Physics cases for pp collisions at 33 - 100 TeV c.m. and luminosity goals

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Primary physics goals for HEP at the energy frontier

- Establish nature of Higgs boson and of electroweak symmetry breaking (EWSB)
- Establish the nature of Dark Matter
- Identify additional sources of CP violation
- Identify the extension of the Standard Model that provides an answer to the above issues

This research is driven by the need to understand the origin of **known** phenomena

There are compelling reasons to believe that the understanding of at least the first two issues must emerge from the study of phenomena at the electroweak energy scale, namely O(TeV).

Is it 1 TeV or 3 TeV? Can't tell. But those questions must find an answer.

Additional, recurrent, themes of exploration

- Elementary nature of quarks and leptons
- Existence of further generations of quarks and leptons, or other forms of elementary particles
- Existence of further fundamental interactions
- Existence of other, more exotic, scenarios: extra dimensions, strings, ...

This research is driven by curiosity, and by a "duty" to keep testing and looking for possible surprises.

There is no compelling reason why any of these phenomena should manifest itself at the O(TeV) scale (unless they are directly related to the solution of the problems discussed in the previous page)

For sure we anticipate new phenomena around the 10^{16} GeV scale: GUT, origin of neutrino masses, inflation, ... , eventually quantum gravity. Sooner or later we'll get there. In the meantime, we take the steps we can afford.

At this time, the one sure fact is the existence of a Higgs at ~125 GeV

- Its exploration provides a benchmark for the assessment of the physics potential of future facilities, and in particular of pp colliders

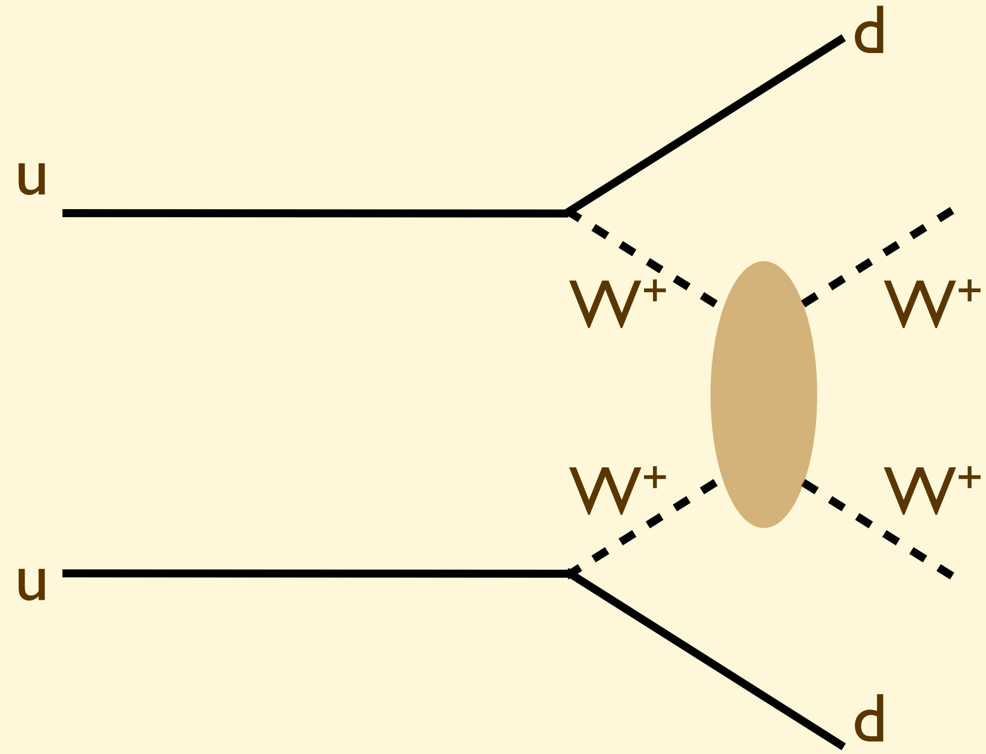
This means measuring things like:

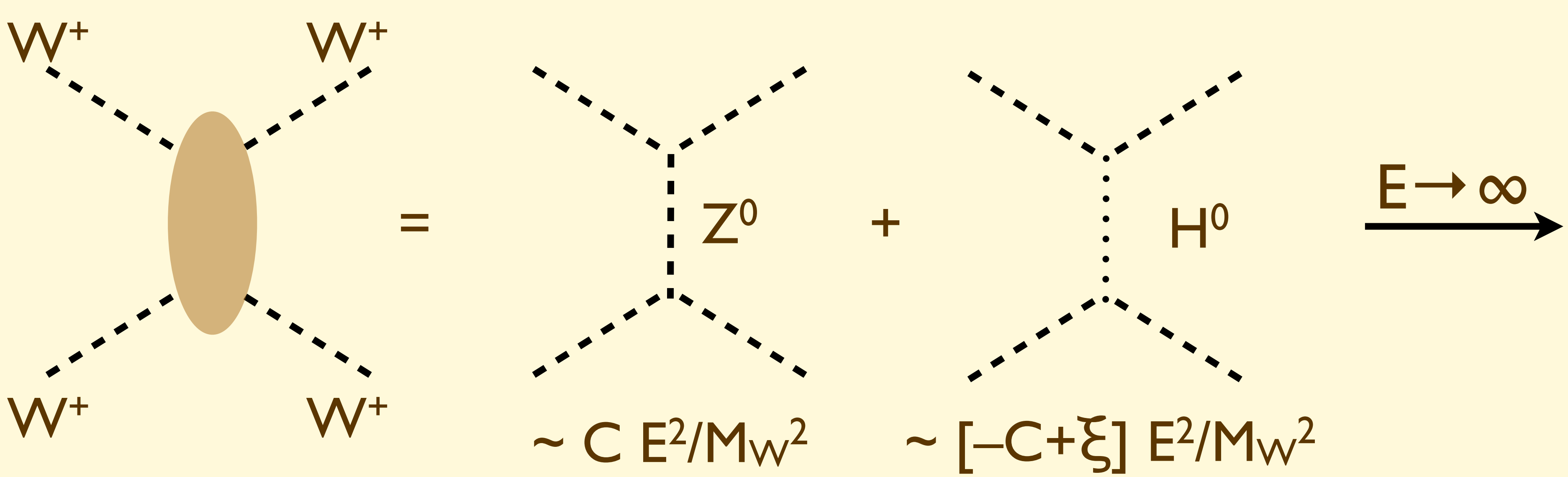
- Higgs couplings to fermions, to gauge bosons and selfcouplings
- Rare decay modes, including possible flavour changing neutral current modes ($H \to \tau\mu$, ...)
- Additional Higgs bosons (doublets, singlets, charged, etc.)

