BEYOND STANDARD MODEL / BSM

Faith and Fate of the Standard Model: A look at the future for Particle Physics

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LPC-IN2P3/CNRS/UCA

Programme co-funded by the European Union

Exergue for this lecture - Nietzsche.

Impregnare il passato e portare avanti il futuro,
tale è il mio presente ...

Féconder le passé et enfanter l'avenir, que tel soit
mon présent.

Zapłodnić przeszłość i zrodzić przyszłość, niech
to będzie moja teraźniejszość.

Запліднювати минуле і народжувати майбутнє
- нехай це буде моїм сьогоденням.

Die Vergangenheit befruchten und die Zukunft
zeugen - das sei mir Gegenwart!

Outline of the lecture

- PART I:
  - Scientific context I: what we think we know.
  - Scientific context II: how do we know what we think we know?

- PART II: Let there be light ! Flashing some anticipations (on a subjective basis) about the experiments / projects which could / will shed light on the Beyond SM.

- PART III: Introduction to the future projects and focus on Circular Colliders project or a long term vision for the Particle Physics. The fundamental scalar of the Nature and the electroweak thresholds.

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Scientific context: SM became a theory

The free parameters of the SM:

- $SU(2)_L \otimes U(1)_Y$ unification:
  - the weak and electromagnetic coupling constants G_F / g_W and α_{EM}.
- After the spontaneous breaking of the symmetry:
  - The nine masses of the fermions: m_f .
  - The masses of the electroweak gauge bosons: m_Z and m_W.
  - The scalar sector parameters: $$V(\phi) = \mu^2\phi^\dagger\phi + \lambda(\phi^\dagger\phi)^2$$

    v (the v.e.v) and m_H .

Scientific context: SM became a theory

The free parameters of the SM

- The CKM matrix elements : it's a 3X3 complex and unitary matrix and hence can be described by means of only **4 independent parameters**. As the masses of the fermions (except for the top quark), these 4 parameters are decoupled from the rest of the theory. A consistency test of these parameters is in order.

- If you like QCD in (and you do), just add $\alpha_{\mathbf{s}}$ (and $\theta^{S}{}_{CP}$).

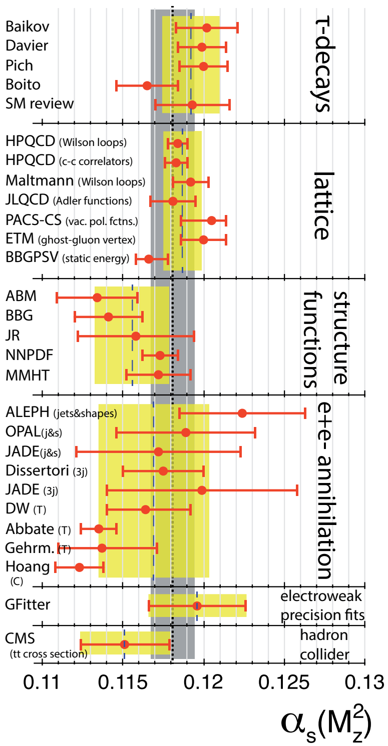
- Neutrino oscillations are implying neutrinos to be massive and to mix $\rightarrow$ 7 parameters to minimally describe them.

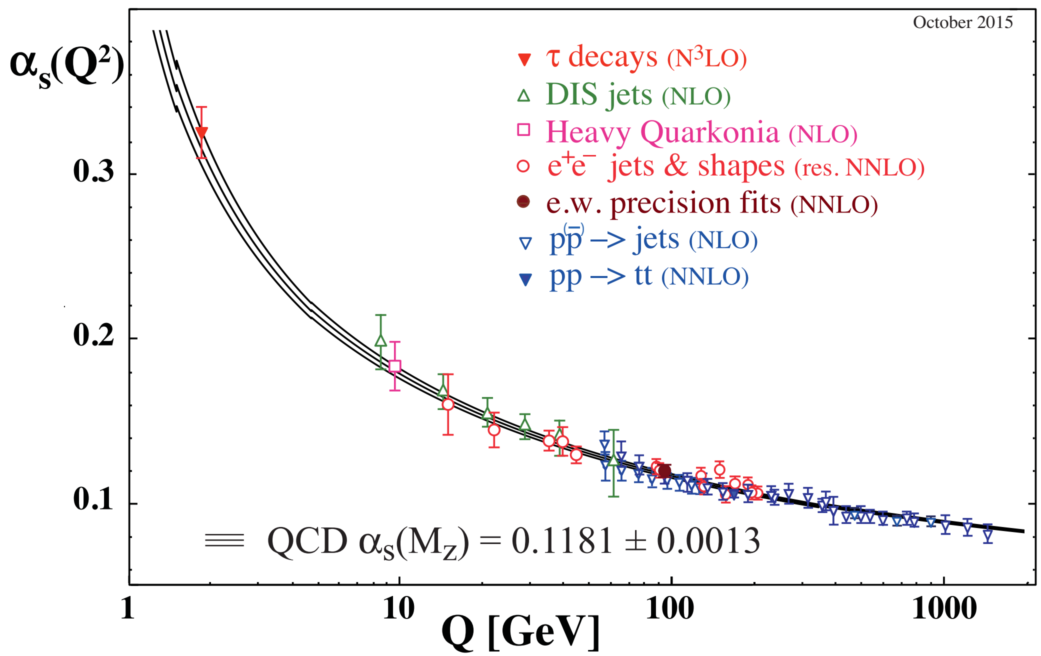
- The number of parameters amounts to 20 (28 w/ neutrinos and strong *CP*). Not all of them are independent though.

Scientific context: SM became a theory

Reorganisation:

- QCD and α_s : LEP and others did great already. Limitation of the consistency test is not yet fully on the theory side for most of the determinations.

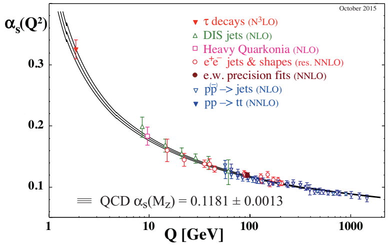




Scientific context: SM became a theory

Reorganisation:

- QCD and α_s / exercise: how to measure α_s from e^+e^- collisions?



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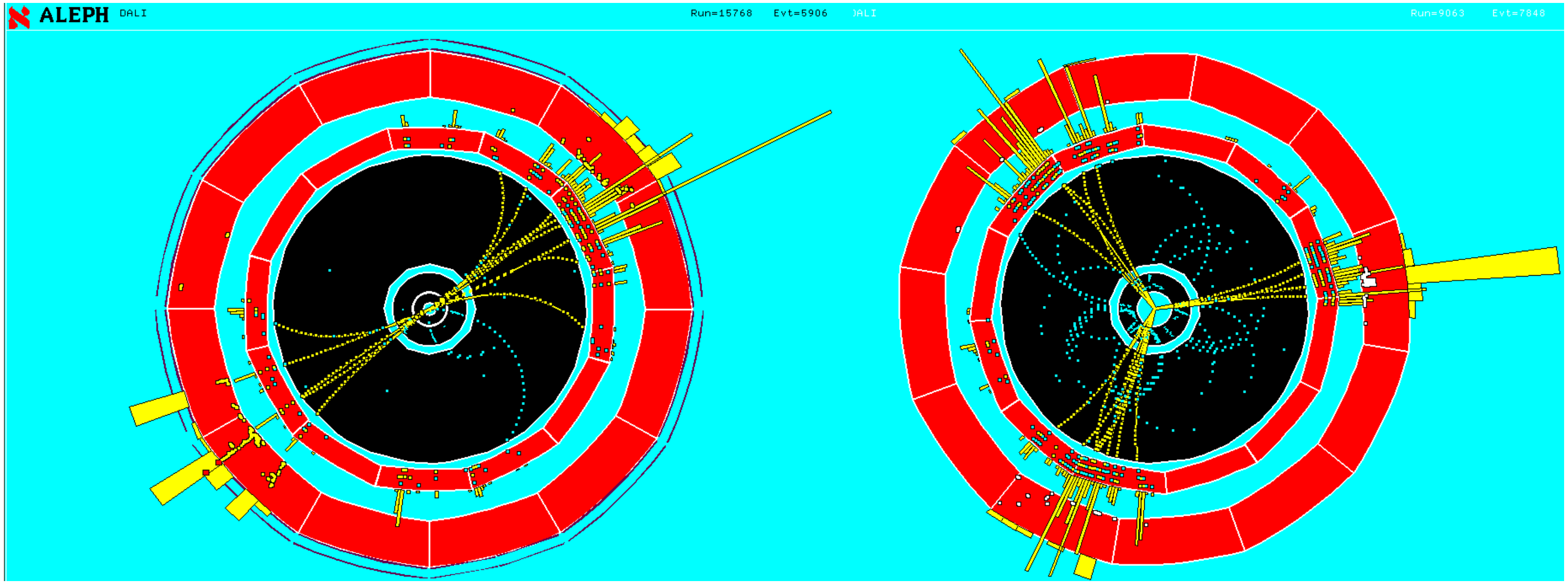

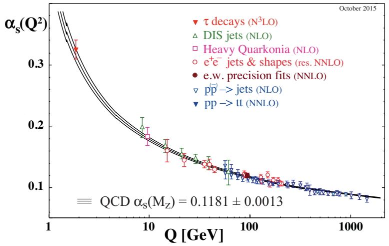

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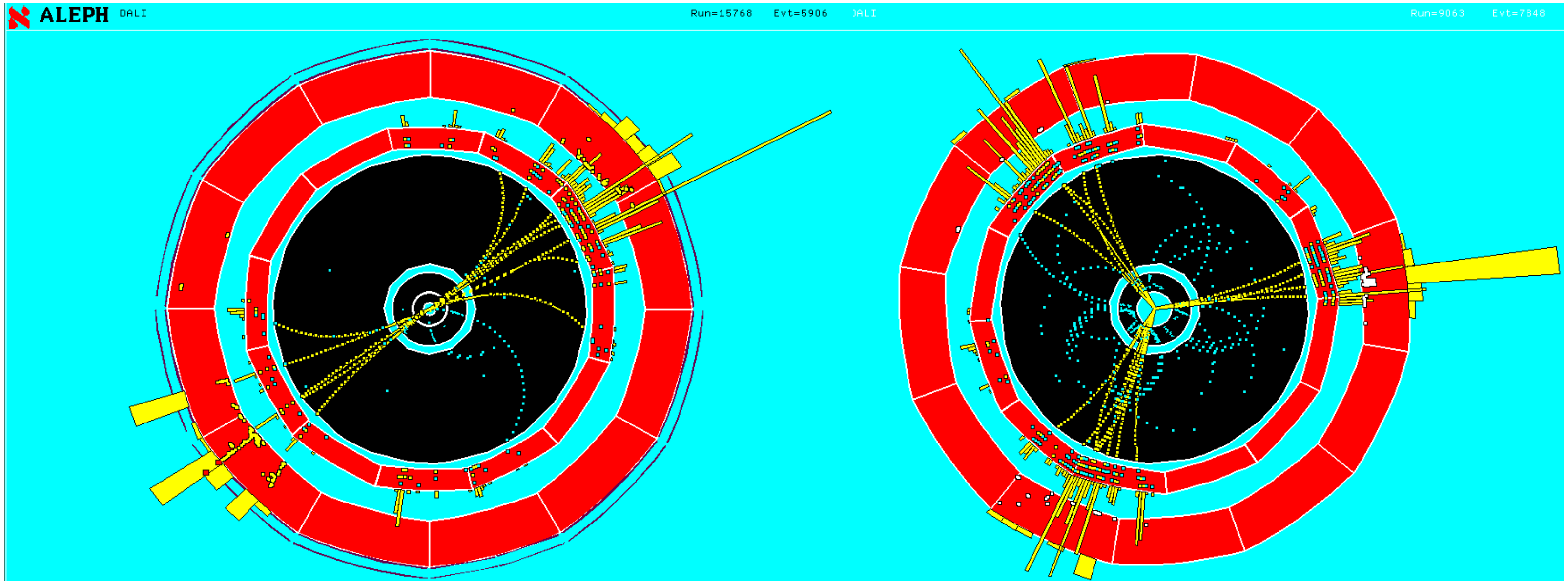
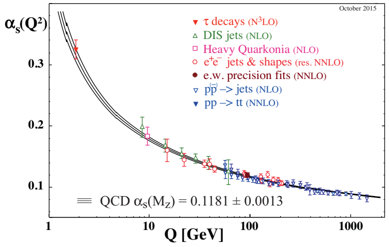


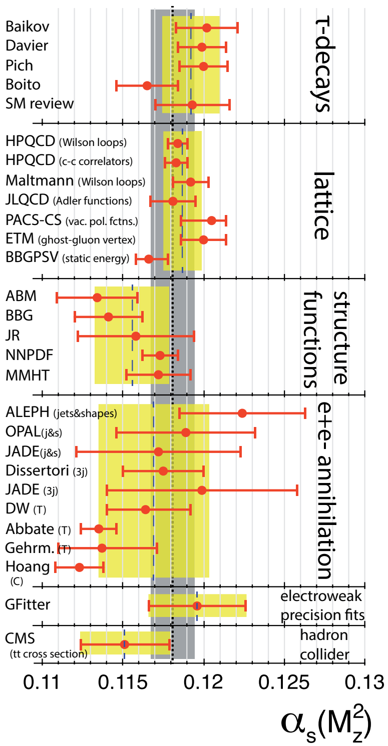


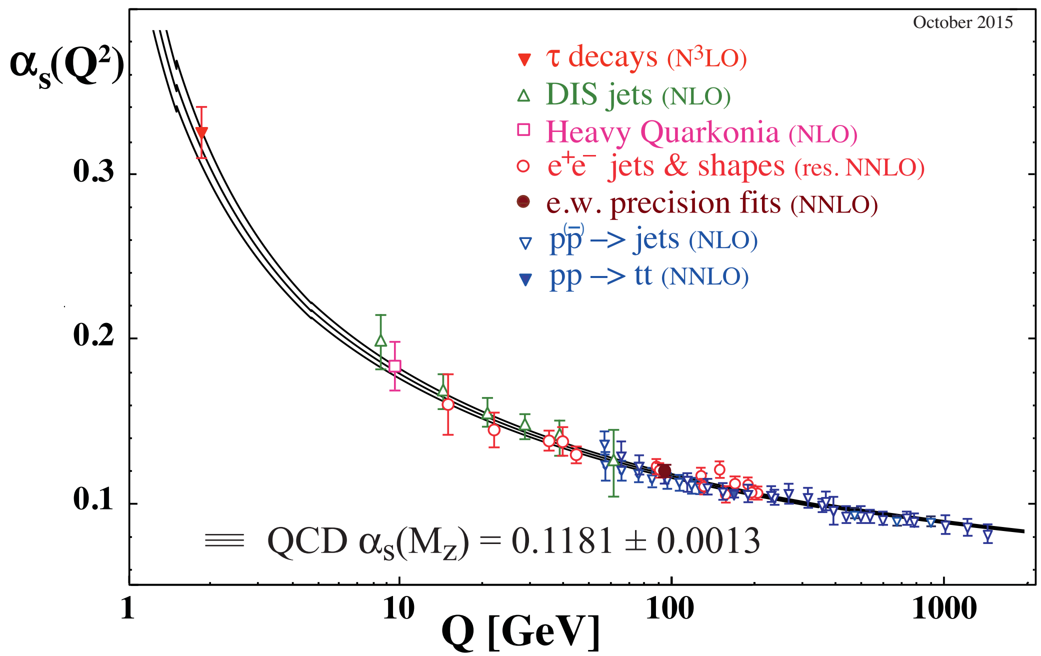
$$R = \frac{\sigma_{3\ \mathrm{jets}}}{\sigma_{2\ \mathrm{jets}}} \sim \alpha_S$$

Scientific context: SM became a theory

Reorganisation:

- QCD IS the theory of strong interactions.

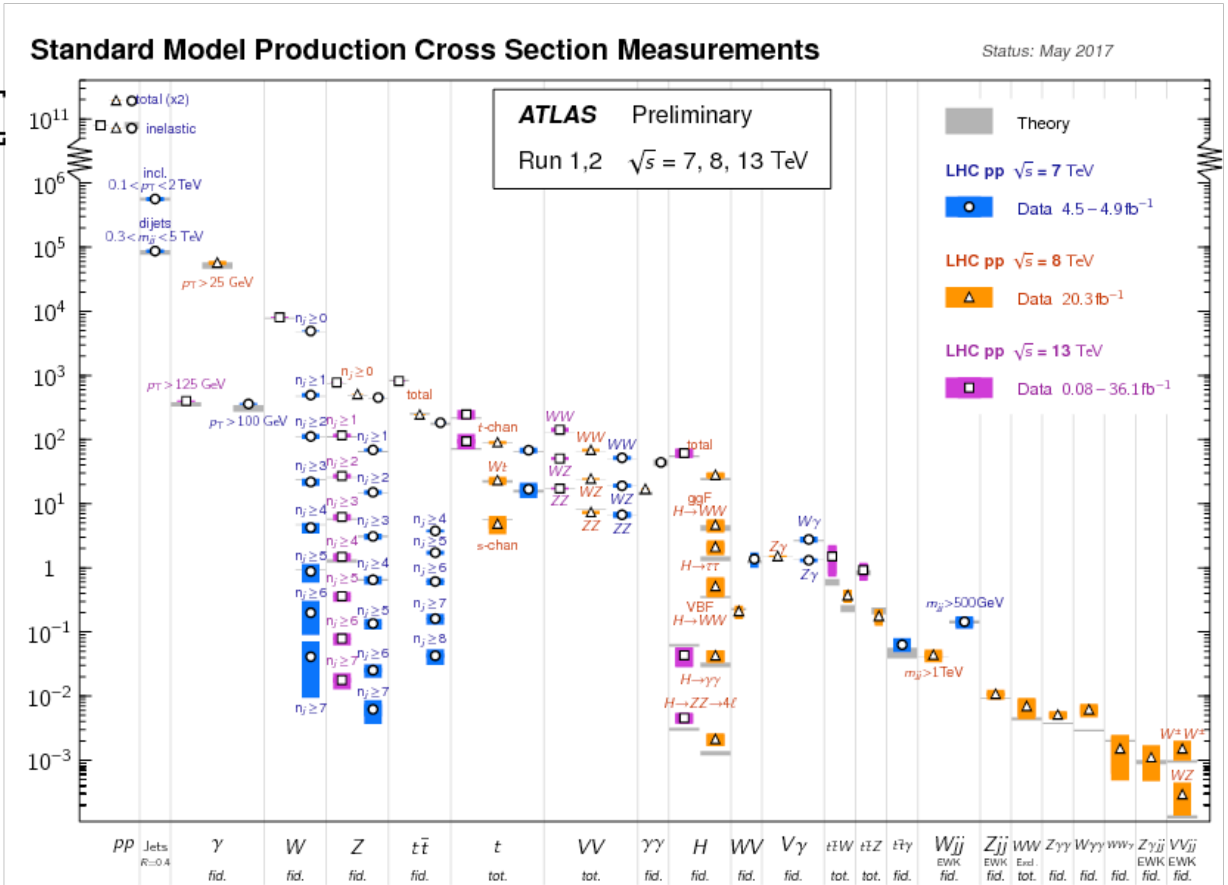




Scientific context: SM became a theory

Reorganisation:

- QCD **IS** the theory of strong interactions.



Scientific context: SM became a theory

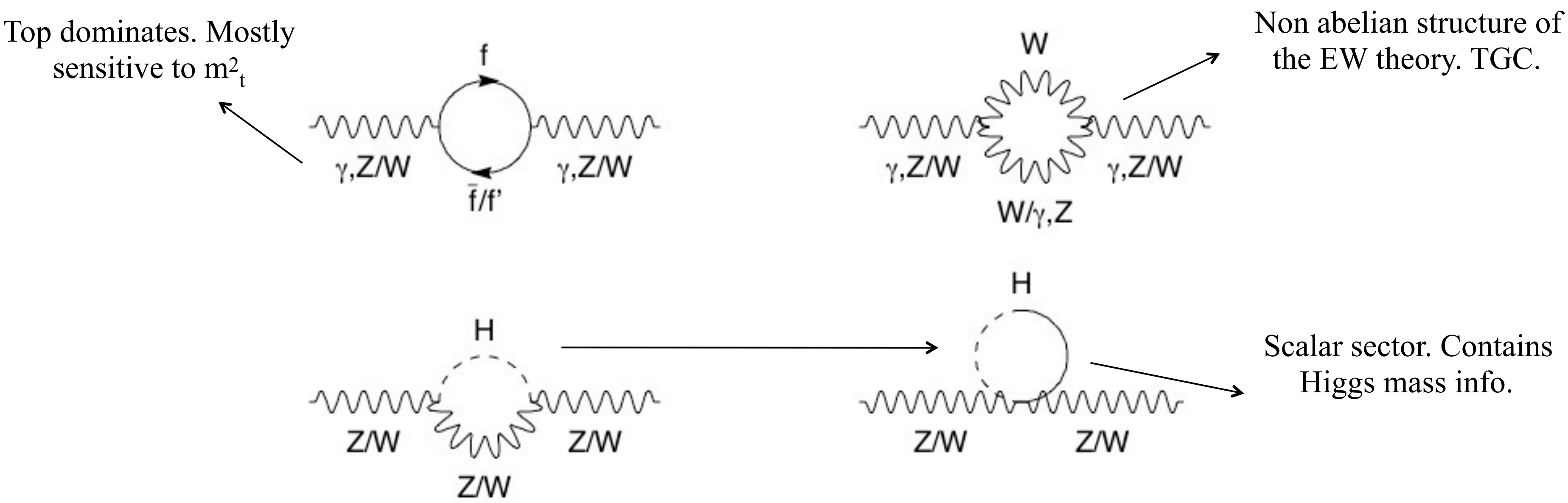
Reorganisation:

- The nine masses of the fermions: m_f.
- They are for 8 of them decoupled from the rest of the SM parameters.
- Nothing much to do here as well till the moment a theory comes with a prediction.
- They are however understood from the Yukawa couplings. We'll come back there.
- The top deserves a special mention.

Scientific context: SM became a theory

Reorganisation: the specific status of the top quark.

- The top quark has a specific status because it enters dominantly in the radiative corrections of the intermediate bosons mass propagators (in particular), *e.g.*



- In turn, a prediction of the top quark mass in the SM is possible in the consistency fit of the SM hypothesis against the electroweak precision observables.

Scientific context: SM became a theory

Reorganisation: the specific status of the top quark.

- The top quark has a specific status because it enters dominantly in the radiative corrections of the intermediate bosons mass propagators (in particular),

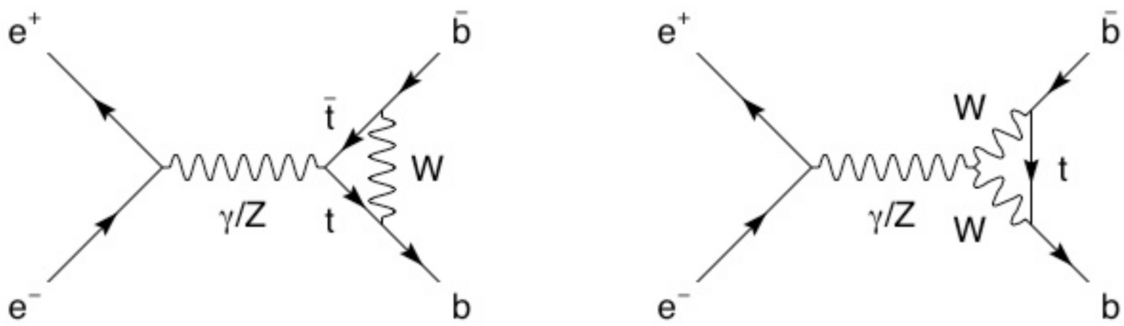
  - *Quand les types de 130 kilos disent certaines choses, les types de 60 kilos les écoutent.*
  - *Коли 130-кілограмові хлопці говорять певні речі, 60-кілограмові слухають.*
  - *Kiedy 130-kilogramowi faceci mówią pewne rzeczy, 60-kilogramowi faceci słuchają.*
  - *When the 130 kilo guys say certain things, the 60 kilo guys listen.*

- From Michel Audiard, french screenplay writer.

Scientific context: SM became a theory

Reorganisation: the specific status of the top quark.

