Hadronic Cross-Section at the Z-pole

FCC Feasibility Study

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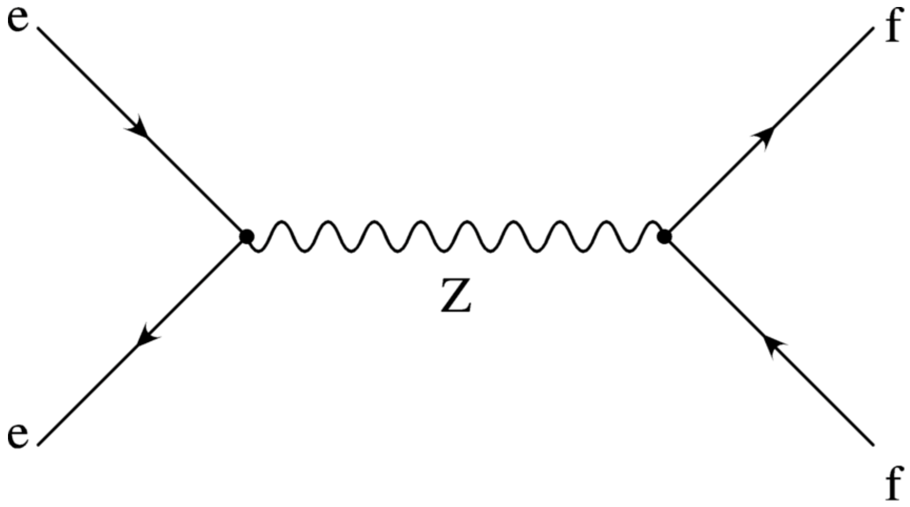
November 20, 2023

Introduction



Electroweak radiative corrections in Z boson decays - Scientific Figure on ResearchGate. Available from: https://www.researchgate.net/figure/The-Z-boson-as-a-resonance-in-e-e-annihilations-A-fermion-antifermion-pair-in-the_fig8_2032467 [accessed 14 Aug, 2023]

The Future Circular Collider is a projected e+e- collider with a circumference of 90.7 km. The FCC feasibility study is being developed to optimize the physics potential of the collider.

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 statics.

Hadronic decays are the most copiously produced decays.

Motivation

- Z pole running will result in an enormous data set ($6x10^{12}$ 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 measure crucial 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, all standard model parameters are known and look to be consistent. Consistency between all measurements will be tested about 3 orders of magnitude more stringently than before, inconsistencies will immediately invoke new physics;

Goals of our analysis

- Adapt and compare FCC-ee simulations of $Z \rightarrow q\bar{q}$ decays to previous results from L3;
- Compare Whizard and KKMC event generators to see whether they agree within uncertainty limits;
- 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:

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

What can we extract?

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

Dependency on

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

Importance of Monte Carlo

Number of background events

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

Acceptance

- Crucial to calculating the cross-section and its uncertainty;
- Two event generators are in significant disagreement about the $Z \rightarrow qq$ 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 Data Taking

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 the data taken in 1994 to reproduce the plots presented in the paper.

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

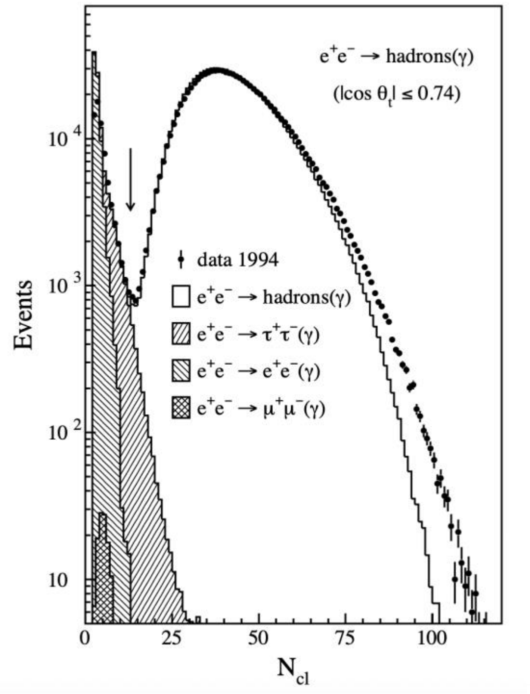
The L3 Collaboration., Acciarri et al., M. Measurements of cross sections and forward-backward asymmetries at the Z resonance and determination of electroweak parameters. Eur. Phys. J. C 16, 1–40 (2000). https://doi.org/10.1007/s100520050001

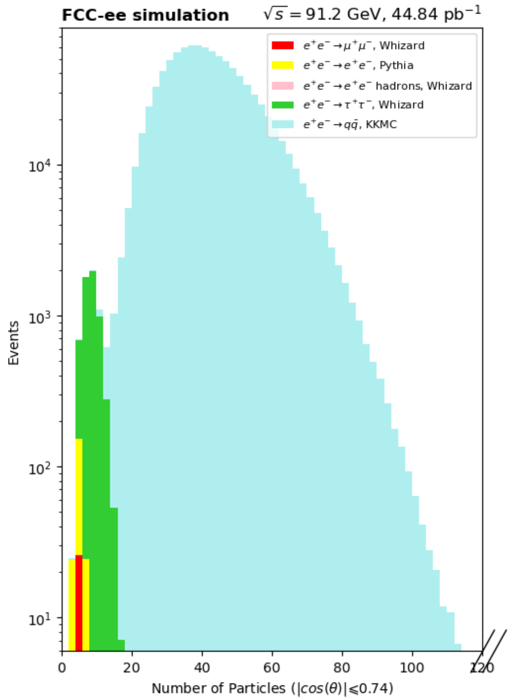
Cuts Utilized

1. The total energy observed in the detector, Evis, normalised to the centre-of-mass energy must satisfy $0.5 < E_{vis}/\sqrt{s} < 2.0$;
2. The energy imbalance along the beam direction, $E_{\parallel}$, must satisfy $|E_{\parallel}|/E_{vis} < 0.6$;
3. The transverse energy imbalance, $E_{\perp}$, must satisfy $E_{\perp}/E_{vis} < 0.6$;
4. The number of particles per event, Nparticles, 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 θ_t is the polar angle of the event thrust axis.

