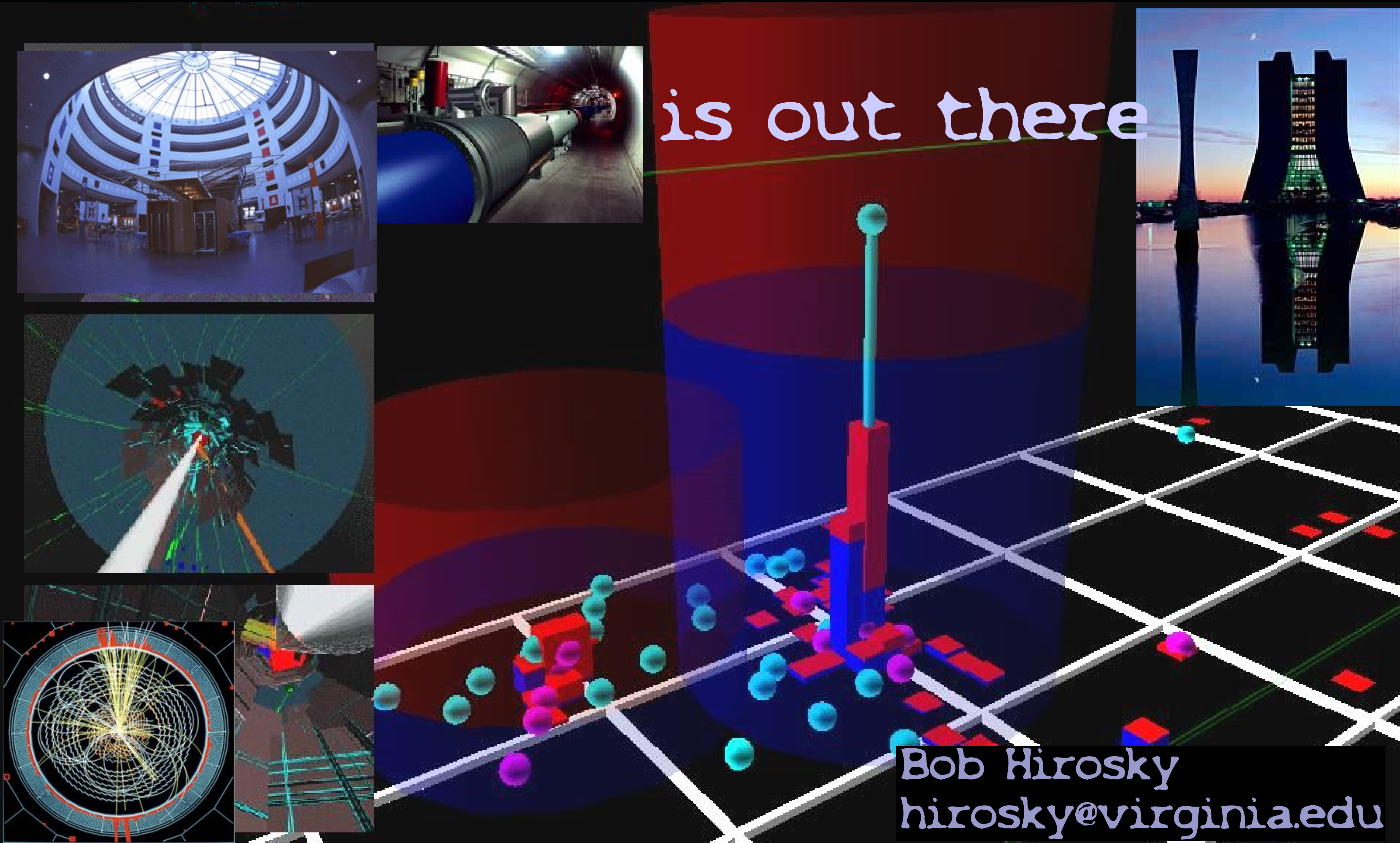
High Energy Experiments: A Smashing good time



is out there

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Meet the Group: CMS and D-Zero Projects

Duncan Brown (PDoc, not pictured)

The basic questions

What are the basic building blocks of everything?

What are the forces of nature?

Some things we know about matter:

Elementary Particles

Charge = +2/3	Quarks	u	c	t	
Charge = -1/3		d	s	b	
Charge = 0	Leptons	e	u	τ	
Charge = -1		ν_e	ν_μ	ν_τ	
		I	**II**	**III**	

Generations of Matter

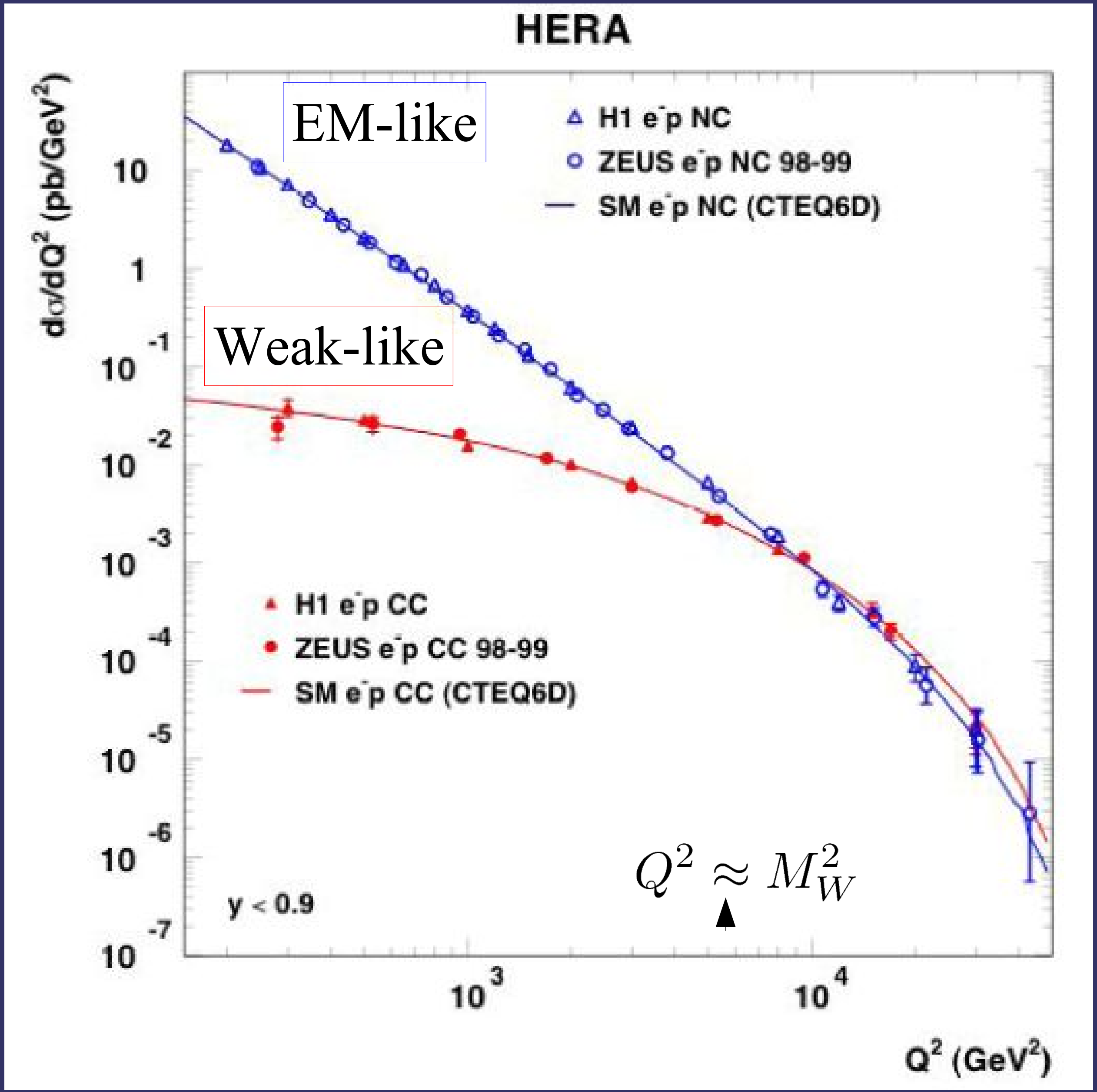
The "periodic table of fermions."

