2026 超级陶粲装置研讨会

超级陶粲装置 Super Tau-Charm Facility

Precision test of QED on radiative Bhabha photons

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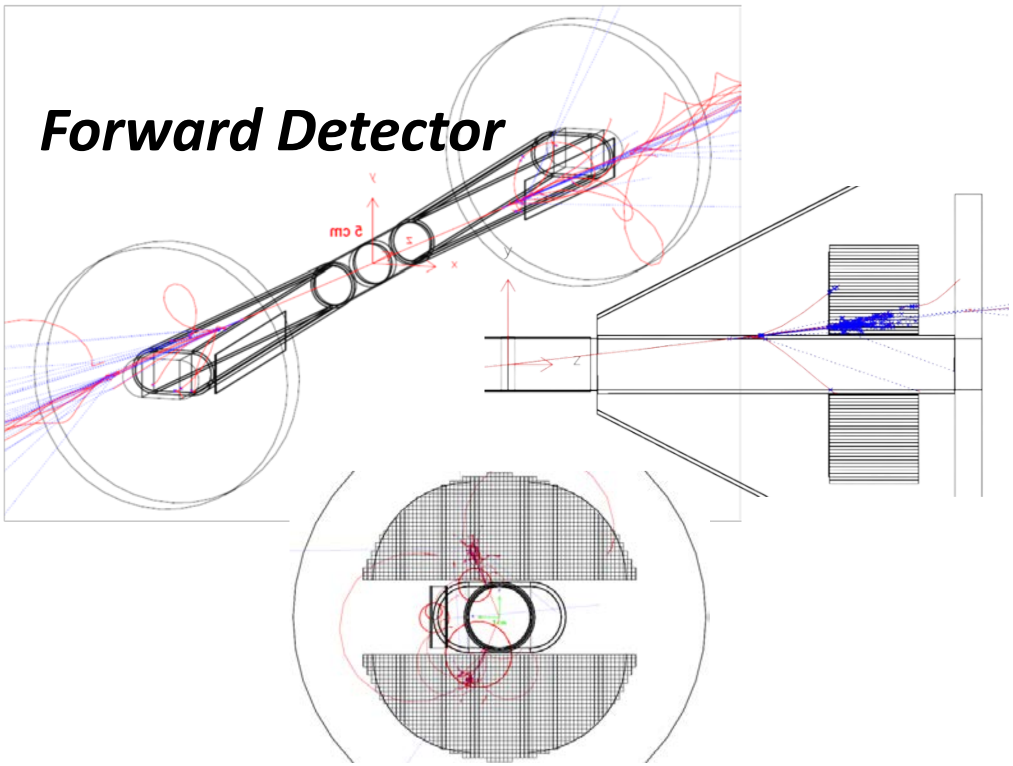
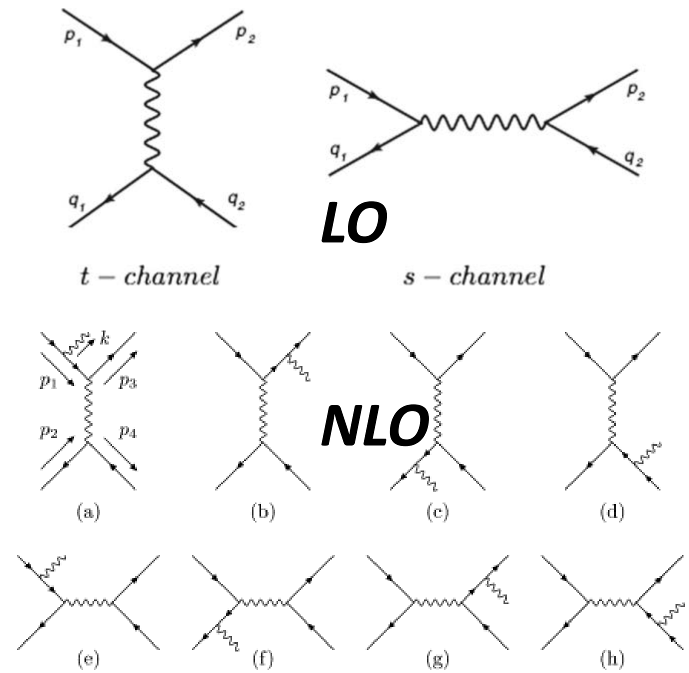
2026.07.02



Radiative Bhabha elastic scattering

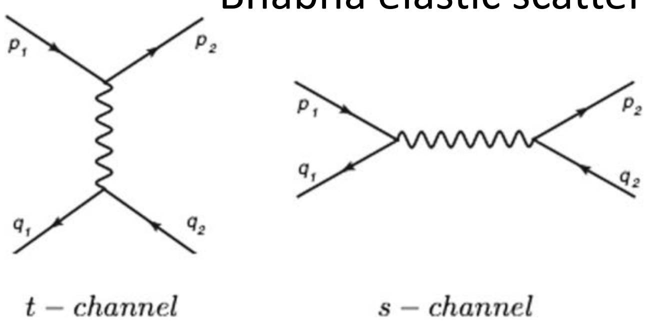


QED processes at e^+e^- colliders

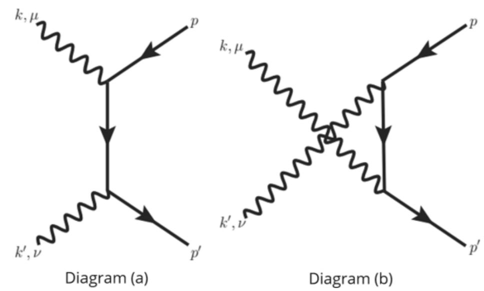
1. Bhabha elastic scattering

2. Two photon interaction

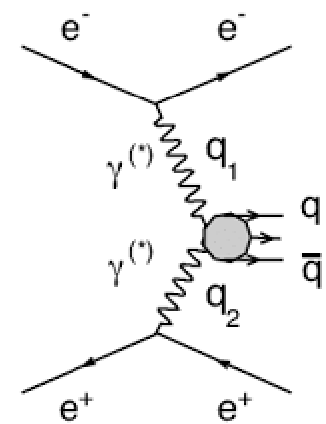
Bhabha elastic scattering



two-photon pair



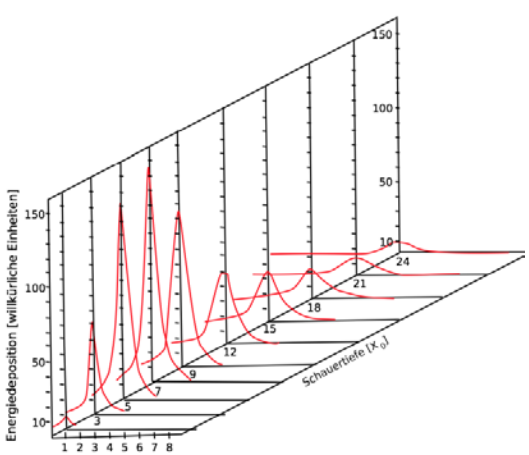
two-photon fusion

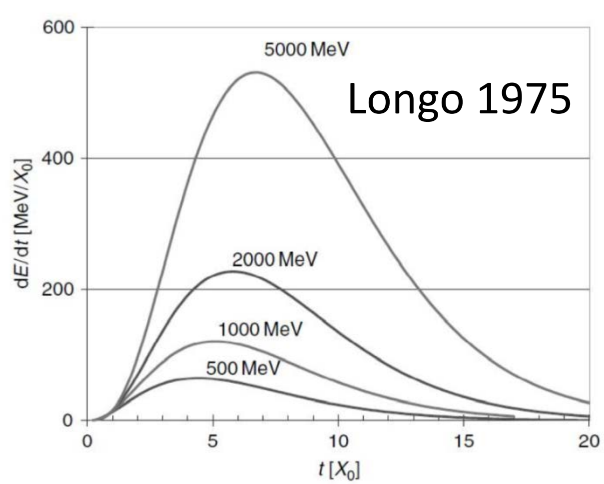


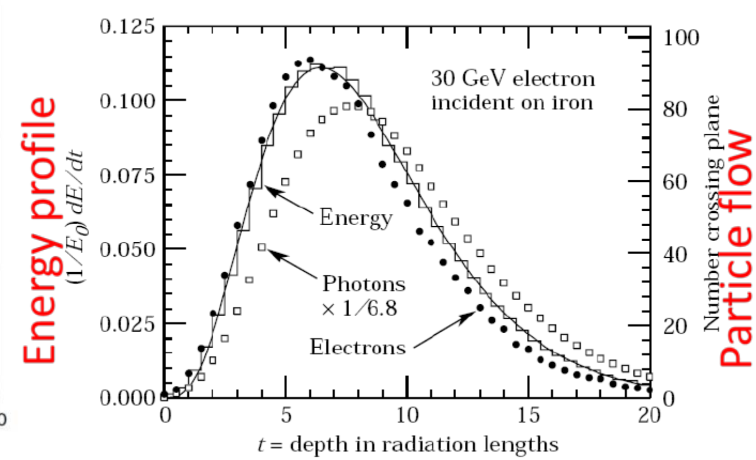
3. Beam background: Sync. Radiation, IP Bremsstrahlung

