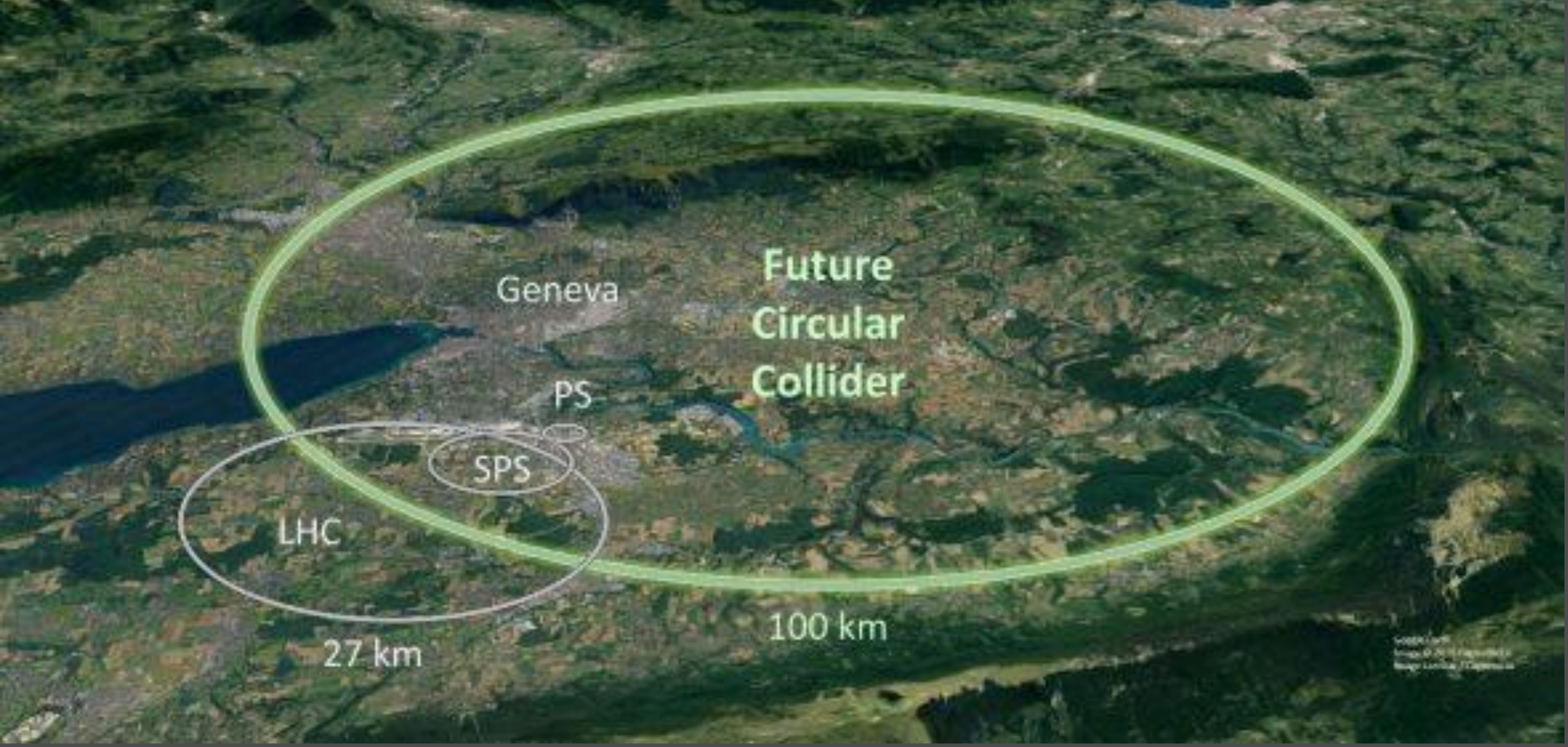


Considerations for lineshape measurements at the FCCee

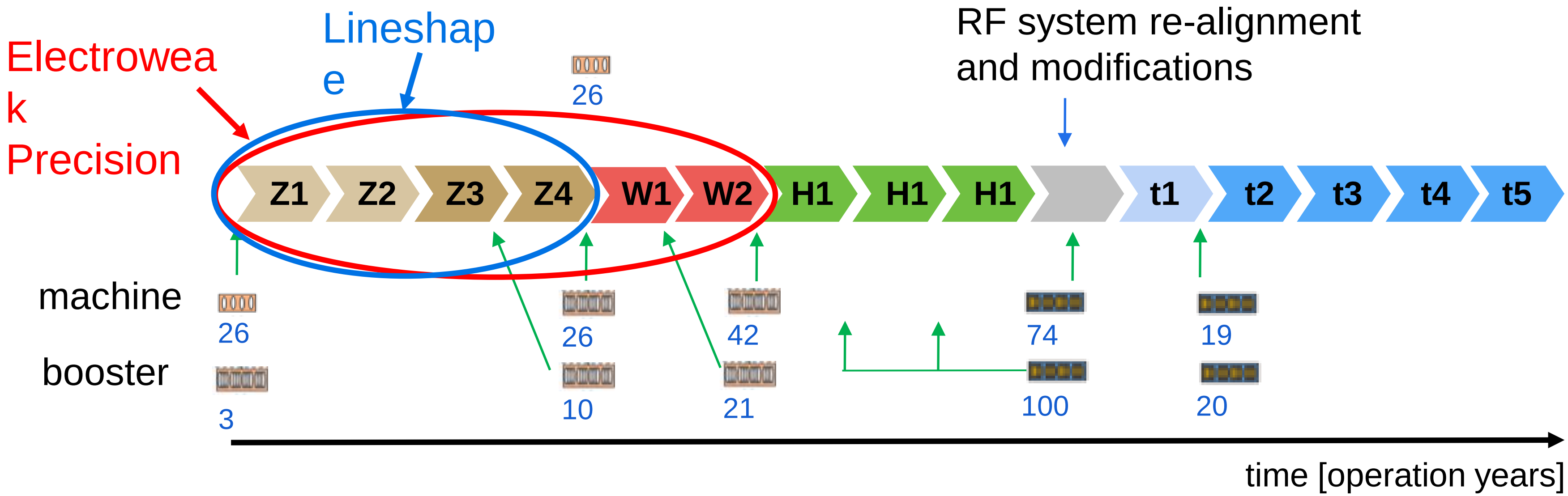
Christoph Paus

April 14, 2023

FCC-ee Run Plan

The baseline run plan for FCC-ee

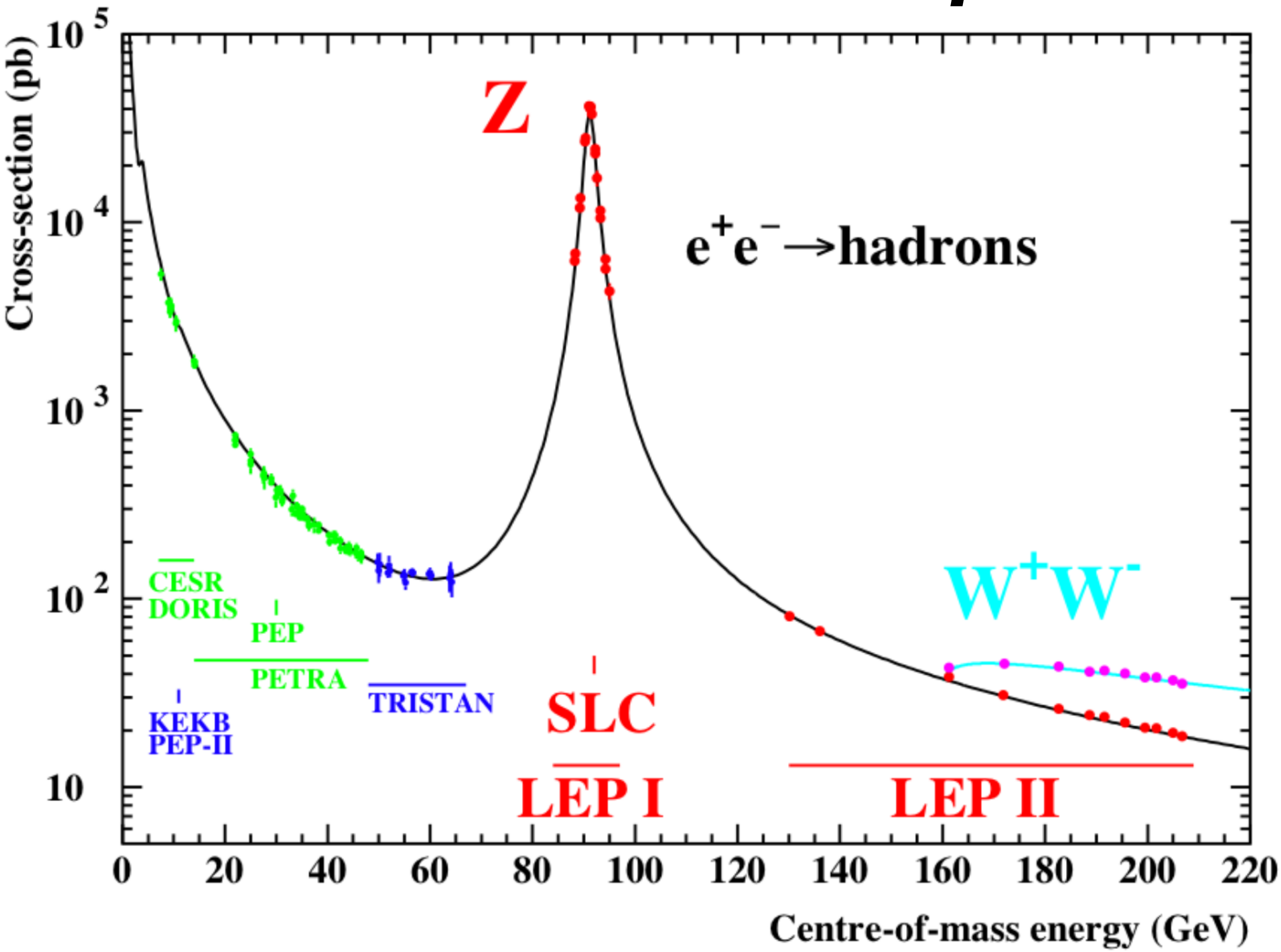
- Z run produces most events followed by the WW run
- It will have highest requirements for detector and accelerator design
- Machine upgrade is well staged



Phase	Run duration (years)	Center-of-mass Energies (GeV)	Integrated Luminosity (ab^{-1})	Event Statistics
FCC-ee-Z	4	88–95	150	3×10^{12} visible Z decays
FCC-ee-W	2	158–162	12	10^8 WW events
FCC-ee-H	3	240	5	10^6 ZH events
FCC-ee-tt	5	345–365	1.5	10^6 $t\bar{t}$ events

$\approx \frac{\Delta_{LEP,St}}{a\,500}$

The Lineshape



Motivation for Precision

At LEP

- Measure crucial fundamental parameters of the standard model
- Z mass, W mass, α_S, α_{QED}, number of light neutrinos
- Convert direct observables like σ, A_{FB}, τ_{POL}, … to pseudo observables
- Constrain indirectly m_t and m_H by 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)