	Force Carriers
γ	EM
g	Strong
Z	Weak
$W^\pm$	

(quantized fields)

Some things we know about matter:

Electroweak Unification



EM/Weak interactions unified at large energy/momentum transfer

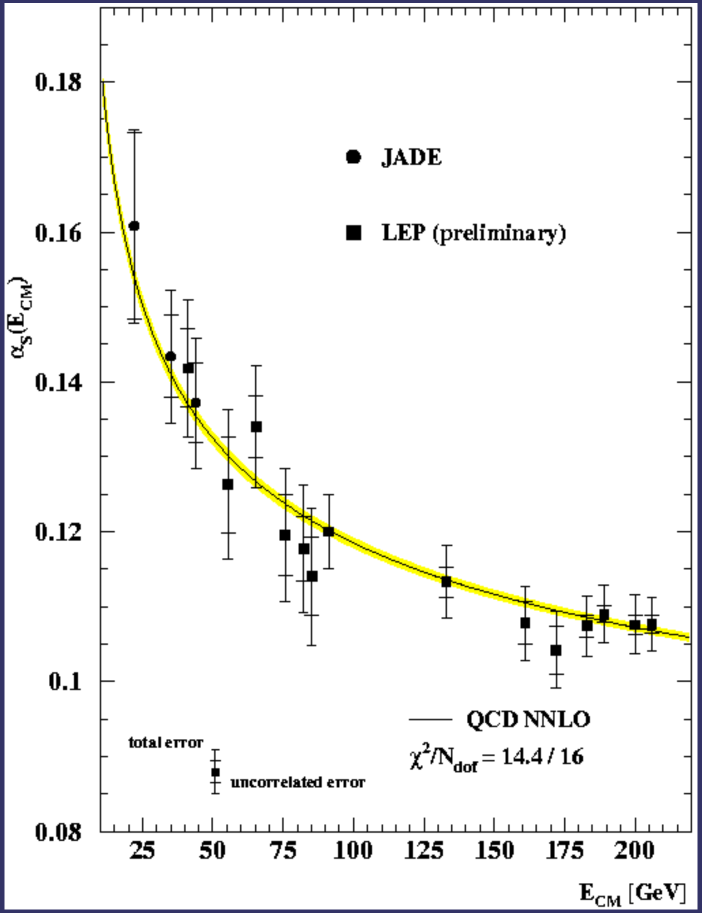
Some things we know about matter:

Quantum Chromodynamics

Gauge theory (like electromagnetism) describes fermions (quarks) which carry an SU(3) charge (color) and interact through the exchange of vector bosons (gluons)

Interesting features:

- gluons themselves have color
- interactions are **strong**
- coupling constant runs rapidly
  becomes weak at momentum
  transfers above a few GeV



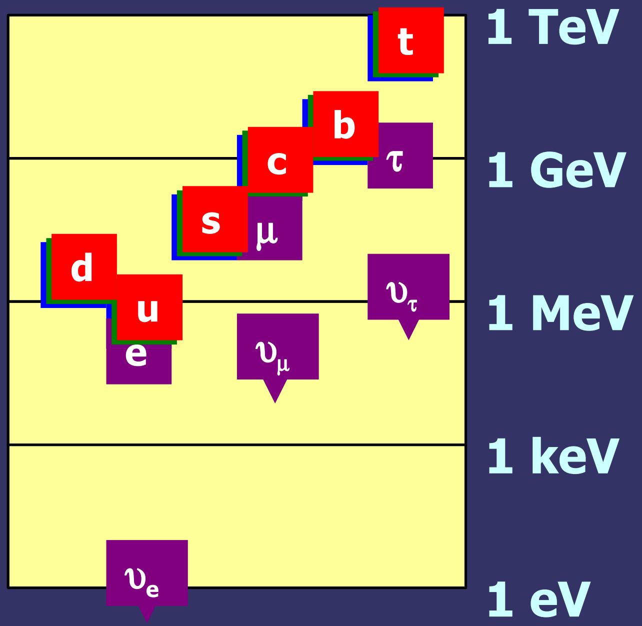
In a more general theory (GUT), expect unification w/ electroweak force

Some things we don't know about matter:

Masses

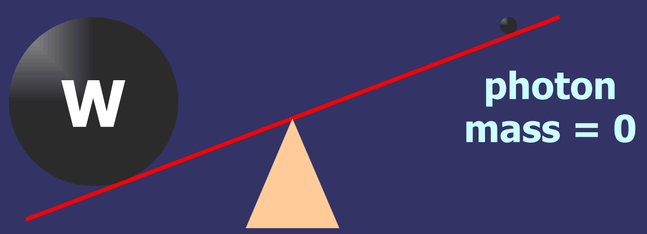
Second and third generations of quarks and leptons are much more massive than first

Origin of mass difference for bosons in EW force?



>12 orders of magnitude in mass!

mass = 80.4 GeV



Electroweak asymmetry

The Higgs Mechanism

In the Standard Model
(Glashow, Weinberg, Salam, ‘t Hooft, Veltmann)

- “electroweak symmetry breaking” through introduction of a scalar field ϕ $\rightarrow$ masses of W and Z
- Higgs field permeates space with a finite vacuum expectation value
  - cosmological implications! (inflation)
- If ϕ also couples to fermions $\rightarrow$ generates fermion masses

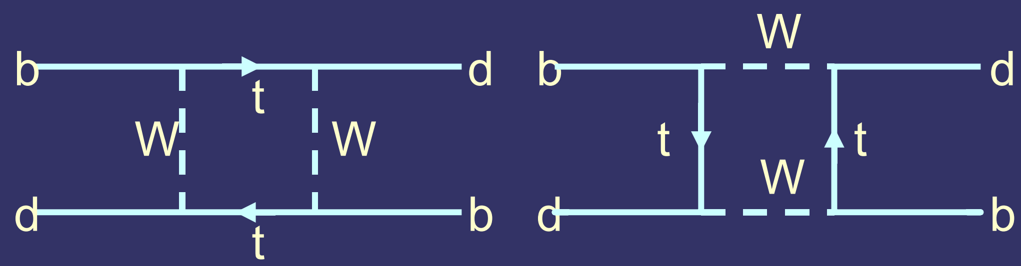
An appealing picture: is it correct?

- One clear and testable prediction: there exists a neutral scalar particle which is an excitation of the Higgs field
- All its properties (production and decay rates, couplings) are fixed except its own mass

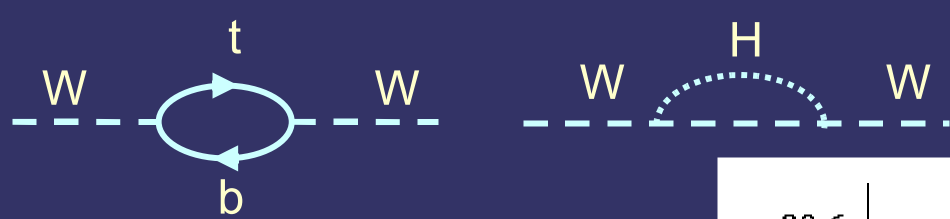
Highest priority of worldwide high energy physics program: find it!

W's, Z's, Top's, and Higgs's (oh my!):

- Fundamental parameters of Standard Model (SM)
- Affect predictions of SM via radiative corrections:
  - BB mixing

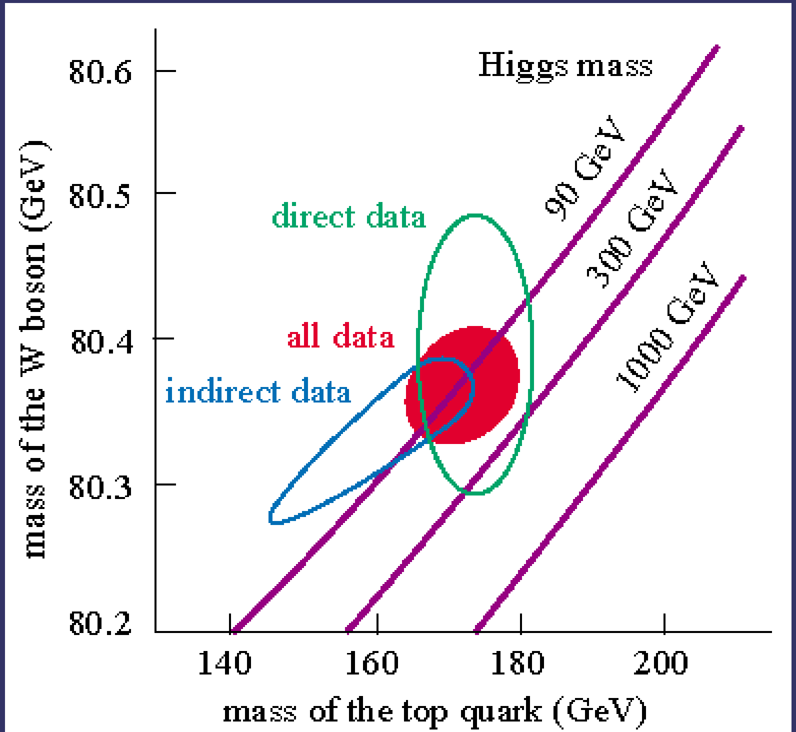


  - W and Z mass



  - measurements of M_W, m_t constrain M_H

- Large mass of top quark
  - may provide clues about electroweak symmetry breaking



The Standard Model is incomplete:

Theoretical problems

- Mass scale for M_{EW}?
- how to achieve grand unification?
- how to include gravity?
- what explains proliferation of quark and lepton types and determines their mixings?

