Theory Overview

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The Standard Model

1. Gauge Sector
   - Strong Interactions
   - Electroweak Interactions
2. Flavour Sector
   - Quark Mixing
3. Electroweak Symmetry Breaking Sector


2004


1979

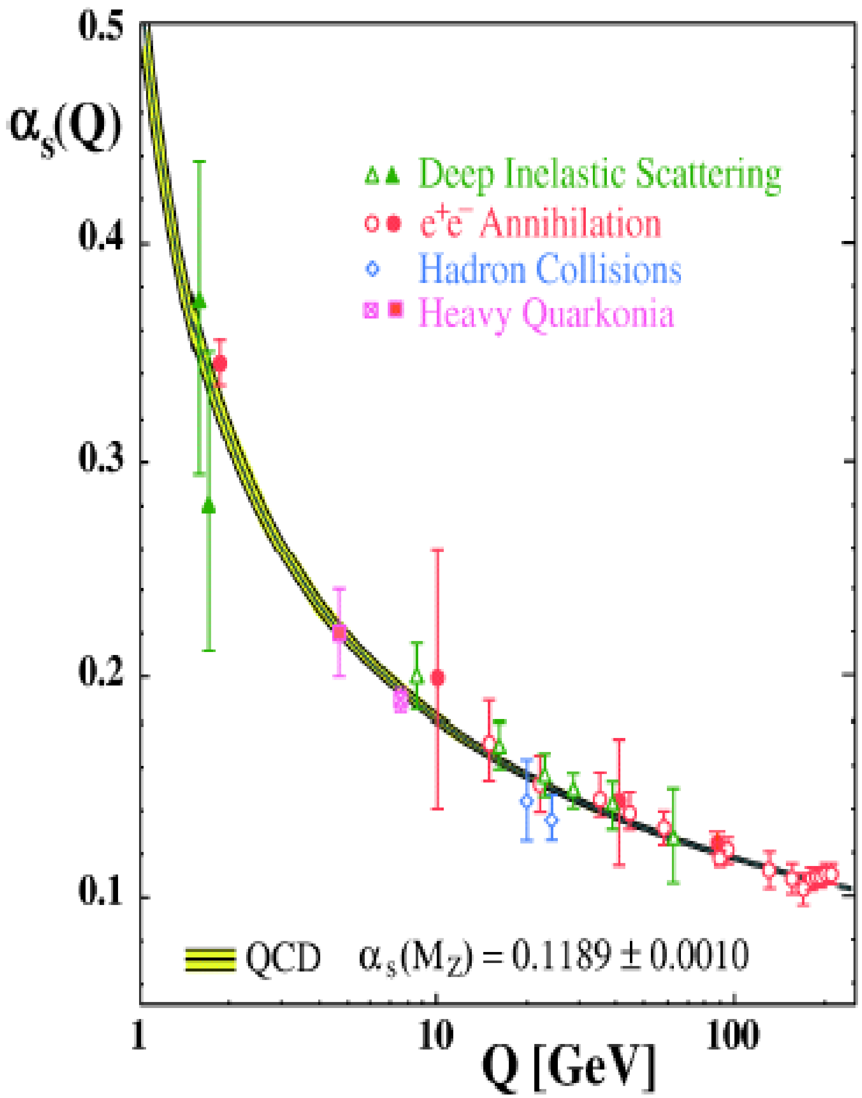

1999

1991

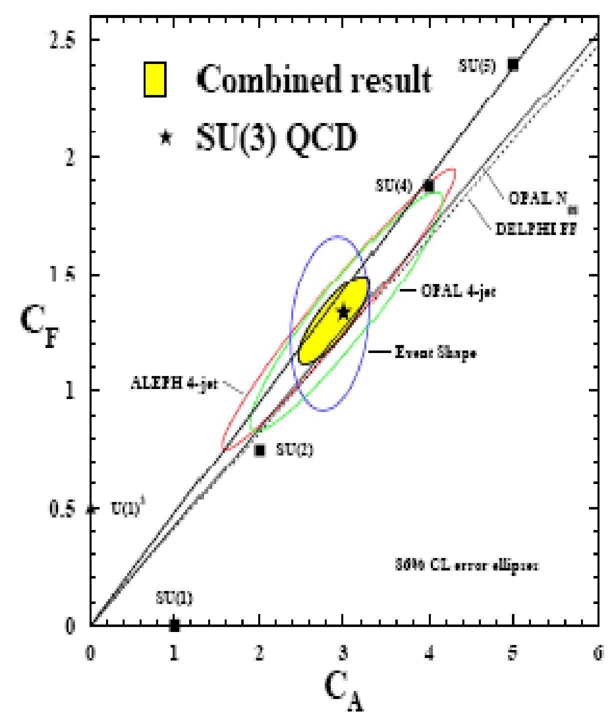
2007

1997

Strong Interactions



LEP, SLC, HERA and TEVATRON confirmed SU(3) in the perturbative region



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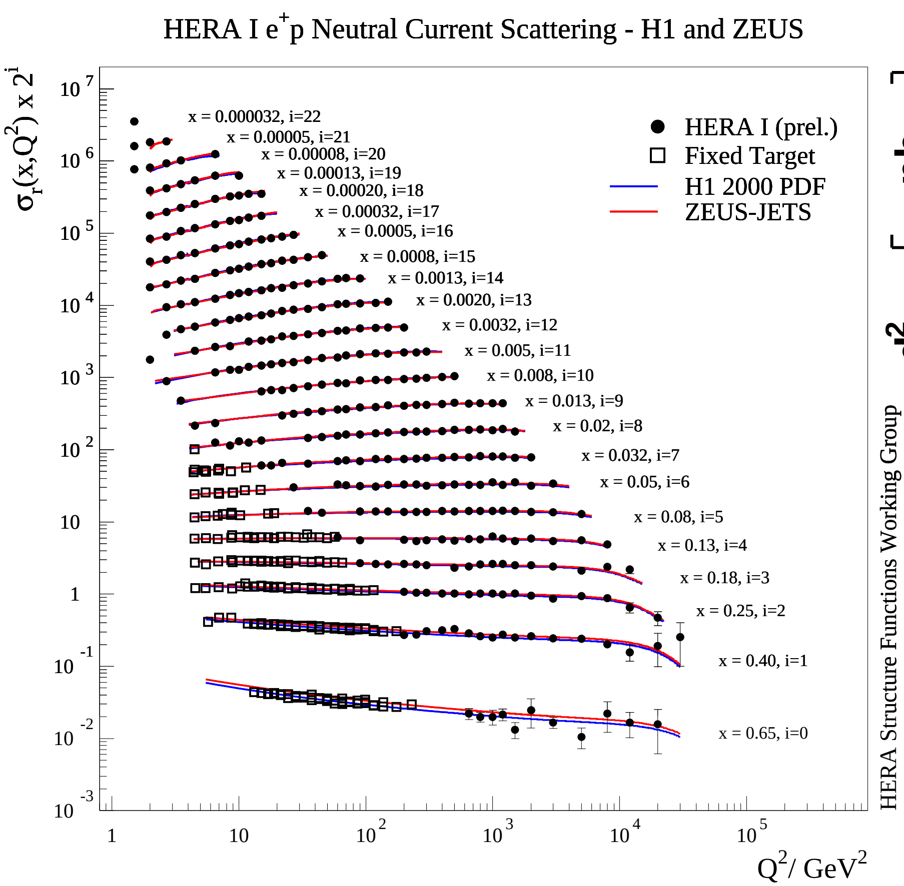
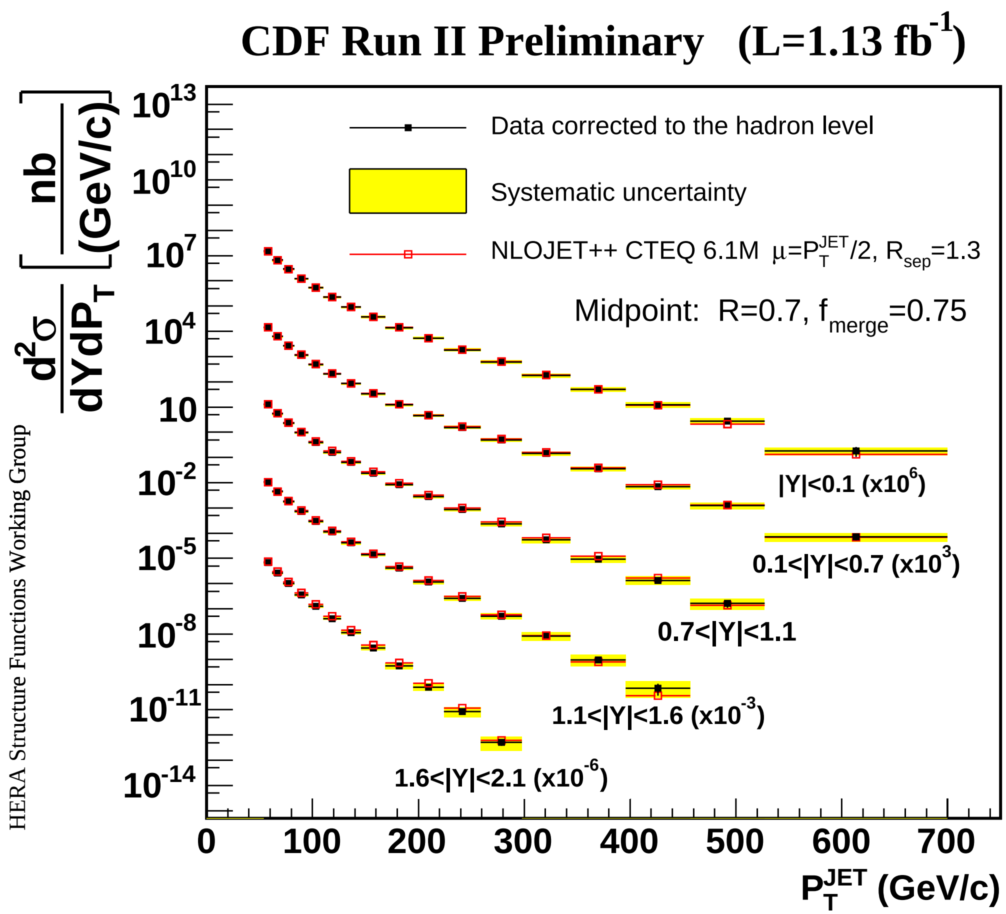
Strong Interactions

