Physics at the LHC

Motivation, Machine, Experiments, Physics

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OUTLINE

- Part 1 – Motivation: Why the LHC?
- Part 2 – Realisation: How the LHC?
  - The accelerator.
  - The experiments ALICE, LHCb, TOTEM and LHCf.
  - ATLAS and CMS.
- Intermezzo: Basics of pp physics
- Part 3 – Results: What at the LHC?
  - Commissioning and performance
  - The rediscovery of the Standard Model.
  - Higgs boson searches.
  - Searches for Supersymmetry and other BSM physics.

Please note: Ask your question immediately and interrupt me in case of doubt. I will try to limit myself in speed and leave enough time for discussion.

PART 1

Motivation: Why the LHC?

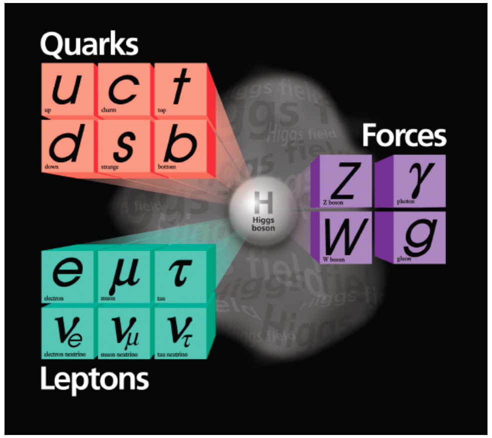
WHY THE LHC? – N GOOD REASONS!

- The Standard Model (SM) is in excellent agreement with basically all measurements – so why worry at all?
- … because we have not yet found the Higgs boson!
  - Without a Higgs, the SM diverges at 1 TeV!
- … because the SM is not really beautiful or simple!
  - It contains too many free parameters! Explanation in fundamental theory?
- … because the SM does not provide gauge-coupling (mass) unification!
  - The three SM couplings do not unify at highest energies!
- … because the SM does not provide a dark-matter candidate!
  - Dark matter is required according galaxy rotation curves etc.!
- … because there are more fundamental questions!
  - Gravity? Gauge structure? Why 3 generations? Connection between leptons and quarks? Hierarchy / fine-tuning problem? Baryon asymmetry? …

THE STANDARD MODEL

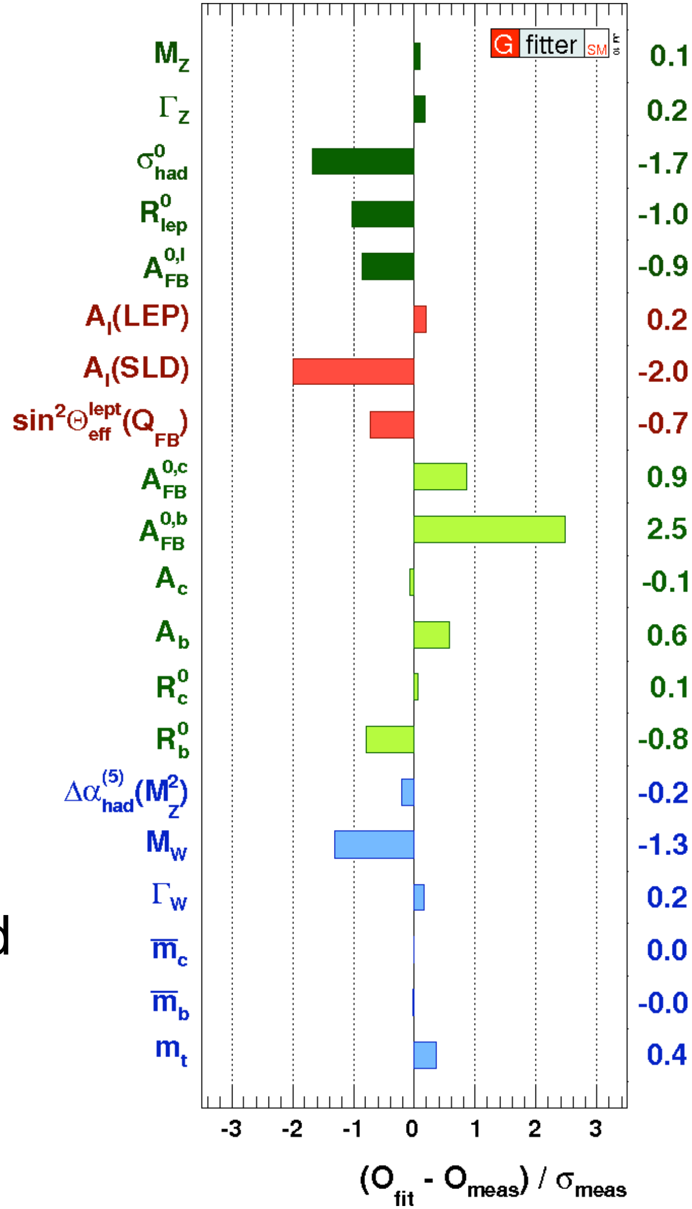
> The SM is an extremely successful theory!

