https://indico.ihep.ac.cn/event/25730/

Achieving 10^{-4} luminosity with LumiCal @ CEPC

2025.04.21
S. Hou

- **LumiCal group** (weekly meetings, onging 2yrs)
- **TDR** design accomplished, aim for 10^{-4}
- **Goal**: IP BPM, Radiative Bahbha, Survey monitoring
- **Prototyping**: Diamond, Tracking multi-scattering
  forward LYSO, BPM @BES III

高能所 **IHEP:** MDI, beam-pipe, mechanics: Haoyu Shi, Quan JI, Longyan He, …
BPM: Jun He, …
AC LGAD: Mei Zhao, …
物理所 **AS**： Generator, GEANT: Suen Hou
吉林大学： Generator, BESIII BPM: Weiming Song, Jiading Gong
南京大学： Generator, GEANT4: Lei Zhang, Renjie Ma, Yilun Wang
Diamond, LYSO: Jialiang Zhang, …
Si tracking: Changhua Hao, Yuhui Miao, Xingyang Sun, Ligang Xia
LumiCal : IHEP: Xiao Cai , Sheng Dong, Jingzhou Zhao, Jie Zhang
prototype : NJU: Lie Zhang, Liangliang Han, Zhenwu Ge

SM LEP to CEPC

SM *Z-lineshape* $e^+e^- \to Z \to q\bar{q}$

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

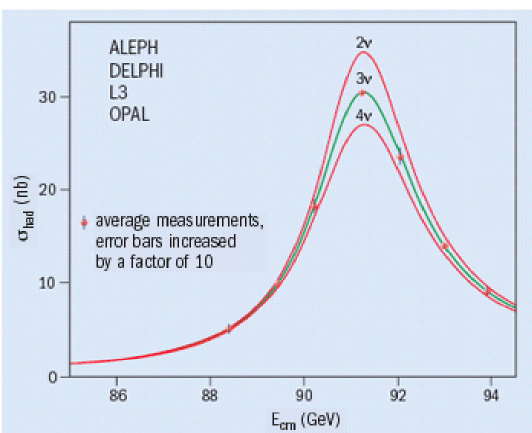
LEP: 17 Million Z (4 IP)
L= 4.3 $10^{31}/cm^2s$ (E=46GeV)
= $1x10^{32}/cm^2s$ (E=100 GeV)

➔

CEPC Z-pole : $2x10^{12}$ events
L~ $10^{36}/cm^2s$ (Z-pole)
dL/L < 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‰**

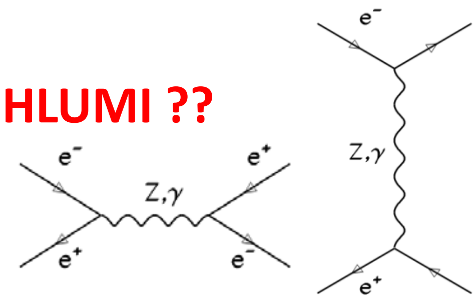


CERNCOURIER 2 November 2005

Bhabha generator

was BHLUMI 4.04 ➔ **still BHLUMI ??**
S. Jadach [CPC 101 (1997) 229]

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



Hardronic correction to reach ***0.01%***

Framework of YFS exponentiation

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

predict ***nγ*** Poisson photons (not confirmed)

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

LEP luminosity achieved

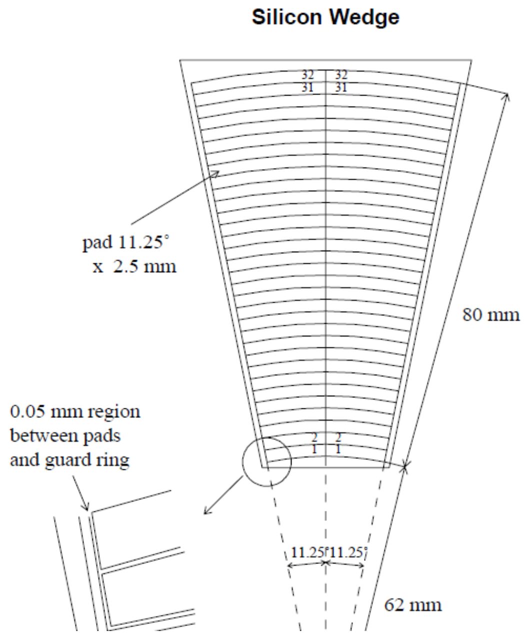
Bhabha events
Not calibrated

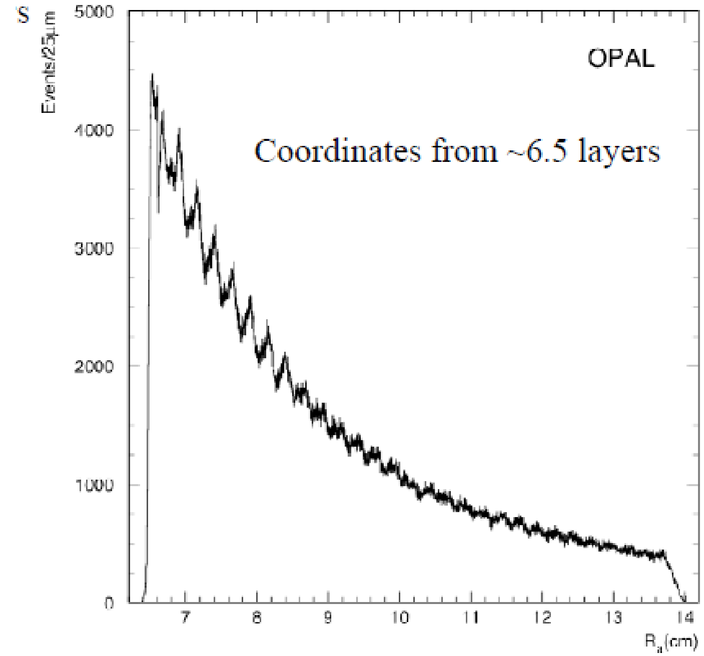
Si pad 2.5mm pitch

EPJC 14 (2000) 373

OPAL precision

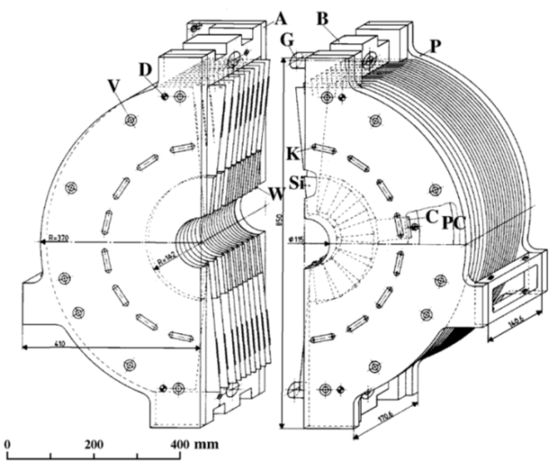
σ_{Bhabha}	79 nb
Expt	**3.4×10^{-4}**
Theo	5.4×10^{-4}

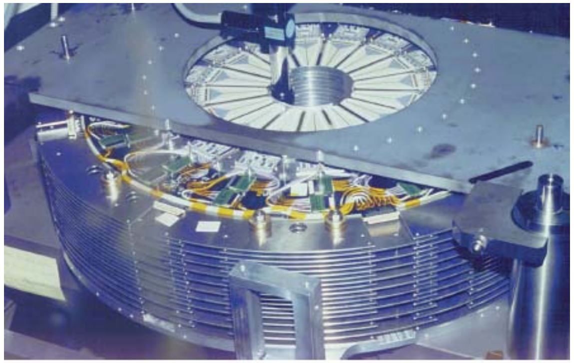


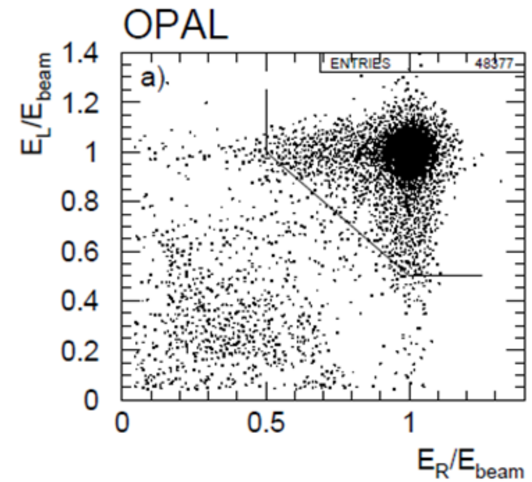


6.2 – 14.2 cm,

θ = 25 – 58 mrad







Radiative Bhabha expt results (only @LEP)

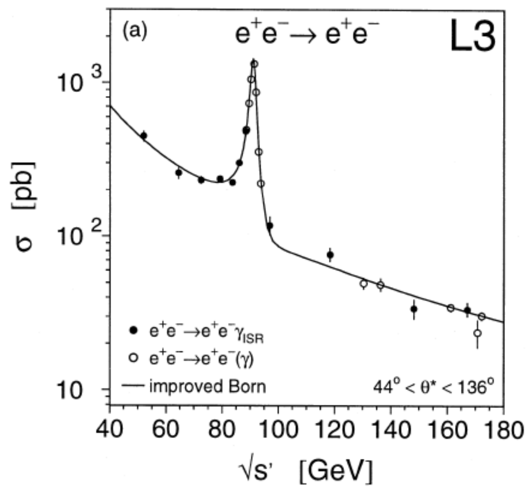
L3 radiative Bhabha with **ISR**

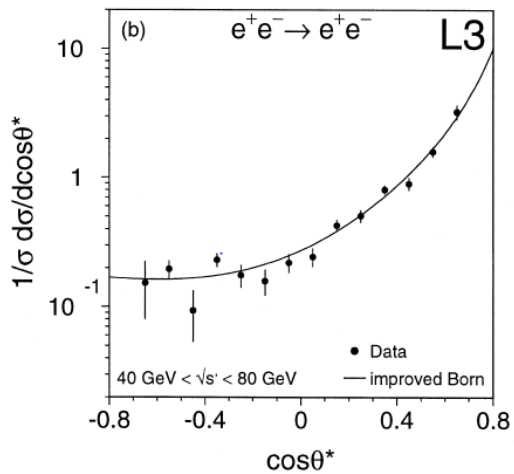
Systematic error at **~1% level**

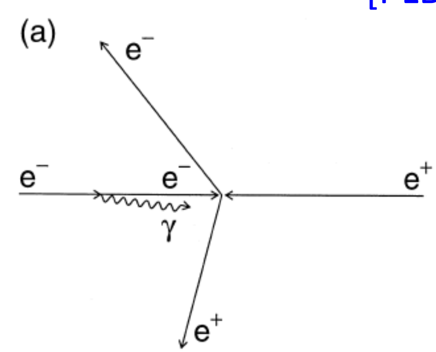
$e^+e^- \rightarrow e^+e^- (\gamma)$

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

[PLB 439, 1998, 183]







TASSO Bhabha

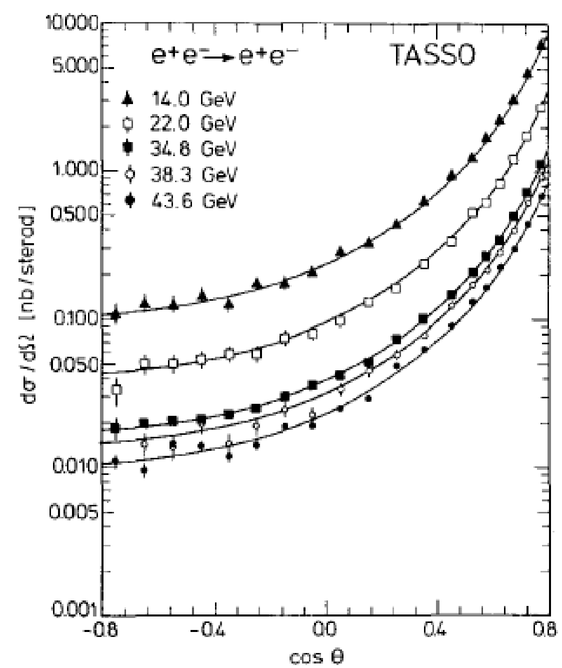
Systematic error **~3%**

√s = 12 ~ 47 GeV

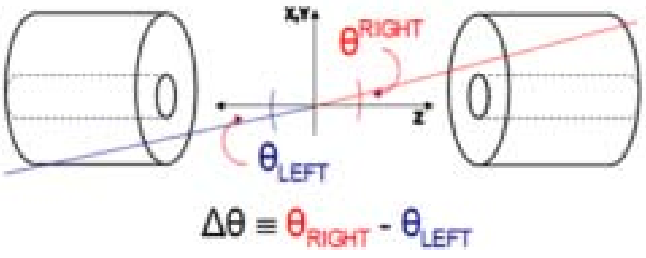
Table 1. Data samples used for the analysis $e^+e^- \rightarrow e^+e^-$

$\langle\sqrt{s}\rangle$ (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]



Bhabha event counting to 10^{-4}



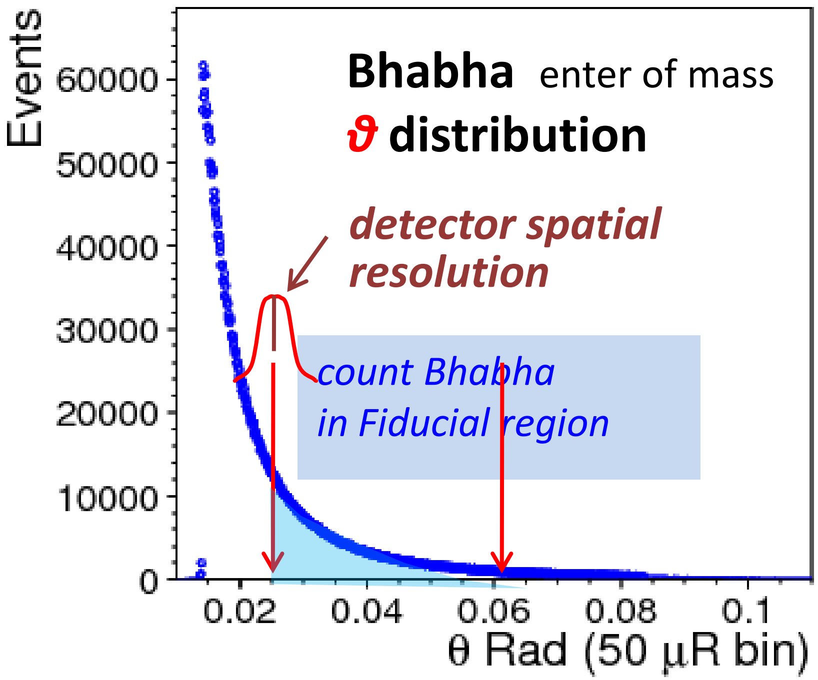
Luminosity $\mathcal{L}$ is derived by

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

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

Bhabha detected for

- *a pair of back-back electrons,*
- *precision 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 = $\delta z \times \vartheta$* ***= 1 μm***

