FCC-ee Electroweak Precision Performance Status

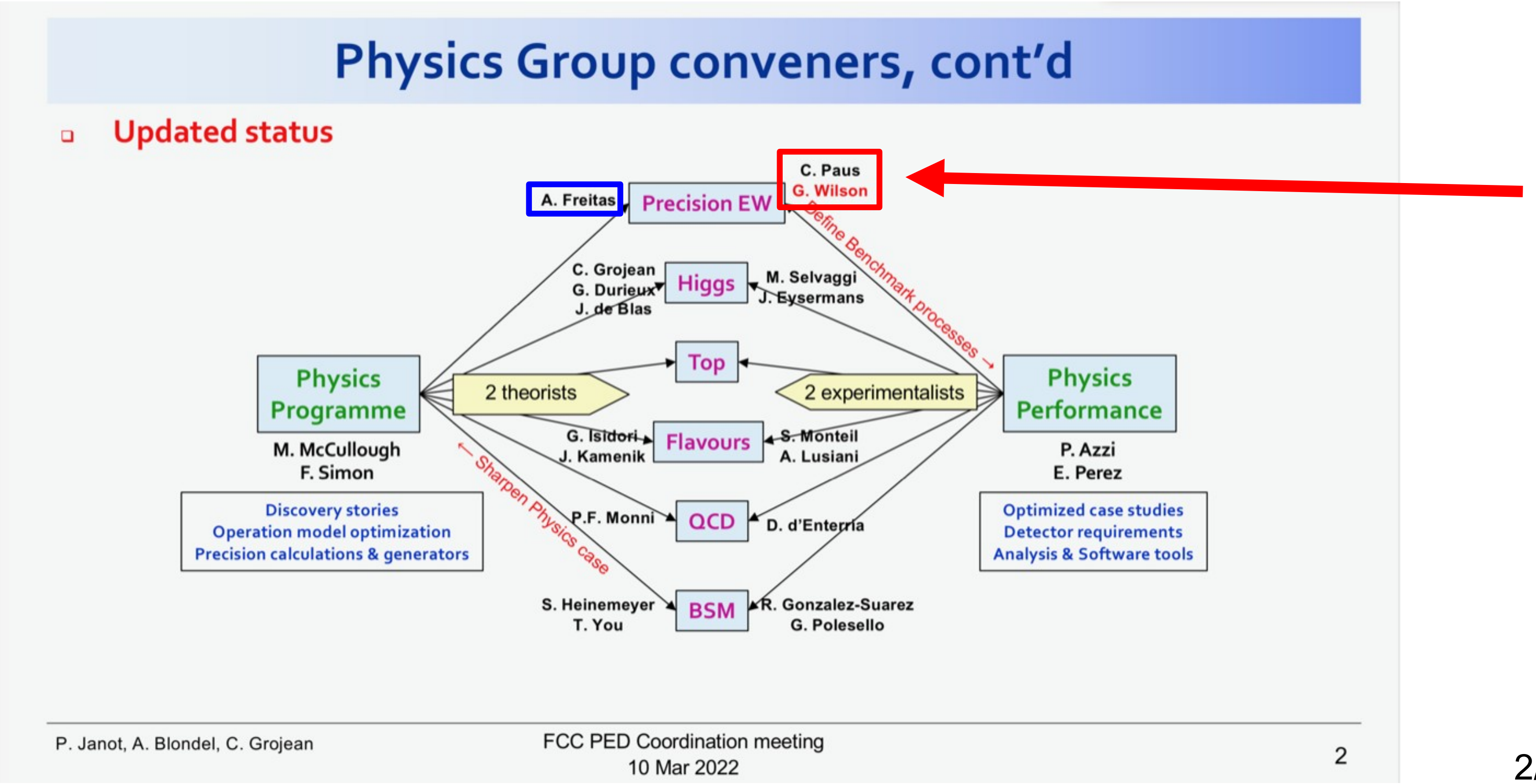
Christoph Paus,
Graham Wilson

FCC Week 2022
May 31, 2022
Paris

The obvious

We are part of the Feasibility Study of the FCC

- It started in 2021 and we have to get going!
- Our task is to figure out what detector (and accelerator) is needed so we can make full use of the future e^+e^- collisions



FCC Organization

FCC Feasibility Study – coordination team and contact persons

Study Support and Coordination
Study Leader: Michael Benedikt
Deputy Study Leader: Frank Zimmermann

- **EU Projects** – NN
- **Collaboration building** – Emmanuel Tsesmelis
- **Communications** – Panagiotis Charitos, James Gillies

Study Support Unit
IT: Sylvain Girod
Procurement: Adam Horridge
Quality control: NN
Resources: Sylvie Prodon
Scheduling, quality mangement: NN
Secretariat: Julie Hadre

Physics, Experiments and Detectors
Patrick Janot, Christophe Grojean

- **Physics programme** – Matthew McCullough, Frank Simon
- **Detector concept** – Mogens Dam
- **Physics performance** – Patrizia Azzi, Emmanuel Perez
- **Software and computing** – Gerardo Ganis, Clément Helsens

Accelerators
Tor Raubenheimer, Frank Zimmermann

- **FCC-ee collider design** – Katsunobu Oide
- **FCC-hh design** – Massimo Giovannozzi
- **Technology R&D** – Roberto Losito
- **FCC-ee booster design** – Antoine Chancé
- **FCC-ee injector** – Paolo Craievich, Alexej Grudiev
- **FCC-ee energy calibration polarization** – Alain Blondel, Jorg Wenninger
- **FCC-ee MDI** – Manuela Boscolo, Mike Sullivan

