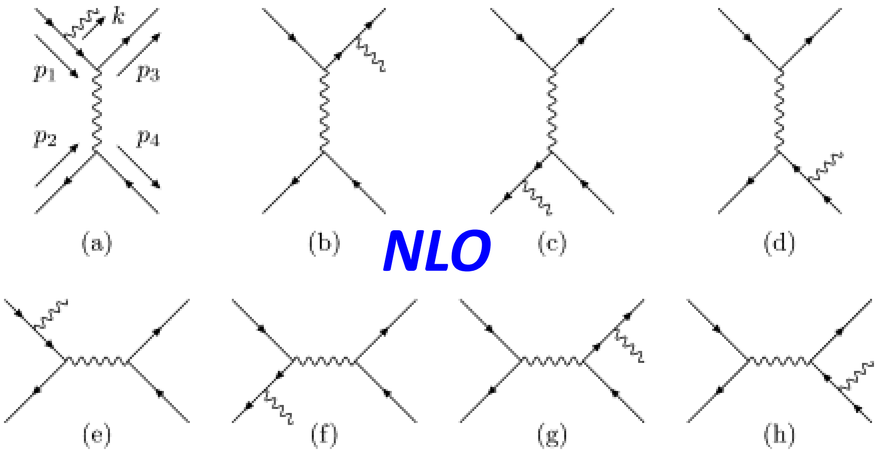
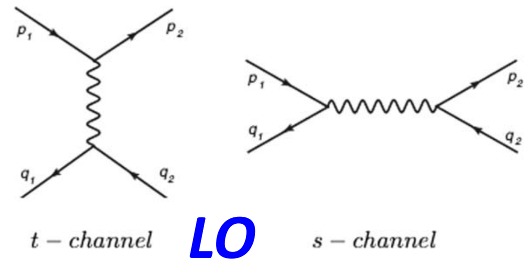
Measuring QED radiative Bhabha to 10^{-4} precision, for CEPC luminosity





2024.06.17

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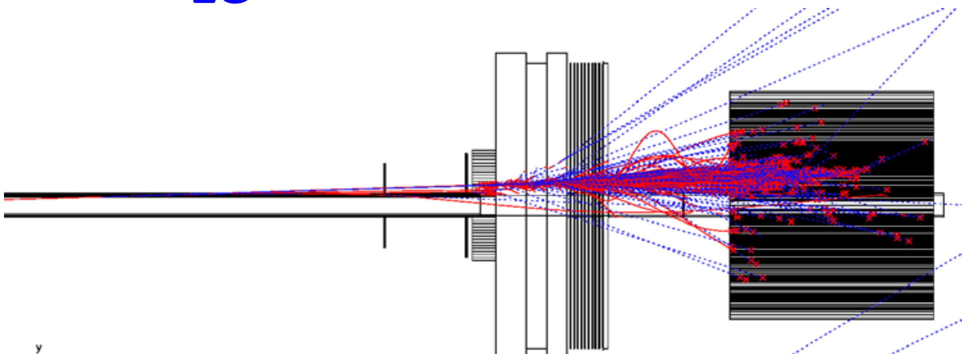
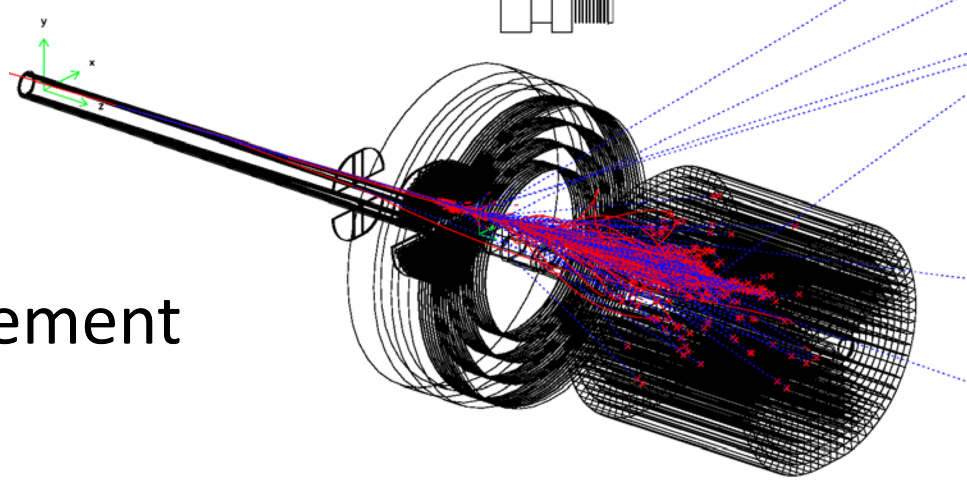


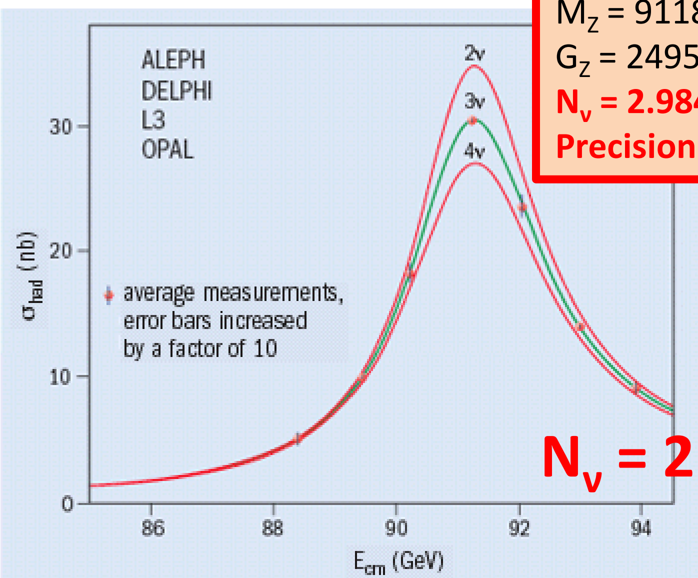


Outline

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

Physics goal at CEPC

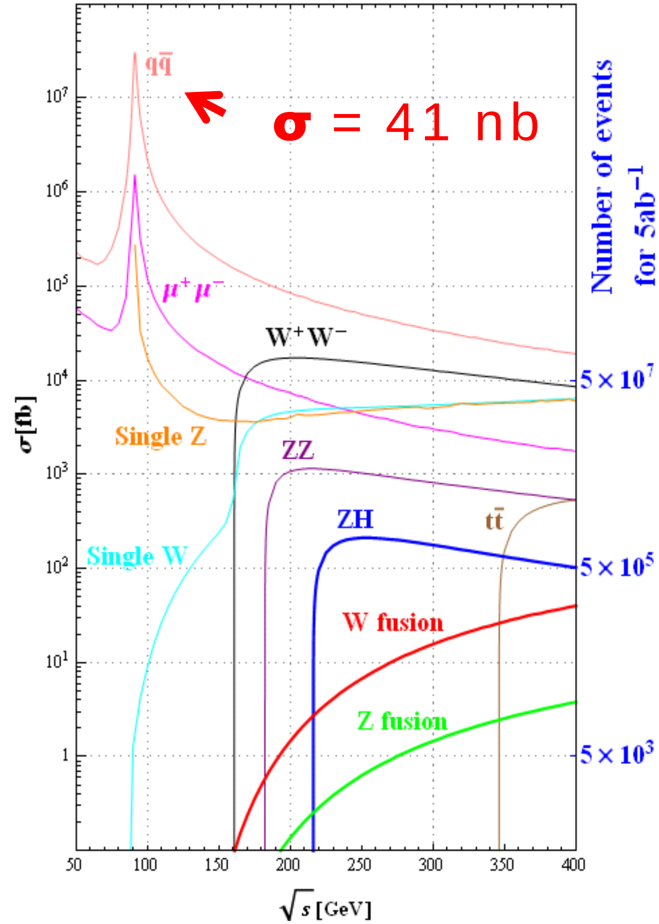
- **Z-lineshape** $e^+e^- \to Z \to q\bar{q}$
- **Luminosity by Bhabha** $e^+e^- \to e^+e^-$



CERNCOURIER 2 November 2005

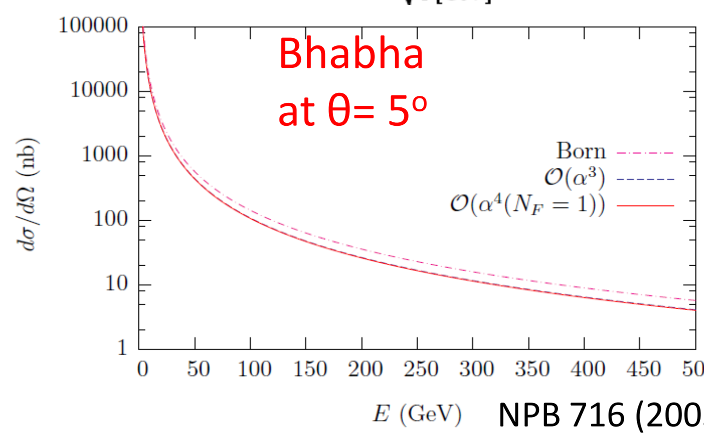
M_Z = 91187.5 ± 2.1 MeV 2.3×10^{-5}
G_Z = 2495.2 ± 2.3 MeV   1‰
N_ν = 2.9840 ± 0.0082
Precision luminosity   3‰

