Hadronic Cross-Section at the Z-pole

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Our approach

We have been studying Z $\rightarrow$ qq decays and extracting cross-section uncertainties. We started by comparing our simulation with the L3 experiment and then moving on to optimizing cut selections for the improved detector. Our goal is to minimize systematic uncertainties so that we can take full advantage of FCC statics.

REPRODUCING A LEP RESULT

L3 Experiment

L3 Data Taking

Table 14. Average centre-of-mass energies, number of selected events, integrated luminosities and measured cross sections with statistical errors for $e^+e^- \to$ 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		

Here we are going to 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

FCC Simulation Details

Sample	Event Generator	Cross-Section (pb)	Events Generated
kkmee_uu_ecm91p2	KKMC	5353.597	2×10^6
kkmc_ee_dd_ecm91p2	KKMC	6752.078	2×10^6
kkmc_ee_cc_ecm91p2	KKMC	5325.479	2×10^6
kkmc_ee_ss_ecm91p2	KKMC	6763.653	2×10^6
kkmc_ee_bb_ecm91p2	KKMC	6586.846	2×10^6
wzp6_ee_mumu_ecm91p2	Whizard	1717.852	2×10^7
wzp6_ee_tautau_ecm91p2	Whizard	1716.135	8.45×10^6
wzp6_gaga_qq_5_ecm91p2	Whizard	11367.36	4×10^6
p8_ee_Zee_ecm91	Pythia	1462.09	1×10^7

In our analysis no distinction was made between the different quark flavours and the five samples were treated as one.

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

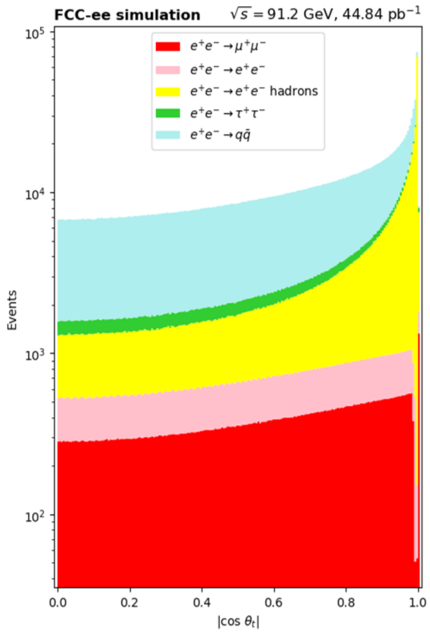
The detector simulation was done using the IDEA detector with Delphes (Winter 2023 campaign).

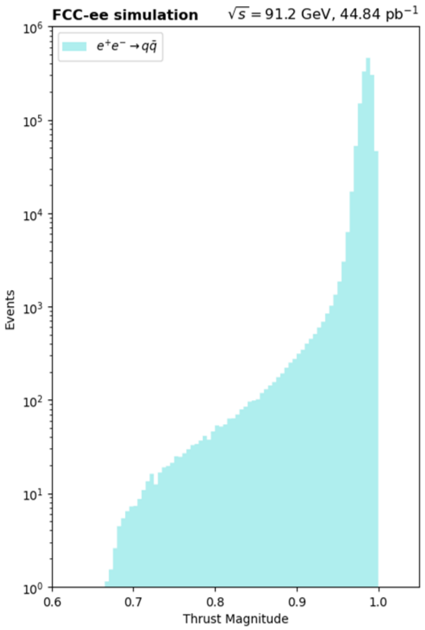
Calculating the thrust and Cos θ_t

Cos θ_t is the cosine of the angle between the *z* axis and the thrust axis.

$$T = \max_{|n|=1}\left[\frac{\sum_i |p_i \cdot n|}{\sum_i |p_i|}\right]$$

The unit vector ***n*** of the thrust axis is the one which maximizes the value of thrust. This represents the direction in which particles are most aligned.