Luminosity systematics ***due to***

event counting in/out fiducial edge

→ *offset on the mean of θ_{min}*

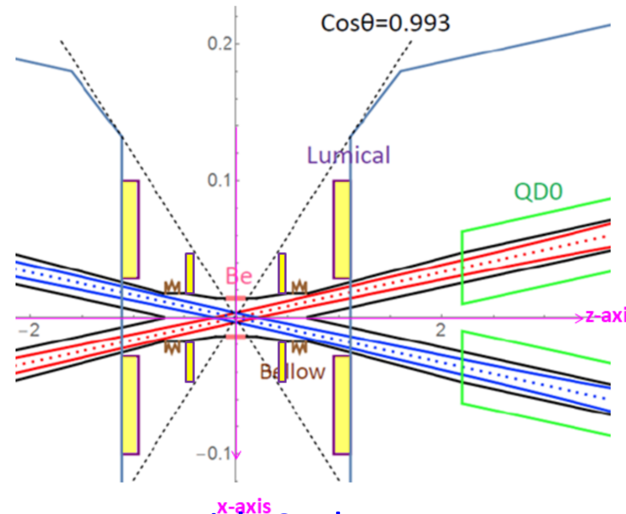
QED BHLUMI $e^+e^- \to e^+e^-(n\gamma)$ at CEPC

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

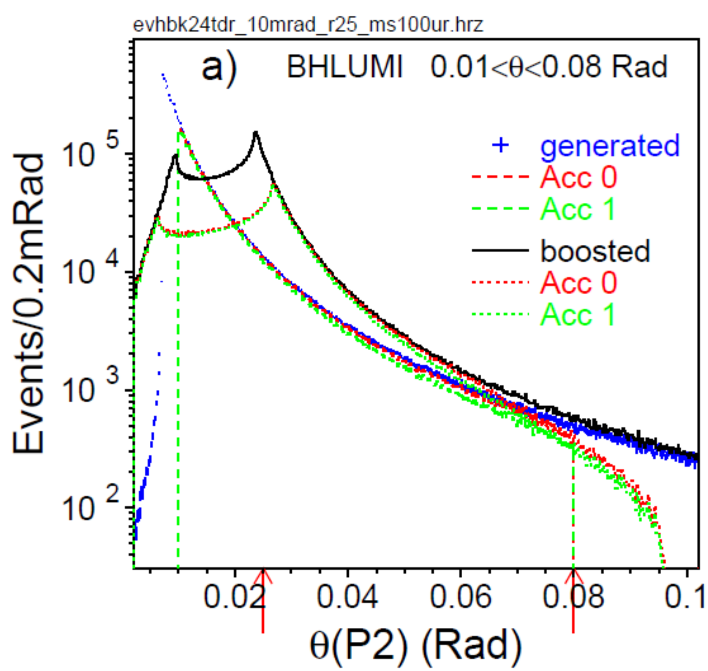
Beam crossing, 33 mRad

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

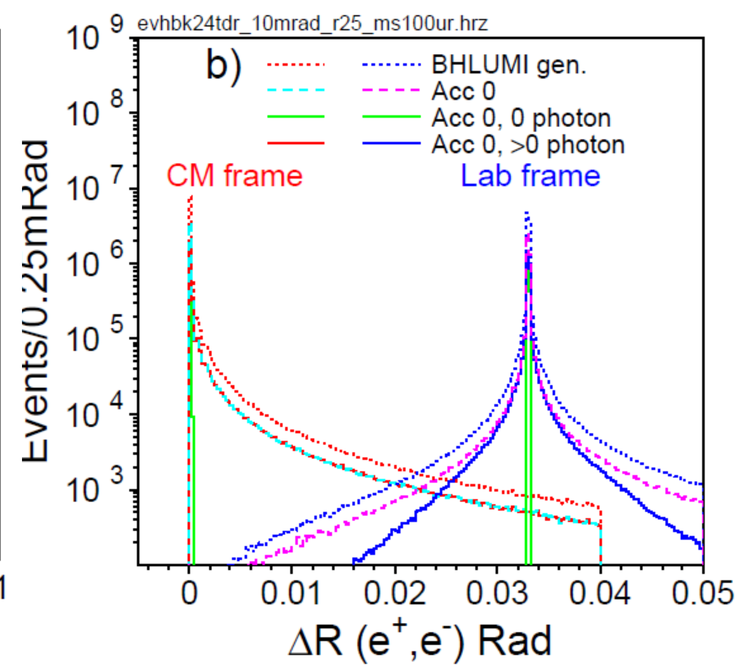


10 M events generated for 10 – 80 mRad,
$\theta(e^{\pm})$ distributed from 7 mRad
ACC0 = 47.9 %
ACC1 = 45.9 %

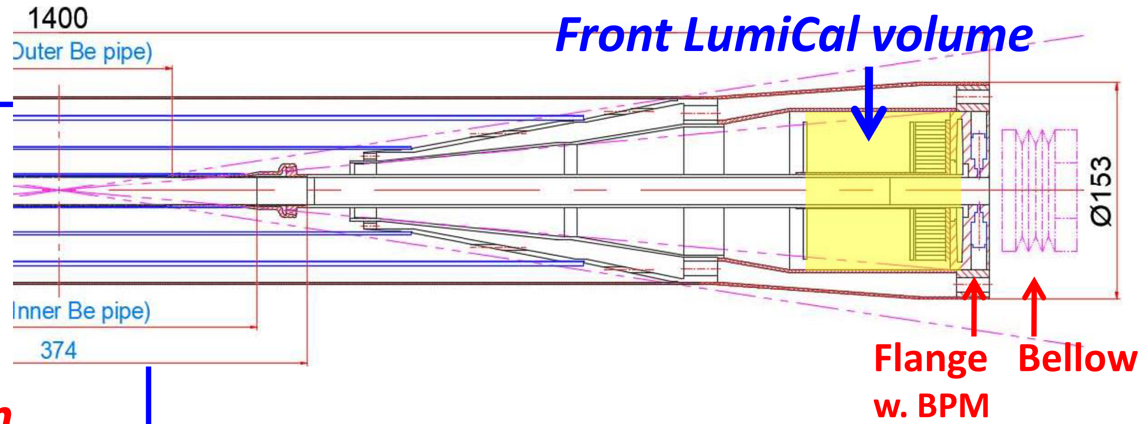
$\theta(e^{\pm})$ shown
for CMS
and boosted
of all generated



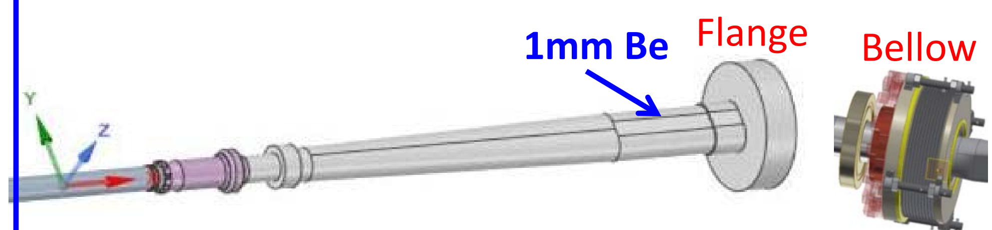
events with 0 photos
Show δ back-back distribution



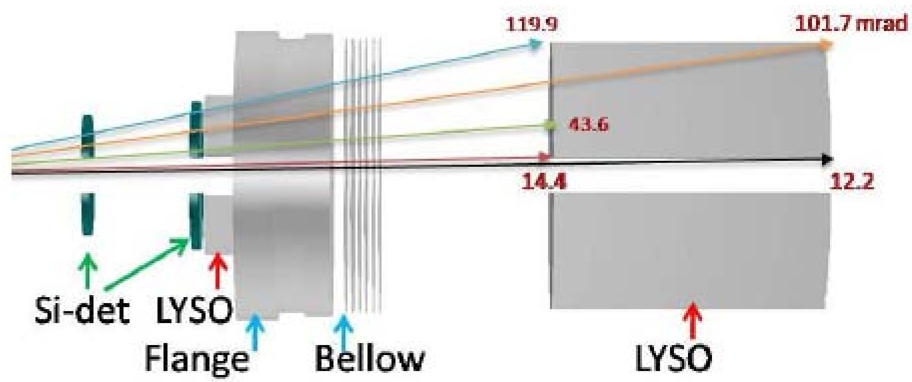
CEPC LumiCal design



- ***L=2x10^{36}***/cm^{2}s^{1} **@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***



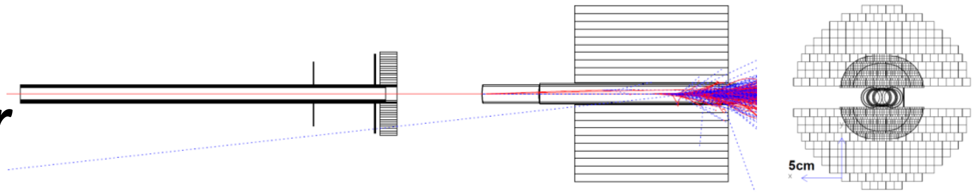
- ***before Flange*** z = 560~700 mm
  - **Low-mass beampipe window**: **Be 1mm thick** traversing @22 mRad traversing L= 45 mm, **= 0.13 X_0 (Be), 0.50 X_0 (Al)**
  - **Two Si-wafers** for e$^{\pm}$ impact θ
  - **2X_0 LYSO** = 23 mm



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

LumiCal acceptance, racetrack beampipe

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



@|z|=1000mm

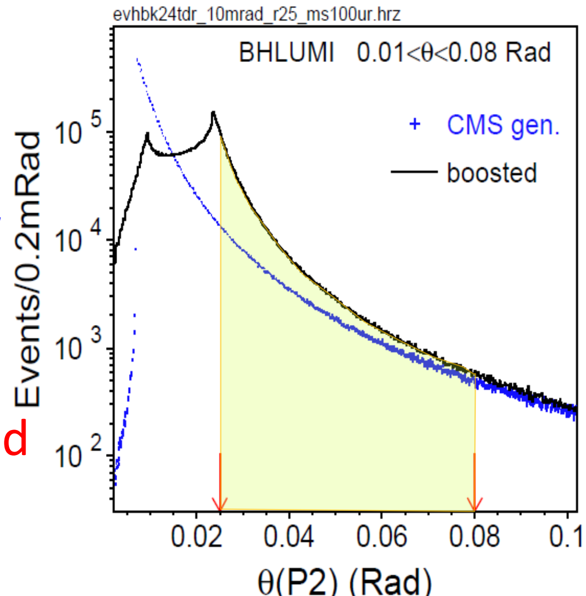
1) Θ > 25mRad outside pipe centers
2) |y|>25 mm
3) Events in shaded area counted for Xsec

