New ideas from the Topical Workshop for CEPC Calorimetry

Yong Liu (IHEP)

CALICE Collaboration Meeting, Utrecht

Apr. 10, 2019

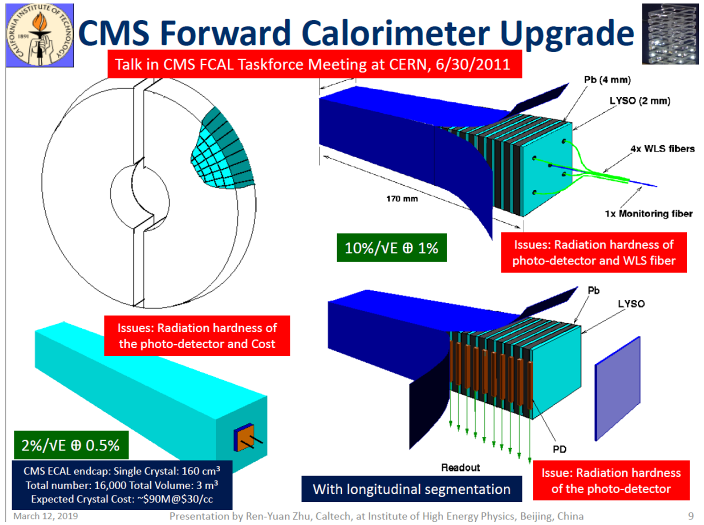
Introduction

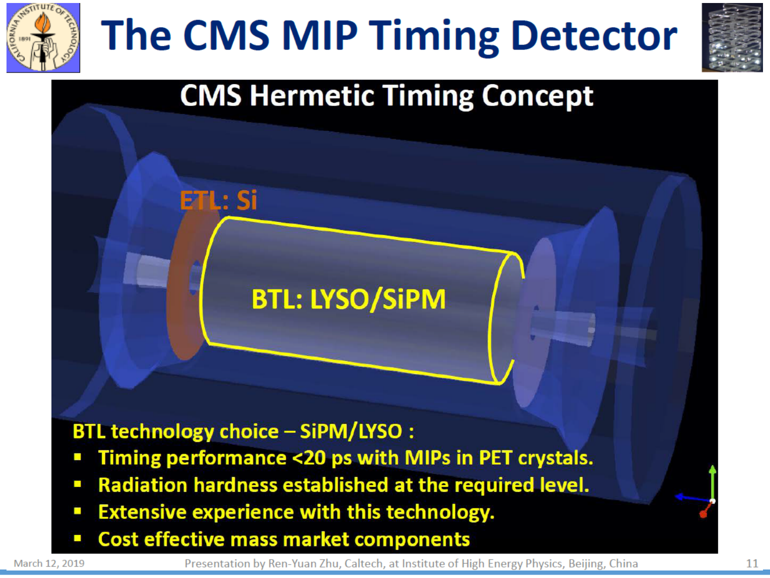
- Topical Workshop on the CEPC Calorimetry
  - March 11-14, 2019
  - https://indico.ihep.ac.cn/event/9195/
  - ~45 participants (and via remote connection)
    - From China, France, Germany, Italy, Korean, US

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

Crystal calorimeters

- Overview
  - Not included in CEPC CDR
  - Optimal intrinsic energy resolution
    - $\leq 3\%/\sqrt{E}$ 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
- Widely open for innovative designs
  - To be compatible with PFA?: high granularity + optimal energy resolution

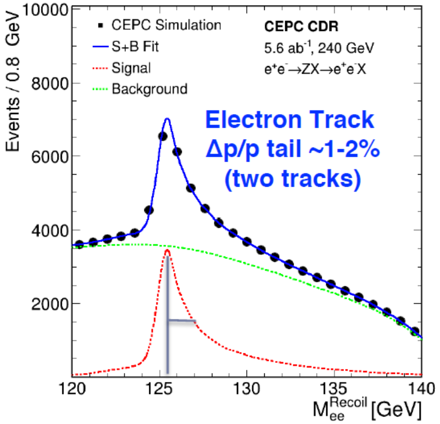




Crystal calorimeter for CEPC

- Physics motivations
  - Electrons' Bremsstrahlung: energy recovery
  - Improve angular resolution and gamma counting
- Performance requirements to be fixed (quantitively)
- Cost estimate: crystal raw materials
  - PbWO crystal for CEPC ECAL: ~131 M$
    - ~12 m^3 for 1 barrel, ~4.4 m^3 for 2 endcaps
    - Based on the unit price $8/cc for PbWO (volume at 10m^3 level)
    - 24X0 in total, R=1.8m, Z=4.7m
- Other possibilities
  - Use crystal for barrel only: radiation and cost
  - Smaller radius for ECAL: e.g. R=1.5m (no TPC)
- Several new designs proposed for CEPC ECAL

