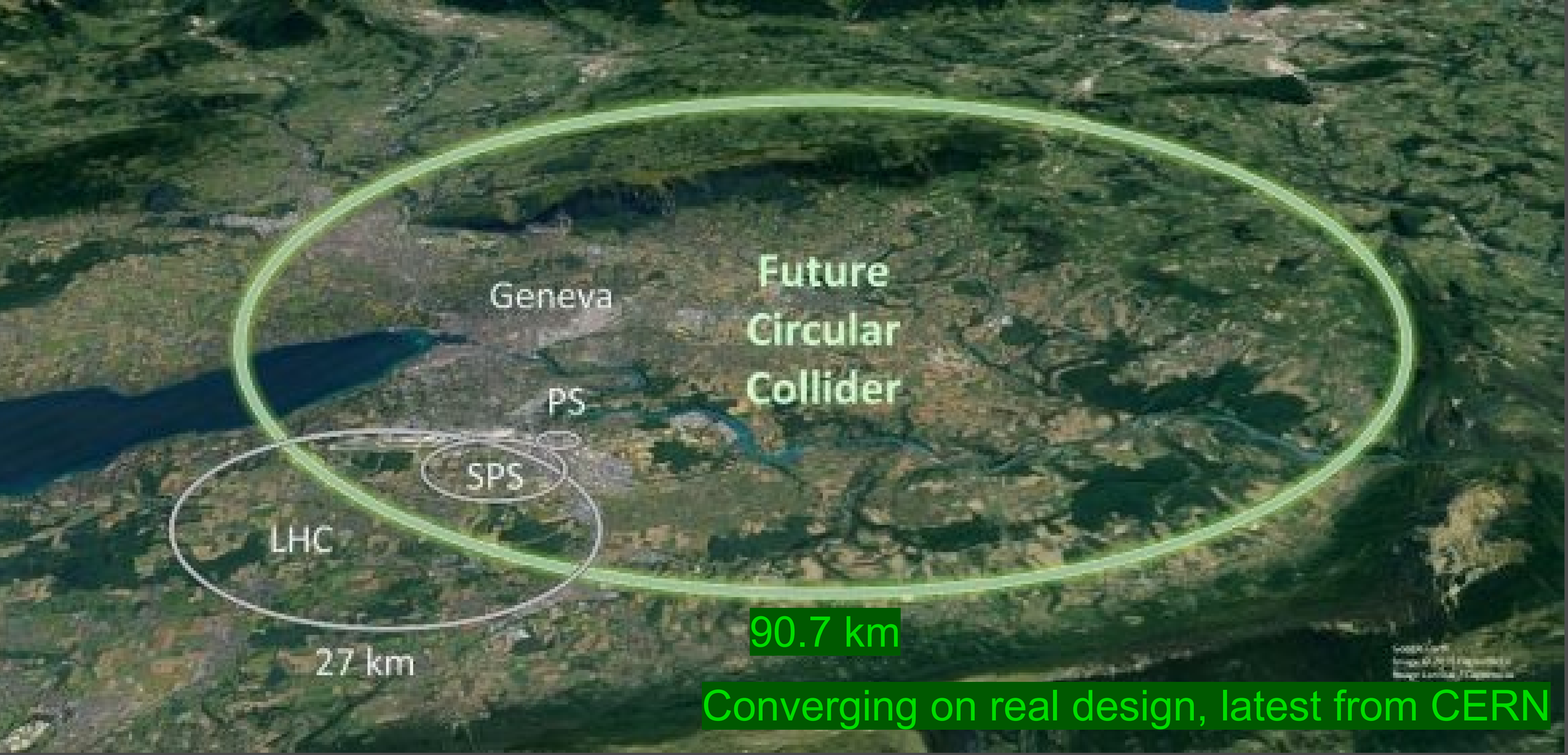



# Electroweak Precision at FCCee

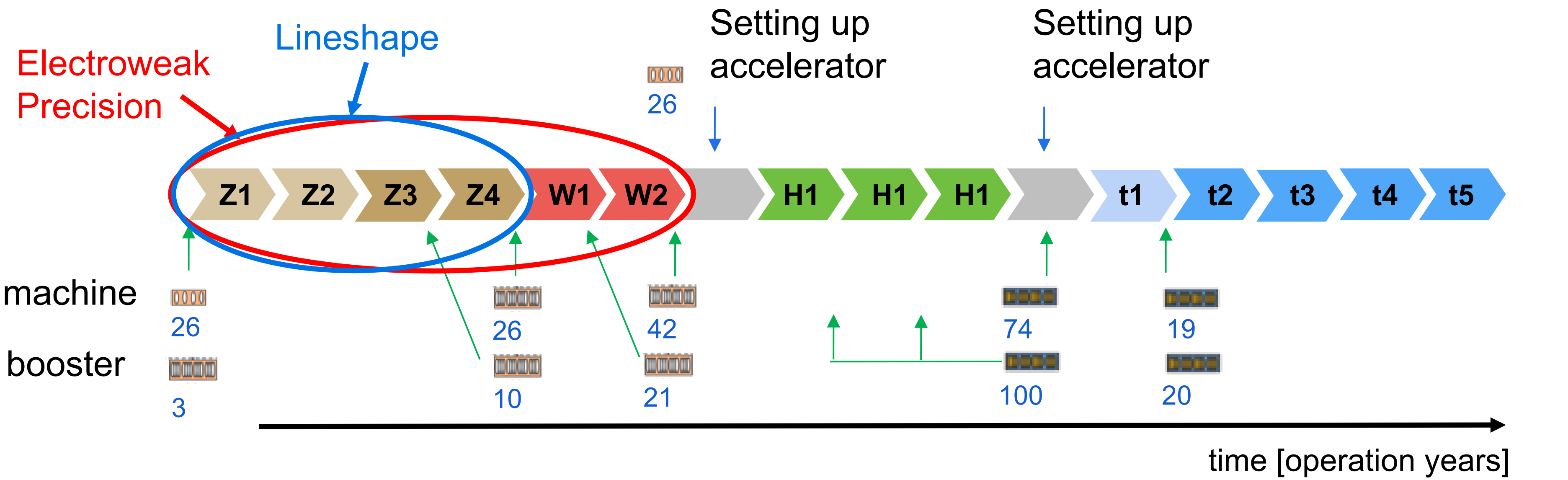
## *A quantum leap into new Era*

ZPW2024, Zurich
Christoph Paus
January 8, 2024

# FCC-ee Run Plan

## The baseline run plan for FCC-ee

- Z run has most events followed by WW run: most stringent exp. requirements
- Baseline run plan was updated for the midterm report of FCC feasibility study to have 4 IPs instead of 2 IPs increasing available event sample by factor of ~1.7

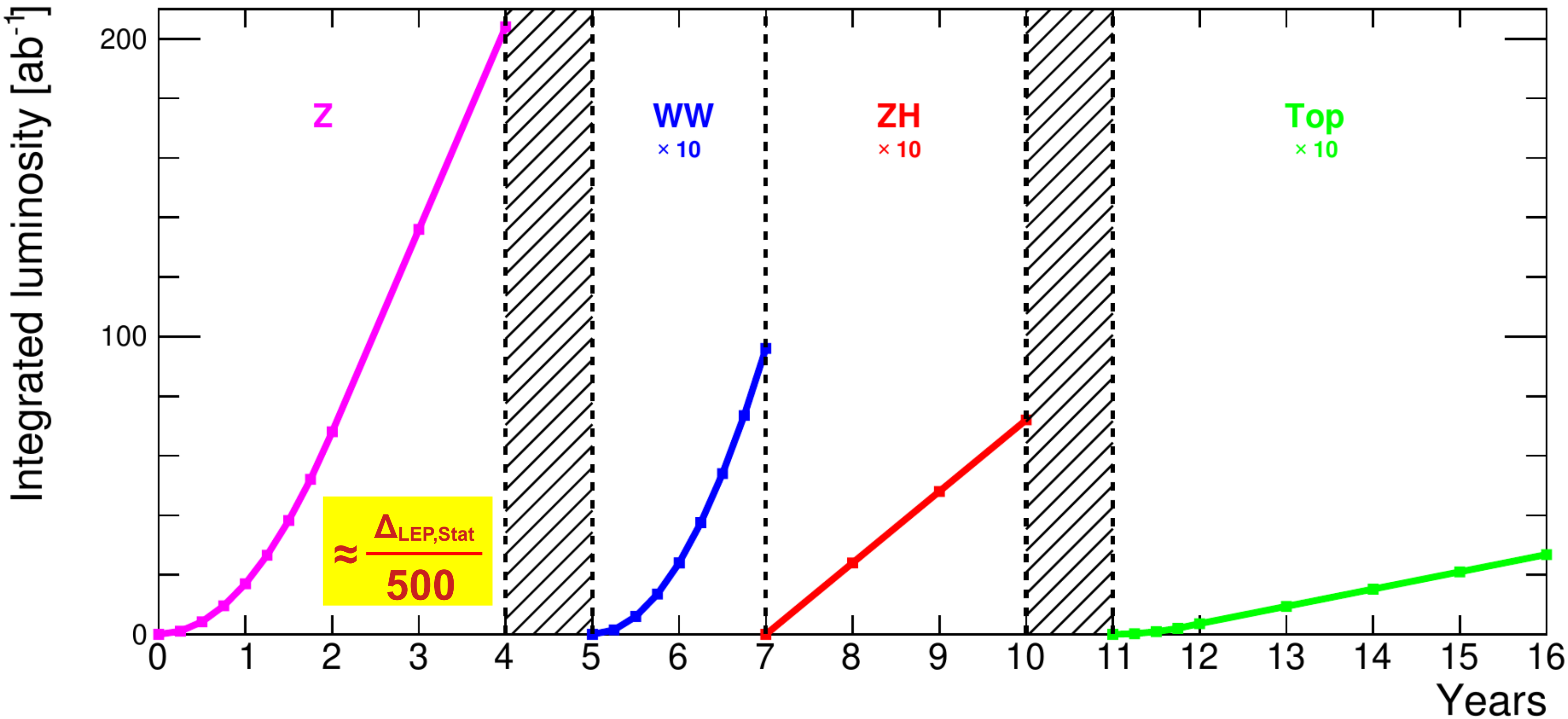



| Working point | Z, years 1-2 | Z, later | WW, years 1-2 | WW, later | ZH | $t\bar{t}$ | |
|---|---|---|---|---|---|---|---|
| $\sqrt{s}$ (GeV) | 88, 91, 94 | | 157, 163 | | 240 | 340–350 | 365 |
| Lumi/IP ($10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$) | 70 | 140 | 10 | 20 | 5.0 | 0.75 | 1.20 |
| Lumi/year ($\mathrm{ab}^{-1}$) | 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 | |

# FCC-ee Run Plan

## Baseline FCC-ee staged running scenario

- Starting with the lowest energy scenario at the Z pole is most obvious to stage the installation of RF cavities
- Z pole running will result in an enormous data set with unprecedented precision
- Precision LEP uncertainties are devised by ~500 (statistical uncertainties, only)

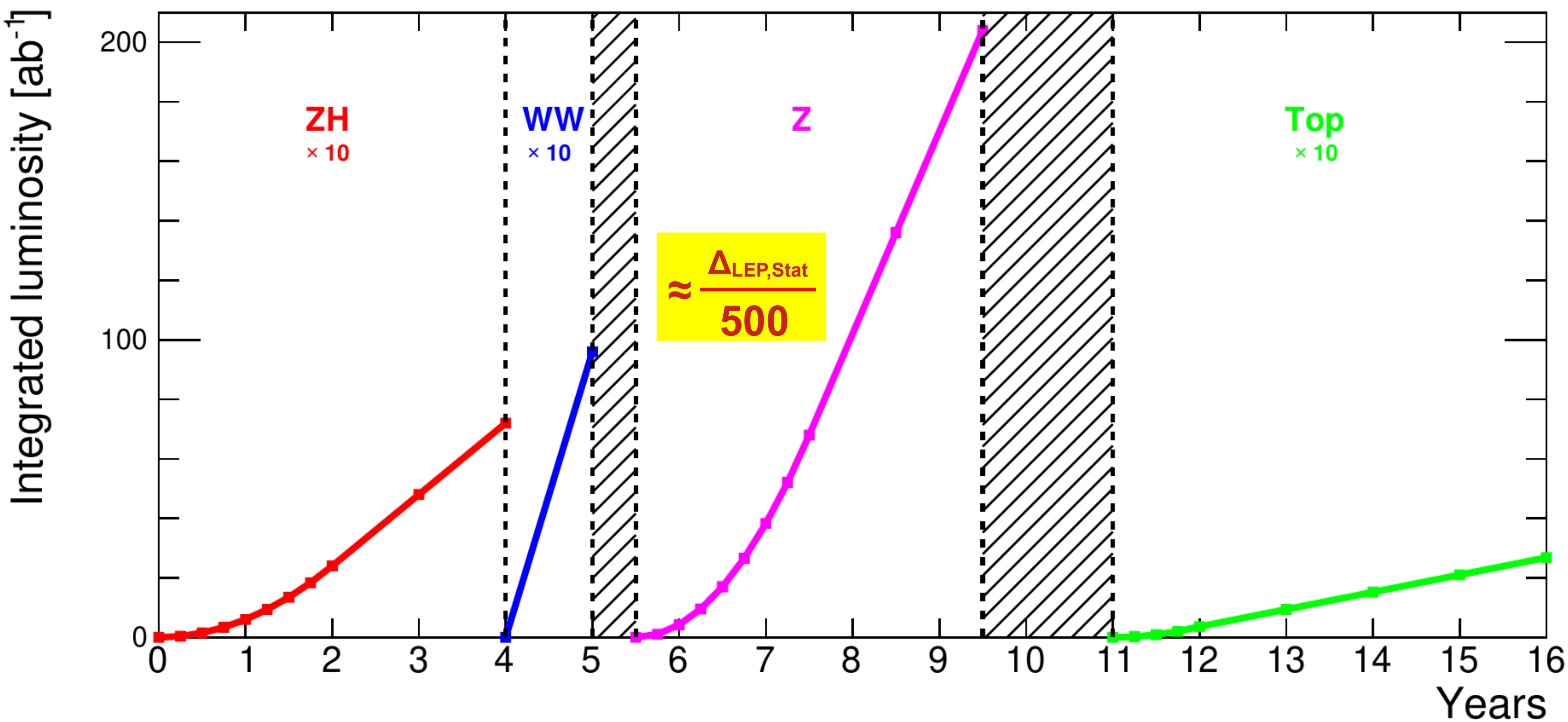



At FCC-ee it takes about a minute to accumulate an entire LEP Z pole dataset

# FCC-ee Run Plan

## Alternate FCC-ee running scenario

- After questions during P5 sessions, whether Higgs factory of FCC-ee could start earlier, an alternative scenario has been developed that also fits into a 16 year operation plan
- The initial ZH and Z pole running will initially ramp up and after development reach the design luminosity




