LumiCal preparation for rTDC

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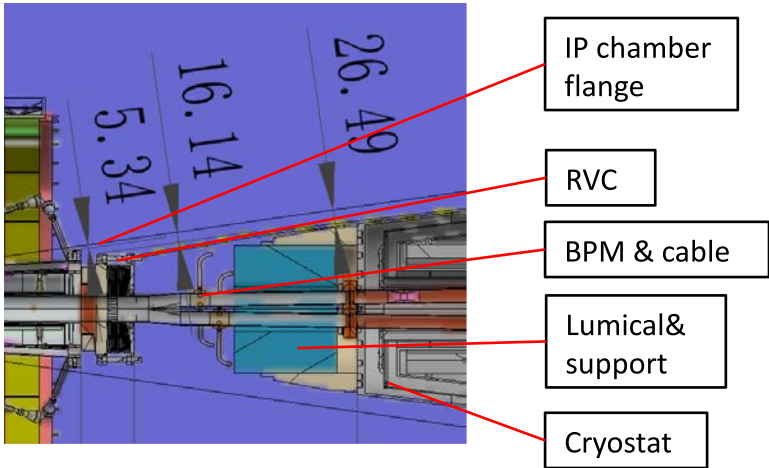
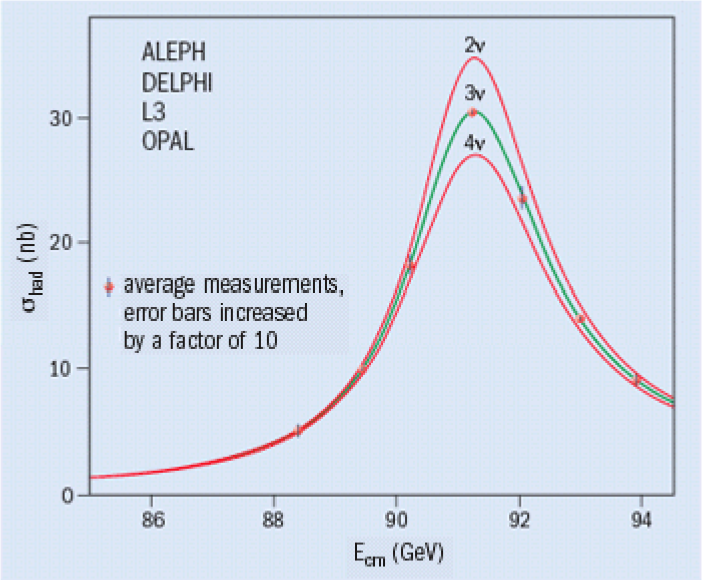


1. Standard Model Z-pole precision measurement



$M_Z = 91187.5 \pm 2.1$ MeV $\quad 2.3 \times 10^{-5}$

$G_Z = 2495.2 \pm 2.3$ MeV $\quad$ 1‰

Nn = 2.9840±0.0082

Precision luminosity $\quad$ 3‰

CERNCOURIER 2 November 2005

Physics goal, cross-section measurements

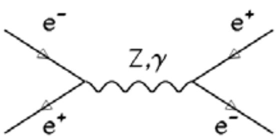
- ***Z-lineshape***

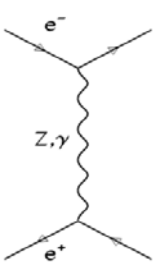
  $e^+e^- \rightarrow Z \rightarrow q\bar{q}$

- **Luminosity by Bhabha**

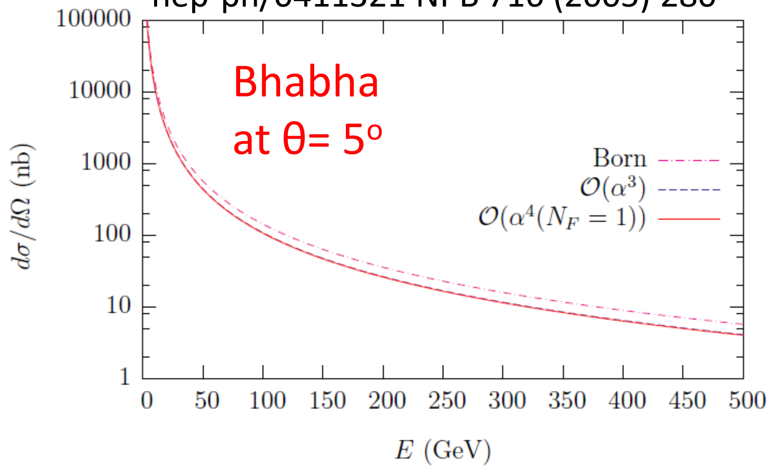
  $e^+e^- \rightarrow e^+e^-$

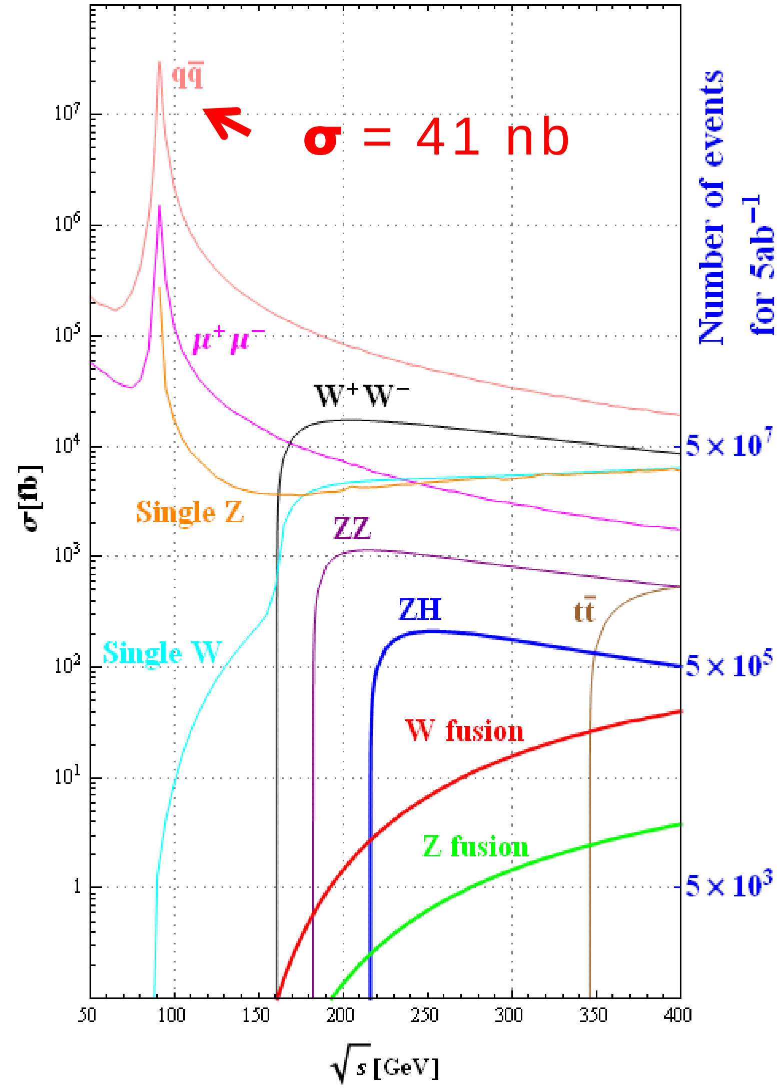
$$\mathcal{L} = \frac{1}{\varepsilon}\frac{N_{\mathrm{acc}}}{\sigma^{\mathrm{vis}}} \qquad \sigma = \frac{16\pi\alpha^2}{s}\left(\frac{1}{\theta_{min}^2} - \frac{1}{\theta_{max}^2}\right)$$





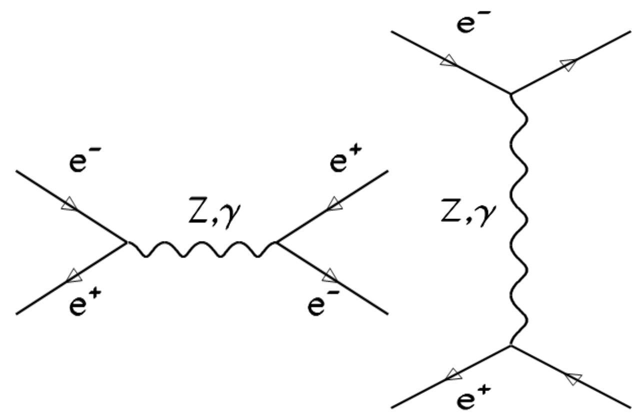
hep-ph/0411321 NPB 716 (2005) 280



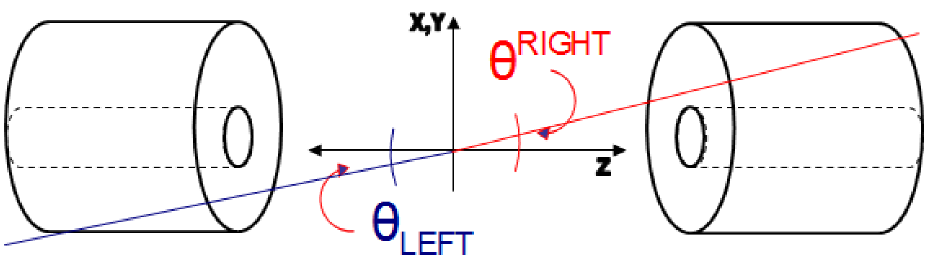


Luminosity by Bhabha elastic scattering

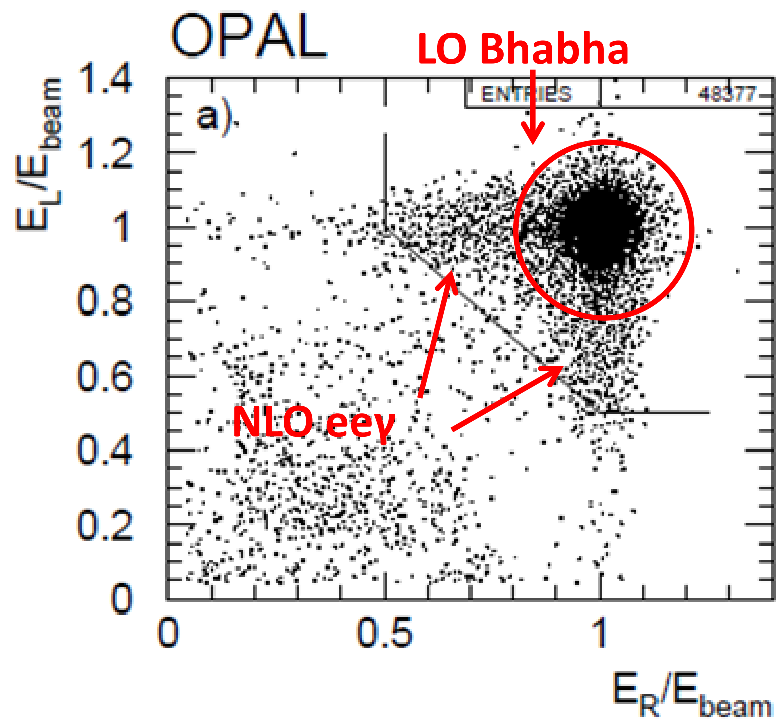
- ***Physics events, e.g. Z-pole,***
  $N = \sigma \cdot \int L$ ***L: Luminosity of e^+e^- collisions***
- ***Luminosity* by counting Bhabha events**
  $e^+e^- \rightarrow e^+e^-(\gamma)$ QED *theo. precision < 0.1%*
  1. ***a pair of electrons,*** $E(e^\pm) = E_{beam}$
     back-to-back
  2. ***precision ϑ of e, e(γ)***
  3. ***within fiducial region***



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



$$\Delta\theta \equiv \theta_{RIGHT} - \theta_{LEFT}$$



Luminosity to 10^{-4} precision

- **Observable cross section** $N = \sigma \cdot \int L$ *L: Luminosity of e^+e^- collisions*
- **Luminosity** measured by counting **Bhabha** *events*, QED precision < 0.1%
  - *a pair of back-back electrons,*
  - *precision ϑ on e,e(γ) in fiducial region*

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

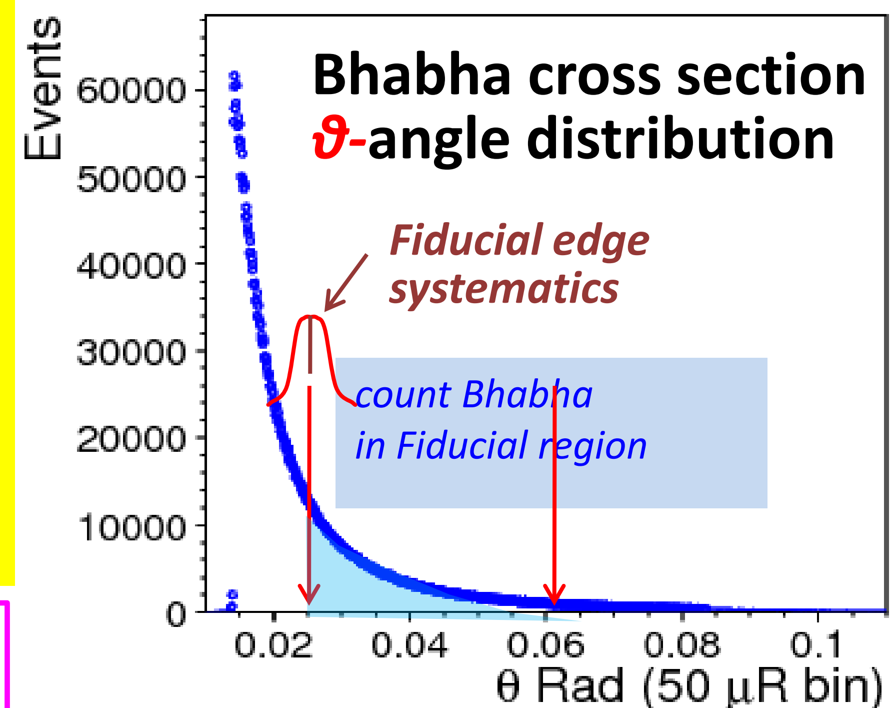
→ Z eq. $dr = \delta z \times \vartheta$ = **1 μm** **dz = 50 μm**

Luminosity systematics

due to **events in/out fiducial edge**

→ offset on the mean of θ_{min}

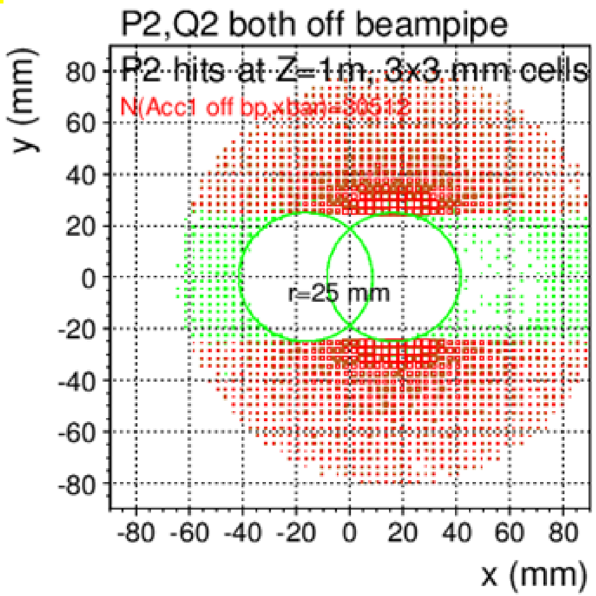
$$e^+e^- \longrightarrow e^+e^-(\gamma)$$