4. Electromagnetic Shower, Calorimetry

a 6 GeV electron in lead







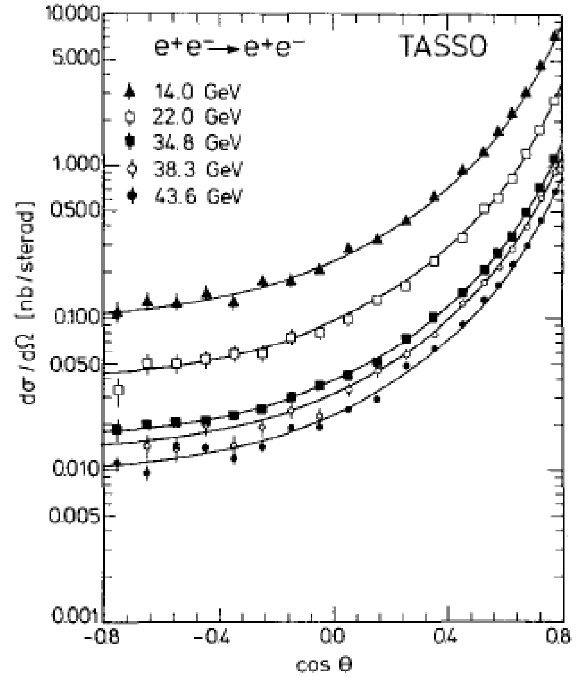
Bhabha experimental results $e^+e^- \to e^+e^- (\gamma)$

- **TASSO** Bhabha [1988, ZPC 37, 171
  Systematic error **~3%**

  √s = 12 - 47 GeV

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

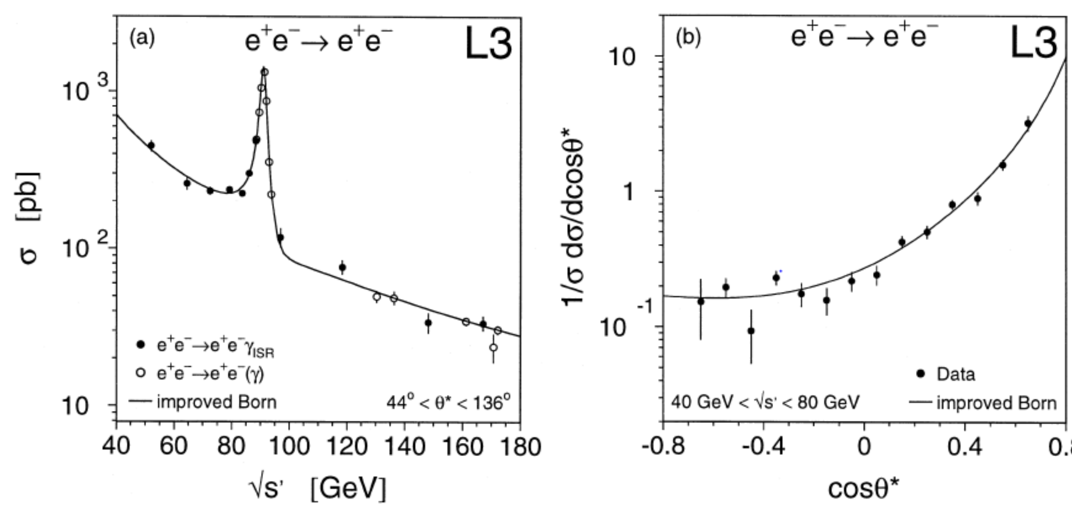
$\langle\sqrt{s}\rangle$ (GeV)	$\int \mathscr{L}\, dt$ (pb^{-1})	N_{Bhabha}
14.0	1.7	10730
22.0	2.7	7106
34.8	174.5	166348
38.3	8.9	6035
43.6	37.1	22951



- **L3** radiative Bhabha with **ISR**
- Systematic error at **~1% level**

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

[1998, PLB 439, 183]



Bhabha Luminosity for SM, R ratio

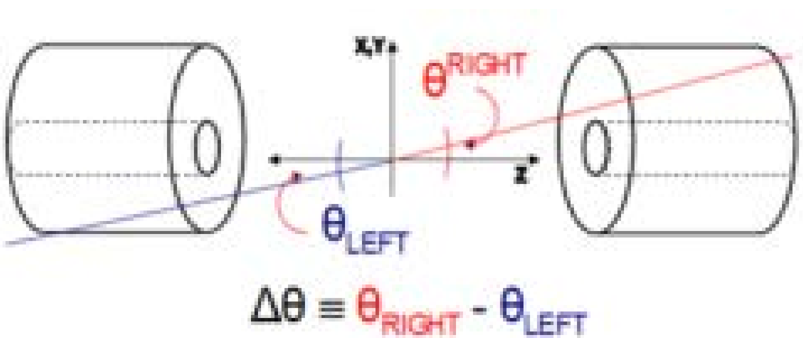
Luminosity $\mathcal{L}$ is derived by Bhahha event counting

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

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

Bhabha detected for

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



R(s) ratio for SM predictions

Requiring precision on

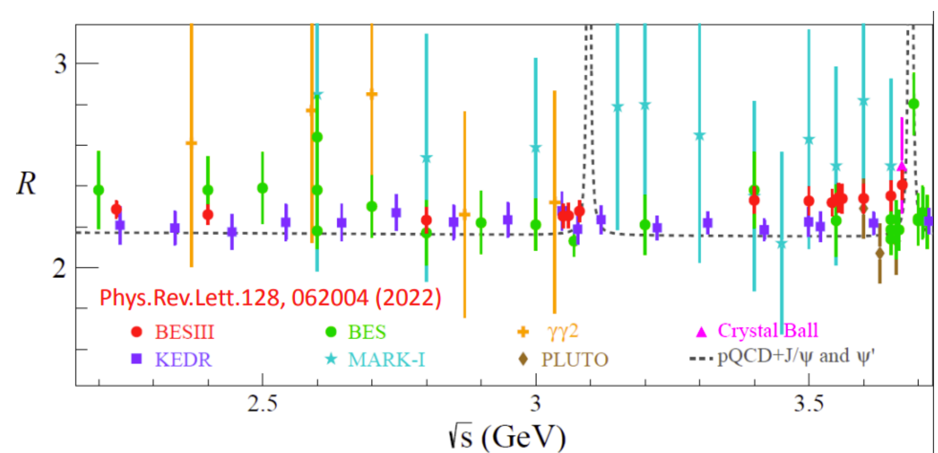
$a_\mu = (g_\mu-2)/2$ and $\Delta\alpha_{had}(M_Z)$

$$a_\mu = \frac{\alpha^2}{3\pi^2}\int_{m_\pi^2}^{\infty} ds\, K(s)\frac{R(s)}{s}$$

$$\Delta\alpha^{(5)}_{\rm had}(M_Z^2) = -\frac{\alpha M_Z^2}{3\pi}\,\mathrm{Re}\int_{m_\pi^2}^{\infty}\frac{R(s)ds}{s(s-M_Z^2-i\epsilon)}$$

BESII in 2–5 GeV, precision 6%

BESIII 2022 3%



Radiative Bhabha, NLO, NNLO $e^+e^- \longrightarrow e^+e^- (n\gamma)$

Methods used for multiple photon corrections

1. **SF:** analytical collinear QED Structure Functions
2. **YFS exponentiation Small angle,** **0.054% BHLUMI (LEP)**
   YFS exponentiation Large ange, **BHWIDE (LEP)**
3. **PS: Parton Shower, Large angle** **0.1% BabaYaga@NLO**

e^+e^- collision luminosity

$$\int \mathcal{L}\, dt = N_{\rm obs}/\sigma_{\rm th}$$

$$\frac{\delta\mathcal{L}}{\mathcal{L}} = \frac{\delta\mathcal{L}_{\rm exp}}{\mathcal{L}_{\rm exp}} \oplus \frac{\delta\sigma_{\rm th}}{\sigma_{\rm th}}$$