At FCC-ee it takes about a minute to accumulate an entire LEP Z pole dataset

# *Motivation for Precision*

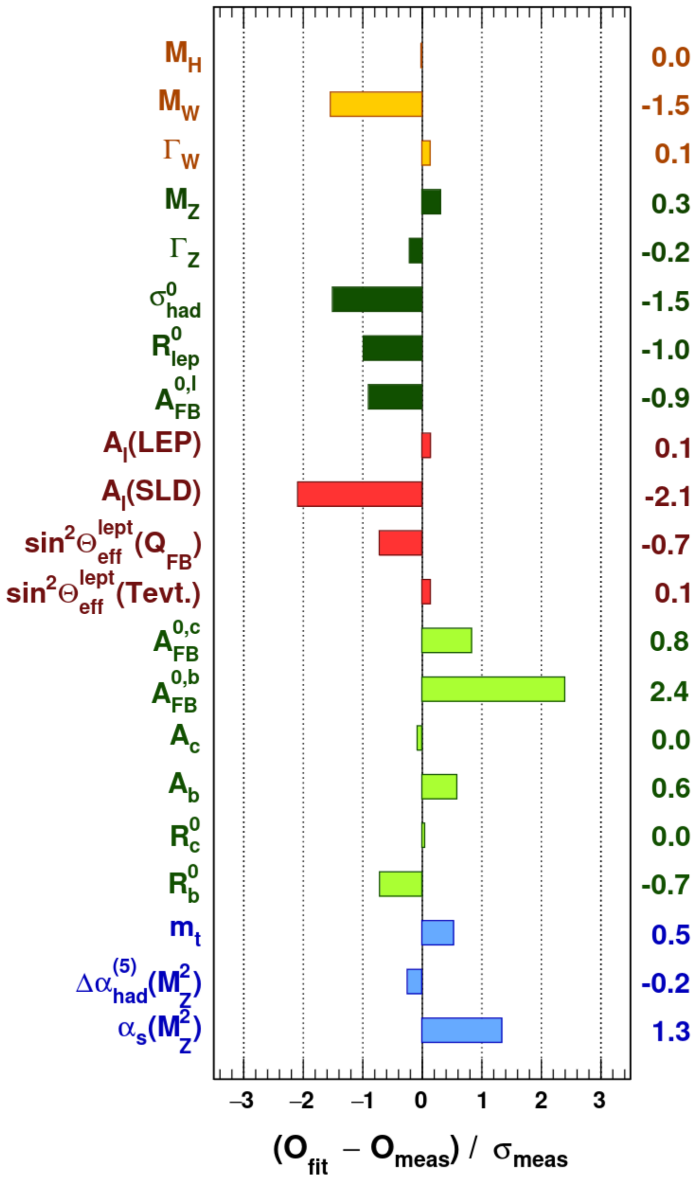
## At LEP

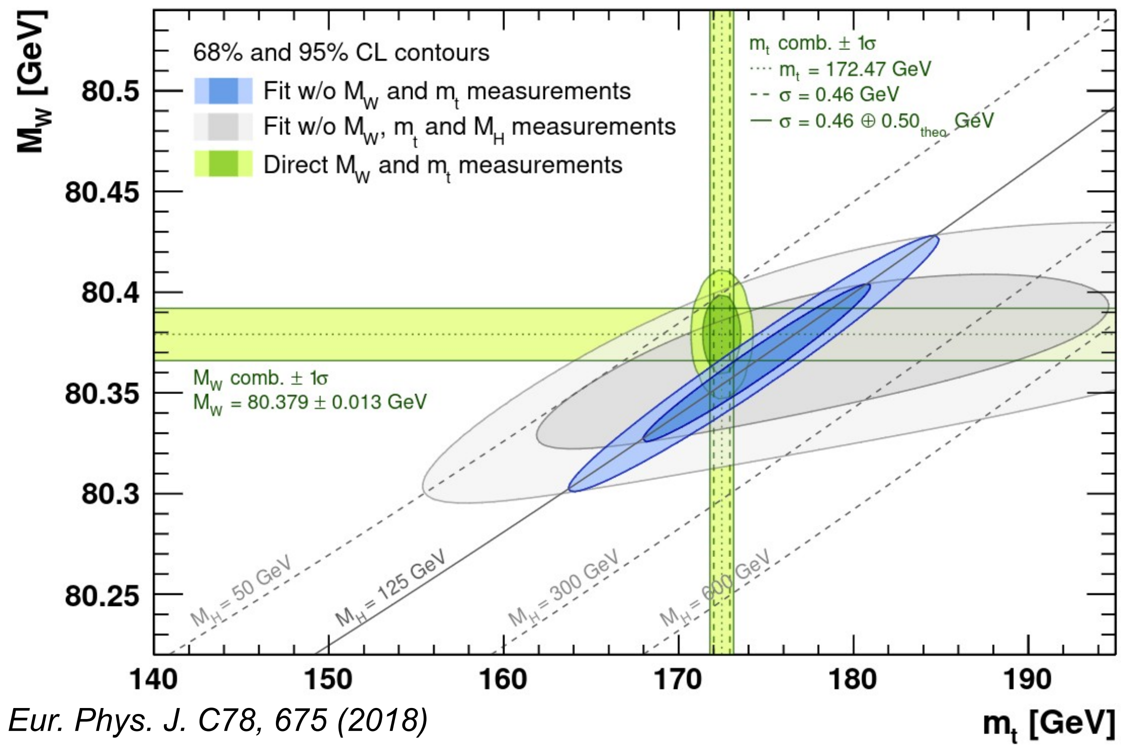
- Measure crucial fundamental parameters of the standard model
- Z mass, W mass, $\alpha_S$, $\alpha_{QED}$, number of light neutrinos
- Convert direct observables like $\sigma$, $A_{FB}$, $\tau_{POL}$, … to pseudo observables
- **Constrain indirectly $m_t$ and $m_H$ using pseudo observables as input**
- Find discrepancies in the measurements indicating the SM is broken or better that there is physics beyond the standard model (BSM)

## For FCC ee

- All standard model parameters are known and look to be consistent
  - Last additions $m_H$ (LHC, 2012) and $m_t$ (Tevatron, 1995)
  - *… neutrinos are another story*
- Consistency between all measurements will be tested about 3 orders of magnitude more stringently than before, **inconsistencies will immediately invoke new physics**

# Latest Status




*Eur. Phys. J. C78, 675 (2018)*

Latest CDF $m_W$ not included

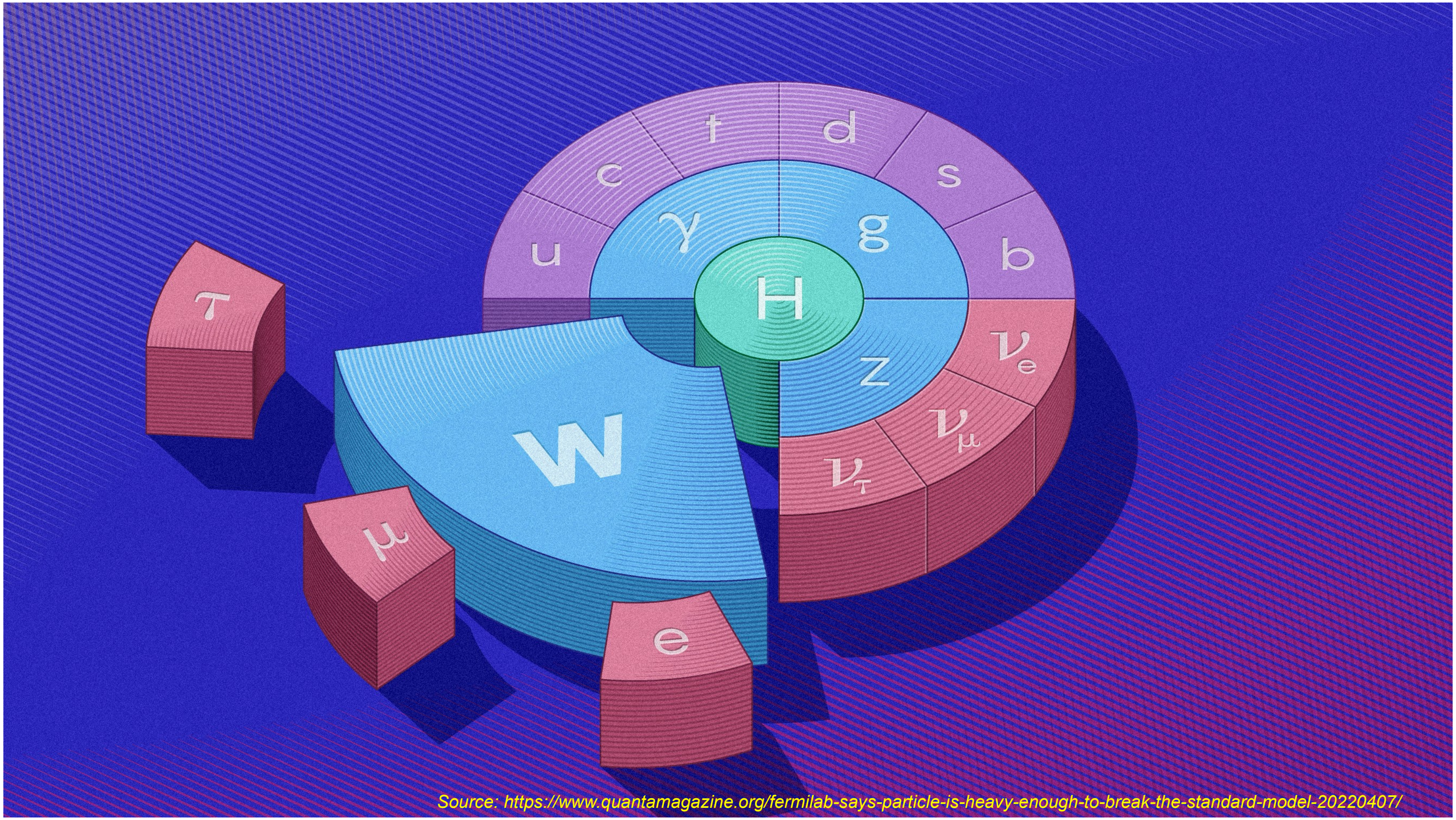
## Comparing

- Measured SM parameters (yellow/green)
- With predictions (in blue) that come indirectly from Pseudo Observables on the left

# Why do precision EW?

## CDF experiments last word

- W mass is too heavy by seven standard deviations !



# Why do precision EW?

## CDF experiments last word

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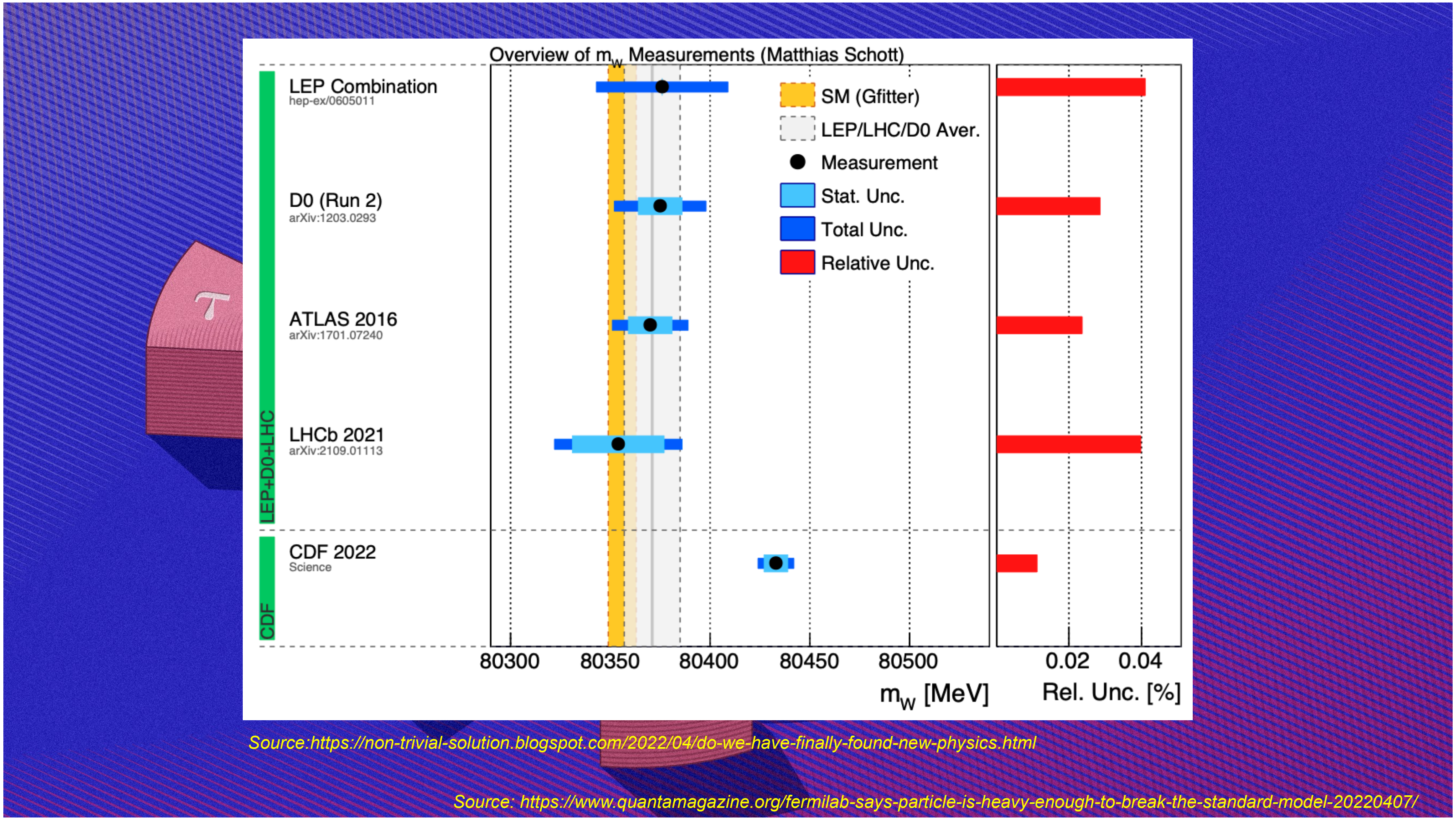


# Lineshape Summary

## Key topics for theory to address

| 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<br>Relation to measured quantities |
| $\Gamma_Z$ (keV) | 2495500 ± 2300 [*] | 4 | 25 | 5 ? | Lineshape QED unfolding<br>Relation to measured quantities |
| $\sigma^0_{had}$ (pb) | 41480.2 ± 32.5 [*] | 0.04 | 4 | 0.8 | Bhabha cross section to 0.01%<br>$e^+e^- \rightarrow \gamma\gamma$ cross section to 0.002% |
| $N_\nu$ ($\times 10^3$) from $\sigma_{had}$ | 2996.3 ± 7.4 | 0.007 | 1 | 0.2 | Lineshape QED unfolding<br>$(\Gamma_{\nu\nu}/\Gamma_{\ell\ell})_{SM}$ |
| $R_\ell$ ($\times 10^3$) | 20766.6 ± 24.7 | 0.04 | 1 | 0.2 ? | Lepton angular distribution<br>(QED ISR/FSR/IFI, EW corrections) |
| $\alpha_s(m_Z)$ ($\times 10^4$) from $R_\ell$ | 1196 ± 30 | 0.1 | 1.5 | 0.4 ? | Higher order QCD corrections for $\Gamma_{had}$ |
| $R_b$ ($\times 10^6$) | 216290 ± 660 | 0.3 | ? | < 60 ? | QCD (gluon radiation, gluon splitting, fragmentation, decays, …) |

