Luminosity measurement and monitoring at CEPC

Lei Zhang

On behalf of CEPC LumiCal team

AS: Suen Hou
NJU: Renjie Ma, Yuhui Miao, Xingyang Sun, Yilun Wang, Xiaoxu Zhang, Jialiang Zhang, Lei Zhang
IHEP: Haoyu Shi, Mei Zhao, Longyan He
JLU: Jiading Gong, Weimin Song

CEPC Workshop, Guangzhou, Nov. 5-10th 2025

Luminosity measurement at CEPC

- Most demanding from Z line-shape and WW threshold
  - Data-sets of $O(10^7-10^8)$, motivating luminosity precision of $O(10^{-4})$

$$\sigma^{\exp}_{e^+e^-\to X} = \frac{1}{\epsilon}\frac{N^{\exp}_{e^+e^-\to X}}{L}$$

- Lumi. Meas.: counting the rate of the well-known process

$$L = \int \mathscr{L}\mathrm{d}t = \frac{1}{\epsilon}\frac{N_0}{\sigma_0^{\mathrm{th}}} \qquad \frac{\Delta L}{L} = \frac{\Delta N_0}{N_0} \oplus \frac{\Delta\epsilon}{\epsilon} \oplus \frac{\Delta\sigma_0^{\mathrm{th}}}{\sigma_0^{\mathrm{th}}}$$

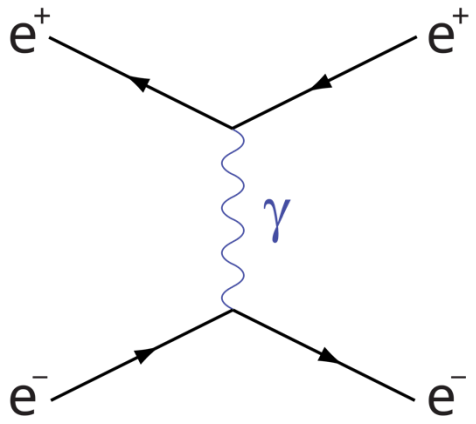
- Requirements for lumi. measurement physics process
  - Large rate, so as not to be statistics limited
  - Clean signature with low background, e.g. electron, photon, muons, etc
  - High-precision theory predictions and MC tools

Small-angle Bhabha scattering (SABS)

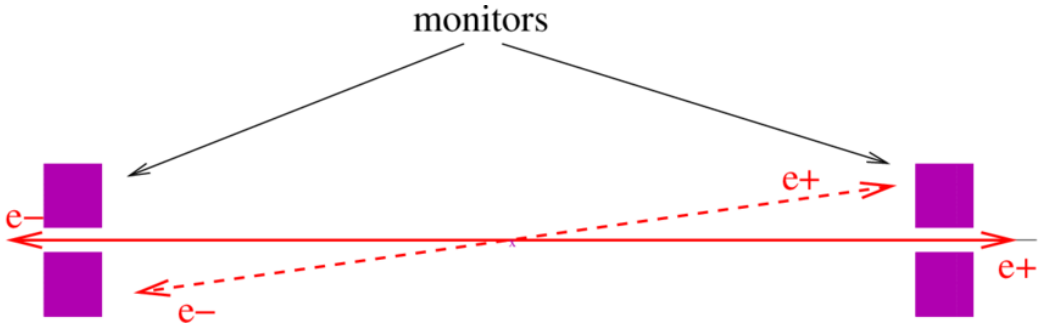
- SABS $e^+e^- \to e^+e^-$, dominant process in e+e- colliders

$$\sigma = \frac{16\pi\alpha^2}{s}\left(\frac{1}{\theta_{min}^2} - \frac{1}{\theta_{max}^2}\right) \qquad \frac{d\sigma}{d\theta} \sim \frac{1}{\theta^3}$$

$$= \frac{1040\ \text{nb GeV}^2}{s}\left(\frac{1}{\theta_{min}^2} - \frac{1}{\theta_{max}^2}\right)$$



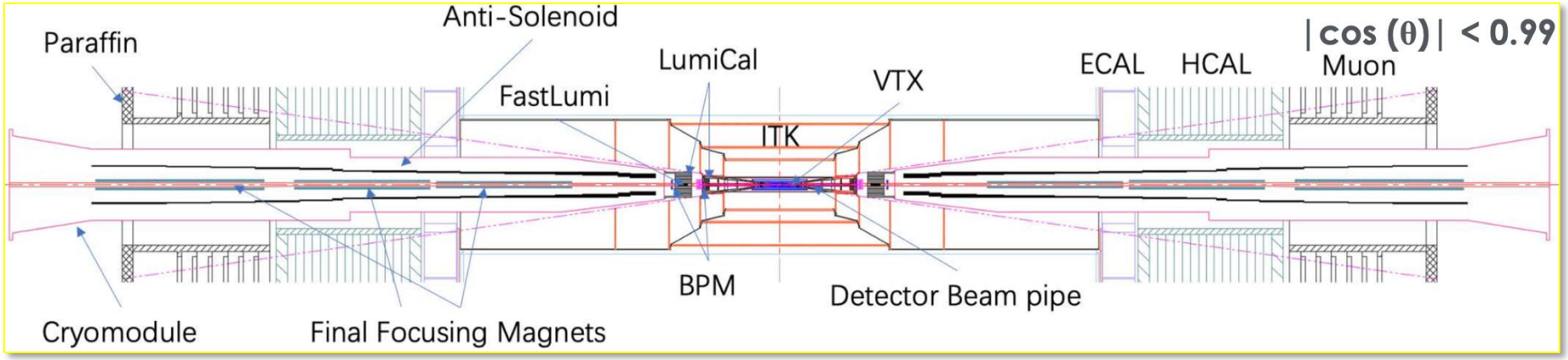
- Peaked in the forward region, at <100 mRad
  - Dedicated detector needed
  - Precision of the low edge positioning is critical

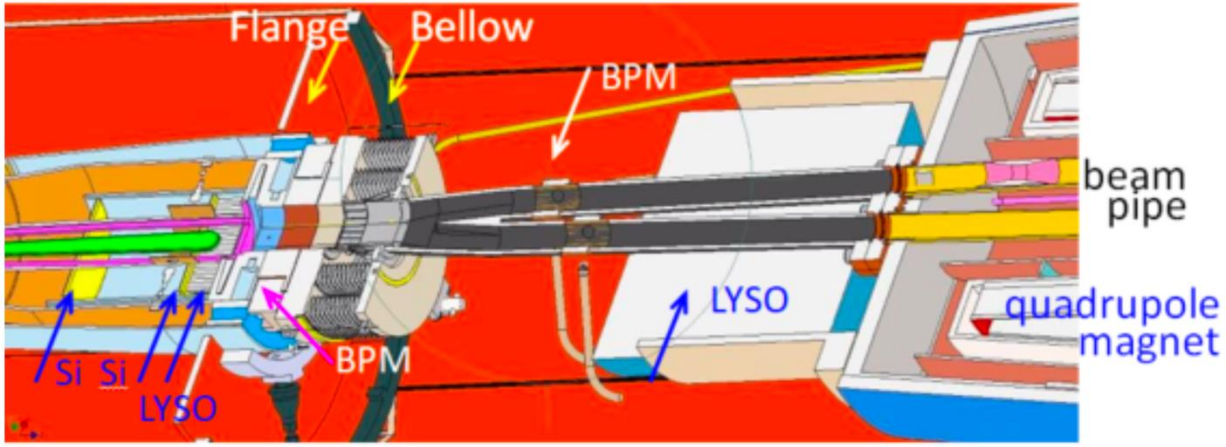


$$\frac{\Delta\mathcal{L}}{\mathcal{L}} \sim \frac{2\Delta\theta}{\theta_{min}}$$

CEPC LumiCal design

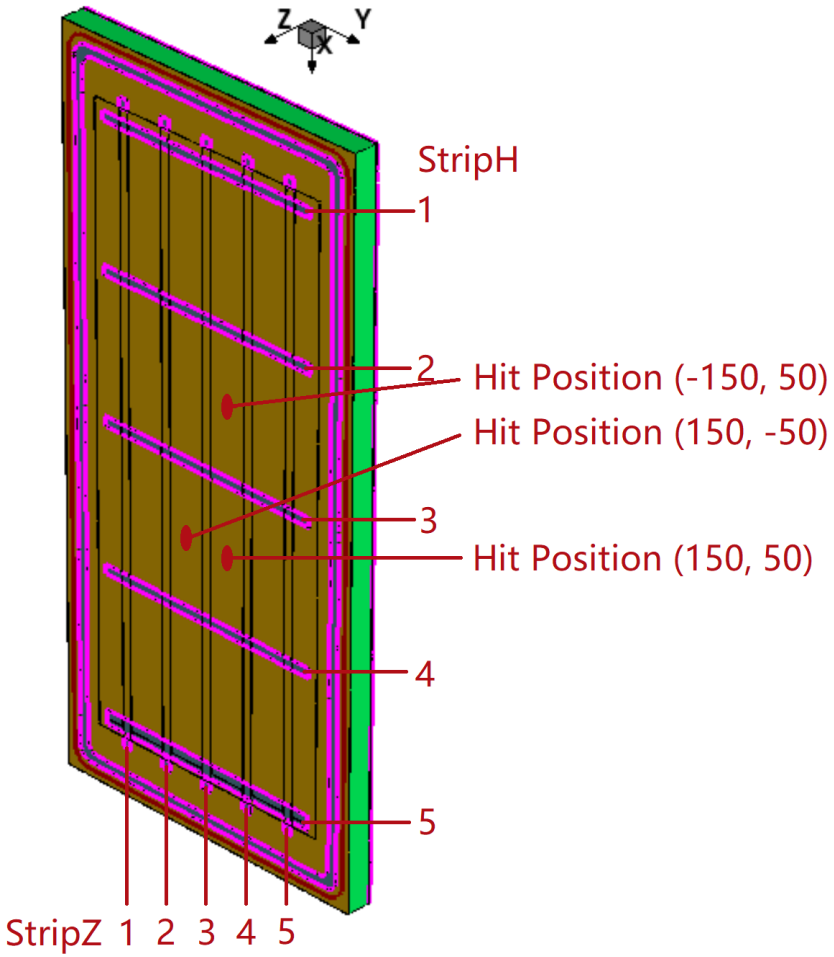
- Two detectors on each side of Interaction Point
  - Low-mass beampipe window: Be 1mm thick, traversing @22 mRad, traversing L= 45 mm, = 0.13 X_0 (Be), 0.50 X_0 (Al)

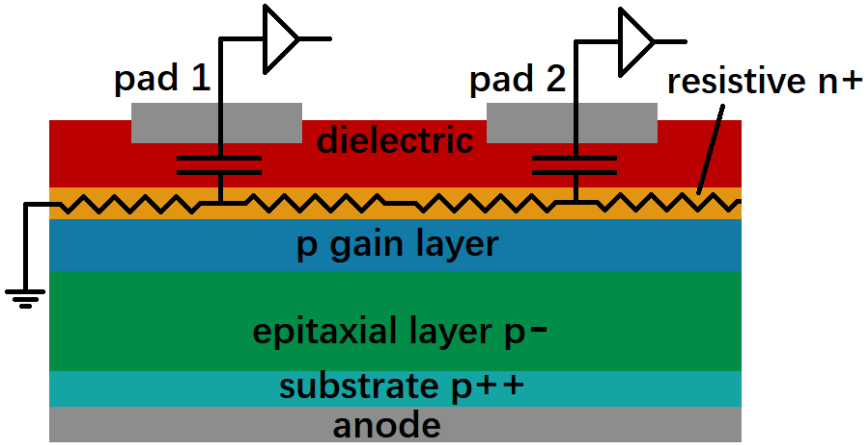




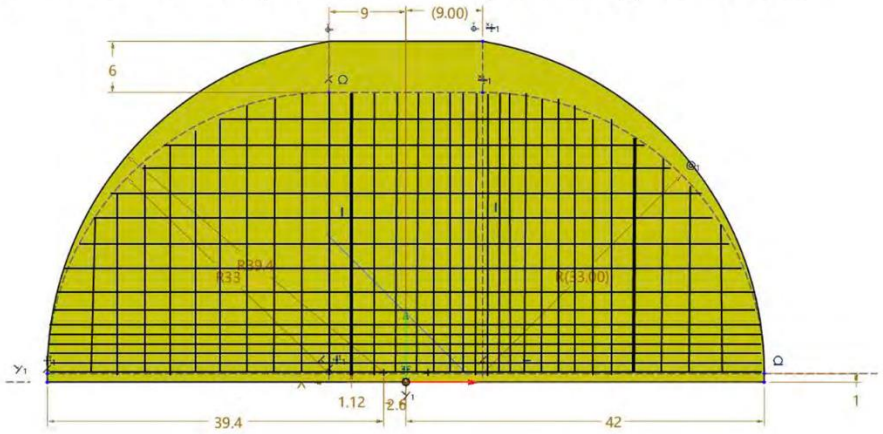
CEPC LumiCal design

- Two layer trackers
  - AC-LGAD: a double AC layer configuration for 2D readout of electron hits