N_ν = 2.9840 ± 0.0082



Bhabha generators

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

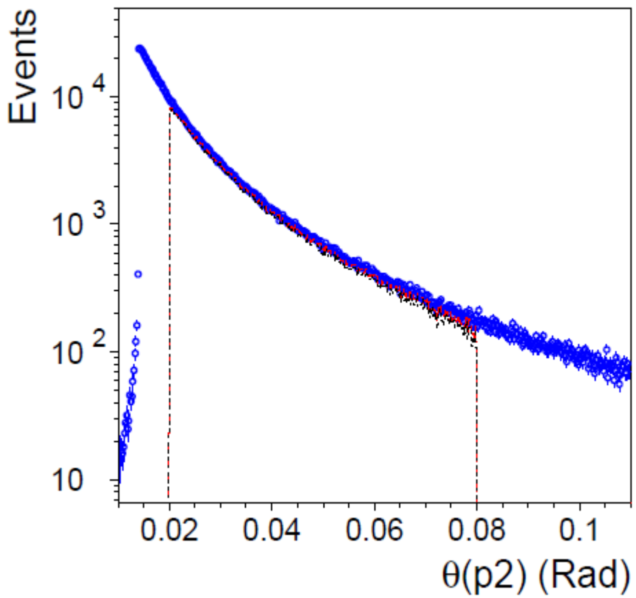


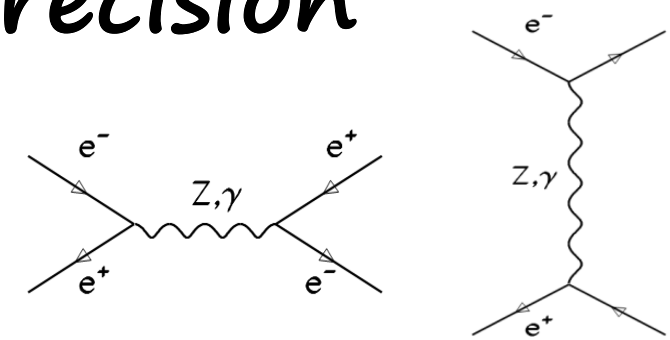
NPB 716 (2005) 280

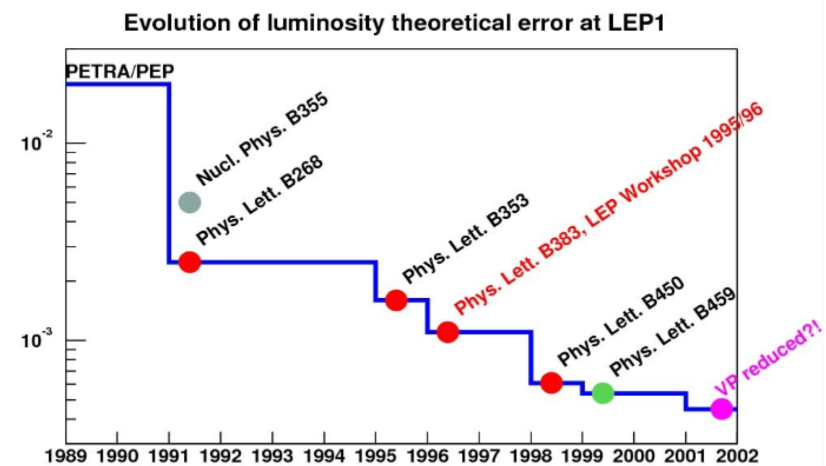
BHLUMI theoretical precision

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

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







BHLUMI 4.04

S. Jadach [CPC 101 (1997) 229]

1999 systematic 0.061 %

2019 systematic 0.037%

Type of correction / Error	1999	Update 2019
(a) Photonic $O(L_e\alpha^2)$	0.027% [4]	0.027%
(b) Photonic $O(L_e^3\alpha^3)$	0.015% [5]	0.015%
(c) Vacuum polariz.	0.040% [6, 7]	0.011% [8, 9]
(d) Light pairs	0.030% [10]	0.010% [11, 12]
(e) Z and s-channel γ exchange	0.015% [13, 14]	0.015%
(f) Up-down interference	0.0014% [15]	0.0014%
(g) Technical Precision	–	(0.027)%
Total	0.061% [16]	0.037%

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

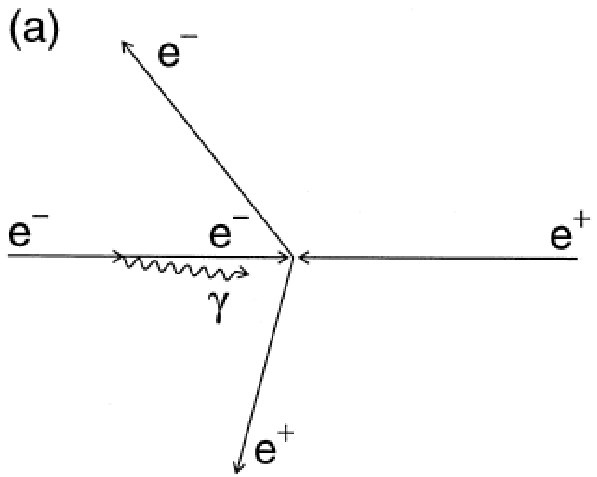
Bhabha measurements $e^+e^- \to e^+e^-(\gamma)$

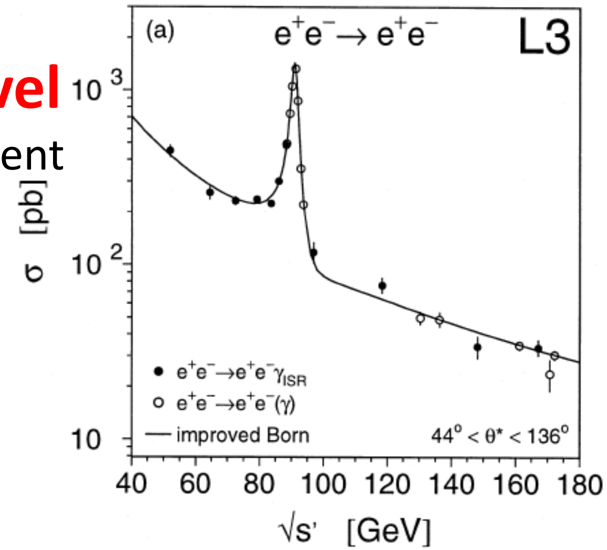
[PLB 439, 1998, 183]

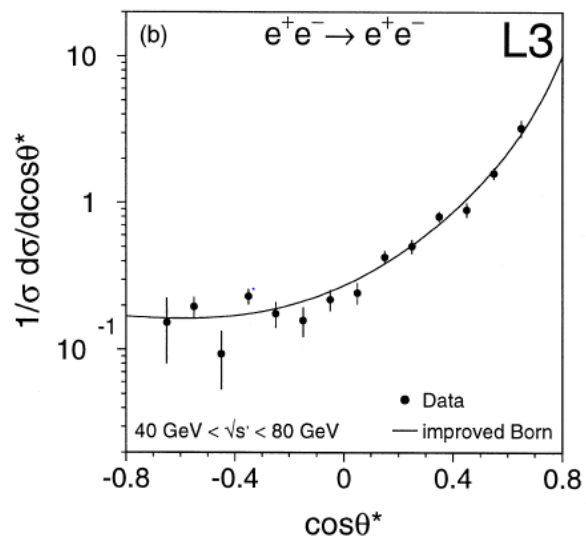
L3 radiative Bhabha, ISR

Systematic error at **~1% level**

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







TASSO Bhabha

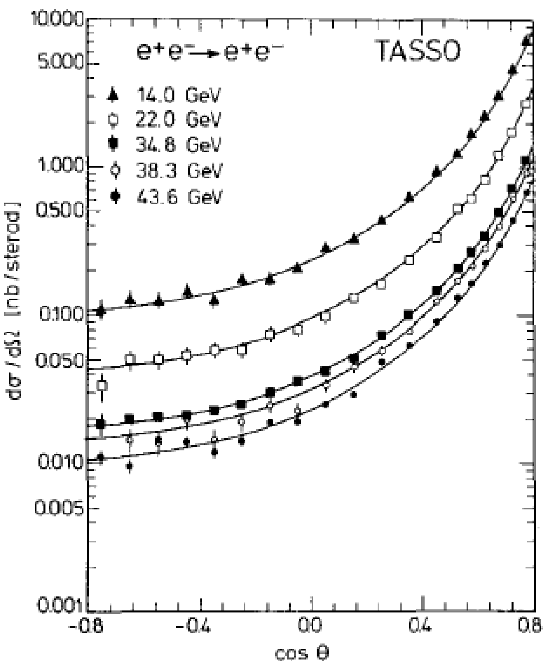
Systematic error **~3%**

$\sqrt{s}$ = 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

[ZPC 37, 1988, 171]



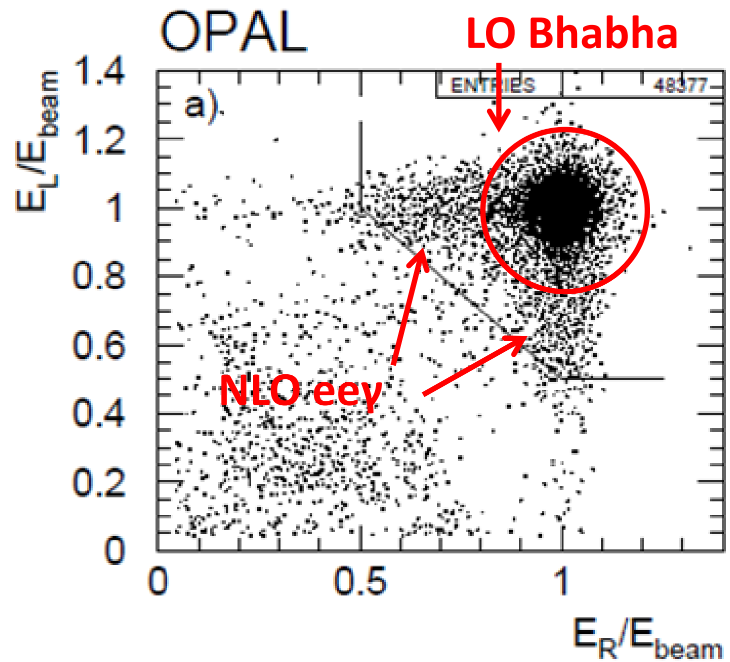
BHLUMI QED on $e^+e^- \to e^+e^-(\gamma)$

LEP forward detector
not capable of e/γ separation

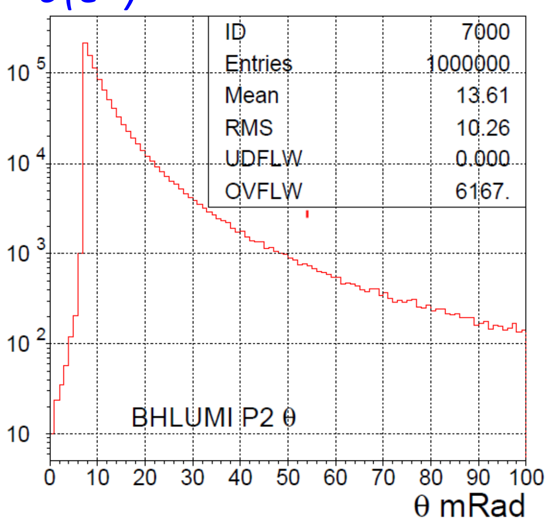
BHLUMI *$e^+e^-\gamma$ prediction*

E_{CMS} = 92.3 GeV θ = 10~80 mRad

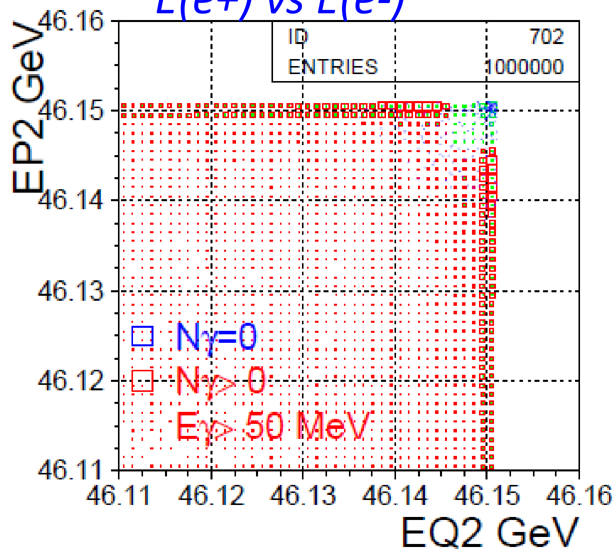
- ***$e^+e^- \to e^+e^- + N\gamma$*** *→ Eγ > 50MeV*
- ***Opening angle*** *Ω(e,γ) vs. r(e) increase w. electron ϑ*
- ***Photon (max. E)*** *examined*



