Fermilab Nov 16, 2007

and

Answering the Great Questions of Particle Physics with Energy and Intensity Frontier Facilities

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Foreword

- **< 1973: theoretical foundations of the SM**
  - renormalizability of SU(2)xU(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 α_S
    - CKM parameters

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The formulation and consolidation of the **SM** is a monumental scientific achievement, with parallels only in

Maxwell theory
Relativity
QM

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  - deeper understanding of the **origin of EWSB**
  - deeper understanding of the **gauge structure of the SM**
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  - **some** understanding of **quantum gravity** (includes understanding of the cosmological constant ~ 0)

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  - 1974: Supersymmetry
  - 1977: See-saw mechanism for ν masses
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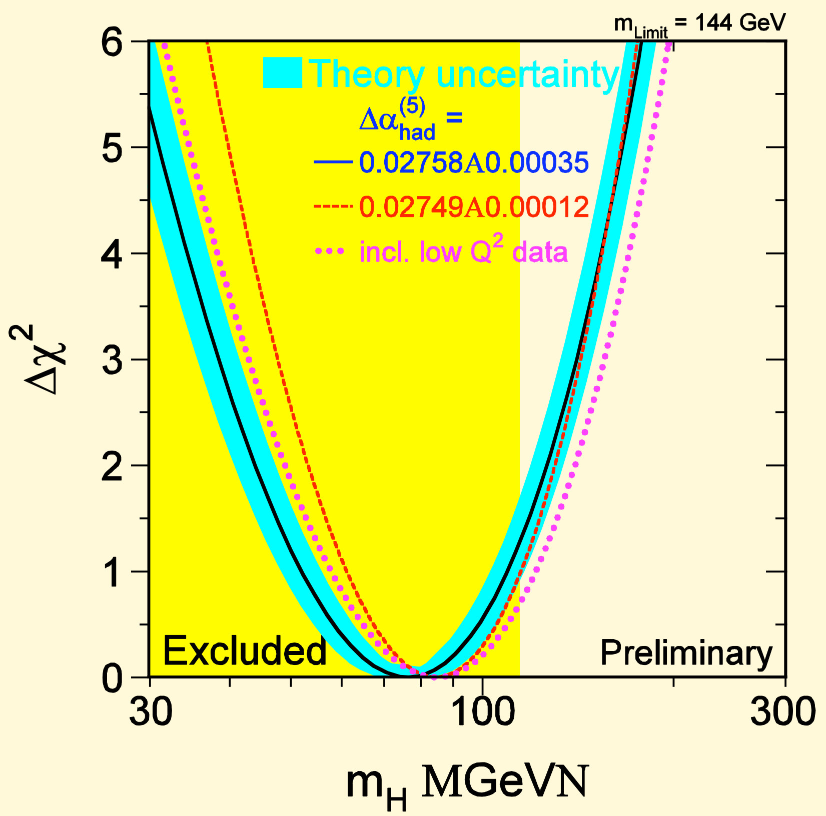
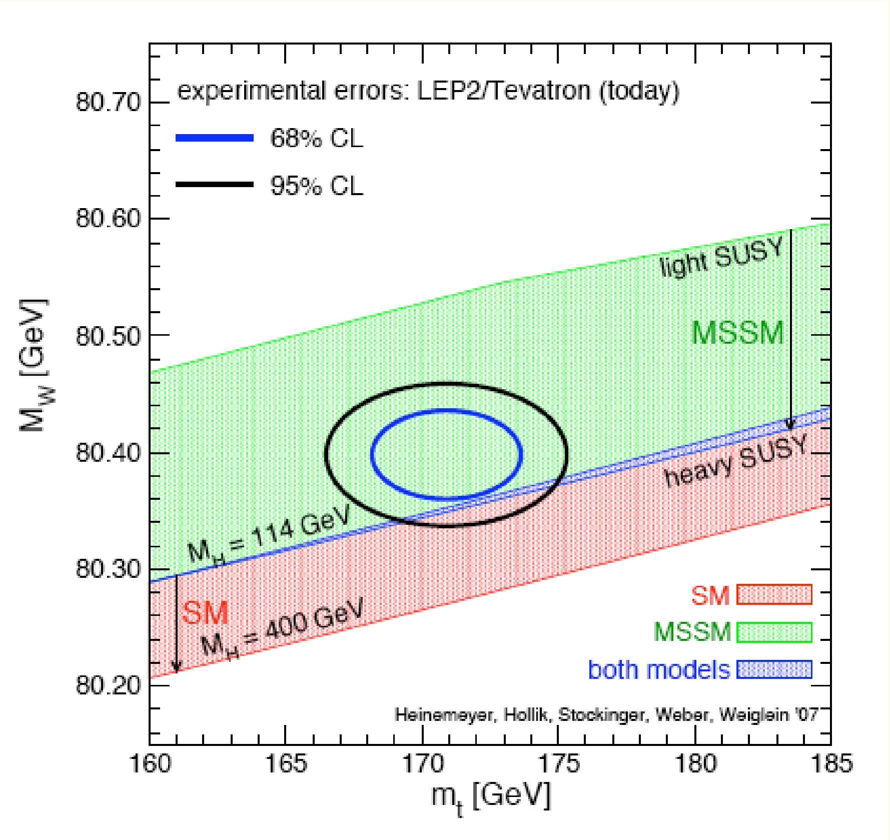
Time is long due for a first direct manifestation of at least one of the new phenomena predicted by the scenarios beyond the Standard Model

But before that, we still need to find out about the Higgs and get some clue about the EWSB mechanism ...



m_H = 76 at the minimum ,



m_H < 144 GeV at 95%CL

The tension with the SM is getting higher and higher ...

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

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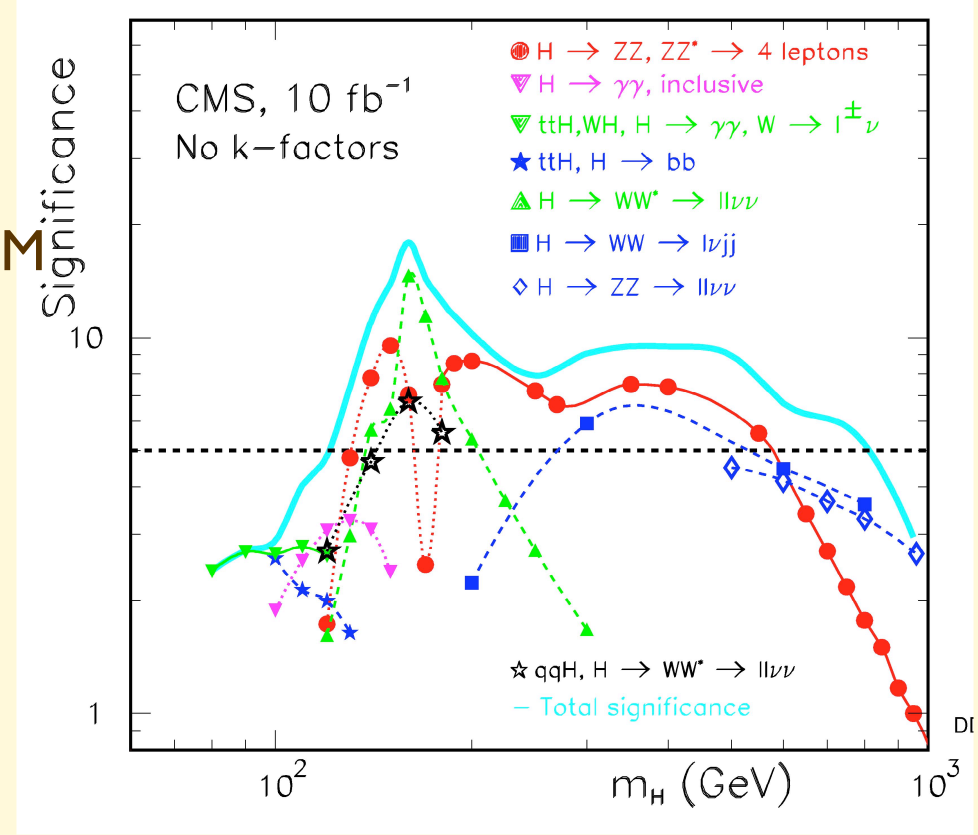
The first conclusive answer to the question of whether a SM-like Higgs mechanism is present in nature

IF SM, then the Higgs boson will be seen with $\int L \leq 15\ fb^{-1}$

- SM production and decay rates well known
- Detector performance for SM channels well understood
- 115< m_H < 200 from LEP and EW fits in the SM



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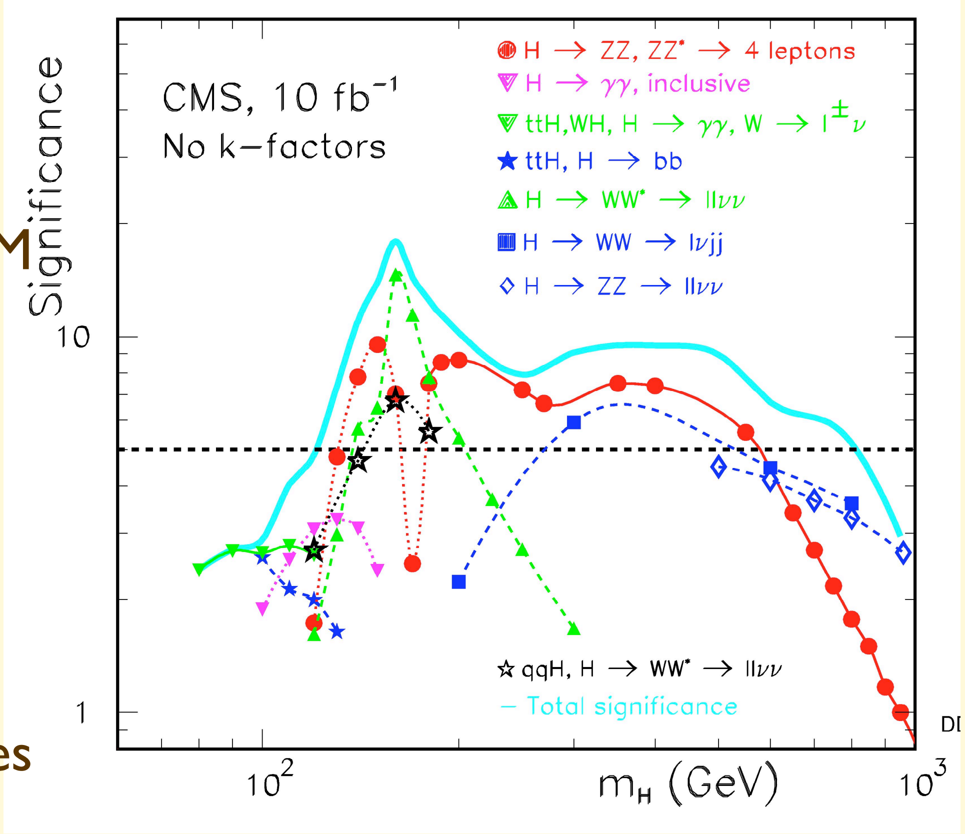

IF seen with SM production/decay rates, but outside SM mass range:

- new physics to explain EW fits, or
- problems with LEP/SLD data

In either case,

- easy prey with low luminosity up to ~ 800 GeV, but more lum is needed to understand why it does not fit in the SM mass range!

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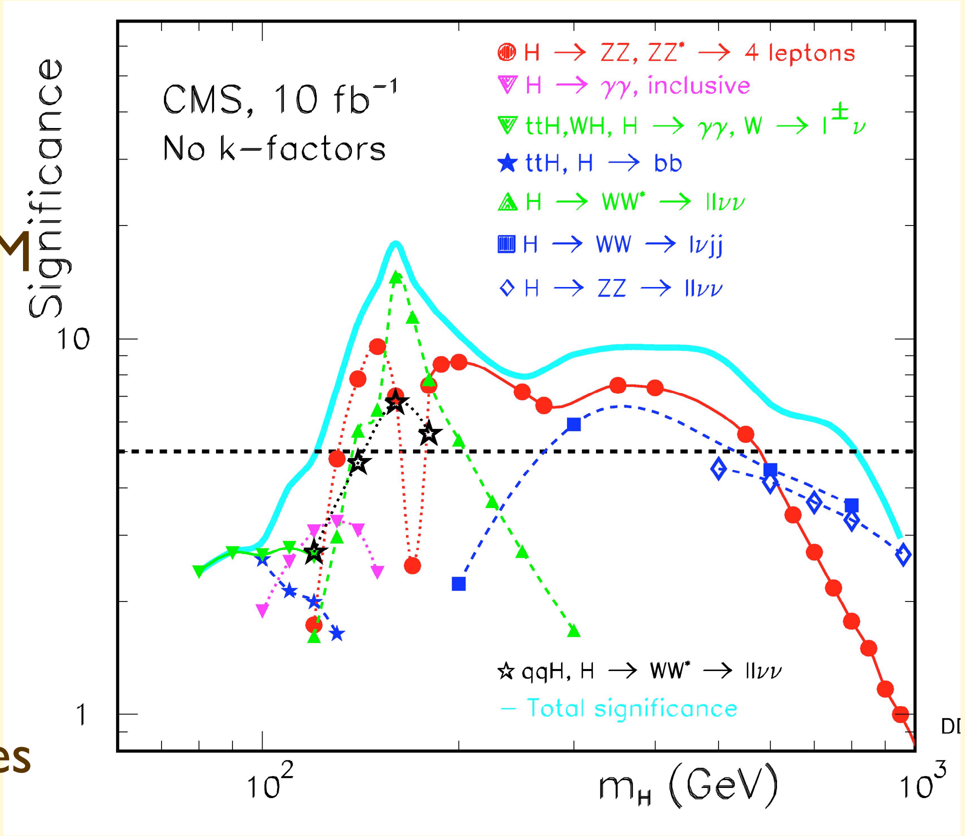

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IF NOT SEEN UP TO m_H ~ 0.8-1 TeV GEV:

$\sigma < \sigma_{SM}$: $\Rightarrow$ new physics

or

BR(H→visible) < BR_{SM}: $\Rightarrow$ new physics

or

m_H>800 GeV: expect WW/ZZ resonances at $\sqrt{s}$ ~ TeV $\Rightarrow$ **new physics**

- **Sorting out non-SM scenarios may take longer than the SM H observation, and may well require LHC luminosities upgrades and/or a LC, but the conclusion about the existence of BSM phenomena will come early and unequivocal**

- **Exposing the mechanism of EW symmetry breaking (EWSB) and identifying the Higgs boson or its alternatives is necessary to set the scene for what's next**

- **When that's done, we'll be cleared to move on to the next layer of deep questions in HEP**

- what is **Dark Matter** ?
- what is the origin of neutrino masses?
- what is the origin of the Baryon Asymmetry of the Universe?
- ......

questions driven by experimental facts: **proven** shortcomings of the SM

- why SU(3)xSU(2)xU(1)? are there new forces? GUT?
- why 3 generations, why their properties?
  - mass spectra
  - mixing patterns
- pointlike? subsctructures? strings?

questions driven by theoretical curiosity, will evolve with new data

- ....
- why D=3+1?
- what is **Dark Energy** ?

questions still lacking a solid, calculable theoretical framework for their formulation

It’s precisely the robustness of the SM, and our consolidated faith in its predictions, that lead to the unavoidable conclusion that it is incomplete

- **Neutrino masses**
- **Dark matter**
- **Baryon asymmetry of the universe**

It’s not any longer a matter of **whether** the SM is incomplete, the existence of BSM physics is **proven** by the above empirical facts.

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Formulating **plausible** and **calculable** BSM scenarios, uniting the pragmatic need to solve the above puzzles and the desire to accommodate answers to the theoretically-inspired questions is today the best we can do to help establish directions and priorities for the field.

Notice that of the 3 empirical proofs that the SM in incomplete:

- **Neutrino masses**
- **Dark matter**
- **Baryon asymmetry of the universe**

at least **two** are directly related to flavour .....