- Gauge structure $SU(3)_C \times SU(2)_L \times U(1)_Y$.
- Three generations of quarks and fermions.
- Massive gauge bosons via Higgs mechanism.

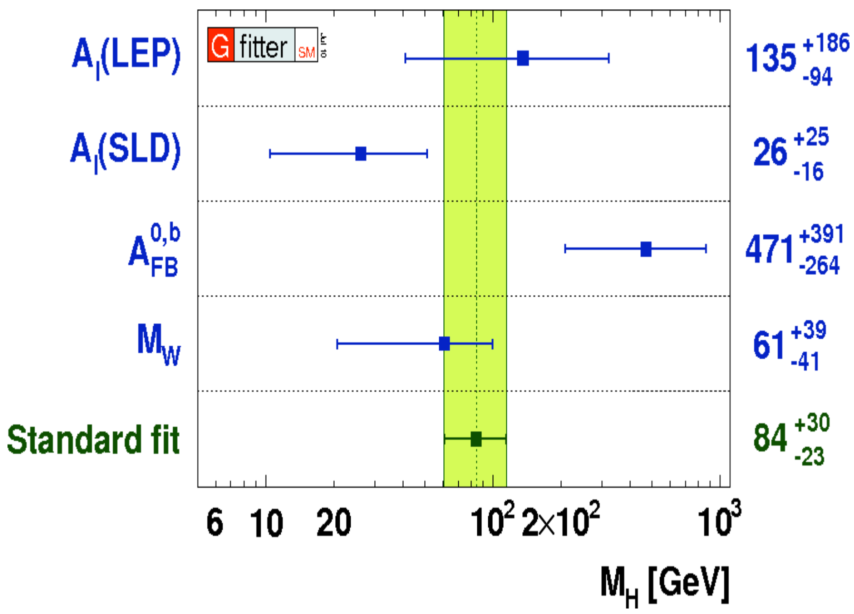


> Up to now basically all HEP results in good agreement with SM predictions!