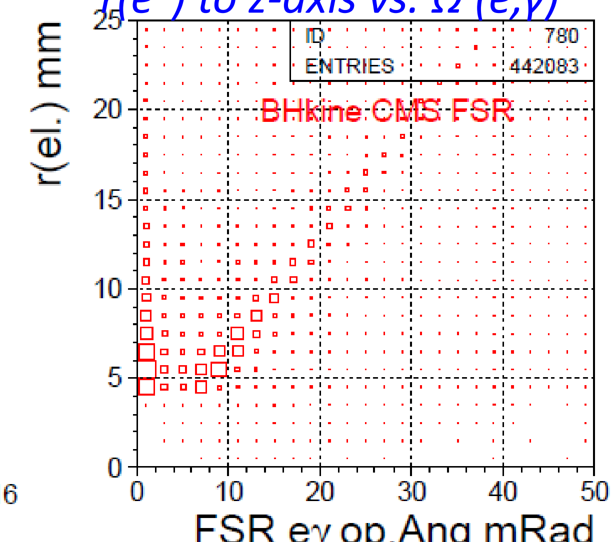
BHLUMI generated
ϑ(e+)



BHLUMI E(γ) cut
E(e+) vs E(e-)



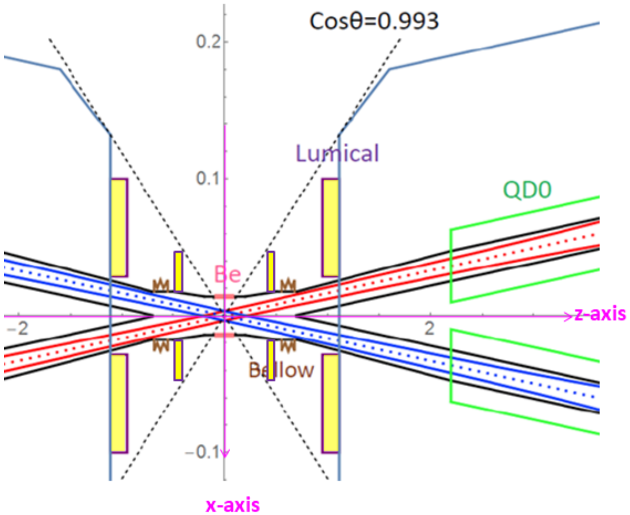
CMS frame
r(e±) to z-axis vs. Ω (e,γ)



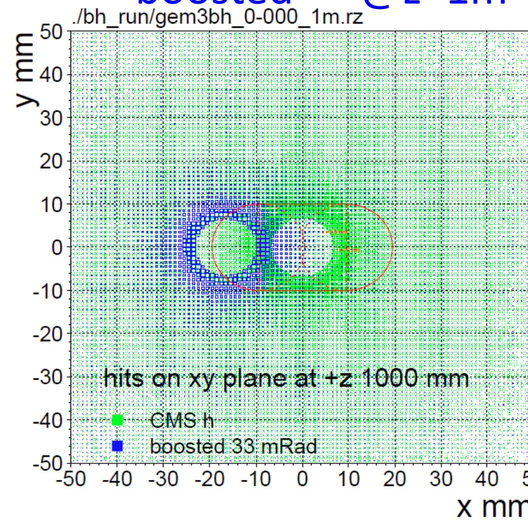
BHLUMI at CEPC boosted $e^+e^- \rightarrow e^+e^-(\gamma)$

E_{CMS} = 92.3 GeV, θ_l= 10~80 mRad

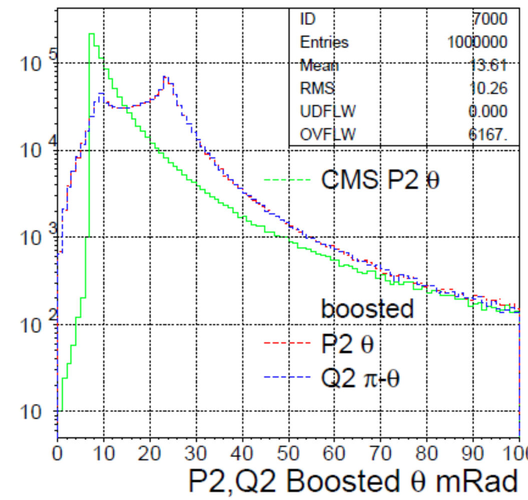
Boosted by beam crossing, 33 mRad



hit (x,y) distributions
generated @z=1m
boosted @z=1m

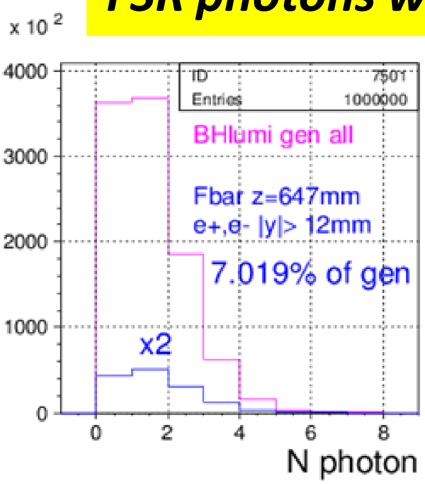


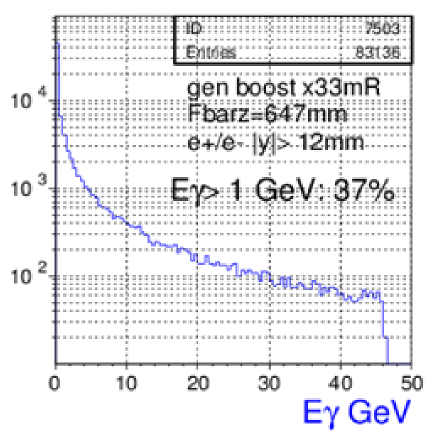
Scattered electron θ
CMS generated (θ>10mR)
x33mR boosted

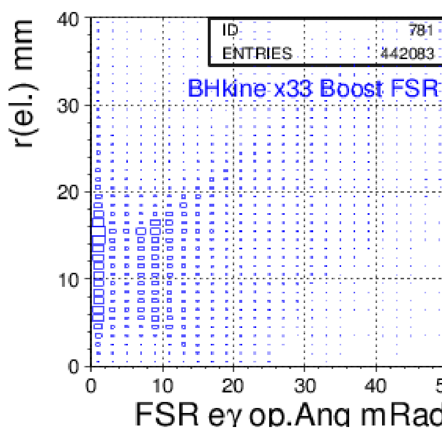


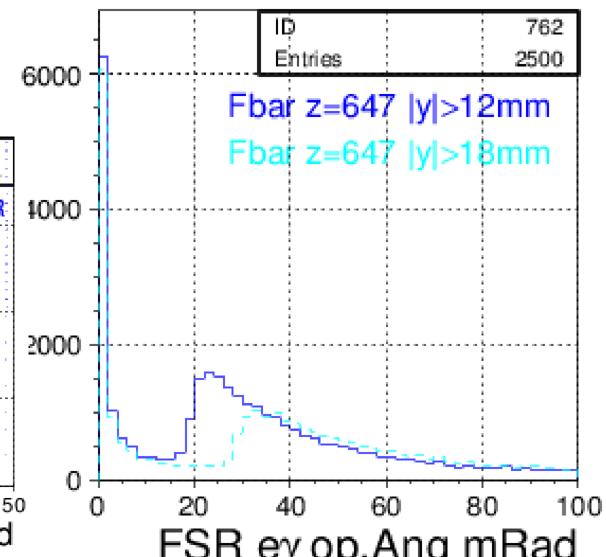
LumiCal selection |y|>12 mm @z=647mm

FSR photons well seperated from electrons



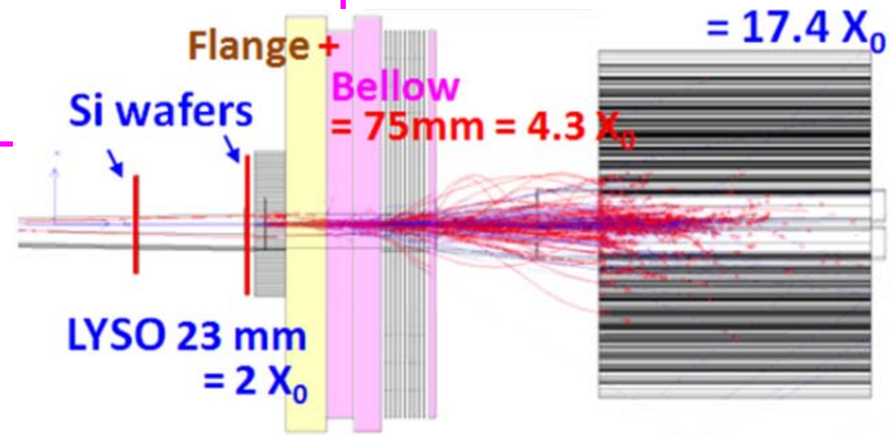




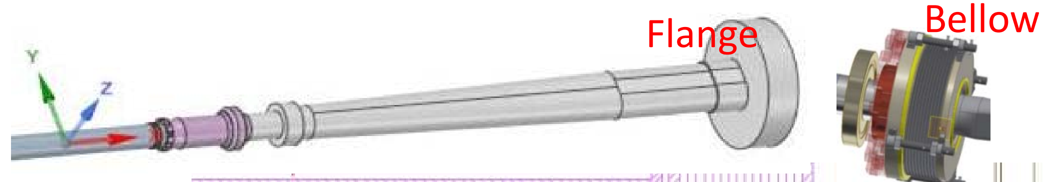


CEPC LumiCal design

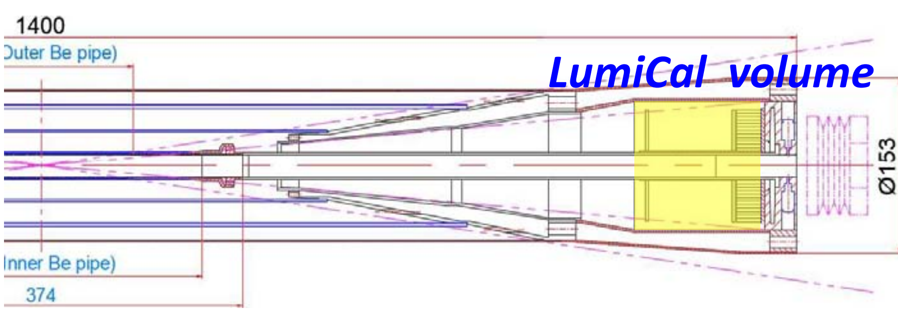
- ***L=2x10^{36}***/cm²s¹ **@Z-pole**, goal is ***10^{-4}*** systematics
  - ***ø 20 mm*** racetrack, beam-crossing: ***33 mRad***
  - IP bunch : ***σ_x σ_y σ_z = 6 μm, 35 nm, 9 mm***
  - Bunch crossing: ***23 ns***

