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2025 超级陶粲装置研讨会

# Precision test of QED and measurement of Luminosity at STCF


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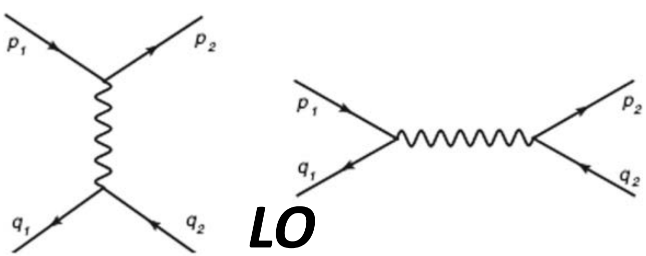
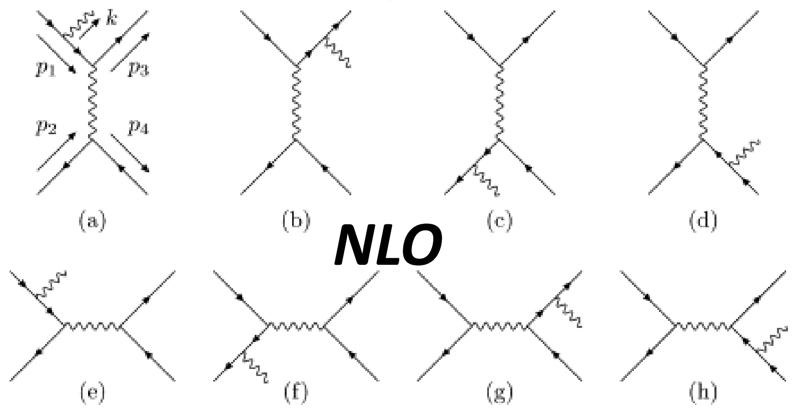
2025.07.03

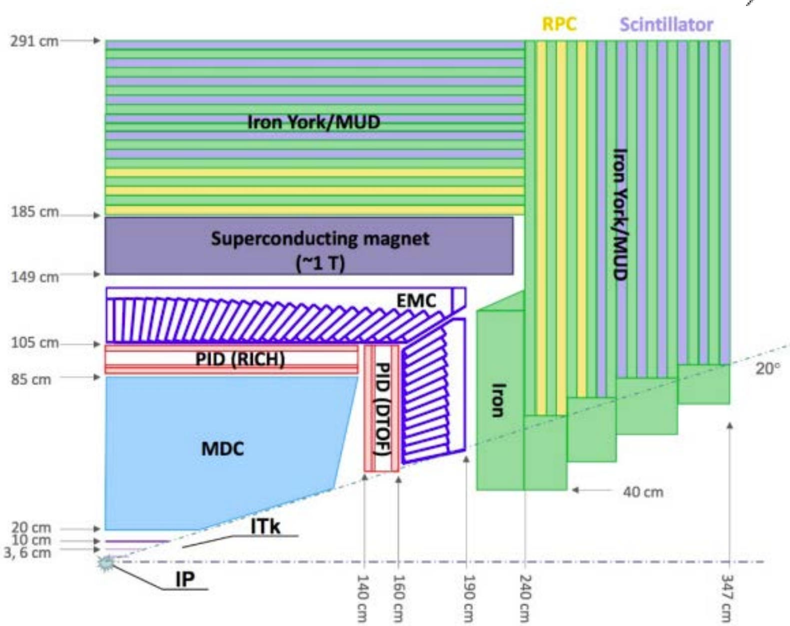

Radiative Bhabha elastic scattering

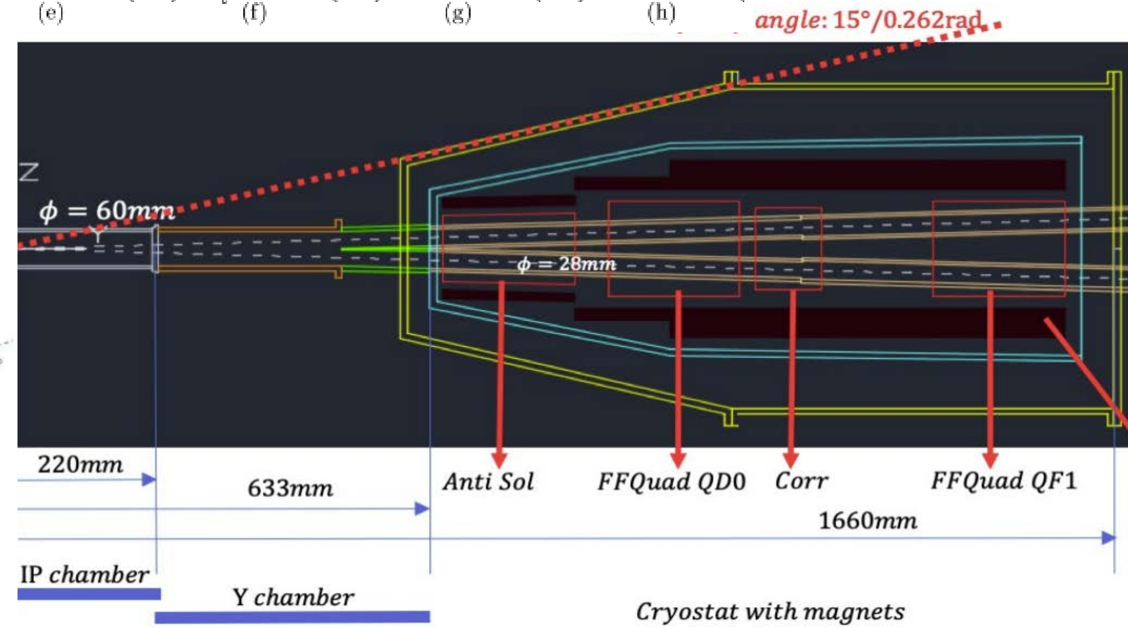



$t - channel$ **LO** $s - channel$

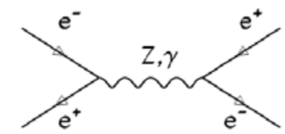


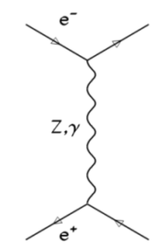

**NLO**



# Luminosity precision to SM, R




*SM* $e^+e^- \to Z \to q\bar{q}$ , *R(s) ratio*

*QED* Luminosity *by counting Bhabha* $e^+e^- \to e^+e^-$

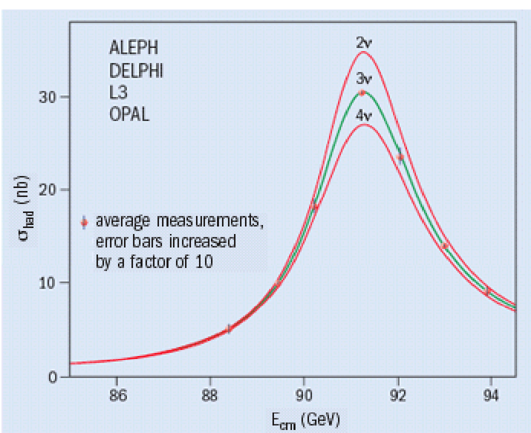
**LEP: 17 Million Z** (4 IP)