- On top of the (universal) propagator corrections, one finds vertex corrections

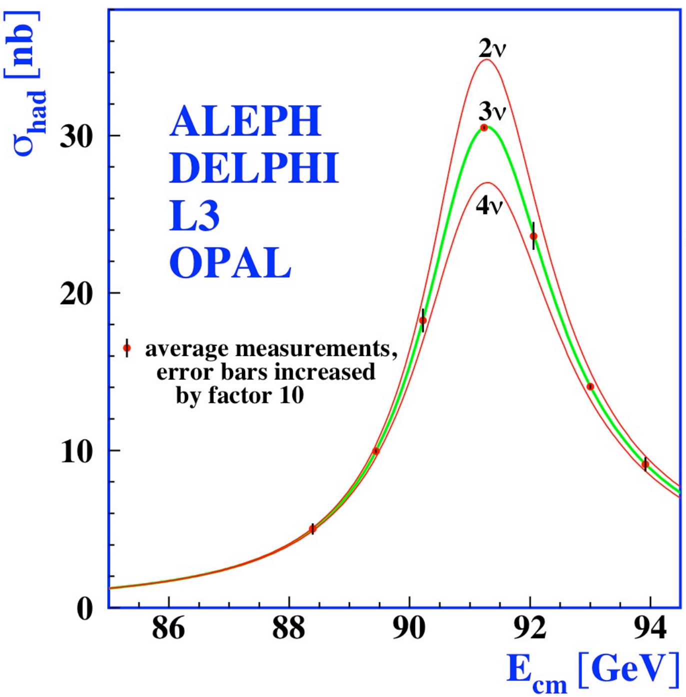


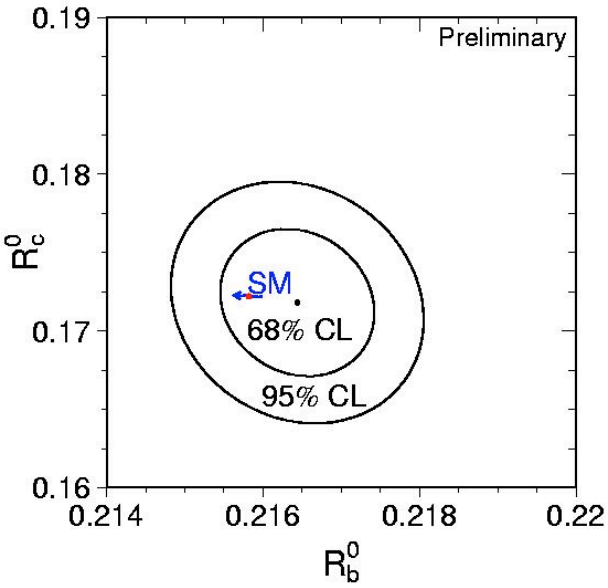
- In SM, these corrections are proportional to the CKM matrix elements V_{tq}.
- Hierarchy (within the SM): $|V_{tb}| \approx 1 \gg |V_{ts}| \approx 0.04 \gg |V_{td}| \approx 0.008$
- Vertex corrections are only relevant for *b* quarks: $\Delta\kappa_b = \frac{G_F m_t^2}{4\sqrt{2}\pi^2} + \ldots$
- A unique observable of interest there: $R_b = P(Z \to bb) / P(Z \to qq)$

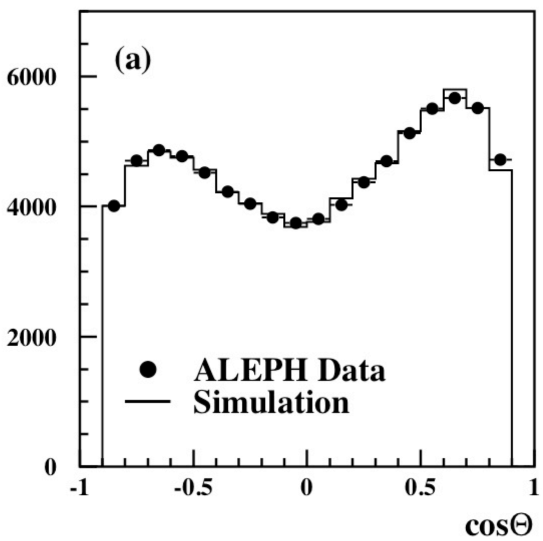
Scientific context: SM became a theory

Reorganisation: the main observables

- Measurements at the *Z* pole



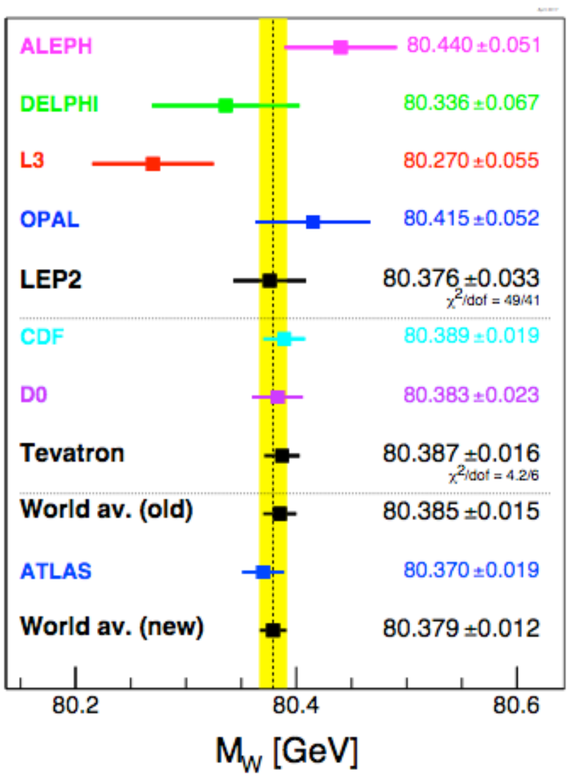


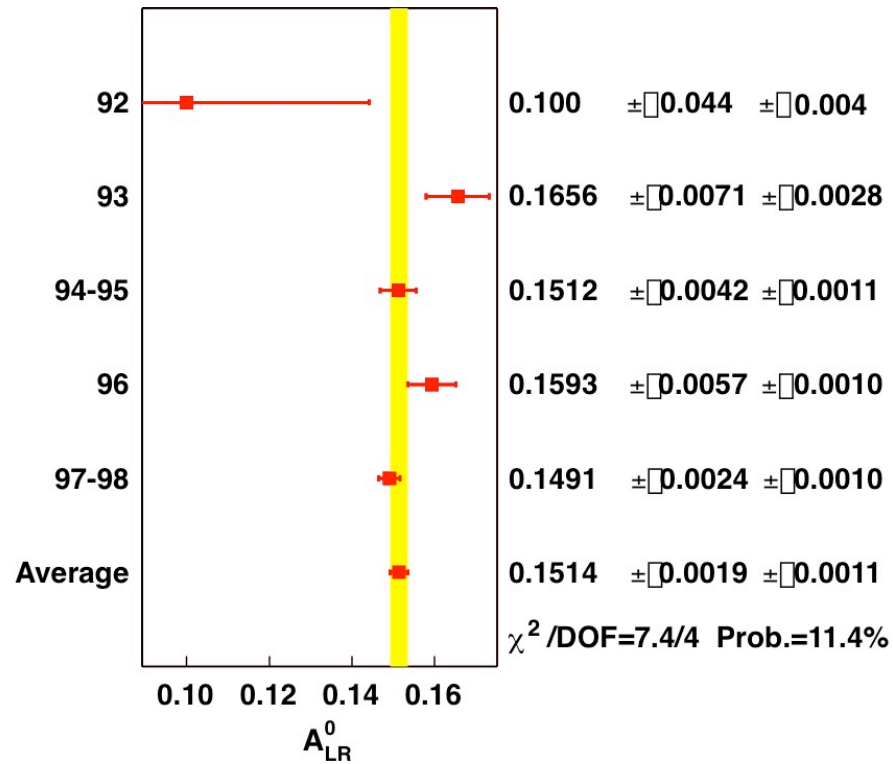


Scientific context: SM became a theory

Reorganisation: the main observables

- Measurements at the *Z* pole and m_W : (universal) propagator corr.

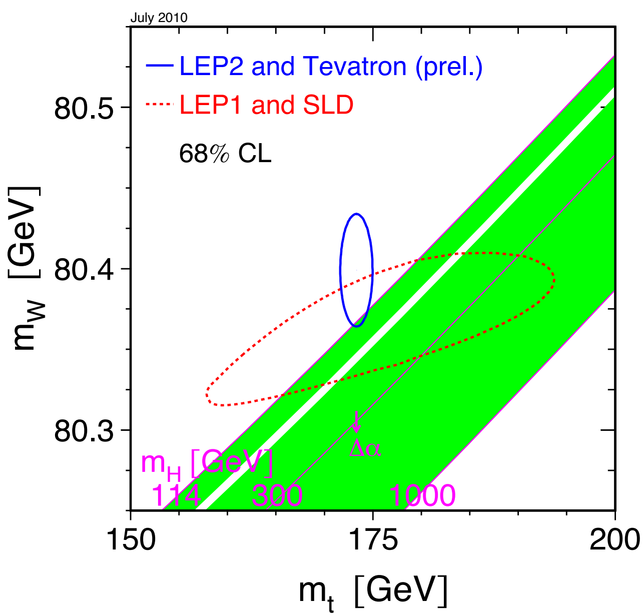


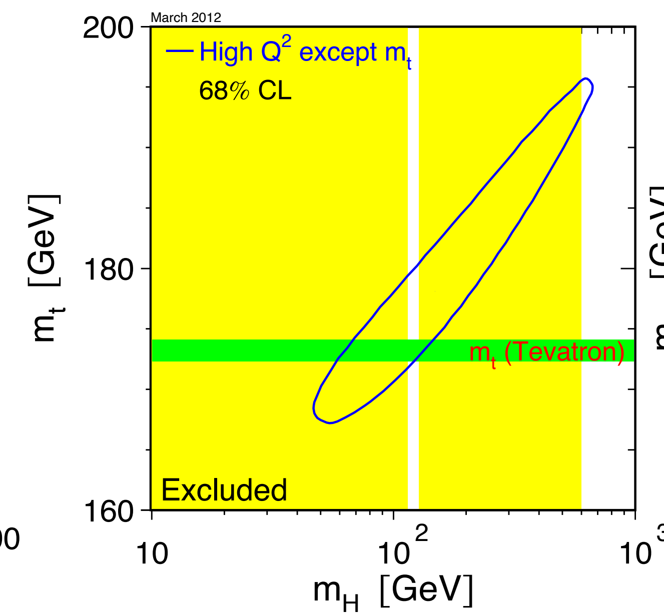


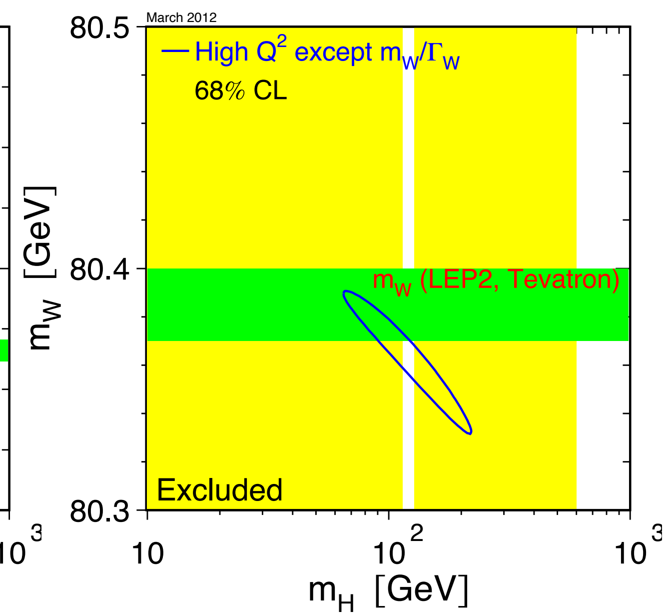
SM became a theory

Reorganisation:

- The rest of the free parameters are part of the so-called electroweak precision observables consistency check. This is the first pillar of the SM. Fix G_F , α_{EM} and m_Z at their measured value and produce a prediction of m_{top} , m_W and m_H. A tremendous success !

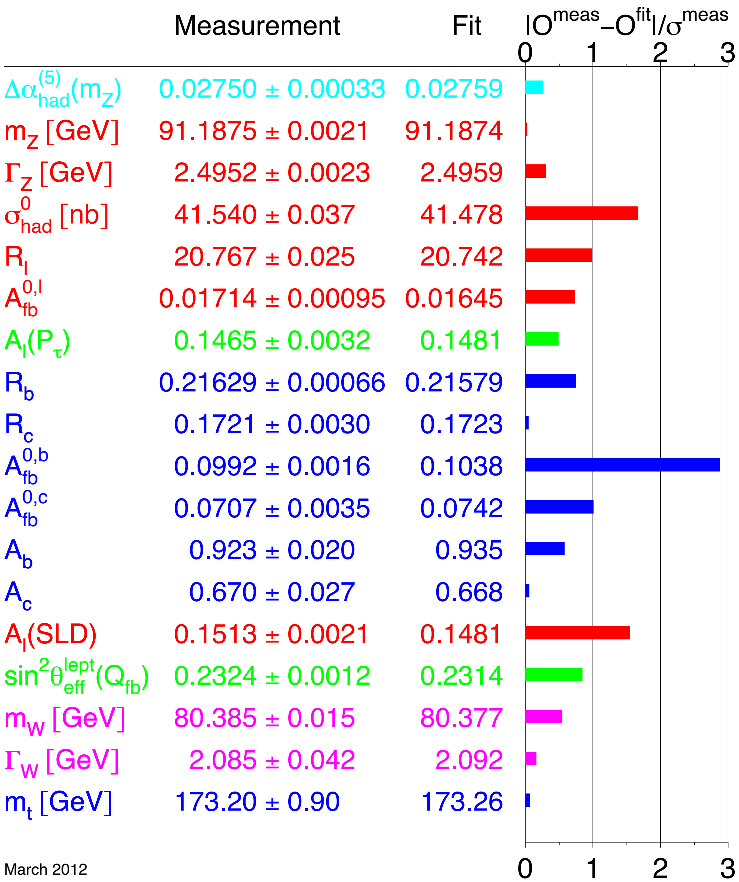






SM became a theory

Reorganisation: spelling out the predictions.

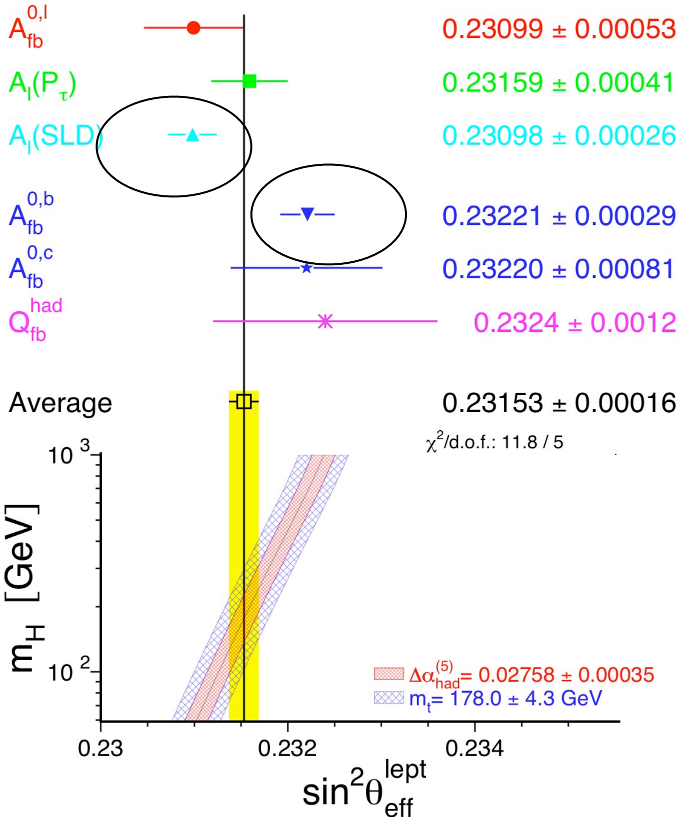


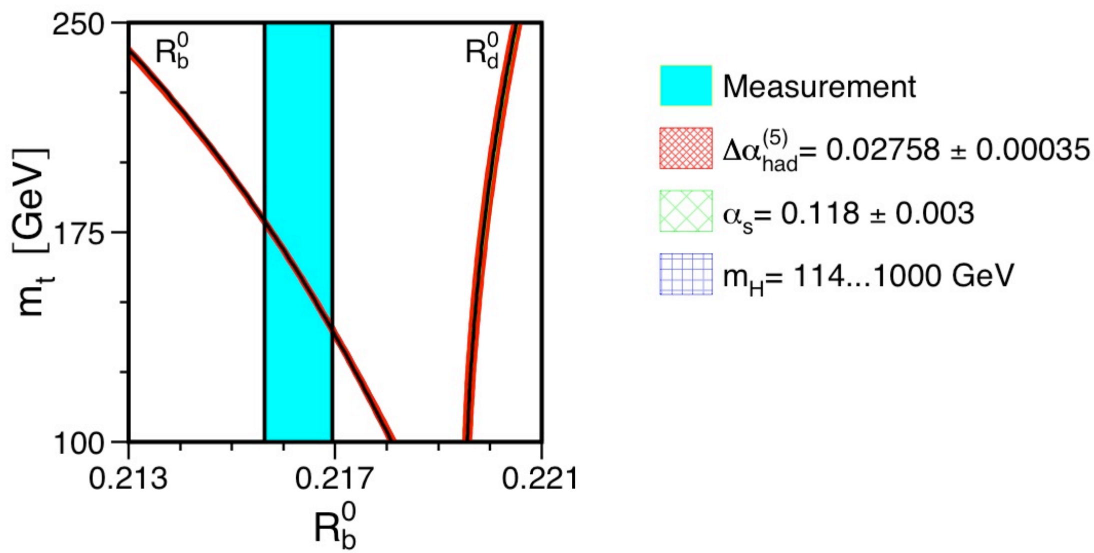
- The SM EW global fit has a remarkable χ^2_{min}/d.o.f = 1.40 (p-value=15%).
- The SM hypothesis passes the test. It does not mean that SM IS the Nature. In Science, one can usually only say NO...
- Two observables depart « with some significance » from their prediction. It happens they are the two most important for the constraint on the Higgs boson.
- One can go one step further and make the metrology of the parameters.

SM became a theory

Reorganisation: spelling out the predictions.

- The information on the top quark is basically brought by $\sin^2\theta_{eff}$ (A_{LR} and A_{FB} – propagator corrections), m_W (again propagator corrections) and R_b (vertex corrections).





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Reorganisation: spelling out the predictions.

- The information on the top quark is basically brought by $\sin^2\theta_{eff}$ (A_{LR} and A_{FB} – propagator corrections), m_W (again propagator corrections) and R_b (vertex corrections).

- Putting all these observables together (and some others) yields a top quark mass prediction of :

$$m_{\text{top}} = 172.6\ {}^{+13.3}_{-10.2}\ \text{GeV}/c^2\ [(\text{indirect} - \text{LEP1})].$$

- basically obtained (w/ three times the current uncertainty) from 1993.

- actually presented at Moriond 1994.

SM became a theory

Reorganisation: spelling out the predictions.

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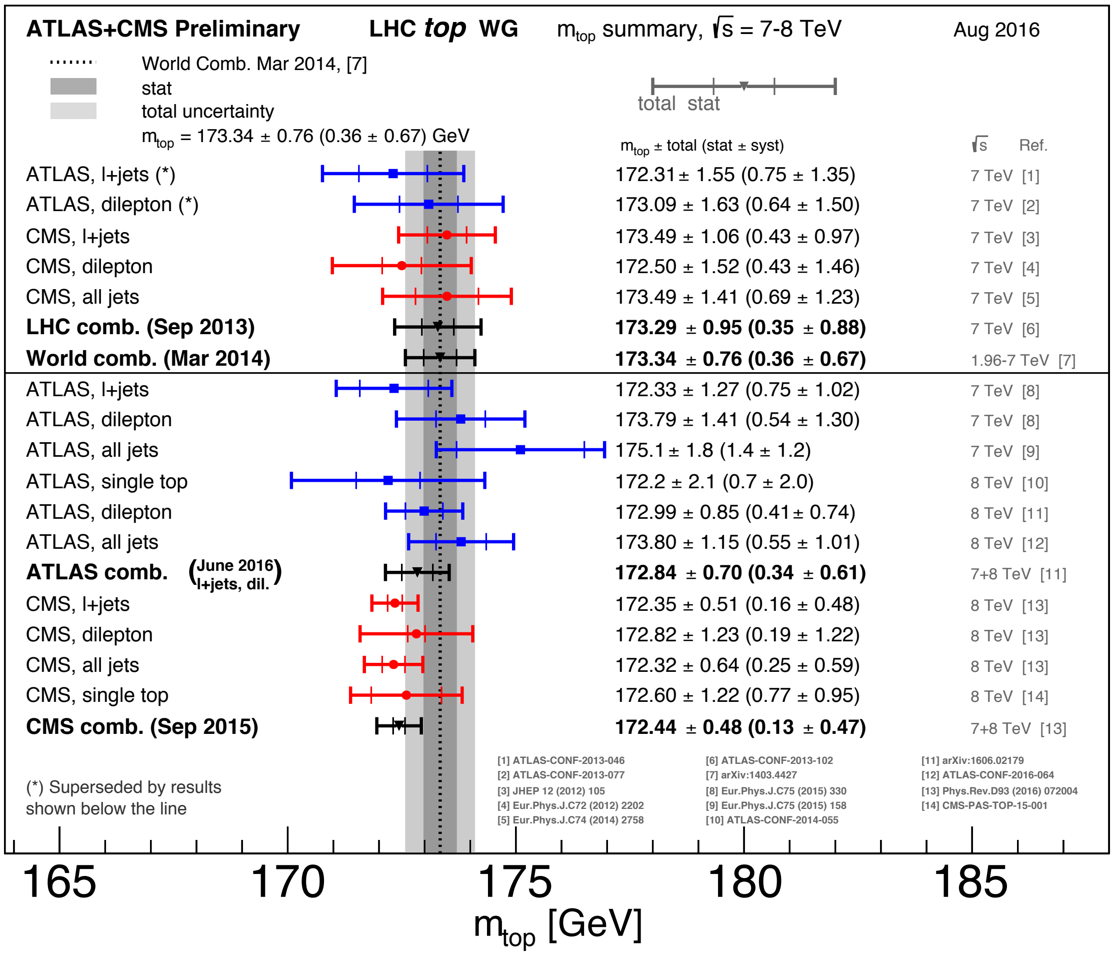


SM became a theory

Reorganisation: spelling out the predictions.

- We must now compare the direct and indirect determinations:

$$m_{\text{top}} = 173.18 \pm 0.96 \text{ GeV}/c^2, \text{ [direct } - \text{ Tevatron]}$$
$$m_{\text{top}} = 172.6^{+13.2}_{-10.2} \text{ GeV}/c^2, \text{ [indirect } - \text{ LEP1]}$$

$$m_{\text{top}} = 172.44 \pm 0.48 \text{ GeV}/c^2, \text{ [direct } - \text{ LHC]}$$

- The agreement is simply remarkable.

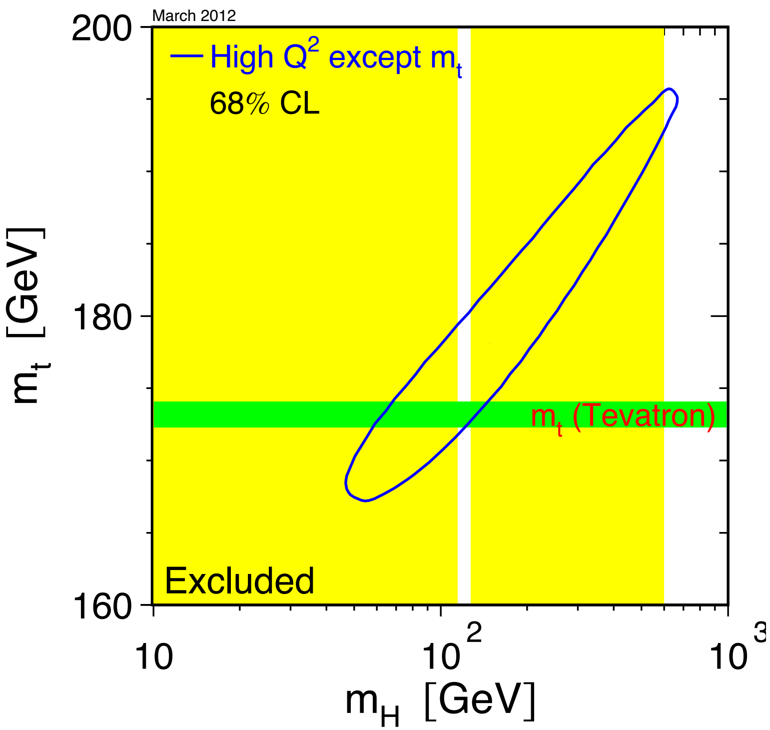
- LEP/SLD + SM predicted the top quark mass.

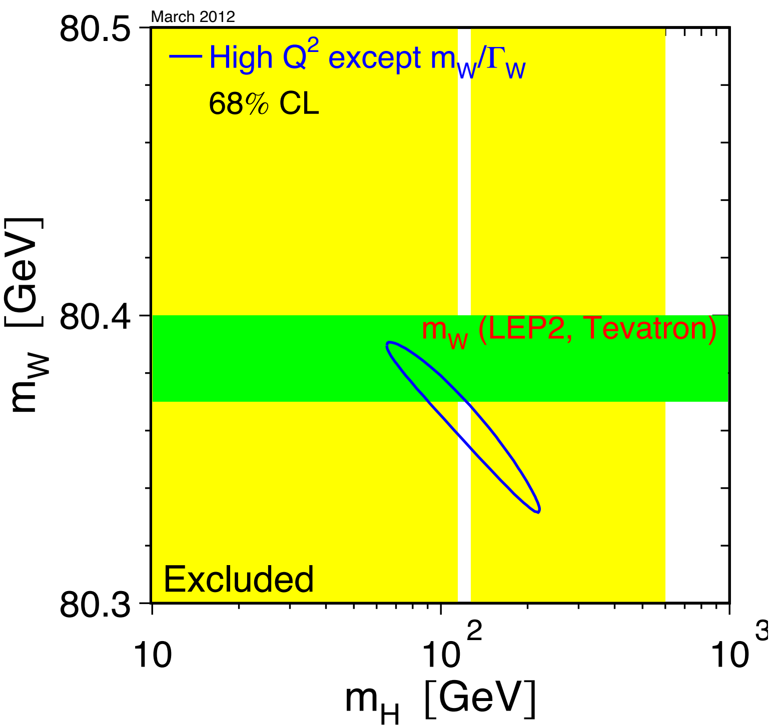
- This is simultaneously a triumph of the Standard Model and the HEP physics experiments. Probe quantum corrections of the electroweak theory to predict the existence of a particle in the Nature.

SM became a theory

Reorganisation: spelling out the predictions.

• Once the top quark is known, it can enter in the EWP consistency and constrain further the rest of the unknown parameters, the Higgs boson.

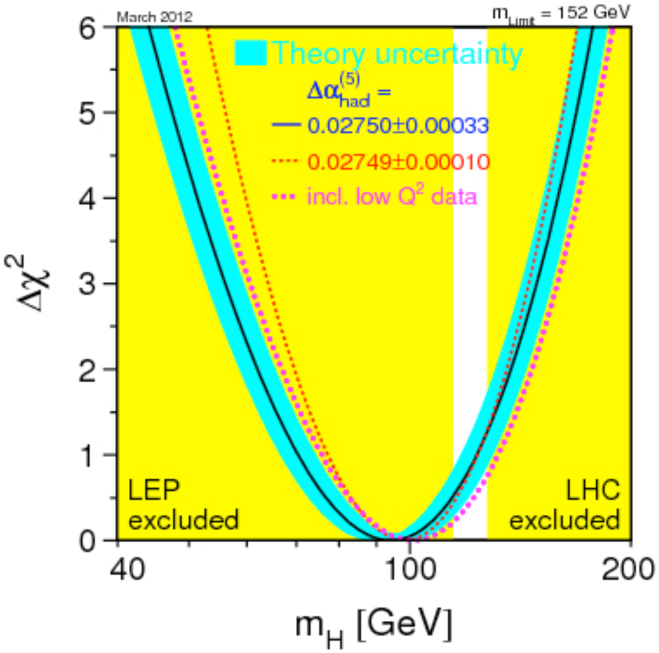




SM became a theory

Reorganisation: spelling out the predictions.

• Once the top quark is known, it can enter in the EWP consistency and constrain further the rest of the parameters, and bound the Higgs boson mass.



$$m_{\mathrm{BEH}} < 152\ \mathrm{GeV}/c^2 \quad 95\%\ \mathrm{CL.}$$

SM became a theory

Reorganisation: spelling out the predictions.

