# Physics beyond the Standard Model at the LHC

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# What do we know at the start of the LHC?

## The Standard Model (SM):

- Relativistic quantum field theory (only known framework to formulate a theory consistent with QM and Special Relativity)
- Local internal (gauge) symmetries, governed by a SU(3)xSU(2)xU(1) algebra, leading to strong and electroweak interactions mediated by gluons, W/Z and photons
- Three families of quarks and leptons, with
  - a diverse mass spectrum: **$10^{-10}$ GeV** ($\nu$) → **$10^{2}$ GeV** (top, W/Z)
  - transitions between quarks generations, with violation of CP
  - transitions between lepton generations only observed so far in the neutrino sector

**Overall extremely complete and successfull description of known phenomena**

# Which issues are open for the LHC and beyond?

**To start with:**

- Identify the Higgs boson, namely the particle responsible for the breaking of the SU(2)xU(1) (a.k.a. electroweak, EW) symmetry and for the generation of mass for W/Z bosons, and for quarks and leptons
- Explore the nature of the Higgs boson, and establish the detailed dynamical mechanism with which the EW symmetry is broken (EWSB):
    - pure SM?
    - Supersymmetry?
    - Extra dimensions?
    - Higgsless?
    - ... ?

- Observing the Higgs boson will seal the SM box, the solid platform standing on which we'll be looking for new horizons and intellectual challenges, which will define the future of HEP:
  - what is **Dark Matter** ?
  - origin of the Baryon Asymmetry of the Universe?
  - ......

well posed questions within the SM, but no positive answer

  - why SU(3)xSU(2)xU(1)?
  - why 3 generations, why their properties?
    - mass spectra
    - mixing patterns

no way to formulate as mathematical problems within the SM

  - .....
  - why gravity? why D=3+1?
  - .....

no way to formulate as mathematical problems within standard quantum field theory

- There are many good ***theoretical*** arguments suggesting that the SM is incomplete or additional structures are required:
    - understanding of quantum gravity
    - hierarchy problem, naturalness of the EW scale
    - couplings' unification at the GUT scale
- **Neutrino masses,** as well as **DM** and **BAU**, provide concrete ***experimental*** indications that we're missing something
    - ➡ Regardless of our personal level of pragmatism and indifference towards theoretical speculations, as scientists **we have to accept the existence of physics Beyond the Standard Model (BSM)**, and as HEP physicists we have a duty to search for it.
- Formulating **plausible** and **calculable** BSM scenarios is today the best we can do to help establish directions and priorities for the field.

**SM=**

**gauge structure** → Accurately tested with Z decays, LEP2 and $m_{top}$ : any room left for BSM effects in EW observables?

**flavour structure** → Accurately tested with B factories, K experiments, LFV, EDM, etc: any room left for BSM effects?

Which direction will provide more fruitful will depend on which BSM scenarios we'll discover

Any planning for future facilities must rely on some theoretical prejudice, perhaps helped by on one or another piece of circumstancial evidence, to anticipate the most likely future surprises

## What will be the main driving theme of the exploration of new physics ?

the gauge sector
(Higgs, EWSB)

the flavour sector
($\nu$ mixings, CPV, FCNC, EDM, LFV)

**The High Energy Frontier**

LHC
SLHC
VLHC
LC
CLIC
....

**The High Intensity Frontier**

**Neutrinos:**
super beams
beta-beams
$\nu$ factory

**Charged leptons**
stopped $\mu$
$l \rightarrow l'$ conversion
e/$\mu$ EDM

**Quarks:**
B factories
K factories
n EDM

# Dark Matter

- Clear cosmological evidence: CMB fluctuations, structure formation
- Whatever its origin, it must be coded somewhere in the Lagrangian of HEP => **it is “our” problem**
- Main ingredients:
  - stable weakly interacting particle
  - mass vs annihilation rate such as to decouple (freeze-out) at the appropriate time and with the appropriate density
- It so happens that the required numerics works out to match the expected behaviour of particles with mass O(100 GeV) and weak coupling:

$$\sigma \sim \alpha^2_W / M^2_W$$

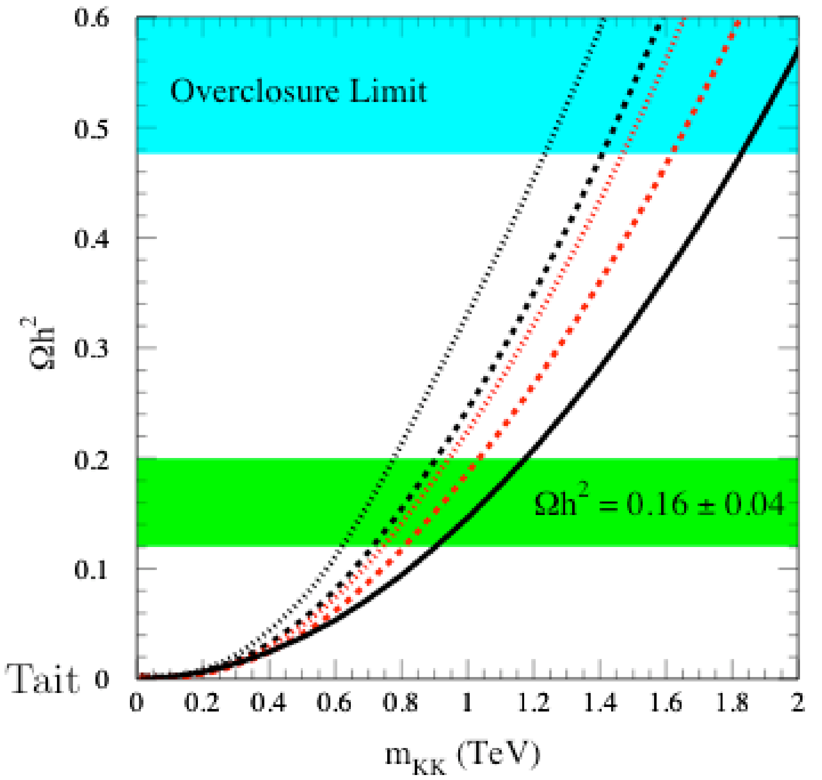
**It is unavoidable to speculate that the origin of DM is directly linked to the phenomena responsible for EWSB**

It is not surprising that most alternative approaches to the "Higgs" problem (little Higgs, extra-dimensions, etc) provide a possible DM candidate:

Mass scale / coupling strength are inherited by the link to EWSB

Stability is associated to discrete symmetries (like SUSY's R parity)

Example from Universal Extra Dimensions (DM=1st photon/ neutrino KK mode)




Géraldine Servant [a,b] and Tim M.P. Tait

hep-ph/0206071

**LEP's heritage is a strong confirmation of the SM, and at the same time an apparent paradox:**

SM fits: m(H)=98+52-36; on the other, SM radiative corrections give

$$\boxed{\delta m_H^2 = \frac{6G_F}{\sqrt{2}\pi^2}(m_t^2 - \frac{1}{2}m_W^2 - \frac{1}{4}m_Z^2 - \frac{1}{4}m_H^2)\Lambda^2 \sim (115\mathrm{GeV})^2 \left(\frac{\Lambda}{400\mathrm{GeV}}\right)^2}$$

How can counterterms artificially conspire to ensure a cancellation of their contribution to the Higgs mass?

The existence of new phenomena at a scale not much larger than 400 GeV appears necessary to enforce such a cancellation in a natural way!

The accuracy of the EW precision tests at LEP, on the other hand, sets the scale for "generic new physics" (parameterized in terms of dim-5 and dim-6 effective operators) at the level of few-to-several TeV.

This sets very strong constraints on the nature of this possible new physics: to leave unaffected the SM EW predictions, and at the same time to play a major role in the Higgs sector.