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

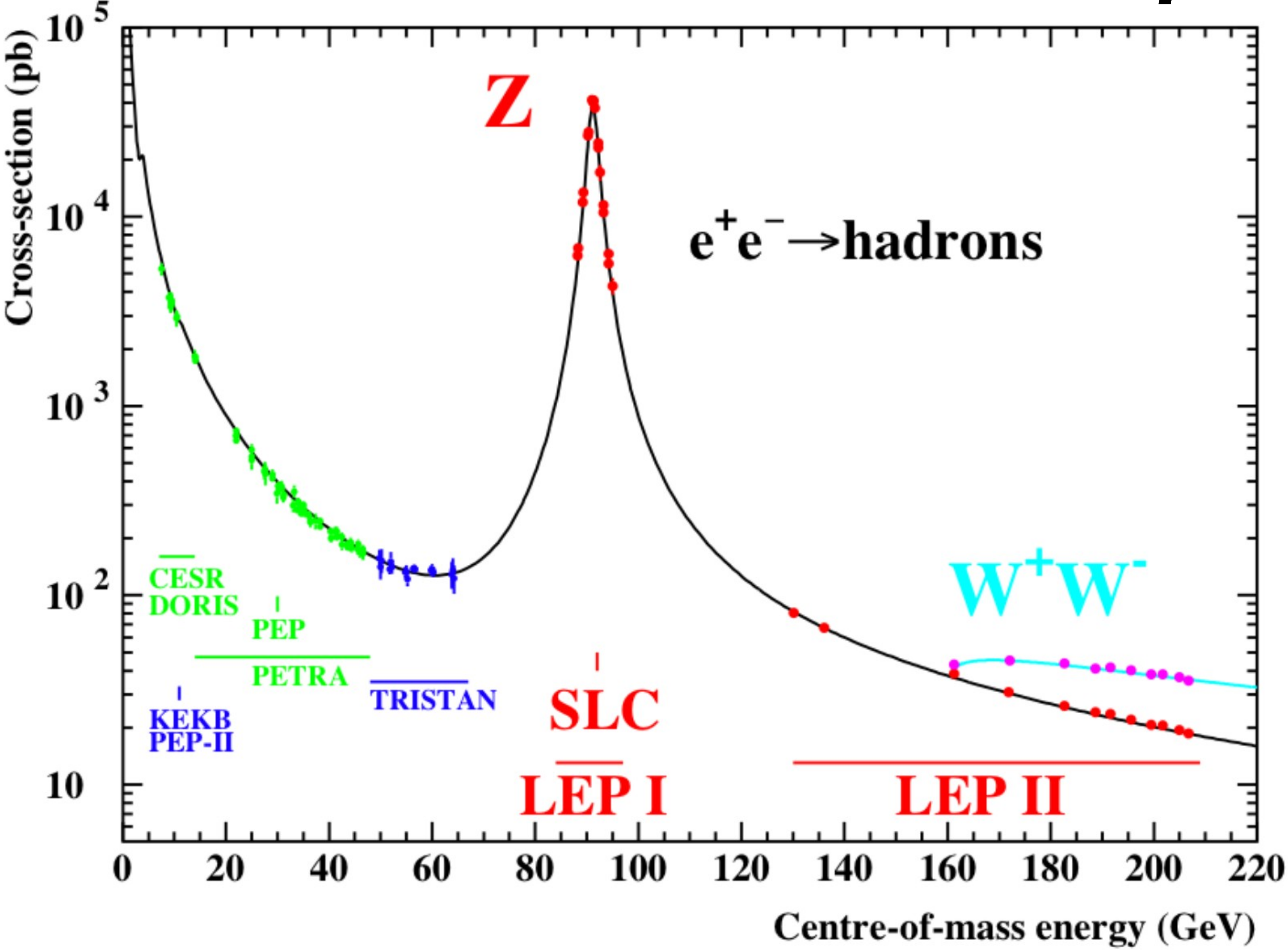
# Asymmetry Summary

## Key topics for theory to address

| Observables | Present value ($\times 10^4$) | TeraZ / GigaZ stat. | TeraZ / GigaZ current syst. | Theory input (not exhaustive) |
|---|---|---|---|---|
| $A_e$ from $P_\tau$ (FCC-ee) | 1514 ± 19 | 0.07 | 0.20 | SM relation to measured quantities |
| $A_e$ from $A_{LR}$ (ILC) | | 0.15 | 0.80 | |
| $A_\mu$ from $A_{FB}$ (FCC-ee) | 1456 ± 91 | 0.23 | 0.22 | Accurate QED (ISR, IFI, FSR) |
| $A_\mu$ from $A_{FB}^{pol}$ (ILC) | | 0.30 | 0.80 | |
| $A_\tau$ from $P_\tau$ (FCC-ee) | 1449 ± 40 | 0.05 | 2.00 | Prediction for non-$\tau$ backgrounds |
| $A_\tau$ from $A_{FB}$ (FCC-ee) | | 0.23 | 1.30 | |
| $A_\tau$ 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

# *The Iconic Lineshape*



# The Lineshape

## 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 ($\Gamma_Z$)
- Hadronic peak cross section ($\sigma_{0,\text{ hadr}}$)
- Ratio of leptons ($R_\ell$)
- ( Number of light neutrinos )

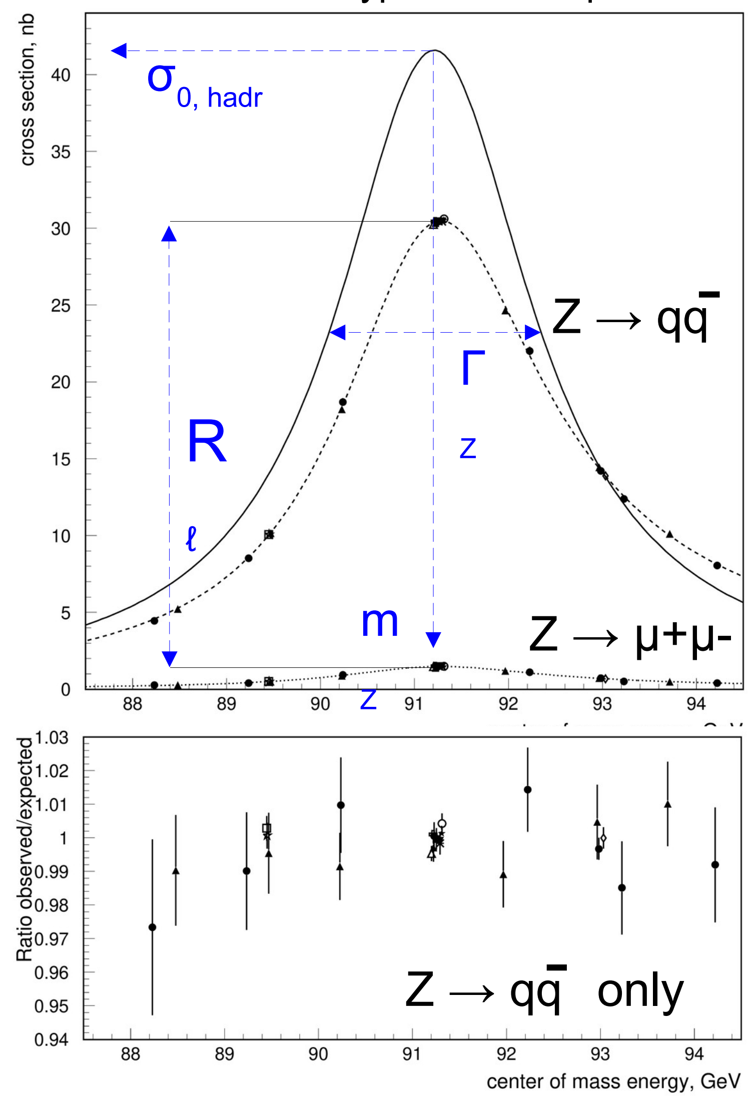
## Hadrons "win" (quarks have color)

- mass, width and $\sigma_0$

## Theory needed

- Deconvolute QED and the EW/QCD corrections…. tricky

Typical LEP experiment



# *Ingredients*

Cross section

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

CM energy: $\sqrt{s}$

- Resonant depolarization and many more 'tricks'

Luminosity: $\mathcal{L}$

- How tightly packed is the beam?
- Basic idea: find accurately calculable process and count, it should not depend on the Z boson (too much).

Event counts: $N_{\mathrm{selected}}$, $N_{\mathrm{background}}$

- Selected events contain signal and the remaining background

Acceptance, $A$, and efficiency, $\varepsilon$

- Acceptance loss: particle outside detector fiducial volume
- Efficiency loss: particle inside detector volume, but not identified

# *Energy Calibration* $\sqrt{s}$

## Resonant depolarization is key

- It will be run in situ using pilot bunches during data taking

## Other important feature

- Absolute calibration will be transported precisely from point-to-point
- Calibration repetition rate needs to be considered
- Beam energy spread and its uncertainty will affect Z width and $\alpha_{QED}(m_Z)$
- Can dimuons/dielectrons to measure beamspread or even center-of-mass energy and help beam calibrations? Needs calibrated muons/electrons using well known resonances… see W mass from LHC/CDF

## Compared to LEP

- Main calibration idea is the same
- ... but much more precise with huge data rate and in situ calibration schemes substantially expanding the scope
- A lot more detail but not for this talk

From: *arxiv:1909.12245*

# Energy Calibration $\sqrt{s}$

## FCC calibration is still in rapid development

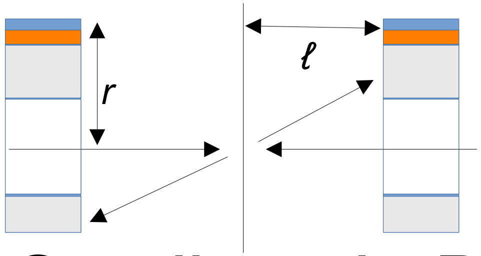
- Latest studies showed a much improved point-to-point uncertainty and more is to come
- The latest study is summarized below
- *Overall uncertainty still needs to be shrunk...*

**Table 15.** Calculated uncertainties on the quantities most affected by the centre-of-mass energy uncertainties, under the final systematic assumptions.

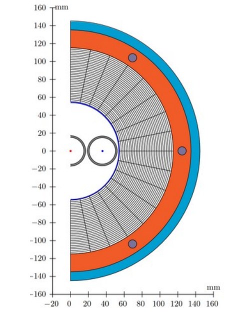
| Observable | statistics | $\Delta\sqrt{s}_{\mathrm{abs}}$ 100 keV | $\Delta\sqrt{s}_{\mathrm{syst-ptp}}$ **40 keV** | calib. stats. $200\,\mathrm{keV}/\sqrt{N^i}$ | $\sigma_{\sqrt{s}}$ $85 \pm \mathbf{0.05}$ MeV |
|---|---|---|---|---|---|
| $\mathrm{m_Z}$ (keV) | 4 | 100 | **28** | 1 | – |
| $\Gamma_\mathrm{Z}$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

From: *arxiv:1909.12245*

Uncertainties have been decreasing but no full update available, yet.




# *Luminosity*



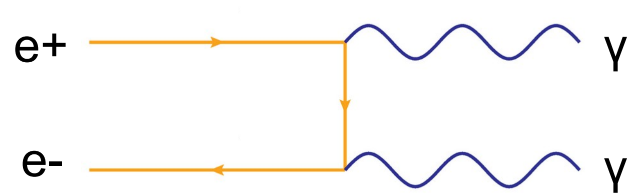
## Small angle Bhabha scattering from LEP?

- Cross section very large (78 nb): good statistical precision
- Need to have excellent control of the geometry: $O(10^{-5})$ precision
  - Precision on radial dimensions $\Delta r \sim 1 \mu m$
  - Half distance between lumi monitors at $\Delta \ell \sim 50\ \mu m$
- Theory prediction improved from 0.061% at LEP to 0.037% recently, but still far from statistical precision of hadronic final states ($\sim 4 \times 10^{-7}$)

From: *arxiv:1912.02067*

## Another clean and copious process?

- $e^+e^- \rightarrow \gamma\gamma$: precise prediction, no Z dependence and clean
- Only 1 in 1000 Z events – accuracy $O(10^{-5})$
- No perfect solution but pretty good




## Best plan, so far

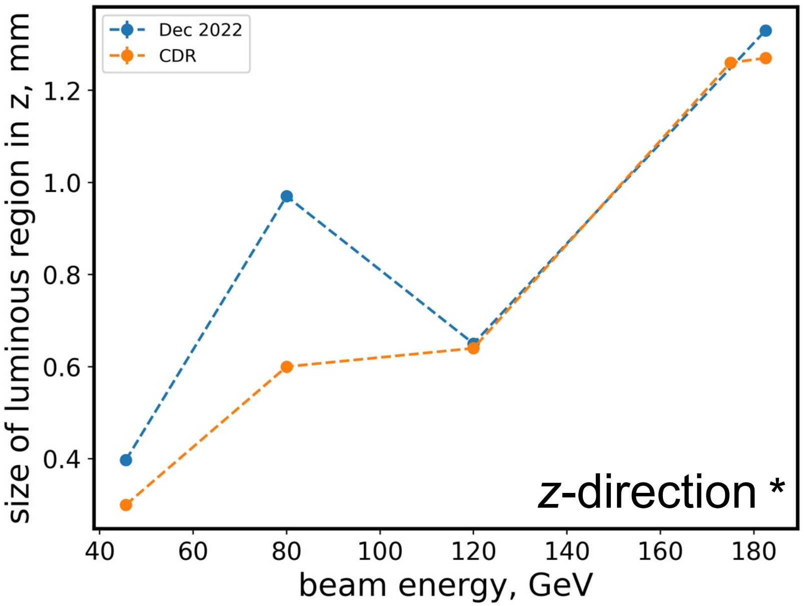
- Use $e^+e^- \rightarrow \gamma\gamma$ as overall normalization (global)
- Bhabha events to extrapolate across CM energies ($\sigma_{theory}$= 14 nb)
- Loose significant precision on $\sigma_{0,\ hadr}$ (# light neutrinos) and
- … some on $m_Z$, $\Gamma_Z$

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

# *Luminous region FCC*

## Size of the luminous region versus beam energy

- *y*-direction [nm], *x*-direction [μm]
- z- direction [mm] … at Z pole below mm level
- vertexing uncertainty at *μm level*




## My conclusion on luminous region?

- Due to well focused beam and pristine vertex reconstruction neither significant beam crossing angle nor uncertainties on those should be an issues
- Event pileup at about 2 in a thousand events can be cleanly identified (μm vertex with 0.4 mm luminous region at Z pole)
- Needs to be careful implemented in MC and confirmed!