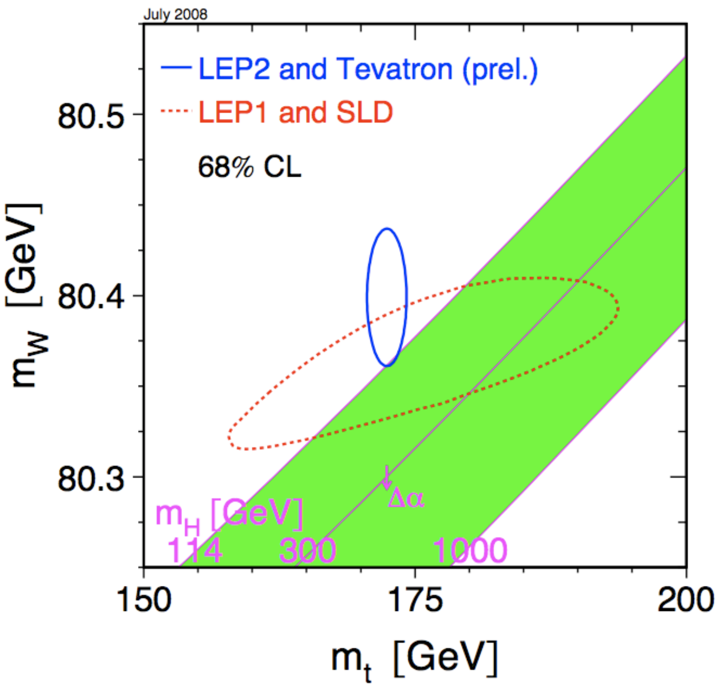
- As expressed in SM fits e.g. from GFITTER.
- No deviations beyond 2.5σ.

