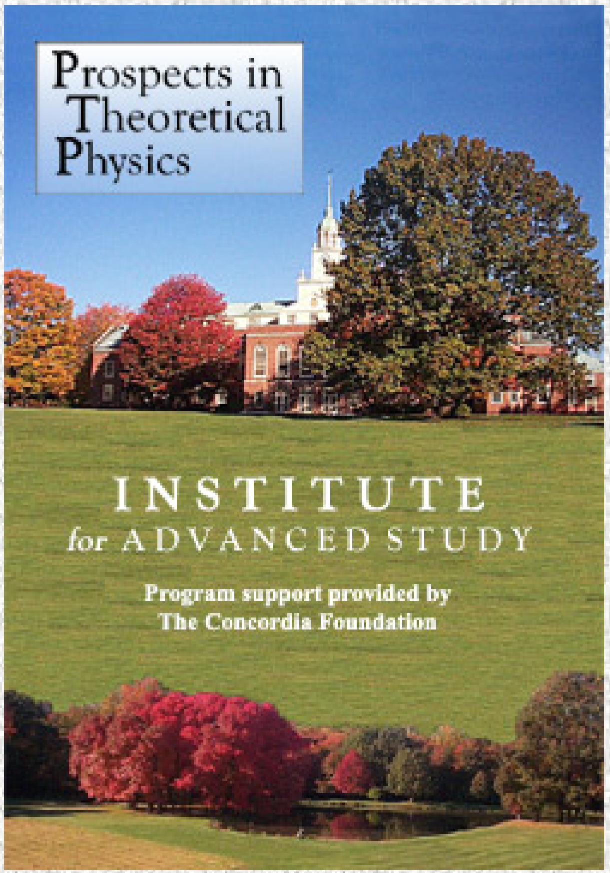
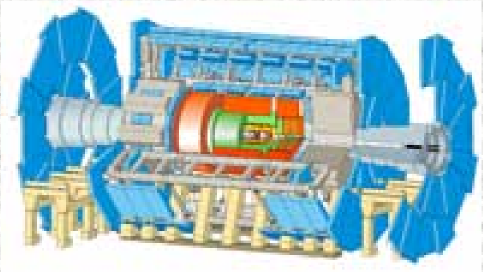
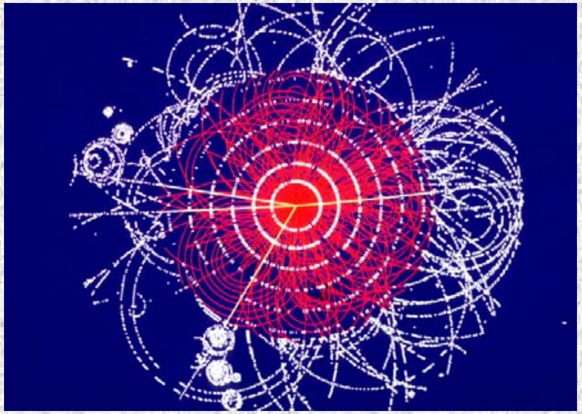
Theory in the LHC Era

Lessons from the 2007 PITP School

Michael Dine







Roadmap

At this school, we have 107 promising young people. I have enjoyed my contact with you.

We are on the threshold of a new era. What is by many measures the largest scientific instrument ever built, and certainly humanity's most powerful microscope, is nearly ready for commissioning. We all need to prepare. This school was for me, and I hope for you, an important step.

I wish I could like to provide you a roadmap from the present moment to the future.

Mapquest

Start:

Present (Truth):

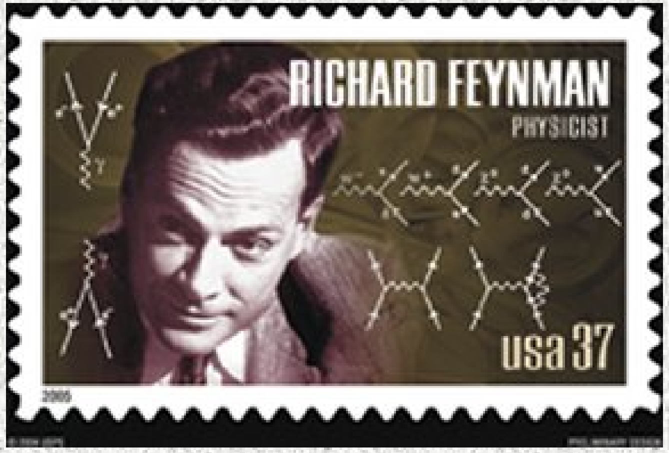
1016 Wingate Ave, Albany, GA 31705, US

End:

Future (Ink):

4545 Park Blvd # 207C, San Diego, CA 92116, US

From your questions, I know that some of you are hoping that I will tell you what problems are interesting now and what you should work on. Others are hoping that I will just sit down. I am reminded of stories of Feynman as a young man, at the Institute and later Cornell, complaining about the older faculty, their rigidity, how they did not appreciate his ideas. I am afraid, at this point, I am older than many of the old geezers of that generation, so I am quite sure I should not be telling you what to do. The best I can do is tell you my perception of the situation we face in the next few years. You may already see things differently; hopefully some of you will have ideas which take us in new directions.



Size of LHC

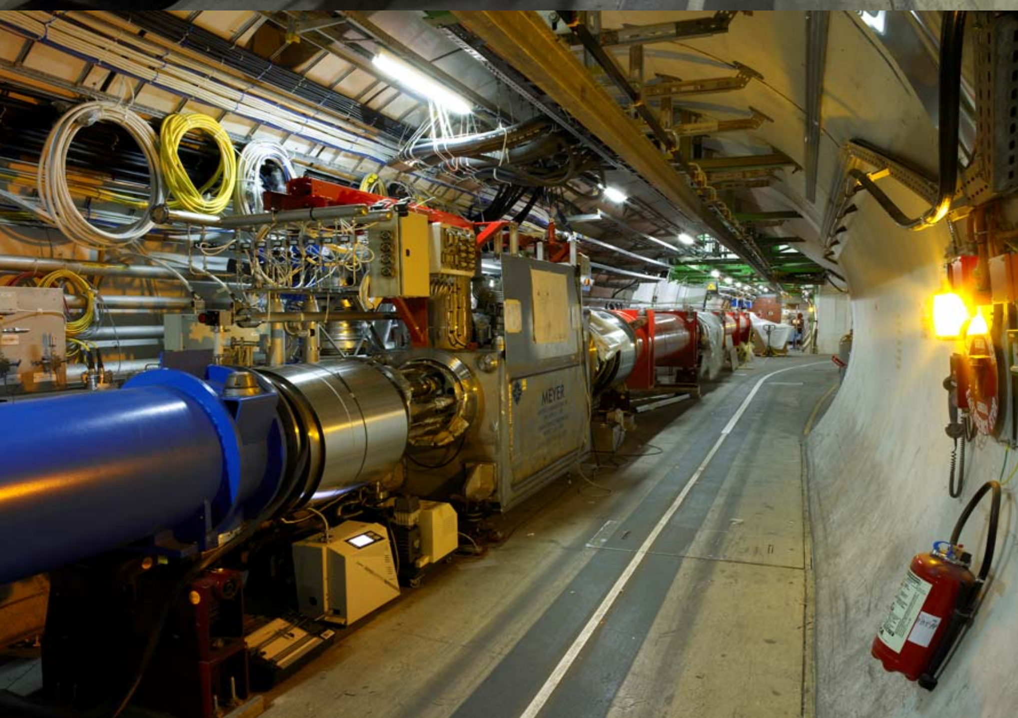
In a magnetic field B, a particle of charge q and momentum momentum p travels in a circle of radius R given by

$$R = \frac{p}{qB}$$

At the LHC, the desired beam energy is 7 TeV and the state of the art dipole magnets have a field of 8 Tesla. Plugging in and converting units gives a radius of 3 km and a circumference of 18 km.

