CEPC Physics and Detector

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

The 2020 International Workshop on

The High Energy Circular Electron Positron Collider

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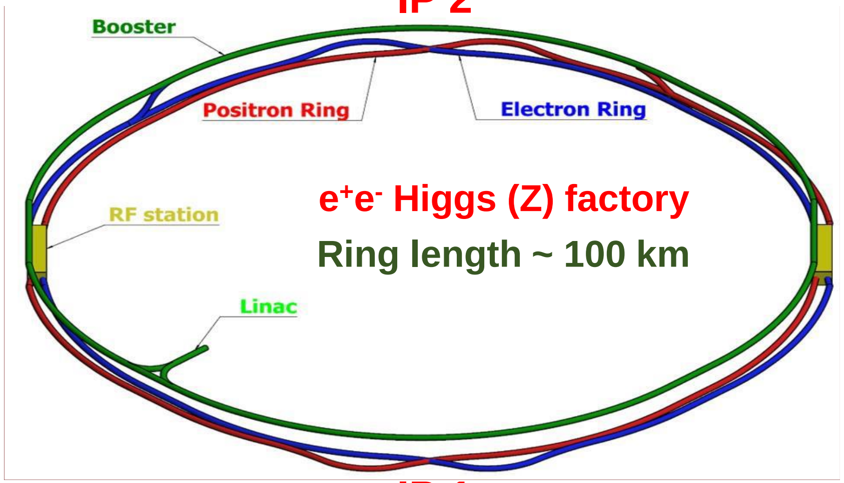
The CEPC Program

- The Circular Electron Positron Collider aims to start operation ~2030's.
- Runs at **ZH** ($\sqrt{s}$ =240 GeV), **Z** (~91.2 GeV), and **W⁺W⁻** (158–172 GeV). It is also possible to run at $t\bar{t}$ (360 GeV).
- No need of hardware change when switching the beam energy.
- Upgradable to a pp collider (SppC) with $\sqrt{s}$ ~ 50–100 TeV.

Two interaction points



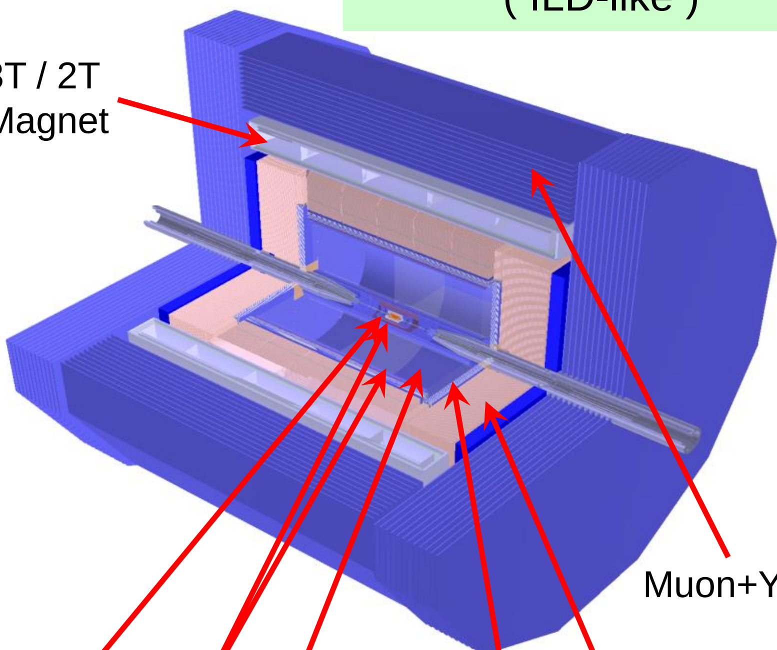
Operation mode	ZH	Z	W^+W^-
$\sqrt{s}$ (GeV)	240	91.2	158-172
L / IP (10^{34} $cm^{-2}s^{-1}$)	**3 (5)**	**32 (102)**	**10 (?)**
Run time (years)	7	2	1
$\int L\,dt$ (ab^{-1}, 2 IPs)	5.6	16	2.6
Event yields	**1×10^6**	**7×10^{11}**	**2×10^7**

Luminosity updated since CDR

Conceptual Detector Designs

Particle Flow Approach
(ILD-like)

3T / 2T Magnet



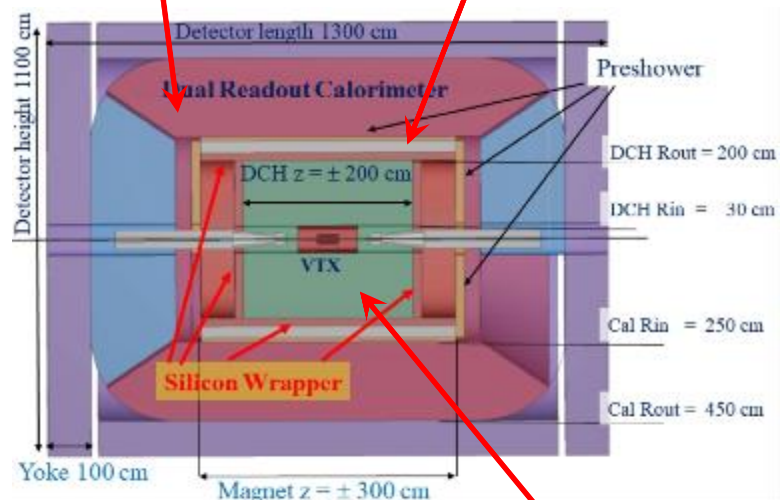
Muon+Yoke

Si Vertex, Si + TPC, PFA ECal &HCal,

IDEA concept
(also proposed for FCC-ee)

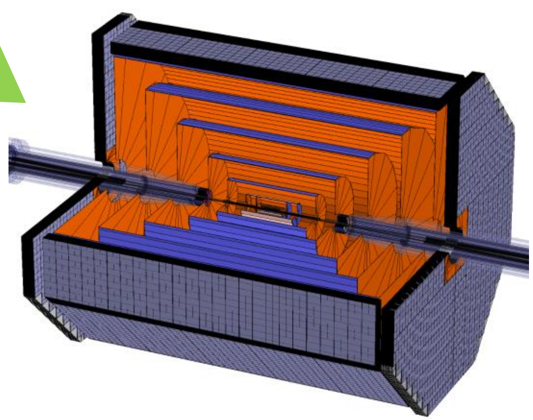
DR Calorimeter

2T Magnet



Drift chamber

Full Silicon Tracker (FST) concept

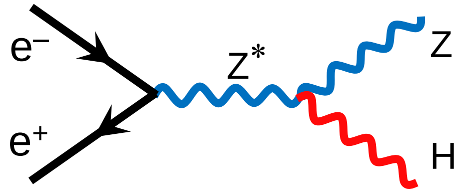


The final two detectors likely are mixtures of different options.

