

Physics at TeV Colliders: from the Tevatron to the LHC

Cargese, July 2010

The path to new physics at the LHC and beyond

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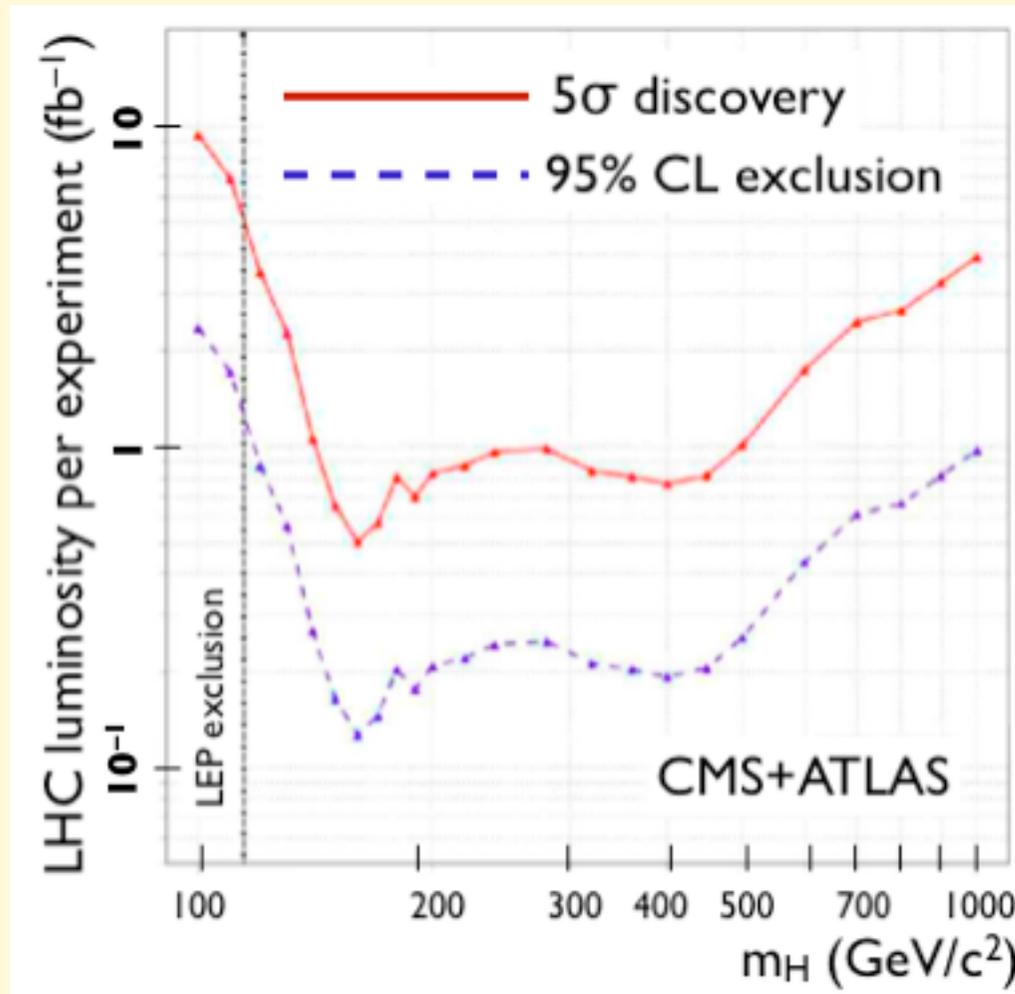
CERN, Geneva

The LHC was designed to answer one question:

is electroweak symmetry broken as postulated in the SM Higgs mechanism?

- 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

Summary of SM Higgs discovery potential



Within ~ 1 -2 yrs at $L \sim 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$ we should have an answer

IF Higgs 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!

IF NOT SEEN UP TO $m_H \sim 0.8$ -1 TeV GEV:

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

or

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

or

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

•Sorting out non-SM scenarios may take longer than the SM H observation, and may well require LHC luminosity upgrades and/or a lepton collider, but the conclusion about the existence of a BSM origin of EWSB 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

We would also like the LHC to help us address the three key experimental shortcomings of the Standard Model:

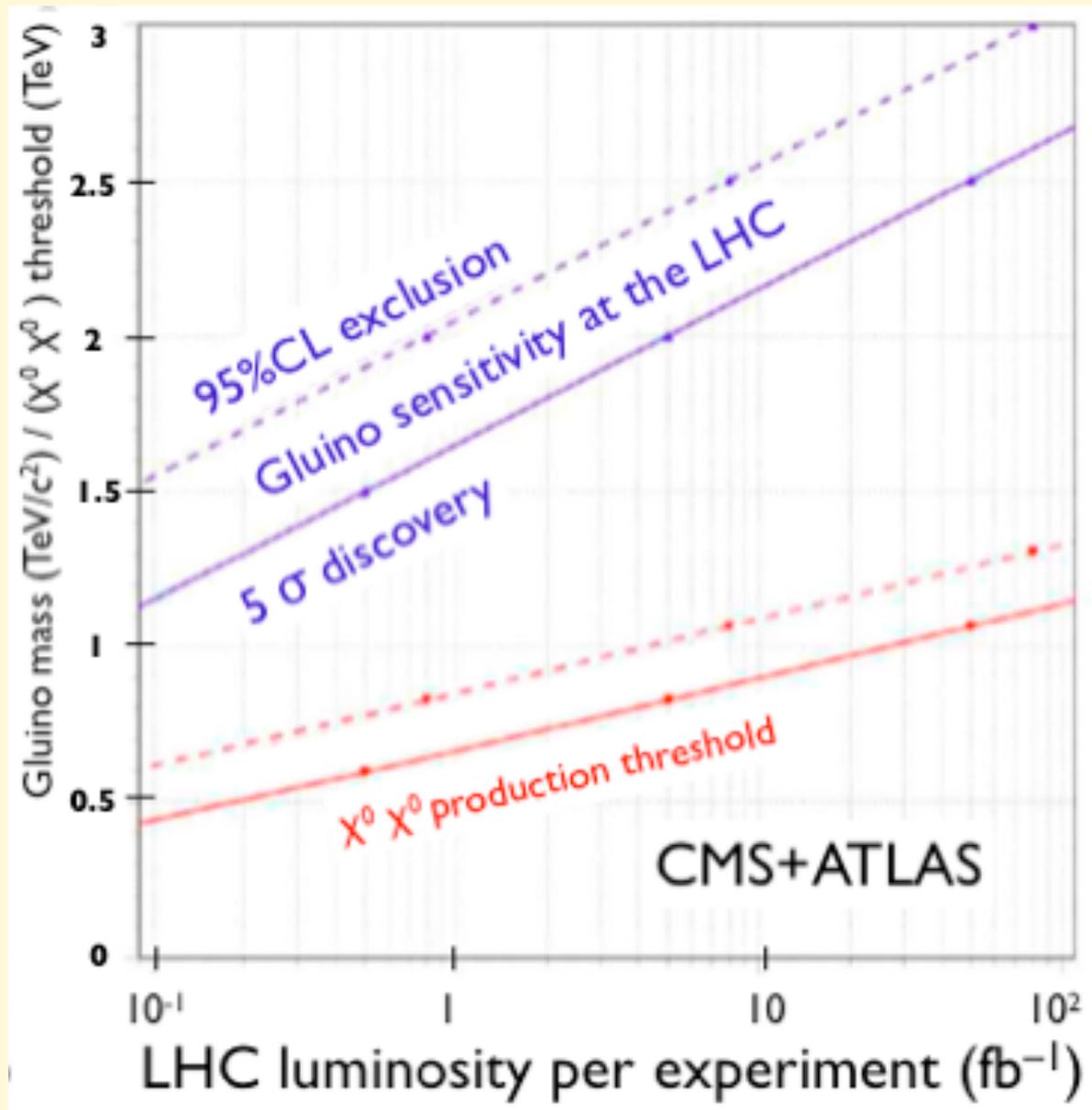
- **Neutrino masses**
- **Dark matter**
- **Baryon asymmetry of the universe**

as well as its theoretical weakness, the **hierarchy problem**

Will the answers to these questions be related to each other?

Which experimental programme, at the LHC and beyond, will allow us to address them?

Example: timeline for SUSY (MSSM) discovery/exclusion



The discovery of SUSY (or whatever else) will only be the beginning of a new era of exploration, dominated by questions like

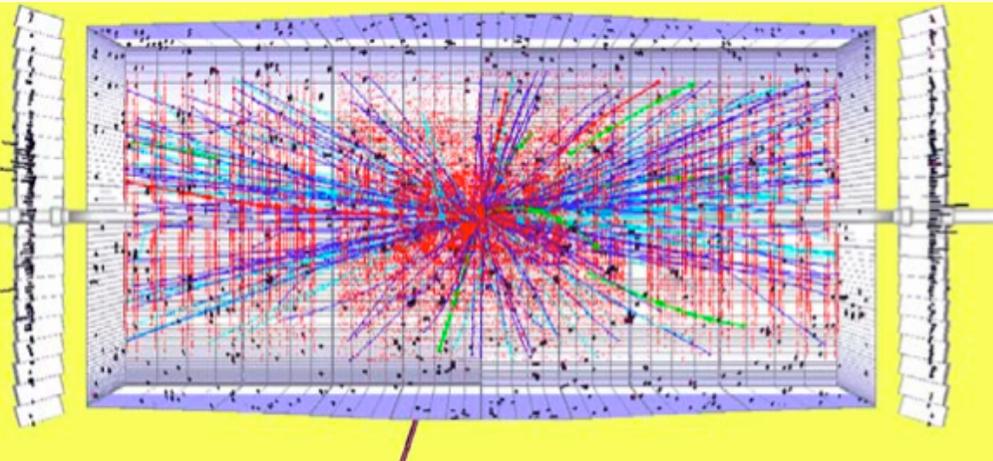
what is the mechanism of SUSY breaking?

New expt'l input will be needed to start addressing such issues. E.g.:

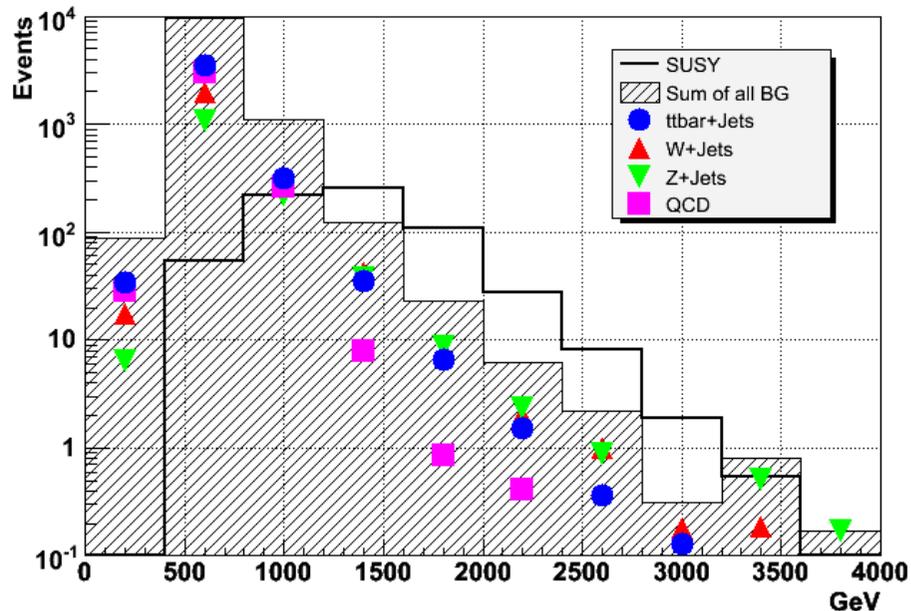
- Chargino/gluino mass spectrum
- Squarks and sleptons masses and mixings
- CP structure of SUSY couplings
-

The LHC inverse problem

Reconstruct the Lagrangian of new physics from the LHC data

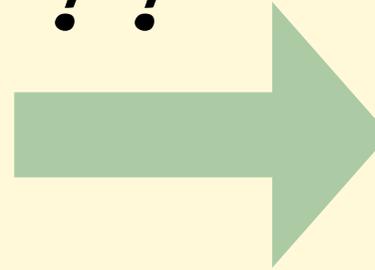


Effective Mass 0lepton SUSY



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

??



