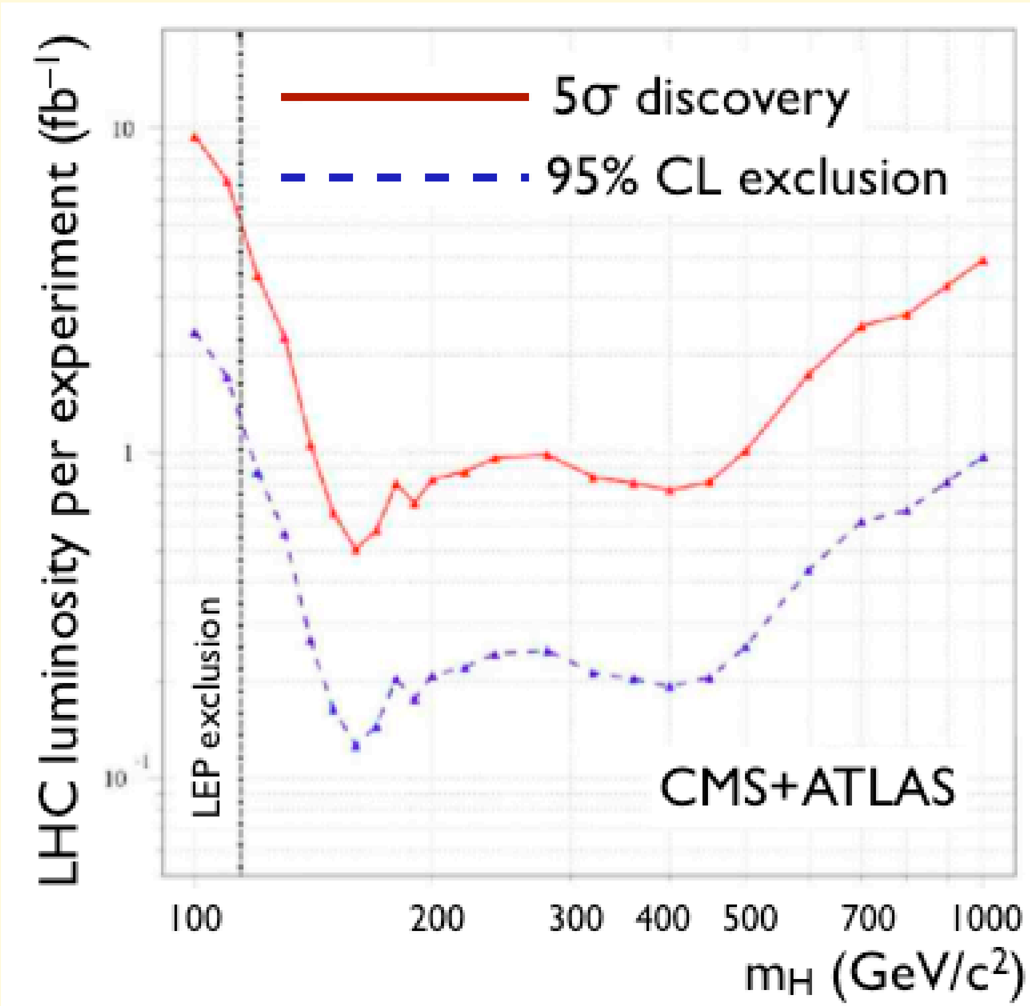
Physics opportunities for the SLHC

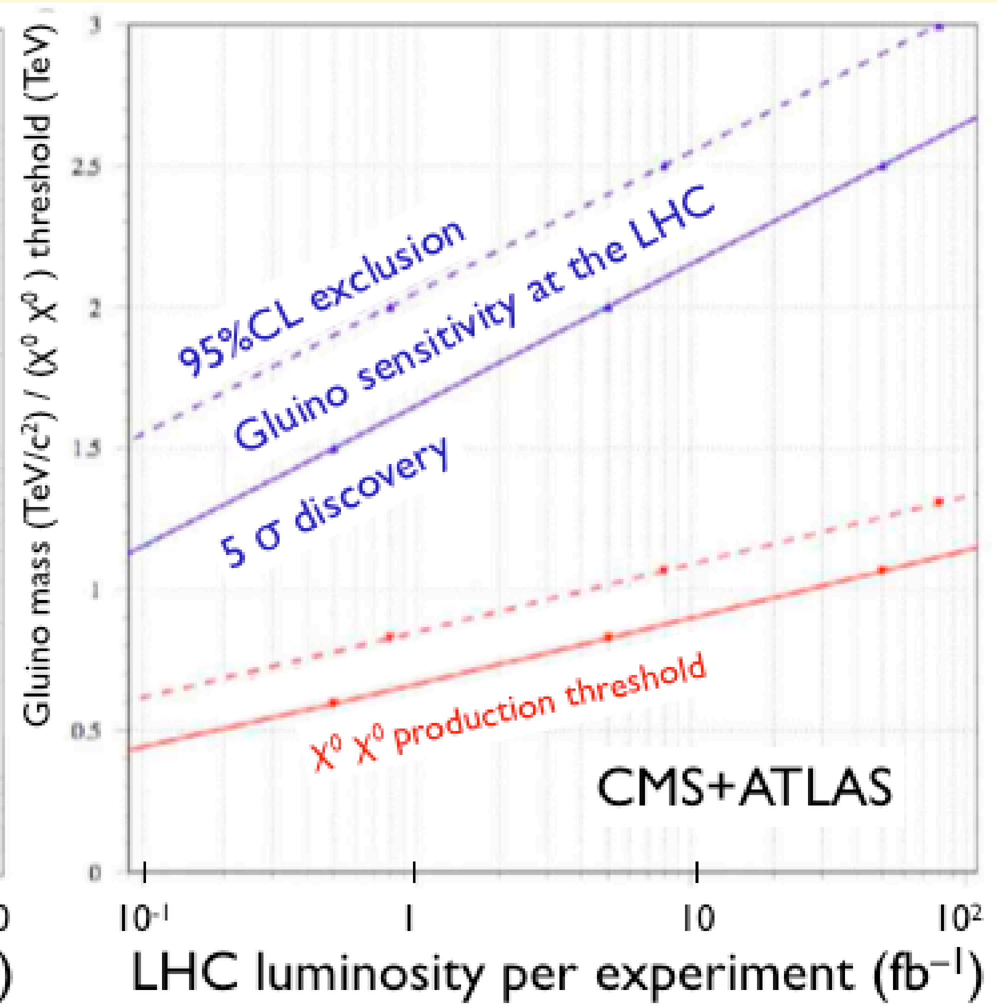
SLHC kickoff meeting
CERN, April 8-9 2008

Michelangelo Mangano
Theory Unit, Physics Department, CERN
michelangelo.mangano@cern.ch

For more details see:
F. Gianotti et al, Eur.Phys.J.C39:293-333,2005, http://arxiv.org/pdf/hep-ph/0204087
D. Denegri, presentation at HHH 04:
http://care-hhh.web.cern.ch/CARE-HHH/HHH-2004/default.html

Summary of discovery potential for Higgs and SUSY with < 10 fb-1





By 2010-11 we should already have a good picture of TeV-scale physics!

WHAT'S NEXT?

It hasn't been easy to establish the SM ....

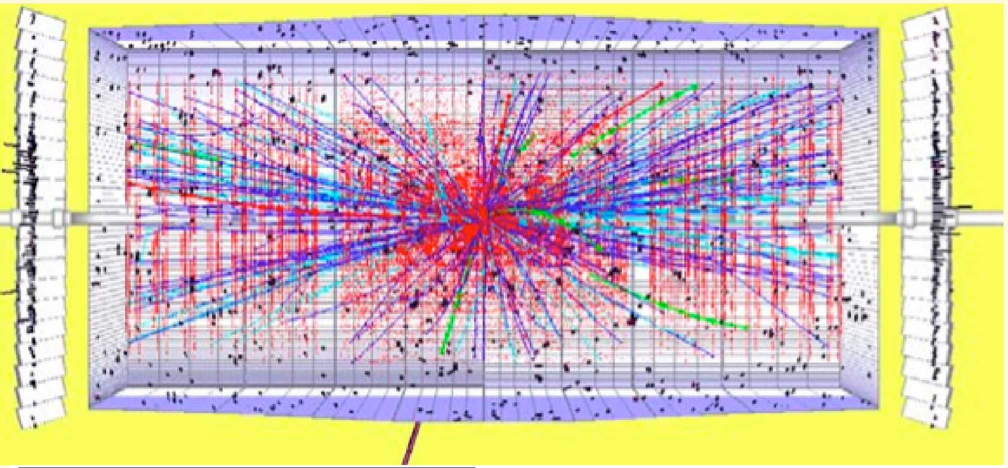
- **< 1973: theoretical foundations of the SM**
  - renormalizability of SU(2)xU(1) with Higgs mechanism for EWSB
  - asymptotic freedom, QCD as gauge theory of strong interactions
  - GIM mechanism and family structure
  - KM description of CP violation
- **Followed by 30 years of consolidation:**
  - **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
    - CP violation in the 3rd generation

