Z → Hadrons at the FCC-ee

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FCC Workshop, Annecy

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Talk outline

Introduction to Precision Physics at the FCC-ee

Overview of the Z lineshape and Hadronic Cross-section

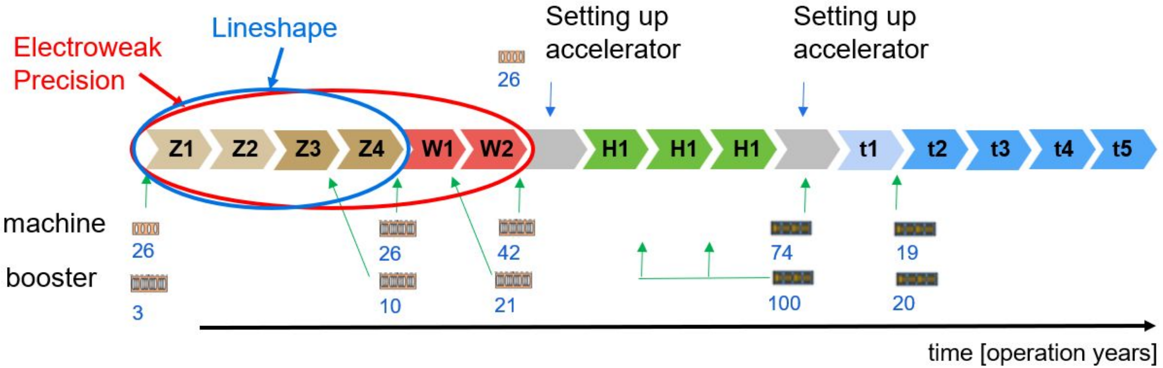
Repeating the LEP Lineshape and Hadronic Cross-section at FCC-ee

Summary and Conclusions

FCC-ee Run Plan

The baseline run plan for FCC-ee

- Z run has most events followed by WW run: *most stringent experimental requirements*
- 4 interaction points instead of 2 (updated for midterm report of FCC feasibility study)
- Sequence to run at different ECM to be defined: priorities (Higgs factory) and/or machine (RF installation)



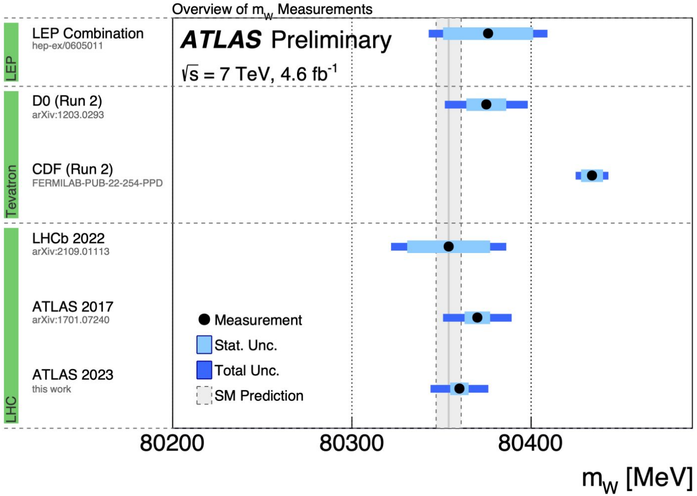
Working point	Z, years 1-2	Z, later	WW, years 1-2	WW, later	ZH	$t\bar{t}$	
$\sqrt{s}$ (GeV)	88, 91, 94		157, 163		240	340–350	365
Lumi/IP ($10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$)	70	140	10	20	5.0	0.75	1.20
Lumi/year (ab^{-1})	34	68	4.8	9.6	2.4	0.36	0.58
Run time (year)	2	2	2	0	3	1	4
Number of events	$6\,10^{12}$ Z		$2.4\,10^{8}$ WW		$1.45\,10^{6}$ HZ + 45k WW $\rightarrow$ H	$1.9\,10^{6}$ $t\bar{t}$ +330k HZ +80k WW $\rightarrow$ H	

Motivation for Precision Physics

No direct indication of new physics at LHC (so far)

- Increased effort in performing precision physics
- Recent examples are W mass, differential cross-sections, α_s
- With a lot of data delivered by HL-LHC we can understand better our detector and constrain experimental systematics

→ HL-LHC will offer competitive precision physics

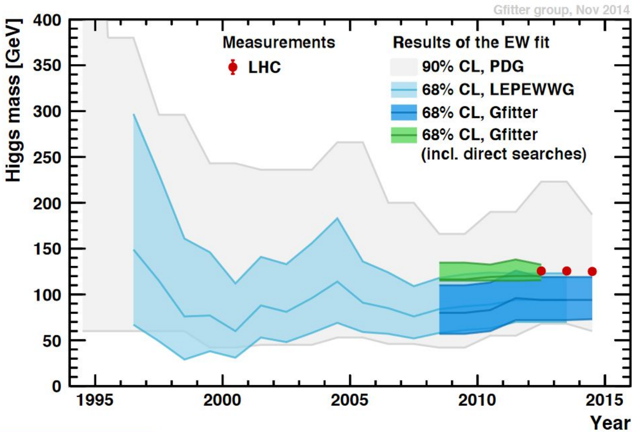


The next step towards high precision physics and probe the self-consistency of the Standard Model *as a whole*

FCC-ee offers the most suitable environment

- Increase the precision with order(s) of magnitude for Z/W physics
- Precisely study the Higgs properties and top

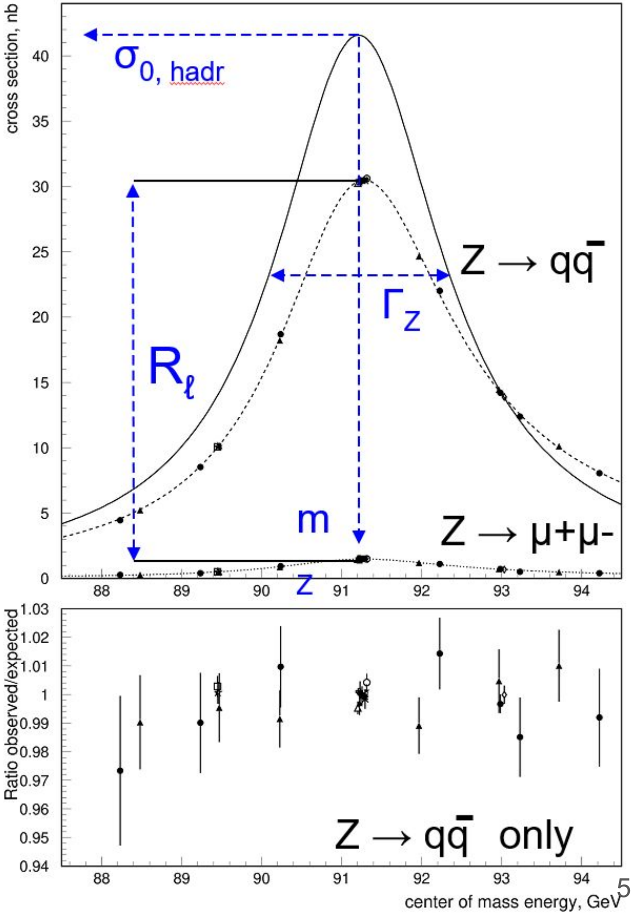
Any deviation or inconsistency will invoke new physics



The Lineshape

Measuring cross-section

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



What can be extracted

- Z mass (m_Z), Z width (Γ_Z)
- Hadronic peak cross section ($\sigma_{0,\ \text{hadr}}$)
- Ratio of leptons (R_ℓ)
- Etc. (number of light neutrinos, α_s)

Largest statistics in hadronic final state

- mass, width and σ_0

Theory needed

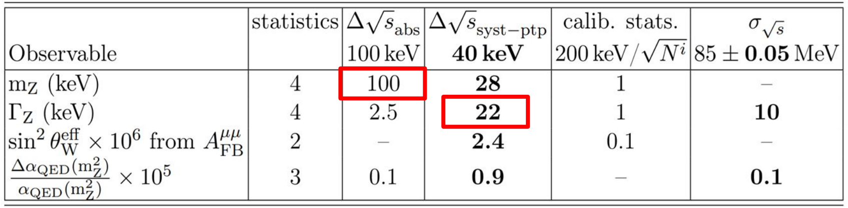
- Deconvolute QED and the EW/QCD corrections
- Precise predictions/Monte Carlo

Lineshape Ingredients

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

Center-of-mass energy

- In situ using Resonant Depolarization (RDP) with non-colliding pilot bunches
- Improved calibration bringing down the uncertainties: absolute (100 keV) and point-to-point (40 keV)
- Beam energy spread 85 MeV ± 50 keV