Pair of P2,Q2 detected

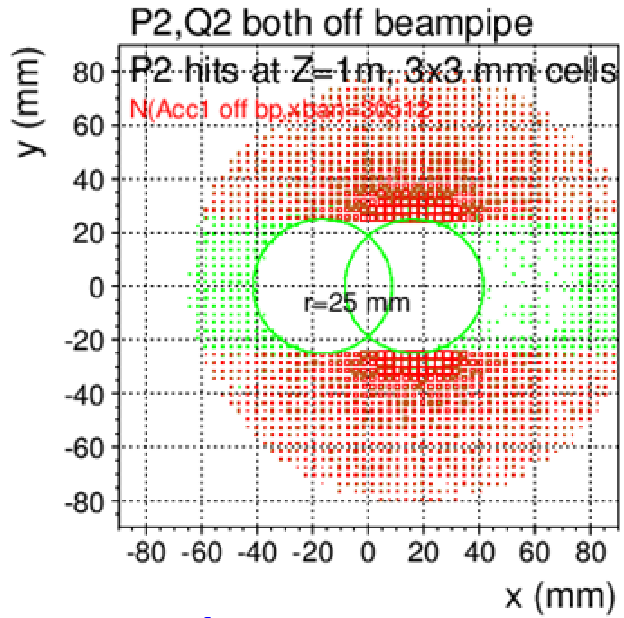
@|z|=1000mm

region |y|<25 mm

10% to r=80 mR full covered



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

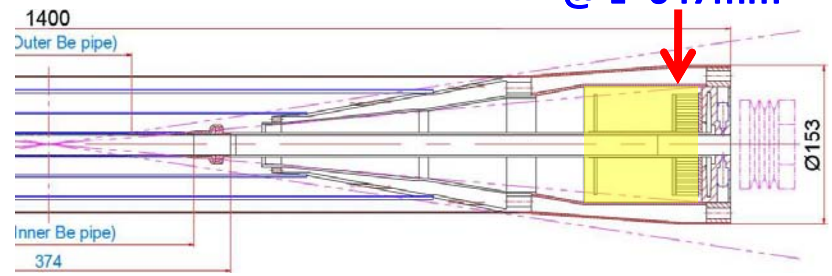


LumiCal acceptance at |z|=1000mm, with RaceTrack pipe r=10mm

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**

Front $2X_0$ LYSO, on radiative e,γ

2X₀ LYSO
@ z=647mm



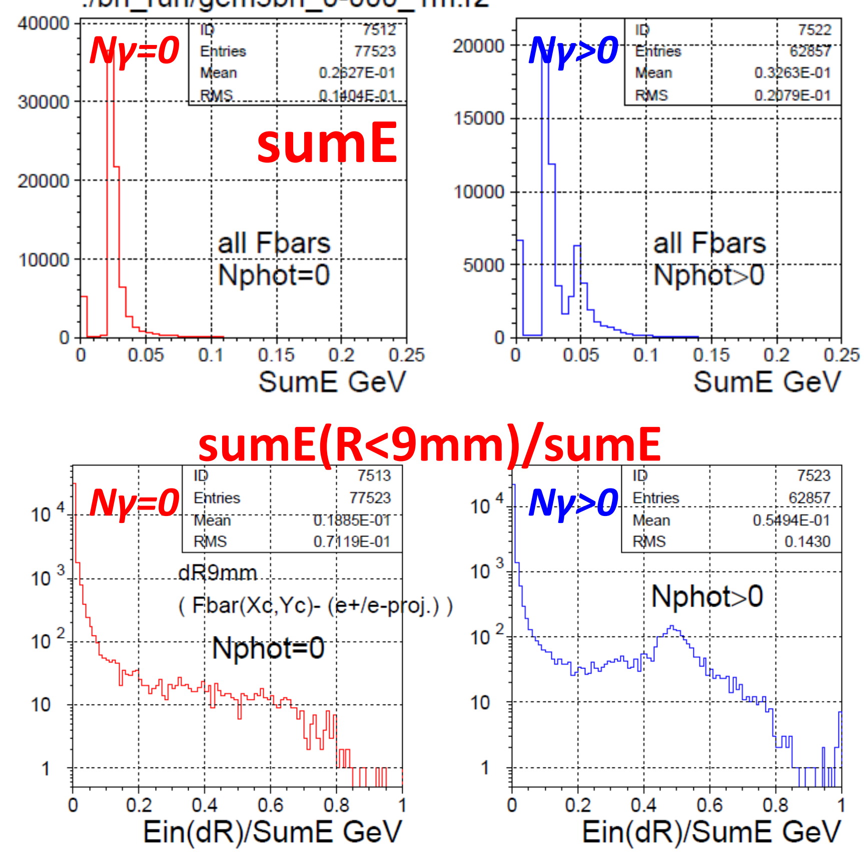
Bhabha hits on LYSO, |y|>12mm

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

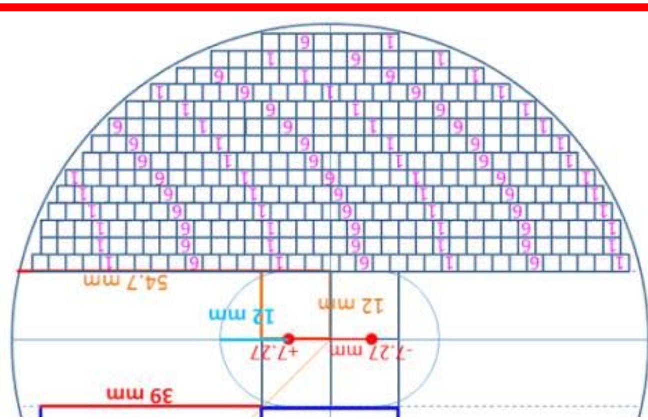
BHLUMI events, GEANT simulation

./bh_run/gem3bh_0-000_1m.rz



sum dE/dx all LYSO bars (a plane)

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



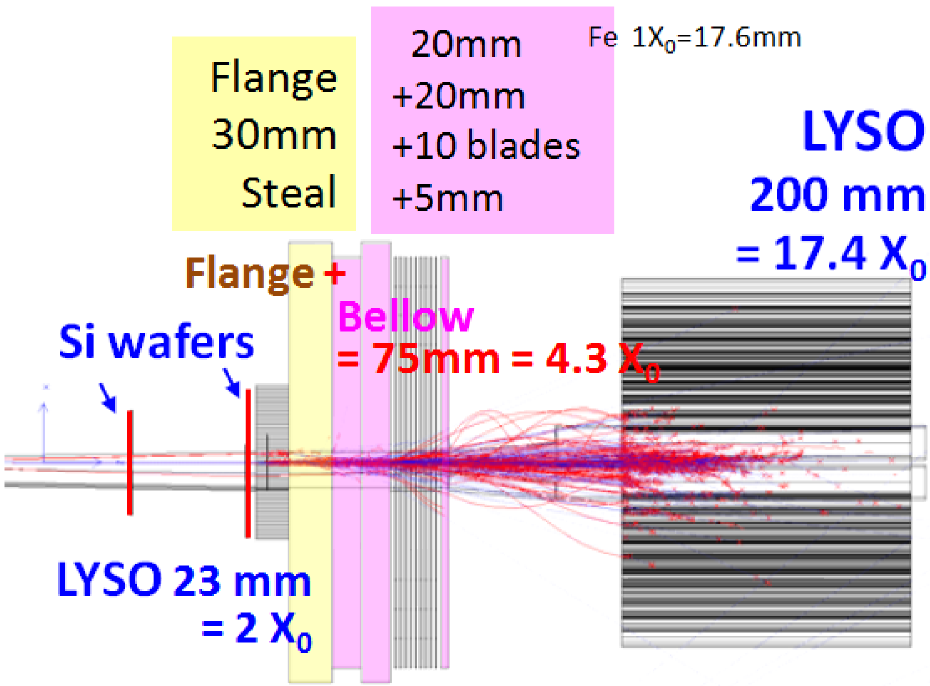
GEANT LumiCal electron shower

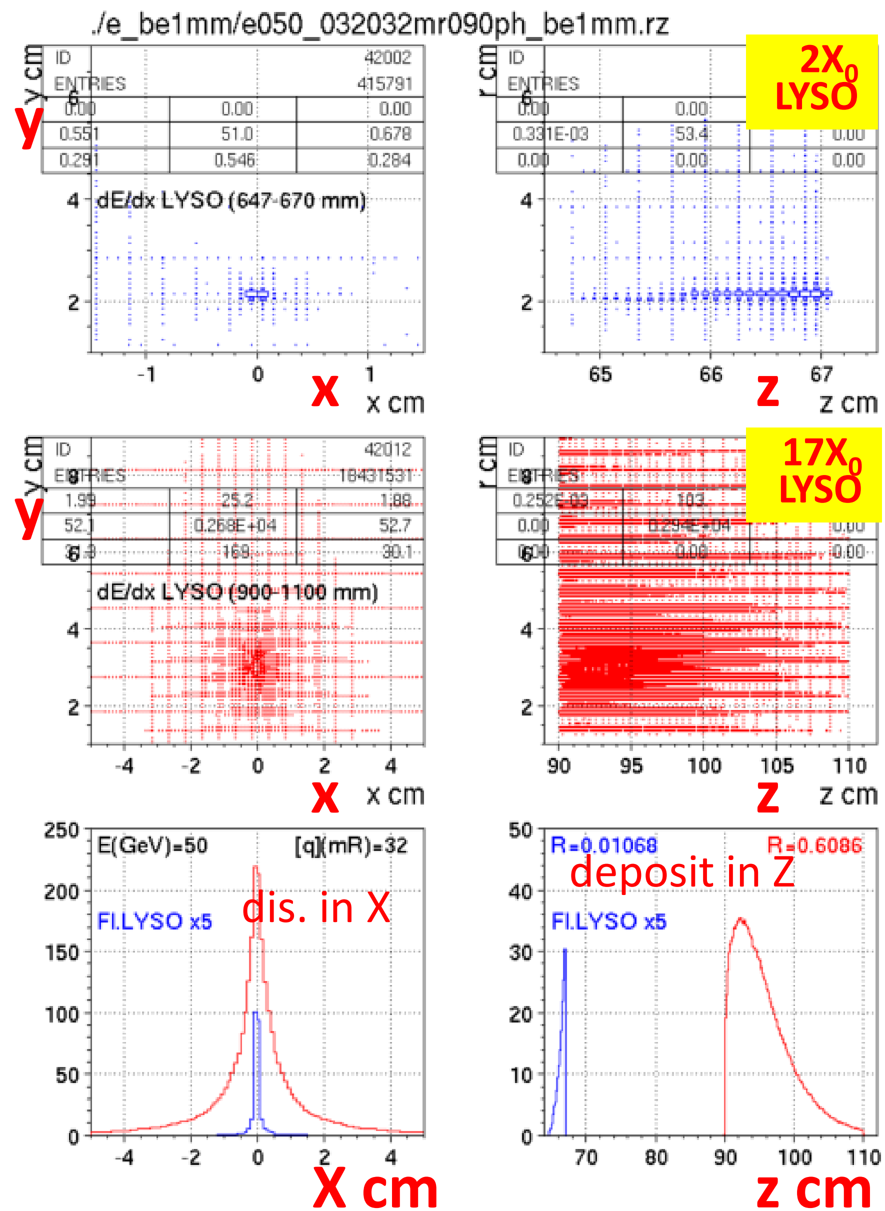
50 GeV electron @ θ = 32 mRad, ϕ=90°

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

Shower deposition, by Sum(dE/dx)