Luminosity errors:
Experiment
Theory

collinear log : $L \equiv \log \frac{s}{m_e^2}$

G. Montagna
Ustron, 2015

$L = \log(s/m_e^2) \simeq 15$	*Large angle @ Flavor*
$L = \log(\lvert t\rvert/m_e^2) \simeq 17$	*Small angle @ LEP*
$L = \log(\lvert t\rvert/m_e^2) \simeq 20$	*Small angle @ $t\bar{t}$ thresh.*

Flavor Factories

collinear log : $L \equiv \log \frac{s}{m_e^2}$

C.M. Carloni Calame
ECFA Higgs CERN 2021

LO	α^0		
NLO	αL	α	
NNLO	$\frac{1}{2}\alpha^2 L^2$	$\frac{1}{2}\alpha^2 L$	$\frac{1}{2}\alpha^2$
h.o.	$\sum_{n=3}^{\infty} \frac{\alpha^n}{n!} L^n$	$\sum_{n=3}^{\infty} \frac{\alpha^n}{n!} L^{n-1}$	$\cdots$

Red: matched PS, SF + NLO

LO	90%		
NLO	10%	0.5%	
NNLO	0.5%	0.05%	0.01%
h.o.	0.01%	$\cdots$	$\cdots$

Typically at flavour factories (on integrated Bhabha σ)

Bhabha: $e^+e^- \to e^+e^-(n\gamma)$ √s dependency

BHWIDE center-of-mass

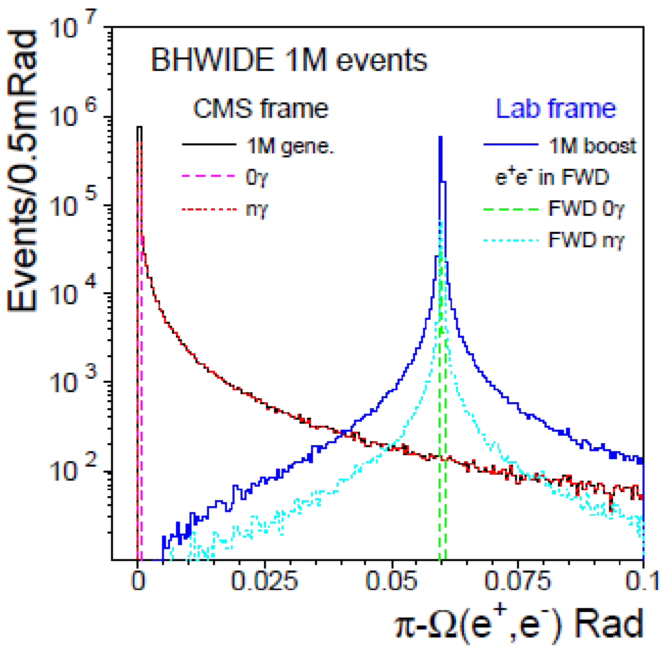
√s = 2 - 10 GeV, θ range 1 – 20°

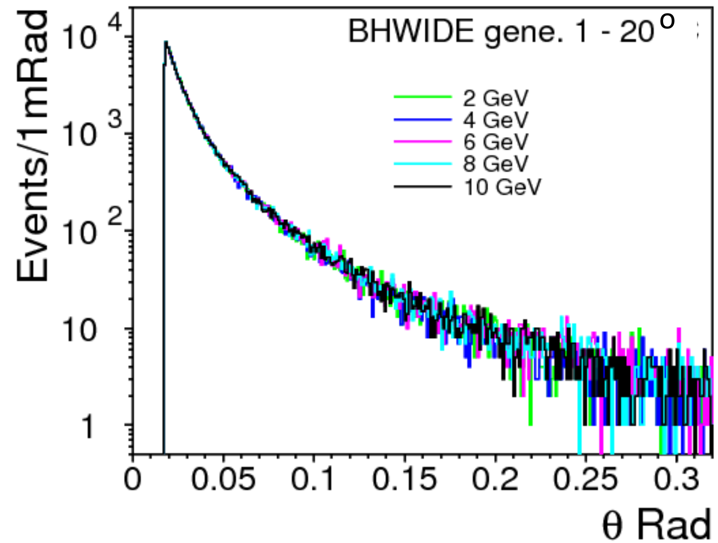
- **θ distribution: well overlapped**
- **Cross section much higher at lower √s**

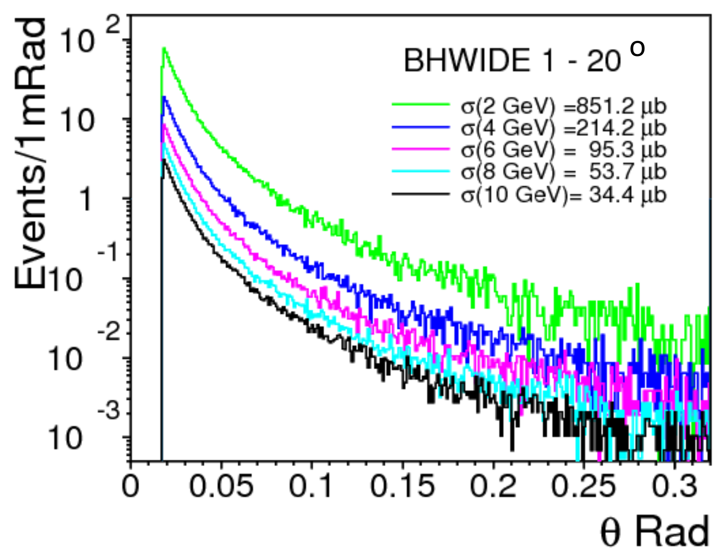
e^+e^- back-to-back

60 mRad beam-crossing boost

Delta/tails for 0γ/nγ events







Bhabha: $e^+e^- \rightarrow e^+e^-(n\gamma)$ cross section

BHLUMI/BHWIDE CM-frame

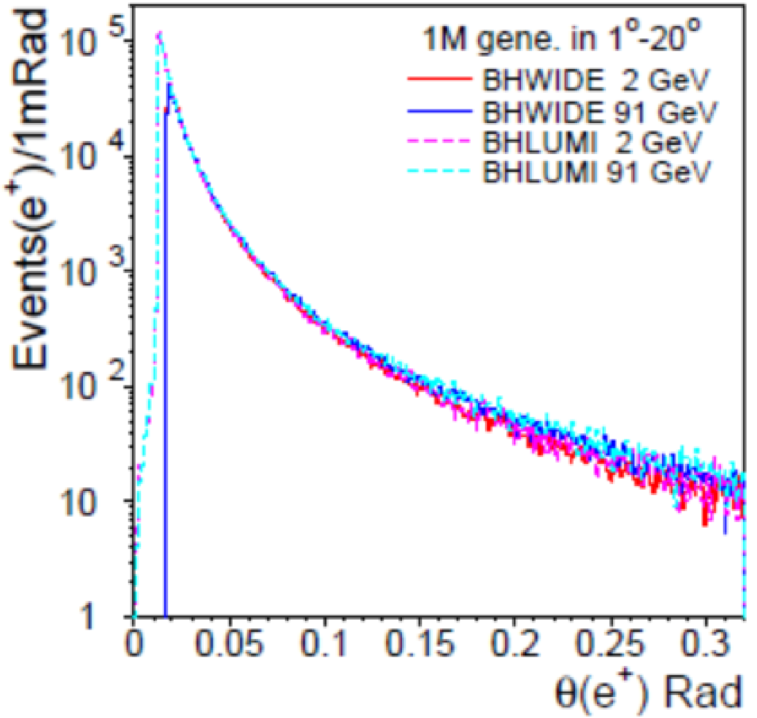
YFS algorithm for radiation

Compare cross section in 1° - 20°

BHLUMI $E_\gamma > 10^{-4}$ Ebeam

BHWIDE $E_\gamma > 10^{-5}$ Ebeam

- **BHWIDE** is for "Large Angle" region **> 6°**
  t-channel effect contributes ?
- ***CM-frame cross section agrees ~0.1%***
- ***FSTD Forward Det. → ~ 2 % deviation***



effect c

BHWIDE $\sqrt{s}$ (GeV)	2	4	6	8	10	91.2	160	240	360
σ(1°-20°) nb	854000	214600	95420	53780	34460	423.4	138.7	62.08	27.78
σ(FWD) nb	139900	35230	15710	8871	5692	71.93	23.68	10.65	4.788
ε(FWD/[1°-20°])	.1638	.1642	.1646	.1649	.1652	.1699	.1708	.1716	.1724