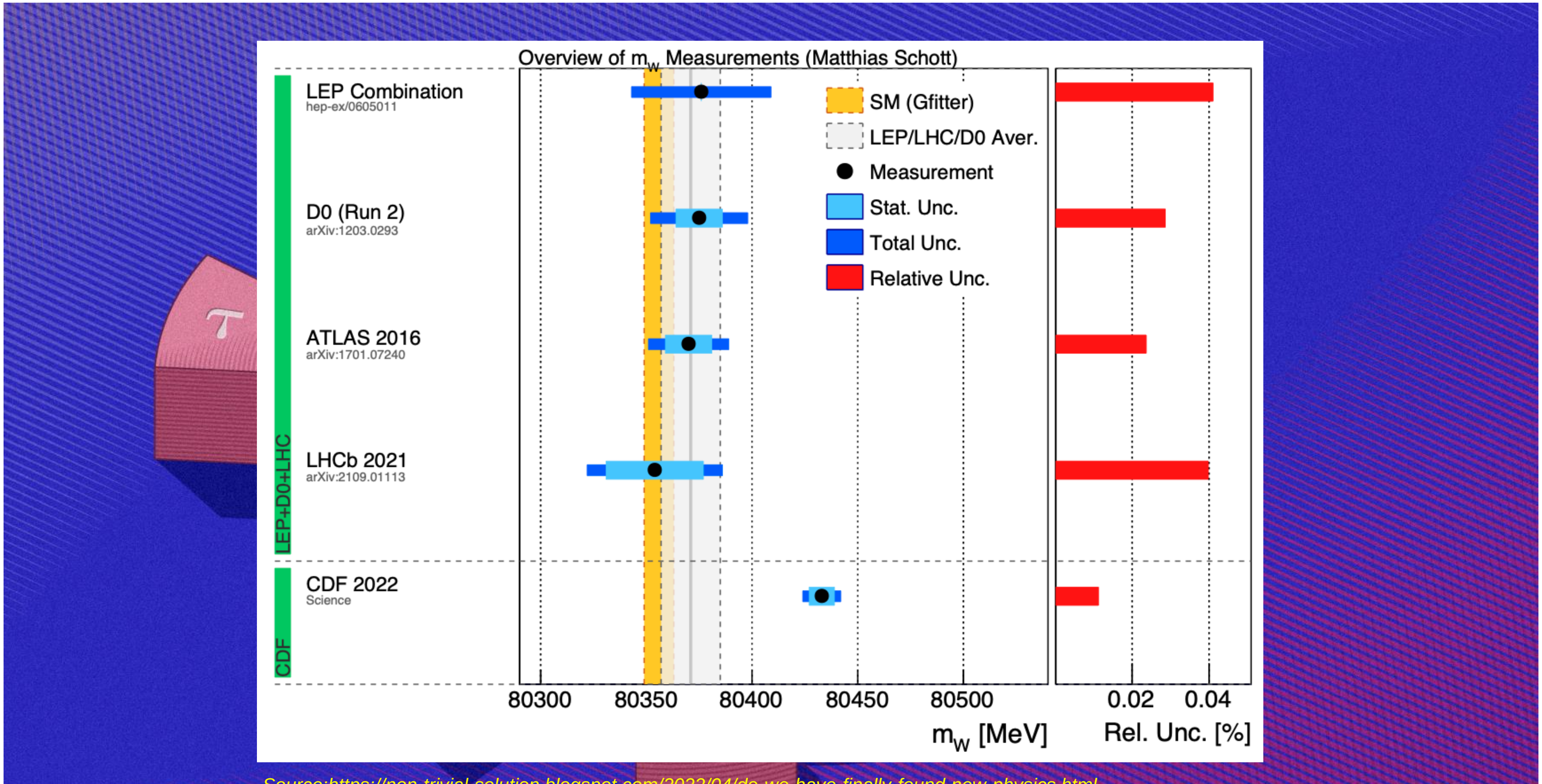
For FCC ee

- 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

Why do precision EW?

CDF experiments last word

- W mass too heavy by seven standard deviations !



Source:https://non-trivial-solution.blogspot.com/2022/04/do-we-have-finally-found-new-physics.html

Source: https://www.quantamagazine.org/fermilab-says-particle-is-heavy-enough-to-break-the-standard-model-20220407/

