

# **Physics from Tevatron to LHC to ILC**

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# What physicists want from you

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- Higher energy
- Higher luminosity
- Higher polarization
- Lower backgrounds
- .... at half the cost !

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## On the other hand

the optimization of a post-LHC programme (SLHC, ILC, CLIC, DLHC) requires further input from the LHC itself

rather than listing all great things that can be done with this and that beam configuration, I'll share with you the deep reasons why physicists expect the forthcoming generation of experiments to open new windows on uncharted territories and to set the benchmarks for the future progress of the field.

# Contents

- Where we stand
- What we expect to learn from the LHC
- Why we need to go beyond the LHC
- A diversified challenge for accelerator science
- Conclusions

# Where we stand

- **< 1973: theoretical foundations of the Standard Model**
  - renormalizability of  $SU(2) \times U(1)$  with Higgs mechanism for EWSB
  - asymptotic freedom, QCD as gauge theory of strong interactions
  - KM description of CP violation
- **Followed by 30 years of consolidation:**
  - **technical theoretical advances** (higher-order calculations, lattice QCD)
  - **experimental** verification, via **discovery** of
    - **Fermions:** charm, 3rd family (USA)
    - **Bosons:** gluon, W and Z (Europe; ... waiting to add the Higgs ...)
  - **experimental** consolidation, via **measurement** of
    - EW radiative corrections
    - running of  $\alpha_s$
    - CP violation in the 3rd generation

# Theory, after 1973

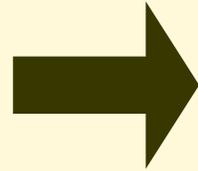
- Theory mostly driven by theory, not by data. Need of
  - deeper understanding of the **origin of EWSB**
  - deeper understanding of the **gauge structure of the SM**
  - deeper understanding of the **family structure of the SM**
  - **some** understanding of **quantum gravity** (includes understanding of the cosmological constant  $\sim 0$ )
- Milestones:
  - 1974: Grand Unified Theories
  - 1974: Supersymmetry
  - 1977: See-saw mechanism for  $\nu$  masses
  - 1979: Technicolor
  - 1986: Superstring theories
  - 1998: Large scale extra dimensions
  - in parallel to the above: development and consolidation of the **SM of cosmology**

# Experiments, after 1973

- **Verification of the SM** (see before)
- **Exploration of BSM scenarios:**

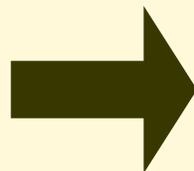
Model	Observable	Outcome
<b>GUT</b>	p decay, n oscillations	nothing yet
<b>SUSY</b>	sparticles	nothing yet
<b>See-saw</b>	$\nu$ mixing	✓
<b>Technicolor</b>	EW data	~ ruled out
<b>Superstrings</b>	??	??
<b>Extra dim</b>	Missing ET, KK modes, etc	nothing yet
<b>Cosmology SM</b>	CMB, nucleosynthesis, structure formation, etc.etc.	✓, with significant surprises (DM, BAU, Dark Energy)

# So, what's in our future?



Discover the Higgs, and  
continue search for BSM  
scenarios developed so far

# Why should something new and exciting happen ?



- \* **theoretical prejudice**
- \* **experimental hints**

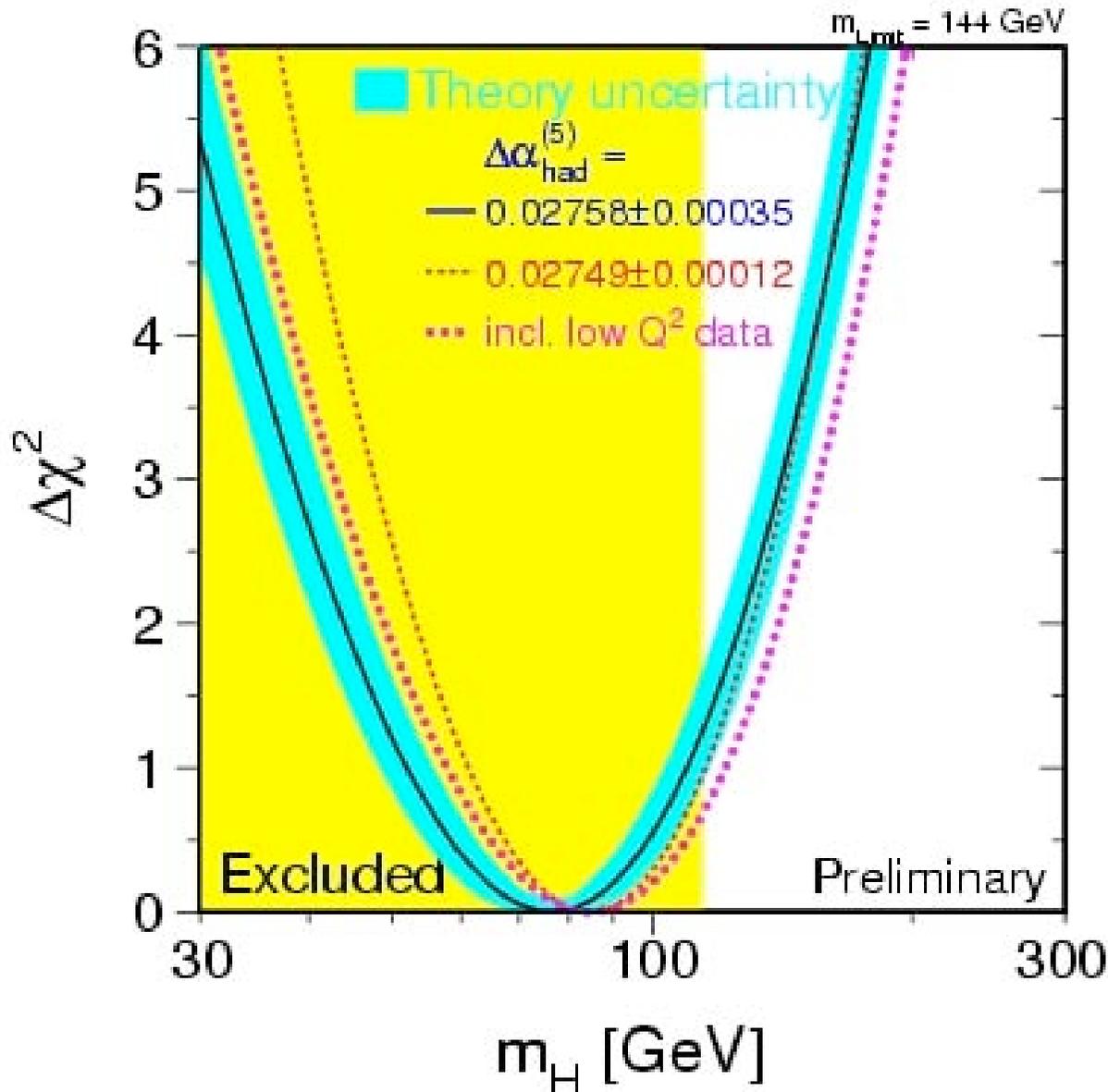
- There are many good ***theoretical*** arguments suggesting that the SM is incomplete or additional structures are required:
  - understanding of quantum gravity
  - hierarchy problem, naturalness of the EW scale
  - couplings' unification at the GUT scale
- **Neutrino masses**, as well as **Dark Matter** and the **Baryon Asymmetry of the Universe**, provide concrete ***experimental*** indications that the **SM** cannot account for all we see in the universe.

