

中国科学院高能物理研究所
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The incoherent pair production simulation study

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On behalf of the CEPC TDAQ Working Group

The 2026 Workshop at the CEPC

TDAQ: from CEPC to FCC

- Same 40 MHz machine — about six times more data per crossing at FCCee
- The difference is content per crossing (≈40 KB vs ≈200 KB), caused by different background assumptions
- CEPC high-lumi Z comes from scaling, so it must be recomputed based on the FCC background simulation

Status of the FCC-ee interaction region desi

Quantity	CEPC / AGORA (high-lumi Z)	FCC-ee (Z pole)
Bunch-crossing rate	43.3 MHz	40 MHz
Luminosity($10^{34}cm^{-2}s^{-1}$)	192	140
Physics rate(Z production)	75 kHz	50 kHz
Beam background	~600 pair / Bunch	~1300 pair/Bunch
Raw data rate	1.6 TB/s	10 TB/s
Content per BX	40 KB / BX	200 KB / BX

TDAQ: what we need to do next, by Fei Li

Subsequent CEPC-Related Talks

- Five Efforts, from background input to online reconstruction:
  - Beam background study
  - L1 hardware design progress
  - High speed readout
  - GPU algorithm and online computing
  - Track reconstruction

The incoherent pair production simulation study	*Boping Chen*
Junior Ballroom III	09:25 - 09:50
L1 trigger hardware design progress on CEPC ref-Detector	*dong Liu*
Junior Ballroom III	09:50 - 10:10
Development and Evaluation of an FPGA-Based RoCEv2 Protocol Stack for High-Throughput Data Transfer in...	
Sheng Dong et al.	

Research on GPU Algorithms and Online Computing	*叙 张*
Junior Ballroom III	11:00 - 11:20
Nonlinear Track Reconstruction Studies towards UKF-Based Tracking for CEPC	*Dr Jahanzeb Akhtar*
Junior Ballroom III	11:20 - 11:40

Introduction

- Two main Beam induce background
  - Single beam; Lumi related
- Focus on incoherent pair production(beamstrahlung)
- Dominant background in CEPC
- Simulated by Guinea-Pig
  - Validate this simulation tool

Sources and Simulation Steps/Tools

- Single Beam
  - Touschek Scattering
  - Beam Gas Scattering(Elastic/inelastic)
  - Beam Thermal Photon Scattering
  - Synchrotron Radiation
- Luminosity Related
  - Beamstrahlung
  - Radiative Bhabha Scattering

From Haoyu

For Ideal beam with high order magnet error
Other errors like misalignment not included yet

- Injection
- SuperKEKB like sudden beam loss
- Failure Case(injection/extraction/Power Loss...)

Will be considered future except power loss

Background	Generation	Tracking	Detector Simu.
Synchrotron Radiation	BDSim/Geant4	BDSim/Geant4	CEPCSW/FLUKA
Beamstrahlung/Pair Production	Guinea-Pig++	SAD	
Beam-Thermal Photon	PyBTH[Ref]		
Beam-Gas Bremsstrahlung	PyBGB[Ref]		
Beam-Gas Coulomb	BGC in SAD		
Radiative Bhabha	BBBREM		
Touschek	PyTSK with SAD		

- One Beam Simulated
- Simulate each background separately
- Whole-Ring generation for single beam BGs
- Multi-turn tracking(200 turns)
  - Using built-in LOSSMAP
  - SR emitting/RF on
  - Radtaper on
  - No detector solenoid yet

Loss Rates with Collimators

- The table blow shows the loss rate in the MDI region for beam loss backgrounds in 50MW Higgs/Z and 10MW Z mode.
- Comparing with Pair Production, the contributions from beam loss are quite low. Pair Production dominates.

Vacuum Level: 10^{-7} Pa, H_2
Uniform

	50MW Higgs	10MW Z	50MW Z
Beam Thermal Photon	0.3 kHz/beam	24.83 Hz/beam	100 Hz/beam
Beam Gas Brems	4.1 kHz/beam	17.9 kHz/beam	7 MHz/beam
Beam Gas Coulomb	87.8 kHz/beam	20.8 MHz/beam	0.2 GHz/beam
Touschek	0.3 kHz/beam	1.3 kHz/beam	1.6 kHz/beam
Pair Production(Gen. Rate)	1.82 GHz in IR	3.2 GHz in IR	25.5 GHz in IR

Three processes for pair production

- Breit-Wheeler (BW)
  - Two real photons from beamstrahlung
- Bethe-Heitler (BH)
  - One real photon from beamstrahlung
  - One virtual photon from electron
- Landau-Lifshitz (LL)
  - Two virtual photon from electrons
- Real photons from beamstrahlung: Sokolov-Ternov formula for photon energy spectrum
- GPig: Virtual photon approximation for BH and LL
  - To simplify the simulation
- Compare analytical and simulation result