Physics Goals

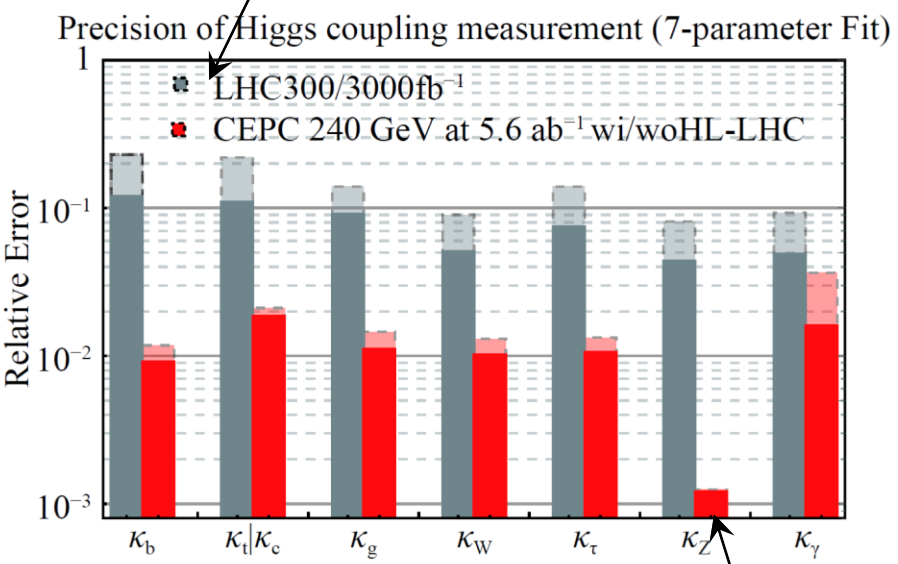
- In its 10-year program, CEPC will produce over **10^6** Higgs, **10^{12}** Z, and **10^8 W** bosons, providing a great opportunity for high precision test of the SM and searching for new physics.
- Higgs runs:
  - Absolute measurements of Higgs boson width & couplings
  - Searching for exotic Higgs decay modes
- Z & WW threshold runs:
  - High precision EW measurements.
  - Rare Z decays.
- It also produces a large sample for flavor physics (b, c, tau) and QCD studies, especially from the runs at the Z pole.
- The CEPC working group has published the Higgs physics white paper: https://doi.org/10.1088/1674-1137/43/4/043002. White papers on the flavor physics, EW, and QCD are in preparation.

Higgs Coupling Measurements



- Higgs boson candidates can be identified through the recoil mass method without tagging its decays
- Model independent measurement of the Higgs boson width.
- Can deliver **≤1%** precision in key measurements of Higgs boson properties, some not accessible at the LHC.
- With recoiling mass technique, it is sensitive to the invisible decays, @ BR ~0.3%.
- Sensitive to exotic decay channels.

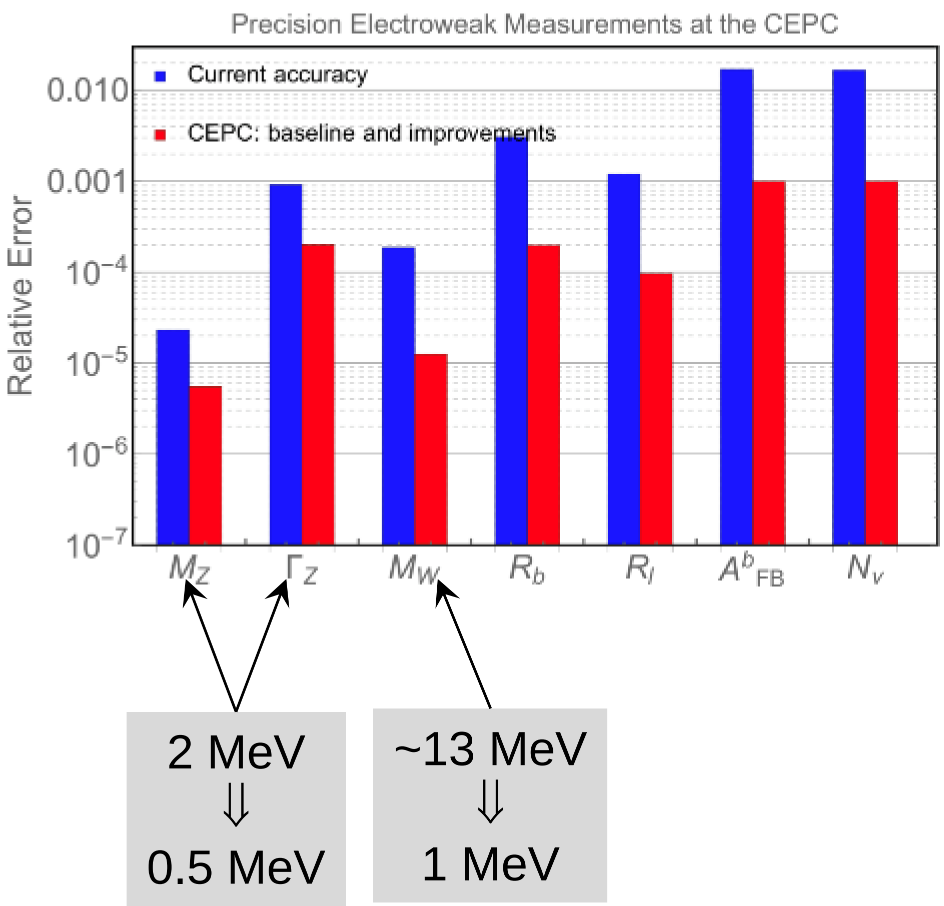
Higgs coupling uncertainty ~ (2-5)% in updated HL-LHC



K_Z uncertainty ~ 0.13%

Most others ~ 1%

Precision 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 10^{12} Z, therefore a huge sample of the b, c & tau.
- It possesses a few key features: clean event background, efficient in e/γ/π^0 reconstruction, high energy to access B_c and b-baryons.
- It 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
$\mathrm{BR}(B_s \to ee)$	2.8×10^{-7} (CDF) [438]	$\sim 7 \times 10^{-10}$ (LHCb) [435]	$\sim$ few $\times 10^{-10}$
$\mathrm{BR}(B_s \to \mu\mu)$	0.7×10^{-9} (LHCb) [437]	$\sim 1.6 \times 10^{-10}$ (LHCb) [435]	$\sim$ few $\times 10^{-10}$
$\mathrm{BR}(B_s \to \tau\tau)$	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 %
$\mathrm{BR}(B \to K^*\tau\tau)$	–	$\sim 10^{-5}$ (Belle II) [442]	$\sim 10^{-8}$
$\mathrm{BR}(B \to K^*\nu\nu)$	4.0×10^{-5} (Belle) [449]	$\sim 10^{-6}$ (Belle II) [442]	$\sim 10^{-6}$
$\mathrm{BR}(B_s \to \phi\nu\bar{\nu})$	1.0×10^{-3} (LEP) [452]	–	$\sim 10^{-6}$
$\mathrm{BR}(\Lambda_b \to \Lambda\nu\bar{\nu})$	–	–	$\sim 10^{-6}$
$\mathrm{BR}(\tau \to \mu\gamma)$	4.4×10^{-8} (BaBar) [475]	$\sim 10^{-9}$ (Belle II) [442]	$\sim 10^{-9}$
$\mathrm{BR}(\tau \to 3\mu)$	2.1×10^{-8} (Belle) [476]	$\sim$ few $\times 10^{-10}$ (Belle II) [442]	$\sim$ few $\times 10^{-10}$
$\frac{\mathrm{BR}(\tau \to \mu\nu\bar{\nu})}{\mathrm{BR}(\tau \to e\nu\bar{\nu})}$	3.9×10^{-3} (BaBar) [464]	$\sim 10^{-3}$ (Belle II) [442]	$\sim 10^{-4}$
$\mathrm{BR}(Z \to \mu e)$	7.5×10^{-7} (ATLAS) [471]	$\sim 10^{-8}$ (ATLAS/CMS)	$\sim 10^{-9} - 10^{-11}$
$\mathrm{BR}(Z \to \tau e)$	9.8×10^{-6} (LEP) [469]	$\sim 10^{-6}$ (ATLAS/CMS)	$\sim 10^{-8} - 10^{-11}$
$\mathrm{BR}(Z \to \tau\mu)$	1.2×10^{-5} (LEP) [470]	$\sim 10^{-6}$ (ATLAS/CMS)	$\sim 10^{-8} - 10^{-10}$

- Extra requirements on detector design:
  powerful PID for π/K separation, good vertex, and ECal.

