Physics motivations for the SLHC

CERN, Academic Training
June 8 2009

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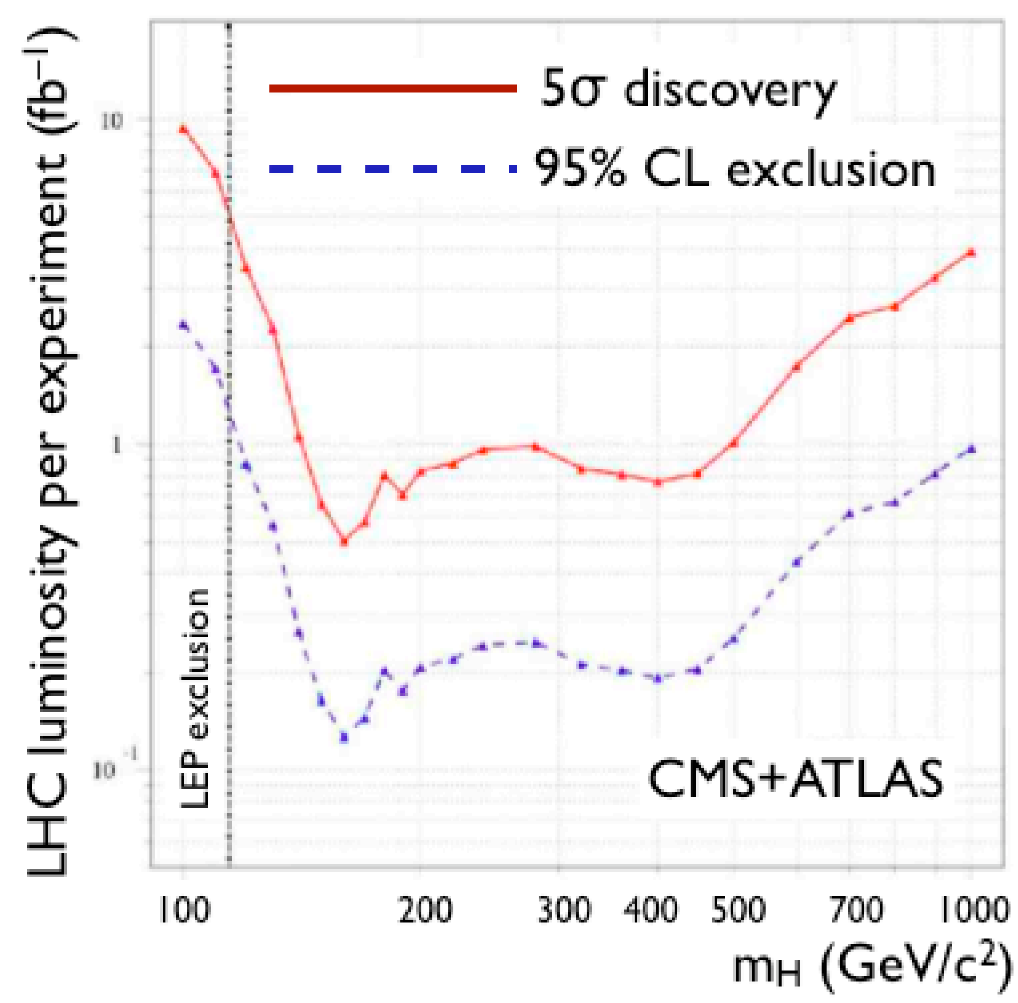
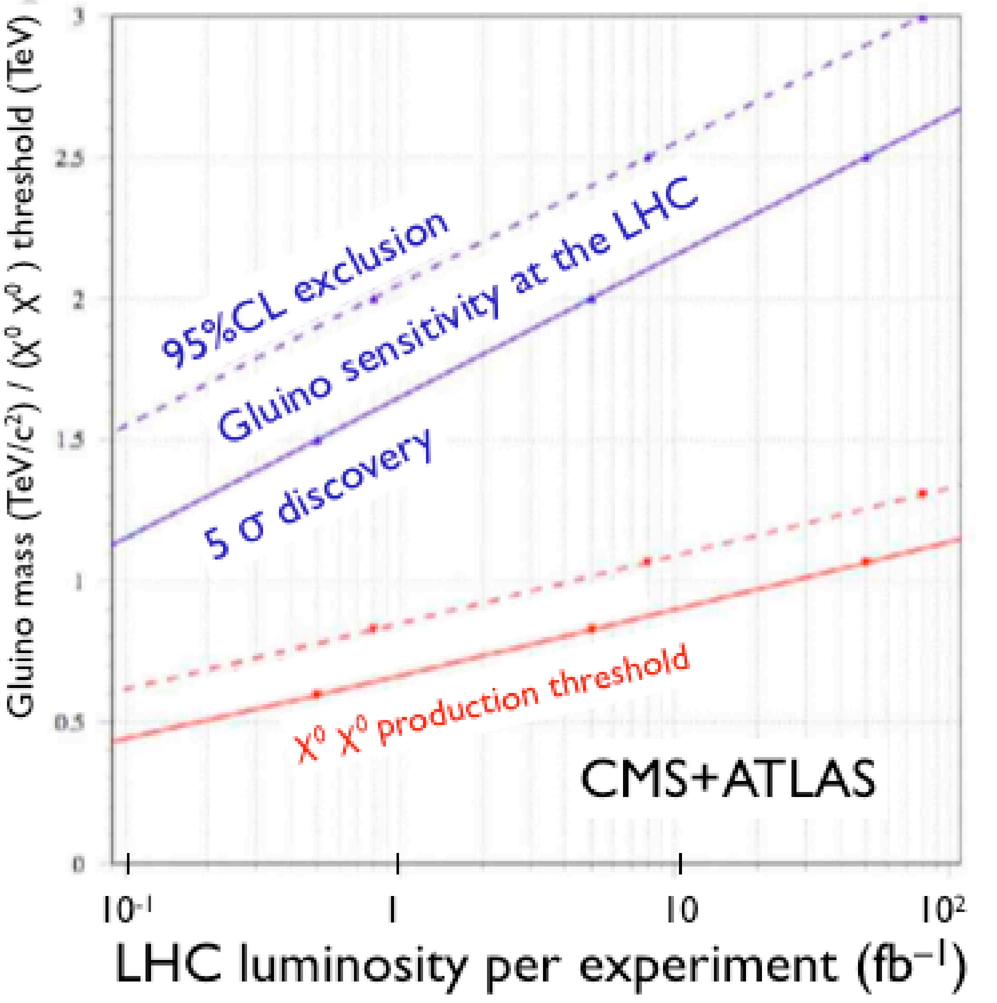
For more details see:
F. Gianotti et al, Eur.Phys.J.C39:293-333,2005, http://arxiv.org/pdf/hep-ph/0204087
D. Denegri, presentation at HHH 04:
http://care-hhh.web.cern.ch/CARE-HHH/HHH-2004/default.html

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





By 2012 we should already have a whole new 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

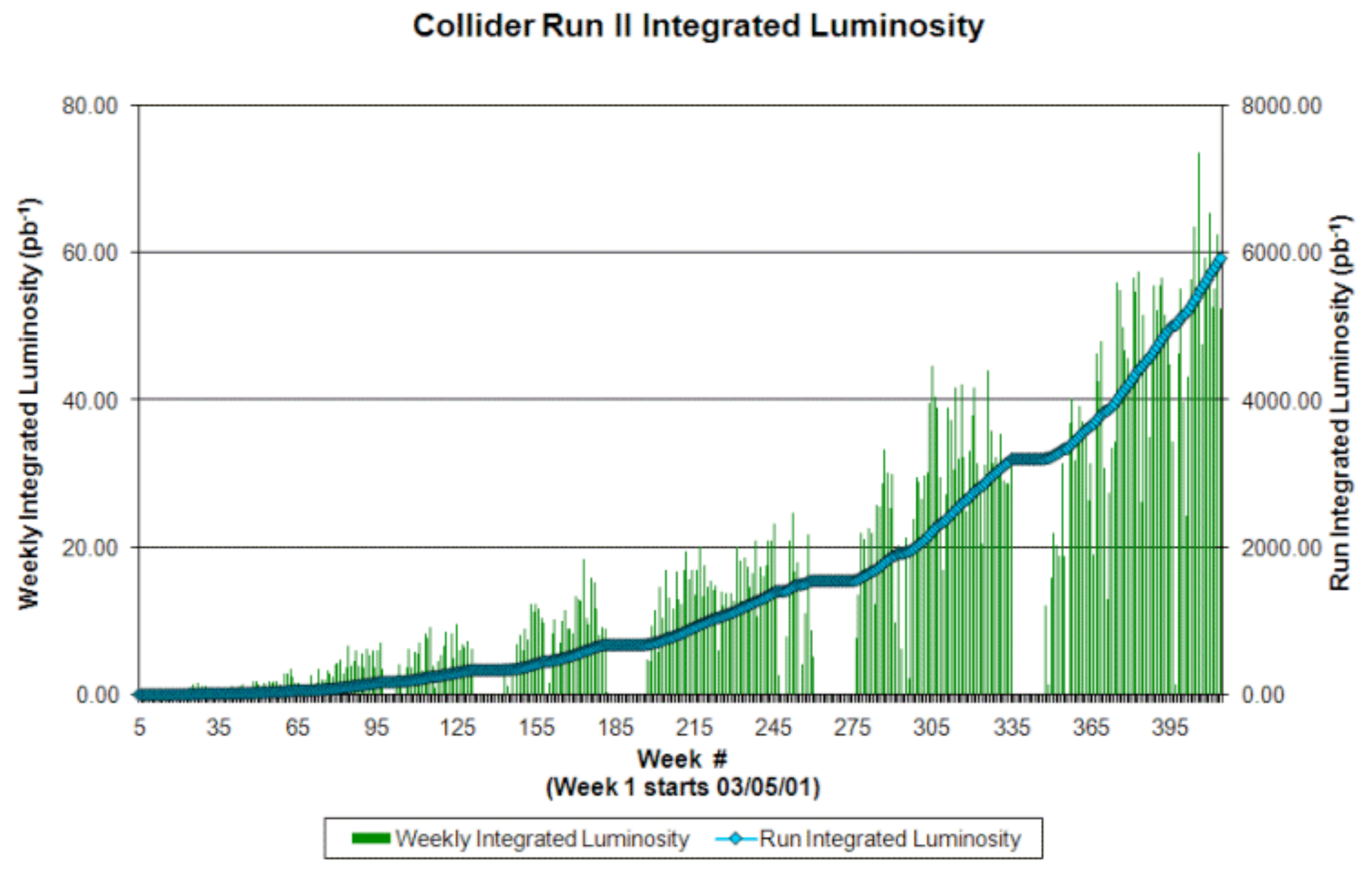
It’s difficult to imagine that it will take less to establish in full the nature of the new physics to be unveiled by the LHC

