Luminosity measurement and monitoring at CEPC

Lei Zhang

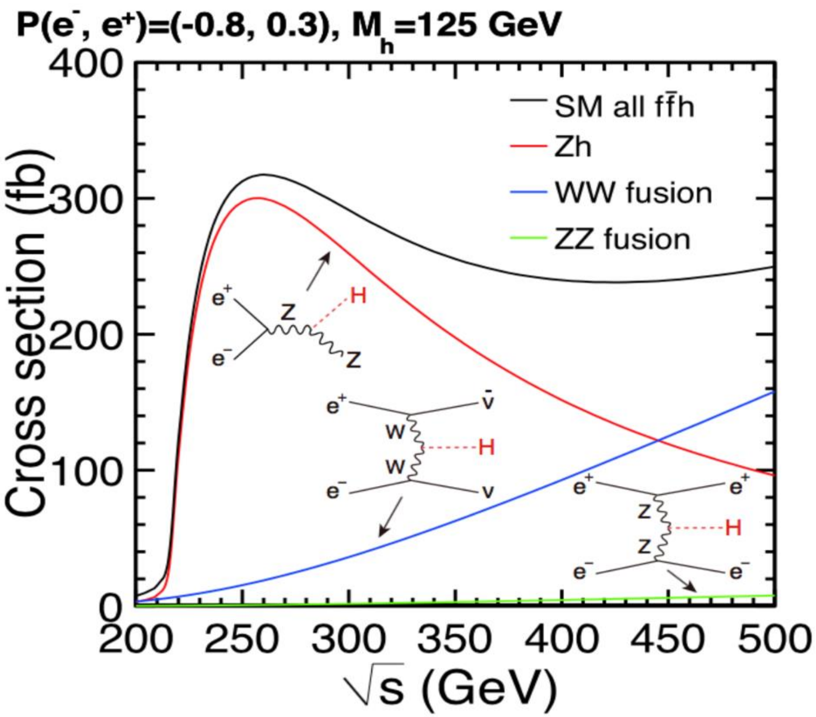
On behalf of the CEPC LumiCal team

- AS: Suen Hou
- Vinca: Ivanka Bozovic
- NJU: Liangliang Han, Yuhui Miao, Xingyang Sun, Jiawei Wan, Yilun Wang, Xiaoxu Zhang, Jialiang Zhang, Lei Zhang
- IHEP: Haoyu Shi, Mei Zhao, Xiao Cai, Sheng Dong
- JLU: Jiading Gong, Weimin Song

CEPC Day, 28 Jan 2025

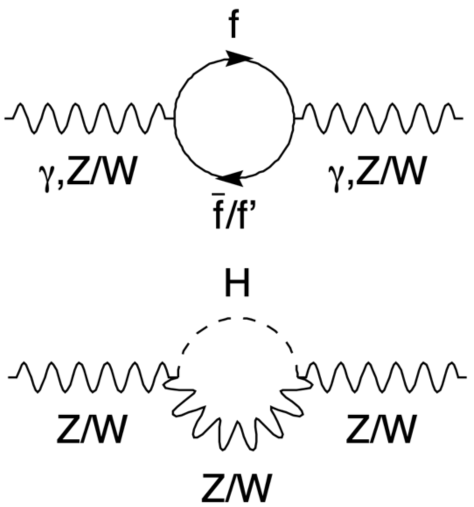
Motivation for Luminosity precision at CEPC

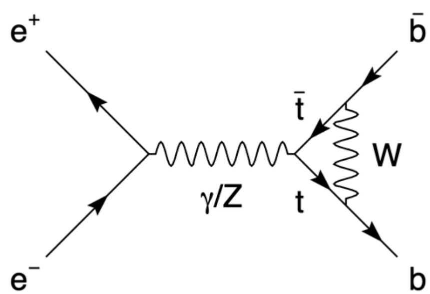
- Higgs: O(10^6) statistics in 15 years operation
- Z: O(10^{12}) statistics in ~4 years



Operation mode	$\sqrt{s}$ (GeV)	$\mathcal{L}$ (10^{34} cm^{-2}s^{-1})	Years	Event yields
H	240	5	15	2.0×10^6
Z	91	26(*)	4	5.6×10^{11}
W^+W^-	155-170	16	1	1.0×10^7(†)

Tests of the quantum structure of SM





Roadmap for CEPC LumiCal

- CEPC project general timescale
  - Higgs mode: ~5+5 year from now
  - Z and WW mode: future upgrade, ~10+15 years from now

Operation mode	$\sqrt{s}$ (GeV)	$\mathcal{L}$ (10^{34} cm^{-2}s^{-1})	Years	Event yields
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- Roadmap
  - First version for Higgs mode, in terms of coverage, precision, background and radiation tolerance, etc.
  - A major upgrade foreseen to meet the requirement for Z pole, with at least 10 year more R&D time

Luminosity measurement at CEPC

- 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) $e^+e^- \rightarrow e^+e^-$
  - Dominant process in e+e- colliders
  - $e^+e^-\rightarrow\gamma\gamma$ and $e^+e^-\rightarrow\mu\mu$ mainly depend on the central detector and will not be discussed in this talk

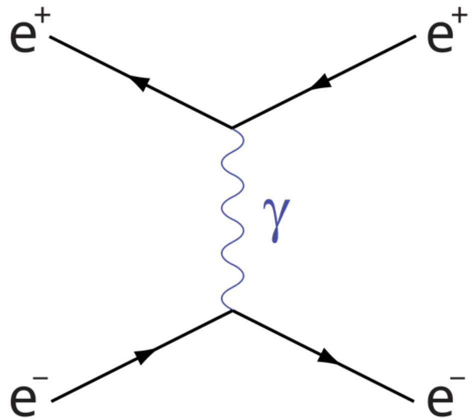
Small-angle Bhabha scattering (SABS)

- Cross section of SABS $e^+e^- \rightarrow e^+e^-$

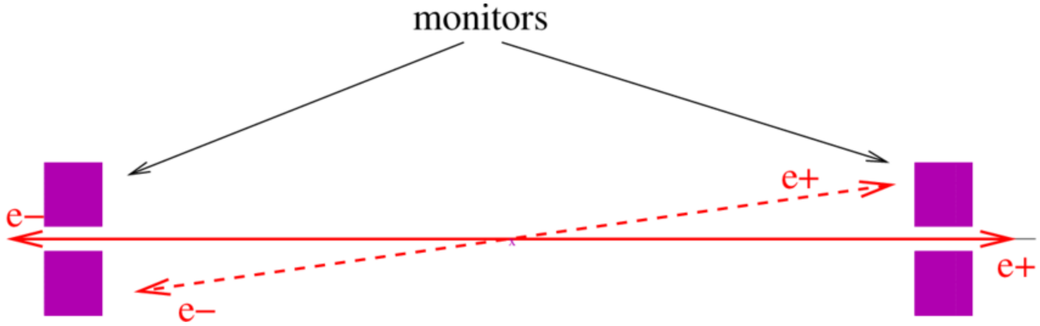
$$\sigma = \frac{16\pi\alpha^2}{s}\left(\frac{1}{\theta^2_{min}} - \frac{1}{\theta^2_{max}}\right)$$

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

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



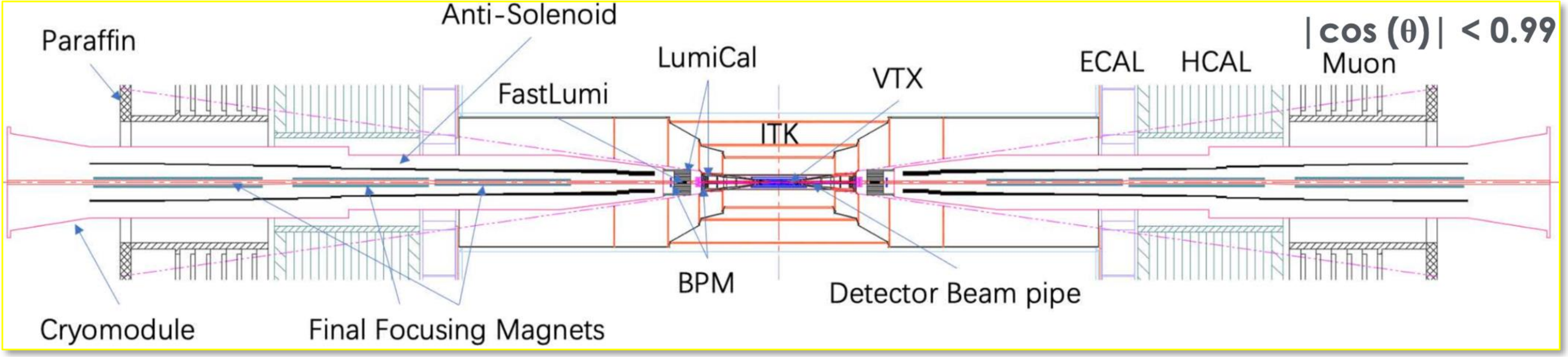
- Peaked in the forward region, at <100 mRad
  - Dedicated detector needed
  - Precision of the low edge positioning is critical

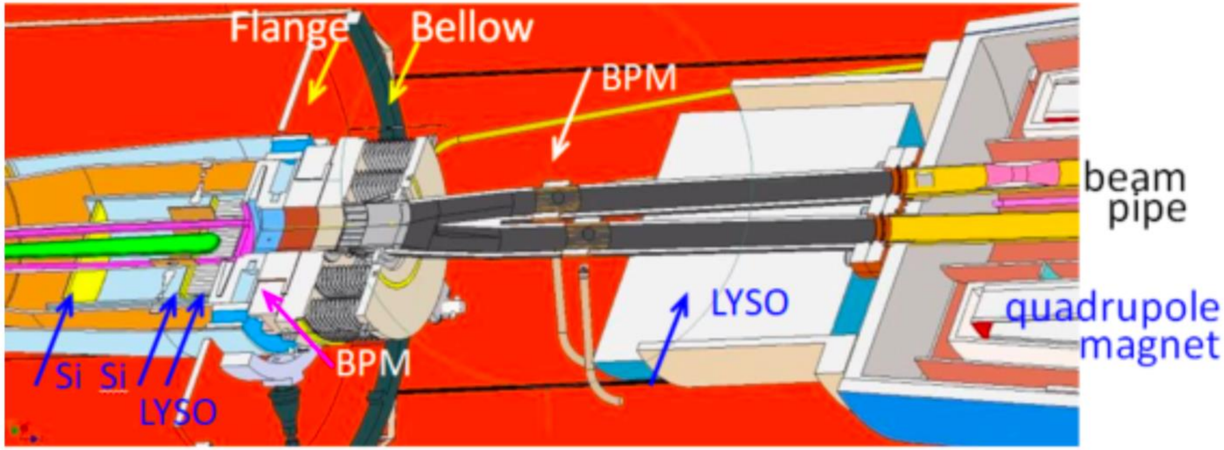


$$\frac{\Delta\mathcal{L}}{\mathcal{L}} \sim \frac{2\Delta\theta}{\theta_{min}}$$