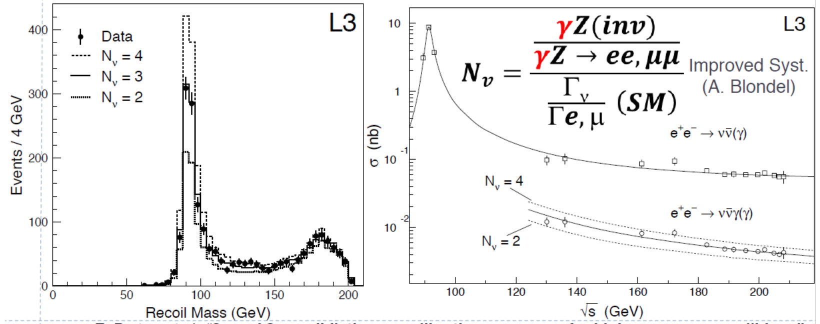
Electrons



Talk from Christopher Tully

EM Resolution and Photon Counting

- **EM Resolution also improves angular measurements and resolves Nγ counting**
- **Recoil photons (~8% of full √s collision rate)**
  - New Physics Searches and Neutrino Counting

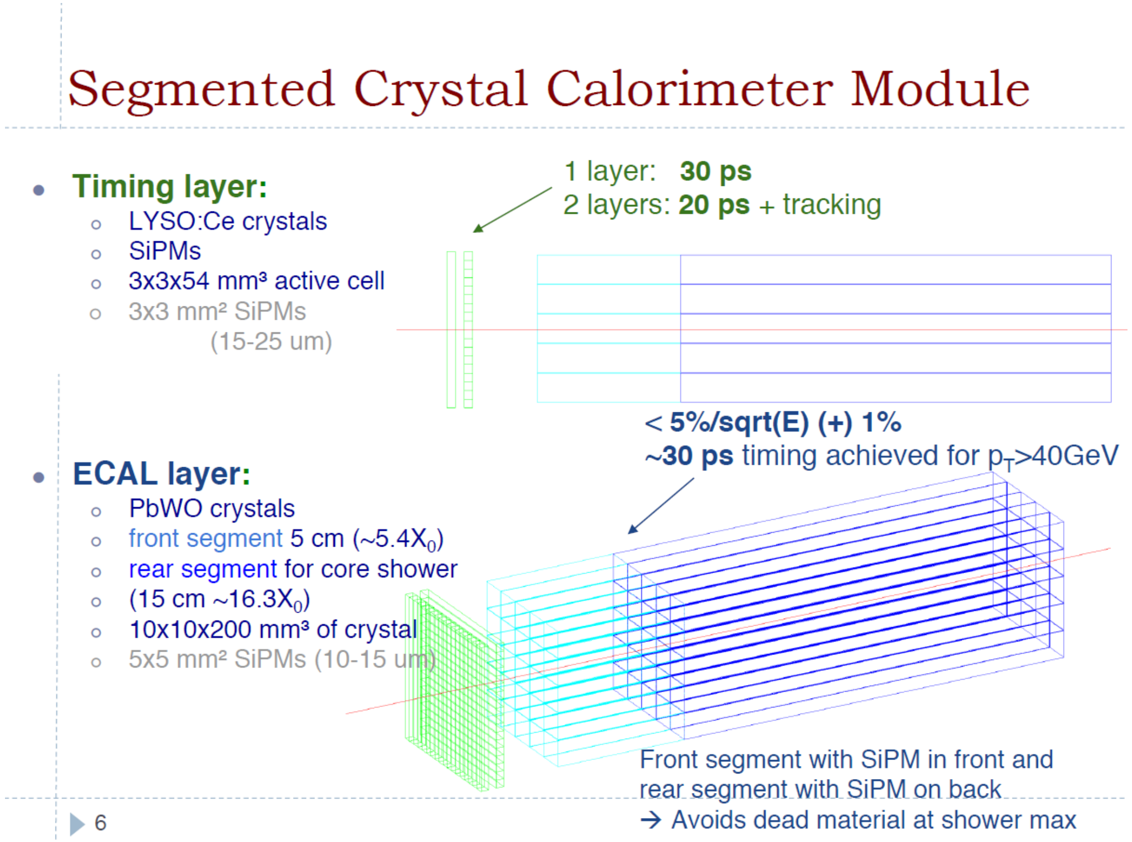


28 E. Bartos *et al.*, "2γ and 3γ annihilation as calibration processes for high energy e+e– colliders," https://arxiv.org/abs/0801.1592

Crystal calorimeter: new designs for CEPC (1)

Christopher Tully (Princeton), Sarah Eno (Maryland)

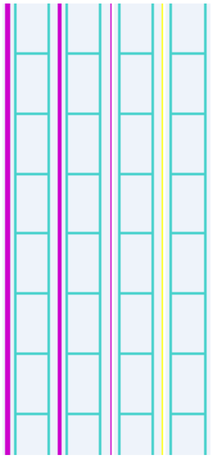
- Comprehensive simulation studies in Geant4
  - 2 timing layers: LYSO and SiPMs (TOF + tracking)
  - 2 ECAL layers: PbWO + SiPMs
- Impacts to energy resolution
  - Dead materials: readout boards, cooling, cables
  - Sub-detector in front: tracker
  - Photostatistics from SiPM
- Calorimeter: other performance
  - Single/pair EM showers, discrimination
- Timing layers
  - LYSO bars: ~20 ps timing resolution
  - Time-of-Flight: Particle ID performance
- Potentially compatible with PFA

