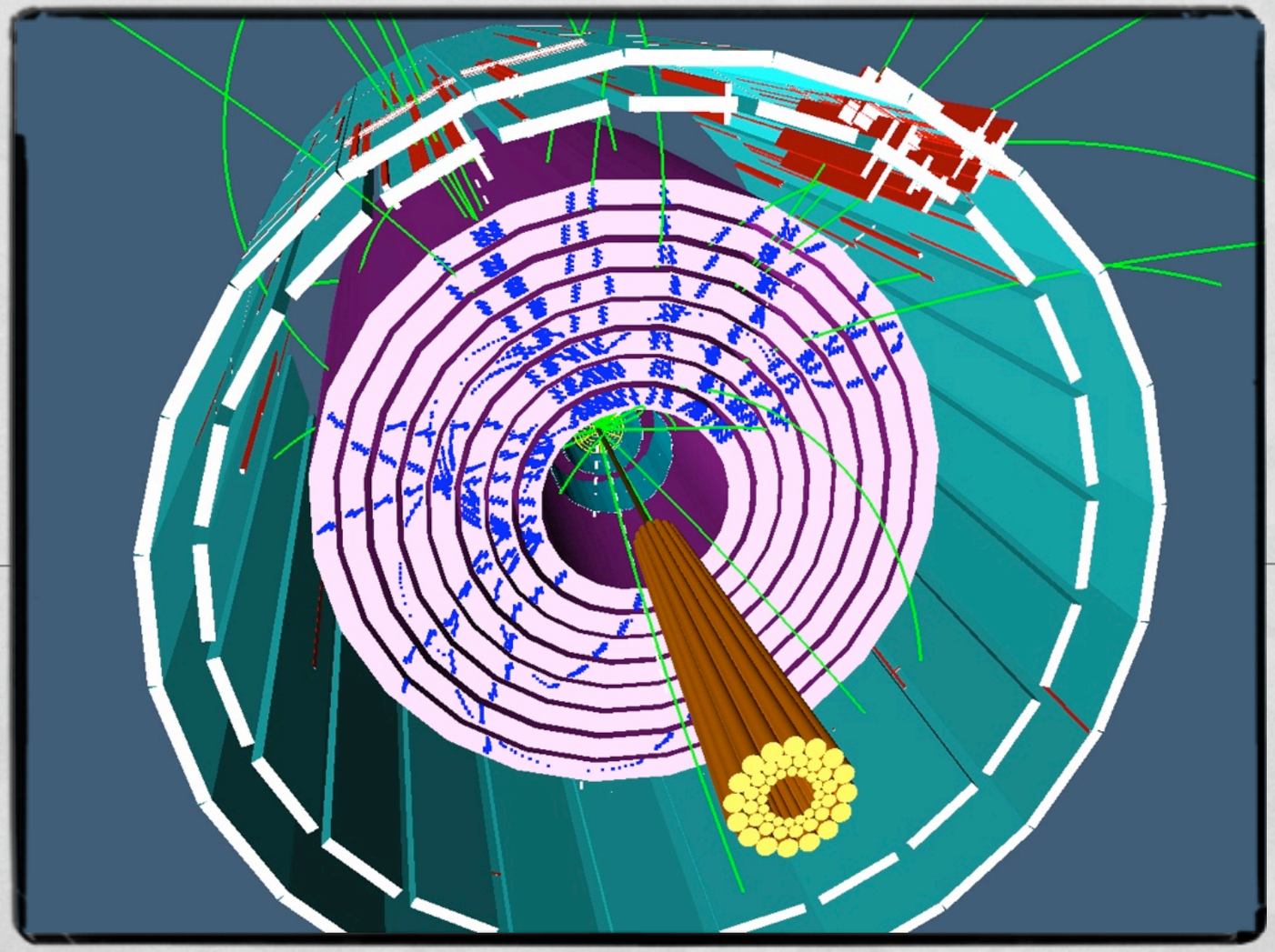
Discoveries at Particle Colliders



The Tevatron at Fermilab

Discoveries at Particle Colliders

Discoveries at Particle Colliders

Particle Physics

Discoveries at Particle Colliders

Colliders

Particle Physics

Discoveries at Particle Colliders

Colliders

The Tevatron

Particle Physics

Discoveries at Particle Colliders

Colliders

The Tevatron

Particle Physics

Discoveries +

Discoveries at Particle Colliders

Colliders

Particle Physics

The Tevatron

Future

Discoveries +

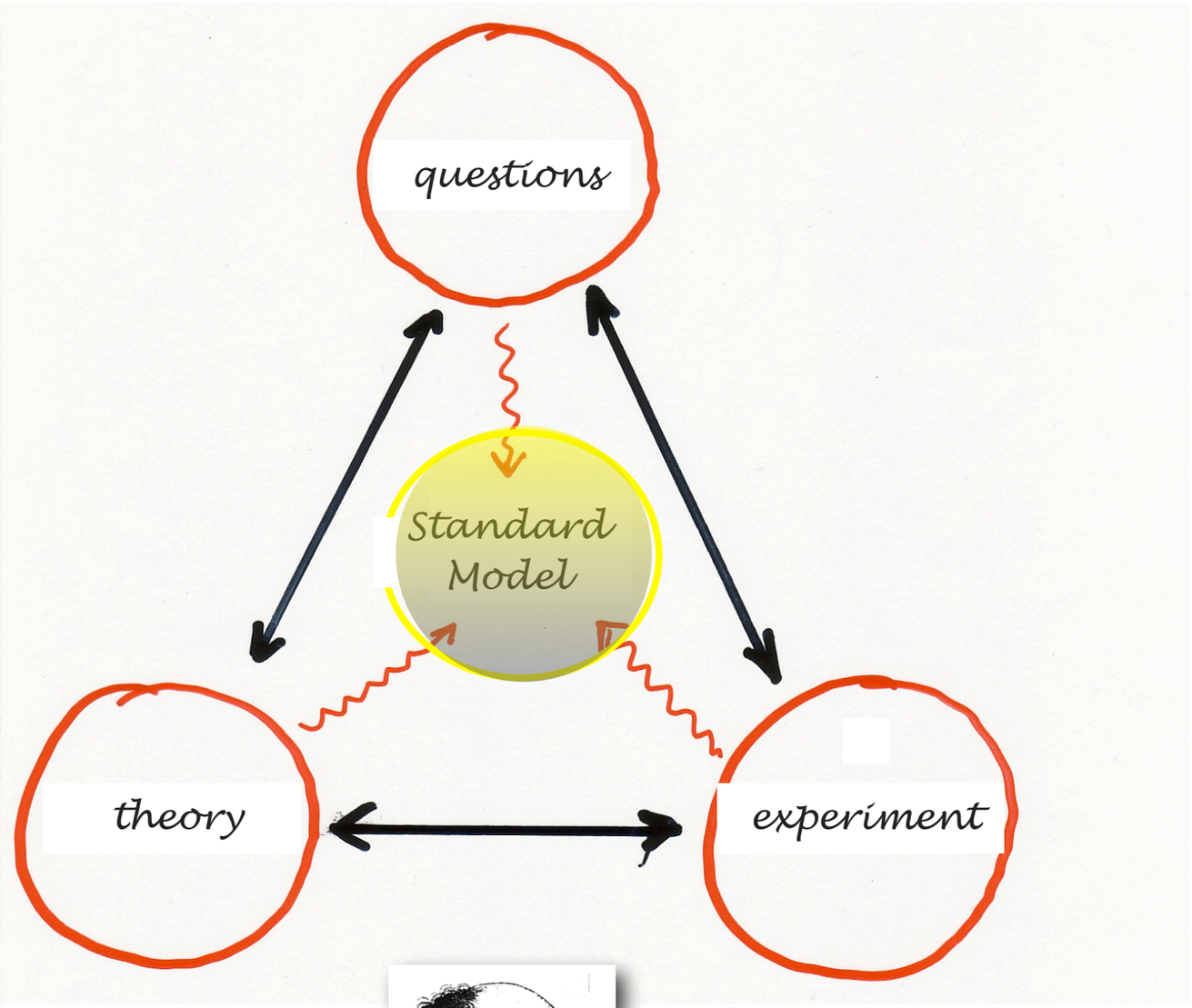
The things we dare ask

And how we dare answer them...

A few “simple” questions

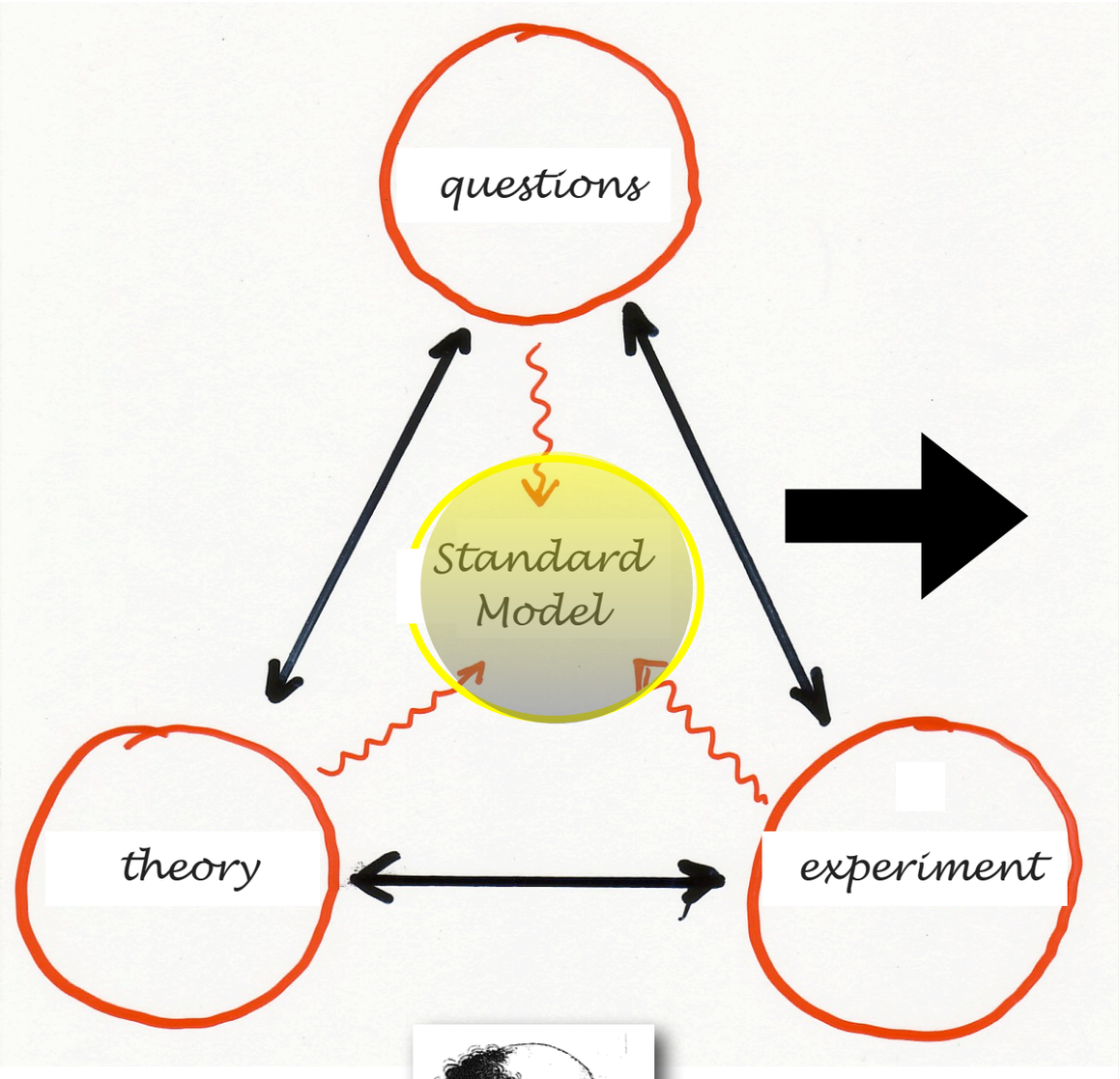
- How does Nature behave at its most fundamental level ?
- What are the elementary building blocks of all matter ?
- How do they interact with each other ?
- How is this connected to the evolution of the Universe ?
- Can all this be described simply ?

