



Luminosity measurement and monitoring at CEPC

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On behalf of the CEPC LumiCal team

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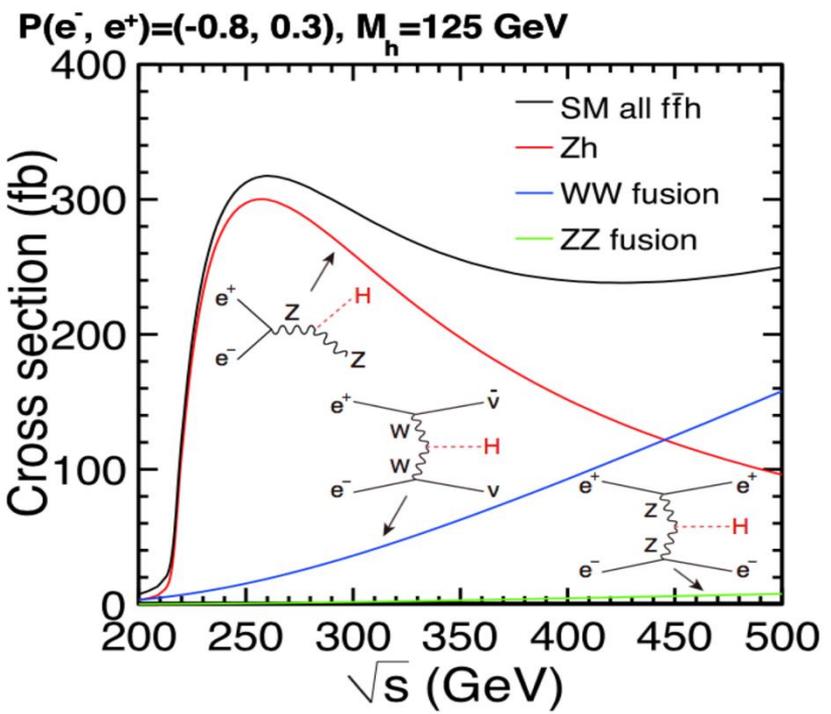
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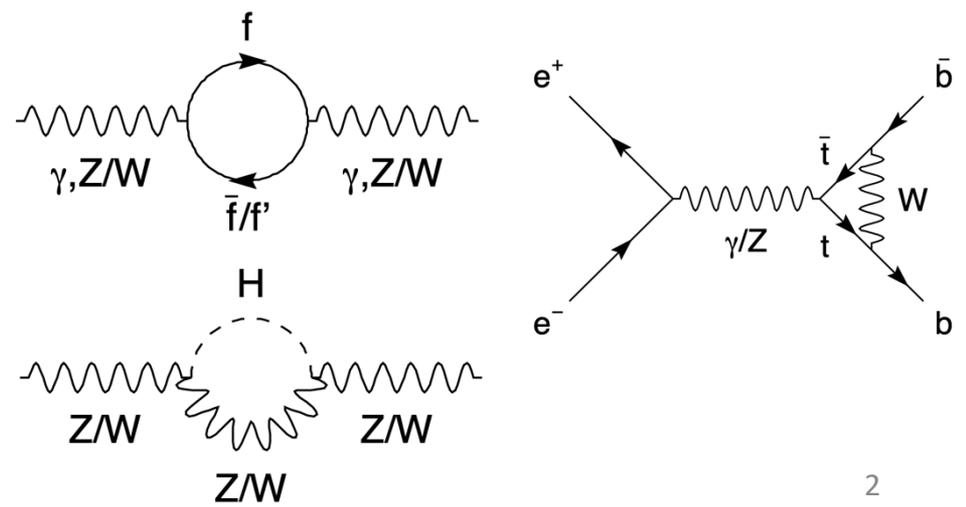
Motivation for Luminosity precision at CEPC

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



Operation mode	\sqrt{s} (GeV)	\mathcal{L} ($10^{34} \text{ cm}^{-2} \text{ s}^{-1}$)	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

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- Roadmap
 - First version to meet the requirement 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

$$L = \int \mathcal{L} dt = \frac{1}{\epsilon} \frac{N_0}{\sigma_0^{\text{th}}} \quad \frac{\Delta L}{L} = \frac{\Delta N_0}{N_0} \oplus \frac{\Delta \epsilon}{\epsilon} \oplus \frac{\Delta \sigma_0^{\text{th}}}{\sigma_0^{\text{th}}}$$

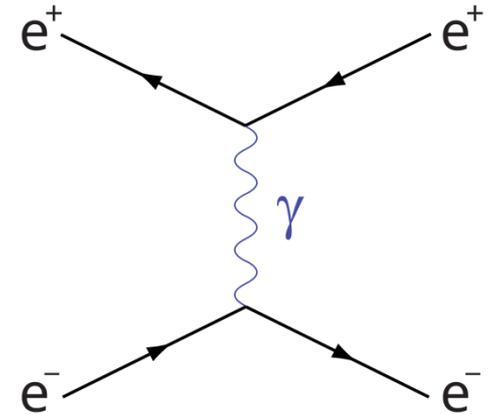
- Requirements for lumi. measurement physics process
 - Large rate, so as not to be statistics limited
 - Clean signature with low background, e.g. electron, photon, muons, etc
 - High-precision theory predictions and MC tools
- Small-angle Bhabha scattering (SABS) $e^+e^- \rightarrow e^+e^-$
 - Dominant 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)

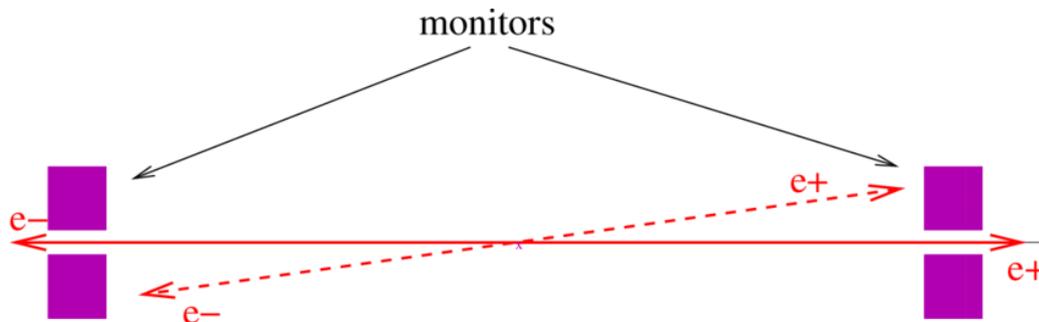
- Cross section of SABS $e^+e^- \rightarrow e^+e^-$

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

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



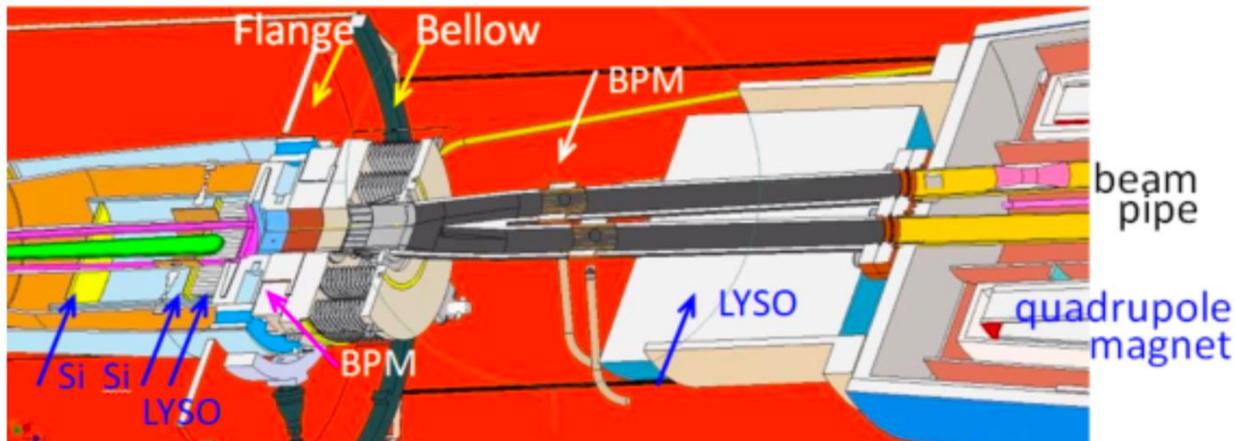
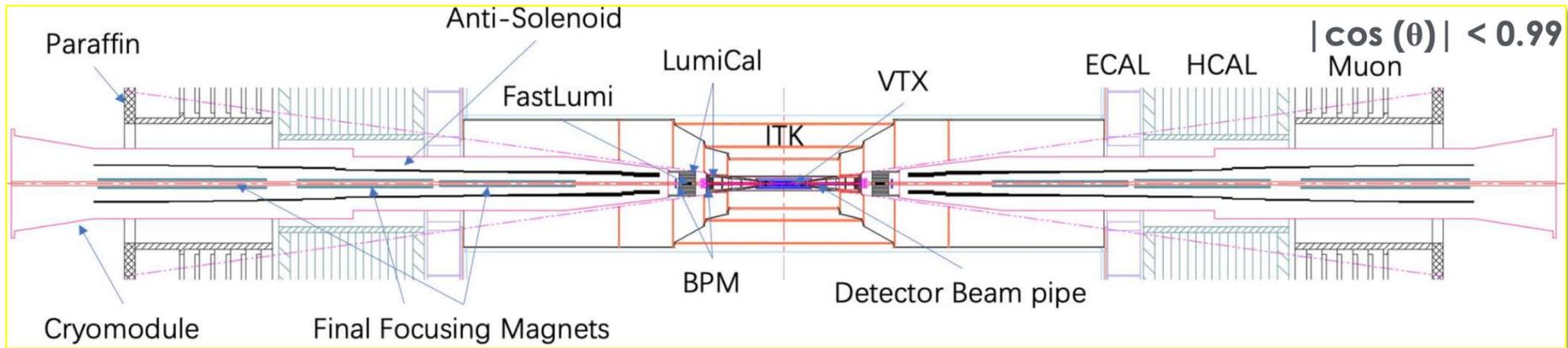
- Peaked in the forward region, at <100 mRad
 - Dedicated detector needed
 - Precision of the low edge positioning is critical



