High-granularity Crystal Calorimeter: R&D progress towards CEPC TDRrd

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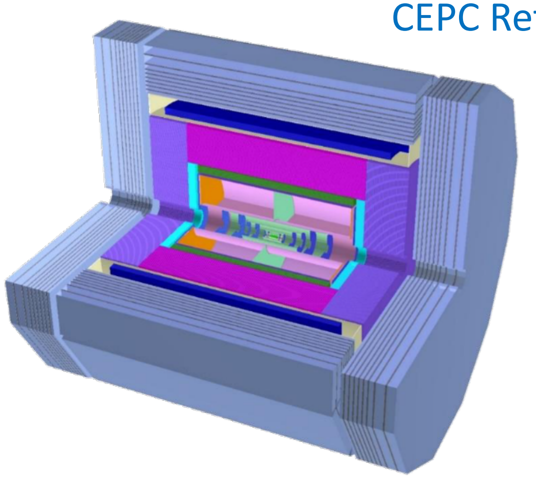
CEPC Day

November 27, 2024

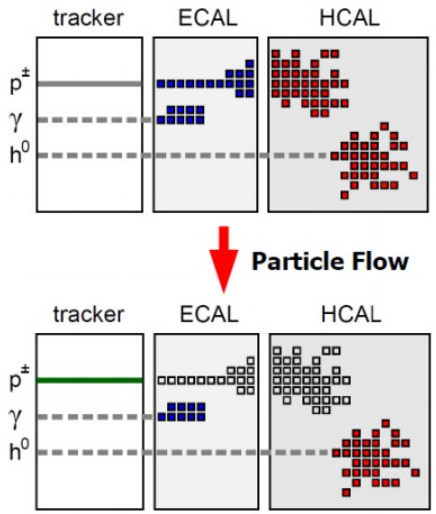
High granularity crystal calorimeter

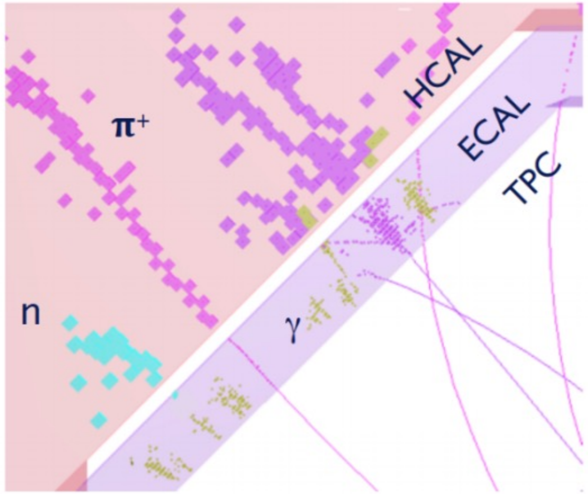
- Calorimetry for future Higgs factories (e.g. CEPC)
  - Precise measurement of Higgs/Z/W bosons, BSM physics, etc.
  - PFA-oriented design: high granularity (transverse, longitudinal)
  - Aim to achieve Boson Mass Resolution (BMR) of 3 - 4%
- CEPC Reference Detector
  - High-granularity crystal calorimeter: selected as **baseline ECAL option**
    - Fine segmentation in crystals: PFA compatible
    - Optimal EM energy resolution better than $3\%/\sqrt{E} \oplus 1\%$

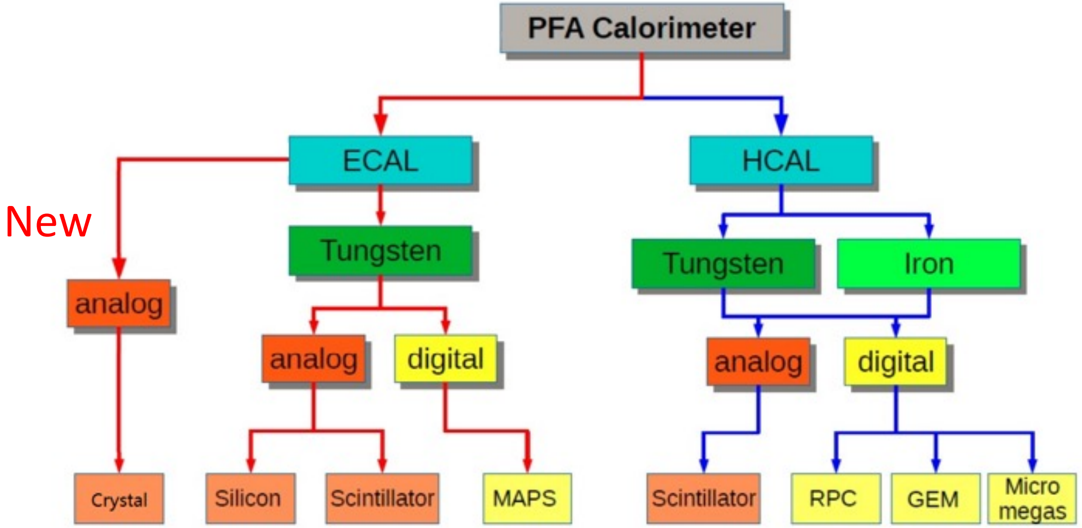
CEPC Reference Detector



Calorimeters: crystal ECAL and ScintGlass HCAL

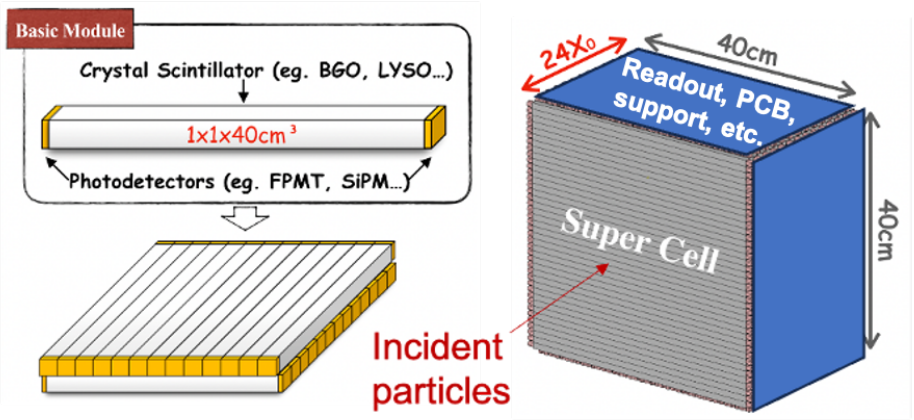




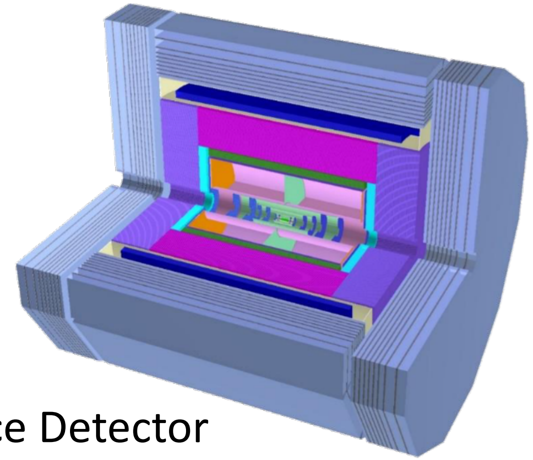


PFA-oriented crystal calorimeter for CEPC

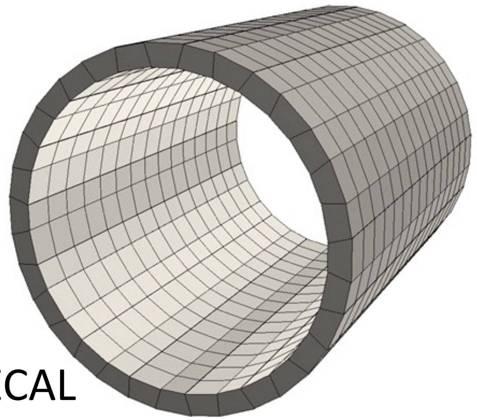
- Focus of this talk: (hardware) R&D activities on **key issues**
  - Crystal-SiPM units in lab and beam tests
    - Response uniformity, timing performance (MIP and EM shower)
  - Crystal calorimeter prototyping and beamtests
    - EM performance, validation of simulation and digitisation
  - Considerations on 2025 planning



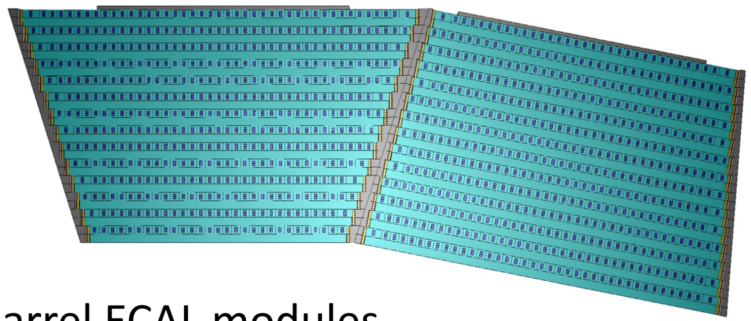
- **BGO bars in $1\times1\times\sim40\ cm^3$**
- **Effective granularity $1\times1\times2\ cm^3$**
- **Modules with cracks not pointing to IP (with an inclined angle of 12 degrees)**