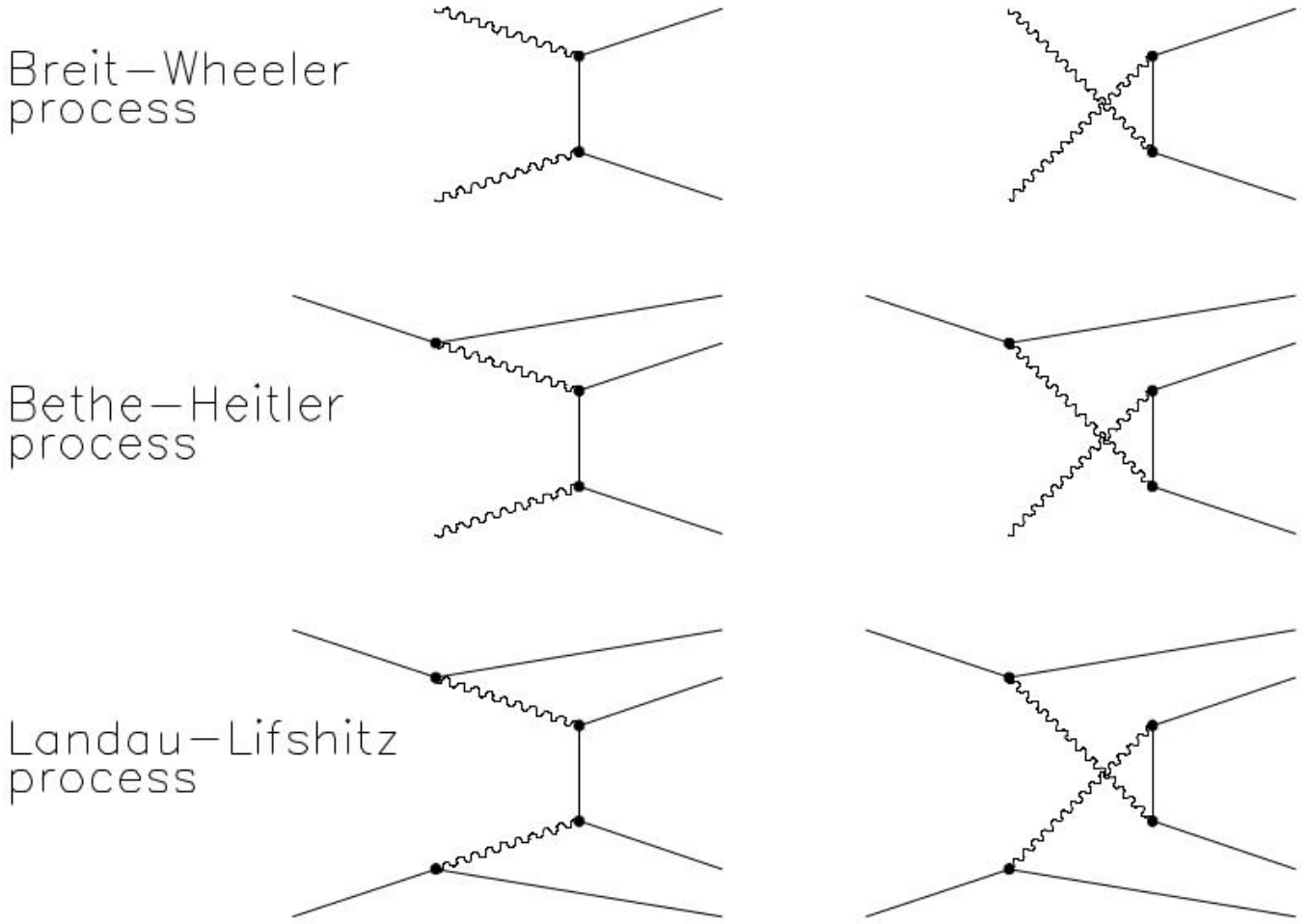
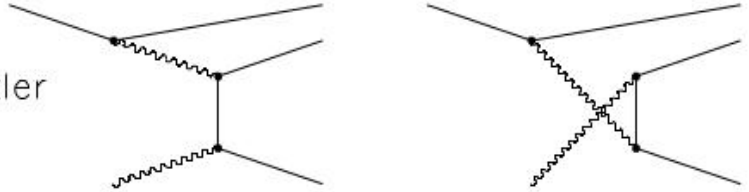
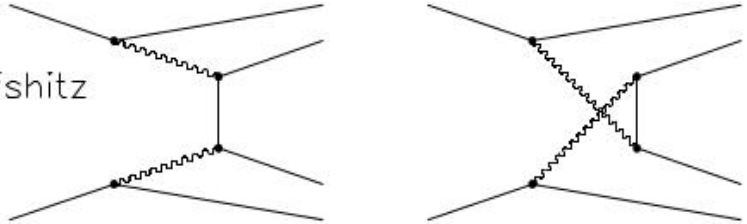


Figure 4.1: The incoherent pair production processes.