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

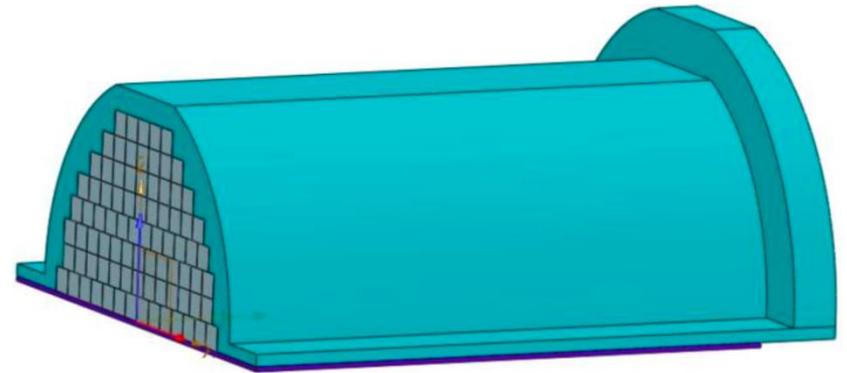
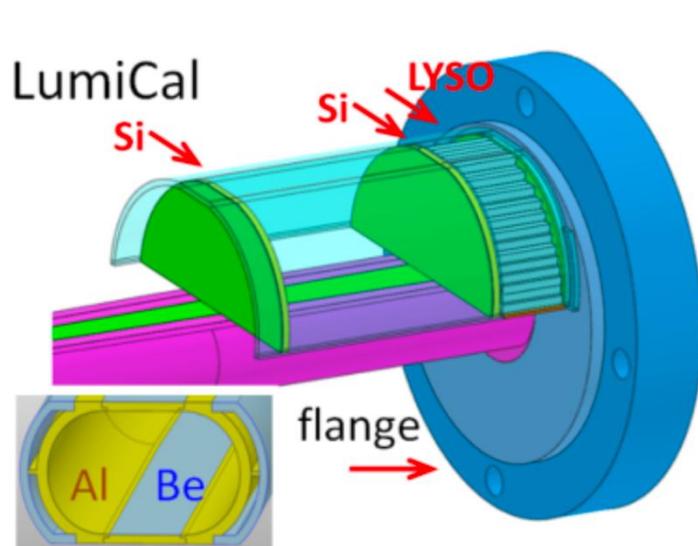
CEPC LumiCal design

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



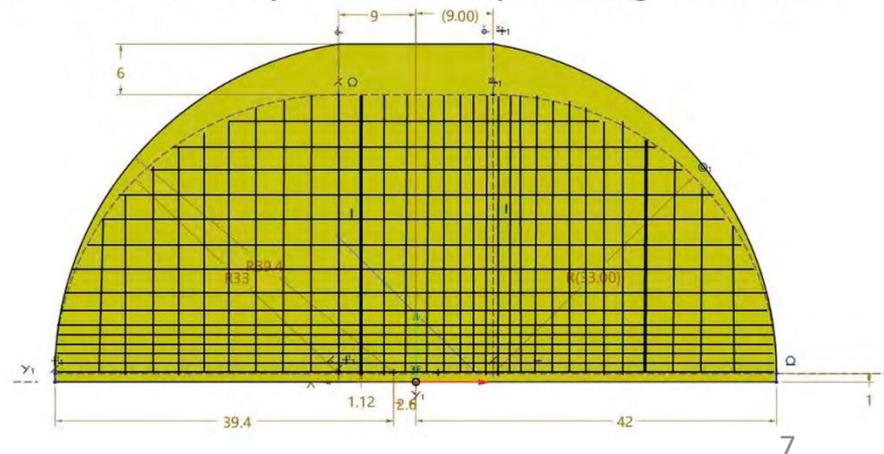
CEPC LumiCal design

- 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)



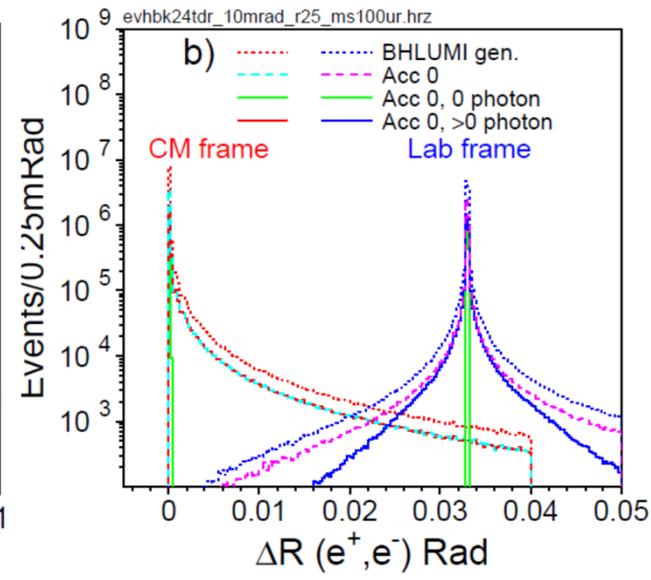
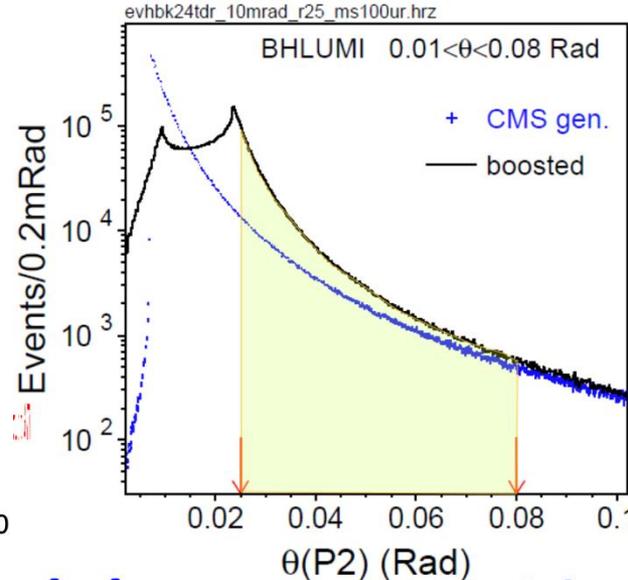
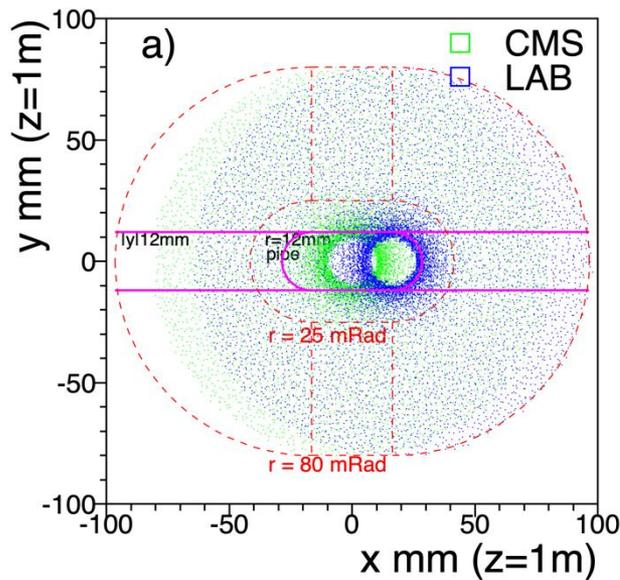
- Two layer AC-LGAD trackers
 - 2D readout of electron hits

