Forward Detectors Design at STCF

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On Behalf of the STCF-FWDR Group

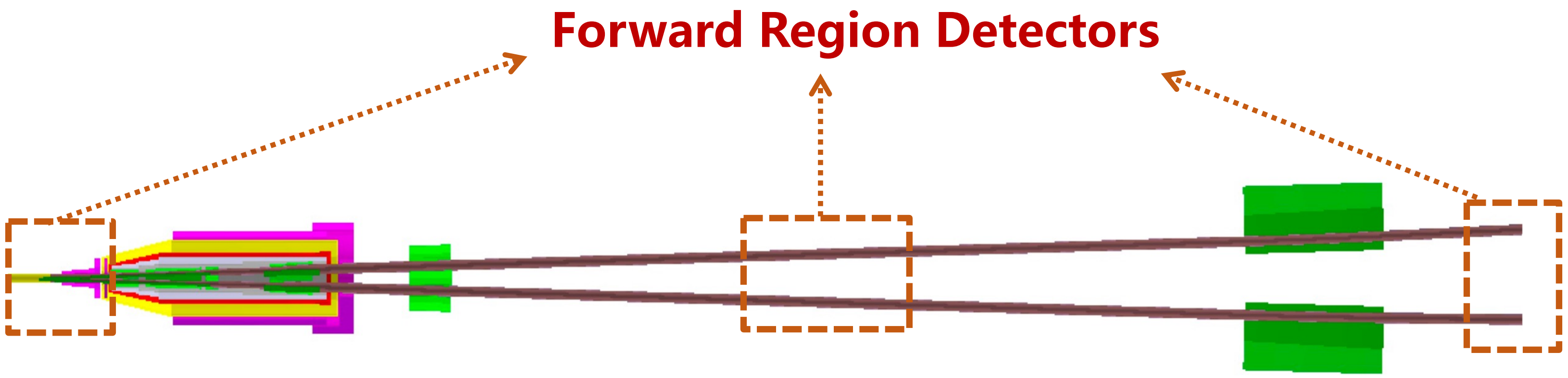
2025/11/26，Huangshan，FTCF2025

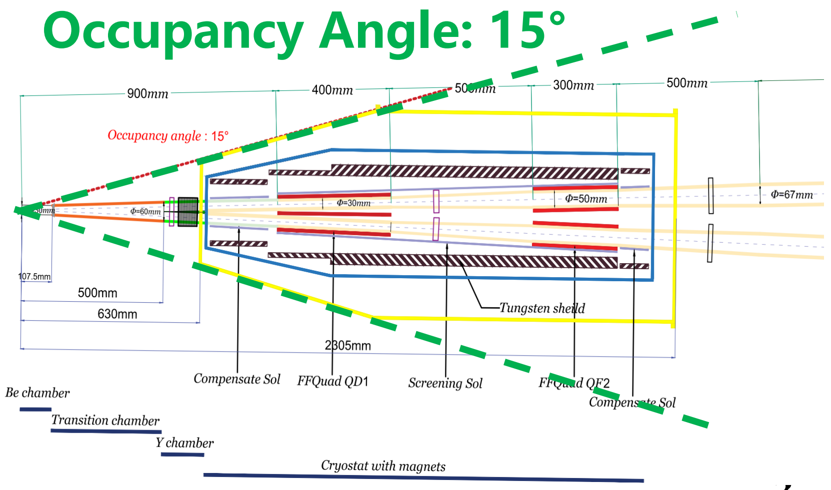
Outline

- Forward Region at STCF
- MDI and Background
- Fast Luminosity Monitor
  - Diamond Detector
  - Cherenkov Detector
- Forward Detector
  - Forward Calorimeter
  - Zero Degree Detector

The Forward Region at STCF

- The Forward Region at STCF refers to the angular area along the beam line near the interaction point, covering very small polar angles close to the beam axis.
- It is crucial for enabling precision measurements and ensuring the overall efficacy of the experiment:
  - Beam Optimization and Background Mitigation
  - Extending the detector acceptance
  - Specialized instrumentation to exploit STCF physics potentials



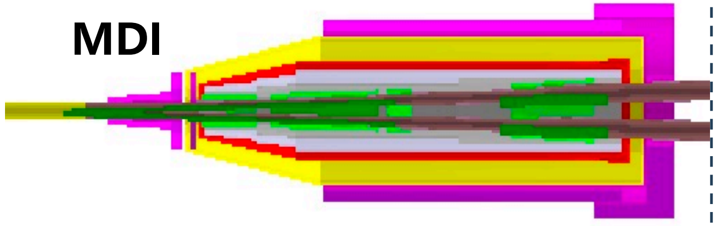


Forward Region - Simulation Framework

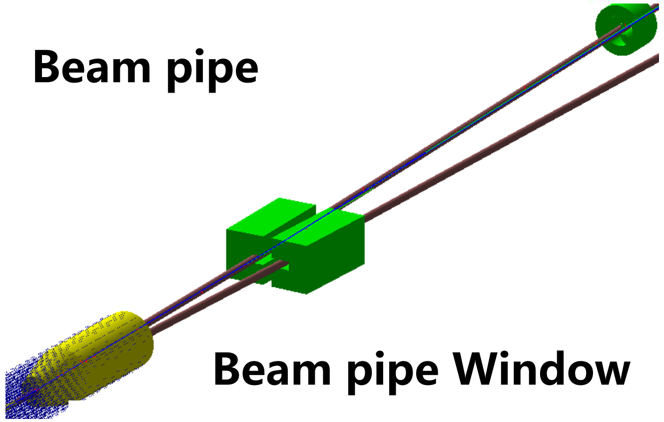
❑ **A detailed simulation framework is built for the design of forward detectors at STCF.**

Geometry

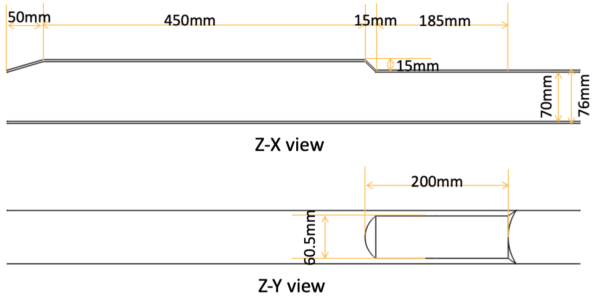
MDI



Beam pipe

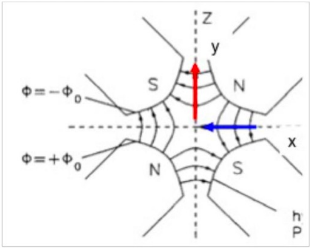


Beam pipe Window

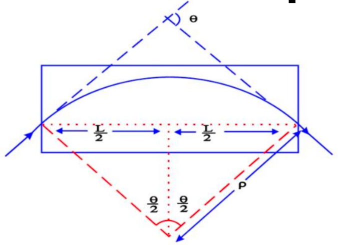


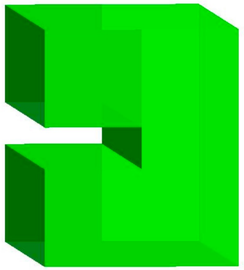
Magnetic Field

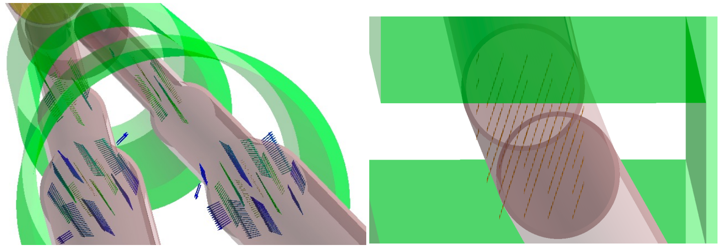
Quadrupole



Dipole







Event Generator

➢ **Several specialized event generators focus on specific processes at STCF, including:**

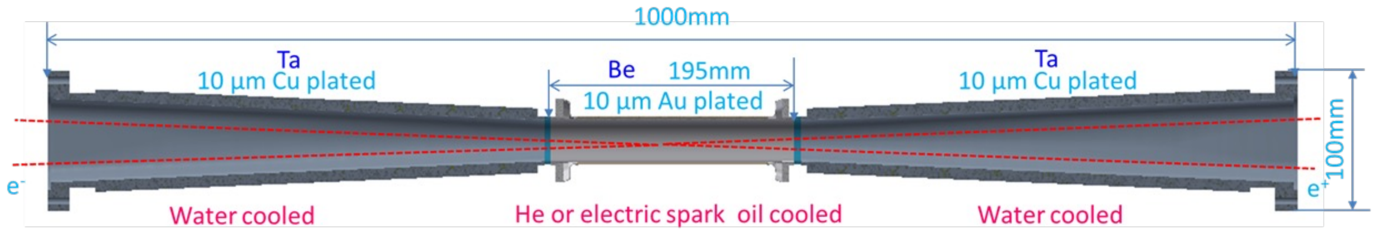
BBBREM: radiative Bhabha
DOI: 10.1016/0010-4655(94)90085-X

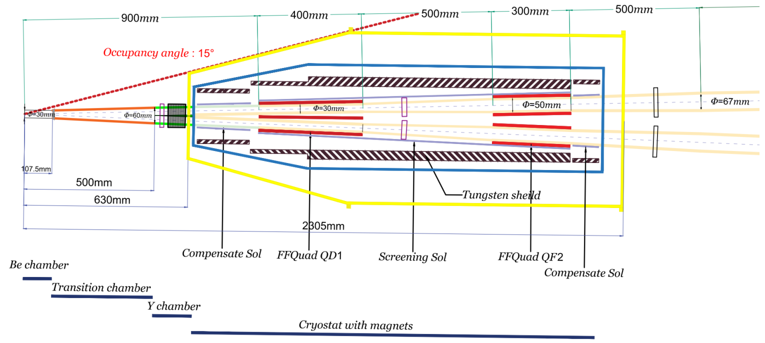
EKHARA: hadrons with tagged photons
DOI: 10.1016/j.cpc.2018.07.021

BHWIDE: small angle Bhabha scattering
DOI:10.1016/S0370-2693(96)01382-2

MDI and Background

- ❑ **The latest version of STCF MDI and inner pipe layout have been implemented.**



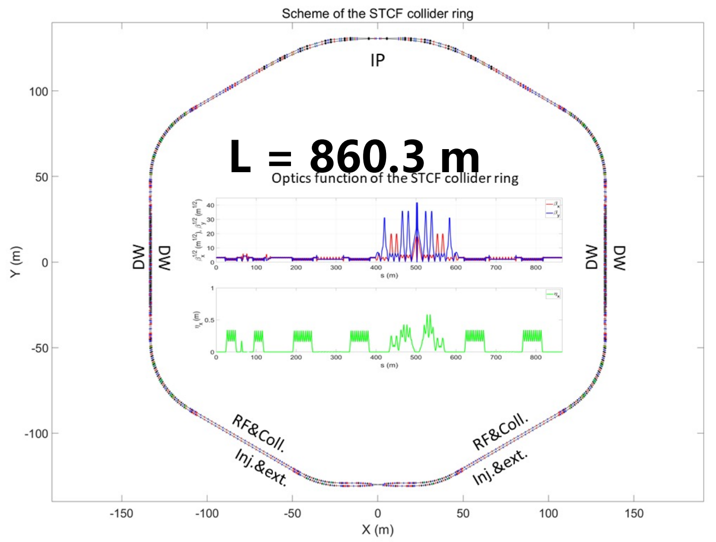


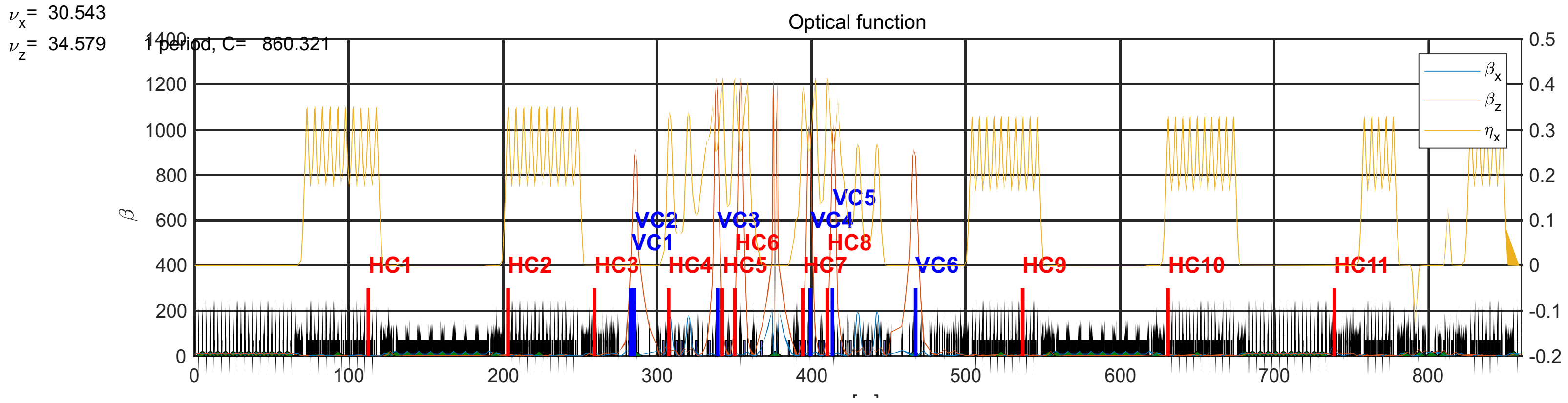
❑ Lattice (v12_c, 2025.05)

