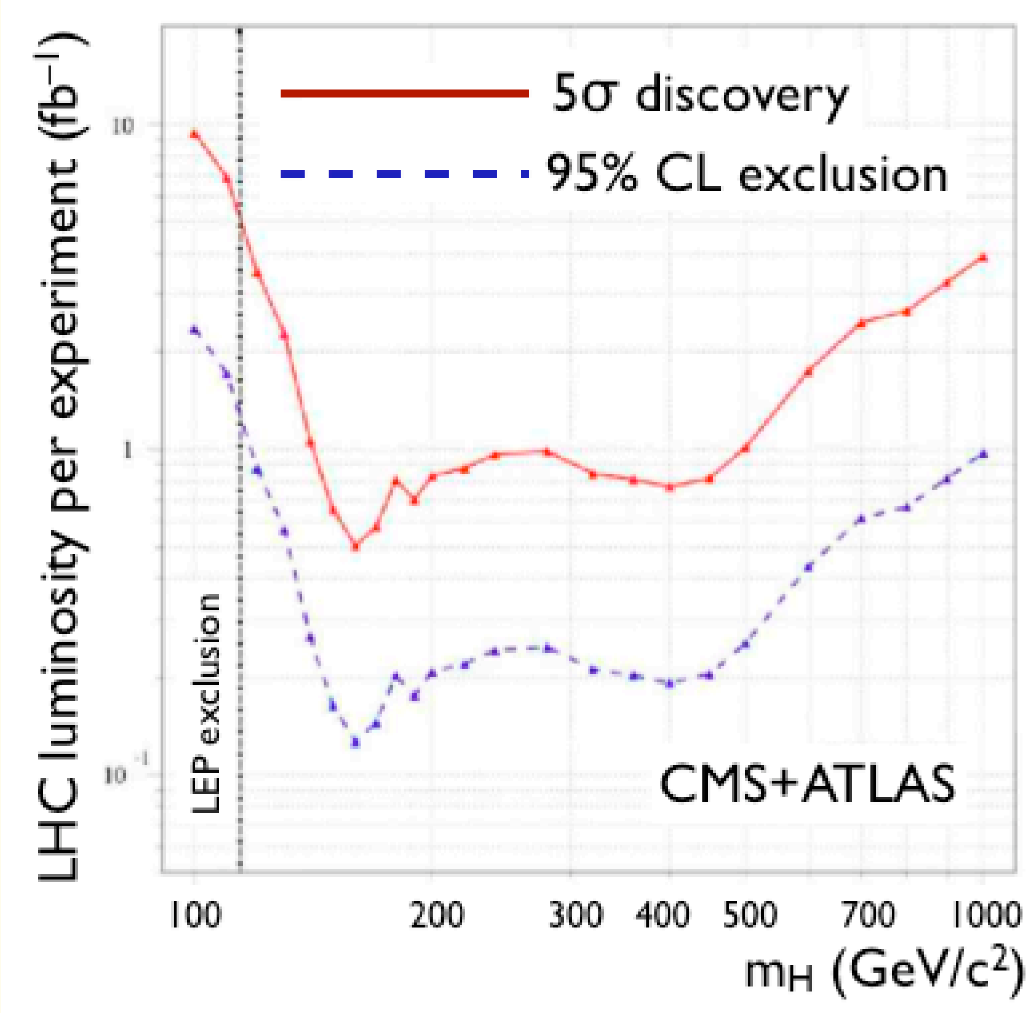
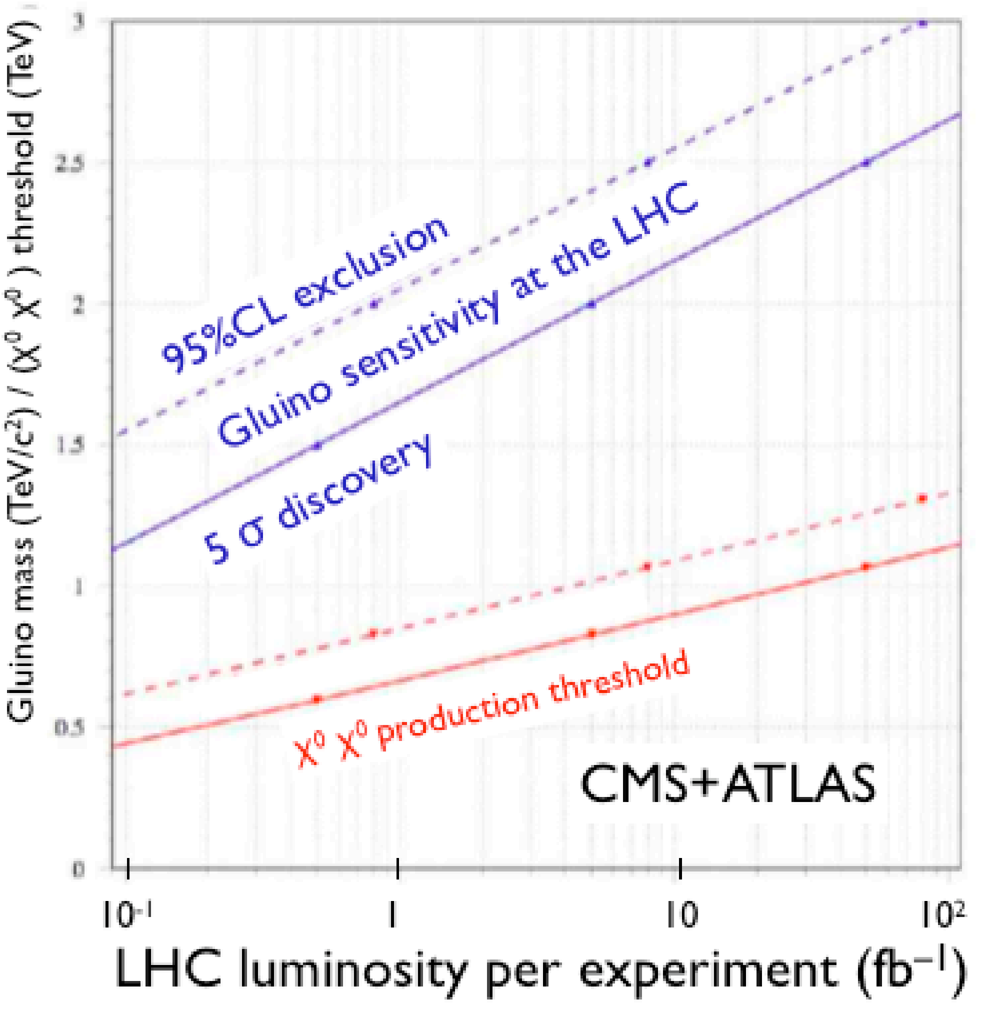
The road from LHC to SLHC to LCs

