Opportunities and Challenges of the Hadronic Cross-Section at the Z-pole

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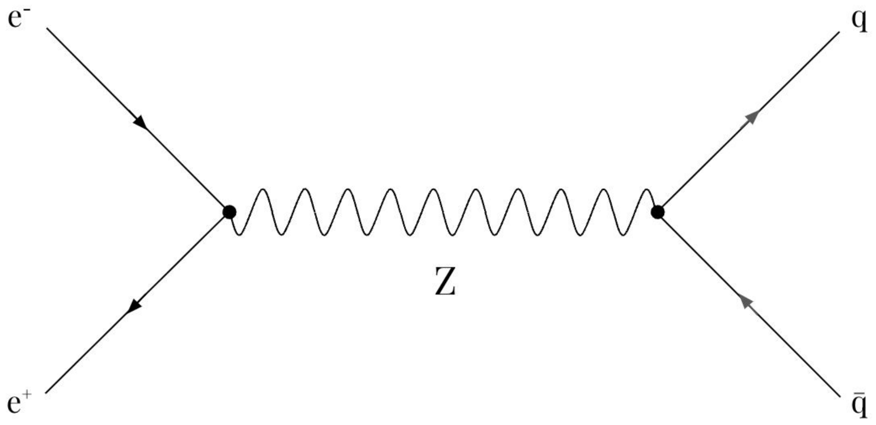
Motivation

- The FCC-ee will collect large data set (5×10^{12} events) at the Z pole with unprecedented detector precision, allowing for some of the most stringent tests of consistency of the Standard Model (SM) to date
- Crucial to understand the possible challenges to this measurement, and make predictions for the physics reach of the experiment



Goals of our analysis

- Project the precision of the FCC-ee measurements of the Z→ qq cross section using state-of-the-art Monte Carlo (MC) under FCC-ee conditions
- Compare different event generators to each other, and to LEP data
- Optimize the analysis to FCC-ee conditions
- Simulate and evaluate the impact of beam backgrounds to this analysis

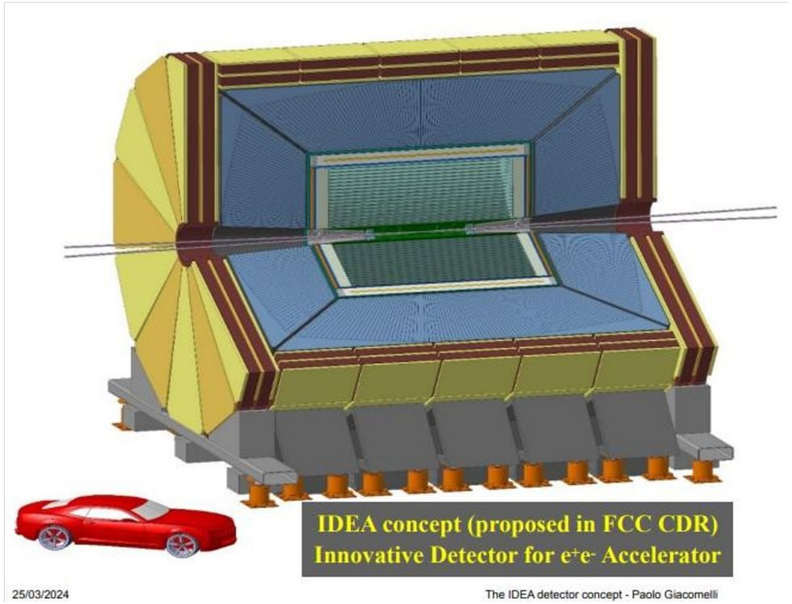
Simulation Conditions

The event generation uses nominal FCC conditions with 4 IPs

Several detector concepts:

- CLD detector: silicon vertex and tracker
- IDEA detector: silicon vertex with drift chamber
- ALLEGRO: IDEA-like tracker with liquid argon calorimeter

IDEA chosen as reference, detector simulation and reconstruction with **Delphes** (Winter 2023 campaign).

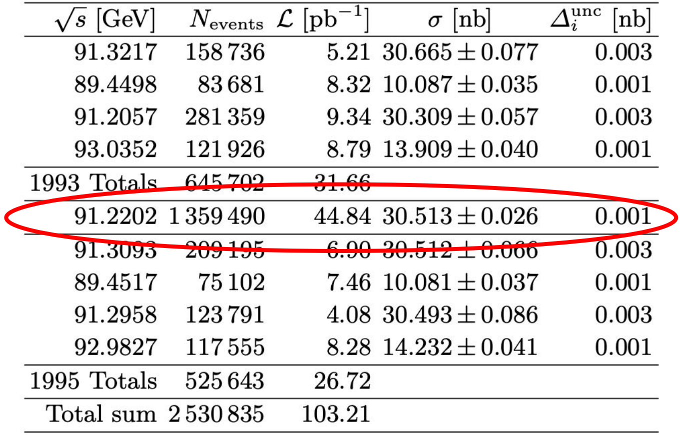


[Giacomelli, Paolo. "The IDEA Detector Concept." INFN Bologna, FCC US Workshop, Mar. 2024]

Opportunities: Reproduce LEP results to greater precision

To compare FCC-ee detector performance to L3, we replicated the distributions and measurements from their 1994 run.

The hadronic Z decays analysis was performed on peak at 91.2202 GeV with luminosity of 44.84 pb^{-1}.



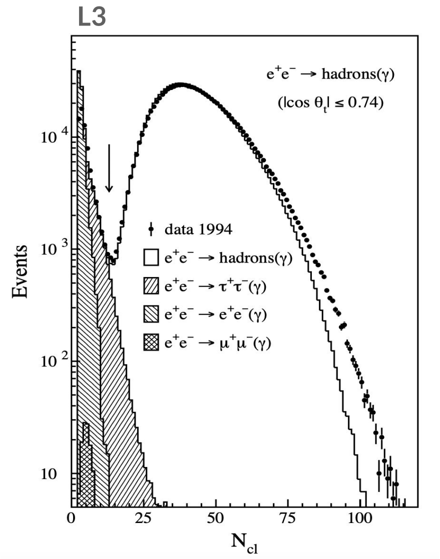
$\sqrt{s}$ [GeV]	N_{events}	$\mathcal{L}$ [pb^{-1}]	σ [nb]	Δ_i^{unc} [nb]
91.3217	158 736	5.21	30.665 ± 0.077	0.003
89.4498	83 681	8.32	10.087 ± 0.035	0.001
91.2057	281 359	9.34	30.309 ± 0.057	0.003
93.0352	121 926	8.79	13.909 ± 0.040	0.001
1993 Totals	645 702	31.66		
91.2202	1 359 490	44.84	30.513 ± 0.026	0.001
91.3093	209 195	6.90	30.512 ± 0.066	0.003
89.4517	75 102	7.46	10.081 ± 0.037	0.001
91.2958	123 791	4.08	30.493 ± 0.086	0.003
92.9827	117 555	8.28	14.232 ± 0.041	0.001
1995 Totals	525 643	26.72		
Total sum	2 530 835	103.21		