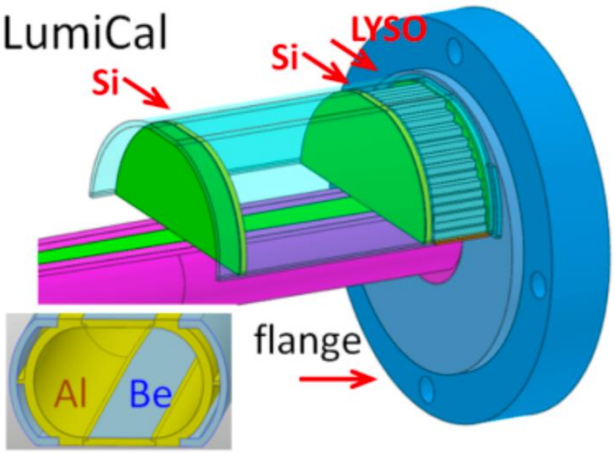


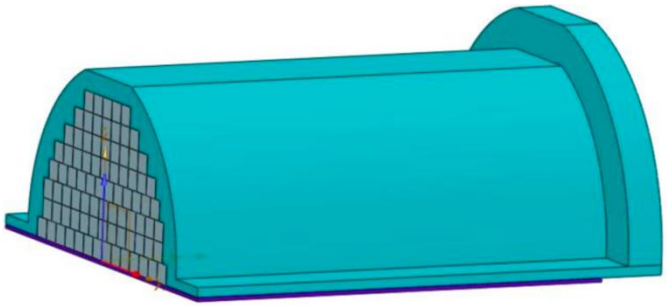
Si-wafer surface plan with sample of segmentation

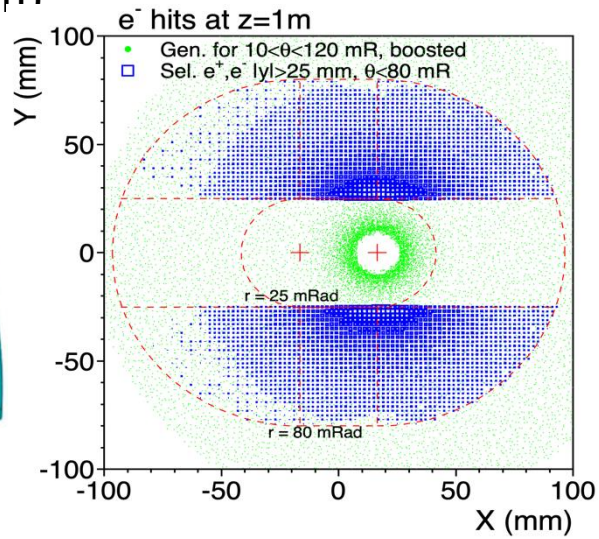


CEPC LumiCal design

- Before flange: $z = 560 \sim 700$ mm: 2 Si-tracker and 2 X_0 LYSO (23 mm)
- After Bellow: $z = 900 \sim 1100$ mm: 13X_0 LYSO (150 mm)



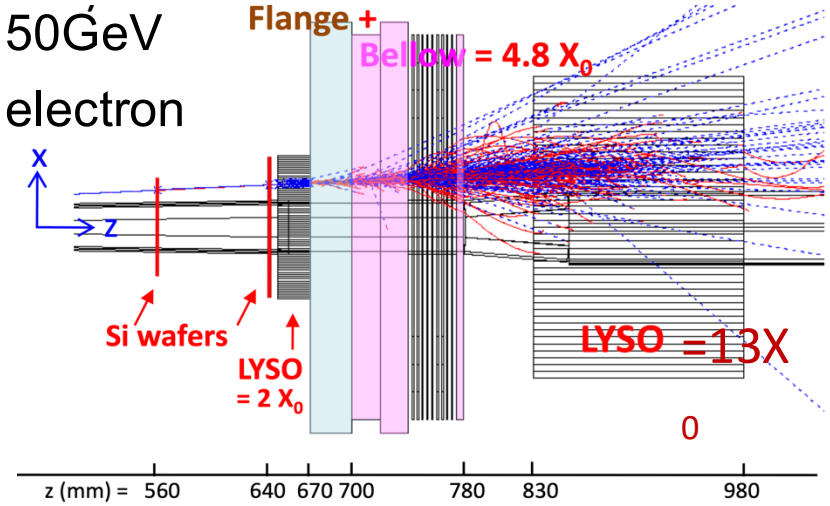


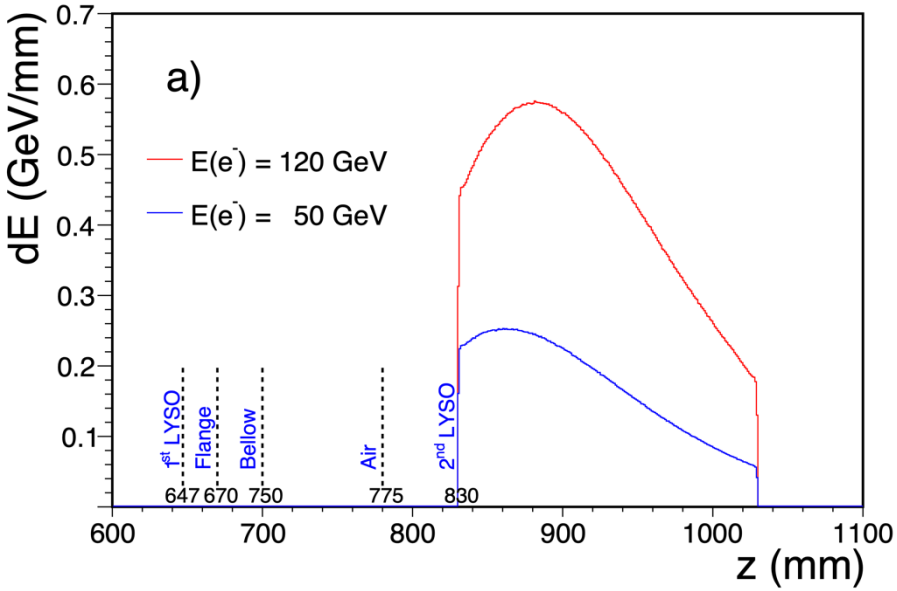


- e^+e^- beam colliding at 33 mRad crossing angle
  - Final state e^+e^- boosted in x direction
- Coverage and Acceptance

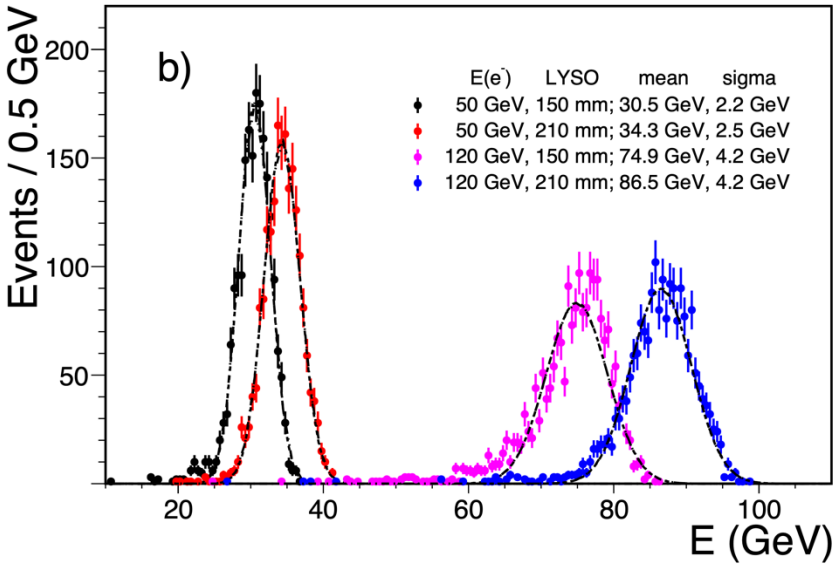
ONE e^+ or e^- detected		e^+, e^- back-to-back detected	
θ>25 mRad	θ>25mR & |y|>25mm	θ>25 mRad	θ>25mR & |y|>25mm
133.5 nb	81.8 nb	85.4 nb	78.0 nb

Energy measurement





- Length vs energy resolution
  - Roughly 4-5%



- Energy profile
  - High granularity can be useful

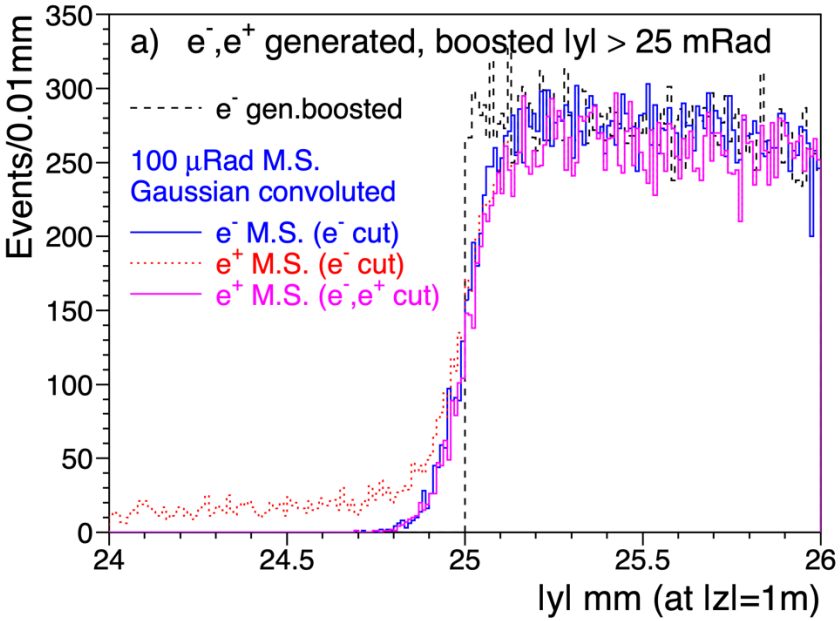
Experimental challenges

- Detector aperture, position and alignment
  - Especially the inner radius
- Electron Multiple scattering
- Position of interaction point (IP)

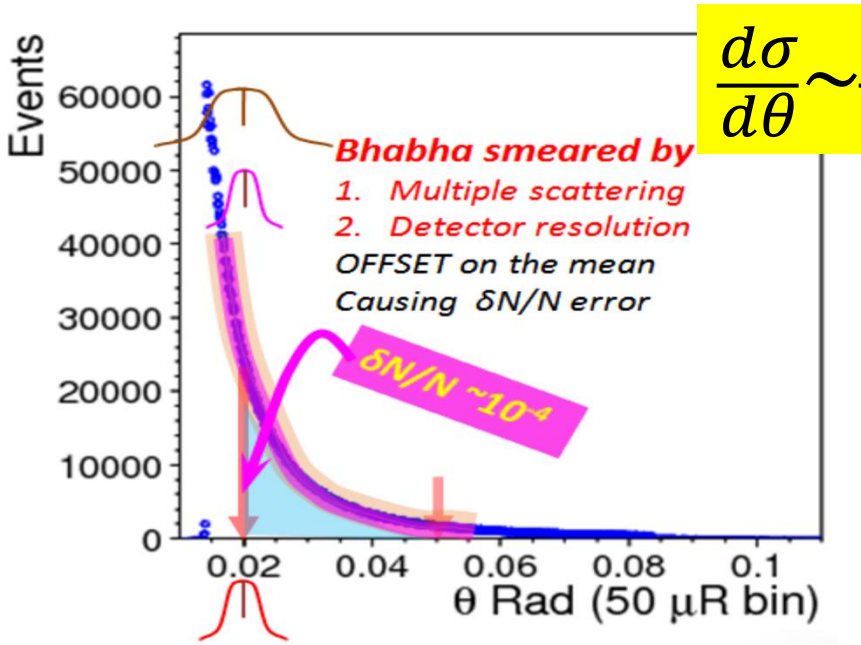
Detector aperture, position and alignment