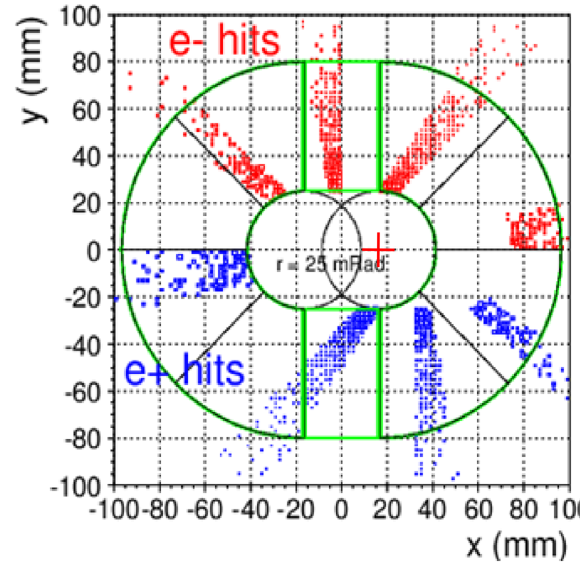


BHLUMI X-section, racetrack beampipe

Acceptance @z=1m
r>25 mm, $|y|$>25 mm

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



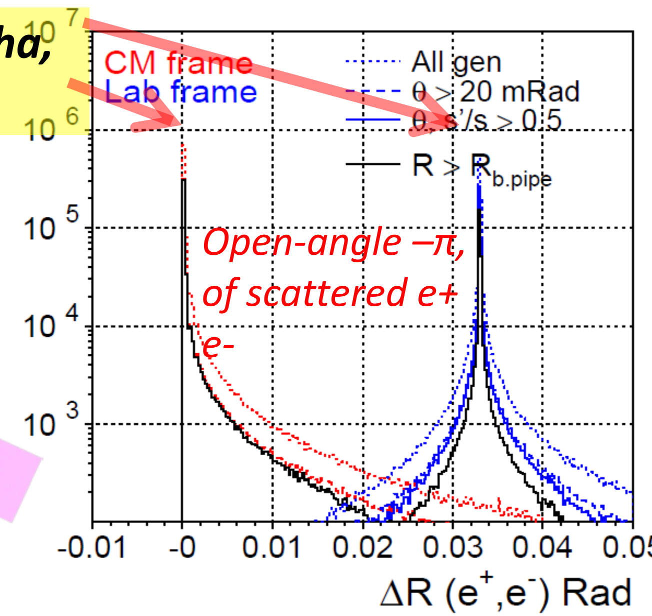


LAB frame

***e^+, e^-* detected**

@ Z=1000 mm

Multi. Scatt., rad. Bhabha,
→ wider back-back



at Z = 1000 mm

LAB ONE e^+ or e^- detected		LAB both e^+, e^- detected	
θ>15 mRad	θ>15mR & $\lvert y\rvert$>15mm	θ>15 mRad	θ>15mR & $\lvert y\rvert$>15mm
395.3	255.9	257.8	245.9
θ>25 mRad	θ>25mR & $\lvert y\rvert$>25mm	θ>25 mRad	θ>15mR & $\lvert y\rvert$>25mm
133.5 nb	81.8 nb	85.4 nb	78.0 nb
θ>30 mRad	θ>30mR & $\lvert y\rvert$>30mm	θ>30 mRad	θ>30mR & $\lvert y\rvert$>30mm
87.2	51.8	54.9	49.1

racetrack

CDR

2. CEPC LumiCal design for racetrack beampipe

Accelerator @ Z-pole high luminosity

$L=2x10^{36}$/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***

LumiCal geometry

- ***LumiCal before Flange***

  z = 560~700 mm

  - **Low-mass window**: **Be 1mm thick**

    traversing @22 mRad traversing L= 45 mm,

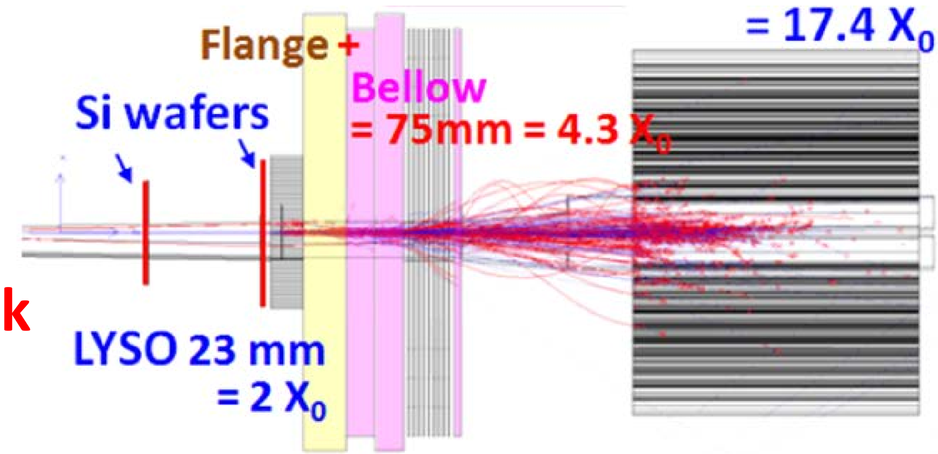
    = 0.13 X_0 (Be), 0.50 X_0 (Al)

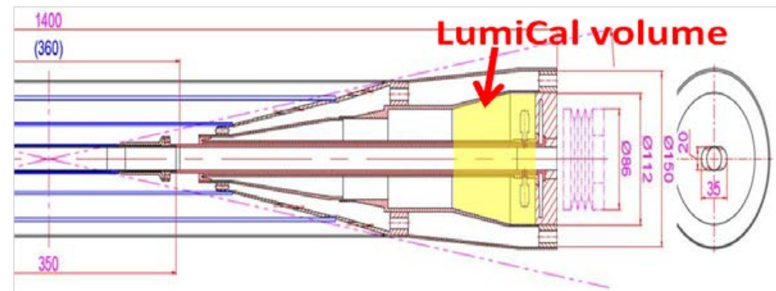
  - **Two Si-wafers** for $e^{\pm}$ impact θ
  - **2X_0 LYSO** = 23 mm