TESLA-Report 1997-08 by Daniel Schulte(Author of GPig)

Analytical cross section for three processes

- BW: determined by the two real photons from beamstrahlung
- BH: determined by one real photon from beamstrahlung and one electron/positron(120 GeV for higgs mode)
- LL: determined by the electron-positron pair(120 GeV for higgs mode)

Process	Cross section
Breit–Wheeler process 	$\sigma_{BW} = \frac{2\pi r_e^2 m^2}{s}\left[\left(2+\frac{2}{\gamma^2}-\frac{1}{\gamma^4}\right)\ln\frac{1+\beta}{1-\beta}-\left(2+\frac{2}{\gamma^2}\right)\beta\right].$
Bethe–Heitler process 	$\sigma_{BH} = \frac{28\alpha r_e^2}{9}\left(\ln\frac{s}{m^2}-\frac{109}{42}\right)$
Landau–Lifshitz process 	$\sigma_{LL} = \frac{\alpha^2 r_e^2}{\pi}\left(\frac{28}{27}\ln^3\frac{s}{m^2}-6.59\ln^2\frac{s}{m^2}-11.8\ln\frac{s}{m^2}+104\right)$

TESLA-Report 1997-08 by Daniel Schulte(Author of GPig)

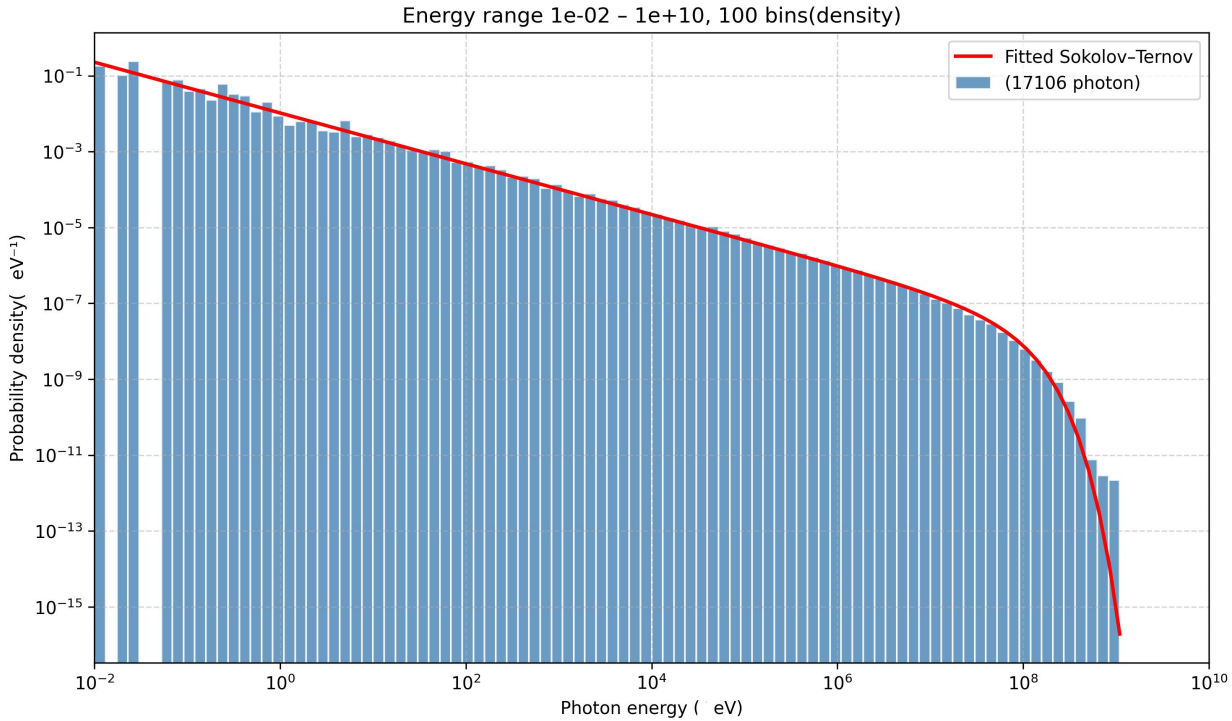
(Real) photon energy spectrum

TESLA-Report 1997-08 by Daniel Schulte(Author of GPig)

The spectrum of the emitted photons is given by the Sokolov-Ternov formula [14]:

$$\frac{\mathrm{d}\,\dot{w}}{\mathrm{d}\,\omega} = \frac{\alpha}{\sqrt{3}\pi\gamma^2}\left[\int_x^\infty \mathrm{K}_{\frac{5}{3}}(x')\mathrm{d}x' + \frac{\hbar\omega}{E}\frac{\hbar\omega}{E-\hbar\omega}\mathrm{K}_{\frac{2}{3}}(x)\right] \quad (2.9)$$

