Precision Electroweak Measurements (FCCee)

FCC Week 2023, London

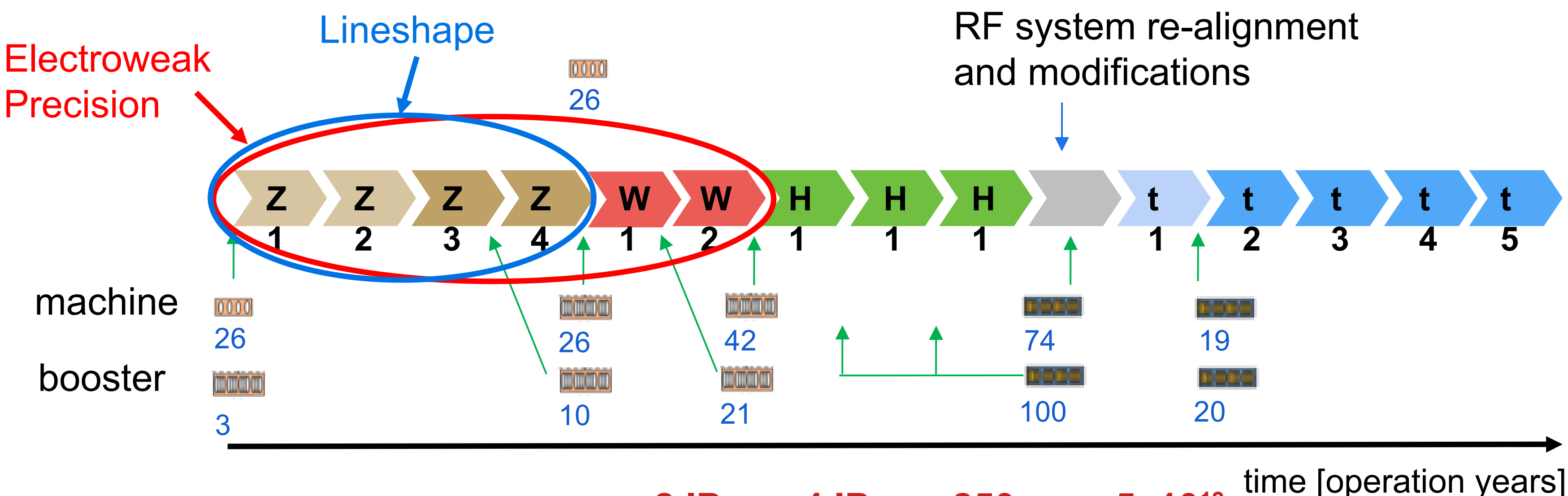
Christoph Paus

June 6, 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



2 IPs → 4 IPs: 250 5x10^12

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

$$\approx \frac{\Delta_{LEP,Stat}}{500}$$

Motivation for Precision

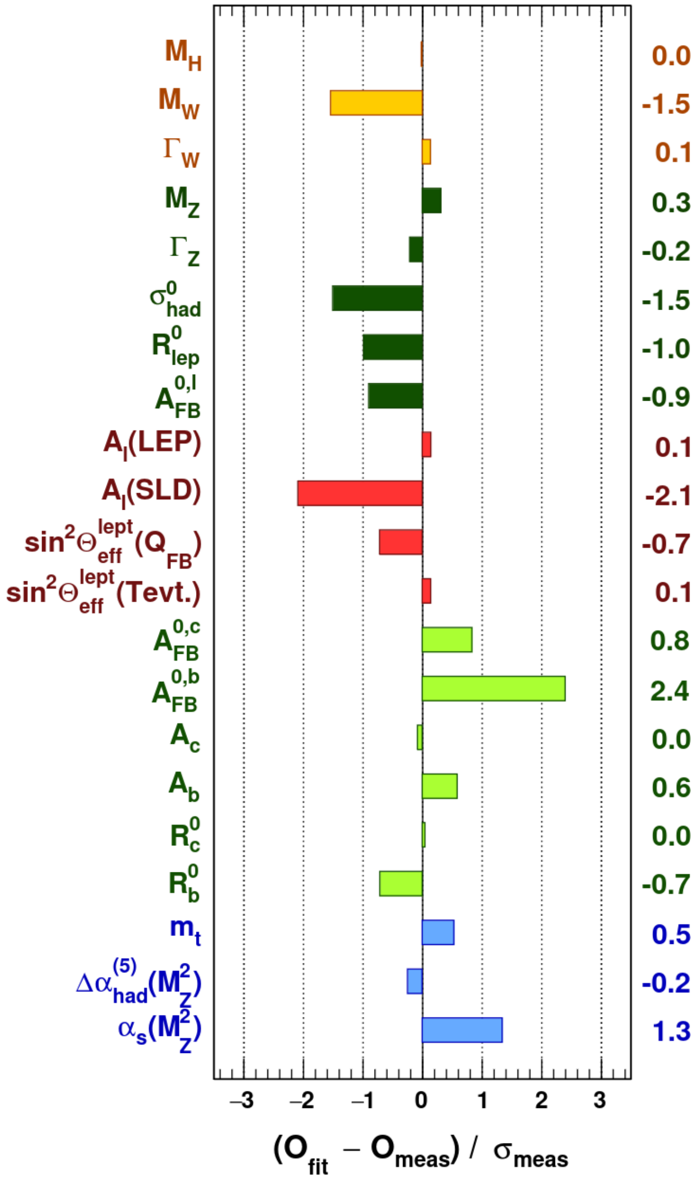
At LEP

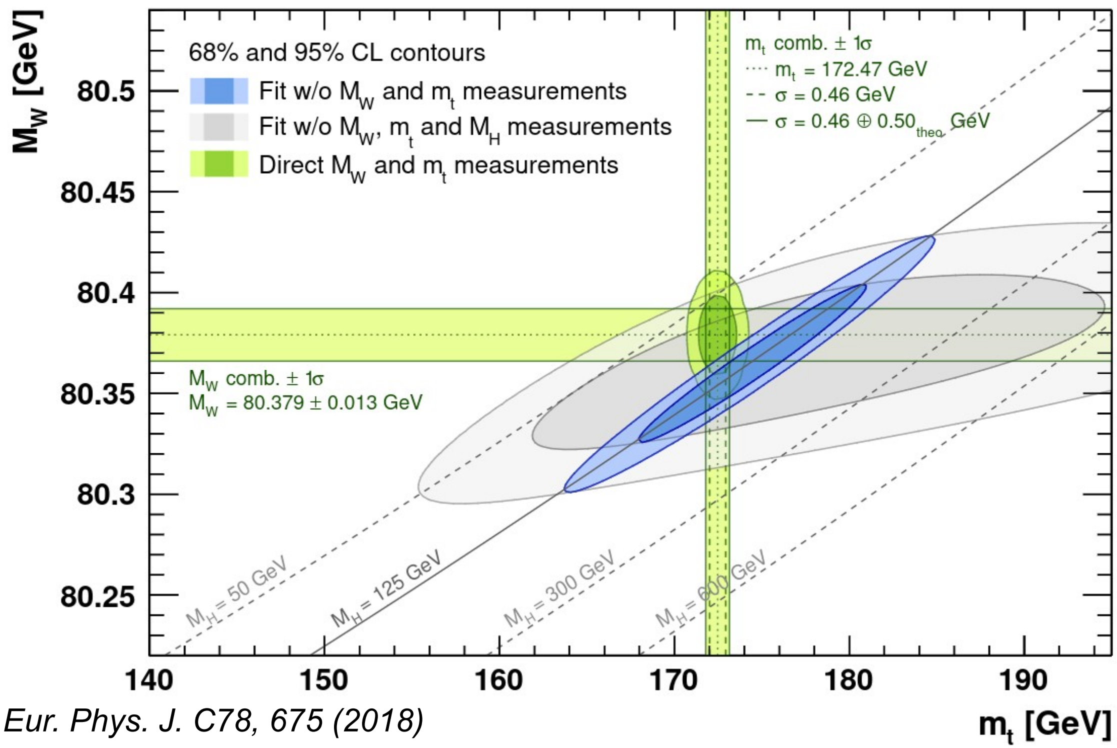
- Measure crucial fundamental parameters of the standard model
- Z mass, W mass, α_S, α_{QED}, number of light neutrinos