CEPC Reference Detector



Barrel ECAL

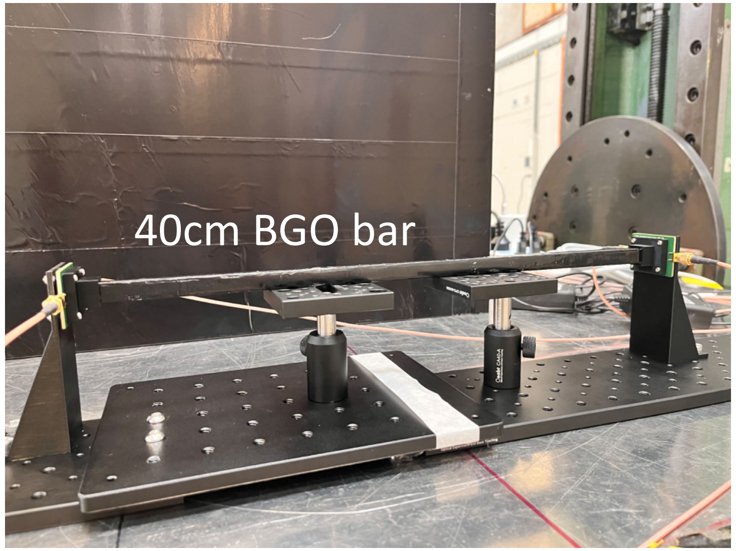


Barrel ECAL modules

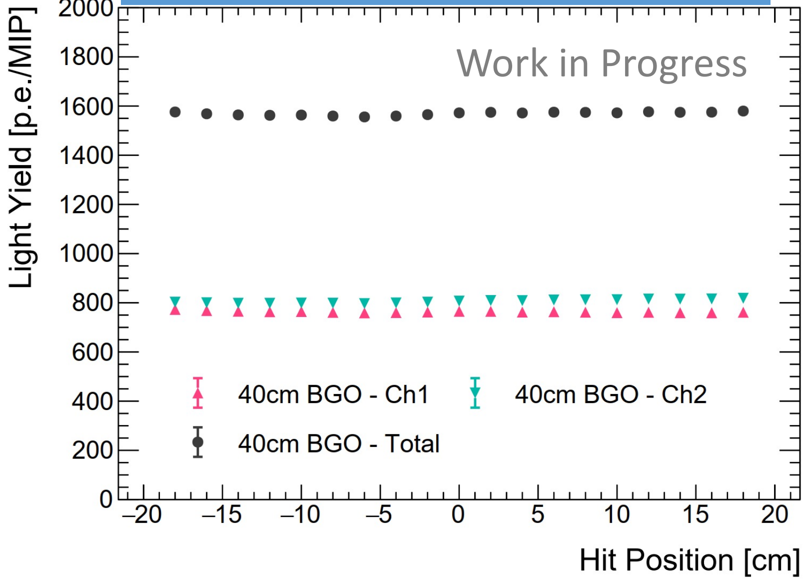
Long BGO bar (40cm): 2024 CERN beamtest

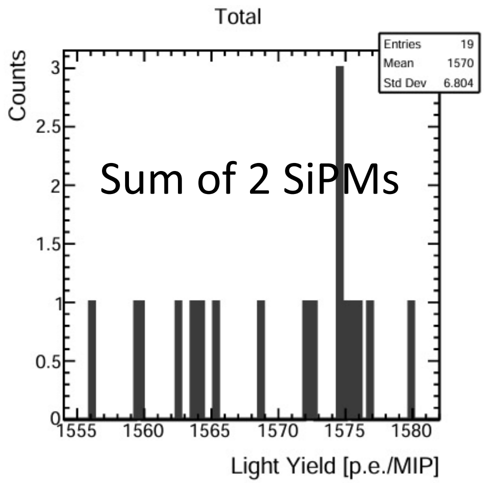
- 40cm BGO bar: uniformity scans with π^- beam
  - Data: MIP energy spectrum with 10 GeV π^-
  - Uniformity (MPV) in RMS/mean = 0.43 %
  - Uniformity (MPV) in (Max-Min)/Mean = 1.5%
- Excellent response uniformity along crystal length

