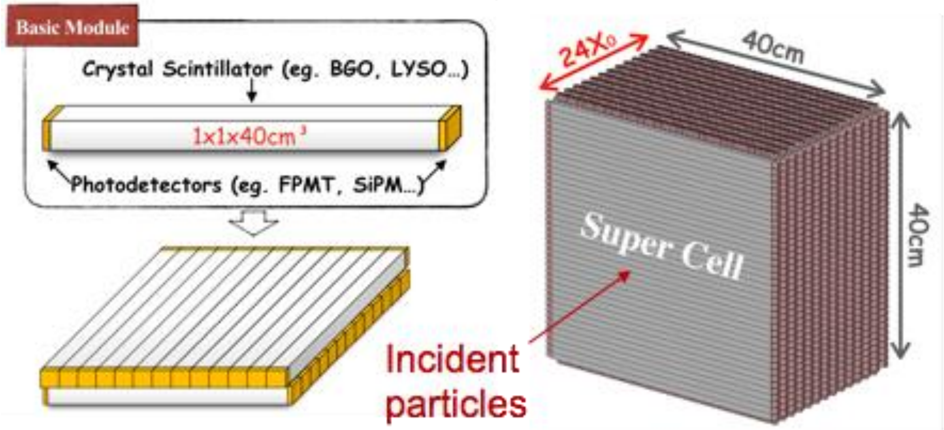
Status of simulation and software development of the crystal ECAL

Yong Liu (for the CEPC Calo-Software team)

CEPC Physics and Detector Plenary Meeting,

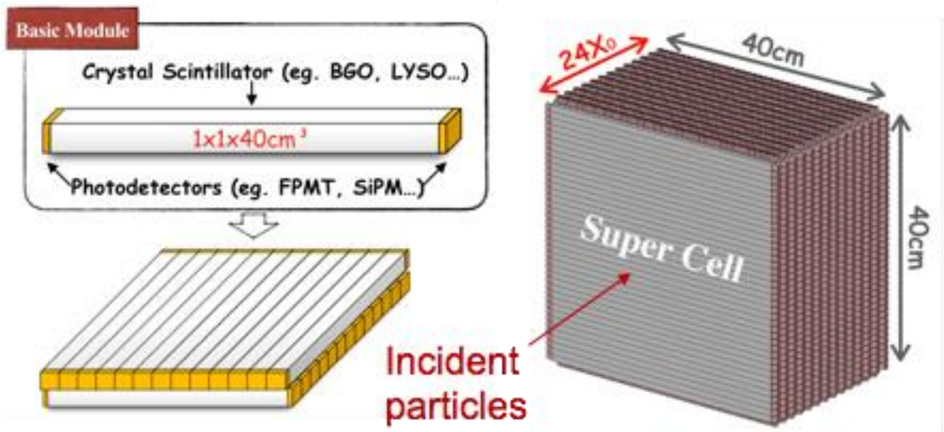
Sep. 16, 2020

Introduction: crystal ECAL



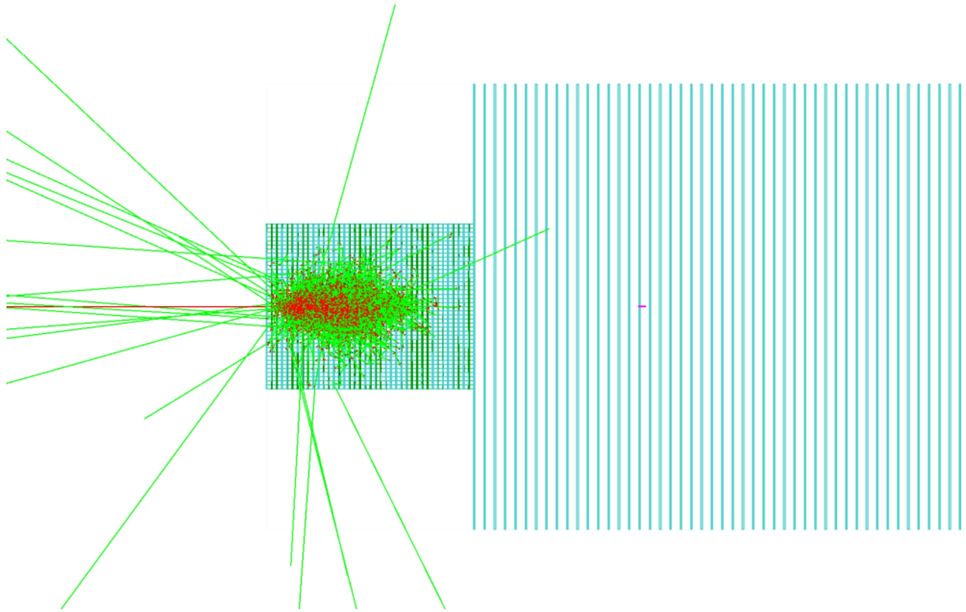
- Motivation:
  - Optimal EM energy resolution: $\frac{\sim 3\%}{\sqrt{E}} \oplus \sim 1\%$
- Currently focus on layout with long crystal bars
  - Long bars: 1×40cm, double-sided readout
  - Super cell: 40×40cm
- Crossed arrangement in adjacent layers
  - Aim for reduction of #channels
  - Timing at two sides: positioning along bar
- Key issues
  - Multiplicity of incident particles (e.g. jets)
    - Separation capability
    - Confusion impact

Crystal ECAL: software and tools at hand



- Geant4 stand-alone simulation
  - Crystal ECAL + Scintillator-Steel HCAL
  - Simple geometry: like prototypes for beamtests
  - Tools: digitizer, grouping into long bars
- CEPCsoft: working horse for the milestone CDR
  - Implementation of crystal ECAL geometry
  - Event display with Druid

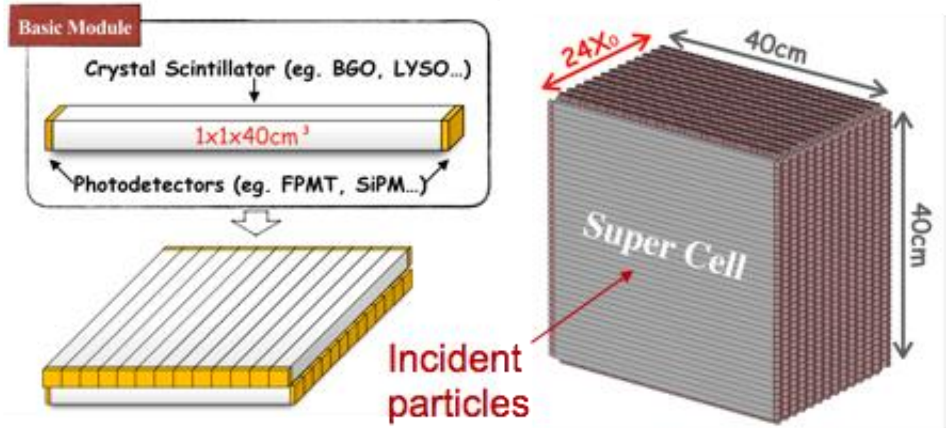
Crystal ECAL: software and tools at hand



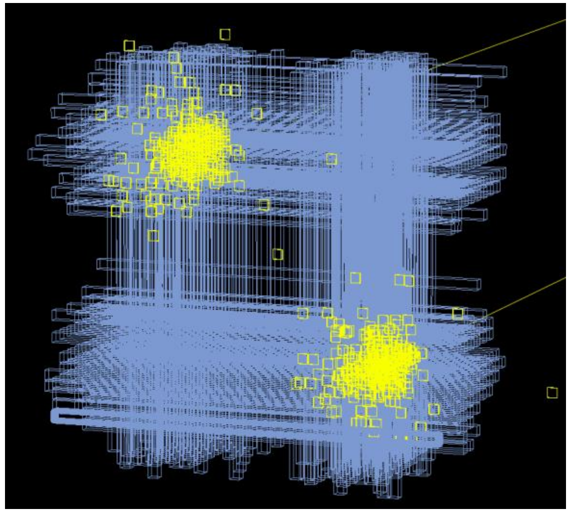
EM shower with a 30 GeV electron

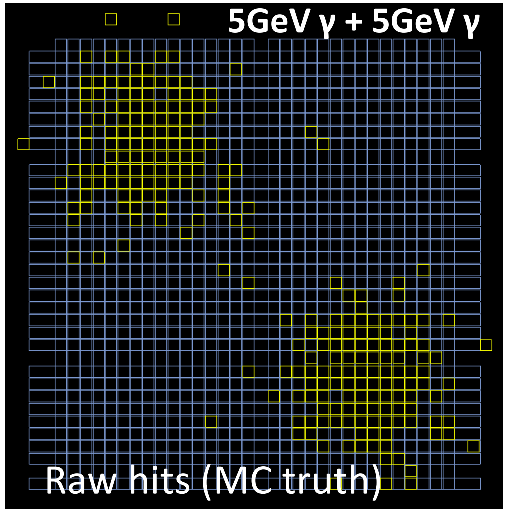
- Geant4 stand-alone simulation
  - Crystal ECAL + Scintillator-Steel HCAL
  - Simple geometry: like prototypes in beamtests
    - Basic ECAL unit: 1cm^3 crystal cubes
  - Tools developed
    - Digitizers for crystal/scintillator and SiPM readout: photo-statistics + ADC precision
    - Group every 40 crystal cubes (1cm^3) along each row as to read a long bar
  - Optimization: first studies done
    - Longitudinal depth: energy leakage correction
    - Transverse size: separation performance of gamma/pion0