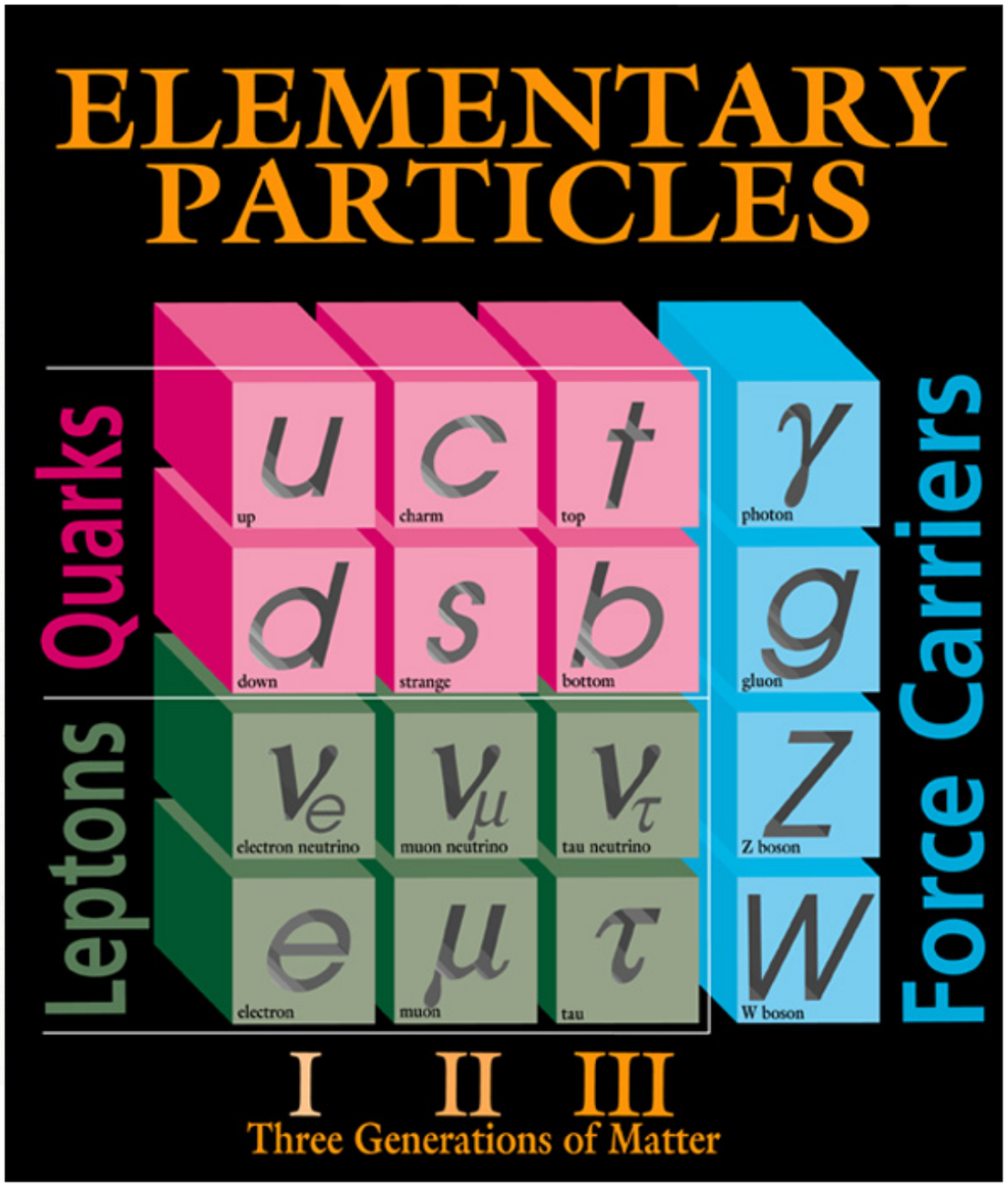
Some remarkable answers



2500 years

Some remarkable answers

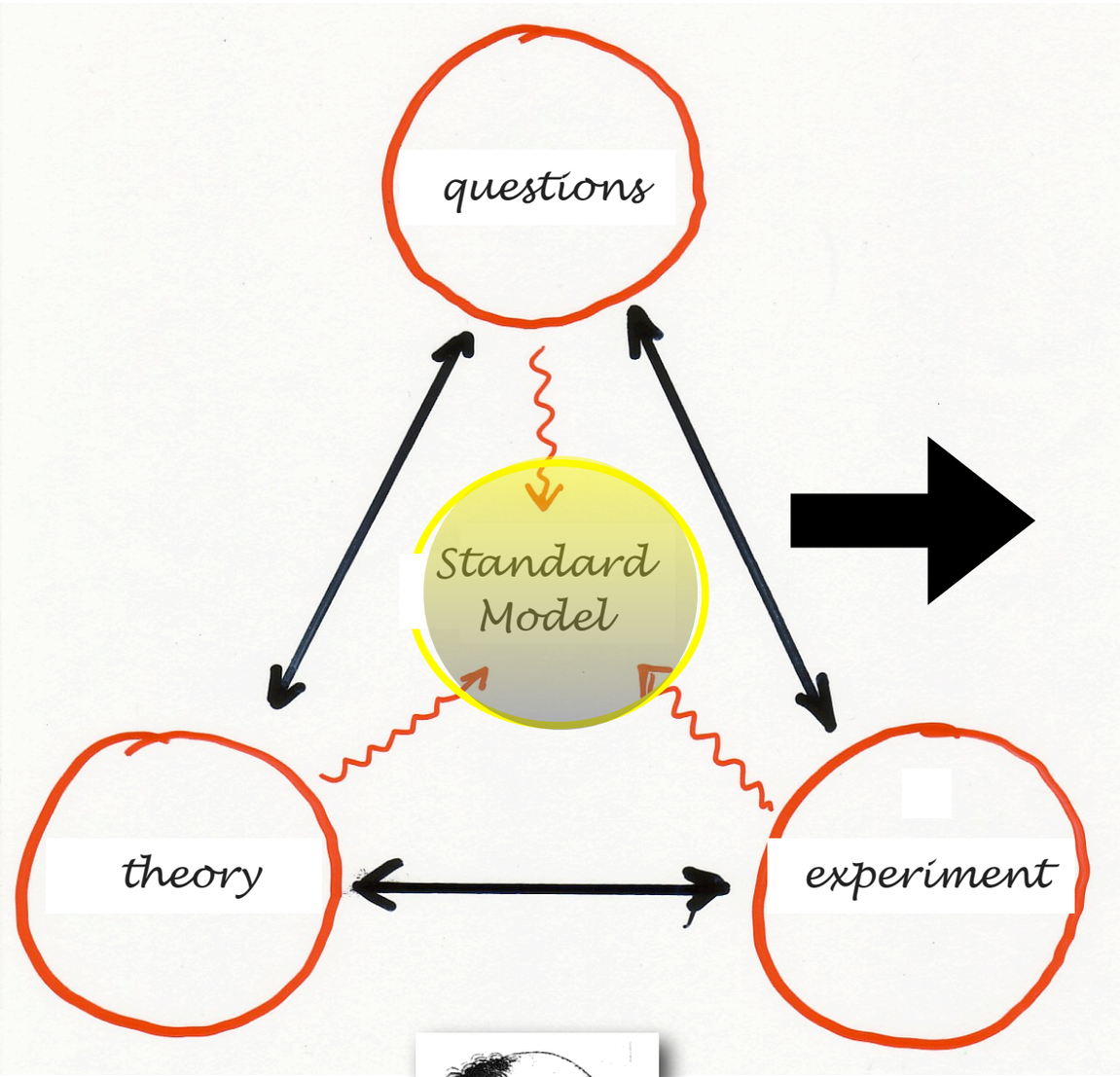




2500 years

anti-particles too !

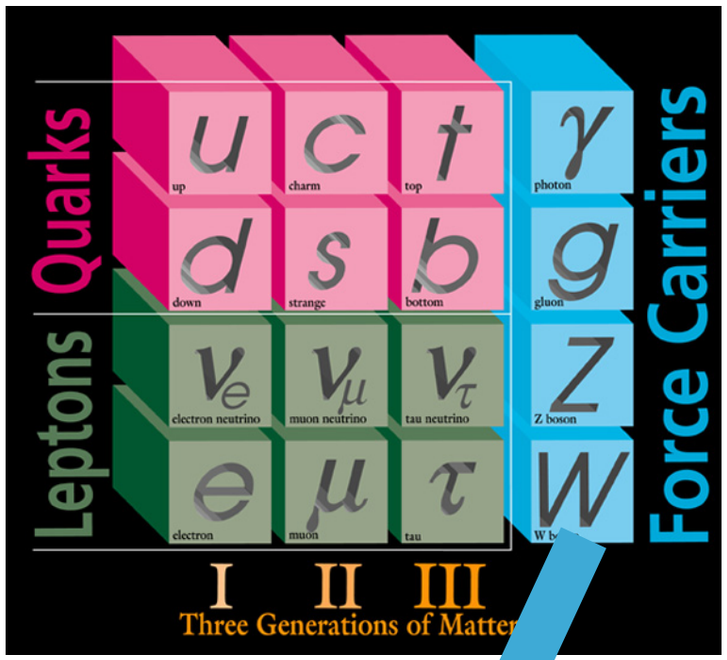
Some remarkable answers

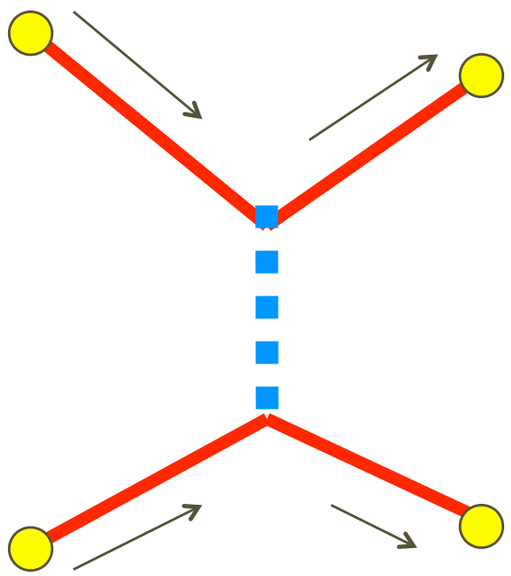


2500 years

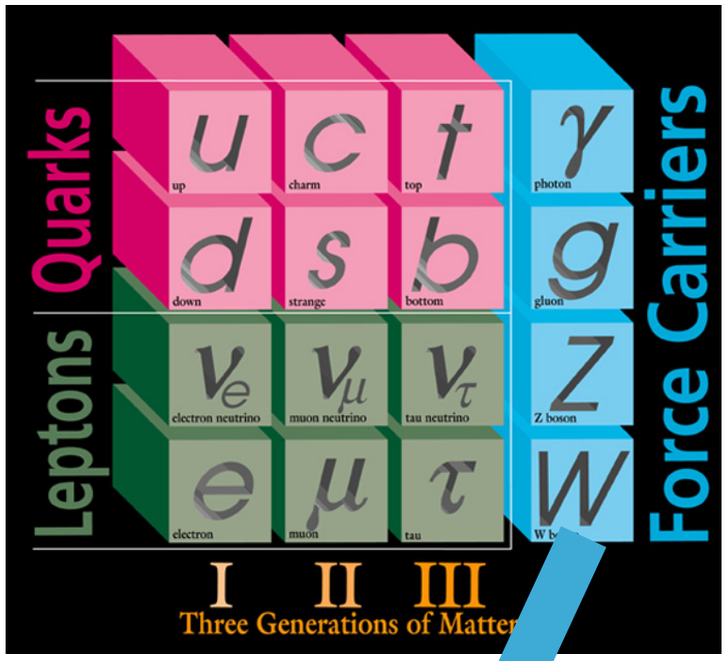
Discovered in:

- Radioactivity
- Cosmic Rays
- Accelerators





Feynman diagrams



Feynman diagrams

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

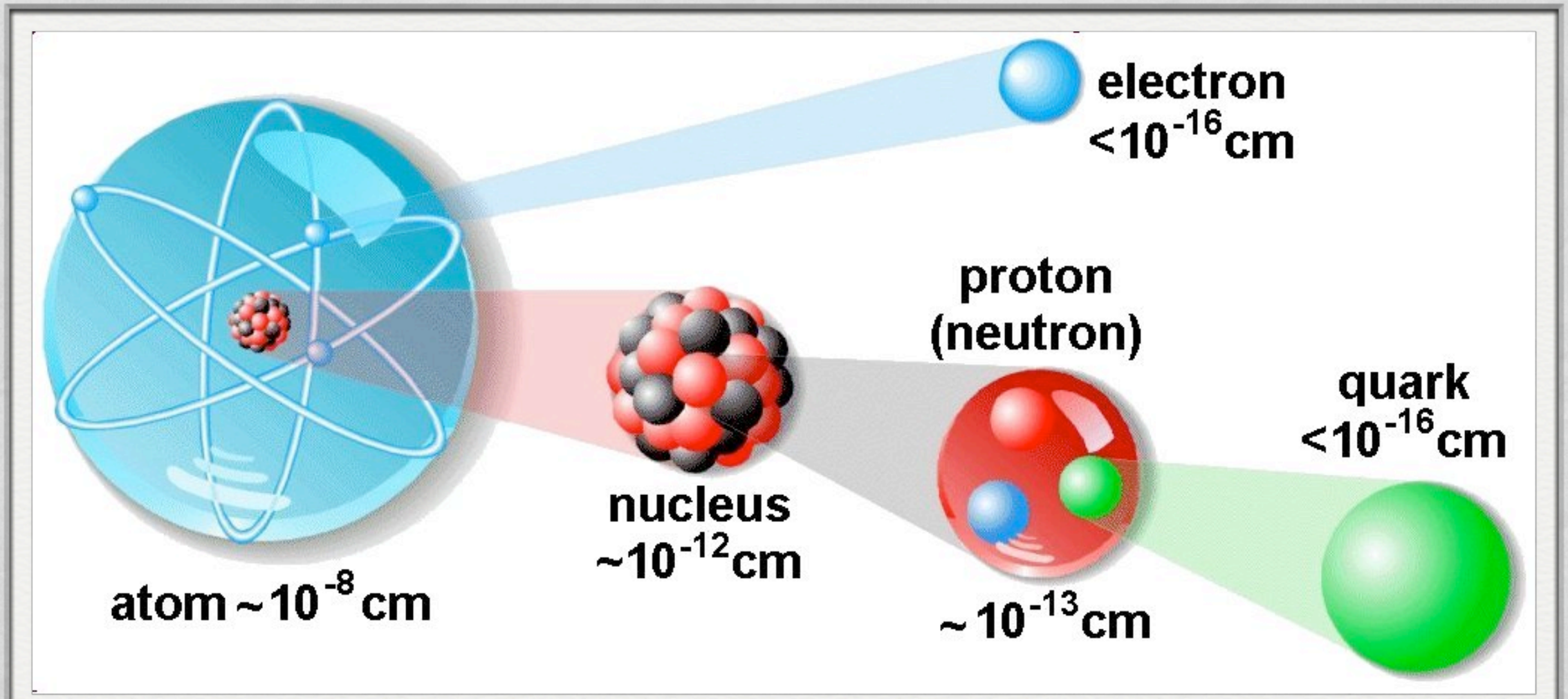
Neutron decay
Beta radioactivity
Neutrino interactions
Burning of the sun

The particle drawings are simple artistic representations

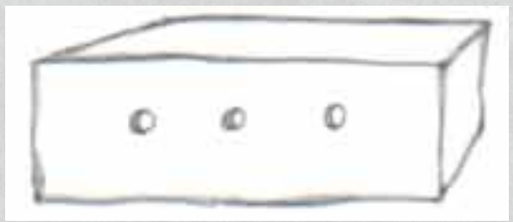
But this is how they really look like

By Roz Chast for Symmetry Magazine, May'07

In perspective



All matter is made of two
types of quarks [up & down] and electrons



The SM Equations

Relativistic Quantum Field Theory

$$\mathcal{L}_{\rm SM} = \mathcal{L}_{\rm Dirac} + \mathcal{L}_{\rm mass} + \mathcal{L}_{\rm gauge} + \mathcal{L}_{\rm gauge/\psi} \ . \tag{1}$$