## Supersymmetry, among others, offers one such possible solution

In Supersymmetry the radiative corrections to the Higgs mass are not quadratic in the cutoff, but logarithmic in the size of SUSY breaking (in this case $M_{stop}/M_{top}$):

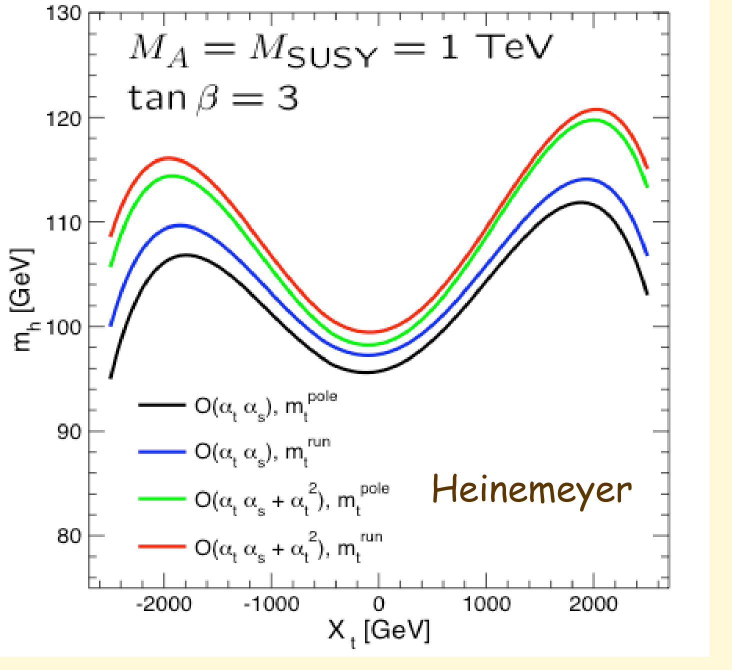
$$m_h^2 < m_Z^2 + \frac{3G_F}{\sqrt{2}\pi^2} m_t^4 \left[ \ln\left(\frac{M_S^2}{m_t^2}\right) + x_t^2\left(1 - \frac{x_t^2}{12}\right)\right]$$ with

$$M_S^2 \equiv \frac{1}{2}(M_{\tilde{t}_1}^2 + M_{\tilde{t}_2}^2) \qquad X_t \equiv A_t - \mu \cot\beta$$

$$x_t \equiv X_t / M_S$$

For $M_{susy}$< 2TeV

$$m_h^{max} \simeq 122 \text{ GeV}, \quad \text{if top-squark mixing is minimal,}$$
$$m_h^{max} \simeq 135 \text{ GeV}, \quad \text{if top-squark mixing is maximal}$$




The current limits on $m_H$ point to M(lightest stop) > 600 GeV. Pushing the SUSY scale towards the TeV, however, forces fine tuning in the EW sector, reducing the appeal of SUSY as a solution to the Higgs mass naturalness:

$$\delta m_Z^2 \sim (90GeV)^2 \left(\frac{M_S}{230GeV}\right)^2 \ln\frac{\Lambda_{UV}}{M_S}$$

In other words, the large value of $m_H$ shows that room is getting very tight now for SUSY, at least in its "minimal" manifestations.

**This makes the case for an early observation of SUSY at the LHC quite compelling**

# Supersymmetry

- Spectrum doubling: one bosonic degree of freedom (dof) of for each fermionic dof, and viceversa
- enhanced relations among and constraints on couplings/masses
- space-time Lorentz symmetry ⇒ particle ↔ antiparticle
- space-time Supersymmetry ⇒ particle ↔ sparticle
- **SUSY has a priori fewer parameters than non-SUSY:**
  - m(particle)=m(sparticle)
  - couplings(particle)=couplings(sparticle)
  - Higgs selfcoupling (λ) related to weak gauge coupling:

$$\lambda\phi^4 \sim g_W\phi^4$$

- All **complexity** and parameter proliferation of SUSY are just a **consequence of SUSY breaking (SSB)**!!