CEPC LumiCal design

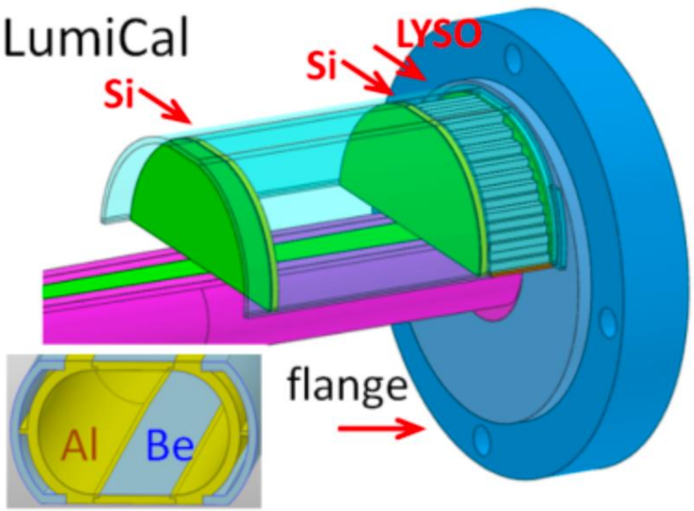
- Two detectors on each side of Interaction Point
  - Low-mass beampipe window: Be 1mm thick, traversing @22 mRad, traversing L= 45 mm, = 0.13 X_0 (Be)

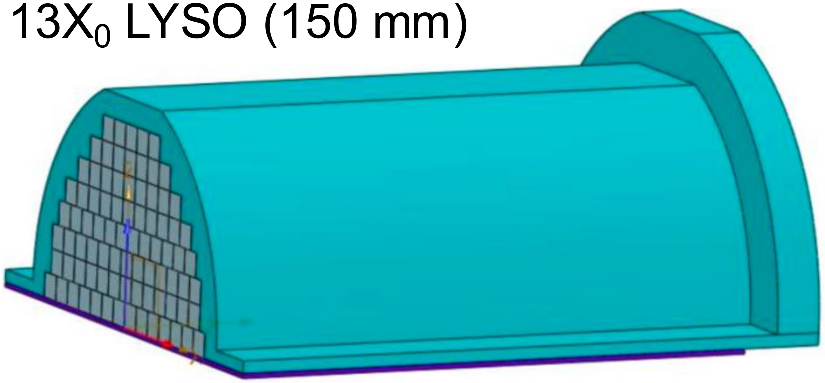




CEPC LumiCal design

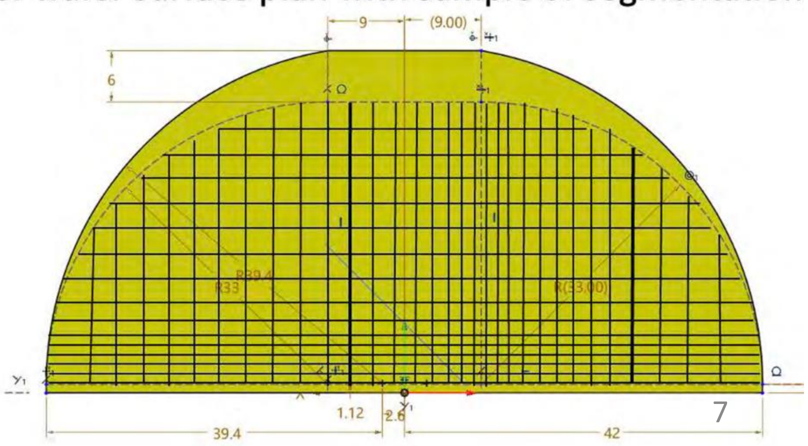
- Before flange: $z = 560 \sim 700$ mm: 2 Si-tracker and 2 X_0 LYSO (23 mm)
- After Bellow: $z = 900 \sim 1100$ mm: $13X_0$ LYSO (150 mm)





- Two layer AC-LGAD trackers
  - 2D readout of electron hits

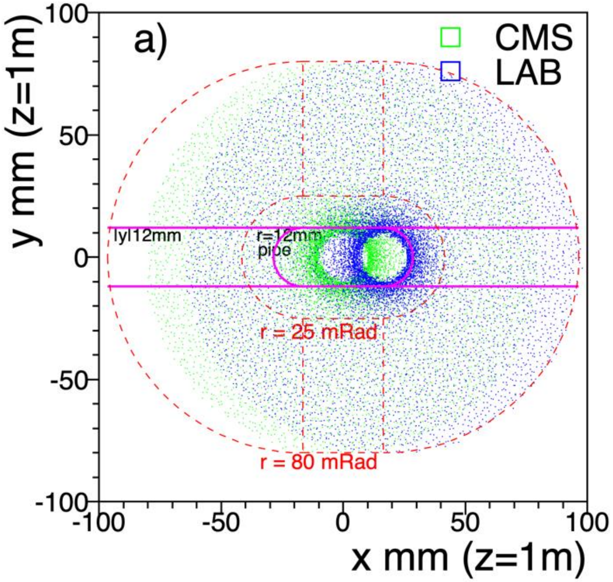
Si-wafer surface plan with sample of segmentation

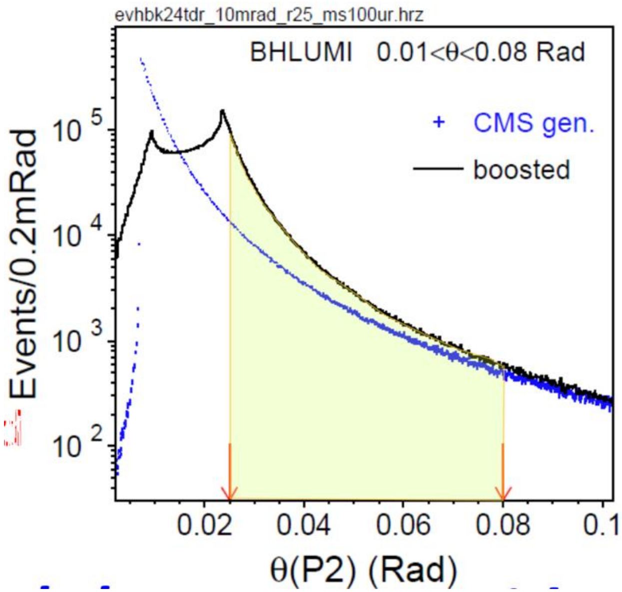


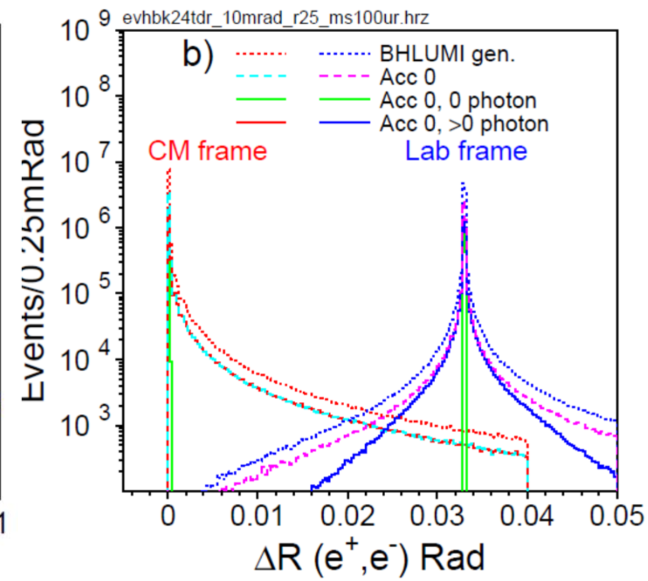
- First 2D sensor manufactured
  - Thanks to OTK group!
- Further iteration needed
  - Setup the test system