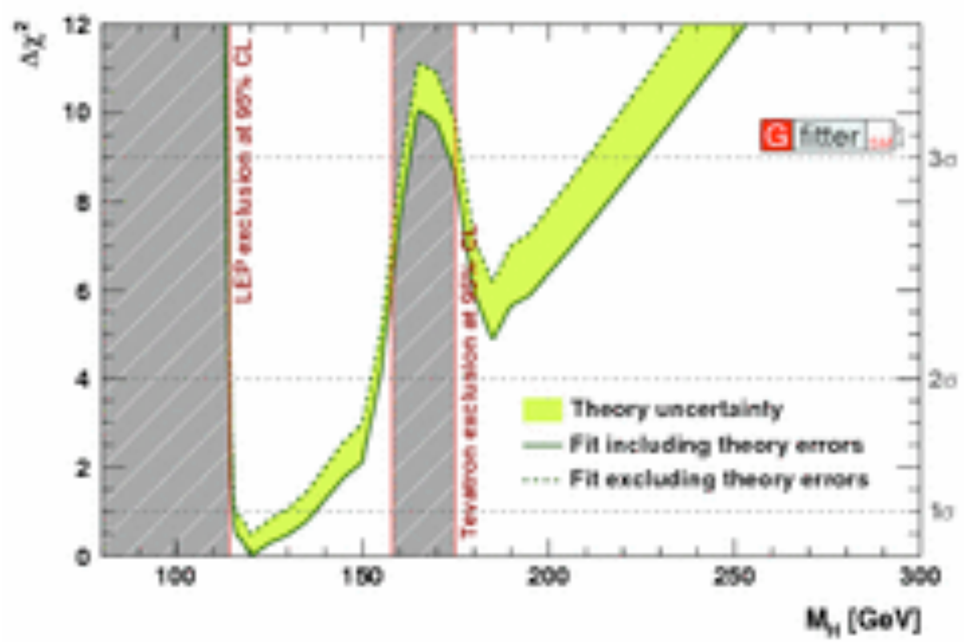


THE HIGGS BOSON

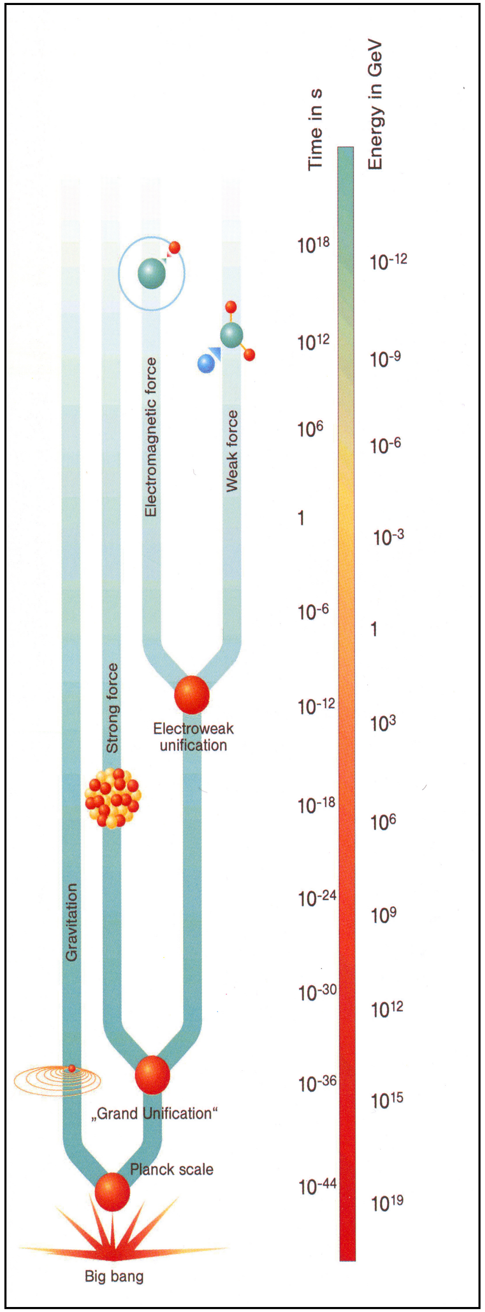


- Without a Higgs boson
  - bosons (and fermions) don't acquire mass.
  - the SM diverges at high energies.
- What do we know about the Higgs?
  - Theory: ~100 < M_H < 1000 GeV
  - EW precision data! SM observables sensitive to M_H → extract parameter!



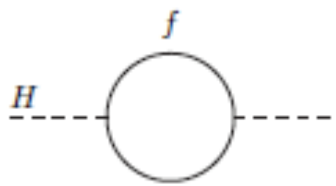


SM, FREE PARAMETERS, UNIFICATION



- First, the SM contains too many free parameters
  - Like masses, couplings, mixing angles …
  - Would like to have them explained!
- Then, the couplings and masses don't unify
  - as one would expect from SM!
- Finally, how come that SM masses are stable?
  - Higgs mass receives quantum corrections like

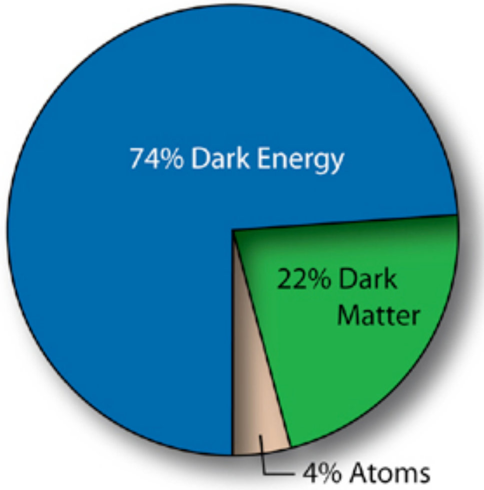
$$\Delta M_H^2 = -\frac{|\lambda_f|^2}{8\pi^2}\Lambda_{UV}^2 \ldots$$

