Millennial Physics at Fermilab

The high energy physics program at the U.S. Premier platform for

DISCOVERY

- Introduction
- Standard Model
- Accelerator complex and detectors
- Remembrance of Things Past
  with an emphasis on the top quark
- The future

Raymond Brock
Department of Physics and Astronomy
Michigan State University
brock@pa.msu.edu

what's coming:

I'm going to present the Fermilab proton-antiproton collider program in two lectures, past and future:

"Run I", from 1993-1996, L = 100 pb^{-1}
"RunIIa", from 3/01 - ~03, L ~ 3,000-5,000 pb^{-1}
"RunIIb", from ~03 - LHC physics, L ~ 20,000 pb^{-1}

Lecture 1: A review of the goals and the facilities

- introduction to the Standard Model of elementary particle physics
- introduction to the accelerator and the experiments

Lecture 2: Results and prospects

- Run I results
- Run II prospects

Lecture 1: The Standard Model, Fermilab Collider, and Detectors

what is Fermilab?

it’s many things to me…

it’s a dedicated scientific community

made up of:

- 1200 physicists, engineers, and staff
- >1000 faculty, post docs, and students from > 80 US & ~20 foreign institutions

it’s an amazing scientific instrument

consisting of:

- A time machine
- A particle accelerator for antirotating beams of protons and antiprotons
- hand-made vehicles to explore the current and the very early universe
- A source of high energy/intensity beams of kaons and neutrinos

it’s a beautiful single-purpose DOE national lab

located at:

- real space: 60 mi west of Chicago
- cyberspace: www.fnal.gov

a truly inspiring place to work

The Standard Model

at light speed…

what is "matter"? - traditionally, only a few real things: protons, neutrons, electrons, and photons connected via the electromagnetic interaction

that's a narrow view, however. Matter is complex.

- **Understanding the "inside" of matter requires relativistic quantum field theory, so we must consider the effects of virtual fields (later)**
- **The geneology of matter can be projected back to ~10^{-30} s after the Big Bang - so the "zoology" of matter is actually diverse**
- **Matter in interaction is crucial: Four distinct kinds of interactions occur: Electromagnetic, Strong, Weak, and Gravitational**

We believe that all four are propagated by integer spin "gauge" bosons: photon, gluon, W/Z, and graviton

The full zoology of elementary particles was *originally* divided into categories based on characteristics (quantum numbers)

1. hadrons: particles which participate in the strong interaction
   baryons: spin n/2 hadrons (Fermions) [protons, neutrons, □, □, etc.]
   mesons: integer spin hadrons (Bosons) [pions, kaons, etc.]
2. leptons: spin 1/2, no participation in the strong interaction
   neutral leptons - [3 neutrinos, only]
   charged leptons [electrons, muons, tau, only]
3. photons: spin 1

actually, a spectroscopy

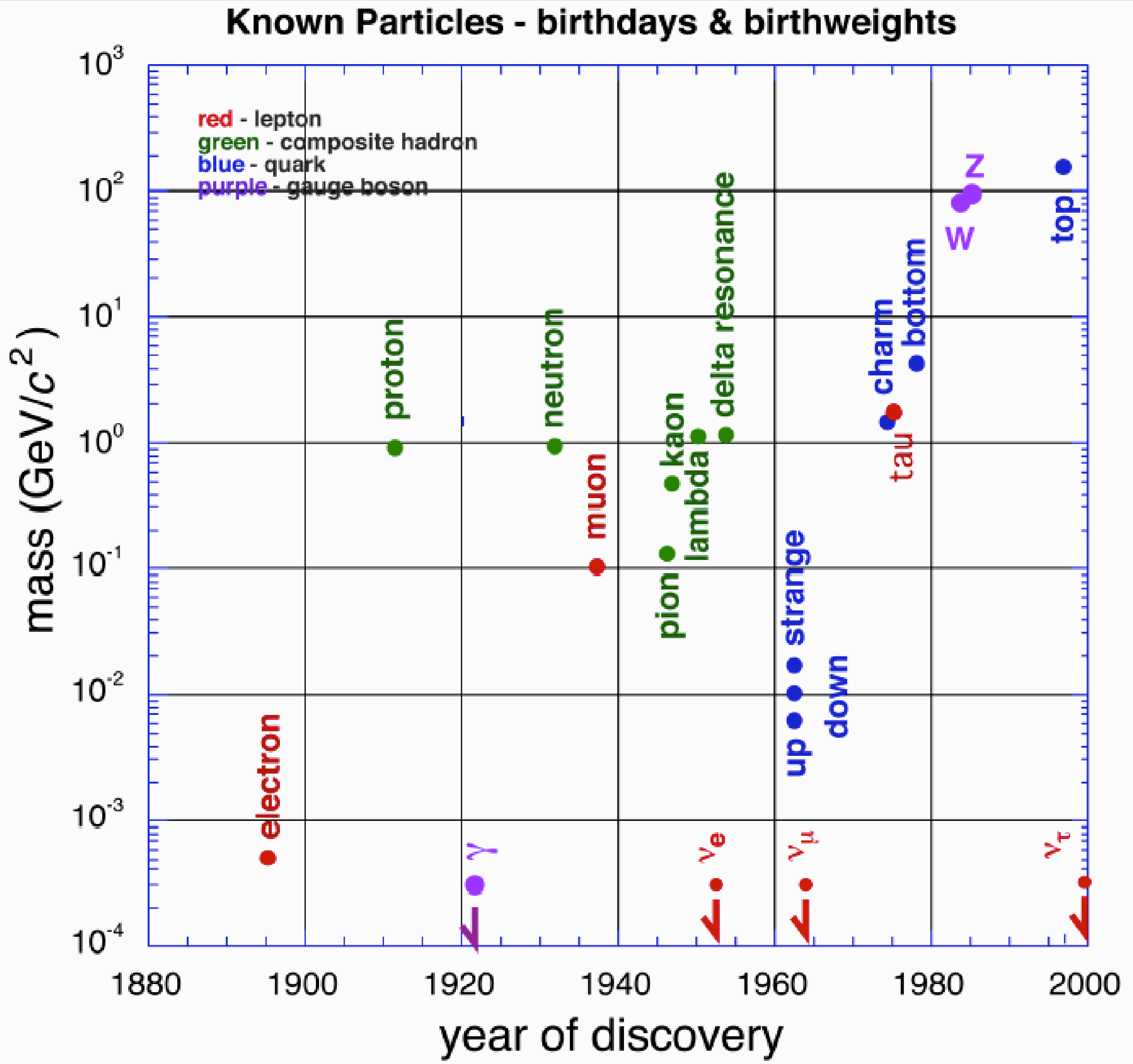
Quark Model cleaned up the mess of 100’s of hadrons:

- hadrons are composite with a spectroscopy built on quantized vibrational and rotational degrees of freedom:

$p = uud; n = udd$

$\square = uud; \square = usd$

- fundamental entities are the (point-sized) quarks and (point-sized) leptons



The four forces are distinctly different…and paradoxically, similar.

- in particular, for two of them…they are the same:

just as Maxwell suggested:

the physics of a magnet

the physics of a electrostatics

electromagnetic force

Weinberg and Salam suggested:

the physics of nuclear beta decay

the physics of electromagnetism

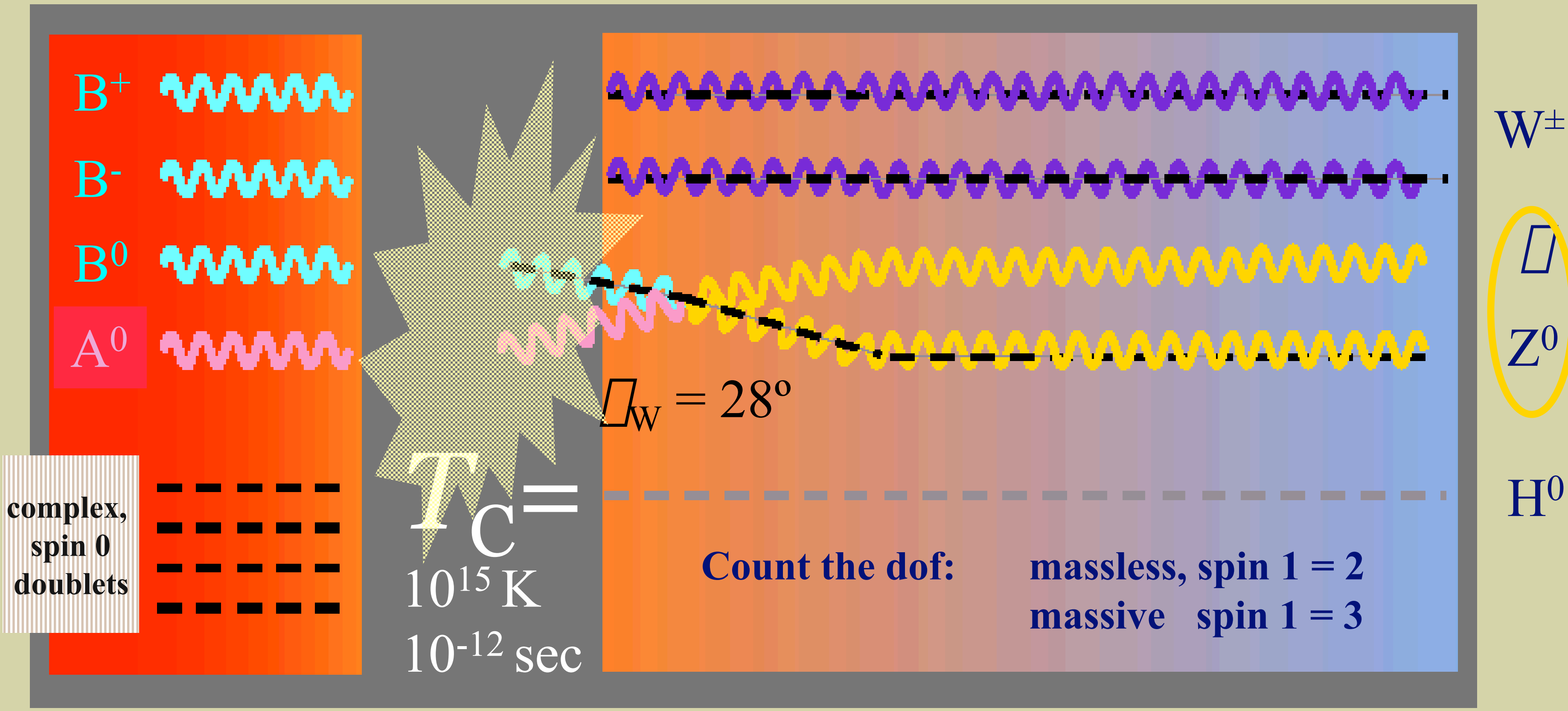
electroweak force

had to be
propogated by a very **massive** field

had to be
propogated by a **massless** field

The scheme for accomplishing this is that of Spontaneous Symmetry Breaking and the Higgs Mechanism

A useful way to think about things: think back…*way* back



You are here…

1 K

10^{+18} sec

Chip Brock, Michigan State University
2001

An adaptation of the mean field theory description of phase transitions invented by Ginsberg and Landau

- based on the notion of Spontaneous Symmetry Breaking - or Hidden Symmetries
- how can a symmetry be “hidden”?

1. a drop of milk is suspended above a bowl of milk
2. it’s released and splashes
3. flutes emerge in the splash…24 “fingers”

Before: perfect axial symmetry around the drop’s trajectory
After: the symmetry is reduced to C_{24}

…where did the symmetry go? This sort of thing bothered Pierre Curie.

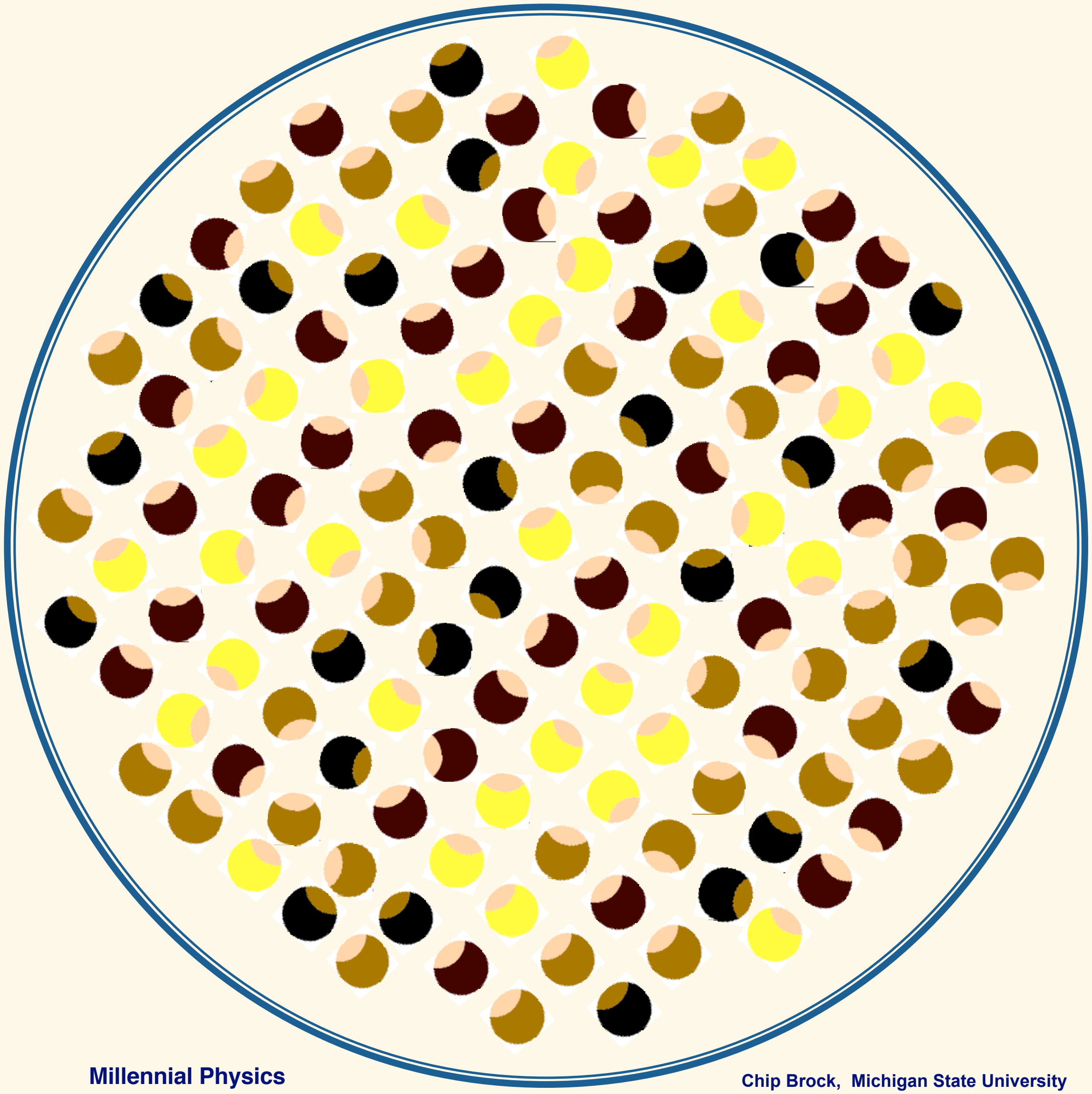
•Landau taught us that a sudden loss of symmetry signals a phase transition
•all 2nd order phase transitions exhibit this behavior and a quasiparticle excitations result: Cooper pairs, magnons, phonons, etc…
•The Higgs Mechanism is the name for the process which occurs and produces a gap - mass - for symmetries associated with infinite range

Masses come from the Higgs Mechanism. An analogy:

a room full of people, randomly oriented talking…

the noise (energy level) in the room is constant and forms a background (ground state) energy which is largely ignored by each member in his individual conversation