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





马仁杰
王翊伦
孙行阳

LumiCal electron LYSO, 5% resolution

LYSO length vs E resolution

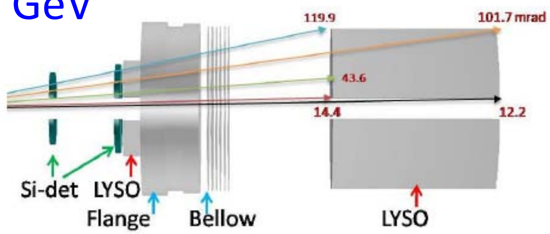
150 mm, 13 X_0, 210 mm, 18 X_0

Electron energies 50 GeV, 120 GeV

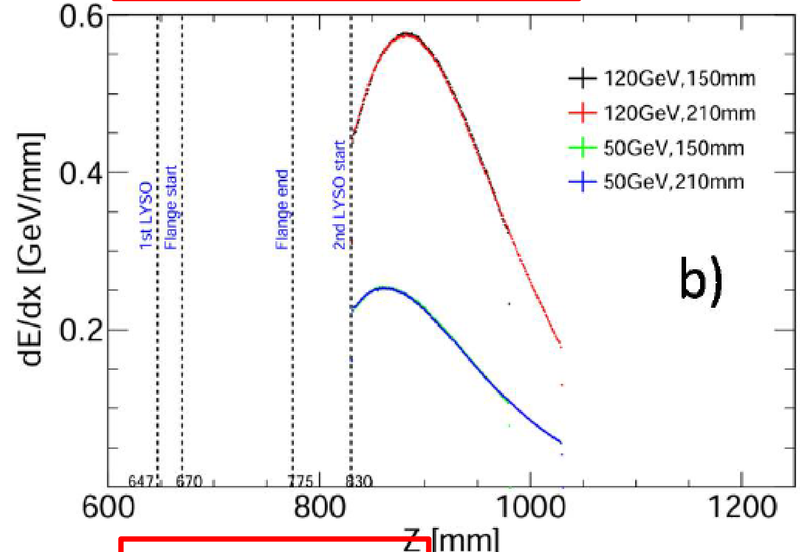
150, 13 X_0 LYSO sufficient

50GeV: RMS 2.5 GeV

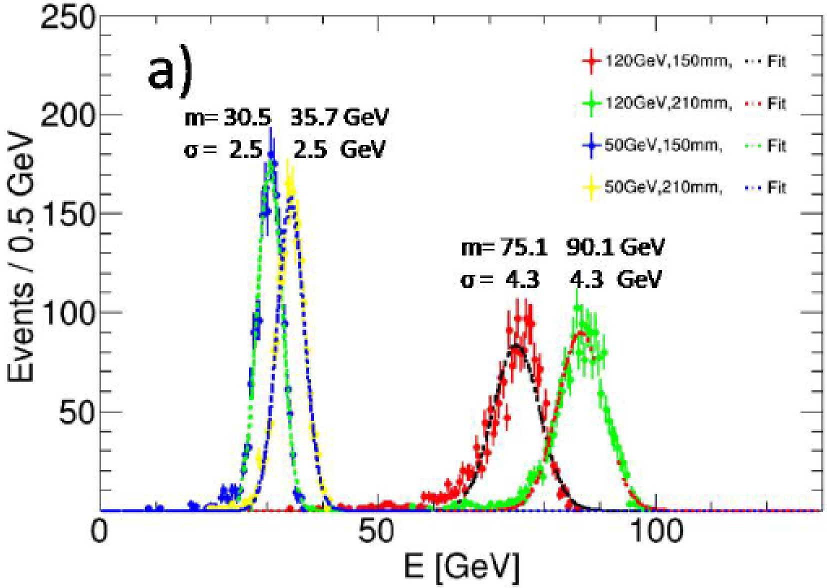
120GeV: RMS 4.3 GeV



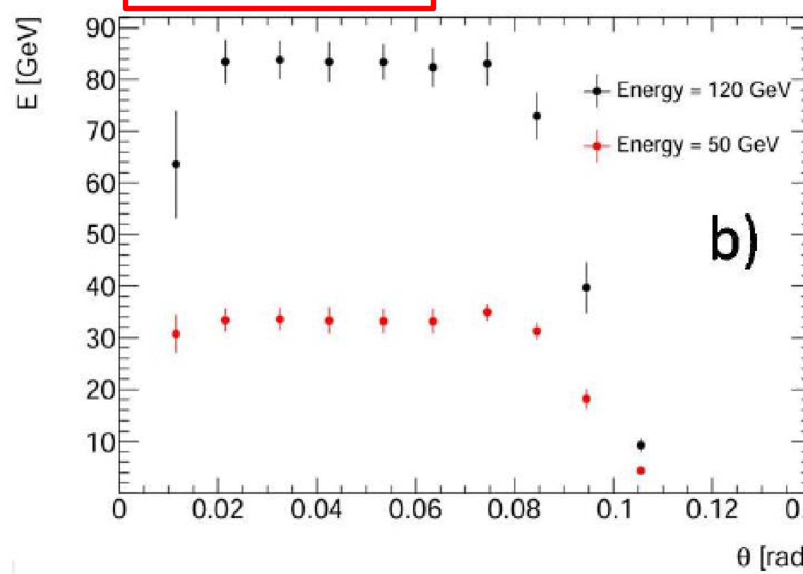
dE/dx in long LYSO



Sum dE/dx in long LYSO



Acceptance



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

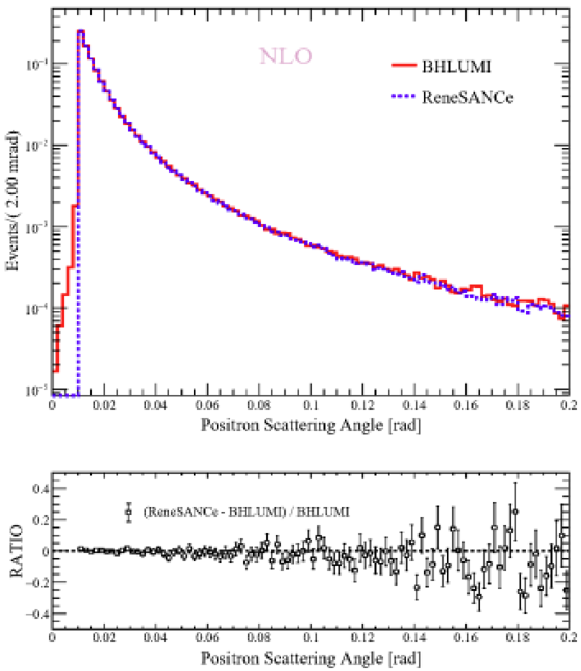
Jiading Gong
Renjie Ma

Compare

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

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

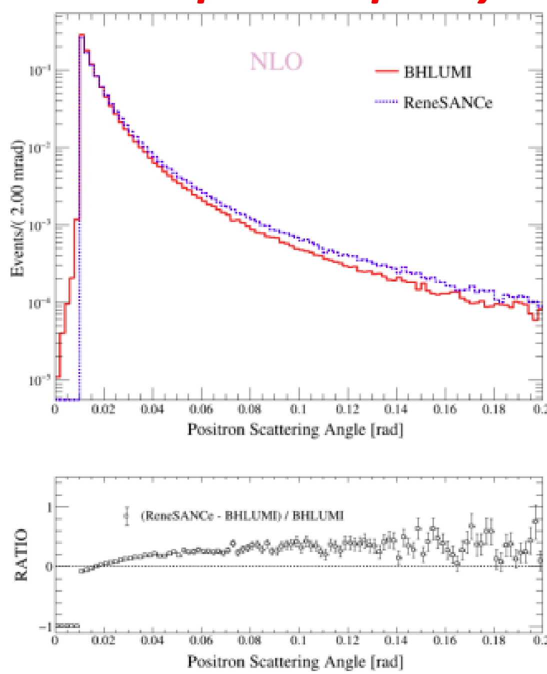
eγ opening angle
Consistent



BHLUMI NLO : 657471
ReneSANCe NLO : 953210

24

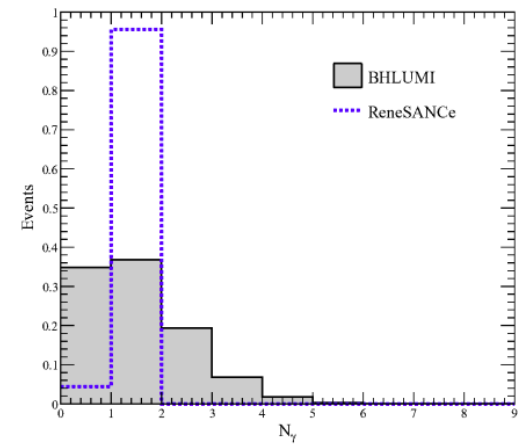
e± theta angle
NLO 0γ discrepency



BHLUMI : 1e+06
ReneSANCe : 1e+06

 # photons
Differ very much

Comparison

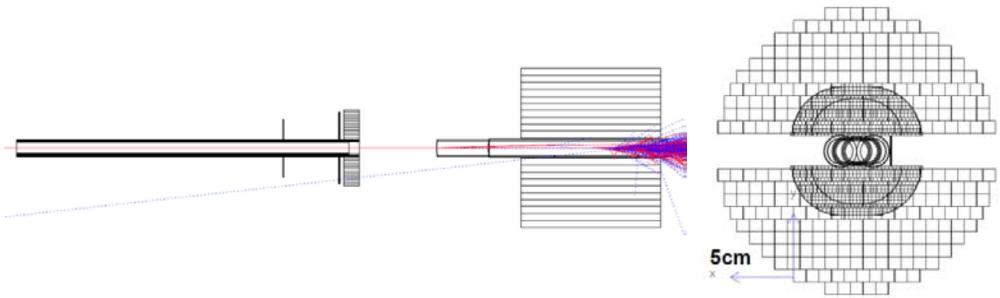


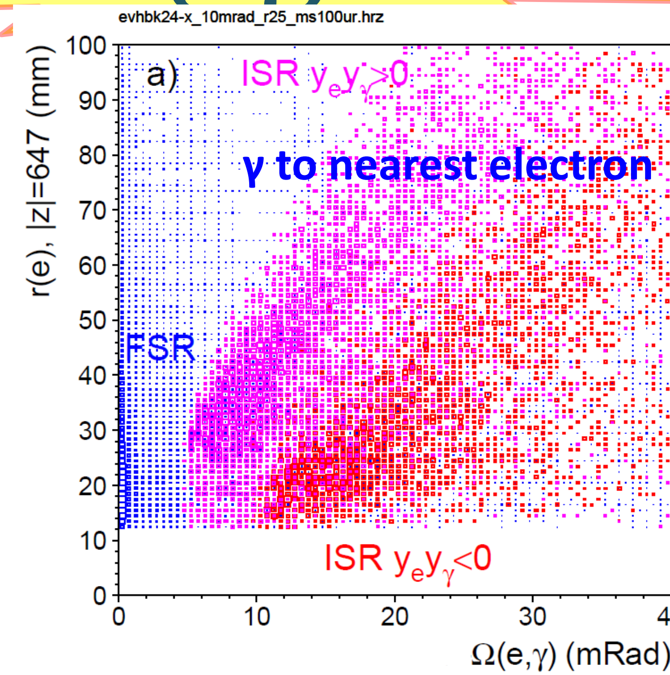
Trial3 : th1= 0.01rad, th2= 0.1rad

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%

Detecting photons in $e^+e^- \rightarrow e^+e^-(n\gamma)$





Bhabha events in LumiCal acceptance

e^+,e^-,γ : |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 %

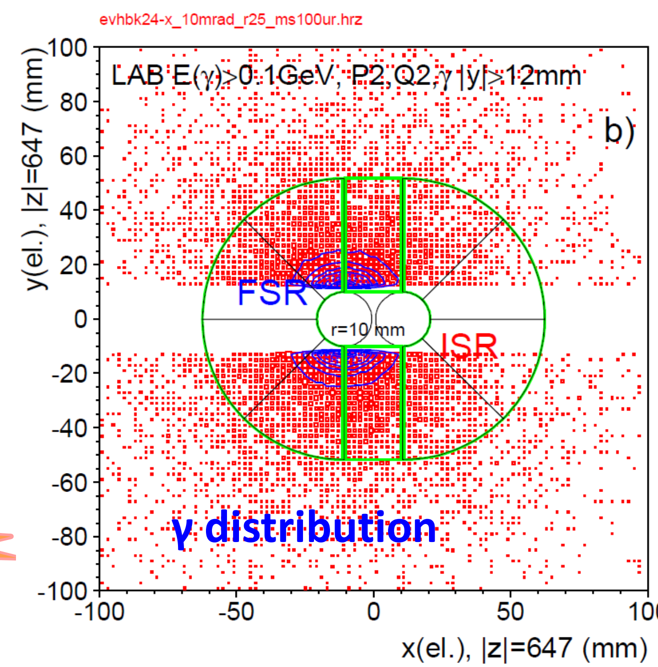
*ISR 20.3%, FSR 19.4%

Detectable Bhabha, e^+,e^-,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**



Challenge: 10^{-4} on Bhabha $e^+e^- \to e^+e^-(n\gamma)$

Bhabha electron θ (set by 2 points) : IP – Si.hit

Requirement: 1 μRad on **mean of θ**

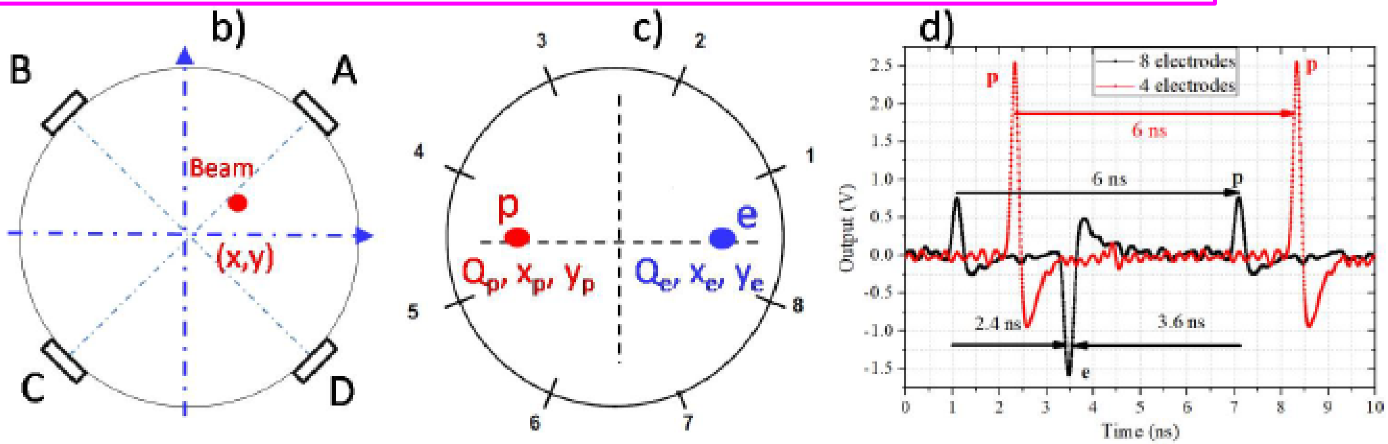
1. **IP by BPM** (beam position monitor) on beam current
   x,y by BPM, z by timing
2. **LumiCal Si-wafer position** mounted on Flanges
   reference to **"beam center"** at Flanges

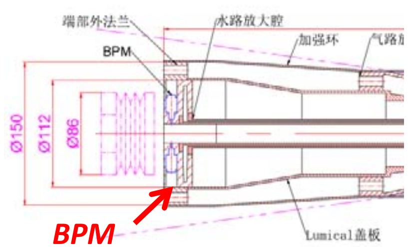
   → 1. **construction** survey to sub-micron
      2. **monitoring** on Flanges **z position**

Survey/monitoring, for Beam IP position

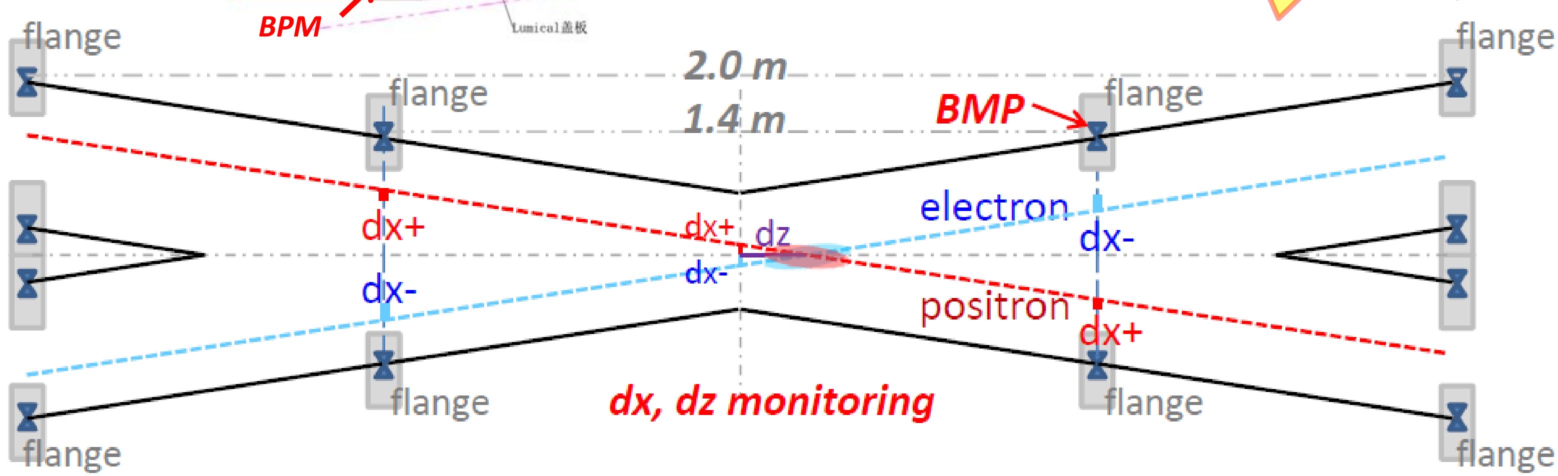
- Beam Probe Monitor ***BPM*, *IP x,y to 1 µm***
- Position monitoring, Flange dx,dy ~1 ***µm***, dz~ ***50 µm***