L = 4.3 $10^{31}$/cm$^2$s (E=46GeV)

= 1x$10^{32}$/cm$^2$s (E=100 GeV)

**$N_\nu$ = 2.9840 ± 0.0082**

| | |
|---|---|
| $M_Z$ = 91187.5 ± 2.1 MeV | 2.3 × $10^{-5}$ |
| $G_Z$ = 2495.2 ± 2.3 MeV | 1‰ |
| **$N_\nu$ = 2.9840 ± 0.0082** | |
| **Precision luminosity** | **3.4x$10^{-4}$** |



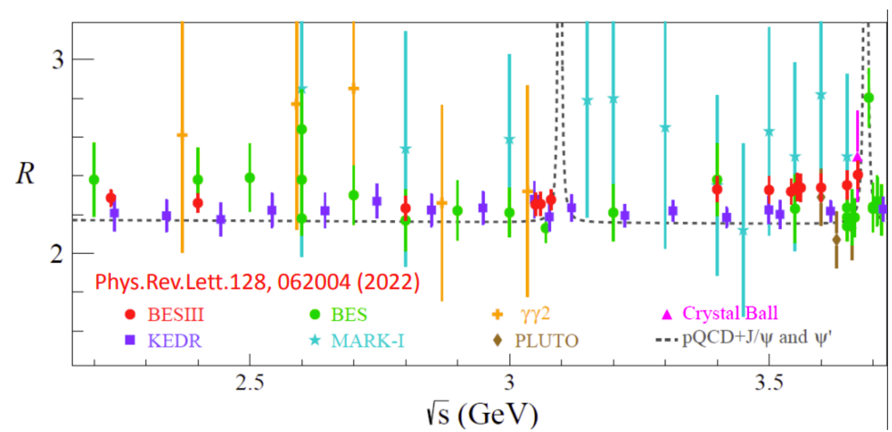

CERNCOURIER 2 November 2005

$R(s)$ ratio for SM predictions

$a_\mu = (g_\mu\text{-}2)/2$ and $\Delta\alpha_{had}(M_Z)$

$$a_\mu = \frac{\alpha^2}{3\pi^2}\int_{m_\pi^2}^{\infty} \mathrm{d}s\, K(s)\frac{R(s)}{s}$$

$$\Delta\alpha_{\rm had}^{(5)}(M_Z^2) = -\frac{\alpha M_Z^2}{3\pi}\,\mathrm{Re}\int_{m_\pi^2}^{\infty}\frac{R(s)\mathrm{d}s}{s(s-M_Z^2-i\epsilon)}$$




BESII in 2–5 GeV, precision ☐6%

BESIII 2022 3%

# QED precision on Bhabha $e^+e^- \to e^+e^- (n\gamma)$

Methods used for multiple photon corrections

1. SF: analytical collinear QED Structure Functions
2. **YFS exponentiation Small angle 0.054% BHLUMI (LEP)**
3. **PS: Parton Shower Large angle 0.1% BabaYaga@NLO (Flavor F.)**

***$e^+e^-$ collision luminosity***
*by coybtubg Bhabha events*

$$\int \mathcal{L}\, dt = N_{\rm obs}/\sigma_{\rm th}$$

$$\frac{\delta\mathcal{L}}{\mathcal{L}} = \frac{\delta\mathcal{L}_{\rm exp}}{\mathcal{L}_{\rm exp}} \oplus \frac{\delta\sigma_{\rm th}}{\sigma_{\rm th}}$$

***Luminosity errors:***
*Experiment*
*Theory*

collinear log : $L \equiv \log \frac{s}{m_e^2}$

G. Montagna
Ustron, 2015

| | | |
|---|---|---|
| $L = \log(s/m_e^2) \simeq 15$ | | *Large angle @ Flavor* |
| $L = \log(\lvert t\rvert/m_e^2) \simeq 17$ | | *Small angle @ LEP* |
| $L = \log(\lvert t\rvert/m_e^2) \simeq 20$ | | *Small angle @ $t\bar{t}$ thresh.* |

***Flavor Factories***

collinear log : $L \equiv \log \frac{s}{m_e^2}$

C.M. Carloni Calame
ECFA Higgs CERN 2021

| | | | |
|---|---|---|---|
| LO | $\alpha^0$ | | |
| NLO | $\alpha L$ | $\alpha$ | |
| NNLO | $\frac{1}{2}\alpha^2 L^2$ | $\frac{1}{2}\alpha^2 L$ | $\frac{1}{2}\alpha^2$ |
| h.o. | $\sum_{n=3}^{\infty} \frac{\alpha^n}{n!} L^n$ | $\sum_{n=3}^{\infty} \frac{\alpha^n}{n!} L^{n-1}$ | $\cdots$ |

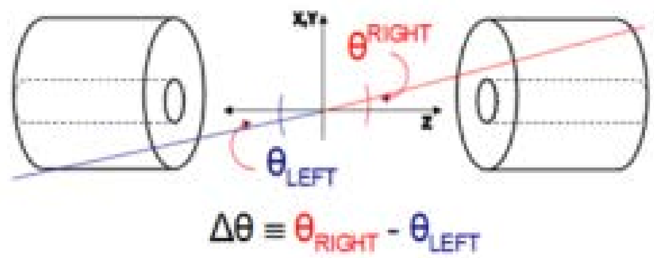
Red: matched PS, SF + NLO

| | | | |
|---|---|---|---|
| LO | 90% | | |
| NLO | 10% | 0.5% | |
| NNLO | 0.5% | 0.05% | 0.01% |
| h.o. | 0.01% | $\cdots$ | $\cdots$ |

Typically at flavour factories (on integrated Bhabha $\sigma$)

