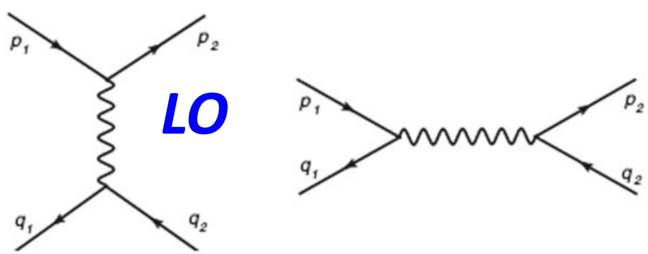
https://indico.ihep.ac.cn/event/22089/sessions/14186/#20241025

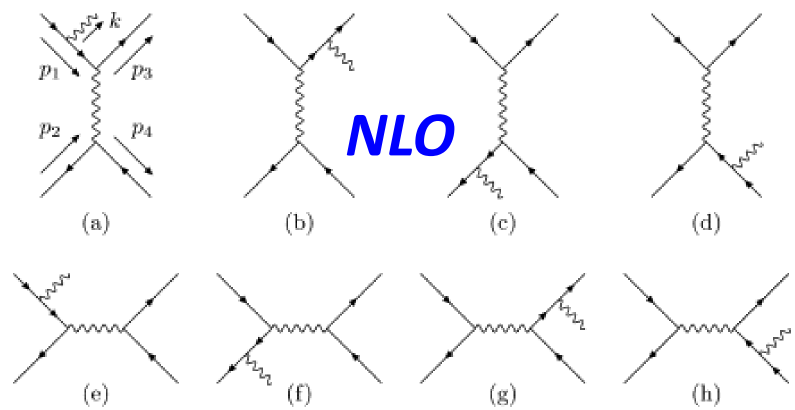
Measuring QED to 10^{-4} with radiative Bhabha for precision, for $e^{+}e^{-}$ collision luminosity

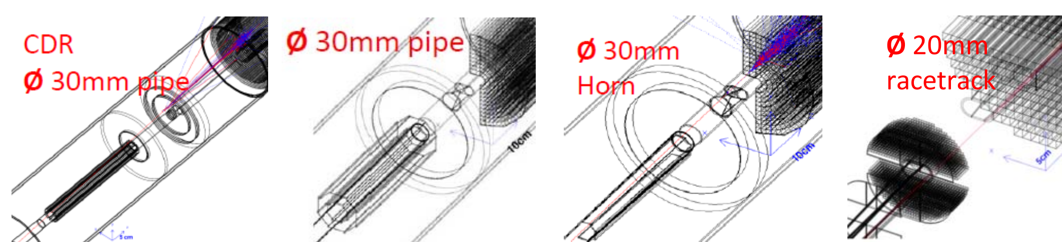
- Theory, BHLUMI precision
- CEPC fast LumiMon, LumiCal design
- Radiative Bhabha measurement

suen@sinica.edu.tw
侯書雲
2024.10.25
14:20



$t - channel$ $s - channel$





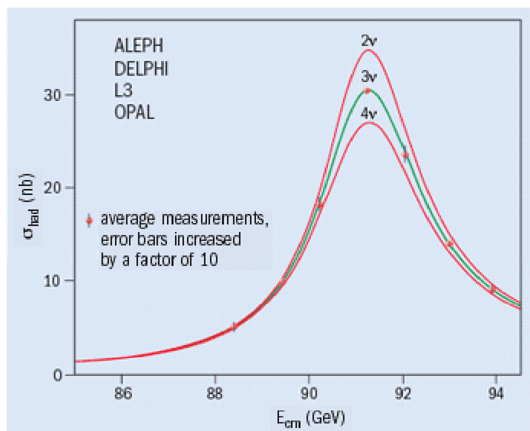
Physics goal at CEPC

- *Z*-lineshape $e^+e^- \to Z \to q\bar{q}$
- **Luminosity by Bhabha** $e^+e^- \to e^+e^-$

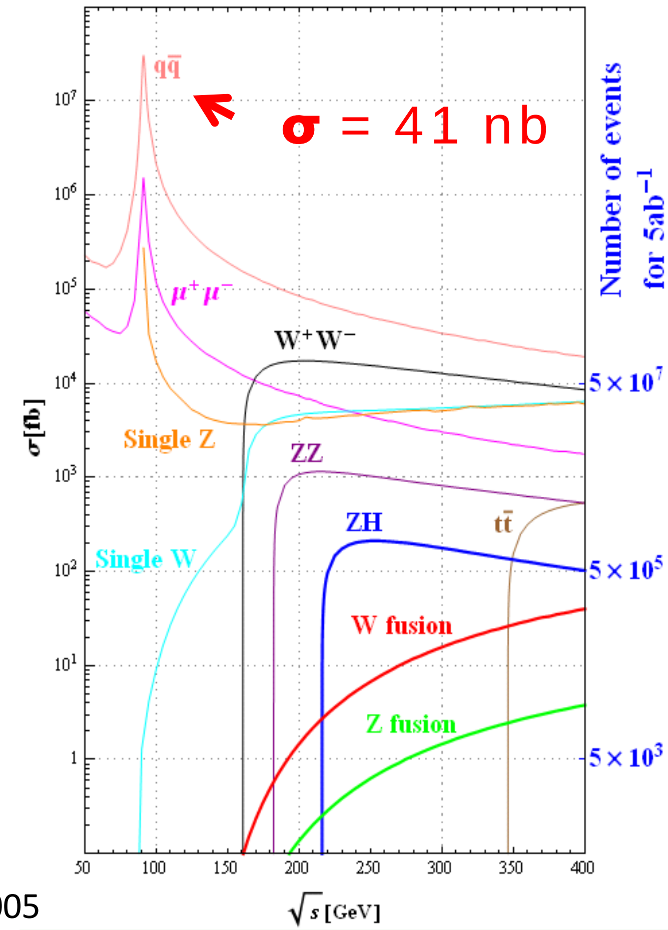
Events at CEPC, x100 to LEP
Luminosity precision, requiring 10^{-4}

N_ν = 2.9840 ± 0.0082

M_Z = 91187.5 ± 2.1 MeV		2.3×10^{-5}
G_Z = 2495.2	± 2.3 MeV	1‰
N_ν = 2.9840	**± 0.0082**	
Precision luminosity		**3‰**



CERNCOURIER 2 November 2005

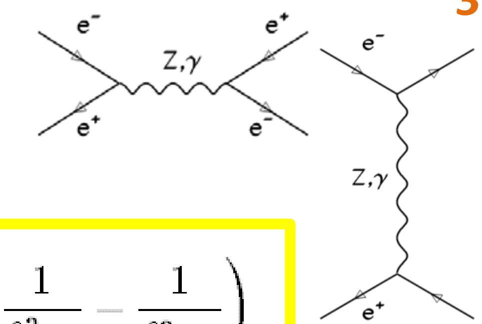


Bhabha generators for MC study

- **BHLUMI 4.04**
  S. Jadach [CPC 101 (1997) 229]
- ReneSANCe 1.0.0
  R.Sadykov [CPC 256 (2020) 107445]

"Compariing Event Generator.."
poster by J.Gong, this workshop

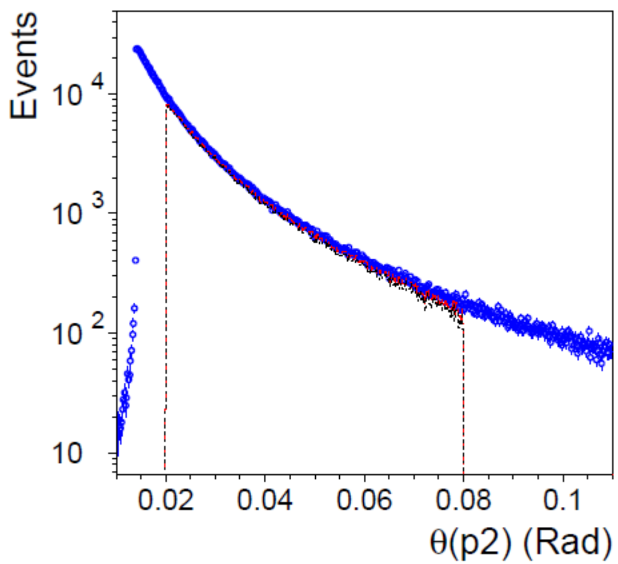
BHLUMI for LEP luminosity



Framework of
YFS exponentiation

$e^+e^- \longrightarrow e^+e^- n\gamma$

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



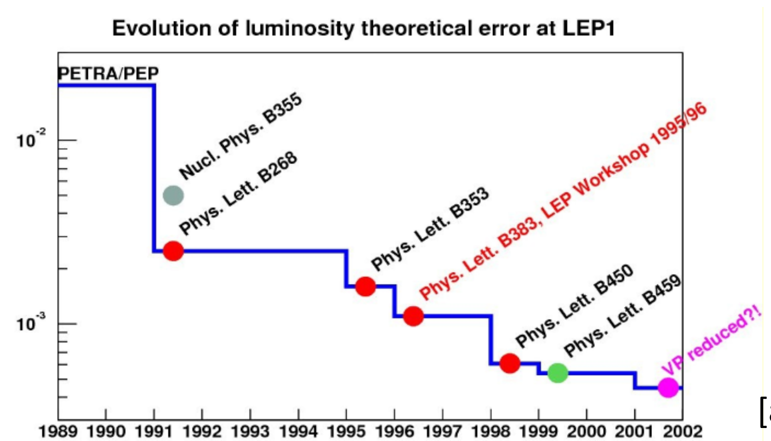
LEP theoretical uncertainties [EPJC 81 (2021) 1047]

Type of correction/error	Update 2019
(a) Photonic $\mathcal{O}(L_e\alpha^2)$	0.027% [8]
(b) Photonic $\mathcal{O}(L_e^3\alpha^3)$	0.015% [9]
(c) Vacuum polariz.	0.009% [7, 10]
(d) Light pairs	0.010% [7]
(e) Z and s-channel γ exchange	0.015% [11, 12]
(f) Up-down interference	0.0014% [13]
(g) Technical Precision	(0.027)%
Total	0.037%

BHLUMI 4.04
S. Jadach [CPC 101 (1997) 229]

2000 systematic ***0.054%***
[NPB 547 (1999) 39]
[PLB 459 (1999) 649]
[OPAL Z^0 lineshape, EPJC 14, 373]

2020 systematic ***0.037%***
[PLB 803 (2020) 135319]



[arXiv:2211.14230]
[PLB 803 (2020) 135319]