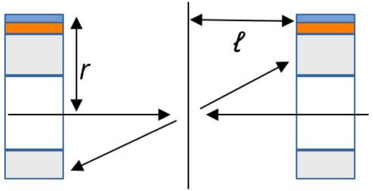
Observable	statistics	$\Delta\sqrt{s}_{\mathrm{abs}}$ 100 keV	$\Delta\sqrt{s}_{\mathrm{syst-ptp}}$ **40 keV**	calib. stats. 200 keV/$\sqrt{N^i}$	$\sigma_{\sqrt{s}}$ 85 ± **0.05** MeV
m_Z (keV)	4	100	**28**	1	–
Γ_Z (keV)	4	2.5	**22**	1	**10**
$\sin^2\theta_W^{\mathrm{eff}} \times 10^6$ from $A_{FB}^{\mu\mu}$	2	–	**2.4**	0.1	–
$\frac{\Delta\alpha_{QED}(m_Z^2)}{\alpha_{QED}(m_Z^2)} \times 10^5$	3	0.1	**0.9**	–	**0.1**

(From: arxiv:1909.12245)

More updates expected this week

EPOL sessions on Thursday. Lumi yesterday

Luminosity – *10^{-4} absolute and 10^{-5} point-to-point achievable?*



- Small-angle Bhabha scattering (large cross-section 78 nb)
  - Forward detection of e^+e^-, excellent control of geometry: Δr ~1μm; Δℓ ~50 μm
  - Theory prediction improved from 0.061% at LEP to 0.037% recently, but still far the 0.01% goal to match with the statistical precision of $\sigma_{0,\ \mathrm{hadr}}$
- Also $e^+e^- \rightarrow \gamma\gamma$ attractive: no Z dependence; 1 per 1000 Z events → *10^{-5}* achievable
- Combination of both to achieve best precision, but more work/understanding needed

From: Eur.Phys.J.Plus (2022) 137:81

Lineshape Ingredients

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

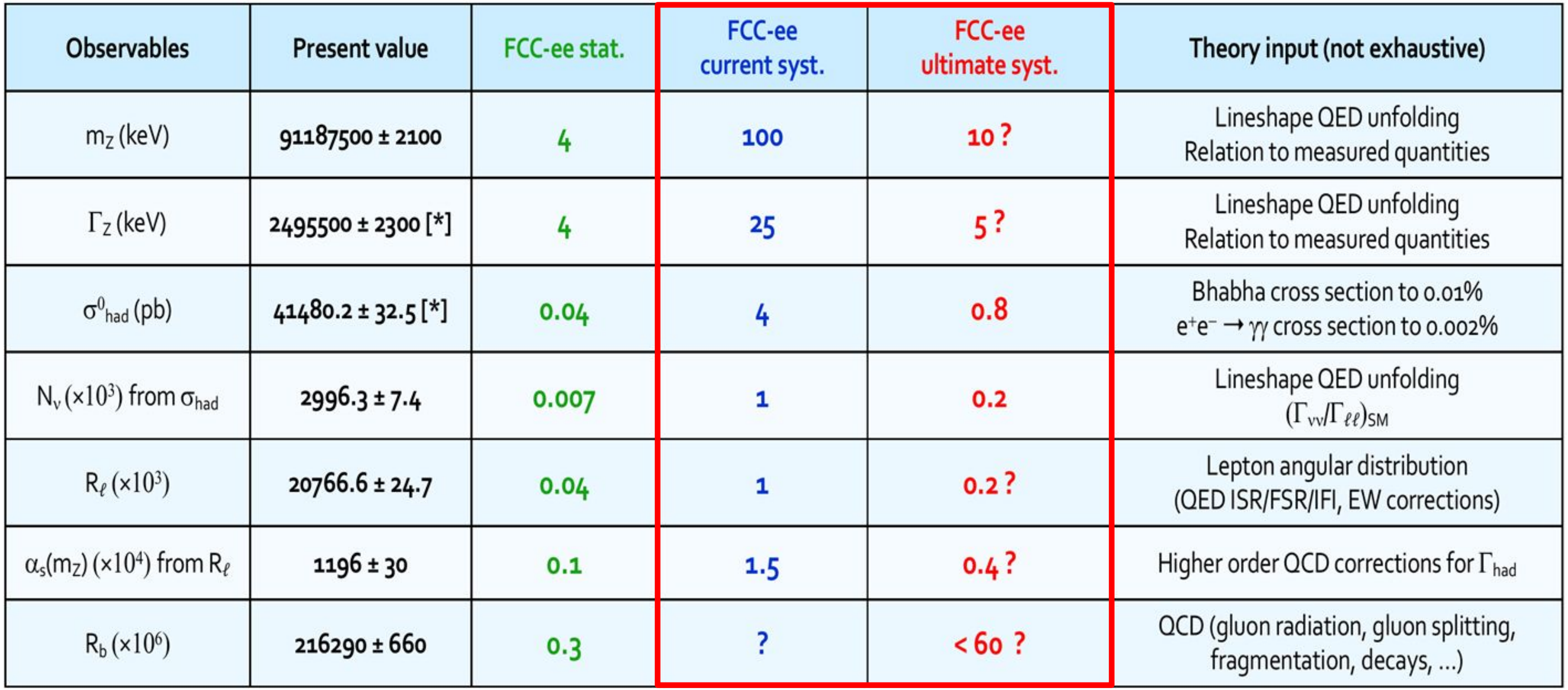
Number of selected events

- Keep as many events as possible to retain statistical power; loose cuts to reduce backgrounds
- Background modeling and subtraction from Monte Carlo
  - Accurate MC with detailed detector description (and detectors will be complicated/granular)
  - Time-dependent following detector and run conditions
- Event pileup: expected rate at about 2 in a thousand events
  - Can be identified: μm vertex precision vs. 0.4 mm luminous region at Z pole
  - To be implemented in MC and studied

Acceptance and Efficiency

- Acceptance loss: particle outside detector fiducial volume
  - The higher the better (more stat + reduced error)
  - Detector granularity and active region
  - Excellent control of geometry and positioning (10^{-5})
- Efficiency loss: particle inside detector volume, but not identified
  - Hermiticity important to avoid dead areas
  - Redundancy to control efficiencies: tracker/muon chambers, tracker/ECAL, tracker/HCAL

Lineshape Expectations



Observables	Present value	FCC-ee stat.	FCC-ee current syst.	FCC-ee ultimate syst.	Theory input (not exhaustive)
m_Z (keV)	91187500 ± 2100	4	100	10 ?	Lineshape QED unfolding Relation to measured quantities
Γ_Z (keV)	2495500 ± 2300 [*]	4	25	5 ?	Lineshape QED unfolding Relation to measured quantities
σ^0_{had} (pb)	41480.2 ± 32.5 [*]	0.04	4	0.8	Bhabha cross section to 0.01% $e^+e^- \to \gamma\gamma$ cross section to 0.002%
N_ν ($\times 10^3$) from σ_{had}	2996.3 ± 7.4	0.007	1	0.2	Lineshape QED unfolding $(\Gamma_{\nu\nu}/\Gamma_{\ell\ell})_{SM}$
R_ℓ ($\times 10^3$)	20766.6 ± 24.7	0.04	1	0.2 ?	Lepton angular distribution (QED ISR/FSR/IFI, EW corrections)
$\alpha_s(m_Z)$ ($\times 10^4$) from R_ℓ	1196 ± 30	0.1	1.5	0.4 ?	Higher order QCD corrections for Γ_{had}
R_b ($\times 10^6$)	216290 ± 660	0.3	?	< 60 ?	QCD (gluon radiation, gluon splitting, fragmentation, decays, ...)

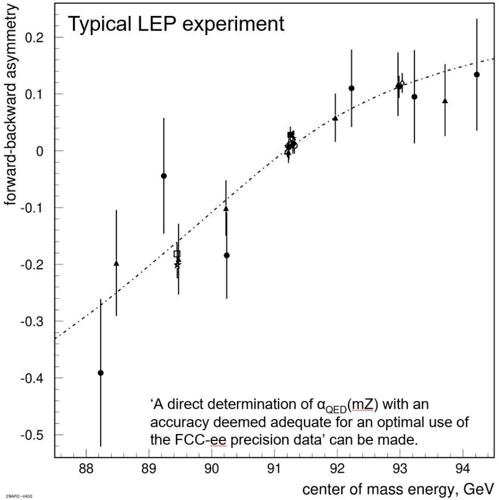
From: P.Janot talk at FCC theory workshop in June 2022

The Second Lineshape

Second lineshape to study the forward-backward asymmetries

- Decouples from cross section, no luminosity uncertainty
- A_{FB} constraints $\sin^2\theta_W^{\mathrm{eff}}$ most significantly at the peak, small statistical uncertainty
- Off-peak points measure $\alpha_{QED}(m_Z)$ just below and above the peak (87.9 or 94.3 GeV)