??
!

extra dims?

gluinos?

Little Higgs?

\mathcal{L}

- Very 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 m_H , etc.

NB

- **< 1973: theoretical foundations of the SM**

- 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 α_s
 - CKM parameters

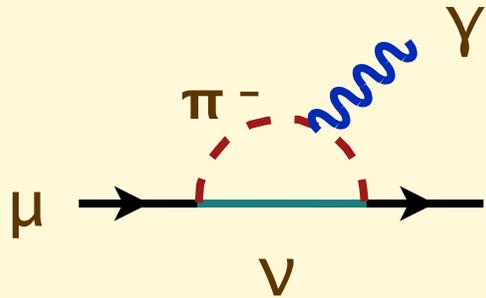
It's unlikely it will take less than 30 yrs to clarify and consolidate the understanding of new phenomena to be unveiled by the LHC!

Notice that of the 3 empirical proofs that the SM is 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 the gauge principle



$$\mu \not\rightarrow e \gamma \Rightarrow V_\mu \neq V_e$$

$K^0 \rightarrow \mu^+ \mu^-$
K- \bar{K} mixing

GIM, charm

ϵ_K , \mathcal{CP}

KM

B_d - \bar{B}_d mixing

large m_{top} , well before EW tests

ν masses

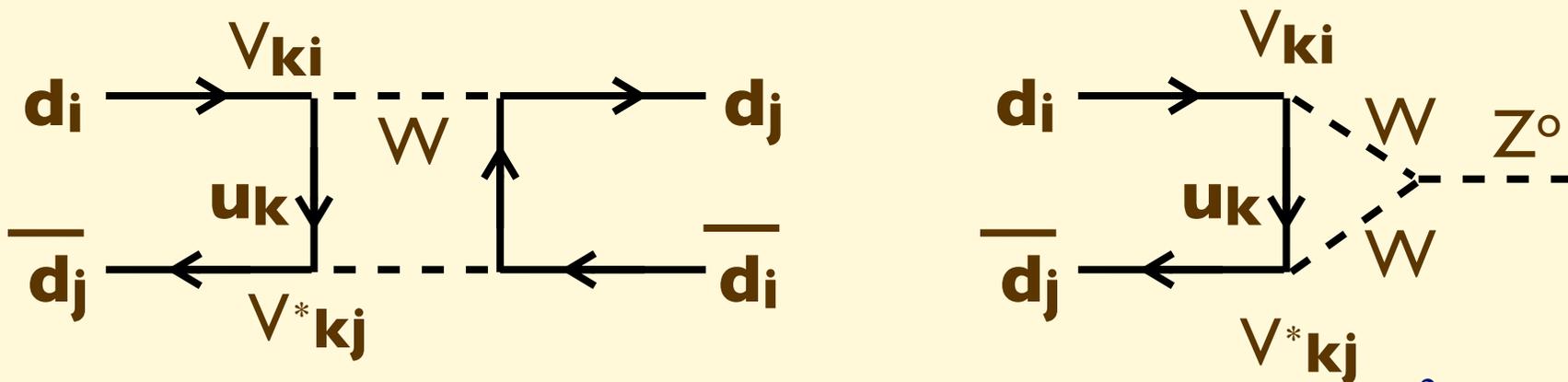
see-saw, SO(10) GUT, ... ?

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:
 - $m_\nu=0 \Rightarrow$ all phases and angles absorbed by field redefinitions, no mixings/CPV at all

What is “flavour physics” ?

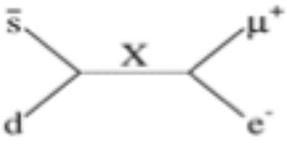
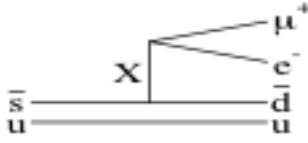
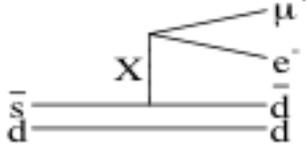
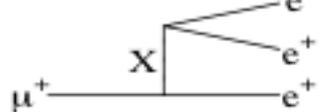
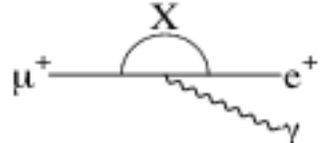
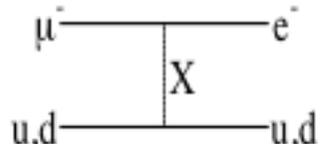
- In the SM, flavour is what deals with the fermion sector (family replicas, spectra and mixings):
 - all flavour phenomena are encoded in the fermion Yukawa matrices.
- Beyond the SM, “flavour” phenomena cover a wider landscape. E.g.
 - FCNC can be mediated by
 - gauge-sector particles, like charged 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 the suppression of FCNC and CPV is present in extensions of the SM
- As soon as these are released, effects are devastating!

Compare the to $O(10 \text{ TeV})$ sensitivity w.r.t. modifications of the gauge/EW sector

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

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 \Rightarrow

**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 $m_{\text{top}} = g/\sqrt{2} m_W$ ($\Leftrightarrow y_{\text{top}} = 1$) ?

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

What will be the main driving theme of the exploration of the new physics revealed by the LHC?

the gauge sector
(Higgs, EWSB)



The High Energy Frontier

LHC
SLHC
VLHC
ILC
CLIC
....

the flavour sector
(ν mixings, CPV, FCNC,
EDM, LFV)



The High Intensity Frontier

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

+ Astrophysics and cosmology

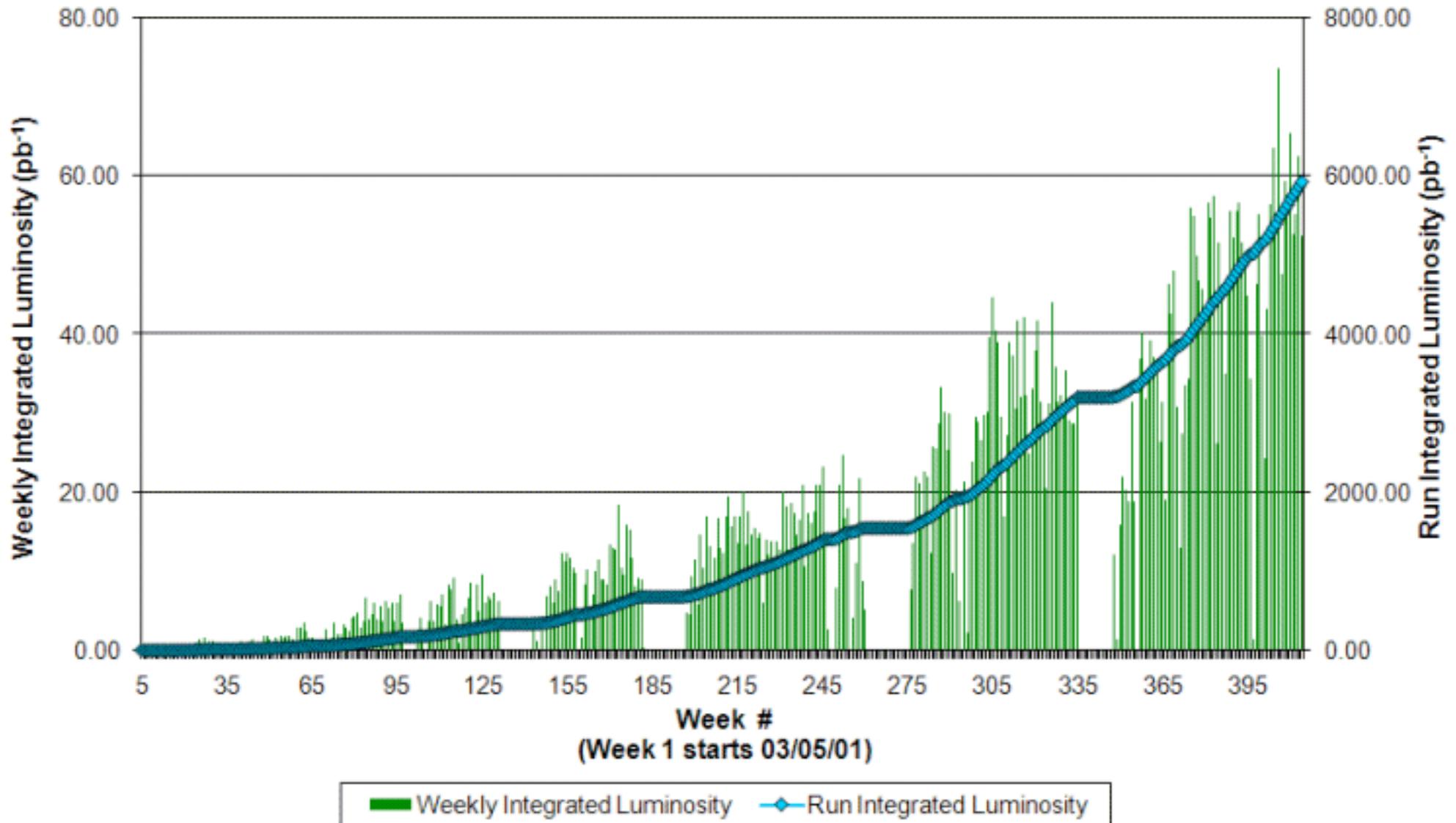
Hadron colliders can deliver results over very long periods of time.

The Tevatron as an example:

- 1987: first physics run
- 1989: first precision measurement of $M(Z^0)$
- 1994: top quark observation
- 1996-2001: upgrade shutdown
- 2006: B_s oscillations
- 2007: $\Delta M_W = 48$ MeV, D-Dbar mixing
- 2008: $\Delta M_{\text{top}} \sim 1.4$ GeV
- 2008: SM-level sensitivity to Higgs at $M(H) \sim 170$ GeV
- B physics, exotic spectroscopy, PDF constraints, etc.etc.
-
- 2012: $3\text{-}\sigma$ sensitivity to SM Higgs, $B_s \rightarrow \mu^+ \mu^-$, ??? ?!!!

The key to this longevity is steady luminosity increases

Collider Run II Integrated Luminosity



The LHC completion and upgrade path

- 2010: pp@7 TeV, luminosity to reach $10^{32}\text{cm}^{-2}\text{s}^{-1}$ by early November, to deliver L_{int} in the range of 10-100pb⁻¹
- 2011: pp@7 TeV, Feb-Nov, $L\sim\text{few } 10^{32}\text{cm}^{-2}\text{s}^{-1}$, $L_{\text{int}}\sim\mathcal{O}(1\text{fb}^{-1})$
- 2012-beg 2013, shut down:
 - consolidate magnet interconnects
 - re-train dipoles for ops at 14 TeV
- 2013-2014: pp@14TeV, $L\sim\text{few } 10^{33}\text{cm}^{-2}\text{s}^{-1}$, $L_{\text{int}}\sim\mathcal{O}(10\text{fb}^{-1})/\text{yr}$
- 2015: shut-down, for detector upgrades, LHC collimators, commissioning of Linac 4,
- 2016 - ~2020 (with short, few-month-long, stops):
 - start with pp@14TeV, $L\sim 10^{34}\text{cm}^{-2}\text{s}^{-1}$, $L_{\text{int}}\sim\mathcal{O}(50\text{fb}^{-1})/\text{yr}$
 - transition to $L\sim 2\times 10^{34}\text{cm}^{-2}\text{s}^{-1}$, $L_{\text{int}}\sim\mathcal{O}(100\text{fb}^{-1})/\text{yr}$
- ~2020: long shutdown, to upgrade the interaction regions, detectors, LHC, etc, to reach $L\sim 5\times 10^{34}\text{cm}^{-2}\text{s}^{-1}$, $L_{\text{int}}\sim\mathcal{O}(300\text{fb}^{-1})/\text{yr}$
- Followed by possibly 10 more yrs of data taking
- >2030: possible energy upgrade to 25-30 TeV?