Key Requirements on Detector

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 be re-evaluated

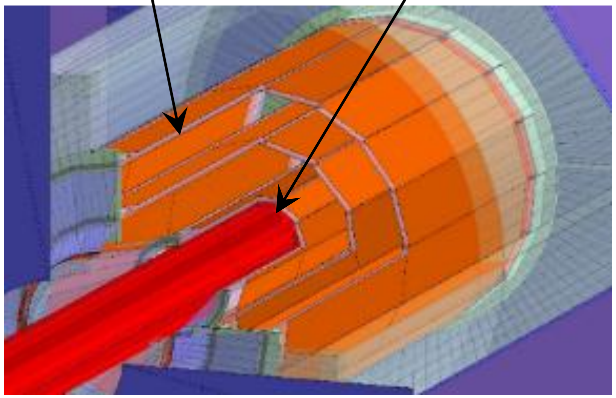
- Excellent PID, for π/K separation up to ~20 GeV.
- High precision luminosity measurement, $\delta L / L \sim 10^{-4}$.

- New interesting physics topics & more simulation studies provide valuable inputs to the detector design.
- The CEPC working group continues on R&D of all sub-systems in the CDR design, and explores various other technologies.
- Selected R&D progresses are reported here.

Silicon Vertex Detector

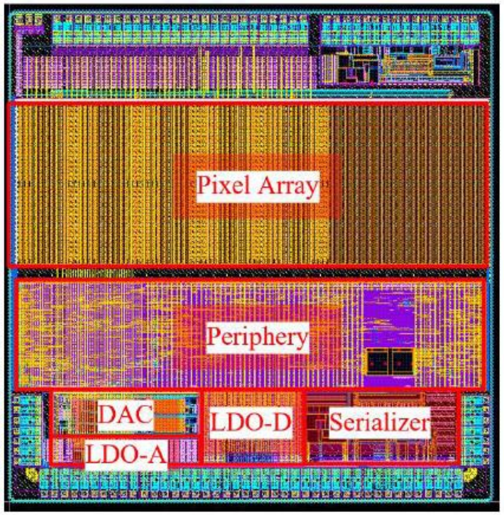
- Goal: σ(IP) ~ 5 μm for high P track.
- CDR design spec:
  - 6-layer silicon pixel CMOS detector, single point resolution ~ 3μm.
  - Low material (0.15% X_0 / layer), low power (< 50 mW/cm^2), rad-hard (1 Mrad/year)
- Developing 2 lines of ASICs:
  - JadePix-3: low power, rolling shutter readout.
  - 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



JadePix-3 Pixel size ~16×23 μm^2

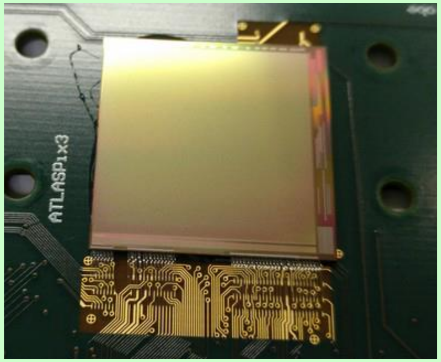
TaichuPix-2, 64×192 array
25×24 μm^2 pixel size

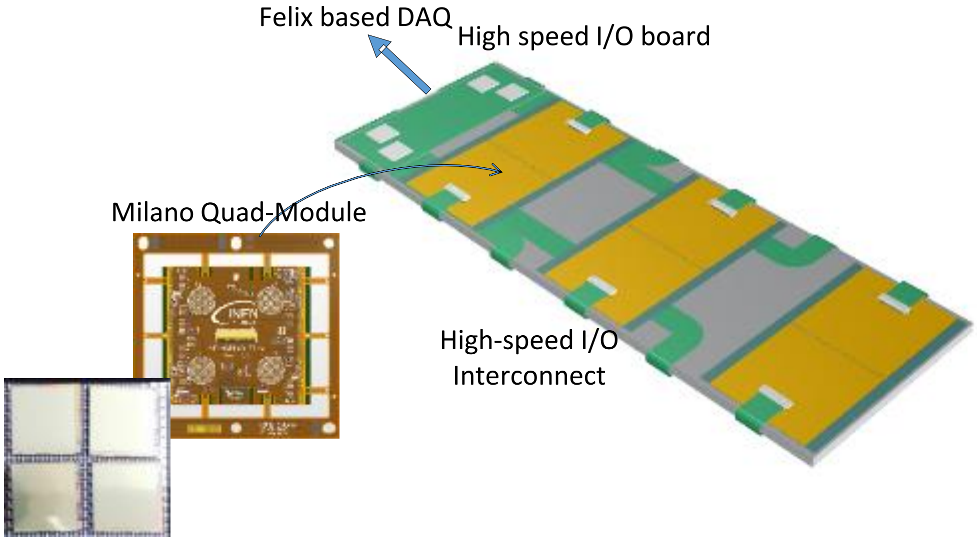


Silicon Tracker

- 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:

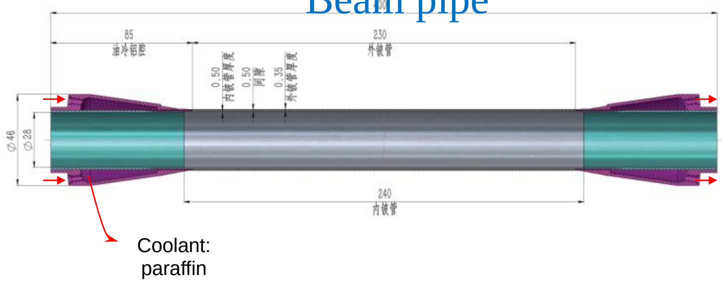
A design optimized for CEPC, basing on ATLASPix3.

Look into domestic production

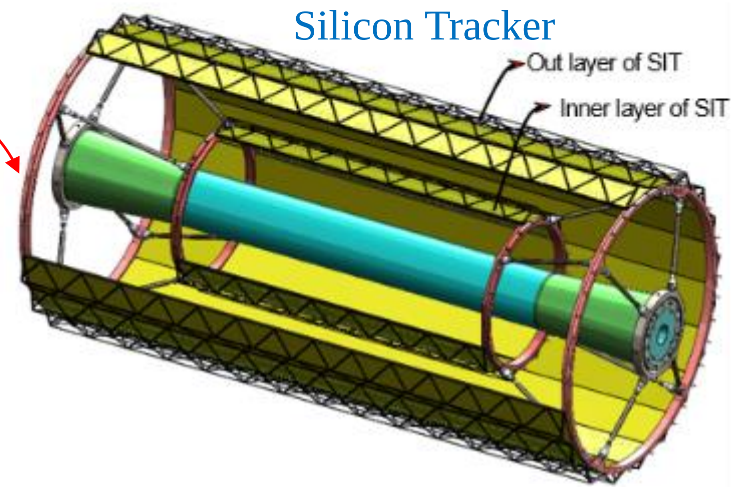
Interaction Region Design

- **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 radius: φ28mm → φ20mm.
- **On-going:** Engineering design of sub-detectors including interfacing, integration installation scheme (focused but not limited to the interaction region).