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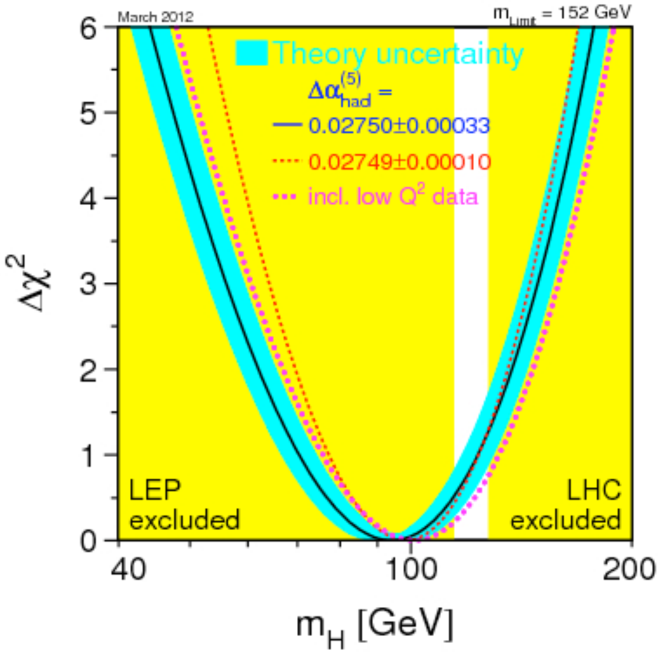

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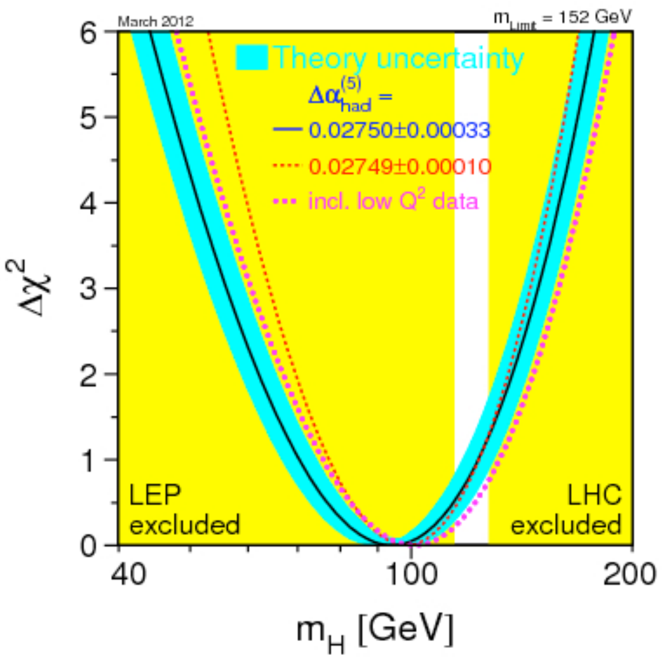
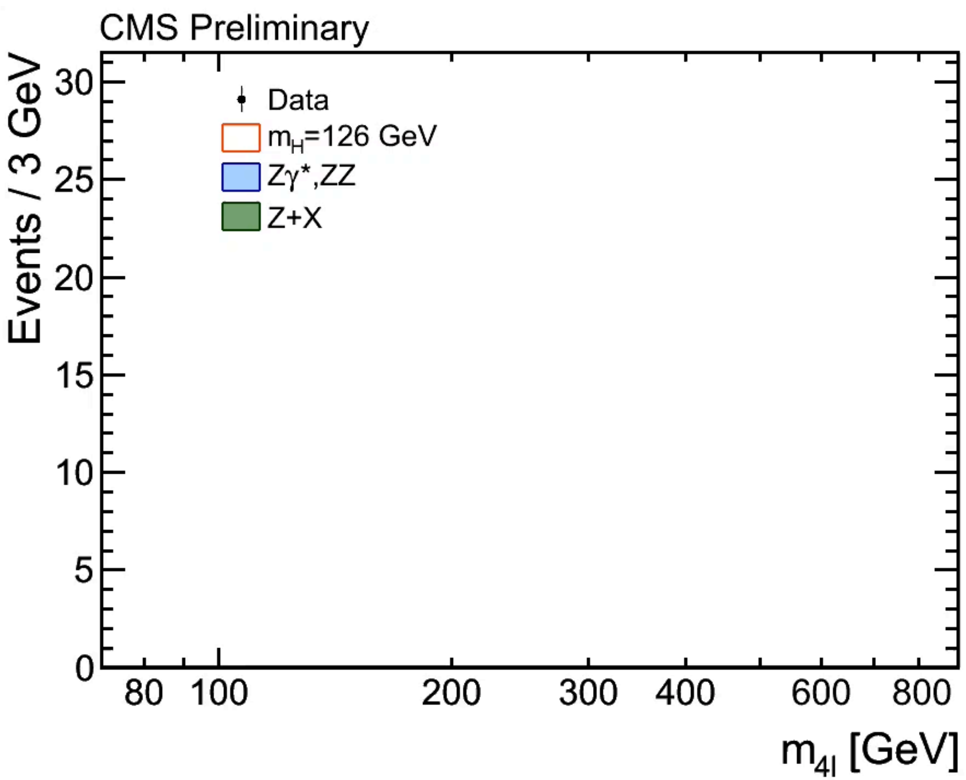
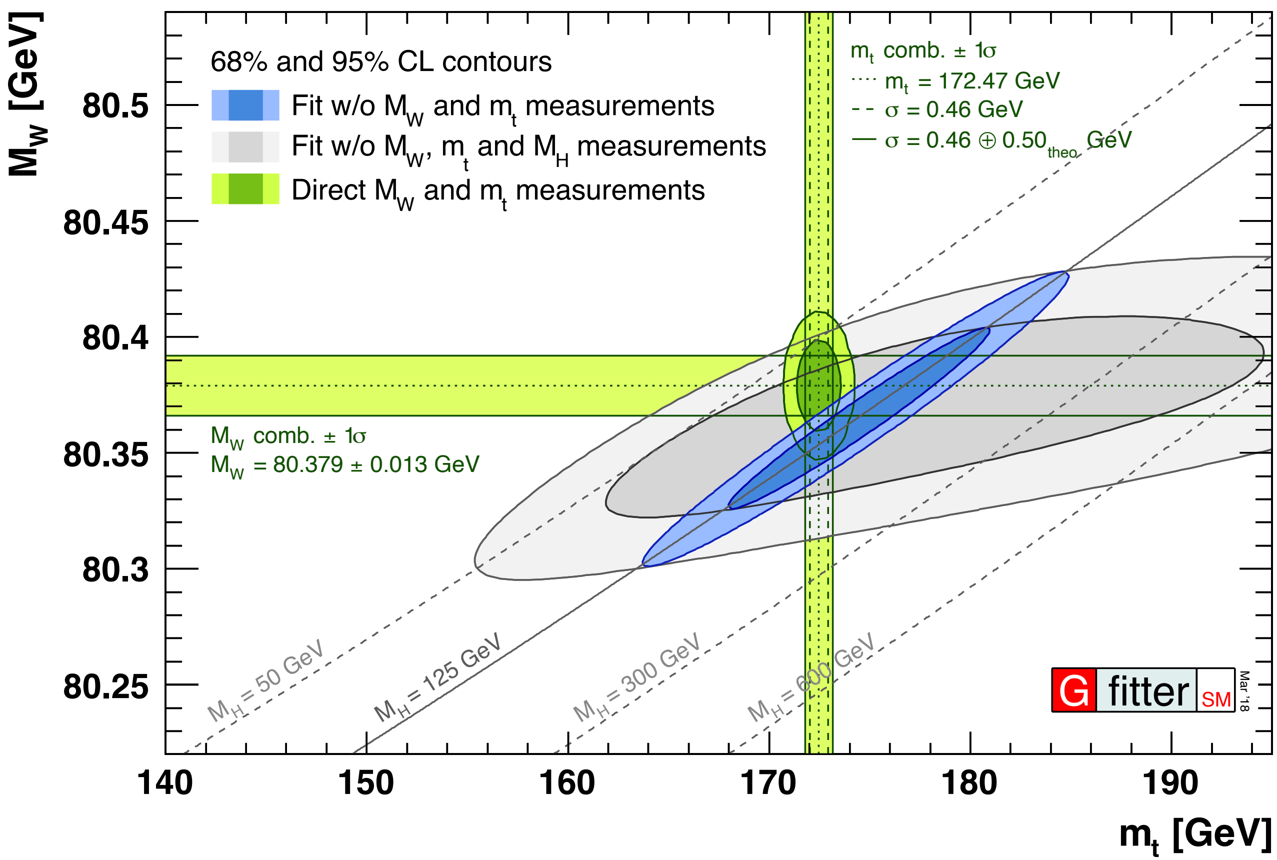




SM became a theory

Reorganisation: spelling out the predictions.

- The modern plot gathering all constraints



SM became a theory

Reorganisation: the narrow bosonic resonance.

- The mass starts to be accurately measured.

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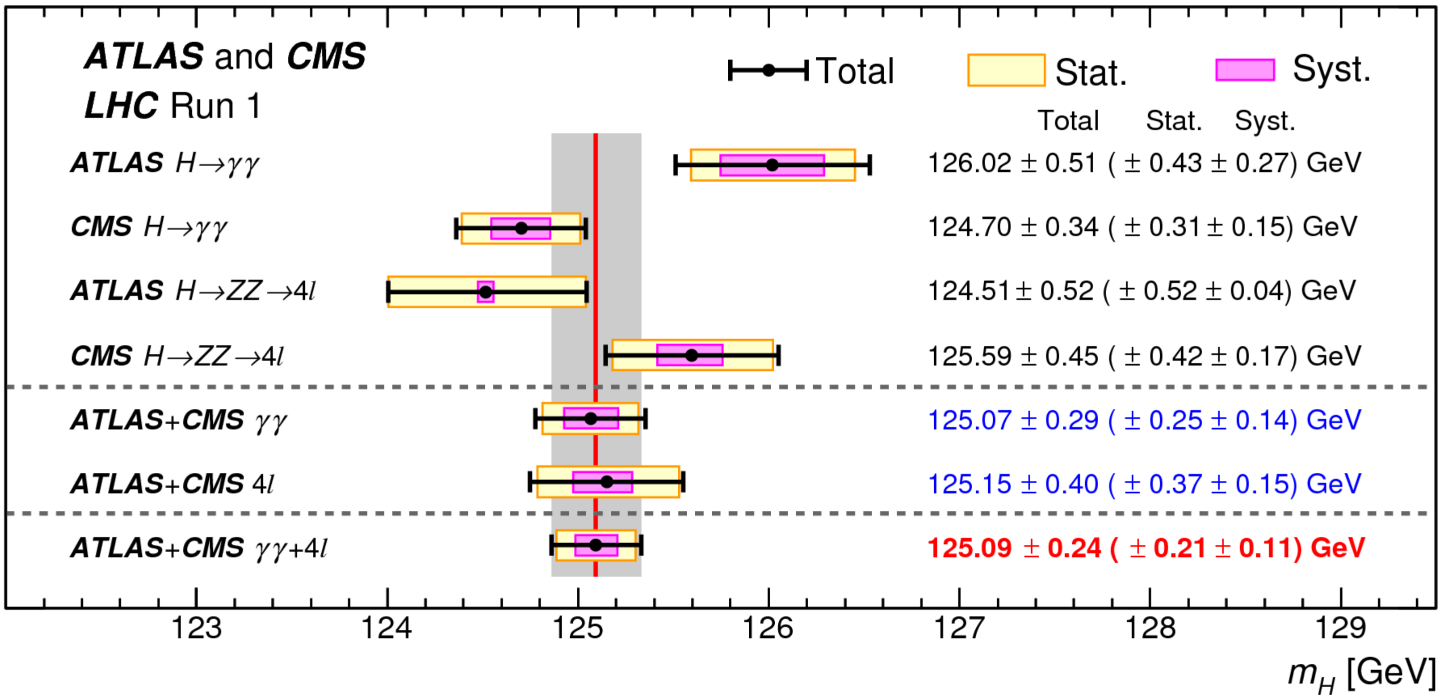
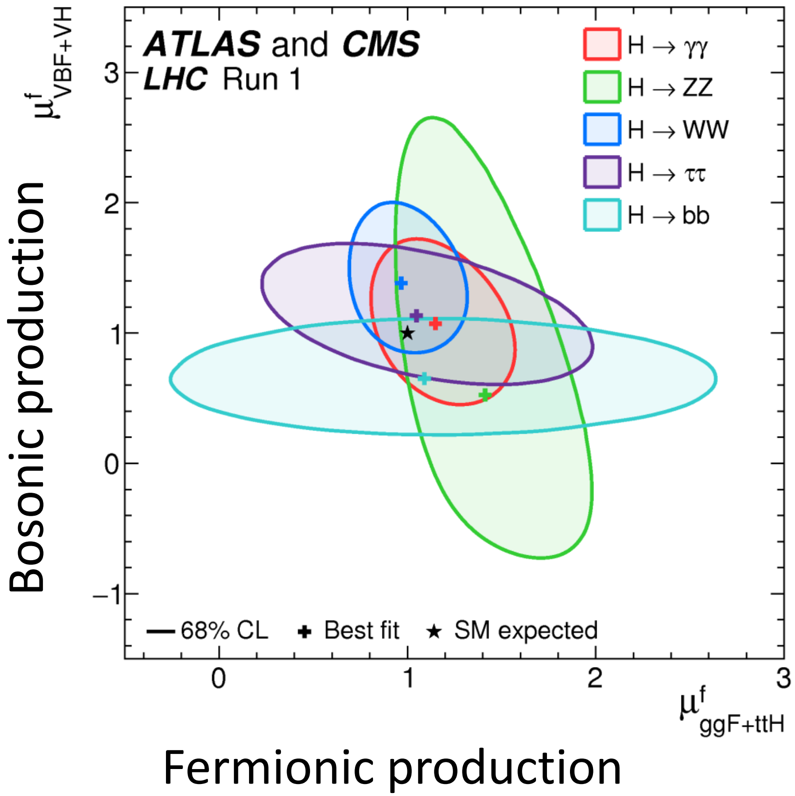


- It is likely a scalar particle (spin /parity properties determined from *ZZ** signal events).

SM became a theory

Reorganisation: the narrow bosonic resonance.

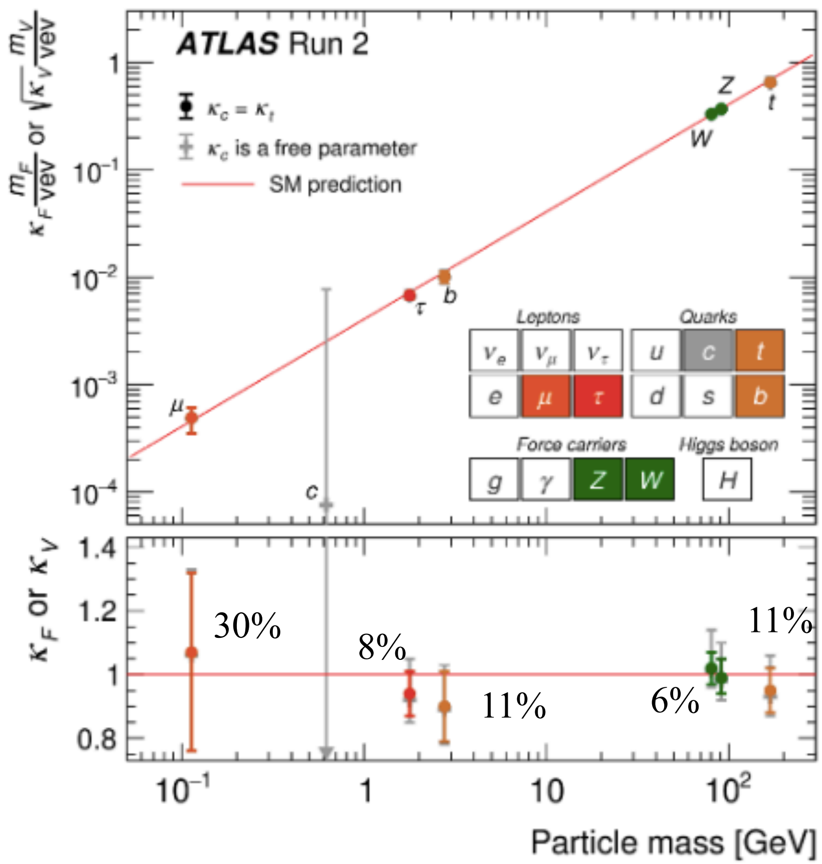
• The couplings are so far (with a modest precision though) in good agreement with the SM predictions.



SM became a theory

Reorganisation: the narrow bosonic resonance.

• The couplings are so far (with a 10-30 % precision though) in good agreement with the SM predictions.



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SM became a theory

Reorganisation: back to quark masses and mass mixing matrix.

[See Alexander and Achille's lectures in this School.]

- Again, the name of the game consists in a global consistency check from a fit of the SM hypothesis against the relevant Flavour observable measurements.

- Most of the constraints are coming from *b*-hadron decays and neutral *B*-meson mixings. These can be *CP*-conserving or *CP*-violating observables.

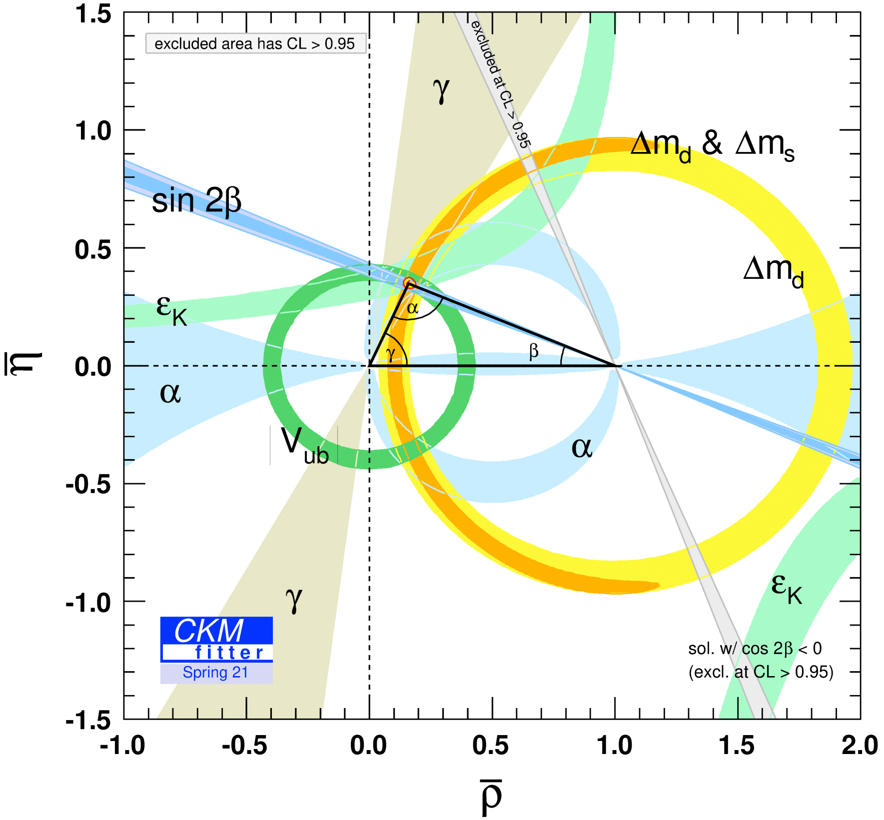
- The global fit relies heavily, as far as *CP*-conserving observables are concerned, on QCD predictions, mostly numerically established (Lattice QCD).

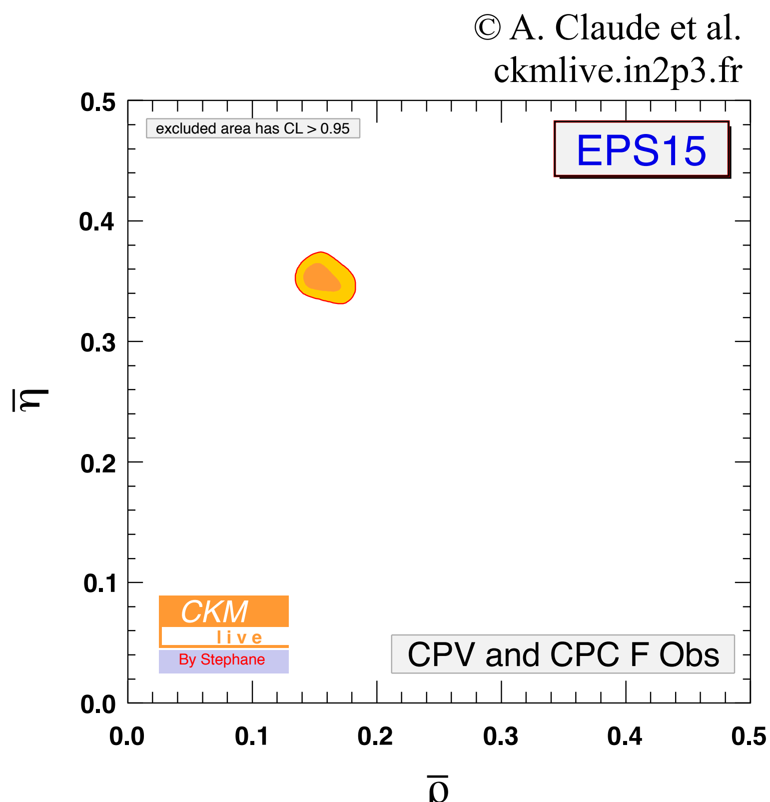
- The observables related to the strange flavour (*K* decays and K^0 mixing) are also consistently described, though suffering from large(r) hadronic uncertainties (long distance physics where LQCD does not apply straightforwardly).

SM became a theory

Reorganisation: back to quark masses and mass mixing matrix.

- The 4 CKM matrix elements are decoupled from the rest of the theory. The consistency check of the SM hypothesis in that sector is the second pillar of the SM:

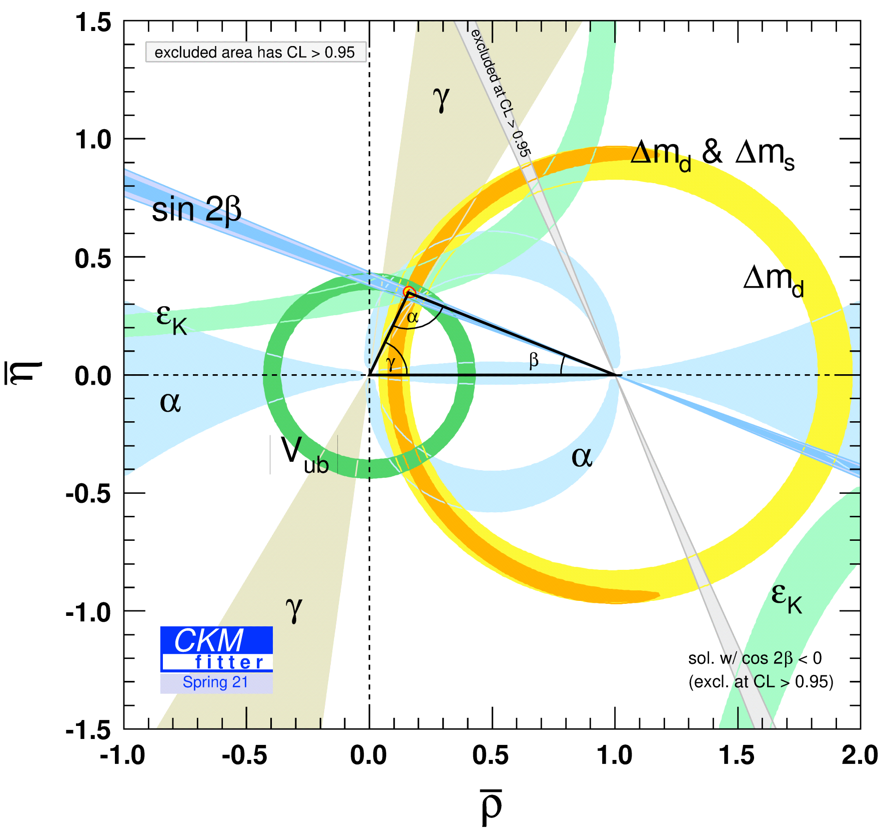




SM became a theory

Reorganisation: back to quark masses and mass mixing matrix.

- Note that Flavour observables are also predicting (well postdicting in that case) the top quark mass



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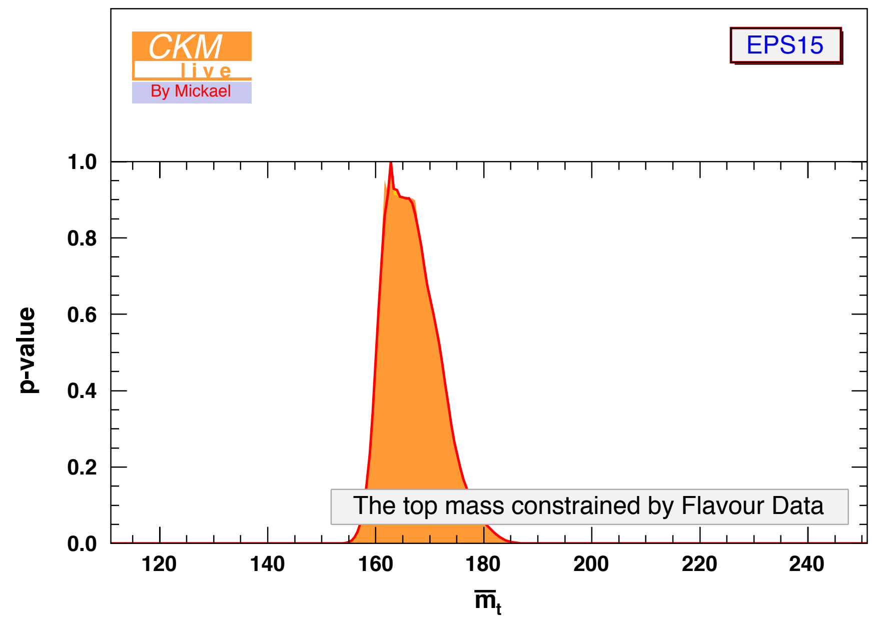

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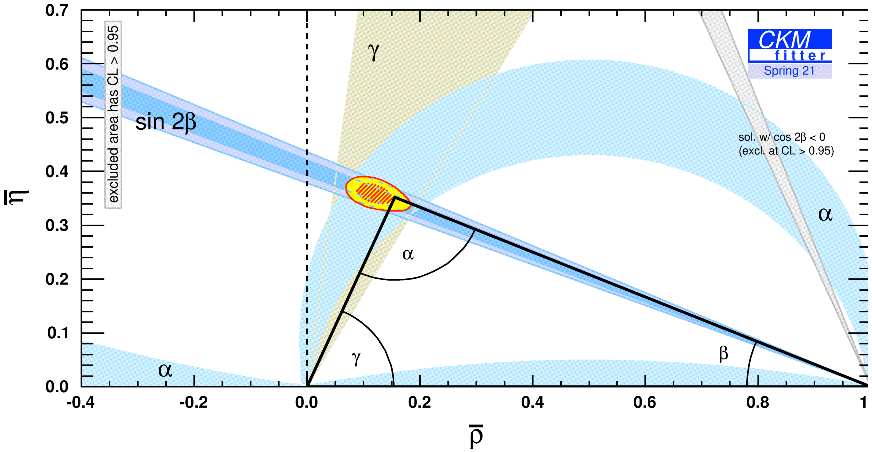
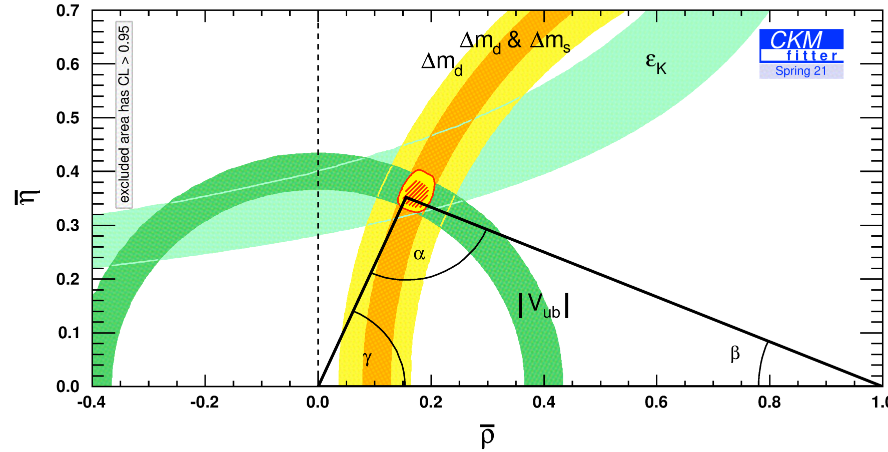


Angles - No theory uncertainty



Sides - Theory uncertainty dom.