Technical Infrastructures
Klaus Hanke

- **Integration** – Jean-Pierre Corso
- **Geodesy & survey** – Hélène Mainaud Durand
- **Electricity and energy management** – Jean-Paul Burnet
- **Cooling and ventilation** – Guillermo Peon
- **Cryogenics systems** – Laurent Delprat
- **Computing and controls infrastructure, communication and network** – Dirk Duellmann
- **Safety** – Thomas Otto
- **Operation, maintenance, availability, reliability** – Jesper Nielsen
- **Transport, installation concepts** – Cristiana Colloca

Host State processes and civil engineering
Timothy Watson

- **Administrative processes** – Friedemann Eder
- **Placement studies** – Johannes Gutleber, Volker Mertens
- **Environmental evaluation** – Johannes Gutleber
- **Tunnel, subsurface design** – John Osborne
- **Surface sites layout, access and building design**

Organisation and financing models
Paul Collier (interim)

- **Project organisation model**
- **Financing model** – Florian Sonnemann
- **Procurement strategy and rules**
- **In-kind contributions**
- **Operation model** – Paul Collier, Jorg Wenninger

from [1]

[1] https://indico.cern.ch/event/1066234/contributions/4594213/attachments/2385608/4077362/220207_FCC-FeasibilityStudyStatus.pdf

Graham Wilson, U. of Kansas

PhD

- 1989 Lancaster University, UK

Profile

- Experimentalist (CERN fixed-target, OPAL, D0, CMS)
- LEP experience on radiative neutrino counting, di-photons, WW cross-section and di-lepton+MET searches.
- Future e+e- collider focus mostly ILC using ILD detector concept
- Including work on center-of-mass energy determination for enabling W and Z EW program at ILC
- Interested in working on areas that advance our understanding of the realistic physics potential of high energy e+e- colliders.?

Other interests

- Hiking and golf

Co-Coordinator for Performance just started

Christoph Paus, MIT

PhD

- 1996 RWTH Aachen, Germany
- Experimentalist (L3)
- Z boson mass and electroweak parameters

Interests

- Electroweak (L3, CMS, FCC-ee)
- Higgs Boson Physics (CMS, FCC-ee)
- Dark Matter searches (CMS)
- B Physics (CDF, CMS)

Other interests

- Stars, machine learning, hockey (on Ice), family

Co-Coordinator for Performance
just started

Ayres Freitas, U. of Pittsburgh

PhD

- University of Hamburg, 2002
- slepton production at e+e- colliders

Interests

- SM electroweak precision physics
- Phenomenology of BSM searches using different probes (colliders, low-energy precision exp, astro/cosmo)

Other interests

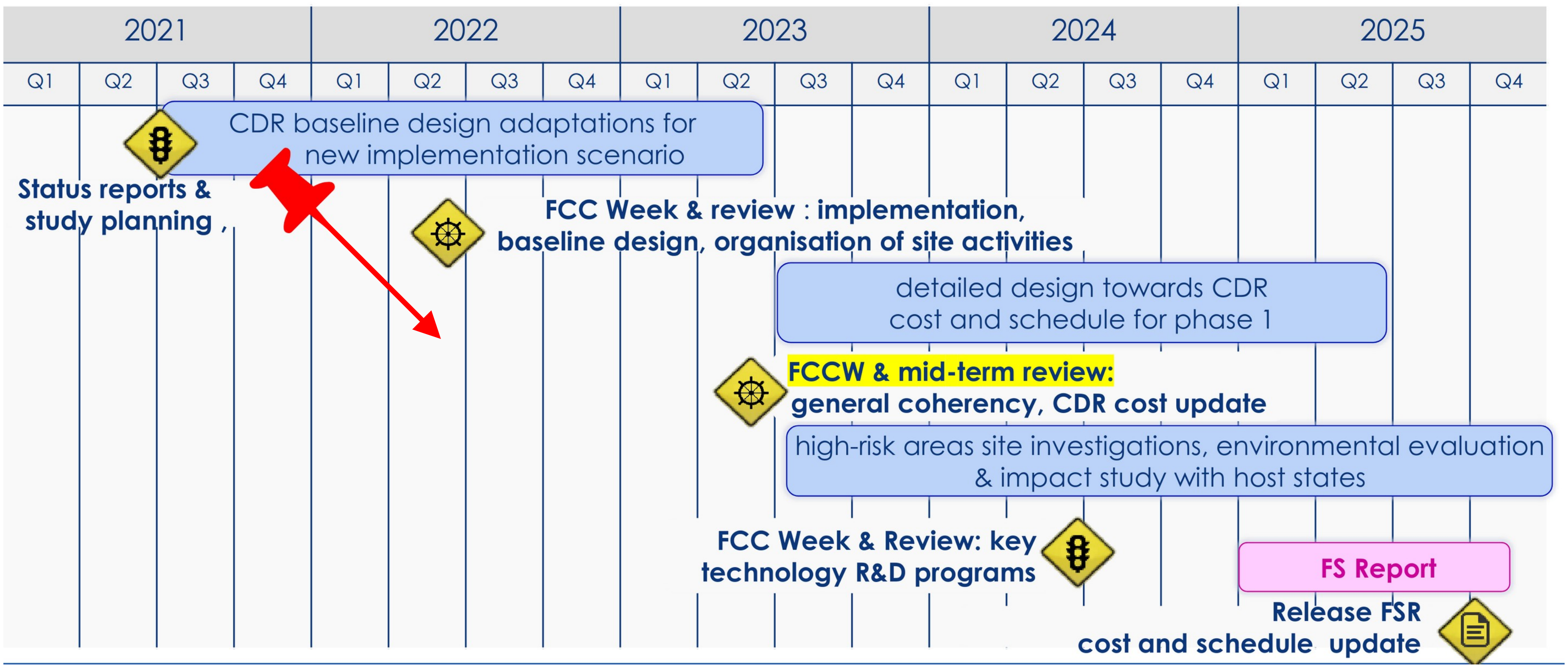
- Environmental sustainability, human rights, music, hiking, card/board games