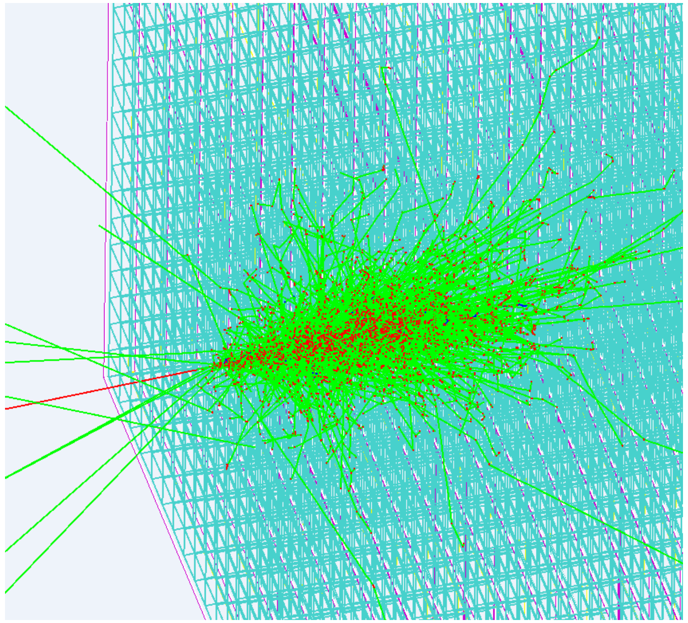


Crystal calorimeter: new designs for CEPC (2)

Yong Liu (IHEP)

- Design: PFA homogenous ECAL
  - Silicon layers: positioning (high granularity)
  - Crystal layers: optimal energy resolution
- First simulation studies in Geant4
  - Energy sampling fraction >90% (with crystal)
  - Stochastic term from energy fluctuations <1%
  - Also investigated the performance (trade-off) when using some absorber for a more compact design
- 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





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

High-density lead glass (~6g/cm³) can be an interesting cost-effective option

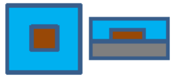
Crystal calorimeter: new designs for CEPC (3)

Junguang Lv, Zhigang Wang (IHEP)

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

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

Option 1: Sampling ECAL

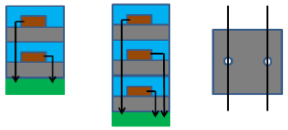


Sensitive Unite(SU)