Experimental problems

- SM fit to electro-weak data has probability of 4.4%
- what is dark matter?
  - new type of matter? – can be produced at the LHC!
  - "dark" because of undiscovered properties of space-time? – can be probed at LHC!

More general theories make predictions that can be tested at the Tevatron & LHC

Beyond the Higgs:

Standard Model works well for observed phonomena and would be completed by the discovery of the Higgs, but the Higgs may be the first window on to a new domain of physics at the electroweak scale

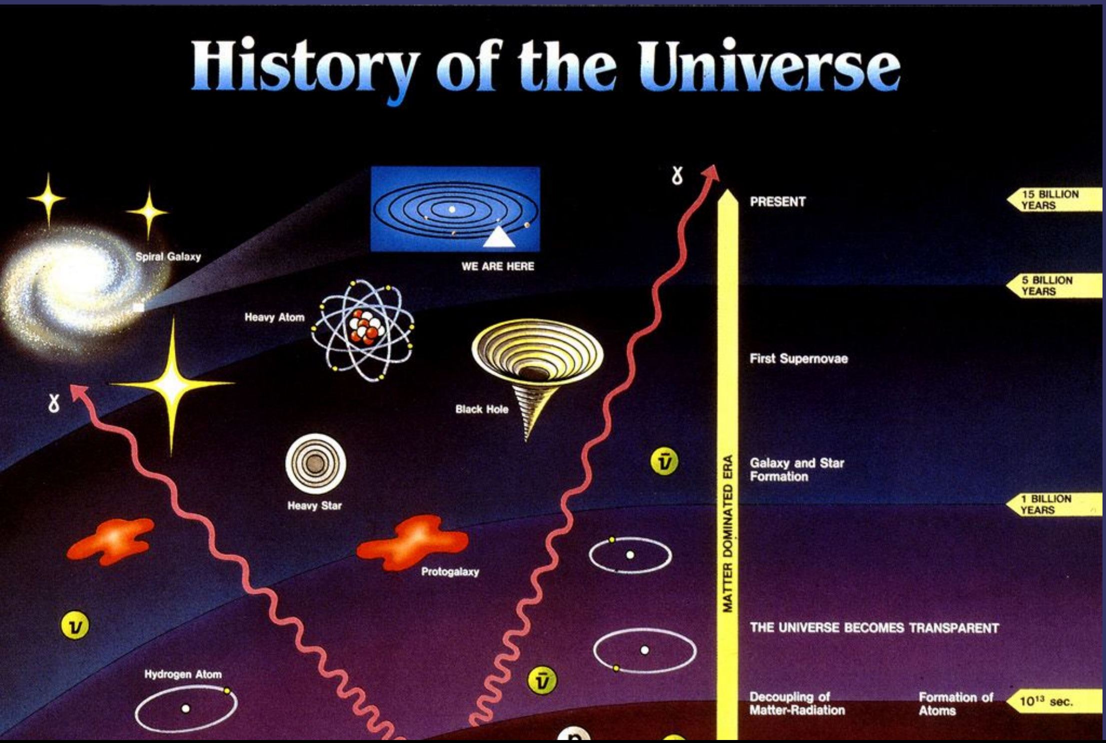
This Higgs is unlike any other particle in the SM (no other elementary scalars)

SM Higgs would have a mass unstable to radiative corrections (quantum effects): m_H would become very large $m_H \sim 10^{15}$ GeV, unless parameters fine tuned at the level of 1 part in 10^{26}

the patterns of the fundamental particles suggest a deeper structure

the SM is a low energy approximation to some more general theory

Theoretically the most attractive option is supersymmetry

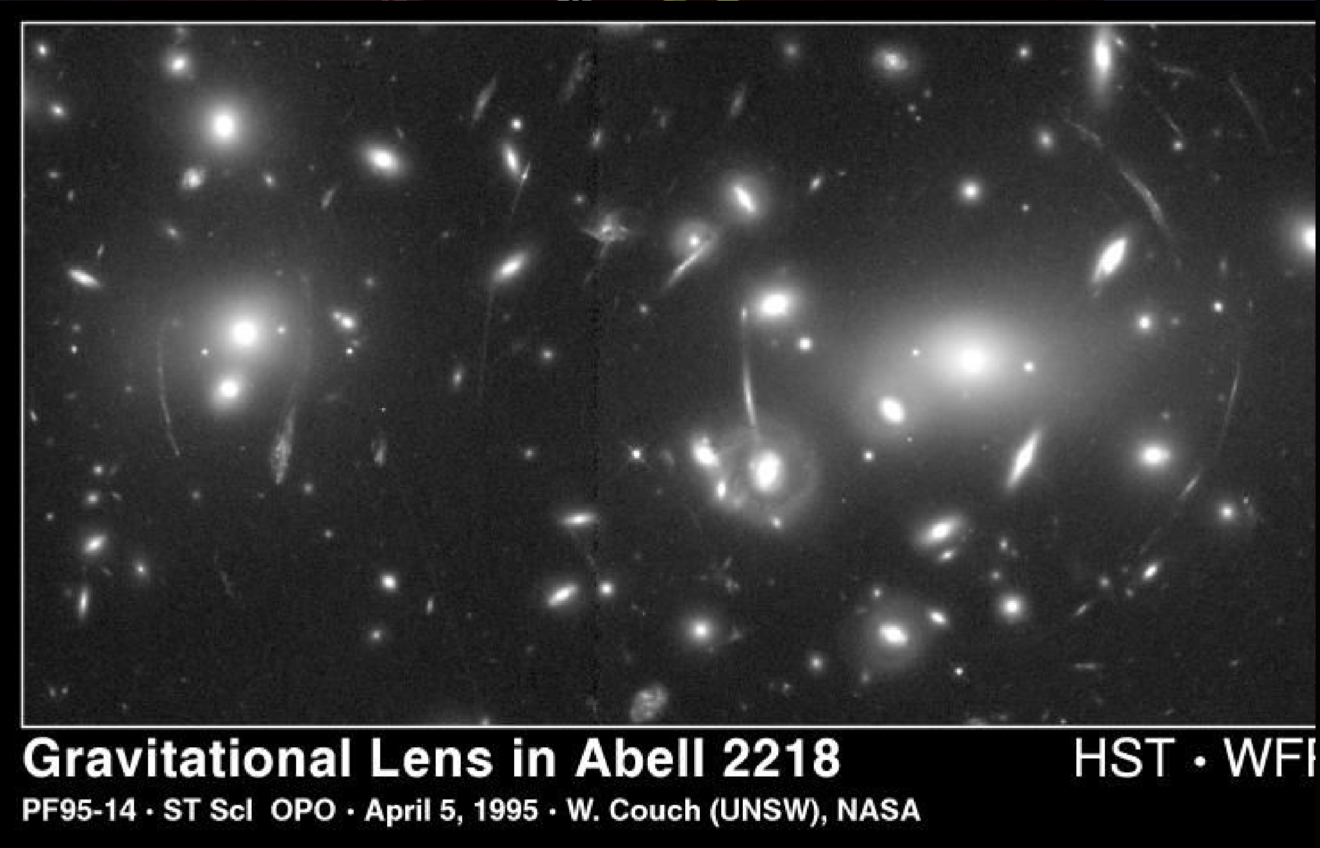


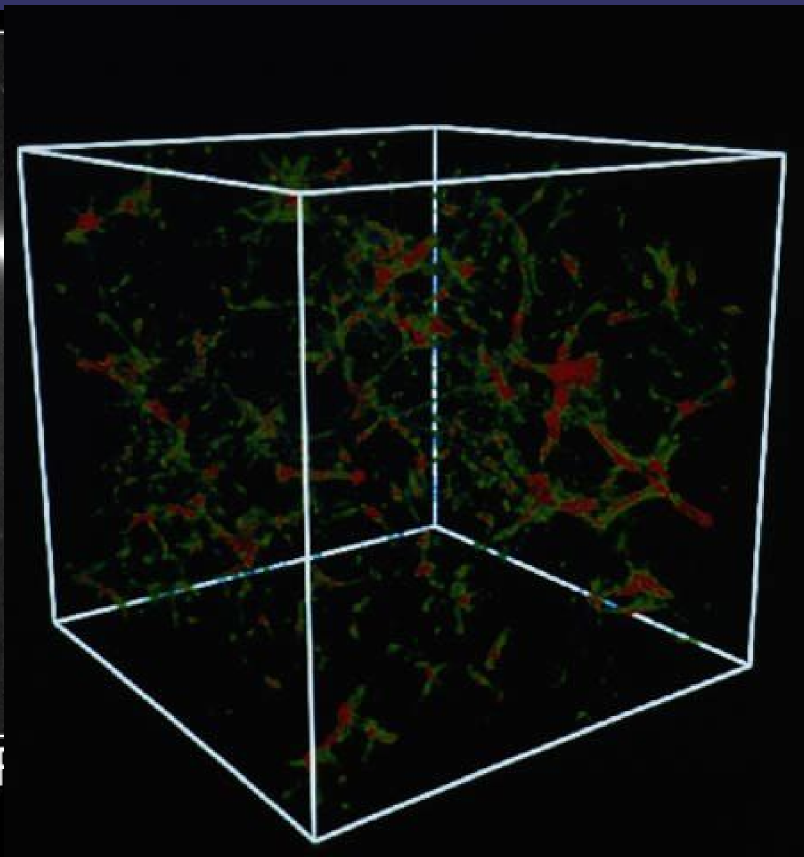
(Now...)

