Searching for new physics at future accelerators

R. Barbieri
Scuola Normale Superiore and INFN, Pisa

5th Rencontres du Vietnam, Hanoi, 5-11 Aug 04

Particle Physics in one page

$$\mathcal{L} = -\frac{1}{4} F^a_{\mu\nu} F^{a\,\mu\nu} + i\bar{\psi} D\!\!\!/\,\psi$$

The gauge sector (1)

$$+\psi_i \psi_{ij} \psi_j h + h.c.$$

The flavor sector (2)

$$+|D_\mu h|^2 - V(h)$$

The EWSB sector (3)

$$+L_i \psi^{\nu}_{ij} N_j + (N_i M_{ij} N_j)$$

The ν-mass sector (4)

(1) best tested, at least to per-mille accuracy

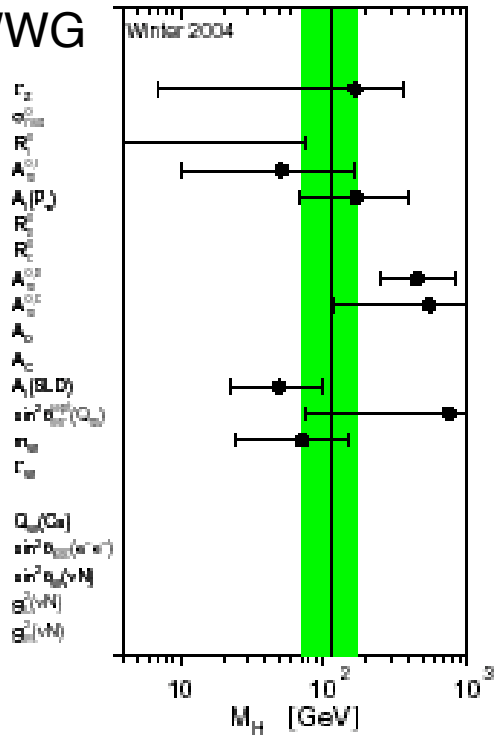
(2) + (4) : main developments of last 5 years, different in nature

(3)The ElectroWeak Symmetry Breaking sector

[The origin of mass? What distinguishes the γ from the W, or the electron from the neutrino? (not electric charge!)]

Consistent with (indirect) observations? Yes, so far

LEPEWWG



Low-energy + Z-pole + LEP2

Type of fit	$10^3\widehat{S}$	$10^3\widehat{T}$	10^3Y	10^3W
One-by-one (light Higgs)	0.0 ± 0.5	0.1 ± 0.6	0.0 ± 0.6	-0.3 ± 0.6
One-by-one (heavy Higgs)	—	2.7 ± 0.6	—	—
All together (light Higgs)	0.0 ± 1.3	0.1 ± 0.9	0.1 ± 1.2	-0.4 ± 0.8
All together (heavy Higgs)	-0.9 ± 1.3	2.0 ± 1.0	0.0 ± 1.2	-0.2 ± 0.8

B, Pomarol, Rattazzi, Strumia

Thoroughly tested? No: Direct $E > G_F^{-1/2}$ only scantily

Predictive? No: $\mu, \square \Rightarrow m_h, G_F (or M_Z)$

Theories, models, scenarios, ... of EWSB

$\Rightarrow$ *Supersymmetry (in various forms)*

$\Rightarrow$ *Higgs as PseudoGoldstone Boson (PGB)*

$\Rightarrow$ *Composite Higgs*

$\Rightarrow$ *Technicolor*

$\Rightarrow$ *Higgsless*

$\Rightarrow$ *Extra-dimensions*

$\Rightarrow$ . . .

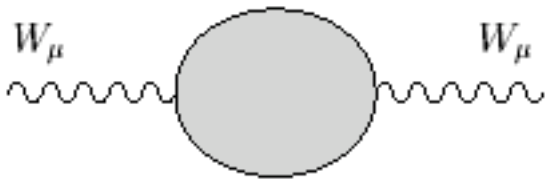
Need a guiding principle (at least for this talk)

The Calculability Principle

(too narrow a view?)