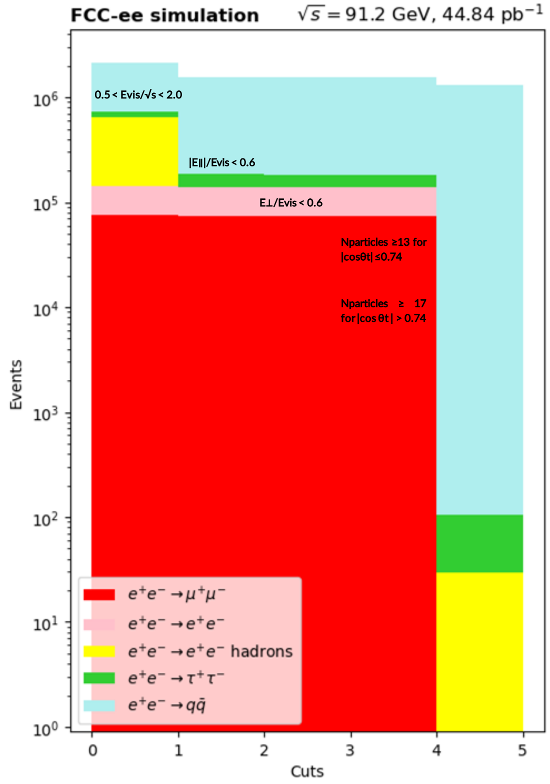


Cuts Utilized

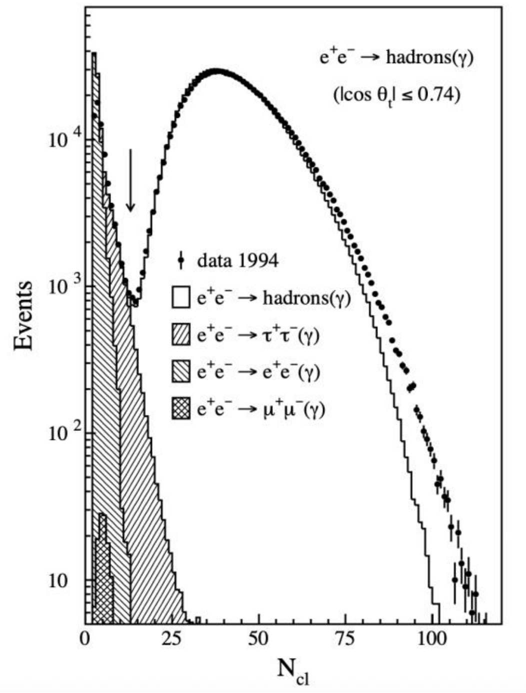
1. The total energy observed in the detector, Evis, normalised to the centre-of-mass energy must satisfy 0.5 < Evis/√s < 2.0;
2. . The energy imbalance along the beam direction, E‖, must satisfy |E‖|/Evis < 0.6;
3. The transverse energy imbalance, E⊥, must satisfy E⊥/Evis < 0.6;
4. The number of particles per event, Nparticles, is required to be:
   a. Nparticles ≥13 for $|\cos\theta_t|$ ≤0.74 (barrel region),
   b. Nparticles ≥ 17 for $|\cos\theta_t|$ > 0.74 (end-cap region), where θt is the polar angle of the event thrust axis.

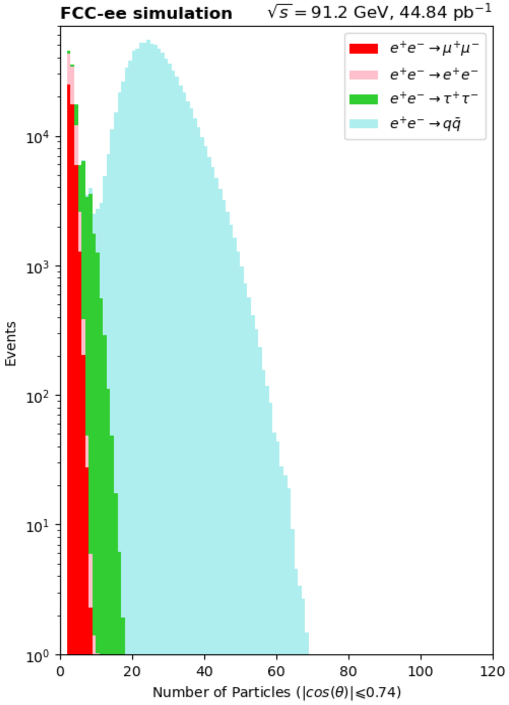
The last cut differs from L3 as they used the number of clusters from energy depositions in the calorimeter while we used the number of particles reconstructed from the tracker, the calorimeter and the muon chamber.