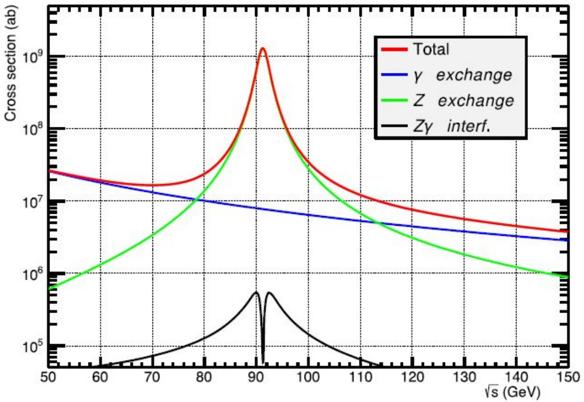
$$\mathrm{A}_{\mathrm{FB}}^{\mu\mu} = \frac{N_{\mathrm{F}} - N_{\mathrm{B}}}{N_{\mathrm{F}} + N_{\mathrm{B}}} \approx f(\sin^2\theta_W^{\mathrm{eff}}) + \alpha_{\mathrm{QED}}(s)\frac{s-m_Z^2}{2s}\, g(\sin^2\theta_W^{\mathrm{eff}})$$

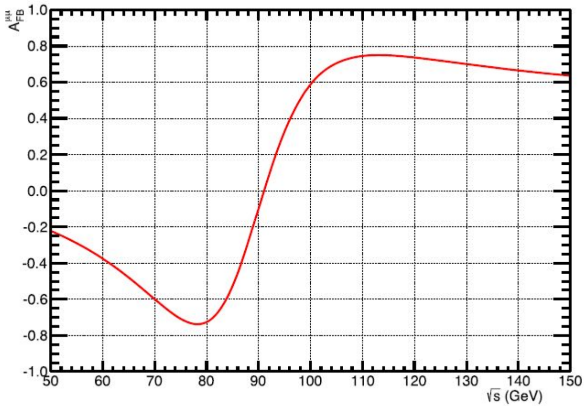


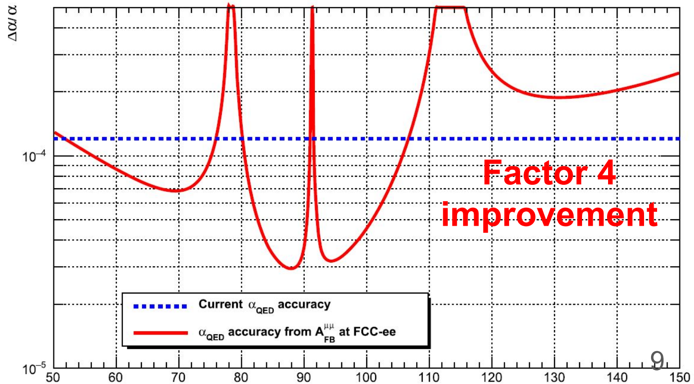
'A direct determination of α_{QED}(mZ) with an accuracy deemed adequate for an optimal use of the FCC-ee precision data' can be made.

Needs accurate MC for ISR, FSR and Interference (IFI)

- QED/SM corrections crucial
- Theoretical uncertainties to the level of ~ 10^{-4}, higher order calcs needed



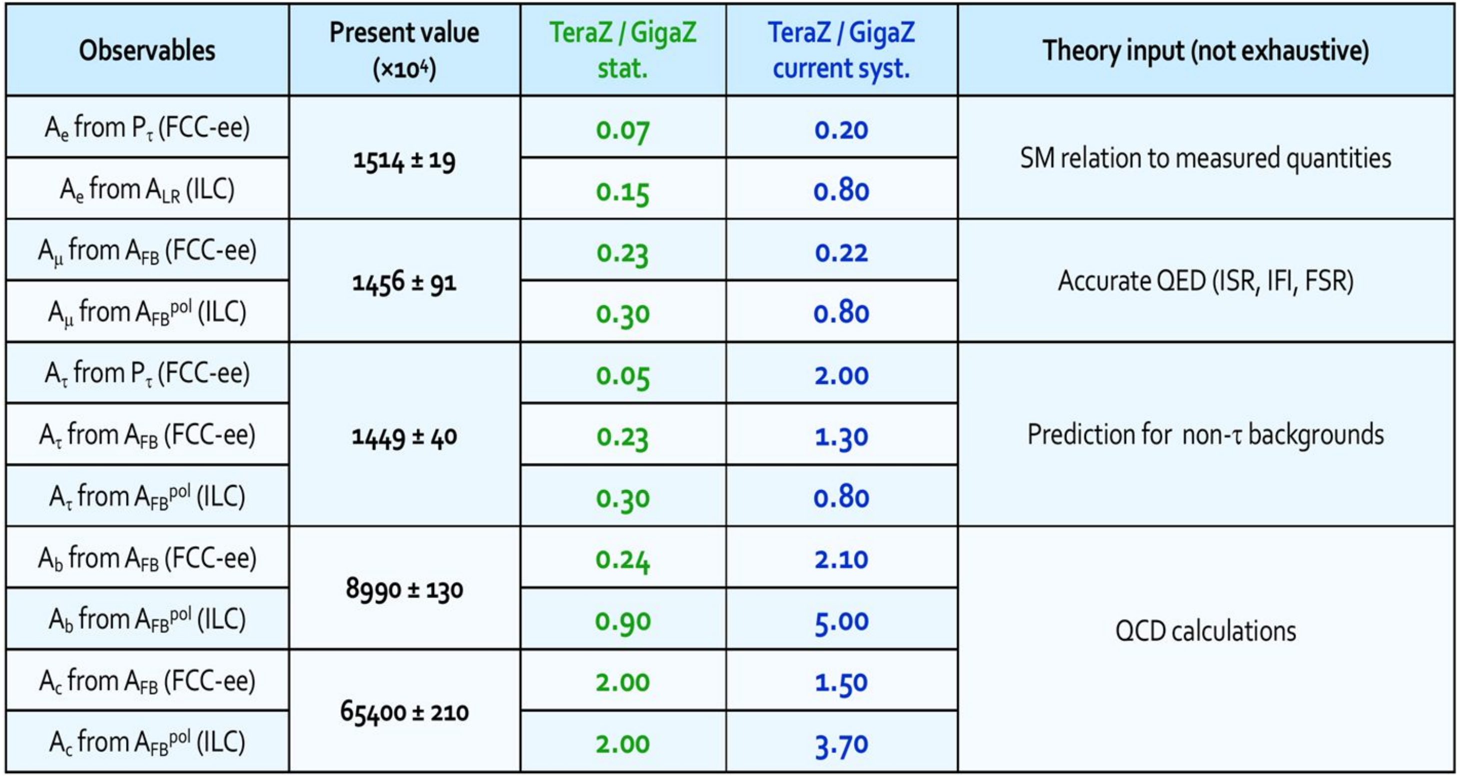




Factor 4 improvement

From: arxiv:1512.05544

Second Lineshape Expectations



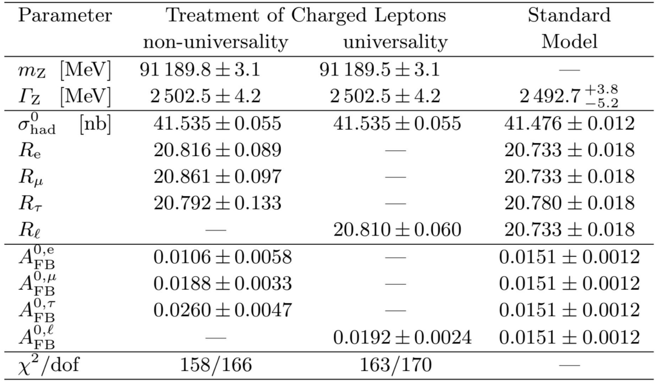
Observables	Present value (×10⁴)	TeraZ / GigaZ stat.	TeraZ / GigaZ current syst.	Theory input (not exhaustive)
A_e from P_τ (FCC-ee)	1514 ± 19	0.07	0.20	SM relation to measured quantities
A_e from A_{LR} (ILC)		0.15	0.80	
A_μ from A_{FB} (FCC-ee)	1456 ± 91	0.23	0.22	Accurate QED (ISR, IFI, FSR)
A_μ from A_{FB}^{pol} (ILC)		0.30	0.80	
A_τ from P_τ (FCC-ee)	1449 ± 40	0.05	2.00	Prediction for non-τ backgrounds
A_τ from A_{FB} (FCC-ee)		0.23	1.30	
A_τ from A_{FB}^{pol} (ILC)		0.30	0.80	
A_b from A_{FB} (FCC-ee)	8990 ± 130	0.24	2.10	QCD calculations
A_b from A_{FB}^{pol} (ILC)		0.90	5.00	
A_c from A_{FB} (FCC-ee)	65400 ± 210	2.00	1.50	
A_c from A_{FB}^{pol} (ILC)		2.00	3.70	

From: P.Janot talk at FCC theory workshop in June 2022

Extracting the SM Parameters from the Lineshape

At LEP, fitting of two-fermion data using Pseudo-Observables (PO)

- Used by both theory and experiment
- Assumptions: QED correct (ISR/FSR/int), weak interaction V-A, effective Born Approx., and Z boson decays to fermions only, photon/Z interference
- Fitting of the entire cross section and forward-backward asymmetry datasets
- Various theory programs are interfaced (TOPAZ0, ZFITTER, ALIBHABHA, MIBA, ….) for radiative corrections
- Experimental uncertainties taken into account



