





## DISCOVERIES AT PARTICLE COLLIDERS

- ★ ROLE OF ACCELERATORS IN PARTICLE PHYSICS
- ★ DISCOVERIES VIA ENERGY & LUMINOSITY
- ★ FOCUS ON THE TEVATRON & LHC
- ★ OUTLOOK

JACOBO KONIGSBERG, U. FLORIDA

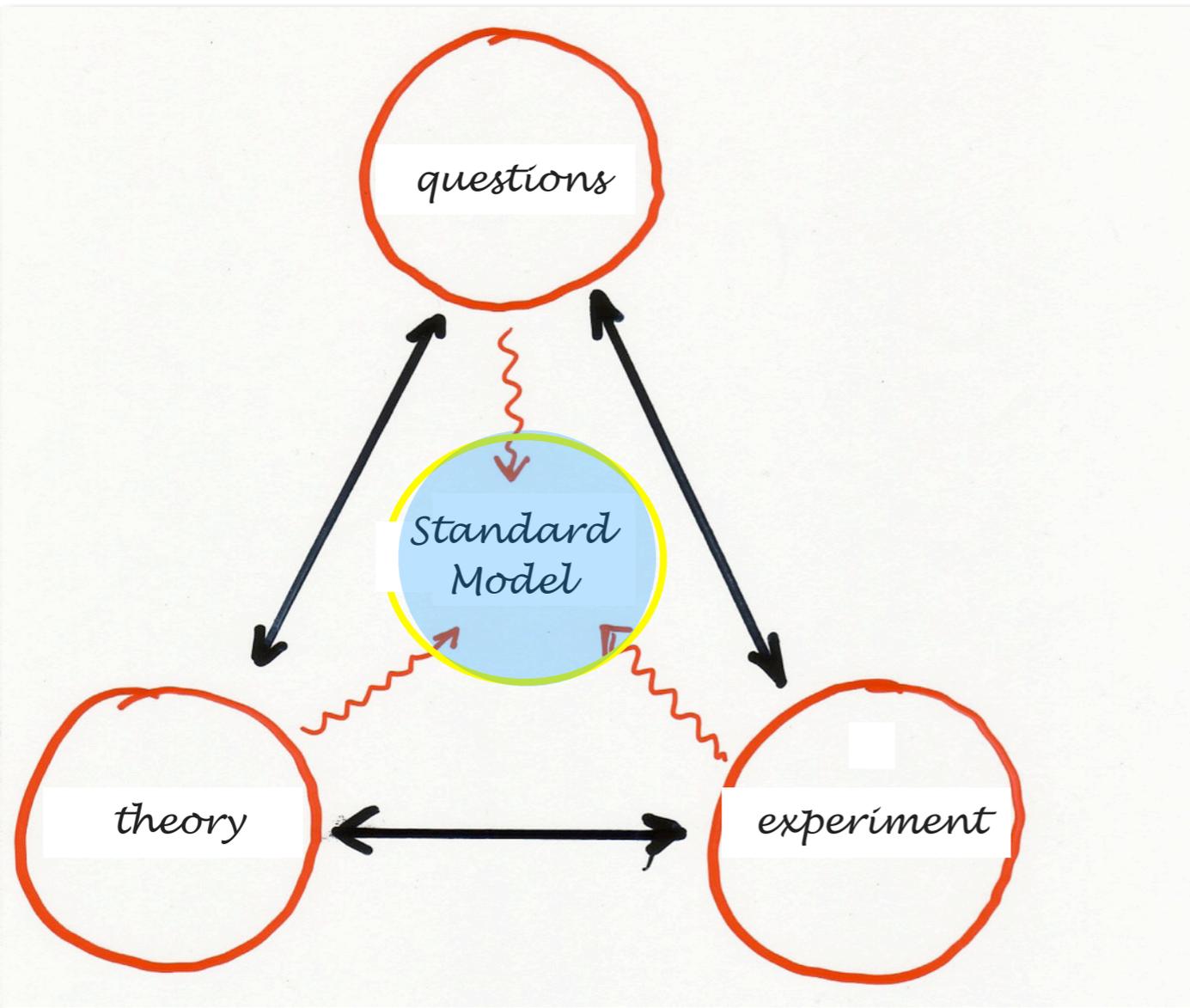
# What we've dared ask...

...and attempted to answer

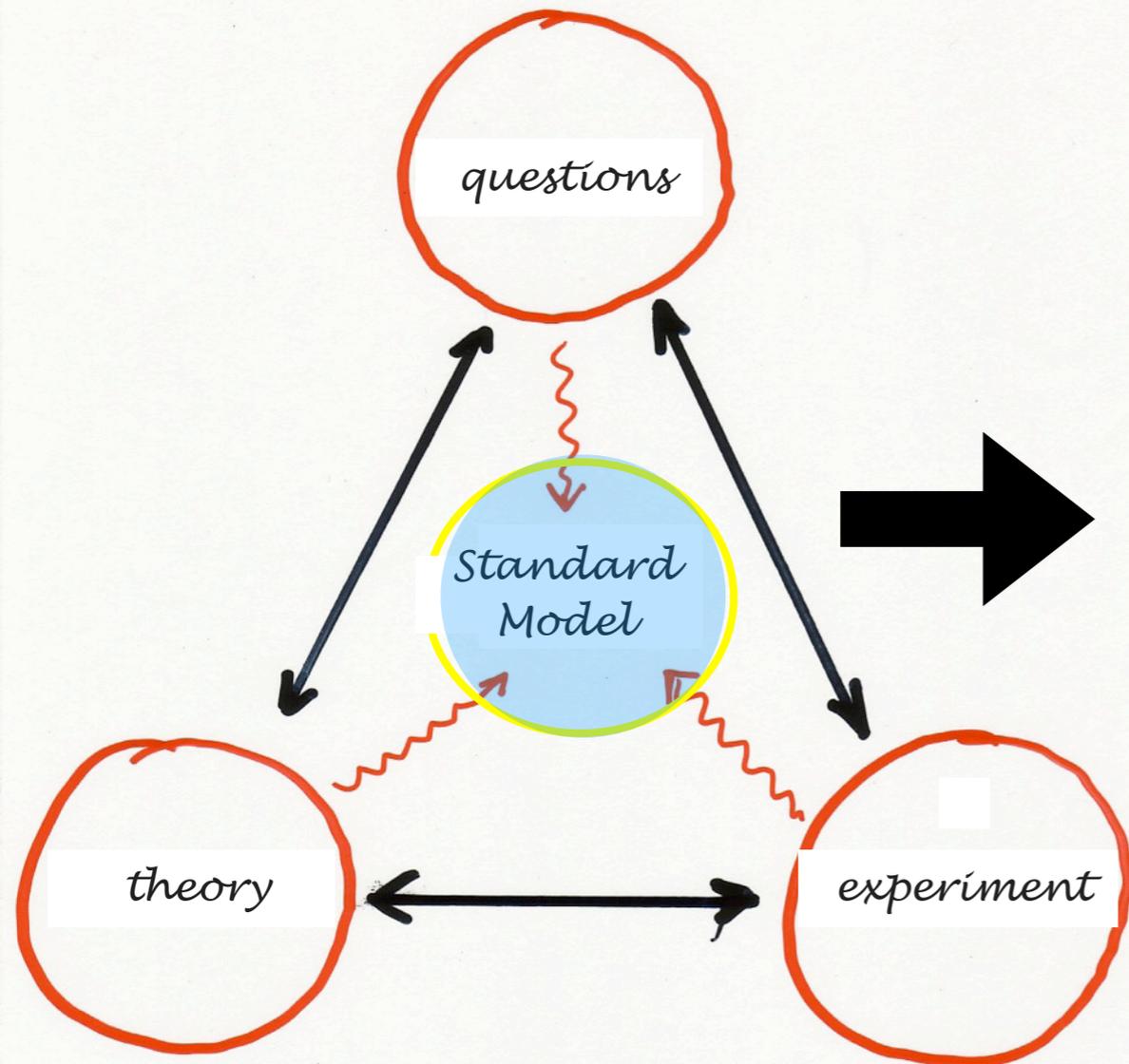


- How does Nature behave at its most fundamental level ?
- What are the elementary building blocks of all matter ?
- How do they interact with each other ?
- How is this connected to the evolution of the Universe ?
- Can all this be described simply ?

# Some remarkable answers



# Some remarkable answers



## ELEMENTARY PARTICLES

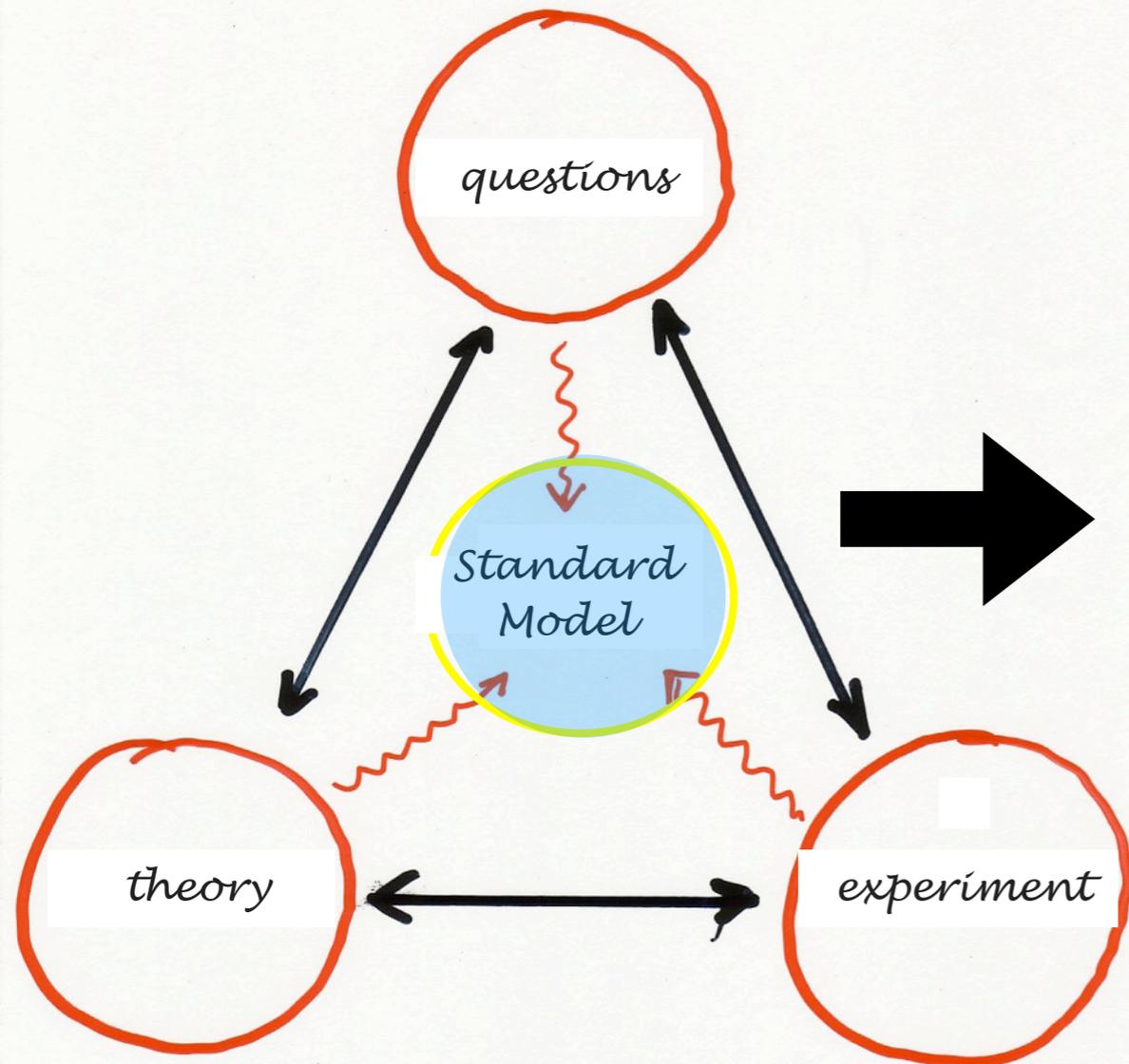
|         |                              |                            |                            |                    |
|---------|------------------------------|----------------------------|----------------------------|--------------------|
| Leptons | $u$<br>up                    | $c$<br>charm               | $t$<br>top                 | $\gamma$<br>photon |
|         | $d$<br>down                  | $s$<br>strange             | $b$<br>bottom              | $g$<br>gluon       |
|         | $\nu_e$<br>electron neutrino | $\nu_\mu$<br>muon neutrino | $\nu_\tau$<br>tau neutrino | $Z$<br>Z boson     |
|         | $e$<br>electron              | $\mu$<br>muon              | $\tau$<br>tau              | $W$<br>W boson     |
|         | I                            | II                         | III                        |                    |

Three Generations of Matter

Force Carriers

anti-particles too !

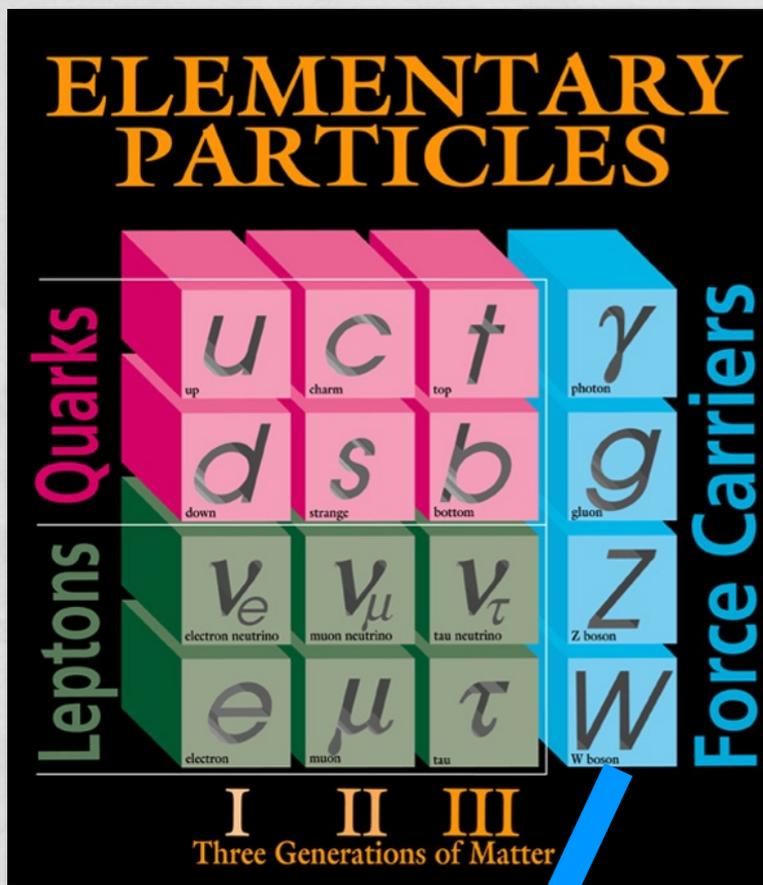
# Some remarkable answers



Discovered in:

- Radioactivity
- Cosmic Rays
- Accelerators

# Fundamental Interactions (forces)



### Strong

**Gluons (8)**

**Quarks**

**Mesons**  
**Baryons**

**Nuclei**

### Electromagnetic

**Photon**

**Charged particles**

**Atoms**  
**Light**  
**Chemistry**  
**Electronics**

### Gravitational

**Graviton ?**

**particles w/ mass**

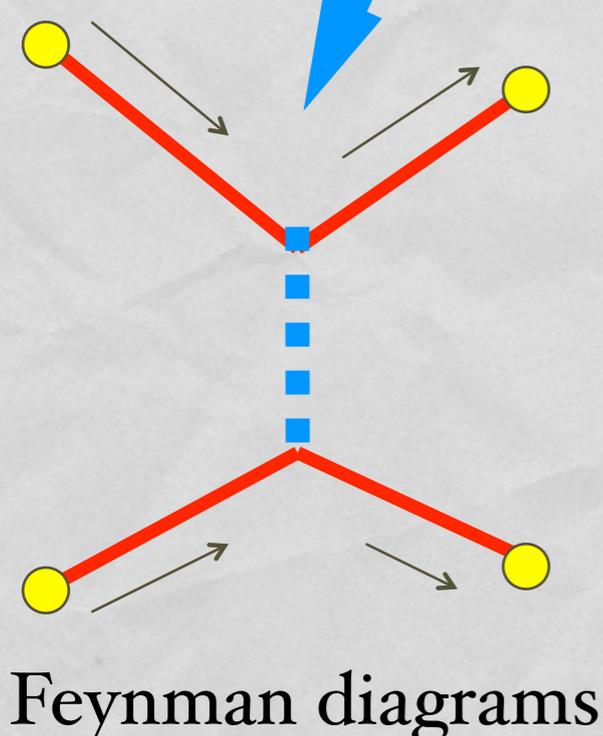
**Solar system**  
**Galaxies**  
**Black holes**

### Weak

**Bosons (W,Z)**

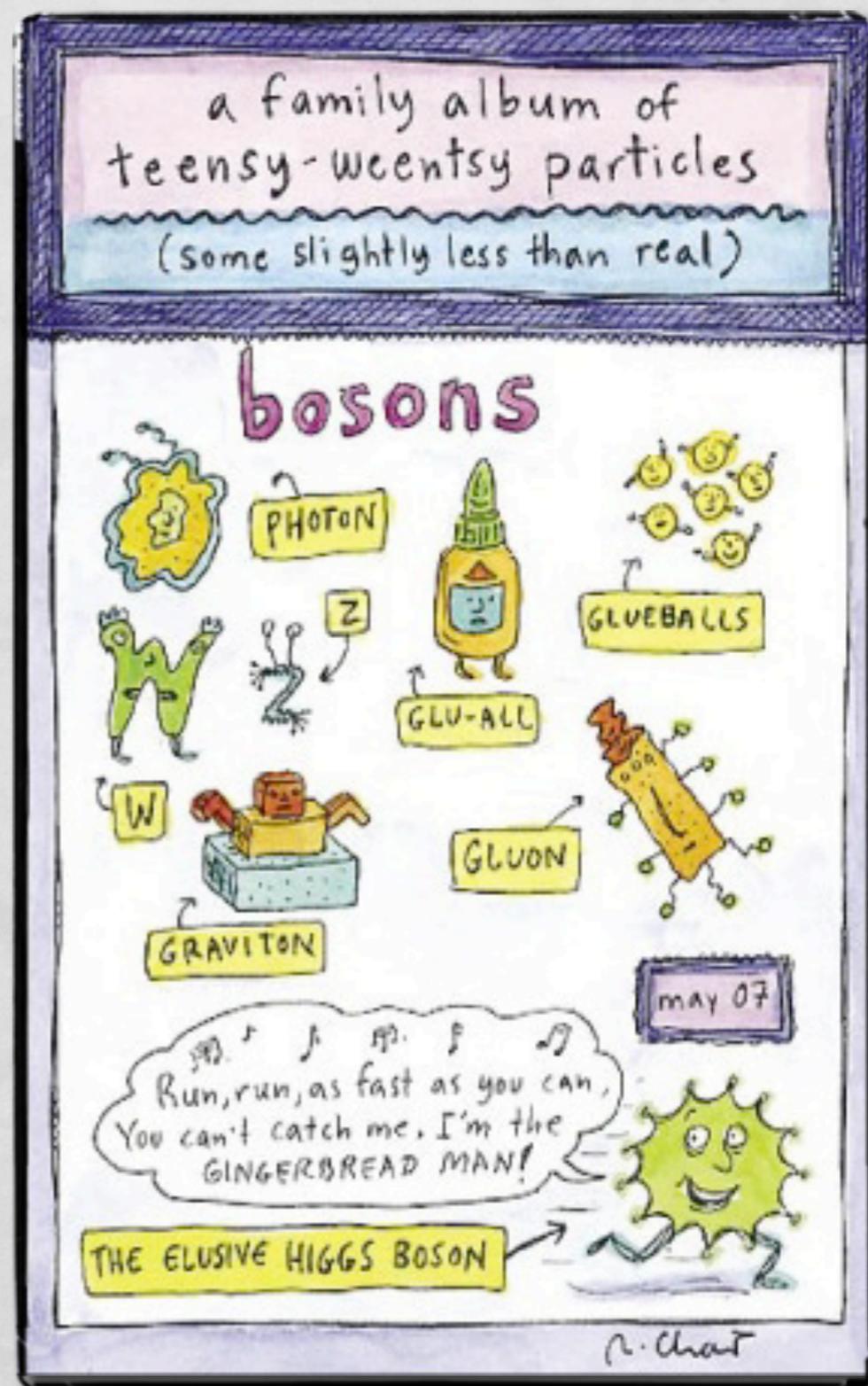
**Quarks & leptons**

**Neutron decay**  
**Beta radioactivity**  
**Neutrino Interactions**  
**Burning of the sun**



The particle drawings are simple artistic representations

# This is how they really look like



By Roz Chast (New Yorker cartoonist) for Symmetry Magazine, May'07

# The SM Equations

$$\mathcal{L}_{\text{SM}} = \mathcal{L}_{\text{Dirac}} + \mathcal{L}_{\text{mass}} + \mathcal{L}_{\text{gauge}} + \mathcal{L}_{\text{gauge}/\psi} . \quad (1)$$

Here,

$$\mathcal{L}_{\text{Dirac}} = i\bar{e}_L^i \partial e_L^i + i\bar{\nu}_L^i \partial \nu_L^i + i\bar{e}_R^i \partial e_R^i + i\bar{u}_L^i \partial u_L^i + i\bar{d}_L^i \partial d_L^i + i\bar{u}_R^i \partial u_R^i + i\bar{d}_R^i \partial d_R^i ; \quad (2)$$

$$\mathcal{L}_{\text{mass}} = -v \left( \lambda_e^i \bar{e}_L^i e_R^i + \lambda_u^i \bar{u}_L^i u_R^i + \lambda_d^i \bar{d}_L^i d_R^i + \text{h.c.} \right) - M_W^2 W_\mu^+ W^{-\mu} - \frac{M_W^2}{2 \cos^2 \theta_W} Z_\mu Z^\mu ; \quad (3)$$

$$\mathcal{L}_{\text{gauge}} = -\frac{1}{4} (G_{\mu\nu}^a)^2 - \frac{1}{2} W_{\mu\nu}^+ W^{-\mu\nu} - \frac{1}{4} Z_{\mu\nu} Z^{\mu\nu} - \frac{1}{4} F_{\mu\nu} F^{\mu\nu} + \mathcal{L}_{\text{WZA}} , \quad (4)$$

where

$$\begin{aligned} G_{\mu\nu}^a &= \partial_\mu A_\nu^a - \partial_\nu A_\mu^a - g_3 f^{abc} A_\mu^b A_\nu^c \\ W_{\mu\nu}^\pm &= \partial_\mu W_\nu^\pm - \partial_\nu W_\mu^\pm \\ Z_{\mu\nu} &= \partial_\mu Z_\nu - \partial_\nu Z_\mu \\ F_{\mu\nu} &= \partial_\mu A_\nu - \partial_\nu A_\mu , \end{aligned} \quad (5)$$

and

$$\begin{aligned} \mathcal{L}_{\text{WZA}} &= ig_2 \cos \theta_W \left[ (W_\mu^- W_\nu^+ - W_\nu^- W_\mu^+) \partial^\mu Z^\nu + W_{\mu\nu}^+ W^{-\mu} Z^\nu - W_{\mu\nu}^- W^{+\mu} Z^\nu \right] \\ &+ ie \left[ (W_\mu^- W_\nu^+ - W_\nu^- W_\mu^+) \partial^\mu A^\nu + W_{\mu\nu}^+ W^{-\mu} A^\nu - W_{\mu\nu}^- W^{+\mu} A^\nu \right] \\ &+ g_2^2 \cos^2 \theta_W (W_\mu^+ W_\nu^- Z^\mu Z^\nu - W_\mu^+ W^{-\mu} Z_\nu Z^\nu) \\ &+ g_2^2 (W_\mu^+ W_\nu^- A^\mu A^\nu - W_\mu^+ W^{-\mu} A_\nu A^\nu) \\ &+ g_2 e \cos \theta_W [W_\mu^+ W_\nu^- (Z^\mu A^\nu + Z^\nu A^\mu) - 2W_\mu^+ W^{-\mu} Z_\nu A^\nu] \\ &+ \frac{1}{2} g_2^2 (W_\mu^+ W_\nu^-) (W^{+\mu} W^{-\nu} - W^{+\nu} W^{-\mu}) ; \end{aligned} \quad (6)$$

and

$$\mathcal{L}_{\text{gauge}/\psi} = -g_3 A_\mu^a J_{(3)}^{\mu a} - g_2 (W_\mu^+ J_{W^+}^\mu + W_\mu^- J_{W^-}^\mu + Z_\mu J_Z^\mu) - e A_\mu J_A^\mu , \quad (7)$$

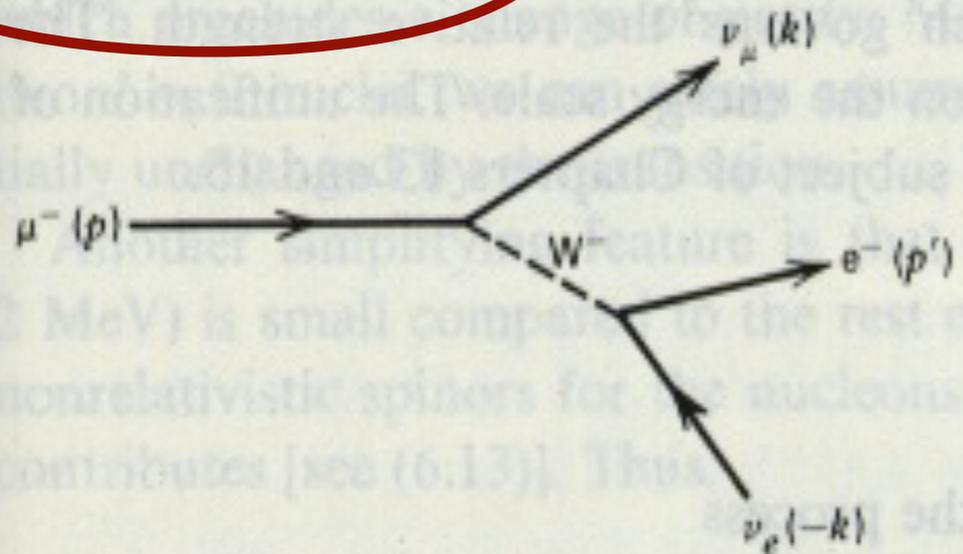
where

$$\begin{aligned} J_{(3)}^{\mu a} &= \bar{u}^i \gamma^\mu T_{(3)}^a u^i + \bar{d}^i \gamma^\mu T_{(3)}^a d^i \\ J_{W^+}^\mu &= \frac{1}{\sqrt{2}} (\bar{\nu}_L^i \gamma^\mu e_L^i + V^{ij} \bar{u}_L^i \gamma^\mu d_L^j) \\ J_{W^-}^\mu &= (J_{W^+}^\mu)^* \\ J_Z^\mu &= \frac{1}{\cos \theta_W} \left[ \frac{1}{2} \bar{\nu}_L^i \gamma^\mu \nu_L^i + \left( -\frac{1}{2} + \sin^2 \theta_W \right) \bar{e}_L^i \gamma^\mu e_L^i + (\sin^2 \theta_W) \bar{e}_R^i \gamma^\mu e_R^i \right. \\ &\quad + \left( \frac{1}{2} - \frac{2}{3} \sin^2 \theta_W \right) \bar{u}_L^i \gamma^\mu u_L^i + \left( -\frac{2}{3} \sin^2 \theta_W \right) \bar{u}_R^i \gamma^\mu u_R^i \\ &\quad \left. + \left( -\frac{1}{2} + \frac{1}{3} \sin^2 \theta_W \right) \bar{d}_L^i \gamma^\mu d_L^i + \left( \frac{1}{3} \sin^2 \theta_W \right) \bar{d}_R^i \gamma^\mu d_R^i \right] \\ J_A^\mu &= (-1) \bar{e}^i \gamma^\mu e^i + \left( \frac{2}{3} \right) \bar{u}^i \gamma^\mu u^i + \left( -\frac{1}{3} \right) \bar{d}^i \gamma^\mu d^i . \end{aligned} \quad (8)$$

# “Elementary” calculations

## Relativistic Quantum Field Theory

$\mu$  decay/



- Remarkable description of Nature
- Remarkable predictive power
- Iterative consistency with experimental data
- Still, some pieces are ad-hoc
- Missing description of Gravity

$$\mathcal{M} = \left( \frac{g}{\sqrt{2}} \bar{u}_{\nu_\mu} \gamma^\sigma \frac{1}{2} (1 - \gamma^5) u_\mu \right) \frac{1}{M_W^2 - q^2} \left( \frac{g}{\sqrt{2}} \bar{u}_e \gamma_\sigma \frac{1}{2} (1 - \gamma^5) u_{\nu_e} \right),$$

initial state

final state

force carrier

# Standard Model of FUNDAMENTAL PARTICLES AND INTERACTIONS

The Standard Model summarizes the current knowledge in Particle Physics, quantum chromodynamics or QCD) and the unified theory of weak and electromagnetic interactions (electroweak). Gravity is even though not part of the "Standard Model."

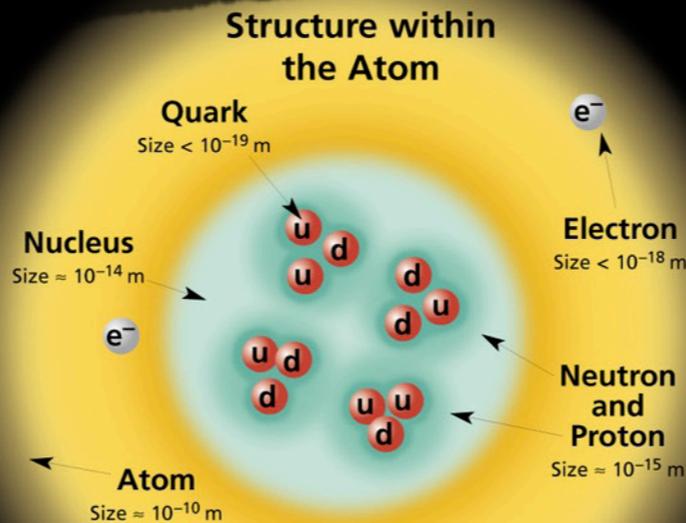
*last ~100 years!*

## FERMIONS

matter constituents  
spin = 1/2, 3/2, 5/2, ...

| Leptons spin = 1/2        |                         |                 |
|---------------------------|-------------------------|-----------------|
| Flavor                    | Mass GeV/c <sup>2</sup> | Electric charge |
| $\nu_e$ electron neutrino | $<1 \times 10^{-8}$     | 0               |
| $e$ electron              | 0.000511                | -1              |
| $\nu_\mu$ muon neutrino   | $<0.0002$               | 0               |
| $\mu$ muon                | 0.106                   | -1              |
| $\nu_\tau$ tau neutrino   | $<0.02$                 | 0               |
| $\tau$ tau                | 1.7771                  | -1              |

| Quarks spin = 1/2 |                                 |                 |
|-------------------|---------------------------------|-----------------|
| Flavor            | Approx. Mass GeV/c <sup>2</sup> | Electric charge |
| <b>u</b> up       | 0.003                           | 2/3             |
| <b>d</b> down     | 0.006                           | -1/3            |
| <b>c</b> charm    | 1.3                             | 2/3             |
| <b>s</b> strange  | 0.1                             | -1/3            |
| <b>t</b> top      | 175                             | 2/3             |
| <b>b</b> bottom   | 4.3                             | -1/3            |



If the protons and neutrons in this picture were 10 cm across, then the quarks and electrons would be less than 0.1 mm in size and the entire atom would be about 10 km across.

## BOSONS

force carriers  
spin = 0, 1, 2, ...

| Unified Electroweak spin = 1 |                         |                 |
|------------------------------|-------------------------|-----------------|
| Name                         | Mass GeV/c <sup>2</sup> | Electric charge |
| $\gamma$ photon              | 0                       | 0               |
| $W^-$                        | 80.4                    | -1              |
| $W^+$                        | 80.4                    | +1              |
| $Z^0$                        | 91.187                  | 0               |

| Strong (color) spin = 1 |                         |                 |
|-------------------------|-------------------------|-----------------|
| Name                    | Mass GeV/c <sup>2</sup> | Electric charge |
| <b>g</b> gluon          | 0                       | 0               |

**Color Charge**  
Each quark carries one of three types of "strong charge," also called "color charge." These charges have nothing to do with the colors of visible light. There are eight possible types of color charge for gluons. Just as electrically charged particles interact by exchanging photons, in strong interactions color-charged particles interact by exchanging gluons. Leptons, photons, and  $W$  and  $Z$  bosons have no strong interactions and hence no color charge.

### Quarks Confined in Mesons and Baryons

One cannot isolate quarks and gluons; they are confined in color-neutral particles called **hadrons**. This confinement (binding) results from multiple exchanges of gluons among the color-charged constituents. As color-charged particles (quarks and gluons) move apart, the energy in the color-force field between them increases. This energy eventually is converted into additional quark-antiquark pairs (see figure below). The quarks and antiquarks then combine into hadrons; these are the particles seen to emerge. Two types of hadrons have been observed in nature: **mesons**  $q\bar{q}$  and **baryons**  $qqq$ .

### Residual Strong Interaction

The strong binding of color-neutral protons and neutrons to form nuclei is due to residual strong interactions between their color-charged constituents. It is similar to the residual electrical interaction that binds electrically neutral atoms to form molecules. It can also be viewed as the exchange of mesons between the hadrons.

**Spin** is the intrinsic angular momentum of particles. Spin is given in units of  $\hbar$ , which is the quantum unit of angular momentum, where  $\hbar = h/2\pi = 6.58 \times 10^{-25} \text{ GeV s} = 1.05 \times 10^{-34} \text{ J s}$ .

**Electric charges** are given in units of the proton's charge. In SI units the electric charge of the proton is  $1.60 \times 10^{-19}$  coulombs.

The **energy** unit of particle physics is the electronvolt (eV), the energy gained by one electron in crossing a potential difference of one volt. **Masses** are given in  $\text{GeV}/c^2$  (remember  $E = mc^2$ ), where  $1 \text{ GeV} = 10^9 \text{ eV} = 1.60 \times 10^{-10} \text{ joule}$ . The mass of the proton is  $0.938 \text{ GeV}/c^2 = 1.67 \times 10^{-27} \text{ kg}$ .

## PROPERTIES OF THE INTERACTIONS

| Baryons $qqq$ and Antibaryons $\bar{q}\bar{q}\bar{q}$                |             |                         |                 |                         |      |
|--|-------------|-------------------------|-----------------|-------------------------|------|
| Baryons are fermionic hadrons. There are about 120 types of baryons. |             |                         |                 |                         |      |
| Symbol   | Name        | Quark content           | Electric charge | Mass GeV/c <sup>2</sup> | Spin |
| <b>p</b>   | proton      | <b>uud</b>              | 1               | 0.938                   | 1/2  |
| $\bar{p}$  | anti-proton | $\bar{u}\bar{u}\bar{d}$ | -1              | 0.938                   | 1/2  |
| <b>n</b>   | neutron     | <b>udd</b>              | 0               | 0.940                   | 1/2  |
| $\Lambda$  | lambda      | <b>uds</b>              | 0               | 1.116                   | 1/2  |
| $\Omega^-$   | omega       | <b>sss</b>              | -1              | 1.672                   | 3/2  |

| Property \ Interaction                                      | Gravitational               | Weak            | Electromagnetic      | Strong                    |                                      |
|---|-----------------------------|-----------------|----------------------|---------------------------|--------------------------------------|
|   |                             | (Electroweak)   |                      | Fundamental               | Residual                             |
| <b>Acts on:</b>   | Mass - Energy               | Flavor          | Electric Charge      | Color Charge              | See Residual Strong Interaction Note |
| <b>Particles experiencing:</b>                              | All                         | Quarks, Leptons | Electrically charged | Quarks, Gluons            | Hadrons                              |
| <b>Particles mediating:</b>                                 | Graviton (not yet observed) | $W^+ W^- Z^0$   | $\gamma$             | Gluons                    | Mesons                               |
| <b>Strength</b> relative to electromag for two u quarks at: |                             |                 |                      | 25                        | Not applicable to quarks             |
| for two u quarks at: $10^{-18} \text{ m}$                   | $10^{-41}$                  | 0.8             | 1                    | 60                        |                                      |
| for two u quarks at: $3 \times 10^{-17} \text{ m}$          | $10^{-41}$                  | $10^{-4}$       | 1                    | Not applicable to hadrons | 20                                   |
| for two protons in nucleus                                  | $10^{-36}$                  | $10^{-7}$       | 1                    |                           |                                      |

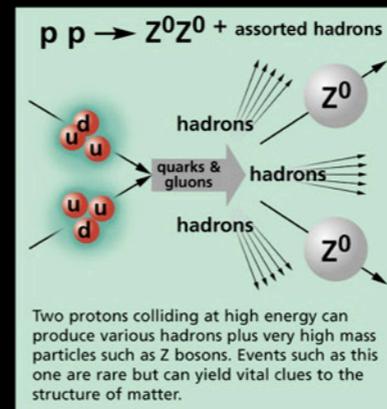
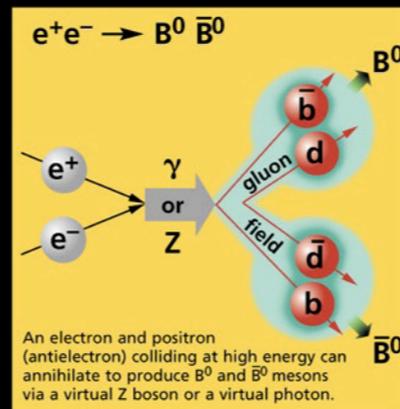
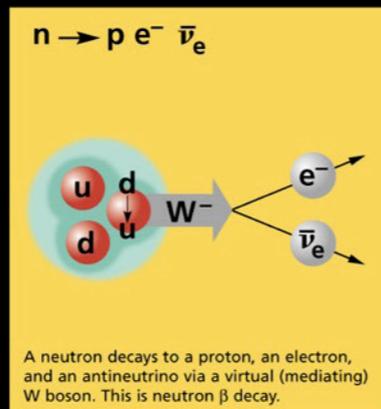
| Mesons $q\bar{q}$  |        |                              |                 |                         |      |
|--|--------|------------------------------|-----------------|-------------------------|------|
| Mesons are bosonic hadrons. There are about 140 types of mesons. |        |                              |                 |                         |      |
| Symbol   | Name   | Quark content                | Electric charge | Mass GeV/c <sup>2</sup> | Spin |
| $\pi^+$  | pion   | <b>u<math>\bar{d}</math></b> | +1              | 0.140                   | 0    |
| $K^-$  | kaon   | <b>s<math>\bar{u}</math></b> | -1              | 0.494                   | 0    |
| $\rho^+$   | rho    | <b>u<math>\bar{d}</math></b> | +1              | 0.770                   | 1    |
| $B^0$  | B-zero | <b>d<math>\bar{b}</math></b> | 0               | 5.279                   | 0    |
| $\eta_c$   | eta-c  | <b>c<math>\bar{c}</math></b> | 0               | 2.980                   | 0    |

### Matter and Antimatter

For every particle type there is a corresponding antiparticle type, denoted by a bar over the particle symbol (unless + or - charge is shown). Particle and antiparticle have identical mass and spin but opposite charges. Some electrically neutral bosons (e.g.,  $Z^0$ ,  $\gamma$ , and  $\eta_c = c\bar{c}$ , but not  $K^0 = d\bar{s}$ ) are their own antiparticles.

### Figures

These diagrams are an artist's conception of physical processes. They are **not** exact and have **no** meaningful scale. Green shaded areas represent the cloud of gluons or the gluon field, and red lines the quark paths.



### The Particle Adventure

Visit the award-winning web feature *The Particle Adventure* at <http://ParticleAdventure.org>

This chart has been made possible by the generous support of:

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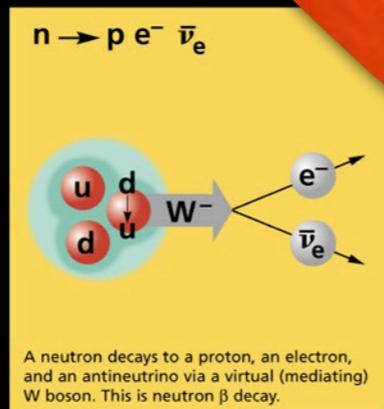
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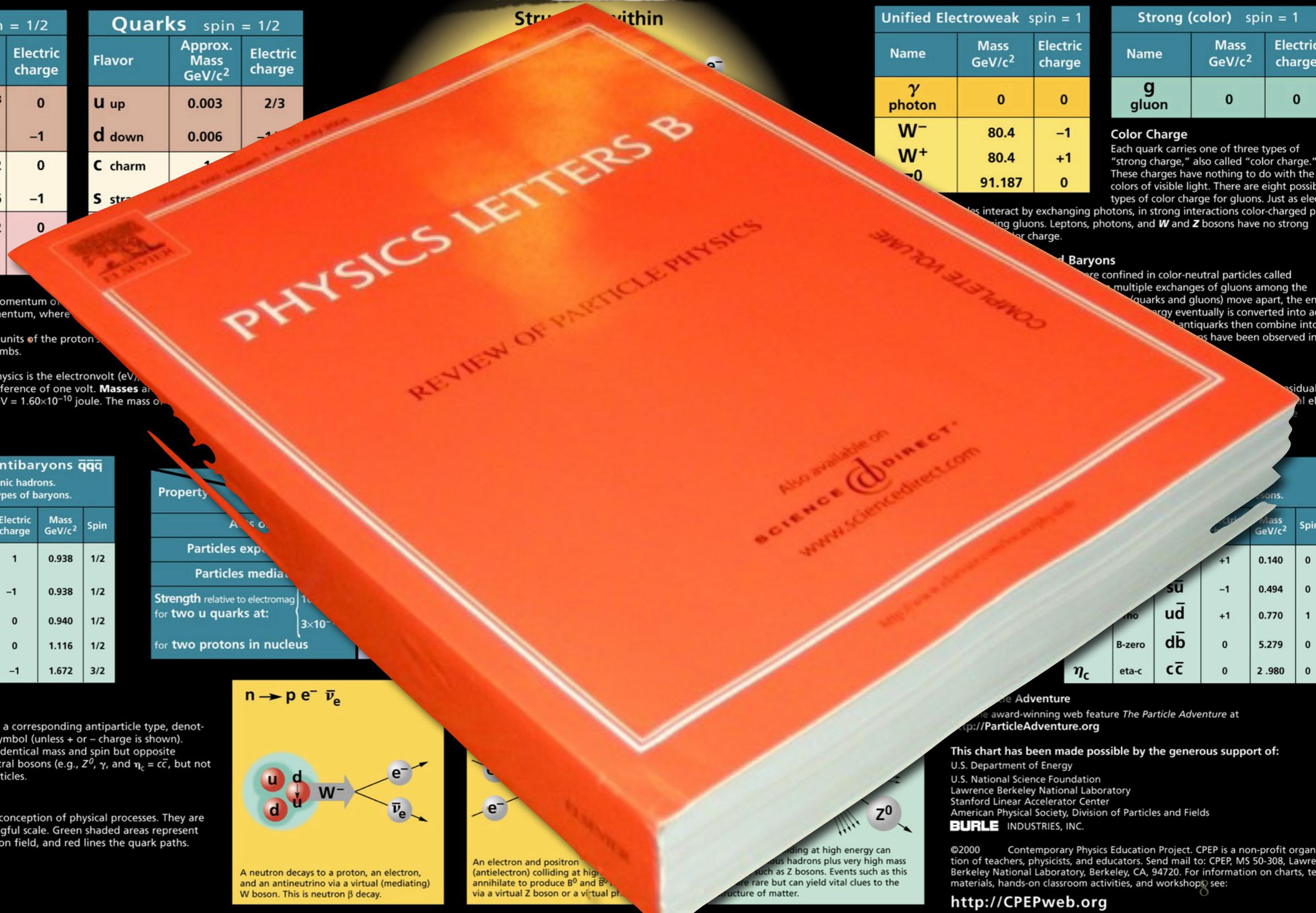
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### Figures

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An electron and positron colliding at high energy can produce a pair of quarks and antiquarks, such as  $Z^0$  bosons. Events such as this are rare but can yield vital clues to the structure of matter.

