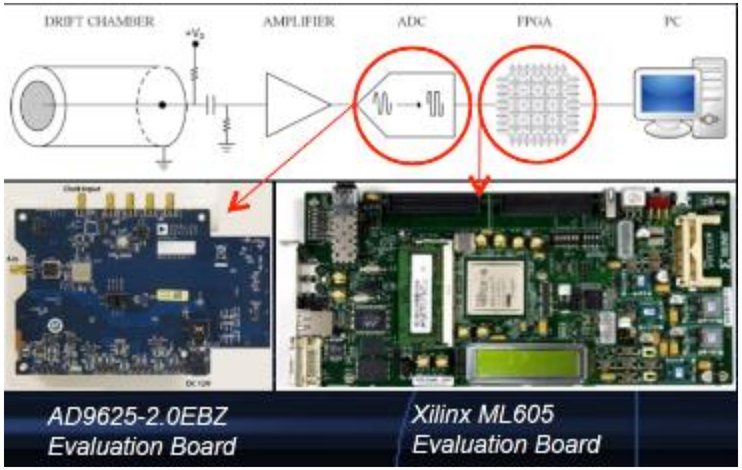
Drift Chamber

The main tracker in IDEA design

- Mechanical structure design with a wire tension recovery scheme at the end plates.
- Drift tube prototype with new types of wires.
- Simulation in Geant4 (in progress) & Garfield.
- Cluster counting electronics for PID. Test different data reduction solutions based on FPGA's with multi-channel approach.







- Charge particle ID is crucial for the flavor physics. Aiming at P < ~ 20 GeV/c.
- Both TPC & DC provide good PID, with dE/dX or dN/dX cluster counting.
- For the FST solution, a supplement PID detector is needed. Combination of different PID detectors is also viable.

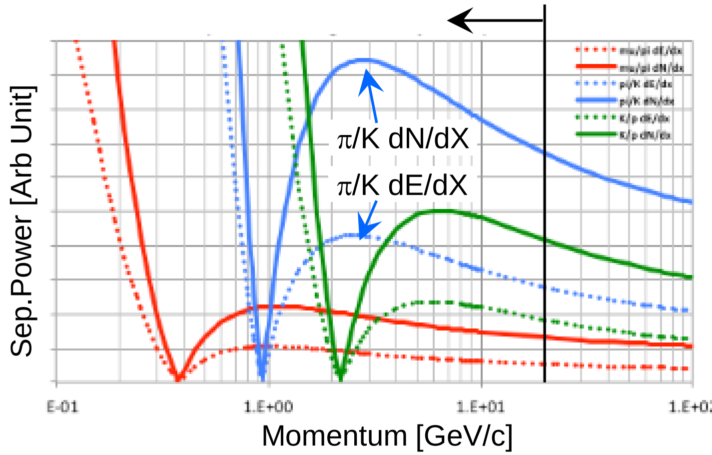
① **Drift chamber** between the outer layers of FST. It is promising in a simple simulation. More work in design optimization, and the physics impact.

② **Time of flight** detectors, e.g. LGAD. The resolution ~20-30 ps today (ATLAS/CMS). Sensor by IHEP & NDL reaches 25ps. By the time of CEPC, 10 ps might be possible.

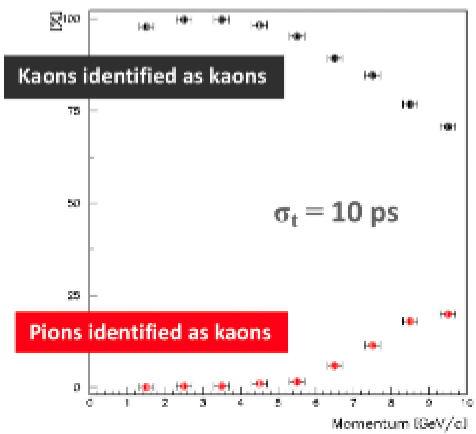
③ A **RICH** of aerogel & gaseous radiators. Space constraint needs to studied.

- More options and studies are needed.