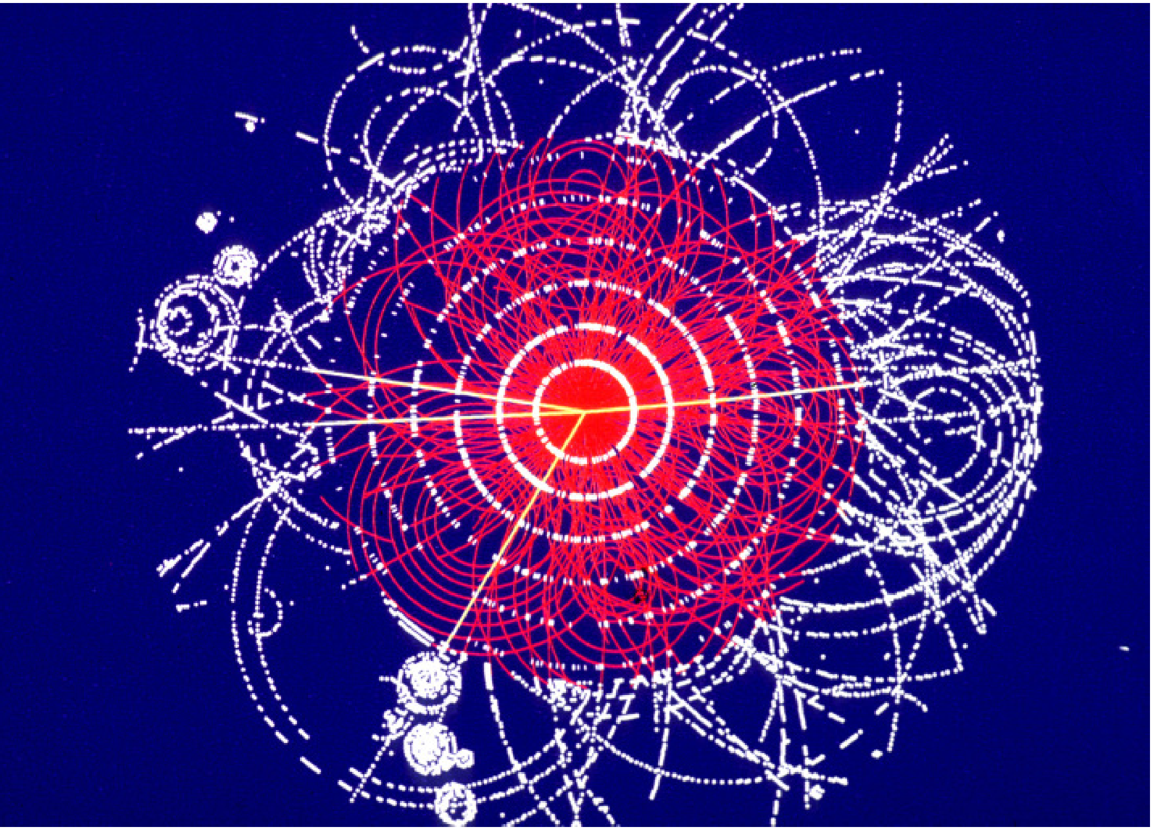
Addition of quadrupoles, RF cavities, etc., increases the circumference of LHC to 27 km.

2 in 1 superconducting dipole magnet being installed in the CERN tunnel



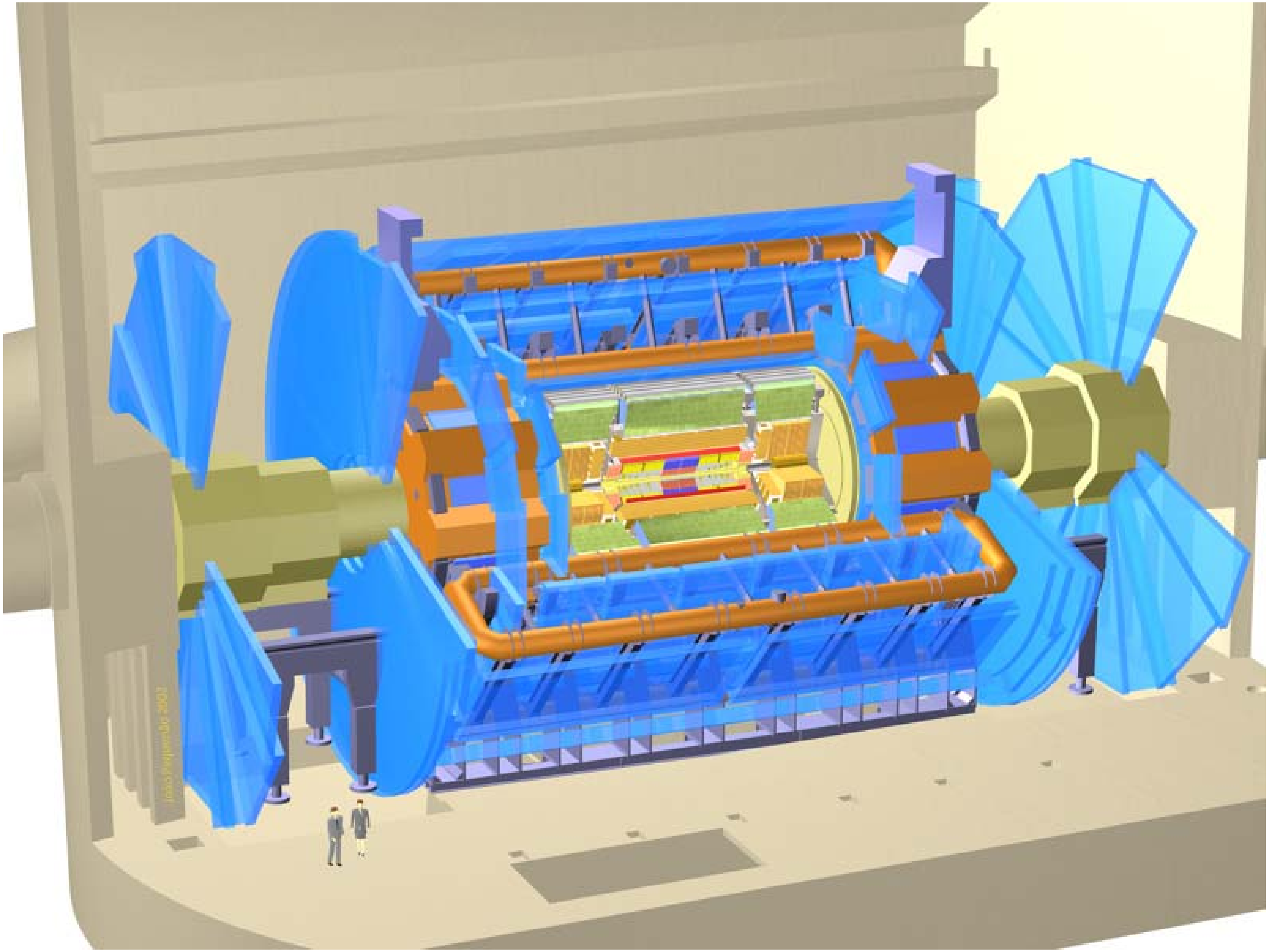
A Challenging Environment

$$gg \rightarrow H \rightarrow Z^0Z^0 \rightarrow \mu^+\mu^-\mu^+\mu^-$$



Simulation of an event in ATLAS detector. White lines are the four muons. The other tracks are due to particles from quarks in the protons. We learned from Ellis, Peskin the basics of tracking and calorimetry, the central role of muons.