- A minimal SUSY extension of the SM, with arbitrary pattern of spontaneous SUSY breaking, has over 100 extra parameters (scalar and gauge-fermion masses, mixings among SUSY partners of quarks and leptons)
- This is not much worse than an arbitrary extension to leptons and hadrons of Fermi's theory of weak interactions, before Feynman, Gell-Mann and Cabibbo, or even before LEP/SLC firmly established the parameters of the SM. One could have needed parameters to describe:
  - non V-A couplings (S, P, T, V+A)
  - non-universal couplings to hadronic currents, and to $\mu$ or $\tau$ currents
  - more complex Higgs structures
  - different realisations of EWSB
- Therefore parameter proliferation in SUSY is most likely the consequence of our current ignorance of the specific dynamics leading to SUSY breaking.

## Benchmark goals for SUSY studies at the LHC:

**+ GET CLUES ON THE MECHANISM OF SUSY BREAKING**
**+ ESTABLISH THE POSSIBLE CONNECTION OF DM AND SUSY**

The search for Supersymmetry is in my view the single most important task facing the LHC experiments in the early days. In several of its manifestations, SUSY provides very clean final states, with large rates and potentially small bg's.

Jets + miss ET (squarks/gluinos)

Same-sign dileptons + MET (gluinos)

$B_s$->$mu^+mu^-$

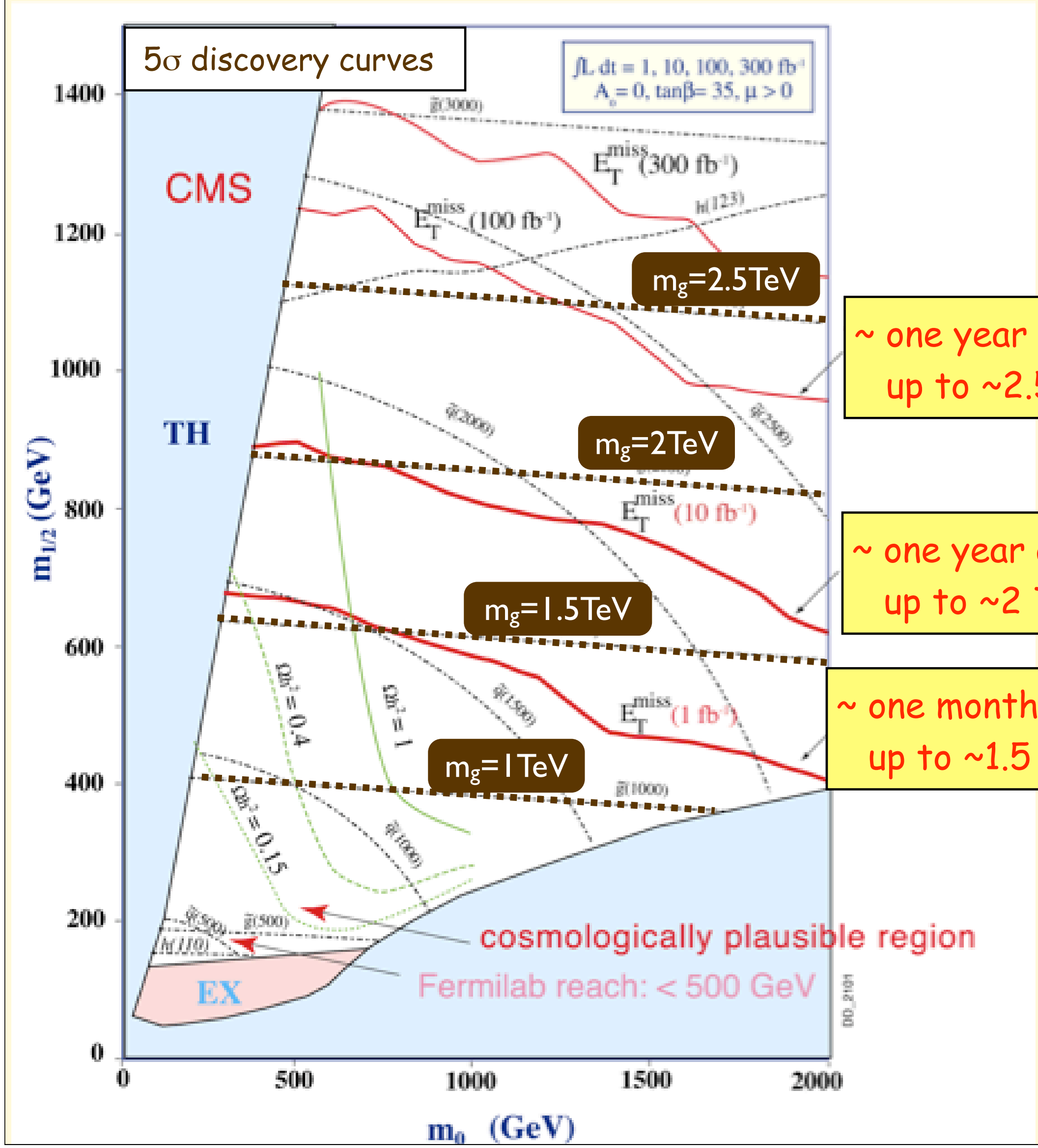
t tbar+ MET (stop production)