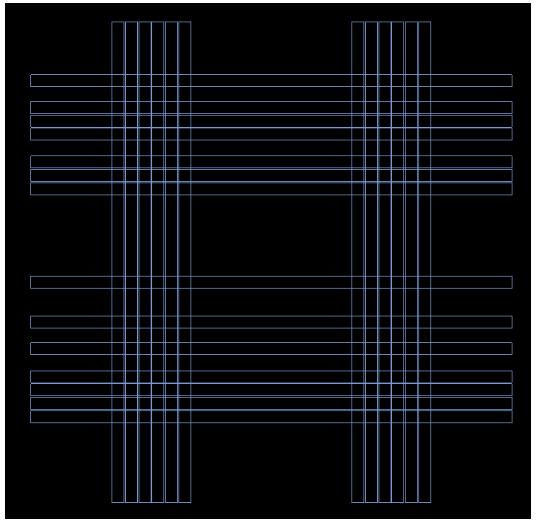
Crystal ECAL: software and tools at hand



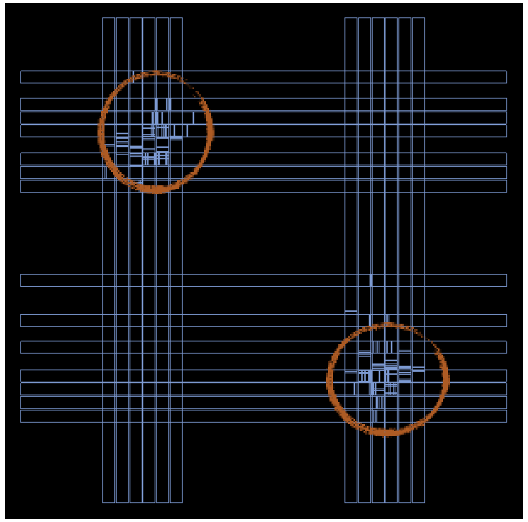
- CEPCsoft: working horse for the milestone CDR
  - Implementation of crystal ECAL geometry
  - Event display: "Druid"
    - Based on the tool that "groups" 40 cubes into a long bar
    - Visualize events in LCIO format (.slcio files)
    - First impression on shower profiles in long bars







After digitisation and require Edep > 1 MIP

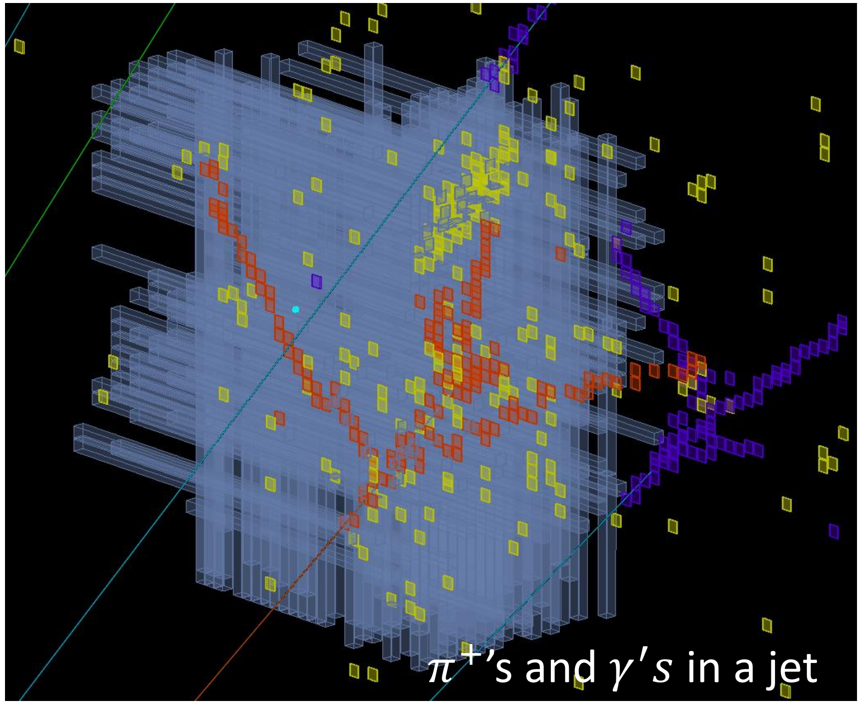


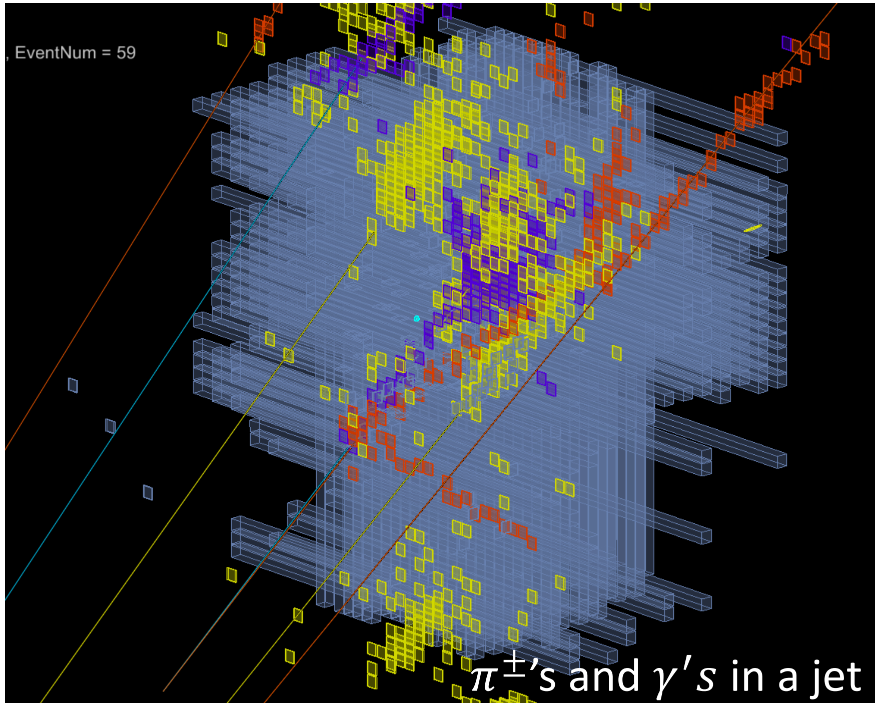
Reconstruction of hit positions using time stamps at two ends

Event display with jets in Druid

Z→qq at 91.2GeV

- Key questions – hints from patterns
  - Can you separate 2 or more particles in a jet?
  - If not, what would be the quantitative impact ?
  - Separation and energy sharing between two neighbouring super cells?