Now (15 billion years)

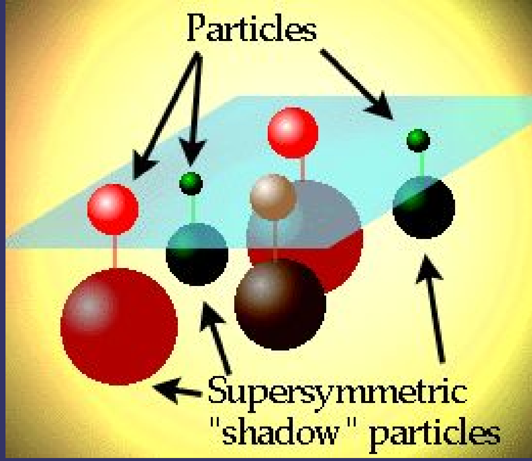
Large scale galactic clustering, mass deficit in universe, lensing

where/what is dark matter?



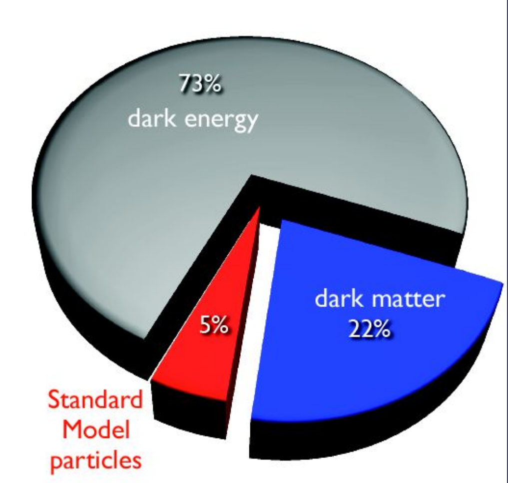


Supersymmetry

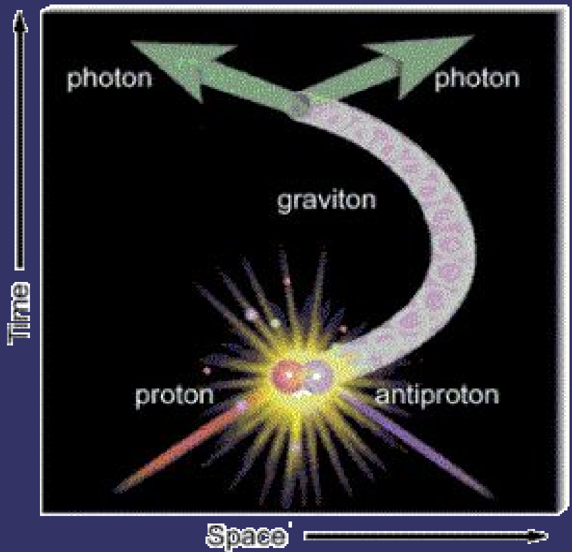


- Introduce a symmetry between bosons and fermions:
  - more massive super-partners for all particles
  - Allows a fundamental scalar (the Higgs) at low mass
    - cancels the divergences in m_H
  - closely approximates the standard model at low energies
  - allows unification of forces with common couplings at higher energies
  - provides a path to the incorporation of gravity and string theory: Local Supersymmetry = Supergravity

- lightest neutral superpartner (neutralino, etc) is massive, weakly interacting + stable → cosmic dark matter candidate!



- Connections w/ gravity: allows TEV scale affects for processes probing extra spacial dimensions
- Flexible framework & calculable!



But, SUSY or other extensions to the Standard Model aren't obvious

example of various analysis channels...

CDF Run II preliminary (927 pb^{-1})

