Electroweak Precision Measurements at FCC-ee

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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."
- Precision results on Z and W bosons

* Not talking about neutrino properties here.

Today's Goals of EW Precision

Electroweak precision measurements

- Standard Model is 'complete': there is no more *wiggle room*
- Constrain phase space of 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

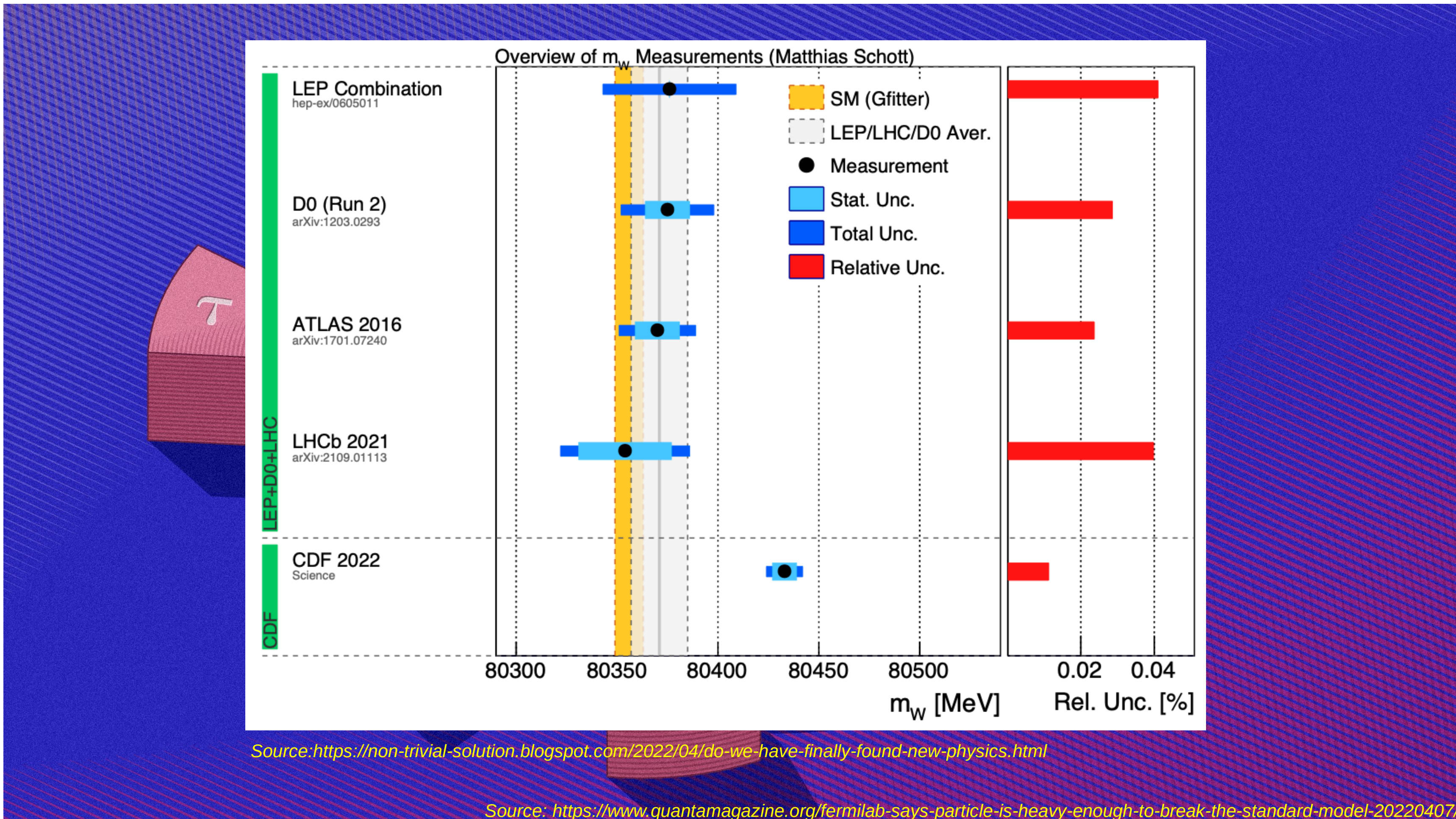
- Create cleanest possible environment
  - Precise theory predictions (avoid QCD & non-elementary particles)
  - Clean particle collisions: control initial state
  - Highest luminosity to reduce statistical uncertainties
- Lepton colliders
  - Electrons easy and abundant (muons – difficult, later?; taus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

FCC-ee is an obvious candidate!