Coordinator for Programme just started

Milestones

Timeline of the FCC-ee feasibility study [1]

- Deliver report by mid 2025
- Intermediate reports in summer 2023 and summer 2024



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EW Precision Recent History

LEP/SLD – golden age of electroweak precision

- W and Z bosons were discovered, but properties fairly vague
- Two crucial building blocks of the Standard Model unknown:
  → top quark and the Higgs boson
- The number of neutrino* families not much constrained

Main relevant goals at the time and the answers!

- Is their another light neutrino family? No (2.9840 ± 0.0082) [1]
- What is the mass of the top? → 162 ± 25 GeV [2]
  - This was right before the Tevatron found it
- What is the mass of the Higgs? → (114.4 <) m_H < 285 GeV [1]
  Heavily relied on the top quark mass measurement at the time
- How well do radiative corrections work? → very well
  - Nobel 1999: G. t'Hooft and M.Veltman
    "for elucidating the quantum structure of electroweak interactions in physics."

* Not talking about neutrino properties here.

EW Precision Our Goals

Electroweak precision measurements

- Standard Model is ‘complete’ there is no more *wiggle room*
- Constrain the phase space of the electroweak theory by performing more precise tests and providing more precise predictions
- Main goal is to find inconsistencies in the Standard Model and claim new physics

Best way to make precision measurements

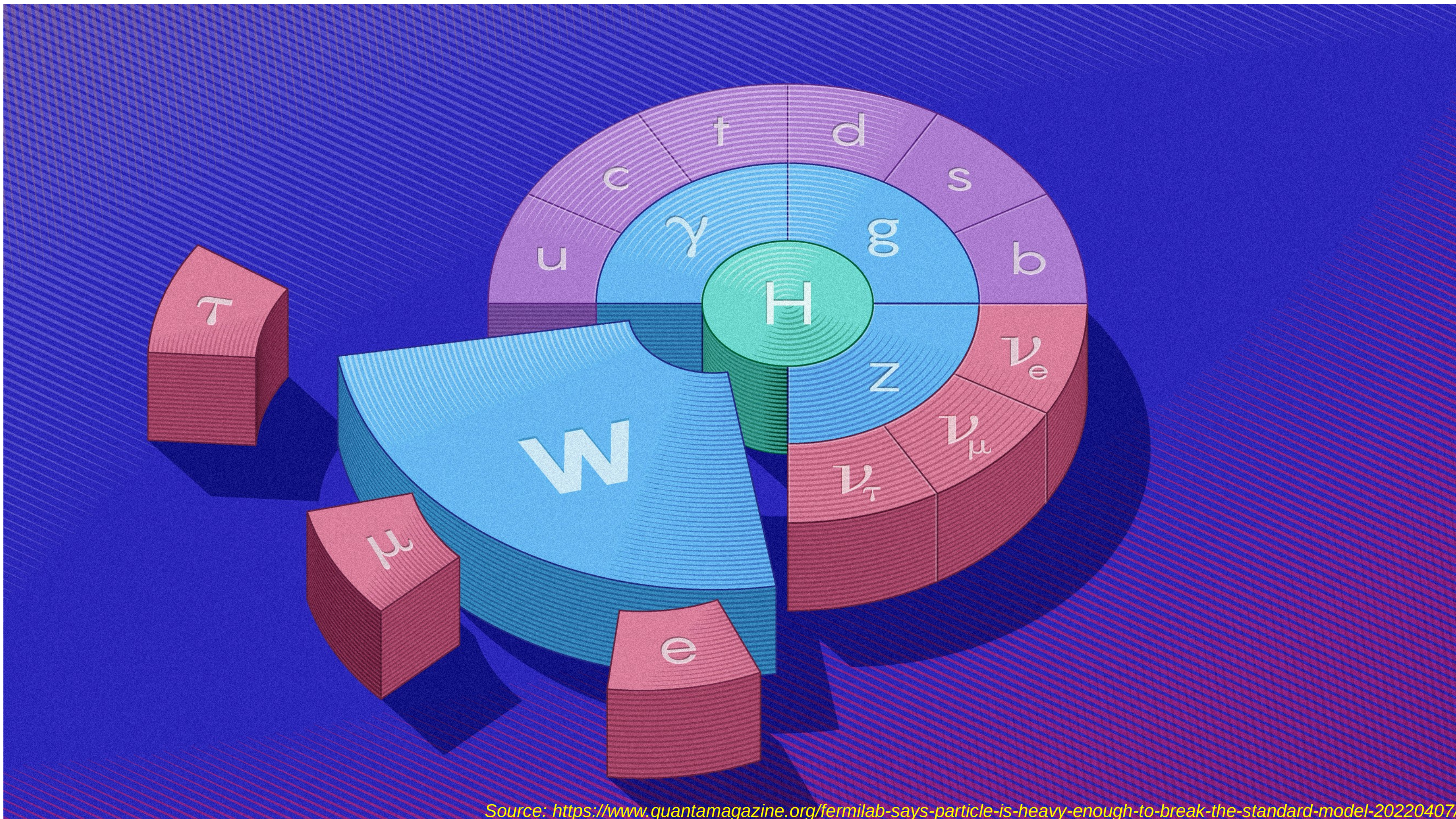
- Create cleanest possible environment
  - Precise theory predictions (avoid QCD & non-elementary particles)
  - Clean particle collisions: control initial state
  - Highest luminosity to reduce statistical uncertainties
- Lepton colliders
  - Electrons easy and abundant (muons difficult, later?; taus – no)
  - Last time we did this was at LEP 1 and 2 with e^+e^- collisions