CLIC Workshop
CERN, October 18 2007

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

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

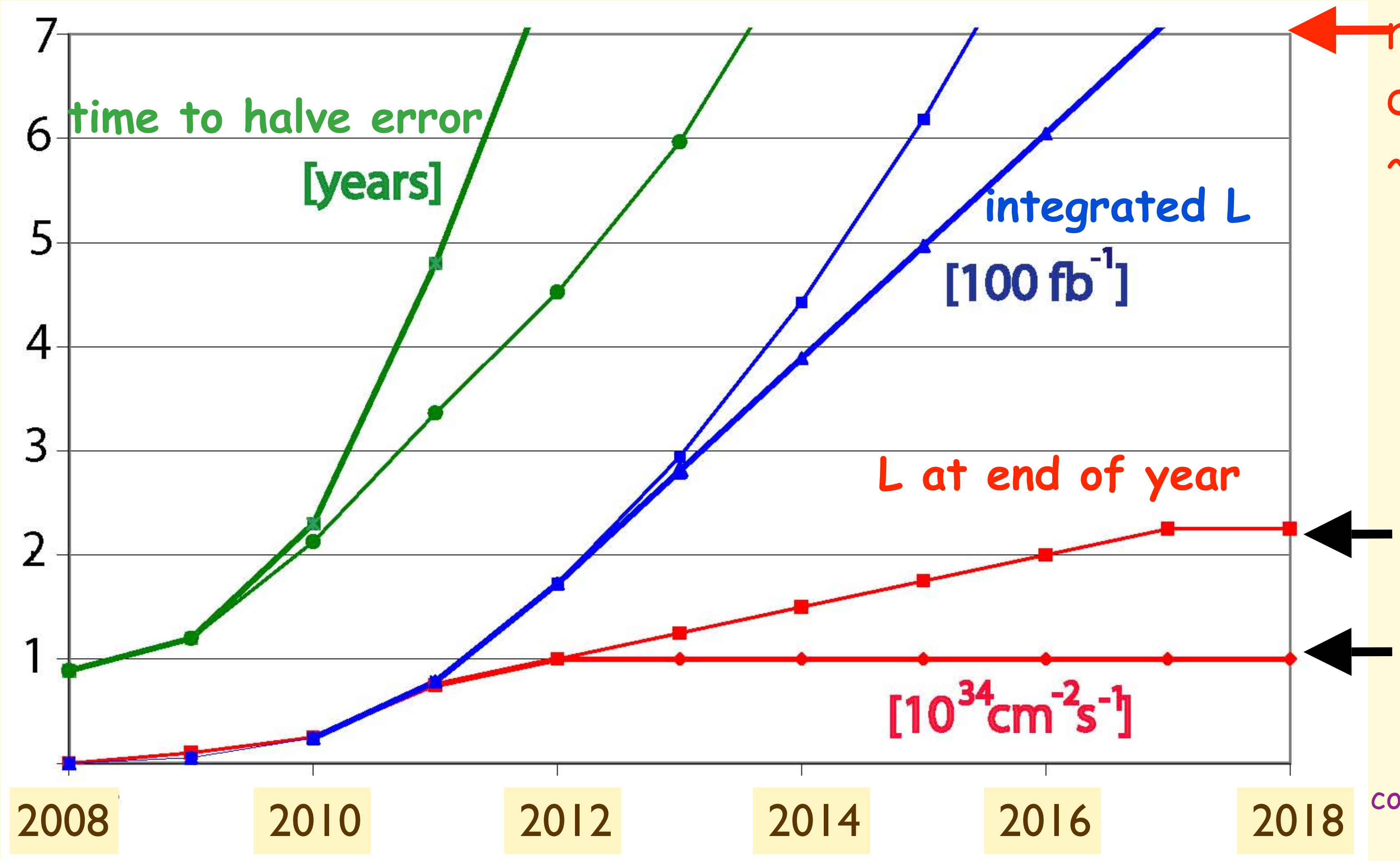




By 2010-11 we should already have a good picture of TeV-scale physics!

WHAT’S NEXT?

time scale of LHC upgrade



radiation damage limit ~700 fb-1

ultimate luminosity

design luminosity

courtesy J. Strait

(1) **life expectancy of LHC IR quadrupole magnets** is estimated to be <10 years due to high radiation doses

(2) the **statistical error halving time** will exceed 5 years by 2011-2012

(3) therefore, it is reasonable to plan a **machine luminosity upgrade based on new low-ß IR magnets before ~2014**

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.:
   - $H \rightarrow \mu^+\mu^-$, $H \rightarrow Z\gamma$
   - top quark FCNCs
3. Push sensitivity to new high-mass scales. E.g.
   - New forces (Z', W_R)
   - Quark substructure
   - ....

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.:
    - $H \rightarrow \mu^+\mu^-$, $H \rightarrow Z\gamma$
    - top quark FCNCs
3. Push sensitivity to new high-mass scales. E.g.
    - New forces (Z', W_R)
    - Quark substructure
    - ....