Here,

$$\mathcal{L}_{\rm Dirac} = i\bar{e}^i_{\rm L}\partial\!\!\!/ e^i_{\rm L} + i\bar{\nu}^i_{\rm L}\partial\!\!\!/ \nu^i_{\rm L} + i\bar{e}^i_{\rm R}\partial\!\!\!/ e^i_{\rm R} + i\bar{u}^i_{\rm L}\partial\!\!\!/ u^i_{\rm L} + i\bar{d}^i_{\rm L}\partial\!\!\!/ d^i_{\rm L} + i\bar{u}^i_{\rm R}\partial\!\!\!/ u^i_{\rm R} + i\bar{d}^i_{\rm R}\partial\!\!\!/ d^i_{\rm R} \ ; \tag{2}$$

$$\mathcal{L}_{\rm mass} = -v\left(\lambda^i_e \bar{e}^i_{\rm L} e^i_{\rm R} + \lambda^i_u \bar{u}^i_{\rm L} u^i_{\rm R} + \lambda^i_d \bar{d}^i_{\rm L} d^i_{\rm R} + {\rm h.c.}\right) - M^2_W W^+_\mu W^{-\mu} - \frac{M^2_W}{2\cos^2\theta_W} Z_\mu Z^\mu \ ; \tag{3}$$

$$\mathcal{L}_{\rm gauge} = -\frac{1}{4}(G^a_{\mu\nu})^2 - \frac{1}{2}W^+_{\mu\nu}W^{-\mu\nu} - \frac{1}{4}Z_{\mu\nu}Z^{\mu\nu} - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \mathcal{L}_{WZA} \ , \tag{4}$$

where

$$\begin{aligned} G^a_{\mu\nu} &= \partial_\mu A^a_\nu - \partial_\nu A^a_\mu - g_3 f^{abc} A^b_\mu A^c_\nu \\ W^\pm_{\mu\nu} &= \partial_\mu W^\pm_\nu - \partial_\nu W^\pm_\mu \\ Z_{\mu\nu} &= \partial_\mu Z_\nu - \partial_\nu Z_\mu \\ F_{\mu\nu} &= \partial_\mu A_\nu - \partial_\nu A_\mu \ , \end{aligned} \tag{5}$$

and

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

and

$$\mathcal{L}_{\rm gauge/\psi} = -g_3 A^a_\mu J^{\mu a}_{(3)} - g_2\left(W^+_\mu J^\mu_{W^+} + W^-_\mu J^\mu_{W^-} + Z_\mu J^\mu_Z\right) - eA_\mu J^\mu_A \ , \tag{7}$$

where

$$\begin{aligned} J^{\mu a}_{(3)} &= \bar{u}^i\gamma^\mu T^a_{(3)} u^i + \bar{d}^i\gamma^\mu T^a_{(3)} d^i \\ J^\mu_{W^+} &= \frac{1}{\sqrt{2}}\left(\bar{\nu}^i_{\rm L}\gamma^\mu e^i_{\rm L} + V^{ij}\bar{u}^i_{\rm L}\gamma^\mu d^j_{\rm L}\right) \\ J^\mu_{W^-} &= \left(J^\mu_{W^+}\right)^* \\ J^\mu_Z &= \frac{1}{\cos\theta_{\rm W}}\left[\frac{1}{2}\bar{\nu}^i_{\rm L}\gamma^\mu\nu^i_{\rm L} + \left(-\frac{1}{2} + \sin^2\theta_{\rm W}\right)\bar{e}^i_{\rm L}\gamma^\mu e^i_{\rm L} + (\sin^2\theta_{\rm W})\bar{e}^i_{\rm R}\gamma^\mu e^i_{\rm R}\right. \\ &\quad + \left(\frac{1}{2} - \frac{2}{3}\sin^2\theta_{\rm W}\right)\bar{u}^i_{\rm L}\gamma^\mu u^i_{\rm L} + \left(-\frac{2}{3}\sin^2\theta_{\rm W}\right)\bar{u}^i_{\rm R}\gamma^\mu u^i_{\rm R} \\ &\quad \left. + \left(-\frac{1}{2} + \frac{1}{3}\sin^2\theta_{\rm W}\right)\bar{d}^i_{\rm L}\gamma^\mu d^i_{\rm L} + \left(\frac{1}{3}\sin^2\theta_{\rm W}\right)\bar{d}^i_{\rm R}\gamma^\mu d^i_{\rm R}\right] \\ J^\mu_A &= (-1)\bar{e}^i\gamma^\mu e^i + \left(\frac{2}{3}\right)\bar{u}^i\gamma^\mu u^i + \left(-\frac{1}{3}\right)\bar{d}^i\gamma^\mu d^i \ . \end{aligned} \tag{8}$$

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XXXXL

Standard Model of

FUNDAMENTAL PARTICLES AND INTERACTIONS

The Standard Model summarizes the current knowledge in Particle Physics. It is the quantum theory that includes the theory of strong interactions (quantum chromodynamics or QCD) and the unified theory of weak and electromagnetic interactions (electroweak). Gravity is included on this chart because it is one of the fundamental interactions even though not part of the "Standard Model."

FERMIONS

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

Leptons spin = 1/2

Flavor	Mass GeV/c^2	Electric charge
ν_e electron neutrino	$<1\times10^{-8}$	0
e electron	0.000511	–1
ν_μ muon neutrino	<0.0002	0
μ muon	0.106	–1
ν_τ tau neutrino	<0.02	0
τ tau	1.7771	–1

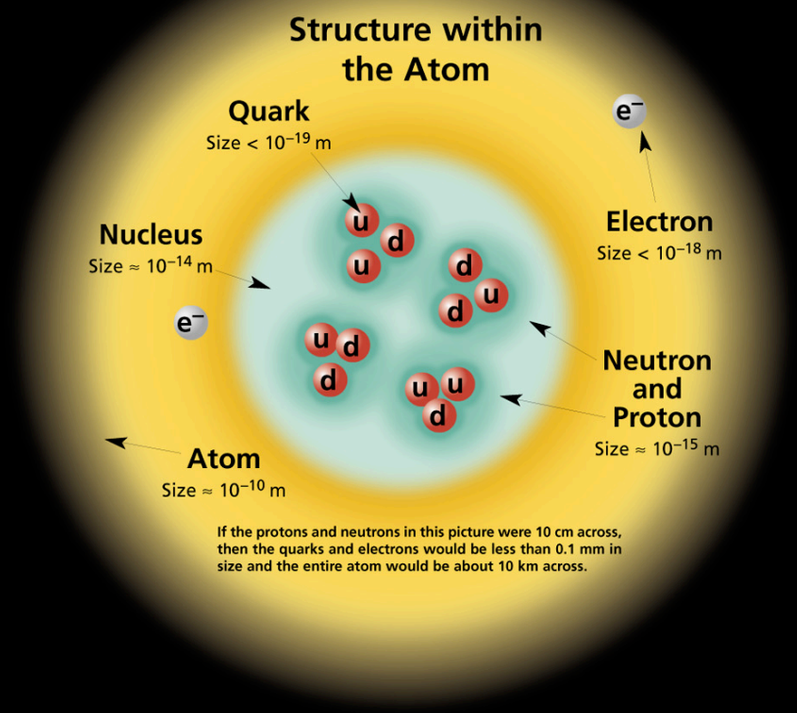
Quarks spin = 1/2

Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.003	2/3
d down	0.006	–1/3
c charm	1.3	2/3
s strange	0.1	–1/3
t top	175	2/3
b bottom	4.3	–1/3

Spin is the intrinsic angular momentum of particles. Spin is given in units of ħ, which is the quantum unit of angular momentum, where $\hbar = h/2\pi = 6.58\times10^{-25}$ GeV s = 1.05×10^{-34} J s.

Electric charges are given in units of the proton's charge. In SI units the electric charge of the proton is 1.60×10^{-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 GeV/c^2 (remember $E = mc^2$), where 1 GeV = 10^9 eV = 1.60×10^{-10} joule. The mass of the proton is 0.938 GeV/c^2 = 1.67×10^{-27} kg.



BOSONS

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

Unified Electroweak spin = 1

Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W^-	80.4	–1
W^+	80.4	+1
Z^0	91.187	0

Strong (color) spin = 1

Name	Mass GeV/c^2	Electric charge
g 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.

PROPERTIES OF THE INTERACTIONS

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

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^2	Spin
p	proton	uud	1	0.938	1/2
$\bar{p}$	anti-proton	$\bar{u}\bar{u}\bar{d}$	–1	0.938	1/2
n	neutron	udd	0	0.940	1/2
Λ	lambda	uds	0	1.116	1/2
Ω^-	omega	sss	–1	1.672	3/2

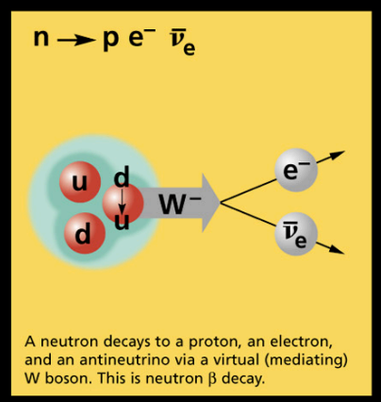
Mesons $q\bar{q}$

Mesons are bosonic hadrons.
There are about 140 types of mesons.

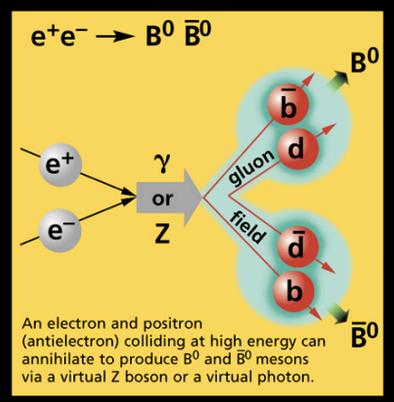
Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
π^+	pion	$u\bar{d}$	+1	0.140	0
K^-	kaon	$s\bar{u}$	–1	0.494	0
ρ^+	rho	$u\bar{d}$	+1	0.770	1
B^0	B-zero	$d\bar{b}$	0	5.279	0
η_c	eta-c	$c\bar{c}$	0	2 .980	0

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, γ, and $\eta_c = c\bar{c}$, but not $K^0 = d\bar{s}$) are their own antiparticles.

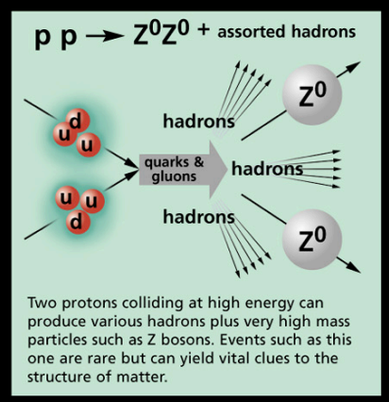
Figures
These diagrams are an artist's conception of physical processes. They are ***not*** exact and have ***no*** meaningful scale. Green shaded areas represent the cloud of gluons or the gluon field, and red lines the quark paths.



A neutron decays to a proton, an electron, and an antineutrino via a virtual (mediating) W boson. This is neutron β decay.



An electron and positron (antielectron) colliding at high energy can annihilate to produce B^0 and $\bar{B}^0$ mesons via a virtual Z boson or a virtual photon.



Two protons colliding at high energy can produce various hadrons plus very high mass particles such as Z bosons. Events such as this one are rare but can yield vital clues to the structure of matter.

The Particle Adventure
Visit the award-winni… *…cle Adventure* at
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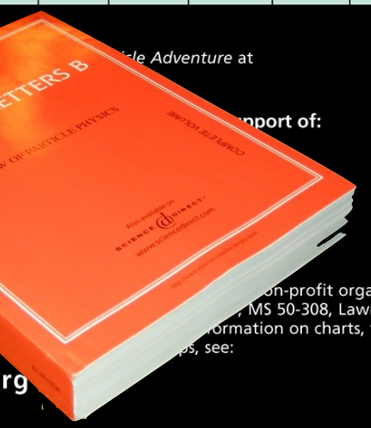
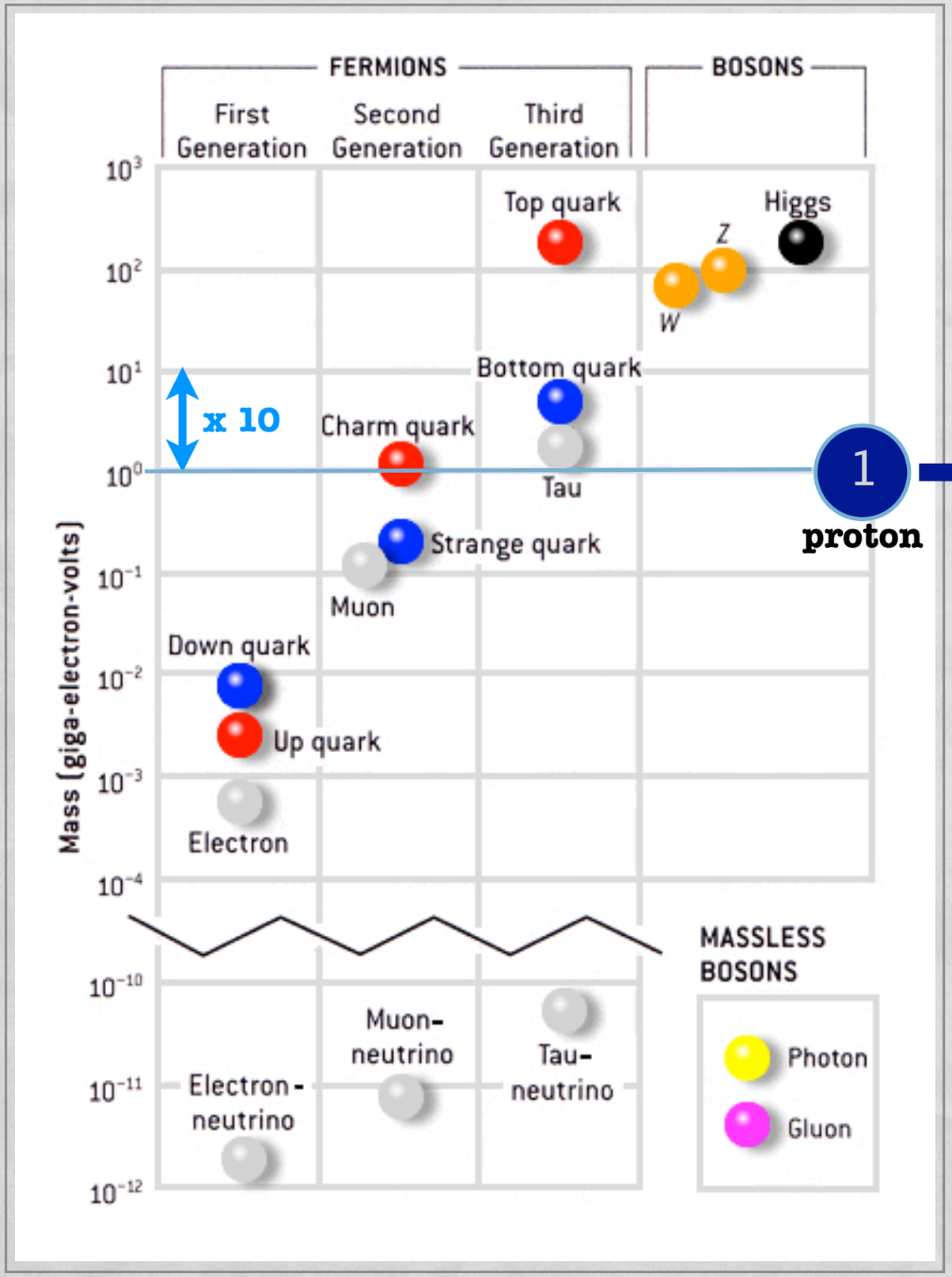


http://CPEPweb.org

Some recognition

- The Standard Model:
  - About 25 Nobel Prizes given to Particle Physics in the last 100 yrs
  - Quarks, leptons, antimatter, force carriers, symmetries, detectors, accelerators and theory