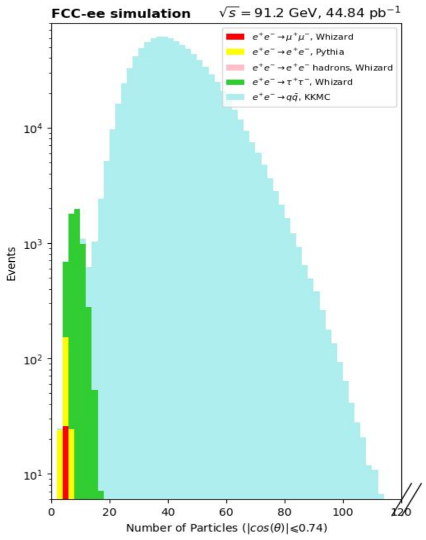
Event Selection

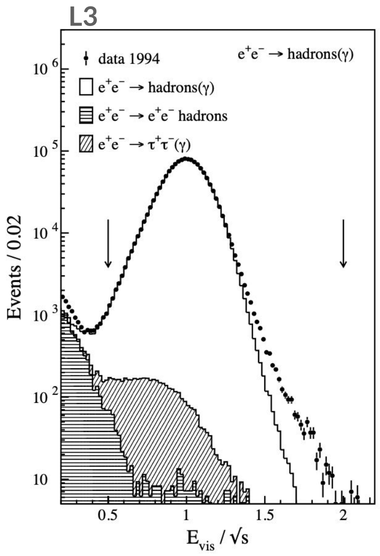
1. Visible Energy: $0.5 < E_{vis}/\sqrt{s} < 2.0$;
2. Longitudinal Energy Imbalance: $|E_{//}|/E_{vis} < 0.6$;
3. Transverse Energy Imbalance: $E_{\perp}/E_{vis} < 0.6$;
4. Number of Particles:
    a. $N_{particles} \geq 13$ for $|\cos\theta_t| \leq 0.74$,
    b. $N_{particles} \geq 17$ for $|\cos\theta_t| > 0.74$,
        i. θ_t polar angle of the event thrust axis.
    c. Difference:
        i. L3→ Counting of calorimeter clusters
        ii. FCC → Tracker, calorimeter and muon chamber (particle flow)

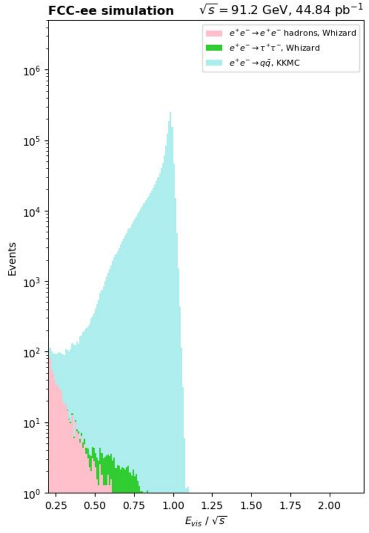
The L3 Collaboration., Acciarri et al., M. Measurements of cross sections and forward-backward asymmetries at the Z resonance and determination of electroweak parameters. Eur. Phys. J. C 16, 1–40 (2000). https://doi.org/10.1007/s100520050001

L3 Comparison





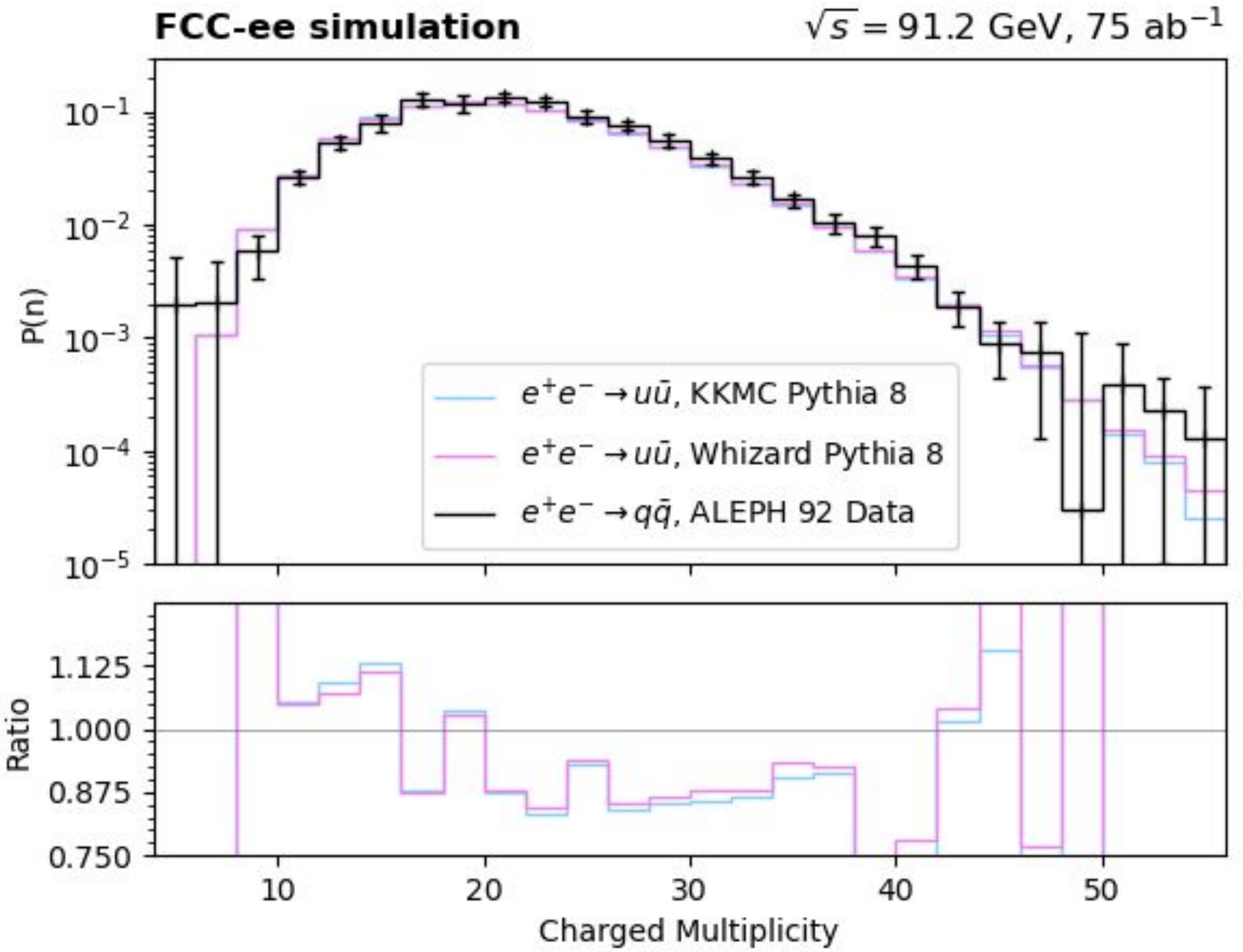




There is good agreement between FCC-ee simulations and the L3 data.

You can see that the better reconstruction at FCC allows better discrimination between signal and background.

The sharp peak instead of a broad smoother curve is due to much improved detector and Particle Flow. The energy resolution of the IDEA detector is significantly better than for all LEP detectors.