** https://github.com/HEP-FCC/FCCeePhysicsPerformance/tree/master/General#vertex-distribution*

# *Importance of Monte Carlo*

## Hadron colliders

- Collisions never use the full center-of-mass energy, protons are complex
- Collisions: full of ‘uninteresting’ events,
- Highly selective before they are written to tape
- Monte Carlo simulation very hard and patched together
- Huge cross sections are very useful for detector and physics calibrations

## Lepton colliders

- Every event uses the ‘full’ center-of-mass energy
- Calculations can be very precise and are reasonable to produce
- Monte Carlo is used for most backgrounds and more inclusive
- Separate calibration data samples are hard to come by

# *Event Counts*

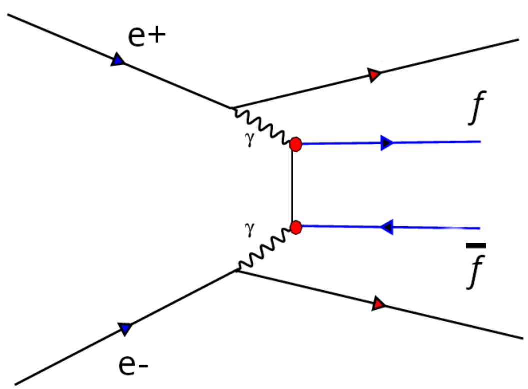
## Number of selected events

- Statistical precision is ultimate limitation; you cannot get better
- Keep as many events as possible, but not let in too much background

## Number of background events

- Monte Carlo predicts it precisely, *if you have enough and it agrees*
- Detailed detector description is crucial (*realistic** Monte Carlo)
- Exception: two-photon collision events notoriously difficult, in particular two photons with hadronic decay products ($e^+e^- \rightarrow e^+e^-$ qqbar)
- Event pileup needs to be accounted for ($2 \times 10^{-3}$)

## Two-Photon events ($e^+e^- \rightarrow e^+e^-$ *ffbar*)




- 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 safer
- Off-peak running, or explicit tagging of $e^+/e^-$?
- Better MC is needed (theory community)

* simulate time dependent effects of detector and other running conditions: MC mapped to specific data recorded

# Acceptance/Efficiency

## Typical numbers

- Excellent control of geometry and positioning: O($10^{-5}$) precision
- In situ active laser alignment systems are crucial (µm precision)
- Definition of the fully active detector borders very important
  - Calorimeters: ~ Molière radius distance from the edges
  - Hermeticity more important than resolution: overlapping detectors to avoid dead areas

## Different final states

- Hadrons hard to miss
  - We look for jets (many particles, broadly spread)
  - Fragmentation/hadronization are an issue: hard to derive systematic uncertainty
  - Reproducing multiplicity traditionally problematic (QCD / Infrared divergent ...)
  - Whizard and KKMC do not agree at all on hadronic shower constitutents
- Leptons easier to miss
  - Cracks or dead areas crucial, definition of fiducial volume most important here
  - Independent subdetectors: tracker/muon chambers, tracker/ECAL, tracker/HCAL, ...
  - Final state much clearer no additional uncertainties (?), collision angle (?)

# *Acceptance/Alignments*

## Philosophy from LEP

- There are many events
- Statistical precision is high
- Measure systematic: it usually stops when you run out of events
- … there are of course limitations to this philosophy

## Alignments and acceptance

- Many events with given detector geometry and positioning will result in precise and accurate alignments, see previous experiments and most recently the LHC ones
- Precise detector acceptance measurement is possible ‘in situ’ for dimuon, dielectron and diphoton events based on tracker and calorimeter information
- This general idea should apply also to the luminosity calorimeter and the small angle Bhabha scattering and the muon detection system… some interesting studies should follow

# $Z \rightarrow$ *Hadrons: A and ε*

## Statistical precision: order $10^{-7} - 10^{-6}$

- LEP – acceptance down to 12° → cos(12°) = 0.9781 (L3)
- FCC - acceptance down to 7° → cos(7°) = 0.9925
  - Enormous improvement in number of *lost particles* (2.2% → 0.75%)
  - Jets are too big to not register: efficiency should be *very* close to 100%
  - No trigger ☺, which is good but redundancy in detectors much needed
  - Tracker versus calorimeter based analysis essential (add timing layer?)
  - Is the detector on and is there any noise? → *realistic* detector Monte Carlo
  - Collision angle should not matter, as long as it is simulated well

| Quantity | 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 |

# *Look at $Z \rightarrow$ Hadrons with FCC tools*

## Basic Selection

$$0.5 < E_{\rm vis}/\sqrt{s} < 2.0$$

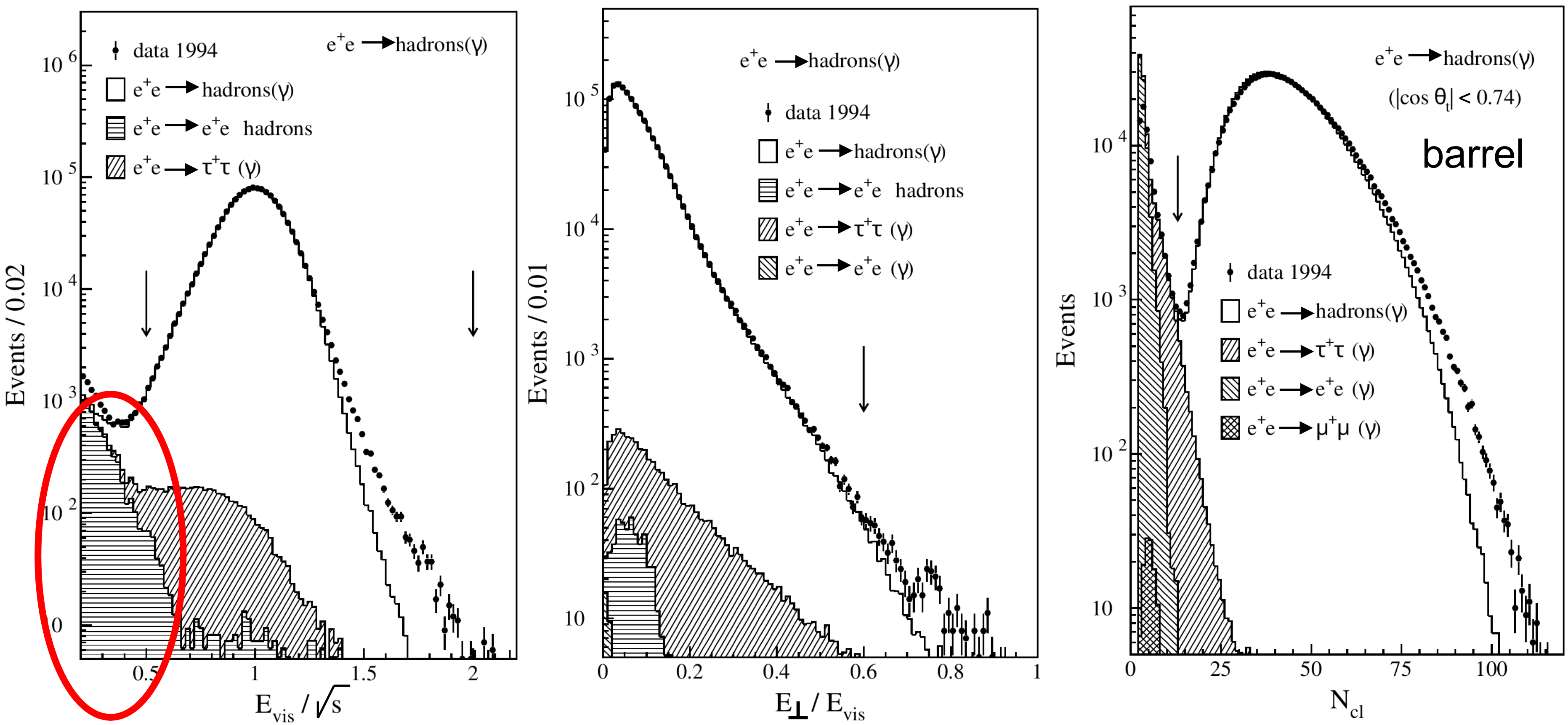
$$n_{\rm particles} > 15$$

$$(E_{\rm long}/E_{\rm vis} < 0.6 \;\;\&\;\; E_{\rm trans}/E_{\rm vis} < 0.6)$$

# Z→Hadrons: Message from LEP

## Example plots for hadron selection at L3

- There is noise, number of clusters in MC do not agree
- Two photon background is leaking



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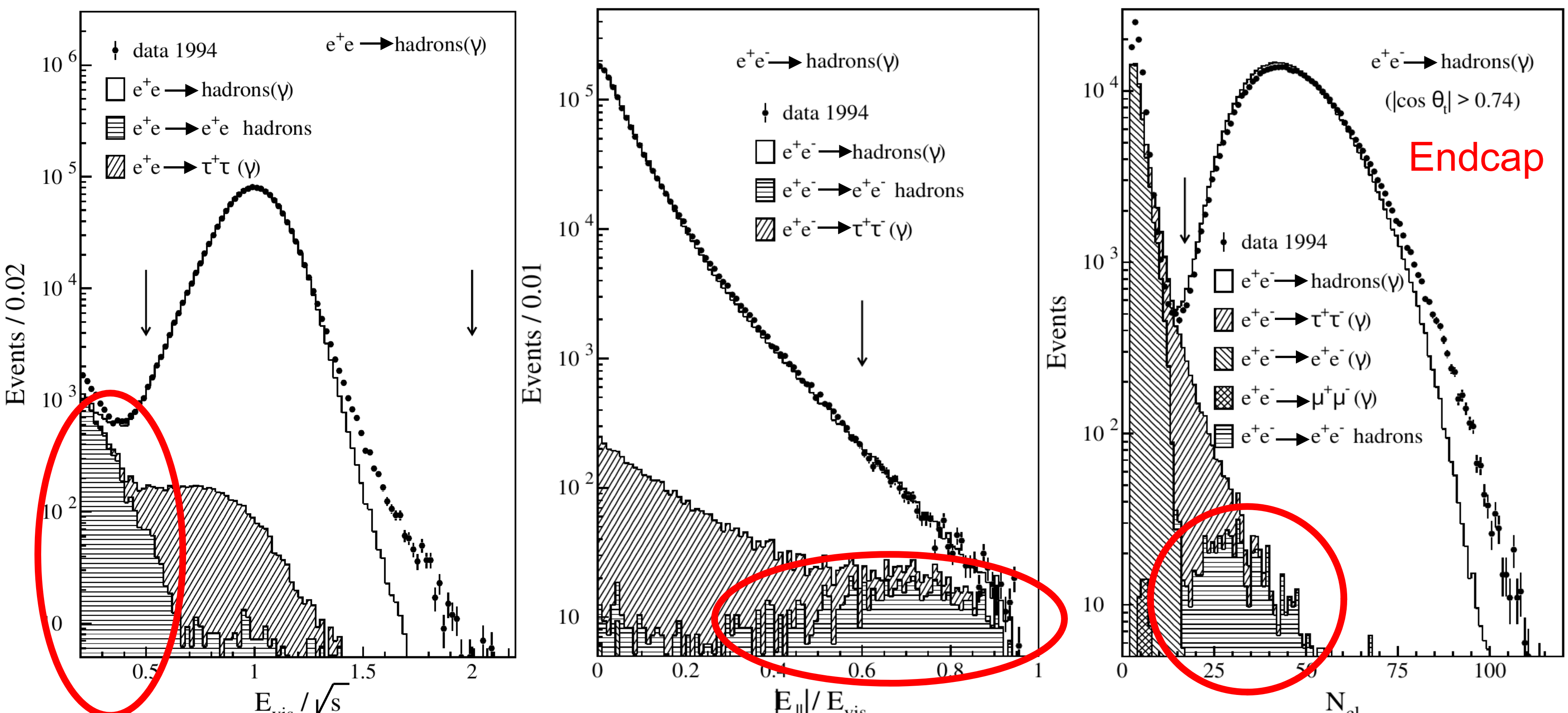
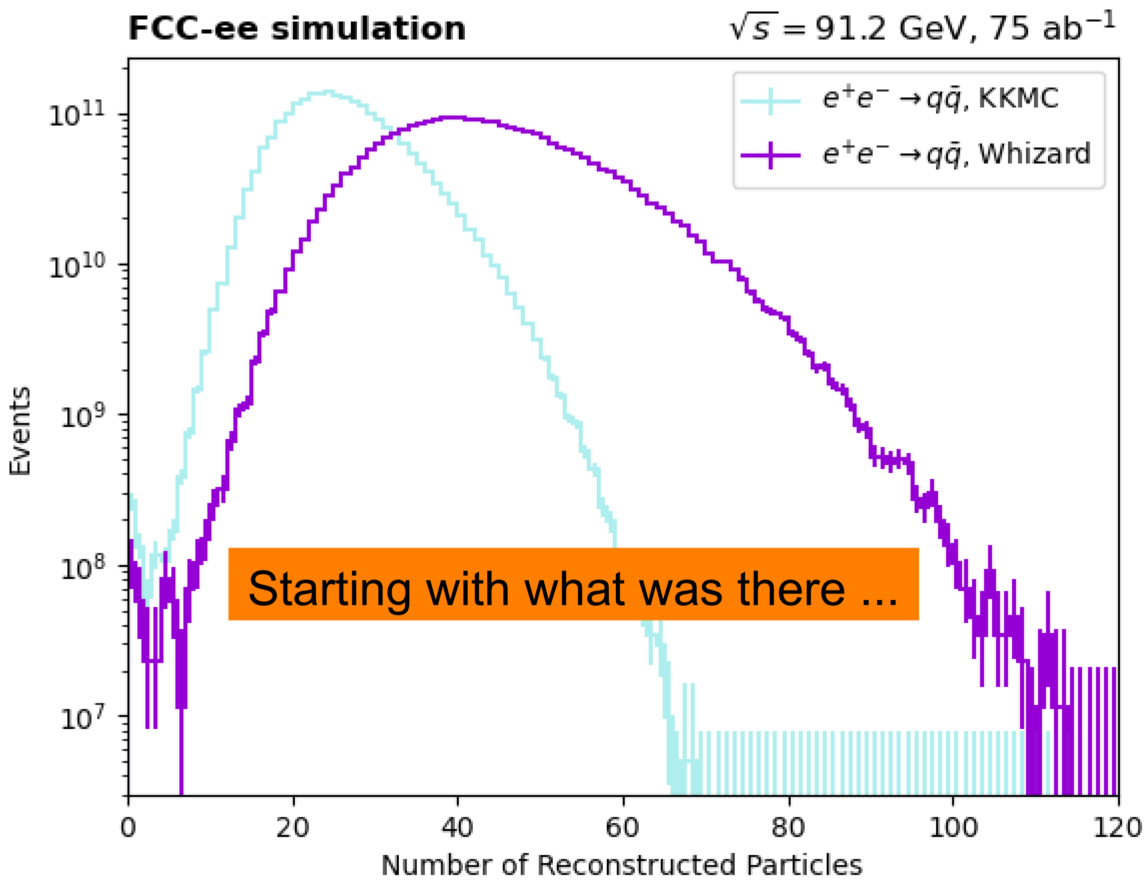


# Z→Hadrons: Multiplicity

Initial comparison – making multi-hadron events at the Z pole (compare two reasonable programs)