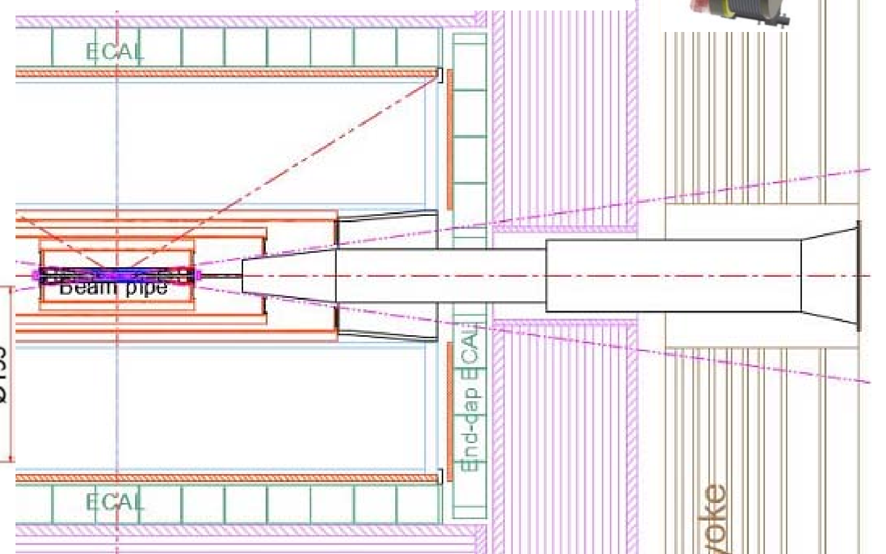


- ***before Flange*** z = 560~700 mm
  - **Low-mass window**: **Be 1mm thick**
    traversing @22 mRad traversing L= 45 mm,
    = 0.13 X$_0$ (Be), 0.50 X$_0$ (Al)
  - **Two Si-wafers** for $e^{\pm}$ impact θ
  - **2X$_0$ LYSO** = 23 mm



- **behind *Bellow*** z= 900~1100 mm
  - **Flange+Bellow : ~60 mm, 4.3 X$_0$**
  - **17.4 X$_0$ LYSO 200 mm**





Bhabha counting to 10^{-4} precision

- ***Event counting $N = \sigma \cdot \int L$***
- ***Luminosity by detecting Bhabha events***
  - *a pair of back-back electrons,*
  - *precision ϑ on e,e(γ) in fiducial region*

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

$$\mathcal{L} = \frac{1}{\varepsilon}\frac{N_{\rm acc}}{\sigma^{\rm vis}}$$

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

Bhabha systematic error

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

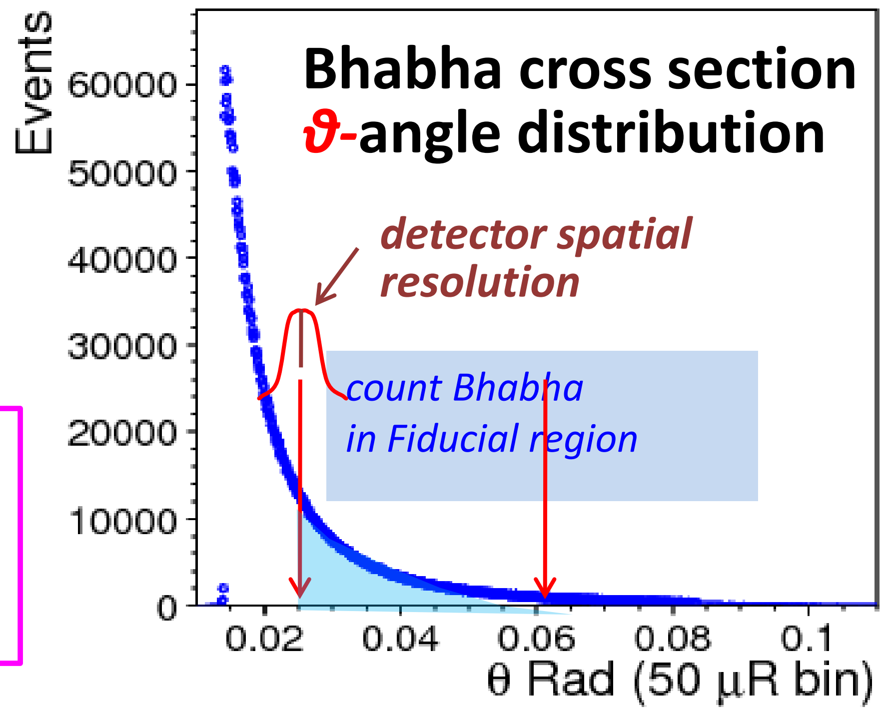
requiring $\delta L/L = 10^{-4}$

at **z = ±1 m**, 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 events in/out fiducial edge

→ offset on the mean of θ_{min}

GEANT beampipe multiple scattering

- ***IP spot*** (σ_x,σ_z)= (0,0) or (6,380μm) ← *compatible*
- boost by 33 mRad beam crossing
- ***50 GeV μ⁺, μ⁻***

  @ (ϑ= ±30 mRad, φ = 1.0, 1.0+π Ra)

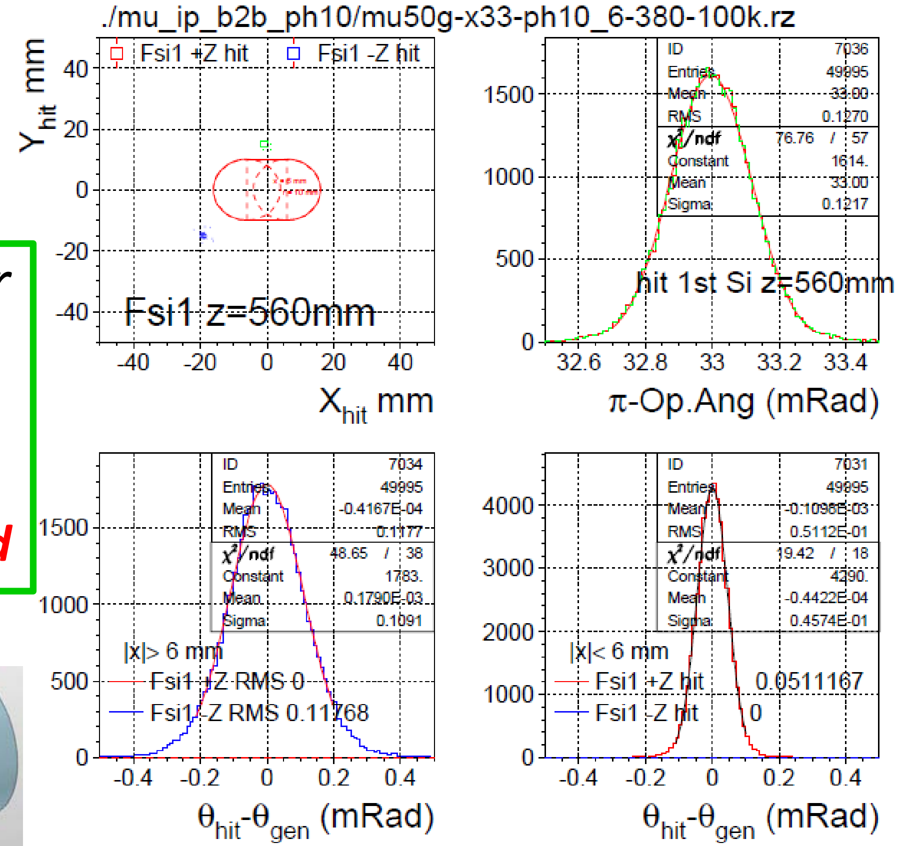
smearing at @z=560mm, 1st Si wafer

|x|< 6.0 mm, 1mm Be

low mass window ***σ(ϑ) = 46 μRad***

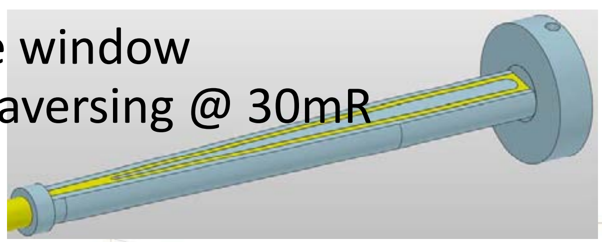
|x|>6.0 mm 1mm Al pipe, ***σ(ϑ) = 109 μRad***