- 1: Real photons from beamstrahlung: Sokolov-Ternov formula(ST) for photon energy spectrum
  - E: electron energy; ω: photon energy
  - $x=(\omega/\omega_c)\times E/(E-\hbar\omega)$
  - ω_c: critical energy (beam property)
    - $\omega c=3/2\times\gamma^3 c/\rho$; ρ: bending radius of the particle
    - Simulation: calculate the ρ based on EM
  - Analytical: fit the photon spectrum withthe ST formula
    - Blue: photon energy from GPig
    - Red: ST distribution



(Virtual) photon energy spectrum

- 2: Virtual photons from electron/positron: Weizacker Williams(WW) approximation for photon energy spectrum

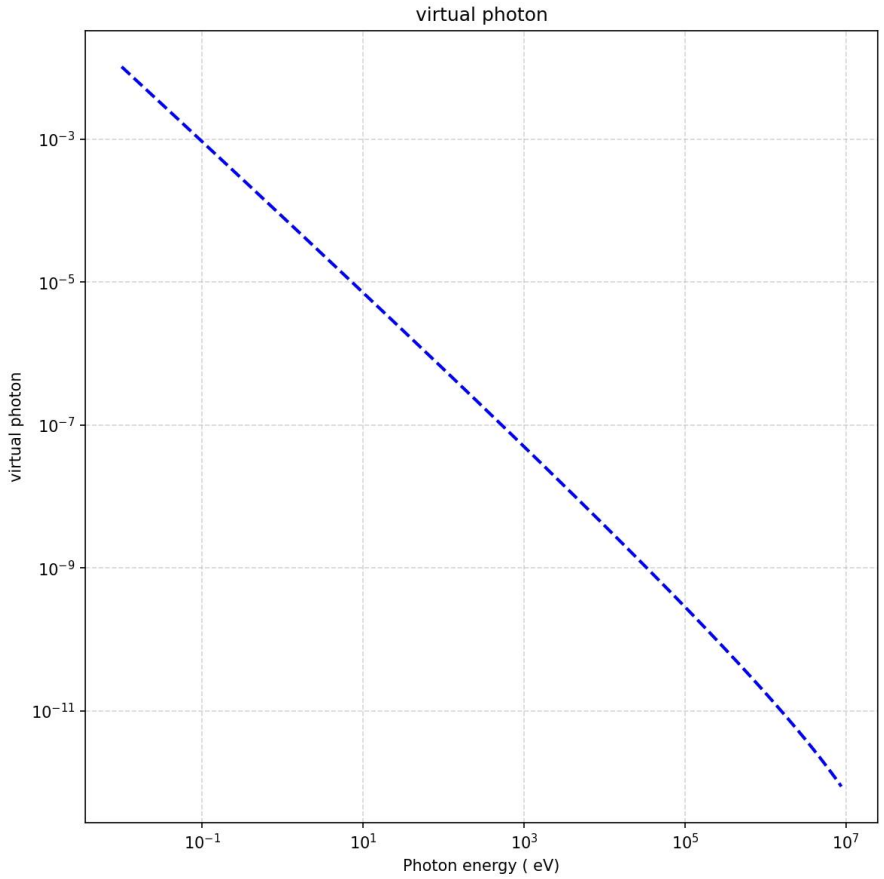
The virtual photon spectrum is approximately given by [34]

$$\frac{\mathrm{d}^2 n_v(x)}{\mathrm{d}\,x\,\mathrm{d}\,Q^2} = \frac{\alpha}{2\pi}\frac{1+(1-x)^2}{x}\frac{1}{Q^2} \tag{4.10}$$

where $xE = \hbar\omega$ is the photon energy and Q^2 its virtuality squared. Integrating over Q^2 one finds

$$\frac{\mathrm{d}\,n_v(x)}{\mathrm{d}\,x} = \frac{\alpha}{2\pi}\frac{1+(1-x)^2}{x}\ln\frac{\hat{Q}^2}{\check{Q}^2} \tag{4.11}$$

TESLA-Report 1997-08 by Daniel Schulte(Author of GPig)



Cross section: Analytical vs GPig

- σBW final = ∫σBW×ST 1×ST2 dω1dω2
- σBH final = ∫σBW×ST ×WW dω1dω2
- σLL final = ∫σBW×WW1×WW2 dω1dω2
- σLL>σBH>σBW
- Analytical ~ simulation, good agreement

LEP	Analytical			GPig		
Xsec	LL(mb)	BH(mb)	BW(mb)	LL(mb)	BH(mb)	BW(mb)
91 GeV	12.9	0.4	0.001	15.2	0.38	0.00081
202 GeV	16.2	1.70	0.084	18.5	1.60	0.071