Si-wafer surface plan with sample of segmentation



LumiCal acceptance

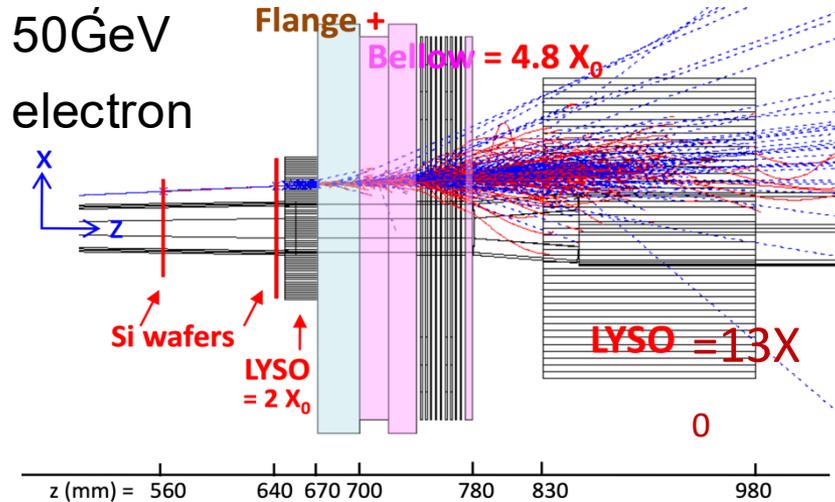
- e^+e^- beam colliding at 33 mRad crossing angle
 - Final state e^+e^- boosted in x direction



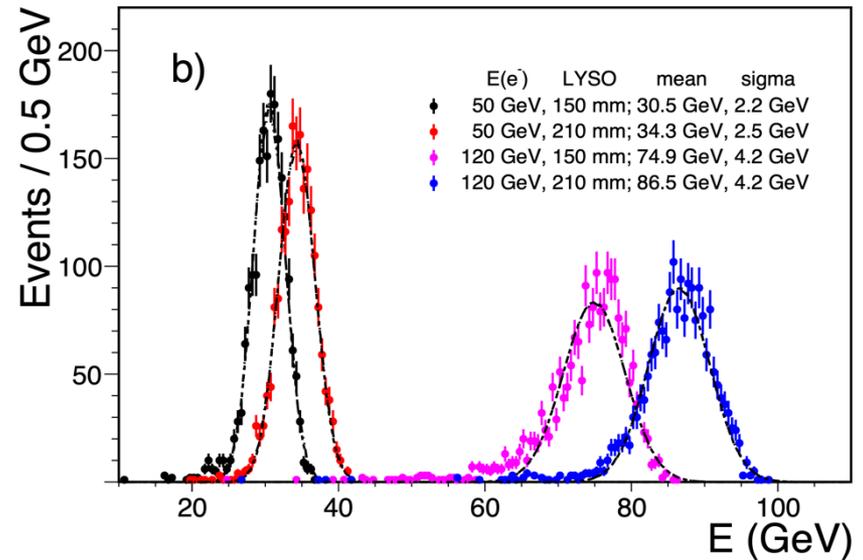
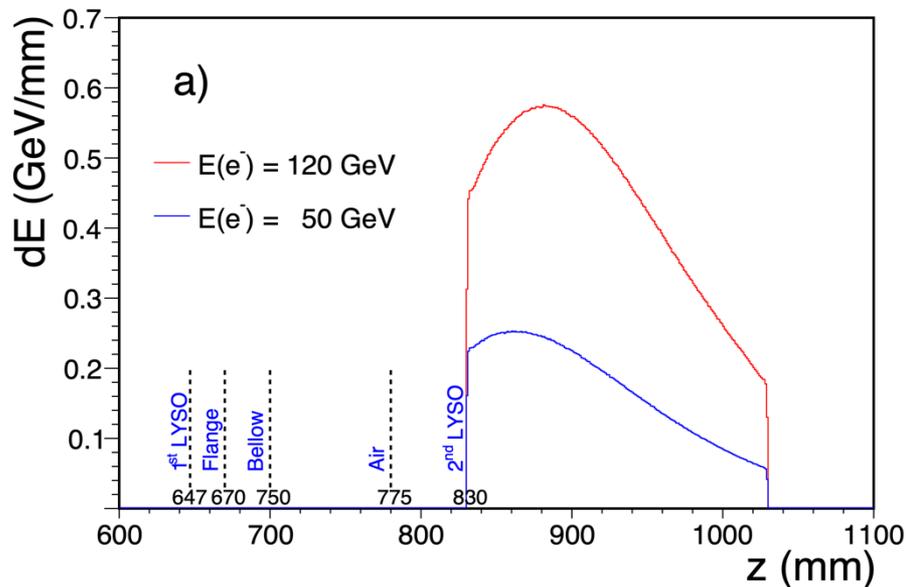
- LumiCal acceptance at $|z|=1000\text{mm}$, with RaceTrack pipe $r=10\text{mm}$

ONE e^+ or e^- detected		e^+, e^- back-to-back detected	
$\theta > 25 \text{ mRad}$	$\theta > 25 \text{ mR} \ \& \ y > 25 \text{ mm}$	$\theta > 25 \text{ mRad}$	$\theta > 25 \text{ mR} \ \& \ y > 25 \text{ mm}$
133.5 nb	81.8 nb	85.4 nb	78.0 nb

Energy measurement

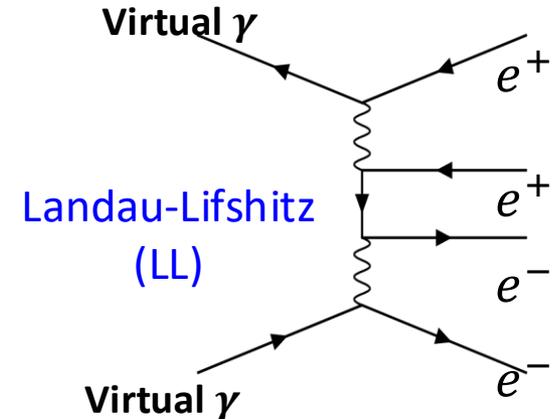
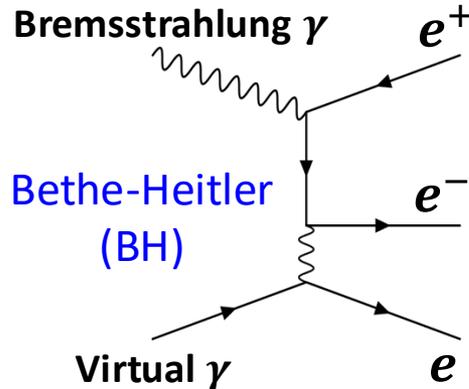
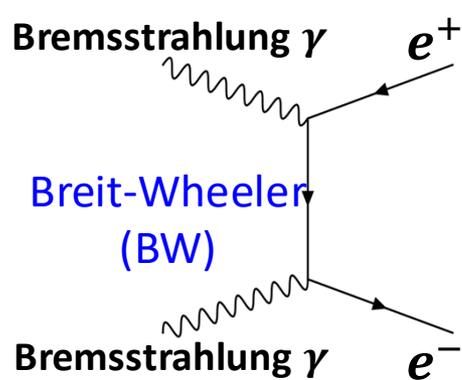