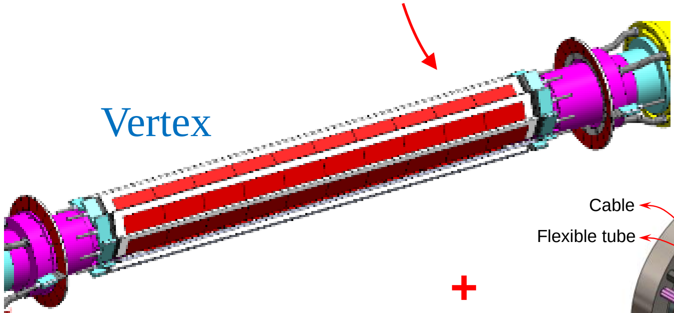
Beam pipe



Silicon Tracker

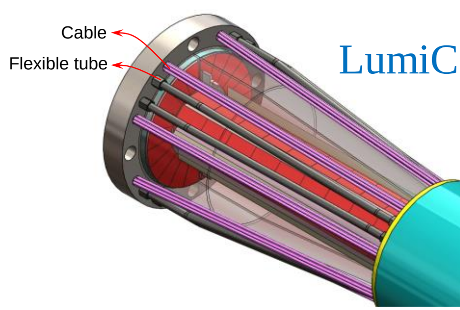


Vertex

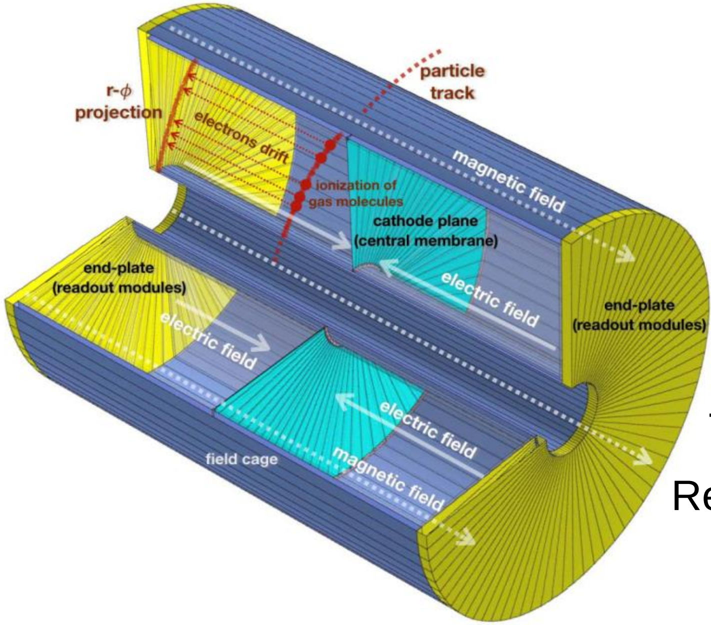


+

LumiCal Tracker



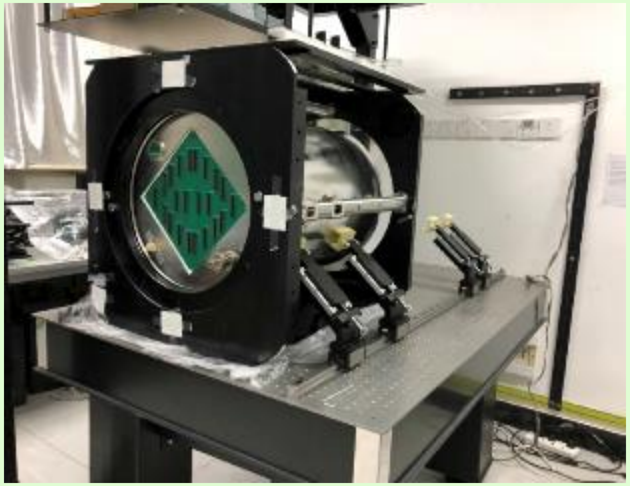
Time Projection Chamber



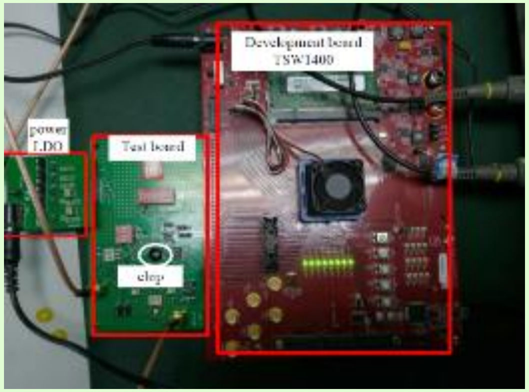
The main tracker

Resol in r-Φ~100 μm

Completed



TPC Prototype + UV laser beams



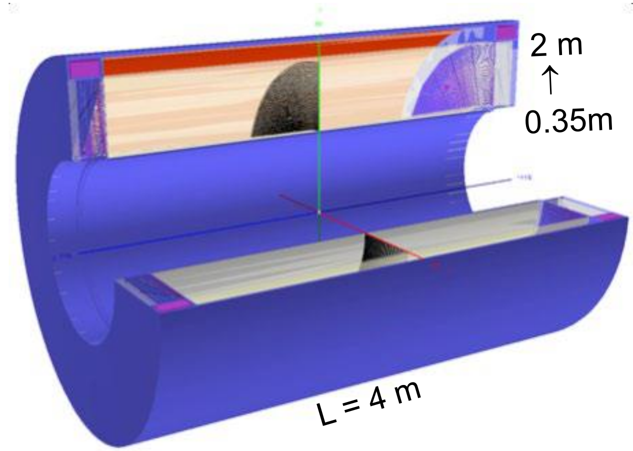
FEE ASIC (65nm CMOS)

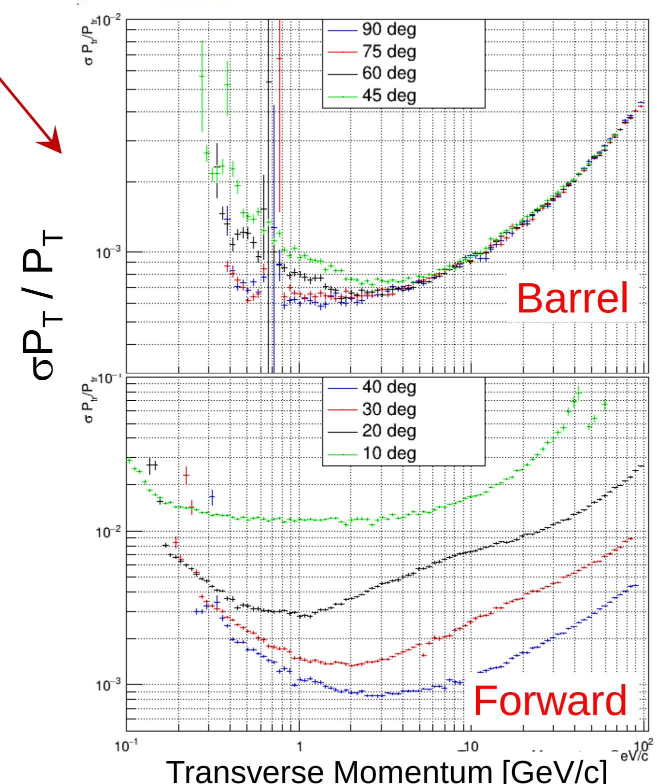
- Challenge: Ion backflow (IBF) affects the resolution.. It can be corrected by laser calibration at low lumin, difficult @ Z-pole.
- Potential solutions to suppress IBF, e.g. Pixel TPC with double meshes.
- When Gain×IBF=1, distortion <16 μm @ L 32 $\times 10^{34}$ cm^{-2}s^{-1}, <49 μm @10^{36} cm^{-2}s^{-1}.