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

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

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

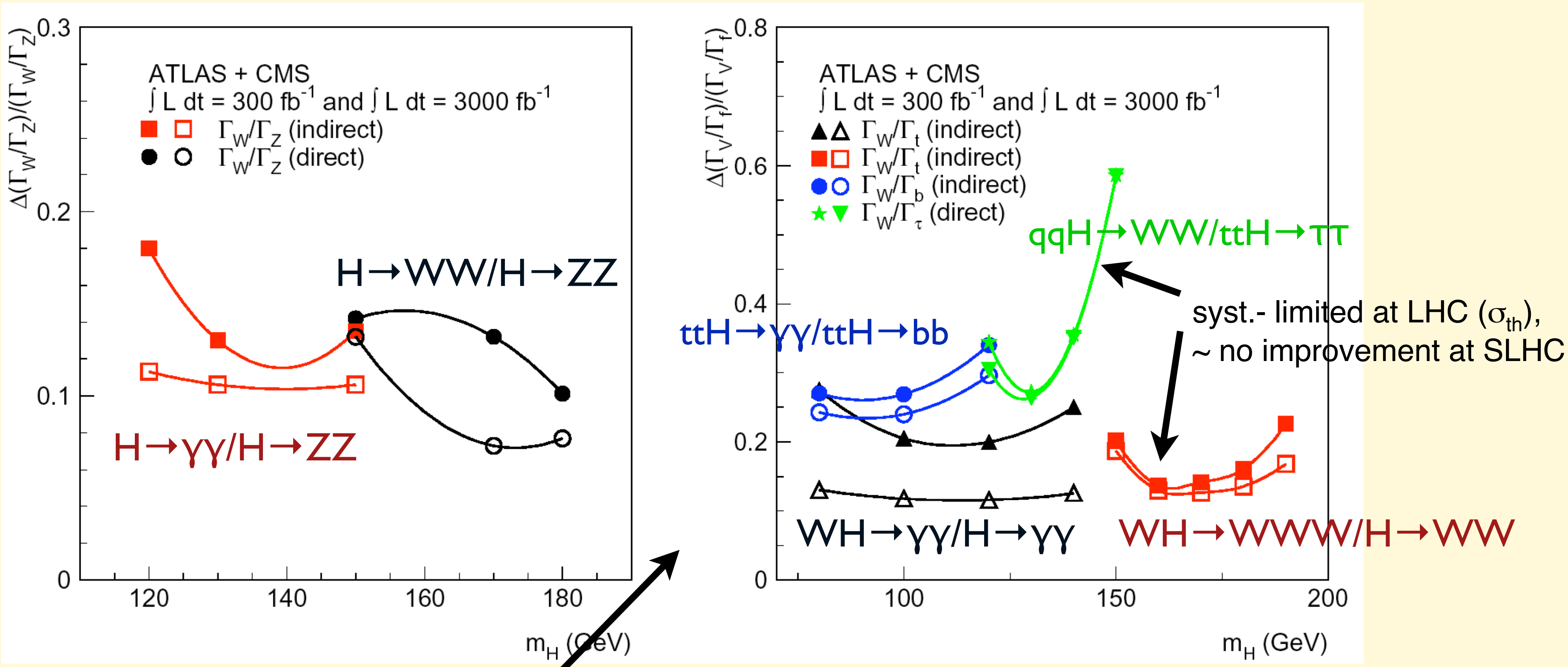
or

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

or

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

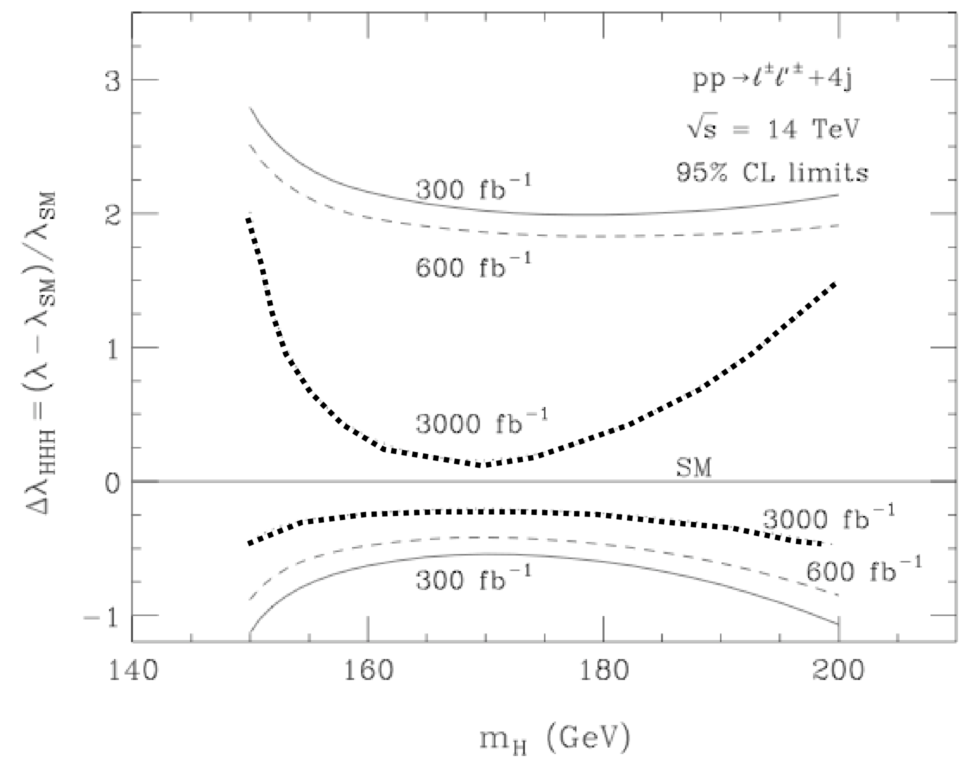
Sorting out these scenarios will take longer than the SM H observation, and may well require SLHC luminosities, and/or LC



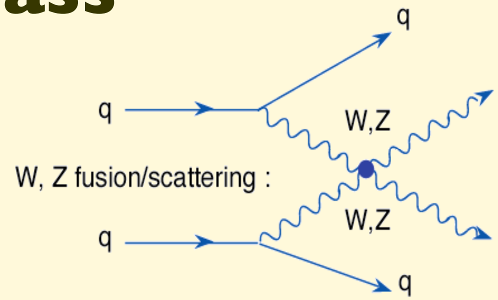
syst.- limited at LHC (σ_{th}),
~ no improvement at SLHC

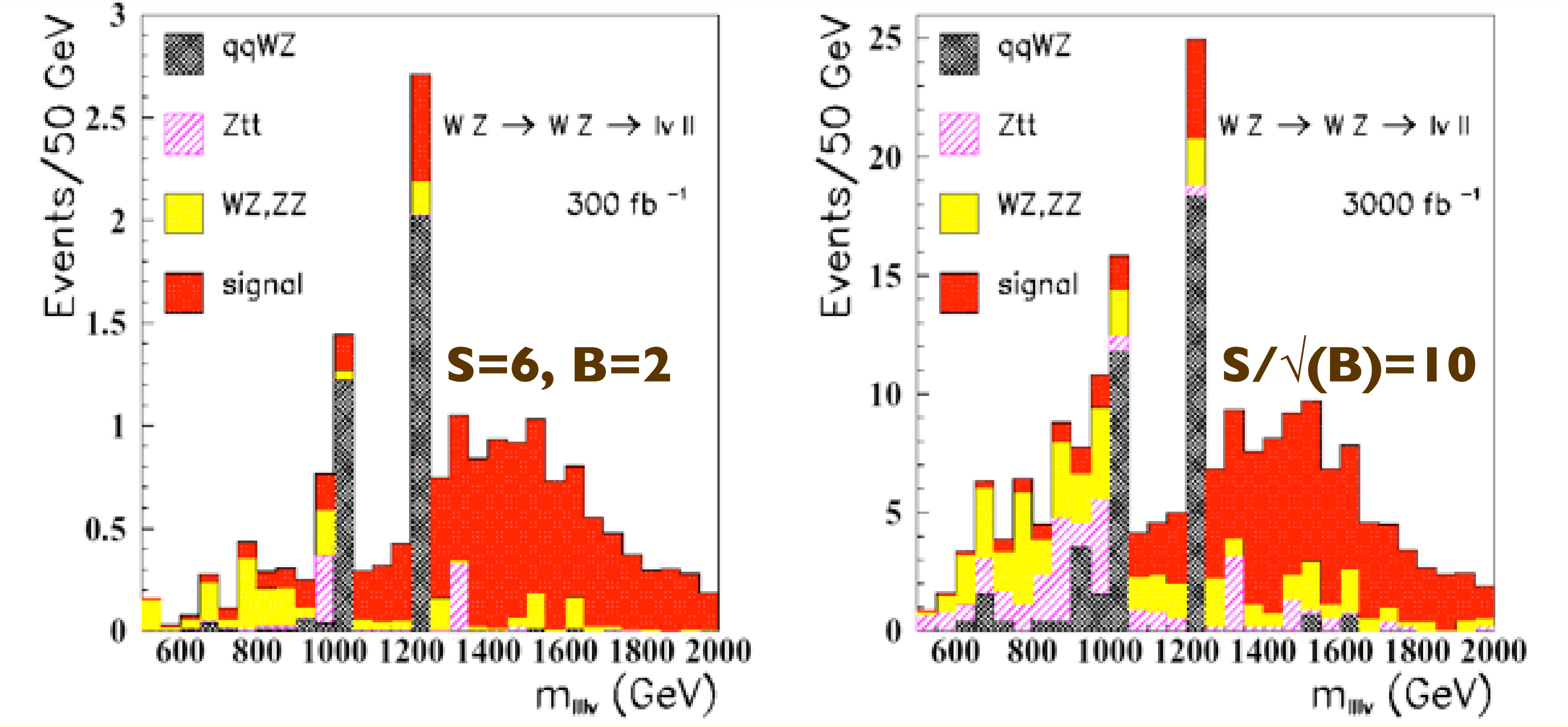
Higgs boson couplings to fermions and gauge bosons

Higgs boson selfcouplings



Strong resonances in high-mass WW or WZ scattering





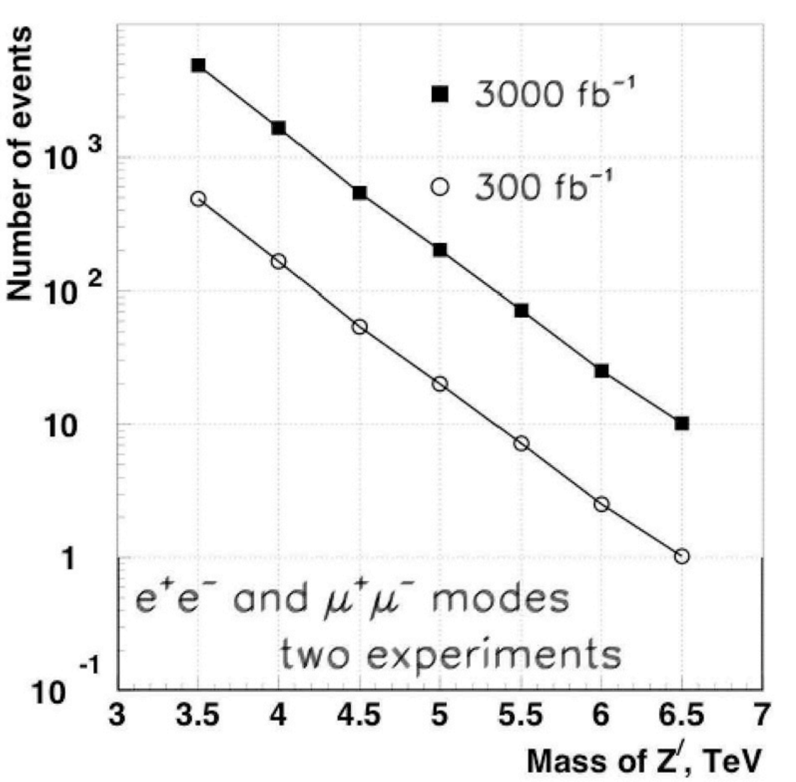
S=6, B=2

S/√(B)=10

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)