Final State	Data	Background	Final State	Data	Background	Final State	Data	Background
$3j\tau+$	71	113.7 ± 3.6	$2e+j$	13	9.8 ± 2.2	$e+\gamma\not{p}$	141	144.2 ± 6
$5j$	1661	1902.9 ± 50.8	$2e+e-$	12	4.8 ± 1.2	$e+\mu-\not{p}$	54	42.6 ± 2.7
$2j\tau+$	233	296.5 ± 5.6	$2e+$	23	36.1 ± 3.8	$e+\mu+\not{p}$	13	10.9 ± 1.3
$be+j$	2207	2015.4 ± 28.7	$2b\ \Sigma p_T > 400$ GeV	327	335.8 ± 7	$e+\mu-$	153	127.6 ± 4.2
$3j\ \Sigma p_T < 400$ GeV	35436	37294.6 ± 524.3	$2b\ \Sigma p_T < 400$ GeV	187	173.1 ± 7.1	$e+j$	386880	392614 ± 5031.8
$e+3j\not{p}$	1954	1751.6 ± 42	$2b3j\ \Sigma p_T < 400$ GeV	28	33.5 ± 5.5	$e+j2\gamma$	14	15.9 ± 2.9
$be+2j$	798	695.3 ± 13.3	$2b2j\ \Sigma p_T > 400$ GeV	355	326.3 ± 8.4	$e+j\tau+$	79	79.3 ± 2.9
$3j\not{p}\ \Sigma p_T > 400$ GeV	811	967.5 ± 38.4	$2b2j\ \Sigma p_T < 400$ GeV	56	80.2 ± 5	$e+j\tau-$	162	148.8 ± 7.6
$e+\mu+$	26	11.6 ± 1.5	$2b2j\gamma$	16	15.4 ± 3.6	$e+j\not{p}$	58648	57391.7 ± 661.6
$e+\gamma$	636	551.2 ± 11.2	$2b\gamma$	37	31.7 ± 4.8	$e+j\gamma\not{p}$	52	76.2 ± 9
$e+3j$	28636	27281.5 ± 405.2	$2bj\ \Sigma p_T > 400$ GeV	415	383.8 ± 9.1	$e+j\mu-\not{p}$	22	13.1 ± 1.7
$b5j$	131	95 ± 4.7	$2bj\ \Sigma p_T < 400$ GeV	161	195.8 ± 8.3	$e+j\mu-$	28	26.8 ± 2.3
$j2\tau+$	50	85.6 ± 8.2	$2bj\not{p}\ \Sigma p_T > 400$ GeV	28	23.2 ± 2.6	$e+e-4j$	103	113.5 ± 5.9
$j\tau+\tau-$	74	125 ± 13.6	$2bj\gamma$	25	24.7 ± 4.3	$e+e-3j$	456	473 ± 14.6
$b\not{p}\ \Sigma p_T > 400$ GeV	10	20.5 ± 4.6	$2be+2j\not{p}$	15	12.3 ± 1.6	$e+e-2j\not{p}$	30	30 ± 4.6
$e+j\gamma$	280	309.4 ± 21.1	$2be+2j$	30	30.5 ± 2.5	$e+e-2j$	2149	2152 ± 40.1
$e+j\not{p}\tau-$	29	14.2 ± 1.8	$2be+j$	28	29.1 ± 2.8	$e+e-\tau+$	14	11.1 ± 2
$2j\ \Sigma p_T < 400$ GeV	96502	92437.3 ± 1354.5	$2be+$	48	45.2 ± 3.7	$e+e-\not{p}$	491	487.9 ± 12
$be+3j$	356	298.6 ± 7.7	$\tau+\tau-$	498	428.5 ± 22.7	$e+e-\gamma$	127	132.3 ± 4.2
$8j$	11	6.1 ± 2.5	$\gamma\tau+$	177	204.4 ± 5.4	$e+e-j$	10726	10669.3 ± 123.5
$7j$	57	35.6 ± 4.9	$\gamma\not{p}$	1952	1945.8 ± 77.1	$e+e-j\not{p}$	157	144 ± 11.2
$6j$	335	298.4 ± 14.7	$\mu+\tau+$	18	19.8 ± 2.3	$e+e-j\gamma$	26	45.6 ± 4.7
$4j\ \Sigma p_T > 400$ GeV	39665	40898.8 ± 649.2	$\mu+\tau-$	151	179.1 ± 4.7	$e+e-$	58344	58575.6 ± 603.9
$4j\ \Sigma p_T < 400$ GeV	8241	8403.7 ± 144.7	$\mu+\not{p}$	321351	320500 ± 3475.5	$b6j$	24	15.5 ± 2.3
$4j2\gamma$	38	57.5 ± 11	$\mu+\not{p}\tau-$	22	25.8 ± 2.7	$b4j\ \Sigma p_T > 400$ GeV	13	9.2 ± 1.8
$4j\tau+$	20	36.9 ± 2.4	$\mu+\gamma$	260	285.5 ± 5.9	$b4j\ \Sigma p_T < 400$ GeV	464	409.2 ± 12.4
$4j\not{p}\ \Sigma p_T > 400$ GeV	516	525.2 ± 34.5	$\mu+\gamma\not{p}$	269	282.2 ± 6.9	$b3j\ \Sigma p_T > 400$ GeV	5394	5285 ± 72.4
$4j\gamma\not{p}$	28	53.8 ± 11	$\mu+\mu-\not{p}$	49	61.4 ± 3.5	$b3j\ \Sigma p_T < 400$ GeV	1639	1558.9 ± 24.1
$4j\gamma$	3693	3827.2 ± 112.1	$\mu+\mu-\gamma$	32	29.9 ± 2.6	$b3j\not{p}\ \Sigma p_T > 400$ GeV	111	116.8 ± 11.2
$4j\mu+$	576	568.2 ± 26.1	$\mu+\mu-$	10648	10845.6 ± 96	$b3j\gamma$	182	194.1 ± 8.8
$4j\mu+\not{p}$	232	224.7 ± 8.5	$j2\gamma$	2196	2200.3 ± 35.2	$b3j\mu+\not{p}$	37	34.1 ± 2
$4j\mu+\mu-$	17	20.1 ± 2.5	$j2\gamma\not{p}$	38	27.3 ± 3.2	$b3j\mu+$	47	52.2 ± 3
3γ	13	24.2 ± 3	$j\tau+$	563	585.7 ± 10.2	$b2\gamma$	15	14.6 ± 2.1
$3j\ \Sigma p_T > 400$ GeV	75894	75939.2 ± 1043.9	$j\not{p}\ \Sigma p_T > 400$ GeV	4183	4209.1 ± 56.1	$b2j\ \Sigma p_T > 400$ GeV	8812	8576.2 ± 97.9
$3j2\gamma$	145	178.1 ± 7.4	$j\gamma$	49052	48743 ± 546.3	$b2j\ \Sigma p_T < 400$ GeV	4691	4646.2 ± 57.7
$3j\not{p}\ \Sigma p_T < 400$ GeV	20	30.9 ± 14.4	$j\gamma\tau+$	106	104 ± 4.1	$b2j\not{p}\ \Sigma p_T > 400$ GeV	198	209.2 ± 8.3
$3j\gamma\tau+$	13	11 ± 2	$j\gamma\not{p}$	913	965.2 ± 41.5	$b2j\gamma$	429	425.1 ± 13.1
$3j\gamma\not{p}$	83	102.9 ± 11.1	$j\mu+$	33462	34026.7 ± 510.1	$b2j\mu+\not{p}$	46	40.1 ± 2.7
$3j\gamma$	11424	11506.4 ± 190.6	$j\mu+\tau-$	29	37.5 ± 4.5	$b2j\mu+$	56	60.6 ± 3.4
$3j\mu+\not{p}$	1114	1118.7 ± 27.1	$j\mu+\not{p}\tau-$	10	9.6 ± 2.1	$b\tau+$	19	19.9 ± 2.2
$3j\mu+\mu-$	61	84.5 ± 9.2	$j\mu+\not{p}$	45728	46316.4 ± 568.2	$b\gamma$	976	1034.8 ± 15.6
$3j\mu+$	2132	2168.7 ± 64.3	$j\mu+\gamma\not{p}$	78	69.8 ± 9.9	$b\gamma\not{p}$	18	16.7 ± 3.1
$3bj\ \Sigma p_T > 400$ GeV	14	9.3 ± 1.9	$j\mu+\gamma$	70	98.4 ± 12.1	$b\mu+$	303	263.5 ± 7.9
$2\tau+$	316	290.8 ± 24.2	$j\mu+\mu-$	1977	2093.3 ± 74.7	$b\mu+\not{p}$	204	218.1 ± 6.4
$2\gamma\not{p}$	161	176 ± 9.1	$e+4j$	7144	6661.9 ± 147.2	$bj\ \Sigma p_T > 400$ GeV	9060	9275.7 ± 87.8
2γ	8482	8349.1 ± 84.1	$e+4j\not{p}$	403	363 ± 9.9	$bj\ \Sigma p_T < 400$ GeV	7236	7030.8 ± 74
$2j\ \Sigma p_T > 400$ GeV	93408	92789.5 ± 1138.2	$e+3j\tau-$	11	7.6 ± 1.6	$bj2\gamma$	13	17.6 ± 3.3
$2j2\gamma$	645	612.6 ± 18.8	$e+3j\gamma$	27	21.7 ± 3.4	$bj\tau+$	13	12.9 ± 1.8
$2j\tau+\tau-$	15	25 ± 3.5	$e+2\gamma$	47	74.5 ± 5	$bj\not{p}\ \Sigma p_T > 400$ GeV	53	60.4 ± 19.9
$2j\not{p}\ \Sigma p_T > 400$ GeV	74	106 ± 7.8	$e+2j$	126665	122457 ± 1672.6	$bj\gamma$	937	989.4 ± 20.6
$2j\not{p}\ \Sigma p_T < 400$ GeV	43	37.7 ± 100.2	$e+2j\tau-$	53	37.3 ± 3.9	$bj\gamma\not{p}$	34	30.5 ± 4
$2j\gamma$	33684	33259.9 ± 397.6	$e+2j\tau+$	20	24.7 ± 2.3	$bj\mu+\not{p}$	104	112.6 ± 4.4
$2j\gamma\tau+$	48	41.4 ± 3.4	$e+2j\not{p}$	12451	12130.1 ± 159.4	$bj\mu+$	173	141.4 ± 4.8
$2j\gamma\not{p}$	403	425.2 ± 29.7	$e+2j\gamma$	101	88.9 ± 6.1	$be+3j\not{p}$	68	52.2 ± 2.2
$2j\mu+\not{p}$	7287	7320.5 ± 118.9	$e+\tau-$	609	555.9 ± 10.2	$be+2j\not{p}$	87	65 ± 3.3
$2j\mu+\gamma\not{p}$	13	12.6 ± 2.7	$e+\tau+$	225	211.2 ± 4.7	$be+\not{p}$	330	347.2 ± 6.9
$2j\mu+\gamma$	41	35.7 ± 6.1	$e+\not{p}$	476424	479572 ± 5361.2	$be+j\not{p}$	211	176.6 ± 5
$2j\mu+\mu-$	374	394.3 ± 24.8	$e+\not{p}\tau-$	48	35 ± 2.7	$be+e-j$	32	34.6 ± 2.6
$2j\mu+$	9513	9362.3 ± 166.9	$e+\not{p}\tau+$	20	18.7 ± 1.9	$be+e-$	62	55 ± 3.1

Numerous specific models proposed

Many tunable parameters affect phenomenology w/o breaking SM as observed.

Majority of proposed models must be wrong, but this is a good thing...

Whatever is out there (and it's ~5x more plentiful than normal matter) will be a surprise!

How do we see any of this?

Analyze states produced in proton-(anti)proton collisions at high energy

$E=Mc^2$, so Big E = Large reach in creating new matter states

Study dynamics of collisions – How do the forces work...

Only by understanding the Standard Model precisely can we hope to find new physics in the dynamics of our collisions

Study massive states – What kinds of things can exist, what are there properties...

Precise knowledge of W, top properties are central to understanding where the Higgs may be...