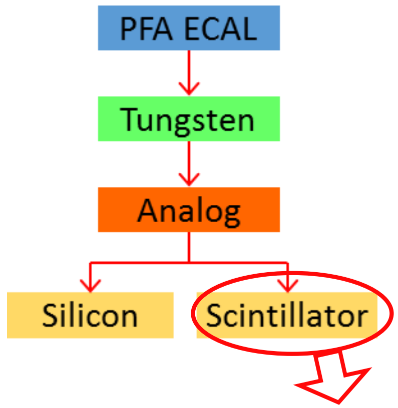
PID workshop @ HKUST IAS, Jan 2021



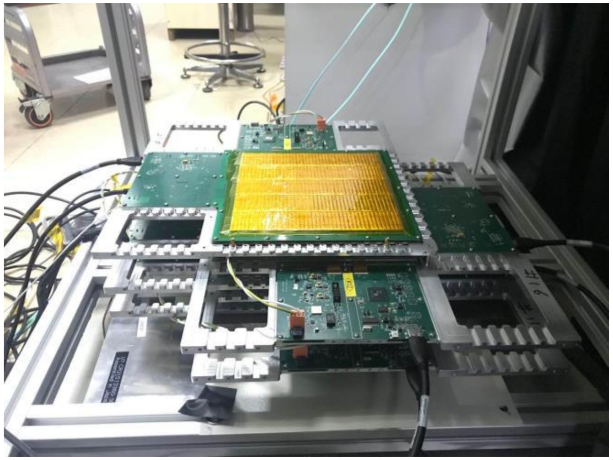
IHEP-NDL LGAD-V2
Pixel size 1.3×1.3 mm²



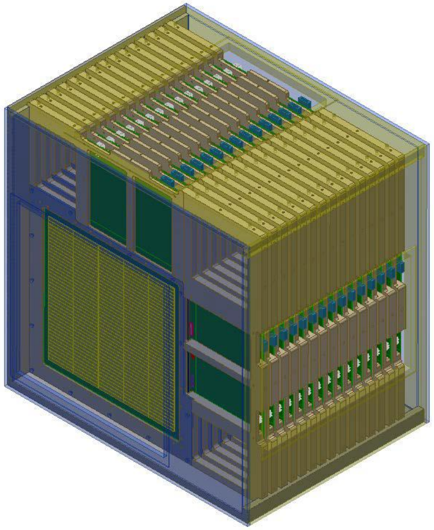
PFA ECAL



Super-layer bench test

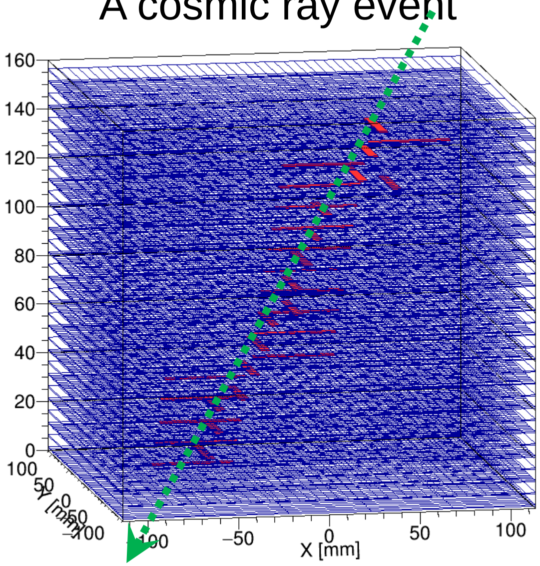


Prototype ScECAL

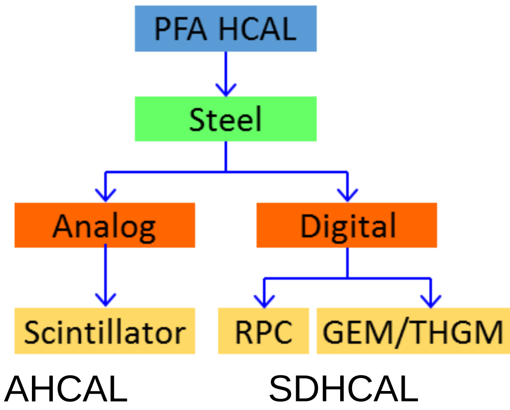


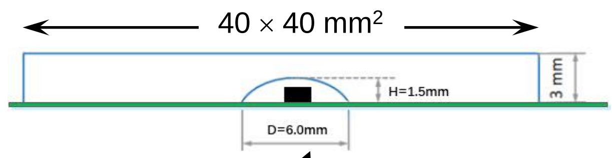
- An alternative PFA ECAL in CDR: scintillator + SiPM as the sensitive detector, tungsten as absorber, totals 24X_0 radiation length.
- A 32-layer prototype has been constructed (Sept 2020):   3.2 mm thick W-Cu plate, scintillator bar size 5×45 mm^2, 1 SiPM/bar.
- It has been tested with cosmic rays, will be tested in electron beams at IHEP (Nov 2020), & DESY (early 2021).