Sample/ Cut	Hadrons	$\mu^+\mu^-$	e^+e^-	$\tau^+\tau^-$	e^+e^- hadrons
Initial	1380249	75779	65560	76228	509712
Cut 1	1370027	74295	65042	45661	50
Cut 2	1368423	74184	64891	44947	29
Cut 3	1365306	74132	64824	43336	29
Cut 4	1298973	0	1	75	28



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

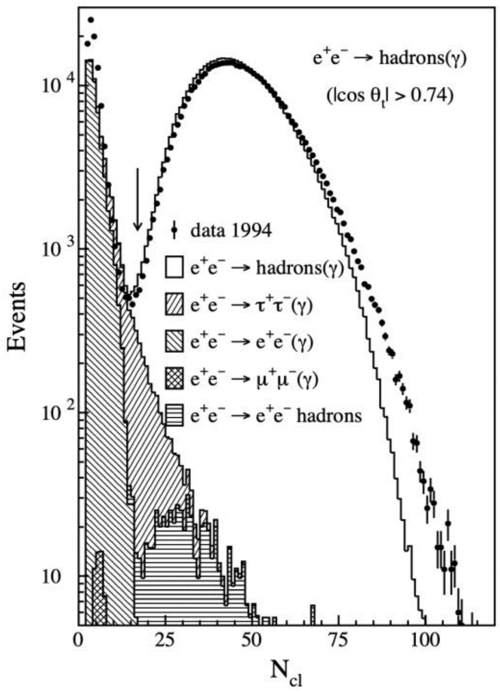


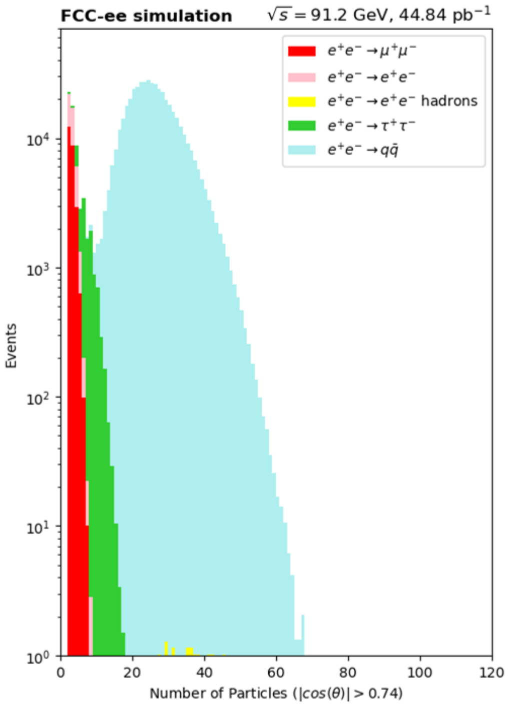


The difference in the physical quantities being plotted are apparent. Since we are also collecting information from the tracker and muon chambers the number of muons is much greater in the FCC simulation than in L3.

You can also note how hadrons and taus present significant less number of particle than clusters.

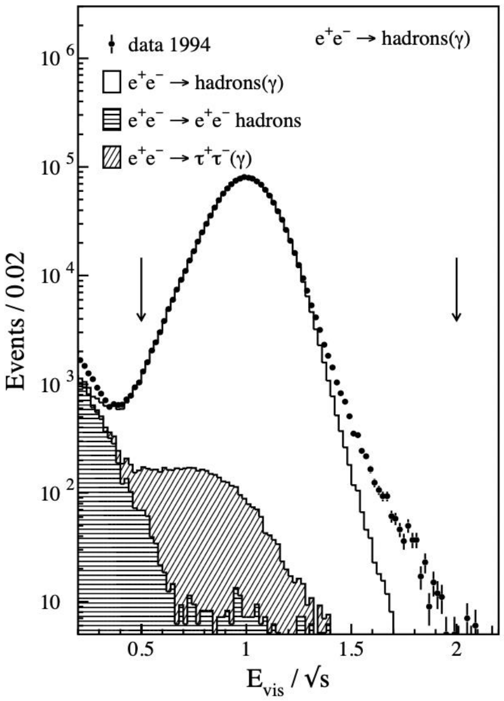
Number of Particles/Clusters (End-Cap Region, N-1 Plot)