SM became a theory

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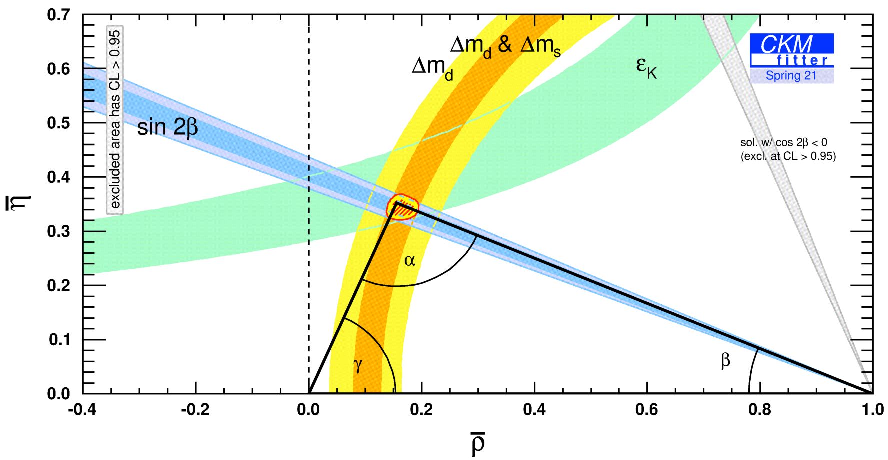
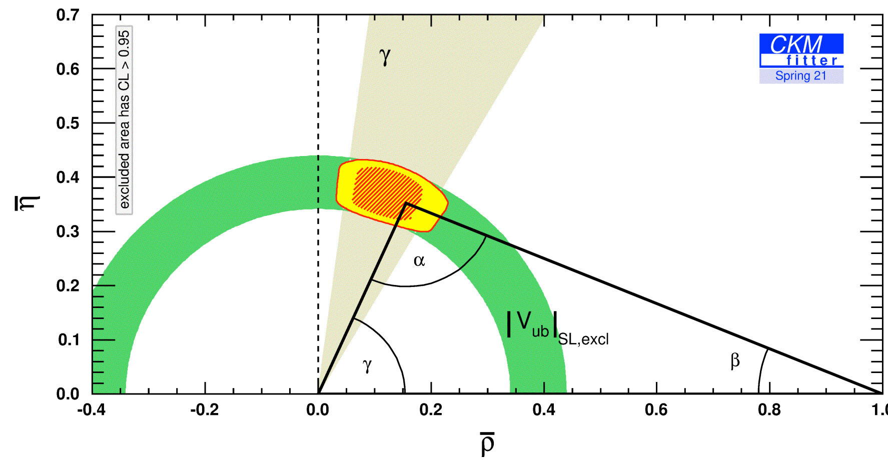


Loops - BSM friendly



Trees - supposedly SM friendly

SM became a theory

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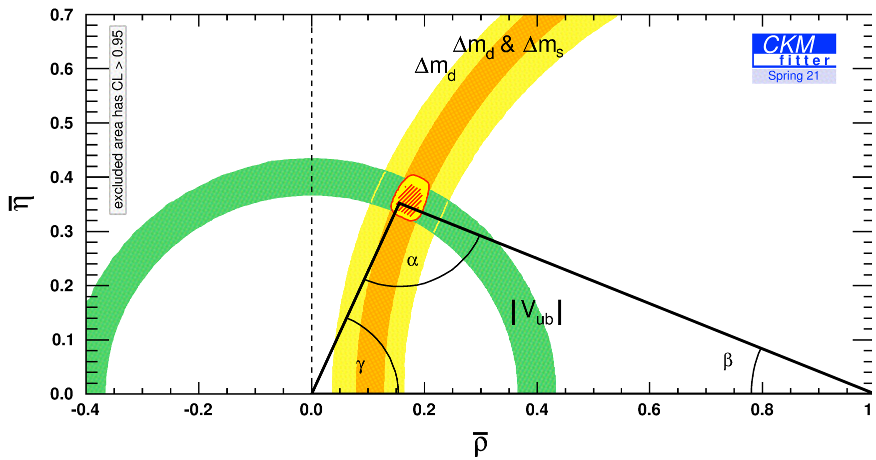
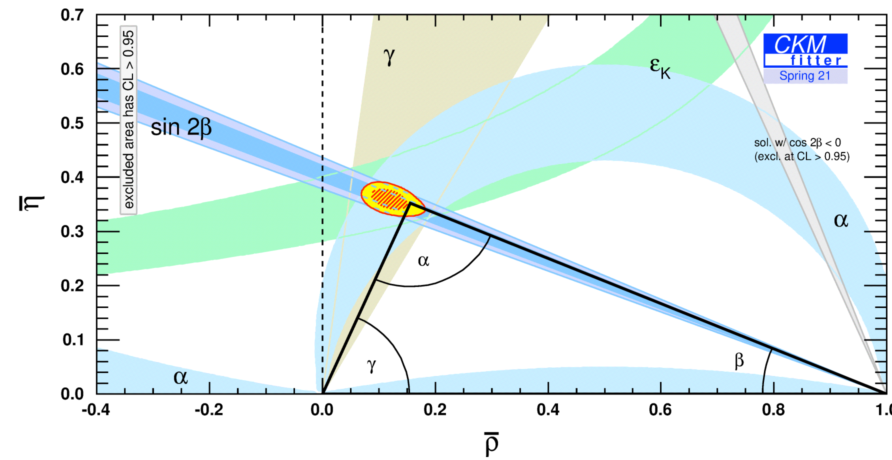


CP-conserving

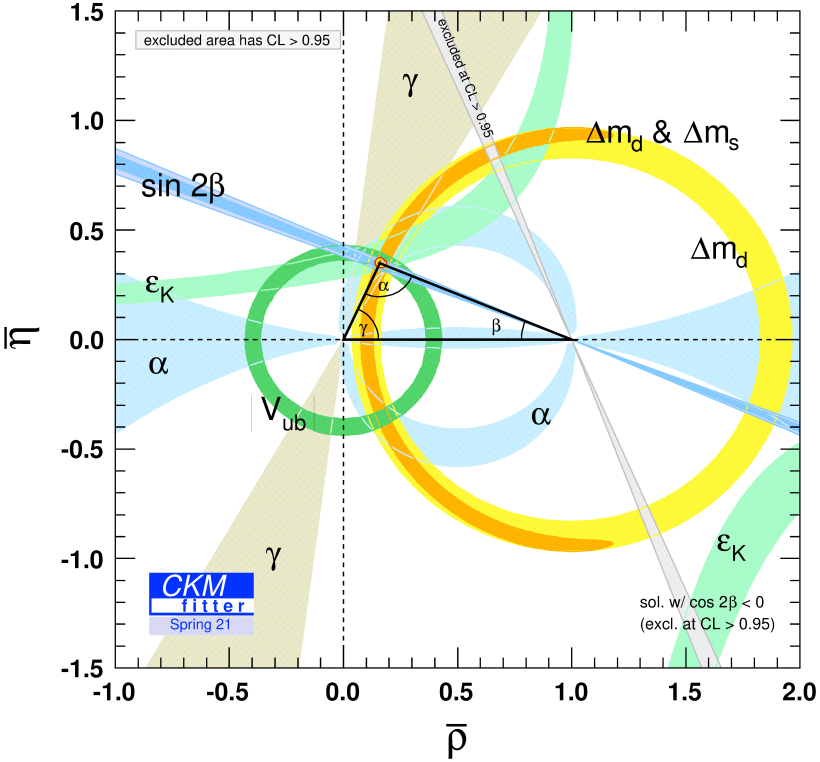


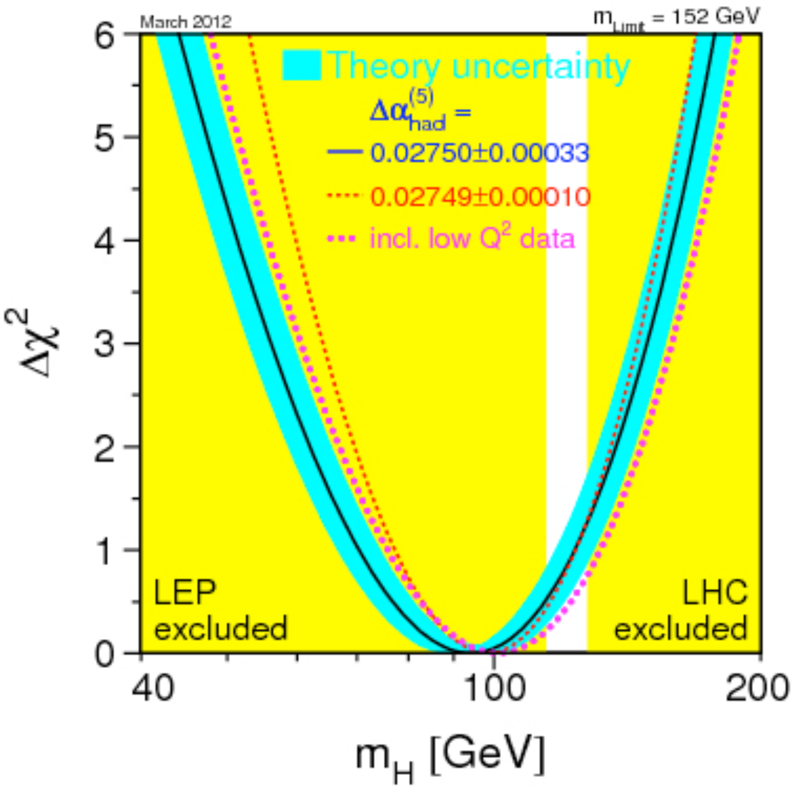
CP-violating

Recap Part I
the two pillars of the SM:
EWPT and quark flavours.

SM became an invincible theory

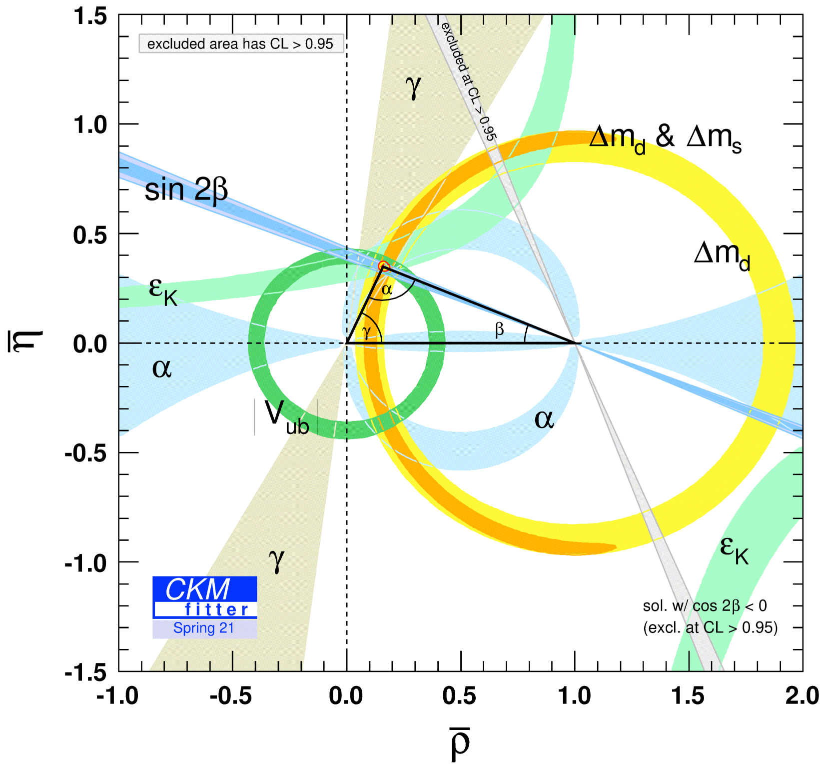
Recap: the two pillars of the SM: EWPT and quark flavours.





SM became an invincible theory

Recap: the two pillars of the SM: EWPT and quark flavours.



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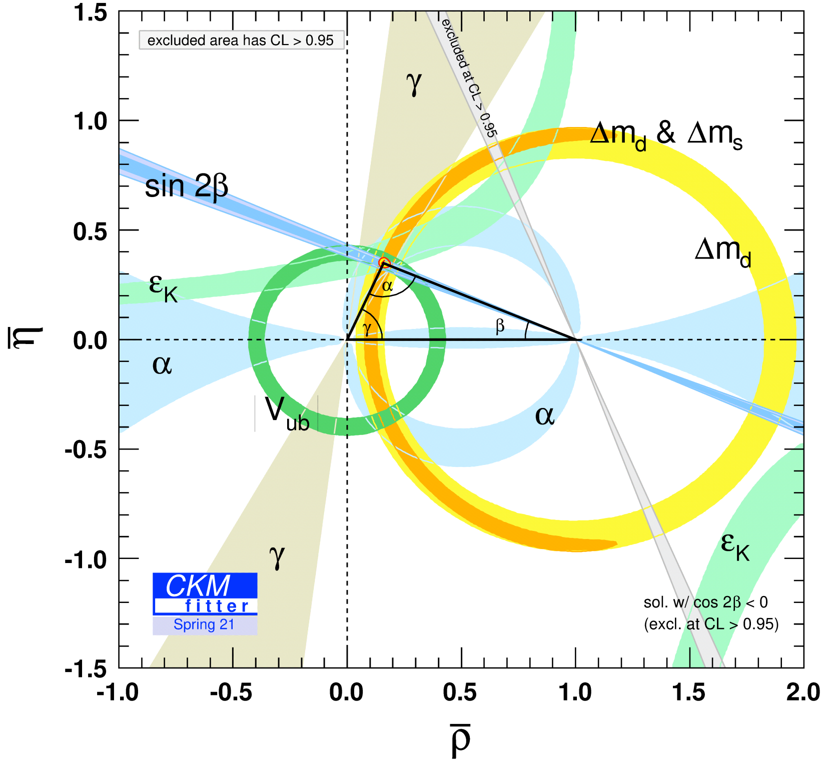

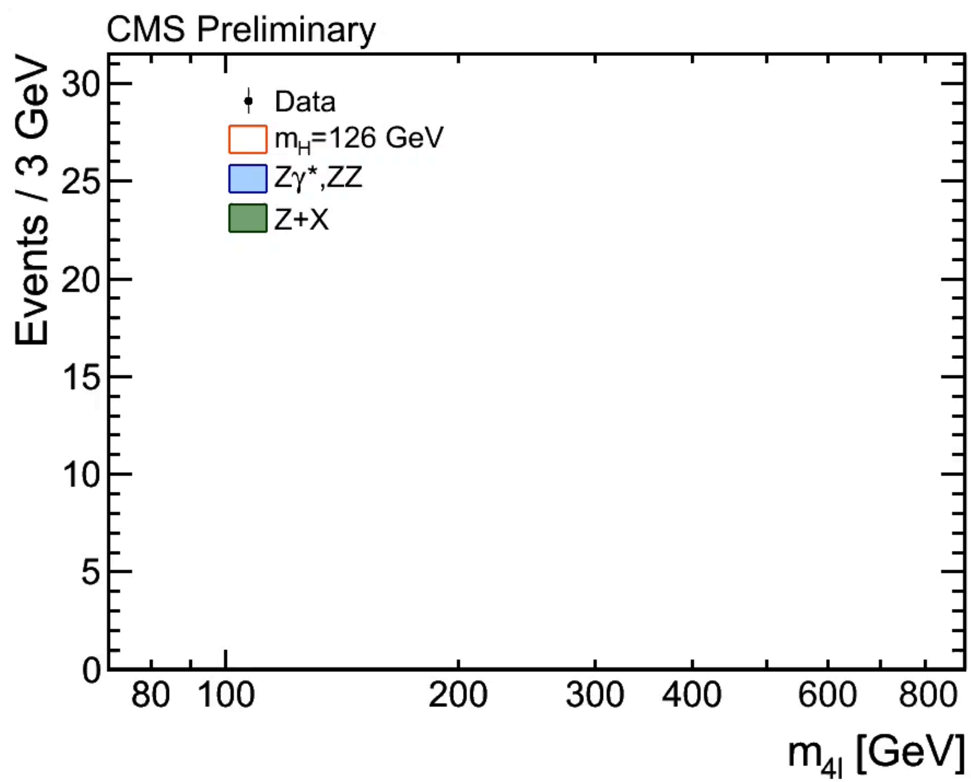

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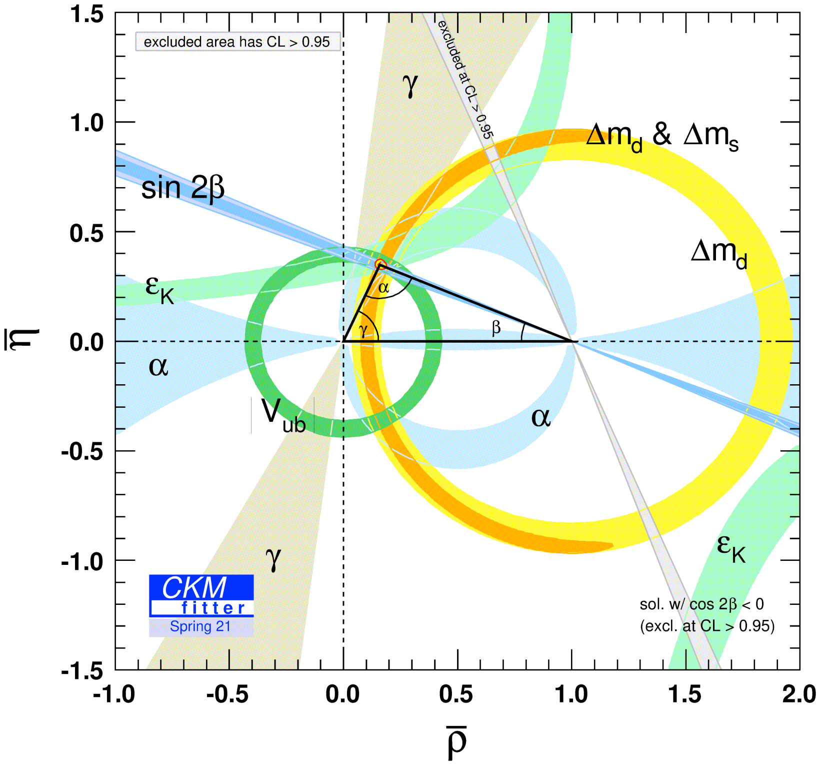

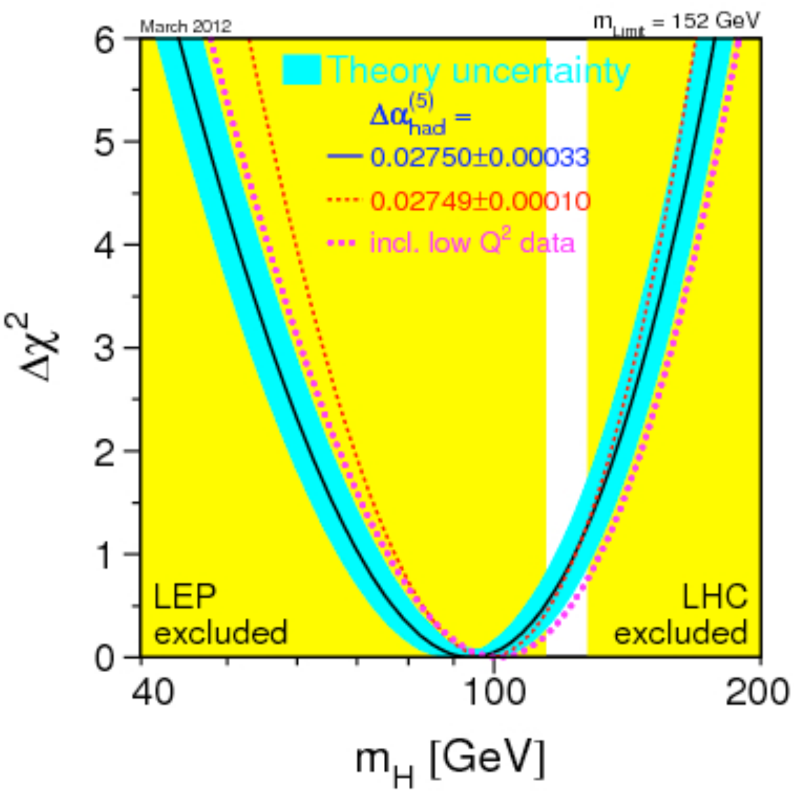

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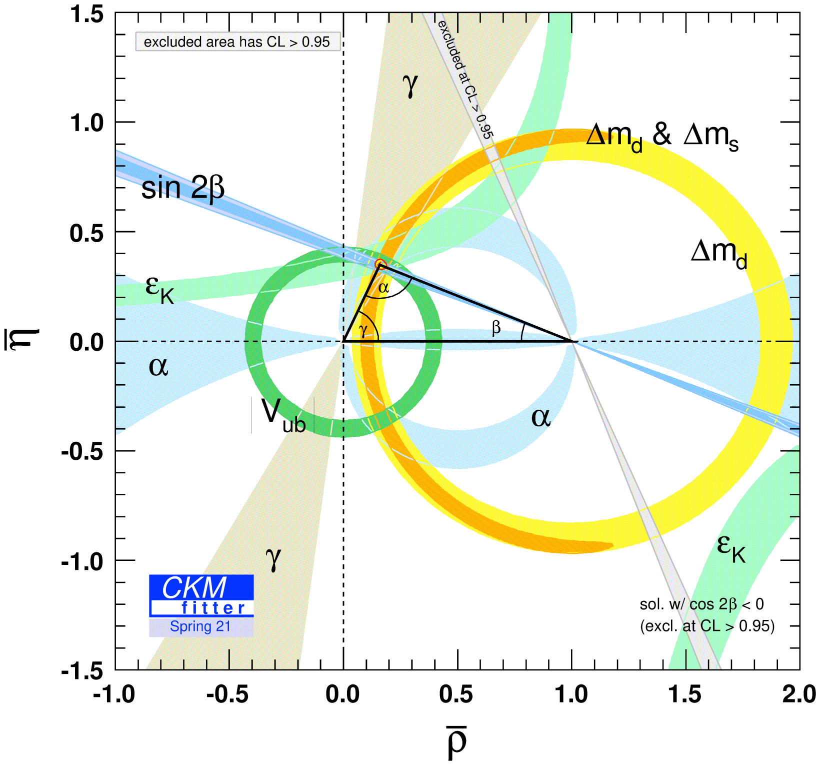

SM became an invincible theory

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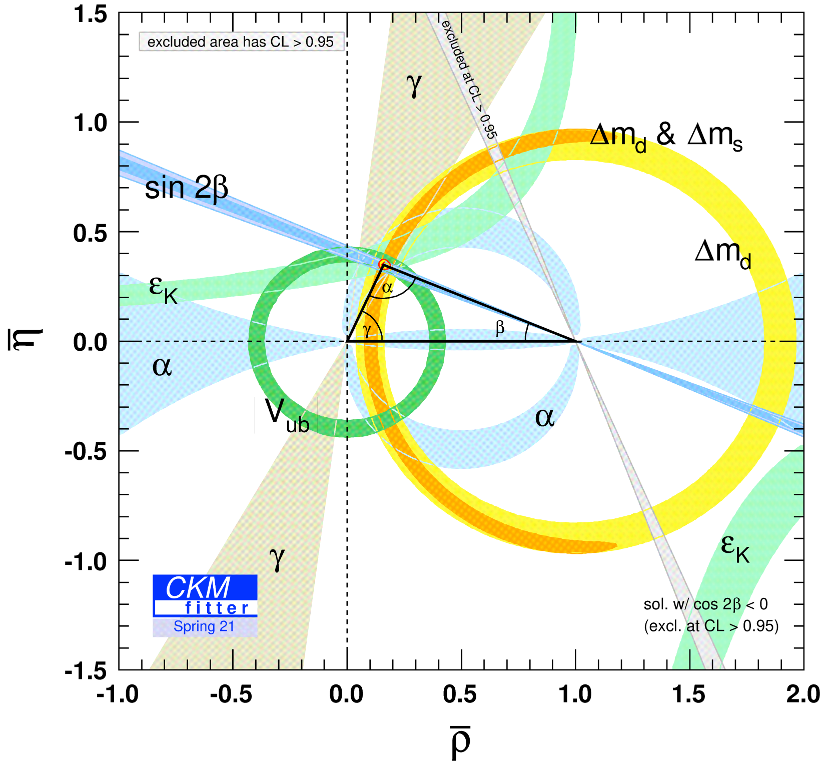
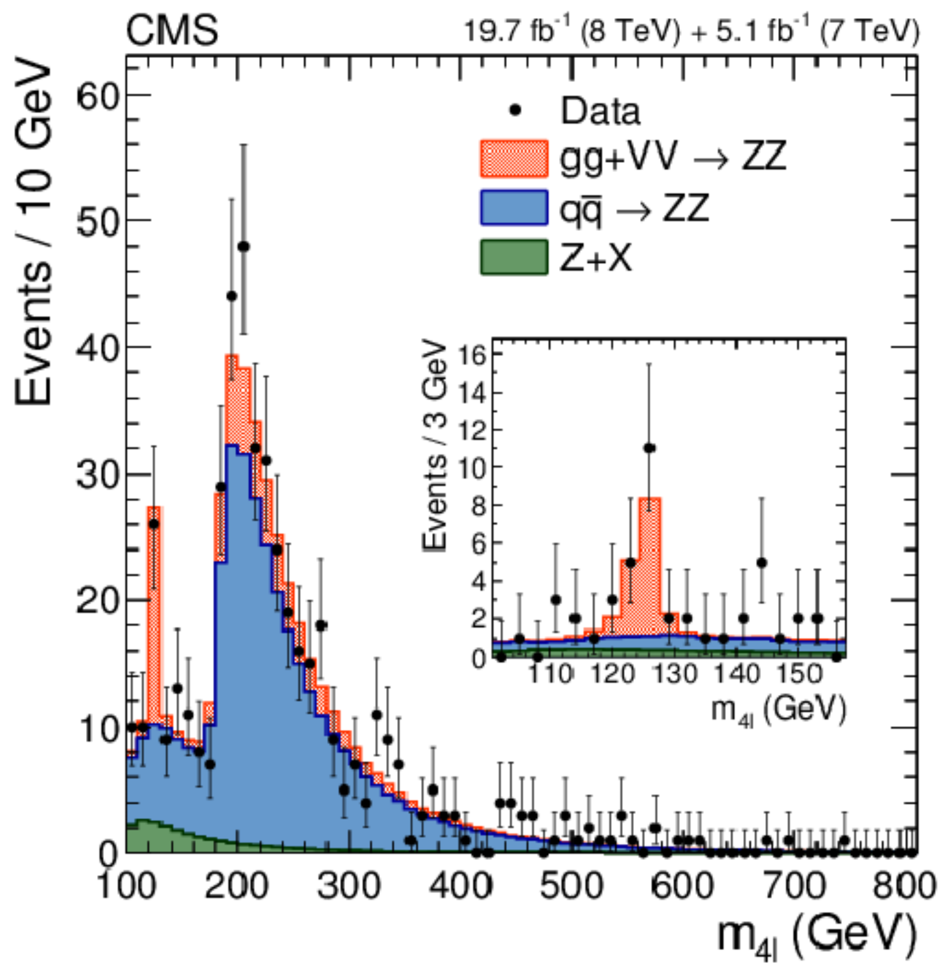
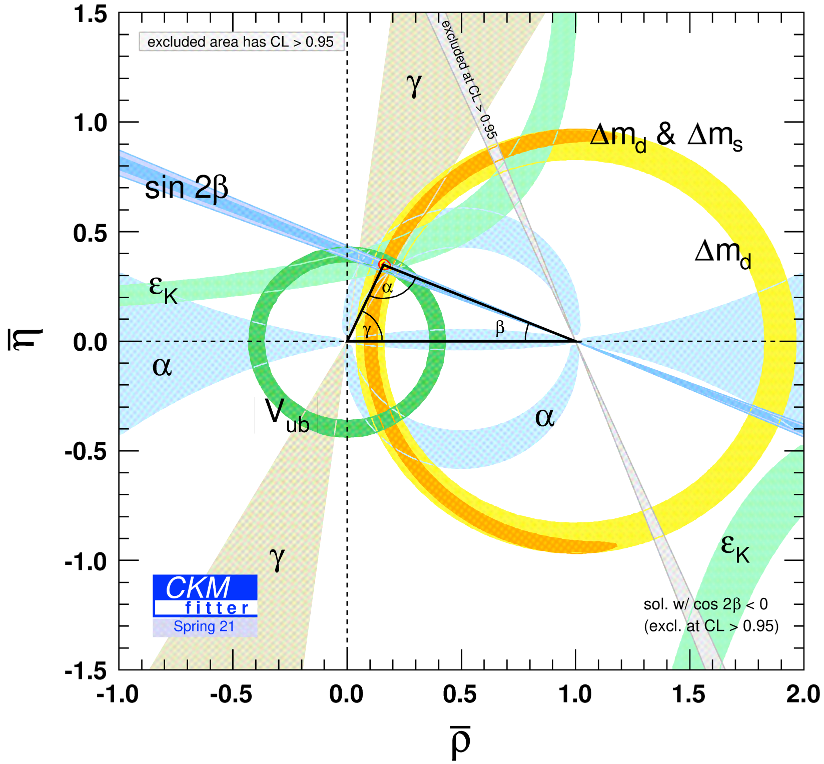




SM became an invincible theory

Recap: the two pillars of the SM: EWPT and quark flavours.