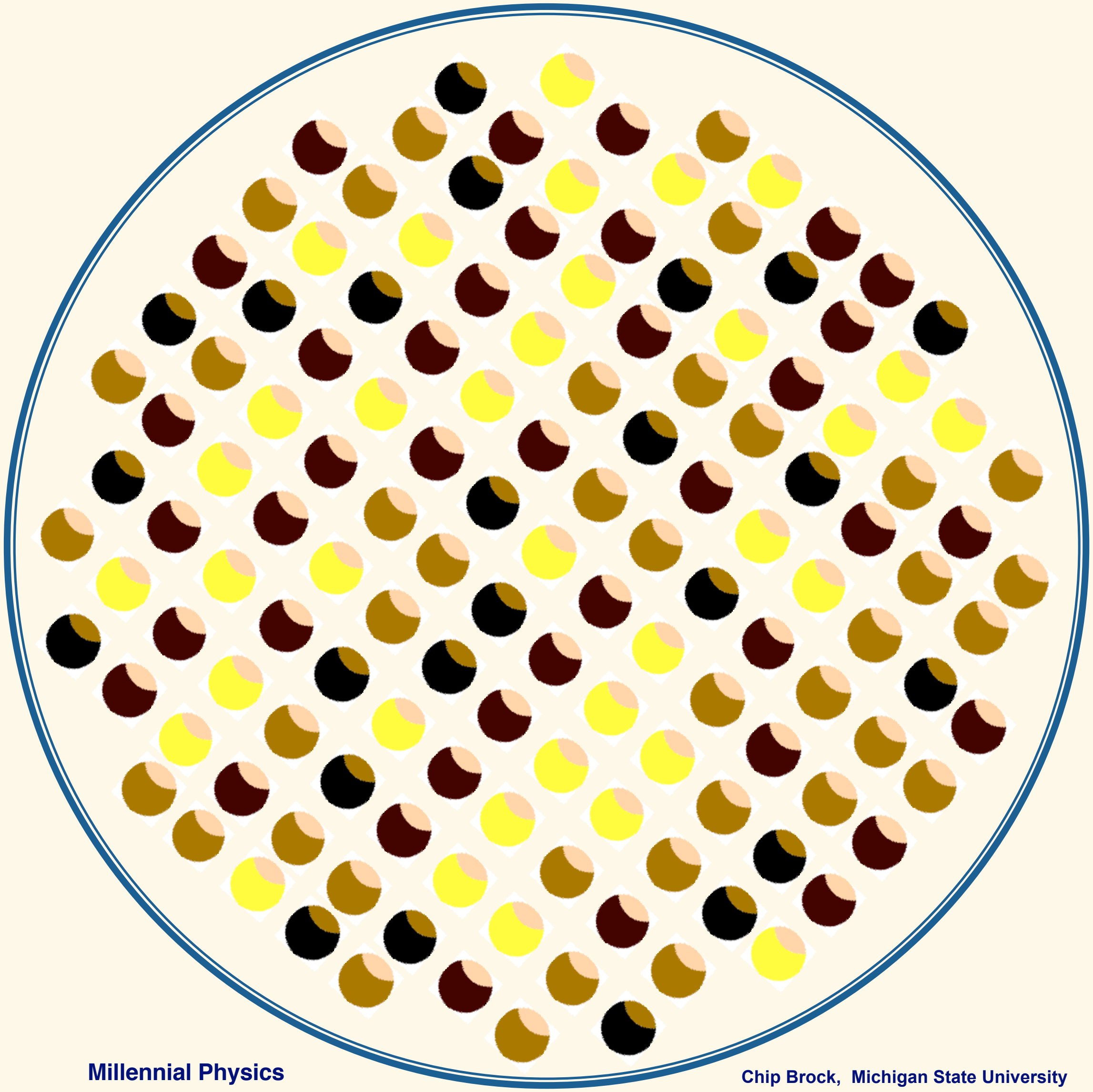
…the ground state energy level is unimportant and tuned out



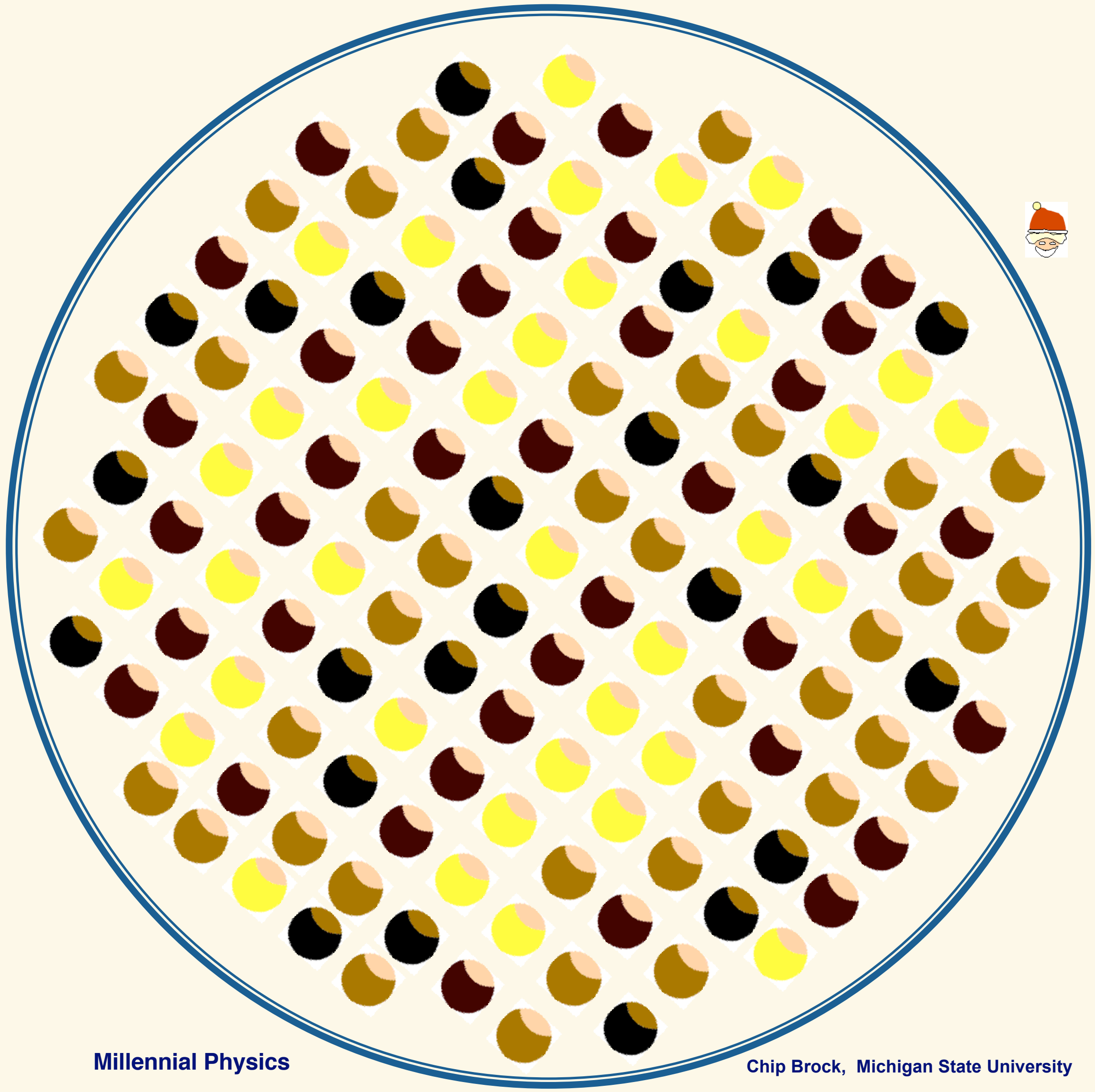
(after David Miller)

sleigh bells ring from the NE corner of the room…

everyone turns to the sound and is immediately silent - so, the energy level in the room is lowered when the randomness is removed



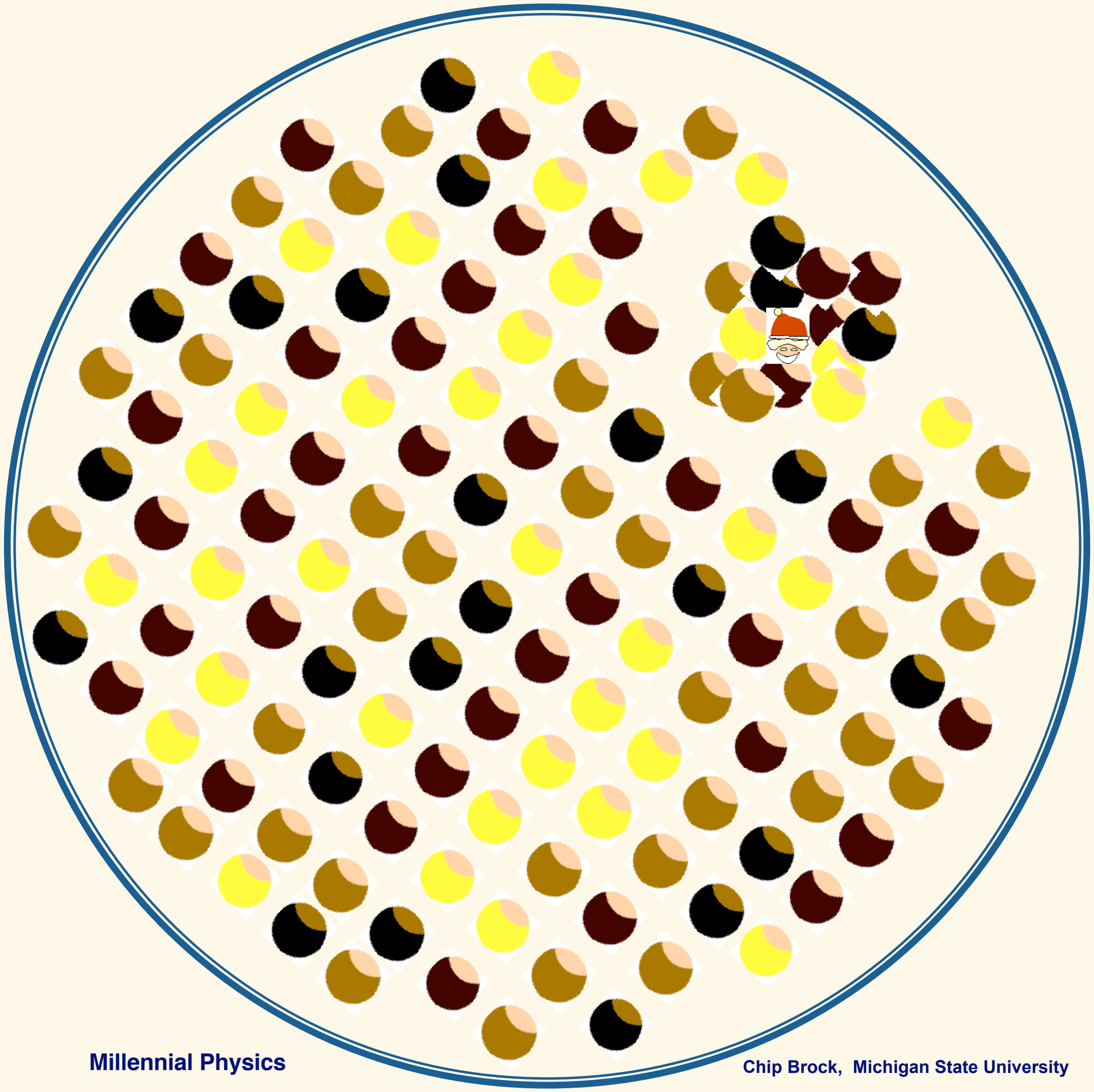
Santa appears

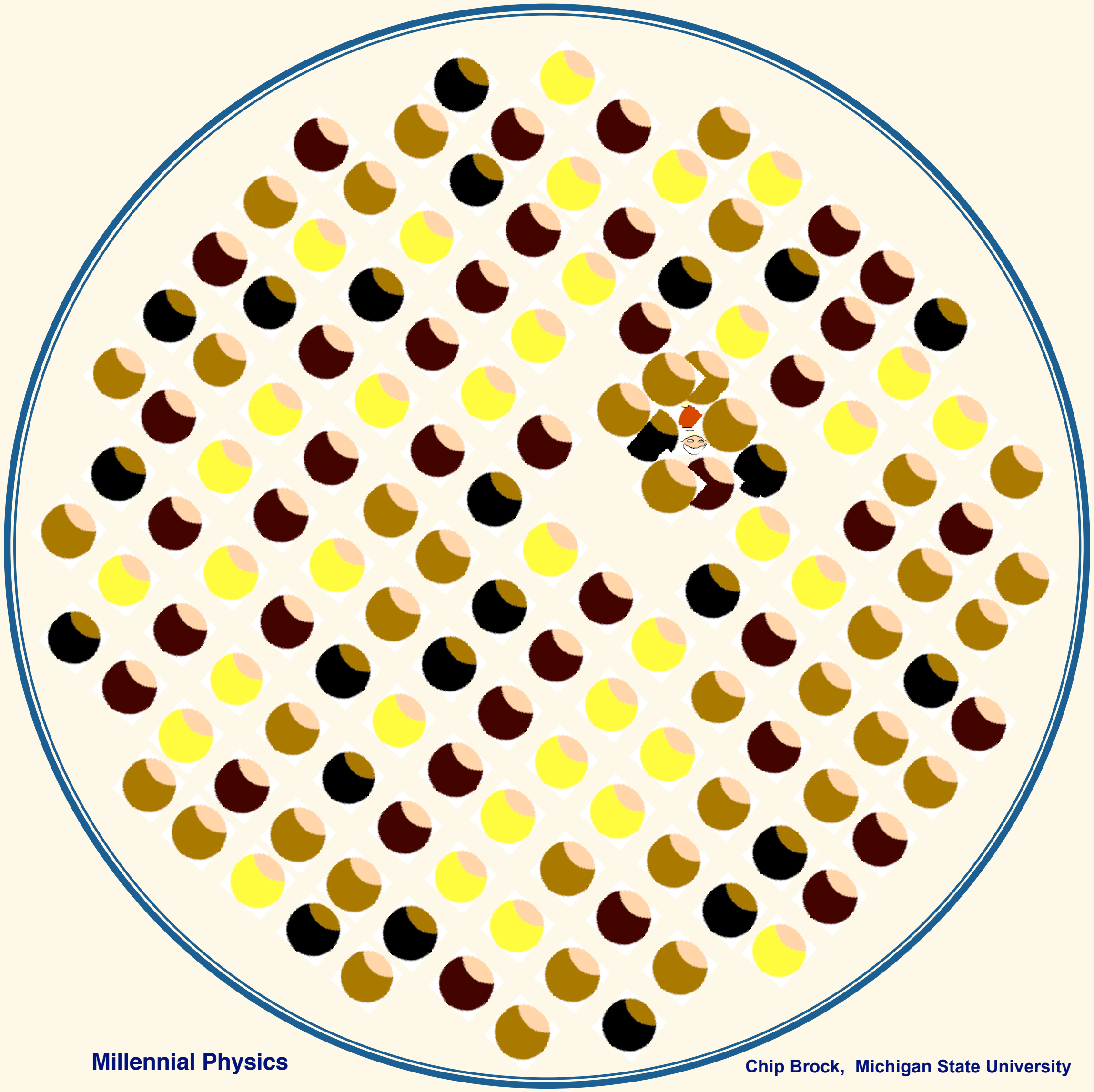


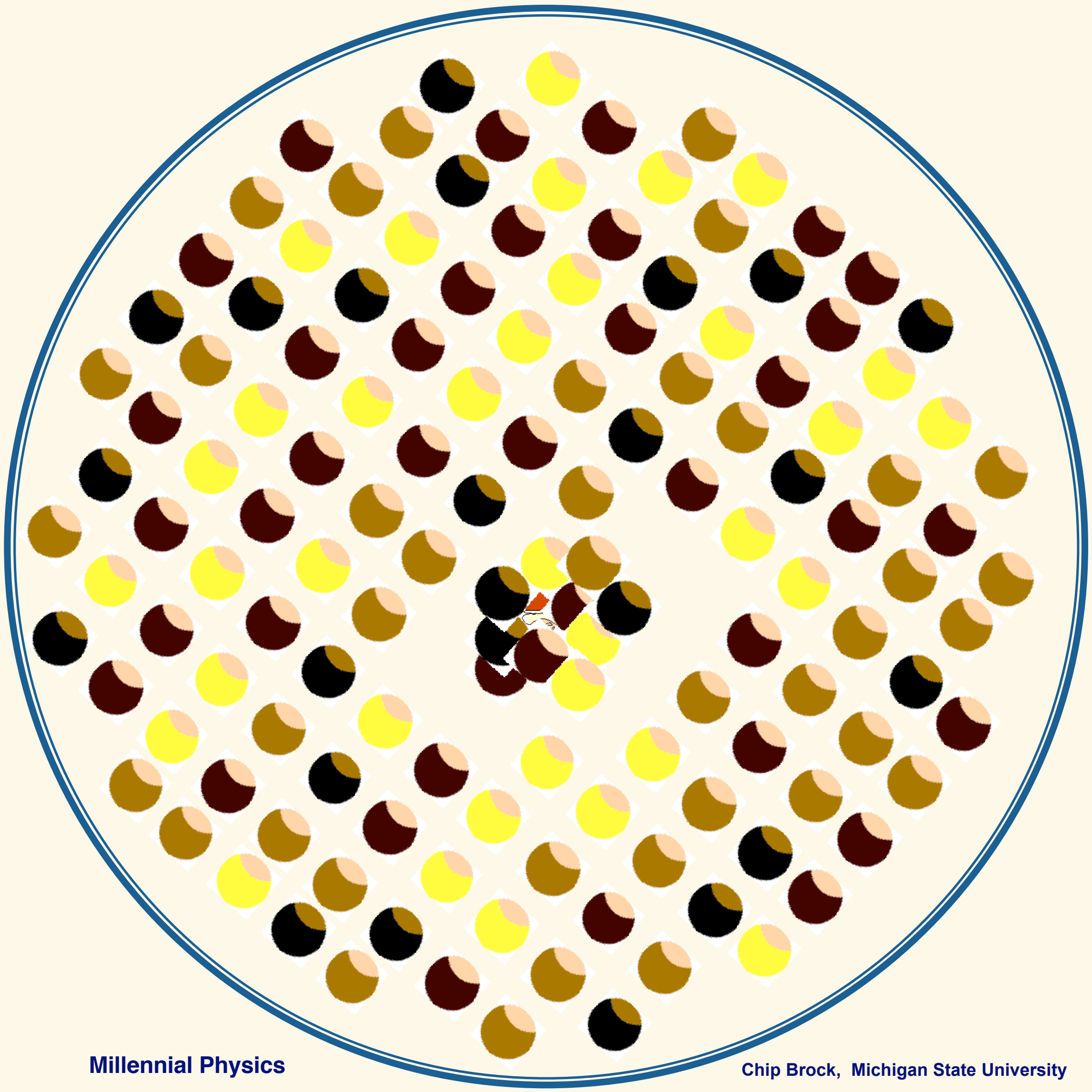
Santa enters the room and attempts to make it across…

his progress is impeded
as if his inertia has increased

ie, as if his *mass* has increased by virtue of his interaction with the people around him.