LEP open data

- One LEP(L3) paper measures the cross section for the ee→eeee
  - BDK for generator(only for LL); LL>>BH/BW
  - Two cut: Angle cut: [44, 136]; energy cut $W_{\gamma\gamma} > 500\text{MeV}$

	Analytical			GPig		
Xsec	LL	BH(mb)	BW(mb)	LL(mb)	BH(mb)	BW(mb)
91 GeV (full space)	12.9 mb	0.4 mb	0.001 mb	15.2	0.38	0.0008 1
202 GeV (full space)	16.2 mb	1.70 mb	0.084 mb	18.5	1.60	0.071
91 GeV (with cut)	2.24 nb	~0	~0	?	?	?
202 GeV (with cut)	2.84 nb	~0	~0	?	?	?

- σLL total = $5\times10^6\times$σLL measure
  - Need to force the GPig to generate electron/positron with the two cut above

4 September 1997

PHYSICS LETTERS B

ELSEVIER

Physics Letters B 407 (1997) 341–350

Production of e, μ and τ pairs in untagged two-photon collisions at LEP

L3 Collaboration

6. Results

The observed numbers of events in the different channels are given in Table 3, together with the predictions of the BDK Monte Carlo generator, including the effects of acceptance and trigger efficiency. The first quoted error on the observed number of events is statistical, the second is systematic. The errors quoted on the predictions are the Monte Carlo statistical errors. In all cases, good agreement is found between the data and the BDK predictions.

The data are then corrected for the detection efficiency and normalized to the integrated luminosity, in order to measure cross sections which can be compared with the QED calculations. For the $e^+e^- \to e^+e^-e^+e^-$ and $e^+e^- \to e^+e^-\mu^+\mu^-$ channels, the comparison is given for the angular range $(44° \leqslant \theta \leqslant 136°)$ and for $W_{\gamma\gamma} \geqslant 500$ MeV. For the reaction $e^+e^- \to e^+e^-e^+e^-$, we find

$\sigma_{\text{data}} = 2.56 \pm 0.01\ (\text{stat.}) \pm 0.05\ (\text{syst.})$ nb