Recent Example - W Mass

CDF experiments last word

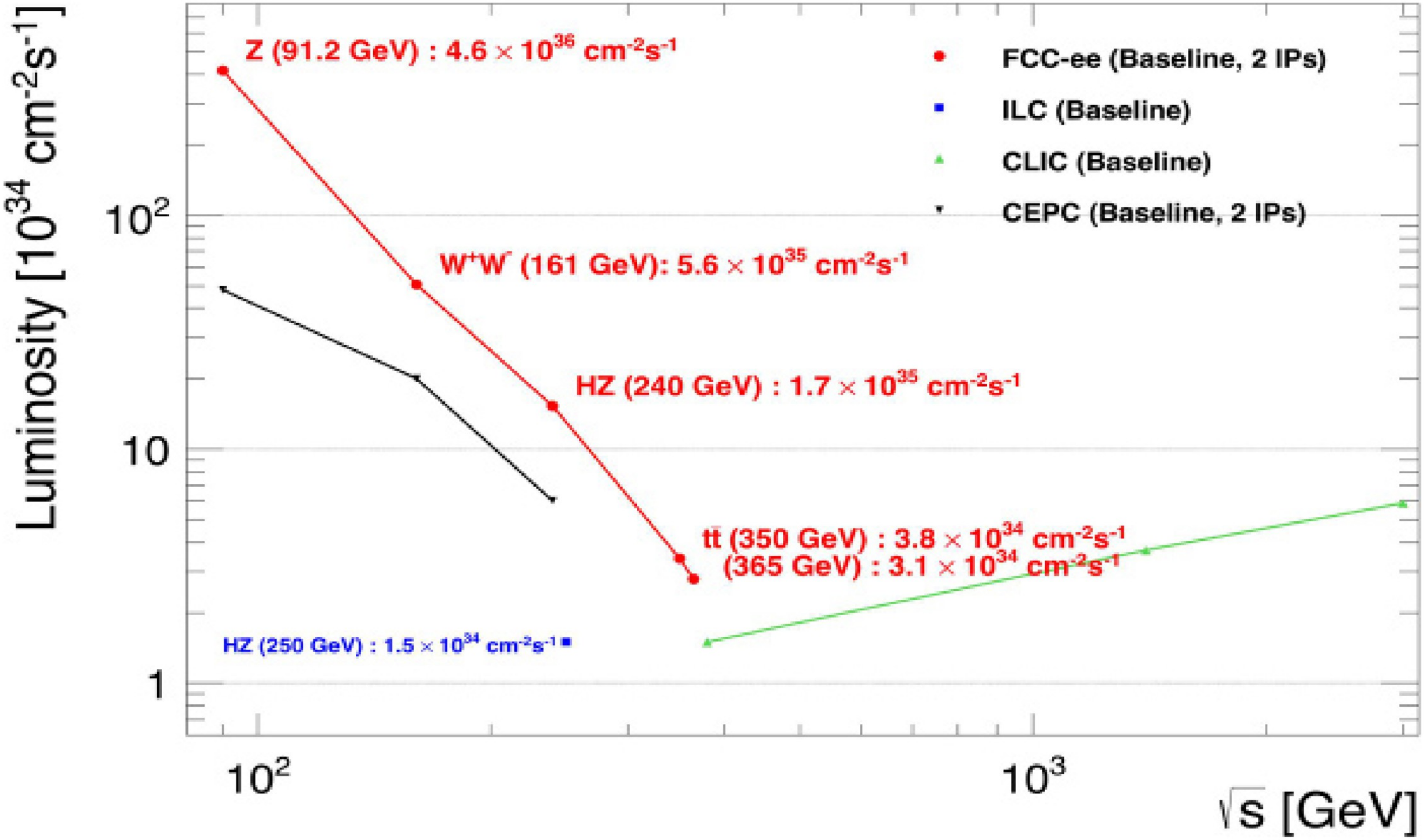
- W mass too heavy by seven standard deviations !