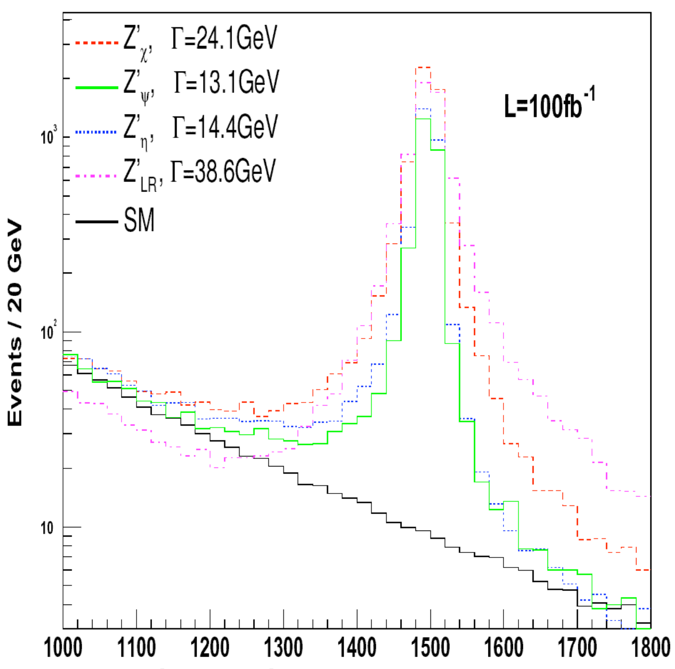
Searching new forces: W', Z'

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

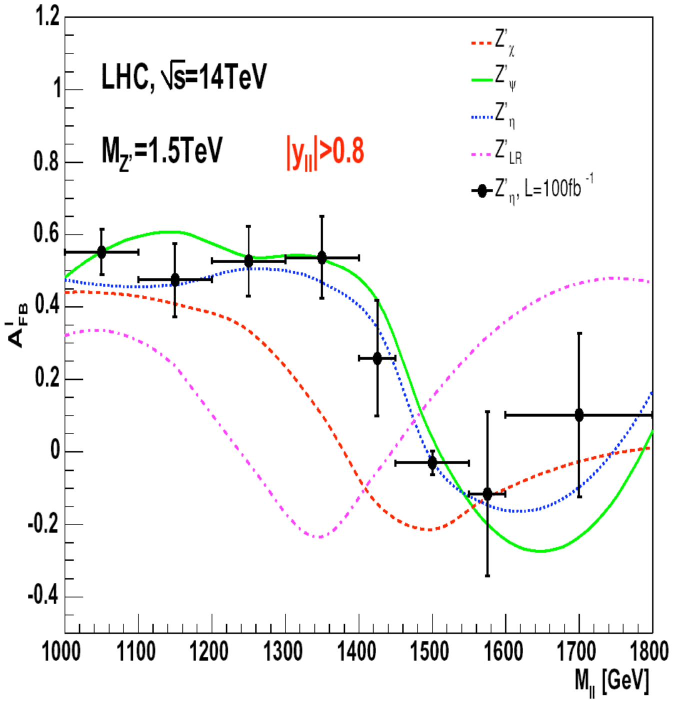


100 fb^{-1} discovery reach up to ~ 5.5 TeV

Differentiating among different Z' models:



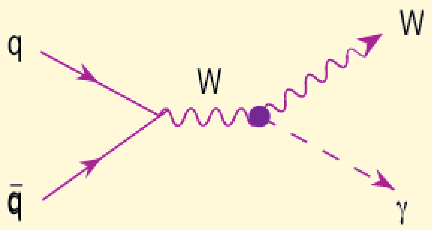
hep-ph/0307020)

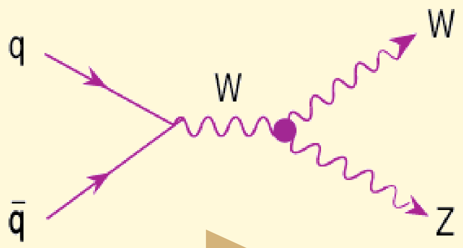


100 fb^{-1} model discrimination up to 2.5 TeV

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

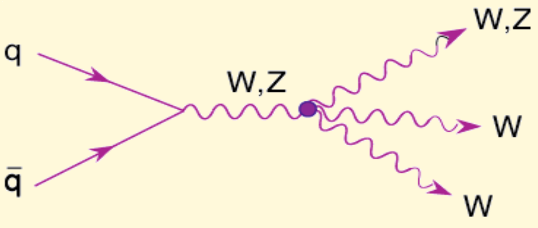
5 parameters describing weak and EM dipole and quadrupole moments of gauge bosons. The SM predicts their value with accuracies at the level of **10^{-3}**, which is therefore the goal of the required experimental precision

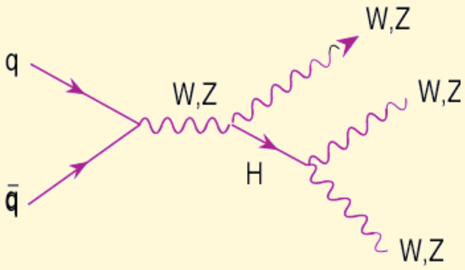


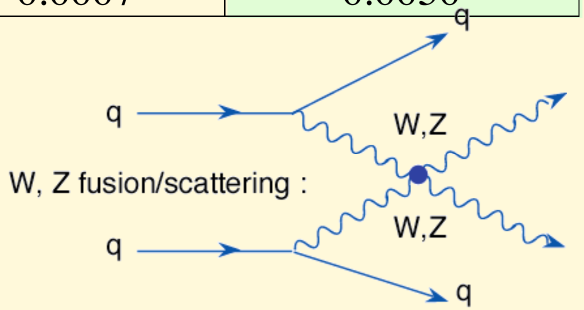


LHC options

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

LHC IR Upgrade Path for high-L

🟩 Phase 1: consolidation of ‘ultimate’ performance with L > 10^{34}cm^{-2}sec^{-1}

-large aperture NbTi triplet magnets using existing spare dipole cables with the goal of introducing additional margins for the LHC operation

-no modifications of the experiment interface and cryogenic infrastructure

-opening the option for operation with $\beta^* = 0.25$m and the LHC ‘ultimate’ beam parameters yielding a performance reach of L = 3 × 10^{34} cm^{-2} sec^{-1}

🟩 Phase 2:

-aims at operation beyond ultimate luminosity (L = 10^{35} cm^{-2} sec^{-1} but the goal is integrated L!!!)

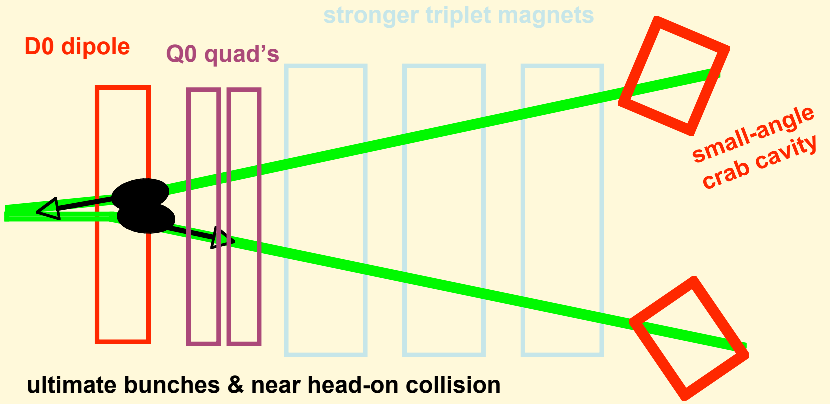
-implies operation in extremely radiation hard environment (35 MGy/year$^{@}$) (less than 1 year lifetime for magnets with nominal triplet layout!)