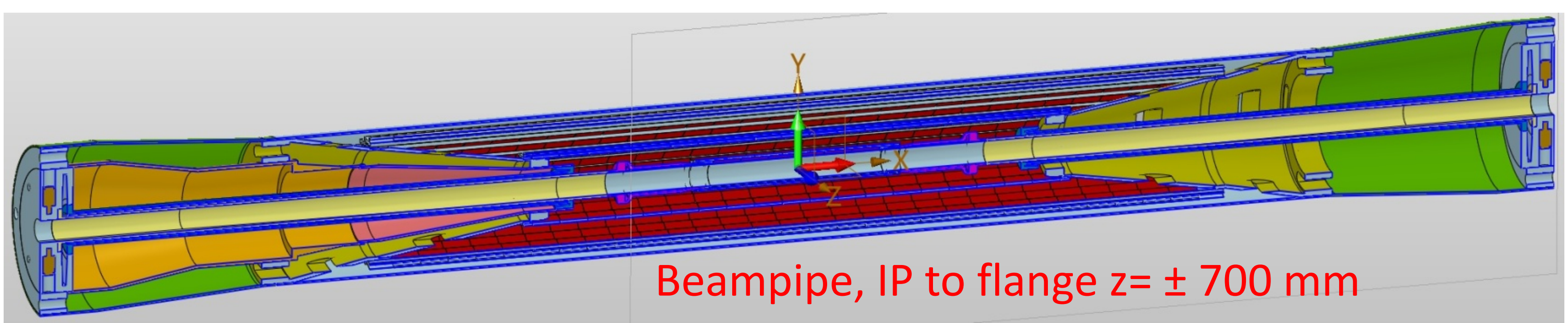
- ***LumiCal* behind Bellow:**

  z= 900~1100 mm

  - **Flange+Bellow : ~60 mm, 6 X_0**
  - **17 X_0 LYSO 200 mm**

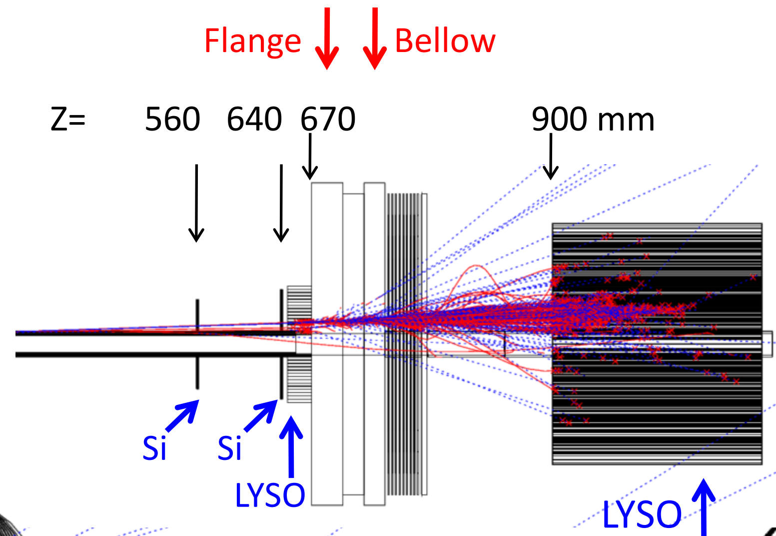


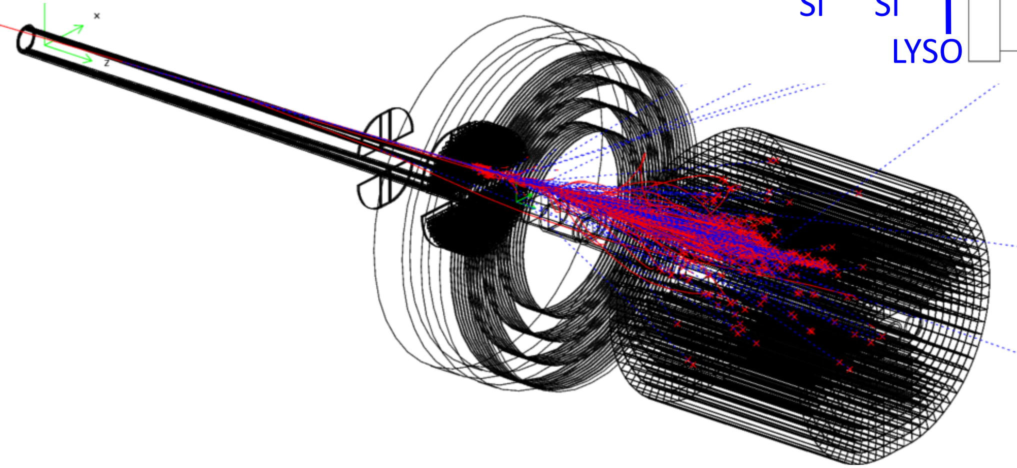


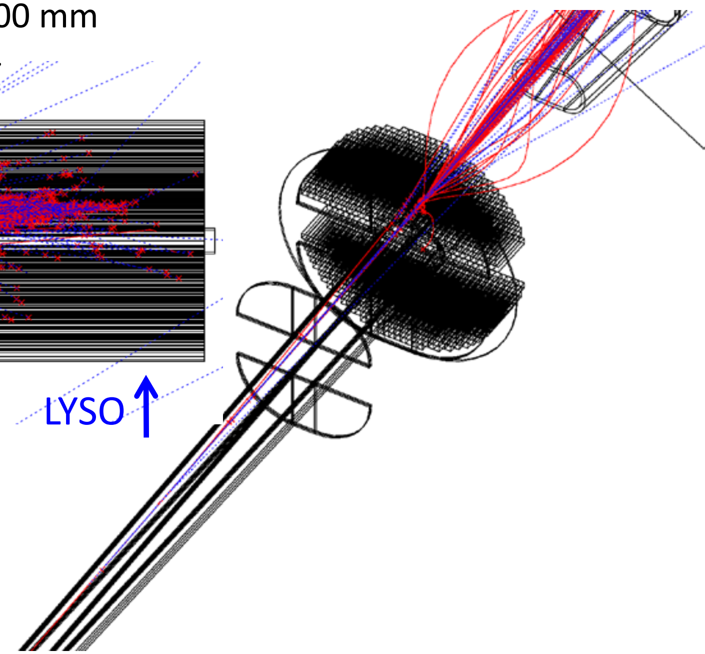


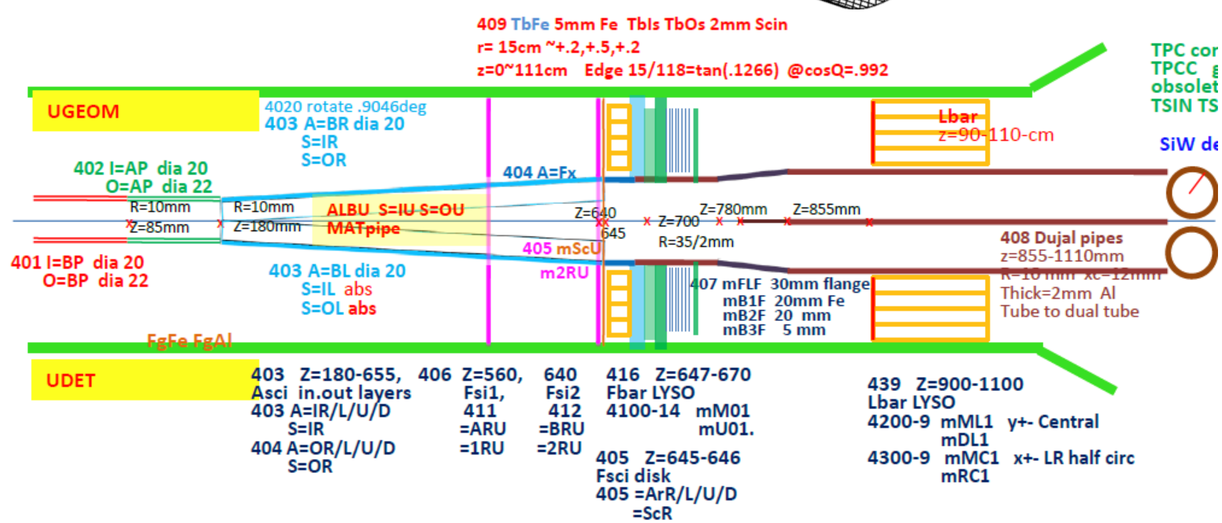
Beampipe, IP to flange z= ± 700 mm

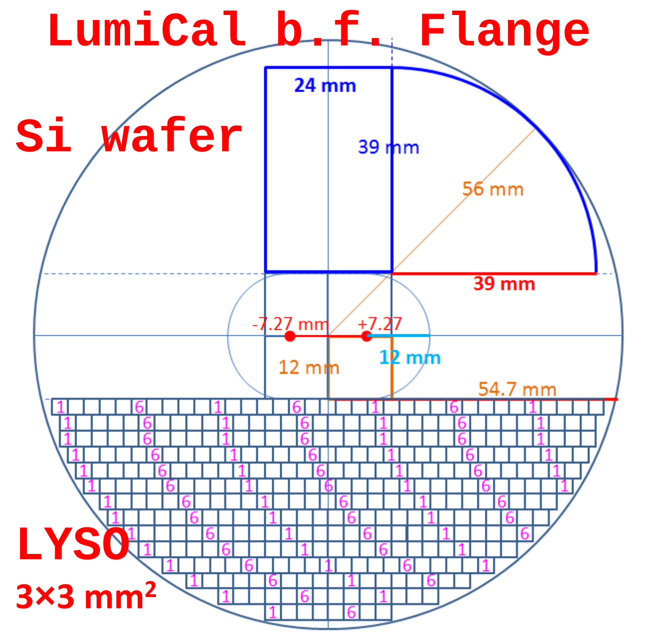
LumiCal GEANT





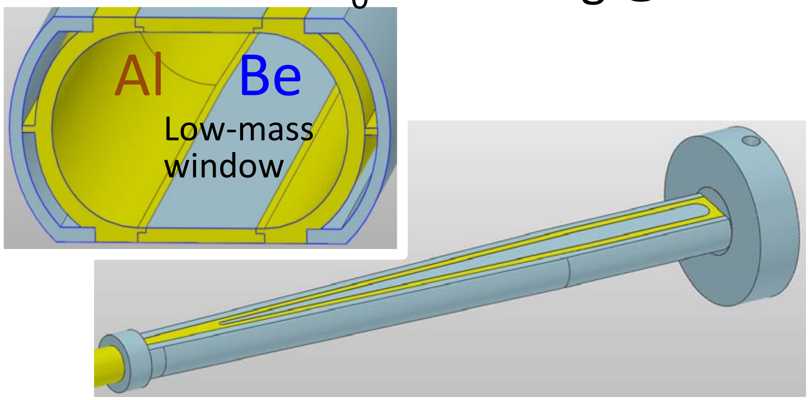






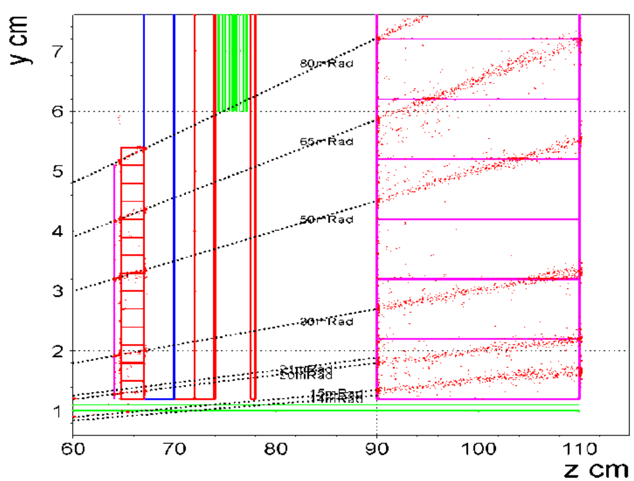
Reduce mult. scatt. & preshower

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



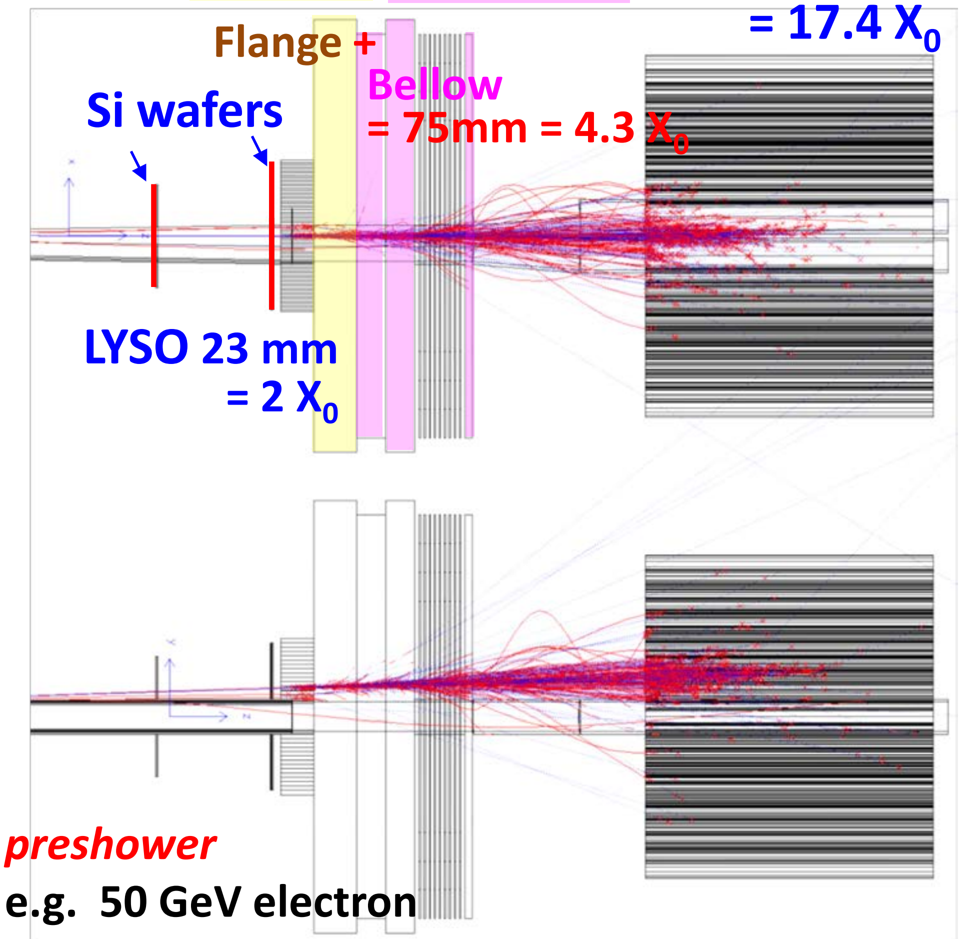
- Mult. Scatt. traversing 1 mm Be pipe symmetric, Gaussian

RMS = 60 μRad @ 30 mRad



Fe $1X_0$=17.6mm

Flange 30mm Steal	20mm +20mm +10 blades +5mm



preshower

e.g. 50 GeV electron

traversing *2mm Al pipe @30mR*

= 67mm thick @30mR = $0.75\ X_0$

GEANT beampipe multiple scattering

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

  @ (ϑ= ±30 mRad, φ = 1.0, 1.0+π Ra)

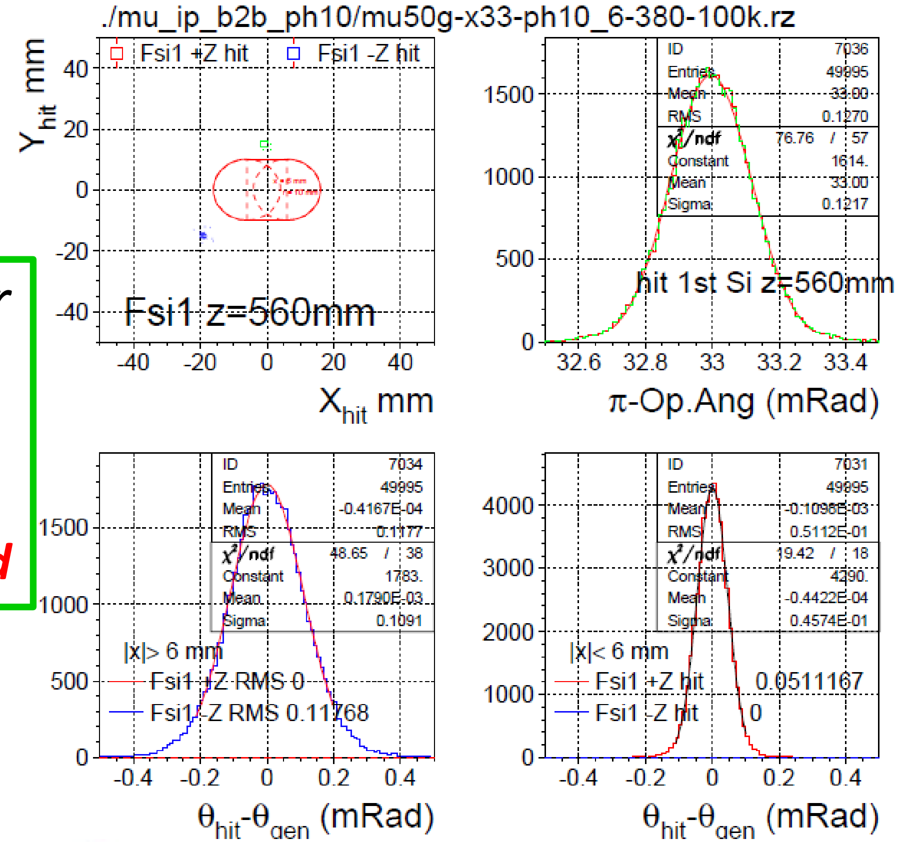
smearing at @z=560mm, 1st Si wafer

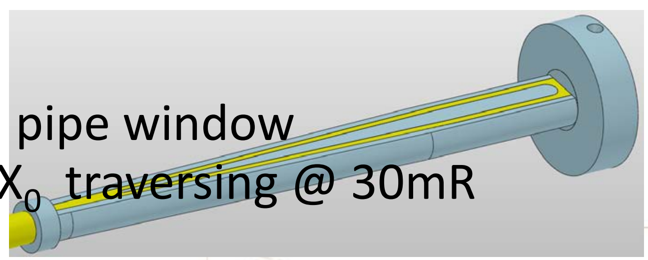
|x|< 6.0 mm, 1mm Be

low mass window ***σ(ϑ) = 46 µRad***

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

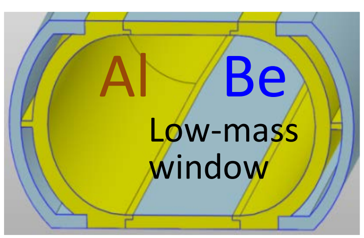
back-to-back ***σ(Ω) = 122 µRad***

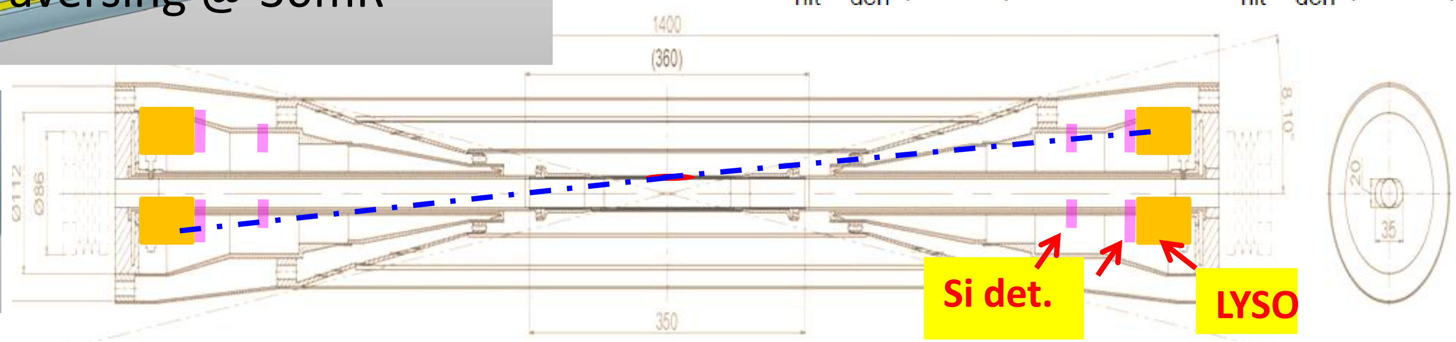




1 mm Be thin pipe window

33mm = 0.09X_0 traversing @ 30mR





Electron hits on 1st Si-wafer, LYSO @z=647mm

IP (σ_x,σ_z) = (6,380 μm) ← *compatible w. (0,0)*

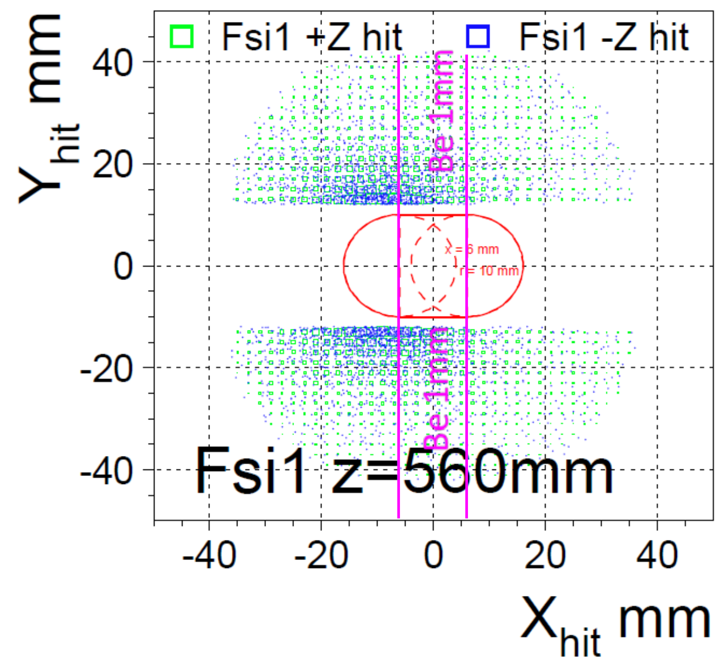
electrons hits

Si wafer @z=560mm

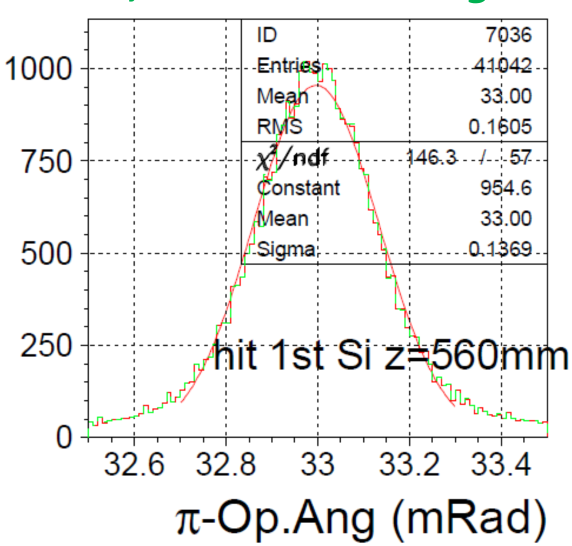
- |x|<6.0 mm ***σ(ϑ)*** **= 54 uR** (1mm Be)
- |x|>6.0 mm ***σ(ϑ)*** **= 95 uR** (1m Al pipe)
- back-back Op.Ang ***σ(Ω)*** **= 137 uR**