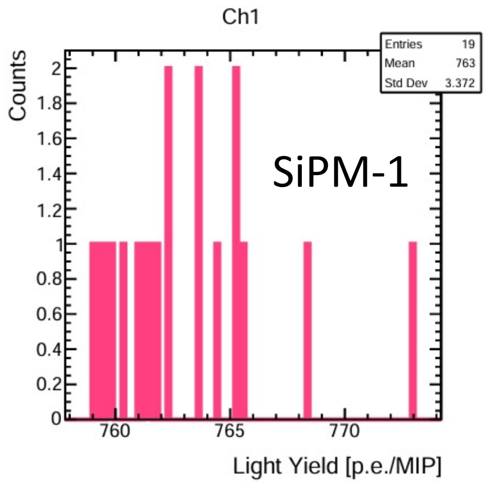
CERN beamtest in Jul. 2024

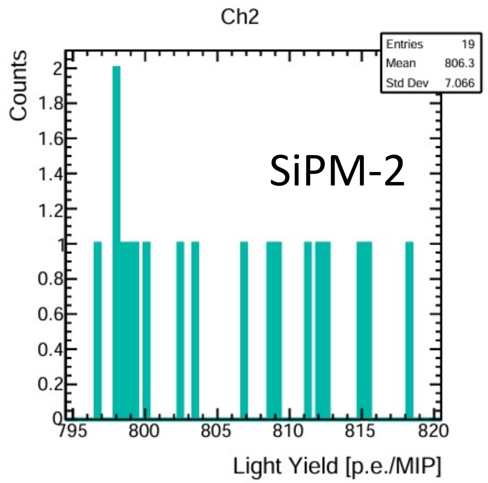


BGO-SiPM response uniformity





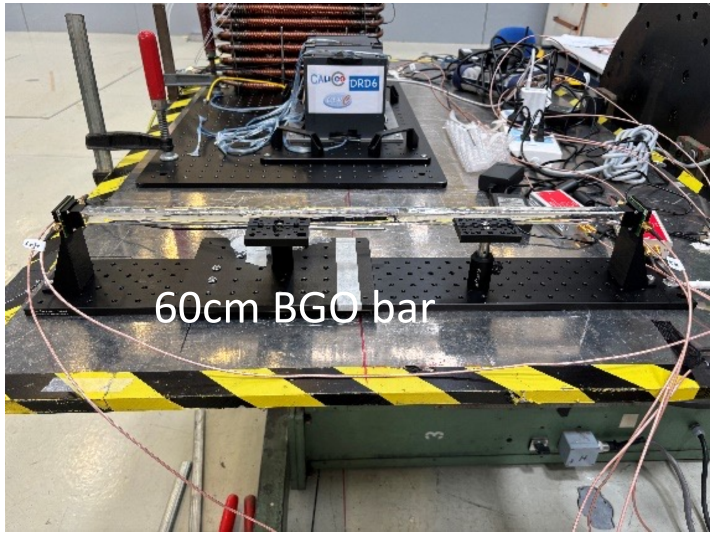




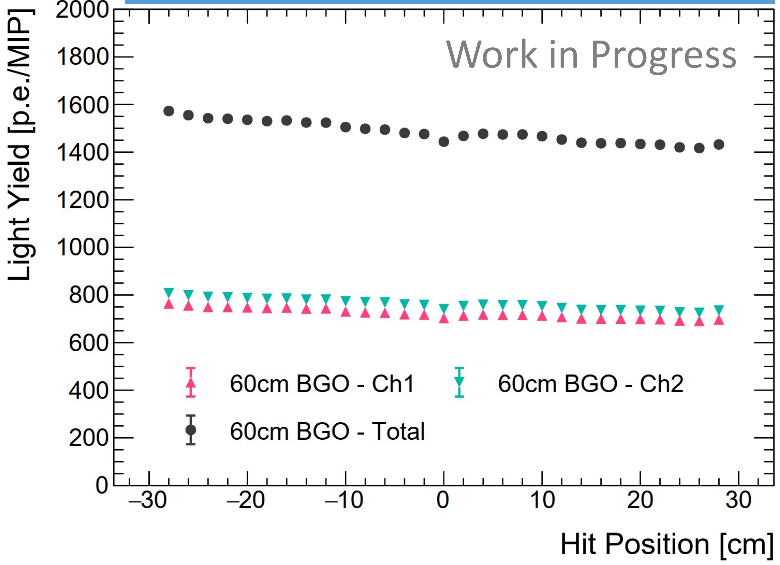
Long BGO bar (60cm): 2024 CERN beamtest

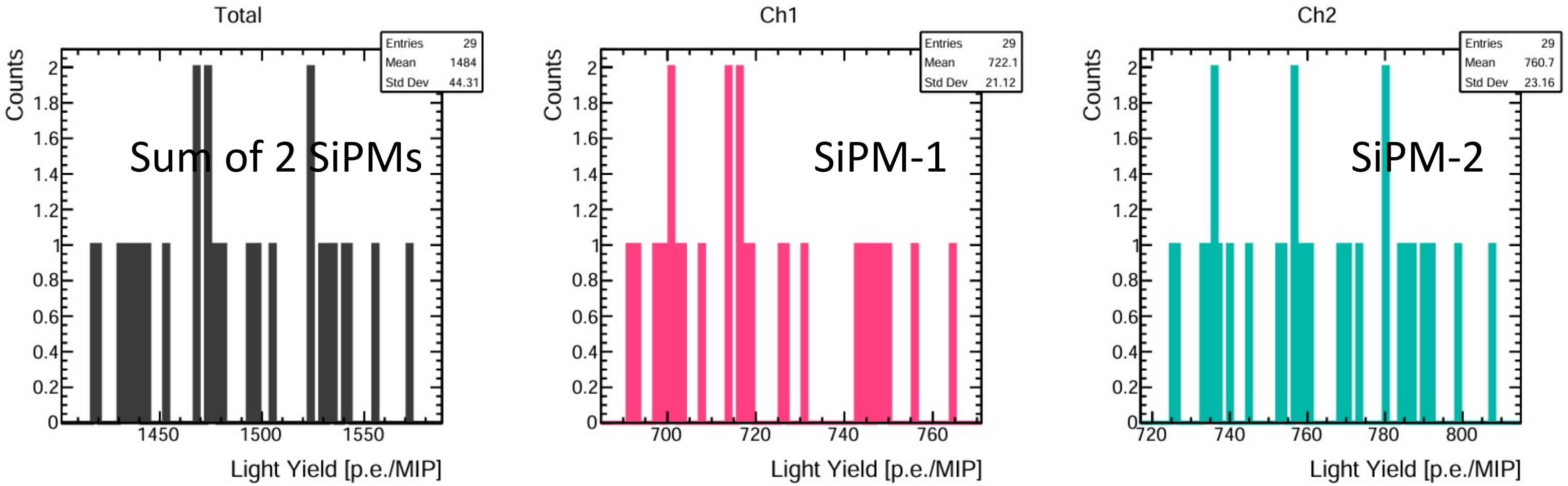
- 60cm BGO bar: uniformity scans with π^- beam
  - Data: MIP energy spectrum with 10 GeV π^-
  - Uniformity (MPV) in RMS/mean = 3.0 %
  - Uniformity (MPV) in (Max-Min)/Mean = 10.5%
- 60cm BGO shows worse uniformity than 40cm (7 times)

CERN beamtest in Jul. 2024



BGO-SiPM response uniformity

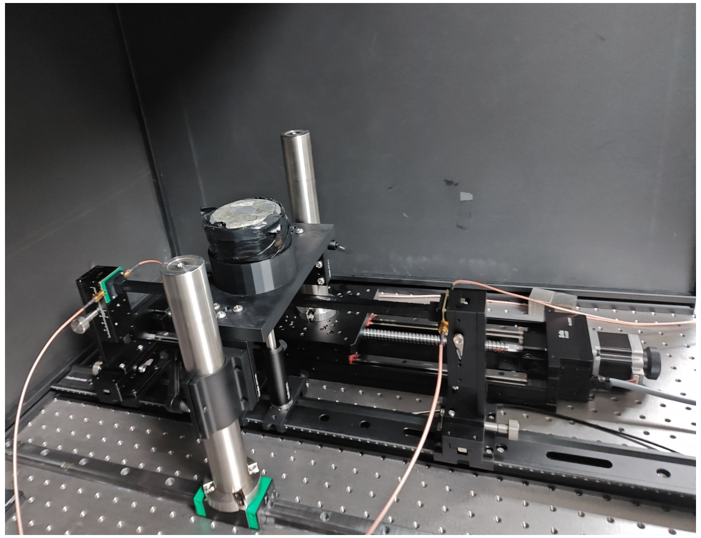




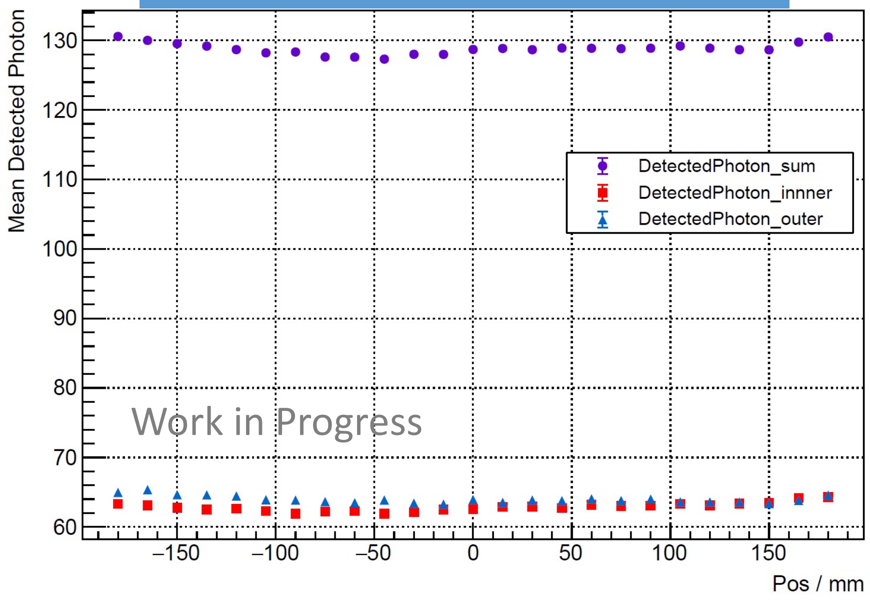
BGO crystal bar: uniformity studies in lab (reminder)

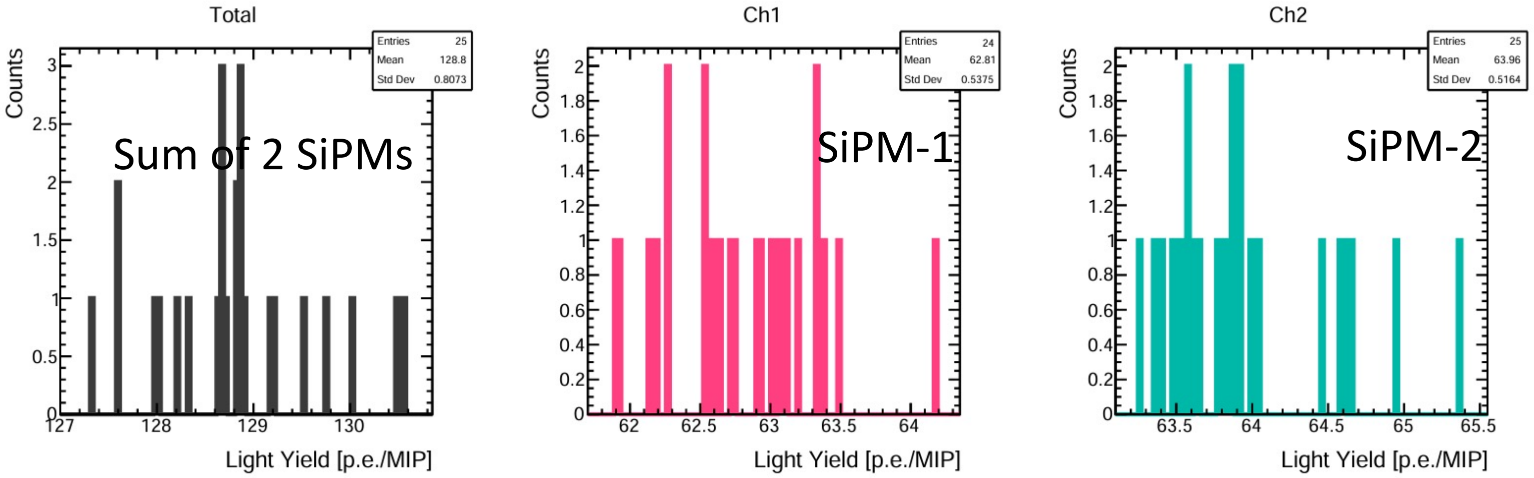
- 40cm long BGO: uniformity scans with Cs-137
  - Data: 662 keV full energy spectrum
  - Uniformity in RMS/mean = 0.6 %
  - Uniformity in (Max-Min)/Mean = 2.5%

