New physics and the post-LHC era

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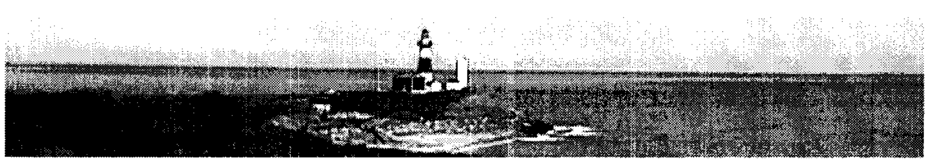
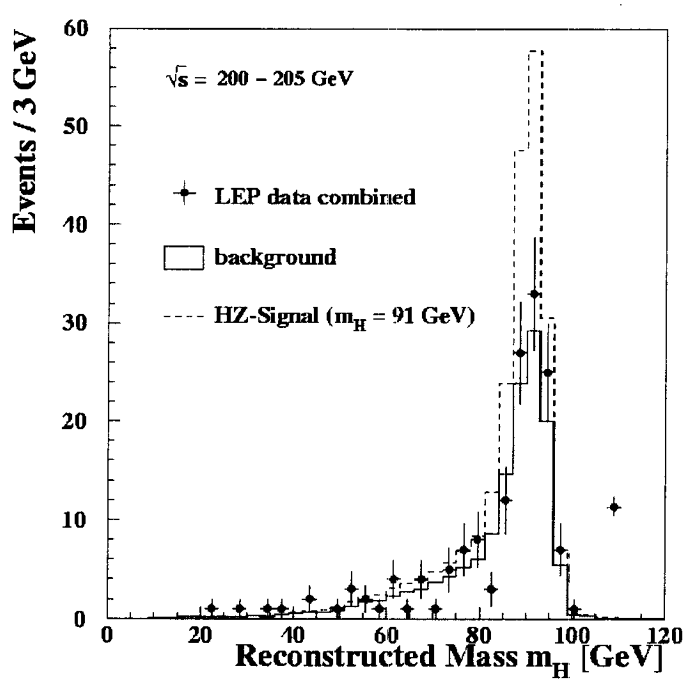


Where are we going and how do we get there?

- Current collider experiments are already probing the weak scale, at $\sqrt{s}$ ~200 GeV and $\sqrt{s_x}$ = 200 - 600 GeV.

- We may get a Higgs discovery from LEP. From the Tevatron Runs IIa and IIb we may get the Higgs and/or new physics associated with electroweak symmetry breaking: supersymmetry, new strong dynamics, etc.



Where are we going and how do we get there?

- With the LHC we will probe the TeV scale, $\sqrt{s_x} \sim$ 1-3 TeV. A possible linear collider could also probe $\sqrt{s}$ ~1 TeV.
- We expect to see a lot of new physics at these machines. One of our main jobs in studying this physics is to look for hints about new physics thresholds at even higher energies.

- If we want to be ready to exploit these exciting discoveries, we better get serious NOW about post-LHC machines.

Future accelerators
2006 – 2012: LHC era

- LHC: $\sqrt{s}$=14 TeV, $\mathcal{L}$=10^{33}-10^{34}.
- LC: $\sqrt{s}$=350 GeV to 1 TeV, $\mathcal{L}$=10^{34}ish.
- ν factory: 1 millimole of muons/year.
- Tevatron Tripler: $\sqrt{s}$=6 TeV, $\mathcal{L}=5 \times 10^{32}$.

2013 – 2025: WITHIN the energy frontier:

- stretch LC: $\sqrt{s}$=1.5 TeV.
- $\gamma\gamma$, e^-e^-: piggyback on LC.
- First Muon Collider: Higgs factory? Heavy Higgs factory?

2013 – 2025: Extending the energy frontier

- upgraded LHC?: $\sqrt{s}$=?.
- CLIC: $\sqrt{s}=3-5$ TeV, $\mathcal{L}=10^{35}$.
- site-filling HEMC: $\sqrt{s}=3-4$ TeV, $\mathcal{L}=10^{35}$.