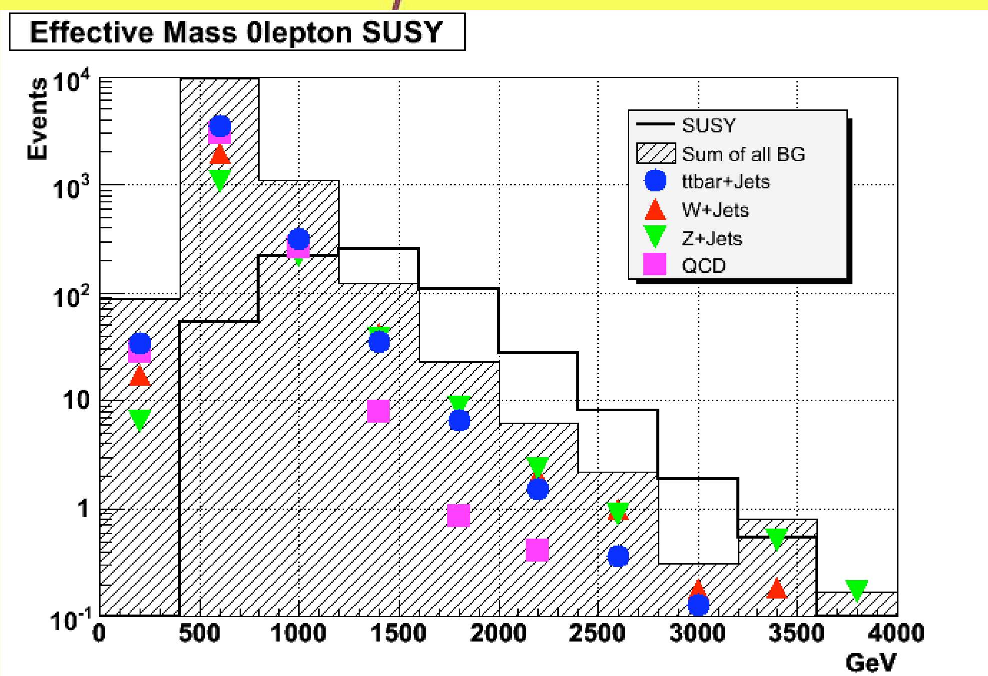
Since 1973:

- 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 ~ 0)
- Milestones:
  - 1974: Grand Unified Theories ☹
  - 1974: Supersymmetry ☹
  - 1977: See-saw mechanism for ν masses ☺
  - 1979: Technicolor ☹
  - 1984: Superstring theories ☹
  - 1998: Large scale extra dimensions ☹

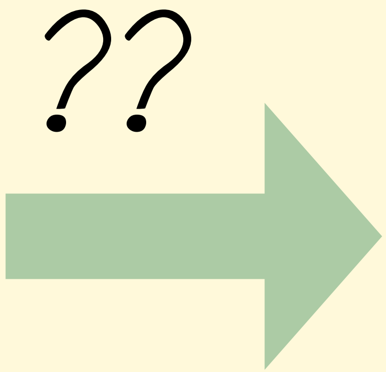
The LHC inverse problem

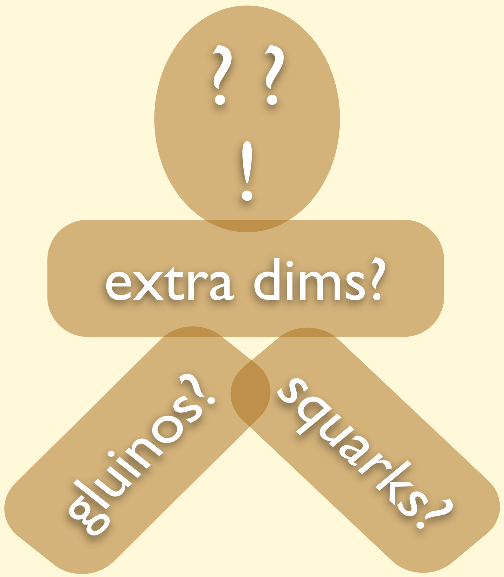
Reconstruct the Lagrangian of new physics from the LHC data





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





$\mathscr{L}$

Why will we need 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.:
   - $H \to \mu^+\mu^-$, $H \to Z\gamma$
   - 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 insensititive to high-lum environment.
Not very demanding on detector performance
Slightly degraded detector performance tolerable

EW symmetry breaking

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

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!