The last cut 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)



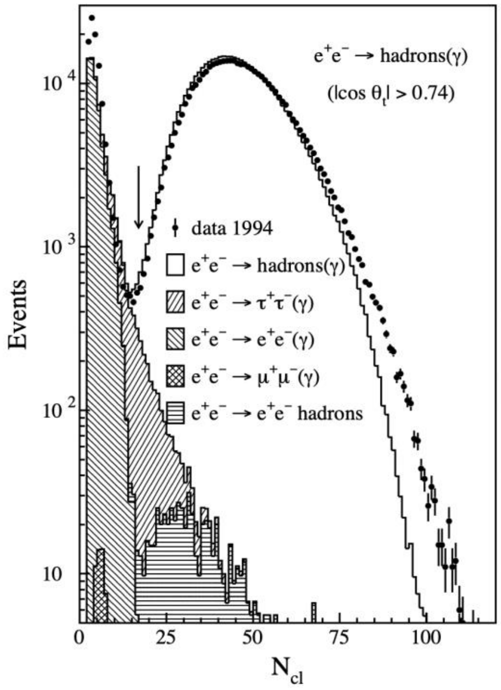


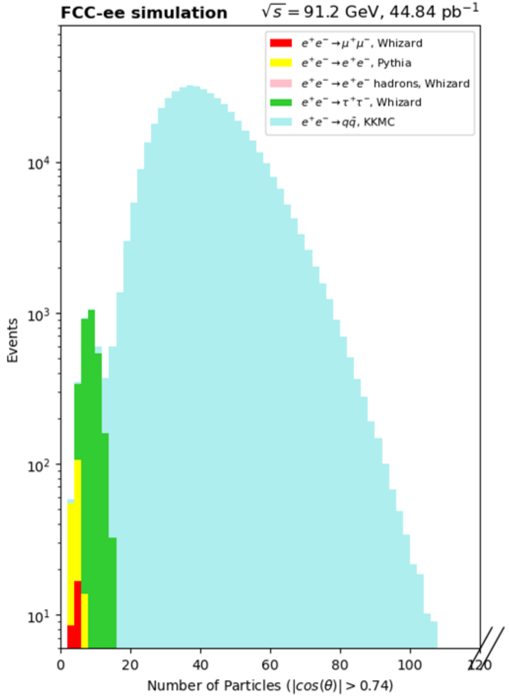
The difference in the physical quantities being plotted are apparent.

Electrons and taus have significantly less particles than clusters.

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

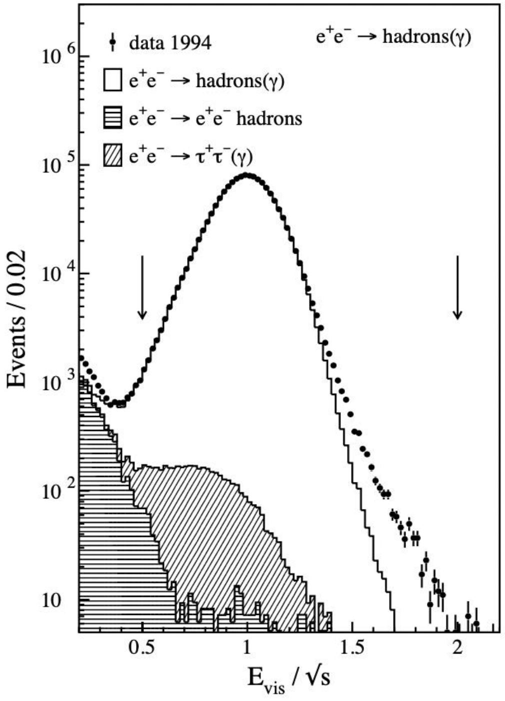
Number of Particles/Clusters (End-Cap Region, N-1 Plot)

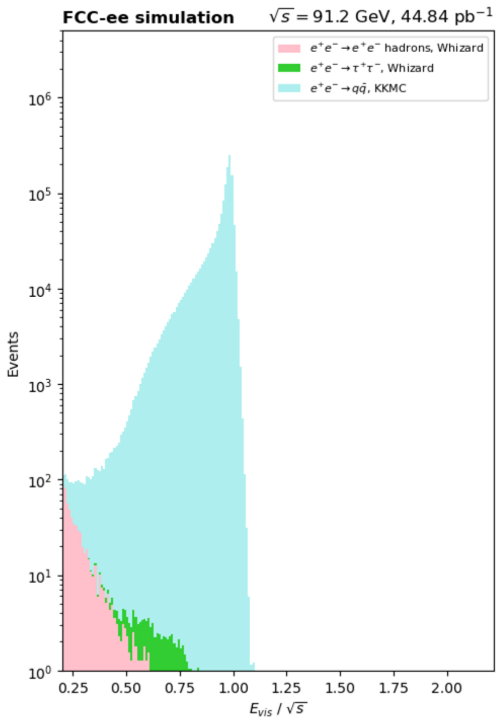




The difference in the physical quantities being plotted are apparent. Here you can see that the two photon background, which is hard to simulate, is completely removed by other cuts.