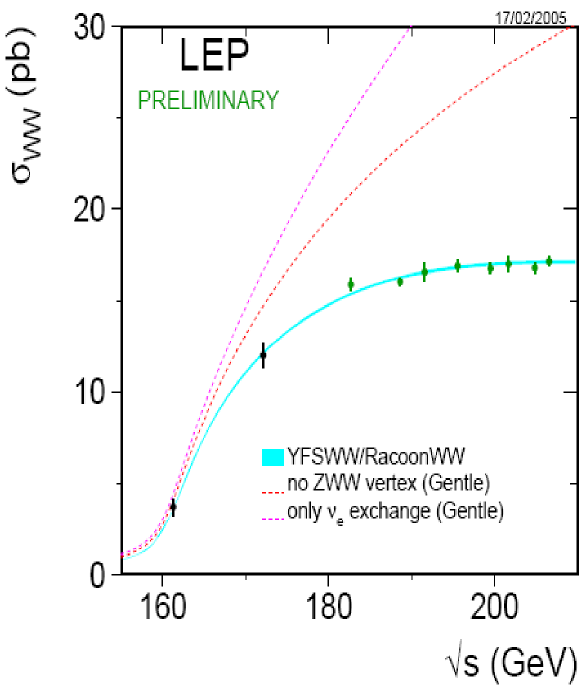


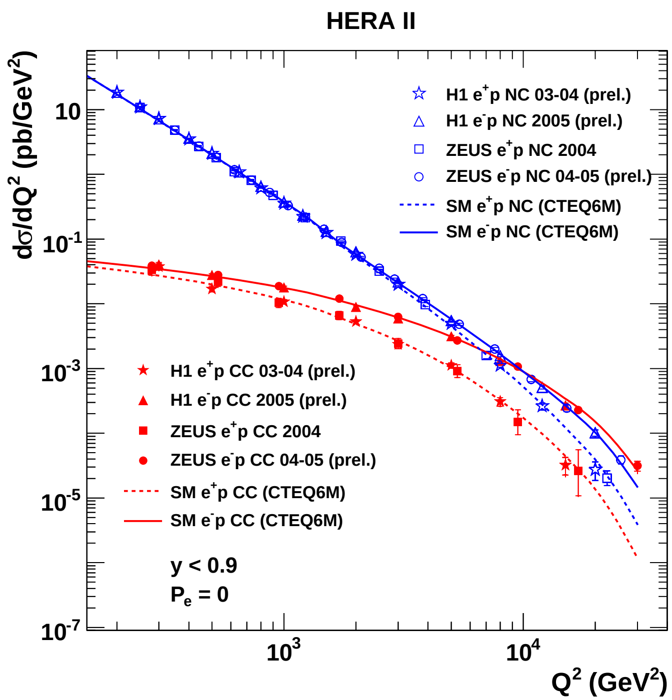


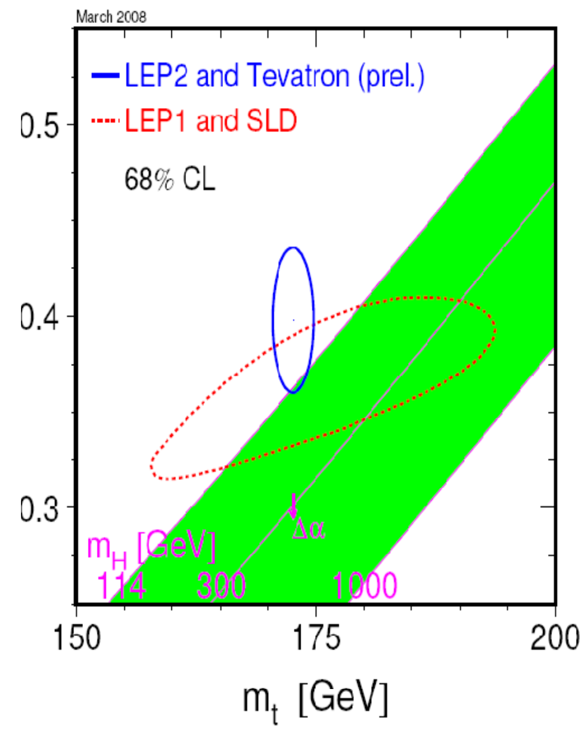
QCD Parton model confirmed

See Jon Butterworth's talk on Tuesday

Electroweak Interactions







See Victoria Martin's talk on Monday

1. Prediction of triple gauge boson couplings
2. Unification of the electromagnetic and weak interactions
3. "Prediction" of the top quark mass from EW radiative corrections

Experimental failures of the SM

- Neutrinos have mass

2002

- Dark Matter in Universe
  - Neutrinos cannot explain large scale structure
    - Are there other sorts of DM candidate?
      - » SUSP LSP?

- Baryon-antibaryon asymmetry of the Universe
  - CKM CP violation too small
    - Are there other sources of CP violation?
      - » Lepton sector? Leptogenesis?
      - » Quark sector?

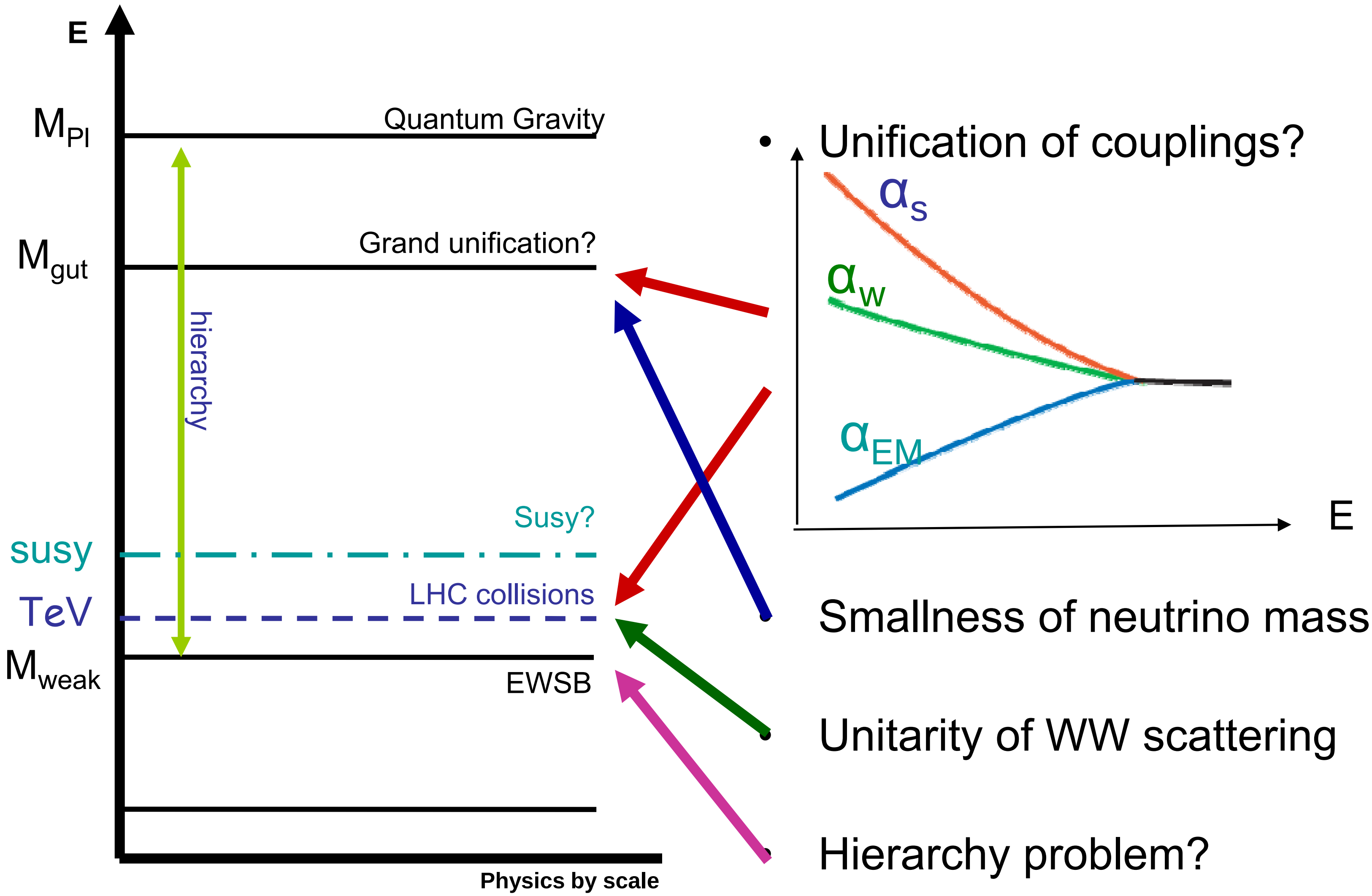
Conceptual limitations of SM

- What is the origin of the fermion mass?
- Why is the gauge structure SU(3)xSU(2)xU(1)?
- Why are there three families?
- Why is the electroweak symmetry broken?
- Why are there 3+1 space-time dimensions?
- How is gravity involved?

(first four questions) } GUT?

(last two questions) } STRING THEORY?

Energy Scales



- Unification of couplings?
- Smallness of neutrino mass
- Unitarity of WW scattering
- Hierarchy problem?

The TEV SCALE

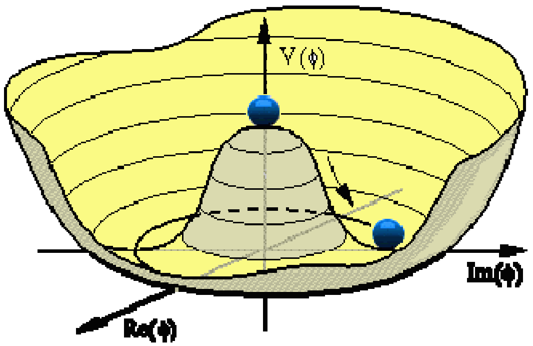
TeV scale physics

What is the mechanism of electroweak symmetry breaking?

- Are there more than three dimensions of space?
- Are space and time embedded into a “superspace”?
- Can dark matter be produced in the laboratory?

EWSB in the SM

Higgs mechanism, spontaneous electroweak symmetry breaking:
Scalar field postulated, gauge-invariant mass terms from coupling to Higgs field



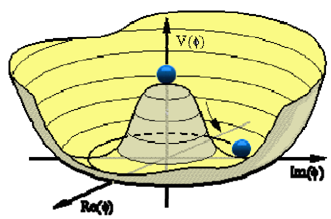
Spontaneous symmetry breaking,
lost degree of freedom ⇒ Goldstone bosons
3 components of Higgs doublet ⇒ longitudinal components of W±, Z;
H: elementary scalar field, Higgs boson

Fermion masses, gauge-boson masses from coupling to Higgs field
⇒ Higgs couplings proportional to masses of the particles

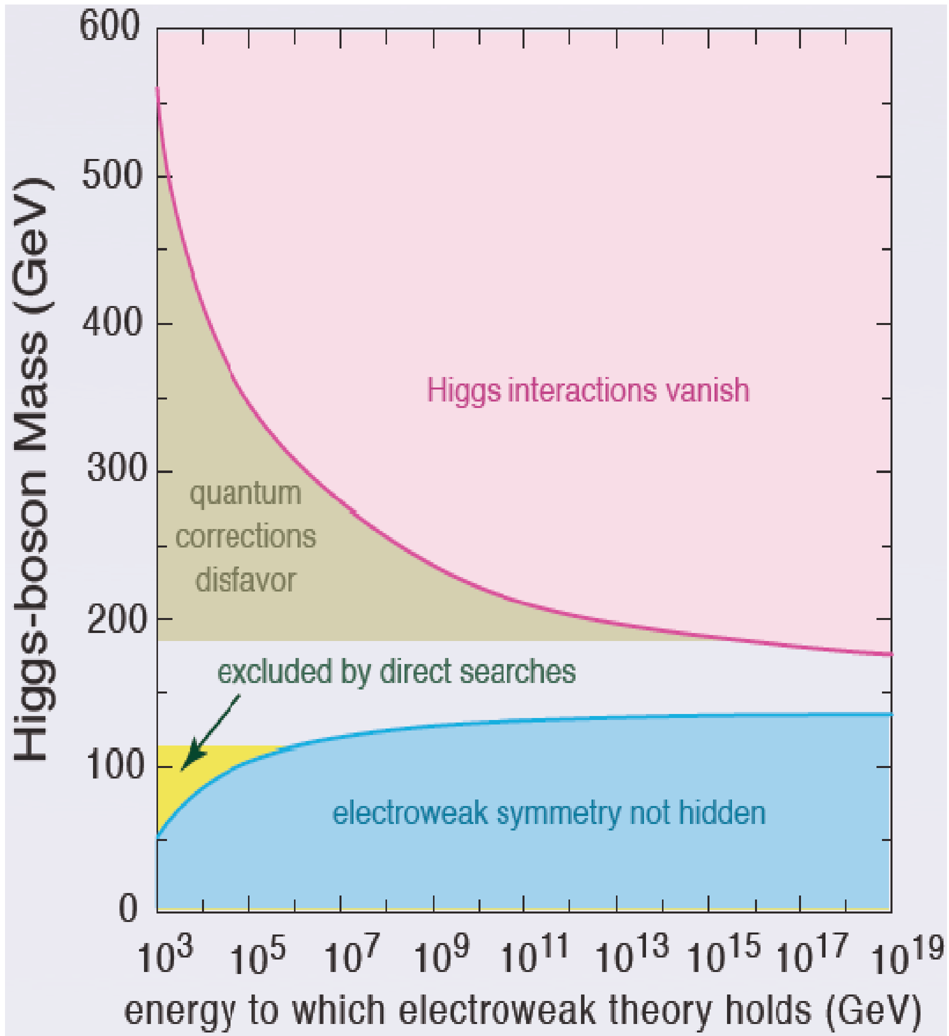
Goldstone bosons give mass to W±,Z
⇒ One physical scalar boson: Higgs boson
Mass of the Higgs boson: free parameter