- Convert direct observables like σ, A_{FB}, τ_{POL}, … to pseudo observables
- Constrain indirectly m_t and m_H by using pseudo observables as input
- Find discrepancies in the measurements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

Latest Status





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

Latest CDF m_W not included

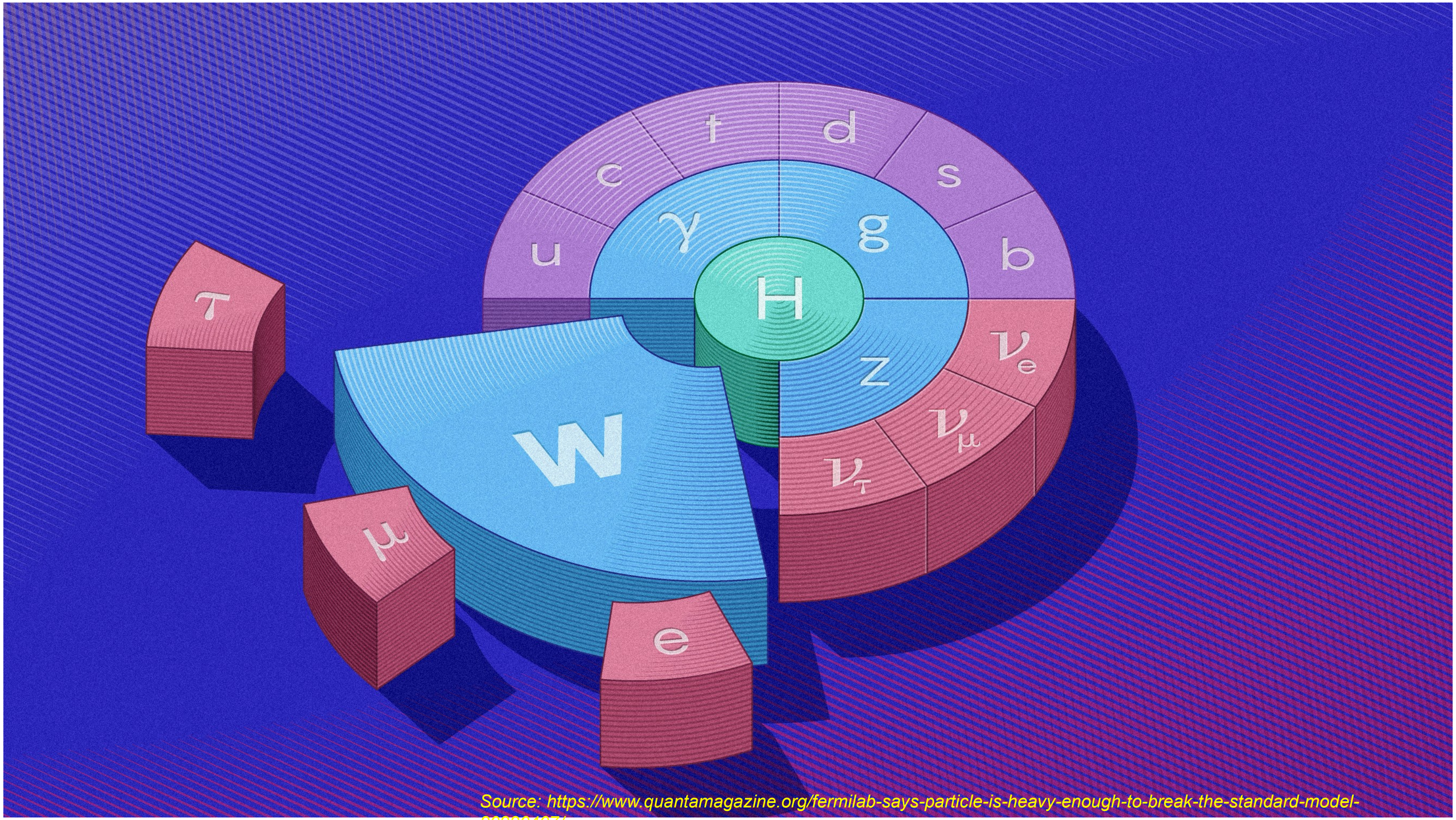
Comparing

- 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 too heavy by seven standard deviations !