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/

Electron-Positron Colliders



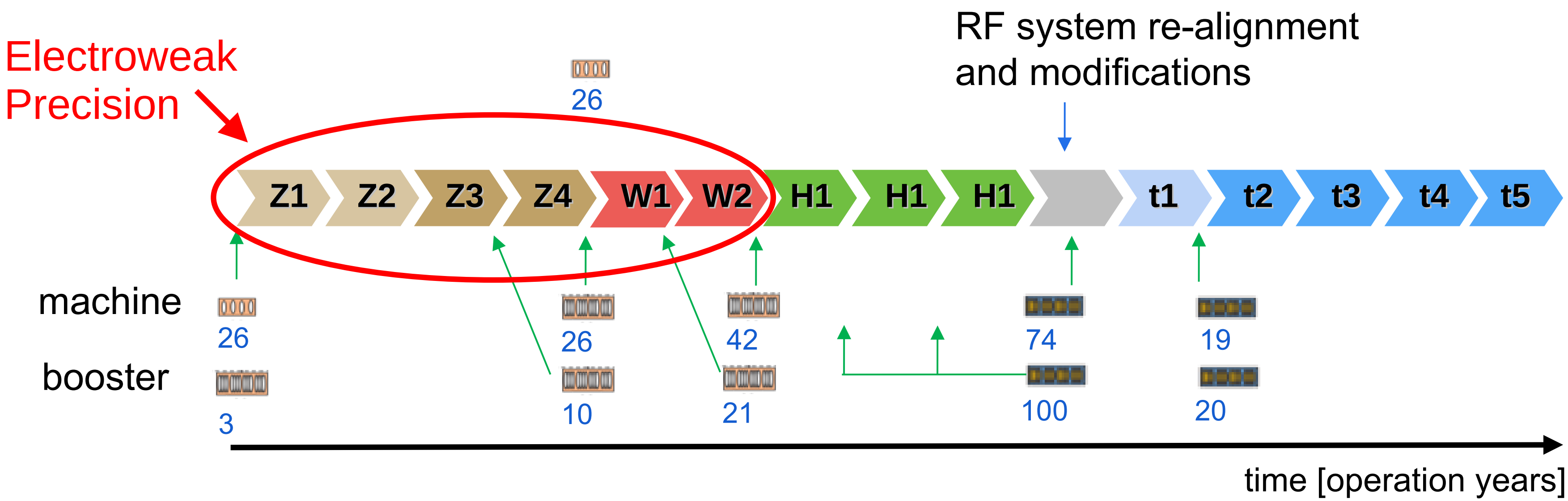
Take away

- Highest luminosity in EW precision region: Z, WW, HZ, and tt area by a lot
- High center of energies do not work due to circular → synchroton radiation

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

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

FCC-ee Electroweak Precision

From the numbers

- FCC-ee will take about half a LEP dataset per minute of operation
  [$3*10^{12}$ / $5*10^{6}$ / *(4yr * 200d * 24hr * 60min) ≈ 0.5 LEPs/min*]

N(FCCee) N(LEP) (Total recording time)

Important conclusions

- Statistical uncertainties improve with respect to LEP by close to 3 orders of magnitude (500)
- A lot of work for experimental and theoretical uncertainties to match statistical precision
- Starting point: determine statistical uncertainties for best case
- Feasibility study of electroweak precision will have to push hard in all directions, and will have most stringent detector requirements