Theoretical constraints M_h

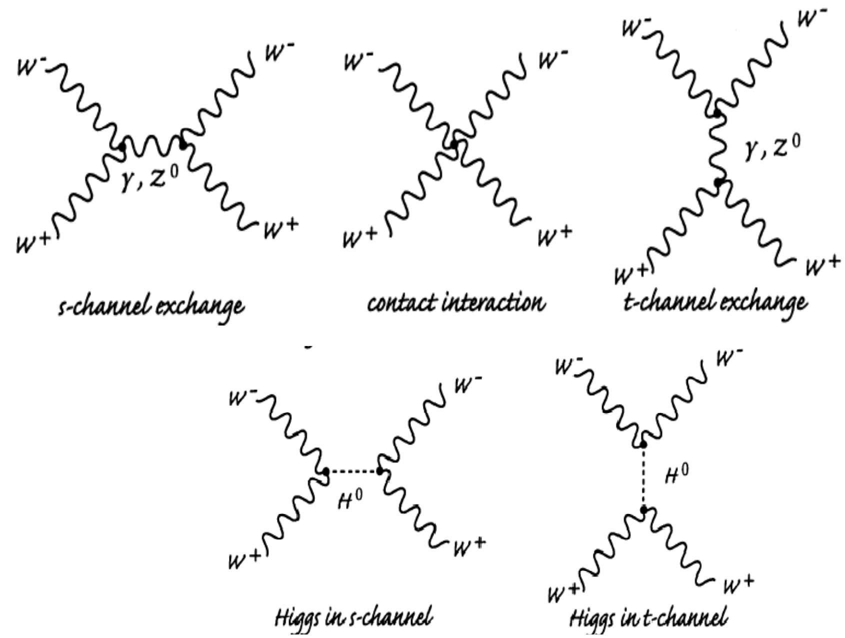
Radiative corrections change the shape of the Higgs potential at large and small Higgs boson mass



- Triviality
  $\Lambda < v \exp(4\pi^2 v^2 / 3M_h^2)$
- Vacuum Stability
  $\Lambda < v \exp(4\pi^2 M_h^2 / 3y_t^4 v^2)$



Unitarity



$$\mathcal{A} = g^2 \left(\frac{E}{M_W}\right)^2$$

$$\mathcal{A} = -g^2 \left(\frac{E}{M_W}\right)^2$$

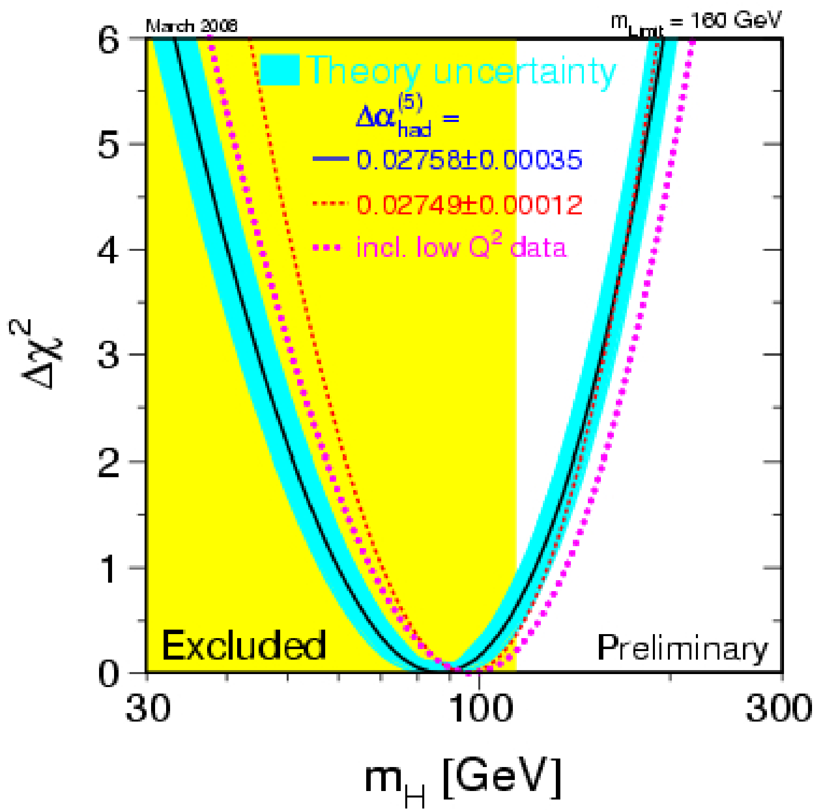
$$\mathcal{A} = g^2 \left(\frac{M_h}{2M_W}\right)^2$$

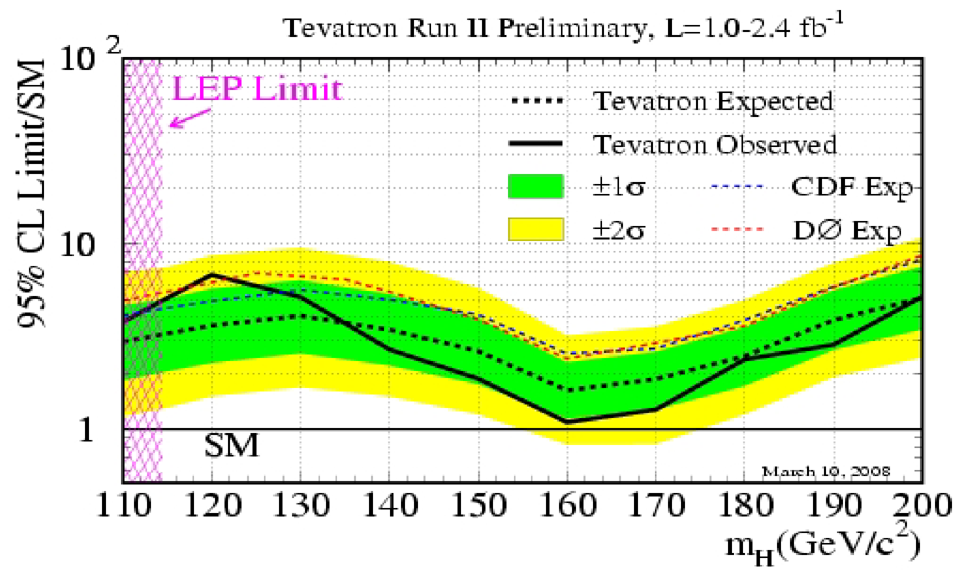
Higgs exchange needed to prevent Unitarity violation in WW scattering

- ➔ M_h < 780 GeV
- ➔ New phenomena required at the TeV scale

Experimental constraints M_h

LEPEWWG 07





See Stefan Soldner-Rembold's talk on Tuesday

Direct searches at LEP and TEVATRON combined with precision electroweak measurements

Tension between indirect bounds and direct search limit has increased

What is the mechanism of EWSB?

- Models with one or more Higgs bosons
  Standard Model (SM), SUSY, (h,H,A,$H^{\pm}$. . . :
  Higgs mechanism, elementary scalar particle(s)

- Strong electroweak symmetry breaking (technicolour, .):
  new strong interaction, non-perturbative effects, resonances, . . .

- Higgsless models in extra dimensions:
  Boundary conditions for SM gauge bosons and fermions on Planck and TeV branes in higher-dimensional space

➡ To preserve unitarity, new phenomena required at the TeV scale

Key questions about EWSB

1. Is EWSB controlled by strong new dynamics? extra dimensions?

2. Is there one Higgs boson? Or several?
3. Does H give mass to the fermions, or only to gauge bosons?
4. How does the H interact with itself?
5. Does the pattern of H decay imply NP?

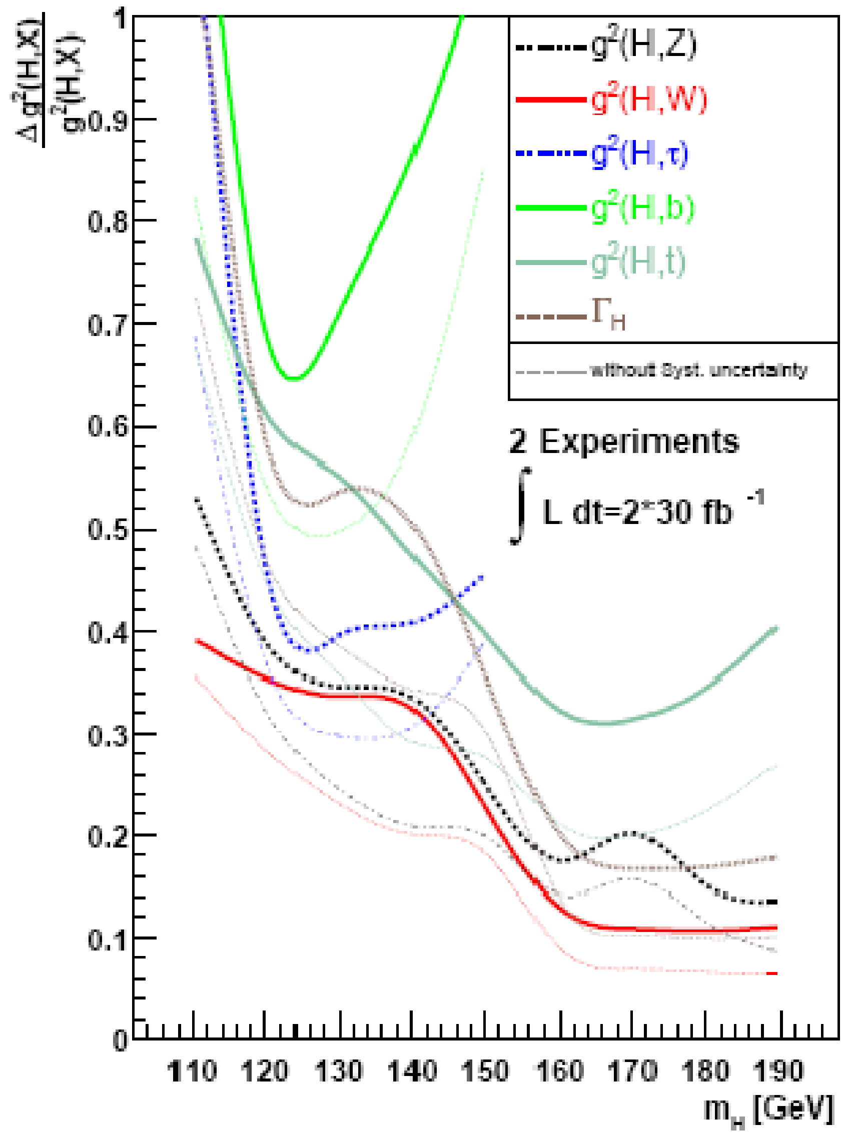
Which Higgs is it?

LHC can only directly measure ratios of couplings

Mild theory assumptions [Higgs coupling to gauge bosons not bigger than in SM] allow the extraction of the couplings themselves

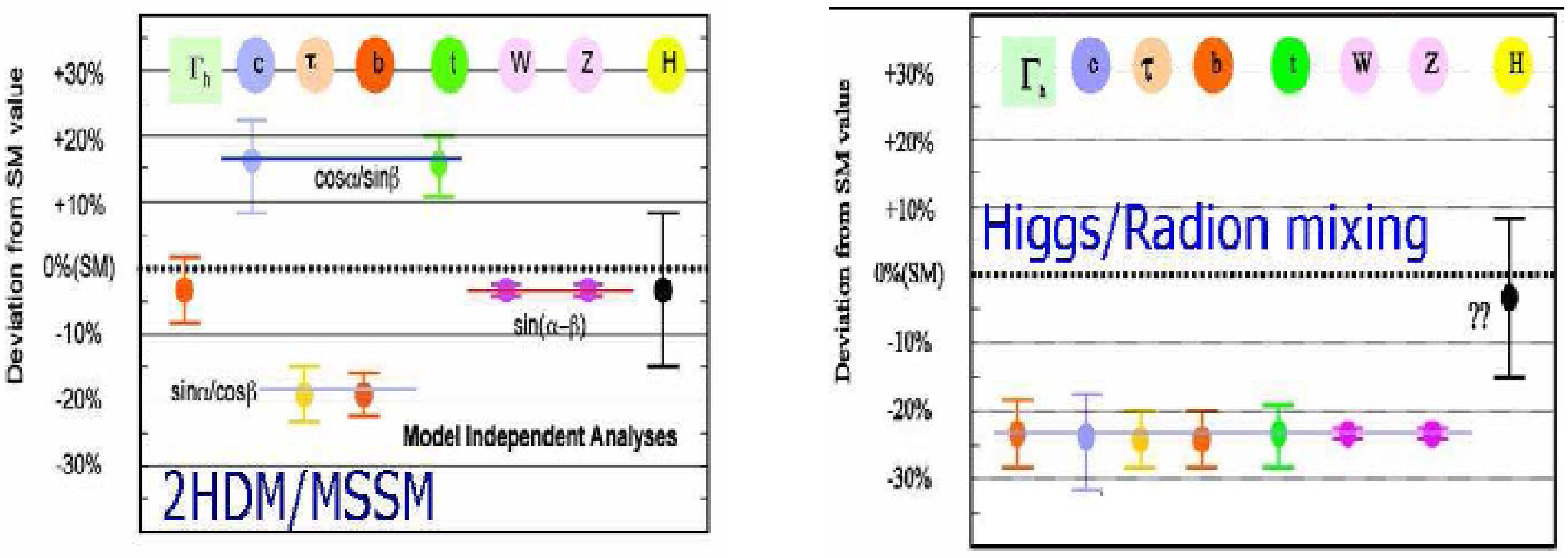
Many theories have, over large part of their parameter space, a light Higgs with properties very similar to those of the SM Higgs boson

➡ High-precision measurements of Higgs properties will be crucial to reveal the nature of EWSB - ILC



Higgs couplings: sensitivity to deviations from the SM

SM vs. BSM physics (ILC):



➡ Precision measurement of Higgs couplings distinguishes between different models

Key questions about EWSB

1. Is EWSB controlled by strong new dynamics? extra dimensions?

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3. Does H give mass to the fermions, or only to gauge bosons?
4. How does the H interact with itself?
5. Does the pattern of H decay imply NP?