BHLUMI $e^+e^- \to e^+e^-(n\gamma)$

BHLUMI simulation

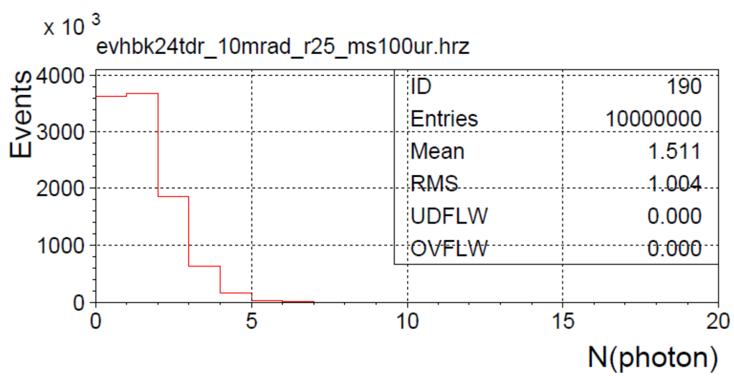
default demo.f setting

E_{CMS} = 92.3 GeV **θ = 10~80 mRad**

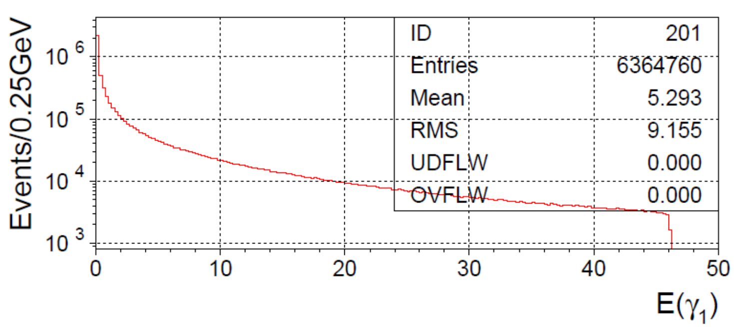
- *Scattered electrons (P2,Q2) from 7 mRad*
- ***$e^+e^- \to e^+e^- + n\gamma$*** *$\to E\gamma > 5MeV$*

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

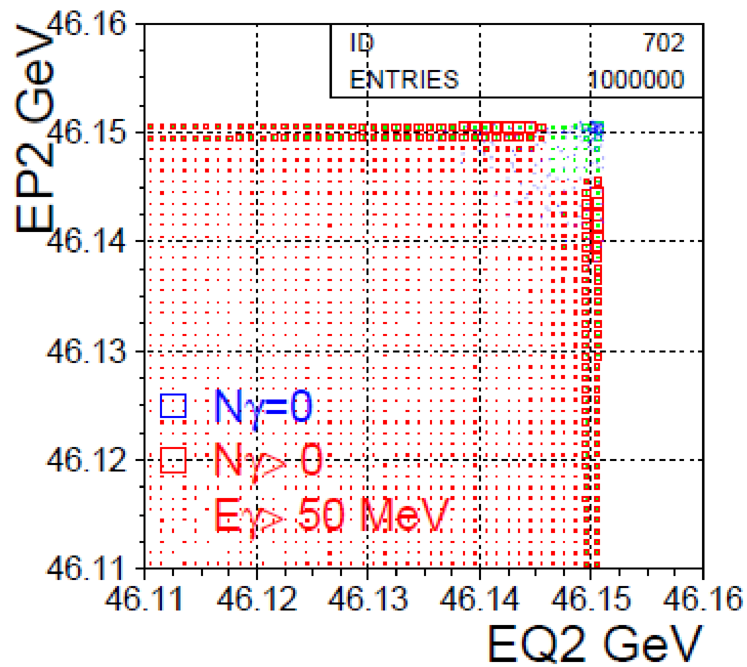
n of photons in events



Genrated photon energy



BHLUMI E(γ)>5MeV
E(e+) vs E(e-)



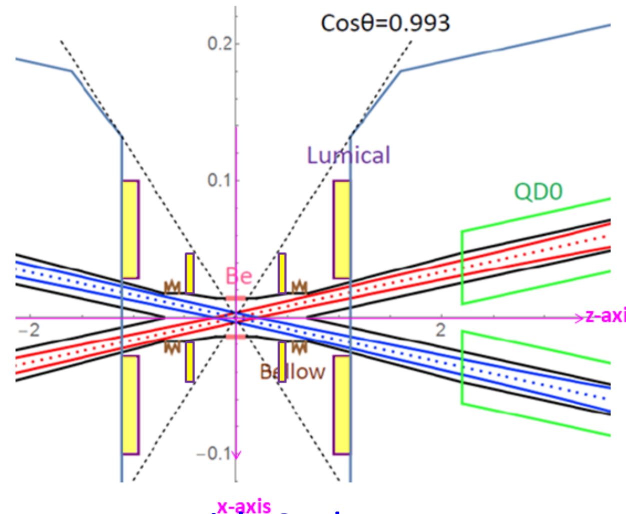
BHLUMI $e^+e^- \to e^+e^-(n\gamma)$ at CEPC

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

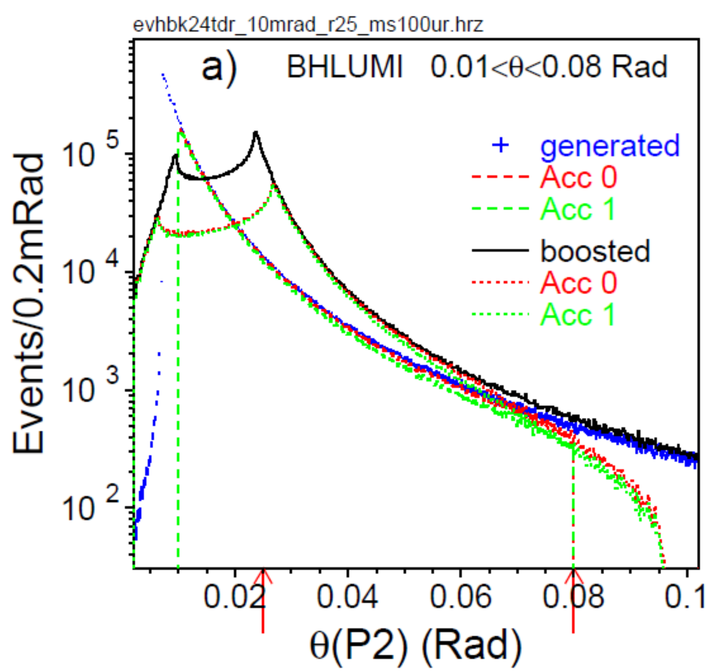
Beam crossing, 33 mRad

➔ Boost in x direct
e^+, e^- offset by 33 mRad

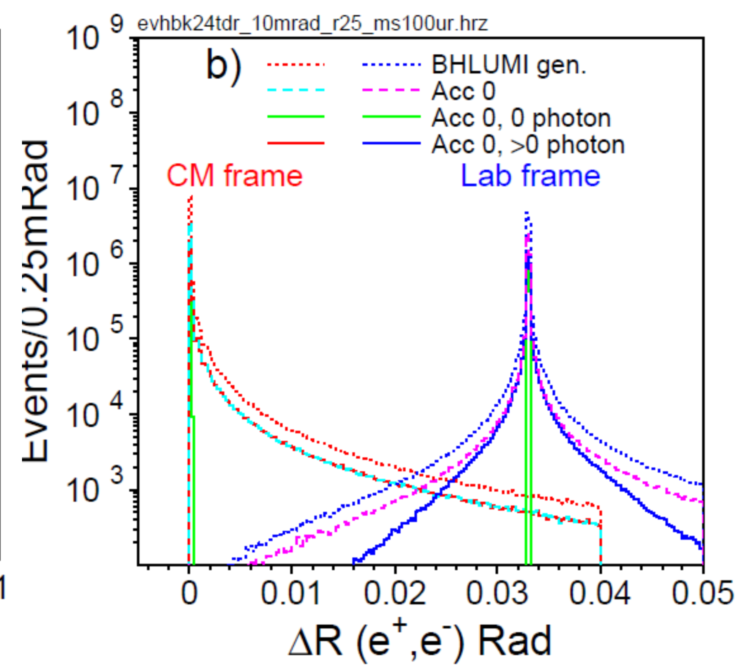


10 M events generated for 10 – 80 mRad,
$\theta(e^\pm)$ distributed from 7 mRad
ACC0 = 47.9 %
ACC1 = 45.9 %

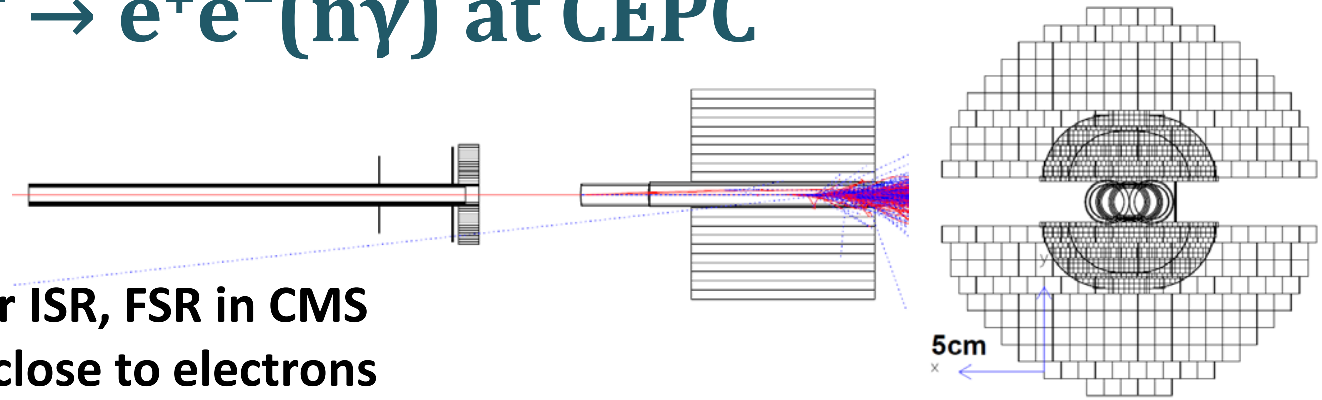
$\theta(e^\pm)$ shown
for CMS
and boosted
of all generated



events with 0 photos
Show δ back-back distribution



BHLUMI $e^+e^- \to e^+e^-(n\gamma)$ at CEPC

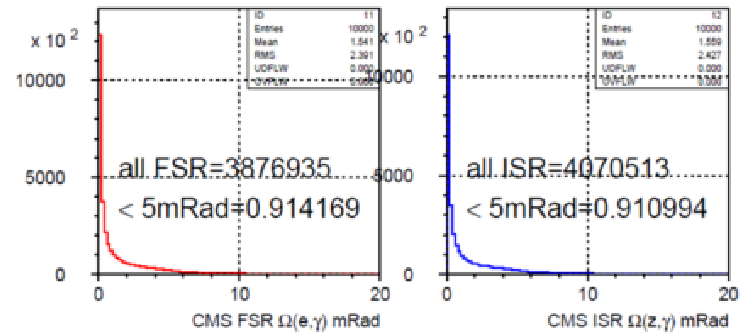


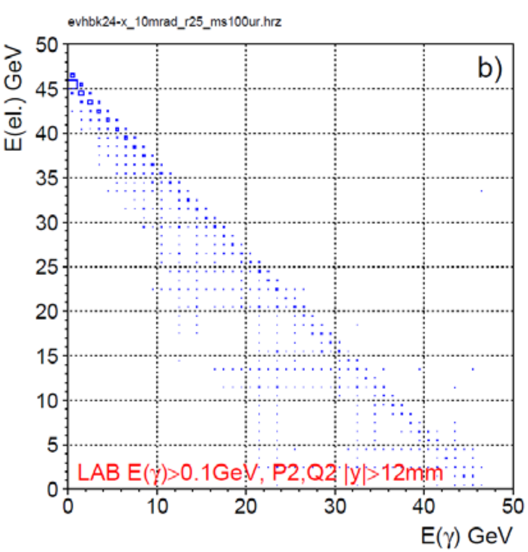
Photons identified for ISR, FSR in CMS with opening angles close to electrons