Key Ingredients: Cross Sections

Center-of-mass energy

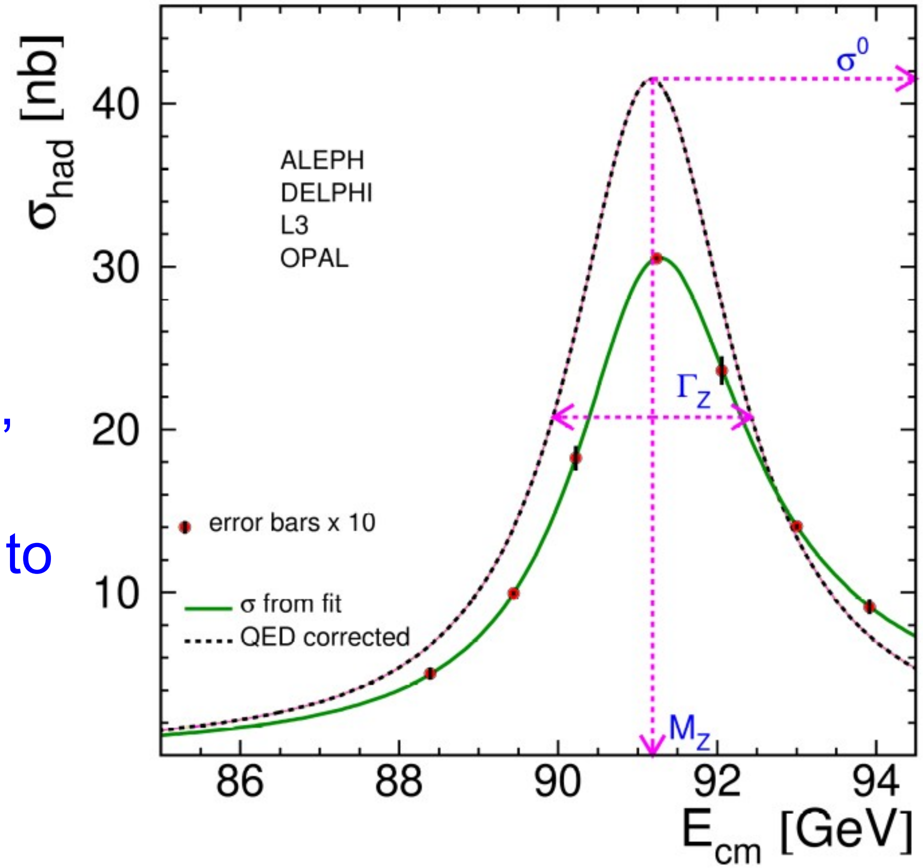
- Drives mass uncertainty

Luminosity

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

Cross sections

- Δ_{stat}: $0(10^{-6})$, Δ_{exp}: $0(10^{-5})$
- total cross section, Z mass, total and partial widths (R_l)
- More data allows for more accurate study of systematics



$$\sigma = \frac{N_{\rm sel} - N_{\rm bg}}{A\varepsilon\mathcal{L}}$$

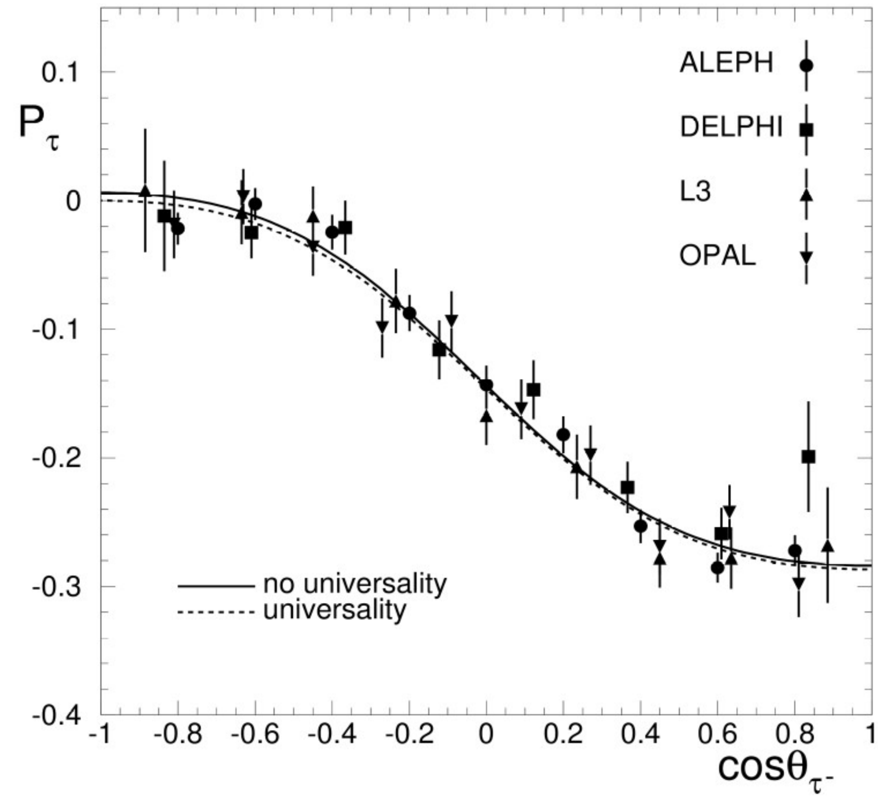
Key Ingredients: Tau Polarization

Tau polarization

- Disentangles asymmetries A_e (scale) and A_τ (slope)
- 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