CEPC WS2023
Jun He



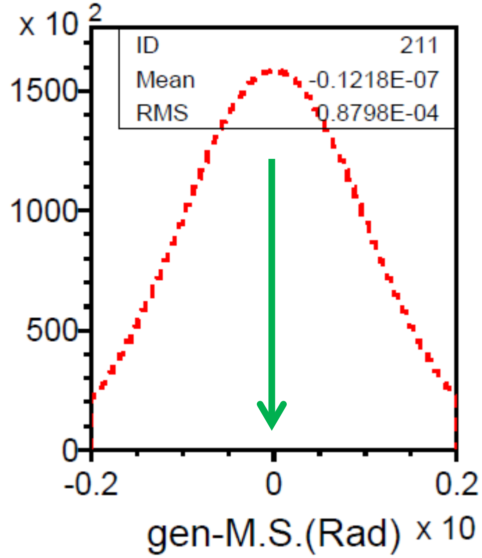


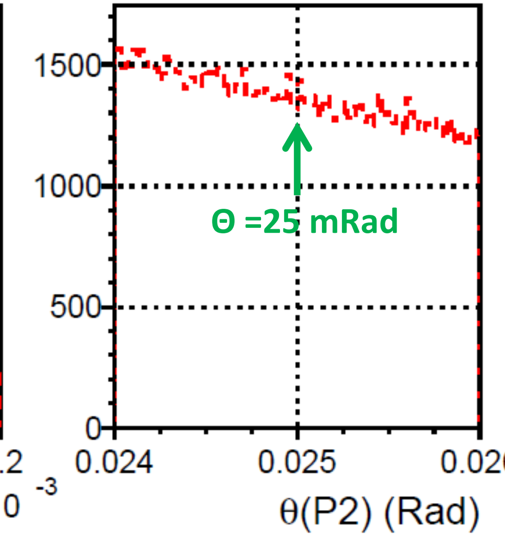
LumiCal 监测
1. 法藍 *dx,dy 1 µm, dz 50 µm*
2. 电子束流 *dx,dy 1 µm*



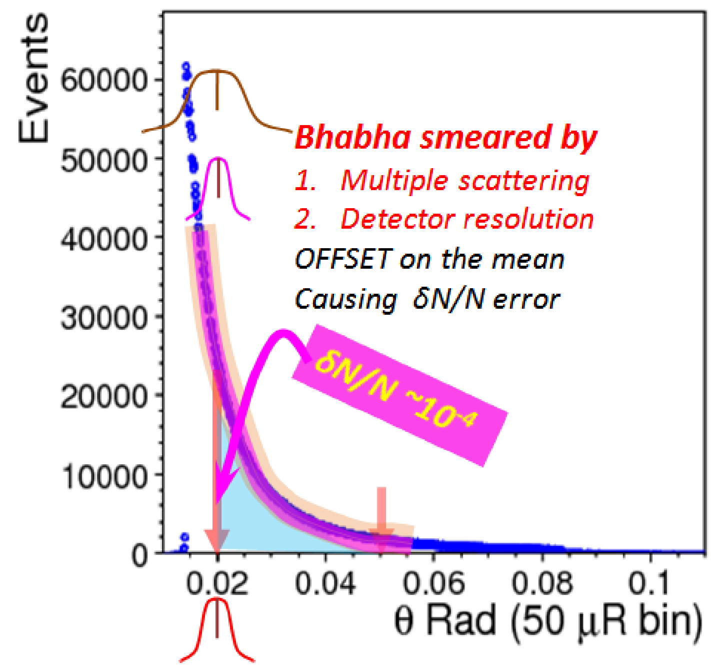
multiple scattering, against 10^{-4}

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)



e^+, e^- back-back, calibrate survey, if narrow

- **Bunch size** $\sigma_x = 6\ \mu m$, $\sigma_y = .035\ \mu m$ $_z = 9\ mm$

➔ *IP spot, 33mRad Xing*

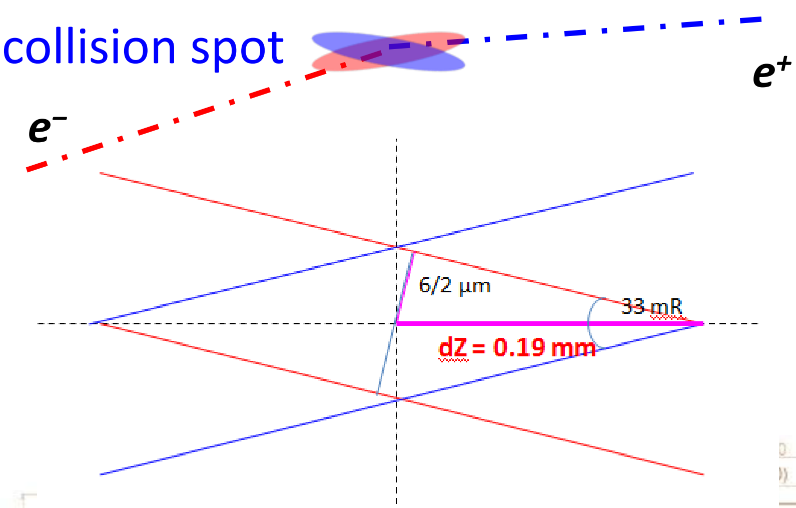
$\sigma_x = 6\ \mu m$, $\sigma_z = 380\ \mu m$

- $Z \longrightarrow e^+, e^-$ at $\vartheta = 30\ mRad$

smearing at @z=560mm

smeared width $\sigma(\vartheta) = 24\ \mu Rad$

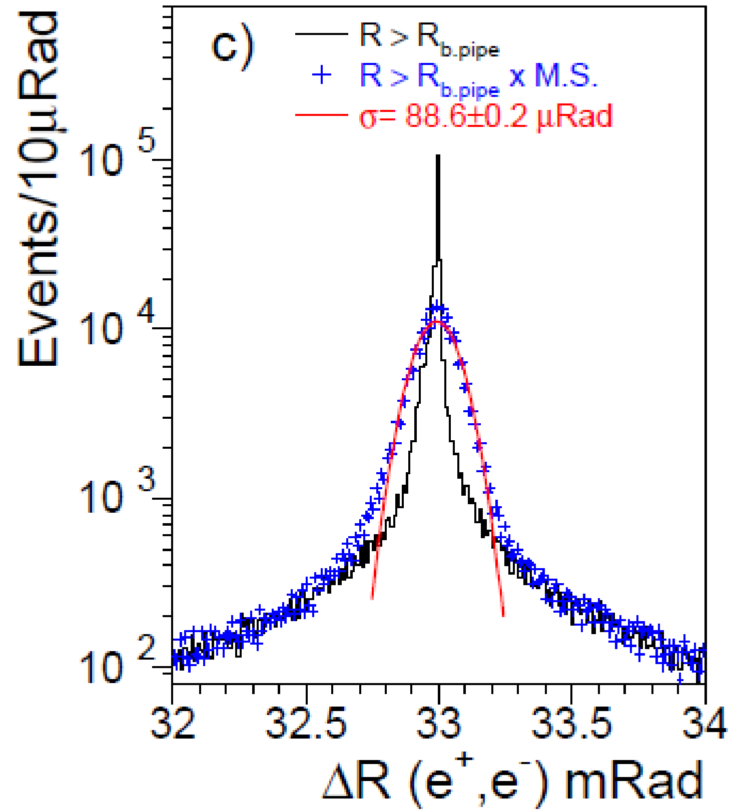
back-to-back $\sigma(\Omega) = 21\ \mu Rad$

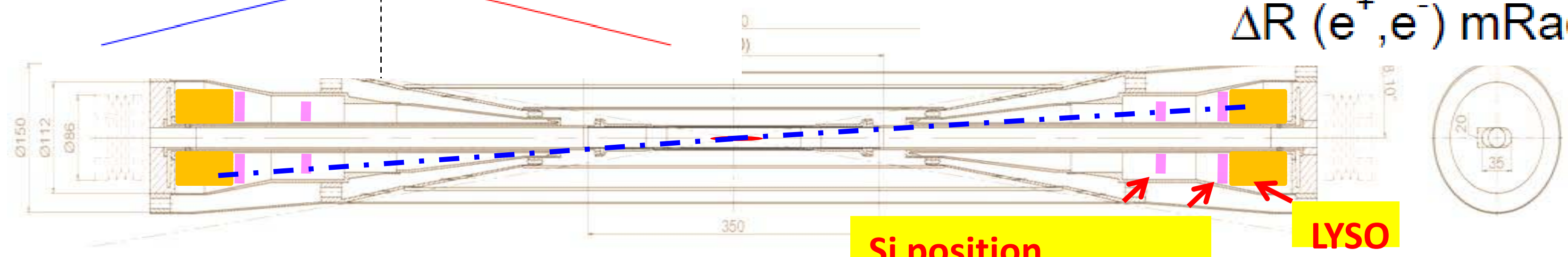


e^+, e^- back-back

BHLUMI scattered e^+, e^-

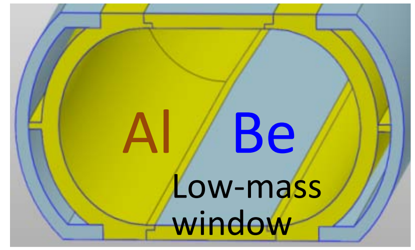
ϑ, φ smeared 100 μR

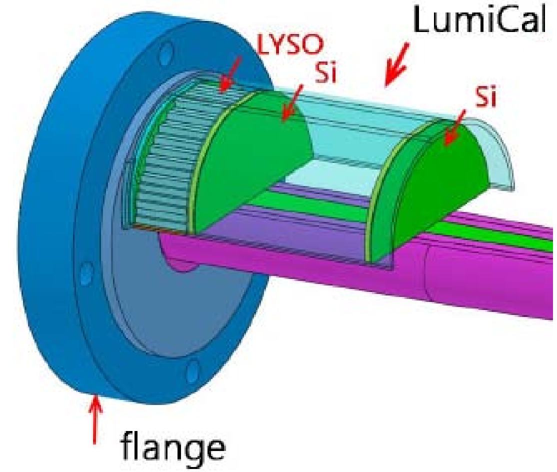




Electron hits on 1st Si-wafer

1 mm Be thin pipe window
33 mm = 0.09 X_0 traversing @ 30mR





IP (σ_x,σ_z) = (6,380 *µm*)

50 GeV e^+, e^-

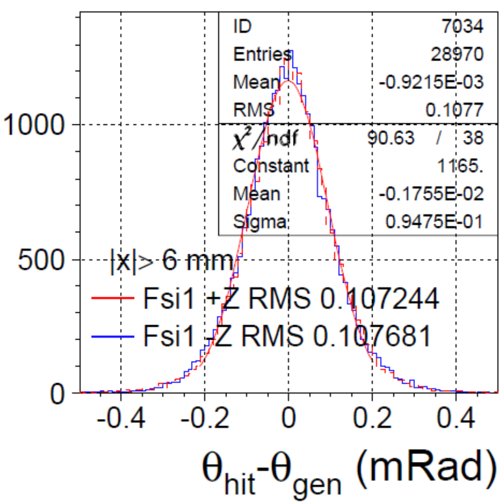
@ (ϑ= ±30 mRad, φ = 1.0, 1.0+π Rad)

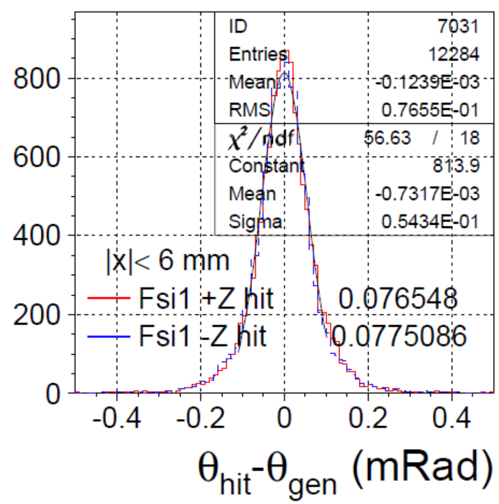
Si wafer @z=560mm

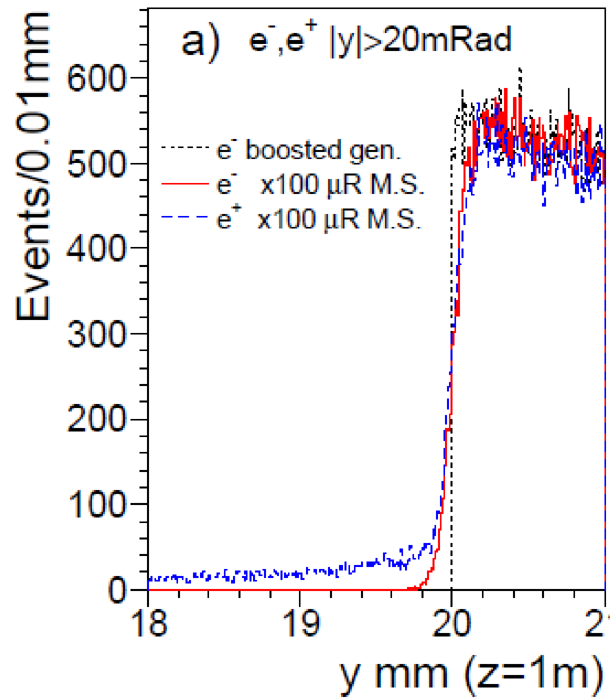
- |x|<6.0 mm $\sigma(\vartheta)$ = 54 µR (1mm Be)
- |x|>6.0 mm $\sigma(\vartheta)$ = 95 µR (1m Al pipe)
- back-back Op.Ang $\sigma(\Omega)$ = 137 µR

Multiple scattering at edge
BHLUMI 100 µR smearing
Both z sizes but on e- side

e± GEANT hit – gen. |x|>6 ***hit – gen. |x|<6***







LumiCal detector/electronics options

Si-wafers for electron impact position

- **Strip** detector 50 or 100 µm pitch, 2D x,y
- **AC LGAD**, 2D long coupling layer

Readout: (LGAD) tracker readout, fast and pileup ID

Calorimetry, LYSO rad-hard bars

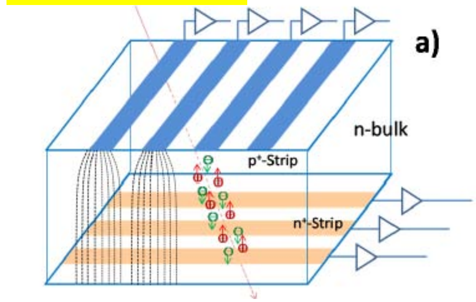
- 2 X_0 (3x3x23mm3) position, e/γ etc
- 13 X0 (10x10x150 mm3) Ebeam electron ID

