Luminosity measurement and monitoring at CEPC

Lei Zhang

On behalf of the CEPC LumiCal team

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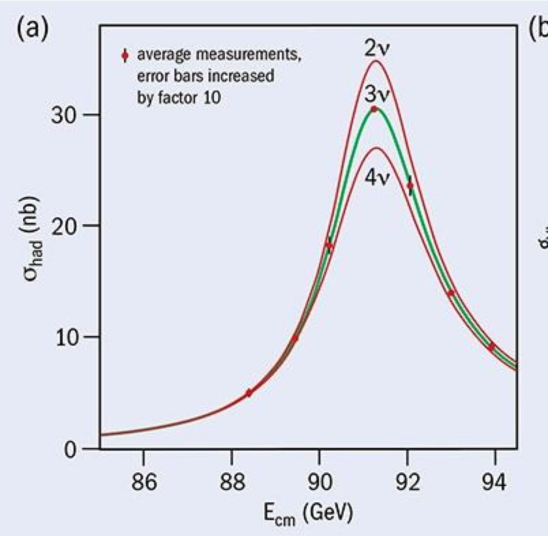
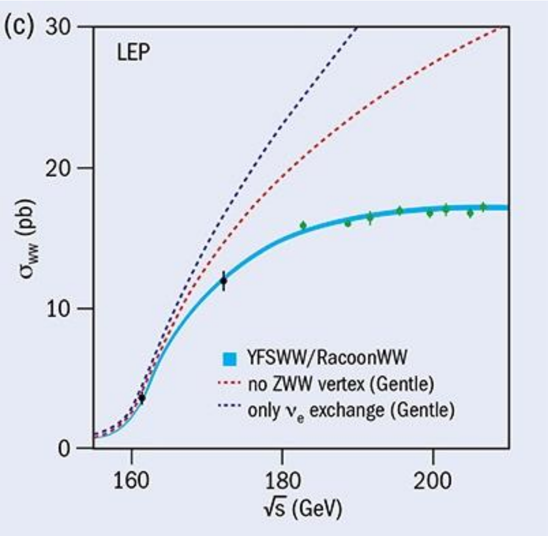
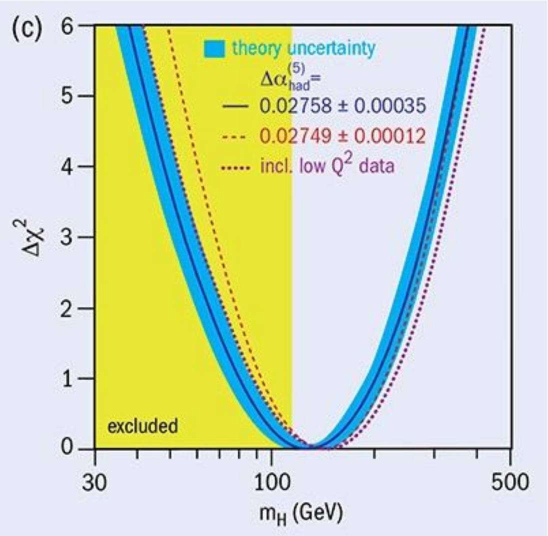
LEP Legacy: EW Precision Measurements







- Z-pole cross-section measurement established $N_\nu = 3$
- WW cross-section measurement established γWW and ZWW triple gauge vertexes: unification of EW interaction
- Z-pole observables, m_W, etc. provide a stringent test of the SM and constrains the Higgs mass

Luminosity measurement at CEPC

- Essential for cross-section and line-shape measurements

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

- Most demanding from Z line-shape and WW threshold
  - Z pole two-fermion production and W^+W^- with data-sets of $O(10^7-10^8)$, motivating a similar $O(10^{-4})$ luminosity precision
  - Total cross section for $e^+e^-\to HZ$ (used for extracting the effective HZZ coupling and the total Higgs boson width)

- Counting the rate of the well-known process

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

Physics processes for luminosity measurement

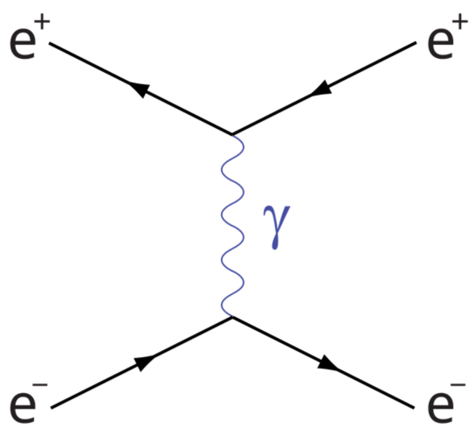
- Requirements:
  - Large rate, so as not to be statistics limited
  - Clean signature with low background, e.g. electron, photon, muons, etc
  - High-precision theory predictions and MC tools, with negligible room for possible new physics contributions.

- Small-angle Bhabha scattering (SABS): ($e^+e^- \to e^+e^-$)
  - Dominant process in e+e- colliders
  - Widely used for lumi. measurement in LEP, BEPC(II), etc

- Other possible processes: Di-photon production: ($e^+e^- \to \gamma\gamma$)

SABS: $e^+e^- \to e^+e^-$

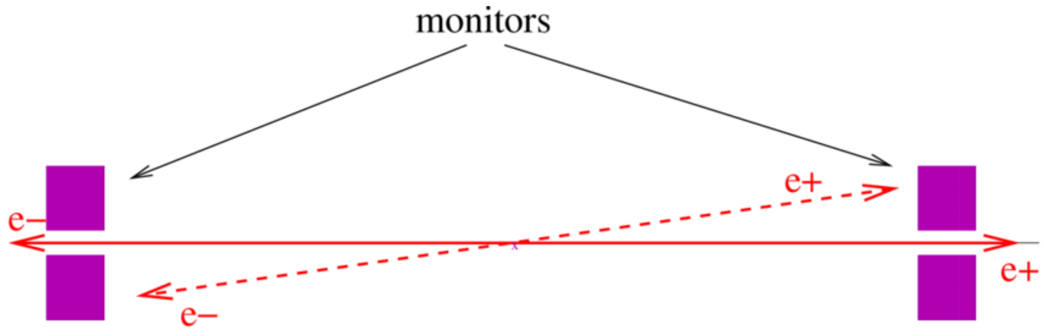
- Large cross section: $\frac{d\sigma}{d\theta} \sim \frac{1}{\theta^3}$



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

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

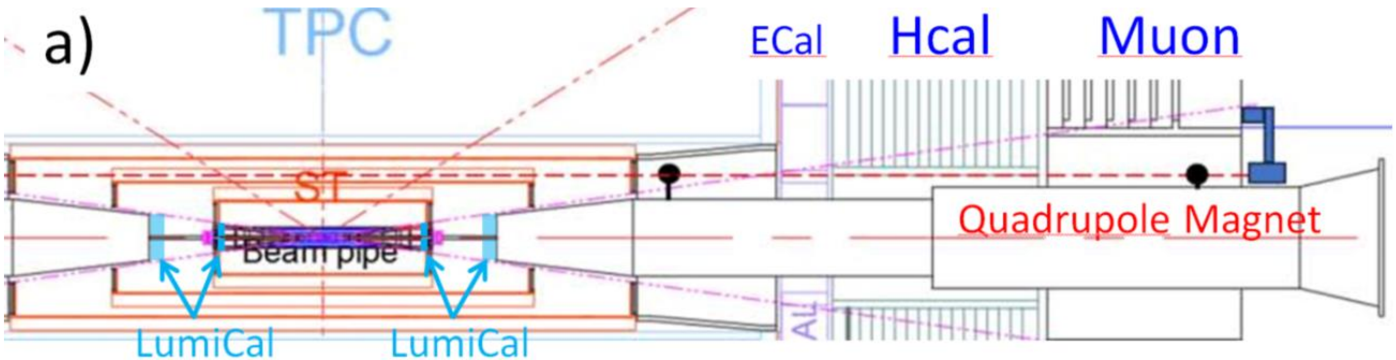
- Peaked in the forward region, at <100 mRad
  - Dedicated detector needed
  - Precision of the low edge positioning is critical



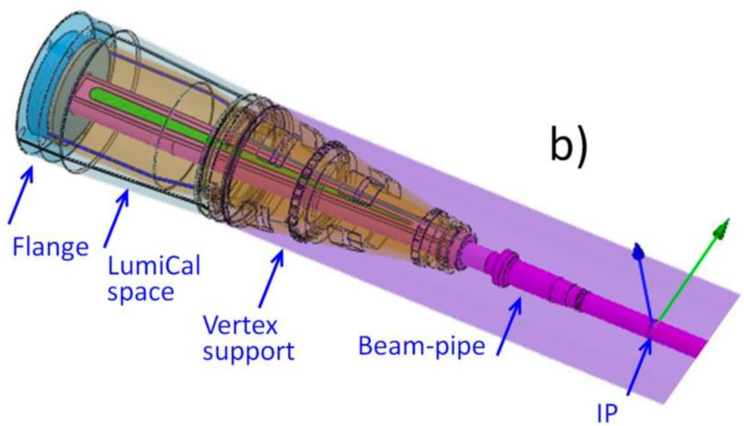
$$\frac{\Delta\mathcal{L}}{\mathcal{L}} \sim \frac{2\Delta\theta}{\theta_{min}}$$