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
 -

Energies/masses in the few-100 GeV range.
Detector performance at SLHC should equal (or improve) in absolute terms the one at LHC

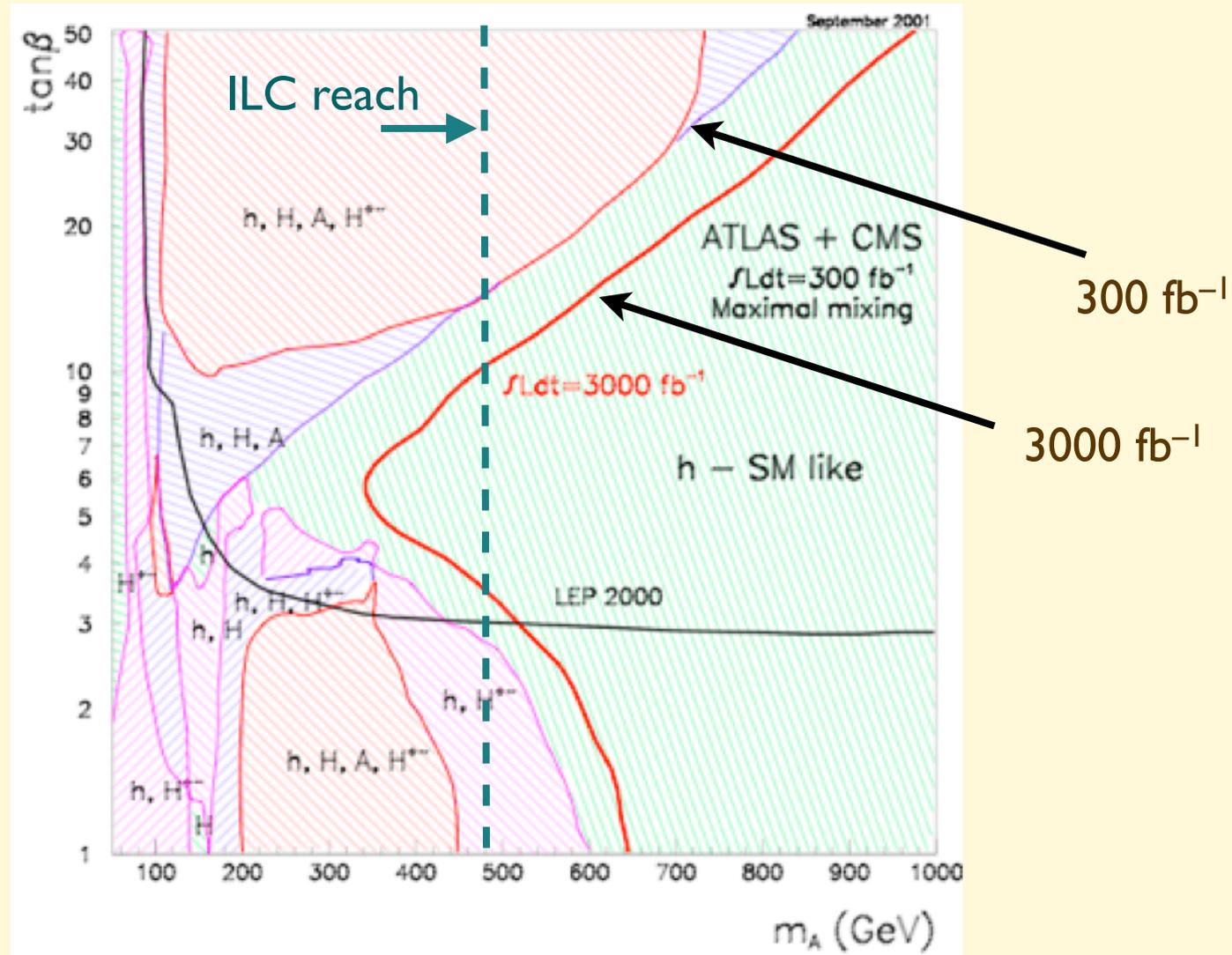
Very high masses, energies, rather insensitive to high-lum environment.
Not very demanding on detector performance
Slightly degraded detector performance tolerable

EW symmetry breaking

List of issues

- Establish nature of Higgs boson and of EWSB:
 - how many doublets? singlets? charged H's?

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



List of issues

- Establish nature of Higgs boson and of EWSB:
 - how many doublets? singlets? charged H's?
 - fundamental or composite?

Signatures of the composite nature of a light higgs

What distinguishes a composite Higgs?

Giudice, Grojean, Pomarol, Rattazzi '07 hep-ph/0703164v2

$$\mathcal{L} \supset \frac{c_H}{2f^2} \partial^\mu (|H|^2) \partial_\mu (|H|^2) \quad c_H \sim \mathcal{O}(1)$$

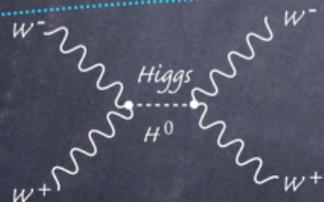
$$H = \begin{pmatrix} 0 \\ \frac{v+h}{\sqrt{2}} \end{pmatrix} \Rightarrow \mathcal{L} = \frac{1}{2} \left(1 + c_H \frac{v^2}{f^2} \right) (\partial^\mu h)^2 + \dots$$

Modified
Higgs propagator

\sim

Higgs couplings
rescaled by

$$\frac{1}{\sqrt{1 + c_H \frac{v^2}{f^2}}} \sim 1 - c_H \frac{v^2}{2f^2}$$



$$= - \left(1 - c_H \frac{v^2}{f^2} \right) g^2 \frac{E^2}{M_W^2}$$

no exact cancellation
of the growing amplitudes

unitarization restored by heavy resonances

Falkowski, Pokorski, Roberts '07

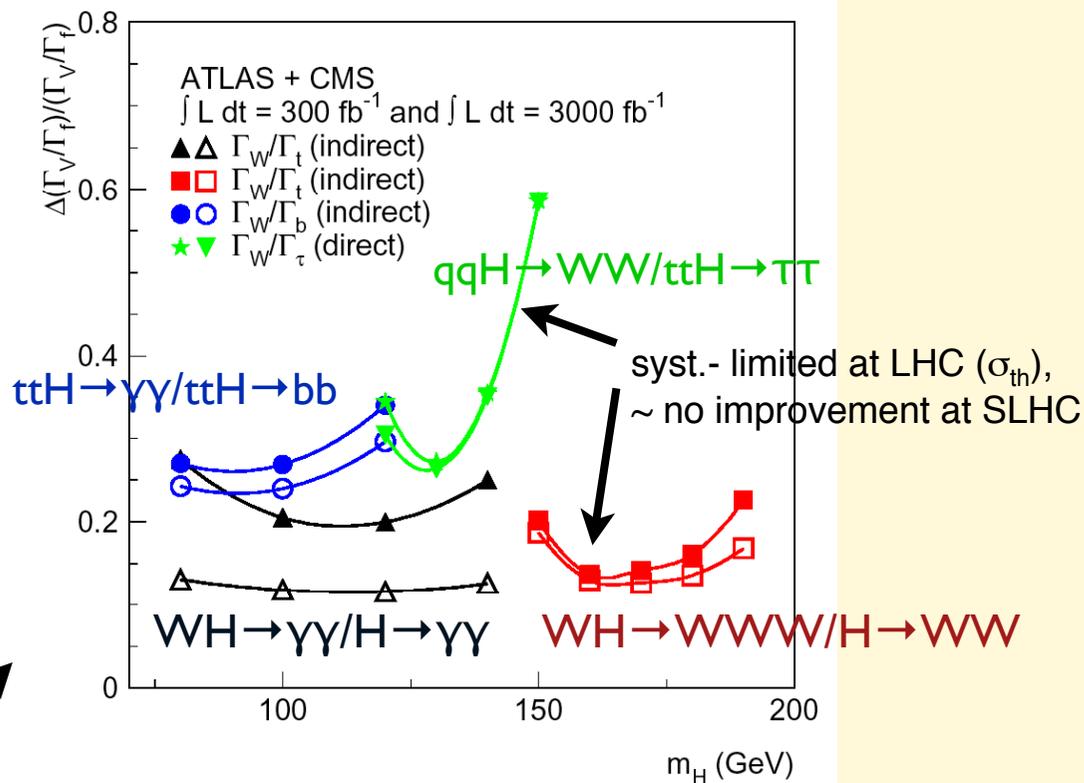
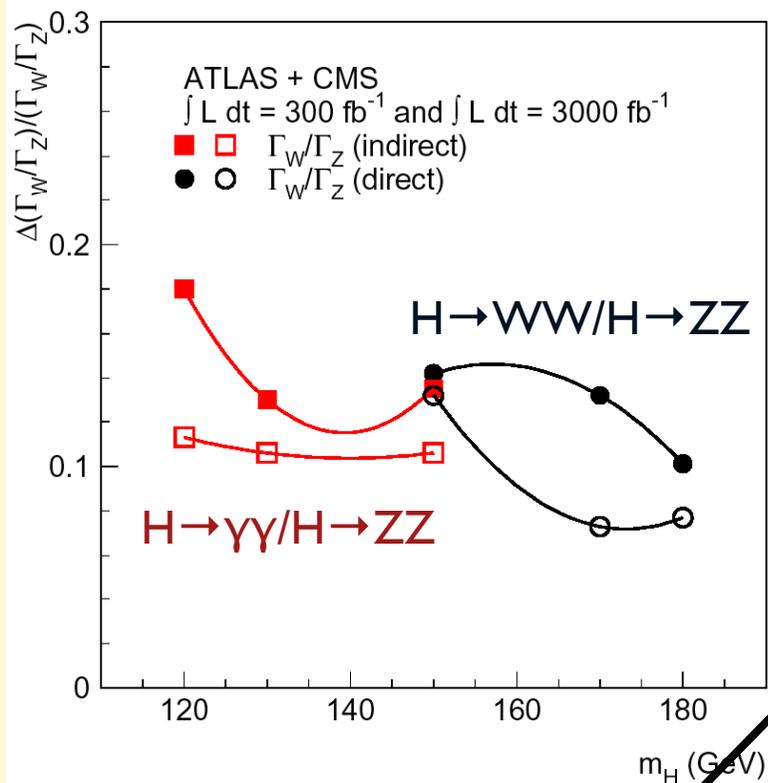
Strong W scattering below m_ρ ?

- Higgs anomalous couplings
- strong WW scattering
- strong HH production
- gauge bosons self-couplings

List of issues

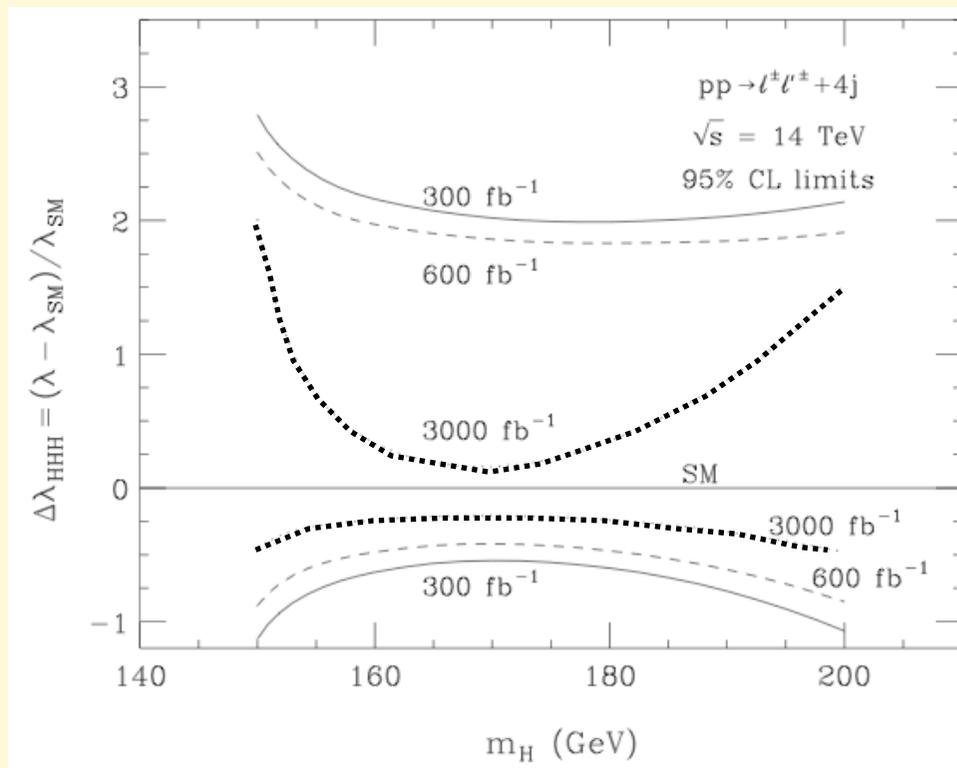
- Establish nature of Higgs boson and of EWSB:
 - how many doublets? singlets? charged H's?
 - fundamental or composite?
- Need to measure, **as accurately as possible***:
 - Higgs couplings to fermions, gauge bosons and selfcouplings
 - Rare decay modes, possible FCNC
 - WW scattering at high E
 - Gauge boson selfcouplings