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

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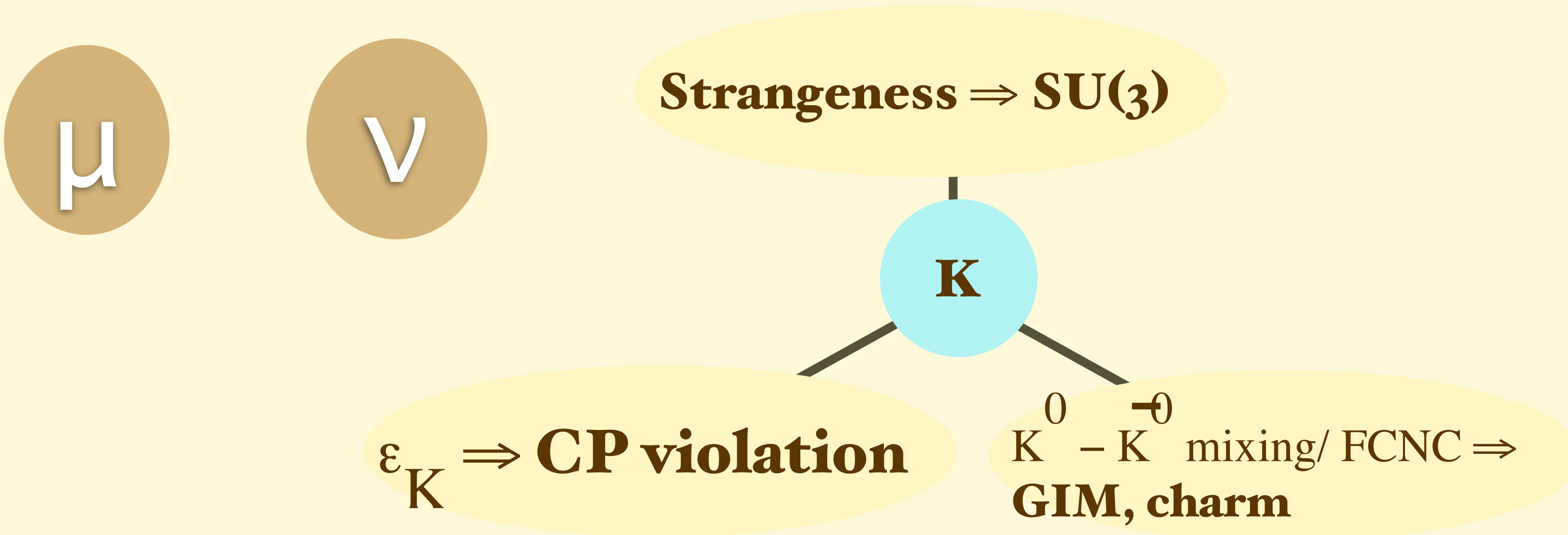


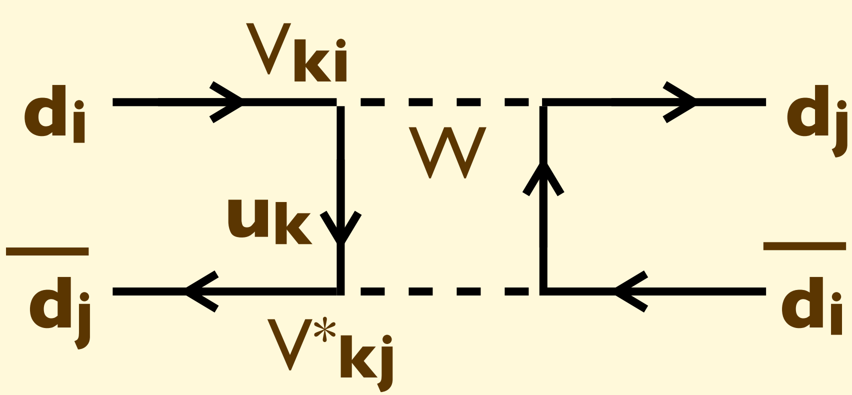
Large B_d mixing (Argus/UA1) ⇨ large m[top], well before EW tests

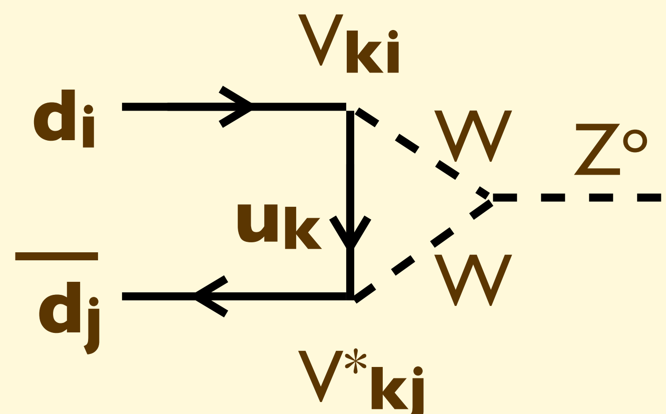
What is “flavour physics” ?

- In the SM, flavour is what deals with the fermion sector (family replicas, spectra and mixings):
  - all flavour phenomena are encoded in the fermion Yukawa matrices.

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

What is “flavour physics” ?

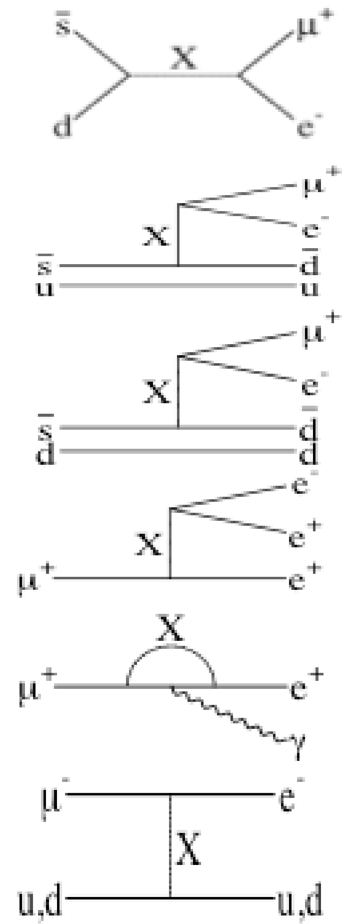
- In the SM, flavour is what deals with the fermion sector (family replicas, spectra and mixings):
  - all flavour phenomena are encoded in the fermion Yukawa matrices.
- Beyond the SM, “flavour” phenomena cover a wider landscape. E.g.
  - FCNC can be mediated by
    - gauge-sector particles, like charged higgses, gauginos, new gauge bosons, or by
    - SUSY scalar partners
  - New flavours in the form of new generations, exotic partners of standard quarks (e.g. Kaluza Klein excitations, T’ in LH), etc.
  - CP violation can reside in gauge/Higgs couplings

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!

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



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

N.B. Once coupling constants – say of EW size – and $O(\theta_c)$ mixings, are included, these scales are not much bigger than the TeV scale accessible at the LHC ⇨

great potential synergy between LHC and flavour observables

EWSB and flavour

- EWSB is intimately related to flavour:
  - No EWSB $\Rightarrow$ fermions degenerate $\Rightarrow$ no visible flavour effect
- In most EWSB models flavour plays a key role. E.g.:
  - Technicolor: tightly constrained by large FCNC
  - Supersymmetry: large value of top mass drives radiative EWSB
  - In several extra-dim models the structure of extra dimensions -- driven by the need to explain the hierarchy problem of EWSB -- determines the fermionic mass spectrum
  - Little Higgs theories $\Rightarrow$ top quark partners
- Why $m_{top} = g/\sqrt{2}\, m_W$ ($\Leftrightarrow y_{top} = 1$) ?

Side remark

- The special role played by the 3rd generation is not limited to the top
- Neutrino mixing is maximal in the 3rd-2nd generation, something which most likely will find an explanation in a complete theory of flavour linking quark and leptons

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the gauge sector
(Higgs, EWSB)

The High Energy Frontier

LHC
SLHC
VLHC
ILC
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the flavour sector (ν mixings, CPV, FCNC, EDM, LFV)

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The High Intensity Frontier

Neutrinos:	**Quarks:**	**Charged leptons:**
super beams	B factories	stopped μ
beta-beams	K factories	$\ell \to \ell'$ conversion
ν factory	n EDM	e/μ EDM

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+ Astrophysics and cosmology

What can we get from more integrated luminosity after LHC's first phase?

1. Improve measurements of new phenomena seen at the LHC. E.g.
   - Higgs couplings and self-couplings
   - Properties of SUSY particles (mass, decay BR's, etc)
   - Couplings of new Z' or W' gauge bosons (e.g. L-R symmetry restoration?)
2. Detect/search low-rate phenomena inaccessible at the LHC. E.g.:
   - $H \rightarrow \mu^+\mu^-$, $H \rightarrow Z\gamma$
   - top quark FCNCs
3. Push sensitivity to new high-mass scales. E.g.
   - New forces (Z', W_R)
   - Quark substructure
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Energies/masses in the few-100 GeV range. Detector performance at SLHC should equal (or improve) in absolute terms the one at LHC

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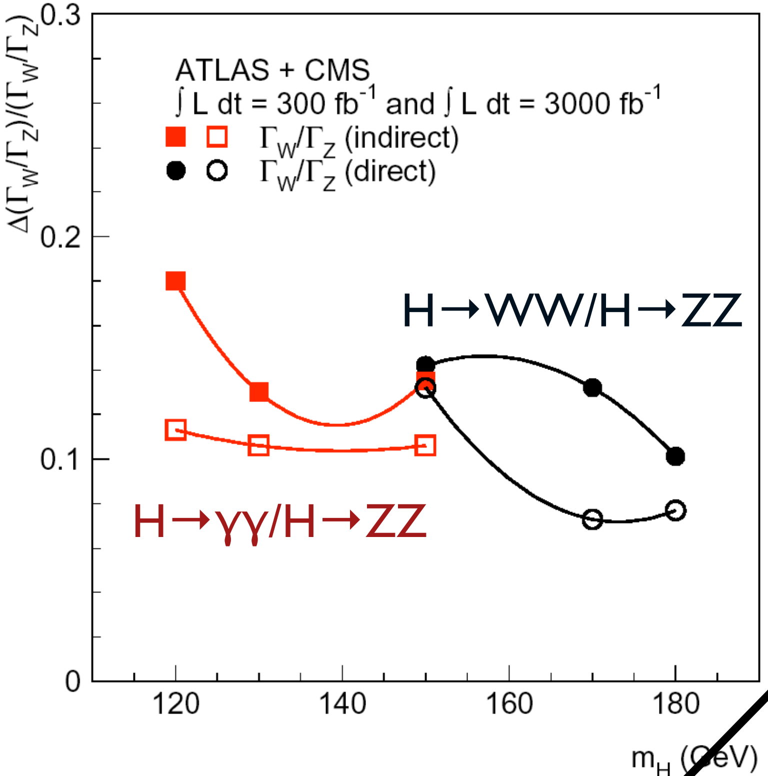
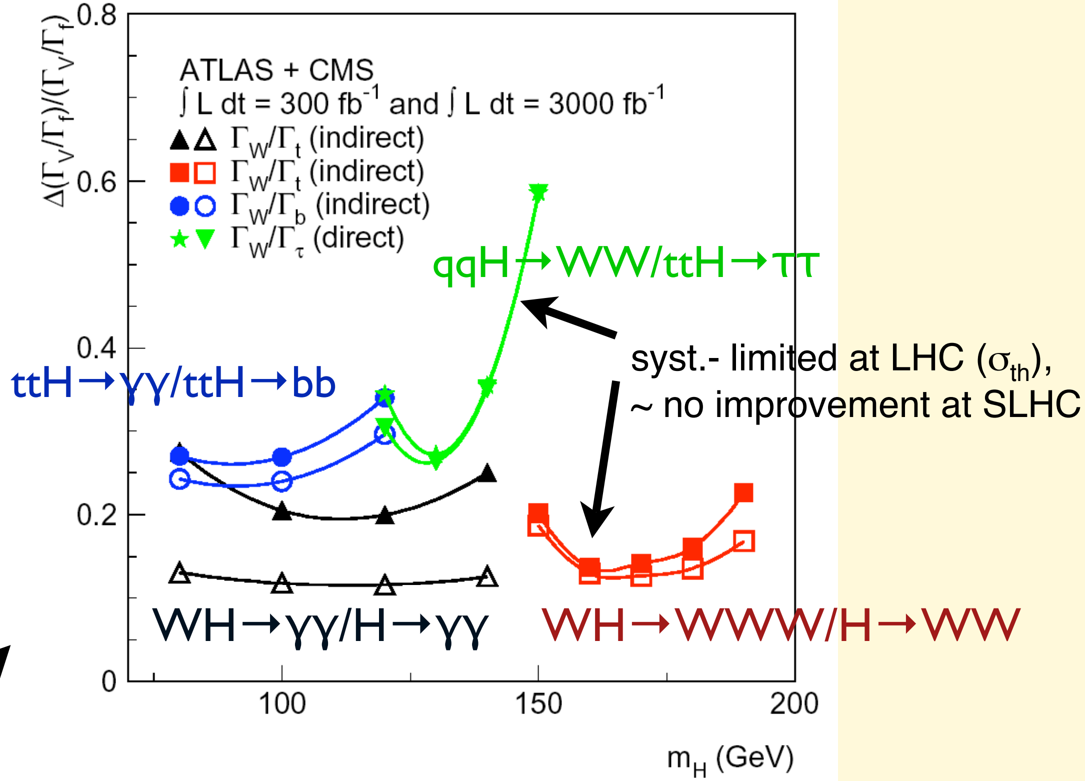
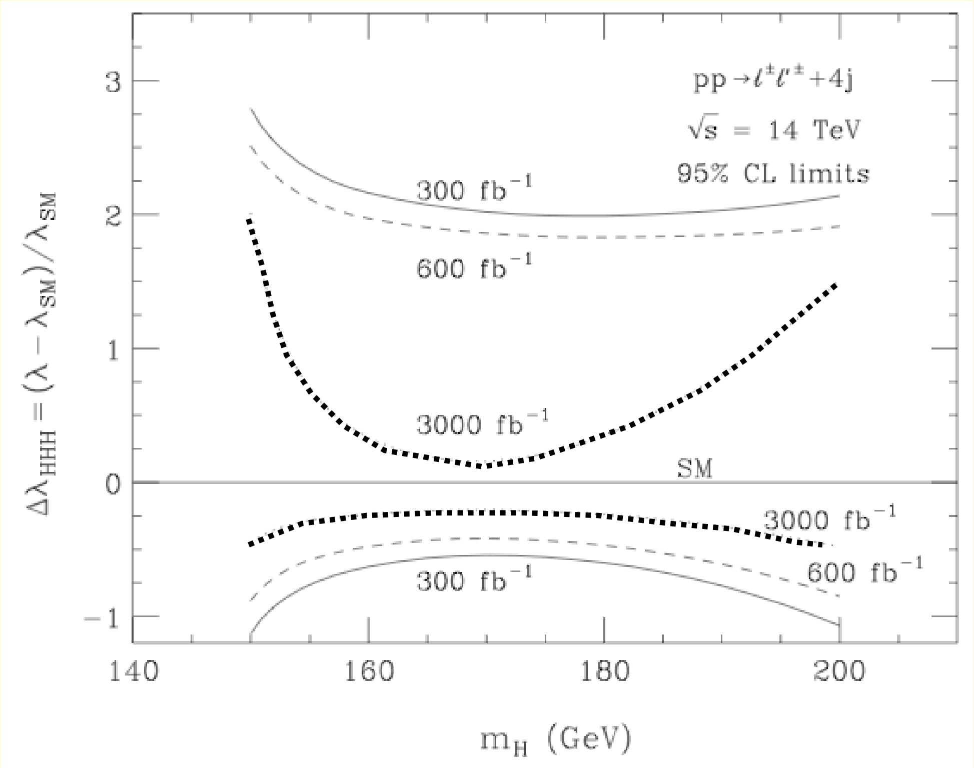


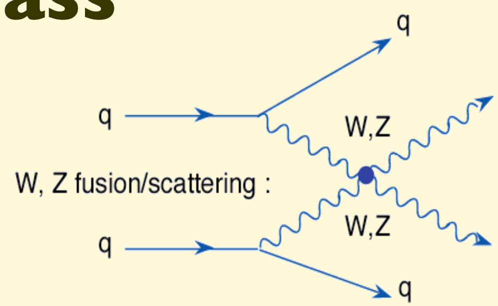


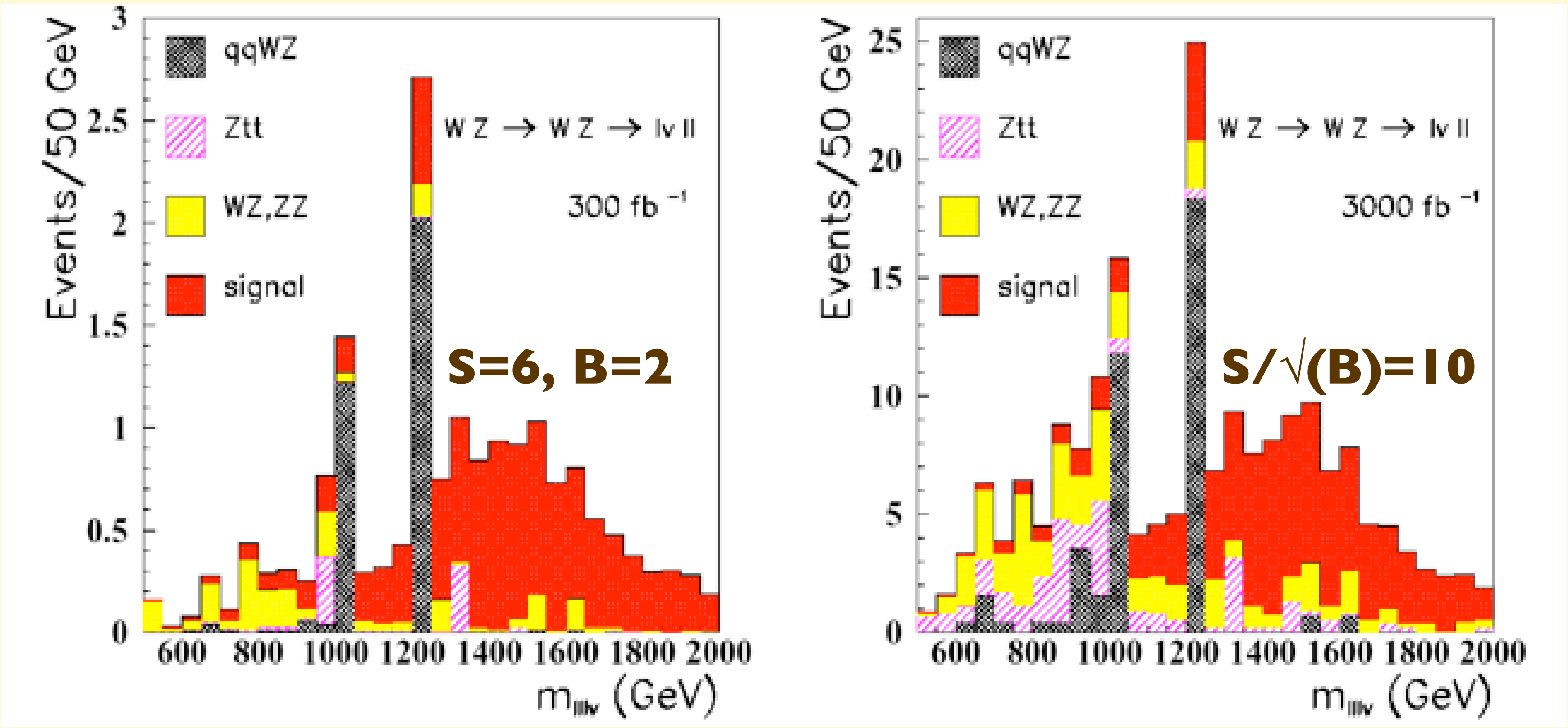
Higgs boson couplings to fermions and gauge bosons