Parameter	Treatment of Charged Leptons non-universality	universality	Standard Model
m_Z [MeV]	$91\,189.8 \pm 3.1$	$91\,189.5 \pm 3.1$	—
Γ_Z [MeV]	$2\,502.5 \pm 4.2$	$2\,502.5 \pm 4.2$	$2\,492.7\,^{+3.8}_{-5.2}$
σ^0_{had} [nb]	41.535 ± 0.055	41.535 ± 0.055	41.476 ± 0.012
R_e	20.816 ± 0.089	—	20.733 ± 0.018
R_μ	20.861 ± 0.097	—	20.733 ± 0.018
R_τ	20.792 ± 0.133	—	20.780 ± 0.018
R_ℓ	—	20.810 ± 0.060	20.733 ± 0.018
$A^{0,e}_{FB}$	0.0106 ± 0.0058	—	0.0151 ± 0.0012
$A^{0,\mu}_{FB}$	0.0188 ± 0.0033	—	0.0151 ± 0.0012
$A^{0,\tau}_{FB}$	0.0260 ± 0.0047	—	0.0151 ± 0.0012
$A^{0,\ell}_{FB}$	—	0.0192 ± 0.0024	0.0151 ± 0.0012
χ^2/dof	158/166	163/170	—

What about FCC-ee?

- Similar approach? Still feasible to use the Pseudo-Observables approach?
- Or direct comparison between MC and Data to extract physics (differential measurements)?
- How to incorporate flexibly theory corrections?
- Modern tools necessary/to be developed to extract physics

Repeating the LEP Lineshape

Refurbish old L3 Fortran code to repeat the Lineshape using the FCC-ee numbers

- Input: 3 energy points: 91.2 GeV: 125 ab^{-1}; 88.0, 94.0 GeV: 40 ab^{-1}
- Output: the pseudo observables: m_Z, Γ_Z and $\sigma_{0,\ hadr}$

1. Statistical uncertainty on hadrons only, nothing else
2. Add fully correlated systematic uncertainty as large as peak stat. uncertainty
3. Add stat. uncertainty on luminosity corresponding to 14 nb cross section
4. Add 1.4 x 10^{-5} syst. fully correlated, and another 10^{-5} uncorrelated on luminosity
5. Add 10 keV correlated uncertainty on ECMS (abs.)
6. Or alternatively 100 keV correlated uncertainty on ECMS (abs.)

Setup	$\Delta(m_{Z})$ (keV)	$\Delta(\Gamma_Z)$ (keV)	$\Delta(\sigma_{0,\ hadr})$ (pb)
1	3.0	2.9	0.026
2	3.0	2.9	0.034
3	3.6	3.6	0.047
4	16	22	0.73
5	18	22	0.73
6	101	22	0.73

Repeating the LEP Hadronic Cross-Section

Repeat the LEP-L3 hadronic cross-section for a single energy point

- Explore different Monte Carlo generators and assess impact on theory
- Modeling of hadronization, particle multiplicities
- Assessment of backgrounds
- Detector requirements in terms of acceptance and efficiency

Use the available FCC analysis framework and tools (FastSim Delphes – IDEA detector)

- Detector simulation very close to ideal but realistic? FullSim?
- (major) differences expected in terms of resolutions, backgrounds etc.

Extrapolate and interpret results to FCC-ee luminosities:

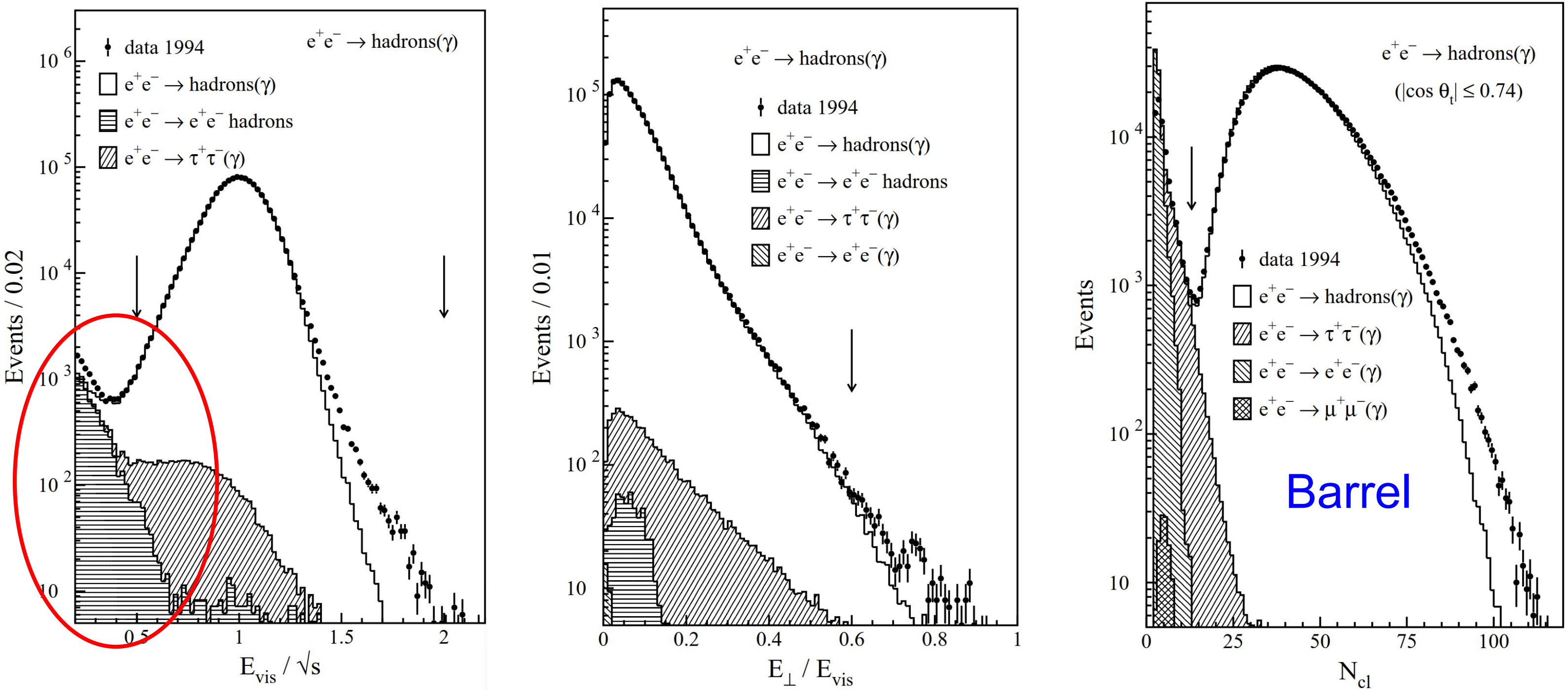
- *Luminosity from 44.84 pb^{-1} to 125 ab^{-1} (1.6 M → 3.8 x 10^6 M)*
- Uncertainty from 8.5 x 10^{-4} to 5 x 10^{-7}

All results work in progress! And much more to study

How it looked like at L3

Selection criteria: $0.5 < E_{vis}/\sqrt{s} < 1.5$; number of clusters/particles > 15; energy imbalance > 0.6

- Calorimetric-based analysis – cluster counting
- Noise in tails, number of clusters in MC do not agree
- Two-photon background is leaking