**Therefore have to accept the existence of physics Beyond the Standard Model**

# **But progress will have to start from the clarification of the missing link of the SM, namely the Higgs mechanism**

- Pin down and explore the mechanism responsible for **electroweak-symmetry breaking**:
  - Discover the Higgs boson
  - Measure its properties
  - If no Higgs boson  $\Rightarrow$  discover whatever else replaces it!

# Current experimental knowledge on $m(H)$



**IN THE SM:**

**Direct searches, LEP2:**

$$m(H) > 114.4$$

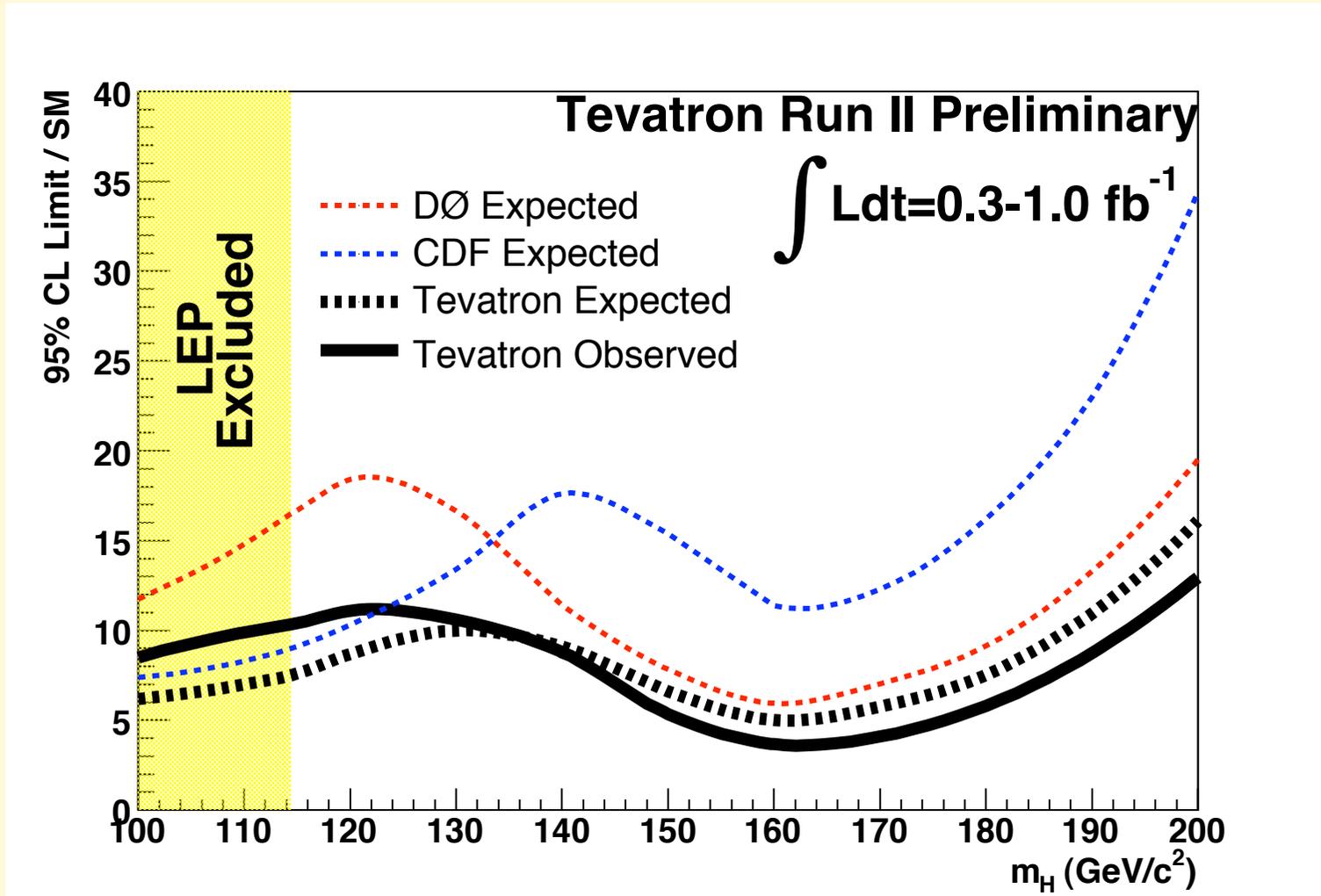
**EW fits,  $m_W$ ,  $m_{\text{top}}$ ,  
LEP2/SLC/Tevatron:**

- $m(H) = 76^{+33}_{-24}$

- $m(H) < 144 \text{ GeV}$   
**95%CL**

- $m(H) < 182 \text{ GeV}$   
**95%CL, with  
 $m_H > 114.4$**

# Status and prospects at the Tevatron



Room for a factor 5–10 improvement by 2009, thanks to more luminosity, higher trigger efficiencies, and smarter analysis tools

# What's the LHC going to tell us about EWSB?

**The first conclusive YES/NO answer to the question of whether the SM Higgs mechanism is valid or not**

EWSB=  
Electroweak  
symmetry  
breaking

# Prospects at the LHC



## SM-like Higgs

5 $\sigma$  discovery with 3-4 fb<sup>-1</sup> over the full mass range 114–1000 GeV

95%CL exclusion with 1 fb<sup>-1</sup> over the full mass range 114–1000 GeV

2–3 $\sigma$  signals (Tevatron-like sensitivity) in the Tevatron sensitive region with few 100 pb<sup>-1</sup>

**2009 will witness a tough race between Tevatron and LHC to constrain or discover the SM Higgs!**

## IF seen outside SM mass range:

- new physics to explain EW fits
- problems with LEP/SLD data (M.Chanowitz)

In either case,

- easy prey with low luminosity up to  $\sim 800$  GeV!