- Length vs energy resolution
 - Roughly 4-5%

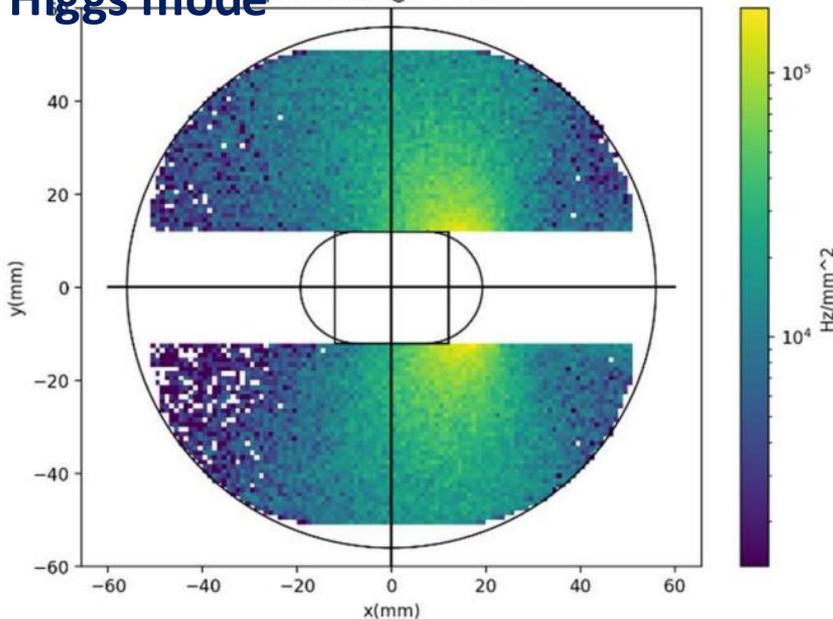


- Energy profile
 - High granularity can be useful

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



Higgs mode pair hit rate@z=640mm

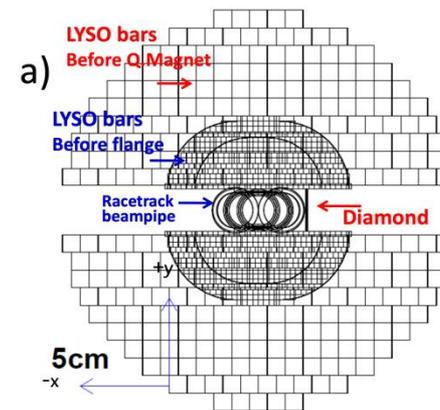
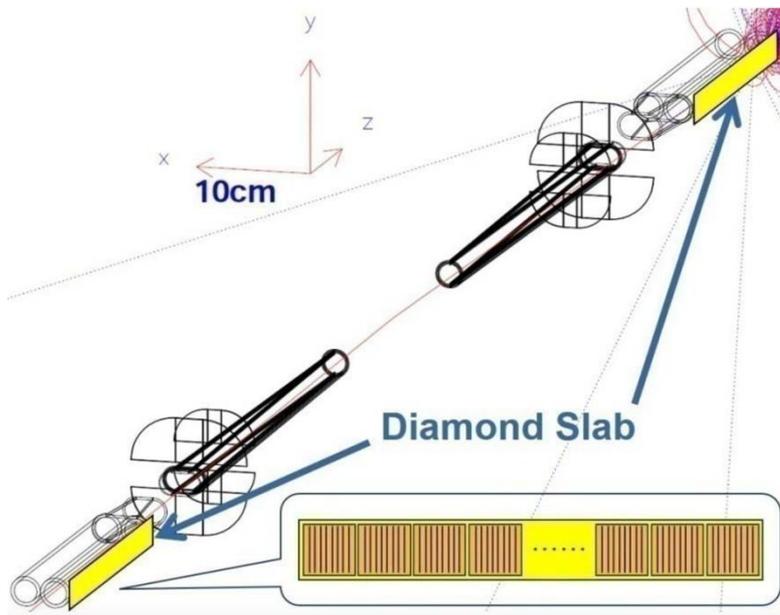


Background rate (preliminary)

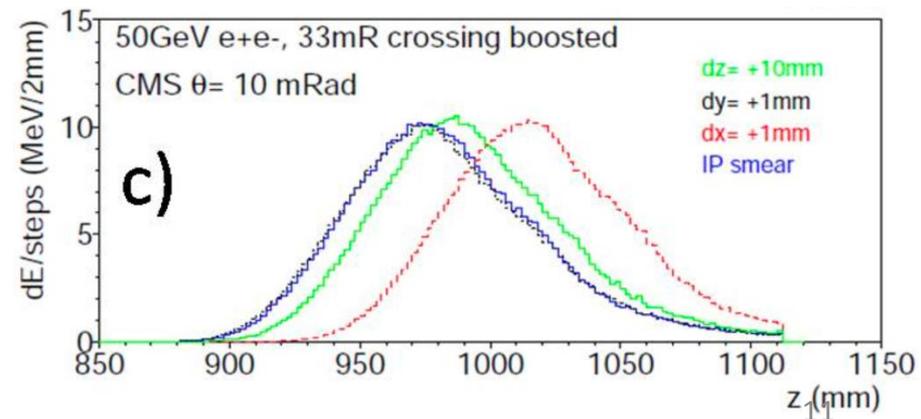
- Higgs and Low Z: $O(<100 \text{ KHz/mm}^2)$
 - Challenging but controllable
- High Z mode: up to $O(1 \text{ MHz /mm}^2)$
 - Further studies and R&D needed

Fast Lumi. monitor

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

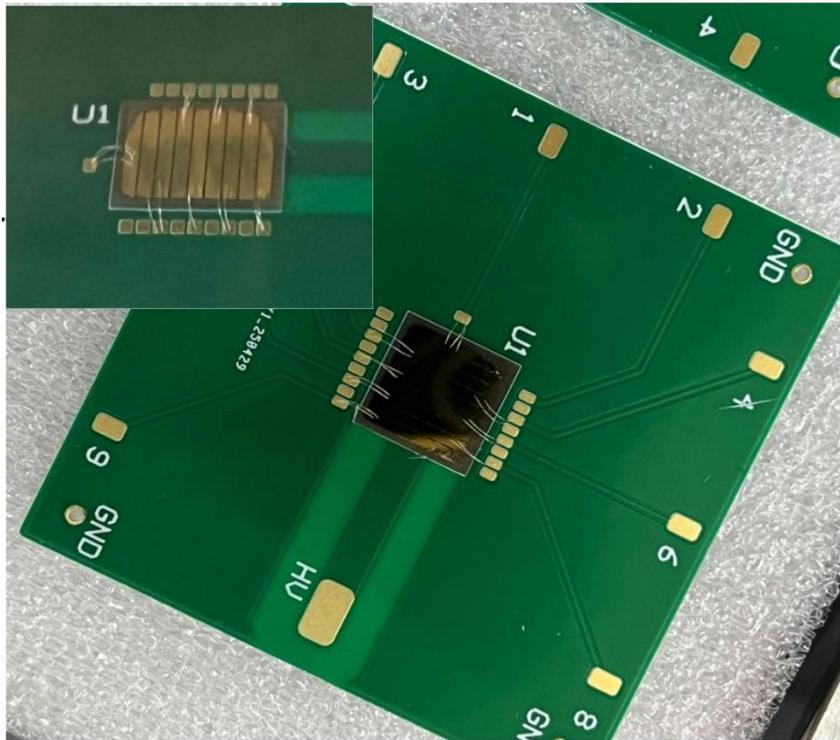


- Differentiate rates on +z v.s. -z to estimate IP offset
 - x,y monitored by BPMs

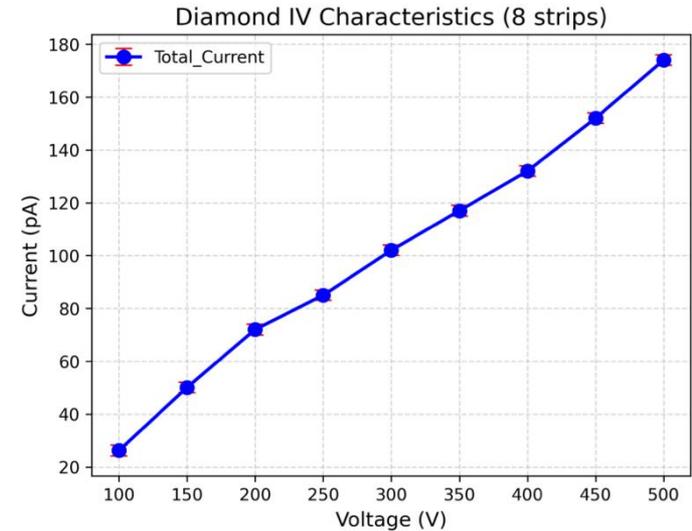


Diamond detector R&D

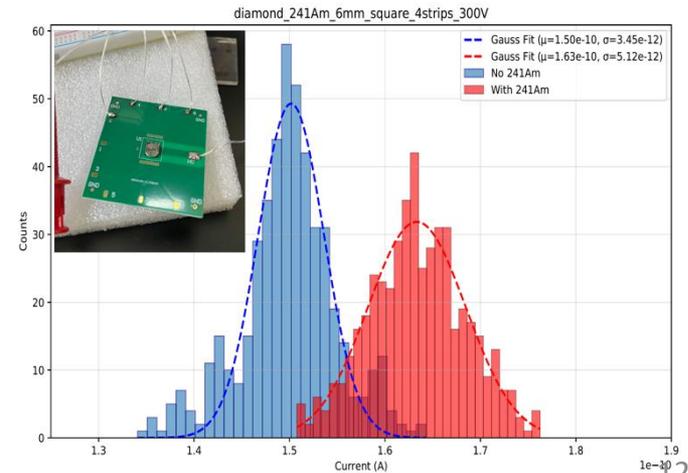
- Strip electrode
 - Full surface process chain