BHLUMI $\sqrt{s}$ (GeV)	2	4	6	8	10	91.2	160	240	360
σ(1°-20°) nb	857800	214300	95430	53830	34460	424.0	138.7	62.08	27.79
σ(FWD) nb	137900	34640	15450	8728	5587	69.00	22.50	10.16	4.567
ε(FWD/[1°-20°])	.1607	.1616	.1619	.1621	.1621	.1627	.1625	.1637	.1644

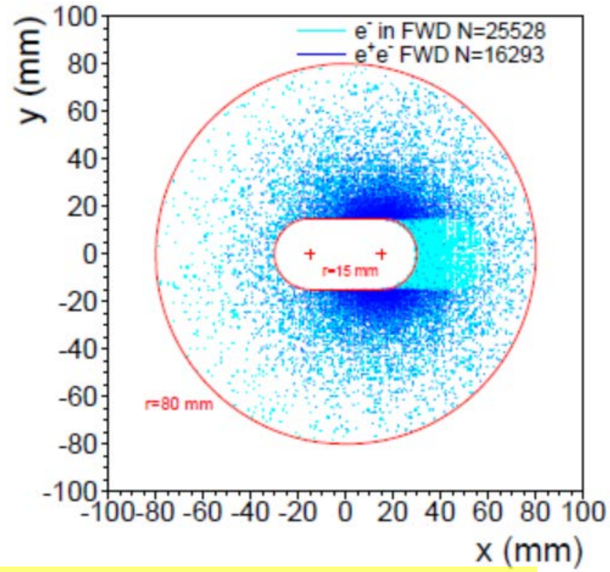
Bhabha STCF FWD acceptance

Forward Det. (FWD) acceptance

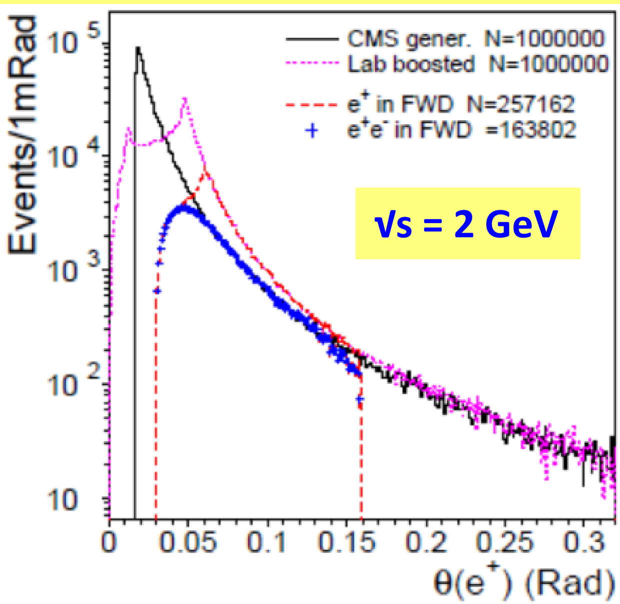
both *e⁺ e⁻ detected in* in FWD

- @|z|= 500mm
- off beampipe Ø = 30 mm; r < 80mm
- 60 mRad beam-crossing boost
  w.r.t. CM generated in 1-20°
  acceptance: ε ~ 16.3 %

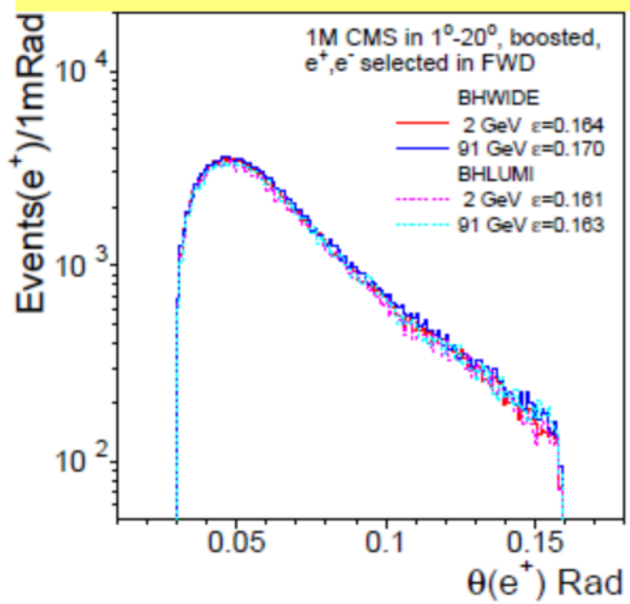
Accepted in FWD @z=500mm



Theta of e+,   gen. to FWD accepted



FWD accepted, BHWIDE/BHLUMI



Radiative Bhabha $e^+e^-(n\gamma)$

BHLUMI/BHWIDE radiative Bhabha

QED radiation calculated with **YFS exponentiation**

nγ in Poisson distribution

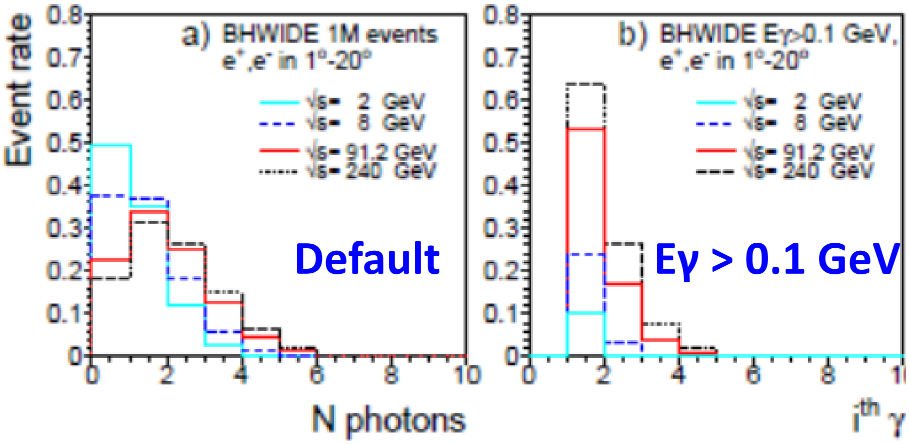
BHLUMI $E\gamma$ cut = $1 \times 10^{-4} \times E_{beam}$ BHWIDE $E\gamma$ cut = $1 \times 10^{-5} \times E_{beam}$

Count photons detectable $E\gamma > 0.1$ GeV

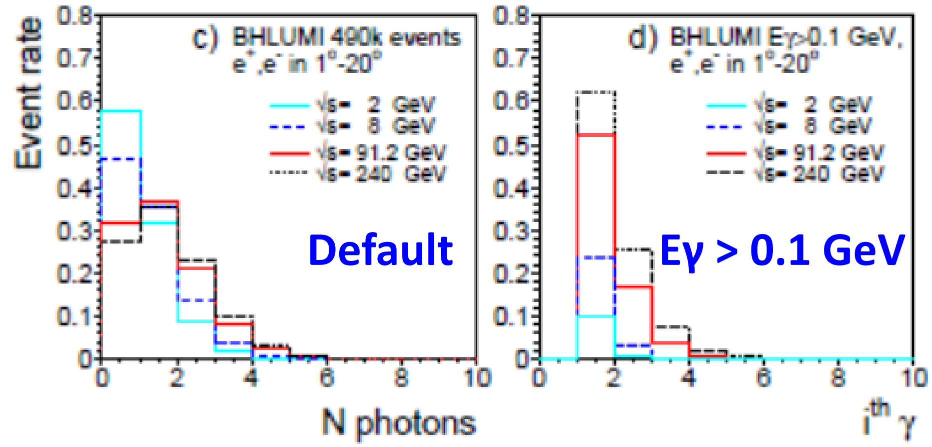
➔ Photons nγ rates well consistent **with BHLUMI/BHWIDE**