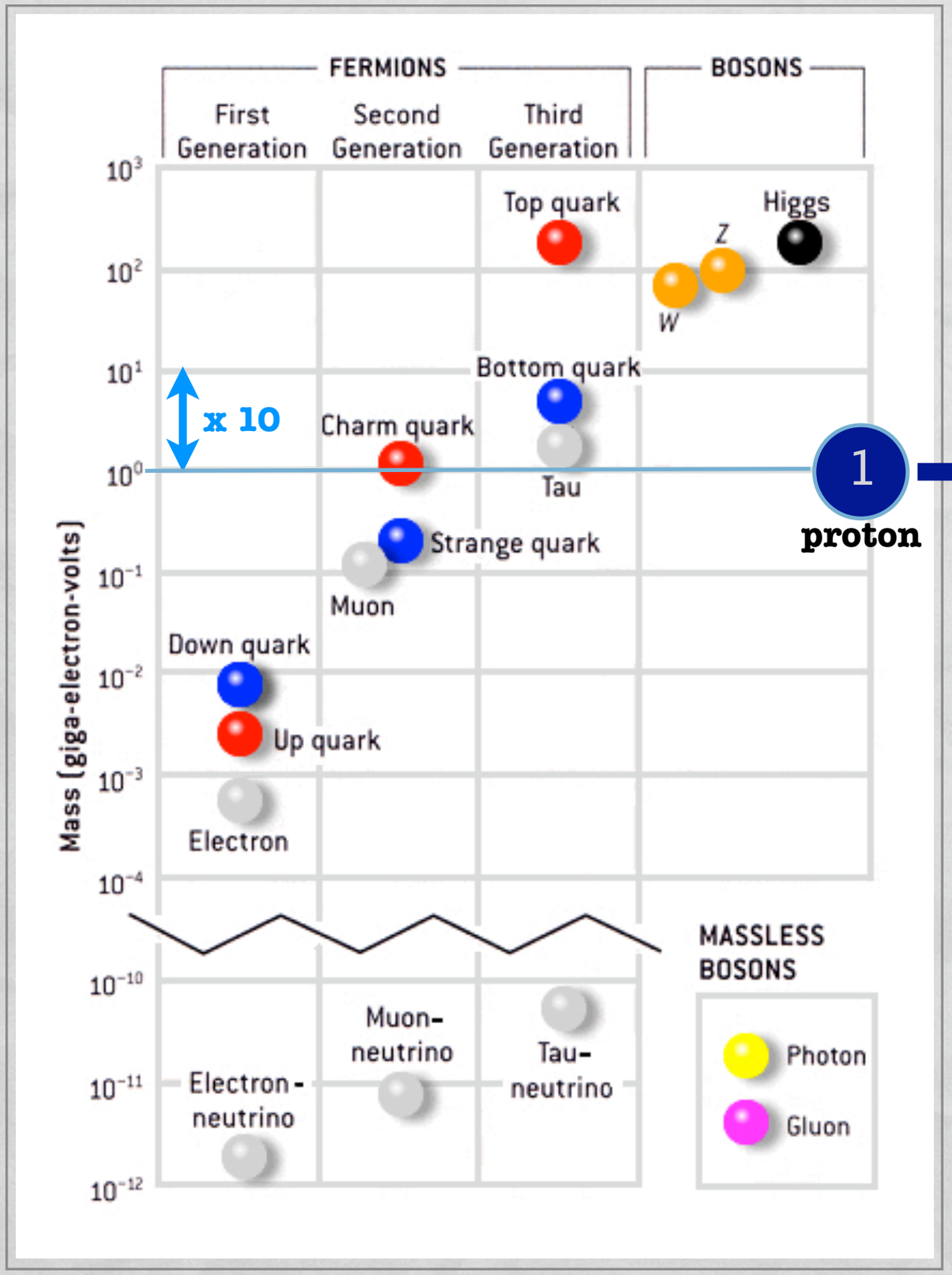
A puzzle: particle masses

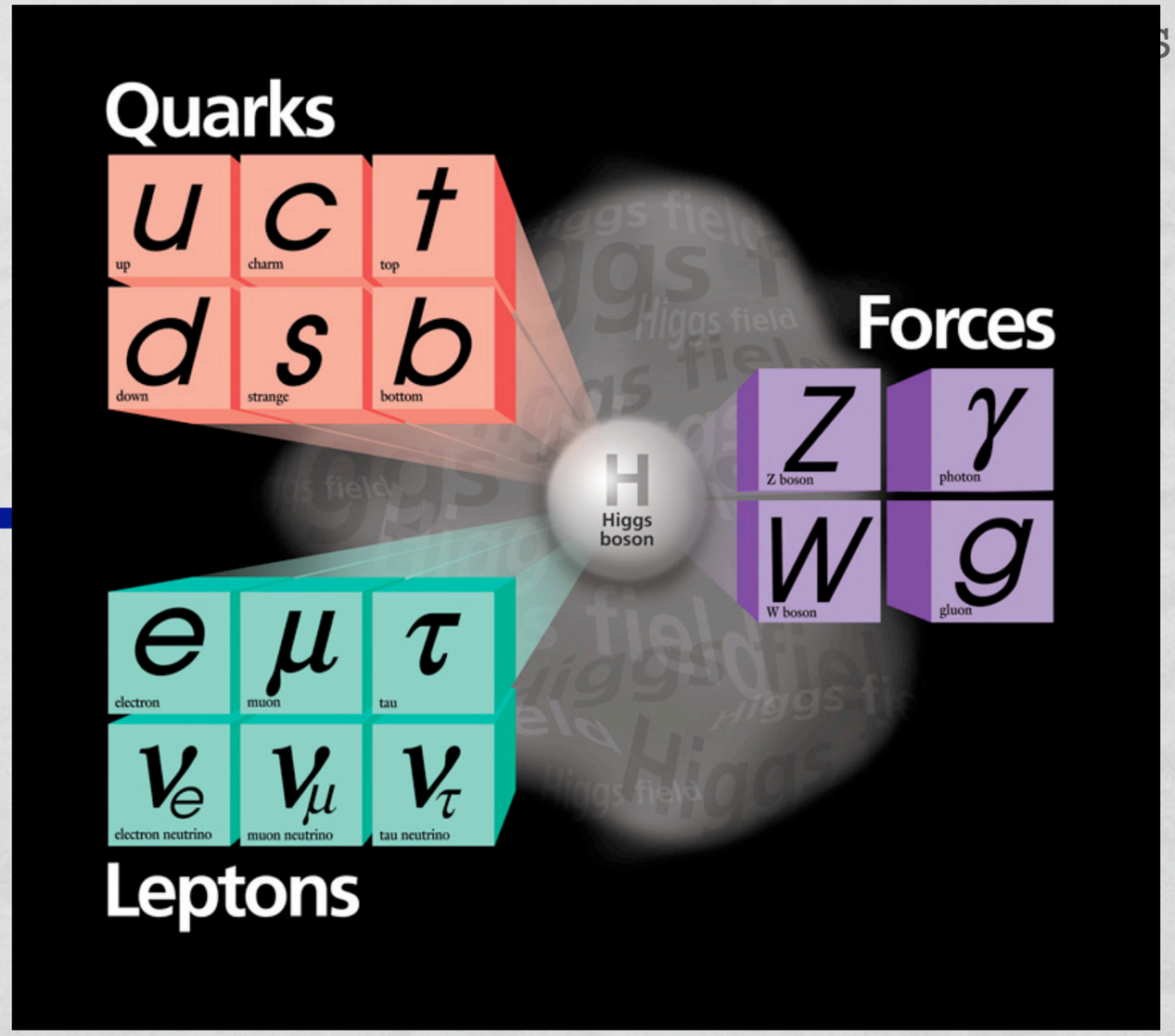


- ☐ 5 orders of magnitude span for quarks
- ☐ Top quark as heavy as a gold atom
- ☐ Neutrinos nearly massless
- ☐ Force carriers have either zero or very larger masses

units: c=1 => m=E proton is 1 GeV

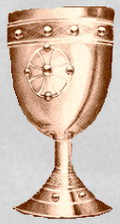
A puzzle: particle masses





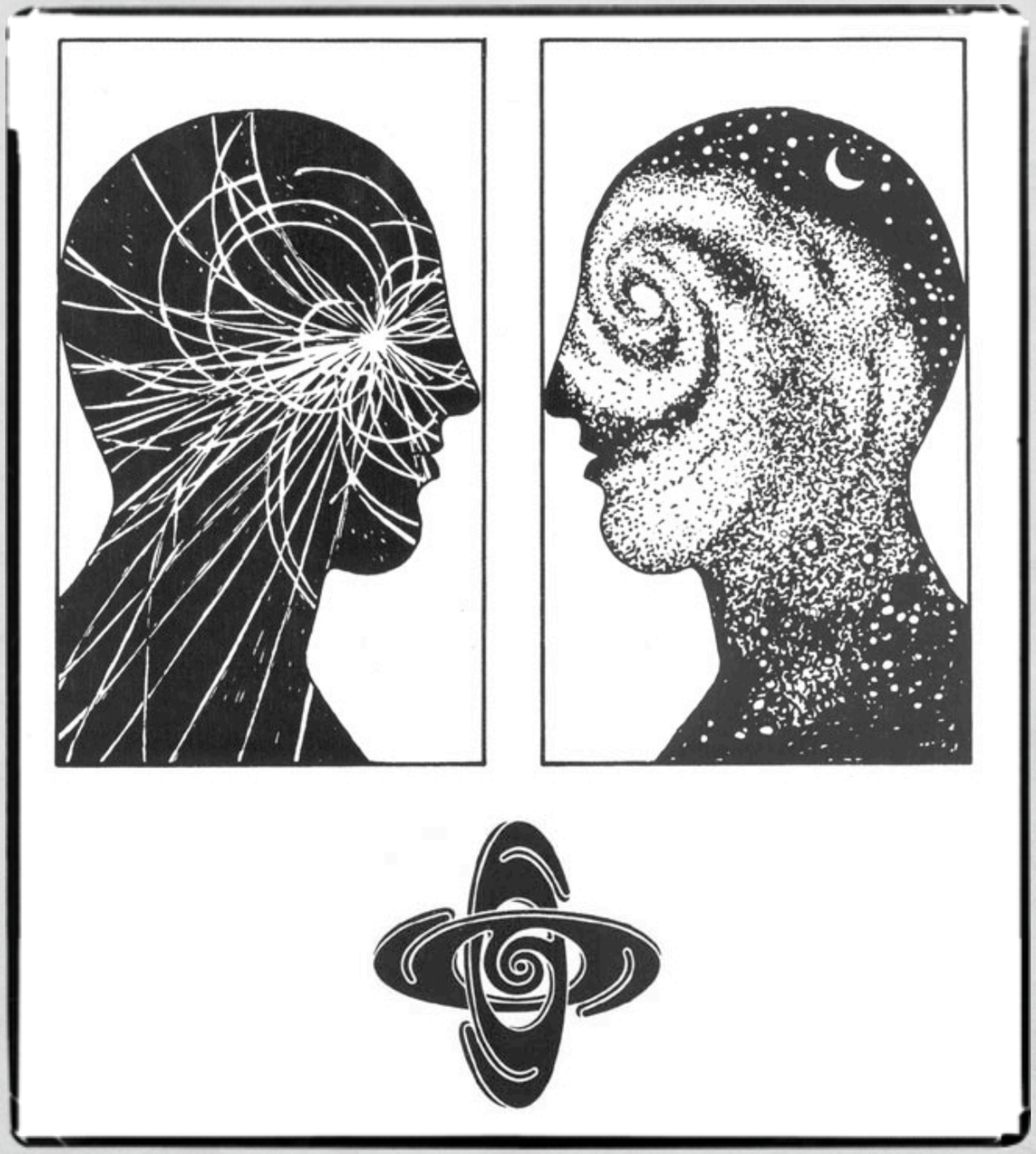
"The Higgs":