π^{+}'s and γ's in a jet



$\pi^{\pm}$'s and γ's in a jet

Crystal ECAL in the new CEPC software framework

Physics and Detector Meetings » Physics and Simulations » Calorimeter software

Calorimeter software

September 2020

- 16 Sep CEPC calorimeter software meeting New!
- 09 Sep CEPC calorimeter software meeting
- 02 Sep CEPC calorimeter software meeting

https://indico.ihep.ac.cn/category/748/

CEPC calorimeter software meeting (9 Sep, 2020)

Time: 9:00-10:15, 9 Sep, 2020
Participants: 刘勇，刘春秀，李刚，李波，方文兴，齐宝华，王悦心，郭方毅，傅成栋，孙胜森，伍灵慧
indico: https://indico.ihep.ac.cn/event/12608/

Minutes (Linghui, Yong):

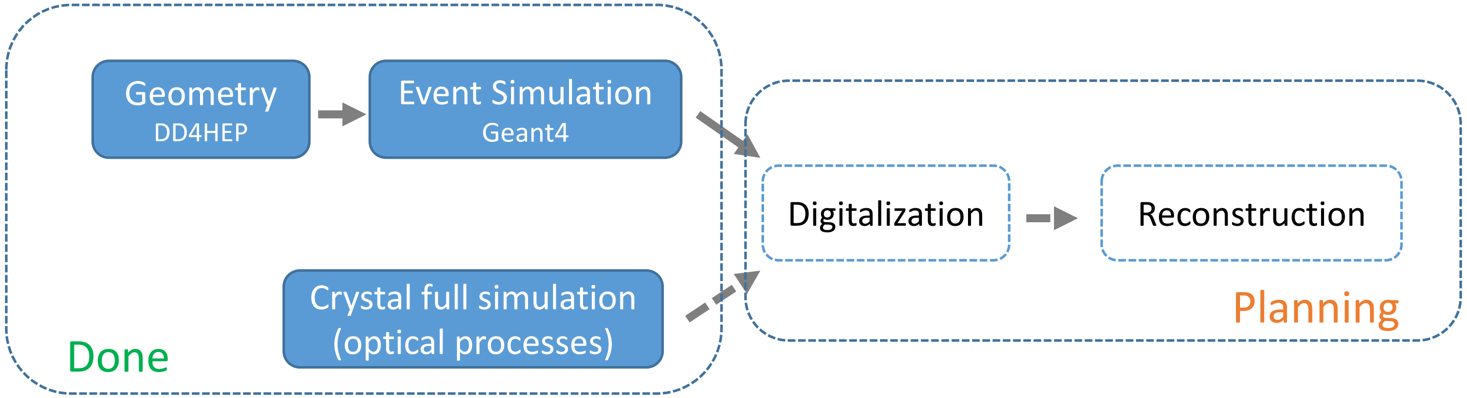
- Two pesentations:
  - G4 full simulation of a single crystal bar
  - ECAL geometry construction with DD4Hep
- Results from the G4 full simulation of a single crystal bar (YL, Baohua Qi)
  - General info on the G4 full simulation
    - Geometry: a single 40x1x1 cm^3 crystal bar, read out by 2 SiPMs at both ends
    - Properties: BGO, SiPM, wrapping
    - Optical photon processes
  - Focus on the timing performance, esp. on the rise edge of detected photons
  - Results in 3 (typical) scenarios
    - Time stamps of detected photons (within the 0-30ns time window)
    - Time stamps of the 1st detected photon per event (T_1st)
    - Time differences of T_1st at both ends
  - Discussions
    - Wrapping: LUT models for surfaces (Chengdong)
    - Tail in the T_1st spectra: originated from (slow) BGO scintillation, or geometric effect?
      - Stimulated many discussions
    - Timing resolution versus positioning resolution, at different incident positions
    - Acceptance: larger SiPM?
      - To be done
- ECAL geometry construction with DD4Hep (Fangyi Guo)
  - Implementation of crystal ECAL with DD4Hep:
    - Barrel ECAL done

Meeting minutes in Jupter

- Task-force established: dedicated to crystal ECAL in CEPCSW
  - Currently ~11 persons (staff and PhD students)
- **Wider participation/collaboration would be highly welcome**
- Weekly group meetings: exchange of latest progress and new ideas
  - Started in early September, 3 meetings till now

Focus of the calo-software team

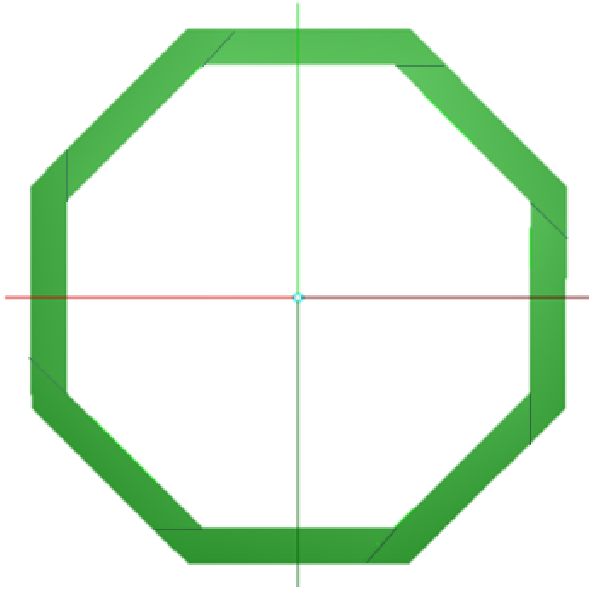
- Implementation of crystal ECAL in CEPCSW
  - Barrel ECAL implemented with DD4HEP
- Validation of digitization within a single long crystal bar
  - Established a Geant4 full simulation model with optical processes
  - Plan to perform measurements: crystal + SiPM with radioactive/light sources

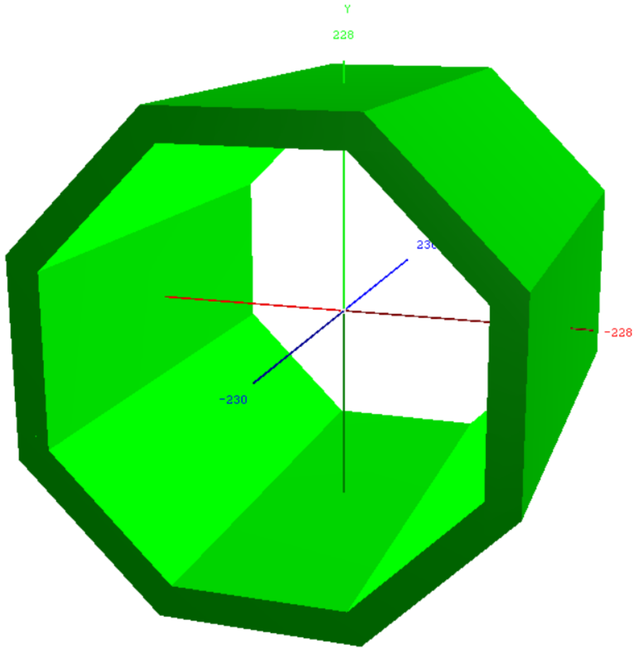


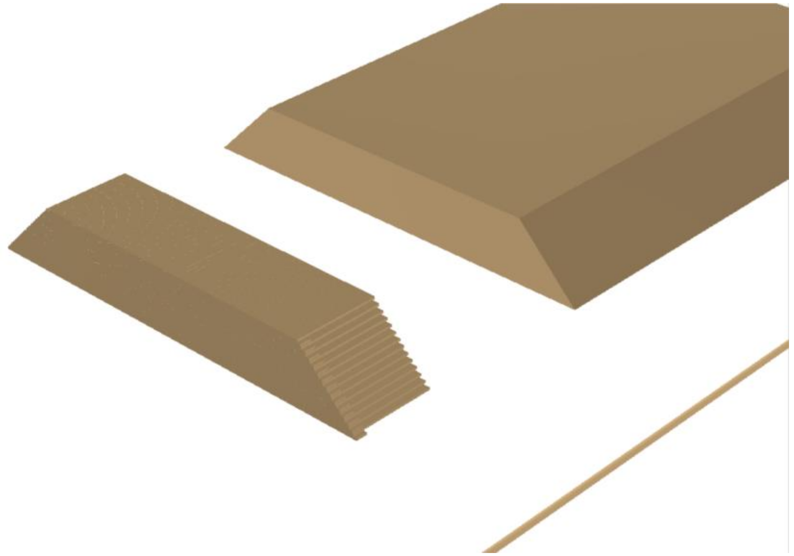
Implementation of crystal ECAL in CEPCSW

- Barrel ECAL implemented with DD4HEP
  - Ideal detector layout: no readout, no supporting structure, etc.
  - $R_0 = 1.8\text{m}, Z = 4.6\text{m}$, Depth=28cm, 28 longitudinal layers
  - 8 parts are exactly the same.
  - Crystal bar: 1cm × 1cm × ~40cm.