Lessons

SM became an invincible theory

Lessons

- The SM has (mostly) cleared so far the attacks from LEP, TeVatron, *B*-factories, LHC and single-observables experiments.

- There are compelling beauty arguments for Beyond Standard Model (BSM) Physics. I will overlook them.

- Instead, three indisputable measurements/observations are crying for BSM:

  - The neutrinos have a mass. Though several ways exist theoretically, it's tempting / natural to enhance the neutral particle content with right-handed states.

  - Dark matter: among last evidences for cosmological dark matter is the observation of a low surface brightness galaxy [ArXiv:1606.06291].

  - Baryonic asymmetry in the Universe.

Scientific context:

A selection of experiment timelines for running projects, on track projects and foreseeable projects

Scientific context: LHC timeline (GPD-wise)

LHC Run I | LHC Run II | LHC Run III, … | HL-LHC

2015 - 20 /fb

2018 - 50 /fb

2026 - 300 /fb

~2040- 3000 /fb

Legend and disclaimer:

- on track or running
- foreseen projects
- timeline mistakes, lumi. approximation, omissions are mine.

Landscape of future colliders - Flavour_centered

LHC(b)

LHC(b) upgrade I

LHCb Upgrade II

2019 - 9 /fb

~2030- 50/fb

~2040 - 300 /fb

2045 - 150 /ab

FCC-*ee*

FCC-*hh*

ILC, CLIC, C3 …

Belle II

Comet-Meg& friends.

KOTO - NA62 ...

ShIP

Legend and disclaimer:

- on track or running
- foreseen projects
- timeline, lumi, mistakes, omissions are mine.

Landscape of future colliders

Why large projects are necessary ?

Are these timescales any reasonable ?

Scientific context: historical timelines

1964 Electroweak unification

Neutral current discovery in 1973 by Gargamelle (CERN).

1979 Glashow, Salam and Weinberg get the Nobel.

1971 EW loops and RN

Top quark mass predicted by LEP, CERN (from M_Z and other EWPO).

Top quark discovered by CDF, FNAL.

1999 t'Hooft and Veltman get the Nobel.

1973 *CP* violation

The *B*-factories establish that the KM paradigm is the dominant source of *CP* violation in *K* and *B* particle systems.

2008 Kobayashi and Maskawa get the Nobel.

1964 Fundamental Scalar

Higgs boson mass cornered by LEP (EWPO) and Tevatron (top and *W* mass).

An alike Higgs boson discovered where said at LHC.

2013 Englert and Higgs get the Nobel.

Landscape of future colliders

Why large projects are necessary ?

Collider Physics for High Energy Physics is mandatory to answer the fundamental questions.

Are these timescales any reasonable ?

If one wants to devise the next-to-HL-LHC, it has to be prepared now.

Scientific context:

[B]SM Scenarii

Scientific context: scenarii

1) Find a new heavy particle at the Run III of LHC:

- HL-LHC can study it to a certain extent.
- If mass is small enough (and couples to electrons), CLIC can be the way.
- Larger energies are needed to study (find) the whole spectrum.
- The underlying quantum structure must be studied.

2) Find no new particle, but non-standard *H* properties

- HL-LHC can study it to a certain extent.
- Higgs factory.
- *Z*, *W*, top factories for the quantum structure.
- Energy frontier (also for precision measurements)

3) Find no new particle, standard H properties but flavour observables departing from SM:

- *Z*, *W*, top factories for the quantum and flavour structure.
- Energy frontier to find the corresponding spectrum.

4) Find no new particle, standard H properties and flavour observables in SM:

- Asymptotic *Z*, *W*, *H*, top factories for asymptotic precision.
- Push the energy frontier to the best of our knowledge.

Outline of the lecture

- Scientific context I: what we think we know.
  Scientific context II: how do we know what we think we know?

- Let there be light ! Anticipations (on a subjective basis) about the experiments / projects which will shed light on the Beyond SM.
  - Lepton flavours at large: magnetic moments, lepton flavour violation, neutrinos & friends.
  - Quark flavours at large: kaons and CKM, charm, beauty.
  - Dark matter, dark matters? Dark matters! Dark Matter ...

- Introduction to the Future Circular Colliders project or a long term vision for the Particle Physics. The fundamental scalar of the Nature and the electroweak thresholds.

Outline of the lecture

- PART I:
  - Scientific context I: what we think we know.
  - Scientific context II: how do we know what we think we know?

- PART II: Let there be light ! Flashing some anticipations (on a subjective basis) about the experiments / projects which could / will shed light on the Beyond SM.

- PART III: Introduction to the future projects and focus on Circular Colliders project or a long term vision for the Particle Physics. The fundamental scalar of the Nature and the electroweak thresholds.

Outline of the lecture

- PART I:
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- PART III: Introduction to the future projects and focus Circular Colliders project or a long term vision for the Particle Physics. The fundamental scalar of the Nature and the electroweak thresholds.

Let there be light !

[Subtitle: there should not be a stone unturned]

- W mass: status
- Flavour anomalies in *b*-quark transitions: status
- The (*g*-2) of the muon:status
- This list is by far not comprehensive ! Dark matter, axions, neutrinos etc…

Lecture @ TESHEP2023

- W mass: where do we stand ?

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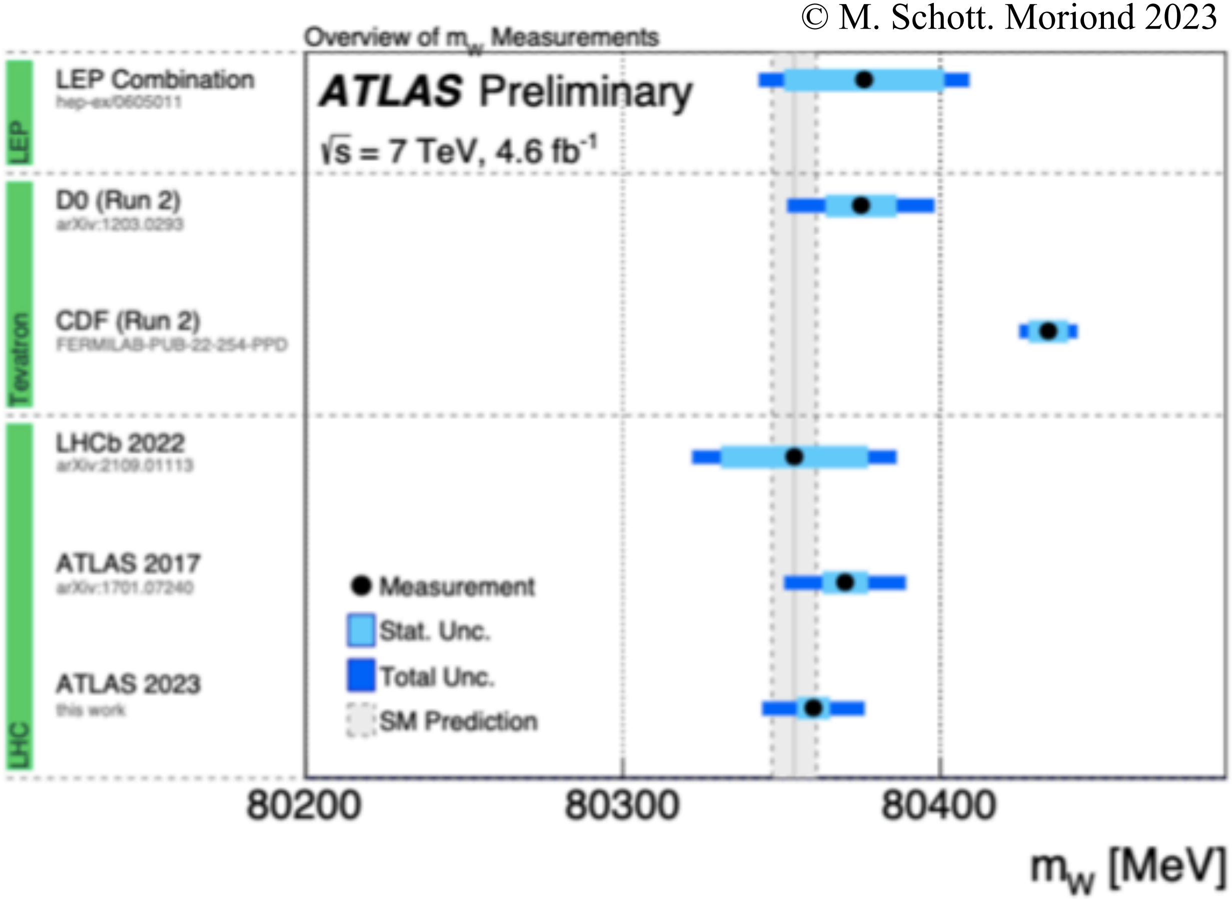

Departure from SM predictions (CDF)

Agreement w/ SM predictions (others)

Disagreement b/w CDF and others

Evidence for experimental systematic bias

If one does not understand, measure more precisely

Lecture @ TESHEP2023

- g-2 of the muon: where do we stand ?

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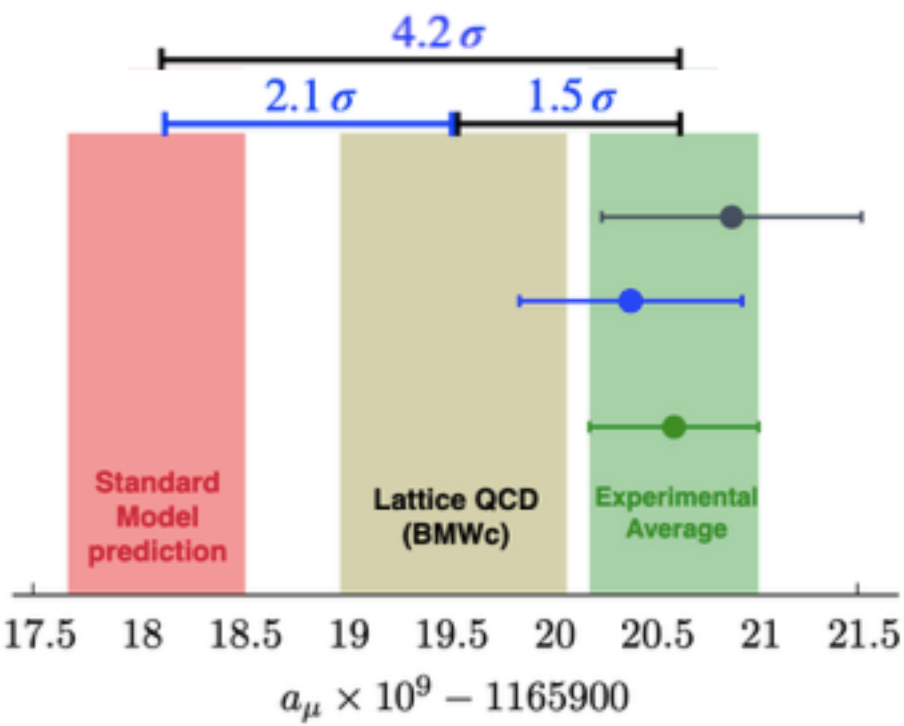
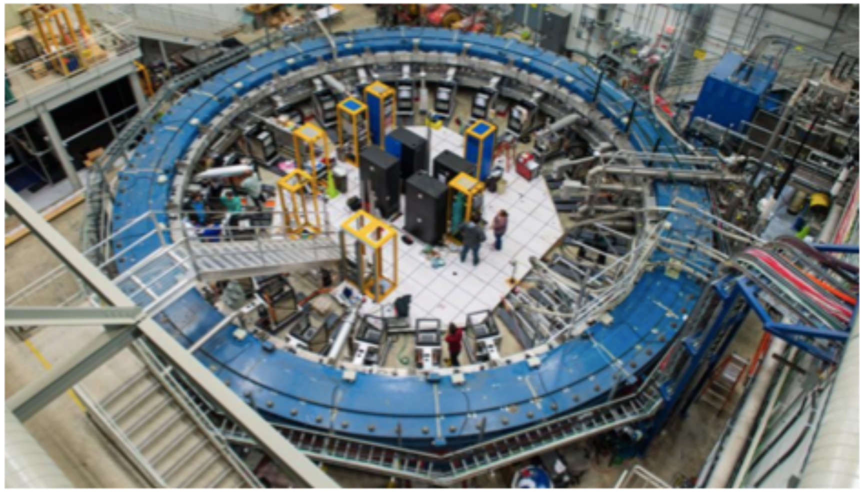




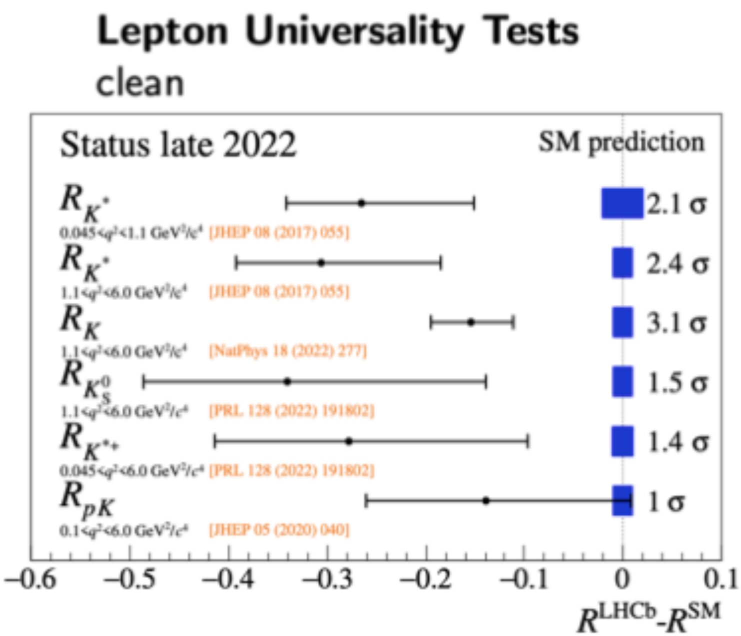
The difference is far larger than the EW corrections

Strong interaction might still explain it

Might also hide the New Physics

Lattice QCD result is also SM !

- b-quark flavour anomalies: where do we stand ?



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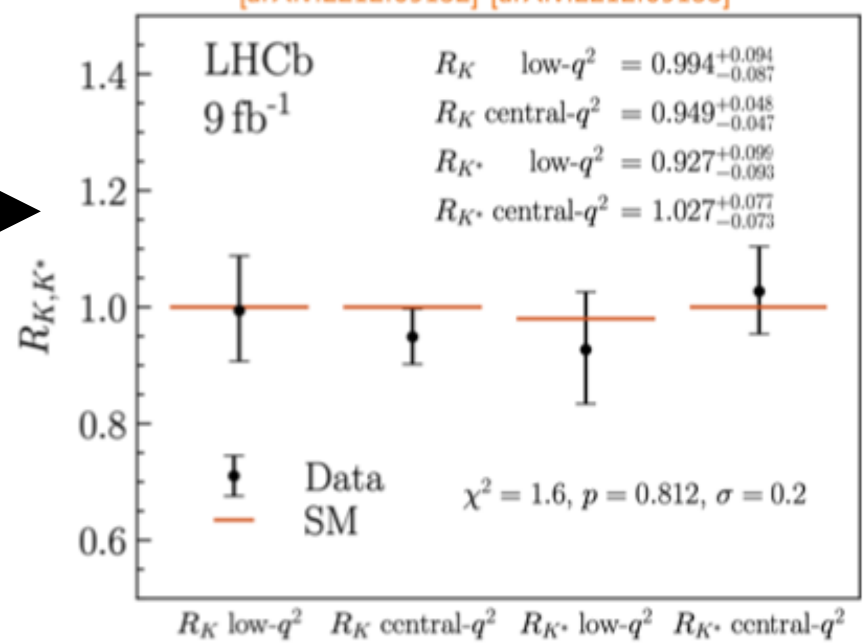
[arXiv:2212.09152] [arXiv:2212.09153]



- The Lepton Flavour Universality breaking evidence in light lepton sector has gone with an alternative analysis.

- b-quark flavour anomalies: where do we stand ?

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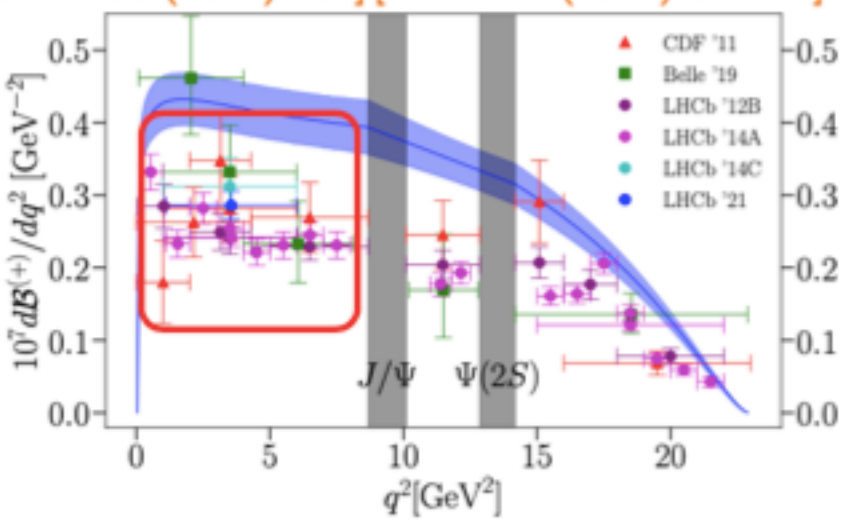
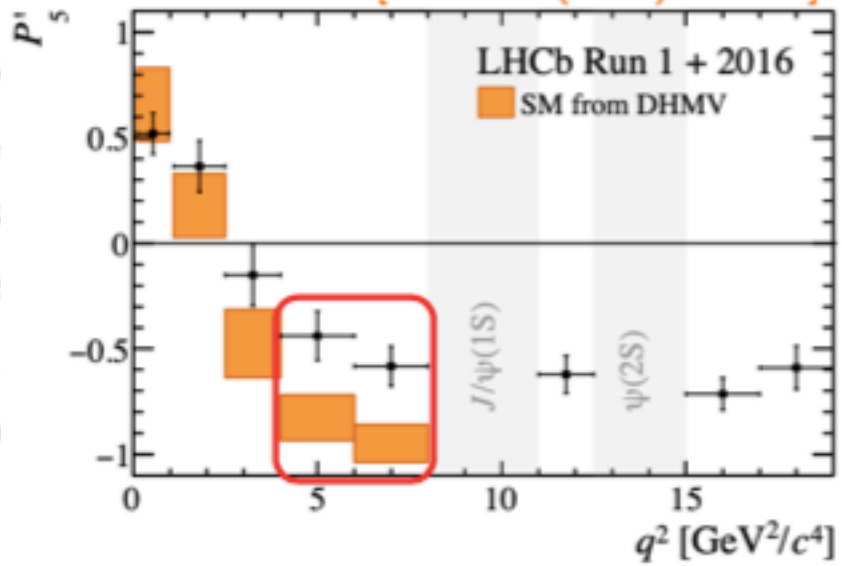
[JHEP 06 (2014) 133] [PRD 107 (2023) 014511]



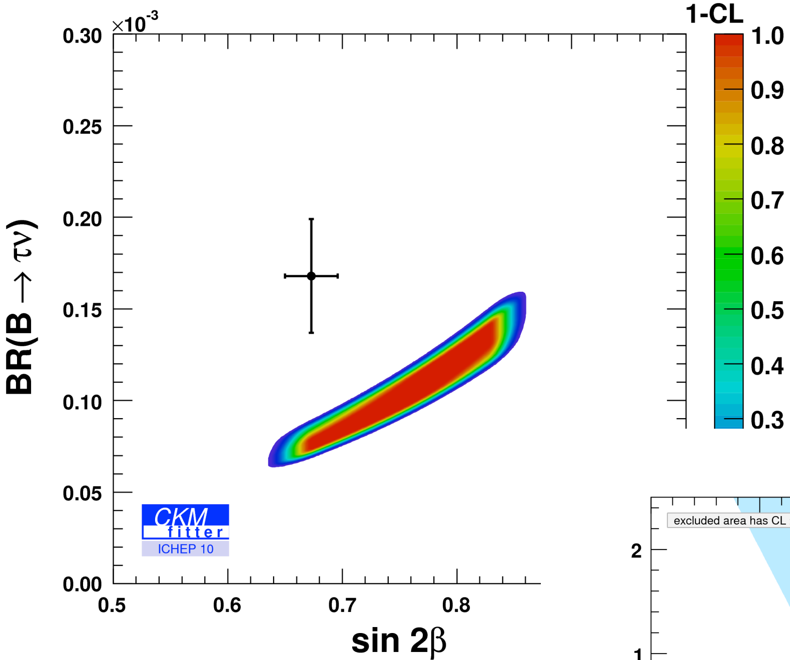
[PRL 125 (2020) 011802]

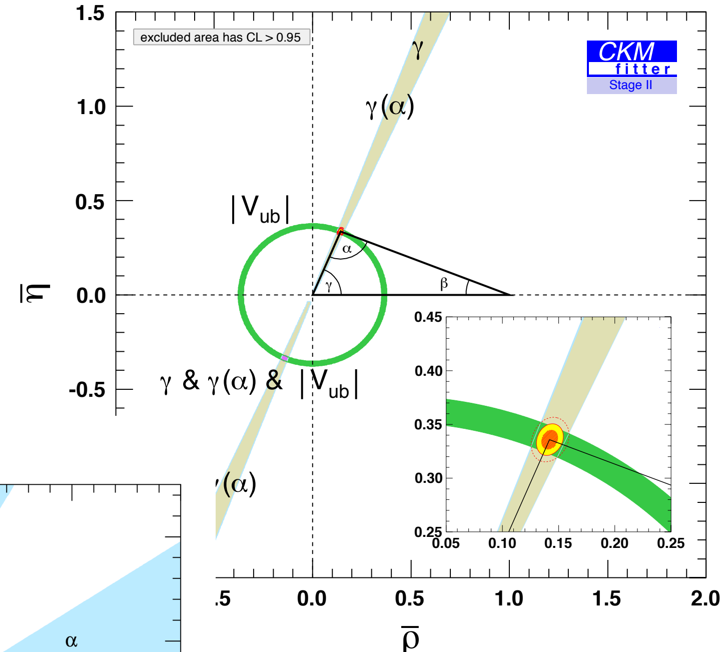


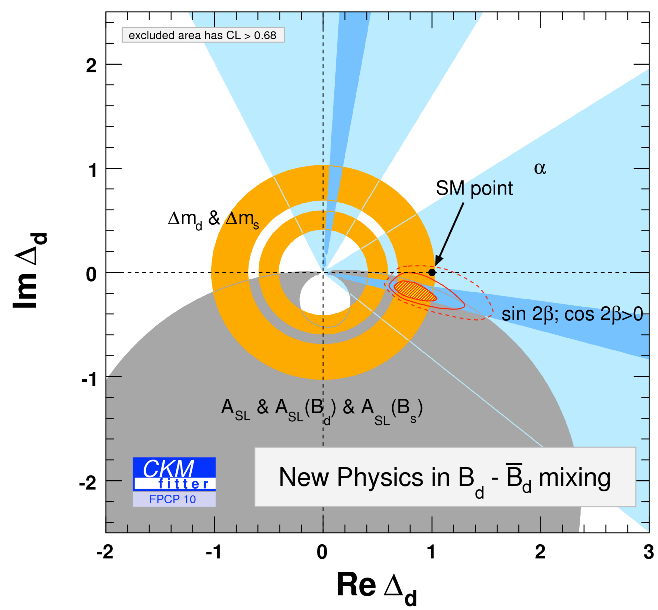
- The other anomalies in $b \to s$ transitions are standing (with predictions plagued though by QCD).

- One historical aparté to conclude this part (2010)
  - Back in early 2010s, the *B*-factories results had established the KM paradigm as a tremendous success of the SM.
  - Yet, a single measurement at the time (it was the first observation of $B^+ \to \tau^+ \nu$) came and has shaken the edifice.
  - It was receiving a “natural” explanation with additional amplitudes contributing to the neutral meson mixing processes.
  - The precision improved and SM stroke back but the precision nowadays is yet limited at 25% on the BF.
  - Re-enforces the need to get that measurement better and the quasi-model-independent NP in mixings at the adequate precision.

- One historical aparté to conclude this part (2010)







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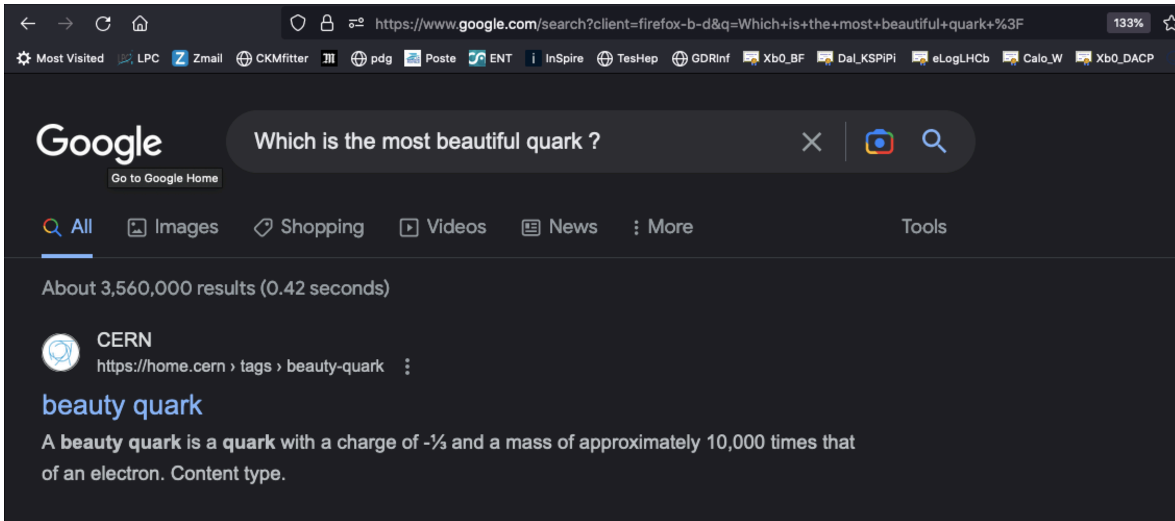

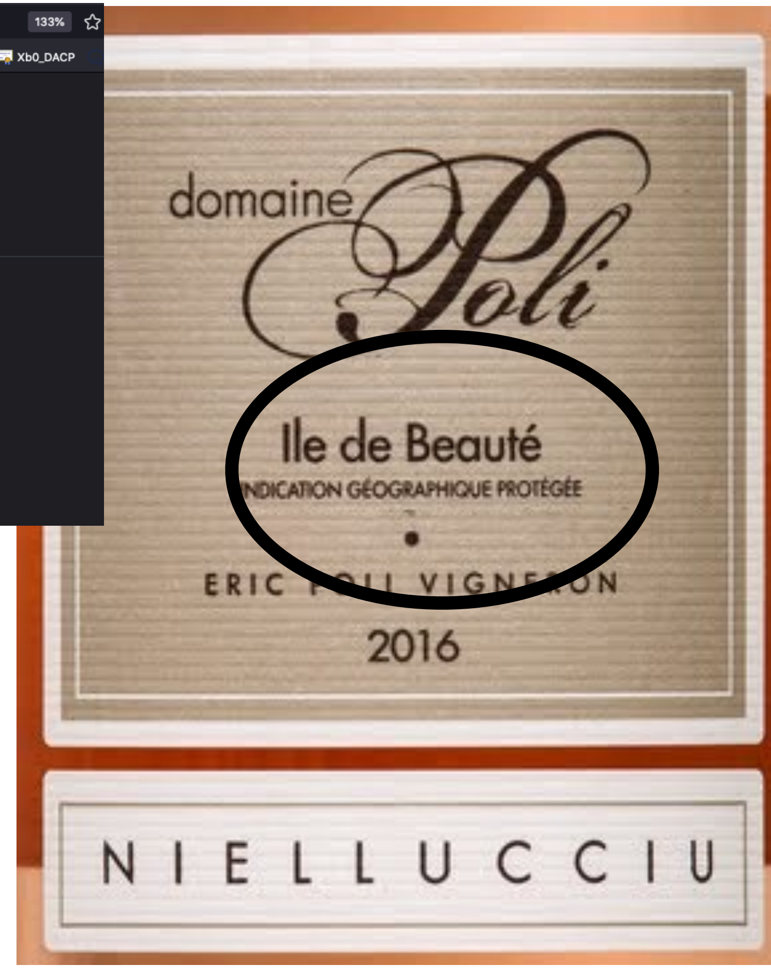

- Beauty Physics has a lot to deliver and the experimental programs are rich for the next two decades.