ALEPH Comparison

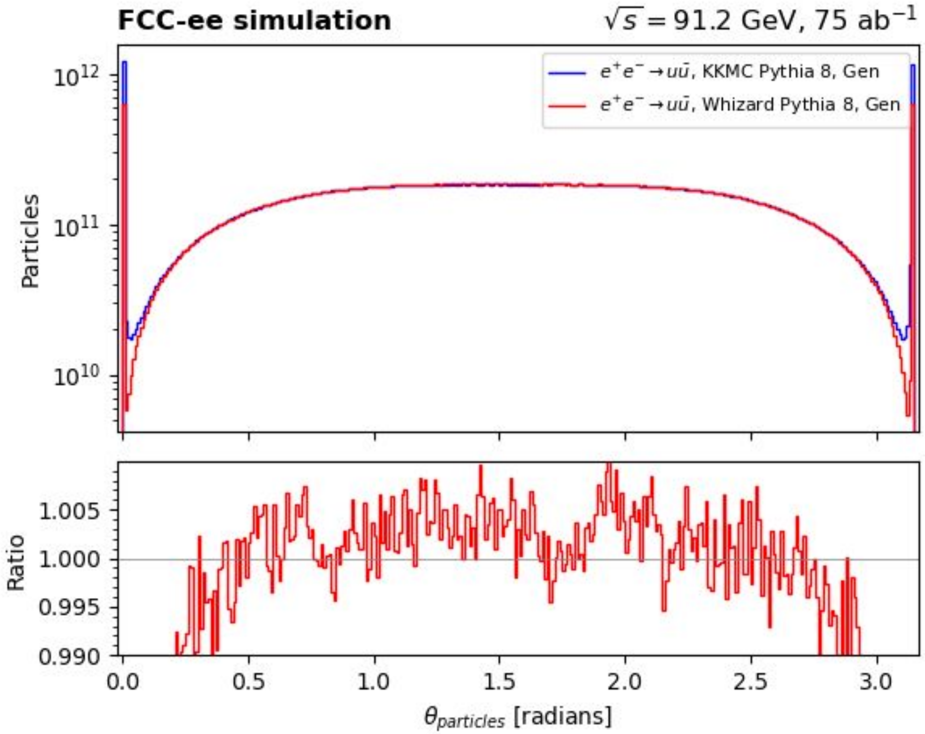
We compare two event generators (gen-level) with unfolded ALEPH data (in black) and found reasonably good agreement.

Residual differences between data and Monte Carlo due to mismodelling in hadronic showering ➜ more work to be done (tuning)

Darta from: https://doi.org/10.1016/S0370-1573(97)00045-8.

Challenge: Event generators comparison

- Compare KKMC versus Whizard
  - Different radiative corrections implemented (ISR, FSR, weak corrections)
- Significant discrepancy between the generators in the $\theta_{particles}$ distribution in the very forward region affects the analysis.
- Differences in the theta distribution are due to the different treatment of the ISR

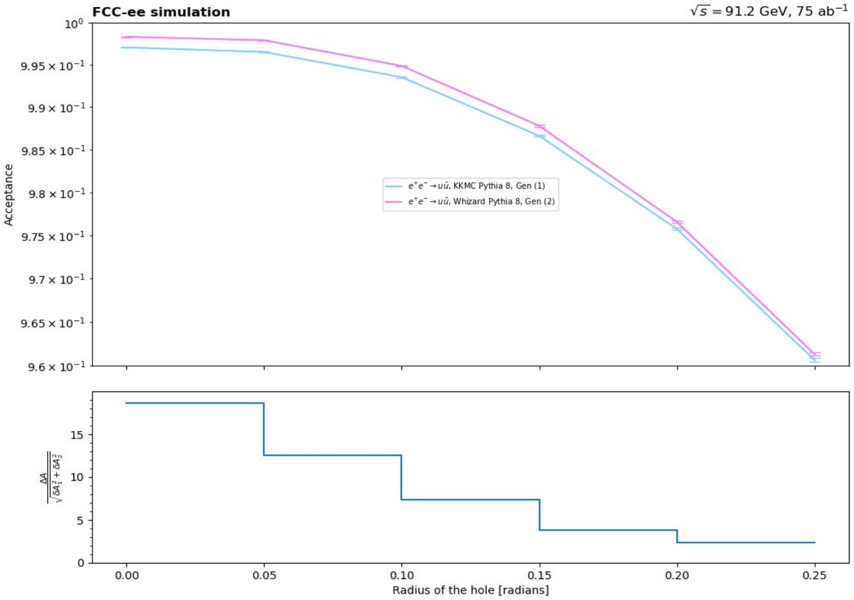


Generator level particles

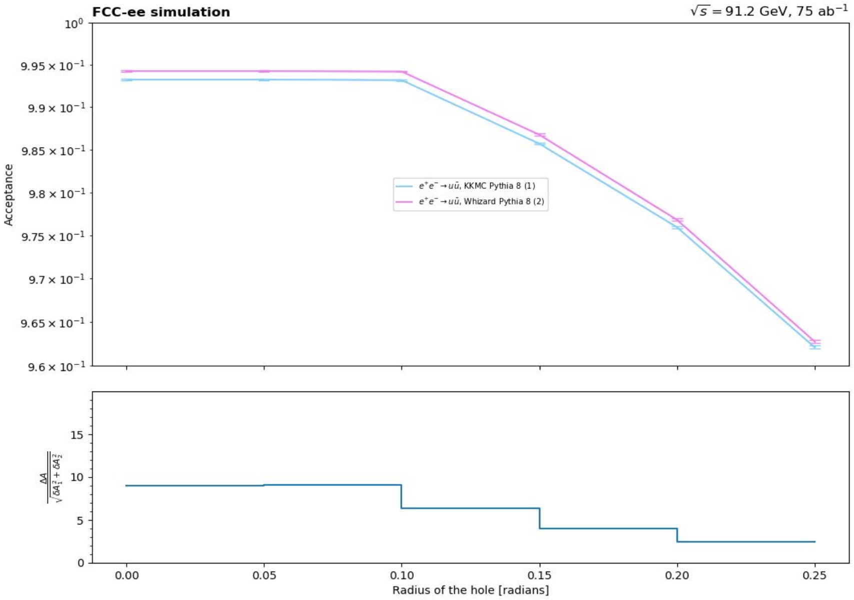
Acceptance & Definition of the detector hole

Filters selected:
$E_{vis}/\sqrt{s} \geq 0.52$, Charged Multiplicity ≥ 4.

Gen-Level



Reconstructed



Large dependence of acceptance with the detector definition that is present in both generators.

The simulations are significantly different.

Expected Uncertainties for Z→hadrons cross-section

Very large acceptance: 99.367 ± 0.006 %

Cross-section σ = 30513 ± 1.63 pb (Input cross-section scaled to L3 measurement)

$$\sigma = \frac{Nsel - Nbg}{L \cdot A \cdot \varepsilon}$$

Source	Absolute Uncertainty [pb]	Relative (%)
Statistics	0.02	7×10^{-7}
Statistical Uncertainty on Background	0.03	1×10^{-6}
Statistical Uncertainty on Acceptance	0.3	1×10^{-5}
Luminosity	1.6	5×10^{-5}
Total	1.63	5×10^{-5}

Calculated with KKMC sample.