Status: finished ideal geometry construction;
Plan: need validation

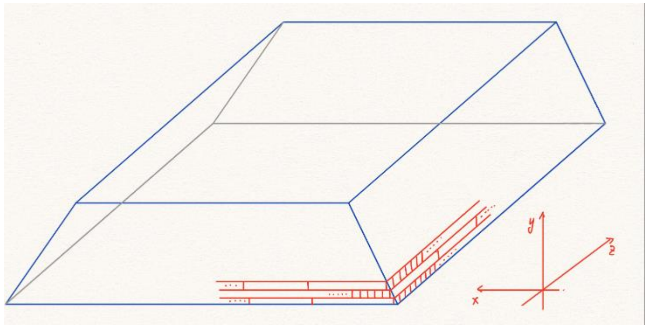






Implementation of crystal ECAL in CEPCSW

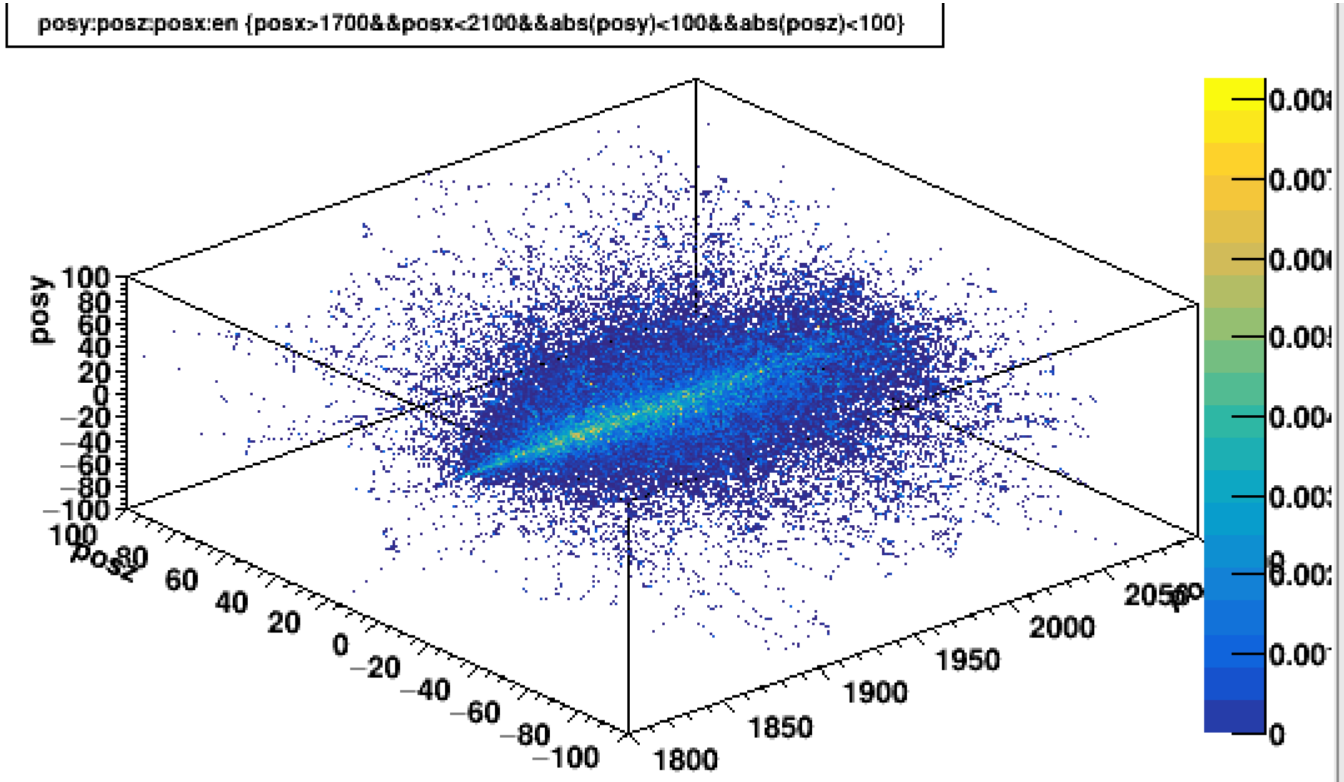
- Crystal ECAL layout: details
  - Odd layers
    - Crystal bar along with phi direction
    - 3~5 bars in each layer, bar length 35~46cm
    - 460 bars in Z direction.
  - Even layers
    - Crystal bar along with z axis.
    - Bar length ~ 38 cm, 12 bars in each layer.
    - 132~184 bars in phi direction.
    - * A 0.7cm gap exists

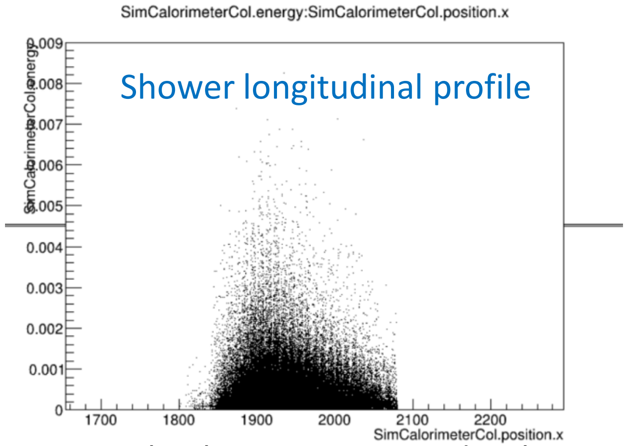


#layer	block length/mm	bar length/mm
1	1867	373.4
3	1827	365.4
5	1787	357.4
7	1747	436.8
9	1707	426.8
11	1667	416.8
13	1627	406.8
15	1587	396.8
17	1547	386.8
19	1507	376.8
21	1467	366.8
23	1427	356.8
25	1387	462.3
27	1347	449.0

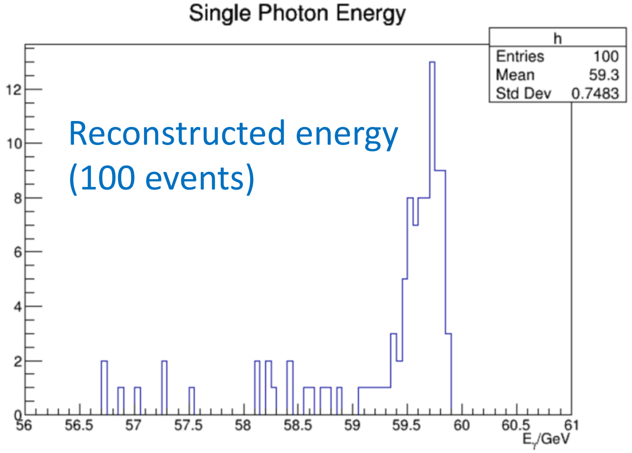
First simulation tests in CEPCSW

- Simulation of EM showers in CEPCSW
  - Run through the whole chain
  - Digitization tool: to be developed



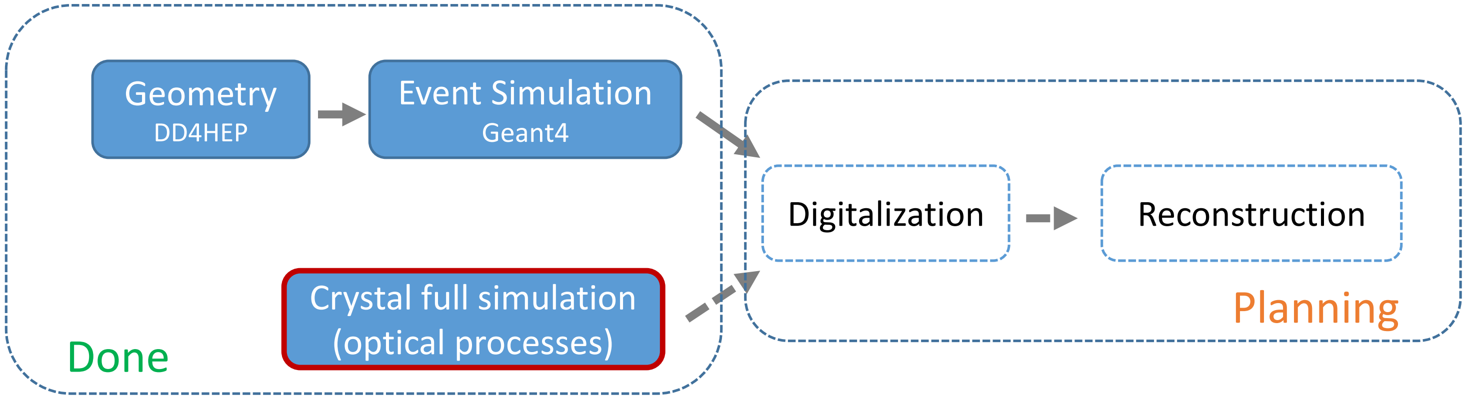


Single photon energy in depth

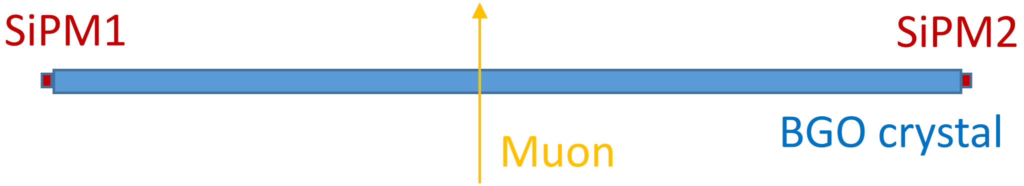


Focus of the calo-software team

- Implementation of crystal ECAL in CEPCSW
  - Barrel ECAL implemented with DD4HEP
- Validation of digitization: within a single long crystal bar
  - Established a Geant4 full simulation model with optical processes
    - Focused on timing properties of scintillation photons
  - Plan to perform measurements: crystal + SiPM with radioactive/light sources
    - Timing resolution – positioning resolution