LYSO ($2X_0$) @z=647mm

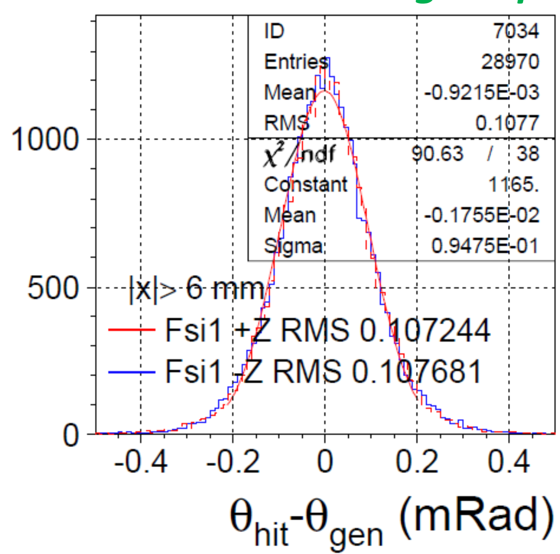
- |x|<7.3 mm ***σ(ϑ)*** **= 54 uR**
- |x|>7.3 mm ***σ(ϑ)*** **= 100 uR**
- back-back Op.Ang ***σ(Ω)*** **= 144 uR**



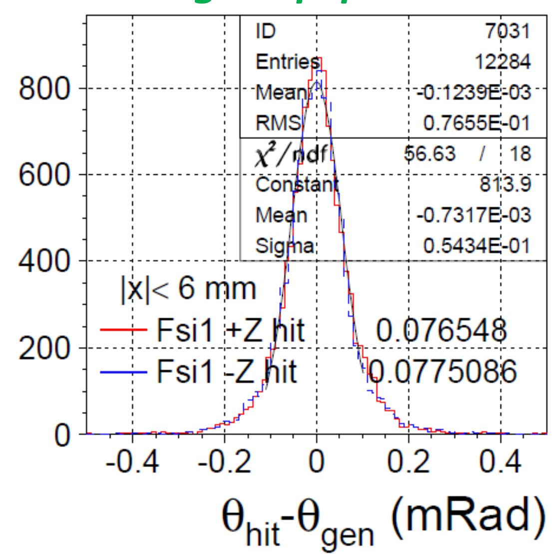
e+,e- back-back angle



e± GEANT hit – gen. |x|>6



hit – gen. |x|<6



GEANT LumiCal electron shower

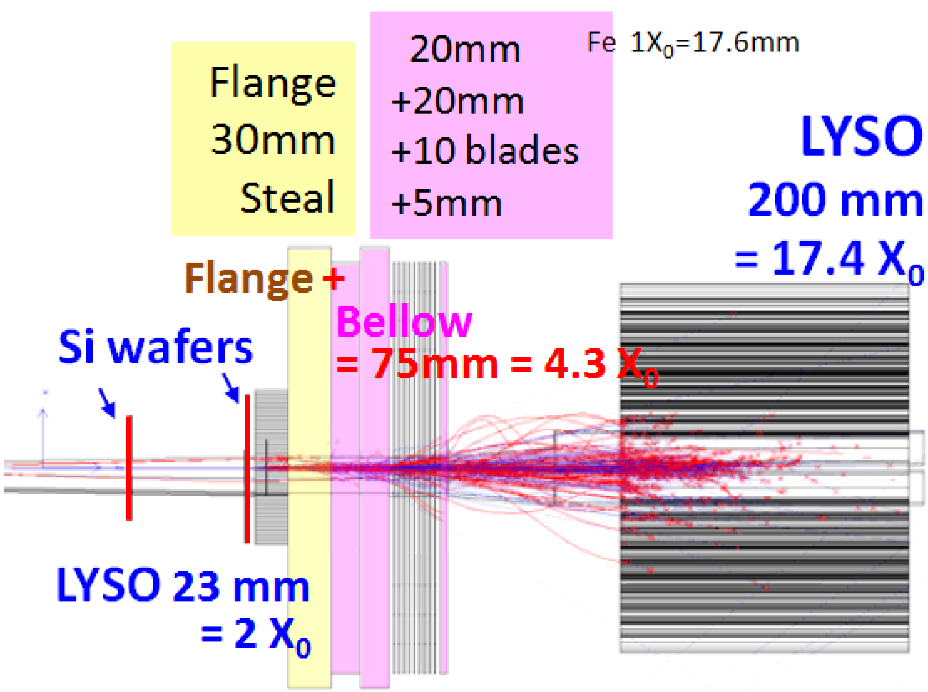
50 GeV electron @ θ = 32 mRad, ϕ=90°

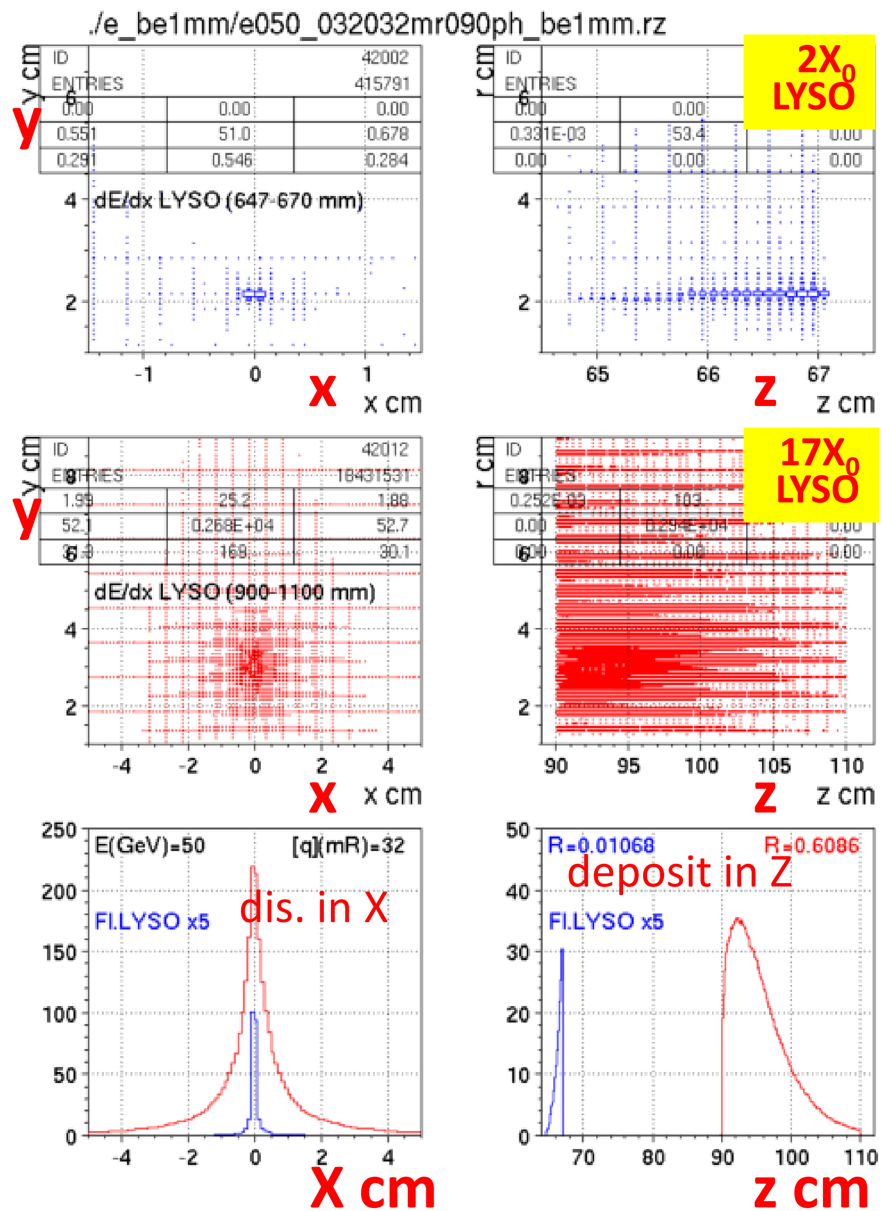
2X0 LYSO + 4.3X0 Flange,Bellow

+ 17X0 LYSO

Shower deposition, by Sum(dE/dx)

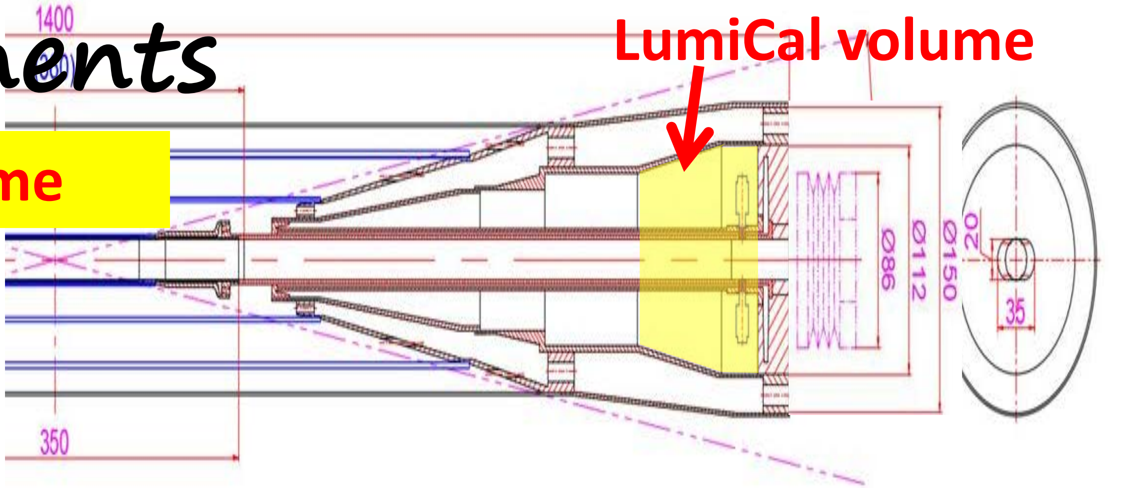
- in front LYSO: ~1.0 %
- in back LYSO: ~ 61 %





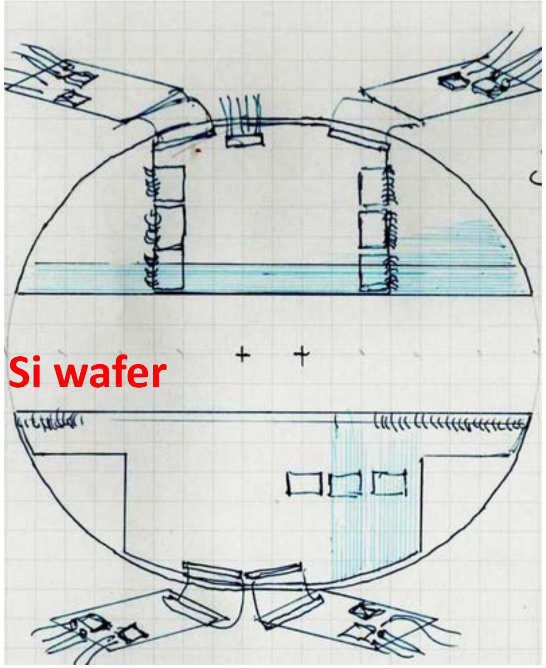
LumiCal conponents

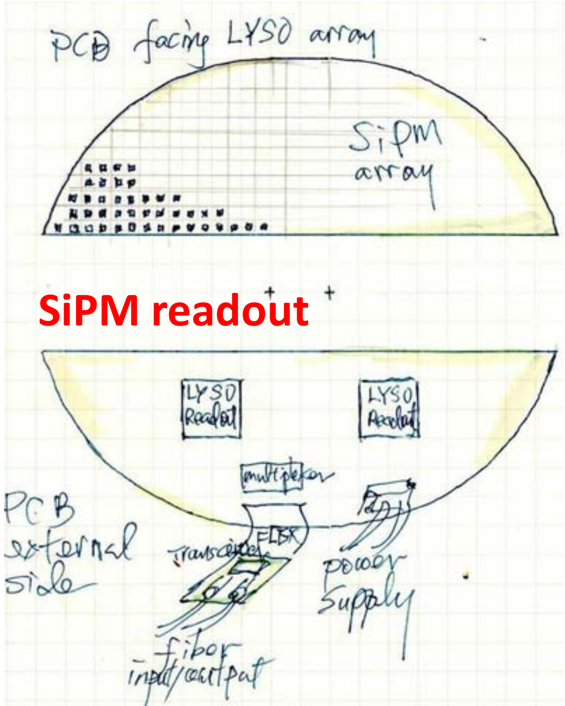
Before flange, VTXdet volume

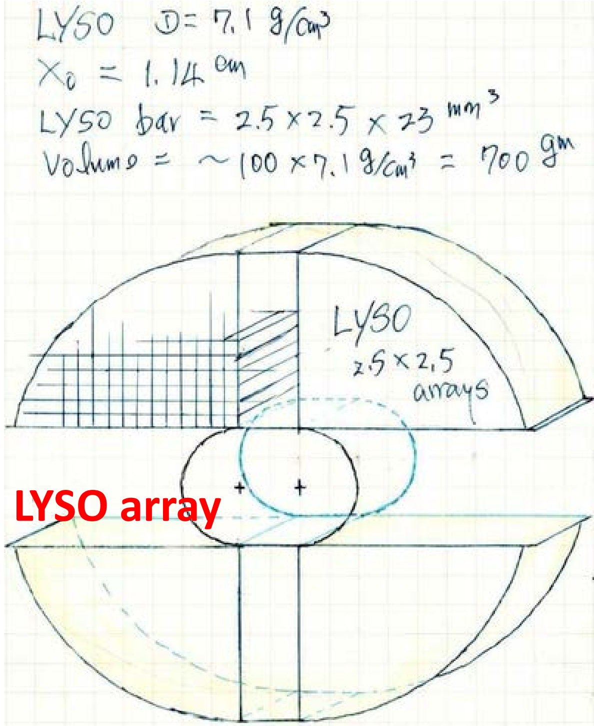


Precision electron θ
e/ γ identification

- **Si tracking layers :** $\sigma_r < 5$ μm
- **LYSO array, 2X_0 :** 2.5x2.5x23 mm^3