LumiCal acceptance

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



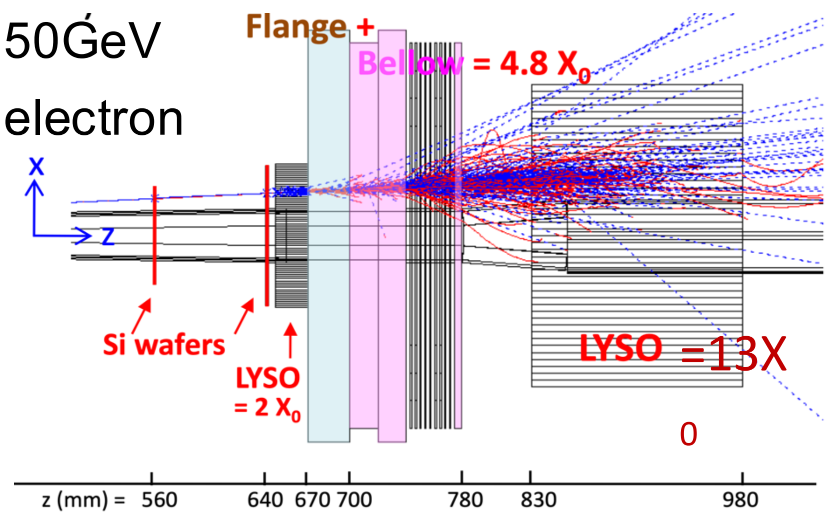


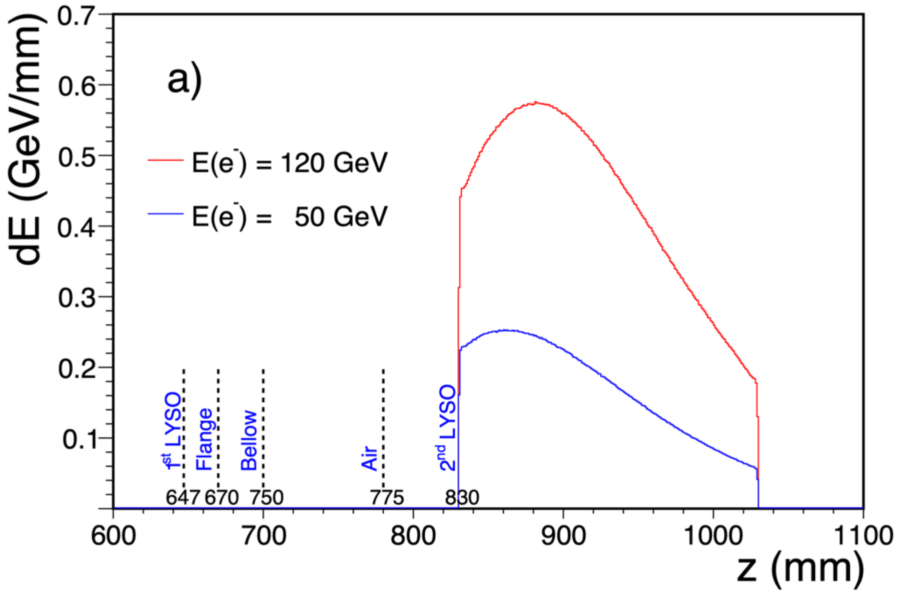


- LumiCal acceptance at |z|=1000mm, with RaceTrack pipe r=10mm

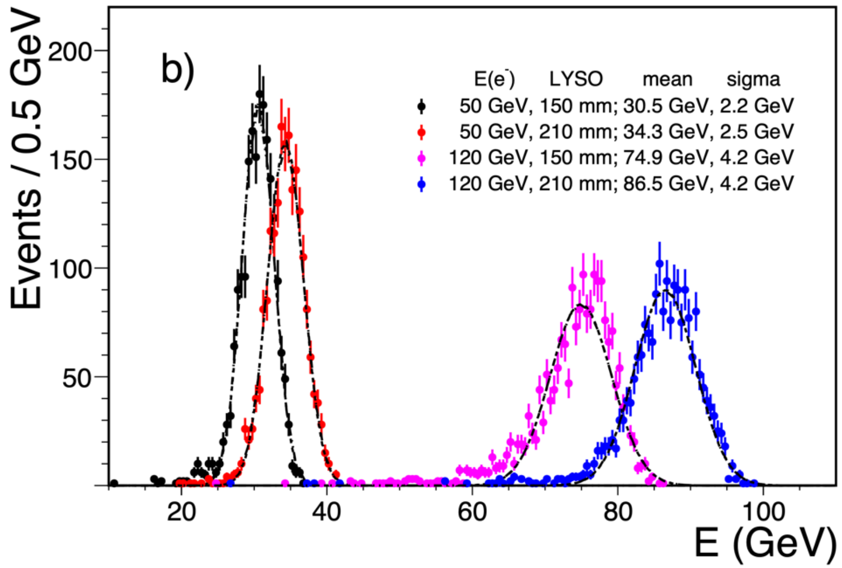
ONE e^+ or e^- detected		e^+, e^- back-to-back detected	
θ>25 mRad	θ>25mR & |y|>25mm	θ>25 mRad	θ>25mR & |y|>25mm
133.5 nb	81.8 nb	85.4 nb	78.0 nb

Energy measurement



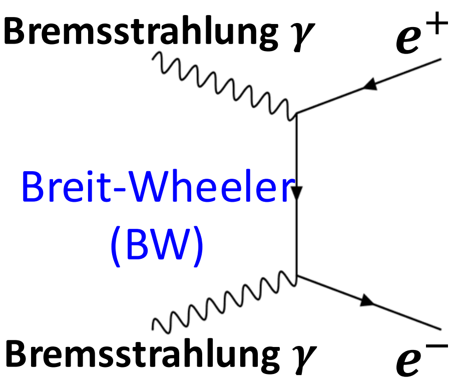


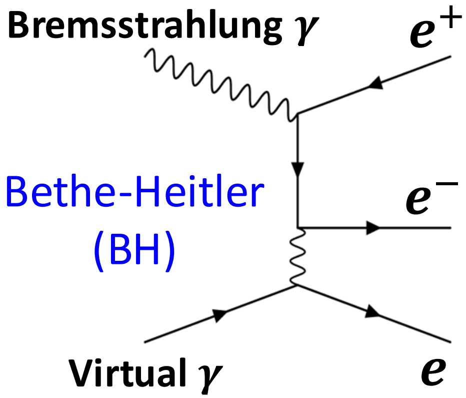
- Length vs energy resolution
  - Roughly 4-5%

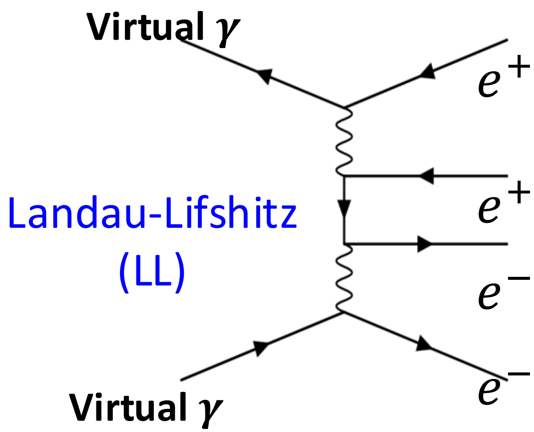


- Energy profile
  - High granularity can be useful

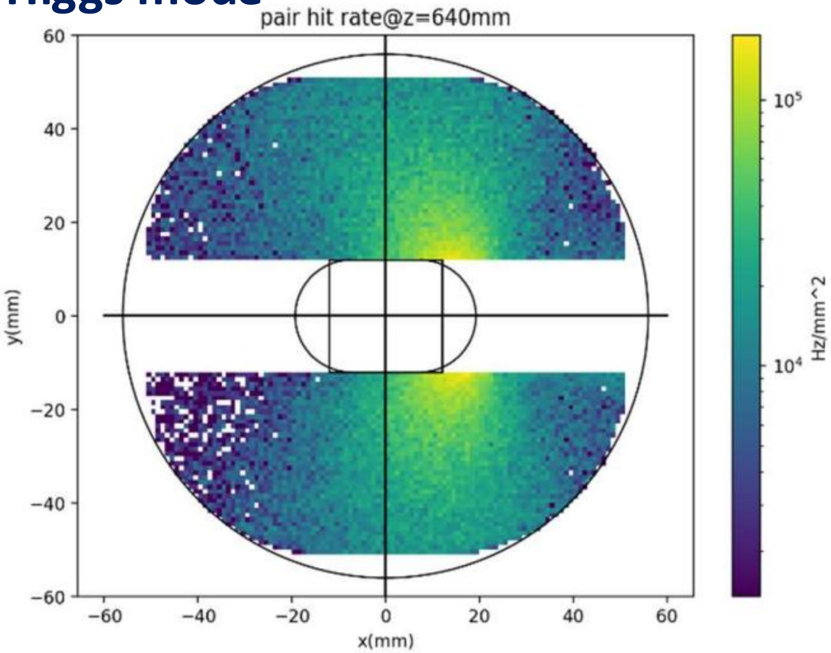
Major background: incoherent $\gamma\gamma \rightarrow e^+e^-$







Higgs mode

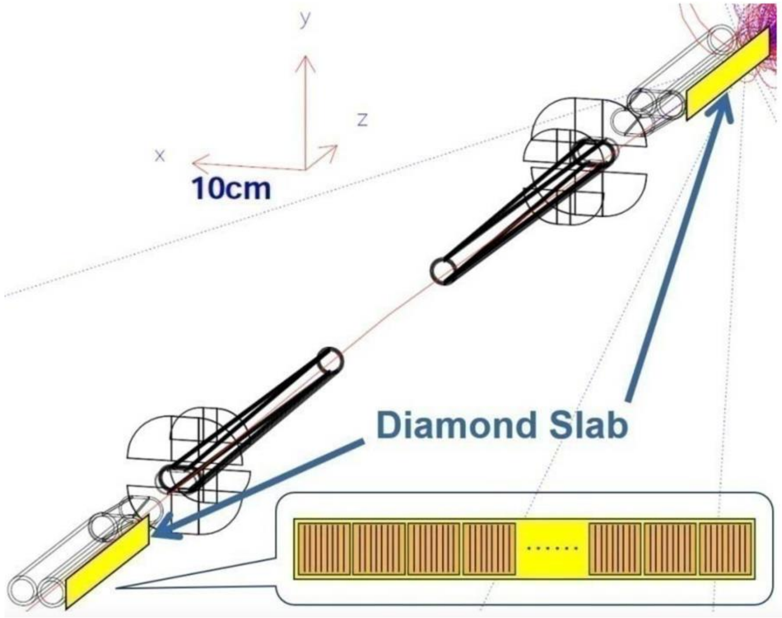


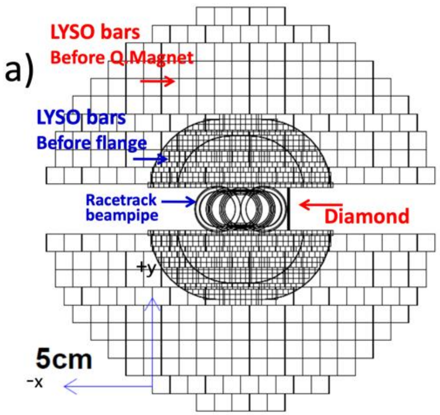
Background rate (preliminary)