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

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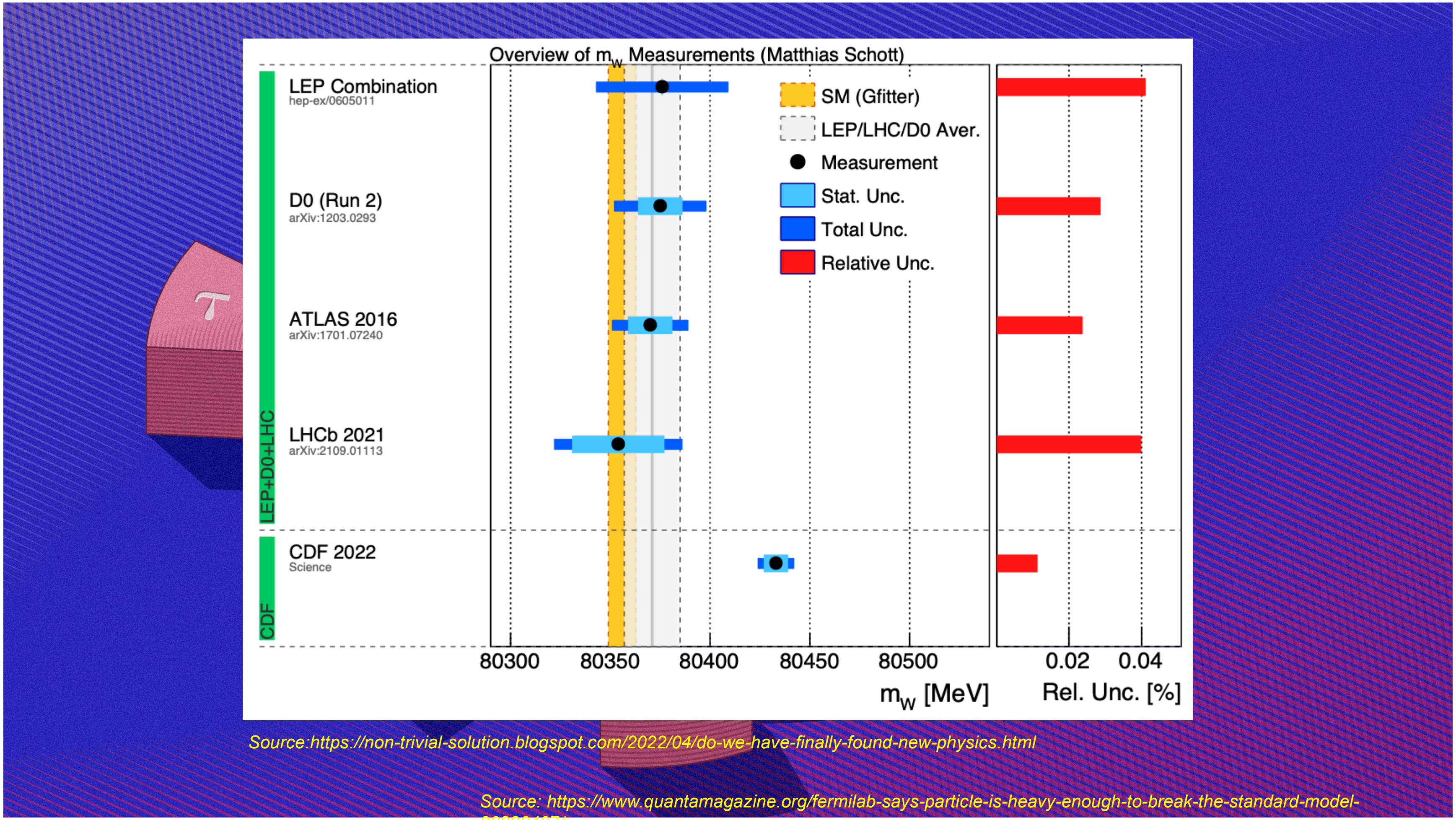

Source:https://non-trivial-solution.blogspot.com/2022/04/do-we-have-finally-found-new-physics.html