The Lineshape

Cross section

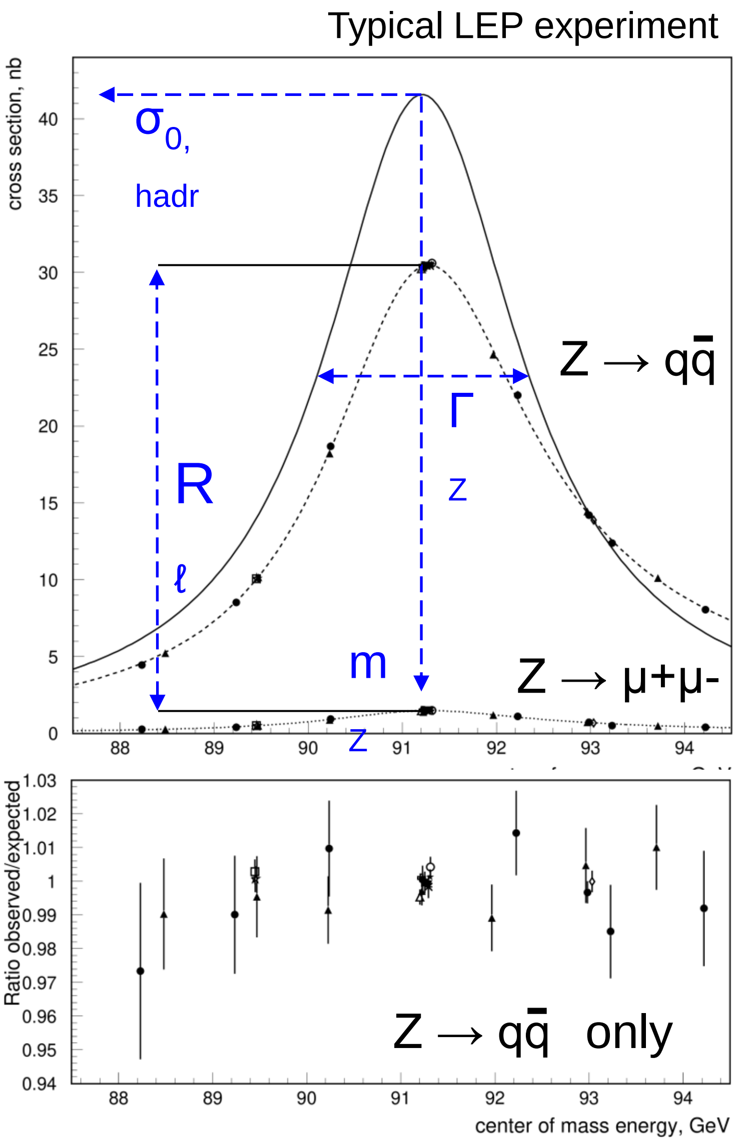
$$\sigma(\sqrt{s}) = \frac{N_{\text{signal}}}{\mathcal{L}} = \frac{N_{\text{selected}} - N_{\text{background}}}{\varepsilon A \mathcal{L}}$$

What can we extract?

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

Hadrons "win" (quarks have color)

- mass, width and σ_0



Ingredients

Cross section

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

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_{selected}, $N_{\text{background}}$

- Selected events contain signal and the remaining background

Acceptance, A, and efficiency, ε

- 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 $\alpha_{QED}(m_Z)$

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 $\sqrt{s}$

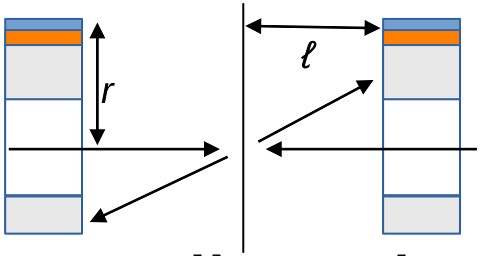
FCC calibration is still in rapid development

- 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...*

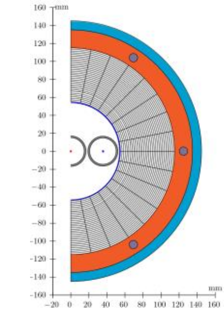
Table 15. Calculated uncertainties on the quantities most affected by the centre-of-mass energy uncertainties, under the final systematic assumptions.

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

From: arxiv:1909.12245

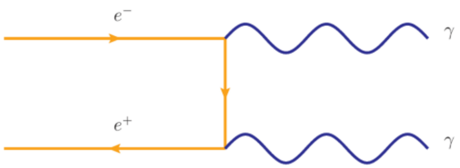


Luminosity



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 Δr ~1μm
  - Half distance between lumi monitors at $\Delta \ell$ ~50 μm
- Theory prediction limiting (already at LEP)



Another clean and copious process?

- $e^+e^- \rightarrow \gamma\gamma$: precise prediction, no Z dependence and clean
- Not very many events (about 1 in 1000 events) – accuracy O(10^{-4})
- No perfect solution but pretty good