## IF NOT SEEN UP TO $m_H \sim 800$ GEV:

$\sigma < \sigma_{SM}$ :

reduced couplings  $\Rightarrow$  **new physics**

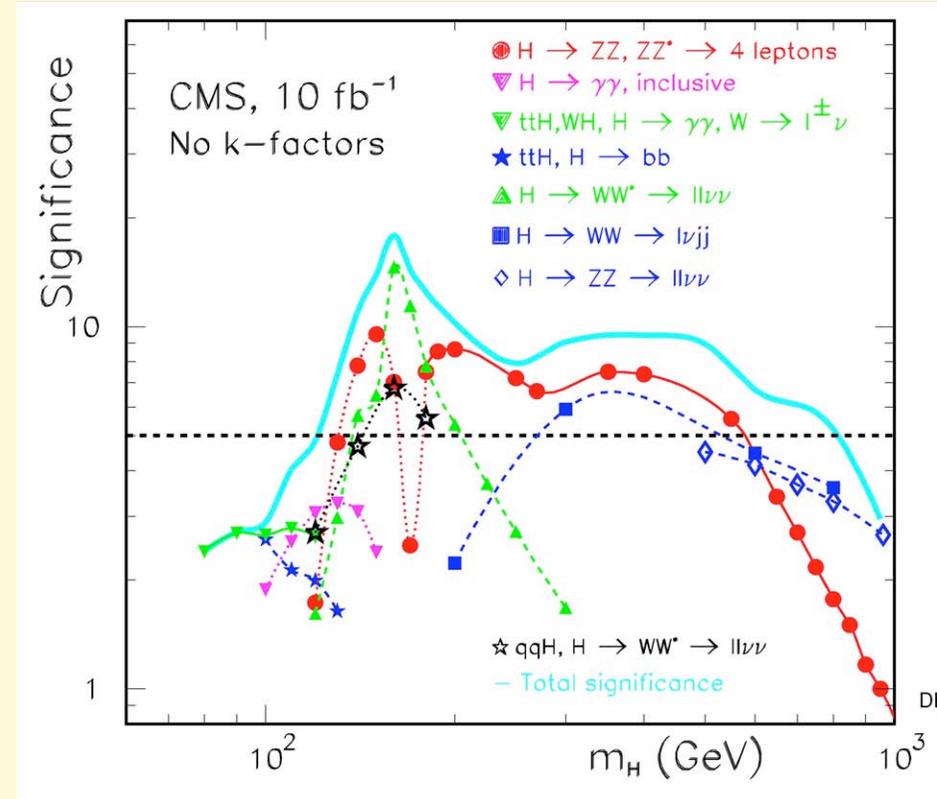
**BR(H  $\rightarrow$  visible)  $<$  BR<sub>SM</sub>:**

reduced couplings  $\Rightarrow$  **new physics**

**$m_H > 800$  GeV:**

expect WW/ZZ resonances at  $\sqrt{s} \sim \text{TeV} \Rightarrow$  **new physics**

It may take longer to sort out these scenarios, but the conclusion about the existence of BSM phenomena will be unequivocal



Discovering the Higgs will put us more or less in the same position as Thompson in 1897. He had the electron, had a theory for its interactions (Maxwell's EM) but was lacking a real theory for the structure of the electron: pointlike? Extended? shell-like?

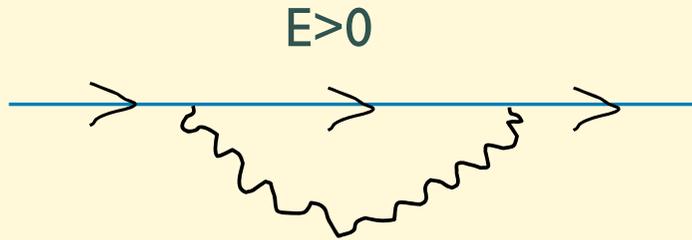
A pointlike electron caused serious conceptual problems (infinite EM field energy), leading to the concept of electron radius:

$$\text{Energy( e EM field )} = m_e c^2 \Rightarrow$$

$$R_e = \alpha / m_e c^2$$

**It took Dirac, and QED, to identify a consistent theory of a pointlike electron**

# Electron self-energy, Lorentz invariance, the positron



$$\Delta(mc^2)_{Coulomb} \sim \frac{e^2}{r}$$

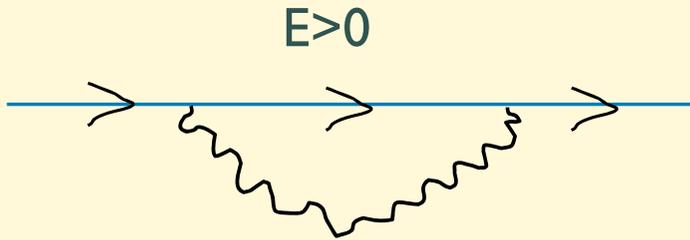
Requiring:

$$\Delta m < m = 0.5 \text{ MeV}$$



$$\Lambda \equiv 1/r < 5 \text{ MeV}$$

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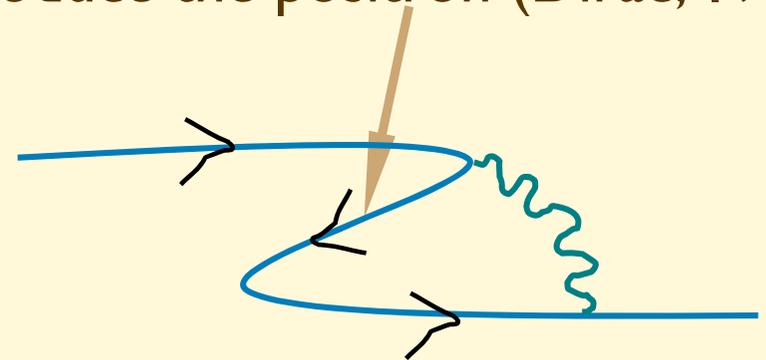
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Introduce the positron (Dirac, 1931)



$$\Delta(m)_{E>0 \oplus E<0} \sim e^2 m \log(\Lambda/m)$$

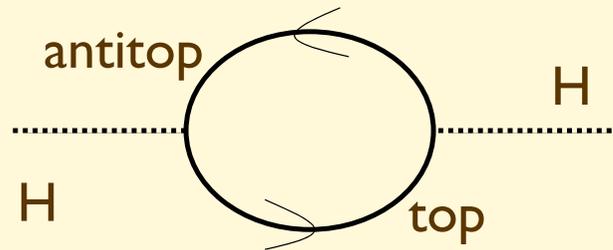
which is a correction of only 10% even at scales of the order of the Plank mass:

$$\Delta(m)_{E>0 \oplus E<0} \sim 0.1 m$$

at

$$\Lambda = 10^{19} \text{ GeV}$$

# The Higgs self-energy



$$\delta m_H^2 \sim \frac{6G_F}{\sqrt{2}\pi^2} m_t^2 \Lambda^2, \quad \Lambda \rightarrow \infty$$
$$\Lambda \sim 1 / R_H$$

**renormalizability =>**

$$m_H^2(v) \sim m_H^2(\Lambda) - (\Lambda^2 - v^2), \quad v \sim 250\text{GeV}$$

**but then:**

$$\frac{m_H^2(\Lambda) - \Lambda^2}{\Lambda^2} \sim \frac{v^2}{\Lambda^2} = O(10^{-34}) \text{ if } \Lambda \sim M_{Planck}$$

**FINE TUNING!**

**Hierarchy problem**

## The problem can be rephrased with the following example:

Ask 10 of your friends to each give you a **random irrational number**, distributed between  $-1$  and  $1$ .

Sum the 10 numbers

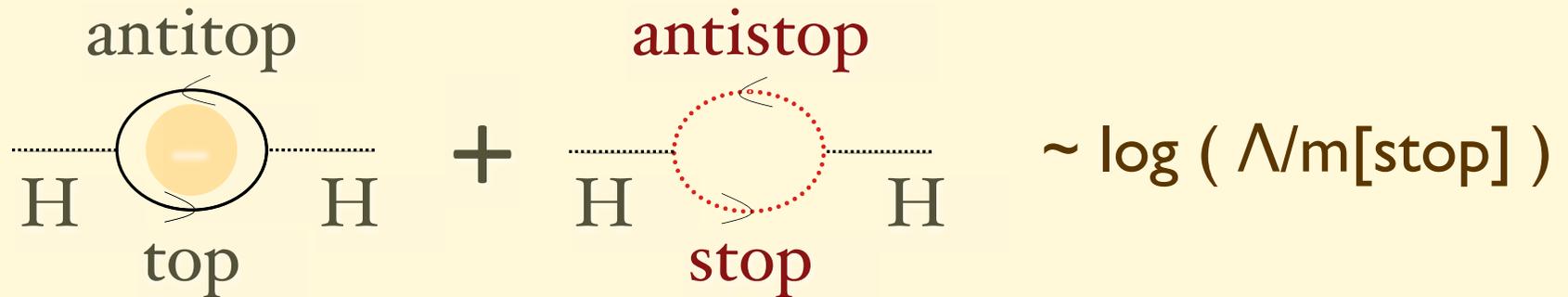
**How would you feel** if the sum were smaller than  $10^{-32}$  ?

Nothing wrong with it, it can happen, but most likely your friends agreed in advance on the numbers to give you, and forced the cancellation with a judicious choice.

**Theorists feel the same about the Higgs mass ....**

**Supersymmetry does precisely this, since the supersymmetric partner of each particle contributes to the Higgs mass with a contribution quadratic in  $\Lambda$  opposite in sign to the SM partner!**

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  $M_{\text{stop}}/M_{\text{top}}$ ):

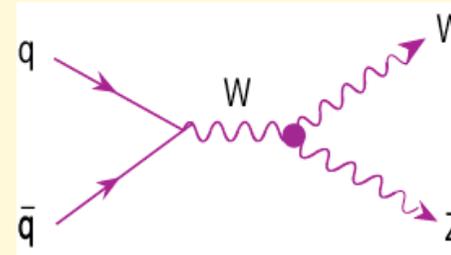
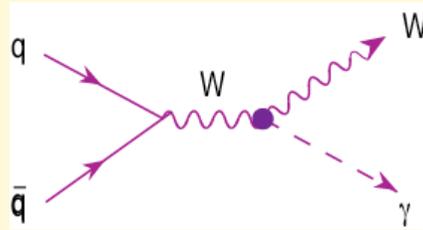


**Other models of new physics achieve this result in similar ways. Only the data will be able to tell us which one is correct!**

**The detailed understanding of the origin of the Higgs will be the primary goal of HEP after the observation of the Higgs**