OR, make a bigger energy jump:

- VLHC: $\sqrt{s}=100-200$ TeV, $\mathcal{L}=10^{35}$.
- ultimate HEMC: $\sqrt{s}\geq 10$ TeV, $\mathcal{L}$ =?.

PHYSICS INPUT WILL HELP US MAKE BETTER CHOICES

Physics questions for future accelerators

- The Standard Model is an effective theory for physics below some high energy cutoff Λ. What is the value of Λ?
- What are the relevant degrees of freedom for the new effective theory at energies above Λ?
- What are the symmetries of this new effective theory?
- What symmetries and organizing principles of the Standard Model turn out to be artifacts of the "low energy" approximation?
- Do the symmetries and organizing principles of the new effective theory explain parameters/hierarchies of the SM, e.g. the flavor problem?
- Does the new effective theory give any hints (e.g. spontaneously broken symmetries) of physics at even higher scales?

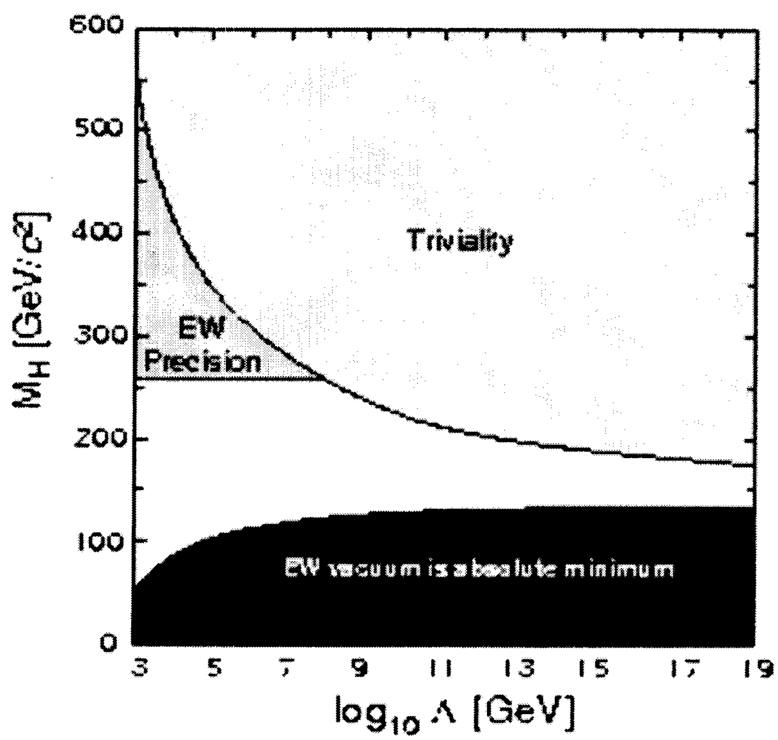
How do we determine Λ for the Standard Model?

- Look for new degrees of freedom:
  - new particles, resonances, solitons.
  - evidence of compositeness, symmetry restoration, symmetry breaking.
  - new spatial dimensions.

- Look for evidence of higher order terms in $\mathcal{L}_{\rm eff}$, e.g. 4-fermion couplings. Note that symmetries and approximate symmetries of the SM may not be respected by the full effective action. Look for FCNC, CP violation, $\mu \to e\,\gamma$, proton decay, etc. etc..

• Look at the Higgs sector, which is more sensitive to Λ for several reasons:

- The hierarchy problem: because of radiative corrections, the Higgs mass is naturally of order Λ.
- If the Higgs mass is large, it becomes strongly coupled at some scale Λ.
- If the Higgs mass is small, it's effective potential becomes unstable at some scale Λ.



-C. Quigg, hep-ph/9905369

What *could be out there?*

• Most theoretical speculation about the new effective theory at high energies involves ADDING things to the Standard Model:

- add particles (e.g. superpartners, techniparticles, messenger sector, Kaluza-Klein or string resonances.)
- add new symmetries or organizing principles (e.g. supersymmetry,)
- add new gauge interactions, dynamics, either strongly coupled (e.g. technicolor) or weakly coupled (e.g. Z' boson).