Best plan, so far

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

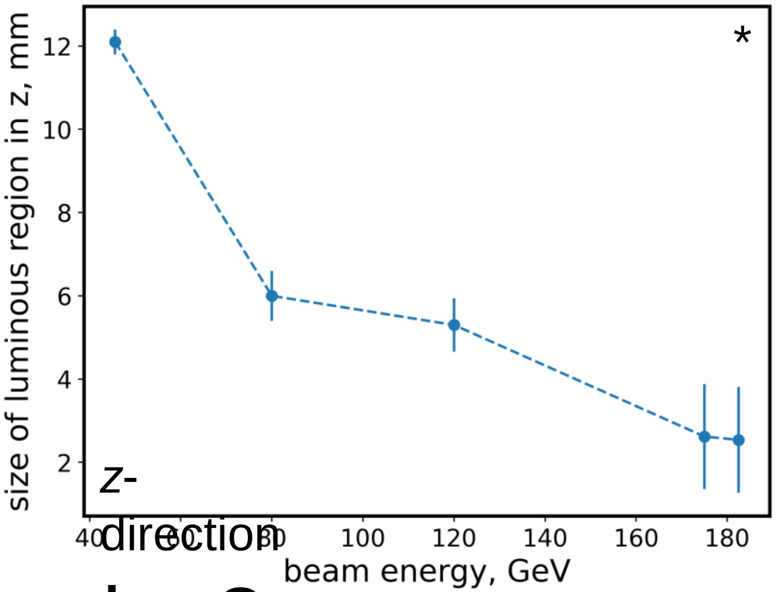
- Use $e^+e^- \rightarrow \gamma\gamma$ as overall normalization (global)
- Bhabha events to extrapolate across CM energies (σ_{theory}= 14 nb)
- Loose significant precision on $\sigma_{0,\ hadr}$ (# light neutrinos) and
- … some on m_Z, Γ_Z

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 in cm
- but uncertainty well 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 cm 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*

Quote of the Day

At a lepton collider
every event is a *signal event*,
while at a hadron collider
every event is a *background event*.

– Anonymous

This means that at lepton colliders we have basically no control regions and we have to heavily rely on Monte Carlo simulation to determine acceptance, efficiency and backgrounds.

Event Counts

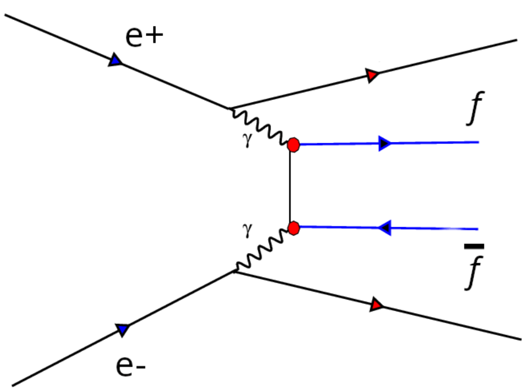
Number of selected events

- 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 (2×10^{-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 ...)
- 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 (?)