Lecture @ TESHEP2023

- Take away messages of the part II
  - There are interesting anomalies that we need to study further with the instruments at hand. We need to be modest: a single measurement can bring a change of paradigm.
  - Anomalies can be either a biased measurement, a failure of the prediction or its precision or New Physics.
  - Theory and experiment should go hand to hand to falsify (or better re-enforce) them.
  - Look everywhere ! But prepare the next ground breaking experiments.

Introduction to the next large scale particle Physics apparatus:

the FCC project or a long term vision for Particle Physics

Intermezzo

The HL-LHC won't likely answer most of the outstanding questions of the field.

Be it only for the accurate study of the Higgs-boson decays, an electron collider is the way to go (or the way we know how to go forward). There is a consensus among the community.

What is not yet consensual is the nature of this collider.

If we say that the next large scale machine must be an electron collider: what are the projects on the table in the world?

Intermezzo

Circular vs Linear. Pros and Cons. It's to you to play.

Intermezzo

Circular vs Linear. Pros and Cons. It's to you to play.

Luminosity ?

Intermezzo

Circular vs Linear. Pros and Cons. It's to you to play.

Intermezzo

Circular vs Linear. Pros and Cons. It's to you to play.

Luminosity: Circular (up to 3 order of magnitude)

Intermezzo

Circular vs Linear. Pros and Cons. It's to you to play.

Intermezzo

Circular vs Linear. Pros and Cons. It's to you to play.

Energy ?

Intermezzo

Circular vs Linear. Pros and Cons. It's to you to play.

Energy ?

Luminosity: Circular (up to 3 order of magnitude)

Energy: Linear (up to 3 TeV st. of the Art vs 400 GeV)

Intermezzo

Circular vs Linear. Pros and Cons. It's to you to play.

Intermezzo

Circular vs Linear. Pros and Cons. It's to you to play.

Beam Energy?

Intermezzo

Circular vs Linear. Pros and Cons. It's to you to play.

Intermezzo

Circular vs Linear. Pros and Cons. It's to you to play.

Luminosity: Circular (up to 3 order of magnitude)

Energy: Linear (up to 3 TeV st. of the Art vs 400 GeV)

Beam Energy: Circular (down to 45 keV !)

Intermezzo

Circular vs Linear. Pros and Cons. It's to you to play.

Intermezzo

Circular vs Linear. Pros and Cons. It's to you to play.

Beam Polarisation?

Intermezzo

Circular vs Linear. Pros and Cons. It's to you to play.

Intermezzo

Circular vs Linear. Pros and Cons. It's to you to play.

Luminosity: Circular (up to 3 order of magnitude)

Energy: Linear (up to 3 TeV st. of the Art vs 400 GeV)

Beam Energy: Circular (down to 45 keV !)

Beam Polarisation: Linear

Intermezzo

Circular vs Linear. Pros and Cons. It's to you to play.

Intermezzo

Circular vs Linear. Pros and Cons. It's to you to play.

Intermezzo

Circular vs Linear. Pros and Cons. It's to you to play.

Experiments?

Intermezzo

Circular vs Linear. Pros and Cons. It's to you to play.

Intermezzo

Circular vs Linear. Pros and Cons. It's to you to play.

Luminosity: Circular (up to 3 order of magnitude)

Energy: Linear (up to 3 TeV st. of the Art vs 400 GeV)

Beam Energy: Circular (down to 45 keV !)

Beam Polarisation: Linear

Experiments: Circular (several IPs vs 1).

Intermezzo

Physics program:

Z pole EWP observables —> Circular. One could argue that polarisation is a plus. LEP lesson is that it is not.

WW threshold —> Circular (need beam energy and lumi.)

ZH threshold —> Circular (need beam energy and lumi.)

tt threshold —> Circular for top mass (need beam energy and lumi.) One could argue that polarisation is a plus.

Above tt threshold —> Only Linear at an affordable cost.

FCC-*ee*

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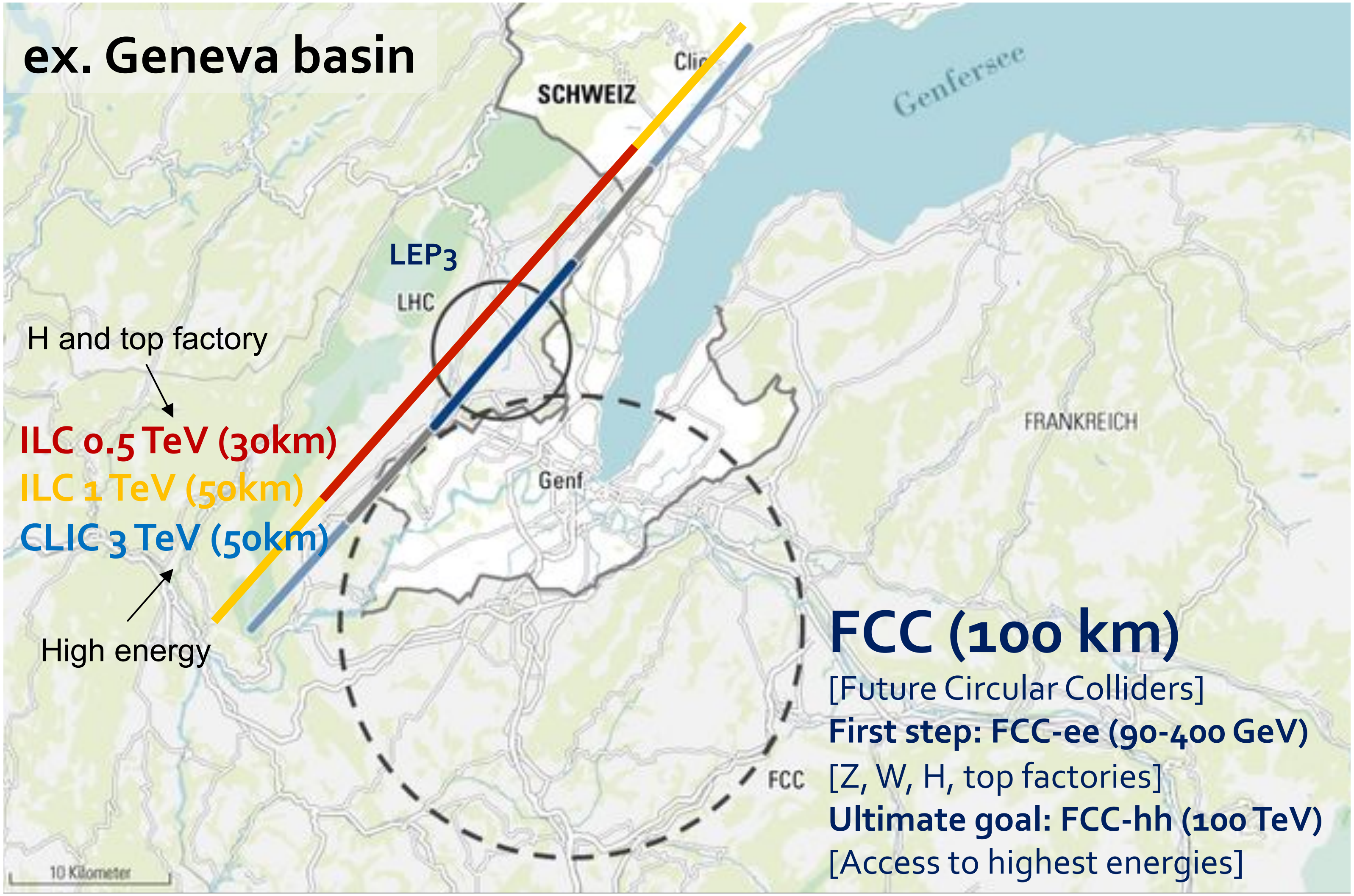


FCC-*ee*

- CepC: e^+e^- collisions at 240 GeV.
- SppC: *pp* collisions at 50-70 TeV.

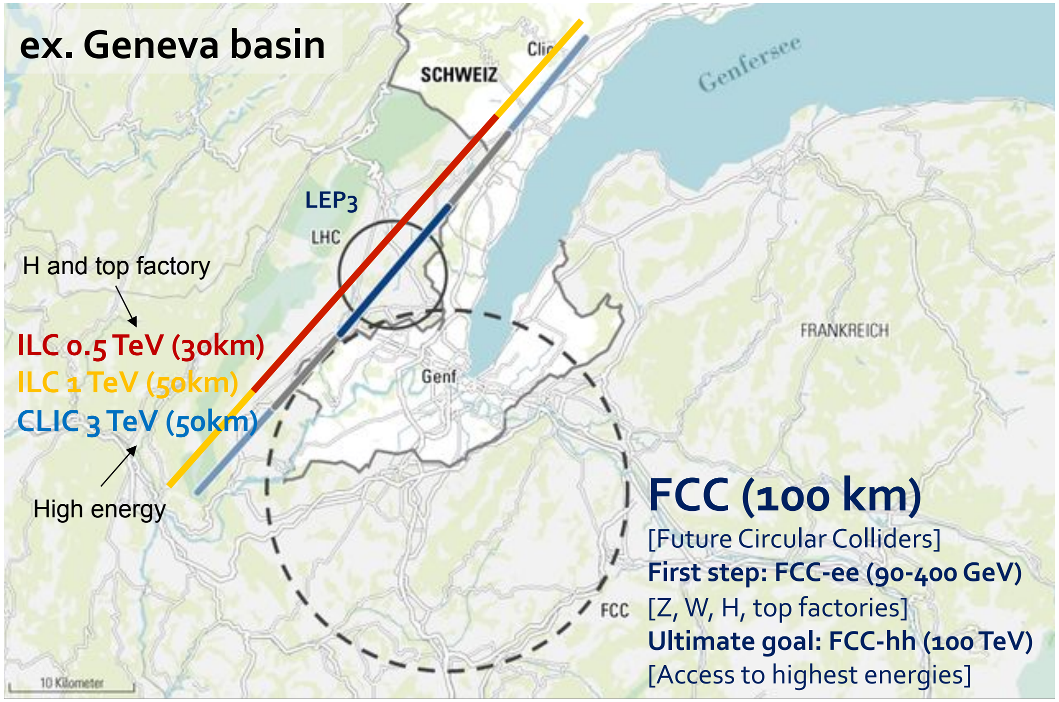
- ILC: longstanding project. Japan delayed the commitment.

FCC project: the Menu

1) Introduction

2) Executive summary of exquisite Physics.

3) Implementation.



1. Introduction to FCC project:

- Starting from the former European HEP strategy 2013

Summary: European Strategy Update 2013
Design studies and R&D at the energy frontier

…."to propose an ambitious **post-LHC accelerator project at CERN** by the time of the next Strategy update":

d) ***CERN should undertake design studies for accelerator projects in a global context,***

- *with emphasis on* ***proton-proton and electron-positron high-energy frontier machines****.*
- *These design studies should be coupled to a vigorous accelerator* ***R&D programme, including high-field magnets and high-gradient accelerating structures****,*
- ***in collaboration with national institutes, laboratories and universities worldwide.***
- **http://cds.cern.ch/record/1567258/files/esc-e-106.pdf**

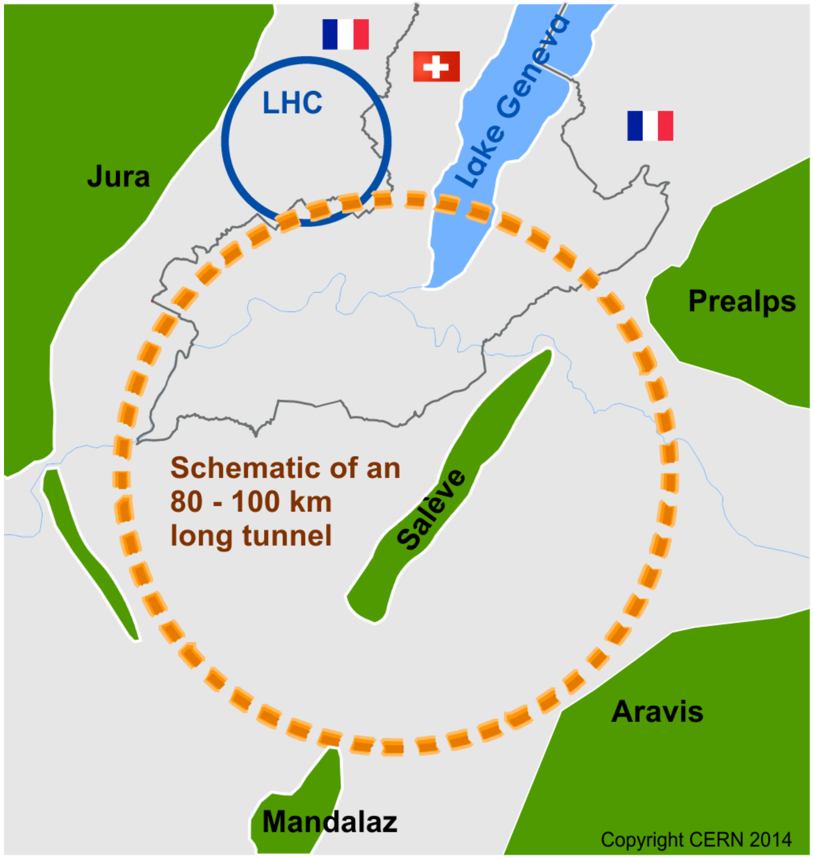
Future Circular Collider Study
Michael Benedikt
FCC Kick-Off 2014
3

- At the time the LHC Run II will have delivered its results, have an educated vision of the reach of future machines for the next round of the European Strategy in 2019.

1. Introduction to FCC: the scope of the project

Forming an international coll. (hosted by Cern) to study:

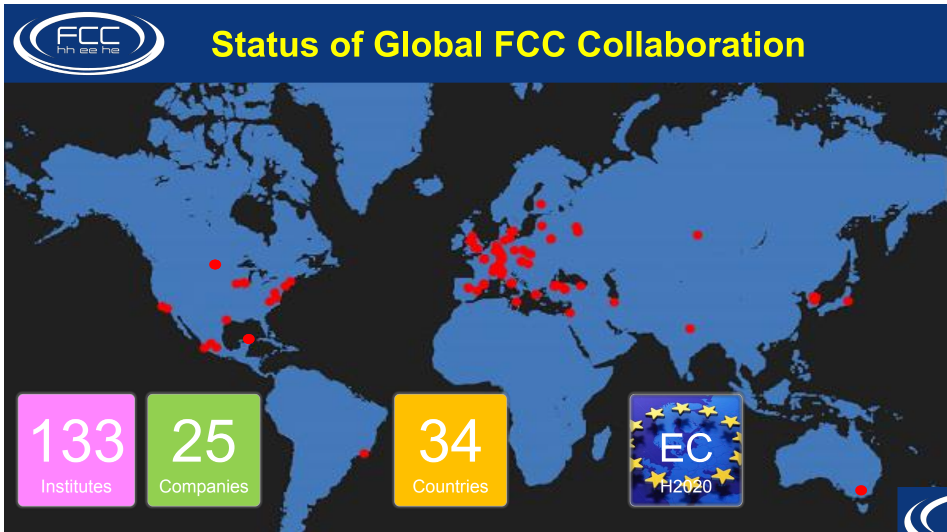
- 100 TeV *pp*-collider (FCC-*hh*) as long term goal, defining infrastructure requirements.
- e^+e^- collider (FCC-*ee*) as potential first step.
- *p-e* (FCC-*he*) as an option.
- 80-100 km infrastructure in Geneva area.



- Conceptual design report and cost review for the next european strategy → 2019 / 2020.

1. Introduction to FCC: the scope of the project

The Design Study is completed and fulfilled the mandate



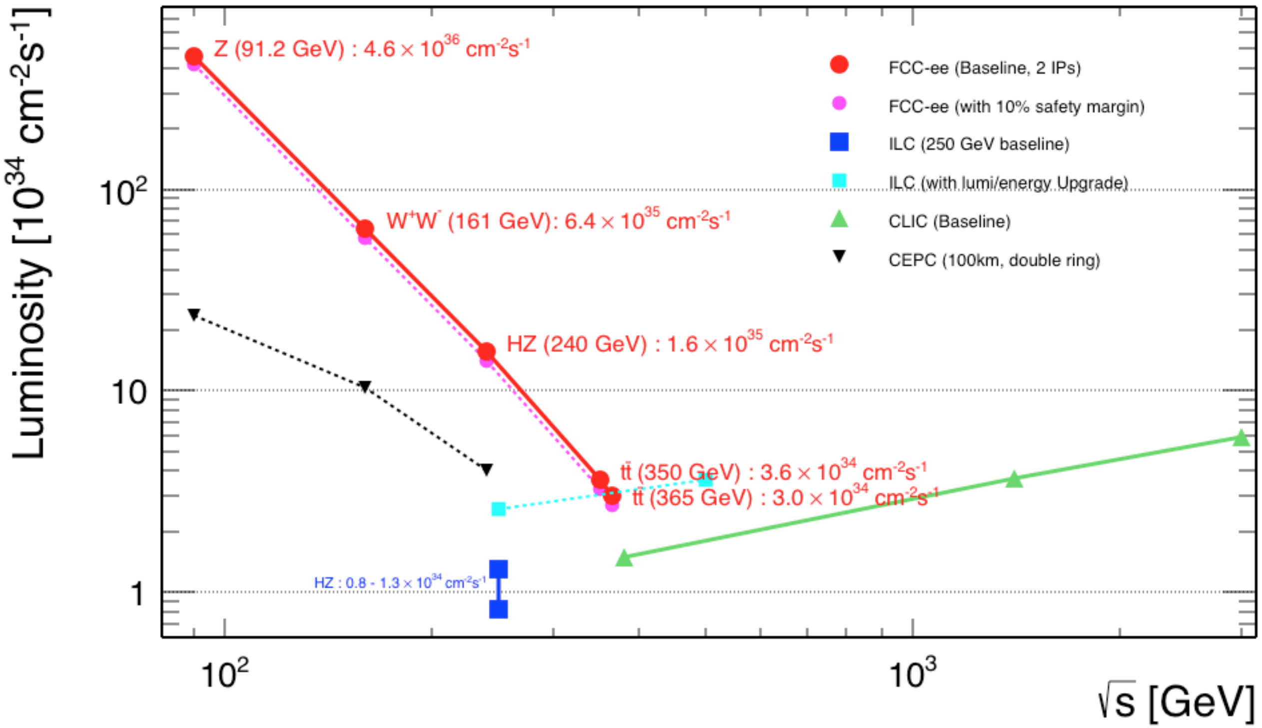
FCC CDR and Study Documentation

- **FCC-Conceptual Design Reports:**
  - **Vol 1 – Physics, Vol 2 – FCC-ee, Vol 3 – FCC-hh, Vol 4 – HE-LHC**
  - Preprints available since 15 January 2019 on http://fcc-cdr.web.cern.ch/
  - CDRs accepted for publication in **European Physical Journal C (Vol 1) and ST (Vol 2 – 4)**
- **Summary documents provided to EPPSU SG in December 2018**
  - **FCC-integral, FCC-ee, FCC-hh, HE-LHC**
  - Accessible on http://fcc-cdr.web.cern.ch/

Future Circular Collider Study
Michael Benedikt
Physics at FCC, 4 March 2019
13

2. Executive Summary by Physics thresholds.

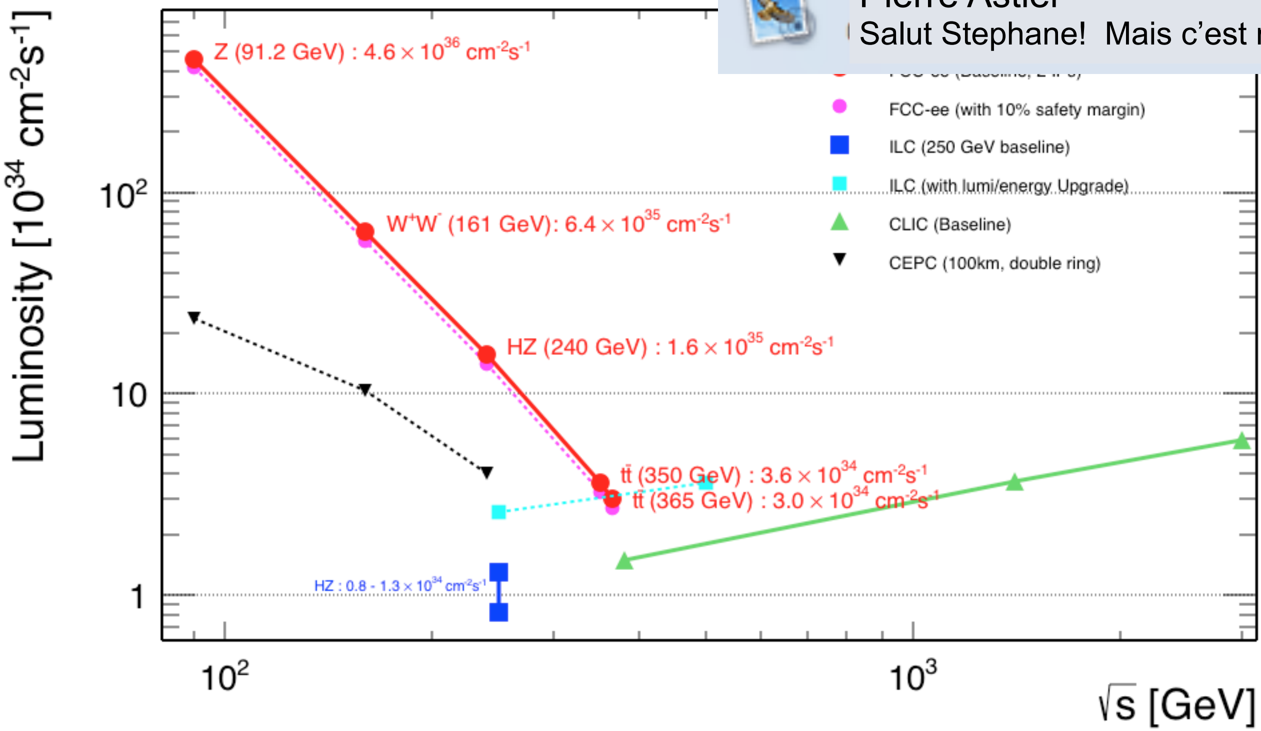
2. Luminosity figure



- The FCC-ee offers the largest luminosities in its whole energy range.

- We‘re speaking here of 10^5 *Z*/s , 10^4 *W*/h, 1.5 10^3 *H* and top /d, in a very clean environment: no pile-up, controlled beam backgrounds, *E* and *p* constraints, without trigger.

2. Luminosity figure



Pierre Astier
Salut Stephane! Mais c'est magnifique ! Let's do this !

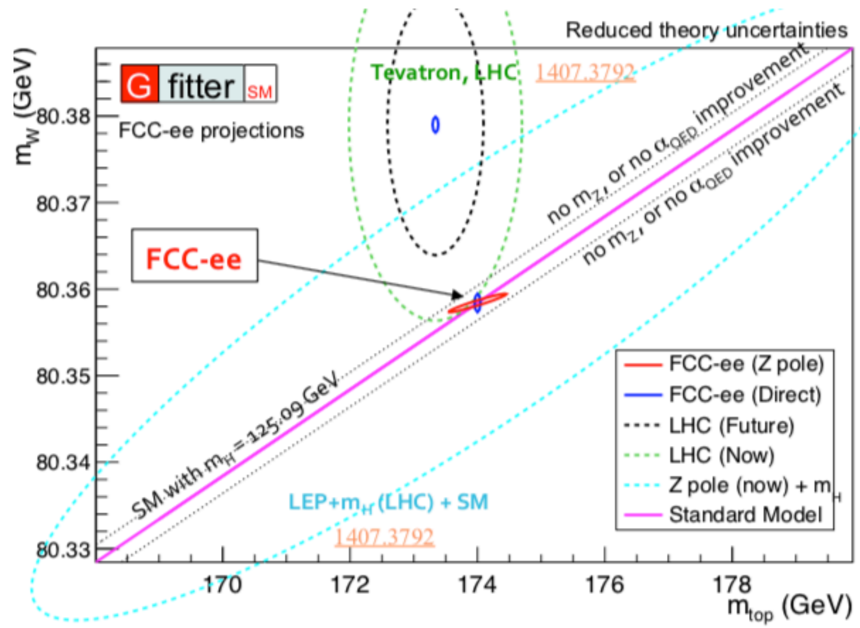
- The FCC-ee offers the largest luminosities in its whole energy range.

- We're speaking here of 10^5 *Z*/s , 10^4 *W*/h, 1.5 10^3 *H* and top /d, in a very clean environment: no pile-up, controlled beam backgrounds, *E* and *p* constraints, without trigger.

2. Big picture.

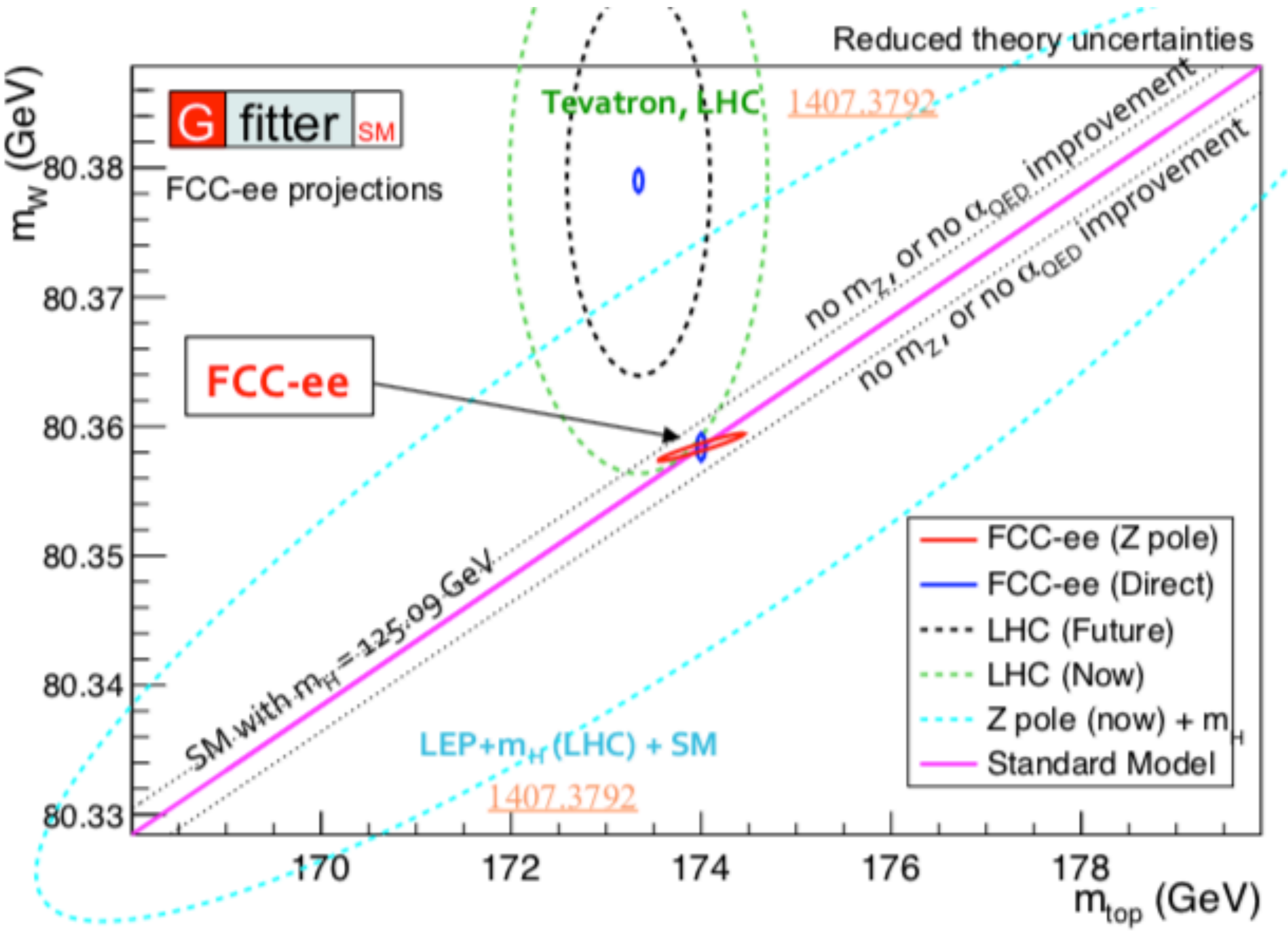
Table 3.1: Measurement of selected electroweak quantities at the FCC-ee, compared with the present precisions.