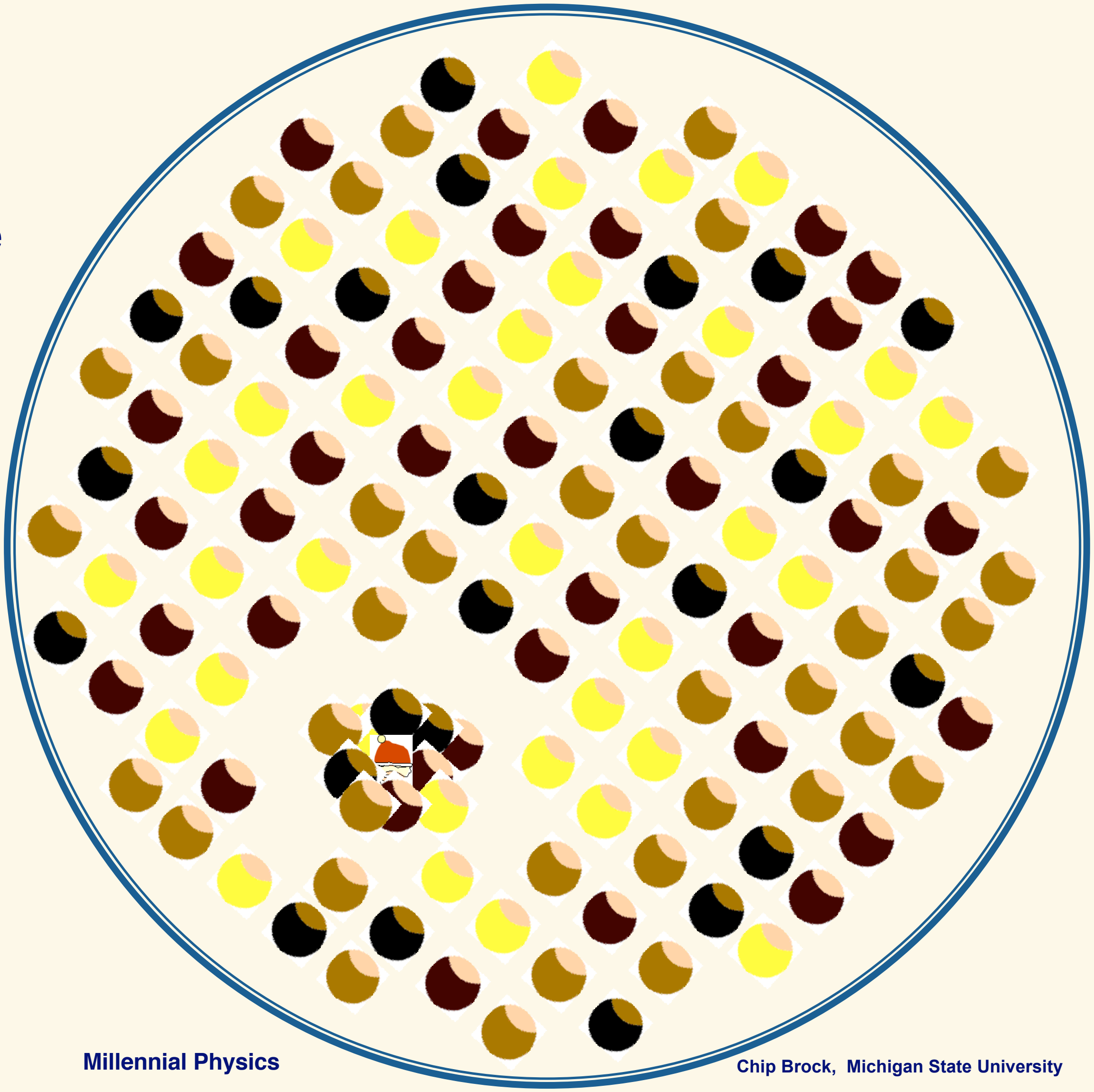


This is the generation of mass.

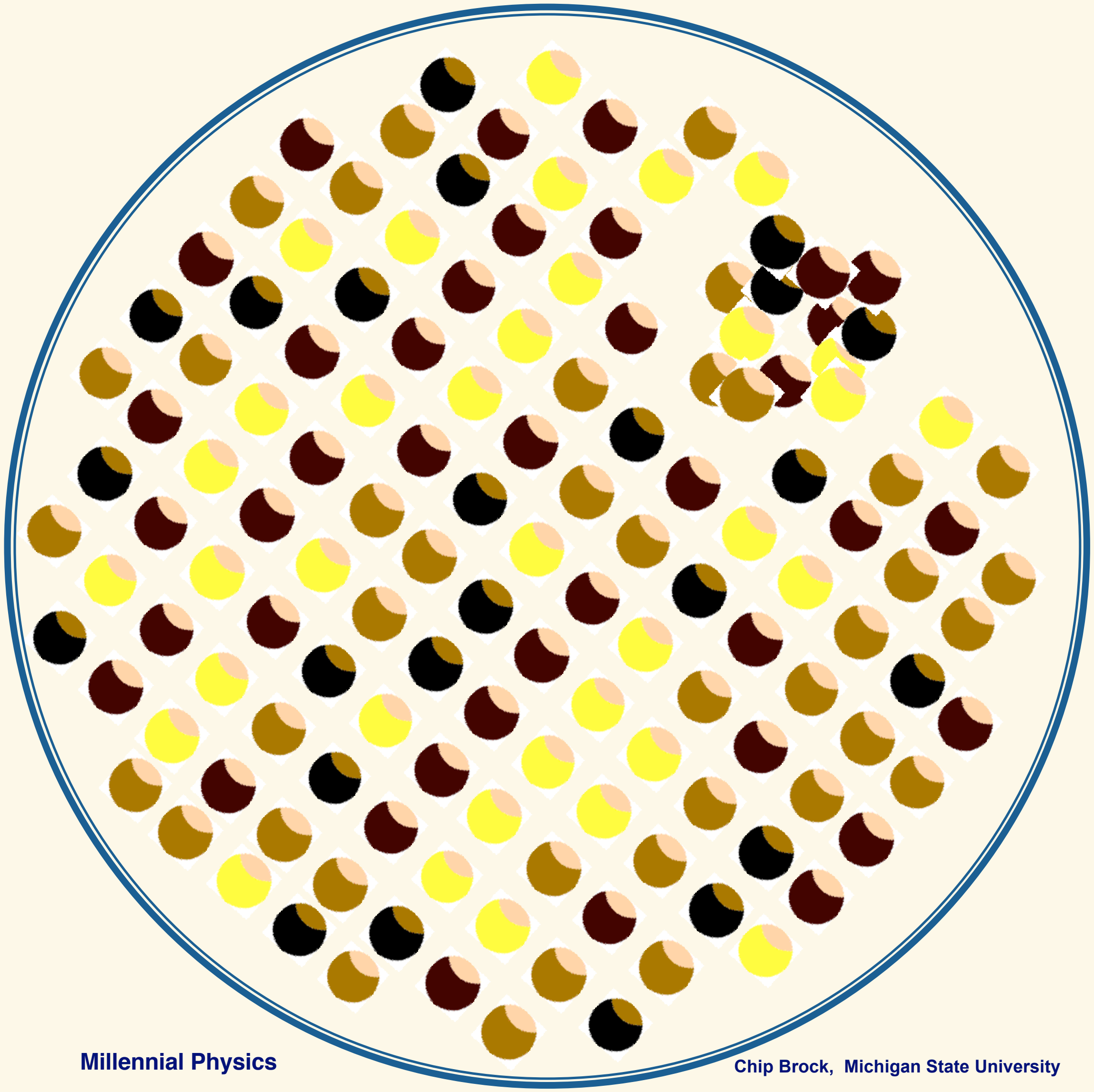
the people are the analog of the Higgs field, triggered by the phase transformation inherent when they turned NE and lowered their energy.

They give “mass” to Santa (particles) by interacting with him…

mass is generated by particle’s interaction with the Higgs field

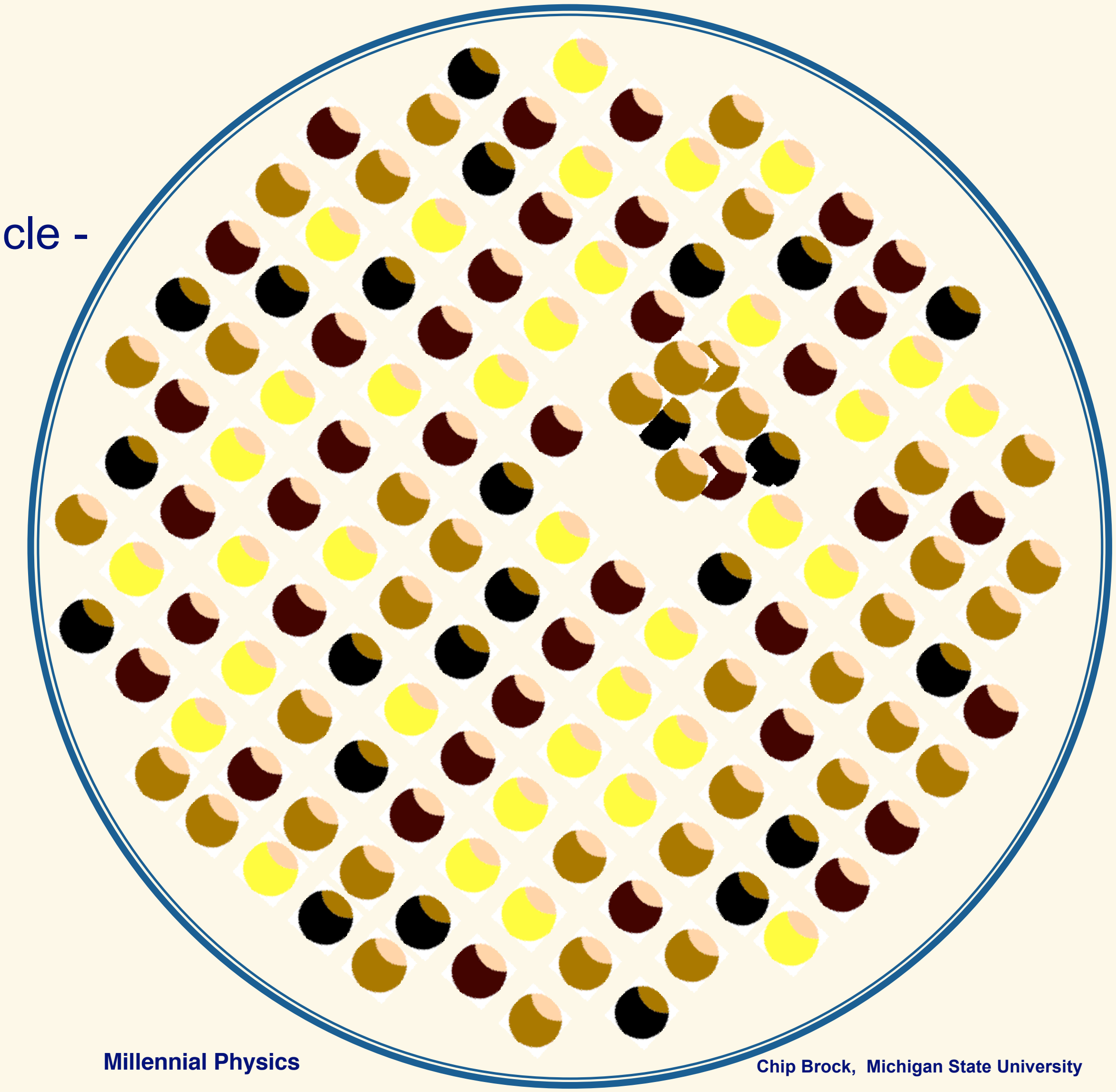


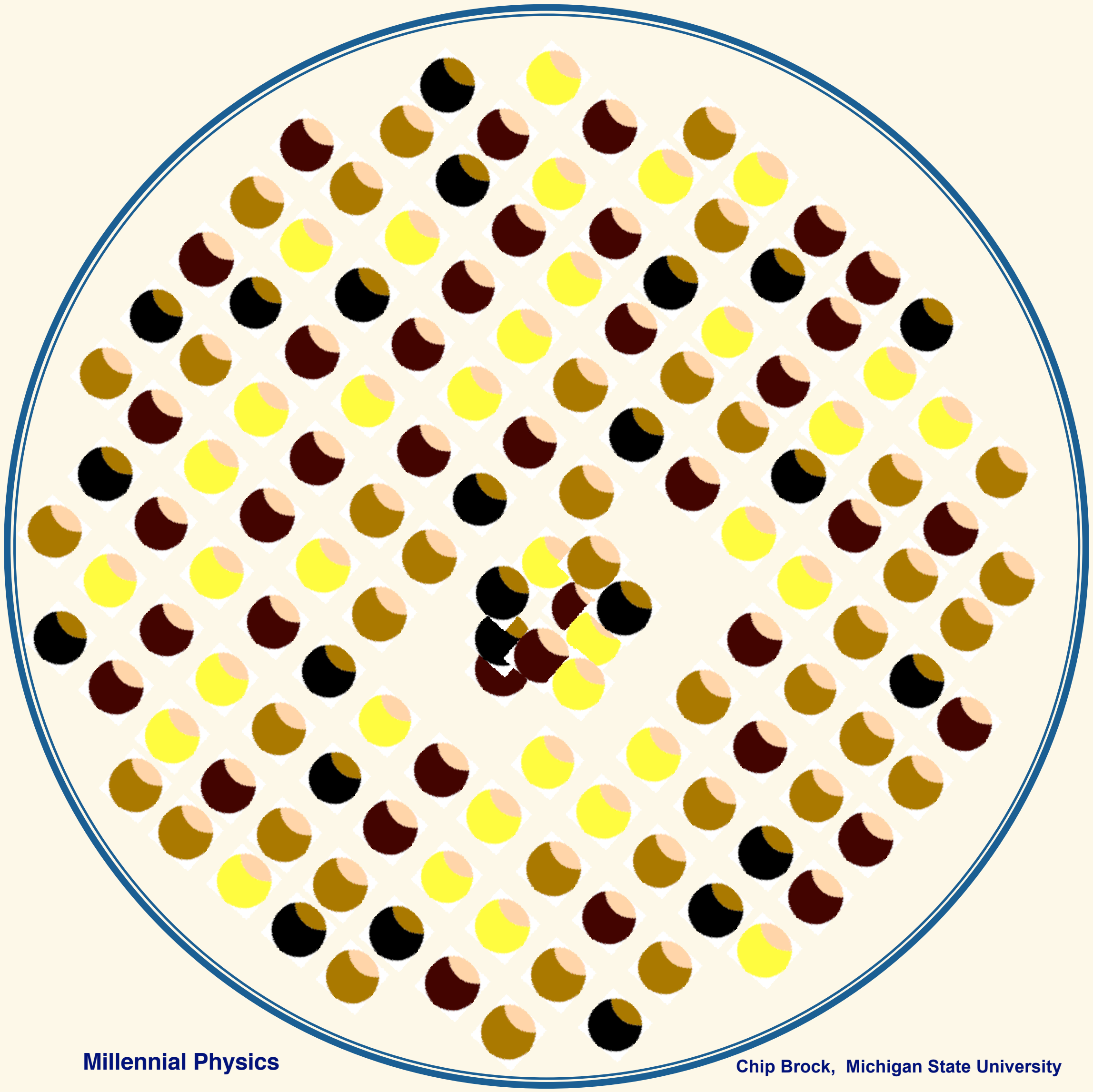
Suppose now, that only the rumor that Santa might arrive starts at the NE corner