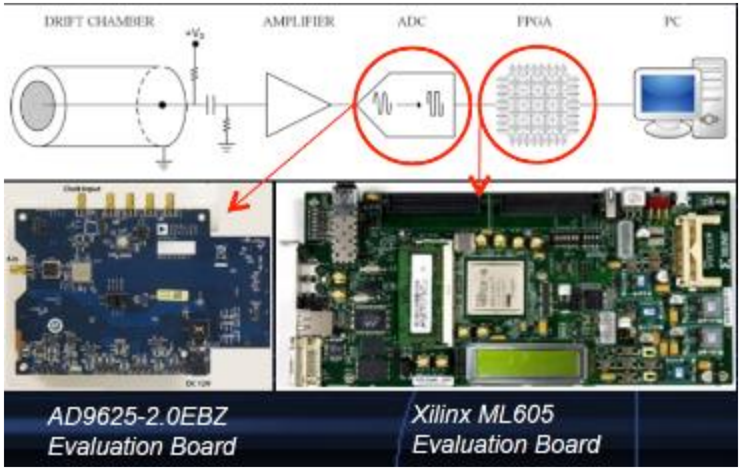
Drift Chamber

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.

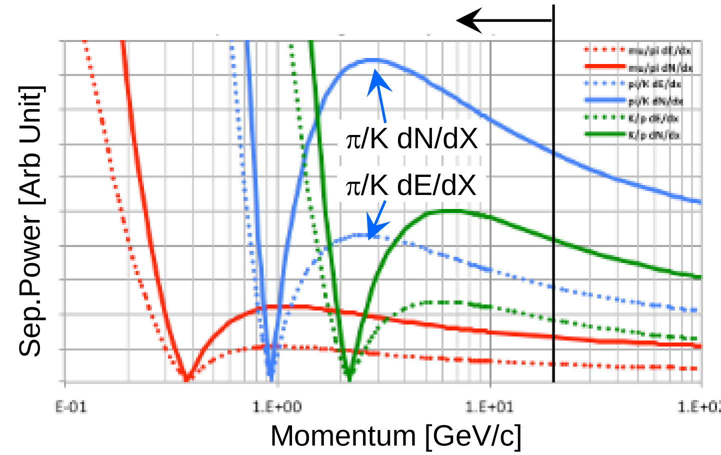






Particle ID Possibilities

- 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.

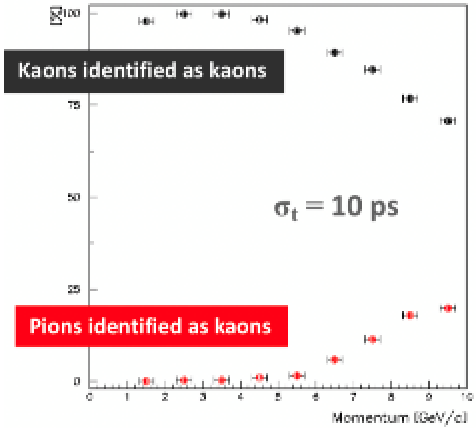


- For the FST solution, a supplement PID detector is needed. Combination of different PID detectors is also viable.

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.

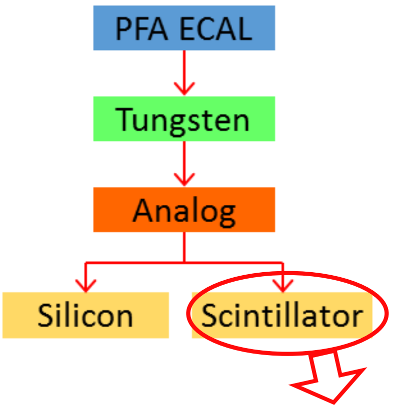
IHEP-NDL LGAD-V2
Pixel size 1.3×1.3 mm^2



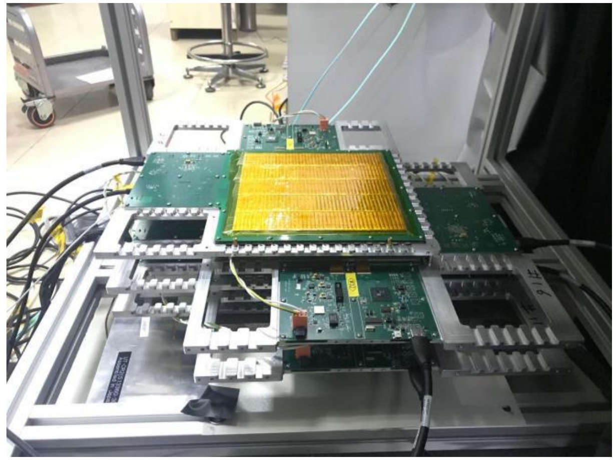
③ A **RICH** of aerogel & gaseous radiators. Space constraint needs to studied.

- More options and studies are needed.