## Compare

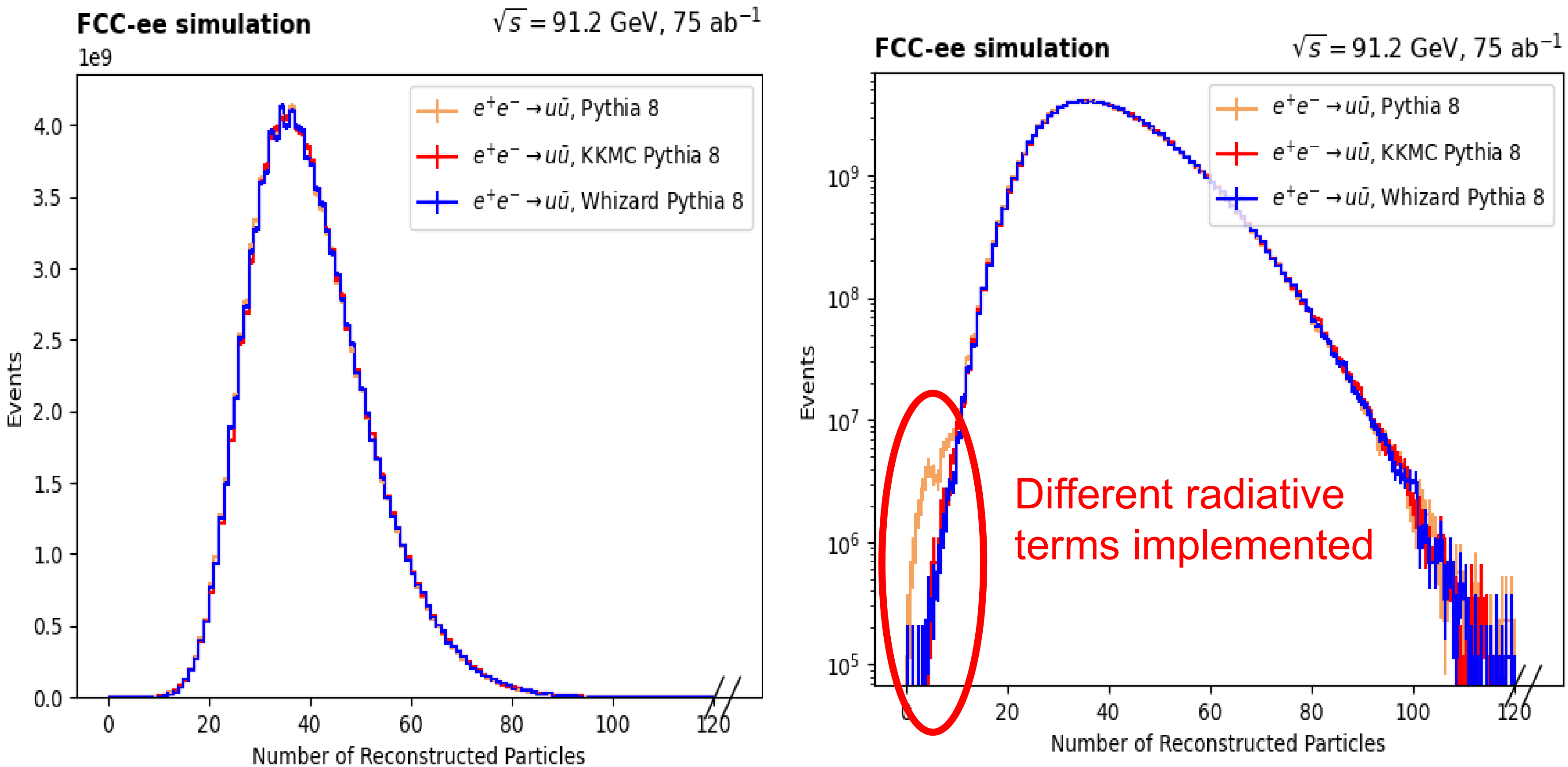
- Different orders implemented
- Pythia for showering
- Pythia 8 versus 6
- KKMC versus Whizard

## Issues

- Shower interface partially disabled
- Various other smaller items

# $Z \rightarrow$*Hadrons: Multiplicity*

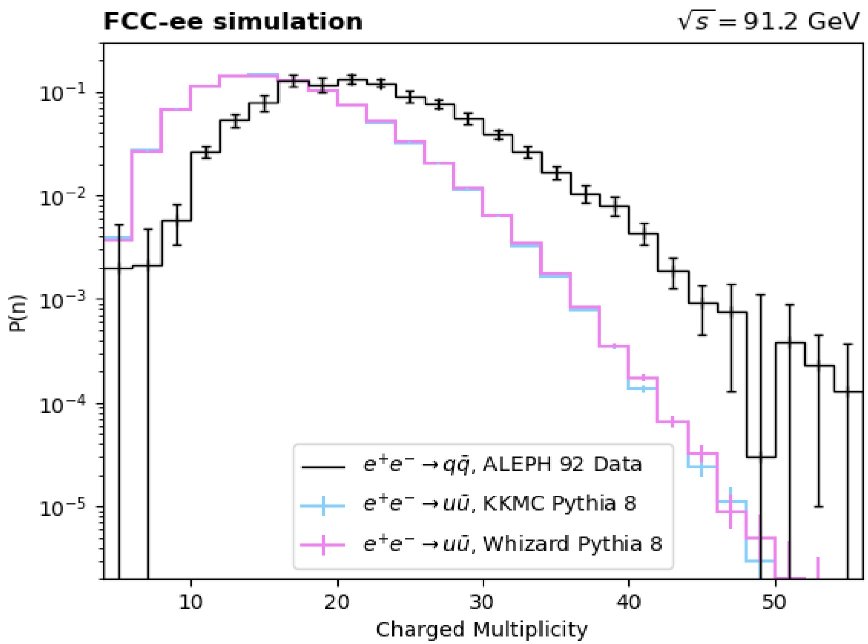
Best status after fixing all problems and a reasonable selection: two MCs look pretty close.



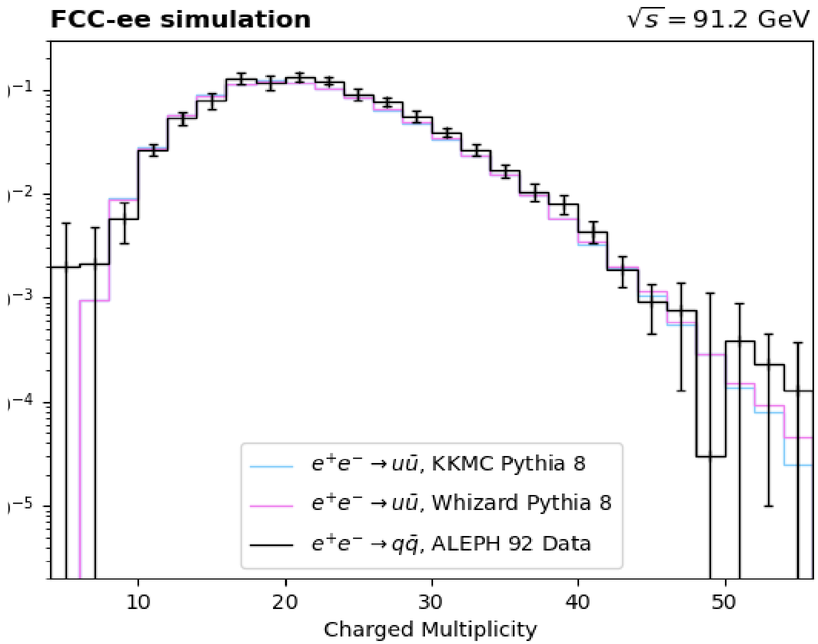
# $Z \rightarrow$ *Hadrons: Multiplicity*

## Compare ALEPH and FCC simulation

- After fixing the comparison issues between KKMC and Whizard
- Reconstructed particles disagreed
- ALEPH plot is fully corrected to gen. particle level




Reconstructed Particles

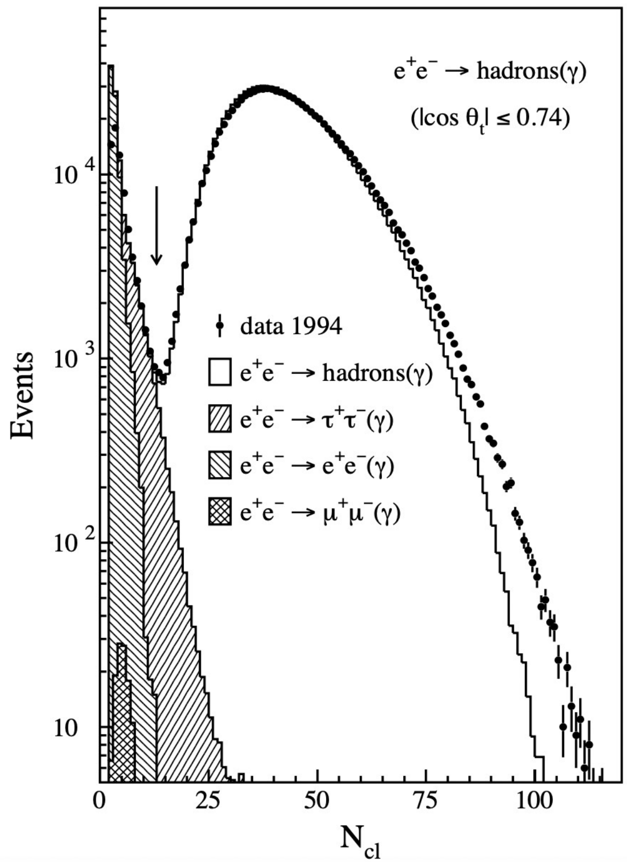


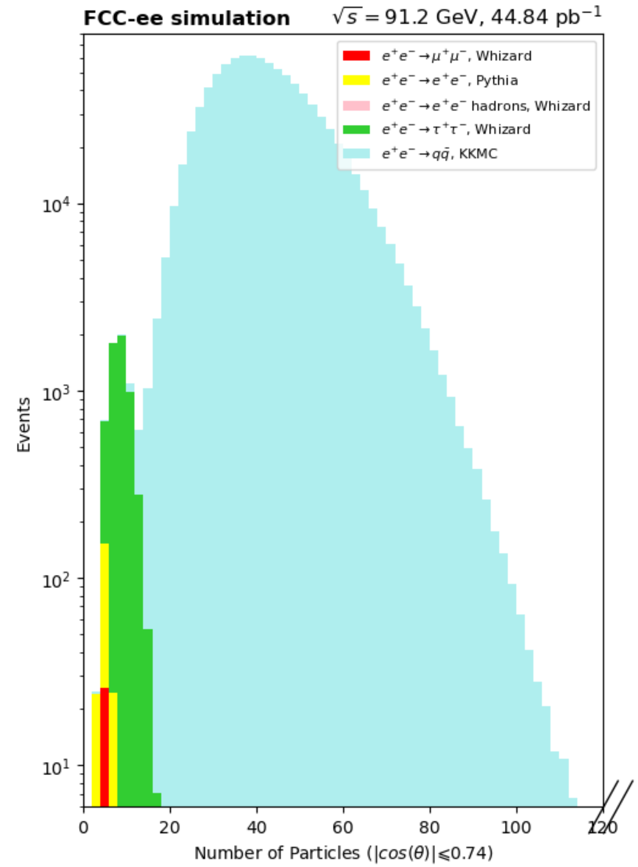

Generator Level Particles

# Z→Hadrons: LEP versus FCCee

## Compare multiplicity in barrel

- Looks quite similar, except background much reduced at FCCee
- Hadrons should look ‘the same’, no two photons in the barrel

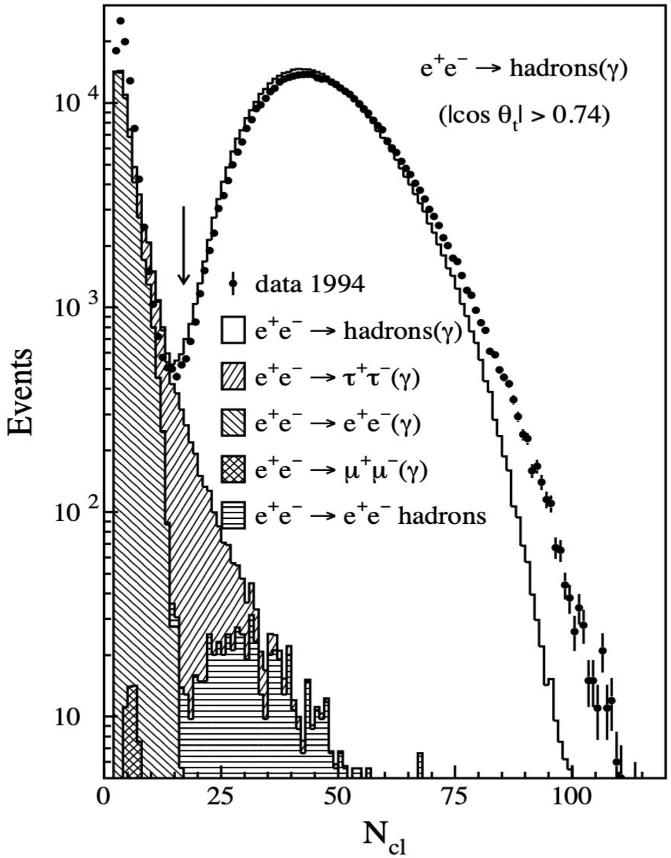


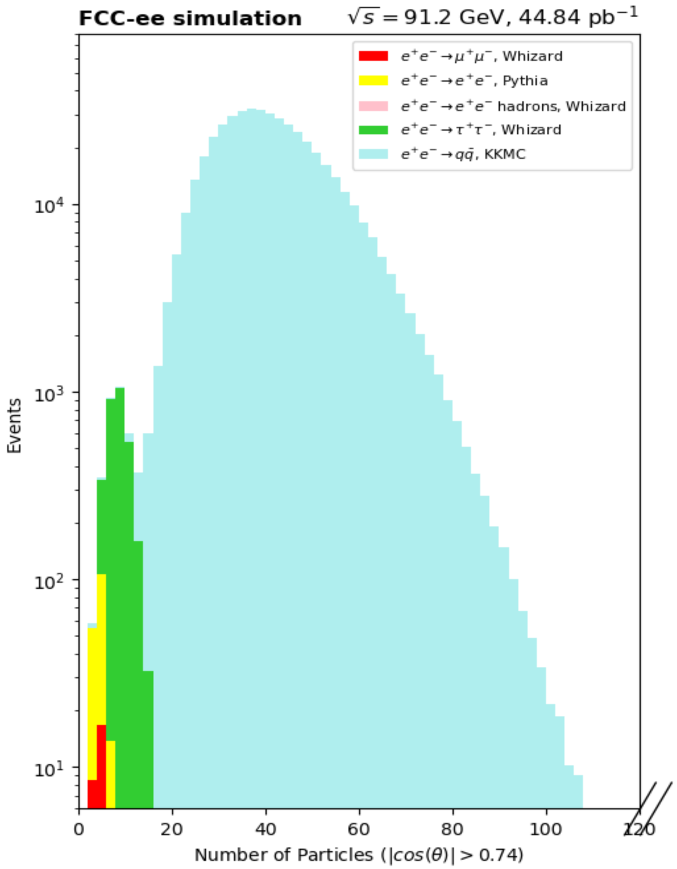



# $Z \rightarrow$Hadrons: LEP versus FCCee

## Compare multiplicity in endcaps

- Looks quite similar, except background much reduced at FCCee
- Hadrons should look 'the same', two photons not there! wrong?

