

# CEPC LumiCal Design

## Update with race-track beampipe

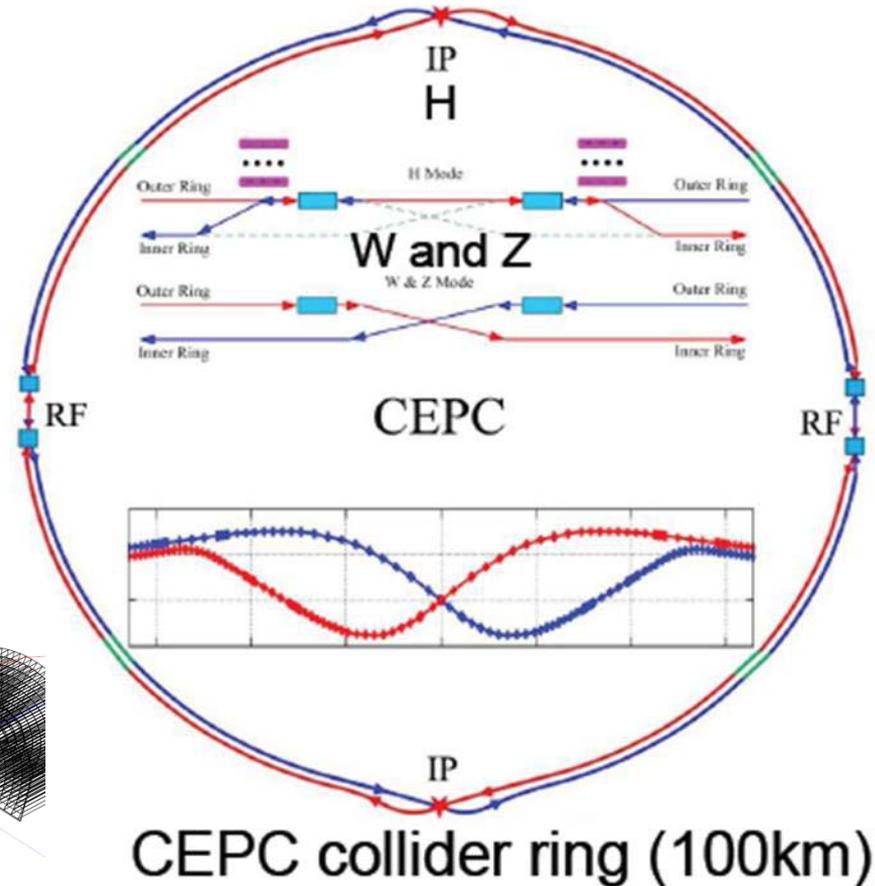
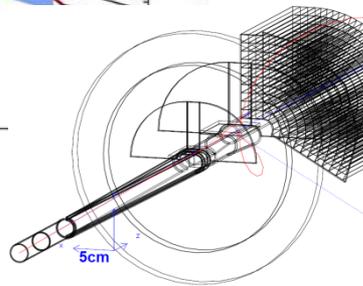
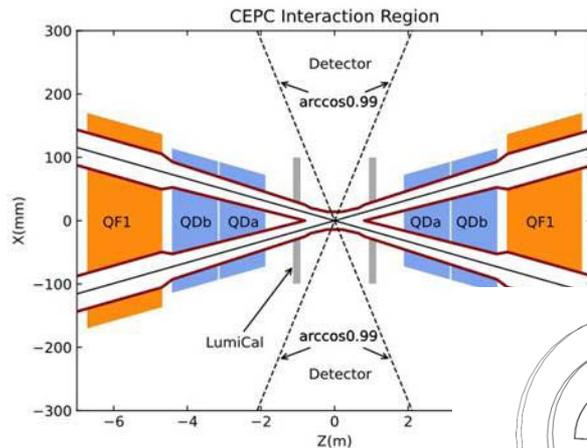
Tu3-EP02

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February 12 - 16, 2023  
Conference: February 14 - 16, 2023

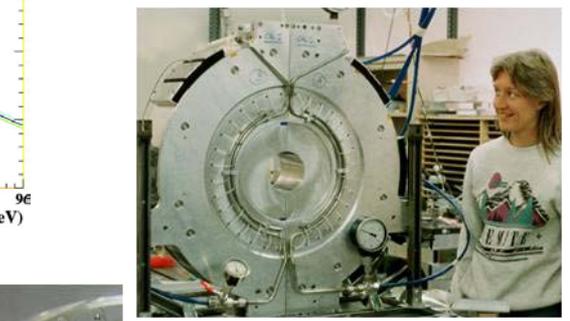
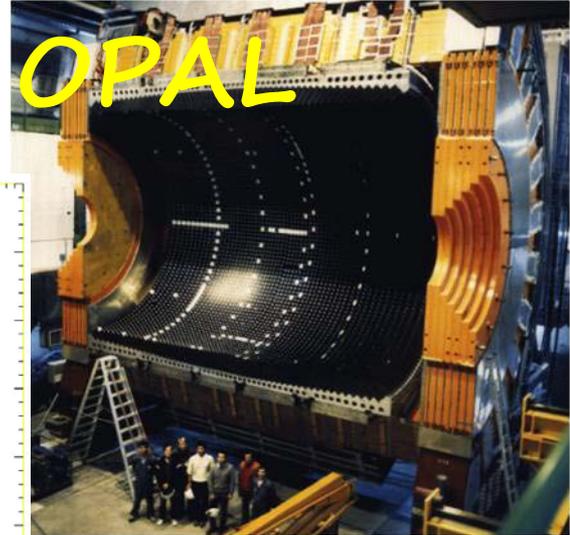
# $e^+e^-$ Collider Luminosity past and future

LEP for Standard Model

SuperKEKB high luminosity

Higgs machines

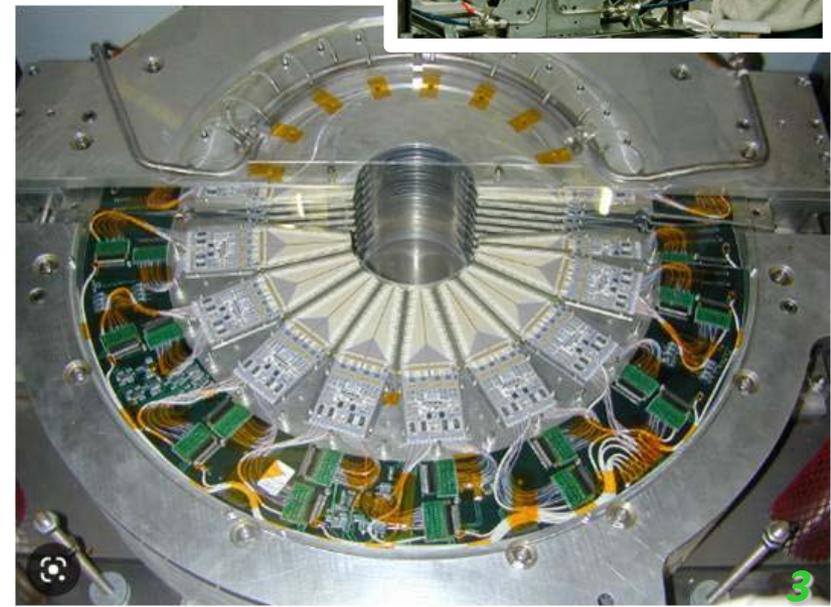
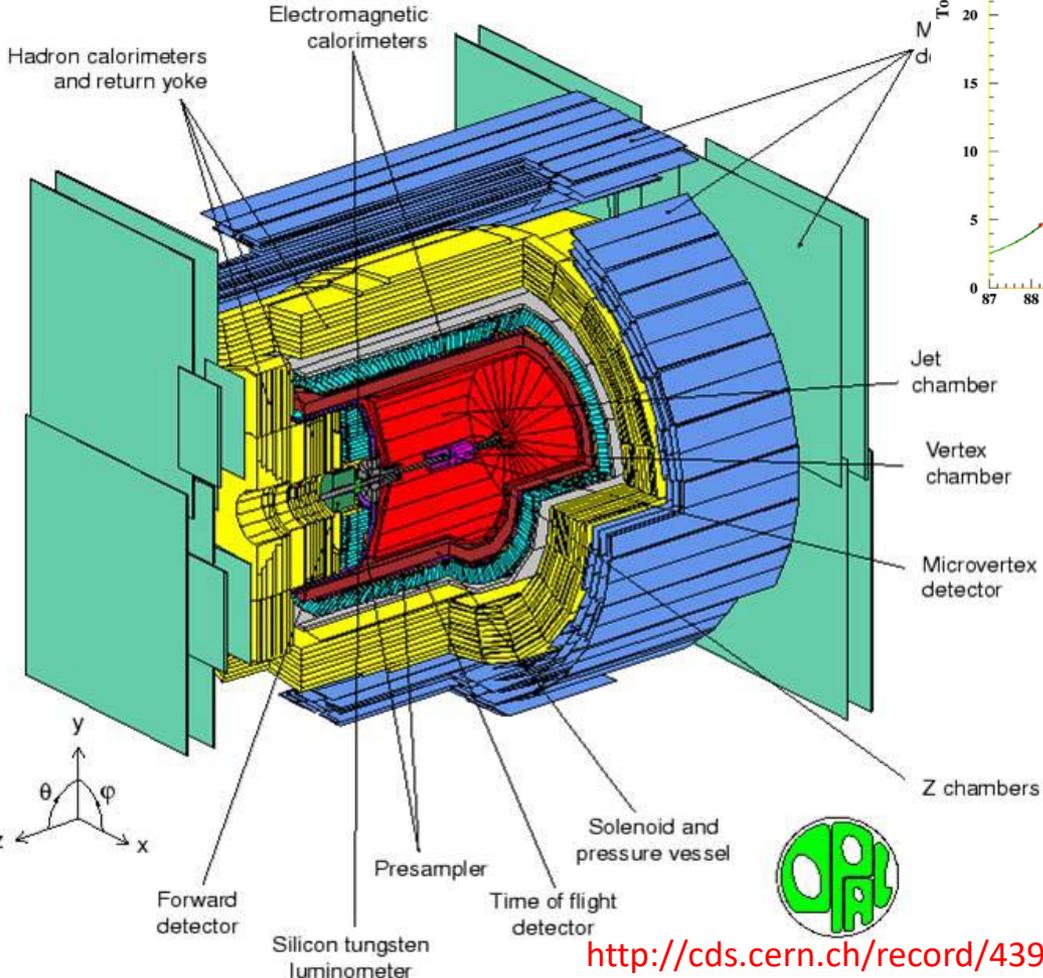
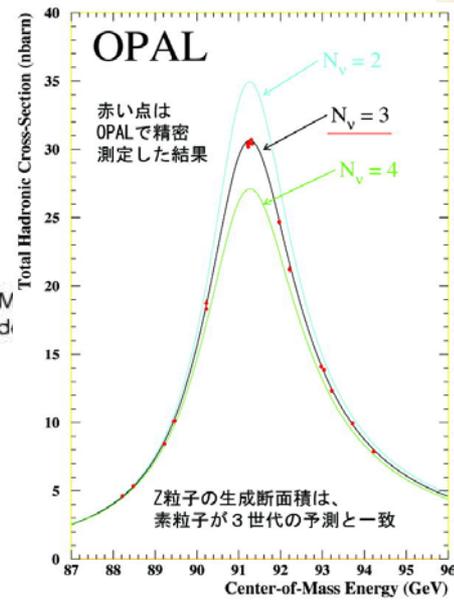
# Precision luminosity @ LEP



Si-W luminosity calorimeter

Eur.Phys.J. C14 373 (2000)