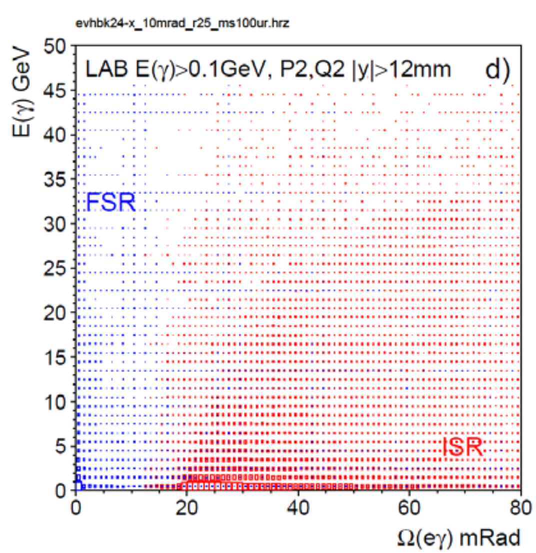
- 91% with $\Omega(e^{\pm},\gamma) < 5$ mRad

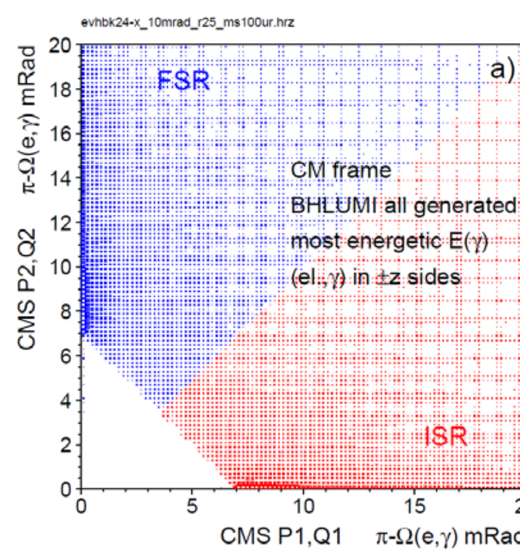
LumiCal acceptance:

- $|y|>12$ mm at LYSO front face $\pm z=647$mm
- boosted $e^{\pm}$ and γ selection applied
- Correlation of $E(e^{\pm})$ and $E(\gamma)$
- ISR vs FSR, by opening angle $\Omega(e^{\pm},\gamma)$ to P2,Q2









Acceptance for $e^+e^- \rightarrow e^+e^-(n\gamma)$ at CEPC

Bhabha events in LumiCal acceptance

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

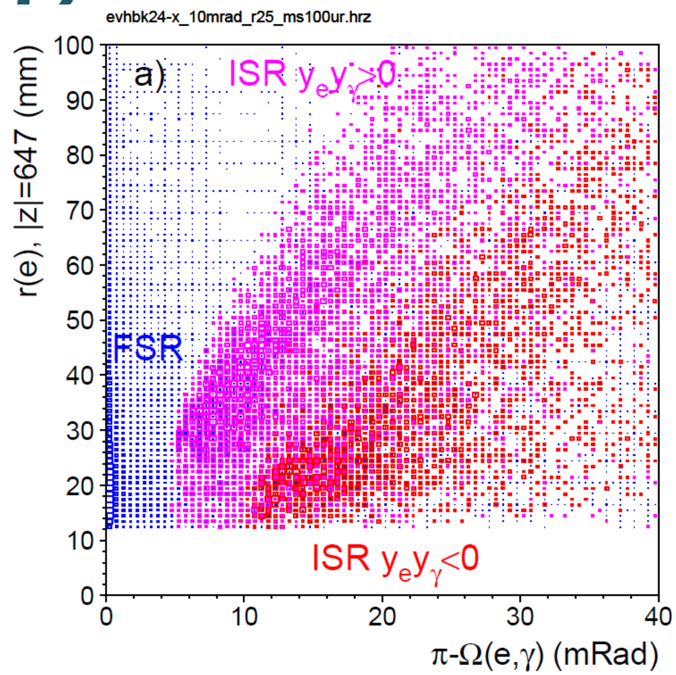
±z Hemispheres	BHLUMI generated	& P2,Q2 |y|>12mm
$e^\pm$	60.3 %	3.87 %
$e^\pm\gamma$	39.7 %*	3.16 %

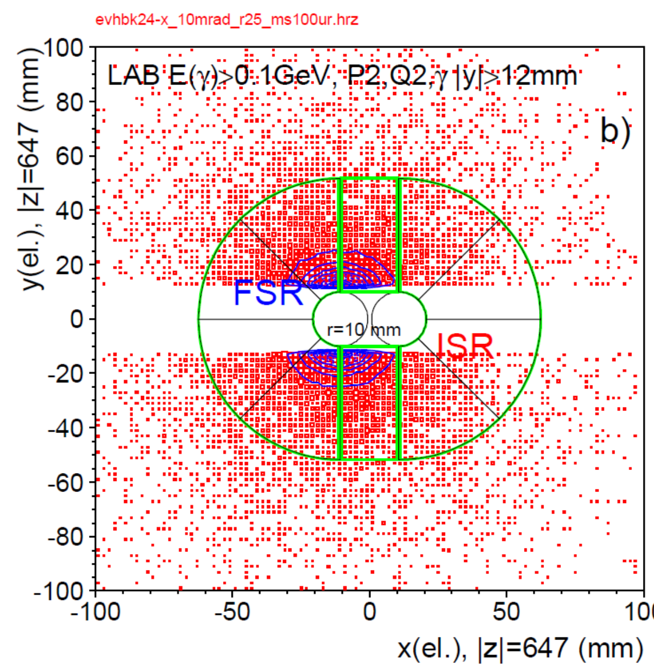
*ISR 20.3%, FSR 19.4%

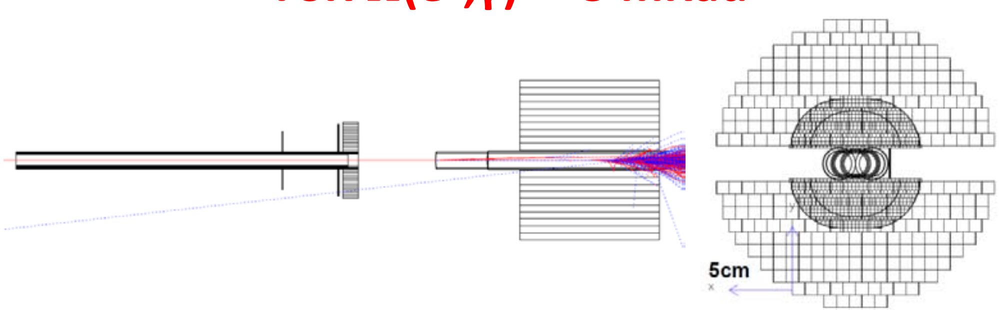
Detectable Bhabha, e^+,e^-,γ : $|y|>12$ mm

±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 % FSR 13.8 % FSR 2.96%*

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







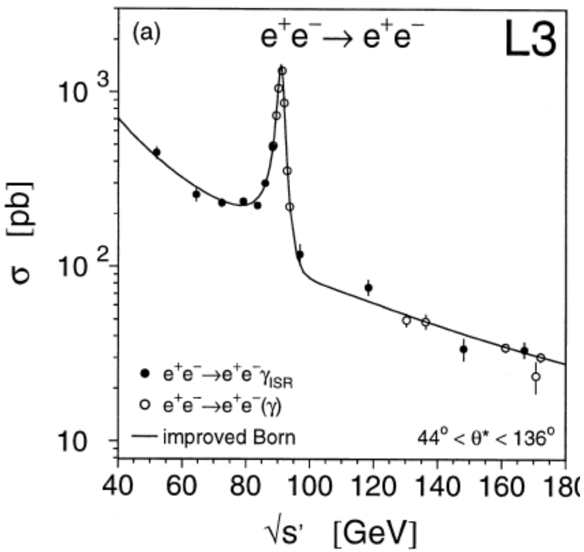
Radiative Bhabha measurements

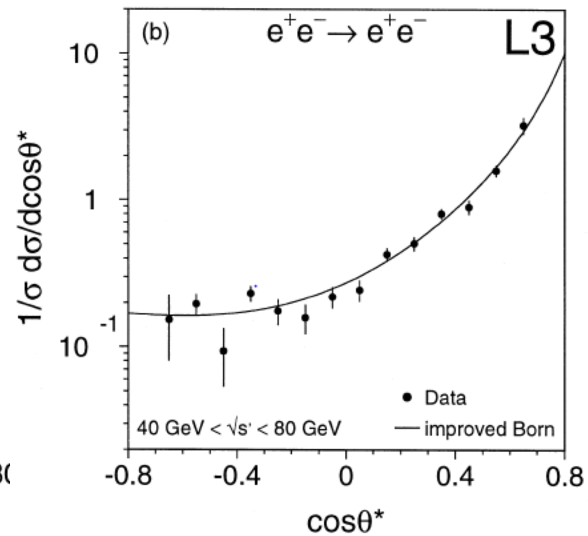
L3 radiative Bhabha with ISR

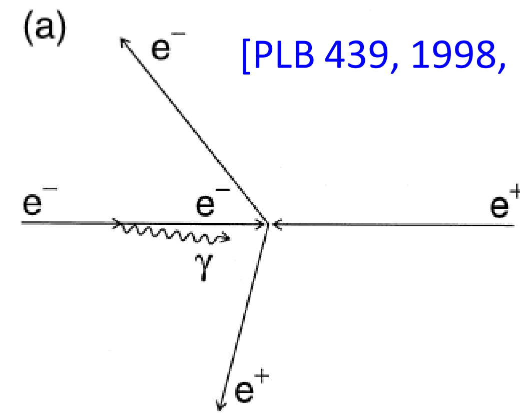
Systematic error at **~1% level**

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

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







[PLB 439, 1998, 183]