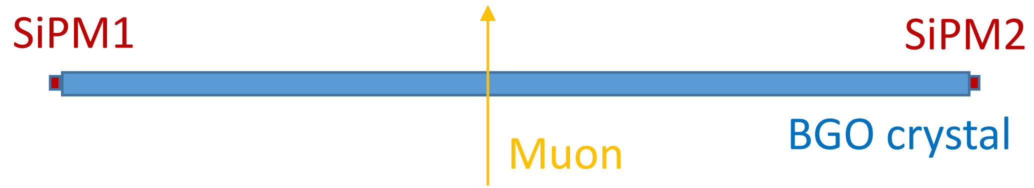


Digitization within a single long crystal bar



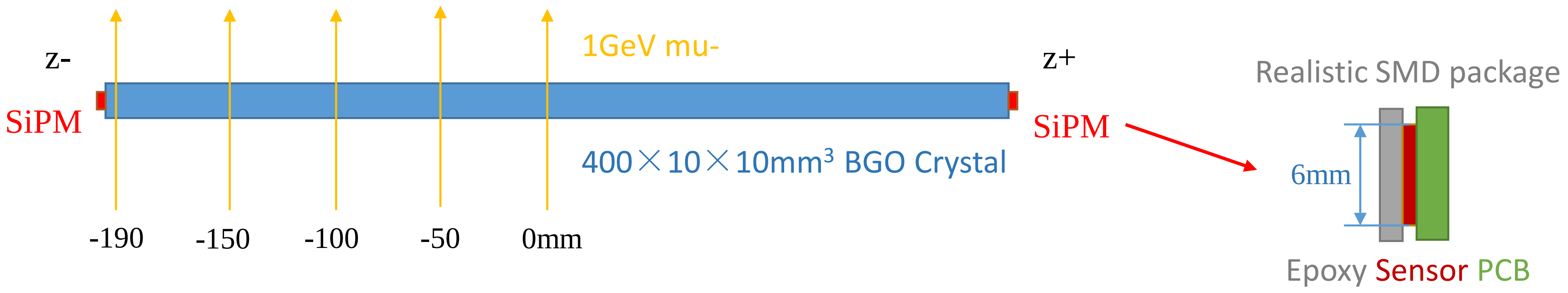
- Geant4 full simulation
  - Geometry
    - A 40cm long crystal bar, 1x1 cm^2 transverse size
    - Read out by two SiPMs at both ends
  - Properties
    - BGO: light yield, decay times (fast and slow), refractive index, transmission (absorption length)
    - Wrapping: ESR foil (~99% reflectivity) with air gaps (total reflections)
    - SiPM: 6x6 or 10x10 mm^2 sensitive area, Photon Detection Efficiency (PDE), realistic SMD package
  - Primary particle: 1GeV muon (for MIP calibration)
  - Optical photon processes:
    - Scintillation, Cherenkov, absorption, refraction/reflection at boundaries

Digitization within a single long crystal bar



- Information extracted from G4
  - Energy deposition: mean ~10 MeV/MIP, determined by crystal thickness
  - #scintillation photons
  - #detected photons at either SiPM
  - Time stamp of each detected photon
    - T0: shooting of the primary particle (muon)
    - Included: scintillation time (~hundreds ns), propagation time (a few ns) within the crystal bar
    - **Excluded: timing uncertainties from SiPMs and electronics**
- Digitization
  - Timing: Choose the time stamp of the 1st photon detected at each SiPM
  - #detected photons : proportional to energy deposition

G4 simulation with optical processes



- Muon: perpendicular incidence
  - 5 hit positions, 500 events at each position (simulation speed ~30s/event)
- Scintillation process: rising edge of signals
  - Rise time constants of BGO scintillation: 60 ps (ideal) vs 2.8 ns (based on measurements)
- Photo-sensor
  - Active area of SiPM: 6mm×6 mm vs 10mm×10 mm

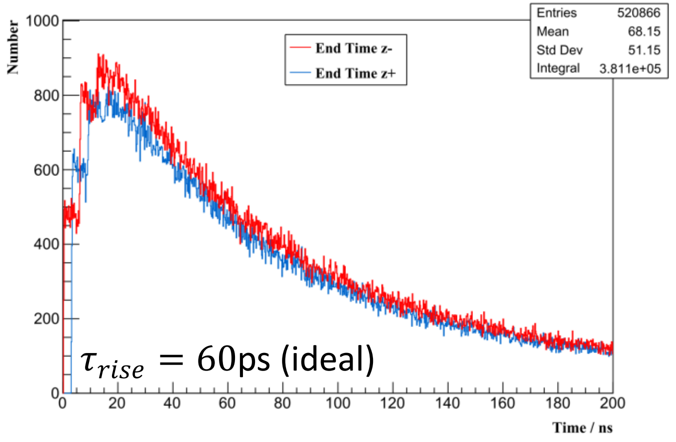
Pulses at SiPMs: scenario 1

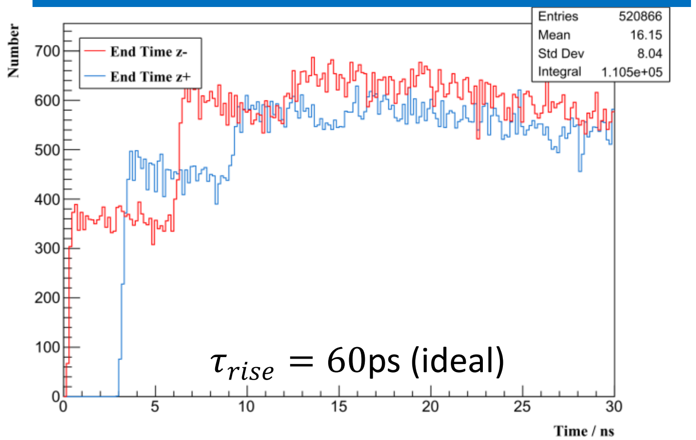
- Pulses at SiPMs: hit position close to one end (1 cm away)

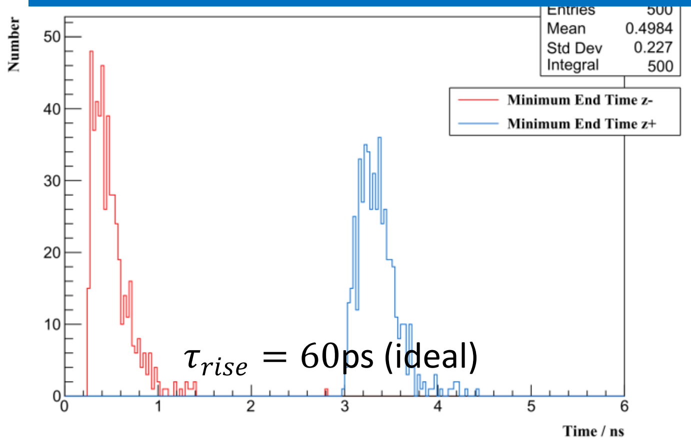
Time stamps: detected photons (0-200ns)