Collider physics = precision studies + direct access to new physics

Literally 100's of thesis topics

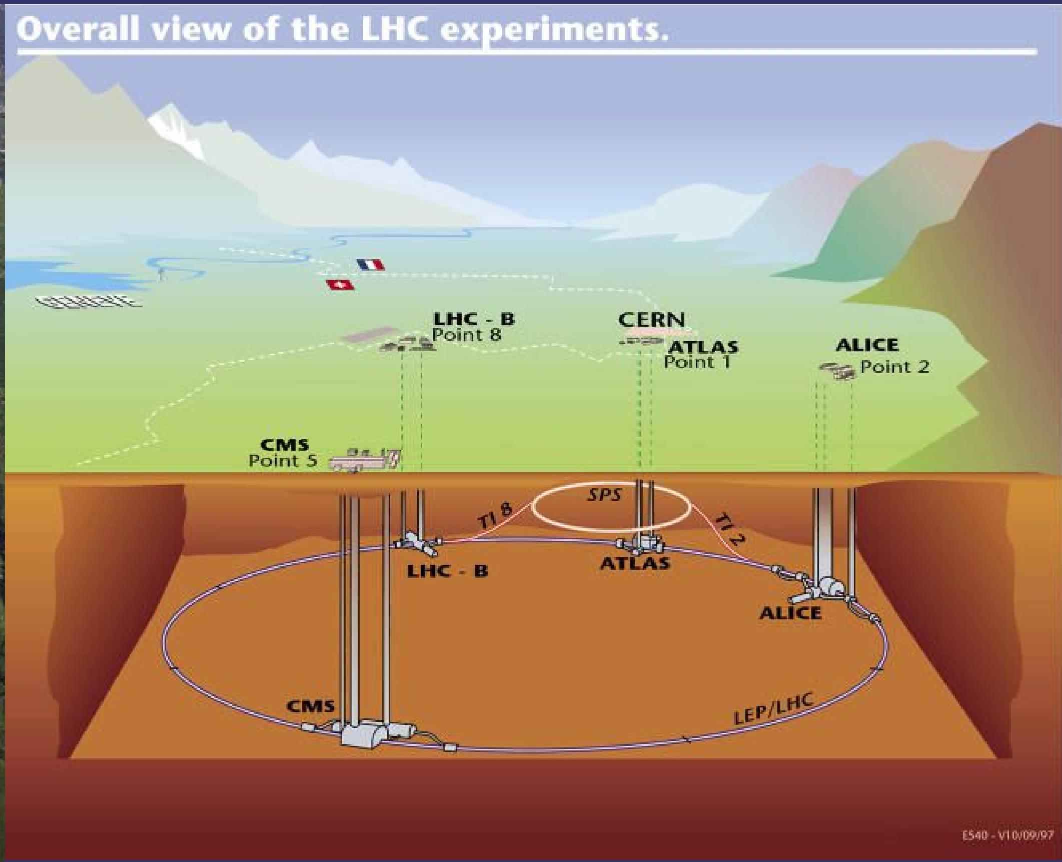
The Labs

Fermilab (Near Chicago)
The Tevatron
proton-antiproton collider
at c.o.m. Energy = ~2TeV

6.3 km circumference

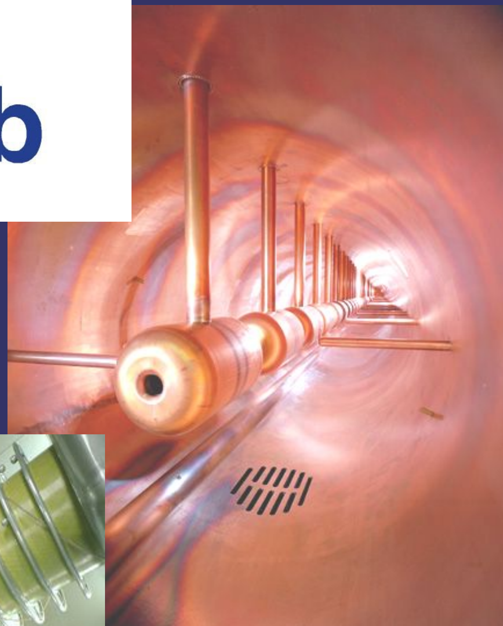
CERN (Geneva, Switzerland)
The LHC
proton-proton collider
at c.o.m. Energy = 14TeV