TASSO Bhabha

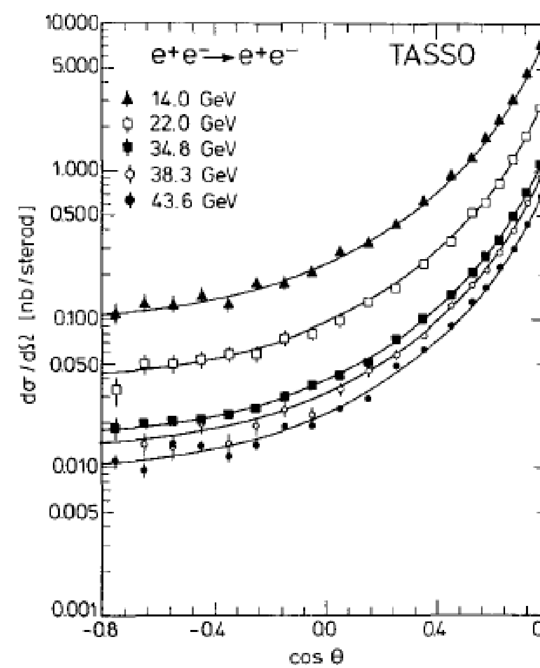
Systematic error **~3%**

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

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

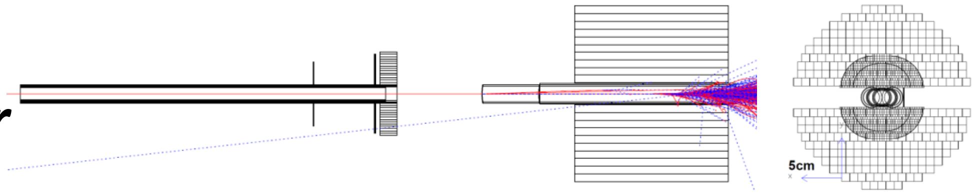
$\langle\sqrt{s}\rangle$ (GeV)	$\int \mathscr{L}\,dt$ (pb^{-1})	N_{Bhabha}
14.0	1.7	10730
22.0	2.7	7106
34.8	174.5	166348
38.3	8.9	6035
43.6	37.1	22951

[ZPC 37, 1988, 171]



LumiCal acceptance, racetrack beampipe

BHLUMI event distribution detecting back-to-back e^+, e^- pair



@|z|=1000mm

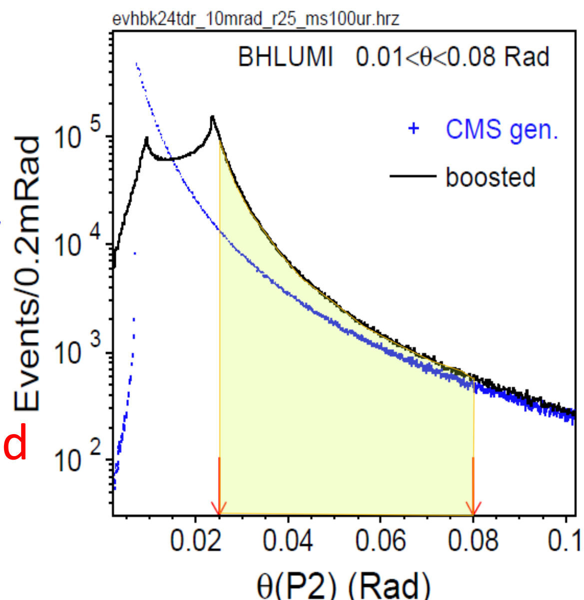
1) Θ > 25mRad outside pipe centers
2) |y|>25 mm
3) Events in shaded area counted for Xsec

Pair of P2,Q2 detected

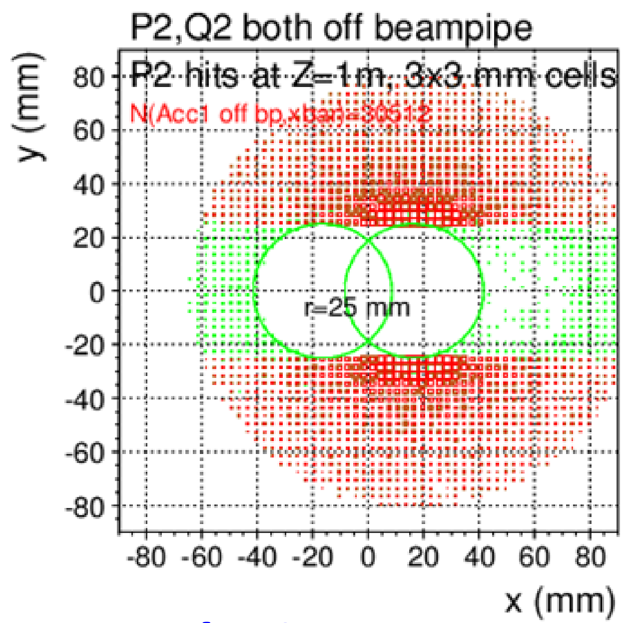
@|z|=1000mm

region |y|<25 mm

10% to r=80 mR full covered



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



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**

Precision for Bhabha event counting to 10^{-4}

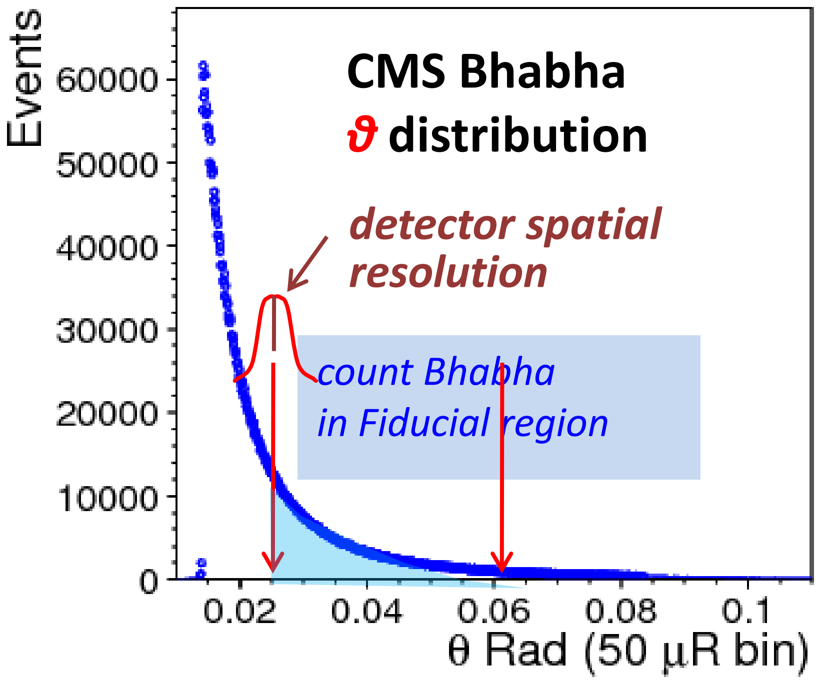
Luminosity $\mathcal{L}$ is derived by

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

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

Bhabha detected for

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



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

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

at ***z = ±1000 mm,*** *ϑ_{min} =* ***20 mRad***

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

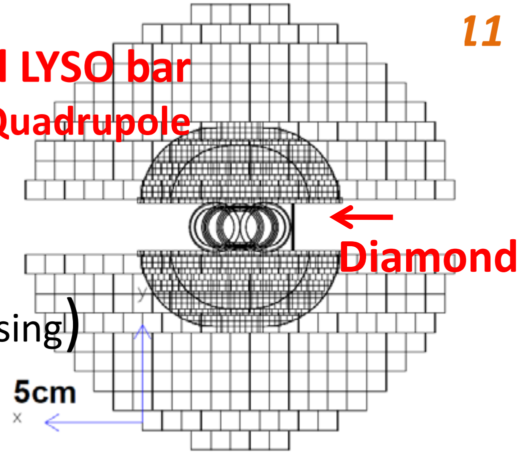
error due to offset on Z

→ ***50 μm*** *on Z eq. dr = δz x ϑ* ***= 1 μm***

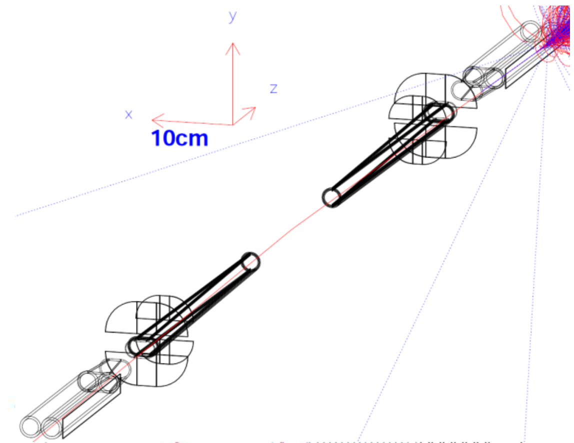
Luminosity systematics ***due to event counting in/out fiducial edge***

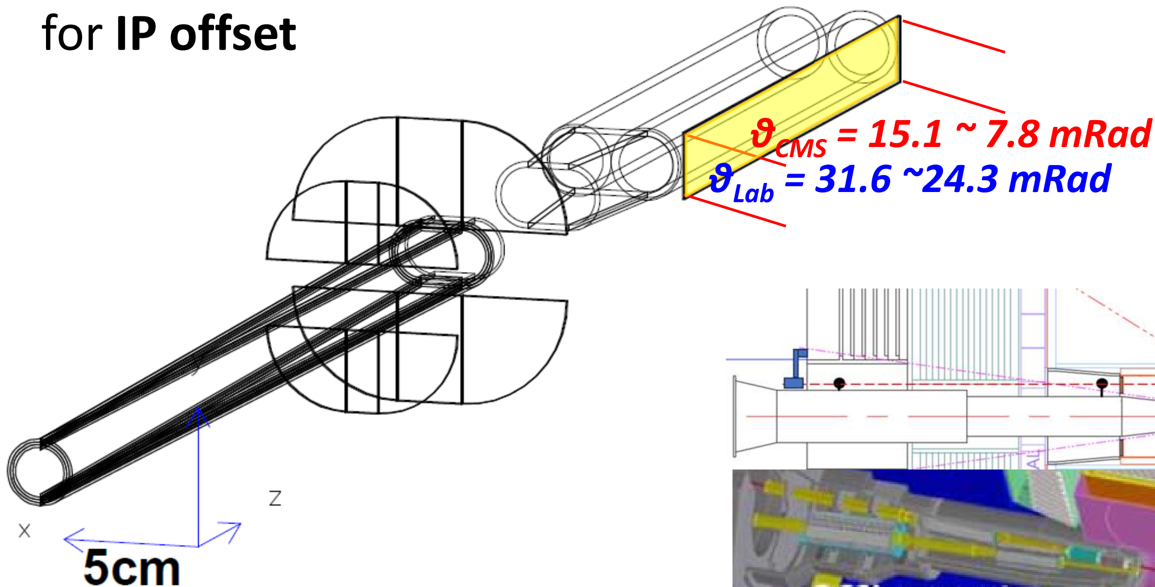
→ ***offset on the mean of θ_{min}***

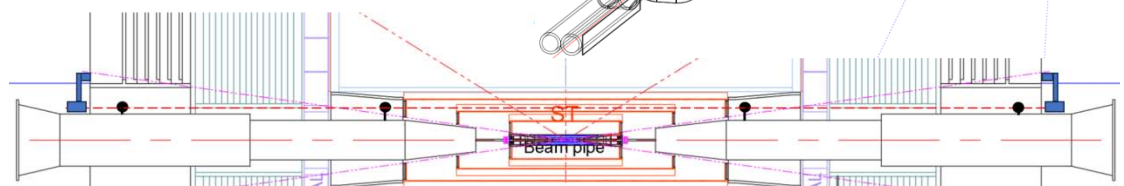
Diamond fast beam monitor

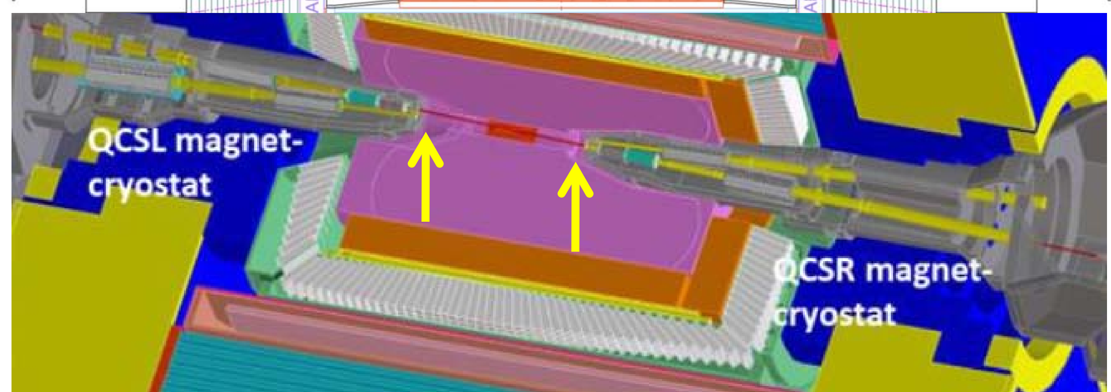


- Beam monitoring on **Bhabha electrons** of ~10 mRad (CMS) ~25 mRad (Lab **33 mRad** beam crossing)
- front of Quadrupole **|z|= 855~1110 mm** **diamond slab,** on sides of beampipe
- differing event rates on +z, -z sides for **IP offset**







