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

FCC Feasibility Study

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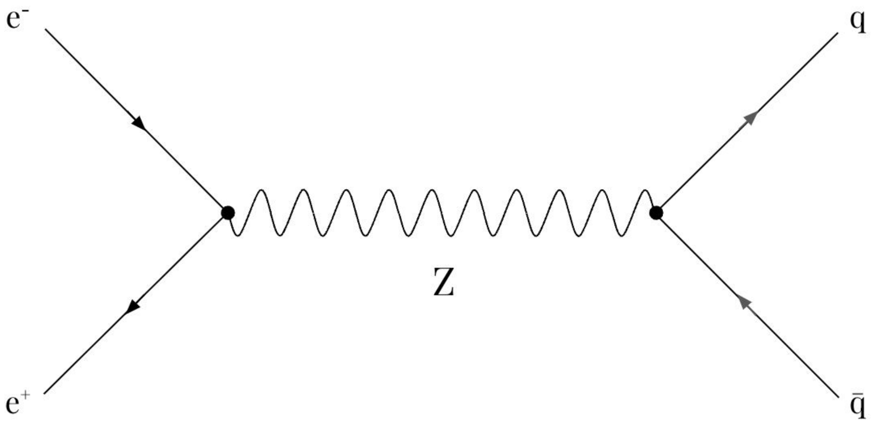
Introduction



We have been studying **hadronic decays at the Z pole** in FCC-ee conditions. Our goal is to minimize systematic uncertainties of the cross-section so that we can **take full advantage of FCC statistics.**

The hadronic channel has the highest cross-section, making it an important benchmark for the possible Physics reach of the FCC-ee.

Motivation

- Z pole running will result in an enormous data set (5×10^{12} events) with unprecedented precision; At FCC-ee it takes about a minute to accumulate an entire LEP Z pole dataset;

- At LEP, the motivation was to measure the fundamental parameters of the standard model and find discrepancies in the measurements indicating the SM is broken or better that there is physics beyond the standard model (BSM);

- At FCC-ee, consistency between all measurements will be tested more stringently than before, inconsistencies will immediately invoke new physics;

Goals of our analysis

- Adapt and compare FCC-ee simulations of Z→ qq decays to previous results from L3;
- Compare Whizard and KKMC event generators in FCC-ee conditions to see whether they agree within uncertainty;
- Study the acceptance generally and as a function of the of the detector hole (where the beam pipe enters);

The Z lineshape

The Cross-Section:

$$\sigma(\sqrt{s}) = \frac{N_{\mathrm{signal}}}{\mathcal{L}} = \frac{N_{\mathrm{selected}} - N_{\mathrm{background}}}{\varepsilon A \mathcal{L}}$$

What can we extract?

- Z mass (m_Z), Z width (Γ_Z)
- Hadronic peak cross section ($\sigma_{0,\ \mathrm{hadr}}$)
- And others

Dependency on

- CM Energy
- Luminosity
- Event counts
- Acceptance, efficiency

Importance of Monte Carlo

Estimate the number of background events

- Monte Carlo is used for most backgrounds;
- Monte Carlo can predict it precisely in most cases;

Estimating acceptance

- Crucial to calculating the cross-section and its uncertainty;
- Two event generators are in significant disagreement about the $Z \to qq$ acceptance, which makes it harder to derive systematic uncertainties;
- This is the focus of our analysis.

Monte Carlo Samples

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

The event generation used nominal FCC parameters for the Beam Energy Spread (0.132 %) and Bunch dimensions

Detector simulation used the **IDEA detector with Delphes** (Winter 2023 campaign).

L3 Comparison

L3 Results

Table 14. Average centre-of-mass energies, number of selected events, integrated luminosities and measured cross sections with statistical errors for $e^+e^- \rightarrow$ hadrons(γ). The cross sections are quoted for $\sqrt{s'} > 0.1\sqrt{s}$. Apart from the uncorrelated part listed, Δ_i^{unc}, systematic errors consist in addition of a fully correlated multiplicative contribution, $\delta_i^{cor} = 0.39^0/_{00}$ and an absolute uncertainty, $\Delta_i^{abs} = 3.2$ pb. Systematic errors from the luminosity measurement (Tables 4 and 6) have to be added. The data sets are ordered following Table 6

$\sqrt{s}$ [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		

Focus on reproducing the results from 1994 run of L3.

The hadronic Z decays analysis was performed on peak at 91.2202 GeV with luminosity of 44.84 pb^{-1} which we are going to be adopting for our simulations of the L3 results.

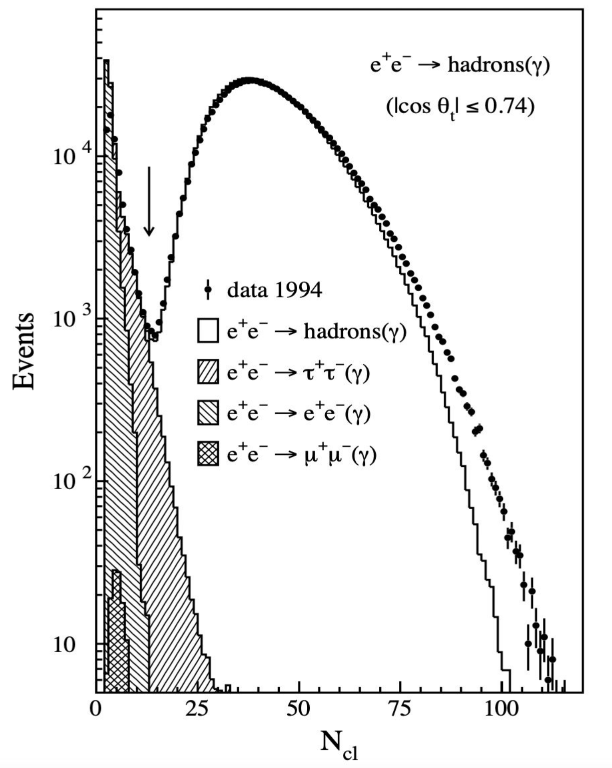
The L3 Collaboration., Acciarri et al., M. Measurements of cross sections and forward-backward asymmetries at the Z resonance and determination of electroweak parameters. Eur. Phys. J. C 16, 1–40 (2000). https://doi.org/10.1007/s100520050001