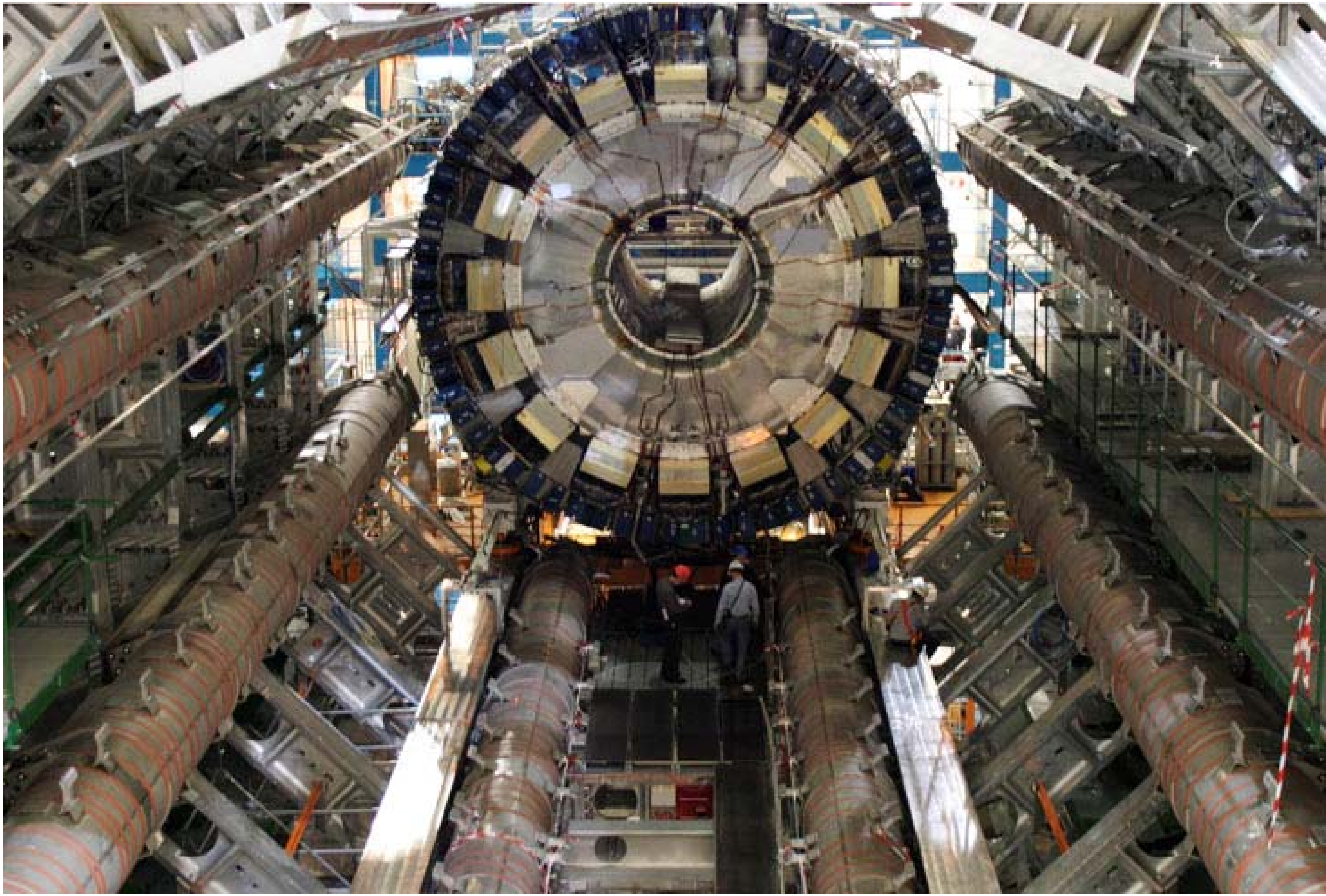
ATLAS Detector

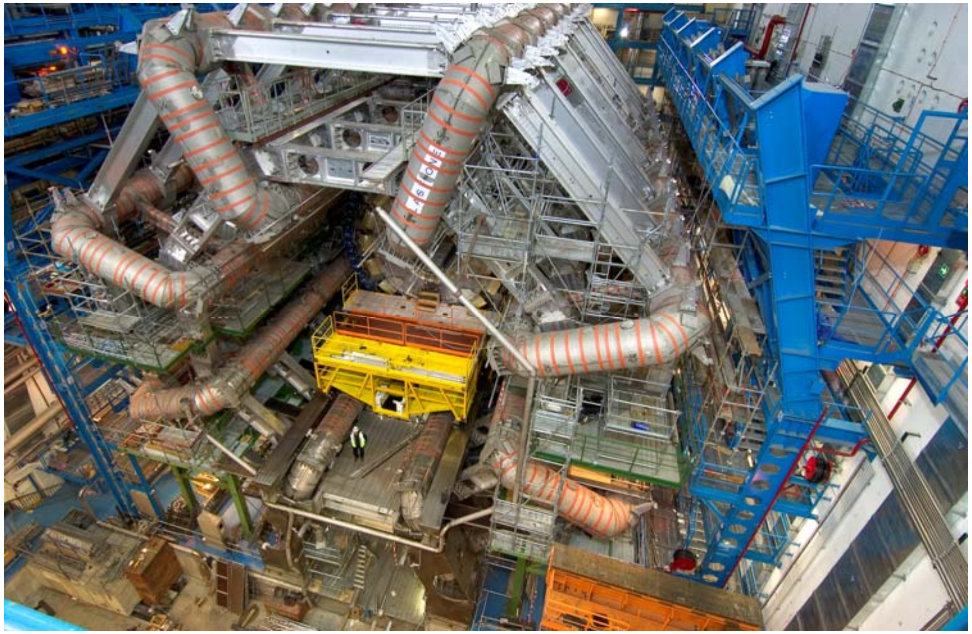


Tracker

Inserting silicon detector into tracker

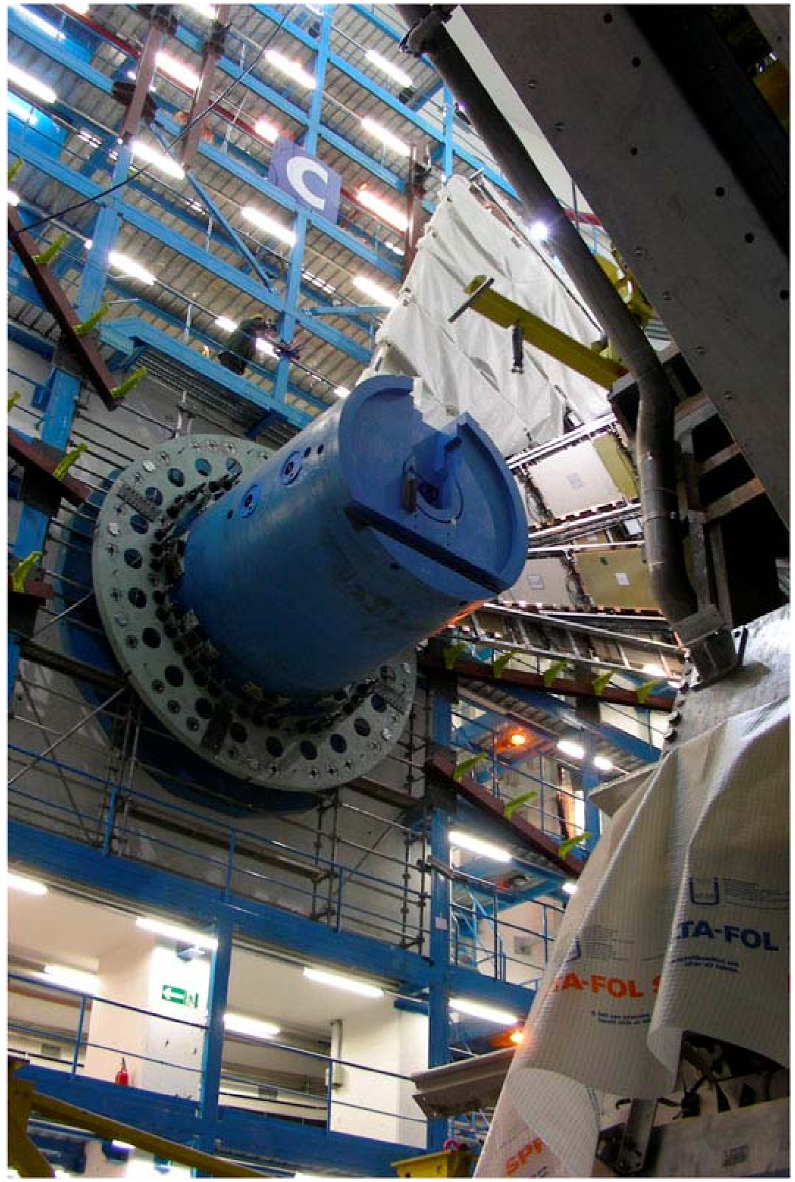
Inserting solenoid into calorimeter





Muon superconducting toroids.