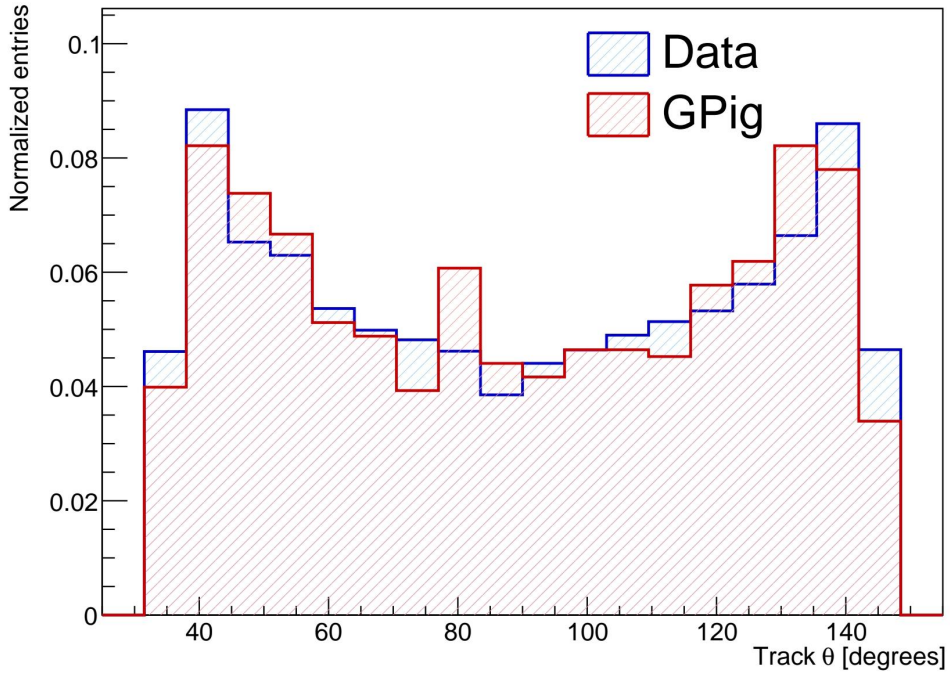
to be compared with

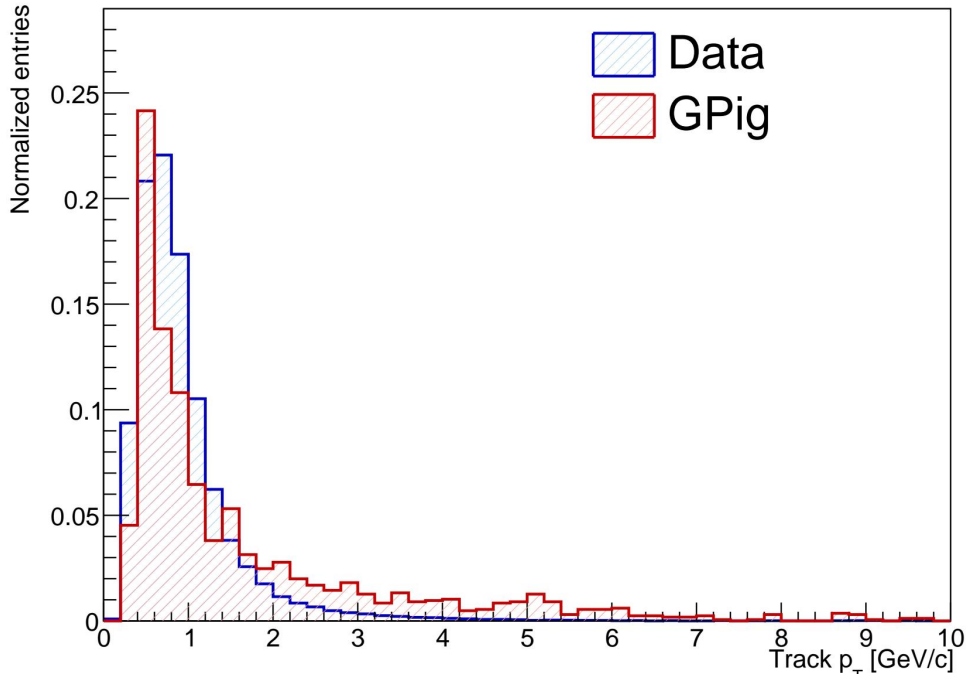
$\sigma_{\text{QED}} = 2.57 \pm 0.02\ (\text{stat.})$ nb.

LEP2 open data

- Try 92~93 data, ECM~91GeV, Lumi~47pb^{-1}. Nevent=5233143. Similar cut is applied:
  - GPig: angle cut: [10, 170]; Energy cut: $W_{\gamma\gamma}$ > 300MeV
  - Veto event if any single track E > 35 GeV
  - Veto event if sum of particle E > 60 GeV
  - Angle cut: [35, 145]; Energy cut: $W_{\gamma\gamma}$ > 500MeV , $pT^2(e^+e^-) < 0.02$ GeV^2

	Data	GPig
Cross section(pb)	X	40049
Ntotal	5233143	1893536
Cut efficiency	0.012	0.0366
Nfinal	65114	69303





Next to do

- We tested the "high level" property
- Next: Low energy component
  - Hit rate for each detector
  - Energy deposition distribution in Calorimeter

Loss Rates with Collimators

- The table blow shows the loss rate in the MDI region for beam loss backgrounds in 50MW Higgs/Z and 10MW Z mode.
- Comparing with Pair Production, the contributions from beam loss are quite low. Pair Production dominates.

Vacuum Level: 10^{-7} Pa, H_2 Uniform

	50MW Higgs	10MW Z	50MW Z
Beam Thermal Photon	0.3 kHz/beam	24.83 Hz/beam	100 Hz/beam
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Beam Gas Coulomb	87.8 kHz/beam	20.8 MHz/beam	0.2 GHz/beam
Touschek	0.3 kHz/beam	1.3 kHz/beam	1.6 kHz/beam
Pair Production(Gen. Rate)	1.82 GHz in IR	3.2 GHz in IR	25.5 GHz in IR

Table 3.6: Beam-induced background levels in sub-detectors at Higgs and Low-Lumi-Zoperation modes, including a safety factor of two.

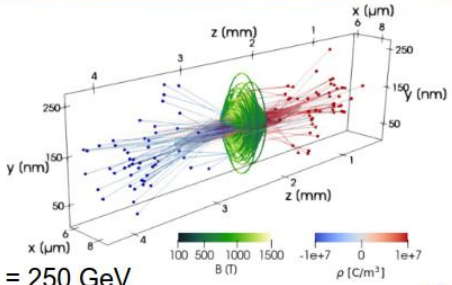
Sub-Detectors	Ave. Hit Rate		Max. Hit Rate		Max. Occupancy [%]	
	Higgs	Low-Lumi-Z	Higgs	Low-Lumi-Z	Higgs	Low-Lumi-Z
VTX [MHz/ cm^2]	0.22	0.52	12	39	2.1×10^{-2}	1.3×10^{-2}
ITK-Barrel [kHz/ cm^2]	0.92	1.7	2.6	6.6	6.4×10^{-3}	1.3×10^{-2}
TPC [kHz/ cm^2]	2.4	5.2	26	24	0.15	0.14
OTK-Barrel [kHz/ cm^2]	0.74	1.3	1.2	2.2	4.2×10^{-3}	9.2×10^{-4}
ECAL-Barrel [MHz/bar]	1.4×10^{-2}	2.2×10^{-2}	1.7	0.66	1.6	0.4
HCAL-Barrel [kHz/gs cell]	4.6×10^{-3}	8.4×10^{-3}	14	24	8.0×10^{-4}	8.0×10^{-4}
ITK-Endcap [kHz/ cm^2]	3.0	5.4	24	50	2.4×10^{-3}	5.0×10^{-3}
OTK-Endcap [kHz/ cm^2]	1.9	3.1	8.2	13	7.4×10^{-2}	12×10^{-2}
ECAL-Endcap [MHz/bar]	0.062	0.10	7.2	13	7.0	1.8
HCAL-Endcap [kHz/gs cell]	0.24	0.24	640	340	8.0×10^{-2}	6.0×10^{-3}
MD-Endcap [Hz/ cm^2]	1.4	0.92	2.5	14	0.18	0.05