Higgs boson selfcouplings



Strong resonances in high-mass WW or WZ scattering

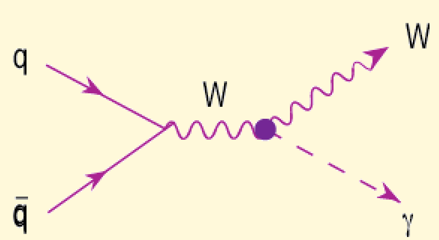


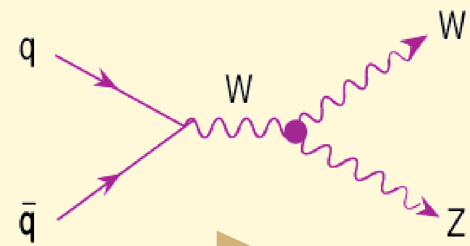


Vector resonance (ρ-like) in $W_L Z_L$ scattering from Chiral Lagrangian model
M = 1.5 TeV, leptonic final states, 300 fb^{-1} (LHC) vs 3000 fb^{-1} (SLHC)

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

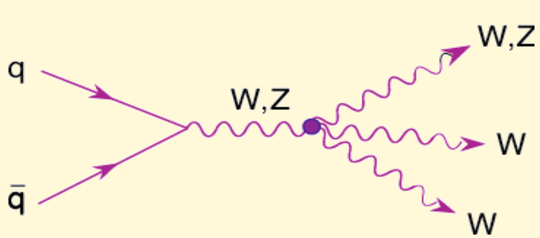
5 parameters describing weak and EM dipole and quadrupole moments of gauge bosons. The SM predicts their value with accuracies at the level of **10^{-3}**, which is therefore the goal of the required experimental precision

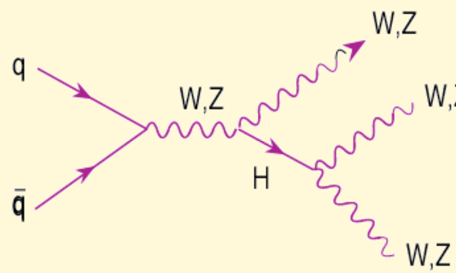


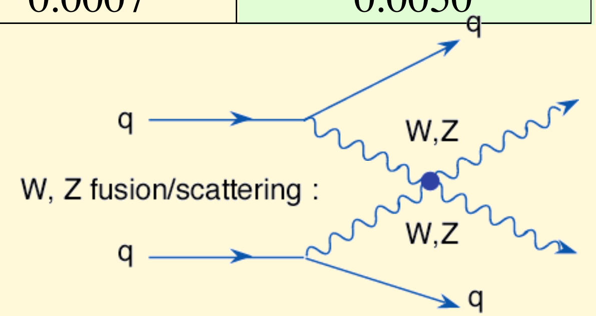


LHC options

Coupling	14 TeV 100 fb^{-1}	14 TeV 1000 fb^{-1}	28 TeV 100 fb^{-1}	28 TeV 1000 fb^{-1}	LC 500 fb^{-1}, 500 GeV
λ_γ	0.0014	0.0006	0.0008	0.0002	0.0014
λ_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^Z_1	0.0038	0.0024	0.0023	0.0007	0.0050

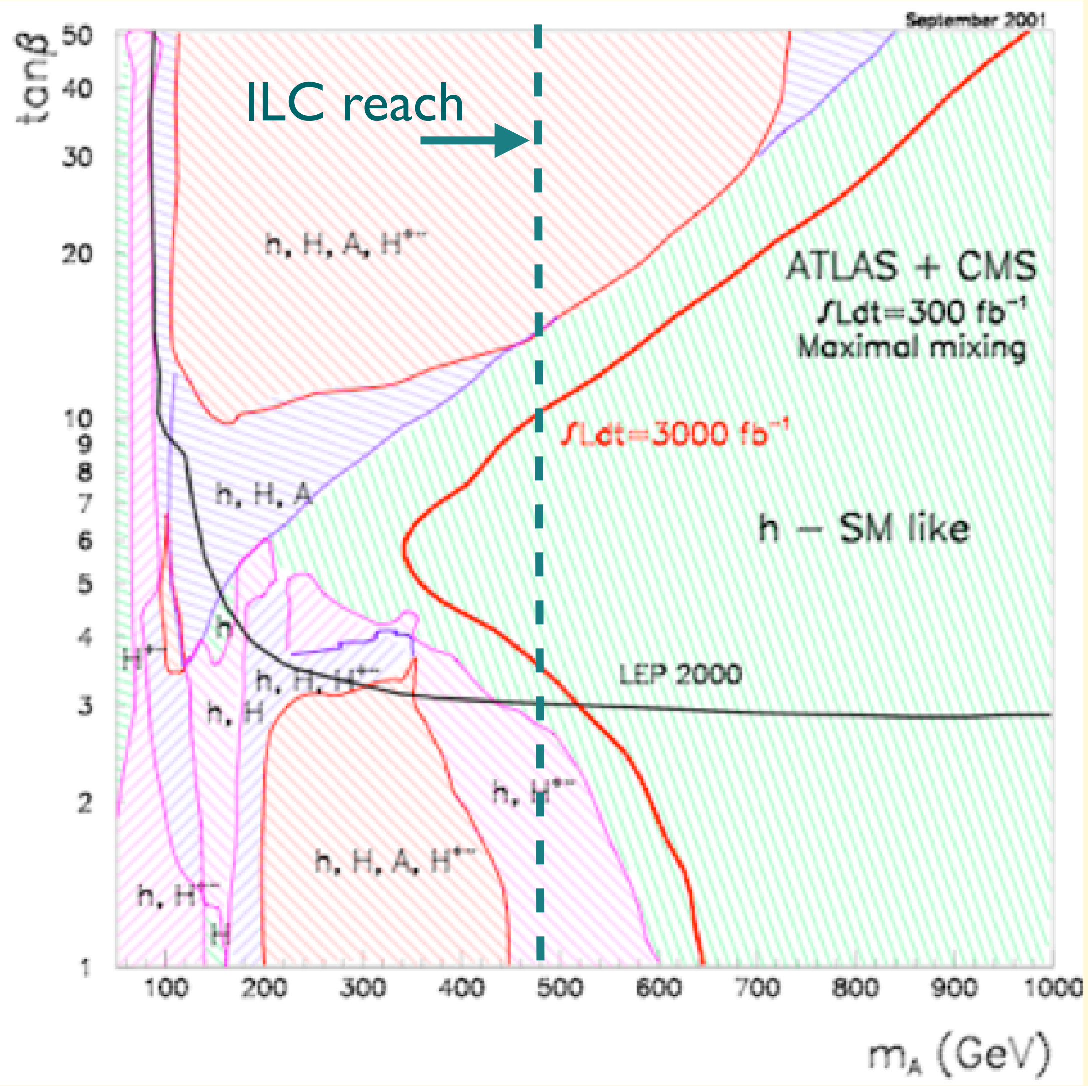




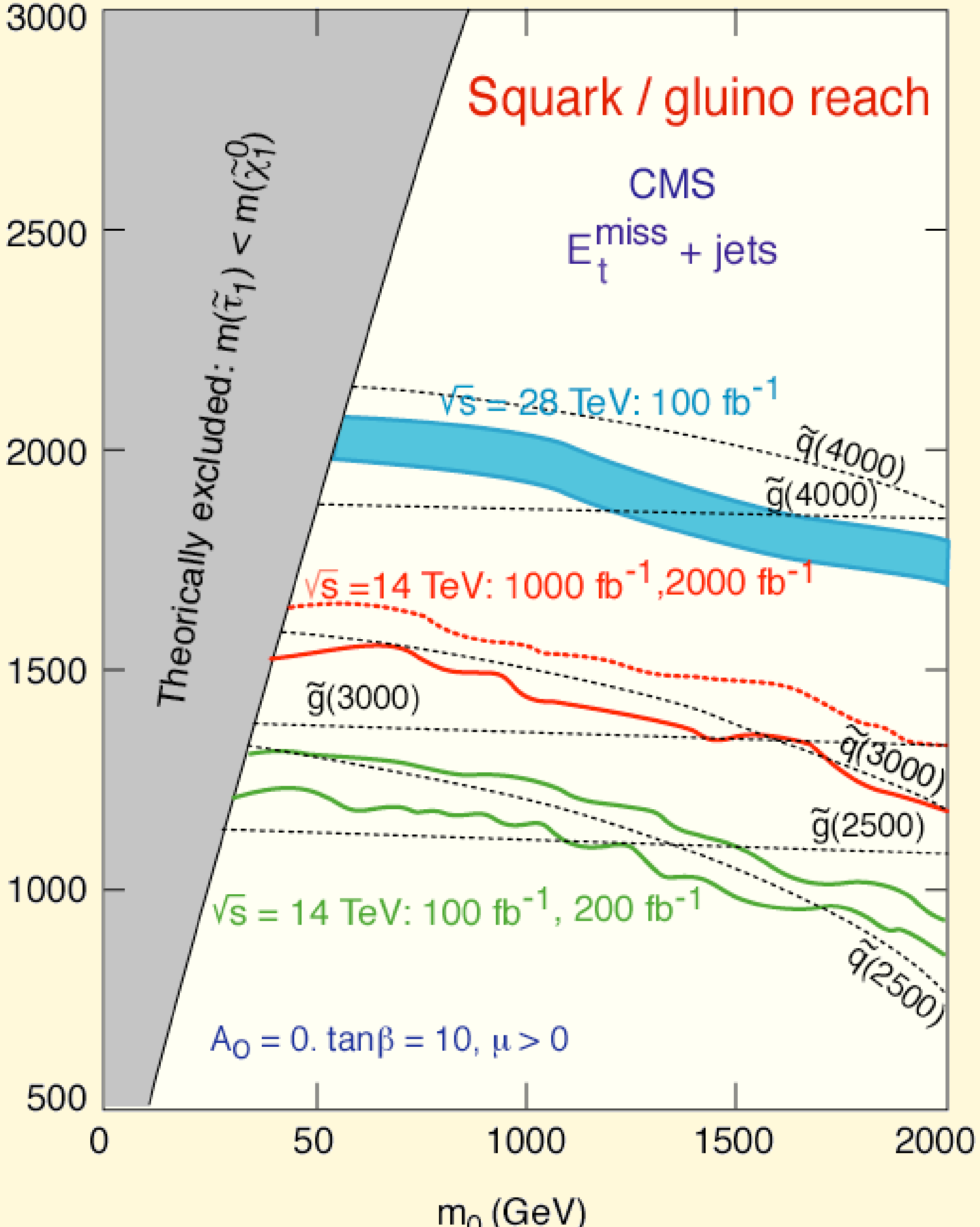


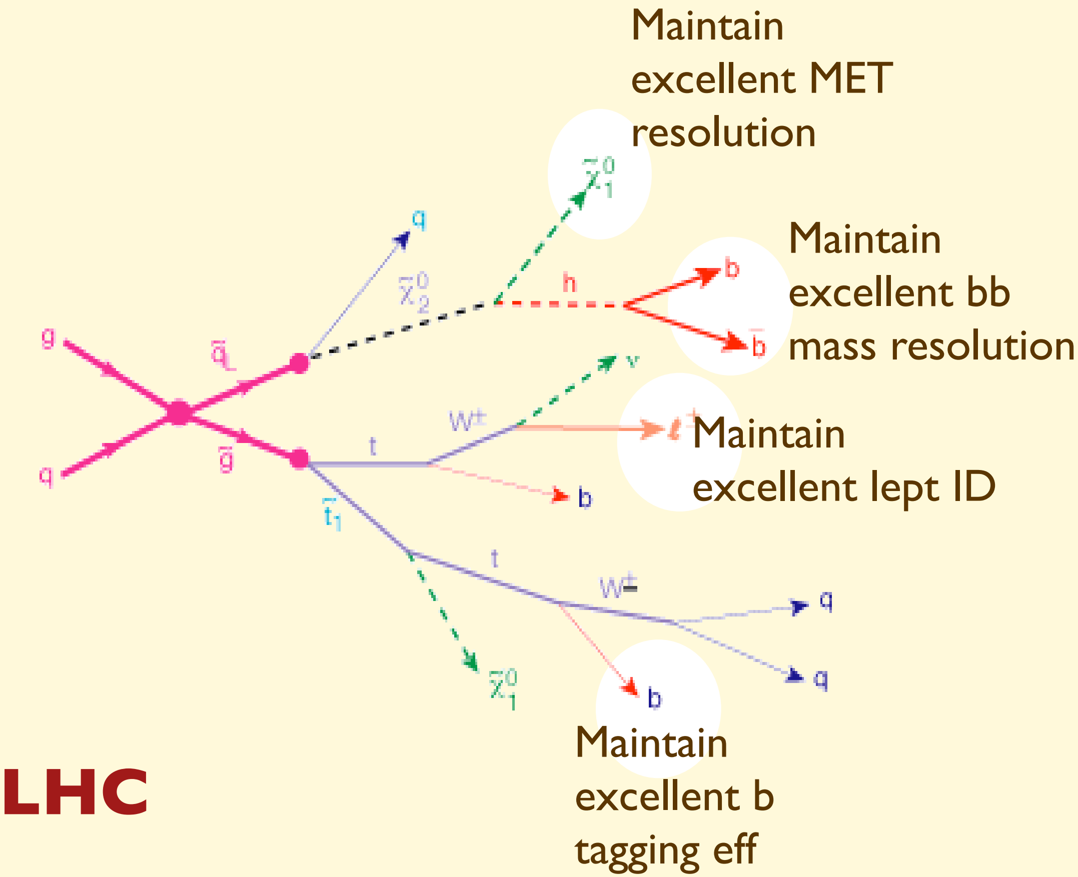
(LO rates, CTEQ5M, k ~ 1.5 expected for these final states)						
Process	*WWW*	*WWZ*	*ZZW*	*ZZZ*	*WWWW*	*WWWZ*
N(m_H = 120 GeV)	2600	1100	36	7	5	0.8
N(m_H = 200GeV)	7100	2000	130	33	20	1.6

Detecting the presence of extra H particles (as expected in SUSY)



SUSY reach and studies

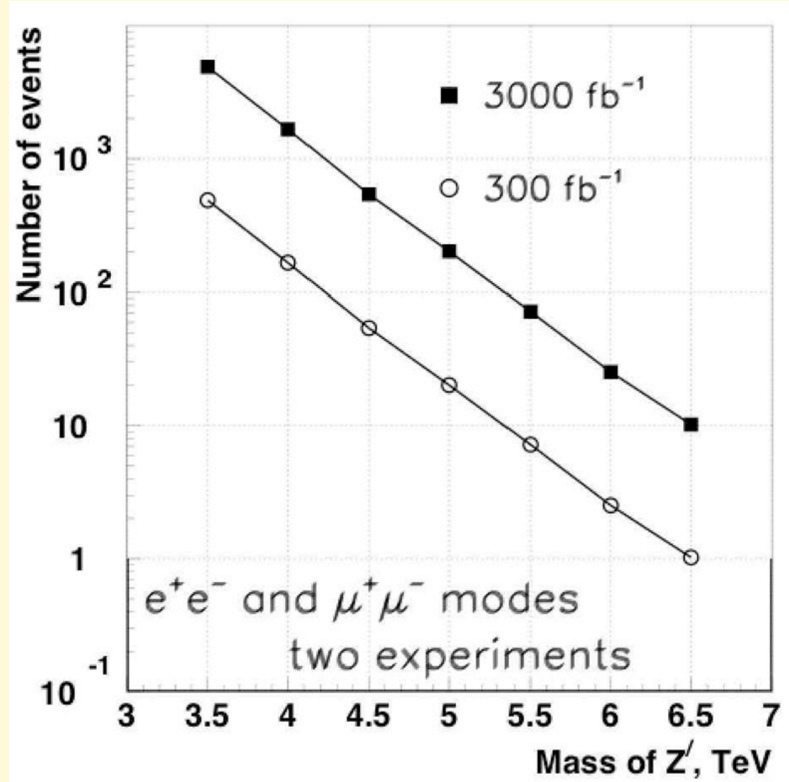




High momentum leptons, but lot of stat needed to reconstruct sparticle mass peaks from edge regions! SLHC luminosity should be crucial, but also need for jets, b-tagging, missing E_t i.e. adequate detector performances (calorimetry, tracker) to really exploit the potential of increased statistics at SLHC…..