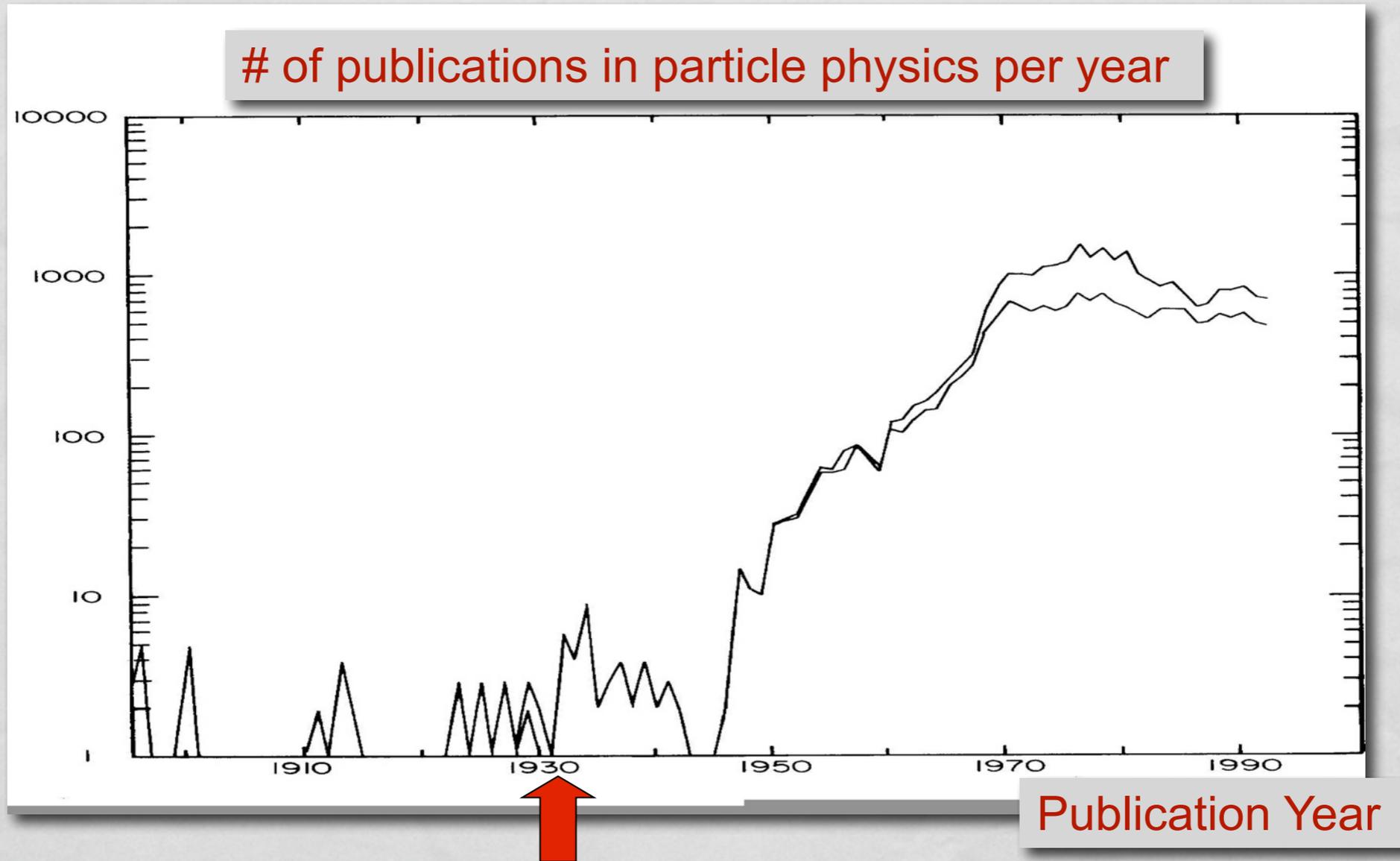


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<http://CPEPweb.org>

# The Role of Particle Accelerators



*The advent of the era of accelerators: a “game changer” - as they say...*



*E. Lawrence*



*John Cockcroft*



*R. Van de Graaff*

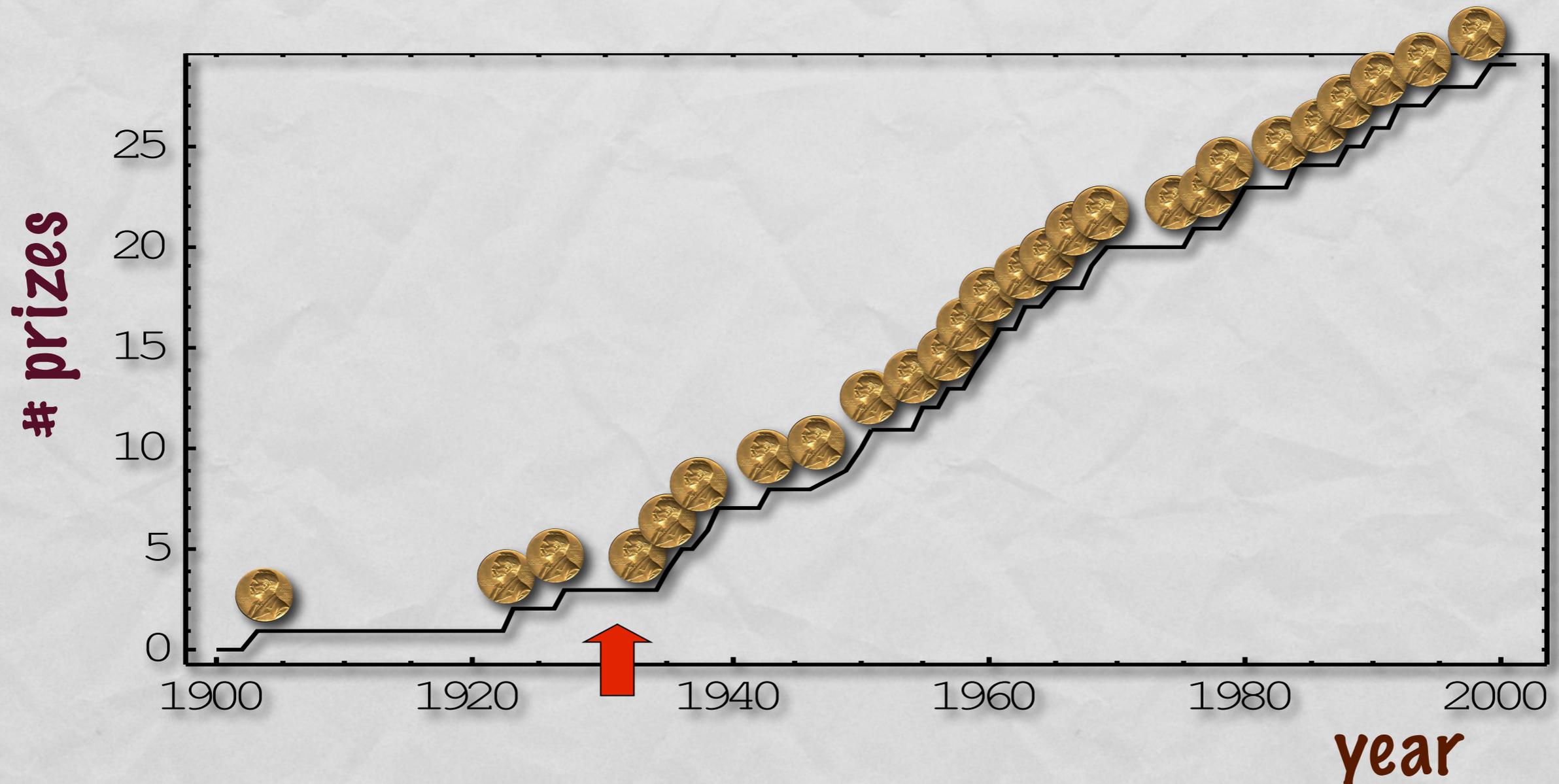
*and collaborators,  
and many others...*

# Some recognition



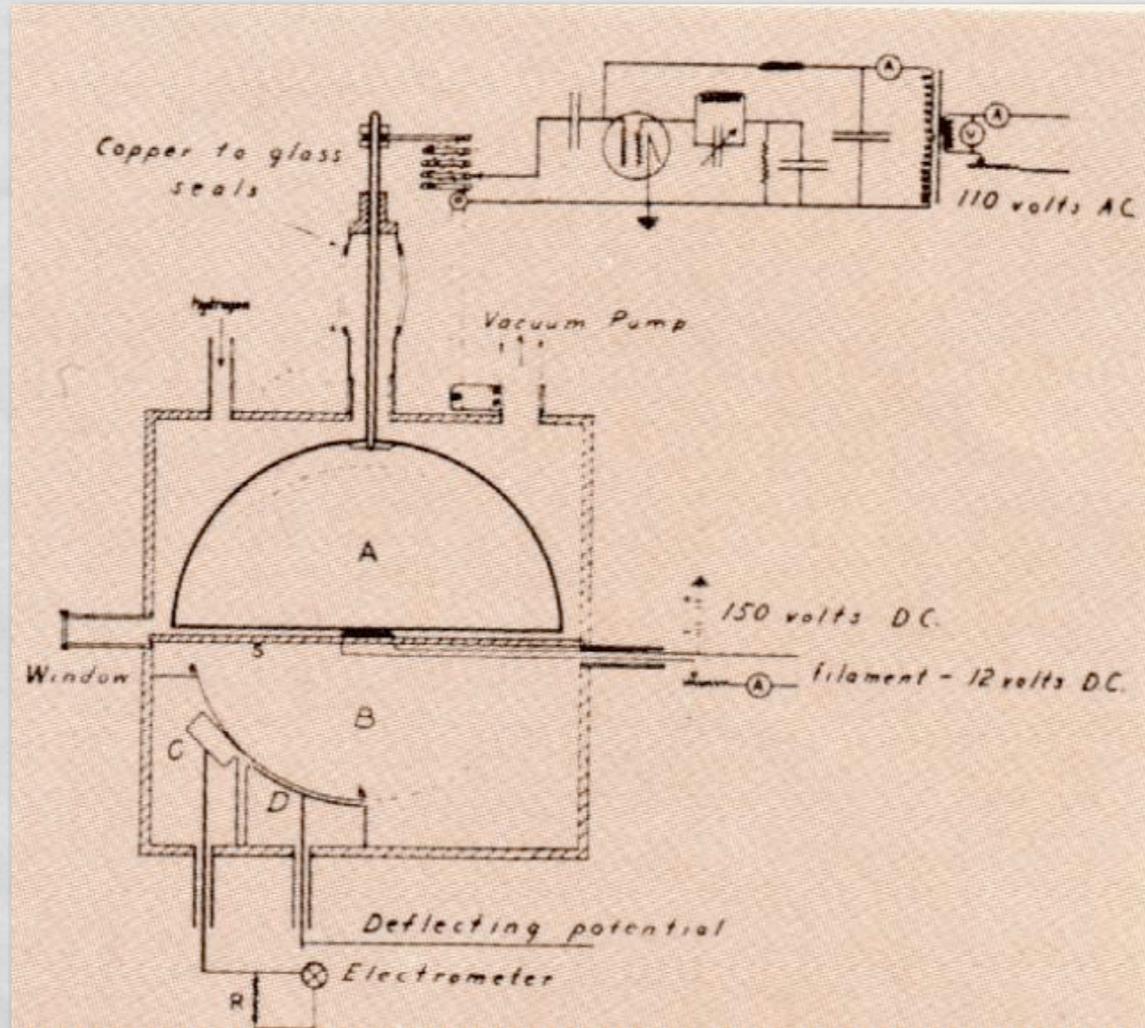
## □ The Standard Model:

- Near 30 Nobel Prizes given to Particle Physics in the last 100 yrs
- Substructure, quarks, leptons, antimatter, force carriers, symmetries, theory, instrumentation & accelerator work

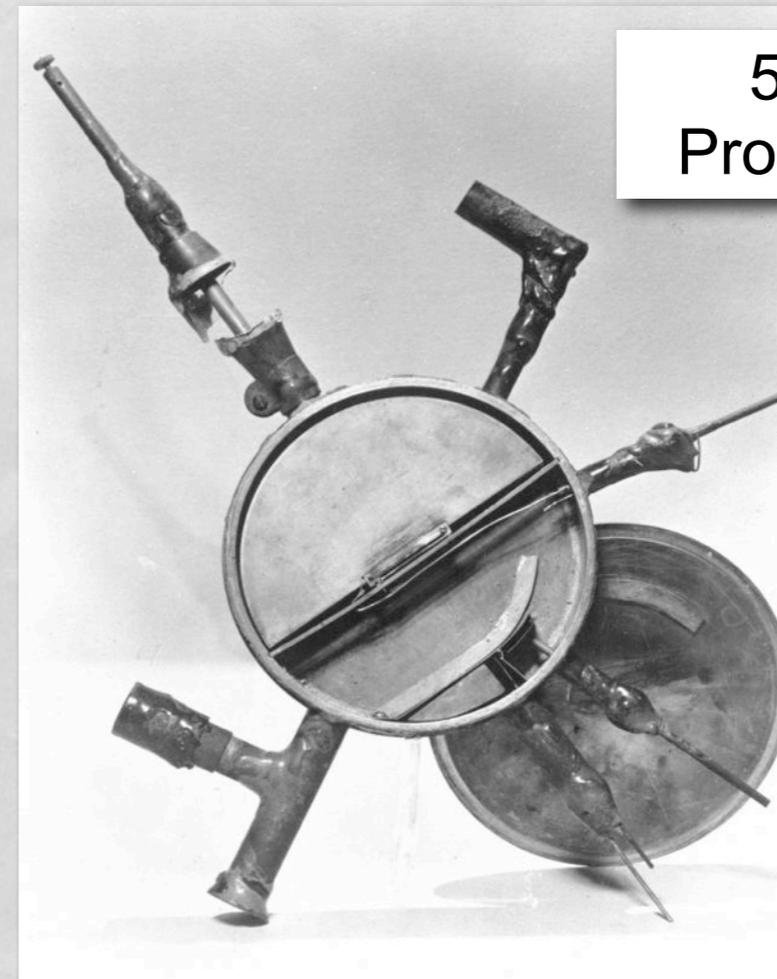


# The First Cyclotron

E. Lawrence



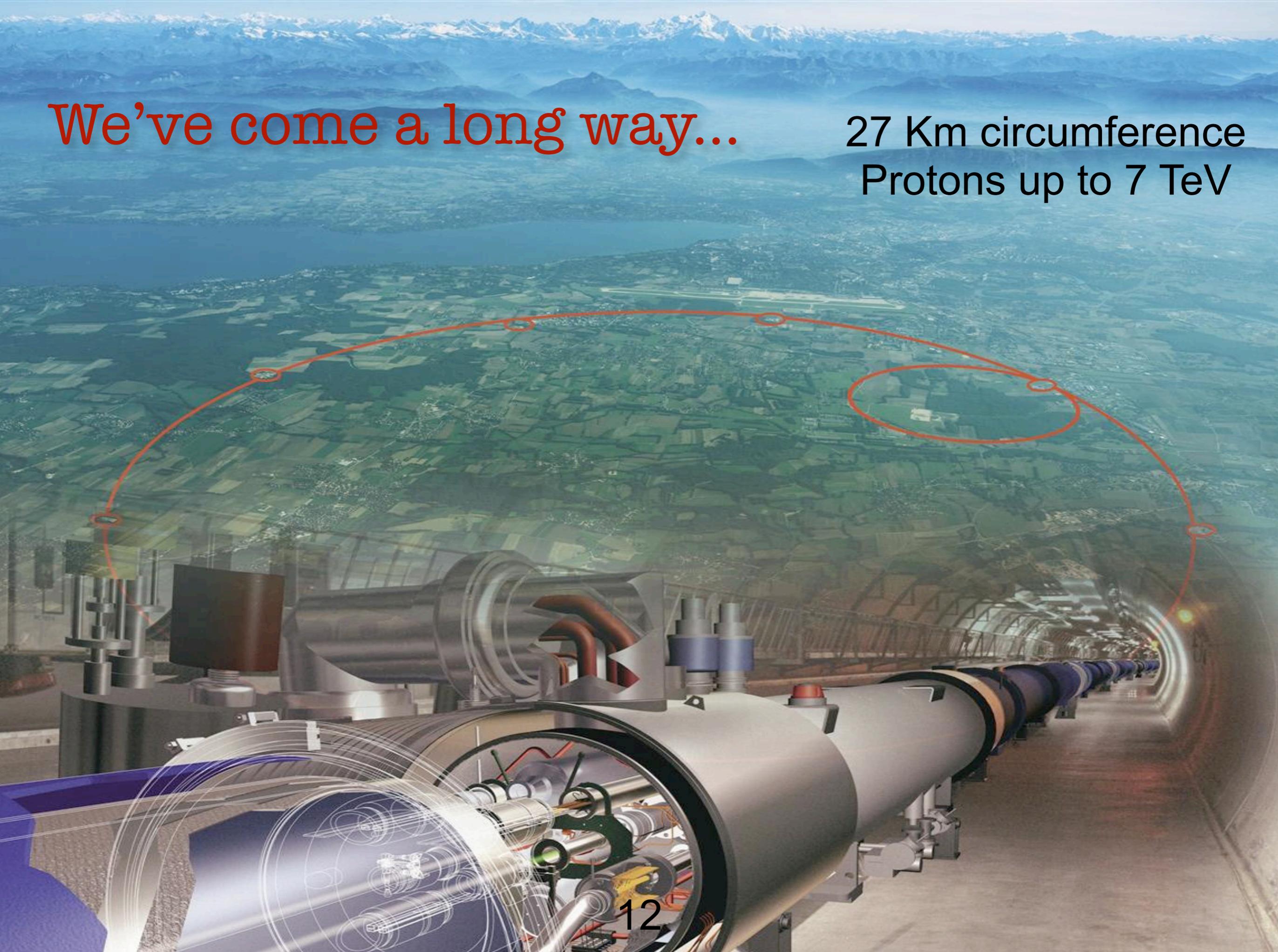
**First successful cyclotron constructed by Lawrence and M. S. Livingston - 1930**



5 in. diameter  
Protons @ 80 KeV

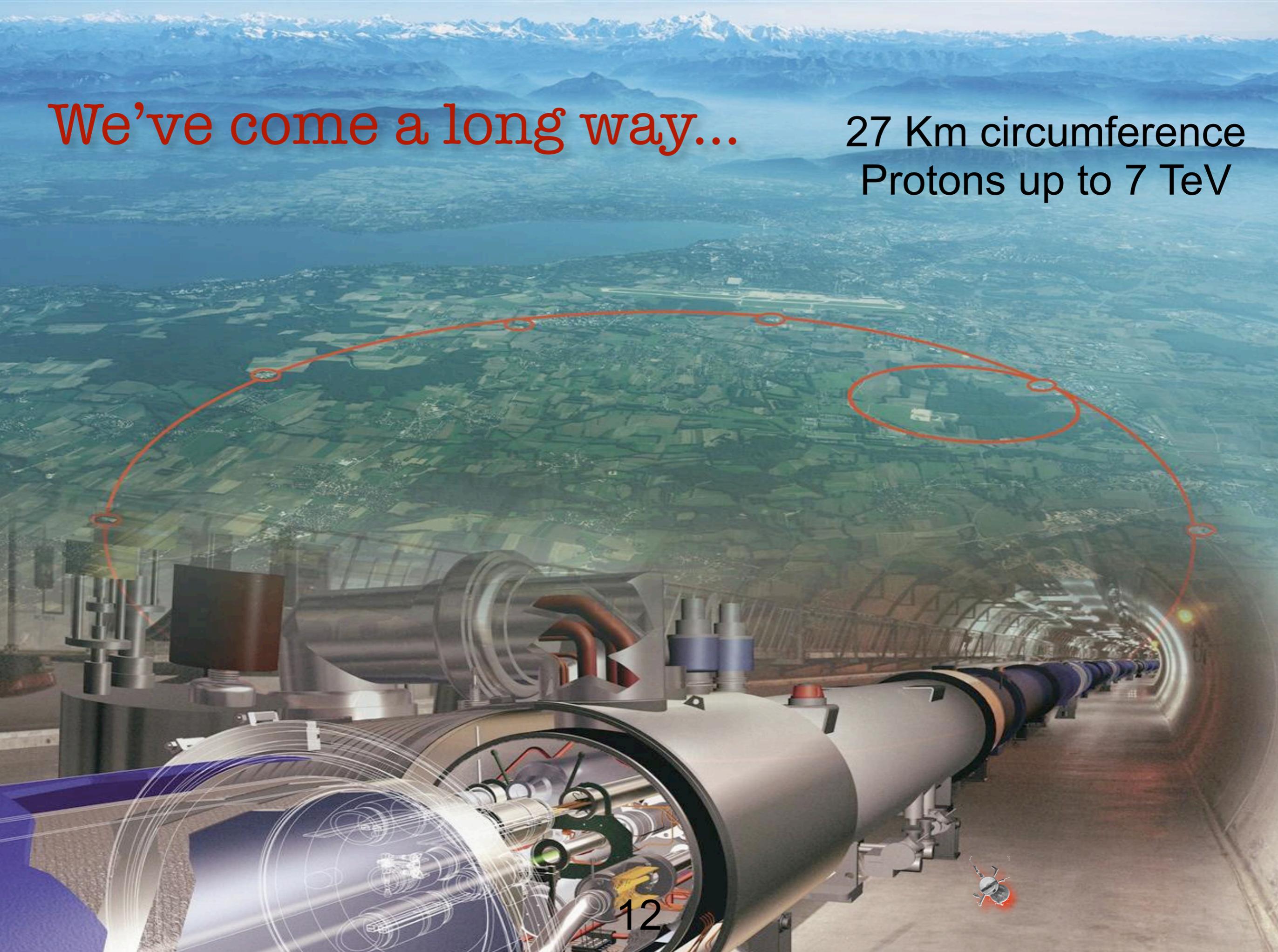
We've come a long way...

27 Km circumference  
Protons up to 7 TeV



We've come a long way...

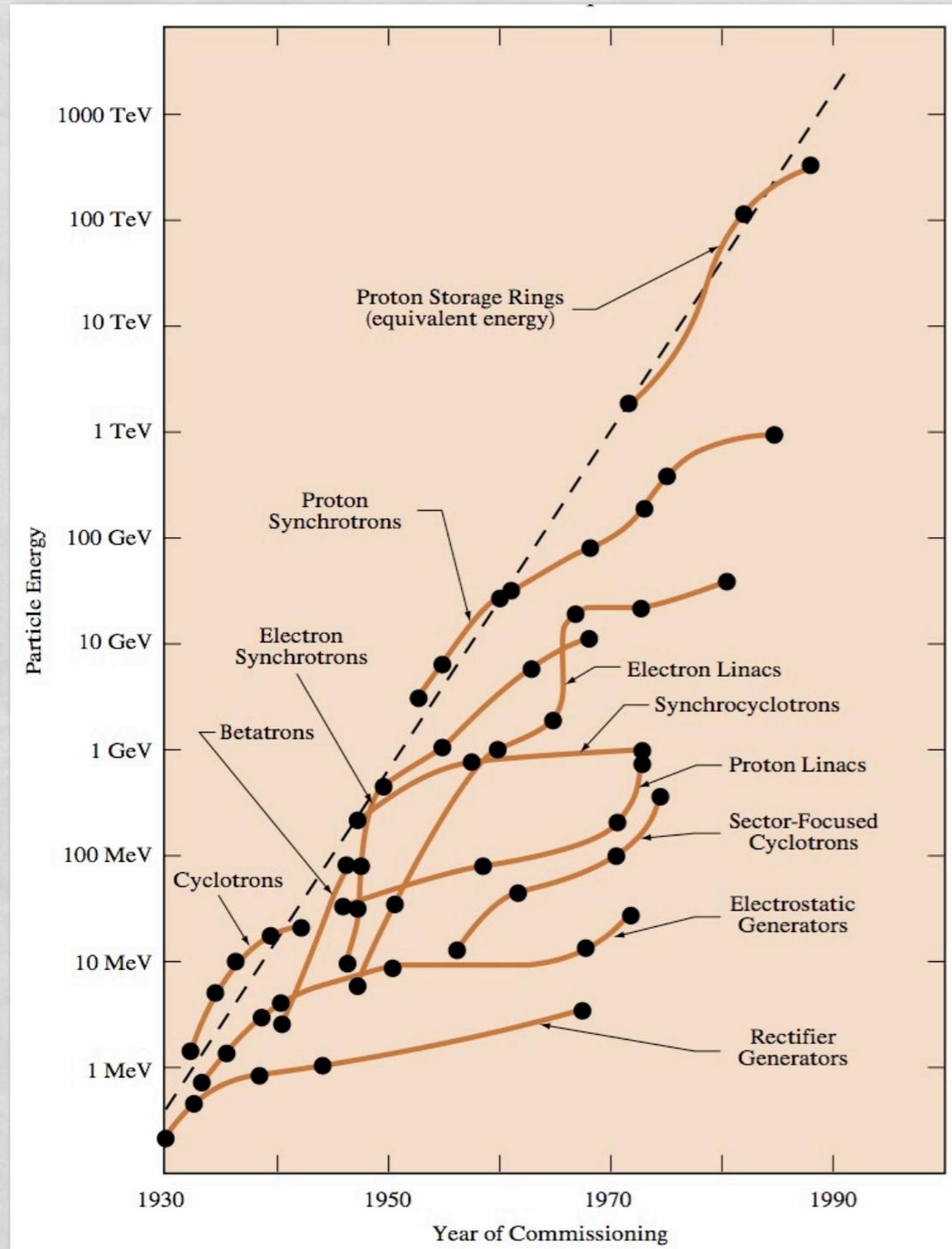
27 Km circumference  
Protons up to 7 TeV



# “E-volution” of Particle Accelerators

Not necessarily smoothly !

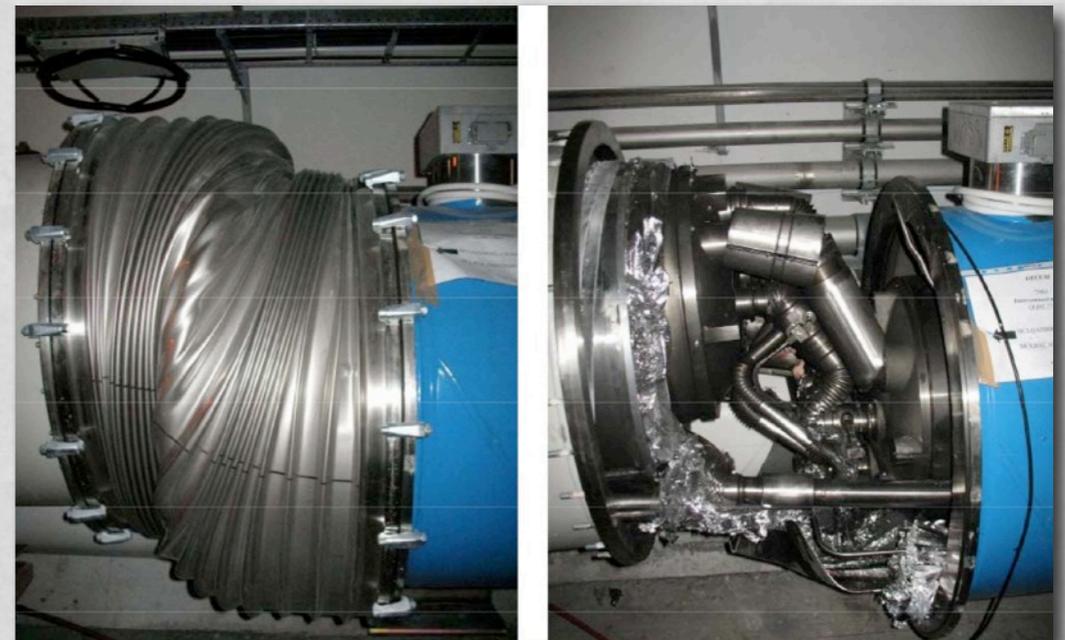
Particle Energy



Year

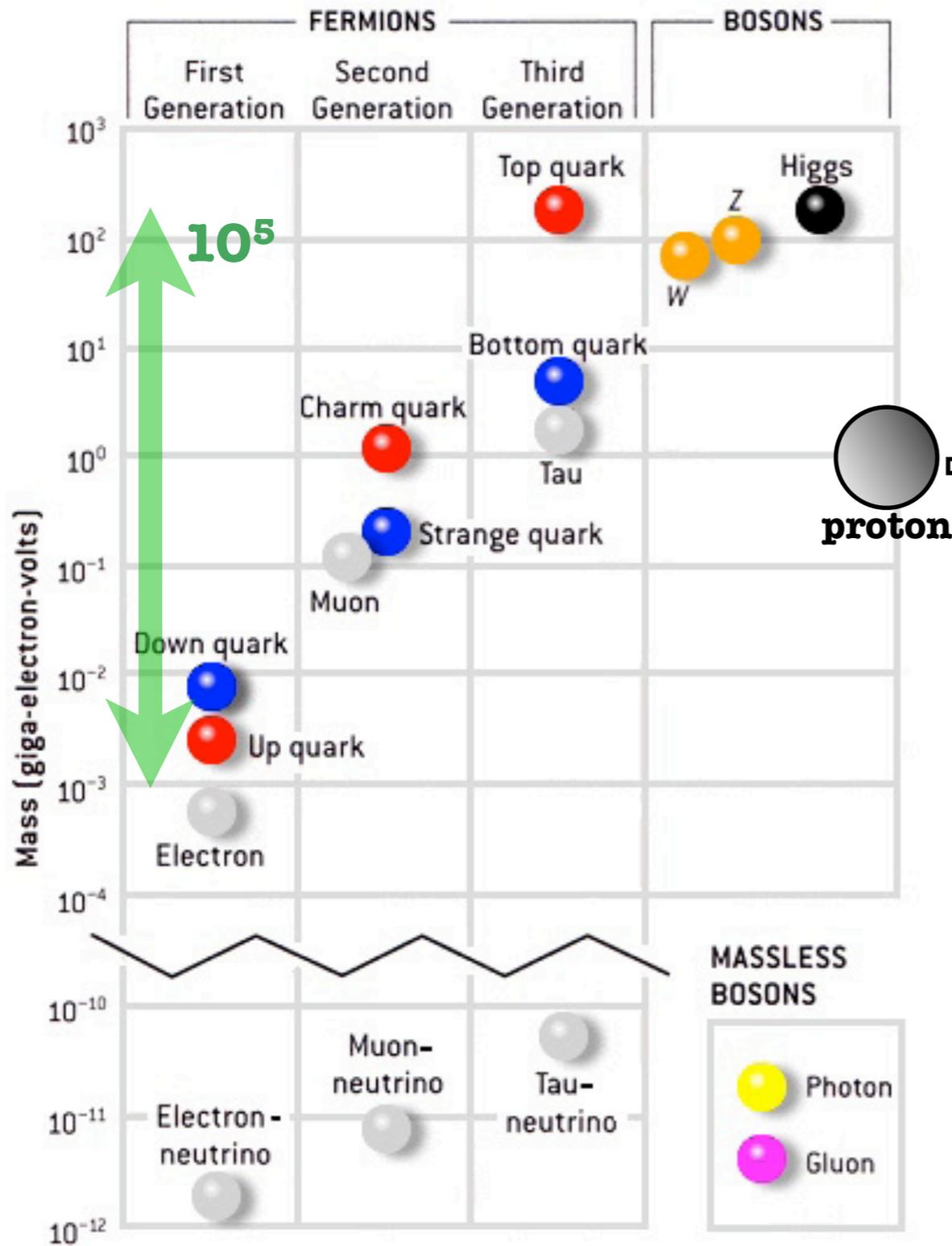


Early particle accelerators, like MIT's Van de Graaff machine, had difficulty containing the high voltages required.

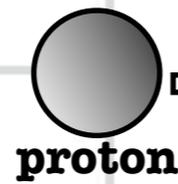


LHC Sept 2008

# BUT major puzzles: particle masses

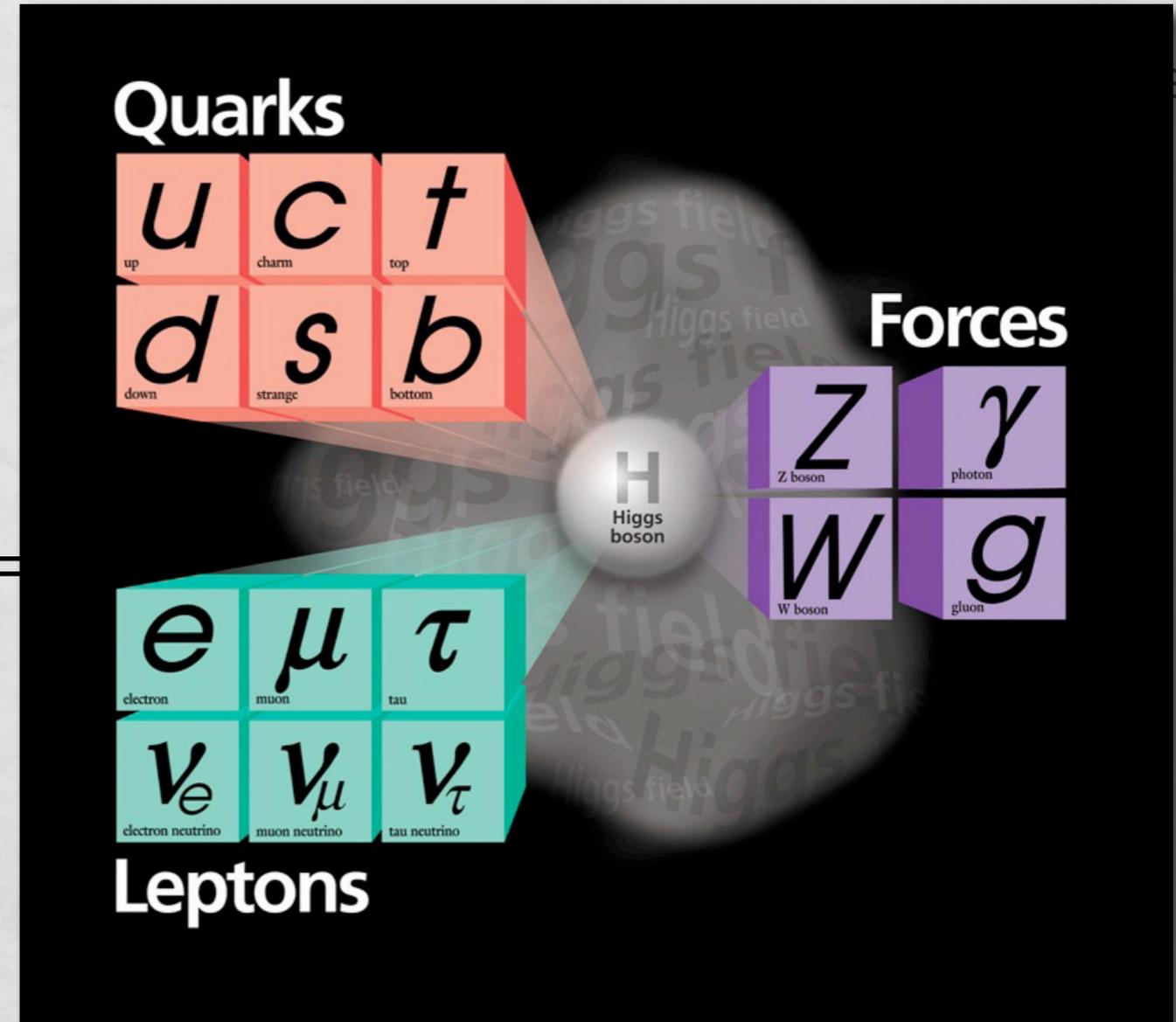
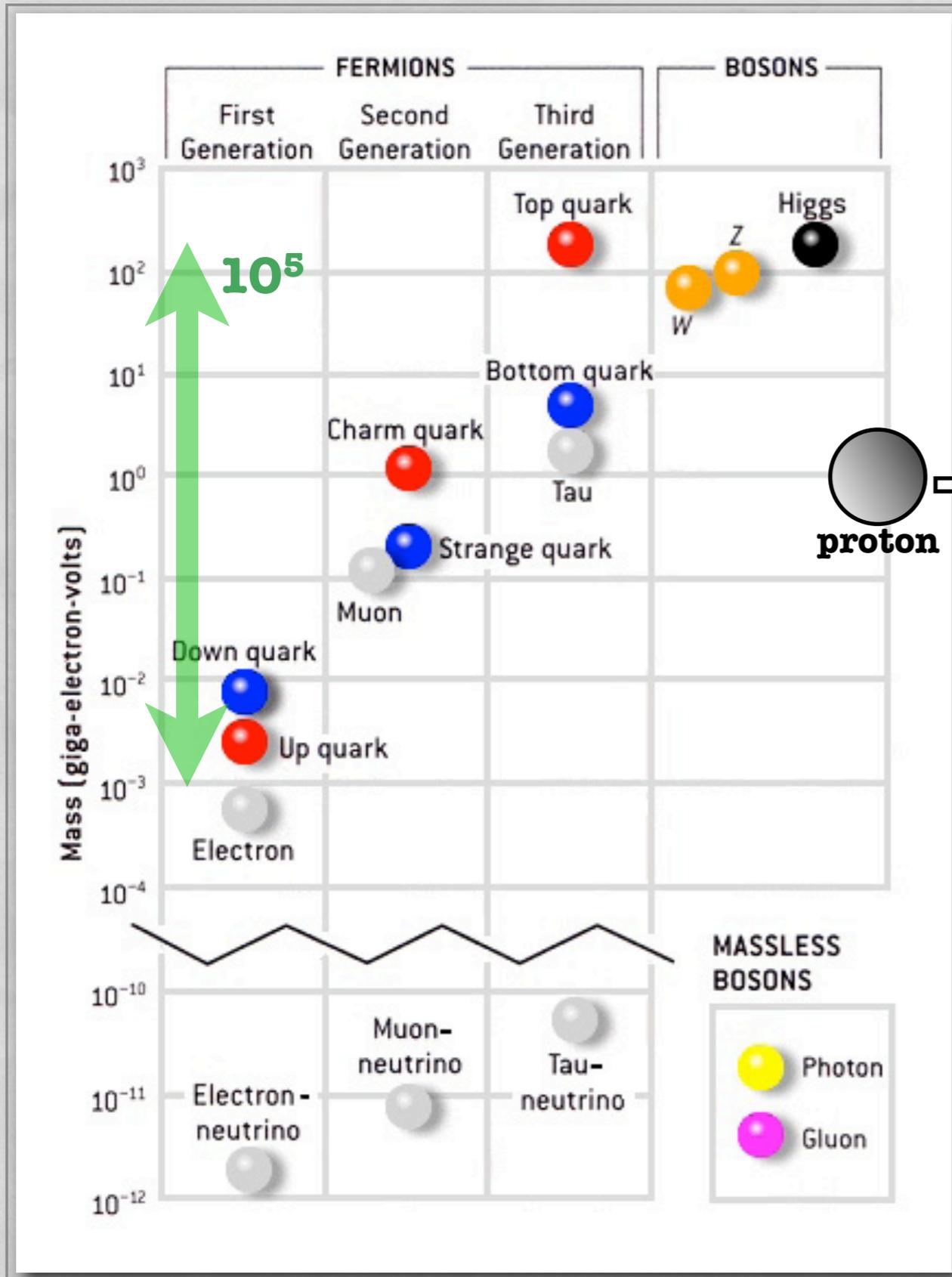


- 5 orders of magnitude span for quarks
- Top quark as heavy as a gold atom
- Neutrinos nearly massless
- Force carriers have either zero or very larger masses



units:  $c=1 \Rightarrow m=E$  proton is 1 GeV

# BUT major puzzles: particle masses

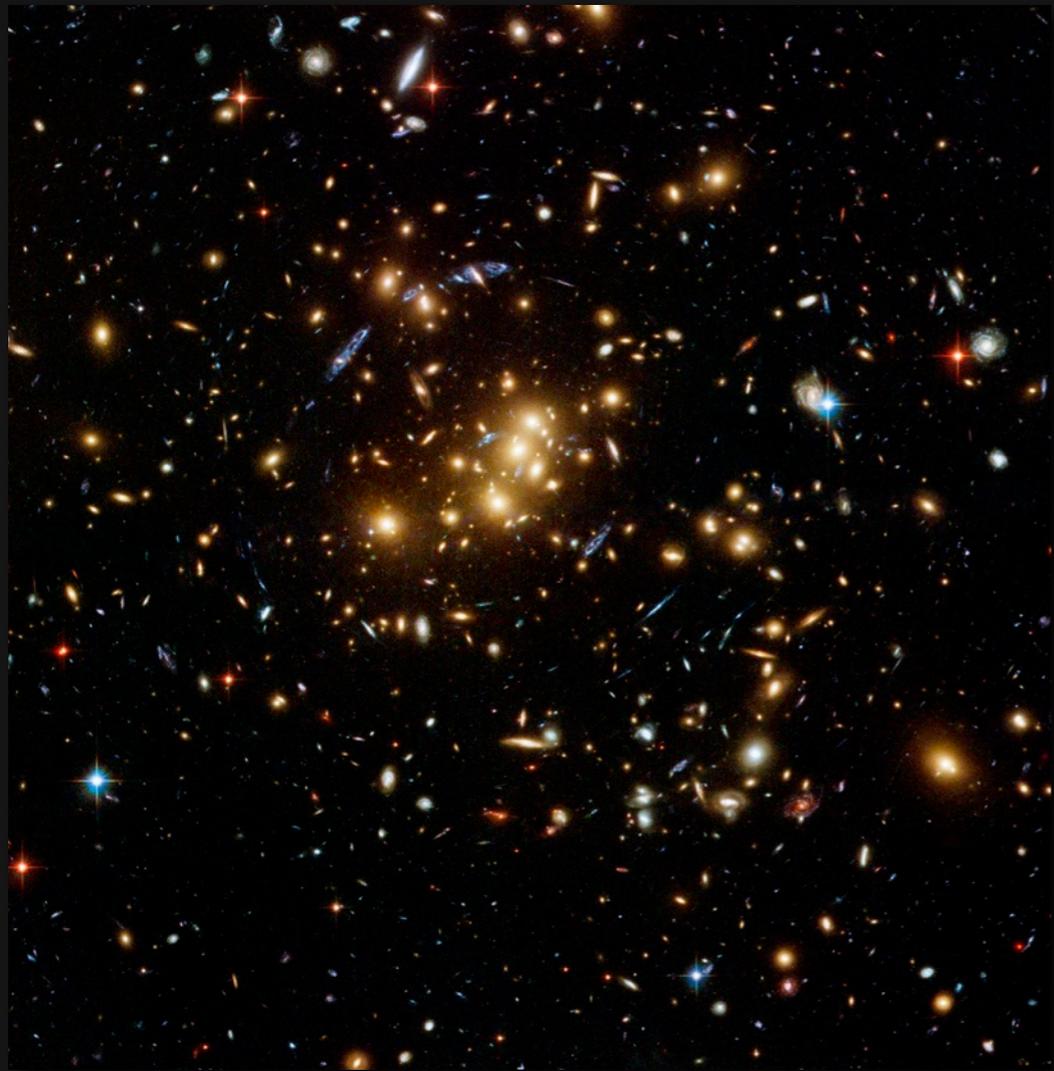


**“The Higgs”**

A new particle/field that generates mass - last SM particle still to be found



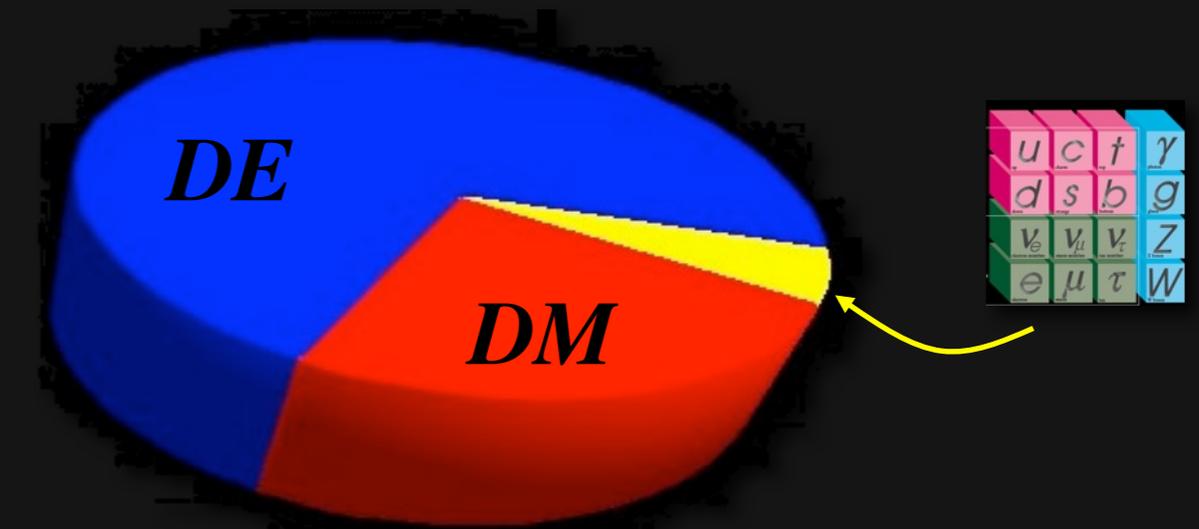
The Higgs



# Another puzzle: “Dark Matter and Dark Energy”

Dark Matter:  
Galaxies rotation  
inconsistent with  
visible mass

Dark Energy:  
The expansion of  
the Universe is  
accelerating



*Physics [particles] beyond  
the Standard Model !*

# A whole new set of deep questions

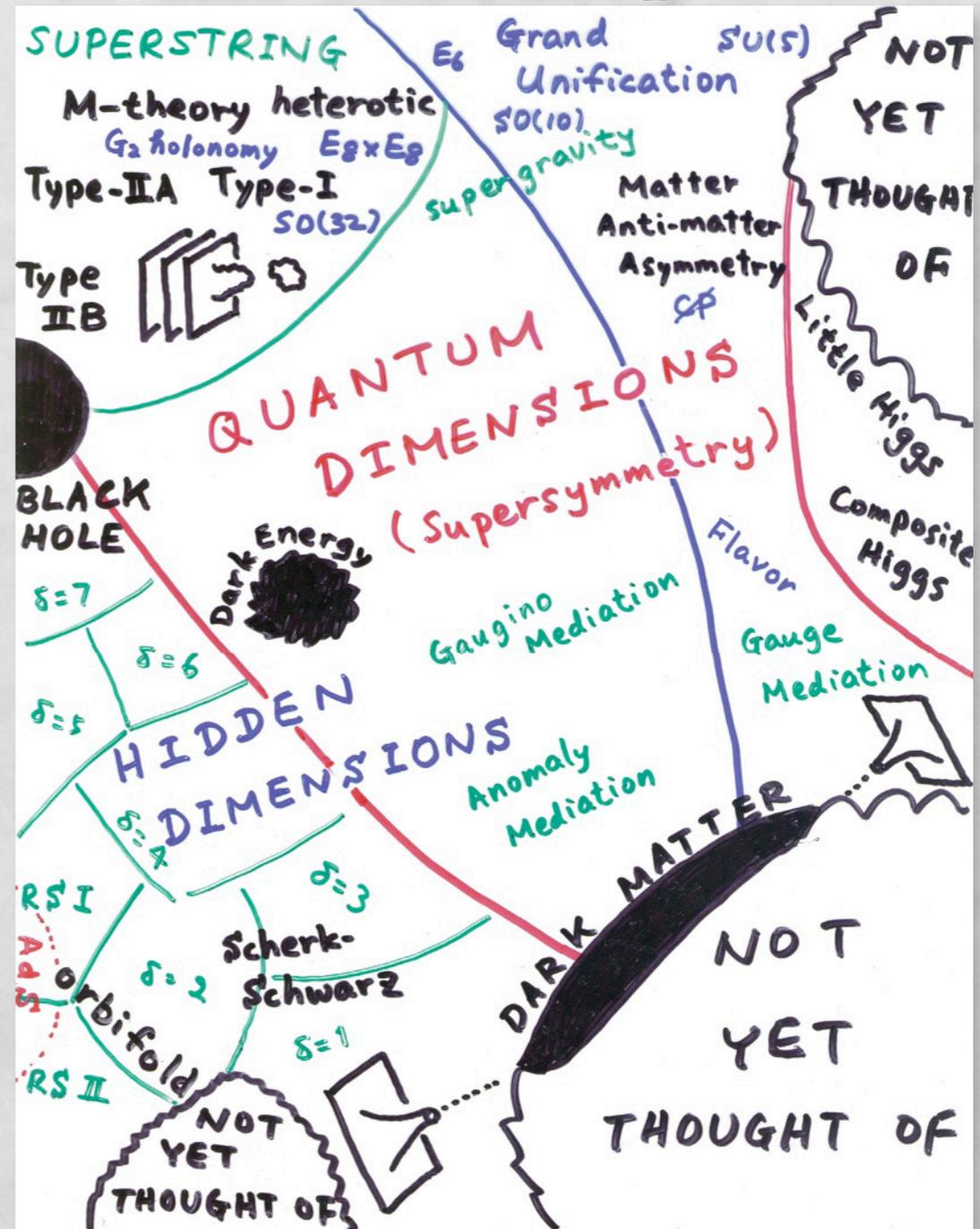
- Why 3 generations of particles ?
- Why the [huge] difference in particle masses ?
- Are all the forces one ?
- Where is all the anti-matter ?
- What are dark matter and dark energy ?
- How does gravity fit in ?



# Theorists at work

[hesitate to say “to the rescue”]

- Strings
- Supersymmetry
- Extended gauge theories
- Multi-Higgs, Little Higgs, Higgs-less
- Technicolor, topcolor
- Compositeness
- Extra dimensions
- Hidden Valleys
- ...



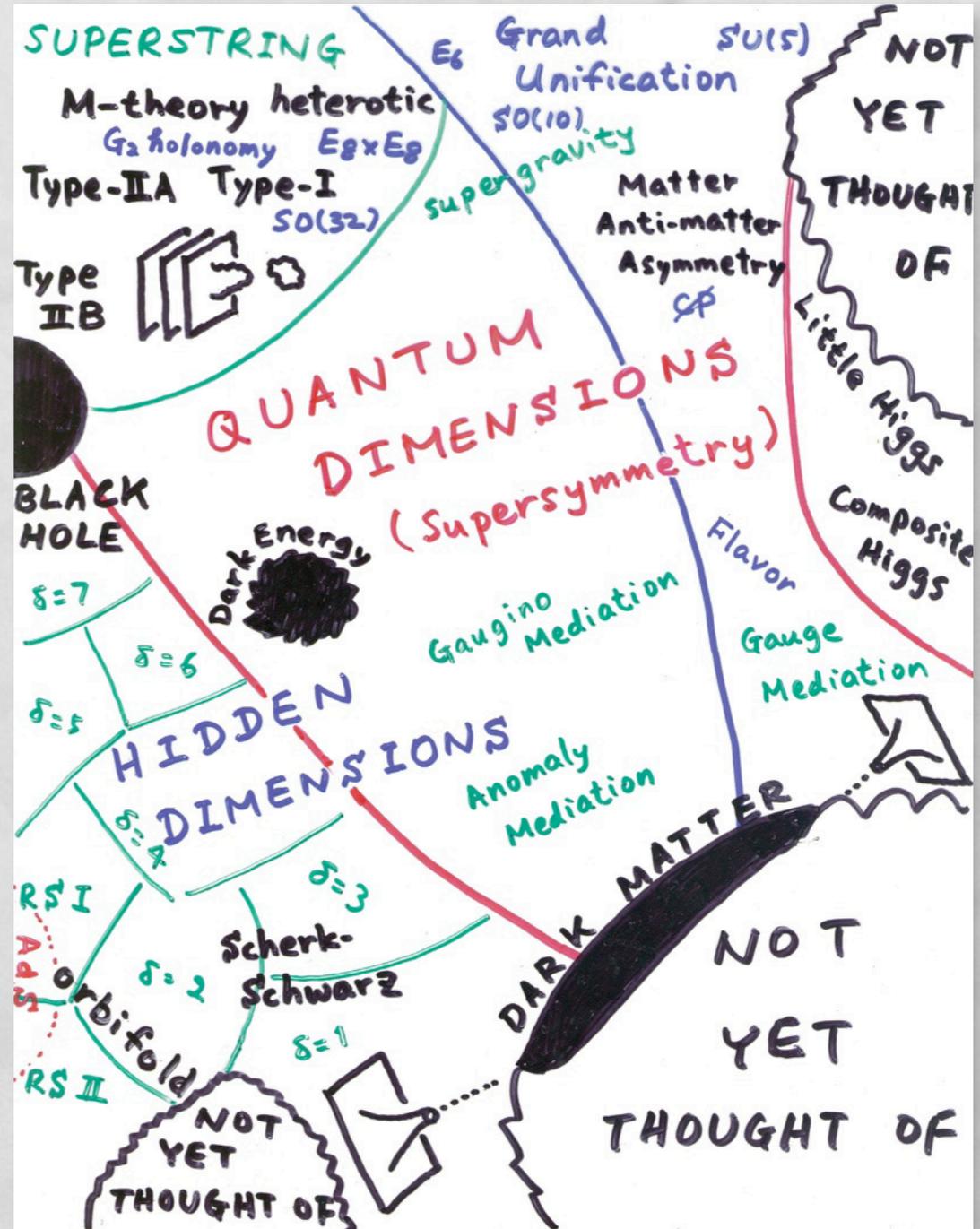
● All of which predict **new particles to be discovered**

# Theorists at work

[hesitate to say “to the rescue”]

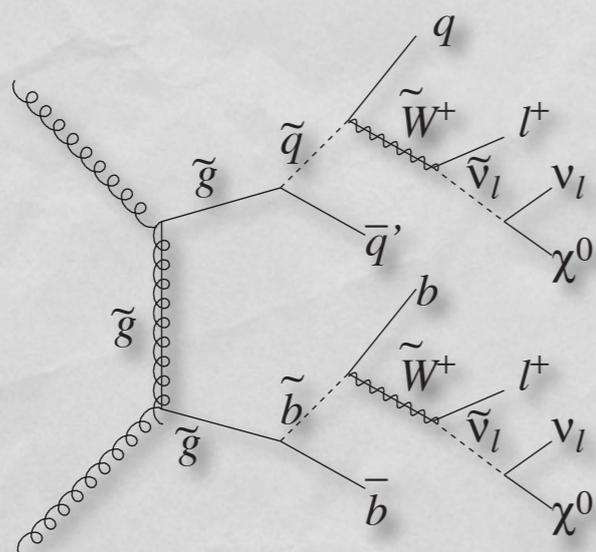
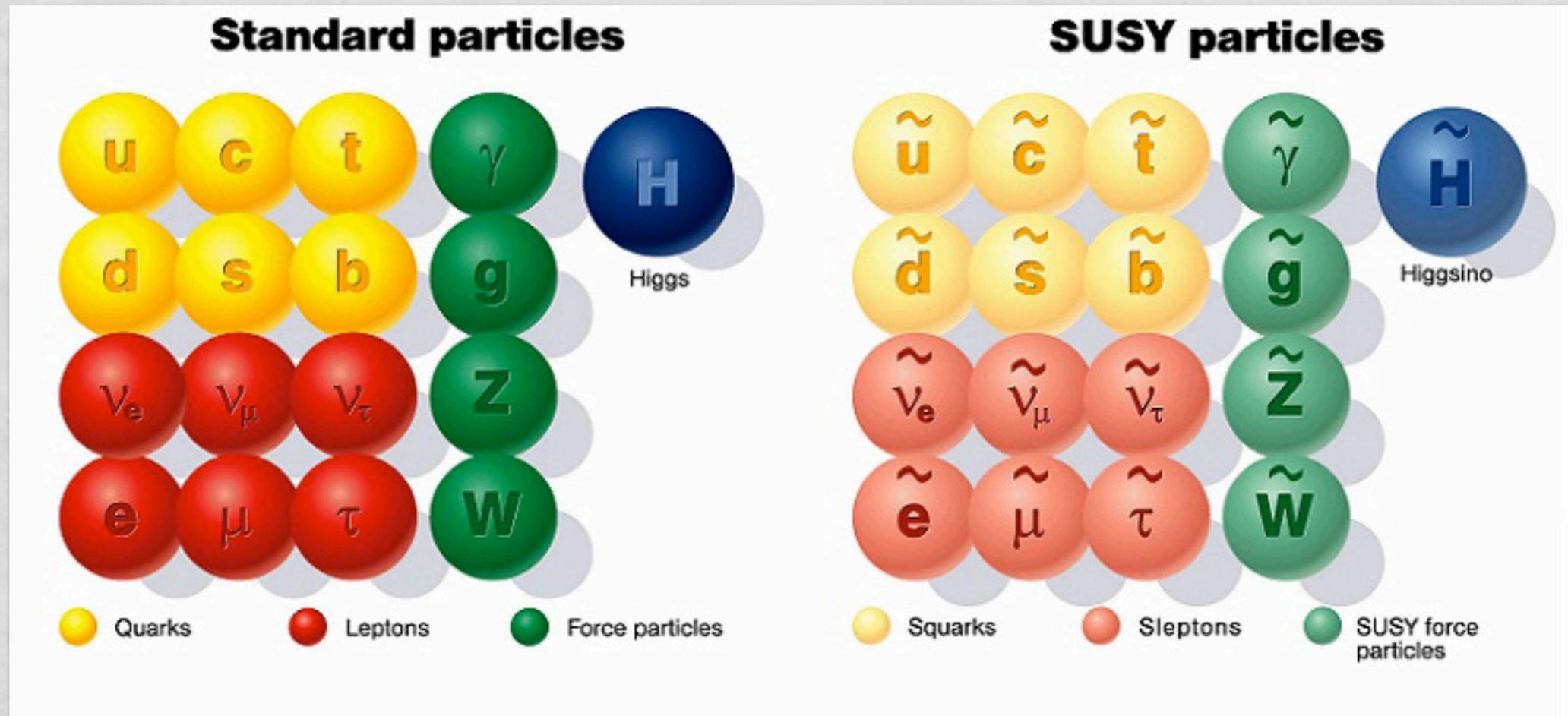
- Strings
- Supersymmetry
- Extended gauge theories
- Multi-Higgs, Little Higgs, Higgs-less
- Technicolor, topcolor
- Compositeness
- Extra dimensions
- Hidden Valleys
- ...