6. What stabilizes M_h on the electroweak scale?
7. Can a light Higgs exist without other new phenomena?

The Standard Model cannot be the ultimate theory

The Standard Model does not include gravity

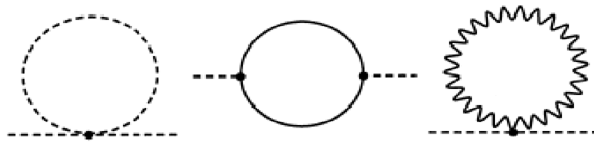
➡ breaks down at the latest at $M_{Planck} \approx 10^{19}$ GeV

Hierarchy problem: $M_{Planck} / M_{weak} \approx 10^{17}$

How can two so different scales coexist in nature?

Physics at M_{weak} is affected by physics at M_{Planck} by quantum effects

➡ Instability of M_{weak}



➡ Would expect that all physics is driven up to the Planck scale

Nature has found a way to prevent this

The Standard Model provides no explanation

Hierarchy problem: how can the Planck scale be so much larger than the weak scale?

⇒ Expect new physics to stabilize the hierarchy

Supersymmetry:

Large corrections cancel out because of symmetry

fermions ⇔ bosons

Extra dimensions of space:

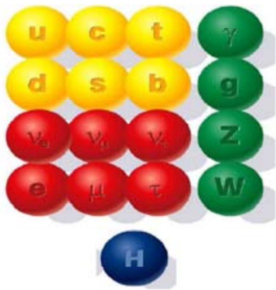
e.g. large extra dimensions,

$$M_{Planck}^2 = M^{n+2}(2\pi R)^n$$

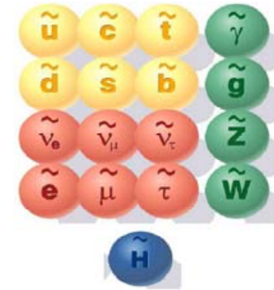
with M ~ TeV

n	R
1	$\sim 10^{12}$ m
2	$\sim 10^{-3}$ m
3	$\sim 10^{-8}$ m
6	$\sim 10^{-11}$ m

➡ observable effects at the TeV scale



Supersymmetry



Each spin-1/2 fermion has a spin-0 boson partner
Each spin-1 boson has a spin-1/2 fermion partner

Minimal Supersymmetric Standard Model (MSSM)

Two Higgs doublets to give masses to up-type and down-type fermions (extra symmetry forbids to use same doublet)

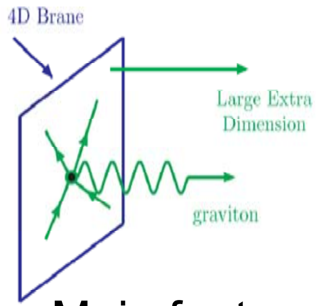
SUSY imposes relations between the parameters, two parameters instead of one:

$$\tan\beta \equiv v_u/v_d, \text{ and } M_A$$

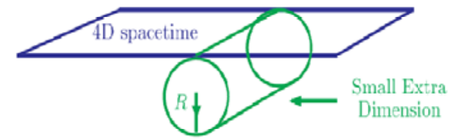
Most general case: no particular SUSY breaking mechanism assumed,

105 new parameters

Bonus: dark matter candidate if R-parity conserved,
light (maybe too light) Higgs



Extra dimensions



Main features: additional KK states of whatever particle can travel in extra dimensions
mass separation **~ 1/R**

Large Extra Dimensions (ADD)

SM in 4-D, gravity in extra dimensions

Extra KK graviton states, with small mass separation (R large)

Phenomenology:

Higher dimension operators

Missing energy

Randall Sundrum (RS)

SM in 4-D, gravity in extra dimension

KK graviton

R ~ 10^{-18} m, M ~ 1 TeV

Phenomenology:

Spin two resonances

Universal Extra Dimensions (UED)

SM in extra dimensions

KK excitations of all particles

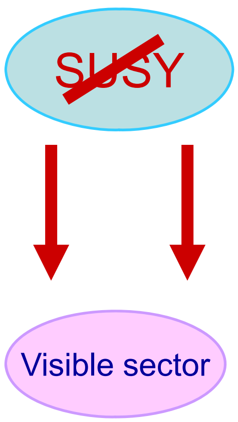
R ~ 10^{-18} m, M ~ 1 TeV

Phenomenology:

Looks like SUSY, but particles have wrong spin

Known unknowns

- What is the source of SUSY breaking?



  - MSUGRA? Gravity mediated
  - GMSB? Gauge mediated
  - AMSB? Anomaly mediated
  - Metastable SUSY breaking?

  What is the SUSY scale?

  How are the SUSY parameters related to each other?

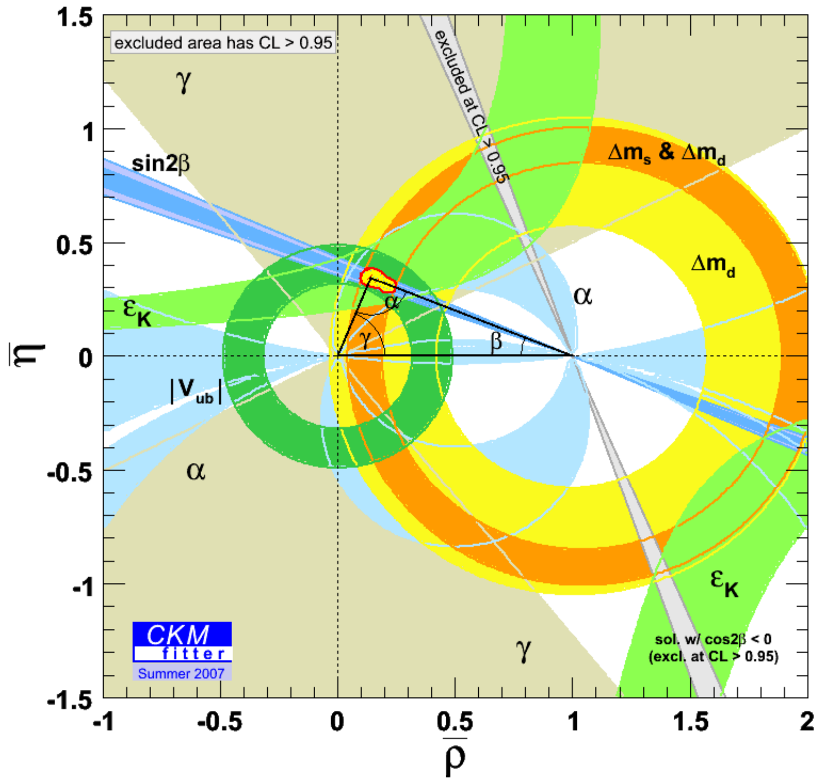
- What stabilises the extra dimensions?
  - How does space compactify?
  - What is the geometry of the extra dimension?

- Is this new physics flavour blind?

Quark Flavour

See Maria Smizanska’s talk

Quark Flavour



- The SM is very successful in describing quark flavour mixing.
- Impressive confirmation of CKM description of mixing and CP violation
- Absence of significant deviations from the SM in processes such as

$$B \to X_s \gamma \, (l^+ l^-)$$

D-$\bar{D}$ mixing

rare K decays

flavour mixing can only appear as ***small*** *corrections to the leading CKM mechanism*

NP in Flavour physics

Three complementary strategies

Model Independent approach

Extended CKM fits
including NP under
general assumptions
(e.g. no NP in treelevel)

very general (useful tool)

no predictive power

no dynamics

EFT approach

(MFV, nMFV...)

predictive (falsifiable)
approaches based only
on few underlying
flavoursymmetry
hypotheses

no dynamics

Explicit models

(SUSY, Little Higgs...)

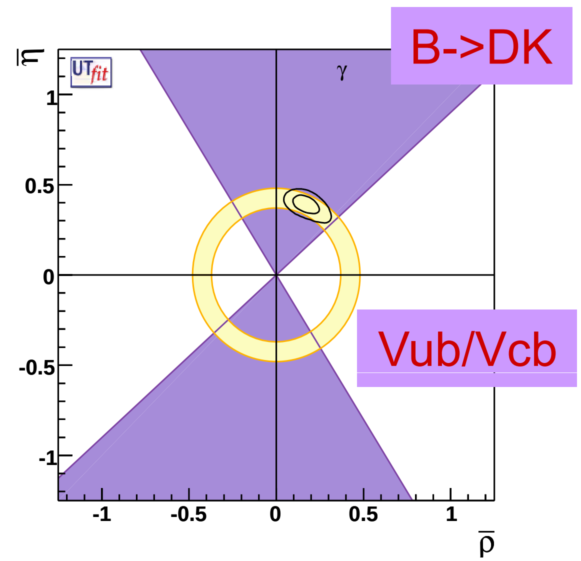
complete theories

many free parameters,
difficult to draw general
conclusions...

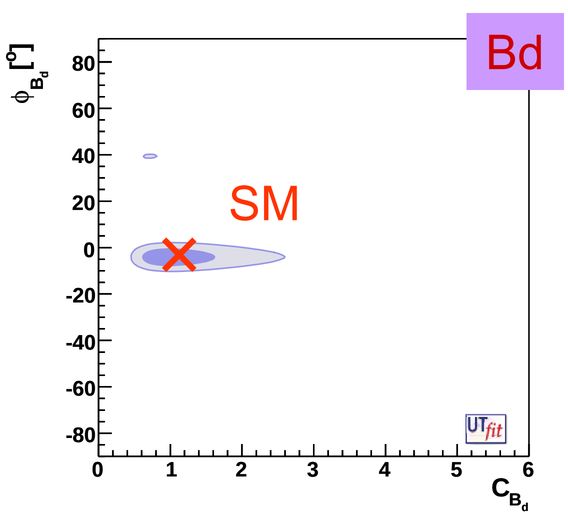
Model independent approach

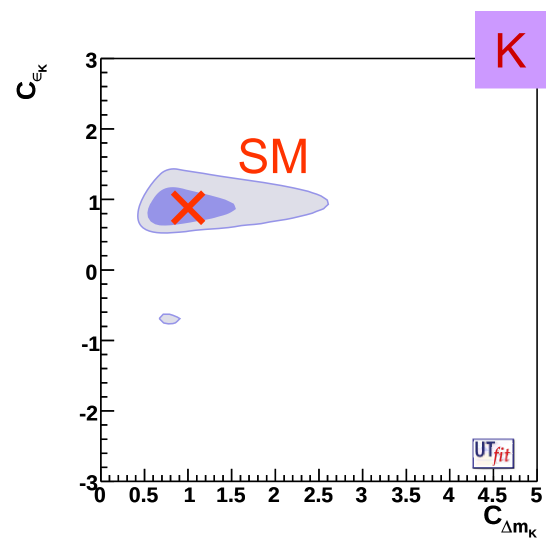
Assume that NP shows up only in loop amplitudes

Use tree processes to determine UT



General fit of NP in neutral meson mixing





$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \sum_{d \geq 5} \frac{c_{NP}}{\Lambda^{d-4}} O_n^d$$

$$M(B_d\text{-}\bar{B}_d) \sim \frac{(y_t V_{tb}^* V_{td})^2}{16\,\pi^2 M_W^2} + c_{NP} \frac{1}{\Lambda^2}$$