# Bhabha event counting to $10^{-4}$

## SM an order improvement to LEP



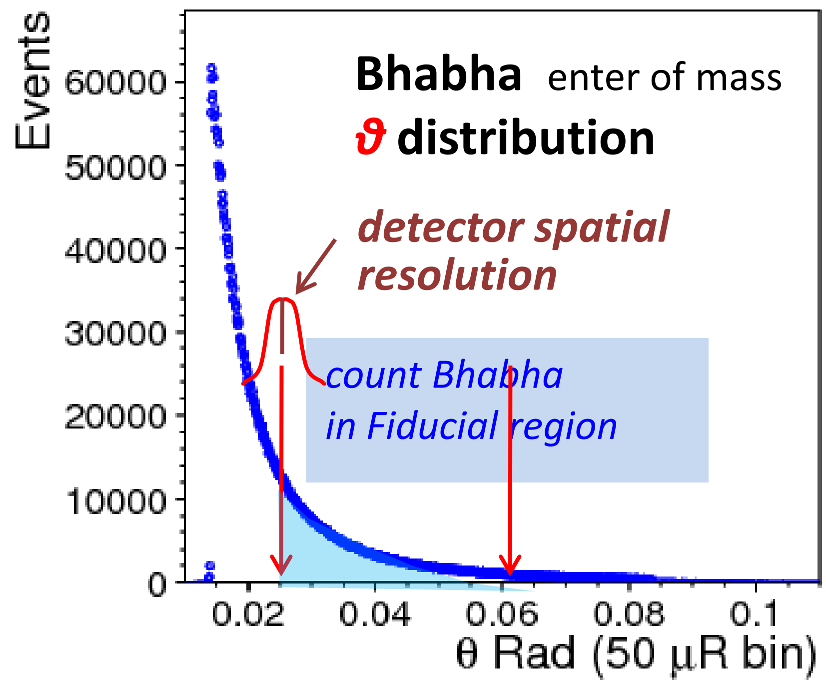

***Luminosity $\mathcal{L}$ is derived by***

***$e^+e^- \rightarrow e^+e^-(n\gamma)$***

$$\mathcal{L} = \frac{1}{\varepsilon}\frac{N_{acc}}{\sigma^{vis}} \qquad \sigma = \frac{16\pi\alpha^2}{s}\left(\frac{1}{\theta^2_{min}} - \frac{1}{\theta^2_{max}}\right)$$

***Bhabha detected for***

- *a pair of back-back electrons,*
- *precision $\vartheta$ of e,e(γ) in fiducial region*




***$\delta L/L \sim 2\,\delta\vartheta/\vartheta_{min}$***

***$\delta L/L = 10^{-4}$***

*at* ***$z = \pm 1000$ mm, $\vartheta_{min}$ = 20 mRad***

→ ***$\delta\vartheta$ = 1 μRad,*** or ***dr = 1 μm***

*error due to offset on Z*

→ ***50 μm** on Z eq. dr = $\delta z \times \vartheta$ **= 1 μm***

***Luminosity systematics** due to*

***event counting in/out fiducial edge***

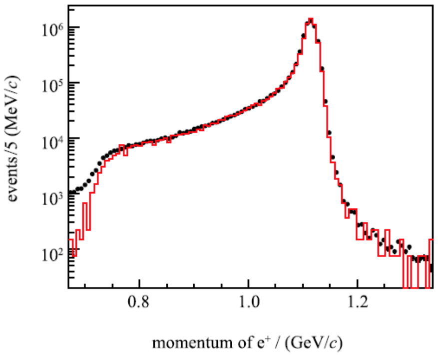
***→ offset on the mean of $\theta_{min}$***

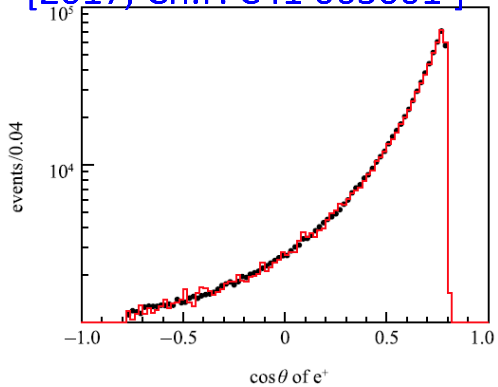
# Bhabha experimental results $e^+e^- \to e^+e^- (\gamma)$

## BESIII Luminosity $(\gamma)e^+e^-$, $(\gamma)\gamma\gamma$
## Systematic error ~0.7%

$\sqrt{s}$ = 2.23 - 4.59 GeV

[2017, Ch.P. C41 063001 ]



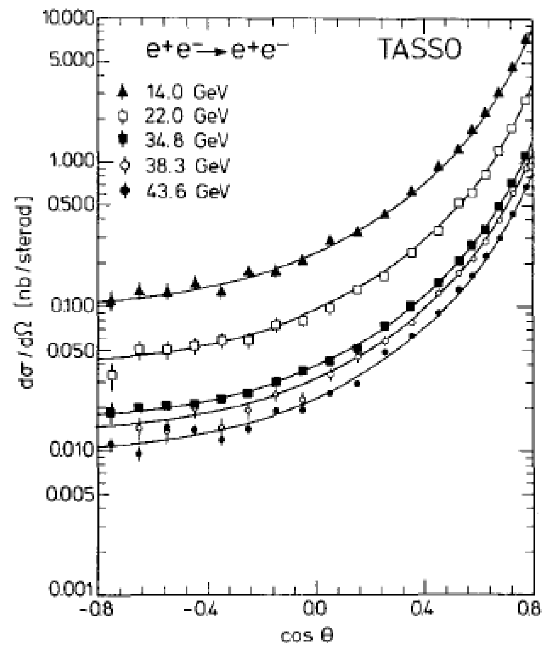




## TASSO Bhabha
## Systematic error ~3%

$\sqrt{s}$ = 12 - 47 GeV

Table 1. Data samples used for the analysis $e^+e^- \to e^+e^-$

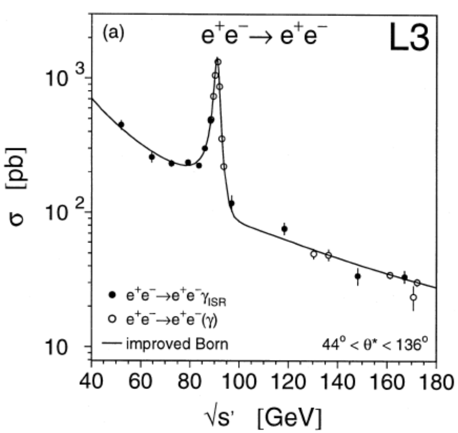
| $\langle\sqrt{s}\rangle$ (GeV) | $\int \mathscr{L}\,dt$ (pb$^{-1}$) | $N_{Bhabha}$ |
|---|---|---|
| 14.0 | 1.7 | 10730 |
| 22.0 | 2.7 | 7106 |
| 34.8 | 174.5 | 166348 |
| 38.3 | 8.9 | 6035 |
| 43.6 | 37.1 | 22951 |

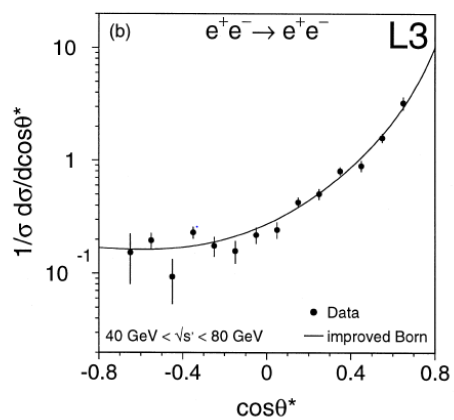



[ 1988, ZPC 37, 171]

## L3 radiative Bhabha with ISR
## Systematic error at ~1% level

$\sqrt{s}$= 50 ~ 170 GeV, 232 pb$^{-1}$, 2856 event




[1998, PLB 439, 183]

