CEPC calorimetry status:
a brief summary of the topical workshop

Yong Liu (IHEP)

CEPC Physics and Detector Meeting

Apr. 3, 2019

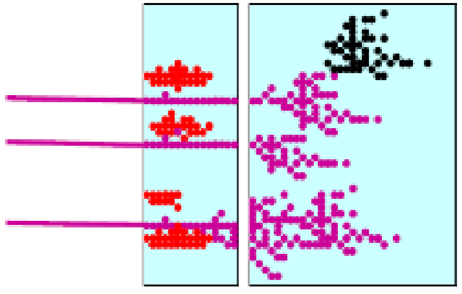
Introduction

- Topical Workshop on the CEPC Calorimetry
  - March 11-14, 2019
  - https://indico.ihep.ac.cn/event/9195/
  - ~45 participants (and via remote connection)
    - From China, France, Germany, Italy, Korean, US

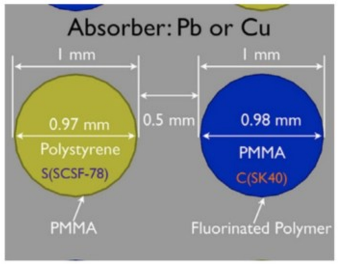
- The first workshop: dedicated to CEPC calorimeters
  - Cover a large range of options
    - Major options: PFA-oriented, crystal, dual readout
  - Fruitful and in-depth discussions
    - Motivations, (expected) performance, pros/cons, cost, occupancy, etc.
  - General impression: very positive feedback from many participants

Calorimeter options: overview

- CEPC CDR: baseline options
  - PFA-oriented: high granularity, sampling calorimeters
  - Optimized for precision measurements of jets ($\sim 30\%/\sqrt{E}$)
  - ECAL: silicon, or scintillator-SiPM (sensitive); tungsten (absorber)
  - HCAL: scintillator-SiPM, or RPC (sensitive); steel (absorber)



- CEPC CDR: alternative option
  - Dual-readout: Cherenkov and scintillation signals (f_{EM} for each event)
    - Aim to improve the intrinsic hadronic energy resolution ($\sim 30\%/\sqrt{E}$)

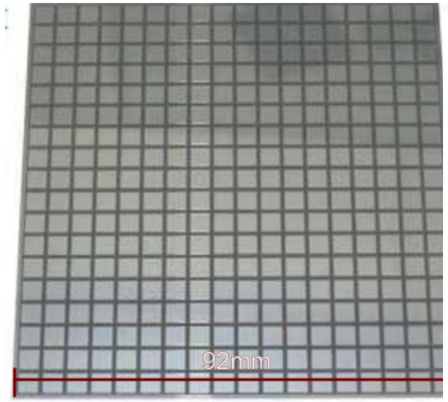


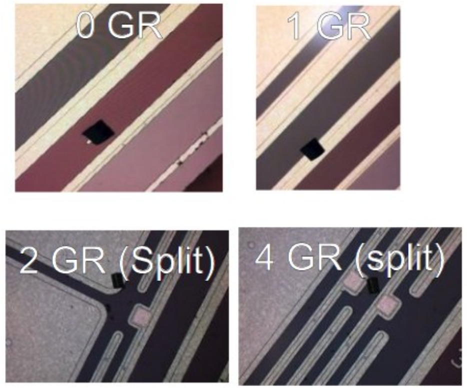
- New proposals: based on crystals
  - Homogenous calorimeter : excellent intrinsic energy resolution
  - Segmentation: to be optimized for PFA
  - Several interesting talks presented

PFA calorimetry: CALICE Si-W ECAL (1)

Vincent Boudry

- Overview
  - 300k wafers (2500m²), 1.2M ASICs; #channels: 77M
  - Cost estimate for ILD: ~158 M€
    - 30 layers ($24X_0$), R=1.8 m
  - Possibly reduce cost by 30-40% for CEPC: <=100 M€
    - 26 layers, R=1.5 m
- Cost driver: Si-sensor
  - ~30% of the SiW-ECAL total cost
  - New: thicker wafers (8”), guard ring studies
- R&D: towards engineering prototype
  - To address technical challenges: complex components
    - Mass production and QA of Si-modules (ASU+Slabs)
  - ~11 years R&D till now: 1st ECAL tech. prototype



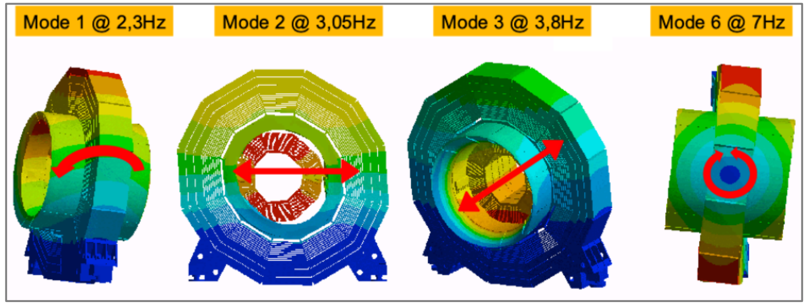


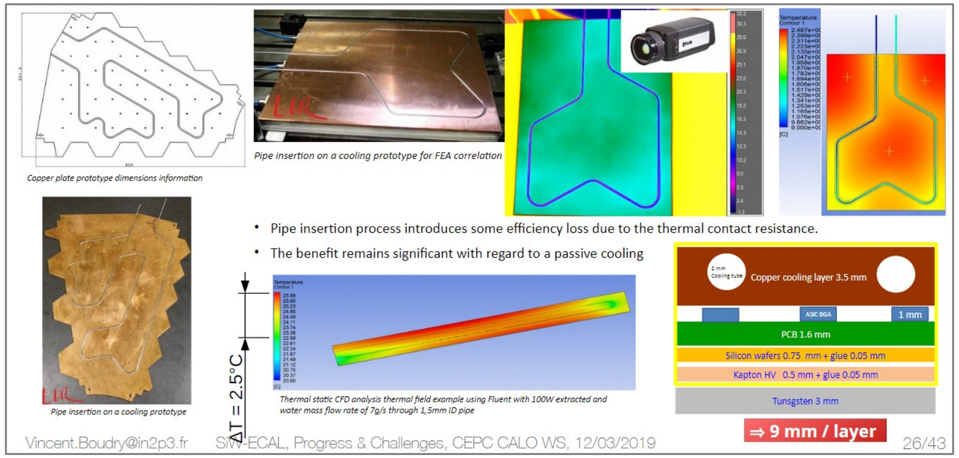
The 1st long slab, under test at DESY (2018)