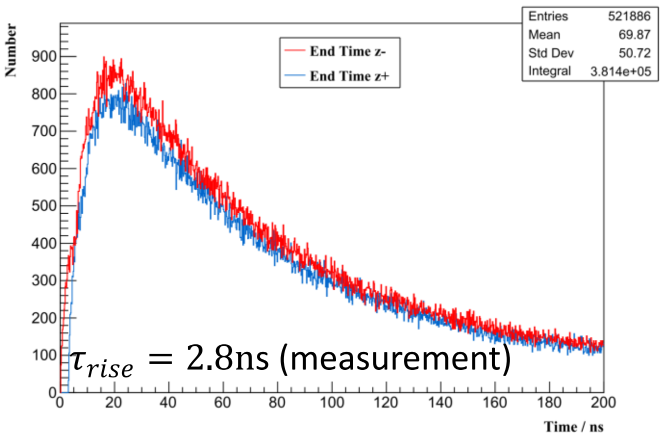
Time stamps: detected photons (0-30ns)

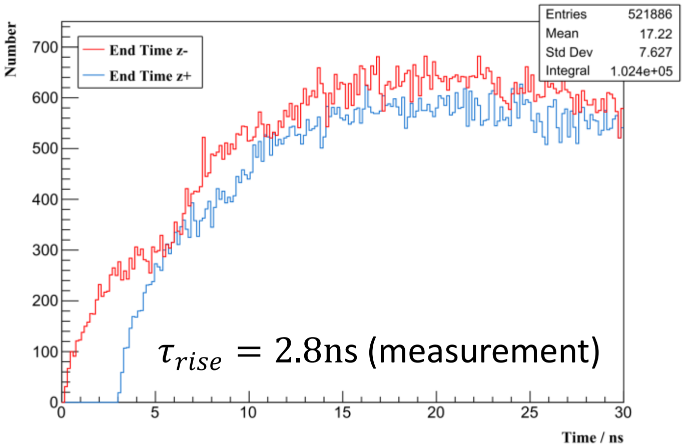
Time stamp of 1st detected photon per event

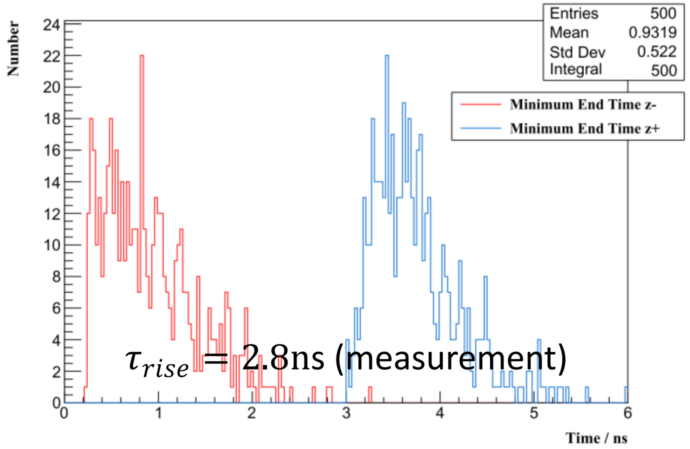








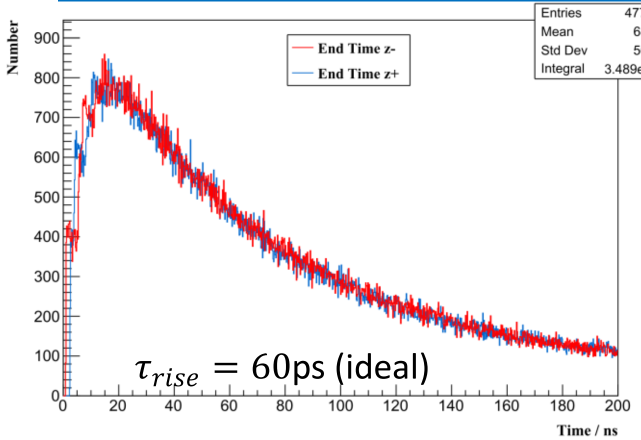


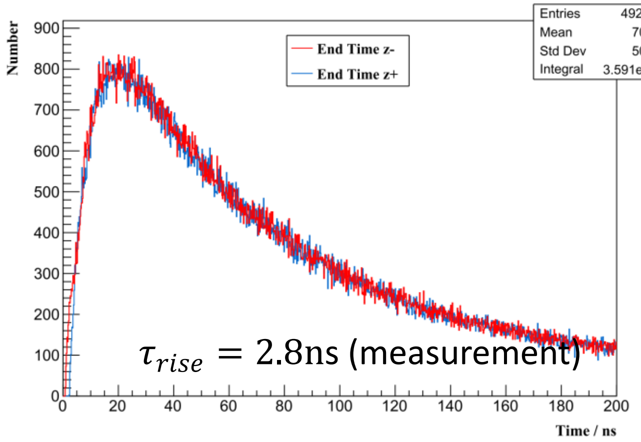


Pulses at SiPMs: scenario 2

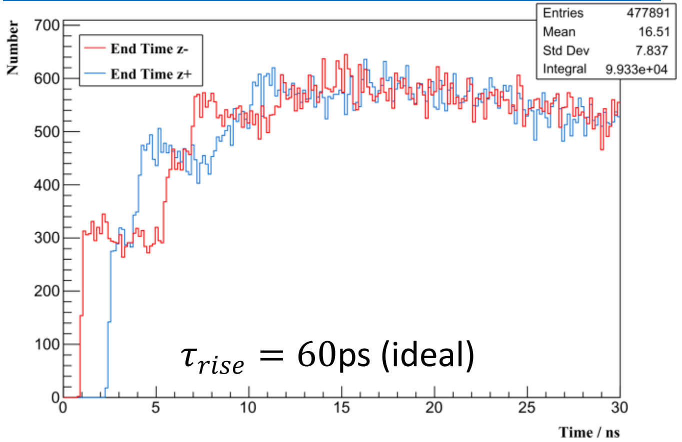
- Pulses at SiPMs: hit position near one end (10 cm away)

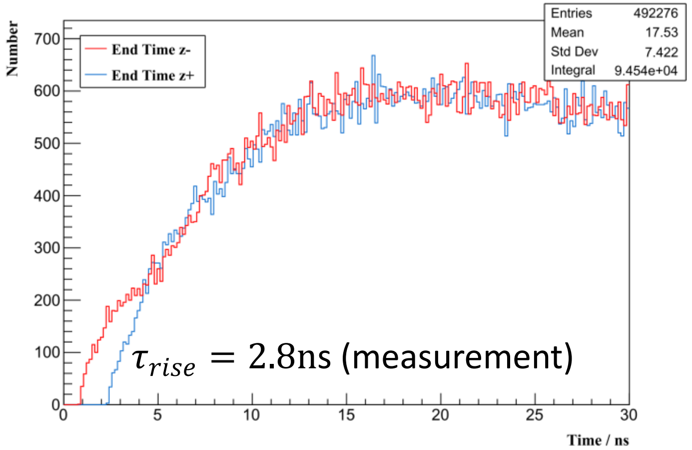
Time stamps: detected photons (0-200ns)



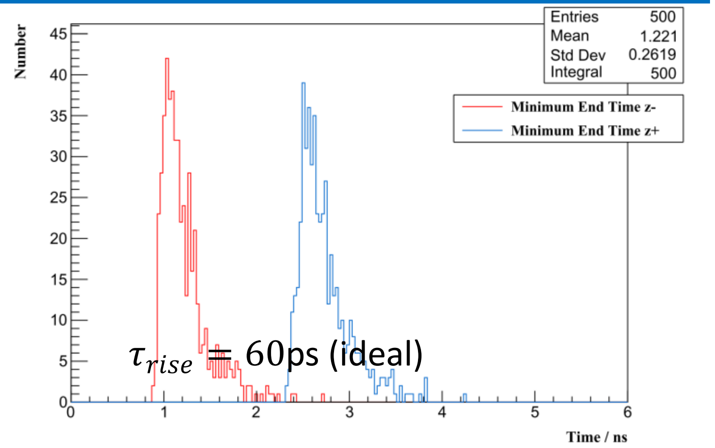


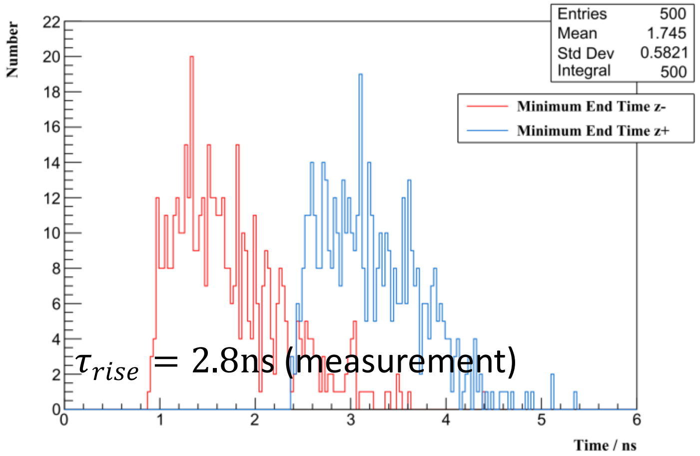
Time stamps: detected photons (0-30ns)