But what really defines the Higgs boson is its role in the breaking of EW symmetry. In particular:

- **its coupling to the longitudinal polarization of W and Z bosons**
- **the resulting unitarization of high-energy WW scattering**

High-energy WW scattering





- constant,
  if WWH coupling SM-like
- $\xi E^2 / M_W^2$,
  if ξ.ne.0

ξ=0 in the SM, can be non-0 e.g. in composite-HIggs models

More precisely:

R.Contino et al, arXiv:1002.1011v2

$$\frac{d\sigma(W_L W_L)/dt}{d\sigma(W_T W_T)/dt}|_{90^\circ} = \left(\frac{\xi}{48}\frac{E_{CM}^2(WW)}{M_W^2}\right)^2 \sim 4\xi^2\left(\frac{E_{CM}(WW)}{800\ \text{GeV}}\right)^4$$

and therefore it takes CM energies of the WW pair well above the TeV to have sensitivity in the range $\xi \ll 1$.

In pp collisions at 14 TeV, with 300fb^{-1}, the statistics drops once M(WW)~1 TeV, and one is sensitive only to values $\xi \gtrsim 0.5$

Since the reach in ξ scales like ~ 1/ E^2 , the sensitivity will improve to O(0.05) at ~50 TeV, and to O(0.01) at ~100 TeV.

This is the reason why the SSC was designed for 40 TeV: it's the energy at which one can start doing quantitative checks of the proper behaviour of high-energy WW scattering

The need to perform this measurement remains today as strong as it ever was, as is the need to attain energies in the range of at least 30-40 TeV for compelling studies.

$$BR(H \to WW) = (1 + O(\xi))\, BR_{SM}(H \to WW)$$

No realistic assessment of the potential of possible future LHC experiments for these measurements is available. Issues include

- geometrical acceptance for the forward/backward jets (at higher energy they extend well beyond the canonical ±5 units in η of today's detectors)
- ability to reconstruct them, in presence of large pileup

Recent assessments of Higgs measurement potential, at HL-LHC

CMS submission to Strategy Group,
https://indico.cern.ch/contributionDisplay.py?contribId=177&confId=175067

Coupling	Uncertainty (%)			
	300 fb^{-1}		3000 fb^{-1}	
	Scenario 1	Scenario 2	Scenario 1	Scenario 2
κ_γ	6.5	5.1	5.4	1.5
κ_V	5.7	2.7	4.5	1.0
κ_g	11	5.7	7.5	2.7
κ_b	15	6.9	11	2.7
κ_t	14	8.7	8.0	3.9
κ_τ	8.5	5.1	5.4	2.0

Plus $H\mu\mu$ coupling to better than 5% at $3000 fb^{-1}$

Scenario 1: same systematics as 2012 (TH and EXP)
Scenario 2: half the TH syst, and scale with 1/sqrt(L) the EXP syst

Note: assume no invisible Higgs decay contributing to the Higgs width

Note: results of scenario 2 @ 3000/fb are overall as powerful as ILC@500GeV !!

More recent assessments

ATLAS submission to Strategy Group,
https://indico.cern.ch/contributionDisplay.py?contribId=174&confId=175067

	with theory systematics	without theory systematics
$H \to \mu\mu$	0.525	0.505
$ttH, H \to \mu\mu$	0.733	0.719
$VBF, H \to \tau\tau$	0.227	0.189
$VBF, H \to \tau\tau$ (extrap)	0.146	0.114
$H \to ZZ$	0.156	0.093
$VBF, H \to WW$	0.668	0.662
$H \to WW$	0.289	0.259
$VH, H \to \gamma\gamma$	0.769	0.768
$ttH, H \to \gamma\gamma$	0.551	0.537
$VBF, H \to \gamma\gamma$	0.336	0.309
$H \to \gamma\gamma(+j)$	0.160	0.120
$H \to \gamma\gamma$	0.145	0.081

Uncertainties on the signal strength, **300 fb^{-1}**

	with theory systematics	without theory systematics
$H \to \mu\mu$	0.207	0.164
$ttH, H \to \mu\mu$	0.260	0.230
$VBF, H \to \tau\tau$	0.202	0.160
$H \to ZZ$	0.134	0.047
$VBF, H \to WW$	0.581	0.574
$H \to WW$	0.289	0.259
$VH, H \to \gamma\gamma$	0.253	0.251
$ttH, H \to \gamma\gamma$	0.206	0.174
$VBF, H \to \gamma\gamma$	0.160	0.105
$H \to \gamma\gamma(+j)$	0.119	0.054
$H \to \gamma\gamma$	0.126	0.040