Automated crystal scan platform



BGO-SiPM response uniformity

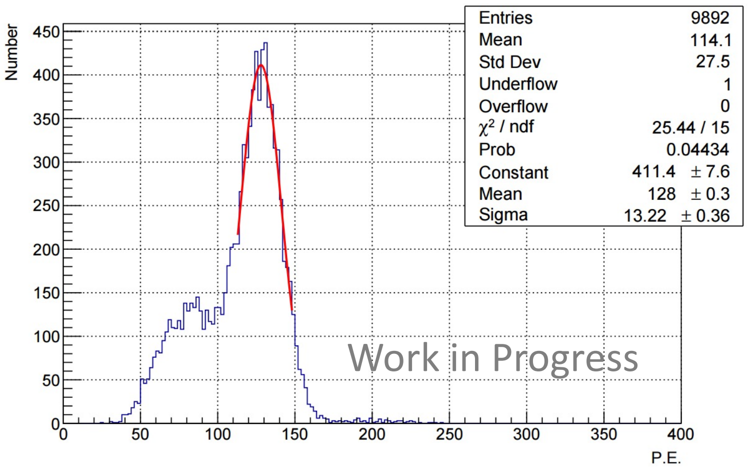




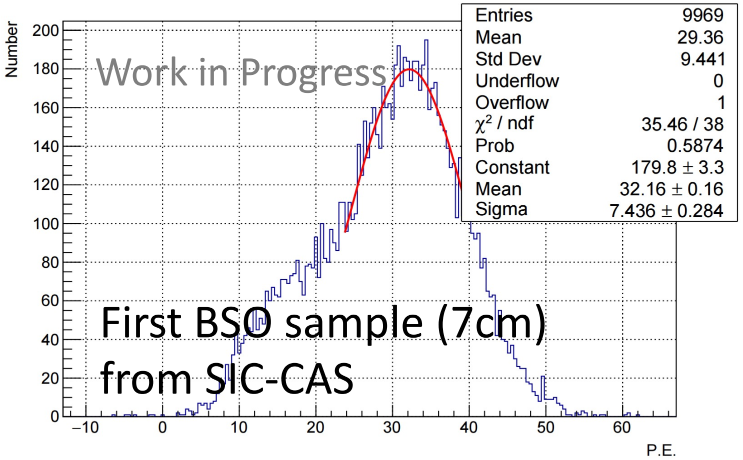
Crystal options: BGO vs. BSO

- Crystal candidates: BSO versus BGO
  - Similar density and moderate light yield
  - BSO with faster scintillation time (100 ns) than BGO (300 ns)
  - BSO with more potentials in cost effectiveness: without using Germanium
- BGO and BSO tested with Cs-137 and cosmic muons in lab
  - BSO shows ~1/4 of BGO light yield: consistent with publications

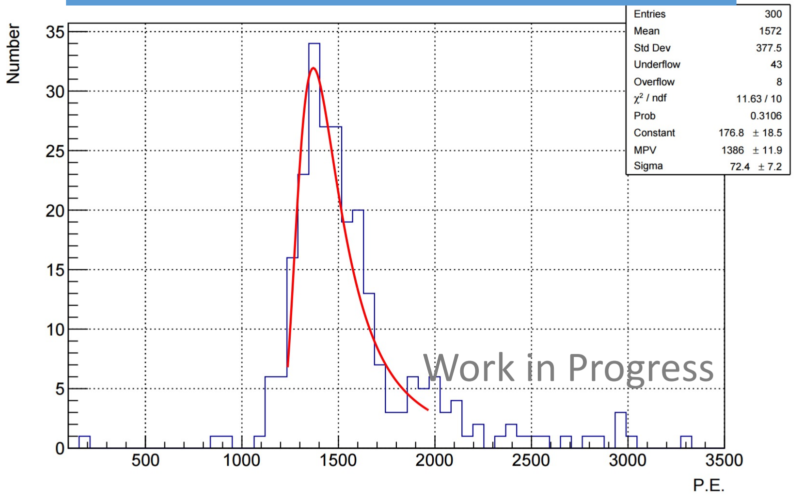
40 cm BGO response to 662 keV gamma



7 cm BSO response to 662 keV gamma



40 cm BGO in cosmic rays: MIP response



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BSO properties: density and X0

Atomic and nuclear properties of bismuth silicate (BSO) $[(Bi_2O_3)_2(SiO_2)_3]$

Quantity	Value	Units	Value	Units
<Z/A>	0.42260	mol g^{-1}		
Density	7.120	g cm^{-3}		
Mean excitation energy	519.2	eV		
Minimum ionization	1.279	MeV $g^{-1}cm^2$	9.103	MeV cm^{-1}
Nuclear interaction length	157.0	g cm^{-2}	22.06	cm
Nuclear collision length	95.5	g cm^{-2}	13.42	cm
Pion interaction length	189.2	g cm^{-2}	26.57	cm
Pion collision length	121.9	g cm^{-2}	17.12	cm
Radiation length	7.81	g cm^{-2}	1.097	cm
Critical energy	10.68	MeV (for e^-)	10.32	MeV (for e^+)
Muon critical energy	183.	GeV		
Molière radius	15.52	g cm^{-2}	2.179	cm
Plasma energy $\hbar\omega_p$	49.98	eV		

Composition:

Elem	Z	Atomic frac*	A	Mass frac
O	8	12.00	15.9990	0.172629
Si	14	3.00	28.0855	0.075759
Bi	83	4.00	208.9804	0.751613
* calculated from mass fraction data				

For muons, $dE/dx = a(E) + b(E)\,E$. Tables of $b(E)$: PDF TEXT
Table of muon dE/dx and Range: PDF TEXT
Explanation of some entries
Note: Mean excitation energy calculated using the ICRU37 Table 5.1 algorithm for liquids and solids
Note: Evalite structure; less common is Bi{12}SiO{20}
Note: Check density. Probably wrong

https://pdg.lbl.gov/2024/AtomicNuclearProperties/HTML/bismuth_silicate_BSO.html

Crystal	Density (gcm^{-3})	Radiation length (mm)	Decay constant (ns)	Peak emission (nm)	Refractive index *n*	Relative light output
BSO	6.80	11.5	~ 100	480	2.06	0.04
BGO	7.13	11.2	~ 300	480	2.15	0.15

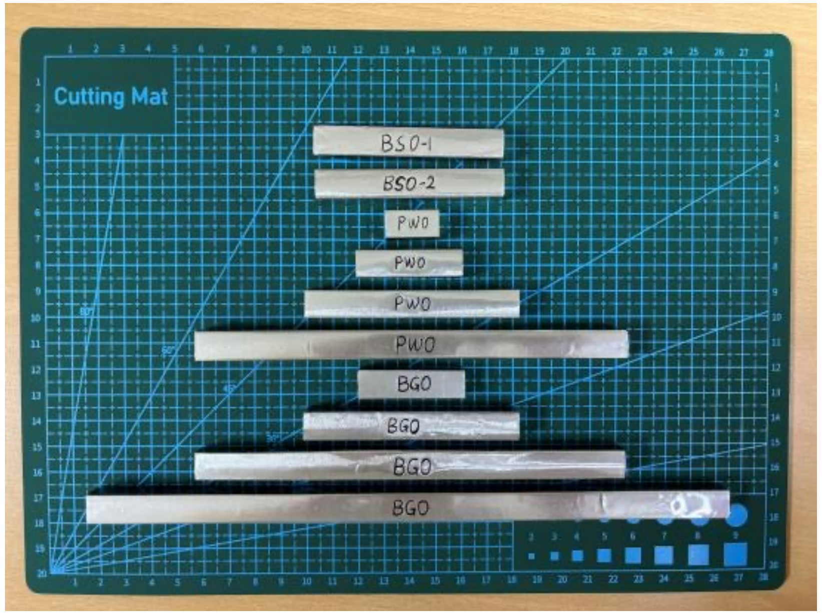
https://doi.org/10.1016/j.nima.2011.03.013

- BSO density and X0: PDG values are wrong
  - BSO in PDG: higher density and shorter X0 than BGO
- BSO crystals produced at SIC
  - Density recently measured by SIC colleagues: 6.78 g/cc
  - Result Consistent with the NIMA publication (6.80 g/cc)
- Will apply updated values in calorimeter simulation

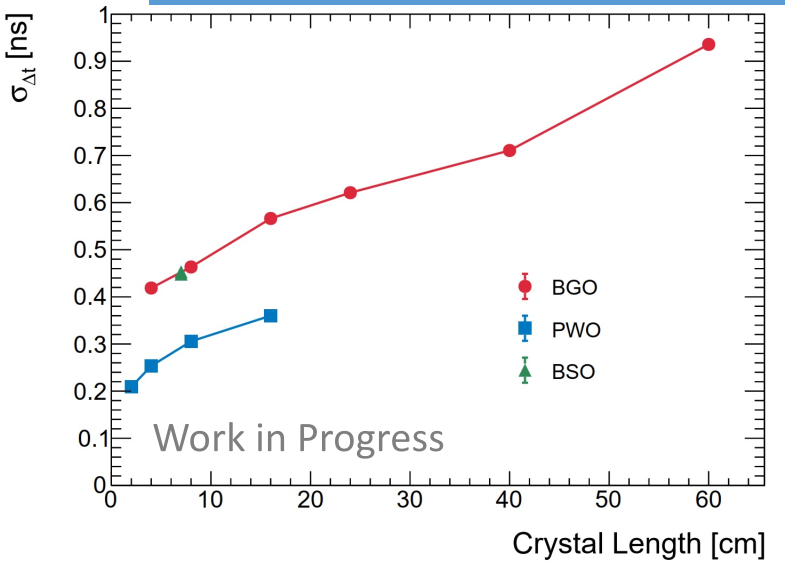
Crystal MIP timing resolution: 2024 CERN beamtest

- Tested different crystal types and lengths with 10 GeV π^-
- BGO (8cm) and BSO (7cm) exhibit similar timing resolution
  - Effects of intrinsic light yield and scintillation time (somehow) cancel out
- PWO shows the best timing resolution, even with a lower light yield
- Timing resolution generally degrades when length increases