For the process Z → qq, the L3 results from the 1994 run:

σ = (30513 ± 26) pb

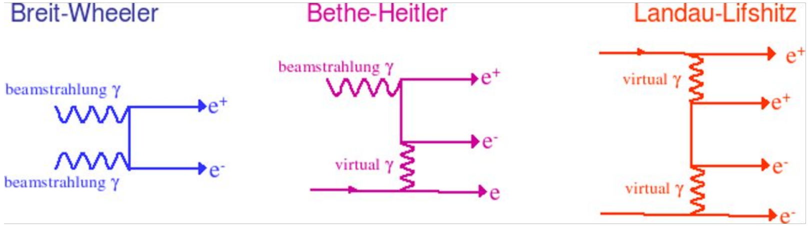
Challenge: Beam Backgrounds

- **Backgrounds in the Machine-Detector Interface (MDI) region:**
  - Incoherent Pair Creation (IPC)
  - Synchrotron Radiation
  - Hadronic Backgrounds
    - Especially important for the Z → hadrons analysis;
- **Critical to assess the impact of processes on the physics of our analysis**
  - For now we are looking at the Z-Pole. Extend this to the other 3 working points of FCCee.
- **The importance of background varies with beam energies, emittance, bunch particle type etc.**

Some of the these processes can be simulated using Guinea-Pig++

- Simulates the interaction of two colliding ultra-relativistic electron-positron beam
- **Includes:**
  - Pinching of the beams
  - Emission of beamstrahlung
  - Production of incoherent pairs
  - Production of hadronic background (also minijets)
  - …

Capable of providing output in the common event data model in the key4hep framework



Two-photon Background

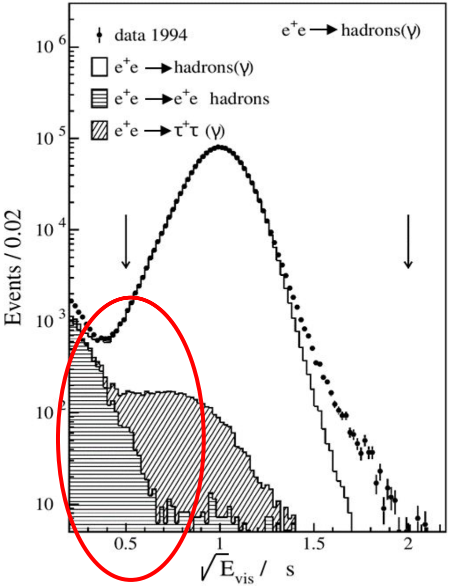
Two-photon events leak into the visible spectrum of Z→hadron phase space

- xsec rises towards low momentum transfer
- Difficult to model
- Mainly untagged scattered electrons/positrons (in beampipe) leading to imbalance of longitudinal energy

For FCC-ee, clearly a better understanding needed

- Key issues: shape in visible energy and number of particles produced
- Tails are sensitive to noise, promoting them to multi-hadron events, other final states
- Off-peak running as “control region”, or explicit tagging of e^+/e^-?
- Better MC is needed (theory community)

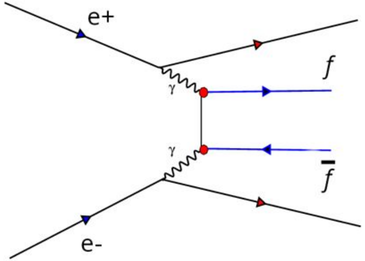
LEP experiments relied on a combination of Monte Carlo and data-driven techniques, though all within stat. uncertainty on the measurement

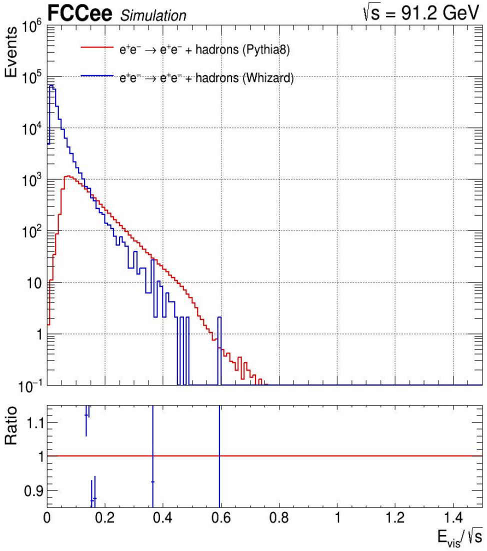


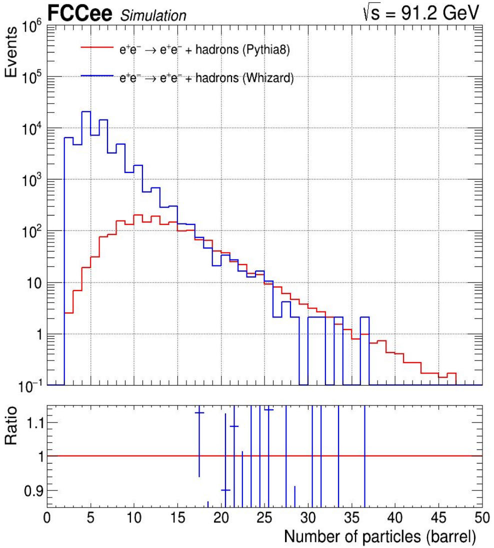
Two-photon Background

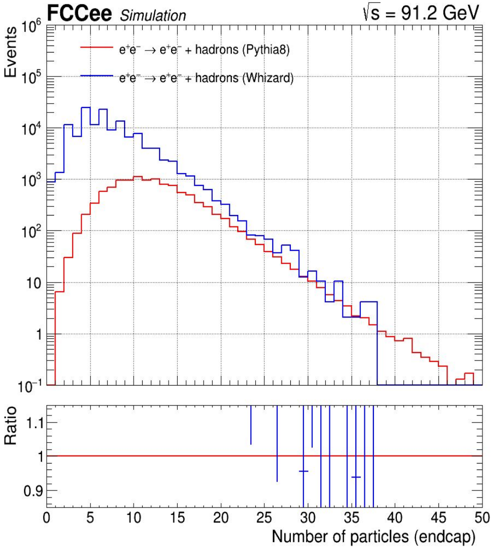
Two-photon → hadrons background can be simulated using different event generators

- **Looked at Whizard and Pythia8 implementations**
  - Pythia pushed towards higher qq energies – different cut-offs in model?
  - Fine-tuning and quantifying differences ongoing
- **Also included in Guinea-pig simulation**
  - Cross-validation ongoing, including other beam-background processes