nγ event rates

BHWIDE



BHLUMI



Radiative Bhabha $e^+e^-(n\gamma)$

BHLUMI/BHWIDE radiative Bhabha

➔ **1st energetic photon, same rates, indep. of √s**

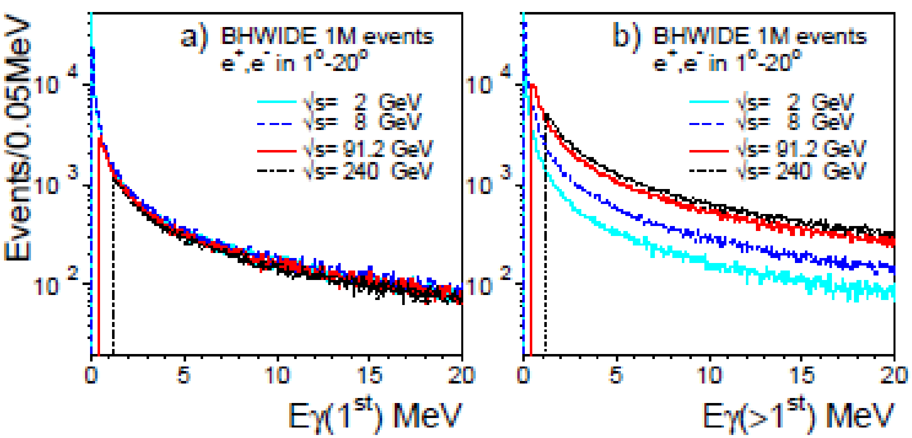
event rates vs Eγ, near threshold **~20 MeV**

well consistent with BHLUMI/BHWIDE

➔ **2nd energetic photon, higher rates with √s**

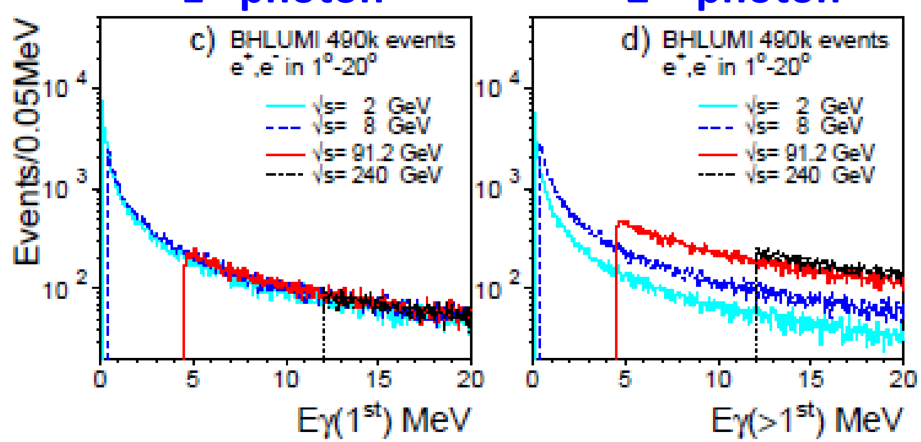
BHWIDE Eγ

1st photon **2nd photon**



BHLUMI Eγ

1st photon **2nd photon**



Radiative Bhabha $e^+e^-(n\gamma)$

BHLUMI/BHWIDE radiative Bhabha

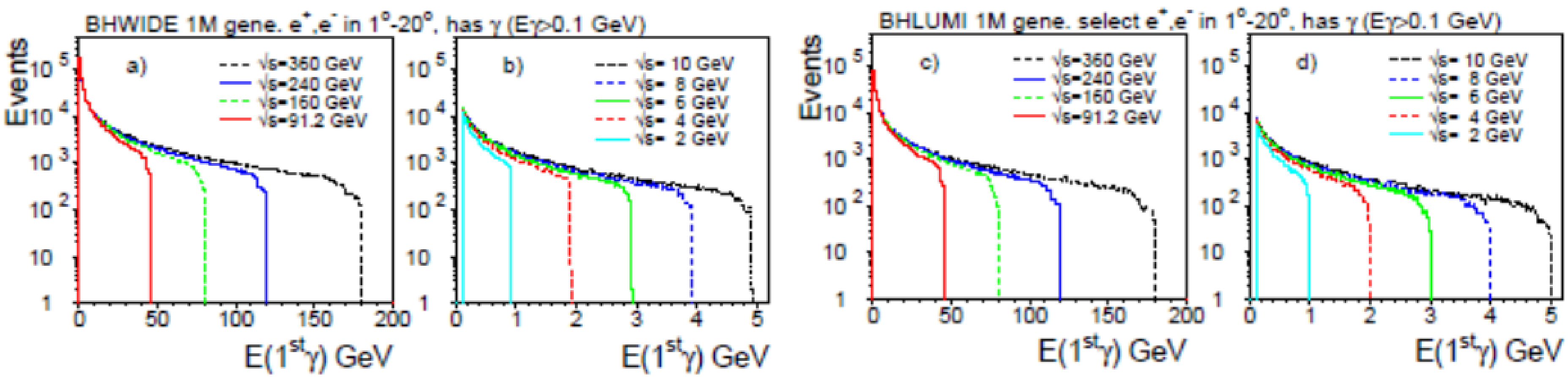
Most energetic energy event rates

➔ **events vs Eγ, at allowed range indept of √s**

➔ **Eγ range reaching E_{beam}**

Eγ, 1st photon in events > 0.1 GeV

BHWIDE **BHLUMI**



Detecting radiative radiative photons

Bhabha scattering, highest event rates @ flavor, Higgs factories

BHLUMI .037% precision

QED basics

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

Radiation by YFS exponentiation

applied in all QED radiation ➔ photons look alike

➔ *Beam background shall look like Bhabha radiation ??*

Photons

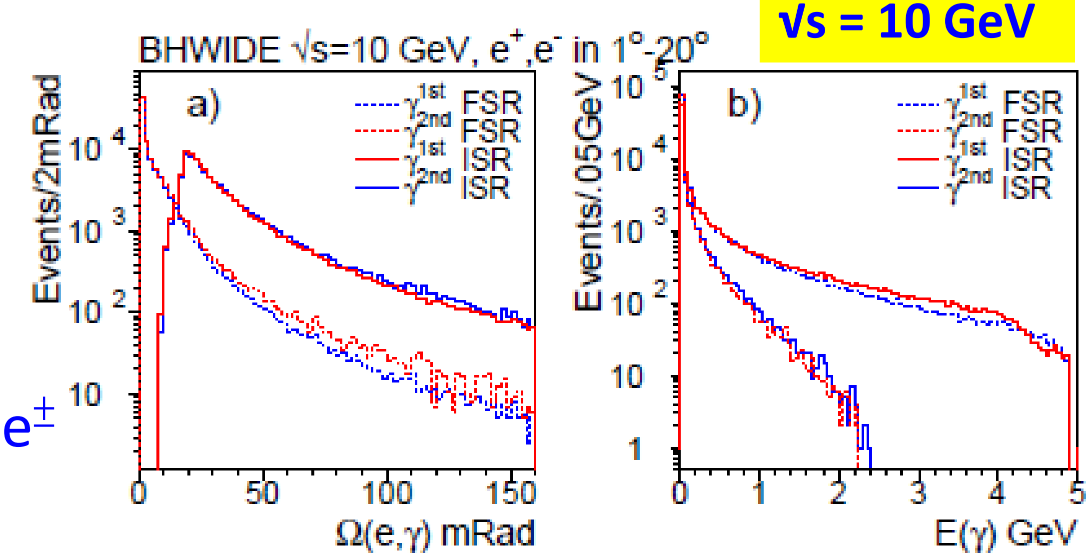
ordered by Eγ

ISR/FSR by

Open Angle Ω(e,γ)

closer to incident/scatter $e^{\pm}$

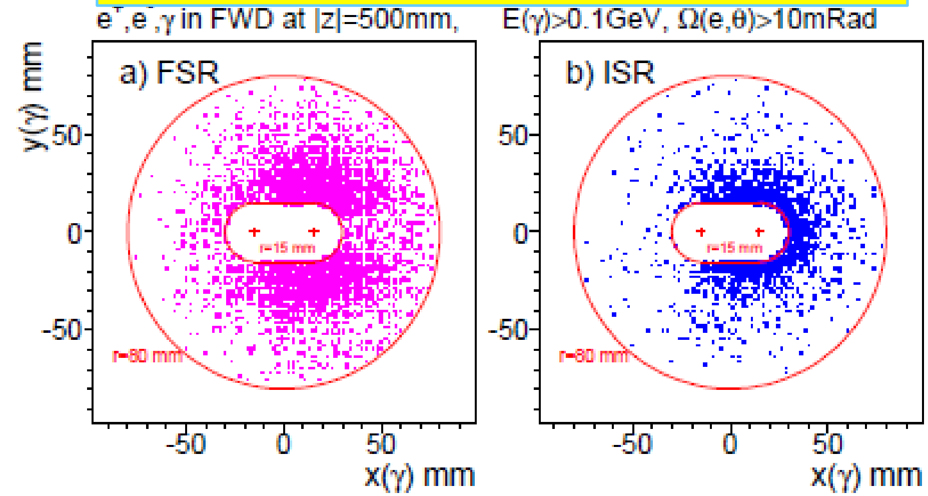
√s = 10 GeV



Rad-Bhabha photons $e^+e^- \rightarrow e^+e^-(n\gamma)$

- **Detect rad-Bhabha $e^+, e^-, \gamma^{1st}, \gamma^{2nd}$**
- **FWD acceptance:**
  off-pipe ϕ30mm, $x_c=\pm$15mm, r<80mm
- **γ selection:**
  $E\gamma$ > 0.1 GeV,
  opening angle $\Omega(e^\pm,\gamma^{1st})$>10 mRad
- **event rate in Bhabha**
  to both e^+, e^- detected in FWD
  either z-side, **$e^\pm$ with γ^{1st} γ^{2ndt} measured**