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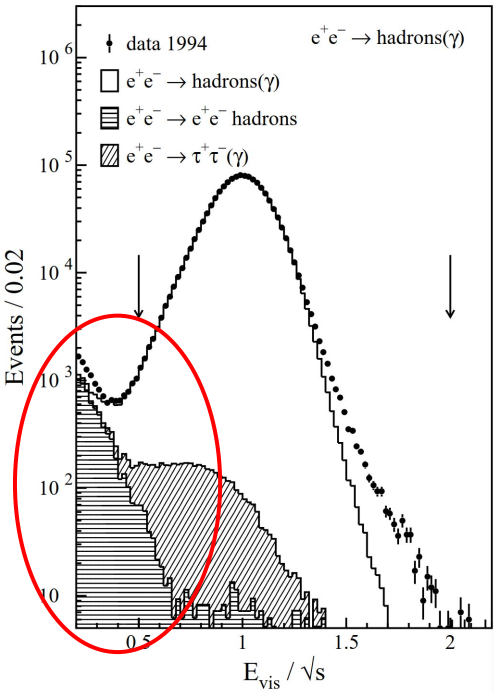
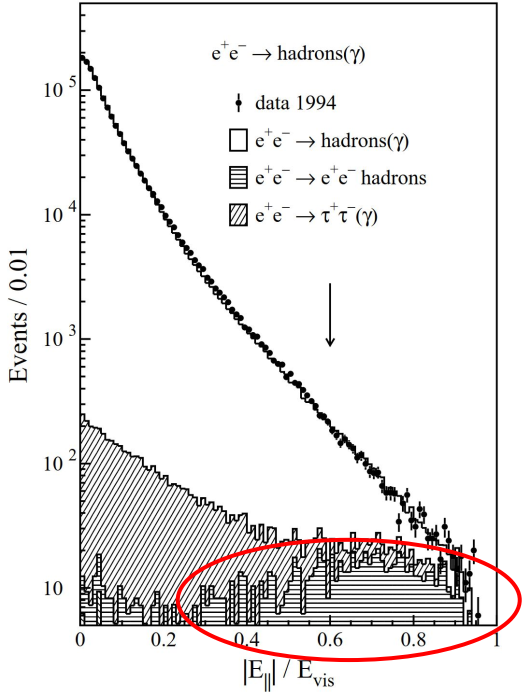
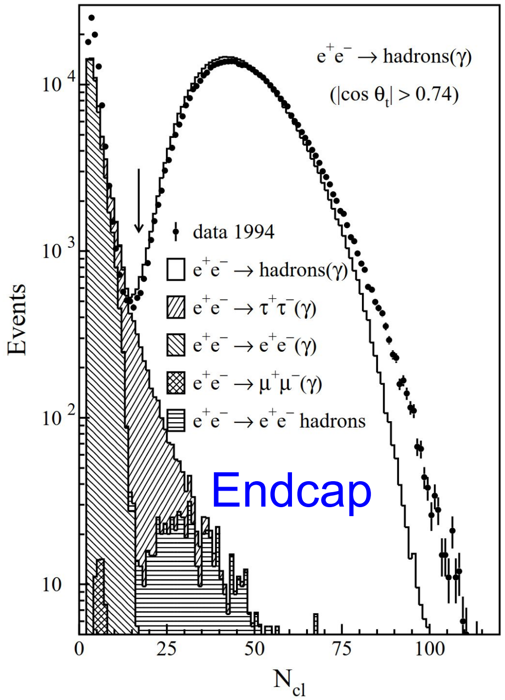
- Two-photon background is leaking (mainly in endcap)



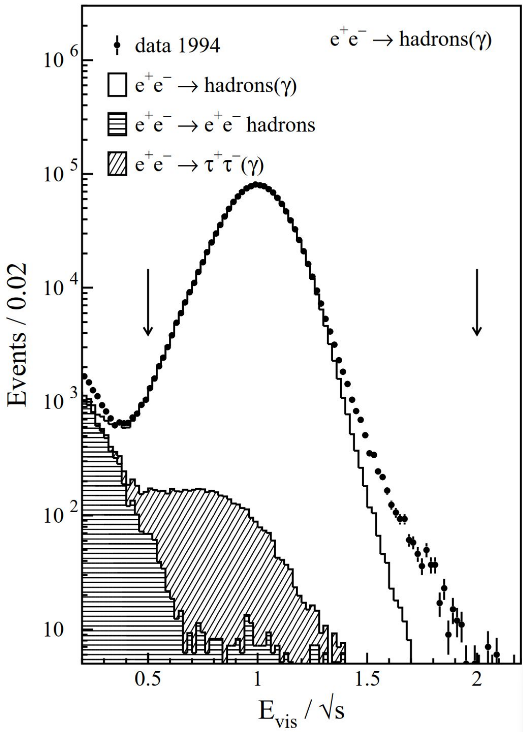


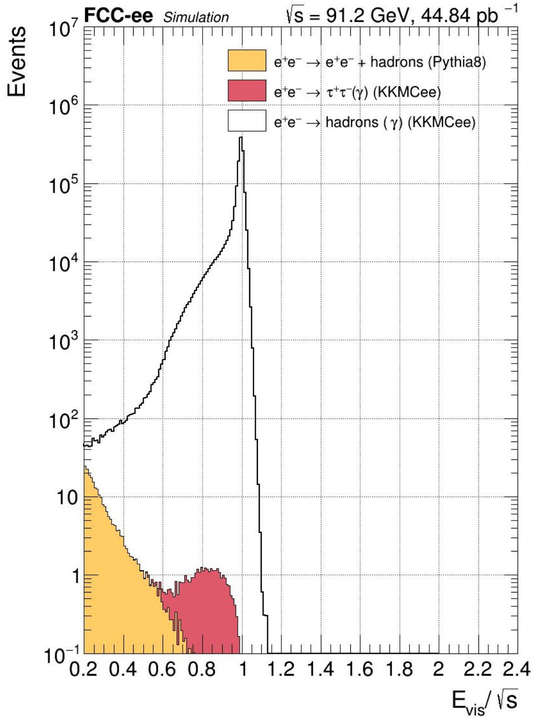


LEP vs. FCC-ee

Comparing the visible energy (normalized)

- Resolution much (much) better at FCC-ee; tail is physics
- Two-photon and Tau background much lower yields

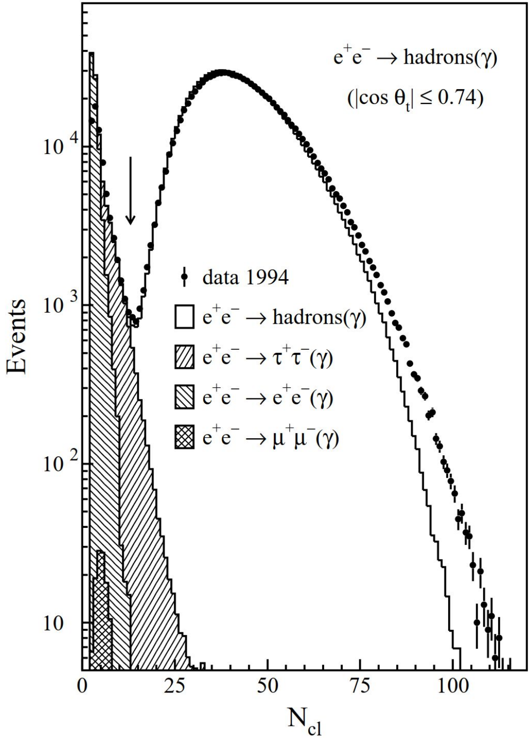


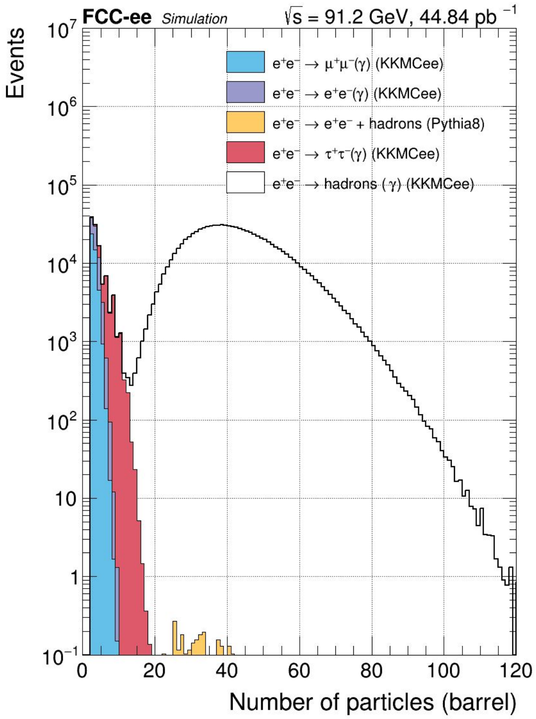


LEP vs. FCC-ee

Cluster/particle multiplicities barrel ($|\cos(\theta_t)| < 0.74$)

- Distributions look quite similar
- Counting definition between clusters (LEP) and Reconstructed particles (FCC-ee)





LEP vs. FCC-ee

Cluster/particle multiplicities endcap (|cos(θ_t)| > 0.74)