Look for models where the Fermi scale (or the Z-mass) can be related to some other physical scale, call it Λ_{NP}, in a calculable manner

Ex: Technicolor



$\Rightarrow$ $M_W = \frac{g_2}{2} f_{\Lambda_{TC}}$

Susskind Weinberg

beautiful, but, when calculable, it appears not to work with data

In any such model: $M_Z = \Lambda_{NP} f(a_i)$ with a_i physical par.s

(can be done if m_h^2 freed from UV-sensitivity)

The C P $\oplus$ consistency with data select (to date):

Supersymmetry, Higgs as a PGB

Supersymmetry (MSSM)

The merits:

⇒ Gauge coupling unification

⇒ Quartic Higgs coupling predicted: $m_h^{tree} \leq M_Z$

⇒ A Dark Matter candidate

⇒ Smootly passes the EWPT

Georgi, Dimopoulos

B, Ferrara, Savoy

Chamseddine, Arnowitt, Nath

Hall, Lykken, Weinberg

Supersymmetry (MSSM): the "problem"

Where are the superpartners?
Where is the Higgs?

Where is Λ_{susy} *?*

In the MSSM Λ_{susy} "typically" within reach of LHC

How typical is "typical"?

$$M_Z^2 = (90GeV)^2 \left(\frac{< m_{\tilde{t}} >}{200GeV}\right)^2 \log\frac{\Lambda_{UV}}{< m_{\tilde{t}} >} \pm \text{ etc.}$$

$$\Lambda_{susy} \equiv < m_{\tilde{t}} >$$

log = 5 ÷ 30

Without accidental cancellations, $< m_{\tilde{t}} >$ well below what is needed to hide the Higgs

$$m_h|_{th} = m_h^{tree}(\leq M_Z) + m_h^{rad}(\log < m_{\tilde{t}} >)$$

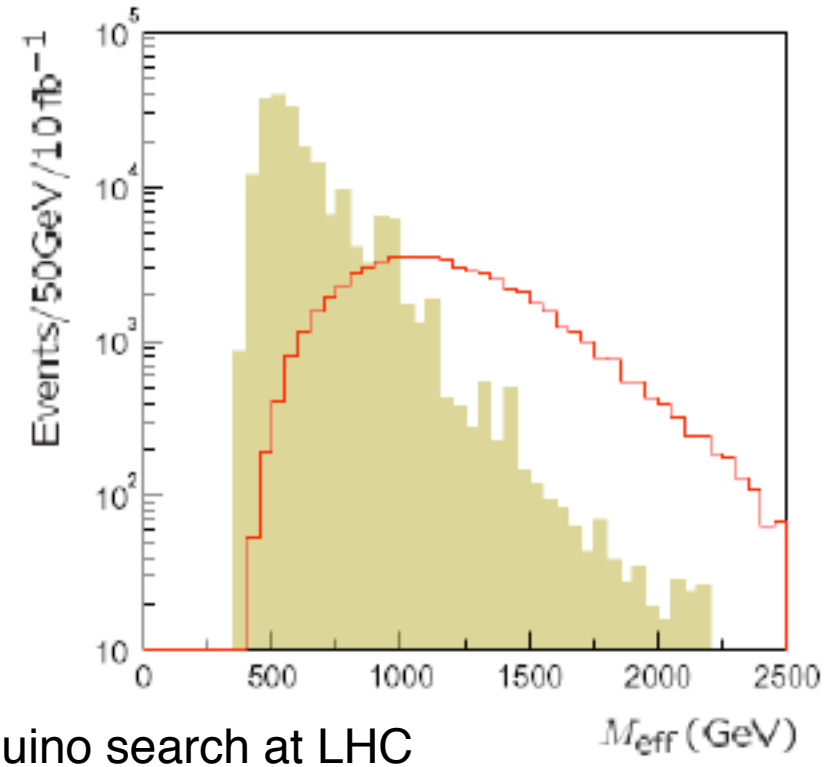
$$m_h|_{exp} > 115GeV \quad \Rightarrow \quad < m_{\tilde{t}} > \geq 500GeV$$