photons+MET (gauge mediated SUSY breaking)

Given the big difficulty and the low rates characteristic of Higgs searches in the critical domain $m_H$<135 GeV, I feel that the **detector and physics commissioning should be optimized towards the needs of SUSY searches rather than light-Higgs** (I implicitly assume that for $m_H$>140 Higgs searches will be almost staightforward and will require proper understanding of only a limited fraction of the detector components -- e.g. muons)

# SUPERSYMMETRY early-discovery potential

Large $\tilde{q}\tilde{q}, \tilde{q}\tilde{g}, \tilde{g}\tilde{g}$ cross-section → ≈ 100 events/day at $10^{33}$ for $m(\tilde{q}, \tilde{g}) \sim 1$ TeV
Spectacular signatures → SUSY could be found quickly

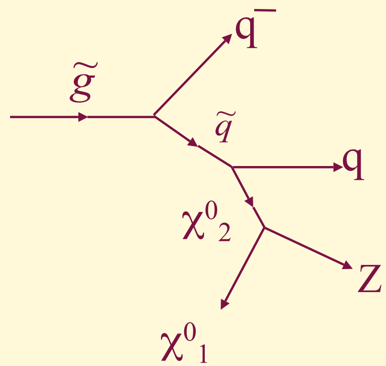



~ one year at $10^{34}$: up to ~2.5 TeV

~ one year at $10^{33}$ : up to ~2 TeV

~ one month at $10^{33}$ : up to ~1.5 TeV

Using multijet + $E_T^{miss}$ (most powerful and model-independent signature if R-parity conserved)




Measurement of sparticle masses will require > 10 fb-1.

For some people the room left for SUSY is too tight. Some skepticism on SUSY has emerged, and a huge effort of looking for alternatives has began few years back, leading to a plethora of new ideas (Higgless-models, Little Higgs, extra-dimensions, etc)

Some of these ideas lead to rather artificial structures, where the problem of the Higgs naturalness is shifted to slightly higher scales, via the introduction of a new sector of particles around the TeV.

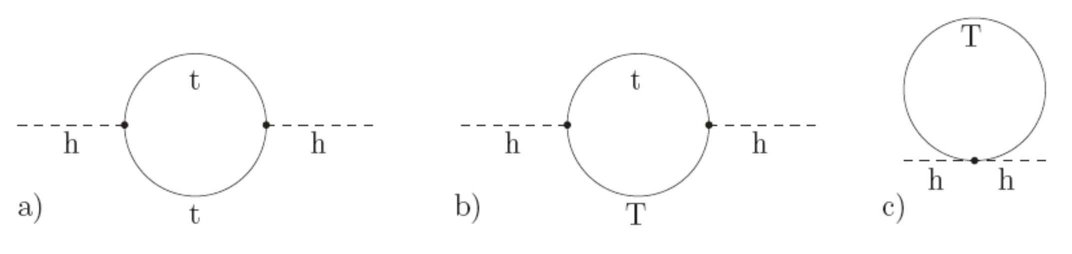
The observation of new phenomena within the first few yrs of run, in these cases, is not guaranteed (nor is it asymptotically)

Few of these scenarios offer the appeal of Supersymmetry, with its clear predictions (calculability), and connections with the other outstanding problems of the Standard Model (Dark Matter, Flavour, CP violation)