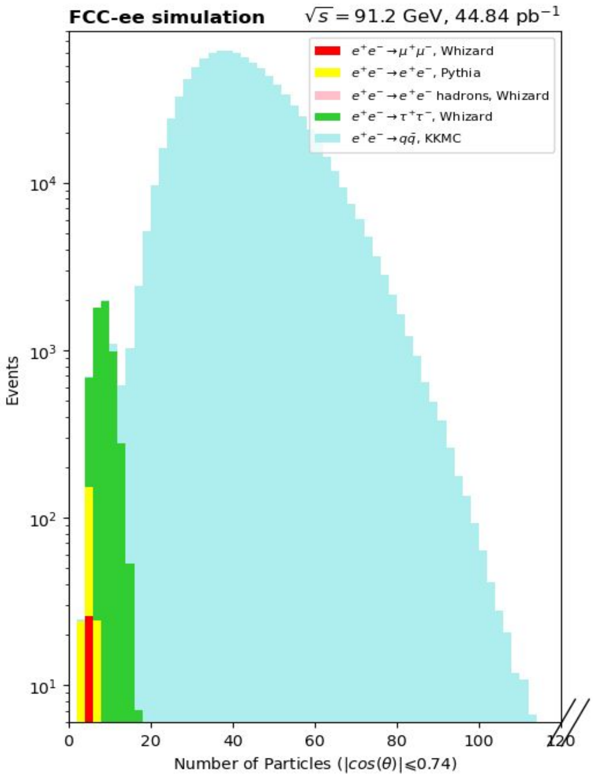
Event Selection

1. $0.5 < E_{vis}/\sqrt{s} < 2.0$;
   a. E_{vis} is the total energy observed in the detector normalised to the centre-of-mass energy;
2. $|E_{//}|/E_{vis} < 0.6$;
   a. $E_{//}$ is the energy imbalance along the beam direction;
3. $E_{\perp}/E_{vis} < 0.6$;
   a. $E_{\perp}$ is the transverse energy imbalance;
4. The number of particles per event, $N_{particles}$, is required to be:
   a. $N_{particles} \geq 13$ for $|\cos\theta_t| \leq 0.74$ (barrel region),
   b. $N_{particles} \geq 17$ for $|\cos\theta_t| > 0.74$ (end-cap region), where θt is the polar angle of the event thrust axis.
   c. This differs from L3 as they used the number of clusters from energy depositions in the calorimeter while we used the number of particles reconstructed from the tracker, the calorimeter and the muon chamber.

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

L3 Plot



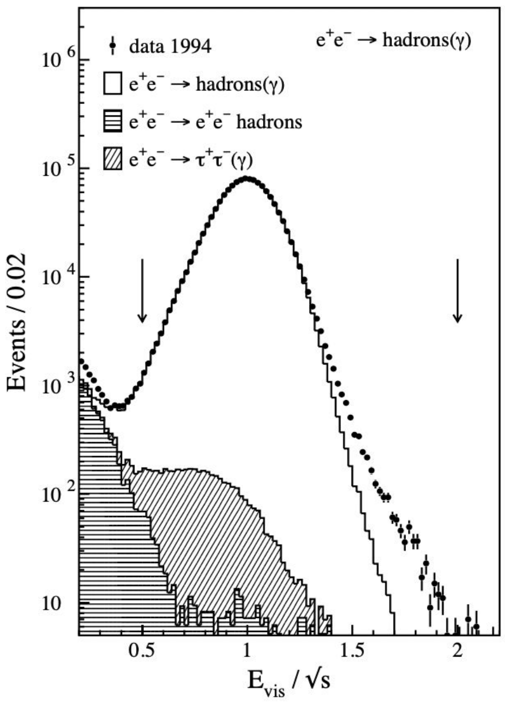


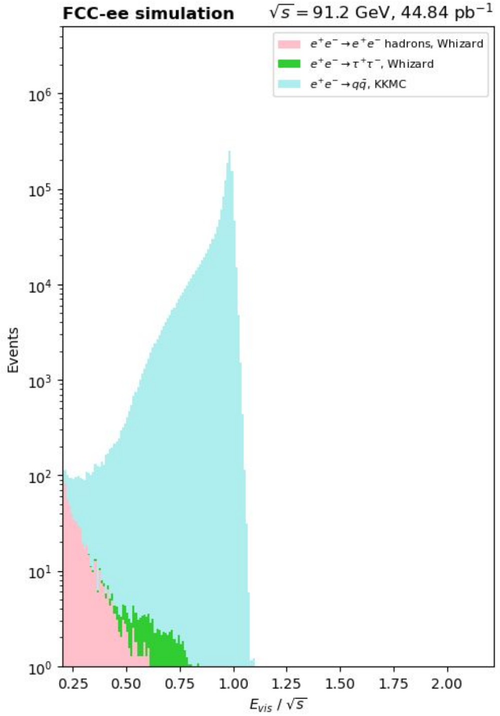
There is good agreement between FCC-ee simulations and the L3 data.

You can see that improved tracking at FCC allows better discrimination between signal and background.

Normalized Scalar Energy (N-1 Plot)

L3 Plot





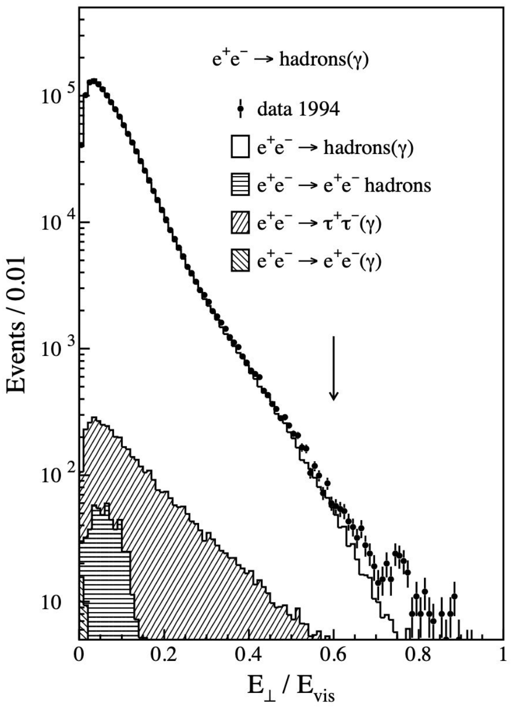
Almost all two photon background (in pink) does not satisfies the requirement 0.5 < $E_{vis}/\sqrt{s}$, explaining the discrepancy in the amount of this background present the previous plot.