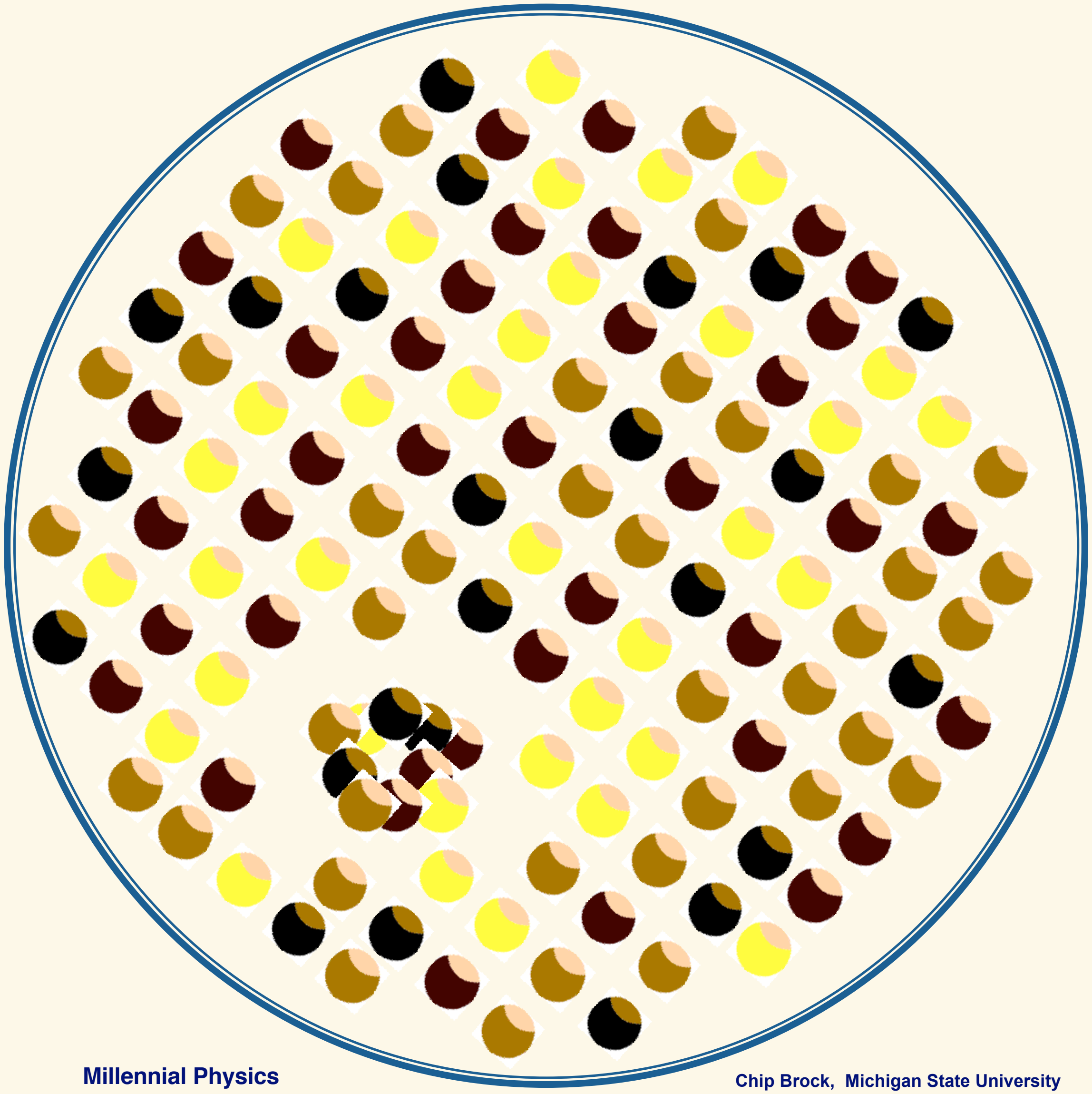
The rumor migrates across the room…

the clustering is the Higgs particle - the quantum of the Higgs field





Finding the Higgs Boson is of fundamental importance to confirming the Standard Model and the veracity of the phase transition, Spontaneous Symmetry breaking scheme.



Standard Model–what we know

Quarks (spin 1/2, charge 2/3 and -1/3)

left-handed:	u	c	t	weak, strong, and electromagnetic interactions
	d	s	b	
right-handed:	u, d, c, s, t, b			electromagnetic and strong interactions

Leptons (spin 1/2, charge 1 and 0)

left-handed:	e	μ	τ	weak and electromagnetic interactions
	ν_e	ν_μ	ν_τ	
right-handed:	e, μ, τ			electromagnetic interactions

Gauge bosons (spin 1, charge 1 and 0)

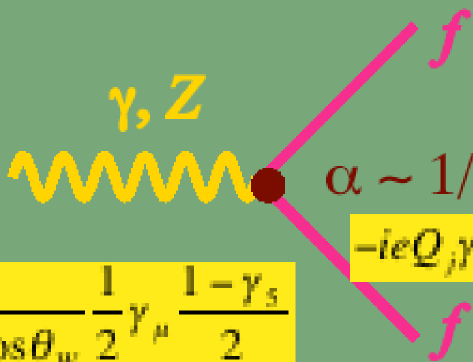
g	*strong,*
γ	*electromagnetic*
$W^{\pm}$	*electromagnetic & weak*
Z^{0}	*electromagnetic & weak*

Higgs (spin 0, charge 0)

H^{0} — *Fills the vacuum and is responsible for mass?*

Feynman diagrams for vertices (fermion interactions)

Neutral electroweak

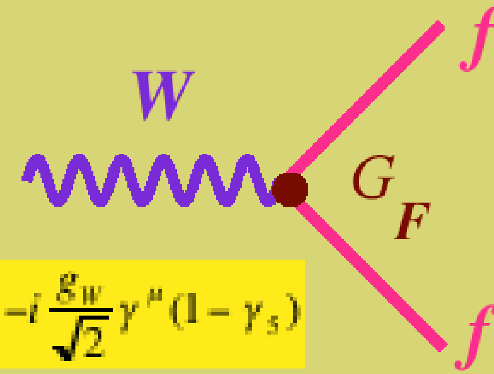


$\alpha \sim 1/137,\ 10^{-4}$

$-ieQ_j\gamma^{\mu}\delta^{ij}$

$\frac{-ie}{\sin\theta_W \cos\theta_W}\frac{1}{2}\gamma_{\mu}\frac{1-\gamma_5}{2}$

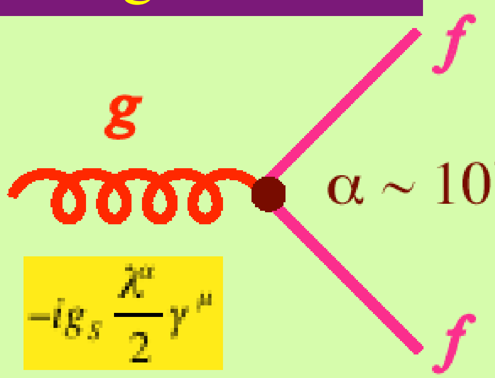
Charged electroweak



$G_F \sim 10^{-5}$

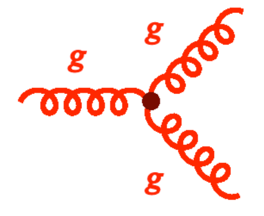
$-i\frac{g_W}{\sqrt{2}}\gamma^{\mu}(1-\gamma_5)$

Strong

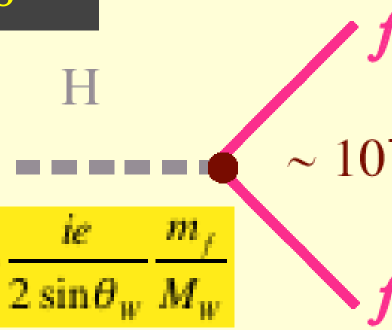


$\alpha \sim 10^{-1}$

$-ig_s\frac{\lambda^{a}}{2}\gamma^{\mu}$



Higgs



$\sim 10^{-5} \bullet m^2{}_f$

$-\frac{ie}{2\sin\theta_W}\frac{m_f}{M_W}$

Important SM relations

- Mixing characterized by an angle, θ_W ("Weinberg" or "weak" angle)

$$\gamma = B^0 \cos\theta_W + W^0 \sin\theta_W$$

$$Z = W^0 \cos\theta_W - B^0 \sin\theta_W$$

$T > T_c$, a triplet of spin 1 bosons, $W^{\pm 0}$ and a singlet, A^0 – $T < T_c$ W^0-A^0 mix

$$e = g_W \sin\theta_W$$

Electromagnetism mixed with weak interactions

$$\frac{G_F}{\sqrt{2}} = \frac{g_W{}^2}{8M_W}$$

Fermi-theory imbedded

$$M_W = \frac{1}{2} g_W \langle v \rangle \cong 80\ \mathrm{GeV}/c^2 \Rightarrow \langle v \rangle \cong 246\ \mathrm{GeV}$$

scale of EW Symmetry breaking

$$M_Z = M_W / \cos\theta_W \cong 90\ \mathrm{GeV}/c^2$$

M_Z constrained by M_W and

- **θ_W can be measured *many* ways…in different reactions**

Standard Model–what we don't know

First, working within a restrictive, successful single model is unusual – it works too well.

Gauge symmetry – a good idea … but why:

- SU(2) x U(1) hard-wired to account for known weak and electromagnetic phenomena. Higher symmetry?

Symmetry breaking

- What is the character of the breaking?

Quarks-leptons?

- Pattern looks suspicious, right? Why?
- 3 sets? Z decay & astrophysics suggest "yes"
- Substructure? Stringyness?

Fermion mixing

- Why is there matter and not Antimatter?
- Do neutrinos also mix, and hence have mass?

Why and how is there mass?

- Thought to be induced by the Higgs field…
  - **Ubiquitous, fills the vacuum acting almost like a viscous medium**
  - **The Cooper Pair of the particle ground state**

Gravity

The puzzle: masses

so, what is it with mass, anyhow?

1 10 50 100 150 200 246 GeV 250

EW symmetry breaking scale

- up: 0.1 GeV/c ^{2}
- down: 0.1 GeV/c ^{2}
- strange: 0.3 GeV/c ^{2}
- charm: 1.5 GeV/c^2
- bottom: 4.5 GeV/c ^{2}
- top: 175 GeV/c^2
- electron: 0.0005 GeV/c^2
- e neutrino: 0
- muon: 0.1 GeV/c^2
- ▯ neutrino: 0
- tau: 1.7 GeV/c^2
- ▯ neutrino: 0
- gluon: 0
- photon: 0
- W: 80 GeV/c^2
- Z: 91 GeV/c^2

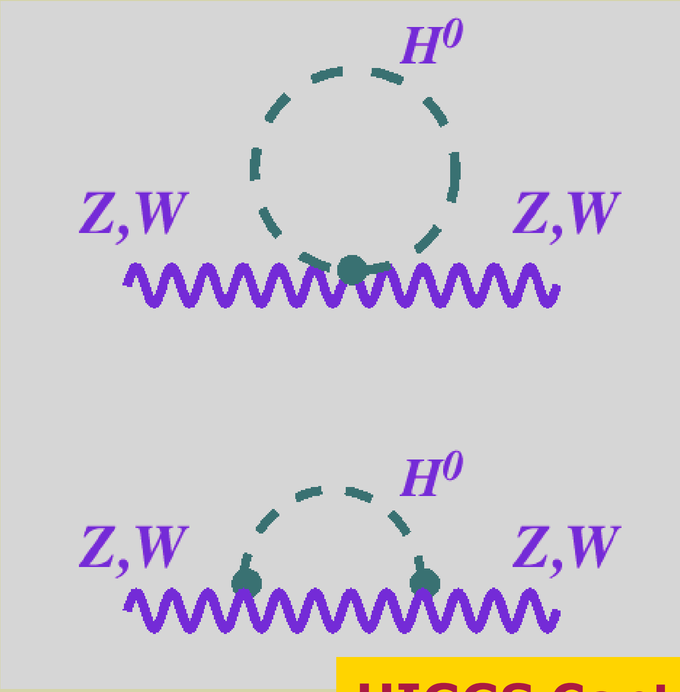
favored from EW measurements but, *logically*, heavier is okay

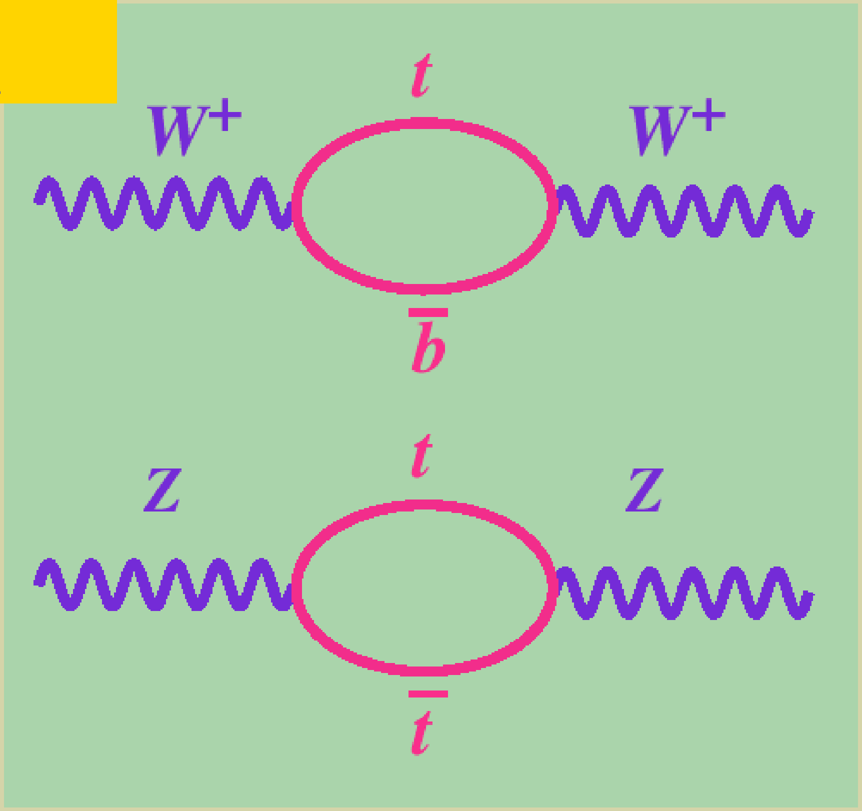
Higgs: > ~ 112 GeV/c ^{2} from LEP

New physics is in the loops

It's a quantum field theory, so IVB Propagators and virtual bubbles contain the hints

TOP Contribution ~ (m^2_{top} / M^2_W)
How we knew where to look, ***then***





HIGGS Contribution ~ $\ln(m^2_{Higgs} / M^2_W)$
How we know where to look, ***now***

HEP, as it's practiced today

hey, it's a job

HEP around the world

In order to probe the important questions we get together with 400-500 of our *closest* friends and perform experiments - obviously, there's a unique character to this work.