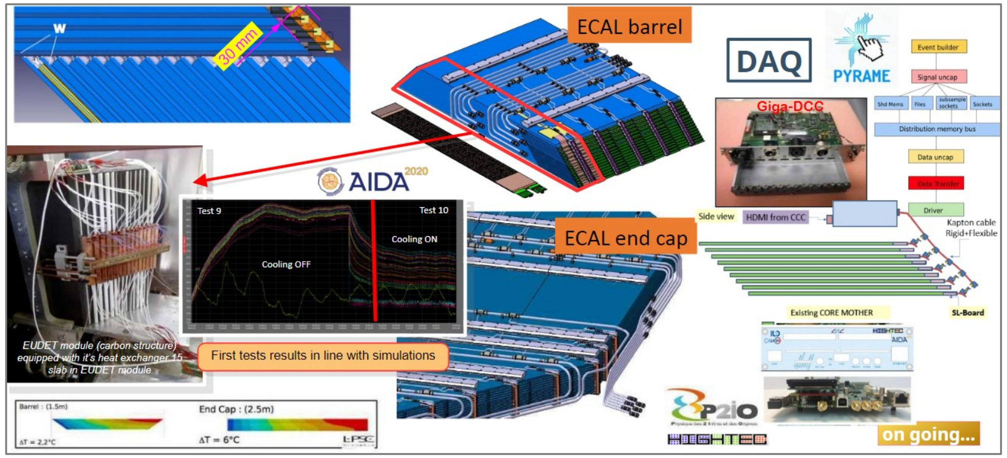
PFA calorimetry: CALICE Si-W ECAL (2)

Vincent Boudry

- Hermetic ECAL: response uniformity
  - Impact from cracks in simulation
- Static and Dynamic Simulations
  - Impact from weight and seismic vibrations
- Services: rails, cables, pipes
- Active cooling: synergy with CMS-HGCAL

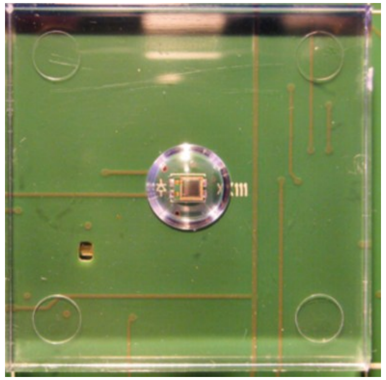


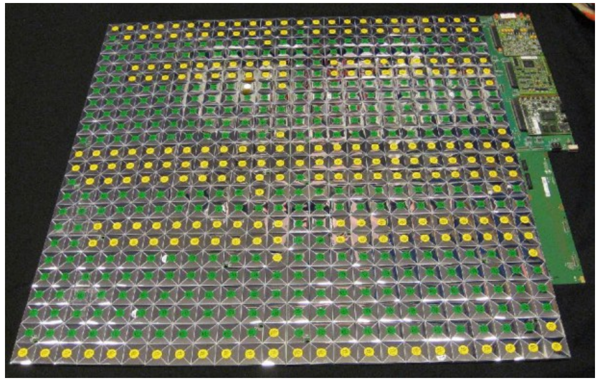


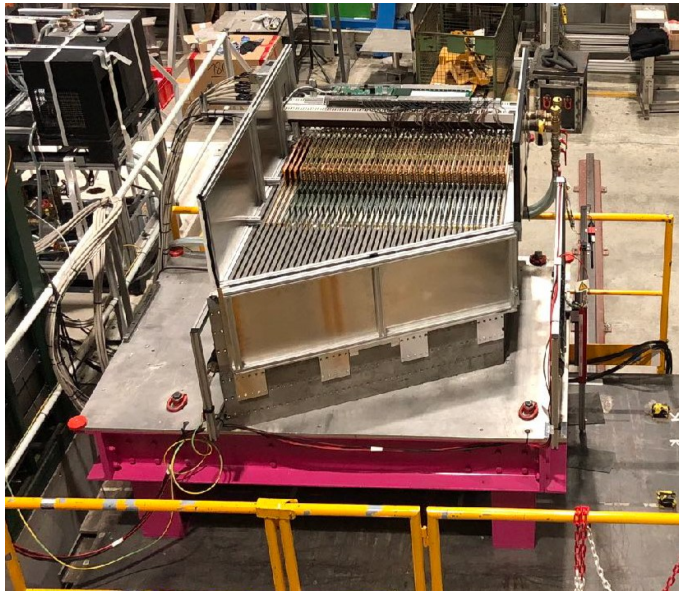


PFA calorimetry: CALICE AHCAL

- Overview
  - Scintillator-SiPMs + Steel
  - #channels: ~8M; 48 layers ($6\lambda_I$)
  - Cost estimate for ILD: ~45 M€
  - PCB: a key cost driver
    - Complex design and stringent requirements
    - **13.2 M€ for readout boards in ILD-AHCAL**
- R&D: towards engineering prototype
  - To address technical challenges
    - Mass production (automated), QA, scalable DAQ
  - 38-39 layers, ~22k channels (~1% ILD-HCAL barrel)
  - Finished in 2018, 3 beam tests at CERN







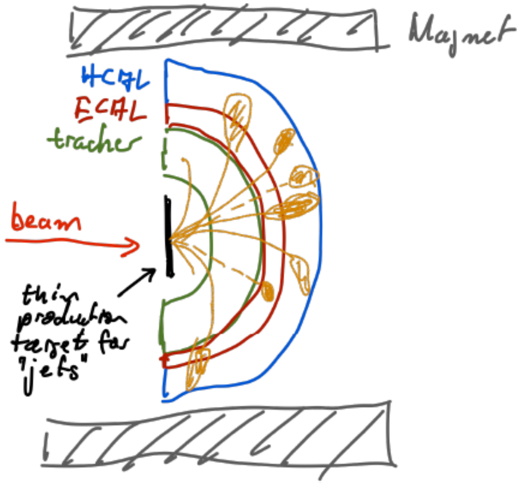
Validation of PFA with test beam?