# Ex: Little Higgs models

- Embed SM in a larger group
- Higgs as pseudoGoldstone boson
- Cancel top loop with a new heavy T quark

$$f \equiv \frac{\Lambda_{strong}}{4\pi}$$




$$\delta m^2_{H,top}(LH) \sim \frac{6 G_F m_t^2}{\sqrt{2}\pi^2} m_T^2 log \frac{\Lambda}{m_T}$$

$$\frac{\Lambda^2}{16\pi^2}\left( +\lambda_t^2 \quad +\lambda_T^2 \quad -2\frac{\lambda_T m_T}{f}\right) = 0$$

- new gauge bosons, Higgses, all heavy

$M_T < 2$ TeV $(m_h / 200 \text{ GeV})^2$
$M_{W'} < 6$ TeV $(m_h / 200 \text{ GeV})^2$
$M_{H++} < 10$ TeV

No satisfactory framework for flavour, all problems shifted to the higher scale of ~ 10 TeV, not much to learn until VLHC available. Very frustrating!

# Ex: Black holes at the LHC

- $M_{Planck}$ ~ O(1 TeV) =>

pp→BH has large rates:

$$\sigma(BH) \sim \left[\sqrt{S}/M_{Planck}^{(D-2)}\right]^{2/(D-3)} \sim S^{1/D-3}$$

| $M$ | $D=8$ | $D=10$ |
|---|---|---|
| 5 TeV | $1.6\times10^5$ fb | $2.4\times10^5$ fb |
| 7 TeV | $6.1\times10^3$ fb | $8.9\times10^3$ fb |
| 10 TeV | 6.9 fb | 10 fb |

- The details of the cross-section growth depend on the internal structure of the extra-dimensional space => probe geometry via BH production and decay properties
- Short distances screened by the BH => **the end of short-distance physics.** The radius of the BH grows with its M, so higher energies probe more and more IR physics (<=> string duality).
- $M_{Planck}$ ~ 1/ ($g^{1/4}$ $L_{string}$ ) => $M_{string}$ < $M_{Planck}$ << $M_{BH}$
- Therefore, once BH become manifest, **experimental string physics is already accessible.**
- Since $M_{BH}$ >~ O(5-10) $M_{string}$ and given that we've seen no strings yet, room for this to happen at the LHC is limited.

In spite of all the attemps to indetify alternative EWSB scenarios, I feel that the trail of evidence for new physics:

*** DM**

*** gauge coupling unification + neutrino masses**

in addition to the theoretical appeal:

*** space-time symmetry**

*** connection with superstrings and gravity**

still singles out **SUSY as the most compelling candidate for the ultimate BSM framework**

# Flavour and BSM

Flavour phenomena have contributed shaping modern HEP as much as, if not more than, the gauge principle

$\mu$

$\nu$

**Strangeness $\Rightarrow$ SU(3)**

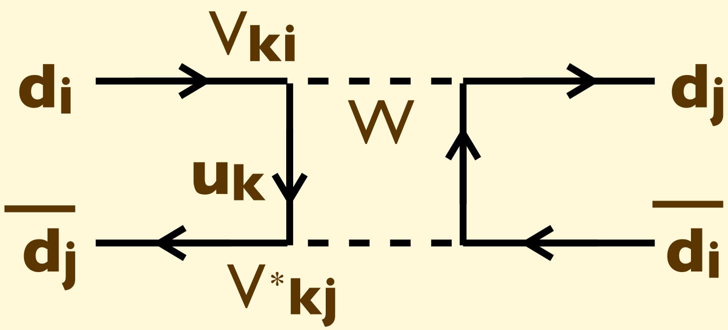
**K**

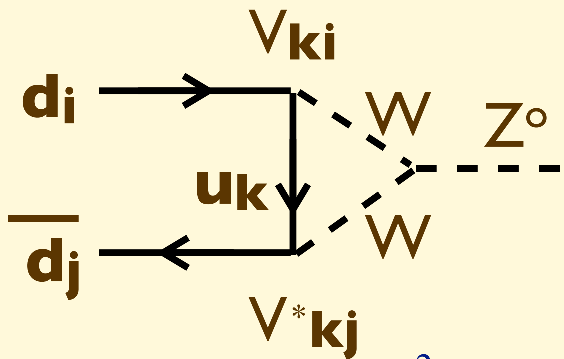
$\varepsilon_K \Rightarrow$ **CP violation**