Systematic uncertainty:  $3.4 \times 10^{-4}$



<http://cds.cern.ch/record/43986>

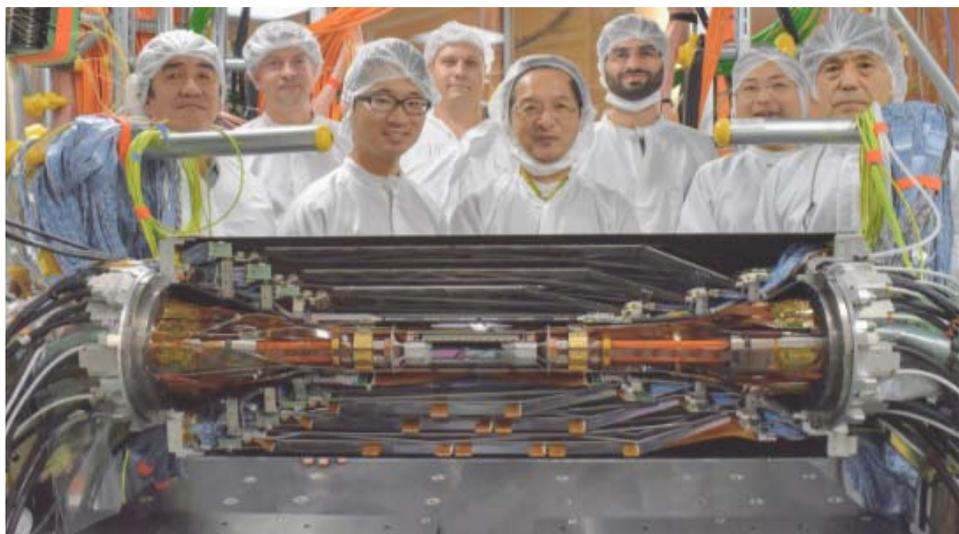
# High luminosity @

# SuperBelle

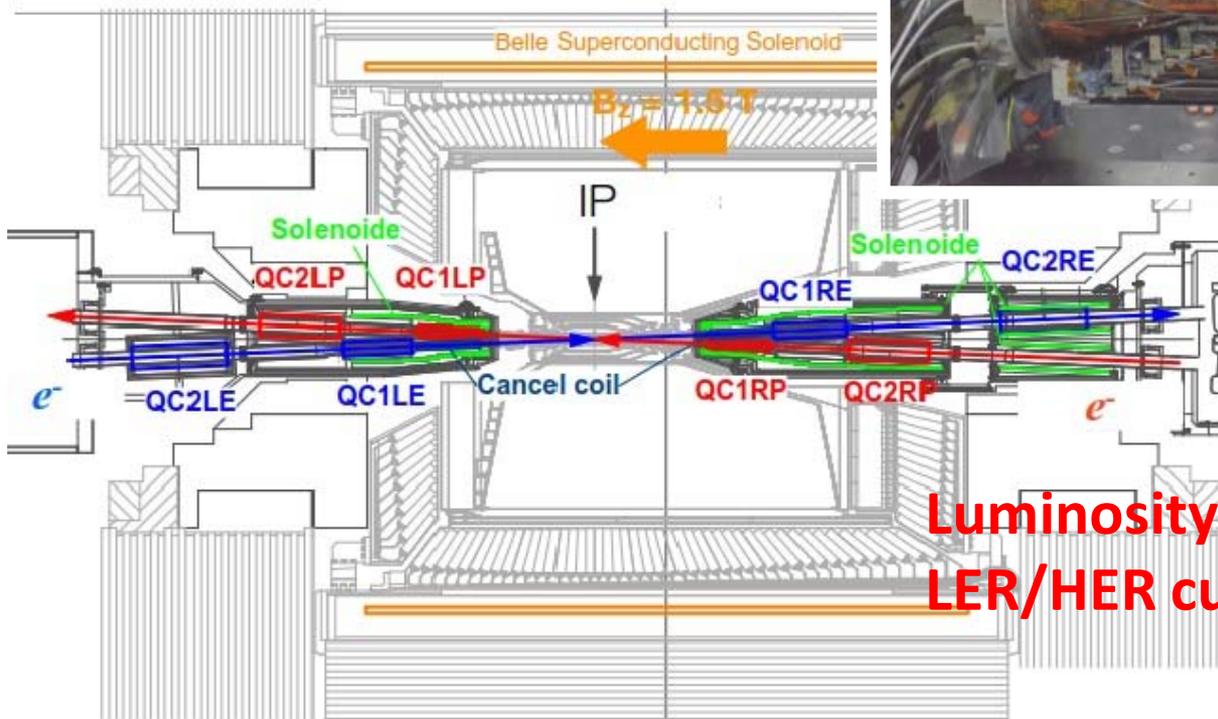
<https://www-superkekb.kek.jp/>

3 km ring

7 GeV  $e^- \rightarrow \leftarrow e^+$  4 GeV

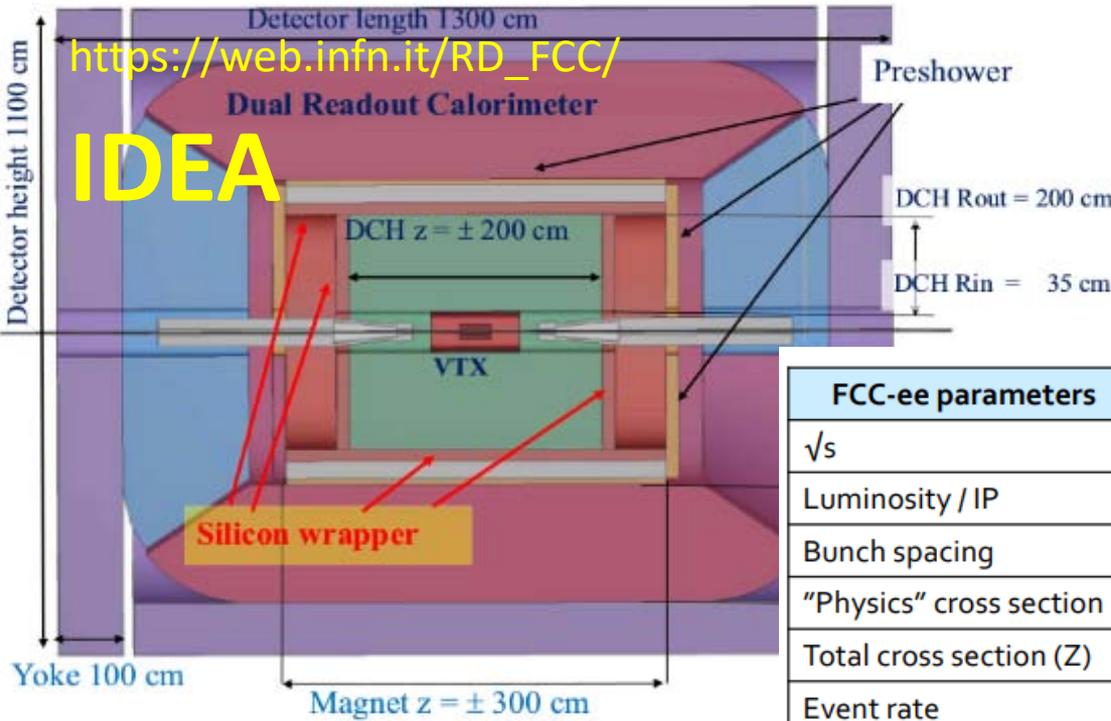
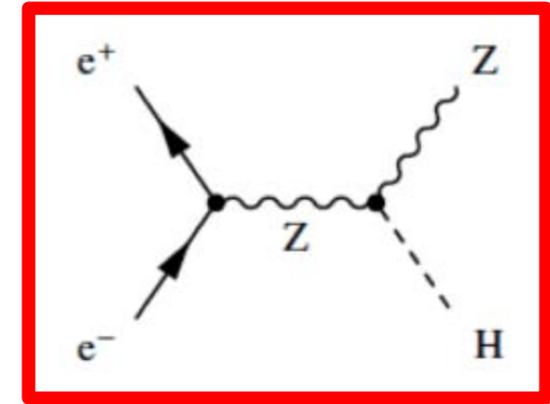


Belle II and QCS

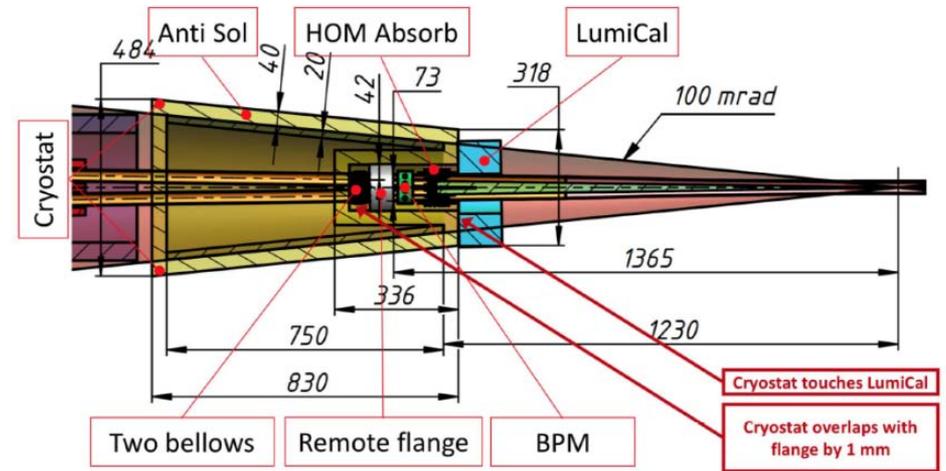
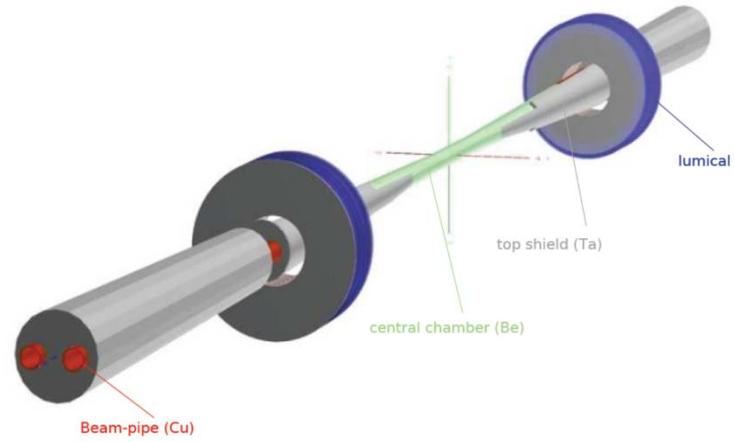


**Luminosity record  $4.7 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$**   
**LER/HER currents 1.4/1.1 A**

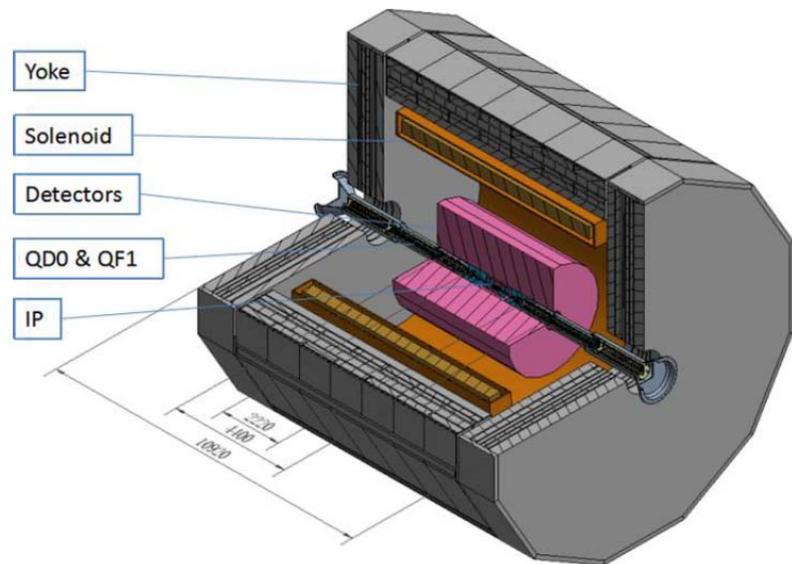
# FCC-ee detector and MDI



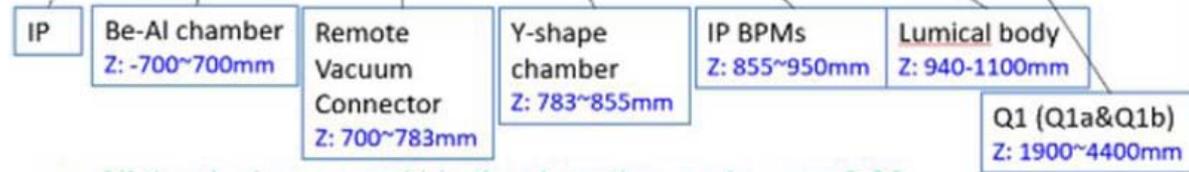
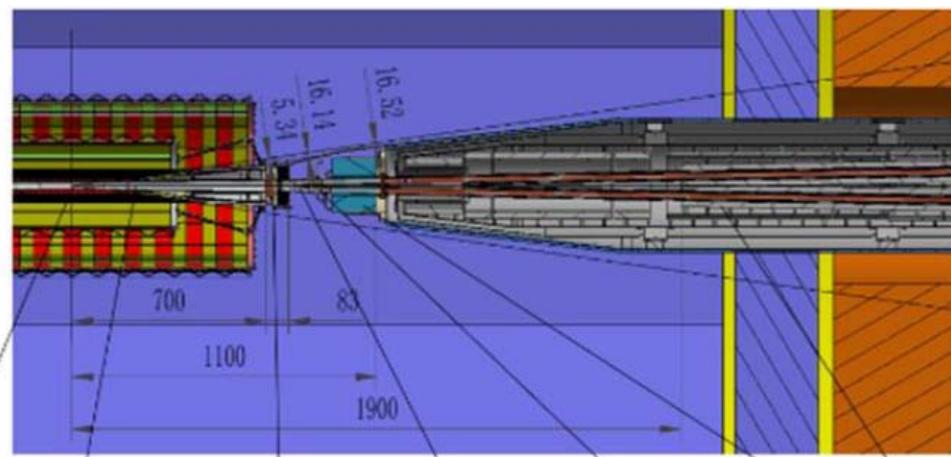
FCC-ee parameters		Z	W+W-	ZH	ttbar
$\sqrt{s}$	GeV	91.2	160	240	350-365
Luminosity / IP	$10^{34} \text{ cm}^{-2} \text{ s}^{-1}$	<b>230</b>	28	8.5	1.7
Bunch spacing	ns	19.6	163	994	3000
"Physics" cross section	pb	40,000	10	0.2	0.5
Total cross section (Z)	pb	40,000	30	10	8
Event rate	Hz	<b>92,000</b>	8,400	1	0.1
"Pile up" parameter [ $\mu$ ]	<b><math>10^{-6}</math></b>	1,800	1	1	1