Frank Simon (MPI)

Validating PFA Performance

Possible Approaches

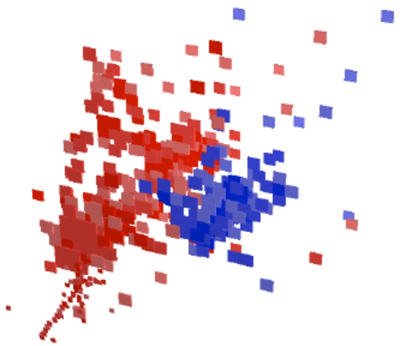
- A fully realistic test of PFA in a test beam is (close to) impossible
  - requires “jets”, tracking and momentum measurement & calorimetry covering all particles

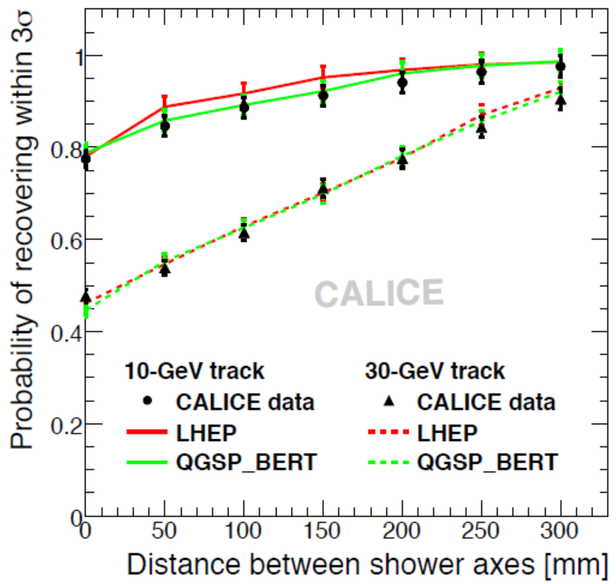


… and even with such a setup there are limitations:
jet energy not very well defined, particle composition, …

➩ The CALICE approach: Factorize the problem: Full PFA in simulations, test individual ingredients in beams

For calorimeters: Energy reconstruction, resolution and two-particle separation





Thoughts on PFA Calorimetry at CEPC - March 2019   Frank Simon (fsimon@mpp.mpg.de)   2

Validation of PFA with test beam?

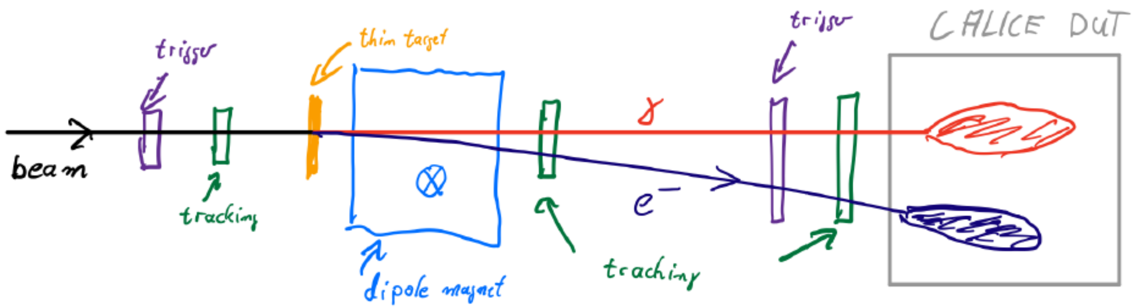
Frank Simon (MPI)

Validating PFA Performance

Possible Approaches

- Still, combined measurements of tracking and calorimetry remain interesting - and in some cases this can also be done with reasonable effort in beam tests:

- One example: Tagged photons - can be used to test electron / photon separation, bremsstrahlung recovery, …



… has for example been used to study a very compact SiW ECAL for luminosity measurements at Linear Colliders

- For hadrons this is much more difficult - impossible to tag neutral hadron energy in that way…: Combined measurements of tracking and calorimetry with a target can be made, but there is very little control - unlikely to yield quantitative performance results, but useful as an integration exercise

Thoughts on PFA Calorimetry at CEPC - March 2019 Frank Simon (fsimon@mpp.mpg.de) 3

Dual-readout calorimeter

Roberto Ferrari (INFN)

- Performance in Geant4 simulation
  - EM resolution: $10.3\%/\sqrt{E} + 0.3\%$
  - Hadronic resolution: $\sim 34\%/\sqrt{E}$
- Cost estimate

INFN PAVIA

accountability – some numbers

	Quantity	U.C.(€)	Cost (M€)
Total volume	474 m^3		
External surface	382 m^2		
Fibre length	230k km	250	57.4
Lead	3338 ton	2000	6.7
# of fibre / SiPM	191M	0.25	47.7
# of ASIC	6M	3	17.9
# of FPGA	23k	500	11.6
Services at al.			13.0
	Total		154.3

+ 3.7 (8.4) M for Iron (Copper)