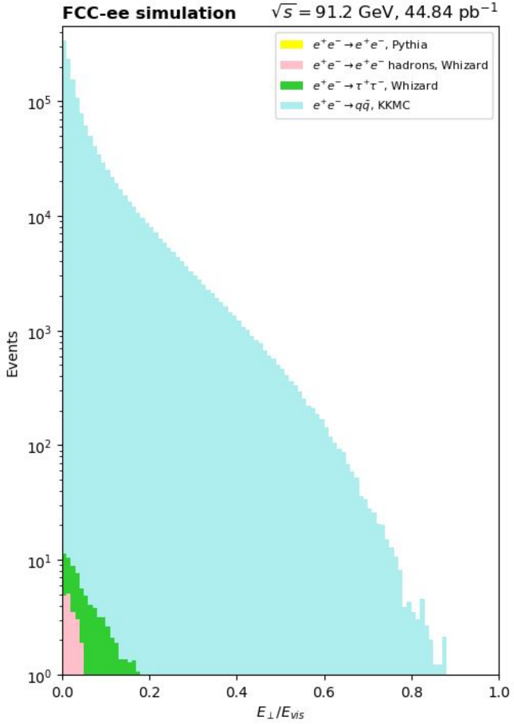
You can see that the better reconstruction at FCC allows better discrimination between signal and background.

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

Transverse Energy Imbalance (N-1 Plot)

L3 Plot





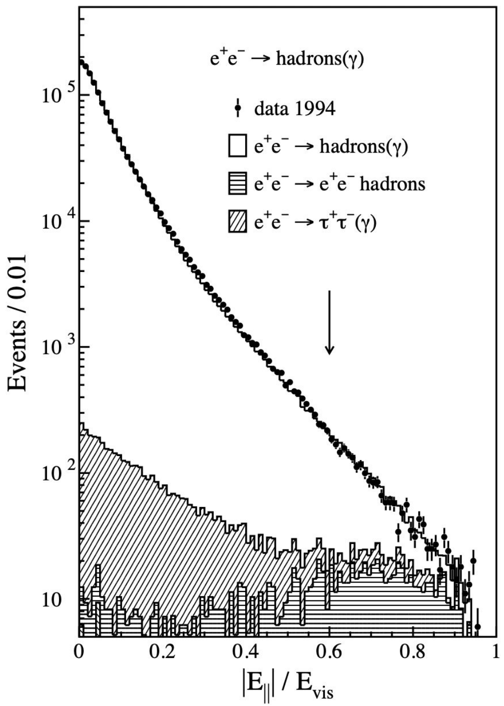
The differences in the filters impact the amount of background, to the point that there is no visible e^+e^-.

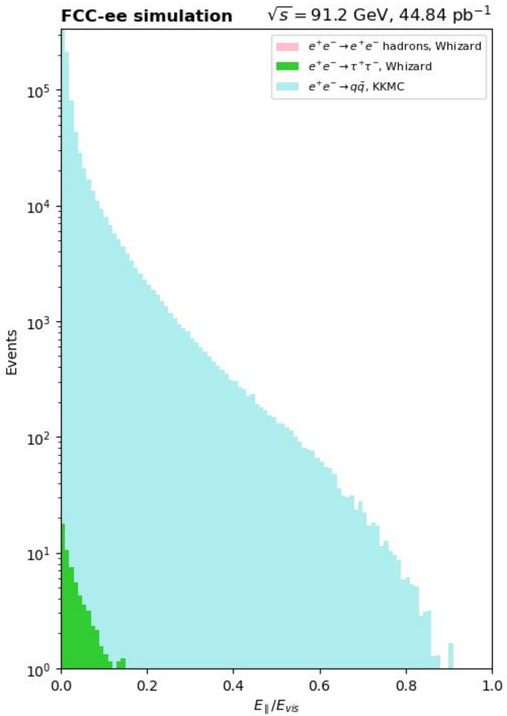
Improvements in the detector also justify the sharper peaking behavior towards 0.

The transverse energy imbalance helps to reject backgrounds not described by Monte Carlo.

Longitudinal Energy Imbalance (N-1 Plot)

L3 Plot





The accuracy of the Monte Carlo (currently under study) description impacts the amount of background: there is no visible two photon background.

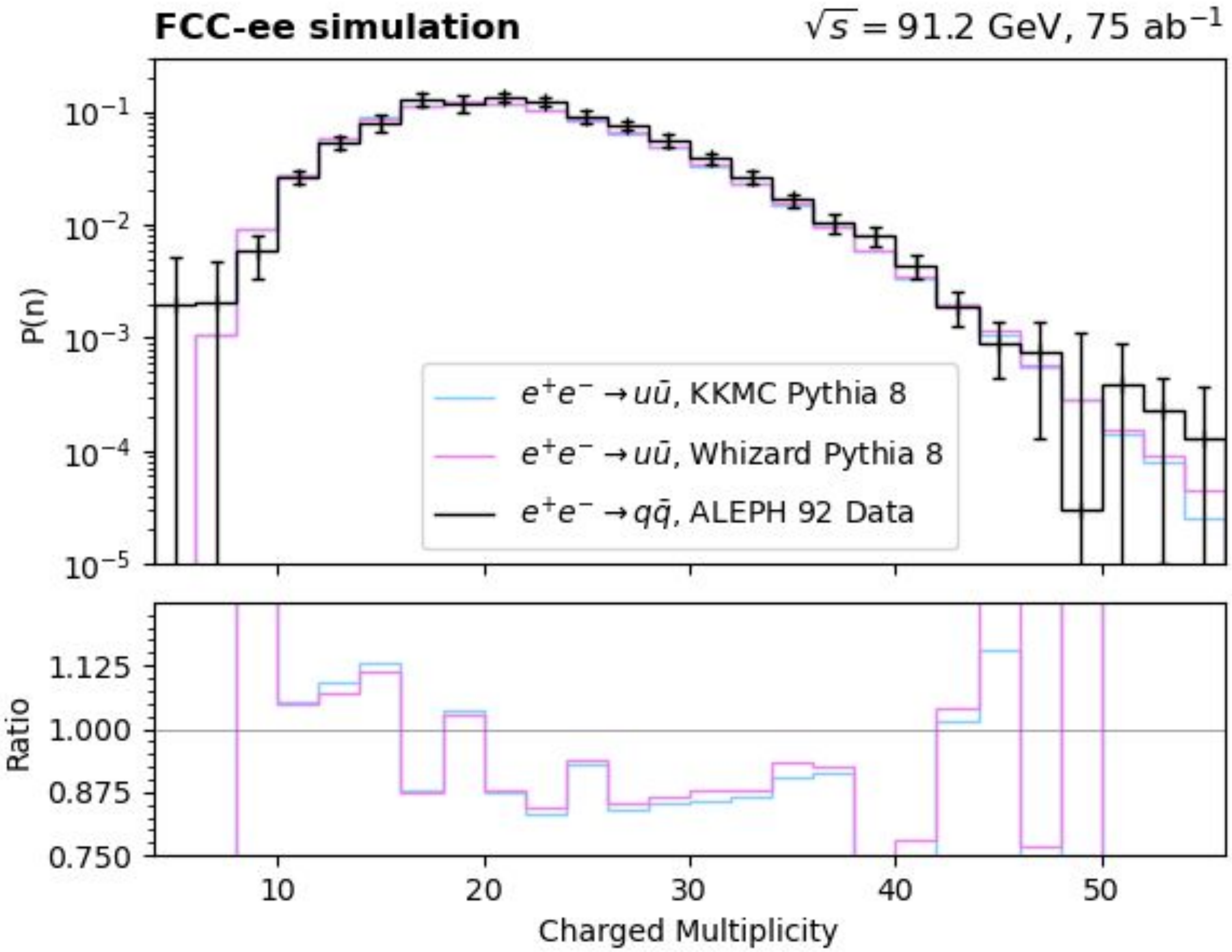
Improvements in the detector also justify the sharper peaking behavior towards 0.