Sacred Cows

• However it is just as likely that at higher energy scales we have much more radical changes:

- qualitatively new degrees of freedom (e.g. strings, membranes, extra dimensions)
- symmetries are broken (e.g. B and L violation)
- sacred principles are violated!

This would not be the first time that sacred cows got ground into hamburger.

History Lessons

- Newtonian mechanics $\Leftrightarrow$ electromagnetism $\rightarrow$ special relativity

Lesson: Galilean invariance is only an approximation, good at low speeds.

- Thermodynamics $\Leftrightarrow$ electromagnetism $\rightarrow$ quantum mechanics

Lesson: Rayleigh's formula for blackbody emittance is only an approximation, good at low frequencies.

- Newtonian gravity $\Leftrightarrow$ special relativity $\rightarrow$ general relativity

Lesson: Newtonian gravity is only an approximation, good for weak gravitational fields and low speeds.

Big Unknowns

- Determine the energy scale and conditions for which the following theoretical assumptions break down:

  - The fundamental dynamical entities are point-like particles.
  - Relativistic quantum field theory (locality, microcausality, CPT).
  - General relativity.
  - Quantum mechanics.

Werner Heisenberg, 1939: quantum mechanics probably breaks down at an energy scale around 1 GeV.

String theory

- Although string theory has not (yet) done a good job of matching to the SM at low energies, it has proven to be a great exercise for liberating our thinking.
- If string theory is correct, both general relativity and quantum field theory break down at some energy scale M_s. We don't know what this string scale is!
- If string theory is correct, the fundamental physical entities are not quarks and leptons, but perhaps a whole collection of particle-like, string-like, and membrane-like objects.
- Furthermore these objects propagate in a 10+1 dimensional spacetime.

“Model-independent” Conclusions

- There is a whole new effective theory waiting to be explored at the TeV scale.
- The new physics will be rich, surprising, confusing, and take a long time to untangle.
- For exploration you will want high energies, reasonable luminosities, and reasonable detectors.
- For detailed studies, you need excellent luminosities and excellent detectors.
- You will need detailed studies not only to unravel the new effective theory, but also to give you hints about physics at even higher scales.

The LHC is not enough

- The LHC can do a lot, including precision measurements.
- But the new physics at the TeV scale will be both rich and confusing.
- Higgs physics will be interesting for a long time! ($\gamma\gamma$ option, s-channel Higgs factory).
- LC + an FMC offer different sensitivities, polarization, reduced backgrounds, better contained events, more precise measurements.

Examples:

- Untangling the neutralino and slepton sectors in SUSY. What kind of SUSY is it?
- Deciphering virtual effects of extra dimensions. Is your Drell-Yan anomaly due to spin 2 Kaluza-Klein graviton exchange?

Precision measurements can pin down new physics scales

- Detailed study for Gauge Mediation at 500 GeV LC.

–Ambrosanio and Blair, hep-ph/9905403

- Case of neutralino NLSP, $\tilde{\chi}_1^0 \to \gamma$G.
- Measure $c\tau$ of $\tilde{\chi}_1^0$ in the range 10 microns to 30 meters, using various techniques:
  - Projective tracking
  - 3D tracking
  - Photon pointing
  - Calorimeter timing
  - Statistical (counting single γ versus 2 γ)
- $c\tau$ has only log sensitivity to the messenger scale, but is proportional to the SUSY breaking scale $\sqrt{F}$:

$$c\tau_{\tilde{\chi}_1^0} \sim \frac{F^2}{M^5_{\tilde{\chi}_1^0}}$$

- Conclusion: with an appropriate detector and 200 fb^{-1}, measure $\sqrt{F}$ to $\pm 5\%$.

Our Dilemma

- If you want a new energy frontier collider in 2020, you had better be doing serious R& D now.
- BUT, we don't yet know how to estimate the next interesting energy scale.
- Will a 3-4 TeV lepton collider or an LHC upgrade be good enough, or do we need to push to a 10 TeV muon collider or 100-200 TeV VLHC?
- LHC/LC data is probably essential for making good decisions. E.g. LHC/LC may data indicate an effective Planck scale of 4 TeV! This affects your choices for $\sqrt{s}$, luminosity, and detector design!