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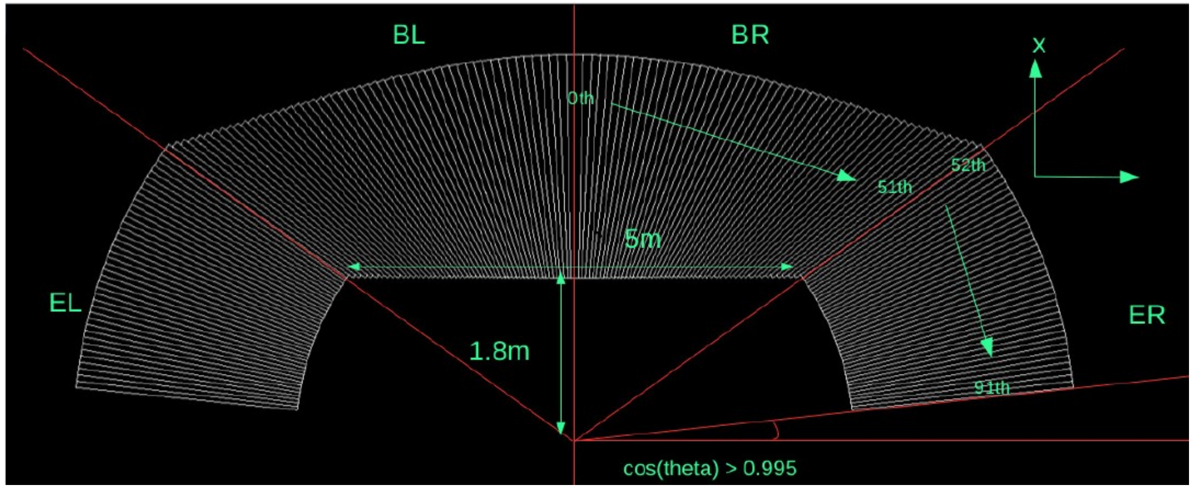
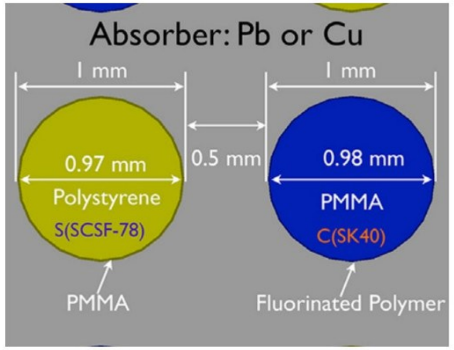
Dual-readout calorimeter: wedge geometry



Fiber arrangement inside a module



(a)

(b)

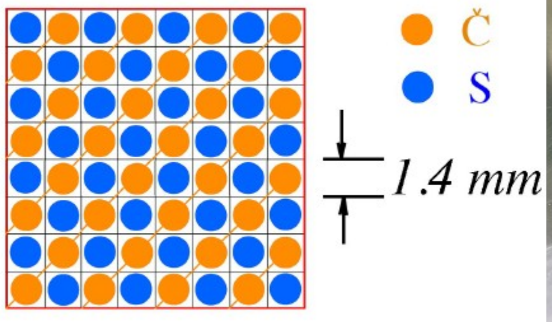
Dimensions of a module

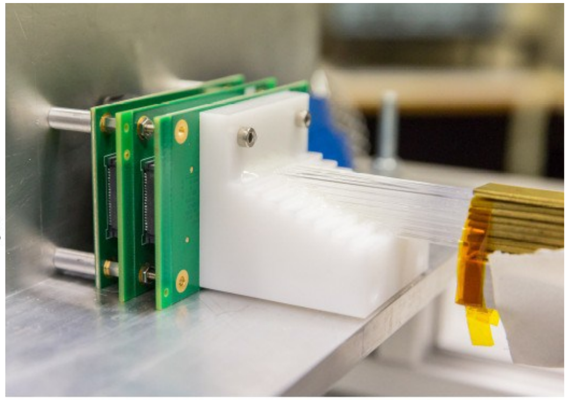
Dual-readout: open issues for CEPC

Roberto Ferrari (INFN)

- Absorber: lead, brass, iron
- Geometry of active material: tiles vs. fibres
- Segmentation: longitudinal and lateral
- Fibre-readout granularity
  - Group several SiPMs in readout
- Front-end electronics (ASIC)
  - Analog charge integration: e.g. SPIROC
  - Digital sampling : e.g. AARDVARC
- Energy reconstruction
  - Dual-readout (established) vs machine learning (new)