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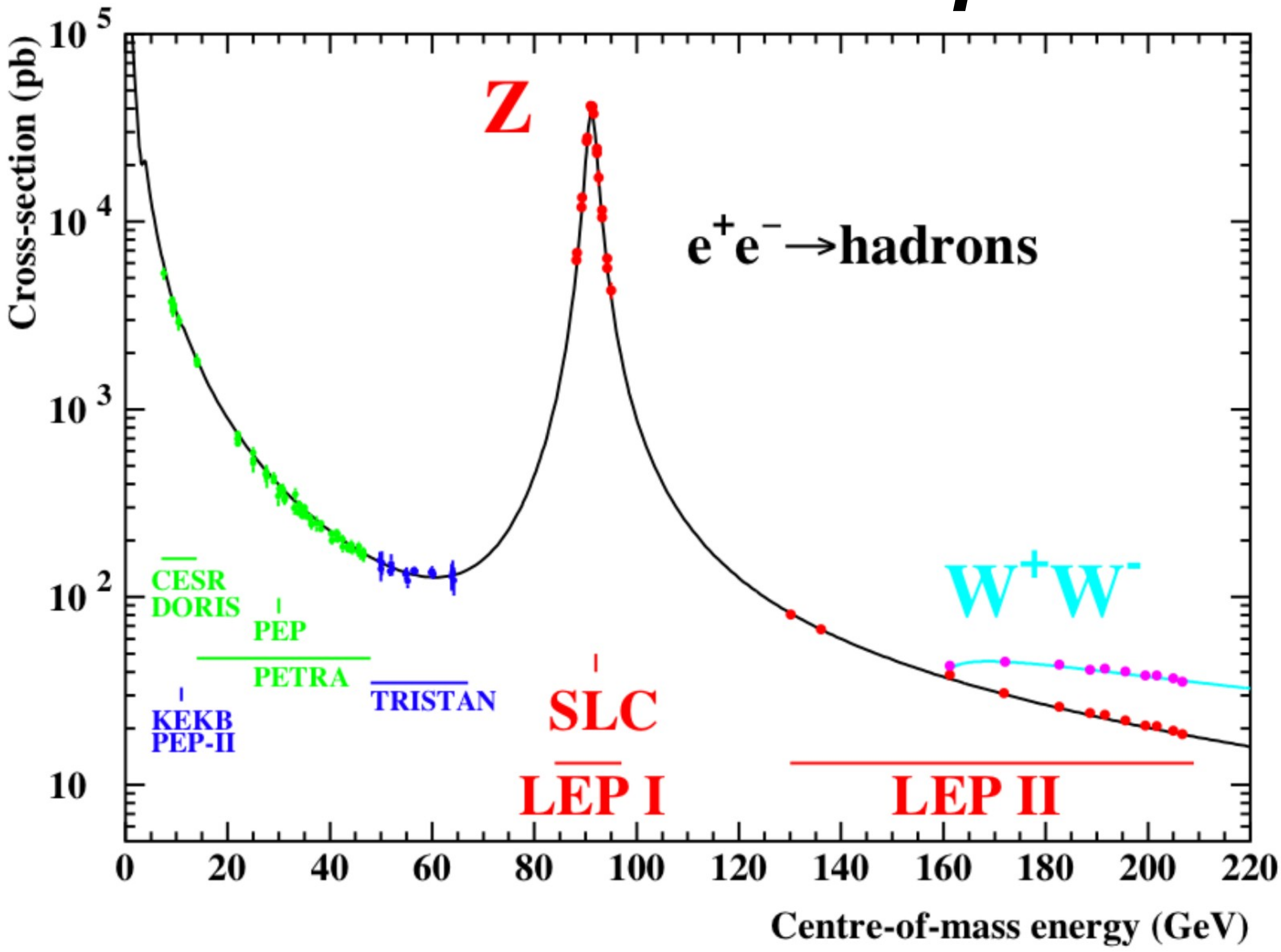
The Lineshape



The Lineshape

Cross section

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

What can we extract?

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

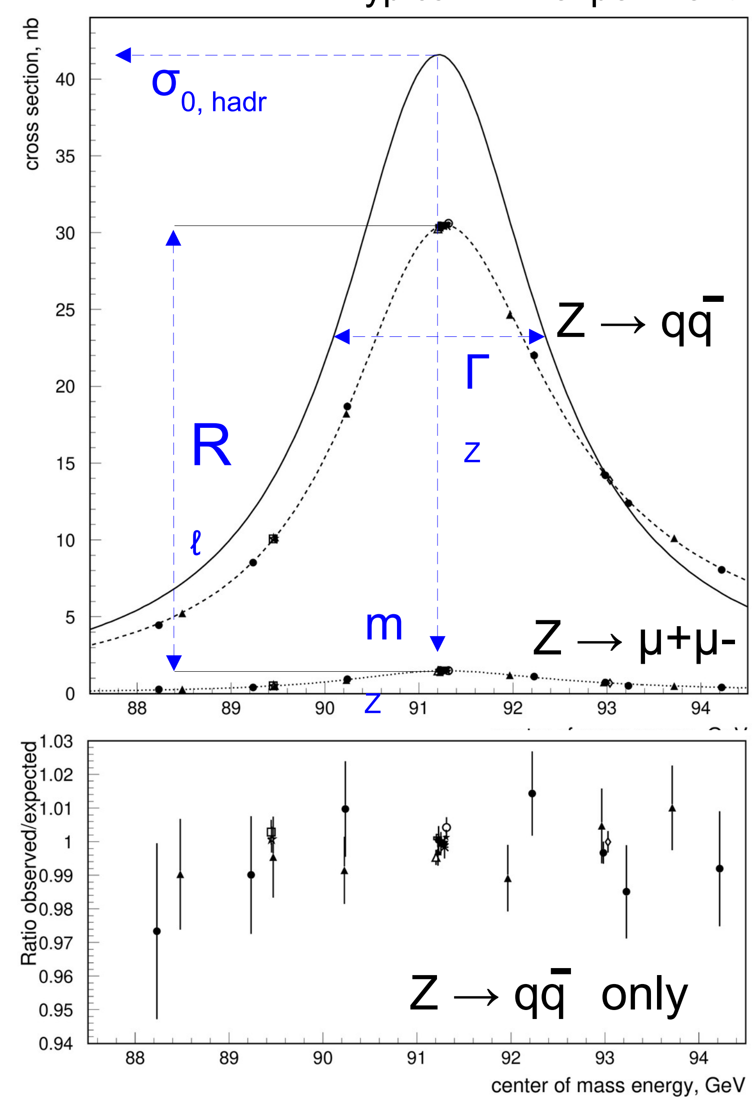
Hadrons "win" (quarks have color)

- mass, width and σ_0

Theory needed

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

Typical LEP experiment



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 $\alpha_{QED}(m_Z)$
- 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	$\Delta\sqrt{s}_{abs}$ 100 keV	$\Delta\sqrt{s}_{syst-ptp}$ **40 keV**	calib. stats. $200\,\text{keV}/\sqrt{N^i}$	$\sigma_{\sqrt{s}}$ $85 \pm \mathbf{0.05}$ MeV
m_Z (keV)	4	100	**28**	1	–
Γ_Z (keV)	4	2.5	**22**	1	**10**
$\sin^2\theta_W^{eff} \times 10^6$ 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**