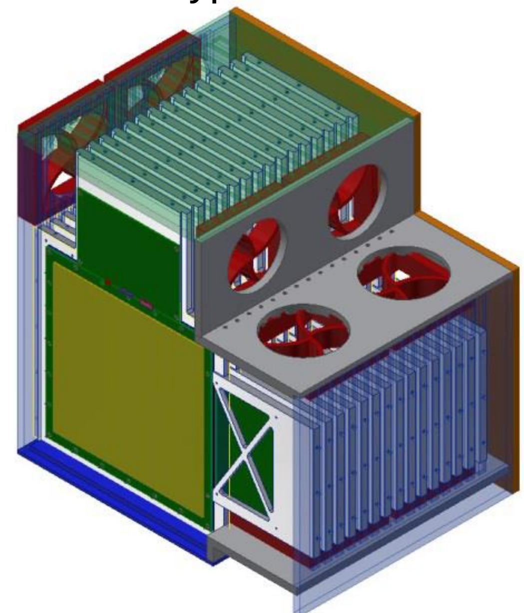
PFA ECAL



Super-layer bench test

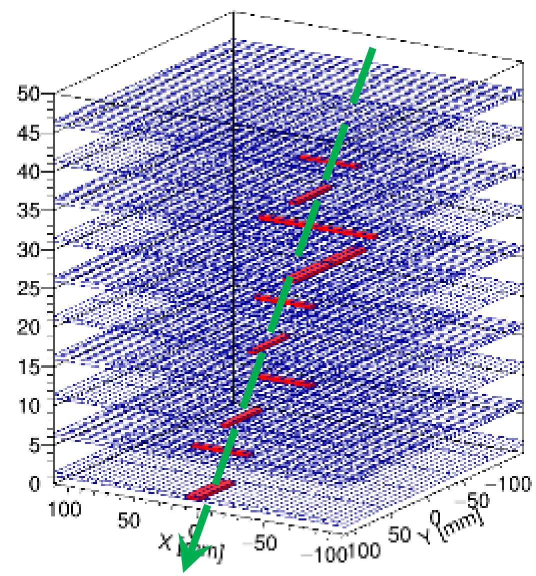


Prototype ScECAL

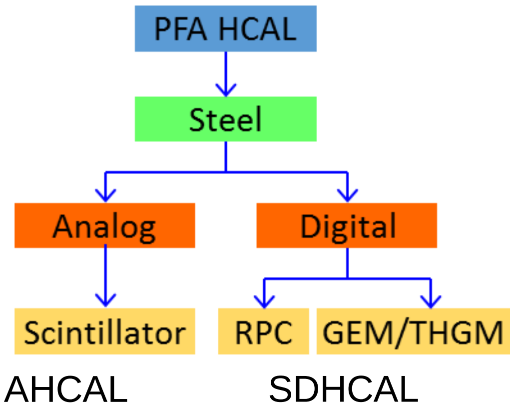


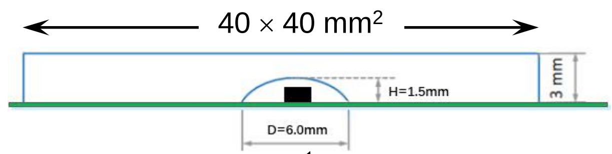
- An alternative PFA ECAL in CDR: scintillator + SiPM as the sensitive detector, tungsten as absorber, totals $24X_0$ radiation length.
- A 30-layer prototype has been constructed: 3.2 mm thick W-Cu plate, scintillator bar size $5 \times 45\ mm^2$, 1 SiPM/bar.
- It has been tested with cosmic rays, will be tested in electron beams at IHEP & DESY.

A cosmic ray event



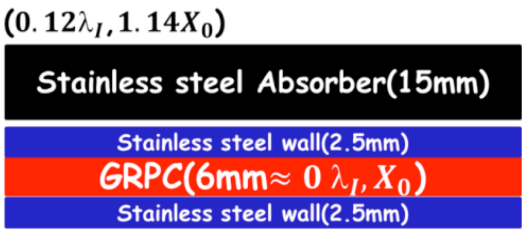
PFA HCAL





- 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.

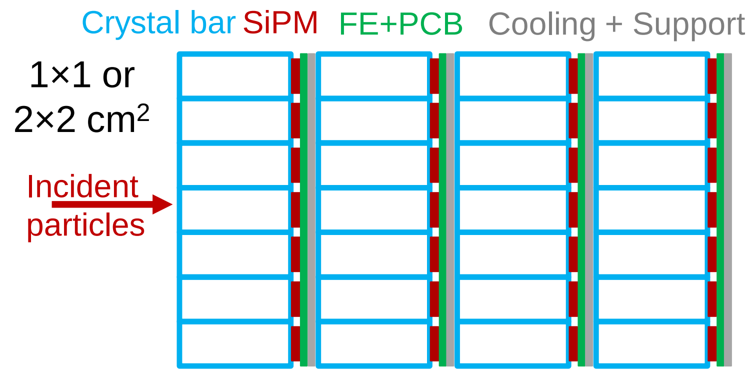
- SDHCAL based on GRPC:
  - Prototype size 1×1×1.4 m³, 48 layers, 1×1 cm² detector cell, 2 cm steel absorber.
  - Construct a 35×50 cm² GRPC before a full size.
- SDHCAL based on MPGD
  - Constructed a 25×25 cm² detector, and studied its performance.



Crystal ECal

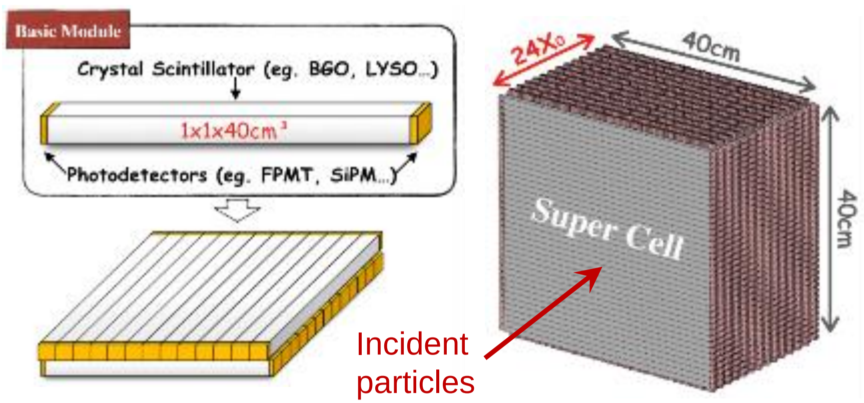
Design 1

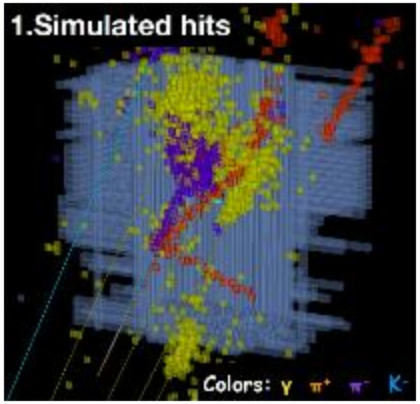
- Single end readout; potentials with PFA
- Study γ/π^0 separation & energy resolution to optimize transverse and longitudinal segmentation.

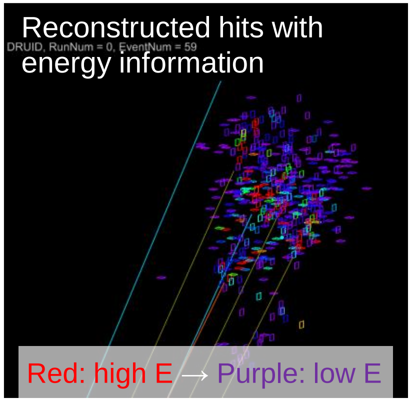


Segments of total length $24X_0$

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.