	Observable	present value ± error	FCC-ee Stat.	FCC-ee Syst.	Comment and dominant exp. error
Z pole	m_Z (keV/c^2)	91186700 ± 2200	5	100	From Z line shape scan Beam energy calibration
	Γ_Z (keV)	2495200 ± 2300	8	100	From Z line shape scan Beam energy calibration
	R_ℓ^Z ($\times 10^3$)	20767 ± 25	0.06	0.2-1	ratio of hadrons to leptons acceptance for leptons
	$\alpha_s(m_Z)$ ($\times 10^4$)	1196 ± 30	0.1	0.4-1.6	from R_ℓ^Z above [29]
	R_b ($\times 10^6$)	216290 ± 660	0.3	<60	ratio of $b\bar{b}$ to hadrons stat. extrapol. from SLD [30]
	σ^0_{had} ($\times 10^3$) (nb)	41541 ± 37	0.1	4	peak hadronic cross-section luminosity measurement
	N_ν($\times 10^3$)	2991 ± 7	0.005	1	Z peak cross sections Luminosity measurement
	$\sin^2\theta_W^{eff}$($\times 10^6$)	231480 ± 160	3	2 - 5	from $A_{FB}^{\mu\mu}$ at Z peak Beam energy calibration
	$1/\alpha_{QED}(m_Z)$($\times 10^3$)	128952 ± 14	4	small	from $A_{FB}^{\mu\mu}$ off peak [20]
	$A_{FB}^{b,0}$ ($\times 10^4$)	992 ± 16	0.02	1-3	b-quark asymmetry at Z pole from jet charge
	$A_{FB}^{pol,\tau}$ ($\times 10^4$)	1498 ± 49	0.15	<2	τ polarisation and charge asymmetry τ decay physics
WW thr.	m_W (keV/c^2)	80350000 ± 15000	600	300	From WW threshold scan Beam energy calibration
	Γ_W (keV)	2085000 ± 42000	1500	300	From WW threshold scan Beam energy calibration
	$\alpha_s(m_W)$($\times 10^4$)	1170 ± 420	3	small	from R_ℓ^W [31]
	N_ν($\times 10^3$)	2920 ± 50	0.8	small	ratio of invis. to leptonic in radiative Z returns
tt thr.	m_{top} (MeV/c^2)	172740 ± 500	20	small	From $t\bar{t}$ threshold scan QCD errors dominate
	Γ_{top} (MeV/c^2)	1410 ± 190	40	small	From $t\bar{t}$ threshold scan QCD errors dominate
	$\lambda_{top}/\lambda_{top}^{SM}$	1.2 ± 0.3	0.08	small	From $t\bar{t}$ threshold scan QCD errors dominate
	ttZ couplings	± 30%	<2%	small	From E_{CM} = 365GeV run



- Ultimate quantum completeness consistency test of the SM.
- The improvements in theory prediction precision is part of the FCC program.

2. The Z pole — 1

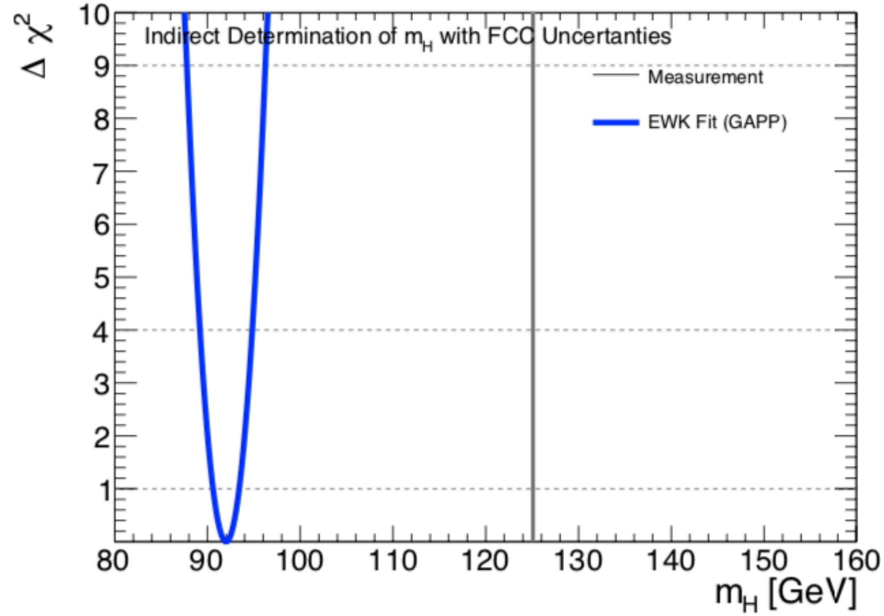


Reduced theory uncertainties
G fitter SM
FCC-ee projections
Tevatron, LHC
1407.3792
FCC-ee
no m_Z, or no α_{QED} improvement
no m_Z, or no α_{QED} improvement
SM with m_H = 125.09 GeV
LEP+m_H (LHC) + SM
1407.3792
FCC-ee (Z pole)
FCC-ee (Direct)
LHC (Future)
LHC (Now)
Z pole (now) + m_H
Standard Model
m_W (GeV)
80.38
80.37
80.36
80.35
80.34
80.33
170
172
174
176
178
m_{top} (GeV)

2. Big picture.

Table 3.1: Measurement of selected electroweak quantities at the FCC-ee, compared with the present precisions.

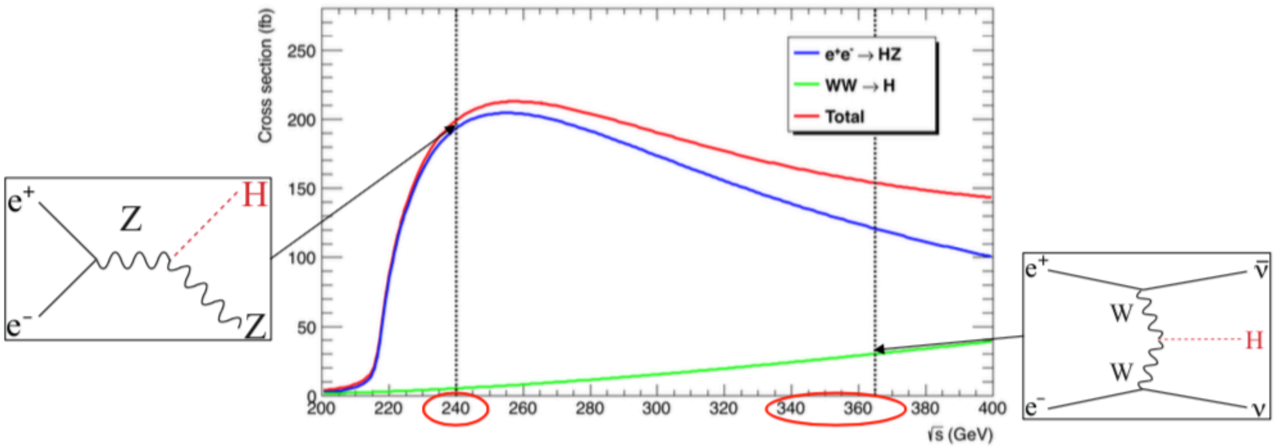
	Observable	present value ± error	FCC-ee Stat.	FCC-ee Syst.	Comment and dominant exp. error
Z pole	m_Z (keV/c^2)	91186700 ± 2200	5	100	From Z line shape scan Beam energy calibration
	Γ_Z (keV)	2495200 ± 2300	8	100	From Z line shape scan Beam energy calibration
	R_ℓ^Z ($\times 10^3$)	20767 ± 25	0.06	0.2-1	ratio of hadrons to leptons acceptance for leptons
	$\alpha_s(m_Z)$ ($\times 10^4$)	1196 ± 30	0.1	0.4-1.6	from R_ℓ^Z above [29]
	R_b ($\times 10^6$)	216290 ± 660	0.3	<60	ratio of $b\bar{b}$ to hadrons stat. extrapol. from SLD [30]
	σ^0_{had} ($\times 10^3$) (nb)	41541 ± 37	0.1	4	peak hadronic cross-section luminosity measurement
	N_ν ($\times 10^3$)	2991 ± 7	0.005	1	Z peak cross sections Luminosity measurement
	$\sin^2\theta_W^{eff}$ ($\times 10^6$)	231480 ± 160	3	2 - 5	from $A_{FB}^{\mu\mu}$ at Z peak Beam energy calibration
	$1/\alpha_{QED}(m_Z)$ ($\times 10^3$)	128952 ± 14	4	small	from $A_{FB}^{\mu\mu}$ off peak [20]
	$A_{FB}^{b}, 0$ ($\times 10^4$)	992 ± 16	0.02	1-3	b-quark asymmetry at Z pole from jet charge
	$A_{FB}^{pol,\tau}$ ($\times 10^4$)	1498 ± 49	0.15	<2	τ polarisation and charge asymmetry τ decay physics
WW thr.	m_W (keV/c^2)	80350000 ± 15000	600	300	From WW threshold scan Beam energy calibration
	Γ_W (keV)	2085000 ± 42000	1500	300	From WW threshold scan Beam energy calibration
	$\alpha_s(m_W)$ ($\times 10^4$)	1170 ± 420	3	small	from R_ℓ^W [31]
	N_ν ($\times 10^3$)	2920 ± 50	0.8	small	ratio of invis. to leptonic in radiative Z returns
tt thr.	m_{top} (MeV/c^2)	172740 ± 500	20	small	From $t\bar{t}$ threshold scan QCD errors dominate
	Γ_{top} (MeV/c^2)	1410 ± 190	40	small	From $t\bar{t}$ threshold scan QCD errors dominate
	$\lambda_{top}/\lambda_{top}^{SM}$	1.2 ± 0.3	0.08	small	From $t\bar{t}$ threshold scan QCD errors dominate
	ttZ couplings	± 30%	<2%	small	From E_{CM} = 365GeV run



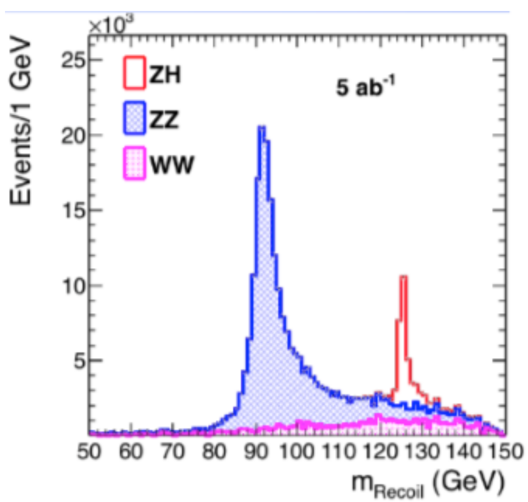
- Ultimate quantum completeness consistency test of the SM.
- The improvements in theory prediction precision is part of the FCC program. Precision 1.4 GeV.

2. The Higgs factory

- Two energy points (240 and 360 GeV) for the program

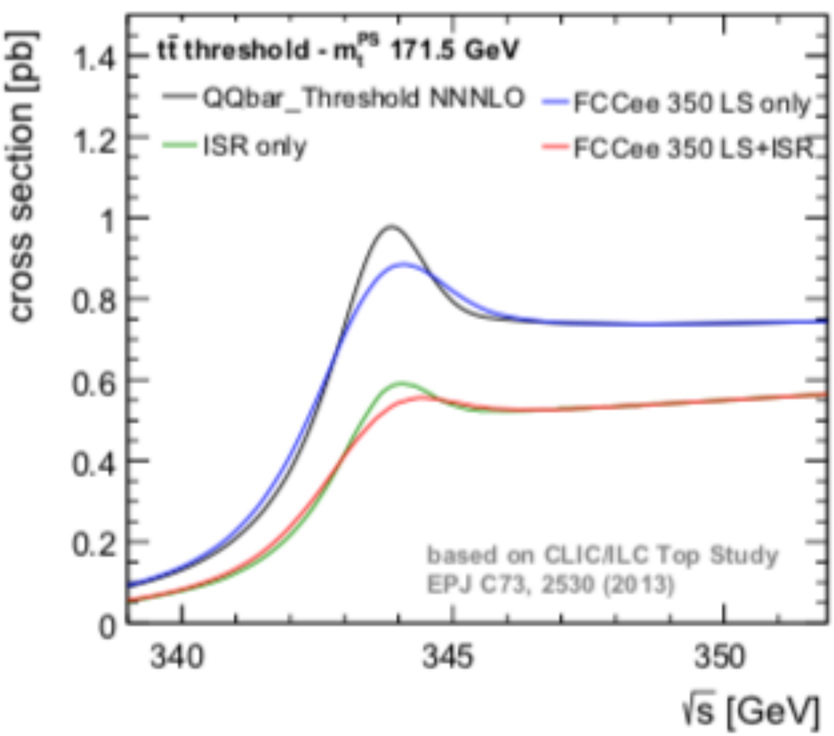


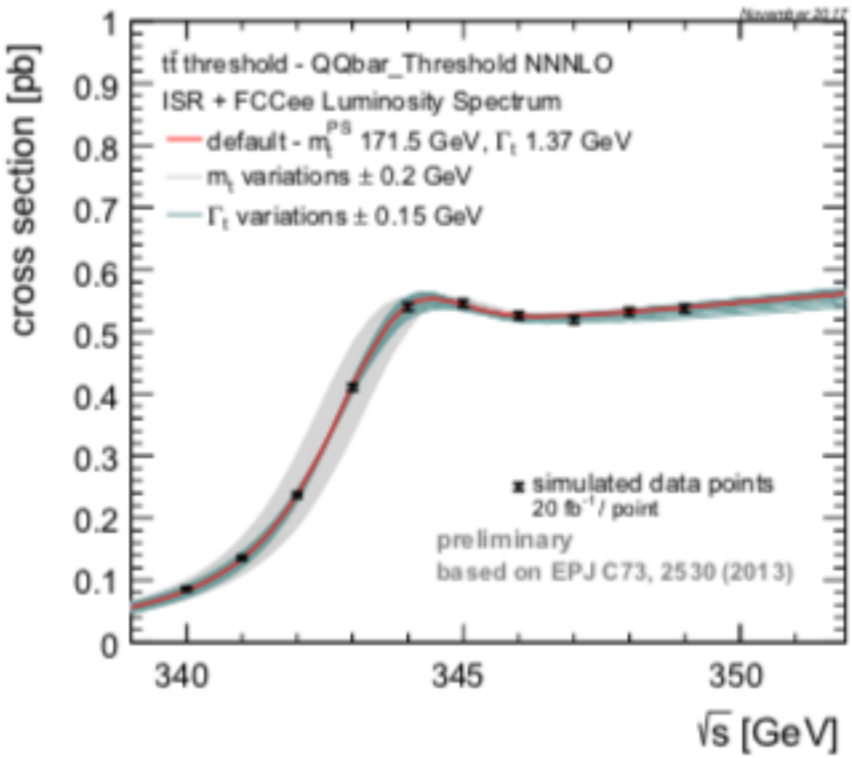
- Invincible precision on the absolute couplings and width. Interplay with HL-LHC.



Collider	HL-LHC	FCC-ee		
Luminosity (ab^{-1})	3	5 @ 240GeV	+1.5 @ 365GeV	+HL-LHC
Years	25	3	**+4**	-
$\delta\Gamma_H/\Gamma_H$ (%)	SM	2.7	**1.3**	1.1
$\delta g_{HZZ}/g_{HZZ}$ (%)	1.3	0.2	**0.17**	0.16
$\delta g_{HWW}/g_{HWW}$ (%)	1.4	1.3	**0.43**	0.40
$\delta g_{Hbb}/g_{Hbb}$ (%)	2.9	1.3	**0.61**	0.55
$\delta g_{Hcc}/g_{Hcc}$ (%)	SM	1.7	**1.21**	1.18
$\delta g_{Hgg}/g_{Hgg}$ (%)	1.8	1.6	**1.01**	0.83
$\delta g_{H\tau\tau}/g_{H\tau\tau}$ (%)	1.7	1.4	**0.74**	0.64
$\delta g_{H\mu\mu}/g_{H\mu\mu}$ (%)	4.4	10.1	**9.0**	3.9
$\delta g_{H\gamma\gamma}/g_{H\gamma\gamma}$ (%)	1.6	4.8	**3.9**	1.1
$\delta g_{Htt}/g_{Htt}$ (%)	2.5	–	**–**	2.4
BR_{EXO} (%)	SM (0.0)	<1.2	**<1.0**	<1.0

2. The top threshold

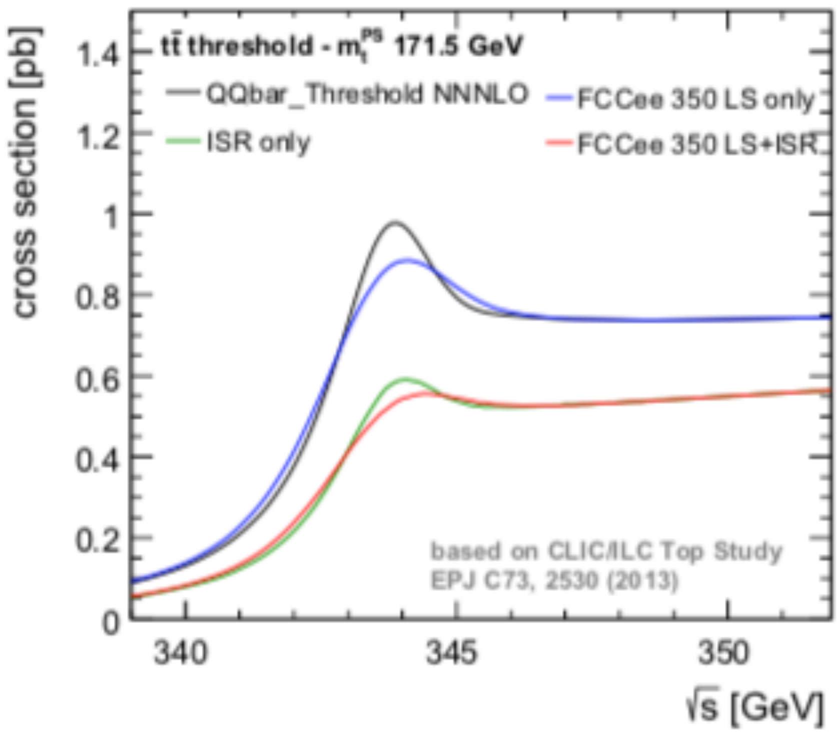


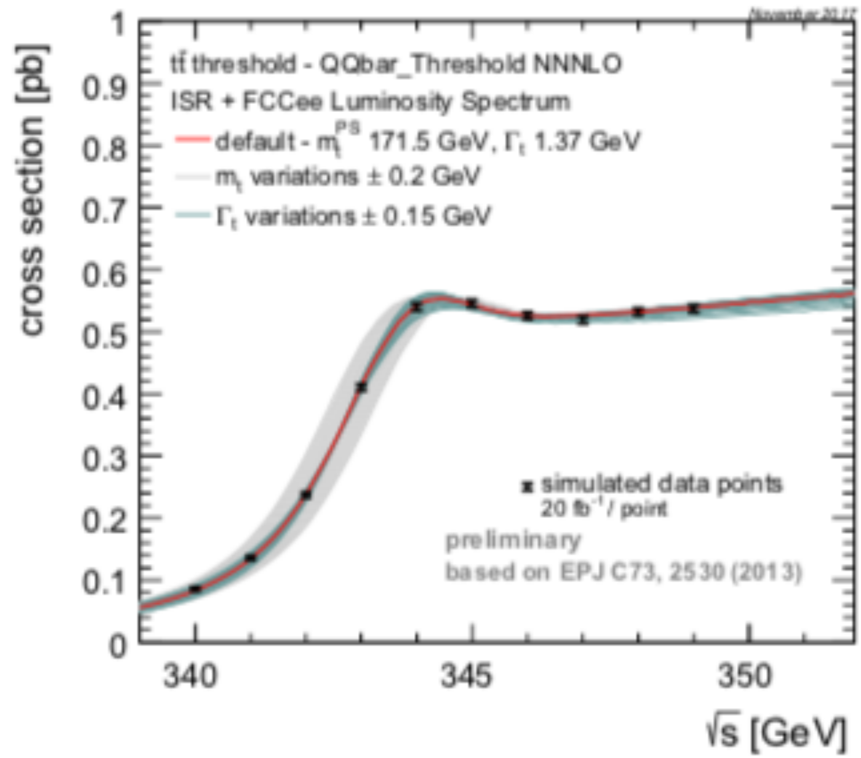


- Can get the top quark mass at the level

2. The top threshold

Sergei Barsuk
Bonjour Stephane! Topiful ! Let's go ahead !



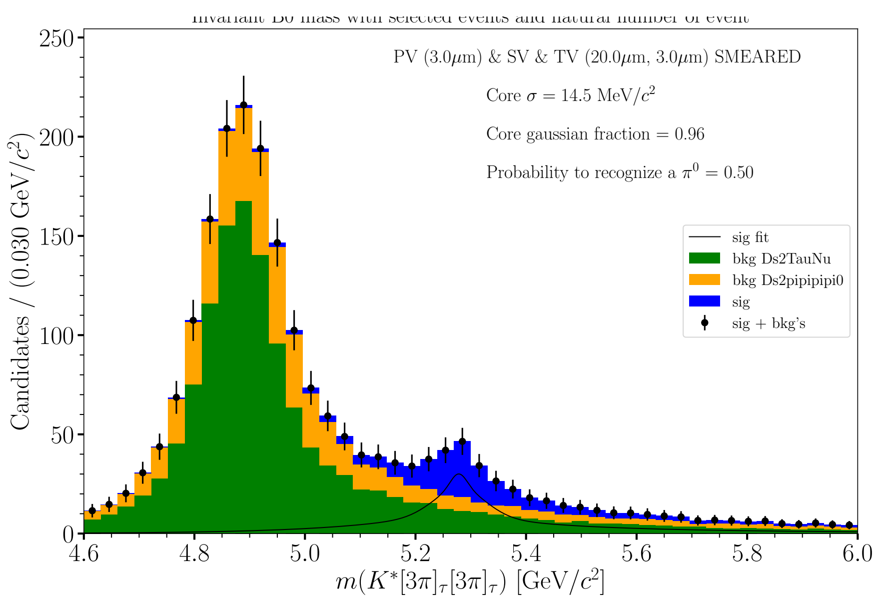


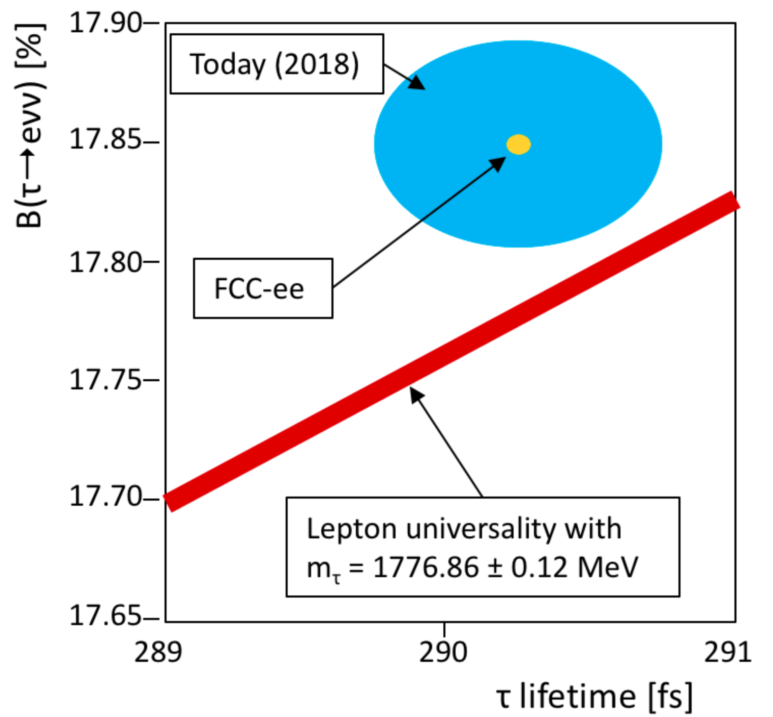
- Can get the top quark mass at the level

2. The Z pole — 2

- The FCC-*ee* statistics and the capacity to fully reconstruct the decay even in the absence of the neutrinos allows to address FCNC transitions with tau in the final state. The reconstruction of the mode $B^0 \to K^{*0}\ \tau^+\tau^-$ as a benchmark has received a special attention in the FCC-*ee* context. The tau Physics as well.

- Third generation couplings still to be tested. FCC-ee is the place to be.