- Detector alignment
  - Especially the inner radius

$$\frac{\delta\sigma^{\mathrm{acc}}}{\sigma^{\mathrm{acc}}} \simeq \frac{2\delta\theta_{\mathrm{min}}}{\theta_{\mathrm{min}}} = 2\left(\frac{\delta R_{\mathrm{min}}}{R_{\mathrm{min}}} \oplus \frac{\delta z}{z}\right)$$



$$\frac{d\sigma}{d\theta} \sim \frac{1}{\theta^3}$$

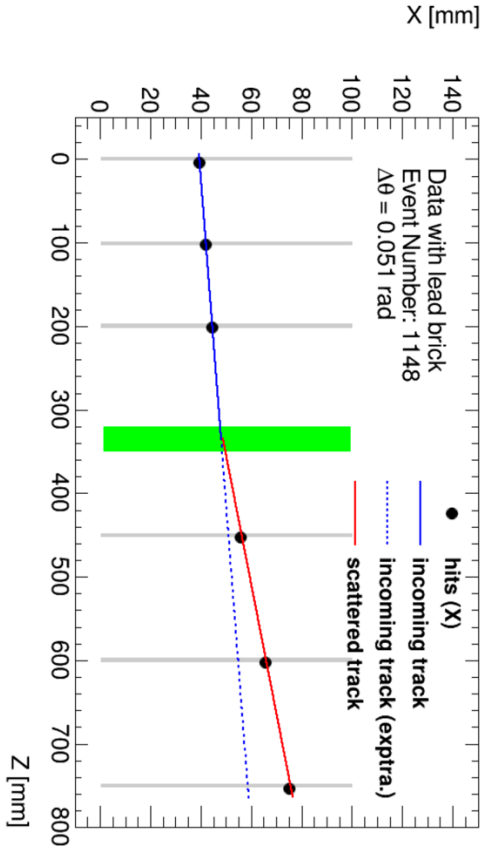


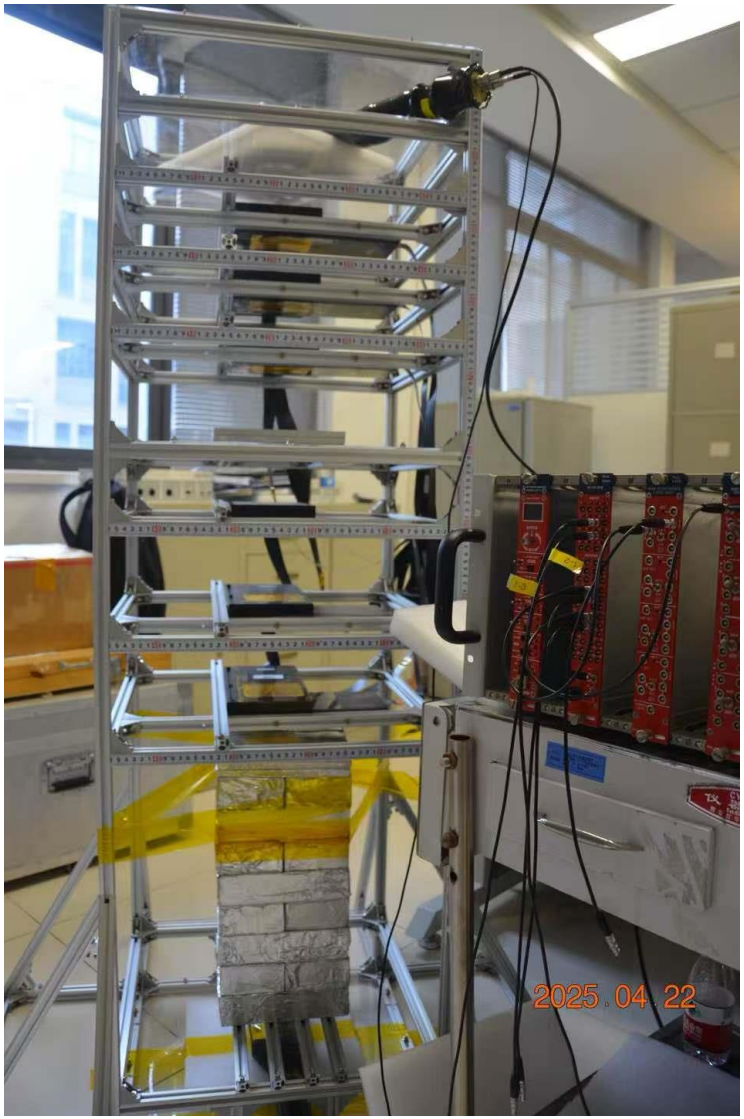
- Final state electron multiple scattering

Multiple scattering

- Conceptual experiment
  - cosmic muon scattering at 30 mm Pb
  - 12 Si-strip tracker
  - Cosmic ray Muon, > 1 GeV filtered

- 6 sets (x,y) with 200 µm pitch

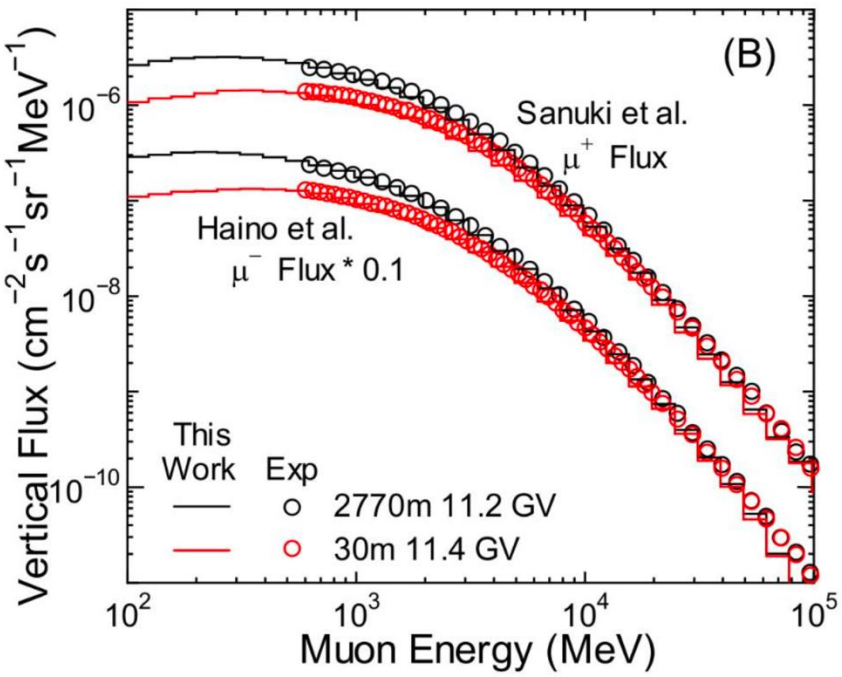


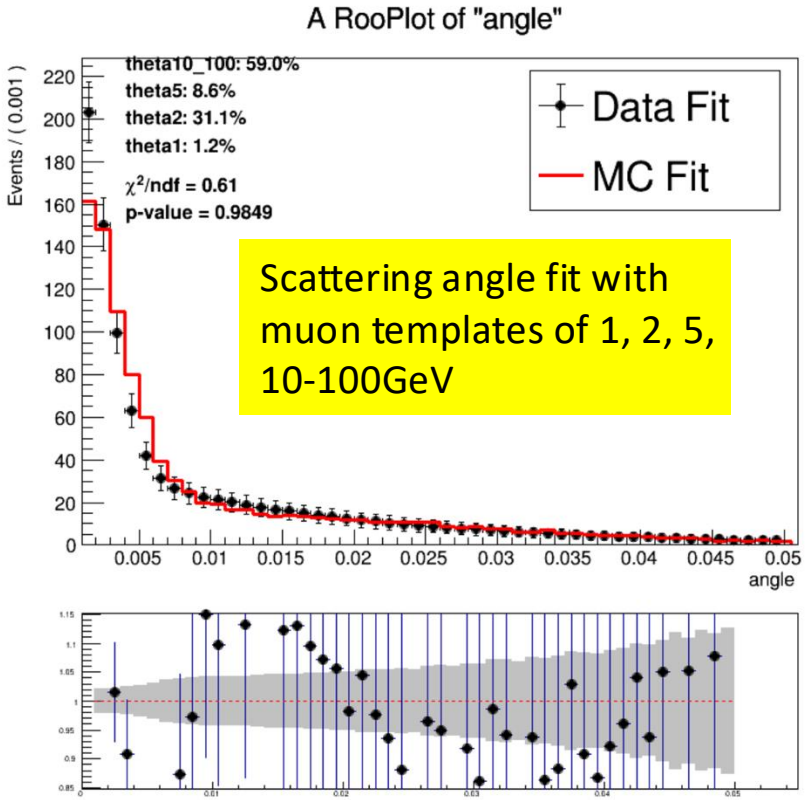


Multiple scattering

- Preliminary results

Cosmic Muon energy spectrum



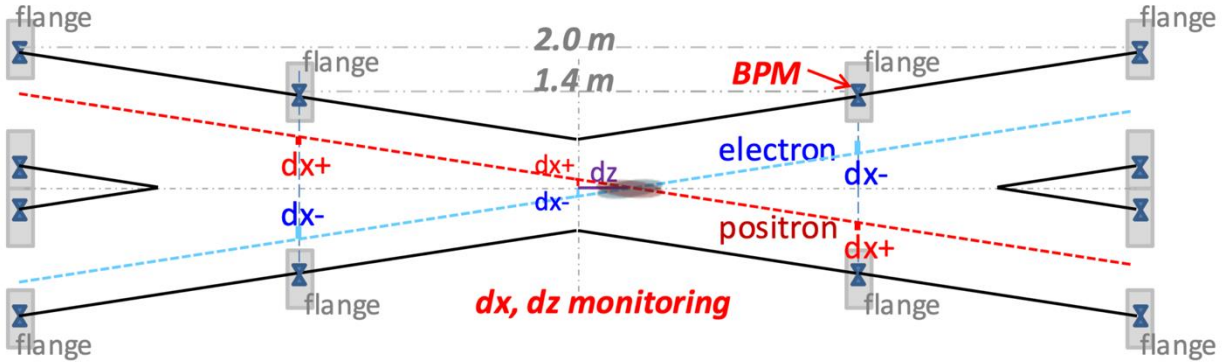


Scattering angle fit with muon templates of 1, 2, 5, 10-100GeV

Ref: Journal.pone.0144679

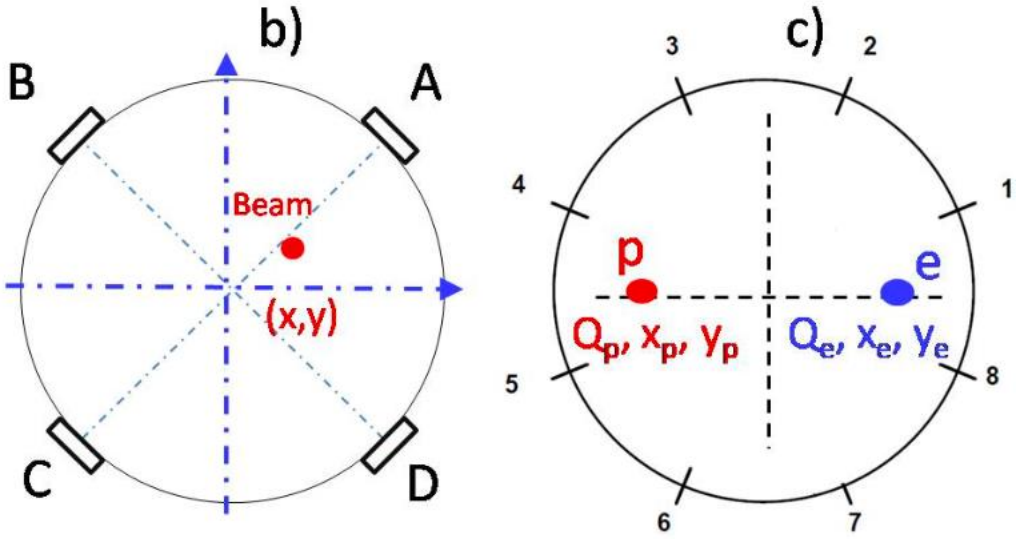
Interaction Position (IP)

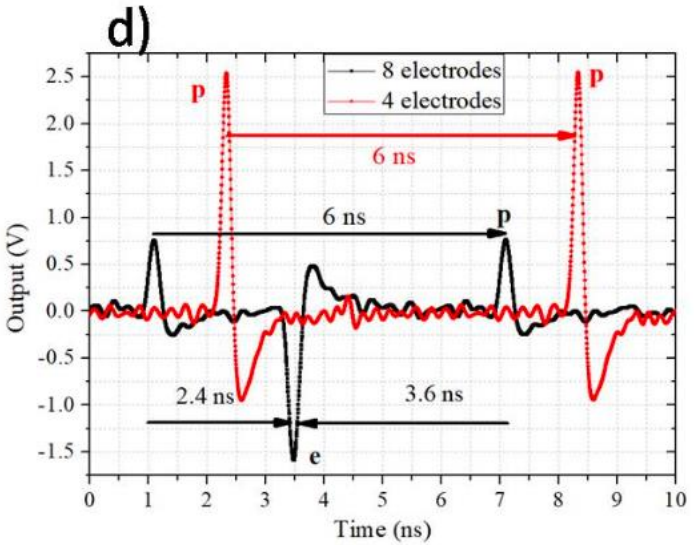
- Real IP position can be shifted



- Beam induced acceptance change
  - Beam-energy asymmetry,
  - IP displacements,
  - Cross section changed with the beam energy,
  - Focusing of final state particles through beam bunches

IP measurement along x-y plane

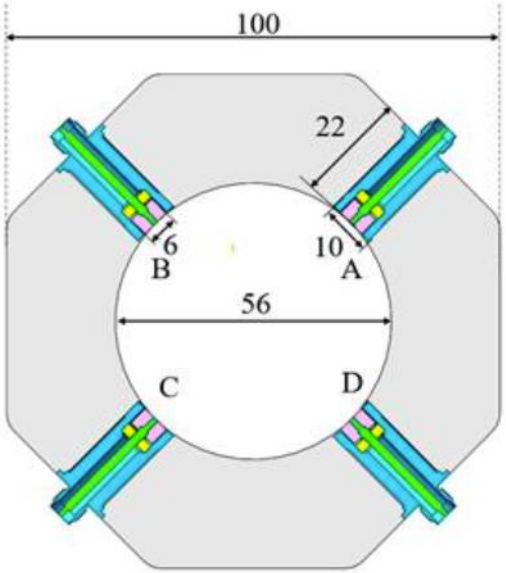




- Beam position monitors (BPMs) inside flanges
  - precise to 1 μm on the beam x,y positions