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

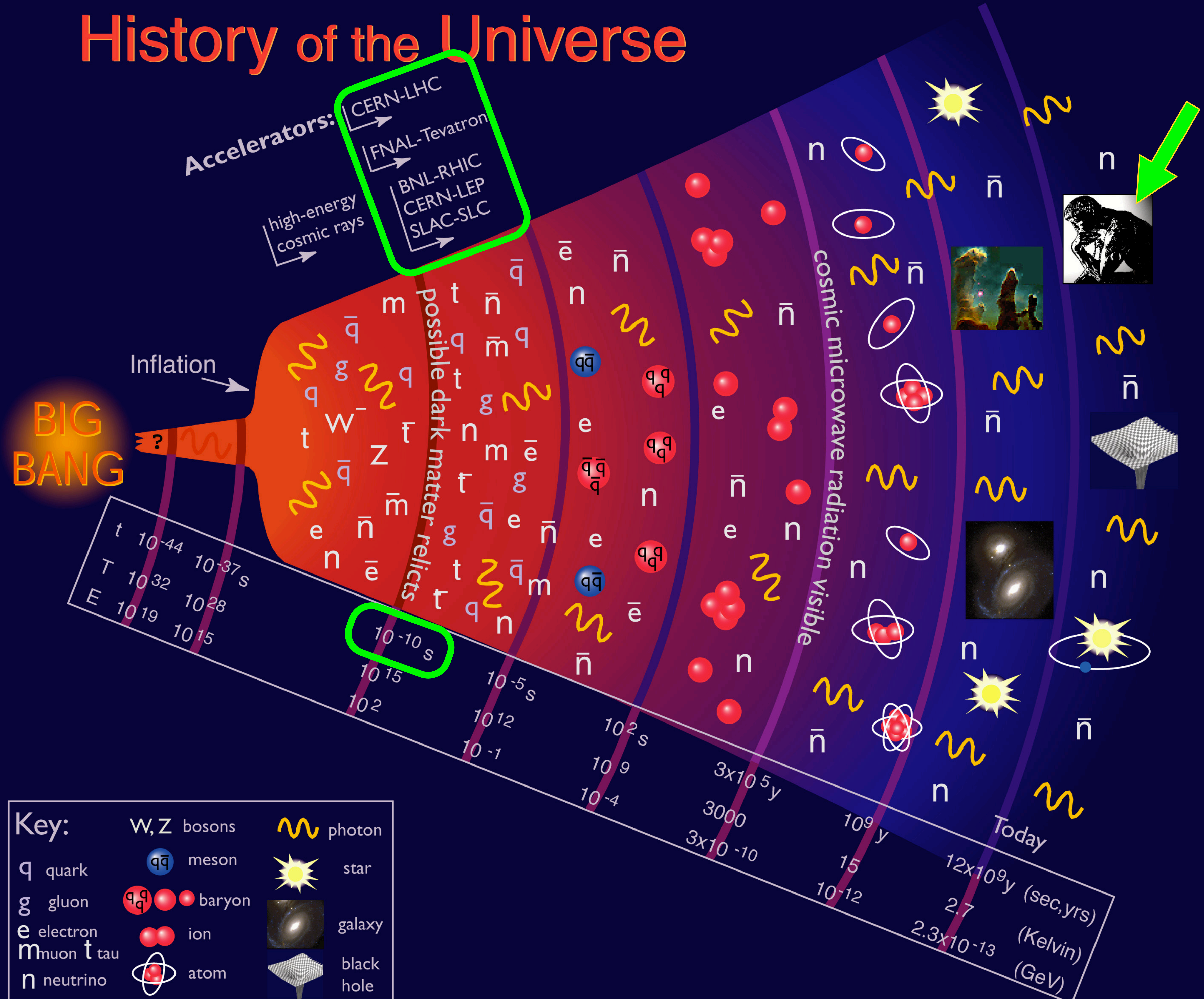


The Higgs

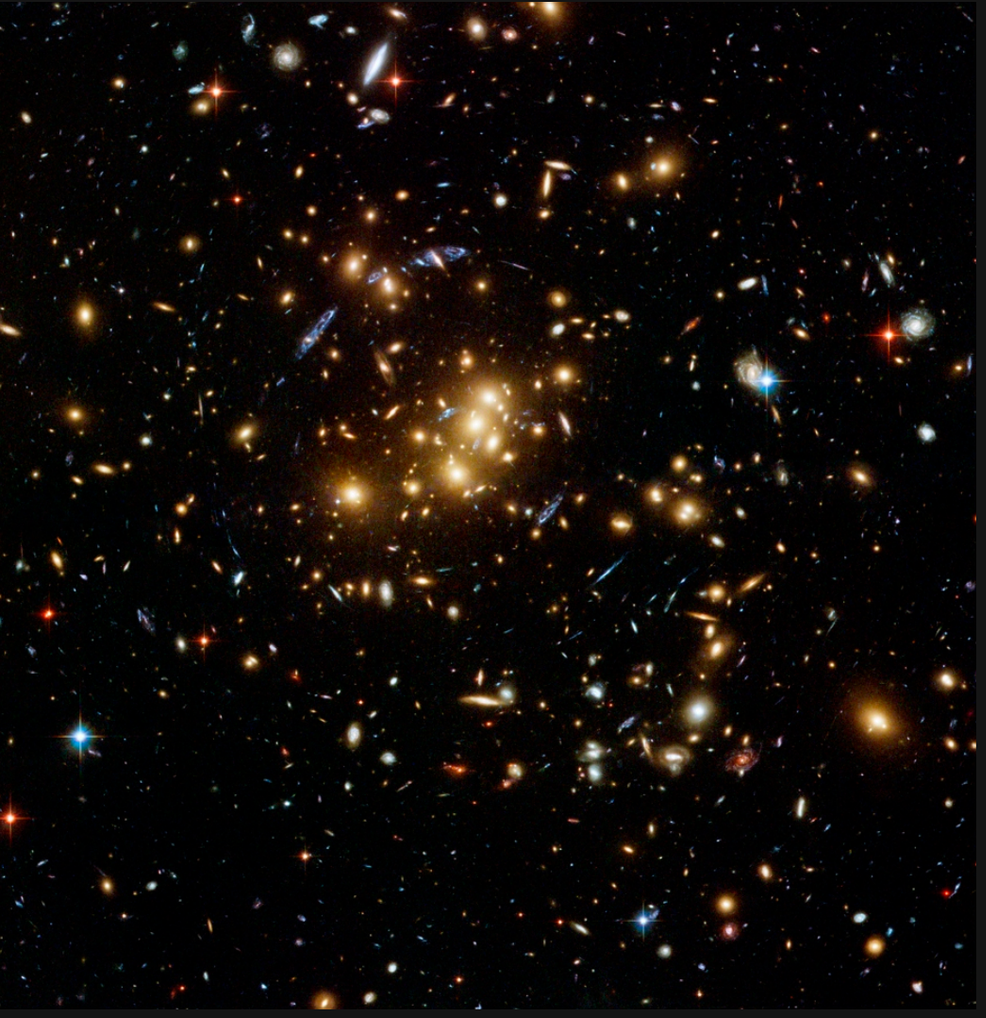
Cosmic Connections



"We are decoding the Universe's most ancient language"

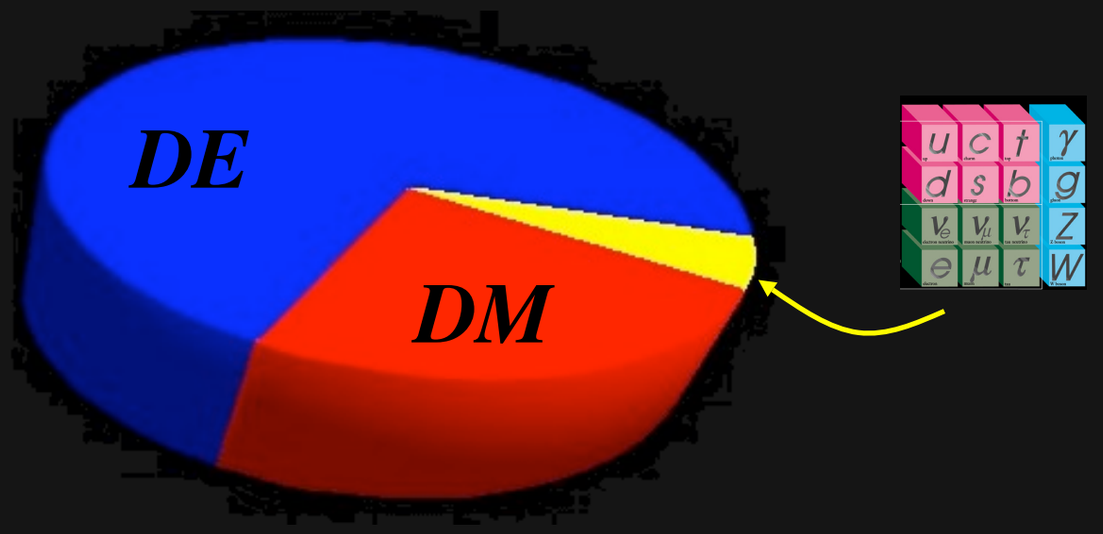


Particle Data Group, LBNL, © 2000. Supported by DOE and NSF



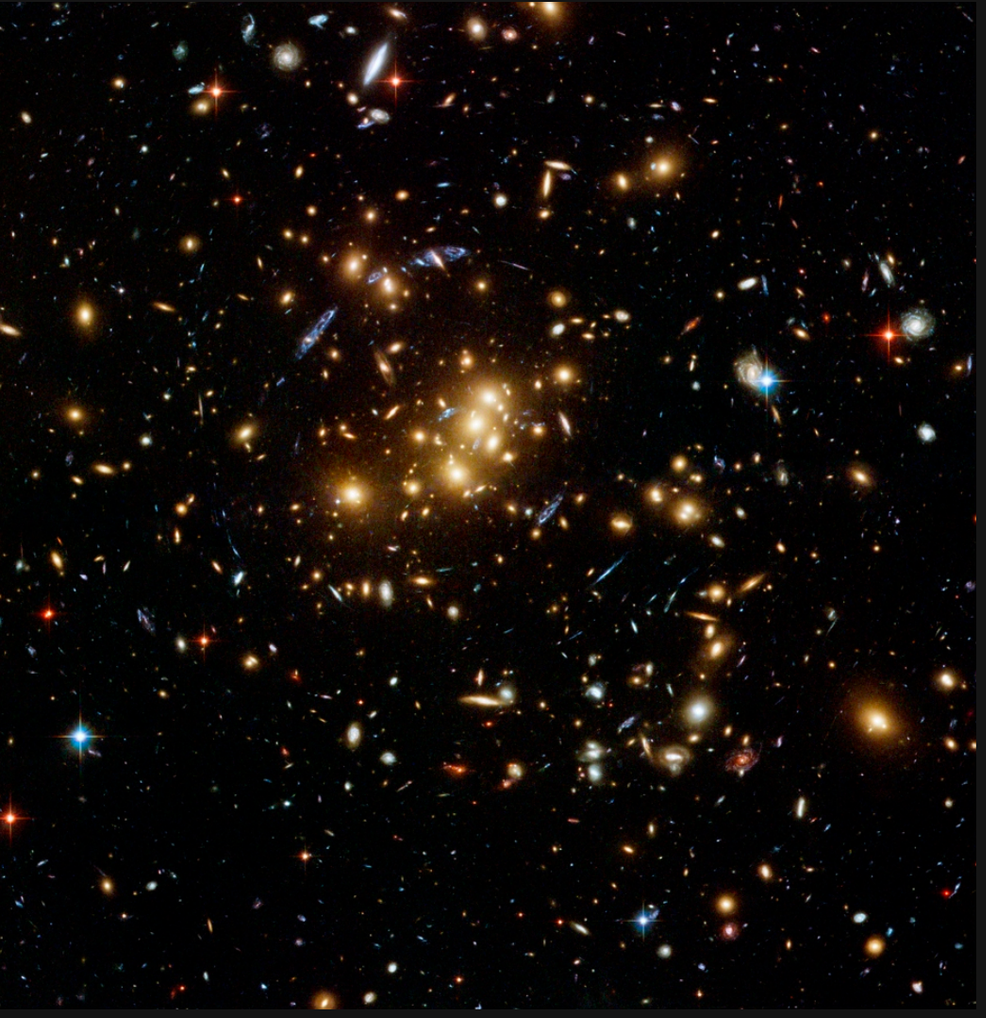
Other puzzles

“Dark Matter and Dark Energy”



Dark Matter:
Galaxies rotation inconsistent with visible mass

Dark Energy:
The expansion of the Universe is accelerating



Other puzzles

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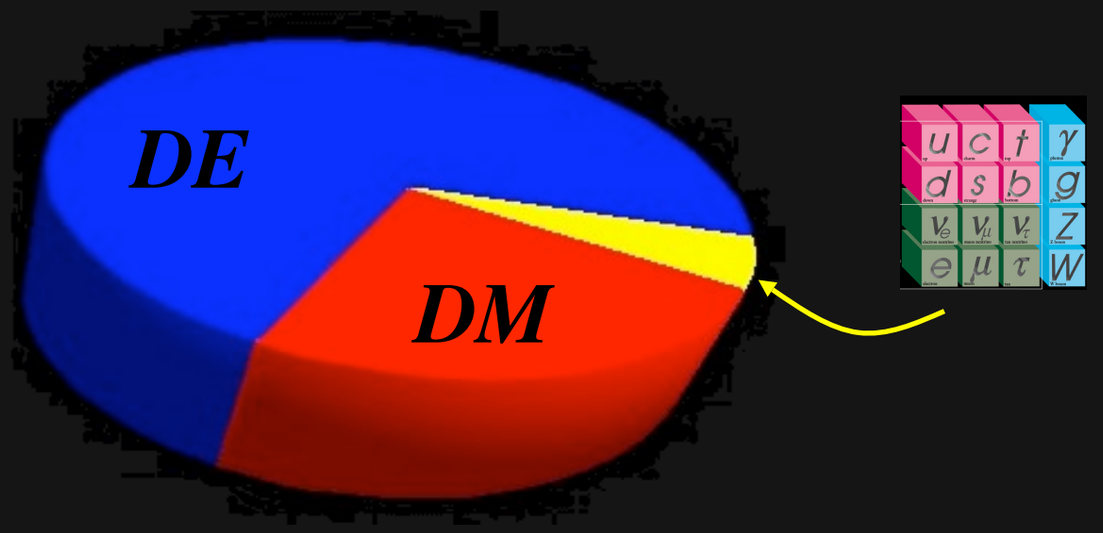


Dark Matter:
Galaxies rotation inconsistent with visible mass

Dark Energy:
The expansion of the Universe is accelerating

Physics [particles] beyond the Standard Model !

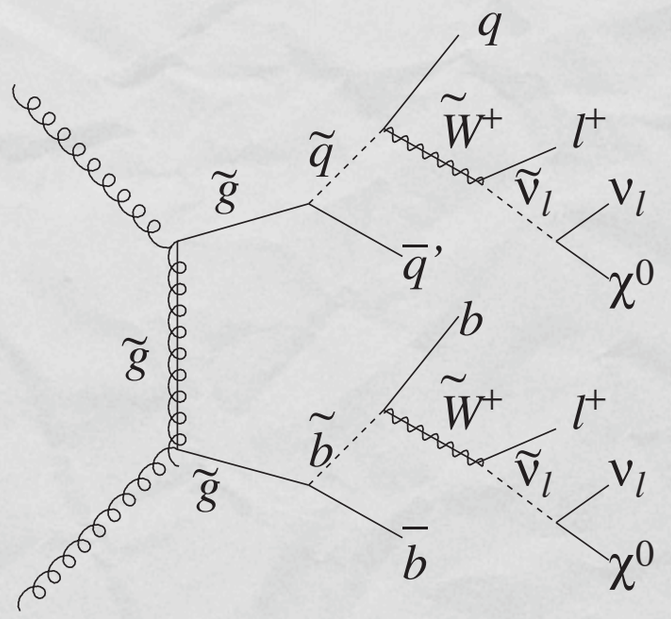
Many [important] new questions

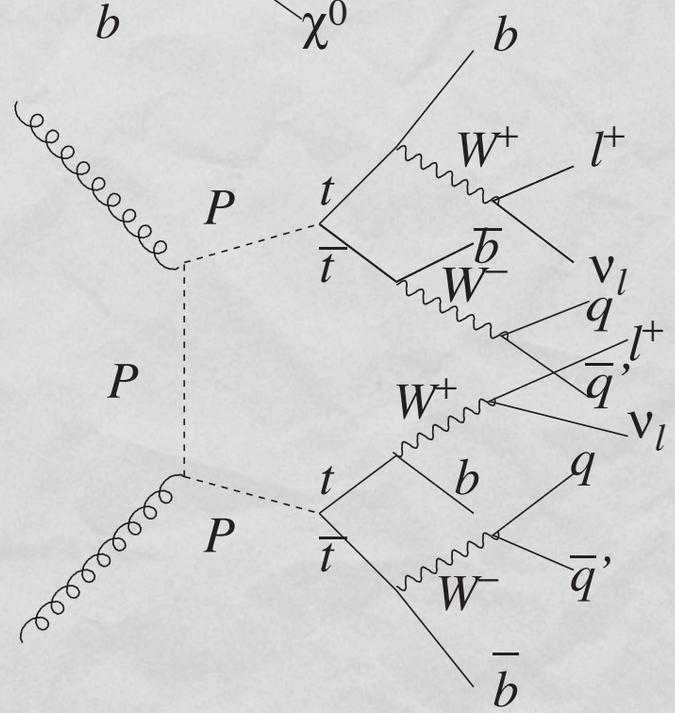
- ☐ Why 3 generations of particles ?
- ☐ Why the [huge] difference in particle masses ?
- ☐ Are all the forces one ?
- ☐ Where is all the anti-matter ?
- ☐ How does gravity fit in ?
- ☐ What are dark matter and dark energy ?