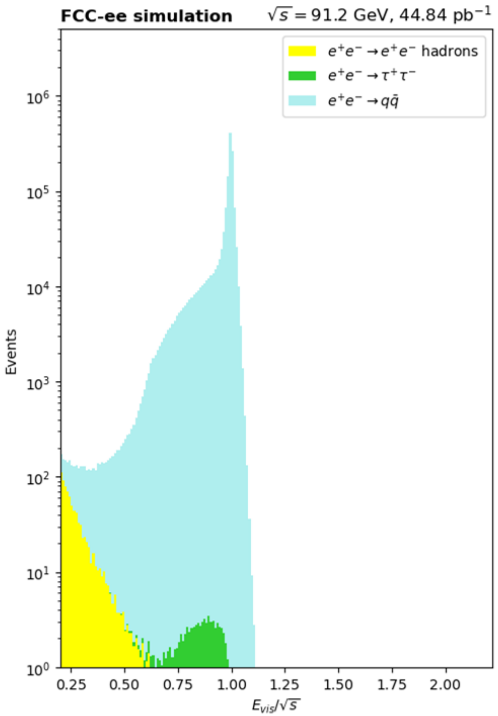




The difference in the physical quantities being plotted are apparent. Here you can see that the two photon background is being affected by some other cut.

Normalized Scalar Energy (N-1 Plot)



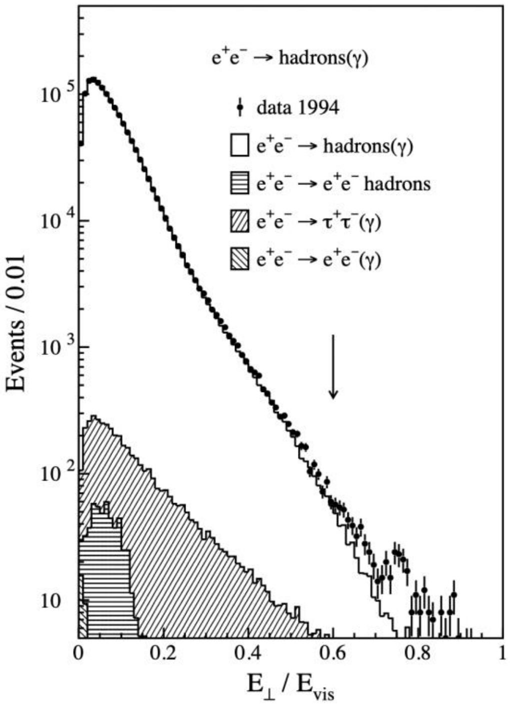


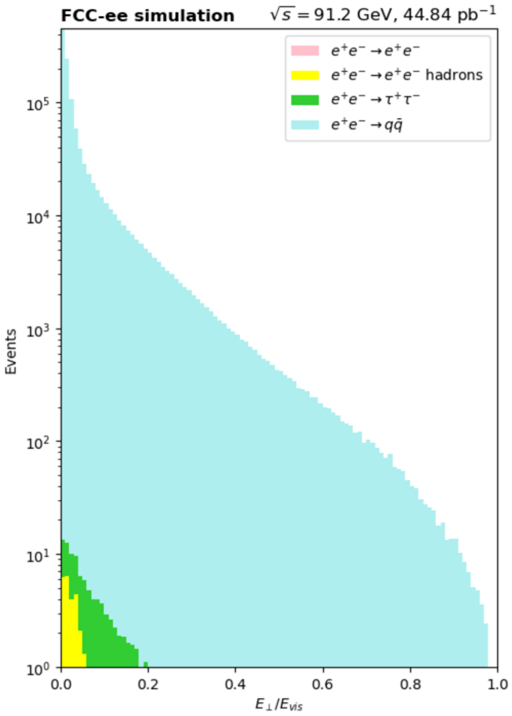
Almost all the two photon background does not satisfies the relation 0.5 < Evis/√s, which explains the discrepancy in the previous plot.

You can also see the effect the difference between Ncl and Nparticles had in the number of taus.

The sharp peak instead of a smooth curve is due to improvements in the detector. The energy resolution of the IDEA detector is much better than L3.