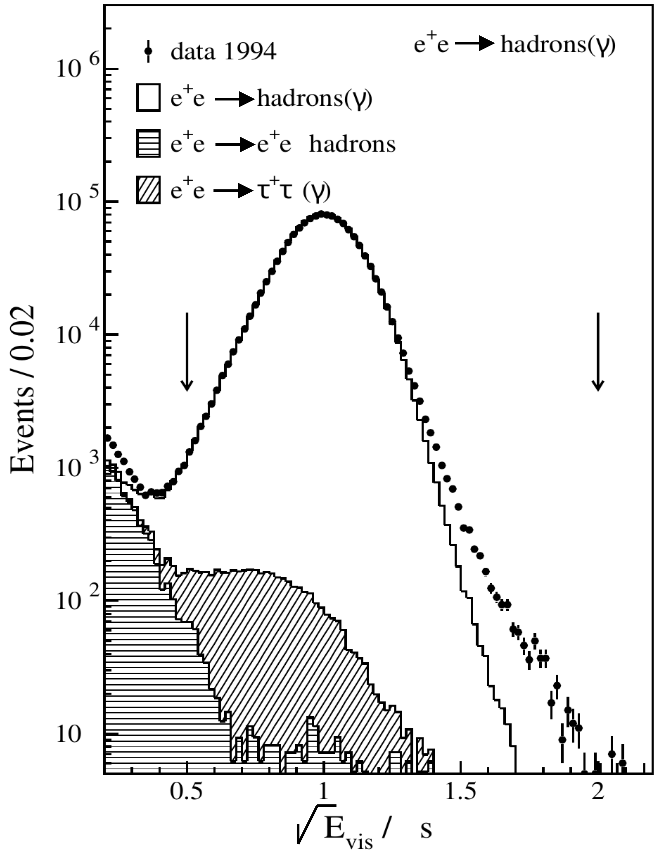


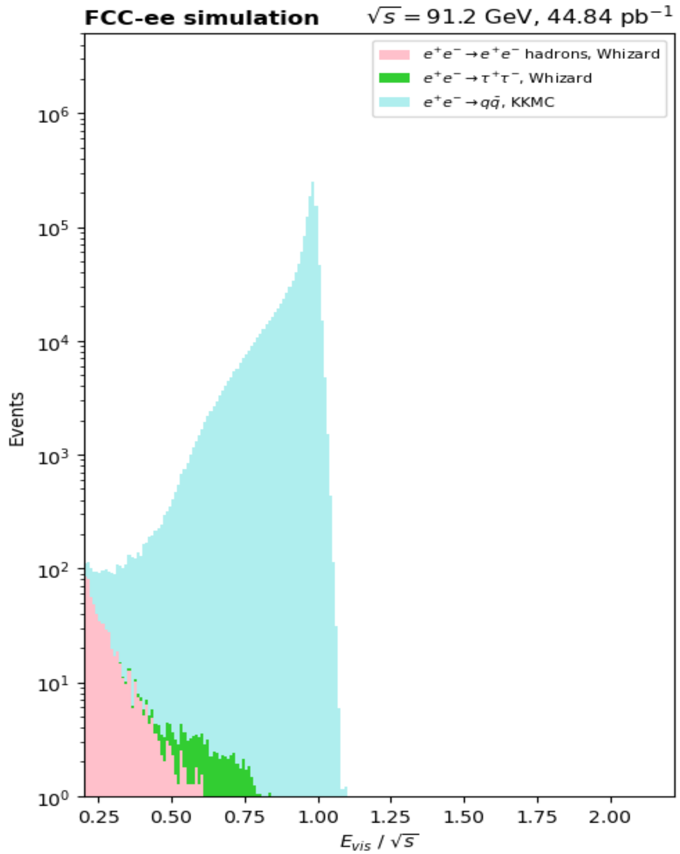



# Z→Hadrons: LEP versus FCCee

## Compare visible energy

- Resolution much better at FCC-ee: lower tail is physics
- Two photon and Tau MC substantially lower with respect to LEP

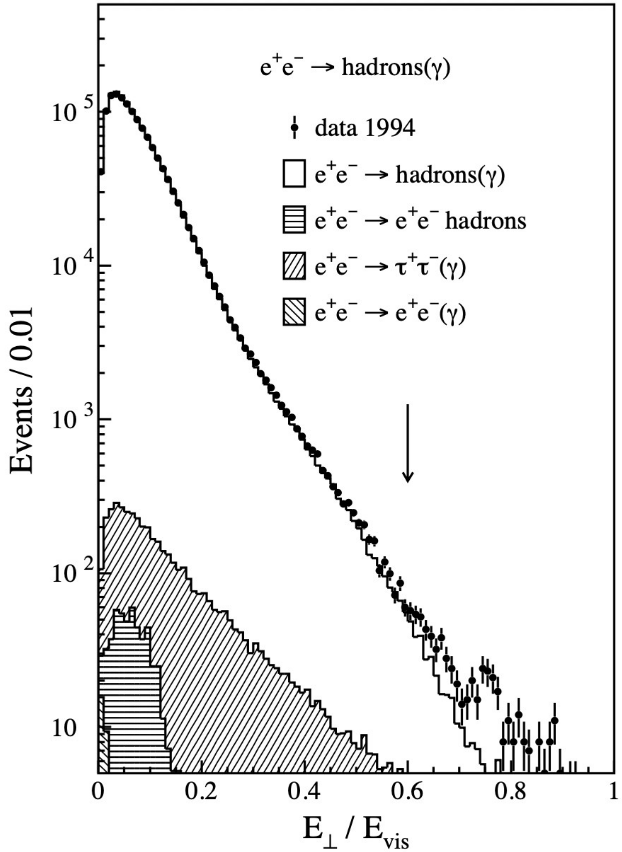


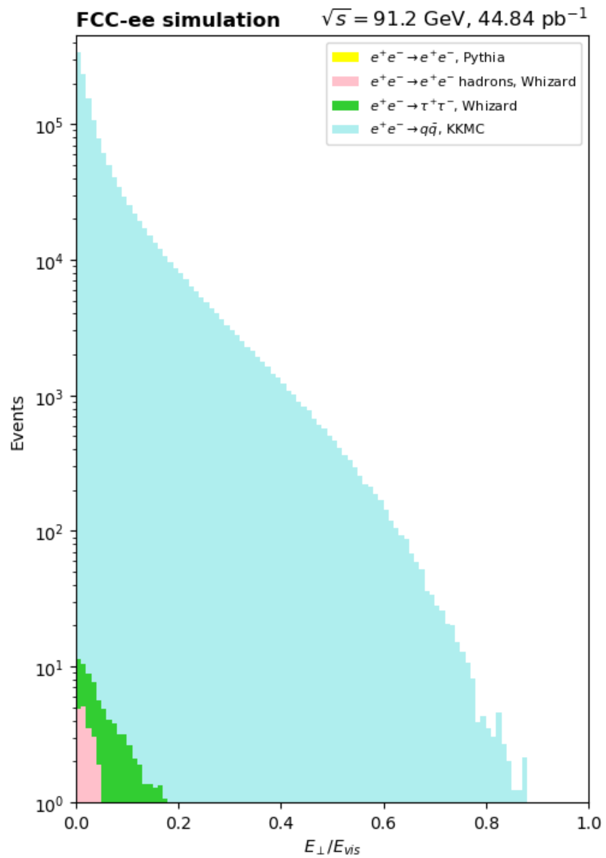



# Z→Hadrons: LEP versus FCCee

## Compare energy imbalance (transverse)

- Resolution much better at FCC-ee: lower tail is physics
- Two photon and Tau MC substantially lower with respect to LEP

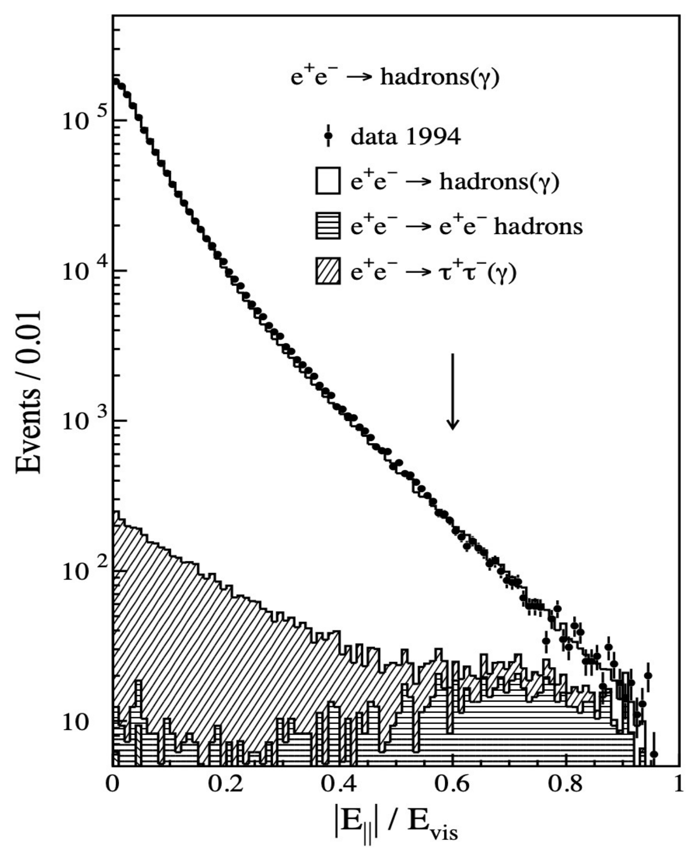


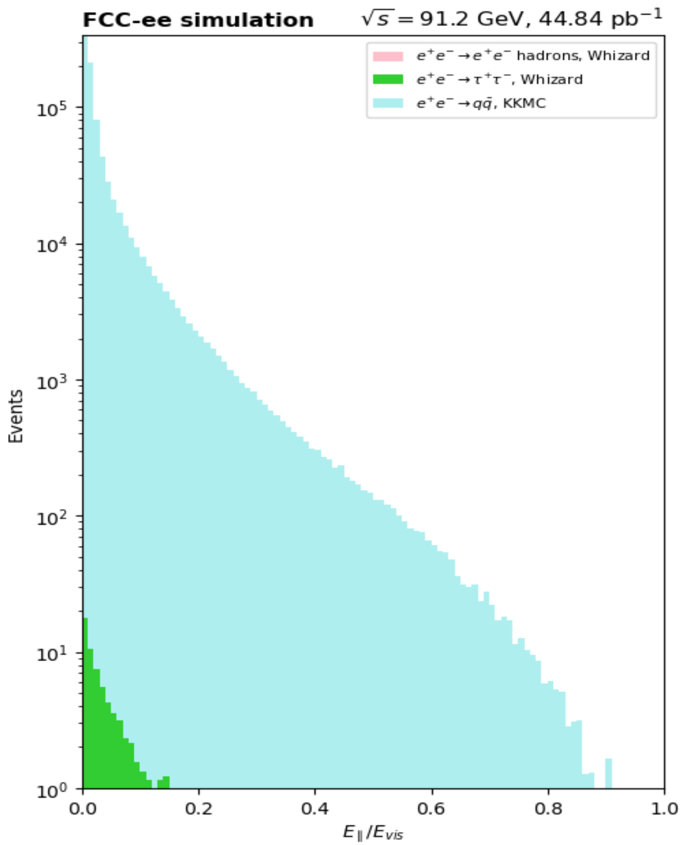



# Z→Hadrons: LEP versus FCCee

## Compare energy imbalance (longitudinal)

- Resolution much better at FCC-ee: lower tail is physics
- Two photon and Tau MC substantially lower with respect to LEP