27 km circumference

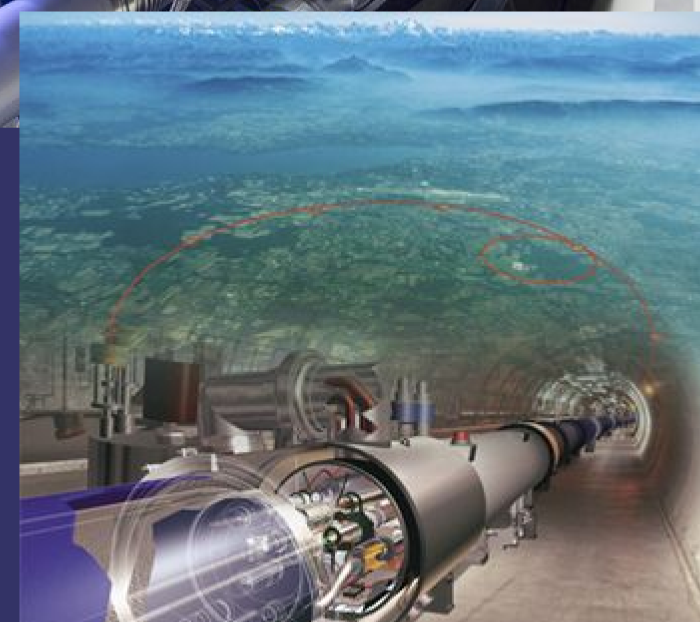


Fermilab

Tevatron

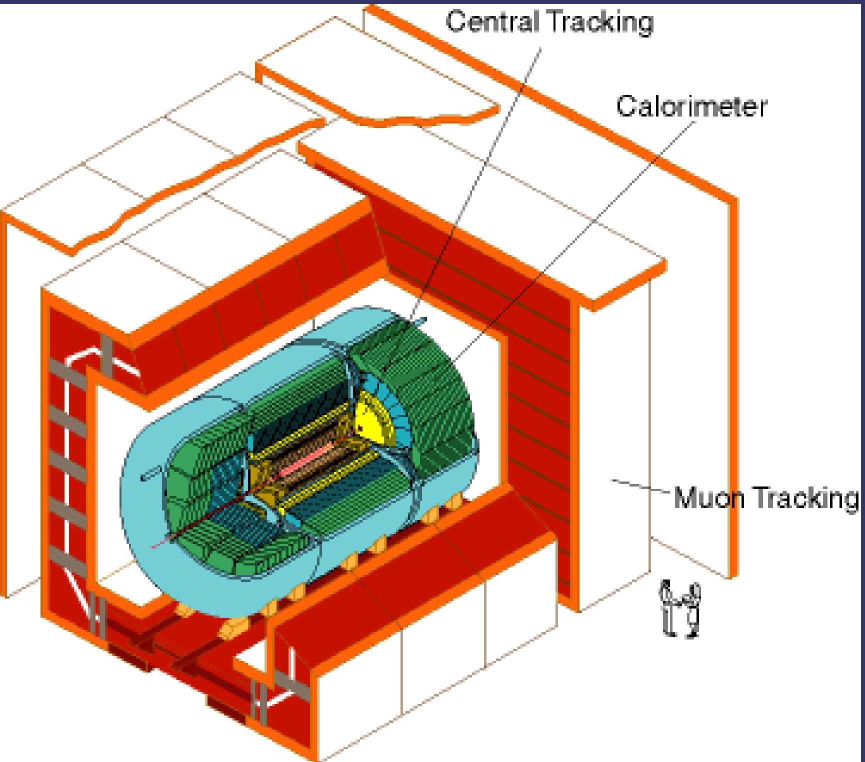


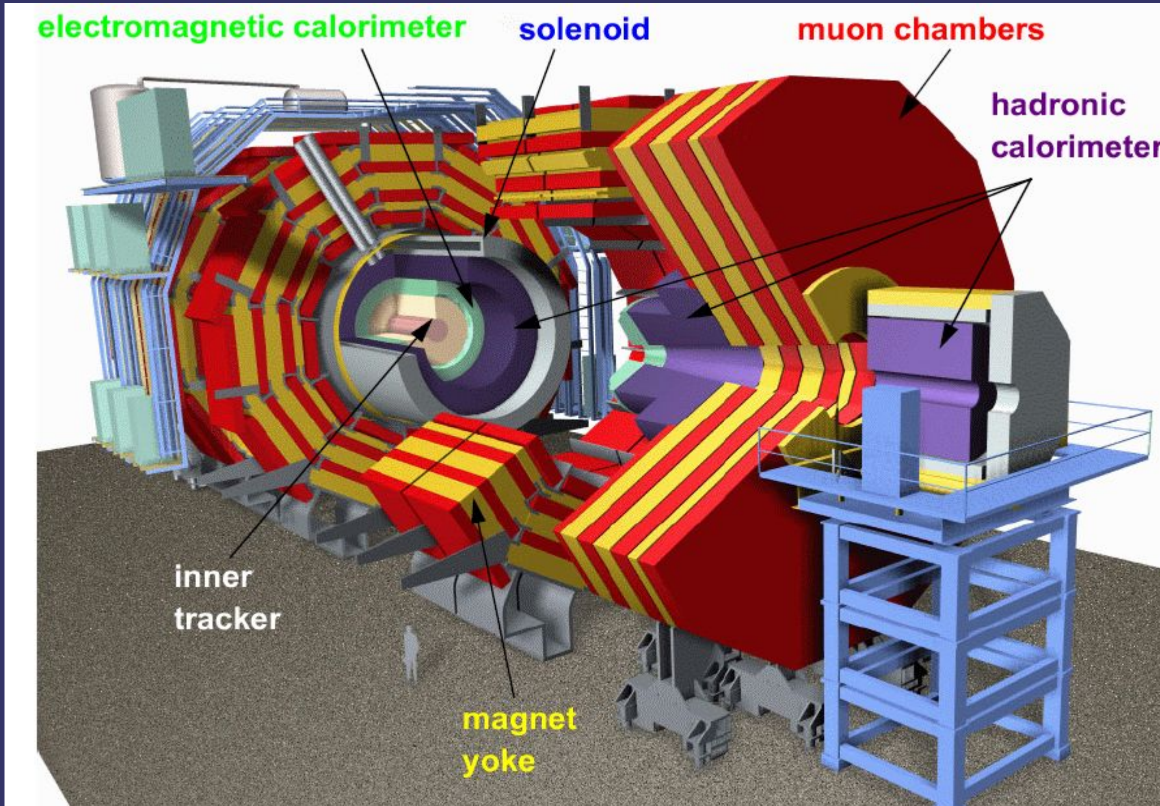
CERN



The Experiments

DØ - Fermilab	CMS - CERN
Weighs 5000 tons	Weighs 12,500 tons
~10^6 channels of information	~10^7 channels of information
Inspects ~3-30 x10^6 collisions/sec.	Inspects ~40-1000 x10^6 collisions/sec.
Running now	First beam: end of 2008