2018 RD52 Brass module: ~112 cm long, 12×12 mm²

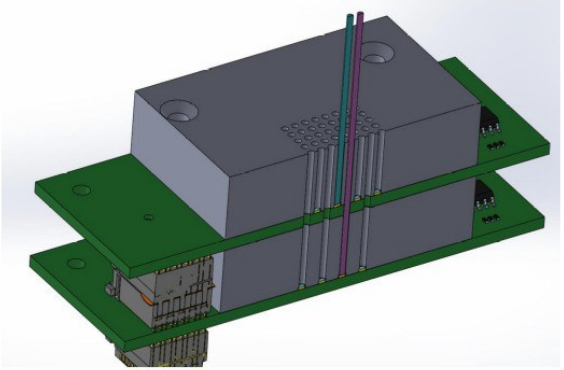




32 (S) + 32 (Č) fibres
$X_0 \sim 29$ mm
$R_M \sim 31$ mm

$\sim (0.4\ R_M)^2 \times 39\ X_0$

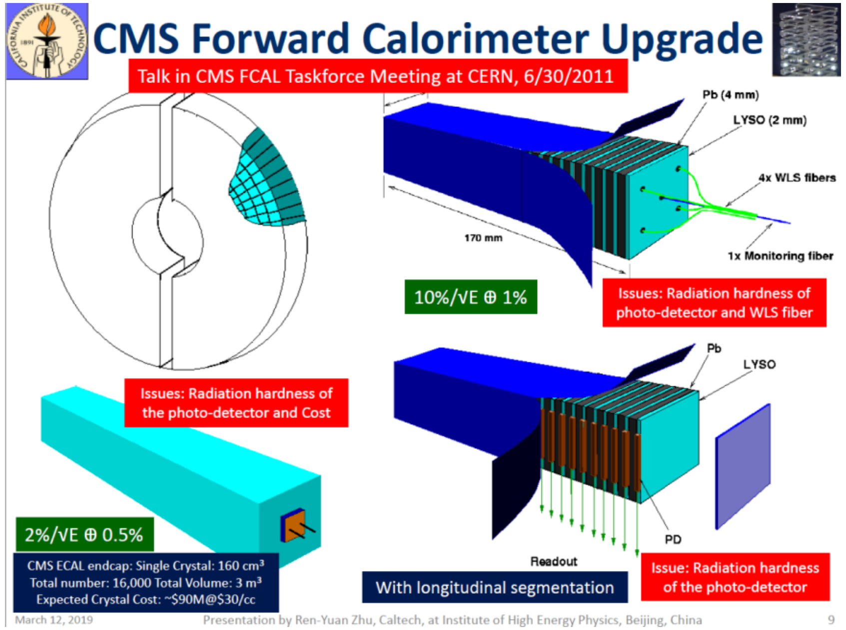
shower cont. ~ 45%
$f_{sampl} \sim 5\text{-}6\%$

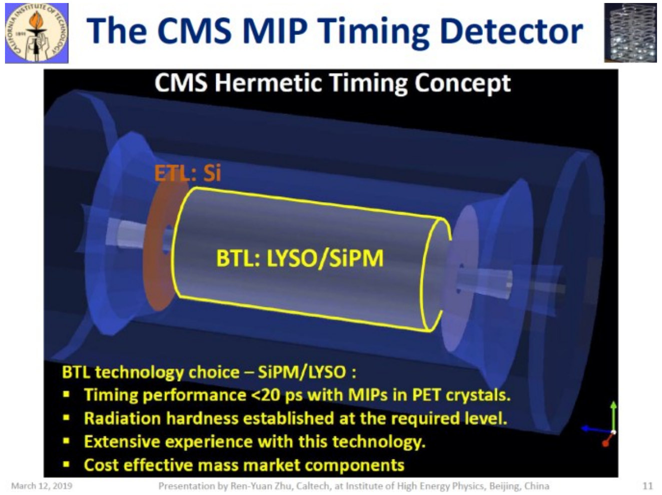


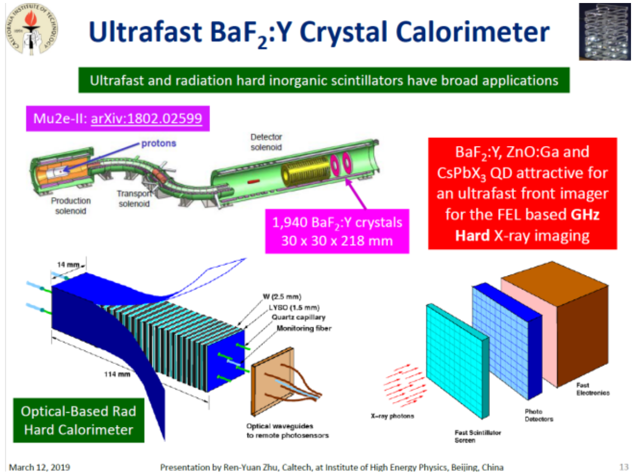
Crystal calorimeters

Ren-Yuan Zhu (Caltech)

- Overview
  - Not included in CEPC CDR
  - Optimal intrinsic energy resolution
    - $\sim 3\%/\sqrt{E}$ or better achieved for electrons/gammas
  - Many successful HEP applications since 1975
    - NaI (Crystal Ball), BGO (L3), CsI (BaBar, Belle, BES3, CLEO…), PbWO (CMS)
  - Future crystal calorimeters in HEP
    - LSO/LYSO for COMET, HERD, and HL-LHC
    - CsI and BaF2:Y for Mu2; PWO for PANDA
- CEPC requirements: not as stringent as HL-LHC
  - Response time, radiation hardness
  - Wide open for innovative detector concepts