- Cross angle at IP = 30 mrad
- Energy spread 7.85×10^{-4} , $\beta_{x(y)}^{IP}$ (m) 0.06 (0.0008) m

❑ Collimator (2025.07)

- Base on AT
- Optimize for Touschek and Beam-Gas

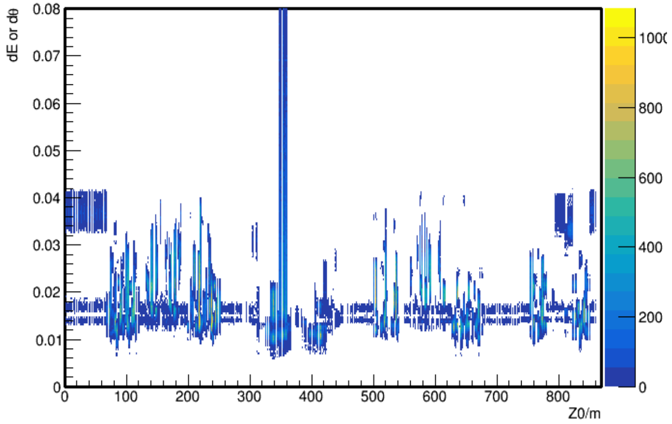




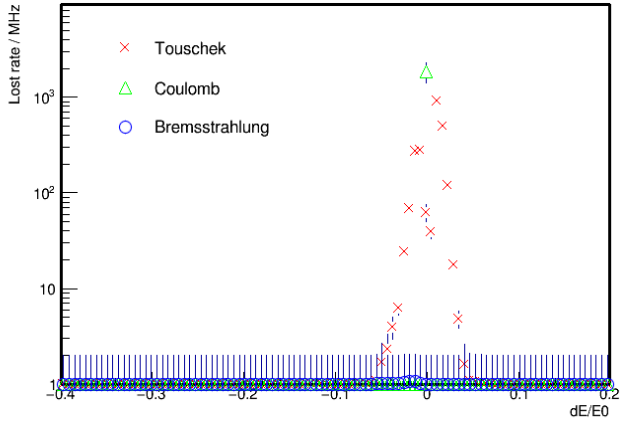
MDI and Background

❑ Background at all ring

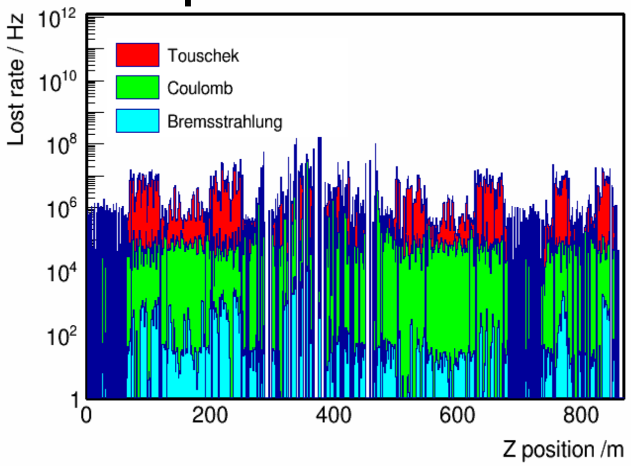
Energy spread at ring



Energy spread source contributions



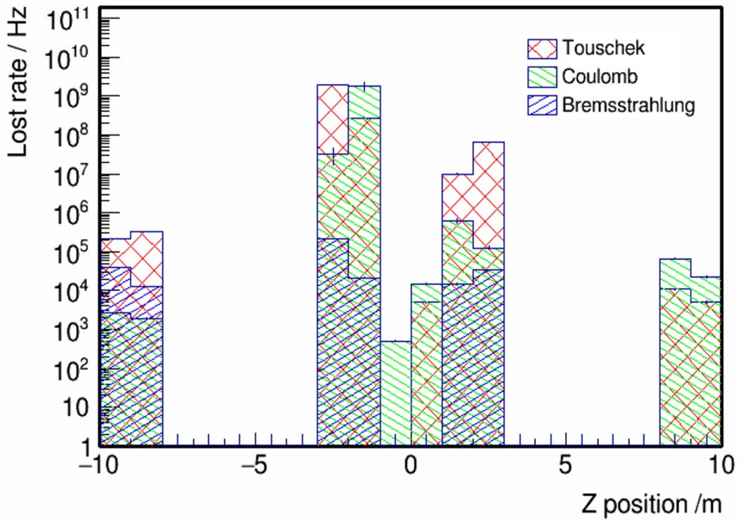
Lost positions



❑ Lost rate at IR: IP±10m

IR: IP ± 10 m	version: v12_c
Total Tous rate	3.6×10^{10} Hz
Tous rate in IR	2.3×10^{9} Hz ~ v7c3 background
Total Brem rate	9.9×10^{6} Hz
Brem rate in IR	3.4×10^{5} Hz
Total Coul rate	6.6×10^{9} Hz
Coul rate in IR	1.9×10^{9} Hz < v12_b
Lifetime	843.6 s

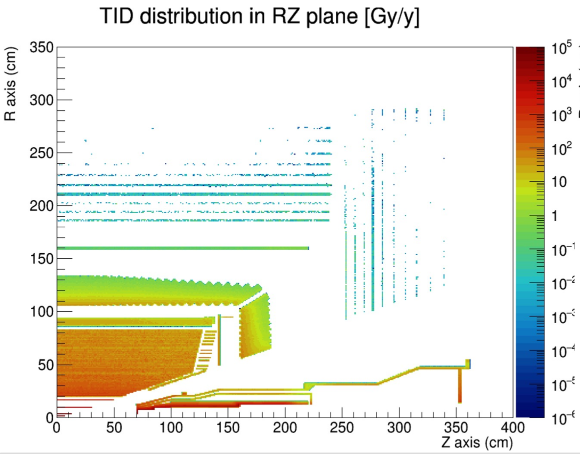
Differential loss rate in IR



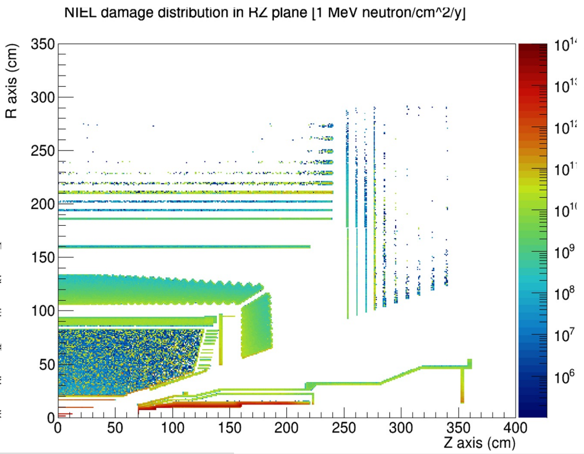
MDI and Background

- The background radiation level in all sub-detector (Ta inner pipe) have been obtained.
- Will continue on the further optimization, especially for the inner detectors.

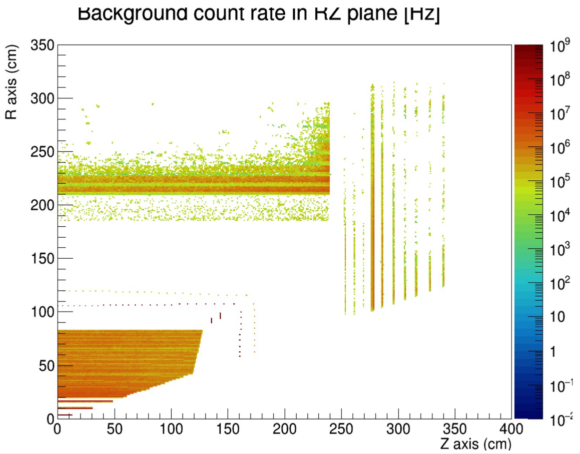
TID v12_c



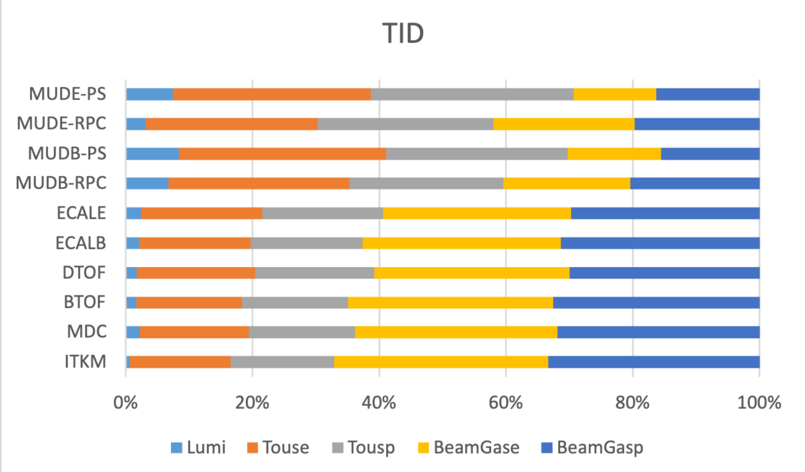
NIEL v12_c

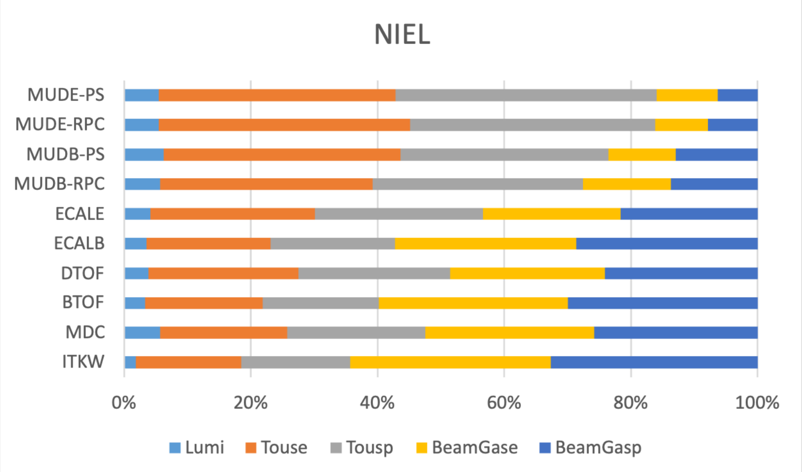


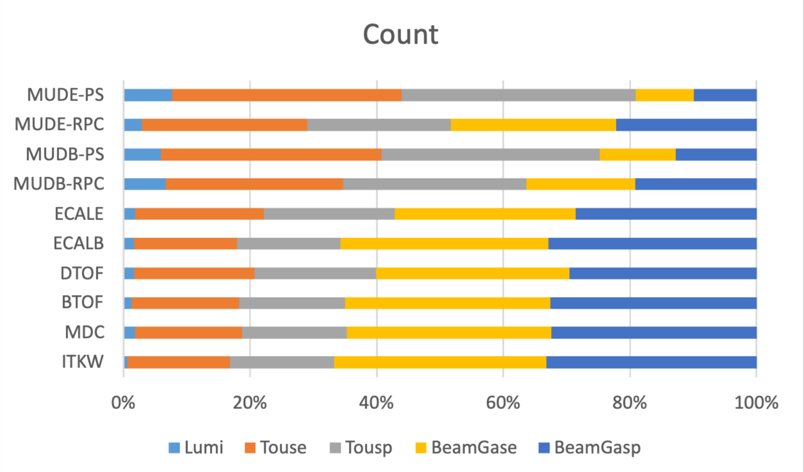
Count v12_c



DETECTOR	TID	NIEL	COUNT
ITKM1	34989	1.85E+12	5.86E+09
ITKM2	3681	4.07E+11	3.84E+09
ITKM3	946	2.71E+11	2.56E+09
MDC	74.42	1.57E+12	5.71E+09
BTOF	12.41	8.64E+10	2.24E+10
DTOF	26.96	1.13E+11	7.66E+09
ECAL-B	5.34	8.51E+10	1.46E+10
ECAL-E	10.77	8.14E+10	5.95E+09
MUD-B-RPC	0.017	4.25E+09	6.78E+07
MUD-B-PS	0.0095	1.15E+11	2.98E+08
MUD-E-RPC	0.011	1.66E+09	2.78E+07
MUD-E-PS	0.0059	2.69E+10	1.29E+08