## Ex: Precise determinations of the self-couplings of EW gauge bosons

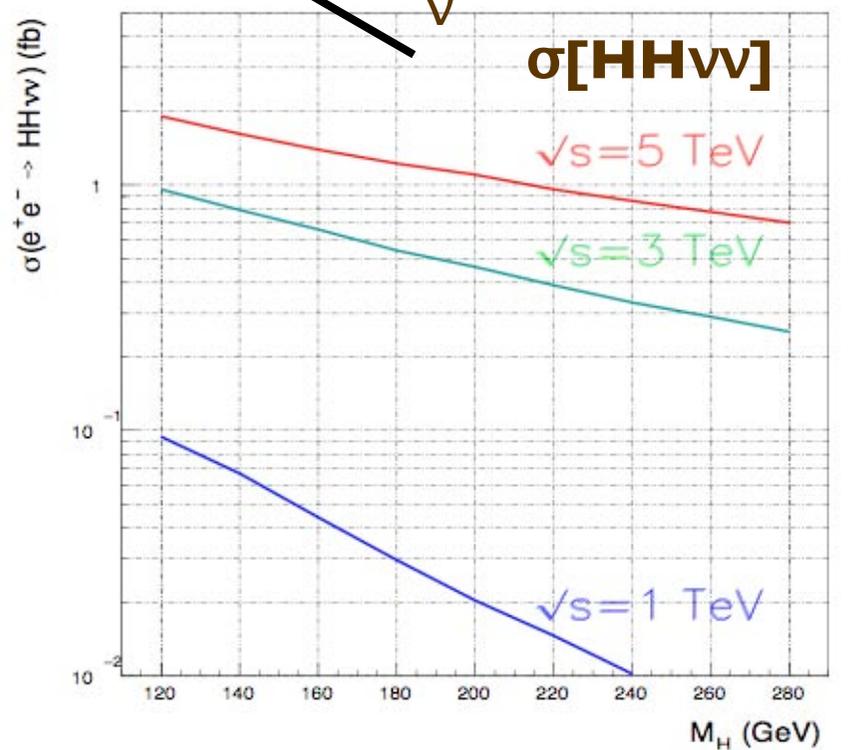
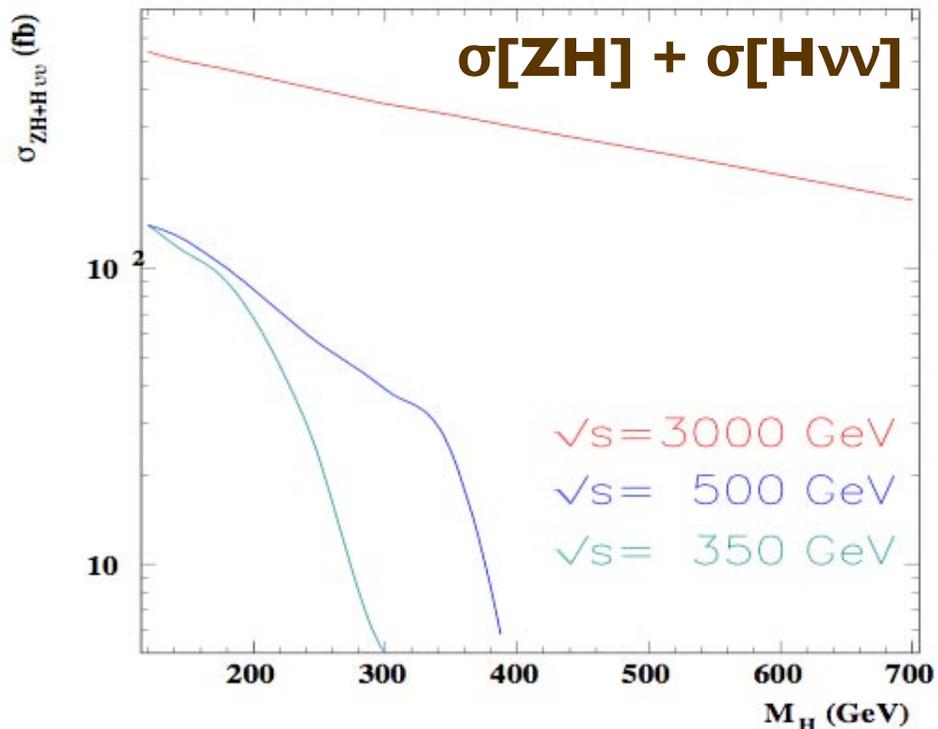
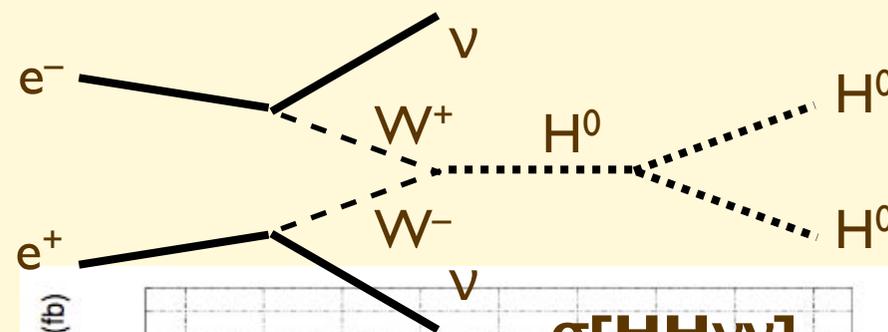
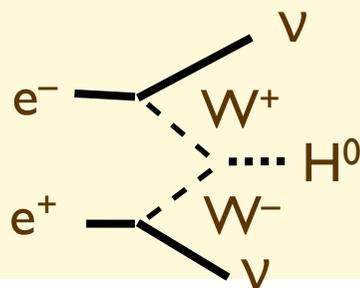
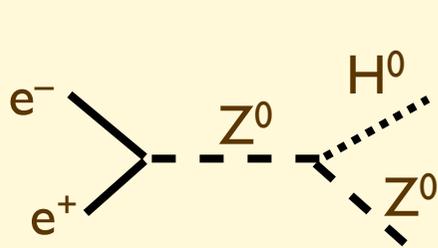
5 parameters describing weak and EM dipole and quadrupole moments of gauge bosons. The SM predicts their value with accuracies at the level of  $10^{-3}$ , which is therefore the goal of the required experimental precision



Coupling	14 TeV 100 fb <sup>-1</sup>	14 TeV 1000 fb <sup>-1</sup>	28 TeV 100 fb <sup>-1</sup>	28 TeV 1000 fb <sup>-1</sup>	LC 500 fb <sup>-1</sup> , 500 GeV
$\lambda_\gamma$	0.0014	0.0006	0.0008	0.0002	0.0014
$\lambda_Z$	0.0028	0.0018	0.0023	0.009	0.0013
$\Delta\kappa_\gamma$	0.034	0.020	0.027	0.013	0.0010
$\Delta\kappa_Z$	0.040	0.034	0.036	0.013	0.0016
$g_1^Z$	0.0038	0.0024	0.0023	0.0007	0.0050