None of which may be true

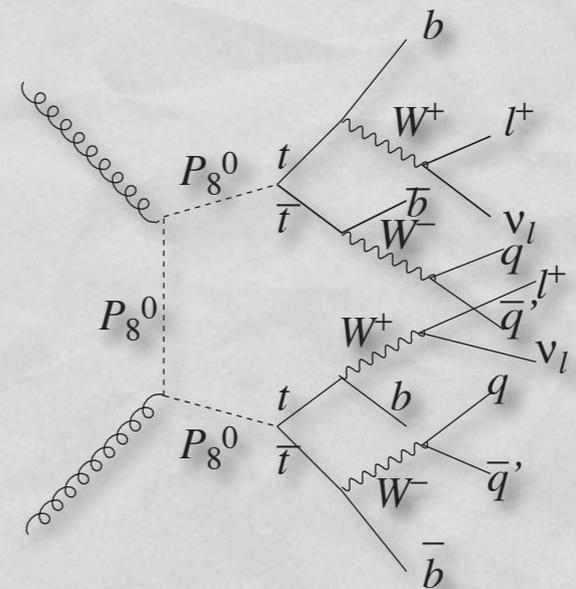


● All of which predict **new particles to be discovered**

# Ex: SuperSymmetry

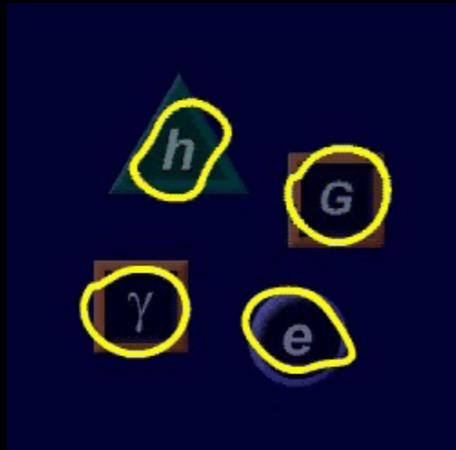


Double the fun !



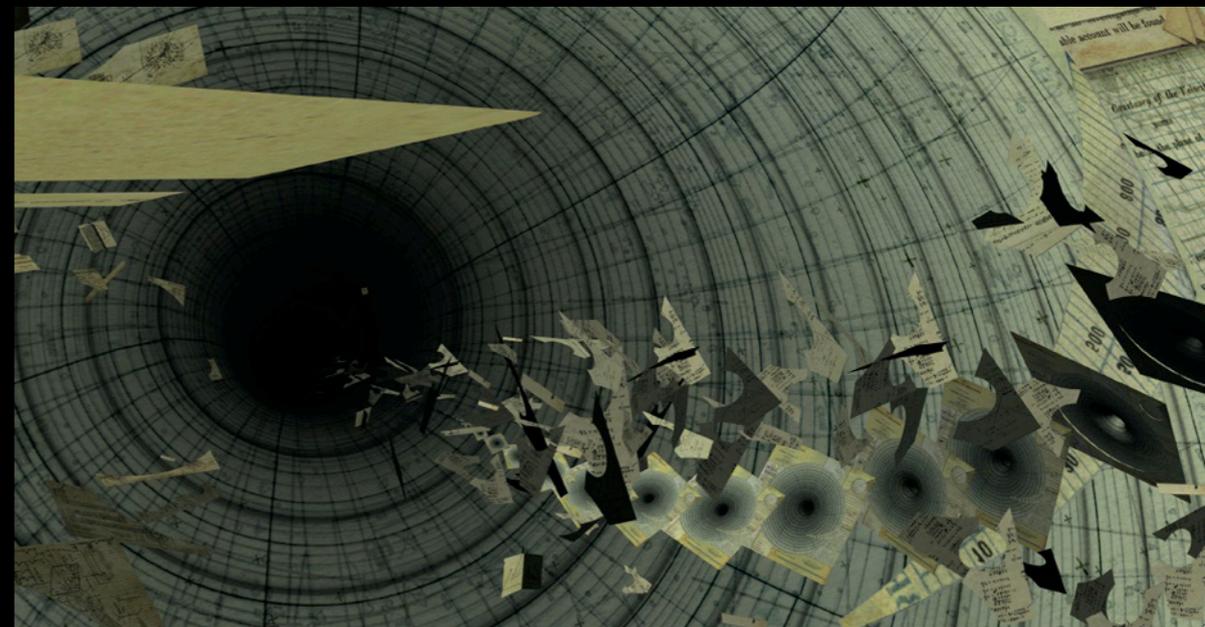
# Ex: SuperStrings

Particles are not structureless points but [tiny] strings. Different particles types can be manifested as different vibration modes



## Potential to explain much (all ?)

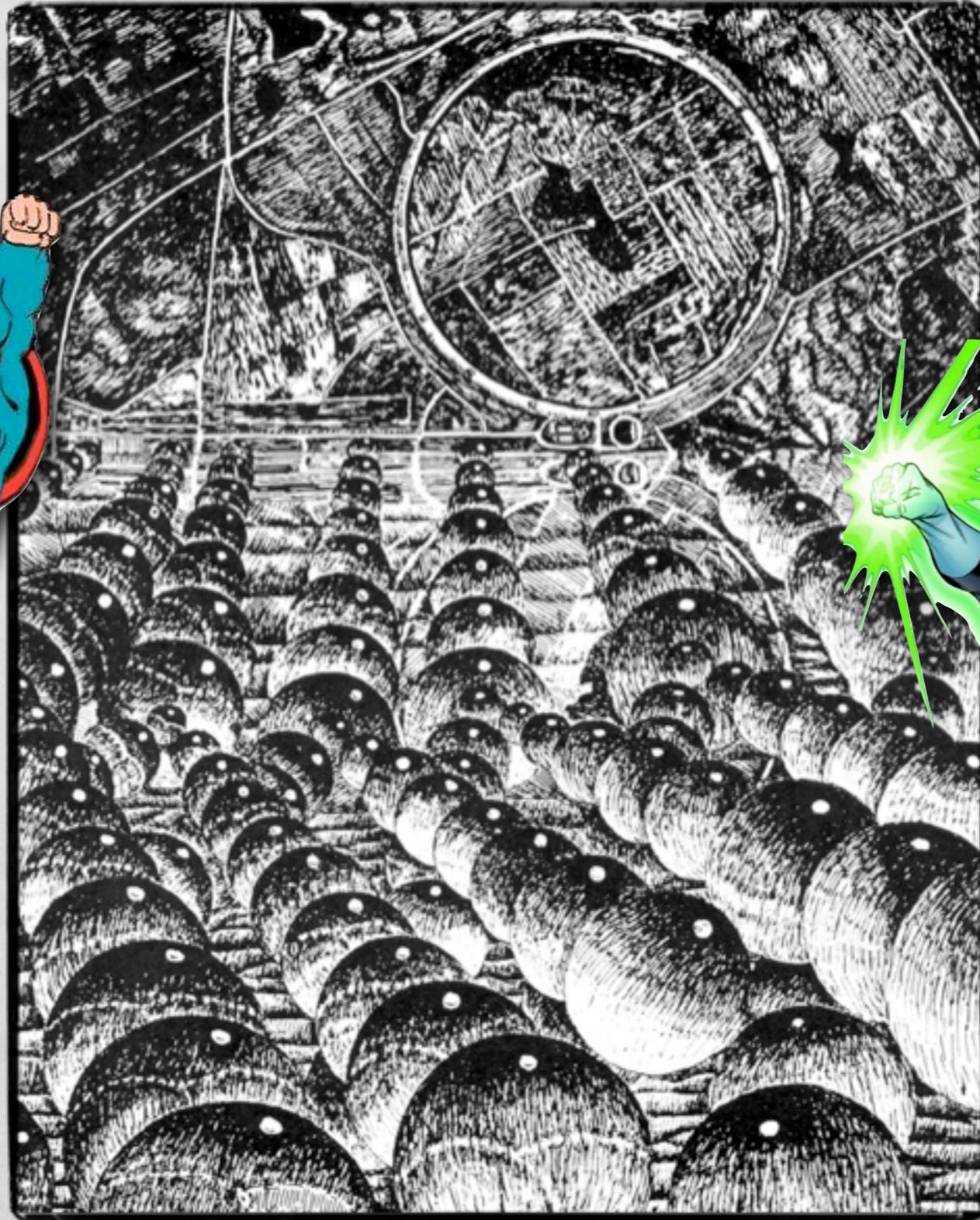
- Particle spectrum
- A single interaction
- Implies SUSY and Extra Dimensions
- contains other objects "branes"  
could even explain gravity
- Has evolved into "M-theory"  
But... the equations have many solutions  
corresponding to different Universes  
The challenge is to find the solution to our Universe... = 42 ?



# Adventures in Collider-land

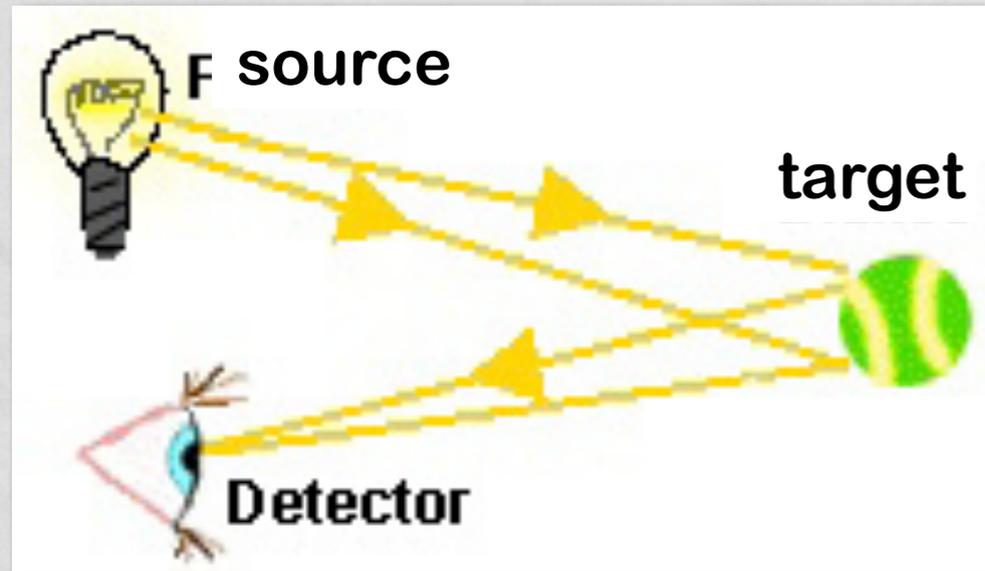


ENERGY

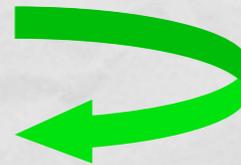


LUMINOSITY

# Accelerators are discovery machines !



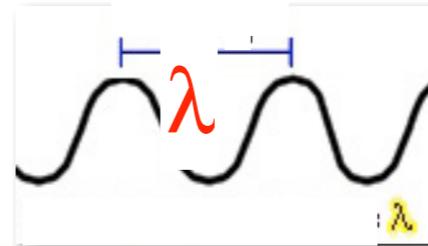
This is how we normally see



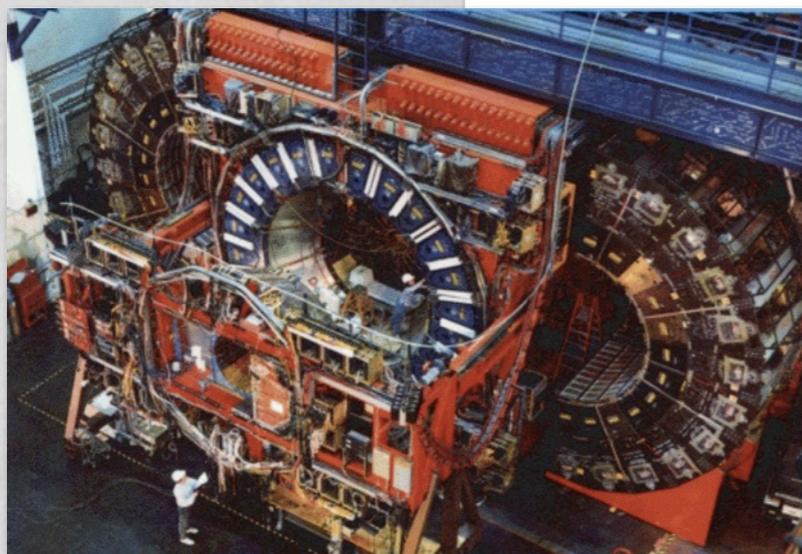
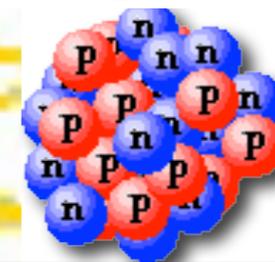
This is how we extend our senses !



Particle  
accelerator



Target



Detector

particles behaves like waves

A hand-drawn diagram of a green wave. A red double-headed arrow above the wave indicates the wavelength, labeled  $\lambda$ .

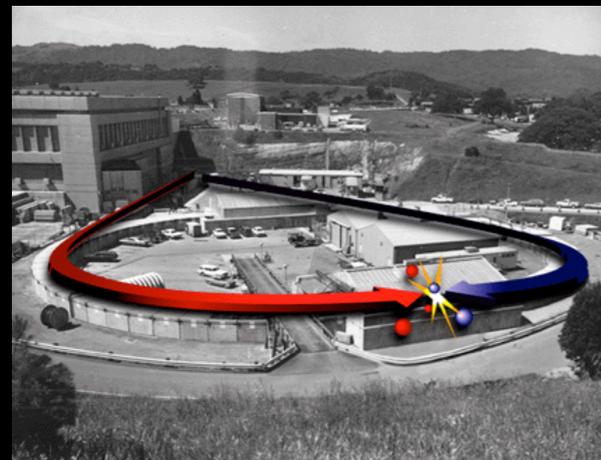
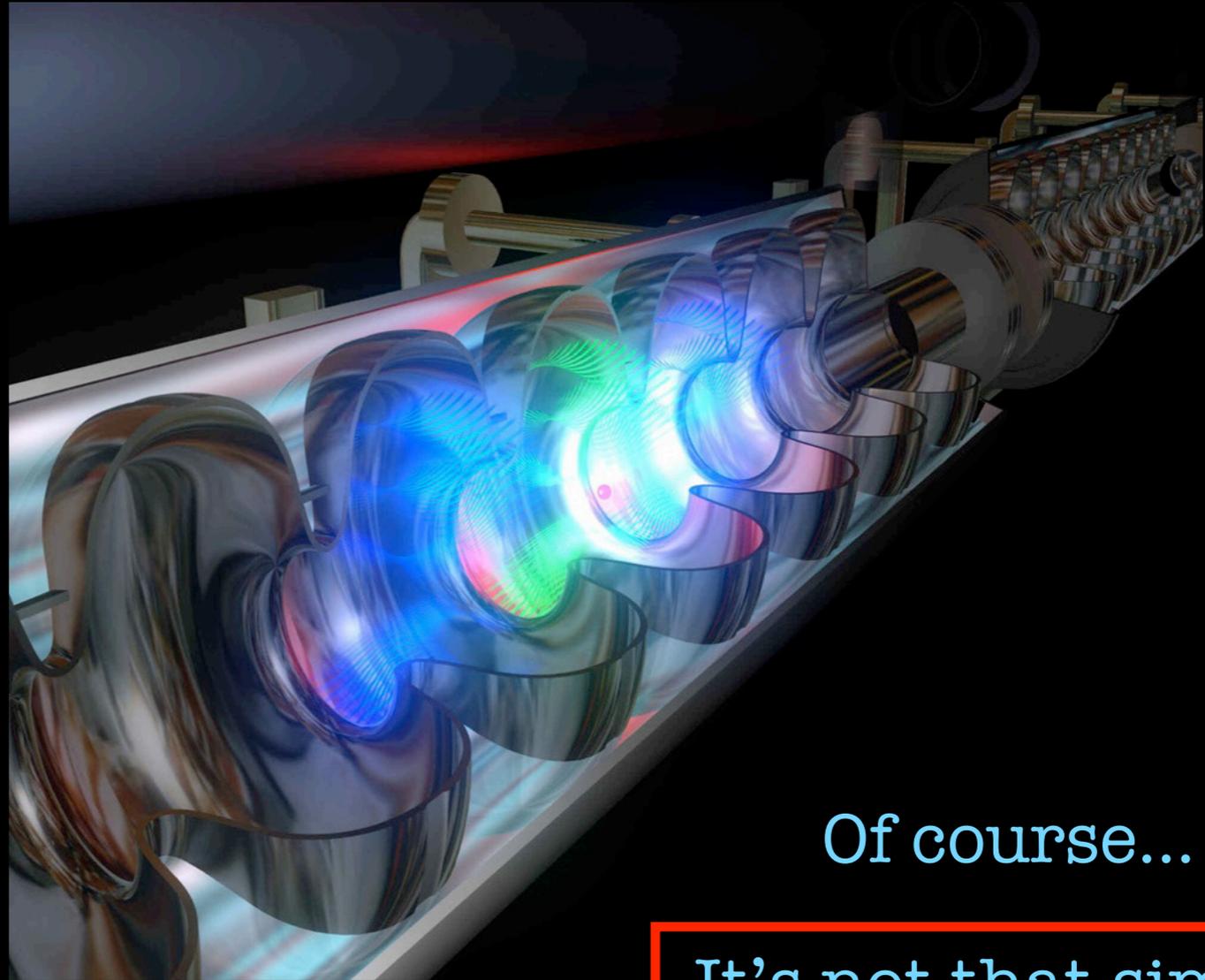
Momentum of particle  $p = \frac{h}{\lambda}$

$h$  ← Plancks constant  
 $\lambda$  ← wavelength

# A simple idea:

# Colliders

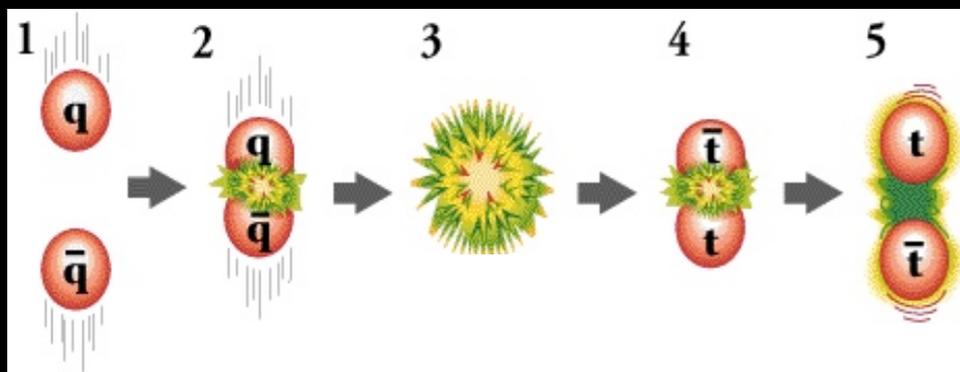
- \* Accelerate charged particles in an electric field
- \* Keep them in orbit using magnets
- \* Collide them against each other or a target
- \* See what comes out...



Of course...

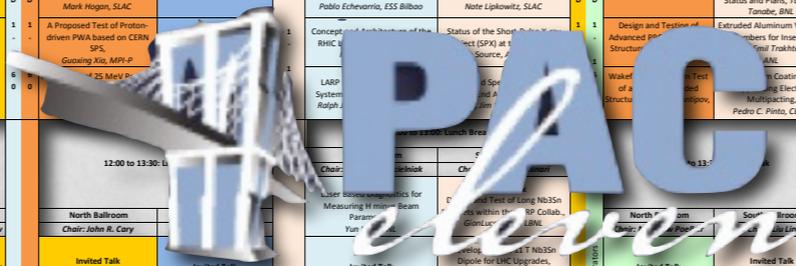
It's not that simple to build Multi TeV / high intensity machines

$$1 \text{ TeV} = 10^{12} \text{ eV}$$



# Here is the evidence:

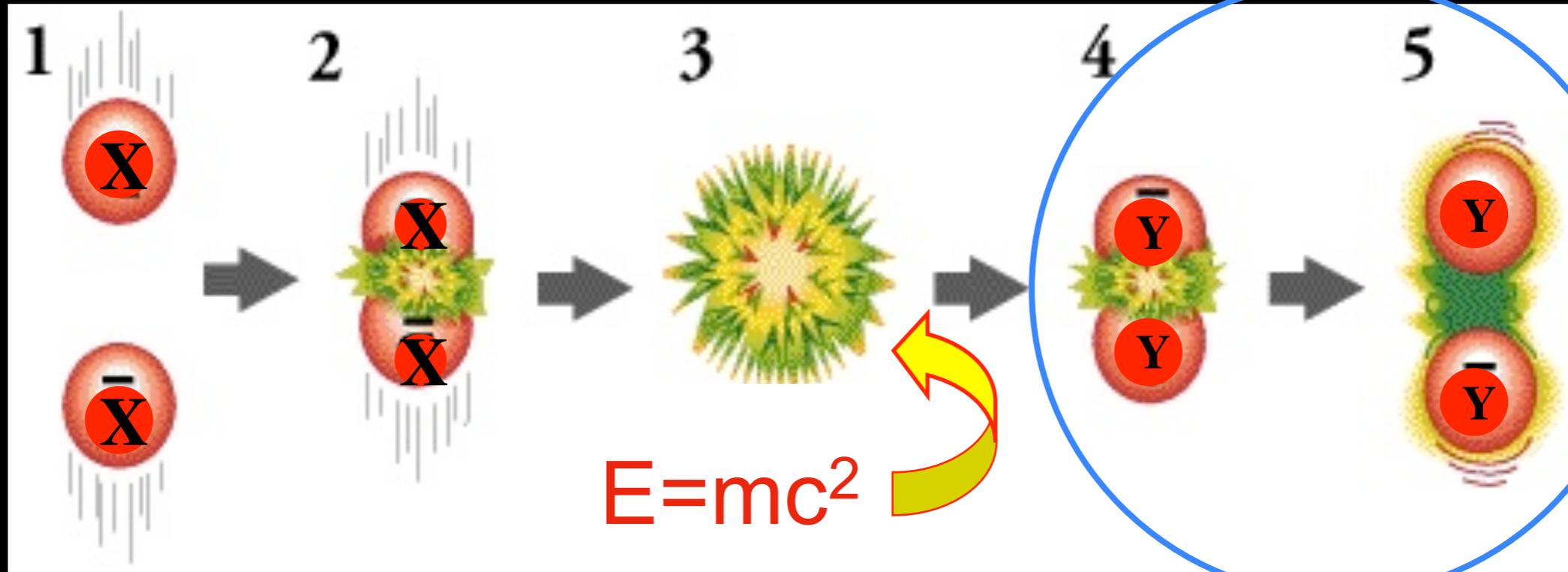
|       |   | PAC'11 Synoptic Table   |  |   |  |   |  |  |  |   |  |
|-------|---|---|--|---|--|---|--|--|--|---|--|
|       |   | Monday, March 28  |  | Tuesday, March 29   |  | Wednesday, March 30   |  | Thursday, March 31   |  | Friday, April 1   |  |
|       |   | 7:30 to 17:30 Registration  |  | 8:00 to 17:00 Registration  |  | 8:00 to 17:00 Registration  |  | 8:00 to 17:00 Registration   |  | 8:30 to 10:00 Registration  |  |
|       |   | Broadway Ballroom   |  | North Ballroom  |  | South Ballroom  |  | North Ballroom   |  | South Ballroom  |  |
|       |   | Chair: Vladimir K. Litvinenko   |  | Chair: Steve Gourlay  |  | Chair: Johan Bengtsson  |  | Chair: Kevin Brown   |  | Chair: Yu-Juan Chen   |  |
| 8:30  | Opening Remarks   |   |  | Recent SuperB Design Choices, Walter Wittmer, SLAC  |  | Invited Talk Accelerator Timing Systems Overview, Javier Serrano, CERN                                |  | Invited Talk Linac Timing, Synchronization and Active Stabilization, Florian Loebl, CLASSE                       |  | Importance of Symmetrizing RF Couplers for Low Emittance Beams, Zenghai Li, SLAC                  |  |
| 8:45  | Plenary Talk Understanding Elementary Particle Physics with High Energy Colliders, Jacobo Kanioglu, University of Florida | High Luminosity Electron-Positron Colliders eRHIC, Vladimir Ptitsyn, BNL  |  | Tutorial on Accelerator-Based Light Sources, Michael Borland, ANL   |  | Invited Talk Simultaneous Orbit, Tune, Coupling, and Chromaticity Feedback at RHIC, Michko Minty, BNL |  | Tutorial on Heavy Ion Driven Inertial Fusion, William M. Sharp, LLNL   |  | Solid State RF Power - The route to 1 Watt per Euro Cent?, Oliver Heel, Siemens AG                |  |
| 9:00  |   | Lattice Design for eRHIC and LCLS, Dejan Trbojevic, BNL   |  | Cornell ERL Research and Development, Christopher Mayes, CLASSE   |  | Real-Time Beam Control at the LHC, Ralph J. Steinhilber, CERN   |  | Muon Collider Final Cooling in 30-50 T Solenoids, Robert B. Palmer, BNL  |  | Status of the Oak Ridge SNS RF Systems, Thomas Hensel, ORNL                                       |  |
| 9:15  |   | Feedback Scheme for Fast Instability in ERL Based Electron Ion Collider, Yue Hao, BNL                                     |  | Resonant Excitation of PW in the Linear and Nonlinear Regime, Patric Muggli, USC                              |  | Conceptual Architecture of the RHIC Upgrade, Steve W. Lee, BNL  |  | Design and Testing of Advanced Structures for Insertion Devices, Paul Trankenberg, ANL                           |  | RF Breakdown Threshold of Accelerator Structures by Magnetic Insulation, Dávidy Stratosik, CLASSE |  |
| 9:30  | 9:30-10:00 Coffee Break   |   |  | 9:30-10:00 Coffee Break   |  | 9:30-10:00 Coffee Break   |  | 9:30-10:00 Coffee Break  |  | 9:30-10:00 Coffee Break   |  |
| 10:00 |   | Invited Talk CERN STAND-1 Detection, Brandon Blackburn, RTN IDS   |  | Invited Talk Acceleration Beyond 1 GeV Using Ionization Induced Injection, Kenneth Marsh, UCLA                |  | Invited Talk Real-Time Beam Control at the LHC, Ralph J. Steinhilber, CERN                            |  | Invited Talk R&D towards a Neutrino Factory or Muon Collider, Status of International MICE, Michael Zisman, LBNL |  | Invited Talk Developments in Superconducting Insertion Devices, Elizabeth R. Moog, ANL            |  |
| 10:15 |   | Inverse-FEL Accelerator for Driving Compact Light Sources, Aaron Tremaine, RadiaBeam                                      |  | Invited Talk Progress Towards a Free-Electron Laser Driven by a Laser-plasma Accelerator, Andrea R. Moir, LMU |  | Improved Energy Changes at the Linac Coherent Light Source, Note Lipkowitz, SLAC                      |  | Muon Collider Final Cooling in 30-50 T Solenoids, Robert B. Palmer, BNL  |  | Optimization of Magnet Stability and Alignment for NLS-II, Sushil Sharma, BNL                     |  |
| 10:30 |   | Comparison of Accelerator Technologies for use in ADS, Bill Weng, BNL   |  | Plasma Wakefield Experiments at FACET, Mark Hogan, SLAC   |  | Conceptual Architecture of the RHIC Upgrade, Steve W. Lee, BNL  |  | Design and Testing of Advanced Structures for Insertion Devices, Paul Trankenberg, ANL                           |  | Invited Talk Technical Challenges in Design and Construction of FRIB, Richard York, NSCL          |  |
| 10:45 |   | Invited Talk State of the Art in Medical and Industrial Linear-Accelerator Systems, David Whitlum, Varian Medical Systems |  | Status of the NLS-II Project, Ferdinand J. Wilke, BNL   |  | Multipurpose Controller Based on a FPGA with EPIC Integration, Pablo Echeverri, ESS Bilbao            |  | Demonstration of a Two-Stage Laser Wakefield Accelerator, Bradley B. Pollock, LLNL                               |  | Magnetic Axis Determination of Pulsed Solenoids, Diego Avelar, LBNL                               |  |
| 11:00 |   | Invited Talk Electron Cloud Experiments at Fermilab: Formulation and Mitigation, Robert M. Zwozick, Fermilab              |  | Plasma Wakefield Experiments at FACET, Mark Hogan, SLAC   |  | Conceptual Architecture of the RHIC Upgrade, Steve W. Lee, BNL  |  | Improved Energy Changes at the Linac Coherent Light Source, Note Lipkowitz, SLAC                                 |  | Insertion Device Development at NLS-II: Status and Plans, Toshiya Tamabe, BNL                     |  |
| 11:15 |   | Invited Talk Maximizing Technology Transfer Benefits to Society, Andreas Peters, HIT                                      |  | A Proposed Test of Proton-Driven PWA based on CERN SPS, Guojing Xia, MPI-P                                    |  | Conceptual Architecture of the RHIC Upgrade, Steve W. Lee, BNL  |  | Status of the Short Pulse FEL (SPX) at the SLAC, Steve W. Lee, BNL   |  | Extruded Aluminum Vacuum Chambers for Insertion Devices, Paul Trankenberg, ANL                    |  |
| 11:30 |   | Invited Talk Non-neutral Plasma Traps for Status of LHC Operations and Physics Programs, Stefano Rodighiero, CERN         |  | Computation of Transfer Maps for Realistic Beamline Elements from Surface Data, Chad E. Mitchell, ANL         |  | Operational Results from the LHC Luminosity Monitors, Aydin Myrzatov, BNL                             |  | Integrated EM & Thermal Simulations with Upgraded VORPAL, David Smith, Tech-X                                    |  | SRF Materials R&D, Lance Cooley, Fermilab   |  |
| 11:45 |   | Invited Talk Tevatron Accelerator Physics and Operation Highlights, Alexander Vaitavich, Fermilab                         |  | Spin Manipulating Polarized Protons and Deuterons, Vasily Morozov, ODU  |  | Status of the ALS Upgrade, Christoph Steier, LBNL   |  | Experience of the Cryogenic System for Taiwan Light Source, Feng Zhen Hsiao, NSRRC                               |  | SRF Materials R&D, Lance Cooley, Fermilab   |  |
| 12:00 | 12:00 to 13:30 Lunch Break  |   |  | Application of the Eigen-Emission Concept to Ultra-bright e-Beams, Leonor Duffy, LBNL                         |  | Upgrade of Accelerator Complex at Pohang Light Source Facility (PLS-II), Kyung Ryul Kim, PAL          |  | The Injector Cryomodule for e-Linac at TRIUMF, Robert E. Lovell, TRIUMF  |  | SRF Materials R&D, Lance Cooley, Fermilab   |  |
| 12:30 |   | Invited Talk Improvements in the RHIC Polarized Proton Operation, Hsueh Huang, BNL  |  | Subpicosecond Electron Bunch Train Production, Yin-E Sam, Fermilab  |  | A Next Generation Light Source Facility at LBNL, John Corlett, LBNL                                   |  | Beam Halo Measurements with an Adaptive Mask, Hao Zhang, UMD   |  | High-Power Options for LANSCE, Robert Garnett, LANL   |  |
| 13:00 |   | Invited Talk Status of the KEK Upgrade, John W. Flanagan, KEK   |  | A Theoretical Model for Emittance Exchange Induced by Linear Coupling, Hong Qin, PPSL                         |  | An VUV FEL for Producing 70-100 MeV Circularly Polarized g-ray Beams, Ying K. Wu, FEL/Duke U          |  | Rec-Resolved Determination of Pulses Overlap in sFLASH, Rossana Tomkowiak, UvH                                   |  | ATLAS Upgrade, Peter Ostromou, ANL  |  |
| 13:30 |   | Invited Talk Results of Beam-on-Beam Compensation Studies at the Tevatron, Guido Stanzani, Fermilab                       |  | Space-Charge Effects in H Low-energy Beam Transport of LANSCE, Yuri Bityagin, LANL                            |  | Emittance Exchange and Bunch Compression, Alexander Zhents, ANL                                       |  | Beam Halo Measurements with an Adaptive Mask, Hao Zhang, UMD   |  | High-Power Options for LANSCE, Robert Garnett, LANL   |  |
| 13:45 |   | Invited Talk Optimizing the e-Beam for Head-on Beam-beam Compensation in RHIC, Yun-Lan Liu, BNL                           |  | Time-Dependent Phase-Space Measurements of Beams in NODC-I, Steven M. Lofe, LBNL                              |  | A Theoretical Model for Emittance Exchange Induced by Linear Coupling, Hong Qin, PPSL                 |  | Beam Halo Measurements with an Adaptive Mask, Hao Zhang, UMD   |  | High-Power Options for LANSCE, Robert Garnett, LANL   |  |
| 14:00 |   | Invited Talk Advanced Crystal Calibration Studies at the Tevatron (T-SR0), Viktoriya Zlobin, Fermilab                     |  | Space-Charge Effects in H Low-energy Beam Transport of LANSCE, Yuri Bityagin, LANL                            |  | A Theoretical Model for Emittance Exchange Induced by Linear Coupling, Hong Qin, PPSL                 |  | Beam Halo Measurements with an Adaptive Mask, Hao Zhang, UMD   |  | High-Power Options for LANSCE, Robert Garnett, LANL   |  |
| 14:15 |   | Invited Talk Beam Losses due to Abort Crab Cavity Failures in HL-LHC, Remy Collinge, BNL                                  |  | Space-Charge Effects in H Low-energy Beam Transport of LANSCE, Yuri Bityagin, LANL                            |  | A Theoretical Model for Emittance Exchange Induced by Linear Coupling, Hong Qin, PPSL                 |  | Beam Halo Measurements with an Adaptive Mask, Hao Zhang, UMD   |  | High-Power Options for LANSCE, Robert Garnett, LANL   |  |
| 14:30 |   | Invited Talk Muon Collider IR and Machine Interface Design, Marko V. Andreev, Fermilab                                    |  | Space-Charge Effects in H Low-energy Beam Transport of LANSCE, Yuri Bityagin, LANL                            |  | A Theoretical Model for Emittance Exchange Induced by Linear Coupling, Hong Qin, PPSL                 |  | Beam Halo Measurements with an Adaptive Mask, Hao Zhang, UMD   |  | High-Power Options for LANSCE, Robert Garnett, LANL   |  |
| 14:45 |   | Invited Talk Responsibility Correction for a Muon Collider, Eliana Gonzalez-Verns, Fermilab                               |  | Space-Charge Effects in H Low-energy Beam Transport of LANSCE, Yuri Bityagin, LANL                            |  | A Theoretical Model for Emittance Exchange Induced by Linear Coupling, Hong Qin, PPSL                 |  | Beam Halo Measurements with an Adaptive Mask, Hao Zhang, UMD   |  | High-Power Options for LANSCE, Robert Garnett, LANL   |  |
| 15:00 | Registration 15:00 - 19:00  | Invited Talk Muon Collider IR and Machine Interface Design, Marko V. Andreev, Fermilab                                    |  | Space-Charge Effects in H Low-energy Beam Transport of LANSCE, Yuri Bityagin, LANL                            |  | A Theoretical Model for Emittance Exchange Induced by Linear Coupling, Hong Qin, PPSL                 |  | Beam Halo Measurements with an Adaptive Mask, Hao Zhang, UMD   |  | High-Power Options for LANSCE, Robert Garnett, LANL   |  |
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| 16:00 |   | Invited Talk Muon Collider IR and Machine Interface Design, Marko V. Andreev, Fermilab                                    |  | Space-Charge Effects in H Low-energy Beam Transport of LANSCE, Yuri Bityagin, LANL                            |  | A Theoretical Model for Emittance Exchange Induced by Linear Coupling, Hong Qin, PPSL                 |  | Beam Halo Measurements with an Adaptive Mask, Hao Zhang, UMD   |  | High-Power Options for LANSCE, Robert Garnett, LANL   |  |
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| 17:00 | Student Poster Set-up   | Invited Talk Muon Collider IR and Machine Interface Design, Marko V. Andreev, Fermilab                                    |  | Space-Charge Effects in H Low-energy Beam Transport of LANSCE, Yuri Bityagin, LANL                            |  | A Theoretical Model for Emittance Exchange Induced by Linear Coupling, Hong Qin, PPSL                 |  | Beam Halo Measurements with an Adaptive Mask, Hao Zhang, UMD   |  | High-Power Options for LANSCE, Robert Garnett, LANL   |  |
| 17:15 | Judges Orientation  | Invited Talk Muon Collider IR and Machine Interface Design, Marko V. Andreev, Fermilab                                    |  | Space-Charge Effects in H Low-energy Beam Transport of LANSCE, Yuri Bityagin, LANL                            |  | A Theoretical Model for Emittance Exchange Induced by Linear Coupling, Hong Qin, PPSL                 |  | Beam Halo Measurements with an Adaptive Mask, Hao Zhang, UMD   |  | High-Power Options for LANSCE, Robert Garnett, LANL   |  |
| 17:30 |   | Invited Talk Muon Collider IR and Machine Interface Design, Marko V. Andreev, Fermilab                                    |  | Space-Charge Effects in H Low-energy Beam Transport of LANSCE, Yuri Bityagin, LANL                            |  | A Theoretical Model for Emittance Exchange Induced by Linear Coupling, Hong Qin, PPSL                 |  | Beam Halo Measurements with an Adaptive Mask, Hao Zhang, UMD   |  | High-Power Options for LANSCE, Robert Garnett, LANL   |  |
| 18:00 |   | Invited Talk Muon Collider IR and Machine Interface Design, Marko V. Andreev, Fermilab                                    |  | Space-Charge Effects in H Low-energy Beam Transport of LANSCE, Yuri Bityagin, LANL                            |  | A Theoretical Model for Emittance Exchange Induced by Linear Coupling, Hong Qin, PPSL                 |  | Beam Halo Measurements with an Adaptive Mask, Hao Zhang, UMD   |  | High-Power Options for LANSCE, Robert Garnett, LANL   |  |
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| 19:00 | Student Poster Session and Reception  | Invited Talk Muon Collider IR and Machine Interface Design, Marko V. Andreev, Fermilab                                    |  | Space-Charge Effects in H Low-energy Beam Transport of LANSCE, Yuri Bityagin, LANL                            |  | A Theoretical Model for Emittance Exchange Induced by Linear Coupling, Hong Qin, PPSL                 |  | Beam Halo Measurements with an Adaptive Mask, Hao Zhang, UMD   |  | High-Power Options for LANSCE, Robert Garnett, LANL   |  |
| 19:30 |   | Invited Talk Muon Collider IR and Machine Interface Design, Marko V. Andreev, Fermilab                                    |  | Space-Charge Effects in H Low-energy Beam Transport of LANSCE, Yuri Bityagin, LANL                            |  | A Theoretical Model for Emittance Exchange Induced by Linear Coupling, Hong Qin, PPSL                 |  | Beam Halo Measurements with an Adaptive Mask, Hao Zhang, UMD   |  | High-Power Options for LANSCE, Robert Garnett, LANL   |  |
| 20:00 |   | Invited Talk Muon Collider IR and Machine Interface Design, Marko V. Andreev, Fermilab                                    |  | Space-Charge Effects in H Low-energy Beam Transport of LANSCE, Yuri Bityagin, LANL                            |  | A Theoretical Model for Emittance Exchange Induced by Linear Coupling, Hong Qin, PPSL                 |  | Beam Halo Measurements with an Adaptive Mask, Hao Zhang, UMD   |  | High-Power Options for LANSCE, Robert Garnett, LANL   |  |
| 21:00 |   | Invited Talk Muon Collider IR and Machine Interface Design, Marko V. Andreev, Fermilab                                    |  | Space-Charge Effects in H Low-energy Beam Transport of LANSCE, Yuri Bityagin, LANL                            |  | A Theoretical Model for Emittance Exchange Induced by Linear Coupling, Hong Qin, PPSL                 |  | Beam Halo Measurements with an Adaptive Mask, Hao Zhang, UMD   |  | High-Power Options for LANSCE, Robert Garnett, LANL   |  |



| Legend |   |
|--------|---|
|        | Tutorial  |
|        | Accelerator Technology                                |
|        | Advanced Concepts and Future Directions               |
|        | Applications of Accelerators, Tech Transfer, Industry |
|        | Beam Dynamics and EM Fields                           |
|        | Colliders   |
|        | Instrumentation and Controls                          |
|        | Light Sources and FELs                                |
|        | Sources and Medium Energy Accelerators                |
|        | Plenary and Awards                                    |

# At the collision point

Discoveries !



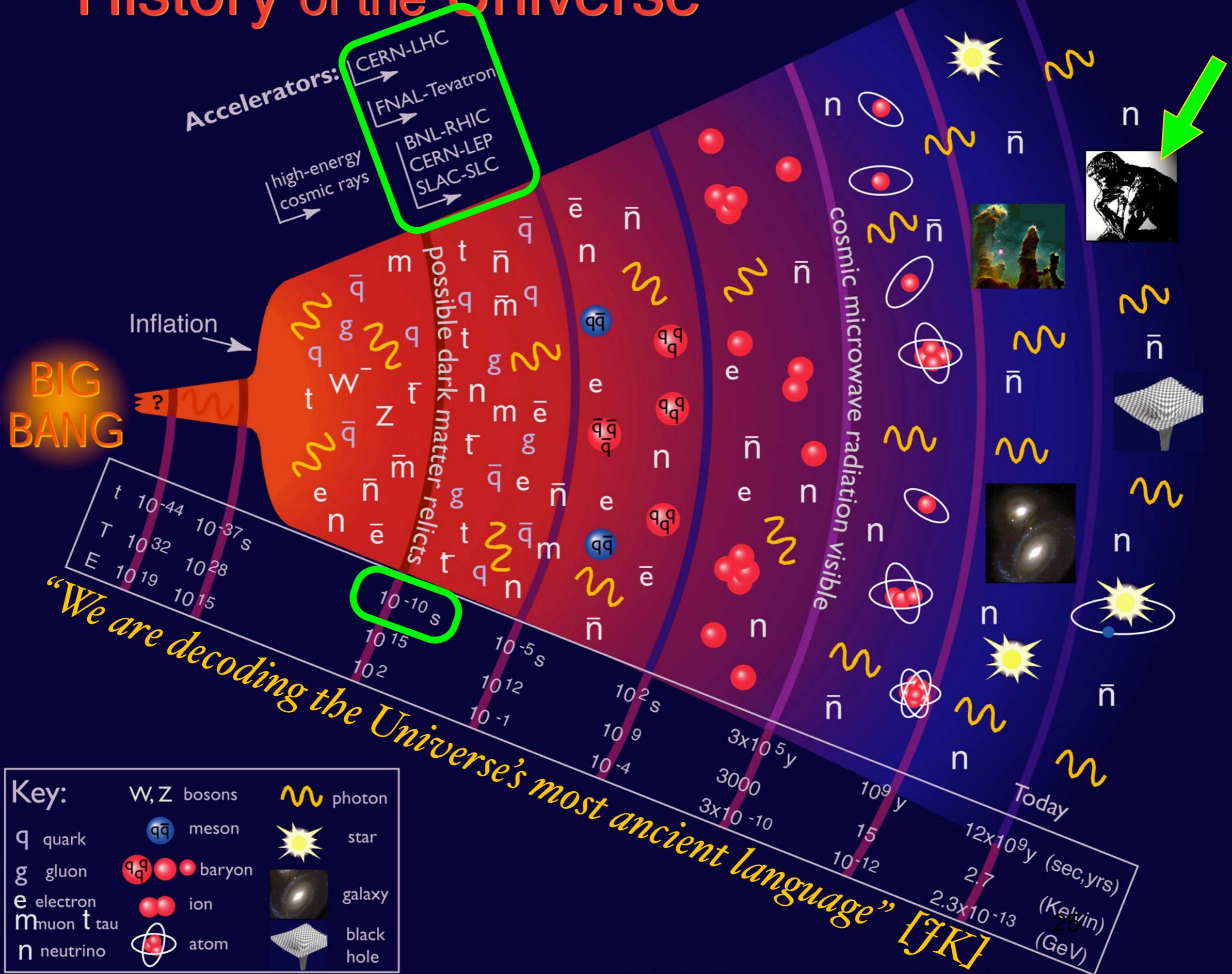
More energy  $\implies$  produce more massive particles

More energy  $\implies$  look in more detail

More energy  $\implies$  go back further in time !