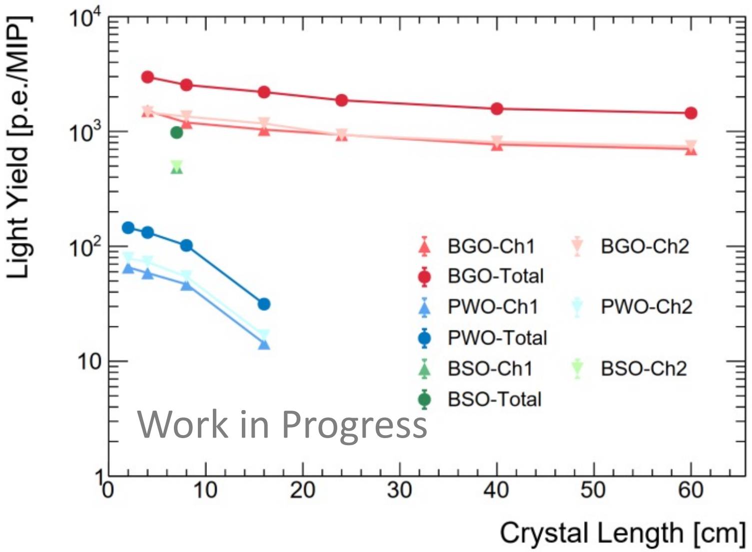
Crystal	Typical τ_{sc}
BGO	300ns
BSO	100ns
PWO	30ns



MIP timing resolution (2 ends)

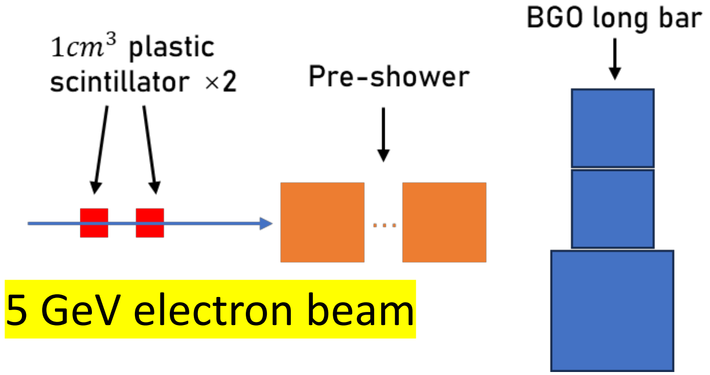


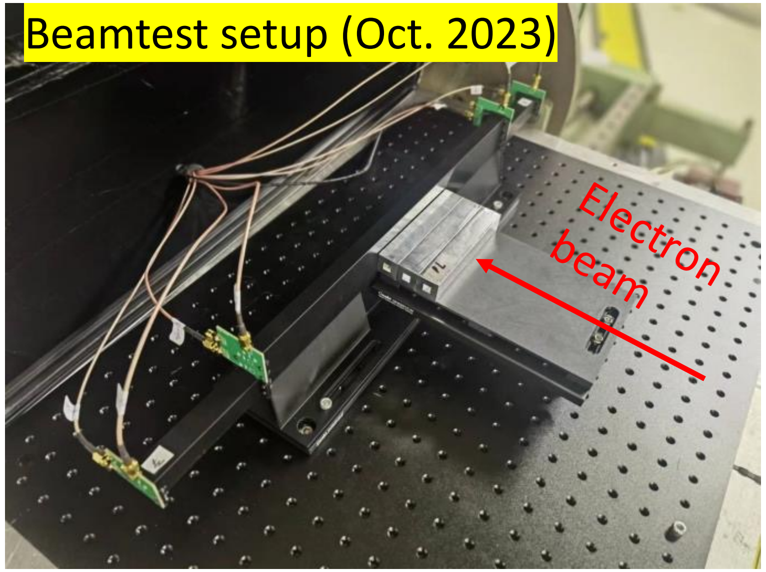
MIP response in p.e.



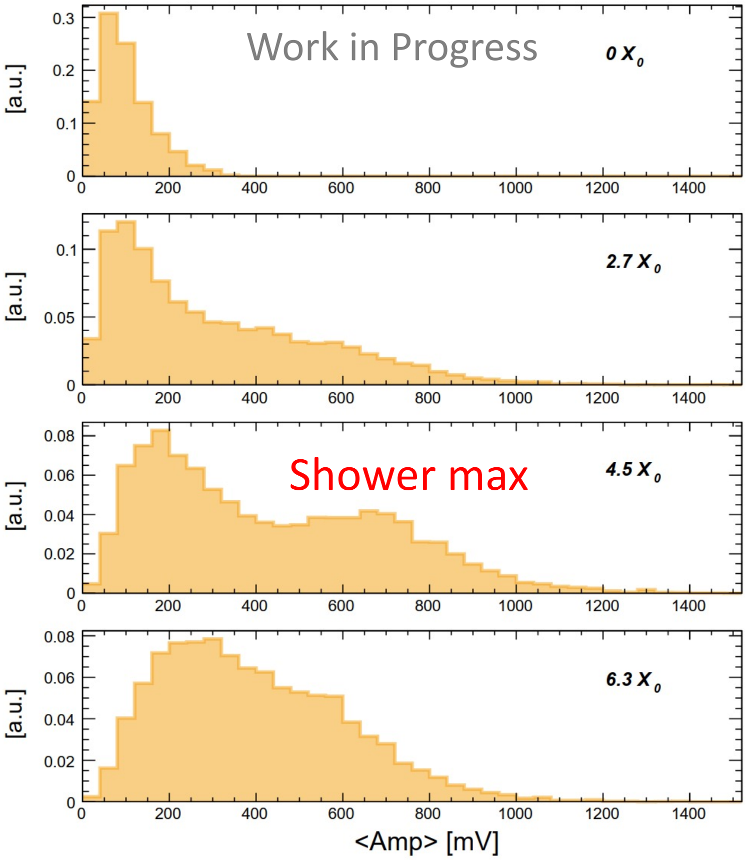
EM shower timing studies: 2023 DESY beamtest