Optimization for FCC-ee

- Since improvements will be made in the detector, we are using different filters to better suit the FCC-ee conditions and improve the significance.
- The luminosity now considered is a projected FCC-ee one of 75 ab^{-1} on peak.
- Need to choose between Z→hadrons event generators
  - Pythia for showering
  - KKMC versus Whizard
    - Different orders implemented

(For now, we are only going to analyse Z → uu. Further studies will also look at other flavors.)

ALEPH Comparison

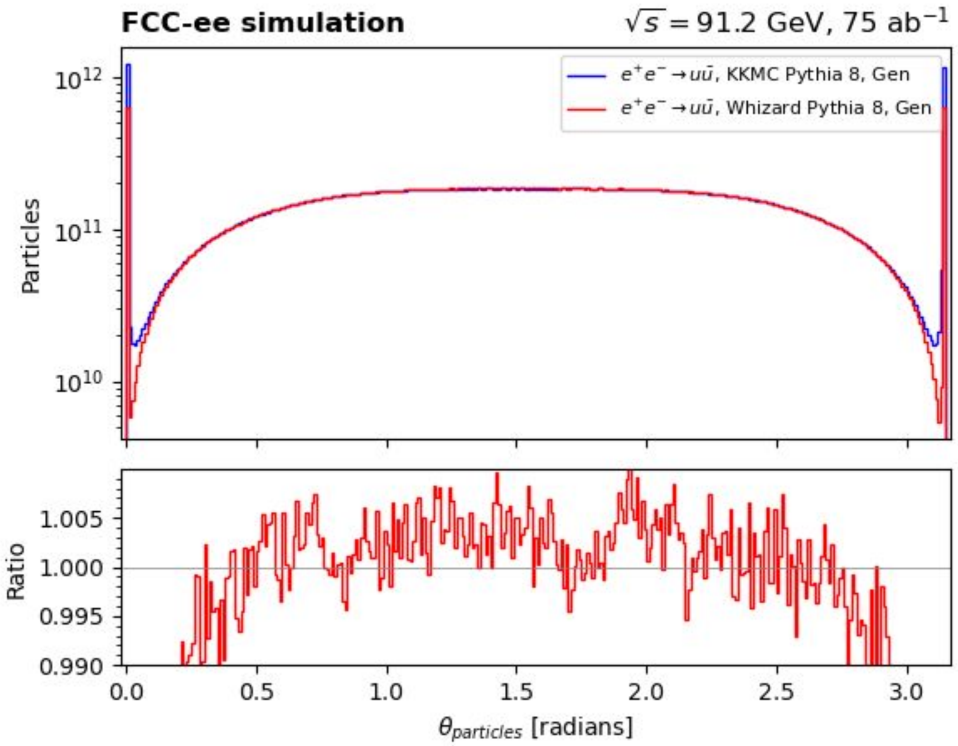


Both generators (gen-level) are in fair agreement with unfolded ALEPH data (in black), even though they might differ from each other in other measurements. The modelling of hadronization and multiplicities should still be improved for FCC-ee.

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

Generator level particles

Comparing KKMC and Whizard at gen level particles

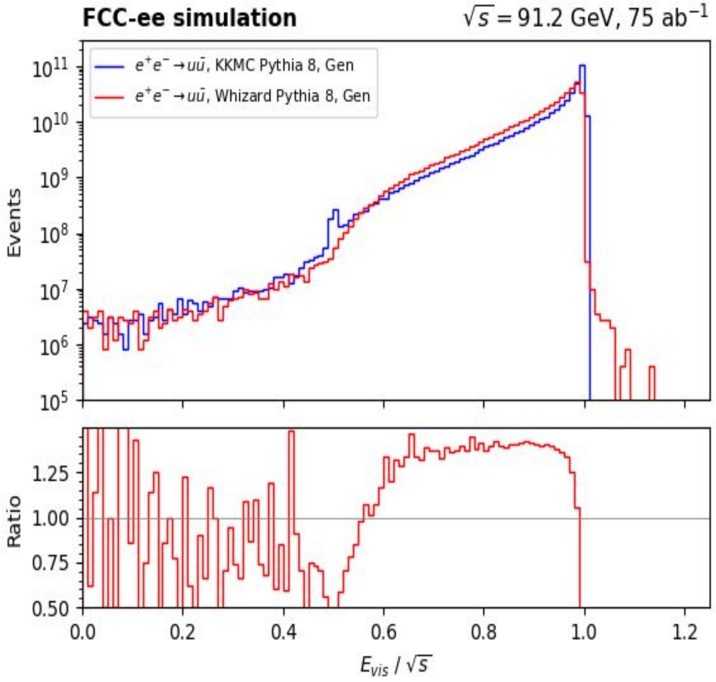


Significant discrepancy between the generators in the $\theta_{\text{particles}}$ distribution in the very forward region affects the analysis.