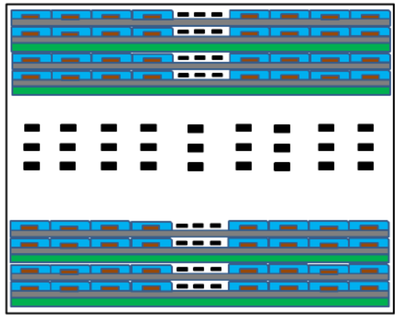
1.5mm/W+2mm/PS+SiPM , 60 layers

PS: 10mmx10mmx2mm

SiPM: 3mmx3m, 5μm pitch, PDE＞10%



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



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￥

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

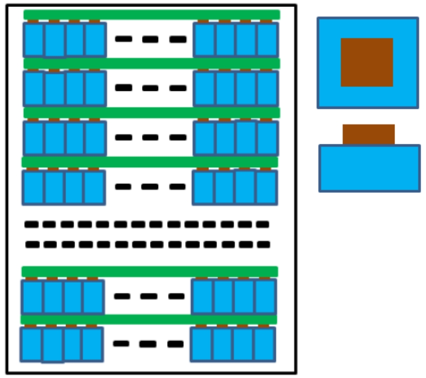
Expected energy resolution

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%

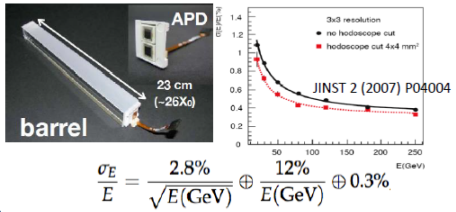
10 layers

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

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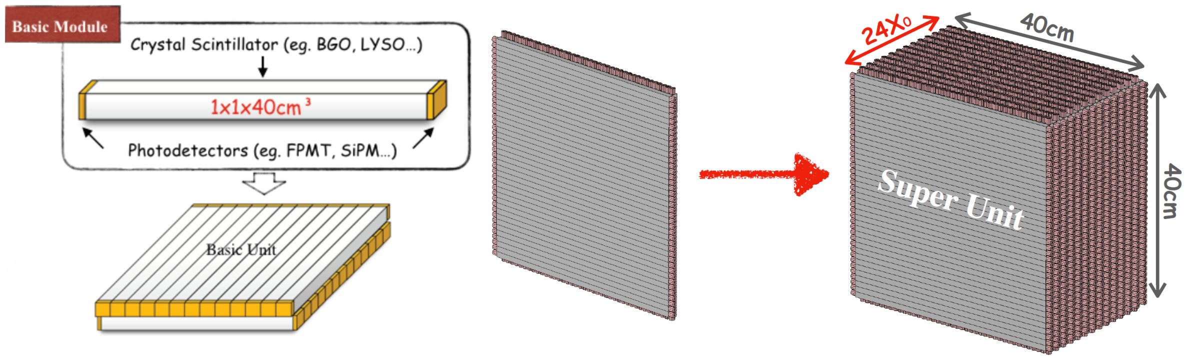
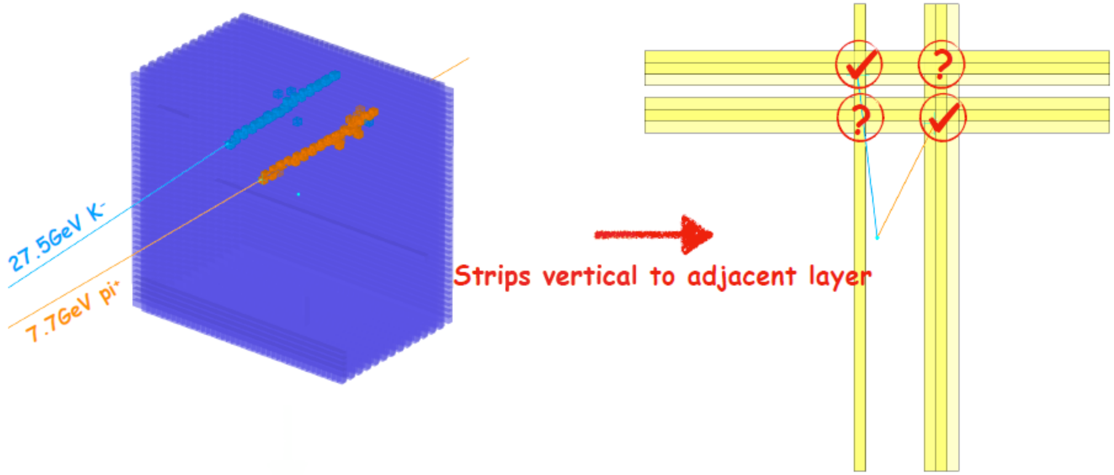
Crystal calorimeter: new designs for CEPC (4)

Manqi Ruan, Yuexin Wang (IHEP)

- Design: crystal bars
  - Read out at both sides: precision timing
  - To reduce #channels
    - #channels: ~1.4M << 25M (Si-W ECAL)
- Simulation studies
  - Separation of multi-particle showers
    - Physics requirement of separation (2 or 4 jets)
    - Energy portion of π^0 in jets
    - $\pi^0 \to \gamma\gamma$ at different energy
  - Timing resolution: 1×1×40cm³ crystal bars
    - Hit-position dependent
    - Double-ended readout: 5 - 45ps
    - Effective position resolution: ~7mm





Summary

- Crystal calorimetry designs proposed: to be compatible with PFA

- Major open issues: to be addressed by further simulation studies
  - Longitudinal segmentation: number of crystal layers
  - Impact from dead materials: especially active cooling plates
  - “Digitizer” in the CEPC software: statistics of scintillation photons and SiPM

- Seeking funding support for further R&D studies: currently under discussion
  - In the framework of MOST: 2020 - 2023, for both CEPC accelerator and detectors
  - Aim: technically prepared to build the accelerator if green light is granted in 2023
  - To promote wider and deeper international collaborations

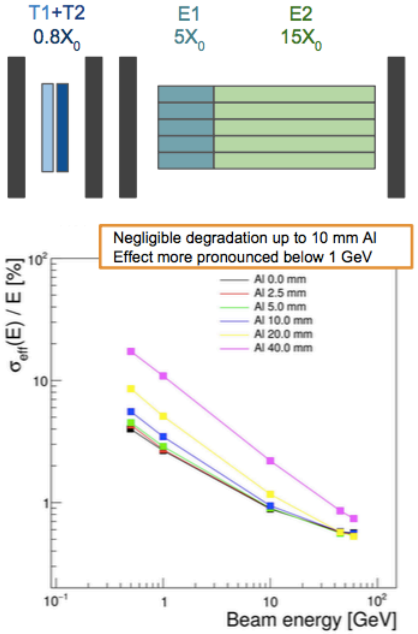
- Discussing to have another topical calorimetry workshop: welcome wider participation