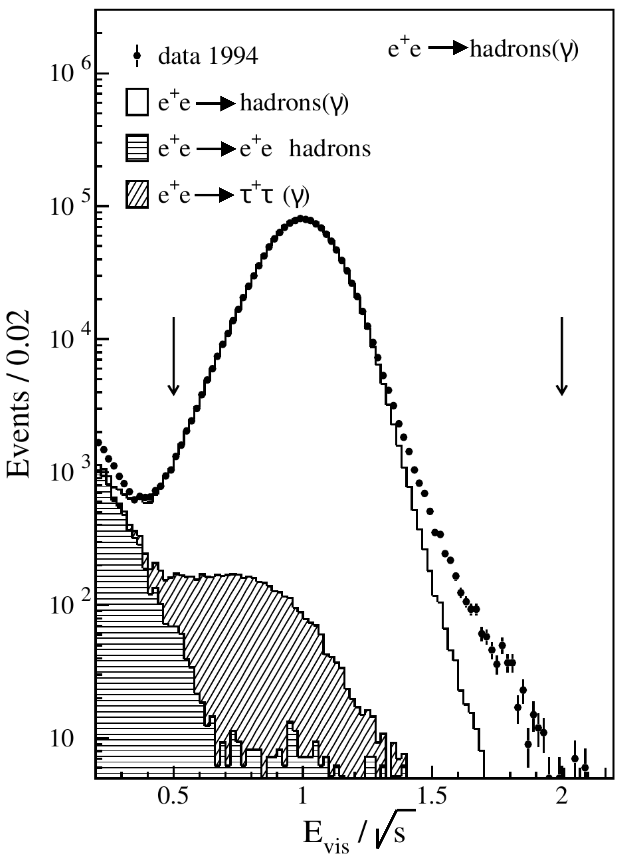


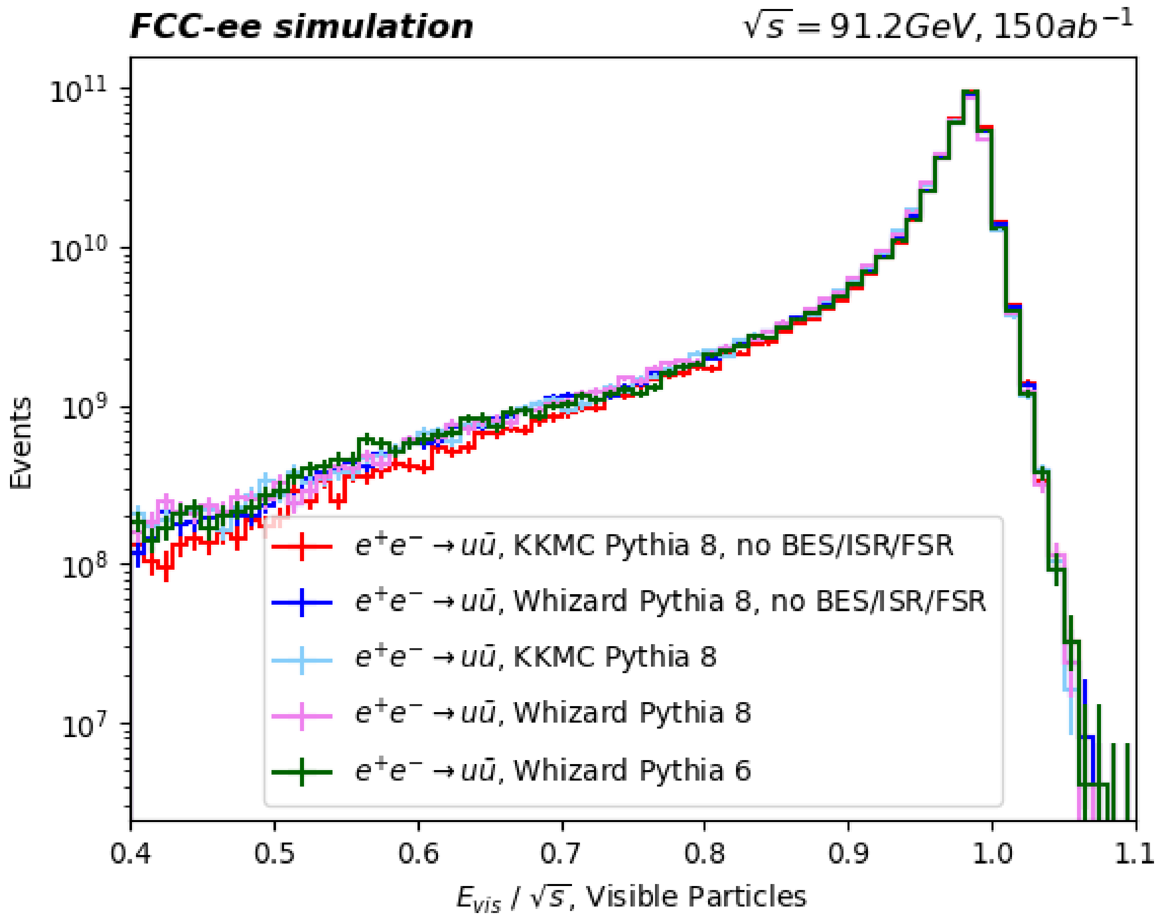



# Z→Hadrons: LEP versus FCCee

## Compare visible energy

- Lower tail clearly needs to be understood very well



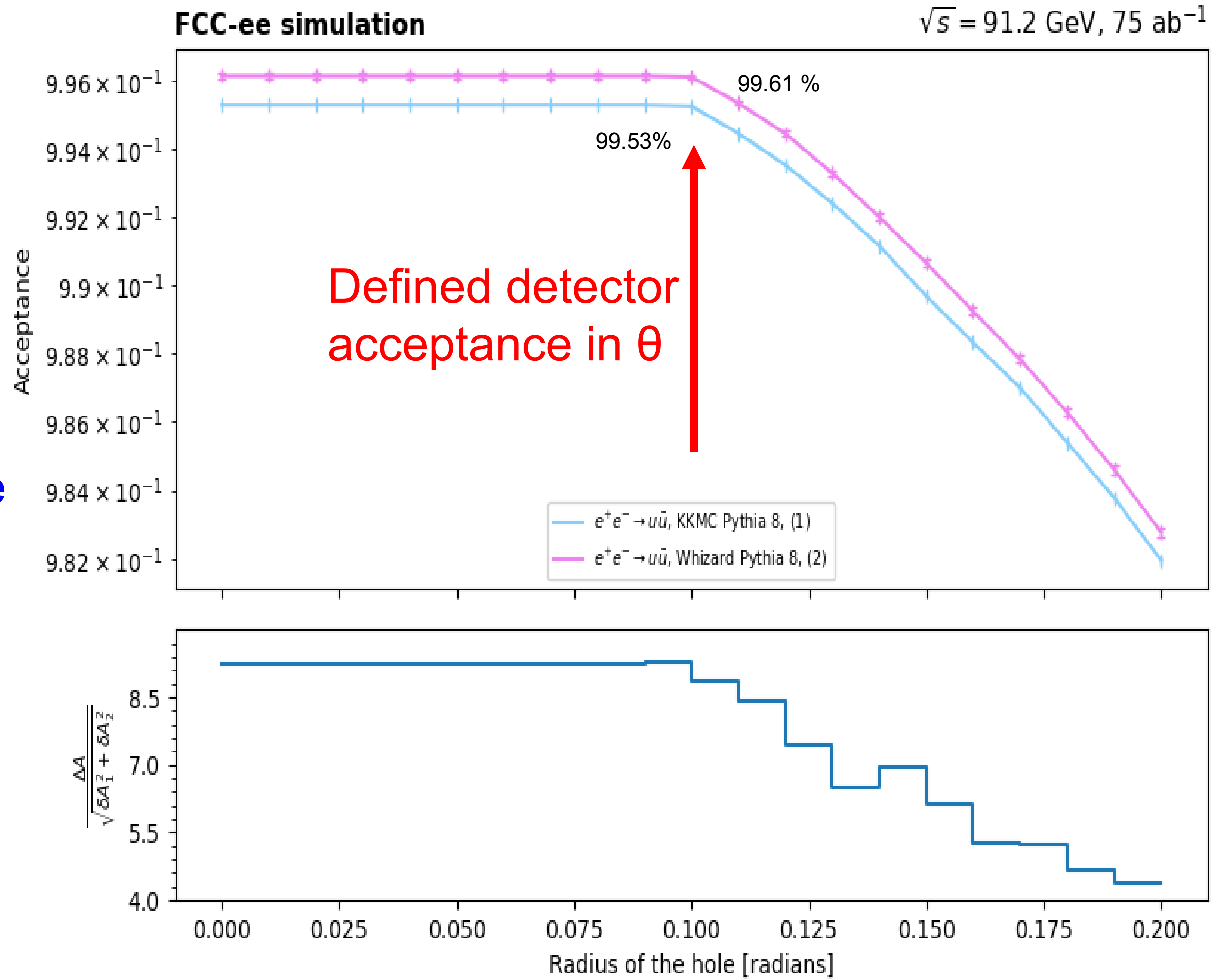
# $Z \rightarrow$ Hadrons: Acceptance

MC comparison not close: 8.7 std difference == 0.1%!

Better MC needed to estimate theory uncertainties

How important is the definition of the detector hole?

- Reject particles smaller than x axis value
- Significant difference
- Make acceptance as large as possible!




**Data driven test**

- Study jet acceptance in the barrel
- Was used at LEP, but might be stat. limited

# *Match Experiment/Theory*

## Undusted L3 program to fit two-fermion data

- LEP/SLC: theory and experiment used Pseudo Observables (PO)
  - Assume: QED correct (ISR/FSR/int), weak interaction V-A, effective Born Approx., and Z boson decays to fermions only, photon/Z interference
- For verification the full L3 cross section and forward-backward asymmetry dataset was fit, including all details and the numbers in the last L3 paper were reproduced with minute differences
- Various theory programs are interfaced (TOPAZ0, ZFITTER, ALIBHABHA, MIBA, ….): ZFITTER is the only program used for the following studies

## What about FCC-ee?

- Is it still feasible to use Pseudo Observables?
- Maybe differential measurements: direct comparison between MC and data needed to extract physics parameters

# *How well can we do?*

## Extract Pseudo Observables: $m_Z$, $\Gamma_Z$ and $\sigma_{0,\, hadr}$

Inputs: hadronic TXS, 3 points: 91.2 GeV: 125/ab; 88.0, 94.0 GeV: 40/ab

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 $E_{CMS}$
6) Or alternatively 100 keV correlated uncertainty on ECMS

| Setup | delta($m_Z$) | delta($\Gamma_Z$) | delta($\sigma_{0,\, hadr}$) |
|---|---|---|---|
| units | [keV] | [keV] | [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 |

# Leptonic Ratios and $\alpha_S$

## Advantage of Ratios (and Asymmetries)

$$R_\ell = \frac{\Gamma_{\text{hadr}}}{\Gamma_\ell}$$

- Relative measurements do not need the luminosity …
- *It seems luminosity will be very hard to pin down to desired precision*
- Provides sensitive test of lepton universality by comparing different lepton flavors
- Quark-lepton universality will be tested and allows a determination of the strong coupling constant, theoretical uncertainties need to be evaluated carefully

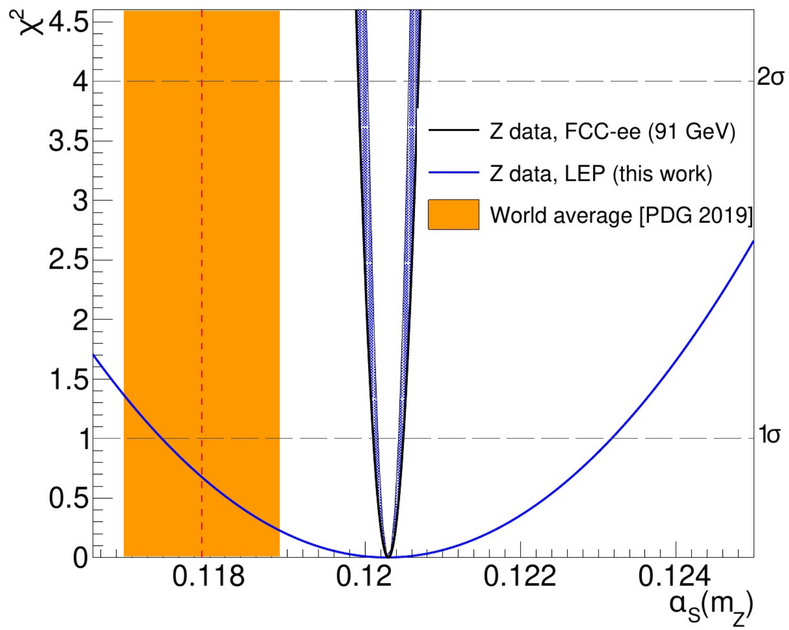
## Limitations at LEP

- $R_\ell$ at LEP has largest experimentally uncertainty from the acceptance

## How about FCCee

- Acceptance at FCCee is substantially improved
  - Coverage is much larger
  - Angular and vertex resolutions much improved
- An expected uncertainty on $R_\ell$ at 0.001 needs theory uncertainty to be improved by about a factor of 4 to approximate exp. precision

$$\alpha_S = x \pm 0.00014(exp) \pm 0.00022(th)$$

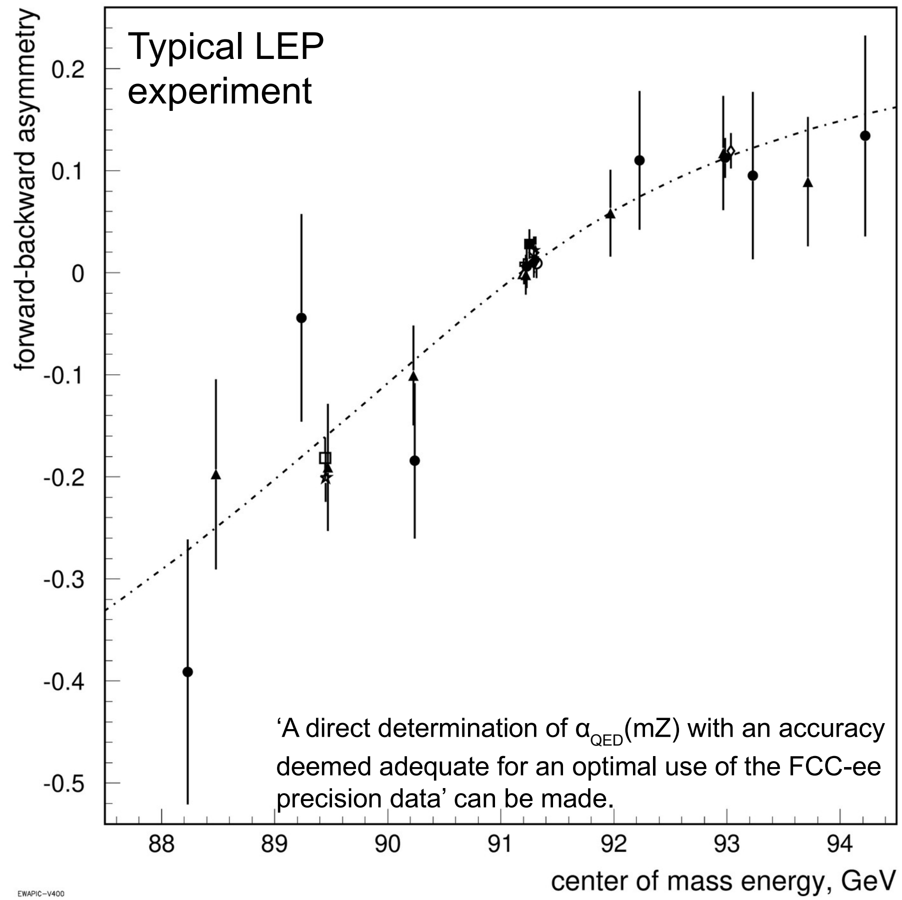



From: https://arxiv.org/pdf/2005.04545.pdf

# The 2nd Lineshape

## Forward backward asymmetries

- Decouples from cross section, no luminosity uncertainty!
- Measures $\sin^2\theta_W^{eff}$ and $\alpha_{QED}(m_Z)$, which mostly decouple
- $A_{FB}$ constrains $\sin^2\theta_W^{eff}$ ($m_t$ and $m_W$) most significantly at peak, small stat. uncertainty
- Needs accurate MC for ISR, FSR and IFI: QED/SM corrections crucial
- Points to measure $\alpha_{QED}(m_Z)$, are just below or just above the Z peak (87.9 or 94.3 GeV)




$$A_{\rm FB} = \frac{3}{4} A_{\rm e} A_f$$

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

From: arxiv:1512.05544

# *The 2nd Lineshape*

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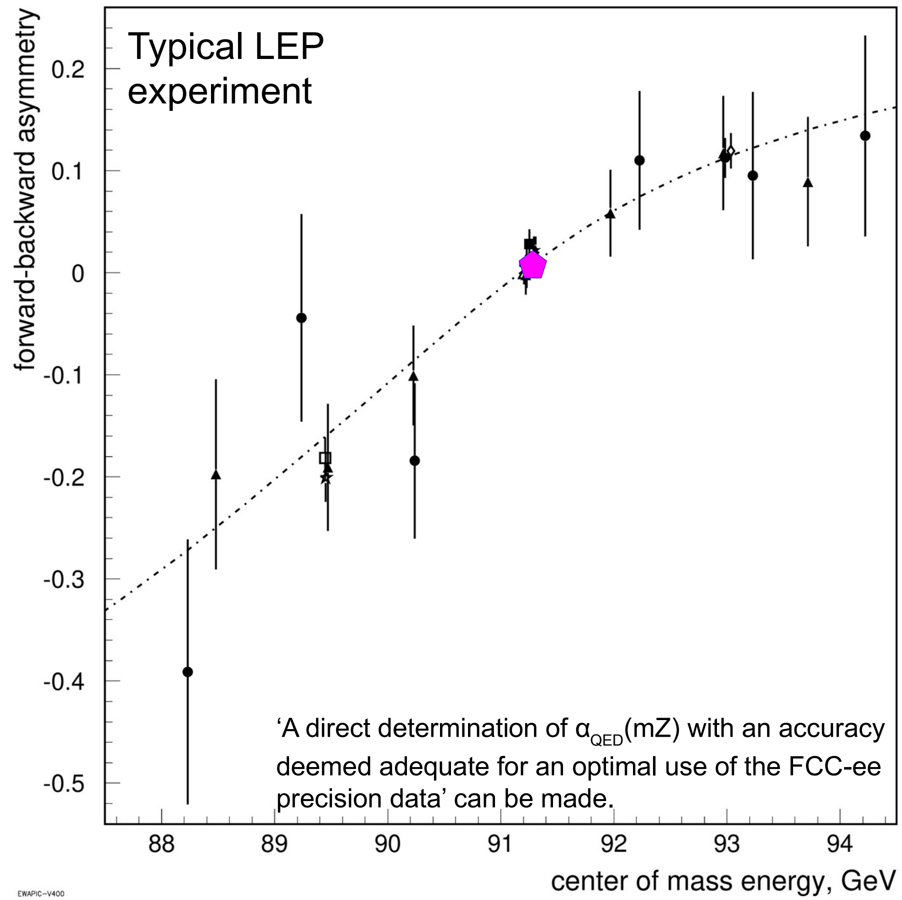