FCC-ee is an obvious candidate!

W Mass Precision Measurement

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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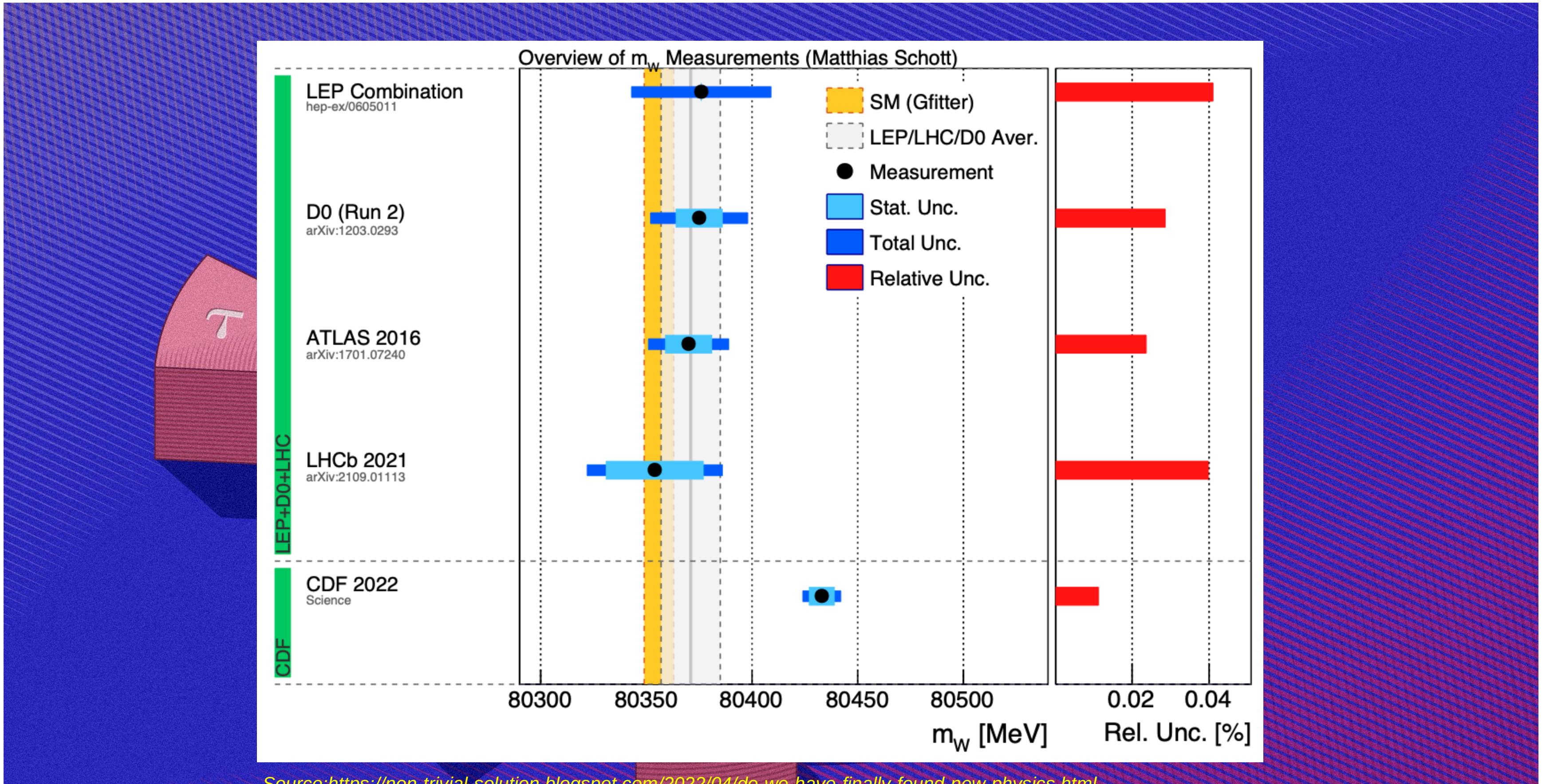


Source:https://non-trivial-solution.blogspot.com/2022/04/do-we-have-finally-found-new-physics.html

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

EW Precision – Join

In simple words

- Electroweak precision is an awesome tool, people have won the Nobel prize for it!
- Join the fun and learn about Electroweak Precision at FCC-ee