# CEPC parameters



Operation mode		ZH	Z	W+W <sup>-</sup>	tt
$\sqrt{s}$ [GeV]		~240	~91.2	158-172	~360
L / IP [ $\times 10^{34}$ cm <sup>-2</sup> s <sup>-1</sup> ]	CDR (2018)	3	32	10	
	Latest	5.0	115	16	0.5



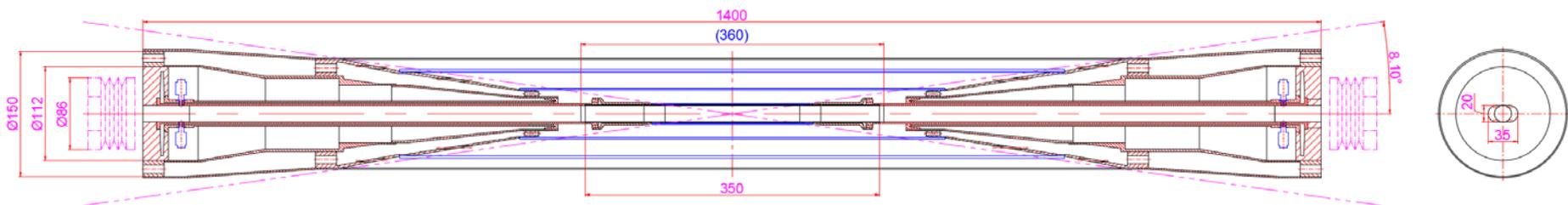
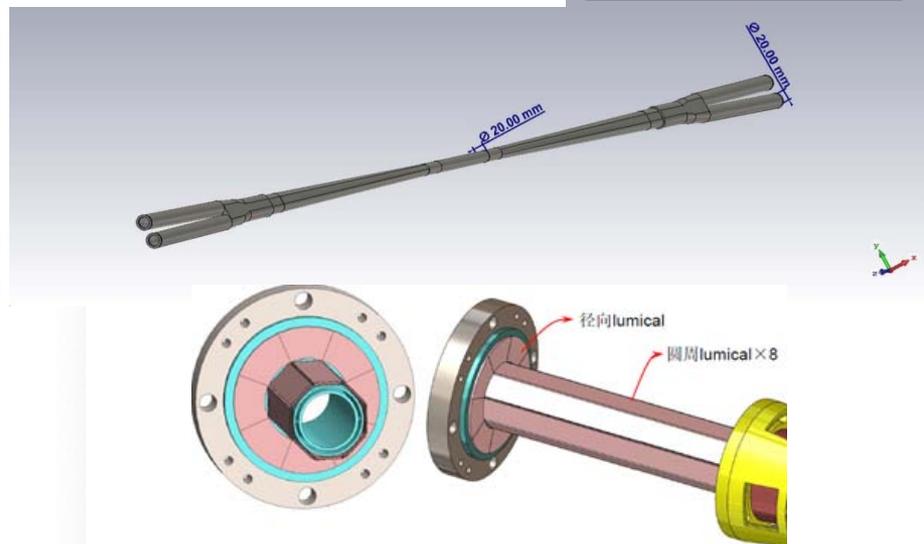
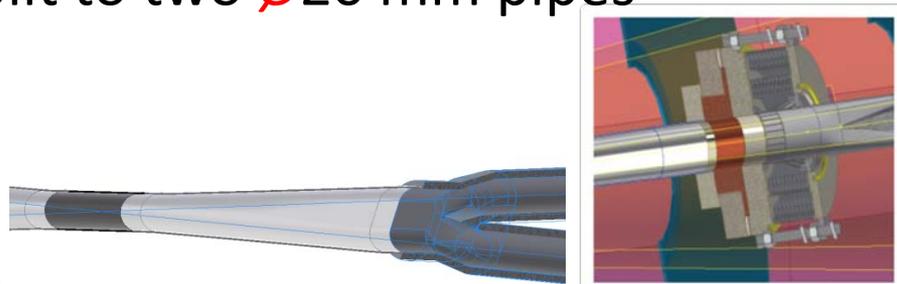
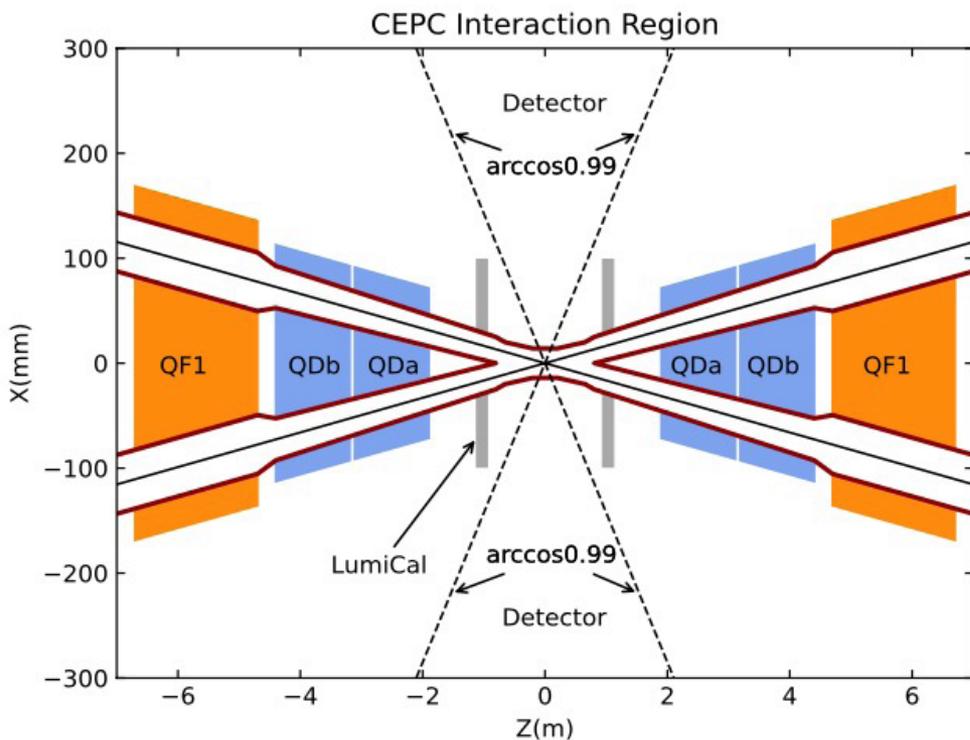
**@Z mass**  
 $L = 1 \times 10^{36}$  cm<sup>-2</sup>s<sup>-1</sup>  
 Bunch crossing = 25 ns  
 IP  $\sigma_x, \sigma_y = 6 \mu\text{m}, 35 \text{nm}$   
 Length  $\sigma_z = 8.7$  mm

	ttbar	Higgs	W	Z
Bunch spacing [ns]	4524	636	257	25 (10% gap)
Bunch population [ $10^{10}$ ]	20	14	13.5	14
Beam current [mA]	3.3	16.7	84.1	803.5
Beam size at IP ( $\sigma_x/\sigma_y$ ) [ $\mu\text{m}/\text{nm}$ ]	39/113	15/36	13/42	6/35
Bunch length (SR/total) [mm]	2.2/2.9	2.3/3.9	2.5/4.9	2.5/8.7

# CEPC Machine Detector Interface (MDI)

- Beam crossing = **33 mRad**
- IP to QDa front ~ 1m

- Racetrack beampipe  $\varnothing 20$  mm @ IP
- split to two  $\varnothing 20$  mm pipes



# CEPC LumiCal toward $10^{-4}$ systematics

- **Racetrack beam-pipe**

IP  $\varnothing 20$  mm; *X* splitting 20 – 35 – 39 mm;  
*Y*  $\varnothing 20$  mm to dual  $\varnothing 20$  mm pipes

- **Bhabha cross section by BHLumi**

boosted, beam crossing 33 mRad

✓ fiducial region: min materials, at  $z=630$ mm with Flange

$\theta_{\min} > 25$  mRad.  $|y_{z=650\text{mm}}| > 15$  mm

➔  $\sigma(\text{Bhabha}) = 78$  nb

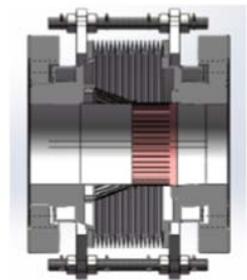
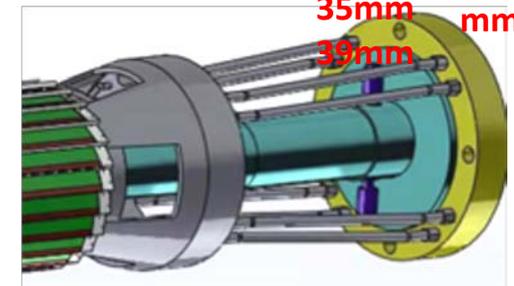
✓ estimate event rate, occupancy, pileup systematics

bunch crossing 32 ns, High-Lumi Z,  $L = 10^{36}$  /cm<sup>2</sup>s

- **Upstream materials, GEANT :**

✓ Multiple Scattering, preshower

✓ Magnet field, helix rotation



# $e^+e^-$ Elastic Scattering

QED Bhabha BHLUMI  
Cross section at CEPC

# Luminosity by Bhabha elastic scattering

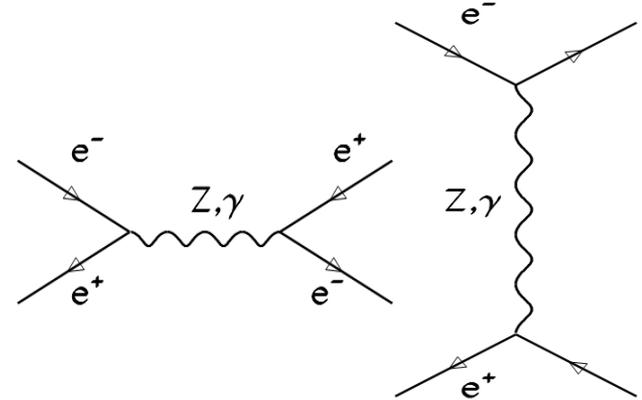
- **Physics events, e.g. Z pole,**

$$N = \sigma \cdot \int L \quad L: \text{Luminosity of } e^+e^- \text{ collisions}$$

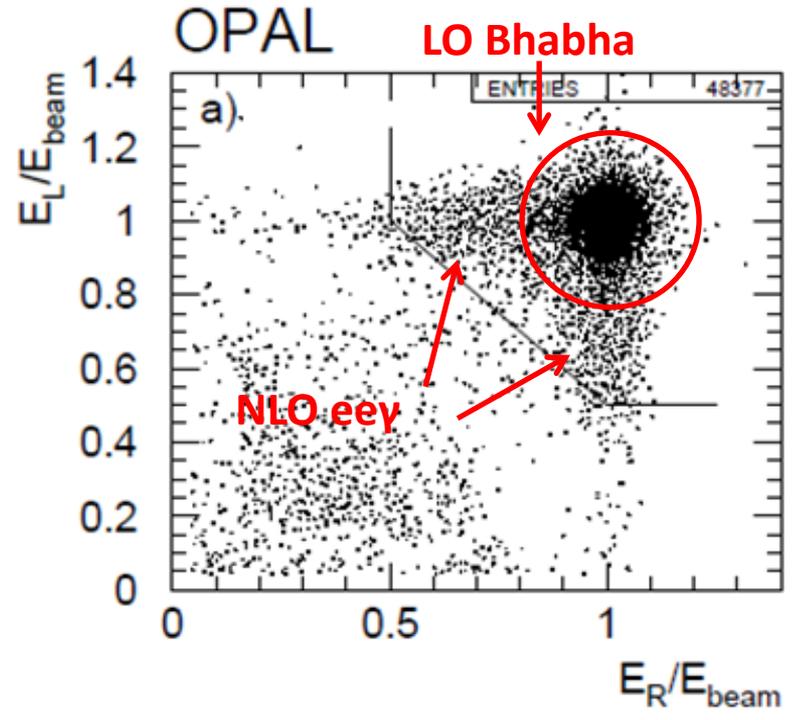
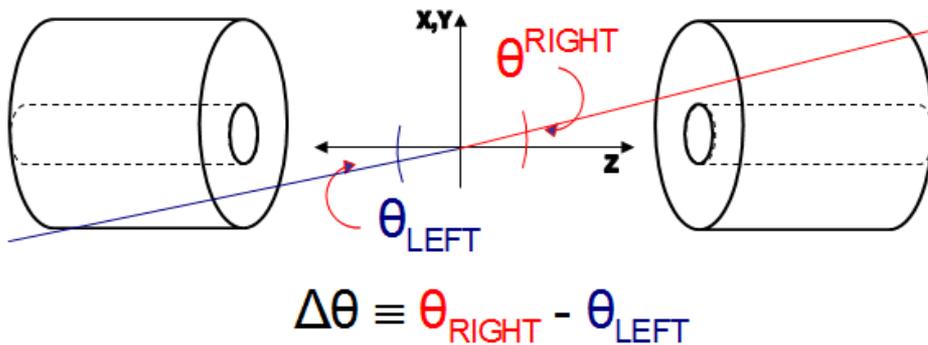
- **Luminosity by counting Bhabha events**