$K^0 - \overline{K}^0$ mixing/ FCNC $\Rightarrow$ **GIM, charm**

# FCNC and CPV in the SM

- Suppression of FCNC and CPV are guaranteed in the SM by the following facts:
  - Quark sector:
    - unitarity of CKM (GIM mechanism)
    - small mixings between heavy and light generations



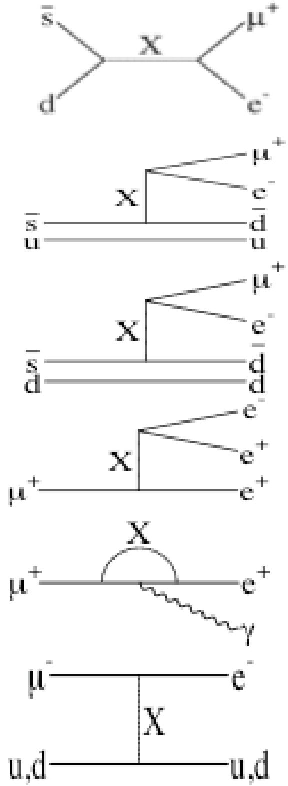

$$\Delta_{ij} \sim \sum_{k=u,c,t} V_{ki} V_{kj}^* \, f(m_k/m_W) \sim \sum_{k=c,t} V_{ki} V_{kj}^* \, m_k^2/m_W^2 \sim V_{ci} V_{cj}^* \frac{m_c^2}{m_W^2} + V_{ti} V_{tj}^*$$

  - Lepton sector:
    - mν=0 ⇒ all phases and angles absorbed by field redefinitions, no mixings/CPV at all

# FCNC beyond the SM

S.Geer

- There is absolutely no guarantee that these properties be maintained in extensions of the SM
- As soon as these are released, effects are devastating!