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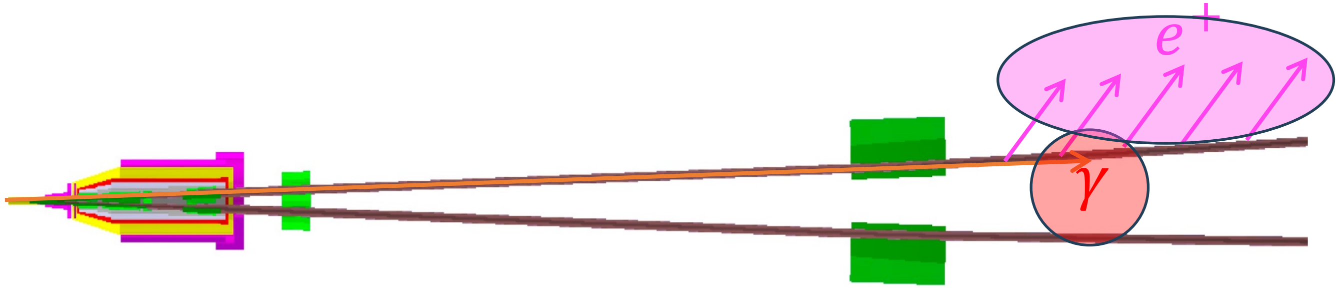
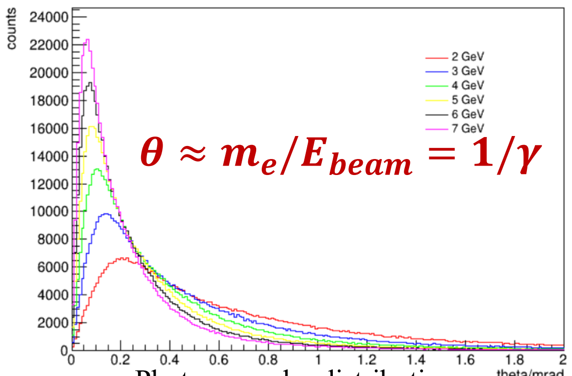
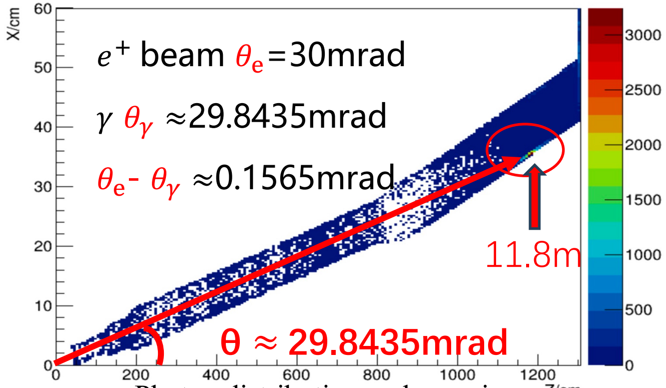
Fast Luminosity Monitor

- At STCF, the Fast Luminosity Monitor System (FastLumi), operating on a **bunch-by-bunch basis,** measures the luminosity for each individual bunch crossing of **4 ns intervals**.
- The FastLumi detects signals of γ and scattered e^+e^- in the radiative Bhabha scattering process ($e^+e^- \rightarrow e^+e^-\gamma$), providing real-time monitoring on instantaneous luminosity.

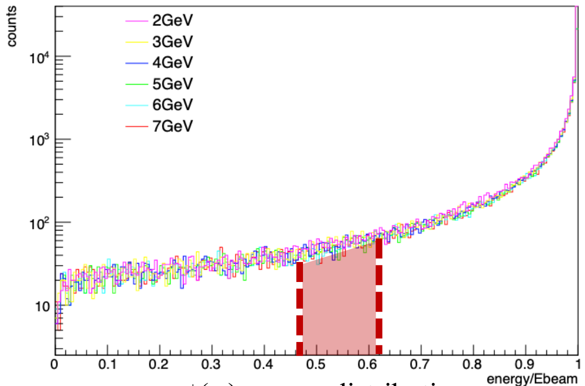




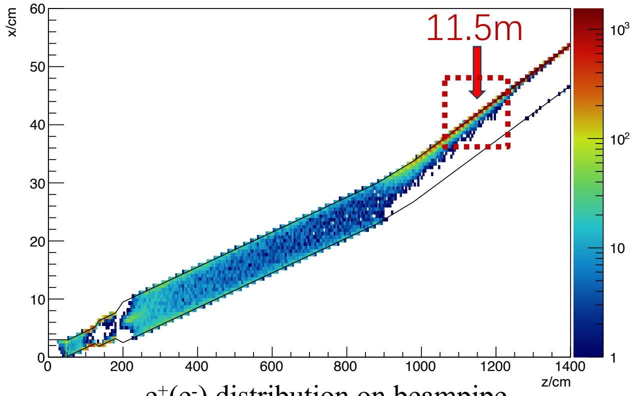
Photon angular distribution



Photon distribution on beampipe



$e^+(e^-)$ energy distribution



$e^+(e^-)$ distribution on beampipe

FastLumi - Diamond Detector

- sCVD Diamond Detector is ideal for FastLumi operation due to its distinctive properties.

Property	Diamond	Silicon
Band gap [eV]	5.5	1.12
Breakdown field [V/cm]	10^7	$3x10^5$
Electron mobility [cm^2/Vs]	1900	1350
Hole mobility [cm^2/Vs]	2300	480
Displacement energy [eV/atom]	43	13-20
Thermal conductivity [W/m.K]	~2000	150
Energy to create e-h pair [eV]	13	3.61
Aver. Signal Created / 100 µm [e0]	3602	8892

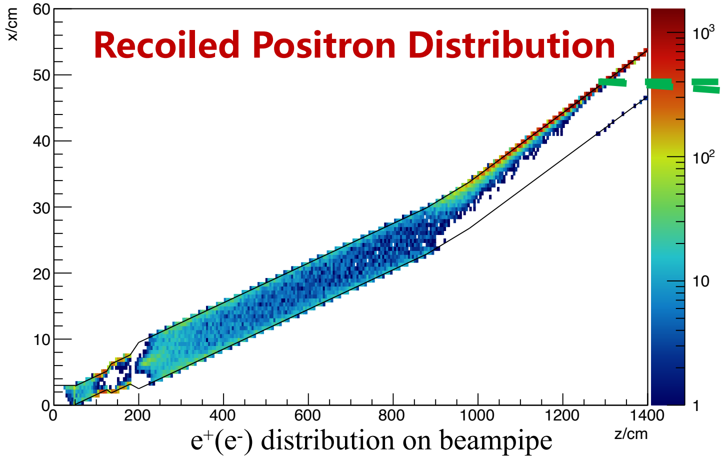
=> **Low Noise**

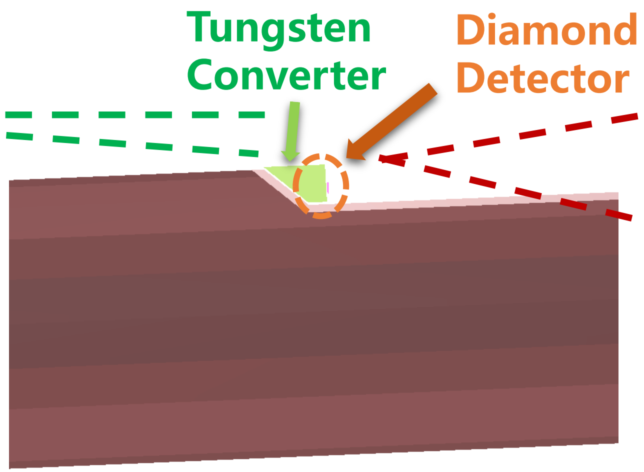
=> **Fast Signal:** (rise time <O(1ns))

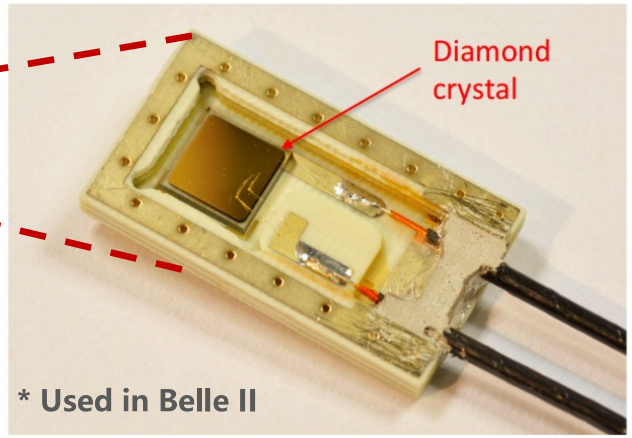
=> **Radiation Hard:** ~10 Mrad

=> **Heat Conductor:** No cooling issue

=> **Lower Signal**



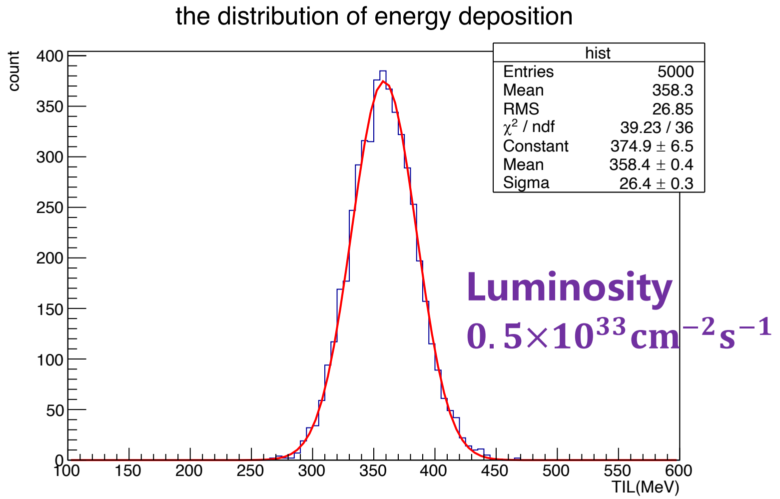


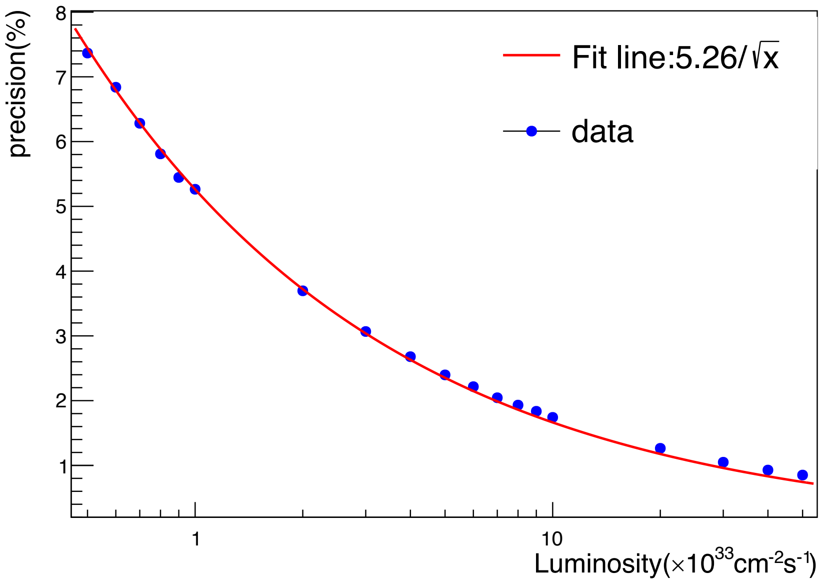


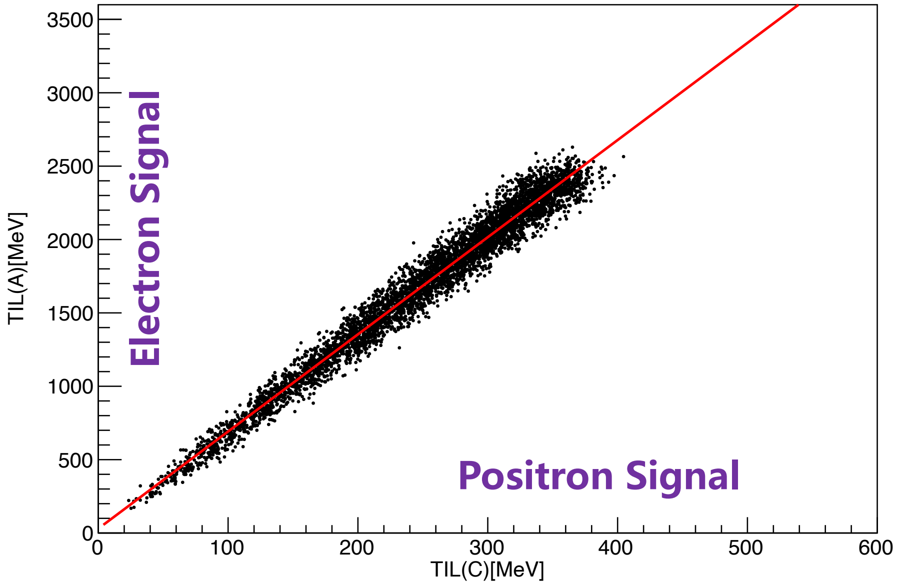
FastLumi - Diamond Detector

❑ Performance Simulation

- Evaluate the **Train Integrated Luminosity (TIL)** in 1 ms for all bunches
- Relative precision is 7% at luminosity $0.5\times10^{33}cm^{-2}s^{-1}$ and reaches 1% at luminosity $0.5\times10^{35}cm^{-2}s^{-1}$
- Two diamond detectors are placed downstream of the electron and positron beams for **inter-calibration**. Strong linear correlation is observed.