Readout: SiPM + ECAL front-end, trigger and pileup ID

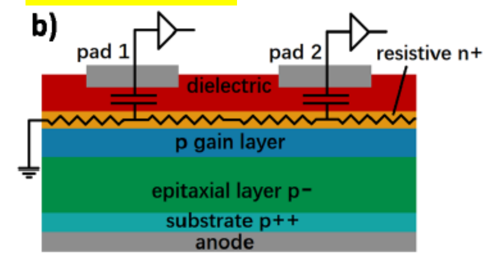
LumiCal trigger

- Single side, long LYSO E> Ebeam/2
- Coincidence +z,-z E> Ebeam/2, event rate @L=10^{36} **0.003 /b.c.** **but Pileup ~10^{-4}** shall be identified

2D Si-strip

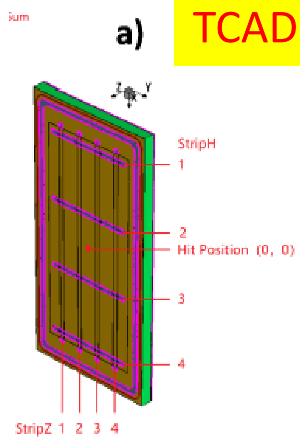


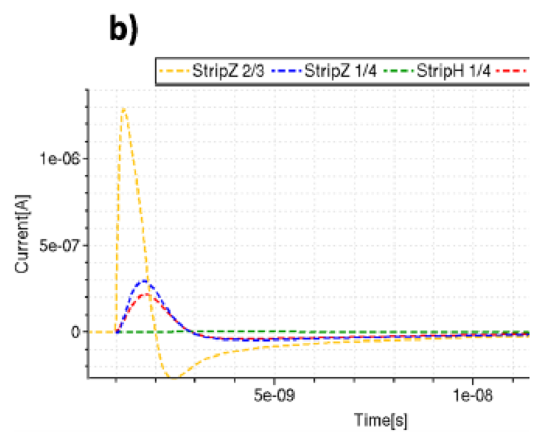
AC LGAD



TCAD model of AC-LGAD

TCAD





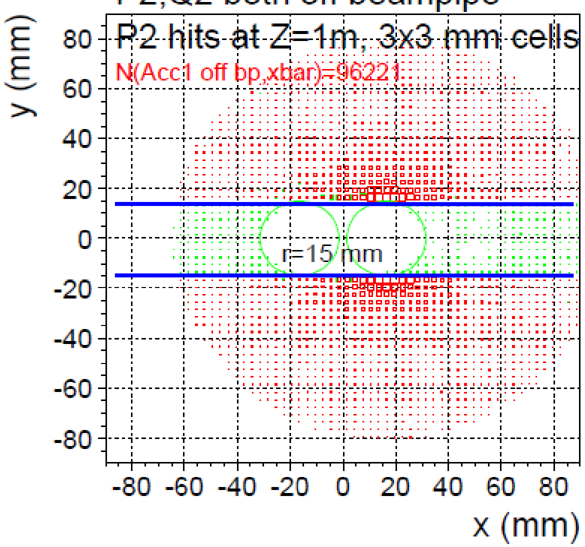
Bhabha event pile-up rate @Z-pole

1. Z-pole (2021 design) L_{max}/IP = **115 x 10^{34}/cm^2s**
2. Bhabha both ***e⁺, e⁻*** detected, X-sec = **100 nb**
   Event rate = (246x10^{-33}) x (115 x 10^{34}) /sec **= *115 kHz***
3. Event rate / 25 ns bunch crossing = **0.003 events /b.c.**
4. **Pile-up: per b.c., @adjacent cell in peak region**
   Pile-up Fraction = 0.018*6cells/2sides = **0.054**

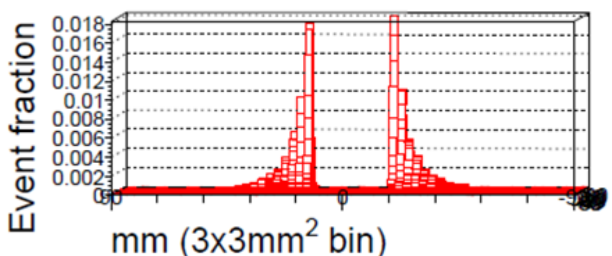
Pile-up event rate = 0.003*0.054 = **1.6 x 10^{-4}** ← ***too high***

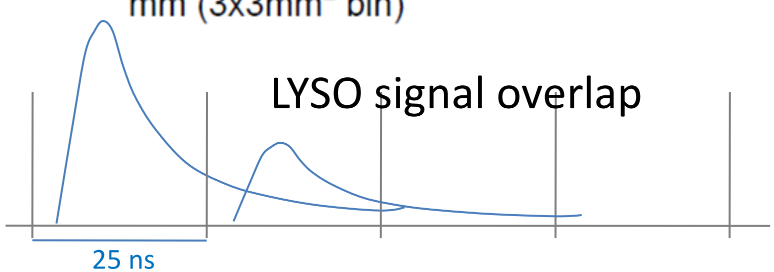
c.f. LEP
L= 1x10^{32}
X-sec= 100nb
*Rate= **10 Hz***

50 GeV e- shower on 3x3 mm² cells



event fraction /(cell of 3x3mm²)
maximum at beampipe edge = 0.018





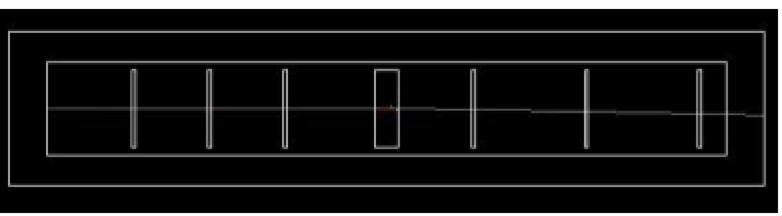
Multiple Scattering, test beam

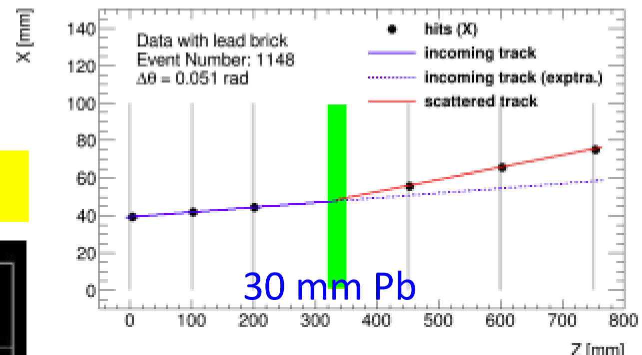
Changhua Hao,
Yuhui Miao,
Xingyang Sun,
Ligang Xia,
Lei Zhang

南京大学–紫金山天文台 **Si-strip station**

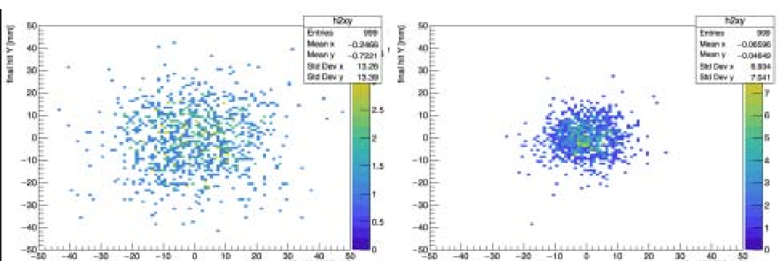
- Cosmic ray Muon, > 1 GeV filtered
- 6 sets (x,y) 200 µm pitch, VA readout

GEANT 30 mm Pb muon scattering

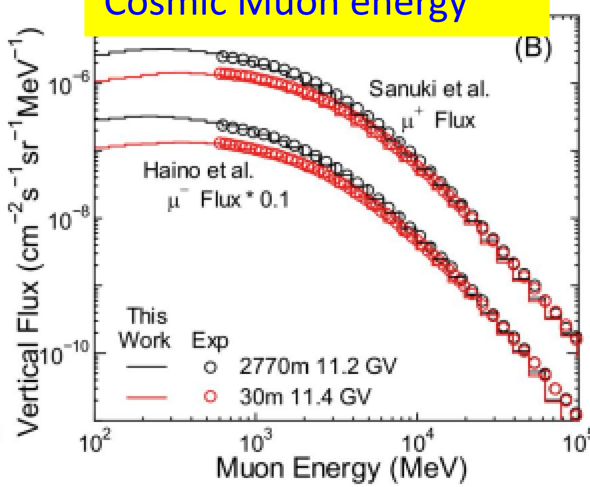


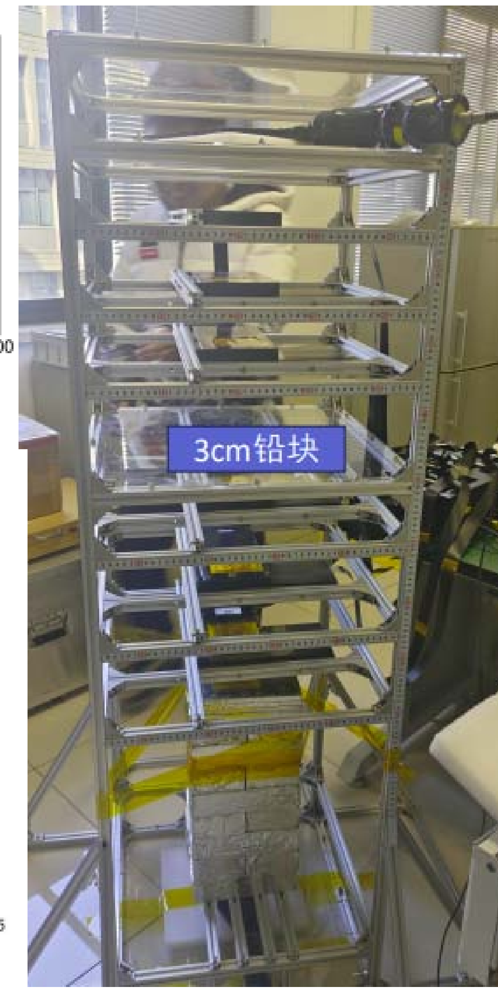


1 GeV muon 2 GeV muon



journal.pone.0144679
Cosmic Muon energy

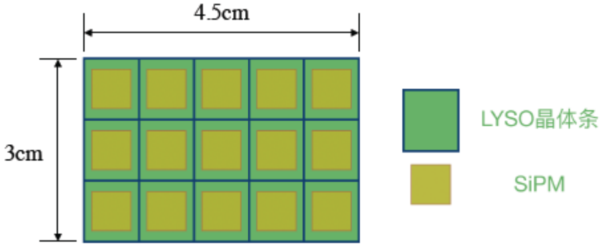




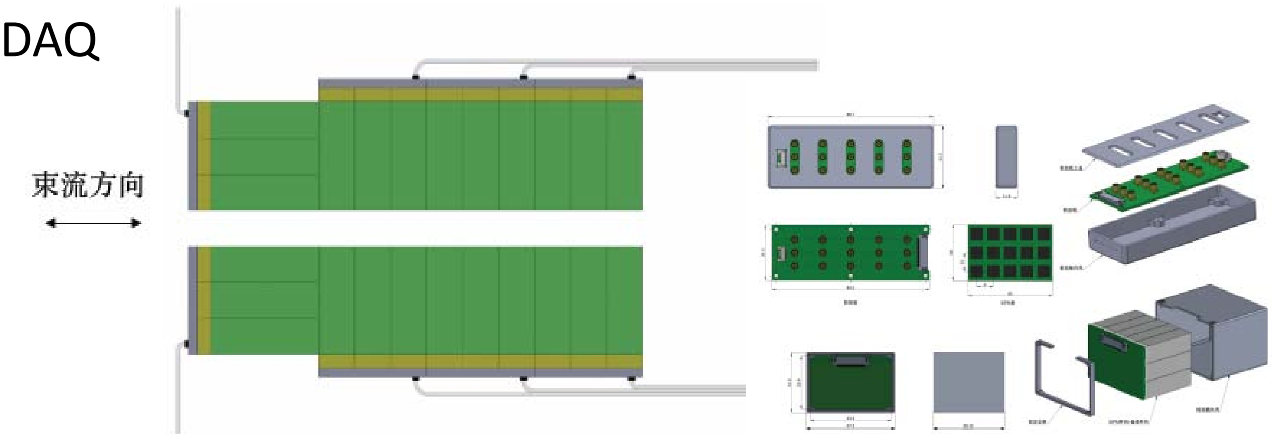
Prototyping, forward LYSO @BES III

BES III forward, between beam pipes, stack total length 120mm

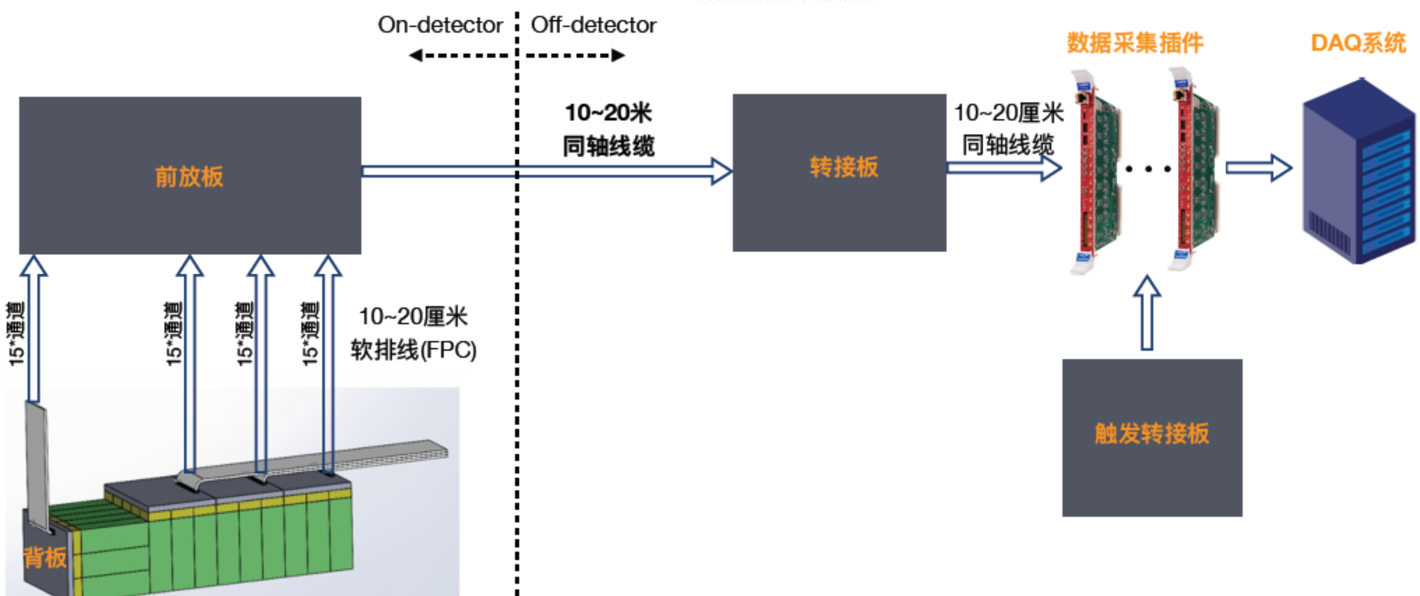
- LYSO crystals 3x5 bars (9x10mm^2 frontface)
- SiPM frontend, to VME DAQ