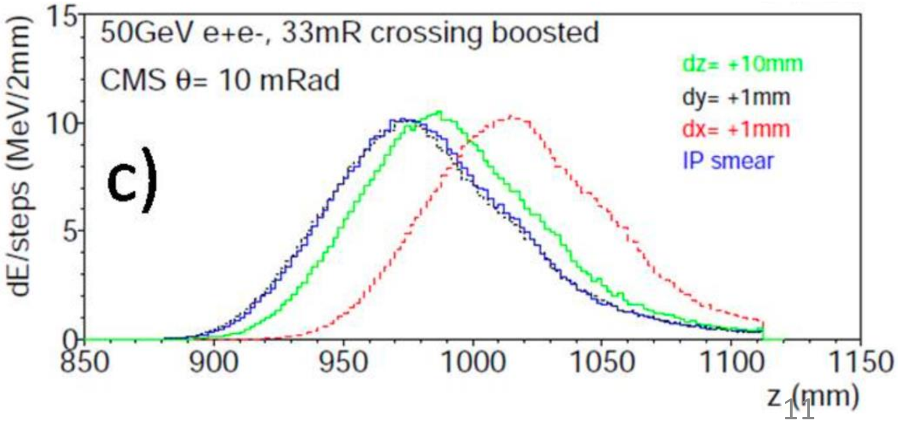
- Higgs and Low Z: O(<100 KHz/mm^2)
  - Challenging but controllable
- High Z mode: up to O(1 MHz /mm^2)
  - Further studies and R&D needed

Fast Lumi. monitor

- Fast beam monitor: diamond detector option
  - |z|= 855~1110 mm, ~10 mRad (CMS) ~25 mRad (LAB)
  - Count Bhabha electrons to monitor fast lumi. and IP along z-axis



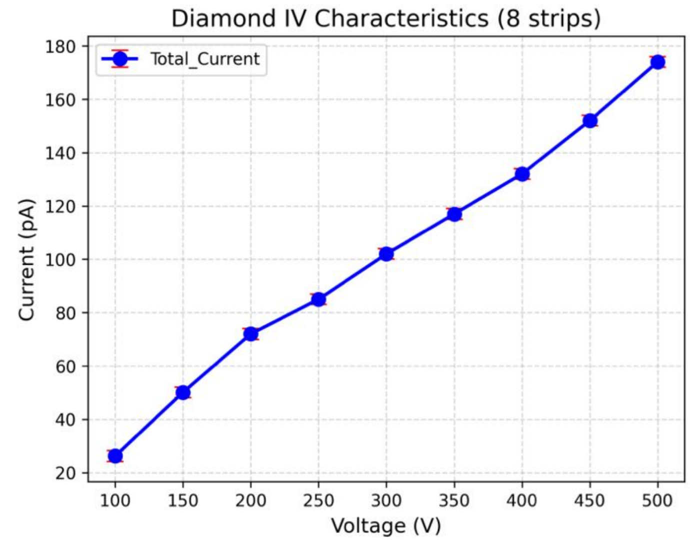


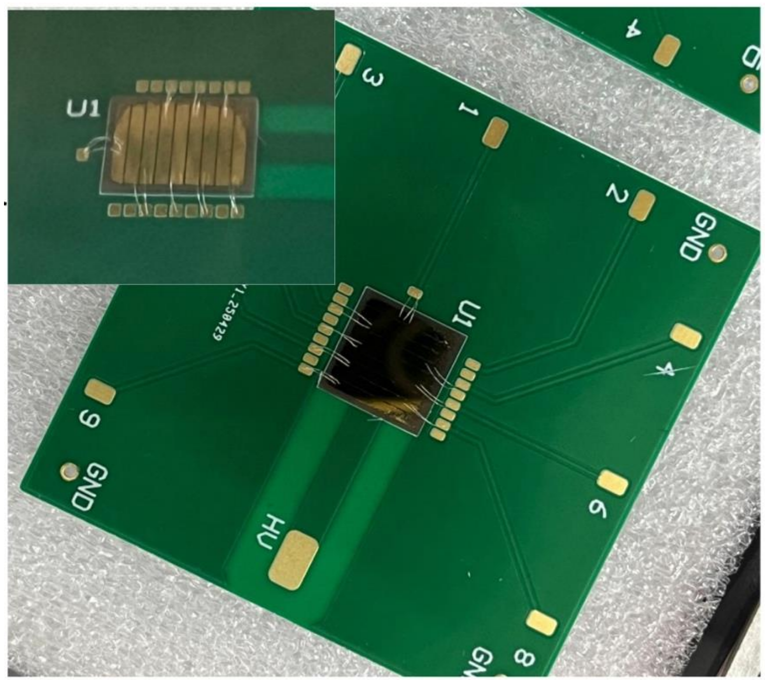


- Differentiate rates on +z v.s. -z to estimate IP offset
  - x,y monitored by BPMs

Diamond detector R&D

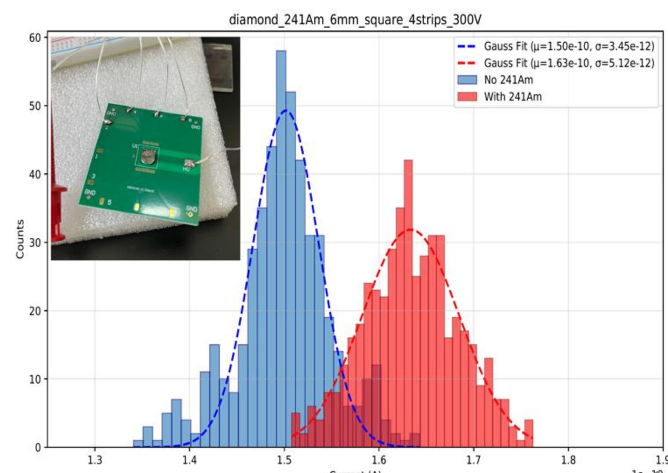
- Strip electrode
  - Full surface process chain with an old diamond chip
- Plan: Need new high quality diamond for further studies, e.g. MIP response, etc.





2. Diamond sensor 9 strips 10 mm × 10 mm

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



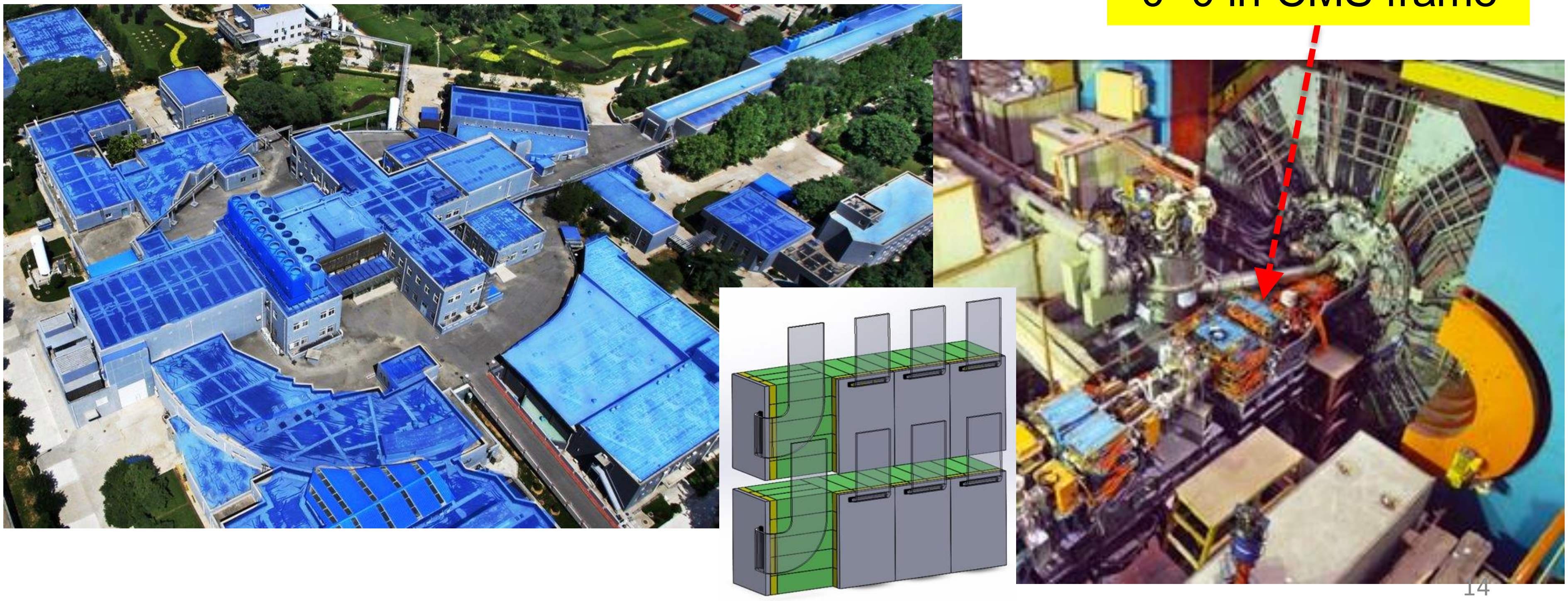
Radiation tolerance

- SiPM largely used in LumiCal
  - Its radiation hardness and long term stability, to be investigated
  - After irradiation, the dark current will be increase
- Possible solutions:
  - Install cooling system to prevent thermal runaway
  - Continue investigation on mitigation and shielding
  - Planning possible replacements in the during stop
  - Foreseen a major upgrade for Z pole mode in >10 years
- Further detector R&D
  - Investigate the radiation hard photo detection technologies
  - Study the new SiPM types in the current colliders, e.g. BEPCII

Tests at BESIII experiment

- BEPCII-BESIII experiment
  - e+e- collider, COM energy: ~2-5 GeV, Luminosity: ~10^{33}cm^{-2}/s
- Zero-Degree-Calorimeter(ZDC)
  - Fast luminosity and ISR photon tagging
  - LYSO+SiPM array, 240 channels in total