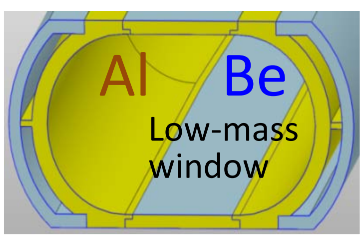
back-to-back ***σ(Ω) = 122 μRad***

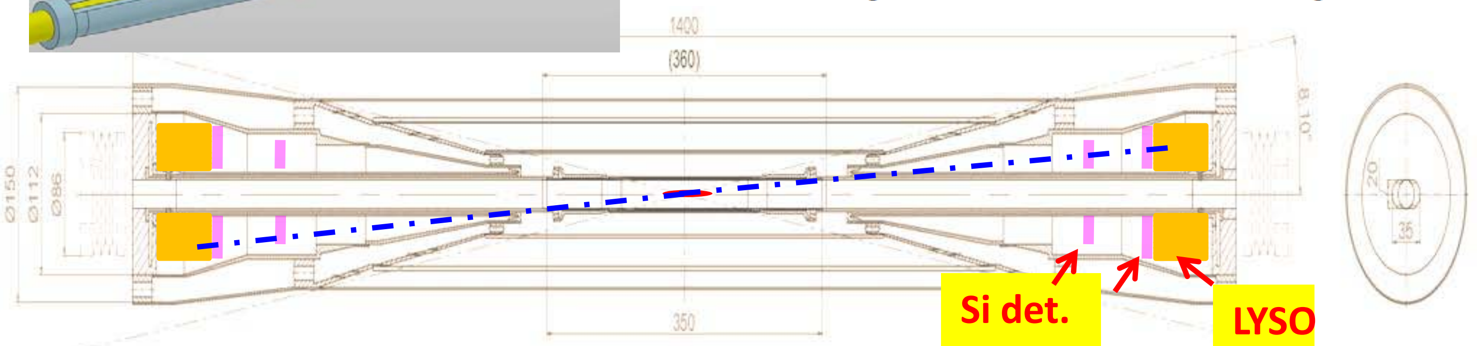


1 mm Be thin pipe window

33mm = $0.09X_0$ traversing @ 30mR







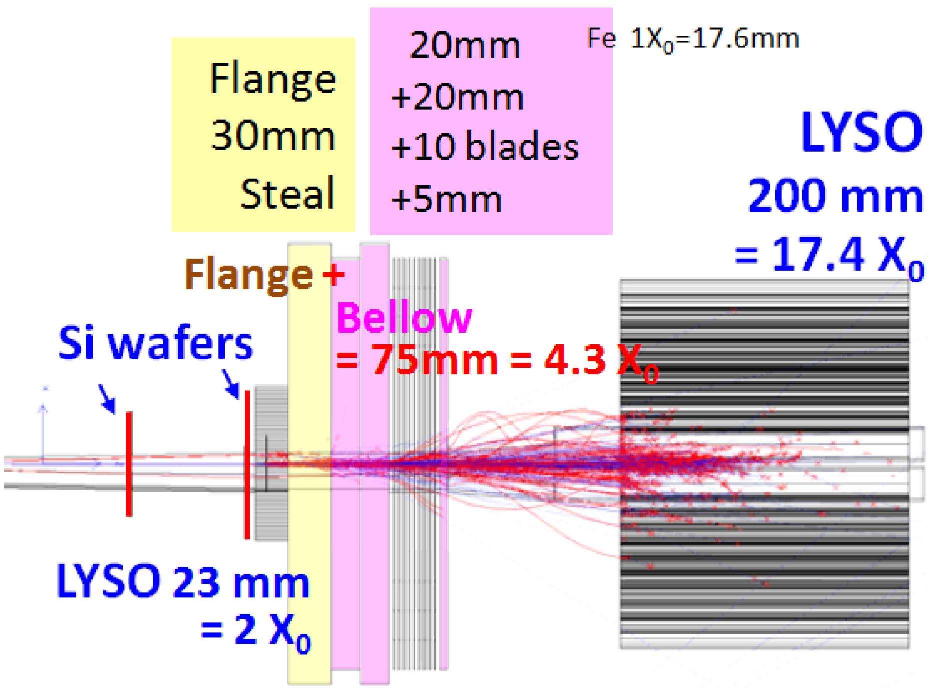
GEANT LumiCal electron shower

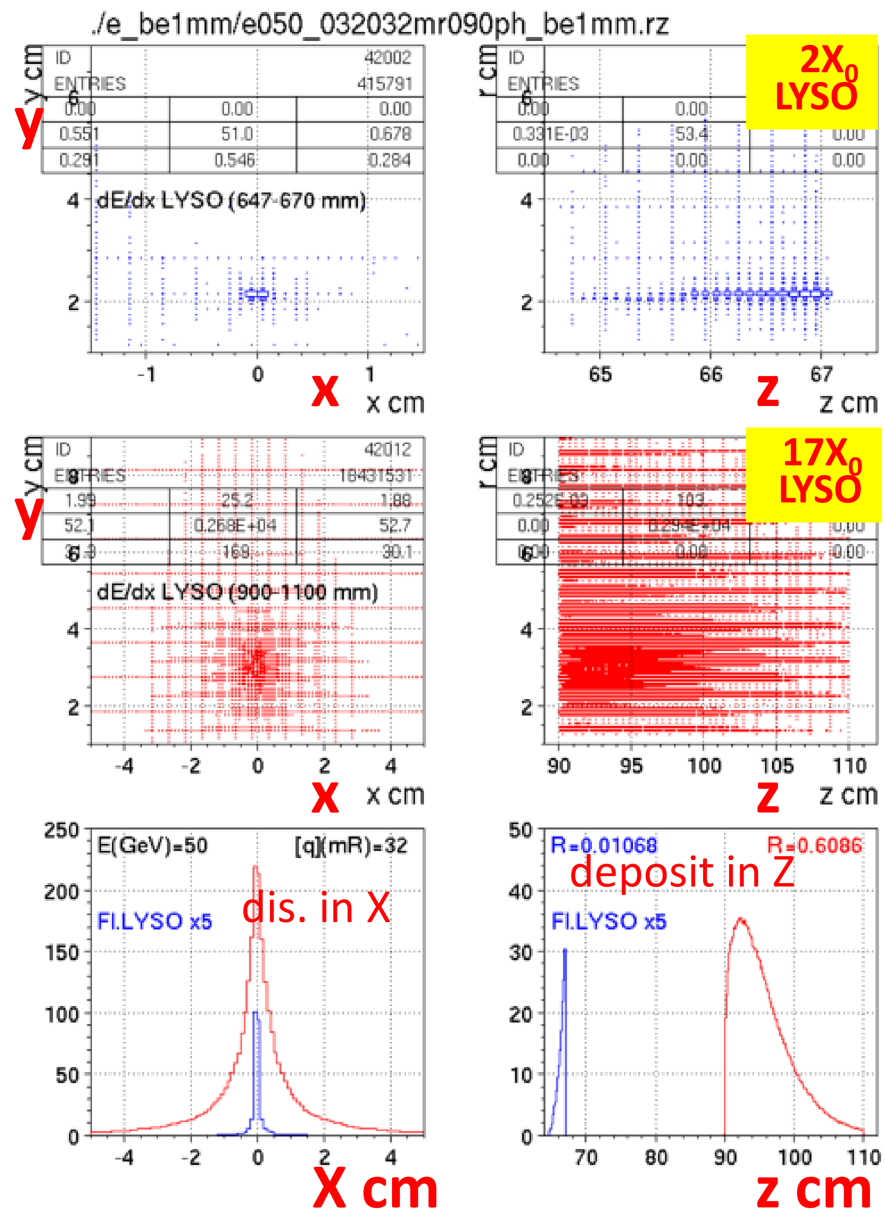
50 GeV electron @ θ = 32 mRad, ϕ=90°

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

Shower deposition, by Sum(dE/dx)

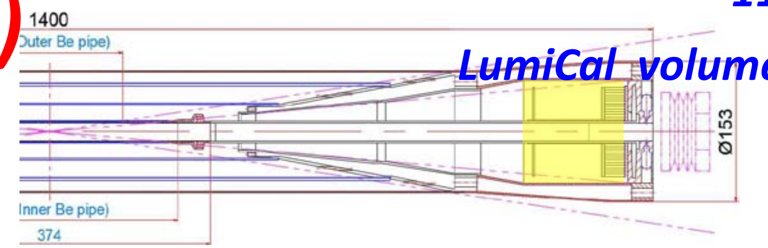
- in front LYSO: ~1.0 %
- in back LYSO: ~ 61 %





$2X_0$ LYSO for $e^+e^- \to e^+e^-(\gamma)$

Bhabha hits on LYSO |y|>12mm



incident particles are $e^{\pm}$,(γ) and secondaries

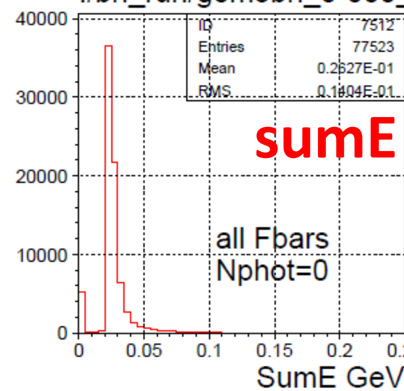
- **GEANT sum dE/dx in each LYSO bars**
  3x3mm², 23 mm long, $2X_0$
- **Deviation to $e^{\pm}$ truth** (impact hit >Eb/2)
  mostly < 0.2mm
- **Hit distributions in a Bar**
  distributed due to Bhabha θ, w./w.o. photon

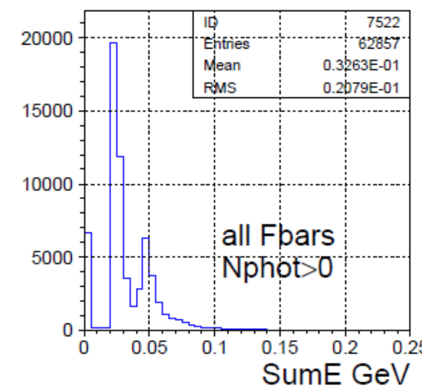
sum dE/dx all LYSO bars (a plane)

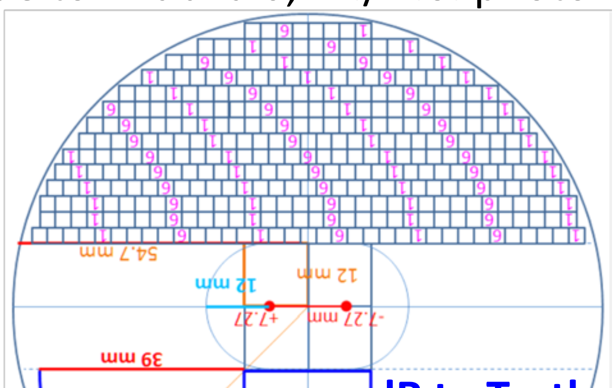
- **$e^{\pm}$ one track : sumE min. 20 MeV**
- **($e^{\pm}$+ FSRγ) : two MIPs, sumE x2**