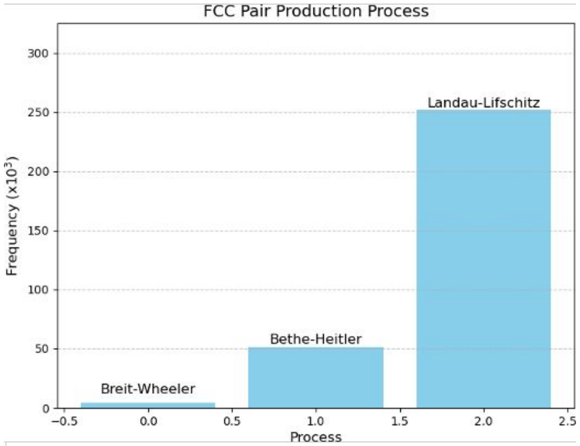
First Look at Guinea-Pig Output

Simulated with FCC-ee conditions at the Z-pole

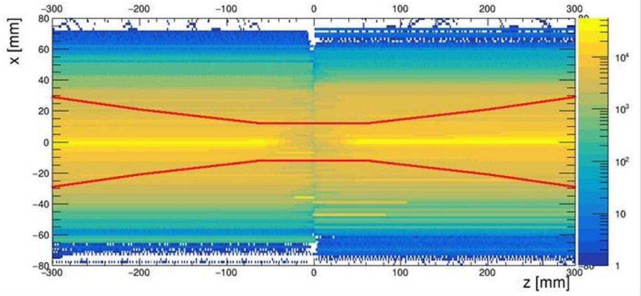
Results agree with Ciarma et al 2022 FCC-ee background study

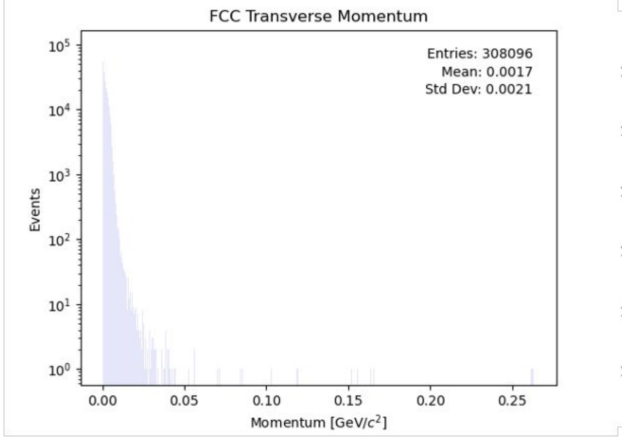
Currently only incoherent pairs simulated,

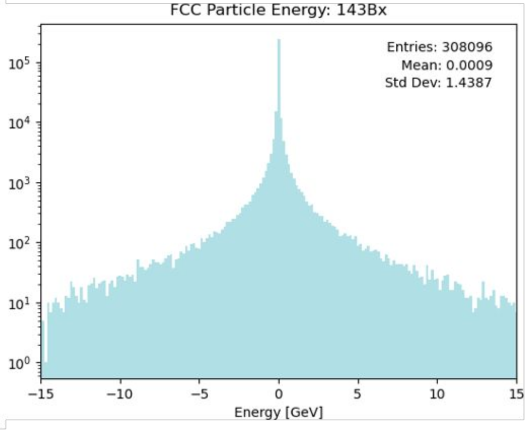
- Validate other processes as well
- Study impact on the Z-> hadrons analysis

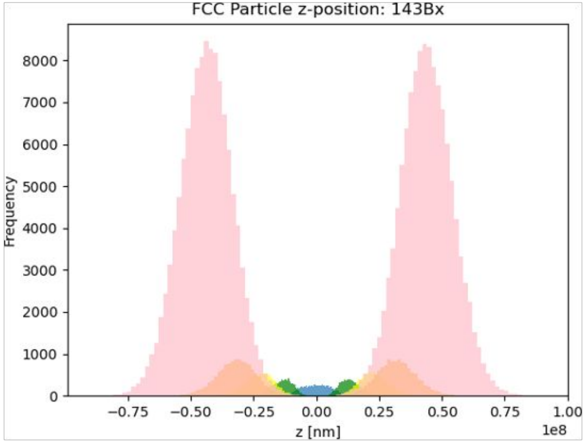

FCC Pair Production Process

FCC-ee Envelope




FCC Transverse Momentum


FCC Particle Energy: 143Bx


FCC Particle z-position: 143Bx

[Ciarma et al. doi : 10.18429/JACoW-eeFACT2022-TUZAT0203]
[Slides from Casey Lawson]

Conclusion & Next Steps

- FCC-ee simulations agree with previous results from LEP;
  - FCC-ee has much better reach compared to existing measurements;
- KKMC and Whizard in disagreement;
  - Acceptances significantly different due to different implementations.
  - Need better Monte Carlo to more accurately simulate hadronic events at the Z pole (hadronization and showering);
- Understand how beam-backgrounds affect the physics potential of FCC-ee
  - For Z → hadrons in particular, look at how this background impacts the cross-section analysis;
  - Further studies with Guinea pig will look at different processes
  - Compare different energy working points.
- Extended study of Guinea pig will be used as inputs for vertex detector design

Acknowledgements

Work on lineshape analysis

- Christoph Paus, Jan Eysermans, Luca Lavezzo

Beam Background analysis:

- Casey Lawson, Lindsey Gray

Extra Slides

Sources of Uncertainty

$$\delta^2_{\sigma} = \left(\frac{1}{L\cdot A}\right)^2 \cdot \delta^2_{sel} + \left(\frac{1}{L\cdot A}\right)^2 \cdot \delta^2_{bg} + \left(\frac{Nsig}{L\cdot A^2}\right)^2 \cdot \delta^2_{A} + \left(\frac{Nsig}{L^2\cdot A}\right)^2 \cdot \delta^2_{L}$$

1. Data Statistics

$$Statistical\ Uncertainty:\ \delta_{sel} = \sqrt{Nsel}$$

2. Statistical Uncertainty on Background

$$\delta_{bg,i} = \sigma L \cdot \frac{\sqrt{n_{sig}\cdot(1-\frac{n_{sig}}{n_o})}}{n_o},\ \delta^2_{bg} = \sum_{i\in bg} \delta^2_{bg,i}$$