Normalized Scalar Energy (N-1 Plot)



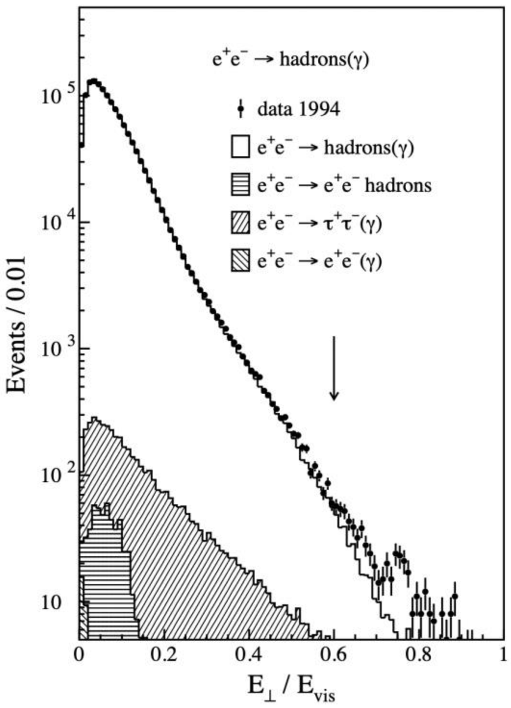


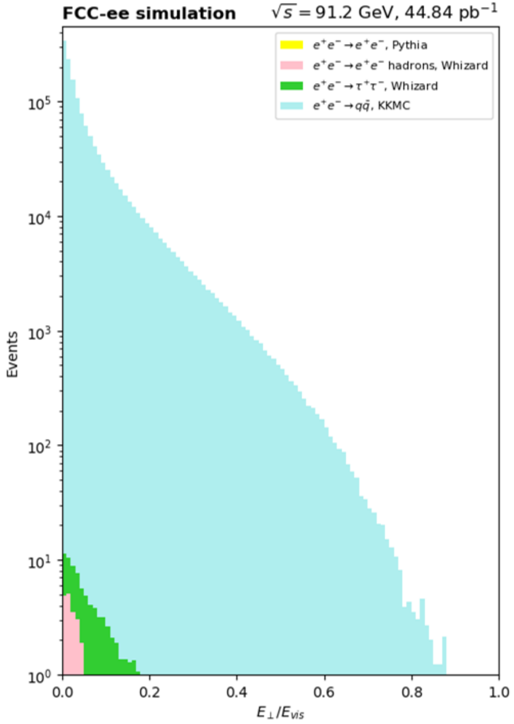
Almost all two photon background does not satisfies the requirement $0.5<E_{vis}/\sqrt{s}$, which explains the discrepancy in the previous plot.

You can also see the effect of this difference between $N_{clusters}$ and $N_{particles}$ had in the number of taus.

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 and in particular the L3 detector.

Transverse Energy Imbalance (N-1 Plot)



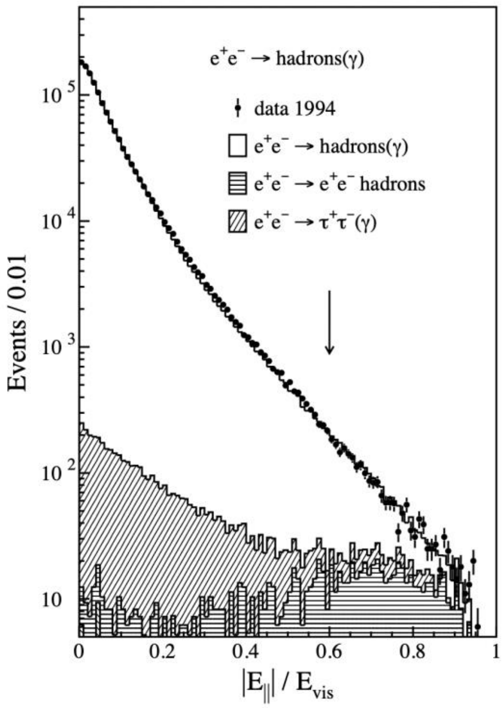


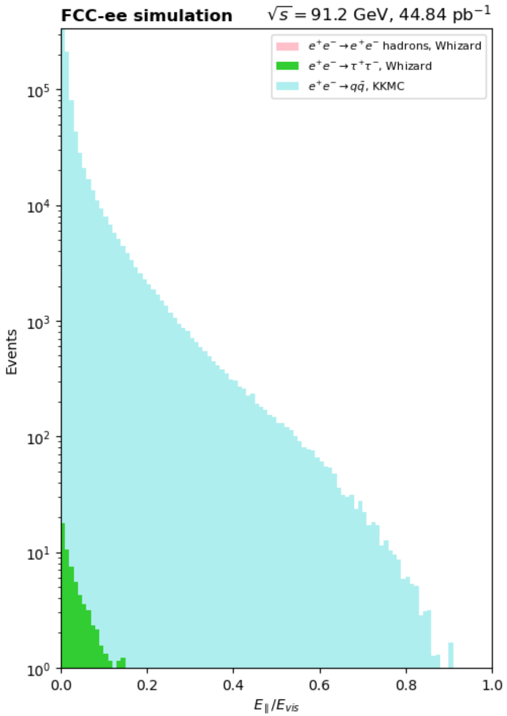
The differences in the filters impact the amount of background, to the point that there is no visible e^+e^-.

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

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

Longitudinal Energy Imbalance (N-1 Plot)





The differences in the filters and possibly the accuracy of the Monte Carlo description impacts the amount of background: there is no visible two photon background.