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

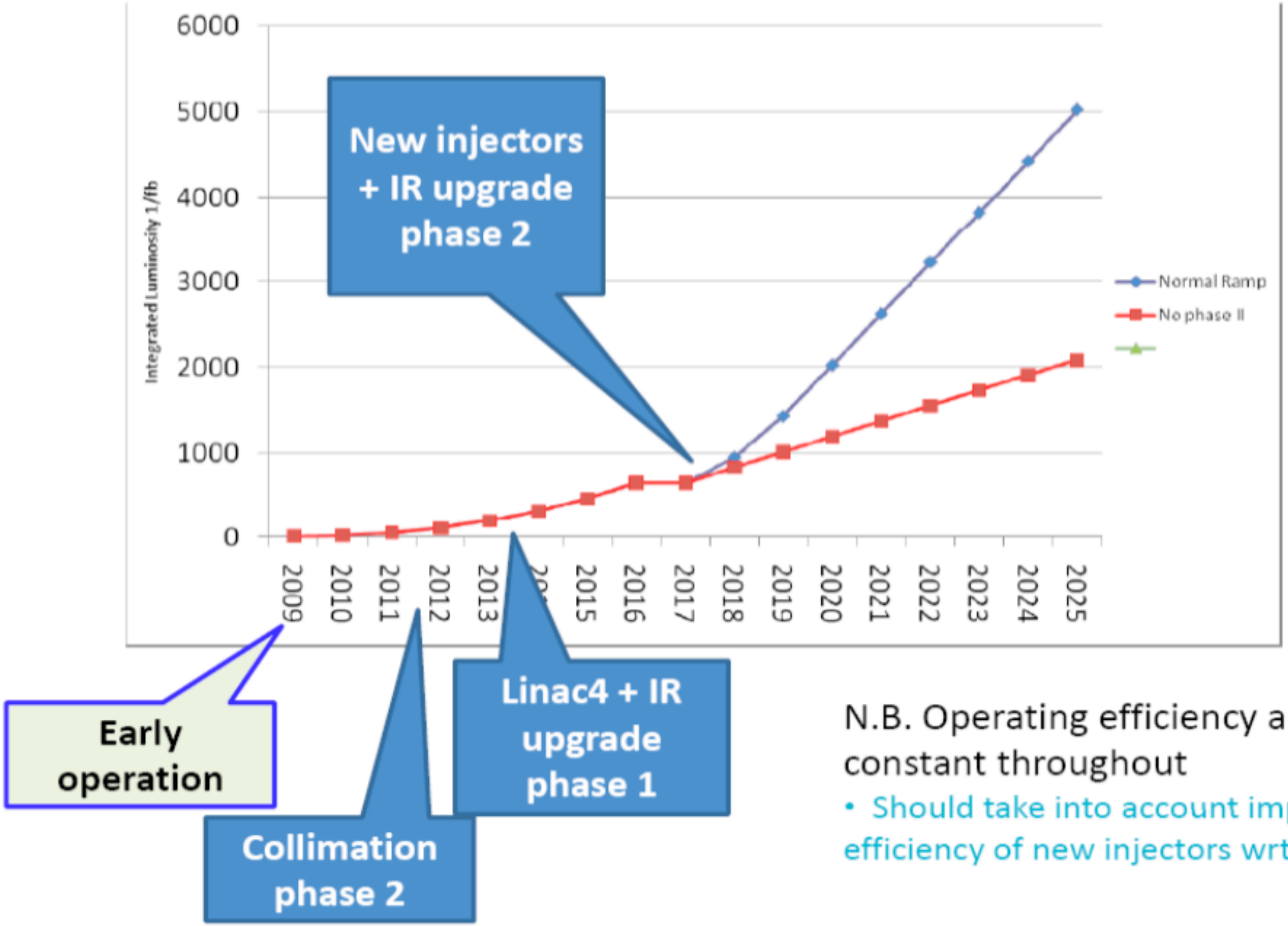
The Tevatron as an example:

- 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: ΔM_W = 48 MeV, D-Dbar mixing
- 2008: $\Delta M_{top} \sim 1.4$ GeV
- 2008: SM-level sensitivity to Higgs at M(H)~170 GeV
- B physics, exotic spectroscopy, PDF constraints, etc.etc.
- ....
- 2012: 3-σ sensitivity to SM Higgs, $B_S \to \mu^+\mu^-$, ... ???? !!!! .....

The key to this longevity is steady luminosity increases



The projected lum profile with the SLHC



New injectors + IR upgrade phase 2

Early operation

Collimation phase 2

Linac4 + IR upgrade phase 1

N.B. Operating efficiency assumed constant throughout

- Should take into account improved efficiency of new injectors wrt. old.

What can we achieve with more 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. Extend sensitivity to 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

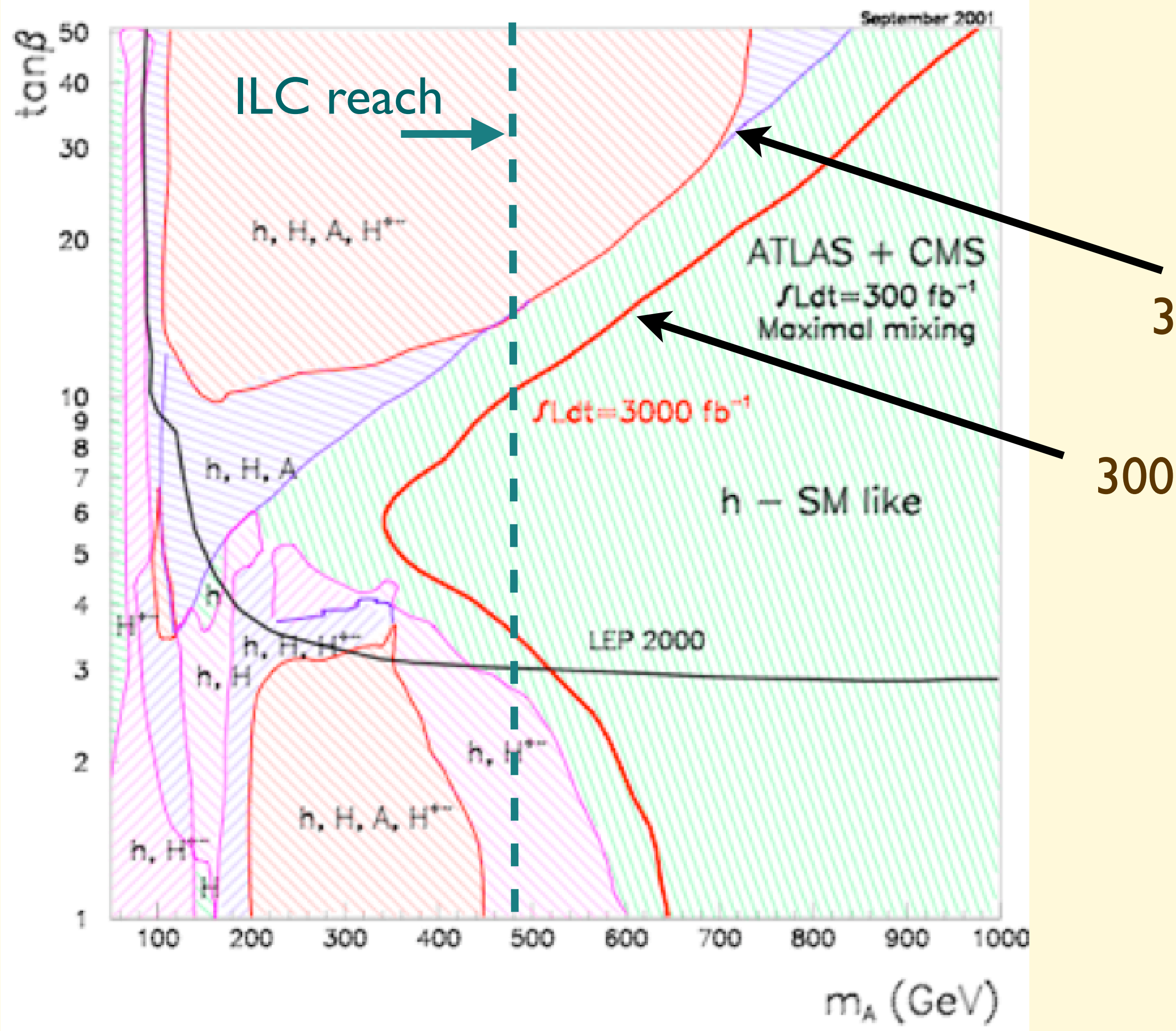
Very high masses, energies, rather insensititive to high-lum environment.
Not very demanding on detector performance
Slightly degraded detector performance tolerable