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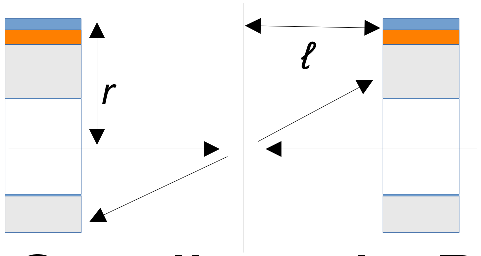
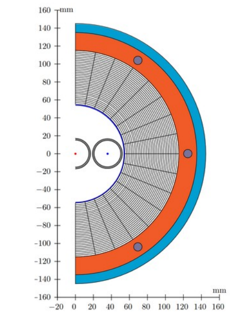


Luminosity



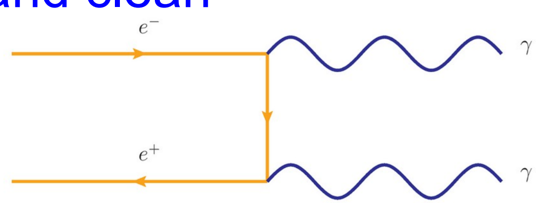
Small angle Bhabha scattering from LEP?

- 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 improved from 0.061% at LEP to 0.037% recently, but still far from statistical precision of hadronic final states (~10^{-6})

https://arxiv.org/abs/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^{-4})
- No perfect solution but pretty good



Best plan, so far

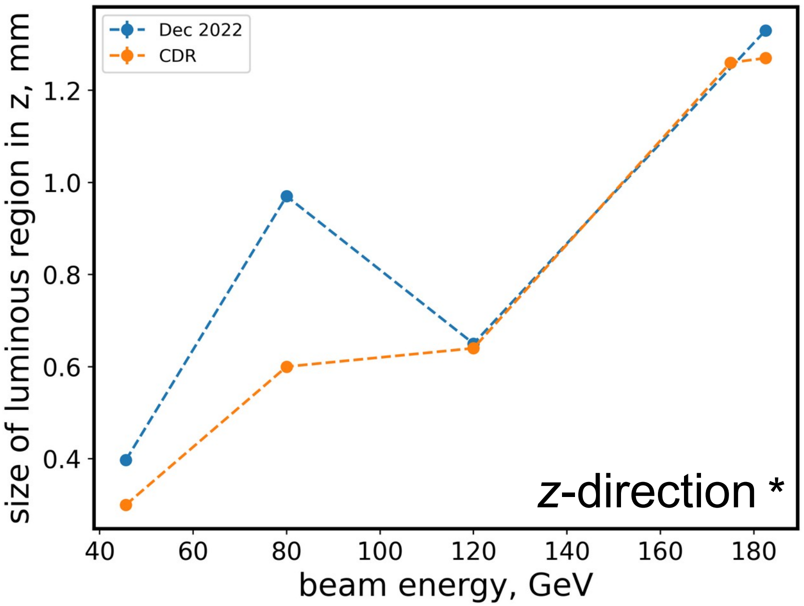
- Use $e^+e^- \rightarrow \gamma\gamma$ as overall normalization (global)
- Bhabha events to extrapolate across CM energies (σ_{theory}= 14 nb)
- Loose significant precision on $\sigma_{0,\,hadr}$ (# light neutrinos) and
- … some on m_Z, Γ_Z

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 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*

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

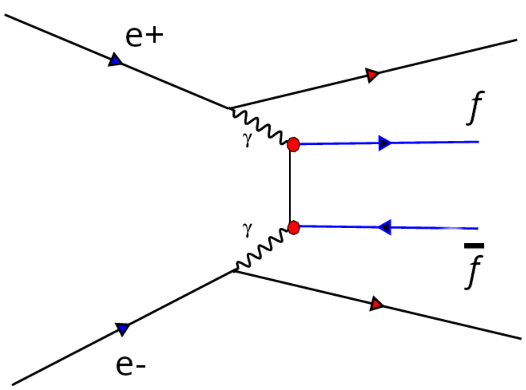
Number of selected events

- 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 ...)
  - Whizzard 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 diphoton (dielectron) events *– see presentation by P.Janot later tomorrow*
- 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