Loop Bar	Nγ=0	Nγ>0

./bh_run/gem3bh_0-000_1m.rz



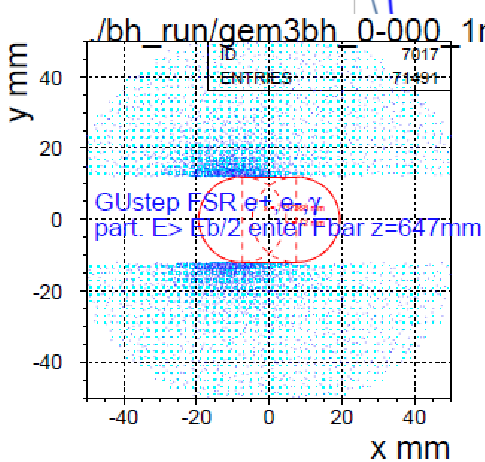


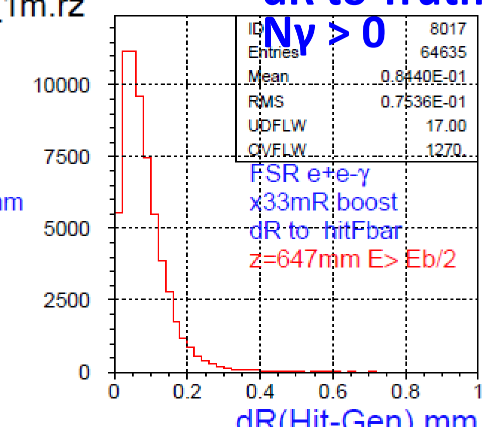


GEANT hits E>Eb/2
33mRad boosted
On LYSO @647mm

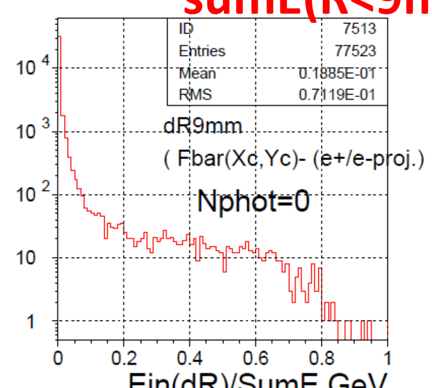
dR to Truth
Nγ > 0

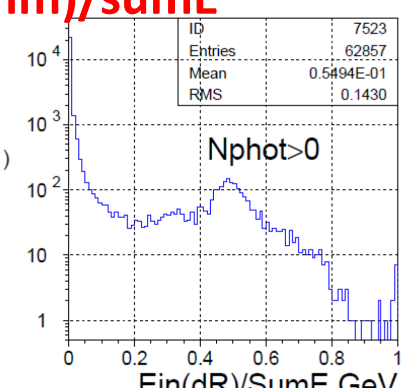
./bh_run/gem3bh_0-000_1m.rz





sumE(R<9mm)/sumE



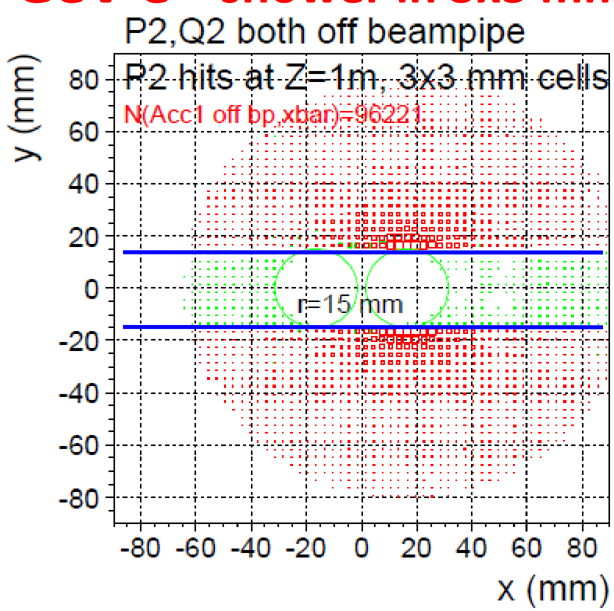


Bhabha event pile-up

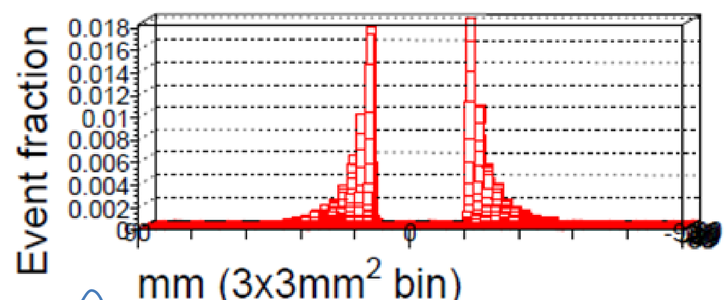
1. High-Lumi Z L_{max}/IP = **115 x 10^{34}/cm^{2}s**
2. Bhabha both ***e⁺, e⁻*** detected, X-sec = **246 nb**
   = (246×10^{-33}) x (115×10^{34}) /s **= *115 kHz***
3. Event rate / 25 ns bunch crossing
   = **0.003 events /b.c.**
4. **Pile-up: next b.c., @adjacent cell**
   Pile-up Fraction = 0.018*6cells/2sides = **0.054**
   Pile-up rate = 0.003*0.054 = **1.6 x 10^{-4}**

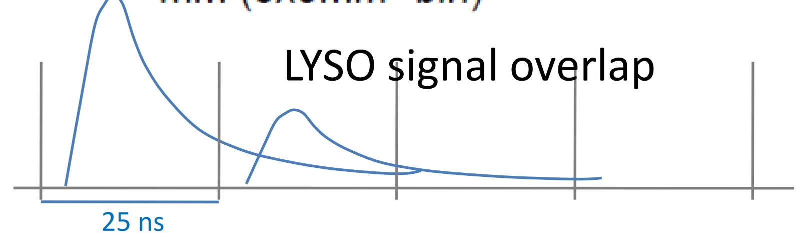
BHLUMI acceptance z = 1000 mm	
LAB both *e⁺, e⁻* detected	
θ>15 mRad	θ>15mR & |y|>15mm
257.8	**245.9**
θ>25 mRad	θ>15mR & |y|>25mm
85.4 nb	**78.0 nb**
θ>30 mRad	θ>30mR & |y|>30mm
54.9	**49.1**

50 GeV e- shower in 3x3 mm^2 cells



event fraction /(cell of 3x3mm^2)
maximum at beampipe edge = 0.018





EM shower in PDG, GEANT simulation

GEANT3 parameters agree with TestBeam

CUTGAM	CUTELE	BCUTE	DCUTE	LOSS	DRAY	MULS
10 keV	10 keV	100 keV	200 keV	1	1	2

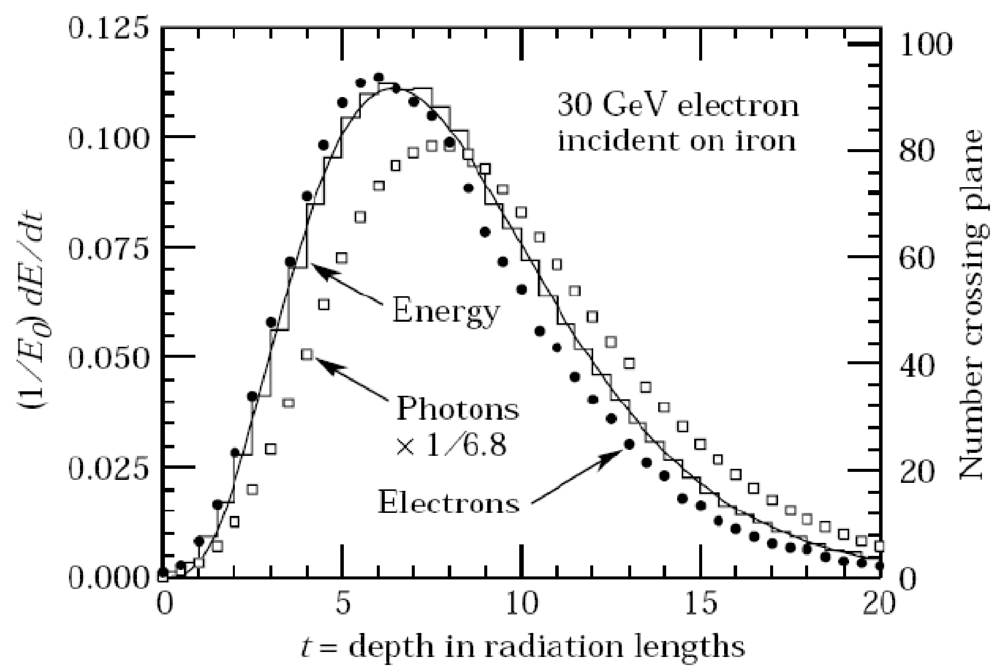
Table 4: GEANT parameters applied in the simulations.

Beam-tests planning for LumiCal:
Si wafer + LYSO SiPM

- 100% quantum efficiency
  for electron Multiple scattering, charged shower multiplicities
- SiPM for photon counting in lateral X_0 layers