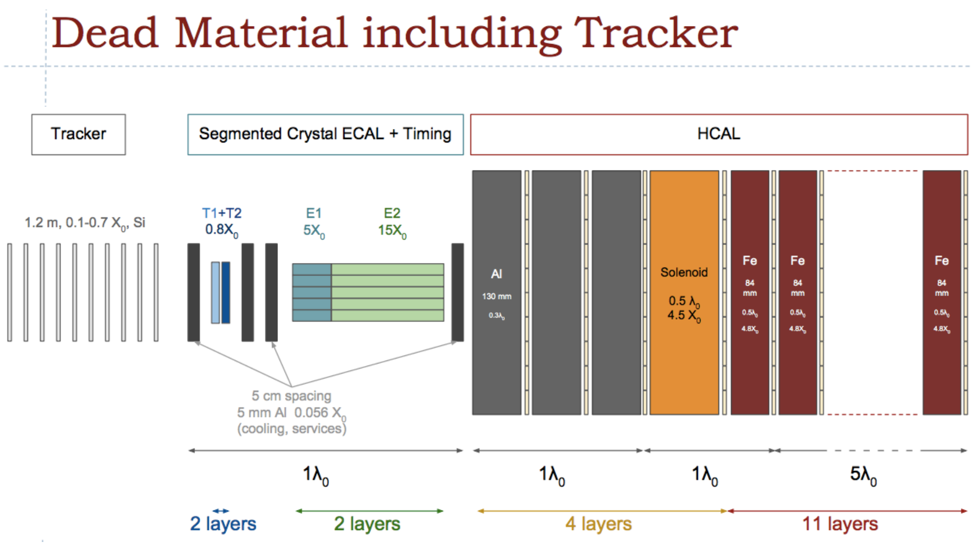
Additional Slides

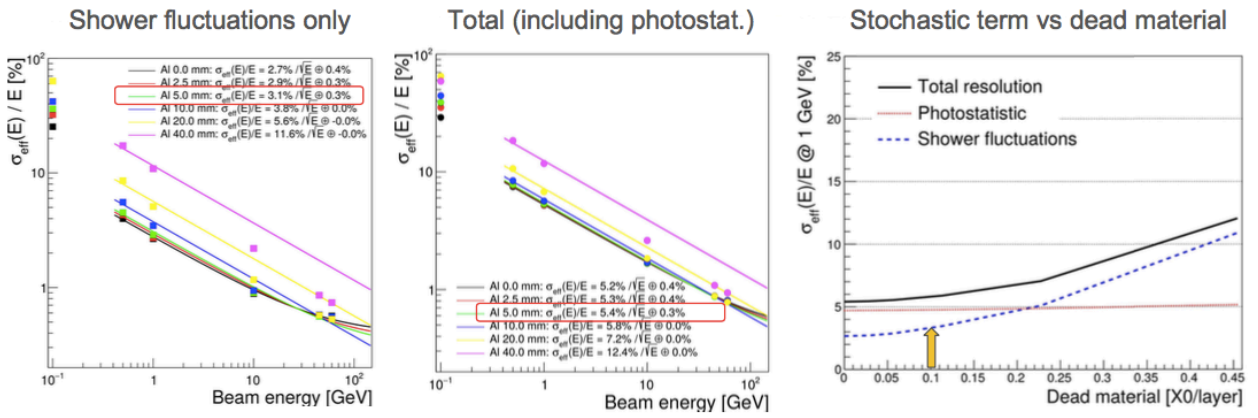
Segmented crystal calorimeter

Christopher Tully (Princeton), Sarah Eno (Maryland)

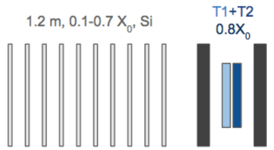
- Services required:
  - FE/ASIC for read-out → PCB material
  - Cooling plate
  - Cables
- Space allocated:
  - 5 cm in front of crystal timing layer T1 (for T1 read-out)
  - 10 cm in front of crystal ECAL E1
    - 5 cm for T2 and 5 cm for E1 → **cooling plate may be shared**
  - 5 cm in rear of crystal ECAL E2 (for E2 read-out)
- Material budget:
  - Realistic cooling plate ~ 3 mm Al → 0.035 X_0
  - PCB ~ 2 mm, + cables, etc
  - **total: 0.056 X_0** (5 mm Al equivalent) for each layer
  - Scan up to 0.5X_0 / layer

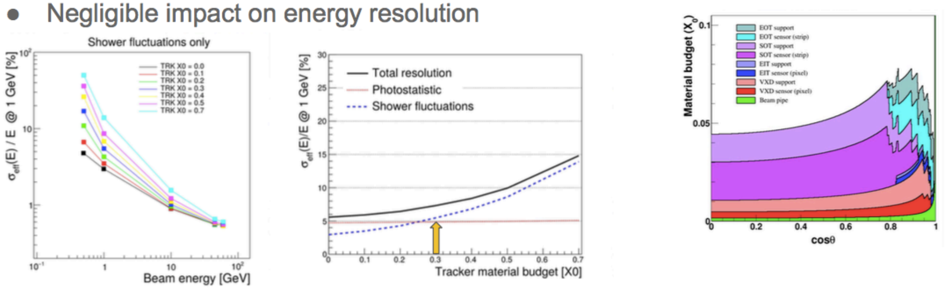






- Study impact of tracker material budget in front of SC-E(P)CAL
- Material budget:
  - Realistic material budget ~0.3X_0 ?
  - Scan up to **0.7X_0**
- Negligible impact on energy resolution