# *Challenge:* QED $\alpha^2 L^2$ *shall be measured*

**Compare $\sqrt{s}$ = 92.3 GeV**

**BHLUMI:** YFS exponentiation $e^+e^- \rightarrow e^+e^-(\mathbf{n\gamma})$

**ReneSANCe:** NLO calculation $e^+e^- \rightarrow e^+e^-(\boldsymbol{\gamma})$

**BHLUMI 4.04**

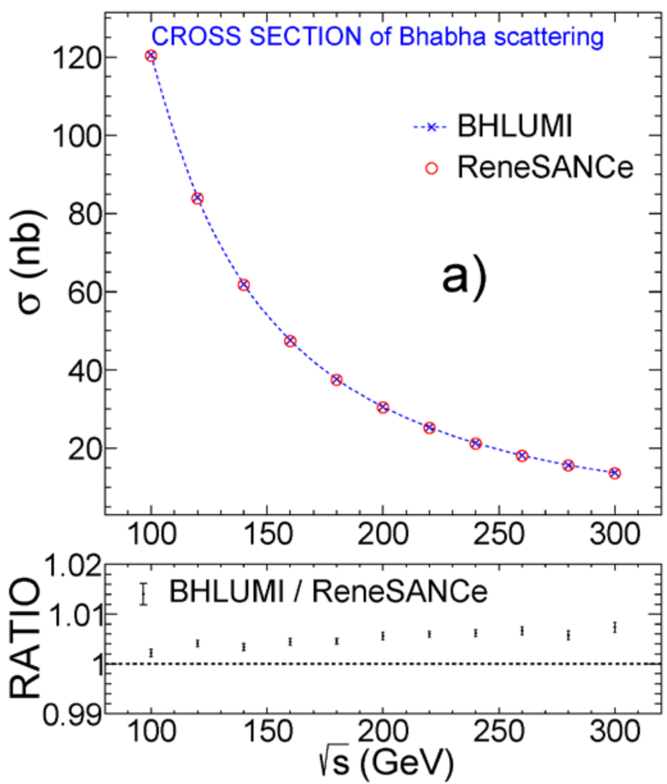
*2020 systematic* ***0.037%***

[PLB 803 (2020) 135319]

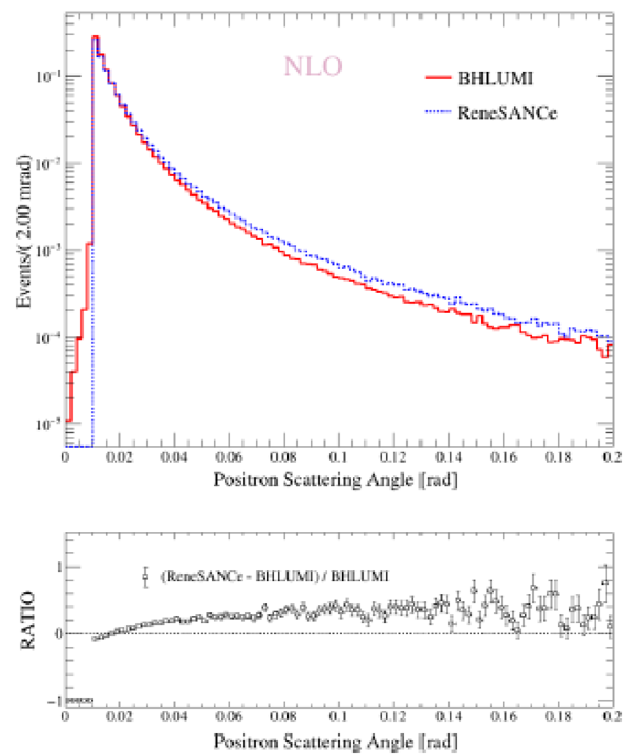
**ReneSANCe**

[CPC 256 (2020) 107455]

***Bhabha***
***Cross section***




**Bhabha $\sqrt{s}$= 92.3 GeV**
**$e^+$ theta angle, all events**




Discrepancy due to 0γ events

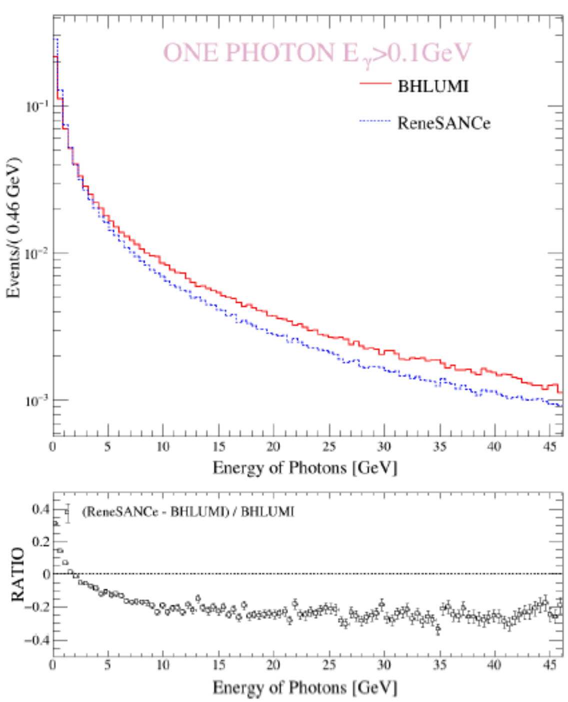
# *Challenge:* QED $\alpha^2 L^2$ *shall be measured*

**BHLUMI:** $e^+e^- \rightarrow e^+e^-(n\gamma)$

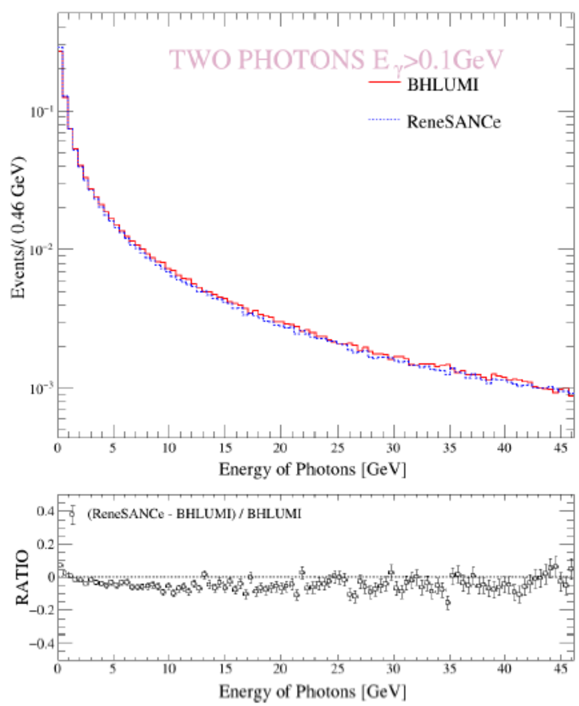
**ReneSANCe:** $e^+e^- \rightarrow e^+e^-(\gamma)$