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

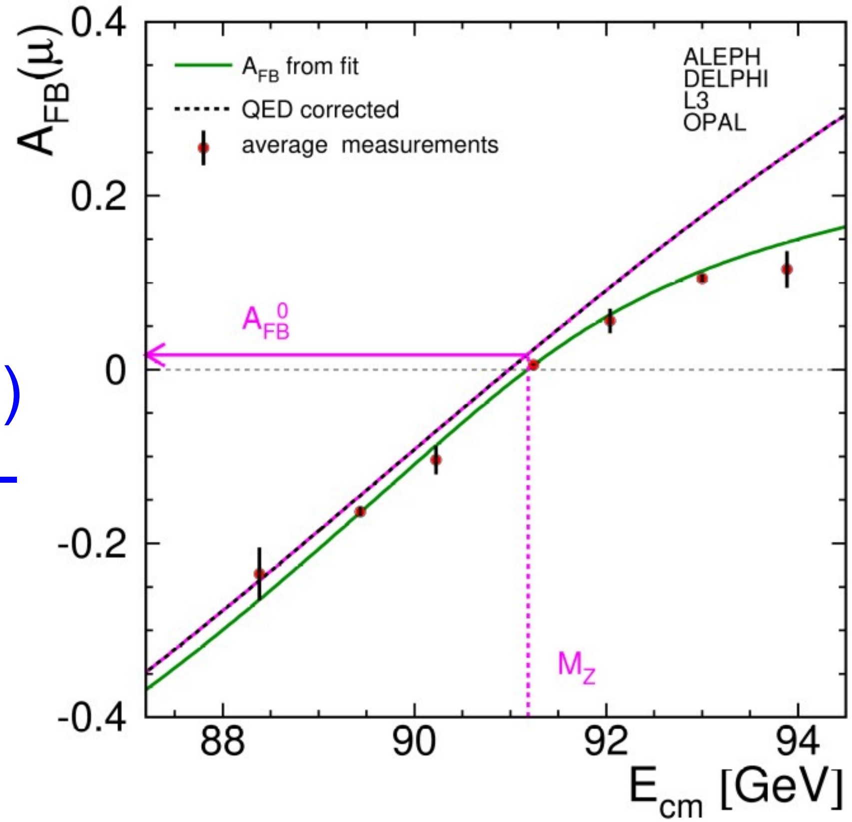
$$A_{\mathrm{FB}} = \frac{3}{4} A_{\mathrm{e}} A_f$$

Key Ingredients: A_{FB}

Forward Backward Asymmetry

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

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



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

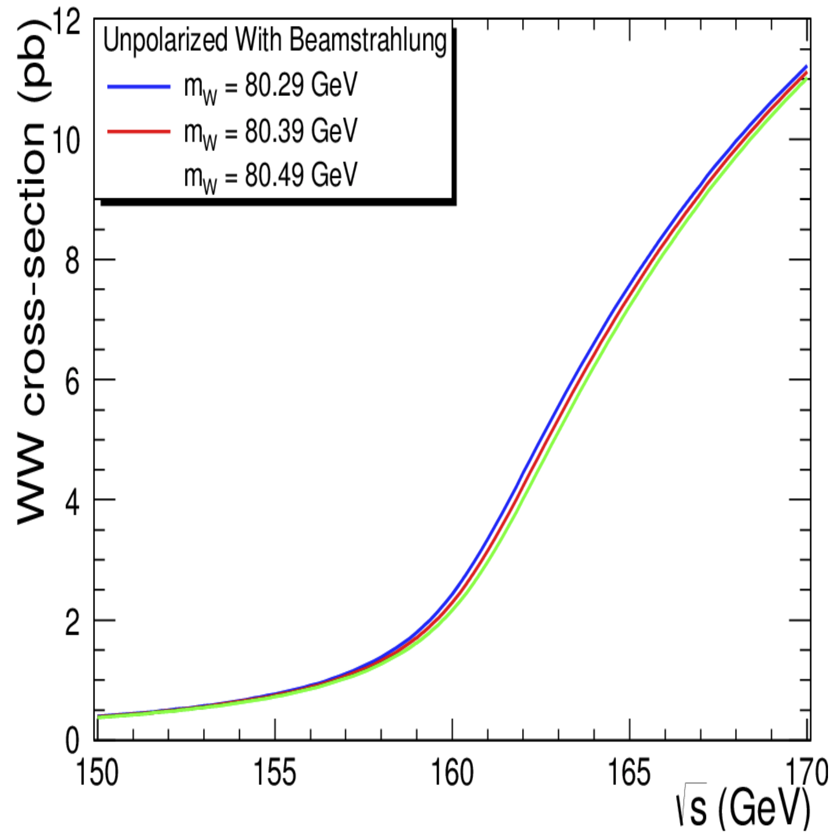
The W Mass at FCC-ee

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
  - Beam energy calibration contributed 300 keV to uncertainty: recent improvement reduced it to 100 keV
  - The main uncertainty is now statistical with 250 keV, but some background needs to be studied (another 100 keV?)
- Direct reconstruction
  - LEP did a competitive analysis
  - Present baseline run scenario will contribute to the W mass



Quick run down of latest numbers

please, take all of them with a grain of salt

Estimates of uncertainties

Quantity	Total	Statistical	Experimental
ΔmZ[MeV]	0.1	0.004	0.1*
$\Delta \Gamma Z$ [MeV]	0.025	0.004	0.025*
$\Delta \sigma had$ [nb]	4.9E-3	3.5E-5	4.9E-3
δRe	1E-5	3.61E-6	1E-5
$\delta R\mu$	1E-5	2.58E-6	1E-5
$\delta R\tau$	1E-5	3.10E-6	1E-5

Lineshape

- All measurements are systematic limited… for now

* Better beam energy calibration are in the works.