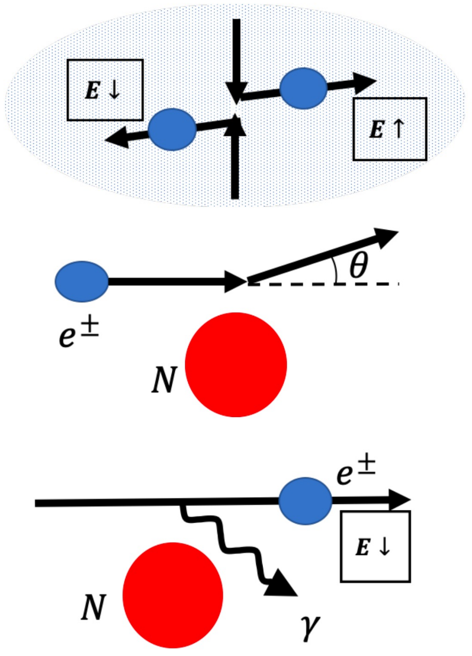


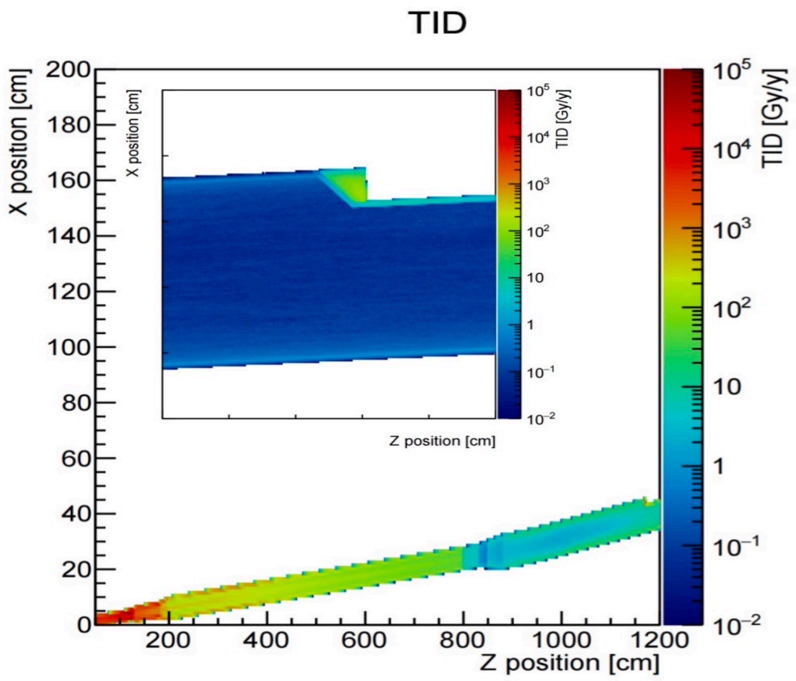


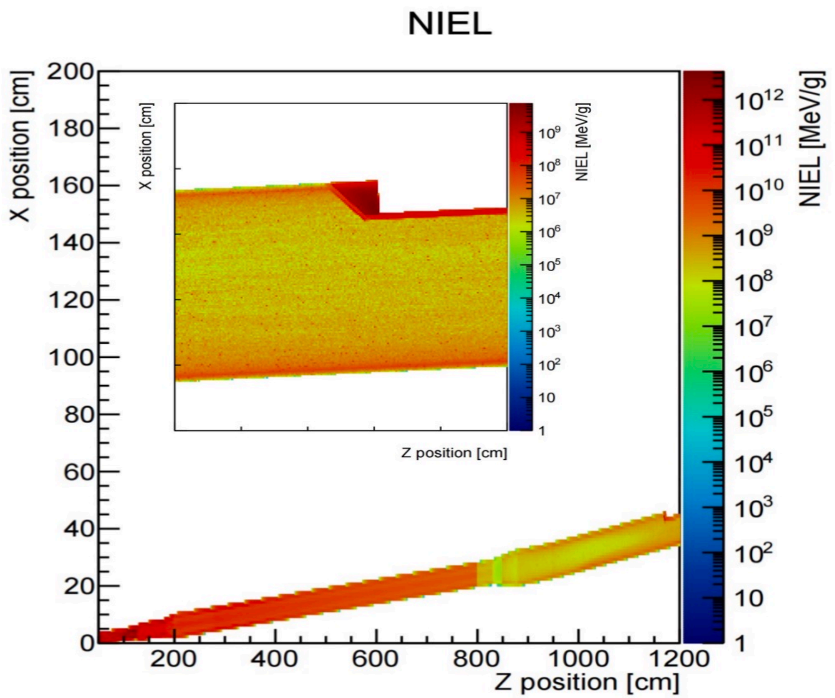
FastLumi - Diamond Detector

❑ Background Simulation

- Two dominant sources of the beam-related background, the Touschek effect and the beam–gas effect
- The background deposition on diamond is less than 20 MeV at 1kHz, Signal/Background yield Ratio > 10
- The radiation dose at the diamond: TID $\sim 457.1\text{Gy/y}$, NIEL $\sim 1.09\times 10^{10}\text{n}_{\text{eq}}/\text{cm}^{-2}/\text{y}^{-1}$, well within limits.







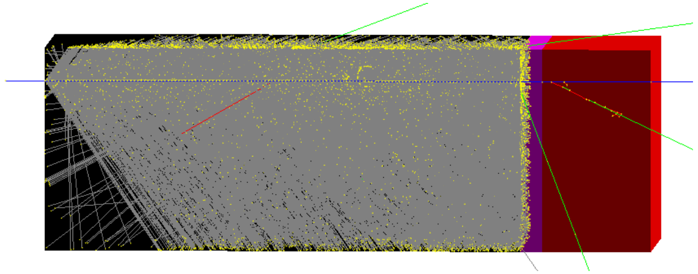
FastLumi - Cherenkov Detector

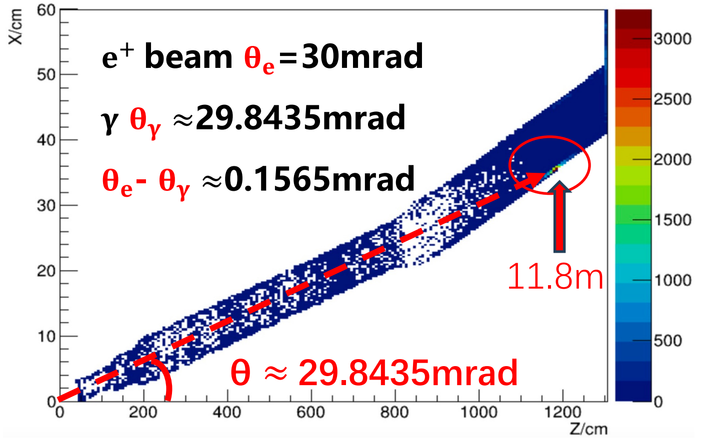
- Alternative signal for FastLumi: radiative Bhabha Photons

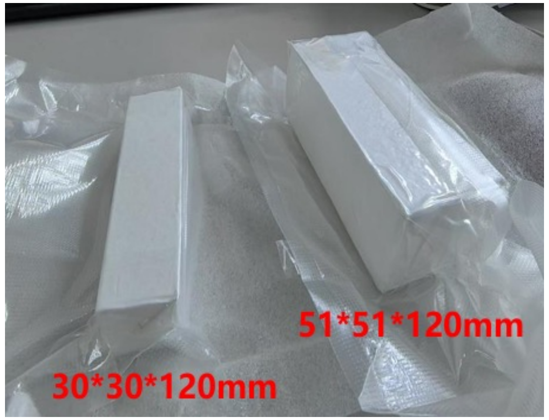
  - To reduce the background of low energy electrons and positrons, Cherenkov detector is chosen for the detection of high energy gammas.

  - **Cherenkov radiator: PbF_2 (Lead fluoride) crystals**
    - Short X_0=0.93 cm → smaller detector
    - Higher index of refraction → light generation.
    - Faster time response → bunch-by-bunch monitor
    - Hard radiation resistance.

- **Detector location: Z ~11.8 m, inside the beam pipes .**







material	PbF2	BGO	LYSO	BaF2	GSO	PbWO4
Radiation length(cm)	0.93	1.1	1.1	2.1	1.4	0.89
Moliere radius(cm)	2.2	2.7	1.9	4.4	2.2	2.2
Refractive index	1.82	2.15	1.82	1.47	1.8	2.16
Luminescence decay time(ns)	1	300	40-44	0.6,620	30	6,30

FastLumi - Cherenkov Detector

❑ Selection of the PMT

- ➢ **HAMAMATSU R2083, with fast rise time (0.7 ns) and high efficiency to blue light.**

❑ Cosmic Ray Test

- ➢ **Plastic scintillator serves as a trigger coupled with PbF2 crystal and undergoes light-shielding treatment**
- ➢ **Verifying the detector's performance and validating the simulation results.**

HAMAMATSU R2083 performance

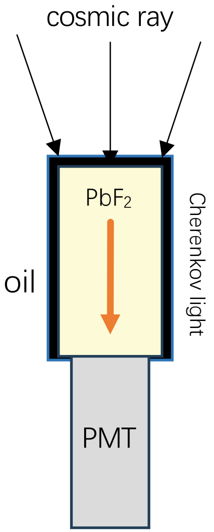
GENERAL

Parameter		Description / Value	Unit
Spectral Response	R2083	300 to 650	nm
	R3377	160 to 650	nm
Wavelength of Maximum Response		420	nm
Photocathode	Material	Bialkali	—
	Minimum Effective Area	ϕ46	mm
Window Material	R2083	Borosilicate glass	—
	R3377	Synthetic silica glass	—
Dynode	Structure	Linear focused type	—
	Number of Stages	8	—
Operating Ambient Temperature		-30 to +50	°C
Storage Temperature		-30 to +50	°C
Base		19-pin glass base with SMA output connector	—
Suitable Socket		E678-19J (supplied)	—
Time Response	Anode Pulse Rise Time	— 0.7 —	ns
	Electron Transit Time	— 16 —	ns
	Transit Time Spread	— 0.37 —	ns

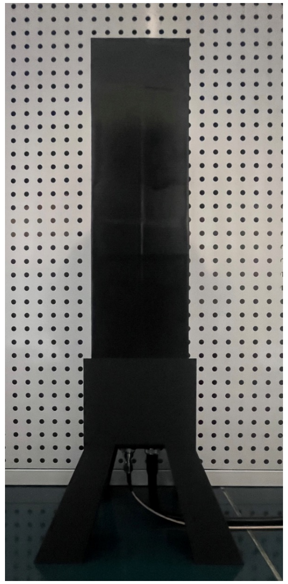
5.1*5.1*12cm^3

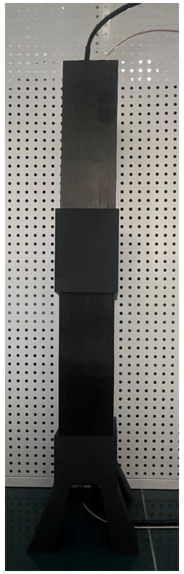
coupling agent：Si oil

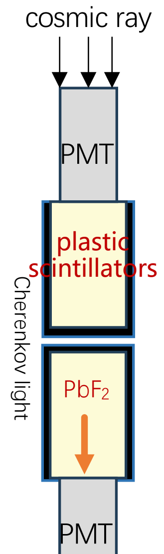
black box



upright crystal







crystal coupling

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Forward Calorimeter

Precision QED Physics @ STCF

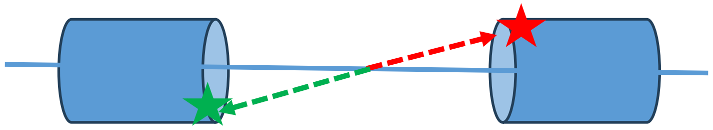
- ❑ Small-angle Bhabha scattering is dominated by t-channel photon exchange, has a large, sharply-peaked cross section, and is the cleanest, most precise "standard candle" at e^+e^- colliders.
- ❑ Precise small-angle Bhabha measurements in the 2–7 GeV range underpin the collider's absolute luminosity, enable a clean determination of the running of α in the space-like regime—impacting muon g−2 and electroweak precision inputs—and provide stringent tests of QED and radiative-correction tools needed for the broader physics program.