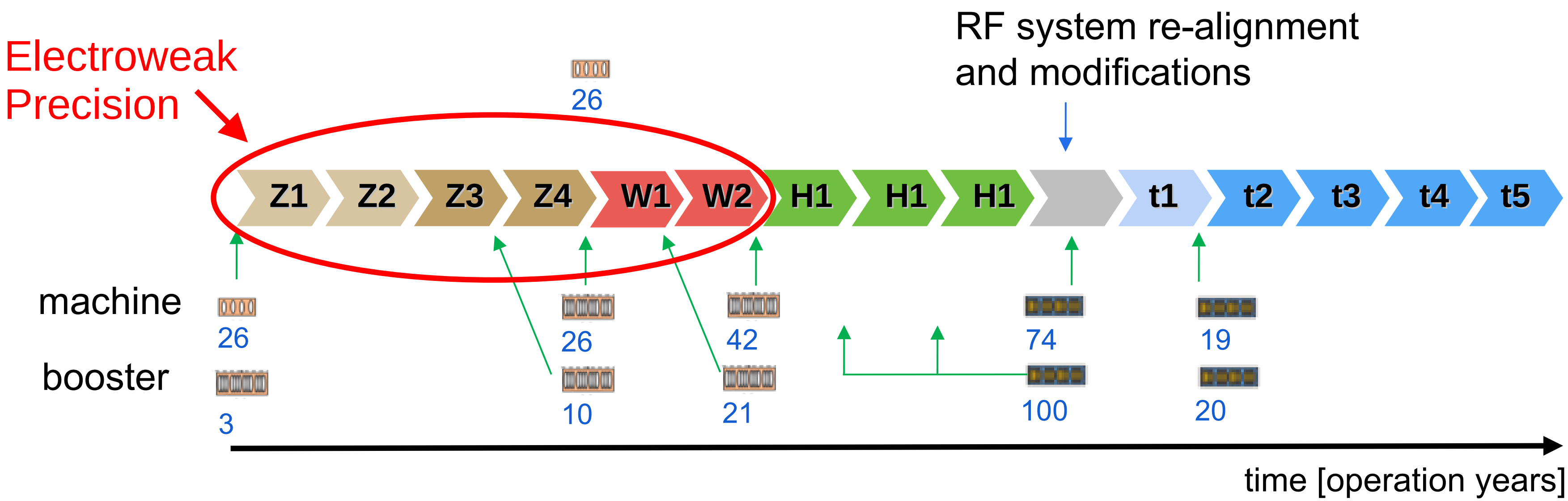
New conveners started

- Kickoff meeting was May 18, will meet June 15 next
- Follow egroup: *FCC-PED-PhysicsGroup-EWPrecision@cern.ch*
- Building on a lot of studies done already, of course

FCC-ee Run Plan

The default 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

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

FCC-ee Electroweak Precision

From the numbers

- Statistical uncertainties with respect to LEP reduce by close to 3 orders of magnitude
- FCC-ee will take about half a LEP dataset per minute of operation
  [$3*10^{12}$ / ($5*10^{6}$) / *(4yr * 200d * 24hr * 60min) ≈ 0.52min*]
- It is hard to believe that without a lot of work the experimental and theoretical uncertainties will be able to match statistical uncertainties
- It is important to determine the statistical uncertainties to see the limiting case
- Set a reasonable goal for the feasibility study to reach systematic uncertainties about a factor of 10 worse than statistical uncertainties.

Key Ingredients

Theory calculations [focus of Programme organization]

- LEP precision will improve by over close to 3 orders of magnitude
- Theory calculations need to ‘keep up’ → CERN workshop next weeks

Center-of-mass energy [focus of energy calib. Group]

- Key to mass measurements: 100 keV at Z / 300 keV at WW

Luminosity measurement

- Unprecedented precision will need special detector design and maybe/probably new methods

Detector Fiducial Volume and Efficiency

- Coverage, detector efficiency
- Precision and reproducibility in Monte Carlo simulations

Background processes

- Theory predictions and signal/background separation
- Ex. two photon production as one difficult example

Bench Mark Processes

Looking at LEP precision measurements [1] for

- Z mass and W mass
- Z width, peak cross section
- R_{lepton} = σ(Z→hadrons) / σ(Z→leptons),
- $\sin^2\theta_{w,eff}$
- Couplings: α_{QED} and α_s
- Tau polarization and exclusive branching ratios
- Lepton universality, lepton flavor violation
- Z pole observables with heavy flavor quarks

Those benchmarks will help us develop requirements for various parts of the detector and theory predictions.

[1] Electroweak reference manuals from LEP+:
Z – https://arxiv.org/abs/hep-ex/0509008
W – https://lepewwg.web.cern.ch/LEPEWWG/2/lep2rep.pdf