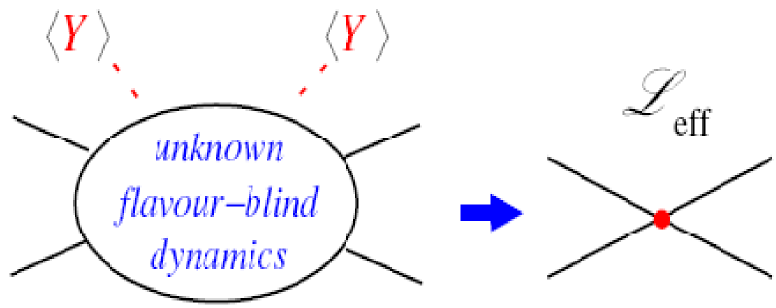
Contribution of new heavy degrees of freedom

c_{NP}:

- ~ 1 — tree/strong + generic flavour → $\Lambda \gtrsim 2\times10^4$ TeV [K]
- $\sim 1/(16\,\pi^2)$ — loop + generic flavour → $\Lambda \gtrsim 2\times10^3$ TeV [K]
- $\sim (y_t V_{ti}^* V_{tj})^2$ — tree/strong + MFV → $\Lambda \gtrsim 5$ TeV [K & B]
- $\sim (y_t V_{ti}^* V_{tj})^2/(16\,\pi^2)$ — loop + MFV → $\Lambda \gtrsim 0.5$ TeV [K & B]

Minimal Flavour Violation (MFV)

Yukawa couplings = unique sources of flavour symmetry breaking also beyond SM

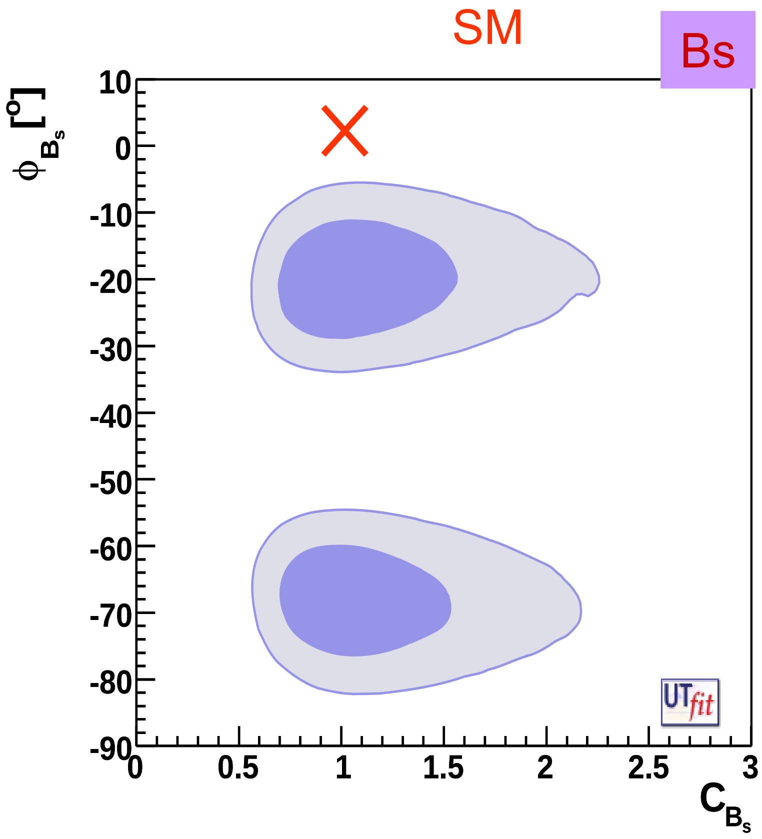


•In other words, any NP effects are suppressed by the same CKM angles that suppressed the SM – nicely avoids constraints from FCNC etc

•General principle which can be applied to any NP model - Arises naturally in some models, UED, GMSB

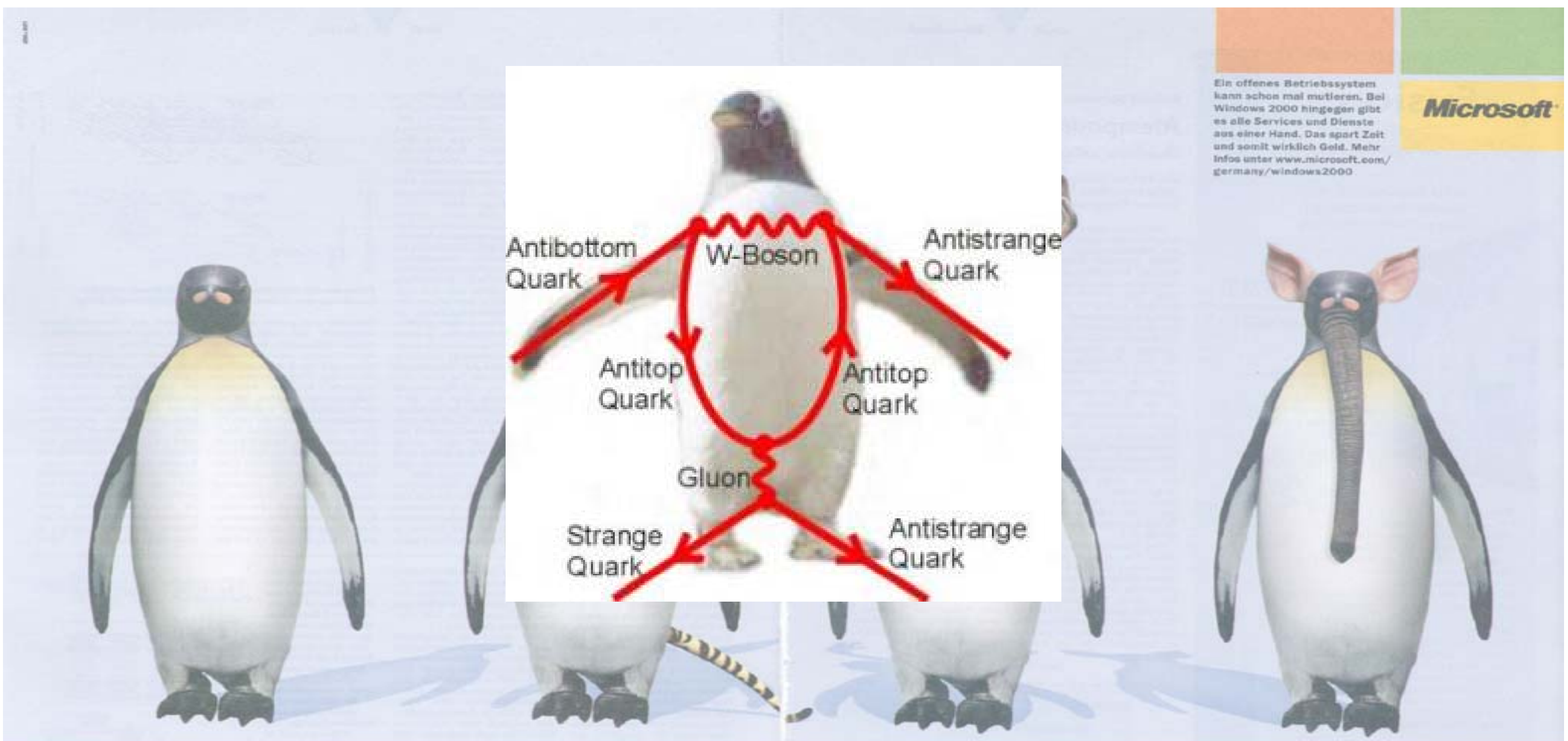
MFV (cont)

- MHV is far from being verified.
- If MHV is correct, have to understand **why?**
- Global symmetry broken by Yukawas?
- Recent study of Bs mixing disfavours MFV

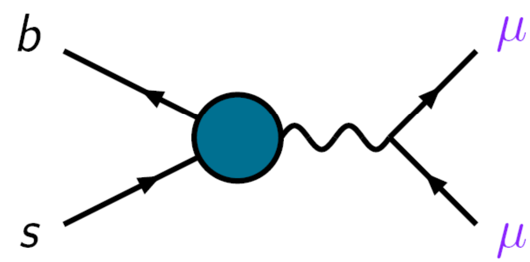


NP Penguins and golden channels

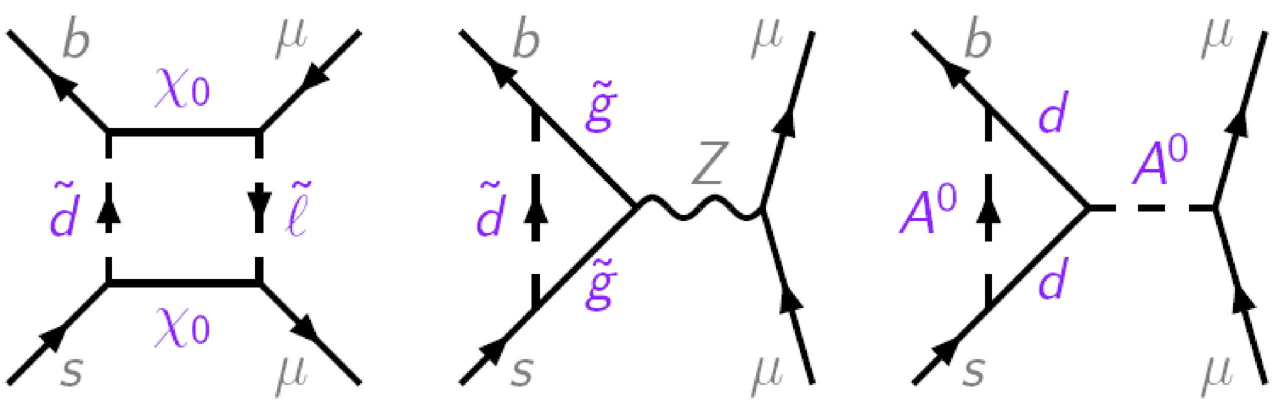
- Processes that are loop induced are particularly sensitive to NP effects
  - Typically penguin dominated processes