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

$Z \to$ *Hadrons: A/ε*

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

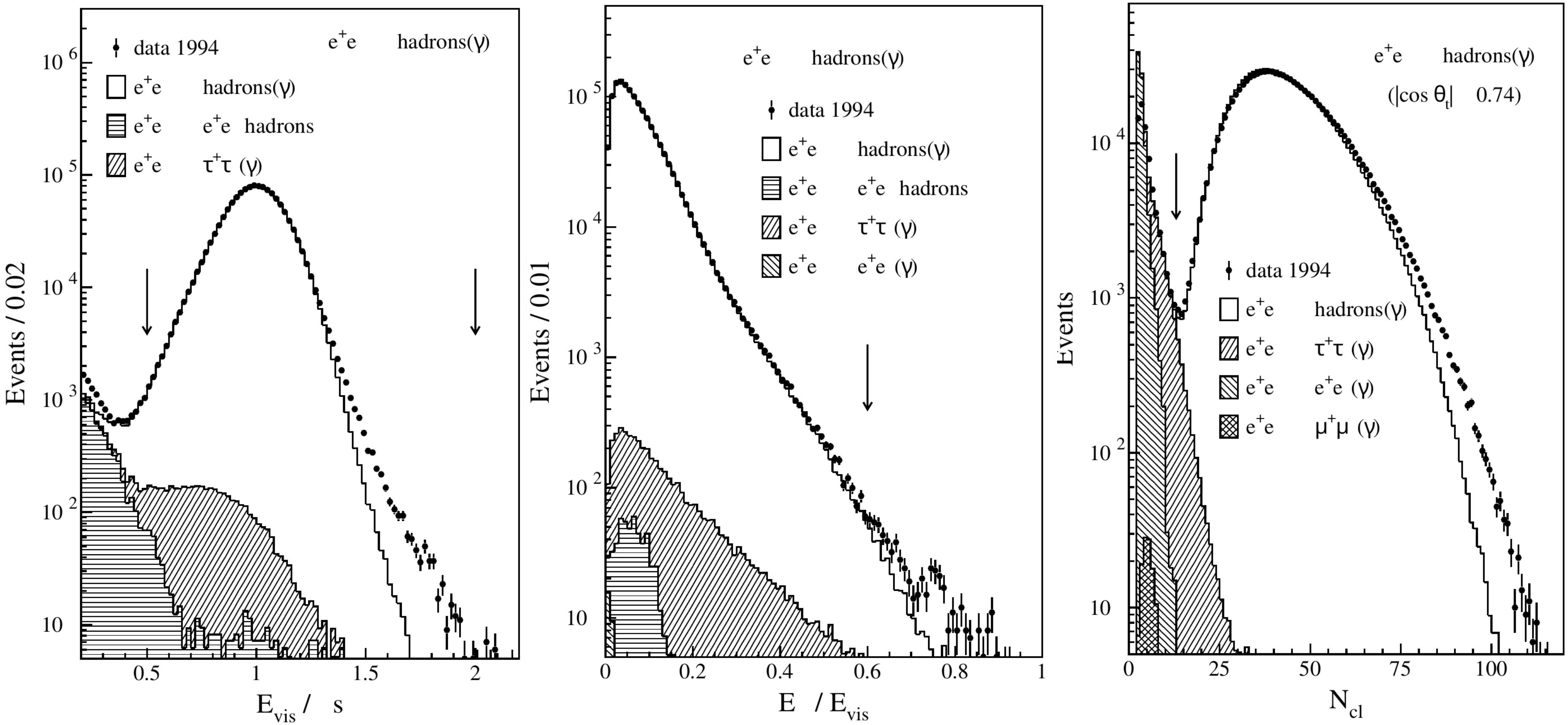
- LEP – acceptance down to 12º → cos(12º) = 0.9781 (L3)
- FCC - acceptance down to 7º → cos(7º) = 0.9925
  - Enormous improvement in number of *lost particles* (2.2% → 0.75%)
  - Jets are too big to not register: efficiency should be *very* close to 100%
  - No trigger ☺, which is good but redundancy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

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



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, Γ_Z and $\sigma_{0, hadr}$

Inputs: hadronic cross sections, 5 points, 50/ab each (250/ab total)

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	0.91	2.6	0.034
2	0.91	2.6	0.057
3	1.4	4.1	0.075
4	8.4	26	4.2
5	13	26	4.2
6	101	26	4.2

Leptonic Ratios and α_S

Advantage of Ratios (and Asymmetries)

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

- 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

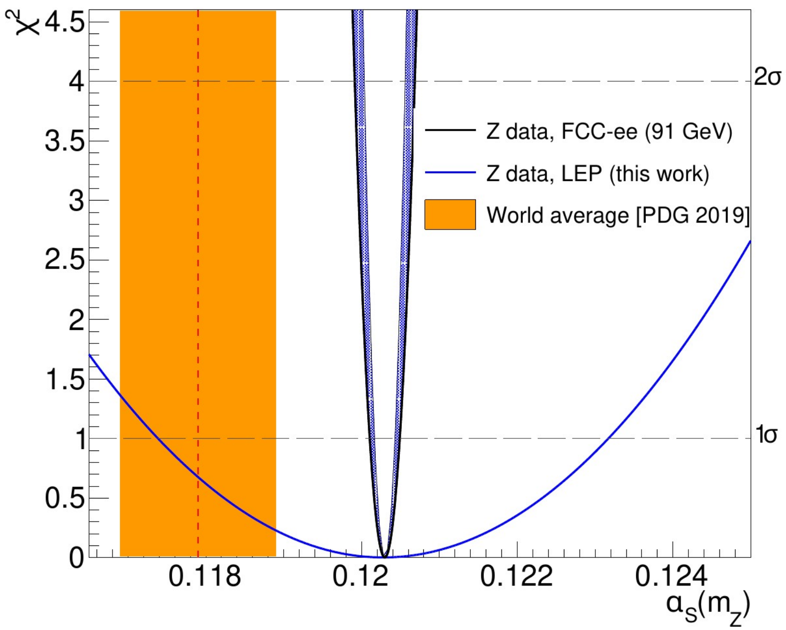
Limitations at LEP

- R_ℓ 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_ℓ at 0.001 needs theory uncertainty to be improved by about a factor of 4 to approximate exp. precision