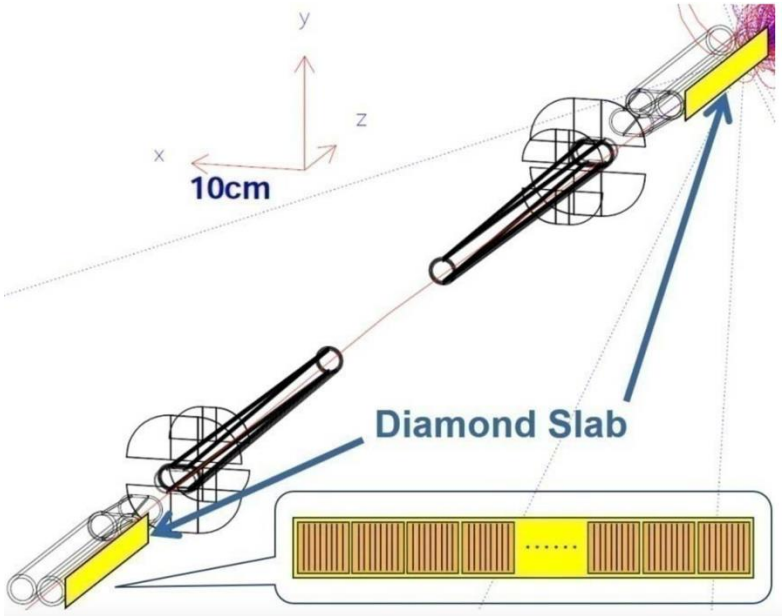
$$x, y = f(x_{raw}, y_{raw})$$

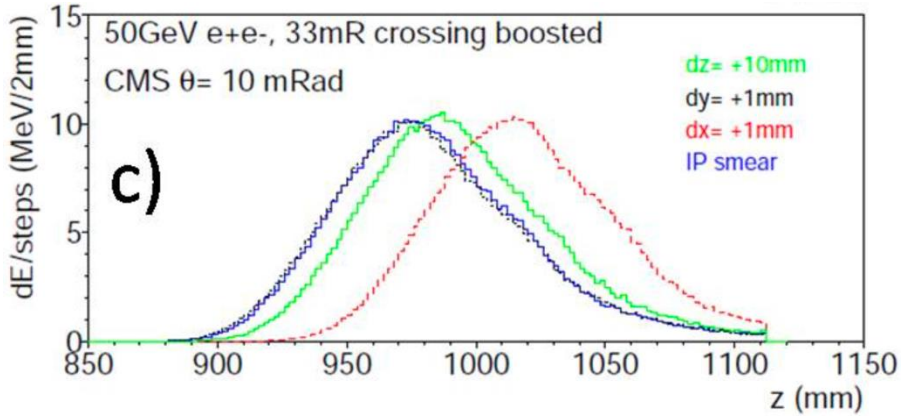
$$x_{raw} = \frac{Va + Vd - Vb - Vc}{Va + Vb + Vc + Vd} \qquad y_{raw} = \frac{Va + Vb - Vc - Vd}{Va + Vb + Vc + Vd}$$



IP measurement along z-axis

- Fast beam monitor: diamond detector option
  - |z|= 855~1110 mm diamond slab, on sides of beampipe
  - monitoring Bhabha electrons of ~10 mRad (CMS) ~25 mRad (LAB)





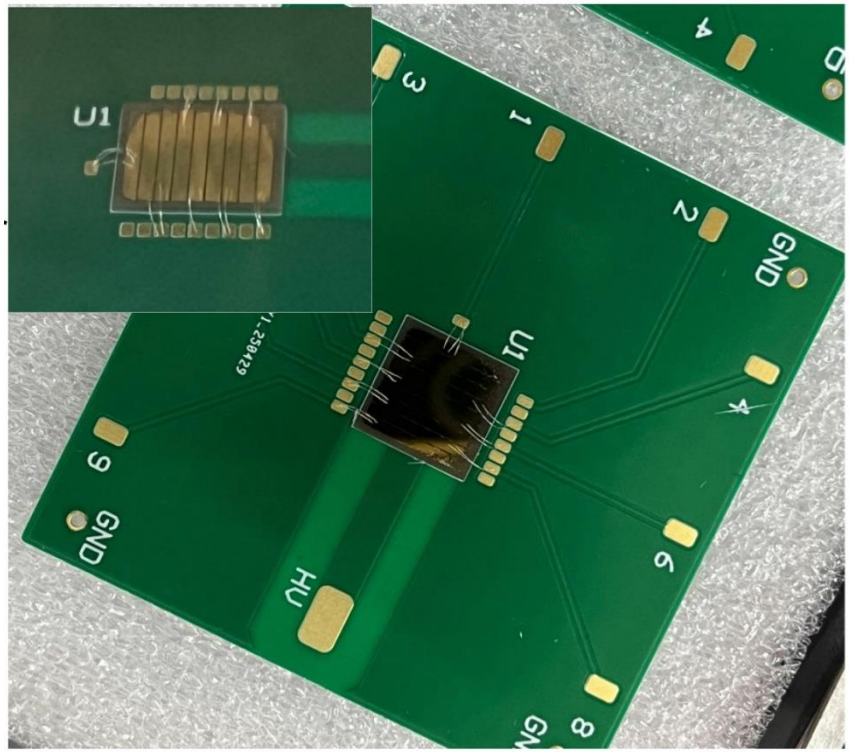
- Differing event rates on +z and -z sides for IP offset

LumiCal Proto-typing

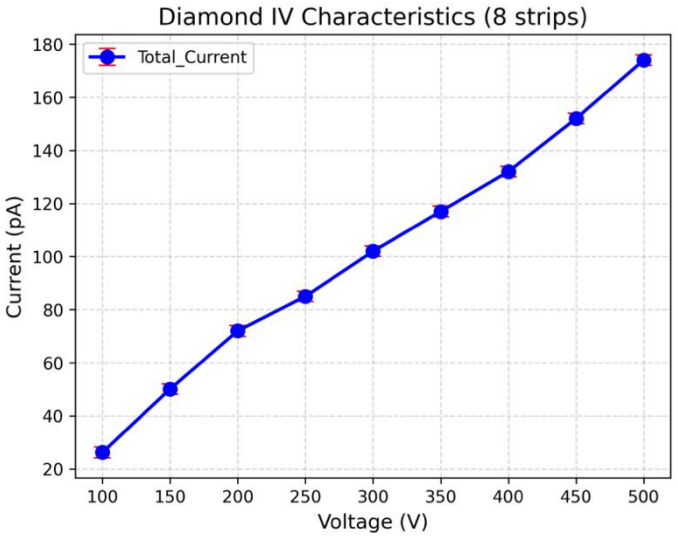
- Diamond detector R&D
- LYSO+SiPM detector R&D
- Tests at BEPCII Synchrotron Radiation beamline
- Future plan: BESIII Zero Degree Calorimeter
  - A middle size proto-type
  - A detector with full trigger and DAQ system

Diamond detector R&D

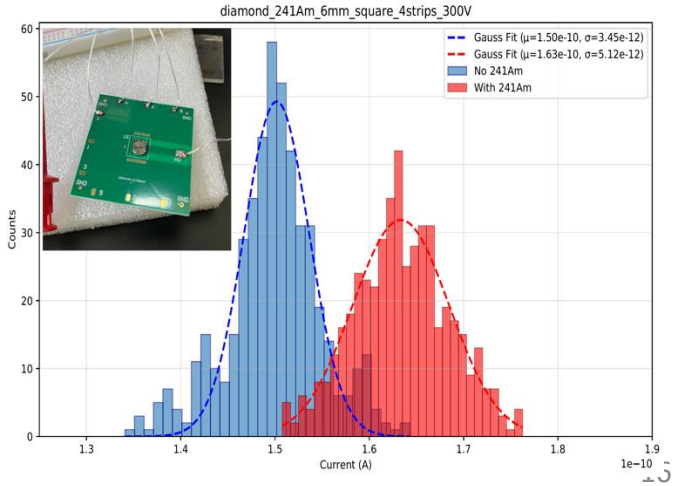
- Strip electrode
  - Full surface process chain



2. Diamond sensor 9 strips 10 mm × 10 mm



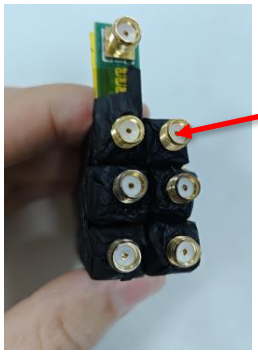
Preliminary tests with source meter:
I-V, Alpha radioactive source



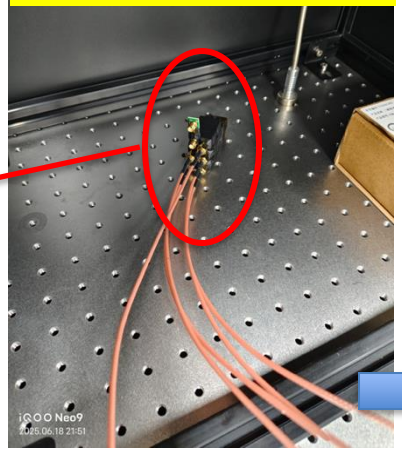
LYSO+SiPM detector R&D

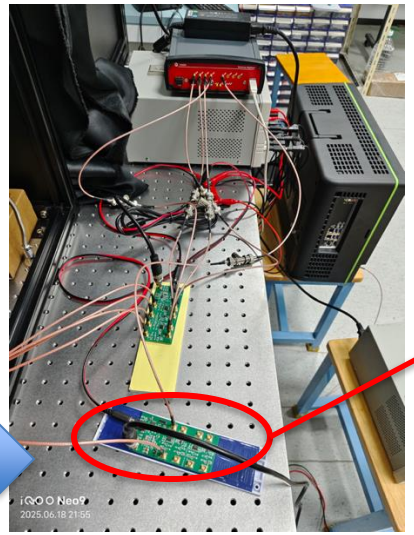
- Integration of LYSO+SiPM module and readout electronics
  - Front-end electronics (1st version)

SiPM readout board

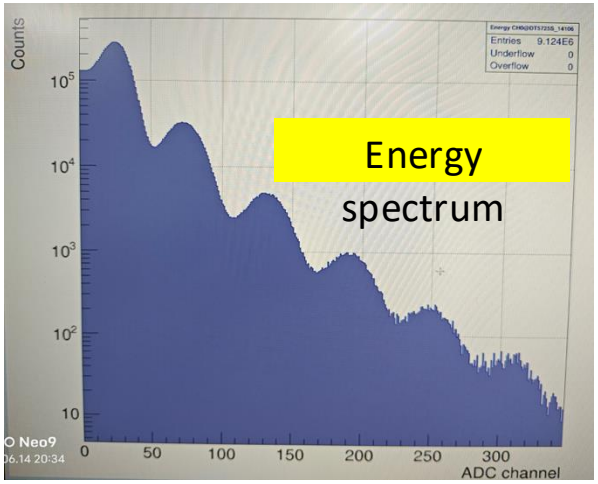


LYSO+ SiPM module





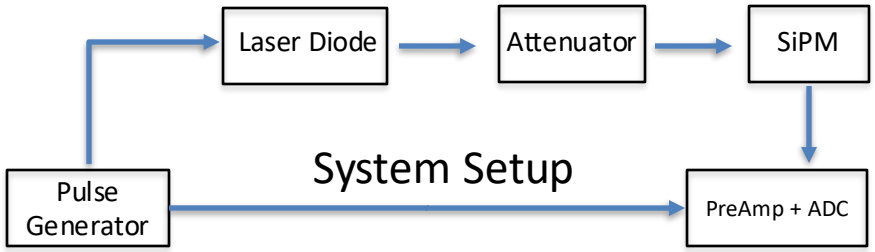
PreAmp board



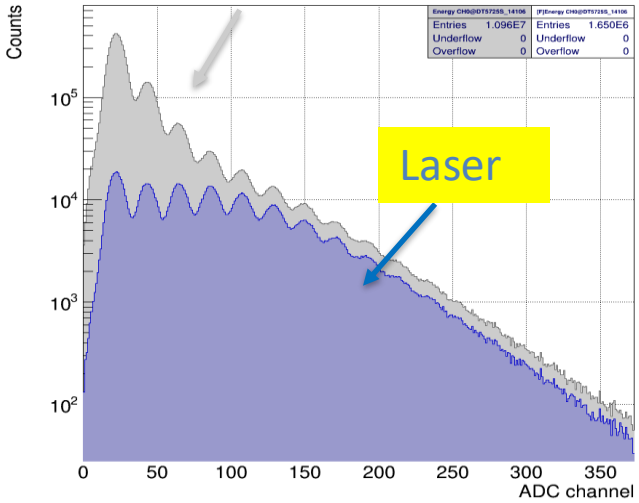
Dark count

LYSO+SiPM: tests at Lab

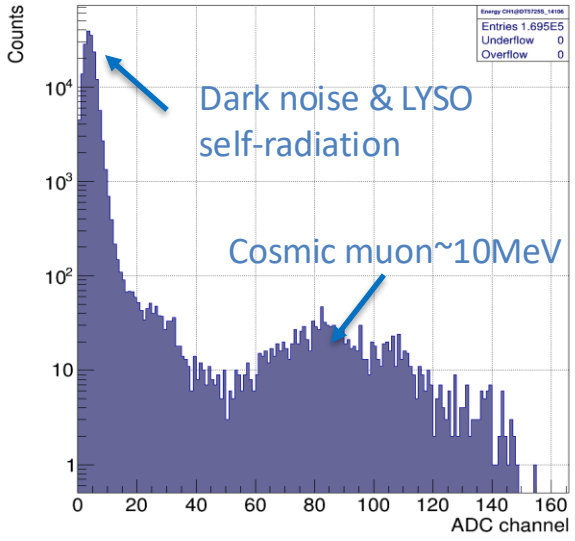
- SiPM test in dark box:
  - Single photon response with laser diode
  - Clear Multiple pixels triggers (五指峰)
  - Indicates low noise, high S/B