$B_s \rightarrow \mu^+\mu^-$

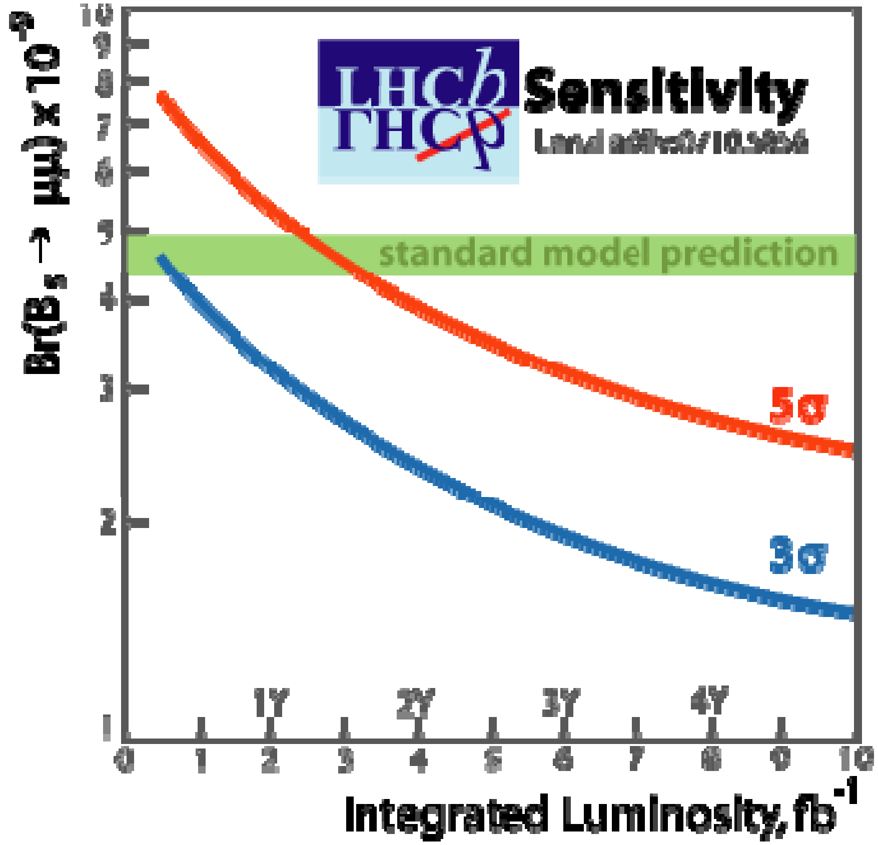


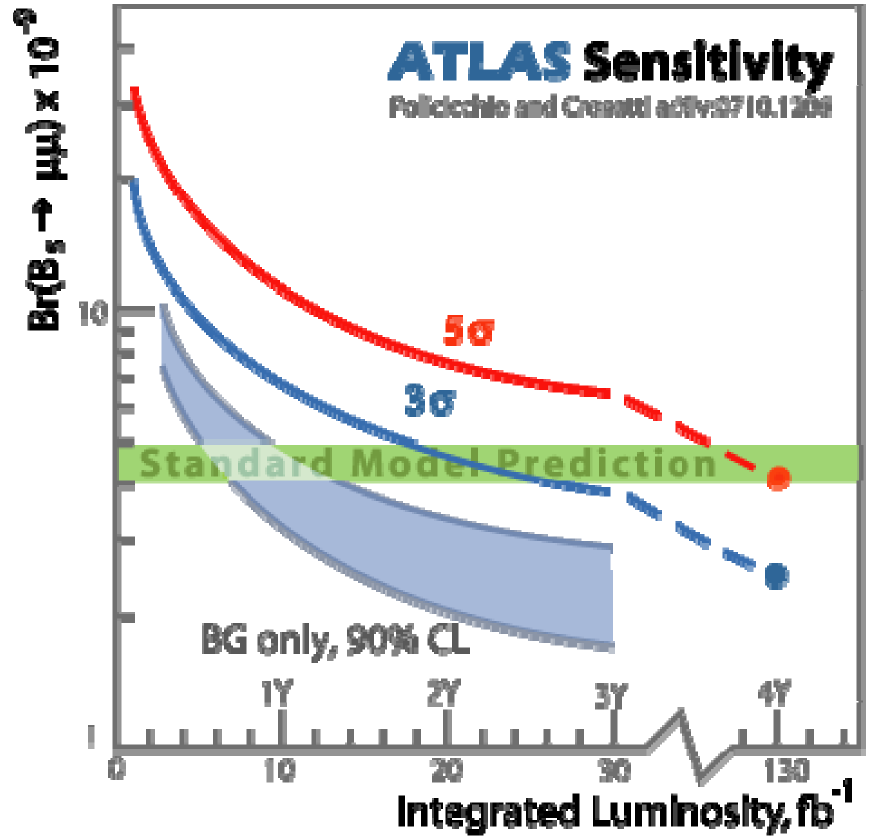
- No tree-level contribution.
- SM suppressed by FCNC and helicity
- Very easy to see in detector
- Additional contributions in any two Higgs doublet model, particularly SUSY



Amplitude proportional to $\tan^3\beta$

$B_s \rightarrow \mu^+\mu^-$





Some SUSY models may suppress the decay below the SM value!

Tanedo

Lepton Flavour

See Neil McCauley's talk

Neutrino Flavour

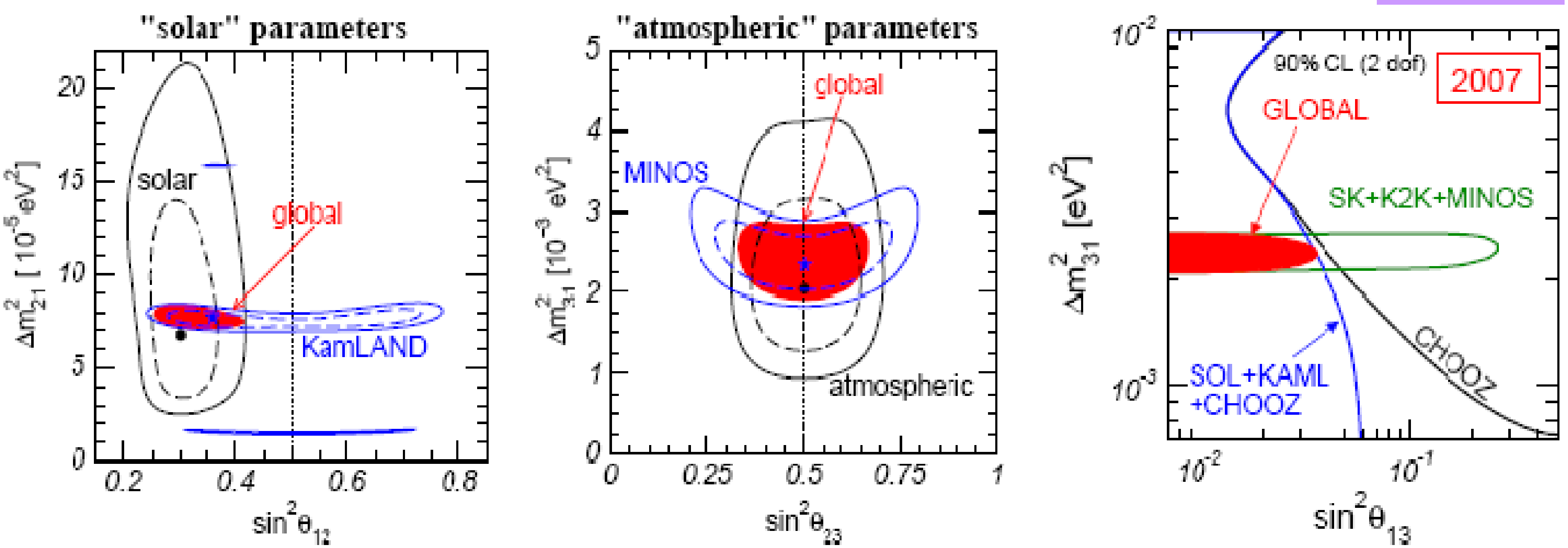
- Clear evidence for neutrino masses and mixing
  - Atmospheric $\nu_\mu \rightarrow \nu_\tau$ and $\nu_\mu \rightarrow \nu_\tau$
  - Solar $\nu_e \rightarrow \nu_{\mu,\tau}$
  - Reactor $\bar{\nu}_e \rightarrow \bar{\nu}_{\mathrm{other}}$
  - Accelerator $\nu_\mu \rightarrow \nu_{\mathrm{other}}$
- Clear indication of phenomena beyond the SM

Neutrino Mixing

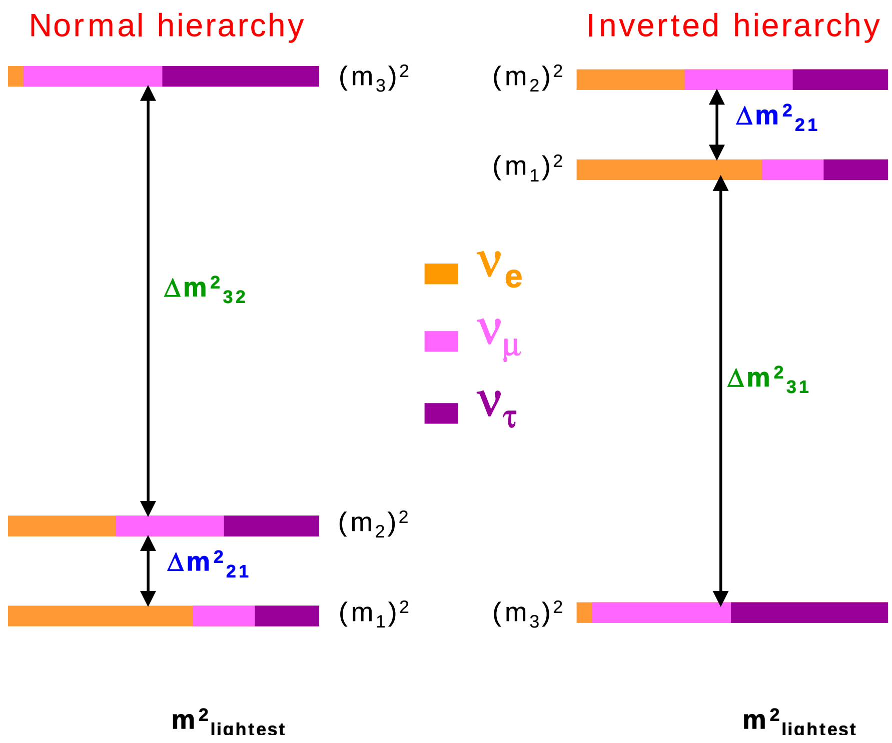
Pontecorvo-Maki-Nakagawa-Sakata

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha/2} & 0 \\ 0 & 0 & e^{i\alpha/2+i\beta} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Schwetz



What we don't know?



- What is θ_{13}? Is $\theta_{13} = 0$?
- Is $\theta_{23} = \pi/4$?
- Does the neutrino sector violate CP? Is δ non-zero? Leptogenesis?
- Is the mass hierarchy normal or inverted?

  Oscillation experiments
- What is the neutrino mass scale?

  Tritium, 0ν2β experiments
- Are neutrinos Dirac or Majorana?

  0ν2β experiments

Why don't we already know neutrino mass hierarchy?

Muon neutrino disappearance experiments (SuperK, K2K, MINOS) measure

$$P_{\mu\mu} = 1 - \sin^2 2\theta_{23} \sin^2\left(\frac{\Delta m^2_{13} L}{4E}\right) + \text{ subleading.}$$

Independent of sign of Δm^2_{13}

Need to probe ν_μ to ν_e oscillations (T2K, Nova) in presence of matter,

So that oscillation probability depends on the relative sign of Δm^2_{13} and the matter potential A

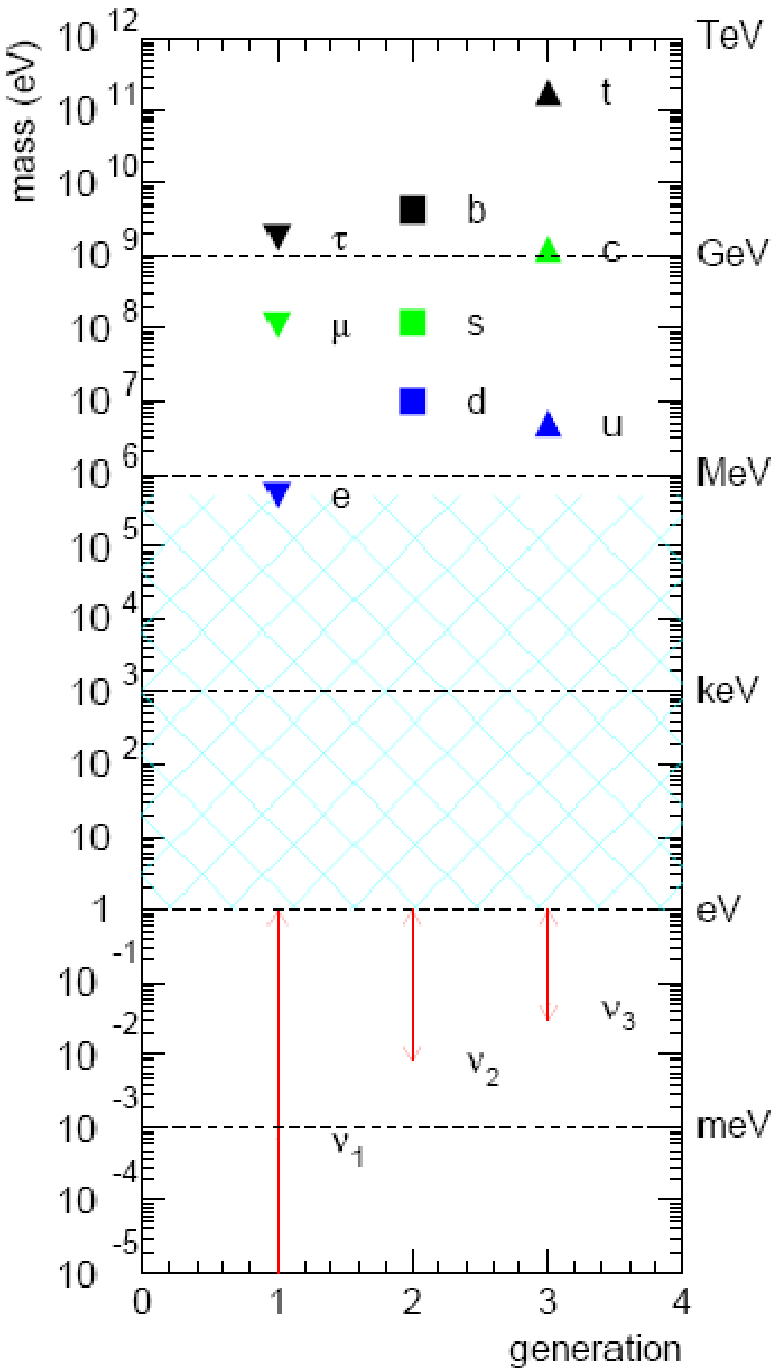
A changes sign for neutrinos/antineutrinos

$$P_{\mu e} \simeq P_{e\mu} \simeq \sin^2\theta_{23} \sin^2 2\theta^{\text{eff}}_{13} \sin^2\left(\frac{\Delta^{\text{eff}}_{13} L}{2}\right),$$

$$\sin^2 2\theta^{\text{eff}}_{13} = \frac{\Delta^2_{13} \sin^2 2\theta_{13}}{(\Delta^{\text{eff}}_{13})^2},$$

$$\Delta^{\text{eff}}_{13} = \sqrt{(\Delta_{13}\cos 2\theta_{13} - A)^2 + \Delta^2_{13}\sin^2 2\theta_{13}},$$

$$\Delta_{13} = \frac{\Delta m^2_{13}}{2E},$$



Implications of Neutrino Mass for NP

Massive neutrinos imply that the SM is incomplete.