A cosmic ray event



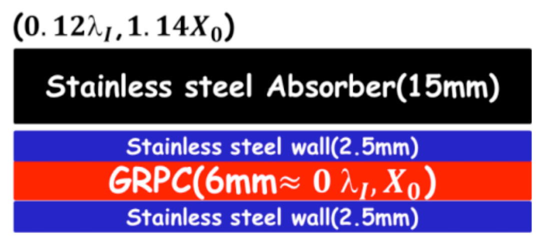
PFA HCAL





- AHCAL of Steel+Scint+SiPM:
  - Prototype size 72×72×100 cm³, 40 layers, 2cm steel plates, 4×4 cm² detector cell.
  - Readout electronics & DAQ are developed.
  - Preparing for production.

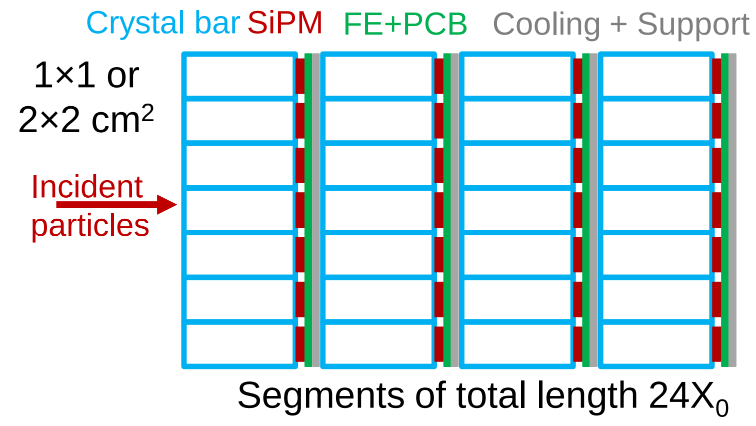
- SDHCAL based on GRPC:
  - Prototype size 1×1×1.4 m³, 48 layers, 1×1 cm² detector cell, 2 cm steel absorber.
  - Construct a 35×50 cm² GRPC before a full size.
- SDHCAL based on MPGD
  - Constructed a 25×25 cm² detector, and studied its performance.



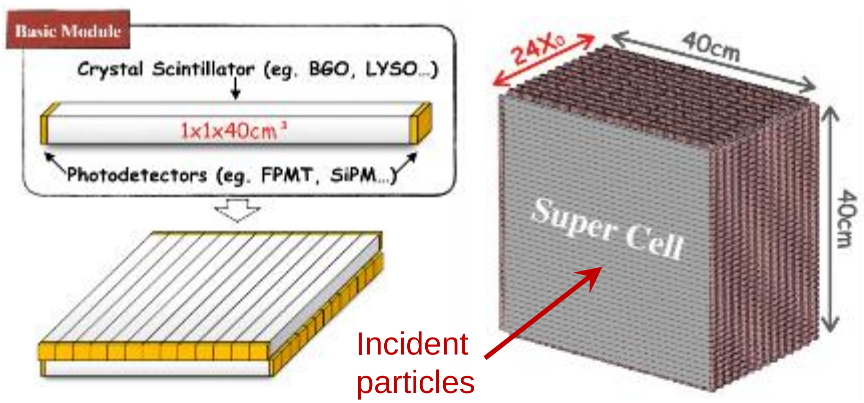
Crystal ECal

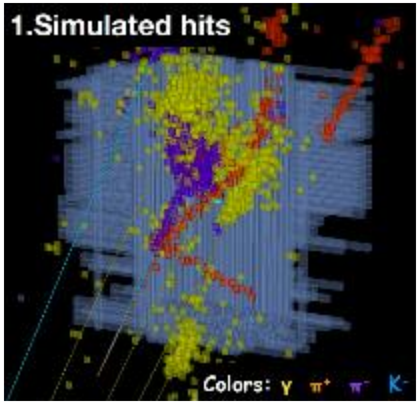
Design 1

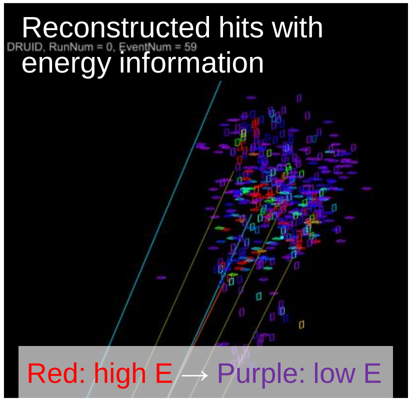
- Single end readout; potentials with PFA
- Study γ/π^0 separation & energy resolution to optimize transverse and longitudinal segmentation.