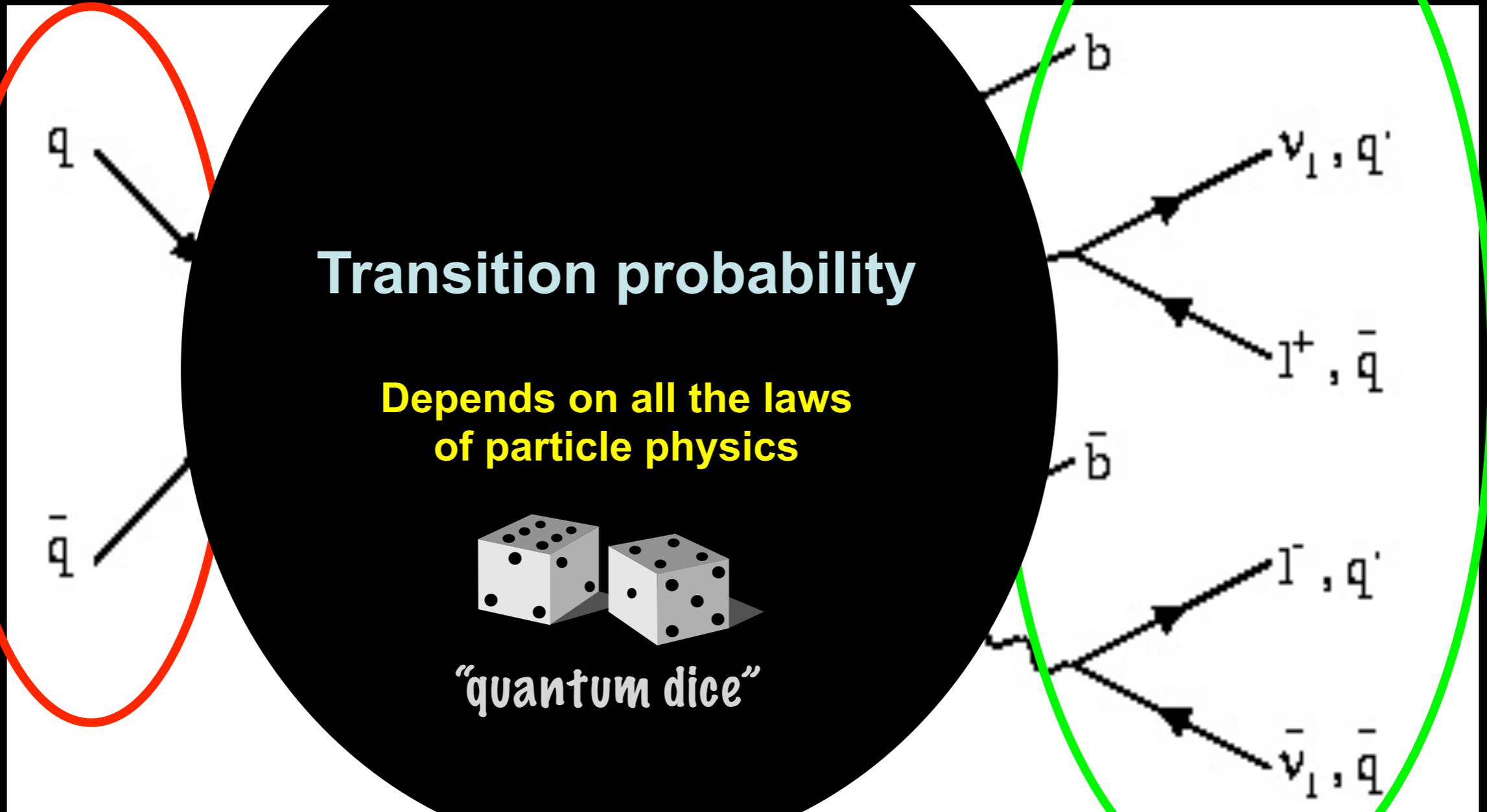
# History of the Universe



# At the collision point

Initial state

Final state



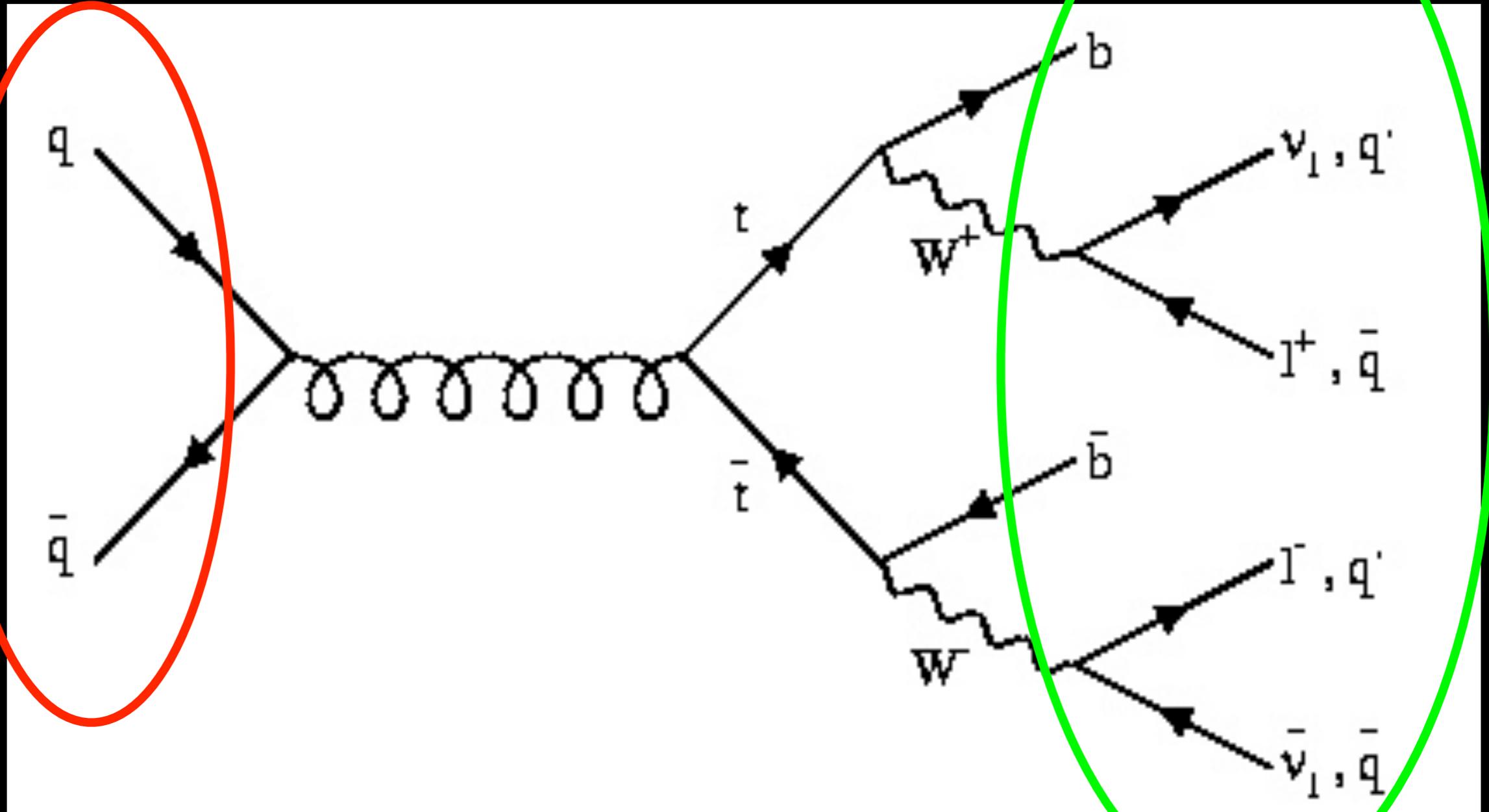
Accelerators

Detectors

# At the collision point

Initial state

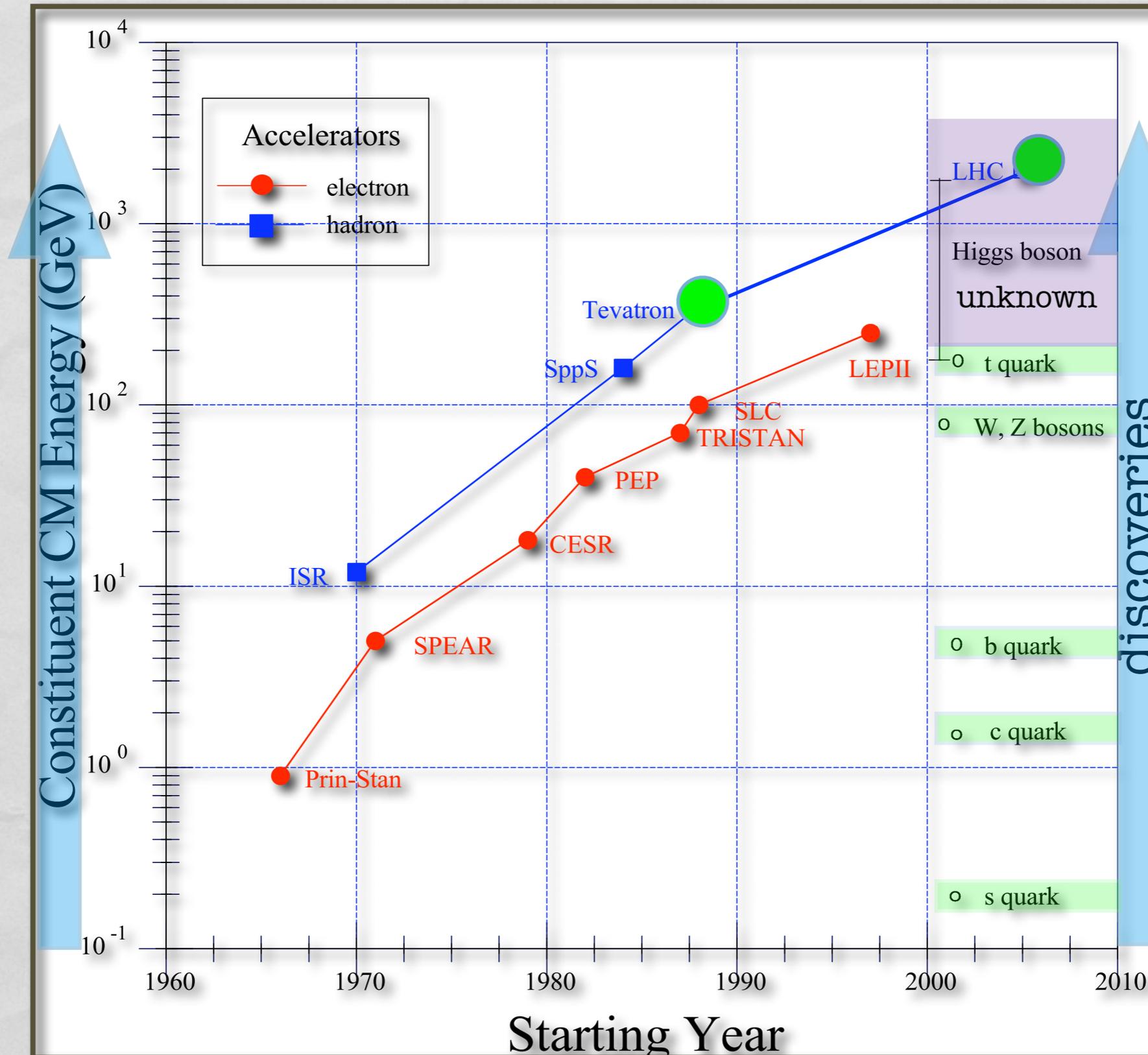
Final state



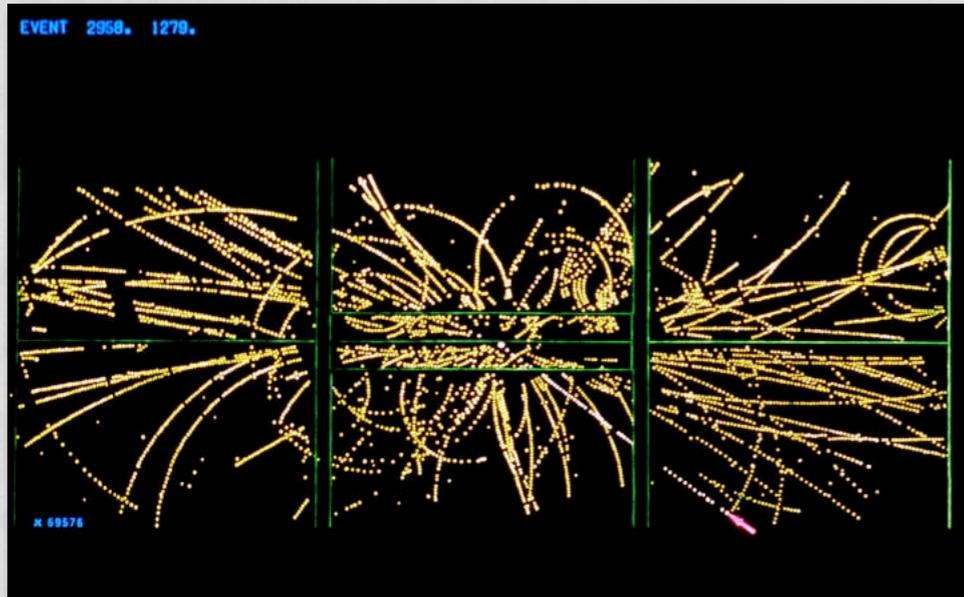
Accelerators

Detectors

# Energy ==> Discoveries



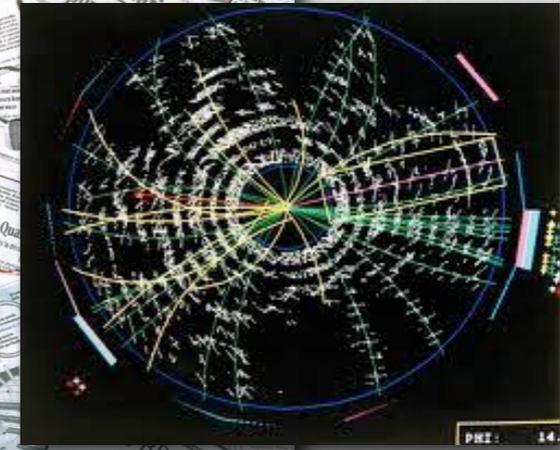
# Some Good Old Particle Discoveries at Accelerators



W-boson 1983  
@SPS-CERN

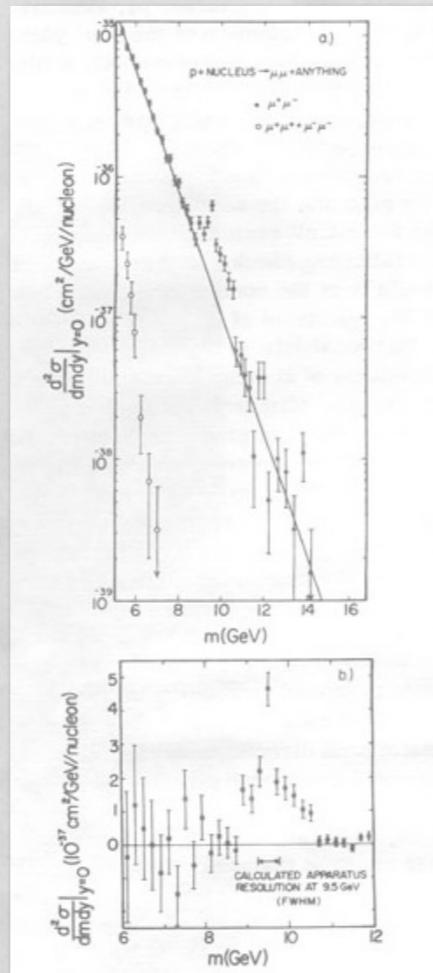
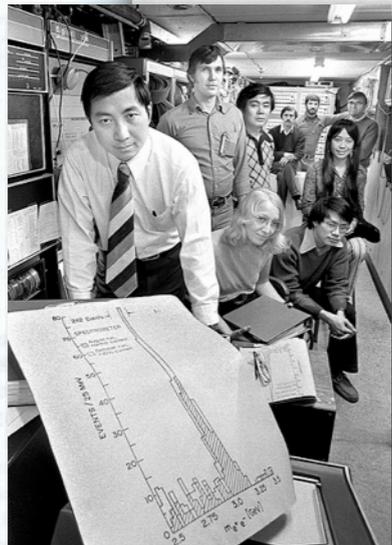
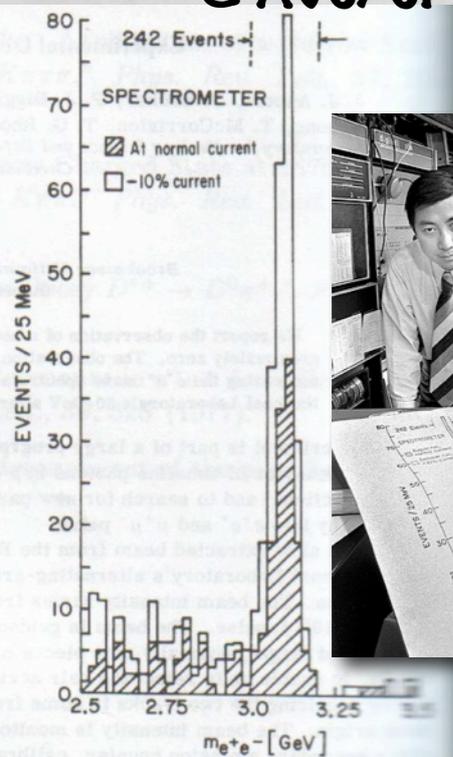


The Top 1995  
@Tevatron

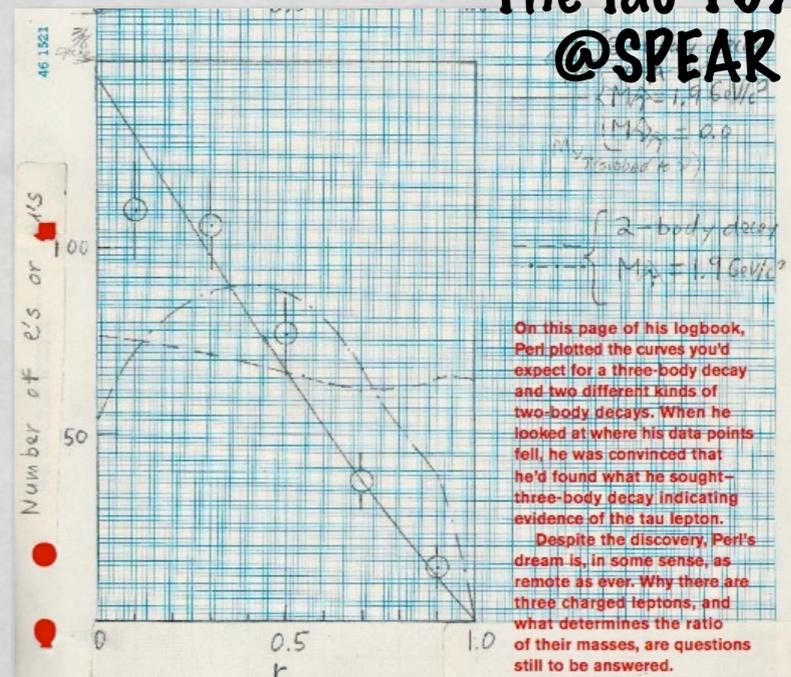


Bottom (upsilon) 1978  
@FNAL

Charm (J/psi) 1974  
@AGS/SPEAR



The Tau 1975  
@SPEAR



On this page of his logbook, Perl plotted the curves you'd expect for a three-body decay and two different kinds of two-body decays. When he looked at where his data points fell, he was convinced that he'd found what he sought—three-body decay indicating evidence of the tau lepton. Despite the discovery, Perl's dream is, in some sense, as remote as ever. Why there are three charged leptons, and what determines the ratio of their masses, are questions still to be answered.

# FOCUS ON

## Fermilab's Tevatron



Proton-antiproton collider

$$E_{cm} = 1.96 \text{ TeV}$$

- 10 million collisions/sec
- Two multi-purpose particle detectors: **CDF** and **DØ**
- First collisions on October 13, 1985 - at CDF



## CERN's LHC



Proton-proton collider

$$E_{cm} = \sqrt{s} \Rightarrow 14 \text{ TeV}$$

- goal: 1 billion collisions/sec
- Two multi-purpose particle detectors: **CMS** and **ATLAS**
- Two specialized detectors: **LHCb** and **ALICE**





# Nominal LHC Parameters Compared to Tevatron



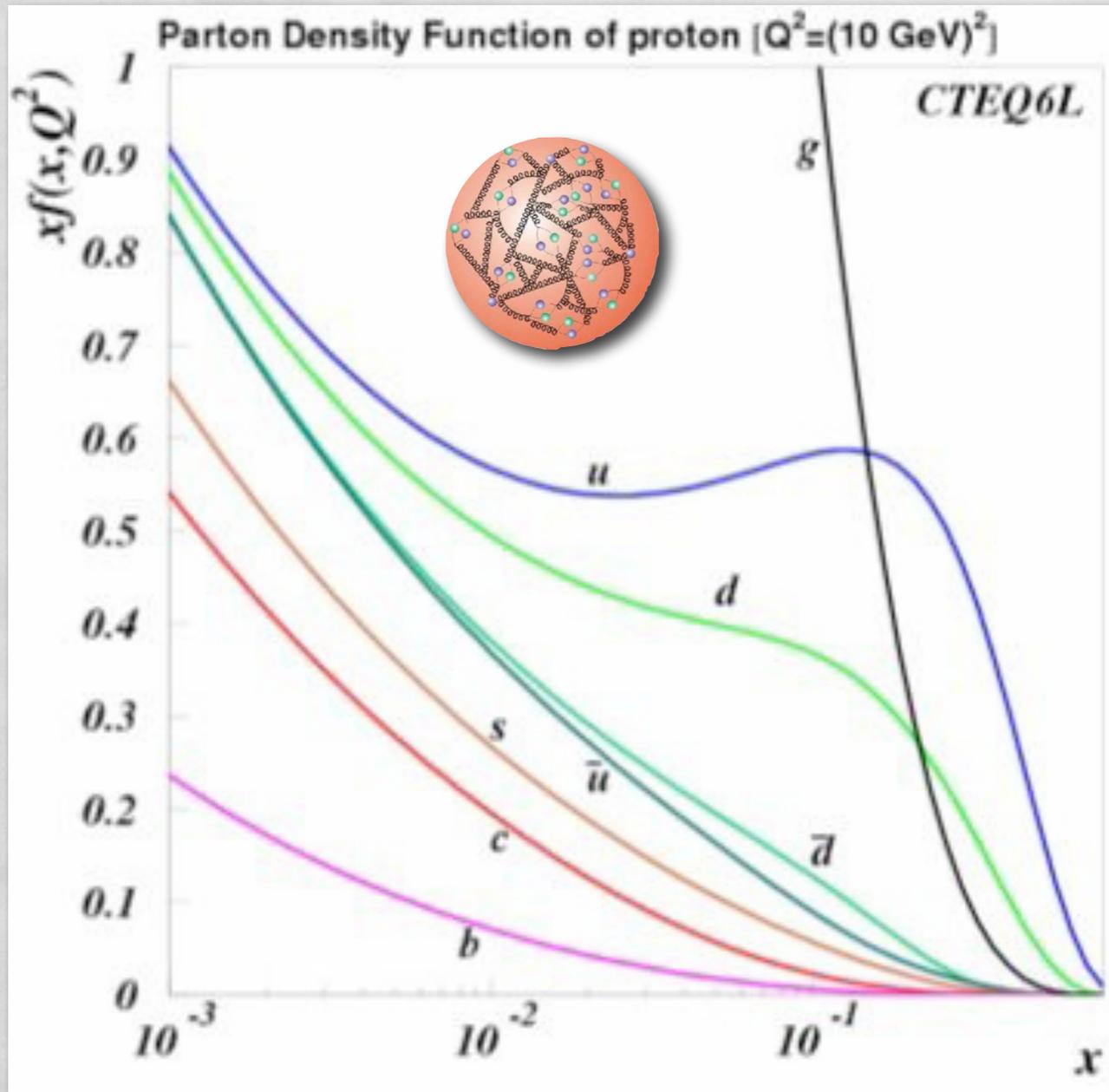
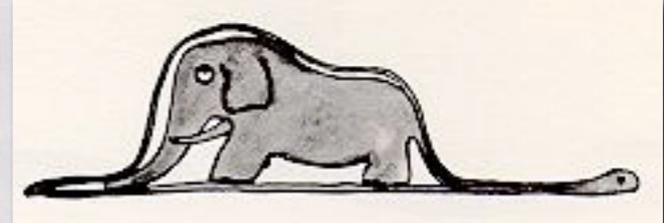
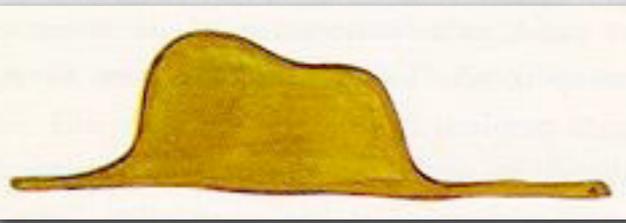
| Parameter             | Tevatron  | “nominal” LHC   |
|-----------------------|---|---|
| Circumference         | 6.28 km (2*PI)                                      | 27 km   |
| Beam Energy           | 980 GeV   | 7 TeV   |
| Number of bunches     | 36  | 2808  |
| Protons/bunch         | 275x10 <sup>9</sup>                                 | 115x10 <sup>9</sup>                                   |
| pBar/bunch            | 80x10 <sup>9</sup>                                  | -   |
| Stored beam energy    | 1.6 + .5 MJ   | 366+366 MJ*   |
| Peak luminosity       | 4x10 <sup>32</sup> cm <sup>-2</sup> s <sup>-1</sup> | 1.0x10 <sup>34</sup> cm <sup>-2</sup> s <sup>-1</sup> |
| Main Dipoles          | 780   | 1232  |
| Bend Field            | 4.2 T   | 8.3 T   |
| Main Quadrupoles      | ~200  | ~600  |
| Operating temperature | 4.2 K (liquid He)                                   | 1.9K (superfluid He)                                  |

$$1.0 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1} \sim 50 \text{ fb}^{-1} / \text{yr}$$

\*2.1 MJ  $\equiv$  “stick of dynamite”  $\Rightarrow$  very scary numbers



# Life in a proton



Parton-parton collisions:

CM energy is smaller than the proton-proton CM energy

At a fixed hadron collider energy:  
More luminosity buys you more chances of collisions at the highest-energies



**X = fraction of proton momentum taken by each parton**

# How many can we find of each?

$$N_{\text{top events}}^{\text{observed}} = \sigma(p\bar{p} \rightarrow t\bar{t}) \cdot L \cdot \varepsilon$$

$\sigma(p\bar{p} \rightarrow t\bar{t}) \sim$  "cross-section"  $\sim$  probability

**Physics** Units: 1 barn =  $10^{-24}$  cm<sup>2</sup>

$\varepsilon = \text{BR} \cdot \text{Acceptance} \cdot \text{Efficiencies}$

**Detectors & Experimental Analysis**

Integrated luminosity

**Accelerator** Units = fb<sup>-1</sup>

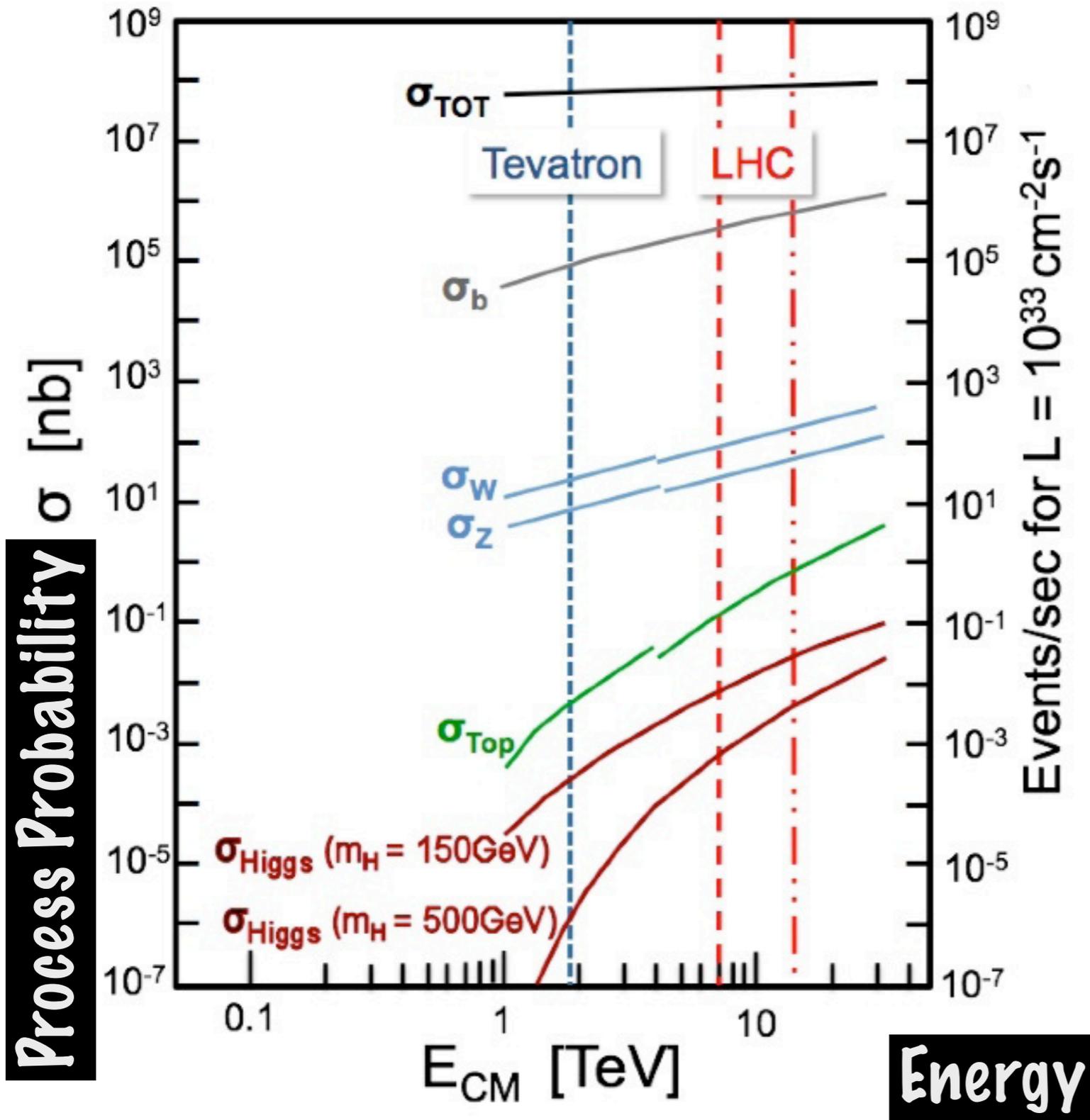
size of dataset  
"inverse femtobarns"

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

$\mathcal{L}$  = instantaneous luminosity [beam intensity]  
Units =  $10^{32}$  cm<sup>-2</sup>s<sup>-1</sup>

$$N_{\text{top events}}^{\text{observed}} = \sigma(pp \rightarrow t\bar{t}) \cdot L \cdot \epsilon$$

A jump in Energy helps



@ Tevatron

Top quarks/ $10^{10}$  collisions

Higgs/ $10^{11}$  -  $10^{12}$  collisions

@ LHC

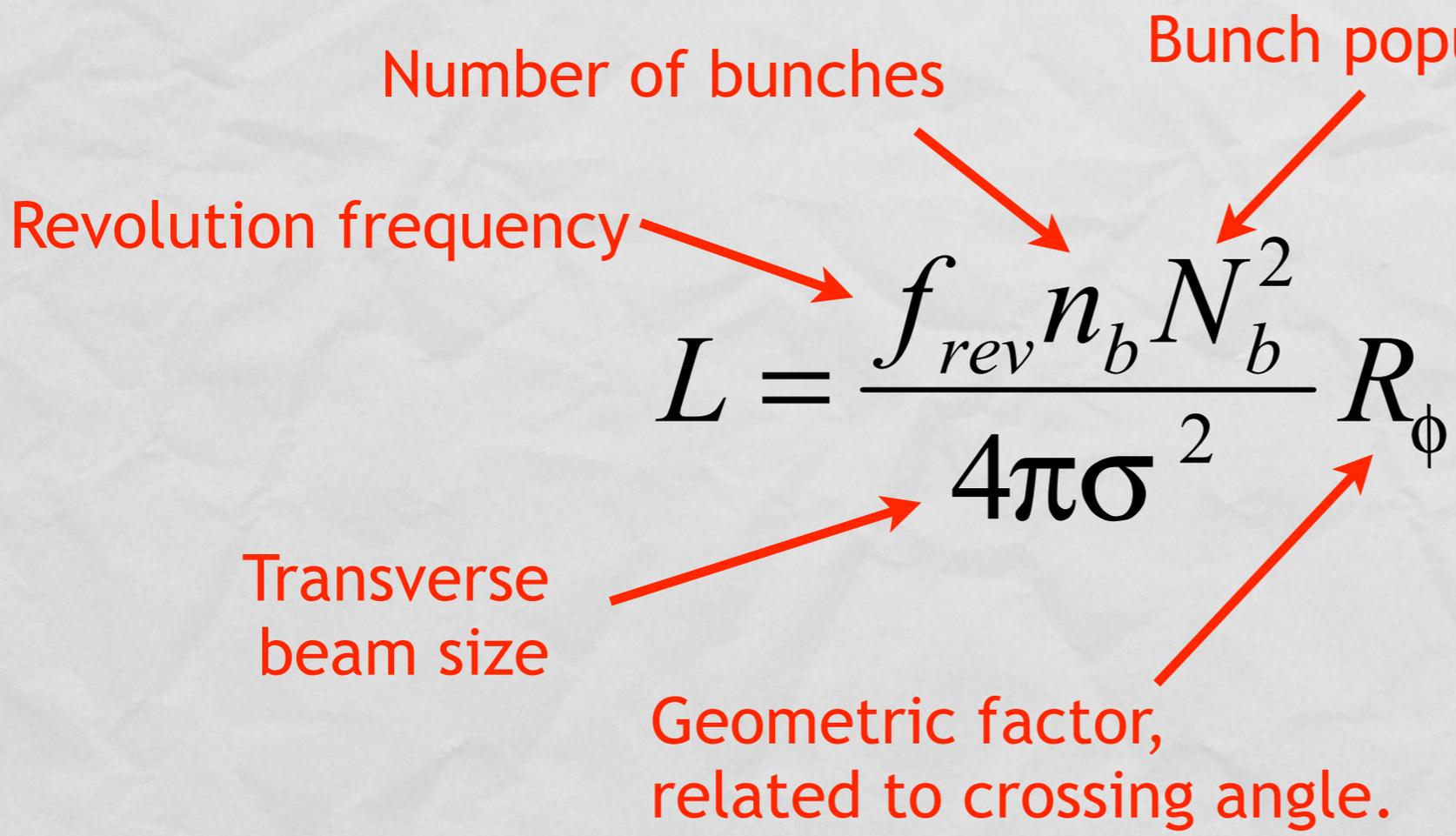
Top quarks/ $10^7$  collisions

Higgs/ $10^9$  -  $10^{10}$  collisions



# Luminosity is paramount

$$N_{\text{top events}}^{\text{observed}} = \sigma(p\bar{p} \rightarrow t\bar{t}) \cdot L \cdot \epsilon$$

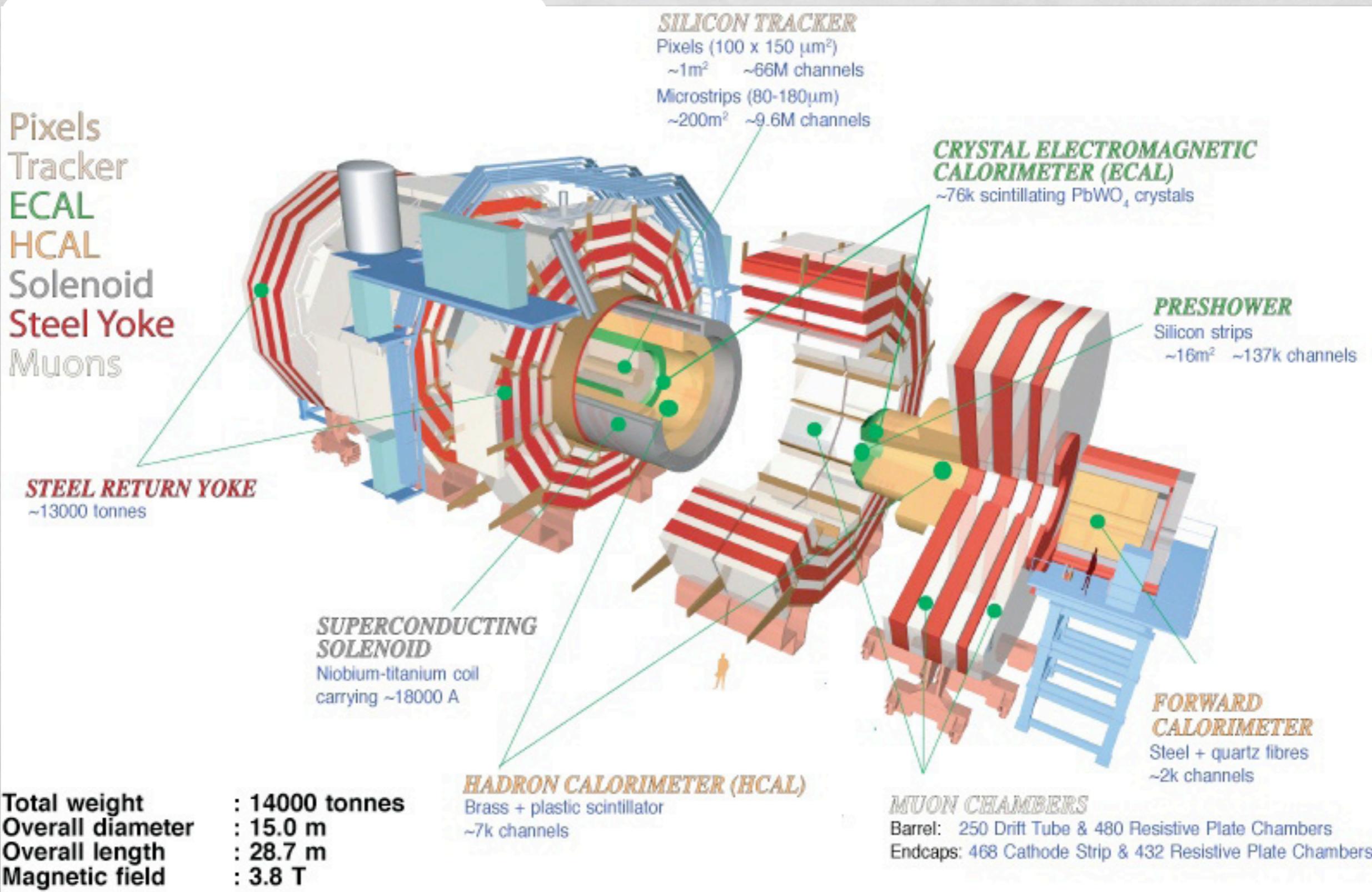


$$L = \frac{N_b^2 n_b f_r \gamma}{4\pi\epsilon_n \beta^*} F$$

| Symbol       | Quantity                                      | Affected by                        |
|--------------|---|------------------------------------|
| $N_b$        | Number of particles per bunch                 | Injector chain                     |
| $n_b$        | Number of bunches                             | Limited by electron cloud effect   |
| $f_r$        | Revolution Frequency                          | Property of LHC                    |
| $\epsilon_n$ | Normalized emittance                          | Injector chain                     |
| $\beta^*$    | Beta function value at Interaction Point (IP) | Interaction region focusing system |
| $F$          | Reduction factor due to crossing angle        | Beam separation schemes            |

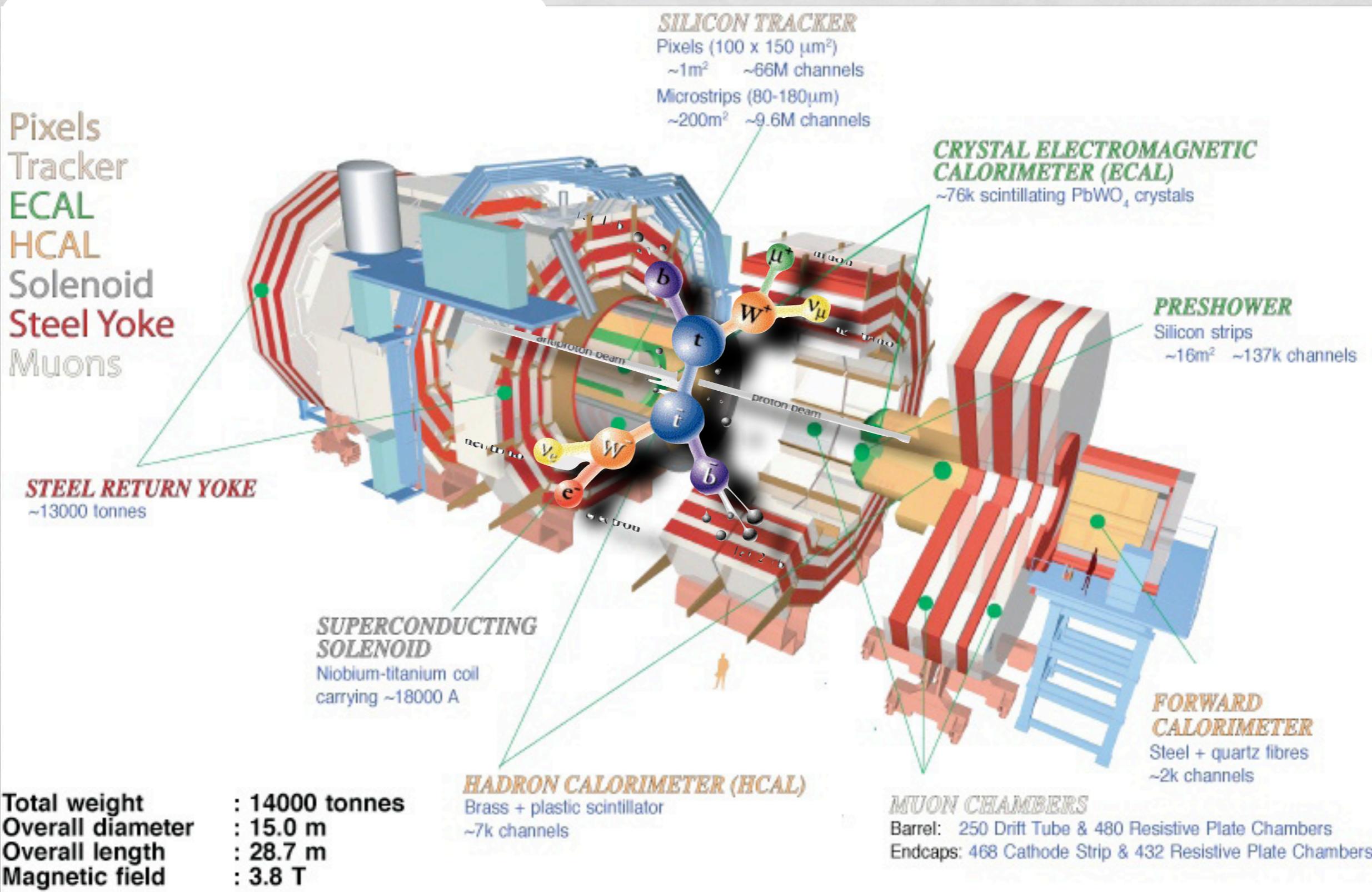
$$N_{\text{top events}}^{\text{observed}} = \sigma(p\bar{p} \rightarrow t\bar{t}) \cdot L \cdot \epsilon$$

And nothing wrong with having awesome detectors



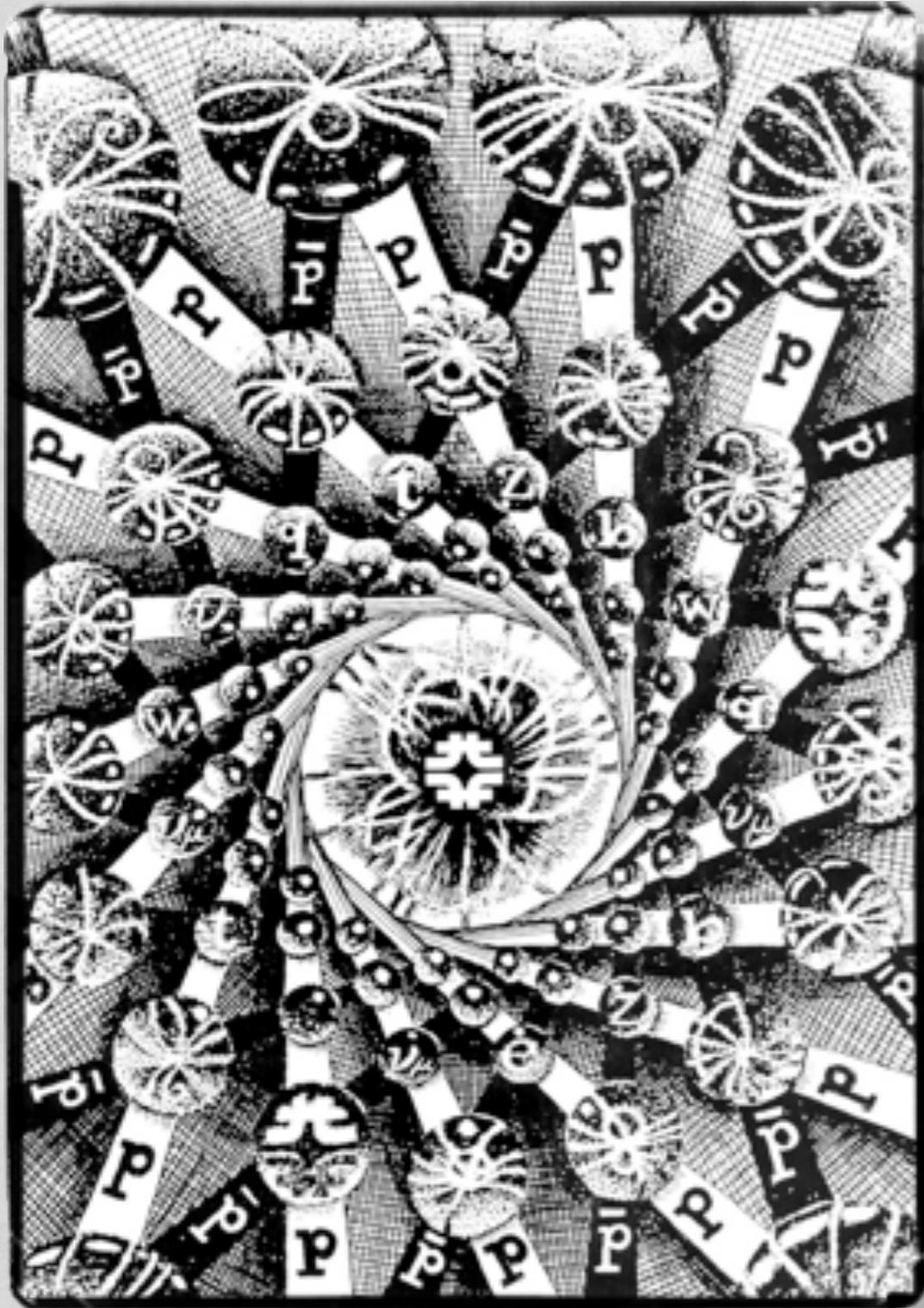
$$N_{\text{top events}}^{\text{observed}} = \sigma(pp \rightarrow t\bar{t}) \cdot L \cdot \epsilon$$

And nothing wrong with having awesome detectors





# The Tevatron: A Storied Odyssey



- Discoveries
  - ✘ New elementary particles
  - ✘ New composite particles
  - ✘ Rare SM processes
  - ✘ Subtle behavior
- New research areas
- Precision measurements
- Tests for New Physics
- Hunting down the Higgs

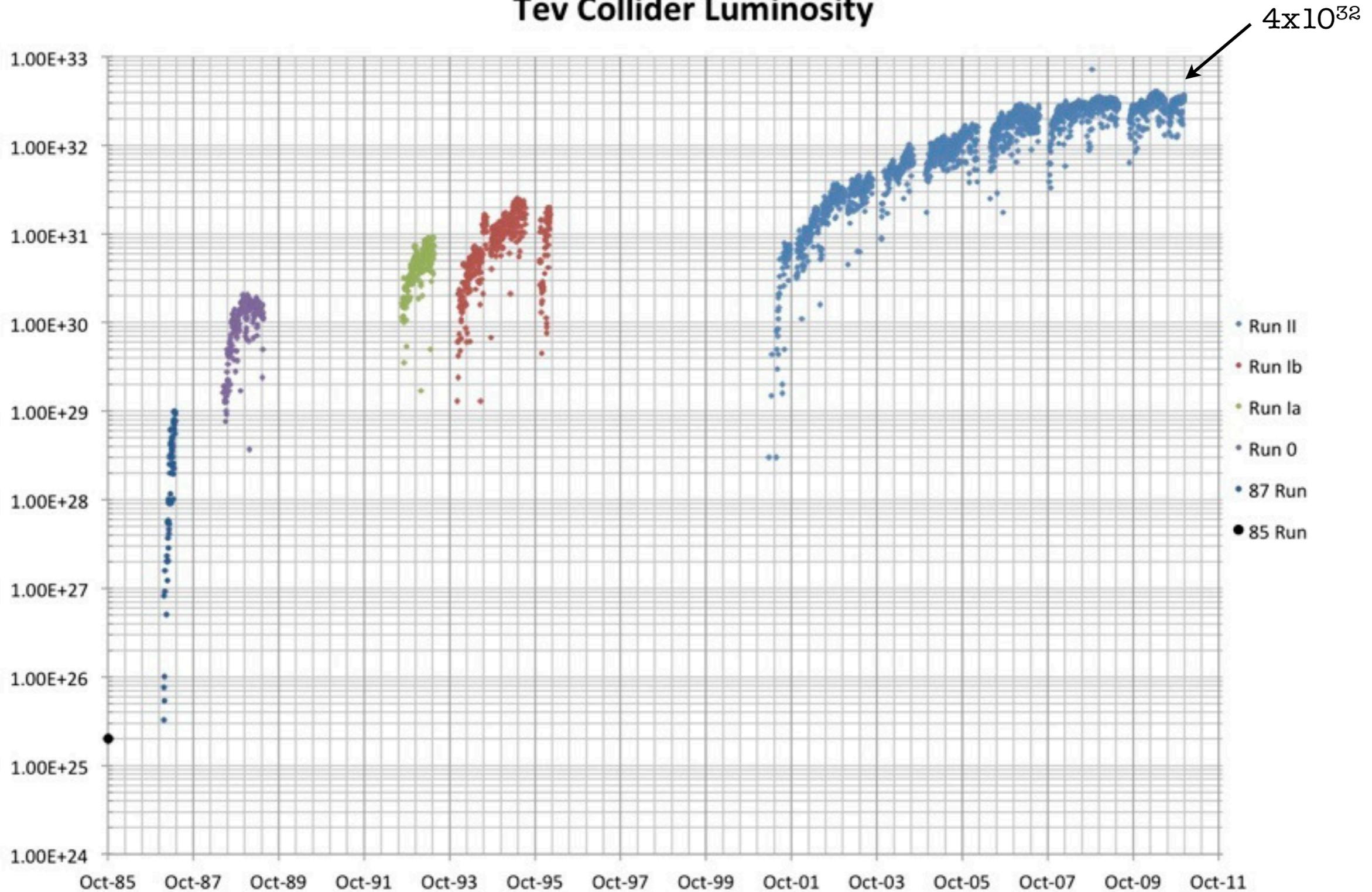
October 2010: 25th Anniversary of the first collisions !