Endcap Muon Sectors

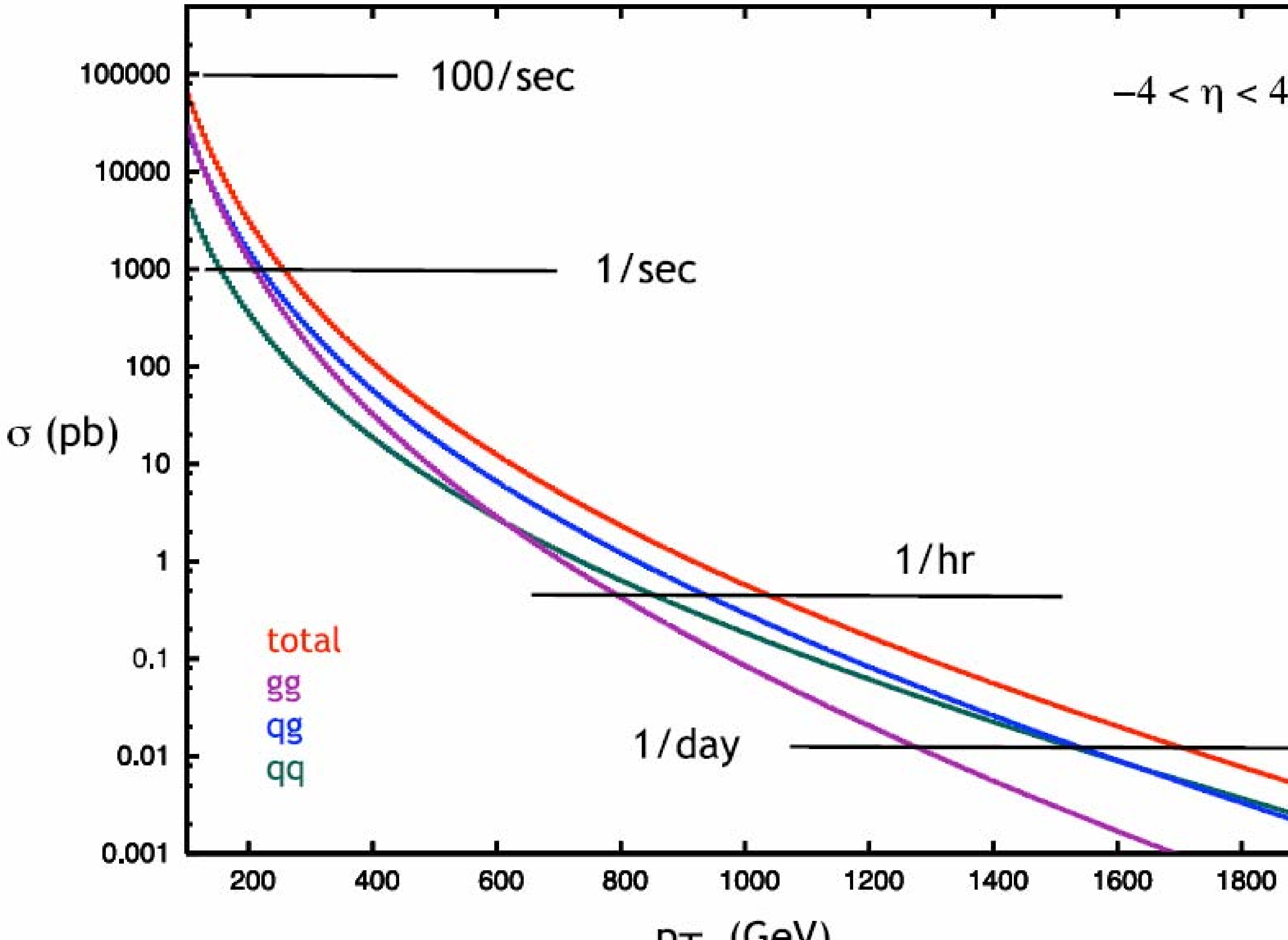


SCALE OF THE PROJECT

- The stored energy in the beams is equivalent roughly to the kinetic energy of an aircraft carrier at 10 knots (stored in magnets about 16 times larger)
- There will be about a billion collisions per second in each detector.
- The detectors will record and store "only" around 100 collisions per second.
- The total amount of data to be stored will be 15 petabytes (15 million gigabytes) a year.

  Equivalent to a stack of CDs 20Km tall per year.

Michael Peskin put this in perspective for us:



100/sec
1/sec
1/hr
1/day
−4 < η < 4
σ (pb)
total
gg
qg
qq
100000
10000
1000
100
10
1
0.1
0.01
0.001
200
400
600
800
1000
1200
1400
1600
1800

To deal with the event rate, we must first demand the presence of jets with sufficiently large values of p_T . We then need to look for other indicators that the reaction is not simple parton-parton scattering:

high deposited energy

central angular distribution

multiple jets

missing p_T

isolated or high p_T leptons

b quarks

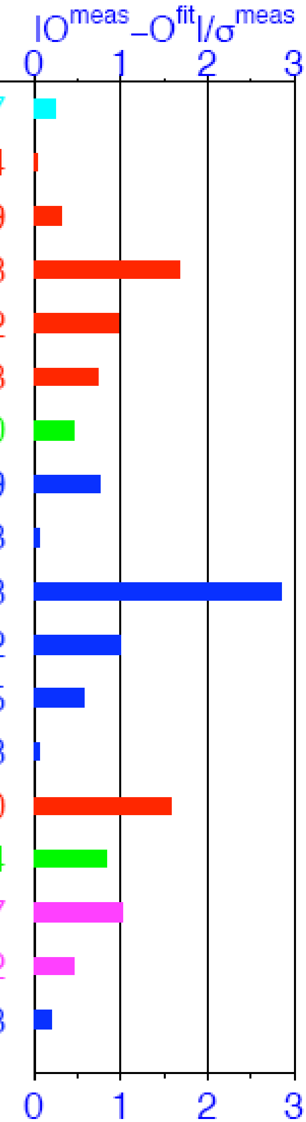
tau leptons

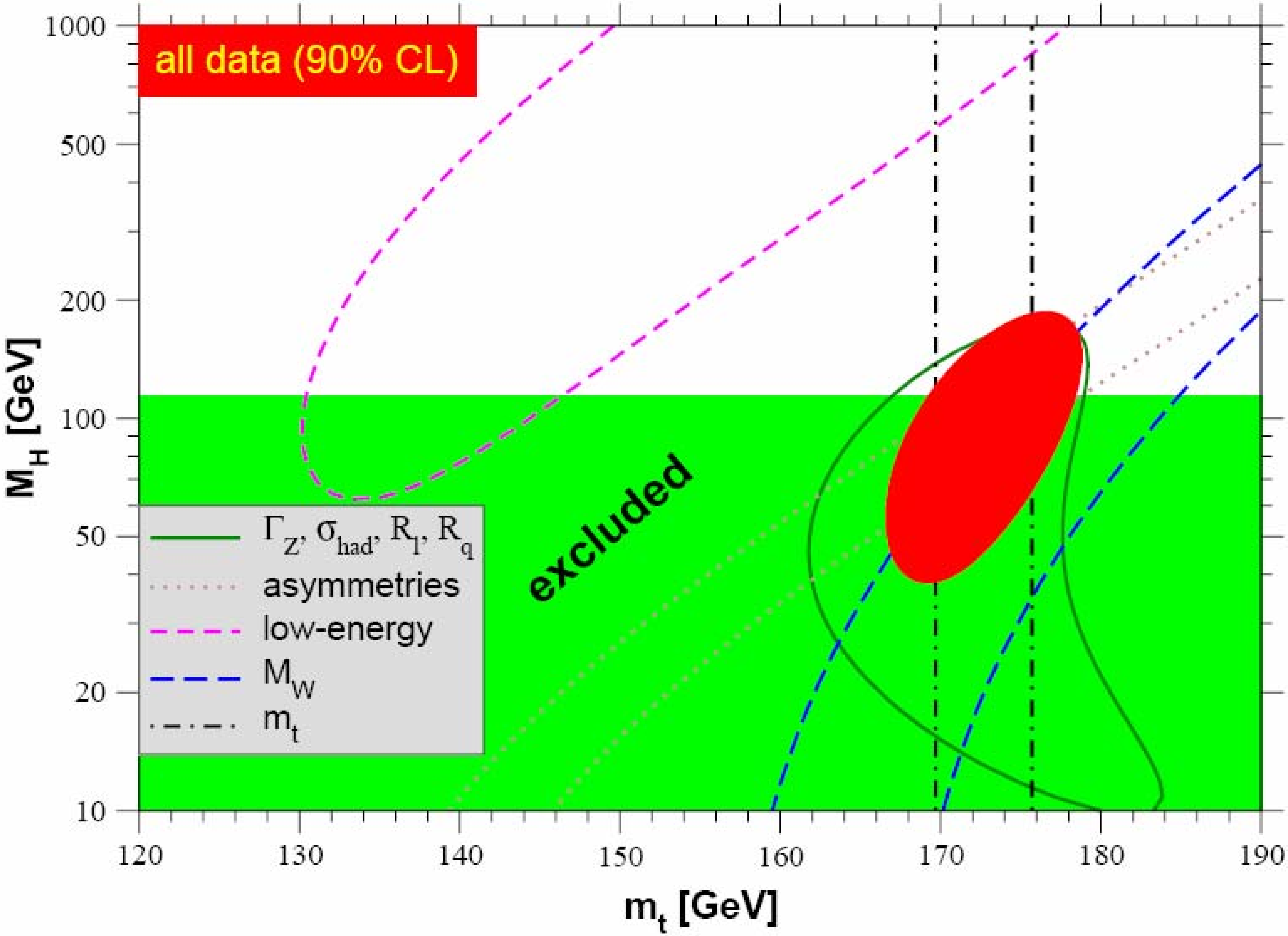
The Standard Model

We approach the LHC with a good deal of understanding of the underlying physics. We were reminded of the basic structure of the Standard Model by Paul Langacker. In the very high luminosity environment of the LHC, we will need to understand these processes with exquisite precision. We are looking for processes with small cross sections, and we can easily be fooled by events which are just unusual Standard Model processes. Among the most valuable contributions you can make to progress in this field is working on these processes, especially doing challenging QCD computations. At the very least, all of us must develop an understanding of the backgrounds to the signals which interest us. We had a small taste of this from the lectures of Steve Ellis, Aneesh Manohar and Michael Peskin, but I urge you when you return home to study the texts Steve mentioned and Michael's suggested readings (and do his homework!) to familiarize yourselves with these issues.

- **Weak neutral current (1973)**
- **QCD (1970's)**
- **W, Z (1983)**
- **Precision tests (1989-2000)**
- **CKM unitarity ($\sim$ 1995-)**
- **t quark (1995)**
- **ν mass (1998-2002)**

	Measurement	Fit
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02758 ± 0.00035	0.02767
m_Z [GeV]	91.1875 ± 0.0021	91.1874
Γ_Z [GeV]	2.4952 ± 0.0023	2.4959
σ_{had}^0 [nb]	41.540 ± 0.037	41.478
R_l	20.767 ± 0.025	20.742
$A_{fb}^{0,l}$	0.01714 ± 0.00095	0.01643
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1480
R_b	0.21629 ± 0.00066	0.21579
R_c	0.1721 ± 0.0030	0.1723
$A_{fb}^{0,b}$	0.0992 ± 0.0016	0.1038
$A_{fb}^{0,c}$	0.0707 ± 0.0035	0.0742
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1480
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.410 ± 0.032	80.377
Γ_W [GeV]	2.123 ± 0.067	2.092
m_t [GeV]	172.7 ± 2.9	173.3





all data (90% CL)
1000
500
200
100
50
20
10
M_H [GeV]
120
130
140
150
160
170
180
190
m_t [GeV]
excluded
Γ_Z, σ_{had}, R_l, R_q
asymmetries
low-energy
M_W
m_t

(Incomplete) References:

(I'll focus on concepts/images)

"The Pink Book" – *QCD and Collider Physics*, R.K. Ellis, W.J. Stirling and B.R. Webber (Cambridge University Press, 1996)

My TSI 2006 lectures - http://www.phys.washington.edu/users/ellis/TSI%20July%2006.htm

The "Primer for LHC Physics" by J.M. Campbell, J.W. Huston, W.J. Stirling, arXiv:hep-ph/0611148v1;

Lectures by George Sterman, et al. – (for more references in formal details) arXiv:hep-ph/0412013v1, arXiv:hep-ph/0409313v1.

QCD Summary on the Web at the Particle Data Group site: http://pdg.lbl.gov/2005/reviews/qcdrpp.pdf

The CTEQ Handbook in Rev. Mod. Phys. Volume 67, Number 1, January 1995, (pp. 157-248) and on the Web: http://www.phys.psu.edu/~cteq/#Handbook