Supersymmetry: the reactions to the problem

1. Never mind a few % accidental tuning

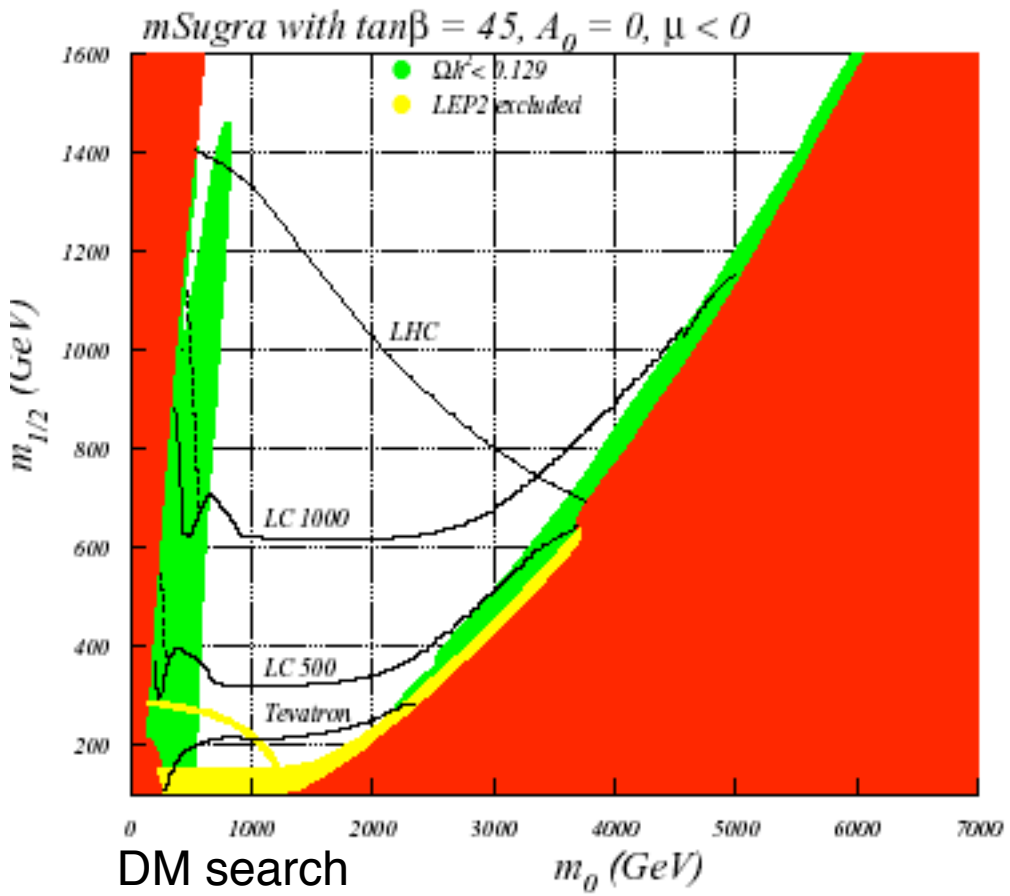
LHC ⊕ LC can systematically explore ~ all of the MSSM parameter space up to a per-mille tuning

$$m_h \leq 125 \div 130 GeV$$



Gluino search at LHC

ATLAS Coll



DM search

Baer et al

2. Increase m_h^{tree} by an extra bit of quartic coupling

$$\lambda^{tree} = \frac{g^2 + g'^2}{8} + \lambda\lambda^{tree}$$

NMSSM, a new gauge contribution, . . .

Haber, Sher
...
Harnik et al
Batra et al

$\Rightarrow m_h \uparrow \quad \leq 150$ GeV, or even significantly higher

Things to watch: gauge unification, EWPT if m_h grows

Phenomenology: in the NMSSM, two extra neutral scalars, sometimes light

3. Reduce the tuning in $M_Z = \Box_{Susy} f(a_i)$

E.g., among several possibilities:

Susy broken by boundary condition on a 5th dimension

(a segment of length $\Box R/2$)

Merits: 1 single Higgs, no fine-tuning

Signal: the stop as the LSP, stable for collider searches

$\tilde{t}\bar{u} \equiv T_0 \qquad \tilde{t}\bar{d} \equiv T^+$: low-β tracks with anomalous dE/dx

$m_{\tilde{t}} = 500 \div 1300 GeV$ most other sparticles at $1/R = 1.5 \div 4 TeV$

$m_h = 110 \div 125 GeV$

Price: give up gauge unification and the DM candidate

B, Hall, Nomura
Marti, Pomarol
B, Papucci, Marandella

4. The tuning is not a criterium at all

[inspired by frustration from the CC problem and ST develop.s]

There are regions in the MSSM parameter space highly tuned, but with a striking signal