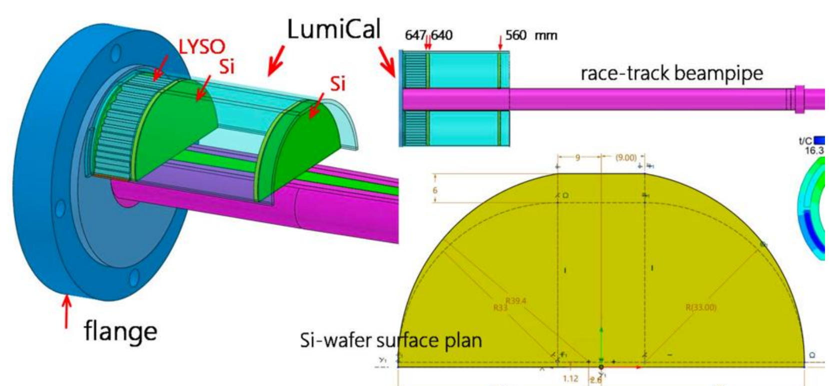
CEPC LumiCal design

- Two detectors on each side of Interaction Point

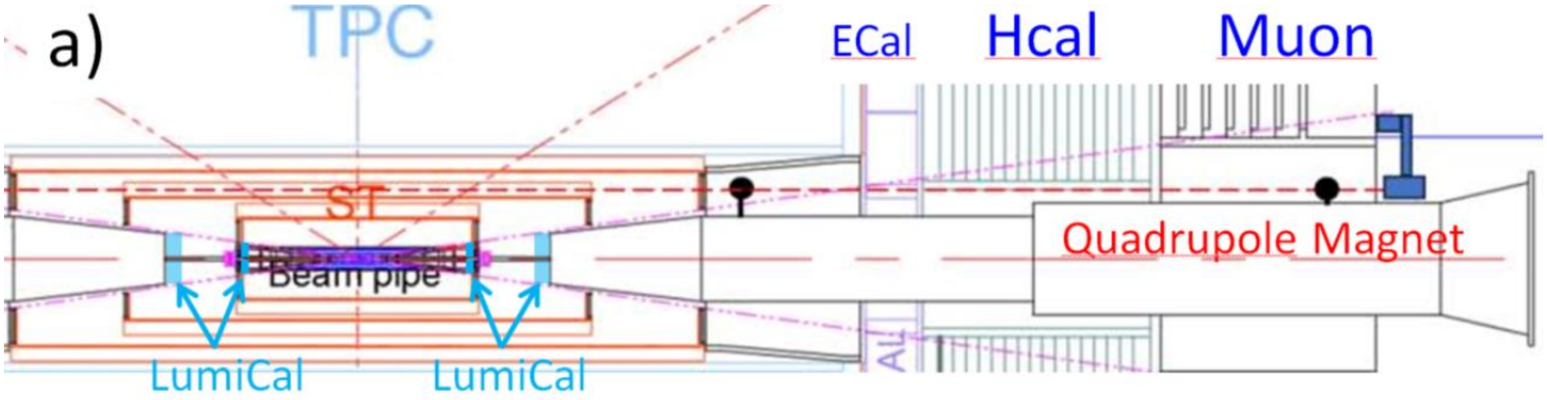


- $z = 560 \sim 700\ \mathrm{mm}$: before Flange
  - Low-mass beampipe window: Be 1mm thick, traversing @22 mRad, traversing L= 45 mm, = 0.13 X_0 (Be), 0.50 X_0 (Al)
  - Two Si-wafers for $e^{\pm}$ impact θ, 2 X_0 LYSO = 23 mm

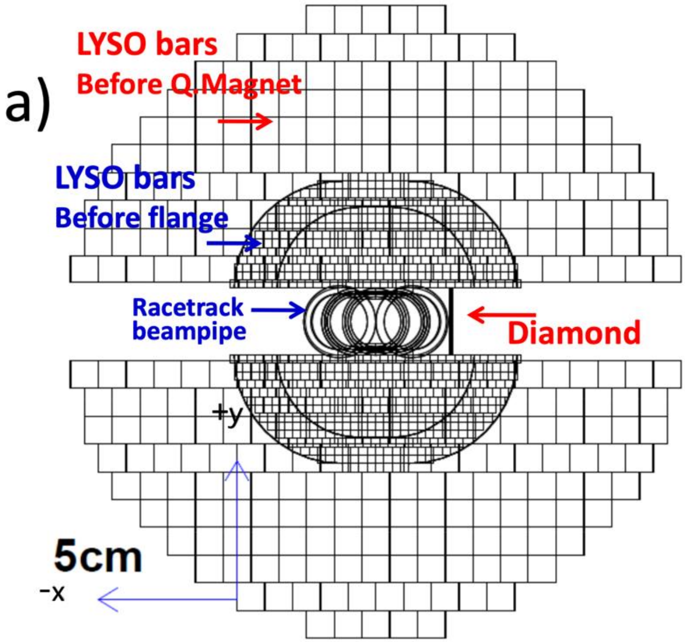


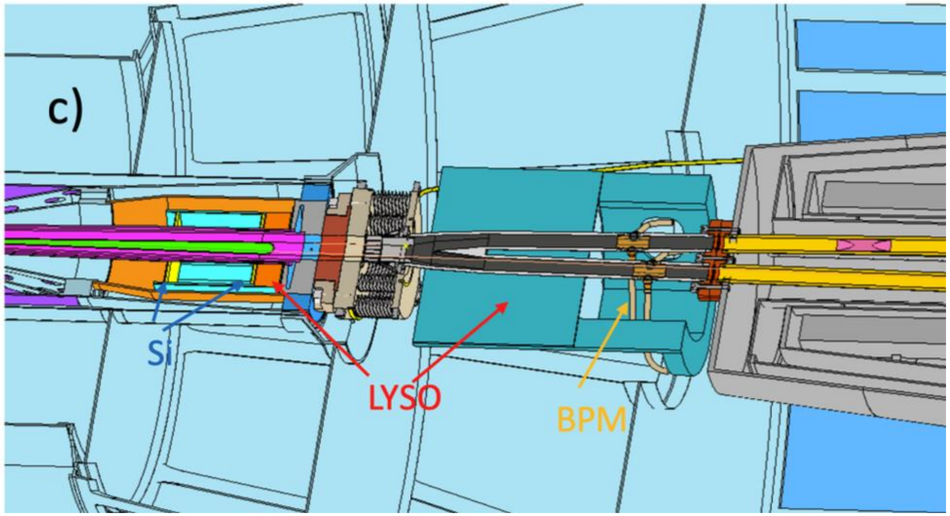


CEPC LumiCal design

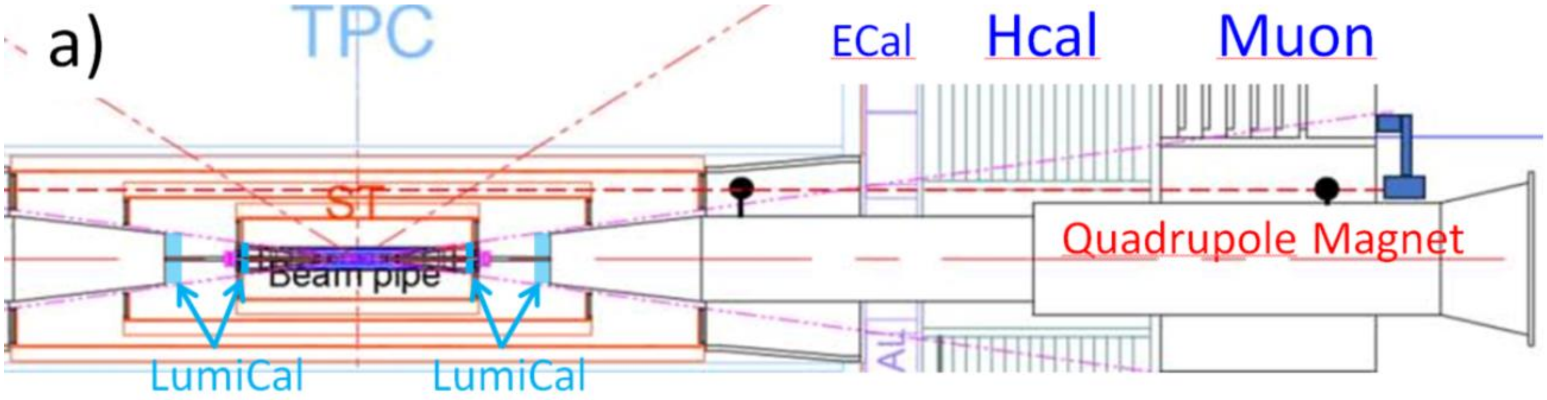


- $z = 900 \sim 1100$ mm: after Bellow
  - Flange+Bellow : ~60 mm, 4.3 X_0
  - LYSO: 150 mm, 13X_0