* There is no information today to meaningfully determine the scale of the ultimate required accuracy



Higgs boson couplings to fermions and gauge bosons

Higgs boson selfcouplings



Rare Higgs decay modes

600 fb⁻¹

6000 fb⁻¹

H → **Z**γ

3.5 σ

11 σ

H → μ⁺μ⁻

< 3.5 σ

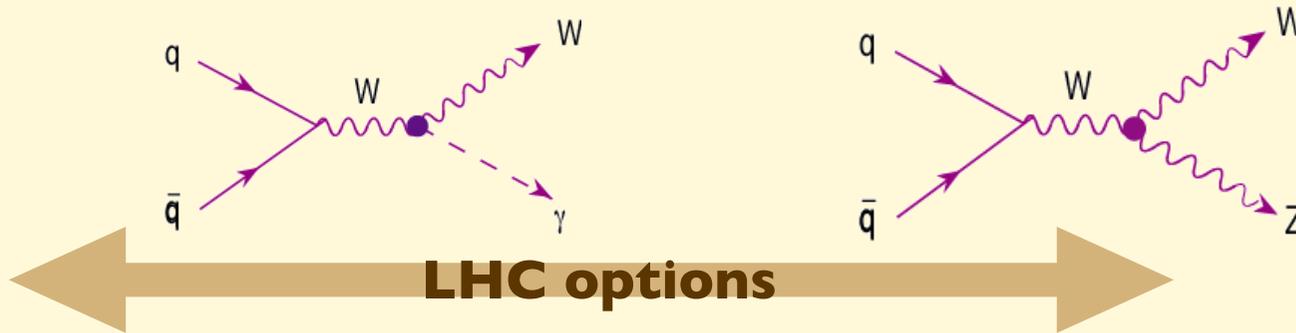
~ 7 σ

m[H] ~ [110-140] GeV

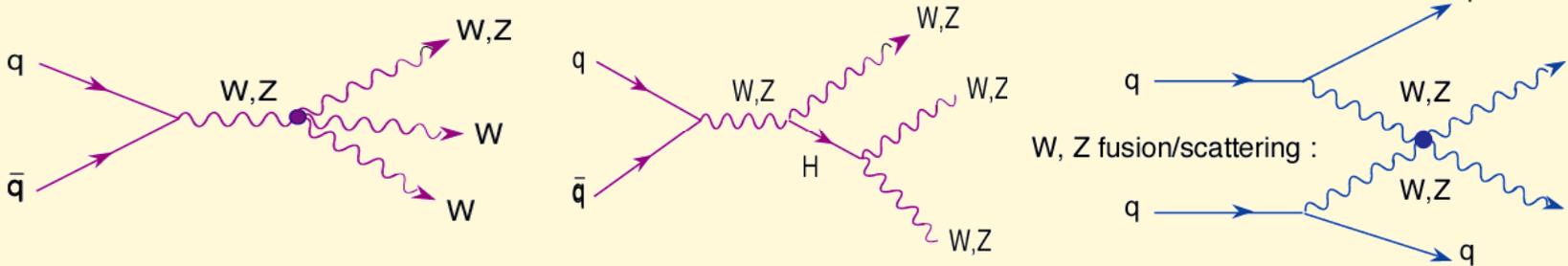
Han, McElrath, hep-ph/0201023

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



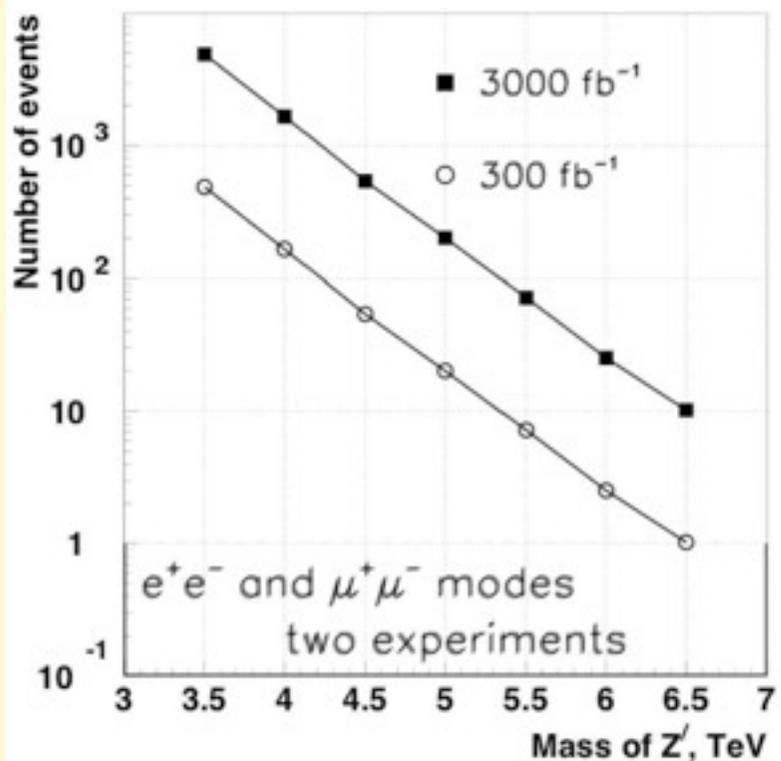
Coupling	14 TeV 100 fb ⁻¹	14 TeV 1000 fb ⁻¹	28 TeV 100 fb ⁻¹	28 TeV 1000 fb ⁻¹	LC 500 fb ⁻¹ , 500 GeV
λ_γ	0.0014	0.0006	0.0008	0.0002	0.0014
λ_Z	0.0028	0.0018	0.0023	0.009	0.0013
$\Delta\kappa_\gamma$	0.034	0.020	0.027	0.013	0.0010
$\Delta\kappa_Z$	0.040	0.034	0.036	0.013	0.0016
g_1^Z	0.0038	0.0024	0.0023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



(LO rates, CTEQ5M, $k \sim 1.5$ 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($m_H = 200$ GeV)	7100	2000	130	33	20	1.6

Searching new forces: W' , Z'

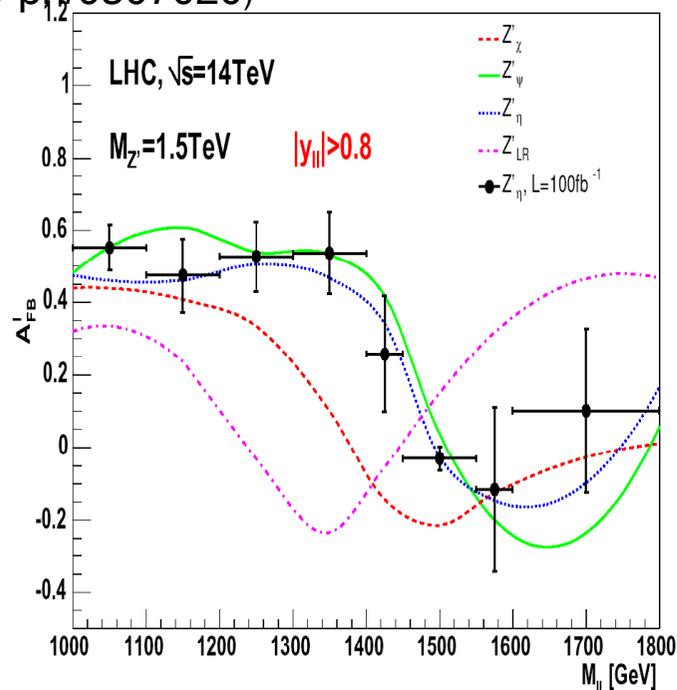
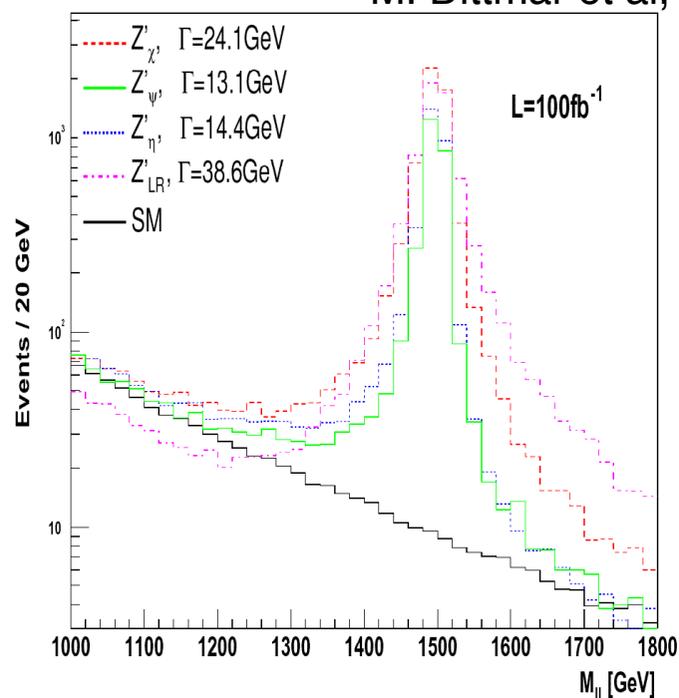
E.g. a W' coupling to R-handed fermions, to reestablish at high energy the R/L symmetry



**100 fb^{-1}
discovery reach
up to ~ 5.5 TeV**

Differentiating among different Z' models:

M. Dittmar et al, hep-ph/0307020)

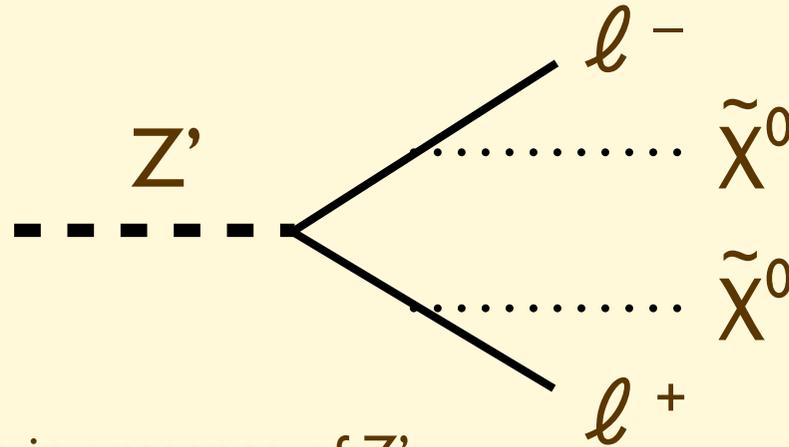


**100 fb^{-1} model
discrimination
up to 2.5 TeV**

A Z' at the LHC is a possible bridge to the quantitative exploration of other new particles below the mass threshold