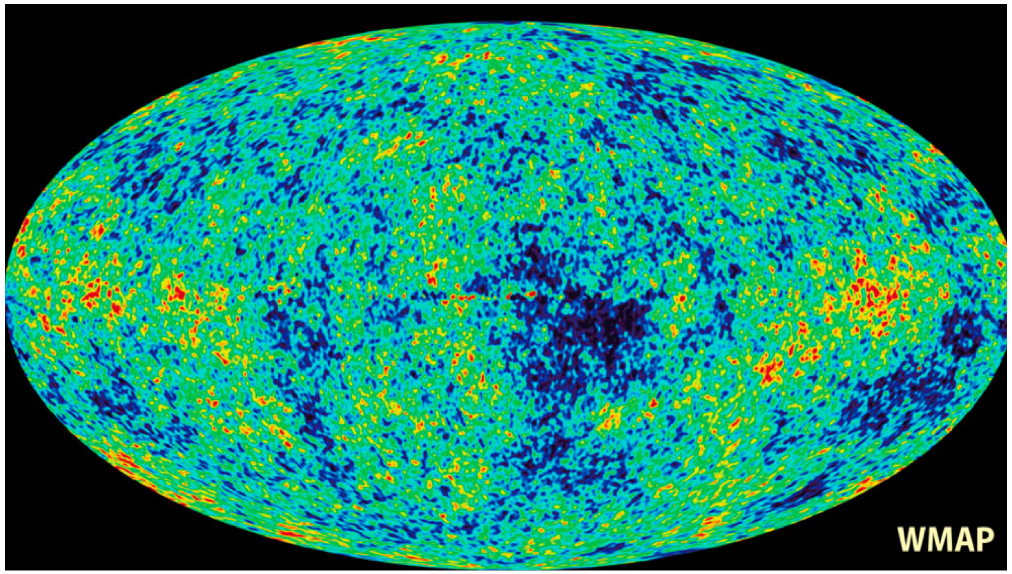


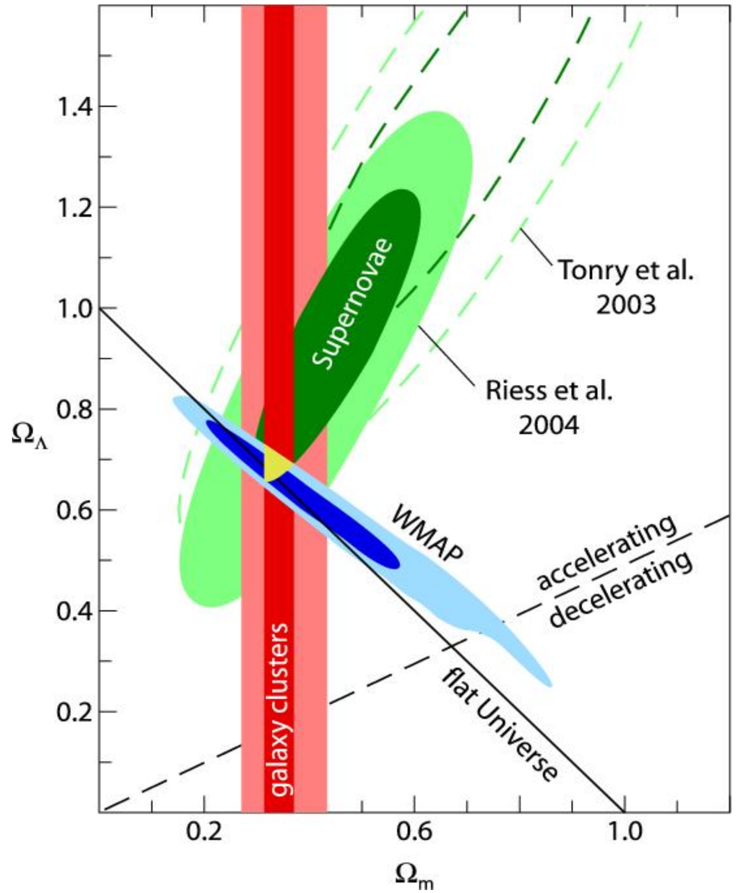
  - Since all masses in SM depend on M_H, they all should suffer from UV cut-off (Planck scale?)
  - Simply decreasing cut-off is artificial – difficult to accommodate in decent theory.
  - Potential cure: supersymmetry (later)!

DARK MATTER

- Visible matter is not all there is!
- How do we know (since 1930s!)?
  - Galaxy rotation curves (next slide)
  - WMAP CMB measurements
  - Structure formation in the universe
  - Gravitational lensing effects
- No particle candidate in the SM!