PDG lateral shower profile of EGS

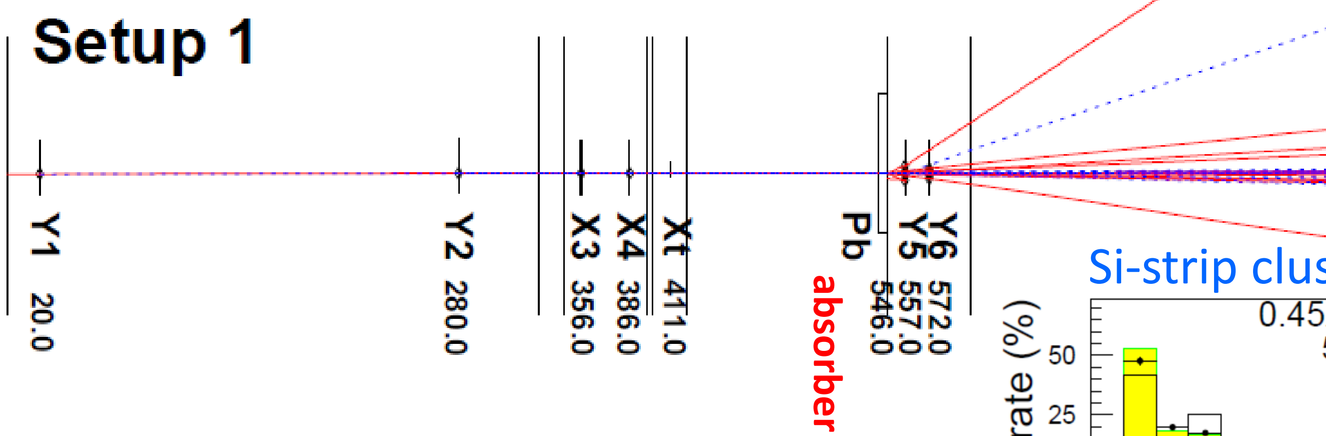
Energy profile



Particle flow

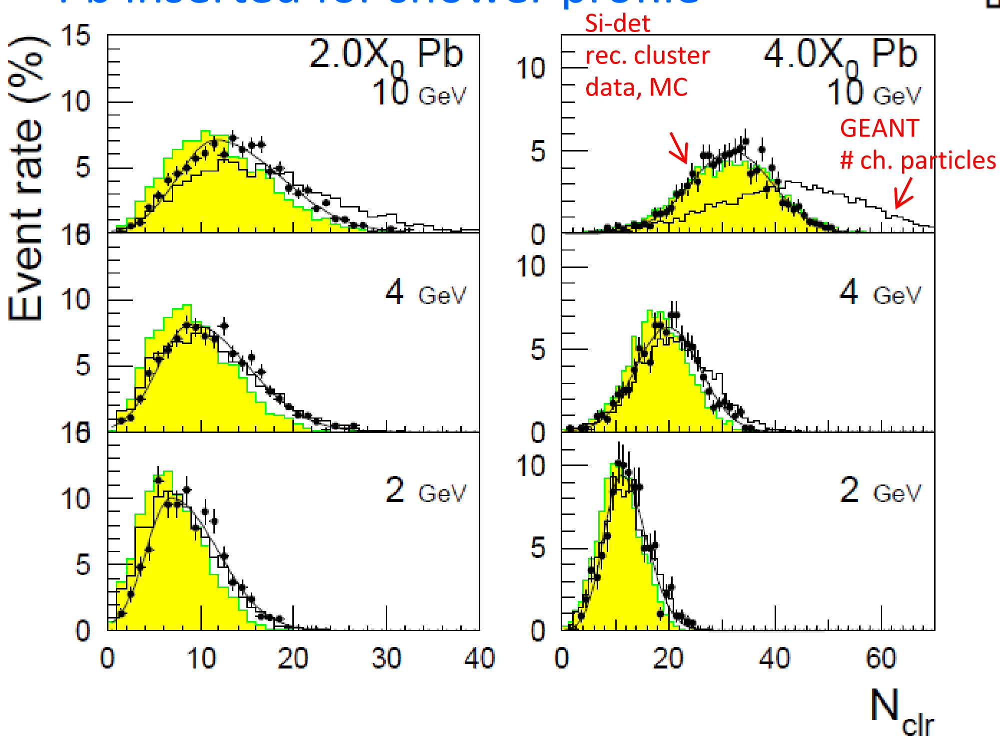
Electron shower multiplicity vs GEANT3

NIM A388 (1997) 135

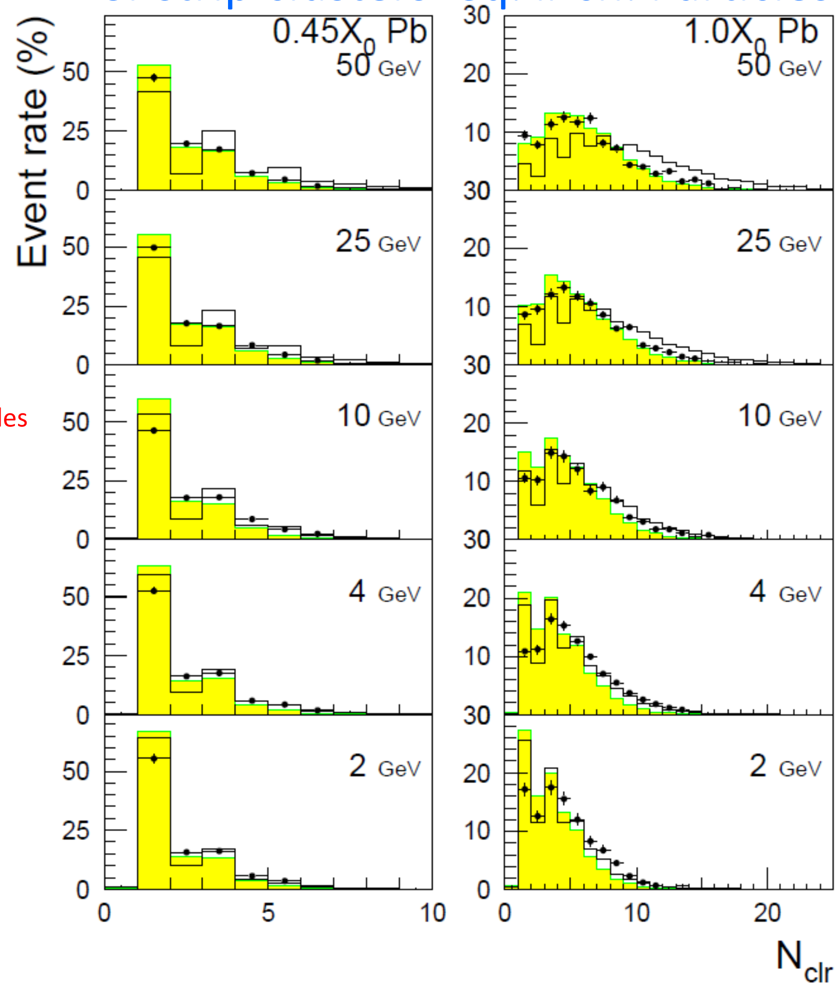


Electron traversing Si-det

Pb inserted for shower profile



Si-strip clusters   eq. # ch. Particles

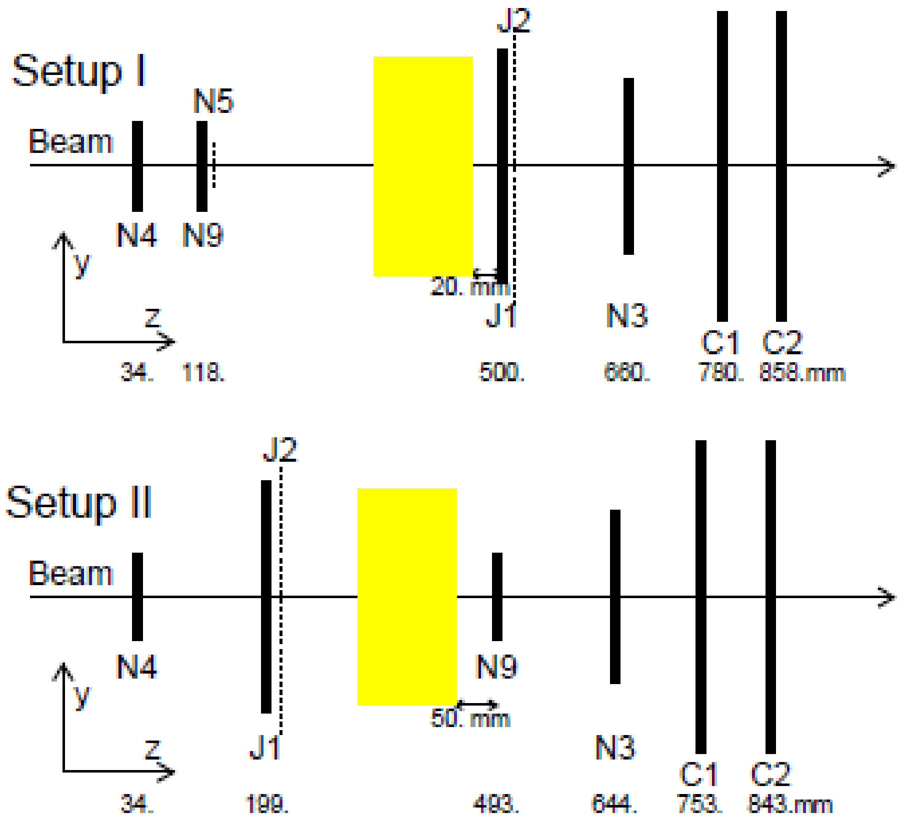


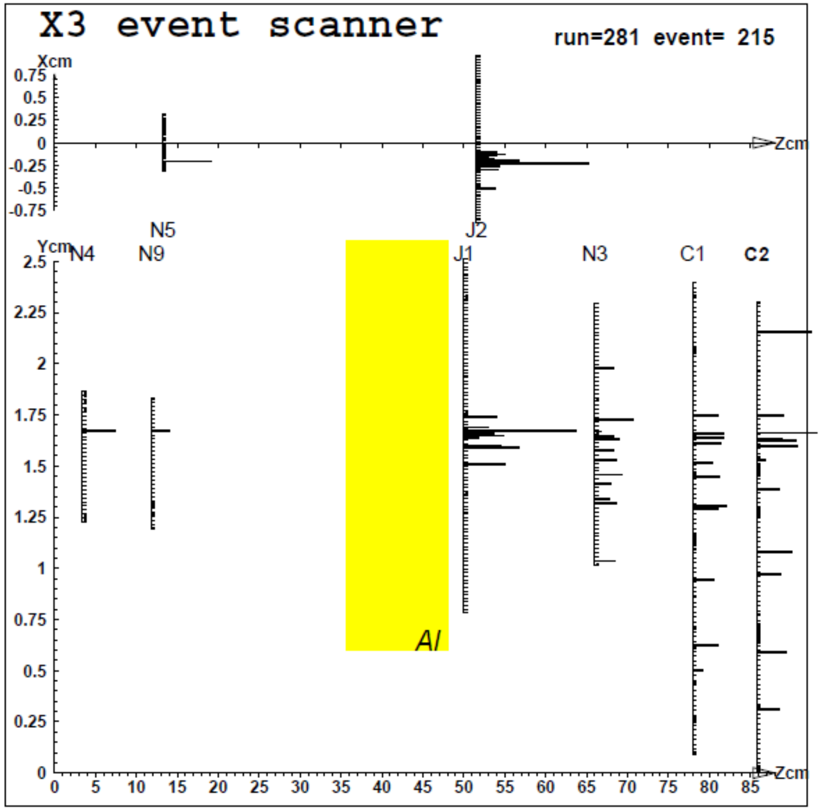
50 GeV Electron shower multiplicity

Charged shower particles, Si-det + Al absorber

NIM A374 (1995) 157

- 50 GeV electrons @ CERN X3
- Si-strip 50um pitch 300um thick
- Al absorber to expand shower distribution