Estimates of uncertainties

Quantity	Total	Statistical	Experimental
ΔAe	2.0E-5	7.0E-6	2.0E-5
ΔAμ	3.2E-5	2.3E-5	2.2E-5
ΔAτ (Tpol)	2.0E-4	5.0E-6	2.0E-4
ΔAτ (AFB)	1.3E-4	1.0E-5	1.3E-4
Δsin2Theta_lept	2.0E-6	1.4E-6	1.4E-6

Couplings / Left-Right asymmetries

- Most limited in terms of systematics is tau polarization

Estimates of uncertainties

Quantity	Total	Statistical	Experimental
ΔAb	0.0028	2.4E-5	1.3E-3
ΔAc	0.0053	2.0E-4	5.3E-3
δRb	<3.0E-4	1.4E-6	<3.0E-4
δRc	<1.5E-3	1.5E-4	<1.5E-3

Heavy flavours and beyond

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

Estimates of uncertainties

Quantity	Total	Statistical	Experimental
ΔmW [MeV]	0.27	0.25	0.1*
ΔΓW [MeV]	1.2	1.2	0.3
ΔmH [MeV]	9.8	6.7	7.1

Statistically matched with experimental uncertainties

- Can we go beyond this because Z mass is more precise?
- How about using the reconstructed mass? More events?
- W mass is presently a hot topic!

* only beam energy, background is probably another 0.1 MeV

Join Electroweak Precision

In simple words

- Electroweak precision is an awesome tool, people have won the Nobel prize for it!
- Make an important contribution, learn about Electroweak Precision

New conveners started

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

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*

Electroweak precision physics 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!
- 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, Jan Eysermans …

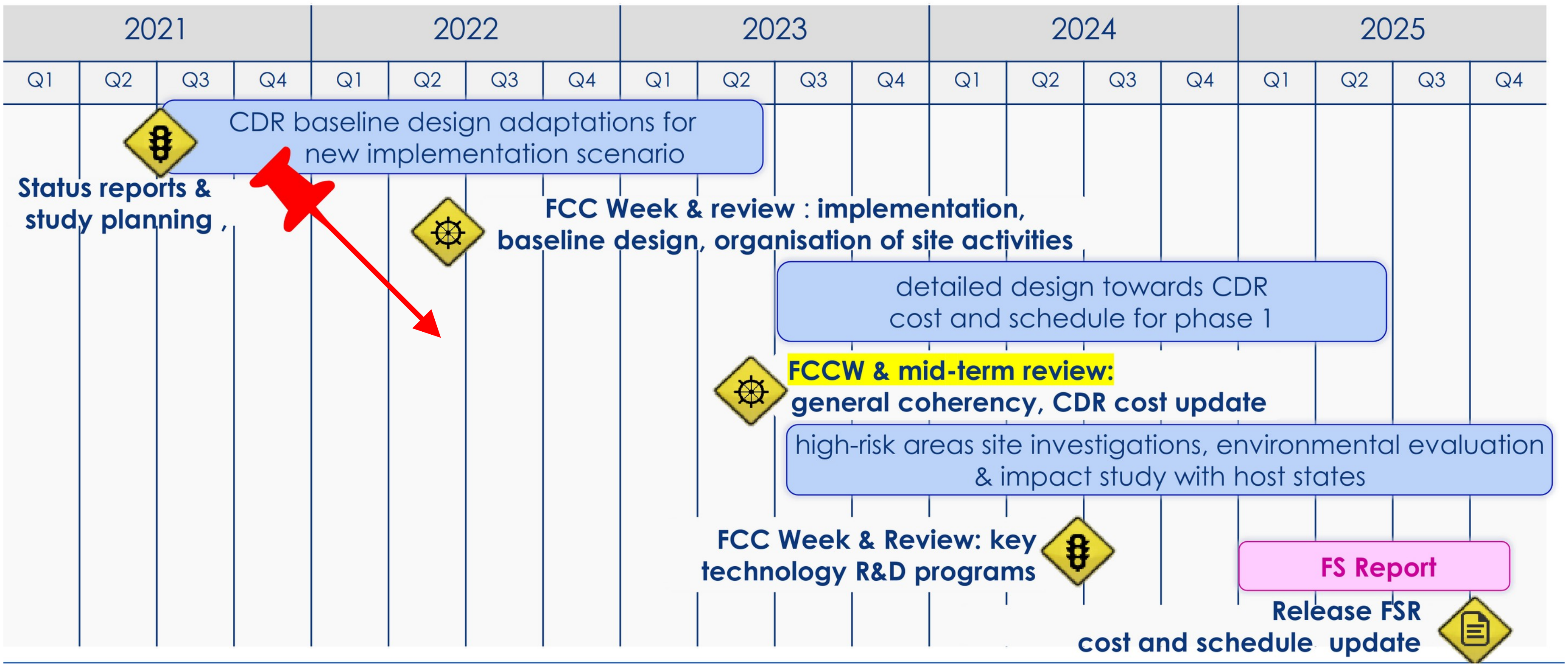
Helping me to get started and provide material and advice.