Uncertainties on the signal strength, **3000 fb^{-1}**

	with theory systematics	without theory systematics
Γ_Z/Γ_g	0.523	0.479
Γ_t/Γ_g	0.519	0.485
Γ_τ/Γ_μ	0.669	0.659
Γ_τ/Γ_μ (extrap)	0.591	0.576
Γ_μ/Γ_Z	0.448	0.448
Γ_τ/Γ_Z	0.417	0.404
Γ_τ/Γ_Z (extrap)	0.283	0.255
Γ_W/Γ_Z	0.254	0.254
Γ_γ/Γ_Z	0.110	0.110
$\Gamma_g \bullet \Gamma_Z/\Gamma_H$	0.156	0.093

Relative uncertainties, **300 fb^{-1}**

	with theory systematics	without theory systematics
Γ_Z/Γ_g	0.284	0.220
Γ_t/Γ_g	0.230	0.153
Γ_τ/Γ_μ	0.251	0.230
Γ_μ/Γ_Z	0.142	0.142
Γ_τ/Γ_Z	0.206	0.181
Γ_W/Γ_Z	0.225	0.225
Γ_γ/Γ_Z	0.029	0.029
$\Gamma_g \bullet \Gamma_Z/\Gamma_H$	0.132	0.047

Relative uncertainties, **3000 fb^{-1}**

	300 fb^{-1}	3000 fb^{-1}
κ_V	3.0% (5.6%)	1.9% (4.5%)
κ_F	8.9% (10%)	3.6% (5.9%)

In ( ):
with TH syst

Also **HH→bbγγ:** 260 events/3000fb^{-1} , 3σ evidence/expt
Expect 30% uncertainty on λ_{HHH}, adding also other decay channels, and combining ATLAS+CMS

Higgs rates at high energy

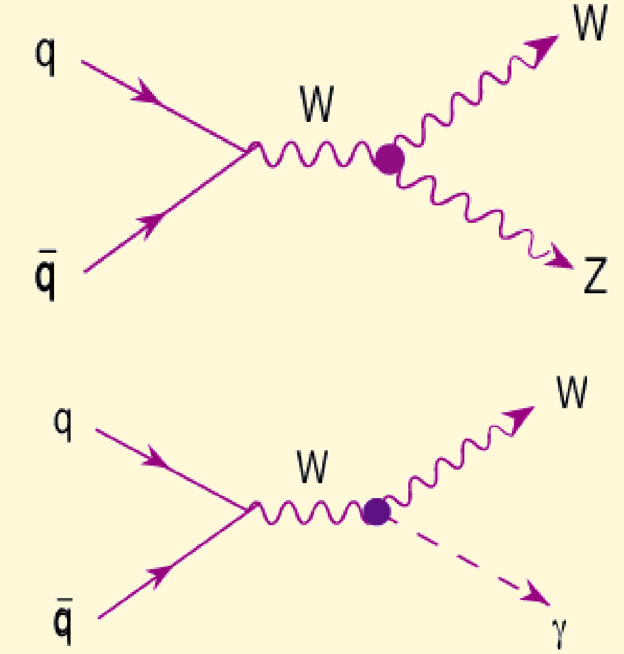
	σ(14 TeV)	R(33)	R(40)	R(60)	R(80)	R(100)
ggH	50.4 pb	3.5	4.6	7.8	11.2	14.7
VBF	4.40 pb	3.8	5.2	9.3	13.6	18.6
WH	1.63 pb	2.9	3.6	5.7	7.7	9.7
ZH	0.90 pb	3.3	4.2	6.8	9.6	12.5
ttH	0.62 pb	7.3	11	24	41	61
HH	33.8 fb	6.1	8.8	18	29	42

$R(E) = \sigma(E\ \mathrm{TeV})/\sigma(14\ \mathrm{TeV})$

No study is available of the concrete performance in the measurement of Higgs couplings, self-couplings and other properties, by possible LHC detectors at these energies

Further explorations of Electroweak Symmetry Breaking:

Precise determinations of the self-couplings of EW gauge bosons

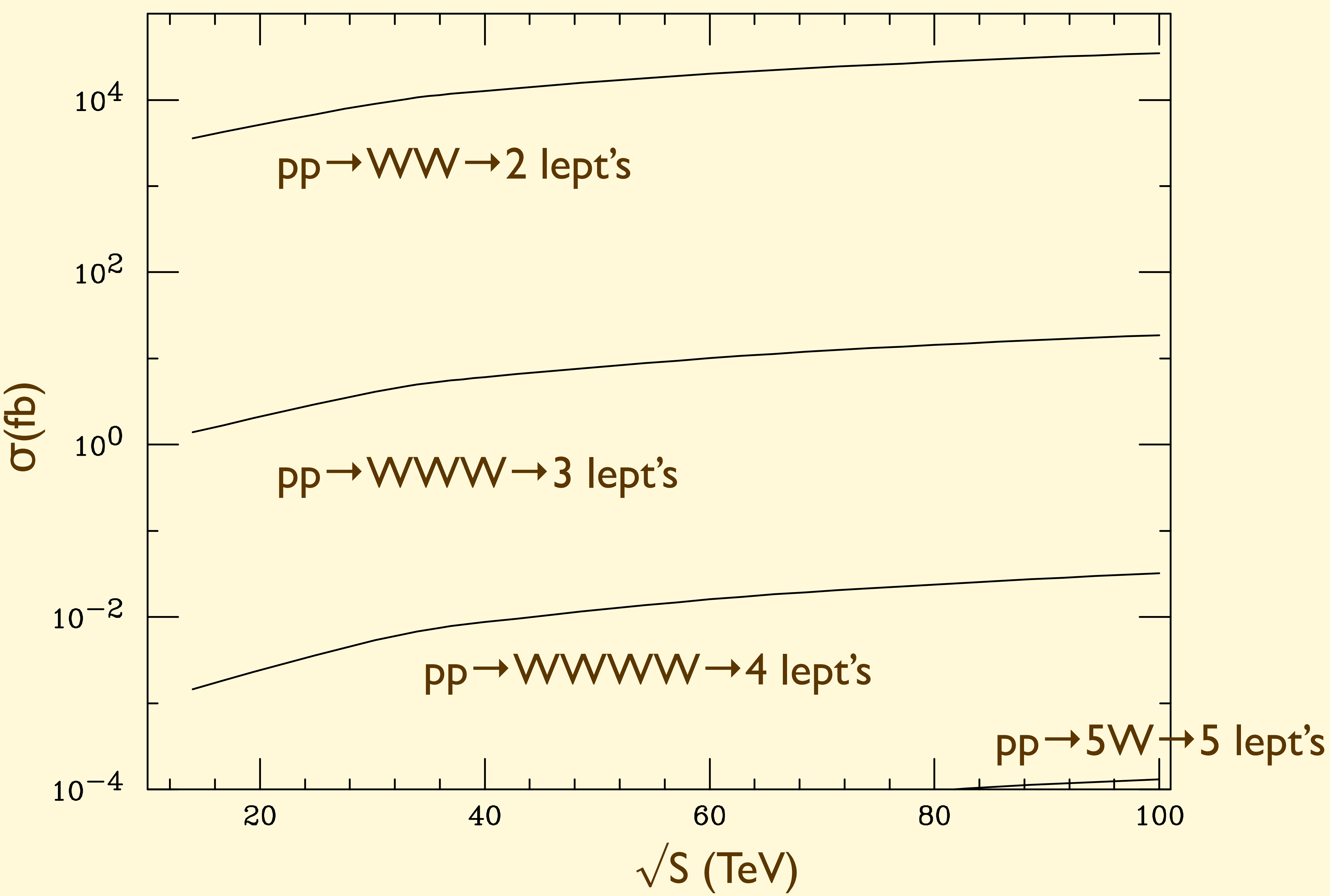


5 parameters describing weak and EM dipole and quadrupole moments of gauge bosons. The SM predicts their value with accuracies at the level of $\mathbf{10^{-3}}$, which is therefore the goal of the required experimental precision

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	0.0009	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

from Gianotti, Mangano, Virdee, et al, hep-ph/0204087

Multi-W cross sections



lept= e,μ

$$\sigma(M, g) \propto \frac{g^2}{M^2} \, L(x = M/\sqrt{S})$$

Production rates can be small either because the mass of the produced object is large, or because the coupling strength is small

To probe higher masses, higher beam energy is clearly preferable

To probe smaller couplings at smaller masses, higher luminosity may be more effective than higher energy

$$\sigma(M,g) \propto \frac{g^2}{M^2} \; L(x = M/\sqrt{S})$$

At fixed mass, cross sections grow when S grows, since

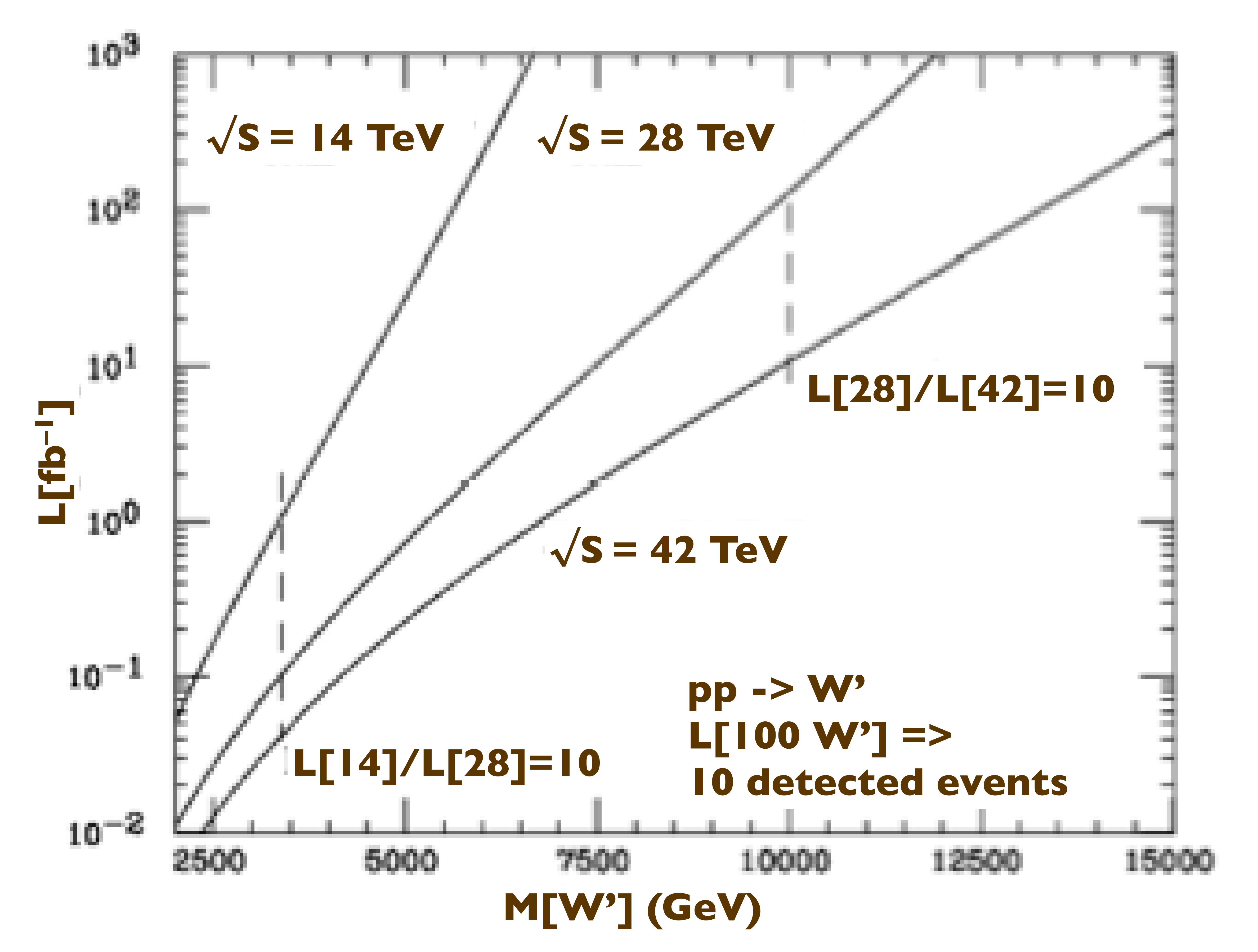
$$L(x) \sim \frac{1}{x^\alpha} \; \log(\frac{1}{x}) \; , \quad \alpha < 1$$