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

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

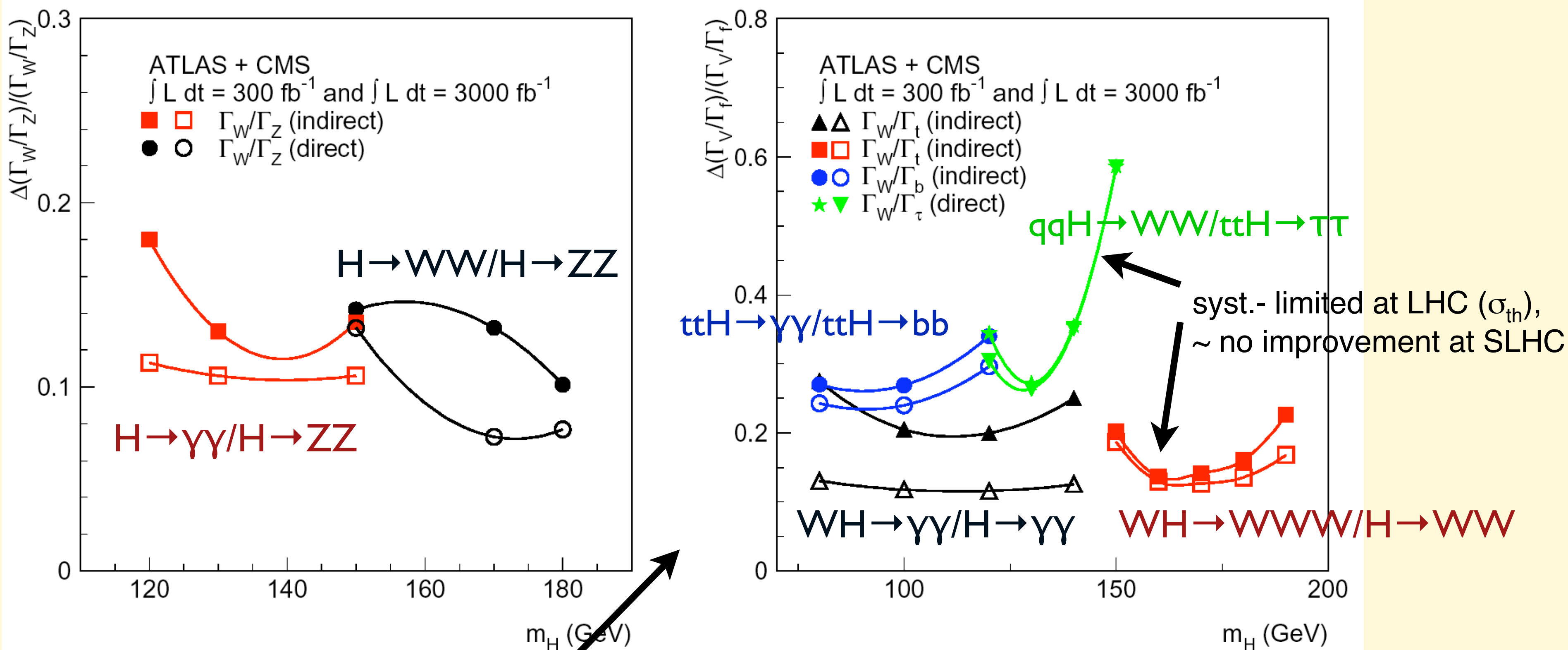
or

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

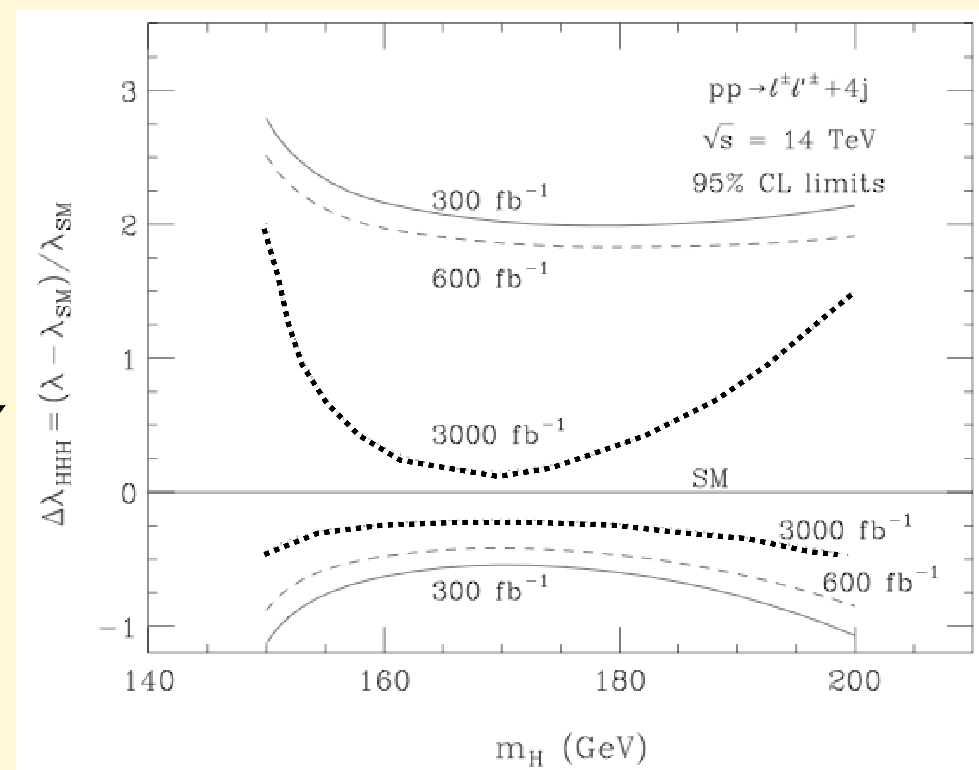
or

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

Sorting out these scenarios will take longer than the SM H observation, and may well require SLHC luminosities, and/or LC



Higgs boson couplings to fermions and gauge bosons

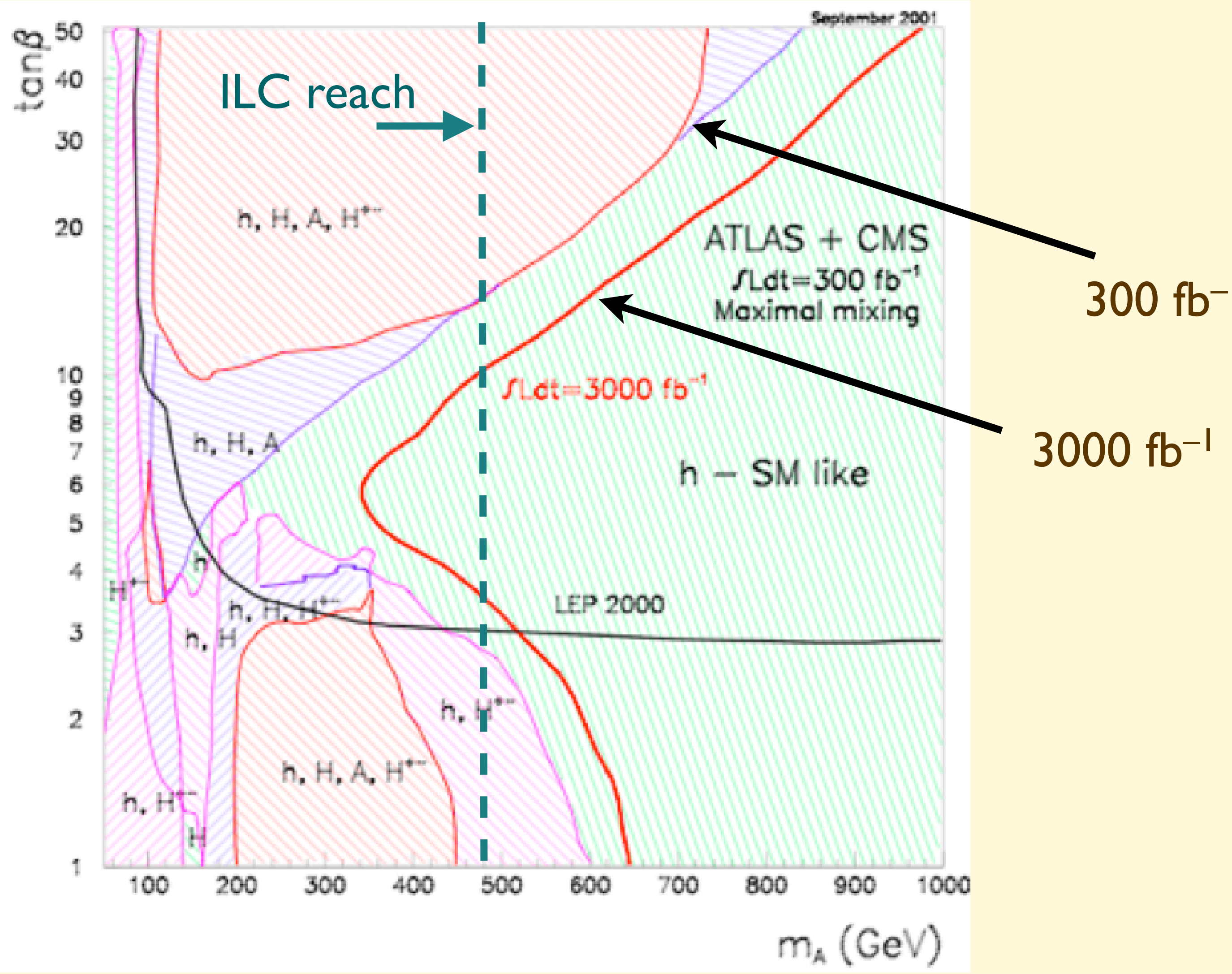


Higgs boson selfcouplings

Rare Higgs decay modes

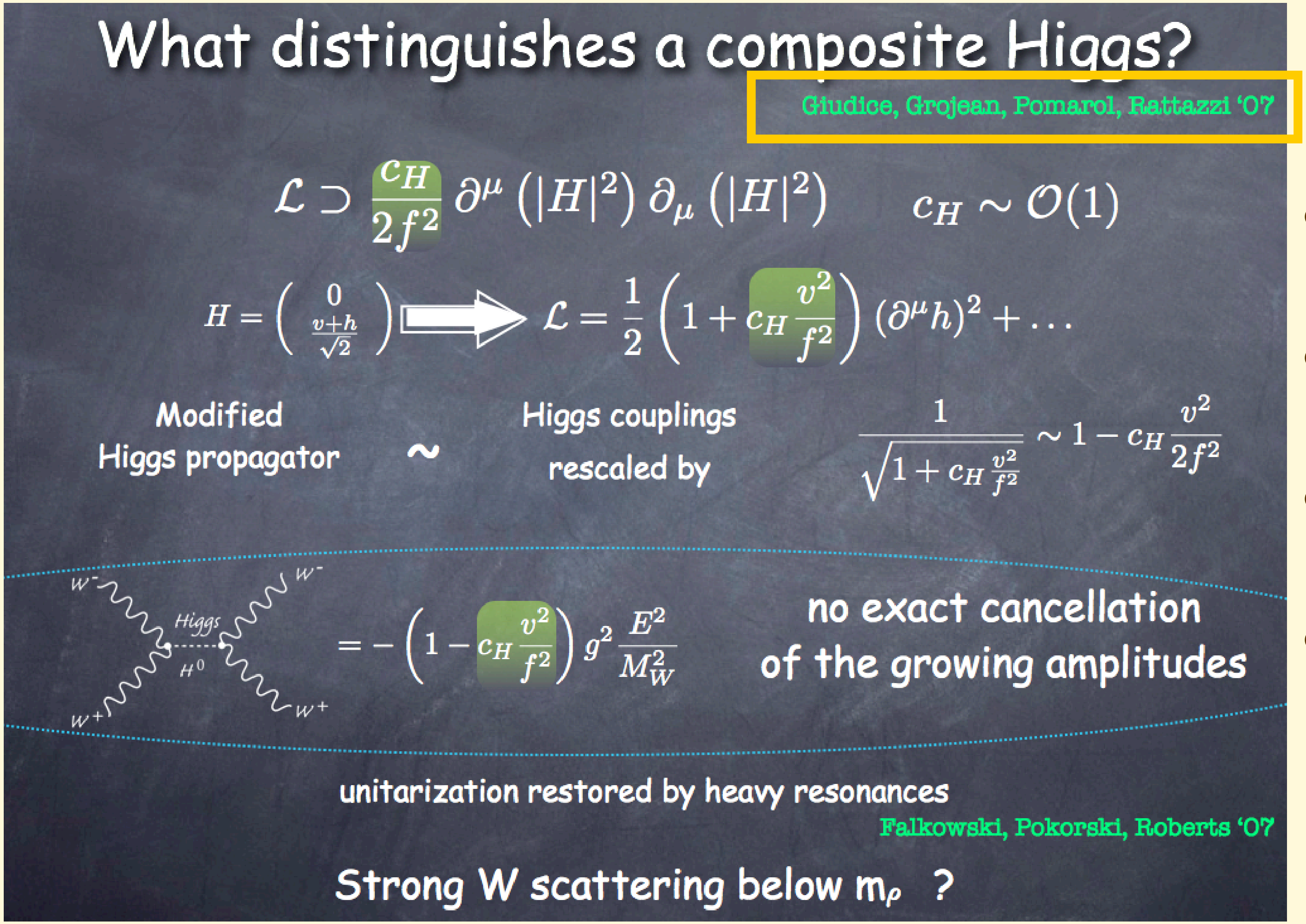
	$600\ \text{fb}^{-1}$	$6000\ \text{fb}^{-1}$
$H \rightarrow Z\gamma$	$3.5\ \sigma$	$11\ \sigma$
$H \rightarrow \mu^+\mu^-$	$< 3.5\ \sigma$	$\sim 7\ \sigma$