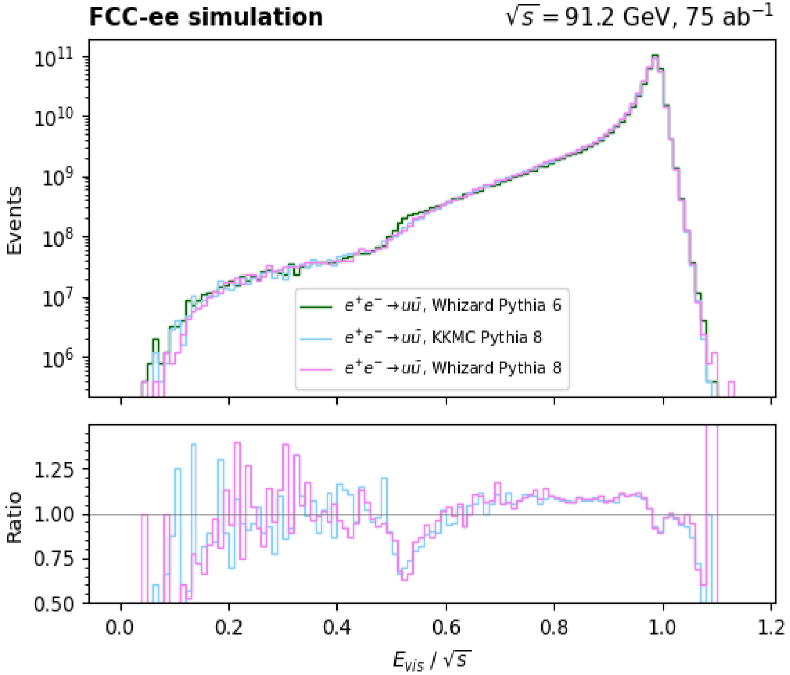
Improvements in the detector also justify the sharper peaking behavior towards 0.

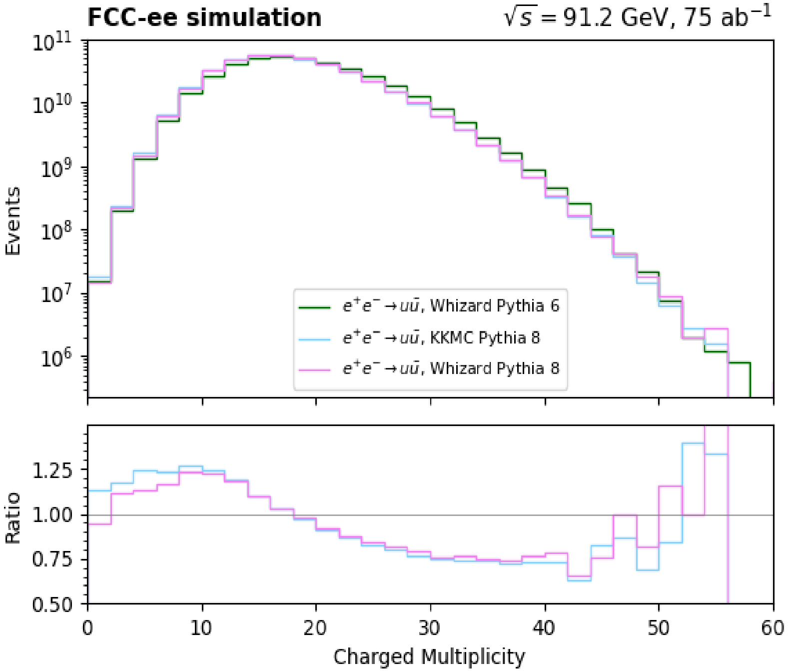
Optimization for FCC-ee

- Since improvements were made in the detector, we are using different filters to better suit the conditions of our simulation and improve the significance (cutting more background while retaining signal events).
- The luminosity now considered is a projected FCC-ee one of 75 ab^{-1}.
- Need to choose between Z→hadrons event generators
  - Pythia for showering
  - Pythia 8 versus 6
  - KKMC versus Whizard
    - Different orders implemented

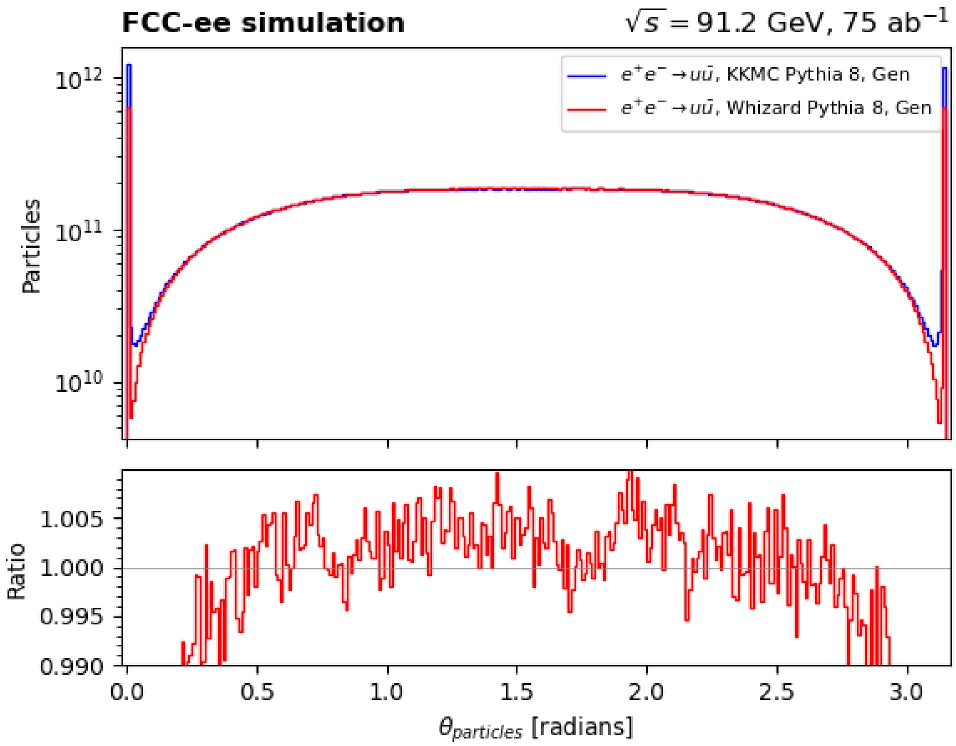
(For now, we are only going to analyse Z → uu. Further studies will also look at other flavors.)