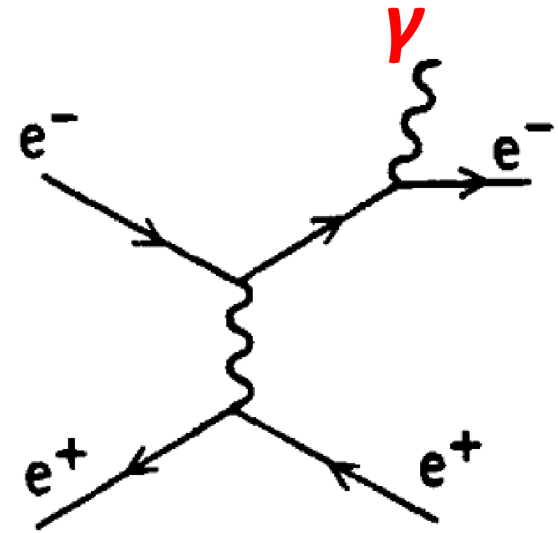




3. QED 10^{-4} measurement on radiative Bhabha

theory by BHLUMI
0.002 precision

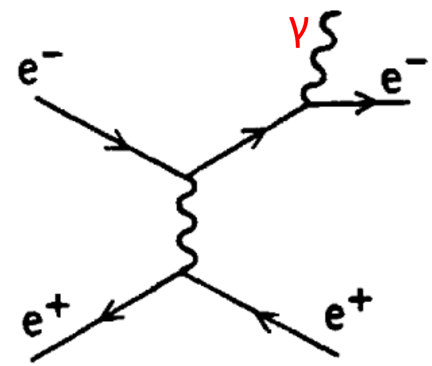
$$e^+e^- \rightarrow e^+e^-\gamma$$

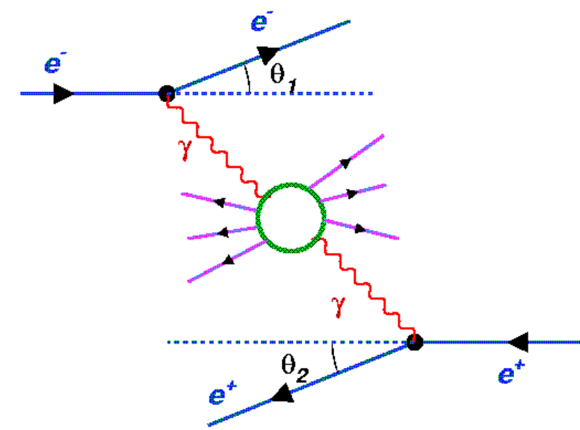


LumiCal Physics application

Pre-shower before flange

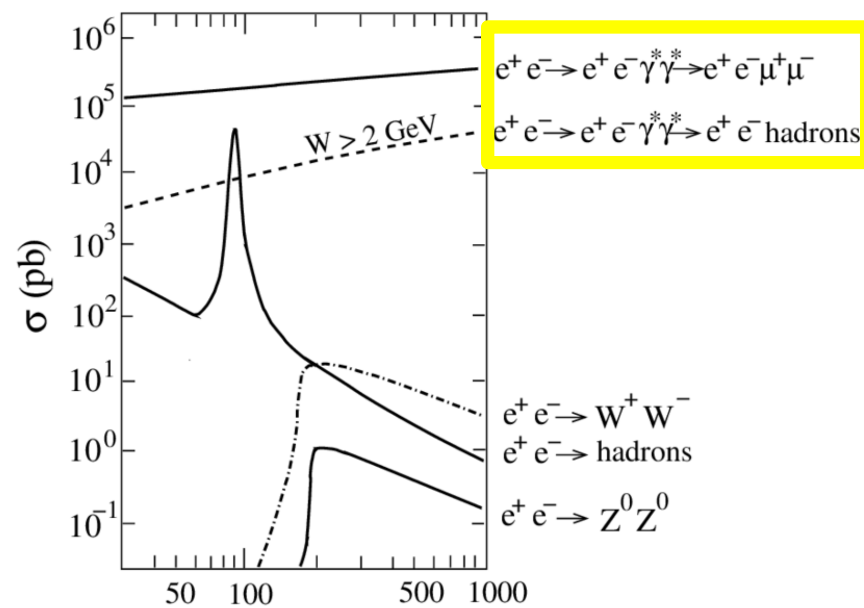
- **two Si wafers:** electron tracking
  5 μm resolution
- 2X0 **LYSO:** e/γ identification



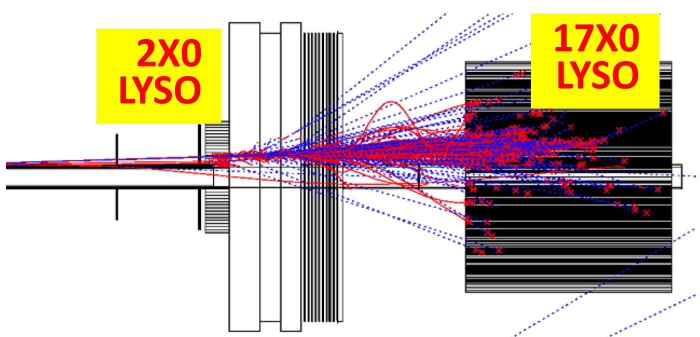


Physics purpose

- Radiative Bhabha,
  e+γ QED 10^{-4} precision
- Two-Photon, electron tagging for Q^2
  Resonances : π^0, η, η', f_2, a_2, η ,η_c, χ_c
  Lepton pairs: γγ → μμ, ττ
  Vector boson pair γγ → ππ, ρρ, KK, pp
  Photon structure $F_2\,(x,Q^2)$
  QCD, heavy flavor γγ → hadrons



V.G. Serbo arXiv:hep-ph/0510335v2

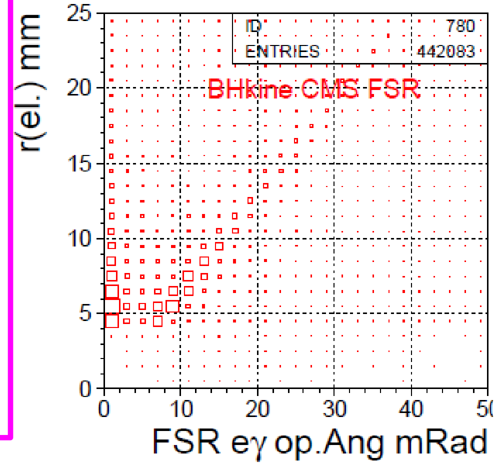


BHLUMI QED generator $e^+e^- \rightarrow e^+e^-(\gamma)$

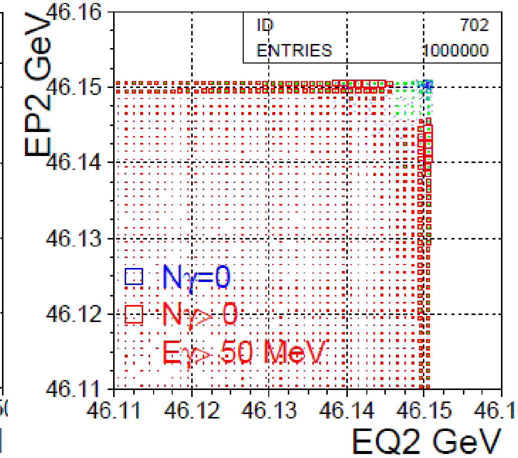
E_{CMS} = 92.3 GeV θ_l= 10~80 mRad

- ***Bhabha***
  $e^+e^- \rightarrow e^+e^- + N\gamma$ *→ Eγ > 50MeV*
- ***Opening angle*** *Ω(e,γ) vs. r(e)*
  increase w. electron ϑ
- ***radiative Bhabha*** *examined for*
  max. photon vs paired electron

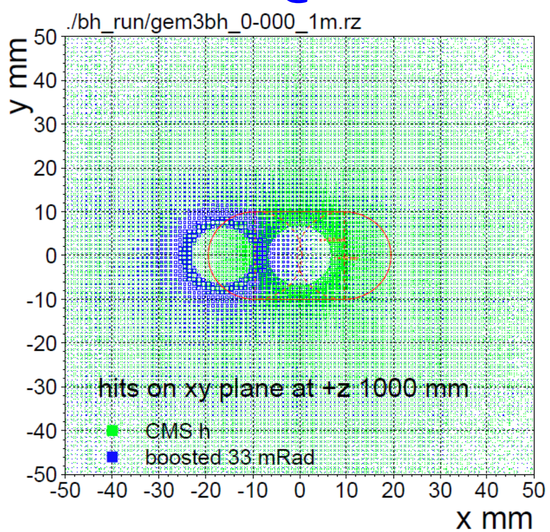
CMS radius(e±) vs. Ω



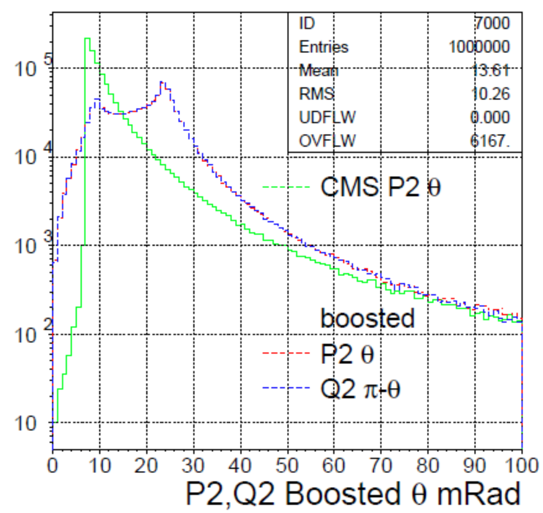
E(e+) vs E(e-)



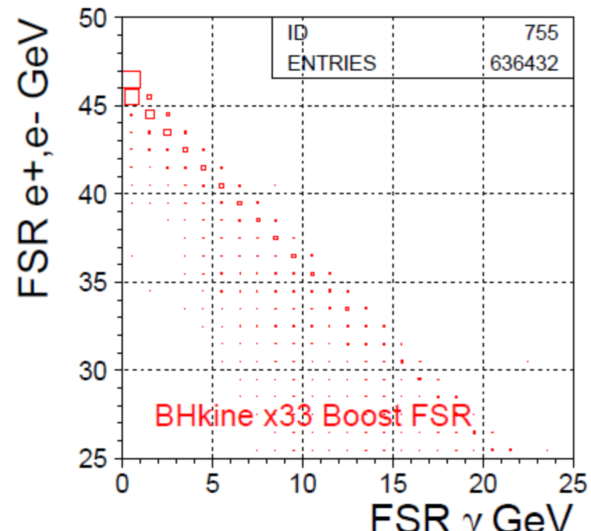
hit (x,y) distributions
generated @z=1m
boosted @z=1m



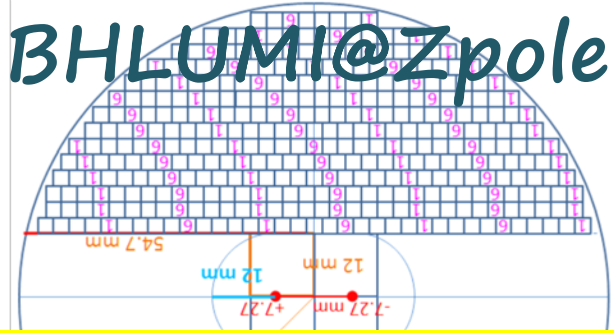
Scattered electron θ
CMS generated (θ>10mR)
x33mR boosted



Radiative Bhabha
E(e±) vs E(γ)

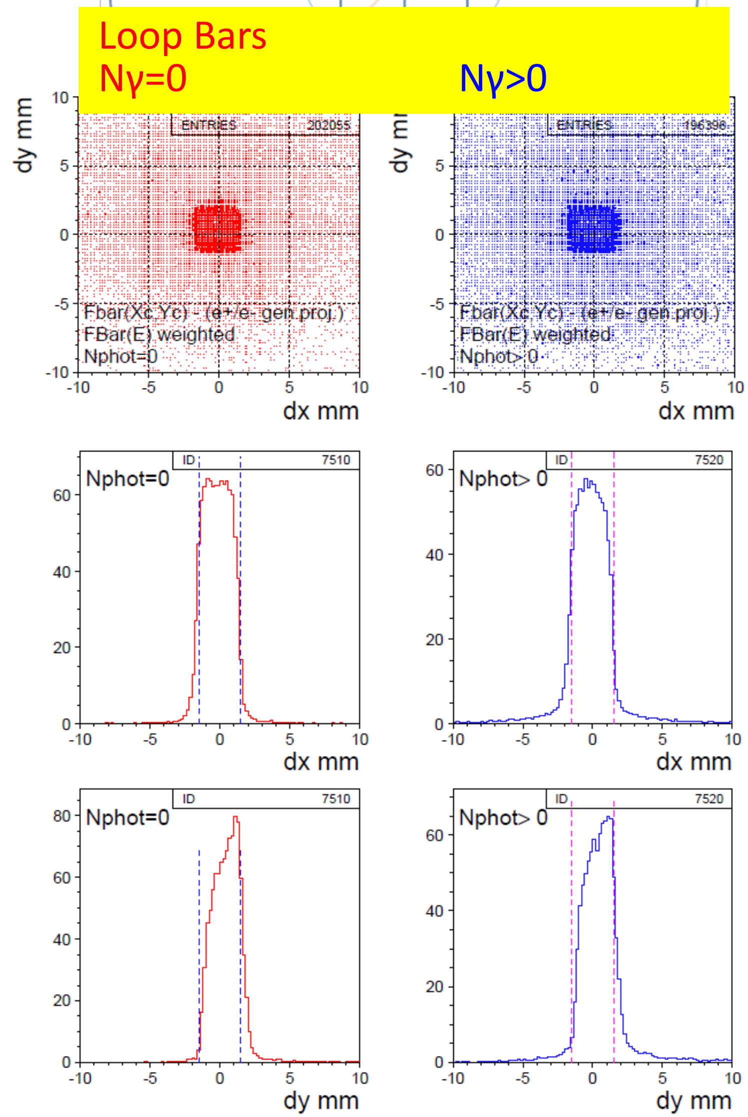


$2X_0$ LYSO bars observables, w. BHLUMI@Zpole

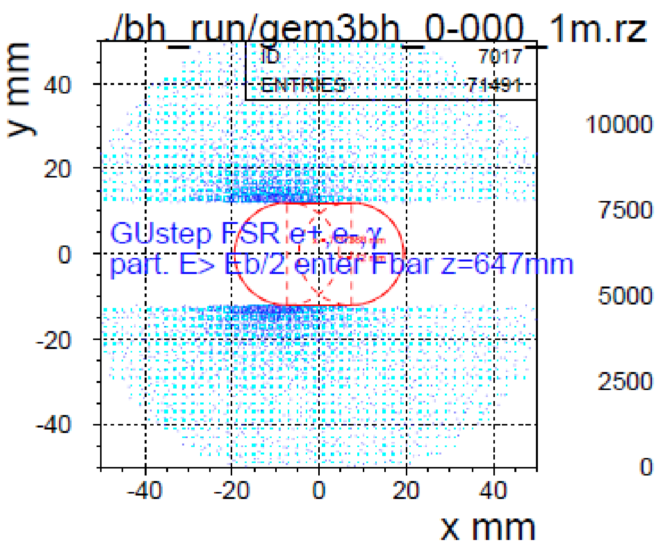


incident particles are e$^{\pm}$,(γ) and secondaries

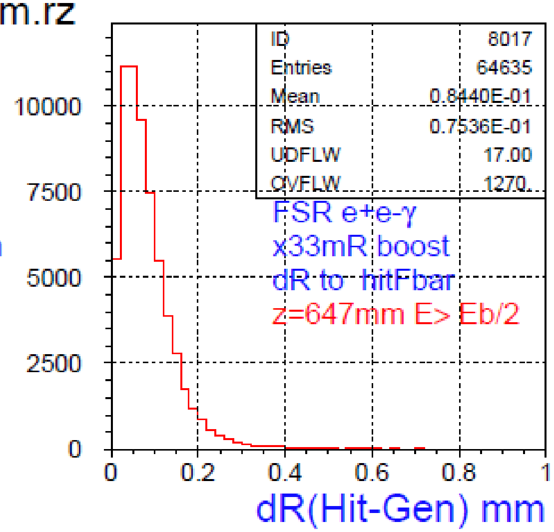
- **GEANT sum dE/dx in each LYSO bars**
  3x3mm^2, 23 mm long, $2X_0$
- **Deviation to e$^{\pm}$ truth** (impact hit >Eb/2)
  mostly < 0.2mm
- **Hit distributions in a Bar**
  distributed due to Bhabha θ, w./w.o. photon