Theorists at work

[hesitate to say "to the rescue" just yet]

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

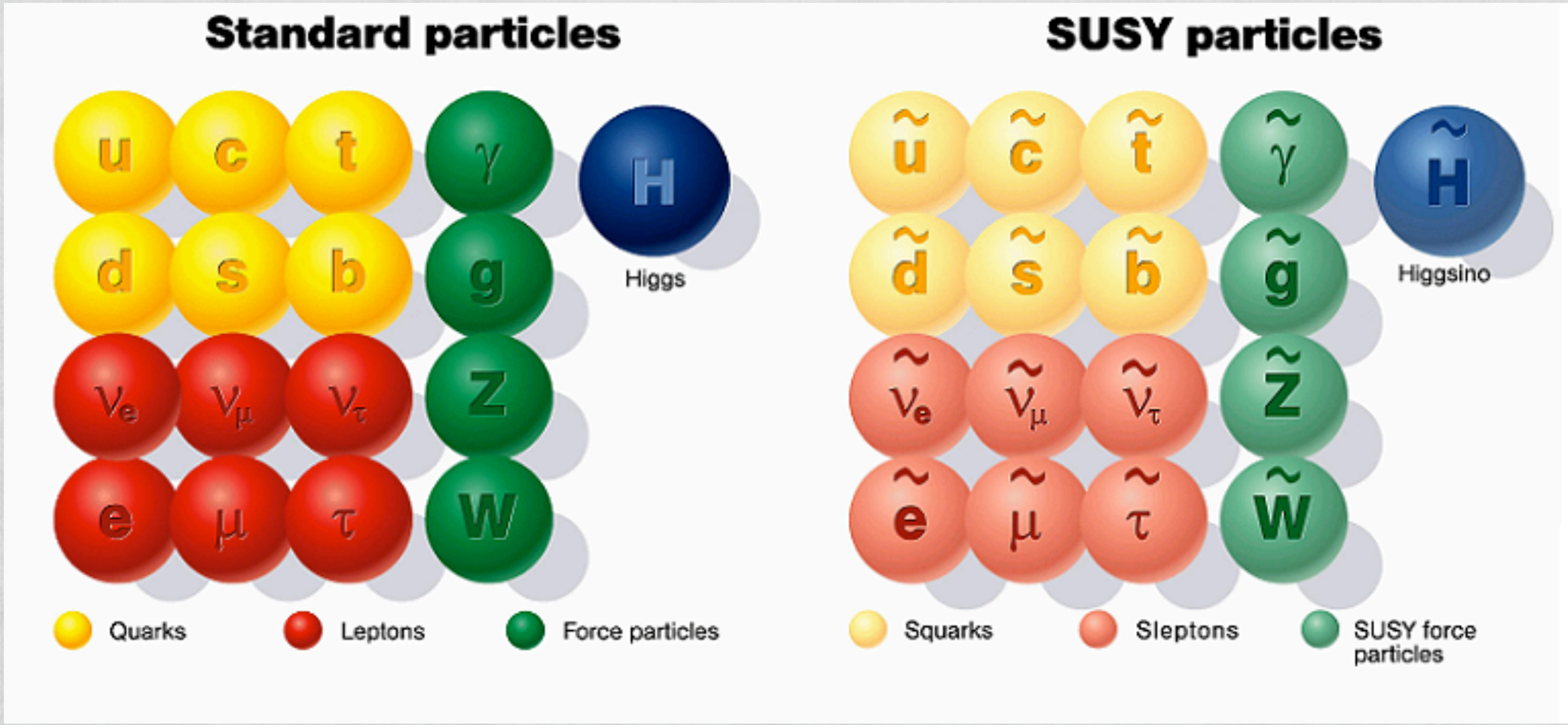




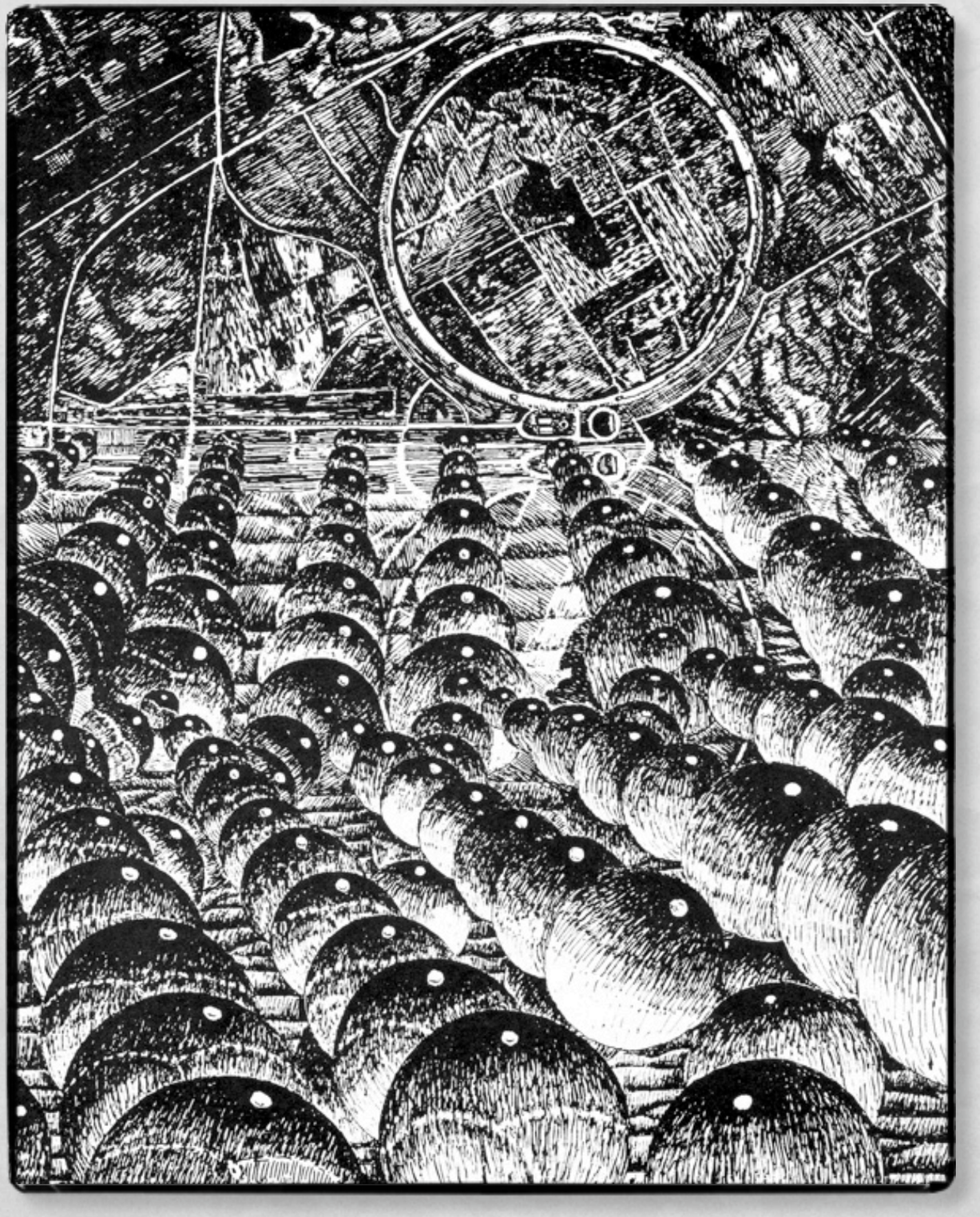
- All of which predict **new particles to be discovered**
- None of which may be true

Ex: SuperSymmetry

- Double the fun !

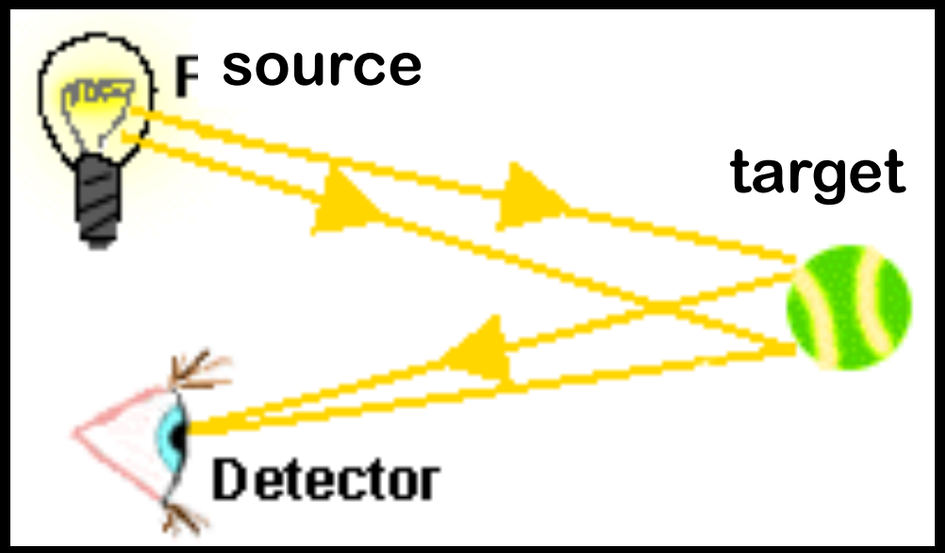


Adventures in collider-land



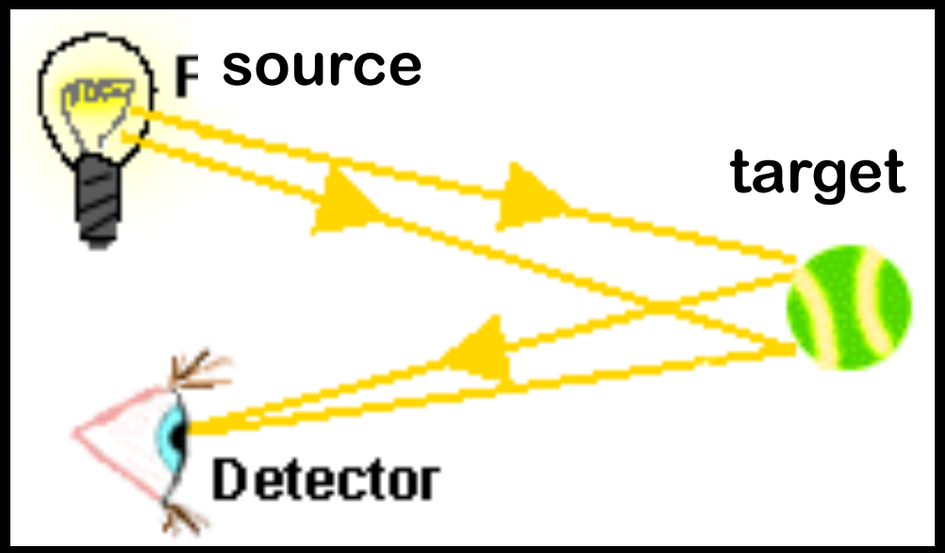
Colliders are
discovery machines !

Colliders are discovery machines !

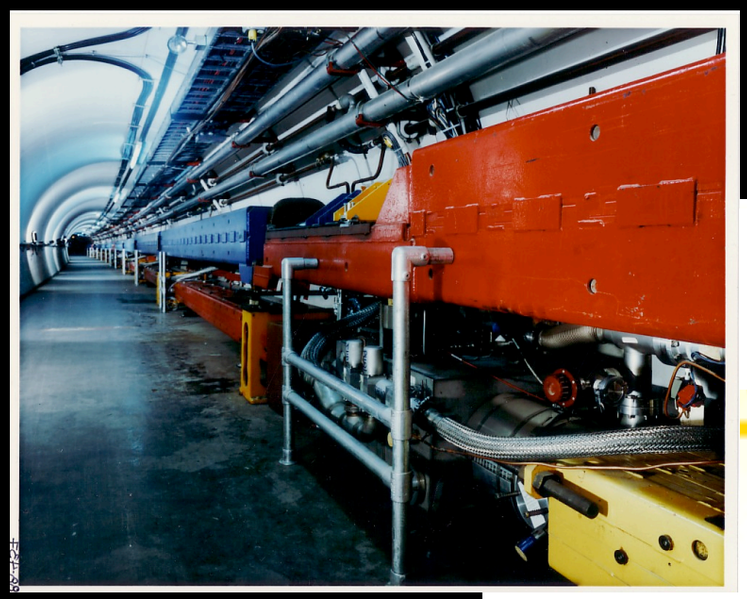


normal vision

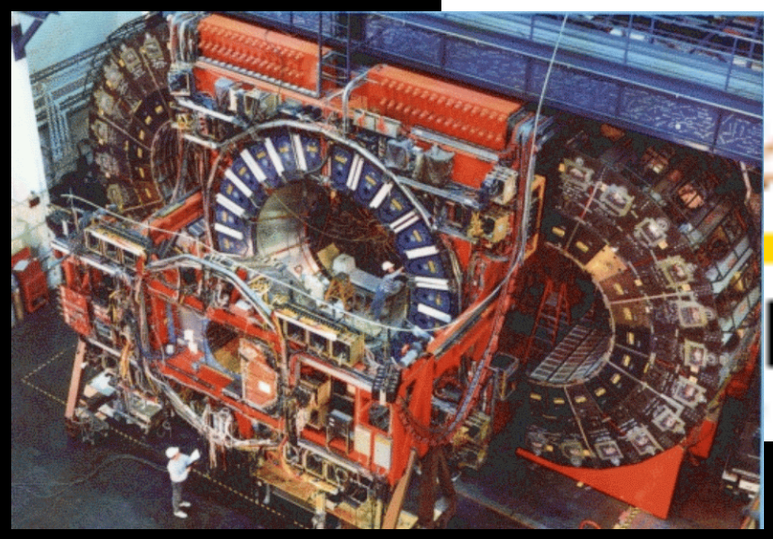
Colliders are discovery machines !