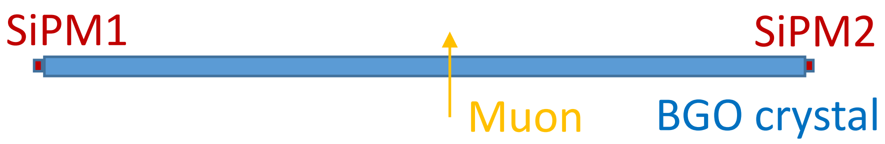
Time stamp of 1st detected photon per event



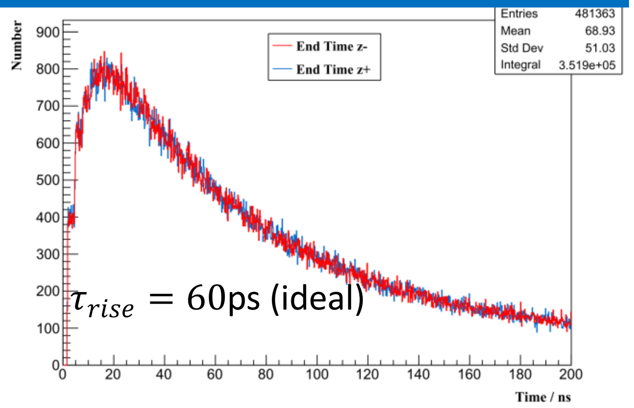


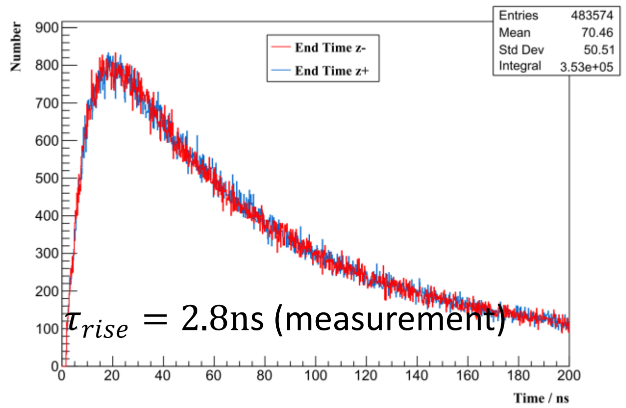
Pulses at SiPMs: scenario 3

- Pulses at SiPMs: hit position in the middle

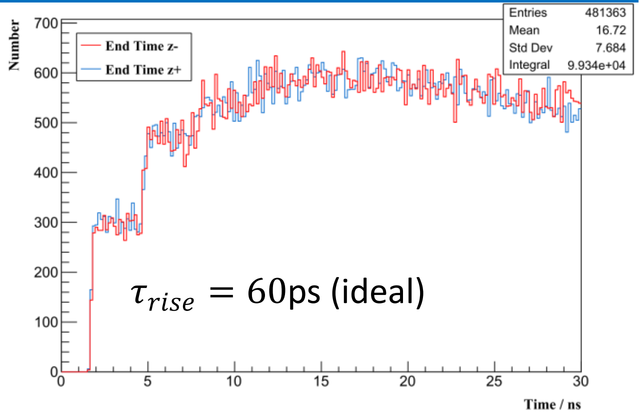


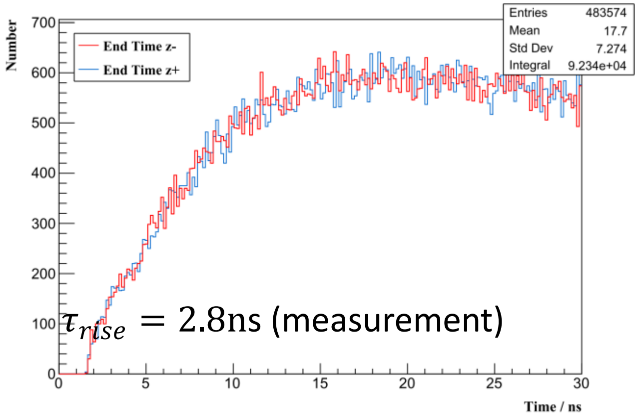
Time stamps: detected photons (0-200ns)



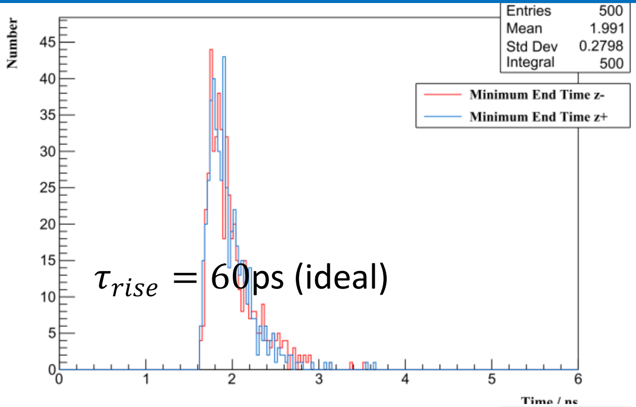


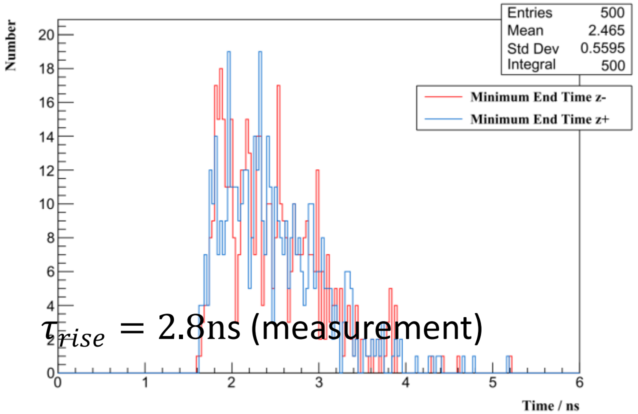
Time stamps: detected photons (0-30ns)