Key Ingredients: Cross Sections

Center-of-mass energy

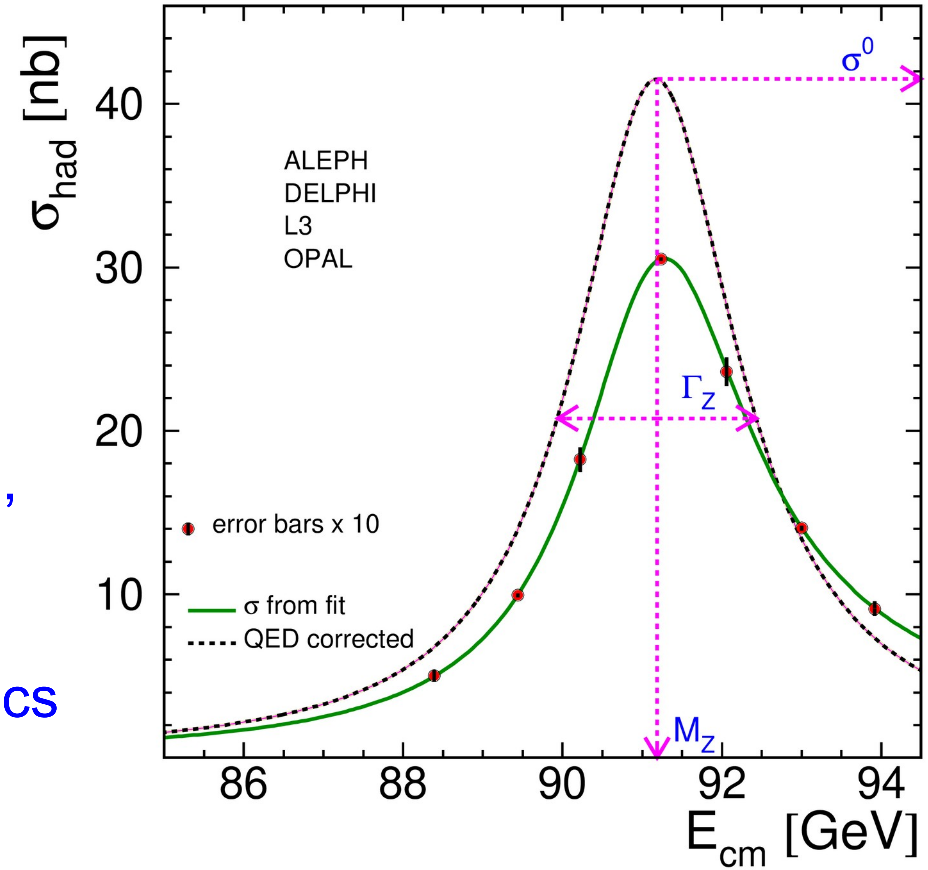
- Absolute uncertainty drives mass uncertainty

Luminosity

- Drives σ^0 uncertainty
- $\Delta_{exp:}$ 0(10^{-4}) small angle Bhabha, strict geometry req.: O(μm)
- Use large angle two photon events to beat theory systematics

Cross sections

- Δ_{stat}: 0(10^{-6}), Δ_{exp}: 0(10^{-5})
- Measure total cross section, Z mass, total and partial widths (R_l)