$e^+e^- \rightarrow e^+e^-(\gamma)$  QED theo. precision  $< 0.1\%$

1. **a pair of electrons,  $E(e^\pm) = E_{\text{beam}}$  back-to-back**
2. **precision  $\vartheta$  of  $e, e(\gamma)$**
3. **within fiducial region**



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



# Bhabha luminosity precision

Luminosity= counting Bhabha events

In a fiducial  $\theta$  region

**systematic error :**

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

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

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

**For  $\delta L/L = 10^{-3}$**

At  $z = \pm 1$  m,  $\theta_{min} = 20$  mRad

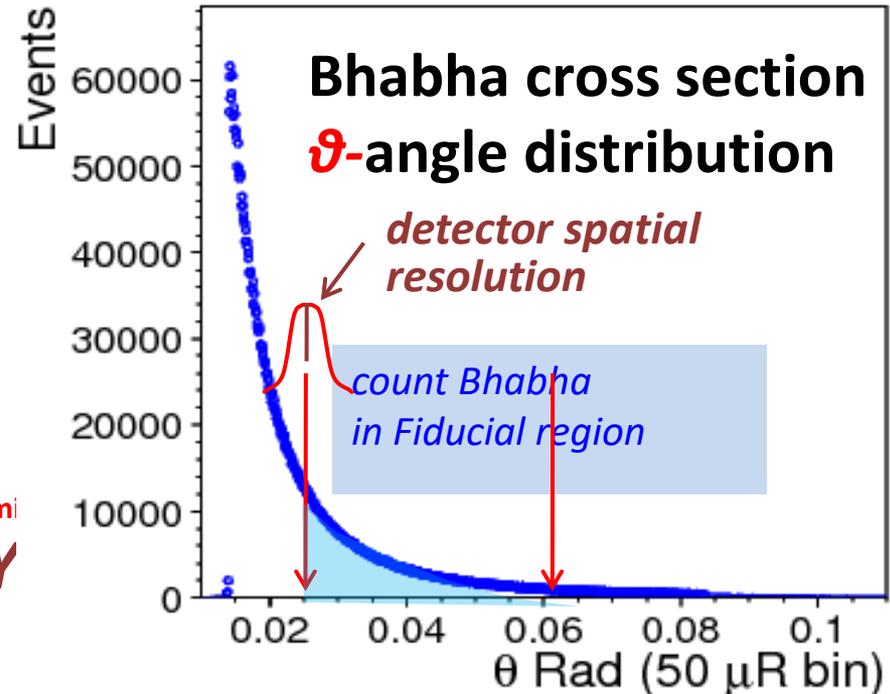
$\rightarrow \delta\vartheta = 10 \mu\text{Rad}$  or  $dr = 10 \mu\text{m}$

Error due to offset on Z

$\rightarrow 1$  mm on Z or  $dr = \delta z \times \vartheta = 20 \mu\text{m}$

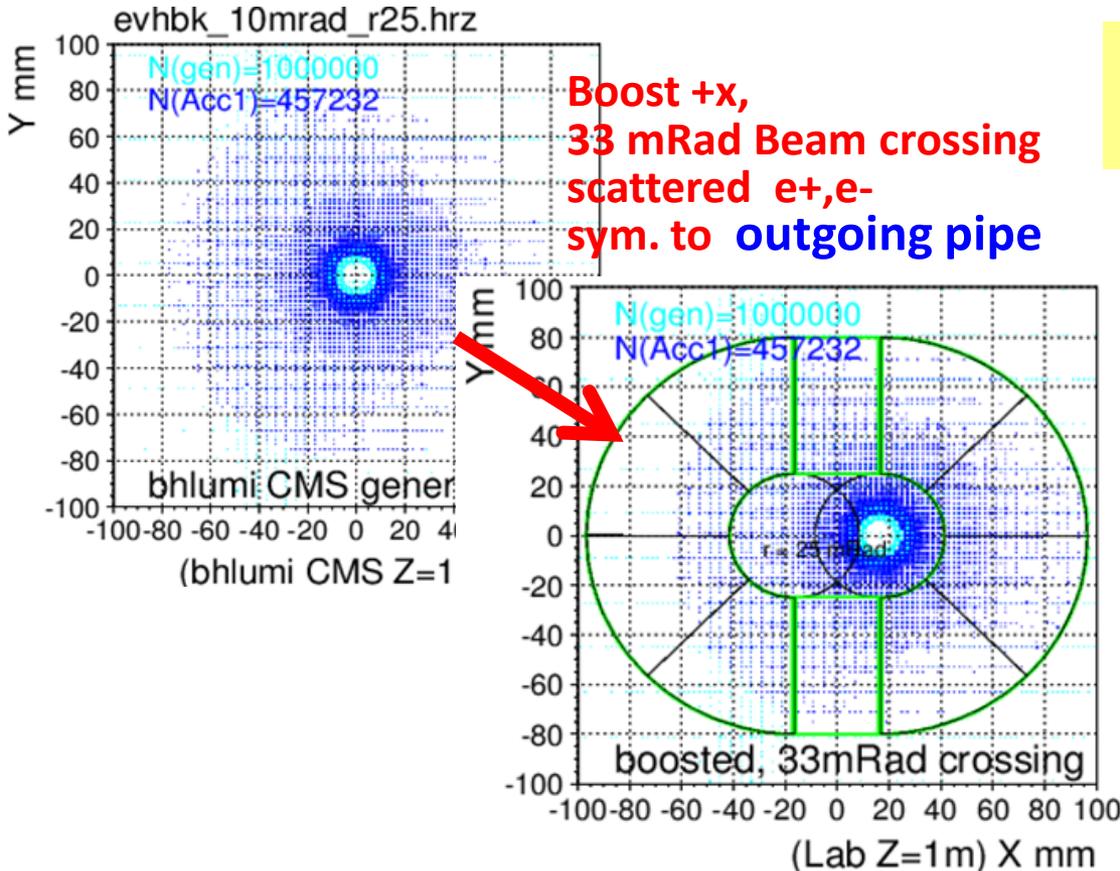
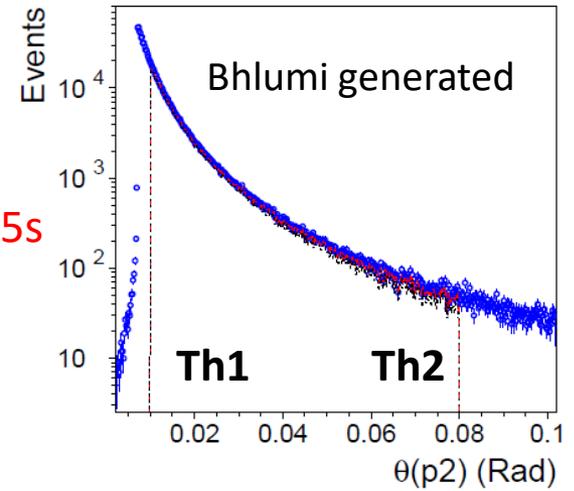
**Off set spatial resolution = offset on mean of  $\theta_{mi}$**

**$\rightarrow$  is the dominant LUMINOSITY**

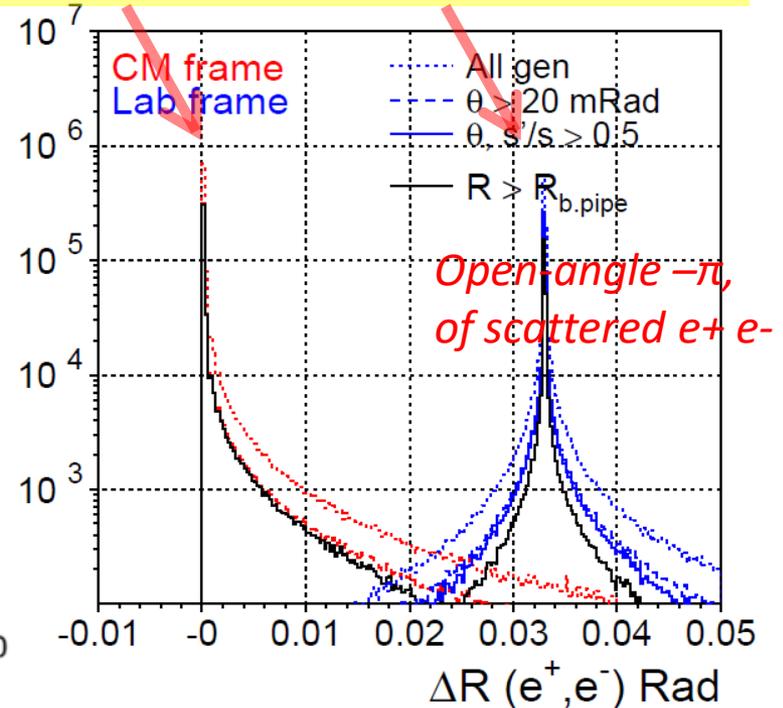


# BHLUMI + beam-crossing

- BHLUMI QED 0.06% precision** (PLB 450, 262)  
CMS  $m_z=92.3$  GeV, fiducial region:  $Th1 < \theta < Th2, s' > 0.5s$
- CEPC boost** :  $e^+e^-$  beam crossing, **33 mRad**
- X-section** : count event fraction in fiducial region



**Multi. Scattering, rad. Bhabha, wider back-back distributions**



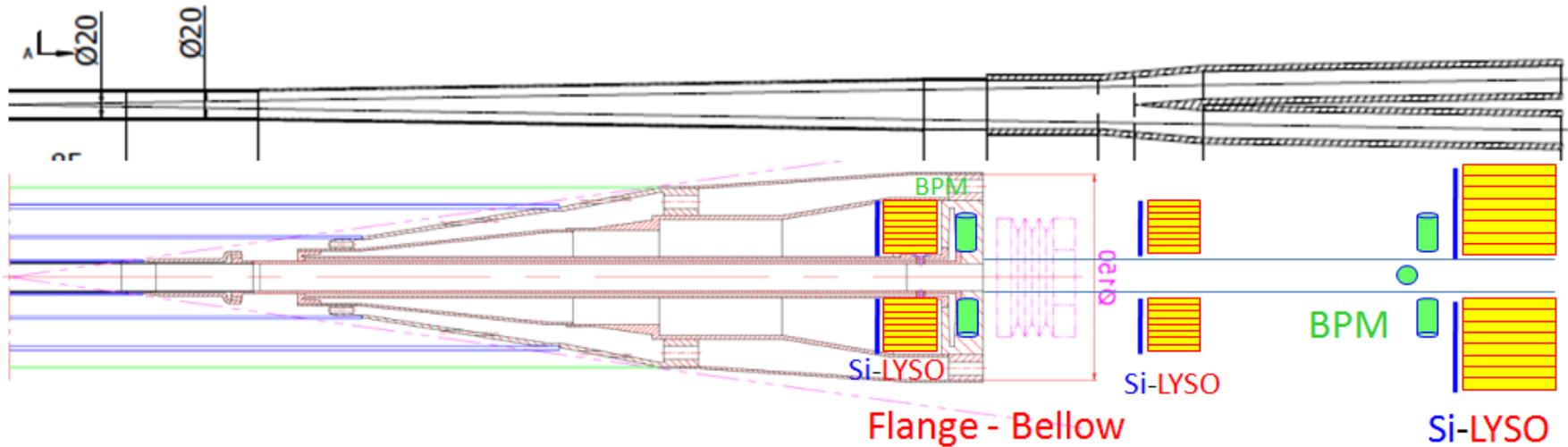
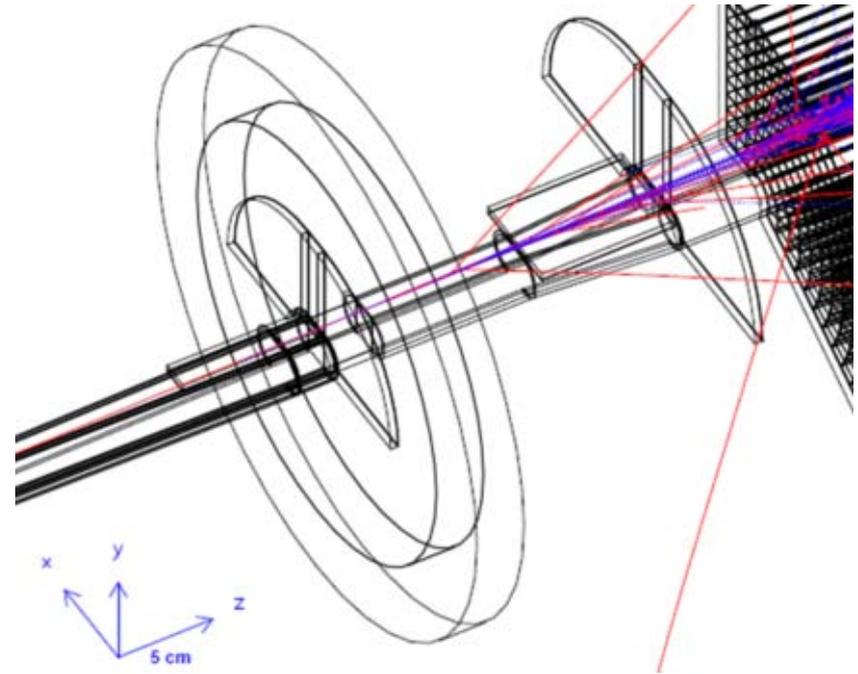
# LumiCal on Racetrack beampipe