7 laboratories in the world dedicated to HEP

- In the US: SLAC (e^+e^-); CESR (e^+e^-); Fermilab ($p\bar{p}$ & assorted)
- In Europe: CERN (e^+e^-); HERA (ep); DAΦNE(e^+e^-)
- In Asia: BEPC(e^+e^-); KEK (e^+e^-)

New facilities are:

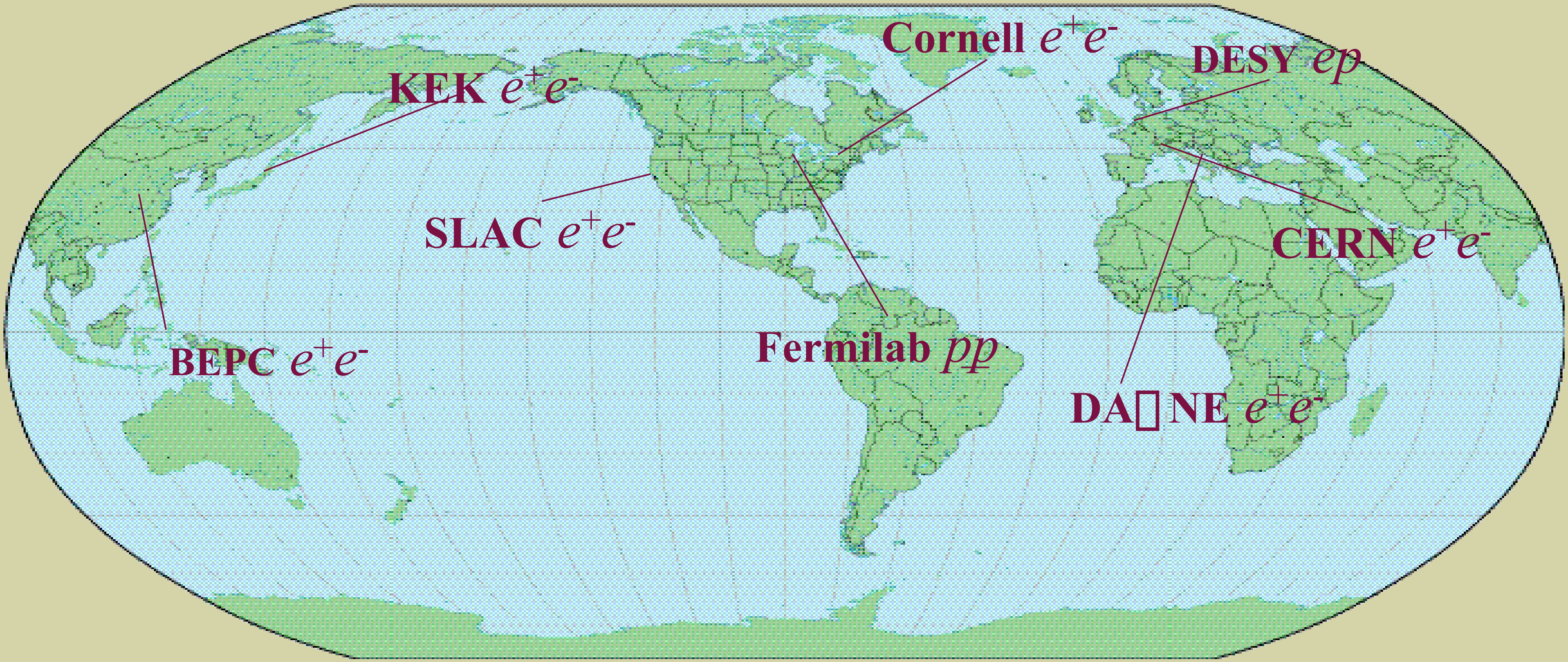
- In the US: $PEPII_{1999}(e^+e^-)$; $CESRII_{1999}(e^+e^-)$; Fermilab $MI_{2000}(p\bar{p})$
- In Europe: LHC_{2007}(pp)
- In Asia: $KEKB_{1999}(e^+e^-)$

The U.S. must figure out how to build a facility beyond LHC, 2010

Imagined facilities include:

– In US: NLC(e^+e^-); muon collider($\mu^+\mu^-$); VLHC(pp)
– In Europe: NLC(e^+e^-), τcharm(e^+e^-)
– In Asia: NLC(e^+e^-)

HEP labs around the world, today.



is a proton-antiproton collider

accelerator physics in one box:

the crucial parameter is the Luminosity, both instantaneous and integrated

$$\mathcal{L} = \frac{N_p N_{\bar{p}} B f_0}{4\pi\sigma^2} \text{ particles} / cm^2 s$$

$$L = \int \mathcal{L}\, dt$$

defined so that the number of events is: $N_{events} = \sigma L$

parameters	Run I (10/92 - 3/96)
N_p (protons[antiprotons]/bunch)	2×10^{11} [6×10^{10}]
B (# bunches in the ring)	6
f_0 (frequency)	50 kHz (3.5 μs bunch spacing
σ^2 (beam "area")	3×10^{-5} cm^2
< $\mathcal{L}$ >	1.6×10^{31} cm^{-2} s^{-1}
beam momentum	900 GeV/c (1.8 TeV in cm)
L	100 pb^{-1}

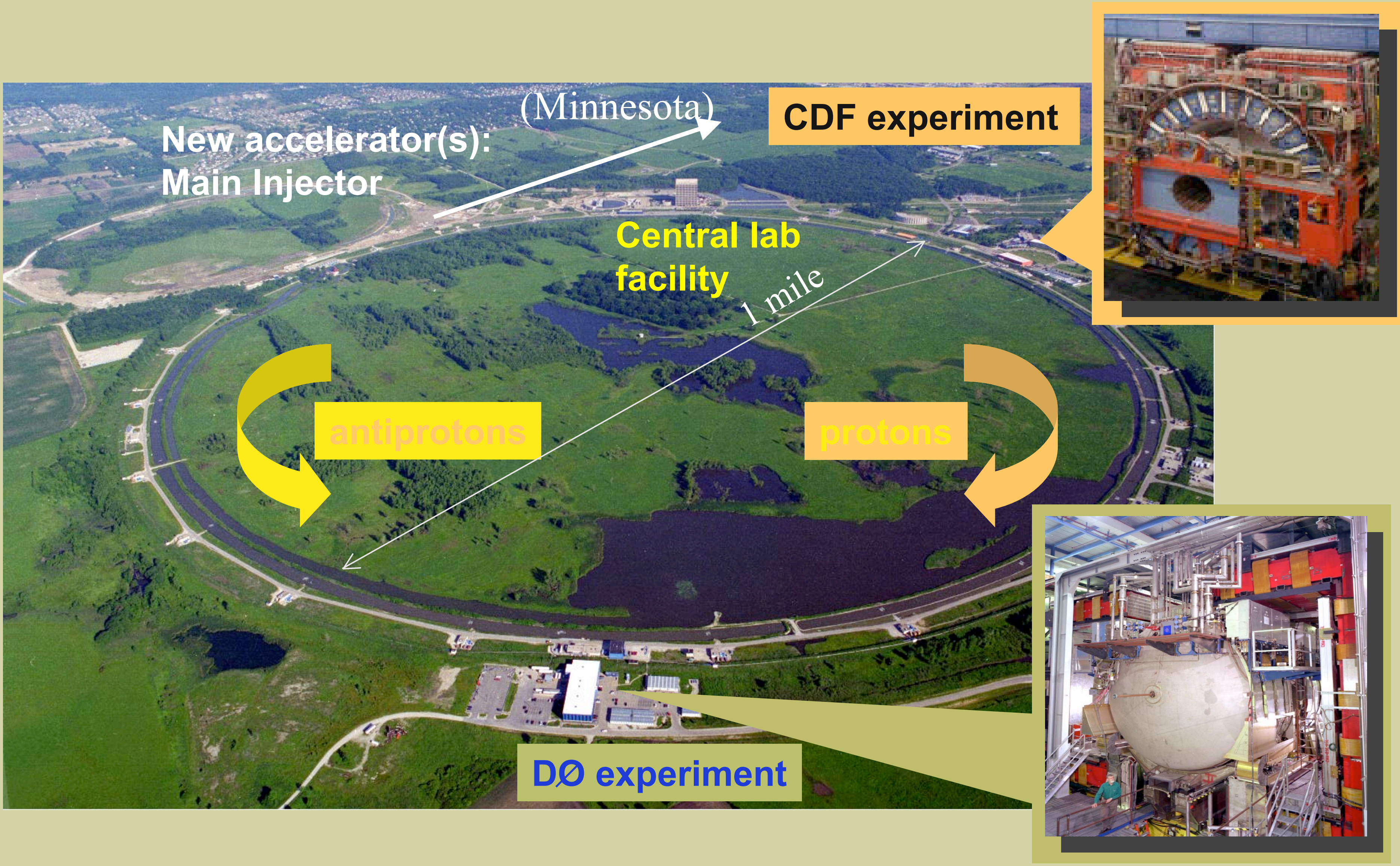
cross section benchmarks:

1 barn (b) = 10^{-24} cm^2

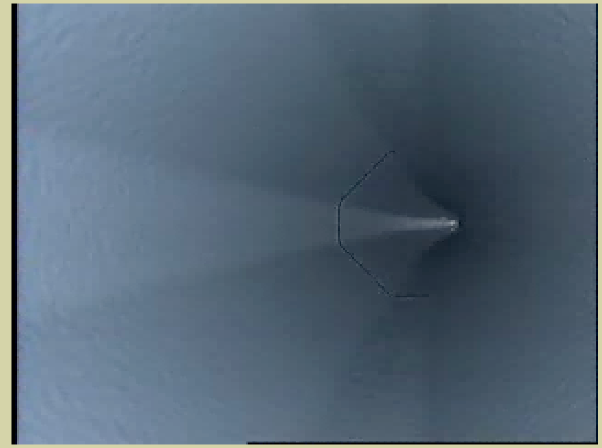
…so 1 pb = 10^{-12} b; 1 fb = 10^{-15} b

process	σ	evts, 100 pb^{-1}
σ_{total}	50 $m\,b$	10^{12}
W	20 nb	2×10^6
t-tbar	5 pb	500

Fermi National Accelerator Laboratory

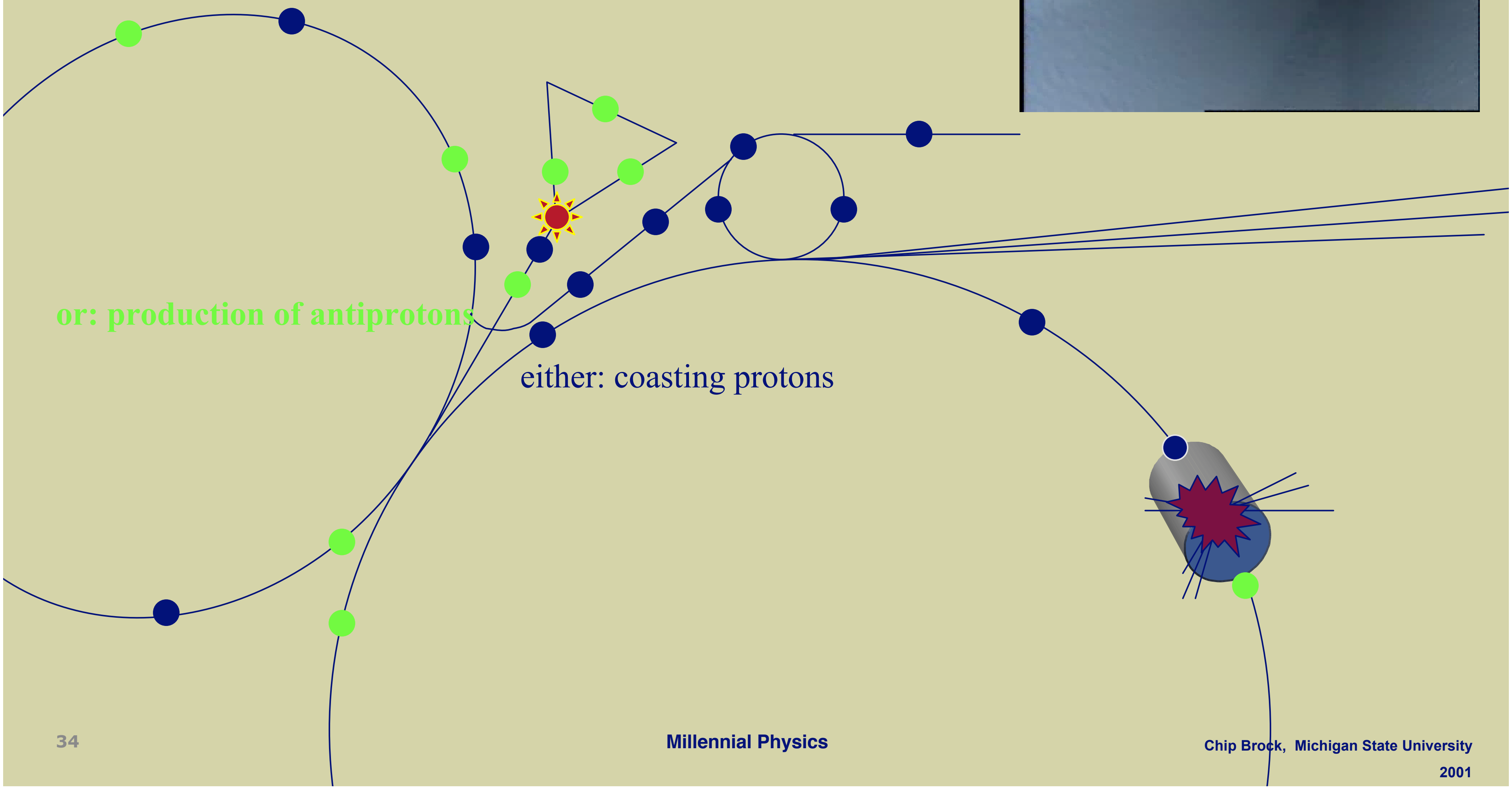


Accelerator Complex - *the time machine*



proton cycle

antiproton cycle



Accelerator performance in Run I with the 900 GeV/beam was staggering

- **Designed** for:

$1x10^{30}$ $s^{-1}cm^{-2}$;

- *actual*:

$\leq 1.6x10^{31}$ $s^{-1}cm^{-2}$

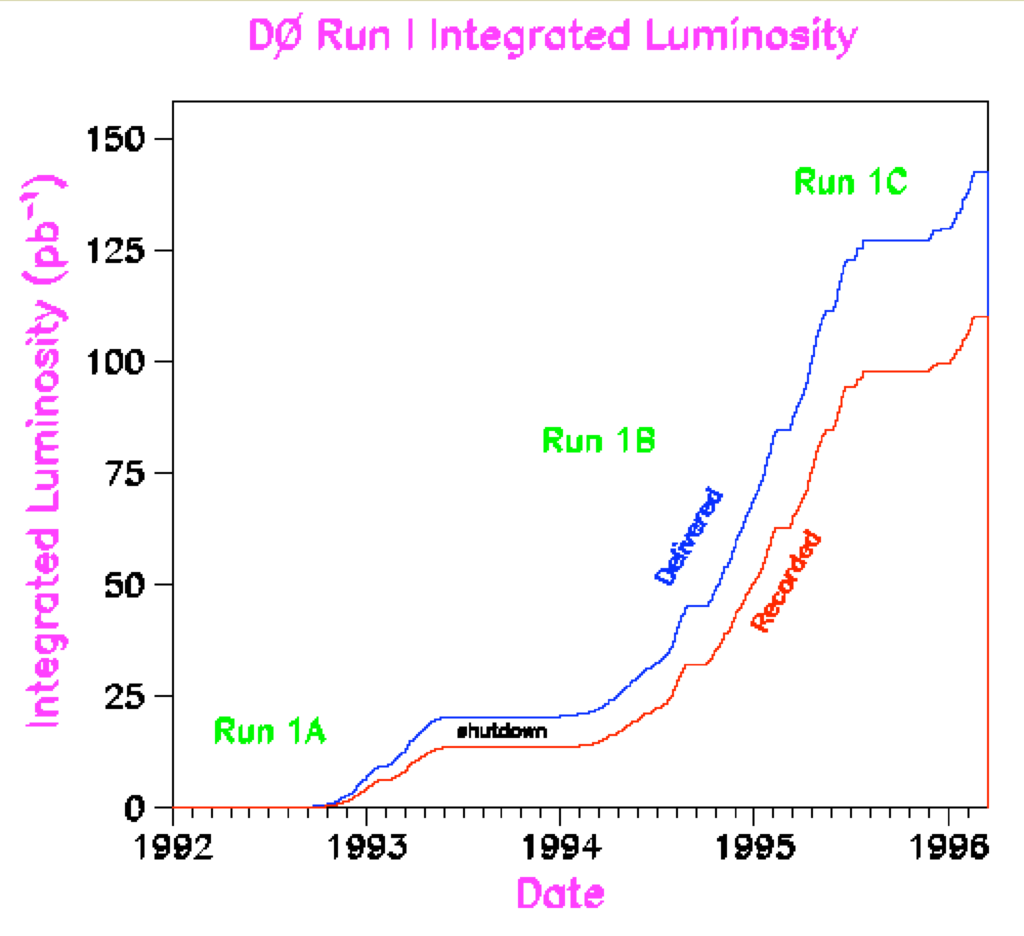
- **Designed** for:

$\int\mathcal{L}dt \sim 5pb^{-1}$;

- *actual*:

$\int\mathcal{L}dt \sim 110\ pb^{-1}$

- 900 GeV/beam; 6 bunches;
- 3.5 μs between bunches
- so, 1-3 int/crossing (important)



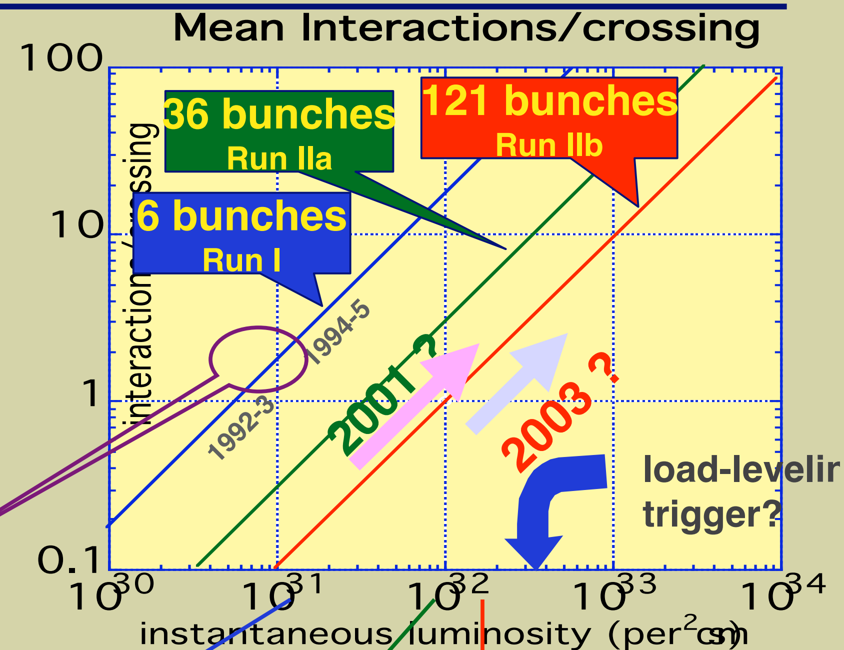
So – it is with some fear and trembling that we anticipate Run II! The Fermilab beams group always exceeds expectations…