As usual

- More data allows for more accurate study of systematics

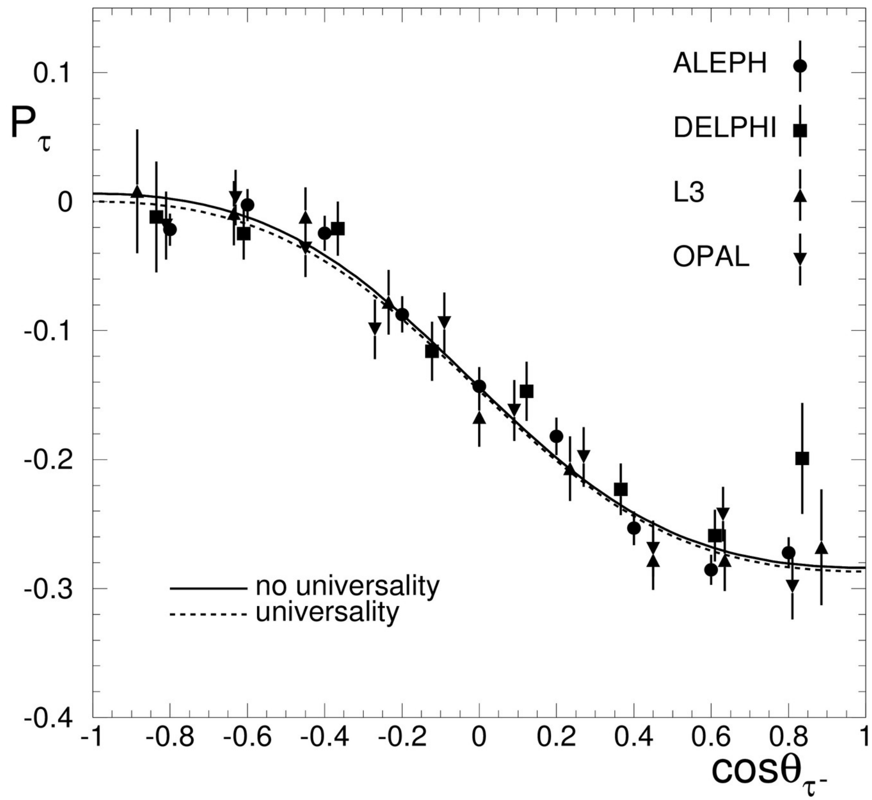
Key Ingredients: Tau Polarization

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



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

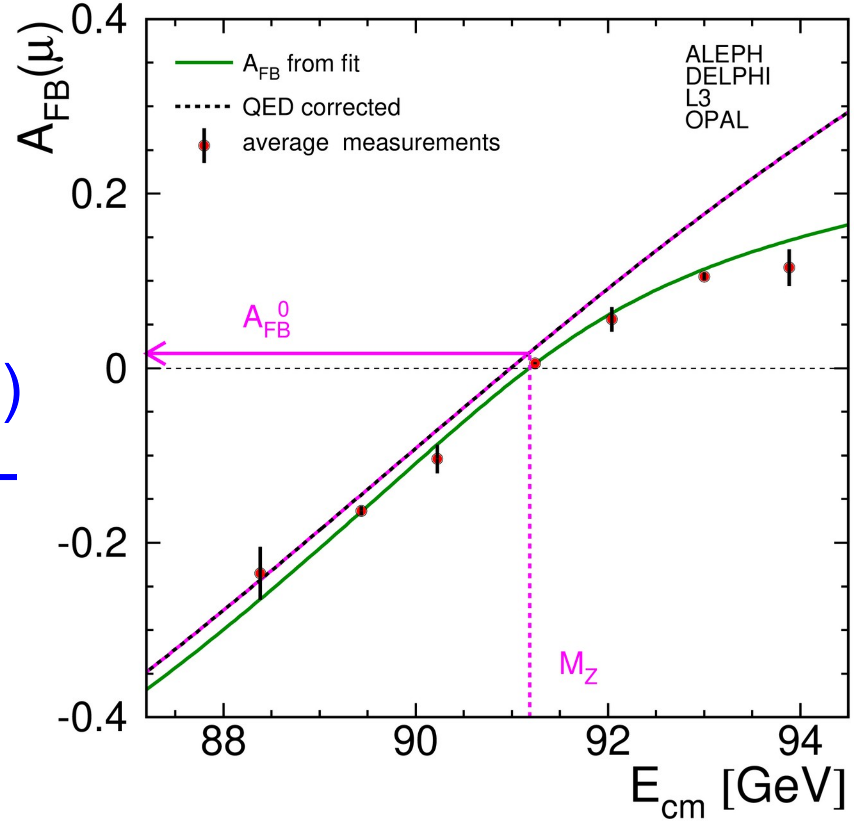
$$A_{FB} = \frac{3}{4} A_e A_f$$

Key Ingredients: A_{FB}

Forward Backward Asymmetry

$$A_{\mathrm{FB}} = \frac{N_{\mathrm{F}} - N_{\mathrm{B}}}{N_{\mathrm{F}} + N_{\mathrm{B}}}$$

- Best A_μ (no lepton universality)
- Main uncertainty from point-to-point beam energy uncertainties and acceptance
- A_e from tau polarization



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

Heavy flavor measurements

Tagging heavy flavors

- FCC-ee detectors will be more sophisticated than LEP silicon detectors as we learned a lot from Tevatron/LHC
  - Mass budget, pixels, number of layers
- Major upgrades of tagging techniques relying on more sophisticated variables and NN techniques
- Better understanding of the theory in jet formation and correlations
- Control samples are enormous and will help improve our understanding (ex. inclusive versus exclusive)

Measurements

- R_b and R_c
- $A_{FB}(b,c) \rightarrow A_b$ and A_c
- Expected experimental uncertainties far from statistical limitations

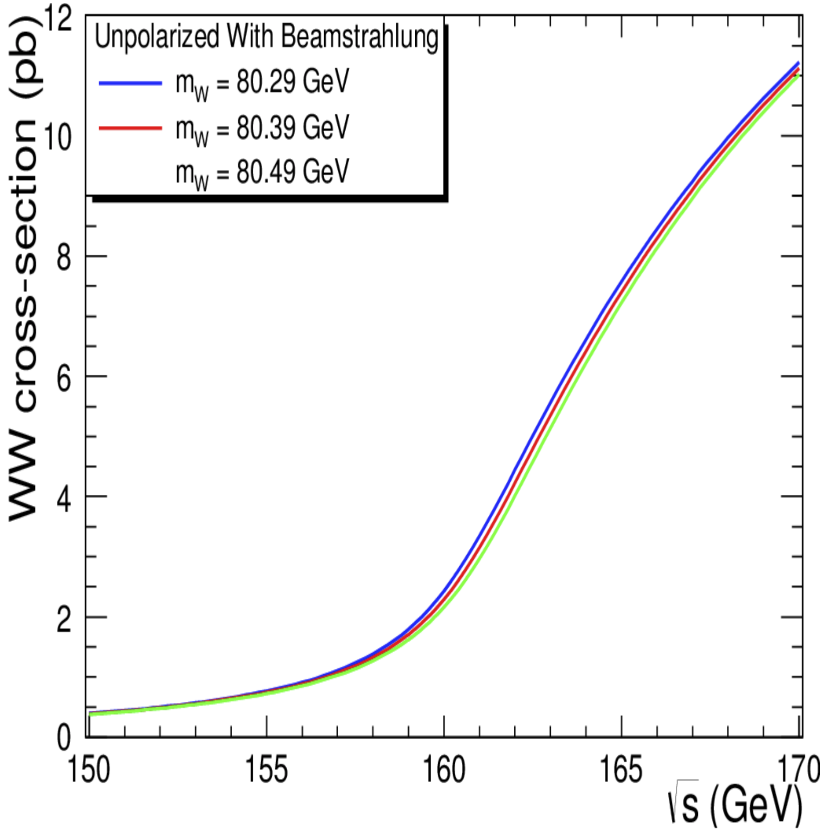
The W Mass

Hot topic right now

- CDF has a number far from the expectations
- LHC and HL-LHC will push and might get to 5 MeV ?