## Racetrack beampipe

- beam-pipe  $r = 10$  mm, flat  $y = \pm 10$  mm
- **33 mRad** beam-crossing,
- boost horizontal,  $e^\pm$  lost into beampipe

## LumiCal sandwiched

- $|y| > 15$  mm
- **Vertical Si-wafers** :  
 $e^\pm$  theta tracking
- **LYSO calo** :  
 $3 \times 3 \times 50$  mm<sup>3</sup> bars

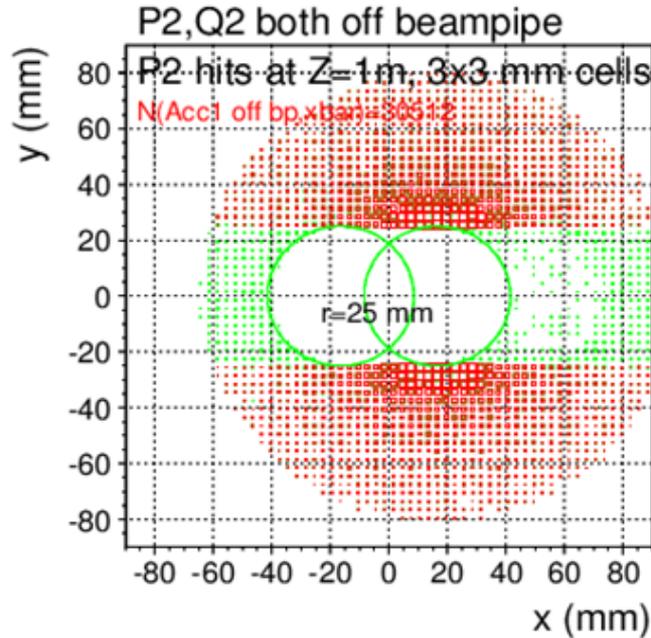


# BHLUMI X-section, racetrack @CEPC

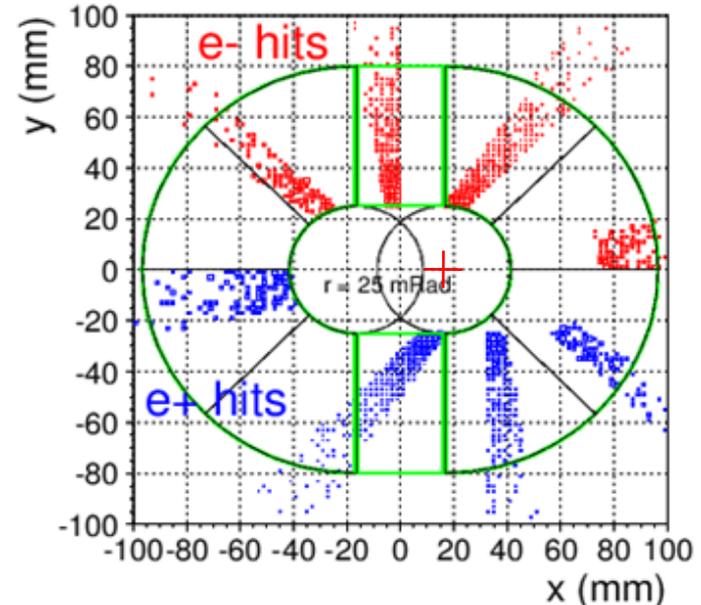
Acceptance @z=1m  $r > 25$  mm,  $|y| > 25$  mm

LAB frame

$e^+$ ,  $e^-$  detected  
@ Z=1000 mm



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



at Z = 1000 mm

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

racetrack

CDR

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

●  $\delta N/N \sim 10^{-4}$   
 in fiducial  $\vartheta$  window

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

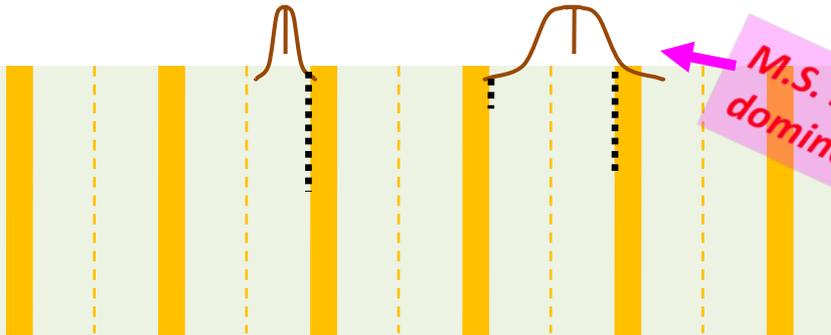
$\delta L/L < 10^{-4}$  for  $\theta_{min} = 20$  mRad

→  $\delta\vartheta = 1\mu\text{Rad}$   $dr=1\mu\text{m}$  @  $z=1\text{m}$

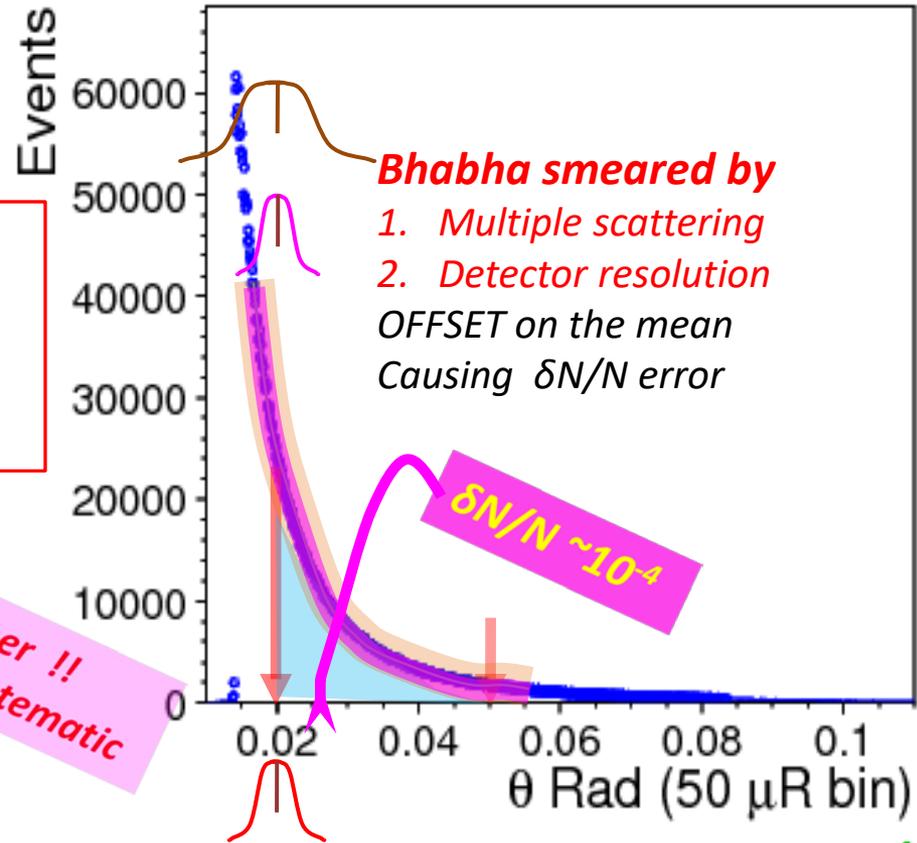
1. Det. Position offset
2. Multi. Scattering, det. Resolution  
 B-field helix
3. Rad. Bhabha, preshower offset

## Si-strip detector

fiducial edge = central line between two strips  
 Multi.Scattering → events flow in/out Fiducial  
 + geo error → **event counting error**



M.S. non-linear !!  
 dominant systematic

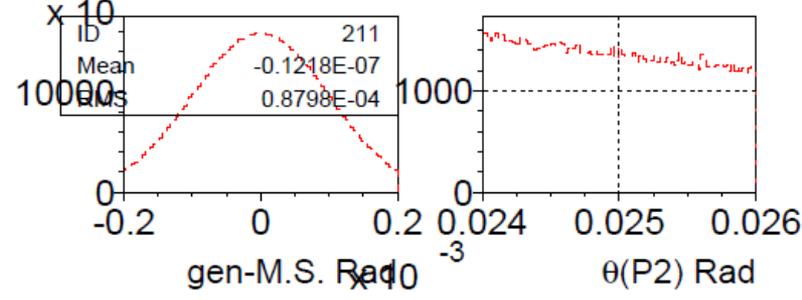
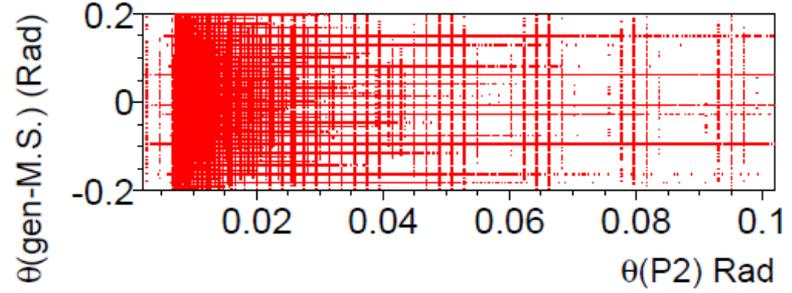
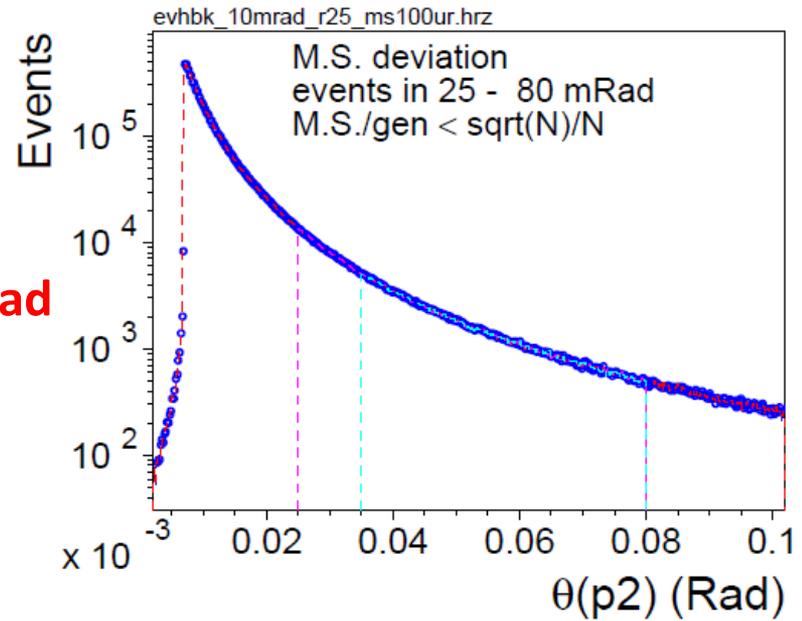
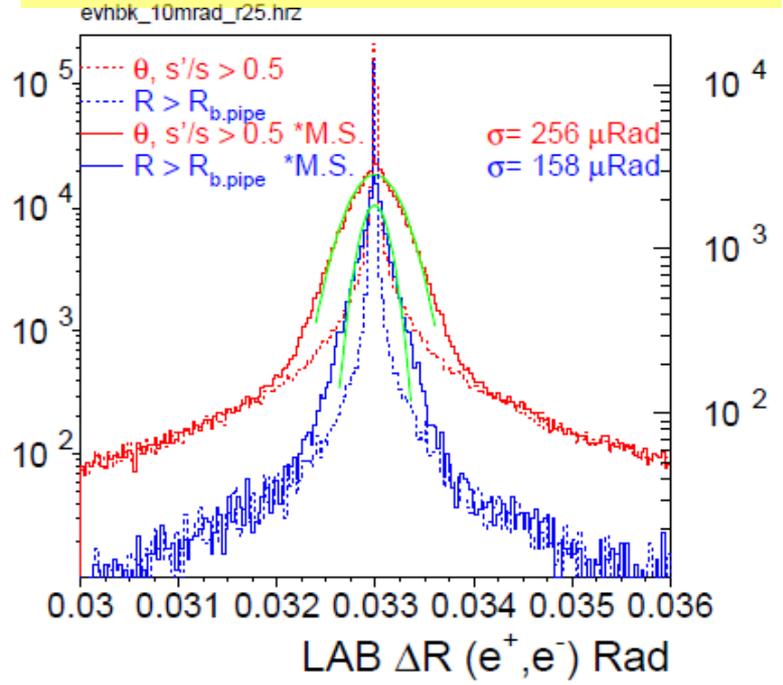