Life at the string scale

- The HEMC may operate above the threshold for stringy effects and/or quantum gravity.
- Any discoveries hinting at M_* or M_s in the multi-TeV range will dramatically change our expectations for what we will observe at the HEMC.
- Because of our poor understanding of string theory, it is hard to sketch detailed scenarios for life above the string scale or the effective Planck scale.
- Two generic expectations are the production of heavier vibrational modes of the string (Reggeization) and the production of mini-black holes

Production of black holes at colliders

- If I collide two particles at an impact parameter less than their Schwarzschild radius, I expect to form a black hole.

- Normally this is not an issue, since the critical impact parameter goes like

$$b_{sch} \sim \frac{\sqrt{t}}{M_p^2} \sim (10^{35}\ \mathrm{GeV})^{-1}$$

- Suppose there are 2 large extra dimensions, with an effective Planck scale M_* in the TeV range. Then

$$b_{sch} \sim \frac{1}{M_*}\left(\frac{\sqrt{t}}{M_*}\right)^{1/3}$$

- Thus future colliders may produce lots of little black holes.

- These black holes decay via Hawking radiation either into the bulk or the brane. The lifetime is of order $1/M_*$.

Detector design for quantum gravity

- Actually we have a poor understanding of such small black holes, and they may escape into extra dimensions once produced.
- Plus quantum gravity and string theory involve lots of other messy junk.
- Fortunately, quantum gravity with s/M_*^2 of order one is much simpler to deal with as long as t/M_*^2 is small.

G. 't Hooft (1987); Verlinde and Verlinde (1991)

- So it may be important to be able to do physics in the forward region at the HEMC!

What do events look like at HEMC?

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PYTHIA will be initialized for
a mu+ on mu- collider
at  10000.000 GeV center-of-mass energy

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  ISUB  Subprocess name            Maximum value

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    1   f + fbar -> gamma*/Z0        1.2603E-10

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```

Event listing (HEP format) Event: 8

particle/jet	PHEP(1,I)	PHEP(2,I)	PHEP(4,I)
mu+	0.00000	0.00000	5000.00000
mu-	0.00000	0.00000	5000.00000
mu+	203.57645	73.31965	4243.37126
mu-	0.00000	0.00000	757.03250
Z0	203.57645	73.31965	5000.40376
b	43.71009	-15.72983	658.60806
b~	159.86636	89.04947	4341.79570
Z0)	203.57645	73.31965	5000.40376
gamma	-203.57571	-73.30043	4969.25770
gamma	-0.00074	-0.01922	30.33854

There are 4 triggerable objects:

No	name	eta	phi	ET	clust
1	jet	3.85	3.48	211.08	1.00
2	jet	-3.86	0.56	159.82	2.00
3	jet	-3.37	5.94	41.18	3.00
4	met	0.00	6.13	11.47	2.00

There are 2 reconstructed objects:

object	name	ET	E-EM	E-had	eta	phi
1	jet	159.82	1833.86	1965.71	-3.86	0.56
2	jet	41.18	288.10	310.22	-3.37	5.94

Event listing (HEP format) Event: 5

particle/jet	PHEP(1,I)	PHEP(2,I)	PHEP(4,I)
mu+	0.00000	0.00000	5000.000
mu-	0.00000	0.00000	5000.000
mu+	0.00000	0.00000	4999.989
mu-	0.01376	-0.00666	4999.994
Z0	0.01376	-0.00666	9999.983
nu-tau	-3256.56287	2305.08795	4999.984
nu-tau~	3256.57663	-2305.09461	4999.999
gamma	-0.01376	0.00666	0.016

Task list for the Physics Working Group

- Classify possible new physics scenarios at 3-4 TeV, 10 TeV, and 100 TeV ? What are the new physics scenarios in which a 3-4 TeV collider is too small an increase over the LHC reach?
- What luminosities are acceptable to probe this physics?
- Classify the event topologies for different types of new physics.
- What will we need to know from the LHC and a 1 TeV LC in order to focus the physics case for a high energy muon collider?