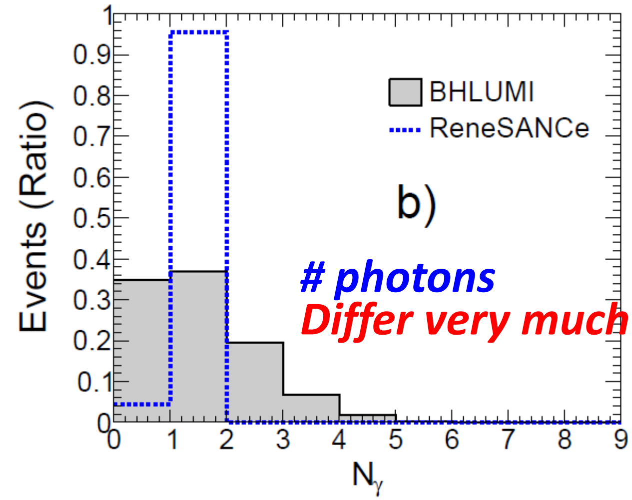
*Photon events*

*1γ events*




*all photons filled*




*BHLUMI E(γ)>5MeV*

| Event final states | BHLUMI generated |
|---|---|
| $e^+e^-$ | 36.4% |
| $e^+(e^-\gamma)$ or $(e^+\gamma)e^-$ | 47.8% |
| $(e^+\gamma)(e^-\gamma)$, | 15.8% |

# Bhabha $e^+e^- \rightarrow e^+e^-(n\gamma)$ at CEPC



## LEP Luminosity template

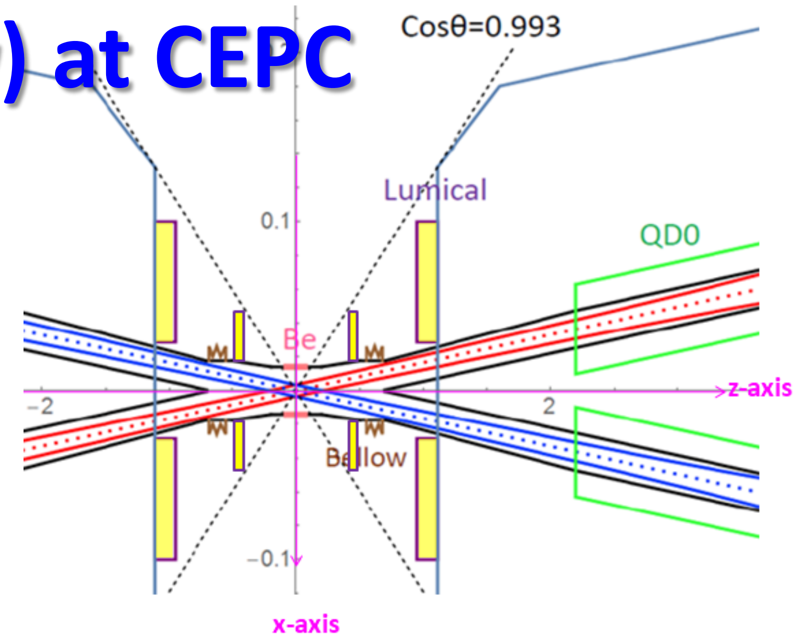
**BHLUMI demo.f cuts**

- **ACC 0** CMS 10 mRad < $\theta(e^{\pm})$ < 80 mRad
- **ACC 1** .and. s'(P2,Q2)/s(P1,Q1) >0.5