**This is the equivalent of the studies of the  $g-2$  of electron and muon**

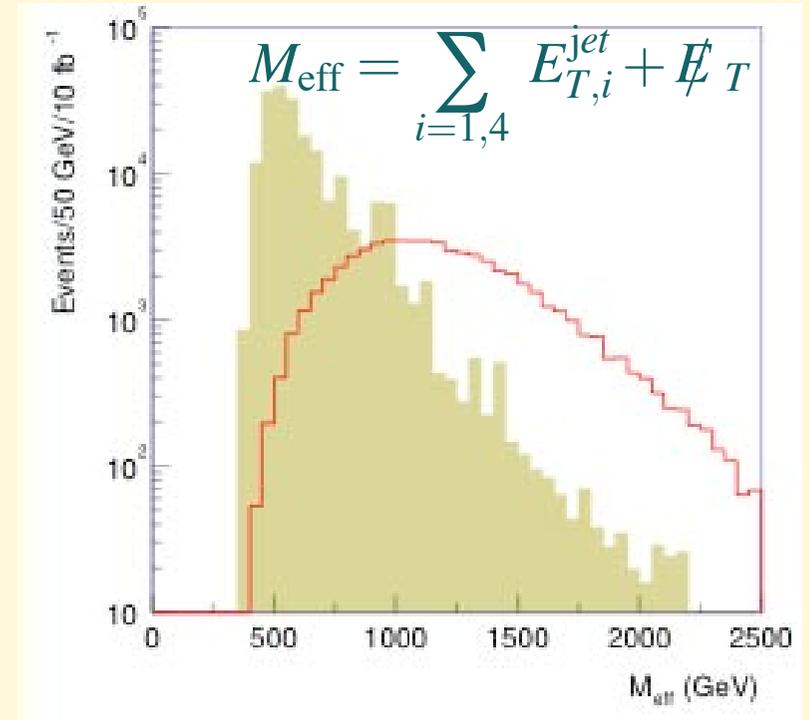
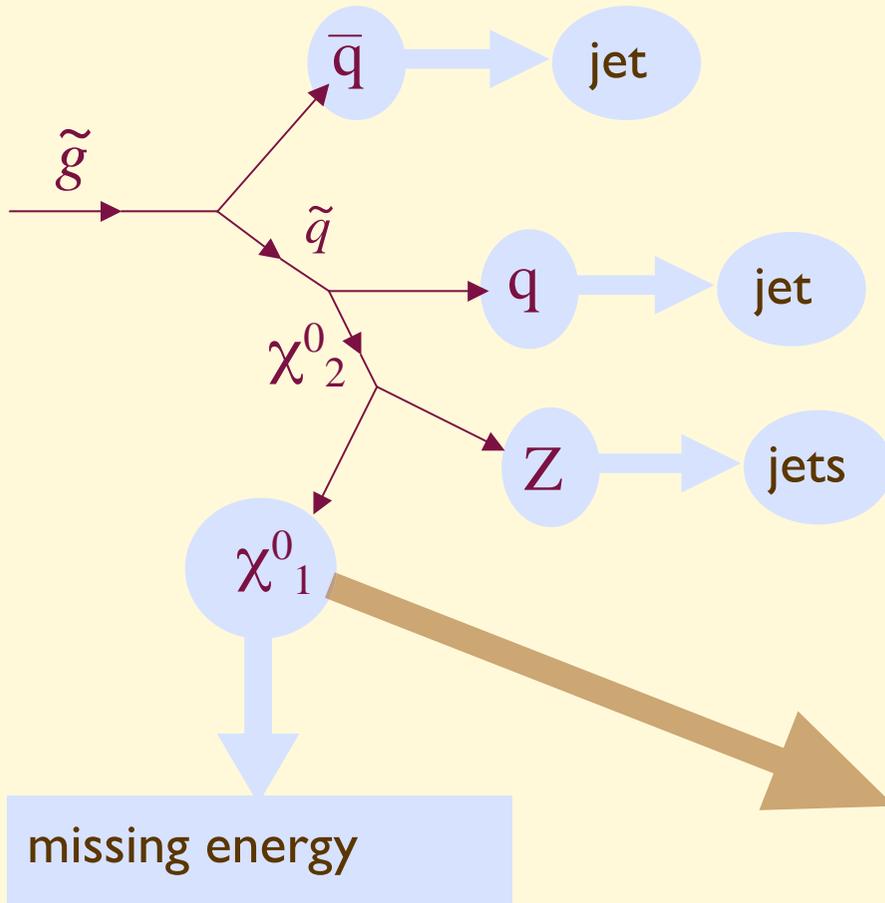
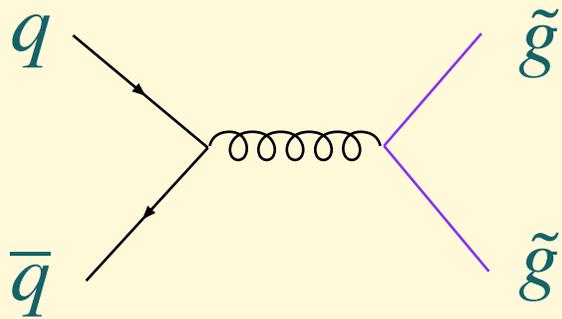
# Example: Higgs couplings