Searching new forces: W’, Z’

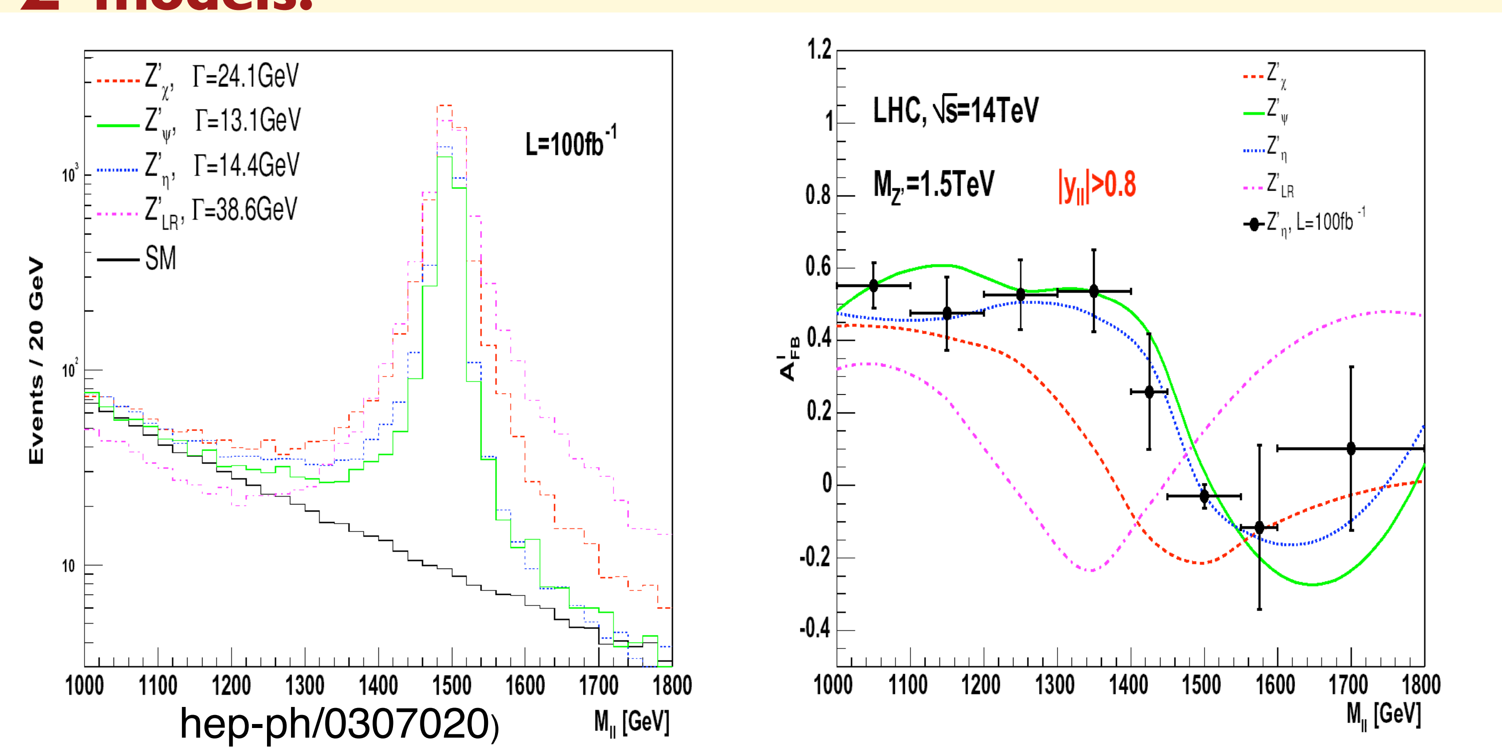
E.g. a W’ coupling to R-handed fermions, to reestablish at high energy the R/L symmetry



100 fb⁻¹ discovery reach up to ~ 5.5 TeV

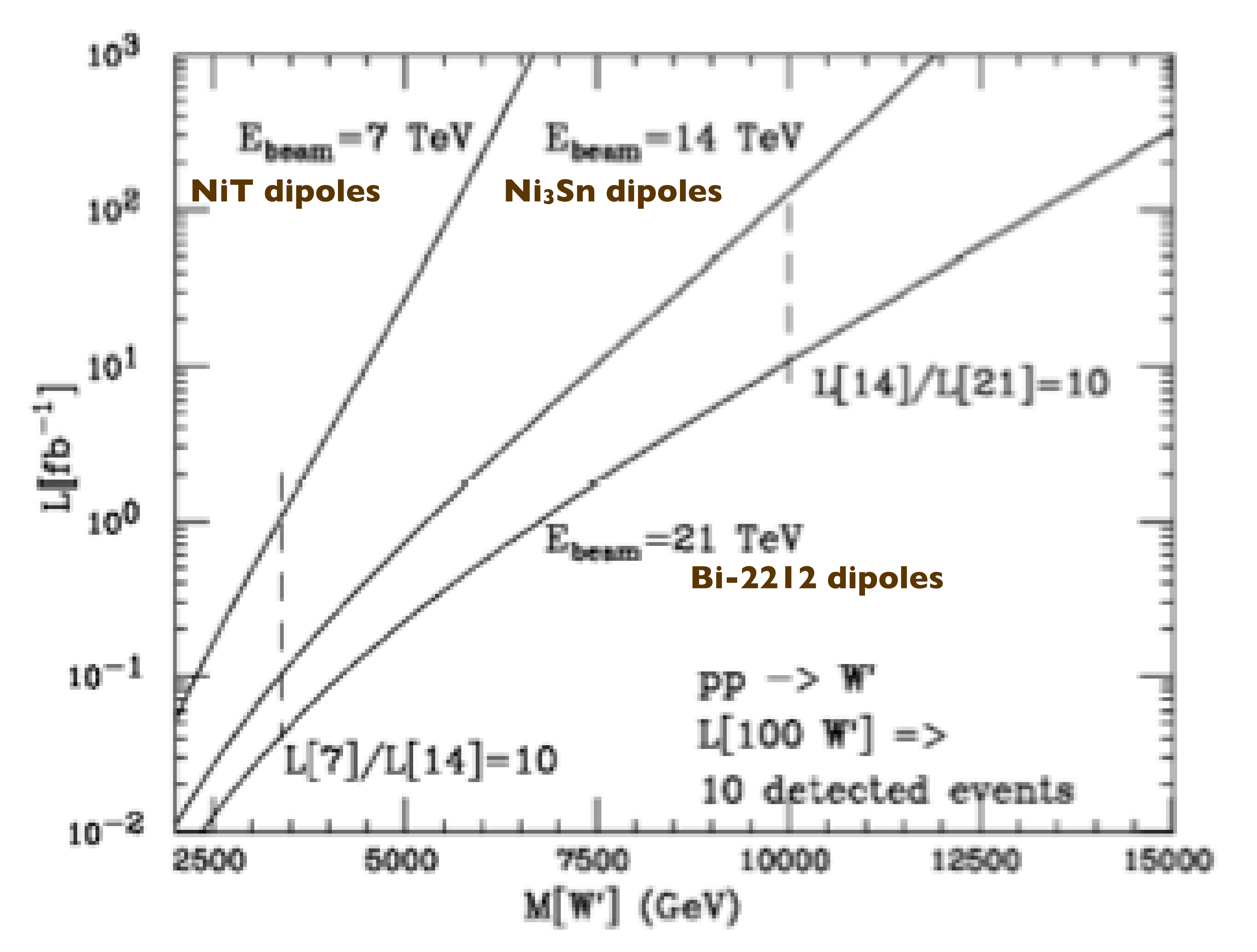
but ….

Differentiating among different Z’ models:



100 fb⁻¹ model discrimination up to 2.5 TeV

Luminosity vs energy



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  - E.g. a 2 TeV Z' benefits more from 10 x statistics at 14 TeV than from 2 x energy

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- **14 → 28 TeV** is great**, 14 → 42** is even better**, but 28 → 42** is probably not worth the cost**, thus 14 → 28 → 42 unlikely**
  - **R&D on all possible future SC magnets should develop in parallel to make the 42 TeV option a viable possibility**

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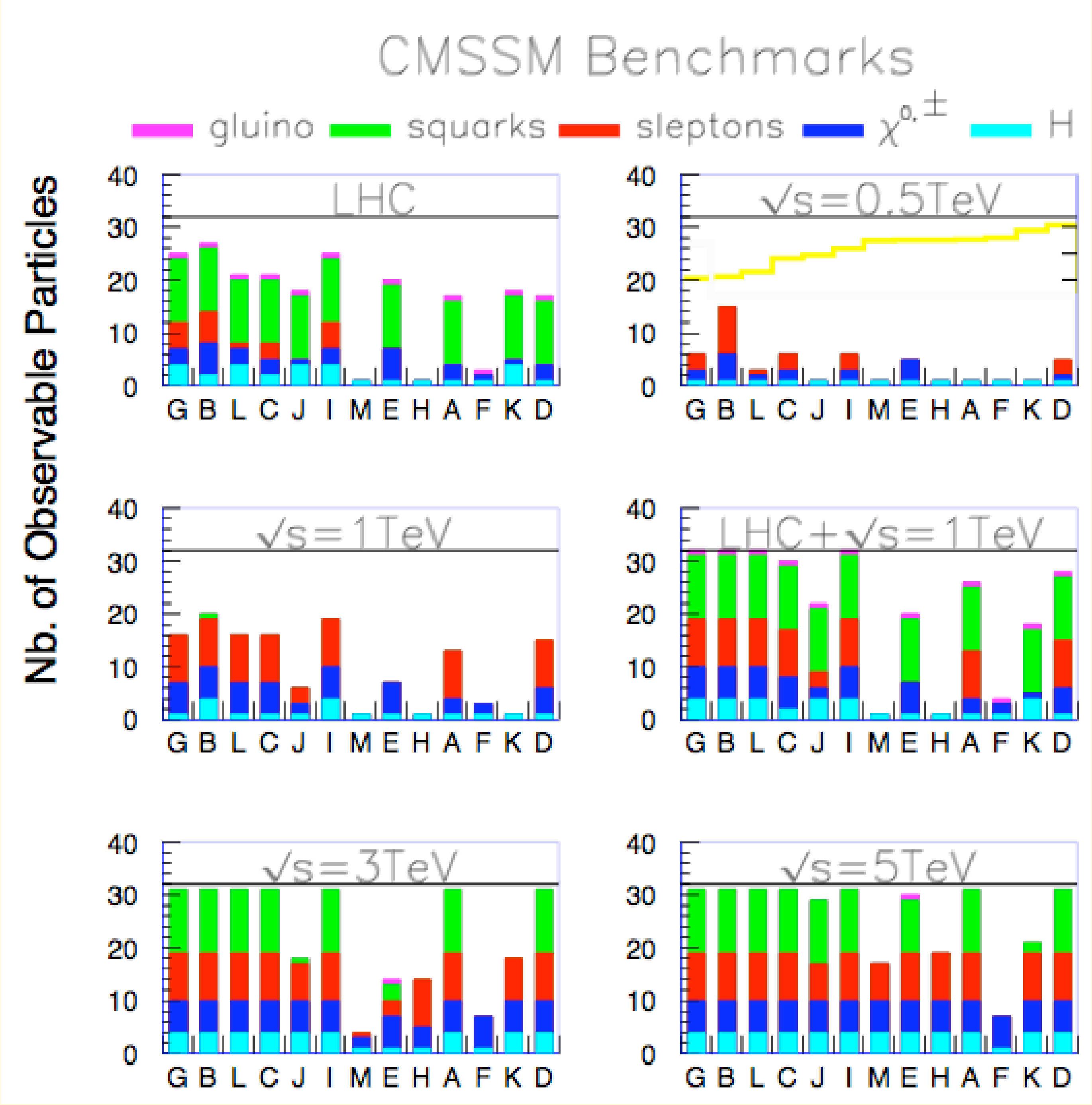
What about the next energy frontier? VLHC?

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 power of the LC would be even more remarkable if one looked at the fine structure of the SUSY skyline

Squark flavour spectroscopy:

$$m_{\tilde{t},L} \quad \text{vs} \quad m_{\tilde{t},R}$$
$$m_{\tilde{b},L} \quad \text{vs} \quad m_{\tilde{b},R}$$
$$m_{\tilde{t},\tilde{b}} \quad \text{vs} \quad m_{\tilde{u},\tilde{d},\tilde{s},\tilde{c}}$$

Squark CKM:

$$\tilde{t} \to W\tilde{b}$$
$$\tilde{q}' \to \tilde{q}$$

Slepton spectroscopy and mixing:

$$\tilde{\ell}' \to \chi^0 \ell$$

Gaugino spectroscopy:

$$m(\chi^{\pm}_{1,2}) \quad m(\chi^0_{1,\dots,4})$$

The power of the LC would be even more remarkable if one looked at the fine structure of the SUSY skyline

Squark flavour spectroscopy:

$$m_{\tilde{t},L} \quad \text{vs} \quad m_{\tilde{t},R}$$
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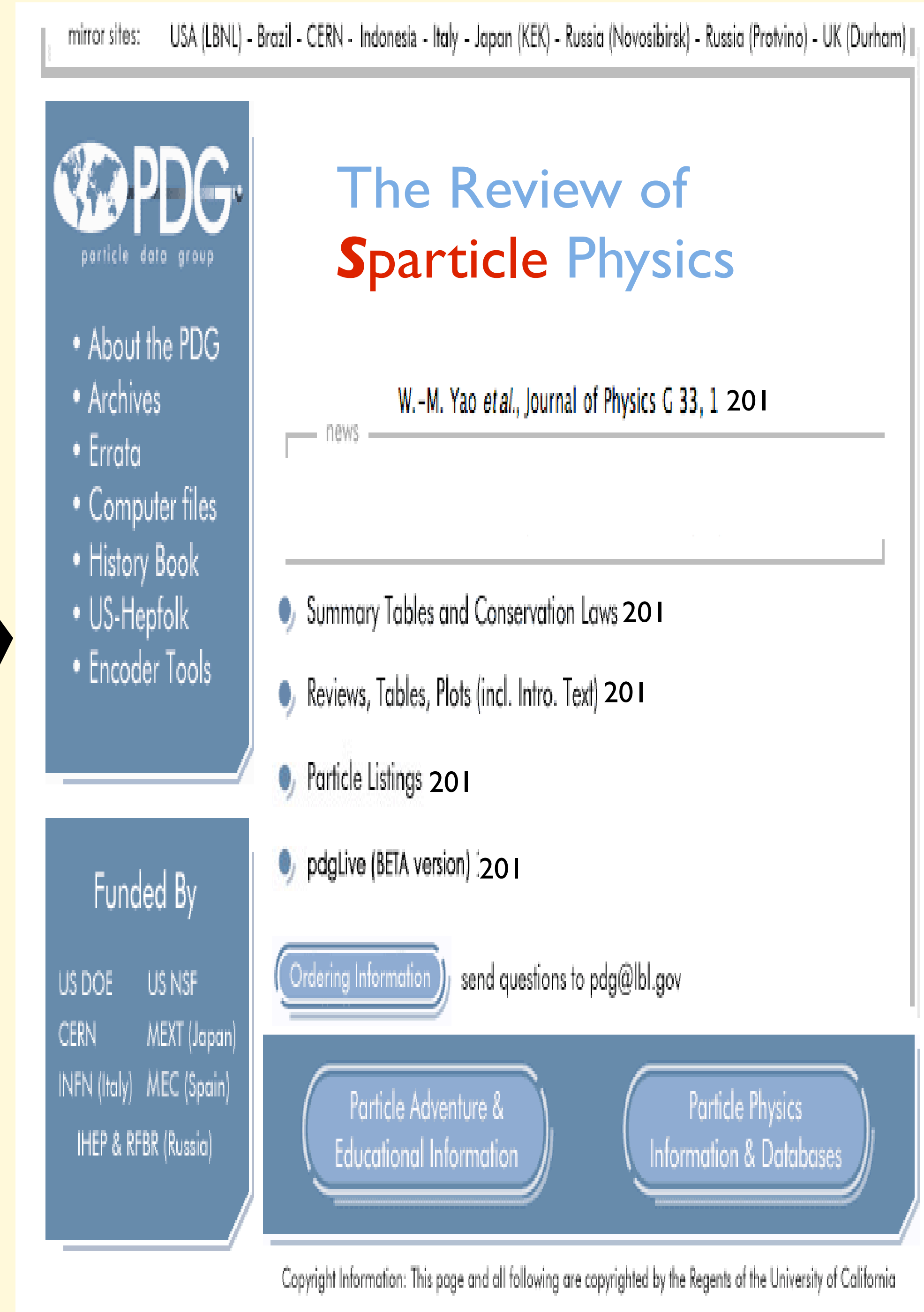
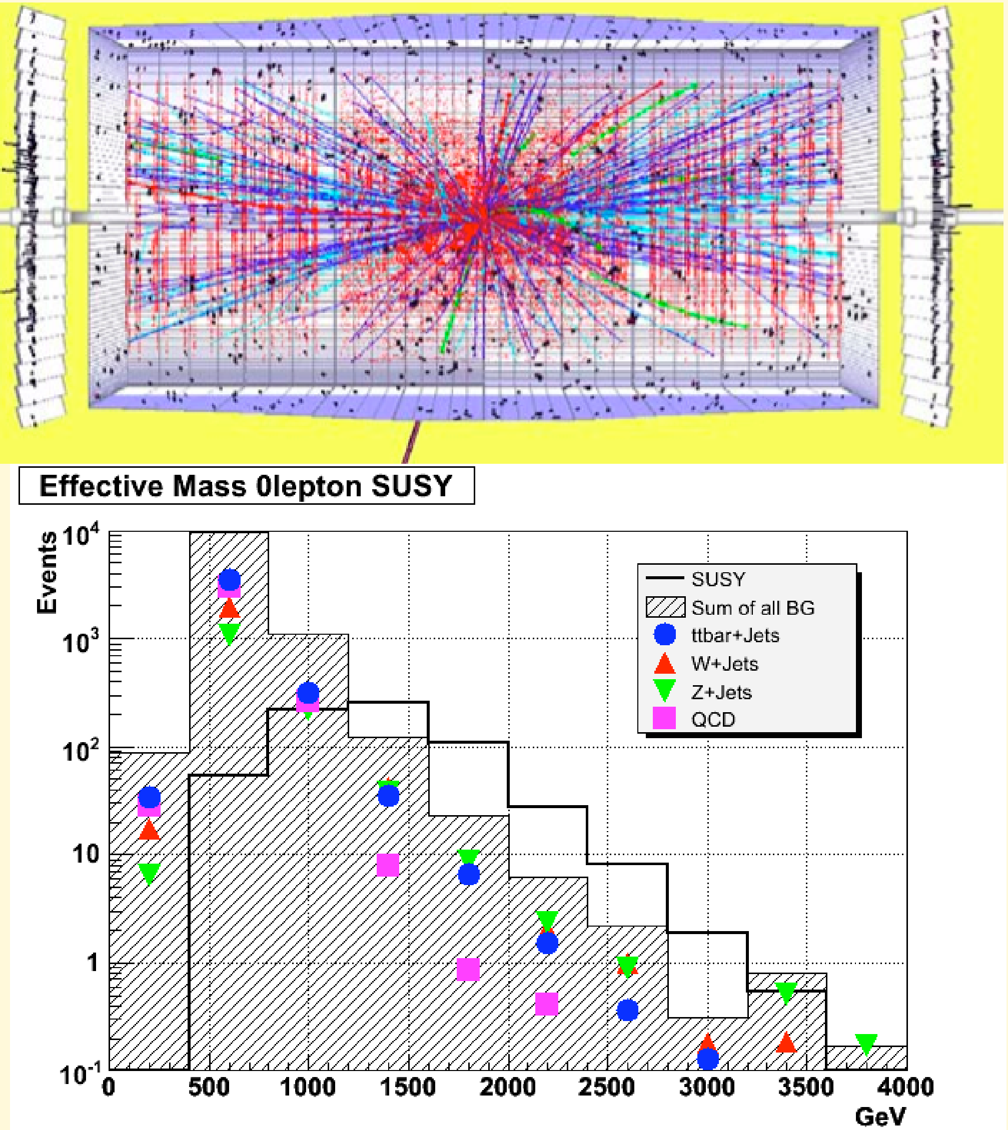
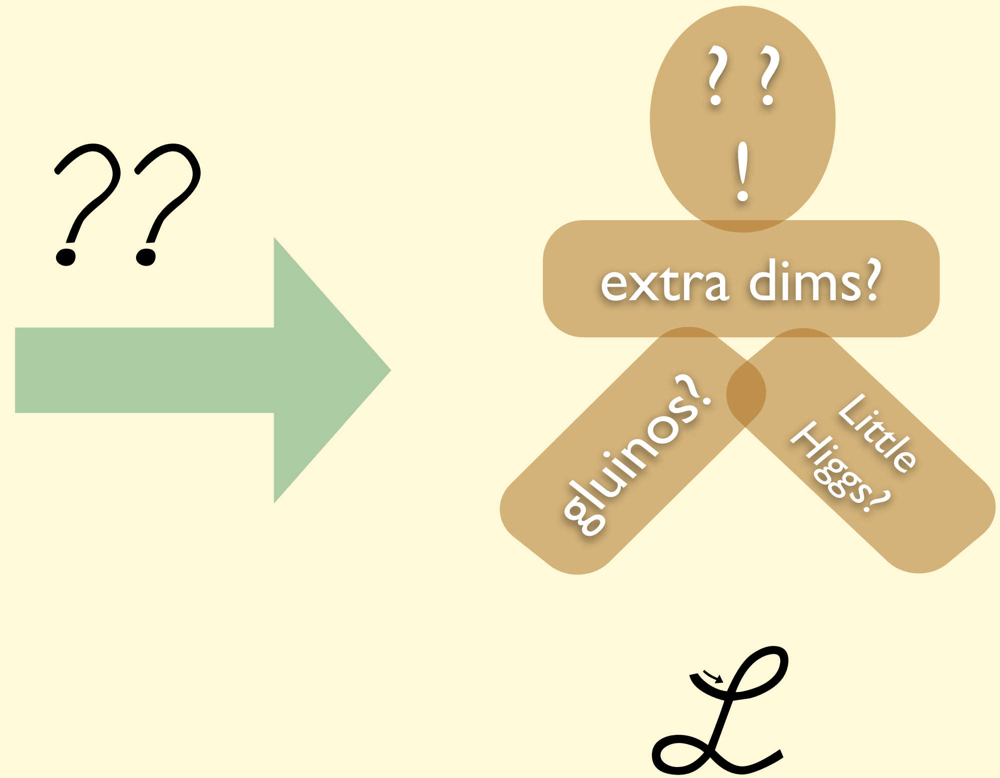