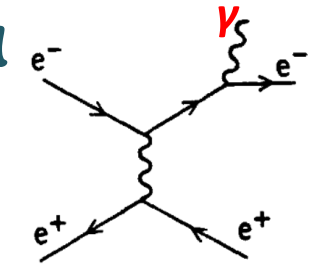
GEANT hits E>Eb/2
On LYSO @647mm



dR to Truth Nγ > 0
(boosted BHLUMI e$^{\pm}$)



$2X_0$ LYSO observables for rad. Bhabha

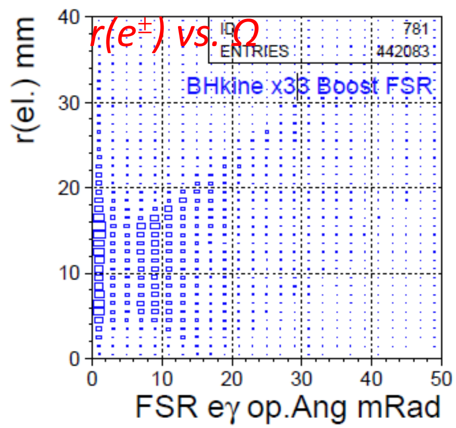


$e^+e^- \rightarrow e^+e^-\gamma$

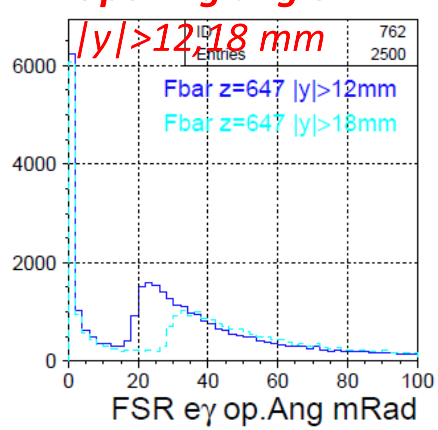
Ω(e±,γ) Opening Angle

- Increase w. electron θ
- r > 12mm, Ω(e,γ) = 20 mRad (13mm@647)

BHLUMI boosted



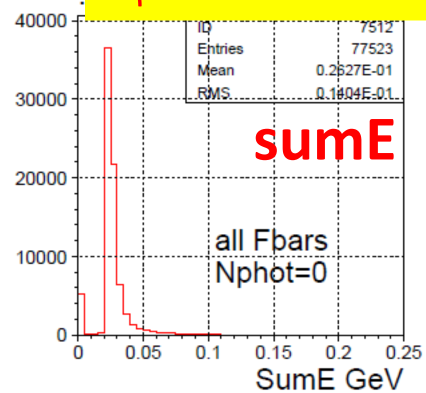
Opening angle Ω

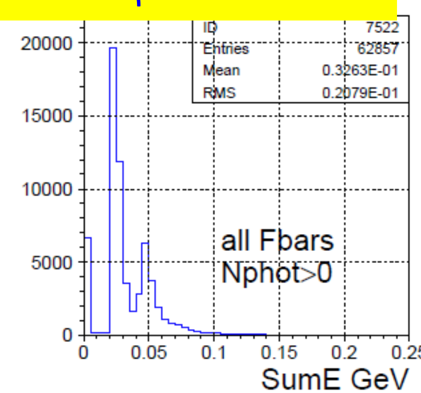


sum dE/dx all LYSO bars (a plane)

- e± one track : sumE min. 20 MeV
- (e±+γ) : two tracks, sumE x2

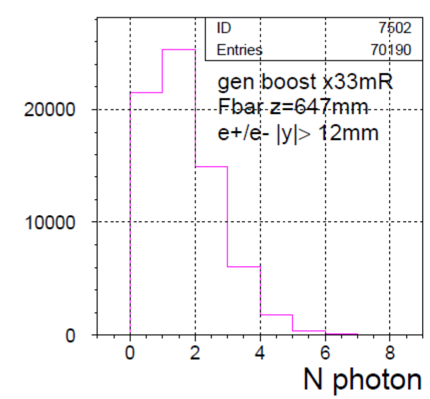
Loop Bars
Nγ=0 Nγ>0

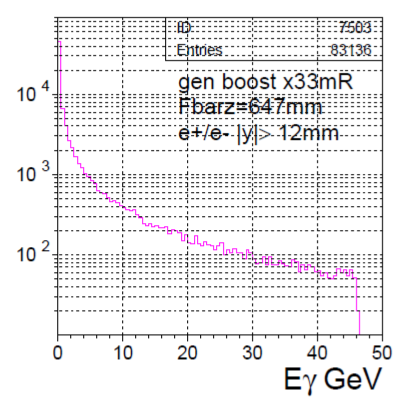




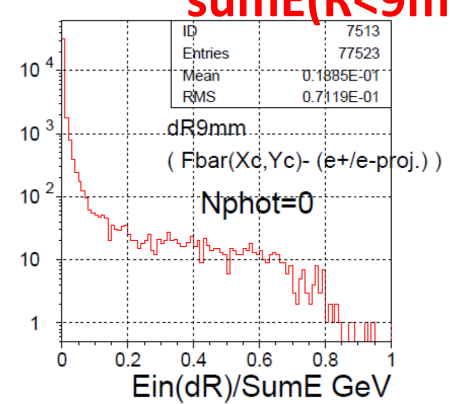
Bhabha hits on LYSO |y|>12mm

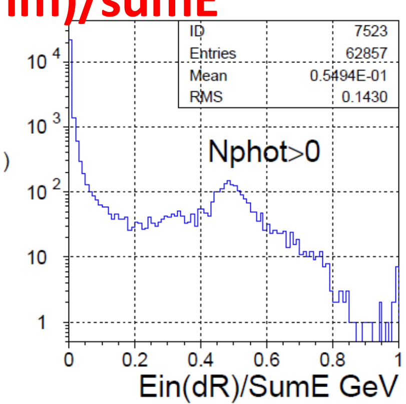
- BHLUMI ~80% having photons





sumE(R<9mm)/sumE





4. Luminosity Systematics to 10^{-4}

Systematics to $\delta L/L \sim 10^{-4}$

- ***$\delta N/N \sim 10^{-4}$ major issues***

1. *Det. Position offset*
2. *Multi. Scattering,*
   det. Resolution, B-field helix
3. *Rad. Bhabha, preshower*

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

$\delta L/L < 10^{-4}$ for θ_{min}= 20 mRad

→ $\delta\vartheta$ = 1 μRad dr=1 μm @ z=1m

Si-strip detector for $\delta N/N \sim 10^{-4}$

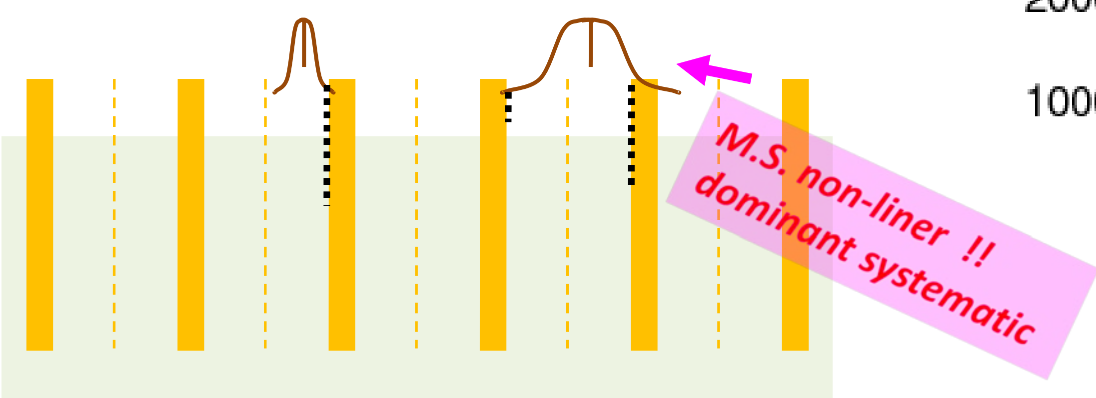
Strip detector Resolution ~ 5 μm

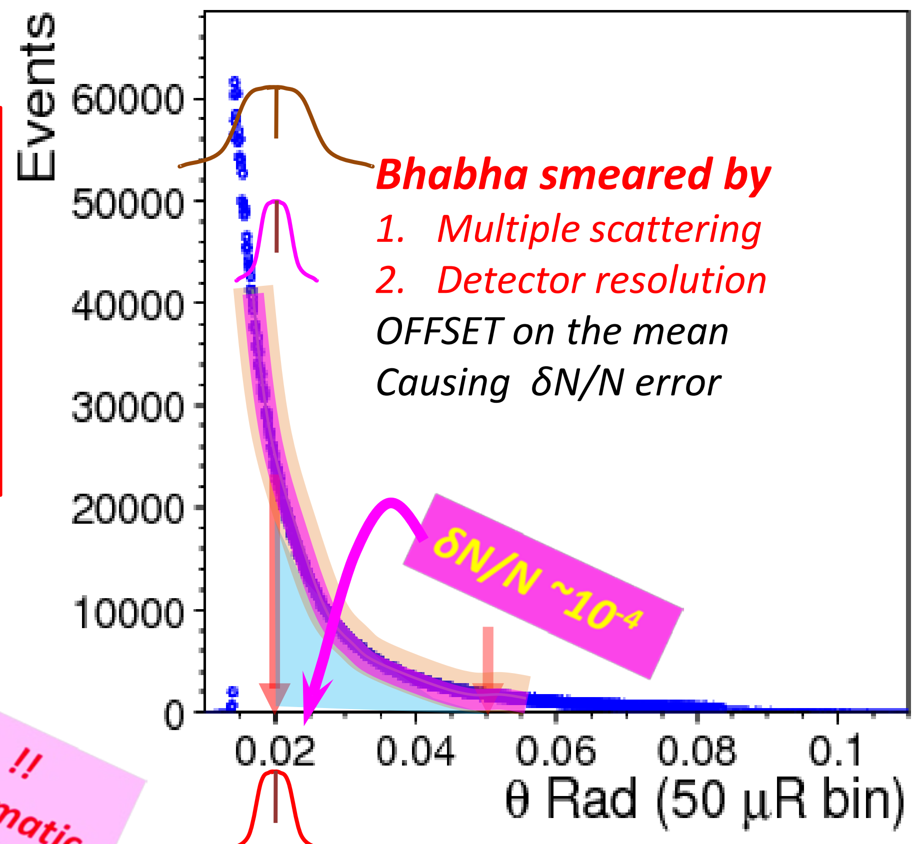
Multiple scattering ~50 μm

Redundent layers for geo-calibration

Symmetric, error on mean → *$\delta N/N \sim 50/\sqrt{N}$*

Survey on position dominant

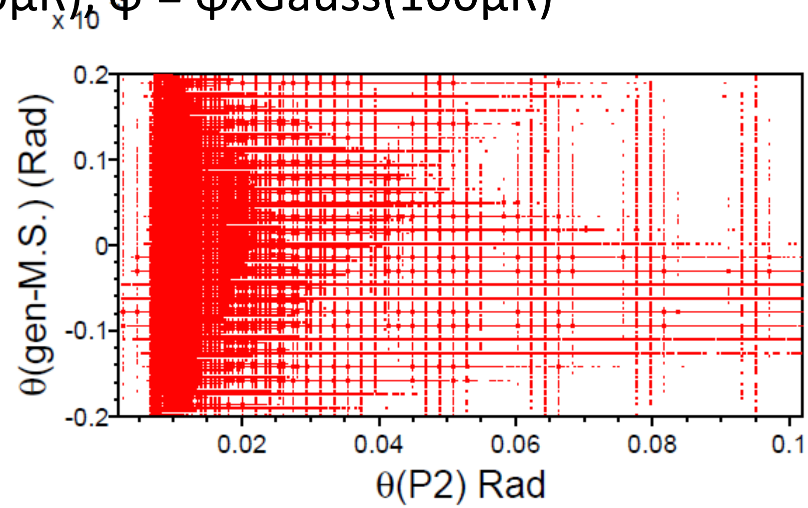


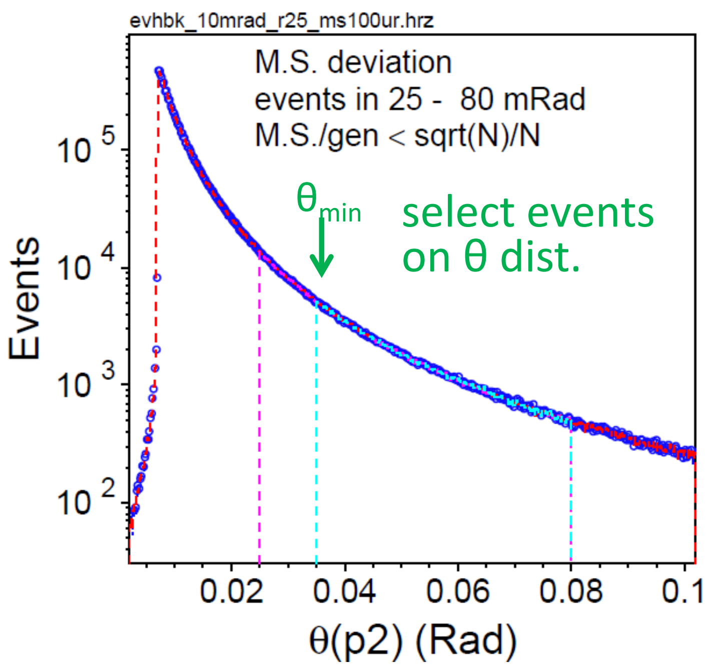


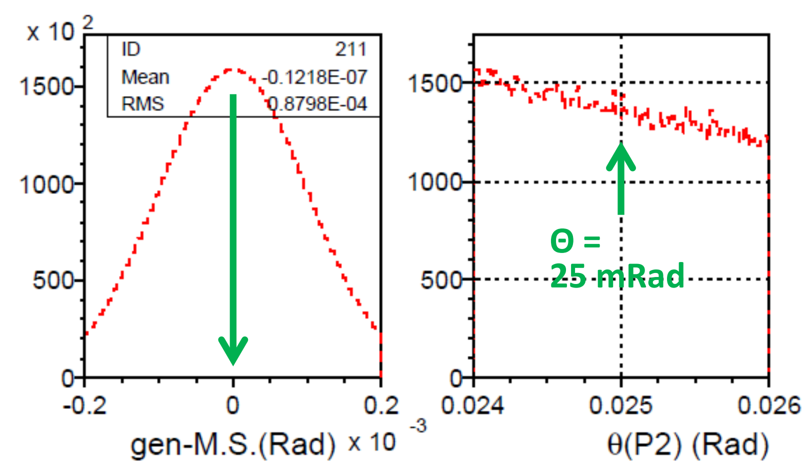
10^{-4} systematics, multiple scattering

1. **BHLUMI** smear θ', ϕ' of scattered e^+, e^-
   Multi. Scatt. 100 μRad θ'= θxGauss(100μR), ϕ'= ϕxGauss(100μR)

2. **δN/N systematics**:
   δN = count event deviation due to M.S.
   M.S 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 by survey of the mean position