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



Signatures of a composite nature of the Higgs

See e.g. C. Grojean, at the CERN 2007 CLIC Workshop,
http://indico.cern.ch/conferenceOtherViews.py?view=standard&confId=17870



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

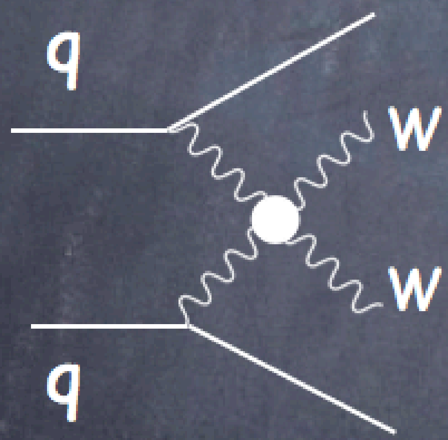
Strong W scattering

Even with a light Higgs, growing amplitudes (at least up to m_ρ)

$$\mathcal{A}\left(Z_L^0 Z_L^0 \to W_L^+ W_L^-\right) = \mathcal{A}\left(W_L^+ W_L^- \to Z_L^0 Z_L^0\right) = -\mathcal{A}\left(W_L^\pm W_L^\pm \to W_L^\pm W_L^\pm\right) = \frac{c_H s}{f^2}$$

$$\mathcal{A}\left(W^\pm Z_L^0 \to W^\pm Z_L^0\right) = \frac{c_H t}{f^2}, \quad \mathcal{A}\left(W_L^+ W_L^- \to W_L^+ W_L^-\right) = \frac{c_H (s+t)}{f^2}$$

$$\mathcal{A}\left(Z_L^0 Z_L^0 \to Z_L^0 Z_L^0\right) = 0$$



$$\sigma\left(pp \to V_L V_L' X\right)_{c_H} = \left(c_H \xi\right)^2 \sigma\left(pp \to V_L V_L' X\right)_{\not H}$$

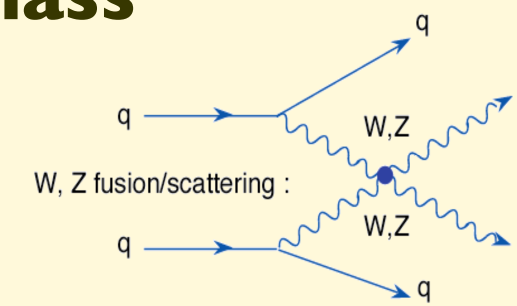
leptonic and semileptonic vector decay channels with 300 fb^{-1} ⇒

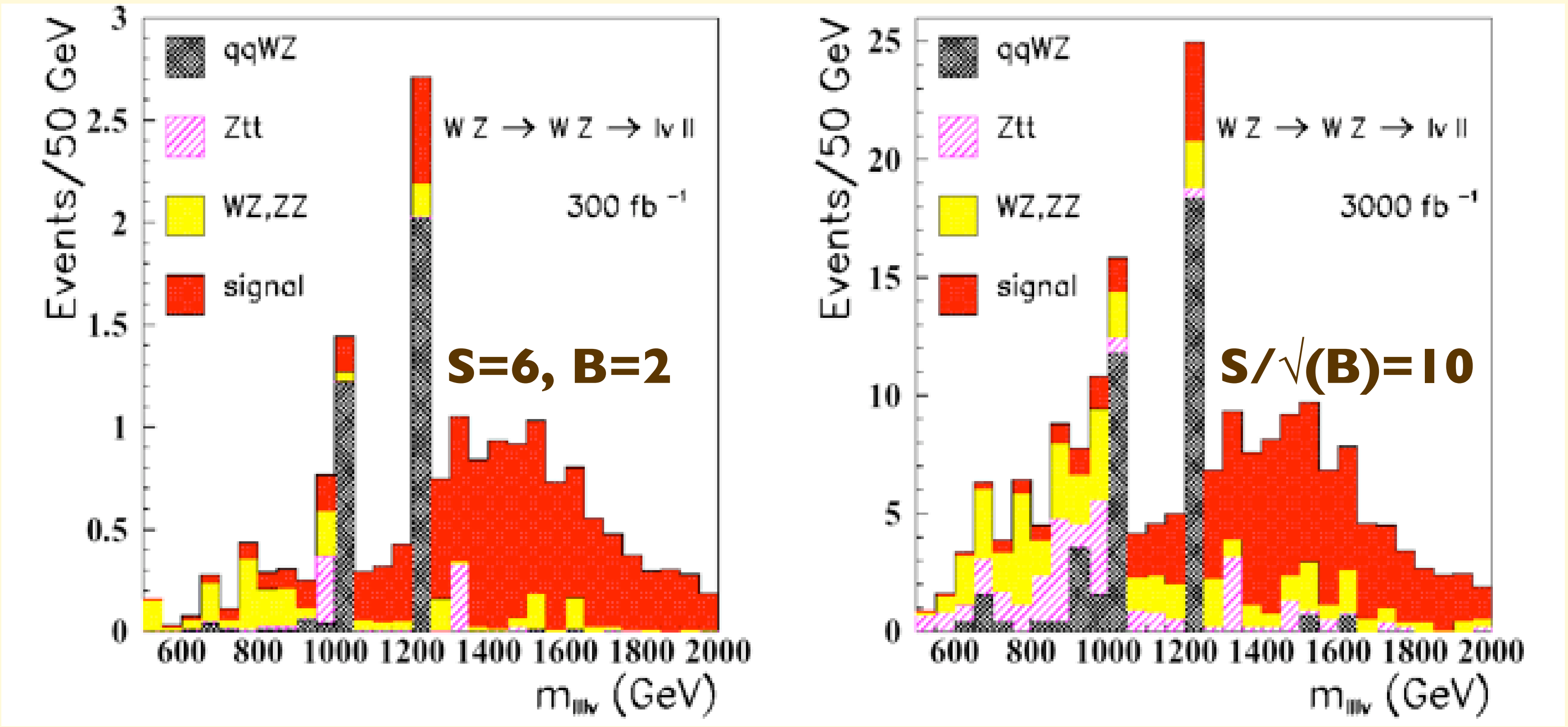
LHC is sensitive to $c_H \frac{v^2}{f^2}$ bigger than 0.5 ~ 0.7