3.3m <z<3.5 m,
θ=0 in CMS frame

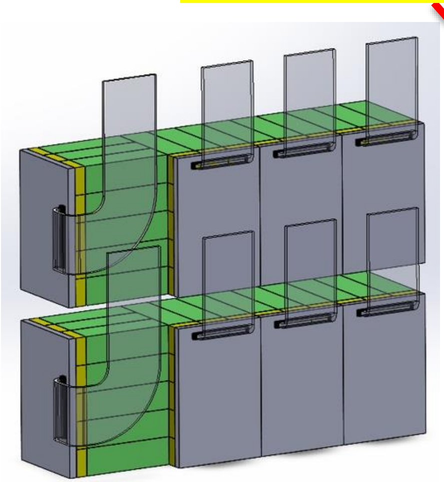


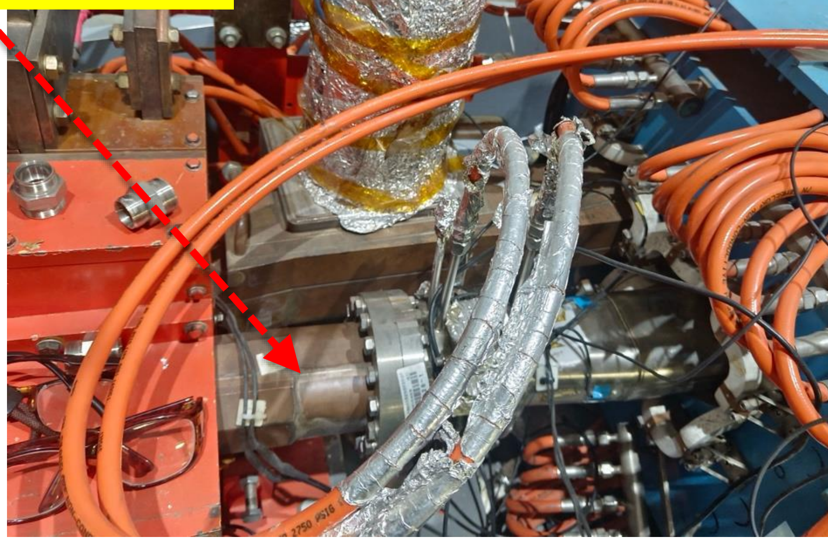
BESIII ZDC: LYSO+SiPM proto-type

- BEPCII-BESIII experiment
  - e+e- collider, COM energy: ~2-5 GeV, Luminosity: ~$10^{33}cm^{-2}/s$
- Zero-Degree-Calorimeter(ZDC)
  - Fast luminosity and ISR photon tagging
  - LYSO+SiPM array, 240 channels in total

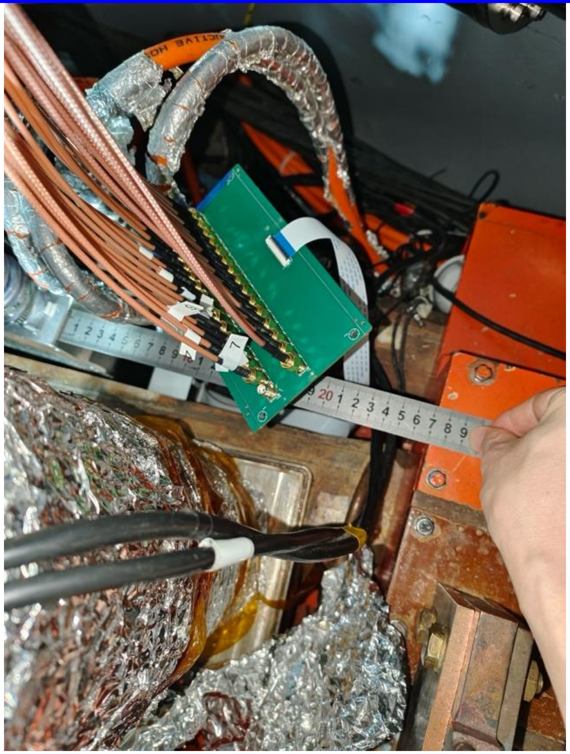
Single detector module test

3.3m <z<3.5 m,
θ=0 in CMS frame

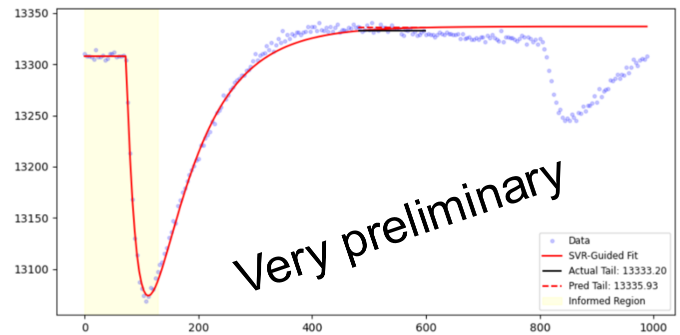


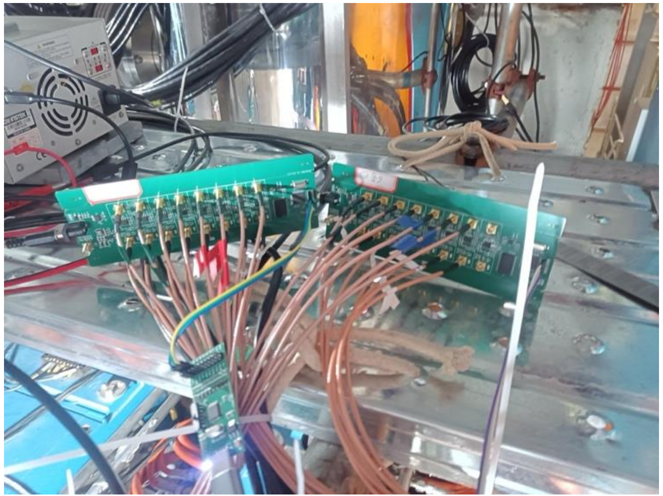


BESIII ZDC: LYSO+SiPM proto-type



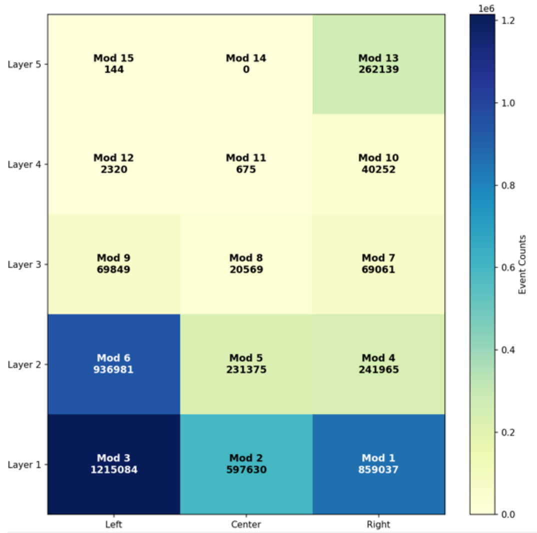
- Pictures of the current test system
  - Pre-amplifier, High voltage fanout, DAQ, etc.
- Long term study and monitor the SiPM performance insitu
  - Waveform reconstruction