Beamtest setup schematics

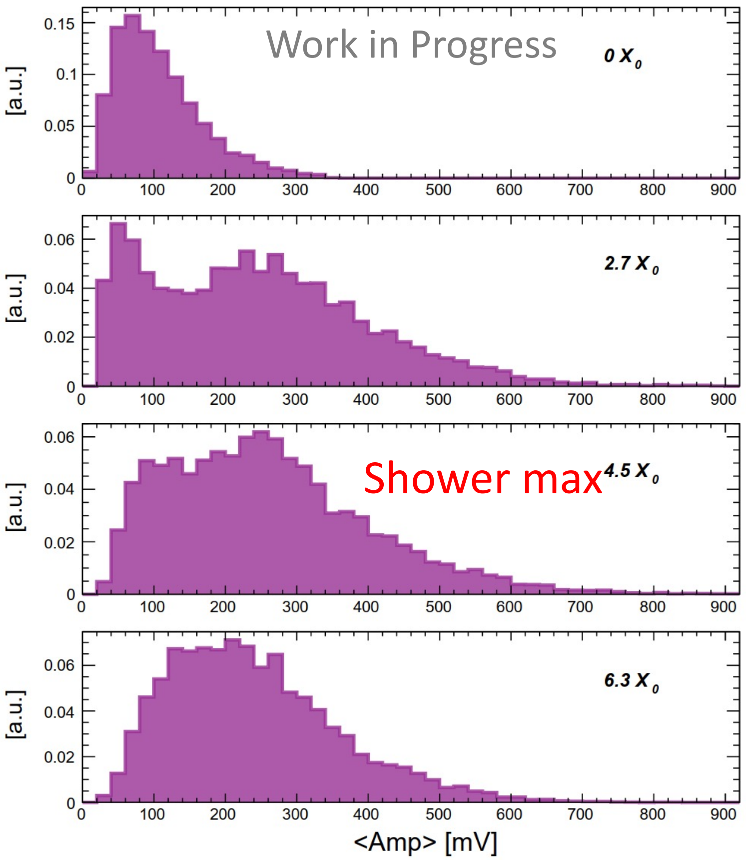




40 cm BGO

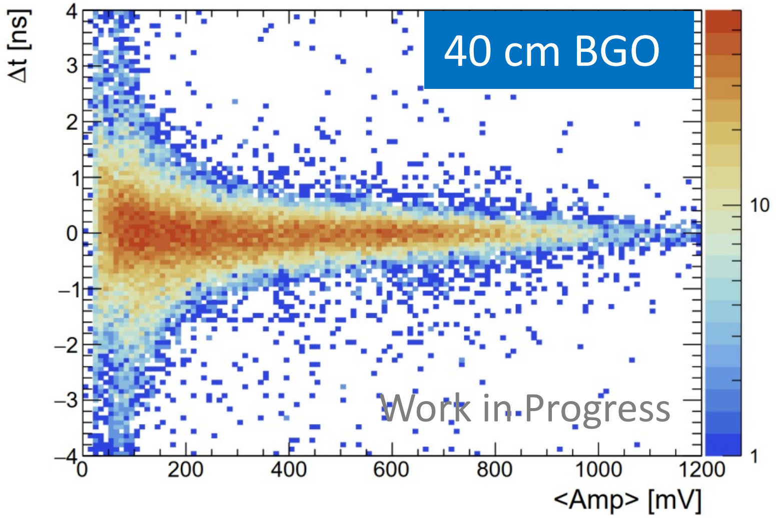


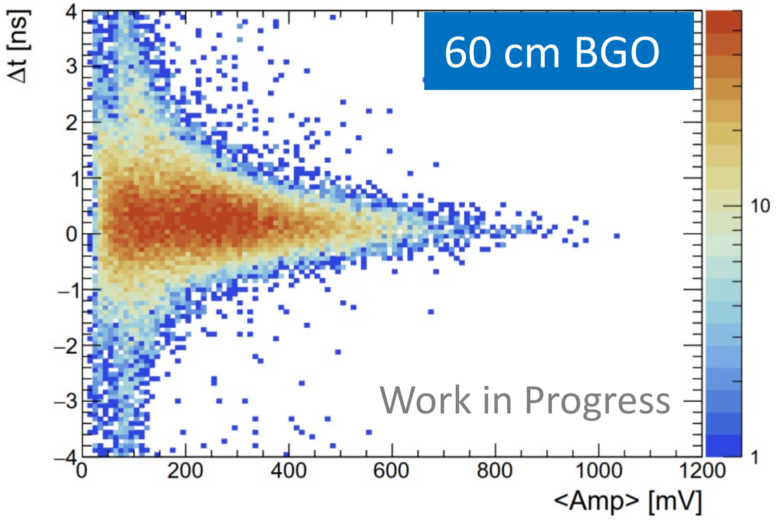
60 cm BGO

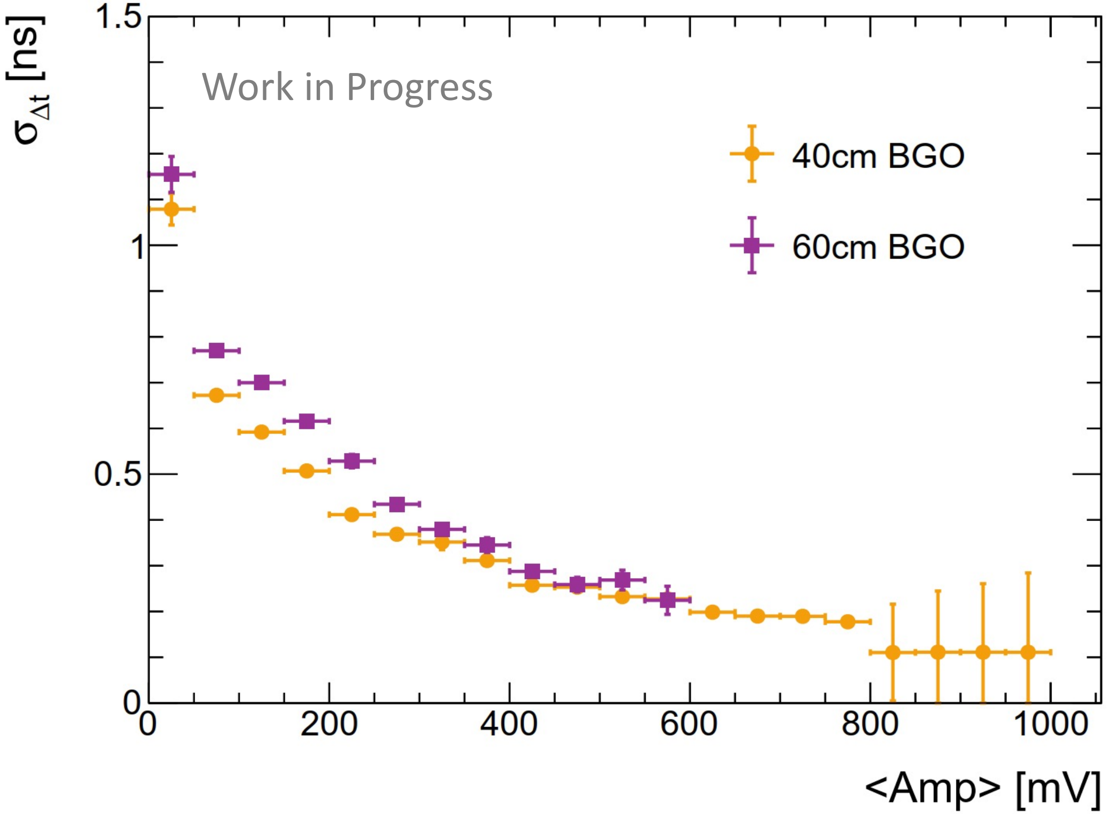


- Signal amplitude distributions with different upstream (pre-shower) materials: to mimic different shower depths and study timing performance

EM shower timing studies: 2023 DESY beamtest

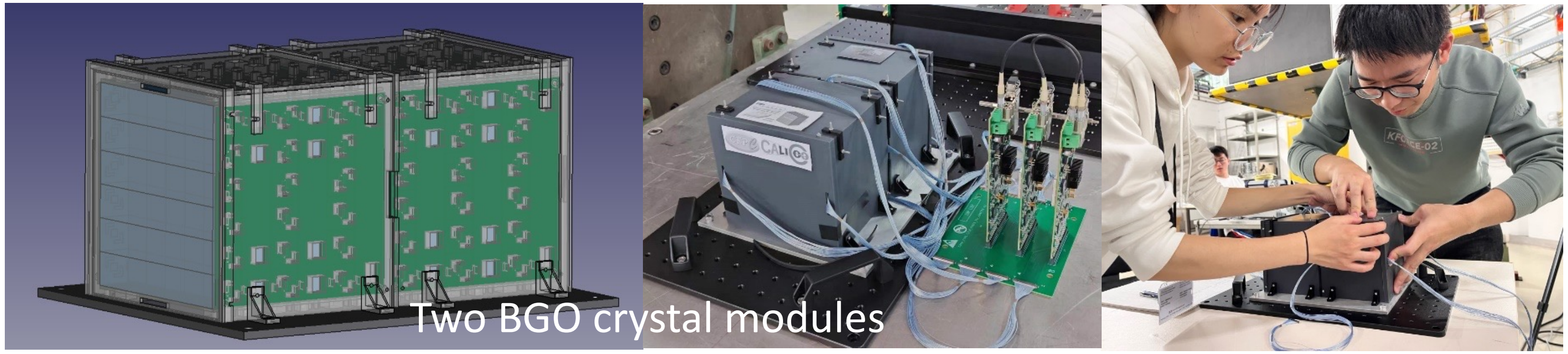




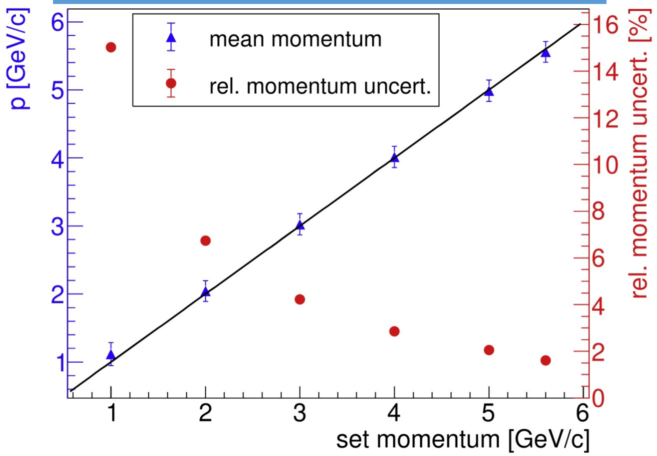


- Quantitative results: timing resolution versus signal amplitude
- Better than 200ps with extremely large signals (shower maximum)
- Reaching the limitation of test stand (2.5 GS/s sampling rate)

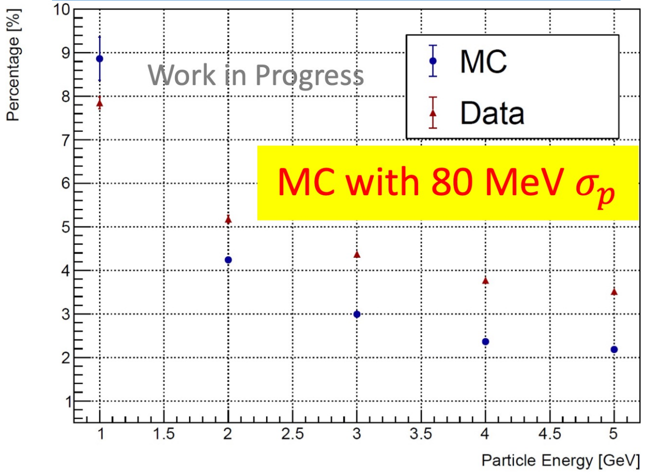
Crystal Calorimeter Prototype: 2023 DESY beamtest