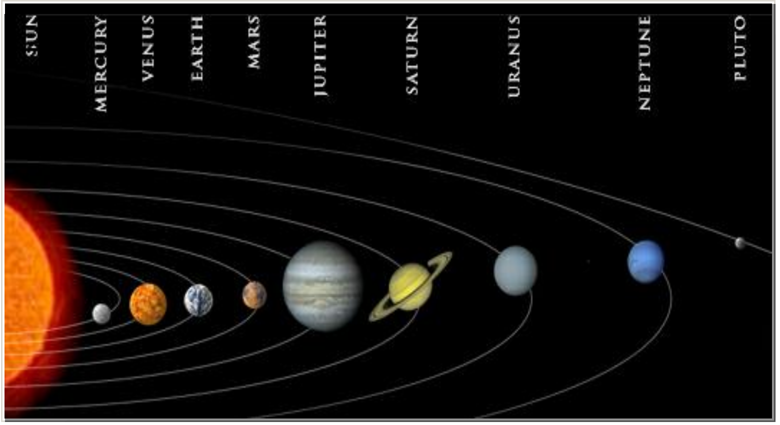


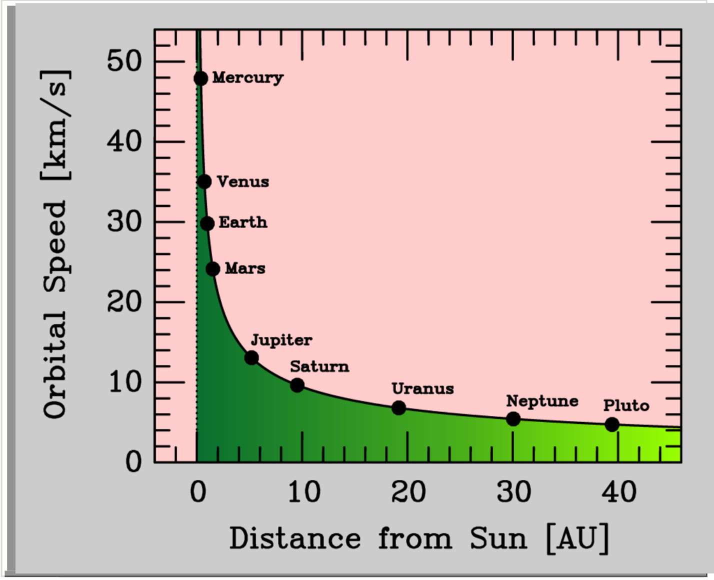


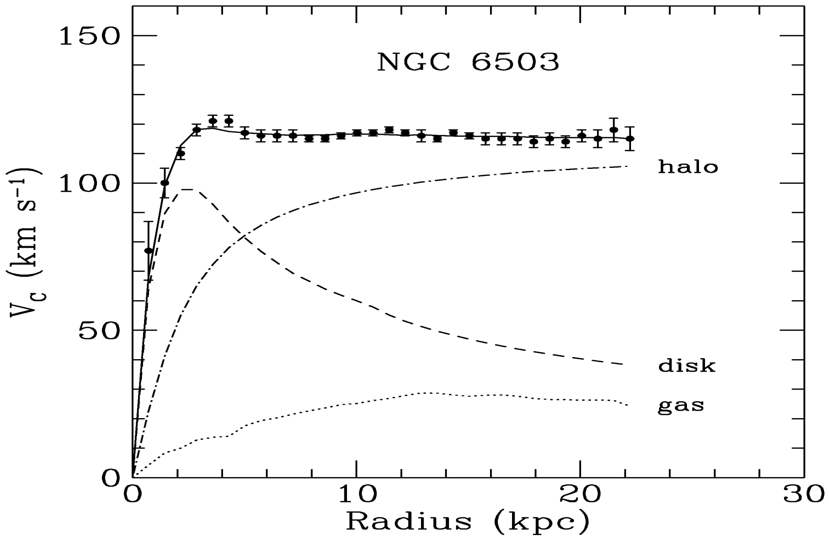
DARK MATTER

- Simple mechanics tells us:
  speed as a measure for eclosed mass!

$$\frac{mv^2}{r} = G\frac{Mm}{r^2} \quad \Rightarrow \quad v \propto \sqrt{M/r}$$







Mass beyond luminous disk of galaxy!!