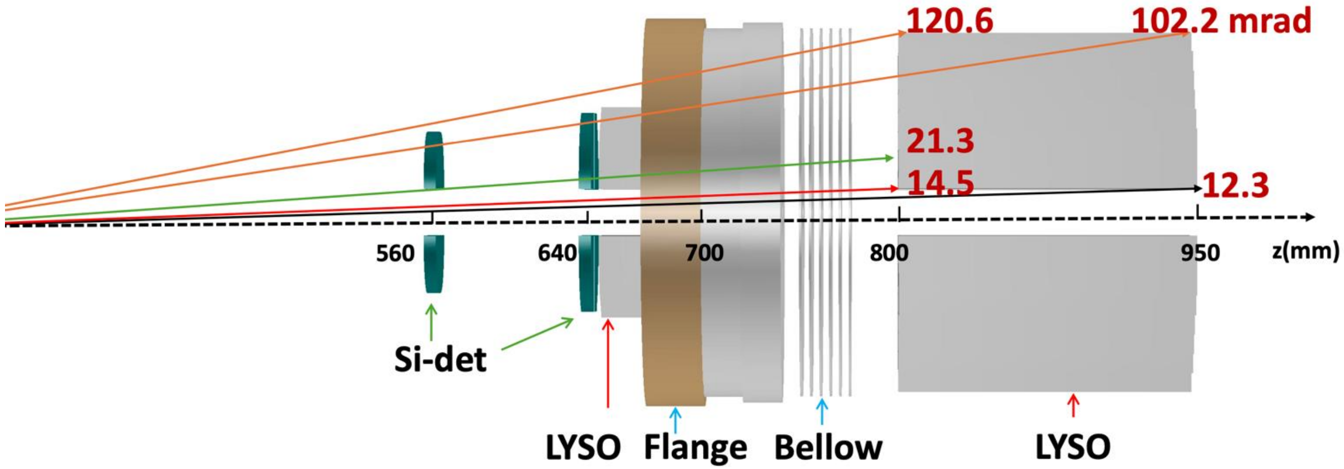




CEPC LumiCal design

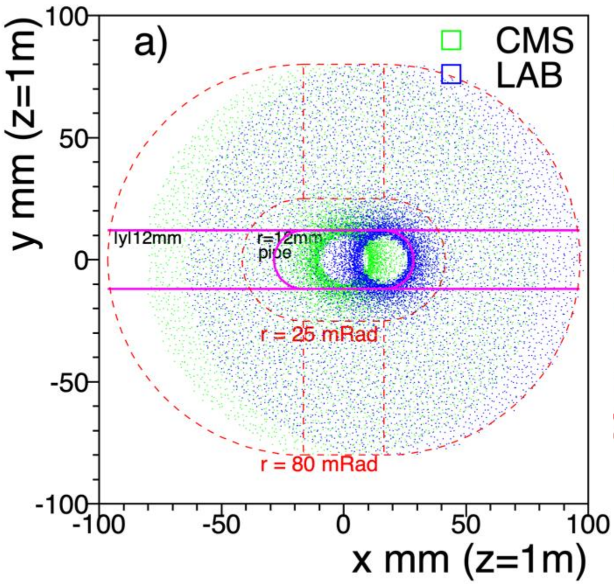


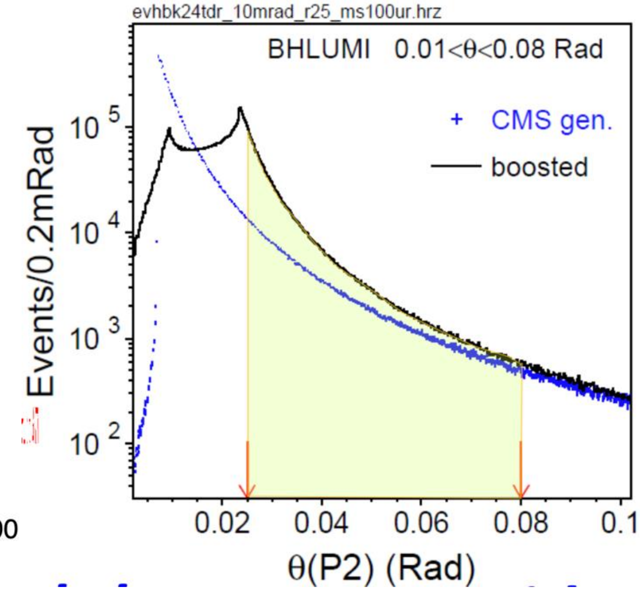
- Geometrical coverage

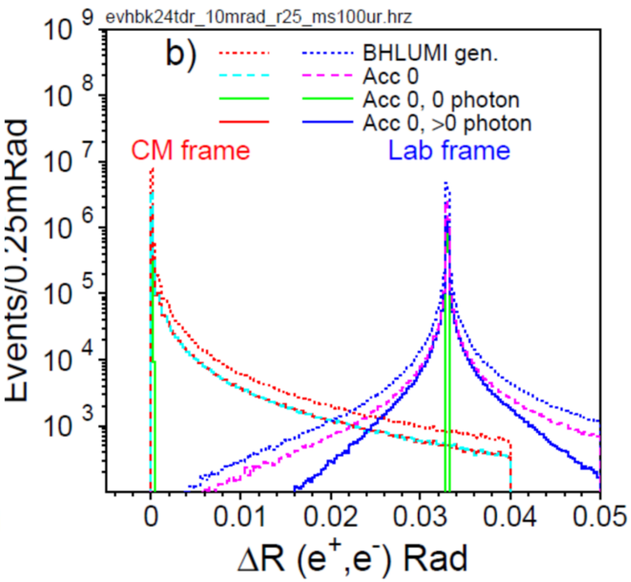


LumiCal acceptance

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





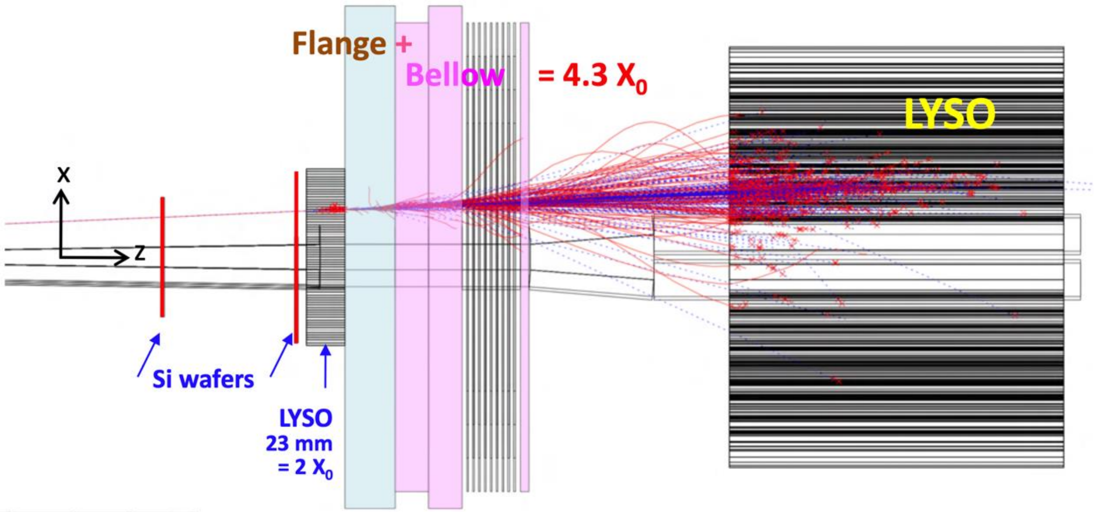


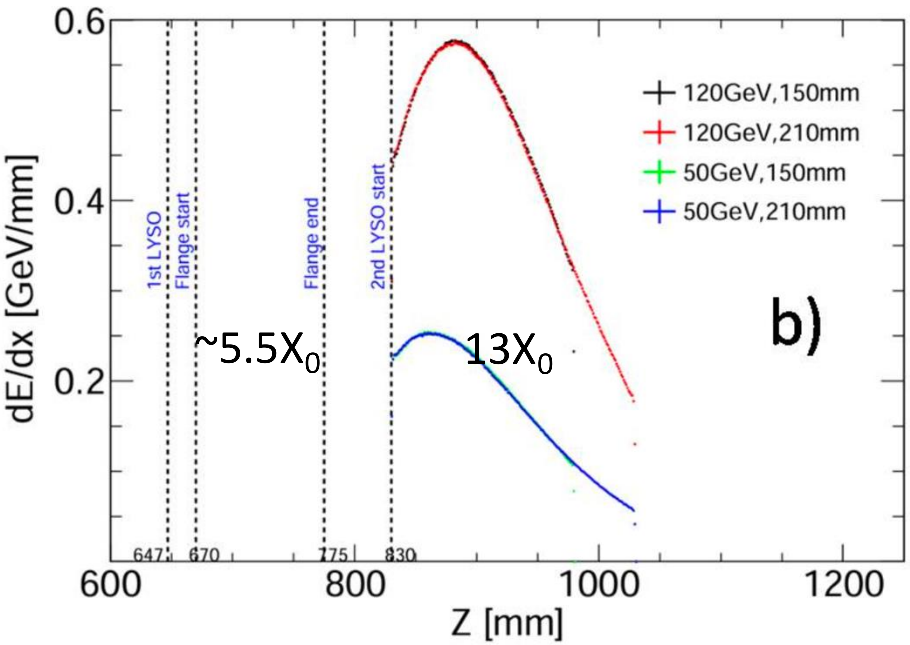
- LumiCal acceptance at |z|=1000mm, with RaceTrack pipe r=10mm