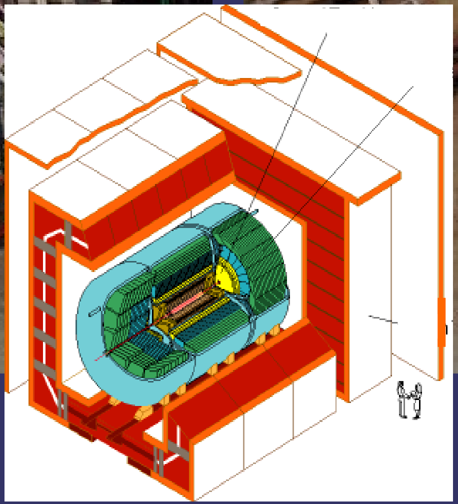




DØ

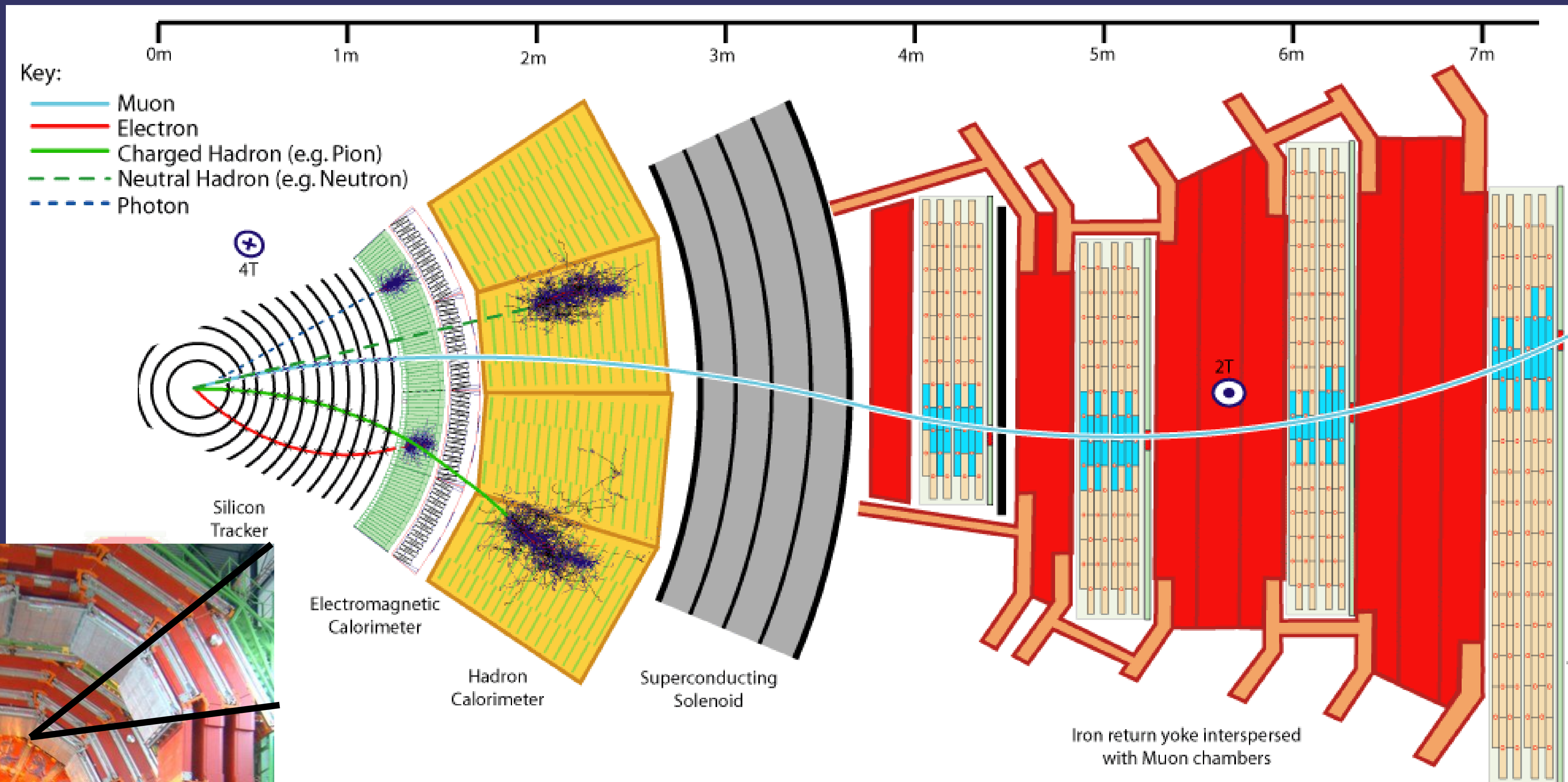
The Calorimeter

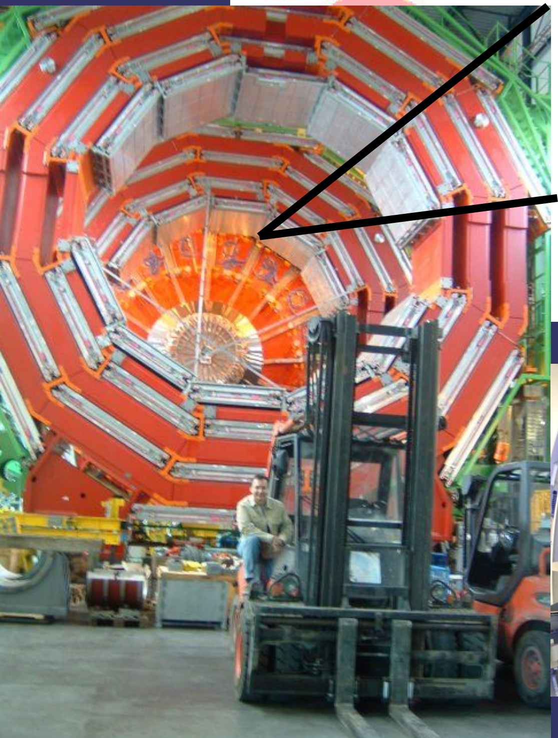
The full cube, w/ muon chambers

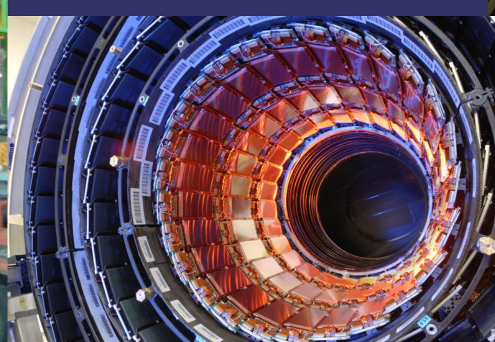


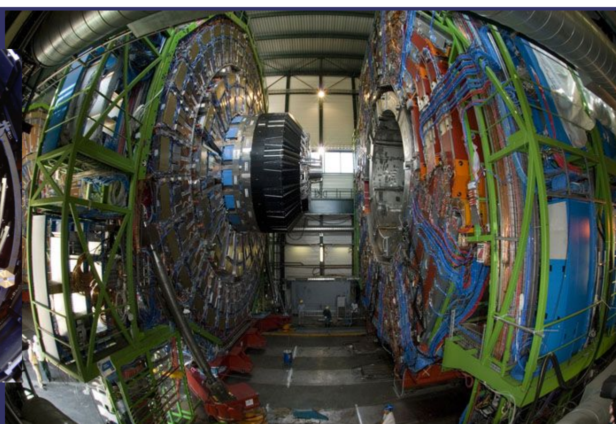
Slice of CMS

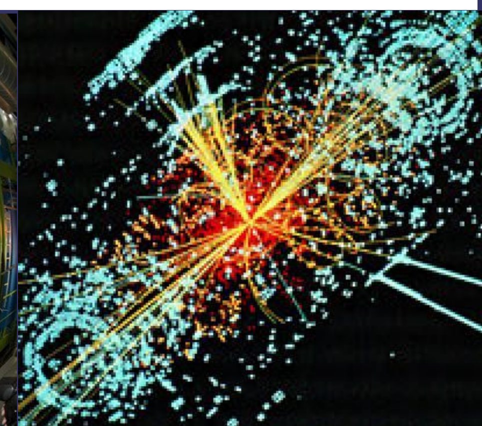
7m











Accumulate world's largest data sets at highest energies before LHC era

massive physics menu includes:

- Precision top physics (first ever)
- Precision EW physics (order of magnitude increase W statistics)*
- Searches: Higgs* and for new physics (explore much of SUSY phase space, extra-dimensions, exotic matter states)
- QCD and proton hadronic structure (new levels of precision, smallest distance scales yet)*
- Heavy flavor physics (Precision measurements in heavy quark sector, relationship between generations, matter antimatter asymmetry,...

The best HEP program happening!

Dukes, Hirosky

LHC: The New Frontier

massive physics menu includes:

- Copious top production
- Test of EW physics to “unitarity limit”
- Copious Higgs production, test SM vs. SUSY Higgs
- Direct observations of SUSY states* or elimination of the lifetime work of many theorists :)
- Order of magnitude increase in reach to physics at smallest distance scales*
- Open to weirdness: black hole production, extremely massive exotic states, new types of strong interactions, extra-dimensions*....

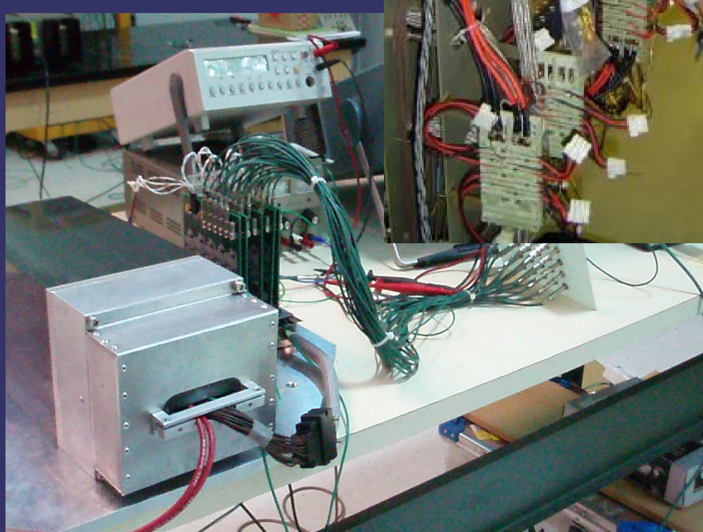
A new era for HEP is only a couple 1 year away!

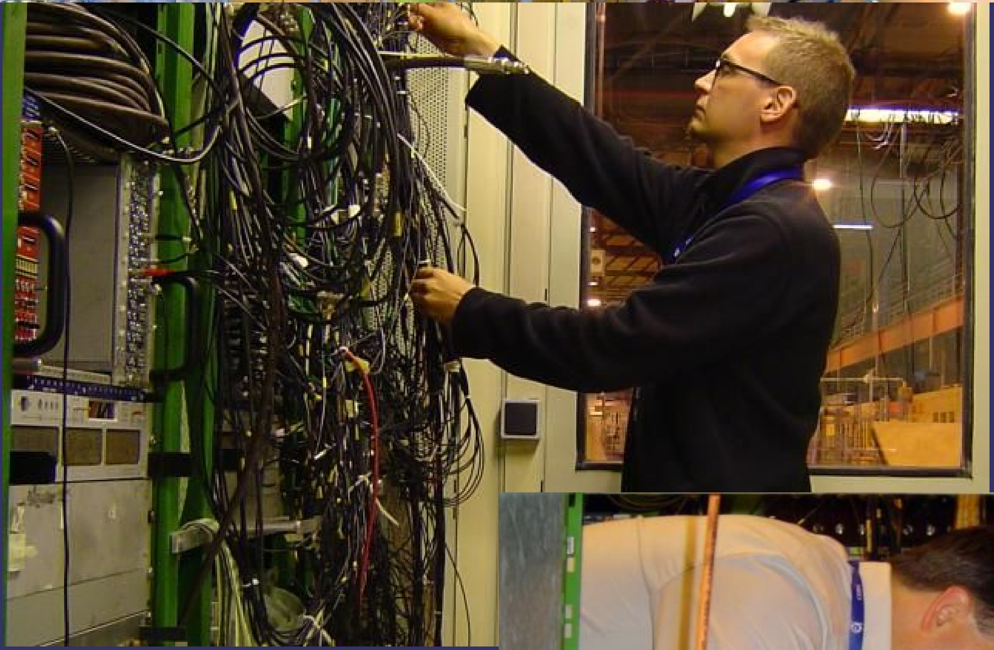
Conetti, Cox, Hirosky

* general group interests at present

Various Technical Projects

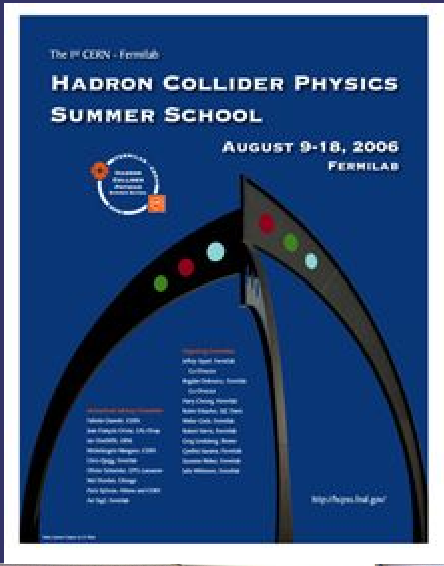




At the CMS test beam

Workshops and Physics Schools



Around CERN

CERN Surroundings

Where do HEP students go?

HEP students and postdocs go many places after completing their research, some (very few really) examples:

- Industry
  - Industrial research and instrumentation design
  - Wireless technology and network infrastructure
  - IT Consulting
  - Financial analysis, modeling
  - Design of medical treatment devices
- Non-Industry
  - Private and public “think tanks”
  - National research laboratories (not only HEP)
  - Law, Media
- Academia
  - 4-year undergraduate colleges
  - Tier-1 research universities

But, you should only choose this or any other research area because you are interested in the physics!

no passion, no progress!

What can you learn along w/ physics?

Lots:

- detector technologies, typical HEP experiments can easily employ many varieties of particle detection – enormous amount of practical physics in development of detector systems
- high performance data readout systems, electronics (HEP detectors must typically process 10's of TB of data each second)
- high performance computing:
  - need to cull above data rate to manageable levels in real time
  - handle data sets at many PetaByte level
- sophisticated data analysis techniques, statistical reasoning, multivariate approaches for problems -> extracting maximal information from data
- working with engineers and detector/accelerator physics experts to bring experiments on-line
- experience w/ detailed simulations of detector systems and physics processes
- working in a large expert physics community, amazing access to expertise in world wide community + opportunities to contribute
- ...

Interested in Experimental HEP?

Expected opportunities for graduate students this year:

experiment	~advisor	colleagues
CMS	Hirosky	(w/ Cox and Conetti)
DØ/NOvA	Dukes	(w/ Hirosky)

To learn more (start by doing some homework):
- seminars, colloquia, ...
- Symmetry Magazine: http://www.symmetrymagazine.org
- CERN Courier: http://cerncourier.com
- Femilab Today: http://www.fnal.gov/pub/today/

Contact me or another group member if you have questions about the group and our projects.

Interested in signing up? I'll be happy to interview interested students after the Fall semester.