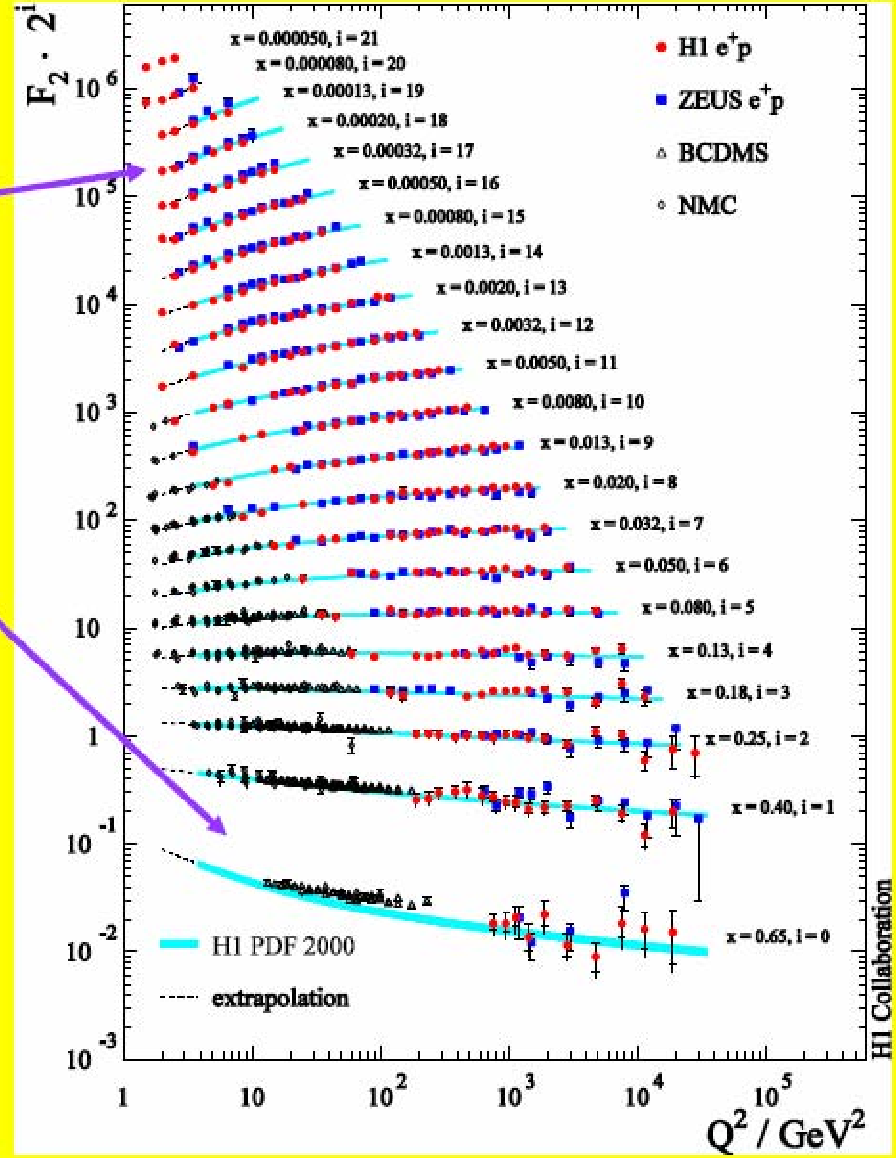
Conclude -

- We expect that the distributions

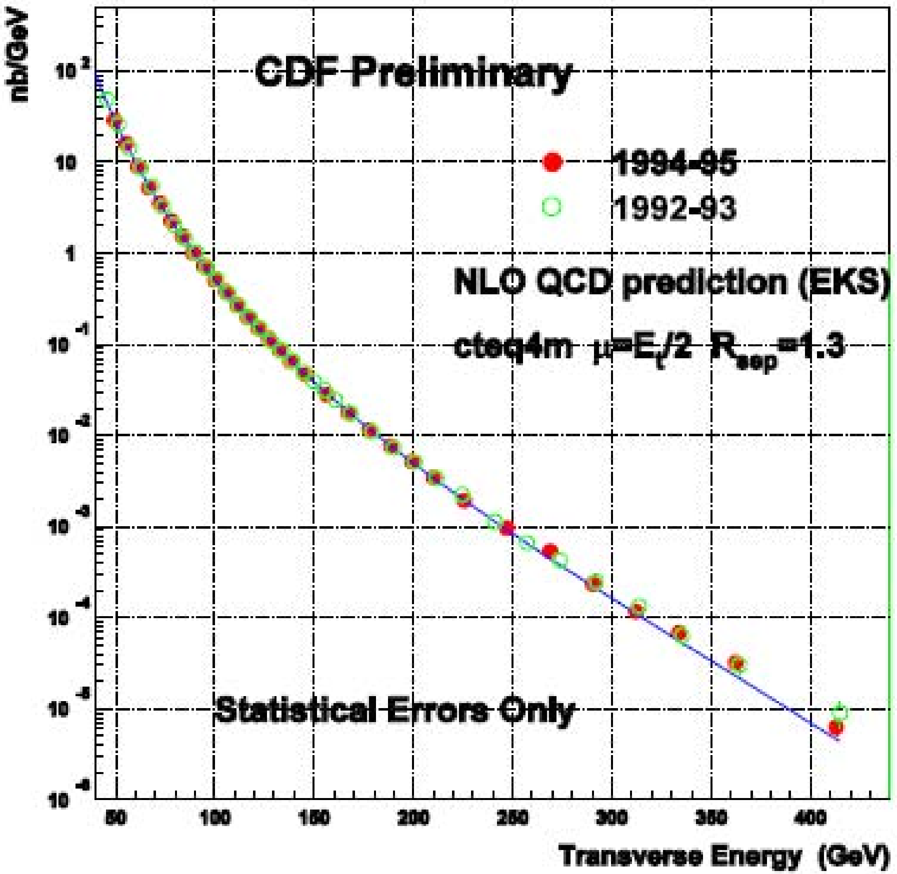
  increase at small *x*

  decrease at large *x*

  as μ = Q increases, and we see this experimentally.



Inclusive Jet cross section

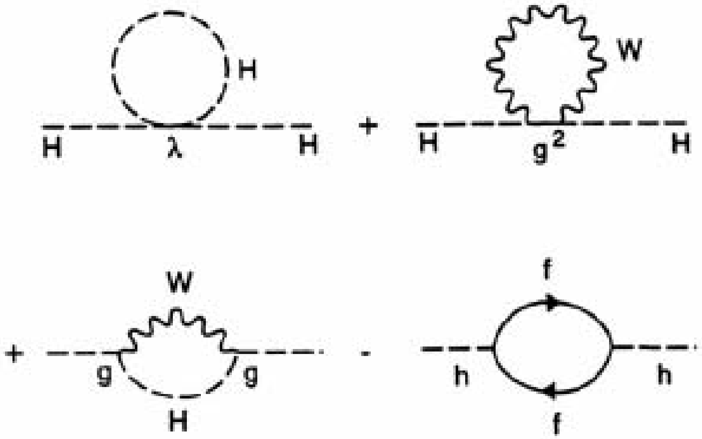


Why Do We Expect New Physics at LHC?

1. Multiplicity of Parameters of Standard Model – doesn’t point to a particular scale.
2. Hierarchy (Langacker, Dine, Thomas, Arkani-Hamed lectures): why isn’t Higgs mass of order largest scales in physics? Does suggest dramatic new physics at the weak scale.
3. Cosmology: dark matter (Matchev) – interactions with strength of order the weak scale and a new stable particle at this scale ! dark matter density comparable to that observed (you acquired skills at doing precise computations).

Hierarchy (Langacker)

- **Higgs/hierarchy problem**
  - **Expect** $M_H^2 = O(M_W^2)$
  - **higher order corrections:** $\delta M_H^2 / M_W^2 \sim 10^{34}$



Dark Matter: some stable, new form of matter. If weak cross section, abundance in correct ballpark.

Abundance:

- Approximate analytic solution

$$\Omega_\chi h^2 = \frac{10^9 GeV^{-1}}{M_{Pl}} \frac{x_F}{\sqrt{g_{¿}(x_F)}} \frac{1}{a+3b/x_F}$$

$$x_F \equiv \frac{m_\chi}{T_F} = \ln\left(c\sqrt{\frac{45}{8}} \frac{g}{2\pi^3} \frac{m_\chi M_{Pl}(a+6b/x_F)}{\sqrt{g_{¿}(x_F) x_F}} \right) \approx 25$$

From where does this formula come? At decoupling, production rate of order

$n_\chi\ \sigma$ » $T_F^3\ e^{-m\chi/T_F}\ \sigma$ » T_F^2/M_p

Solve iteratively: T_F » $m_\chi\ /\ln(m_\chi\ M_p\ \sigma)$

Independent of details, we have roughly:

$\rho_\chi(T_\Phi)$ » $(T_F M_p\ \sigma\ )^{-1}\ \ m_\chi$

Divide by $g^*\ T_F^3$ to obtain ratio to photons; $\sigma = G_F^2\ T_F^2$

Matchev taught you techniques to do these computations in great detail.

SUSY

We spent a lot of time at this school on supersymmetry (10 dedicated lectures). Is this where you should put your time?