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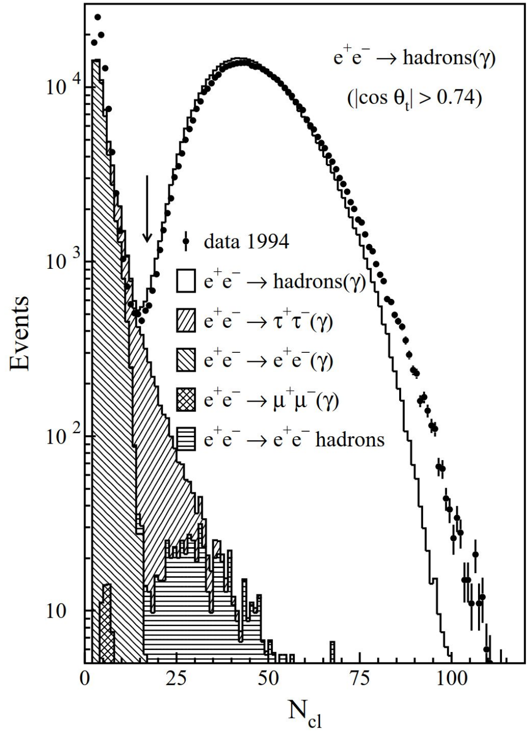
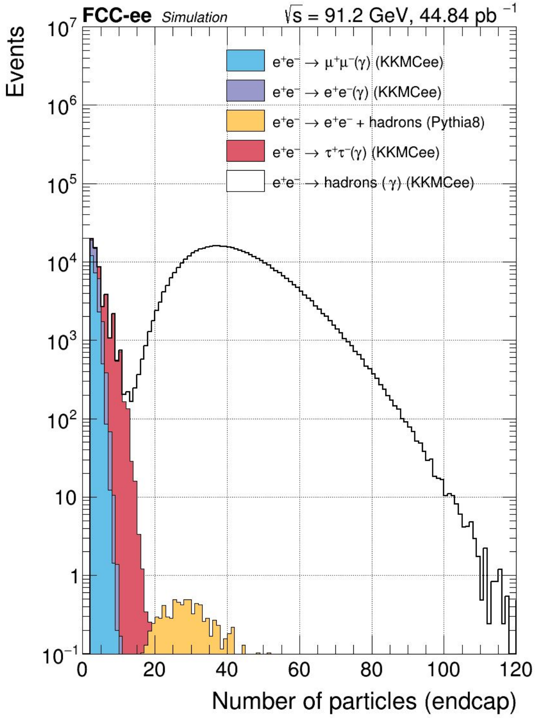
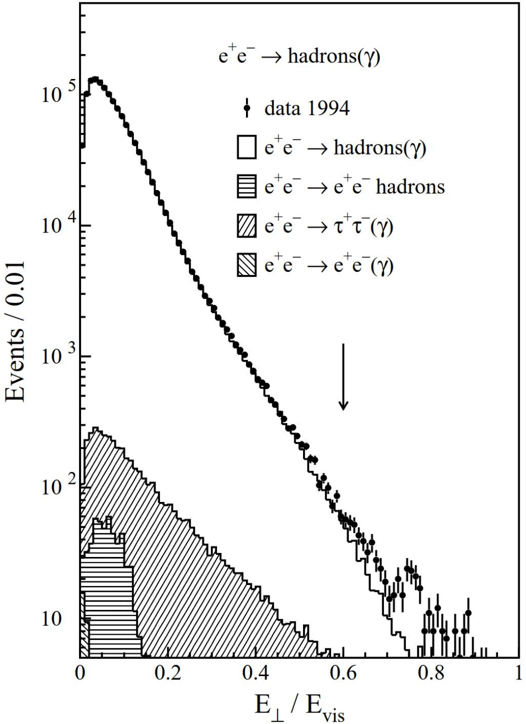


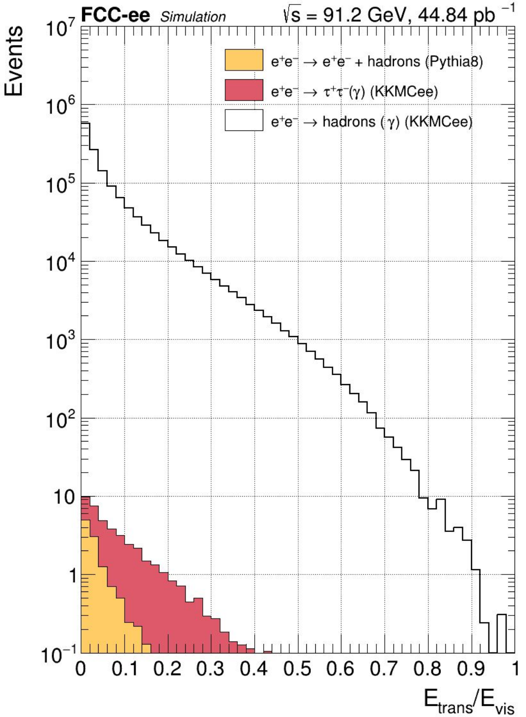


LEP vs. FCC-ee

Transverse energy imbalance

- Resolution much (much) better at FCC-ee
- Tau lower, two-photon in the right place





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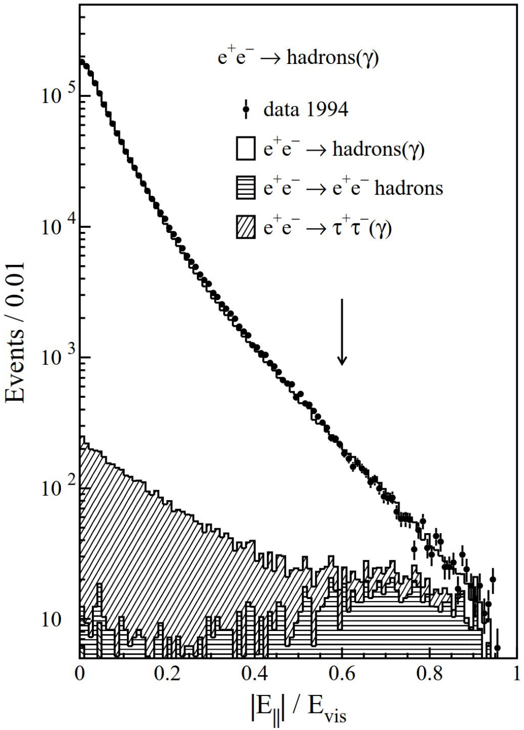
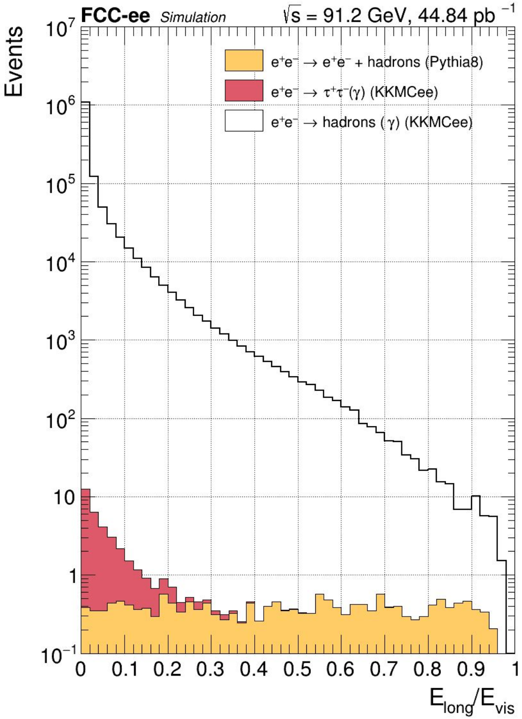




Acceptance and Efficiency considerations

Comparison of acceptance

- LEP – acceptance down to 12º → cos(12º) = 0.9781 (L3)
- FCC-ee – acceptance down to 7º → cos(7º) = 0.9940 (IDEA)

Z → hadrons have very high acceptance

- Enormous improvement in number of lost particles (2.2% → 0.75%)
- Jets are too big to not register: efficiency very close to 100%
- No trigger, which is good but redundancy in detectors much needed for precise efficiency determination
- Tracker vs. calorimeter based analysis essential (add timing layer?) → PID
- Detector/machine conditions, noise → realistic detector Monte Carlo
  - Collision angle should not matter, as long as it is simulated well – to be implemented and checked
  - Beam energy spread already implemented

Quantity/Detector	ALEPH	DELPHI	L3	OPAL
Acceptance	s’/s > 0.1	s’/s > 0.1	s’/s > 0.1	s’/s > 0.1
Efficiency	99.1	94.8	99.3	99.5
Background	0.7	0.5	0.3	0.3

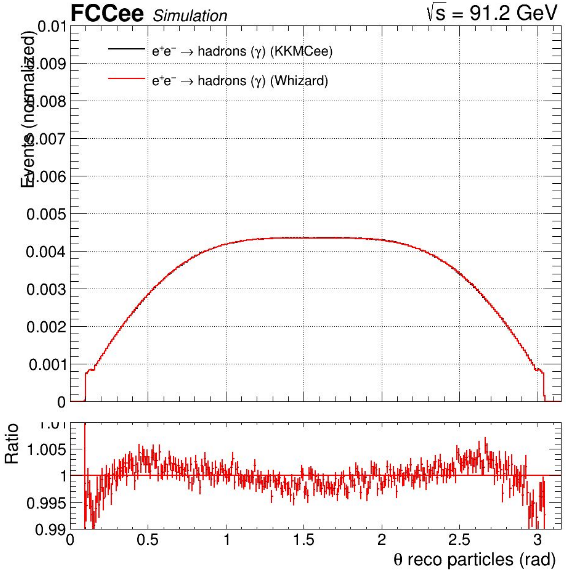
Acceptance of Different Generators

Acceptance defined as: #events after all selection cuts / # initial events

- Reduced by geometrical cuts in detector (beam pipe) → to be maximized to minimize the error on A
- Whizard and KKMC do not close with 0.07 %
- Underlying distribution of polar angle of particles different leading to sizeable acceptance differences
- Residual generator differences to be understood to understand nature of discrepancy

Generator	**Acceptance (%)**	**Stat. Error (% abs.)**
Whizard	99.46	0.0017
KKMCee	99.39	0.0035
Difference	0.07	0.0039