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

Example: 50GeV electron

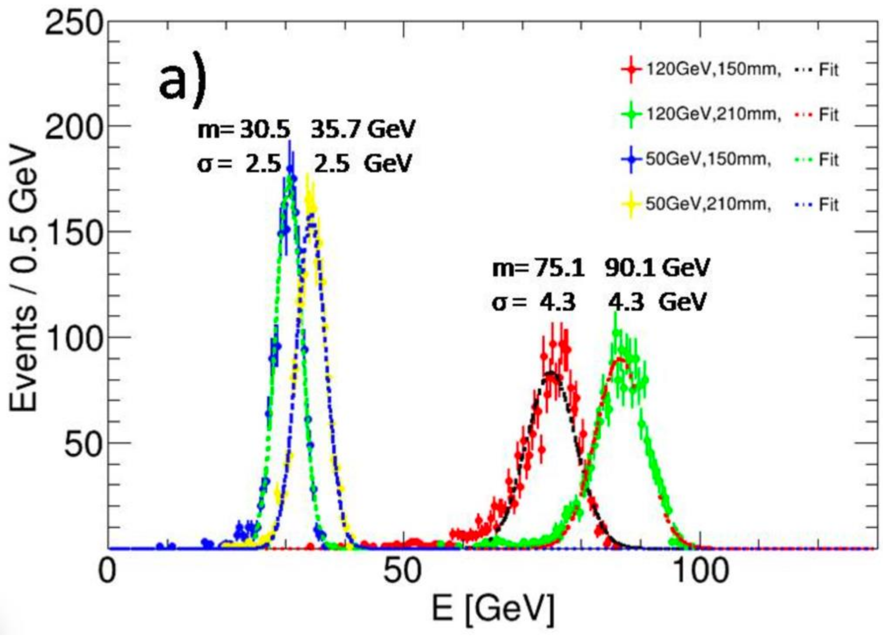


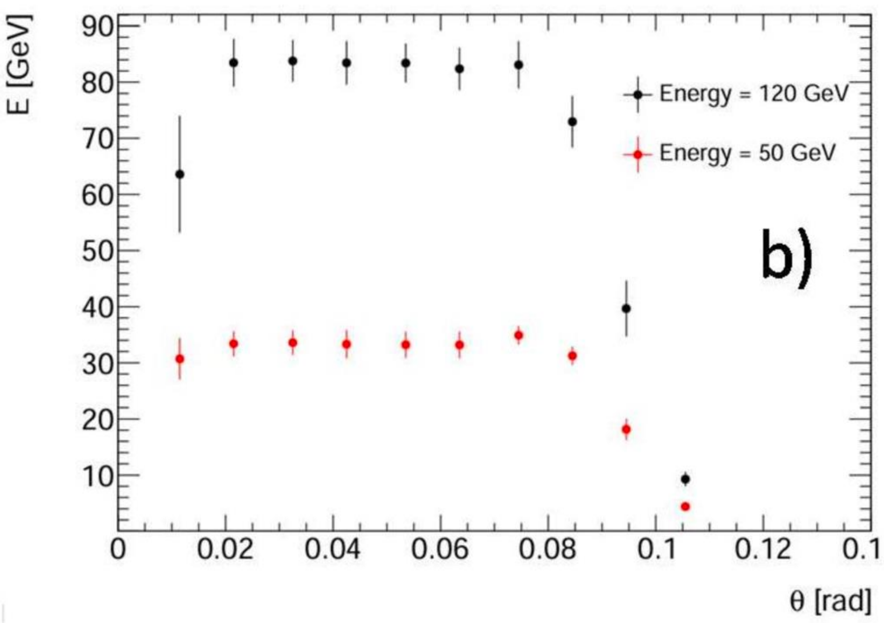


- Energy deposition in LYSO:
  - 50, 120 GeV electrons
- Note: high granularity can be useful

Energy measurement

- LYSO length vs energy resolution
  - LYSO length: 150 mm ~ 13 X_0, 210 mm ~ 18 X_0
  - 50GeV: RMS 2.5 GeV
  - 120GeV: RMS 4.3 GeV



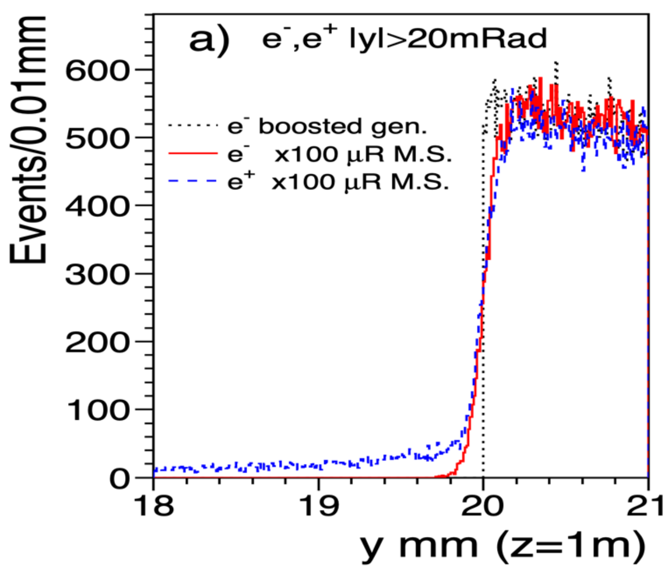


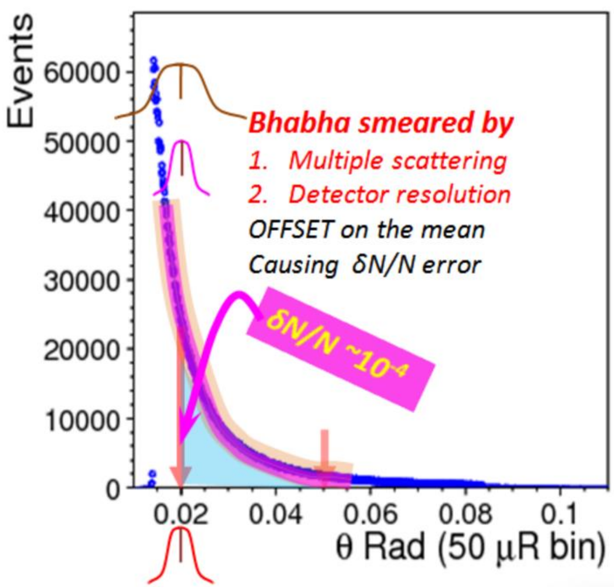
Experimental challenges

- Detector (luminometer) aperture, position and alignment
  - Especially the inner radius

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

- Electron hit measurement: Multiple scattering modeling

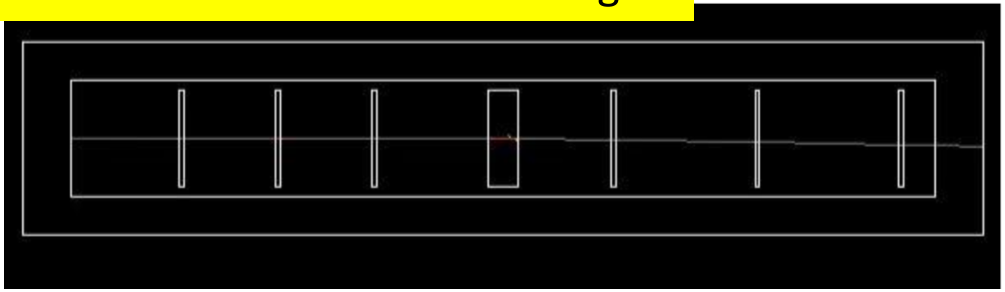


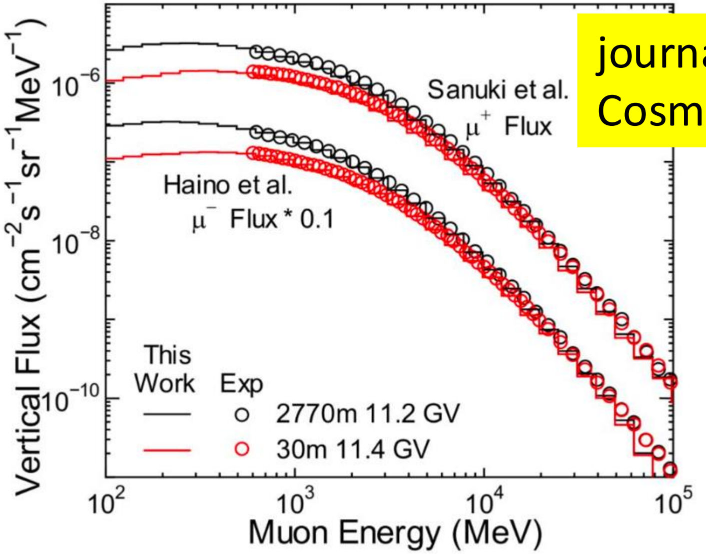


Multiple scattering test at NJU

- 12 Si-strip tracker
  - Cosmic ray Muon, > 1 GeV filtered
  - 6 sets (x,y) 200 μm pitch

GEANT 30 mm Pb muon scattering





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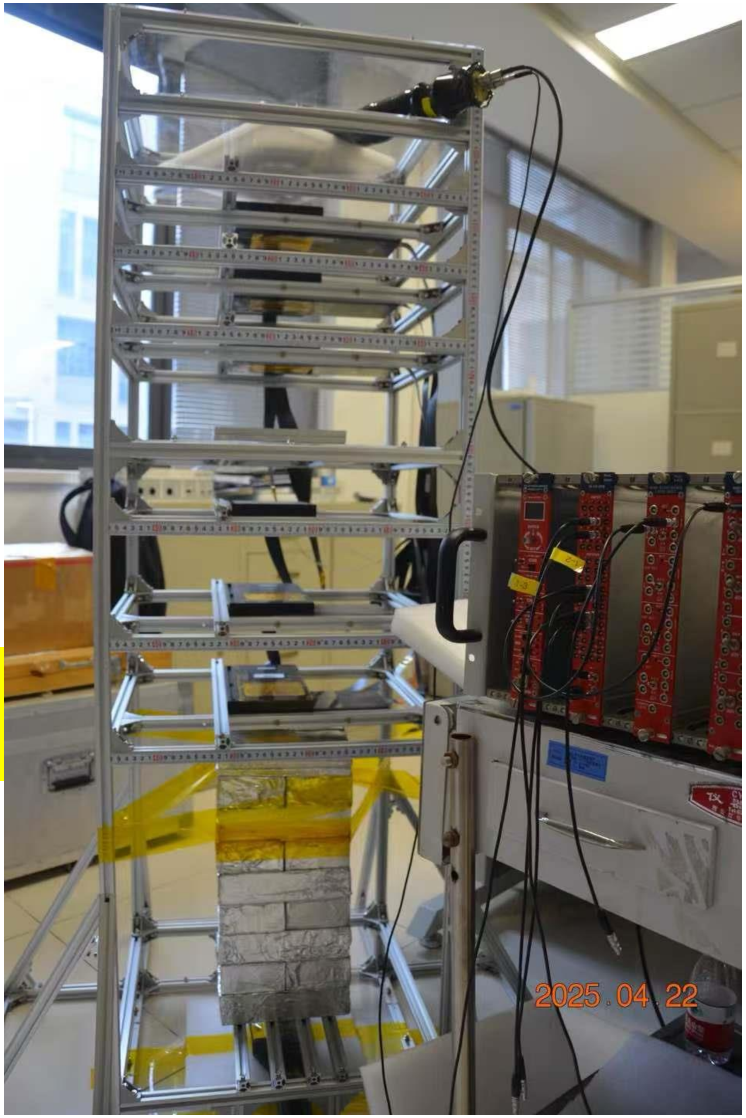
Cosmic Muon energy