Extras

Milestones

Timeline of the FCC-ee feasibility study [1]

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



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

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

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

Heavy flavor measurements

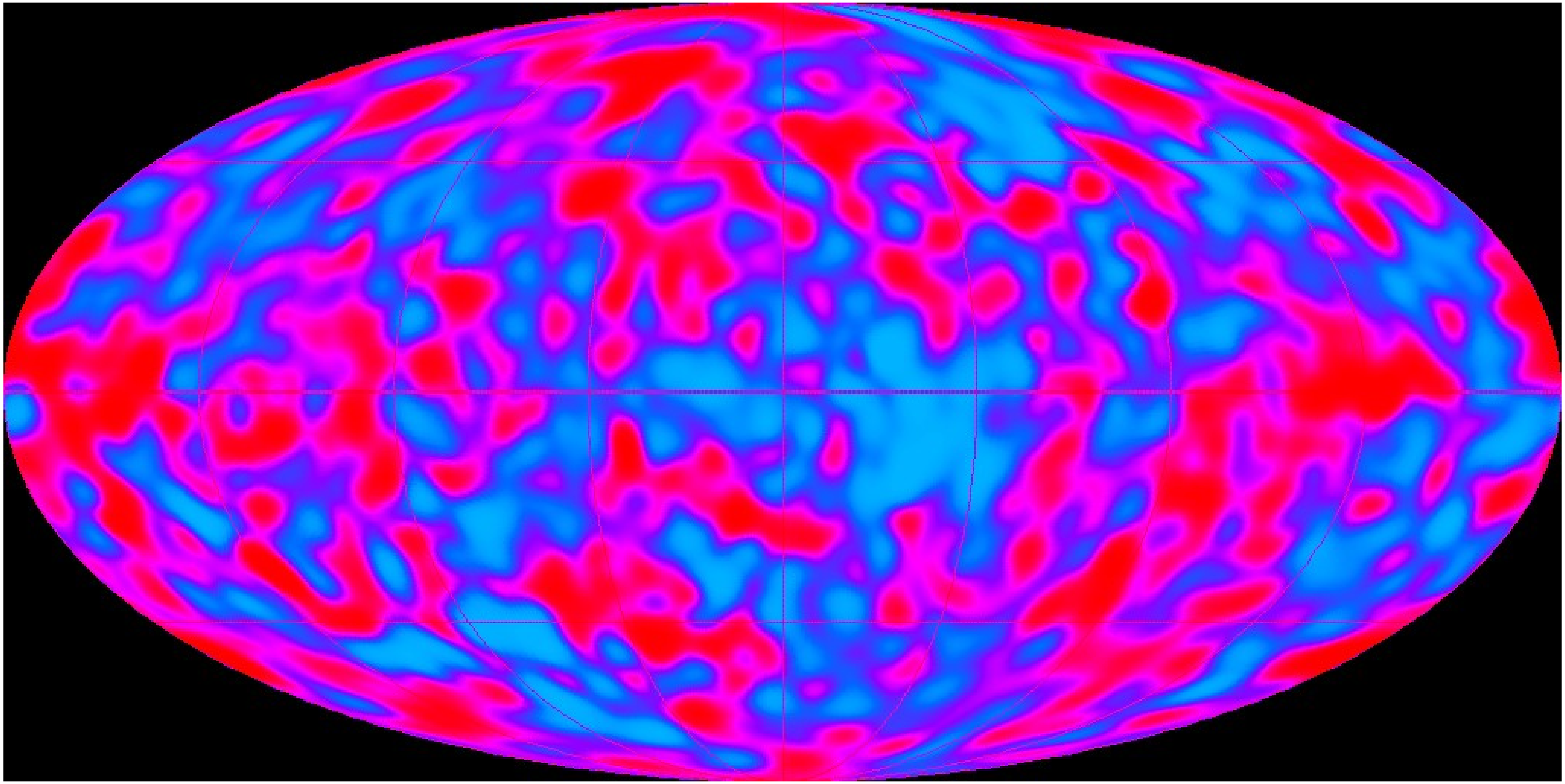