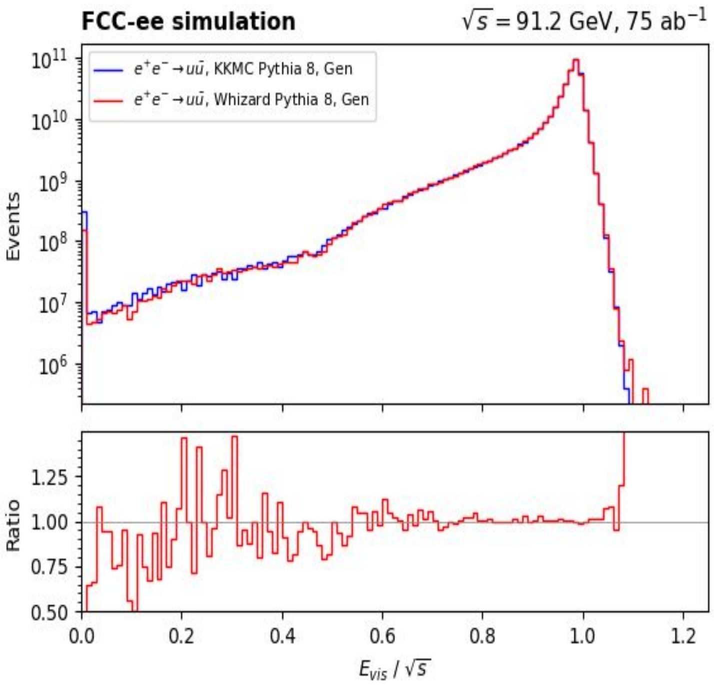
Differences in the theta distribution are due to the different treatment of the ISR, calculation order of the hard interaction and potential extra radiative corrections applied.

This introduces a difference in the acceptance of the generators that decreases if we restrict the analysis to select particles only away from the end of the detector.

Visible Energy in different detector hole definitions



No cut on radius of detector hole



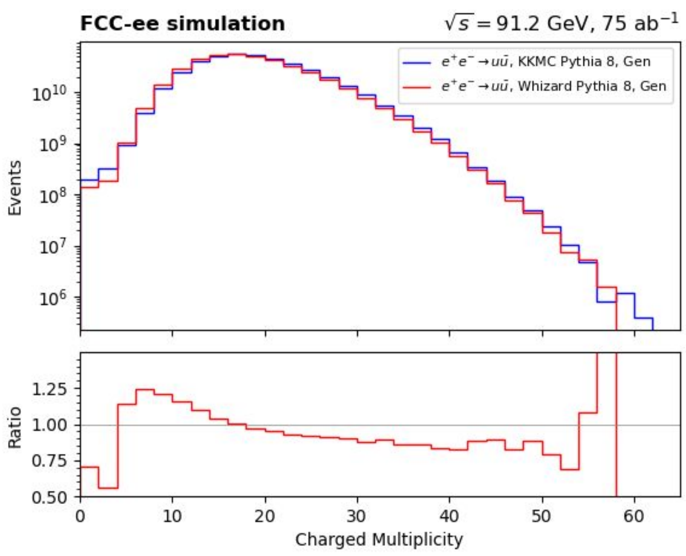
Hole of radius 0.1 radians

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

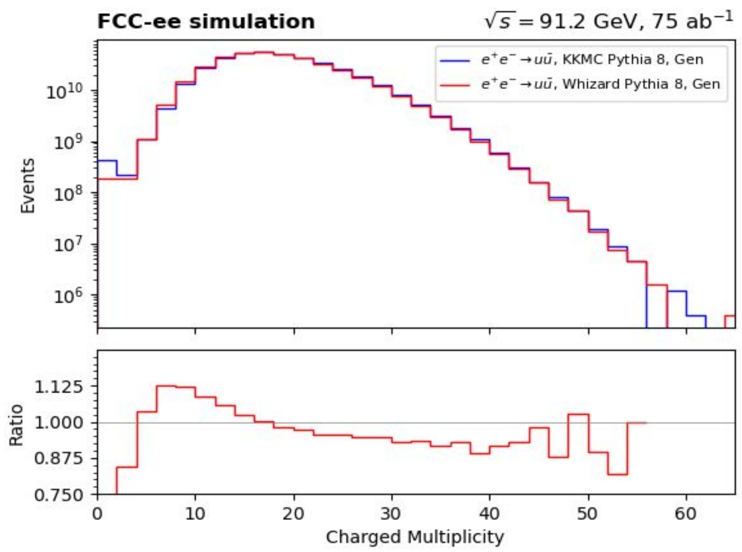
This is due to different implementations and should not account as a systematic uncertainty.