Successes:

1. Hierarchy: stability (Dine,Thomas); explained if breaking of SUSY dynamical (Seiberg)
2. Precision Electroweak (Arkani-Hamed)
3. Unification (Thomas)
4. Dark matter (Matchev)

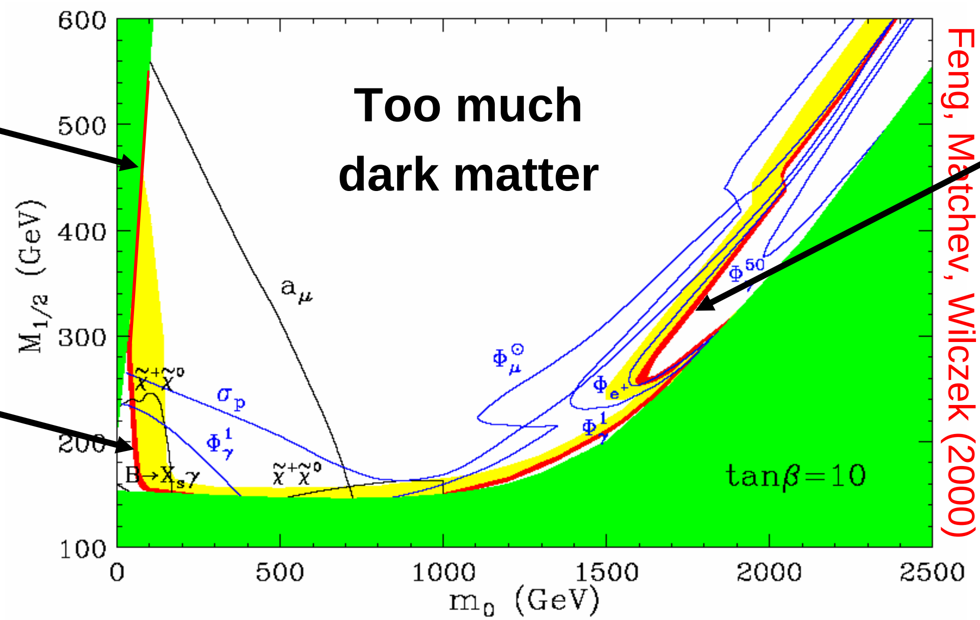
Minimal Supergravity (MSUGRA)

- A simple and popular model: universal BC at $M_{\mathbf{GUT}}$

Ω_{DM} stringently constrains the model

Co-annihilation region

Bulk region



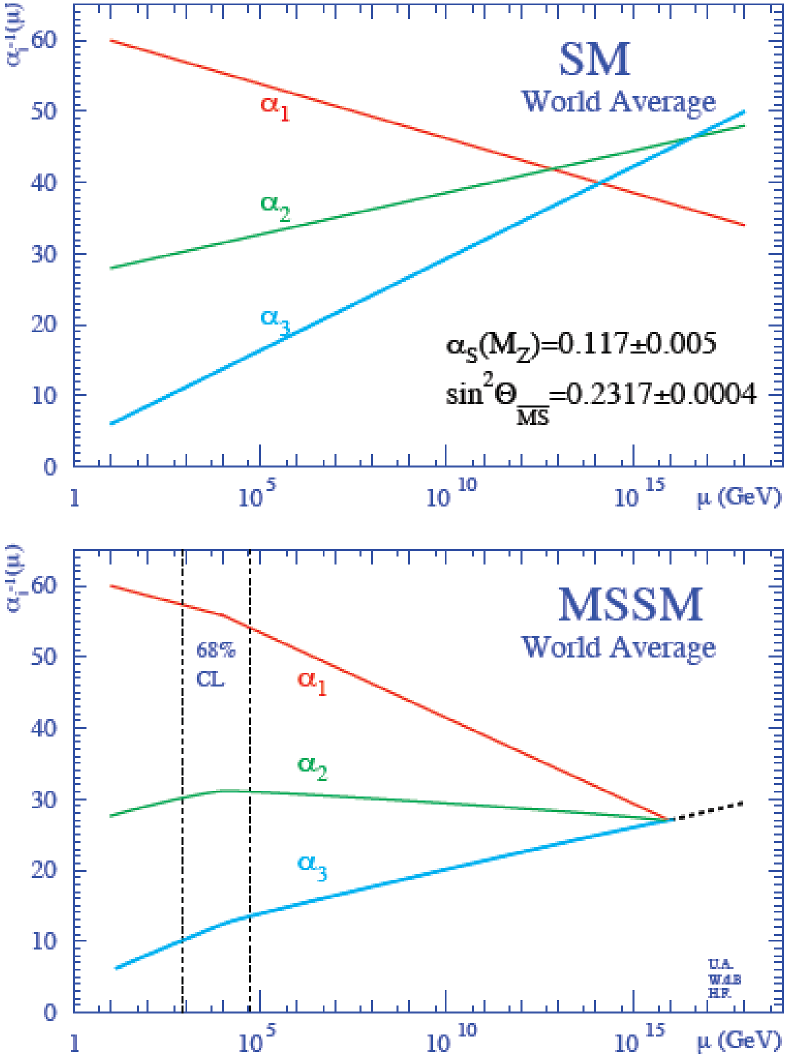
Focus point region

Yellow: pre-WMAP

Red: post-WMAP

Cosmology highlights certain regions, detection strategies

- **Gauge unification: GUTs, string theories**
  - $\alpha + \hat{s}^2_Z \rightarrow \alpha_s = 0.130 \pm 0.010$ **(MSSM)** (non-SUSY: 0.073(1))
  - $M_G \sim 3 \times 10^{16}$ **GeV**
  - **Perturbative string:** $\sim 5 \times 10^{17}$ **GeV (10% in** $\ln M_G$**). Exotics:** $O(1)$ **corrections.**



Dynamical SUSY Breaking (Seiberg lectures)

Hierarchies:

$m_{susy} = M \exp(-8\,\pi^2/b\, g^2)$

Now have an extensive understanding of these phenomena. Some of you may try to build a compelling model. What sorts of implications for low energy physics?

1. **Gauge mediation? Something else we haven't thought of (susy flavor problem)**
2. **μ problem (gaugino, higgsino masses)?**
3. **Identity of dark matter**
4. **Others?**

Suppose Evidence for Supersymmetry

1. Experimental questions (Peskin): is it really supersymmetry, spectrum, interactions. Questions to settle at LHC; questions which require ILC.
2. Dark matter at colliders: finding the dark matter particle, measuring required parameters to compute relic density (Matchev, Peskin).
3. Mediation mechanisms: can we distinguish (Luty, Peskin)?
4. Building more microscopic models: can we provide an elegant model of dynamical supersymmetry breaking? (Seiberg) Can we explain, predict? Is there any hope of probing the underlying dynamics?

Reasons for Skepticism

Thomas: The problems of supersymmetric models are

1. **Telling us a great deal about the supersymmetric spectrum.**
2. **Telling us supersymmetry isn't there.**

1. **Natural scale might be expected to be M_Z. E.g. in MSSM, at classical level, $m_h < M_Z$. But limits on Higgs about 114; on susy partners 100-250.**
2. **Flavor puzzle. As in Nir's lectures, points to a particular structure. Perhaps gauge mediation?**
3. **Gauge coupling unification? What about proton decay. Simplest SU(5) more or less ruled out.**
4. **Other flavor issues: CP (e.g. quark,lepton electric dipole moments).**
5. **Other flavor issues, e.g. b ! s + γ.**

Little Hierarchy

Perhaps the Higgs mass is the most serious source of concern. In the MSSM, radiative corrections can be large. Loop corrections to Higgs quartic proportional to:

$$\delta\lambda = \frac{6y_t^4}{16\pi^2} ln(m_{\tilde{t}}/m_t)$$

(large tan β) If $m_{\tilde{t}} \sim 1TeV$, or large mixing, $m_h > 114$.

But this requirement of large physical Higgs mass leads to tuning of *lagrangian* parameters:

$$\delta m^2 = -\frac{12y_t^2}{16\pi^2} m_{\tilde{t}}^2 \ln(\Lambda/m_{\tilde{t}})$$

Λ is the underlying scale of supersymmetry breaking. If $\Lambda = M_{GUT}$, this correction is of order 100 times M_Z^2, implying a 1% fine tuning.