Design 2 (*current focus*)







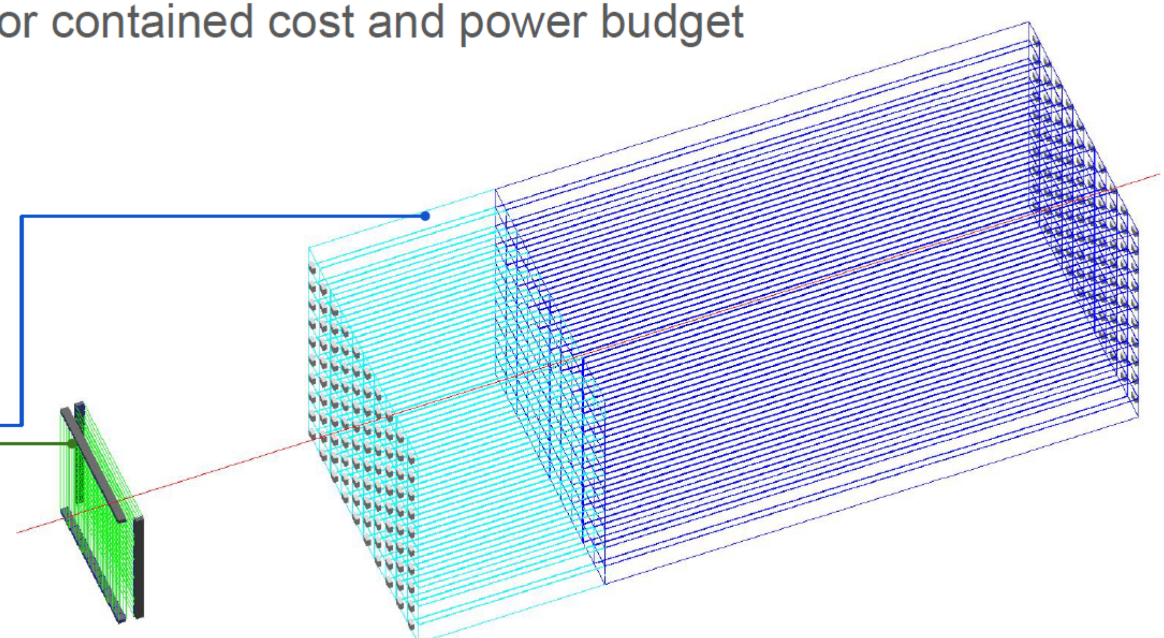
- Crystal bar perpendicular to particles. Significant reduction of number of channels.
- Measure timing at both ends for position along bar. Reconstruction is a big challenge.
- Preparing software for a full simulation to estimate the impact on physics.

Another Crystal ECAL Design

Also exploring a design of adding a time layer to the longitudinal solution.

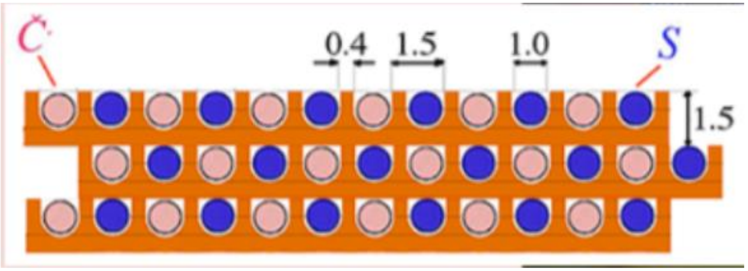
- ***SCEPCAL:*** a **S**egmented **C**rystal **E**lectromagnetic **P**recision **C**alorimeter
- **Transverse and longitudinal segmentations** optimized for particle identification, shower separation and performance/cost
- Exploiting **SiPM readout** for contained cost and power budget