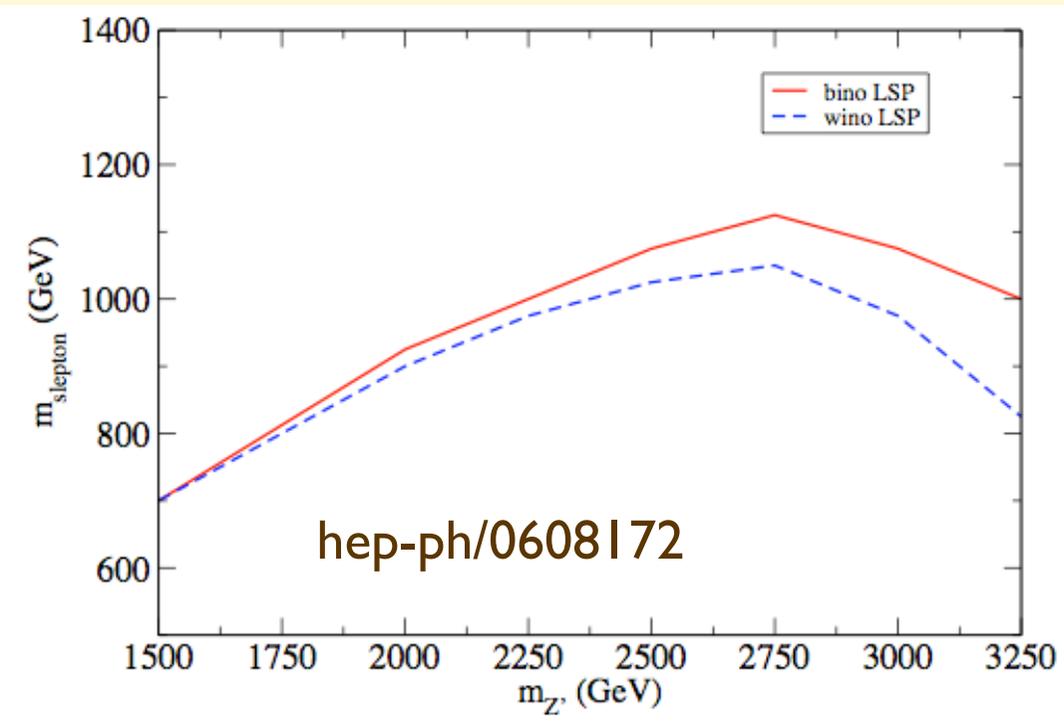
E.g., in Supersymmetry

$$Z' \rightarrow \tilde{\ell}^+ \tilde{\ell}^-$$



Measure mass and properties of neutralinos, the DM candidate

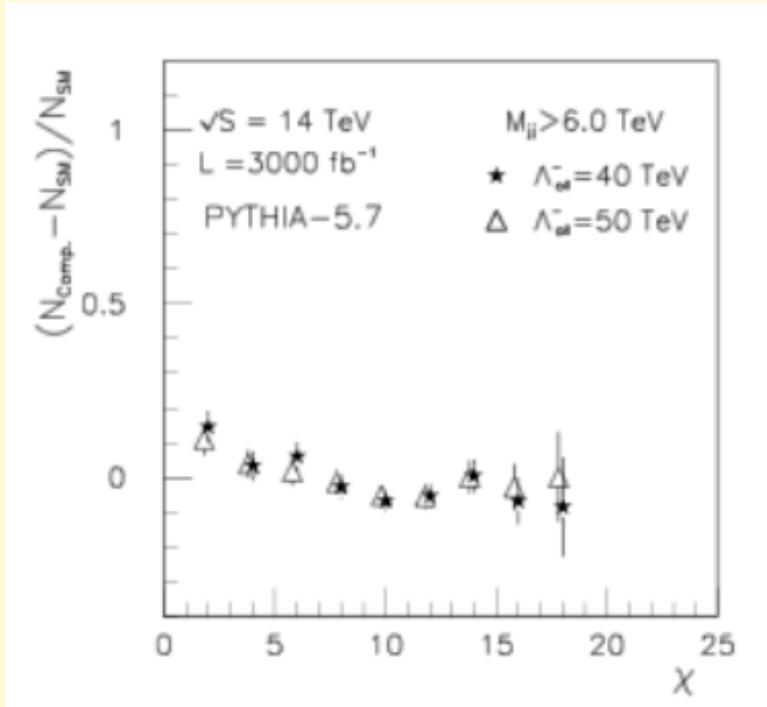
100/fb slepton discovery reach in presence of Z'
(the limit in MSSM is only 2-300 GeV if no Z')



The LHC could be a Z' factory, greatly extending its ability to determine the properties of new particles, behaving almost as an e^+e^- collider

In this case, more and more luminosity would be essential!

Quark compositeness



Study large- E_T production and angular distributions at large M_{JJ}

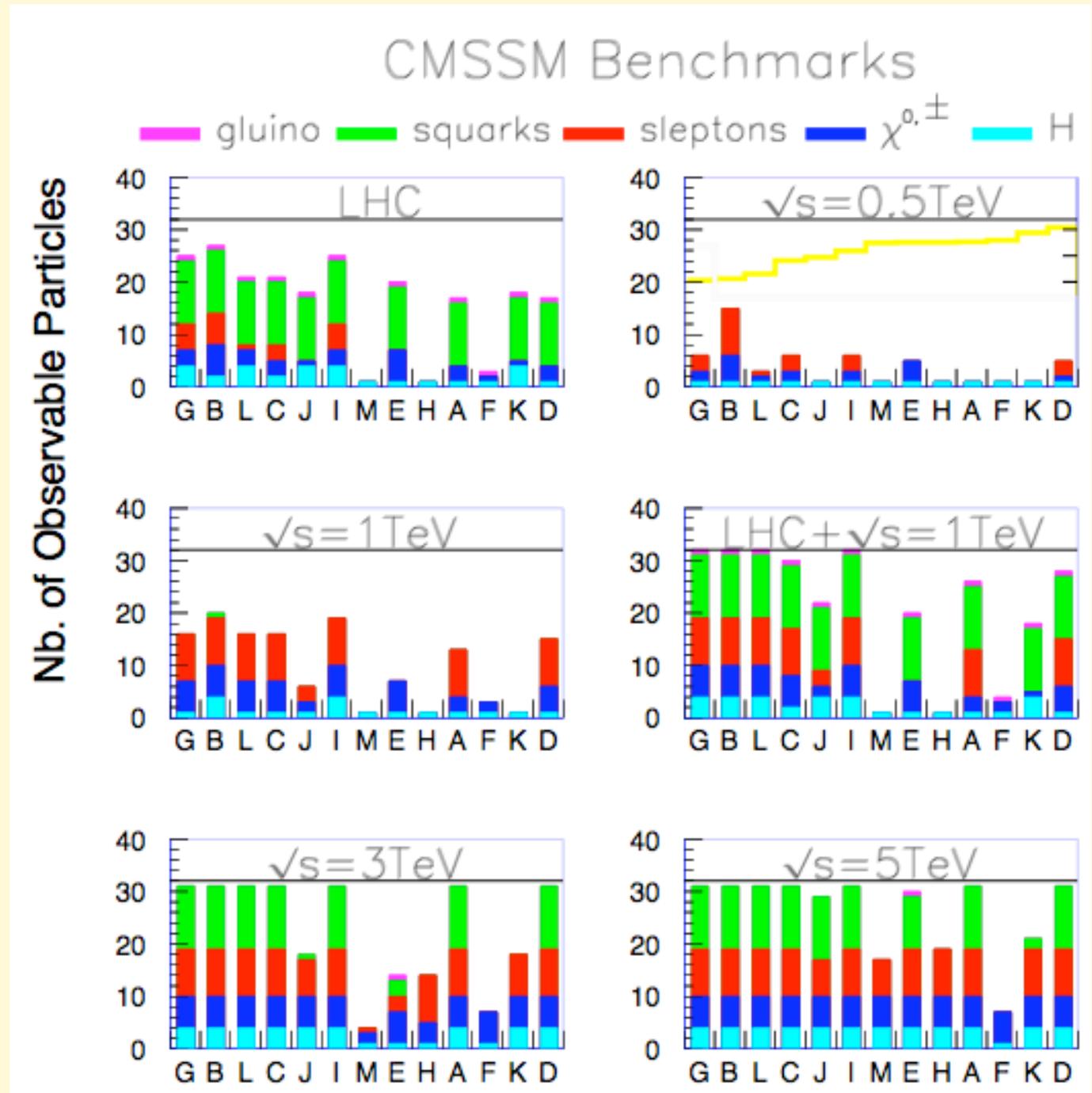
95% sensitivity

	14 TeV, 300 fb ⁻¹	14 TeV, 3000 fb ⁻¹	28 TeV, 300 fb ⁻¹	28 TeV, 3000 fb ⁻¹
$\Lambda(\text{TeV})$	> 40	> 60	> 60	> 85

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

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_{23}^2 $	Δm_{12}^2	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 $\Rightarrow \Omega_{\nu} < 0.015, m_{\nu} < 0.23$ eV

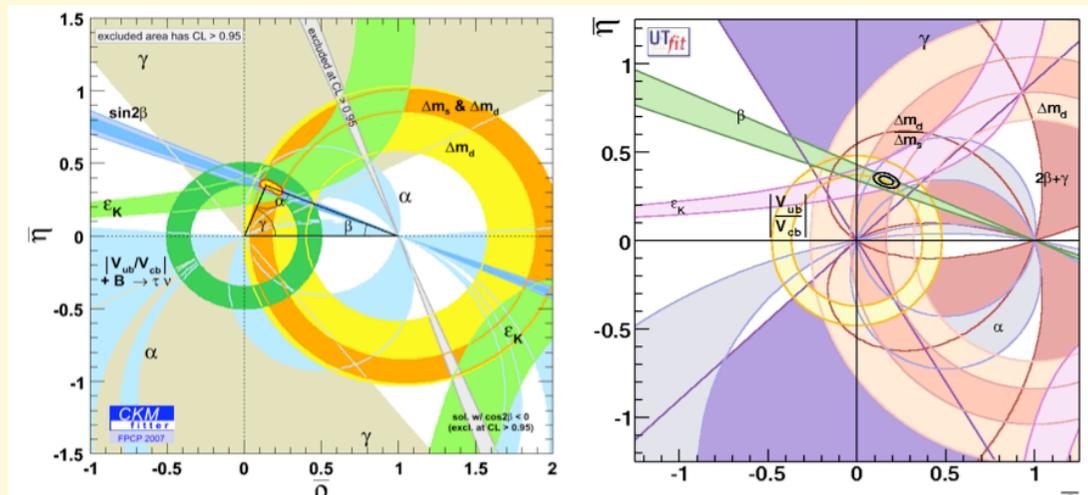
The completion of the neutrino programme, with the full determination of

- 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



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 \Rightarrow Higgs field giving Dirac ν 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)) \Rightarrow Yukawa ν -mass matrix = Up-quark Yukawa matrix

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

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

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

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

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

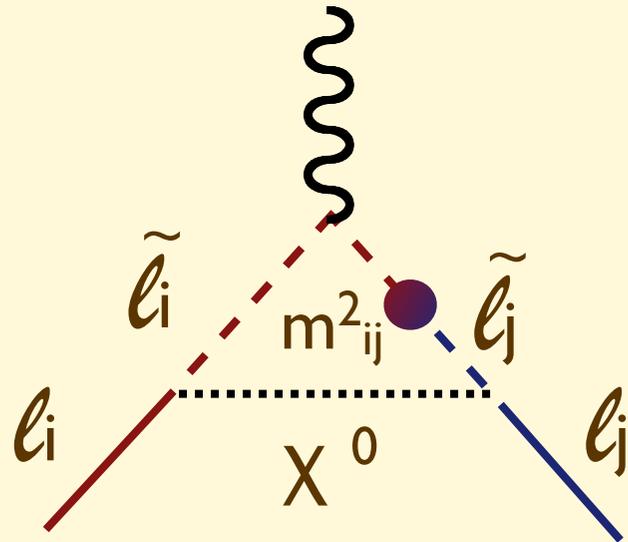
Even more interestingly, quark mixings induce charged **slepton** mixing via RG evolution from M_{GUT} to $m(N_R)$:

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

SUSY breaking param's
nu mixing param's

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

$l_i \rightarrow l_j \gamma$ transitions:



Possible scenarios:

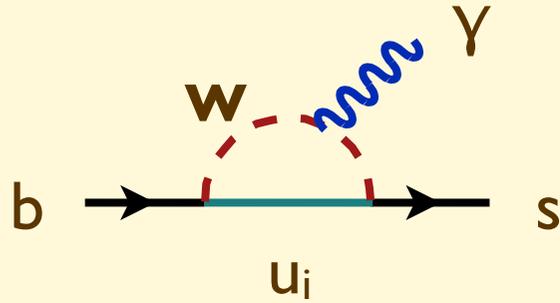
$$O_{\mu e} = V_{td} V_{ts} \quad \text{“CKM scenario”}$$

$$O_{\tau\mu} = V_{tb} V_{ts}$$

$$O_{\mu e} = U_{e3} U_{\mu 3} \quad \text{“MNS scenario”}$$

$$O_{\tau\mu} = U_{\tau 3} U_{\mu 3}$$

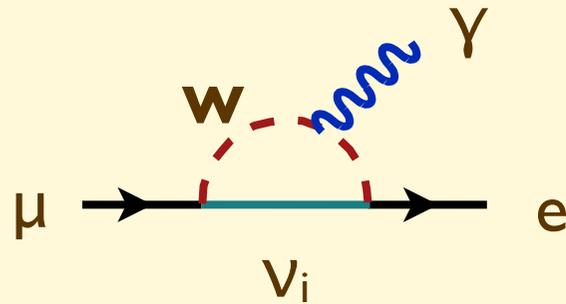
In the SM



GIM

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

$O(1)$



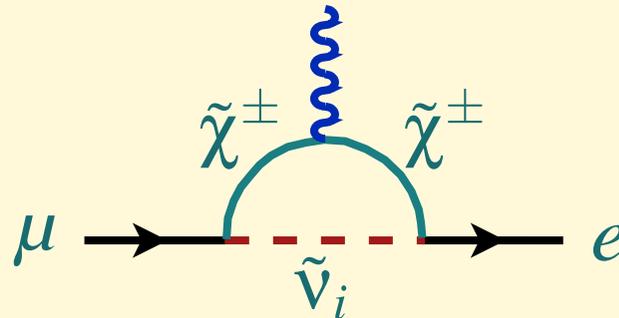
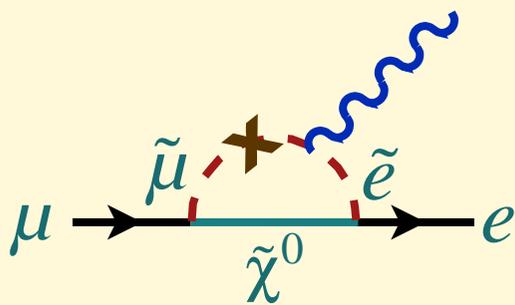
$$\propto \left| \frac{m_1^2 - m_2^2}{m_W^2} M_{12} M_{11}^* + \frac{m_3^2 - m_2^2}{m_W^2} M_{32} M_{31}^* \right|^2 \sim \frac{\Delta m_{23}^4}{m_W^4} s_{23}^2 c_{31}^2 s_{31}^2$$

$O(10^{-49})$

The smallness of $B(\mu \rightarrow e\gamma)$ 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



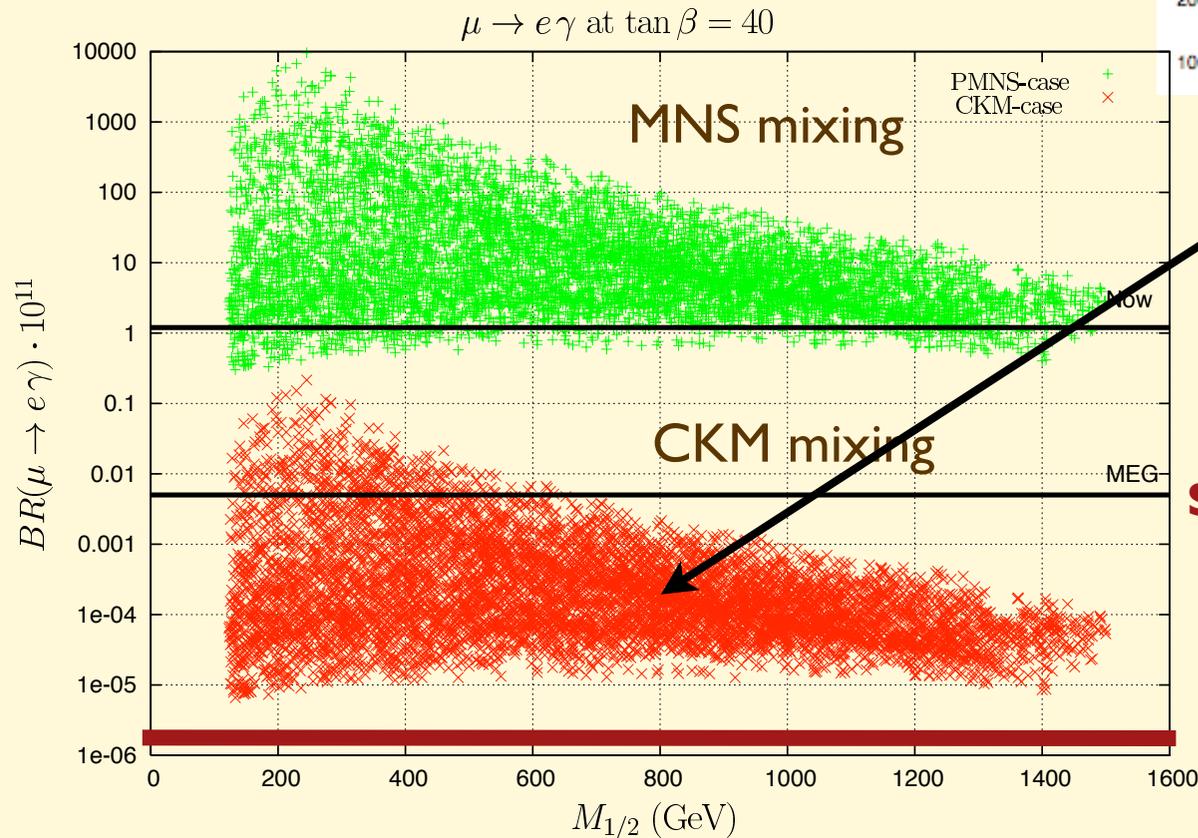
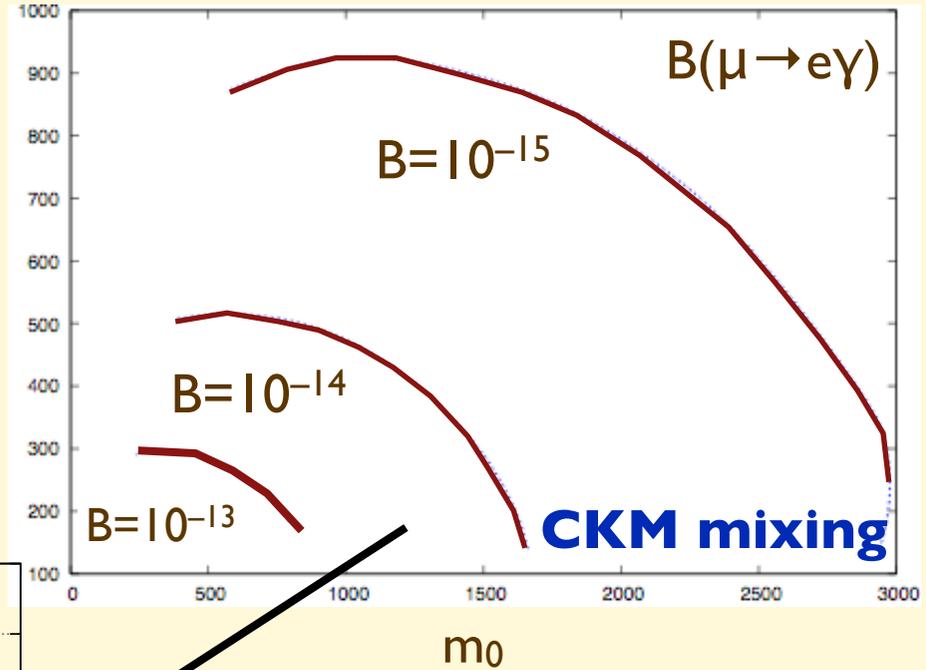
$$B \propto \left| \frac{\Delta m^2(\tilde{\nu})}{m_{\tilde{\chi}}^2} \times \epsilon_{12}^2 \right|^2$$

Examples of LHC-($\mu \rightarrow e\gamma$) synergy:

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

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

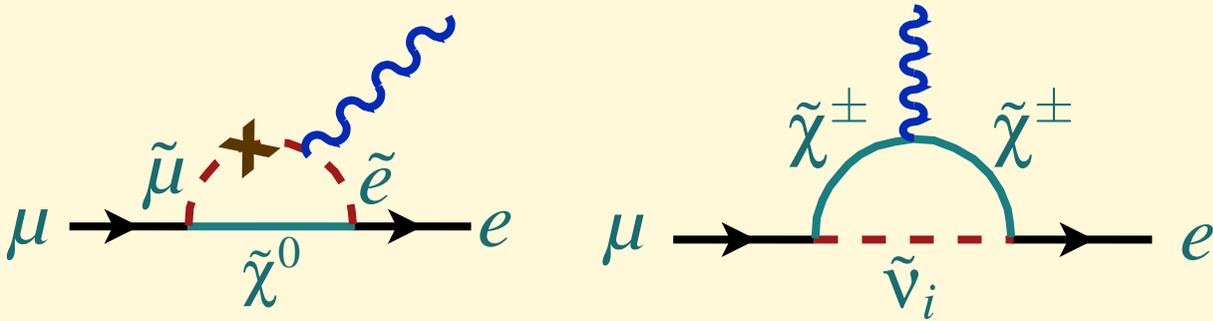
$m_{1/2}$



SO(10) mSUGRA scan
with $m(\text{squark}) < 2.5\text{ TeV}$
Calibbi et al, hep-ph/0605139

Sensitivity of MEG experiment

Sensitivity of Project-X mu2e conversion



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

Assuming that the BNL data are explained by SUSY,

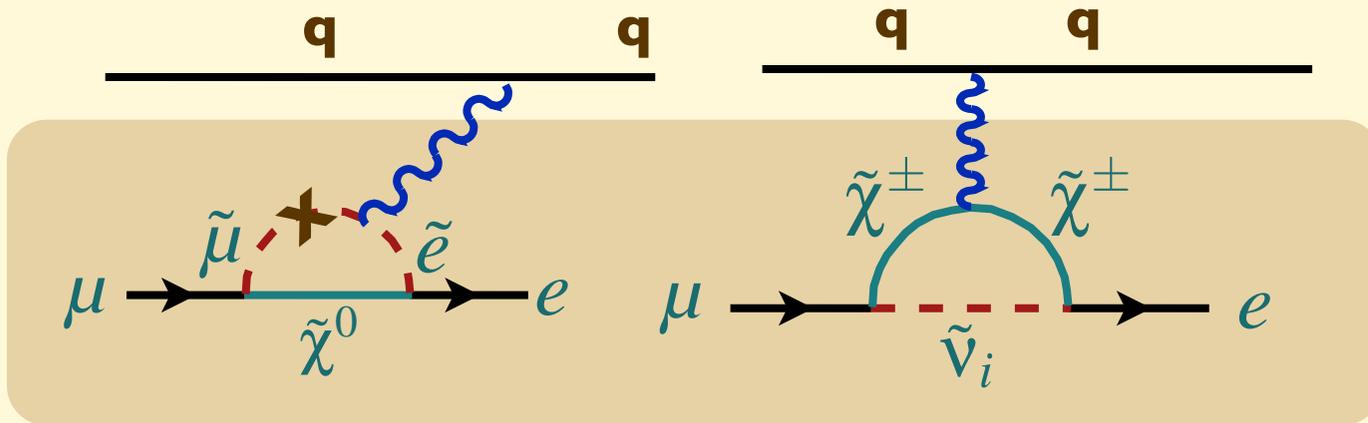
$$(g-2)_\mu^{\text{data}} - (g-2)_\mu^{\text{SM}} = (g-2)_\mu^{\text{SUSY}}$$

sets a scale for $m(\text{SUSY}) \sim 100 \text{ GeV}$

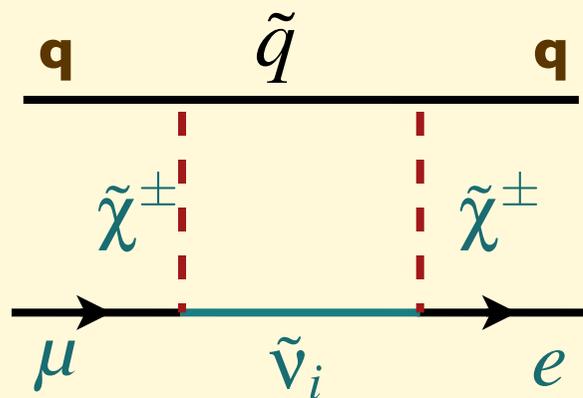
Current $B(\mu \rightarrow e\gamma)$ limits then indicate mass splittings in the slepton sector of few 10s MeV !!