Bagger et al '95
Butterworth et al. '02

C. Grojean

Strong resonances in high-mass WW or WZ scattering





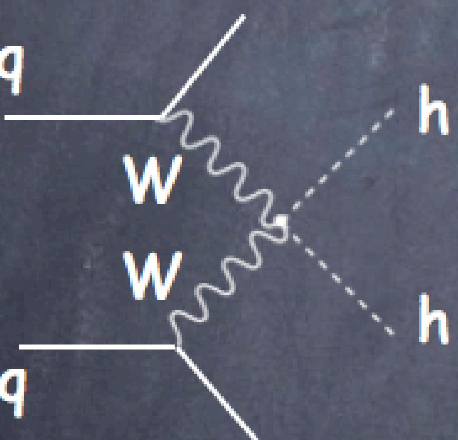
Vector resonance (ρ-like) in $W_L Z_L$ scattering from Chiral Lagrangian model
M = 1.5 TeV, leptonic final states, 300 fb^{-1} (LHC) vs 3000 fb^{-1} (SLHC)

Strong Higgs production

O(4) symmetry between W_L, Z_L and the physical Higgs

strong boson scattering ⇔ strong Higgs production

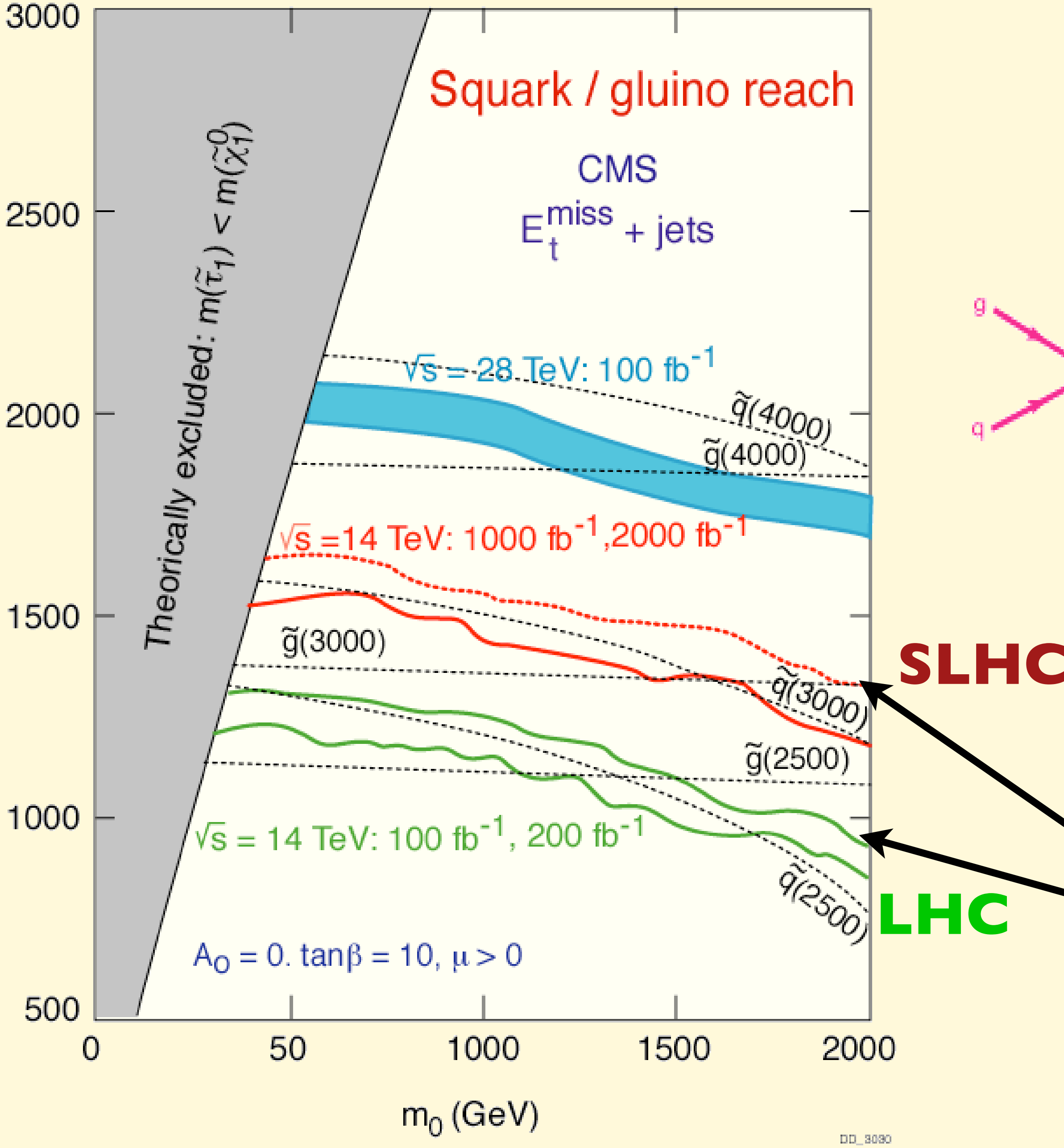
$$\mathcal{A}\left(Z_L^0 Z_L^0 \to hh\right) = \mathcal{A}\left(W_L^+ W_L^- \to hh\right) = \frac{c_H\, s}{f^2}$$



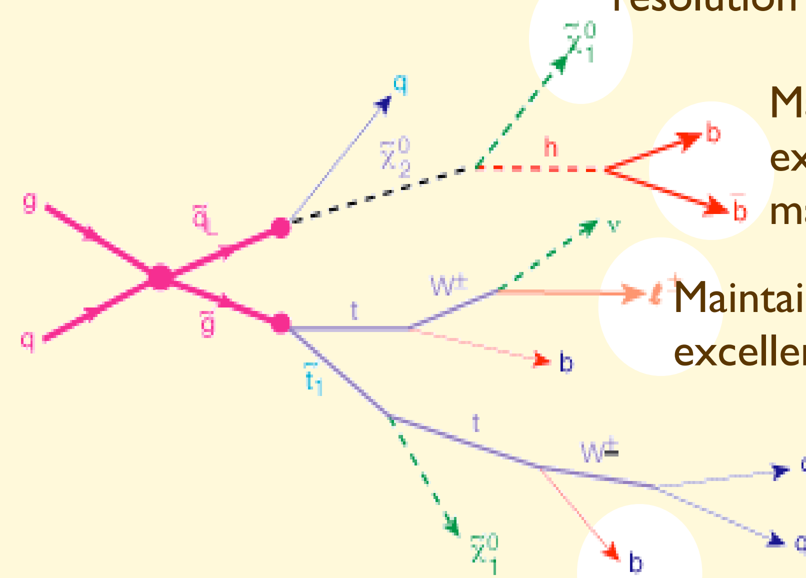
signal:
- hh → bbbb
- hh → 4W → $\ell^\pm \ell^\pm \nu\nu$jets