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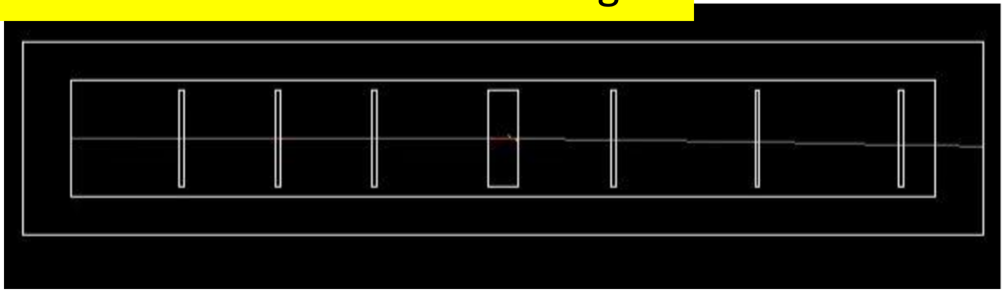
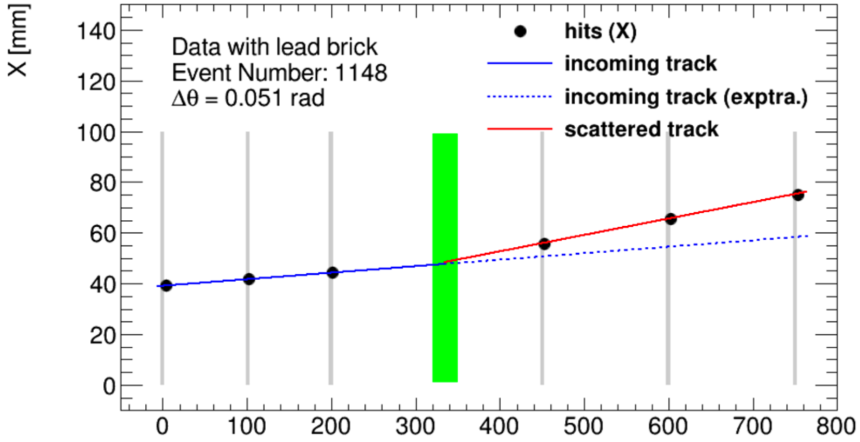
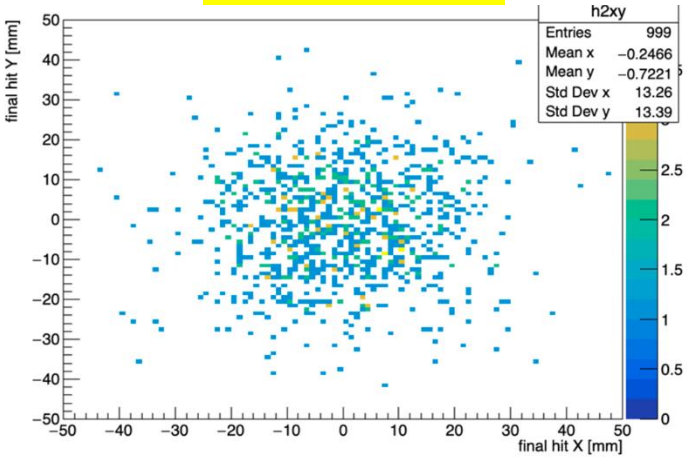


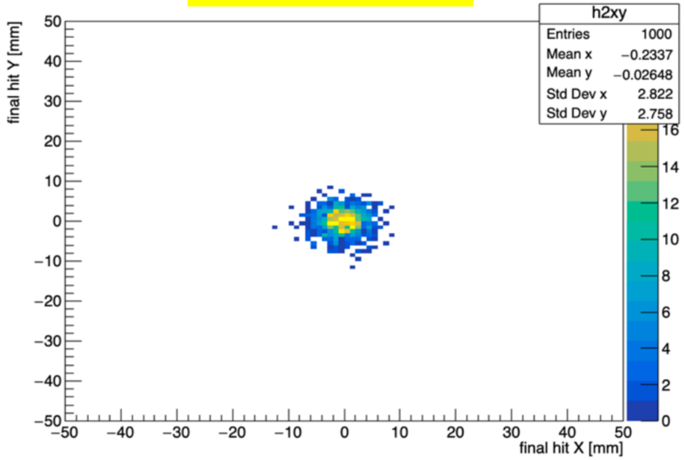


30 mm Pb

1 GeV muon

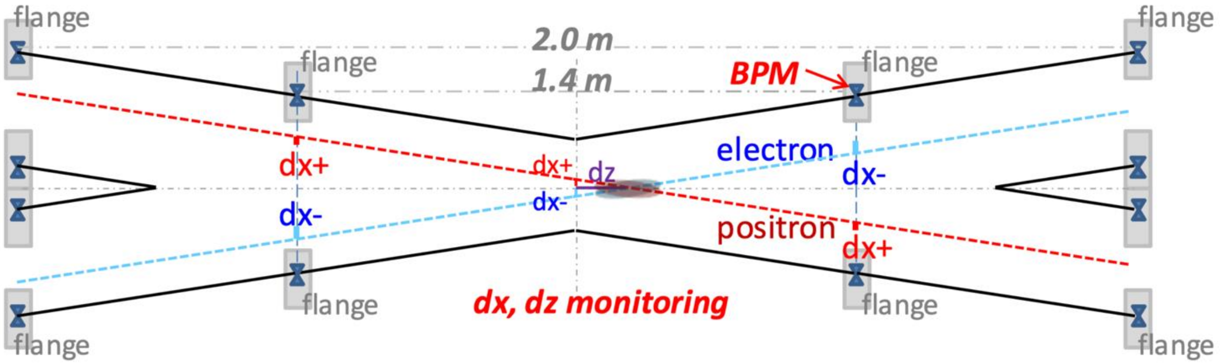


5 GeV muon



Experimental challenges

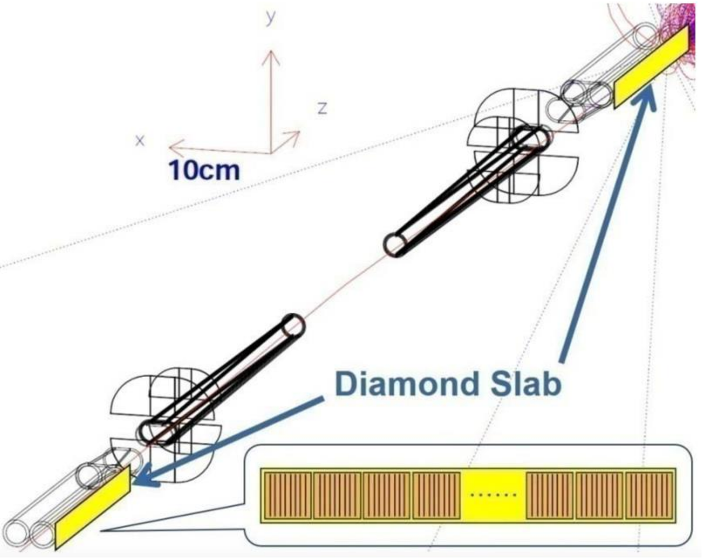
- Real IP position

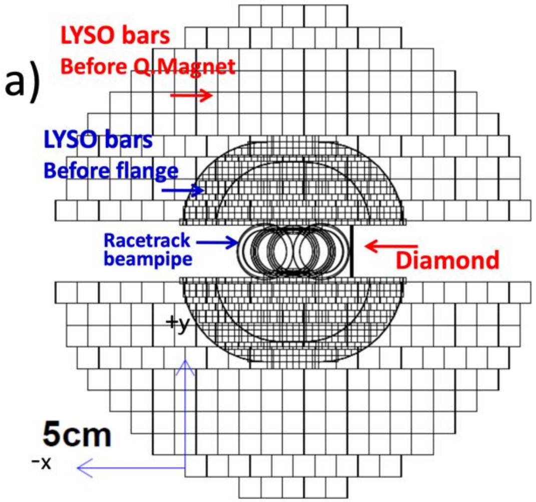


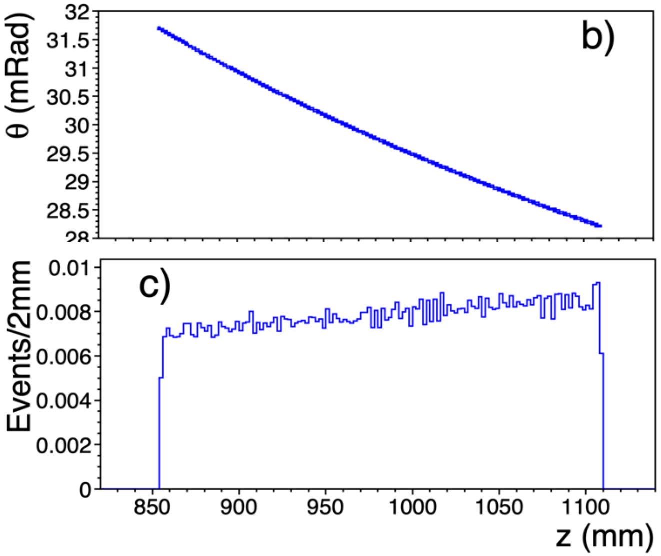
- Beam induced acceptance change
  - Beam-energy asymmetry,
  - IP displacements,
  - Cross section changed with the beam energy,
  - Focusing of final state particles through beam bunches