"Split-Supersymmetry" : $m_{\tilde{f}} >> m_{\tilde{g}}, m_{\tilde{h}}$

A long-lived ÷ effectively stable gluino

$\tilde{g}g \equiv R_0 \qquad \tilde{g}q\bar{q} \equiv M_0 \qquad \tilde{g}u\bar{d} \equiv M_1$

while keeping all "standard" MSSM merits,

except naturalness

$m_h \leq 150 \div 160 GeV$

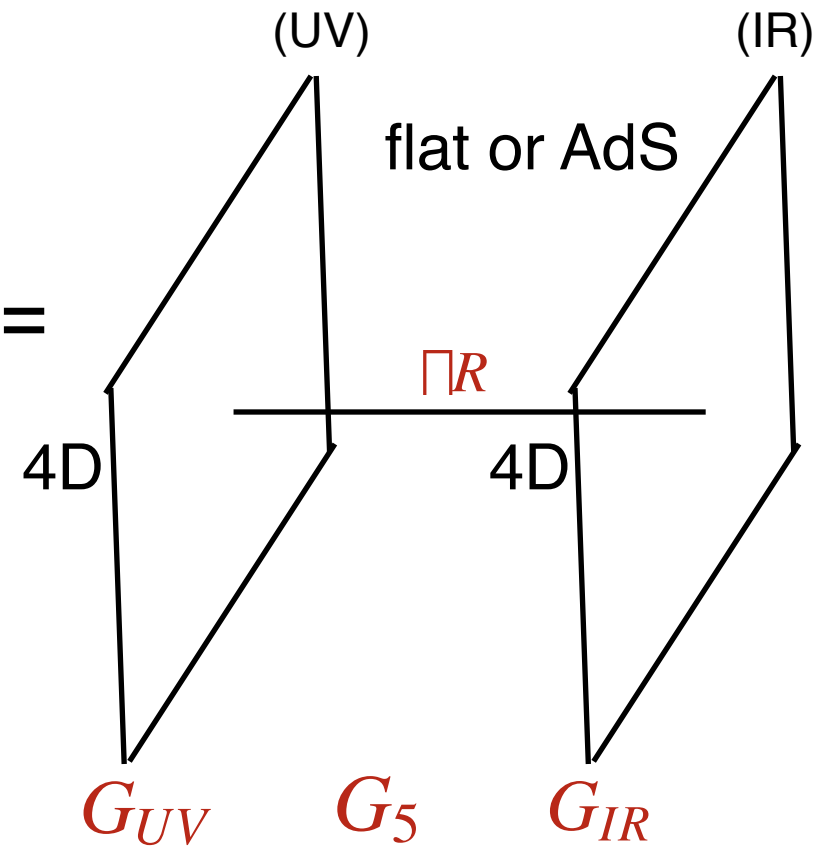
Arkani-Hamed, Dimopoulos
Giudice, Romanino

Strongly interacting models of EWSB

We used to think: When calculable, they don't work

Why the new interest, then? Mostly from extra-D,
which can improve calculability (sic!)

Space-time =



$\frac{1}{R} \simeq$ mass of the KK states

Where we (matter) live
is model dependent

Concrete realizations

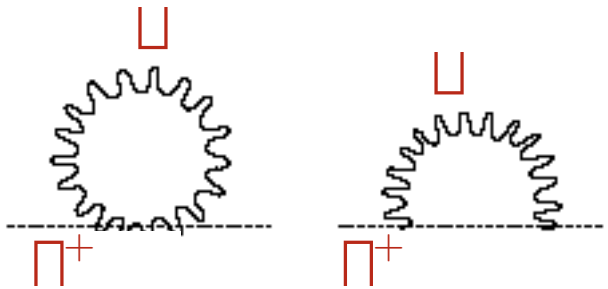
Several, mostly dependent on the choice of $G_5, \quad G_{UV}, \quad G_{IR}$

Inspection of models still under way: Higgsless, composite Higgs, . . .

Csaki et al
Agashe et al, ...