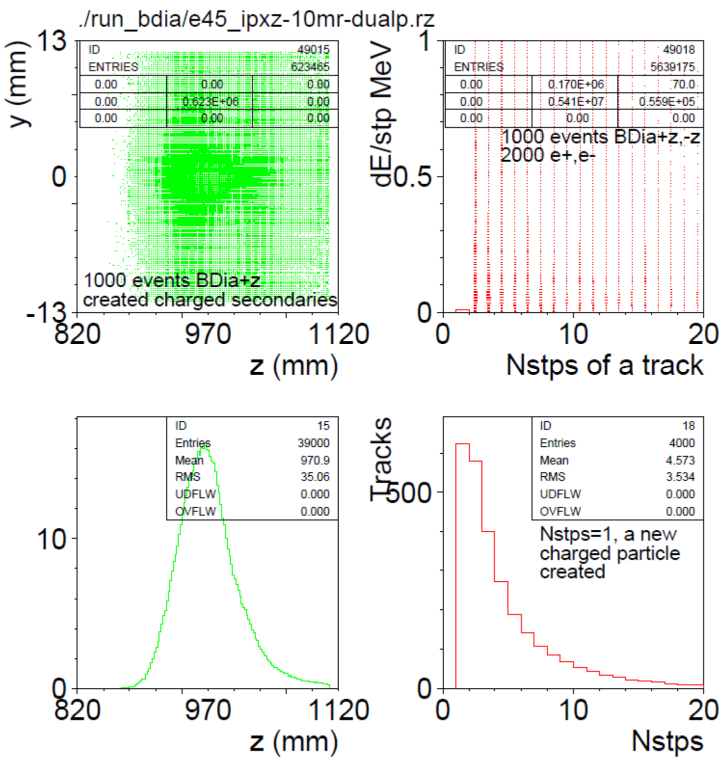


"Fast diamond beam monitor"
G. Fan, J. Zhang, poster this workshop

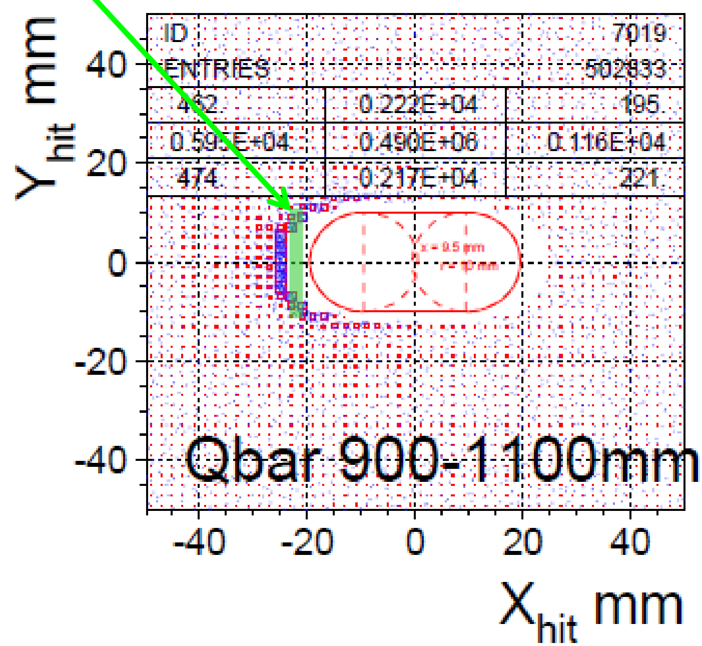
50 GeV electron shower on diamond

- 50 GeV electrons at CMS **10 mRad**, boosted in Lab **26.5 mRad**
- GEANT shower in **3 mm thick Cu beampipe (~300 mm traversing)**
- Measuring dE/step of **charged tracks** (>100 keV) **in diamond**

3mm Cu pipe, @26.5 mRad
ch. Multiplicity Cu+diamond = 620
Shower spread in z: σ_z= 30 mm



Diamond slab covering 8~15 mRad
X-sec order of ~100 nb

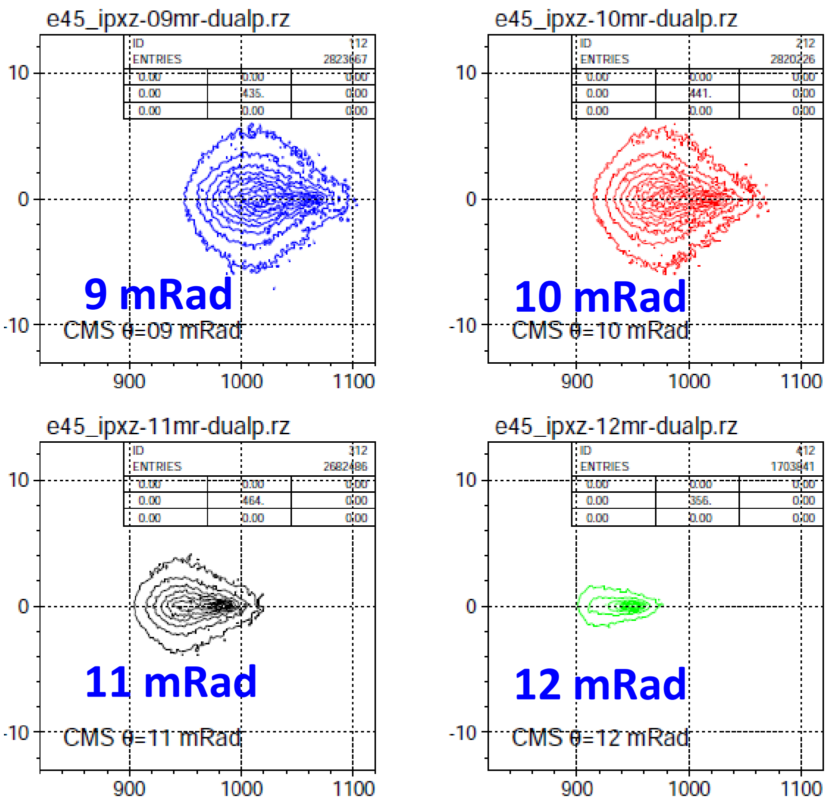


Event rate @Z, L=1x10^{36}/cm^{2}s
= (100x10^{-33}) x (1 x 10^{36}) /s = *~100 kHz*

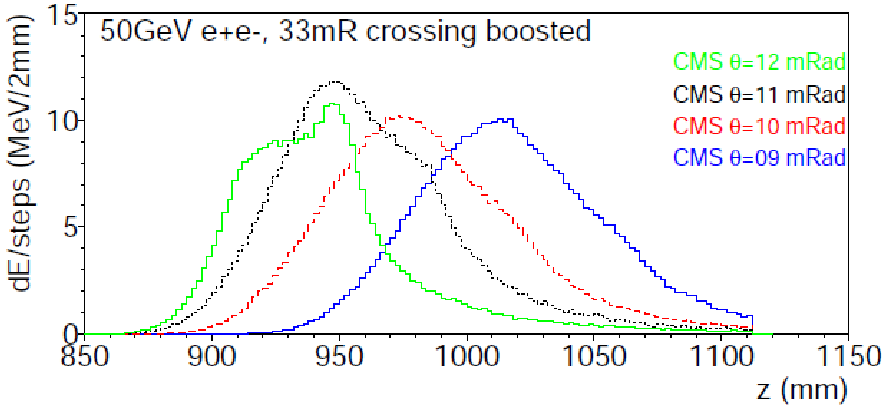
Electron shower spread in θ on diamond

- Shoot 50 GeV electrons at CMS **9 ~ 12 mRad**, **Lab 25.5 ~ 28.5 mRad**
- dE/step deposits of charged tracks (>100keV) in diamond