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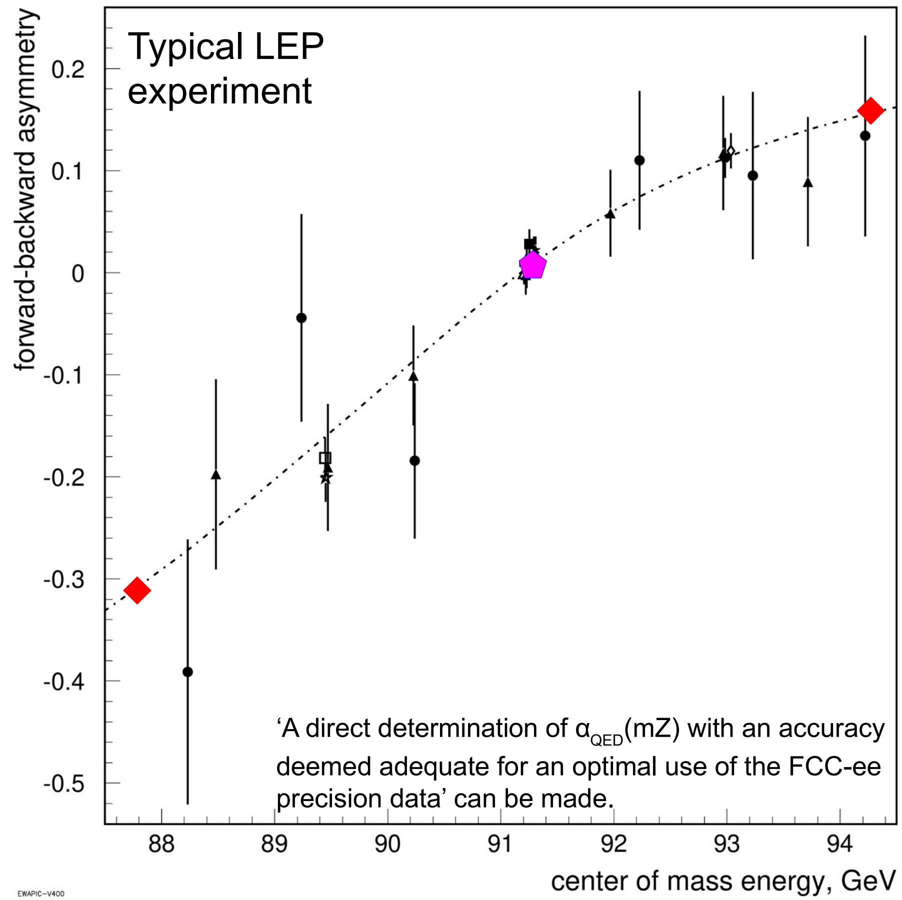


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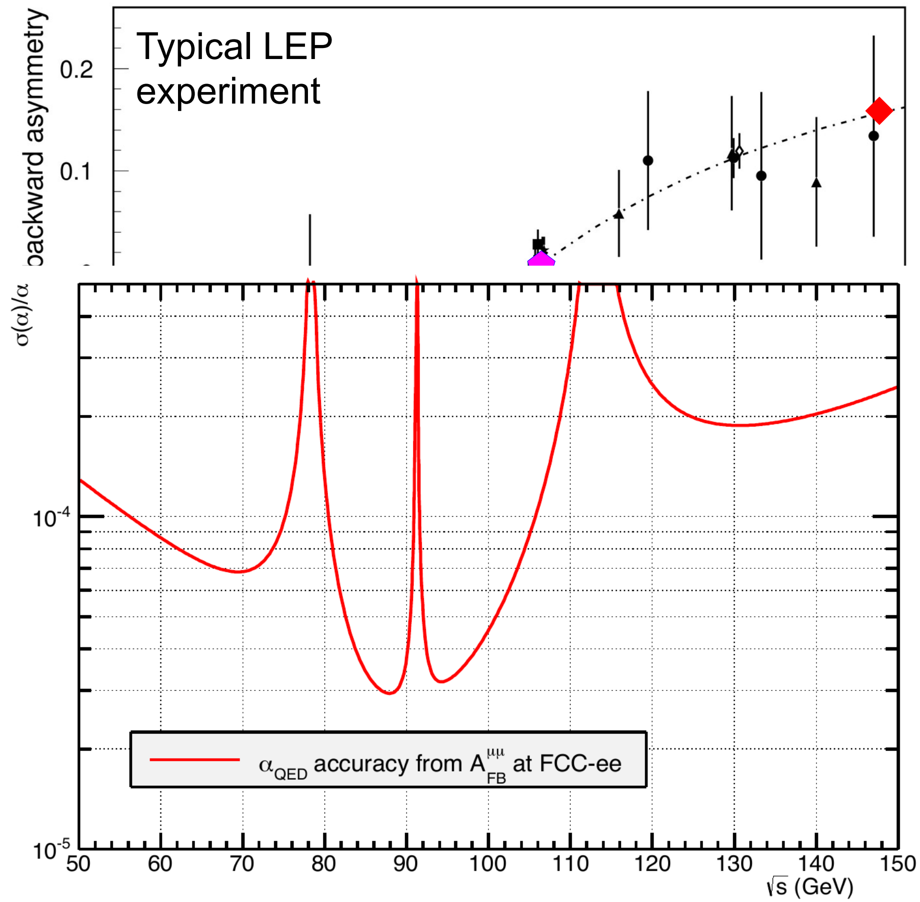


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From: arxiv:1512.05544

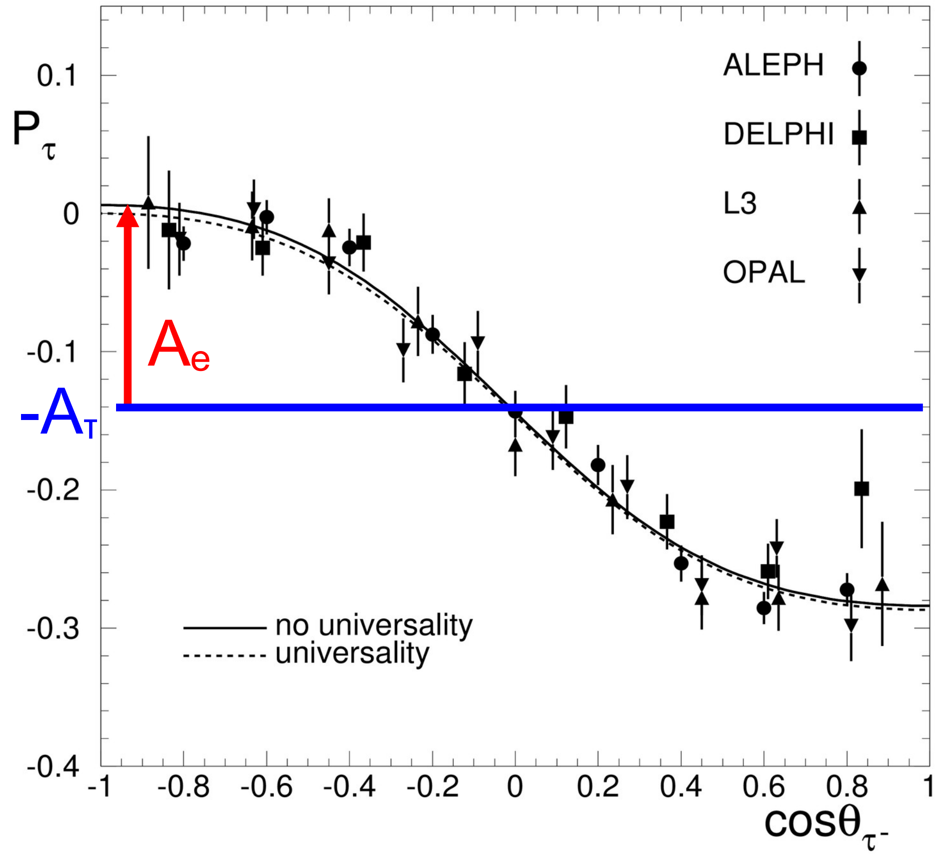
# Key Ingredients: Tau Polarization

## Tau polarization

- Disentangles left-right asymmetry $A_e$ and $A_\tau$
- Enables to decorrelate the remaining fermion $A_{FB}$
- Provides best $A_e$ and $A_\tau$

## Limitations

- Main issue is the non-tau background and its proper estimate
- Massive calibration samples should provide sufficient control over background but this has to be proven




$$P(\cos\theta) = \frac{\mathcal{A}_\tau(1+\cos^2\theta) + 2\mathcal{A}_e\cos\theta}{(1+\cos^2\theta) + 2\mathcal{A}_e\mathcal{A}_\tau\cos\theta}$$

$$A_{FB} = \frac{3}{4}A_e A_f$$

# *Heavy Flavours*

$$R_{\mathrm{b,c(,s)}} = \frac{\Gamma_{\mathrm{b,c(,s)}}}{\Gamma_{\mathrm{hadr}}}$$

## Ratios $R_{b,c,(s)}$

- Sensitive to potential top/W vertex modification
- Expect substantial improvements at FCCee, LEP was experimentally and theoretically limited
- **Much better vertex detector and vertexing algorithms**
- Is it possible to tag strange quarks? Studies show that yes….
- Substantial improvement needed in details of quark production: gluons radiation and splitting, decay models and fragmentation (b, c, … s)

## Forward-backward asymmetries → $A_{b,c(,s)}$

- Building on the taggers developed for heavy flavor ratios
- Double tagging techniques from LEP will be very useful to contain systematic uncertainties
- Careful though, hemisphere correlations turned out to be a big issue during LEP
- QCD uncertainties are fully correlated between all measurements, studies show that tight cuts on acollinearity will substantially improve the situation
- This will result in precise new $A_{b,c(,s)}$ measurements
- Exclusive decays can also help

# LEP/SLC vs FCCee

## Key points of comparison: $m_W$ and $\sin^2\theta_W^{eff}$

LEP measured

$$\sin^2\theta_{\mathrm{W}}^{\mathrm{eff}} = 0.23153 \pm 0.00016$$

predicted

$$\sin^2\theta_{\mathrm{W}}^{\mathrm{eff}} = 0.231488 \pm 0.000029_{mt} \pm 0.000015_{mZ} \pm 0.000035_{\alpha QED}$$
$$\pm 0.000010_{\alpha S} \pm 0.000001_{mH} \pm 0.000047_{\mathrm{theory}}$$
$$= 0.21349 \pm 0.00007_{\mathrm{total}}$$

FCC projected

$$\sin^2\theta_{\mathrm{W}}^{\mathrm{eff}} = 0.23153 \pm 0.000002$$

projected prediction

$$\sin^2\theta_{\mathrm{W}}^{\mathrm{eff}} = 0.231488 \pm 0.000001_{mt} \pm 0.000001_{mZ} \pm 0.000009_{\alpha QED}$$
$$\pm 0.000001_{\alpha S} \pm 0.000000_{mH} \pm 0.000047_{\mathrm{theory}}$$

LEP measured

$$m_{\mathrm{W}} = 80.379 \pm 0.012 \ \mathrm{GeV}$$

predicted

$$m_{\mathrm{W}} = 80.3584 \pm 0.0055_{mt} \pm 0.0025_{mZ} \pm 0.0018_{\alpha QED}$$
$$\pm 0.0020_{\alpha S} \pm 0.0001_{mH} \pm 0.0040_{\mathrm{theory}} \mathrm{GeV}$$
$$= 80.358 \pm 0.008_{\mathrm{total}} \mathrm{GeV}$$

FCC projected

$$m_{\mathrm{W}} = 80.379 \pm 0.0003 \ \mathrm{GeV}$$

projected prediction

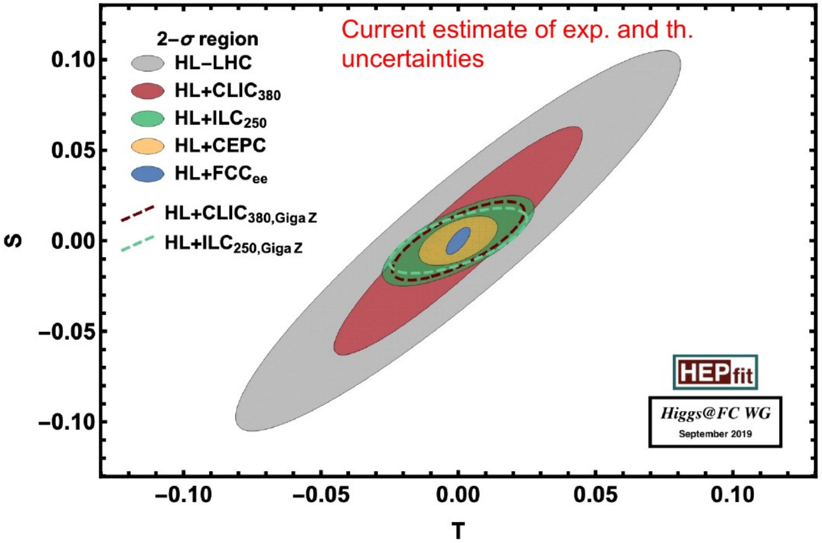
$$m_{\mathrm{W}} = 80.3584 \pm 0.0001_{mt} \pm 0.0001_{mZ} \pm 0.0005_{\alpha QED}$$
$$\pm 0.0002_{\alpha S} \pm 0.0000_{mH} \pm 0.0040_{\mathrm{theory}} \mathrm{GeV}$$

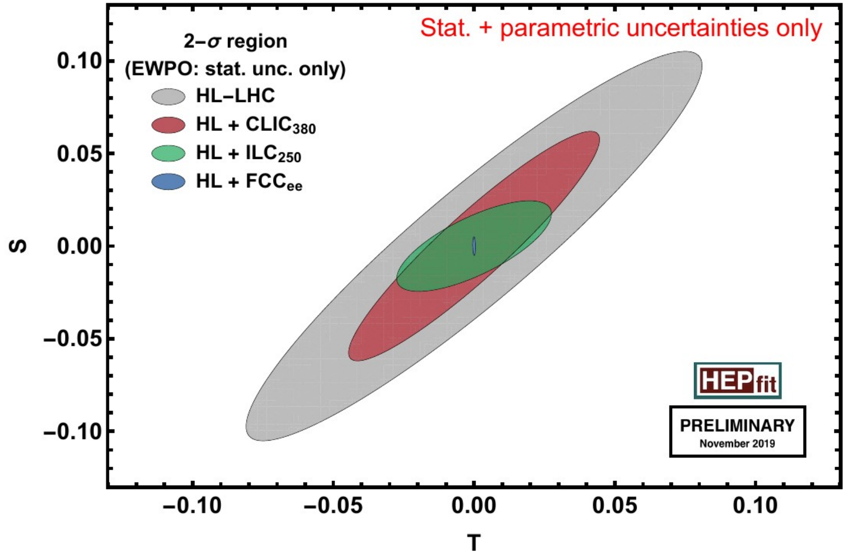
Projections by Sven Heinemeyer

# LEP/SLC vs FCCee

## Example for new physics in W or Z propagator

- *S* and *T* variables parametrize this new physics
- FCCee is doing very well but it is clear we can do much better, if
  - Experimental systematics can be controlled and if theory calculations are precise enough to match statistical uncertainties




Improvements in calculations by factors of 10-20 needed to match the statistical uncertainties, but also experimentalists need to do a lot of work to establish that statistical boundary can really be reached.

# Conclusions

## New era in precision electroweak physics

- Profound test of standard model at Z pole and WW threshold: re-measure parameters up to 3 orders of magnitude more precisely: $m_Z$, $\alpha_{QED}(m_Z)$, ...
- Severe constraints from pseudo observables on: $m_W$, $m_t$, ...
- Far reaching consequences for predictions

## We are not there yet though ...

- Luminosity measurement fundamentally limits $\sigma_{0,\ hadr}$ (# light neutrinos) and puts some limitations on uncertainties for $m_Z$, $\Gamma_Z$
- Energy calibration largest contribution to Z boson mass uncertainty
- Many experimental uncertainties are believed to be manageable, but significant work is needed to prove this *(see next slide)*
- Detailed detector status monitor and in situ inclusion of it into the MC will be key for precision results
- **Hadronic final states: acceptance uncertainty? Compare MC?**
- **Two photon processes most worrisome, especially for hadronic Z decays**

# *Thank you*

## Work on lineshape analyses

- Jan Eysermans, Luca Lavezzo, **Marina Malta Nogueira**
- Tim Neumann, Sofia Lara, Casey Lawson, Bella Torres, Denis Siminiuc, Brenda Chow, Rujuta Sane

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