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

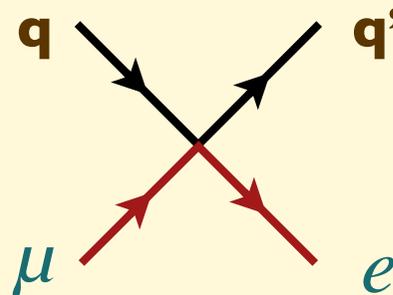
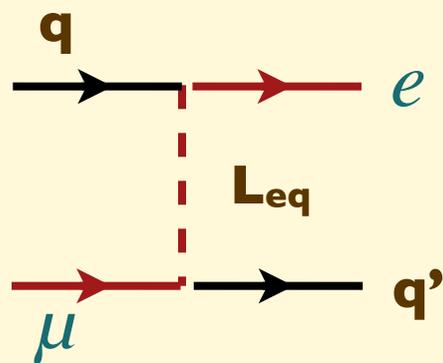
$\mu \rightarrow e \gamma$ vs $\mu N \rightarrow e N$ complementarity



$\mu \rightarrow e \gamma$ diagrams



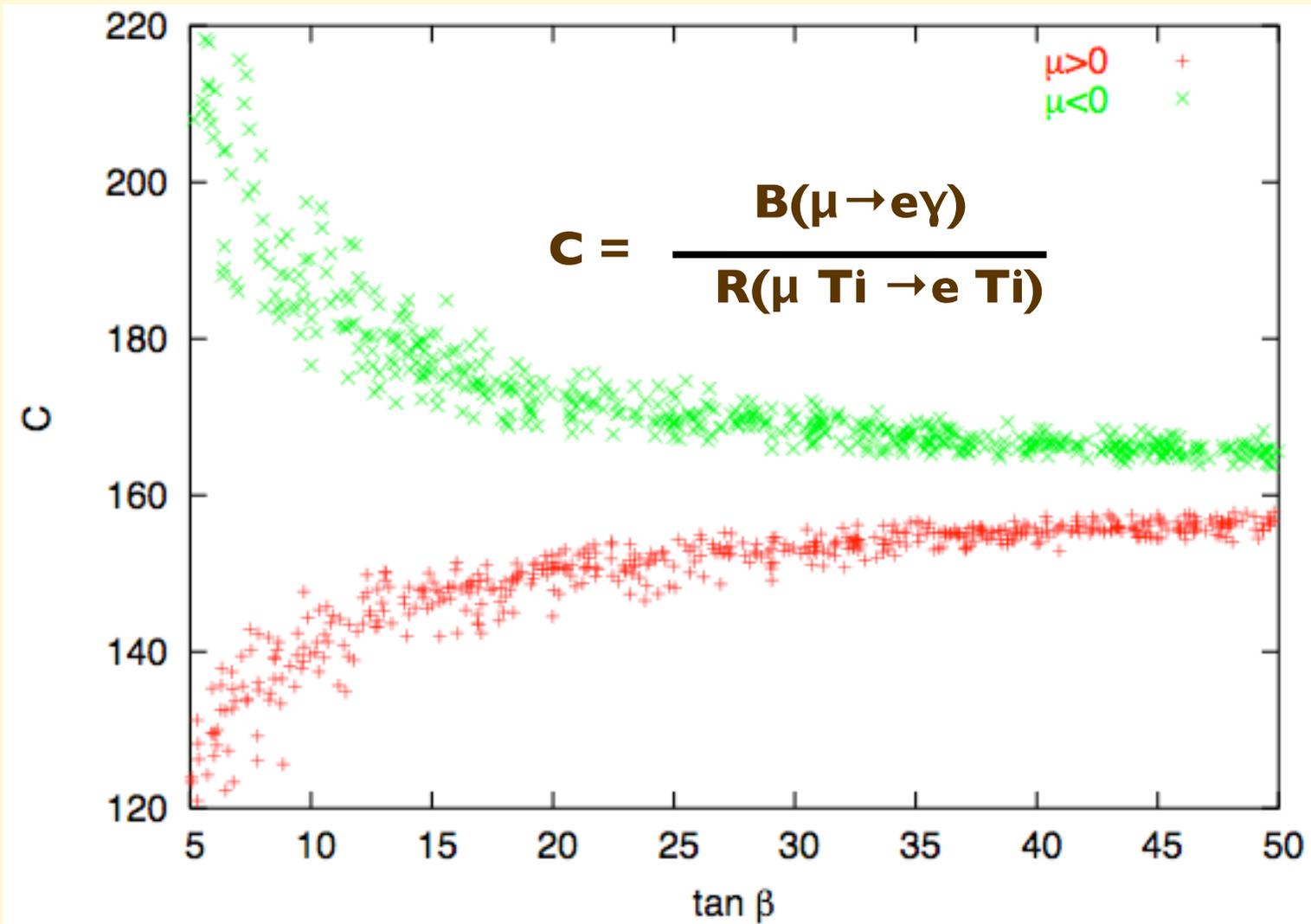
extra contributions,
sensitive to additional
model parameters



extra contributions,
sensitive to other
underlying dynamics



$K \rightarrow e \mu$?



C Yagouna, hep-ph/0502014

$\mu \rightarrow e \gamma$

Current limits on $B(\mu \rightarrow e \gamma)$

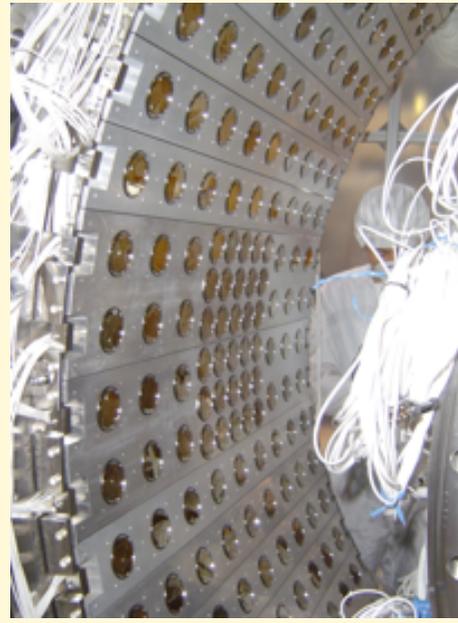
mode	upper limit (90% C.L.)	year	Exp./Lab.
$\mu^+ \rightarrow e^+ \gamma$	1.2×10^{-11}	2002	MEGA / LAMPF
$\mu^+ \rightarrow e^+ e^+ e^-$	1.0×10^{-12}	1988	SINDRUM I / PSI
$\mu^+ e^- \leftrightarrow \mu^- e^+$	8.3×10^{-11}	1999	PSI
$\mu^- \text{ Ti} \rightarrow e^- \text{ Ti}$	6.1×10^{-13}	1998	SINDRUM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

Future:

near: $\mu \rightarrow e \gamma$

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

- o First data taking 2008, single-event sensitivity at $BR < 5 \times 10^{-12}$
- o Run Fall 2009 underway, full detector => match current limits
- o New 2-yr run to start April 2010
- o ultimate sensitivity: $BR < 1 \times 10^{-14}$ at 90%CL by 2011



medium: $\mu \rightarrow e \text{ conv}$

MU2e at Fermilab

- o 1st stage DoE approval achieved Fall 09. Could be taking data by 2016
- o sensitivity: $R(\mu \rightarrow e) < 6 \times 10^{-17}$ @90%CL $\rightarrow 10^{-18}$ with Project-X



(i.e. $BR < \sim 10^{-14}$ if only $(\mu \rightarrow e \gamma)$ diagrams contribute)

More physics with charged leptons

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

Example of correlations between ν and quark-sector observables

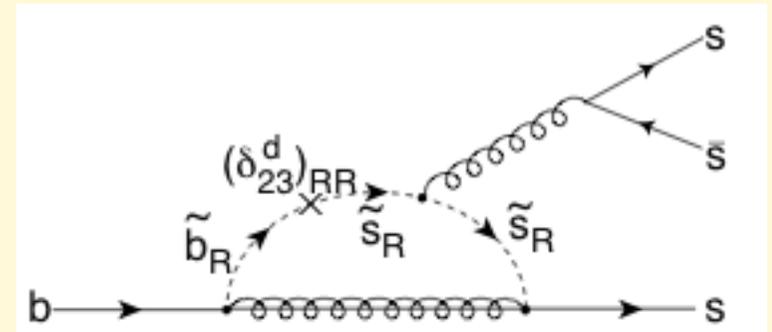
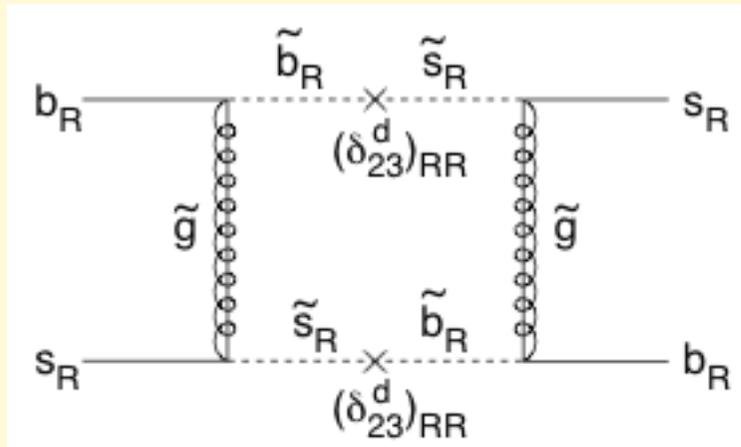
$$L_m \propto y_{i,j}^{d,\ell} \mathbf{16}_i \mathbf{16}_j H_d + y_{i,j}^{u,\nu} \mathbf{16}_i \mathbf{16}_j H_u + y_{i,j}^R \mathbf{16}_i \mathbf{16}_j H_R^{126}$$

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

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

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

This has no direct 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:

B_s mixing, CP violation in $B_s \rightarrow \phi \psi$ (~ 0 in the SM)