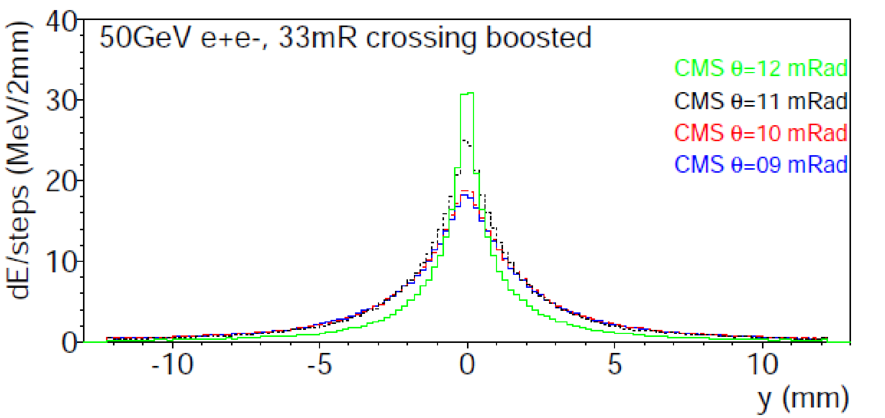
dE/steps in y-z diamond slab on +z side



dE/steps in z profile



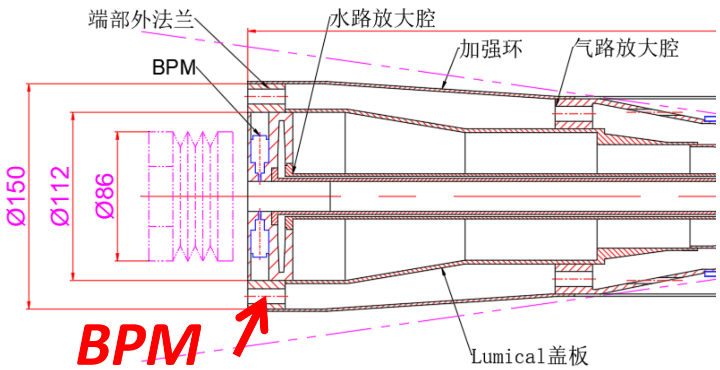
dE/steps in y profile

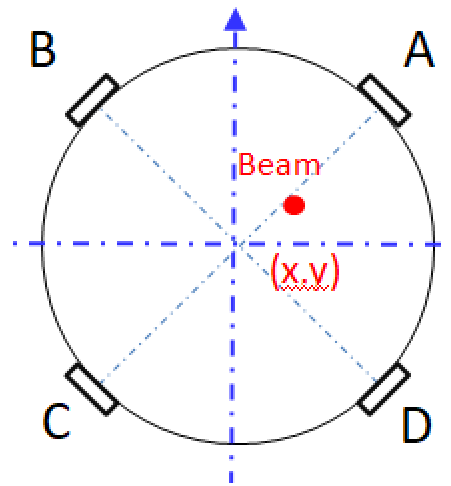


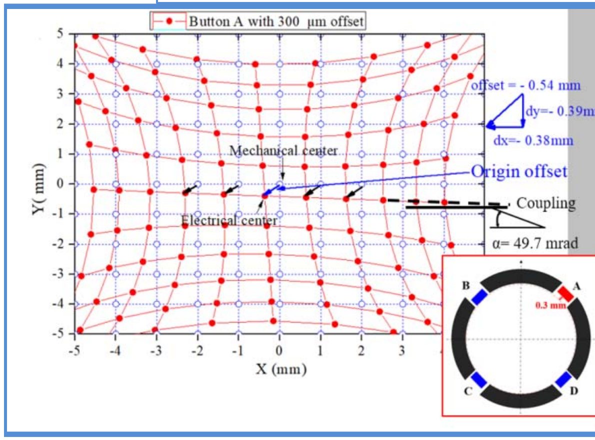
Survey/monitoring, for Beam IP position

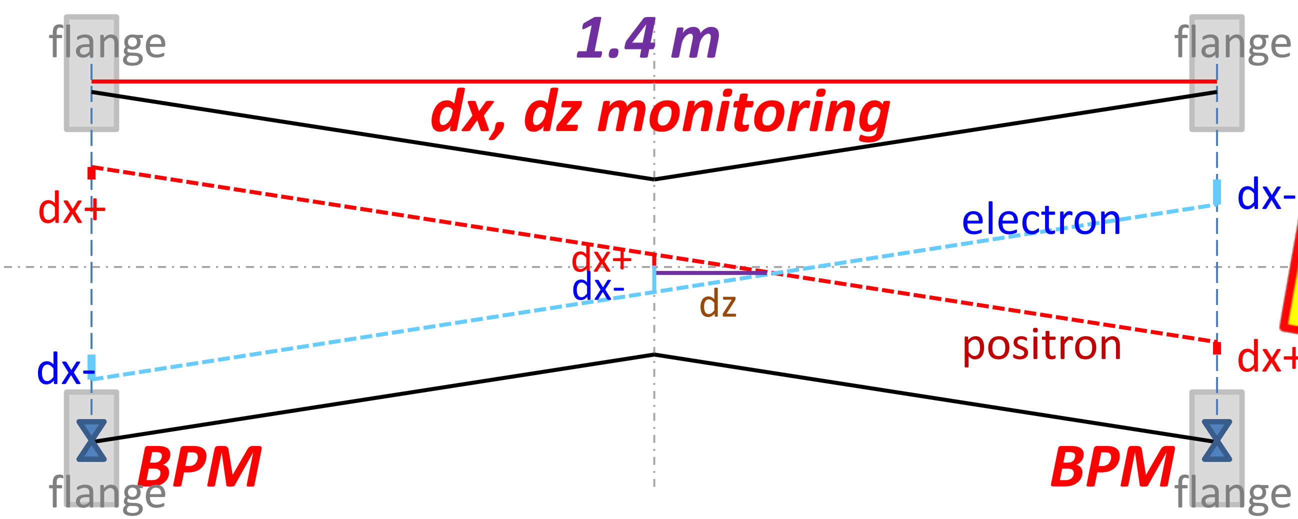
- Beam Probe Monitor ***BPM***
- Position monitoring, Flange dx,dy ~1 ***μm***, dz~ ***50 μm***

CEPC WS2023, J. He









LumiCal 挑战
监测位置
1. 法藍 *dx,dy 1 μm, dz 50 μm*
2. 电子束流 *dx,dy 1 μm*

Smearing @ IP position of BHLUMI

- **bunch size $\sigma_x = 6\ \mu m$, $\sigma_z = 9\ mm$**

➔ ***IP spot, 33mRad Xing***

$\sigma_x = 6\ \mu m$, $\sigma_z = 380\ \mu m$

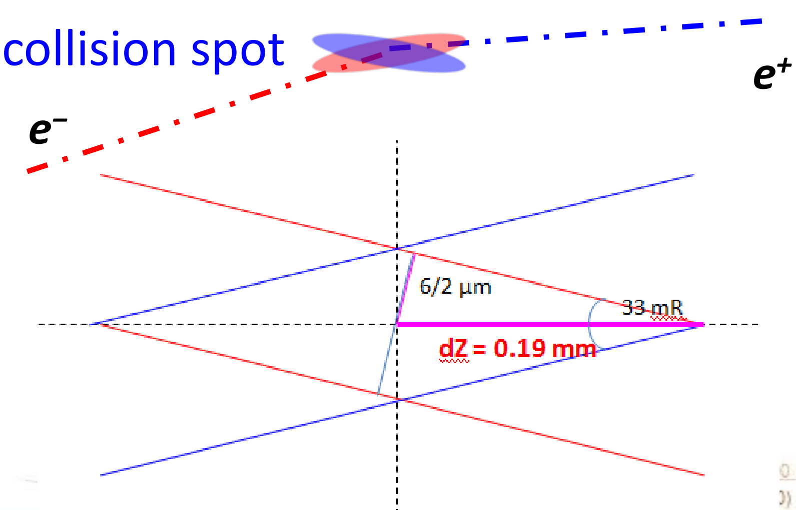
- ***$Z \rightarrow e^+, e^-$ at ϑ=30 mRad***