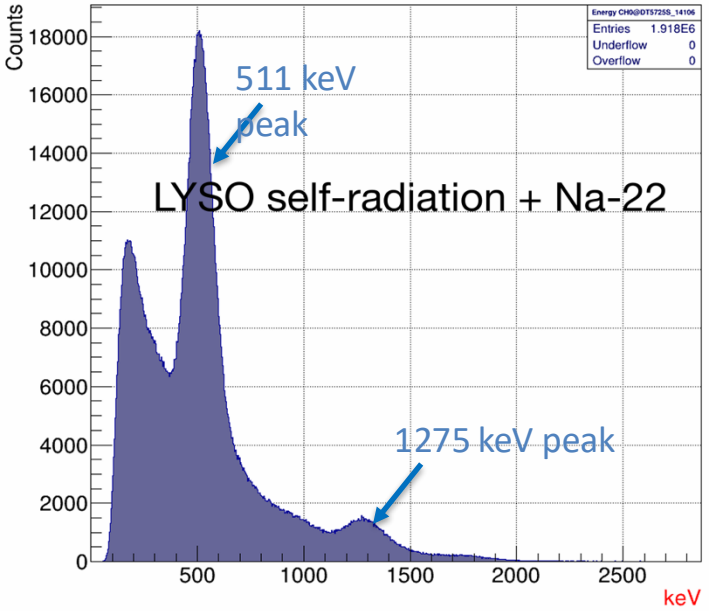


Dark count + laser

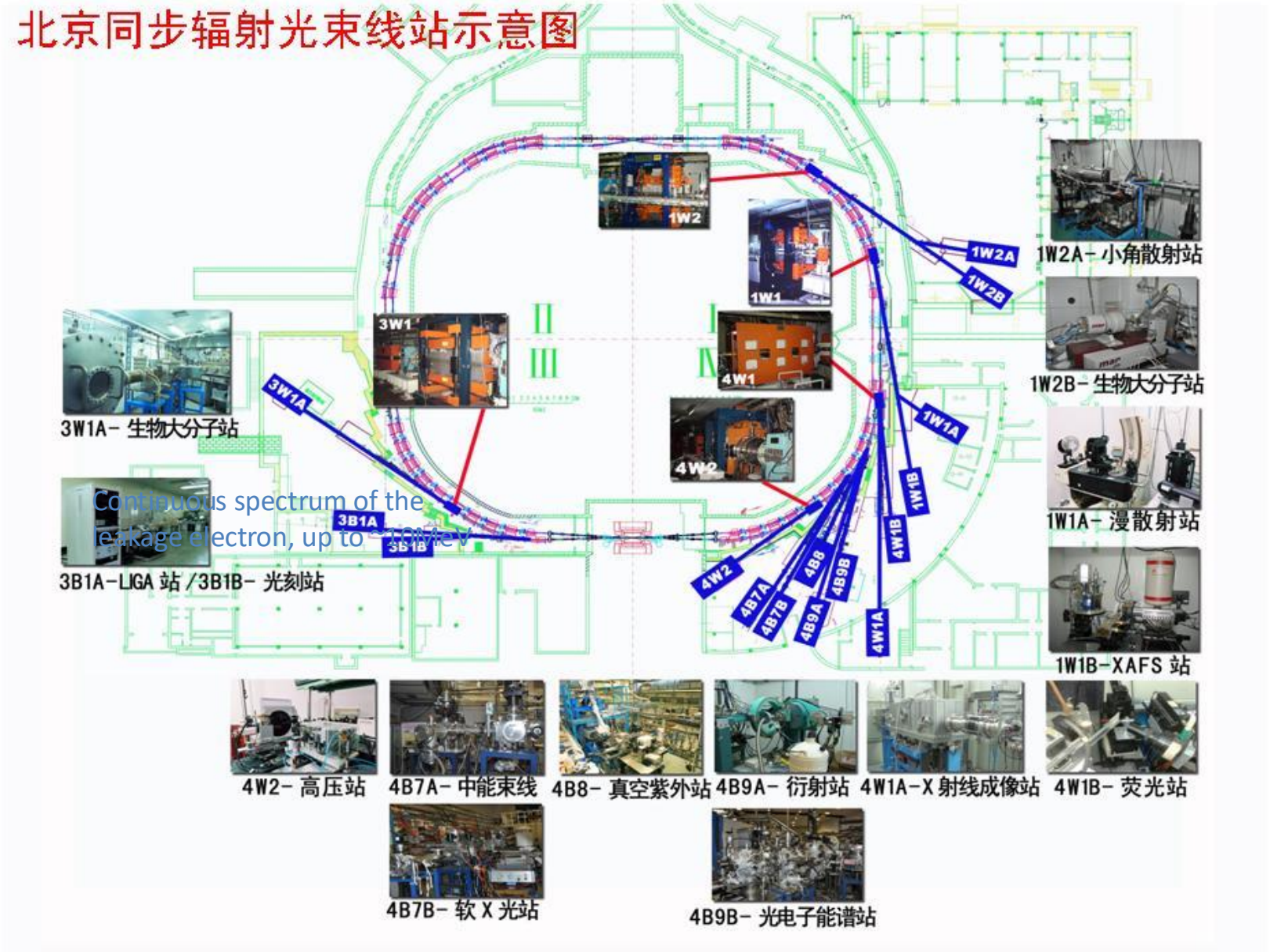


- Cosmic muon and ^{22}Na





High energy electron sources

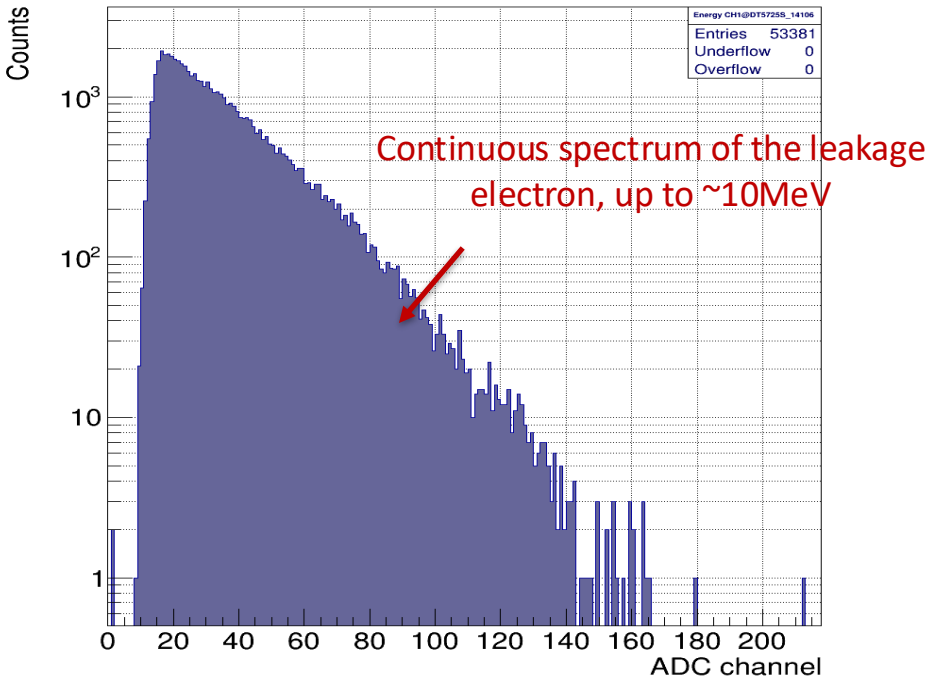


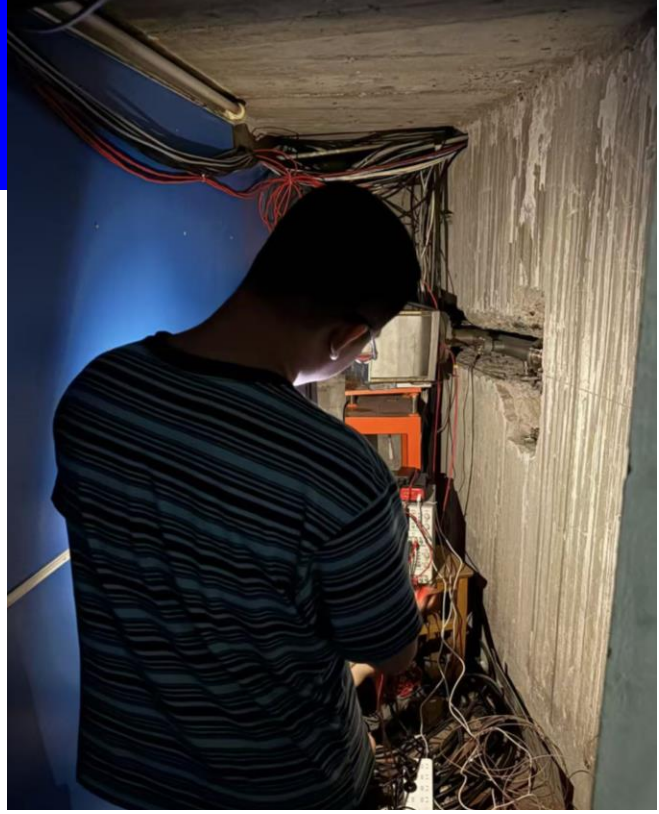
Continuous spectrum of the leakage electron, up to ~10MeV

Test @ BSRF

- First trial @ BSRF
  - Use leakage electrons of BSRF

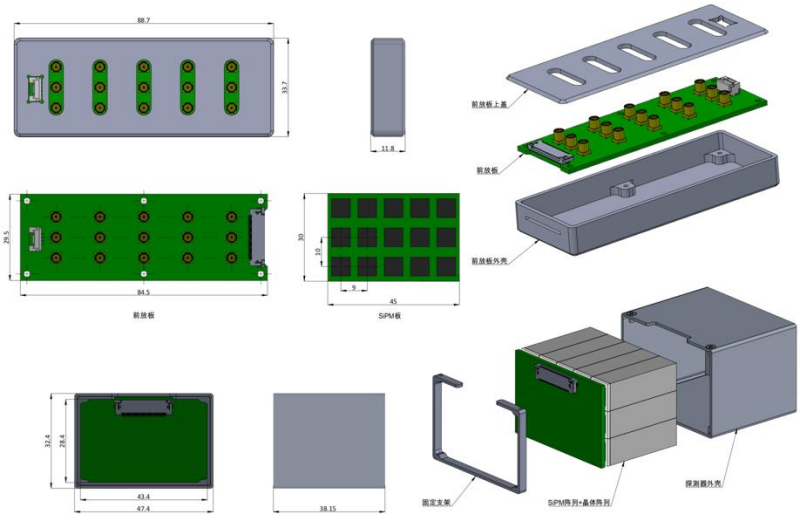
Thanks Zhe Duan and Zhijun Liang!