Generator level particles

Charged Multiplicities in different detector hole definitions



No cut on radius of detector hole

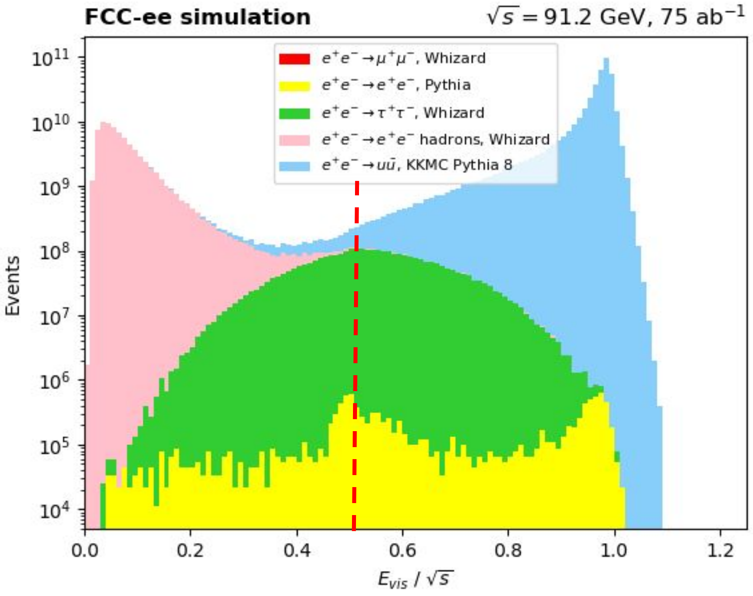


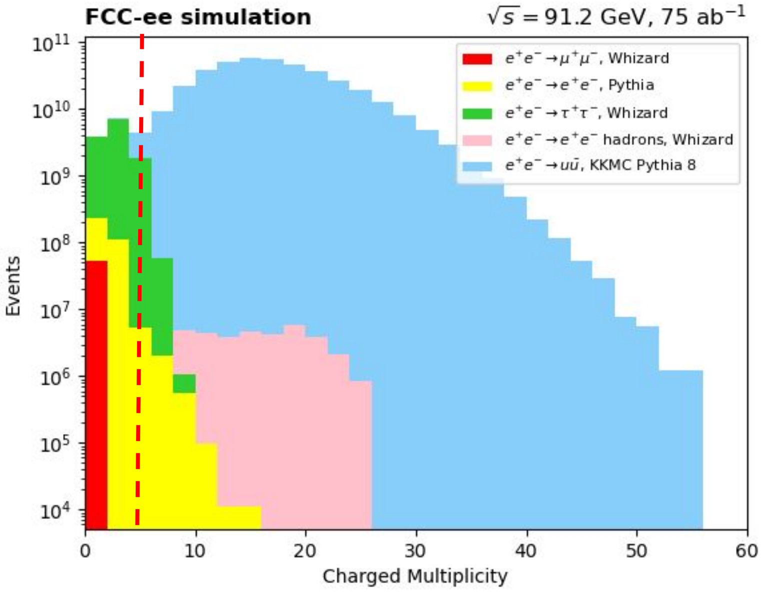
Hole of radius 0.1 radians

The charged multiplicity is in better agreement than the visible energy, but there are still significant differences present, even though both agree with ALEPH.

Generator level particles

N-1 Plots

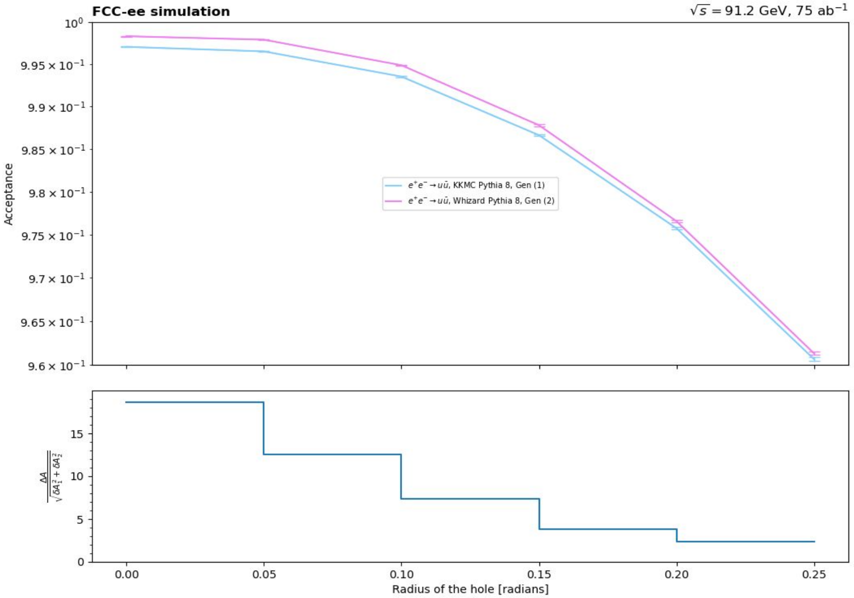




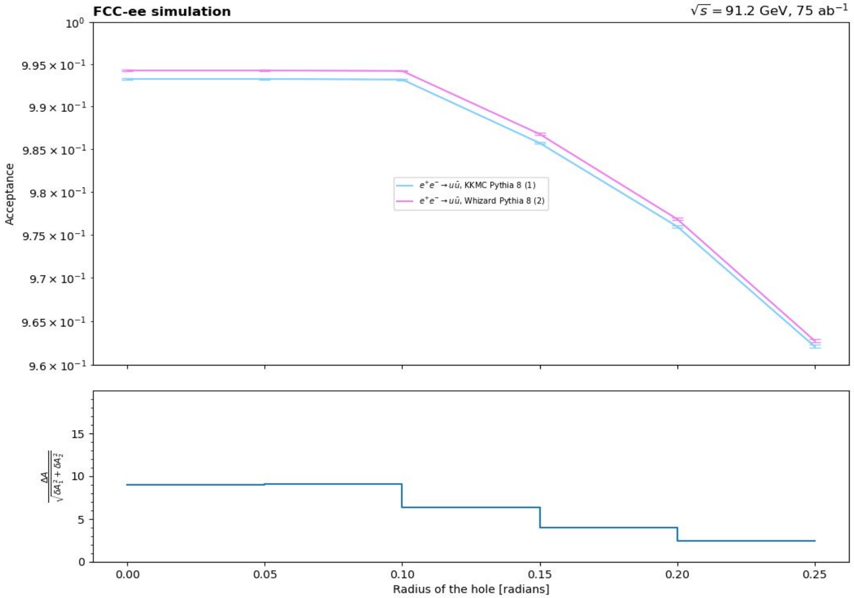
Filters selected: $E_{vis}/\sqrt{s} \geq 0.52$, Charged Multiplicity ≥ 4.

Acceptance & Definition of the detector hole

Gen-Level



Reconstructed



Great dependence of acceptance with the detector definition that is present in both generators. The simulations are significantly different.

FCC-ee Uncertainties

For the process Z → qq, we have for FCC-ee:

A = (99.367 ± 0.006) %, σ = (30513 ± 1.63) pb

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

Conclusion & Next Steps

- FCC-ee simulations agree nicely with previous results from L3;
    - FCC-ee has much better reach compared to existing measurements;

- KKMC and Whizard are in disagreement;
    - They present different distributions in end-cap regions.
    - Their acceptance are significantly different.
    - These differences come from the different implementations.
    - We are still in need of better Monte Carlo to more accurately simulate hadronic events at the Z pole and the hadronization and the showering;

- Extend the FCC-ee simulation analysis for different quark flavors.

Thank you!