The closest to a realistic, calculable model:

> The Higgs as a PGB, like the π^+ in QCD $\oplus$ QED of massless quarks



$$m^2_{\pi^+} \simeq \frac{\alpha}{4\pi} f^2_{QCD}$$

(in fact, one wants to do better than this)

The history : $4D \Longrightarrow 5D \Longrightarrow 4D$

Georgi, Kaplan
Arkani-Hamed, Cohen, Georgi
Contino, Nomura, Pomarol
Scrucca, Serone, Silvestrini

Back to 4D: the little Higgs models

Keep the essence of 5D, while avoiding its constraints by suitable (somewhat *ad hoc)* tricks

$G_5 \simeq G_{gl}$ broken to H_{gl} $\quad G_{IR} \simeq H_{gl}$ $\quad G_{UV} \simeq G_{gauge}$

Problems: give the Higgs a quartic self-coupling and a top Yukawa consistent with observations

(Too) many models:

The "littlest" $\quad f = \square_{LH}$ $\quad$ The "simplest"

Global $\quad SU(5) \xrightarrow{f} SO(5)$ $\quad (SU(3)XU(1))^2 \xrightarrow{f} (SU(2)XU(1))^2$

Gauge $\quad (SU(2)XU(1))^2 \Longrightarrow SU(2)XU(1)$ $\quad SU(3)XU(1) \Longrightarrow SU(2)XU(1)$

Arkani-Hamed et al $\quad$ Kaplan, Schmaltz

Phenomenology of Higgs as PGB

Perelstein, Peskin, Pierce

t $\Longrightarrow$ T (T' , T", ...) $\quad m_T \geq 1 \div 2TeV$

$pp \to T + j + X \quad (qb \to q\prime T) \quad T \to th, tZ, bW$

LHC: Events/$300 fb^{-1} \quad (m_T = 2TeV) \approx 10^3$

W,Z $\Longrightarrow$ W_H, Z_H (V' , V", ...) $\quad m_V \geq 1 \div 2TeV$

production rates and decay modes model dependent

LHC: Events/$300 fb^{-1} \quad (m_V = 2TeV) \leq 10^5$

$m_h = ?$

Question: How low can f be? T-parity, LEP2 constraints, ...

Cheng, Low

Schmaltz

A road map to the discovery/test of EWSB physics *(cum grano salis, please)*

	MSSM NMSSM	5D-Susy	Split-Susy	Higgs as PGB
LHC	√ ~	√ ~	√ ~	√ ~
LC(500 GeV)	√ √	— ~	√ √	— ~
LHC ⊕ LC	very significant	add indirect evidence	crucial for test	add indirect evidence