Electron shower profile vs GEANT3

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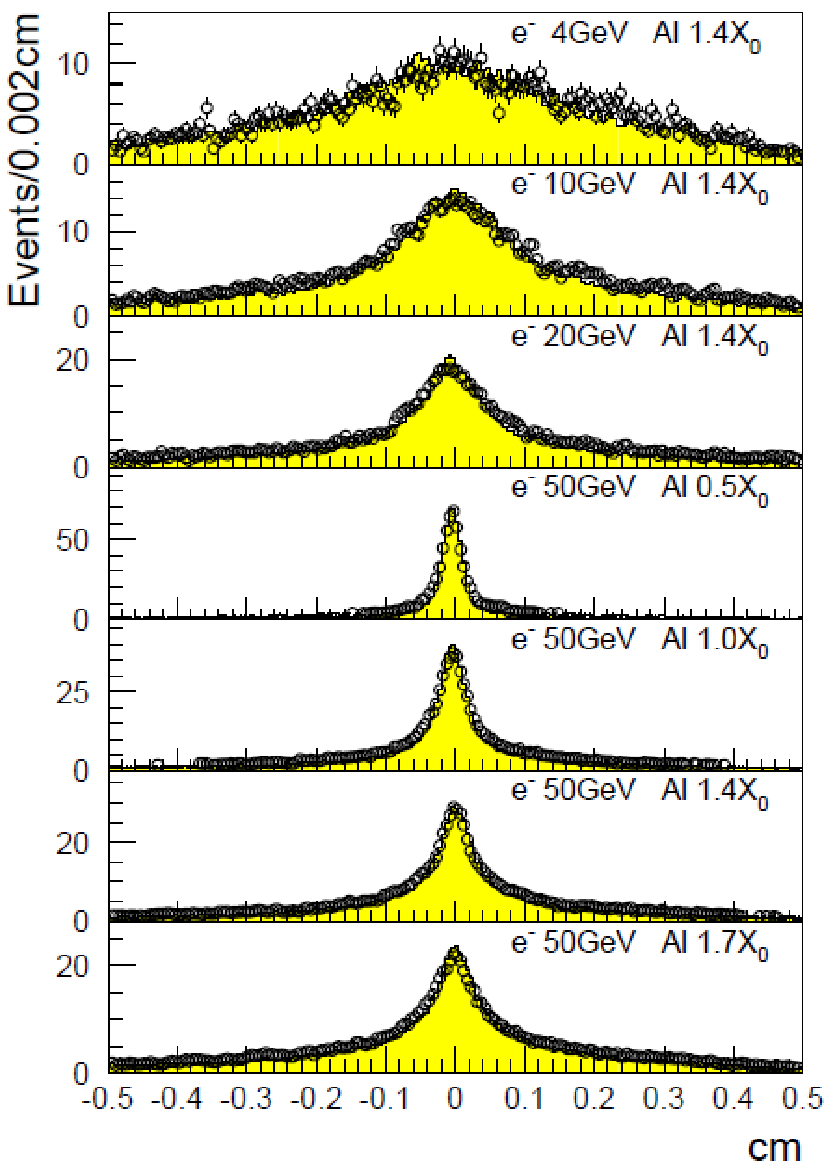
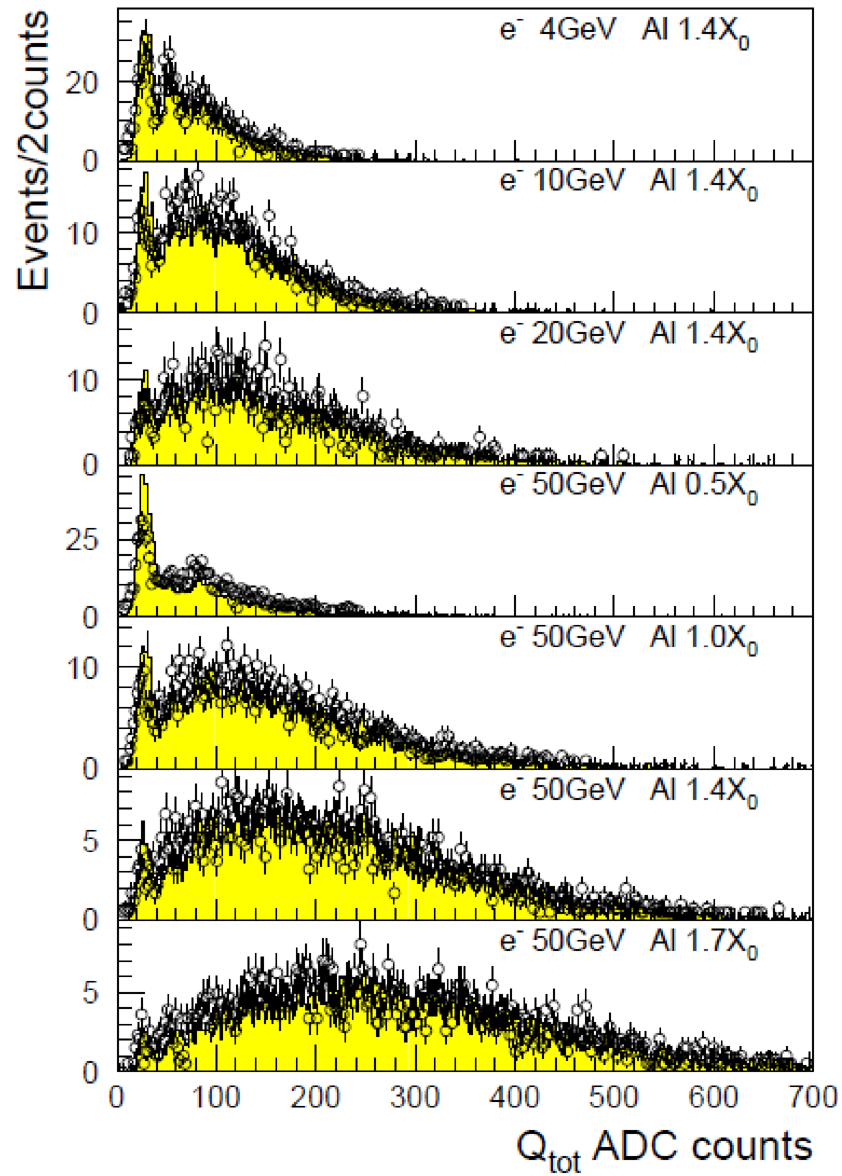
GEANT3 simulation of traversing charged-particle signal randomly from Landau of data, shared to 2 Si-strips

Hits on N3





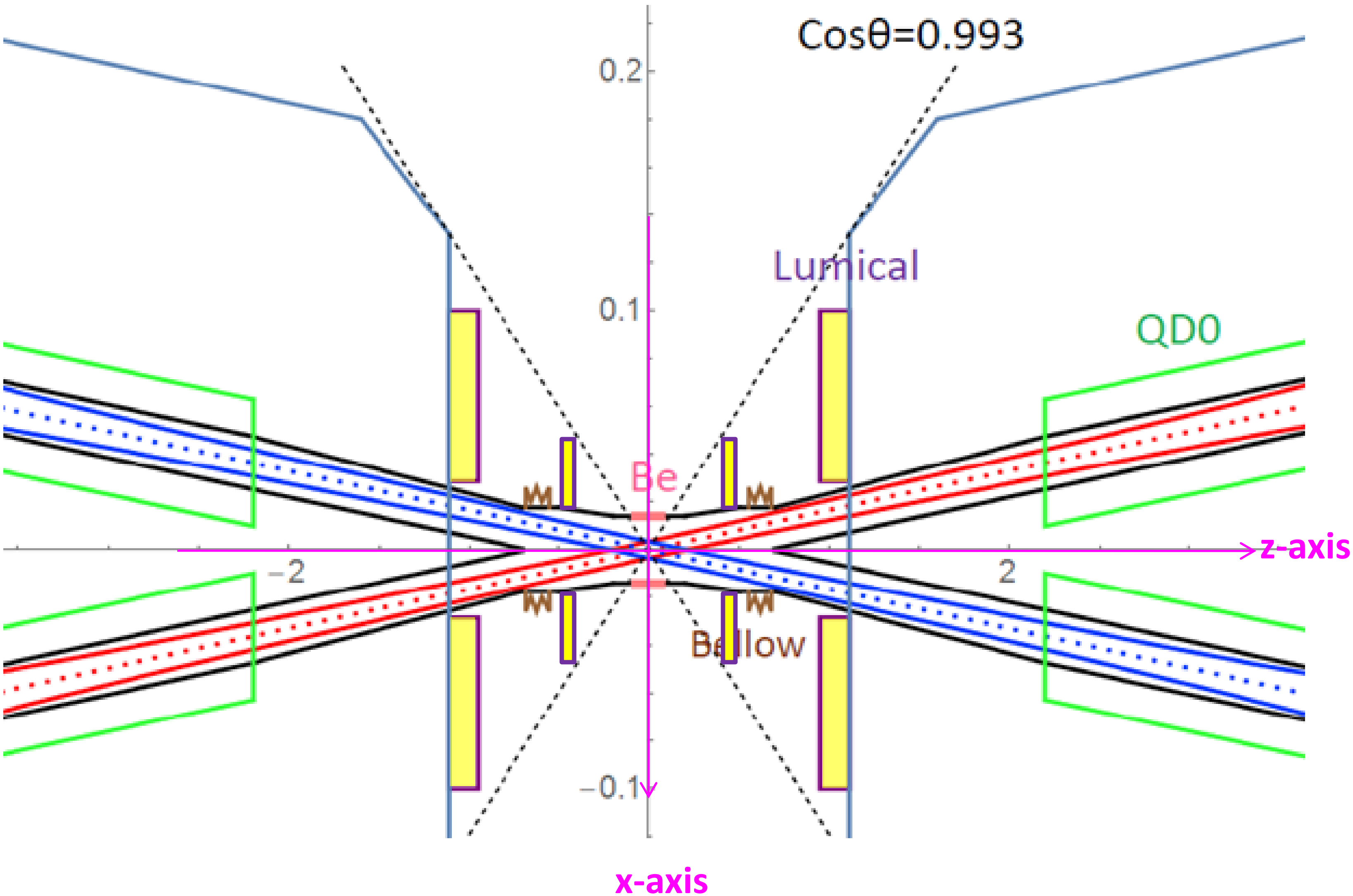
summary

Detecting Bhabha for QED/luminosity to 10^{-4}

Det. Tech has advanced

- **100% Quan. Efficiently**
  Si-strip on electrons
  SiPM on LYSO photons
- **Si-strip + LYSO ($2X_0$)**
  e/γ separation for Rad. Bhabha
- **Testbeam on e, γ to confirm**
  multiple scattering
  preshower spectra

backup


Cosθ=0.993
0.2
0.1
−0.1
Lumical
QD0
Be
Bellow
z-axis
−2
2
x-axis