Work on lineshape analysis

- Christoph Paus, Jan Eysermans, Luca Lavezzo

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

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

3. Statistical Uncertainty on Acceptance

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

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

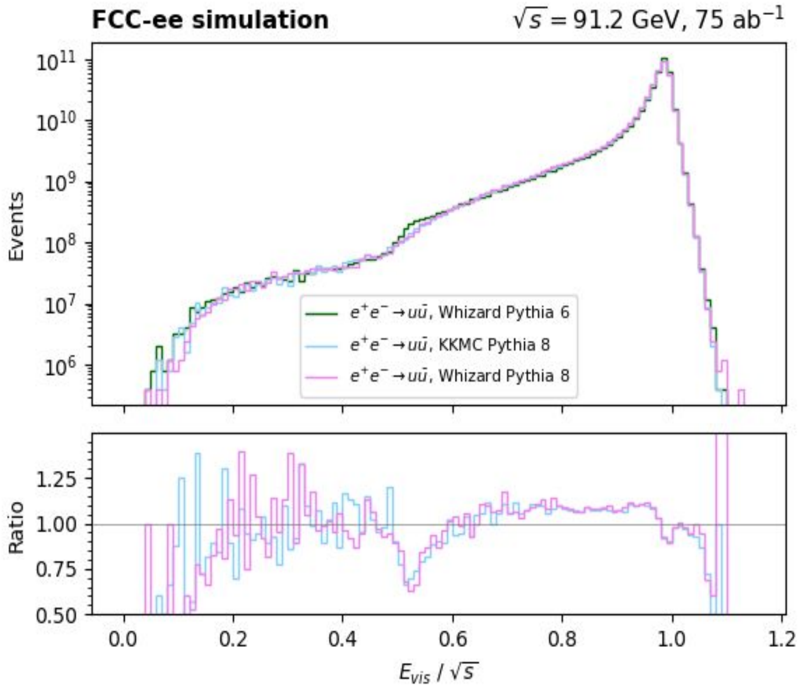
A = Acceptance

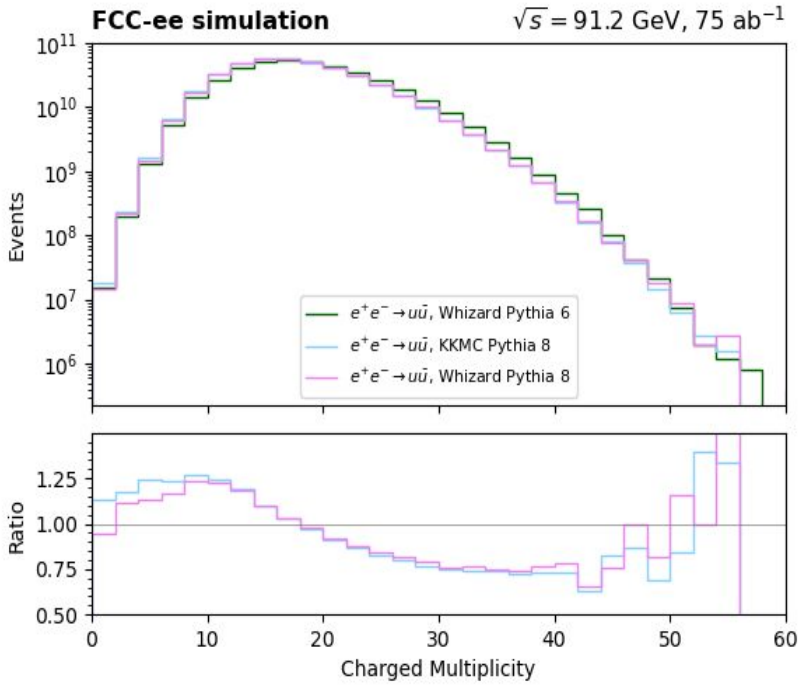
L = Luminosity

ε = Efficiency (taken to be 1)