IP bunch smearing

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

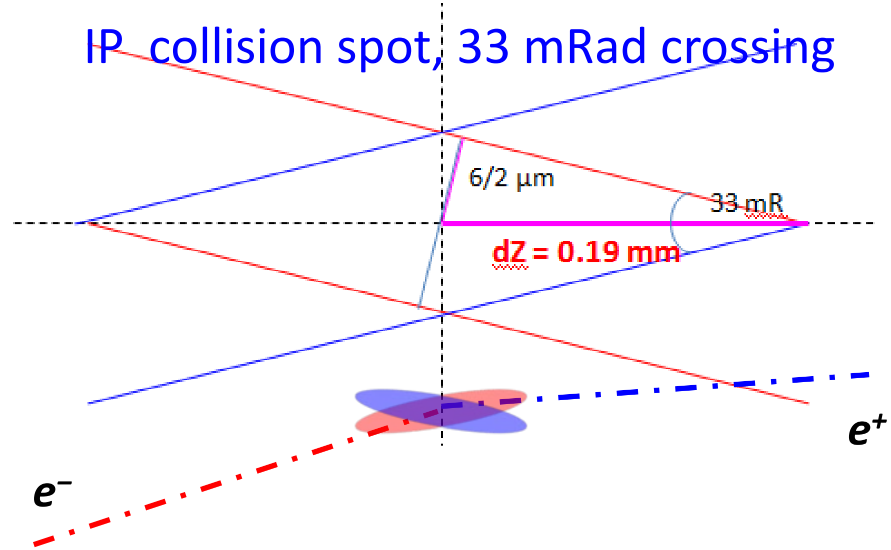
➔ ***IP spot*** $\sigma_x = 6\ \mu m,\ \ \sigma_z = 380\ \mu m$

- boost by 33 mRad beam crossing
- ***Z*** $\longrightarrow$ **e^+, e^- at** ϑ**=30 mRad**

  smearing at @z=560mm

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

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

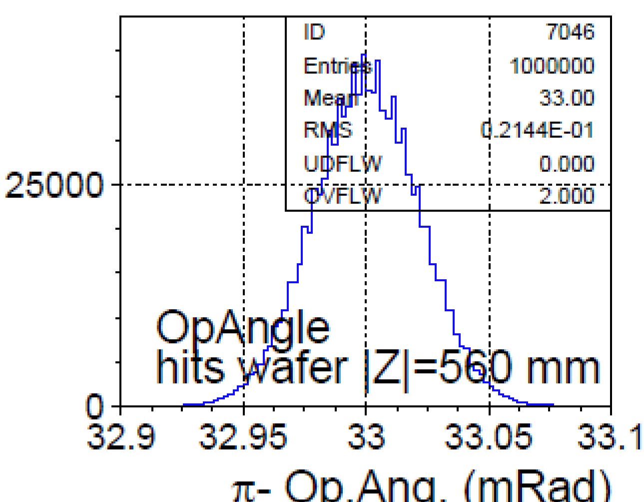


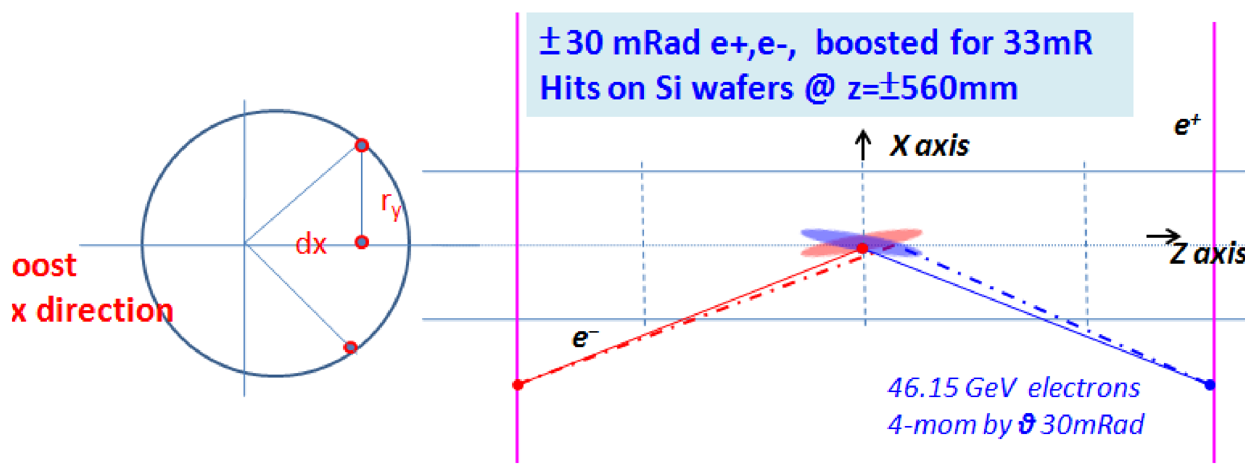
CMS (*ϑ=30 mR, φ= π/2), E=46 GeV* ➔ ***boosted***

V1=(0, +16.8, +560) mm **V1=(9.2, +16.8, +560) mm**

V2=(0, -16.8, -560) mm **V2=(9.2, -16.8, -560) mm**

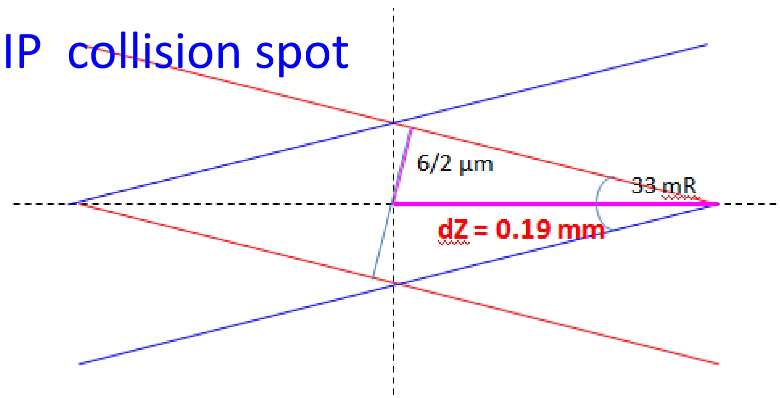
back-to-back





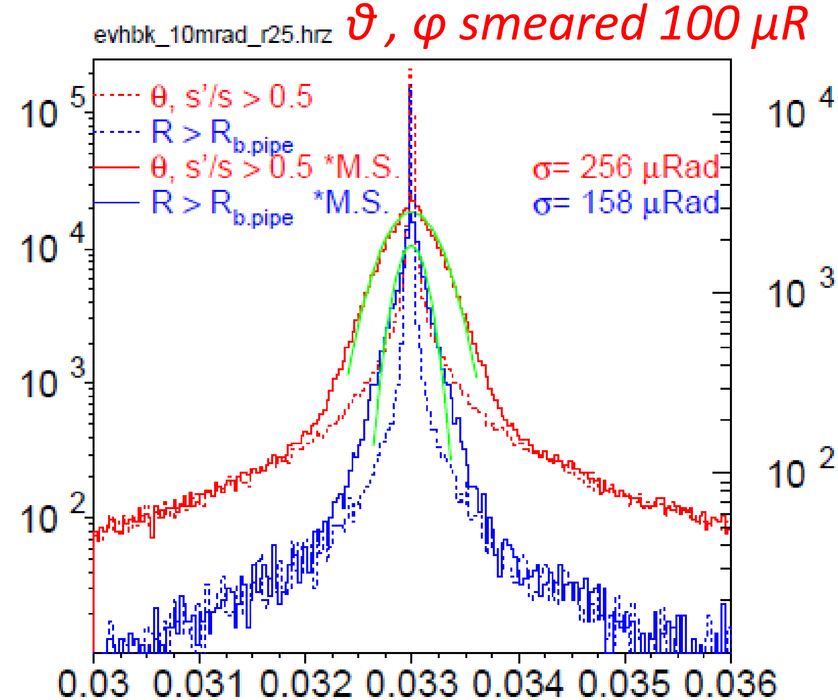
Tracking of IP position

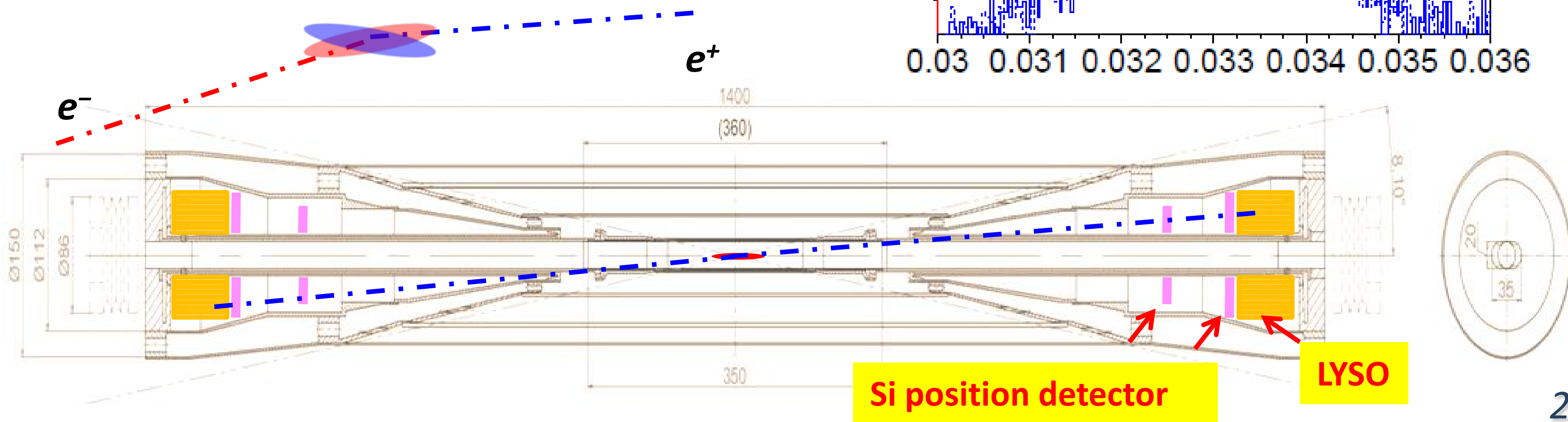
- **Deviation to electron θ by IP spread**
  beam bunch ***σ_x = 6 μm σ_z = 9 mm***
  crossing @ 33 mRad
- **Beam crossing spot: σ_z = 0.38 mm**



e+, e− *back-back angle*

compare scattered e+, e−
ϑ , φ smeared 100 μR





Survey precision for 10^{-4} on Luminosity

LumiCal within beampipe flange

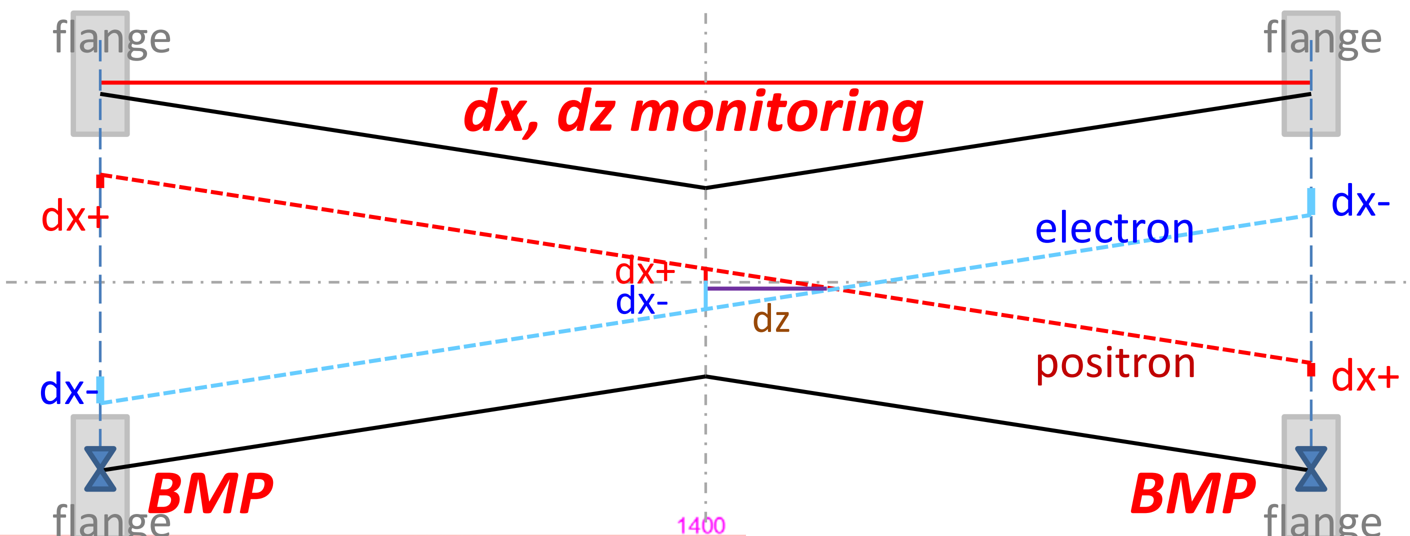
- Multiple scattering : ***~ 50 μm***
- e,γ cluster-size in LYSO: ***~ 100 μm***
- error on mean of (Bhabha $> \theta_{min}$) ***<10^{-4}***

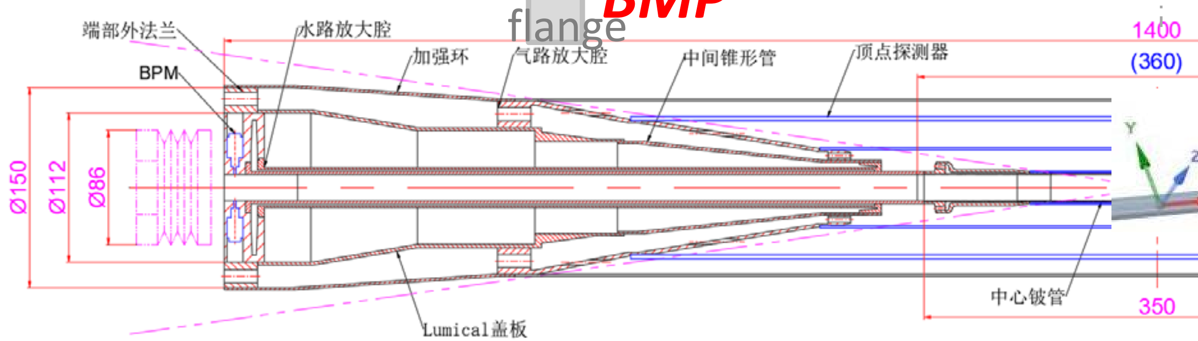
survey on ***Si wafer position***

requires ***σy = 1 μm, σz = 50 μm***

Survey monitoring

- Beam Monitoring Probe ***BPM*** on beam line crossing IP
- Survey (Flange+ to Flange-) (1.4m) to ***50 μm***