Masses of neutrinos far out of line with other fermion masses (six orders of magnitude)

What is the new SM?
--Need more information

What scale of NP do neutrino masses imply?

What are the options?

Option 1: EFT

SM is an effective field theory, good up to some scale Λ (assume > 1TeV)
Only one possible dimension 5 operator

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} - \frac{\lambda_{ij}}{2\Lambda} L^i H L^j H + \mathcal{O}\left(\frac{1}{\Lambda^2}\right)$$

After EWSB, only consequence is neutrino mass

$$m_{ij} = \lambda_{ij} \frac{v^2}{\Lambda}$$

Neutrino masses suppressed by v/Λ relative to quark masses

Data requires $\Lambda < 10^{15}$ GeV assuming $\lambda \sim O(1)$ -- GUT scale?

Neutrinos are Majorana – Lepton number is violated

Option 2: Seesaw Mechanism

A renormalizable Lagrangian, with three extra gauge singlet fields N^i

$$\mathcal{L} = \mathcal{L}_{SM} + \lambda_{ij} L^i H N^j - \sum_{i=1}^{3} \frac{M_i}{2} N^i N^i + h.c.$$

Data constraint – any extra neutrino's should be sterile

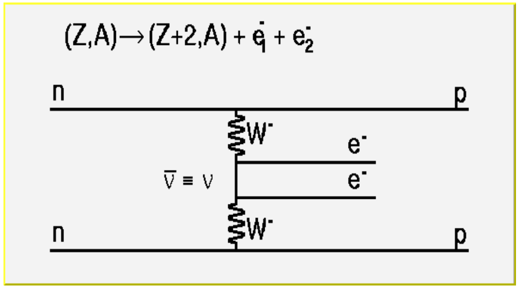
Theory prejudice – $M \sim 10^{15}$ GeV (GUT scale) or $M \sim 1$ TeV (EWSB scale)

No real constraint on M

$M = 0$: six neutrinos fuse into three Dirac neutrinos $m_{ij} = \lambda_{ij} v$
$U(1)_{B-L}$ is global symmetry of Lagrangian

$M >> v$: three active light neutrinos ~ $m \sim \lambda^2 v^2/M$
and three heavy sterile neutrinos ~M
neutrinos are Majorana – Lepton number is violated

Dirac/Majorana?



Q Are left-handed neutrinos, their own antiparticles?

A massive neutral fermion (s=1/2) is described by 4 or 2 degrees of freedom:

Dirac: particle/antiparticle left/right handed helicity

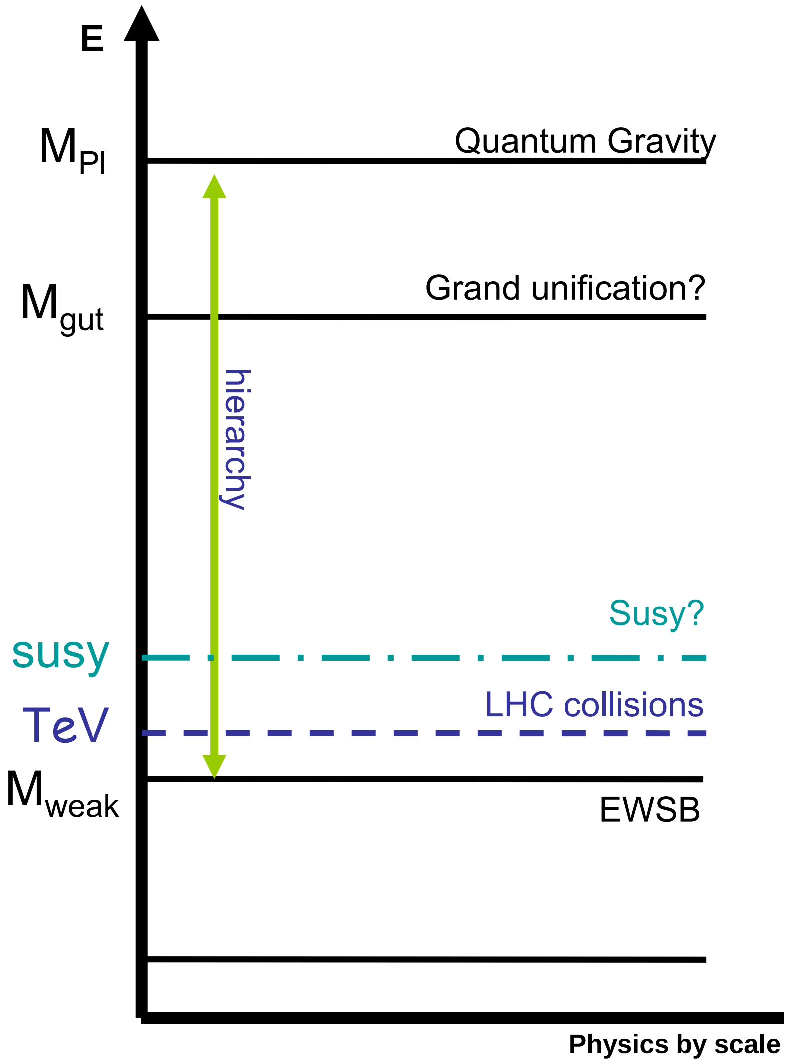
$\nu_L, \bar{\nu}_L, \nu_R, \bar{\nu}_R$

Majorana: only two states $\nu_L, \bar{\nu}_R$

Q Is lepton number violated?

Majorana neutrinos are their own antiparticles and, therefore, cannot carry "any" quantum numbers

Summary



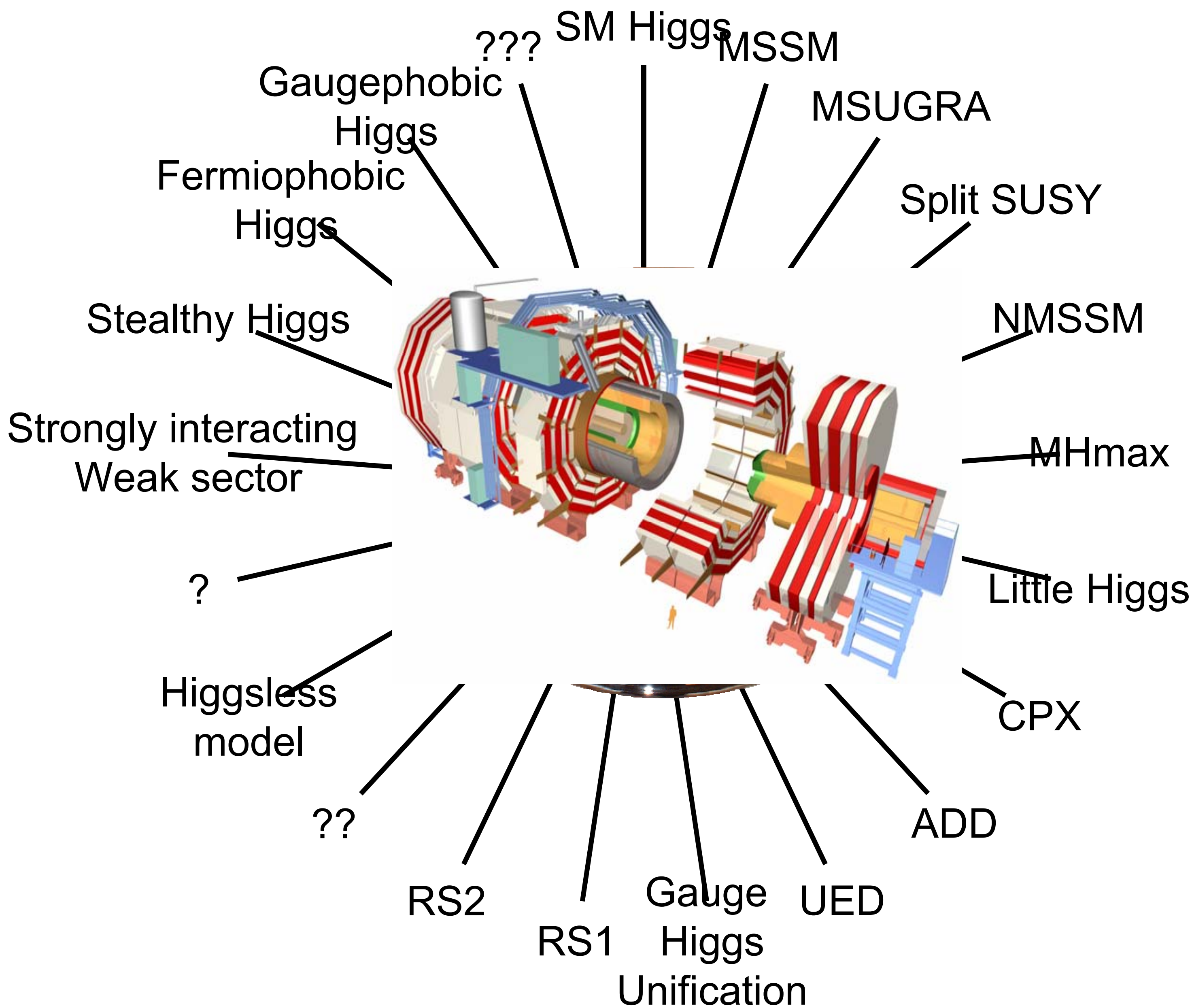
Many new and emerging links between high energy frontier, flavour physics, precision experiments and cosmology

Need a broad based programme to discriminate between many, many theoretical ideas.

With the LHC, "discoveries are guaranteed…at least the Higgs boson…likely observe new symmetries of nature, new particles and forces"

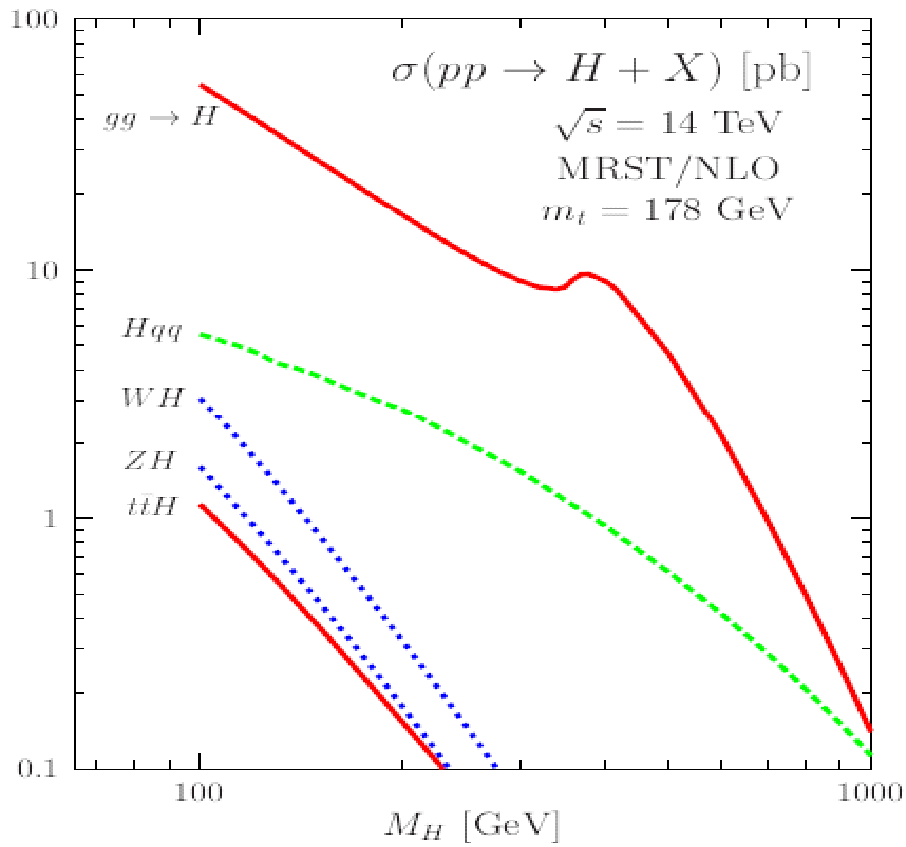
Most exciting time since discovery of jets/W/Z/SUSY/top at UA1/UA2 in 1982/3.