Tagging heavy flavors

- 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

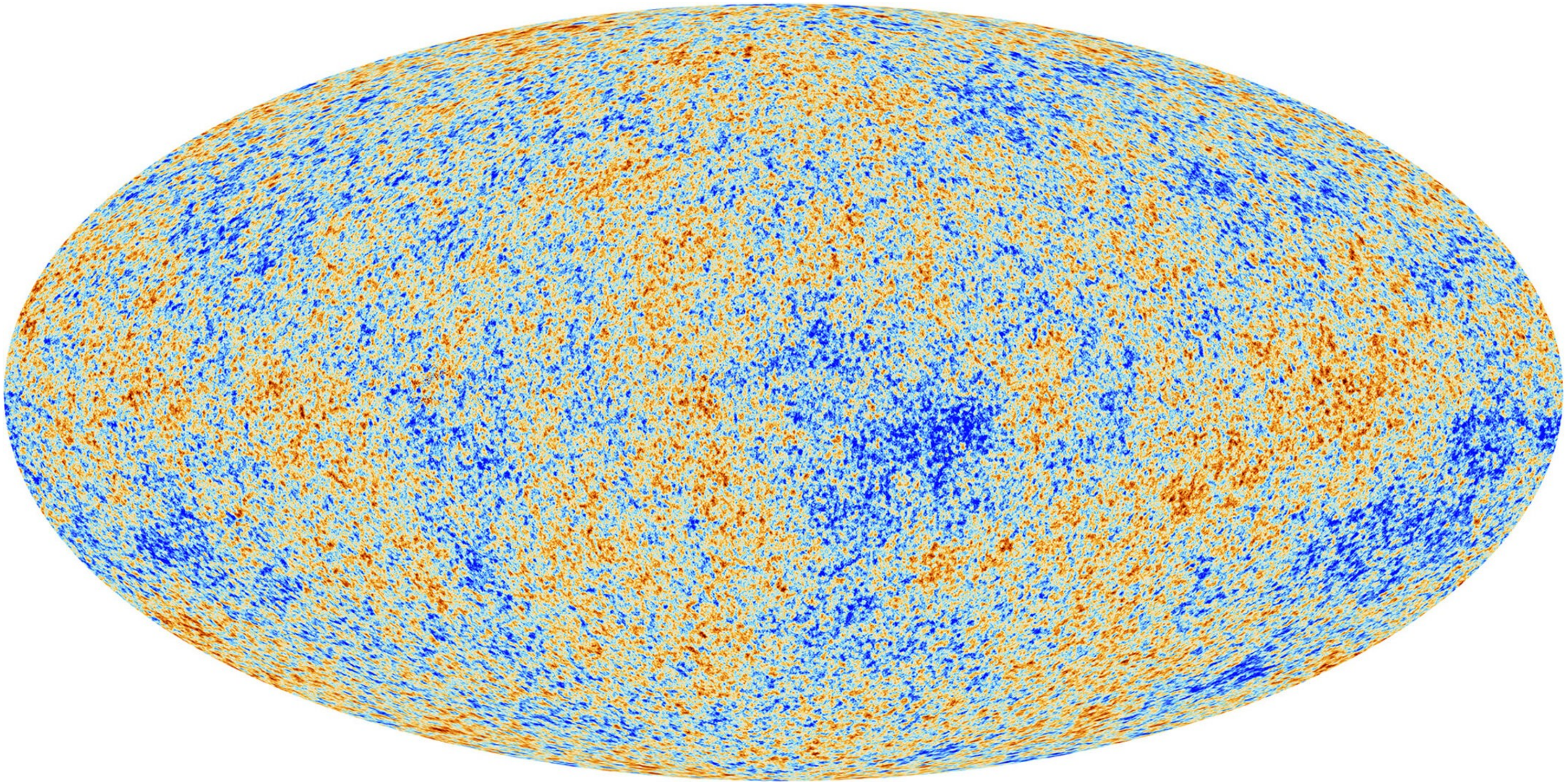
- R_b and R_c
- $A_{FB}(b,c) \rightarrow A_b$ and A_c
- Expected experimental uncertainties far from statistical limitations

Compare CMB studies



COBE 1990 - 1992

Compare CMB studies



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