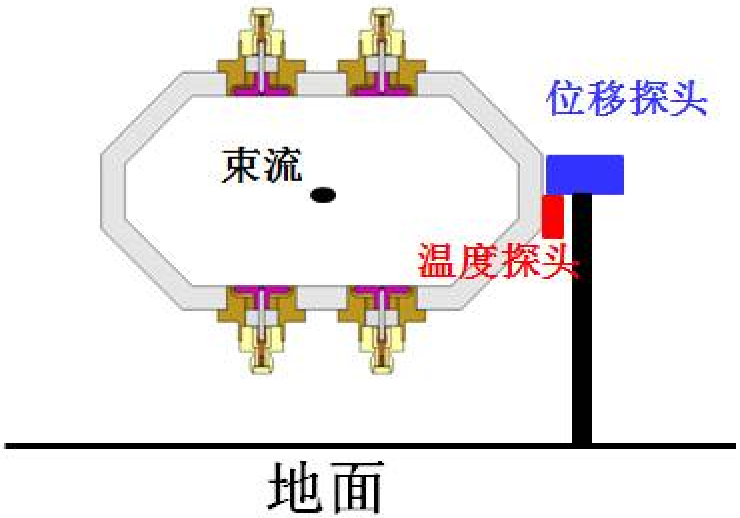




LumiCal position 1 μRad versus IP, beam-line

微米级精度

- 温度引起的形变，改变电中心、机械中心



束流位置测量

随艳峰、何 俊

高能所加速器中心束测组

2022-05-06

東莞

LumiCal precision, 1 μRad to the IP → survey/monitor:

1. x,y w.r.t BPM position
2. add Z position monitor

BPM 共 672 个 （14 个/7BA × 48 个 7BA）

BPM 电子学要求:

1，高 I/O data 速度，支持多种数据输出方式(FT，TBT，22 kHz，10 Hz)

2，较大范围(束流中心线+/-7 mm 范围)的准确的 mapping 和 calibration

3，实验室测试，BPM 位置分辨率在 80 nm 量级

4，束流位置分辨率（10Hz 闭轨数据，0.1μm；22kHz 快轨道数据，0.3μm，逐圈数据：1μm。）

5. TDAQ requirement

1. **探测器名和基本功能（比如TPC，测带电粒子径迹）：**
   LumiCal, 测量加速器束流e^+e^-碰撞亮度 Luminosity
   架设在束流管 ±z = 700 mm，法蓝内外，探测低角度电子，
   在e^+e^-碰撞时区内，筛选 Bhabha 弹性碰撞正负电子对事例，
   Monte Carlo QED 计算探测器事例量，反推出 Integrated Luminosity。
   准度要求 10^{-4}。
2. **需要探测的物理量（比如时间，能量，原初电离dE/dx, 原初电离束团数dN/dx, 闪烁光，等等）：**
   探测粒子： Ebeam 正负电子, 及跟随的 Final State Radiation 低能光子 (>~ 1GeV)
   在 bunch crossing 25 nsec，分辨束流正负电子弹性反射
   硅探测器： 电子 theta, phi 角度, 极端驱近 1 uRad 精准位置，
   LYSO 晶调： 标定 >Ebeam/2 电子，及区隔邻近的 FSR 光子
3. **探测器对电子学输出的通道数，**
   电子碰撞点硅条探测器: 每侧两层共4层，每层4k ch. 总共16k 通道数
   LYSO 晶条 SiPM 读出: 每侧 分前(2X0) 后(17X0) 共4套 LYSO
   每套 $170cm^2$, 需1.7k ch. 总共 7k通道数
4. **单通道预计计数率，**
   Z lumi Lmax = 115 x 1034/cm^2s, LumiCal Bhabha 探测器覆盖截面 100 nb
   Event rate = $(246x10^{-33})$ x (115×10^{34}) /sec = *115 kHz*
   Event rate / 25 ns bunch crossing = 0.003 events /b.c.
   lowest theta (束流管上/下) hot LYSO 3x3 mm^2 6-cell cluster
   event fraction = 0.12, **最热区每LYSO cell事例量 ➔ 0.00016 events/b.c.**

5. **信号特征：电荷？电流？电压？上升、下降时间，宽度？**
   硅条: PN 二级 25k 电子电荷, ADC 需要极快, 宽 50 ns 内, 在 25 ns B.C. 前后事例分辨开
   LYSO SiPM: ADC 需要极快, 宽 50 ns 内, 在 25 ns B.C. 前后事例分辨开,
   12bit 100 GeV 线性能量测量
6. **信号传输方式（比如同轴电缆，PCB，接插件），阻抗特性。**
   前端PCB 缆线空间紧迫，可能放 ADC， serializer 接 10 Gbps 光纤读出
   不做 trigger, 接 FPGA 做事例筛选
7. **最小、最大信号（也就是动态范围）。**
   硅条 测 MIP 单点电离电荷
   LYSO SiPM 比照 ECAL 量测 300 MeV 到 100 GeV 电子
8. **对数字化的要求（LSB, 精度，线性度）。**
   LYSO SiPM 比照ECAL,
   需要监测 Pileup, 因此，每25 ns B.C. 做一次 Signal Level comparator 确认临接事例讯号是否被叠高
9. **探测器的工作温度和范围，如果电子学需要散热，可否和探测器温控在一起？有无对电子学的功耗限制和多少。**
   LumiCal 硅条及 SiPM 工作温度跟顶点探测器一致，约20 °C
   LumiCal 每层硅条 4k 通道需 40颗读出chip 估计发热 10W 内，
   LYSO 每套 1.7k 通道也在 10W 内。 每Z侧 40W，地线接到束流管冷确面。

Bhabha pile-up rate @High-Lumi Z

1. High-Lumi Z (2021 design) L_{max}/IP = **115 x 10^{34}/cm^2s**
2. Bhabha both ***e^+, e^-*** detected, X-sec = **246 nb**

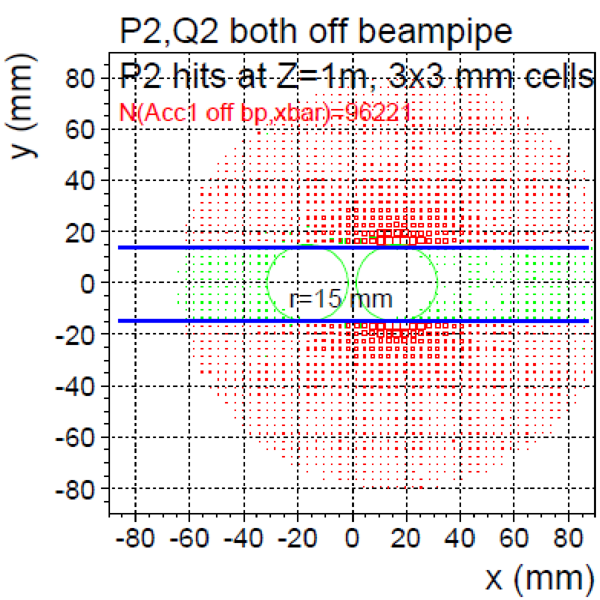
   Event rate = (246×10^{-33}) x (115×10^{34}) /sec **= *115 kHz***
3. Event rate / 25 ns bunch crossing = **0.003 events /b.c.**
4. **Pile-up: next b.c., @adjacent cell in peak region**

   Pile-up Fraction = 0.018*6cells/2sides = **0.054**

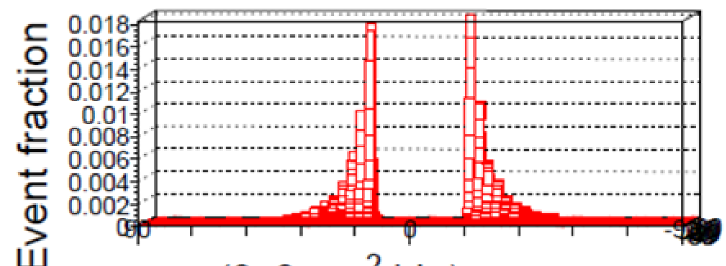
Pile-up event rate = 0.003*0.054 = **1.6×10^{-4}** **in 3x3 mm^2 cells**

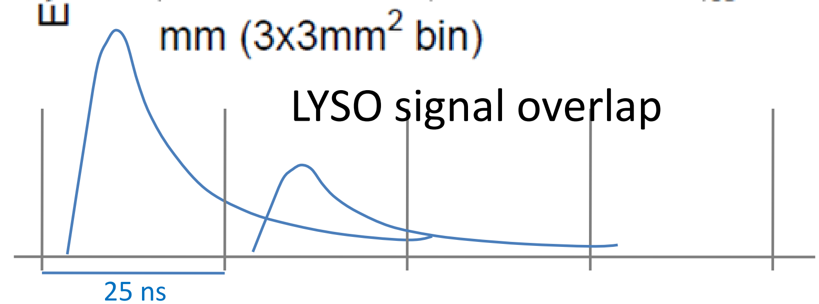
c.f. LEP
L= 1×10^{32}
X-sec= 100nb
*Rate= **10 Hz***

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



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





$Z \rightarrow q\bar{q}$ pile-up rate @High-Lumi Z

1. High-Lumi Z (2021 design) L_{max}/IP = **$115 \times 10^{34}/cm^2s$**
2. **$Z \rightarrow q\bar{q}$**, X-sec = **41 nb**

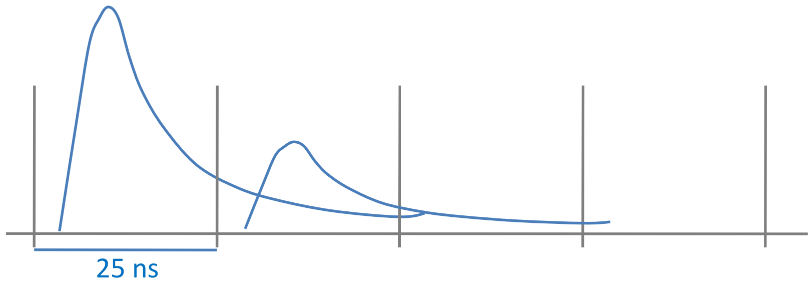
   Event rate = $(41 \times 10^{-33}) \times (115 \times 10^{34})$ /sec = ***47 kHz***

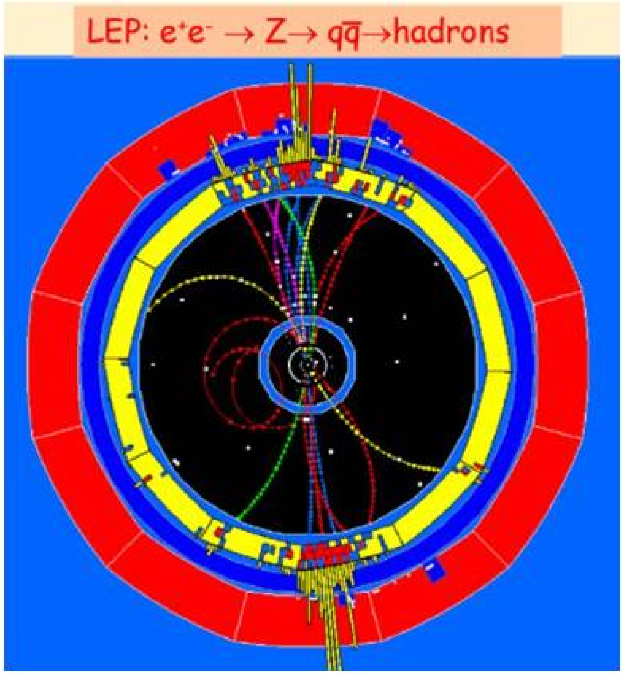
   bunch cross = 40 MHz
3. Event rate / 25 ns bunch crossing = **0.001 events /b.c.**
4. **next b.c. having a $Z \rightarrow q\bar{q}$**

Pile-up rate 4π coverage ~ 1×10^{-3}

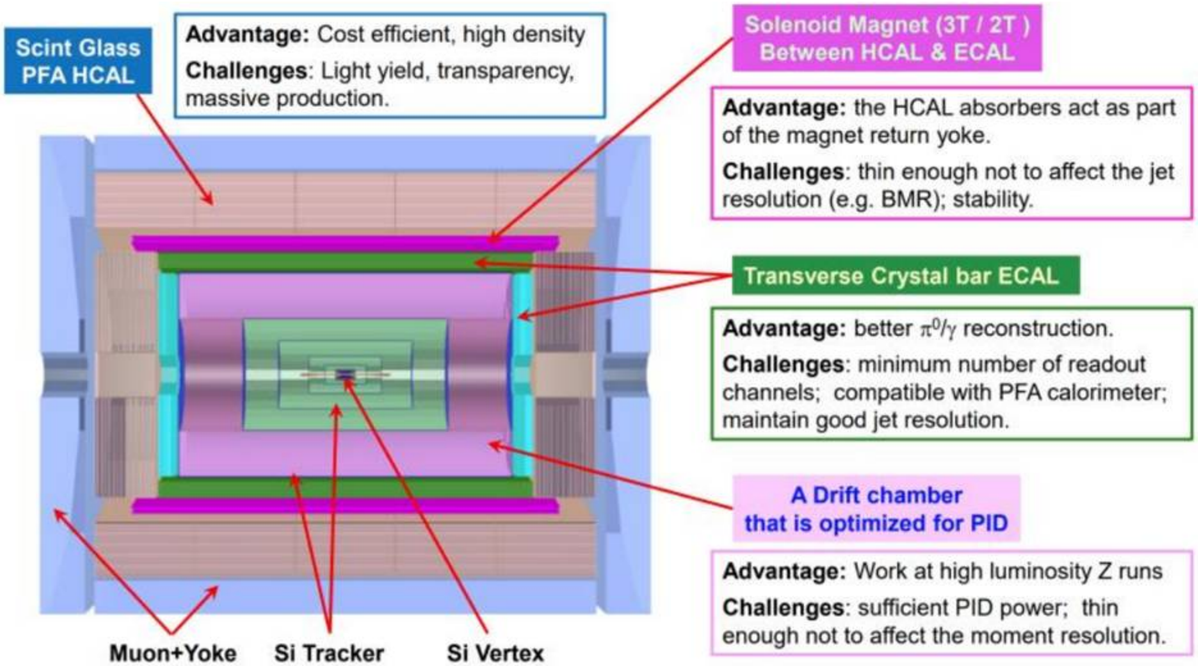
if BCID not identified

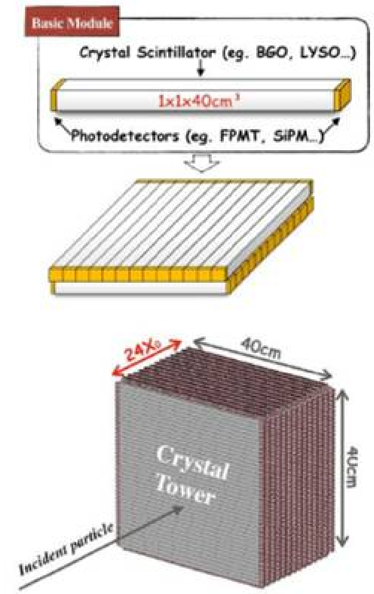
- **pileup of two 2-jets ➔ 4-jet**
- **rare decay precision ~1×10^{-3}**





SiPM w. Comparator in MIP layers





- Crystals arranged to be orthogonal between layers
- Readout from two sides

SiPM output

ECAL front $2X_o$ layers, LumiCal $2X_o$ decks

1. High-gain signal (ADC of multi BC)
2. 3-bit (8 levels) comparator per BC