3. Statistical Uncertainty on Acceptance

$$\delta_A = \frac{\sqrt{n_{sig}\cdot(1-\frac{n_{sig}}{n_o})}}{n_o}$$

4. Luminosity Uncertainty

$$\delta_L = 0.015\ ab^{-1}$$

Nsig = Number of signal events after all cuts

No = Number of signal events before all cuts

Nsel = Number of signal + background events after all cuts

Nbg = Number of background events after all cuts

A = Acceptance

L = Luminosity

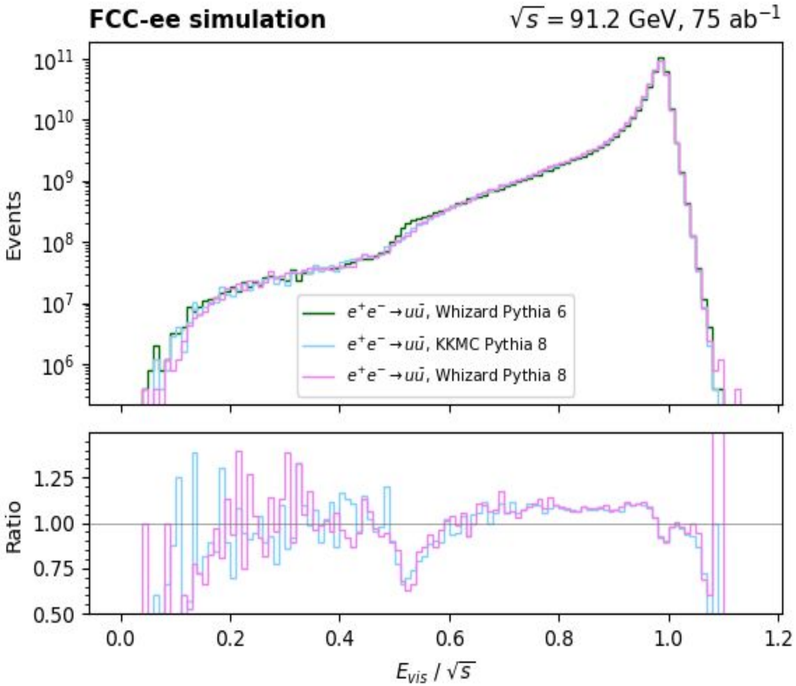
ε = Efficiency (taken to be 1)

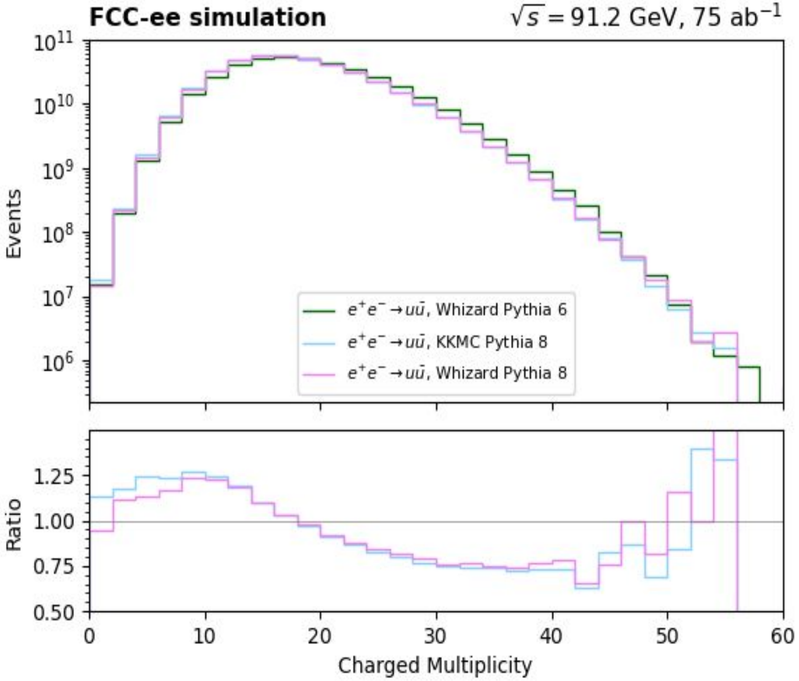
n's represent raw Monte Carlo count

Monte Carlo Samples

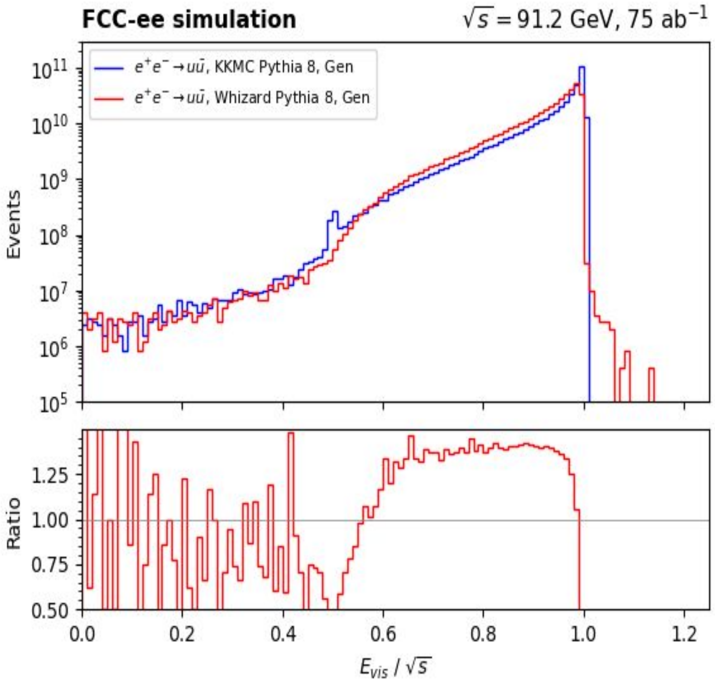
Process	Event Generator	Cross-Section (pb)	Events
$e^+e^- \rightarrow u\bar{u}$	KKMC	5353.596845	1×10^6
$e^+e^- \rightarrow dd$	KKMC	6752.078	2×10^6
$e^+e^- \rightarrow cc$	KKMC	5325.479	2×10^6
$e^+e^- \rightarrow ss$	KKMC	6763.653	2×10^6
$e^+e^- \rightarrow bb$	KKMC	6586.846	2×10^6
$e^+e^- \rightarrow u\bar{u}$	Whizard (Pythia 6)	5353.596845	1×10^6
$e^+e^- \rightarrow u\bar{u}$	Whizard (Pythia 8)	5353.596845	1×10^6
$e^+e^- \rightarrow \mu^+\mu^-$	Whizard	1717.852	2×10^7
$e^+e^- \rightarrow \tau^+\tau^-$	Whizard	1716.135	8.45×10^6
$e^+e^- \rightarrow e^+e^-$ hadrons	Whizard	11367.36	4×10^6
$e^+e^- \rightarrow e^+e^-$	Pythia	1462.09	1×10^7