## Expected accuracy, ILC

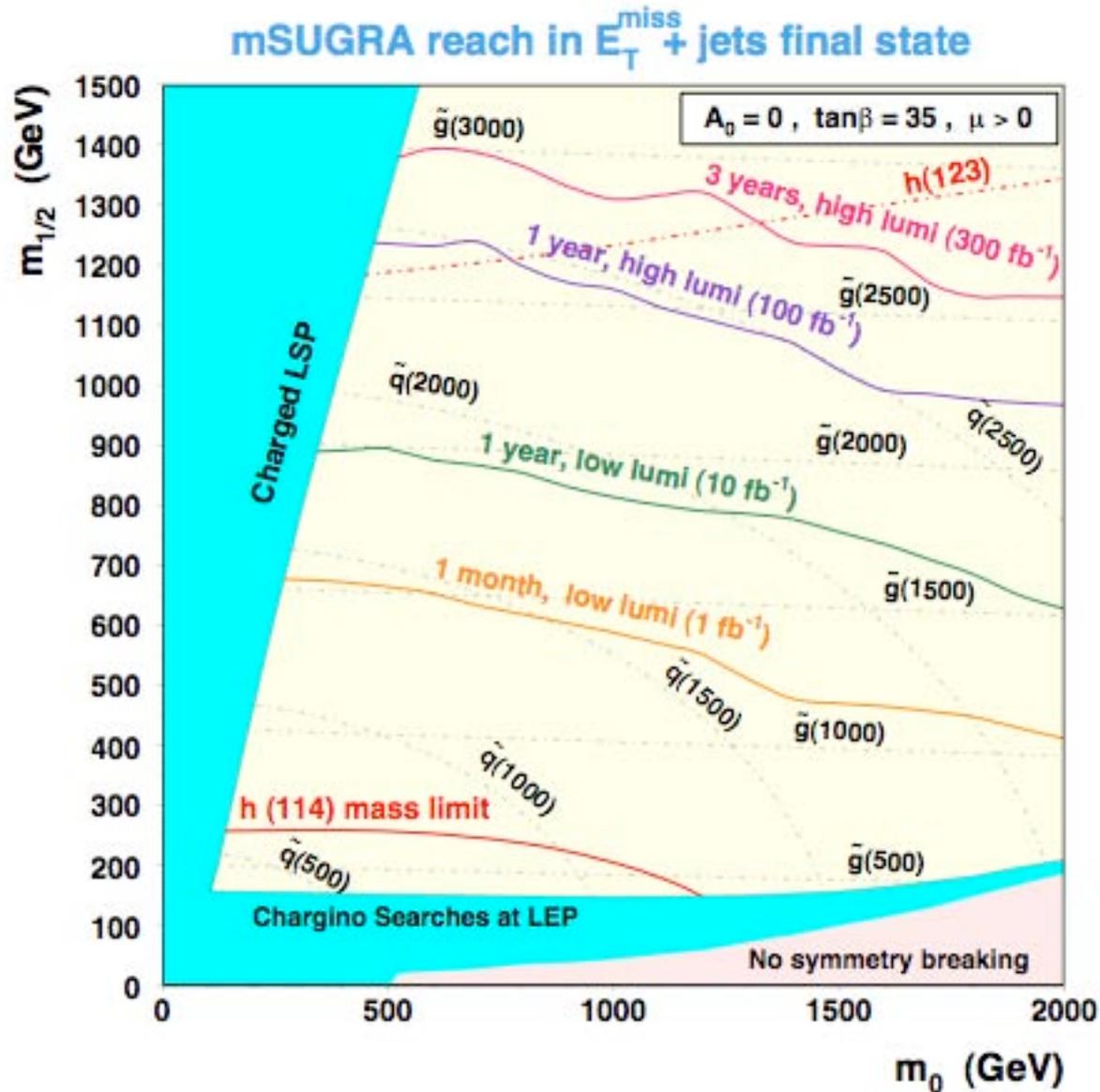
Coupling	$m_H = 120$ GeV	$m_H = 140$ GeV
$g_{HWW}$	$\pm 0.012$	$\pm 0.020$
$g_{HZZ}$	$\pm 0.012$	$\pm 0.013$
$g_{Htt}$	$\pm 0.030$	$\pm 0.061$
$g_{Hbb}$	$\pm 0.022$	$\pm 0.022$
$g_{Hcc}$	$\pm 0.037$	$\pm 0.102$
$g_{H\tau\tau}$	$\pm 0.033$	$\pm 0.048$

# Supersymmetry signals at the LHC



dark matter candidate

# Inclusive Supersymmetry searches



Expected reach in the overall mass scale for gluinos and squarks:

**1fb-1  $\Rightarrow$  1-1.5 TeV**

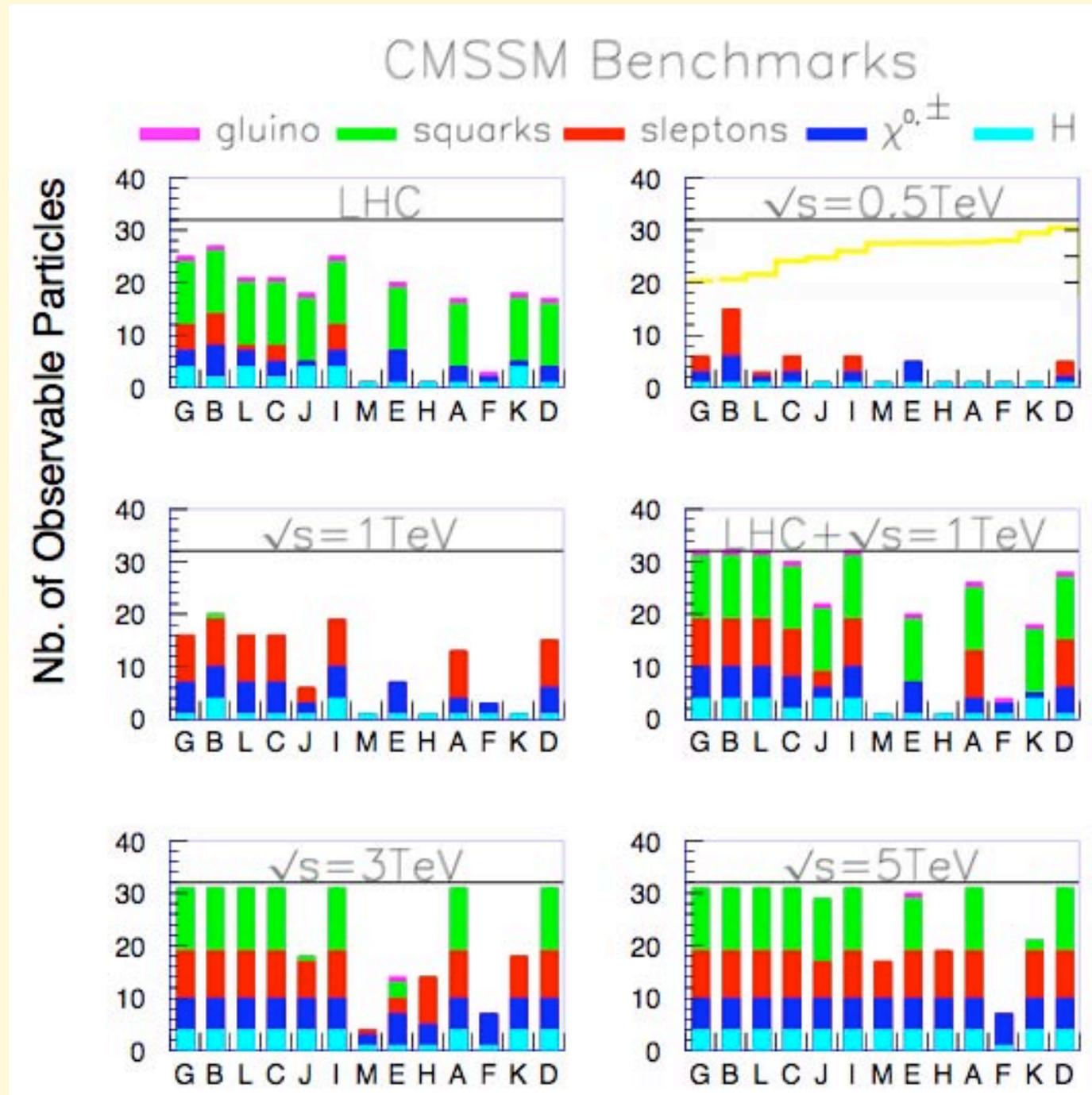
**10fb-1  $\Rightarrow$  1.5-2 TeV**

**100fb-1  $\Rightarrow$  2.5 TeV**

**Well in the range where we expect particles solving the hierarchy problem to be!**

# SUSY Beyond the LHC: ILC/CLIC

**Example:**  
 Exploration of the Supersymmetric particle spectrum, for 10 different SUSY models



Reference: Physics at CLIC,  
 Battaglia, De Roeck, Ellis,  
 Schulte eds.,  
 hep-ph/0412251

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

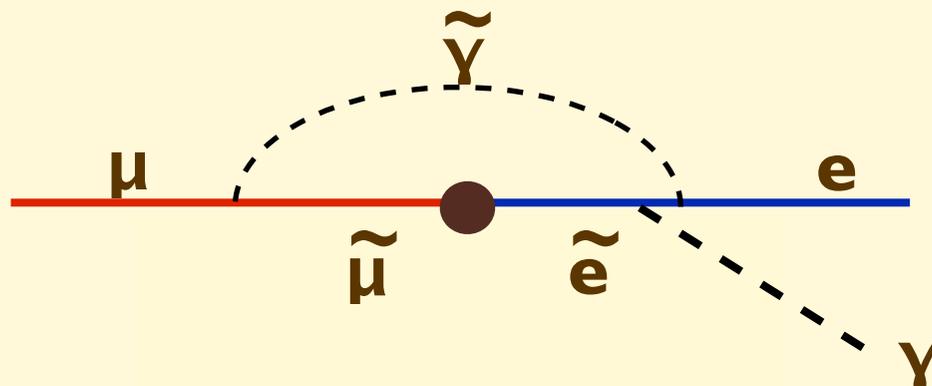
While there is no guarantee that any deviation from the SM will be found, the existence of physics BSM will demand and fully justify these studies: we'll be measuring the properties, however trivial, of something which we know exists, as opposed to blindly looking for “we don't know what” as we are unfortunately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

**B physics studies at the LHC and at future SuperB factories, a rich K physics programme and possibly new studies of the charm sector, will naturally complement the measurements in  $\nu$  physics and searches for Lepton Flavour Violation phenomena.**

# Possible implications of neutrino masses and mixing

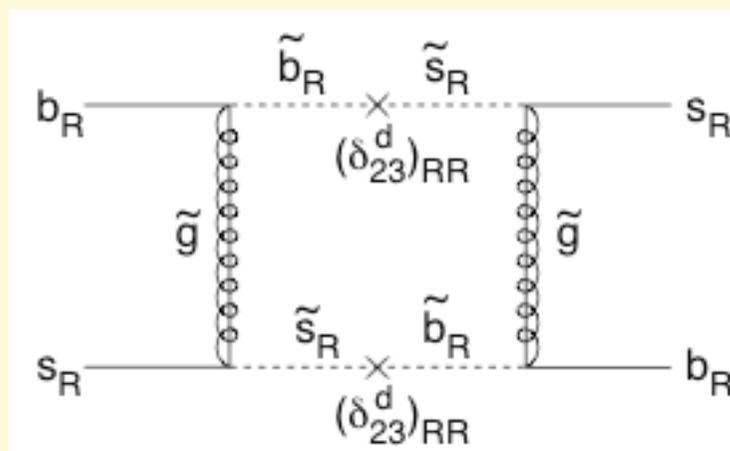
## $\nu$ mixing sees-saw + SUSY

- ↪ mixing among charged sleptons
  - ↪ charged-lepton flavour violation, e.g.  $\mu \rightarrow e\gamma$



or:

- ↪ mixing among right-handed b and s quarks
  - ↪  $B_s$  mixing, CP violation in  $B_s \rightarrow \phi\psi$  ( $\sim 0$  in the SM)



# 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

### Quarks:

B factories  
K factories  
n EDM

e/ $\mu$  EDM

# Conclusions

- Particle physics is on the verge of **major discoveries**
- Accelerator-based experiments are still the **primary exploration tools** to clarify the nature of particle physics phenomena
- The TeV scale plays a crucial role for PP.
  - $m_H$  is expected to be below 1 TeV, and within LHC's reach
  - but the dynamics of EWSB could manifest itself only at larger scales,  $O(\text{few TeV})$
- ➡ demands for a  $\times 10$  increase in the energy reach (CLIC, VLHC) will likely be justified few years from now
- The complete exploration of new phenomena will not only require pushing the energy frontier, but also the intensity frontier, with a diversified spectrum of higher-performance low-energy flavour factories
- In the meantime, let us enjoy the forthcoming output of many years of work on the LHC, and make sure it bear fruits!