# Smearred $100\mu\text{Rad}$ as Multiple scattering

- 1. Scattered  $e^+, e^-$   $\theta' = \theta + \delta^{100\mu\text{R}}$ ,  $\phi' = \phi + \delta^{100\mu\text{R}}$   
 $\delta$  = Gaussian smearing as **Multiple Scattering** in theta, phi
- 2.  $\delta N/N$  systematics:

$\delta N$  = symmetric Gaussian  $\rightarrow$  @  $\theta_{\min} = 25 \text{ mRad}$   
 Bhabha shift  $100 \mu\text{Rad}$   $\delta N/N \sim 0$

**Multiple scattering  $100 \mu\text{R} \rightarrow$  wider back-back distributions**



# Bhabha event pile-up rate @High-Lumi Z

1. High-Lumi Z (2021 design)  $L_{\max}/IP = 115 \times 10^{34}/\text{cm}^2\text{s}$

*c.f. LEP*

2. Bhabha both  $e^+$ ,  $e^-$  detected, X-sec = **100 nb**

$L = 1 \times 10^{32}$

Event rate =  $(246 \times 10^{-33}) \times (115 \times 10^{34}) / \text{sec} = 115 \text{ kHz}$

X-sec = 100nb

Rate = 10 Hz

3. Event rate / 25 ns bunch crossing = **0.003 events / b.c.**

**4. Pile-up: next b.c., @adjacent cell in peak region**

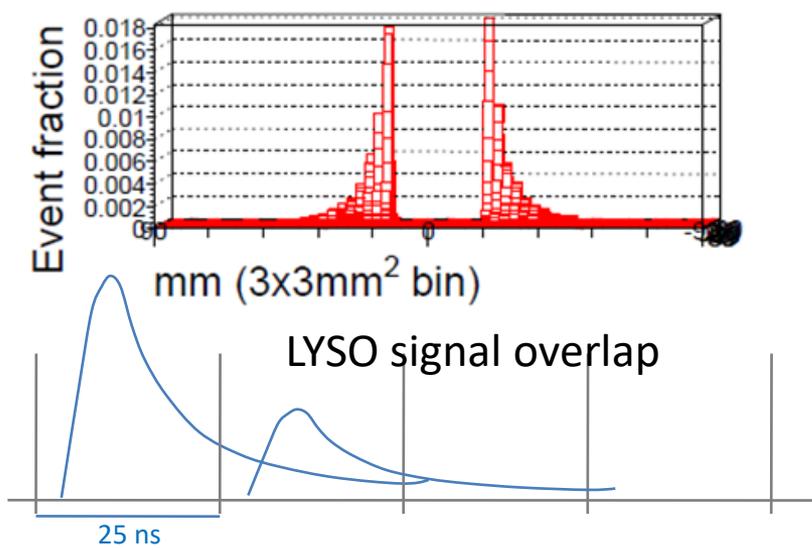
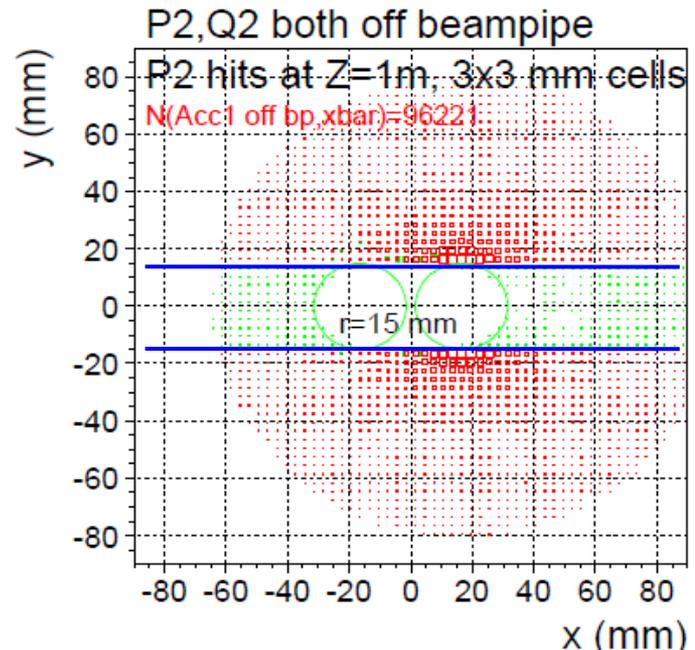
Pile-up Fraction =  $0.018 \times 6 \text{ cells} / 2 \text{ sides} = 0.054$

**Pile-up event rate =  $0.003 \times 0.054 = 1.6 \times 10^{-4}$**

**> systematic criteria**

## 50 GeV $e^-$ shower in $3 \times 3 \text{ mm}^2$ cells

event fraction / (cell of  $3 \times 3 \text{ mm}^2$ )  
 maximum at beampipe edge = **0.018**



# Beampipe material

GEANT estimation

multiple scattering + preshower

Magnetic field

# M.S. & preshower caused by beampipe

- **Beam Pipe**  
**possible 1mm Be ??**

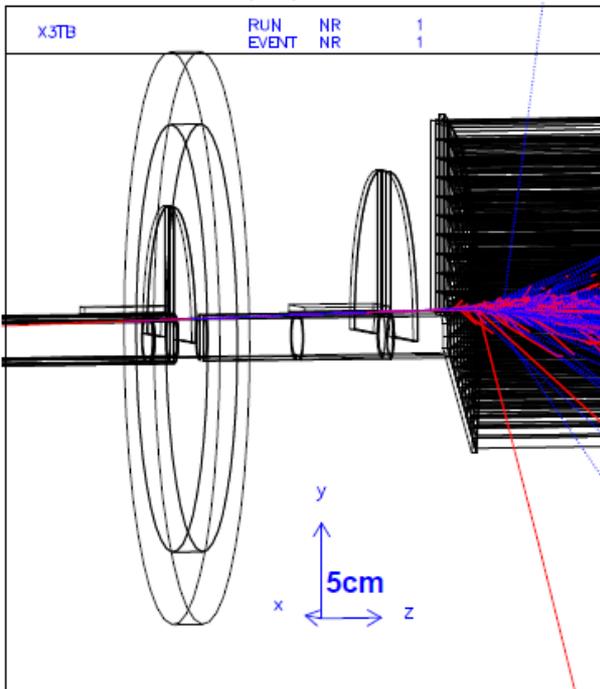
→  $< 0.2 X_0$

- **Preshower @  $z < 1m$**   
**Background to tracker**

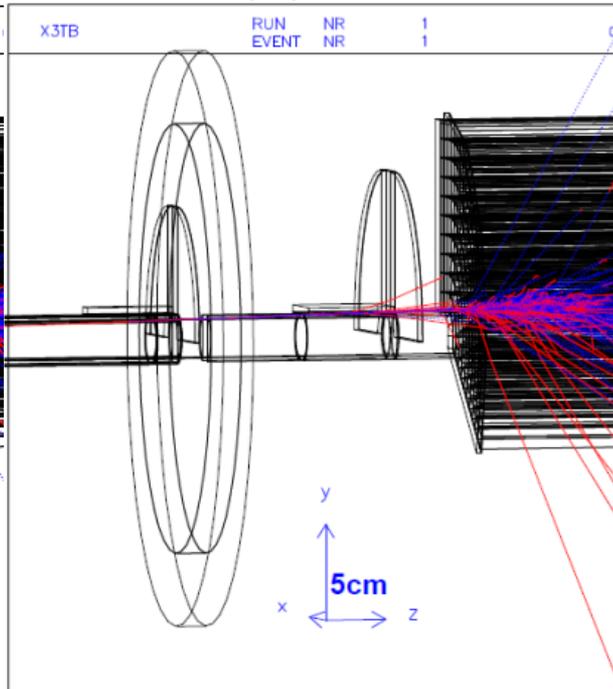
## 2mm beam-pipe, material budget

	$\tan\theta = 2\text{mm}/L$	$1/\tan\theta$	Be $X_0=353\text{mm}$	Al $X_0=89\text{mm}$	Cu $X_0=14.4\text{mm}$	CosQ
15mRad L= 133 mm	66.66	0.378 $X_0$	1.498 $X_0$	9.259 $X_0$	.9999	
<b>20mRad L= 100 mm</b>	<b>49.99</b>	<b>0.283 <math>X_0</math></b>	<b>1.123 <math>X_0</math></b>	<b>6.944 <math>X_0</math></b>	.9998	
25mRad L= 80 mm	39.99	0.227 $X_0$	0.899 $X_0$	5.554 $X_0$	.9997	
30mRad L= 67 mm	33.32	0.189 $X_0$	0.749 $X_0$	4.628 $X_0$	.9996	
35mRad L= 57 mm	28.56	<b>0.162 <math>X_0</math> (LEP)</b>	0.642 $X_0$	3.967 $X_0$	.9994	
50mRad L= 40 mm	19.98	0.113 $X_0$	0.449 $X_0$	2.775 $X_0$	.9996	
65mRad L= 31 mm	15.36	0.087 $X_0$	0.345 $X_0$	2.134 $X_0$	.9996	
80mRad L= 25 mm	12.46	0.071 $X_0$	0.280 $X_0$	1.732 $X_0$	.9996	