To scale the discovery reach in mass as the growth in energy, means however to keep x=M/$\sqrt{S}$ constant. Then

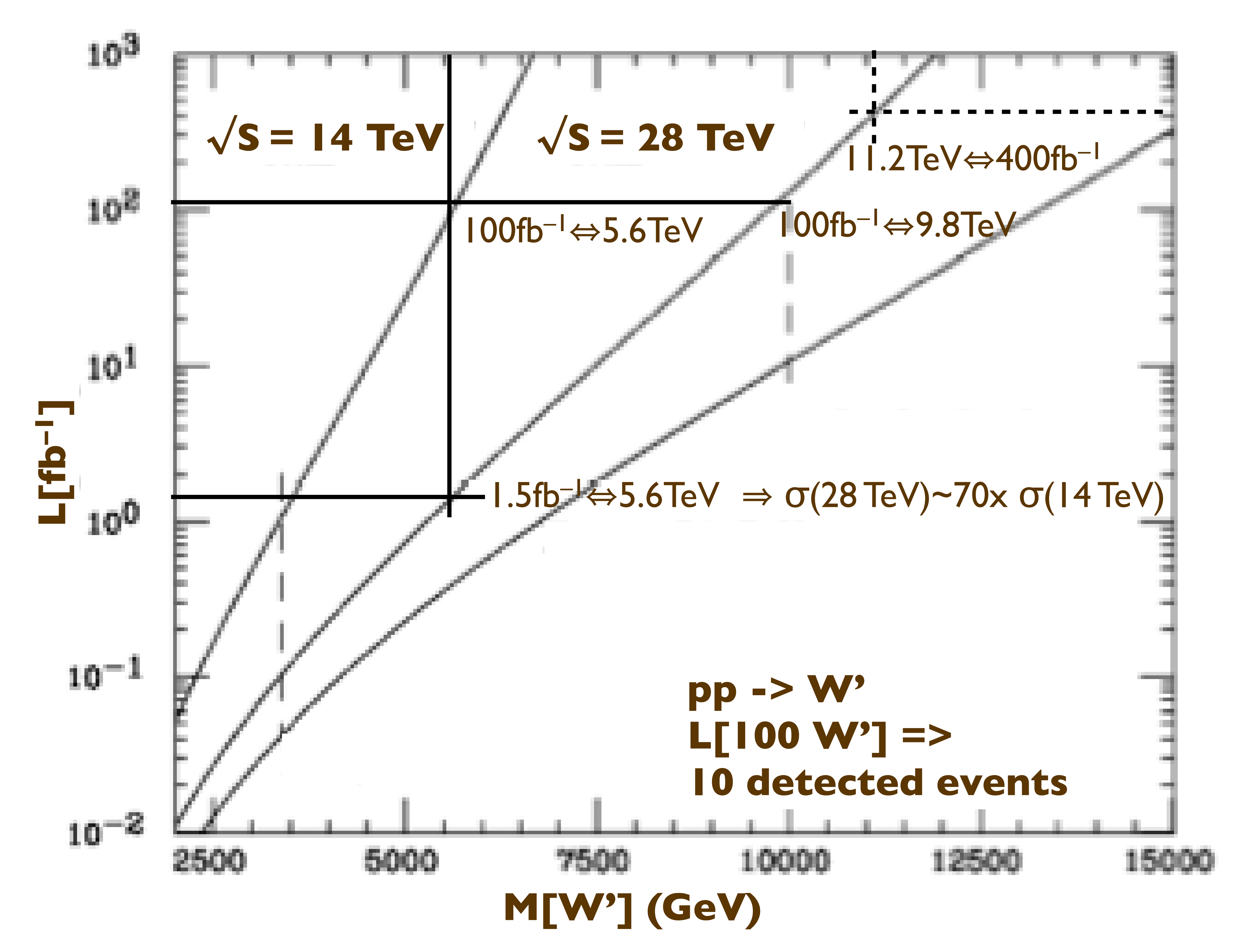
$$\sigma(M,g) \propto \frac{g^2}{S} \; \frac{L(x)}{x}$$

Thus the cross-sections for searches go like 1/S, and the machine luminosity must grow accordingly.