Different Event Generators

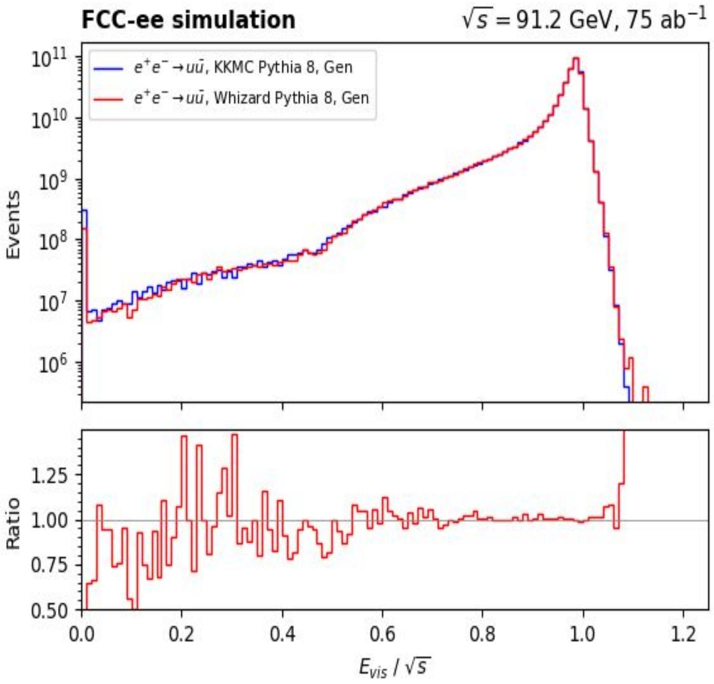




Visible Energy in different detector hole definitions



No cut on radius of detector hole



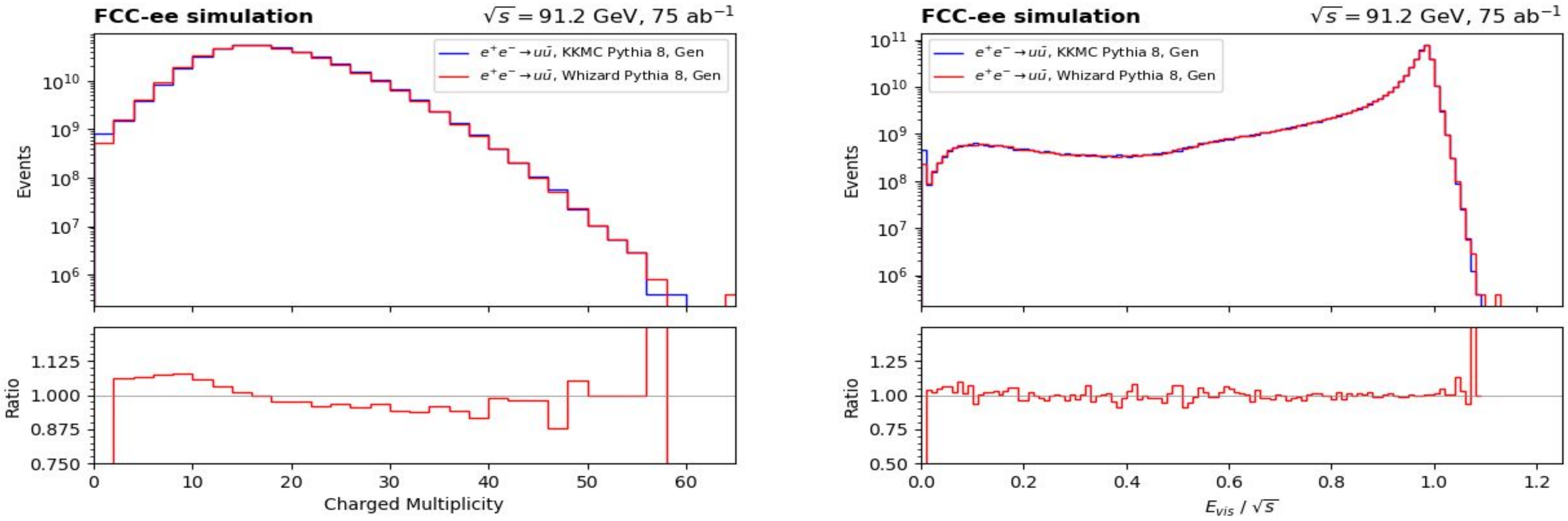
Hole of radius 0.1 radians

Large discrepancy between generators that decreases as you select only particles away from the end of the detector.

This is due to different implementations and should not account as a systematic uncertainty.

Generator level particles

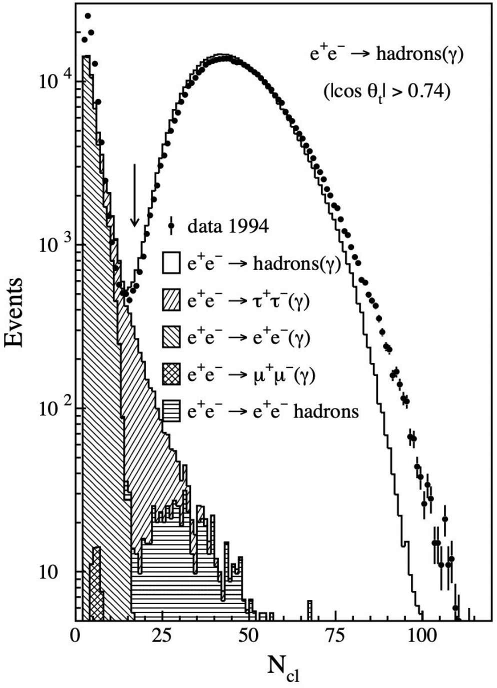
Gen level particles with detector definition on 0.3 radians

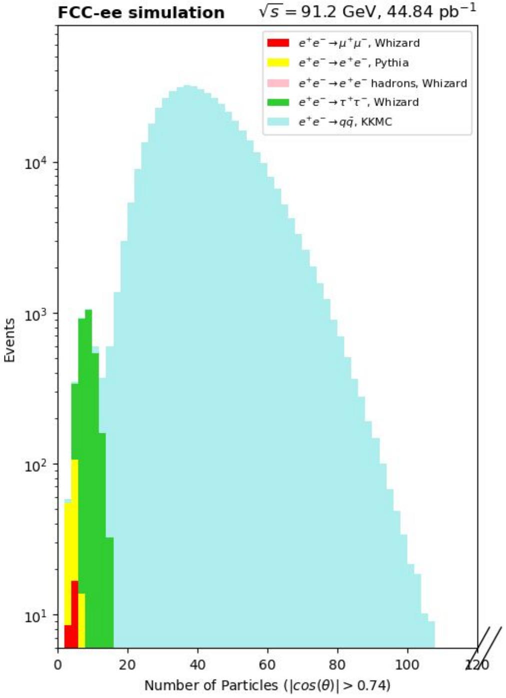


You can see much better agreement between KKMC and Whizard away from the edges of the detector.

Number of Particles/Clusters (End-Cap Region, N-1 Plot)