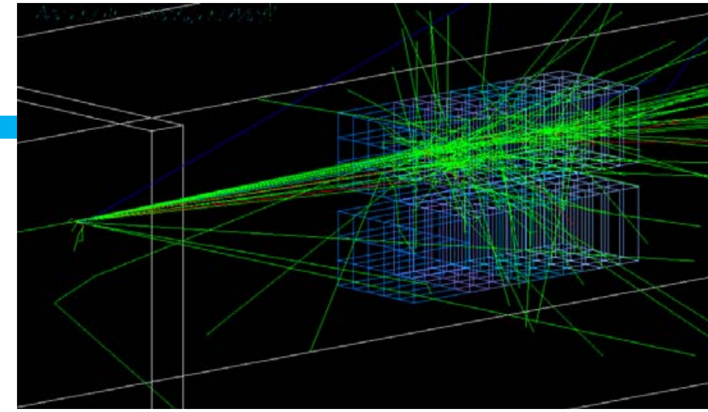
LYSO与SiPM耦合截面视图



探测器端面图



GEANT LYSO @BES III



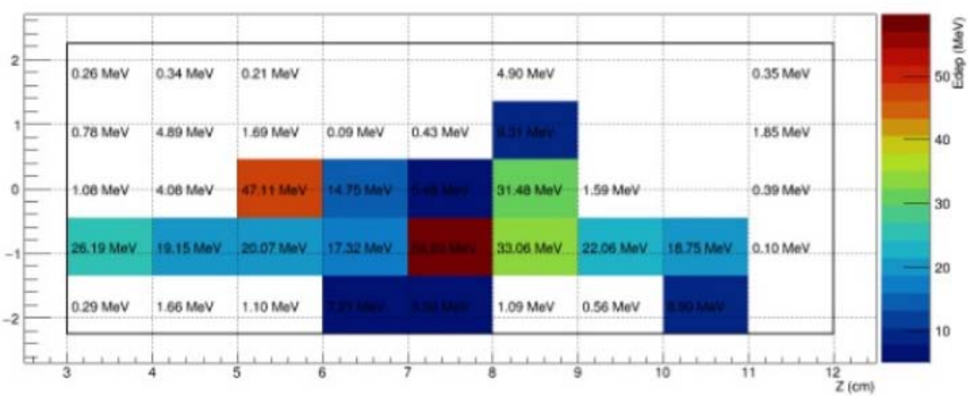
BES III forward, between beam pipes

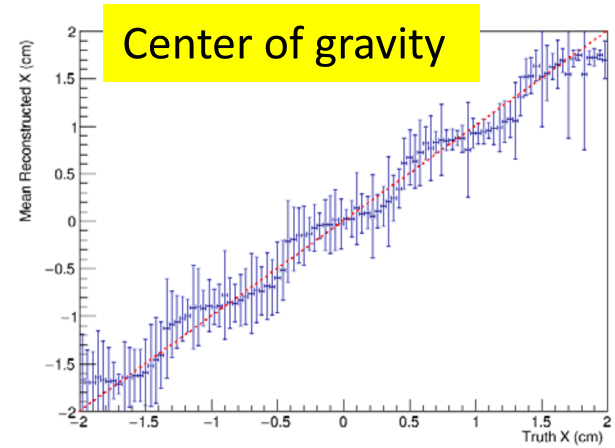
- Electron impact position analysis
- Position by Center-of-Gravity
- Calibrated for correction

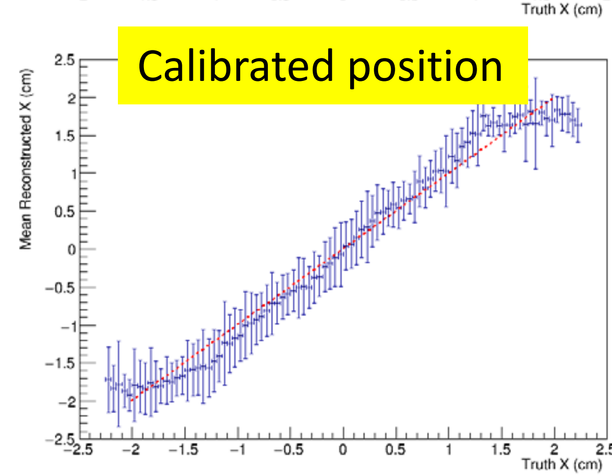
LYSO dE/dx

GEANT 1 GeV electron passing

1.45 cm Cu beam pipe materials

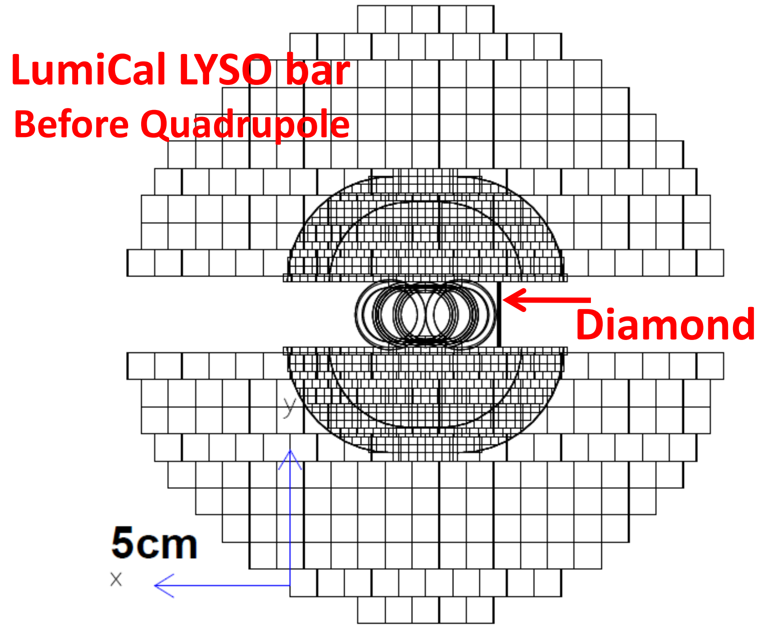


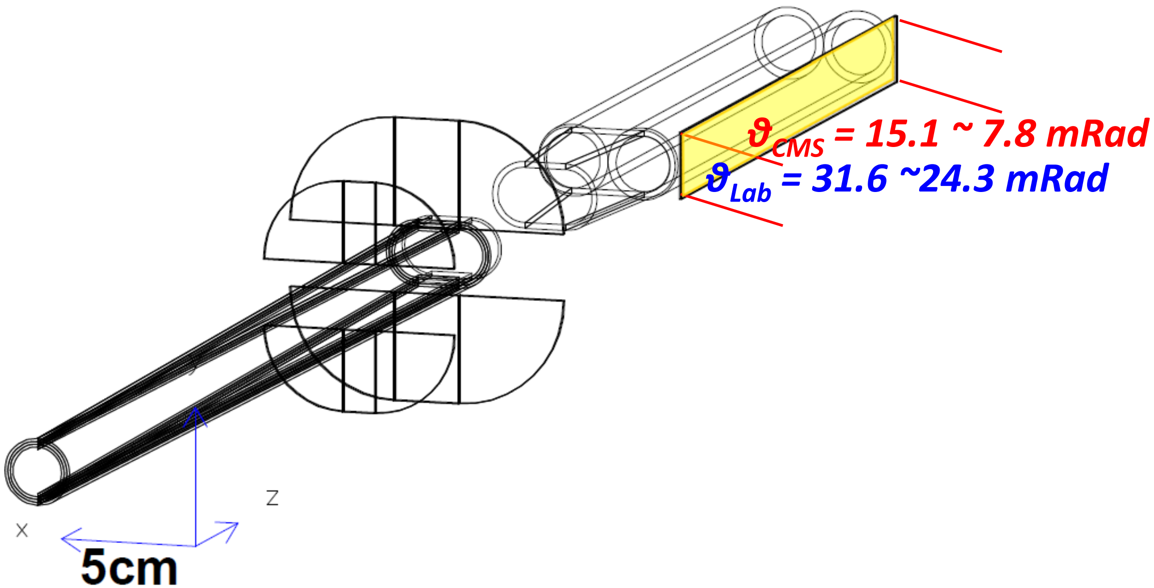


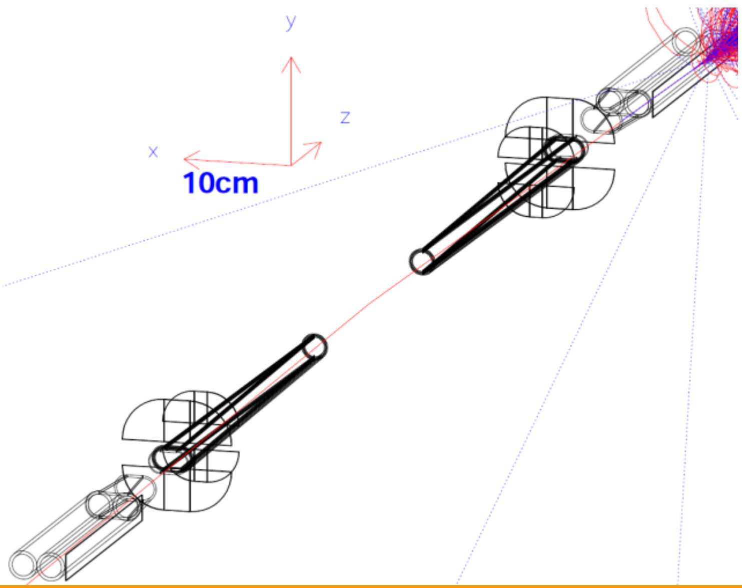


Diamond fast beam monitor

- Beam monitoring
  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**



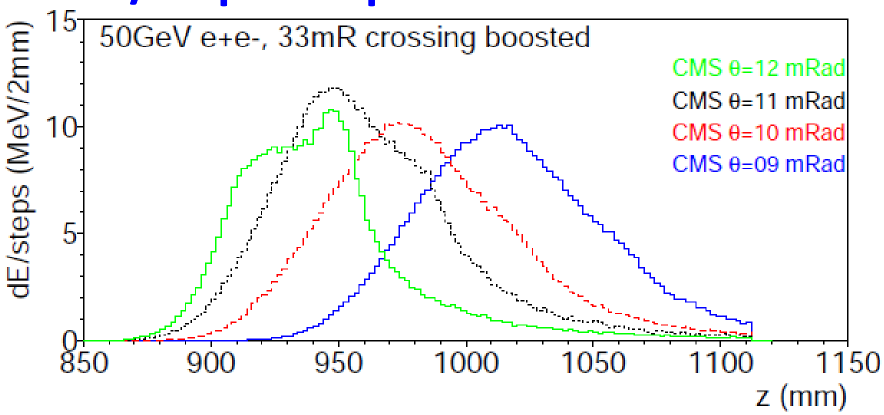




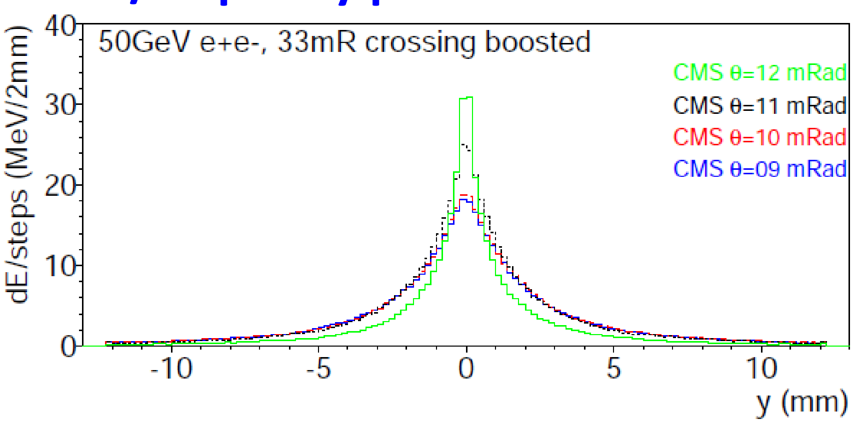
50 GeV electron on diamond

- 50 GeV electrons at CMS **9 ~ 12 mRad, Lab 25.5 ~ 28.5 mRad**
- **3 mm thick Cu beampipe (~300 mm traversing)**
- dE/step of **charged tracks** (>100 keV) **in diamond**