smearing at @z=560mm

smeared width ***$\sigma(\vartheta)$ = 24 µRad***

back-to-back ***$\sigma(\Omega)$ = 21 µRad***

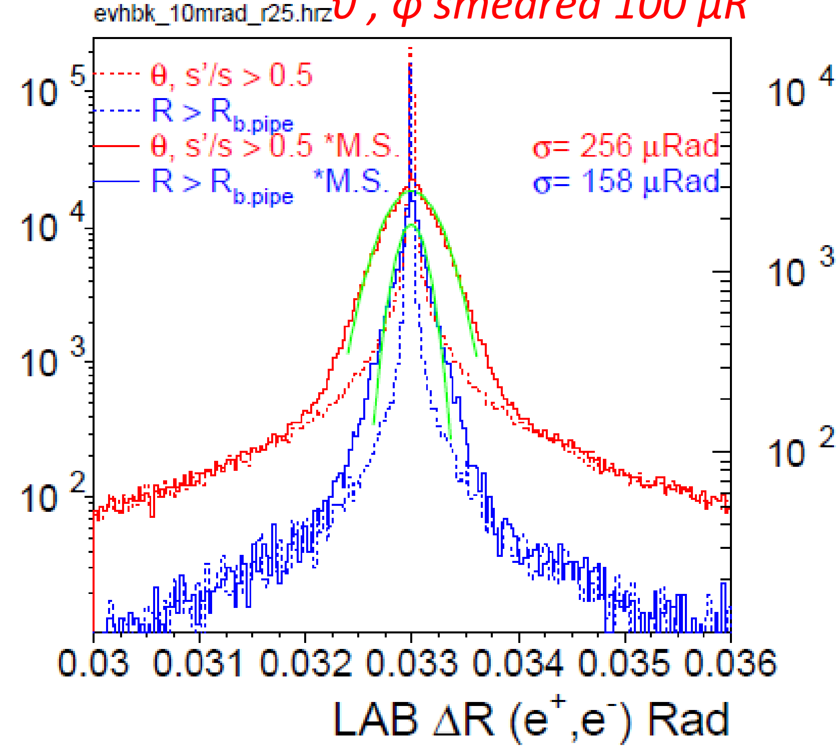
IP collision spot

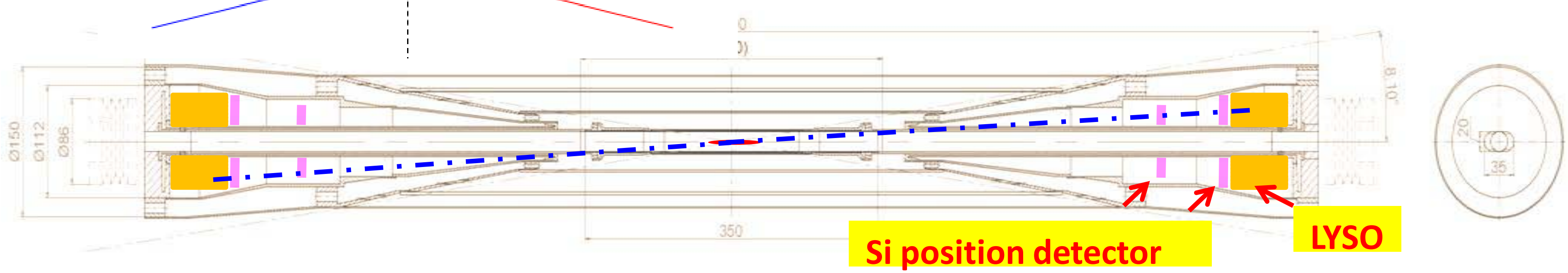


e^+, e^- *back-back*

compare scattered e^+, e^-

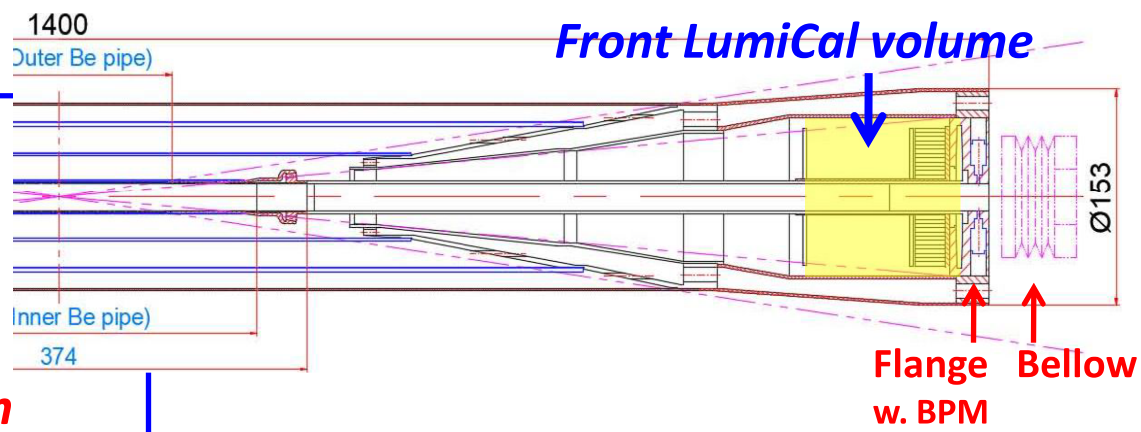
ϑ, φ smeared 100 µR

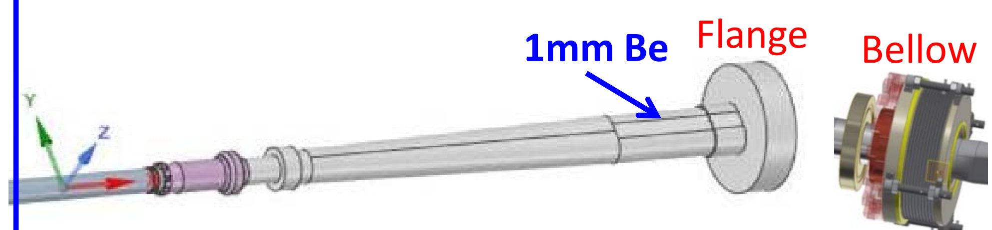


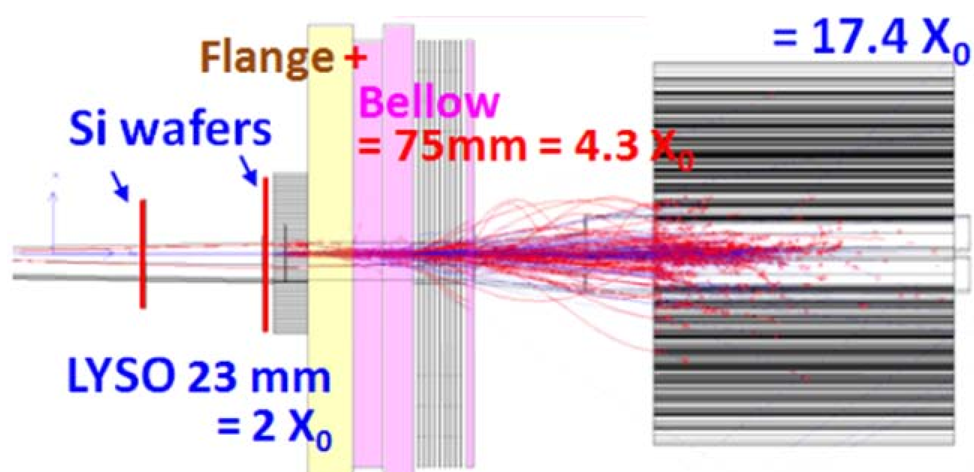


CEPC LumiCal design

- ***L=2x10^36*/cm²s¹ @Z-pole,**
  - ***ø 20 mm*** racetrack, beam-crossing ***33 mRad***
  - IP bunch : ***σ_x σ_y σ_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 traversing 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**
  - **17.4 X_0 LYSO 200 mm**







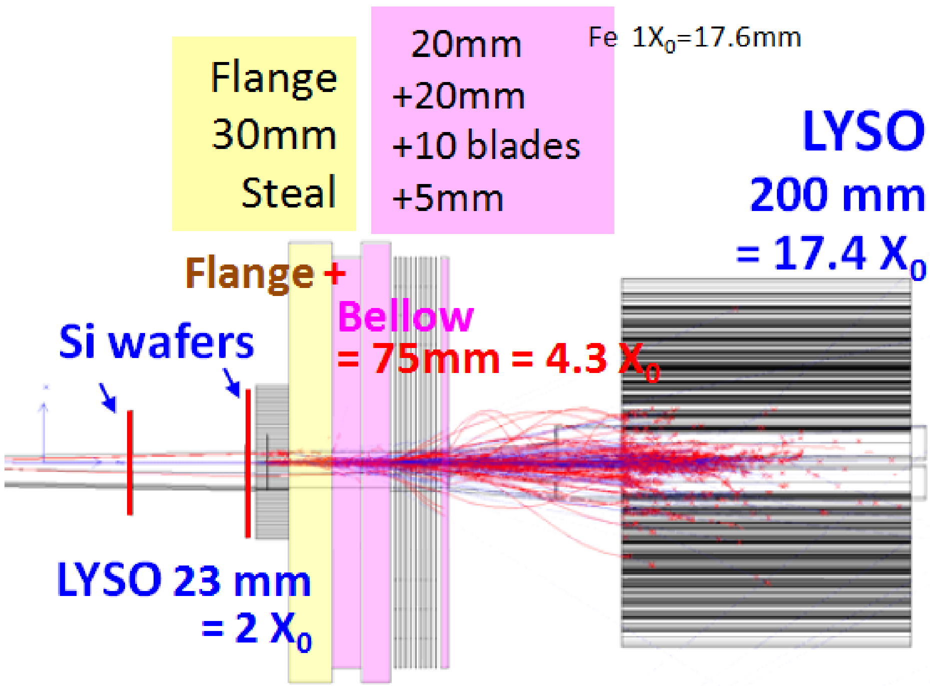
GEANT LumiCal electron shower

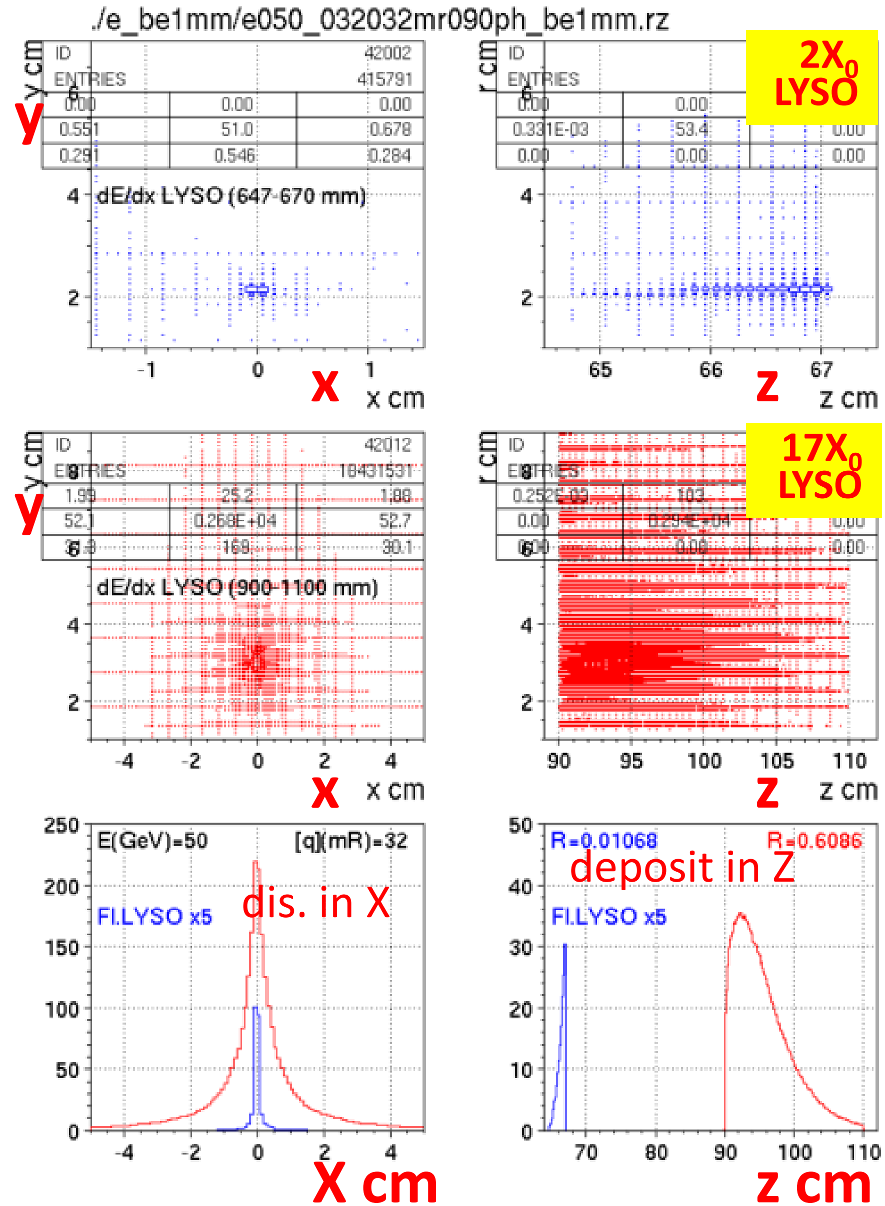
50 GeV electron @ θ = 32 mRad, φ=90°

- 2X0 LYSO + 4.3X0 Flange,Bellow
  + 17X0 LYSO

Shower deposition, by Sum(dE/dx)

- in front LYSO: ~1.0 %
- in back LYSO: ~ 61 %





Front $2X_0$ LYSO, on radiative e,γ

Bhabha hits on LYSO, |y|>12mm

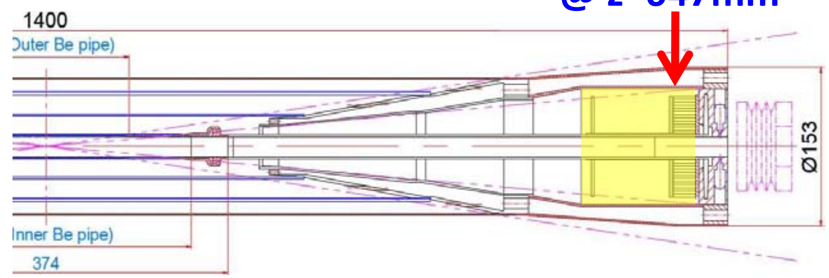
Incident particles are $e^{\pm}$,(γ)

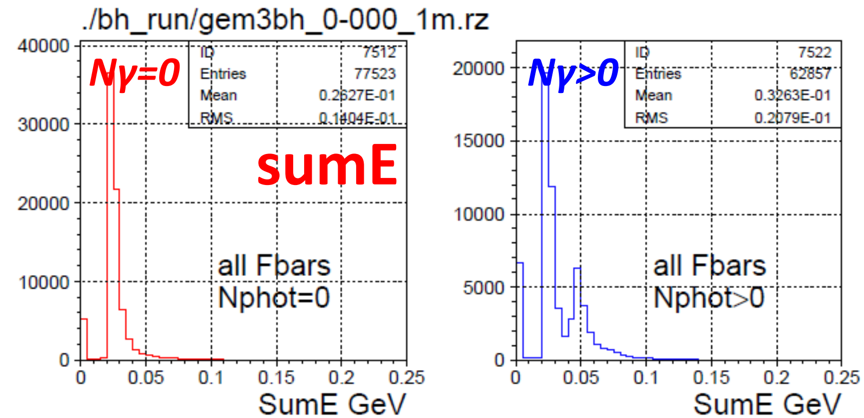
- **GEANT sum dE/dx in each LYSO bars**
  $3x3mm^2$, 23 mm long, $2X_0$
- **Deviation to $e^{\pm}$ truth** (impact hit $>E_b/2$)
  mostly < 0.2mm
- **Hit distributions in a Bar**
  distributed due to Bhabha θ, w./w.o. photon

sum dE/dx all LYSO bars (a plane)