The LHC inverse problem

Reconstruct the Lagrangian of new physics from the LHC data



$$M_{eff}\ (GeV) = \sum_{i=1,4} E_T\ (i) + E_T^{\ miss}$$



The LHC Inverse Problem, Supersymmetry, and the ILC

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Stanford Linear Accelerator Center, 2575 Sand Hill Rd., Menlo Park, CA 94025, USA

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High Energy Physics Division, Argonne National Laboratory, Argonne, IL 60439, USA and
Enrico Fermi Institute, University of Chicago, 5640 South Ellis Avenue, Chicago, IL 60637, USA

We address the question whether the ILC can resolve the LHC Inverse Problem within the framework of the MSSM. We examine 242 points in the MSSM parameter space which were generated at random and were found to give indistinguishable signatures at the LHC. After a realistic simulation including full Standard Model backgrounds and a fast detector simulation, we find that roughly only one third of these scenarios lead to visible signatures of some kind with a significance ≥ 5 at the ILC with $\sqrt{s} = 500$ GeV. Furthermore, we examine these points in parameter space pairwise and find that only one third of the pairs are distinguishable at the ILC at 5σ.

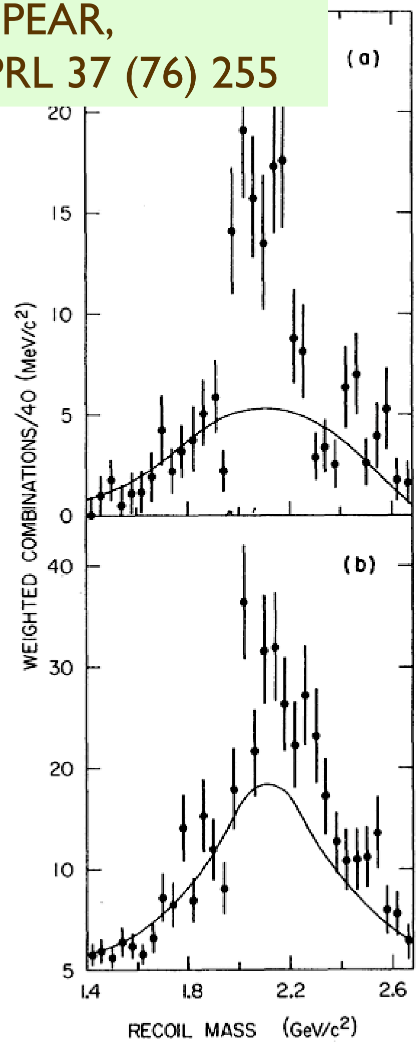
arXiv:0711.1374

See also Arkani-Hamed et al, hep-ph/0512190

A non-trivial example of discovery from the past: open charm

Data:

SPEAR,
PRL 37 (76) 255



Recoil mass of a $K^+\pi^-$ system

Recoil mass of a $K^+\pi^-\pi^+\pi^-$ system

o Obscure structure of recoil system
o No evidence of $D^\pm$

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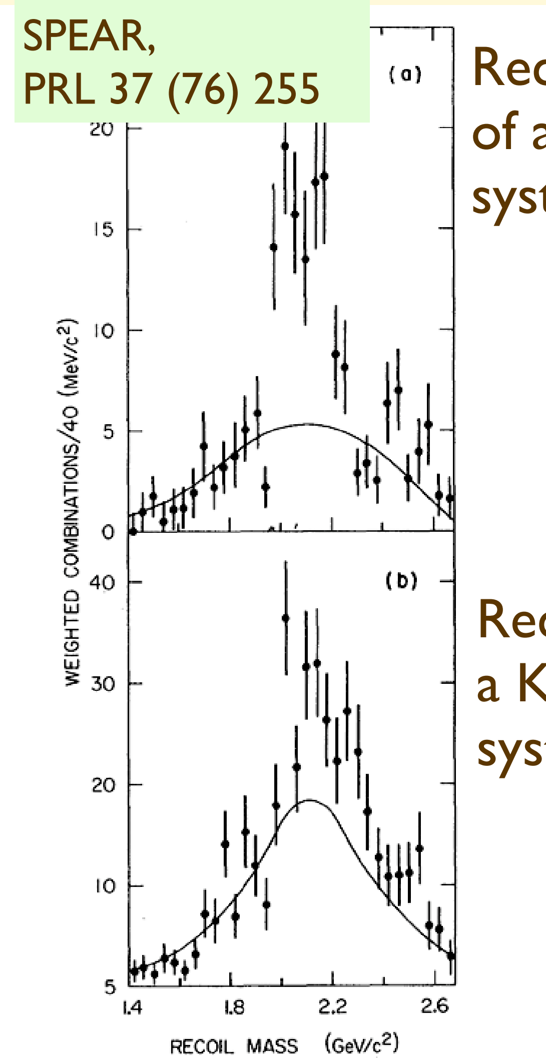


Recoil mass of a $K^+\pi^-$ system

Recoil mass of a $K^+\pi^-\pi^+\pi^-$ system

o Obscure structure of recoil system

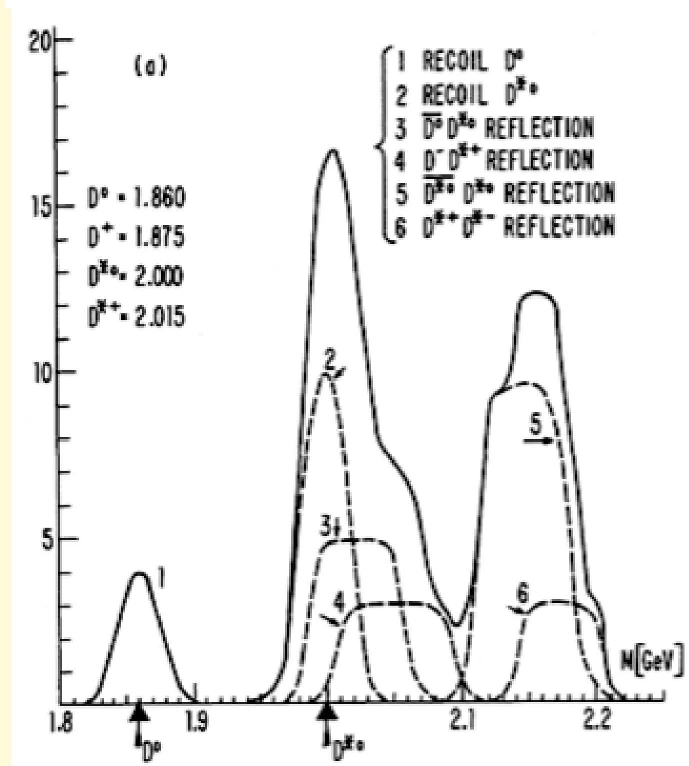
o No evidence of $D^\pm$

Interpretation:

De Rujula, Georgi, Glashow, PRL 37 (76) 398

$$D^{*+} \to \begin{cases} D^0\pi^+, & Q=15\text{ MeV}, \quad B\sim 90\%, \\ D^+\pi^0, & Q=5\text{ MeV}, \quad B\sim 10\%, \\ D^+\gamma, & Q=140\text{ MeV}, \quad B\sim 1\%, \end{cases}$$

$$D^{*0} \to \begin{cases} D^0\pi^0, & Q=5\text{ MeV}, \quad B\sim 90\%, \\ D^+\pi^-, & Q=-5\text{ MeV}, \quad B\sim 0, \\ D^0\gamma, & Q=140\text{ MeV}, \quad B\sim 10\%. \end{cases}$$



DD : D* D : D* D* = 1 : 3 : 7 ⇒

$D^0 : D^+ = 7 : 1$

- I doubt the LHC inverse problem can be solved by global fits of many distributions from either LHC or ILC.
- More likely, the understanding of the new physics will emerge from a step-by-step consolidation of prominent features of the data, restricting more and more the class of models first, and their parameters later.
- Single key inputs, even if only partially accurate, can provide more valuable information than dozens of vaguely suggestive hints. For example, if SUSY:
    - the relation between gluino and chargino mass,
    - evidence for GMSB in the final states (prompt photons and MET),
    - the determination of the stop parameters and mH, etc.

We could be lucky, e.g. have SUSY plus a 2–3 TeV Z' that decays to most SUSY states, turning the LHC into a CLIC-like SUSY factory!

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But is likely that the process of decoding the new discoveries will be a long and complex one

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 in flavour phenomena, the existence of physics BSM will demand and fully justify these studies: we'll be measuring the properties of something that we know exists, as opposed to blindly looking for "we don't know what" as we are unfortunately doing today!

In many cases theoretical precision is not an issue.

The most exciting observables vanish in the SM:

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Electric dipole moments

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The most exciting observables vanish in the SM:

LFV

Electric dipole moments

CP violation in tau decays

Neutrinos

- LEP: 3 weakly interacting neutrinos with $m<M_Z/2$
- 2 relative masses, one absolute mass scale, 3 mixing angles, 1 CKM phase δ, 2 extra relative phases if Majorana

$\|\Delta m^2_{23}\|$	Δm^2_{12}	m_1	$\sin^2\theta_{12}$	$\sin^2\theta_{23}$	$\sin^2\theta_{13}$	δ_i
$\sim 2.6\times 10^{-3}$	$\sim 7\times 10^{-5}$	?	0.2-0.4	0.3-0.7	<0.05	?

- Iff all $\theta_{ij}\neq 0$ and at least one phase $\delta\neq 0$, then CPV
  - Leptogenesis (lepton-driven B asymmetry of the Universe)
- Dark Matter: WMAP ⇒ $\Omega_\nu<0.015$, $m_\nu<0.23$ eV

The completion of the neutrino programme, with the full determination of

mass hierarchy

majorana vs dirac nature

full spectrum of masses and mixing angles

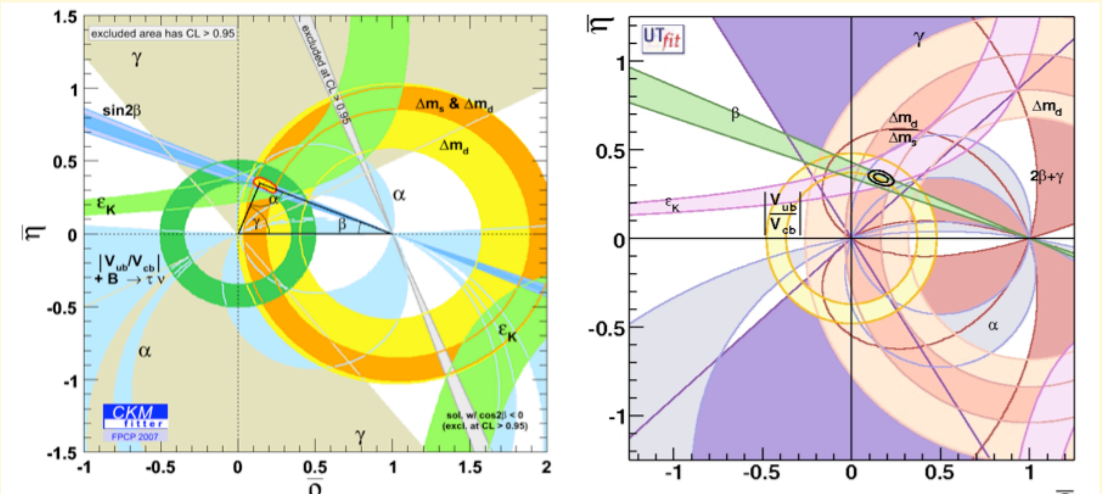
CPV phase(s)

will "just" put us in the position we are today in the quark sector: we know masses and mixings, but have no idea where they come from.

This is not enough.

- To interpret these parameters we need to establish a **connection with the other sectors of the theory**

- We need a **redundancy of inputs** to expose deviations from the simple mixing picture. The equivalent of all redundant measurements of CKM offered by the many channels where we measure CKM angles and phases



- A complete programme of neutrino physics **requires** additional information beyond what is provided by neutrinos themselves

➡ Flavour phenomena in the charged-leptonic and in the hadronic sectors are a **crucial** component of a comprehensive exploration of neutrino physics

The High Intensity Frontier

Neutrinos:	**Quarks:**	**Charged leptons:**
super beams	B factories	stopped μ
beta-beams	K factories	$\ell \to \ell'$ conversion
ν factory	n EDM	e/μ EDM

Comment

- Let’s not call this “precision physics”, let’s insist the goal is discovery. How about something like

Low Energy Discovery (LED) physics

Neutrinos and SUSY

For details and refs, see: Masiero, Profumo, Vempati, Yaguna, hep-ph/0401138

The merging of neutrino masses, SUSY and GUT leads to very interesting constraints and consequences:

SUSY ⇒ Higgs field giving Dirac υ mass = Higgs field giving up-quark masses

$$L_m \propto y_\ell H_d L_i L_i^c + y_\nu^{ij} H_u L_i N_j + M_N^{ij} N_i N_j$$

GUT (e.g. SO(10)) ⇒ Yukawa ν-mass matrix = Up-quark Yukawa matrix

$$L_m \propto y_{i,j}^{d,\ell} \mathbf{16}_i \mathbf{16}_j H_d + y_{i,j}^{u,\nu} \mathbf{16}_i \mathbf{16}_j H_u + y_{i,j}^{R} \mathbf{16}_i \mathbf{16}_j H_R^{126}$$

where $\mathbf{16} = (u_L, d_L, u^c, e^c)_{10} + (d^c, L)_5 + N^c$

⇒ one entry in the neutrino Yukawa matrix is of order of the top Yukawa coupling!