➔ new magnet technology and /or special protection / absorber elements

Courtesy of O. Brüning

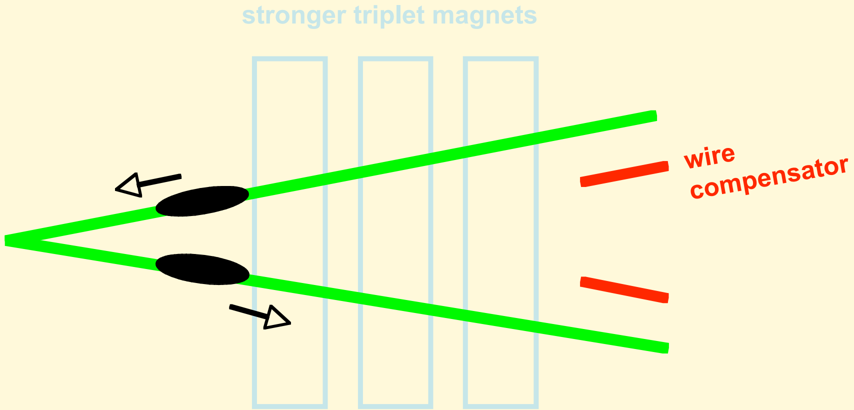
Phase-2 Upgrade Options

ES (early separation): Low β^* (8cm$^{@}$ ➔ 14cm$^{\$}$) with 'ultimate' beam parameters requiring significant hardware modifications in the IR & detector regions (25ns)



- D0 dipole at 3m from IP
- Q0 quads at 13 m from IP, **Nb_3Sn**
- ~300 evts/Xing

LPA (large piwinski angle): operation with larger than 'ultimate' beam intensities and 'flat bunches' but without modifications in the detector regions (50ns)



- β^* = 25 cm , longer bunches, high charge
- standard **Nb Ti** quads, no crabs
- ~400 evts/Xing

Courtesy of O. Brüning

Phase 2 Beam Parameter Options@

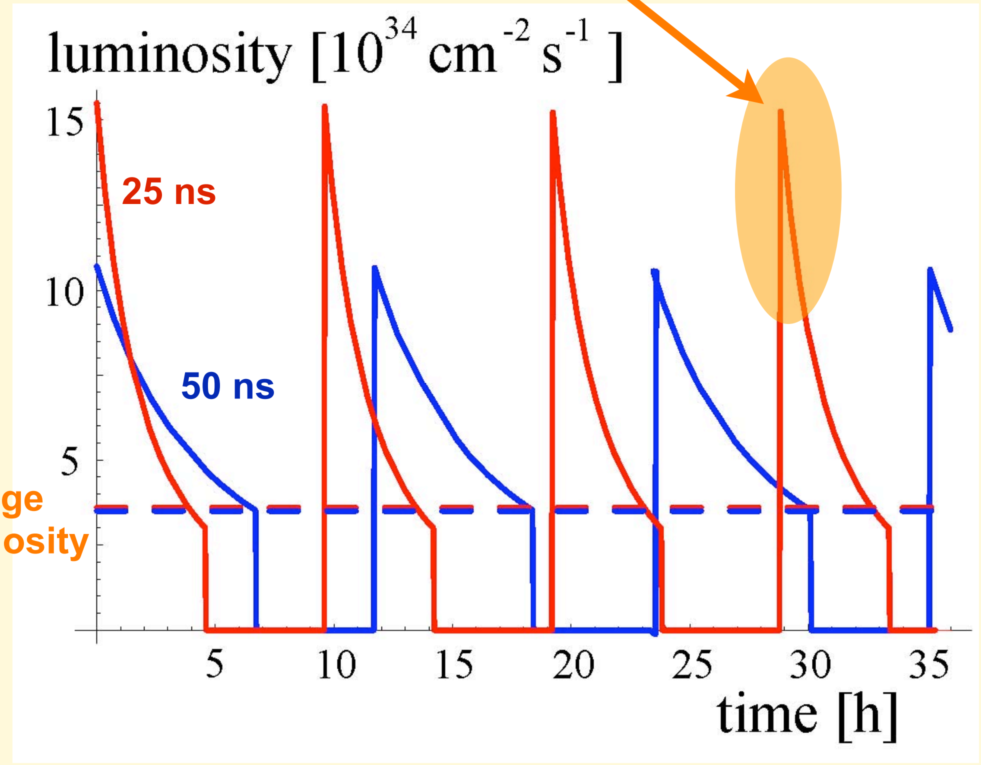
parameter	nominal	ultimate	ES (25ns)	LPA (50ns)
Protons per bunch	$1.15\ 10^{11}$	$1.7\ 10^{11}$	$1.7\ 10^{11}$	$4.9\ 10^{11}$
Total beam current	0.58 A	0.86 A	0.86 A	1.22 A
Longitudinal bunch profile	Gauss	Gauss	Gauss	Flat
β^* at the IPs	0.55m	0.5m	8cm (→14cm)	25cm
Full crossing angle at the IPs	285μrad	315μrad	0μrad	381μrad
Peak luminosity [$\mathrm{cm}^{-2}\ \mathrm{sec}^{-1}$]	$1\ 10^{34}$	$2.3\ 10^{34}$	$15.5\ 10^{34}$	$10.7\ 10^{34}$
Peak events per crossing	19	44	294	403
Initial luminosity lifetime	25h	14h	2.2h (wo leveling)	4.5h (wo leveling)
Stored beam energy	370MJ	550MJ	550MJ	780MJ
Additional requirements	-	-	Large aperture triplet magnets	Large aperture triplet magnets
			Efficient absorbers / radiation hard	Efficient absorbers / radiation hard
			(wire compensators)	(wire compensators)
			D0	
			Crab cavities	
			luminosity levelling	flat beam operation
			Cryoplant upgrade	Cryoplant upgrade

Courtesy of O. Brüning

@LUMI'06 workshop proceedings

🟩 luminosity leveling:

(plot from F. Zimmermann in Beam'07
studied by G Sterbini & J-P Koutchouk)



initial luminosity peak may not be useful for physics (set up & tuning?)

average luminosity

➔ potential loss of integrated luminosity due to initial luminosity tuning

➔ short luminosity life time

➔ high event rate at beginning of run

➔ changing the luminosity during a physics run can counter act the above problems for the price of a small loss in integrated luminosity (ca. 10% for T_{turn} = 5h [G. Sterbini & J-P Koutchouk Beam'07])

➔ luminosity variation can be done either via β^* (difficult in operation [Tevatron]) or crossing angle adjustments

➔ feasibility and efficiency not yet demonstrated in real operation

Courtesy of O. Brüning

LHC Performance Evolution: Integrated Luminosity$^{@}$

🟩 nominal: $L = 10^{34}\ \mathrm{cm}^{-2}\ \mathrm{sec}^{-1}$

→ $T_{turn} = 10h$; $\tau_{lumi} = 15h$ → $L_{integrated} = 70\ \mathrm{fb}^{-1}$

→ $T_{turn} = 5h$; $\tau_{lumi} = 15h$ → $L_{integrated} = 80\ \mathrm{fb}^{-1}$ → weak impact of T_{turn}

🟩 ultimate: $L = 2.3 \times 10^{34}\ \mathrm{cm}^{-2}\ \mathrm{sec}^{-1}$

→ $T_{turn} = 10h$; $\tau_{lum} = 10h$ → $L_{integrated} = 127\ \mathrm{fb}^{-1}$

→ $T_{turn} = 5h$; $\tau_{lumi} = 10h$ → $L_{integrated} = 155\ \mathrm{fb}^{-1}$ → moderate impact of T_{turn}

🟩 Phase IIa: $L = 15.5 \times 10^{34}\ \mathrm{cm}^{-2}\ \mathrm{sec}^{-1}$ (Lumi'06 in Valencia)