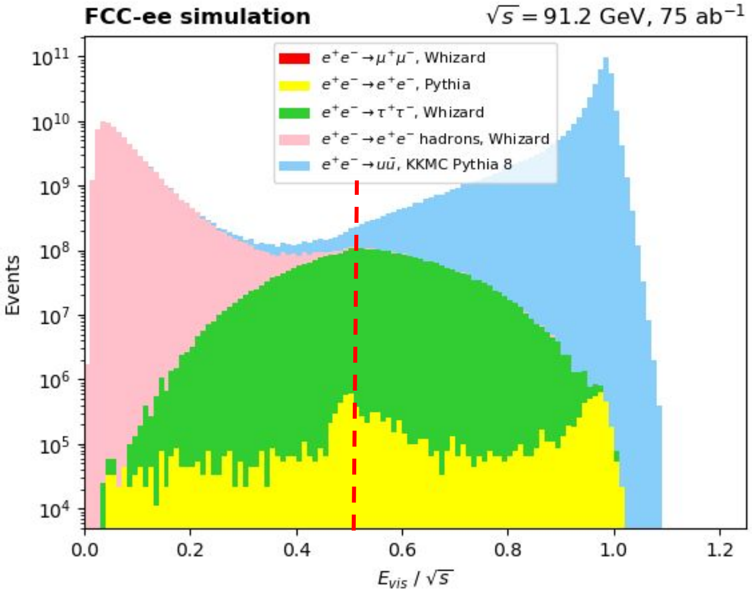
L3 Plot

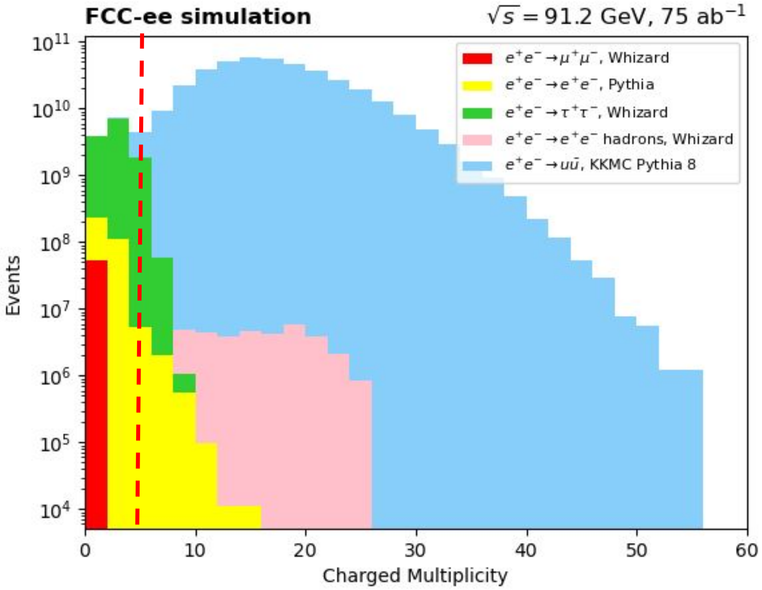




Here you can see that the two photon background, which is hard to simulate, is completely removed by other cuts.

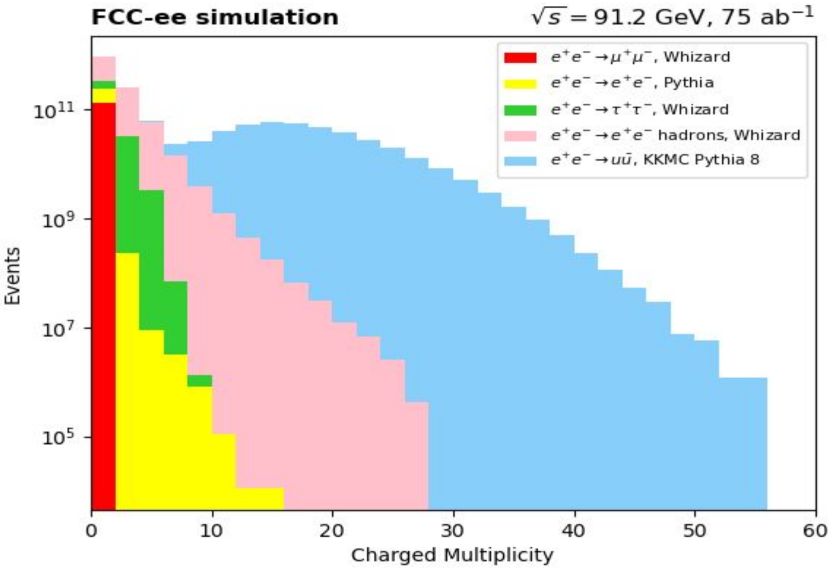
N-1 Plots

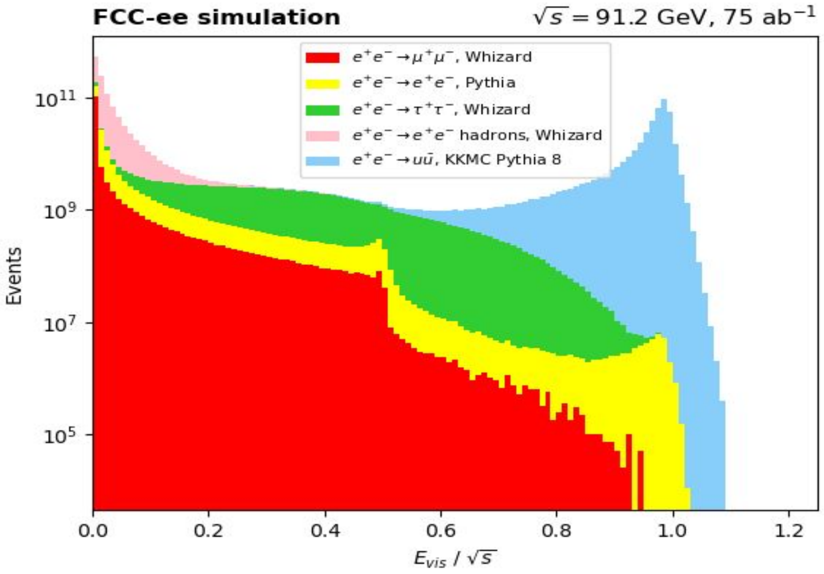




Filters selected: $E_{vis}/\sqrt{s} \geq 0.52$, Charged Multiplicity ≥ 4.

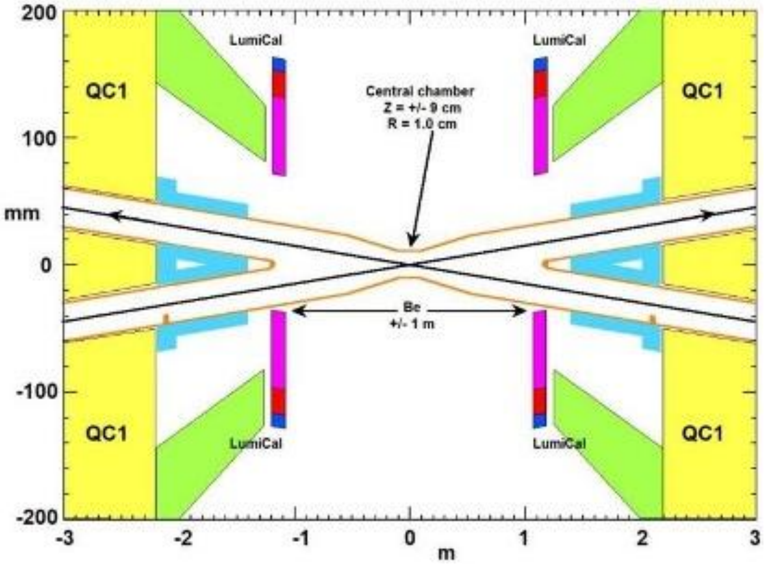
Distributions with no filters applied





FCC-ee Beam Parameters

Variable	Definition	Input FCC [Z]
energy	The energy of the particles in GeV.	45.6
particles	The number of particles per bunch in units of [10^10]	24.3
beta_x	The horizontal beta function in mm	100
beta_y	The vertical beta function in mm	0.8
espread	The RMS value of the relative energy spread of the beam particles.	0.00038
sigma_x	The horizontal beamsize in nm	8426.1
sigma_y	The vertical beamsize in nm.	33.7
sigma_z	The longitudinal beamsize in µm, the RMS value	15400.0
angle_x	The horizontal angle in rad	0.015



Key distinguishing feature:
30 mrad crossing angle

[Slides from Casey Lawson]