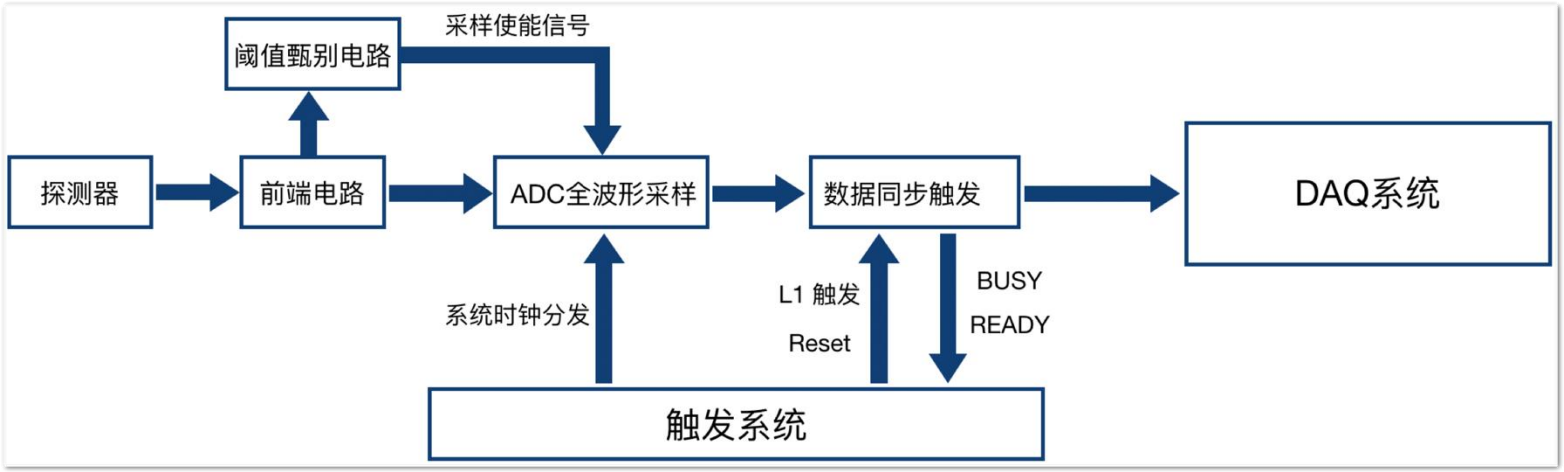




Next prototype: a middle size detector

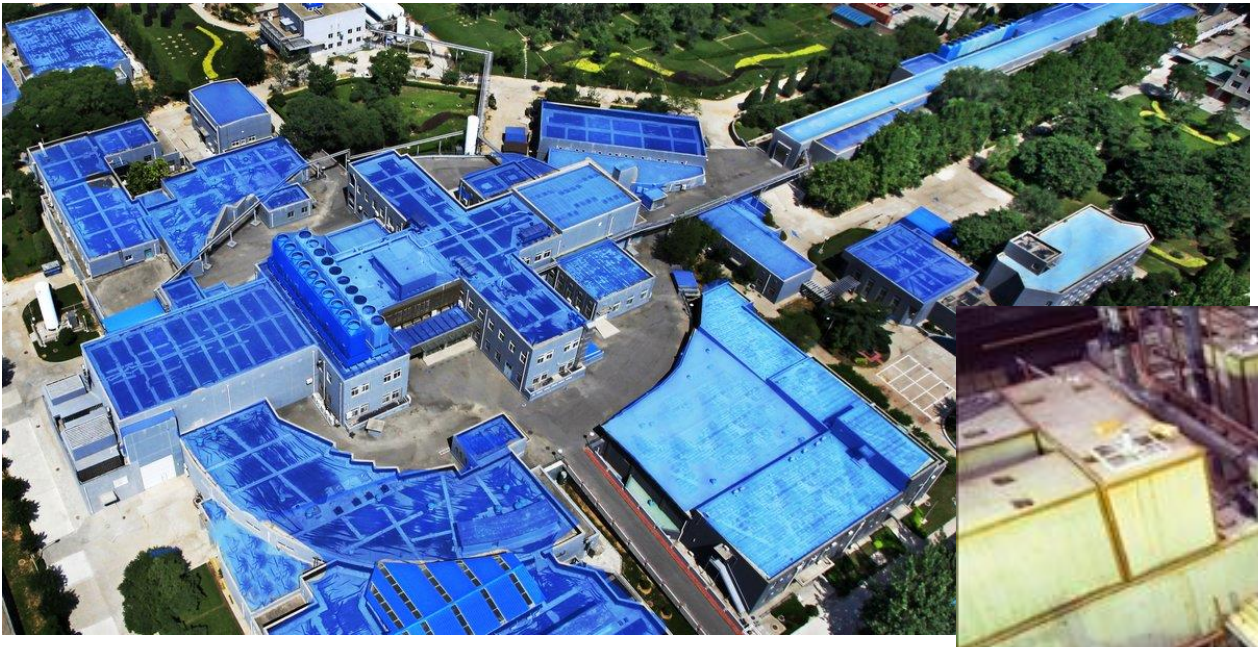
- 3x5 array of 1x1x3 cm^3 LYSO+SiPM
  - Full chain of detector, electronics, cabling, connection, shielding and Trigger & DAQ system





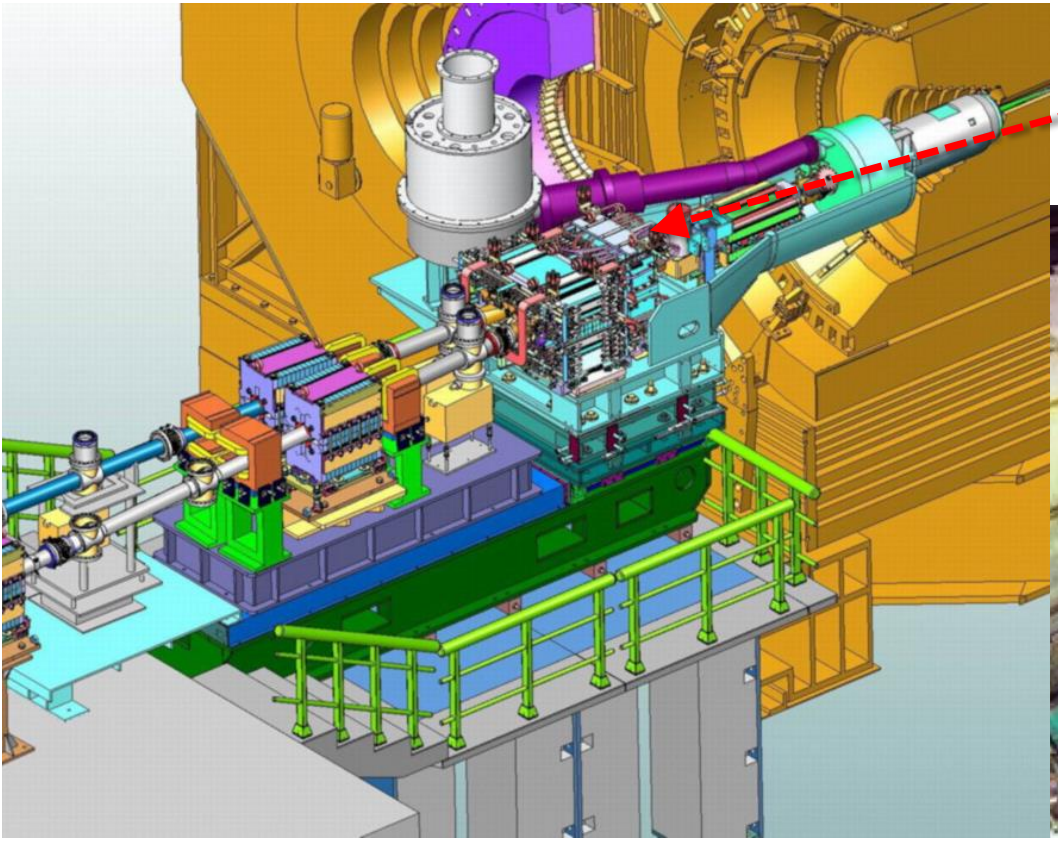
Future test at BESIII experiment

- BEPCII-BESIII experiment
  - e+e- collider, COM energy: ~2-5 GeV, Luminosity: ~$10^{33}cm^{-2}/s$
  - BESIII detector: Multi-purpose detector covering 4 solid angle

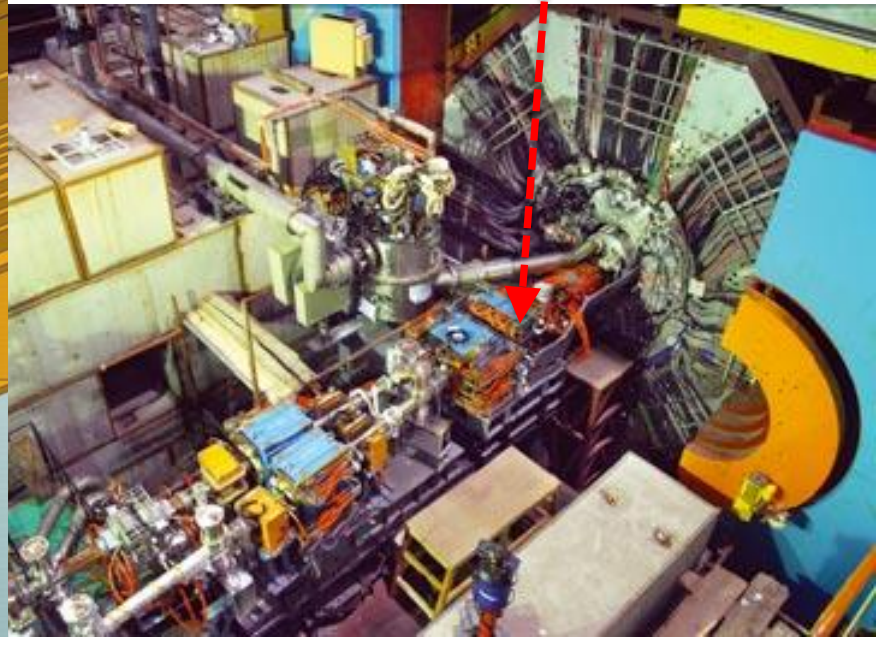


Future test at BESIII experiment

- BEPCII-BESIII experiment
  - e+e- collider, COM energy: ~2-5 GeV, Luminosity: ~$10^{33}cm^{-2}/s$
  - BESIII detector: Multi-purpose detector covering 4 solid angle
  - Zero-Degree-Calorimeter(ZDC): fast luminosity and ISR photon tagging

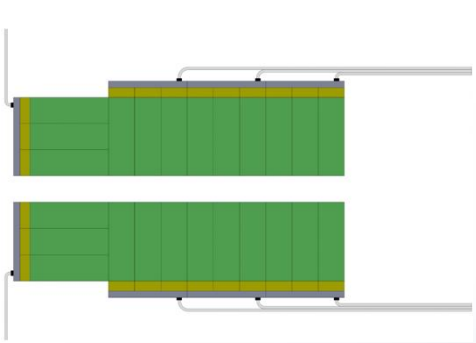


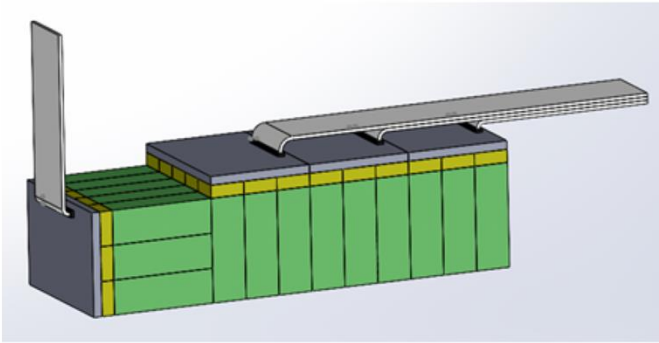
- 3.3m <z<3.5 m, θ=0 in CMS frame



Future test at BESIII experiment

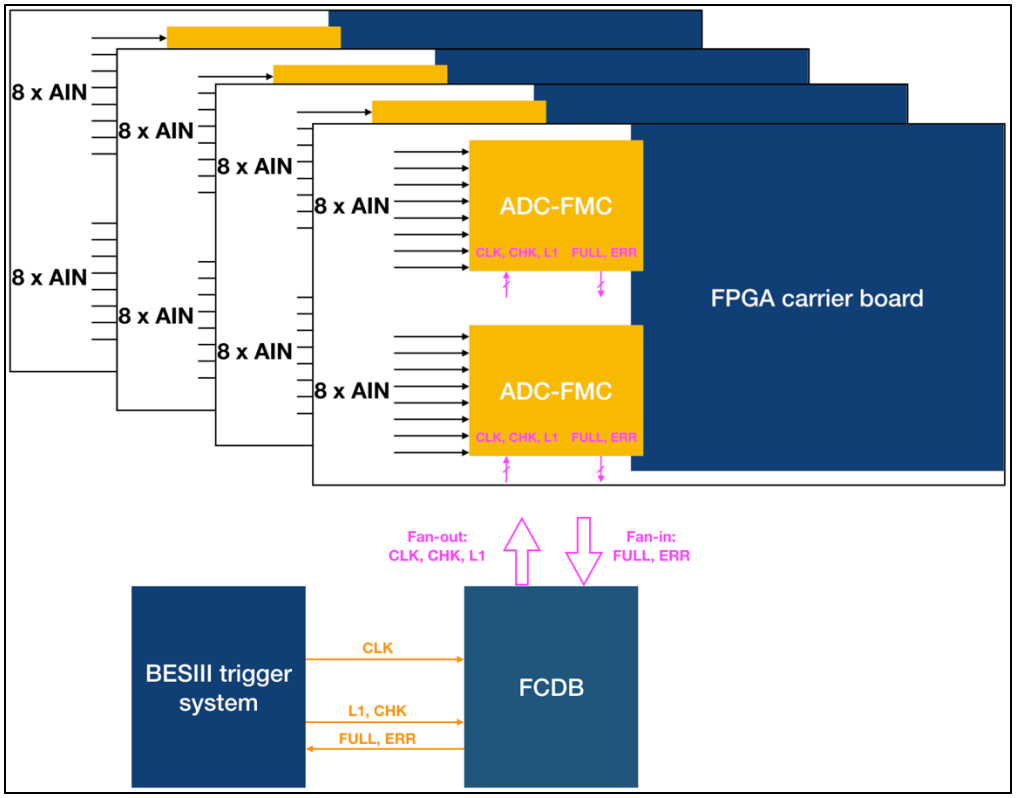
- Great place for LumiCal prototyping
  - ZDC: LYSO+SiPM array, 240 channels in total
  - Diamond detector and Si-tracker, near the copper window
  - Running-time background study and stability study





ZDC: ADC, Trigger, DAQ

- Readout electronics design
  - Trigger board(FCDB): Interface to BESIII trigger system
  - ADC board(ADC-FMC): Carrier board through FMC connector