Segmented crystal calorimeter

Channel count and cost estimate

	T1+T2 (TIMING)	E1+E2 (ECAL)
Area barrel	53	53
Area endcap	19	19
Total area (barrel+endcaps)	**72 m²**	**72 m²**
# Channels barrel	977k	859k
# Channels endcaps	344k	374k
Total # of channels (barrel + endcaps)	**1.3 M**	**1.2 M**
Crystal cost	10 M€	78 M€
SiPM cost (+monitoring for ECAL only)	8 M€	8.5 M€
Electronics cost	5 M€	4.5 M€
Cooling+power+mechanics cost	5 M€	5 M€
Sub-total cost (barrel+endcaps)	28 M€	**96 M€**
Total cost (barrel+endcaps)	~124 M€	

- Geometrical assumptions for cost estimate:
  - **Barrel**
    - Radius = 1.8 m
    - Length = 4.7 m
    - Area ~ 53 m²
    - Pointing geometry → saving ~20% channels

  - **Endcaps (x2)**
    - Inner radius = 0.3 m
    - Outer radius = 1.75 m
    - Area ~19 m²
- Details of the cost estimate here

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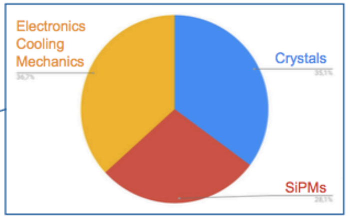
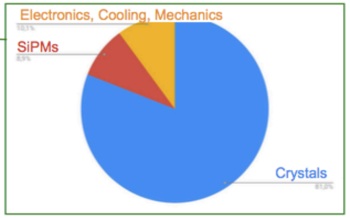
Summary

- **Channel count** in **S-CEPCal** is limited to **~2.5M**
  - 625k channels/layer
- Cost drivers in **TIMING** layers (tot ~28M€):
  - **35%** crystals, **28%** SiPMs, **37%** electronics+cooling+mechanics
- Cost drivers in **ECAL** layers (tot ~96M€):
  - **81%** crystals, **9%** SiPMs, **10%** electronics+cooling+mechanics
- Power budget driven by electronics: ~74 kW
  - 18.5 kW/layer
- Room for optimization of the detector performance vs cost



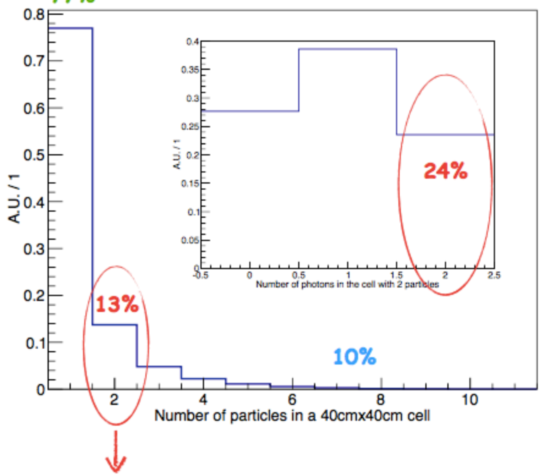


Calorimeter with crystal bars

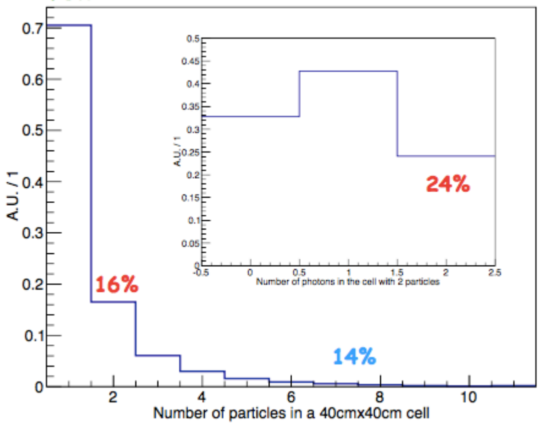
Manqi Ruan, Yuexin Wang (IHEP)

Physics requirement of separation

Z->qq (2 jets)



qqH->bb (4 jets)



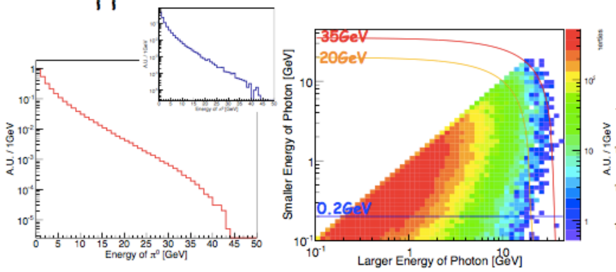
Charged + Charged
Charged + Neutral → Tracker

Neutral + Neutral → Only Calorimeter

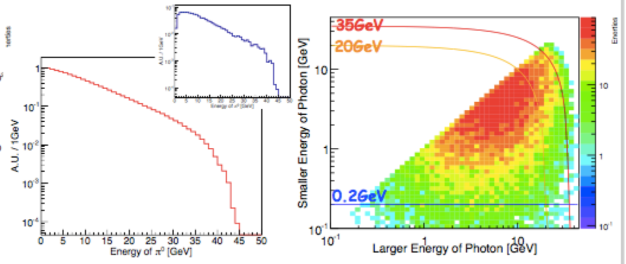
γ + γ (more than 80%~85% decayed from π^0) -> Reconstruction of π^0