- **Timing layer** — $\sigma_t \sim 20$ ps
  - LYSO:Ce crystals (~$1X_0$)
  - 3x3x54 mm³ active cell
  - 3x3 mm² SiPMs (15-20 um)
- **ECAL layer** — $\sigma_E/E \sim 3\%/\sqrt{E}$
  - PbWO crystals
  - Front segment (~$6X_0$)
  - Rear segment (~$16X_0$)
  - 10x10x200 mm³ crystal
  - 5x5 mm² SiPMs (10-15 um)



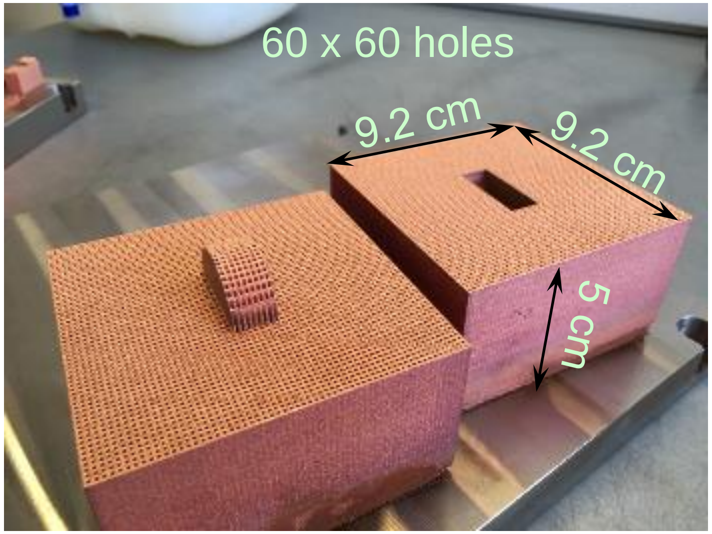
Dual Readout Calorimeter

- The calorimeter in the IDEA design is a DR CAL, for both EM & hadronic showers.



Cu absorber, 1 mm fibers

3-D printing of a Cu absorber by Korean colleagues

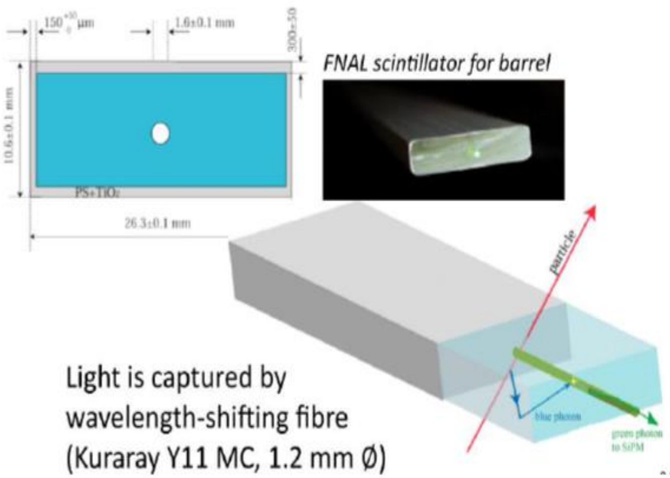


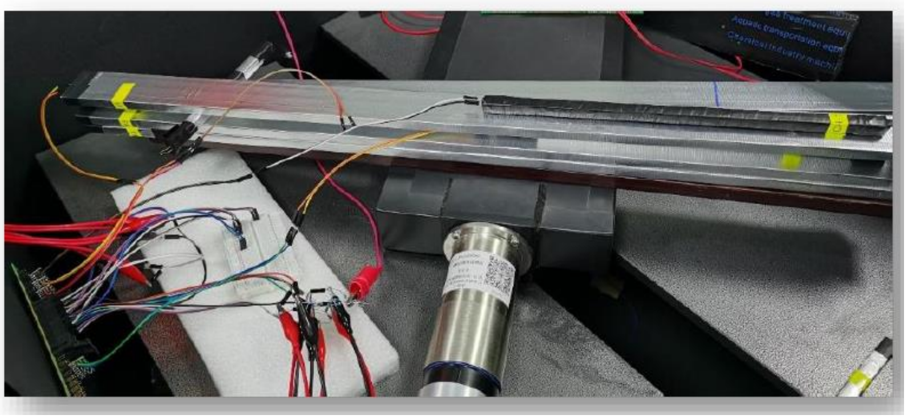
- Detector performance has been studied in simulation.
- Physics performance of benchmark channels, both standard approach & deep learning algorithm.
- Prototype modules are to be built, first an EM prototype by early 2021, then the hadronic size module.
- A 60×60–hole Cu absorber from 3-D printing looks promising.