Transverse Energy Imbalance (N-1 Plot)

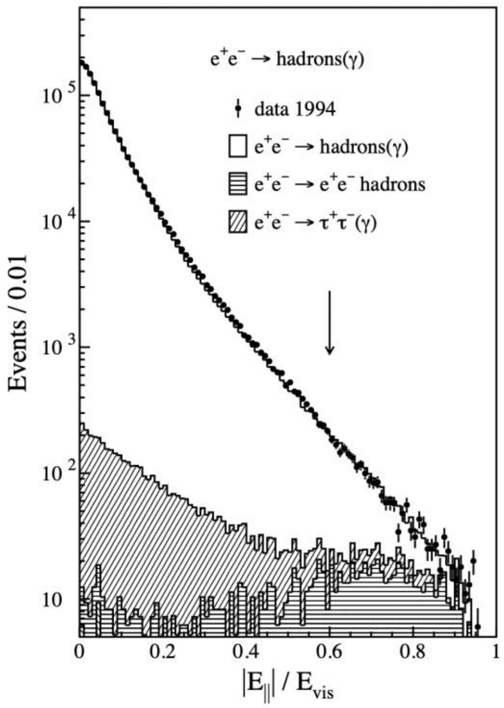


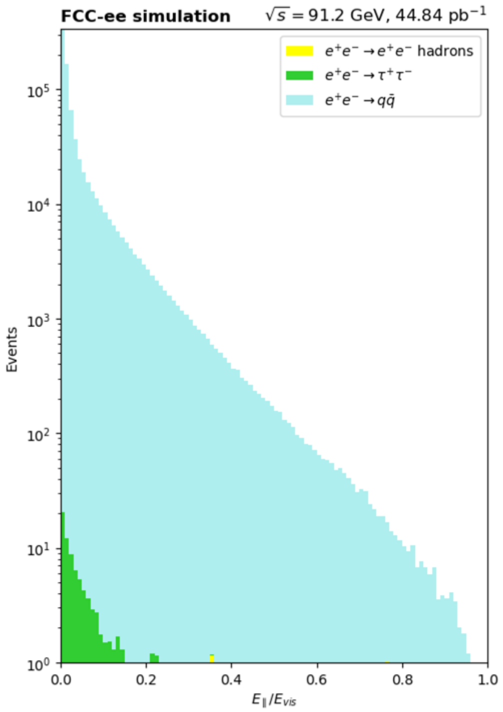


Again we can see how the differences in the filters impacted the amount of background, to the point that there is no visible e^+e^-.

Improvements in the detector also justify the smoothness of the curve going up to 1.0.

Longitudinal Energy Imbalance (N-1 Plot)





Again we can see how the differences in the filters impacted the amount of background, to the point that there is almost no visible two photon background.

Improvements in the detector also justify the smoothness of the curve going up to 1.0.