C. Grojean

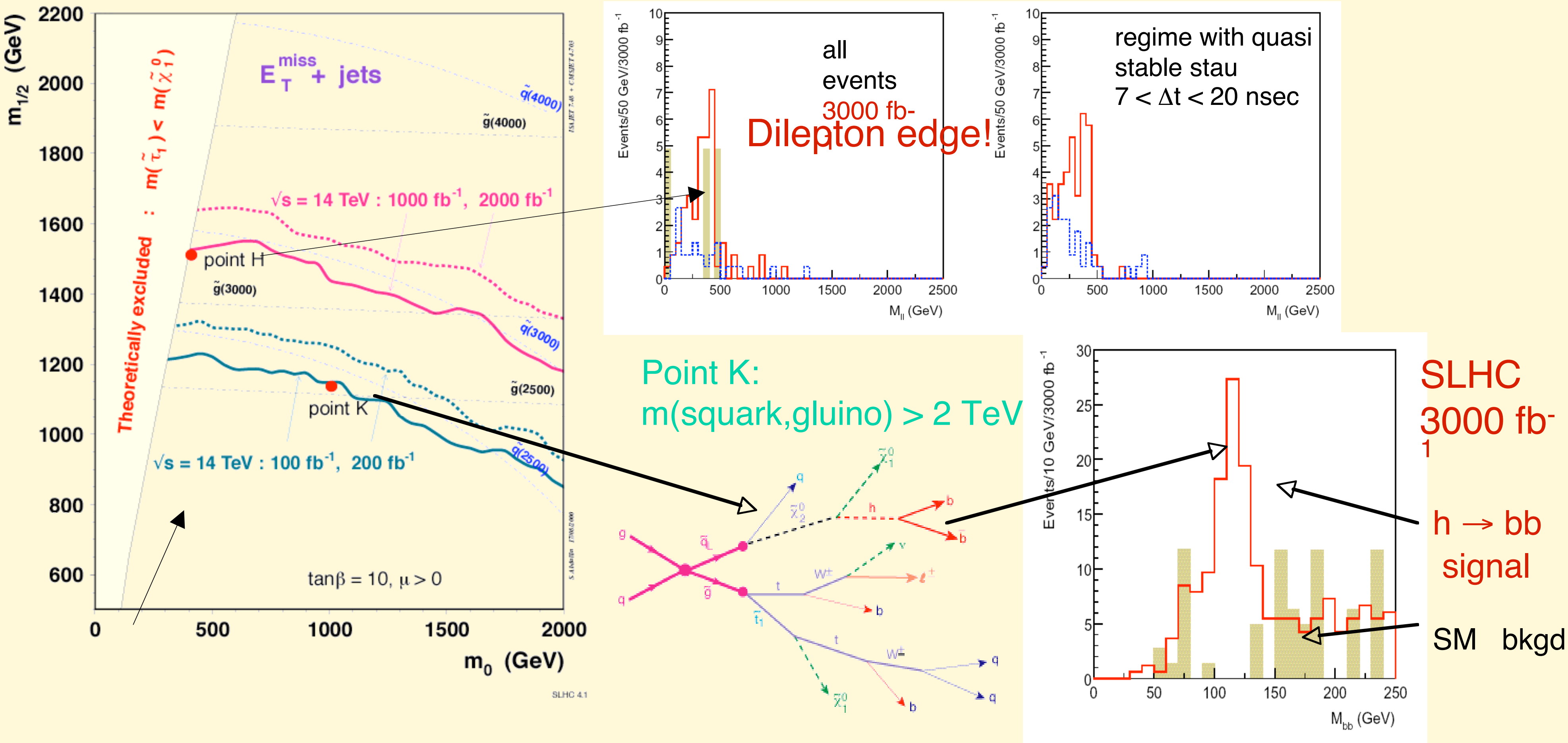
SUSY reach and studies



M reach ~ 500 GeV more than LHC



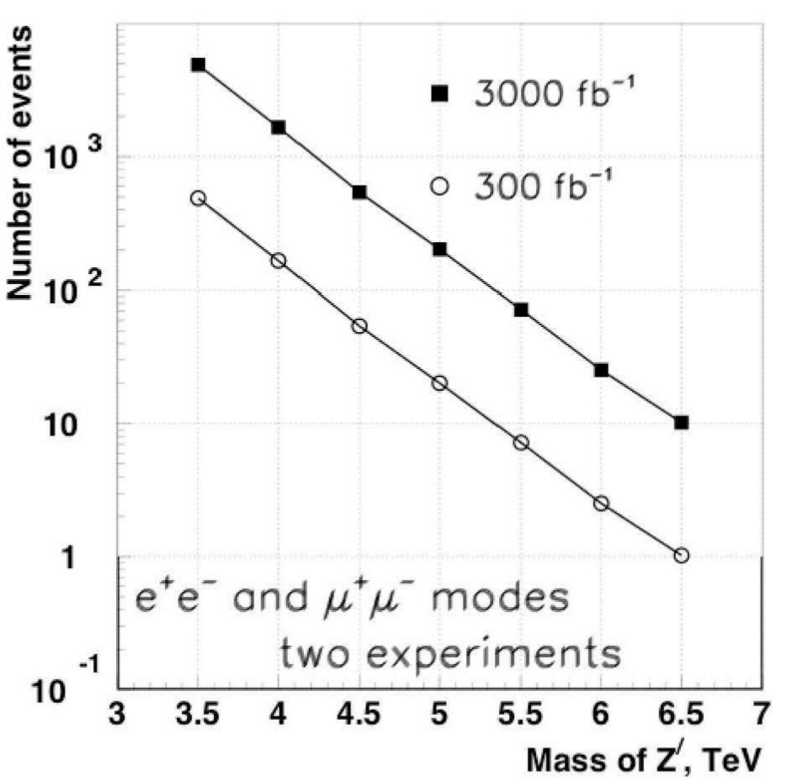
Sparticle spectroscopy



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…..

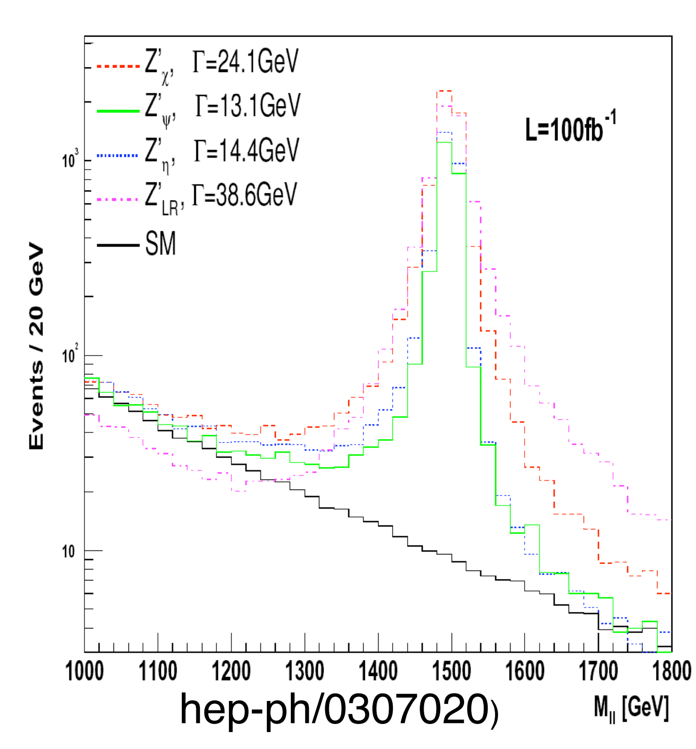
Searching new forces: W’, Z’

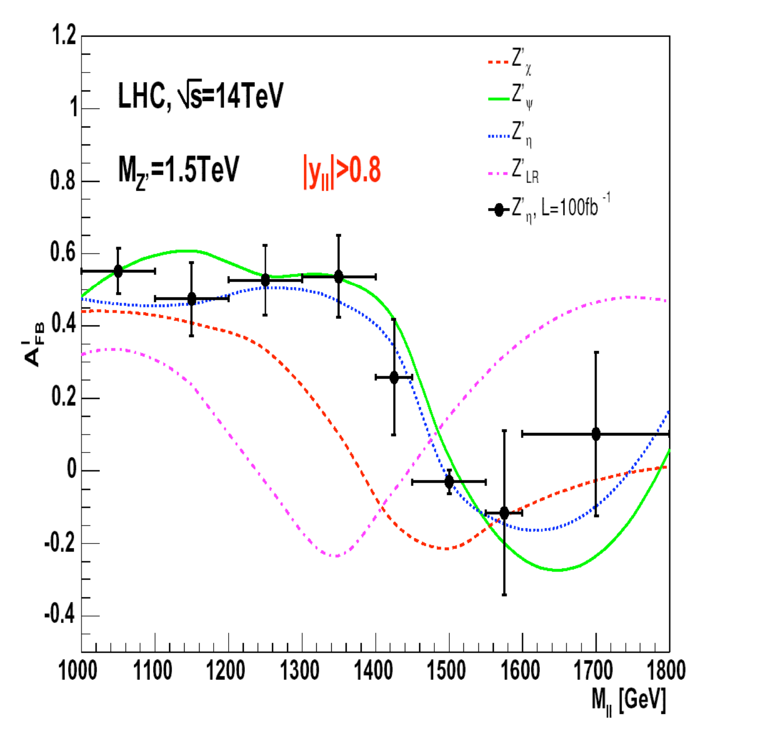
E.g. a W’ coupling to R-handed fermions, to reestablish at high energy the R/L symmetry



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

Differentiating among different Z’ models:

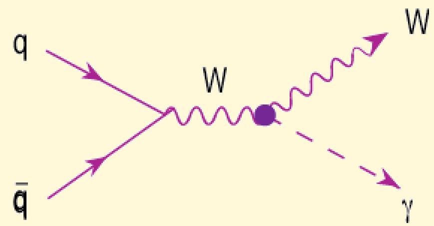


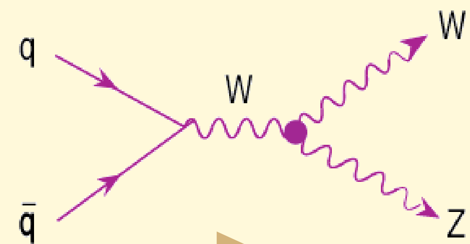


$100\ fb^{-1}$ model discrimination up to 2.5 TeV

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

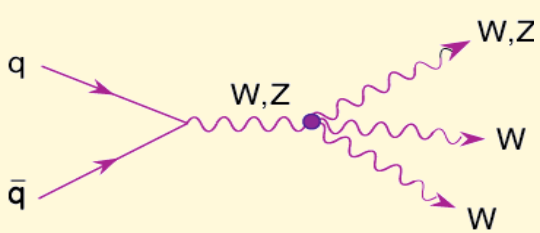
5 parameters describing weak and EM dipole and quadrupole moments of gauge bosons. The SM predicts their value with accuracies at the level of **10^{-3}**, which is therefore the goal of the required experimental precision