- Dual readout in crystal ECAL is also being explored.

Muon Detector

- **RPC** R&D applies to both SDHCAL & Muon.
- An alternative is **μ-RWELL** technology. The concept was proved. Currently focus mainly on industrialization and cost reduction.
- New activities on **Scintillator** Muon detector. R&D overlaps with Belle II KLM.
  - Prototype will be ready in 2021.
  - Scintillator strips: domestic product, improving quality & cost-reduction.
  - WLS fiber: purchased Kuraray, Investigating Chinese products. Focusing on optical couplings.
  - SiPM: Hamamatsu S13360-13**CS, also looking into domestic product and MPPC option.



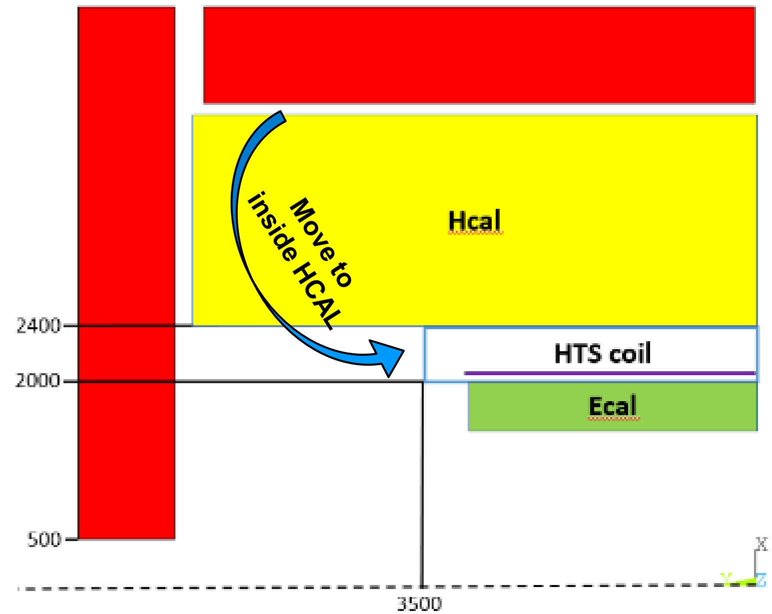


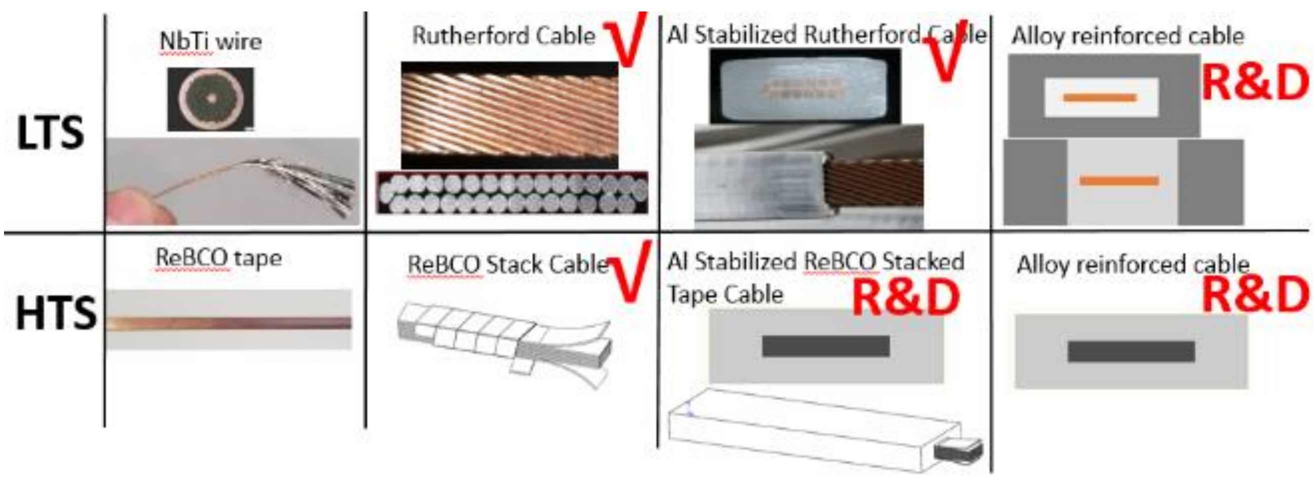
Achieved σ_t~2ns,

Aim for 100-200 ps.