Measurements

- Threshold scan
  - Main limitation is the beam energy calibration: 300 keV (expecting update)
- Direct reconstruction (not in default plan)
  - Has large potential using dimuon absolute calibration



Quick run down of latest numbers

Estimates of uncertainties

Quantity	Total	Statistical	Experimental
ΔmZ[MeV]	0.1	0.004	0.1
ΔΓZ [MeV]	0.025	0.004	0.025
Δσhad [nb]	3.5	0.000035	0.0049
δRe	0.0003	3.61E-06	1E-05
δRμ	5E-05	2.58E-06	1E-05
δRτ	0.0001	3.10E-06	1E-05

Lineshape

- All measurements are systematic limited…
- Mass and width are essential

Estimates of uncertainties

Quantity	**Total**	**Statistical**	**Experimental**
ΔAe	1.7E-05	7.00E-06	2.00E-05
ΔAμ	2.3E-05	2.31E-05	2.20E-05
ΔAτ (Tpol)	4.5E-05	5.00E-06	2.00E-04
ΔAτ (AFB)		1.00E-05	1.30E-04
Δsin2Theta_lept	--	1.40E-06	1.40E-06

Couplingd / Left-Right asymmetries

- Most limited in terms of systematics is tau polarization

Estimates of uncertainties

Quantity	Total	Statistical	Experimental
ΔAb	0.0028	2.38E-05	0.00129
ΔAc	0.0053	2.00E-04	0.0053
δRb	<0.0003	1.39E-06	<0.0003
δRc	0.0015	1.50E-04	<0.0015

Heavy flavors and beyond

- Systematics is very limited and lots of new techniques and sideas available, statistically very powerful
- How about ‘strange’?

Estimates of uncertainties

Quantity	Total	Statistical	Experimental
ΔmW [MeV]	0.4	0.25	0.3
ΔΓW [MeV]	1.2	1.2	0.3
ΔmH [MeV]	11 ?	2.5	2

Statistically matched with experimental uncertainties

- Can we go beyond this?
- How about using the reconstructed mass?
- W mass is presently a hot topic!

Conclusion

FCC-ee – Electroweak Precision

- About a million times LEP for precision Z, W measurements
- A quantum leap into a new era, unprecedented precision tests of the Standard Model: *about one LEP per minute*

Precision is a driver

- The design of the FCC-ee detectors will have most stringent constraints from electroweak precision measurements
- Theory calculations need to match precision that can be accomplished by experiments

Great time to join

- A lot of good work done, but much more work is needed!
- Delphes simulation can only achieve so much
- Join us and help drive detector design and theory calculations

Thanks to

Patrick Janot, Graham Wilson, Ayres Freitas, Juan Alcaraz, Alain Blondel, Emmanuel Perez, Patricia Azzi, Roberto Tenchini …

Helping me to get started and provide material and advice.

More slides

Some Upcoming Events

Workshops

- 05/30 – 06/03, 2022: FCC week in Paris
- 06/07-17, 2022 CERN workshop "Precision calculations for future e+e-colliders: targets and tools"
  - Week 1: select key physics questions and observables
  - Week 2: status and advancements in multi-loop calculations required to match the precision goals

Talks

- ICHEP 2022, Bologna, July 6-13, https://www.ichep2022.it/, "EWK precision measurements at FCC-ee"
- IPA 2022, Vienna, Sept. 5-9. https://indico.cern.ch/event/837621/, Talk: The FCC-ee Project, plans & physics potential
- SUSY 2022, Univ. Ioannina (GR), June: https://indico.cern.ch/event/1083758/, Potential talk: SUSY at FCC-ee
- Flavour-2022, Quy Nhon, Aug. 2022: https://indico.in2p3.fr/event/20329/, Potential talk: Flavour at FCC-ee
- Top-2022, Durham, Sept 2022: https://conference.ippp.dur.ac.uk/event/925/, Potential talk: Top physics at FCC-ee
- NuFact meeting, July-Aug. 2022: https://indico.fnal.gov/event/53004/, Potential talk: HNL at FCC-ee
- PSI2022, October: http://www.psi.ch/psi2022, Potential talks: Precision tau physics, rare Z and/or Higgs decays
- Higgs 2022, Pisa, Nov. 2022, Potential talks: Higgs physics at FCC-ee/FCC-hh

Existing studies

The entire conceptual design report has plenty of relevant studies: Alain will introduce them to us next...

We would like to collect existing studies and more importantly the people and integrate them here and provide constructive environment to progress towards the feasibility report!

Tools we have

Theory programs…

- Need thorough re-evaluation of uncertainties to match up experimental precision

Monte Carlo Simulation

- The majority is Delphes only detector simulation
- Decent number of samples for studies available

Detailed detector description

- Full simulation needs to be developed and become more common in the next 1-2 years
- Delphes studies could help identifying areas where detailed simulations are essential and others where Delphes simulations are enough for now

How to proceed?

We need to create a community and therefore we need people

- Experts, analyzers, aficionados and listeners from both sides of the aisle: experimentalists and theorists

We need a forum where we can discuss and get ourselves organized

- Let's meet regularly: *once a week, or once in two weeks, or maybe once a months?*
- Initially we need to collect people, information, ideas and make a plan: *please send your interestes and work done already*
- … then we need to work :-)

We need to provide a work setup with documentation