Run 2 and beyond

more instantaneous luminosity means:

- more physics
- more overlapping collisions

must try to balance the load of simultaneous collisions due to high instantaneous luminosities by more bunches, tricks…



tough Run I conditions

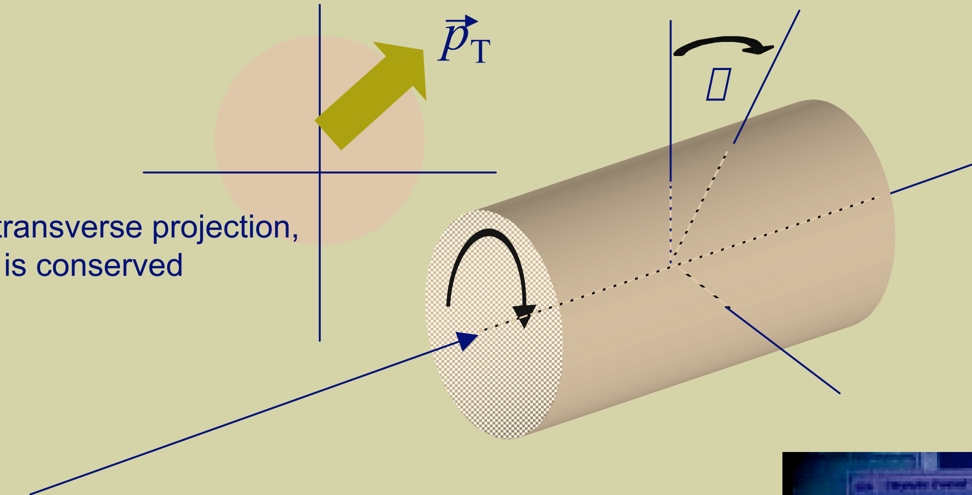
parameters	Run I (10/92 - 3/96)	Run IIa (3/01 - ?)	Run IIb
N_p (protons[antiprotons]/bunch)	2 x 10^{11} [6 x 10^{10}]	2.7 x 10^{11} [3 x 10^{11}]	2.7 x 10^{11} [3 x 10^{11}]
B (# bunches in the ring)	6	36	121
f_0 (frequency)	50 kHz (3.5μs bunch spacing)	50 kHz (396ns bunch spacing)	50 kHz (132ns bunch spacing)
σ^2 (beam "area")	3 x 10^{-5} cm^2	3 x 10^{-5} cm^2	3 x 10^{-5} cm^2
< $\mathcal{L}$ >	**1.6 x 10^{31} cm^{-2} s^{-1}**	**0.9 x 10^{32} cm^{-2} s^{-1}**	**1.6 x 10^{32} cm^{-2} s^{-1}**
beam momentum	900 GeV/c (1.8 TeV in com)	1000 GeV/c (2.0 TeV in com)	1000 GeV/c (2.0 TeV in com)
L	100 pb^{-1}	7 fb^{-1}	20-25 fb^{-1} ?

Tevatron detectors

measured in units of small suburban houses

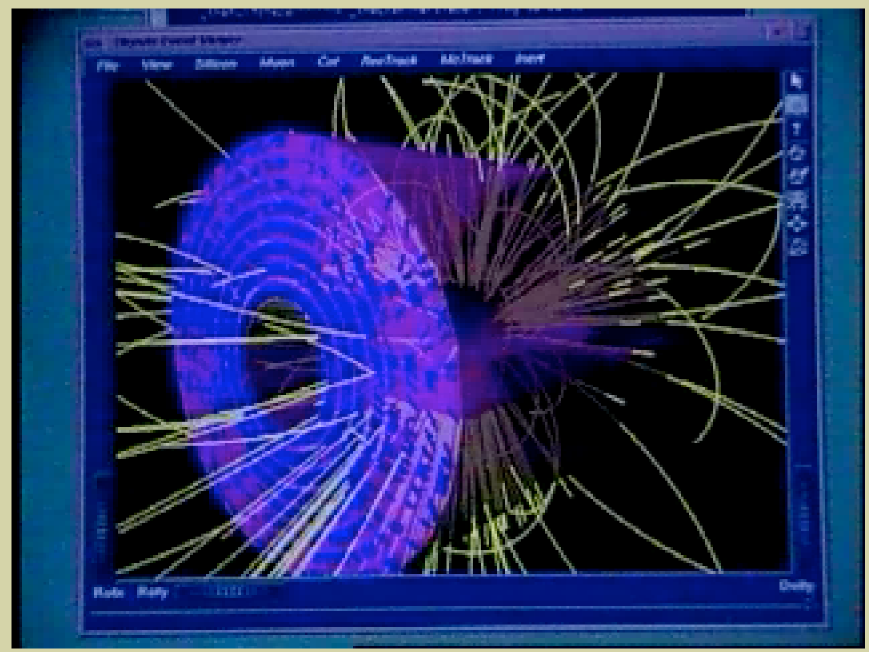
glossary and geometry

typically built around a cylindrical geometry



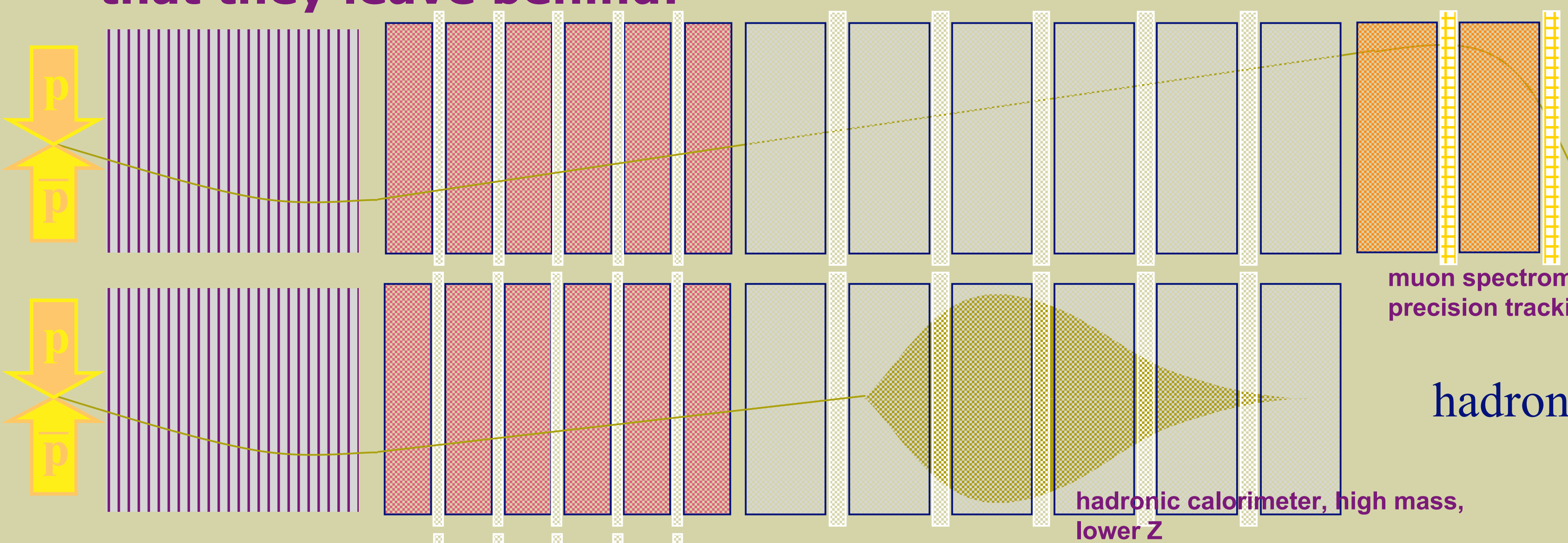
rely on the transverse projection, momentum is conserved

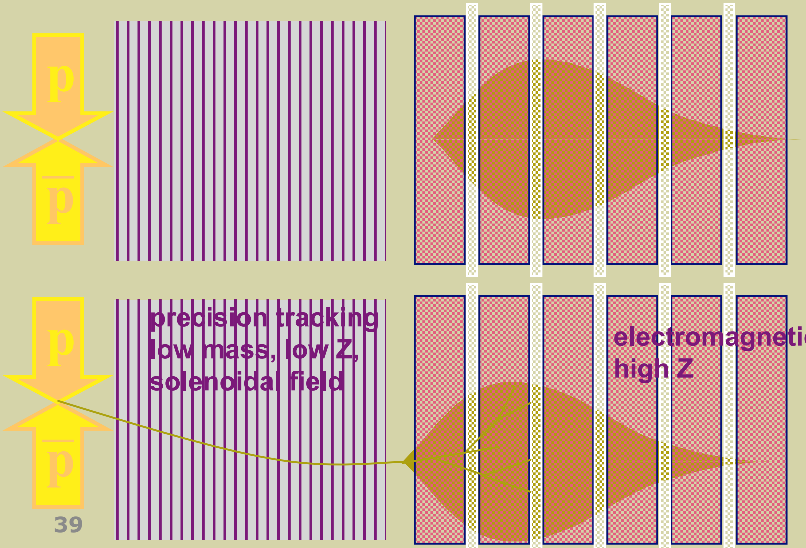
angle measurement is in terms of "pseudorapidity" $\eta = \ln(\tan(\theta/2))$, additive under Lorentz boosts



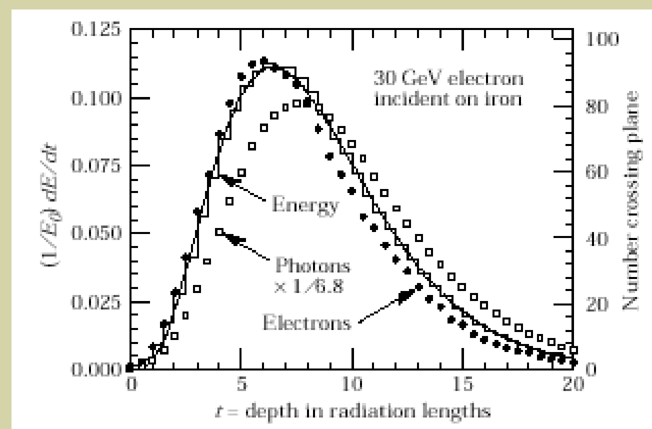
how do we detect particles?

– by the electromagnetic and strong interaction fingerprints that they leave behind:

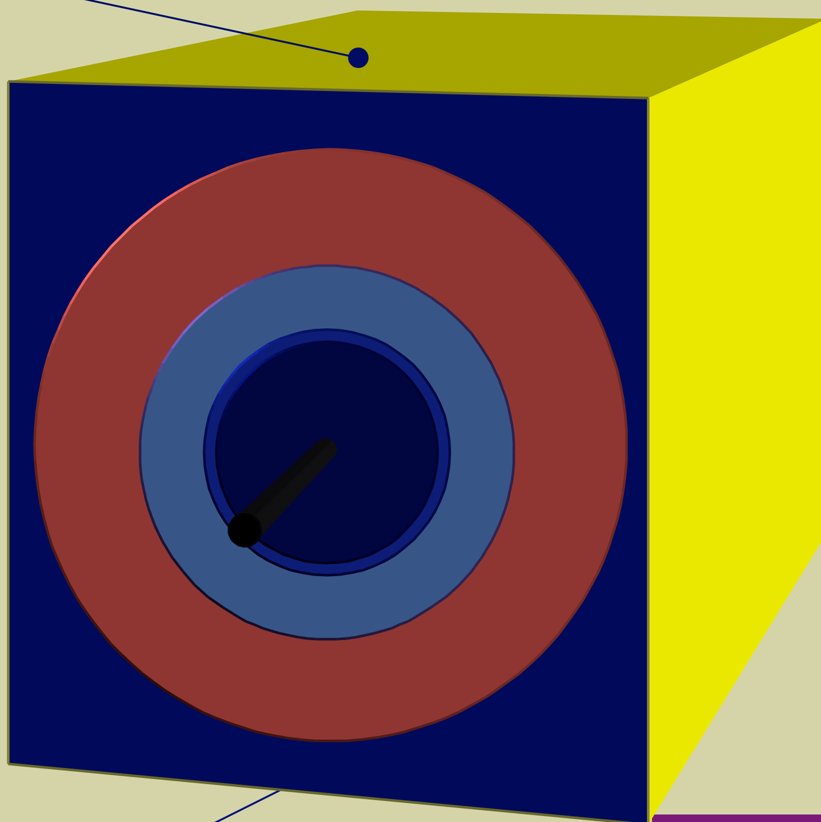




showers

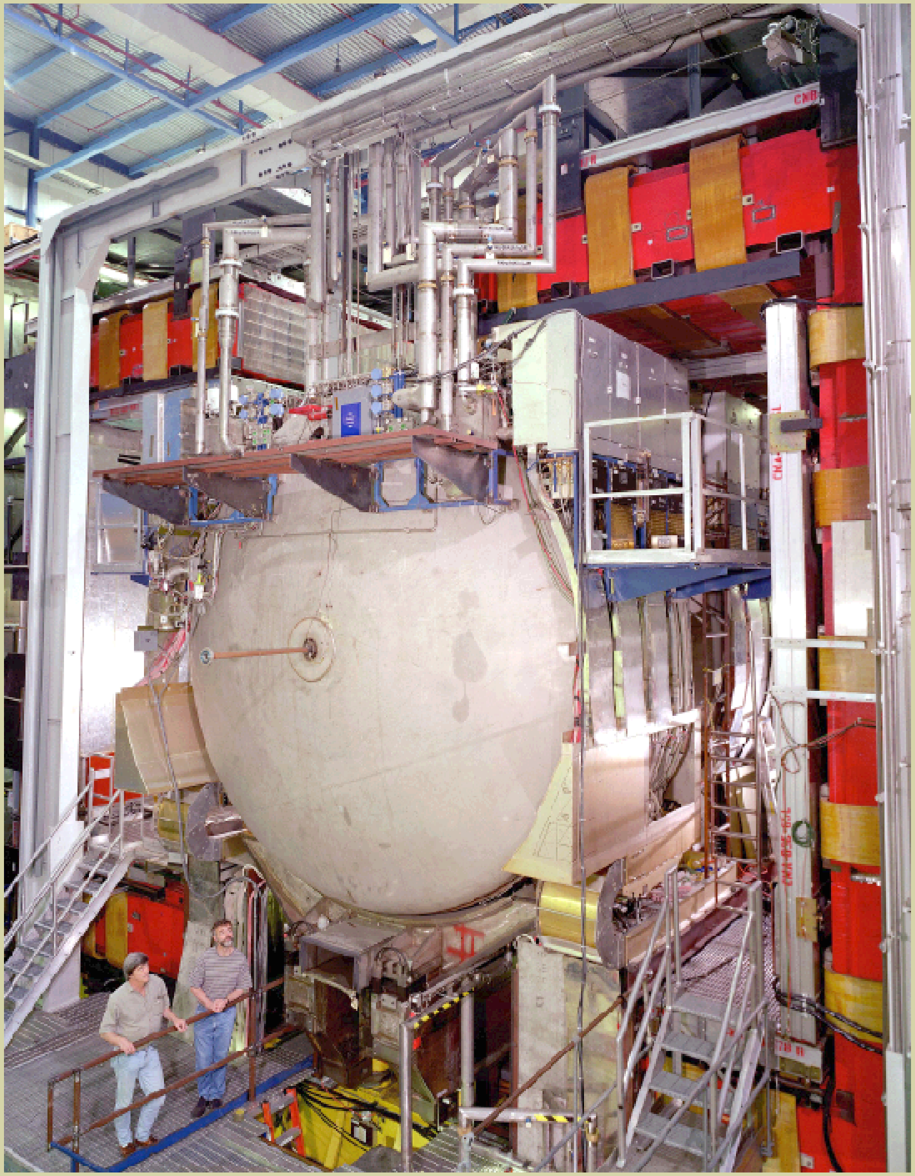


Generic colliding beam detector-*the vehicles*

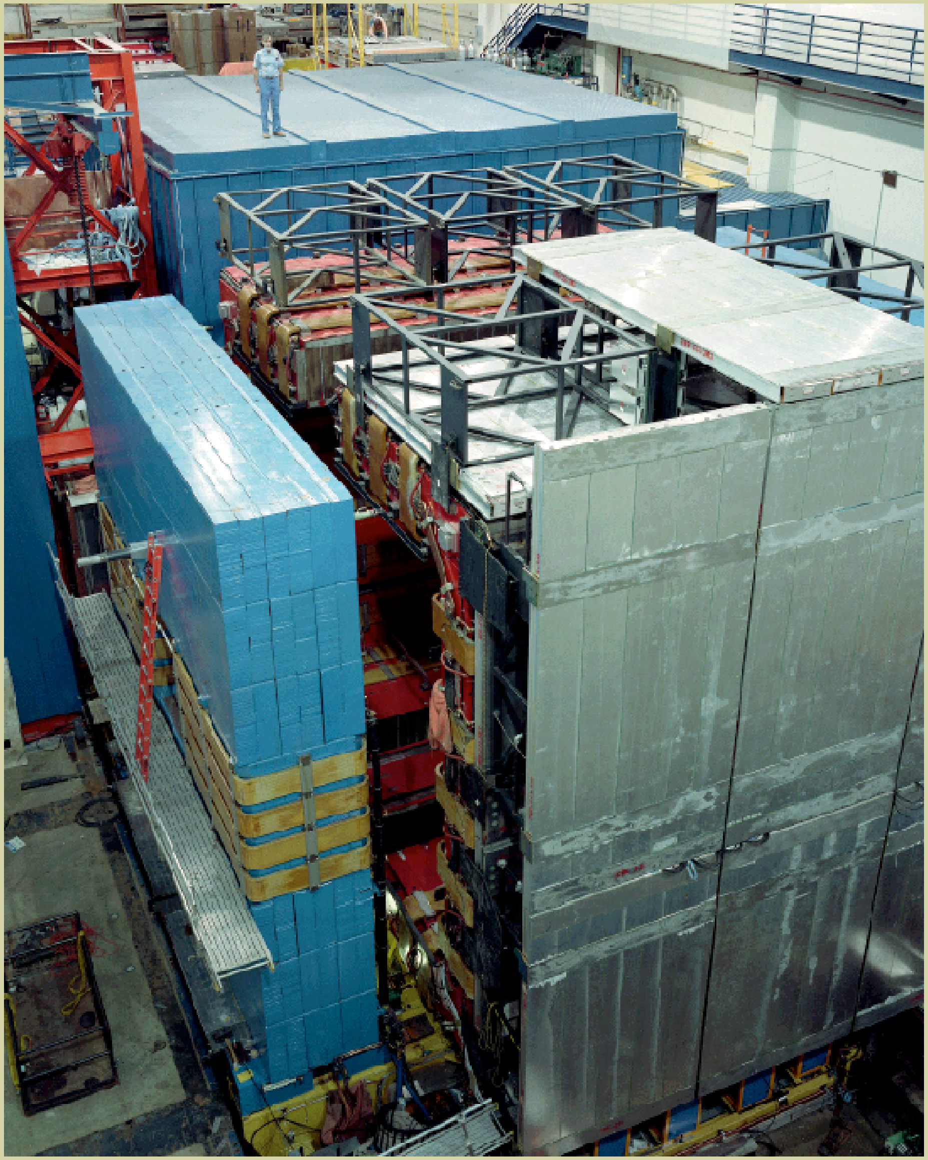


DØ: 74 institutions, from 17 countries

...inside



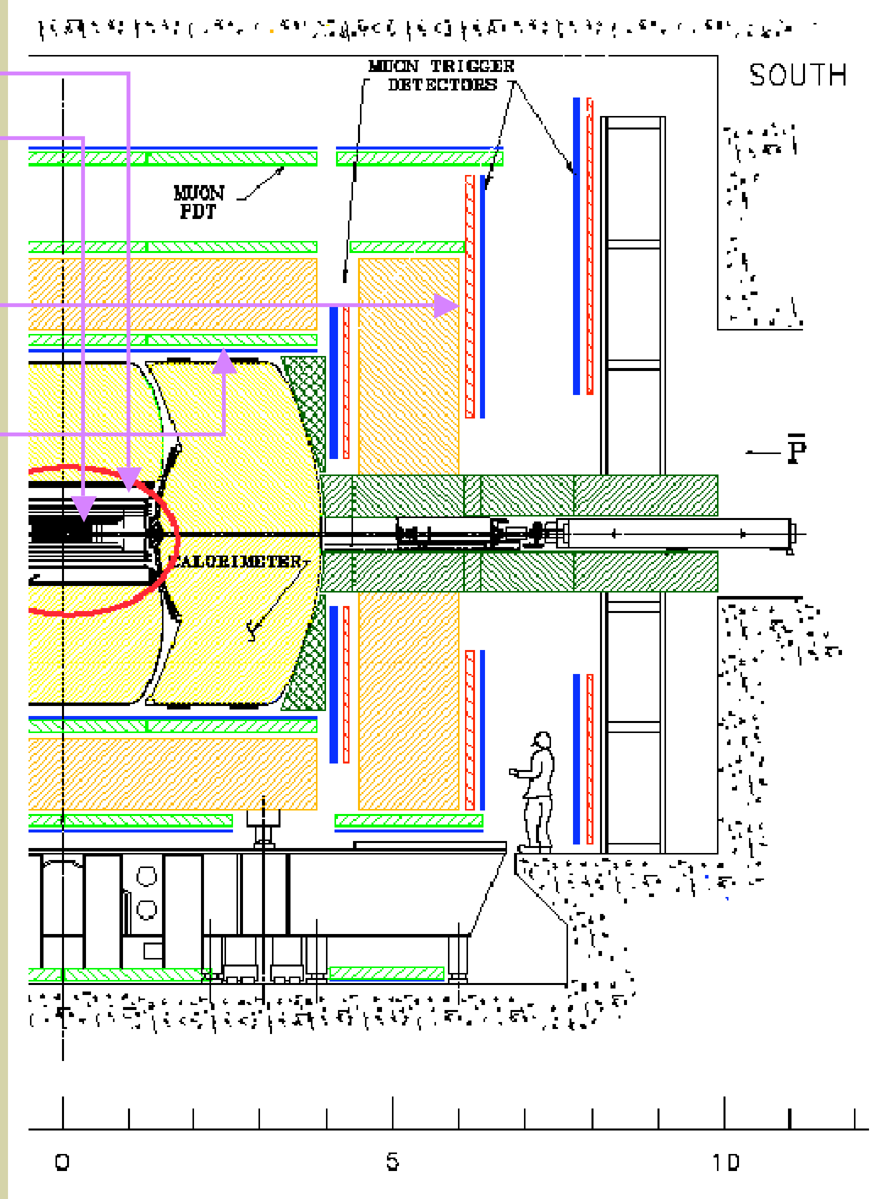
the DØ detector



DØ detector, Y1.999-2.003k

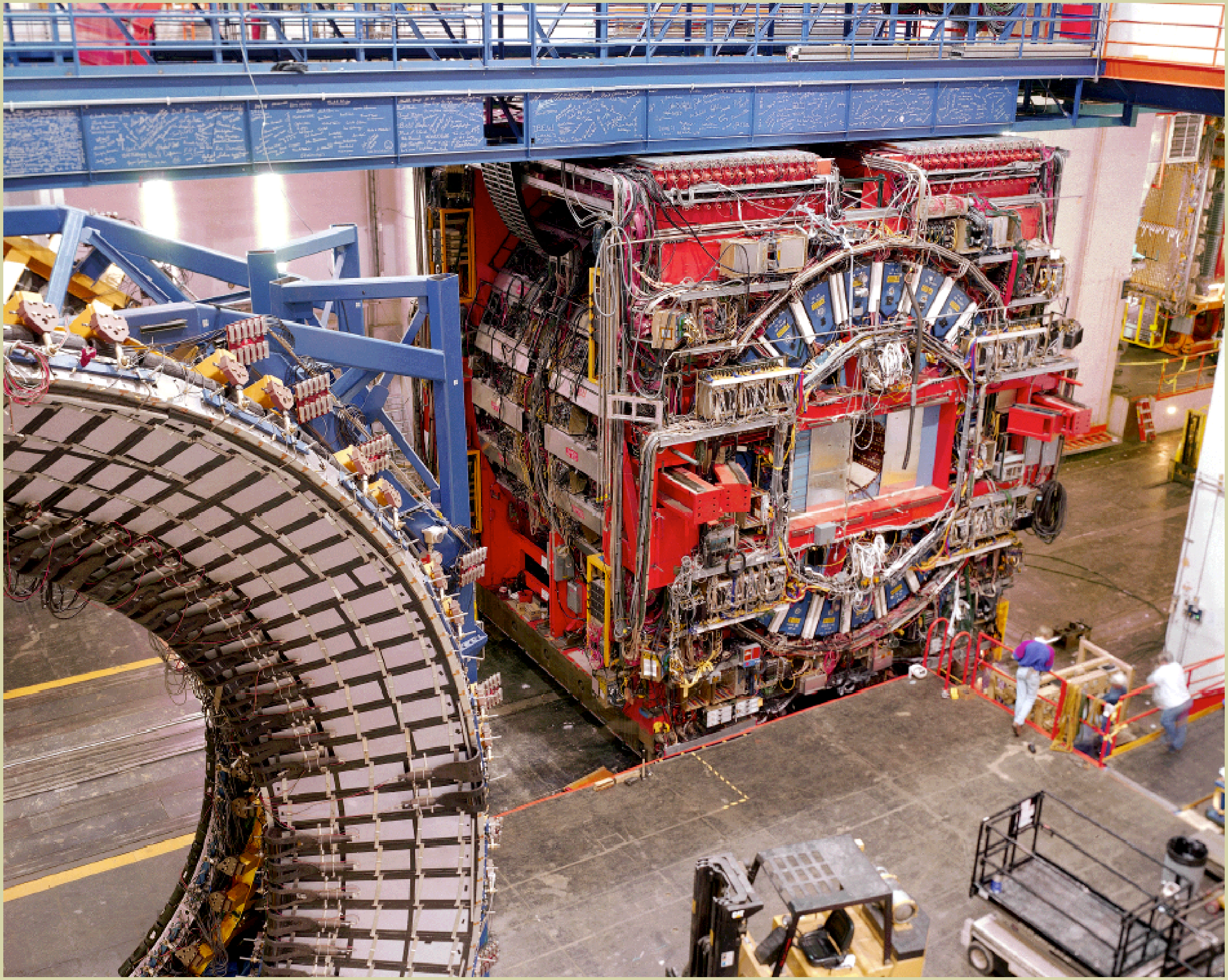
- **magent:** **2T, 60cm x 2.8m superconducting solenoid**
- **tracking:** **$\delta p_T/p_T \approx 5\%$ for p_T=10 GeV/c muons, $\eta < \sim 1.8$**
  - 1) Si: 4 layer barrels (dbl/sgl) & dbl-sided disks
  - ($|\eta| \leq 3$), 0.8M ch.
  - 2) SciFi: 8 layers ribbon dblets, 77k ch. w/VLPC readout
  - 3) preshower: central ($\eta < \sim 1.5$), 6k ch./fwd, 16k ch.
- **muons:** **forward and central**
  - 1) central: faster gas; deadtimeless; bottom scint.; ϕtrg scint
  - 2) forward: timing/trk-matching pixel cntrs; 3 layer prop min-drift
- **trigger:** **significant upgrade**

  1) 10kHz L1; 1KHz 100μs L2; 100ms 50 Hz L3



- all very ambitious upgrades

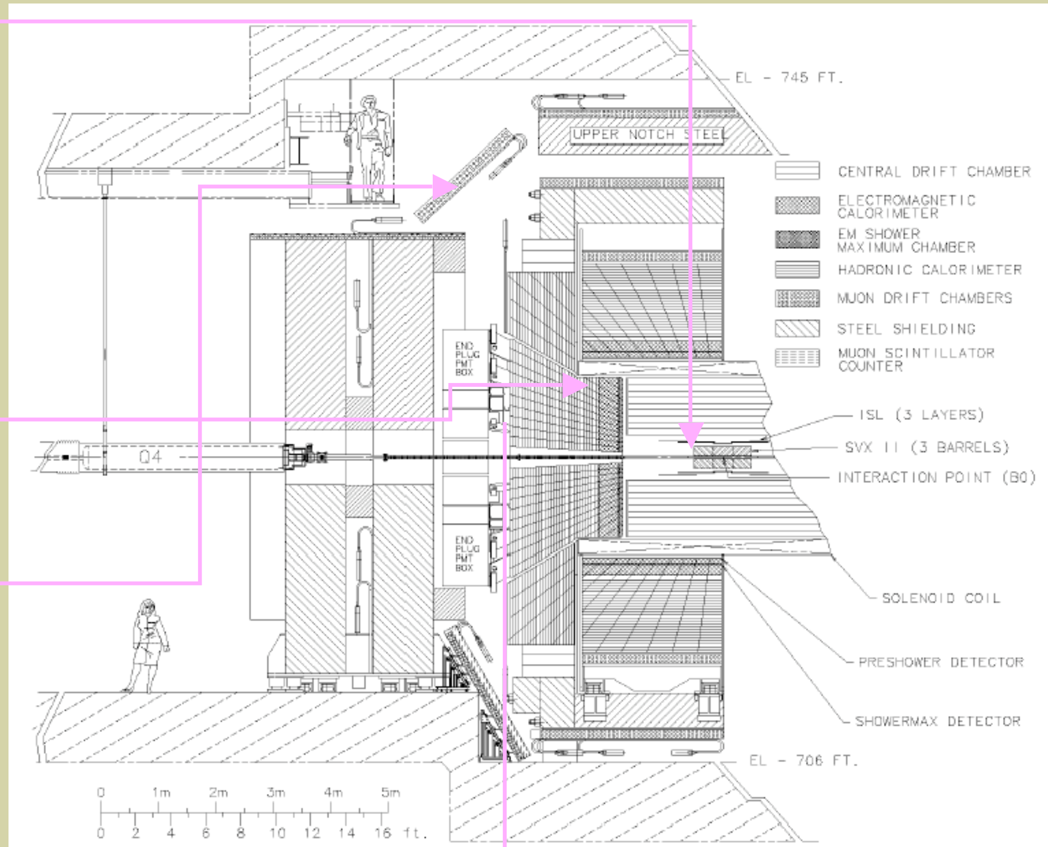
cdf detector



CDF detector, Y1.999-2.003k

- **tracking: significant upgrade**
  - 1) Si: 5 layer, dbl sided strips
  - ($|\eta| \le$ ~2.5); ISL strips
  - ($1 \le |\eta| \le 2$)
  - 2) outer: smaller, open-cell COT drift chmbr. 180μm
  - 3) Si vertex trigger (SVT)
- **calorimeter: significant upgrade, forward**
  - 1) endplug: ($1.1 \le |\eta| \le 3.6$), scint. tiles w/ WLS fiber readout
- **muons: moderate upgrade**
  - 1) intermediate muon system
- **trigger: significant upgrade**

1) 50kHz L1; 0.3KHz 20μs L2; 50 Hz L3



tomorrow

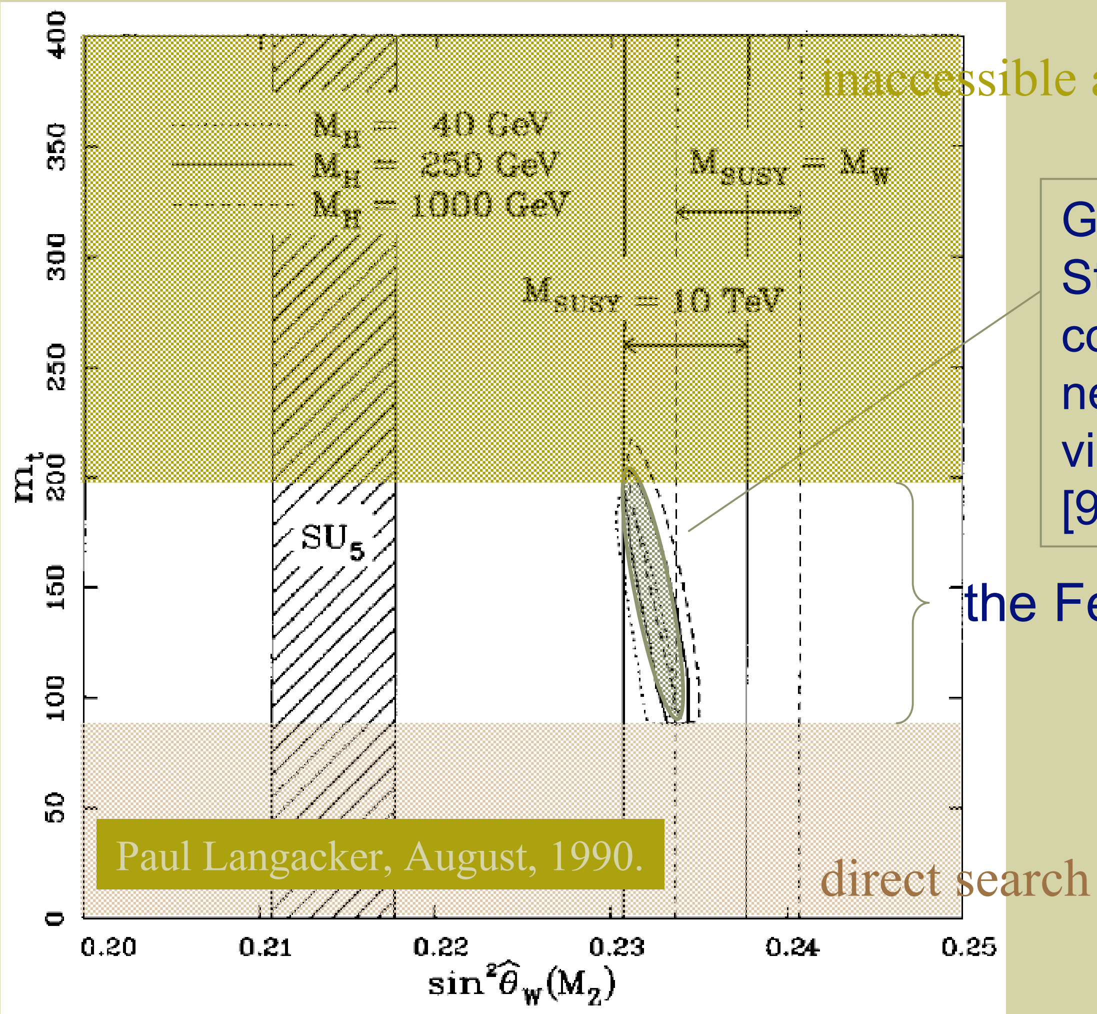
physics results from Run 1 and prospects for physics in Run 2

fermilab's back yard

back

in 1990:

the Standard Model had set the trap for the top quark to have a mass measurable at Fermilab:



Global fit to the field theory of the Standard Model involving: comparison of Z pole parameters, neutrino scattering, atomic parity violation, electron scattering [90% CL]

The field theory worked… as predicted.