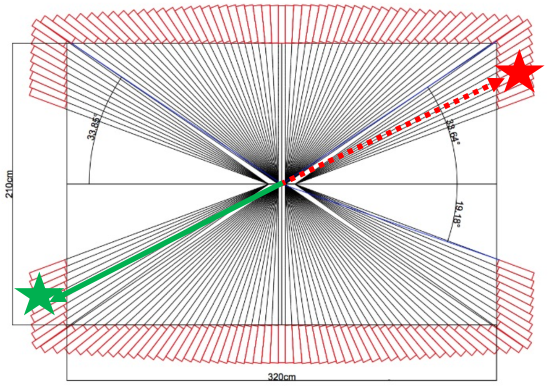
Small angle in Forward Calo

- dominantly t-channel, space-like α(t);
- QED is under excellent control with soft/collinear resummation;
- Per-mille-level predictions are achievable.

Large angle in endcap ECAL

- sizable s-channel and t–s interference;
- stronger sensitivity to hard FSR/ISR;
- Theory uncertainty is typically larger than for small-angle.

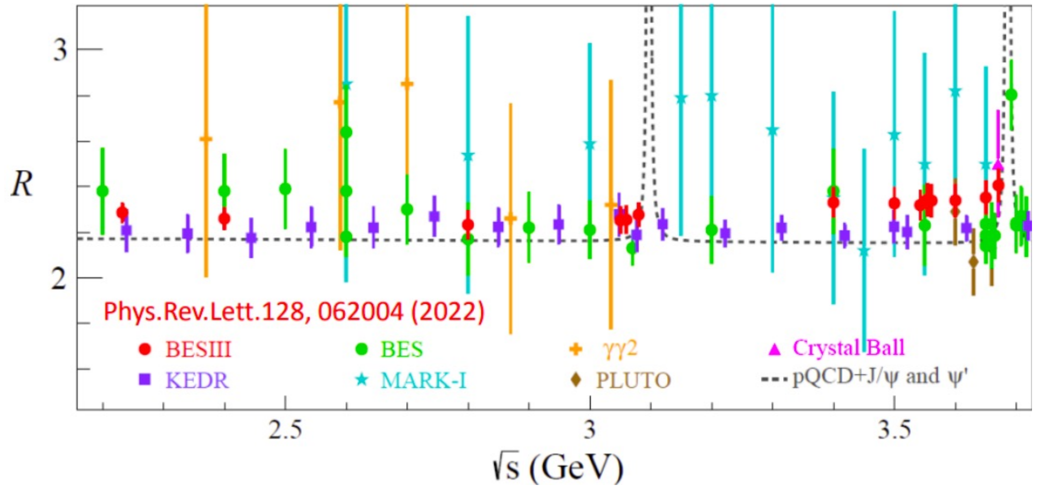




Forward Calorimeter

- **Physics process** $e^+e^- \to e^+e^-(n\gamma)$
  - *R(s)* ratio for SM predictions $a_\mu = (g_\mu - 2)/2$ and $\Delta\alpha_{had}(M_Z)$

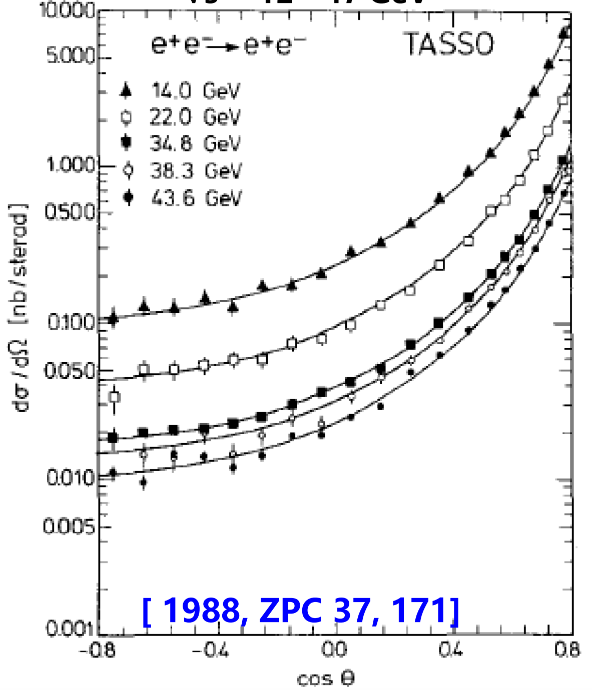
    where $a_\mu = \frac{\alpha^2}{3\pi^2}\int_{m_\pi^2}^{\infty} ds K(s)\frac{R(s)}{s}$, $\Delta\alpha_{had}^{(5)} = -\frac{\alpha M_Z^2}{3\pi} Re\int_{m_\pi^2}^{\infty}\frac{R(s)ds}{s(s-M_Z^2-i\epsilon)}$



- **Bhabha experimental status**
  - **BESIII** Luminosity $(\gamma)e^+e^-, (\gamma)\gamma\gamma$ Systematic $\sim 0.7\%$
  - **L3** radiative Bhabha with **ISR** Systematic error at ~1% level
  - **TASSO** Bhabha Systematic error $\sim 3\%$

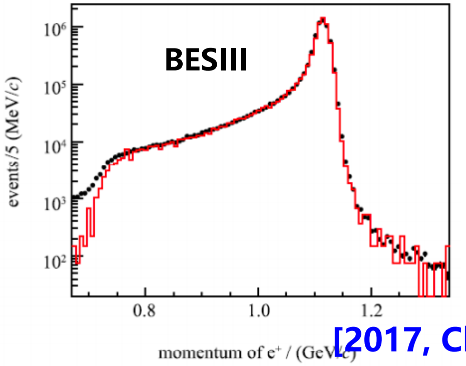
In STCF we can aim better.

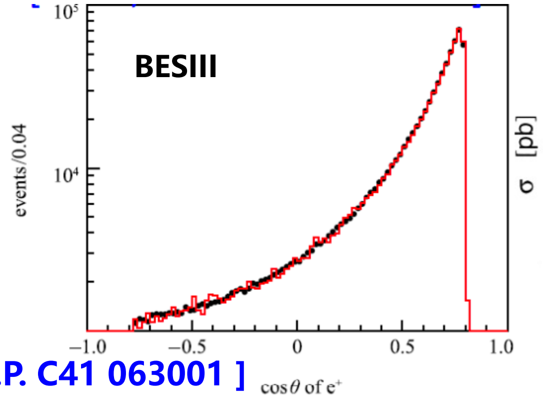
√s = 12 - 47 GeV



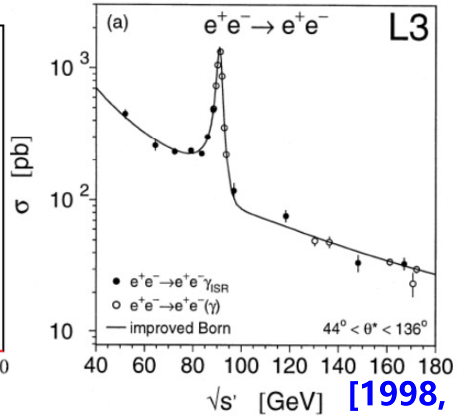
√s= 50 - 170 GeV, 232 pb^{-1}, 2856 event

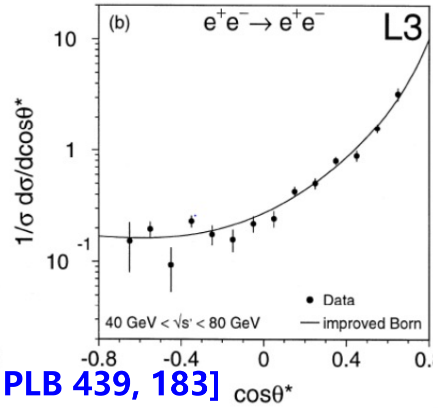
√s = 2.23 - 4.59 GeV





[2017, Ch.P. C41 063001]



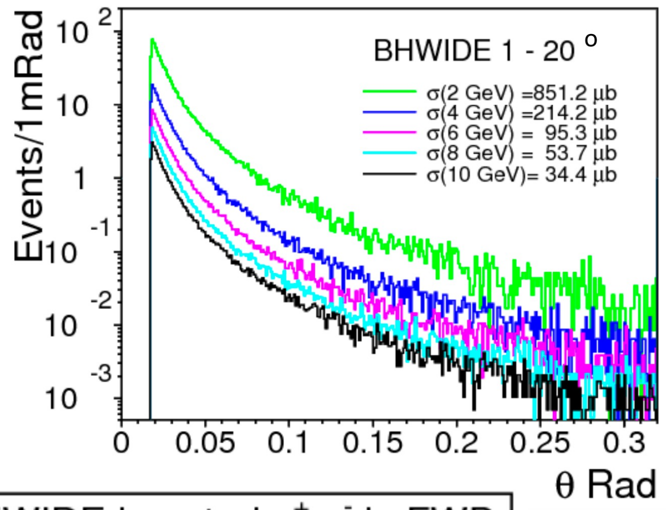


[1998, PLB 439, 183]

Forward Calorimeter - Simulation

- Simulation with BHWIDE generator on small and large Bhabha events

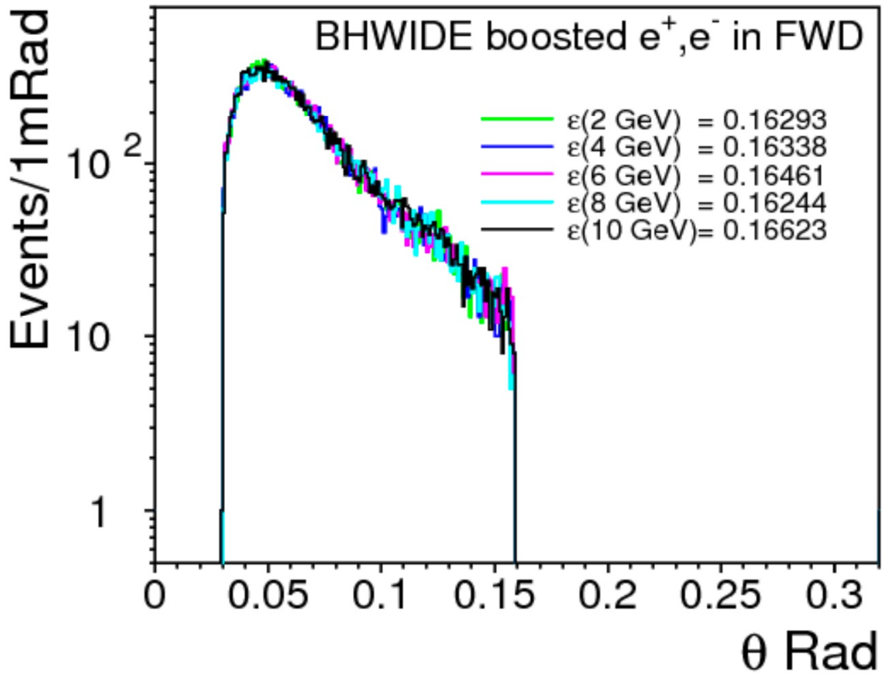
CM frame cross section σ; scattered e± > 0.1 GeV; back-to-back 0 - π					
√ s GeV	2	4	6	8	10
1 – 20 deg	851000 nb	214200 nb	95300 nb	53700 nb	34400 nb
20 – 160 deg	1800 nb	455 nb	204 nb	115 nb	73.9 nb



- **For small angle Bhabha at $\sqrt{s} = 2 - 10GeV$**
  - **Boost with 60 mRad beam-crossing angle**
  - **Collect and measure those events both e^+e^- in the expected forward calorimeter:**

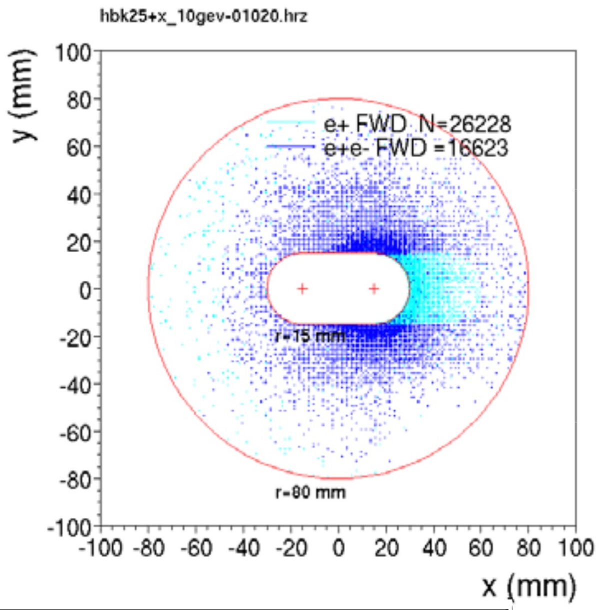
  @ |z|= 500mm, off beampipe Ø = 30 mm; r < 80mm