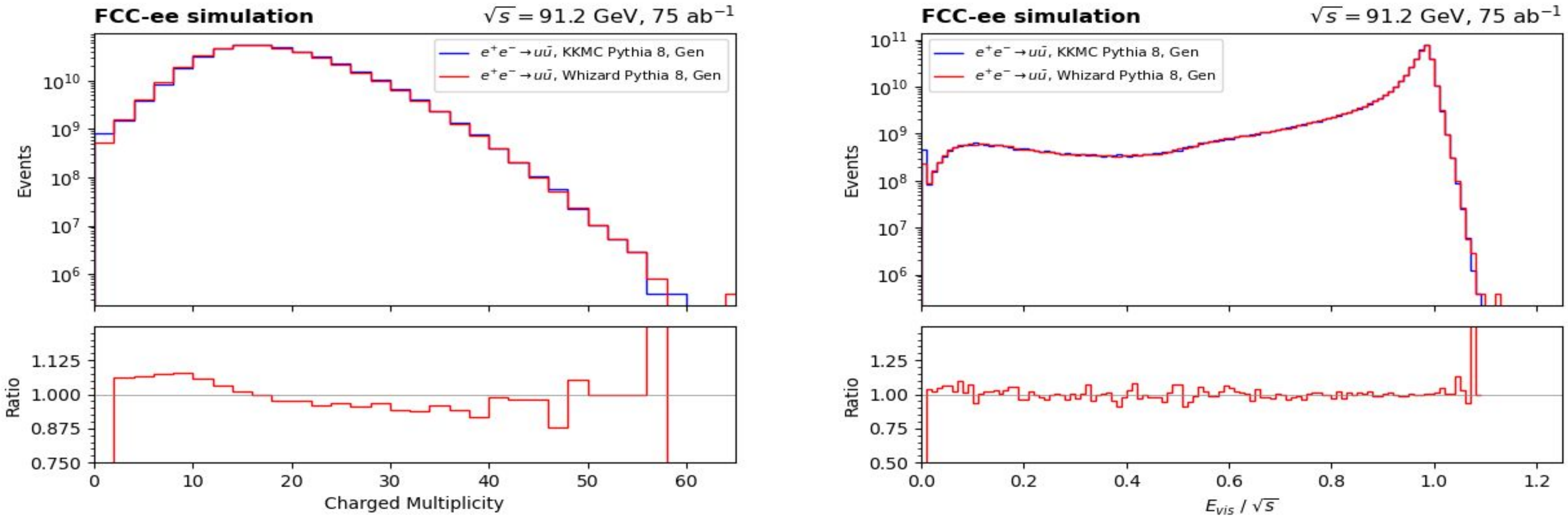
n's represent raw Monte Carlo count

Different Event Generators





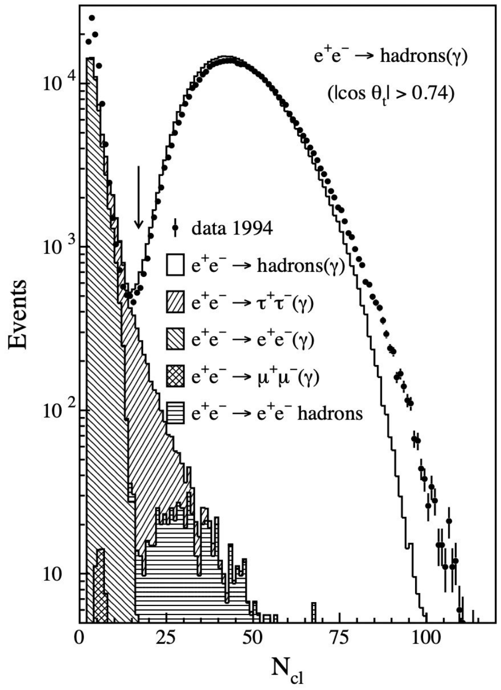
Gen level particles with detector definition on 0.3 radians

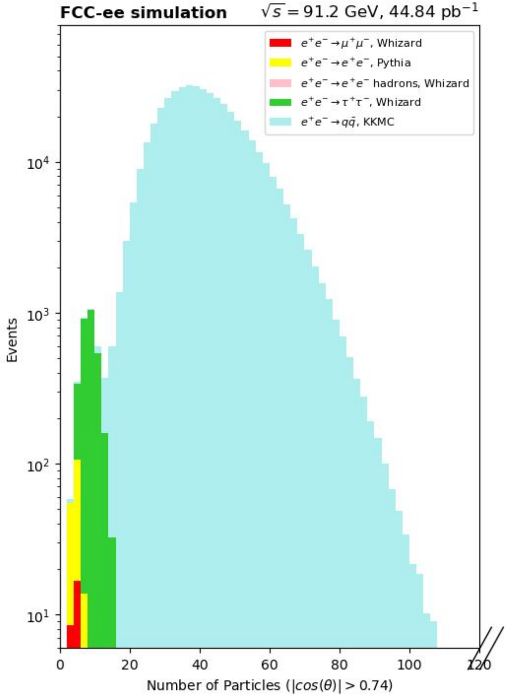


You can see much better agreement between KKMC and Whizard away from the edges of the detector.

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

L3 Plot

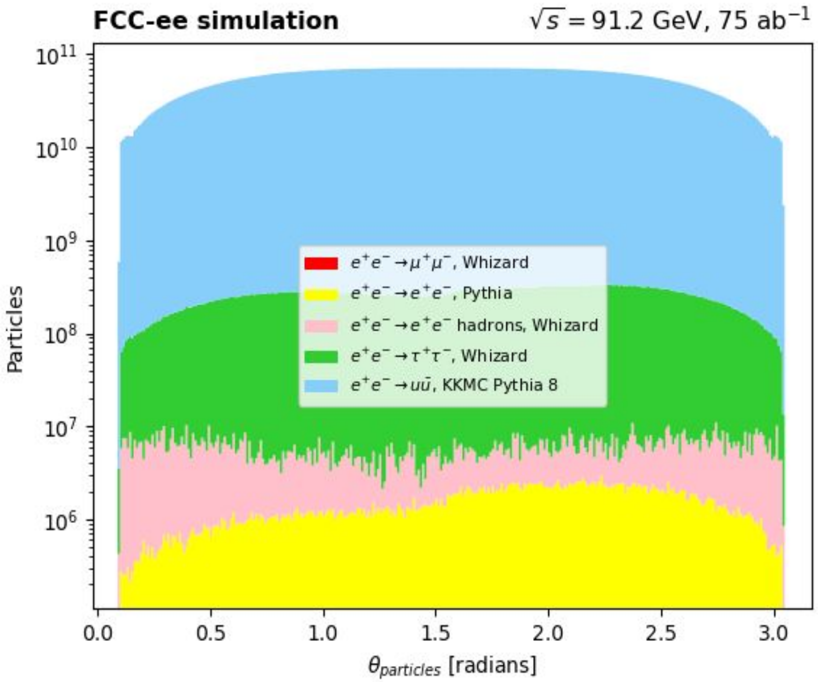


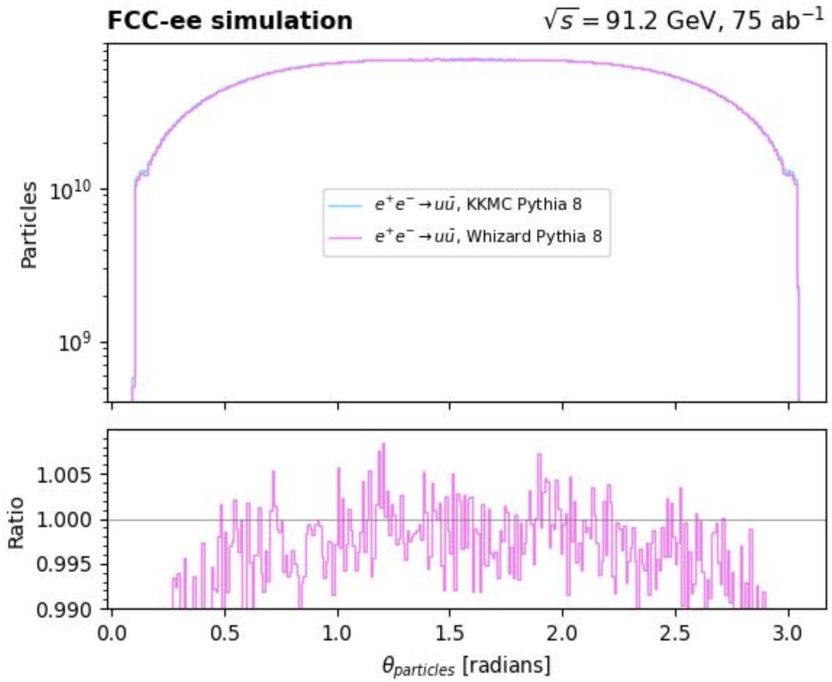


Here you can see that the two photon background, which is hard to simulate, is completely removed by other cuts.

Other group at MIT has being studying this background.

Theta distribution with detector definition on 0.1 radians





Distributions with no filters applied