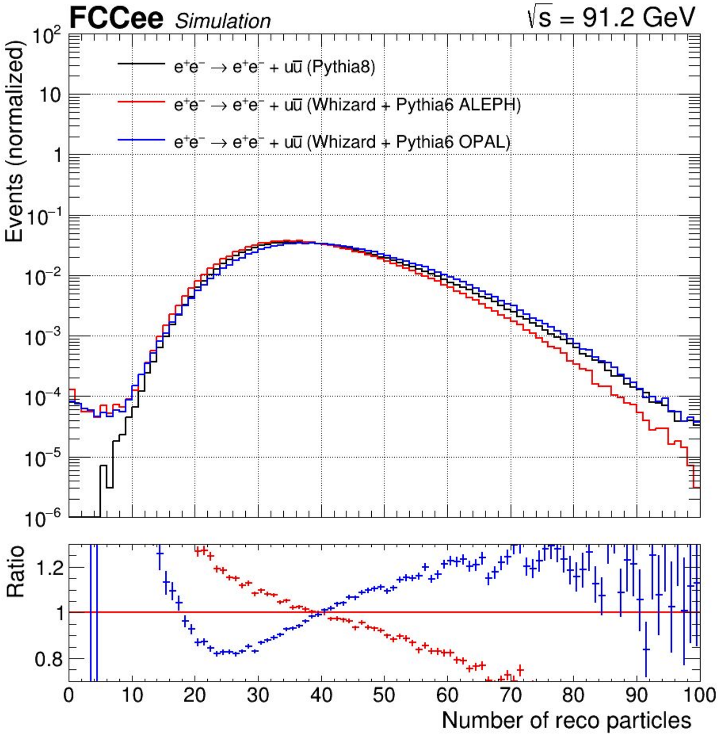
Corresponds to a 6×10^{-4} uncertainty on the cross-section



Particle Multiplicity

Compare Pythia hadronization and showering modelling

- Several tunes available: Pythia defaults, OPAL, ALEPH
- Pythia 8 vs Pythia 6
- Different generators (Whizard, Pythia)



Non-negligible differences between different configurations

- More studies needed (modern Pythia8 tunes for e^+e^-)
- Differences are sufficiently large to be studied with LEP statistics ?

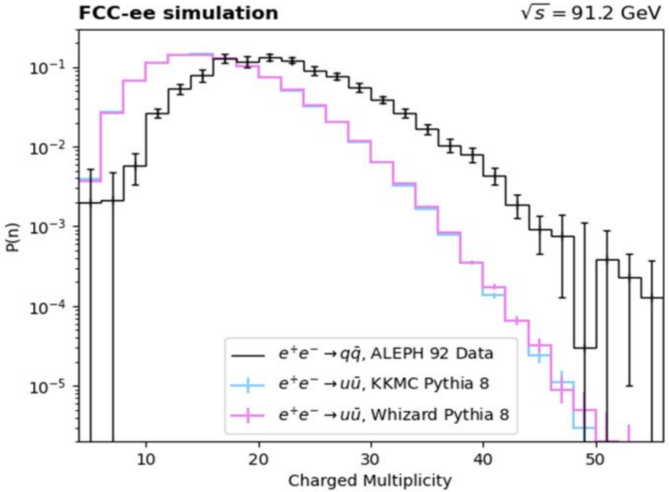
Particle Multiplicity – ALEPH comparison

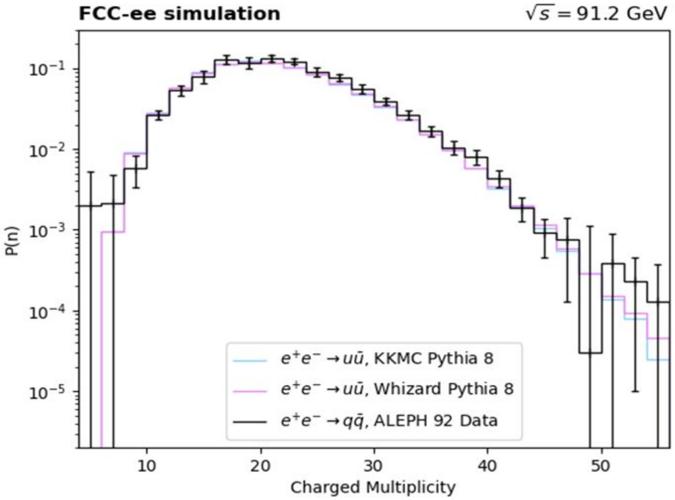
Comparison of charged particle multiplicity

- Unfolded charged particle distribution from ALEPH available
- Good agreement obtained to first order – need to compare systematically

More in-depth studies needed → *with LEP data in edm4hep*? (see talk M.Maggi this morning)

- Different hadronization and showering: tunes and implementations (Pythia, Herwig, …)
- Factorize differences of generator vs. hadronization/showering

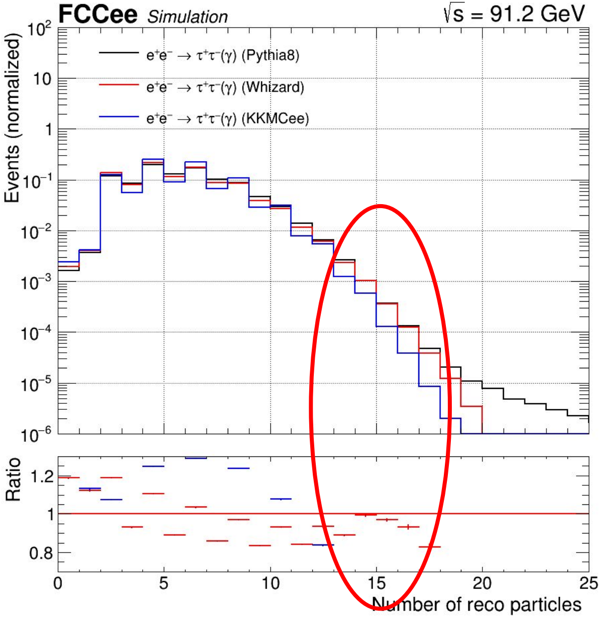


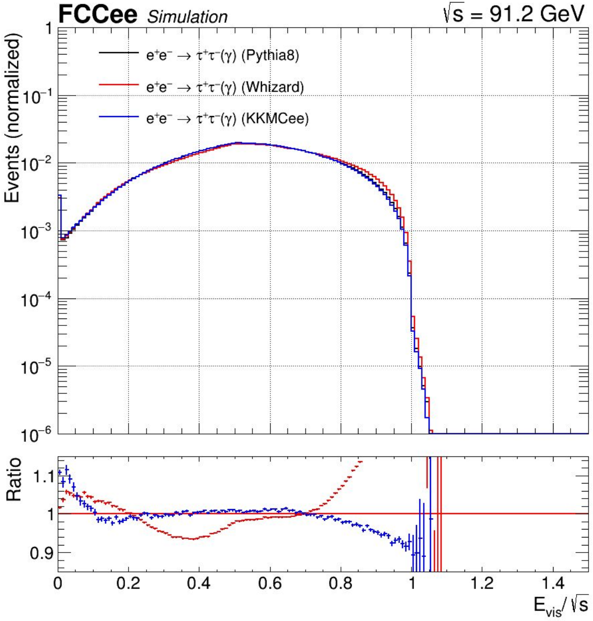


Tau Background

Tau background mainly cut based on particle multiplicity

- High tau prongs have larger uncertainties and are in the signal region for hadron cross-section
- Strongly depends on the Tau BRs used: 10-20% difference around cut value N=15
- Mainly comes from different Tau BR (Tauola vs Pythia) – *to be verified*, and BRs to be aligned
- Correlated impact on the visible energy





Two-photon Background

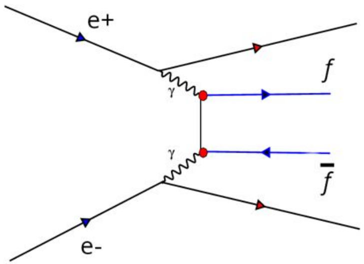
Two-photon events leak into the visible spectrum of Z→hadron phase space

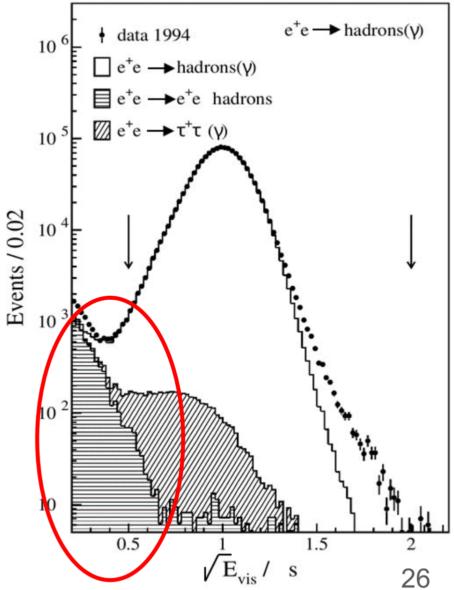
- Non-negligible background; xsec rises towards low momentum transfer
- Difficult to model – large errors on cross-section and shapes (visible energy, number of particles), especially at low energies
- Mainly untagged scattered electrons/positrons (in beampipe) leading to imbalance of longitudinal energy