**Beam crossing, 33 mRad**

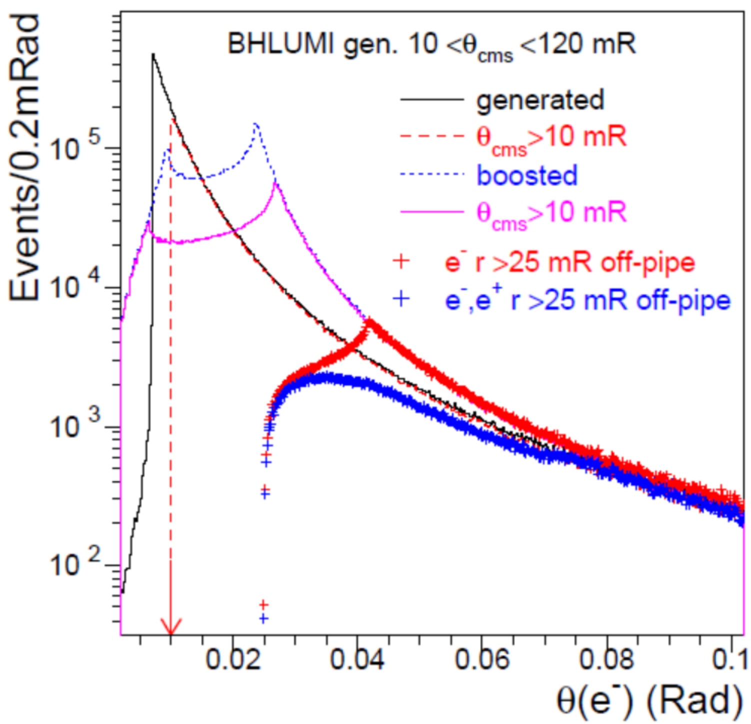
➔ Boost in x direct

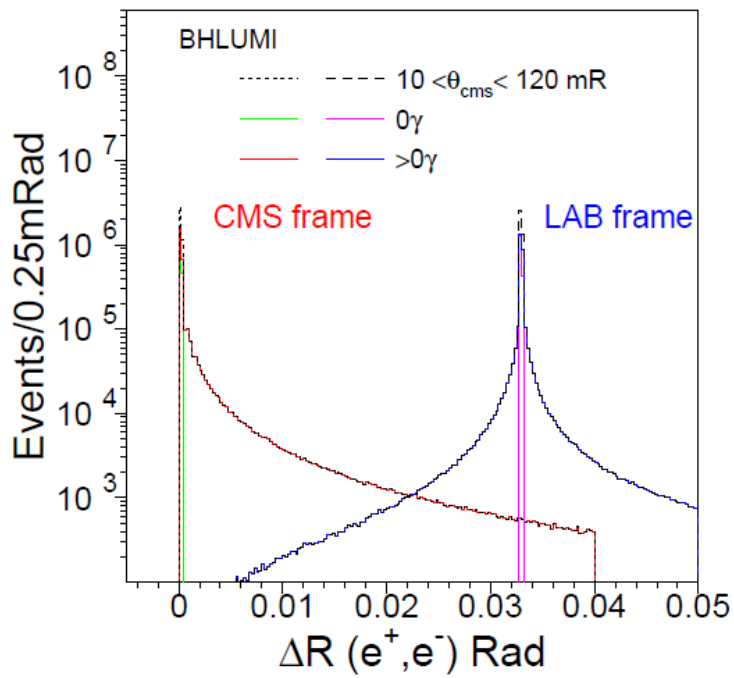
$e^+$, $e^-$ offset by 33 mRad




events with 0 photos

Show δ back-back distribution



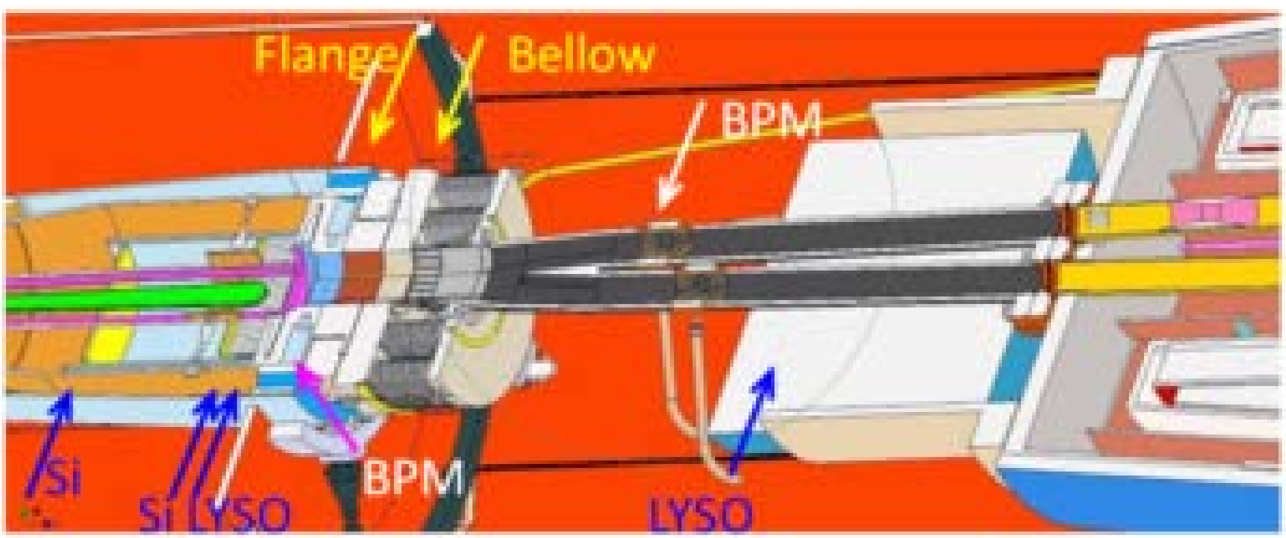



# CEPC LumiCal design

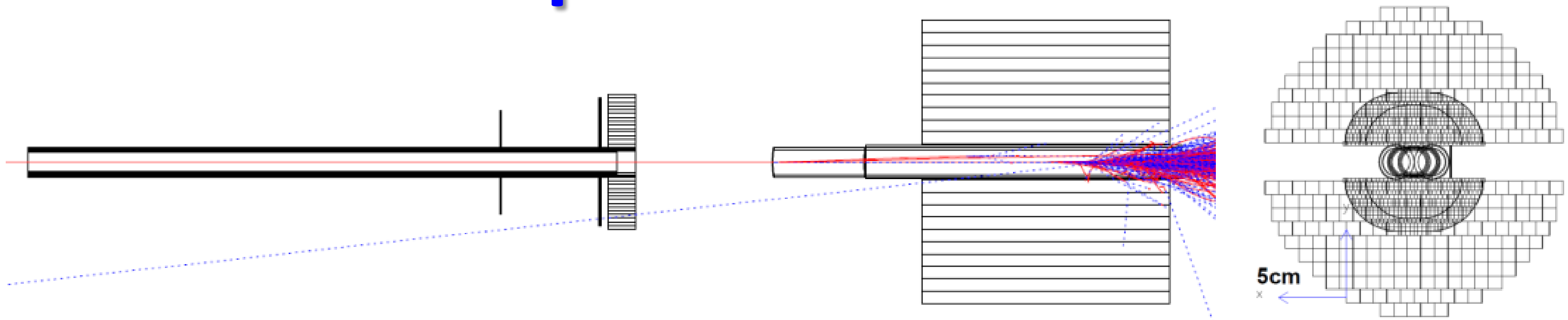
- ***L=2x10^36*/cm²s¹ @Z-pole,**
  - ***ø 20 mm*** racetrack, beam-crossing ***33 mRad***
  - IP bunch : $\sigma_x\ \sigma_y\ \sigma_z$ ***= 6 μm, 35 nm, 9 mm***
  - Bunch crossing: ***23 ns***

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

- ***behind Bellow*** z= 900~1100 mm
  - **Flange+Bellow : ~60 mm, 4.3 $X_0$**
  - **$13X_0$ LYSO 150 mm**



# CEPC LumiCal acceptance



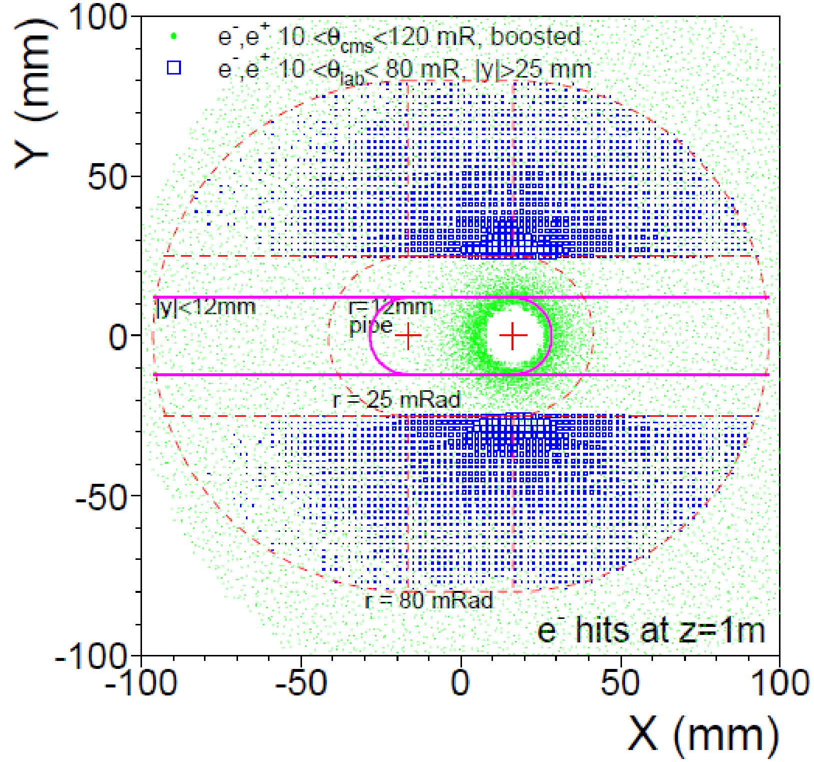

***BHLUMI event distribution***

***detecting back-to-back $e^+$, $e^-$ pair***

*@|z|=1000mm*

1) Θ > 25mRad outside pipe centers
2) |y|>25 mm
3) Events in shaded area counted for Xsec

***$e^+$, $e^-$*** back-to-back symmetric to out-going pipe center

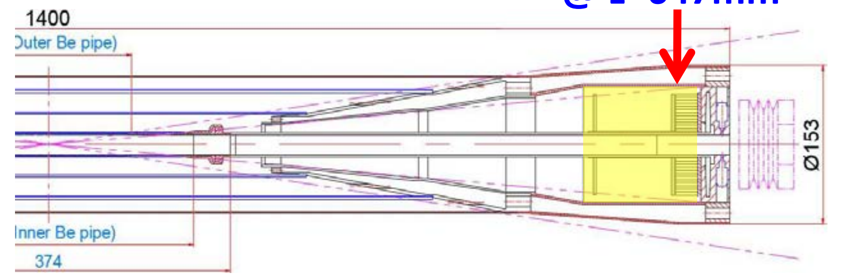



***LumiCal acceptance at |z|=1000mm***

| $e^+$, $e^-$ back-to-back detected | |
|---|---|
| θ>25 mRad | θ>25mR & \|y\|>25mm |
| **85.4 nb** | **78.0 nb** |