EW symmetry breaking

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)



ILC reach

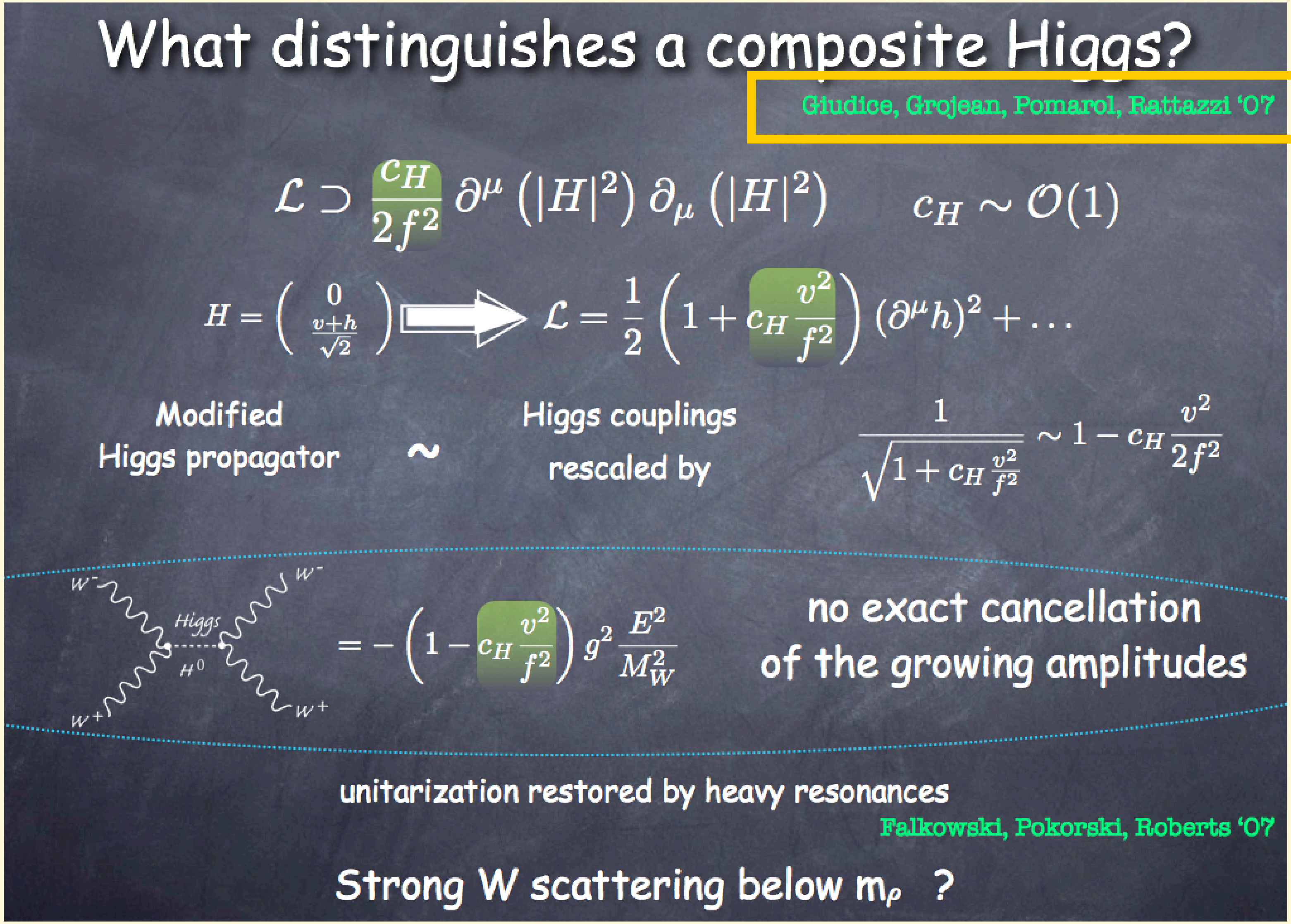
300 fb^{-1}

3000 fb^{-1}

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**

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

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

Modified Higgs propagator ~ 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 ?

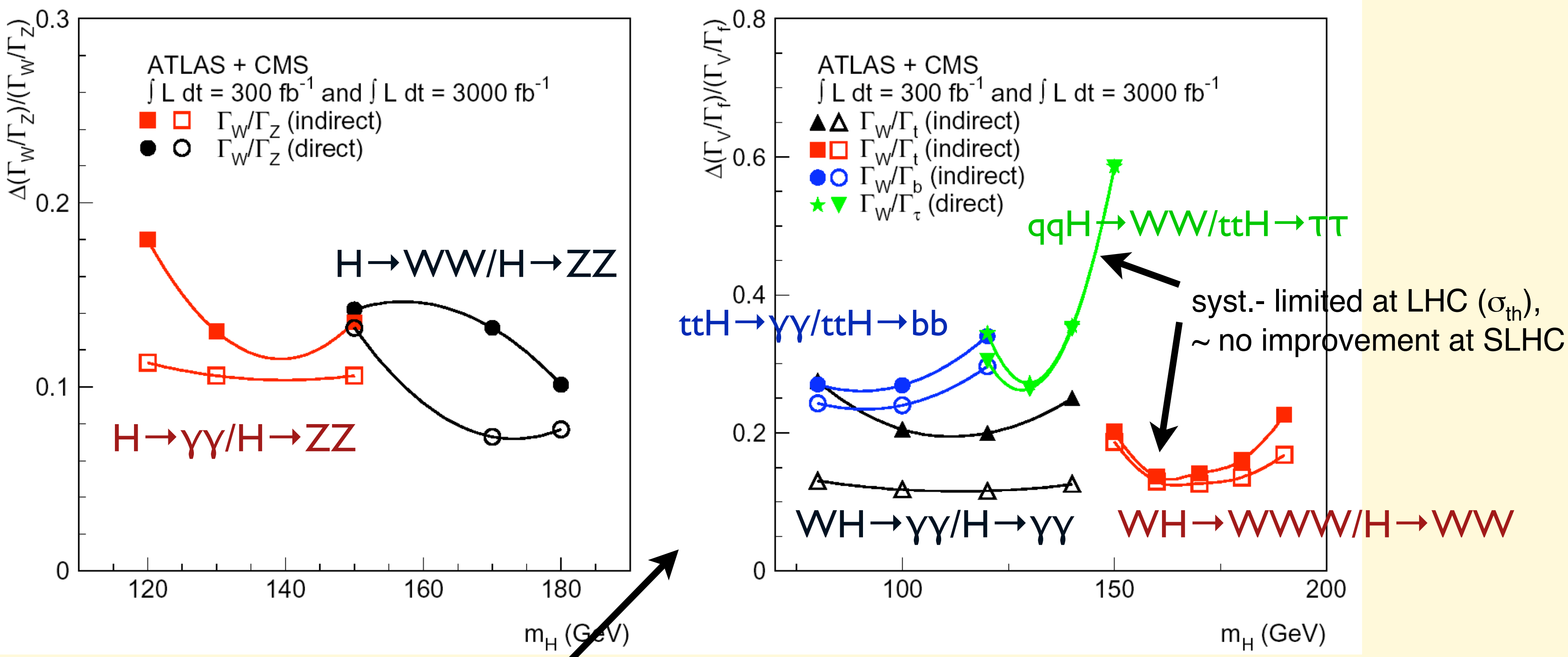
- Higgs anomalous couplings
- strong WW scattering
- strong HH production
- gauge bosons self-couplings