$\sqrt{s}$ =10 GeV $e^\pm$ γ^{1st} (FSR) $e^\pm$ γ^{1st} (ISR)



BHWIDE	2	4	6	8	10	91.2	160	240	360
$R_{\rm FWD}$ (e^+e^-in FWD $+ n\gamma$)	.563	.619	.649	.673	.684	.799	.821	.835	.850
$R_{\rm FWD}$ .and. $E_\gamma > 0.1$ GeV	.119	.188	.232	.266	.291	.552	.615	.656	.695
$R_{\pm z}(\gamma^{1st}{\rm ISR})$	.0040	.0049	.0058	.0064	.0063	.0095	.0103	.0103	.0102
$R_{\pm z}(\gamma^{1st}{\rm FSR})$ **Ω(eγ)>10mR**	.0094	.0126	.0147	.0162	.0169	.0262	.0272	.0291	.0301
$R_{\pm z}(\gamma^{2nd}{\rm ISR})$ **Eγ>0.1 GeV**	.000052	.000073	.00013	.00018	.00022	.00084	.00089	.0011	.0012
$R_{\pm z}(\gamma^{2nd}{\rm FSR})$	.000098	.00028	.00040	.00060	.00071	.0024	.0029	.0036	.0040
BHLUMI									
$R_{\rm FWD}$ (e^+e^-in FWD $+ n\gamma$)	.480	.533	.561	.583	.599	.719	.743	.757	.774
$R_{\rm FWD}$ .and. $E_\gamma > 0.1$ GeV	.120	.188	.233	.265	.293	.555	.614	.653	.693
$R_{\pm z}(\gamma^{1st}{\rm ISR})$	.0048	.0054	.0059	.0065	.0067	.0096	.0103	.0105	.0105
$R_{\pm z}(\gamma^{1st}{\rm FSR})$ **Ω(eγ)>10mR**	.0092	.0126	.0150	.0164	.0169	.0257	.0273	.0283	.0307
$R_{\pm z}(\gamma^{2nd}{\rm ISR})$ **Eγ>0.1 GeV**	.000058	.000070	.00017	.00027	.00028	.00070	.00096	.0010	.0012
$R_{\pm z}(\gamma^{2nd}{\rm FSR})$	.000077	.00031	.00047	.00051	.00063	.0025	.0028	.0033	.0039

Perspective for measuring Bhabha @ STCF

BHWIDE $\sqrt{s}$ = 2 – 10 GeV

scattered $e^{\pm}$ > 0.1 GeV; $\Omega(e^+e^-)$: 0-π

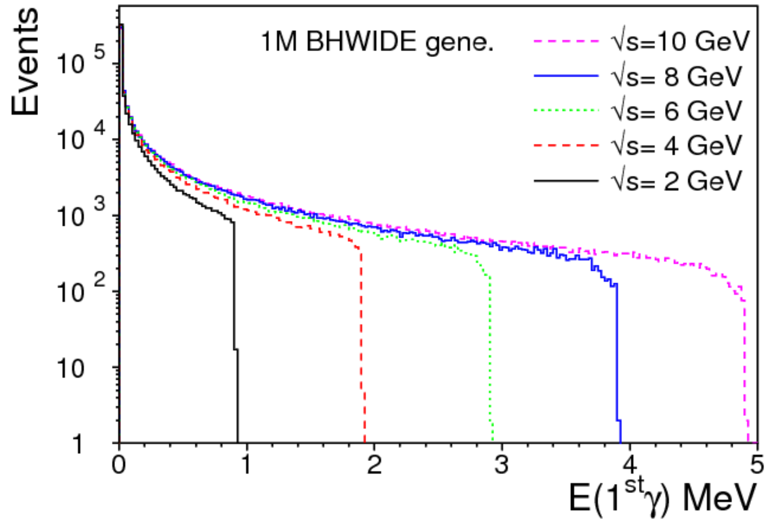
CMS generted for σ(1-20°)

Acceptance **e^+e^-** in FWD **= 16.5%**

Both **e^+e^-** fall in FWD

event ratio with

- **0/nγ** generated
- **γ^{1st}** Eγ>0.1 GeV, $\Omega(e^{\pm},\gamma^{1st})$>10 mR