# CEPC LumiCal Front $2X_0$ LYSO

$2X_0$ LYSO @ z=647mm

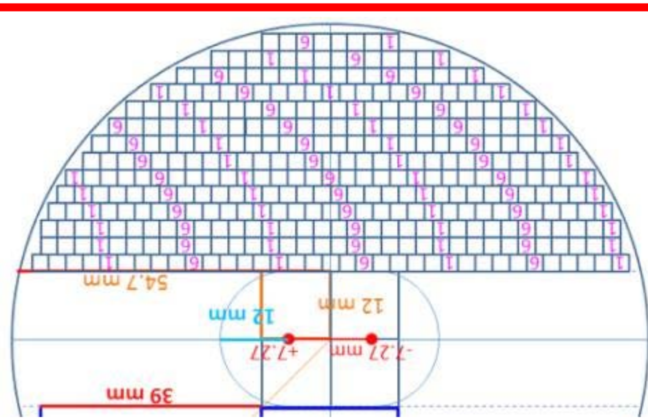



## Bhabha hits on LYSO, |y|>12mm

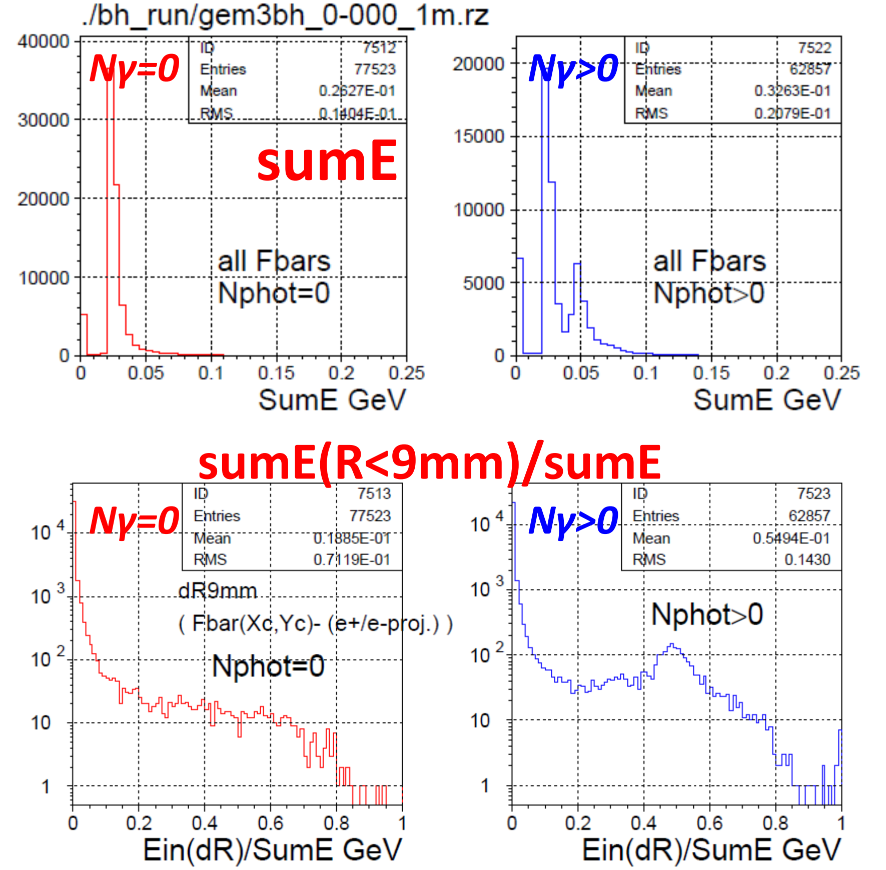
## Incident particles are $e^{\pm}$,(γ)

- **GEANT sum dE/dx in each LYSO bars**
  3x3mm$^2$, 23 mm long, $2X_0$
- **Deviation to $e^{\pm}$ truth** (impact hit $>E_b/2$)
  mostly < 0.2mm
- **Hit distributions in a Bar**
  distributed due to Bhabha θ, w./w.o. photon

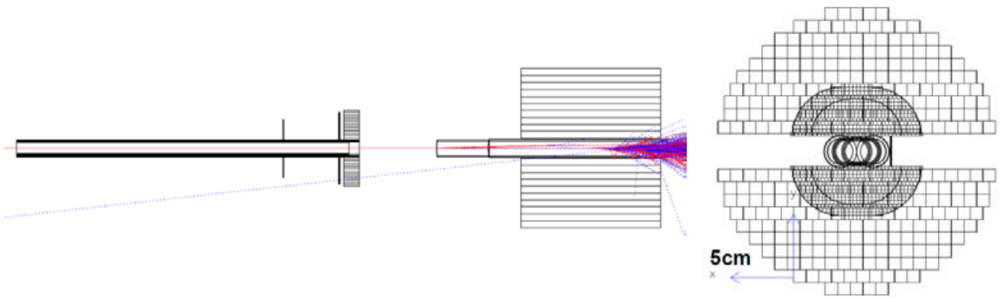
**sum dE/dx all LYSO bars** (a plane)
- $e^{\pm}$ one track : **sumE min. 20 MeV**
- ($e^{\pm}$+ FSRγ) : **two MIPs, sumE x2**

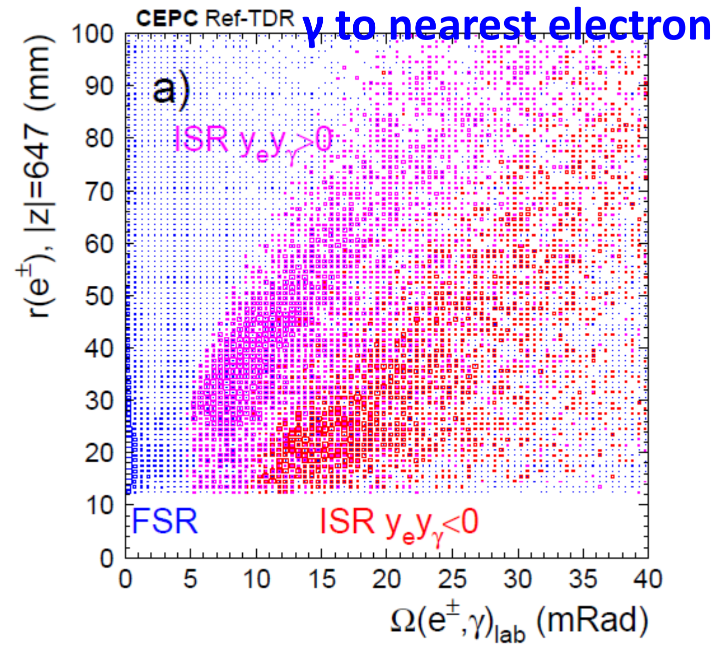


**BHLUMI events, GEANT simulation**



# Photons in $e^+e^- \to e^+e^-(n\gamma)$ @Z-pole




## Bhabha events in LumiCal acceptance

**$e^+,e^-,\gamma$ : |y|>12 mm at LYSO front face ±z=647mm**

| ±z Hemispheres | BHLUMI generated | & P2,Q2 \|y\|>12mm |
|---|---|---|
| $e^\pm$ | 60.3 % | 3.87 % |
| $e^\pm\gamma$ | 39.7 %* | 3.16 % |