→ $T_{turn} = 10h$; $\tau_{lum} = 2.5h$ → $L_{integrated} = 374\ \mathrm{fb}^{-1}$

→ $T_{turn} = 5h$; $\tau_{lumi} = 2.5h$ → $L_{integrated} = 535\ \mathrm{fb}^{-1}$ → big impact of T_{turn} (50%)

🟩 Phase IIb: $L = 6.2 \times 10^{34}\ \mathrm{cm}^{-2}\ \mathrm{sec}^{-1}$ (BEAM'07 at CERN)

→ $T_{turn} = 5h$; $\tau_{lumi} = 7h$ → $L_{integrated} = 370\ \mathrm{fb}^{-1}$ → still significant impact of T_{turn}

→ only efficient with luminosity leveling and if $T_{turn} \leq 5h$

$^{@}$O Brüning at Beam'07 assuming 200 days of operation per year

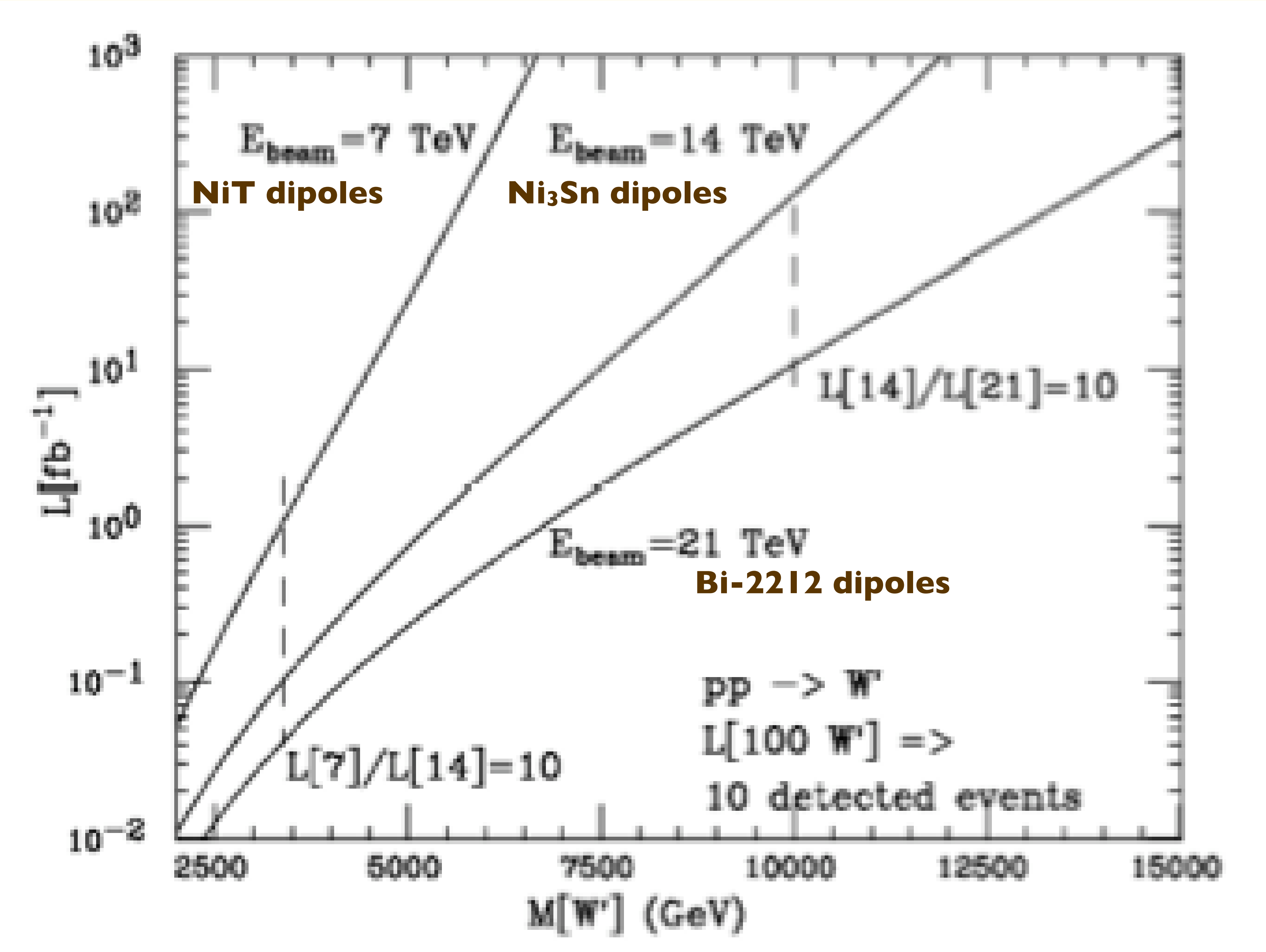
Courtesy of O. Brüning

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	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



NiT dipoles

Ni_3Sn dipoles

Bi-2212 dipoles

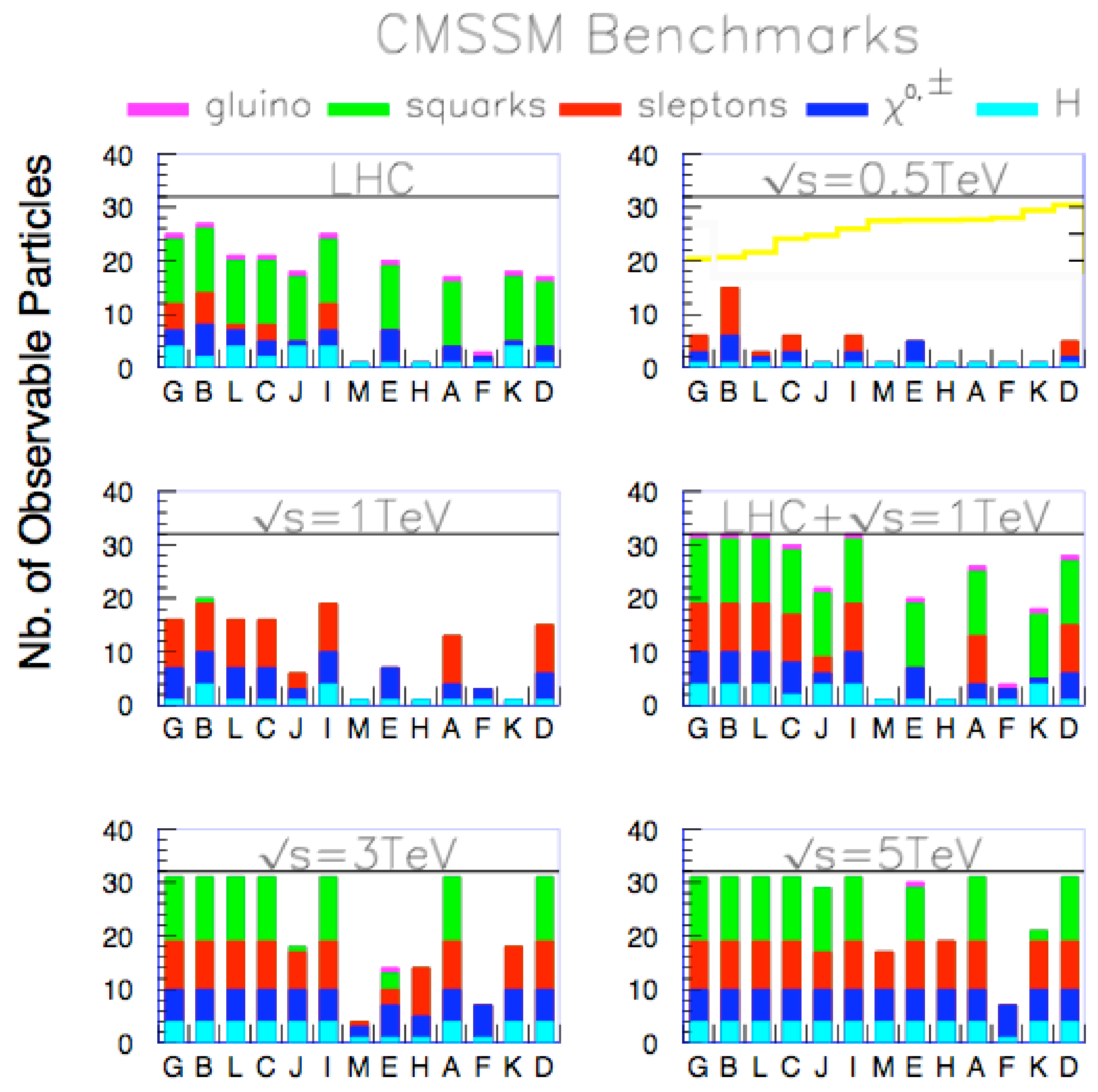
Comments

- 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**
  - **R&D on all possible future SC magnets should develop in parallel to make the 42 TeV option a viable possibility**