Proportion of different energy π^0

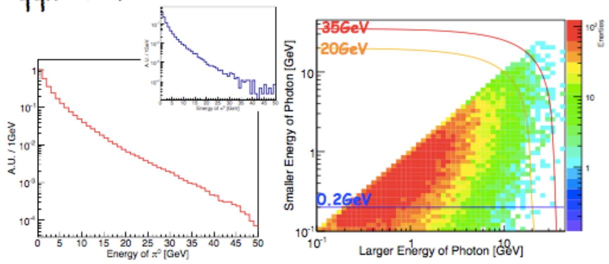
Z -> qq



Z -> ττ



qqH -> X

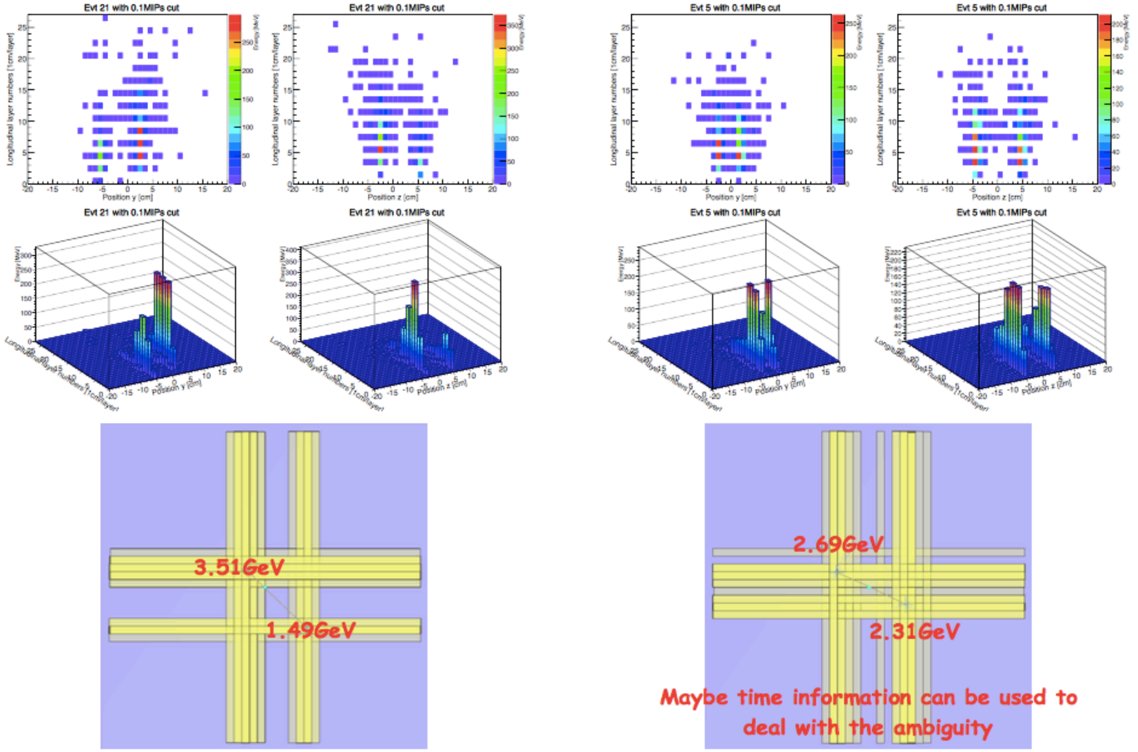


	Z->qq	qqH->X	Z->ττ
E_{π^0} > 20GeV	0.42%	0.66%	14.9%
E_{π^0} > 35GeV	0.02%	0.1%	1.8%
E_γ < 0.2GeV	45%	42%	7.5%

Calorimeter with crystal bars

Manqi Ruan, Yuexin Wang (IHEP)

π⁰ -> γγ at 5GeV



Maybe time information can be used to deal with the ambiguity

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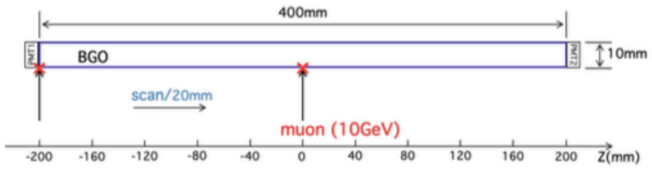
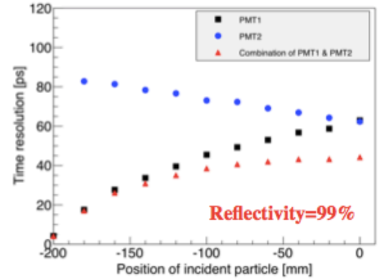
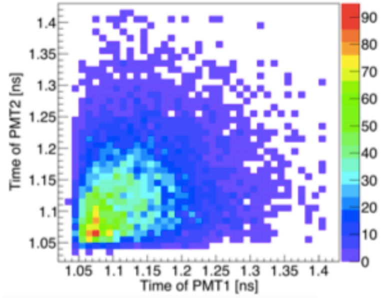
Time measurement