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

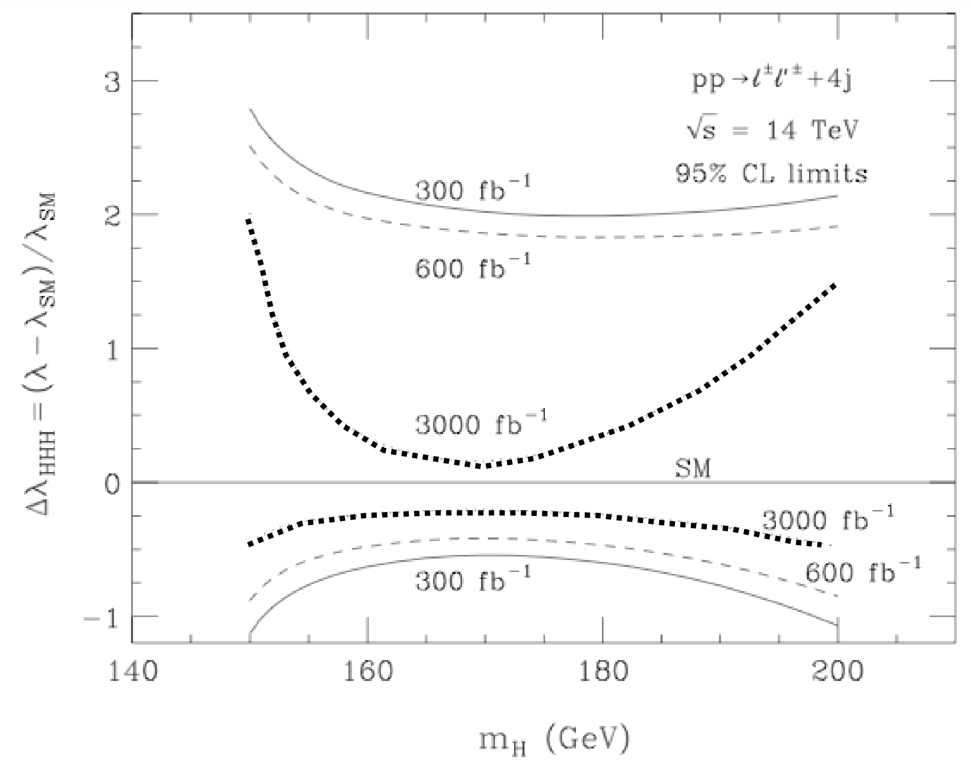
List of issues

- 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

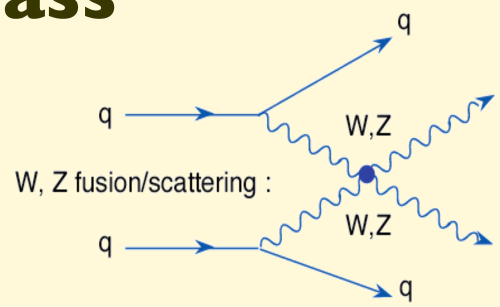
Rare Higgs decay modes

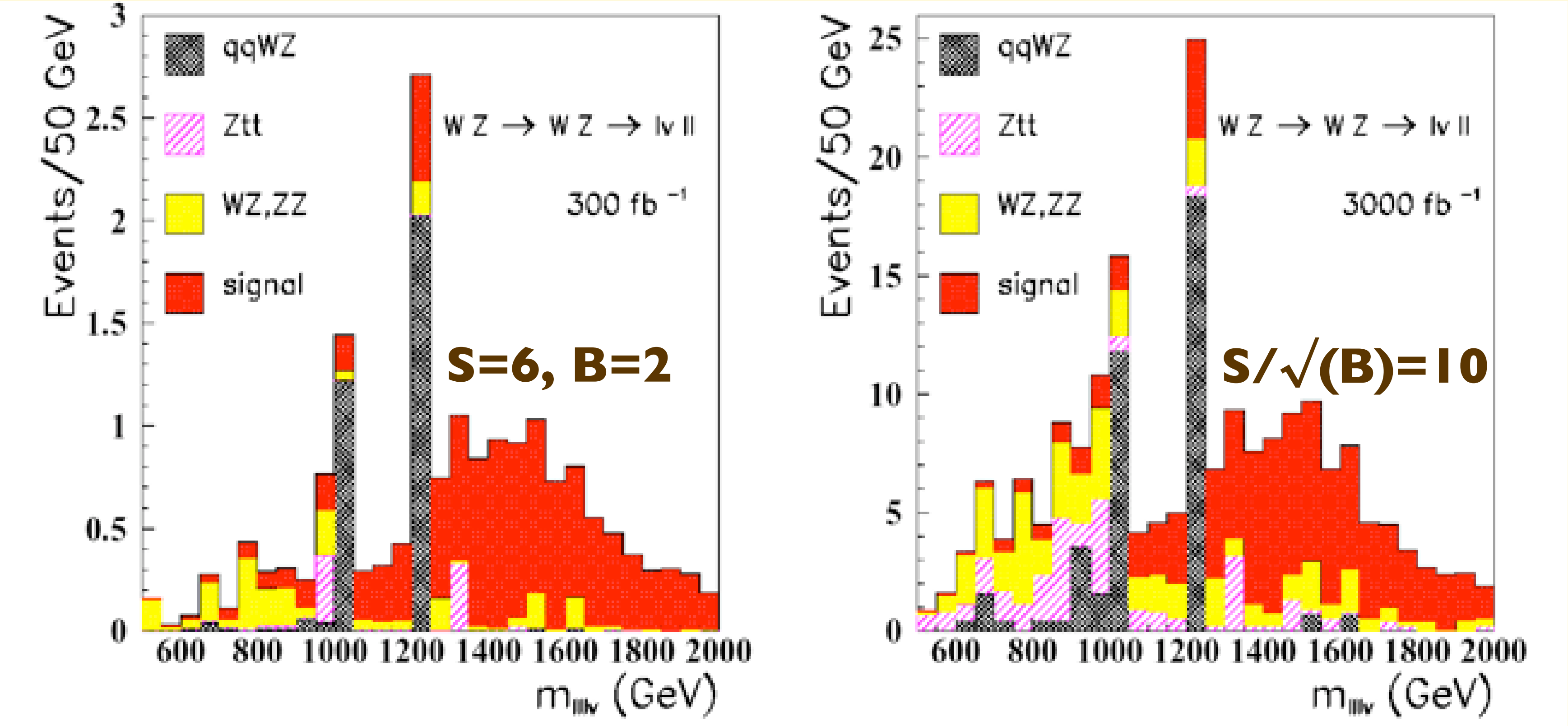
	$600\ \text{fb}^{-1}$	$6000\ \text{fb}^{-1}$
$H \to Z\gamma$	$3.5\ \sigma$	$11\ \sigma$
$H \to \mu^+\mu^-$	$< 3.5\ \sigma$	$\sim 7\ \sigma$

Han, McElrath, hep-ph/0201023

m[H] ~ [110-140] GeV

Strong resonances in high-mass WW or WZ scattering

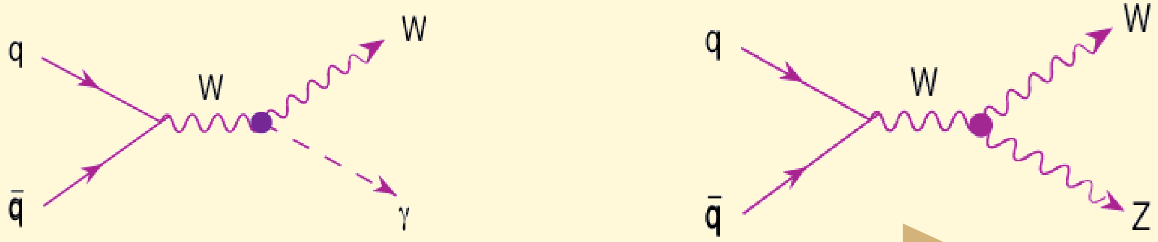




Vector resonance (ρ-like) in $W_L Z_L$ scattering from Chiral Lagrangian model
M = 1.5 TeV, leptonic final states, 300 fb^{-1} (LHC) vs 3000 fb^{-1} (SLHC)

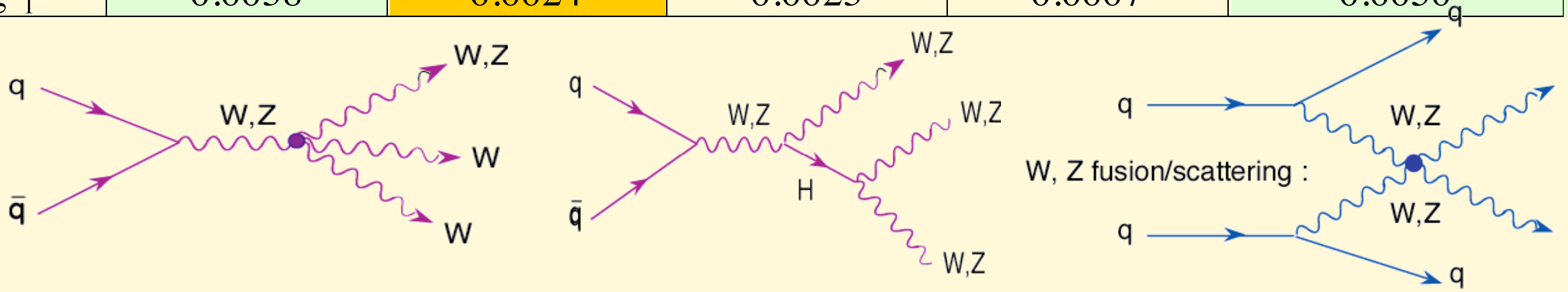
Precise determinations of the self-couplings of EW gauge bosons