⇒ $m(N_R) = f(m_{up}, m_\nu) \approx (m_t^2 / m_\nu, \; m_c^2 / m_\nu, m_u^2 / m_\nu)$

⇒ $m_\nu > m_t^2 / M_{GUT}$ to ensure that $m(N_R) < M_{GUT}$

Even more interestingly, quark mixings induce charged **slepton** mixing via RG evolution from M_{GUT} to $m(N_R)$:

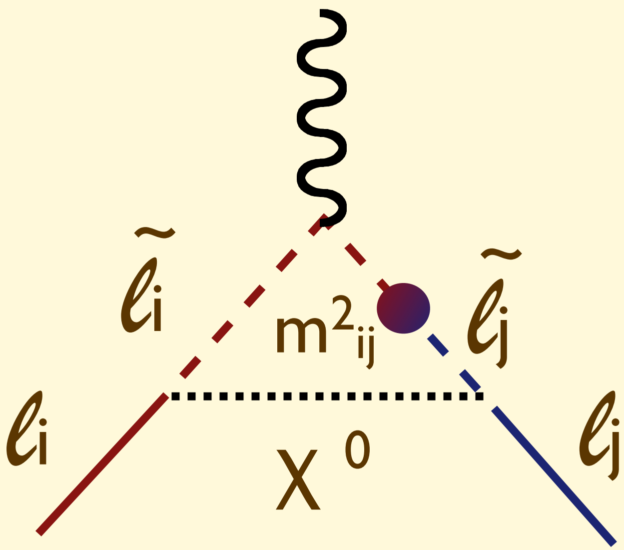
$$(m^2_{\tilde{L}})_{ij} \sim -\frac{3m_0^2 + A_0^2}{8\pi^2}\, y_t^2\, O_{ij} \log\frac{M_{GUT}}{M_{N_R}}$$

SUSY breaking param's

nu mixing param's

$$y_t^2\, O_{ij} = \sum_k y_{ik}^{\nu}\, y_{jk}^{\nu *}$$

$\ell_i \rightarrow \ell_j\, \gamma$ transitions:

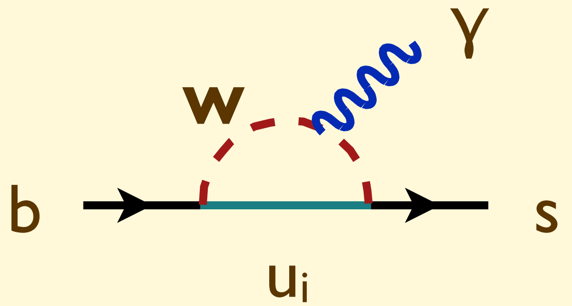


Possible scenarios:

$O_{\mu e} = V_{td} V_{ts}$ "CKM
$O_{\tau\mu} = V_{tb} V_{ts}$ scenario"

$O_{\mu e} = U_{e3} U_{\mu 3}$ "MNS
$O_{\tau\mu} = U_{\tau 3} U_{\mu 3}$ scenario"

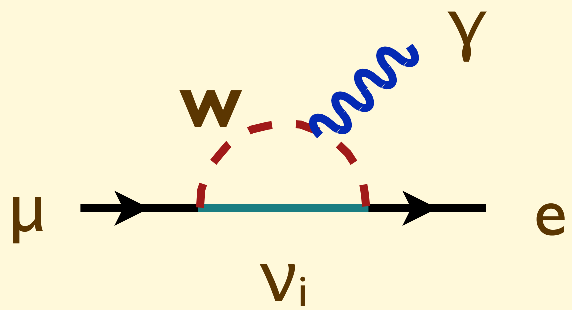
In the SM



GIM

O(1)

$$\propto \left| \frac{m_c^2 - m_u^2}{m_W^2} V_{cb}V_{cs}^* + \frac{m_t^2 - m_u^2}{m_W^2} V_{tb}V_{ts}^* \right|^2 \sim \frac{m_t^4}{m_W^4} |V_{tb}V_{ts}^*|^2$$



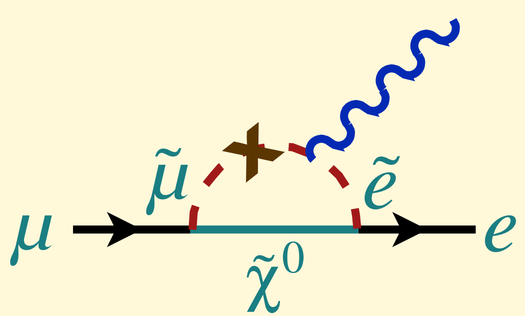
O(10^{-49})

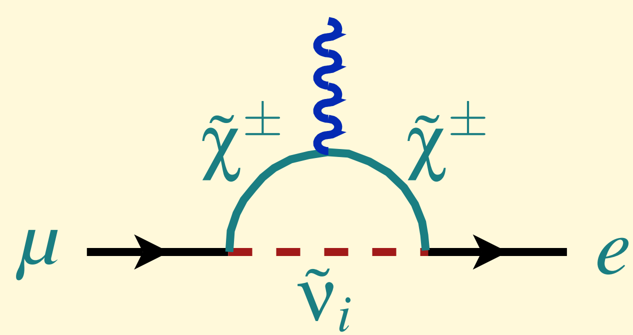
$$\propto \left| \frac{m_1^2 - m_2^2}{m_W^2} M_{12}M_{11}^* + \frac{m_3^2 - m_2^2}{m_W^2} M_{32}M_{31}^* \right|^2 \sim \frac{\Delta m_{23}^4}{m_W^4} s_{23}^2\, c_{31}^2\, s_{31}^2$$

The smallness of B(μ→eγ) is entirely due to the smallness of ν masses (and splittings)

The moment we have new states in the loop, the rates goes up!

Example: SUSY



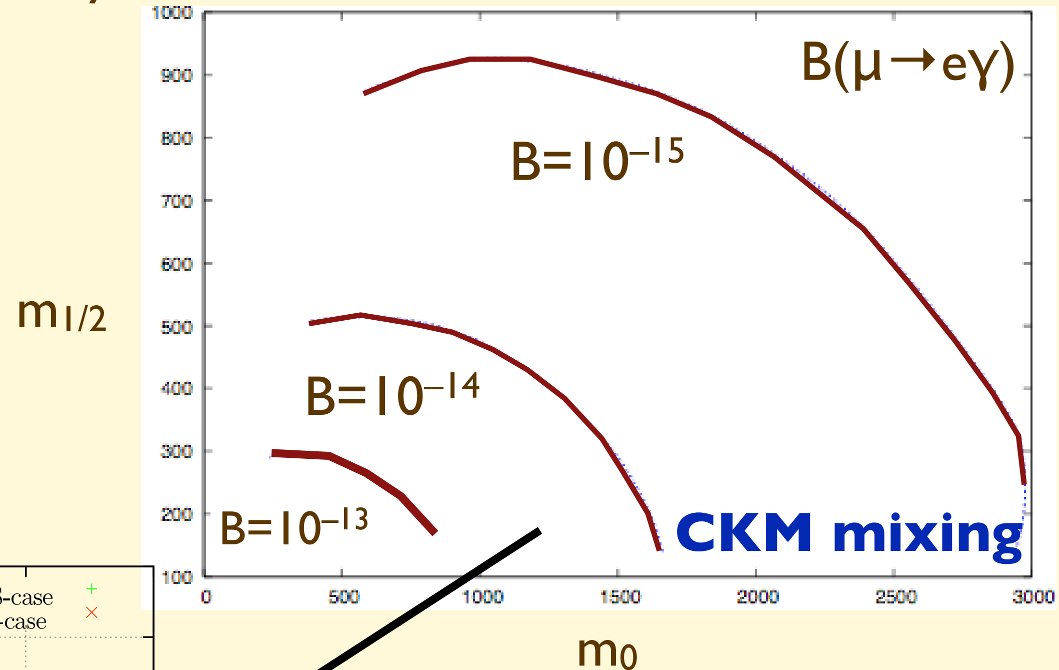


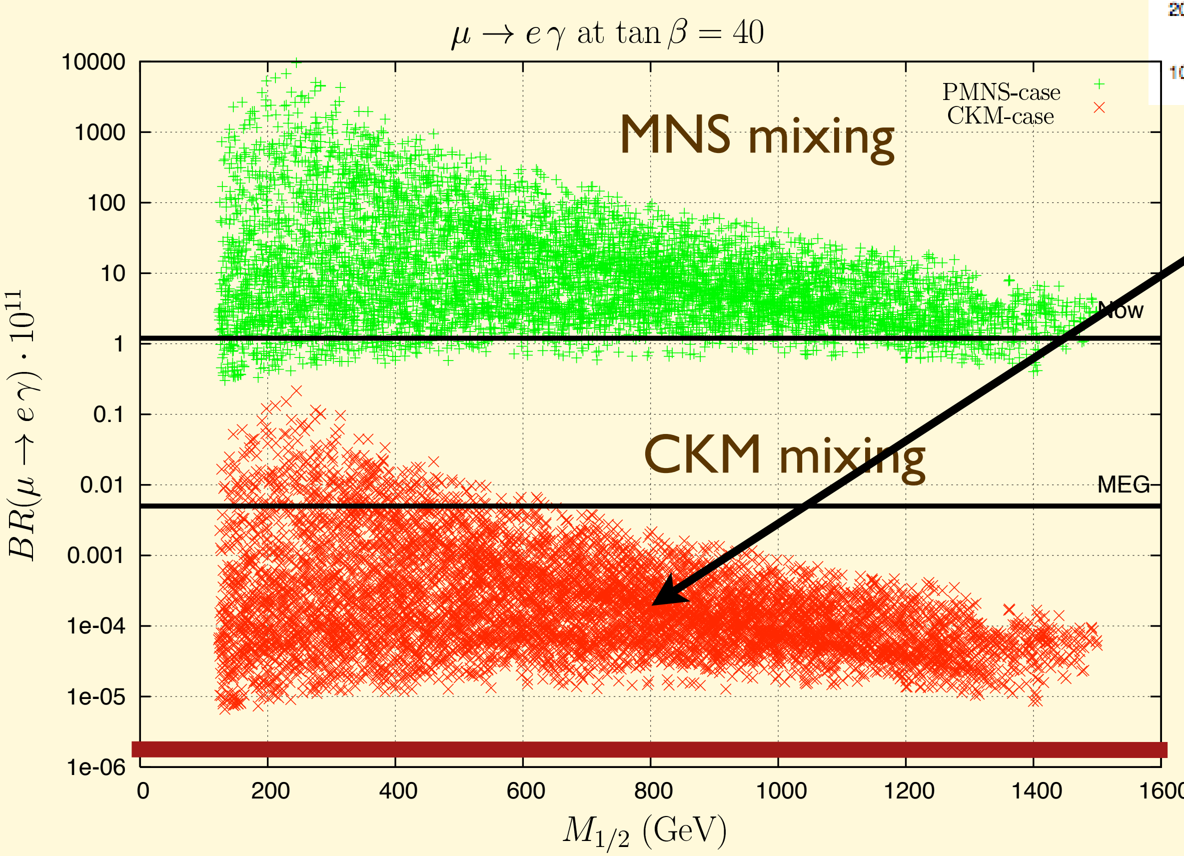
$$B \propto \left| \frac{\Delta m^2(\tilde{\nu})}{m_{\tilde{\chi}}^2} \times \varepsilon_{12}^2 \right|^2$$

Examples of LHC-(μ→eγ) sinergy: I

SO(10) GUT scenario, slepton mixign induced by RG evolution

To push to the ultimate LHC squark reach (m~2.5–3 TeV) may require sensitivity to $B(\mu\to e\gamma) \sim 10^{-15}$





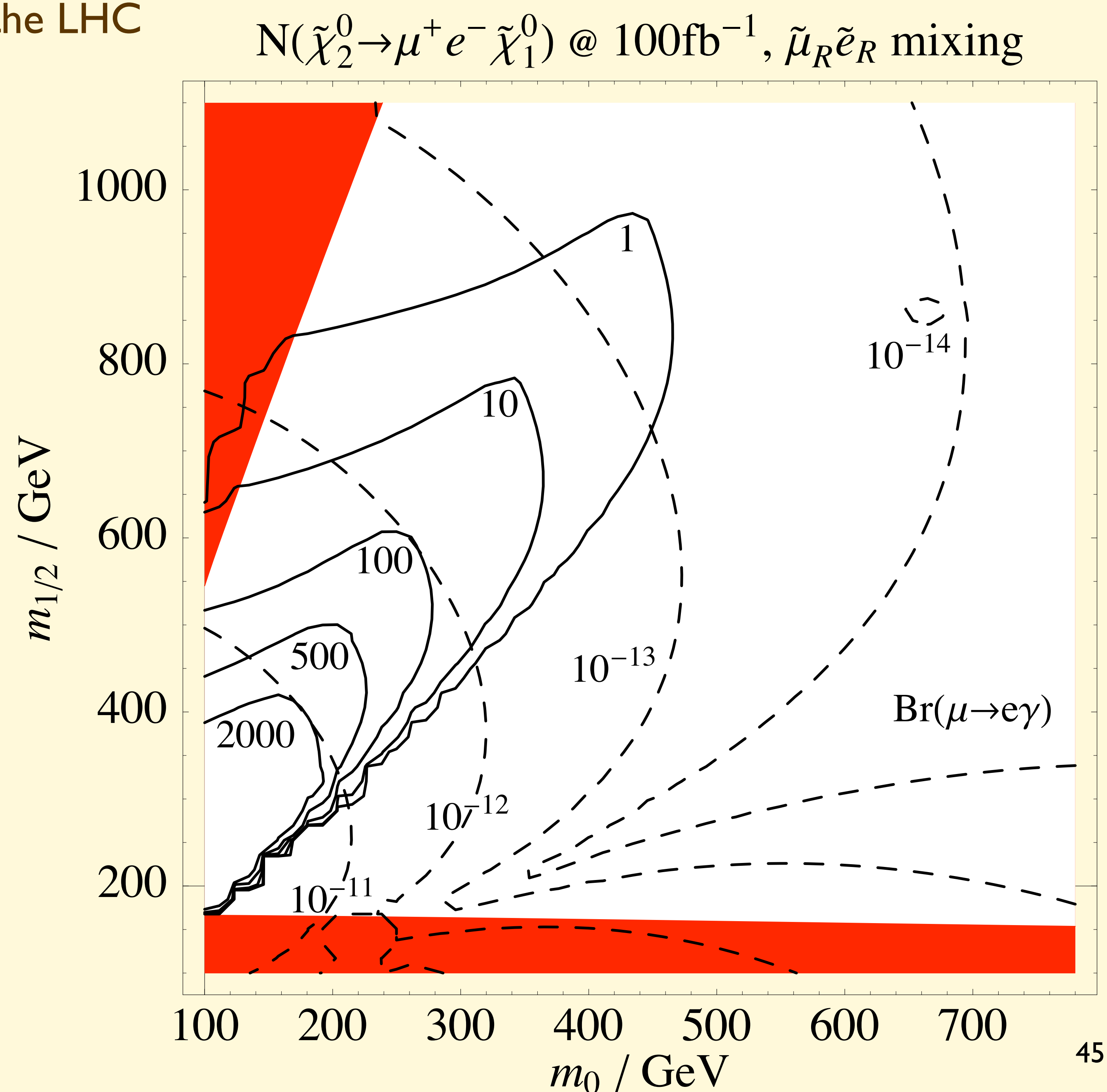
Project-X

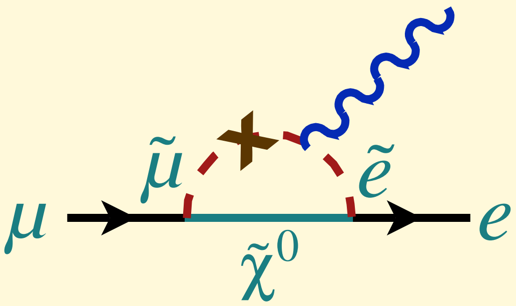
SO(10) mSUGRA scan with m(squark)<2.5 TeV

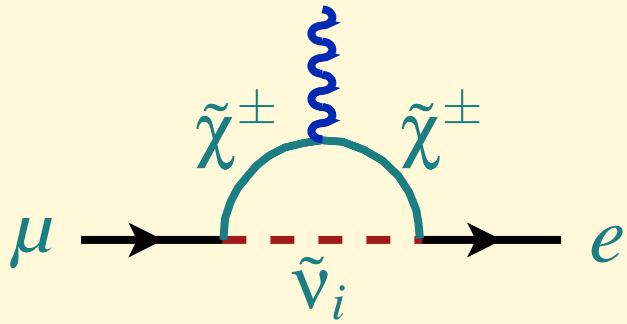
Calibbi et al, hep-ph/0605139

Examples of LHC-(μ→eγ) sinergy: II

Direct observation of LVF at the LHC







Neglecting mixing, these diagrams are also responsible for $(g-2)_\mu$

Assuming that the BNL data are explained by SUSY,

$$(g-2)_\mu^{data} - (g-2)_\mu^{SM} = (g-2)_\mu^{SUSY}$$

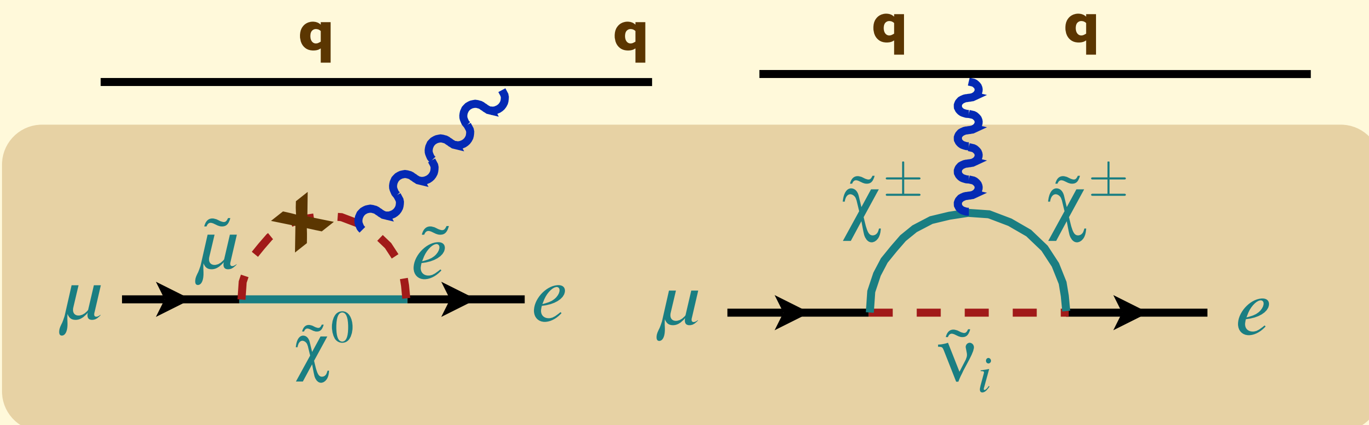
sets a scale for m(SUSY) ~ 100 GeV

Current B($\mu \rightarrow e\gamma$) limits then indicate mass splittings in the slepton sector of few 10s MeV !!