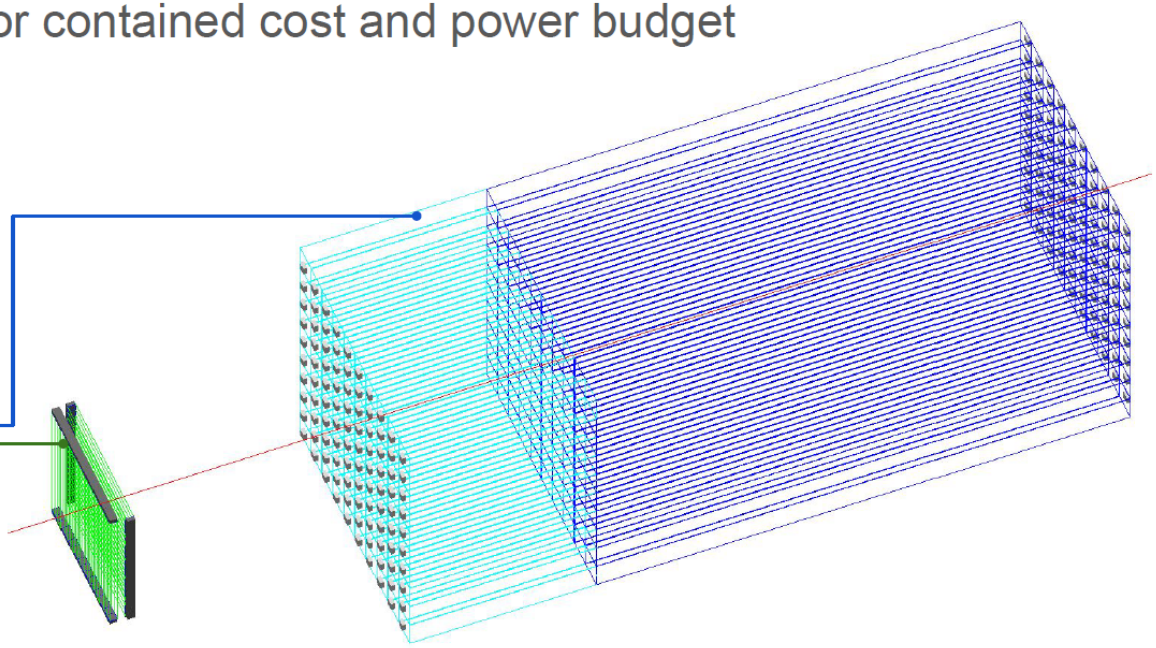
Another Crystal ECAL Design

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

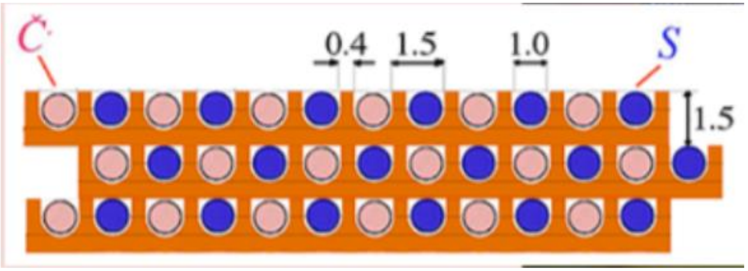
- **Timing layer** — $\sigma_t \sim 20$ ps
  - LYSO:Ce crystals (~1X_0)
  - 3x3x54 mm³ active cell
  - 3x3 mm² SiPMs (15-20 um)

- **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)



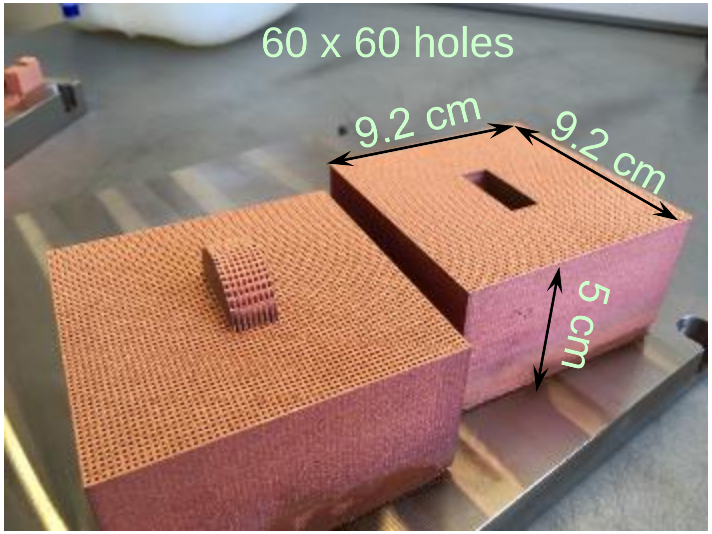
Dual Readout Calorimeter

- 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

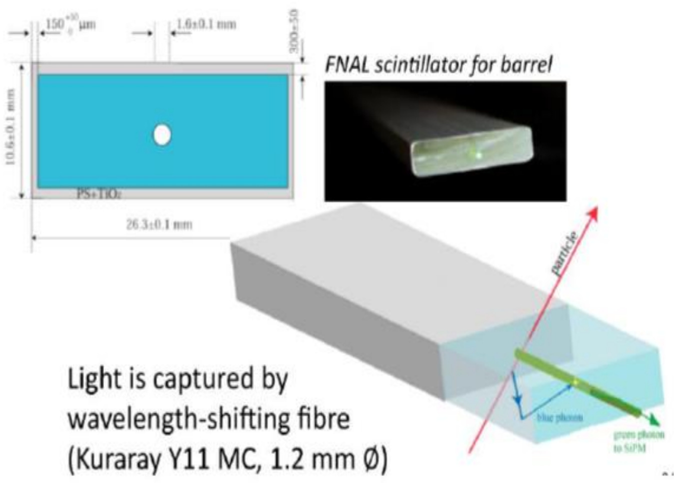


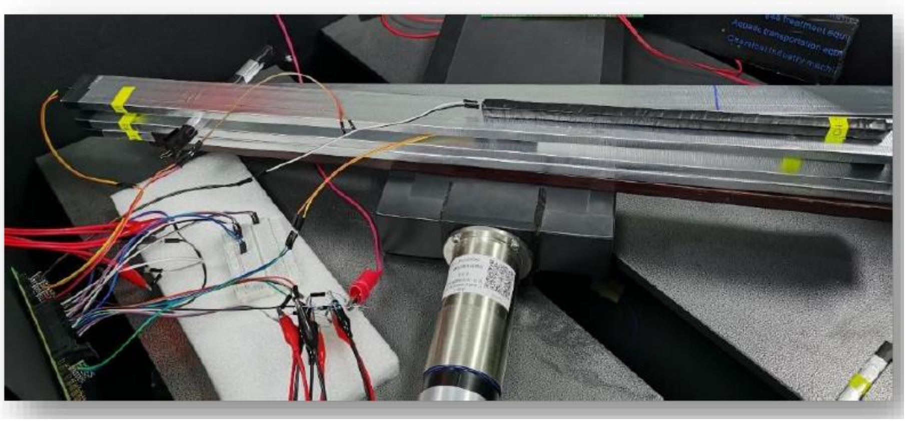
- Detector performance has been studied in simulation.
- Physics performance of benchmark channels, both standard approach & deep learning algorithm.
- Prototype modules are to be built, first an EM prototype by early 2021, then the hadronic size module.
- A 60x60–hole Cu absorber from 3-D printing looks 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 det. 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 in domestic product and MPPC option.