POSSIBLE SOLUTIONS?

A POSSIBLE SOLUTION …

> Supersymmetry or SUSY!

- Invented in 1974 by Wess and Zumino: an extension of the SM; reduces to SM at low energies.
- Connects SM particles to SUSY partners and fermions with bosons:

$$Q|fermion\rangle = |boson\rangle$$
$$Q|boson\rangle = |fermion\rangle$$

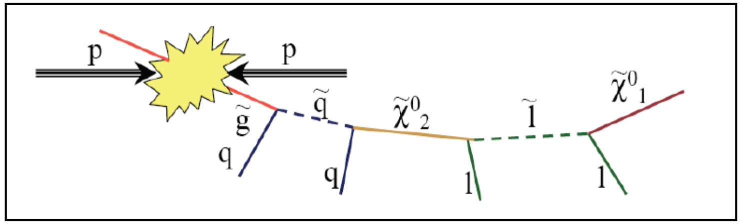
- Spin is changed by one half unit:

Spin	SM particles	SUSY partners	Spin
1/2	Leptonen (e, ν_e, …) Quarks (u, d, …)	Sleptonen ($\tilde{e}$, $\tilde{\nu}_e$, …) Squarks ($\tilde{u}$, $\tilde{d}$, …)	0
1	Gluonen $W^{\pm}$ Z^0 Photon (γ)	Gluinos Wino Zino Photino ($\tilde{\gamma}$)	1/2
0	Higgs	Higgsino	1/2
2	Graviton	Gravitino	3/2

> SUSY has a solution for many problems – and even connects to strings and thus allows inclusion of gravity at highest scales.

- But … model with many parameters (>100) – for phenomenological purposes need to introduce assumptions ➔ “MSSM” with five parameters.

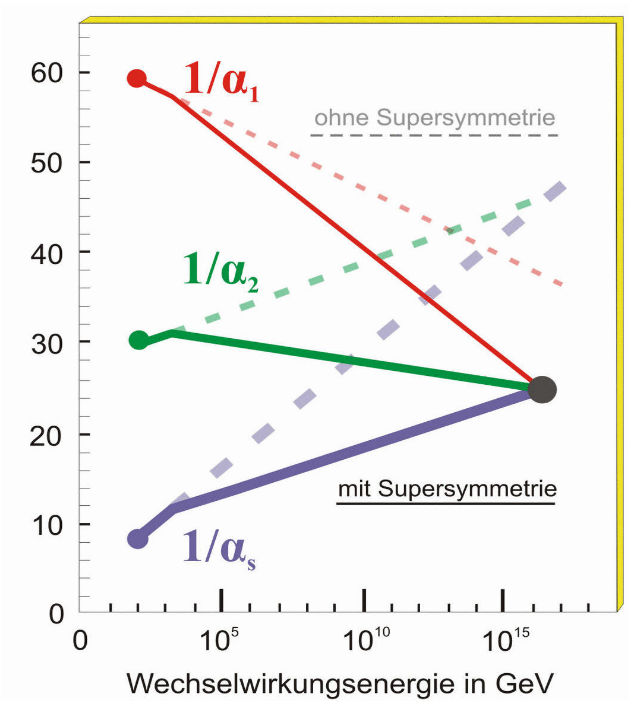
A POSSIBLE SOLUTION …



> SUSY …

- Provides a dark-matter candidate via the lightest supersymmetric particle (LSP) – in many cases a neutralino – that escapes detection in our experiments.
- Allows unification of gauge couplings (and masses). SUSY particles introduce additional corrections with opposite sign:
  ➔ Cancellation of divergencies, no need for finetuning.

$$\Delta M_H^2 = -\frac{|\lambda_f|^2}{8\pi^2}\Lambda_{UV}^2 \ldots \qquad \Delta M_H^2 = \frac{\lambda_S}{16\pi^2}\left[\Lambda_{UV}^2 + \ldots\right]$$



- SUSY would also help in view of structure formation, connection to gravity etc.