Next: WarpX

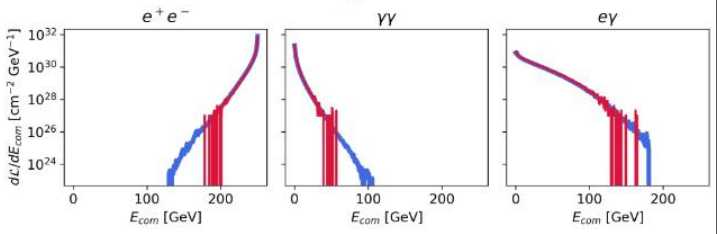
- GPig: no active maintenance
- WarpX: an advanced open-source Particle-In-Cell code
  - Multi-physics packages (incl. ionization, atomic, fusion and collisional physics, as well as quantum electrodynamics)
  - Developed by an international multidisciplinary team
  - May be used also for FCC in future

Beam-Beam simulations in WarpX

Excellent agreement between WarpX and Guinea-Pig with flat ILC beams

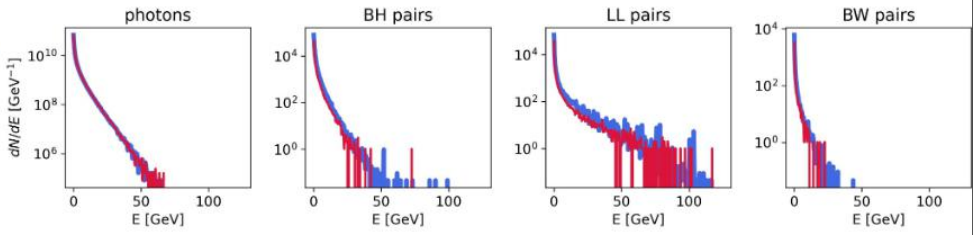


luminosity distributions



- E_{COM} = 250 GeV
- N = 2×10^{10}
- σ_z = 300 μm
- σ^*_x = 516 nm | σ^*_y = 7.7 nm
- ϵ_x = 5 μm | ϵ_y = 35 nm
- flat beams
- significant disruption
  D_x = 0.30, D_y = 24.39
- max quantum parameter
  $\chi = \Upsilon \sim 0.3$

particle distributions: beamstrahlung photons & incoherent pairs



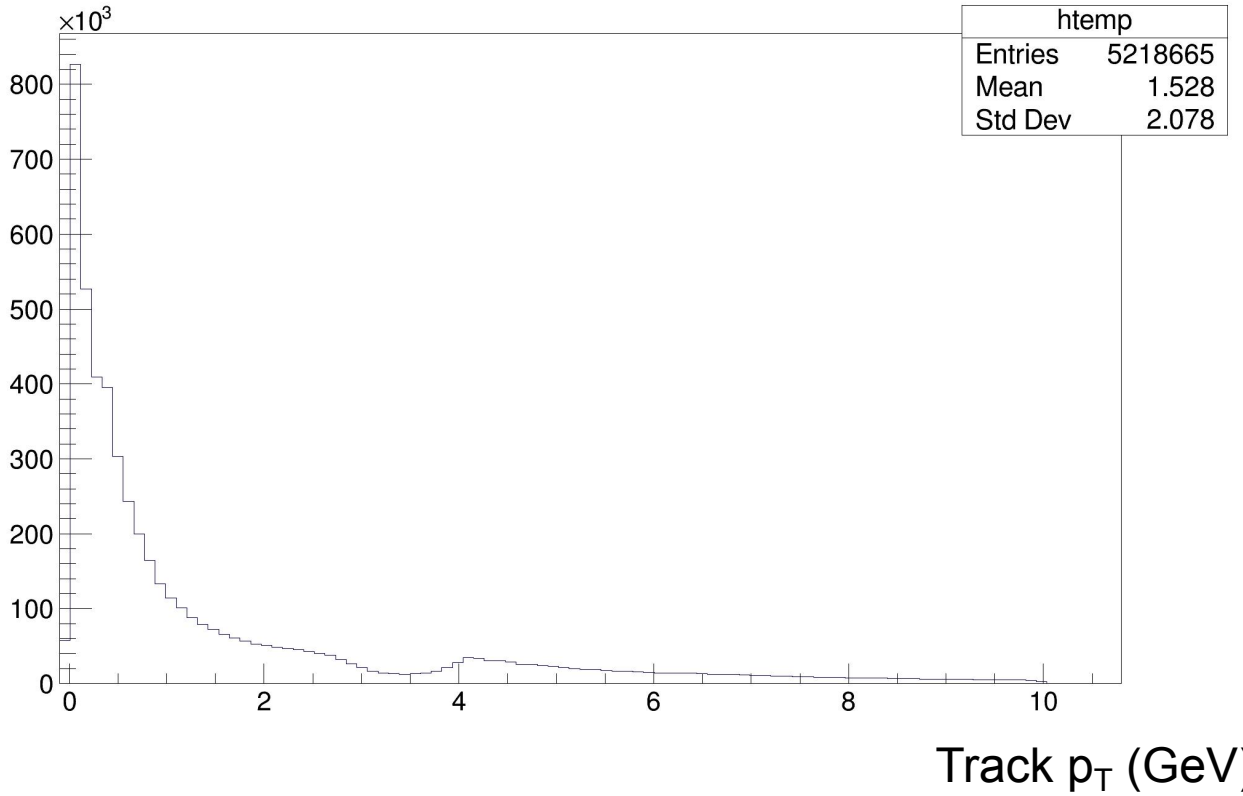
[The International Linear Collider: Report to Snowmass 2021]