Different Event Generators





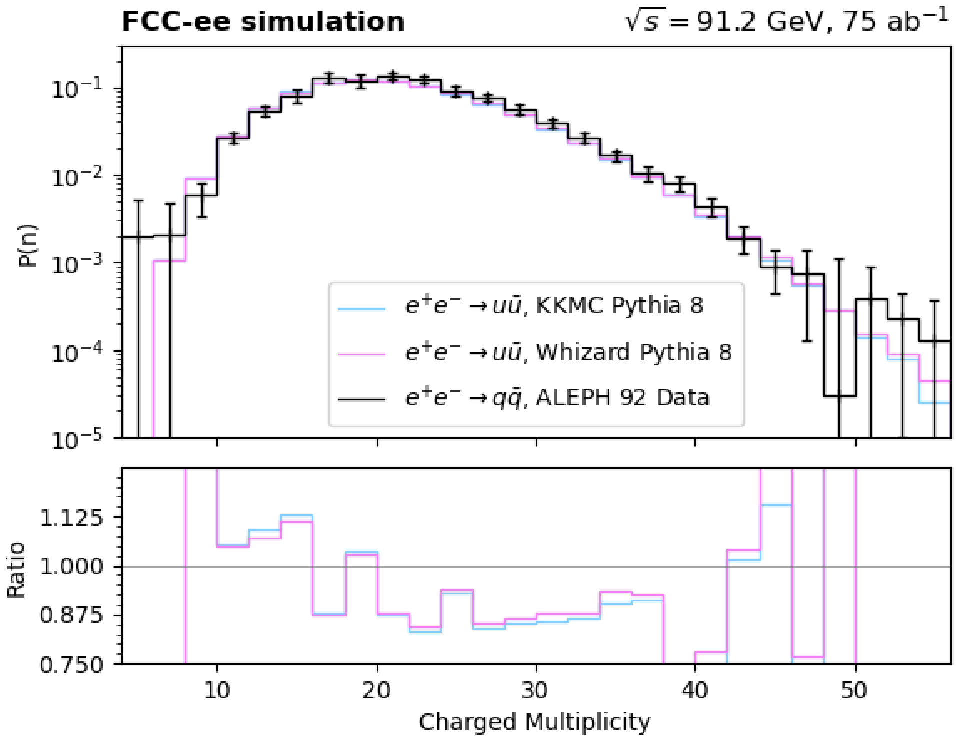
Comparing KKMC and Whizard (Pythia 8) at gen level particles



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

We suppose the different description of Initial State Radiation (ISR) is causing this discrepancy, but this needs confirmation.

ALEPH Comparison

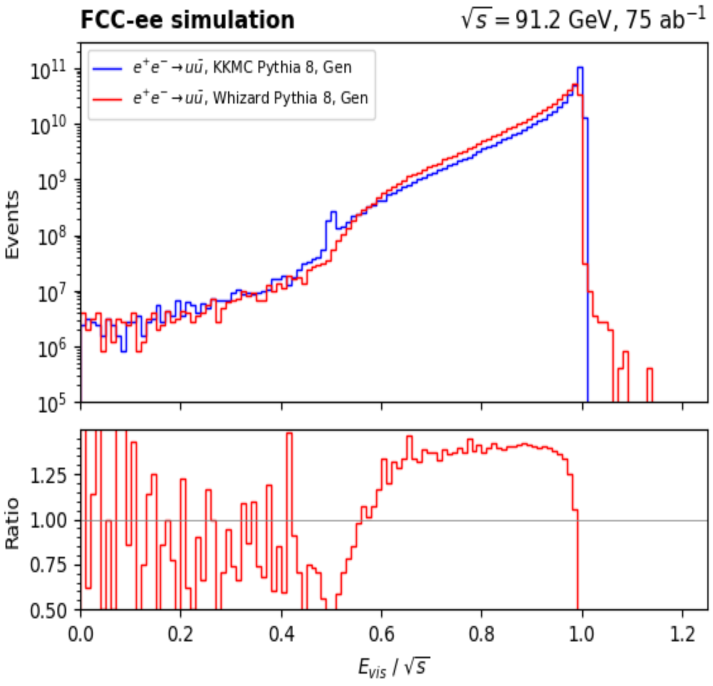


Both generators are in good agreement with ALEPH data, even though they might differ from each other in other measurements.

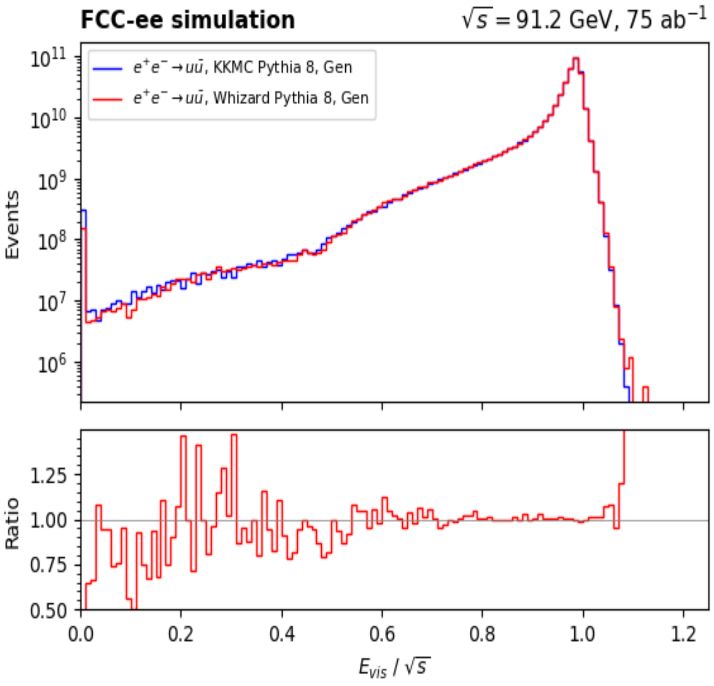
Studies of Quantum Chromodynamics with the ALEPH detector, Physics Reports, Volume 294, Issues 1–3, 1998, Pages 1-165, ISSN 0370-1573, https://doi.org/10.1016/S0370-1573(97)00045-8. (https://www.sciencedirect.com/science/article/pii/S0370157397000458)