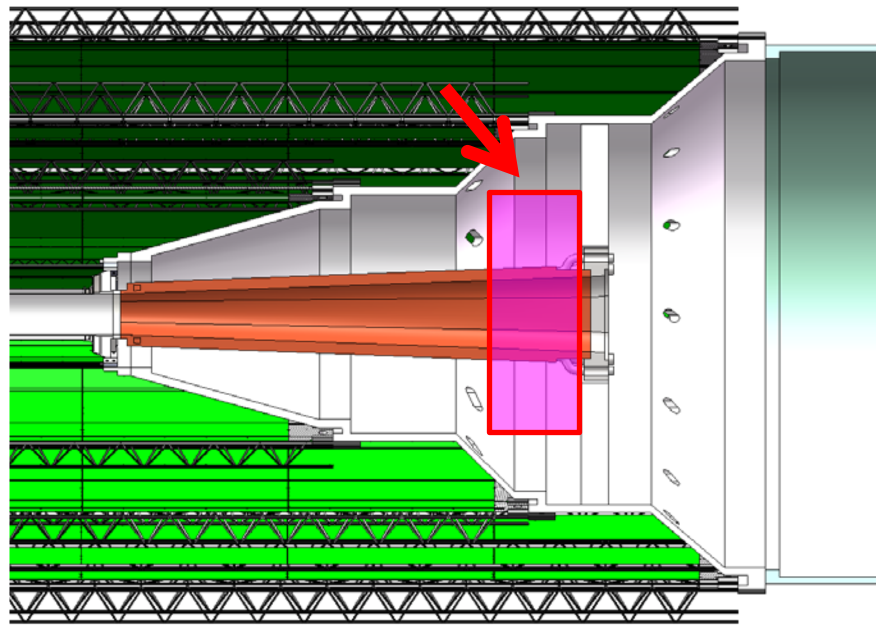


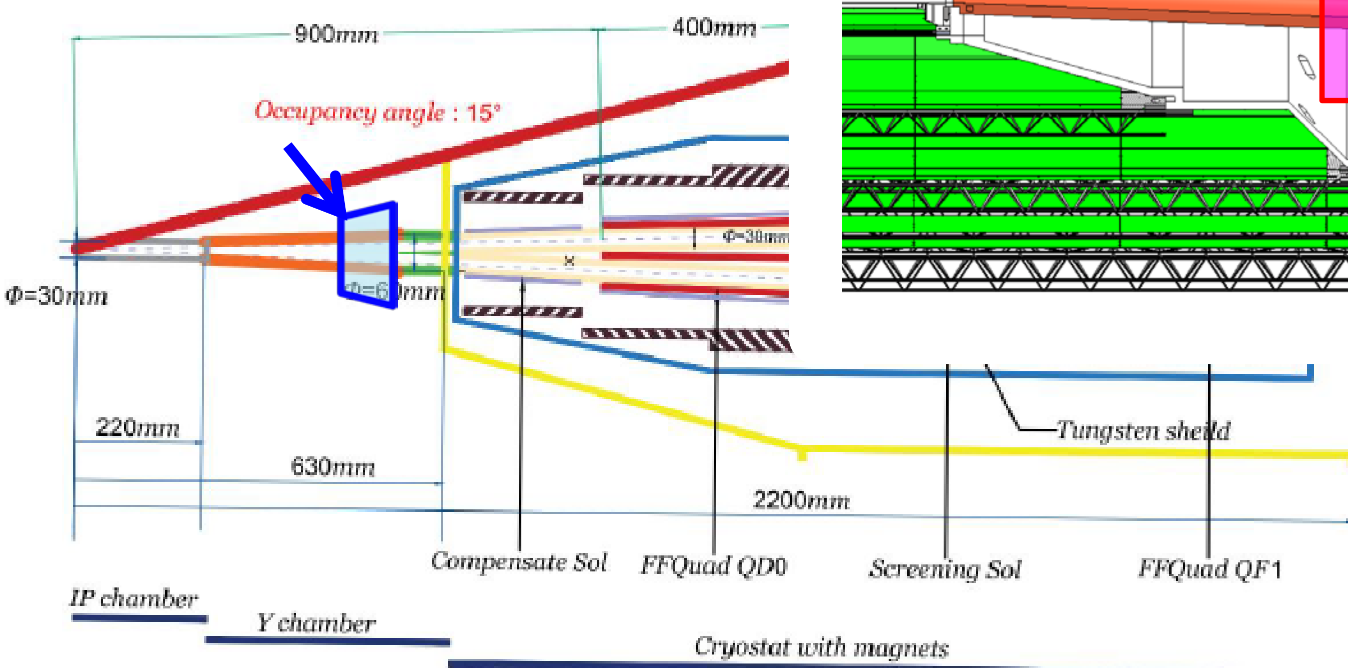
Detected in each z-side	**$\sqrt{s}$ =**	**10 GeV**	**8 GeV**	**6 GeV**	**4 GeV**	**2 GeV**
both e^+e^- in FWD	$e^{\pm}$,0γ	56.1 %	57.1 %	59.1 %	61.6 %	66.0 %
	$e^{\pm}$,nγ	43.9 %	42.9 %	40.9 %	38.4 %	34.0 %
$e^{\pm},\gamma^{1s}$ in FWD E_{γ}> 0.1GeV, $\Omega(e^{\pm},\gamma^{1st})$>10mR	**$e^{\pm},\gamma^{1s}$**	**ISR 0.63 %** **FSR 1.69 %**	**ISR 0.64 %** **FSR 1.62 %**	**ISR 0.58 %** **FSR 1.47 %**	**ISR 0.50 %** **FSR 1.26 %**	**ISR 0.40 %** **FSR 0.94 %**

Forward Calorimeter @ STCF

60 – 240 mRad (3.4°-14°), Z = 350 – 500 mm

- Precision QED radiative Bhabha to **better than 10^{-3}**
- e/γ by Si-det + Crystal
  - **2D, Si strip, 50 μm pitch**
  - **LYSO, 2x2 mm², 50 mm long**

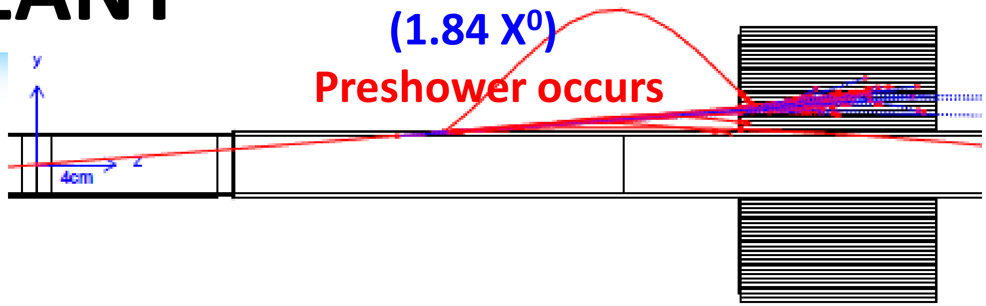


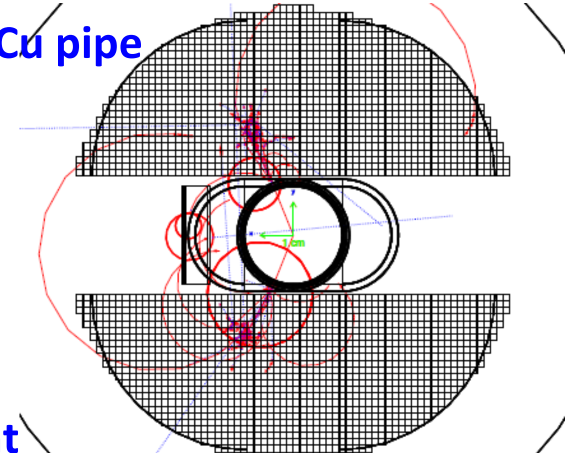


GEANT

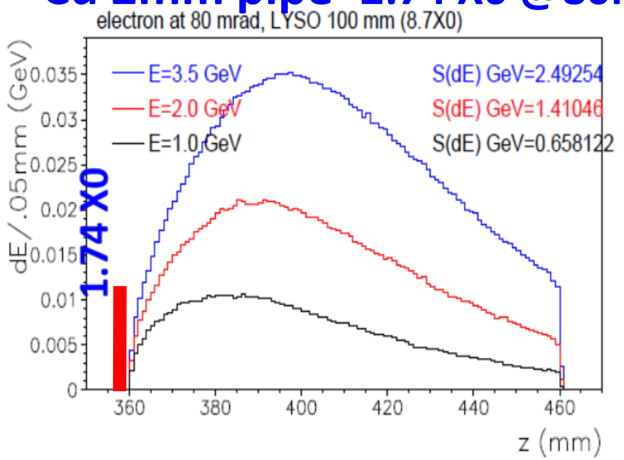
3.5 GeV e^- 80 mrad passing 2 mm Cu pipe (1.84 X^0)

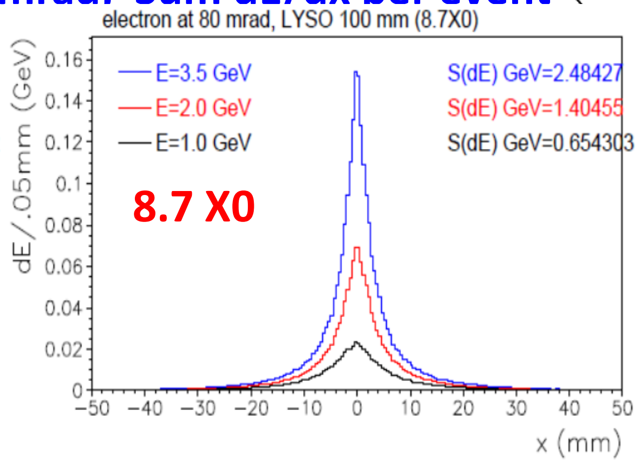
Preshower occurs

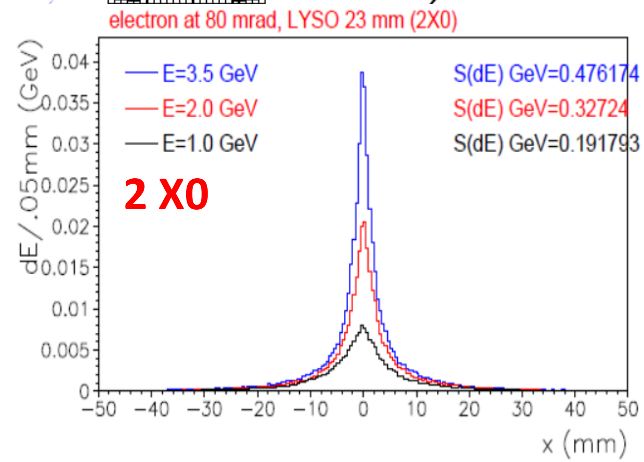




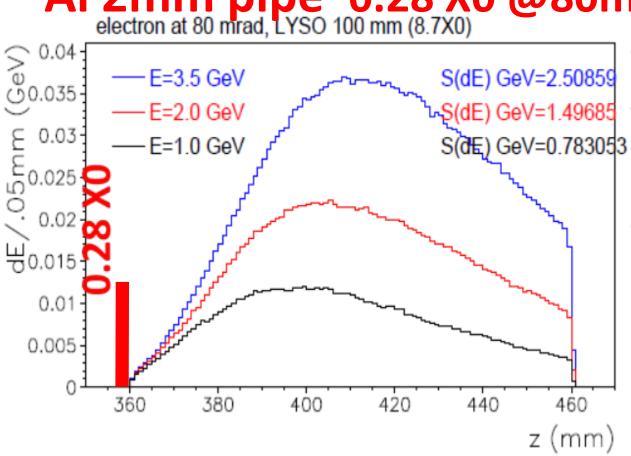
Cu 2mm pipe 1.74 X0 @80mrad. Sum dE/dx per event