Summary

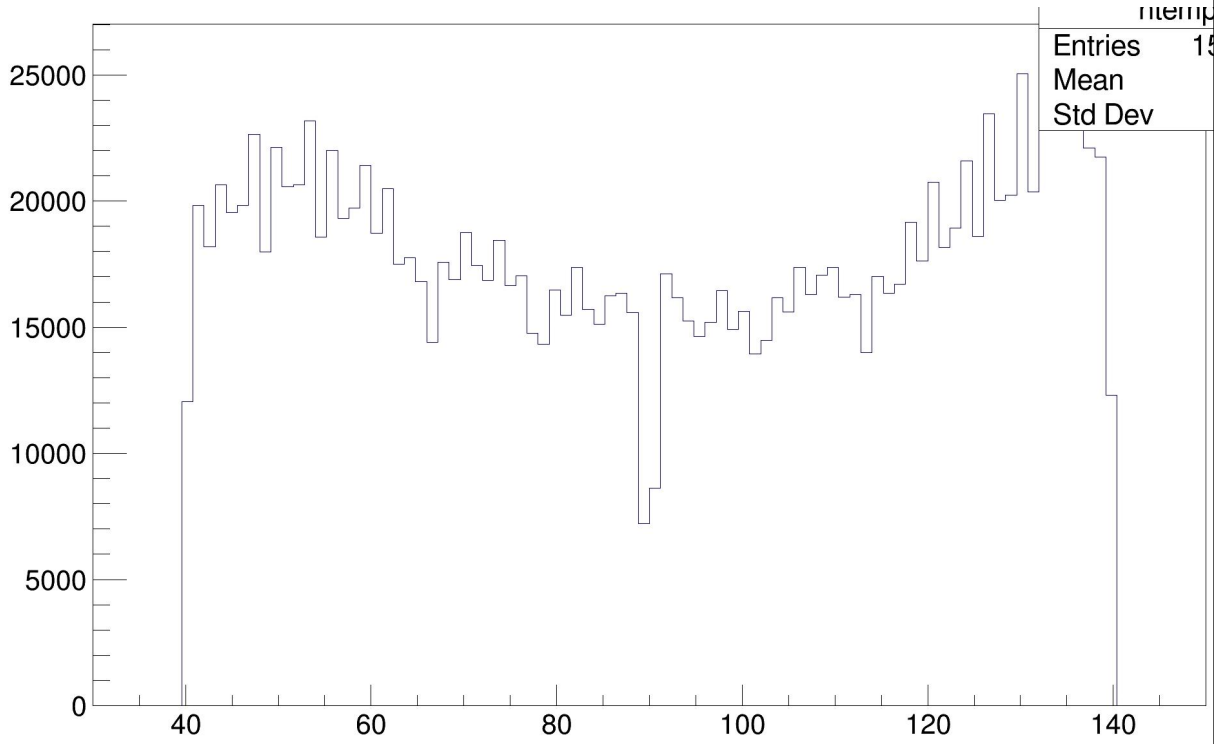
- Compare the analytical and simulation results
  - Analytical ~ simulation
- Next to do:
  - Compare hit/energy distribution with LEP2 data
  - Try WarpX

Backup

Backup



Track p_T (GeV)



Track θ