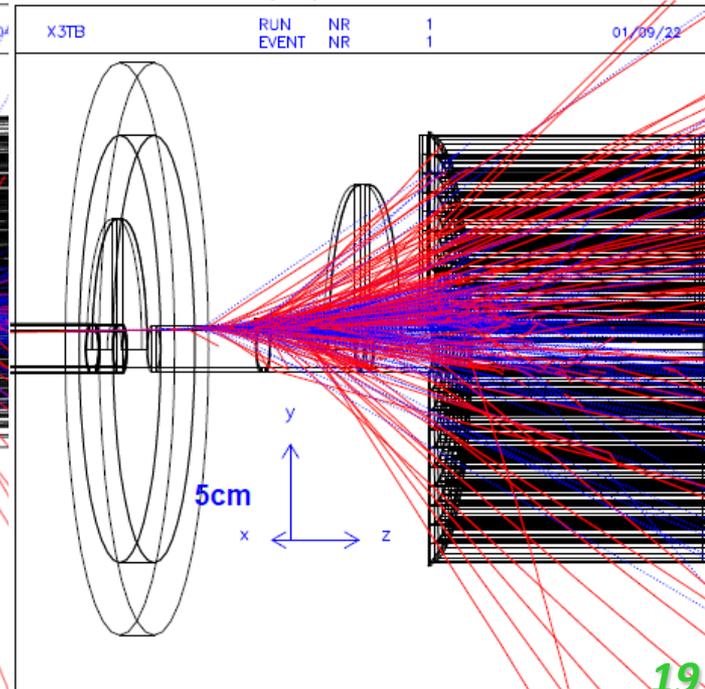
Be 2mm pipe



Al 2mm pipe



Cu 2mm pipe



# Multi. Scattering

1mm Be pipe,  
10 mm Al Flange

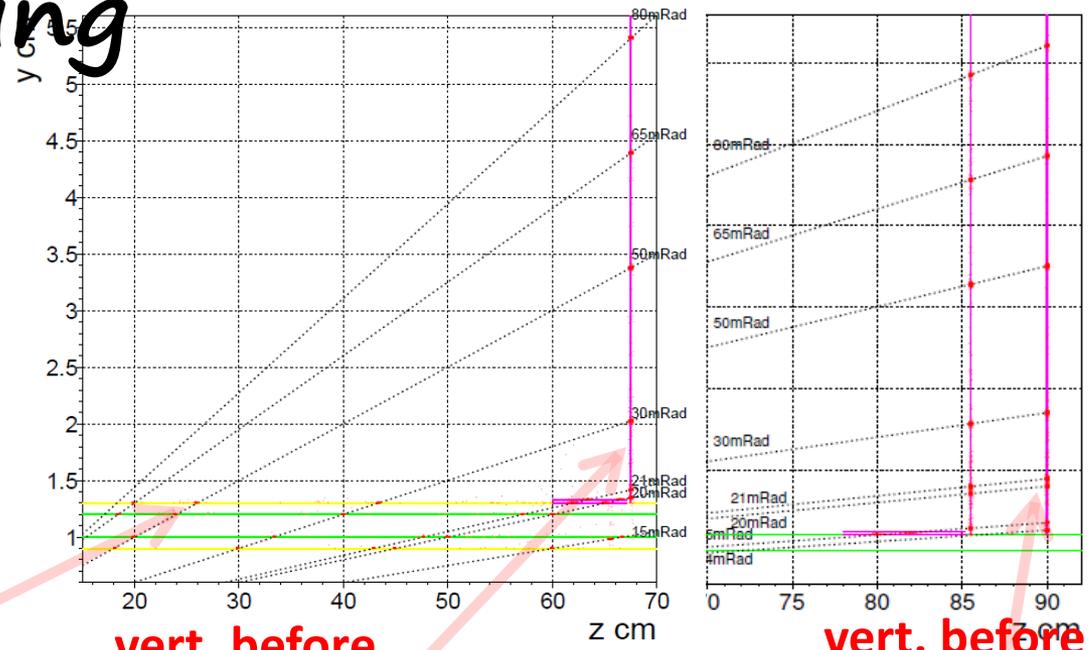
50 GeV muon  
Multiple scattering only

$\theta$  to z:  
 $r/z = \tan \theta$

Exit pipe

vert. before  
flange z=655mm

vert. before  
Qpole z=900mm



Muon $\theta$	$1/\tan\theta$	Exit pipe		Slab / pip		B.F flange		B.H flange		B.H flange		B.H flange	
		dz	d $\theta$	dz	d $\theta$	dr	d $\theta$	dz	d $\theta$	dr	d $\theta$	dr	d $\theta$
80	12.5					53 um	76 uR			74 um	87 uR	80 um	88 uR
65	15.4	32 um	11 uR			58 um	85 uR			84 um	98 uR	90 um	100 uR
50	20.0	43 um	9 uR			53 um	77 uR			79 um	92 uR	82 um	94 uR
30	33.3	160 um	12 uR			48 um	70 uR			76 um	88 uR	83 um	92 uR
21	47.6	396 um	18 uR	1.05 mm	36 uR	32 um	47 uR			72 um	84 uR	82 um	91 uR
<b>20</b>	<b>50.0</b>	449 um	16 uR	1.25 mm	40 uR	<b>31 um</b>	<b>46 uR</b>			74 um	87 uR	<b>85 um</b>	<b>95 uR</b>
15	66.7							1.63 mm	32 uR	36 um	43 uR	46 um	52 uR
14.5	69.0							1.78 mm	32 uR	33 um	37 uR	42 um	46 uR

# Smeared by Multi. Scat, Preshower

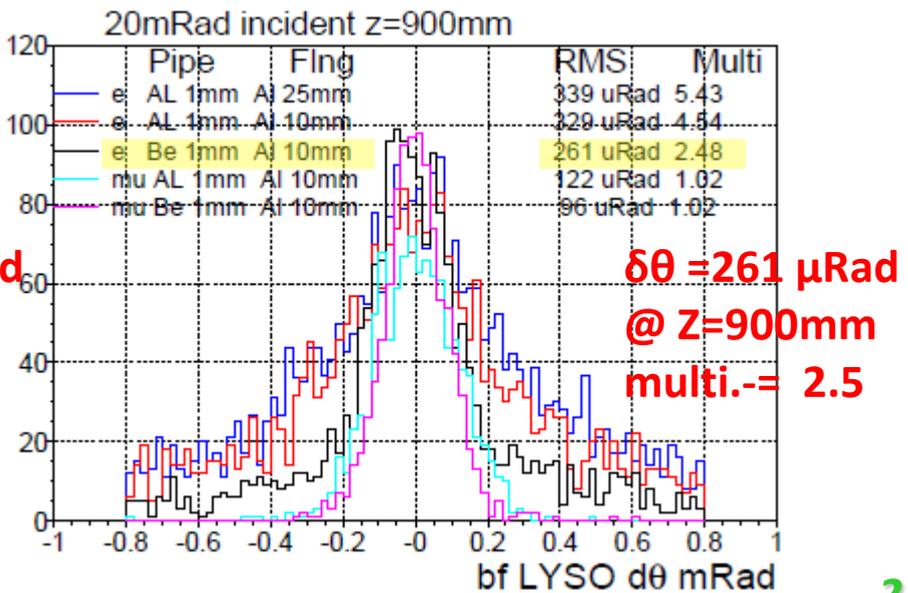
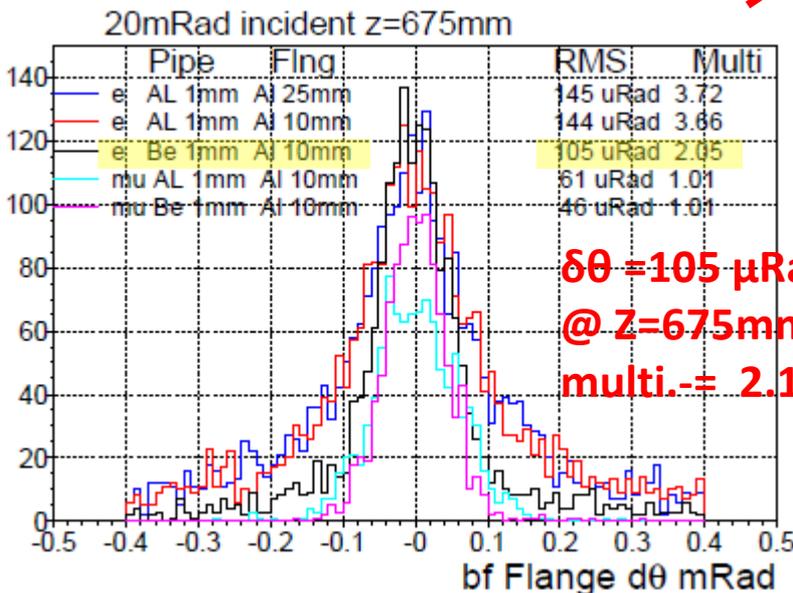
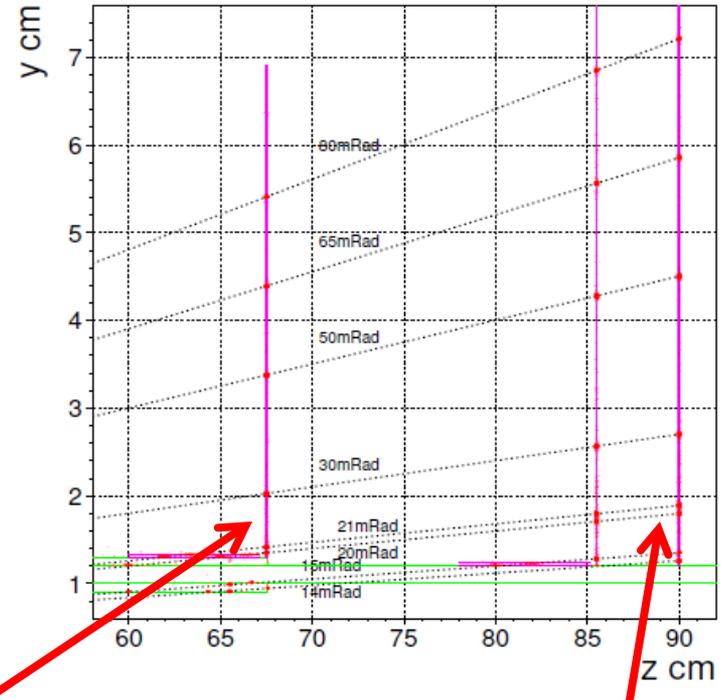
50 GeV muon, electrons @  $\theta=20$  mRad

**Muon:** multiple scattering only

**Electron:** M.S. + EM bremsstrahlung

**E.M. shower** → shower multiplicity  
widen position resolution

Ref: Be 1 mm pipe, @20 mRad,  $1/\tan \theta = 50$   
50 GeV 20mRad electrons

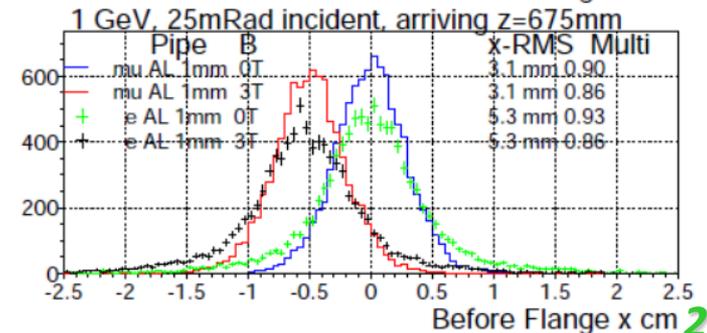
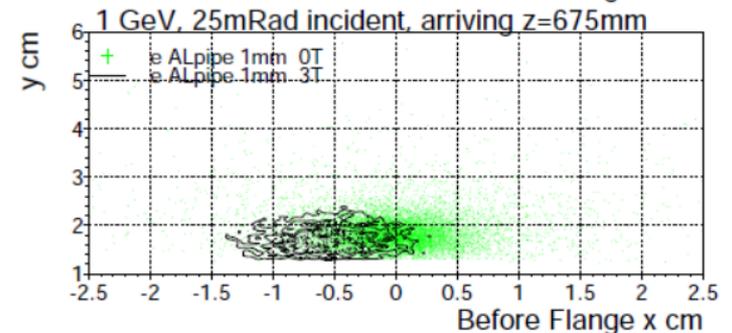
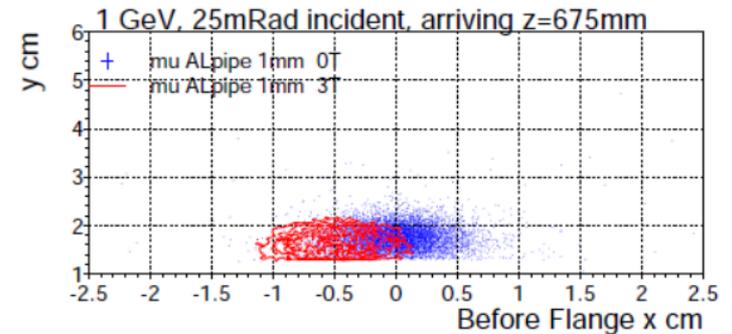
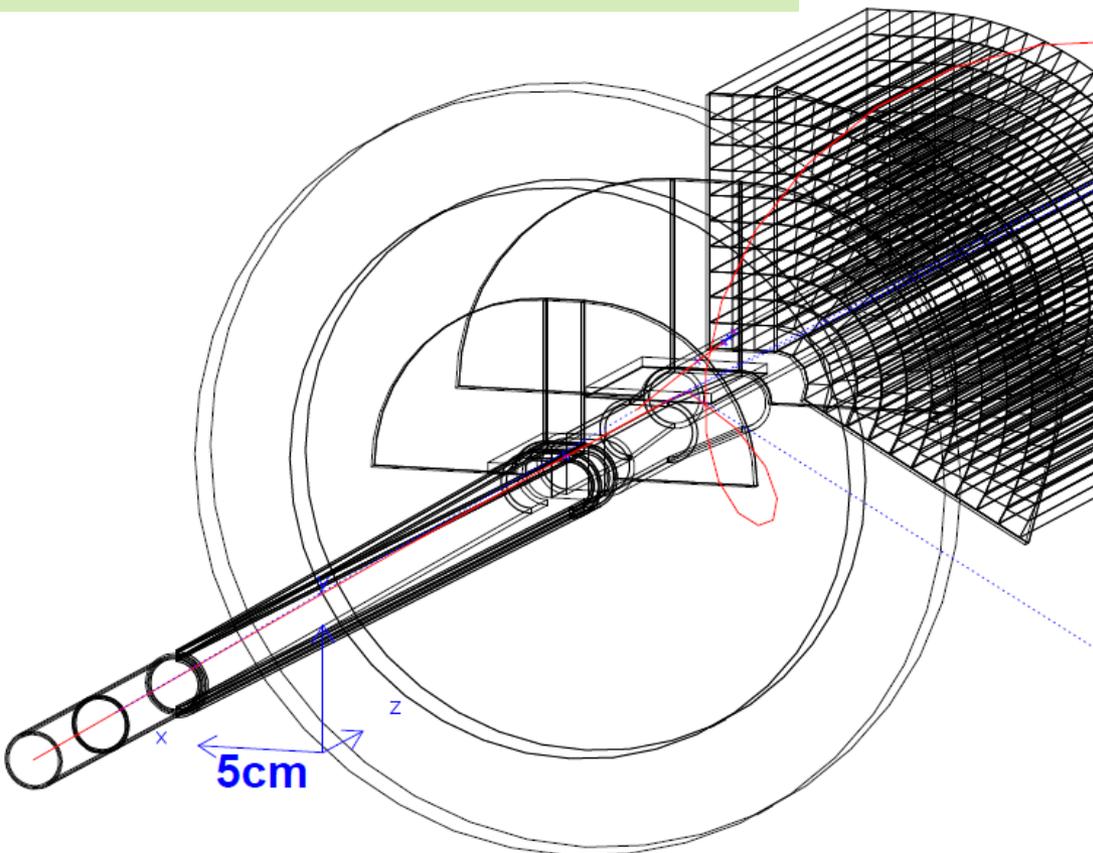