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:

$$\tilde{t} \longrightarrow W\tilde{b}$$

$$\tilde{q}' \longrightarrow \tilde{q}$$

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 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:

$$\tilde{t} \to W\tilde{b}$$

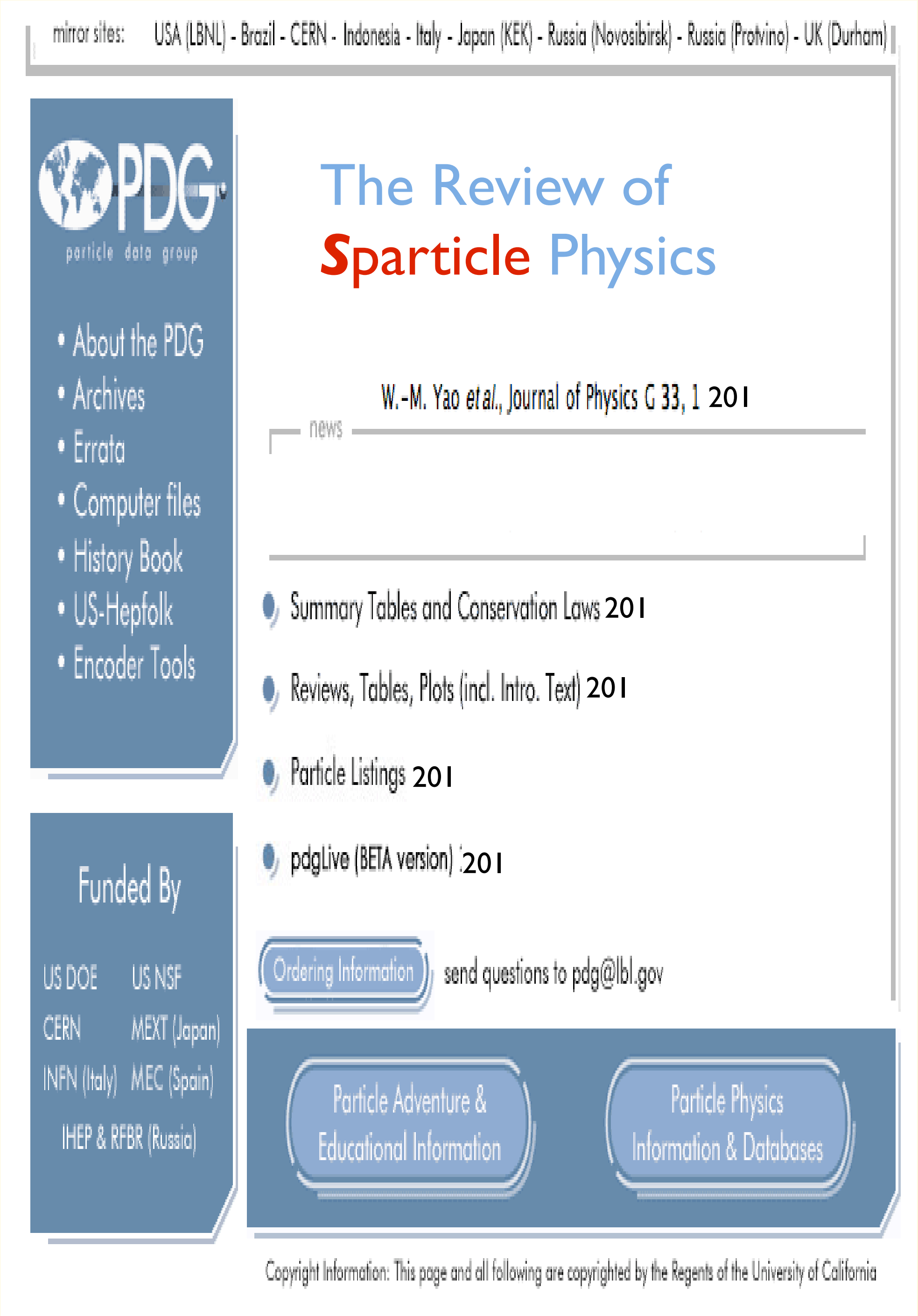
$$\tilde{q}' \to \tilde{q}$$

Slepton spectroscopy and mixing:

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

Gaugino spectroscopy:

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



mirror sites: USA (LBNL) - Brazil - CERN - Indonesia - Italy - Japan (KEK) - Russia (Novosibirsk) - Russia (Protvino) - UK (Durham)

PDG particle data group

- About the PDG
- Archives
- Errata
- Computer files
- History Book
- US-Hepfolk
- Encoder Tools

Funded By

US DOE US NSF
CERN MEXT (Japan)
INFN (Italy) MEC (Spain)
IHEP & RFBR (Russia)

The Review of
Sparticle Physics

W.-M. Yao *et al.*, Journal of Physics G 33, 1 201

news

- Summary Tables and Conservation Laws 201
- Reviews, Tables, Plots (incl. Intro. Text) 201
- Particle Listings 201
- pdgLive (BETA version) 201

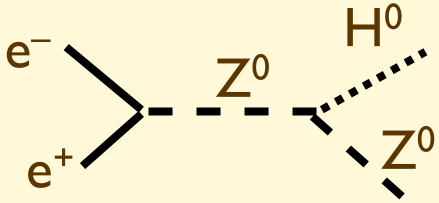
Ordering Information send questions to pdg@lbl.gov

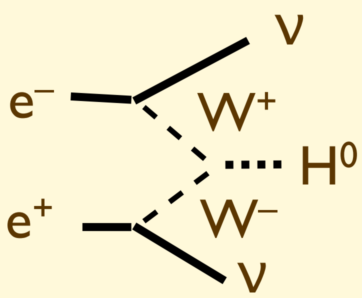
Particle Adventure & Educational Information

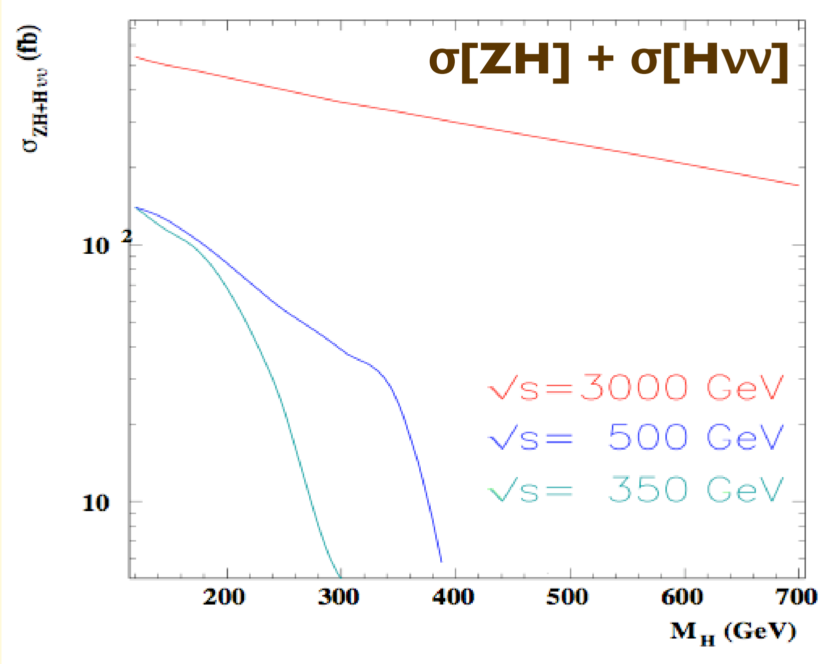
Particle Physics Information & Databases