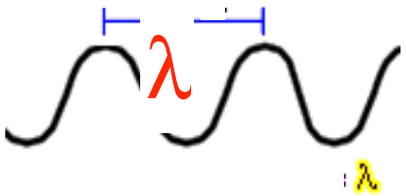
normal vision



Collider vision



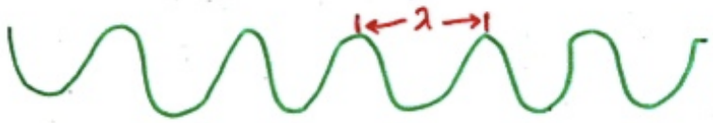
Particle accelerator



Target

Detector

particles behaves like waves



Momentum of particle $p = \frac{h}{\lambda}$ ← Plancks constant ← wavelength

Particle Accelerators

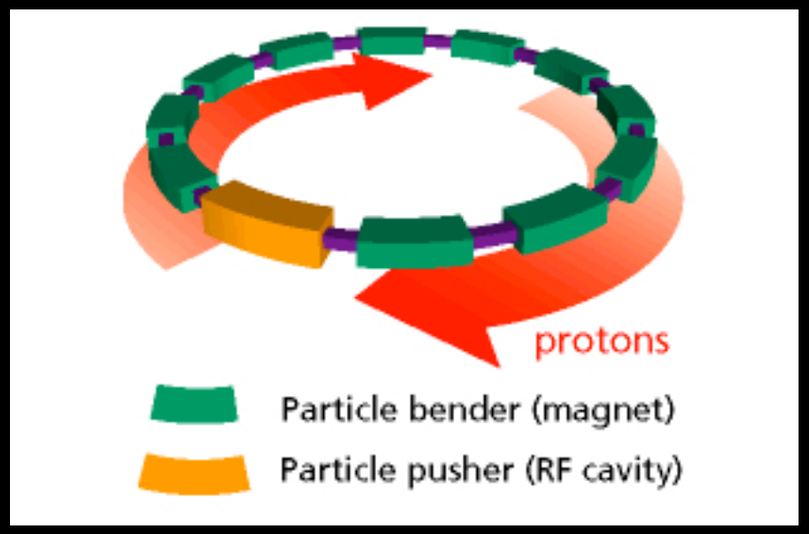
A simple idea:

* Accelerate charged particles in an electric field

* Keep them in orbit using magnets

* Collide them against each other

* See what comes out...



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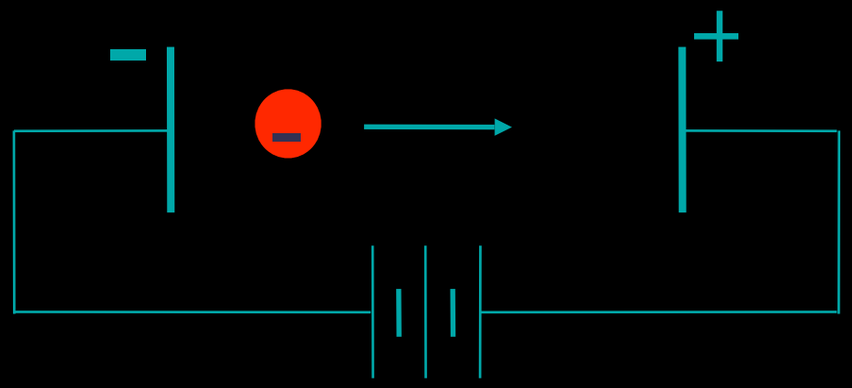
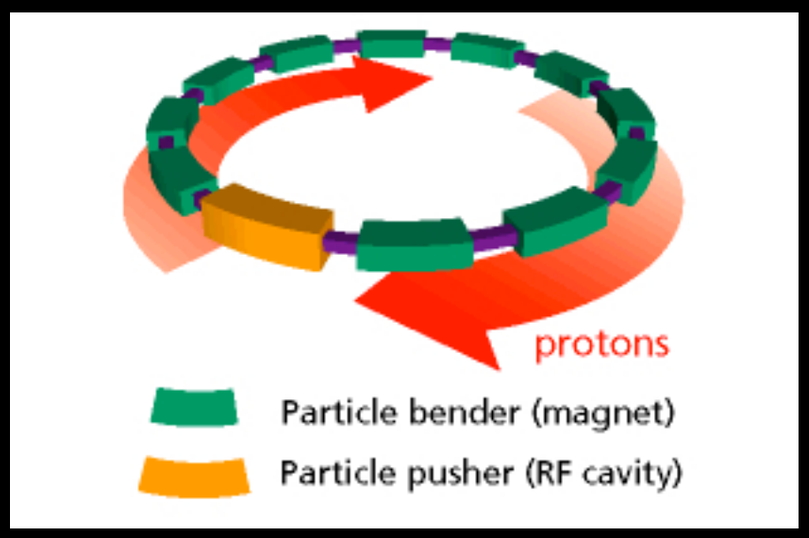


1 electron-Volt
= energy gained by one electron in a 1-Volt electrostatic potential

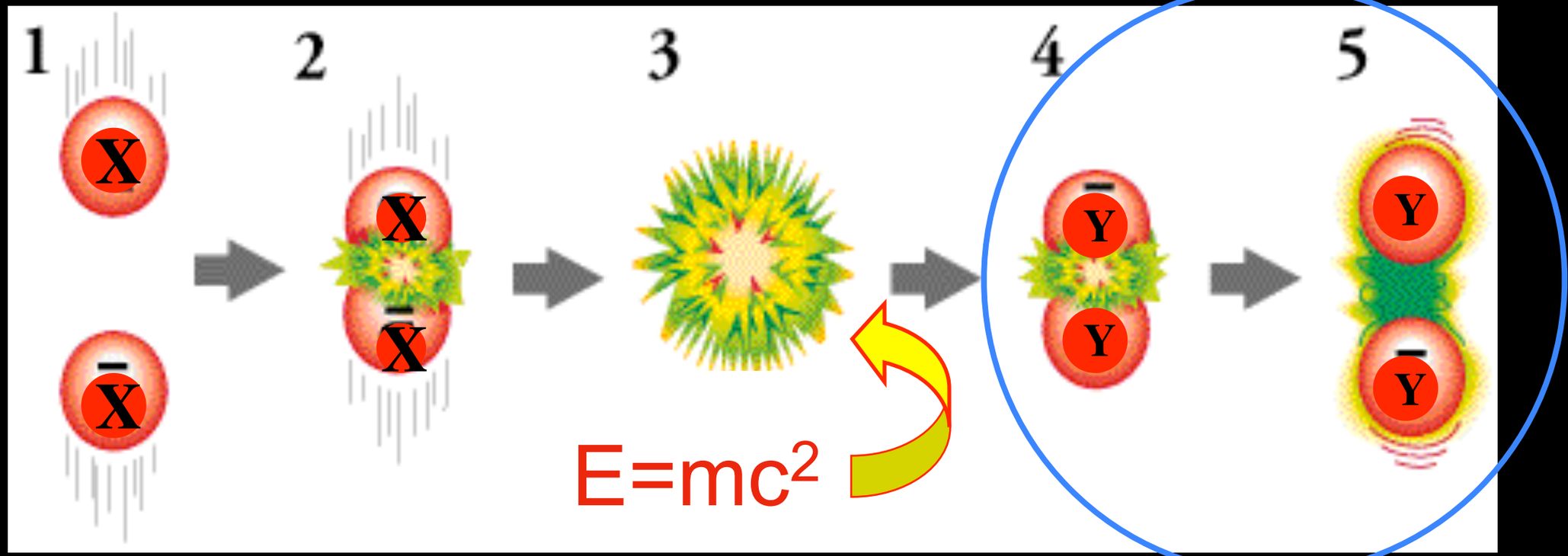
It's not that simple to get to Tera-electronVolts

1 TeV = 10^{12} eV



At the collision point

Discoveries !



More energy ==> produce more massive particles

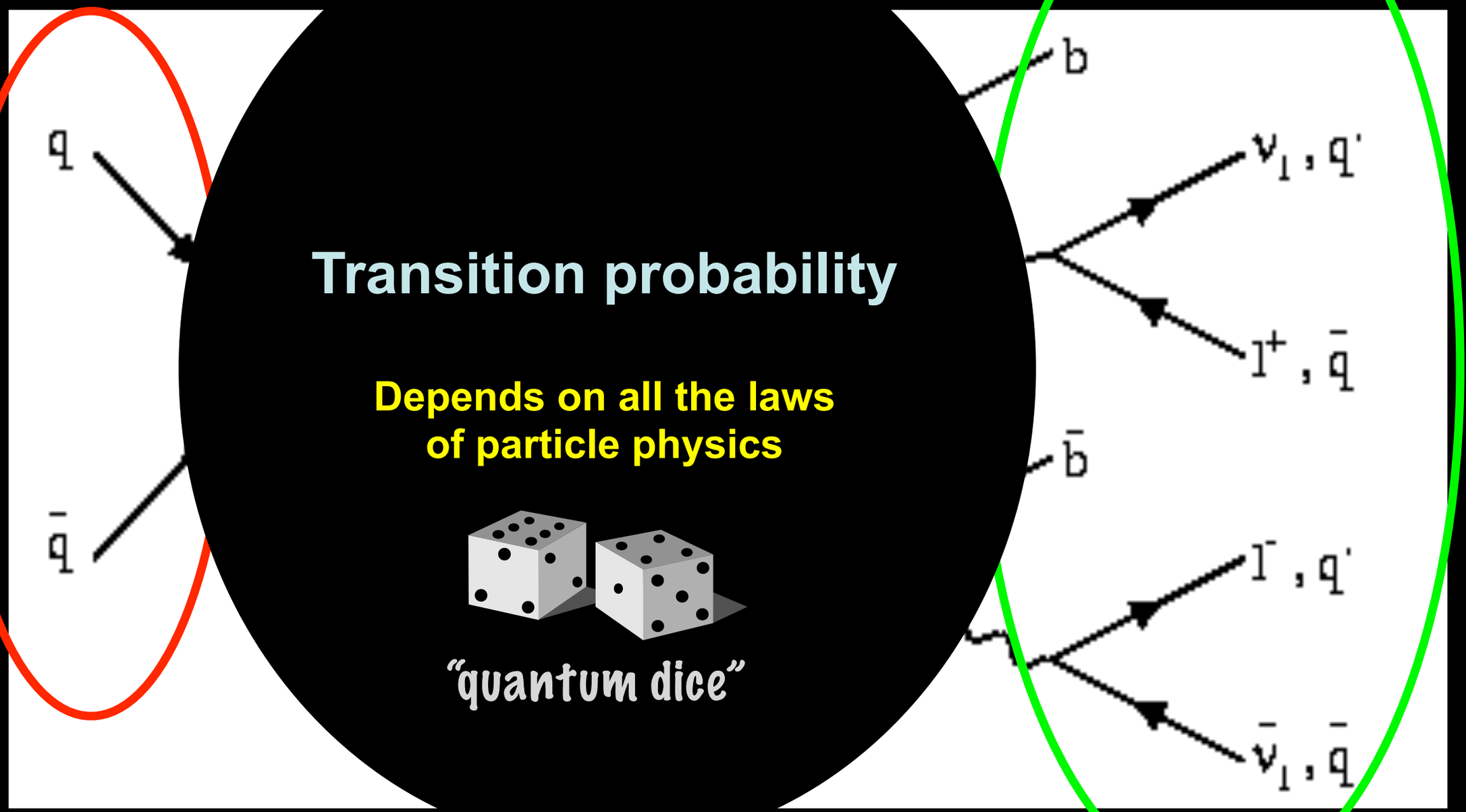
More energy ==> look more closely [small λ]

More energy ==> go back further in time !

At the collision point

Initial state

Final state



Transition probability

Depends on all the laws of particle physics

"quantum dice"