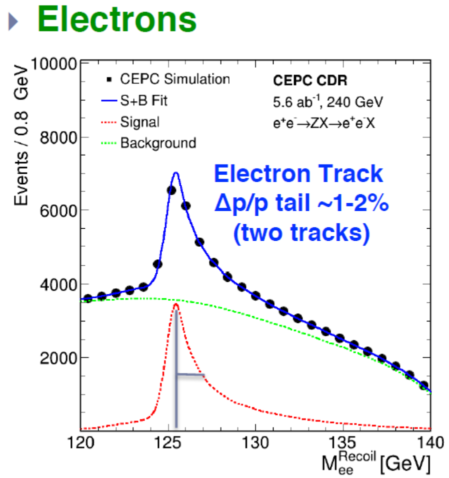




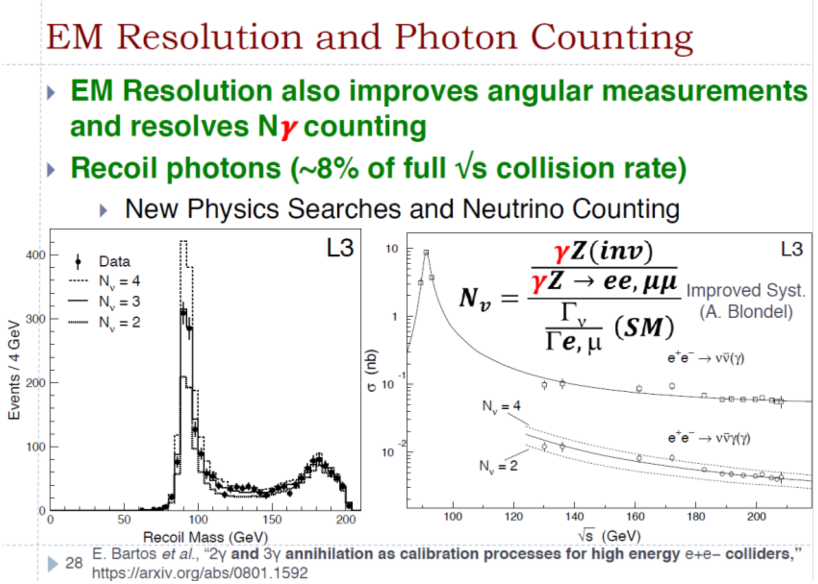


Crystal calorimeter for CEPC

- Cost estimate: crystal raw materials only (made by YL)
  - PbWO crystal for CEPC ECAL: ~131 M$
    - ~12 m^3 for barrel, ~4.4 m^3 for 2 endcaps
      - 24X0 in total, R=1.8m, Z=4.7m
    - Based on the price $8/cc for PbWO (volume at 10m^3 level)
- Physics motivations
  - Electrons' Bremsstrahlung: energy recovery
  - Improve angular resolution, and gamma counting
  - Recoil photons: new physics and neutrino counting
- Several new designs proposed for CEPC ECAL
  - Christopher Tully (Princeton), Sarah Eno (Maryland)
  - Yong Liu (IHEP)
  - Junguang Lv, Zhigang Wang (IHEP)
  - Manqi Ruan, Yuexin Wang (IHEP)



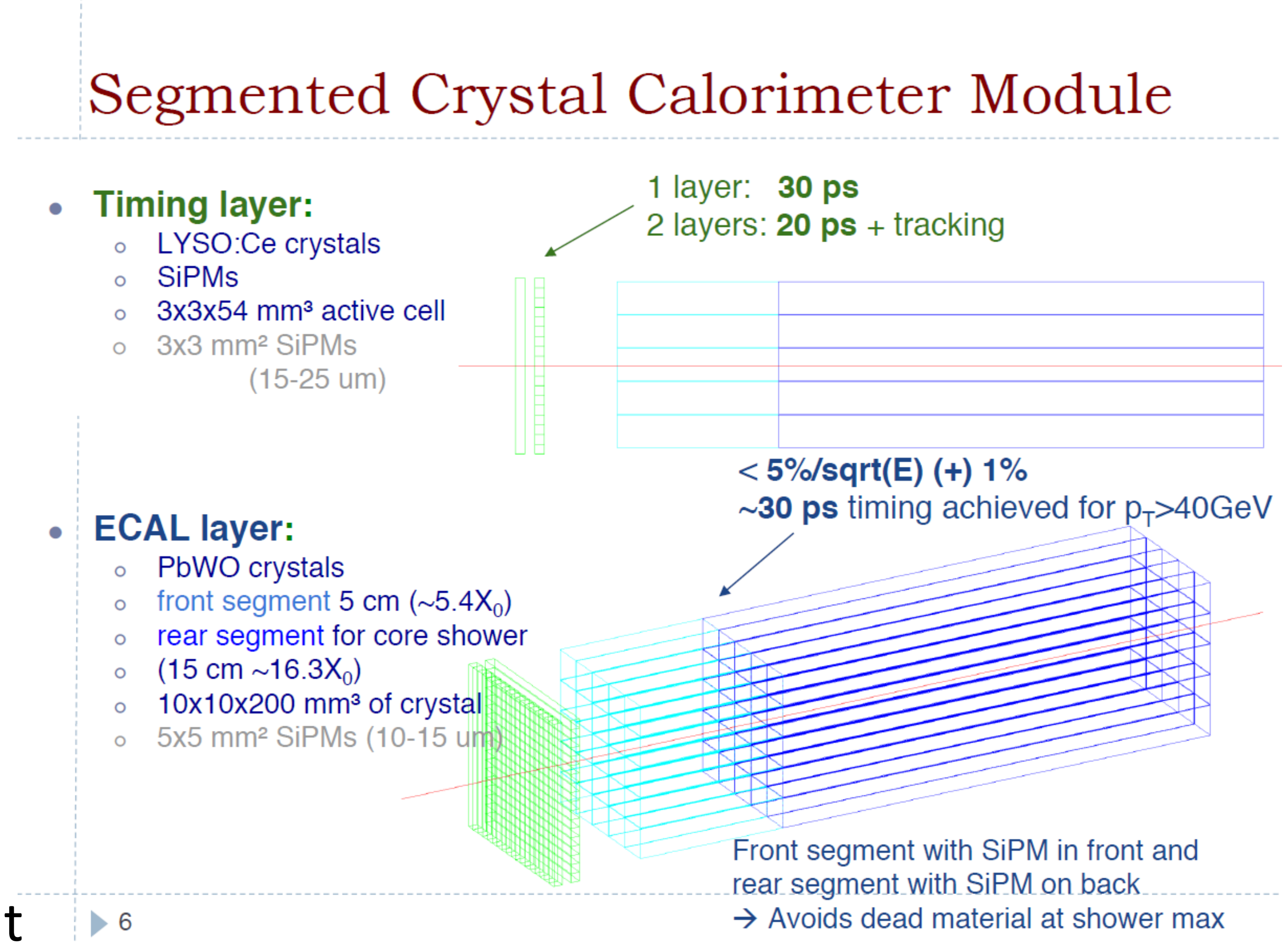
Talk from Christopher Tully



Crystal calorimeter: new designs for CEPC (1)

Christopher Tully (Princeton), Sarah Eno (Maryland)