Experimental challenges

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

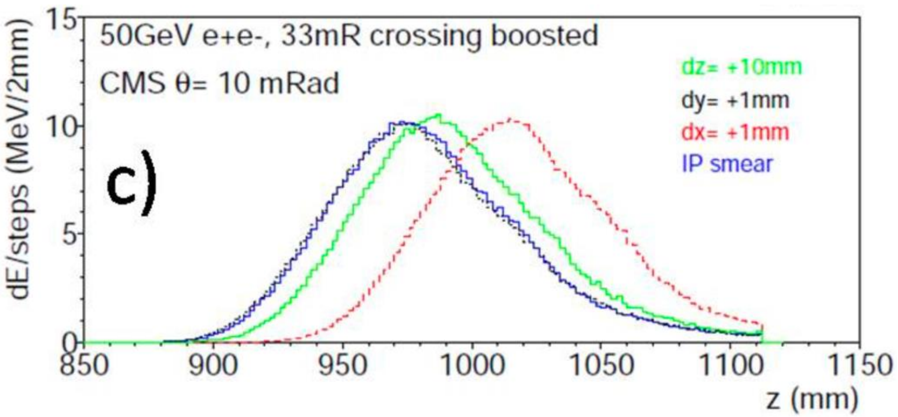




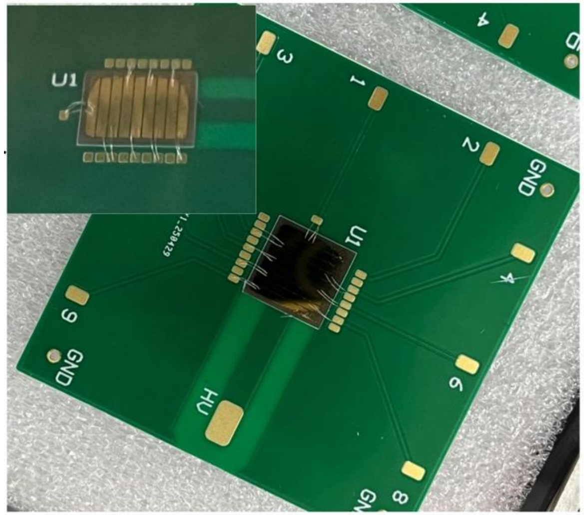


Monitoring IP offset

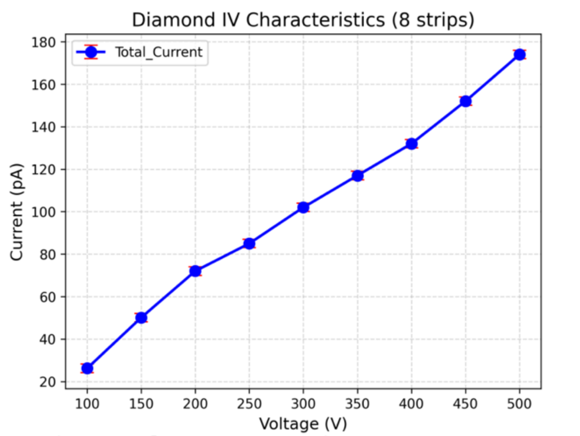
- Differing event rates on +z, -z sides for IP offset



- Diamond detector R&D at NJU
  - Preliminary tests with source meter: I-V, alpha radioactive source



2. Diamond sensor 9 strips 10 mm × 10 mm



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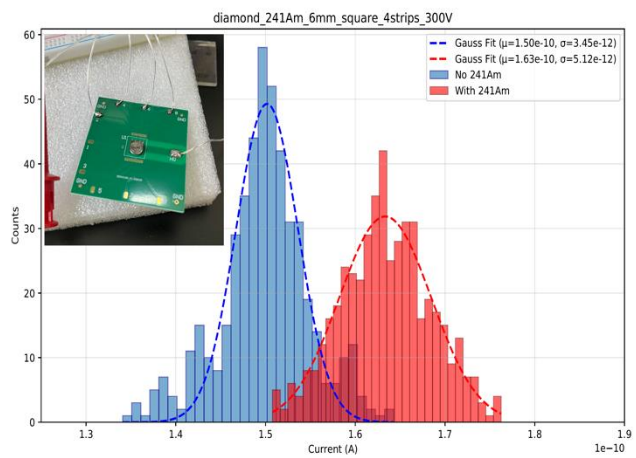
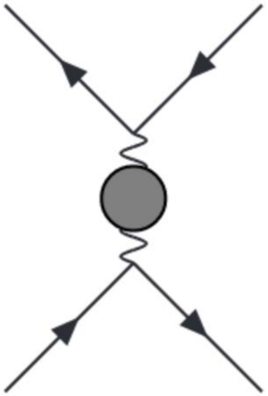
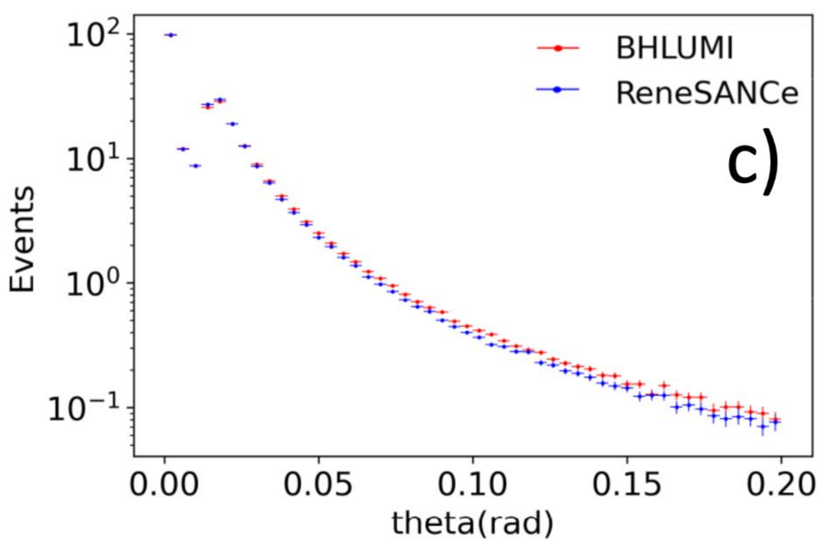
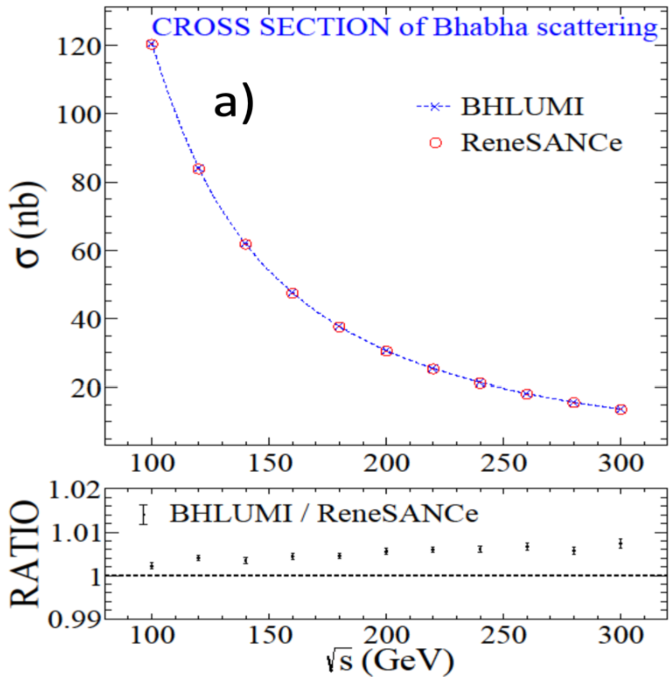


Theoretical challenges



- 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]

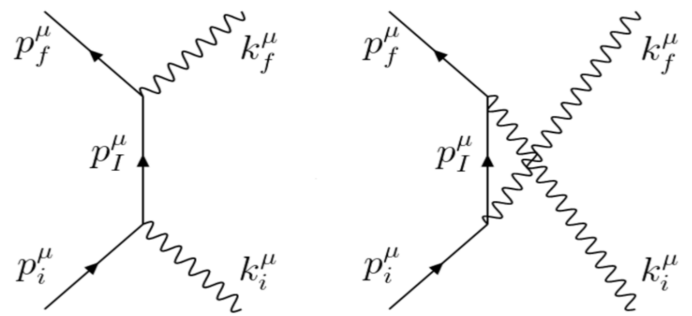




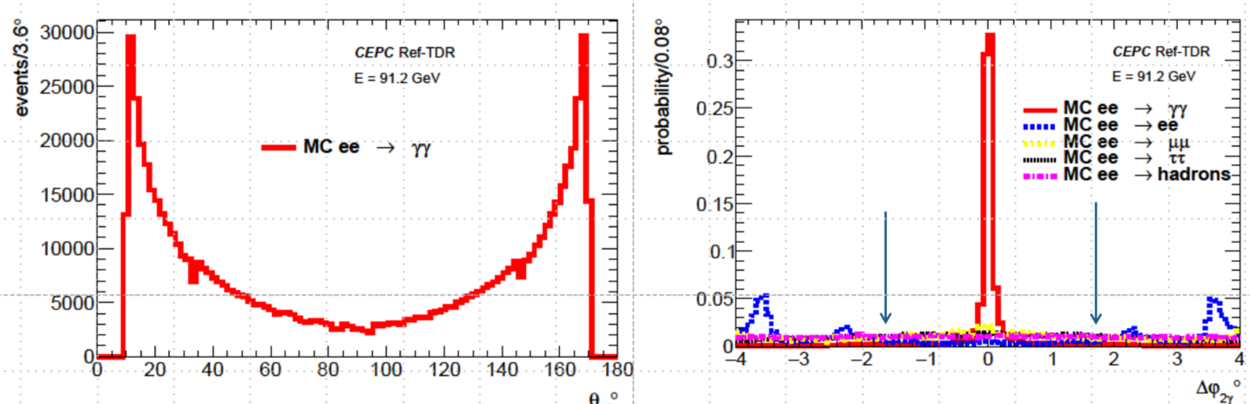
Alternative process: di-photon ($e^+e^-\to\gamma\gamma$)