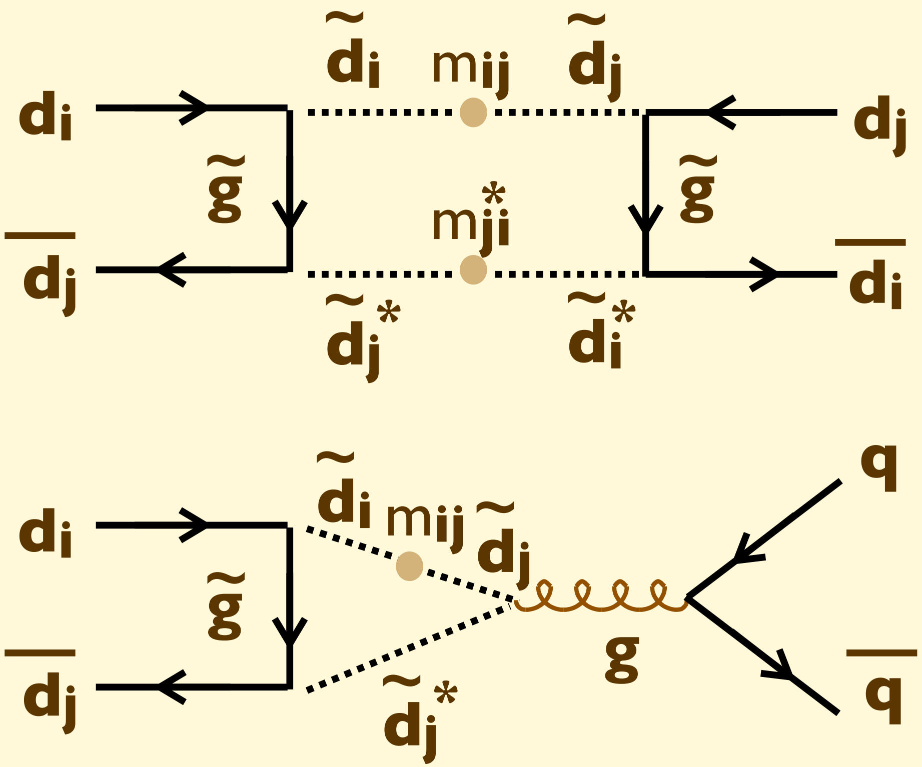



| | |
|---|---|
| $B(K_L \to \mu e) < 4.7 \times 10^{-12}$ | $M_X > 150\ \mathrm{TeV}/c^2$ |
| $B(K^+ \to \pi^+\mu^+e^-) < 4 \times 10^{-11}$ | $M_X > 31\ \mathrm{TeV}/c^2$ |
| $B(K_L \to \pi^0\mu^+e^-) < 3.2 \times 10^{-10}$ | $M_X > 37\ \mathrm{TeV}/c^2$ |
| $B(\mu^+ \to eee) < 1 \times 10^{-12}$ | $M_X > 86\ \mathrm{TeV}/c^2$ |
| $B(\mu^+ \to e^+\gamma) < 1.2 \times 10^{-11}$ | $M_X > 21\ \mathrm{TeV}/c^2$ |
| Normalized Rate $< 6.1 \times 10^{-13}$ | $M_X > 365\ \mathrm{TeV}/c^2$ |

Compare the to O(10 TeV) sensitivity w.r.t. modifications of the gauge/EW sector

How can the new physics we need to understand the open problems of HEP leave no trace of FCNC?

# Example: Squark mixing




$\Delta F=2$ ($B$-$\bar{B}$, $K$-$\bar{K}$ mixing)

$\Delta F=1$ penguins:
$b \to s\,\bar{s}\,s$

If the squark mass matrix is not aligned with the quark mass matrix, new sources of FNCN and of CPV

The discovery of Supersymmetry or other new phenomena at the LHC will dramatically increase the motivation for searches of **new phenomena in flavour physics.**

While there is no guarantee that any deviation from the SM will be found, the existence of physics BSM will demand and fully justify these studies: we'll be measuring the properties, however trivial, of something which we know exists, as opposed to blindly looking for "we don't know what" as we are unfortunately doing today!

**Discoveries of BSM physics at the LHC should be accompanied by a rich and complete programme at LHCb and SuperB factories, rare K decays, and possibly new studies of the charm sector, which will naturally complement the measurements in $\nu$ physics and searches for Lepton Flavour Violation phenomena.**

# FLAVOUR IN THE ERA OF THE LHC

## a Workshop on the interplay of flavour and collider physics

### First meeting: **CERN, November 7-10 2005**

The goal of this Workshop is to outline and document a programme for flavour physics for the next decade, addressing in particular the complementarity and synergy between the LHC and the flavour factories vis a vis the discovery and exploration potential for new physics.

The format of the Workshop will follow the standard CERN experience, with an opening meeting with plenary sessions and with the start of the WG activities, followed by 2-3 meetings of the WG's to take place during the following year, and a final plenary meeting at the end.

# A programme for flavour physics at the LHC

- B/D decays
- Flavour phenomena in top decays:
    - FCNC
    - anomalous couplings: constraints from indirect EW precision tests and B decays, versus potential for direct measurements in top decays
- stop/sbottom vs other squark: separation and identification
- slepton spectroscopy: separation of selectron/smuon/stau
- sneutrino mixing, lepton-number violation, CP violation
- other inputs for FCNC decays: chargino/neutralino spectrum
- non-SUSY BSM & flavour/CP violation: which scenarios?

# The LHC will be our first and, for a long time, only direct probe of the TeV scale

**Rates for new phenomena will be $10^3$ times larger in the region of asymptotic Tevatron reach, and the exploration will extend to regions as yet totally unchartered**

**The immense rates, and striking signatures, will make it possible to extract signals of BSM physics early on**

**LHC discoveries will not settle once and forever all the questions in HEP, but we expect they will firmly define the framework within which to phrase and address them**

**A truly exciting future is ahead of us!**