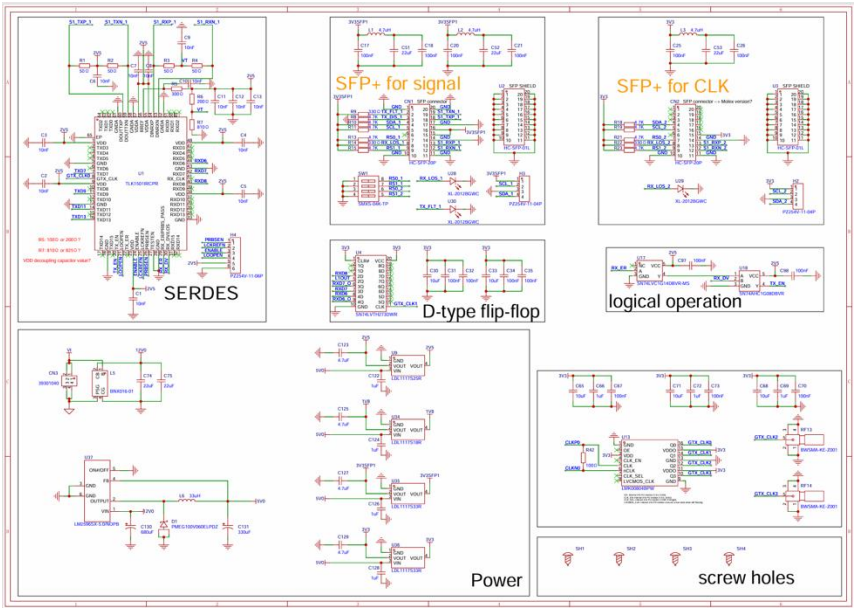


- FPGA carrier board: Process digitized signal from ADC, send to DAQ

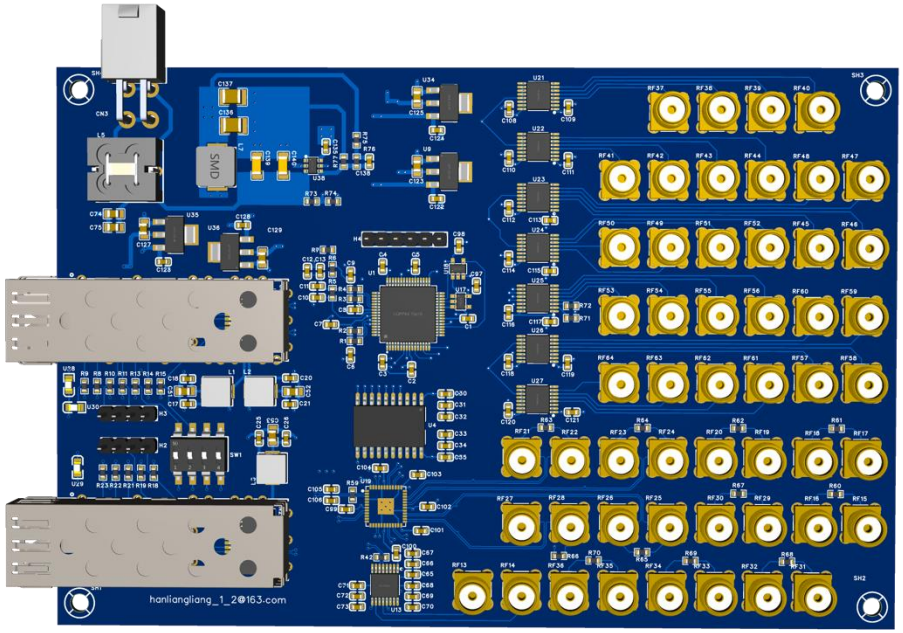
Trigger&data flow

ZDC: ADC, Trigger, DAQ

- Trigger board (FCDB)
  - Fan out system clock, L1 and check signals
  - Fan in feed-back signals from ZDC electronics
  - Design is finished, production ongoing



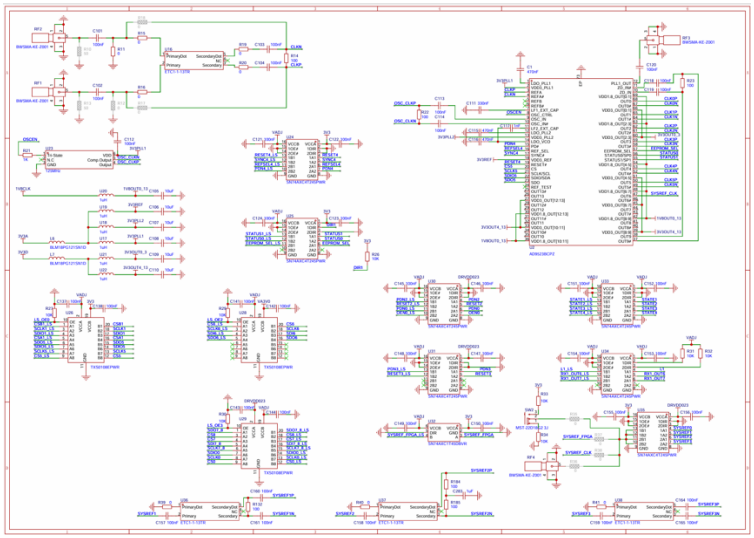
Schematic



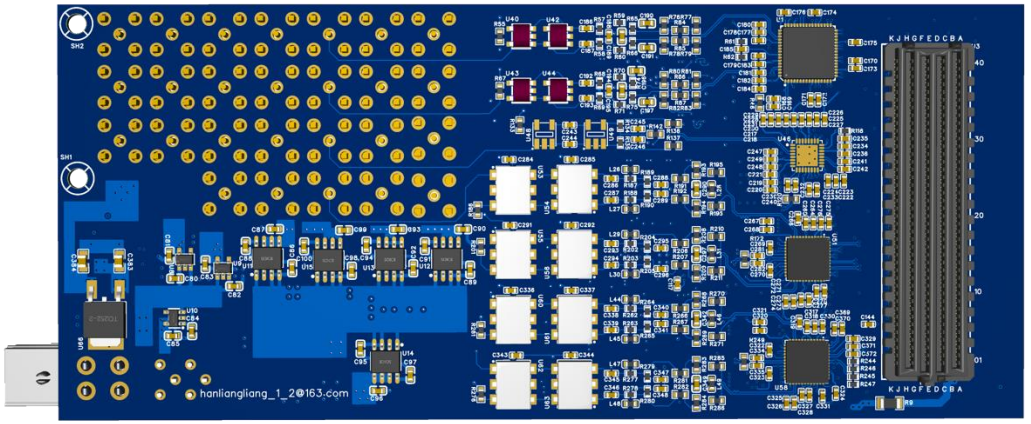
PCB 3D view

ZDC: ADC, Trigger, DAQ

- ADC board (ADC-FMC)
  - 8-channel analog inputs with 14-bit resolution and 250MSPS sampling rate
  - Design is finished, production ongoing
  - Dedicated firmware development



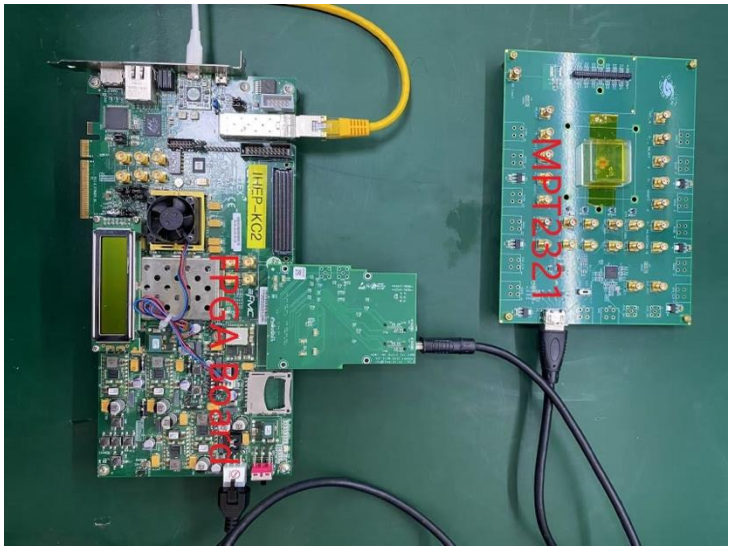
Schematic

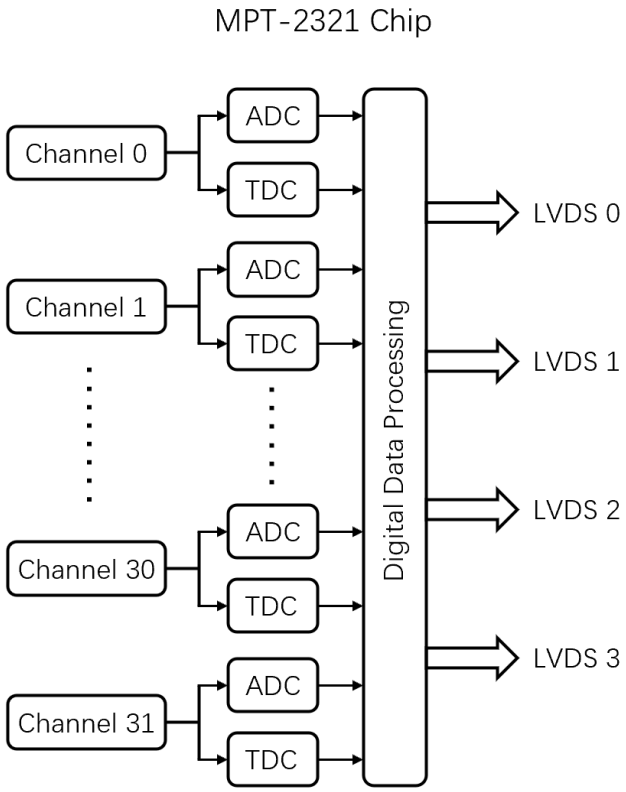


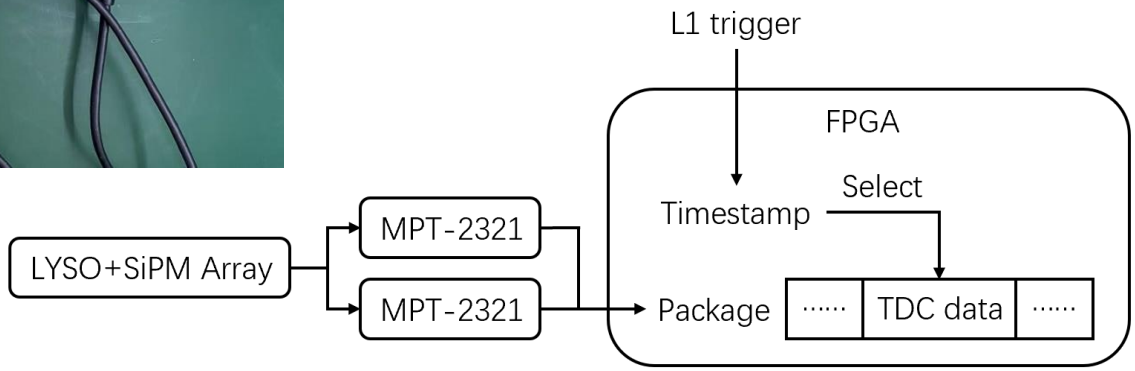
PCB 3D view

Future upgrade: ASIC based readout

- MPT-2321: SiPM Signal Processing Chip
  - 32 input channels
  - 12-bit ADC, 20-bit TDC with 50ps resolution
  - Automatic gain selection: low and high gains
  - Single channel rate: 2.7MHz







Summary

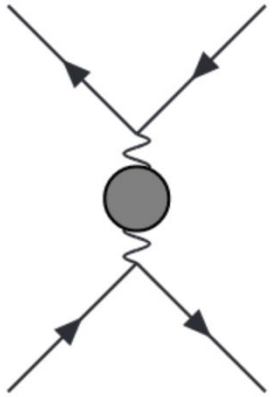
- CEPC LumiCal system preliminary design presented
  - Targeted for the small angle Bhabha scattering events
  - Performance, e.g. acceptance, efficiency, etc. studied with GEANT4
- To reach the precision of O(10^{-4})
  - Survey procedure to reach 1 μm, with accelerator experts
  - More solid background study and mitigation
- Extensive detector R&D
  - LYSO+SiPM and Diamond detector R&D
  - Tests at BSRF, thanks to the help from B2 accelerator team
  - BESIII-ZDC: a middle size prototype for B2 fast luminosity and ISR tag

Thanks to B2 accelerator and BESIII team

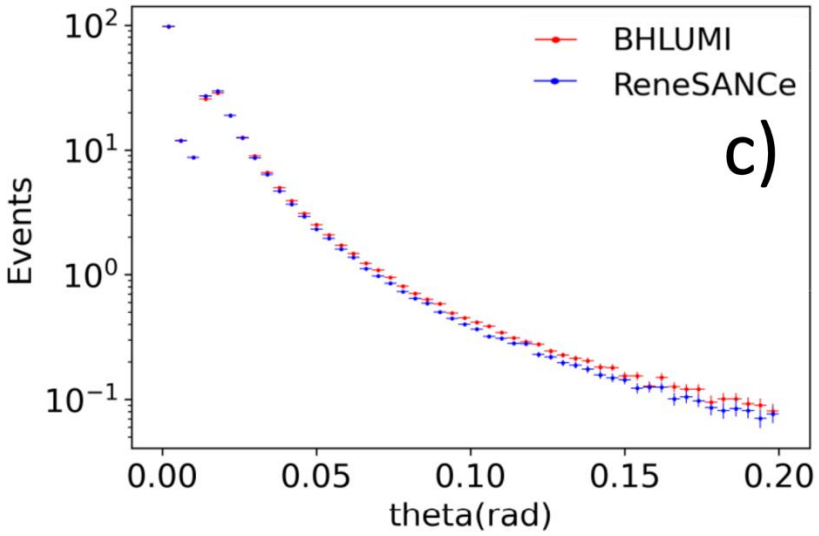
The end

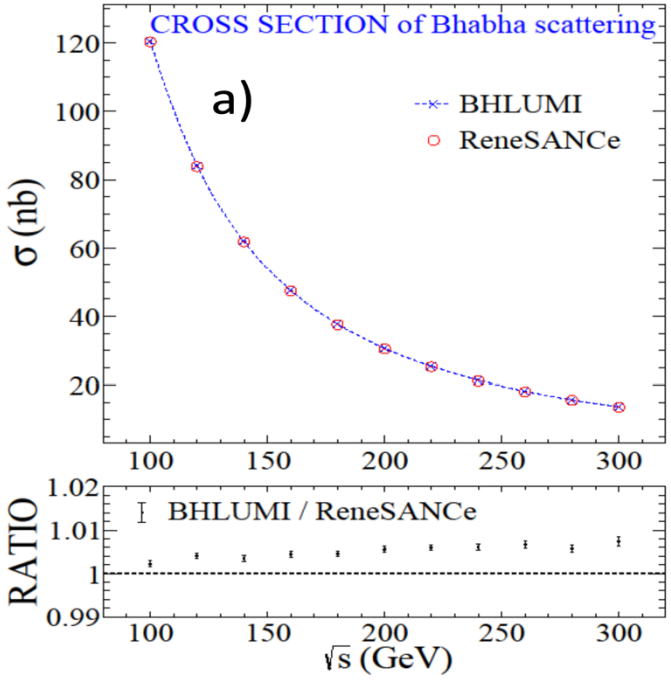
(backup)Theoretical challenges

- Hadronic vacuum polarisation contribution
  - Extracted from data for e^+e^-→hadrons or from lattice QCD
  - Data-driven from (BelleII, BESIII, CMD-3, SND), expected the uncertainty to be reduced below 10^{-4} level