# Magnetic Field bending $B_z = 3T$

1 GeV electron, 3T Helix

1GeV electron @25mRad  
1 mm Al pipe, 25mm Flange  
M.S. +3T Helix z=675mm

2 mm Al pipe, 20mm Flange



# *Discussion*

# LumiCal Summary

## 1. Ø20 mm Racetrack beampipe

Bhabha X-section fiducial

→ **lower  $\theta_{\min}$**

Beampipe material 1mm Be pipe

→ **Multi.Scatt.  $\delta\theta \sim 100 \mu\text{R}$**

## 2. Lumical optimization:

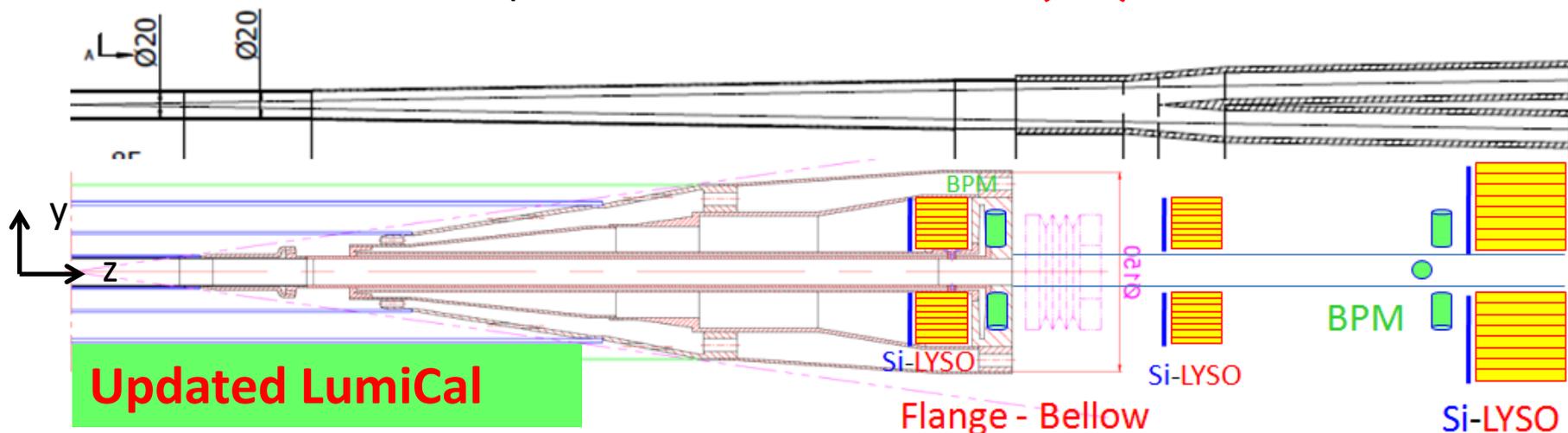
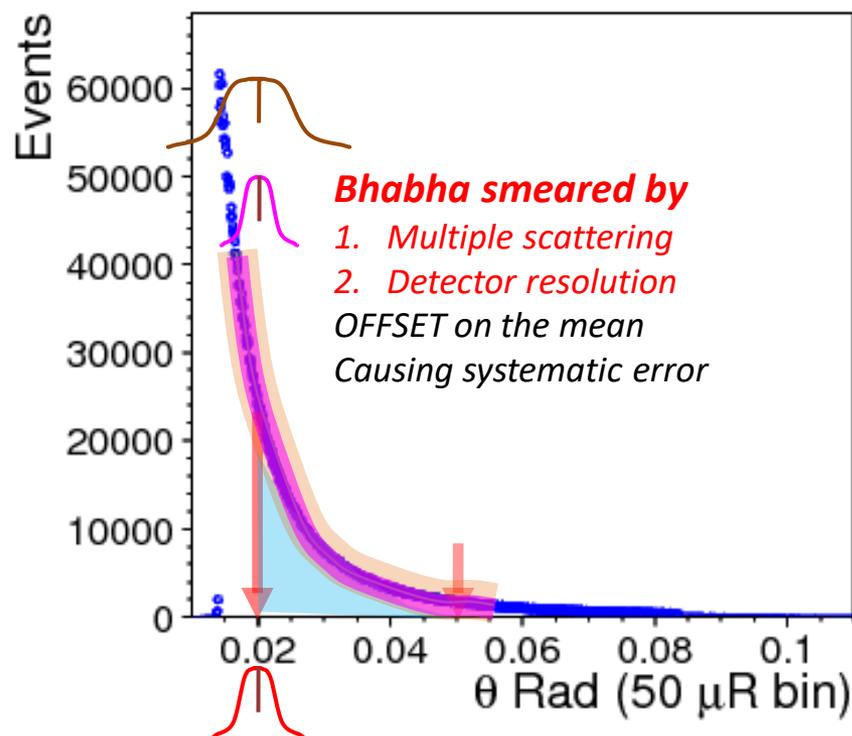
### Si+LYSO sectors

○ before Flange:

impact position, e, $\gamma$  ID, preshower

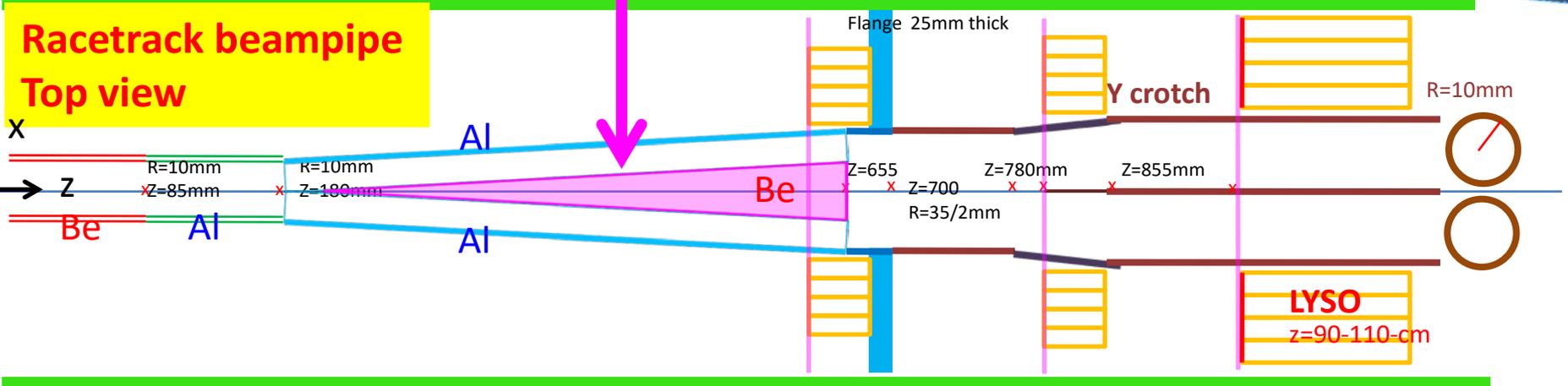
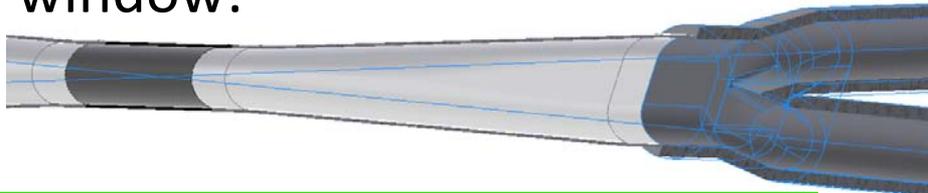
○ after Bellow:

Y-crotch sector, Qpole sector

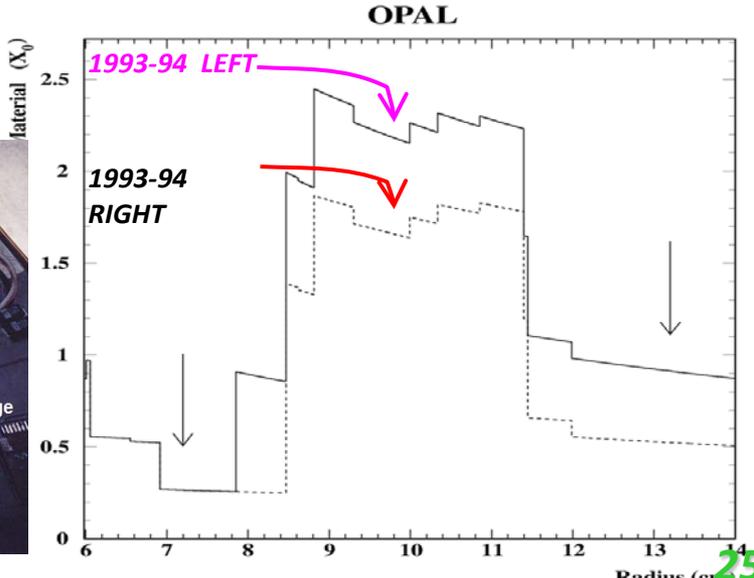
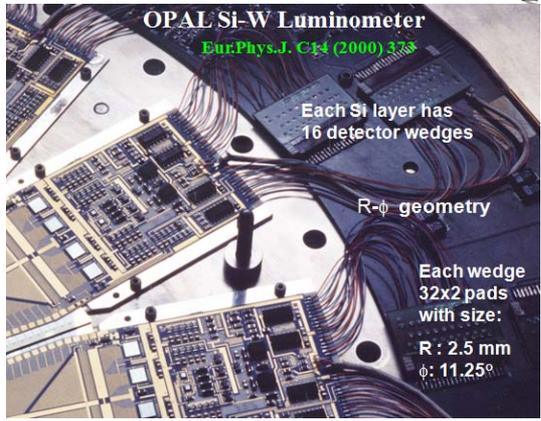
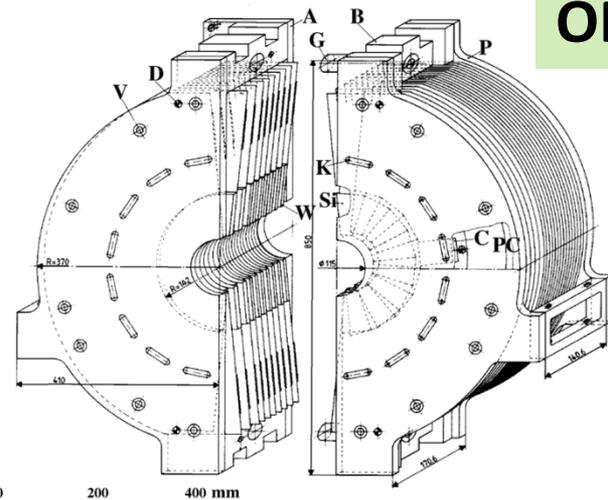


# Beampipe material budget

Low-mass window  $< 0.07 X_0$  (20mR) window:  
 single layer Be slab 0.5mm



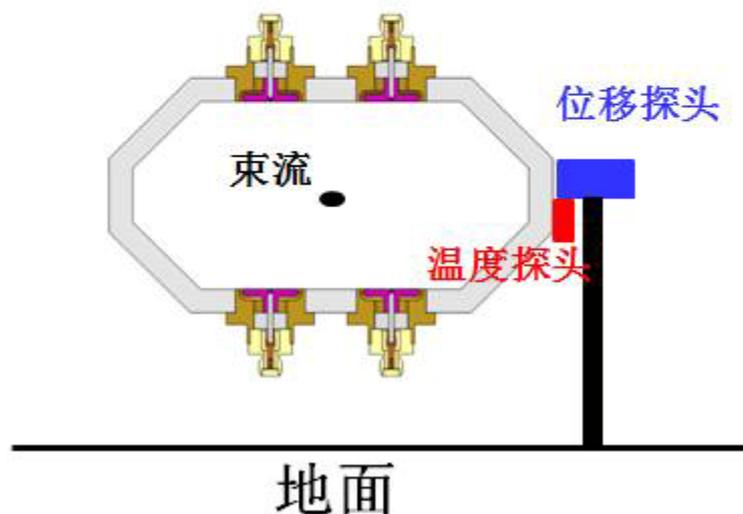
## OPAL mechanics



# LumiCal position $1 \mu\text{Rad}$ 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

东莞

**LumiCal precision,  $1 \mu\text{Rad}$  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 $\pm 7$  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,  $0.1 \mu\text{m}$ ; 22kHz 快轨道数据,  $0.3 \mu\text{m}$ , 逐圈数据:  $1 \mu\text{m}$ 。)

# Industrial measurement tools, e.g. keyence

## Detector assembly precision

- measure lower fiducial edge to <math>< 1 \mu\text{m}</math>
- easy under microscope and survey equipments

AS\_85026\_SI-F1000\_C\_611297\_US\_1126-7

Best in its Class  
RESOLUTION: **1 nm**  
World's Smallest  
MICRO-HEAD SIZE:  
 **$\varnothing 2 \text{ mm}$  ( $\varnothing 0.08''$ )**



### SI Series Measurement Principles (Spectral-Interference type) micro-head ultra high accuracy

AS\_86990\_MEASUREMENT\_GC\_611914\_US\_1018-9