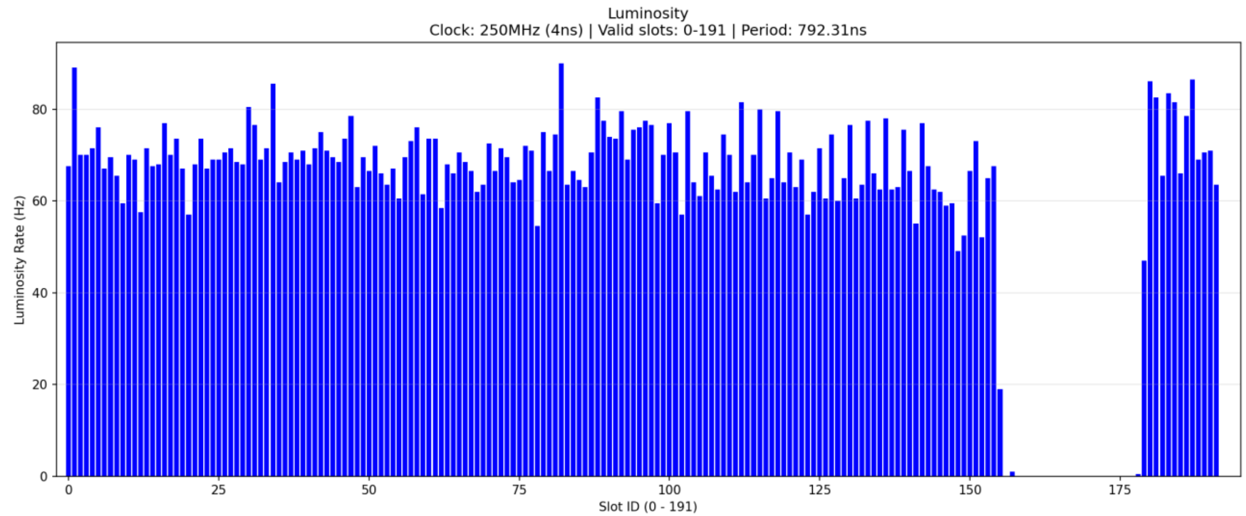




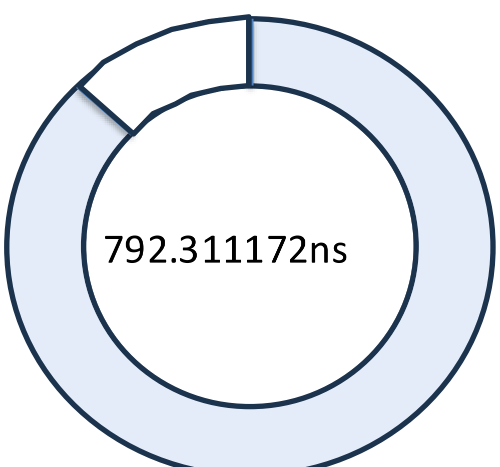
Very preliminary results

Event rate at each channel

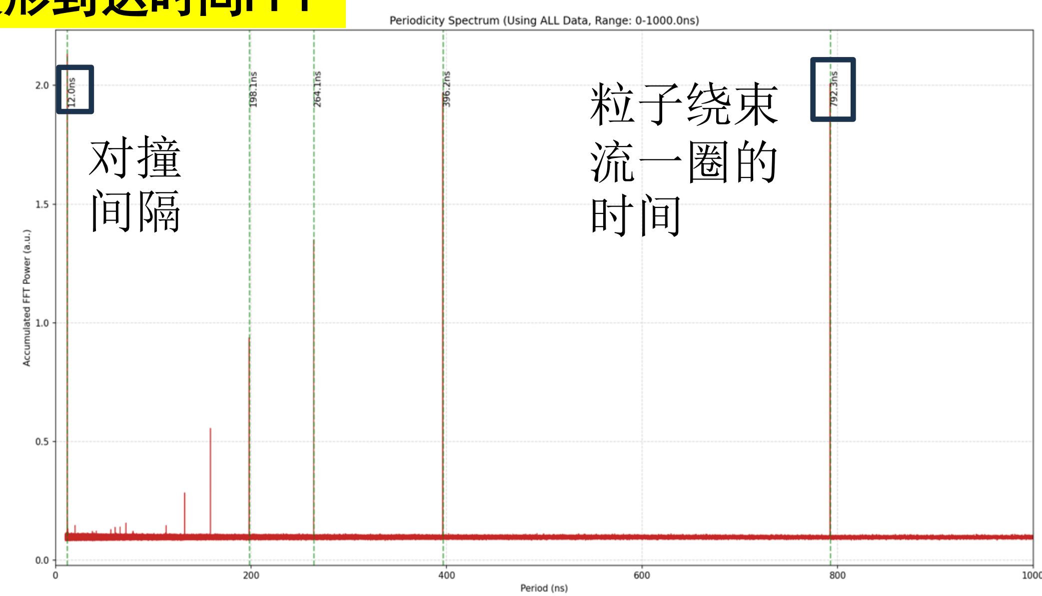




BEPCII time structure

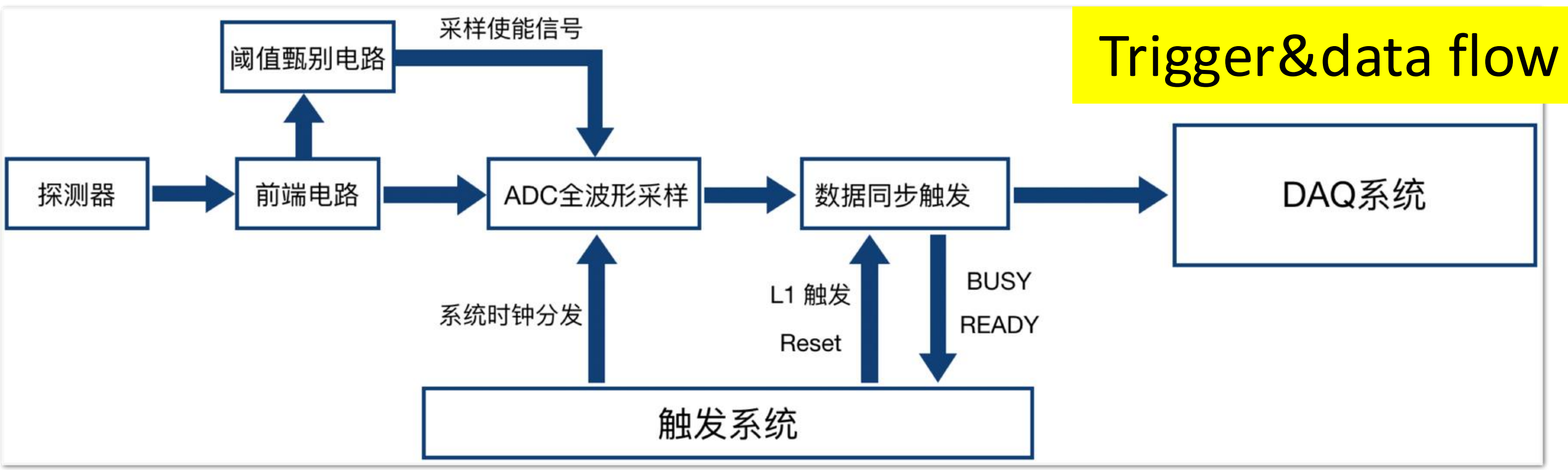


波形到达时间FFT



BESIII ZDC: Electronics & TDAQ

- 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

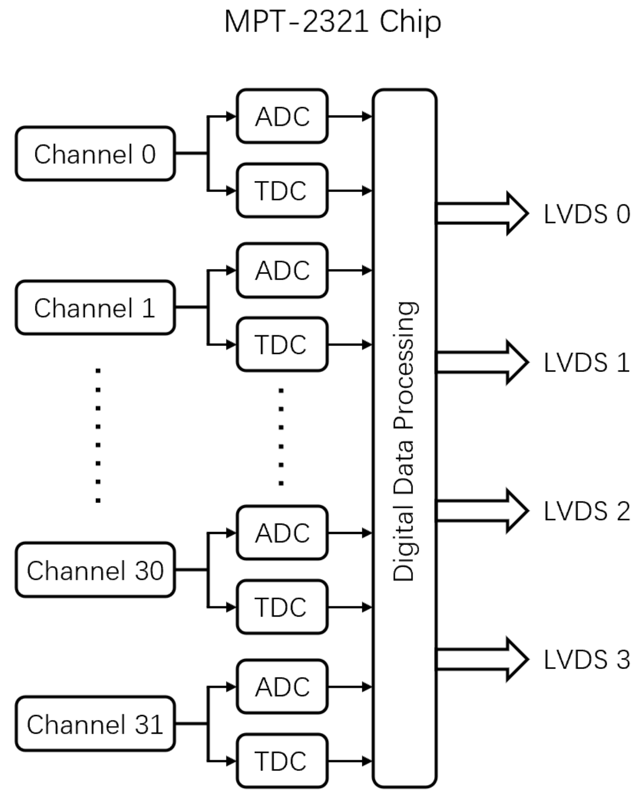


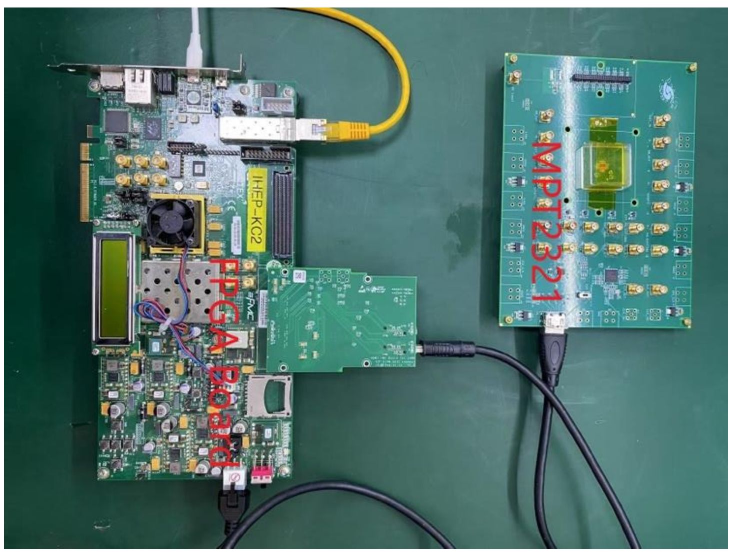
- Ideal test place for wireless communication!

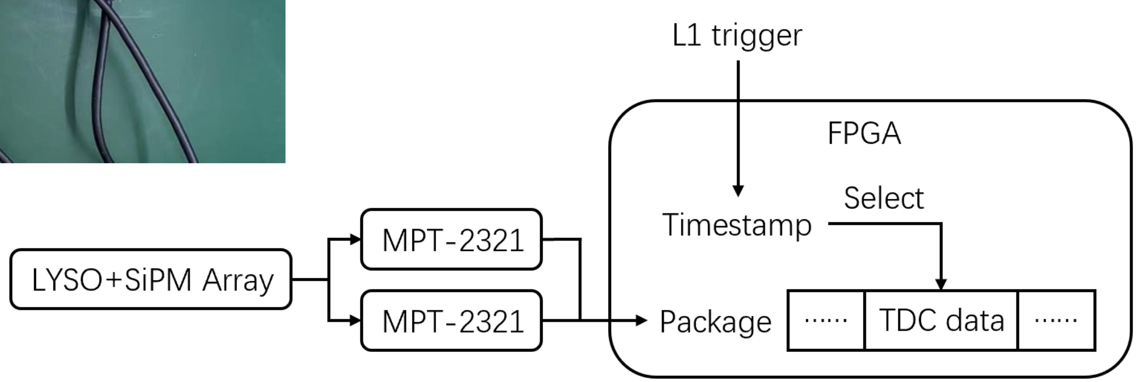
On-site

2. LYSO+SiPM calorimeter

- Future upgrade: ASIC based readout
- MPT-2321: SiPM Signal Processing Chip
  - 32 input channels
  - 12-bit ADC, 20-bit TDC with 50ps resolution







Summary

- CEPC LumiCal system design finished
- Extensive detector R&D performed
  - Si tracker: first version of novel 2D AC-LGAD sensor produced
    - Need to setup the test system and resources for future iterations
  - LYSO+SiPM calorimeter:
    - Get support from BEPCII luminometer upgrade
    - Prototyping and tests on-going at collider
  - Daimond: surface process tested with an old diamond chip
    - Need high quality diamond for further R&D

The end

Experimental challenges

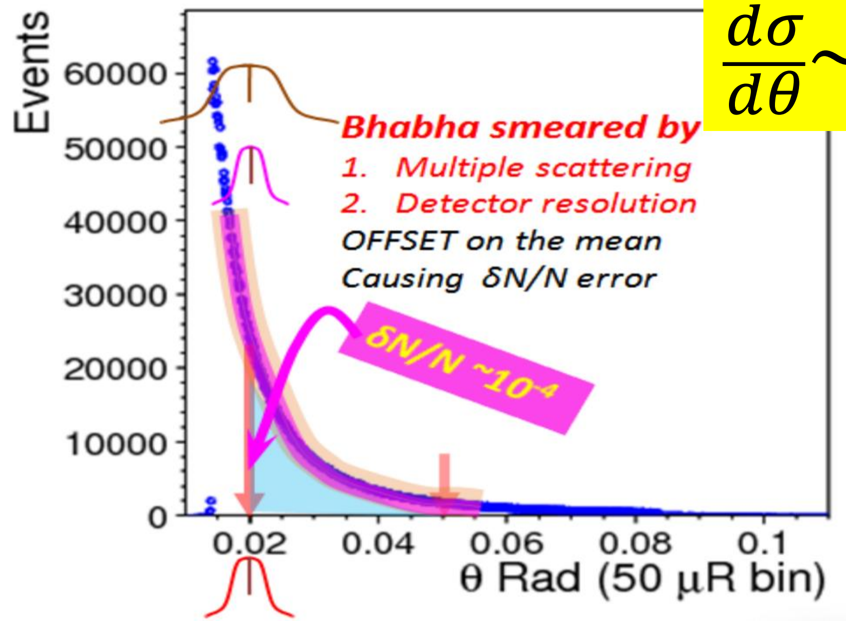
- Detector aperture, position and alignment
  - Especially the inner radius
- Electron Multiple scattering
- Position of interaction point (IP)
- Radiation tolerance