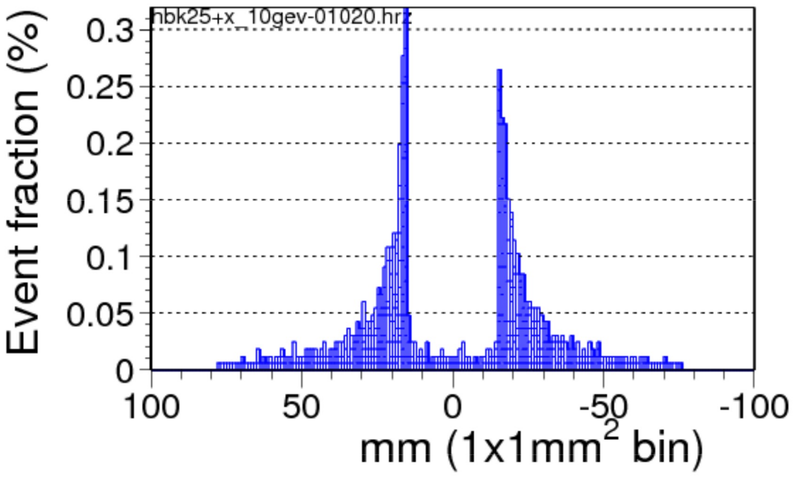
  - **The acceptance rate ε ~ 16.3 %**



Forward Calorimeter - Simulation

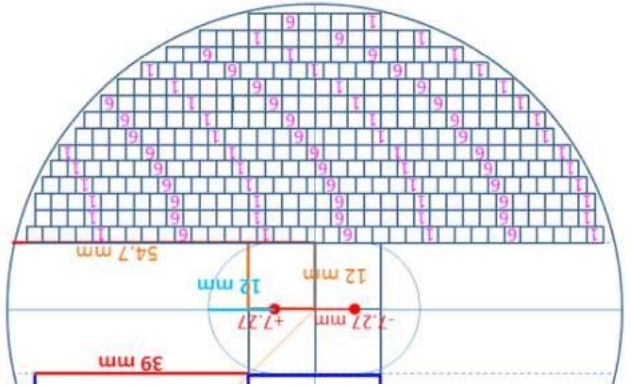
- Estimation on the event rate of Bhabha signals in the Forward Calorimeter
  - σ=34.4k nb; acceptance ε=16.6%; event fraction ~0.3 % in 1x1 mm² hottest cell;
  - $\sigma \times \varepsilon \times 0.3\% = 34400 \times 0.166 \times 0.003 = 17.1$ nb
  - Bhabha event rate at the detector: (17.1 nb) × (5 × 10^{34} /cm² sec) = 857 /sec
  - Per 100 ns event pile-up rate at 2 GeV: 21.2k/10^7= 0.0021



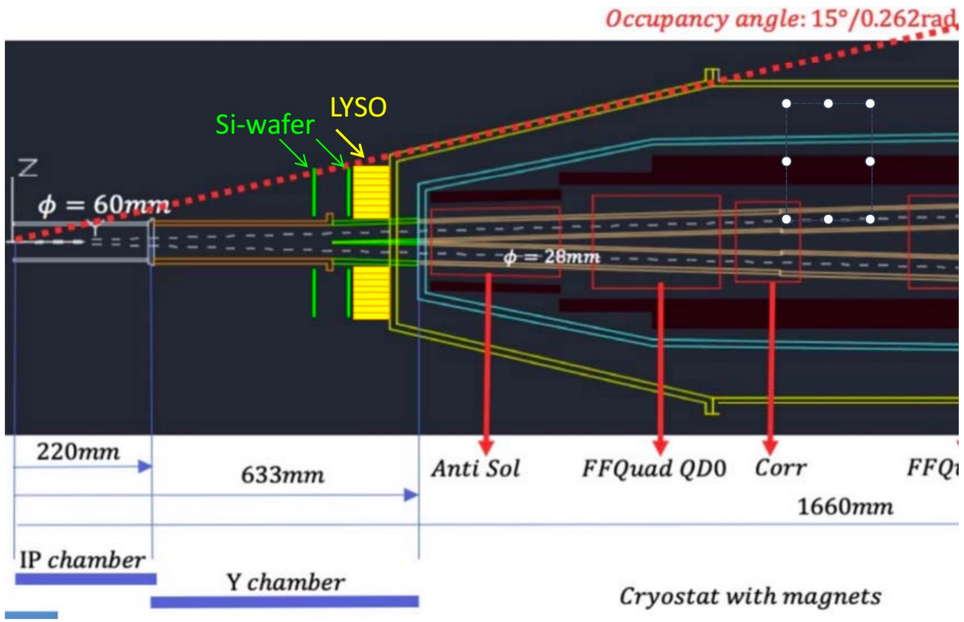


CMS cross section σ; scattered e± > 0.1 GeV; back-to-back 0-π					
√s GeV	2	4	6	8	10
1 – 20°	851k nb	214k nb	95k nb	54k nb	34.4k nb
both e± in FWD (off-pipe ϕ30mm, r<80mm)					
FWD ε	0.163	0.163	0.165	0.162	0.166
1x1 mm² hottest cell, electron hit rate					
Ev. /sec	21.2k	5.33k	2.37k	1.34k	0.86k

Forward Calorimeter of Si+LYSO



- Forward detector for Bhabha Lumi; two-photon $e^{\pm}$ - tagging
- Measure Radiative Bhabha, for Luminosity higher than 10^{-3}. $e^{\pm}(\theta, \varphi)$ to 10 uRad, e/γ radiative photon to QED NLO
- Detector Specification:
  - Si-wafer: 2D strip, 100 μm pitch, $e^{\pm}$ impact θ, φ
  - LYSO 10 X_0: for shower max to 10 GeV of $e^{\pm}(E_{beam})$
- Experimental Challenge:
  - Be, Ta beam pipe: Preshower background should be reduced
  - High precision alignment needed.



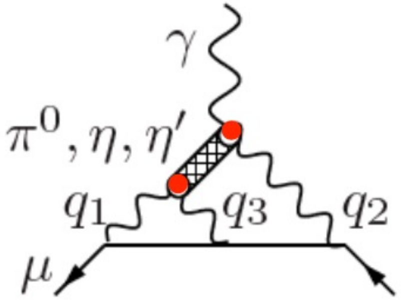
Zero Degree Detector

$\gamma^* \gamma^*$ Physics @ STCF

- One of the main theoretical uncertainties to the $a_\mu = (g_\mu - 2)/2$ comes from **Hadronic Light by Light scattering (HLbL)** calculation, which can be calculated by the cross section of:

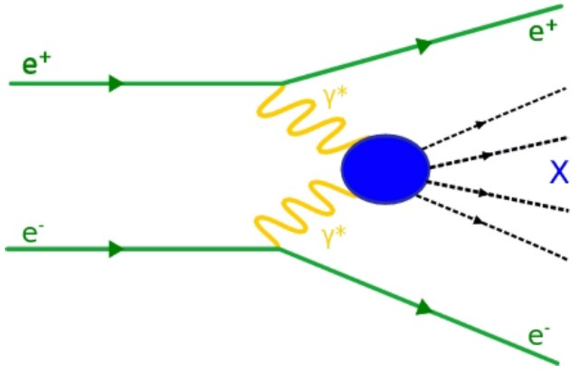
$$e^+ e^- \to e^+ e^- \gamma^* \gamma^* \to e^+ e^- X$$

where $X = \pi^0, \pi\pi, \eta$



Contribution	Value $\times 10^{11}$
Experiment (E821 + E989)	116 592 061(41)
QED	116 584 718.931(104)
Electroweak	153.6(1.0)
HVP (e^+e^-, LO + NLO + NNLO)	6845(40)
HLbL (phenomenology + lattice + NLO)	92(18)
Total SM Value	116 591 810(43)
Difference: $\Delta a_\mu := a_\mu^{\mathrm{exp}} - a_\mu^{\mathrm{SM}}$	251(59)

- A Zero Degree Detector (ZDD) can efficiently capture **low-angle, high-energy $e^+ e^-$ pairs** to tag two-photon processes.
- ZDD consists of two subdetectors, one close to the IP and the other one in the far end.



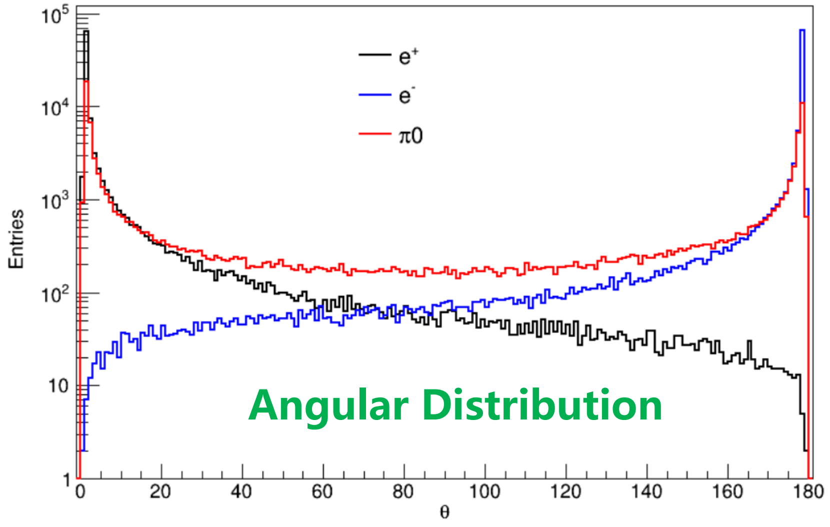
Tagged by ZDD

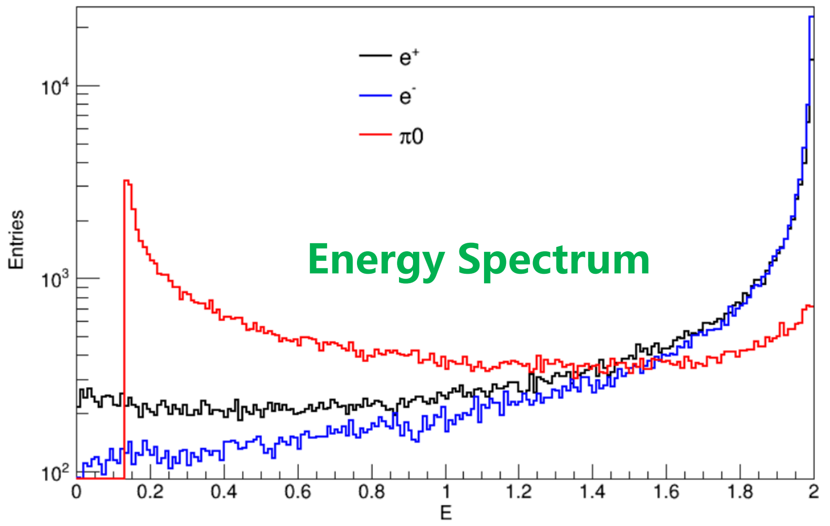
Measured In STCF detector

Tagged by ZDD

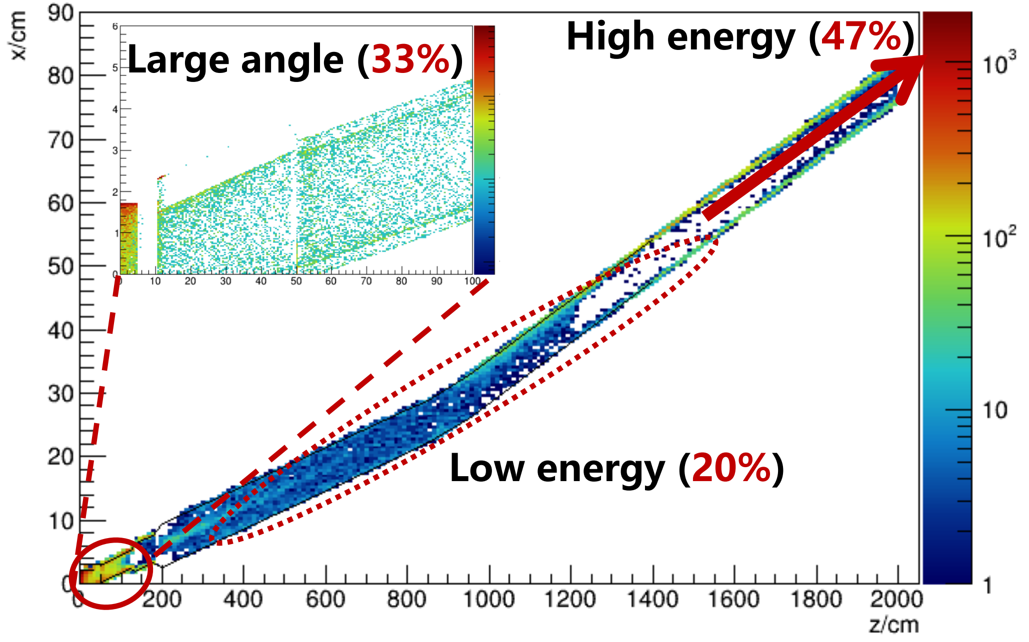
ZDD Simulation

- Simulation using Ekhara generator in the STCF of two-photo process $e^+e^- \to e^+e^-\pi^0$ @4GeV





- At the near IP position, large angle $e^+(e^-)$ with low energy, meanwhile suffer from high background;
- At the far end, small angle $e^+(e^-)$ but with high energy, and the energy is strongly correlated to beampipe exit positions.