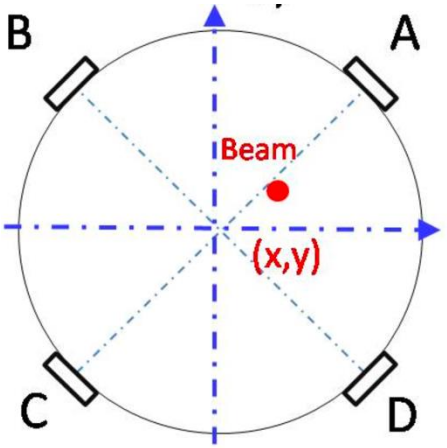
- Generator studies
  - BHLUMI 4.04 S. Jadach, 0.037% precision [PLB 803 (2020) 135319]
  - ReneSANCe, a recent NLO generator [CPC 256 (2020) 107455]





Beam Position Monitor

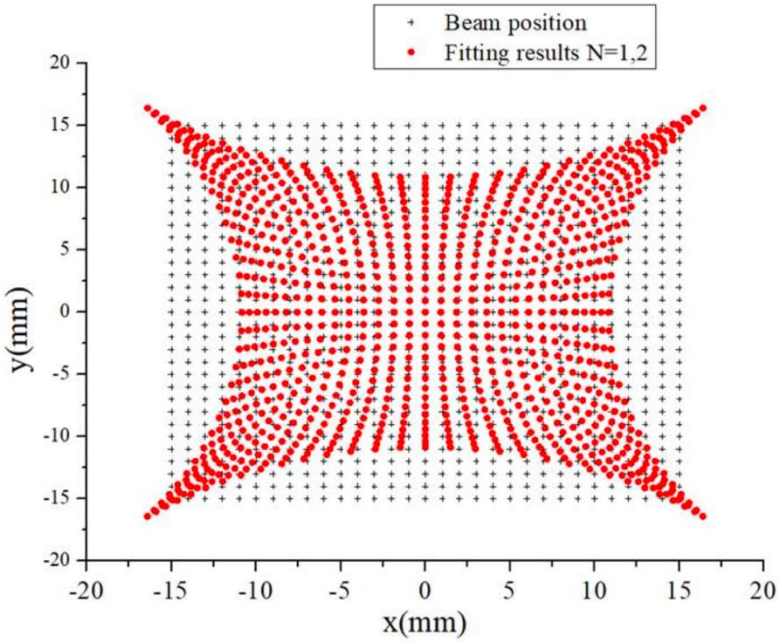
- Survey/monitoring, for Beam IP position
  - Beam Probe Monitor BPM , IP x,y to 1 μm
  - Position monitoring, Flange dx,dy ~1 μm, dz~ 50 μm

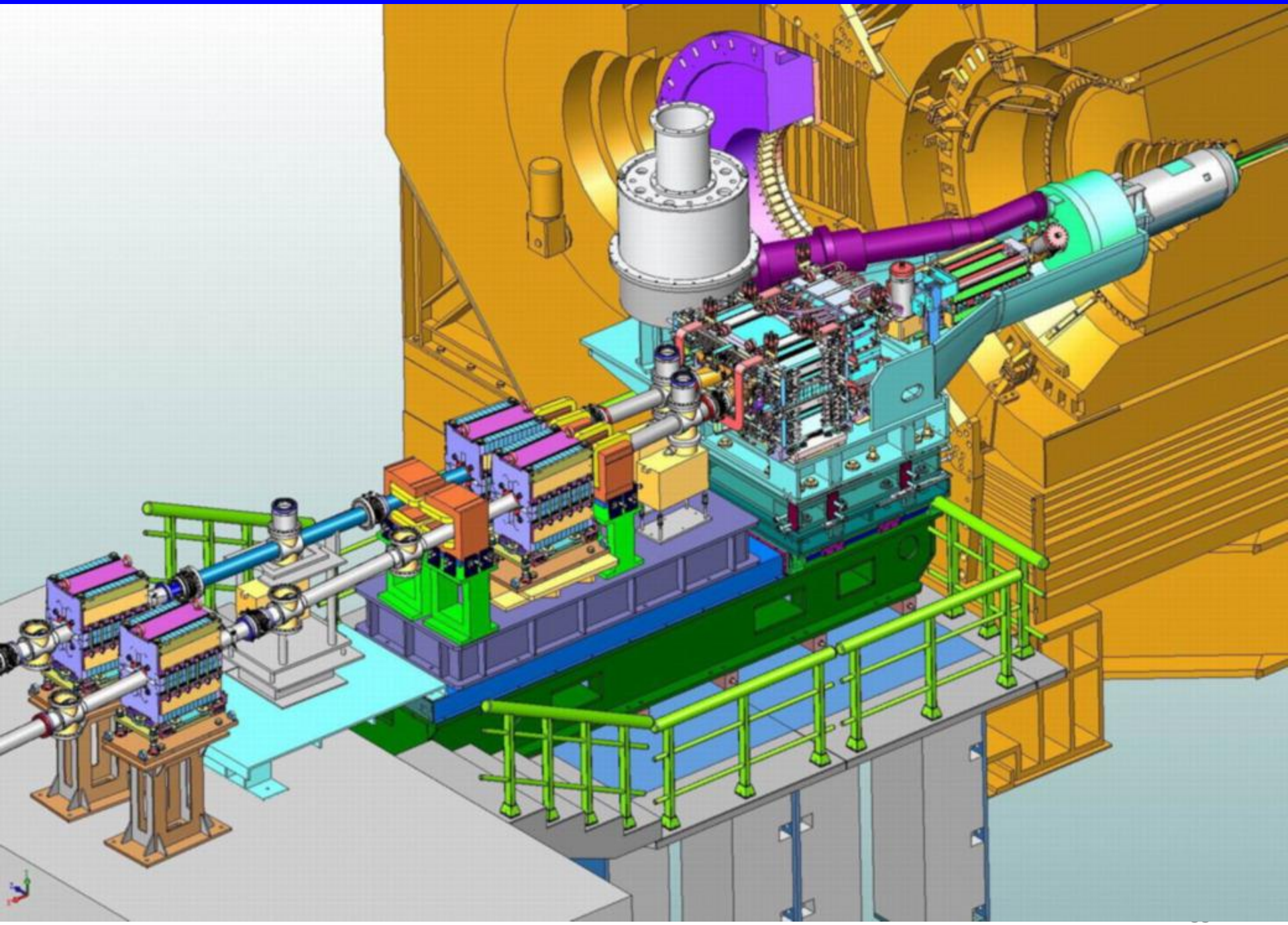


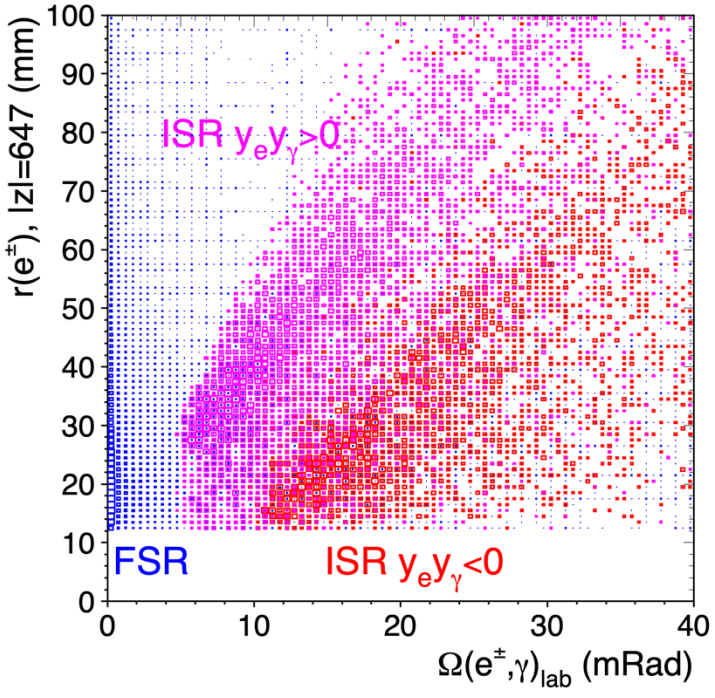
$$x, y = f(x_{raw}, y_{raw})$$

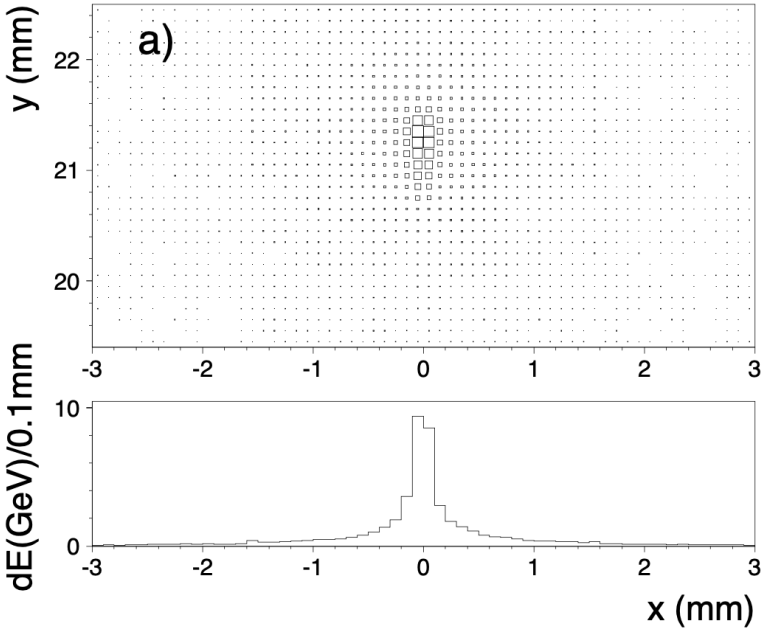
$$x_{raw} = \frac{Va + Vd - Vb - Vc}{Va + Vb + Vc + Vd}$$

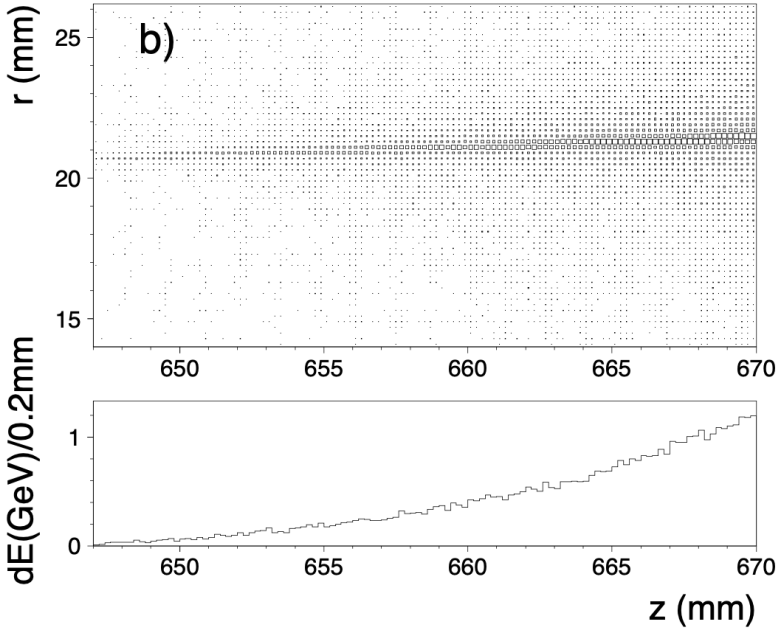
$$y_{raw} = \frac{Va + Vb - Vc - Vd}{Va + Vb + Vc + Vd}$$






r(e±), |z|=647 (mm)
Ω(e±,γ)lab (mRad)
ISR yeyγ>0
FSR
ISR yeyγ<0


a)
y (mm)
dE(GeV)/0.1mm
x (mm)


b)
r (mm)
dE(GeV)/0.2mm
z (mm)