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

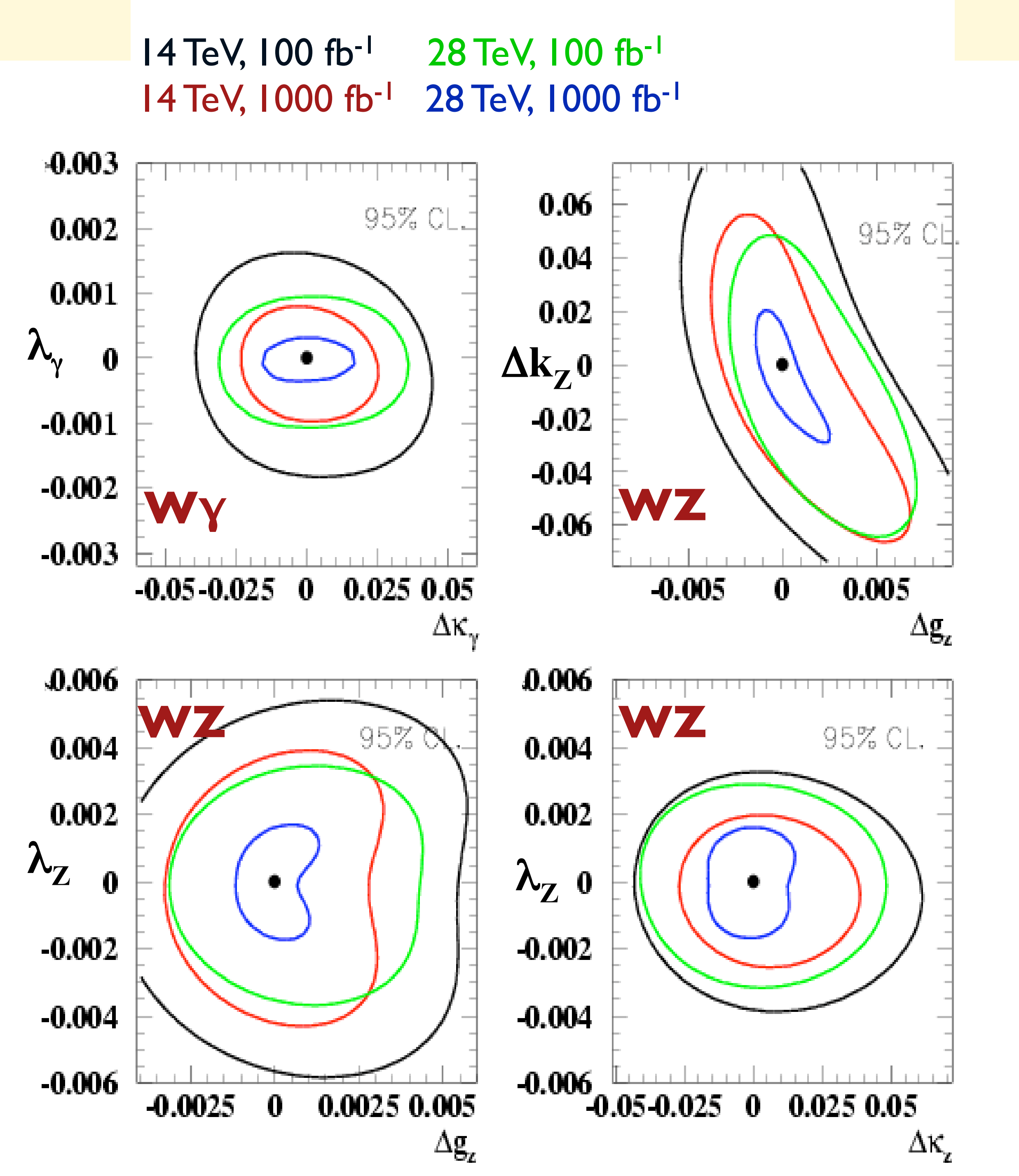


LHC options

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}

Top properties

1) tbW coupling

$$\begin{aligned}\mathcal{L} \;=\; & -\frac{g}{\sqrt{2}}\bar{b}\,\gamma^{\mu}\left(V_L P_L + V_R P_R\right) t\, W_{\mu}^{-} \\ & -\frac{g}{\sqrt{2}}\bar{b}\,\frac{i\sigma^{\mu\nu}q_{\nu}}{M_W}\left(g_L P_L + g_R P_R\right) t\, W_{\mu}^{-} + \mathrm{h.c.}\end{aligned}$$

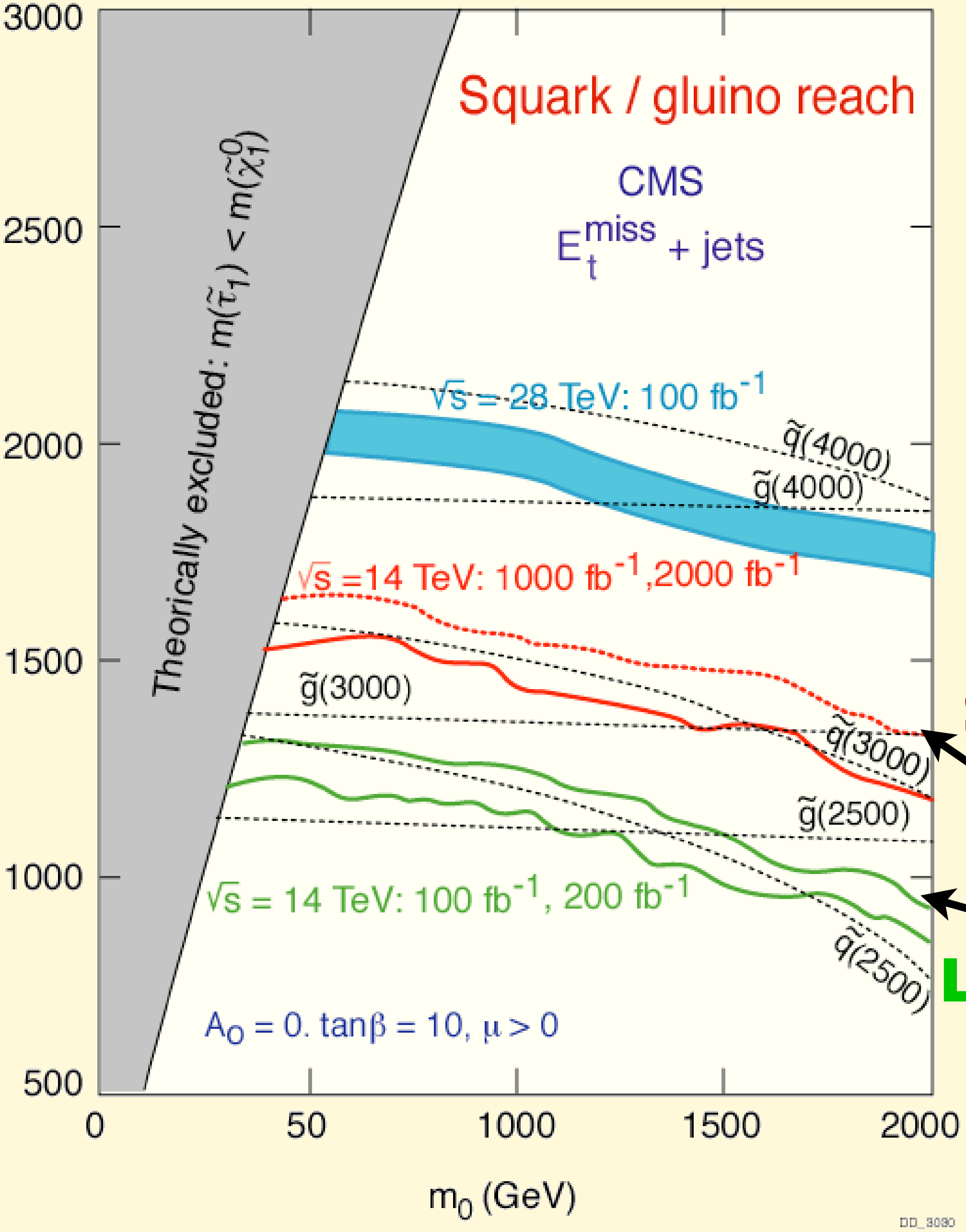
Probe anomalous couplings by measuring lepton FB asymmetry in the top rest frame

1σ limits:	min	max
V_R	-0.10	0.16
g_L	-0.08	0.05
g_R	-0.02	0.02

2) FCNC decays

BR	SM	2-Higgs	SUSY RPV	exotic Qs	Today	LHC 100fb-1
t→qZ	10^{-13}	$\leq 10^{-6}$	$\leq 10^{-4}$	$\leq 10^{-2}$	≤ 0.08 (LEP)	$\leq 6.5 \times 10^{-5}$
t→qγ	10^{-13}	$\leq 10^{-7}$	$\leq 10^{-5}$	$\leq 10^{-5}$	≤ 0.003 (HERA)	$\leq 1.8 \times 10^{-5}$
t→qg	10^{-11}	$\leq 10^{-5}$	$\leq 10^{-3}$	$\leq 10^{-4}$	≤ 0.29 (CDF)	$\leq 4.3 \times 10^{-4}$