Luminosity vs energy



Luminosity vs energy

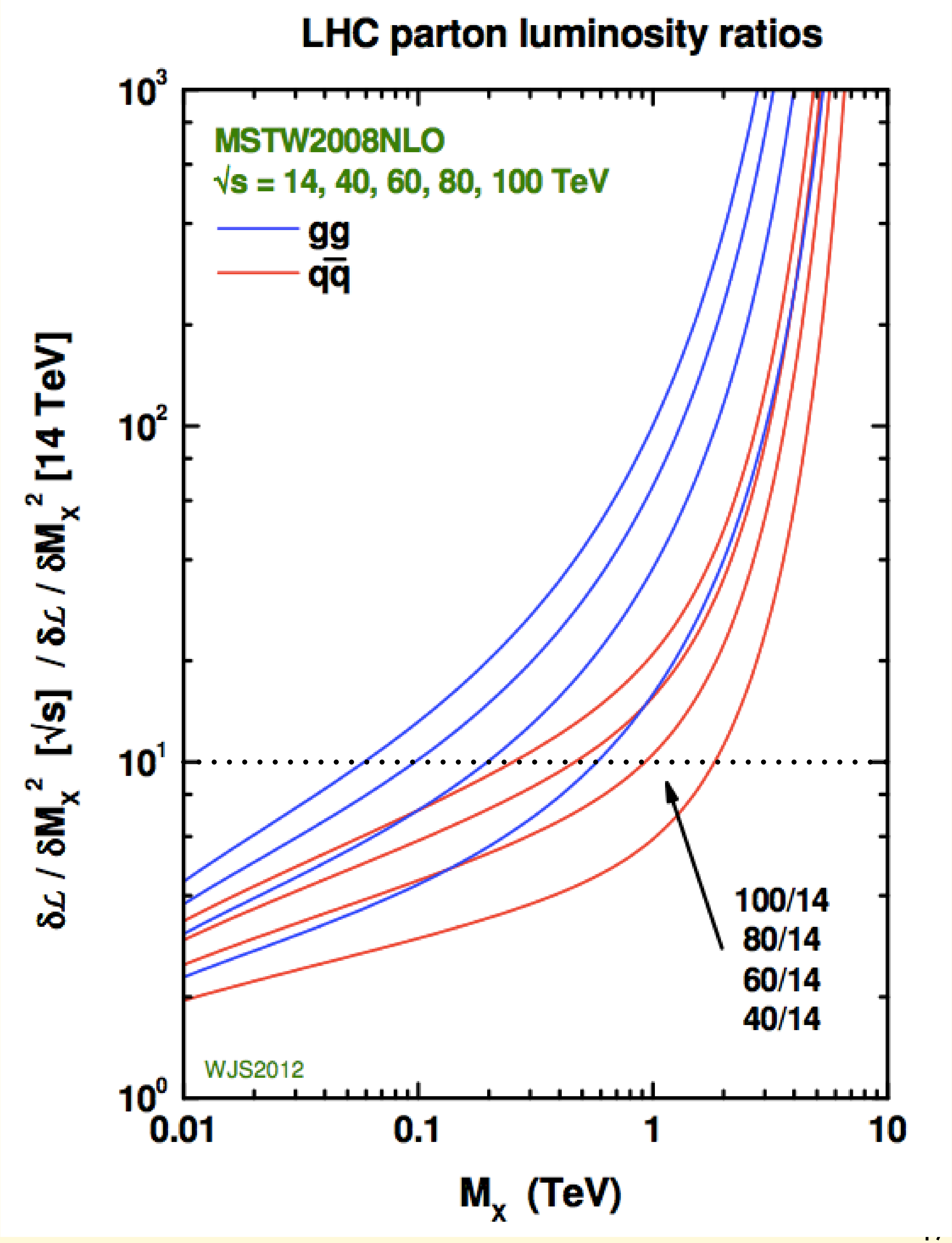


The gluon-gluon luminosity grows faster than q-qbar.