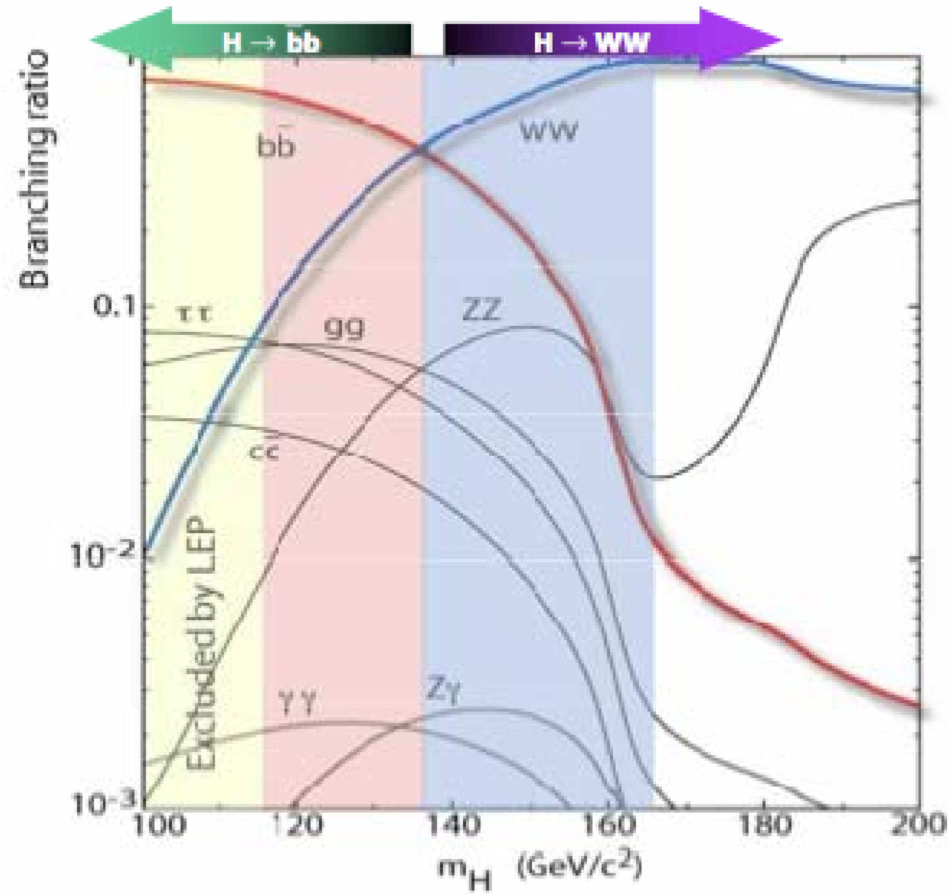
Data from the high energy frontier eagerly awaited
Time to place your bets!



SPARE SLIDES

Higgs production and decay

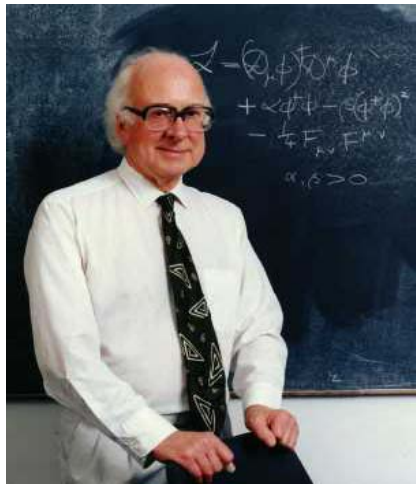




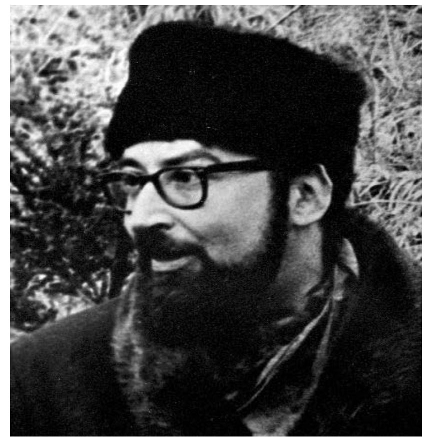
Well established phenomenology, over to ATLAS and CMS

The men behind the Higgs

Robert Brout



Peter Higgs



Francois Englert

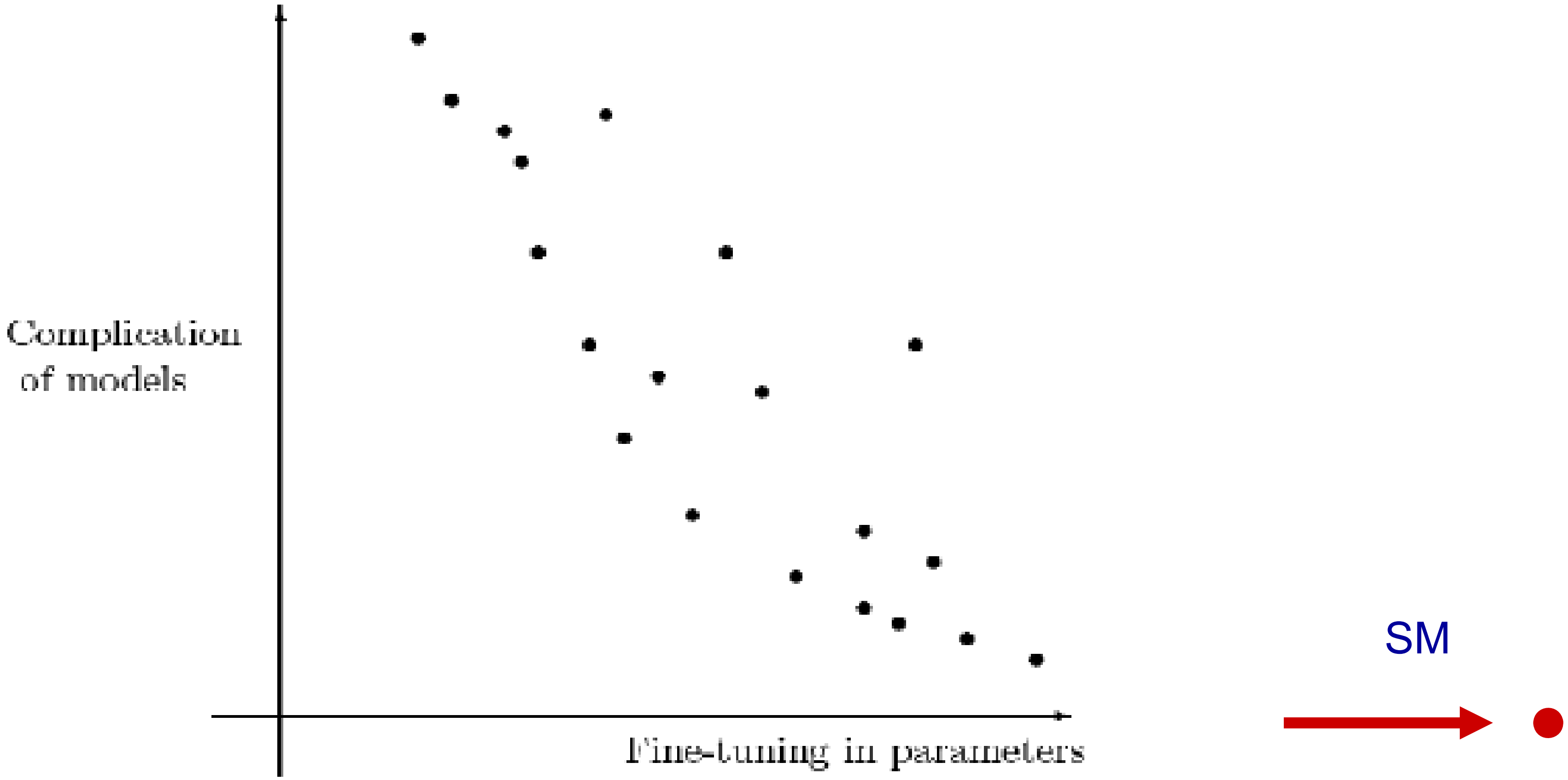
1964 Physics Letters (15 September),

Physical Review Letters (19 October)

1997 European Physical Society Prize

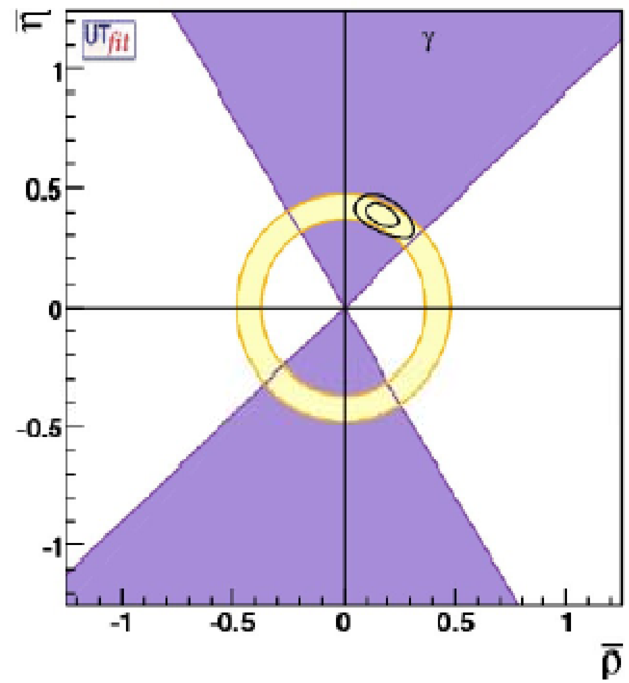
1964 Physical Review Letters (31 August)

Models of EWSB: fine-tuning vs. complexity



Improved CKM fits

Improving the determination of the CKM matrix from tree-level processes will certainly offer a valuable tool to improve constraints on NP (including MFV models).



Two key observables:

- γ from various $B_{(s)} \to D(\bar{D})$ modes

good prospects of improvements from LHCb

- V_{ub} from $B \to \pi l \nu$

more difficult [super-B + Lattice ?]

Flavour physics in the LHC era

LHC [high p_T]

A *unique* effort toward the high-energy frontier

[to determine the energy scale of NP]

Flavour physics

Improved CKM fits

Rare B decays

CPV in the Bs system

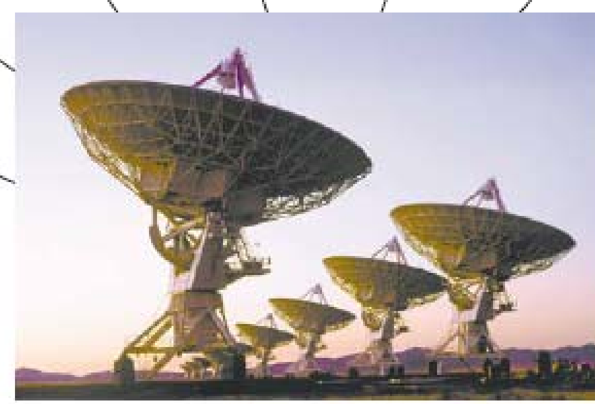
LFV in μ & τ decays

Universality tests in B & K

EDMs

Rare K decays

g-2



A *collective* effort toward the high-intensity frontier

[to determine the flavour structure of NP]