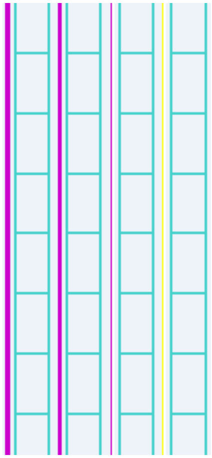
- Comprehensive simulation studies
  - Quantitative studies in Geant4
- Impacts to energy resolution from
  - Dead materials
    - Readout boards, cooling plates, cables
  - Sub-detector in front: tracker
  - Photostatistics (SiPM)
- Calorimeter: other performance
  - Single/pair EM showers
  - $e^{-}/\pi^{\pm}$ discrimination
- Timing layers
  - LYSO bars: ~20 ps timing resolution
  - Time-of-Flight: Particle ID performance
- Compatible with PFA and dual readout

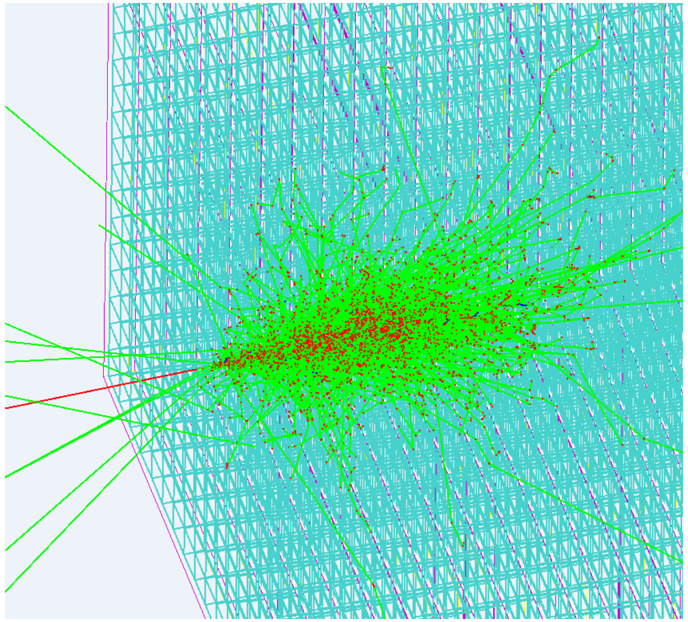


Crystal calorimeter: new designs for CEPC (2)

Yong Liu (IHEP)

- Design: PFA homogenous ECAL
  - Silicon layers (high granularity): positioning
  - Crystal layers: optimal energy resolution
    - Note: all PFA calos till now are sampling calorimeters
- First simulation studies in Geant4
  - Energy sampling fraction >90% (with BGO)
  - Stochastic term from energy fluctuations <1%
  - Also investigated the performance (trade-off) when using some absorber for compactness
- Open issues: worthwhile for further studies
  - Photostatistics from SiPM, crystal-SiPM coupling
  - Impact from dead materials: e.g. between layers
  - Longitudinal sampling frequency
  - Transverse granularity in crystal layers





$$\sigma_E/E = \frac{0.8\%}{\sqrt{E}} \oplus 0.3\%$$

If high-density lead glass (~6g/cm³) can be produced, an interesting cost-effective option

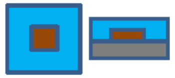
Crystal calorimeter: new designs for CEPC (3)

Junguang Lv, Zhigang Wang (IHEP)

- Option 1: crystal tiles + absorber
  - Cost estimate: 0.7-2B CNY; expected performance: $\sigma_E/E \leq 6\%/\sqrt{E}$
- Option 2: crystal blocks
  - Cost estimate: ~1.2B CNY; expected performance: $\sigma_E/E \leq 4\%/\sqrt{E}$

MC simulation studies: not done yet; neccessary for performance/optimization

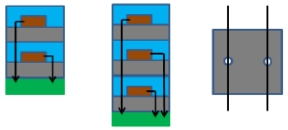
Option 1: Sampling ECAL



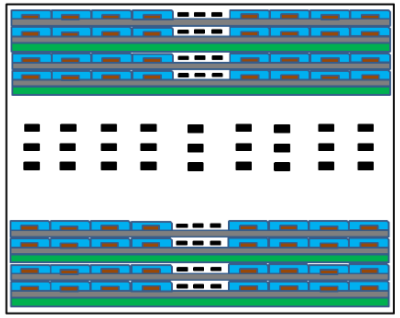
Sensitive Unite(SU)

1.5mm/W+2mm/PS+SiPM , 60 layers

PS: 10mmx10mmx2mm
SiPM: 3mmx3m, 5μm pitch, PDE>10%



Two or three even six SU connected together to readout as one channel
-**Read Unite (RU)**



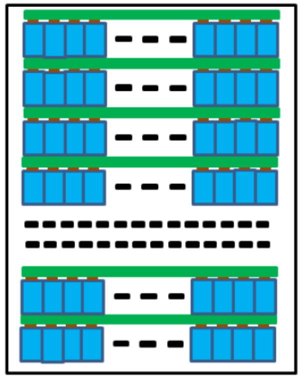
Tot: 90mm/W + 120mm/PS + 90mm/Electronics

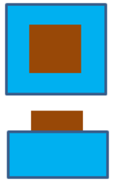
Cost
SiPM, 3mm×3mm，15￥/piece.   Electronics: 100 ￥/channel ?
30 RL ~20 M ch ~ 2 billion ￥,
20 RL ~13 M ch ~ 1.3 bilion￥,
10 RL ~6.7Mch ~ 0.67 bilion￥

Expected energy resolution
σE/E ≤ 6%/√E(GeV) ?
Need detailed MC study

Sampling fraction and light output are much higher than the Sci-ECAL in CDR, necessary to get a good energy resolution.