=> production of strongly interacting particles benefits the most from higher E

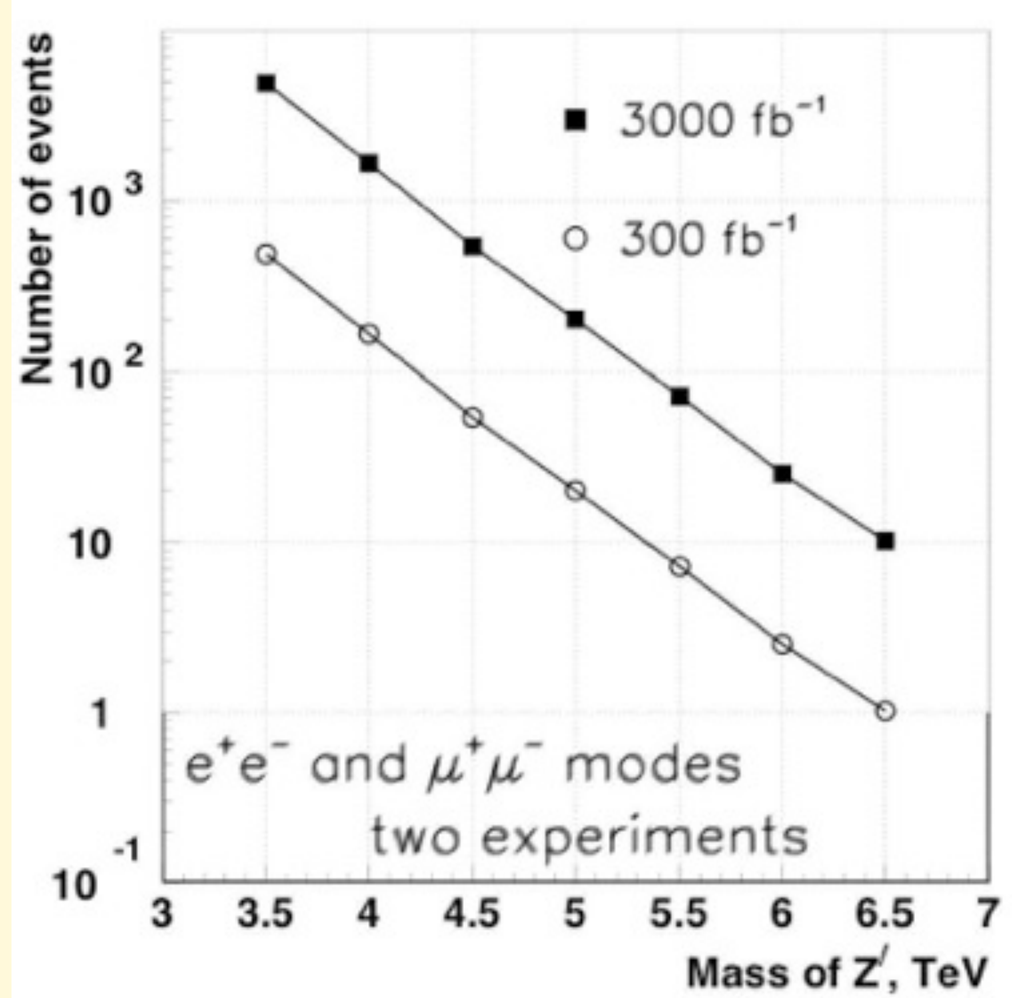
Production rate of TeV-scale systems in the gg channel increases by over 100 going from 14 to 100 TeV

=> rate growth is much faster than linear in the region near threshold



Searching new forces: W’, Z’

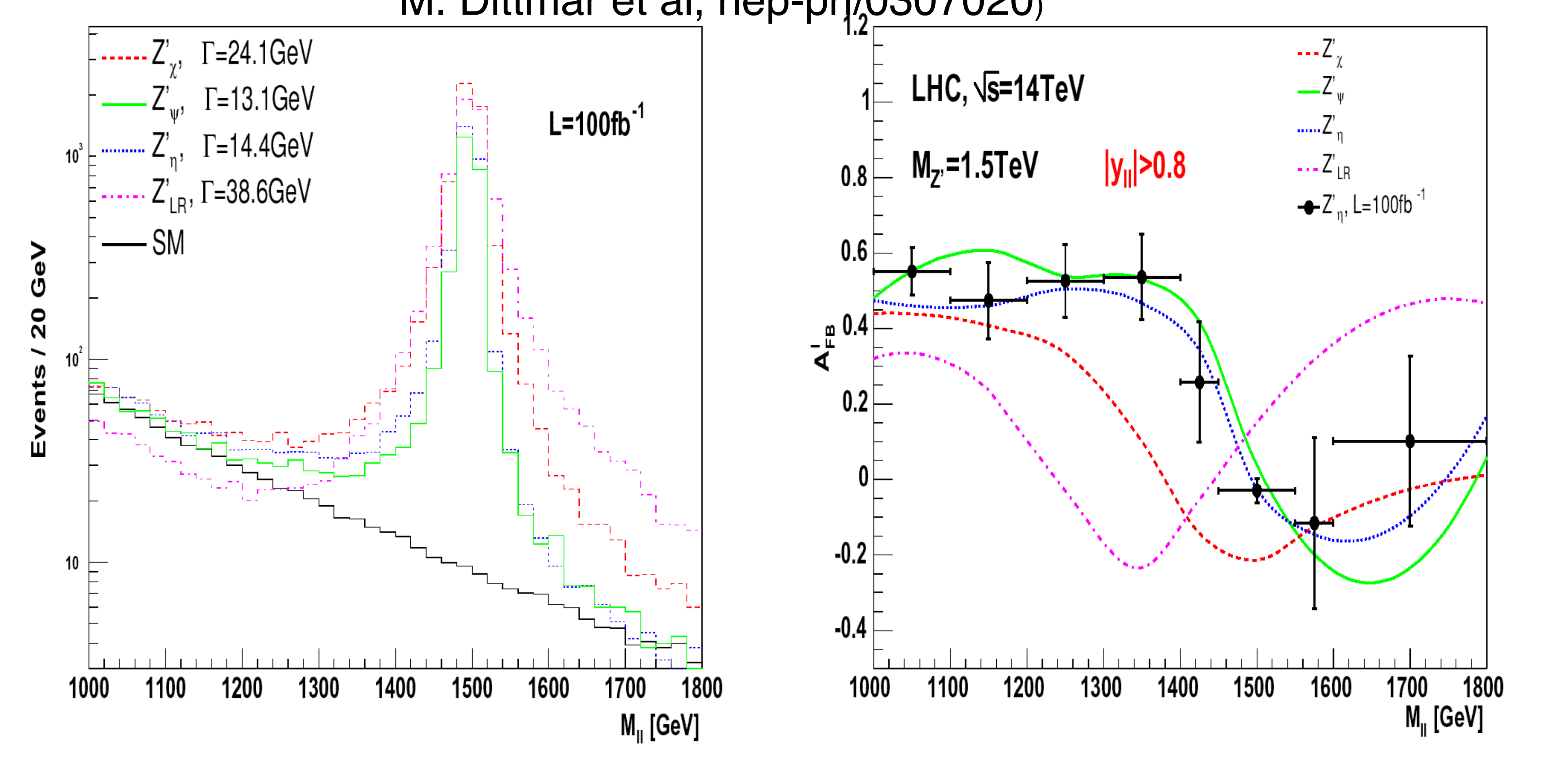
E.g. a W’ coupling to R-handed fermions, to reestablish at high energy the R/L symmetry