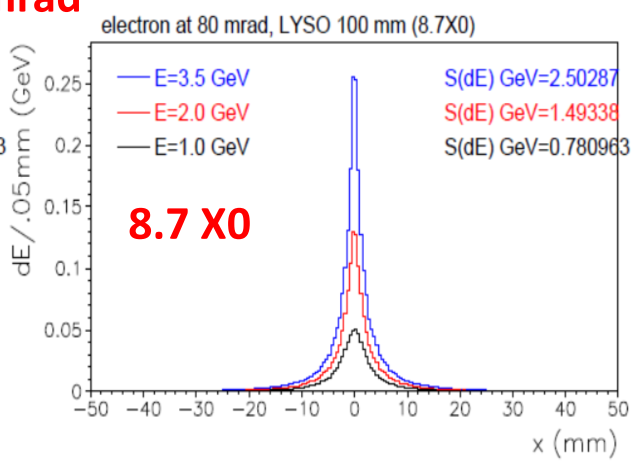


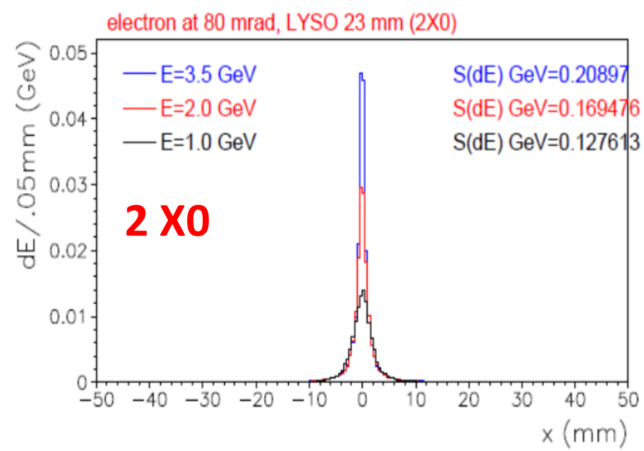




Al 2mm pipe 0.28 X0 @80mrad



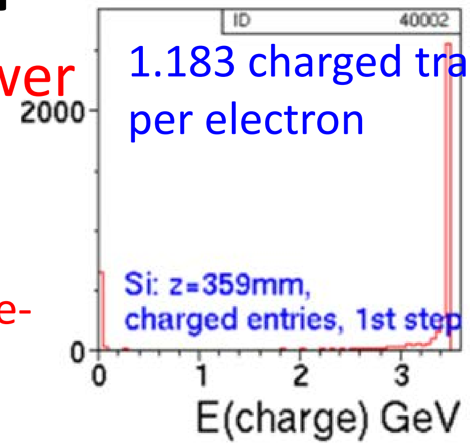


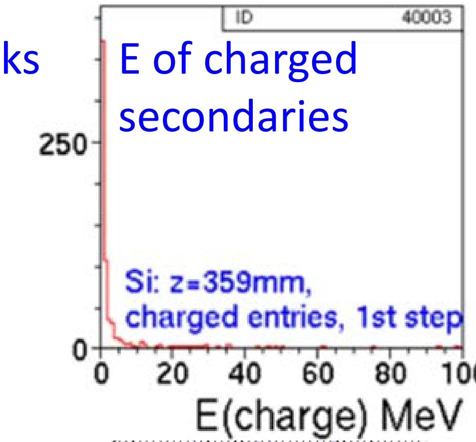


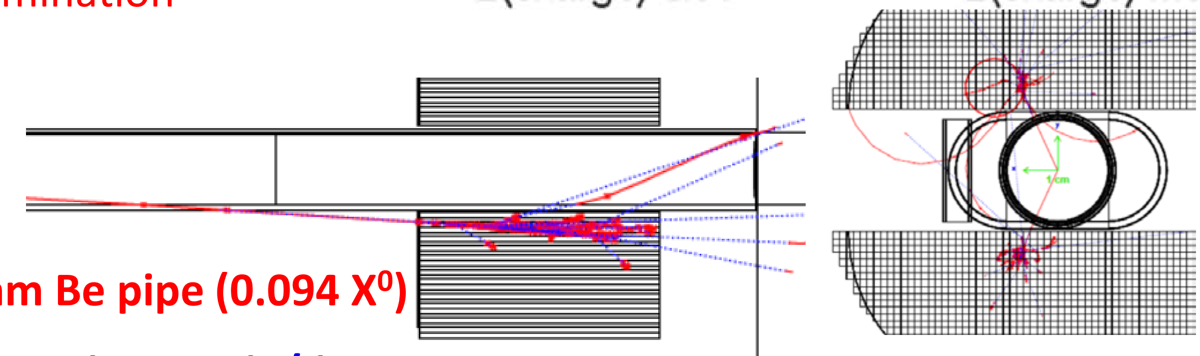
2 mm Be pipe, mini pipe materials

Be pipe to minimize electron shower in forward/tracking volume

- Si before LYSO,
- No. of incident charge tracks in Si : 1.18/e-
- Most secondaries <10 MeV
- >100 MeV cut ➔ 1% contamination

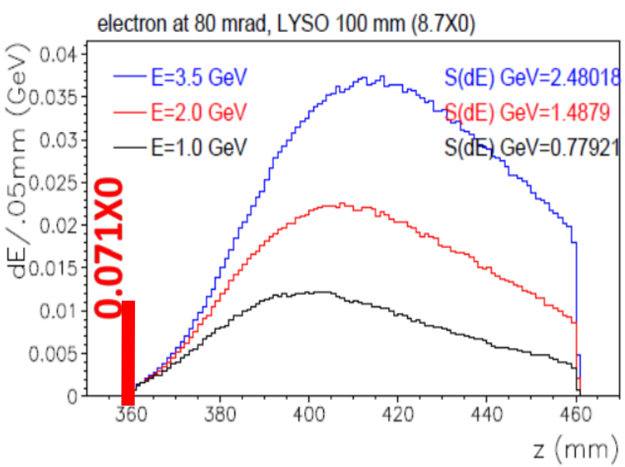


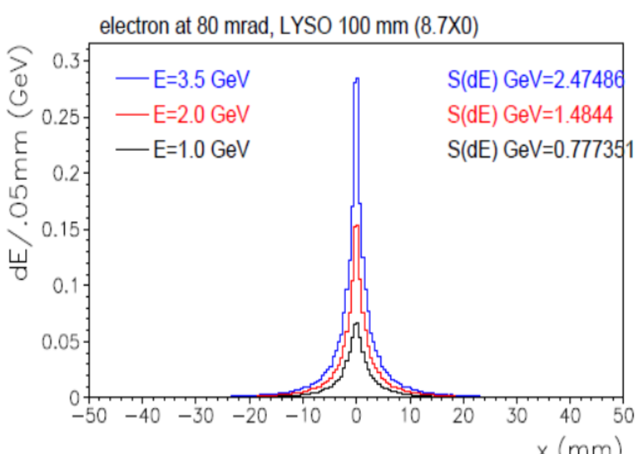


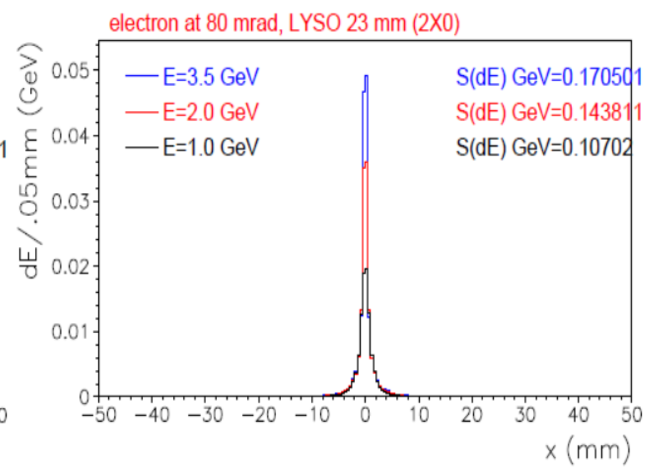


3.5 GeV e⁻ 60mrad, **2 mm Be pipe (0.094 X^0)**

Be 2mm pipe 0.071 X0 @80mrad, Sum dE/dx per event







Discussion

- **Proposal for detecting QED radiative photons**
  Forward Bhabha high statstics
  Better than 10-3 prevision
- **Forward detector within ITKM cone**
  Si + LYSO for e/γ measurements
- **Be beam pipe**
  Minimized preshower
  minimum upstream background to tracking volume