Parameter	Value
发光光谱峰位能量 Photon Energy	2.59eV (480nm)
发光光谱半峰宽 Photon Energy Width	0.6987eV (420-550nm)
快成分时间常数 FastTime Constant	60ns
慢成分时间常数 SlowTime Constant	300ns
光衰减长度 Absorption Length	7-15m
光产额 Scintillation Yeild	9000-10000/MeV
折射率 Refractive Index	2.15





Independent time measurement

Intrinsic time resolution of 1×1×40cm³ BGO crystal:

- **Single-ended readout, 5 - 90ps**
- **Double-ended readout: 5 - 45ps, effective position resolution, ~7mm**

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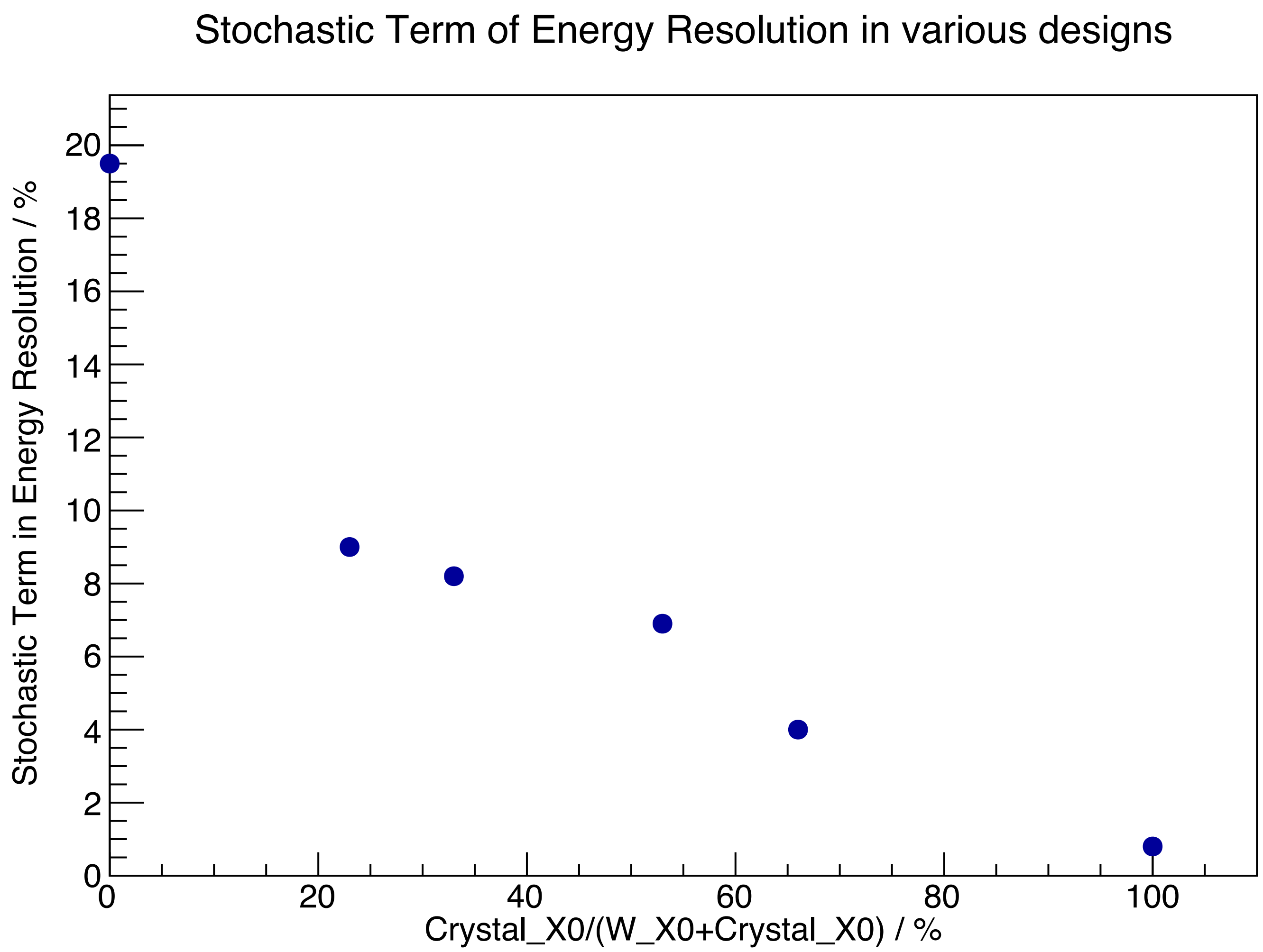
Calorimeter with silicon and crystal layers



- SiW and SiSc as 2 major options
- Introduce thin W-absorber plates for greater compactness
  - Si-Sc-W super-layers
  - Varying W/crystal thickness
  - Trade off energy resolution
- Note: digitiser not yet implemented in the simulation
  - Energy fluctuations only
  - Impact from scintillation photons and SiPM: to be studied