$Z \rightarrow$ Hadrons: A/ε

Statistical precision: order 10^{-7} – 10^{-6}

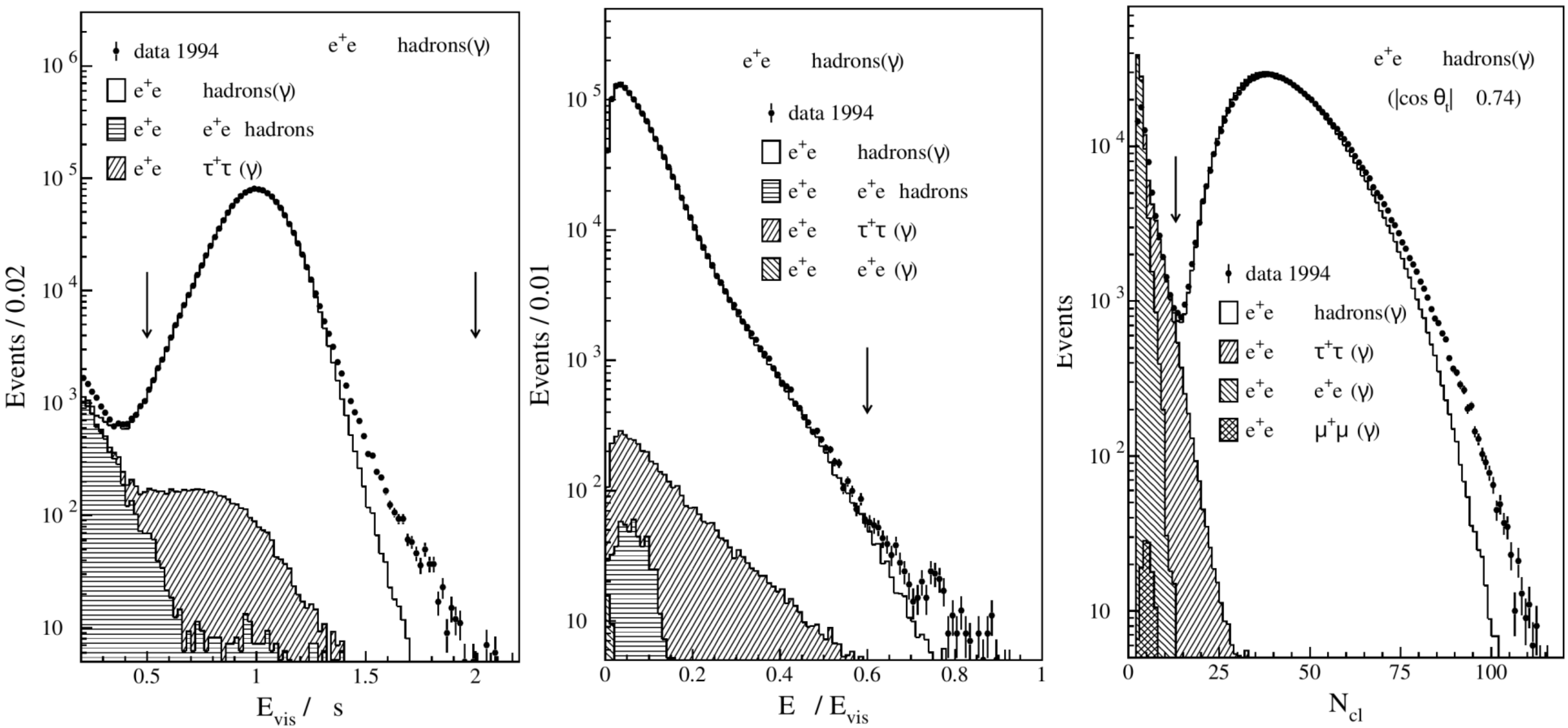
- LEP – acceptance down to 12º → cos(12º) = 0.9781 (L3)
- FCC - acceptance down to 7º → cos(7º) = 0.9925
  - Enormous improvement in number of *lost clusters* (2.2% → 0.75%)
  - Jets are too big to not register: efficiency should be *very* close to 100%
  - No trigger ☺, which is good but redundancy 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

Z→Hadrons: Message from LEP

Example plots for hadron selection at L3

- There is noise, number of clusters in MC do not agree
- Two photons are leaking



Extracting PO ‘à la LEP’

Undusted L3 program to fit two-fermion data

- 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
  - If anyone is interested it is available in github but before using a proper README will be needed
  - It is complex to use but with a little bit of patience it can be quite useful
  - For some of us old timers it offers another chance to make your kumac skills shine, remember PAW, KUIP, SIGMA and COMIS?
  - Big shout out to Martin Grünewald who saved my/our program and send me a copy from his never failing backups!
- Eventually we need to figure out how to do this for real with FCC data: Is Fortran making a come back?

How well can we do?