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

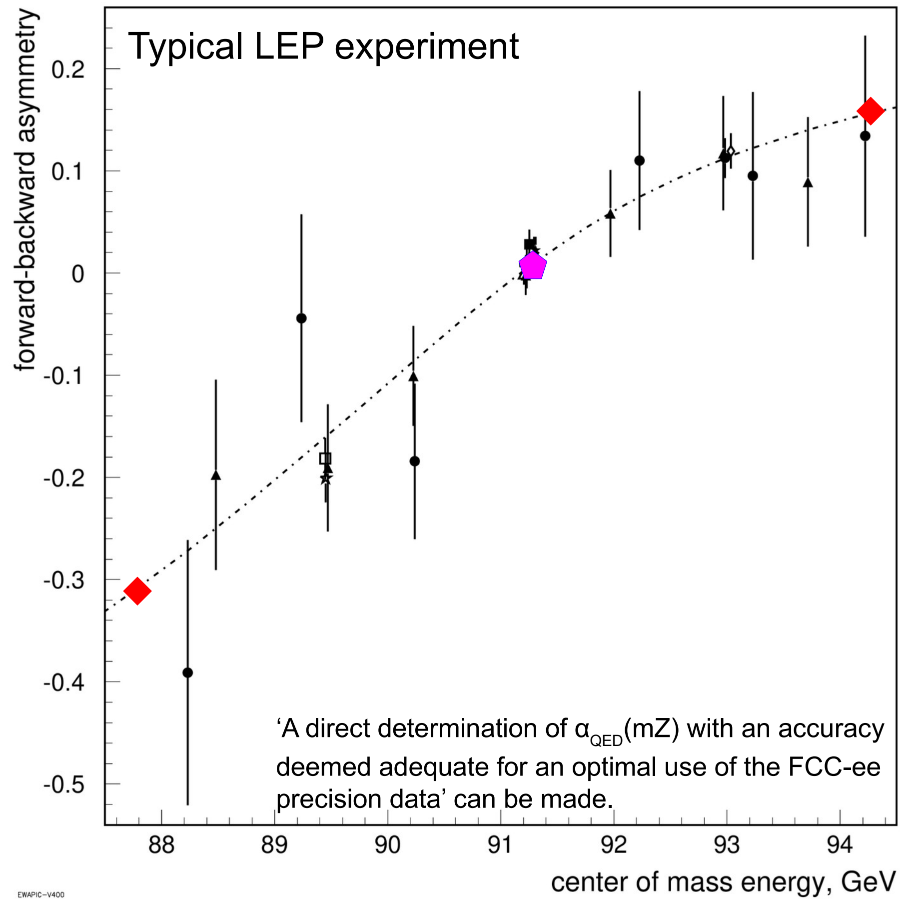


From: https://arxiv.org/pdf/2005.04545.pdf

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) ◆



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

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

From: arxiv:1512.05544

The 2^{nd} Lineshape

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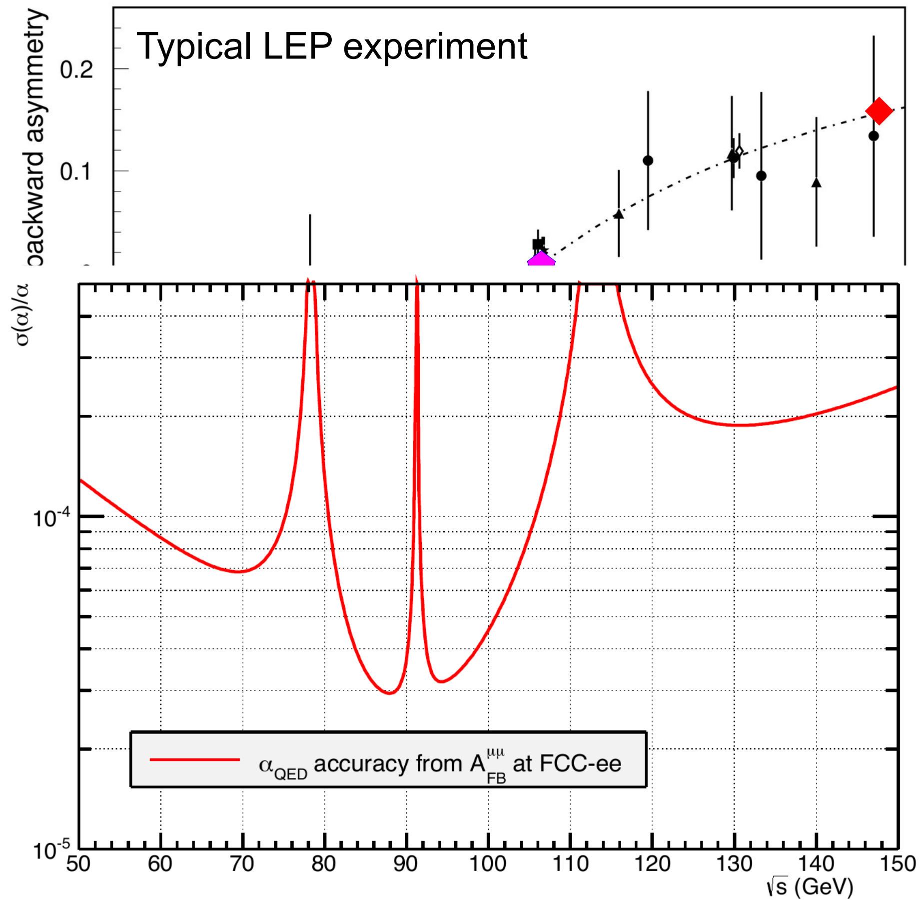