Generator level particles

Visible Energy in different detector hole definitions



No cut on radius of detector hole



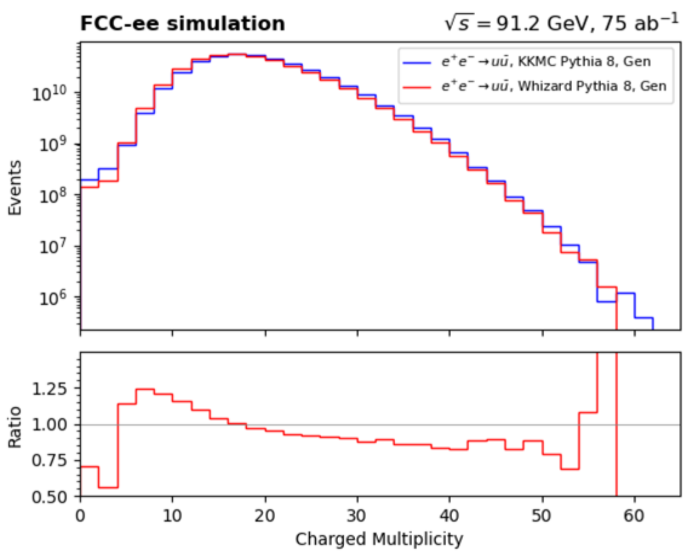
Hole of radius 0.1 radians

Large discrepancy between generators. It decreases as you select only particles away from the end of the detector, but it is still significant.

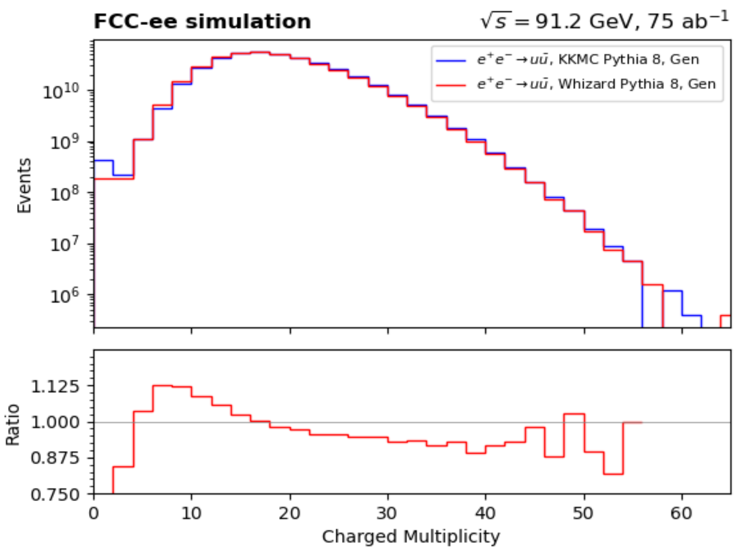
This is likely due to different implementations and should not account as a systematic uncertainty.