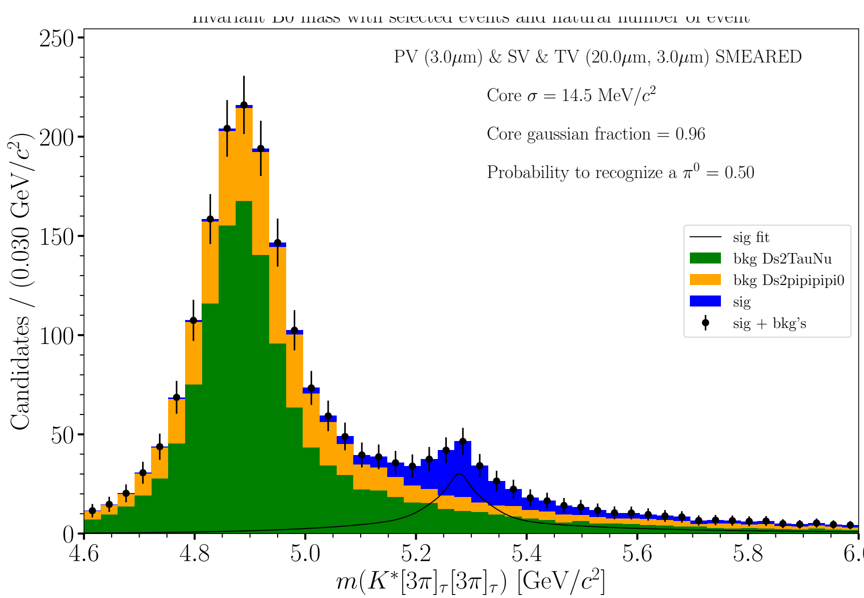


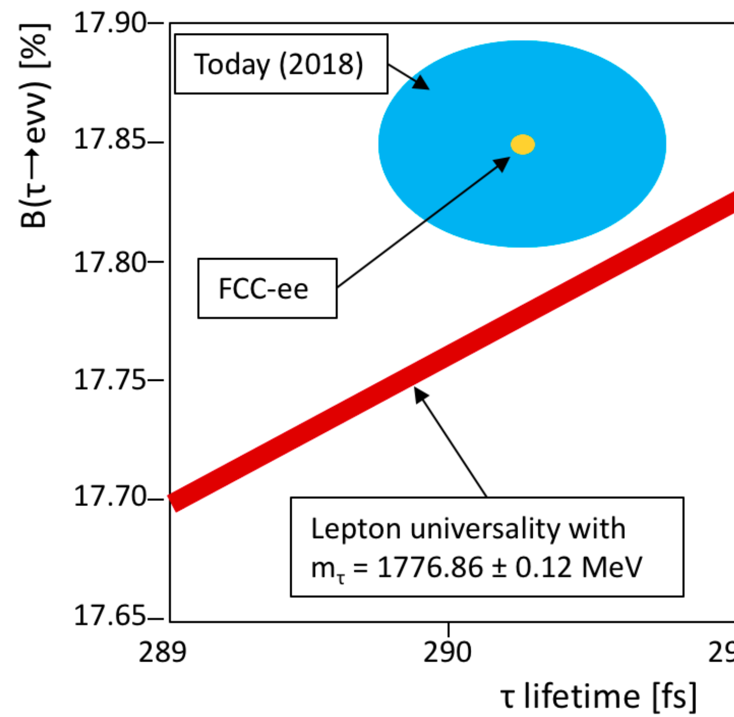
2. The Z pole — 2

- The FCC-*ee* statistics and the capacity to fully reconstruct the decay even in the absence of the neutrinos allows to addres[...] state. The reconstruction of the mode $B^0 \to K^{*0}\tau^+\tau^-$ as a benchmark has received a special attention in the FCC-*ee* context. The tau Physics as well.

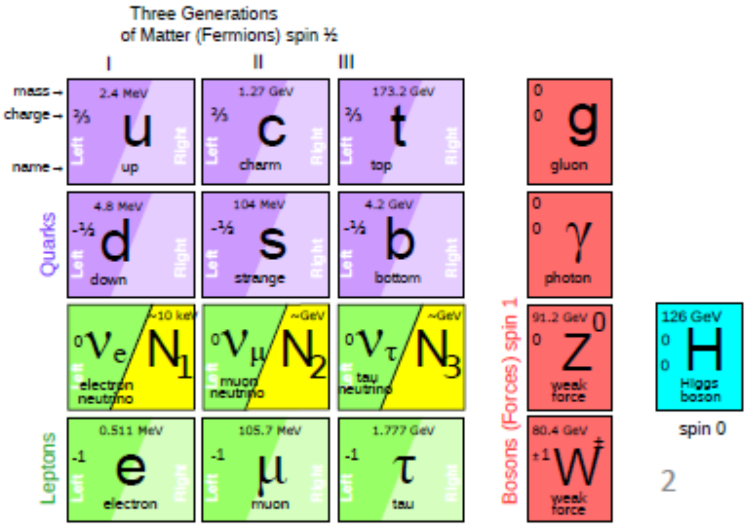
Achille Stocchi
Caro Stephane! Fantastico! Forza!

- Third generation couplings still to be tested. FCC-ee is the place to be.





2. And so much more



arXiv:1411.5230

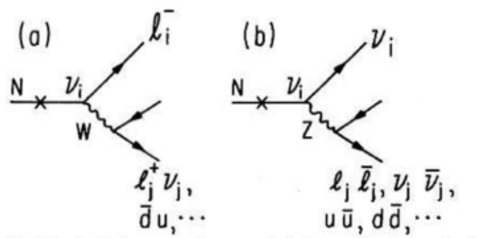
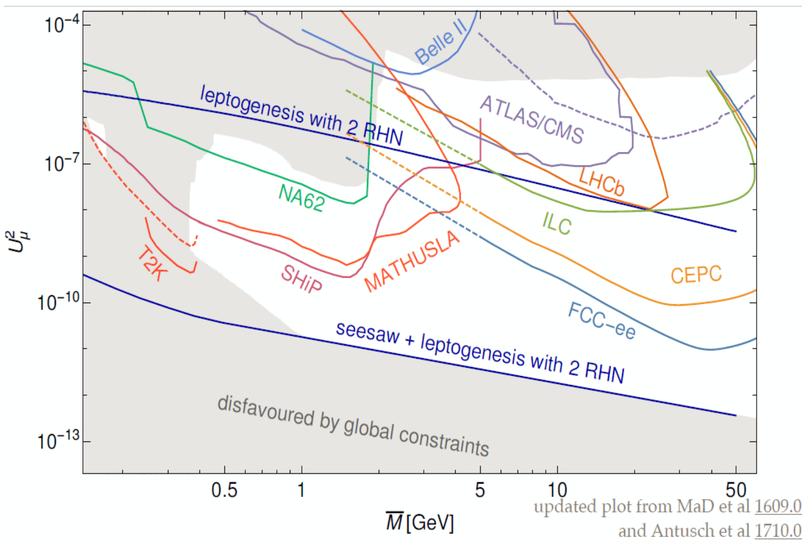
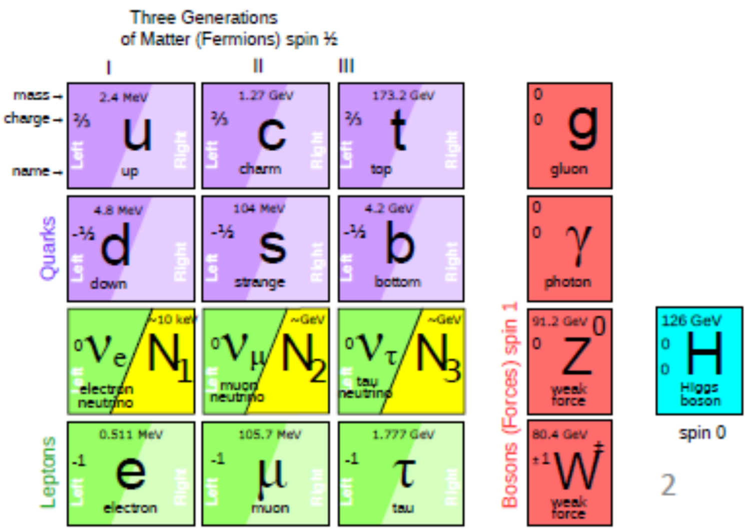


FIG. 2. Typical decays of a neutral heavy lepton via (a) charged current and (b) neutral current. Here the lepton l_i denotes e, μ, or τ.



updated plot from MaD et al 1609.09069
and Antusch et al 1710.03744
cf. also Cai et al 1711.02180

2. And so much more



arXi

Alexander Korchin
Привіт, Стефане! Чудово! And ALPS as well!

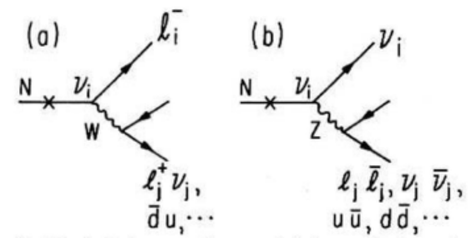
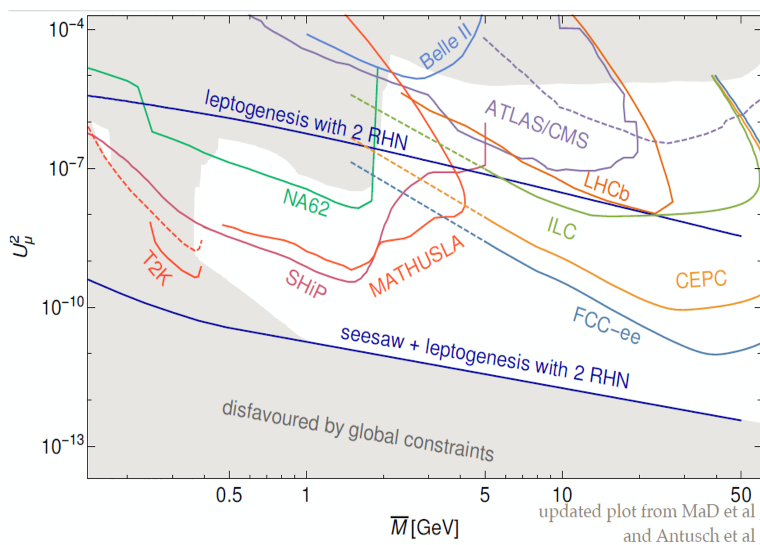


FIG. 2. Typical decays of a neutral heavy lepton via (a) charged current and (b) neutral current. Here the lepton l_i denotes e, μ, or τ.

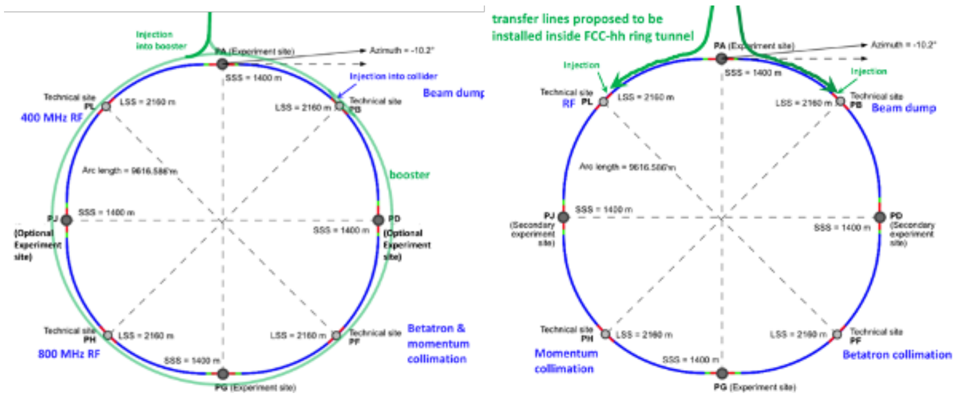


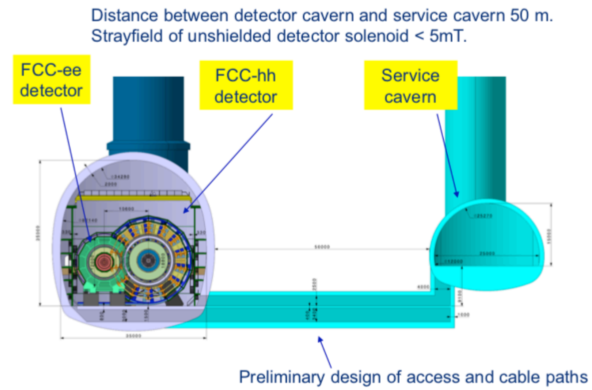
updated plot from MaD et al 1609.09069
and Antusch et al 1710.03744
cf. also Cai et al 1711.02180

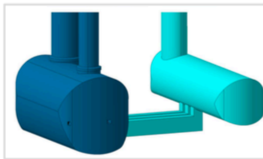
3. Implementation

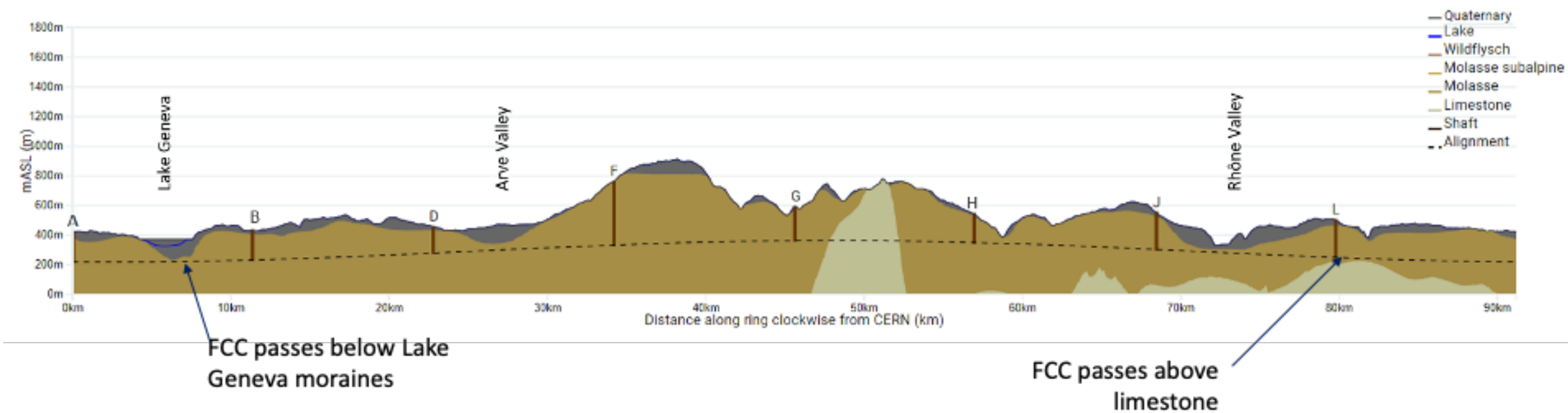
3. The FCC implementation — Civil engineering

- Machine footprints, experimental caverns, geological studies



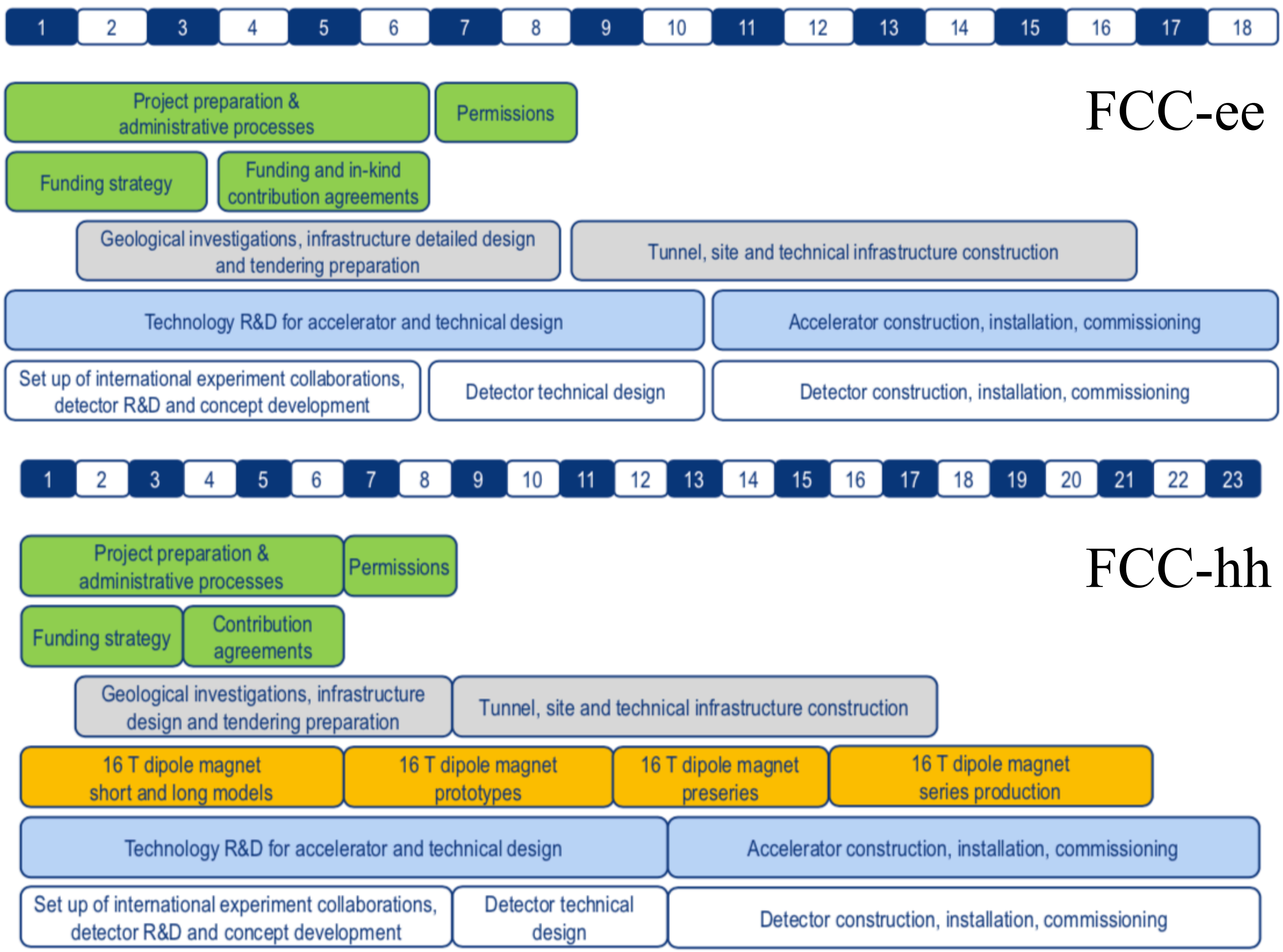






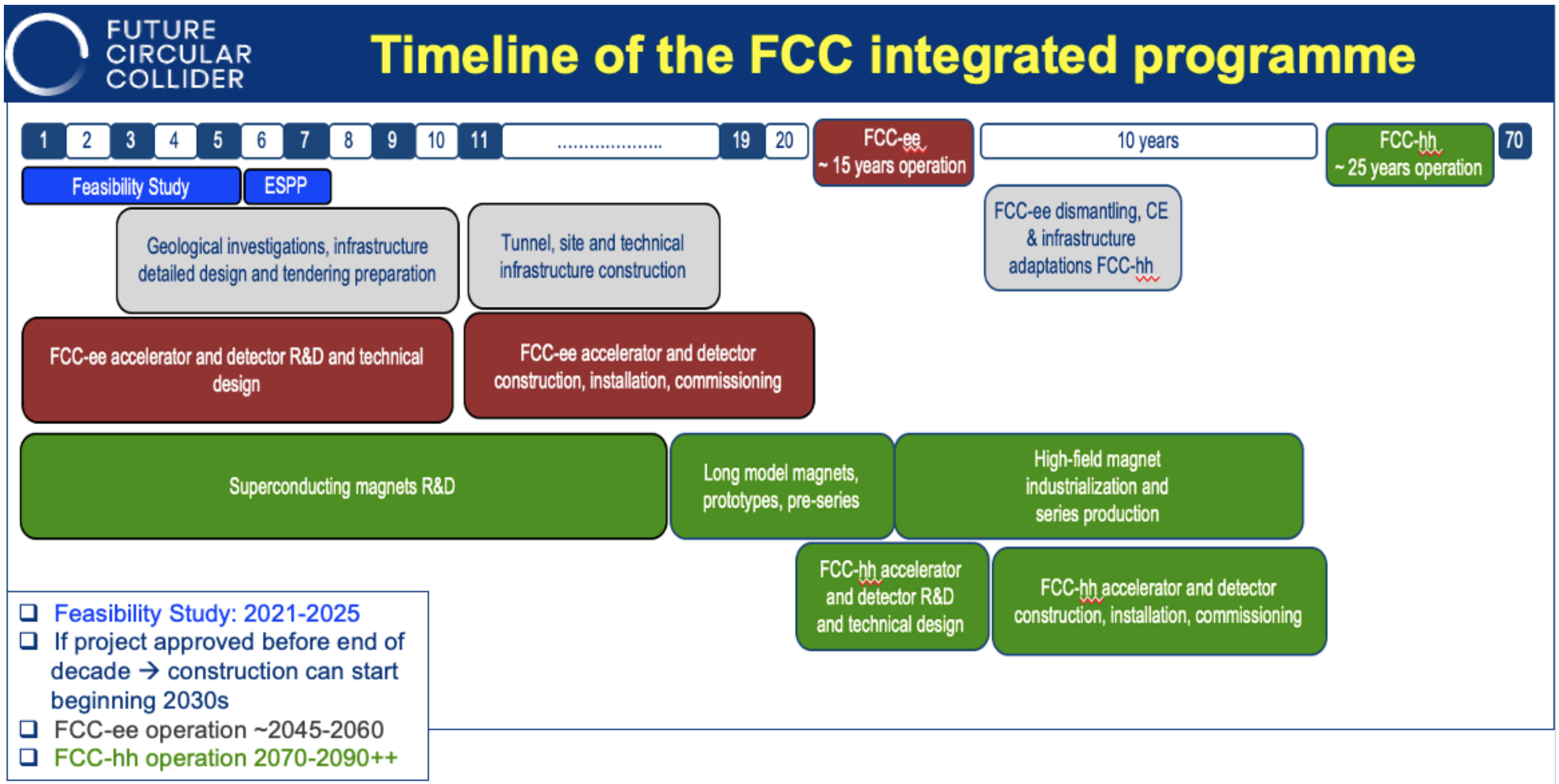
3. The FCC implementation — Timelines

- Eighteen years towards Physics. Without human and financial constraints, one would do particle physics seamlessly



3. The FCC implementation — Timelines

- Eighteen years towards Physics. No overlap in Physics between the end of HL-LHC and FCC-*ee.* The big picture.



- Is it crazy to plan a Physics program for seventy years?

3. The FCC implementation

- Is it reasonable to plan a Physics program for seventy years? It was.
- The previous HEP European planning was only for … 60 years !

PHYSICS WITH VERY HIGH ENERGY
e^+e^- COLLIDING BEAMS

CERN 76-18
8 November 1976

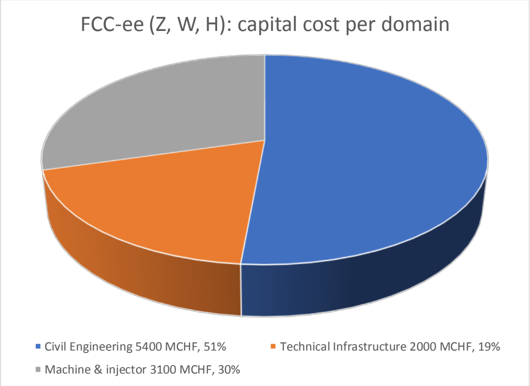
L. Camilleri, D. Cundy, P. Darriulat, J. Ellis, J. Field,
H. Fischer, E. Gabathuler, M.K. Gaillard, H. Hoffmann,
K. Johnsen, E. Keil, F. Palmonari, G. Preparata, B. Richter,
C. Rubbia, J. Steinberger, B. Wiik, W. Willis and K. Winter

ABSTRACT

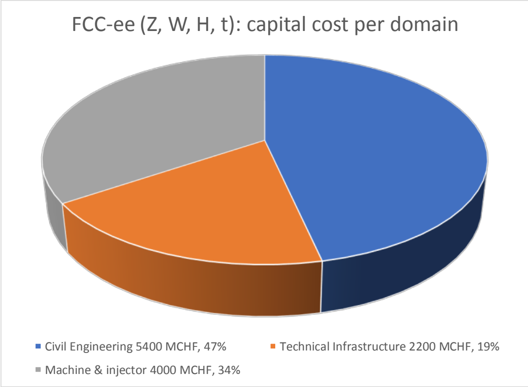
This report consists of a collection of documents produced by a Study Group on Large Electron-Positron Storage Rings (LEP). The reactions of

FCC-ee cost estimate

Total construction cost phase1 (Z, W, H) amounts to 10,500 MCHF
- 5,400 MCHF for civil engineering (51%)
- 2,000 MCHF for technical infrastructure (19%)
- 3,100 MCHF accelerator and injector (20%)



Complement cost for phase2 (tt) amounts to 1,100 MCHF
- 900 MCHF for RF, 200 MCHF for associated technical infrastructure



3. The FCC implementation — Cost

FCC-ee c

Marie-Hélène Schune
Excellent! Il est temps de conclure.

Total construction cost phase1 (Z, W, H) amounts to 10,500 MCHF

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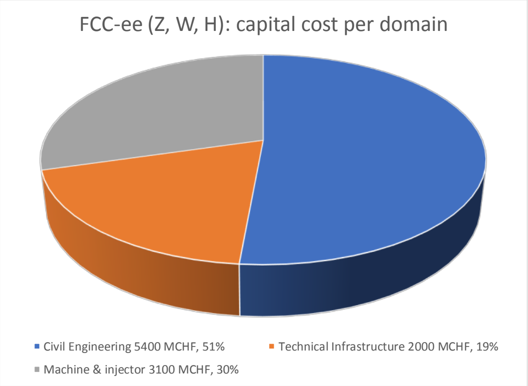

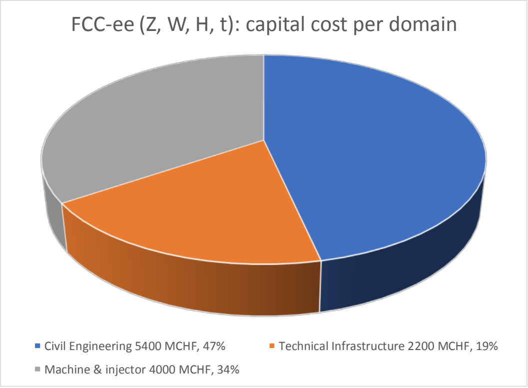

Complement cost for phase2 (tt) amounts to 1,100 MCHF

- 900 MCHF for RF, 200 MCHF for associated technical infrastructure

Summaries

Scientific context: scenarii

1) Find a new heavy particle at the Run III of LHC:

- HL-LHC can study it to a certain extent.
- If mass is small enough (and couples to electrons), CLIC can be the way.
- Larger energies are needed to study (find) the whole spectrum.
- The underlying quantum structure must be studied.

2) Find no new particle, but non-standard *H* properties

- HL-LHC can study it to a certain extent.
- Higgs factory.
- *Z*, *W*, top factories for the quantum structure.
- Energy frontier (also for precision measurements)

3) Find no new particle, standard H properties but flavour observables departing from SM:

- *Z*, *W*, top factories for the quantum and flavour structure.
- Energy frontier to find the corresponding spectrum.

4) Find no new particle, standard H properties and flavour observables in SM:

- Asymptotic *Z*, *W*, *H*, top factories for asymptotic precision.
- Push the energy frontier to the best of our knowledge.

Summary

1) Find a new heavy particle at the end of Run III analyses of LHC:
- HL-LHC can study it to a certain extent.
- If mass is small enough (and couples to electrons), CLIC can be the way.
- Larger energies are needed to study (find) the whole spectrum [FCC-hh].
- The underlying quantum structure must be studied [FCC-ee].

2) Find no new particle, but non-standard *H* properties
- HL-LHC can study it to a certain extent.
- Higgs factory [ILC,FCC-ee].
- *Z*, *W*, top factories for the quantum structure [FCC-ee].
- Energy frontier (also for precision measurements) [FCC-hh].

3) Find no new particle, standard H properties but flavour observables departing from SM:
- Asymptotic *Z*, *W*, top factories to fix the energy scale [FCC-ee].
- Energy frontier to find the corresponding spectrum [FCC-hh].

4) Find no new particle, standard H properties and flavour observables in SM:
- Asymptotic *Z*, *W*, *H*, top factories for asymptotic precision [FCC-ee].
- Push the energy frontier to the best of our knowledge [FCC-hh].

Summary

1) There are scenarii for which any continuation of the particle Physics requires FCC project.

2) There is no scenario in which FCC project does not bring an invaluable path.

3) The timeline is commensurate with the other world scale projects.

We are orphan of a no-loose theorem. We should try to build another one to find the next relevant energy scale. Some hints are there.

Meanwhile, we need to not leave a stone unturned. Flavour anomalies, (c)LFV experiments, edms, neutrinos …

You are entering in the field at fascinating times!

Summary: think out of the box !

Summary: and design the appropriate experiments!