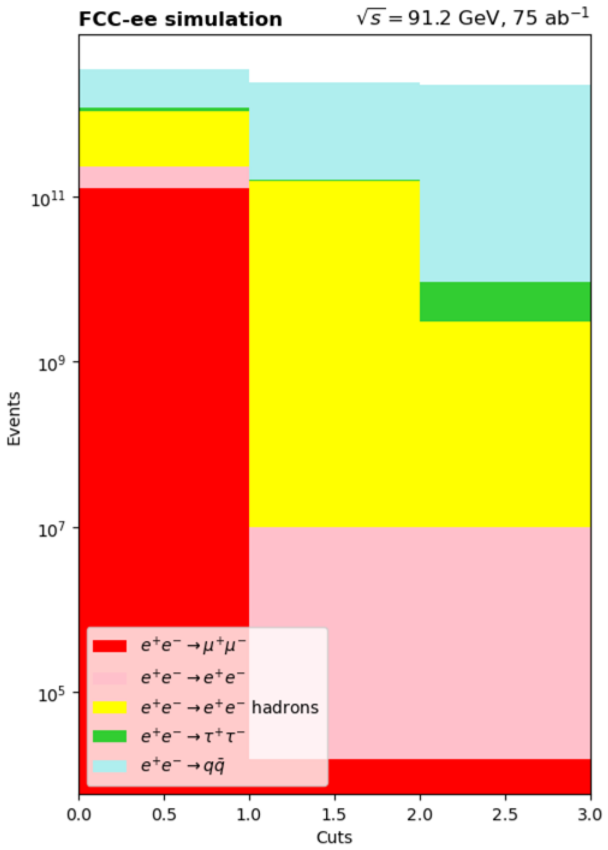
Optimizing Filters for FCC analysis

Cuts Utilized

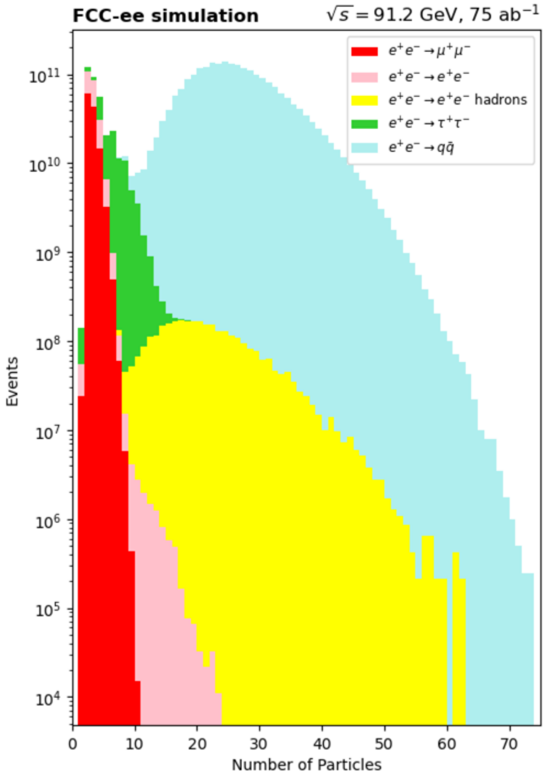
1. The number of particles per event, Nparticles, is required to be Nparticles ≥10
2. The total energy observed in the detector, Evis, normalised to the centre-of-mass energy must satisfy Evis/√s > 0.248

Note: The transverse and longitudinal energy imbalance were NOT cut on, as these variables were used in the A LEP experiment to eliminate detector noise, something that could not be properly simulated in MC for FCC

Sample/ Cut	Hadrons	$\mu^+\mu^-$	e^+e^-	$\tau^+\tau^-$	e^+e^- hadrons
Initial	2.3086×10^{12}	1.2675×10^{11}	1.0966×10^{11}	1.2750×10^{11}	8.5255×10^{11}
Cut 1	2.3026×10^{12}	0	9.7594×10^{6}	6.2406×10^{9}	1.5291×10^{11}
Cut 2	2.2972×10^{12}	0	9.7594×10^{6}	6.2404×10^{9}	2.8987×10^{9}



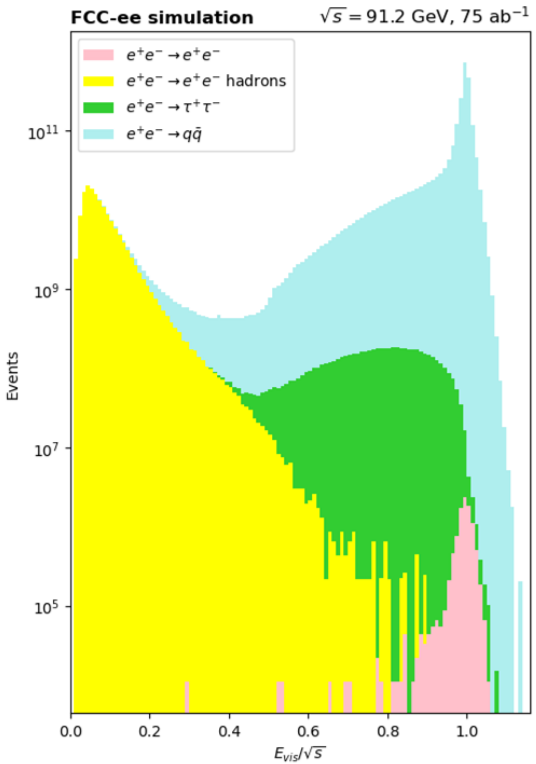
Number of Particles/Clusters (N-1 plot)



Number of Particles/Clusters ≥ 10

	Before Cut	After Cut	Retained
# Signal Events	2.3086×10^{12}	2.3026×10^{12}	99.738814%
# Background Events	1.2165×10^{11}	1.5916×10^{11}	13.083866%

Normalized Scalar Energy (N-1 Plot)