2. Diamond sensor 9 strips 10 mm × 10 mm



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



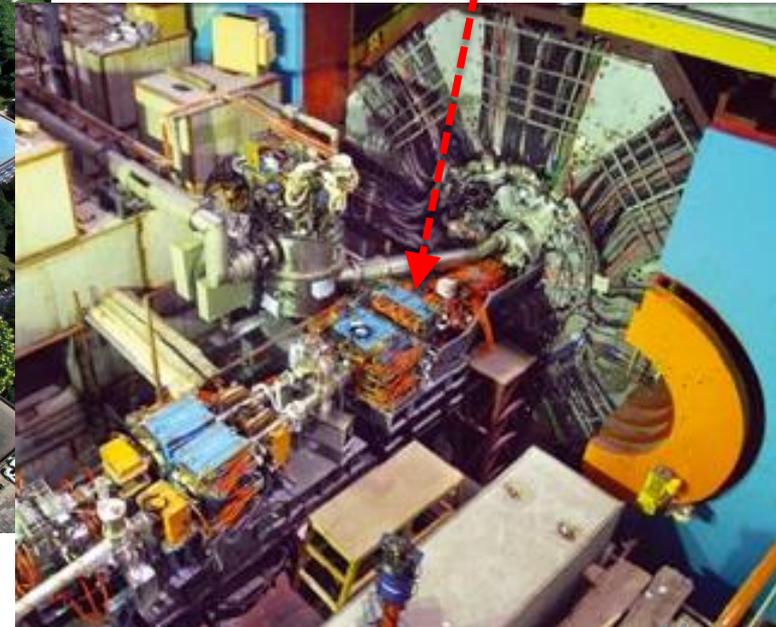
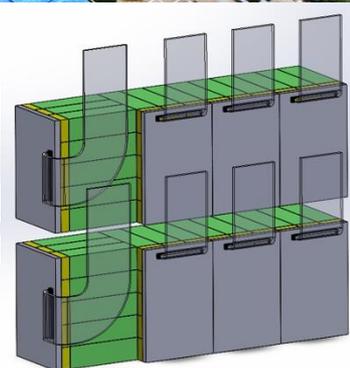
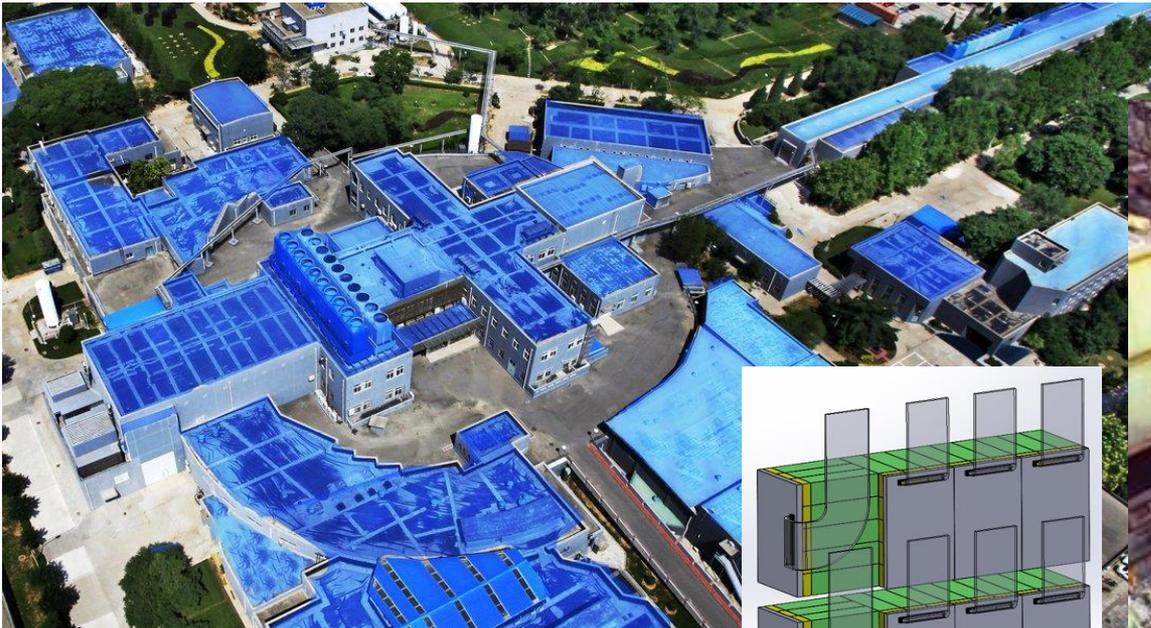
Radiation tolerance

- 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: $\sim 2\text{-}5\text{ GeV}$, Luminosity: $\sim 10^{33}\text{cm}^{-2}/\text{s}$
- Zero-Degree-Calorimeter(ZDC)
 - Fast luminosity and ISR photon tagging
 - LYSO+SiPM array, 240 channels in total

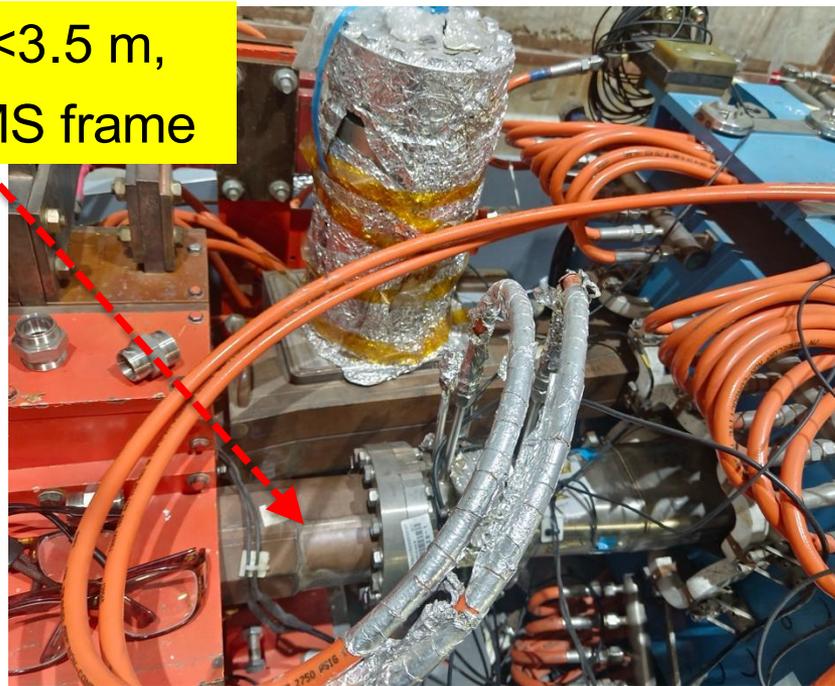
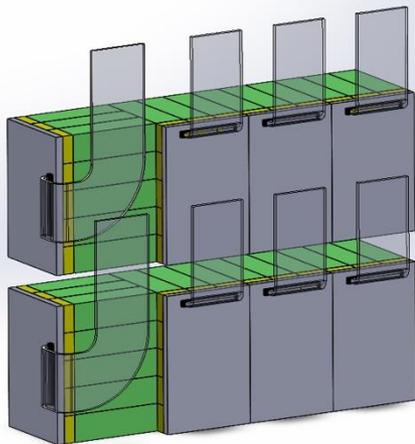
$3.3\text{m} < z < 3.5\text{m}$,
 $\theta = 0$ in CMS frame