dE/steps in z profile

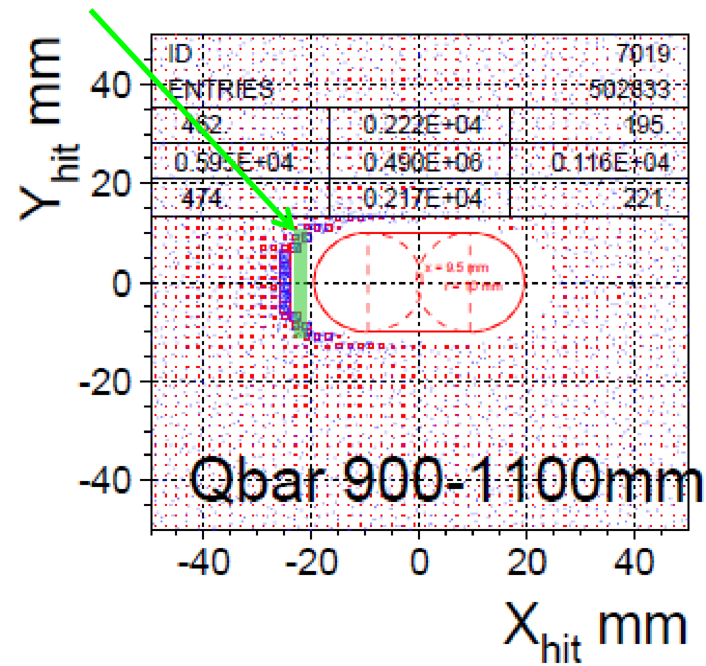


dE/steps in y profile



Diamond slab covering 8~15 mRad

X-sec order of ~100 nb



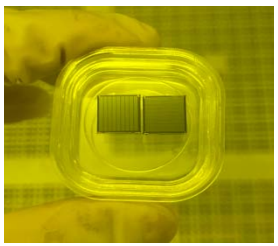
Event rate @Z, L=1x10^{36}/cm^{2}s

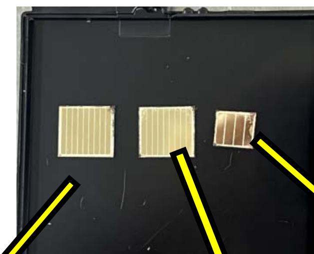
= (100x10^{-33}) x (1 x 10^{36}) /s = *~100 kHz*

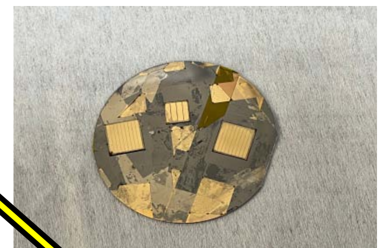
Producing diamond pads

Jialiang Zhang
Wang Yilun

- Two prototype microstrip diamond sensor successfully fabricated
- Pitch of 1.0 mm on 10 mm × 10 mm
- Pitch of 1.35 mm on 6 mm × 6 mm diamond

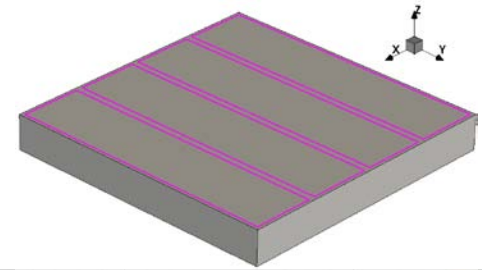


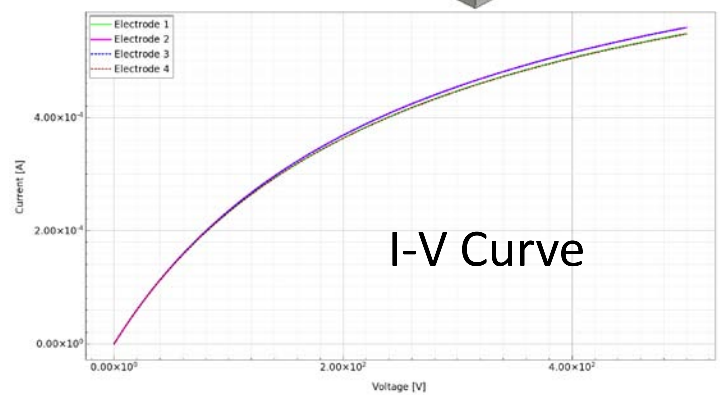




Post-litho development

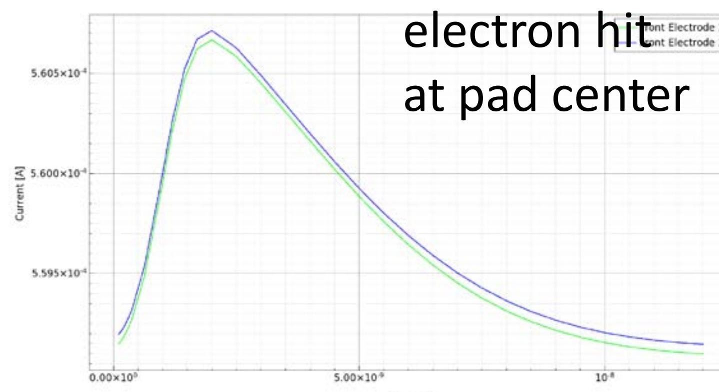
TCAD simulation



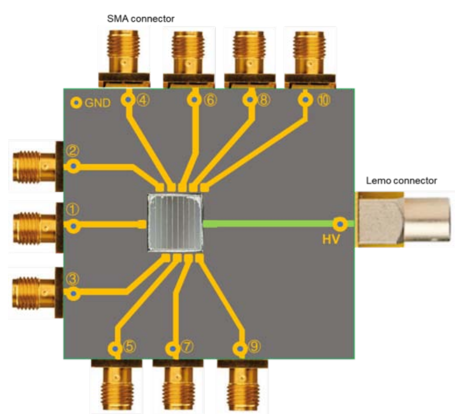


I-V Curve

Perpendicular electron hit at pad center



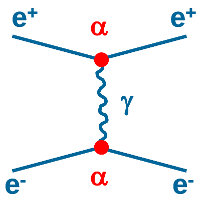
Test PCBs preparation



Backup

Giovanni Abbiendi
INFN – Sezione di Bologna

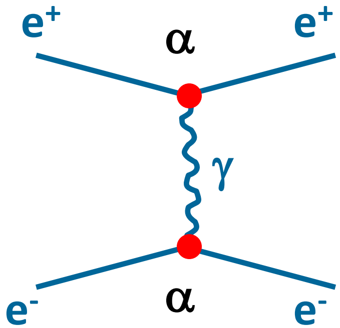
- **Introduction**
- **Small-angle Bhabha scattering:**
  - **virtues**
  - **new OPAL analysis (PR407)**
  - **crucial experimental issues**
  - **theoretical uncertainties**
  - **results**
- **Existing measurements (s, t channel)**
  - **comparison with L3 result**
- **Conclusions**



40th Rencontres de Moriond - *Electroweak Interactions and Unified Theories*, La Thuile, 5-12.3 2005

Small-angle Bhabha scattering

an almost **pure QED** process. Differential cross section can be written as:



$$\frac{d\sigma}{dt} = \frac{d\sigma^{(0)}}{dt}\left[\frac{\alpha(t)}{\alpha_0}\right]^2 (1+\varepsilon)(1+\delta_\gamma) + \delta_Z$$

Born term for t-channel single γ exchange

$$\frac{d\sigma^{(0)}}{dt} = \frac{4\pi\alpha_0^2}{t^2}$$

$\alpha_0 \cong 1/137.036$

$$\left(\frac{1}{1-\Delta\alpha(t)}\right)^2$$

Effective coupling factorized

Photonic radiative corrections

s-channel γ exchange correction

Z interference correction

$$\delta_Z\,,\,\delta_\gamma \ll \varepsilon$$

experimentally: high data statistics, very high purity

This process and method advocated by Arbuzov et al., Eur.Phys.J.C 34(2004)267

Small-angle Bhabha scattering

BHLUMI MC (S.Jadach et al.) calculates the photonic radiative corrections up to $O(\alpha^2 L^2)$ where $L = \ln(|t| / m_e^2) - 1$ is the **Large Logarithm**

Higher order terms partially included through YFS exponentiation

Many existing calculations have been widely cross-checked with BHLUMI to decrease the theoretical error on the determination of Luminosity at LEP, reduced down to 0.054% (0.040% due to Vacuum Polarization)

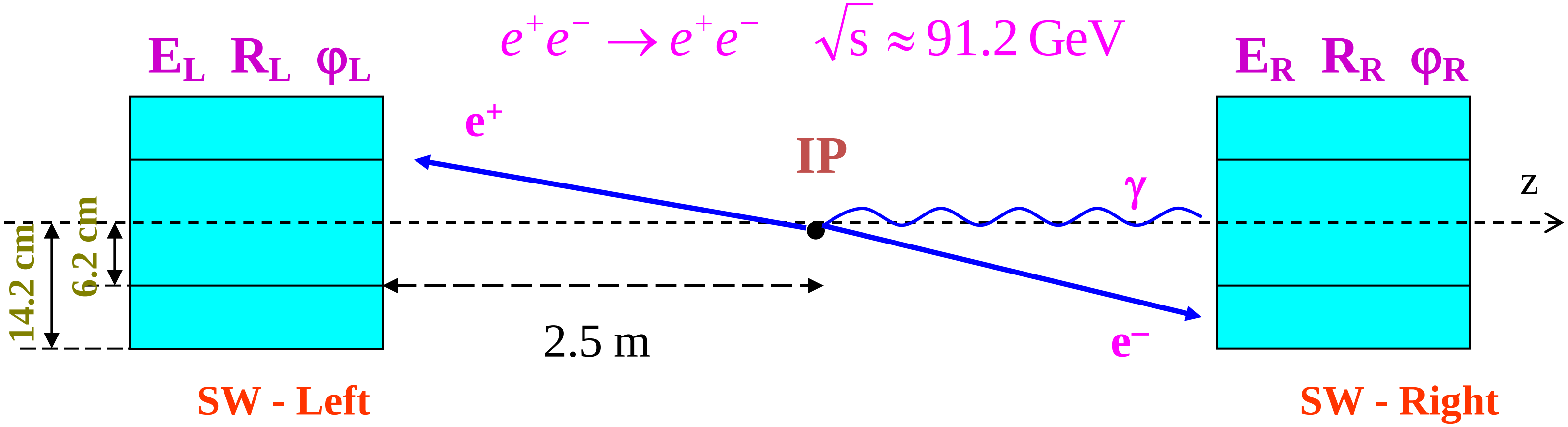
Size of the photonic radiative corrections (w.r.t. Born = 1*)*

Canonical coefficients					
		$\theta_{min} = 30$ mrad		$\theta_{min} = 60$ mrad	
		LEP1	LEP2	LEP1	LEP2
$\mathcal{O}(\alpha L)$	$\frac{\alpha}{\pi} 4L$	137×10^{-3}	152×10^{-3}	150×10^{-3}	165×10^{-3}
$\mathcal{O}(\alpha)$	$2\frac{1}{2}\frac{\alpha}{\pi}$	2.3×10^{-3}	2.3×10^{-3}	2.3×10^{-3}	2.3×10^{-3}
$\mathcal{O}(\alpha^2 L^2)$	$\frac{1}{2}\left(\frac{\alpha}{\pi}4L\right)^2$	9.4×10^{-3}	11×10^{-3}	11×10^{-3}	14×10^{-3}
$\mathcal{O}(\alpha^2 L)$	$\frac{\alpha}{\pi}\left(\frac{\alpha}{\pi}4L\right)$	0.31×10^{-3}	0.35×10^{-3}	0.35×10^{-3}	0.38×10^{-3}
$\mathcal{O}(\alpha^3 L^3)$	$\frac{1}{3!}\left(\frac{\alpha}{\pi}4L\right)^3$	0.42×10^{-3}	0.58×10^{-3}	0.57×10^{-3}	0.74×10^{-3}

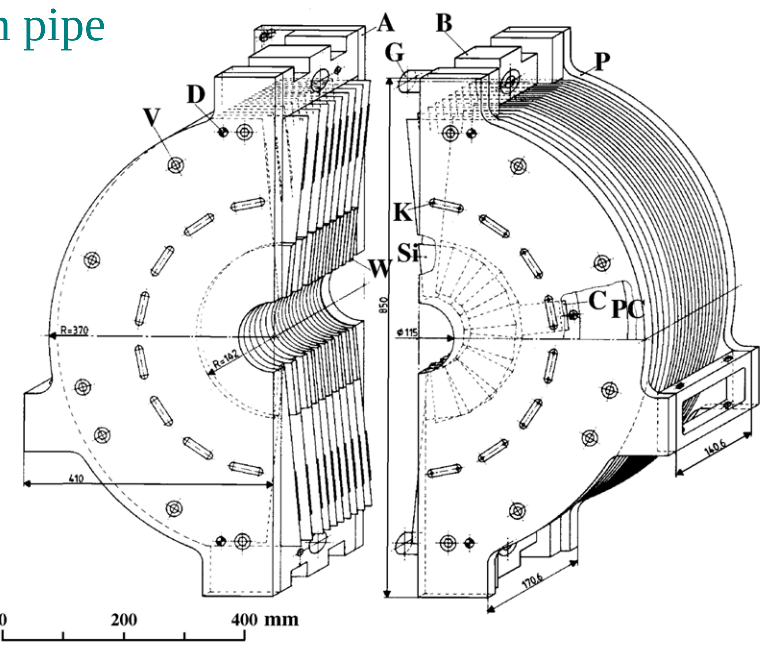
First incomplete terms

} $O(\alpha^2 L)$, $O(\alpha^3 L^3)$

Small-angle Bhabha scattering in OPAL



2 cylindrical calorimeters encircling the beam pipe at ± 2.5 m from the Interaction Point



19 Silicon layers

18 Tungsten layers

Total Depth 22 X_0 (14 cm)

Each detector layer divided into 16 overlapping wedges

Sensitive radius: **6.2 – 14.2 cm**, corresponding to **scattering angle** of **25 – 58 mrad** from the beam line