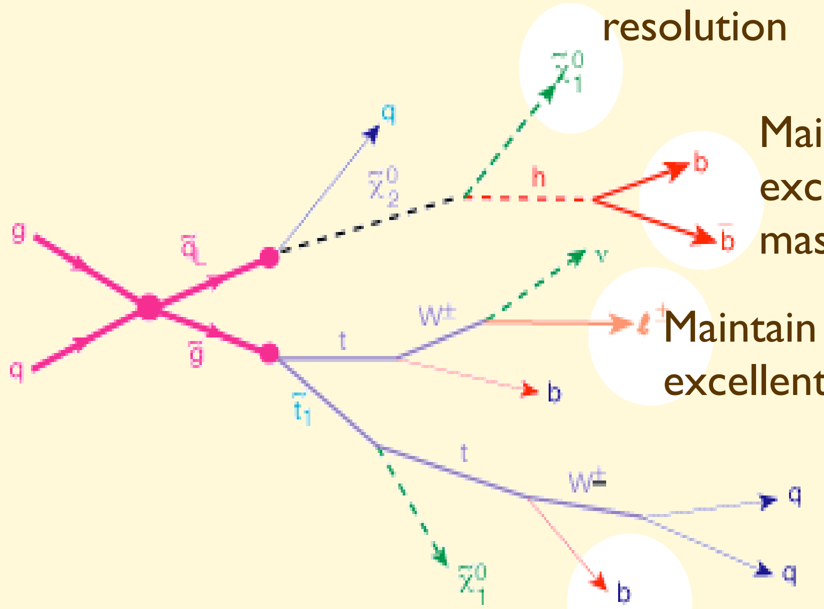
SUSY reach and studies



SLHC

LHC

M reach ~ 500 GeV more than LHC



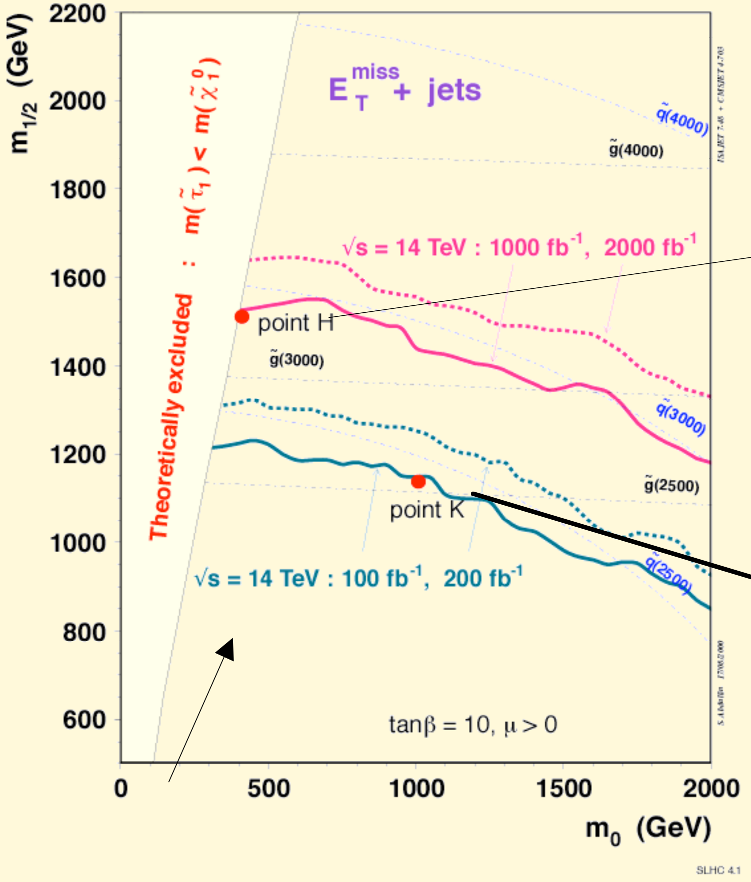
Maintain
excellent MET
resolution

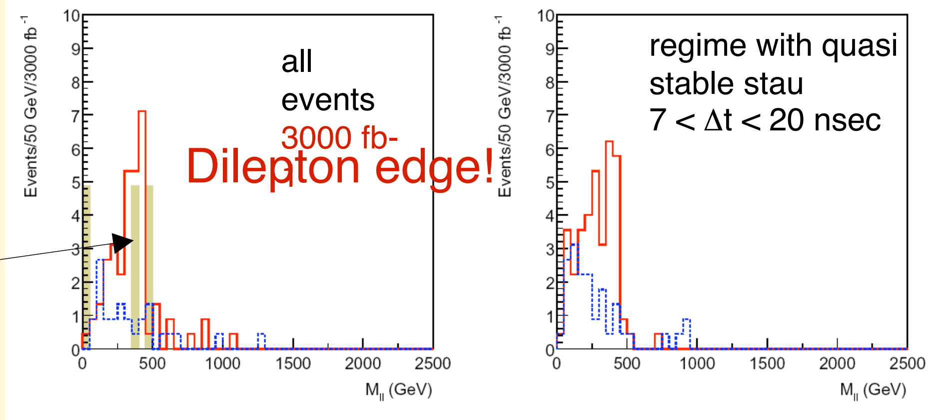
Maintain
excellent bb
mass resolution

Maintain
excellent lept ID

Maintain
excellent b
tagging eff

Sparticle spectroscopy



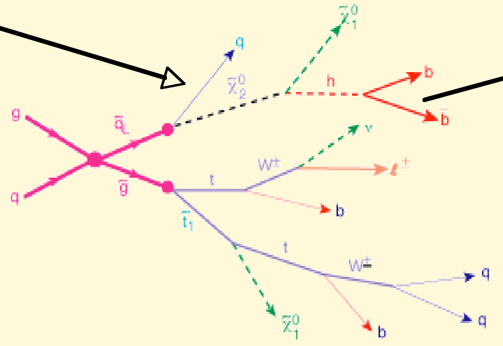


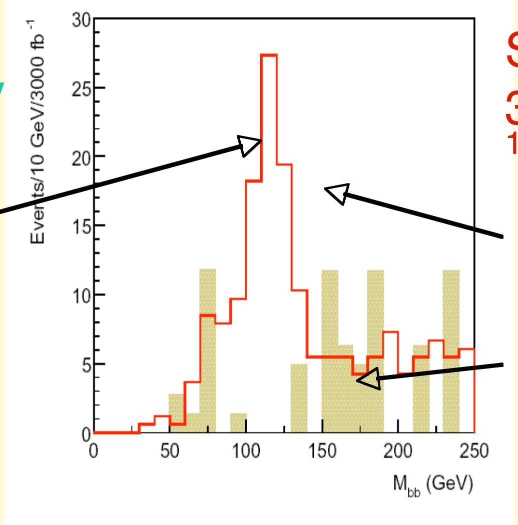
all events 3000 fb-1

Dilepton edge!

regime with quasi stable stau
7 < Δt < 20 nsec

Point K:
m(squark,gluino) > 2 TeV





SLHC
3000 fb-1

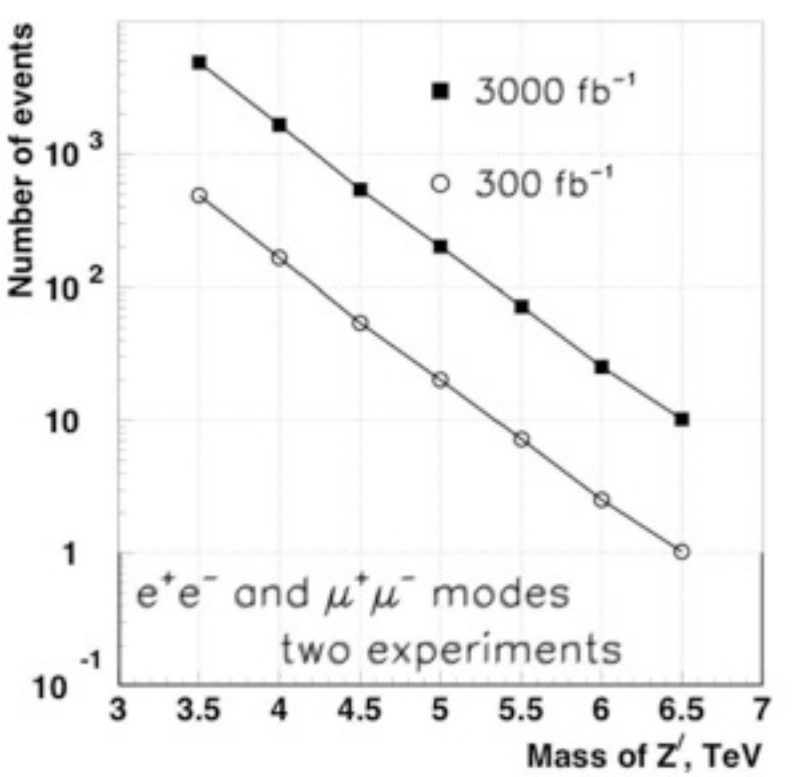
h → bb
signal

SM bkgd

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'

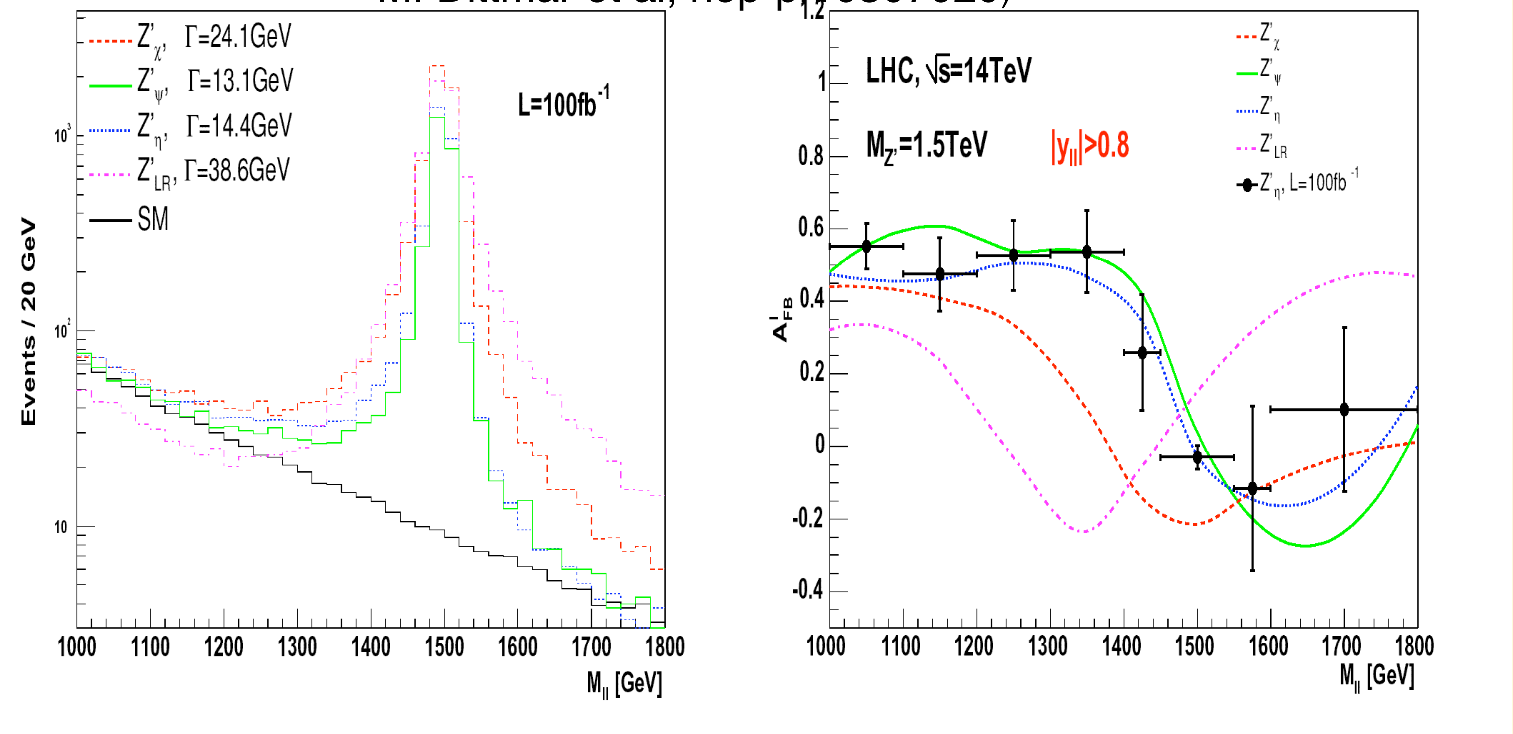
E.g. a W' coupling to R-handed fermions, to reestablish at high energy the R/L symmetry