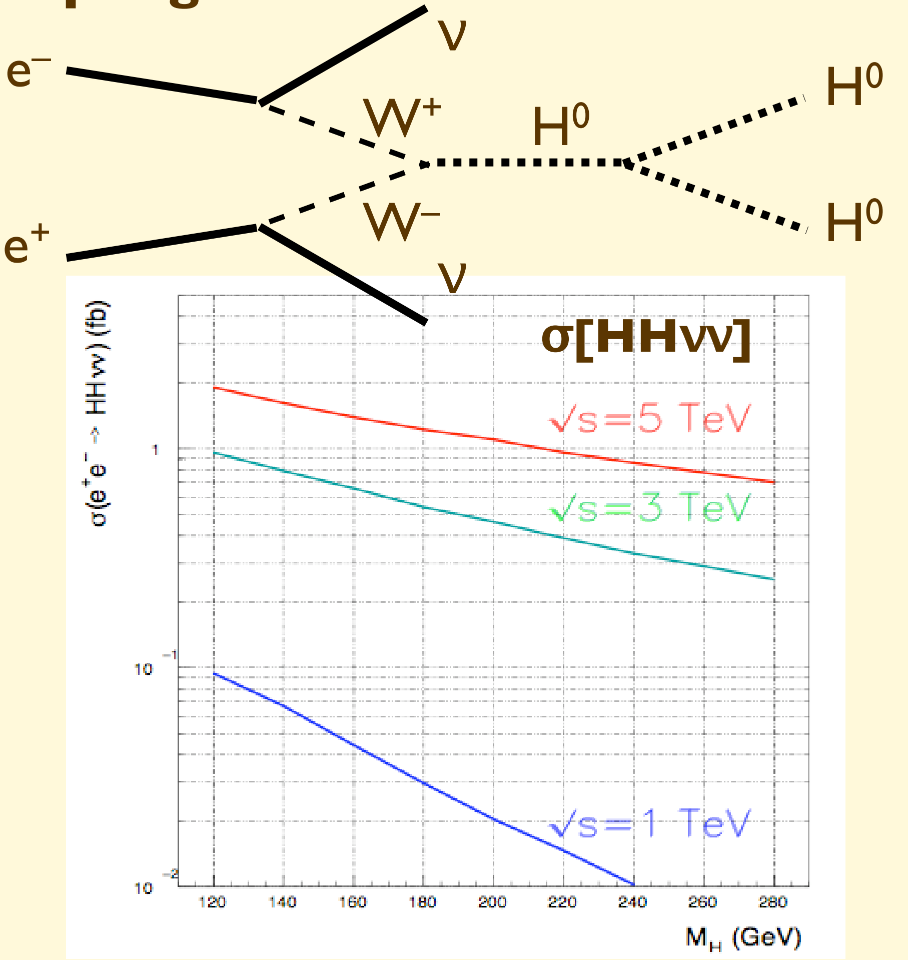
Copyright Information: This page and all following are copyrighted by the Regents of the University of California

Example: Higgs couplings

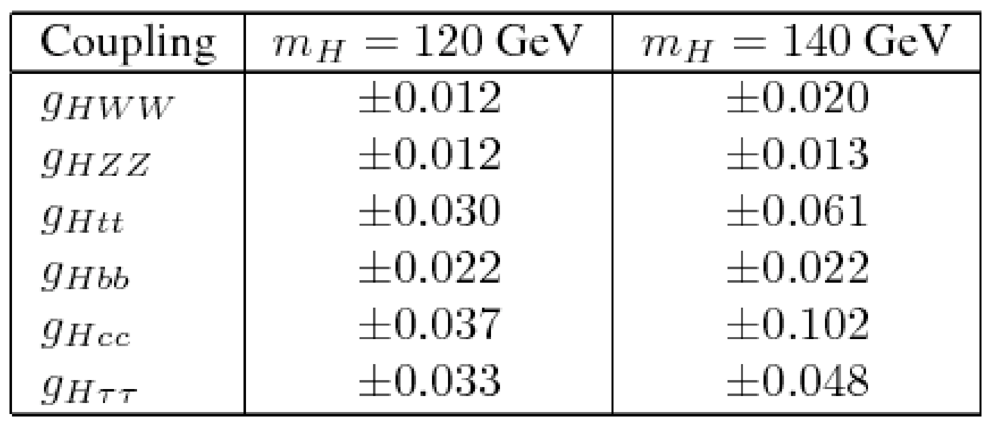






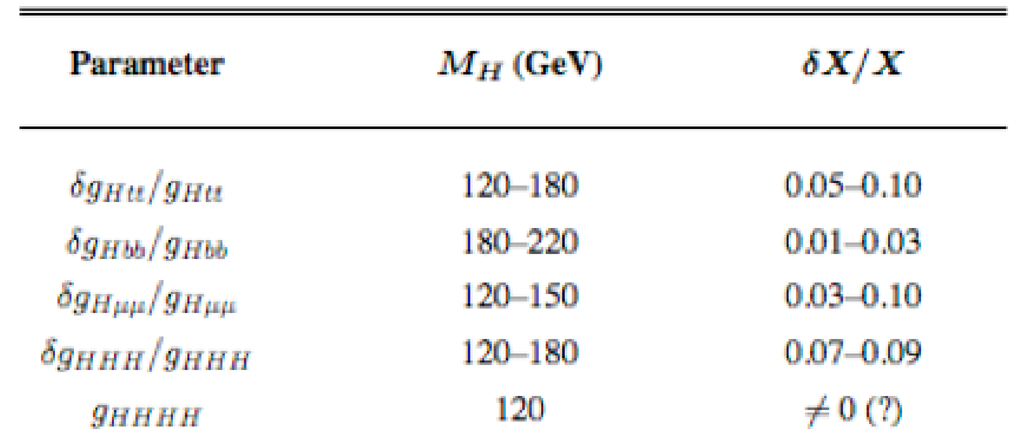


Expected accuracy, ILC



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

Expected accuracy, CLIC@3TeV, 5ab⁻¹



Parameter	M_H (GeV)	$\delta X/X$
$\delta g_{Htt}/g_{Htt}$	120–180	0.05–0.10
$\delta g_{Hbb}/g_{Hbb}$	180–220	0.01–0.03
$\delta g_{H\mu\mu}/g_{H\mu\mu}$	120–150	0.03–0.10
$\delta g_{HHH}/g_{HHH}$	120–180	0.07–0.09
g_{HHHH}	120	$\neq 0$ (?)

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

the gauge sector
(Higgs, EWSB)

The High Energy Frontier

LHC
SLHC
VLHC
LC
CLIC
....

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

The High Intensity Frontier

Neutrinos:
super beams
beta-beams
ν factory

Charged leptons
stopped μ
$\ell \to \ell'$ conversion
e/μ EDM

Quarks:
B factories
K factories
n EDM

Conclusions

- Particle physics is on the verge of **major discoveries**
- 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) (see Grojean talk)

  ➡ **demands for a x10 increase in the energy reach (CLIC, VLHC) will likely be fully justified few years from now**
- The complete exploration of new phenomena will not only require pushing the energy frontier, but also the intensity frontier, with a diversified spectrum of higher-performance low-energy flavour factories
- In the meantime, let us enjoy the forthcoming output of many years of work on the LHC, and make sure it bear fruits!