**$\sin 2\beta(B \rightarrow \phi K_s) \neq \sin 2\beta$
 $(B \rightarrow \psi K_s)$**

EDMs

● Flavour-conserving CPV

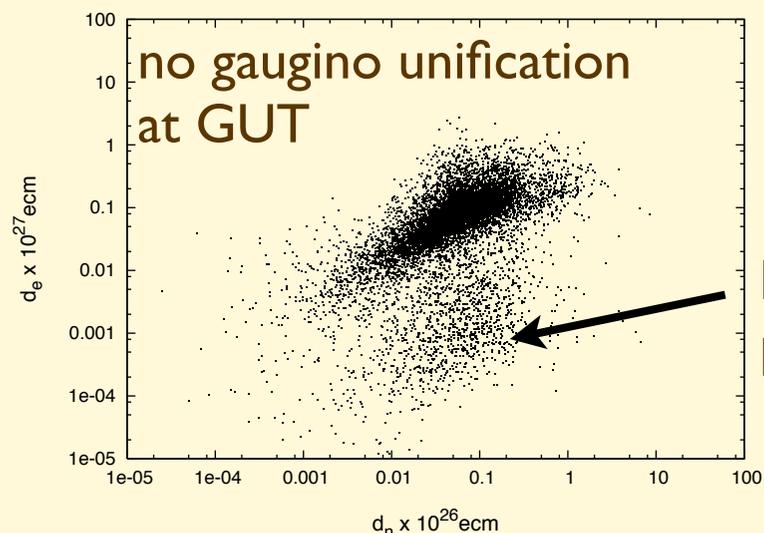
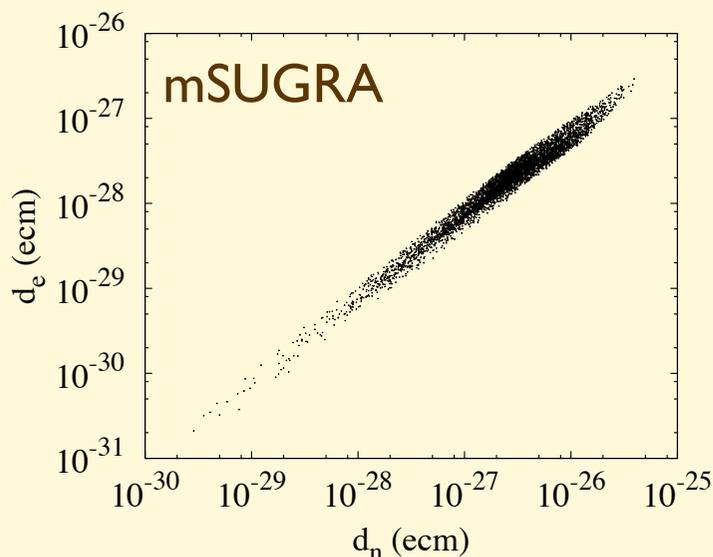
- Sensitive probes of CPV in extended gauge sectors (e.g. SUSY gluinos, gauginos, higgsinos)



Probes of mechanisms to generate the antimatter asymmetry of the universe

d_e / d_n correlations:

SUSY: $d_e / d_n \sim m_e/m_q \sim 0.1$



Extra-dim, 2HDM: $d_e / d_n \ll 1$

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 unpaired 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: $d_{\text{neutron}} = 3 \times 10^{-26}$ 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

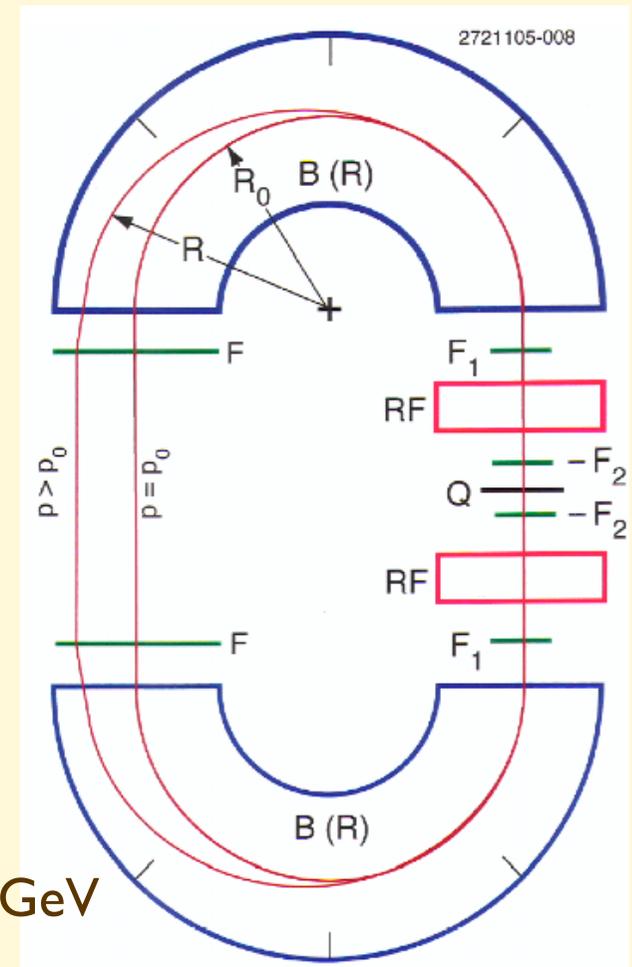
- o R&D and construction of new detectors/beamline
- o new runs 2009-2011 (ILL) and 2011-2014 (PSI)
- o Goal: $d_{\text{neutron}} < \sim 2 \times 10^{-28}$ e cm/yr

⇒ 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: $\sigma_d = 2.5 \times 10^{-29}$ e cm/yr



Rare K decays

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

E391 at KEK, final result:

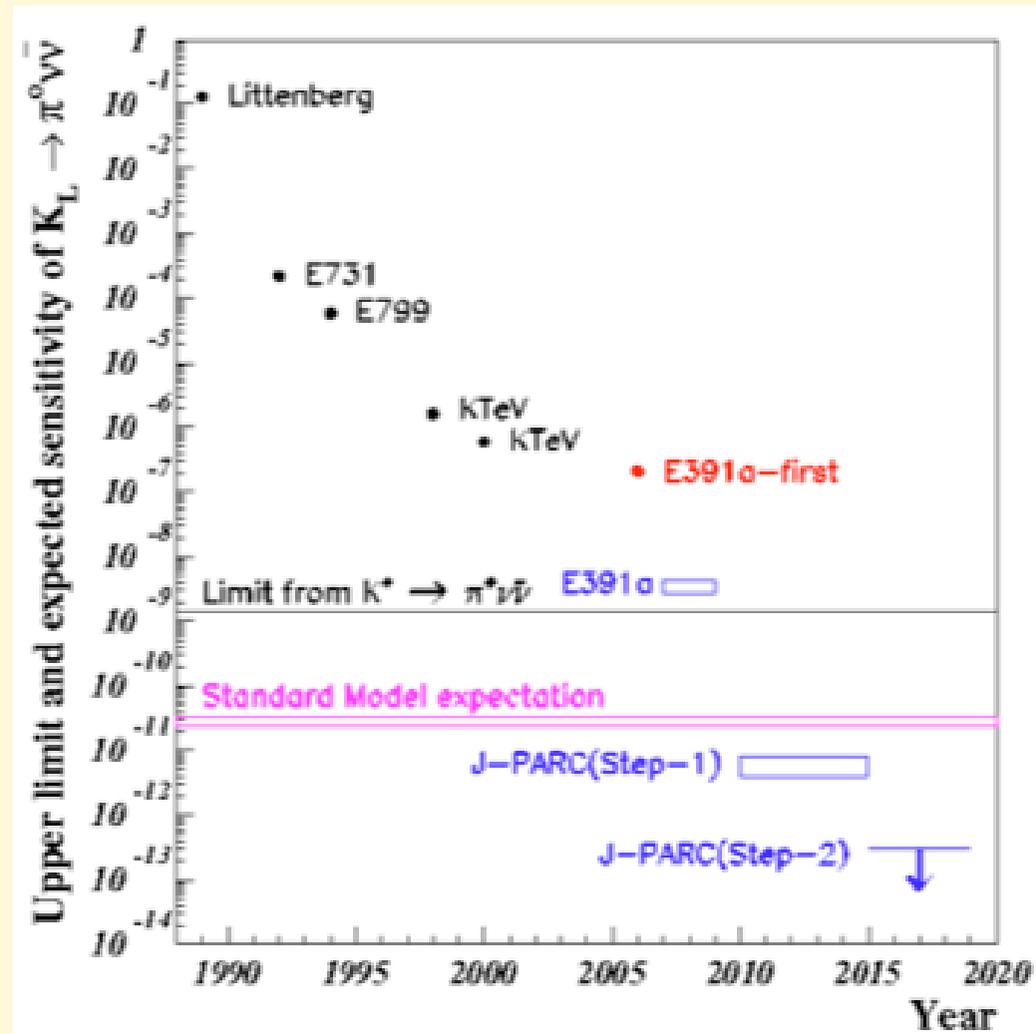
$$B(K_L^0 \rightarrow \pi^0 \nu \nu) < 2600 \times 10^{-11} \text{ @ 90\% CL}$$

arXiv:0911.4789

KOTO (E14) at JPARC

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

- o Aim to 3000 x rate[E391]
- o Detector completion: 2010
- o Beam construction/survey: 2009. Status: K_L observed, Dec 7
- o Data: 2012-20
- o Goal: $O(10^{-13})$, $\Delta BR \sim 10\%$



Rare K decays, CERN

$K^+ \rightarrow \pi^+ \nu \nu$ $B(K^+ \rightarrow \pi^+ \nu \nu)_{E787/949 \text{ BNL}} = 1.73 \pm 1 \times 10^{-10}$ (3 events, arXiv:0808.2459)

$B(K^+ \rightarrow \pi^+ \nu \nu)_{SM} = 0.85 \pm 0.07 \times 10^{-10}$

Expected reduction to 4% error via NNLO + better input parameters (m_{top} , etc)

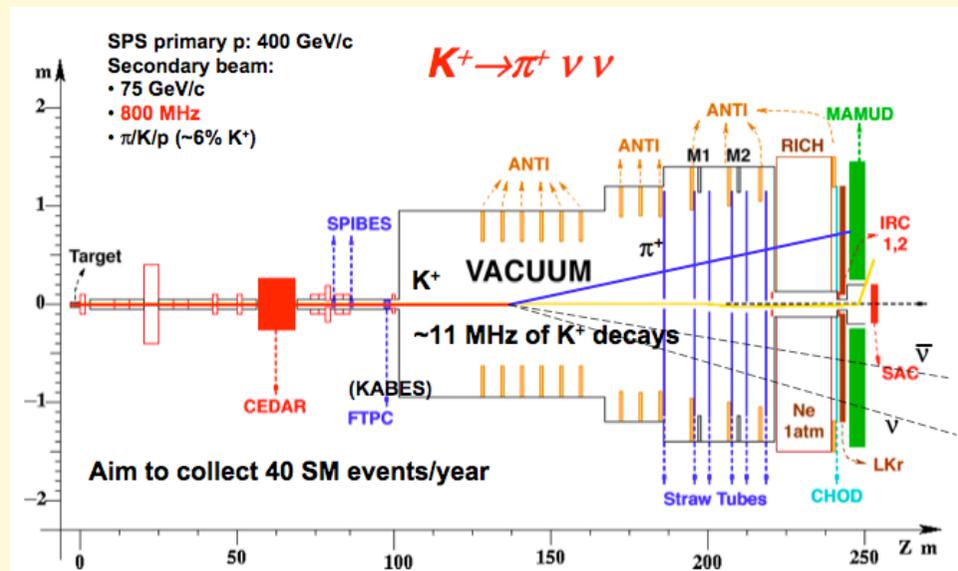
NA62

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

o R&D ongoing, with 2007 run for $R_{e/\mu} = \Gamma(K \rightarrow e \nu) / \Gamma(K \rightarrow \mu \nu)$ to 0.3%

o Ready for beam: Fall 2012

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



$K_L^0 \rightarrow \pi^0 e^+ e^-$ $K_L^0 \rightarrow \pi^0 \mu^+ \mu^-$

$K_L^0 \rightarrow \pi^0 \nu \nu$

NA48/4

NA48/5

Require more protons than available from the SPS today

2015, a dream scenario

- SUSY is seen at LHC, with squarks/gluinos at ~ 1 TeV, weak sparticles at ~ 0.1 TeV
- Observe in parallel:
 - LHC: $B_s \rightarrow \mu^+ \mu^-$ at rates $> SM$, and NA62: $K^+ \rightarrow \pi^+ \nu \nu$ at rates $> SM$
 - MEG: $\mu \rightarrow e \gamma$
 - ILL/PSI: neutron EDM
 - large $\theta_{13} \rightarrow$ measurable CP violation in nu mixing
- Z' at 2–2.5 TeV seen at LHC:
 - open decays to all SUSY sparticles \Rightarrow very accurate studies
 - the LHC turns into a Z' factory
 - CLIC is above threshold to further study it in the future
- Direct DM detection underground fits well neutralino properties
-

It's a dream, but not an impossible one !

Conclusions

- **Progress in the field will be 100% driven by new and better experimental data.** We are running out of ideas and tools 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
- Maintaining **diversity** in the exp'l programme is our best investment for HEP.