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

Differentiating among different Z' models:

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

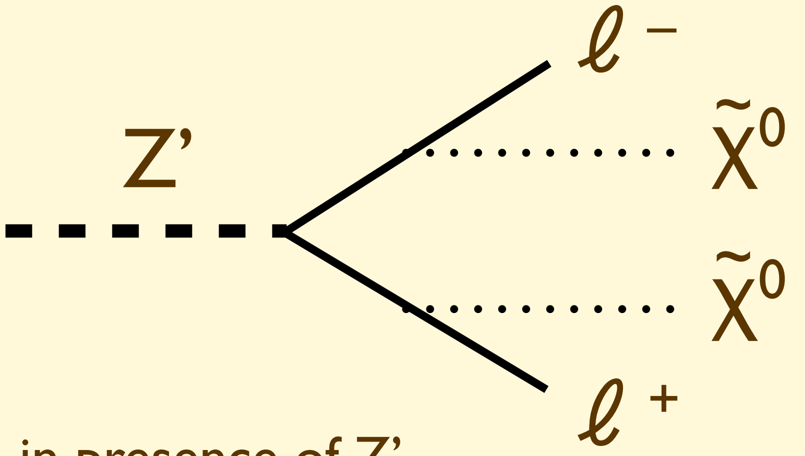


100 fb^{-1} model discrimination up to 2.5 TeV

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

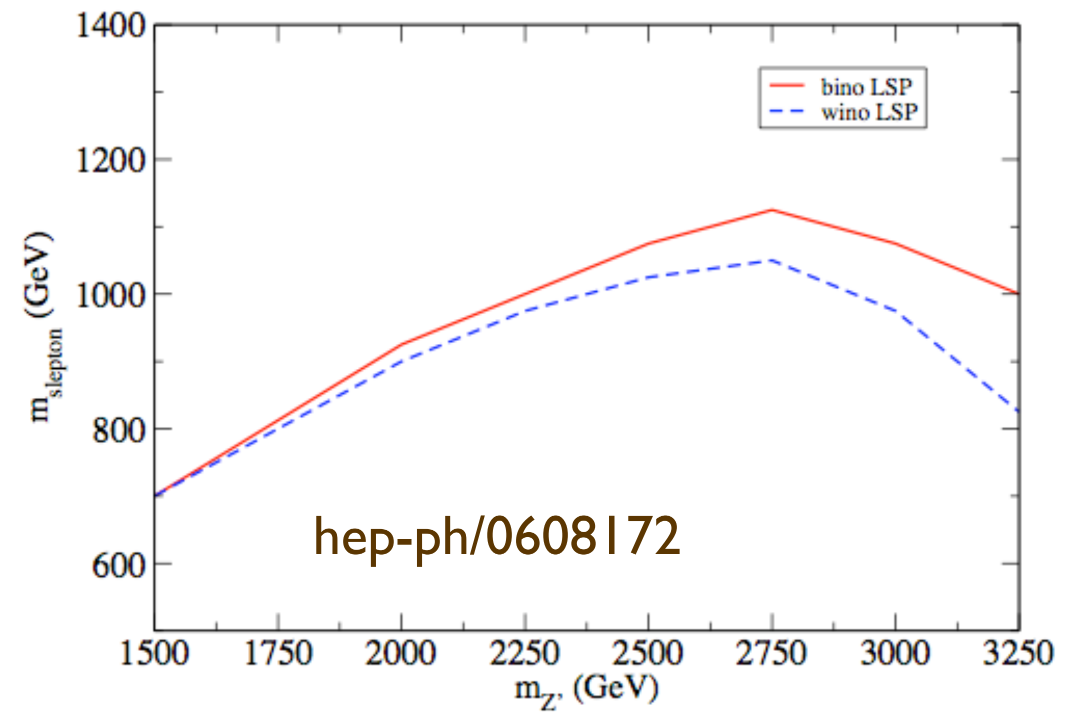
E.g., in Supersymmetry

$Z' \to \tilde{\ell}^{\,+}\ \tilde{\ell}^{\,-}$



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')



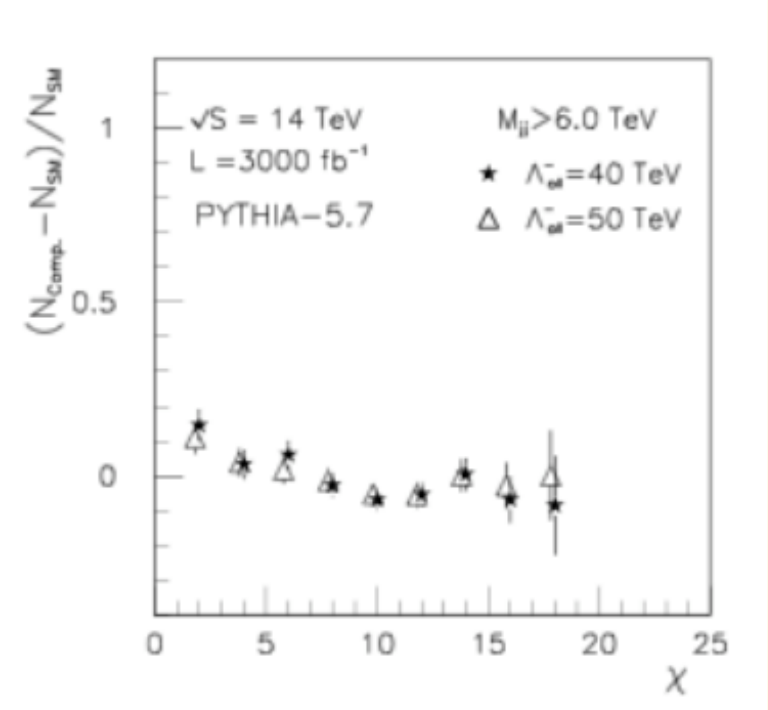
hep-ph/0608172

Matthew Baumgart, Thomas Hartman, Can Kilic, Lian-Tao Wang

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}
Λ(TeV)	> 40	> 60	> 60	> 85

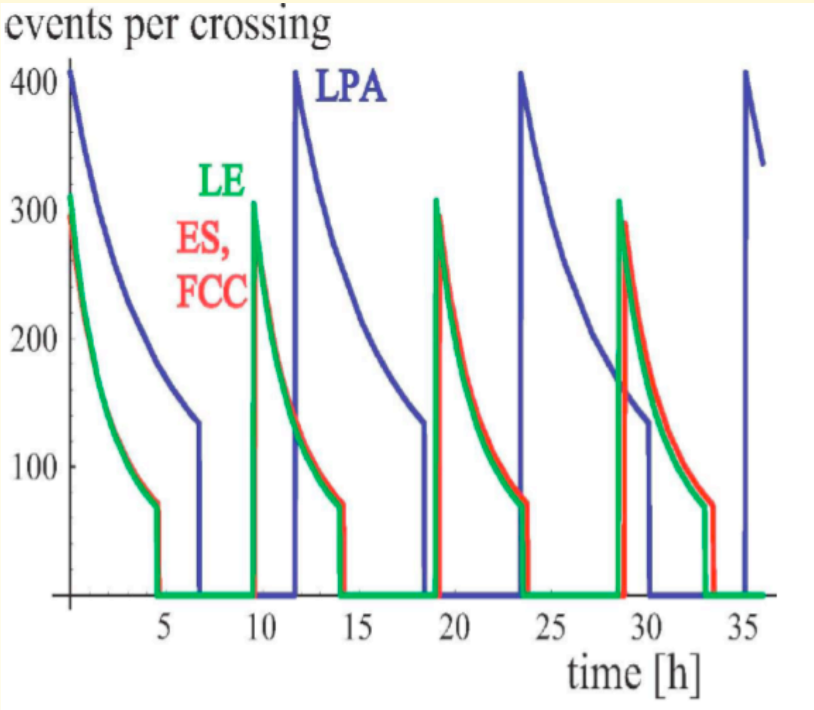
More

- Flavour physics:
    - an essential part of the LHC programme
    - LHCb phase-I upgrade, work in progress
    - role in phase II ?
- Heavy ions?