Summary

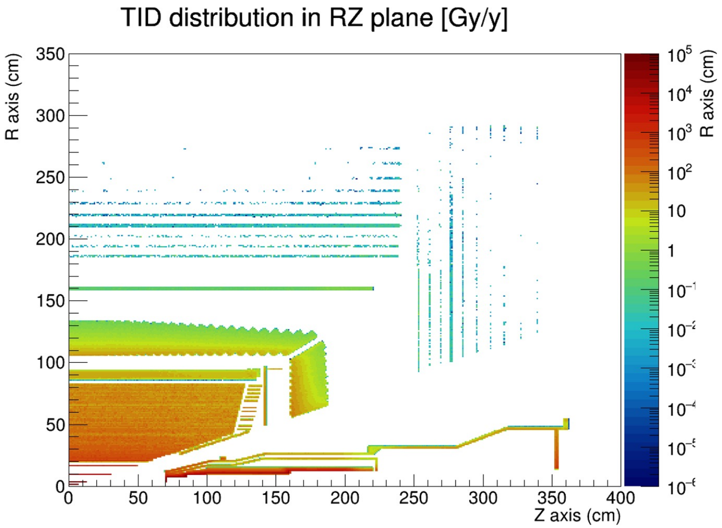
- Forward Region at STCF is unique to precision measurement to physics as well as accelerator quantities.
- The MDI design and Background simulation is actively ongoing to optimize the Forward Region.
- With Fast Luminosity Monitor System, STCF can achieve precision measurement of real-time luminosity for the beam diagnostics and tuning.
- With Forward Calorimeter, STCF can probe the highest precision of QED physics.
- With Zero Degree Detector, STCF can contribute to the long standing problem of muon g-2.

Within the Forward Region, STCF can step further forward!

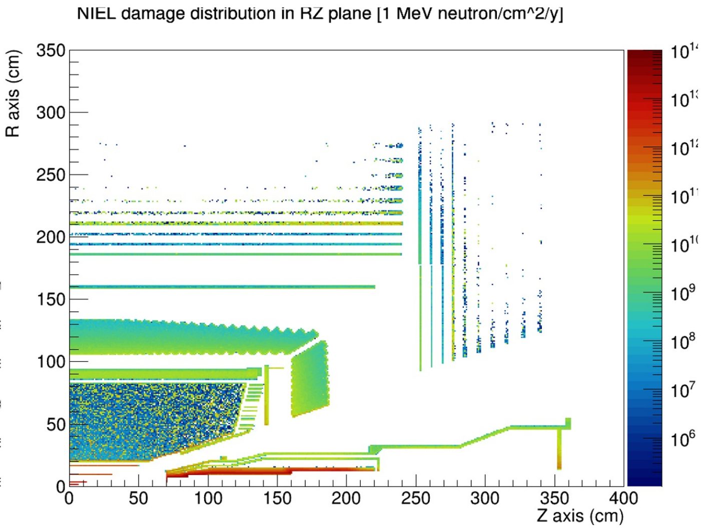
Backup Slides

Inner pipe Ta → Cu

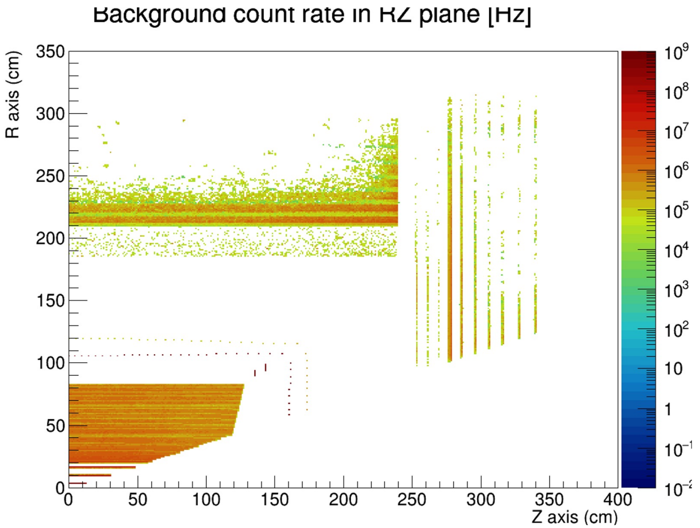
TID v12_c - Ta



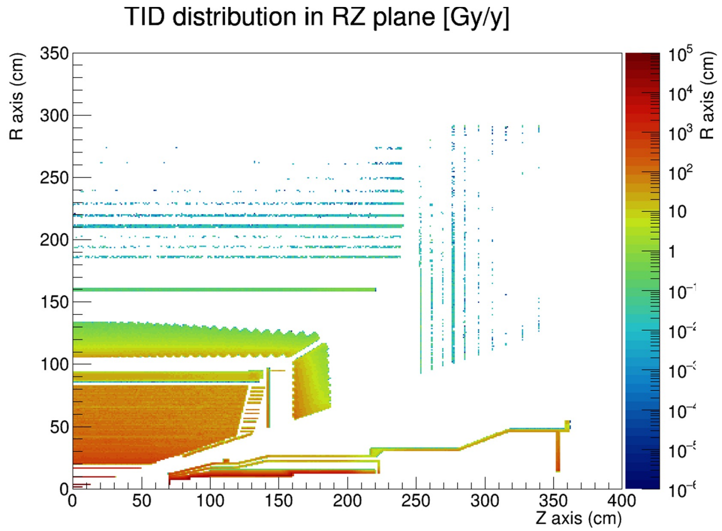
NIEL v12_c - Ta



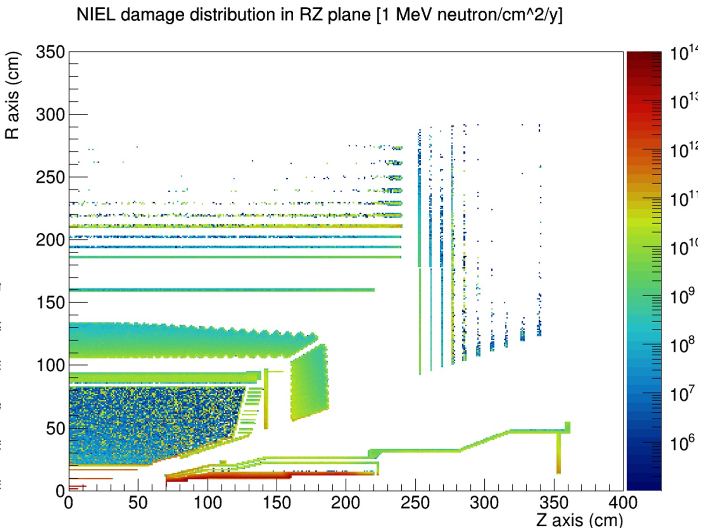
Count v12_c - Ta



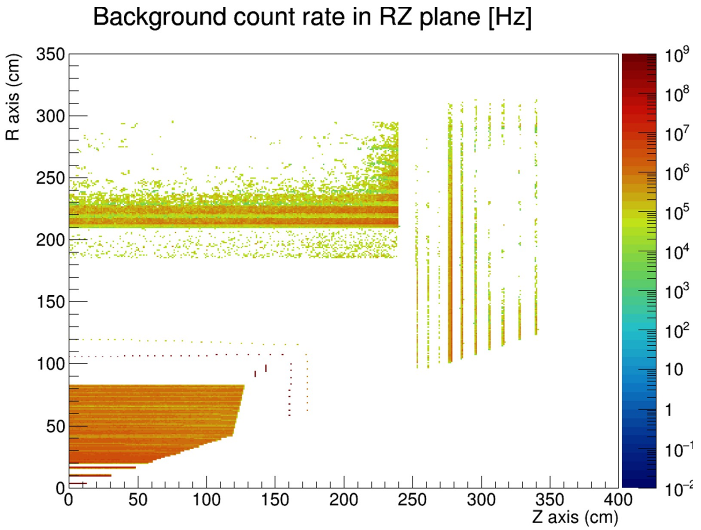
TID v12_c - Cu



NIEL v12_c - Cu



Count v12_c - Cu



Inner pipe Ta → Cu

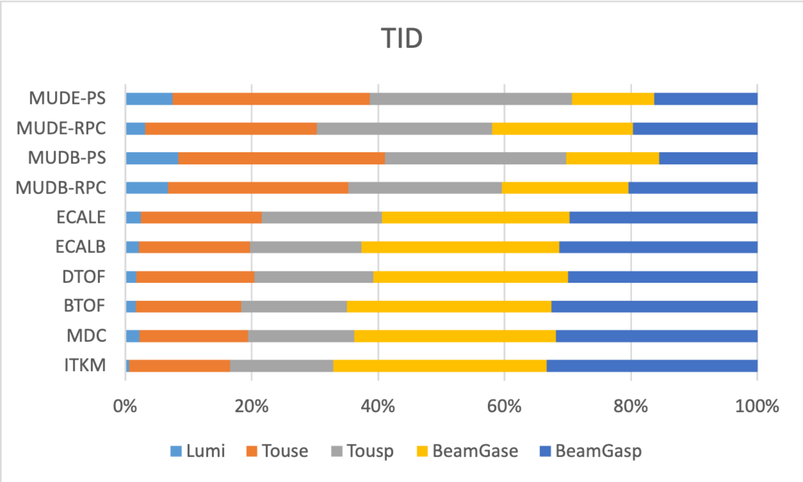
v12_c - Ta

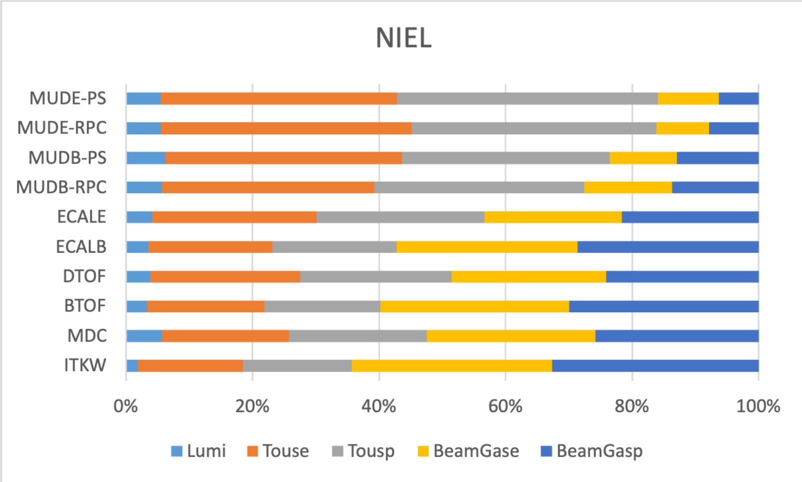
DETECTOR	TID	NIEL	COUNT
ITKM1	34989	1.85E+12	5.86E+09
ITKM2	3681	4.07E+11	3.84E+09
ITKM3	946	2.71E+11	2.56E+09
MDC	74.42	1.57E+12	5.71E+09
BTOF	12.41	8.64E+10	2.24E+10
DTOF	26.96	1.13E+11	7.66E+09
ECAL-B	5.34	8.51E+10	1.46E+10
ECAL-E	10.77	8.14E+10	5.95E+09
MUD-B-RPC	0.017	4.25E+09	6.78E+07
MUD-B-PS	0.0095	1.15E+11	2.98E+08
MUD-E-RPC	0.011	1.66E+09	2.78E+07
MUD-E-PS	0.0059	2.69E+10	1.29E+08