➔ Many 'SUSY addicts'! But other possibilities: large extra dimensions, Little Higgs models, Technicolor, strings, alternative Higgs, compositeness, leptoquarks …

WHY A LARGE HADRON COLLIDER?

> $E = mc^2$

- We know that new particles are heavy
  → need high energy to produce them!
- Because of uncertainty principle, smaller substructures require higher momentum (resolution $\lambda \sim 1/p$)

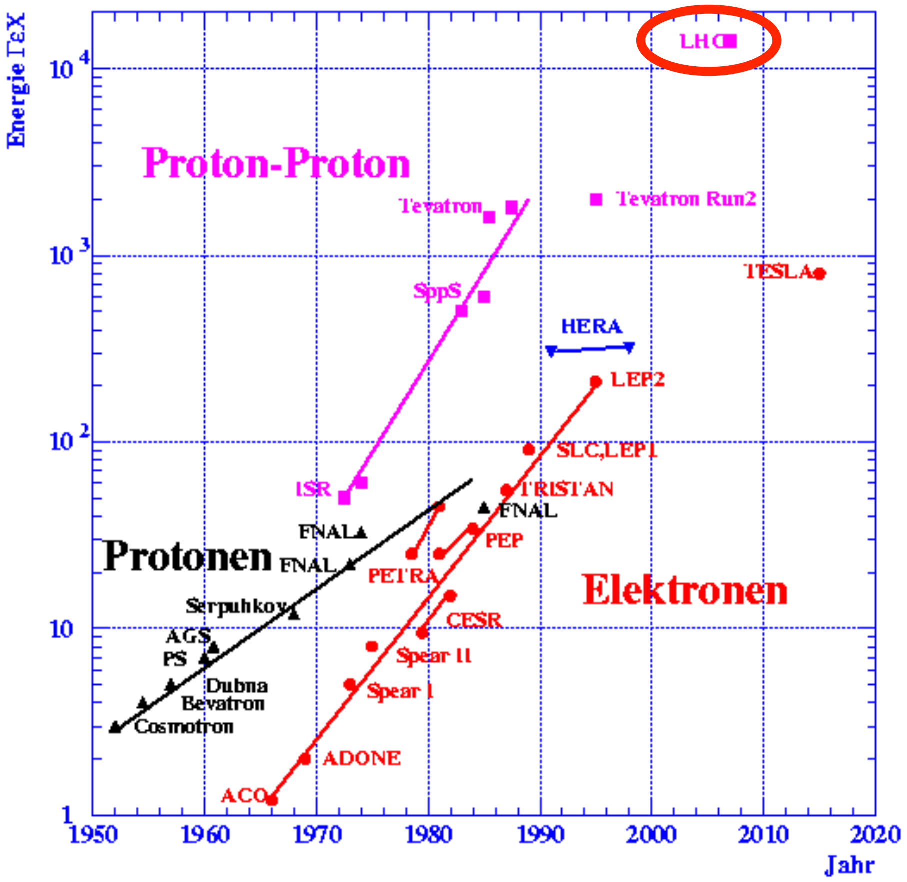
> Discoveries with hadron machines!

- Then precision physics at lepton colliders.
- By the way: bosons discovered in Europe!

> Large radius: synchrotron radiation!

- Energy lost per orbit:

$$W = \oint P_S dt = P_S \frac{2\pi R}{c} = \frac{e^2}{3\varepsilon_0} \cdot \frac{1}{(m_0 c^2)^4} \cdot \frac{E^4}{R}$$



➔ Large Hadron Collider!