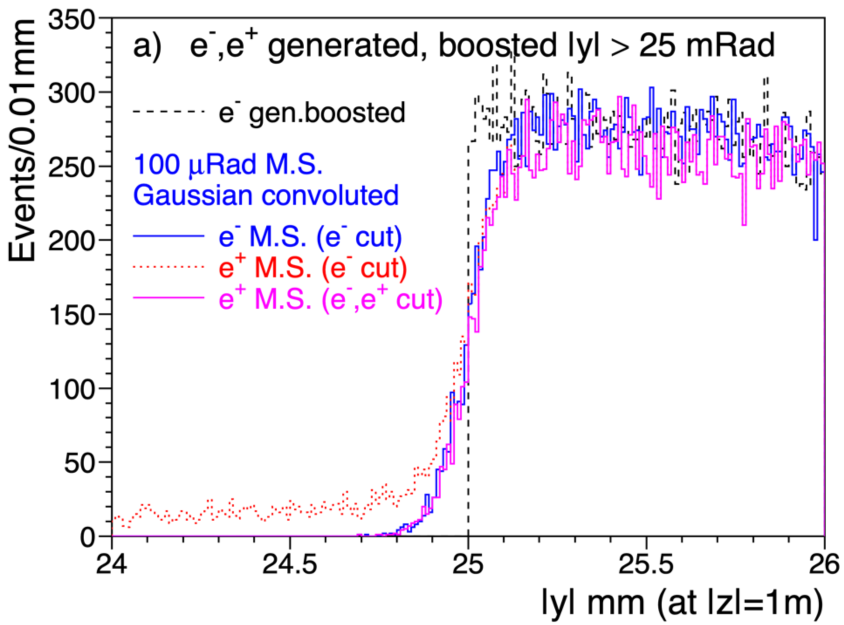
Detector aperture, position and alignment

- Detector alignment
  - Especially the inner radius

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

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



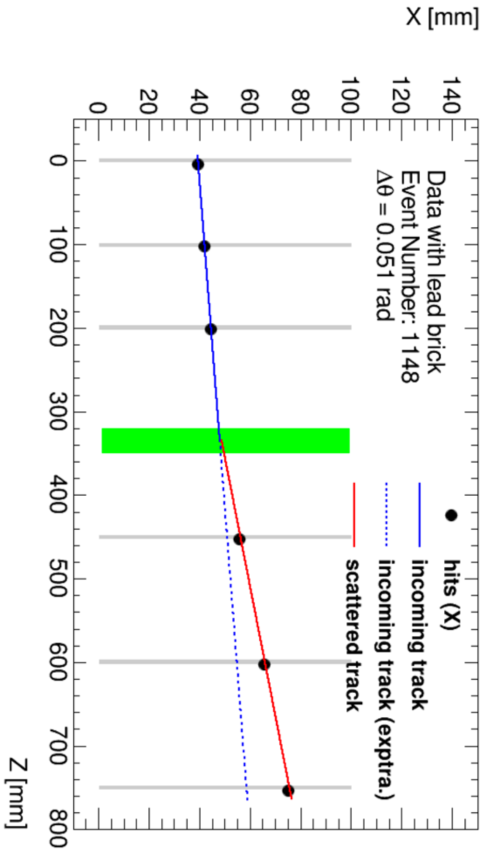


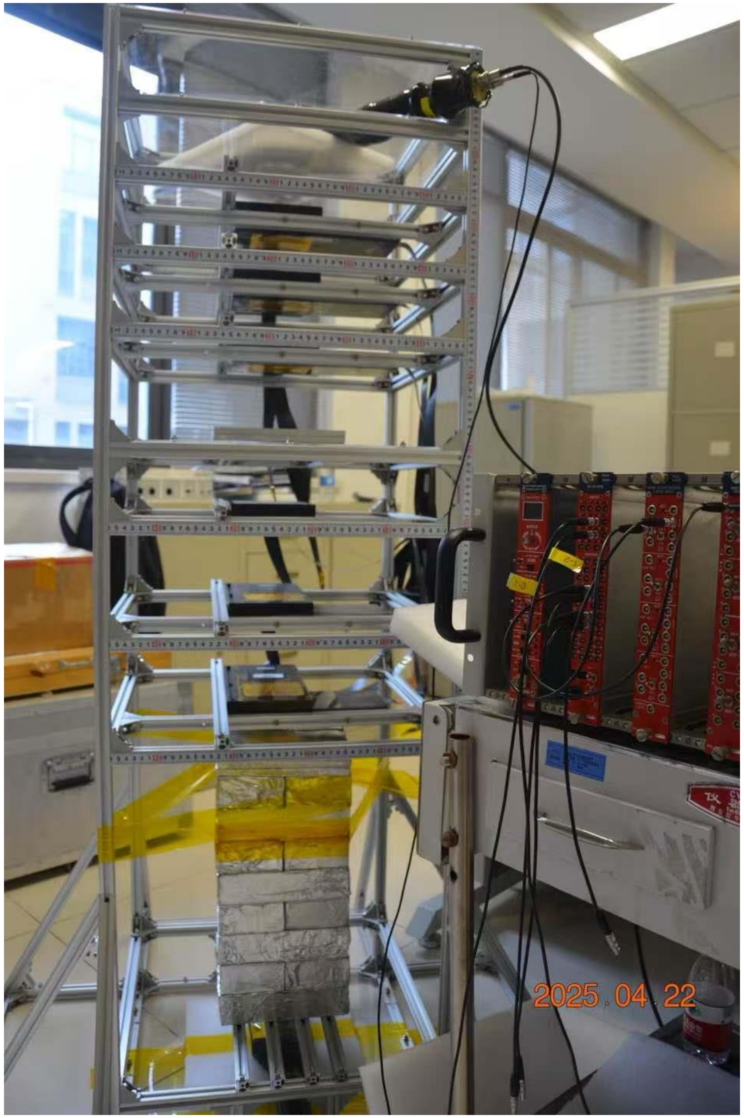
- Final state electron multiple scattering

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

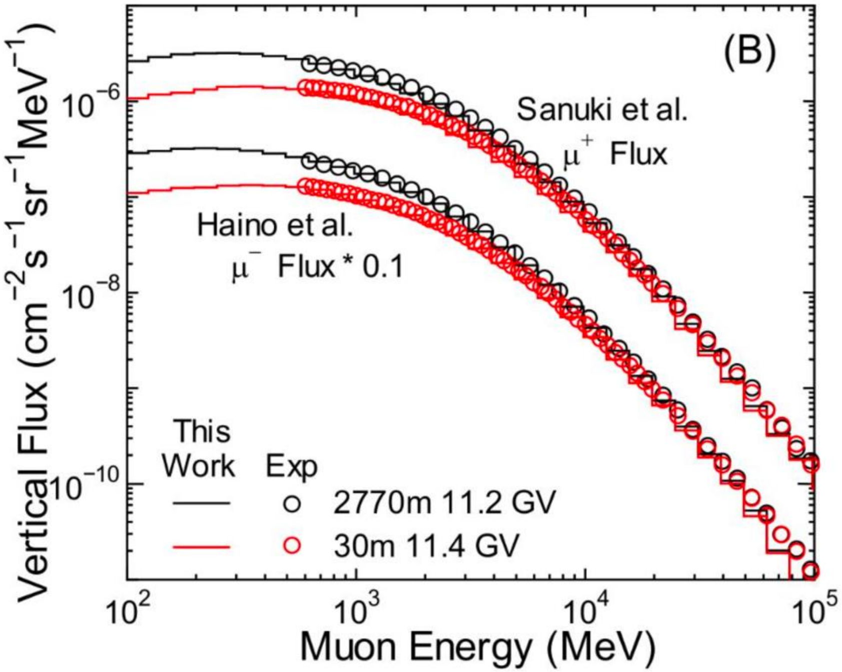


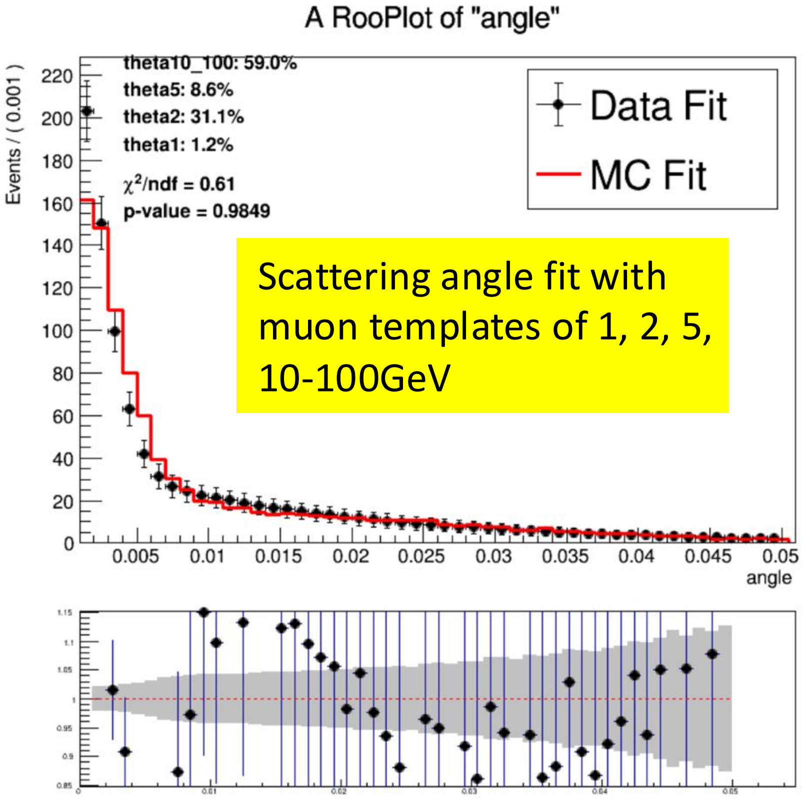


Multiple scattering

- Preliminary results

Cosmic Muon energy spectrum



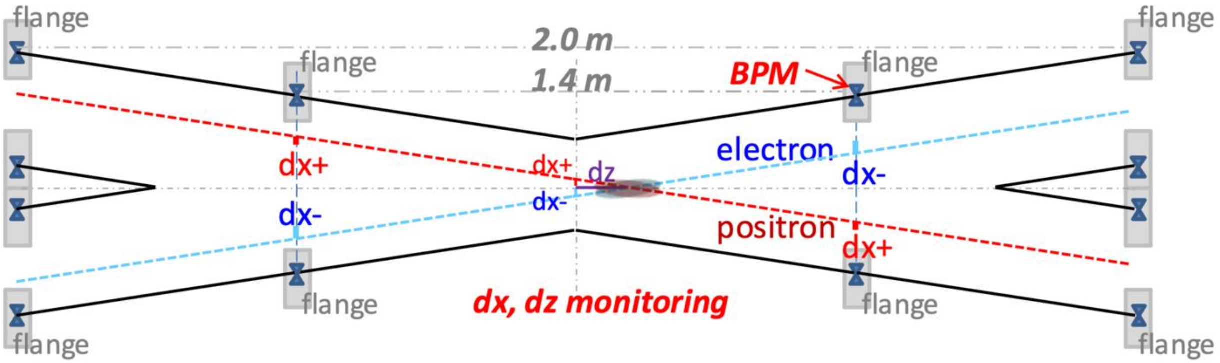


Scattering angle fit with muon templates of 1, 2, 5, 10-100GeV

Ref: Journal.pone.0144679

Interaction Position (IP)