⊕under favorable parameter conditions

√ = likely

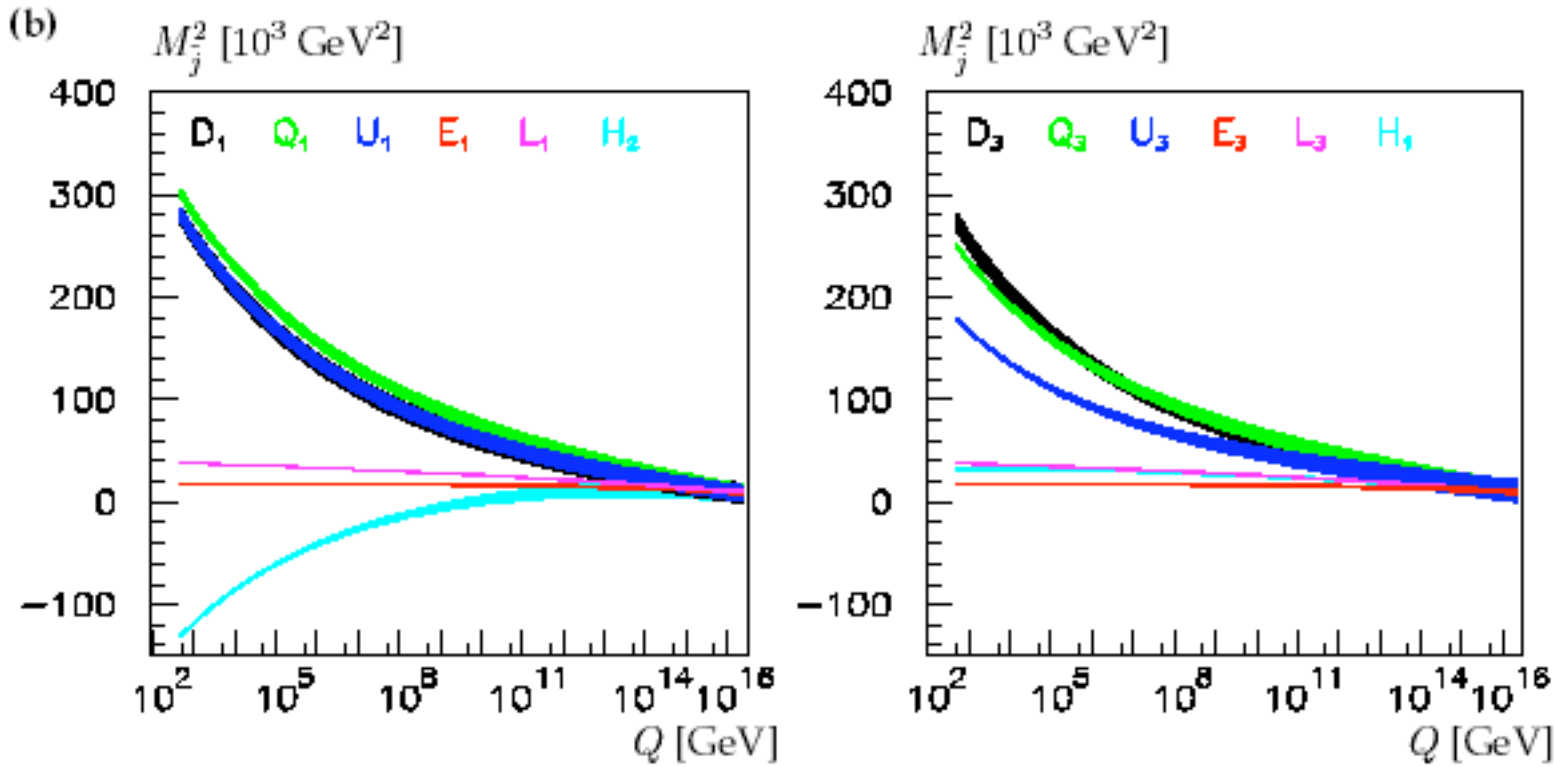
~ = incomplete

— = unlikely

RED = Discovery

BLU = Test

High-energy extrapolation of the sfermion masses from measurements at a LC



(in a favorable point of the MSSM par. space)

Allanach et al

95% sensitivity reaches for a basic choice of contact interactions

$$\mathcal{L} = \frac{4\pi}{\Lambda^2}(\bar{f}\gamma_\mu f)_{L,R}(\bar{f}\gamma_\mu f)_{L,R}$$

		LHC Λ [TeV]				LC Λ [TeV]			
model		LL	RR	LR	RL	LL	RR	LR	RL
eeqq:	Λ_+	20.1	20.2	22.1	21.8	64	24	92	22
	Λ_-	33.8	33.7	29.2	29.7	63	35	92	24
ee$\mu\mu$:	Λ_+					90	88	72	72
	Λ_-					90	88	72	72
eeee:	Λ_+					44.9	43.4	52.4	52.4
	Λ_-					43.5	42.1	50.7	50.7

LHC/LC Study Group

LC ($L_{int} = 1 \quad ab^{-1}$ and polarized beams)

Current LEP2 in the 10 ÷ 25 TeV range

Estimated uncertainties on precision electroweak observables

	now	LHC	LC	Giga-Z
$\Delta sin^2\theta_{eff}(10^{-5})$	16 (?)	15	?	1.3
$\Delta M_W[MeV]$	34	15	10	7
$\Delta M_t[GeV]$	4.3	1.0	0.2	0.1
$\Rightarrow \frac{\Delta m_h}{m_h}$	60%	15-20%	10-15%	5-10%

$$sin^2\theta_{eff}(M_t, m_h, \alpha(M_Z))$$

$$M_W(M_t, m_h, \alpha(M_Z))$$

Conclusions (specific)

$\Rightarrow$ Two physical principles behind "calculable models" of EWSB:

Supersymmetry: Has far reaching consequences. Its specific realizations (and the corresponding signals) still debated

Higgs as PGB: Resurrected by 5D, though not easy to make it work. 4D Little Higgs models consistent (somewhat ad hoc?)

$\Rightarrow$ If naturalness is a good guide, the LHC will find signals of new physics

$\Rightarrow$ For their full interpretation, a LC at 500 GeV often (though not always) very significant

Conclusions (general)

- EWSB as the most (?) compelling/promising open problem in particle physics
- Energies above the Fermi scale only scantily explored so far in a direct way!
- A variety of options (although not on equal footing). Best to be open minded
- Uncovering the mechanism of EWSB ⇒ a revolution in fundamental physics