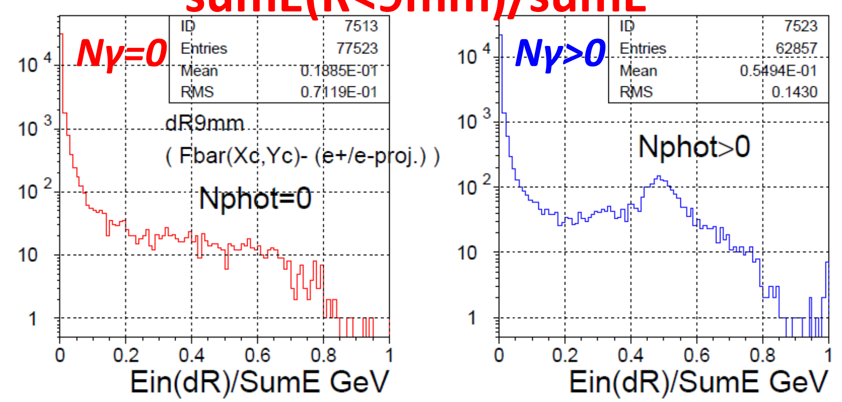
- **$e^{\pm}$ one track : sumE min. 20 MeV**
- **($e^{\pm}$ + FSRγ) : two MIPs, sumE x2**

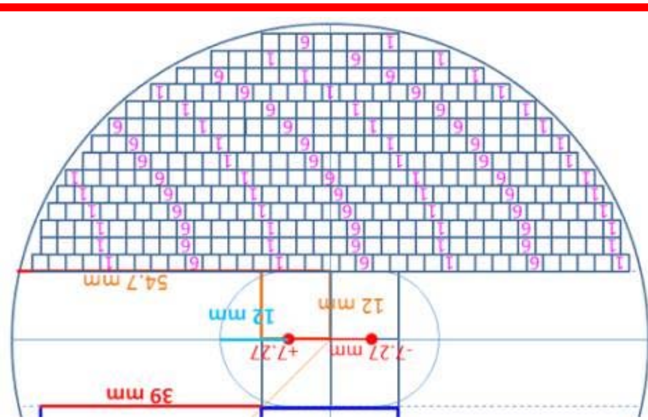
$2X_0$ LYSO
@ z=647mm





sumE(R<9mm)/sumE

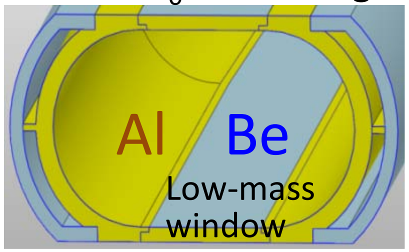




Electron hits on 1st Si-wafer

1 mm Be thin pipe window

33mm = $0.09X_0$ traversing @ 30mR

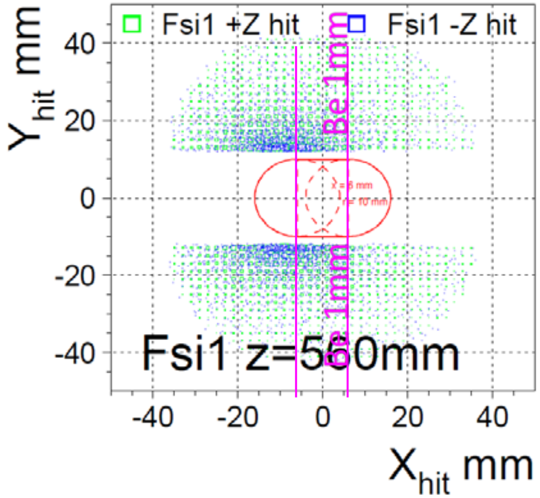


IP $(\sigma_x,\sigma_z) = (6{,}380\ \mu m)$

50 GeV e^+, e^- @ ($\vartheta = \pm 30$ mRad, $\varphi = 1.0, 1.0+\pi$ Rad)

Si wafer @z=560mm

- $|x|<6.0$ mm $\sigma(\vartheta) = 54\ \mu R$ (1mm Be)
- $|x|>6.0$ mm $\sigma(\vartheta) = 95\ \mu R$ (1m Al pipe)
- back-back Op.Ang $\sigma(\Omega) = 137\ \mu R$



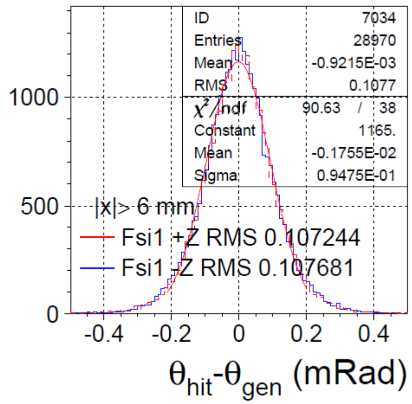
NJU GEANT4 validation, test-beam preparation

Be(1mm): $\sigma(\vartheta) = 30\ \mu R$

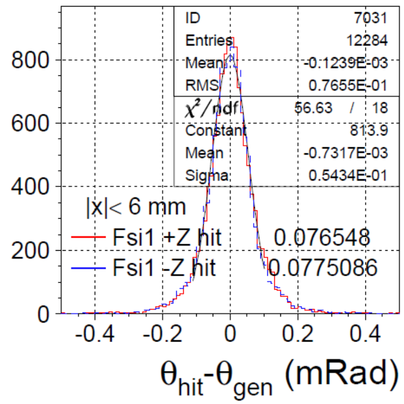
Be(2mm): $\sigma(\vartheta) = 50\ \mu R$

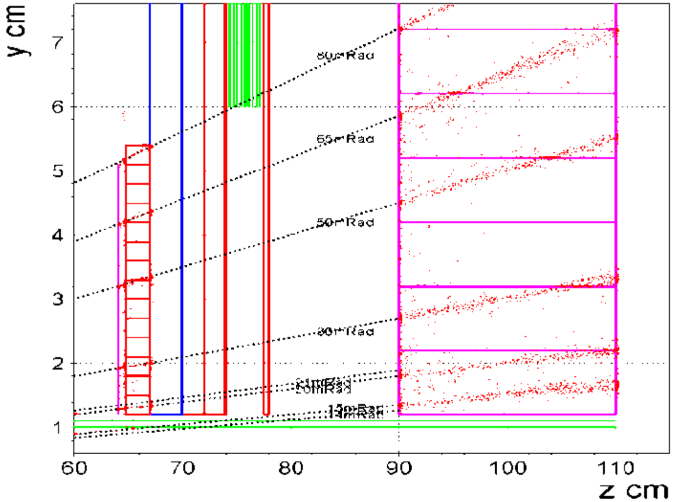
➔ GEANT tracking steering, testbeam confirmation

e± GEANT hit – gen. |x|>6



hit – gen. |x|<6





multiple scattering, against 10^{-4}

1. BHLUMI scattered e^+, e^-

Multi. Scatt. smearing 100 μRad

$\theta' = \theta \cdot \sigma\,(100\mu R)$, $\phi' = \phi \cdot \sigma(100\mu R)$

2. δN/N due to σ(100μR) smearing

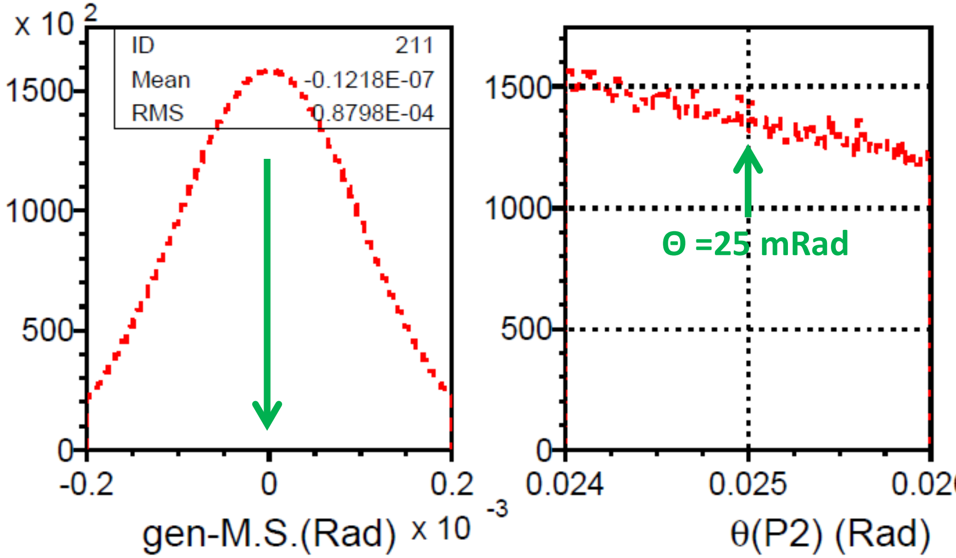
δN = deviation due to Multi.Scatt.

effect is Gaussian, Symmetric

at θ_{min}= 25 mRad, slope of Bbhabha

in neiboring 100 μRad bins to 25mR

δN(@25mR)/N(25-80 mR) < 10^{-4}

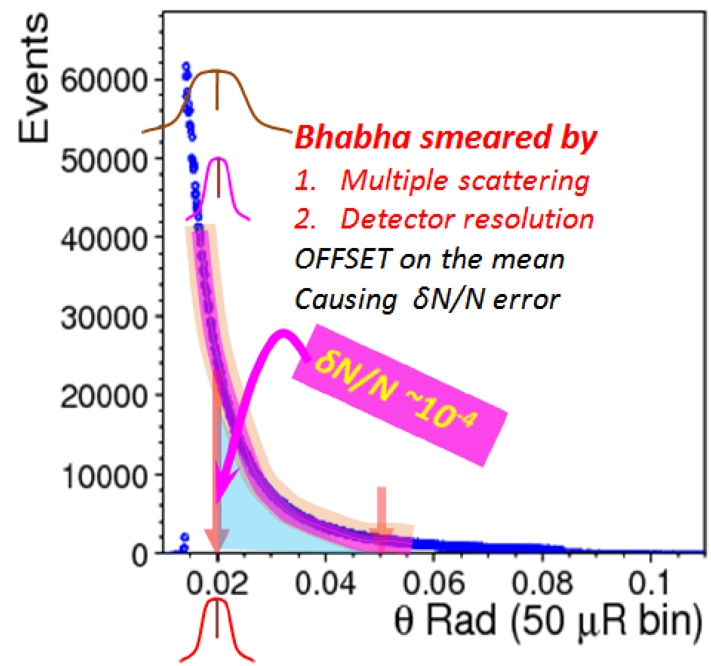


10^{-4} is determined

1. Multi.Scatt. distribution

2. survey of the mean position

(shift of the arrow)



Achieving 10^{-4} on Radiative Bhabha

Bhabha electrons, θ deviated by radiative photon

measuring e,γ vs QED predictions and cross section

- Si-det on electron θ, multi.scatt. ~50 μRad
- ISR/FSR of e,γ in LYSO, 3x3 mm^2 segmentation

Beam line, IP measurement

slow control & monitoring on beam x,y positions

- 1 μm precision on single beam position
- e^+,e^- beam line crossing → IP position,
  x,y, and z by beam-crossing, with the means better than 1 μm

Test beams preparation for

- Multiple scattering by ~1° of 1mm thick Be
- Electron shower sampling, in CEPC MDI configuration