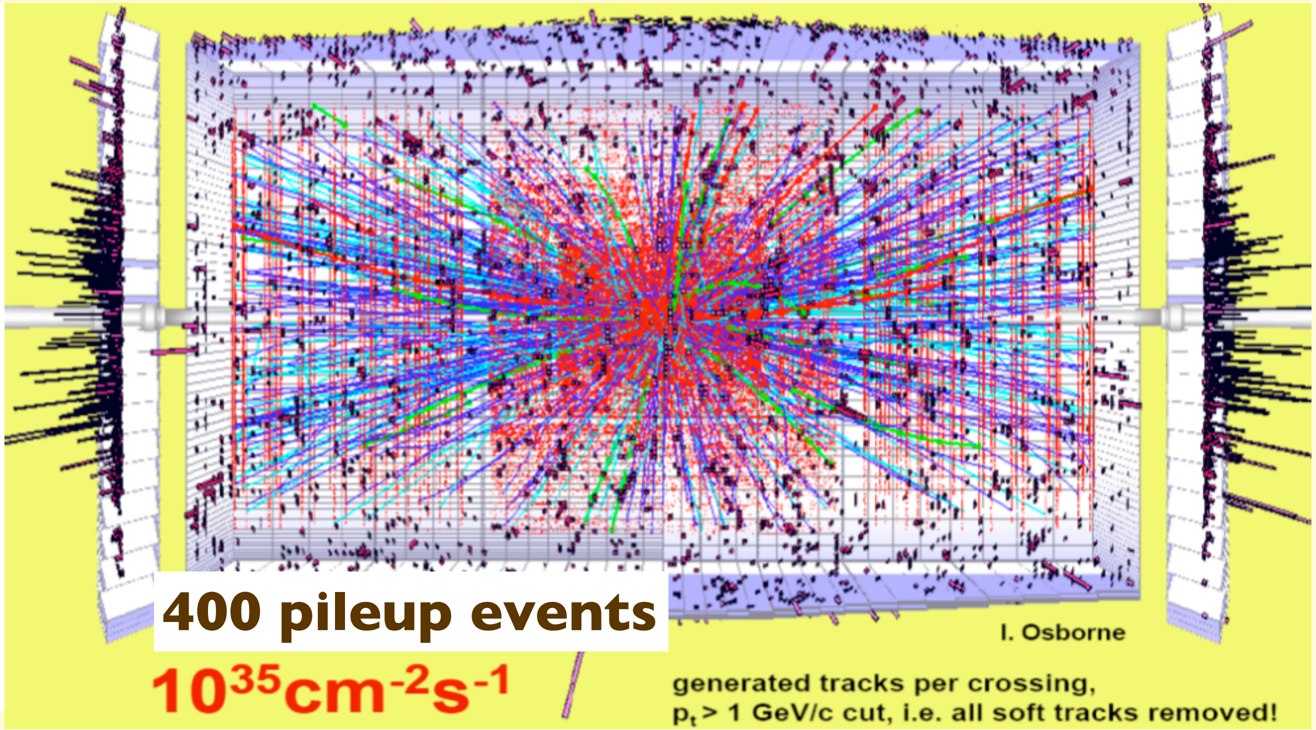
Limitations of the current assessment of the physics potential

- Actual potential heavily depends on the detector performance in the high-luminosity regime
- Only realistic detector simulations, including the details of the running conditions and of the detector configurations, can provide reliable results
- These are missing since both running conditions and detector configs are too crudely determined today to do a complete job
- The studies documented so far assumed a performance of the upgraded detectors at 10^{35} equal to performance at 10^{34} (except for some degradation in muon acceptance and fwd calorimeter resolution)
- ⇒ **See Marzio Nessi lecture tomorrow !!**

Example: Pile-up



Lum profiles of 4 different upgrade scenarios



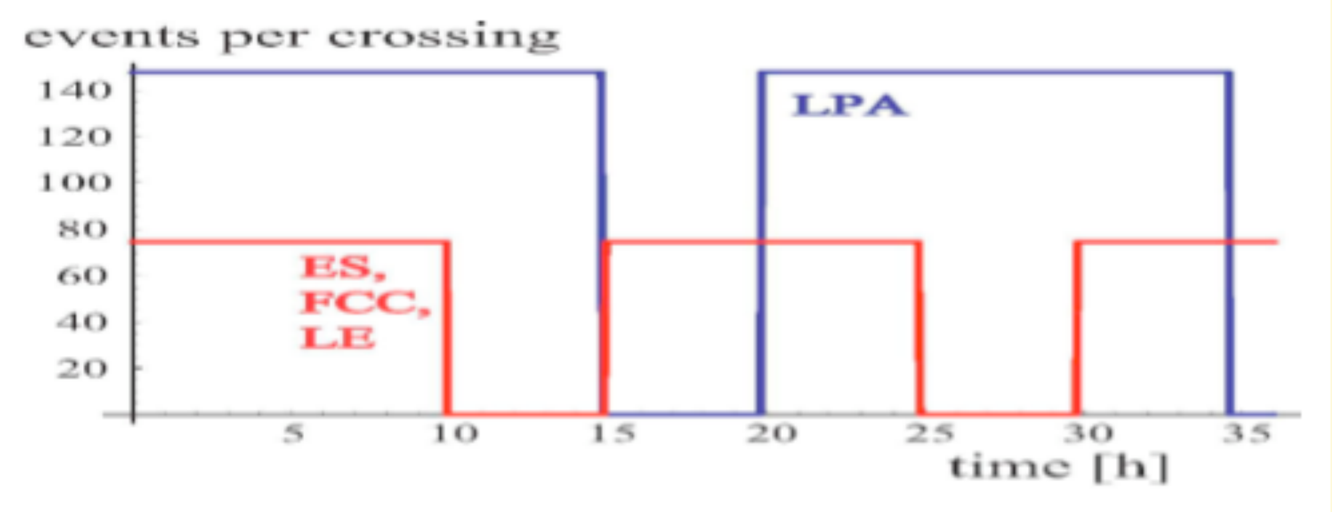
400 pileup events

$10^{35}\mathrm{cm}^{-2}\mathrm{s}^{-1}$

I. Osborne

generated tracks per crossing, $p_t > 1$ GeV/c cut, i.e. all soft tracks removed!

Things could improve with Luminosity leveling:

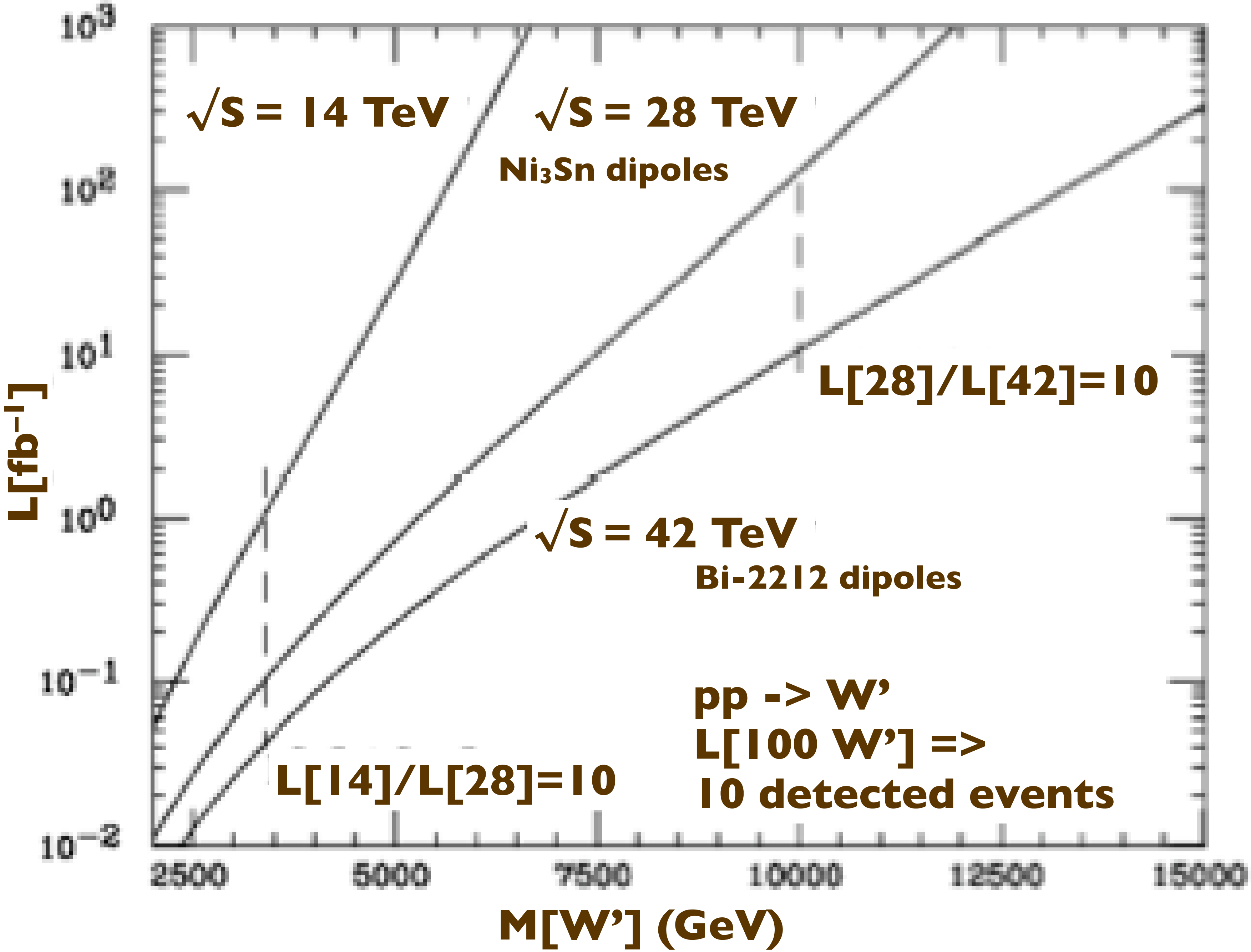


Benchmarks for detector performance at SLHC

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 - strong WW scattering	- 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	fake rate	Pileup
	Mass spectroscopy	mass resolution	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?

Final remarks

- It is far too early to assess the concrete potential of the SLHC to explore the consequences of the LHC findings
  - we don't know what these findings are ....
  - .... thus we don't know how to optimize the detectors/machine
- The LHC remains, nevertheless, the only concrete prospect available within the time scale of ~ 15-20 years to gain a deeper insight in the issue of EWSB, and **all possible ways to push its performance should be explored**
- The lesson from the Tevatron is that once data are available, the experimental ingenuity can deliver the "impossible":
  - b tagging, B_S mixing, ...
  - M[W] to less than 40 MeV, M[top] to 1 GeV,
- The challenge to operate both accelerator and detectors at $L=10^{35}$ is nevertheless formidable. Once more is known about the physics landscape, an appropriate optimization between luminosity and detector performance can lead to great improvements