# 25 year Luminosity Evolution

A 7 orders of magnitude tour de force



## Tev Collider Luminosity

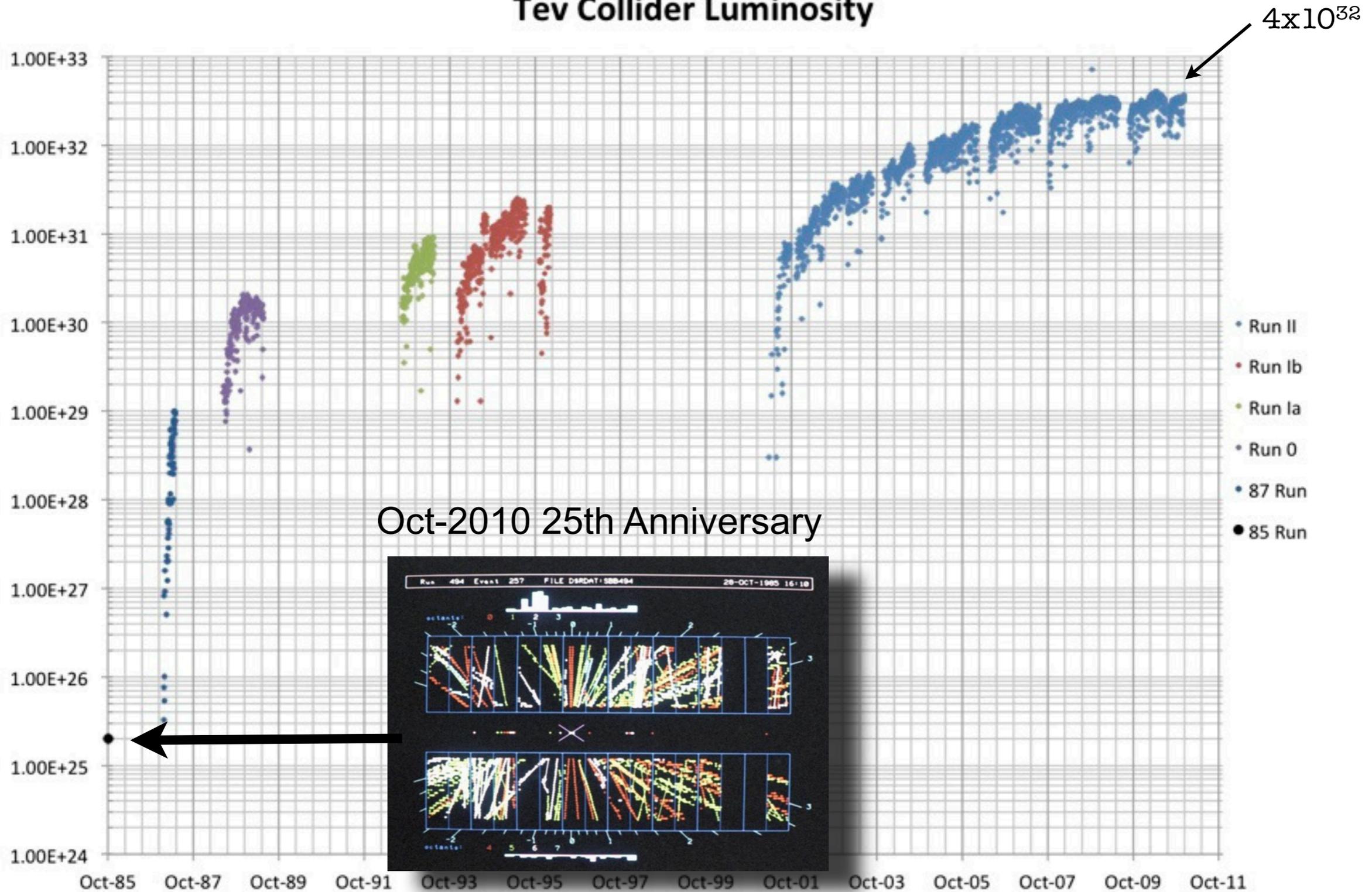


# 25 year Luminosity Evolution

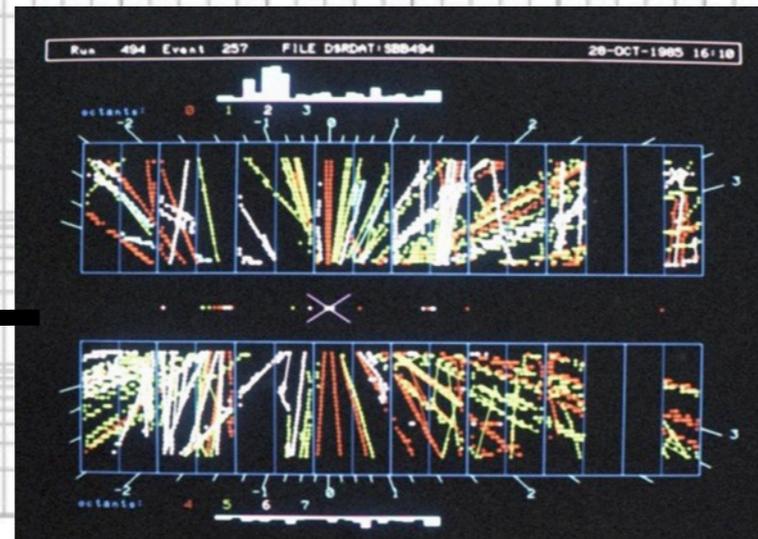
A 7 orders of magnitude tour de force



## Tev Collider Luminosity



Oct-2010 25th Anniversary

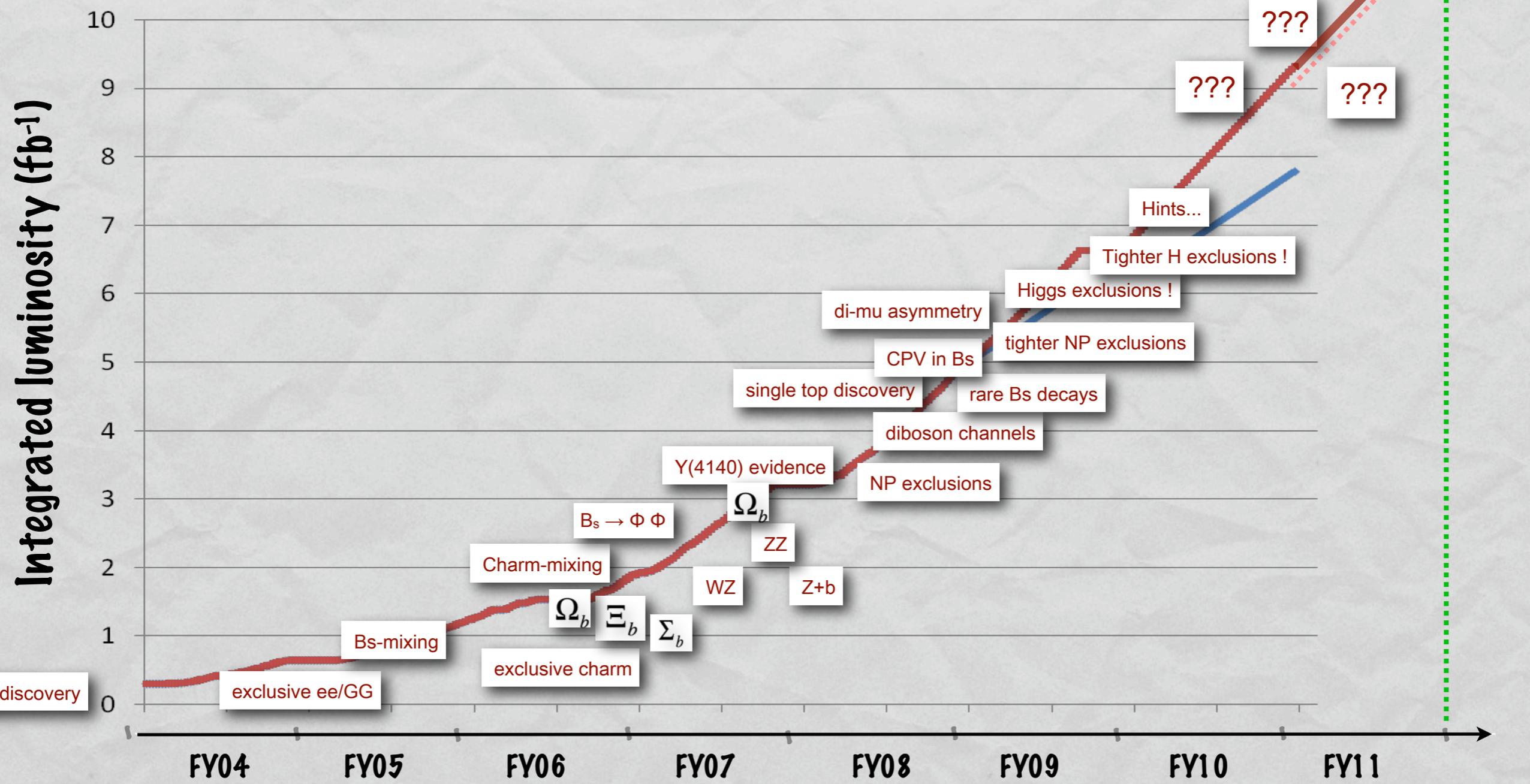




# A Luminosity Story

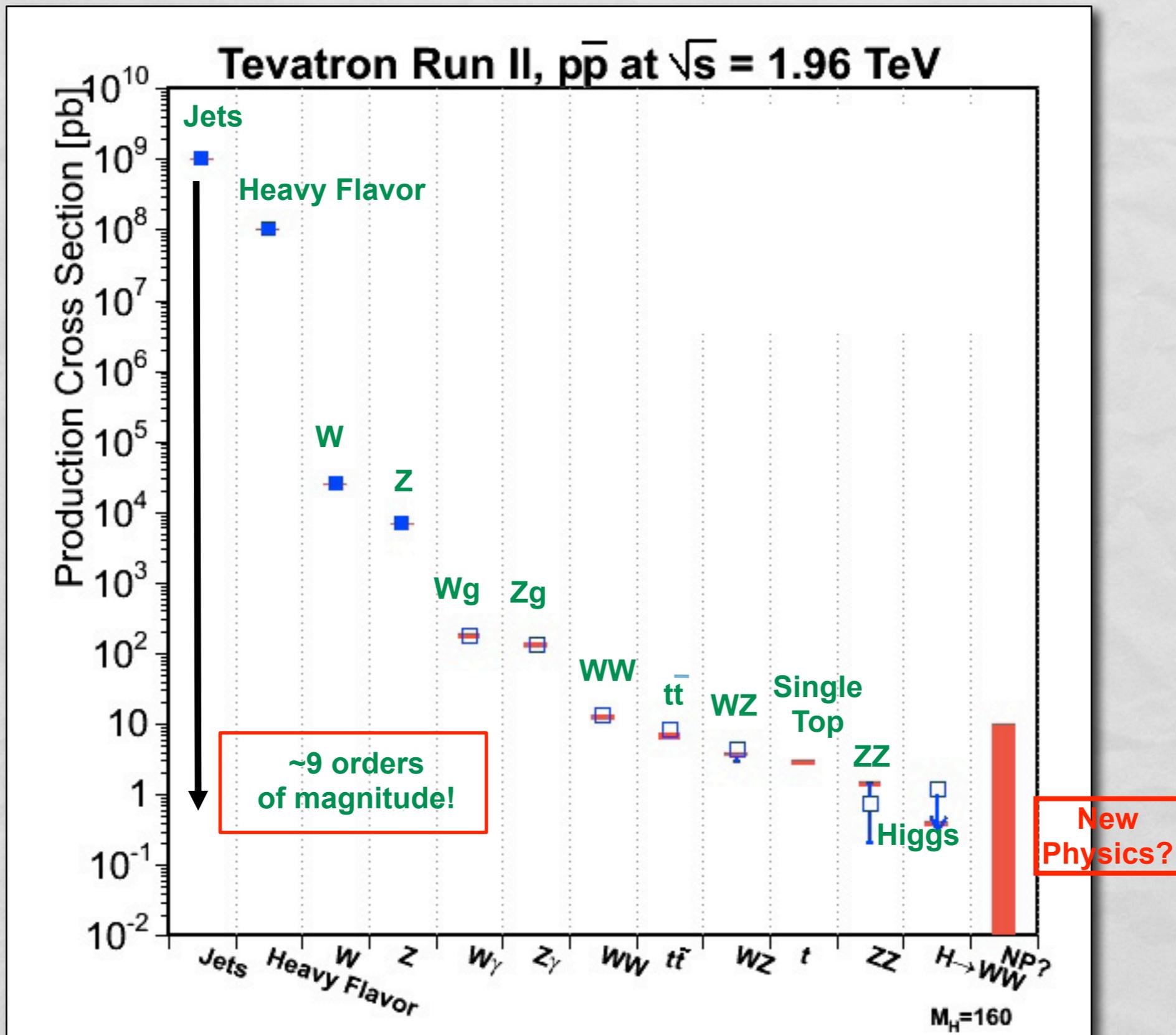


In many ways - even at fixed E - hadron colliders are a nearly inexhaustible source of physics



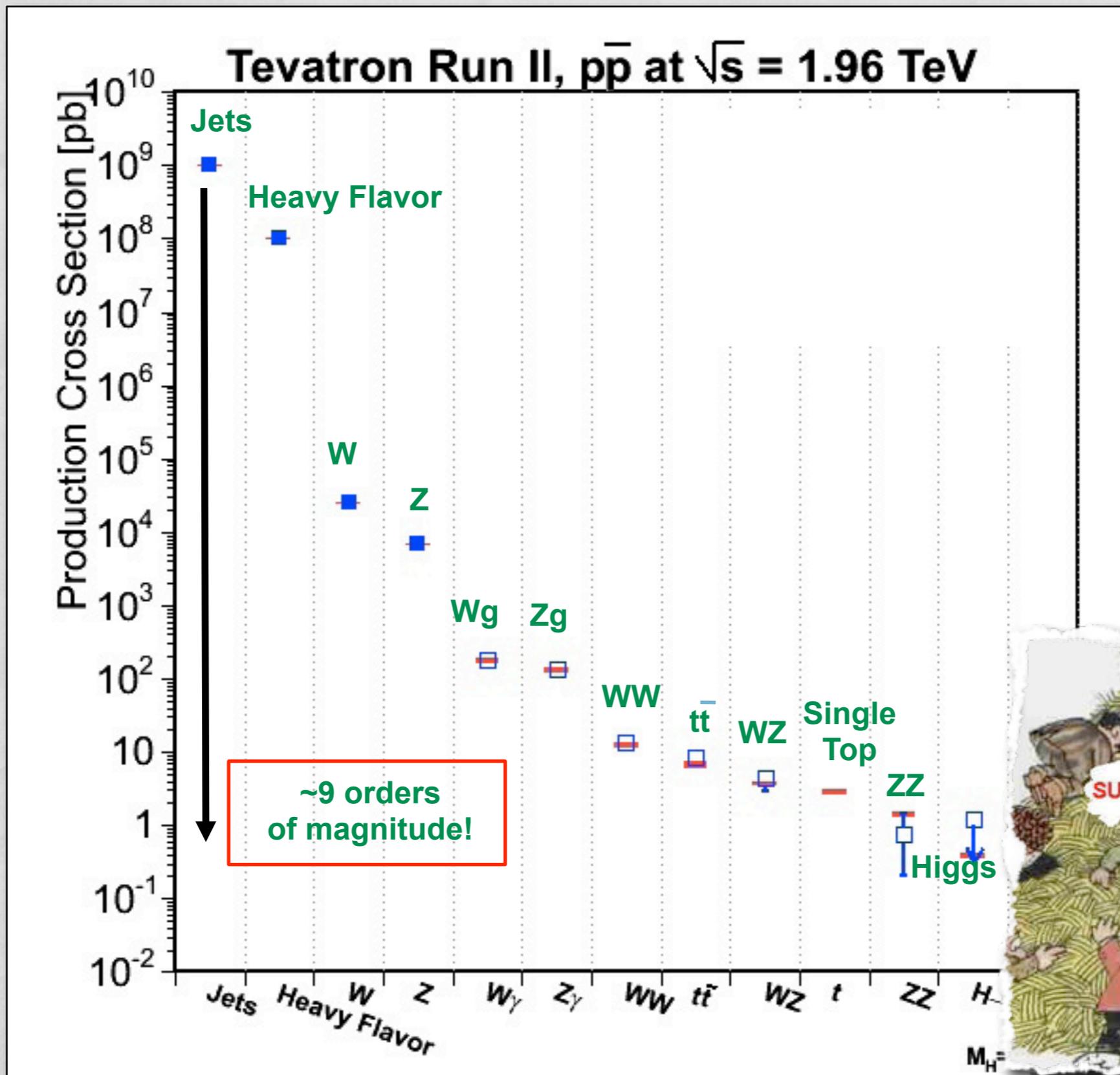


# Digging...





# Digging...



- Physicists Discover Top Quark (1995)
- CDF Results Raise Questions on Quark Structure (1996)
- Collider Run II Begins at Fermilab (2001)
- Fermilab Results Change Higgs Mass Estimate (2004)
- What Happened to the Antimatter? Fermilab's DZero Experiment Finds Clues in Quick-Change Meson (2006)
- Fermilab's CDF scientists make it official: They have discovered the quick-change behavior of the B-sub-s meson, which switches between matter and antimatter 3 trillion times a second. (2006)
- Experimenters at Fermilab discover exotic relatives of protons and neutrons (2006)

- DZero finds evidence of rare single top quark; Observation marks a step closer to finding Higgs boson (2006)
- CDF precision measurement of W-boson mass suggests a lighter Higgs particle
- Tevatron collider yields new results on subatomic matter, forces (2007)
- Fermilab physicists discover "triple-scoop" baryon (2007)
- Back-to-Back b Baryons in Batavia (2007)
- Prelude to the Higgs:  
A work for two bosons in the key of Z (2008)
- Fermilab physicists discover "doubly strange" particle (2008)



# Discoveries on the Horizon?

arXiv.org > hep-ex > arXiv:1005.2757

High Energy Physics - Experiment

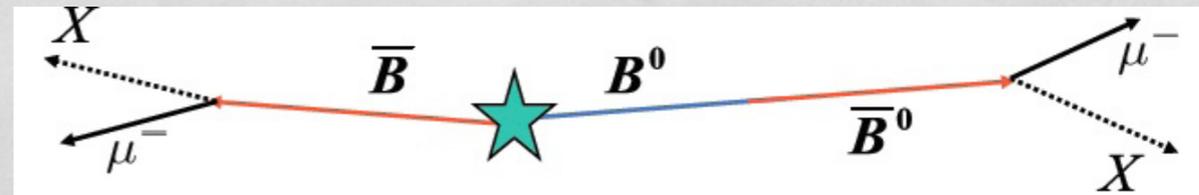
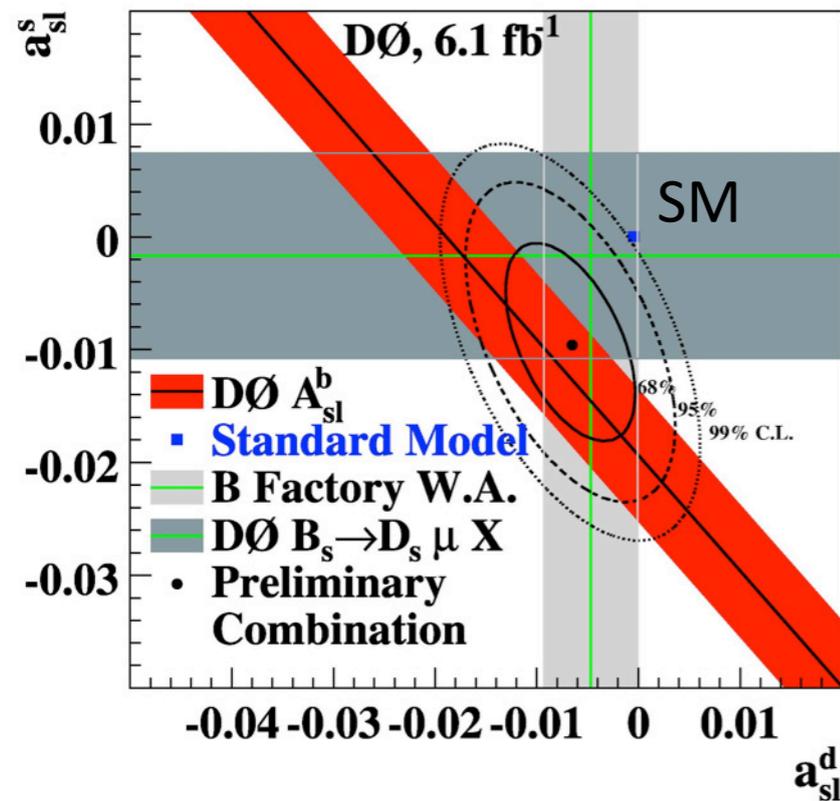
## Evidence for an anomalous like-sign dimuon charge asymmetry

The D0 Collaboration: V.M. Abazov, et al

(Submitted on 16 May 2010)

We measure the charge asymmetry  $A^b_{sl}$  of like-sign dimuon events in  $6.1 \text{ fb}^{-1}$  of  $p\bar{p}$  collisions recorded with the D0 detector at a center-of-mass energy  $\sqrt{s} = 1.96 \text{ TeV}$  at the Fermilab Tevatron collider. From  $A^b_{sl}$ , we extract the like-sign dimuon charge asymmetry in semileptonic  $b$ -hadron decays:  $a^b_{sl} = -0.00957 \pm 0.00251 (\text{stat}) \pm 0.00146 (\text{syst})$ . This result differs by 3.2 standard deviations from the standard model prediction  $a^b_{sl}(\text{SM}) = (-2.3^{+0.5}_{-0.6}) \times 10^{-4}$  and provides first evidence of anomalous CP-violation in the mixing of neutral  $B$  mesons.

Comments: Submitted to Phys. Rev. D  
Subjects: High Energy Physics - Experiment (hep-ex)  
Report number: Fermilab-Pub-10/114-E  
Cite as: arXiv:1005.2757v1 [hep-ex]



$$A^b_{sl} \equiv \frac{N_b^{++} - N_b^{--}}{N_b^{++} + N_b^{--}}$$



# Discoveries on the Horizon?



arXiv.org > hep-ex > arXiv:1101.0034

High Energy Physics - Experiment

## Evidence for a Mass Dependent Forward-Backward Asymmetry in Top Quark Pair Production

The CDF Collaboration: T. Aaltonen, et al

(Submitted on 30 Dec 2010)

We present a new measurement of the inclusive forward-backward  $t\text{-}\bar{t}$  production asymmetry and its rapidity and mass dependence. The measurements are performed with 5.3 fb<sup>-1</sup> of  $p\text{-}\bar{p}$  collisions at  $\sqrt{s} = 1.96$  TeV, recorded with CDF II at the Fermilab Tevatron. Significant inclusive asymmetries are observed in the laboratory and  $t\text{-}\bar{t}$  rest frame, and are consistent with CP conservation under interchange of  $t$  and  $\bar{t}$ . In the  $t\text{-}\bar{t}$  rest frame, the asymmetry increases with the  $t\text{-}\bar{t}$  rapidity difference,  $\Delta y$ , and with the invariant mass  $M_{t\text{-}\bar{t}}$  of the  $t\text{-}\bar{t}$  system. Parton-level asymmetries are derived in two regions of each variable, and the asymmetry is found to be most significant at large  $\Delta y$  and  $M_{t\text{-}\bar{t}}$ . For  $M_{t\text{-}\bar{t}} > 450$  GeV/c<sup>2</sup>, the parton-level asymmetry in the  $t\text{-}\bar{t}$  rest frame is  $A^{t\text{-}\bar{t}} = 0.475 \pm 0.114$  compared to a next-to-leading order QCD prediction of  $0.088 \pm 0.013$ .

Comments: 23 pages, 18 figures, submitted to Physical Review D

Subjects: High Energy Physics - Experiment (hep-ex)

Report number: Fermilab-Pub-10-525-E

Cite as: arXiv:1101.0034v1 [hep-ex]

symmetrybreaking  
extra dimensions of particle physics  
A joint Fermilab/SLAC publication

VOLUME 08  
FEBRUARY

VIEW CURRENT ISSUE

### Interesting effect at the Tevatron hints at new physics

March 18, 2011 | 9:00 am

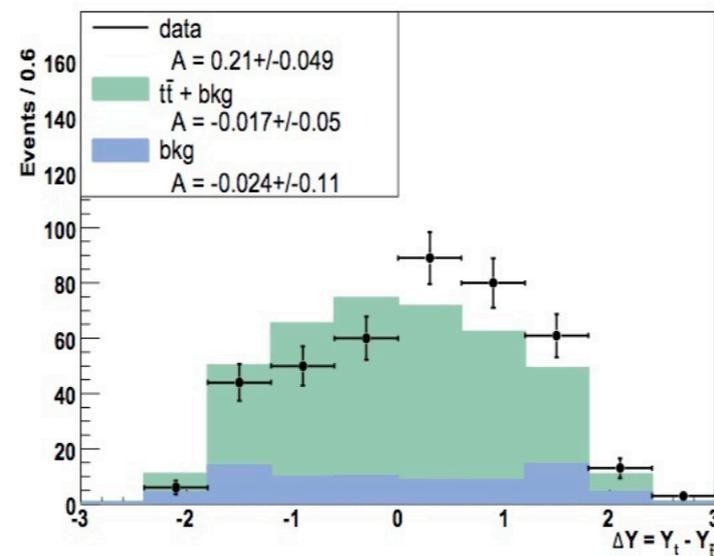
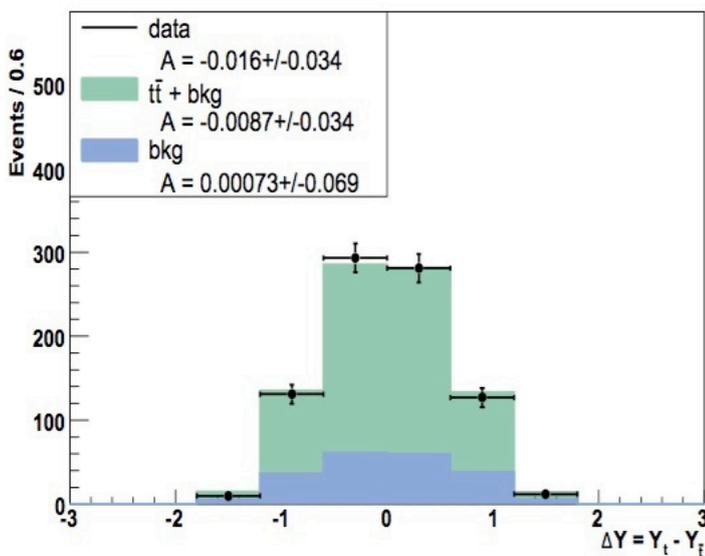


FIG. 12: Top: The distribution of  $\Delta y$  at low mass (left) and high mass (right).

The Tevatron Collider may be on the verge of discovering new physics according to mounting evidence from the CDF collaboration.

It is not the Higgs.

Search for new physics through the study of a process recently discovered at the Tevatron, the top quark.

Top quarks and anti-particles, anti-top quarks, are produced in pairs at the Tevatron, detectors note the particles and anti-particles. Theory predicts that the particles will travel in opposite directions over the other, traveling that way about 90 degrees.

The DZero collaboration and the CDF collaboration seemed to be picky 15 percent of the time. Top quarks went forward and anti-top quarks went backward. The CDF collaboration announced results with an even larger asymmetry.



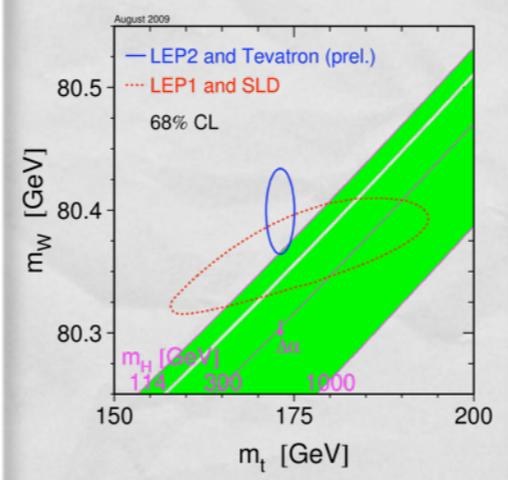
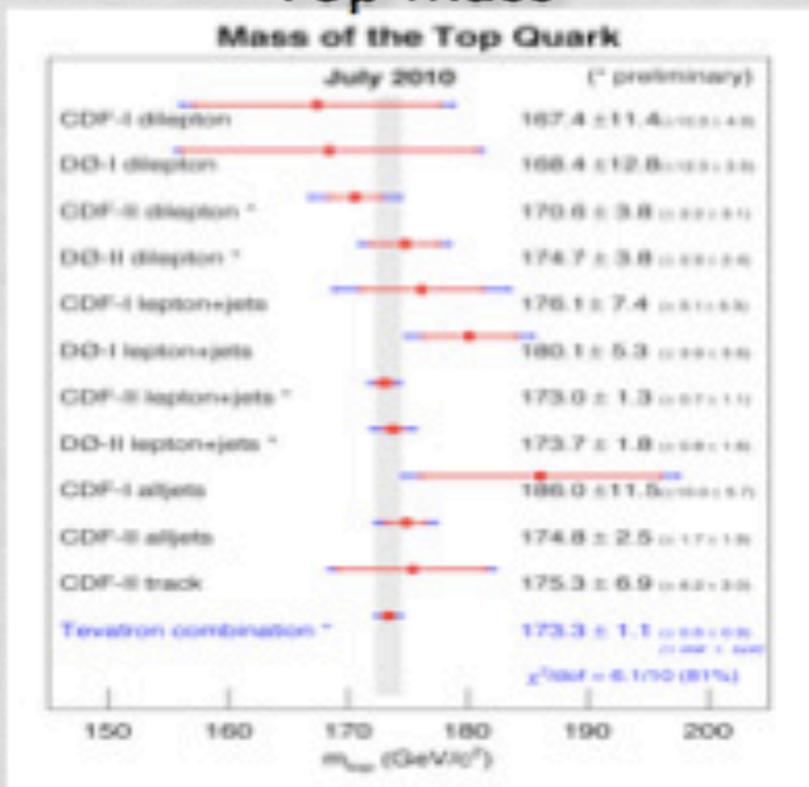
Fermilab's Wilson Hall in the shape of a  $t$ , the symbol for the top quark.



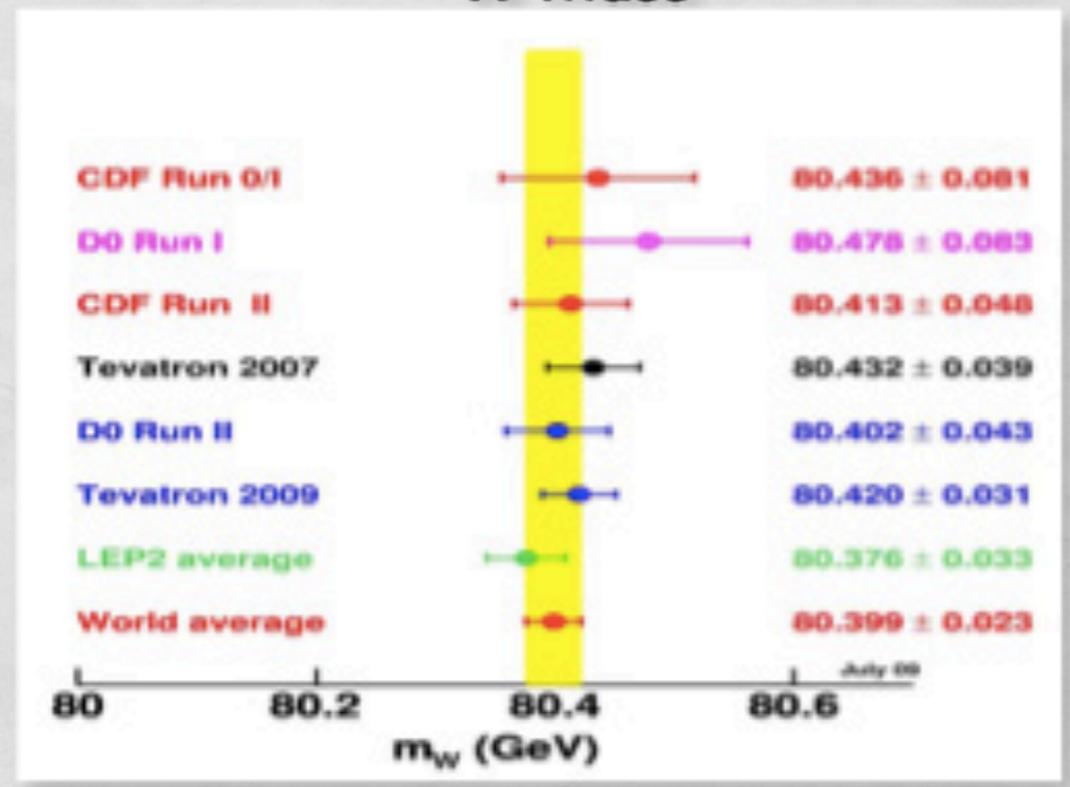
# Legacy measurements



## Top mass

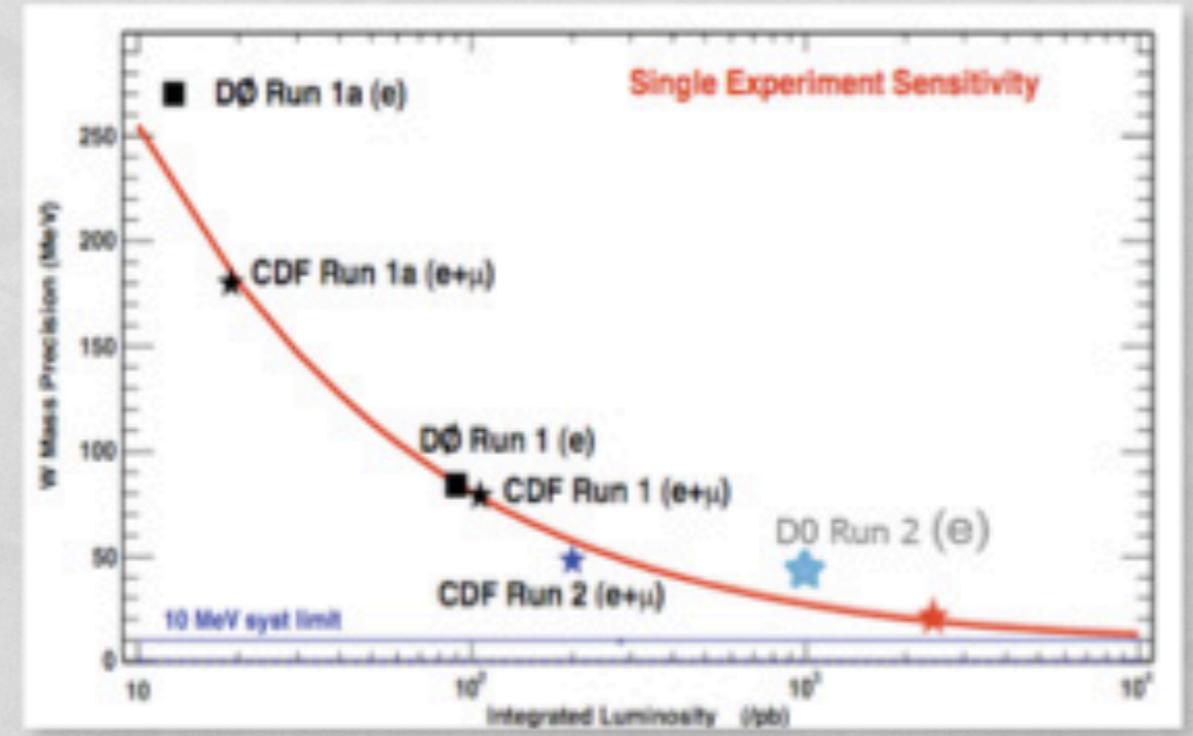
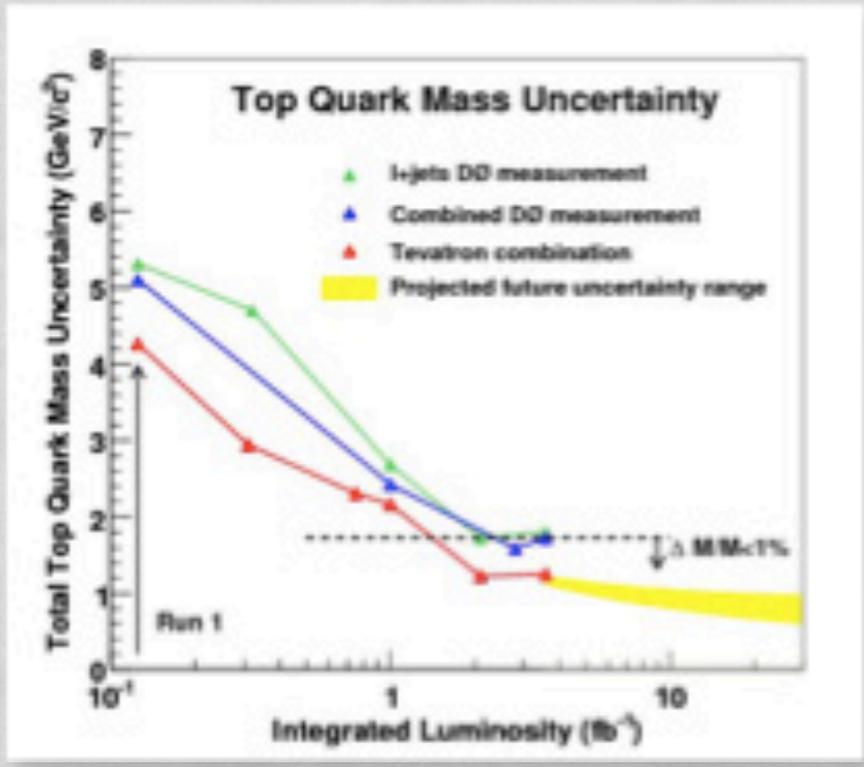


## W mass



Current Tevatron precision: **0.7%**

Current Tevatron precision: **0.04%**





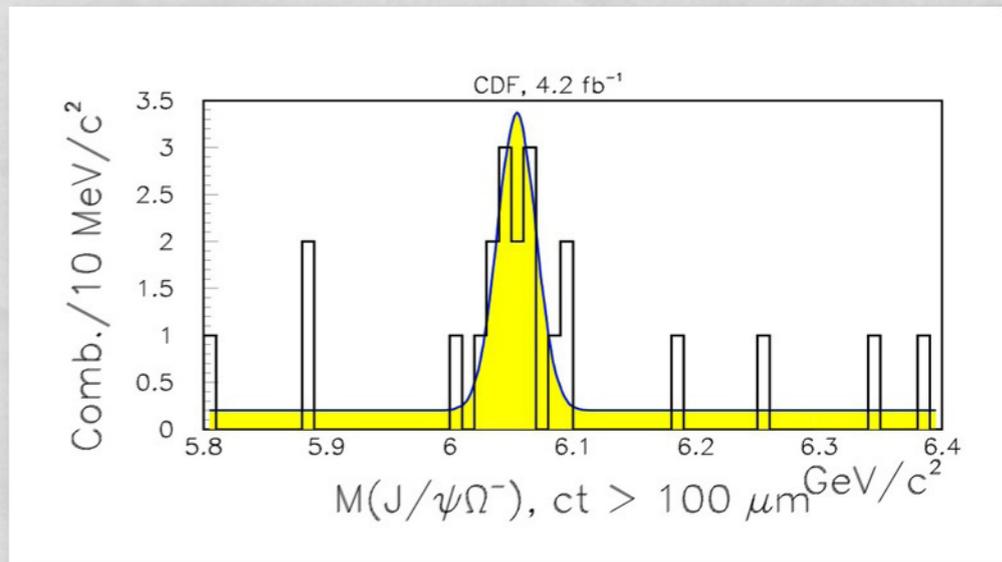
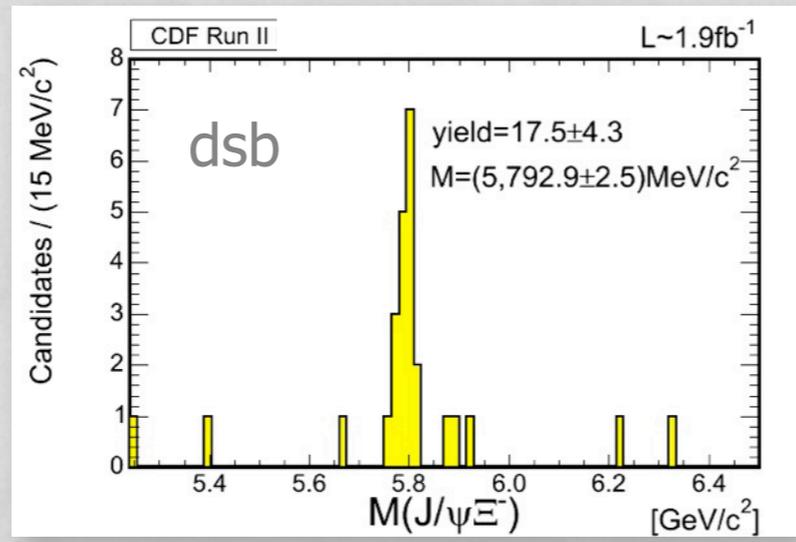
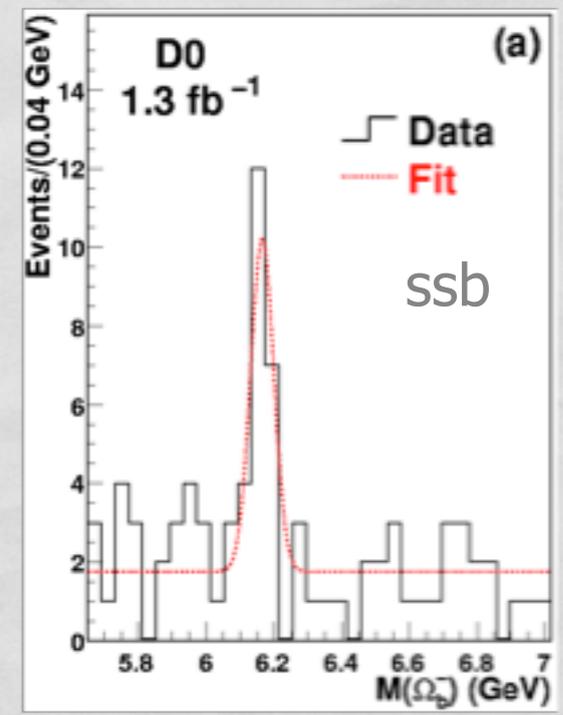
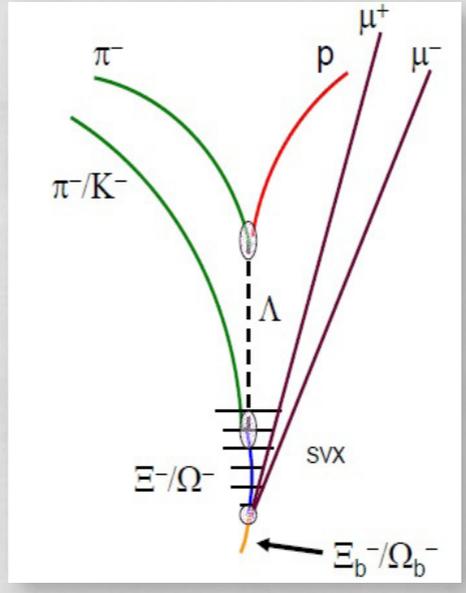
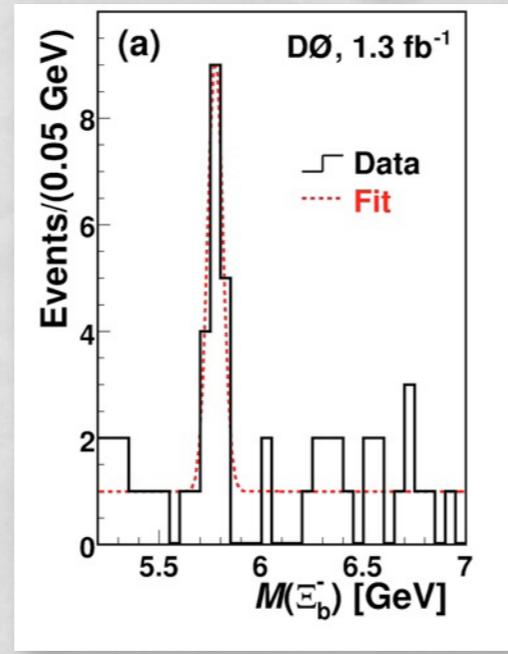
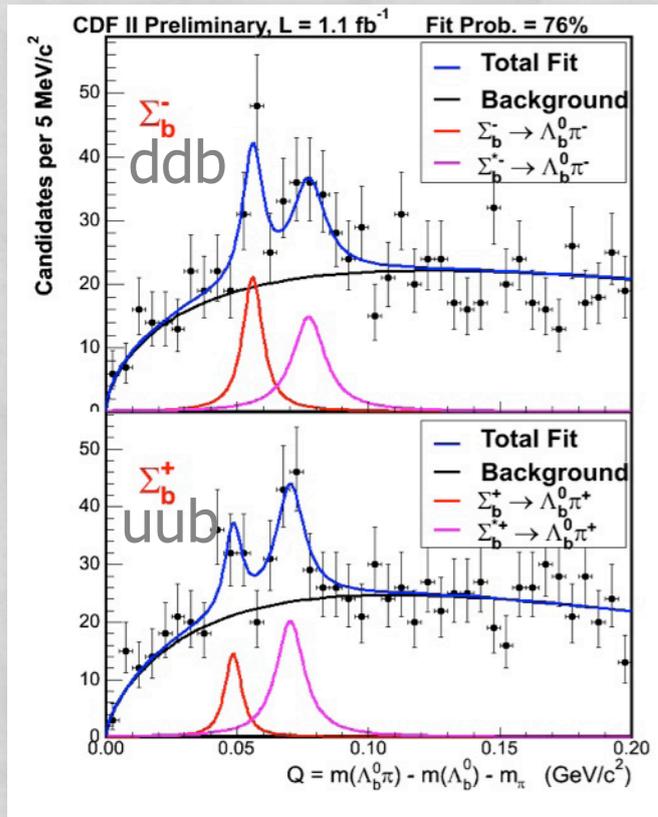
# Observation of new heavy baryons



## $\Xi_b$

## $\Omega_b$

## $\Sigma_b$



2006

2007

2008/2009



# Searches for new particles

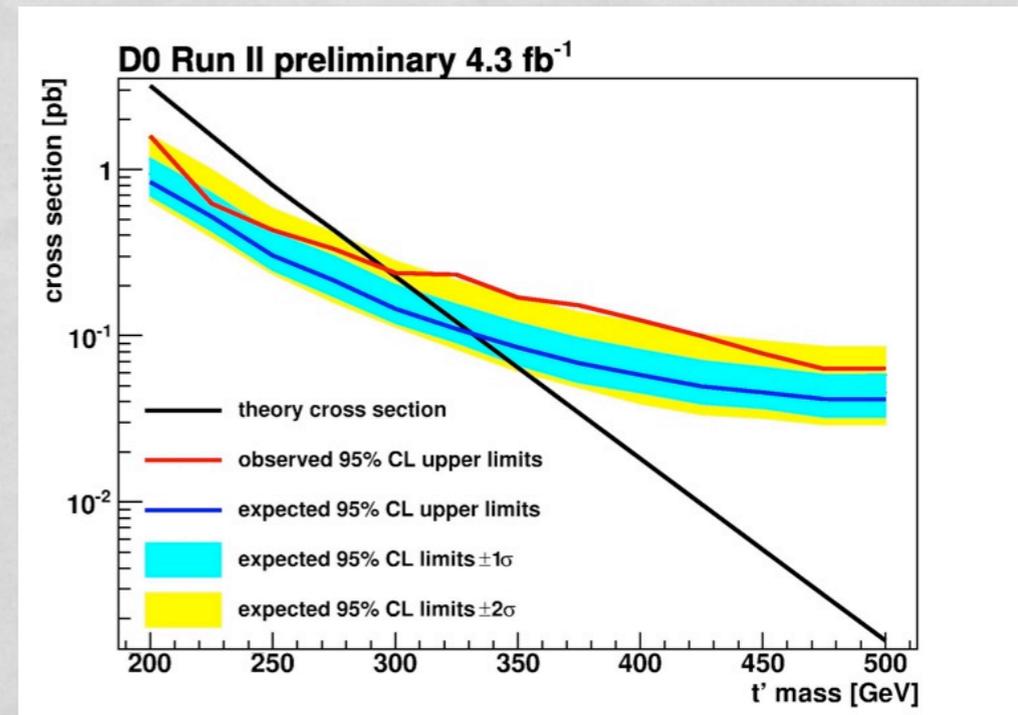
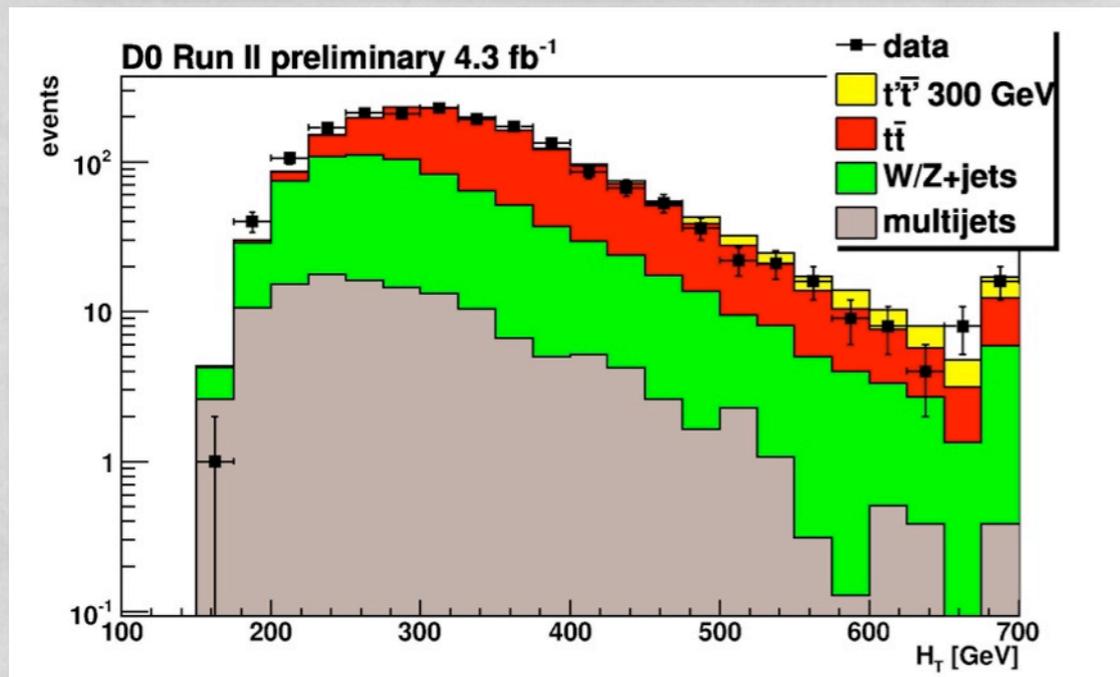
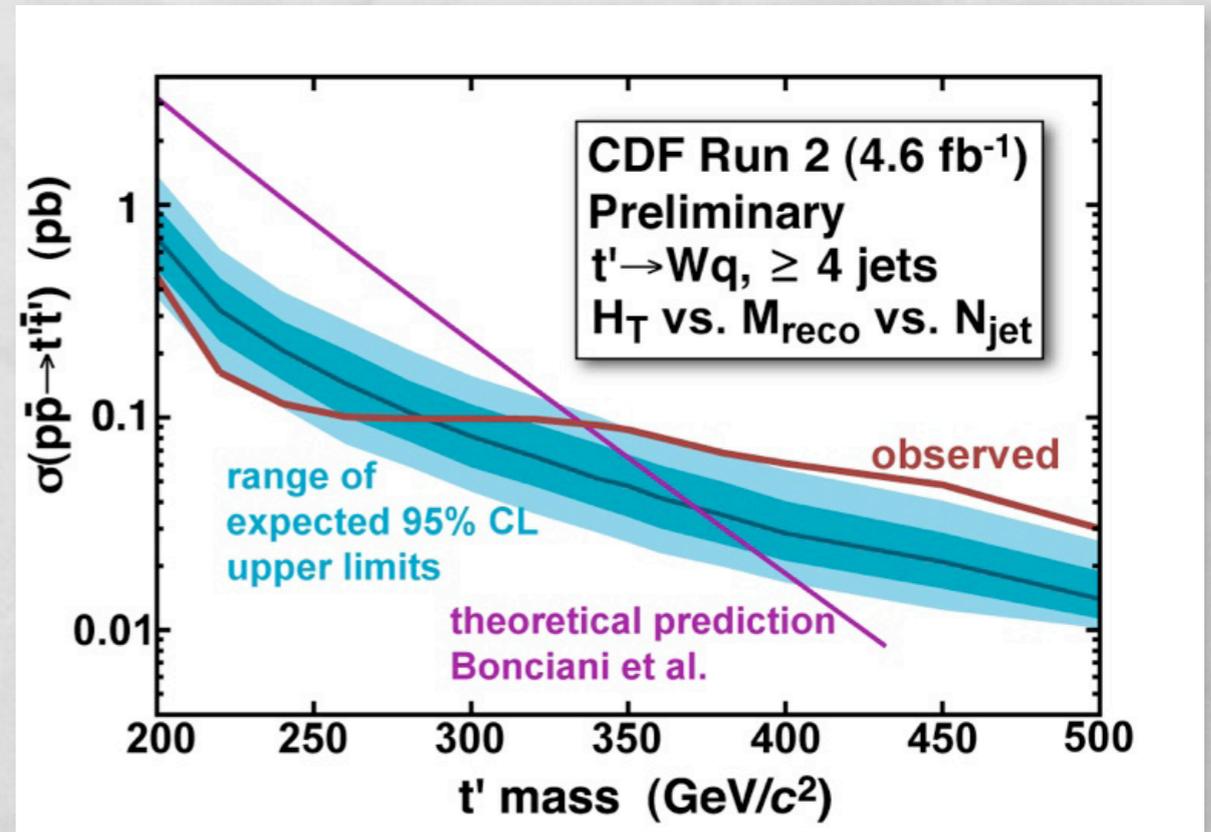
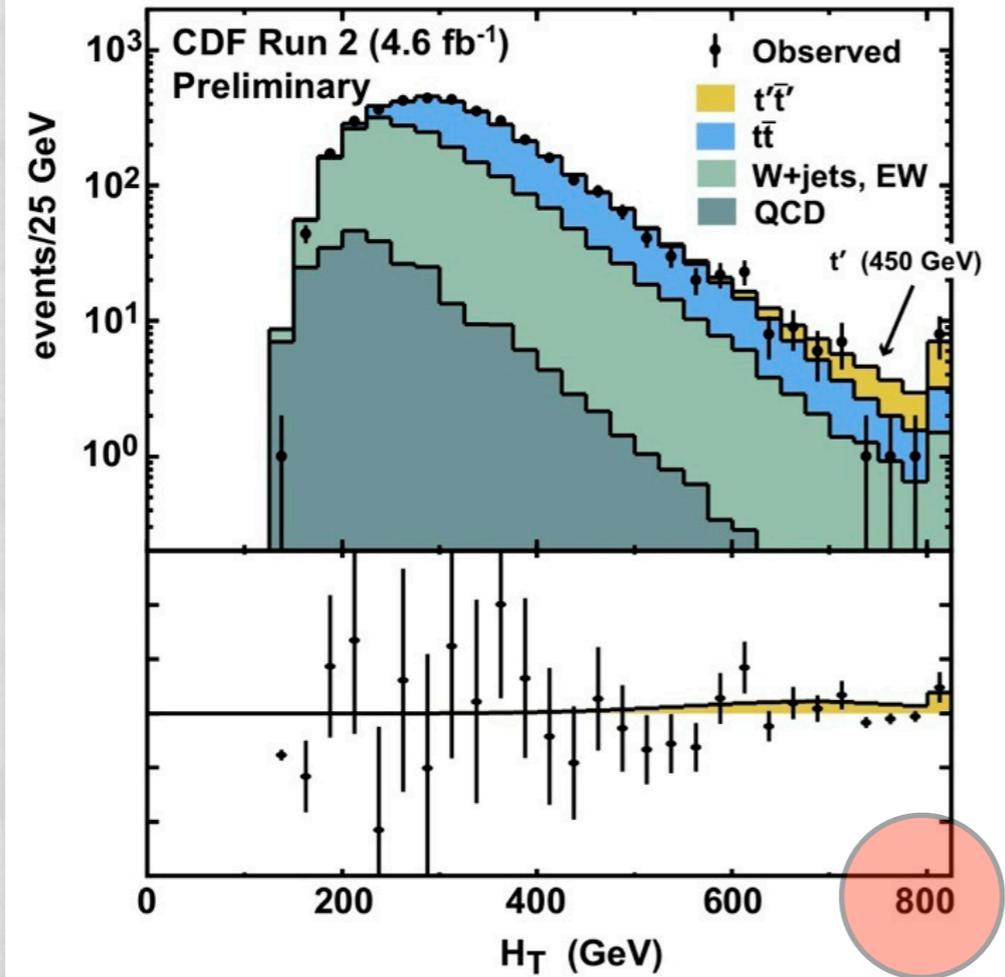