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

For FCC-ee, clearly a better understanding needed

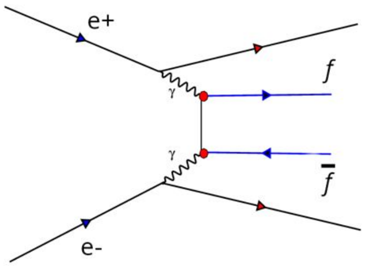
- Key issues: shape in visible energy and number of particles produced
- Tails are sensitive to noise, promoting them to multi-hadron events, other final states
- Off-peak running as “control region”, or explicit tagging of e^+/e^-?
- Better MC is needed (theory community)





Two-photon Background

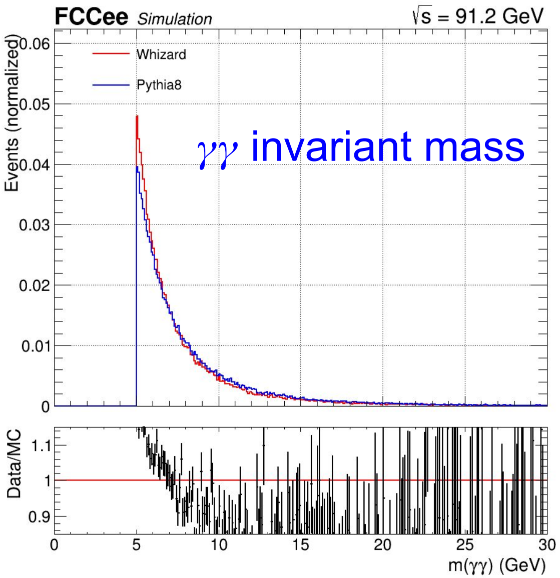
Explore different MC generators: Whizard and Pythia

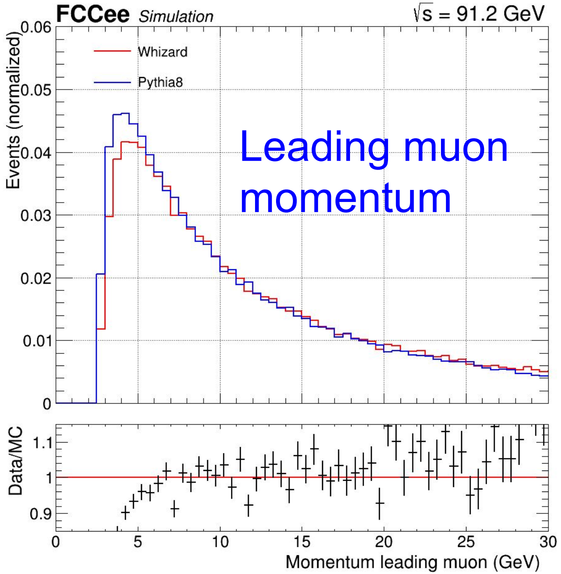


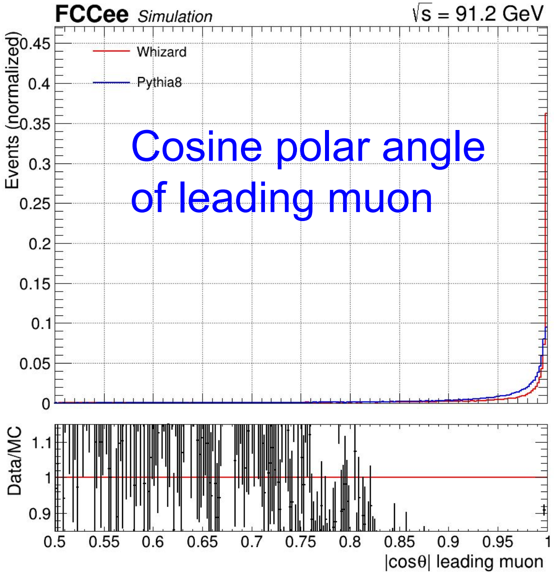
- Both implemented two-photon as Equivalent Photon Approximation (EPA)
- Introduces beam structure functions to describe the process

Compare "simplest" $\mu\mu$ final state and *tune*, then check on hadrons

- Differences observed, work in progress (iterating with authors)


$\gamma\gamma$ invariant mass

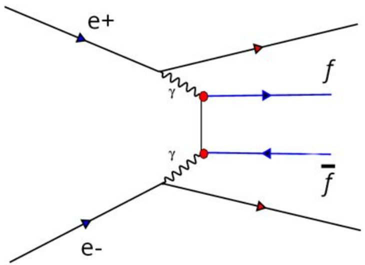

Leading muon momentum

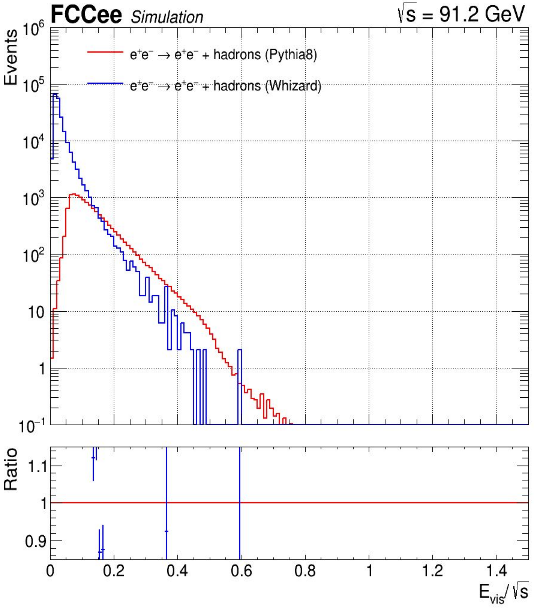

Cosine polar angle of leading muon

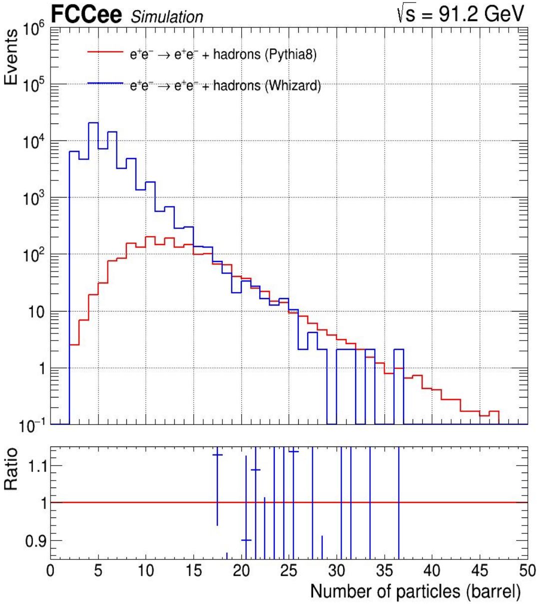
Two-photon Background

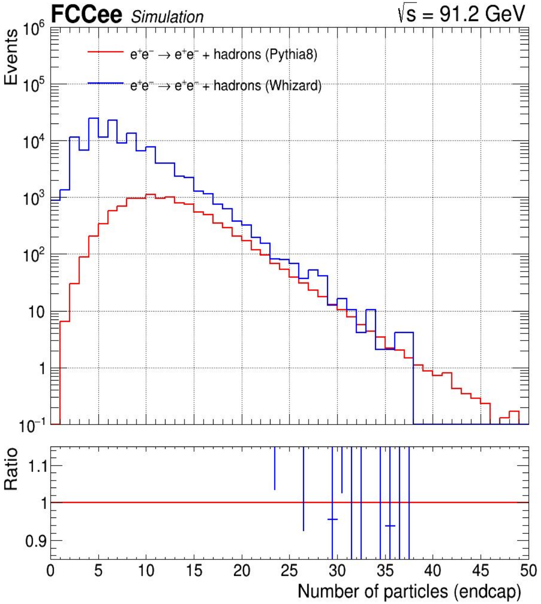
Comparison Whizard and Pythia8 for two-photon → hadrons

- Pythia pushed towards higher qq energies – different cut-offs in model?
- Fine-tuning and quantifying differences ongoing









Summary and Conclusions

Electroweak Physics at FCC-ee will improve main SM parameters up to 3 orders of magnitude

Clearly, this puts enormous constraints on the machine, theory and detectors

- Luminosity and energy calibration
- Detector requirements to cope with acceptance and efficiency
- Many inputs needed from theory community to have improved MC and reduce theoretical uncertainties

Started to explore the Z lineshape with the FCC tools

- More realistic simulation, comparison with LEP
- Extrapolate findings to FCC-ee luminosities and assess the residual experimental/theoretical uncertainties
- Especially fragmentation/hadronization and two-photon background under study
- **Presented preliminary results… and much more exciting work ahead!**