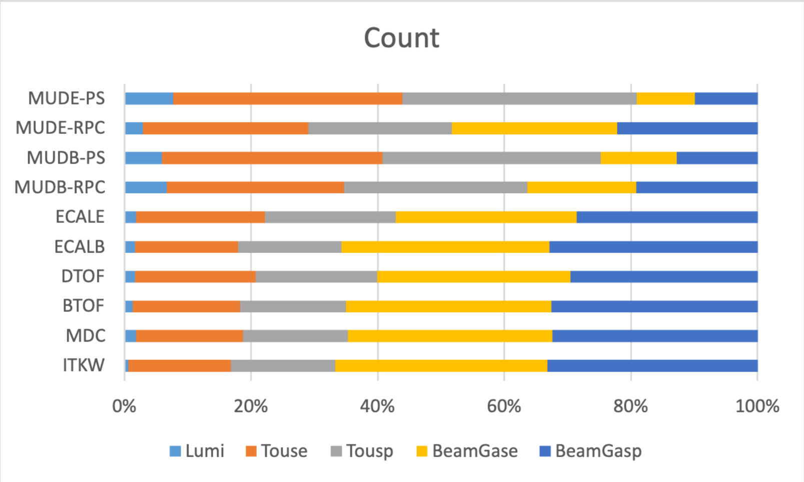
v12_c - Cu

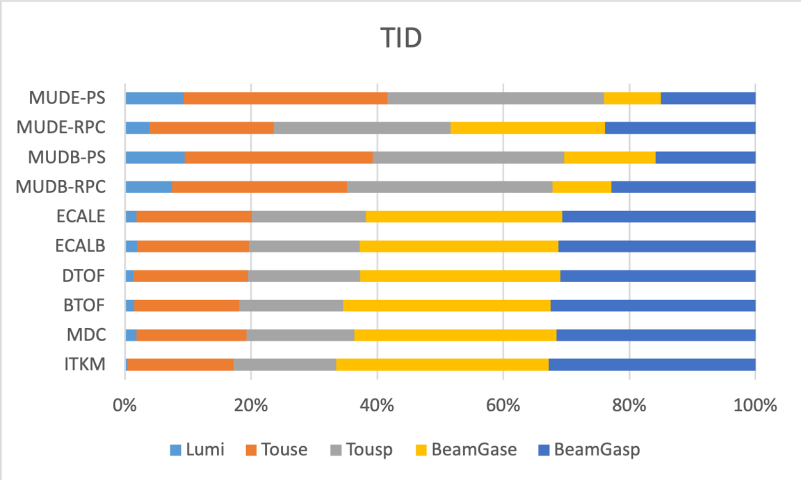
DETECTOR	TID	NIEL	COUNT
ITKM1	54682	2.29E+12	8.97E+09
ITKM2	5544	3.57E+11	5.78E+09
ITKM3	1182	2.1E+11	3.08E+09
MDC	86.99	1.34E+12	7.36E+09
BTOF	12.60	7.93E+10	1.97E+10
DTOF	35.42	1.33E+11	9.63E+09
ECAL-B	4.82	7.76E+10	1.22E+10
ECAL-E	14.39	9.54E+10	7.14E+09
MUD-B-RPC	0.014	4.31E+09	6.12E+07
MUD-B-PS	0.0094	1.17E+11	2.96E+08
MUD-E-RPC	0.010	1.60E+09	3.18E+07
MUD-E-PS	0.0062	2.79E+10	1.27E+08

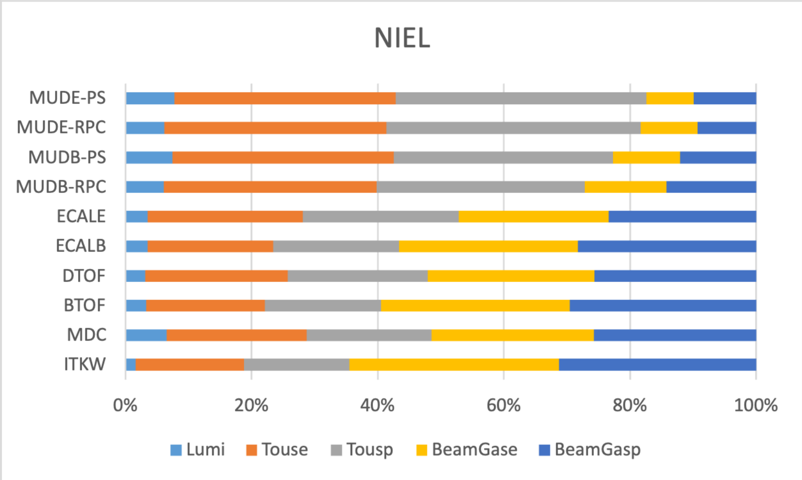
Inner pipe Ta → Cu

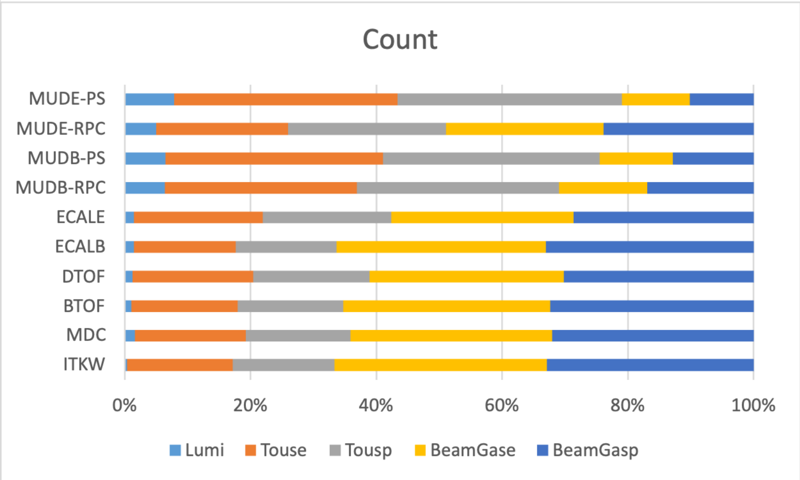












Outline

- Forward Region at STCF
- MDI and Background
- Fast Luminosity Monitor
  - Diamond Detector
  - Cherenkov Detector
- Forward Detector
  - Forward Calorimeter
  - Zero Degree Detector
- **Beam Energy Measurement**

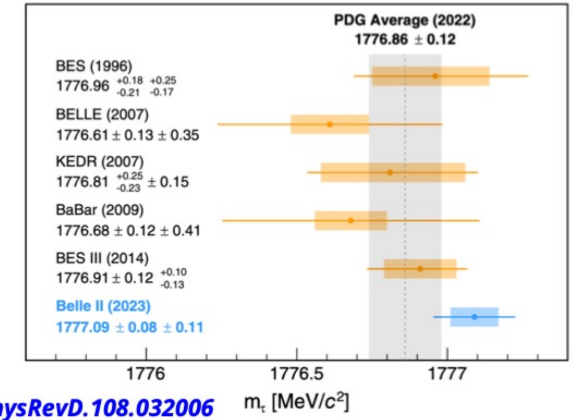
Beam Energy Measurement

❑ Motivation

- **Precise measurements of particle masses and scattering cross sections**
- **The uncertainty of beam energy is the main systematic of τ mass measurements in BESIII and Belle II**

TABLE II. Summary of systematic uncertainties in the τ-mass measurement.

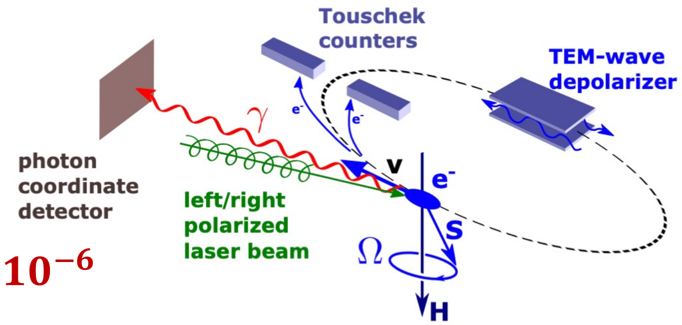
Source	Uncertainty (MeV/c^2)
Knowledge of the colliding beams:	
Beam-energy correction	0.07
Boost vector	< 0.01
Reconstruction of charged particles:	
Charged-particle momentum correction	0.06
Detector misalignment	0.03
Total	0.11

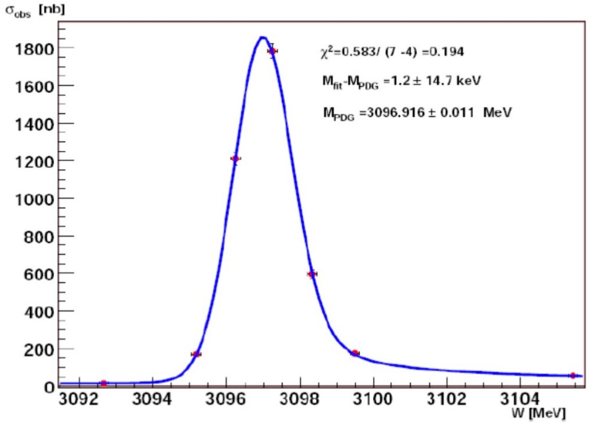


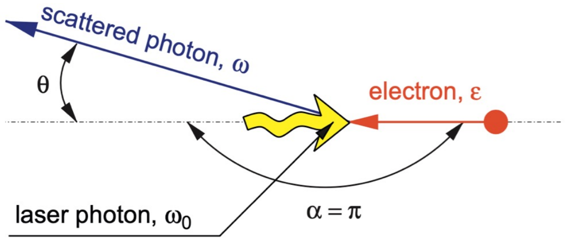
PhysRevD.108.032006

❑ Method

- **Resonant Depolarization accuracy: $10^{-5} \sim 10^{-6}$**
- **Energy Scale Calibration of the J/ψ and ψ' Resonances accuracy: $10^{-4} \sim 10^{-5}$**
- **Inverse Compton Scattering accuracy: $10^{-4} \sim 10^{-5}$**



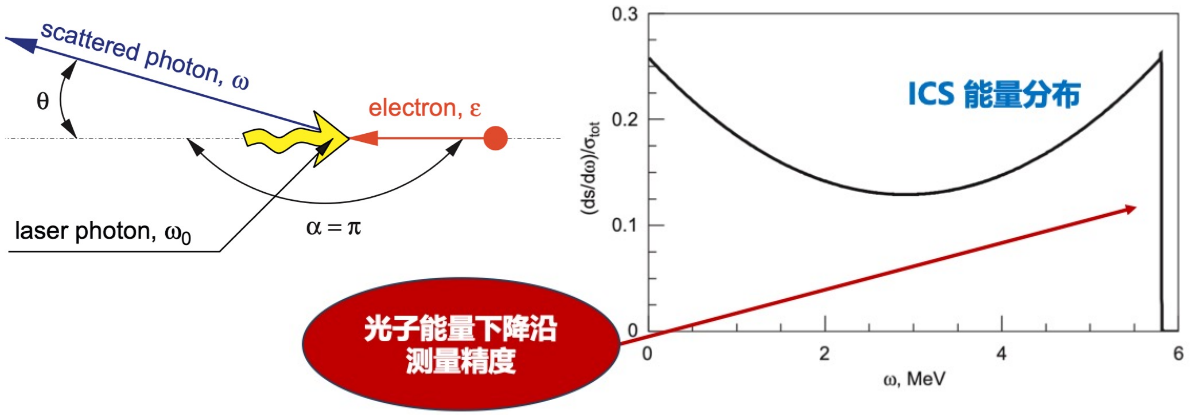




Beam Energy Measurement

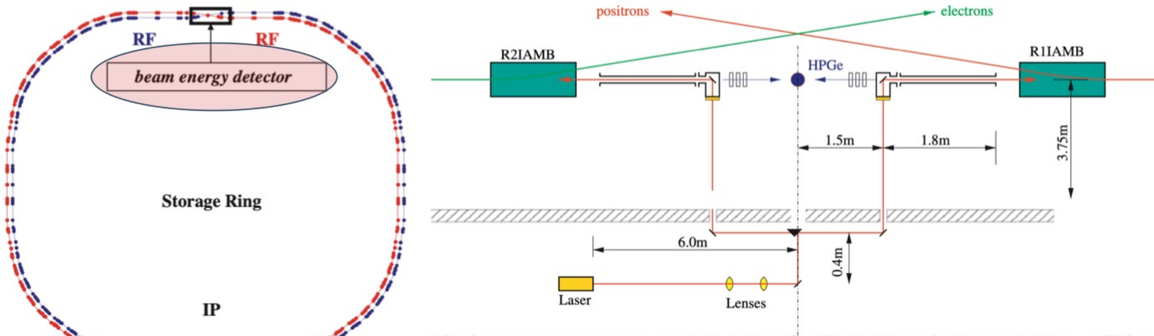
❑ Inverse Compton process

- Measuring scattered photo max energy ω_{max}, beam energy is given by $\varepsilon = \frac{\omega_{max}}{2}[1 + \sqrt{1 + \frac{m_e^2}{\omega_0 \omega_{max}}}]$
- measuring accuracy $\sqrt{\left(\frac{1}{2}\frac{\Delta\omega_{max}}{\omega_{max}}\right)^2 + \left(\frac{1}{2}\frac{\Delta\omega_0}{\omega_0}\right)^2 + \left(\frac{\Delta m}{m}\right)^2}$



❑ BESIII Beam Energy Measurement (BEMS)

- Consisting of Laser, optical system and HPGe detector
- With a beam current of 1 mA and a laser power of 1 W, the photon yield from inverse Compton scattering is ~17,000 photons per second.
- Accuracy: $3.5\times10^{-5}(e+)$, $4.29\times10^{-5}\ (e-)$



The beam energy measurement system for the Beijing electron–positron collider
NIM A 659 (2011) 21–29

❑ HPGe detector <2.5GeV

- As the photon energy increases, the FWHM of energy broadens and the resolution will be limited.
- detection efficiency decreases.

1.74 keV @ 1.33 MeV 60Co line