- SUSY pushed up in energy
  - charginos/neutralinos  $> O(200)$  GeV
  - squarks  $> O(400)$  GeV  
(all gluino masses)
  - gluinos  $> O(300)$  GeV  
(all squark masses)
  - stop, sbottom  $> O(250)$  GeV

- Other models and new generation particles also up
  - $b'$  and  $t'$   $> O(400)$  GeV
  - $W'$  and  $Z'$   $> O(800)$  GeV

# tt samples - keep an eye on:

## t-prime search





# The Higgs Hunt

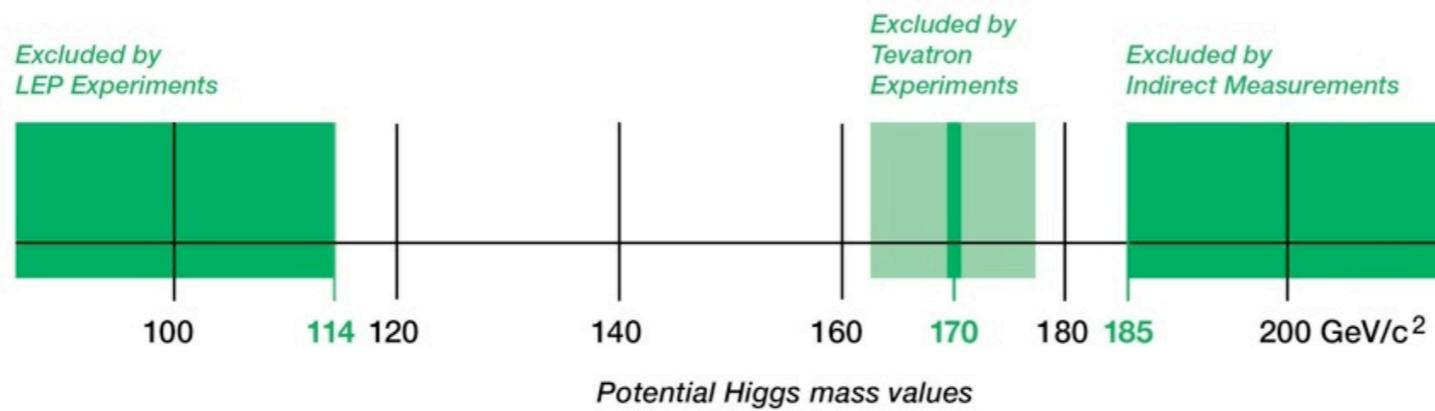


## Search for the Higgs Particle

Status as of the end of FY08

90% confidence level

95% confidence level



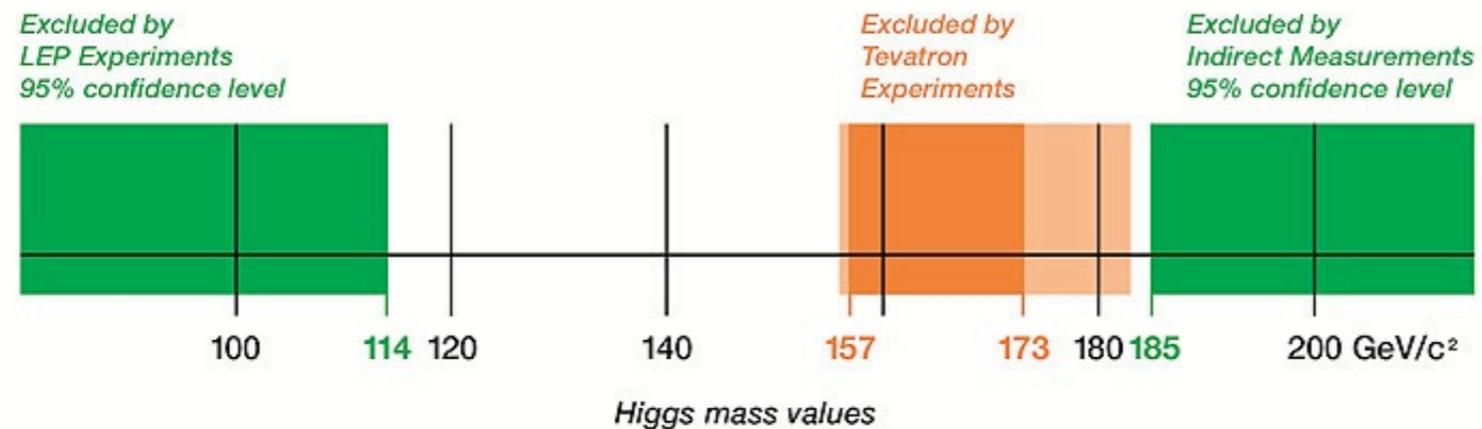
2008

## Search for the Higgs Particle

Status as of March 2011

90% confidence level

95% confidence level



2 yrs later

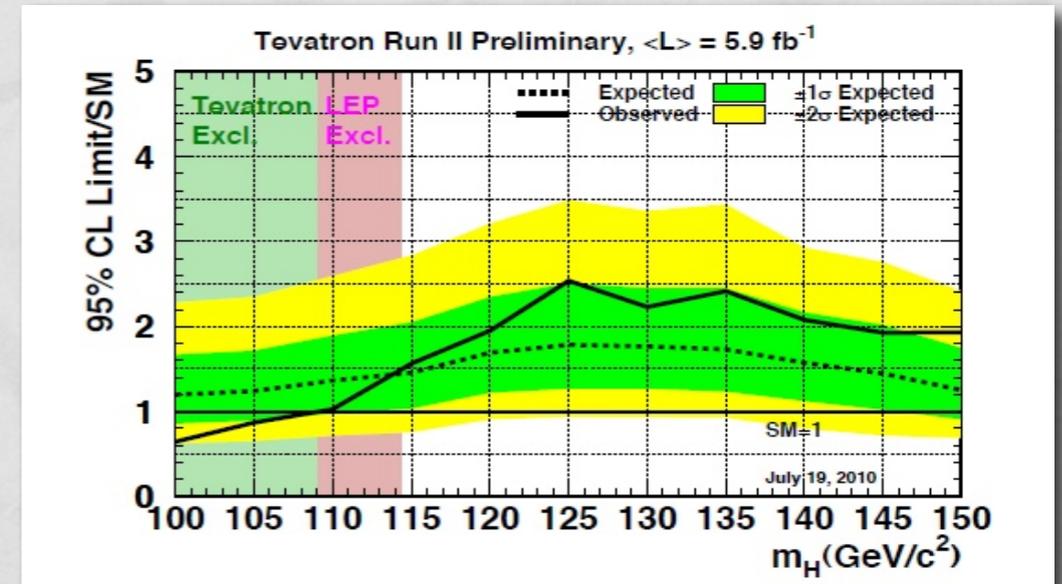
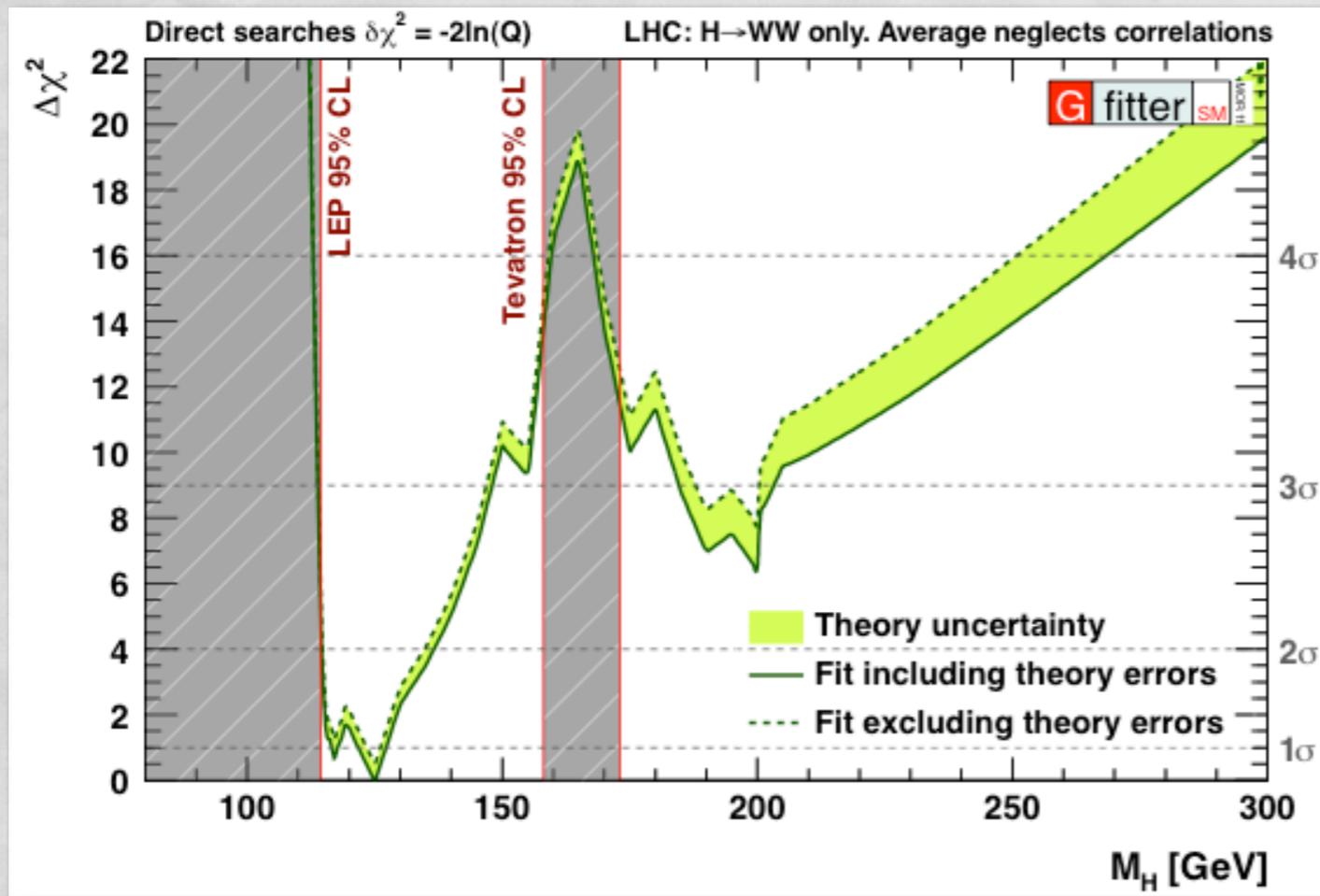


# The Higgs Hunt



Artwork by

~Inv. probability vs Higgs Mass

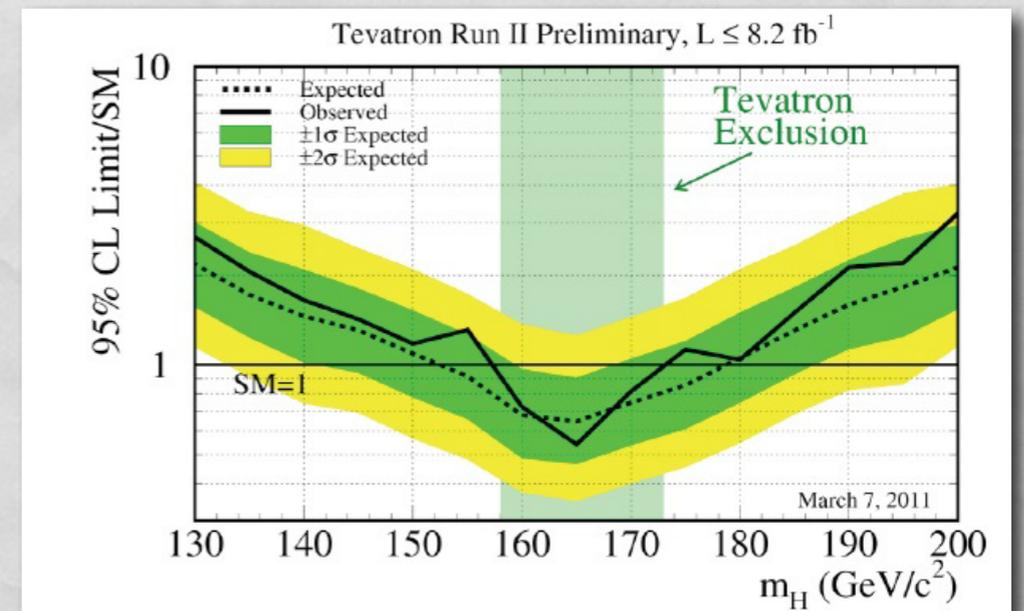


“low” mass

Most probable value:

$$M_H = 120.2^{+12.3}_{-4.7} \text{ GeV}$$

2-std. dev. interval ~ [114,145]



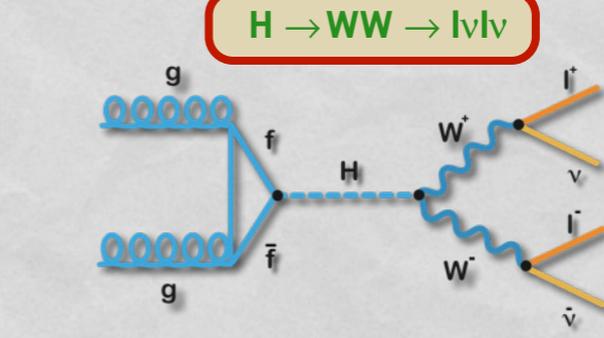
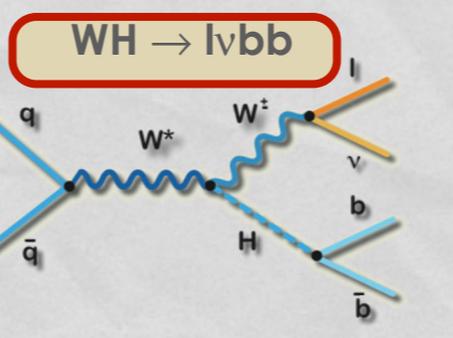
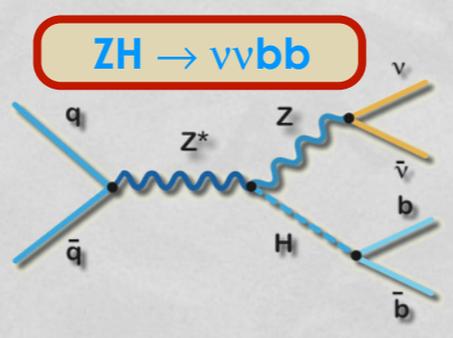
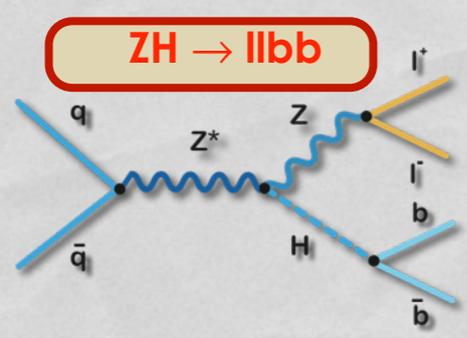
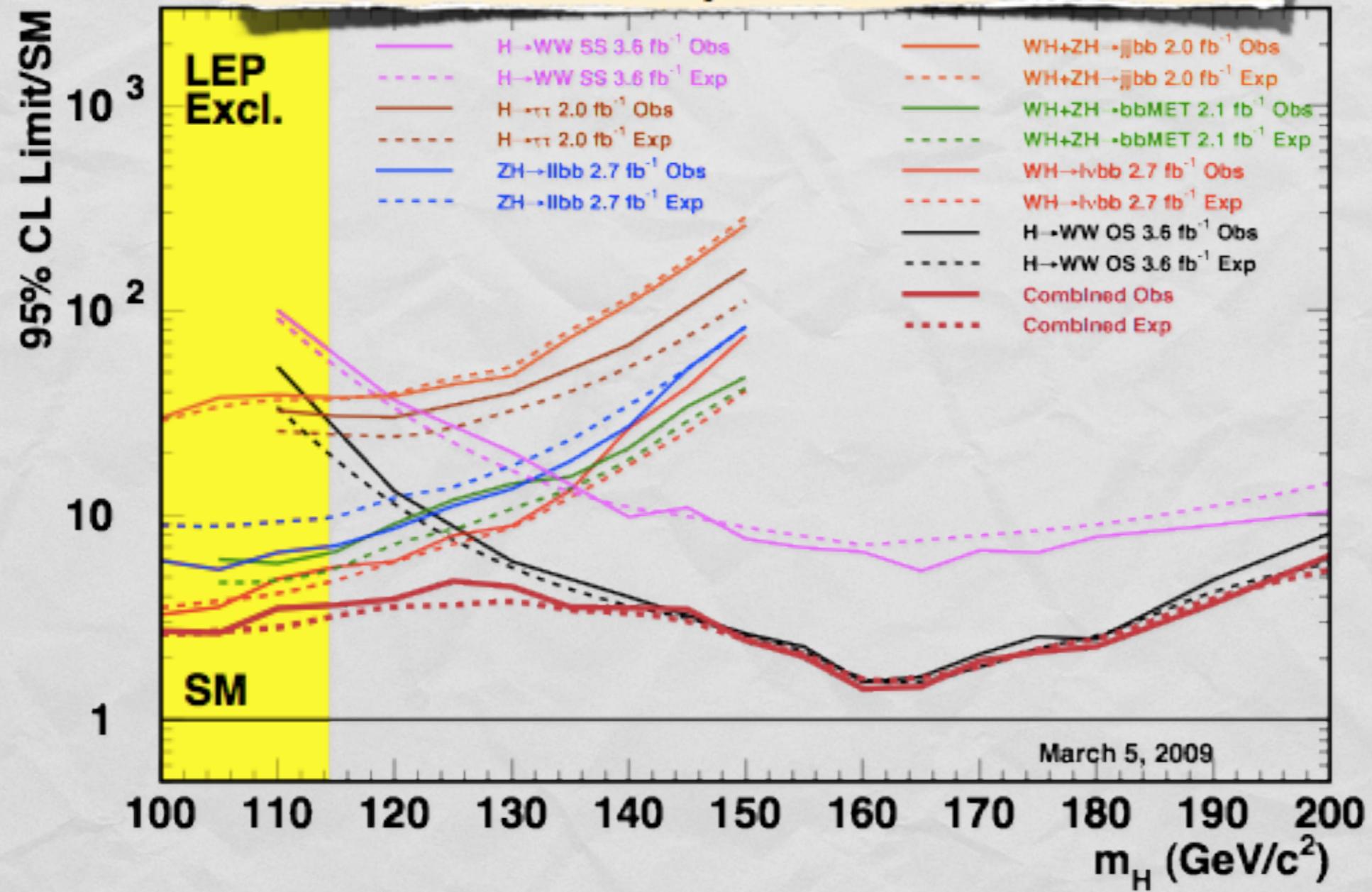
“high” mass



# The Higgs search: a monumental effort



>100 distinct analysis channels (cdf+d0)



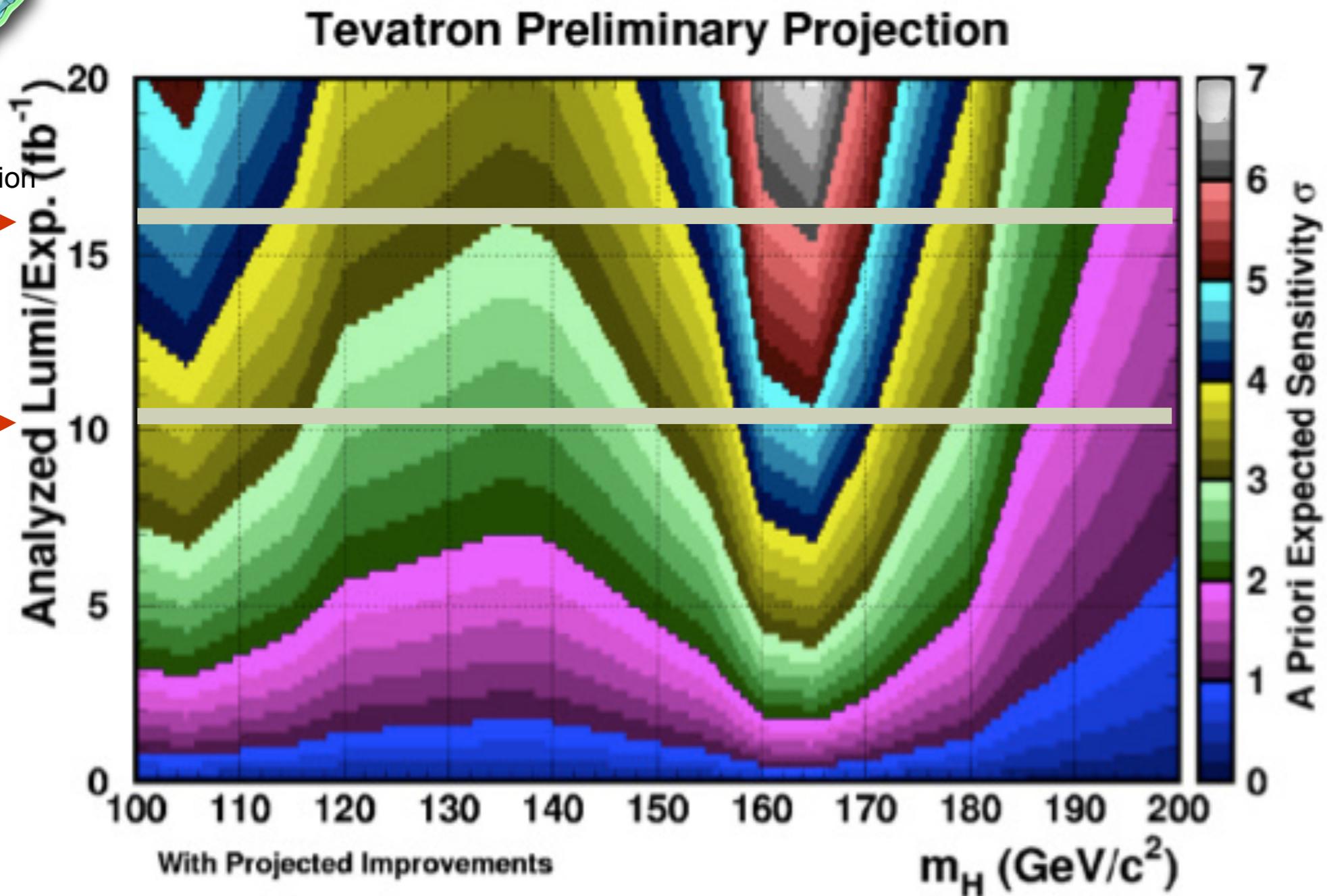
# Higgs reach with more Luminosity



Run 3 extension



End of Run 2



**With 10  $\text{fb}^{-1}$  analyzed  $> 95\%$  CL sensitivity is possible for all allowed SM masses!**

**Final tevatron results sometime in 2012...**

# The New [big] Kid in Town



The Tevatron

The LHC

# The LHC plan to conquer the World

## Top physics priorities at the LHC (ATLAS&CMS):

G. Altarelli

- Clarify the EW symmetry breaking sector
- ~~Search~~<sup>find</sup> for new physics at the TeV scale
- Identify the particle(s) that make the Dark Matter in the Universe

### Also:

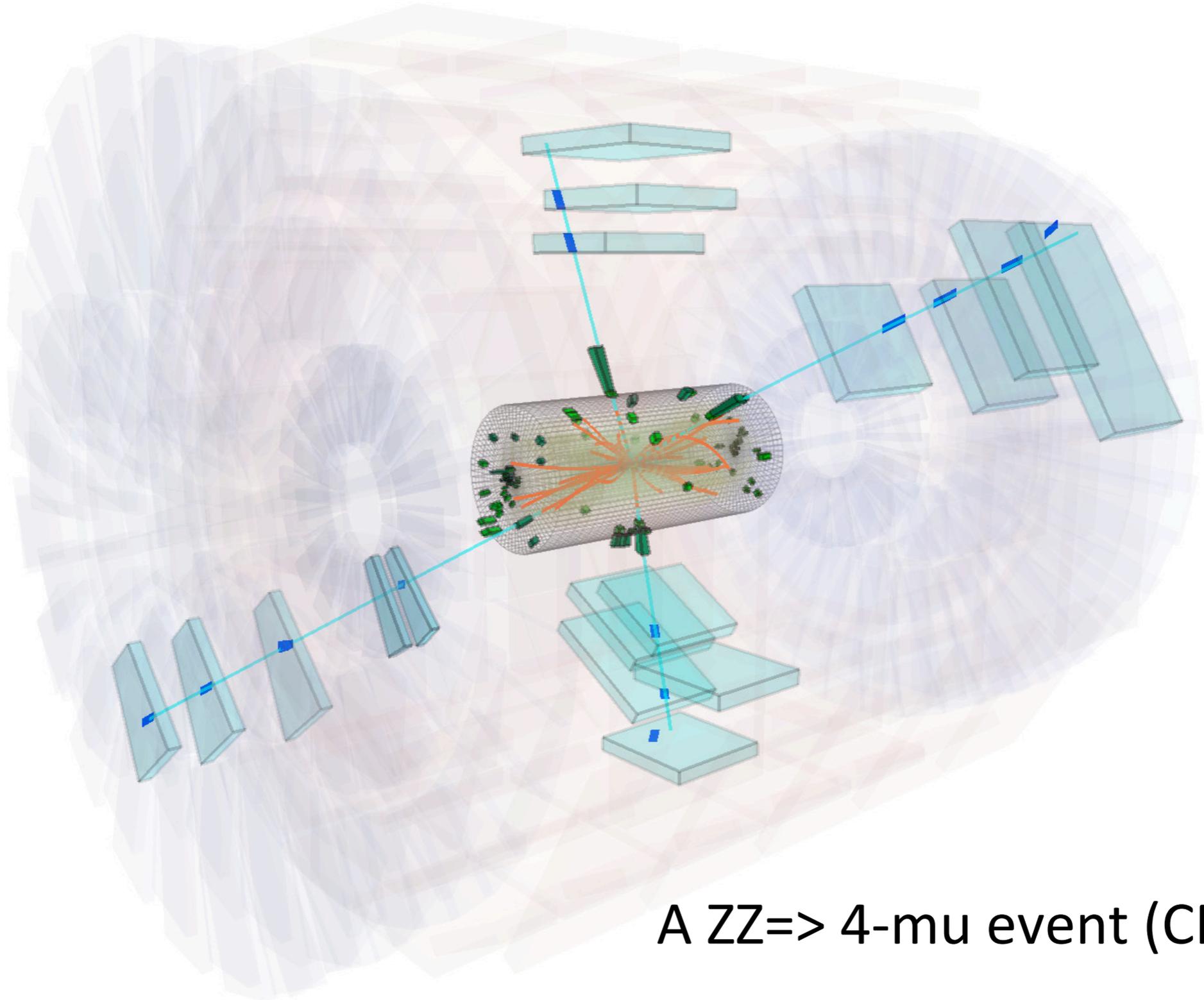
- LHCb: precision B physics (CKM matrix and CP violation)
- ALICE: Heavy ion collisions & QCD phase diagram

⊕ At this point, fresh input from experiment is badly needed

The future of particle physics rests on the LHC

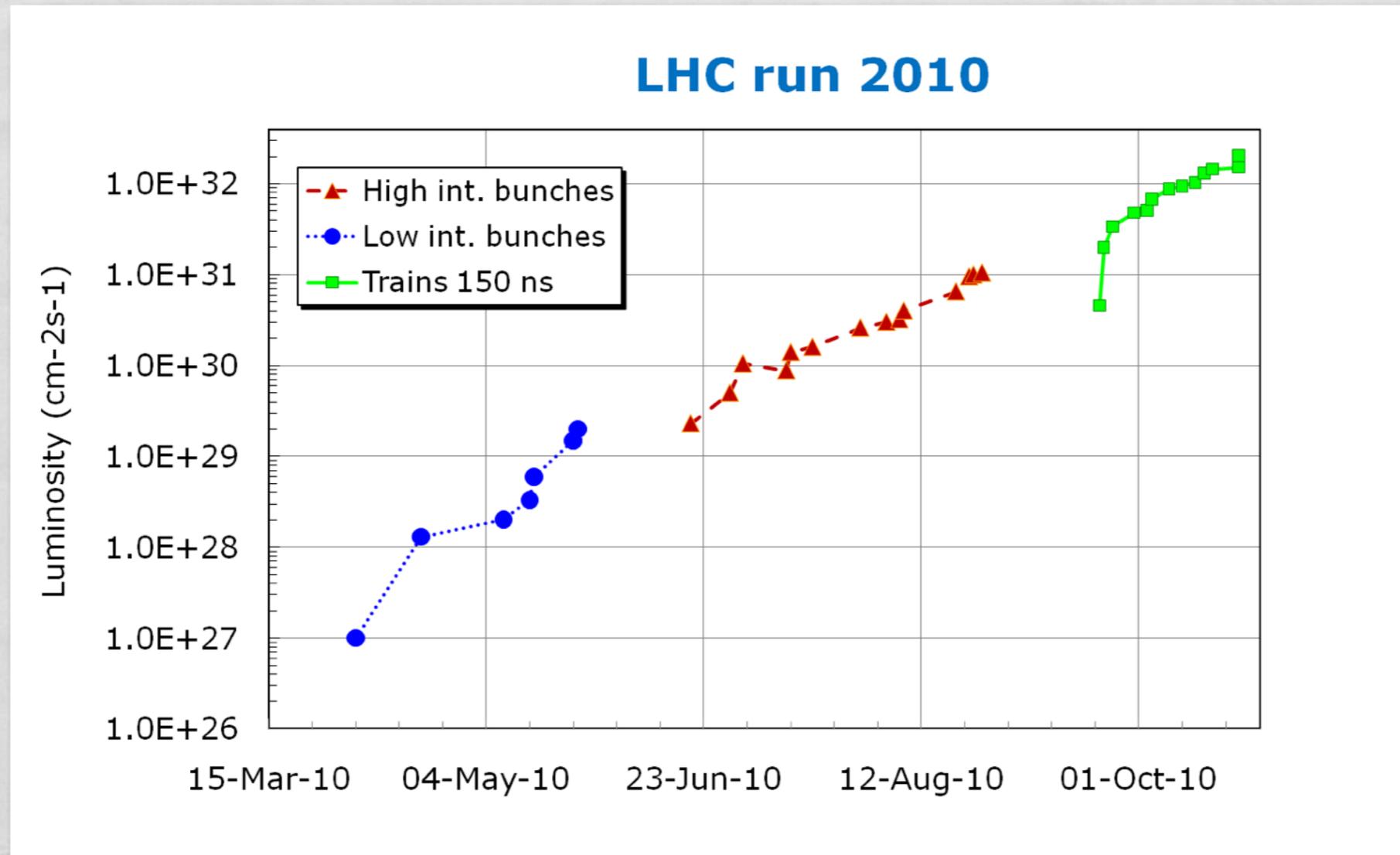
The LHC (with the luminosity upgrade) has the potential to last for 15-20 years

# They sure have nice event displays !



A  $ZZ \Rightarrow 4\text{-}\mu$  event (CMS)

# LHC's 2010 Run



**CM Energy @ 7 TeV**

**Integrated luminosity ~48 pb<sup>-1</sup>**

# Amazing Physics Output !

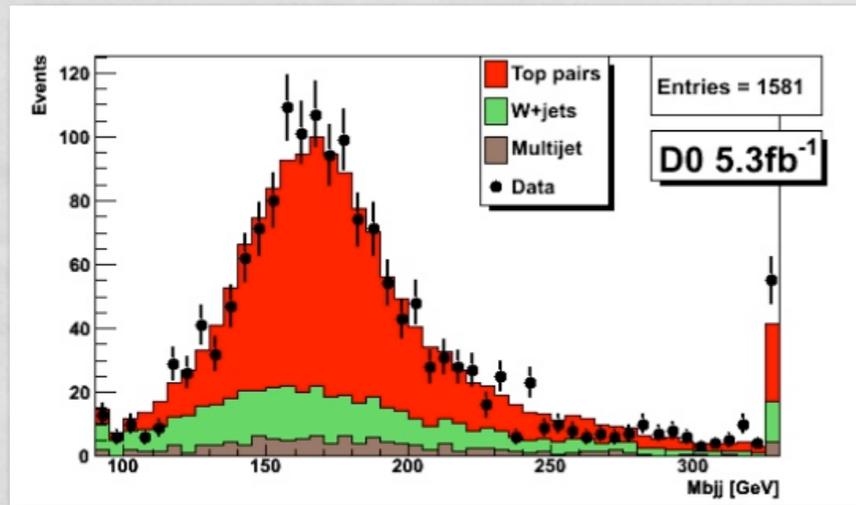
- Expect 100-200 publications from this Run
  - Detectors very well understood
  - Tevatron experience in all areas well integrated
  - Enough data to validate the Standard Model
  - In some cases reach for new physics surpassing the Tevatron
- Slew of new results presented at Winter Conf.
- It is wonderful to see results from these two colliders, together.

# Amazing Physics Output !

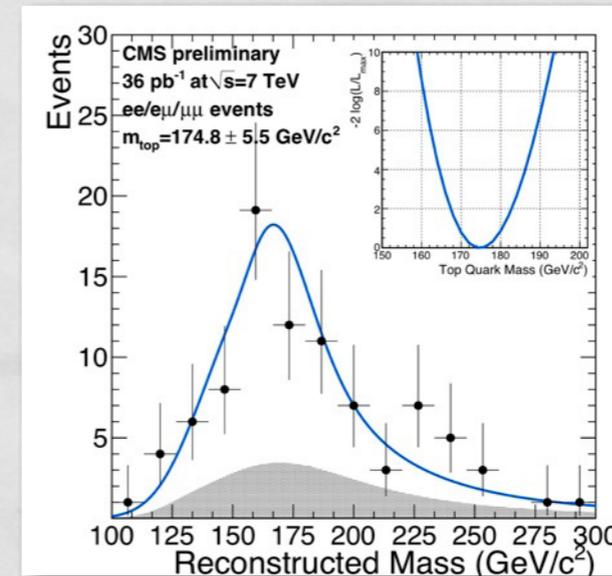
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  - Enough data to validate the Standard Model
  - In some cases reach for new physics surpassing the Tevatron
- Slew of new results presented at Winter Conf.
- It is wonderful to see results from these two colliders, together.
- And from the rest of the particle physics experiments as well !



# Universality of the laws of Physics



## Top quarks in the US



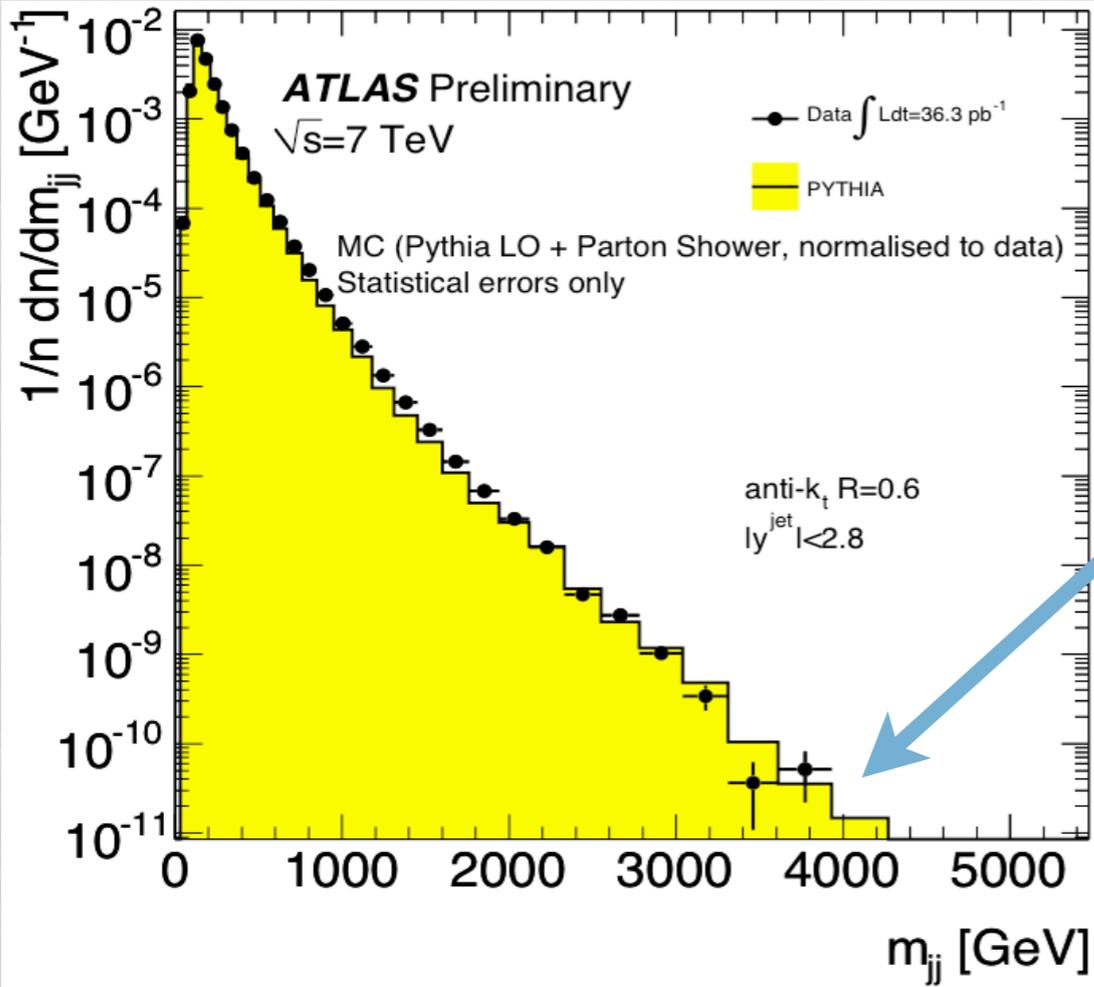
## Top quarks in Europe

"All people know the same truth,  
our lives consist of how we choose to  
distort it."



W. Allen - Deconstructing Harry

# di-jet production

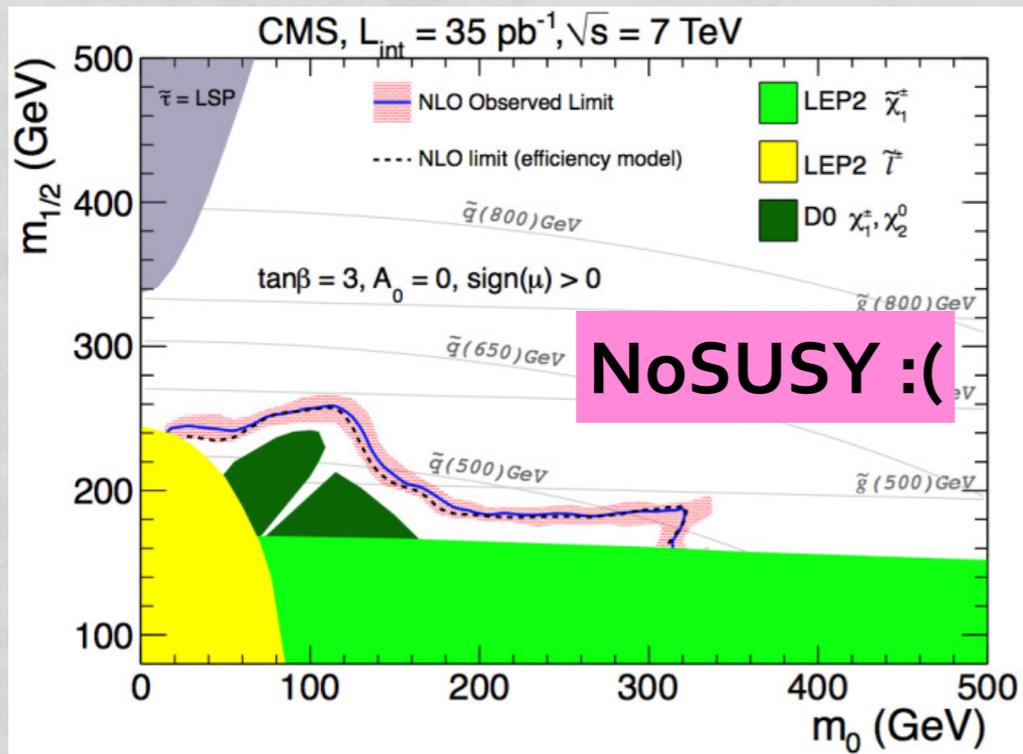


At the Terascale already !