Solenoid Magnet

- Changes after the CDR design:
  - Significant reduction of the yoke material
  - Solenoid coil placed between Hcal & Ecal.
- Challenges: **low mass, ultra-thin, high strength cable**.
- Some of the on going R&D:
  - Domestic LTS and HTS cables,
  - Large coil winding process,
  - Low mass vacuum vessel structure





Accelerator R&D

Progress and plan are reported in a designated presentation by Prof Jie Gao.

- Very active R&D program towards **TDR**, based on the CDR design.
- The design is further optimized, for possible higher luminosity/IP: $(3 \rightarrow 5) \times 10^{34}$ $cm^{-2}s^{-1}$ for Higgs runs, and $(32 \rightarrow 101) \times 10^{34}$ $cm^{-2}s^{-1}$ for Z mode (2T).

CEPC Accelerator TDR R&D Priority, Plan and Test Facilities

① CEPC 650MHz 800kW high efficiency klystron(80%), to complete fabrication by the end of 2021, to finish test in year 2022.

② High precision booster dipole magnets: which are critical for booster operation, to complete a full-size magnet model in 2021.

③ CEPC 650MHz SC accelerator system, including SC cavities and cryomodules: to complete test cryomodule in 2022.

④ Collider dual aperture dipole magnets, dual aperture quadrupoles and sextuple magnets: to complete full-size model in 2022

⑤ Vacuum chamber system: to complete fabrication and costing test in 2022

⑥ SC magnets including cryostats: to complete short test model in 2022

⑦ MDI mechanic system: remote vacuum connection to be tested in 2022

⑧ Collimator: to complete model test in 2022

⑨ Linac components: to complete key component tests in 2022

⑩ Civil engineering design: to complete reference implementation design in 2022

⑪ Plasma wake field injector: to complete the electron accelerator test in 2022.

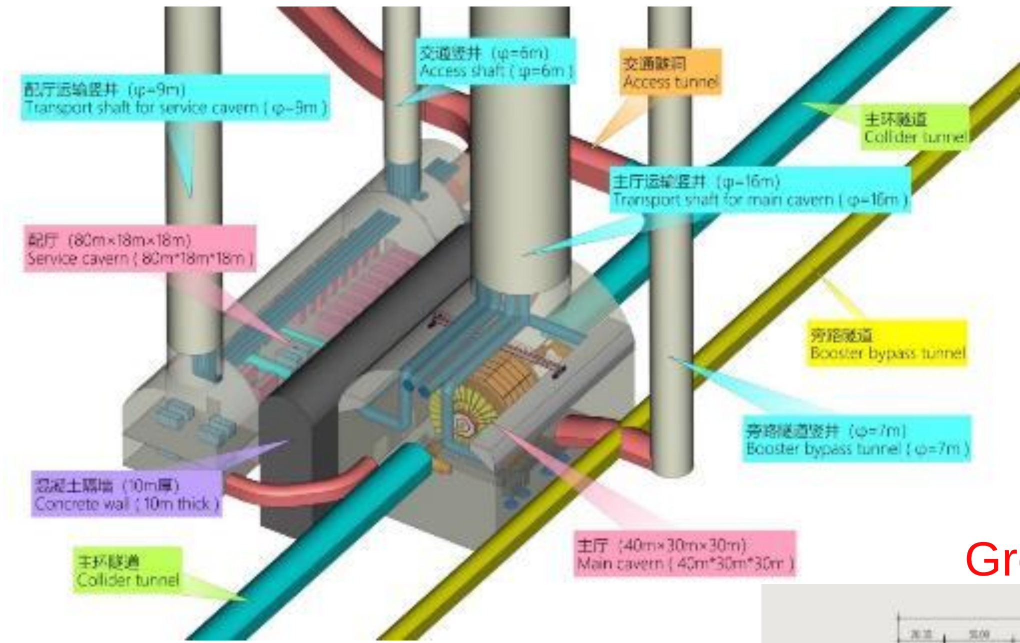
⑫ 18KW@4.5K cryoplant: industrial partner