100 fb⁻¹ discovery reach up to ~ 5.5 TeV

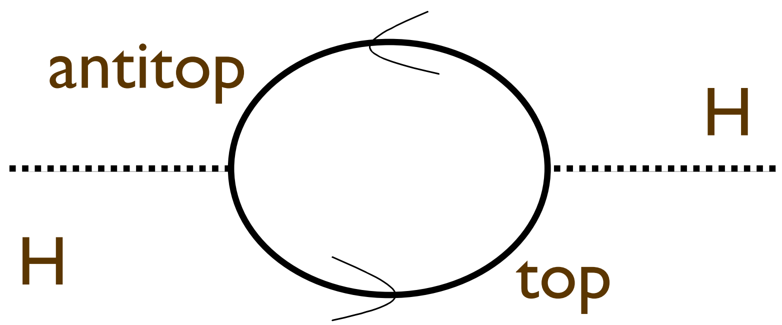
Differentiating among different Z’ models:

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



100 fb⁻¹ model discrimination up to 2.5 TeV

The Higgs self-energy



$$\delta m_H^2 \sim \frac{6G_F}{\sqrt{2}\pi^2} m_t^2 \Lambda^2 \quad , \quad \Lambda \to \infty$$

Λ ~ 1 / R_H

renormalizability =>

$$m_H^2(v) \sim m_H^2(\Lambda) - (\Lambda^2 - v^2) \quad , \quad v \sim 250\text{GeV}$$

but then:

$$\frac{m_H^2(\Lambda) - \Lambda^2}{\Lambda^2} \sim \frac{v^2}{\Lambda^2} = O(10^{-34}) \text{ if } \Lambda \sim M_{Planck}$$

FINE TUNING!

Hierarchy problem

Solution

Tie the Higgs mass to some symmetry which protects it against quadratic divergencies

Supersymmetry

H (scalar) ↔ fermion

$$\delta m_e = \frac{\alpha_{em}}{3\pi} m_e \log \frac{\Lambda}{m_e}$$

Gauge symmetry

H (scalar) ↔ 5th component of a gauge bosons in 5 dimensions or more

=> extra dimensional theories

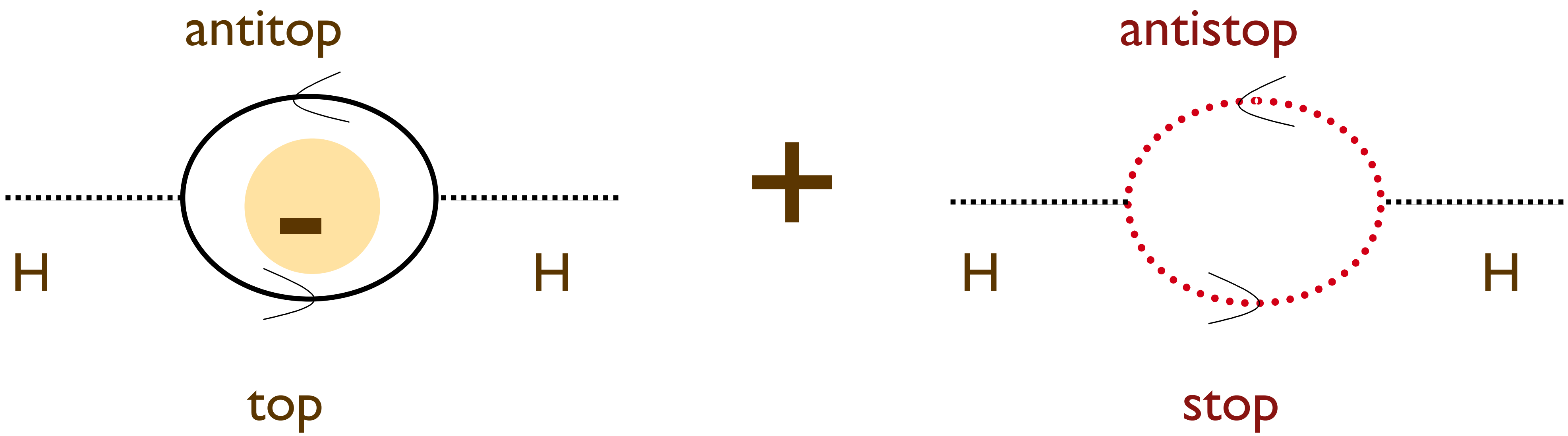
Global symmetry

H → H + a ⇒ $L(H)=L(\partial H)$

=> Little Higgs theories, Technicolor
H=pseudo-goldstone boson

In all cases, new particles must appear at a scale O(TeV) to cancel the quadratic divergence and remove the fine tuning

Ex: Supersymmetry



$$\delta m_H^2 \sim G_F\, m_t^2\, m_t^2\, \log \frac{m_{\tilde{t}}}{m_t}$$

Final remarks

- The single most compelling case for a high-E pp collider is, today, the study of WW scattering. This case has been there for over 25 year!
- The exploration of the BSM model(s) that will encompass a more complete understanding of the EWSB, and possibly of Dark Matter, CP violation, etc, will unavoidably require pushing farther and farther the high energy frontier.
- Current strong limits from the LHC@8TeV, already strongly limit the potential for high-statistics studies at 14 TeV and point in a natural way to the high-energy upgrade as the best way to perform quantitative studies of discoveries to be made at 14 TeV, and to extend the search potential of LHC@14TeV