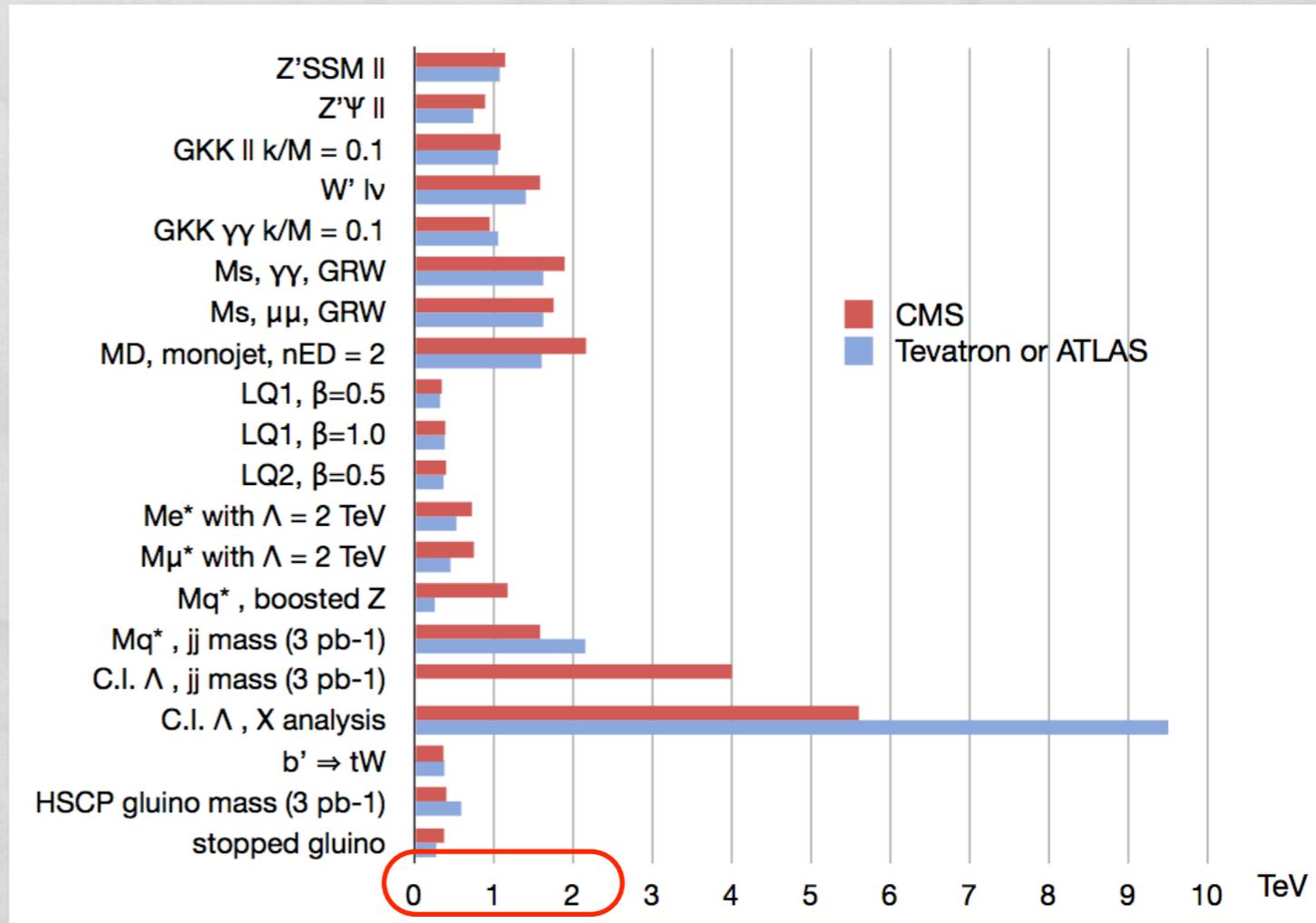


Uncharted waters

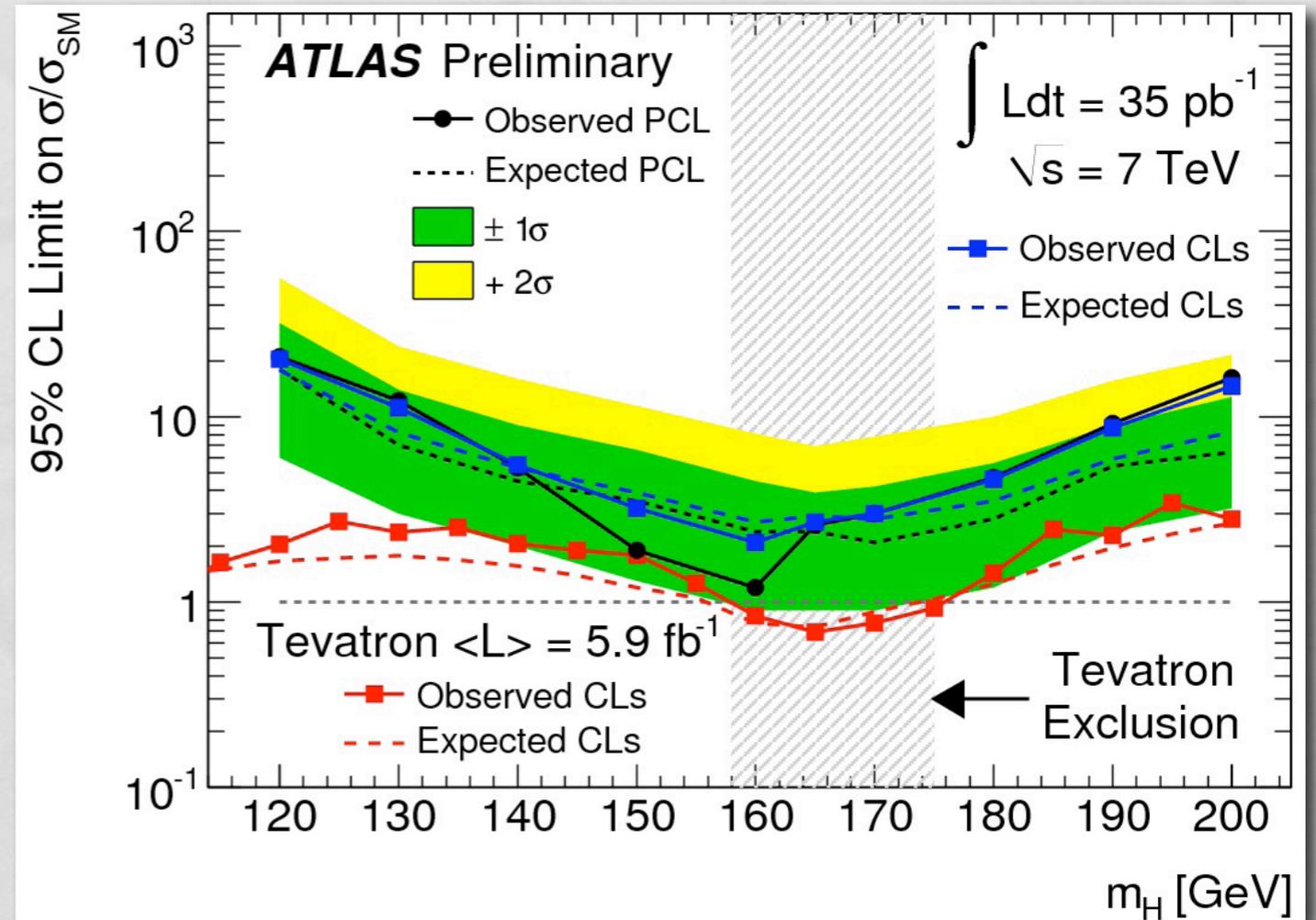
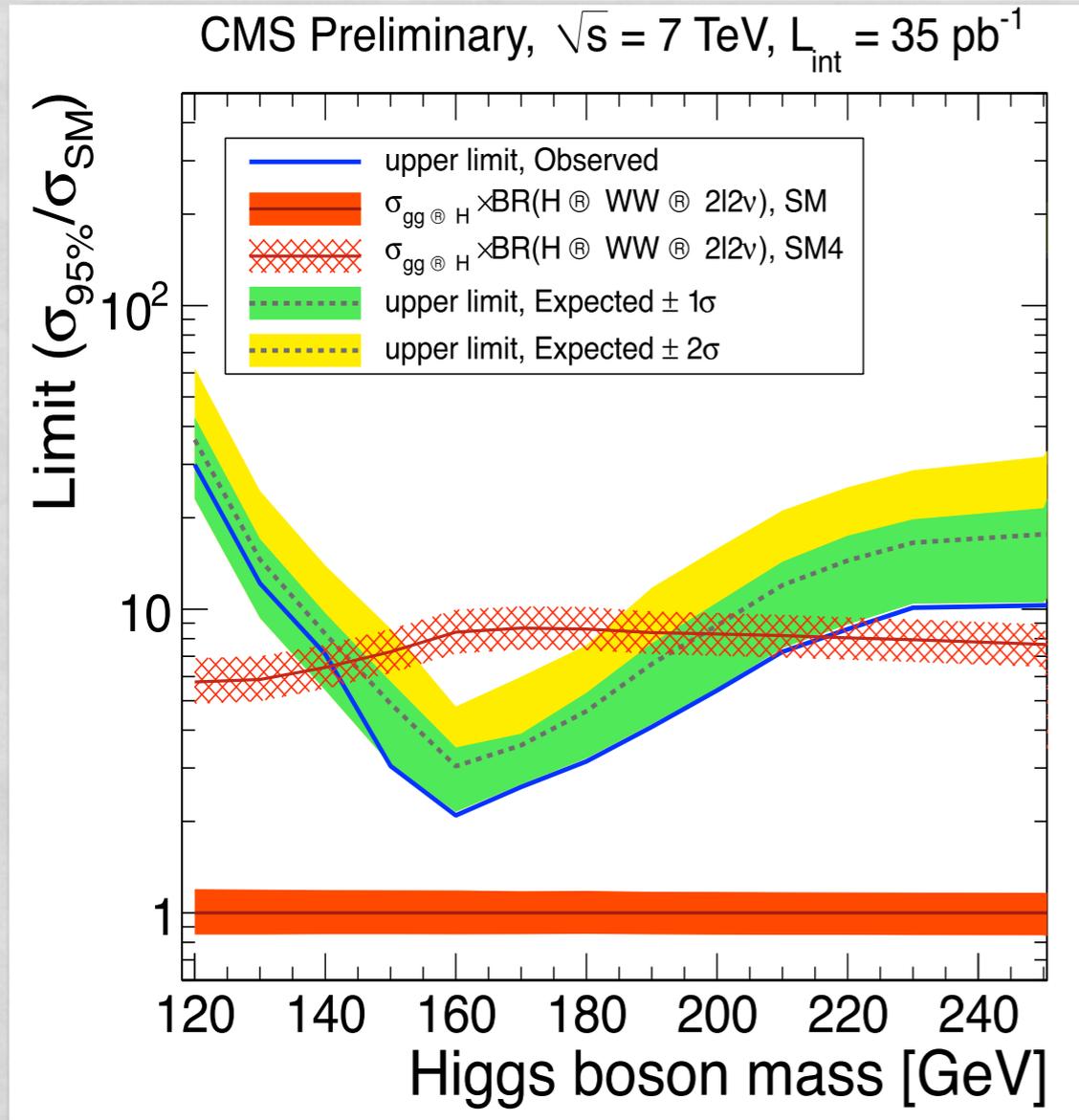
Collision CM Energy up to 4 TeV !



# LHC Searches for New Physics-2010



# LHC enters the Higgs arena: $H \Rightarrow WW$



| 95 % CL Limit for $M_{\text{H}} = 160 \text{ GeV}$ | CMS (Bayesian) |
|--|----------------|
| Expected   | 3.0 x SM       |
| Observed   | 2.1 x SM       |

| 95 % CL Limit for $M_{\text{H}} = 160 \text{ GeV}$ | ATLAS ( $\text{CL}_s$ ) |
|--|-------------------------|
| Expected   | 2.7 x SM                |
| Observed   | 2.1 x SM                |

# Expected Higgs mass coverage (GeV)

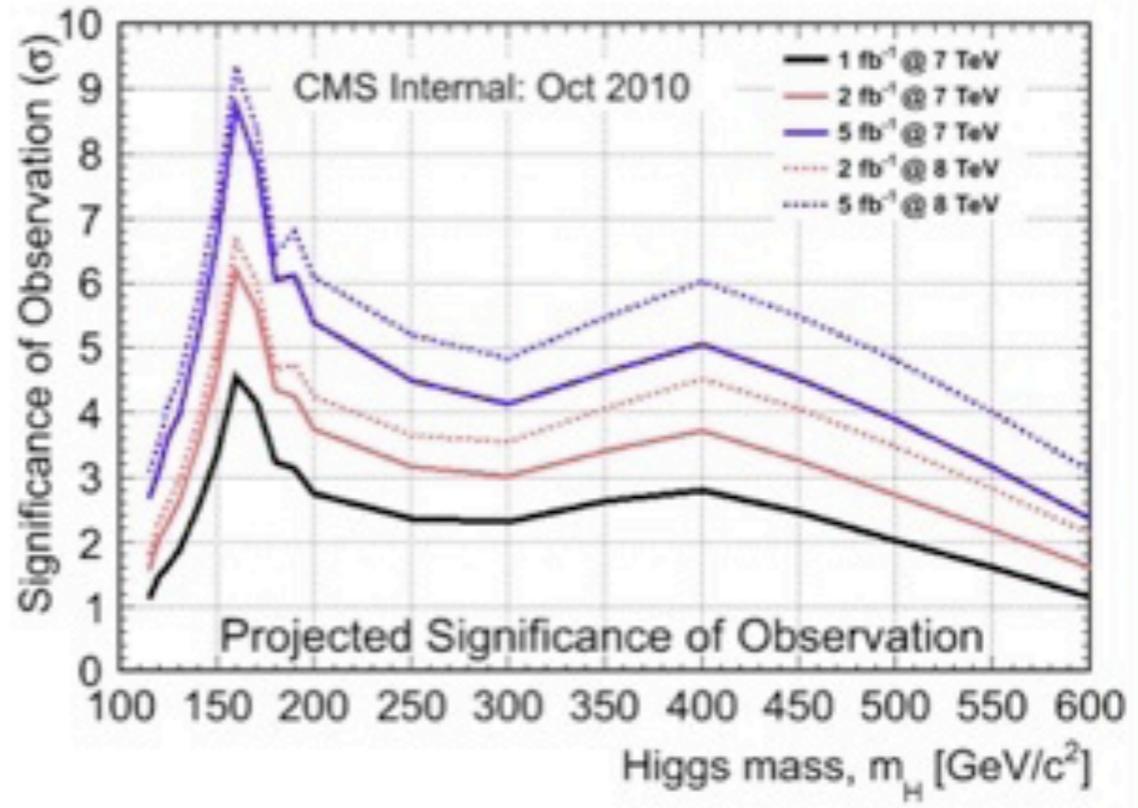
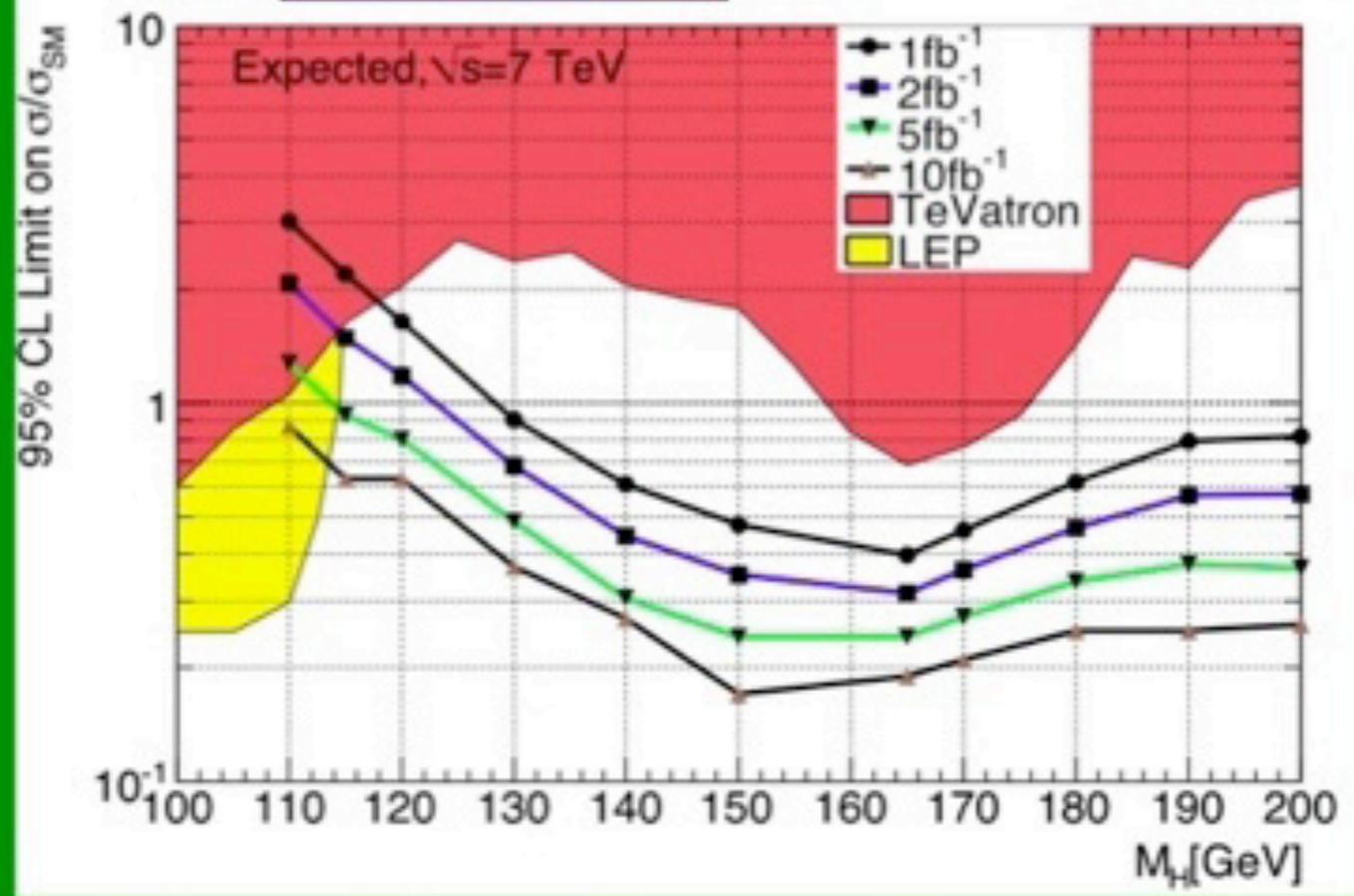
ATLAS and CMS internal and very preliminary



| Luminosity per expt and    | Comments          | ATLAS+CMS 95% CL exclusion | ATLAS+CMS 3σ evidence | ATLAS+CMS 5σ discovery |
|----------------------------|-------------------|----------------------------|-----------------------|------------------------|
| 1 fb <sup>-1</sup> 7 TeV   | 2011              | 123-550 GeV                | 130-450 GeV           | 152-174 GeV            |
| 1 fb <sup>-1</sup> 8 TeV   | 2011 (?)          | 120-570                    | 127-500               | 150-176                |
| 2.5 fb <sup>-1</sup> 7 TeV | 2011 "aggressive" | 114-600                    | 123-530               | 138-220                |
| 5 fb <sup>-1</sup> 7 TeV   | 2012 (if run)     | 114-600                    | 114-600               | 124-510                |
| 5 fb <sup>-1</sup> 14 TeV  | 2013              |                            |                       | > 115                  |
| 30 fb <sup>-1</sup> 14 TeV | ~2014             |                            |                       | H → bb at 4-5 σ ?      |

From Fabiola Gianotti

ATLAS internal



# Betting on the Higgs Observation

The Prediction Market

User Name

Password

[Live Help](#) [Login Help](#) [Log In!](#)

Home
Signup
Markets
Trade
Intrade Labs
Forum

**Current Contracts** ?

Find:  [Go](#)

- [Most Traded](#)
- [Upcoming](#)
- [Business](#)
- [Climate and Weather](#)
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- [Foreign Affairs/International](#)
- [Security](#)
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- [Legal](#)
- [Politics](#)
- [Real Estate](#)
- [Scientific](#)
- [Social and Civil](#)
- [Technologies](#)
- [Test: Company Valuation](#)
- [Transportation](#)
- [Show Expired](#)

**Scientific - Higgs Boson Particle**

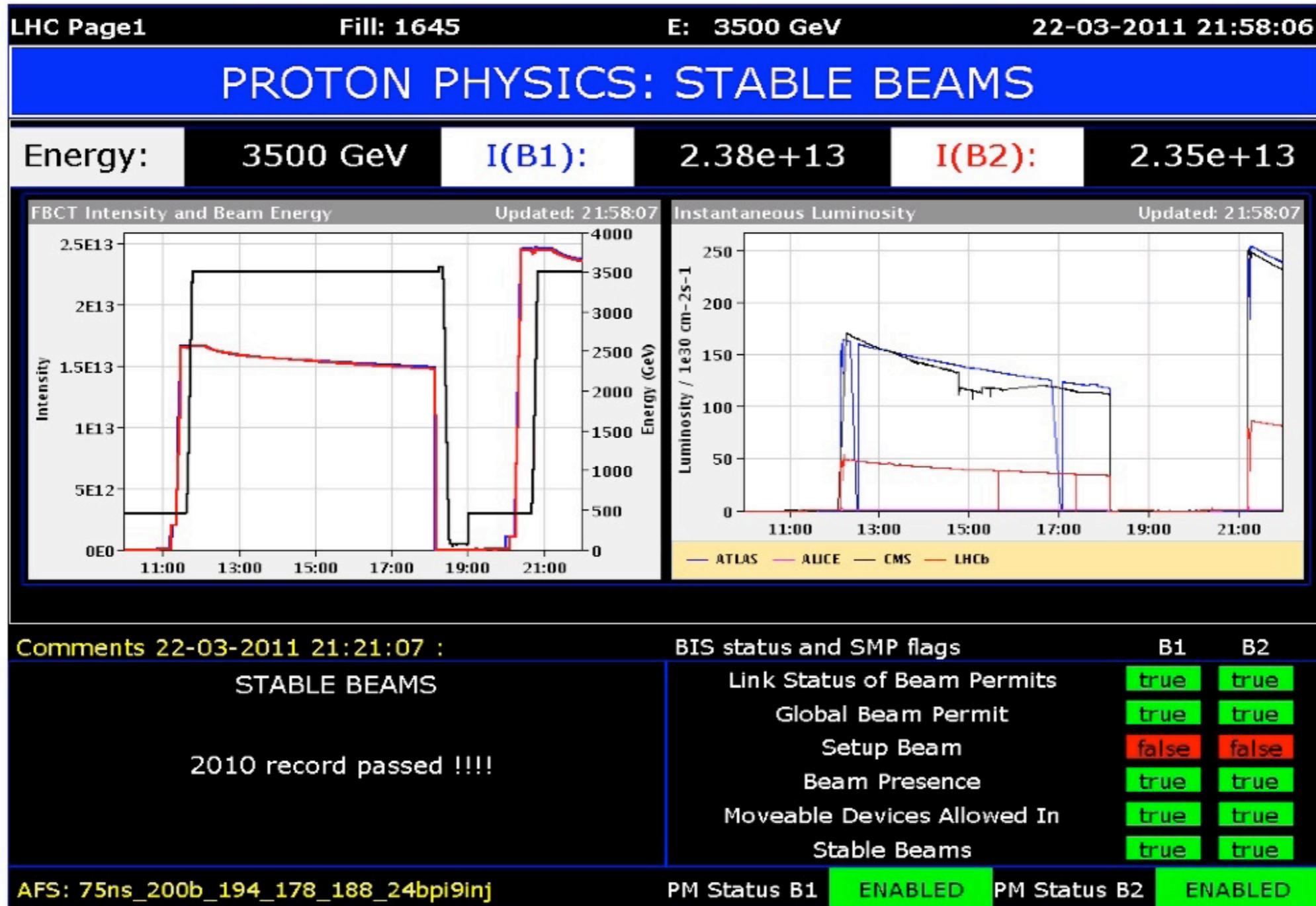
**Observation of the Higgs Boson Particle** -

| Contract   |                       | Bid  | Ask  | Last | Vol | Chge |
|--|-----------------------|------|------|------|-----|------|
| <a href="#">HIGGS.BOSON.DEC11</a><br>Higgs Boson Particle to be observed on/before 31 Dec 2011 | <a href="#">Trade</a> | 5.0  | 12.0 | 10.0 | 133 | 0    |
| <a href="#">HIGGS.BOSON.DEC12</a><br>Higgs Boson Particle to be observed on/before 31 Dec 2012 | <a href="#">Trade</a> | 8.2  | 18.9 | 13.0 | 31  | 0    |
| <a href="#">HIGGS.BOSON.DEC13</a><br>Higgs Boson Particle to be observed on/before 31 Dec 2013 | <a href="#">Trade</a> | 15.0 | 29.0 | 15.0 | 80  | 0    |
| <a href="#">HIGGS.BOSON.DEC14</a><br>Higgs Boson Particle to be observed on/before 31 Dec 2014 | <a href="#">Trade</a> | 16.0 | 30.0 | -    | 0   | 0    |
| <a href="#">HIGGS.BOSON.DEC15</a><br>Higgs Boson Particle to be observed on/before 31 Dec 2015 | <a href="#">Trade</a> | 20.0 | 51.0 | -    | 0   | 0    |

Mar 13 - 3:52AM GMT

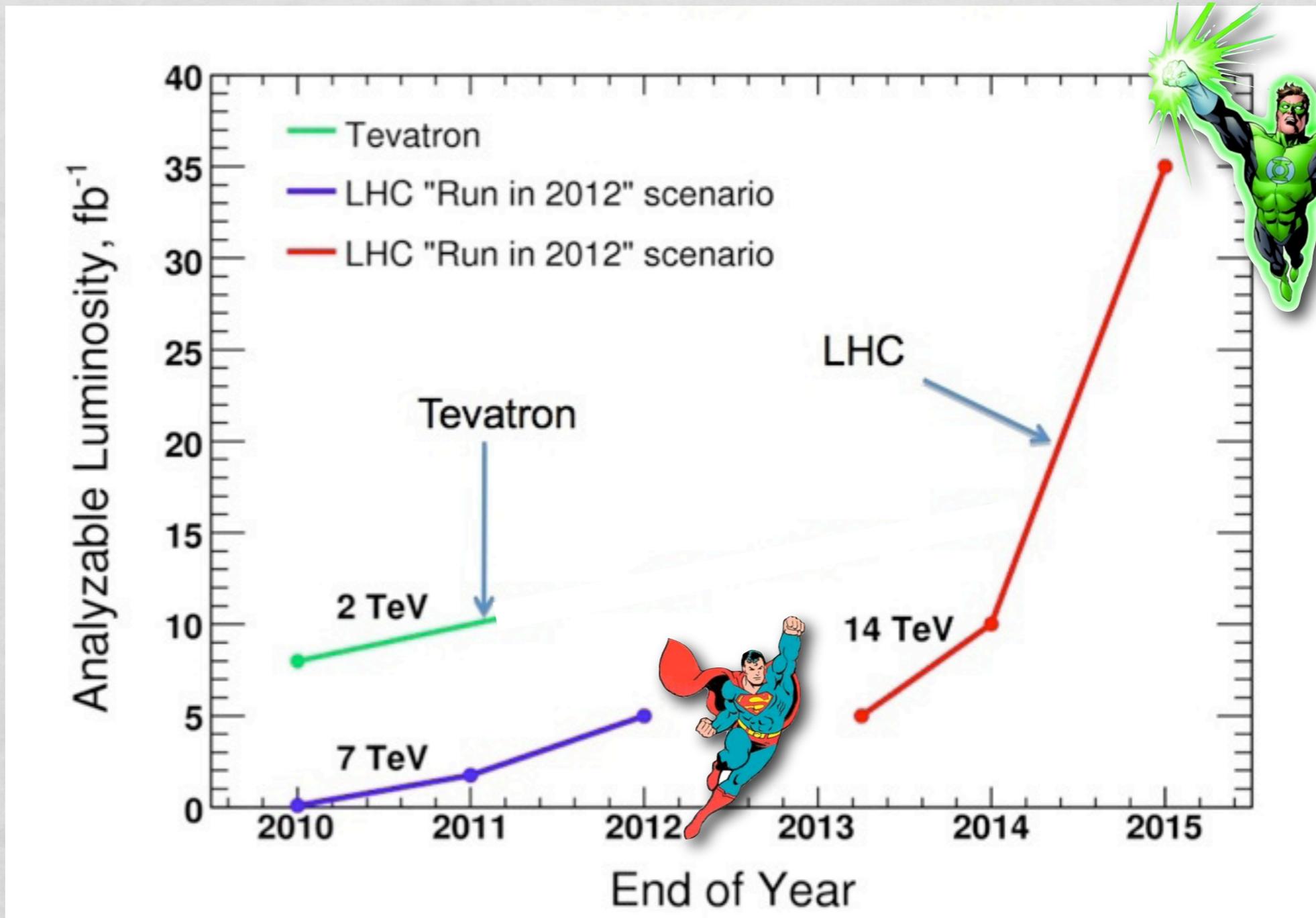
# THE LHC SHOW CONTINUES !

New record instantaneous luminosity last night  $\mathcal{L} \approx 2.5 \times 10^{32} \text{cm}^{-2}\text{s}^{-1}$

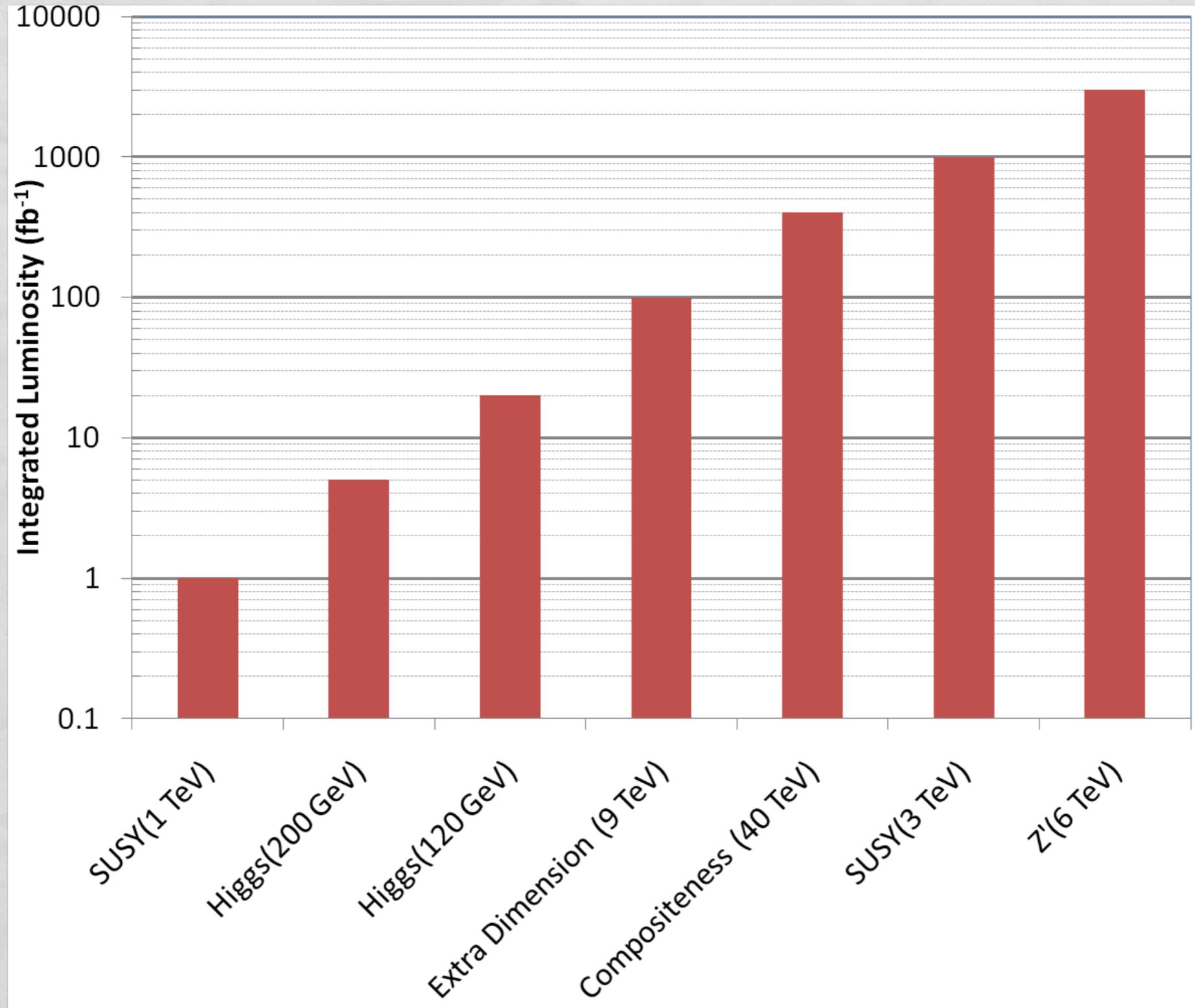


If  $10^{33}$  achieved by the end of April  $\sim 1 \text{fb}^{-1}$  before the end of June becomes a realistic goal.

# The next few years



# Will more reach will finally yield New Physics ?

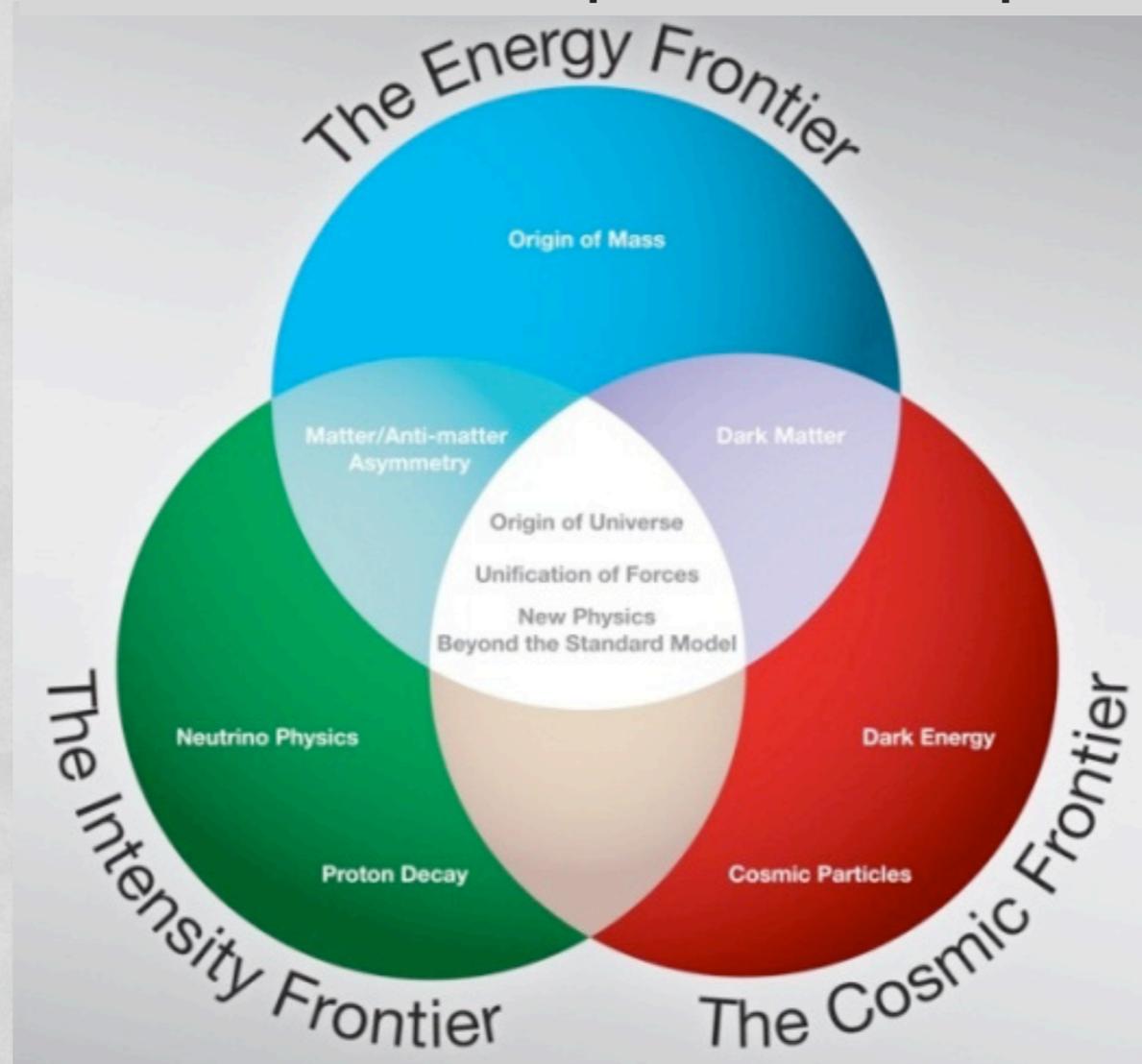


# In Summary

- We appear to be standing at the threshold of a most thrilling journey of discoveries and, as theories and predictions run wild, present and upcoming experiments embark in the ultimate hunt:

the unknown

HEP has a comprehensive plan

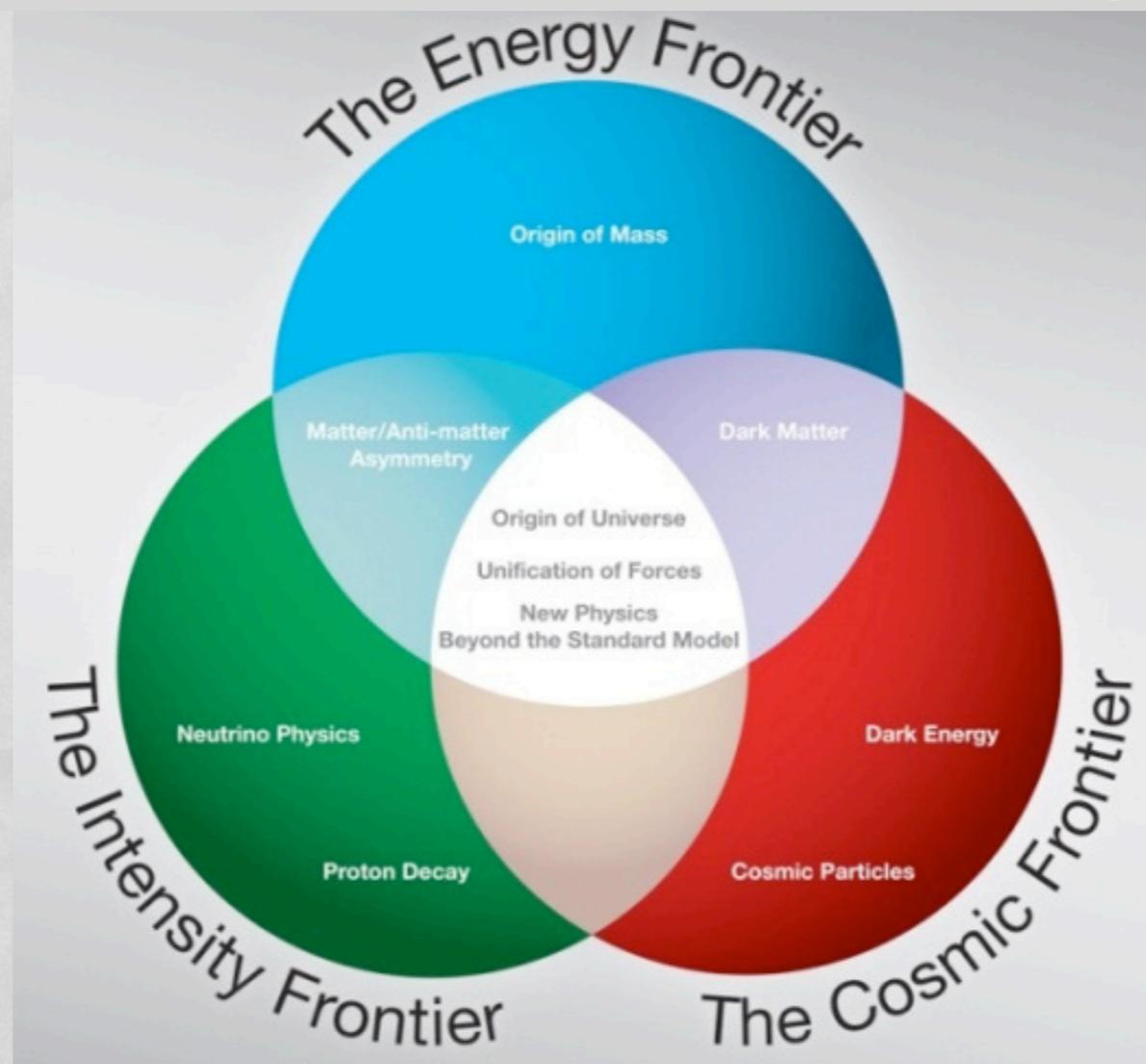


# In Summary

- We appear to be standing at the threshold of a most thrilling journey of discoveries and, as theories and predictions run wild, present and upcoming experiments embark in the ultimate hunt:

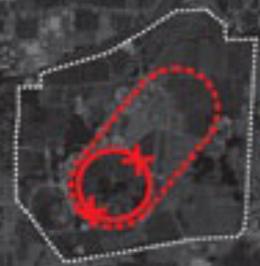
the unknown

Which should provide some fascinating answers



# ANSWERS THAT WILL HELP DETERMINE THE FUTURE COLLIDERS

POSSIBLE ONLY THANKS TO YOUR WORK !



Muon Collider  
d=2km

x



LHC  
d=8.4km

x

ILC  
l=30km

x

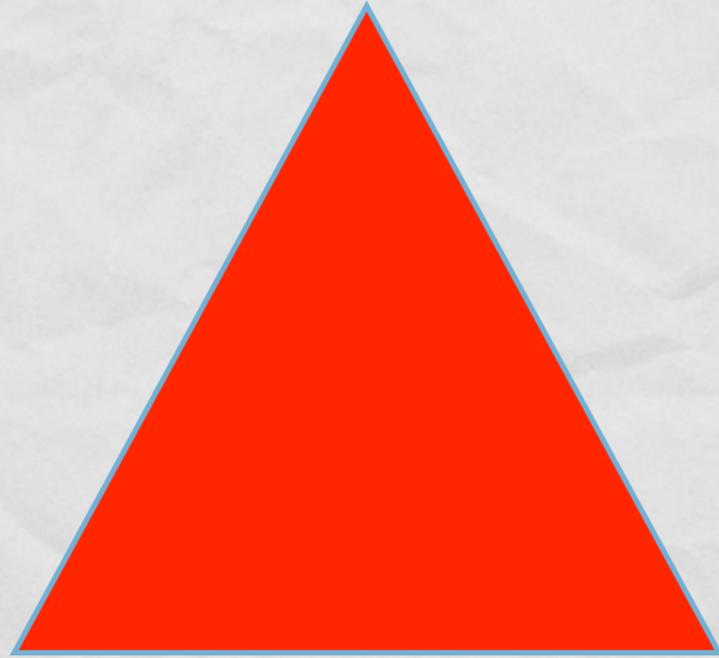
CLIC  
l=50km

VLHC  
d=74km

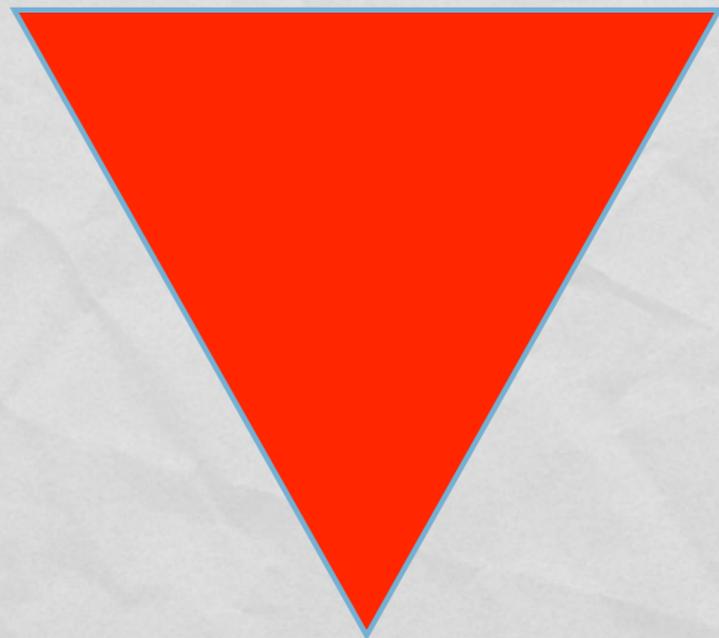
THANKS FOR THE INVITATION !

"What is a thing? The question is very old. What remains new is that it must always be asked"

- Martin Heidegger, What is a thing?



**BACKUP**

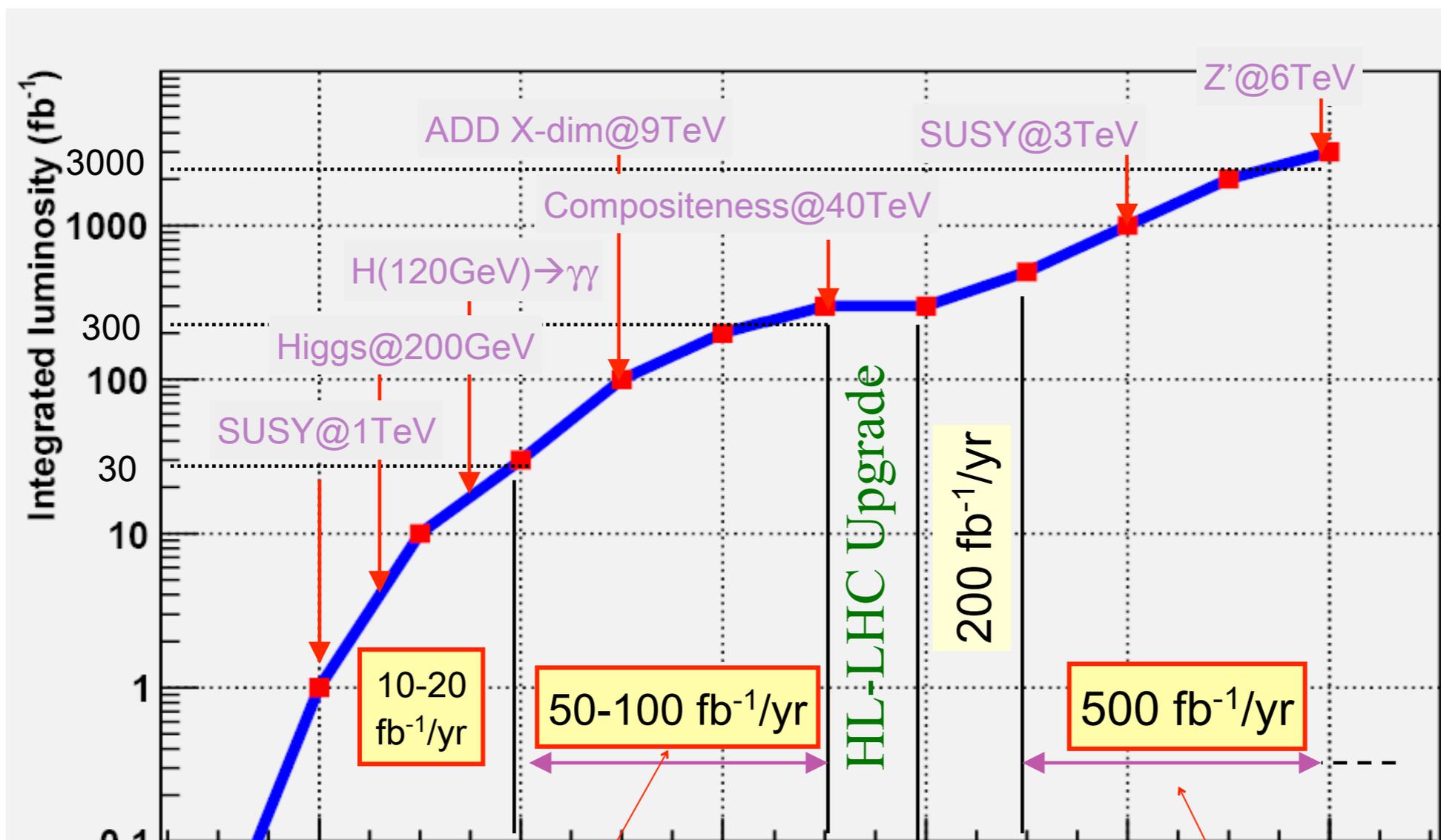




# The Long Road to Discovery



- Even with the higher luminosity, still need a lot of time to reach the discovery potential of the LHC



Note: VERY outdated plot. Ignore horizontal scale.

Could conceivably get to 3000 fb<sup>-1</sup> by 2030.

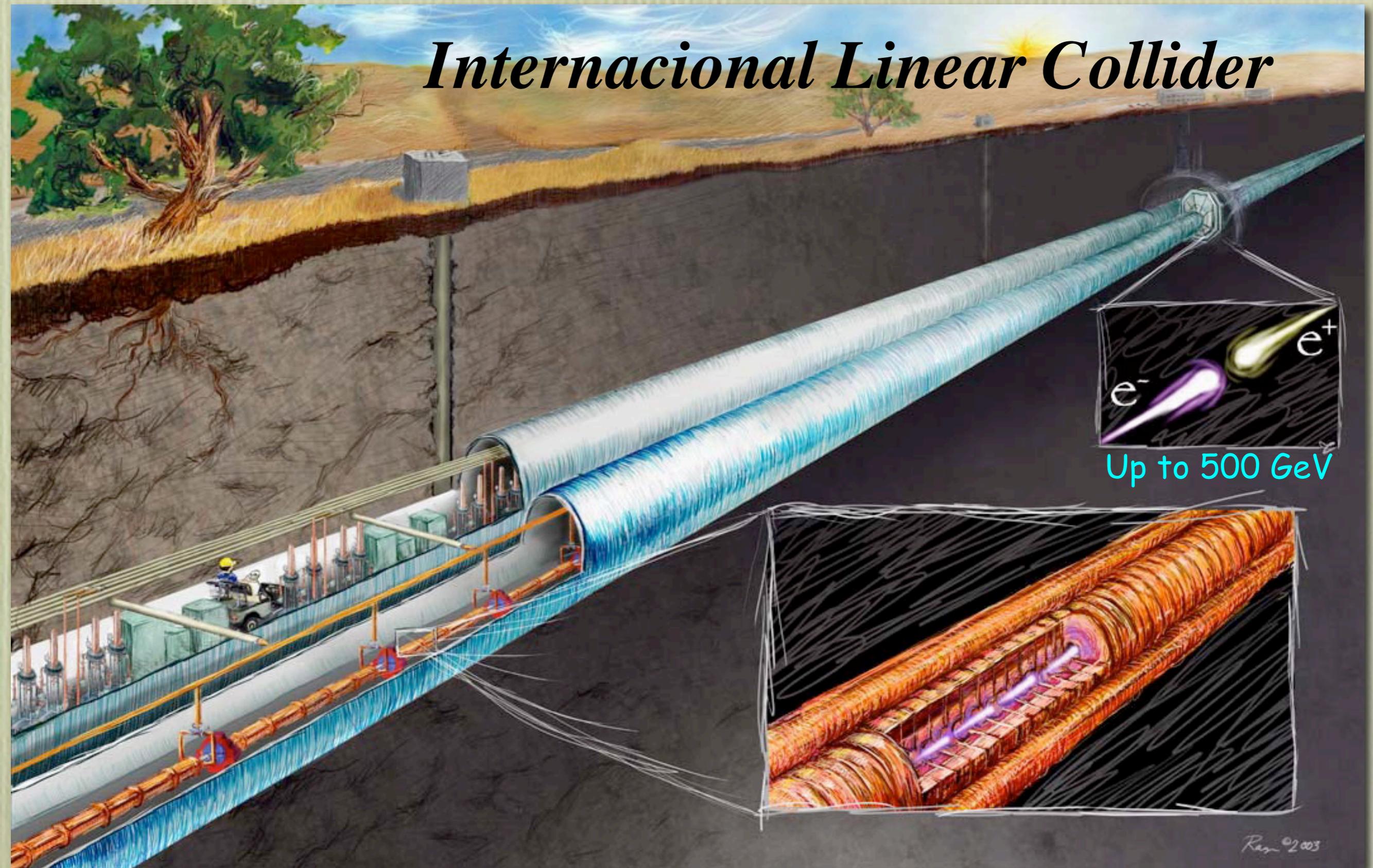
50 x Tevatron luminosity

250 x Tevatron luminosity

- Lots of new challenges between now and then!