Option 2: Segmented crystal ECAL



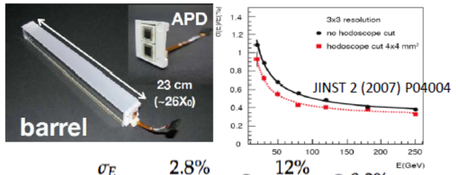


Tot: 10X22mm(25 rad. length)PbWO4
+ 10X8mm /Electronics

Readout unit:
PbWO4 crystal：10mmx10mmx22mm
SiPM: 6mmx6mm, 5μm pitch, PDE>10%
10 layers

The linear range of SiPM: 4.8 x10^5 pe
dE/dX of MIPs in **=22.4MeV ~ 150pe?**
Dynamic range of is 1-3.2x10^3 MIPs

Reference : CMS PbWO4 ECAL



$$\frac{\sigma_E}{E} = \frac{2.8\%}{\sqrt{E(\mathrm{GeV})}} \oplus \frac{12\%}{E(\mathrm{GeV})} \oplus 0.3\%$$

Cost
Crystal:5\$/cc? 1.46X10^{7}cc ~0.51 billion￥
Electronics, 6.6M ch ~0.66 billion￥
Total: ~ 1.2 billion ￥

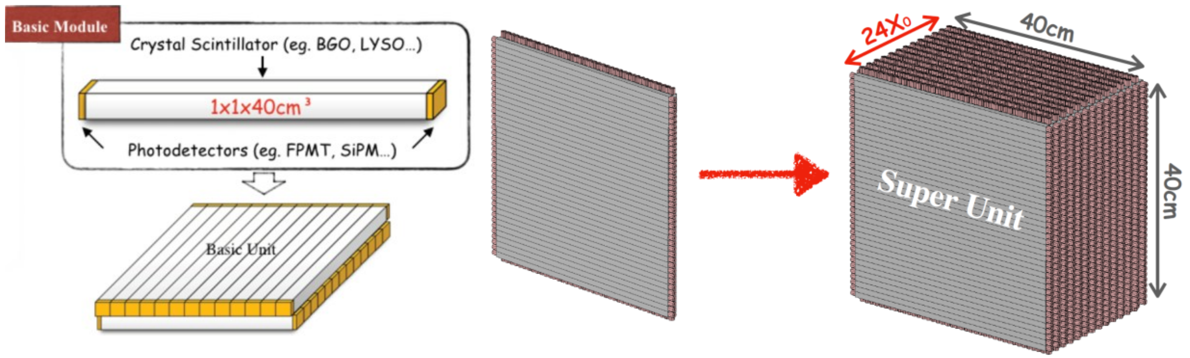
Expected energy resolution:
σE/E ≤ 4%/√E(GeV) ?
Need detailed MC study

6

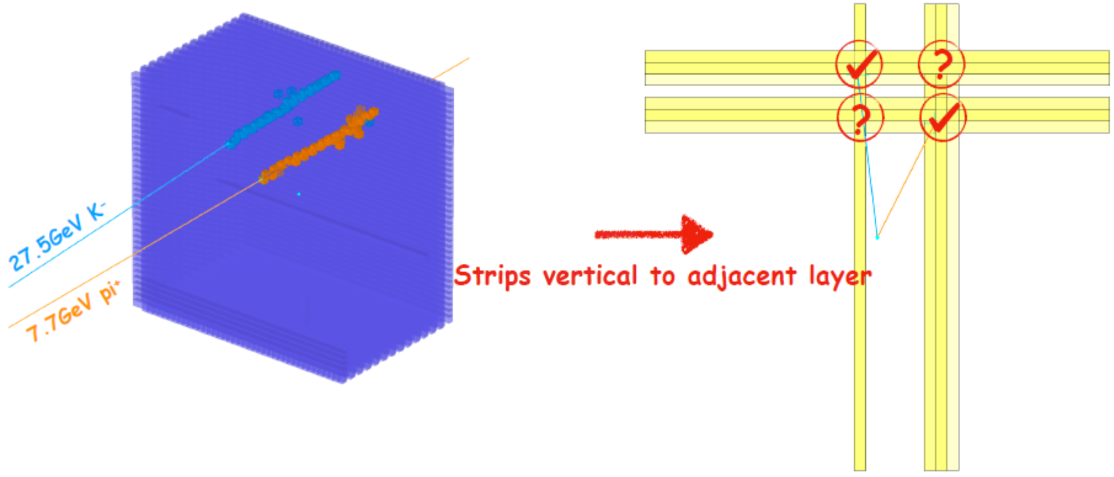
Crystal calorimeter: new designs for CEPC (4)

Manqi Ruan, Yuexin Wang (IHEP)

- Design: crystal bars
  - Read out at both sides
  - Rely on precision timing measurements
  - To reduce #channels
    - BGO #channels ~ 1.4M << 25M (Si-W ECAL)



- Simulation studies
  - Separation of multi-particle shower (key issue)
    - Physics requirement of separation (2 or 4 jets)
    - Energy portion of π^0 in jets
    - $\pi^0 \rightarrow \gamma\gamma$ at different energy
    - Timing info may deal with ambiguity
  - Timing resolution: 1×1×40cm³ BGO crystal
    - Hit-position dependent
    - Double-ended readout: 5 - 45ps
    - Effective position resolution, ~7mm



Detector Design Philosophy

Bing Zhou (Michigan)

- **LEP/L3, SSC/L*, LHC ATLAS/CMS detectors**
  - **Benchmarks: $H \rightarrow \gamma\gamma$, $H \rightarrow 4\mu$, $Z' \rightarrow ll$**
  - Lepton, photon, jet energy precision; b-tagging, vertex (inner tracking precision, now add timing detector to handle pile-up)
  - Both ATLAS and CMS emphasize muon detection (never compromise the muon spectrometer, but different treatment for momentum measurement)
- **ILC, CEPC, CLIC (FCC-ee?) (Benchmark to guide the detector design?)**
  - PFA (finely segmented calorimeter) (Bench mark: Separate $Z/W \rightarrow qq$?)
  - Relax some requirement on lepton/photon energy measurement?
  - Factor of 10 – 100 more readout channels?
- CEPC philosophy: never compromise EM calorimeter and inner tracker? Or to build the most powerful PFA calorimeter?

Summary

- Triggered in-depth discussions on several options
- Just beginning: many more interesting designs and studies will follow
- Next topical workshop for CEPC calorimetry: under discussion