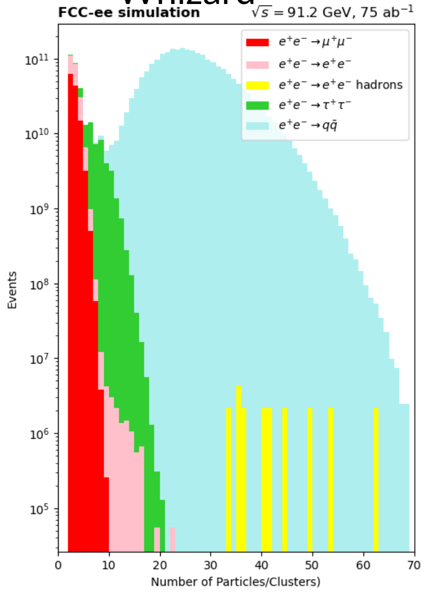
Normalized scalar energy > 0.248

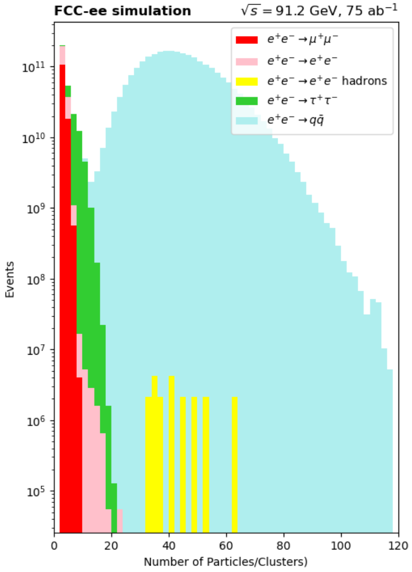
	Before Cut	After Cut	Retained
# Signal Events	2.3026×10^{12}	2.2972×10^{12}	99.765934%
# Background Events	1.5916×10^{11}	9.1488×10^{9}	5.7481814%

Event Generator Discrepancy

KKMC

Whizard





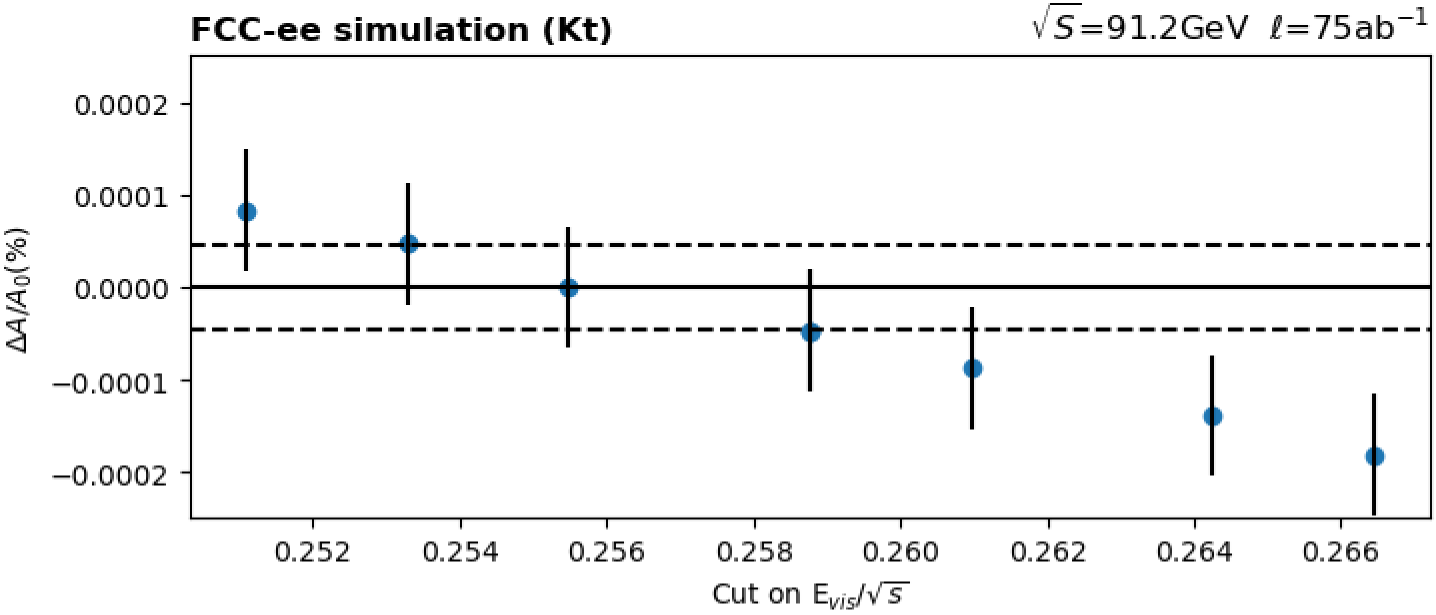
Background: Whizard Samples
Signal: KKMC/Whizard