BESIII ZDC: LYSO+SiPM proto-type

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

3.3m $< z < 3.5$ m,
 $\theta = 0$ in CMS frame



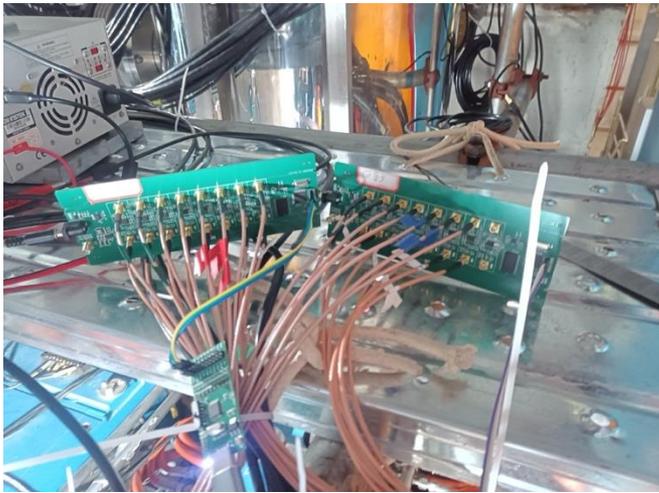
Single detector
module test



BESIII ZDC: LYSO+SiPM proto-type

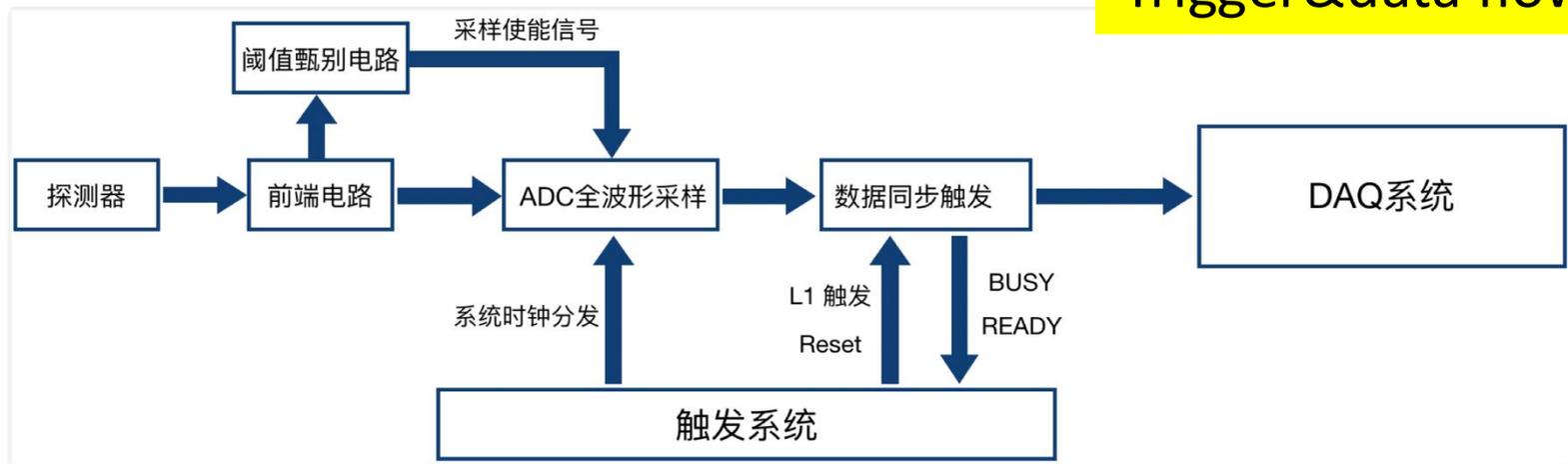


- Pictures of the current test system
 - Pre-amplifier, High voltage fanout, DAQ, etc.
- Long term study and monitor the SiPM performance insitu



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



Summary

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

The end

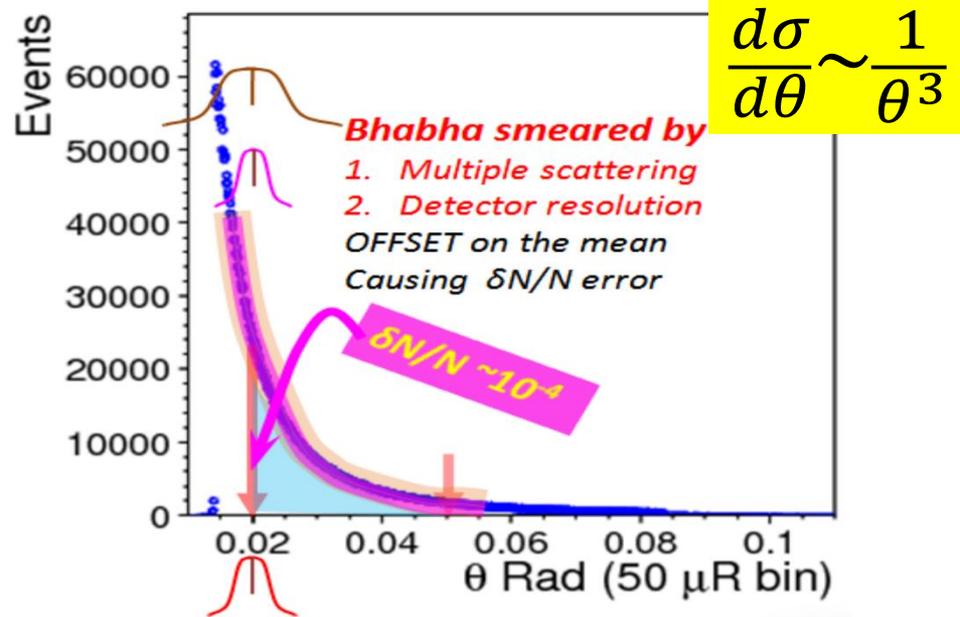
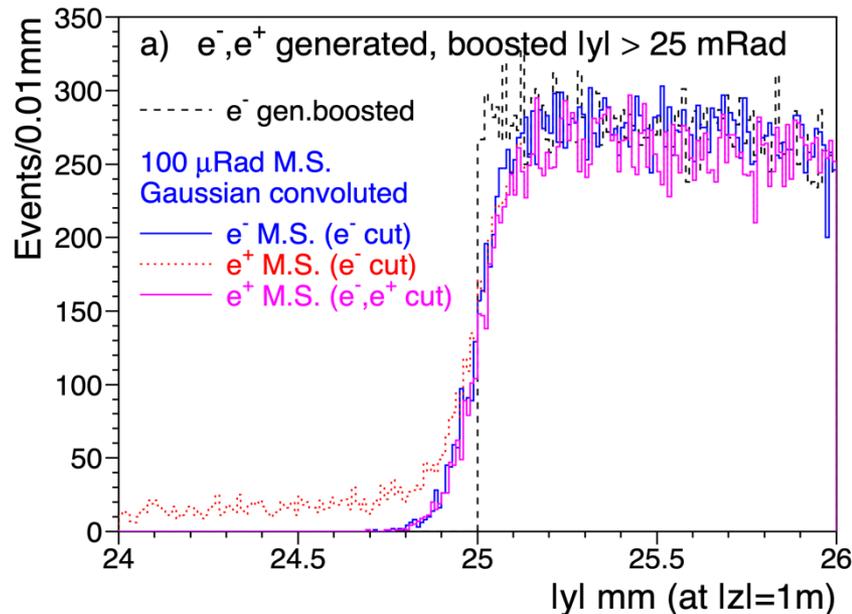
Experimental challenges