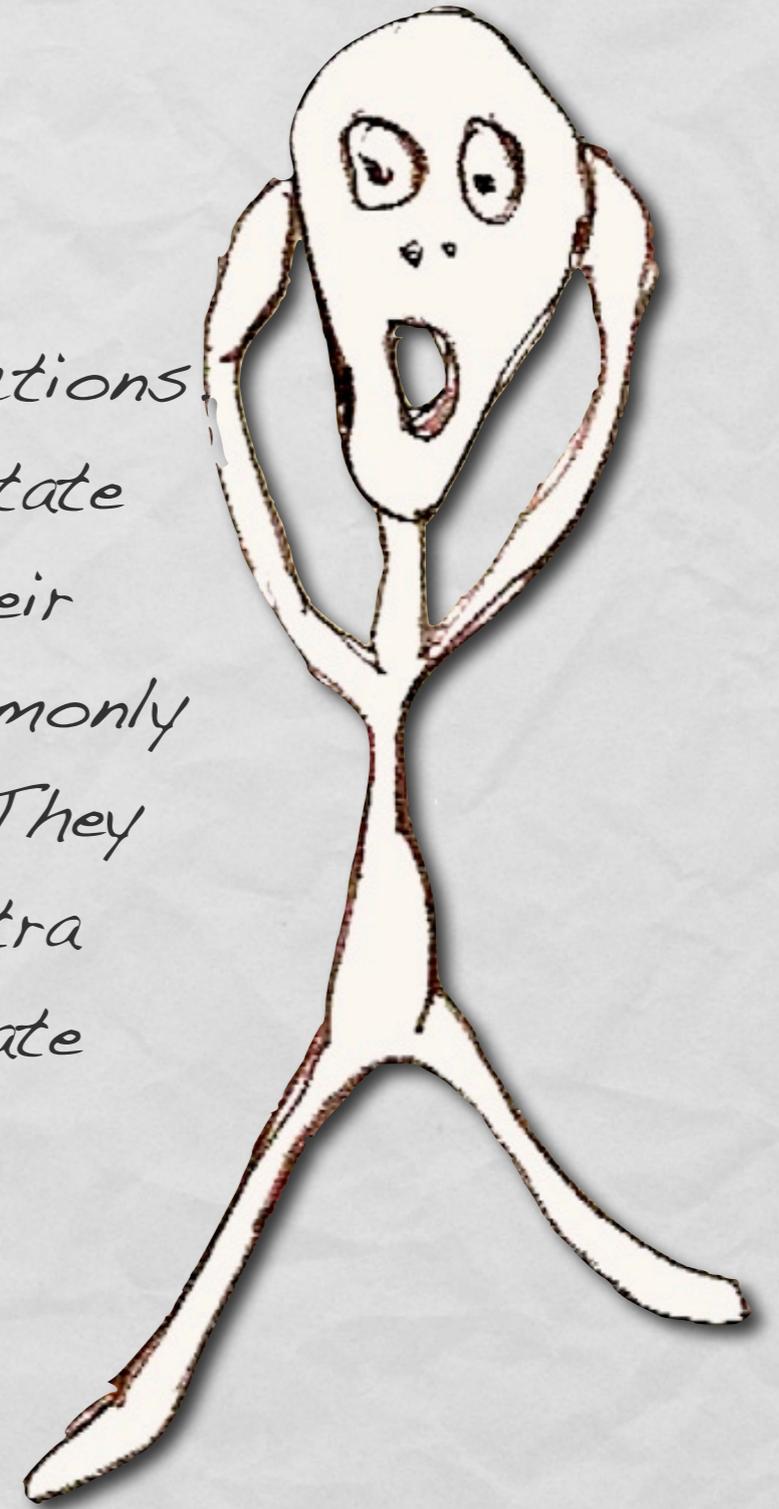
# New accelerators to study the New Physics

## *Internacional Linear Collider*



# Other discoveries

*"Particles created by non-abelian Blog-Blog interactions. Bloginos typically are produced in a very excited state and with a high degree of spin. Even though all their properties have not yet been determined, it is commonly agreed that they exhibit considerable truthiness. They also have the annoying ability to propagate into extra dimensions, away from the blogosphere, and generate lots of phone calls." - JK*



*The Blogino*

# International Collaborations (ex: FNAL)

27 countries



16 countries



23 countries



# Today, ~30,000 accelerators are in operation around world

- Discovery science



- Materials research / manufacturing

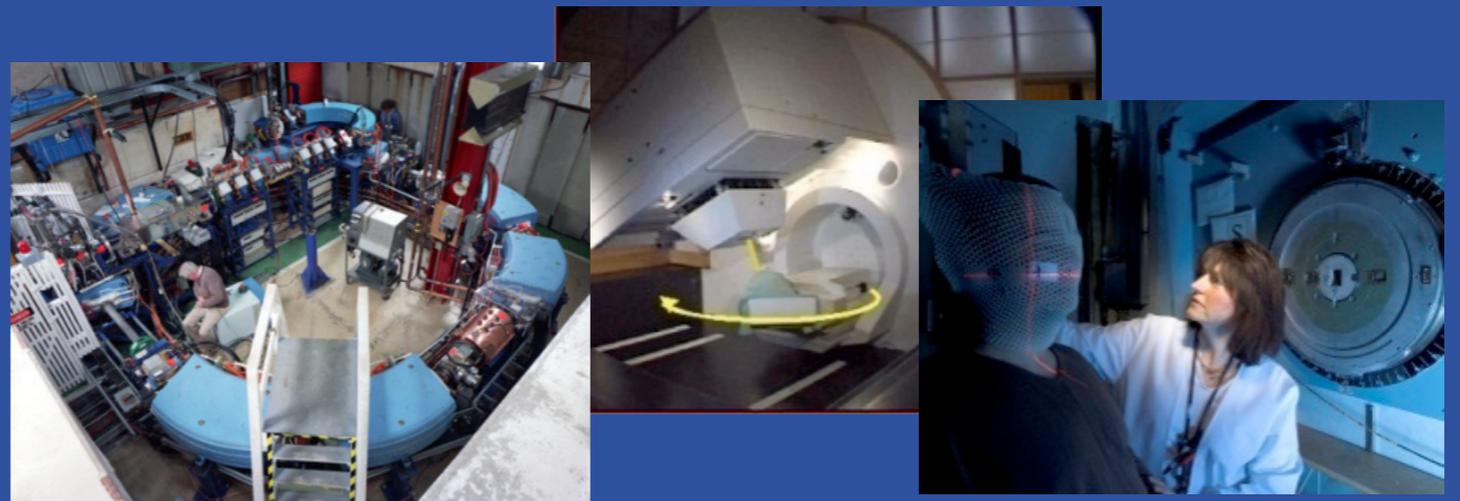


- National security



- Energy and the environment

- Medicine



# References

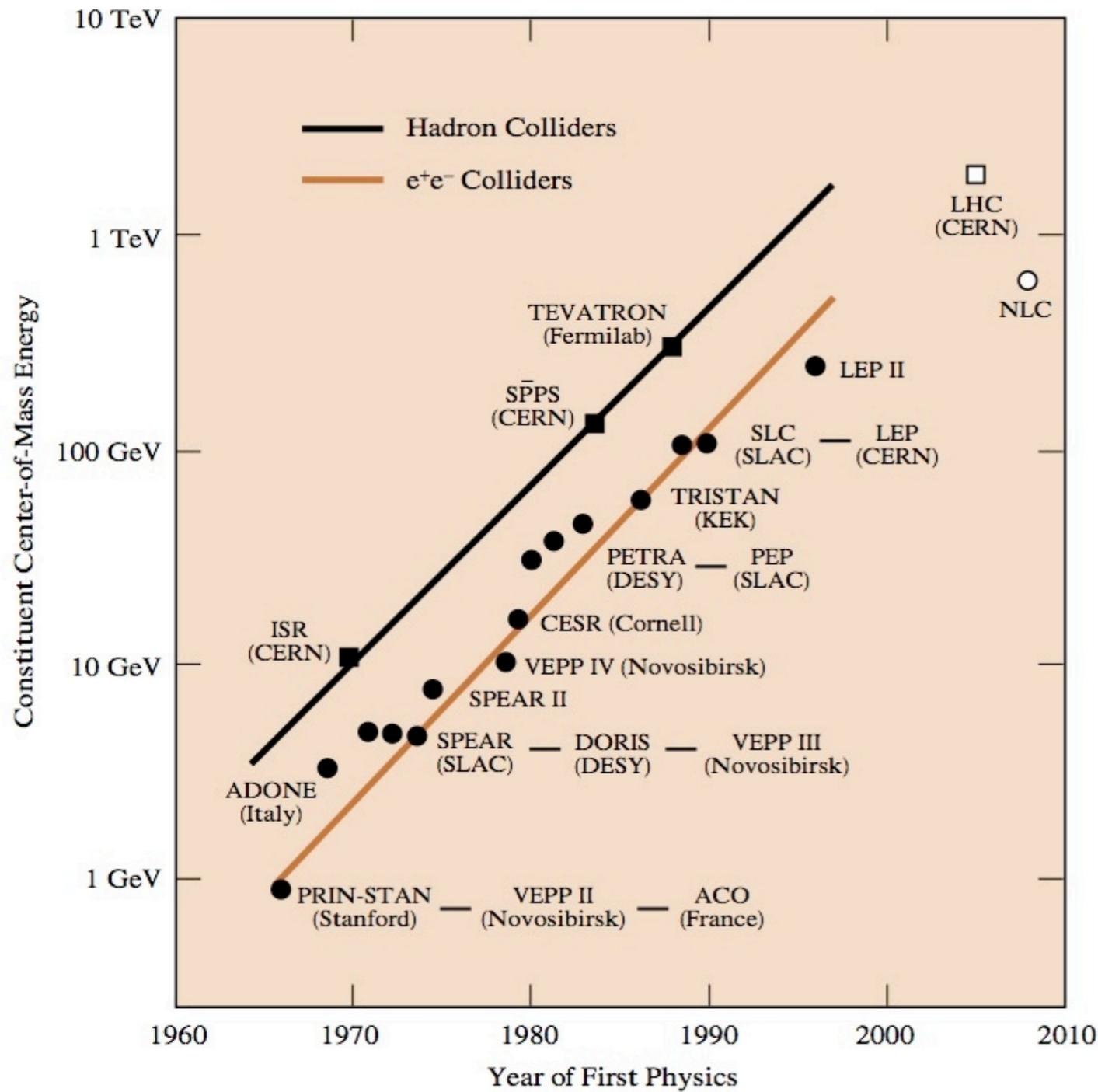
## The Tevatron Program

- ✦ CDF: <http://www-cdf.fnal.gov/physics/physics.html>
- ✦ DO: <http://www-d0.fnal.gov/results/>

## The LHC program

- ✦ CMS: <https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResults>
- ✦ ATLAS: <https://twiki.cern.ch/twiki/bin/view/AtlasPublic>

# more



*Right: The energy in the constituent frame of electron-positron and hadron colliders constructed (filled circles and squares) or planned. The energy of hadron colliders has here been derated by factors of 6–10 in accordance with the fact that the incident proton energy is shared among its quark and gluon constituents.*



# Machine upgrade path

**SHUTDOWN**

**Phase-0 : 15 months: 2012 to spring 2013**

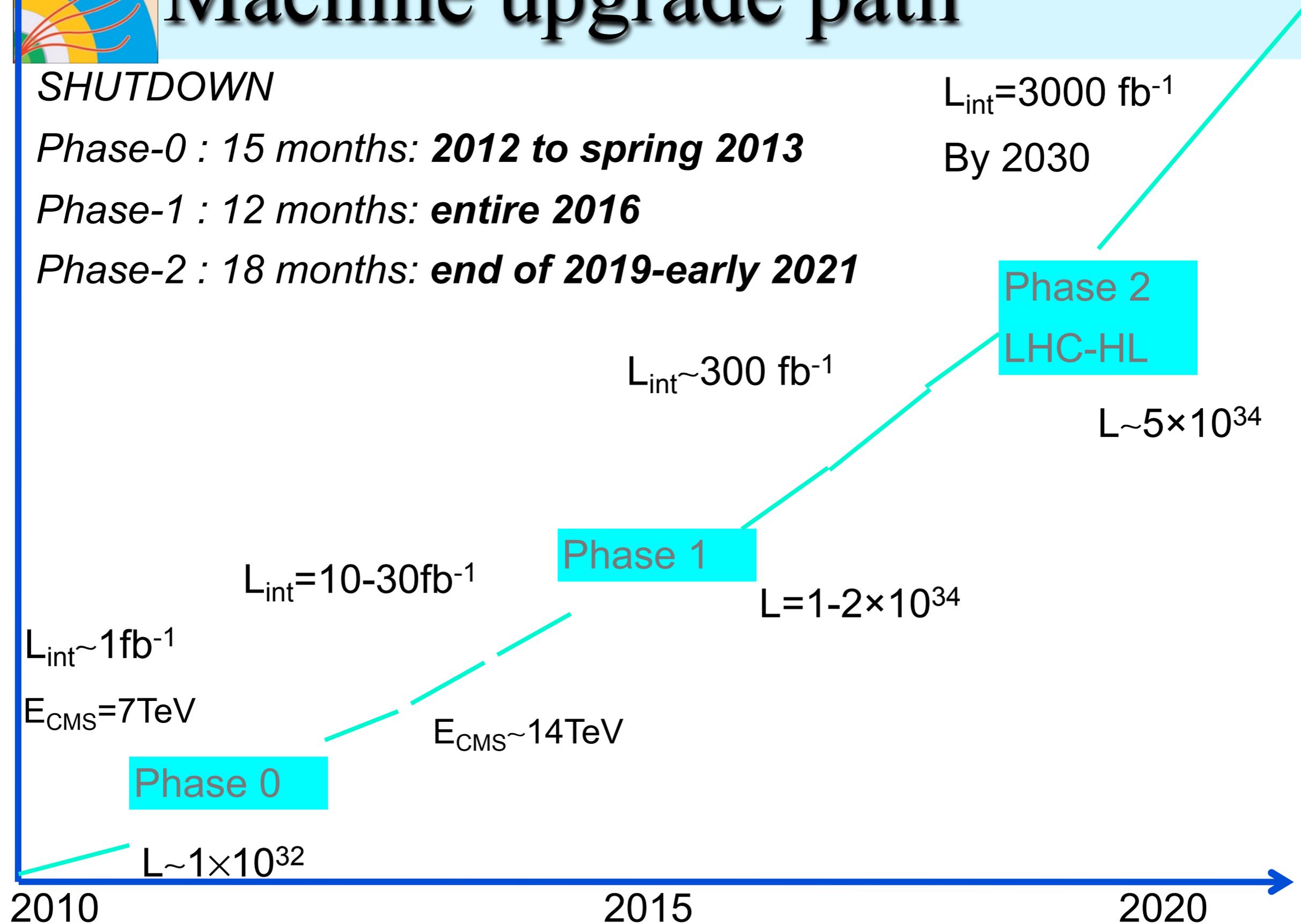
**Phase-1 : 12 months: entire 2016**

**Phase-2 : 18 months: end of 2019-early 2021**

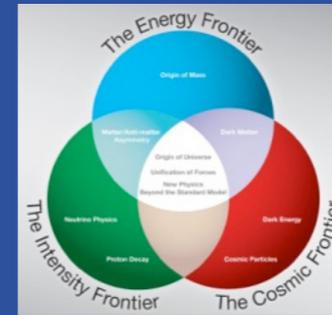
$L_{int}=3000 \text{ fb}^{-1}$

By 2030

Integrated luminosity



# Future of Fermilab



|   |  |   |  |
|---|--|---|--|
| <p>Tevatron<br/>LHC</p>                             | <p>LHC</p>   | <p>LHC Upgrades<br/>ILC??</p>                             | <p>LHC<br/>ILC, CLIC or<br/>Muon Collider</p>  |
| <p>MINOS<br/>MiniBooNE<br/>MINERvA<br/>SeaQuest</p> | <p>NOvA<br/>MicroBooNE<br/>g-2?<br/>SeaQuest</p>           | <p>LBNE<br/>Mu2e</p>                                      | <p>Project X<br/>(LBNE, <math>\mu</math>, K,<br/>nuclear, ...)<br/><math>\nu</math> Factory ??</p> |
| <p>DM: ~10 kg<br/>DE: SDSS<br/>P. Auger</p>         | <p>DM: ~100 kg<br/>DE: DES<br/>P. Auger<br/>Holometer?</p> | <p>DM: ~1 ton<br/>DE: LSST<br/>WFIRST??<br/>BigBOSS??</p> | <p>DE: LSST<br/>WFIRST??</p>   |

Now

2013

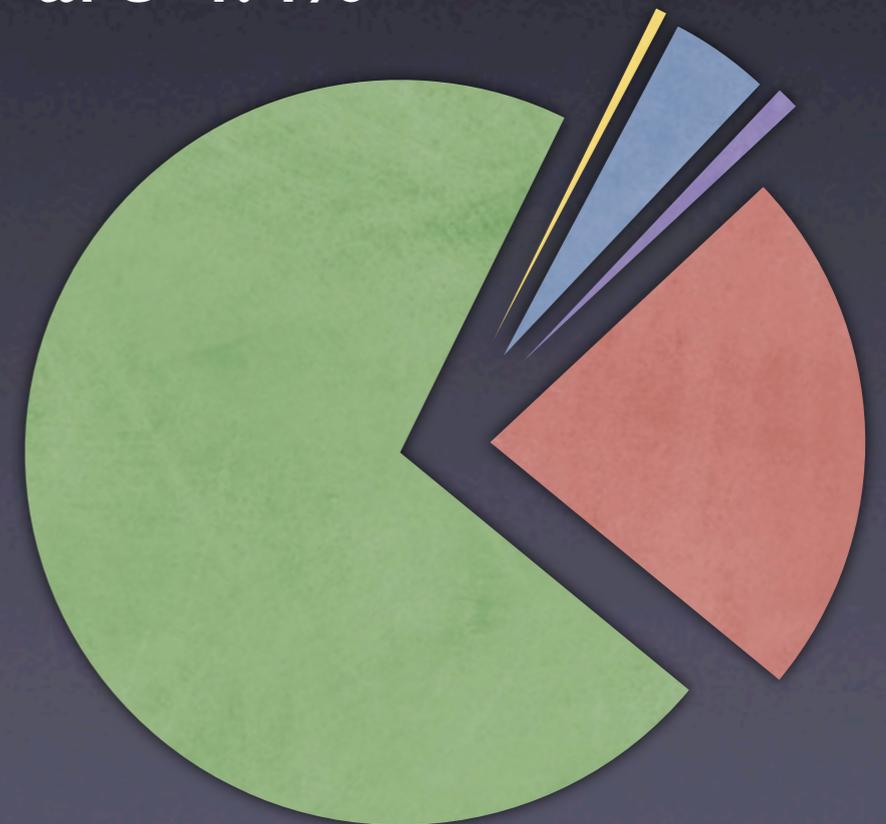
2016

2019

2022

# Energy Budget of the Universe

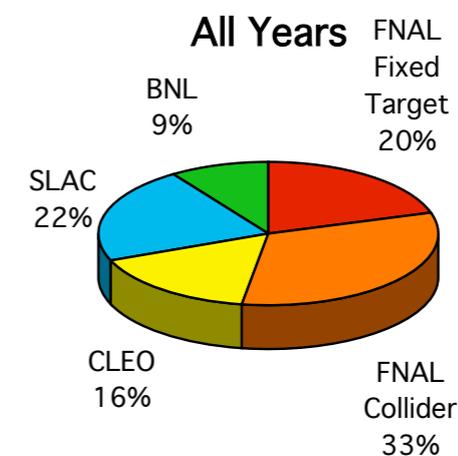
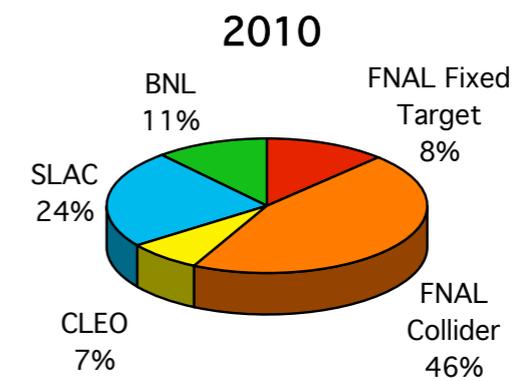
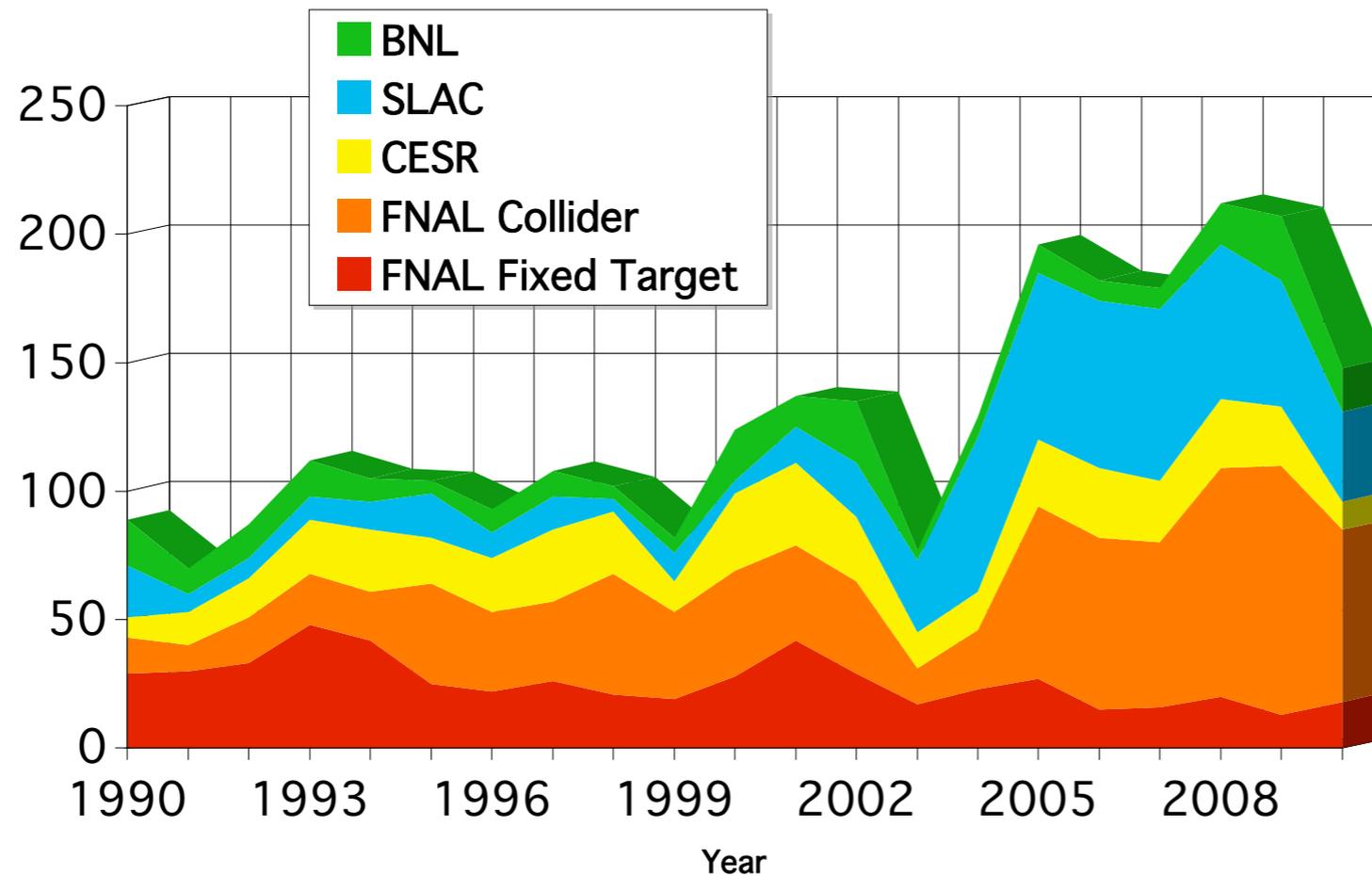
- Stars and galaxies are only ~0.5%
- Neutrinos are ~0.1–1.5%
- Rest of ordinary matter (electrons, protons & neutrons) are 4.4%
- Dark Matter 23%
- Dark Energy 73%
- Anti-Matter 0%
- Dark Field ~10<sup>62</sup>%??



# U.S. Experimental Journal Publications

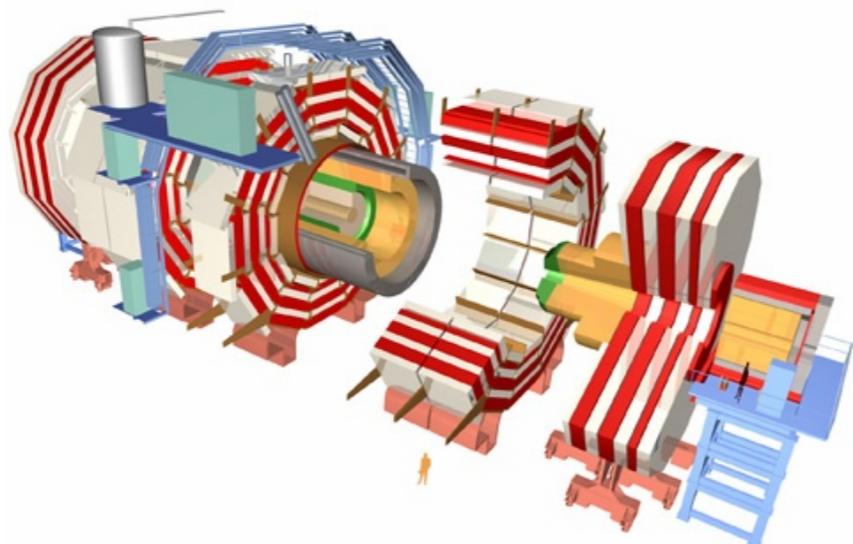
□ Tevatron publication at  $\sim 100/\text{year}$  !

Experimental HEP Publications 1990-2010

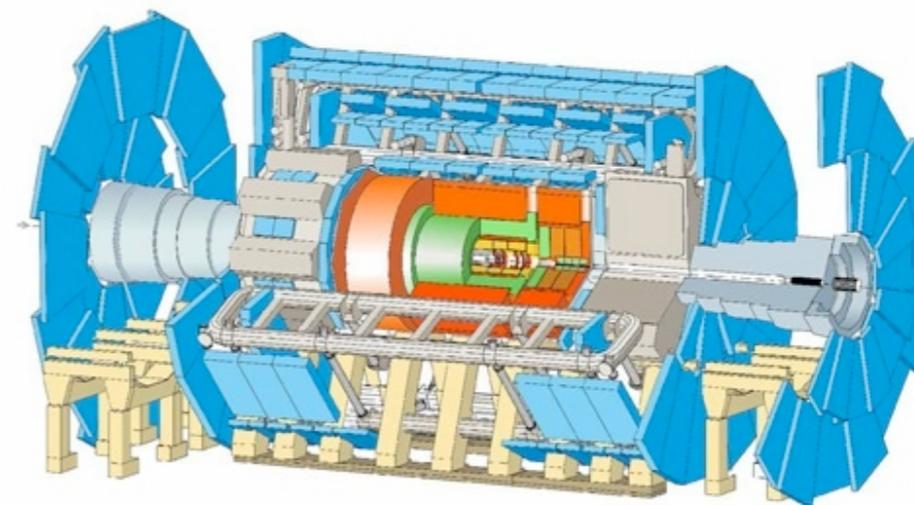




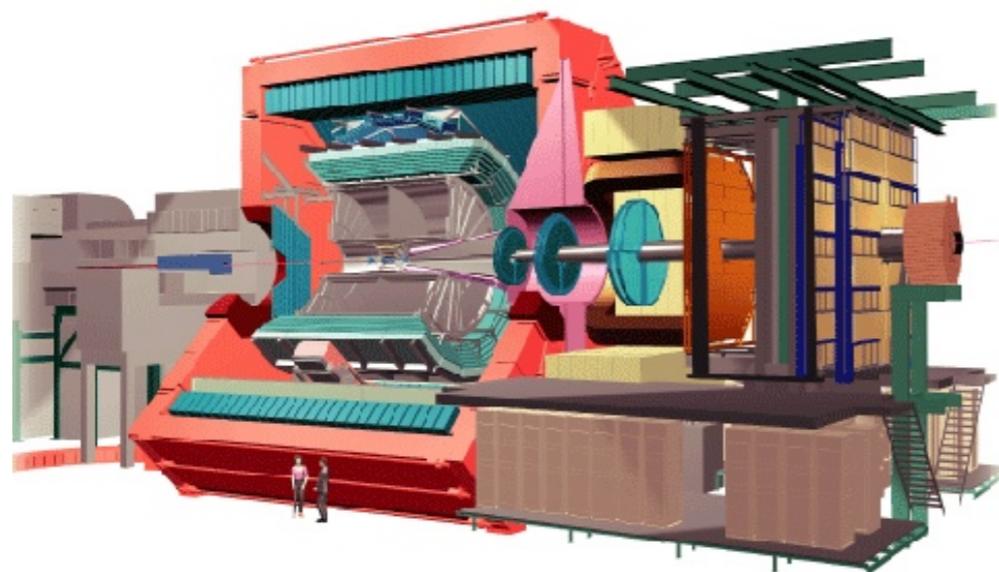
○ Huge, general purpose experiments:



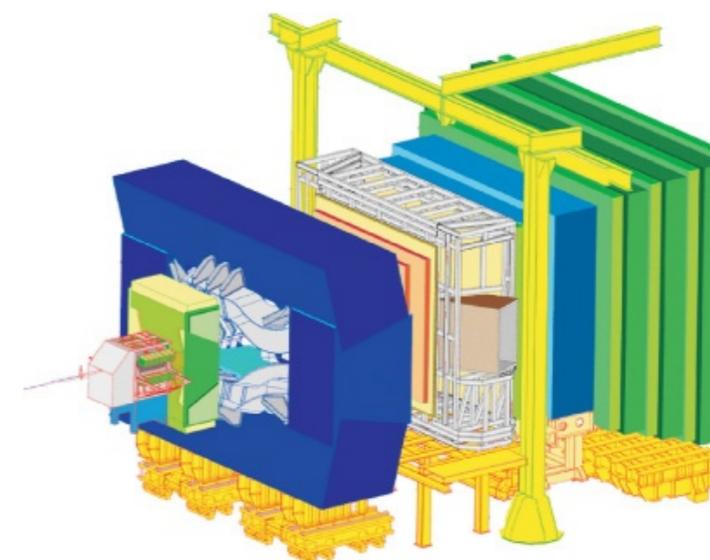
Compact Muon Solenoid (CMS)



A Toroidal LHC Apparatus (ATLAS)

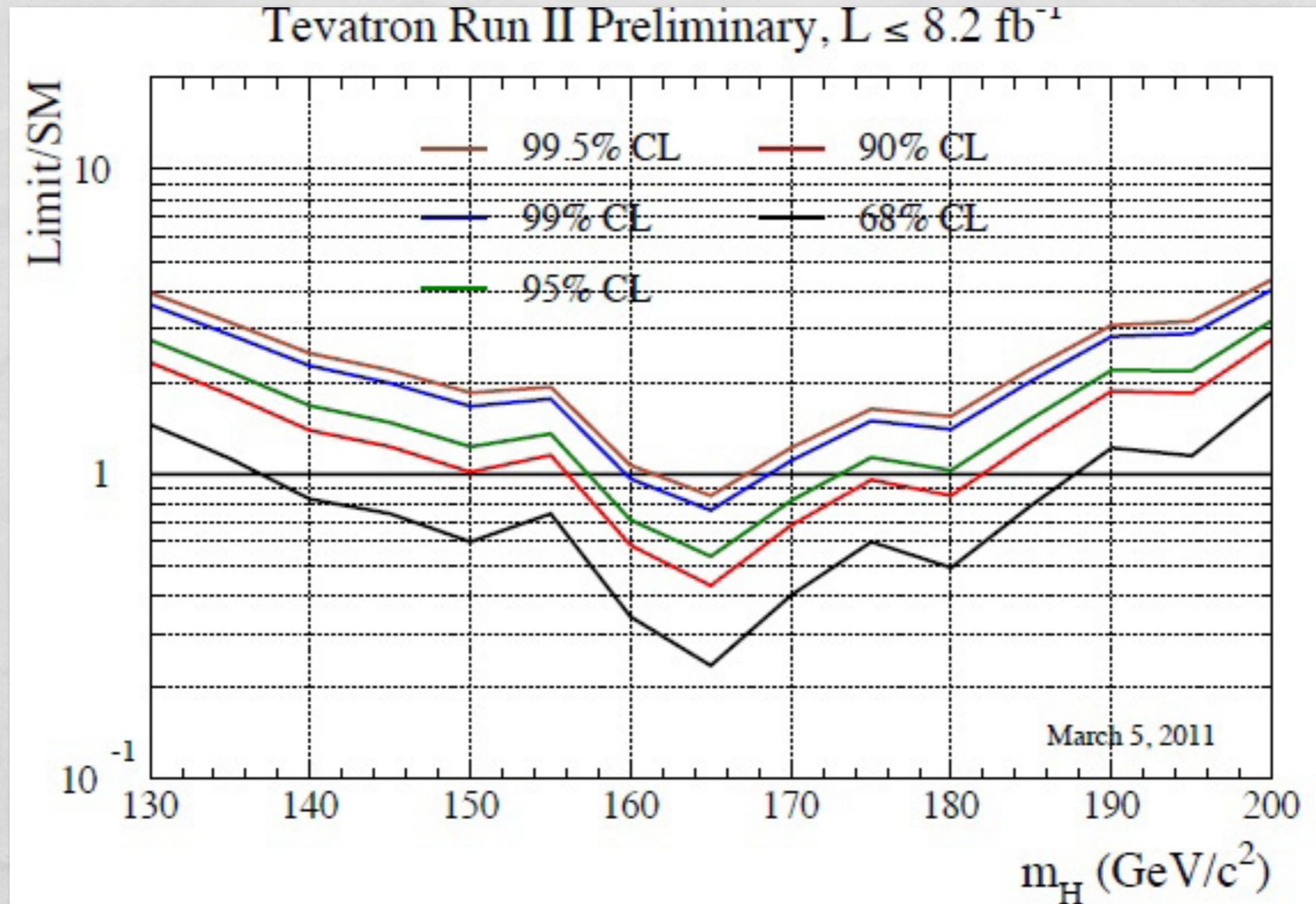


A Large Ion Collider Experiment (ALICE)



B physics at the LHC (LHCb)

# Tevatron Combination



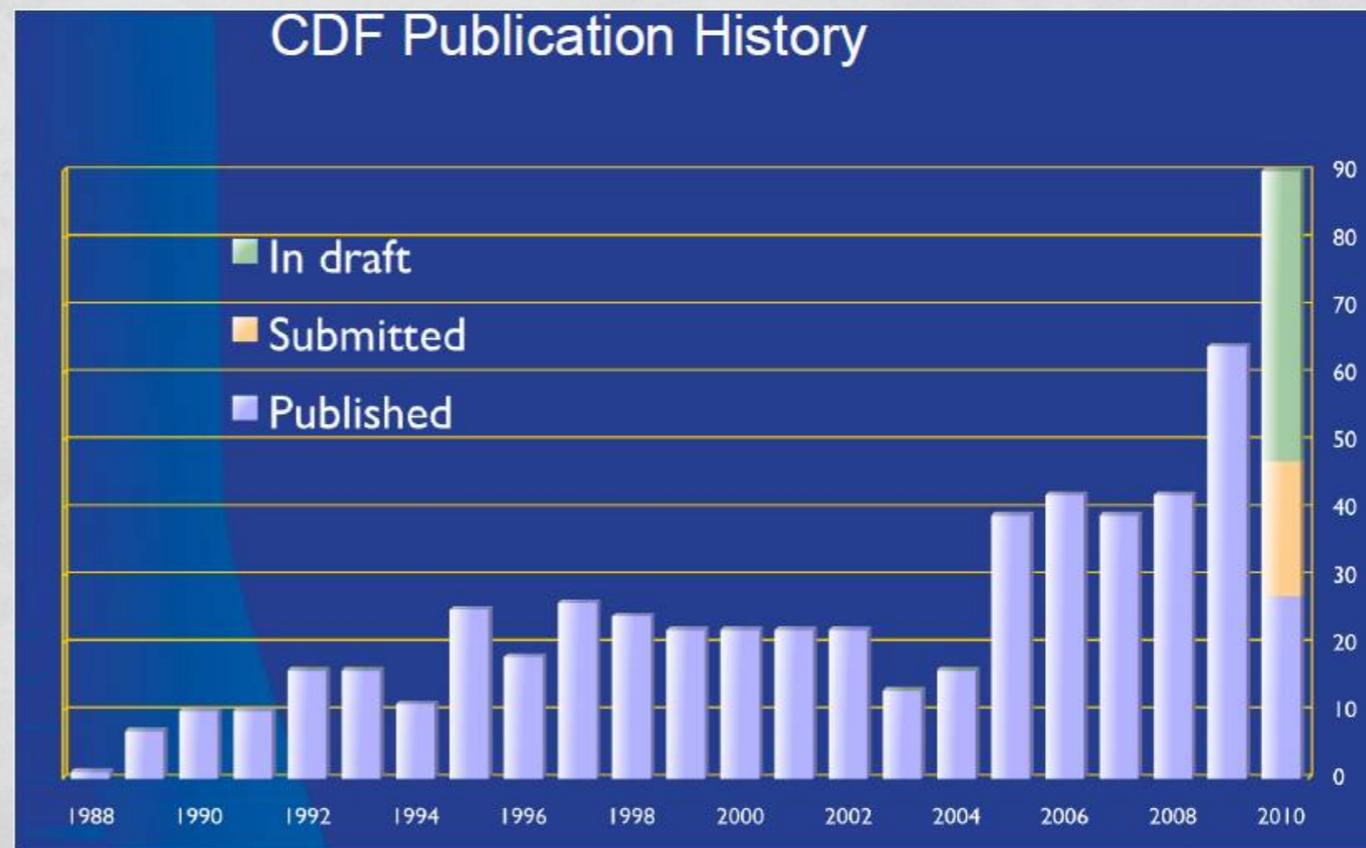
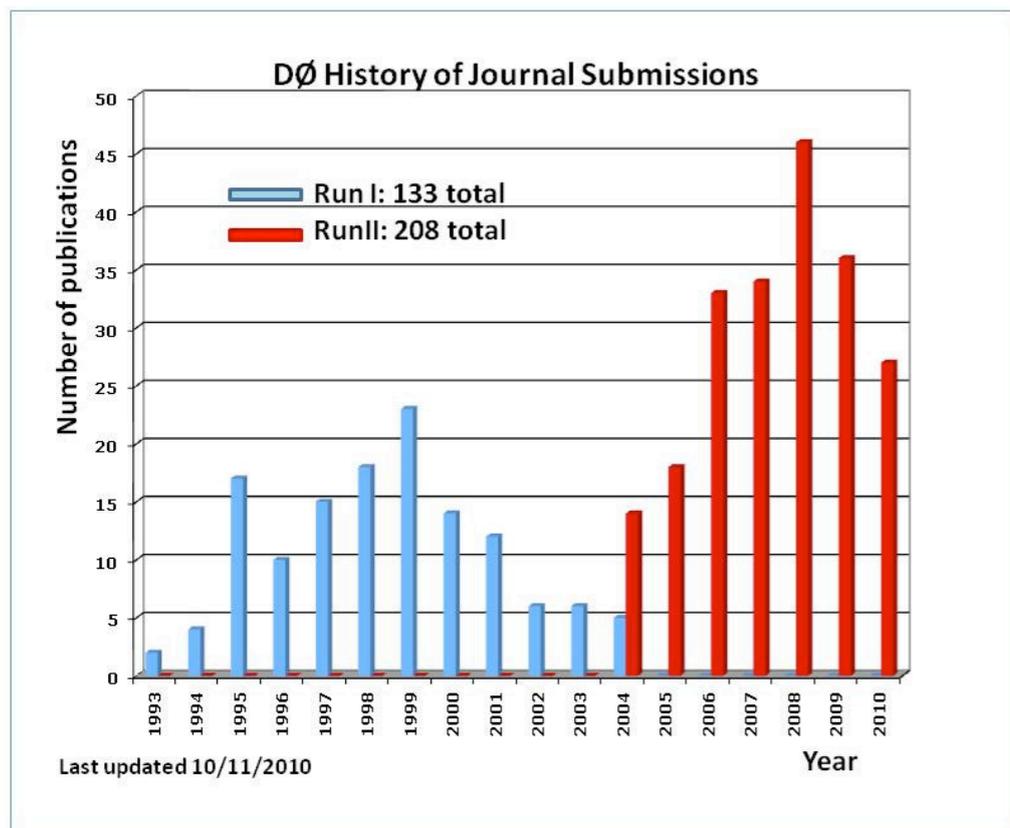
SM Higgs of  $162 < m_H < 166 \text{ GeV}$  excluded @99.5% CL



# Tevatron Physics Output



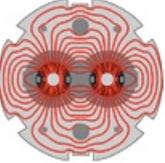
- Stable tools and well understood detectors and data



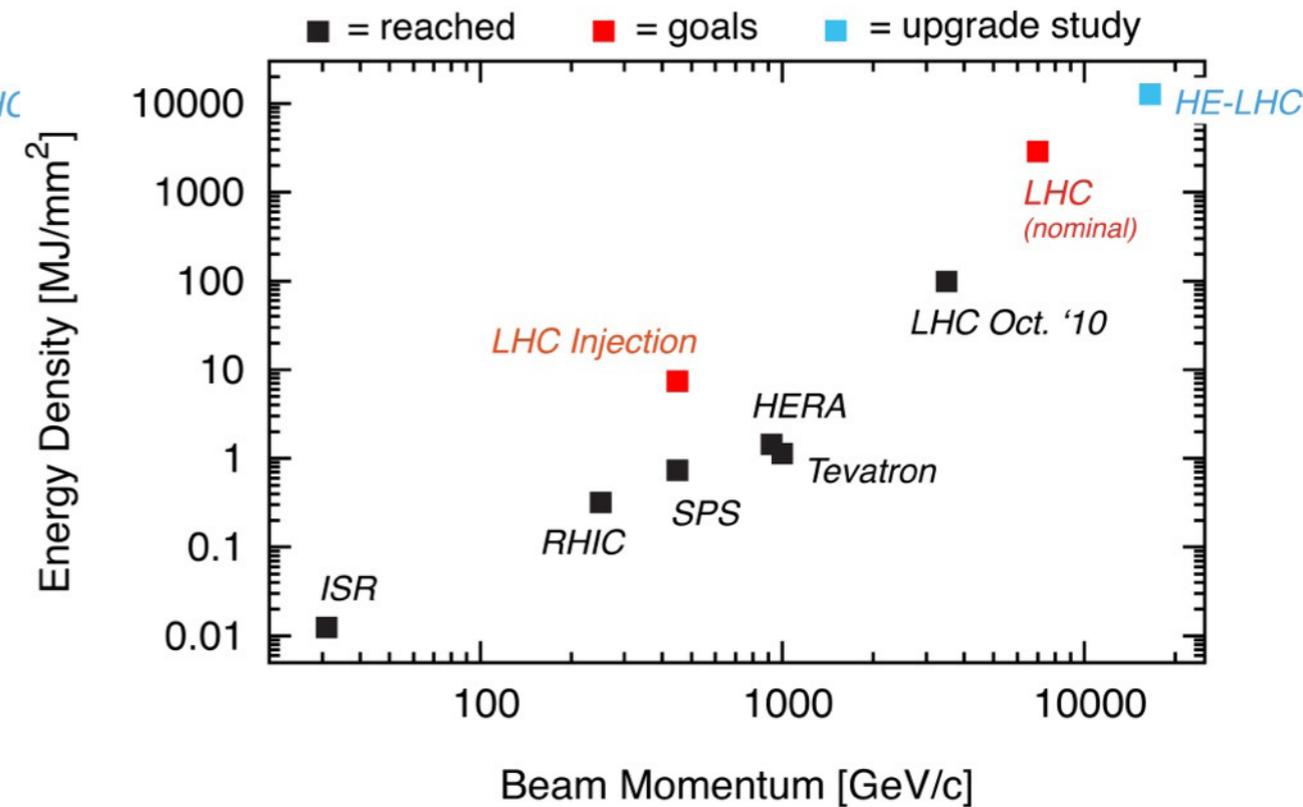
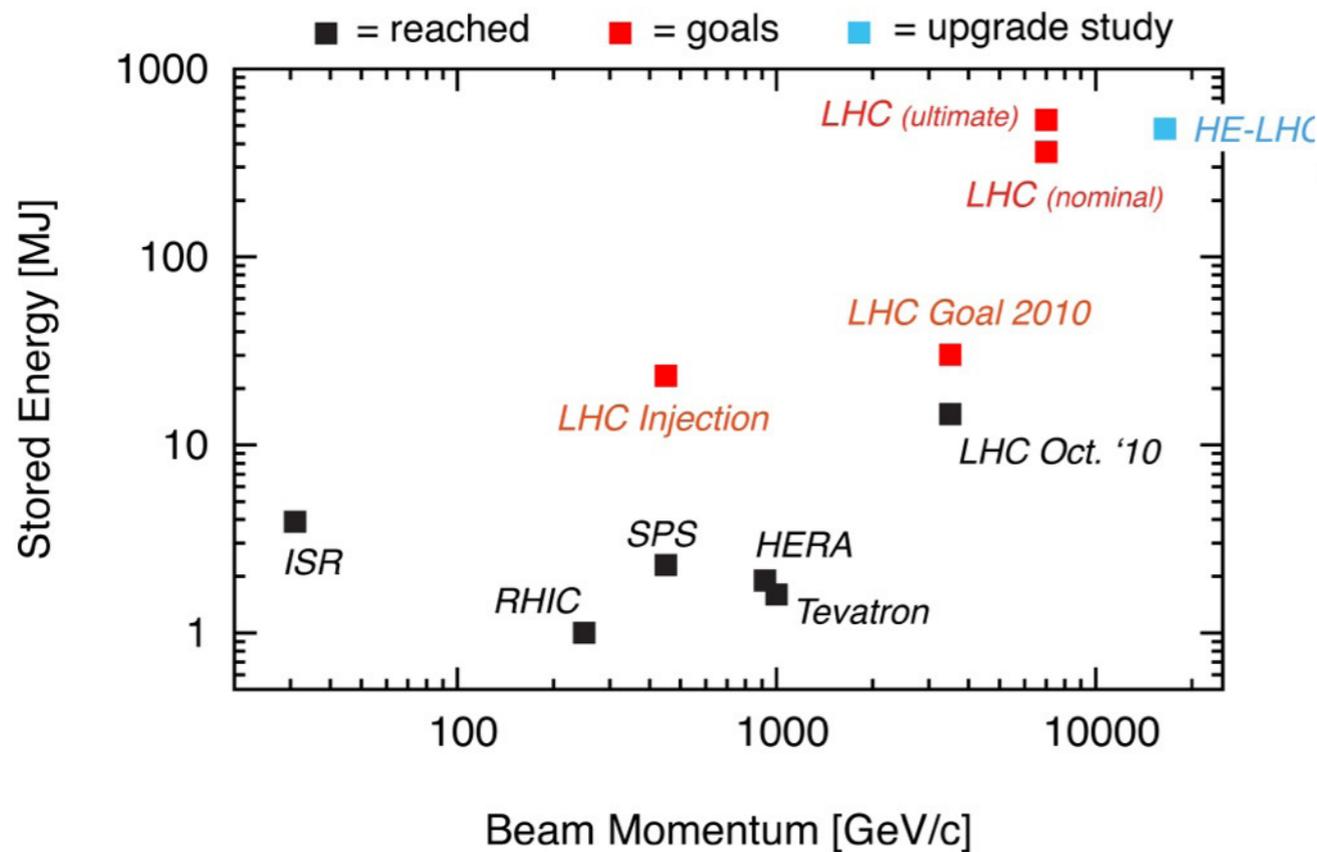
- In 2009 about 50 journal publications/experiment/yr
- About 60 Ph.D.'s / year over the last few years



# Stored Energy and Energy Density



LARP



## ⊙ LHC already

- ~1 order of magnitude beyond Tevatron in stored energy
- ~2 orders of magnitude beyond Tevatron in energy density

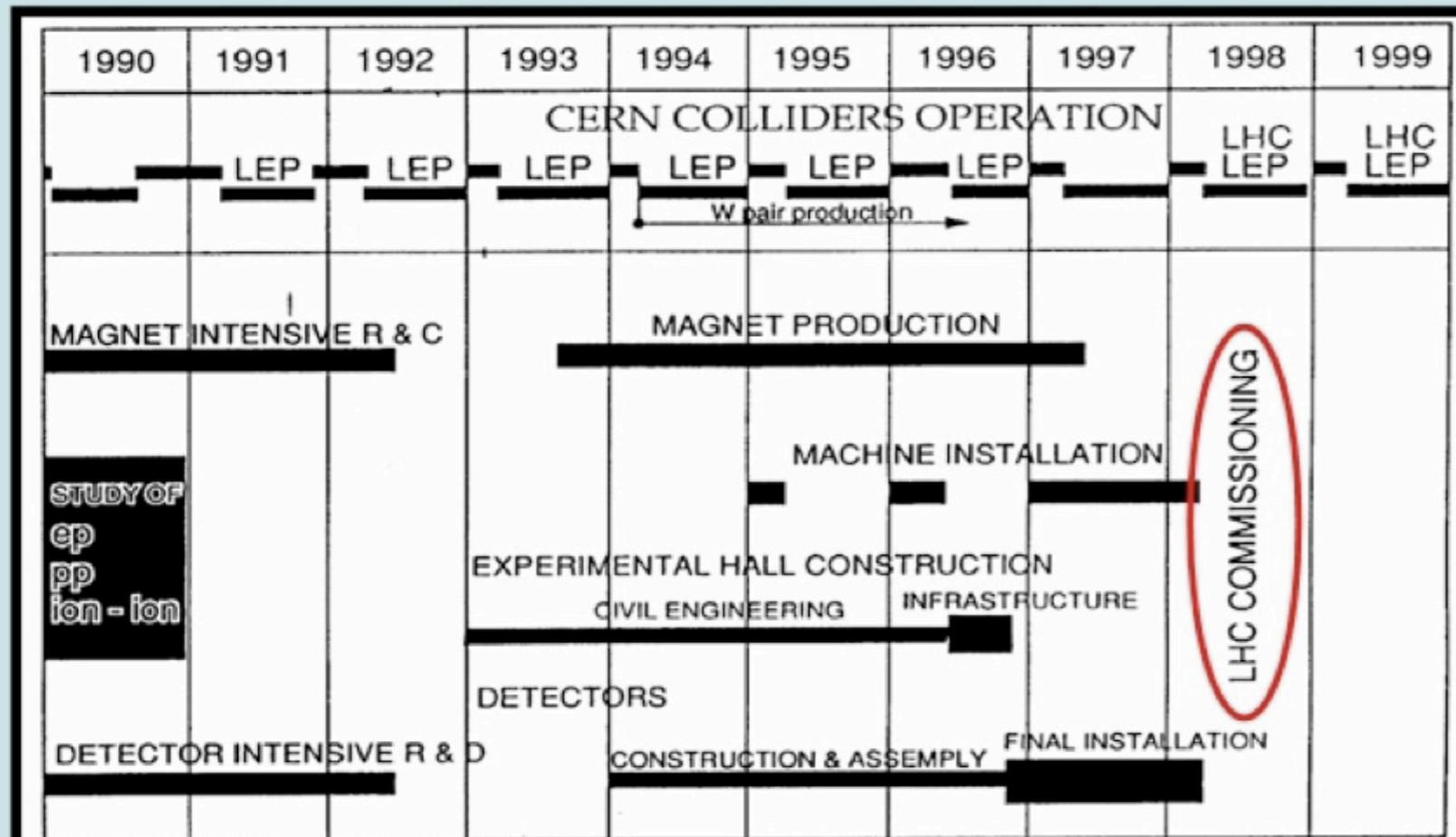
## ⊙ Machine protection dominates all aspects of LHC operation.

# Schedules...

□ Over the years

## LHC Schedule

First meetings of the proto-collaborations in 1989 ...



C. Rubbia - Large Hadron Collider Workshop, Aachen 1990

Figure 18 - Construction schedule of the LHC

**You are NOT here !!!**