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

Inputs: hadronic cross sections, 5 points, 30/ab each

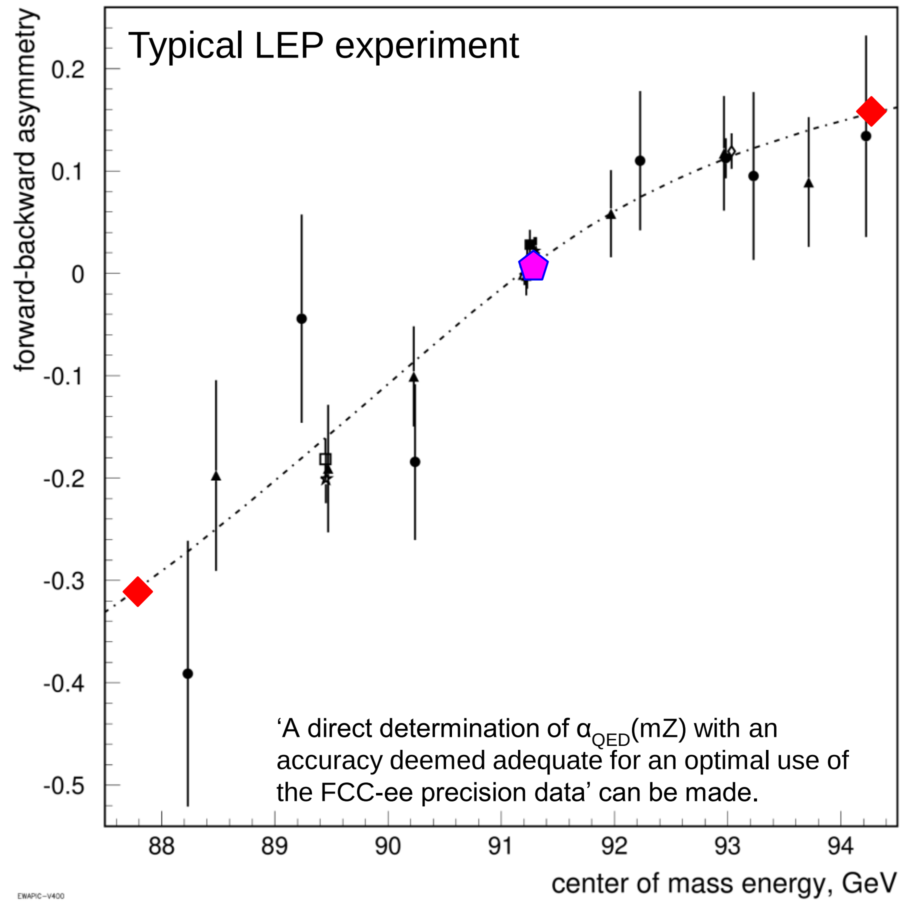
1) statistical uncertainty on hadrons only, nothing else
2) Add fully correlated systematic uncertainty as large as peak stat. uncertainty
3) Add stat. uncertainty on luminosity corresponding to 14 nb cross section
4) Add 10^{-4} syst. fully correlated, and another 10^{-5} uncorrelated
5) Add 10 keV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

Setup	delta(m_Z)	delta(Γ_Z)	delta($\sigma_{0, hadr}$)
units	[keV]	[keV]	[pb]
1	1.2	3.4	0.044
2	1.2	3.4	0.044
3	1.7	5.2	0.076
4	8.4	26	4.2
5	13	26	4.2
6	101	26	4.2

The 2 Lineshape

Forward backward asymmetries

- Decouples from cross section
- Measures $\sin^2\theta_W^{eff}$ and $\alpha_{QED}(m_Z)$, which mostly decouple
- Points to measure $\alpha_{QED}(m_Z)$, are just below or just above the Z peak (87.9 or 94.3 GeV)
- A_{FB} constrains $\sin^2\theta_W^{eff}$ (m_t and m_W) most significantly at peak, small stat. uncertainty



$$A_{FB}^{\mu\mu} = \frac{N_F - N_B}{N_F + N_B} \approx f(\sin^2\theta_W^{eff}) + \alpha_{QED}(s)\frac{s - m_Z^2}{2s} g(\sin^2\theta_W^{eff})$$

From: arxiv:1512.05544

Conclusions

New era in precision electroweak physics

- Profound test of the standard model at Z pole: 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, Γ_Z
- Energy calibration of the beam is largest contribution to Z boson mass uncertainty right now, but progress will be made
- 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
- Two photon processes most worrisome, in particular for hadrons

Next steps

Develop simulated data analysis setup

- Generate full Monte Carlo setup: start with LEPx10 equivalent samples
- Produce 'modified' MC with Delphes mixing it together so it appears as real detector data: LEPx1 equivalent
- Go through full analysis process and see how *modifications* affect the analyses
- Setting up a sample of 5×10^{12} events is not trivial, but will be needed to test detailed systematic effects at that level once first 'single LEP' is completed
- Tau (polarization), Heavy flavour measurements and Bhabha's need to follow to make the picture complete, maybe QFB?
- 7 GB per 10^6 hadronic decays $\rightarrow$ 7 PB for 10^{12} events (Delphes)

A word on theory and parameter extraction

- Theory uncertainties are making good progress but more work will be needed – I did not include is but landscape looks encouraging
- Is the old LEP style fit of pseudo observables still feasible? The latest ZFITTER and TOPAZ0 implementations are pretty convoluted