Solutions to these problems?

Little Hierarchy:

1. Additional degrees of freedom beyond those of the MSSM to increase tree level quartic, small top squark mass. (Scott, Nima, “compress spectrum”).
2. Small Λ (low energy gauge mediation).

Proton decay: not a traditional gut (e.g. string theory?)
Flavor: gauge mediation
B ! s + γ : slightly heavy higgs? Cancellations?

Predictions? More interesting physics? Or just excuses?

Alternatives to SUSY

Given all of the reasons for skepticism about SUSY, clearly want to consider alternatives. Nima gave us a framework in which to organize the set of popular ideas:

1. Technicolor
2. Composite Higgs
3. Warped extra dimensions
4. Large extra dimensions
5. …

These models pose other challenges. Most severe are problems connected with precision electroweak corrections (S and T parameters, Γ(Z! b + b^c)).

With any reasonable scoring, SUSY looks best of this set. But many of us would bet we are missing something; experiment may tell. You should certainly be trying to come up with new ideas!

Flavor, Neutrinos

Flavor: CKM, including CP, now well understood in SM

Flavor severely constrains possible new physics at TeV scales. Something like Minimal Flavor Violation required.

Neutrinos do represent new physics, and we should remember that there will be opportunities to explore this physics in the coming decade. (Nir)

But, there is a dreaded possibility looming

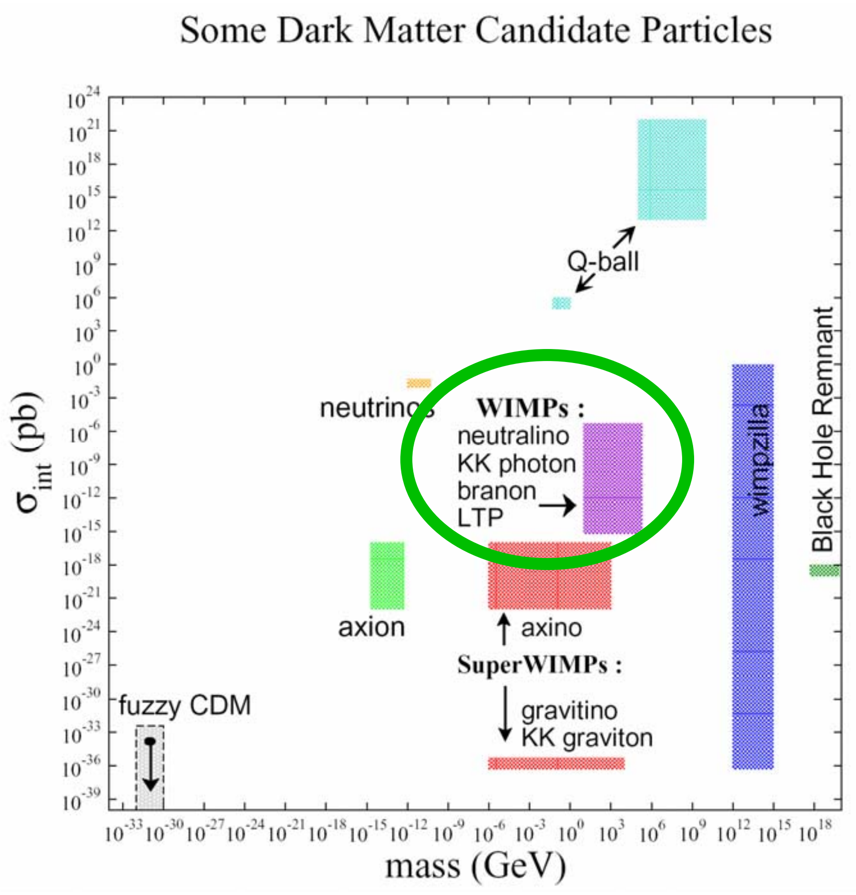
Perhaps the focus on hierarchy is misguided; dark matter from some other, higher energy source (axions a well-motivated possibility). Unification an accident. If only a single Higgs, no problems with precision electroweak, flavor….

Hierarchy: Higgs a problem of a dimension two operator; we already have a problem at dimension zero: cosmological constant. Probably not solved by additional degrees of freedom at low energies. Why shouldn't Higgs be similar?

Only (credible, at least mildly) solution to cosmological constant: enviromental selection (in the spirit of last week's literary event, "that principle which cannot be named" NBN).

DARK MATTER CANDIDATES

- There are many candidates
- Masses and interaction strengths span many, many orders of magnitude
- But not all are equally motivated. Focus on:
  - WIMPs: natural thermal relics



Dark Matter Scientific Assessment Group,
U.S. DOE/NSF/NASA HEPAP/AAAC Subpanel (2007)

Environmental Selection: What's at Stake?

As we heard from Nima this morning, it is plausible that NBN could select for a Higgs mass of the order observed. This might happen without any relic of susy, warping, or otherwise (this has been widely debated in the string community, with no satisfactory resolution). If so, we might simply find a light higgs at LHC, and nothing else. This, for me at least, is the most discouraging scenario; I am not sure what role there is for phenomenologists or string theorists in such a world.

Nima did give a more optimistic perspective: we might make discoveries which appear tuned (e.g. split susy), which we could account for through environmental considerations.

I want to reassure you (as Nima did) that it is quite possible that there is low energy susy (or technicolor or warping, or some other rational explanation of hierarchies) even if environmental selection is important. Indeed, this would be, at some level, a pleasing resolution of the hierarchy problem. After all, when we we speak of tuning (Thomas's ``naturalness dogma") what we have in mind is that there is a distribution of theories, from which what we observe is selected, without great difficulty. Low energy susy would be likely if an exponential distribution of susy breaking scales.

$$m_{susy} = \exp(-8\,\pi^2/g^2)$$

If g^2 distribution flat (as it is in some regimes of the landscape), hierarchy explained, just as we would expect.

For thinking about phenomenology at LHC, cosmology of dark matter, nothing would change unless, perhaps, we could make a priori arguments for the nature of susy breaking (gauge mediation at low scales?).

Stated in this way, the NBM problem is a problem principally for string theorists or others thinking “top down.” Those of us who want to think in this way have to decide if this is the correct framework in which to understand the emergence of the laws of physics at low energies, and whether any features can be predicted from knowledge of distributions, cosmology, selection effects (Arkani-Hamed this morning).

Time to Go Home!

I hope you have enjoyed the school and learned a lot.
Last words of advice:

1. **Work hard! You have heard some outstanding lectures, but in two weeks, there is only so much any of us can absorb. Go home, study your notes, do the homework.**
2. **Get ready for the LHC. There isn't much time! Understand the basics of the machine and the detectors, QCD and background issues. Remember Michael Peskin's sage remark: "Signal is irrelevant. It's all about the background."**
3. **Understand the ideas which have been developed for TeV physics.**
4. **Think hard! Delve deeper into the issues you think may be important and that interest you. Show us the way!**

Acknowledgements

This has been an extraordinary school, due to the efforts of many people. I would like to thank, first, all of the lecturers, who gave great thought and energy to their presentations.

I wish to express my appreciation to Igor Klebanov, Juan Maldacena, and Ed Witten for their special lectures.

I would like to thank all of the staff, especially Susan Higgins, Michelle Sage, Lisa Fleischer, and Michael Ciccone's staff, including Dario Mastroianni (AV for lecturers)
and Nelson Lopez (supply purchasing, grocery bus reservations) and Herman Joachim (copying materials). We have all enjoyed wonderful facilities, excellent food, and even beautiful weather (in late July!).

I would like to thank Peter Goddard and the IAS for hosting this school. I wish to thank my co-organizers Chiara Nappi and Nathan Seiberg for all of their work and wisdom.