- 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

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

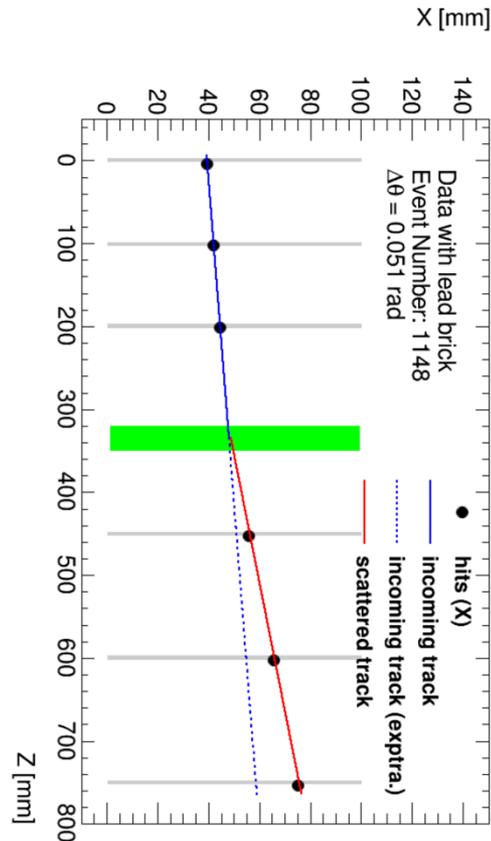


- Final state electron multiple scattering

Multiple scattering

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

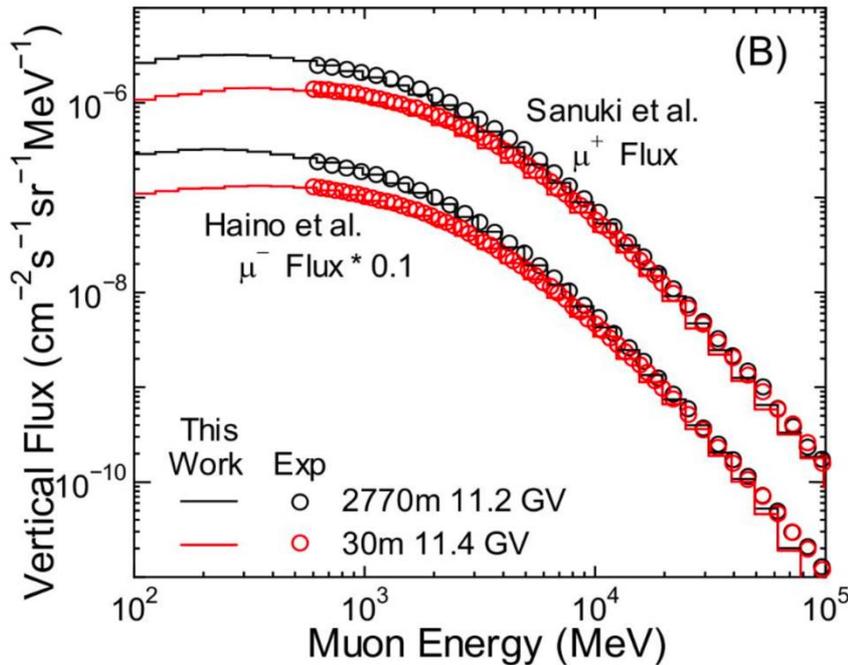
- 6 sets (x,y) with 200 μm pitch



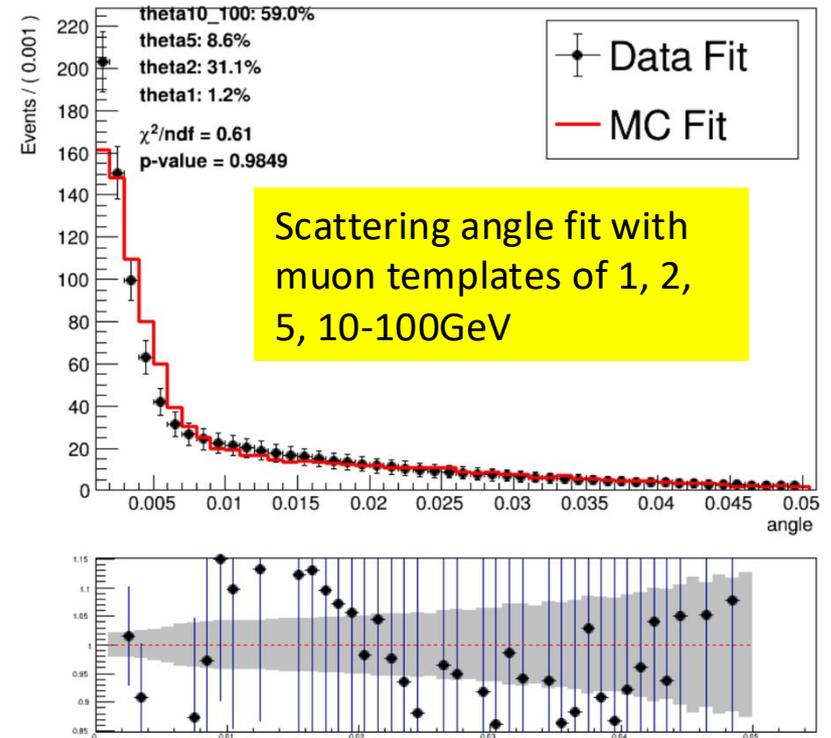
Multiple scattering

- Preliminary results

Cosmic Muon energy spectrum

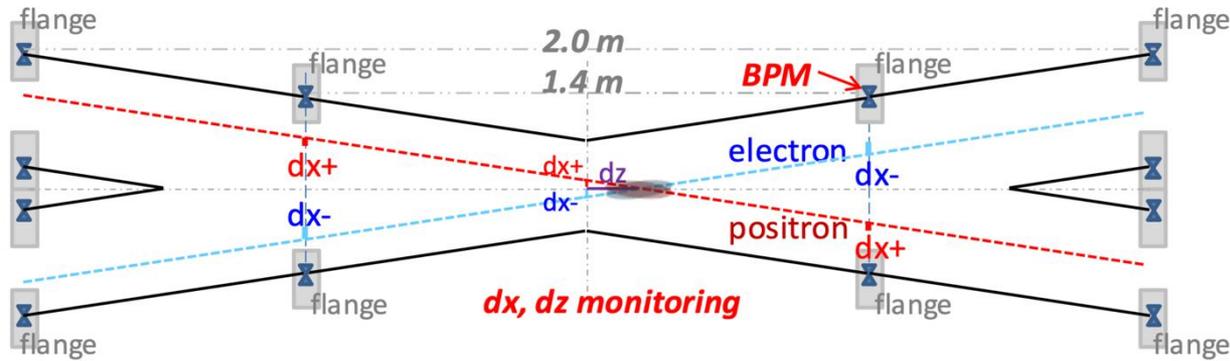


A RooPlot of "angle"



Interaction Position (IP)

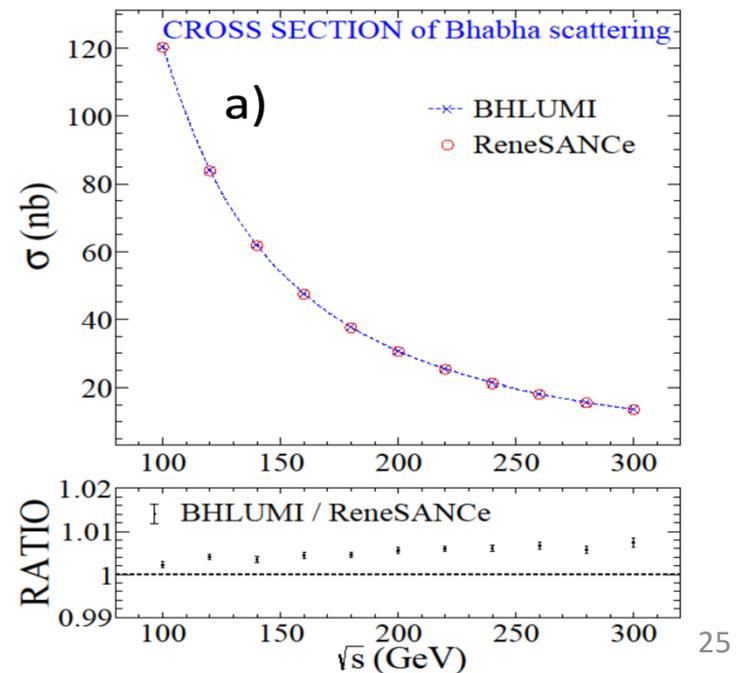
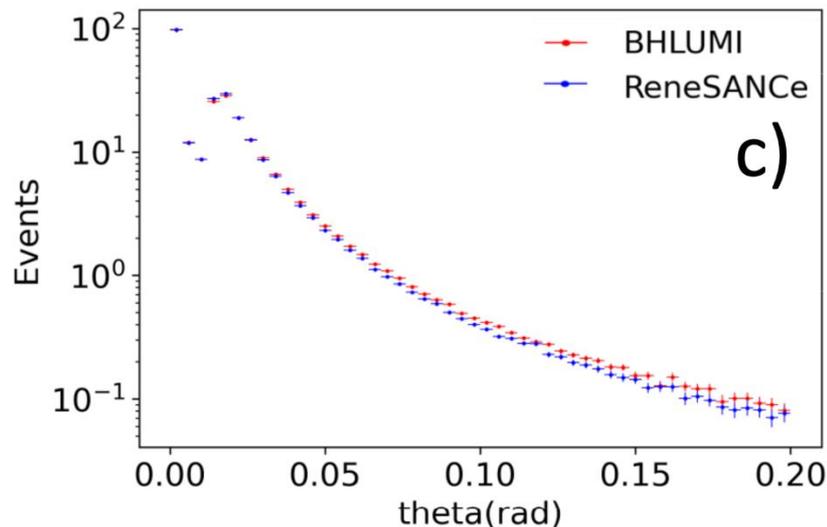
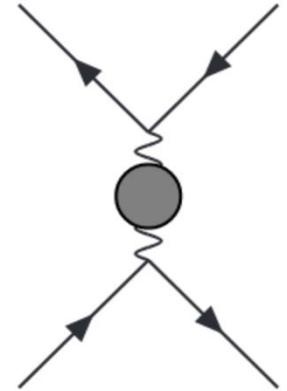
- Real IP position can be shifted



- 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 $O(1 \mu\text{m})$ on the beam x,y positions

Theoretical challenges

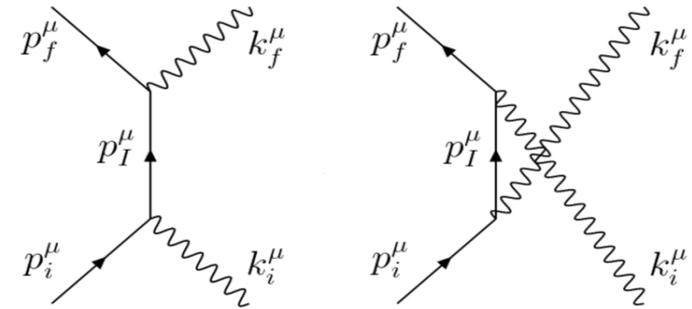
- Hadronic vacuum polarisation contribution
 - Extracted from data for $e^+e^- \rightarrow \text{hadrons}$ or from lattice QCD
 - Data-driven from (BelleII, BESIII, CMD-3, SND), expected the uncertainty to be reduced below 10^{-4} level
- Generator studies
 - BHLUMI 4.04 S. Jadach, 0.037% precision [PLB 803 (2020) 135319]
 - ReneSANcE, a recent NLO generator [CPC 256 (2020) 107455]



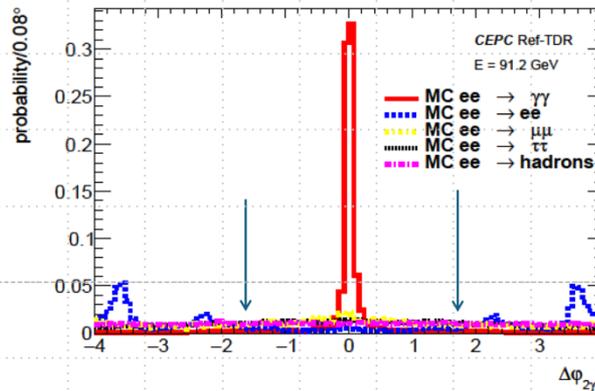
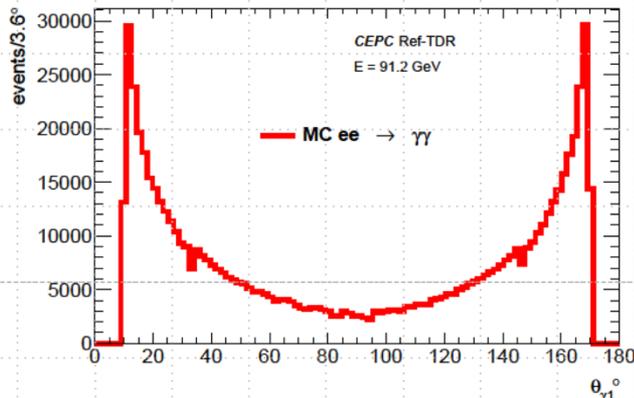
Alternative process: di-photon ($e^+e^- \rightarrow \gamma\gamma$)

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

- 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 $10 < \theta < 170^\circ$



If we want to increase statistics by using $10 < \theta < 170^\circ$ selection then 10^{-4} contamination from the $ee \rightarrow ee$ process appears.