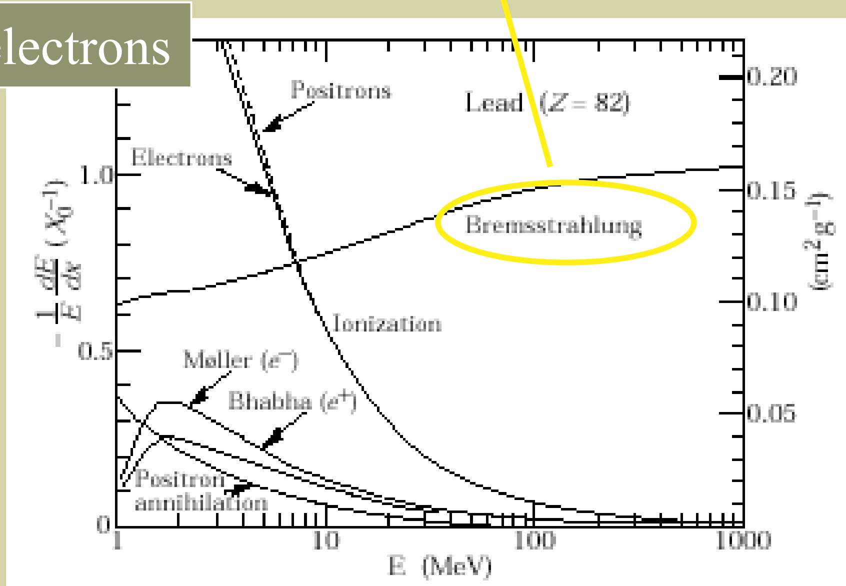
back

electrons and photons shower

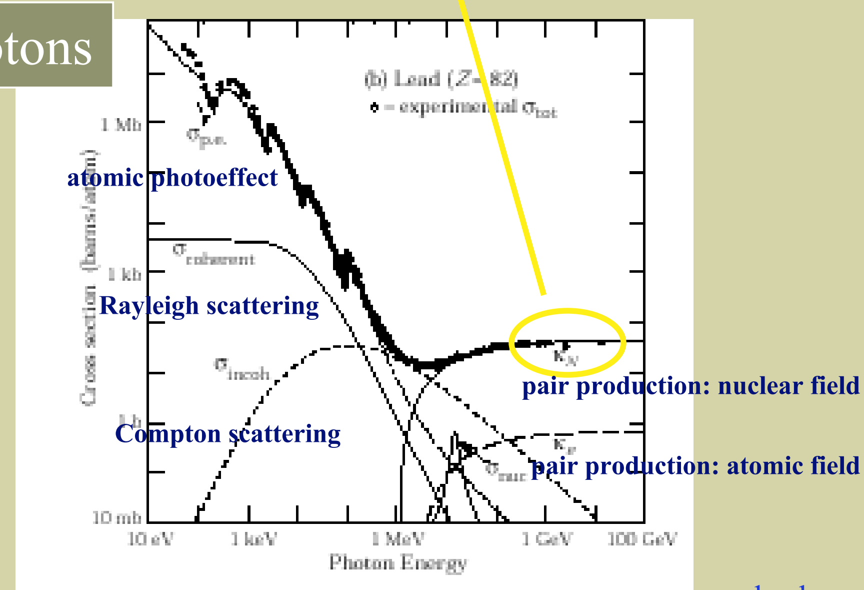
electrons preferentially radiate in the presence of a charged nucleus at high energies

photons preferentially pair produce in the presence of a charged nucleus at high energies

electrons



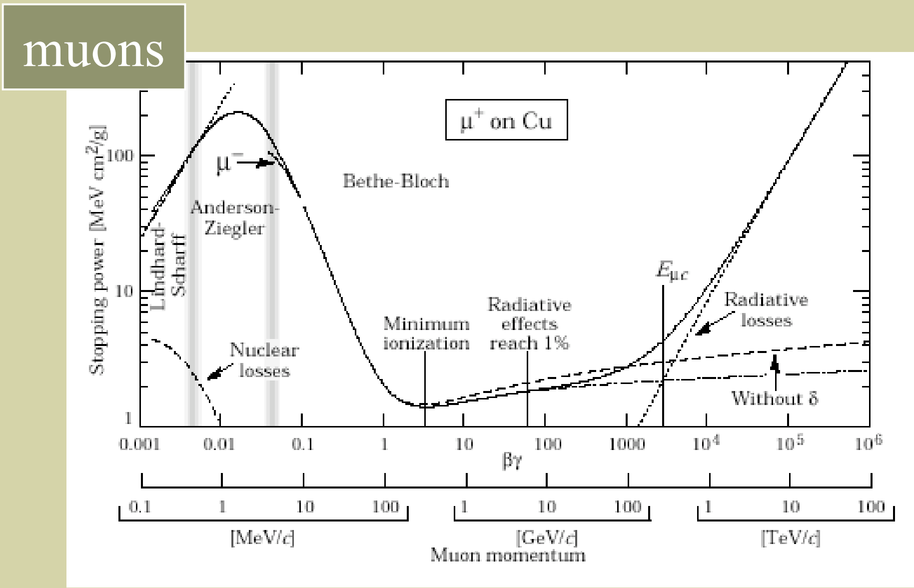
photons



back

muons keep going...

muons simply minimally ionize according to the Bethe-Bloch formula



back

What do we think we know? - *The Standard Model on one slide:*

There are 4 fundamental forces among matter, radiation, and a fundamental scalar

- **Characterized by their interaction strengths**
- **Coupled to specific "charges" carried by matter/electrons**

Electrons come in 3 kinds ("leptons")

- ***e, □, □*- ordered by their masses**

Matter is composite to the scale of 10^{-20}cm

- **Quarks: *u, d, s, c, b, t* - ordered by their masses**

Radiation comes in 4 related forms

- **Spin 1 carriers, one for each of the fundamental interactions: electromagnetism (□ & *Z*); electroweak (*W* & *Z*), strong (*g*)**

Broken Symmetry is a fundamental concept and driving theme

The description: "*The Standard Model*" (SM)

We stole a good idea:

Critical phenomena

- A change of symmetry known since Landau as indicating a phase change
- In the mean field approximation, a model of 2nd order PT:
  - **Near the critical point, the free energy is modified – order parameter idea unifies diverse critical phenomena descriptions**
  - **A quasiparticle model makes a field theoretic description meaningful**
    - **Results in a Bose excitation, with a dispersion relation in which $E \rightarrow 0$ as $k \rightarrow 0$ (Goldstone Theorem)**

      Relativistically, this means "massless"

Anderson-Higgs phenomenon

- A loophole - suggesting the breaking of a continuous symmetry, in the presence of a long-range force results in a Bose excitation in which $E \rightarrow$ const as $k \rightarrow 0$ (*"massive"*)

Carry this into relativistic field theories:

Anderson-"Higgs Boson"

- In BCS superconductivity, the Cooper pairs are the excitation resulting from the broken (gauge) symmetry associated with passage below the critical temperature
  - **They are "everywhere" in the ground state - macroscopic**
  - **They are massive (the gap)**
  - **They set up supercurrents which repel an external magnetic field**
    - **Meisner effect…mathematically, a skin depth is the same as a relativistic mass associated with the magnetic field**
    - **The Cooper pairs, give a mass to the photon in the ground state of a superconductor**

"our" Higgs boson has the same characteristics

- It "gives" mass to the fields and matter
- Appears in the SM associated with a scale of ~ 246 GeV

What are the major problems?

A single model of Nature *- a very unusual situation*

- Which now works too well:
  - **too many parameters, too much arranged by hand**
- But it is an intellectual and experimental achievement of millennial proportions - taught us that the gauge phenomenon and language of phase transitions are universal

What is the character of the broken symmetries?

- A schizophrenic notion - at once Reductionist and yet linked with Complexity
- What is the major Gauge Group?

How granular are the “fundamental” entities?

- Is there additional substructure?

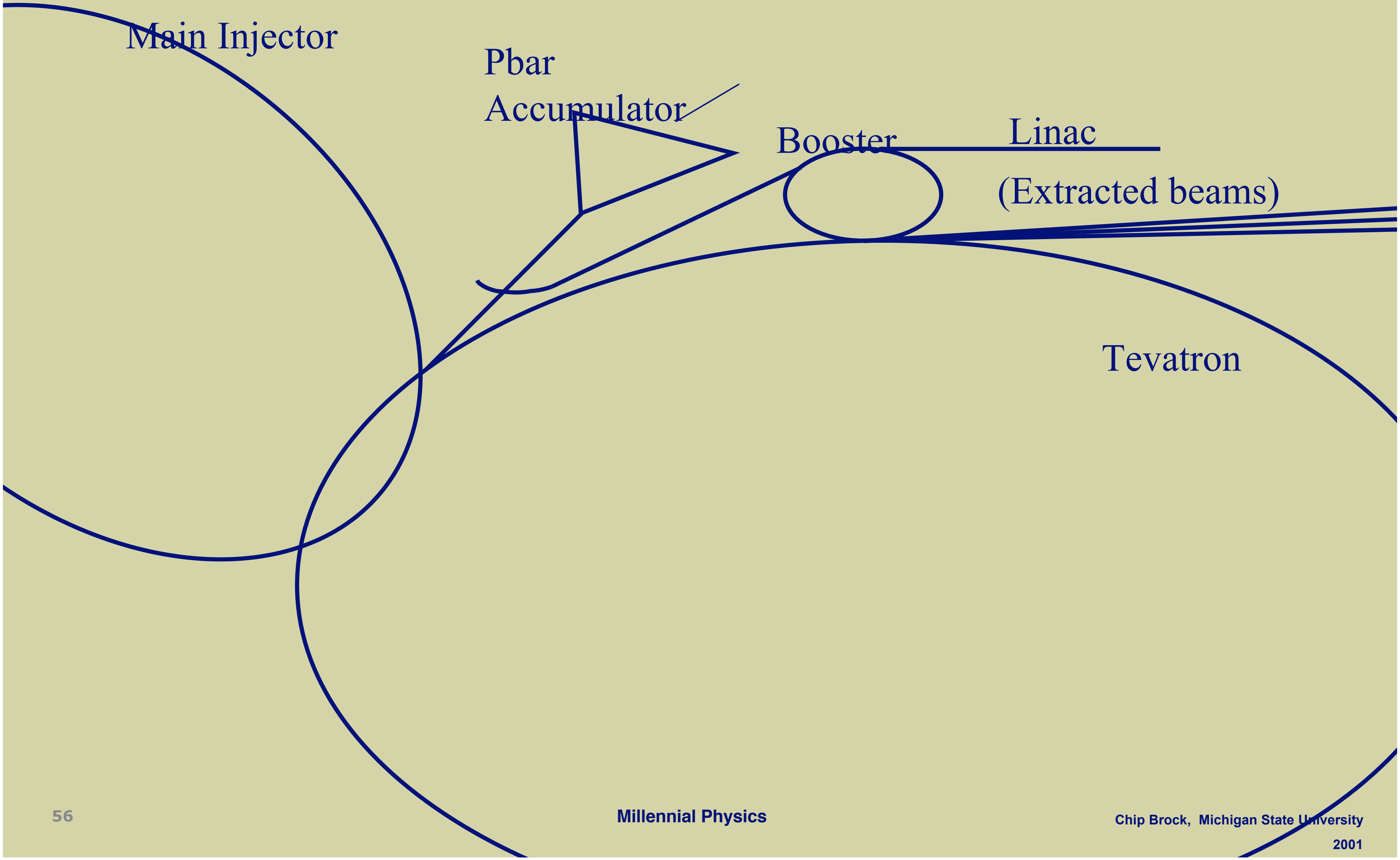
How do fundamental quanta acquire mass?

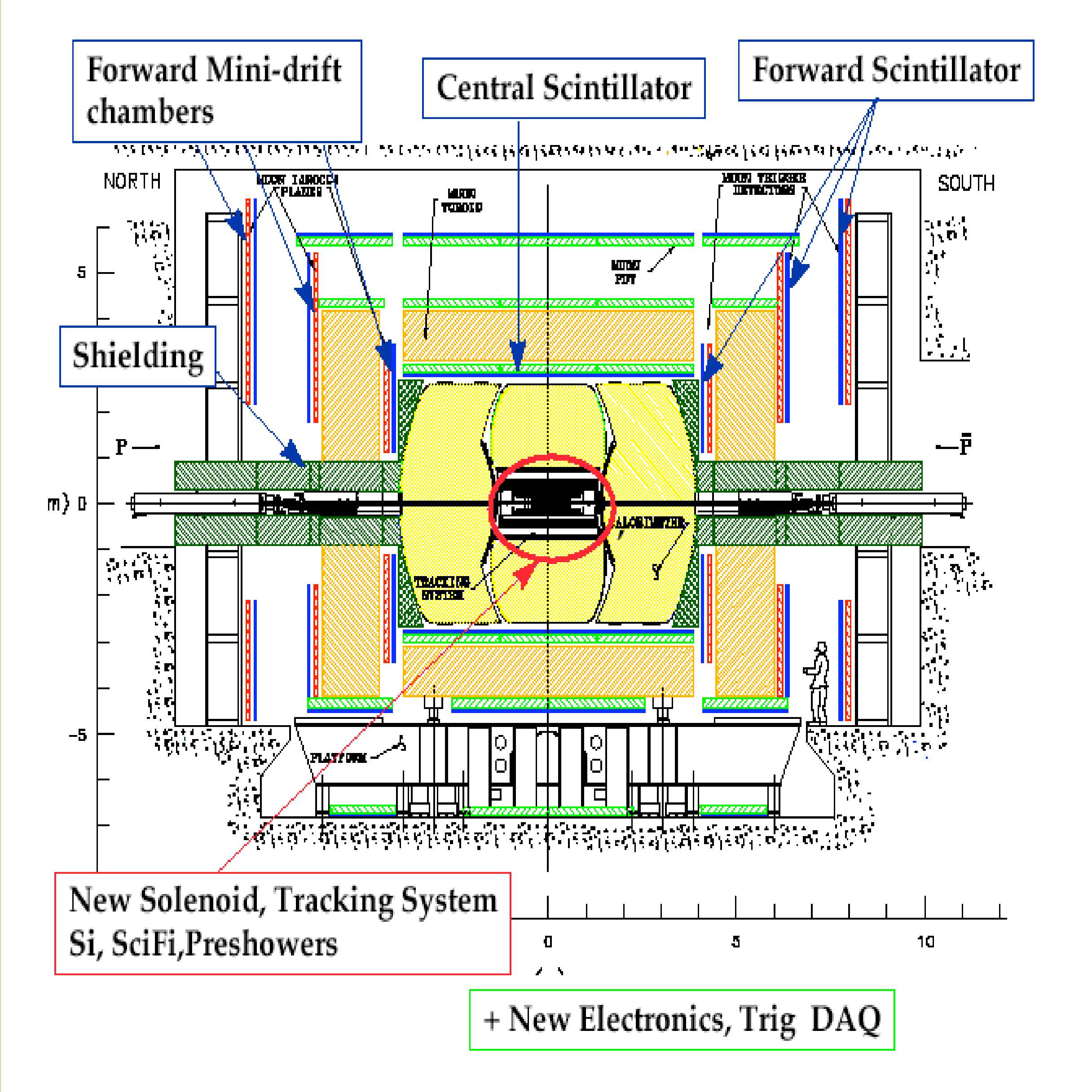
Why is there Matter and not AntiMatter?

Are “particles” actually stringy?

Accelerator Complex - *the time machine*

A mixture of future technologies




Forward Mini-drift chambers
Central Scintillator
Forward Scintillator
Shielding
NORTH
SOUTH
New Solenoid, Tracking System
Si, SciFi,Preshowers
+ New Electronics, Trig DAQ