- Real IP position can be shifted

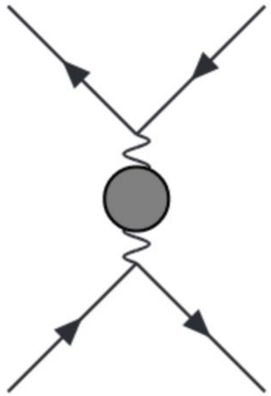


- Beam induced acceptance change
  - Beam-energy asymmetry, IP displacements,
  - Cross section changed with the beam energy,
  - Focusing of final state particles through beam bunches

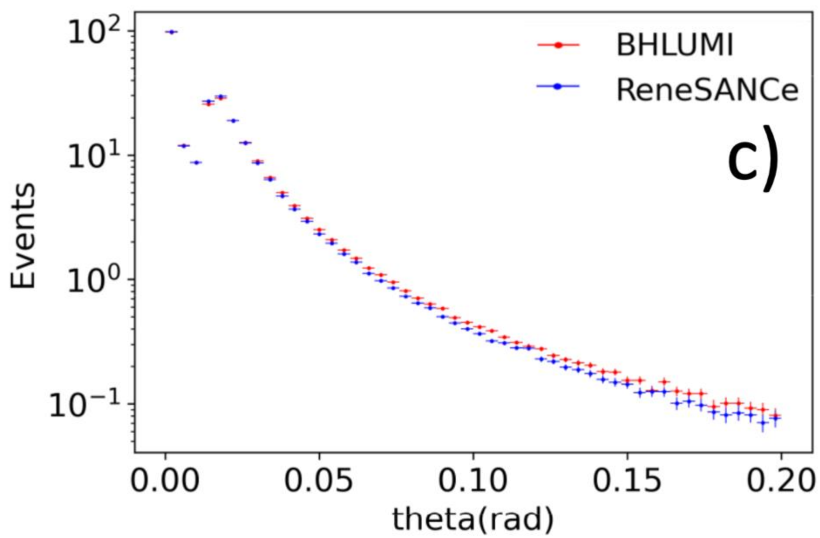
- IP measurement along x-y plane
  - Beam position monitors (BPMs) inside flanges
  - Precision O(1 μm) on the beam x,y positions

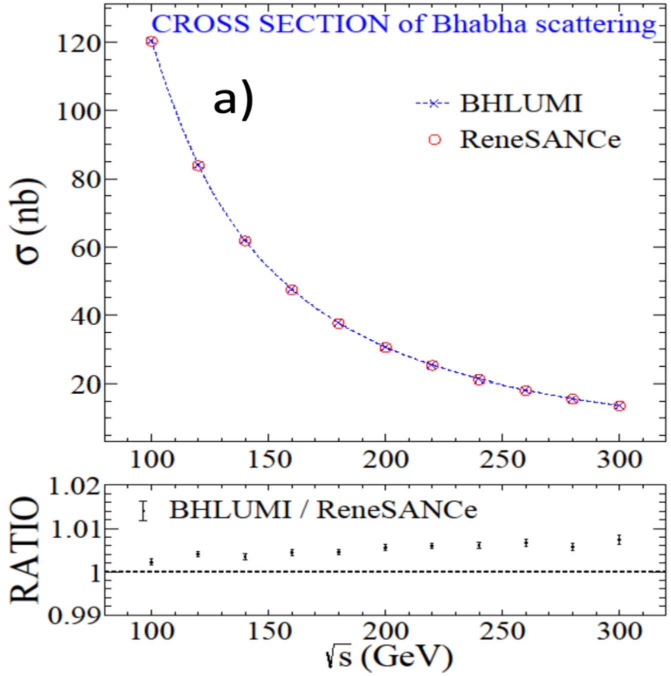
Theoretical challenges

- Hadronic vacuum polarisation contribution
  - Extracted from data for $e^+e^- \rightarrow$ 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]

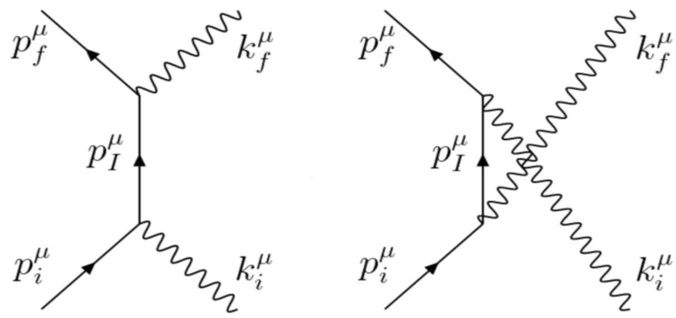




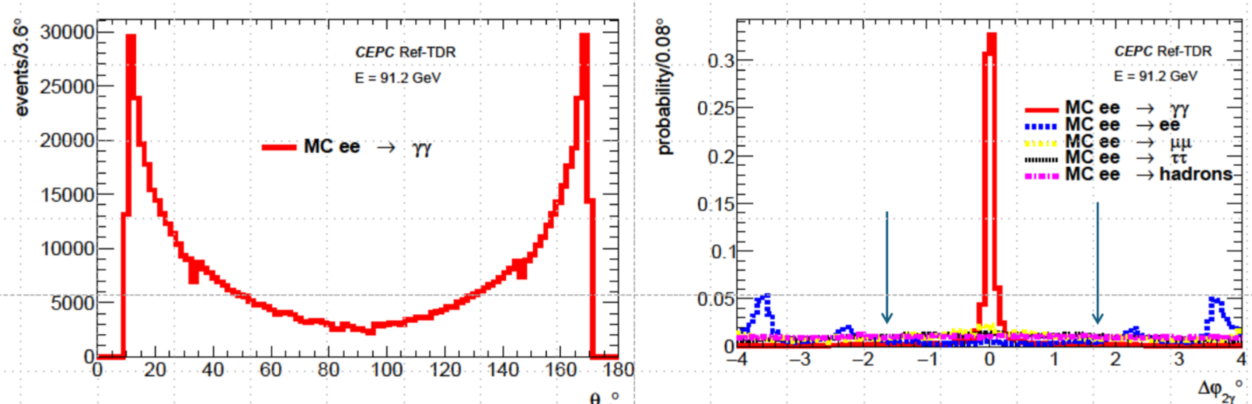
Alternative process: di-photon ($e^+e^-\to\gamma\gamma$)

$$\sigma_{\gamma\gamma}(\theta > \theta_{\min}) = 130\ \text{nb}\ (1 - P_{e^-} P_{e^+})\left(\log_e\left(\frac{1+\cos\theta_{\min}}{1-\cos\theta_{\min}}\right) - \cos\theta_{\min}\right)/\ s[\text{GeV}^2]$$

- QED process: $d\sigma/d\theta \sim 1/\theta$
- Potentially advantages over SABS
  - Severe metrology requirements
  - Significant impact of the hadronic vacuum polarisation



Relaxed selection 10<θ<170°



If we want to increase statistics by using 10<θ<170° selection then 10^{-4} contamination from the ee → ee process appears.

To suppress this ee → ee background the condition **abs($\Delta\varphi_{2\gamma}$) <1.75** could be used. In this case:

ee → γγ 688081 events selected from 1M (~69% efficiency)

ee → ee 0 events selected from 200k (without abs($\Delta\varphi_{2\gamma}$) <1.75 2 events selected)

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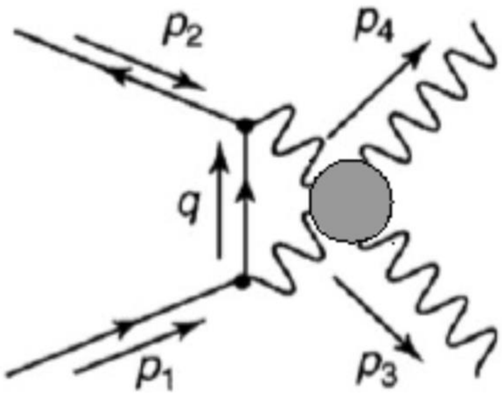
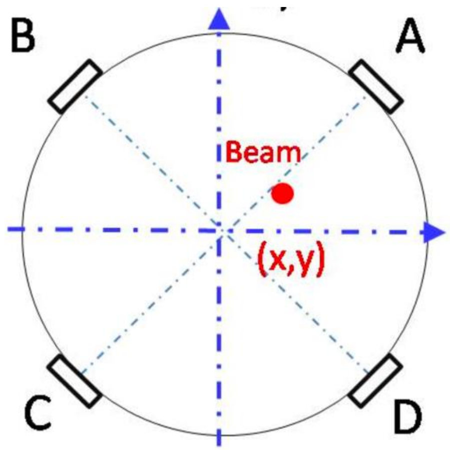
Di-photon: challenges

- Experimental
  - Statistical precision, ~1000 times smaller than SABS
  - Acceptance/metrology: looser than the SABS. But, here for the whole central detector, with several components
- Theoretical
  - Photon vacuum polarisation (Hadronic light-by-light (lbl) scattering) only appears one order higher than in SABS, but with larger uncertainty.
  - Estimated from data driven hadronic models or lattice QCD



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



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

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

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