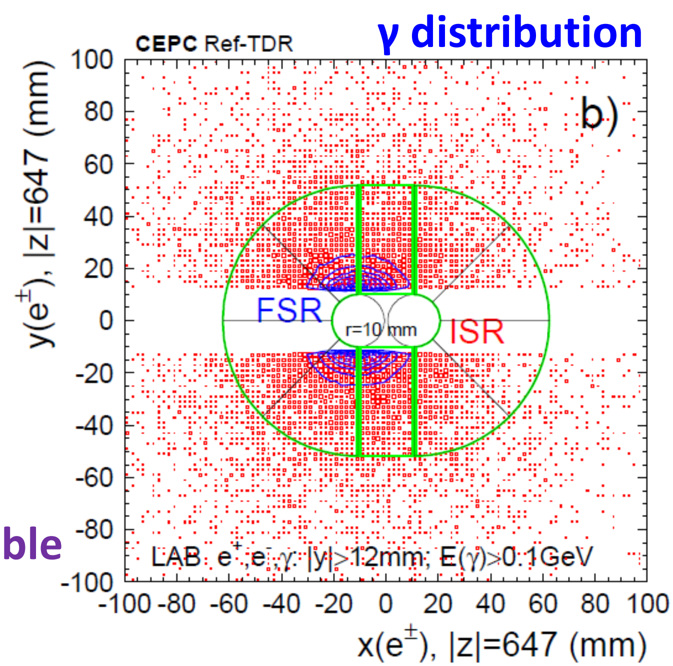
*ISR 20.3%, FSR 19.4%

## Detectable Bhabha, $e^+,e^-,\gamma$ : |y|>12 mm

| ±z Hemispheres | P2,Q2 \|y\|>12mm | & E(γ)>0.1GeV \|y(γ)\|>12mm |
|---|---|---|
| $e^\pm$ | 55.1 % | 14.7 % |
| $e^\pm\gamma$ | 44.9 % | ISR 0.89 %<br>FSR 13.8 %<br>**FSR 2.96%*** |

measurable

***FSR $\Omega(e^\pm,\gamma)$ > 5 mRad**



# Forward Calorimeter @ STCF

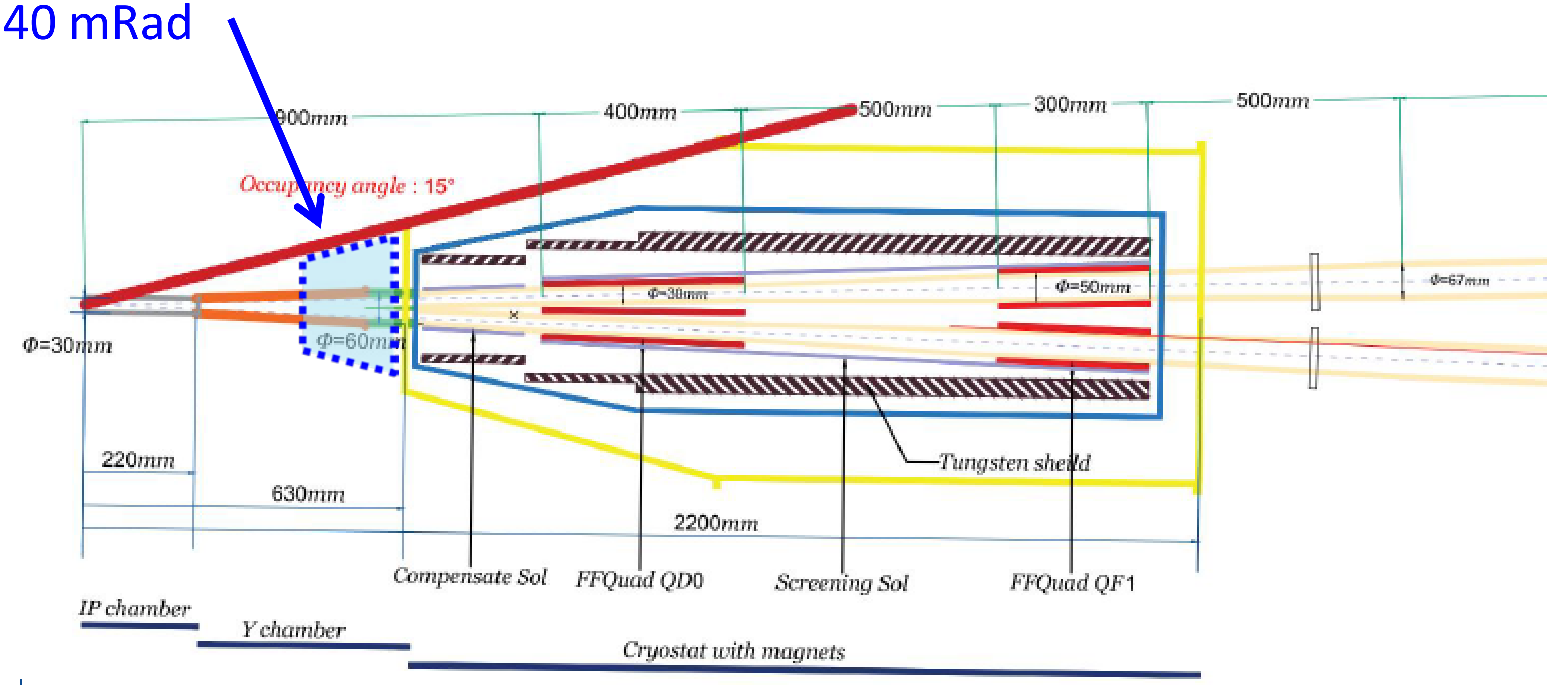
## Small Angle Bhabha 60 – 240 mRad ( 3.4° - 14°)

- Precision QED Bhabha at Flavor factories to **better than $10^{-3}$**
- e/γ by Si-det + Crystal → NLO, NNLO radiative Bhabha detection

**Propose: Forward region**

Z = 450 – 630 mm

Θ = 60 – 240 mRad



# Proposing precision Bhabha @ SCTF

**QED Bhabha needs NNLO on hadronics to $10^{-4}$**
**Detecting Bhabha to better than $10^{-4}$:**

- detect e/γ: identify radiative Bhabha deviation
- Si-det on electron θ: multi. scattering ~50 μRad
  mean-on-error on Bhabha counting
- monitoring IP: BPM on electron beams to 1 μm
- monitoring LumiCal: survey to beam-pipe centers on flanges
  Δz of flanges on +,-z side < 50 μm/1.4m