Beam momentum spread: measurement at TB21



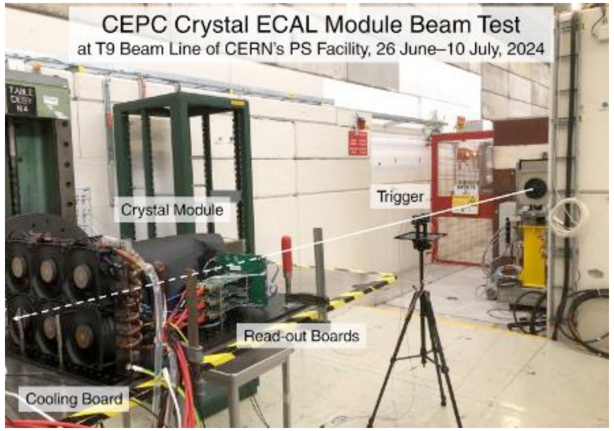
EM resolution: data vs. MC

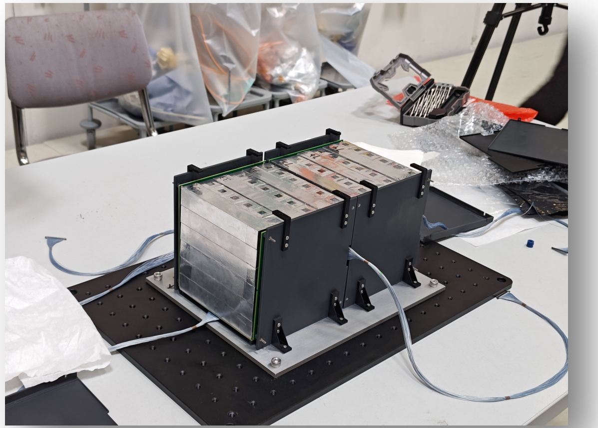


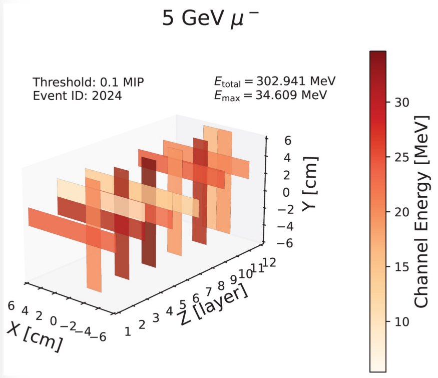
- Crystal calorimeter modules: with total depth of $21X_0$
- First beamtest: electron beam (1-6 GeV) at DESY TB22
  - Motivations: system integration, EM shower performance
  - EM Performance: dominated by TB22 beam momentum spread
  - DESY beamline momentum spreads
    - TB21: measured with dipole magnet and beam telescope **~16% (at 1GeV)**
    - **TB22: no direct measurements**, expected at ~8% at 1 GeV from our testbeam data; but spread seems not to follow 1/p function as in TB21

Crystal Calorimeter Prototype: 2024 CERN beamtest

- Data taking with muon and electron beams CERN PS-T9
  - MIP calibration (5 GeV muons), EM performance (1– 10 GeV electrons)
  - Extensive studies on detector calibration, simulation digitisation, beam momentum
  - Considerably smaller beam spread than DESY beamline
    - Crucial for testing high-precision detectors like crystal calorimeters
- Extensive studies on PS-T9 beamline simulation with CERN beamline physicist
  - Confirmed larger beam momentum spread in data than expected from beamline lattice (~1%)
  - Quantified beam momentum spread due to Beam Instrumentation in upstream

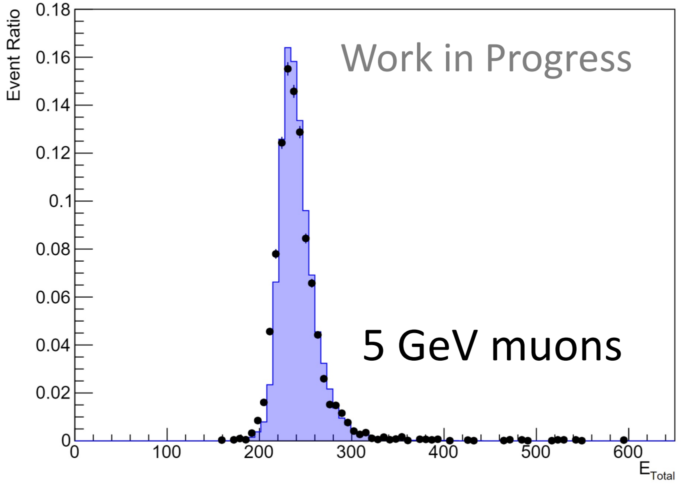


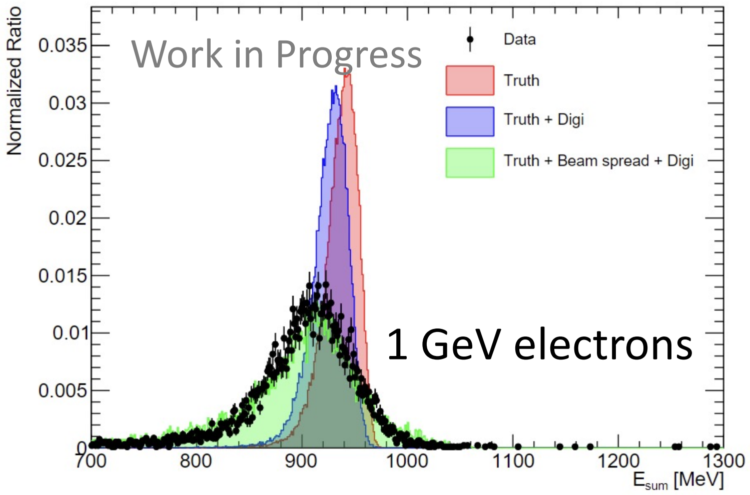


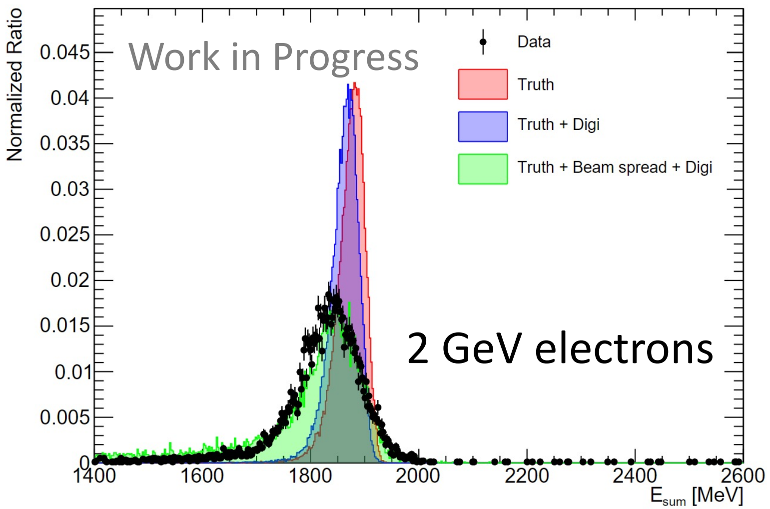


Crystal Calorimeter Prototype: 2024 CERN beamtest

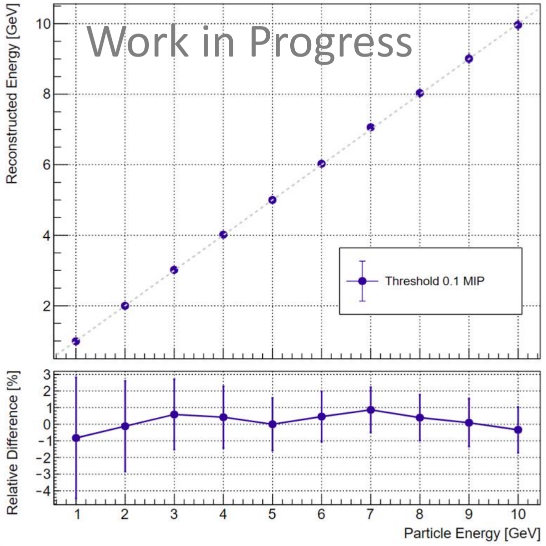
- MIP calibration with 5 GeV muons
  - Done for all 144 channels, and also High Gain and Low Gain modes per ASIC channel
  - Data and MC (simulation + digitisation) reach reasonable consistency in MIP energy spectrum
- EM performance with 1 – 10 GeV electrons
  - Use beam momentum from <u>beamline simulation</u> as an input to <u>calorimeter simulation</u>
  - Energy spectra: simulation + digitisation can generally reproduce data