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

- 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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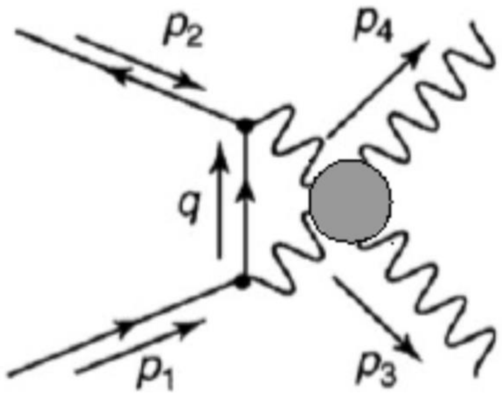
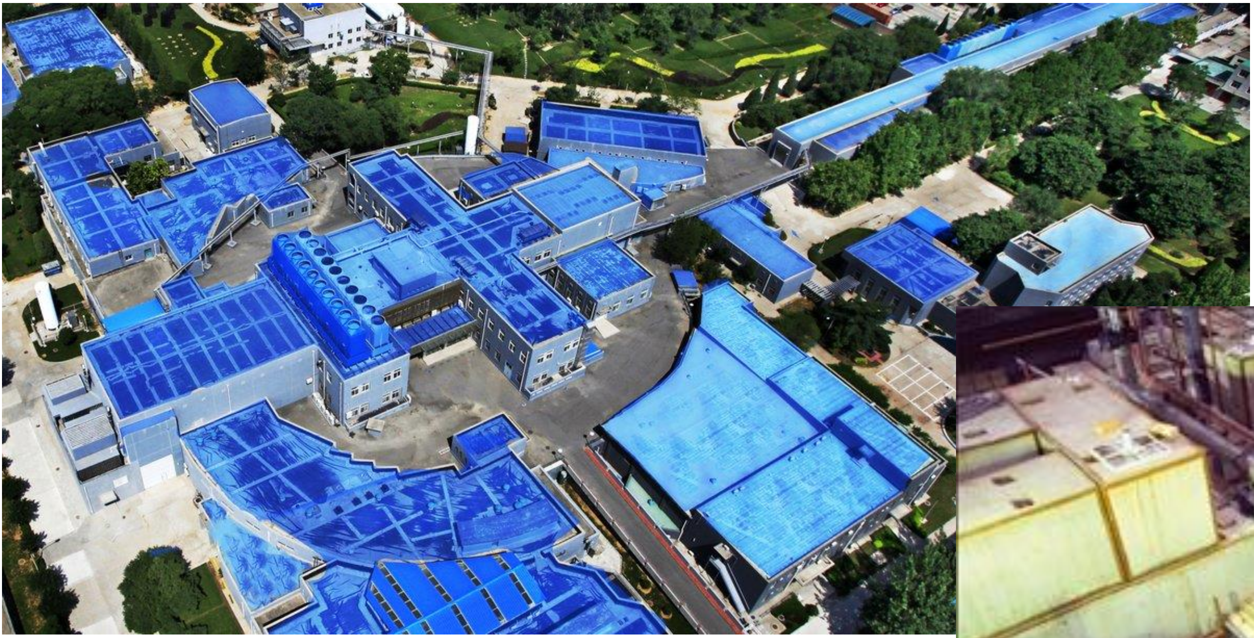
Di-photon: challenges

- 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



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



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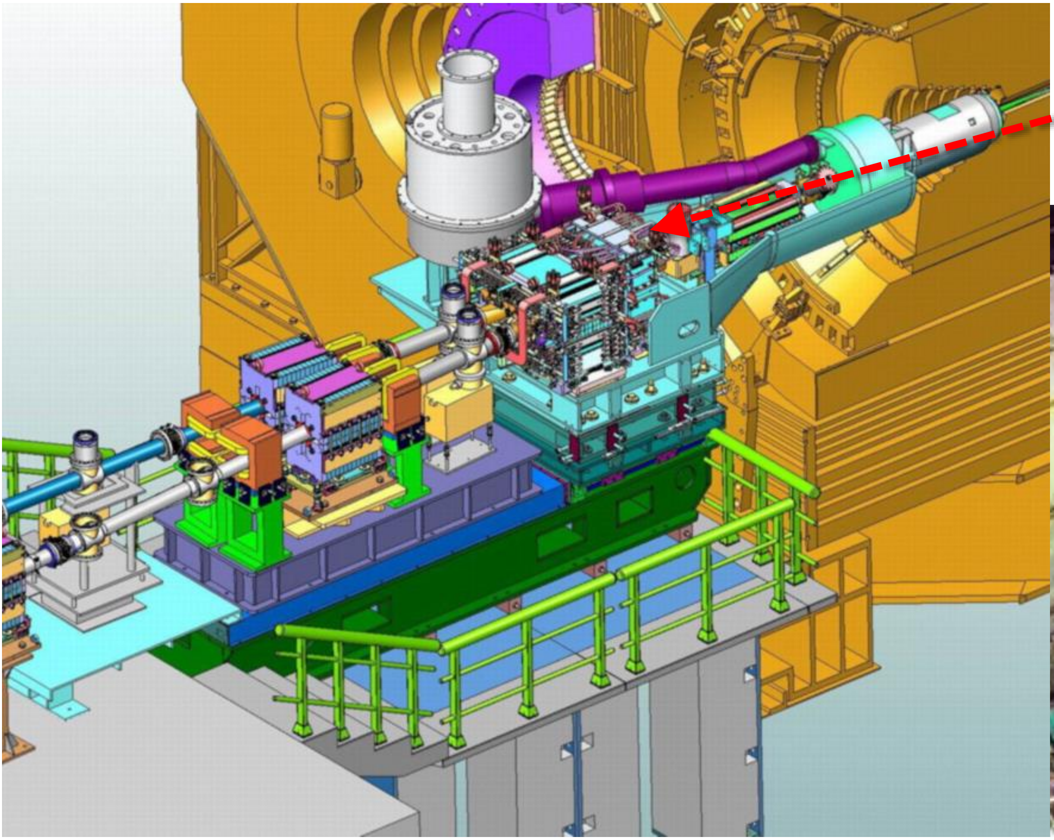
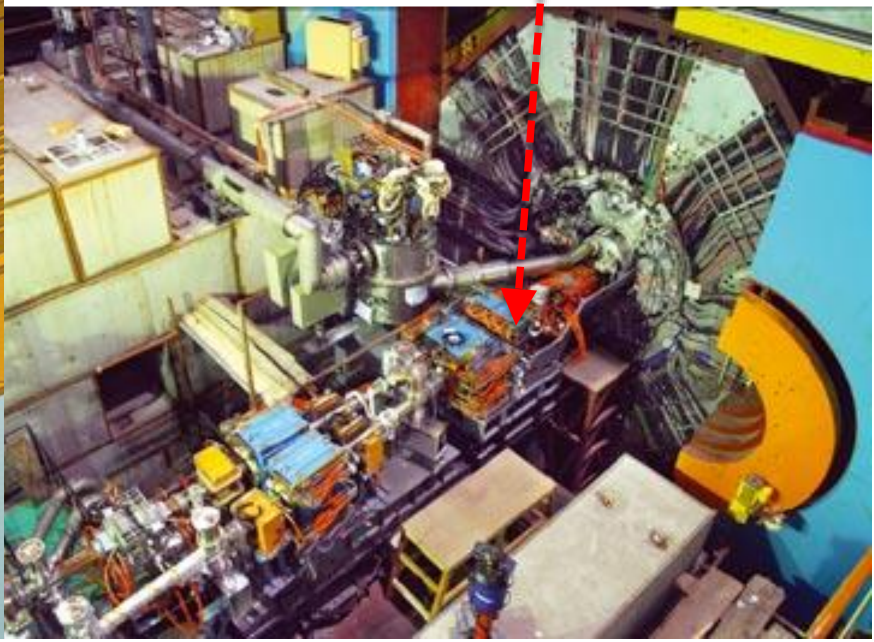
  - e+e- collider, COM energy: ~2-5 GeV, Luminosity: ~10^{33}cm^{-2}/s
  - BESIII detector: Multi-purpose detector covering 4 solid angle
  - Zero-Degree-Calorimeter(ZDC): fast luminosity and ISR photon tagging



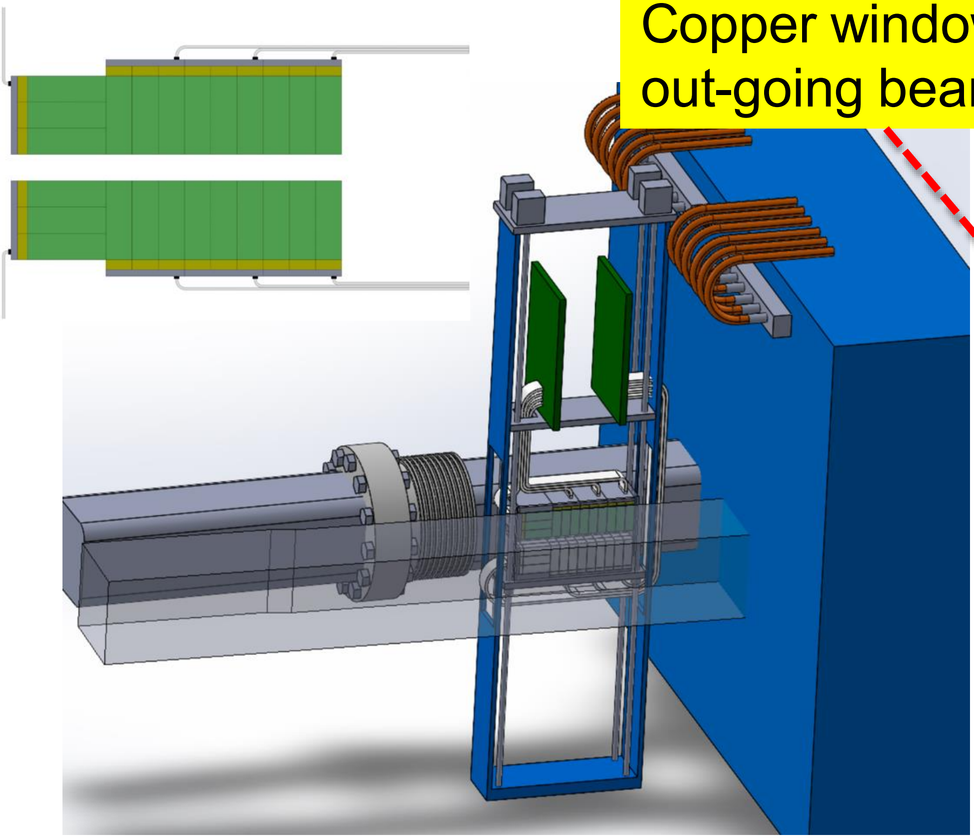
- $3.3\text{m} < z < 3.5$ m,
  $\theta=0$ in CMS frame