Determine source of discrepancy between event generators

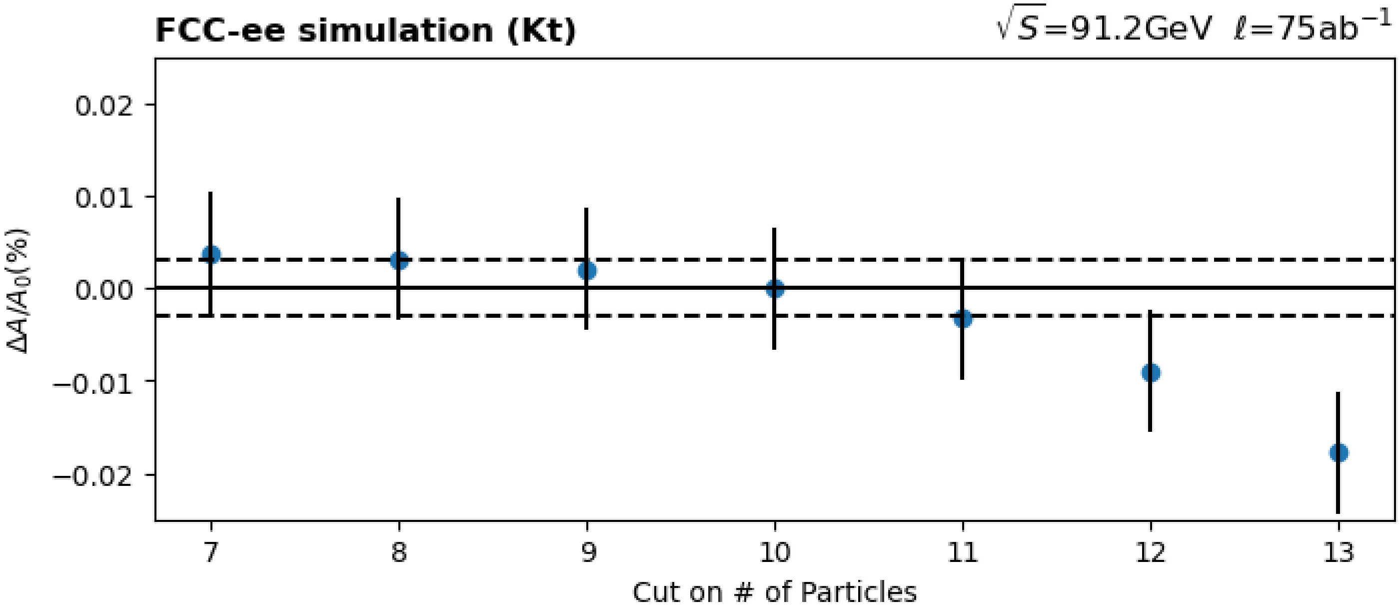
Has significant impact on optimal cut parameters

Assessing Uncertainties

Uncertainty Plots



Uncertainty Plots



Calculating Hadronic Cross-Section

Nsel - Nbg = 2.297386×10^{12} events

L = 75 ab^{-1}

A = (99.513 ± 0.002) %

σ = (30781.6 ± 0.9) pb

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

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)

Sources of Uncertainty

1. Data Statistics

$$Statistical\ Uncertainty = \sqrt{Nsel + Nbg}$$

1. Statistical Uncertainty on Acceptance

$$\delta_A = \frac{\sqrt{Nsig \cdot (1 - \frac{Nsig}{No})}}{No}$$

1. Luminosity Uncertainty

$$\frac{\delta_L}{L} = 2 \times 10^{-5}$$

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)

Total Uncertainty

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

Source	Absolute Uncertainty [pb]	Relative (%)
Statistics	0.02	7×10^{-5}
Statistical Uncertainty on Acceptance	0.7	2×10^{-3}
Luminosity	0.7	2×10^{-3}
Total	0.9	3×10^{-3}

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)

Conclusion

- FCC-ee allows for cross section measurement ___ orders of magnitude more precise
- The improved energy resolution allows FCC to have much cleaner representation of the visible energy.
- The differences between event generators still needs to be studied.
- Explore detector deadzone impact on cosΘ, cross section error (financially feasible?)
- MIT engaging in push for US participation in FCC research while training future generation of physicists

Thank You!