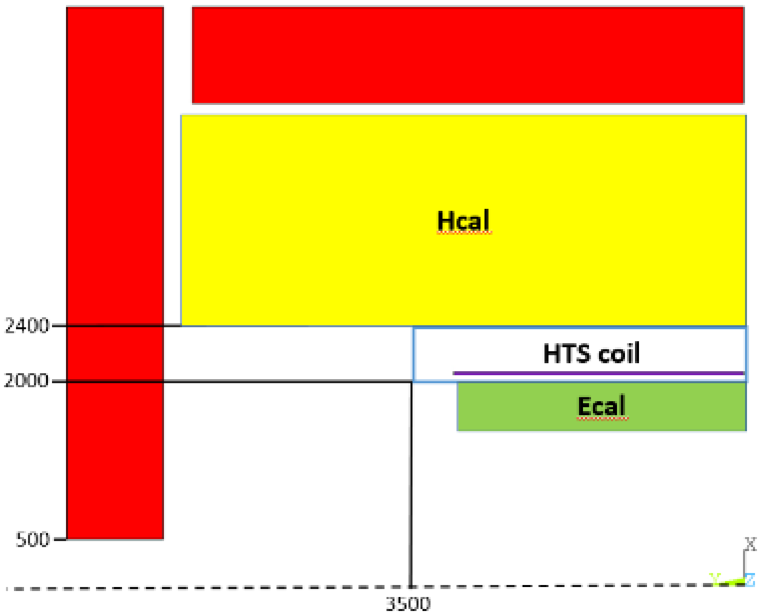


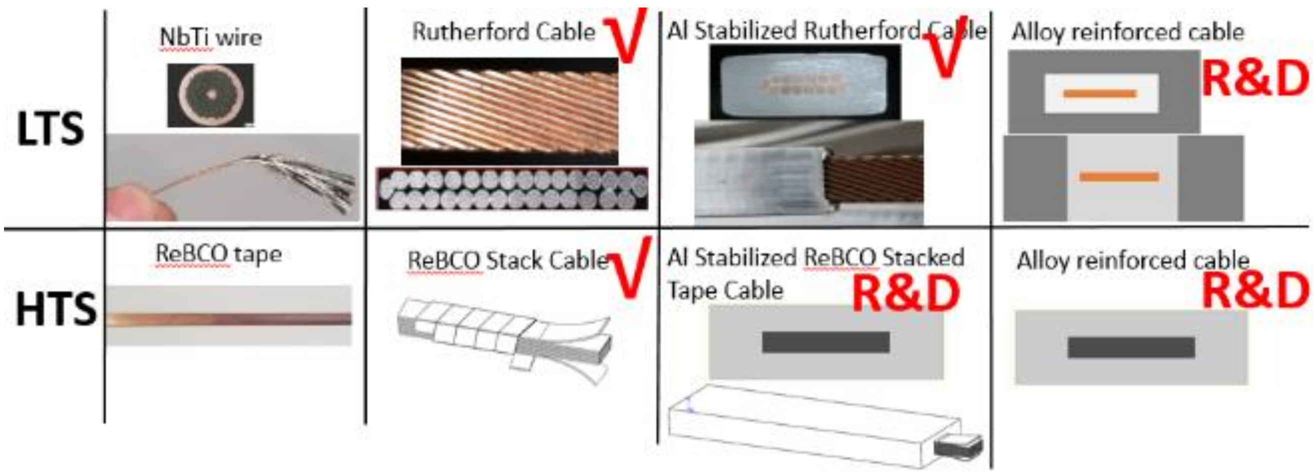


Achieved σ_t~2ns,
Aim for 100-200 ps.

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

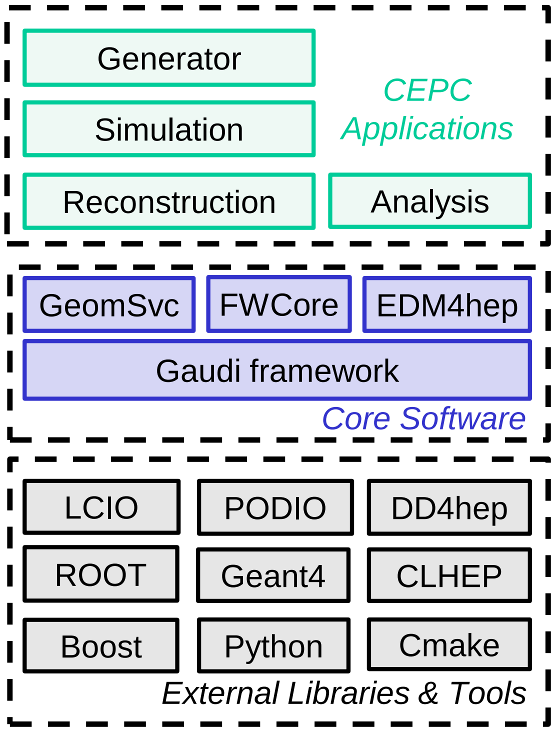


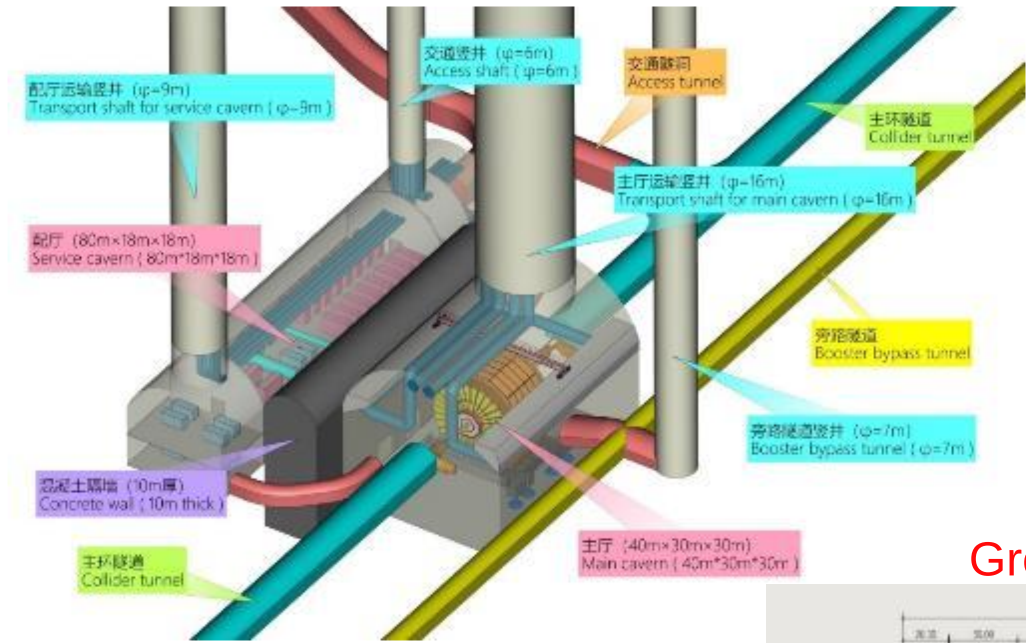


CEPC Software

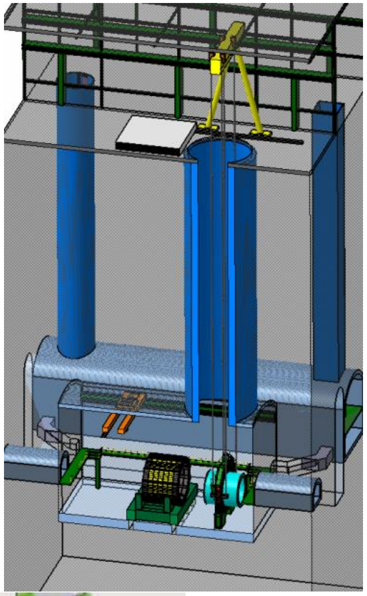
- Core software, external libraries & tools are the base of the CEPCSW. More packages and components will be added when available.
- CEPC applications are created for CDR design. With new type of detectors introduced, corresponding codes are being developed.
- Recent added CEPC applications:
  - Software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





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



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

Ground level buildings

Final Comments

- The CEPC provides great opportunity in high precision test of SM and search for new physics.
- The CEPC working group is actively exploring different detector technologies, listed in the CDR, or new solutions.
- We aim to form international experiment collaborations for both IP's, and release the detector TDRs in couple of years.
- We welcome new collaborators to this quest.
- A few potential topics are listed on the next page, in case you need one to start with. Of course contributions in other topics are also welcome. If you are interested, or have any interesting idea to contribute, please contact us.

Potential Topics

- Advanced reconstruction algorithms and software within the CEPCSW frame, to address the physics requirement at CEPC Higgs/Z operation.
- Implementation of detector performance that is currently achievable and projection of a few years later, for a more realistic detector simulation.
- Analysis of benchmark physics topics, especially in the flavor physics & QCD, and providing input and requirement to the detector design.
- Beam background and radiation level assessment near the interaction region.
- High precision luminosity measurement that delivers a10^{-4} precision.
- Particle identification solutions for tracks of $P < \sim 20$ GeV.
- Silicon sensor, low mass mechanical support and cooling for Vertex and Si Tracker.
- Evaluate and improve the TPC operation at high hit rate.
- Optimize calorimeter design for better γ/π^0 reconstruction and jet resolution.
- Technologies that help transferring data off the FE, including wireless communication, optical communication, and data reduction.
- High order EW/QCD correction, as the theoretical uncertainty is comparable with the experimental one.