Time stamp of 1st detected photon per event

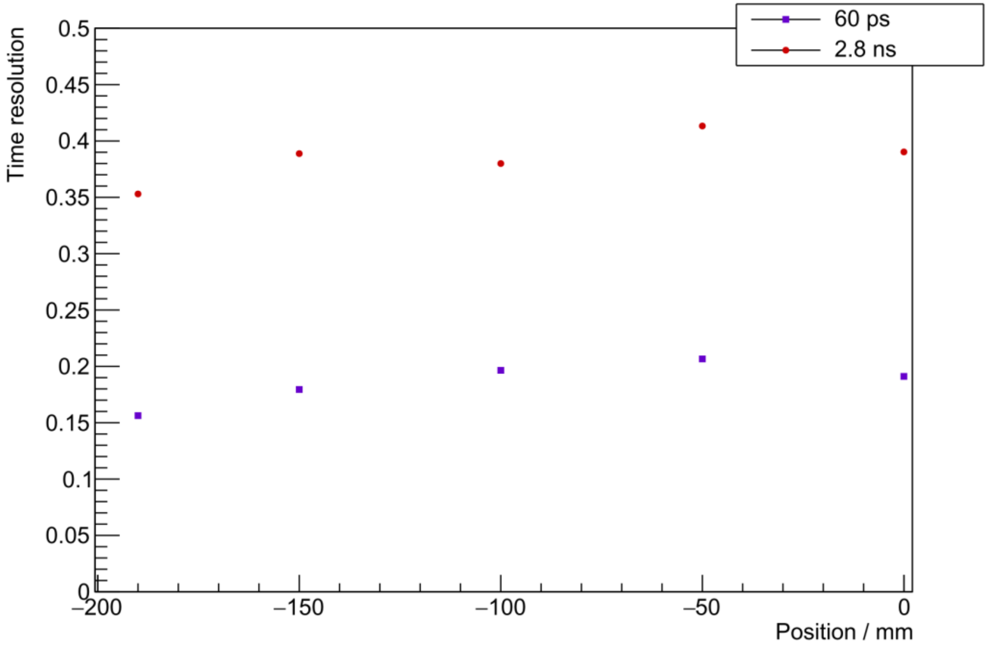


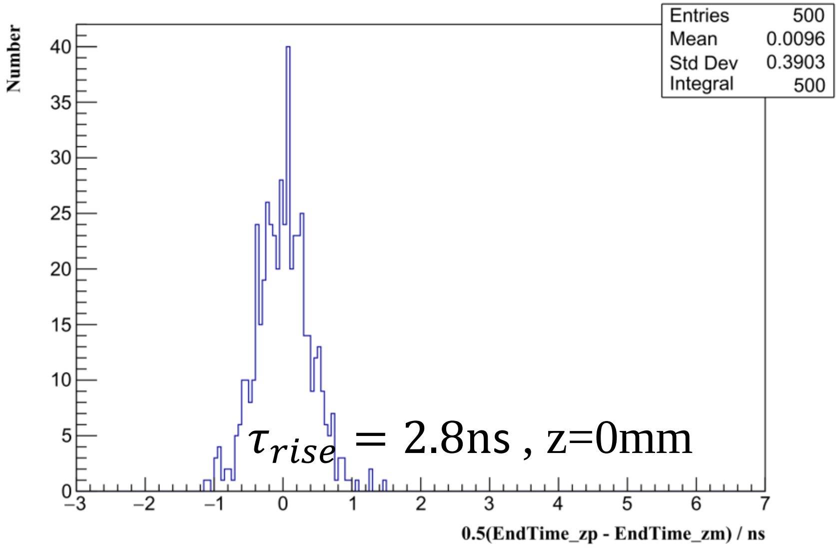


Time resolution

- Time resolution: Standard Deviation of (Time_SiPM2 – Time_SiPM1)/2

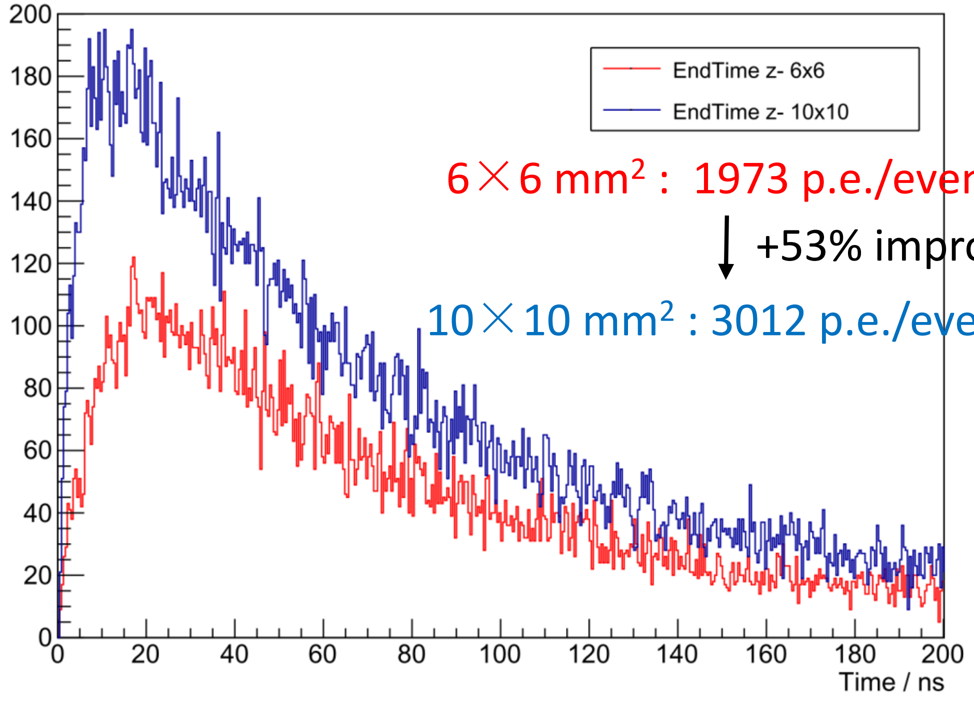
Hit Position in Z	0mm	-50mm	-100mm	-150mm	-190mm
$\tau_{rise} = 60\text{ps}$ (ideal)	191 ps	207 ps	197 ps	179 ps	156 ps
$\tau_{rise} = 2.8\text{ns}$ (measurement)	390 ps	413 ps	380 ps	389 ps	353 ps





Impact of SiPM sensitive areas

- Larger SiPM
  - More photons, steeper rising edge
  - #photons increase limited to acceptance angle (total reflections)

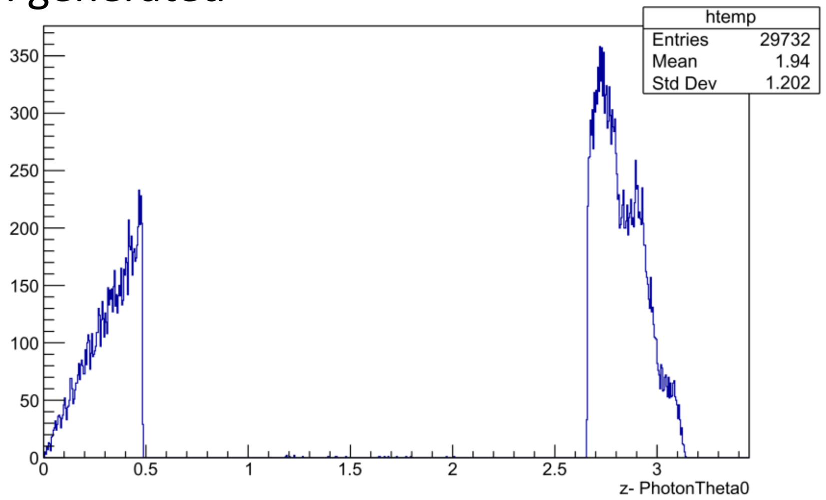


6×6 mm^2 : 1973 p.e./event

↓ +53% improvement

10×10 mm^2 : 3012 p.e./event

Polar angles along z (crystal length) of photons when generated



- Reflection index of BGO = 2.15, critical angle ≈ 27.7°
- Only photons in a special solid angle can be detected
- Can be improved with better crystal-SiPM coupling

Near future activities

- CEPCSW Tutorial and detector study: Sep. 17-18, 2020
  - https://indico.ihep.ac.cn/event/12341/
  - Target audience: graduate students and senior undergraduates
  - Format: in-person + online
  - Introduction on CEPC sub-detectors + hands-on exercise

Thursday, 17 September 2020

08:00 - 10:00	General introduction		
	09:00	**Welcome speech** *10'*	Speaker: Prof. Xinchou LOU (高能所)
	09:10	**CEPC physics and detectors** *50'*	Speaker: LI Gang (EPC.IHEP)
10:00 - 10:30	Break		
10:30 - 12:00	Software basics		
	10:30	**Software ABC: linux, git, root, and GEANT4** *1h30'*	Speaker: Xin Shi (IHEP)
12:00 - 14:00	Lunch break		
14:00 - 16:00	Detector Simulation		
	14:00	**Introduction to CEPCSW** *1h0'*	Speaker: Dr. Jiaheng Zou (高能所)
	15:00	**DD4HEP: detector description** *1h0'*	Speaker: Chengdong FU (IHEP)
16:00 - 16:30	Break		
16:30 - 18:10	Detector simulation		
	17:05	**Simulation of a simple detector in CEPCSW** *1h0'*	Speaker: Dr. Tao LIN (高能所)

Friday, 18 September 2020

08:00 - 10:20	CEPC Detector		
	09:00	**CEPC tracker system** *40'*	Speaker: Dr. Hongbo ZHU (IHEP)
	09:40	**Tracking reconstruction** *40'*	Speaker: Ms. Yao Zhang (Institute of high energy physics, Beijing China)
10:20 - 10:40	Break		
10:40 - 12:10	CEPC detector		
	10:45	**CEPC Calorimeters** *40'*	Speaker: Dr. Yong Liu (Institute of High Energy Physics)
	11:25	**Calorimeter reconstruction** *40'*	Speaker: 文兴 方 (高能所)
12:10 - 14:00	Break		
14:00 - 16:00	CEPC detector: Questions & Answers		

Summary and plans

- Task force established for crystal ECAL
  - Implementation of detector layout in the new software framework (CEPCSW)
  - Development of a digitization tool for long crystal bars
    - Steady progress made with G4 full simulation
    - Plan to validate the simulation results with measurements
  - Need to fully exploit existing tools
    - Druid for event display with jets: patterns for separation and reconstruction
    - Geant4 stand-alone simulation for ECAL + HCAL