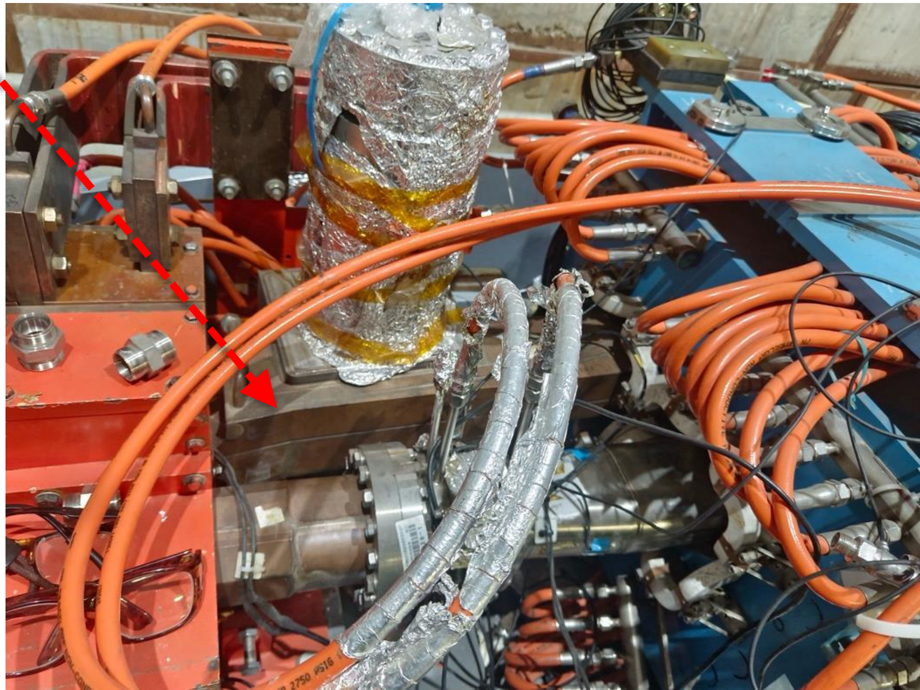


Future test at BESIII experiment

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

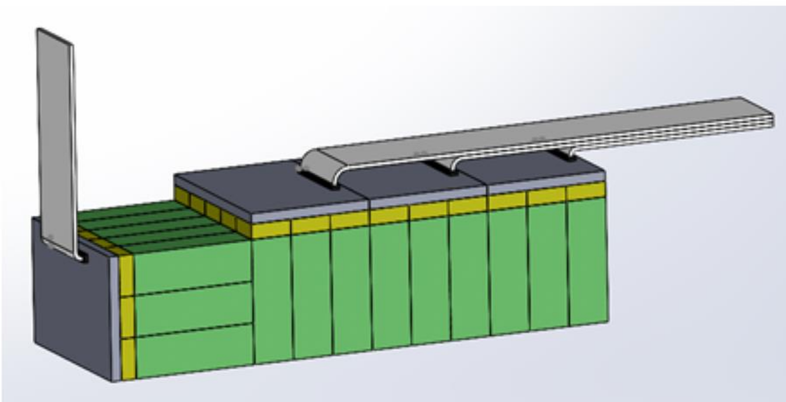
Copper window of out-going beampipe

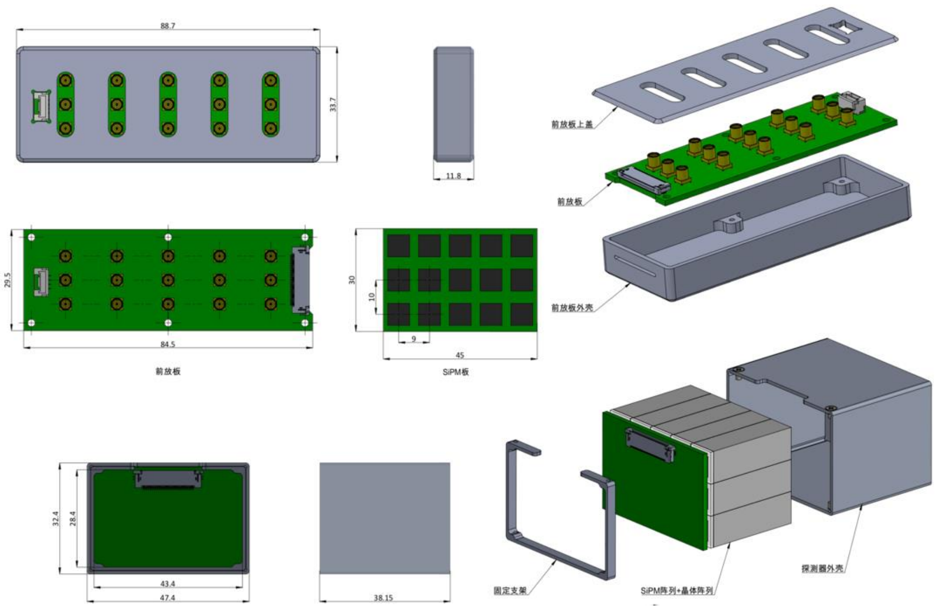


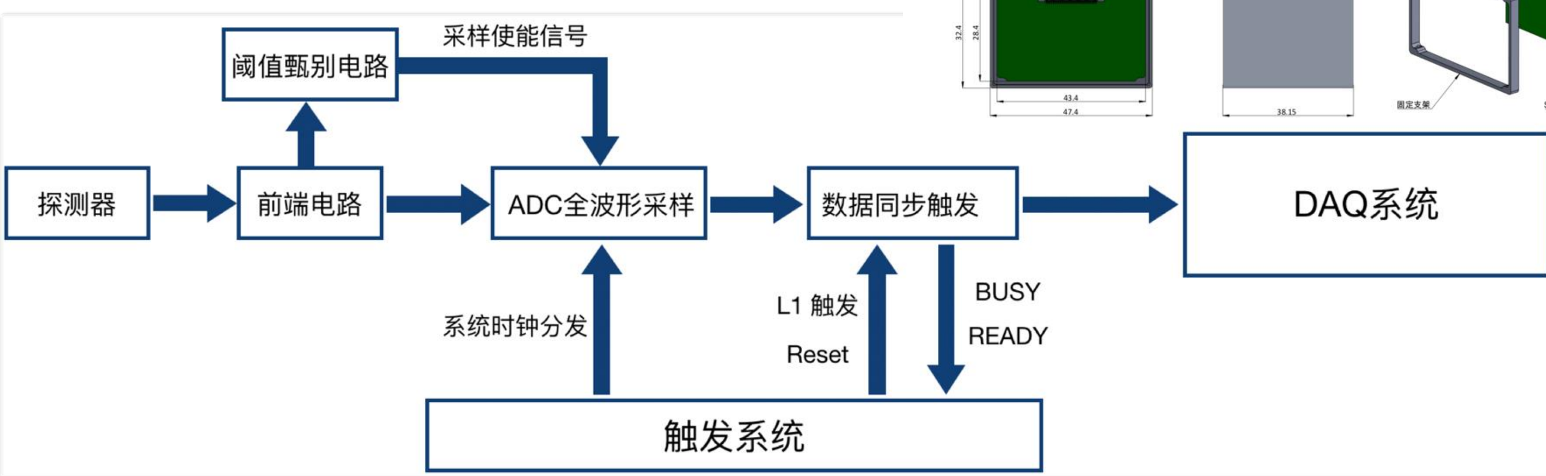


ZDC: preliminary design

- LYSO+SiPM array and modular design
  - Both timing and energy measurement, join in the BESIII DAQ







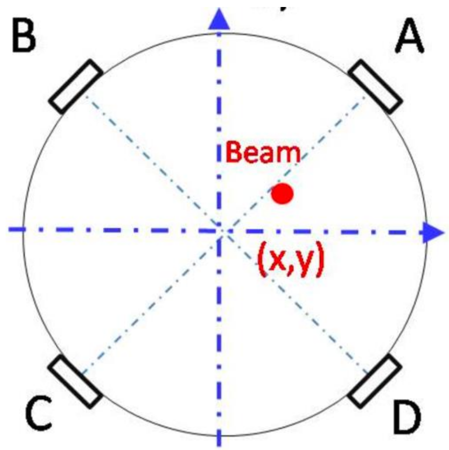
Summary

- CEPC LumiCal system preliminary design presented
  - Targeted for the small angle Bhabha scattering events, the stat of the art generators investigated
  - Performance, e.g. acceptance, efficiency, etc. studied with GEANT4
  - Very preliminary feasibility study on diphoton process
- Relevant detector R&D extensively
  - LYSO+SiPM and Diamond detector R&D
  - Dedicated experiment to validate the multiple scattering effect
  - Full functional detector prototype planed and synergized with BESIII-ZDC
- Just the beginning of journey to O(10^{-4})
  - Define the survey procedure to reach 1 μm, with accelerator experts
  - More solid background study and mitigation needed
  - Theoretical understanding of the relevant processes

The end

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



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

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

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