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From: arxiv:1512.05544

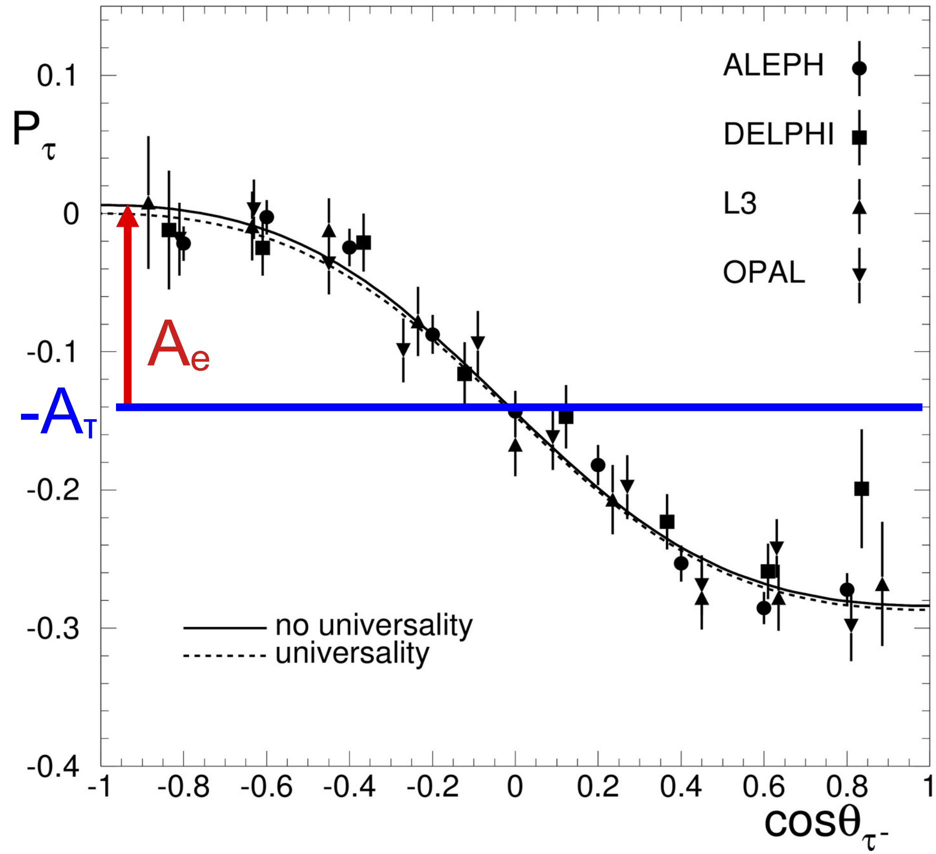
Key Ingredients: Tau Polarization

Tau polarization

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

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



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

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

Heavy Flavours

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

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

- 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

– talk by Lars Roehrig tomorrow

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 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

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_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

LEP/SLC vs FCCee

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

LEP measured

$$\sin^2\theta_W^{\text{eff}} = 0.23153 \pm 0.00016$$

predicted

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

FCC projected

$$\sin^2\theta_W^{\text{eff}} = 0.23153 \pm 0.000002$$

projected prediction

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

LEP measured

$$m_W = 80.379 \pm 0.012 \text{ GeV}$$

predicted

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

FCC projected

$$m_W = 80.379 \pm 0.0003 \text{ GeV}$$

projected prediction

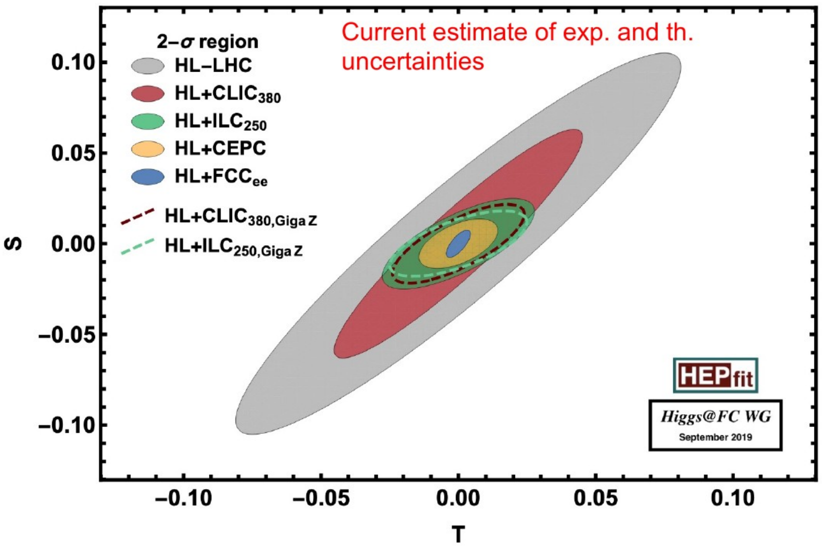
$$m_W = 80.3584 \pm 0.0001_{mt} \pm 0.0001_{mZ} \pm 0.0005_{\alpha QED}$$
$$\pm 0.0002_{\alpha S} \pm 0.0000_{mH} \pm 0.0040_{\text{theory}} \text{GeV}$$

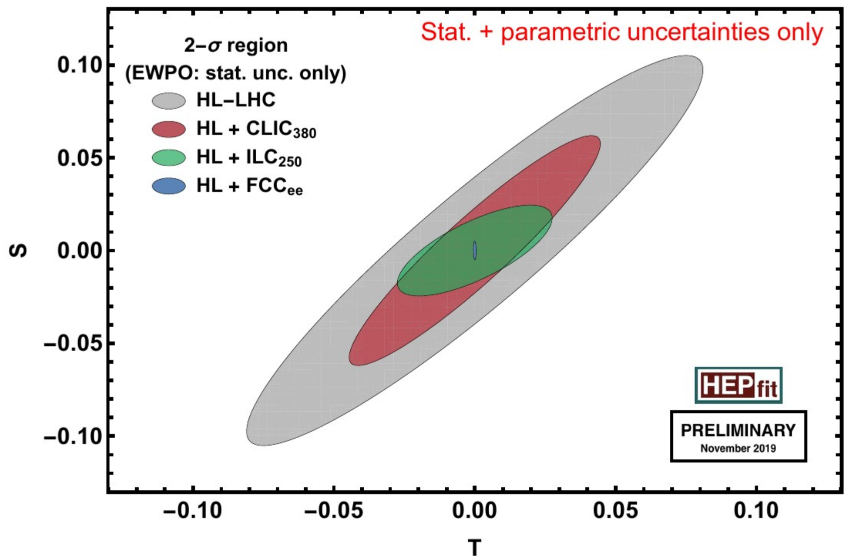
Projections by Sven Heinemeyer

LEP/SLC vs FCCee

Example for new physics in W or Z propagator

- *S* and *T* variables paramterize 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, Γ_Z
- Energy calibration of the beam is largest contribution to Z boson mass uncertainty right now, but progress looks very promising
- 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
- 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 → 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 *– see talk by Janusz Gluza yesterday*
- Is the old LEP style fit of pseudo observables still feasible? The latest ZFITTER and TOPAZ0 implementations are pretty convoluted

More slides …

Questions for Theory

Comparing experimental data and theory

- Can we continue to use LEP like Pseudo Observable approach?
- We need very detailed Monte Carlo to include higher order effects for acceptance calculations and accurate background description
- Background from two-photon production: poor description especially for hadronic final states

Identifying discrepancies with Standard Model

- Compare precision determination of m_W and $\sin^2\theta_W^{eff}$ with Standard Model predictions
- More generally use effective parametrizations to single out specific sources of potential discrepancies: *S, T, U* parameters
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