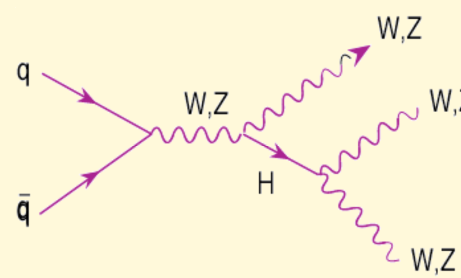


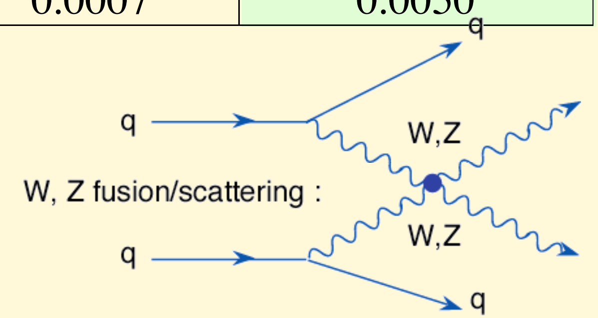


LHC options

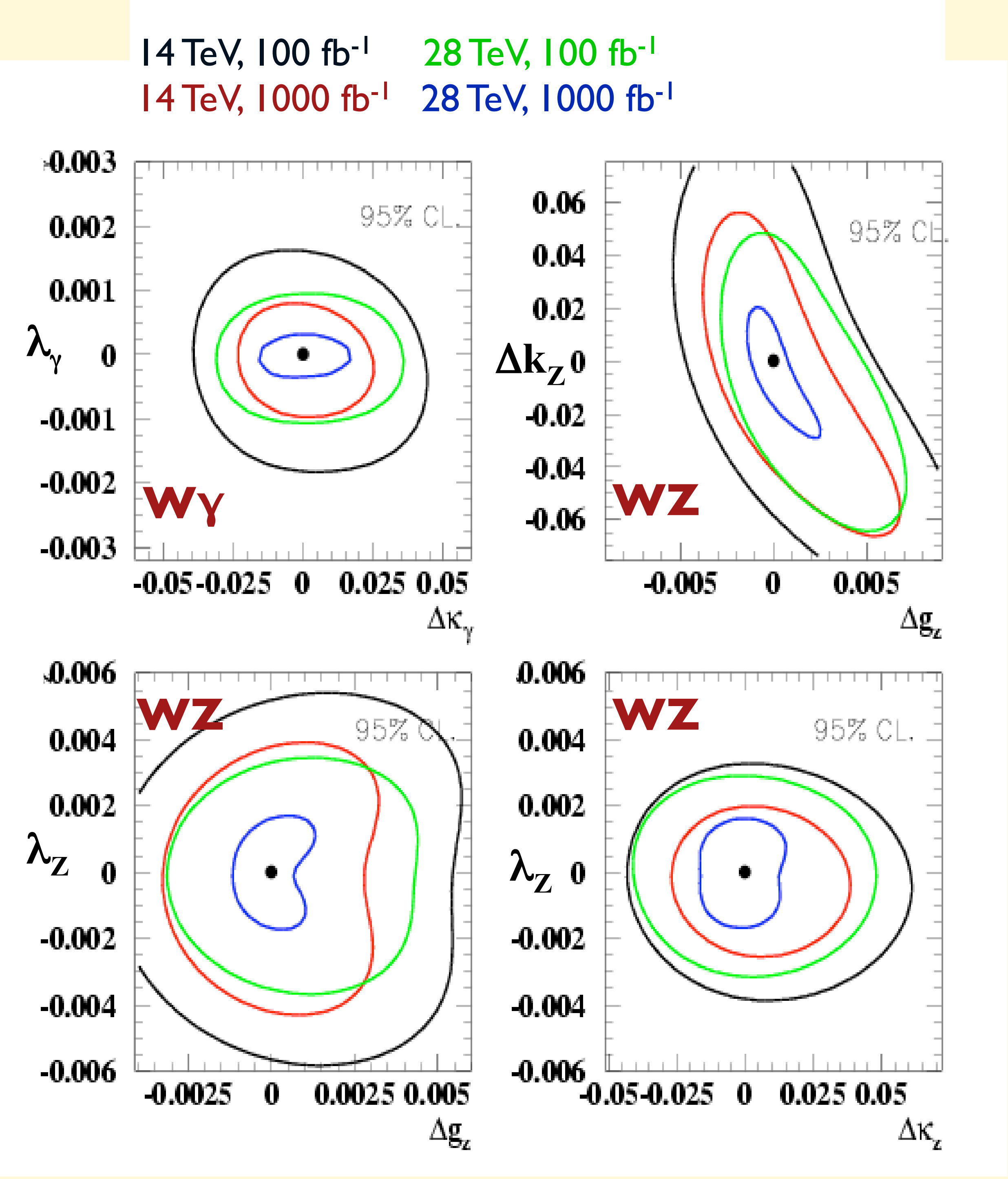
Coupling	14 TeV 100 fb^{-1}	14 TeV 1000 fb^{-1}	28 TeV 100 fb^{-1}	28 TeV 1000 fb^{-1}	LC 500 fb^{-1}, 500 GeV
λ_γ	0.0014	0.0006	0.0008	0.0002	0.0014
λ_Z	0.0028	0.0018	0.0023	0.009	0.0013
$\Delta\kappa_\gamma$	0.034	0.020	0.027	0.013	0.0010
$\Delta\kappa_Z$	0.040	0.034	0.036	0.013	0.0016
g^Z_1	0.0038	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



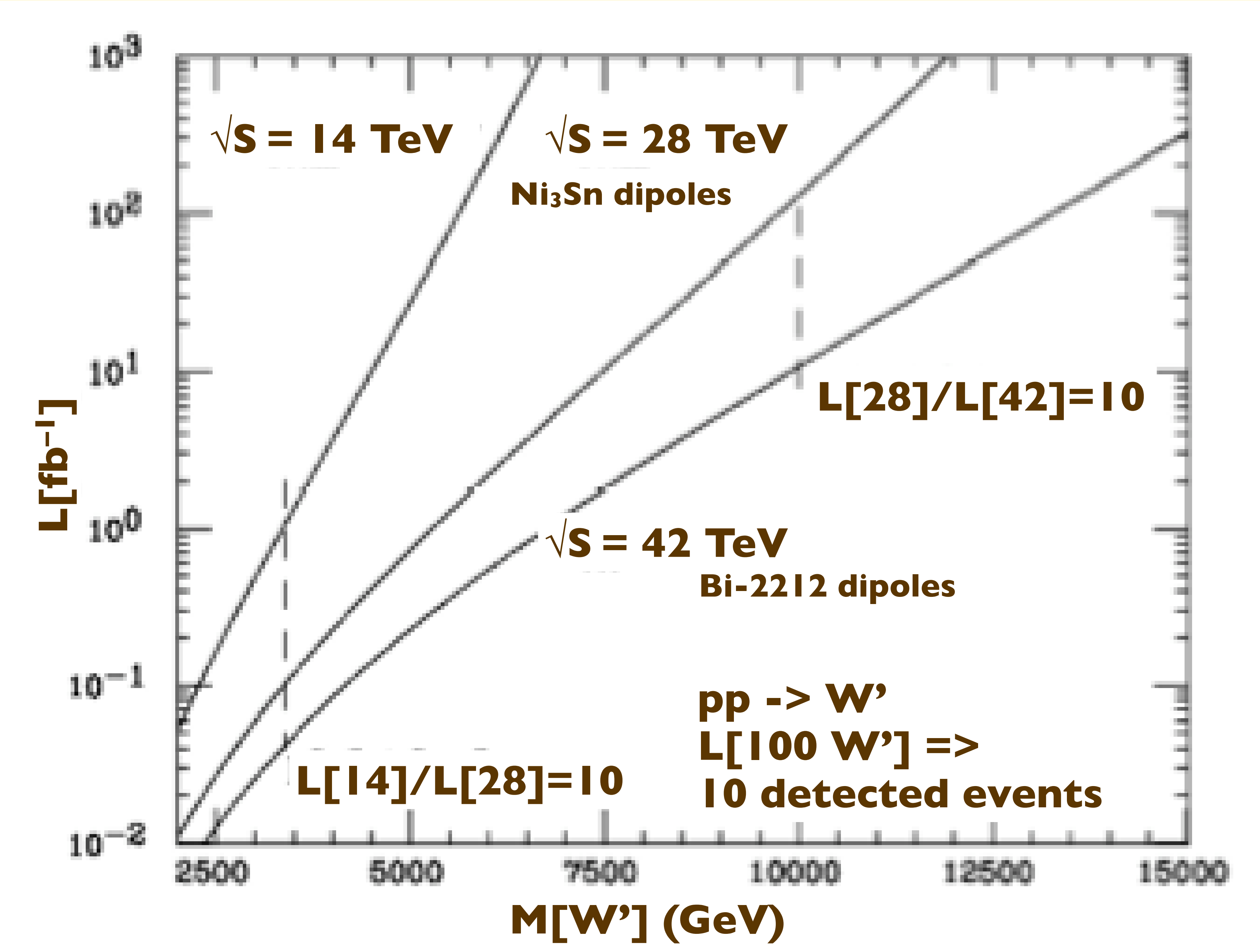
14 TeV, 100 fb-1
28 TeV, 100 fb-1
14 TeV, 1000 fb-1
28 TeV, 1000 fb-1
95% CL
Wγ
WZ
WZ
WZ
λγ
Δκγ
Δkz
Δgz
λz
Δgz
λz
Δκz
0.003
0.002
0.001
0
-0.001
-0.002
-0.003
-0.05 -0.025 0 0.025 0.05
0.06
0.04
0.02
0
-0.02
-0.04
-0.06
-0.005 0 0.005
0.006
0.004
0.002
0
-0.002
-0.004
-0.006
-0.0025 0 0.0025 0.005
0.006
0.004
0.002
0
-0.002
-0.004
-0.006
-0.05 -0.025 0 0.025 0.05