- …

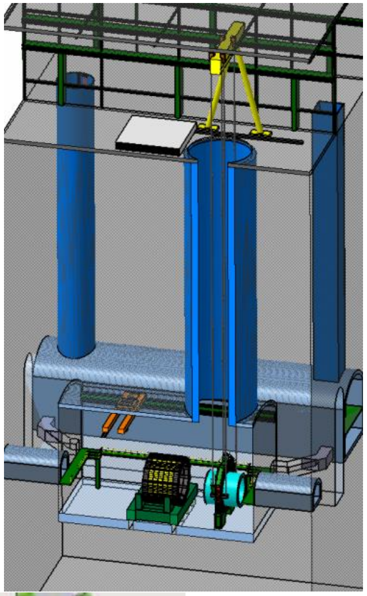
SppC technology R&D

- Ion based superconducting materials and high field magnets.

The Experimental Hall



An 1K-ton gantry crane for large heavy objects.



Ground level buildings

Main cavern

- Host the detector
- 40*30*30 m^3 (L*H*W)
- One main access shaft, Ø16 m

Auxiliary cavern

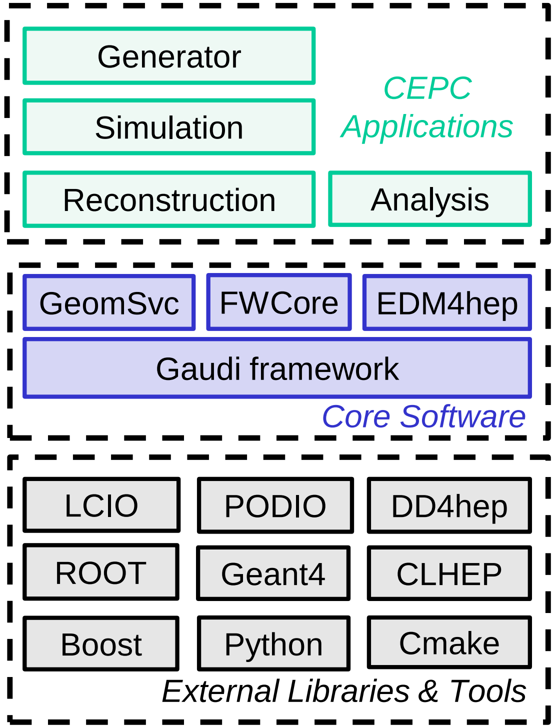
- Peripheral equipment and devices
- 80*18*18 m^3 (L*H*W)
- One service shaft Ø9 m
- One personnel access shaft Ø6 m

CEPC Software

- Core software, external libraries & tools are the base of the CEPCSW. More packages and components will be added when available.
- CEPC applications are created for CDR design. With new type of detectors introduced, corresponding codes are being developed.

- Recent added CEPC applications:
  - Software for SiTrk + DC design, detector description and track fitting.
  - Cluster counting method of DC
  - Simulation and simplified digitization of the crystal bar ECal.
- Work to be done
  - Further development of simulation & reconstruction for SiTrk+DC and Crystal bar ECal.
  - Non-uniform magnetic field & piling-up of beam backgrounds in simulation
  - Algorithms for building reconstructed particles
  - Continue to check the consistence of software, with benchmark performance studies.

CEPCSW structure



International Participation & Collaboration

- International workshops (with emphasis on CEPC):
  - In China: Beijing (2017.11, 2018.11, 2019.11),
    Shanghai (2020.10): ~400 participants, more international speakers (97 >91).
  - In Europe: Rome (2018.05), Oxford (2019.04), Marseille (2020.05 →2021)
  - In USA: Chicago (2019.09), DC (2020.04)

- IAS HEP program (HKUST), annually since 2015.
  - 2020.01: Conference; Mini-workshops: MDI, Experiment & detector, Physics potential
  - 2021.01: Conference; Mini-workshops: Particle ID, ...

- Continue to have various topic specific workshops:
  - 2020.05: MDI workshop
  - 2020.07: Detector concept with a crystal ECAL
  - 2020.08: Detector & accelerator mechanics

- International Advisory Committee operates since 2015, and just had the 6th annual meeting (2020.10.28-29). Intern. Accelerator Review Committee, Intern. Detector R&D Review Committee started function in 2019.11.

- Active in international detector R&D: CALICE, LPTPC, RD* collaborations, …

- Snowmass: 35 LOIs (4 CEPC/SppC, 13 detector, 1 software, 17physics)

CEPC Roadmap and Schedule (Ideal)

CEPC Project Timeline