Generator level particles

Charged Multiplicities in different detector hole definitions



No cut on radius of detector hole

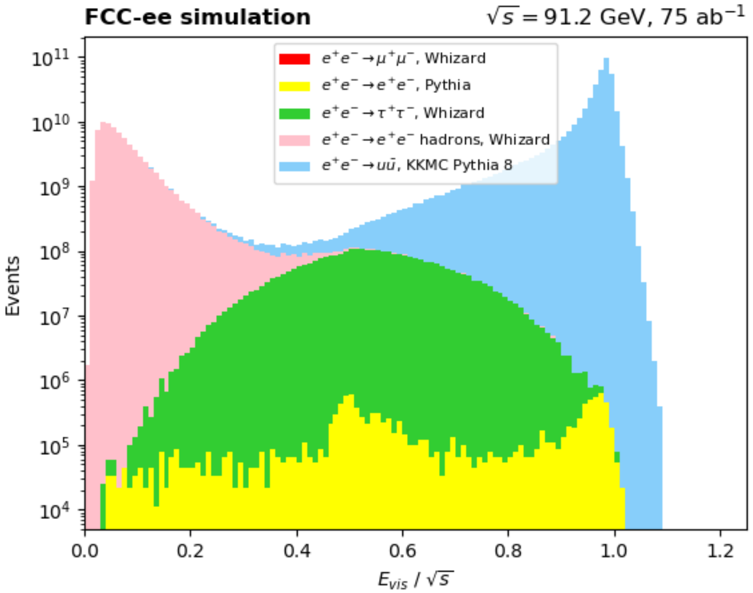


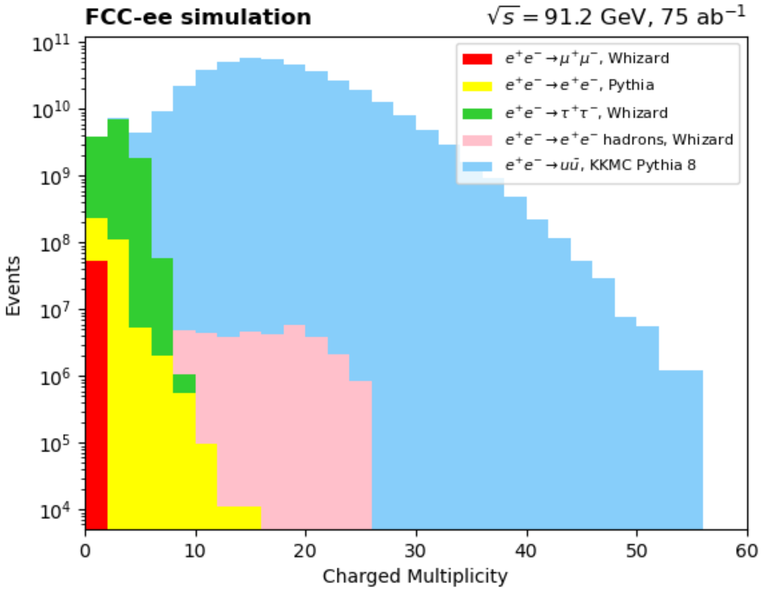
Hole of radius 0.1 radians

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

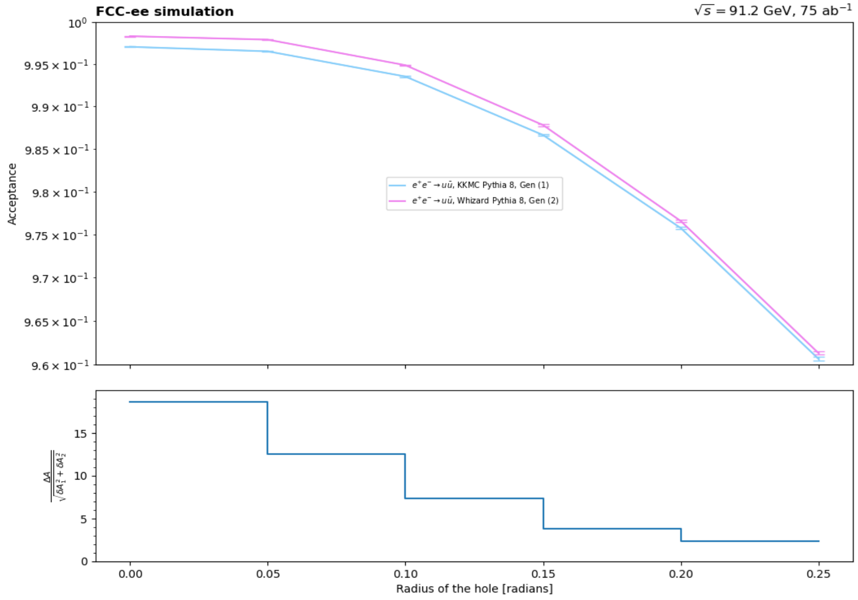
N-1 Plots

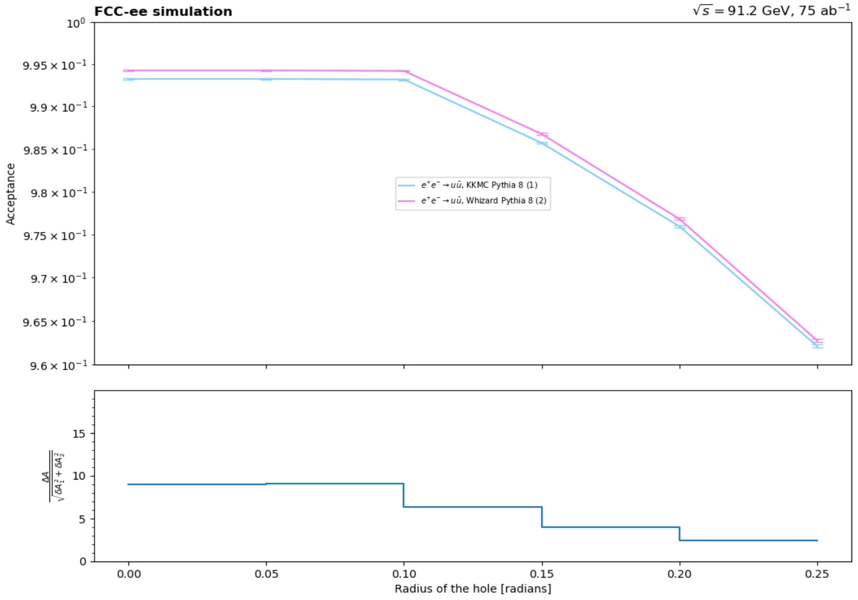




Filters selected: Evis/√s ≥ 0.52, Charged Multiplicity ≥ 4.

Acceptance & Definition of the detector hole





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

Conclusion & Next Steps

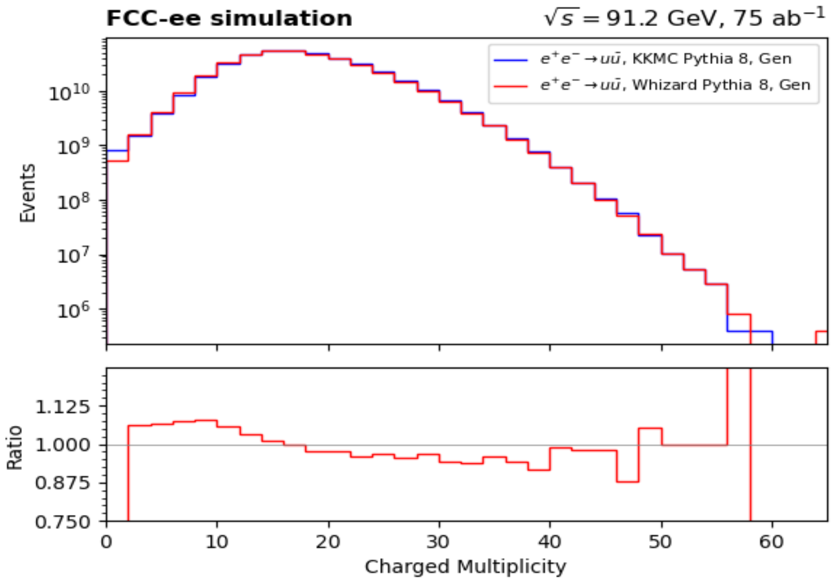
- FCC-ee simulations agree nicely with previous results;
- KKMC and Whizard are in clear disagreement;
  - We need to understand better the reason. Following studies will be performed;
- Extend the FCC-ee simulation analysis for different quark flavors.