Benchmarks for detector performance at SLHC

The performance at 10^{34} should be taken as a minimal reference goal

Object	Physics benchmark	Performance benchmark	Detector issue
b jets & tau	Higgs identification, BR measurements	Tagging efficiency vs purity (statistics and bg suppression)	Tracking Pileup
b jets	Higgs mass determination, bg suppression	Mass resolution in the ~ 1-few x 100 GeV region	Pileup
fwd jets	Vector boson fusion: - measure H couplings - if no H, search strong WW phenomena	- jet tagging efficiency/fake rate vs jet E_T - jet E_T resolution	Final focus magnets: - acceptance - bg - resolution Pileup
cen jets	Jet vetoes for vector boson fusion Mass spectroscopy	fake rate mass resolution	Pileup Pileup
electrons	W/Z ID, SUSY decays, etc W'/Z' properties	ID efficiency vs fake rate	Pileup
muons	W/Z ID, SUSY and H decays, W'/Z' properties, etc.	Forward acceptance, fake rate	albedo forward efficiency final focus geometry

Luminosity vs energy



Comments

- Whether Energy or Luminosity is a better upgrade path depends on where and what the new physics is (unless Lum is allowed to increase with E as Lum ∝ S).
  - E.g. a 2 TeV Z' is requires more statistics, rather than more E

- **14 → 28 TeV** is great**, 14 → 42** is even better**, but 28 → 42** is probably not worth the cost**, thus 14 → 28 → 42 unlikely.** Implications for magnet R&D programme?

Discovering new physics will be the beginning, not the end!

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:

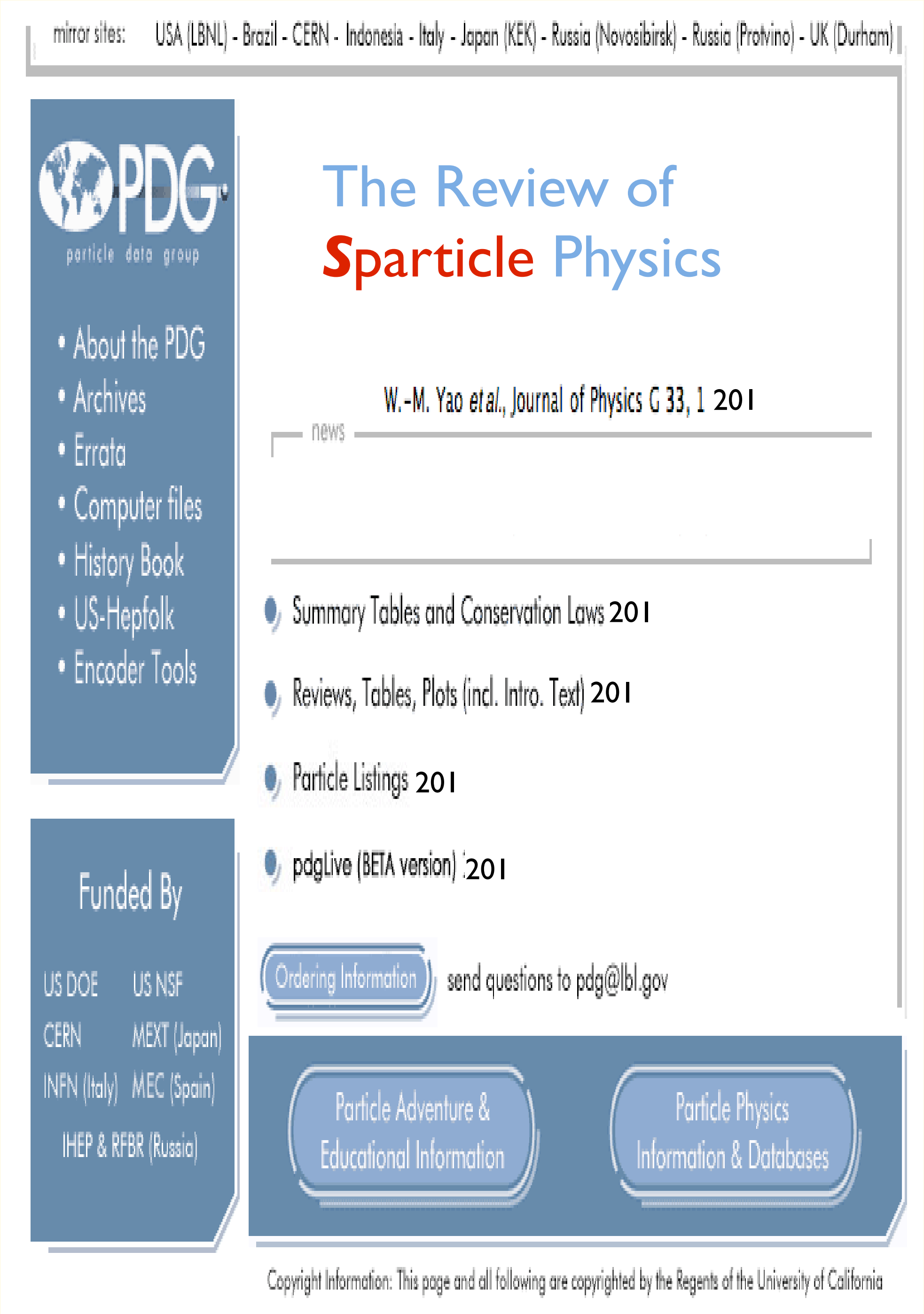
$$\tilde{t} \longrightarrow W\tilde{b}$$
$$\tilde{q}' \longrightarrow \tilde{q}$$

Slepton spectroscopy and mixing:

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

Gaugino spectroscopy:

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



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 ν physics and searches for Lepton Flavour Violation phenomena.

An role should be foreseen in the upgrade for a continued B-physics programme with LHCb

Conclusions

- Except for the Higgs, we cannot anticipate what will be discovered
- Any hint of new physics will require many years of work, and very diverse experimental inputs, to pin down the next "standard model"
- x10 Lum will
  - typically increase mass range for limits/discovery by 30%
  - improvement in measurements etc strongly dependend on final state and detector performance
- 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(few TeV)

➡ **demands for a x10 increase in the luminosity (and likely 2xenergy!) will likely be fully justified few years from now**

- Try to preserve a diverse programme, with a role for flavour physics as well