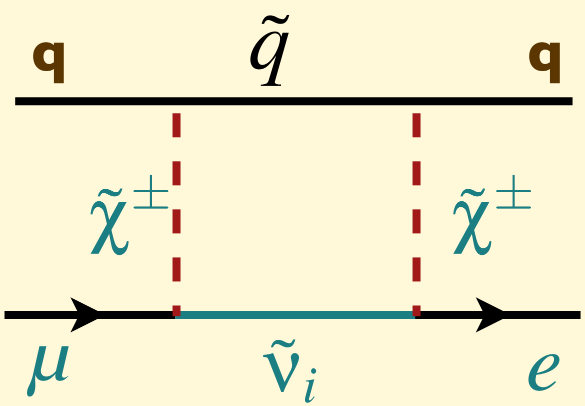
Sensitive to natural mass splittings $m(\tilde{\mu})-m(\tilde{e}) \sim O(m_\mu)$

μ→eγ vs μN→eN complementarity

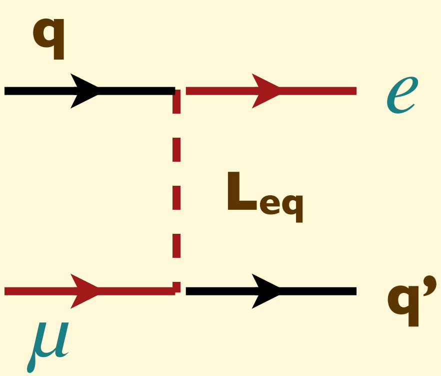
Shall we need μN→eN at FNAL if MEG sees μ→eγ ?

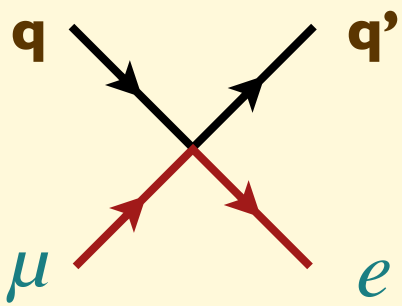


μ→eγ diagrams



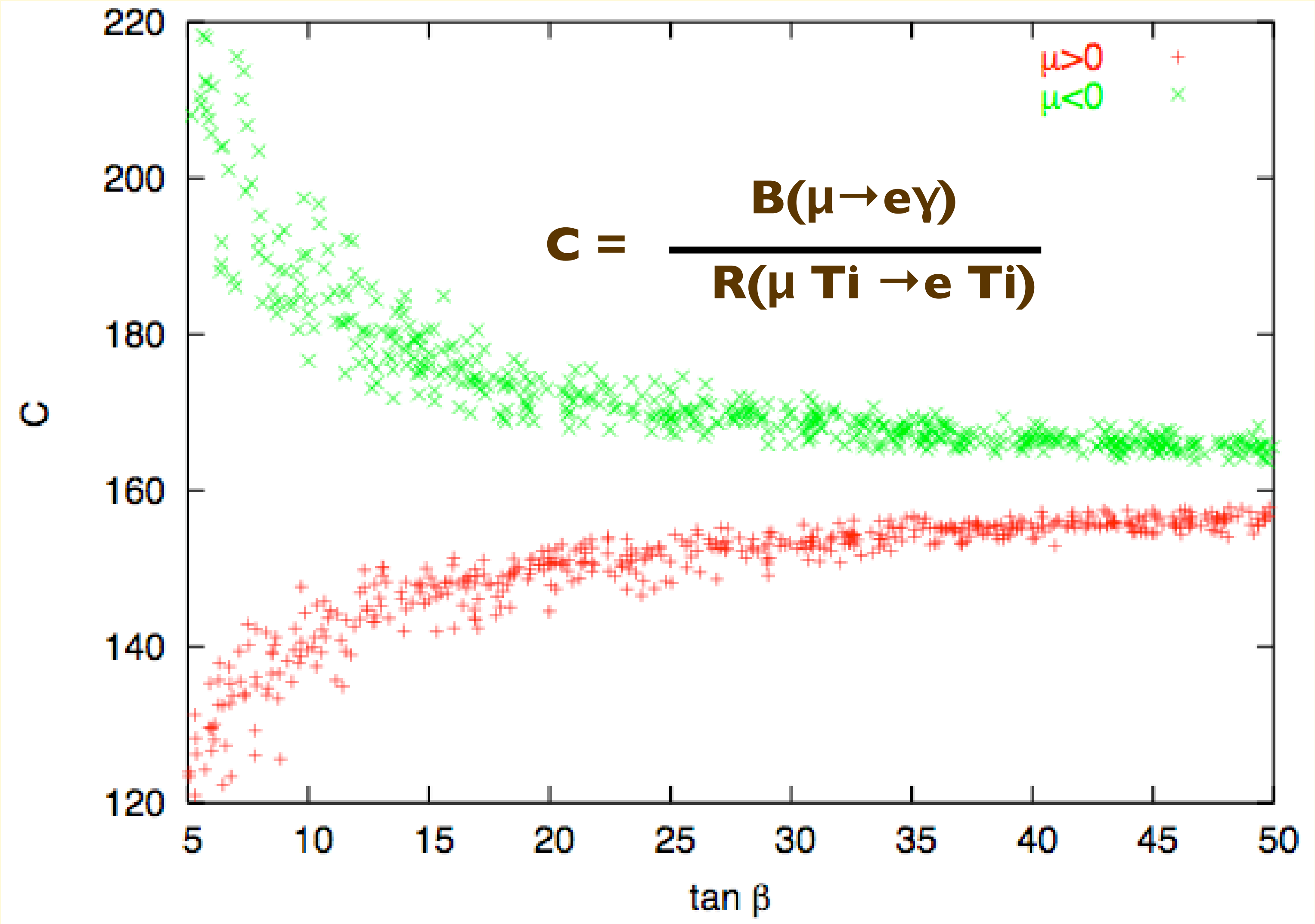
extra contributions, sensitive to additional model parameters





extra contributions, sensitive to other underlying dynamics

K→eμ?



C Yagouna, hep-ph/0502014

More physics with charged leptons

- $\mu \to eee$ (typically $O(\alpha)$, but $O(1)$ in LH models)
- $\tau \to \mu\,\gamma$ $\tau \to e\,\gamma$: model-dependent correlations with $\mu \to e\gamma$
- $\tau \to \mu\mu\mu$ (LHCb ?)
- CP violation in SM-allowed τ decays?
  - $O(10^{-3})$ CP asymmetry in $\tau \to \nu K\pi$ ⇨ $B(\tau \to \mu\,\gamma) \sim O(10^{-9})$
- .....

Example of correlations between ν and quark-sector observables

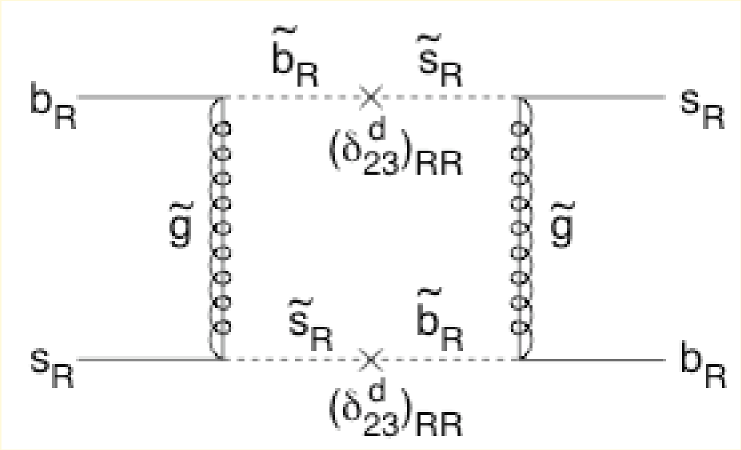
$$L_m \propto y^{d,\ell}_{i,j}\,\mathbf{16}_i\mathbf{16}_j H_d + y^{u,\nu}_{i,j}\,\mathbf{16}_i\mathbf{16}_j H_u + y^{R}_{i,j}\,\mathbf{16}_i\mathbf{16}_j H^{126}_R$$

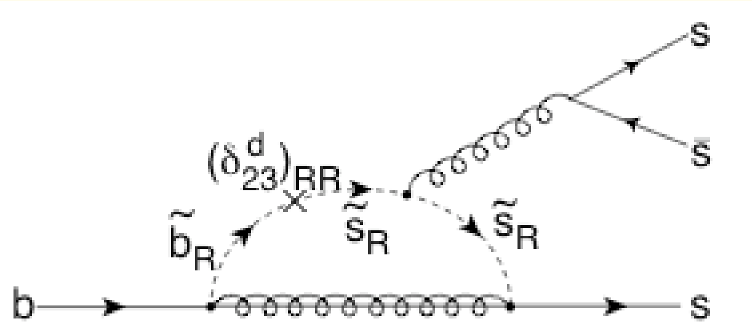
$$\mathbf{16} = (u_L, d_L, u^c, e^c)_{10} + (d^c, L)_5 + N^c$$

A large mixing between ν_μ and ν_τ implies a large mixing between

$$(b_R , \bar{\nu}_\tau , \tau^+) \qquad (s_R , \bar{\nu}_\mu , \mu^+)$$

This has no impact on phenomenology, since right-handed quarks do not couple to weak interactions. However it leads to a large mixing between the scalar partners of R-handed squarks, and to interactions like





with potentially large contributions to:

Bs mixing, CP violation in Bs→φψ (~0 in the SM)

sin2β(B→φKs) ≠sin2β(B→ψKs)

$\mu \to e\,\gamma$

Current limits on B($\mu \to e\,\gamma$)

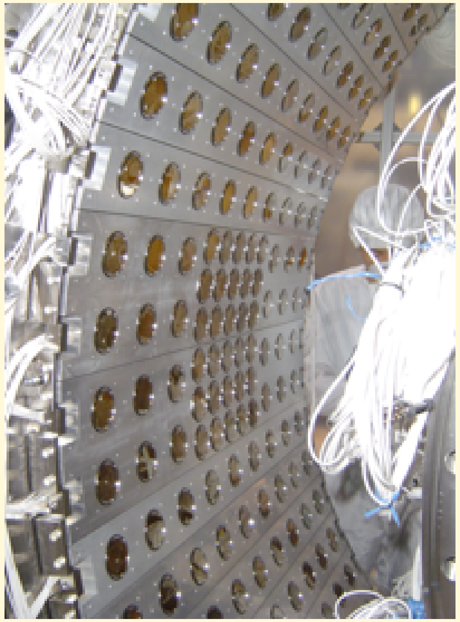
mode	upper limit (90% C.L.)	year	Exp./Lab.
$\mu^+ \to e^+\gamma$	1.2×10^{-11}	2002	MEGA / LAMPF
$\mu^+ \to e^+e^+e^-$	1.0×10^{-12}	1988	SINDRUM I/ PSI
$\mu^+e^- \leftrightarrow \mu^-e^+$	8.3×10^{-11}	1999	PSI
μ^- Ti $\to e^-$Ti	6.1×10^{-13}	1998	SINDRUM II / PSI
μ^- Ti $\to e^+$Ca*	3.6×10^{-11}	1998	SINDRUM II / PSI
μ^- Pb $\to e^-$Pb	4.6×10^{-11}	1996	SINDRUM II / PSI
μ^- Au $\to e^-$Au	7×10^{-13}	2006	SINDRUM II / PSI

Future:

near: $\mu \to e\,\gamma$

MEG at PSI http://meg.web.psi.ch/

- o Full detector ready for data taking by end 2007
- o 2 year goal: BR<$\mathbf{1x10^{-13}}$ at 90%CL if no event seen
- o expected single-event sensitivity: BR<$\mathbf{1x10^{-14}}$ at 90%CL



far: $\mu \to e$ conv

PRISM/PRIME AT J-PARC

http://www-ps.kek.jp/jhf-np/NuclPart/0701/Day2_PM/KUNO-J-PARC2007.pdf

- o asymptotic sensitivity: BR=$\mathbf{5x10^{-19}}$
- o From the minutes of J-PARC PAC mtg, Jan 2007:
  "The PAC ... urges KEK and the Collaboration to have a close communication to solve the remaining key issues such as the beamline layouts and the high quality pulsed beam generation in slow extraction"

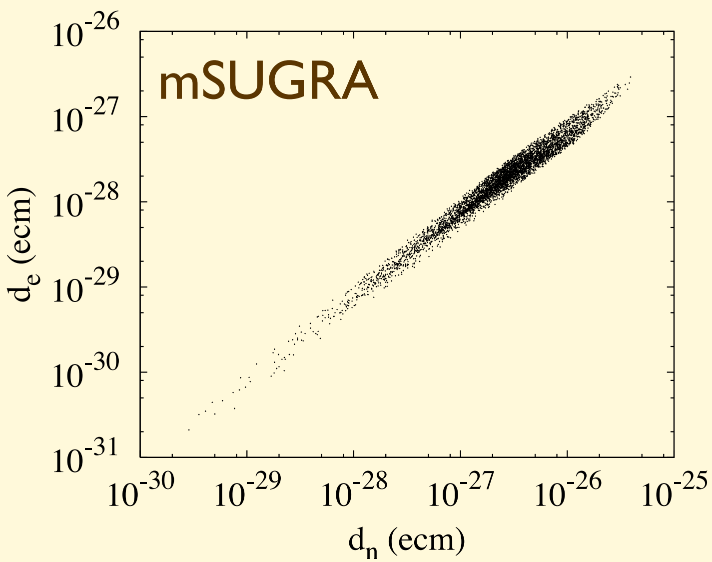
EDMs

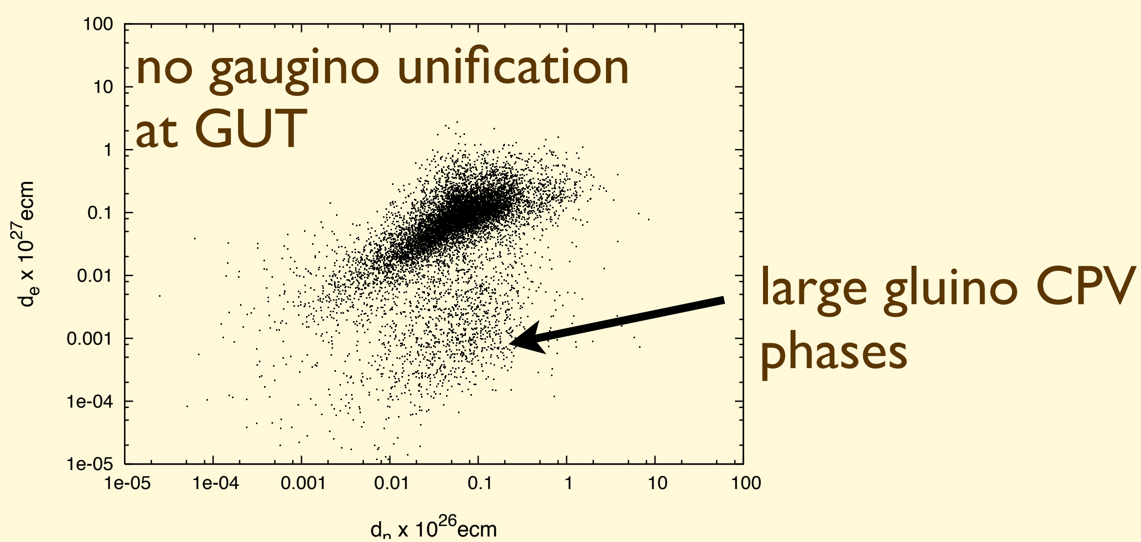
- **Flavour-conserving CPV**
- **Sensitive probes of CPV in extended gauge sectors (e.g. SUSY gluinos, gauginos, higgsinos)**

Probes of mechanisms to generate the antimatter asymmetry of the universe

d_e / d_n correlations:

SUSY: d_e / d_n ~ m_e/m_q ~ 0.1





Extra-dim, 2HDM: d_e / d_n <<1

Atoms:

paramagnetic (Tl):	**– fundamental electron EDM**
	– CPV eeqq interactions
diamagnetic (Hg):	**– fundamental electron EDM**
	– fundamental quark EDM and θ_{QCD}
	– CPV eeqq interactions
heavy molecules with unaired electrons (YbF):	**– fundamental electron EDM**

Neutron:

– fundamental quark EDM and θ_{QCD}
– higher-dim CPV qq operators (int^{ns} with gluinos, etc)

Neutron EDM

Current limit: $d_{neutron}$ = **3x10^{-26}** e cm

C.A. Baker et al, (RAL, Sussex, ILL Grenoble)
http://arxiv.org/pdf/hep-ex/0602020

Forthcoming experiments with ultracold neutrons:

ILL (Grenoble) and **PSI**

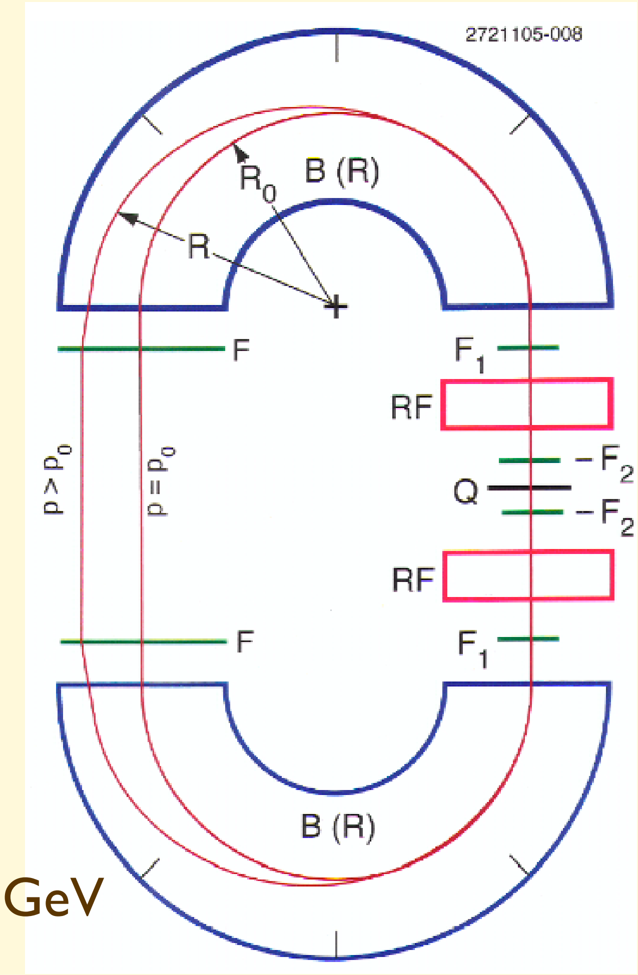
- o R&D and construction of new detectors/beamline
- o new runs 2009-2011 (ILL) and 2011-2014 (PSI)
- o Goal: $d_{neutron}$ < **~2 x 10^{-28}** e cm/yr

⇨ **probe SUSY CPV phase of O(10^{-4})**

Deuteron EDM in a storage ring

Orlov, Morse, Semertzidis,
http://arxiv.org/pdf/hep-ex/0605022

- o Inject deuterons from LEIR, CERN's low-energy ion ring used to prepare heavy ion beams for the LHC
- o Sensitivity: σ_d = **2.5x10^{-29}** e cm/yr



1.5 GeV

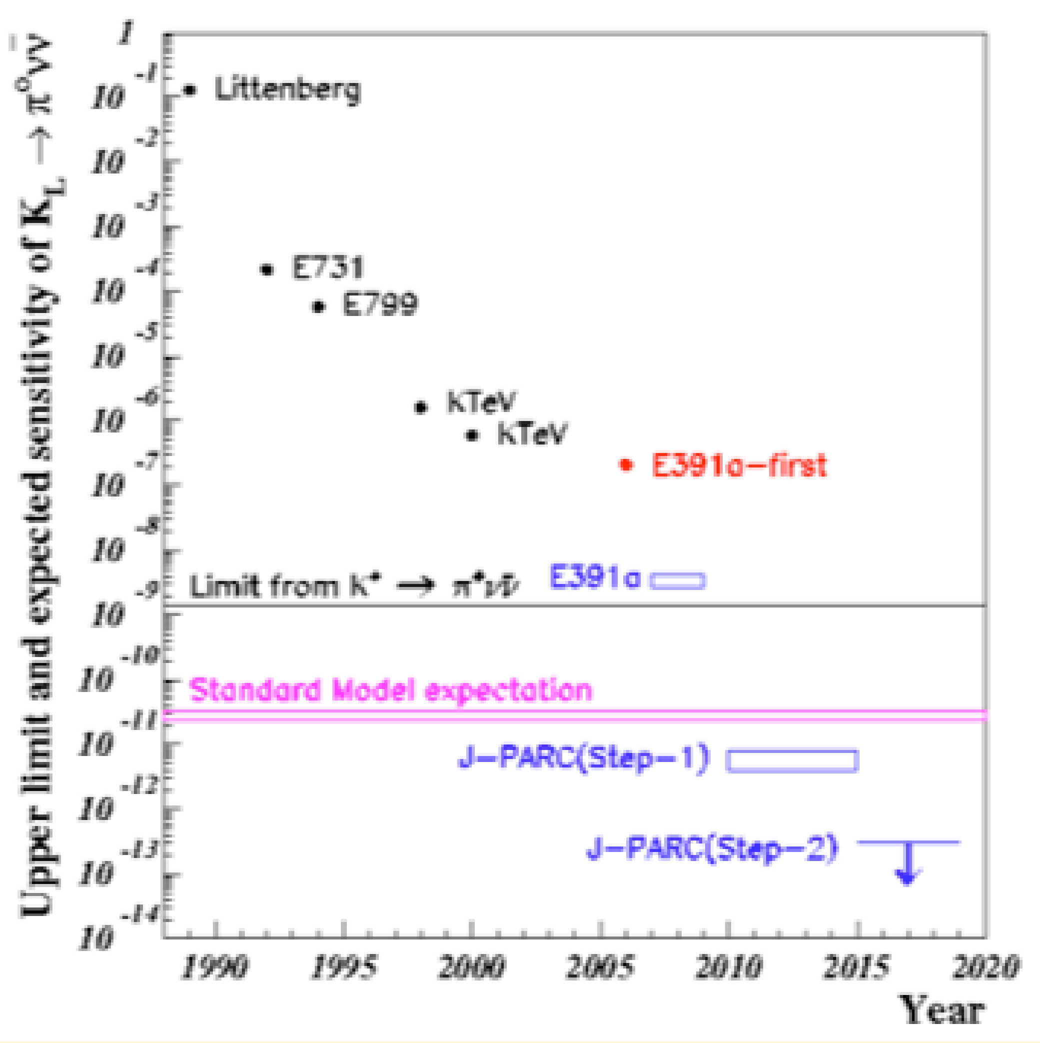
Rare K decays

$K_L^0 \rightarrow \pi^0 \nu \nu$ $B(K_L^0 \rightarrow \pi^0 \nu \nu)_{SM}$ = **$2.8 \pm 0.4 \times 10^{-11}$**

E391 at KEK, ongoing

E14 at JPARC
http://www-ps.kek.jp/jhf-np/NuclPart/0701/Day2_AM/E14.ppt.pdf

- Being reviewed for approval by JPARC PAC
- Detector completion: 2008-09
- Beam survey: 2008-09
- Data: 2010-20
- Goal: $O(10^{-13})$, $\Delta BR \sim 10\%$



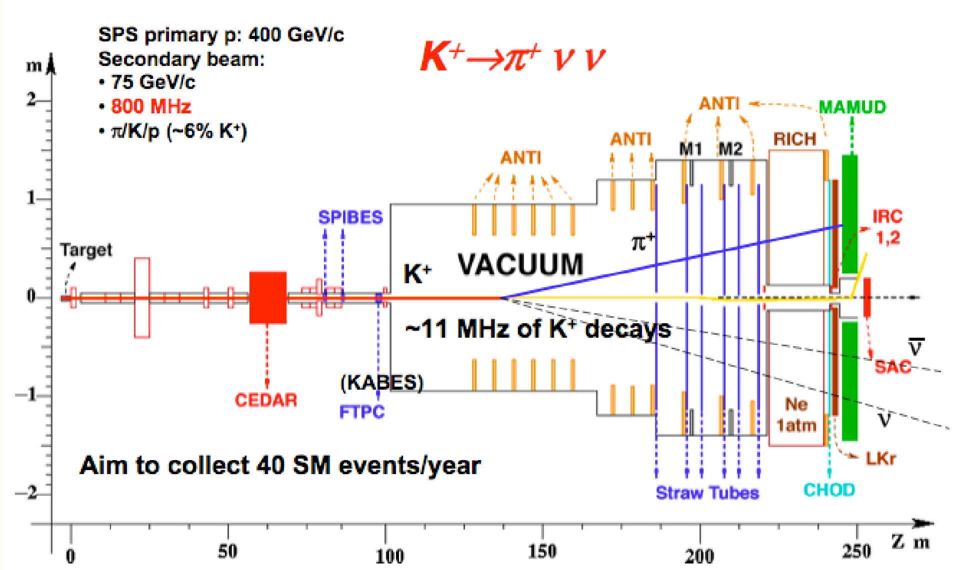
Rare K decays, CERN

$K^+ \to \pi^+ \nu \nu$ $B(K^+ \to \pi^+ \nu \nu)_{E787/949\ BNL}$ = **$1.5 \pm 1 \times 10^{-10}$** (3 events, hep-ex/0403036)

$B(K^+ \to \pi^+ \nu \nu)_{SM}$ = **$8.0 \pm 1.1 \times 10^{-11}$** Expected reduction to 4% error via NNLO +better input parameters (m_{top}, etc)

NA62, a.k.a. NA48/3 or P-326

http://na48.web.cern.ch/NA48/NA48-3/



o R&D: 2006-07, with 07 run for $R_{e/\mu} = \Gamma(K \to e\ \nu) / \Gamma(K \to \mu\ \nu)$ to 0.3%

o Construction (if approved): 2008-10

o Goal: 80 events (@SM rate) in 2 yrs of run, S/B=10/1 ⇒ $\delta|V_{td}|$=10%

o Currently in the limbo of MTP's "Theme 4" (YNM= 'yes, but no money')

$K_L^0 \to \pi^0 e^+e^-$ $K_L^0 \to \pi^0 \mu^+\mu^-$ **NA48/4**

$K_L^0 \to \pi^0 \nu \nu$ **NA48/5**

Require more protons than available from the SPS today

More examples were explored during the CERN Workshop on

Flavour in the era of the LHC

WG reports which will appear soon

Flavour in the era of the LHC

HOME

Committees

- International Advisory C.
- Local Organizing C.

Meetings

- Nov 7-10 2005, Agenda
- Feb 6-8 2006, Agenda
- May 15-17 2006, Agenda
- October 9-11 2006, Agenda
- March 26-28 2007, Agenda
- Upload your talks

Registration/Mailing list

- Registration is closed
- Registered participants final mt

Working groups

- 1. Collider aspects of flavour physics at high Q
- 2. B/D/K decays
- 3. Flavour in the lepton sector, EDMs, g-2, etc

Logistics

- How to get to CERN
- Information on the Hostel
- Local Hotels

FLAVOUR IN THE ERA OF THE LHC

a Workshop on the interplay of flavour and collider physics

Opening plenary meeting: CERN, November 7-10 2005

2nd meeting (WGs): CERN, Feb 6-8 2006
3rd meeting (WGs): CERN, May 15-17 2006
4th meeting (WGs): CERN, Oct 9-11 2006

5th and final meeting (WGs): CERN, Mar 26-28 2007

o Working group reports being finalized, expected delivery June 2007

o Continued activities on the interplay between collider and flavour physics

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 3 meetings of the WG's to take place during the following year, and a final plenary meeting at the end.

http://cern.ch/mlm/FlavLHC.html

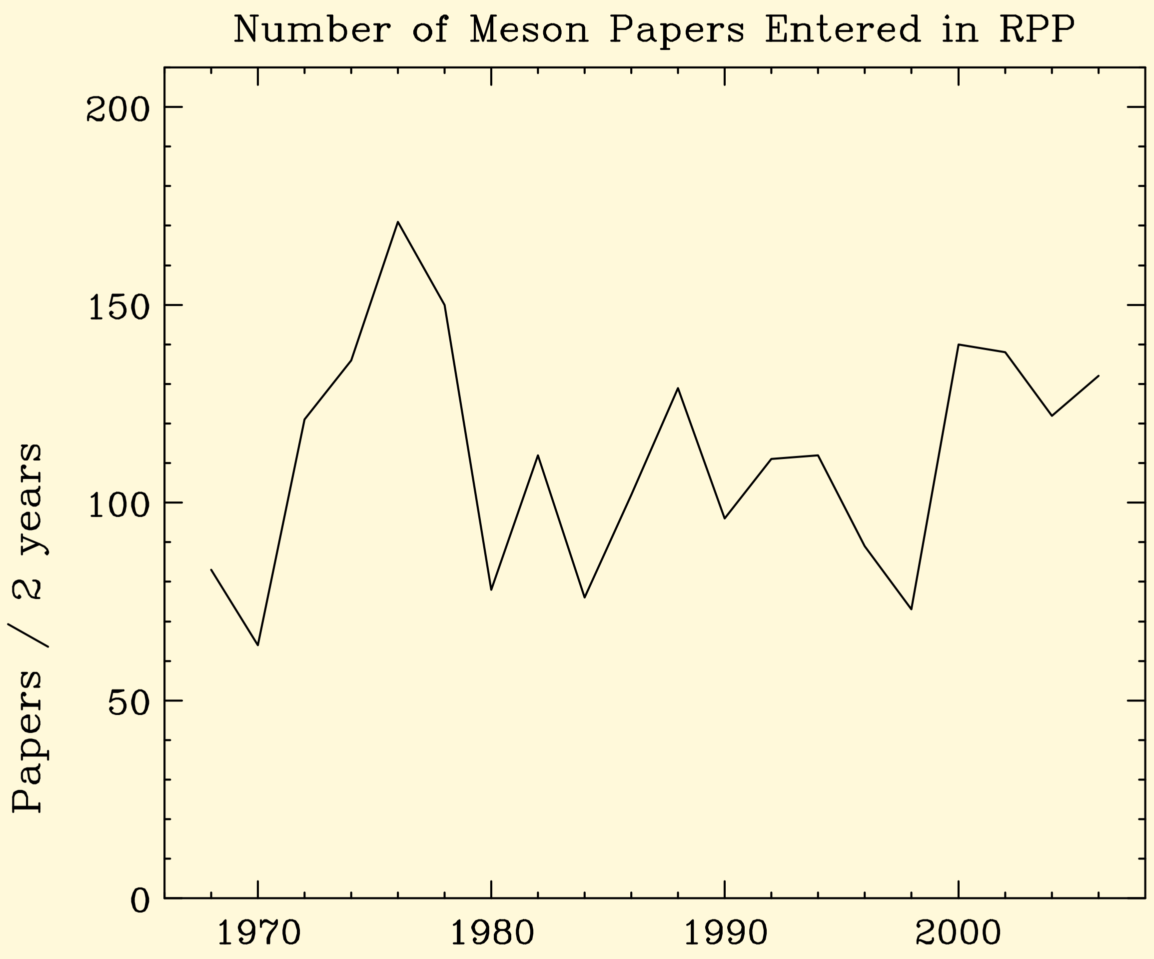
https://twiki.cern.ch/twiki/bin/view/Main/ColliderAndFlavour

Other HEP topics: which future in the LHC era and beyond?

Hadron spectroscopy

Other HEP topics: which future in the LHC era and beyond?

Hadron spectroscopy



Other SM-dynamics topics: which future in the LHC era and beyond?

Hadron spectroscopy

- o scalar sector: q qbar, tetraquarks ?
- o 'exotic' charm(ed) meson spectroscopy
- o pentaquarks and other exotica

Facilities

Super-B factories, Dafne, BES (Beijing)
GSI (p pbar annihilation at few GeV)
CERN fixed target (Compass, NA49)?
RHIC? FNAL?

Proton structure

- o PDFs
- o polarized / generalized PDFs , transversity, etc

LHC?
LeHC? (J.Dainton et al, http://arxiv.org/pdf/hep-ex/0603016)
eRHIC
JLAB

Heavy ions

- o QCD critical point
- o ?????

LHC? CERN SpS?
RHIC? GSI?
... don't really know yet what we'll need after the LHC HI programme

Conclusions

- **Progress in the field will be 100% driven by new and better experimental data.** Theorists have pretty much exhausted their arsenal of weapons to make progress based on first principles only. Nevertheless, we created scenarios for BSM physics which, in addition to addressing the most outstanding **theoretical puzzles** and the **established deviations** from the SM (DM, BAU, nu mixing), predict galore of new phenomena at energy and accuracy scales just **behind the corner**
- Whether or not new physics is seen at the LHC, maintaining **diversity** in the exp'l programme is our best investment for HEP
  - An ambitious and far-sighted **ν** programme is a mandatory element of the HEP future
    - clear goals, benchmarks, and direct impact on our ability to uncover new information about nature: **GUT, CPV, BAU**
  - **but its full exploitation requires a broader approach**
  - A global flavour physics programme **(LFV**, **CP/FCNC in the quark sector, EDMs)** is an essential component of the HEP research, mandatory to explore the nature of the new BSM framework (e.g. to identify the SUSY breaking scenario)