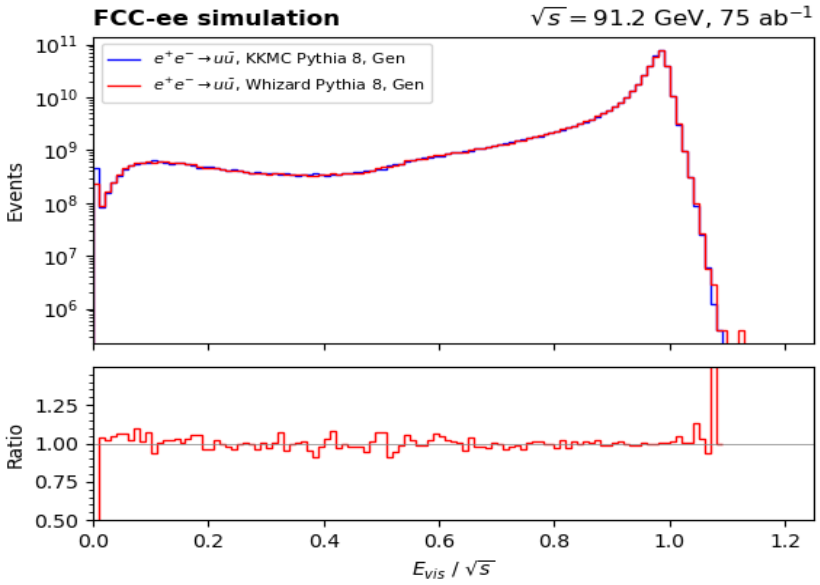
Thank you!

Work on lineshape analyses

- Christoph Paus, Jan Eysermans, Luca Lavezzo
- Tim Neumann, Sofia Lara, Casey Lawson, Bella Torres, Denis Siminiuc, Brenda Chow, Rujuta Sane

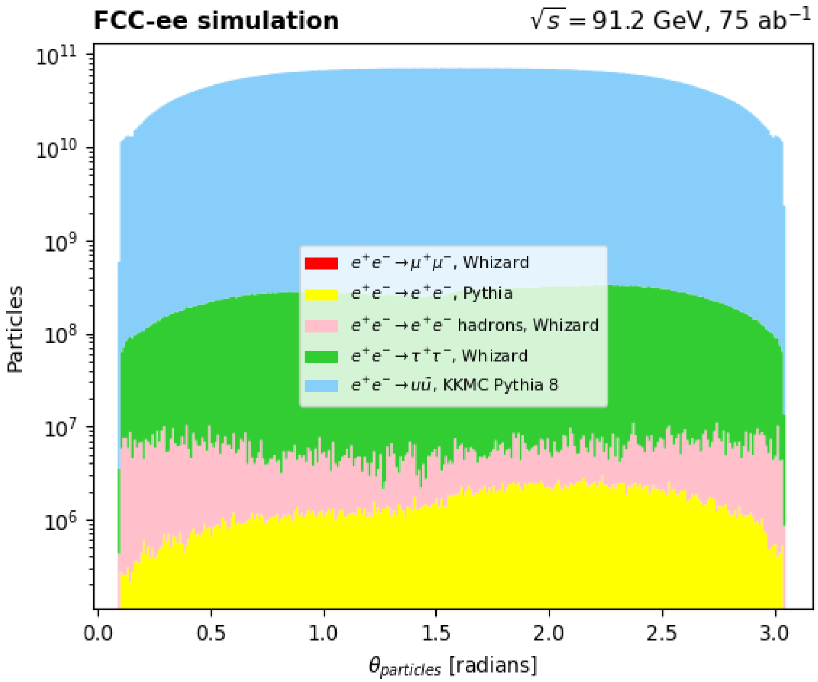
Gen level particles with detector definition on 0.3 radians

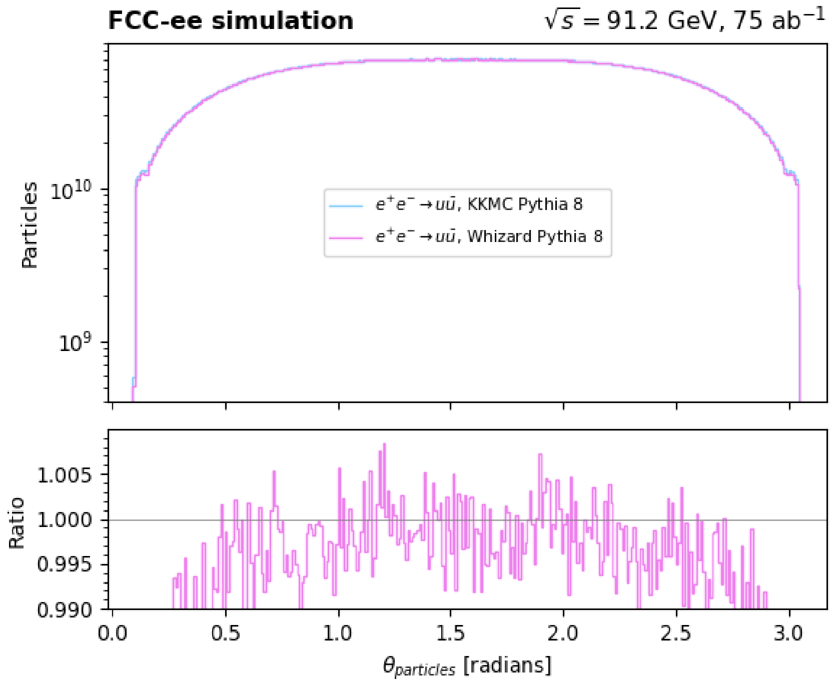




You can see much better agreement between KKMC and Whizard away from the edges of the detector.

Theta distribution with detector definition on 0.1 radians





Distributions with no filters applied