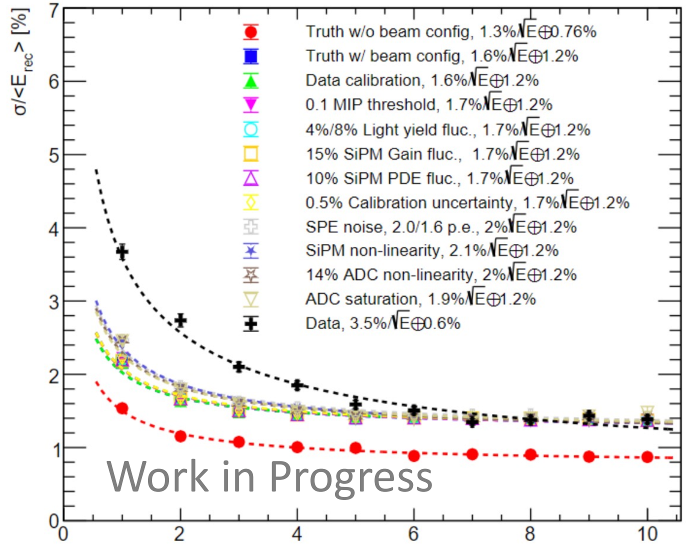






Crystal Calorimeter Prototype: EM performance





- Studies based on electron data in 1 – 10 GeV
  - Data taken with *beam instrumentation* in upstream: Cherenkov detectors (XCET), SciFi trackers (beam profilers)
- EM response linearity within $\pm 1\%$
  - Better understanding of calibration precision (~0.5%) and corrections of crosstalk in ASIC neighbouring channels
- EM energy resolution
  - Preliminary EM performance after excluding beam momentum spread: $< 2\%/\sqrt{E} \oplus 1\%$
- Dedicated digitisation model for crystal prototype
  - Generally well validated by electron beam data
- Ongoing studies
  - Corrections for SiPM and ASIC with large signals (high energy)
  - Further discussions on beamline simulation

Summary and planning

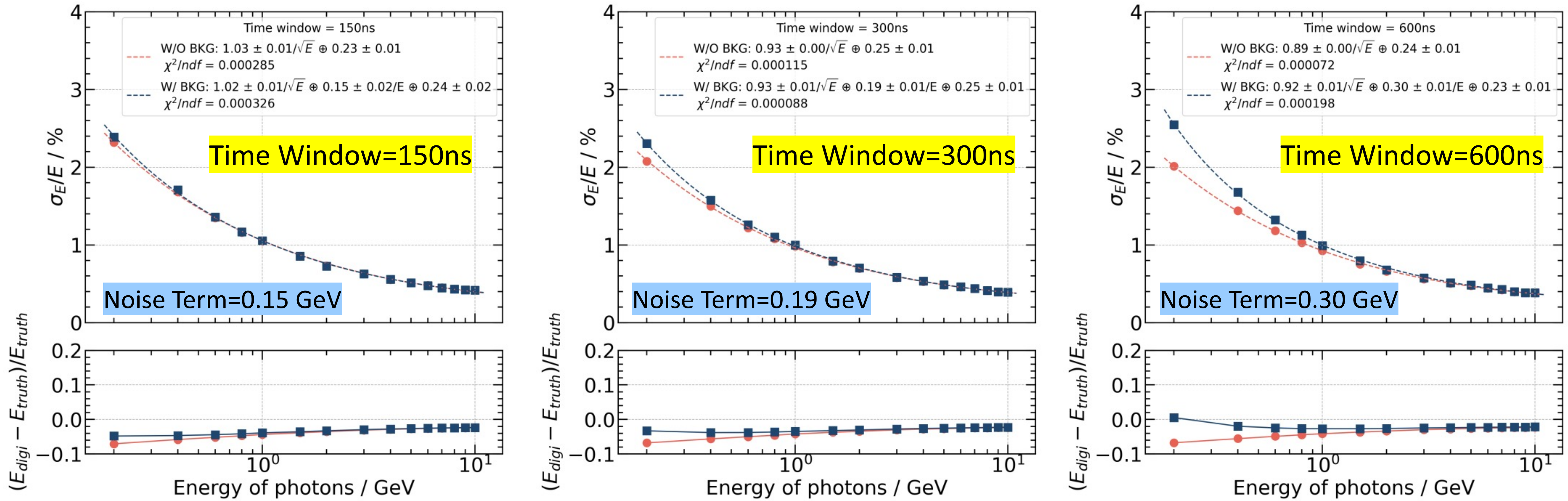
- CEPC crystal calorimeter R&D: steady progress to address key issues
  - Crystal-SiPM units
    - Comprehensive studies in response uniformity, timing performance (MIP and EM shower)
  - Crystal calorimeter prototype
    - Promising results on EM performance and validation of simulation and digitisation with data
- Considerations on R&D planning in 2025
  - To fully exploit existing testbeam data (1-10 GeV) in 2023/2024: finish data analysis and prepare publications (also as references for CEPC Ref-TDR)
  - To study performance with BSO crystals and also SiPMs from domestic vendors
  - Crystal calorimeter prototype: performance with beam energy above 10 GeV
  - To measure SiPM-crystal signals as large as ~30 GeV (the upper limit for one channel in CEPC ECAL)
    - To evaluate the response linearity with testbeam data
    - To provide a solid input for SiPM-readout ASIC design
    - Need further discussions and planning for beamtest preparations

Thank you!

Backup Slides

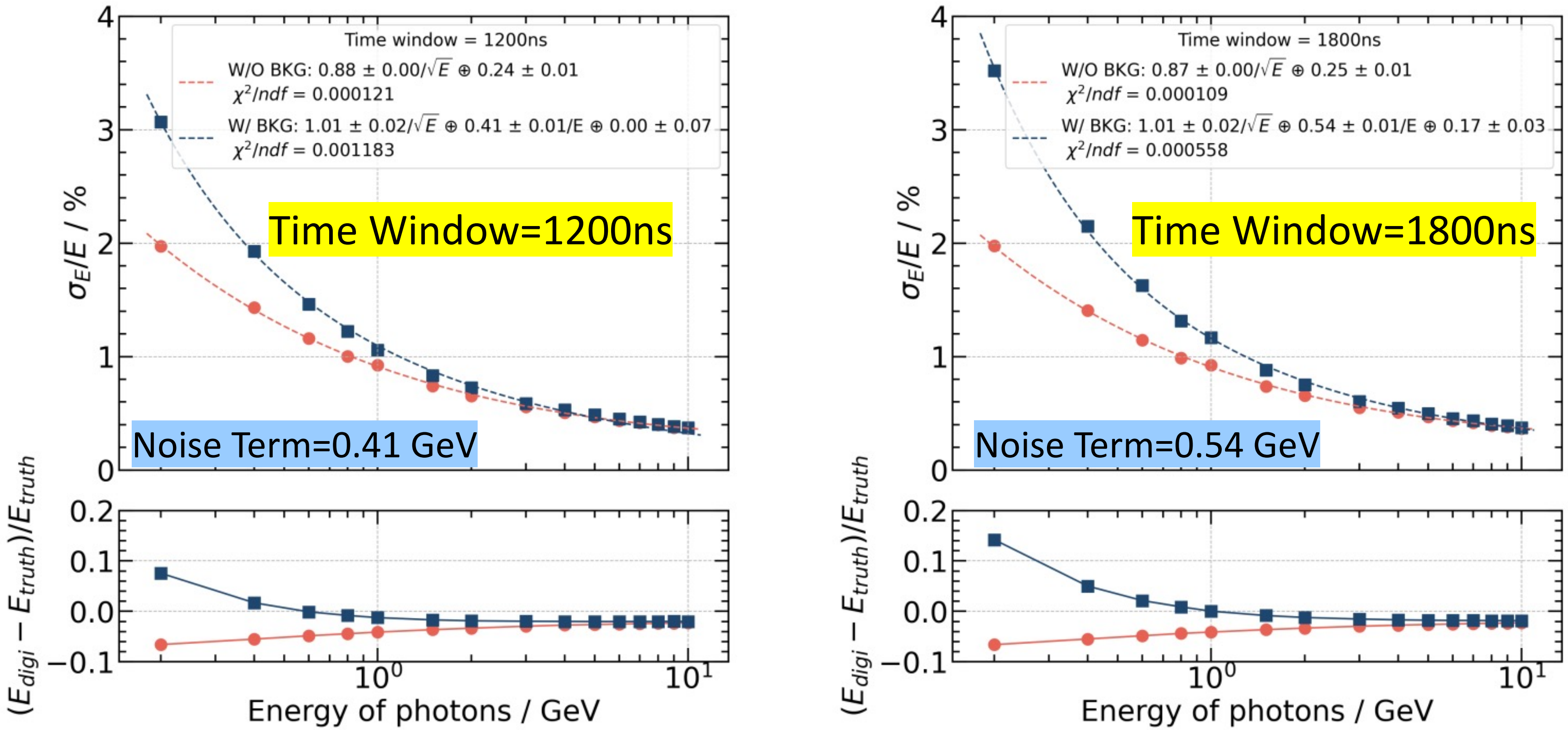
Beam backgrounds: impacts to EM performance

- Beam-induced backgrounds at 50MW Higgs mode
  - Varying ECAL time window: 150 ns – 1800 ns
  - Preliminary results: significant contribution to the noise term



Beam backgrounds: impacts to EM performance

- Beam-induced backgrounds at 50MW Higgs mode
  - Varying ECAL time window: 150 ns – 1800 ns
  - ECAL time window: trade-off in crystal scintillation signals and beam backgrounds



Reminder: *shaping time of 87.5 ns* in beamtests of crystal calorimeter prototype

BGO-SiPM: gated time window studies

- BGO-SiPM unit: MIP signal (in p.e.) versus time window
  - 200 ns time window: effective for collecting over 50% of the photons
  - Bear in mind: for each SiPM, ~100 p.e./MIP is required for stochastic term <3%