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

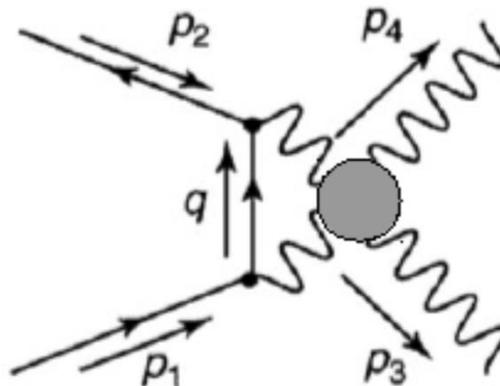
$ee \rightarrow \gamma\gamma$ 688081 events selected from 1M (~69% efficiency)

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

A. Kharlamov, et al

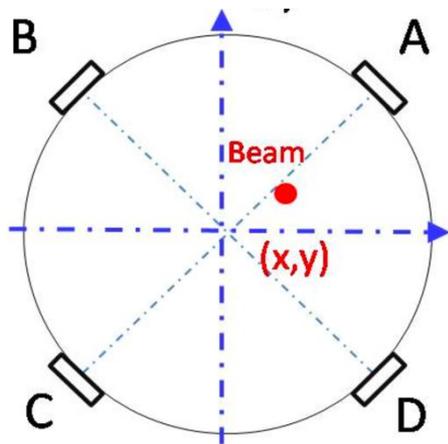
Di-photon: challenges

- 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

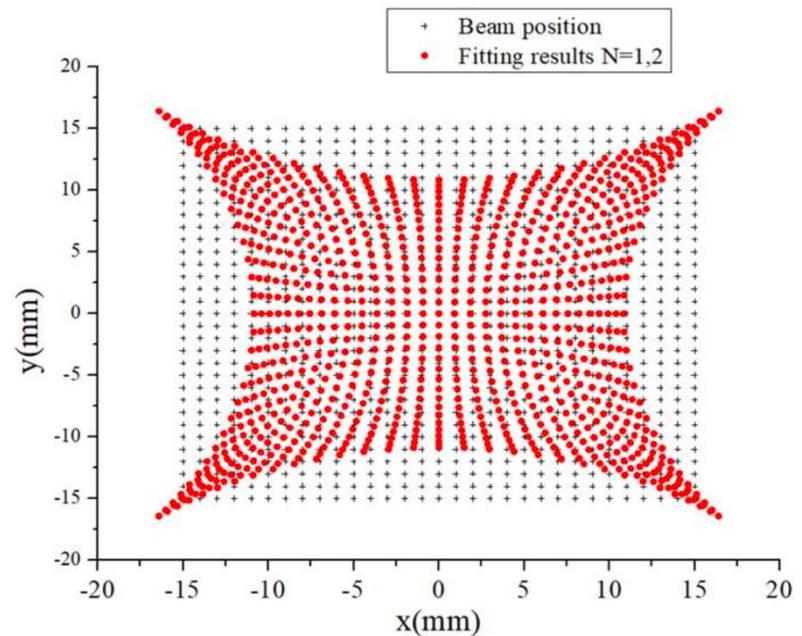
- Survey/monitoring, for Beam IP position
 - Beam Probe Monitor BPM , IP x,y to 1 μm
 - Position monitoring, Flange dx,dy $\sim 1 \mu\text{m}$, dz $\sim 50 \mu\text{m}$

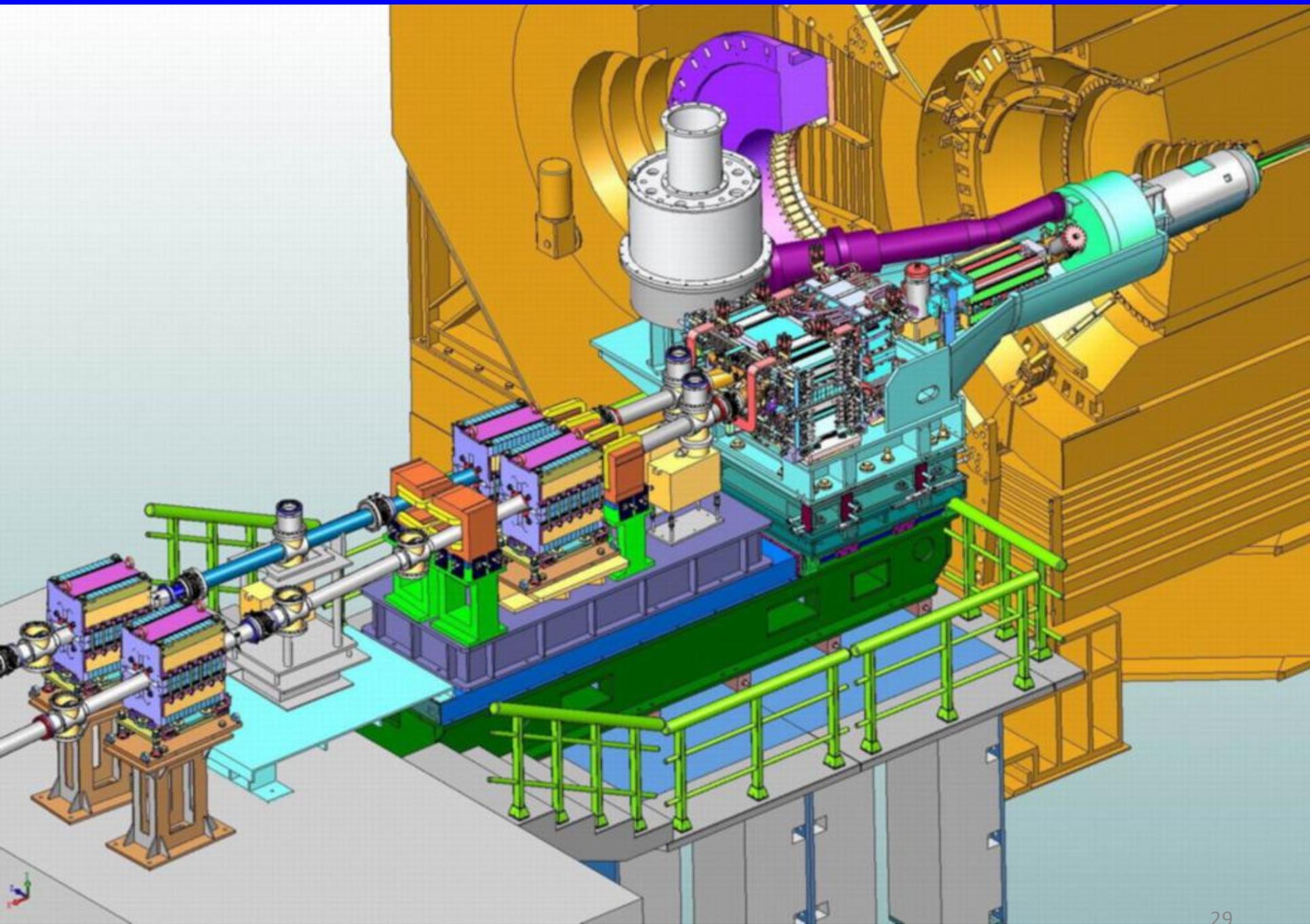


$$x, y = f(x_{raw}, y_{raw})$$

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

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





Some open Questions

- Radiative production of additional fermion pairs is currently not implemented in typical MC programs for SABS and $\gamma\gamma$ production.
 - What is their impact in the experimental analysis of the luminosity measurements?
- What is (quantitatively) the impact of beamstrahlung on the overall luminosity determination?
 - Will the beamstrahlung spectrum need to be obtained from simulation, or can be determined from in-situ measurements?
- Are there other processes besides $e^+e^- \rightarrow e^+e^-$ and $e^+e^- \rightarrow \gamma\gamma$ that could be useful for luminosity measurements?