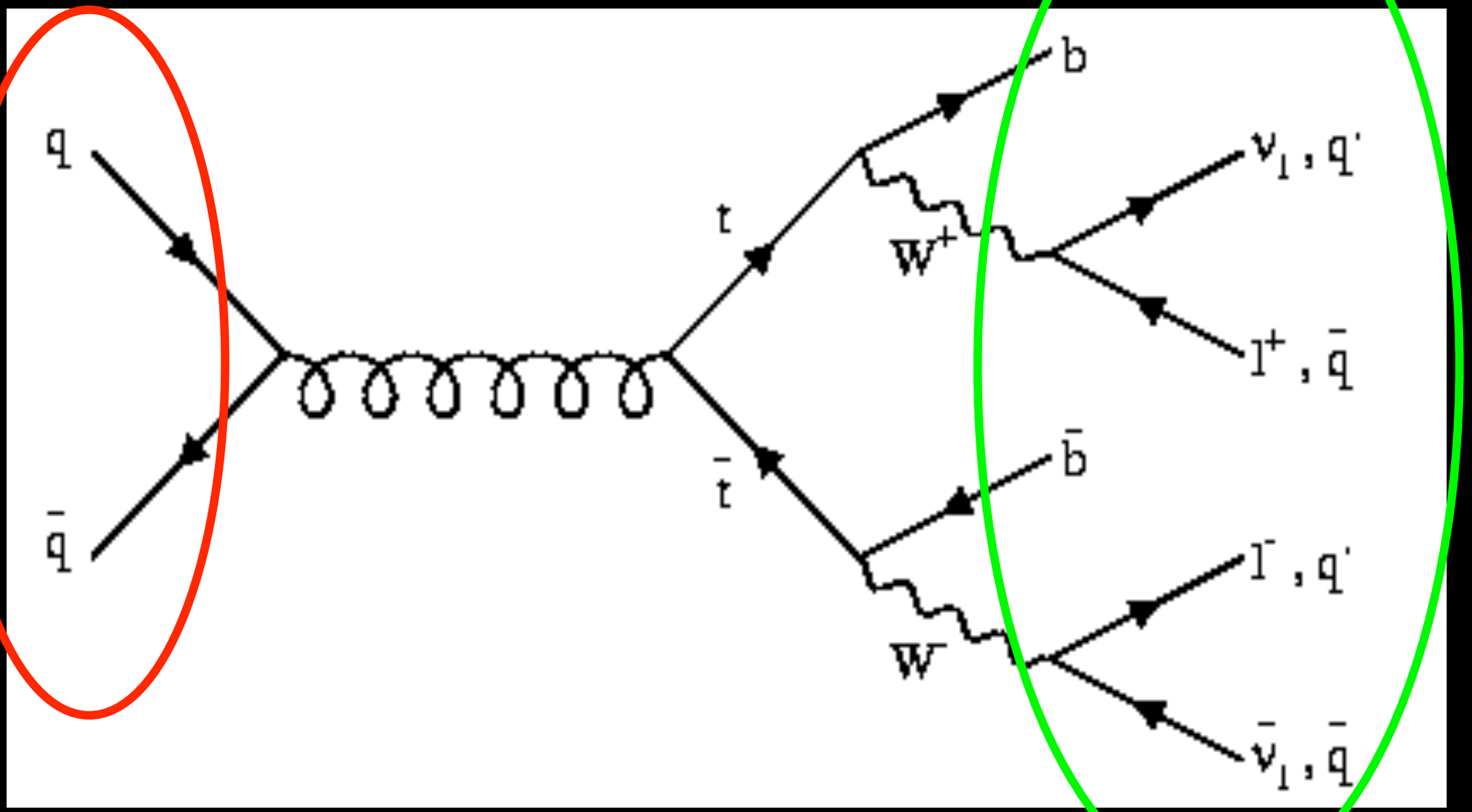
Accelerators

Detectors

At the collision point

Initial state

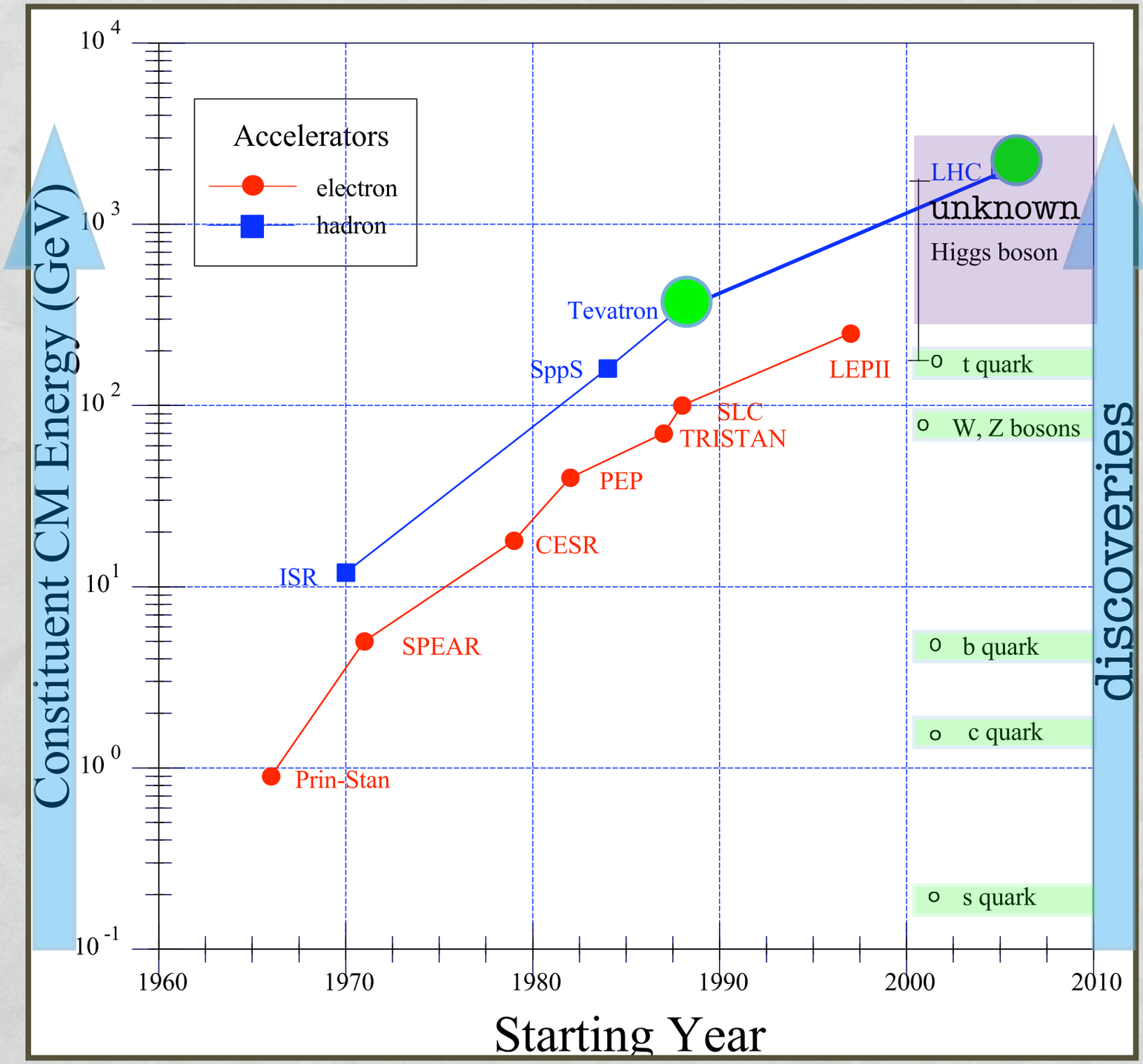
Final state



Accelerators

Detectors

The “E”volution of particle accelerators



Fermilab's Tevatron

Proton-antiproton collider

Ecm = 1.96 TeV

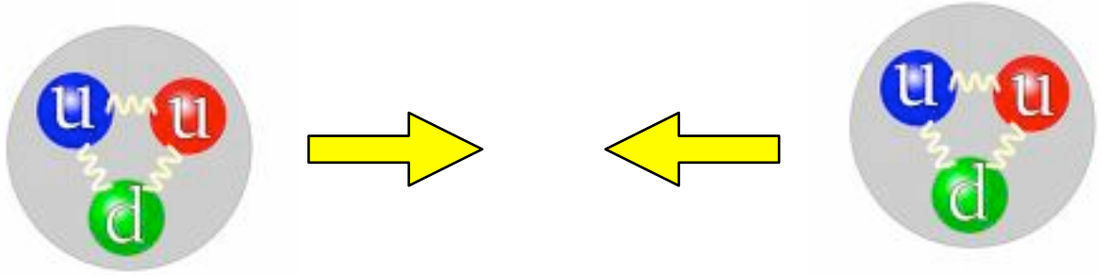
- 1 km diameter
- 36 x 36 bunches
- 280 Billion protons/bunch
- 80 Billion anti-p/bunch
- 2 million collisions/sec

- Two multi-purpose particle detectors: CDF and DØ

- First collisions on October 13, 1985 - at CDF

- Several big upgrades and continuous improvements

- 1992-1996 "Run I"
- 2001 ==> 2010? "Run II"



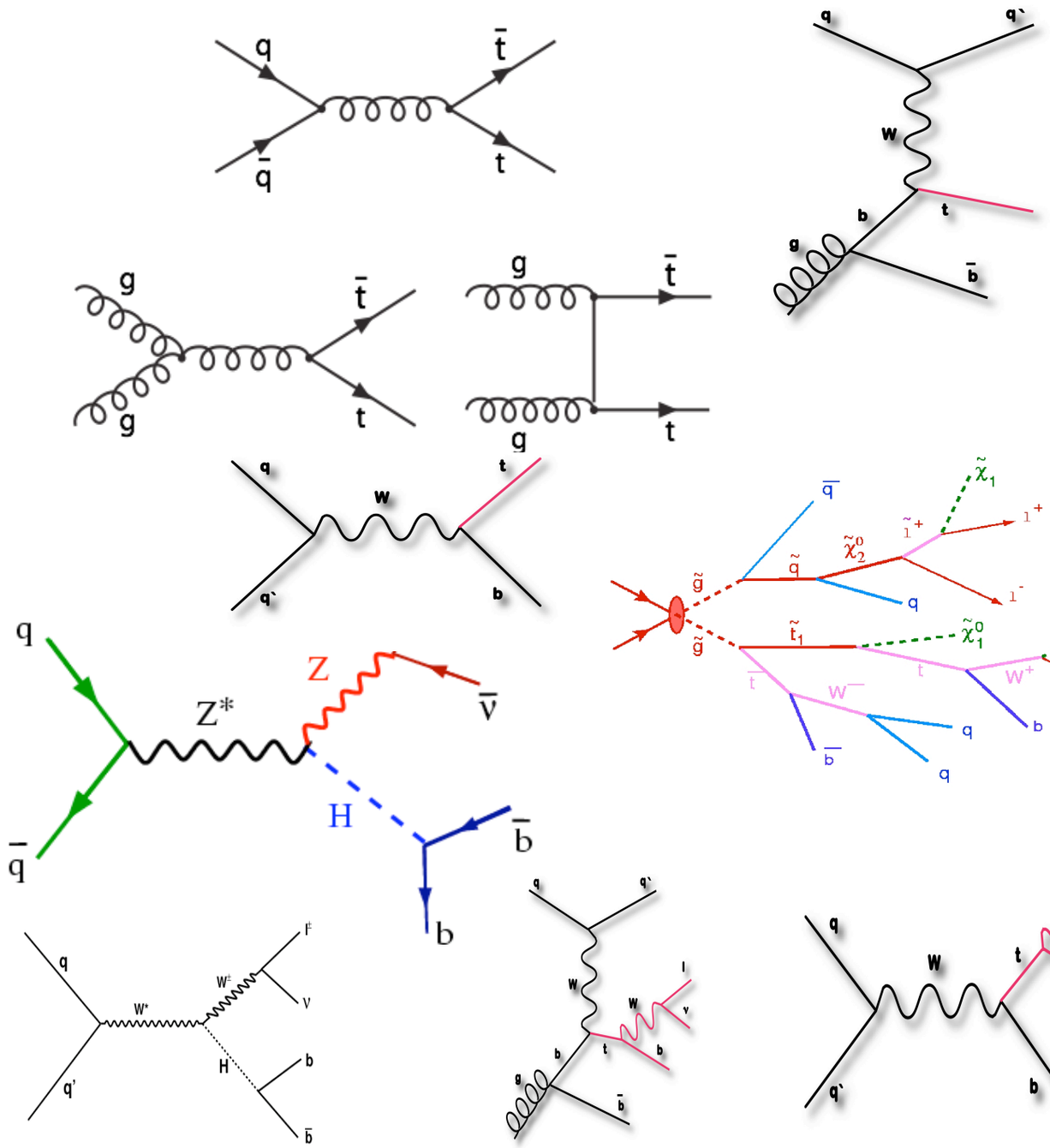
protons are 3-quark baryons + X

Hadron Colliders

hadrons = composite particles:

- mesons = made of a quark and an antiquark
- baryons = made of 3 quarks

We can make a lot of stuff at the Tevatron



"Particles, particles, particles"

How many can we find of each?

$$N^{\text{observed}}_{\text{top events}} = \sigma(p\bar{p} \to t\bar{t}) \cdot L \cdot \varepsilon$$

ε = BR · Acceptance · Efficiencies

Detectors & Experimental Analysis

$\sigma(p\bar{p} \to t\bar{t})$ ~ "cross-section" ~ probability

Physics Units: 1 barn = 10^{-24} cm^2

Integrated luminosity

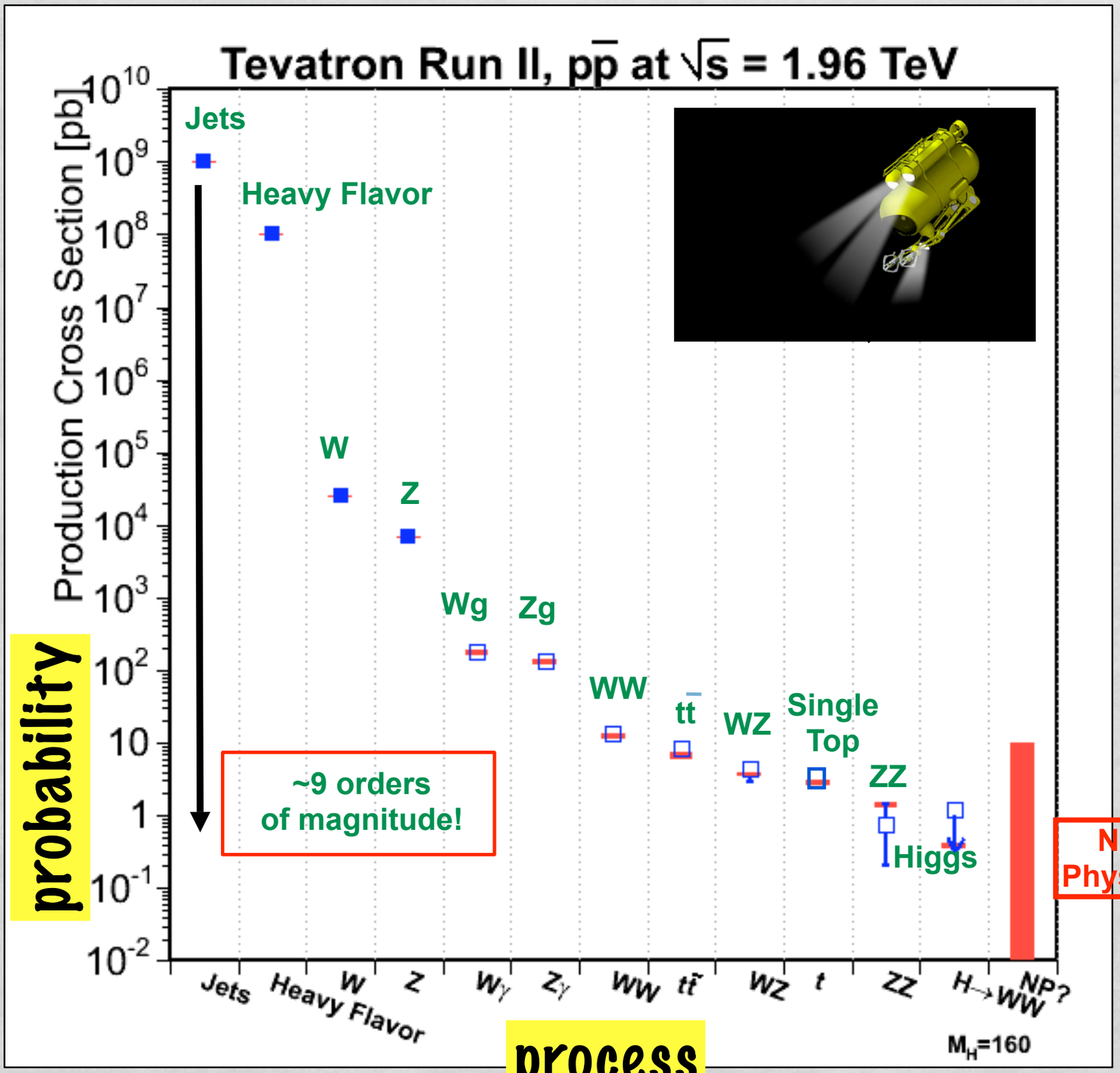
Accelerator Units = fb^{-1}

size of dataset "inverse femtobarns"

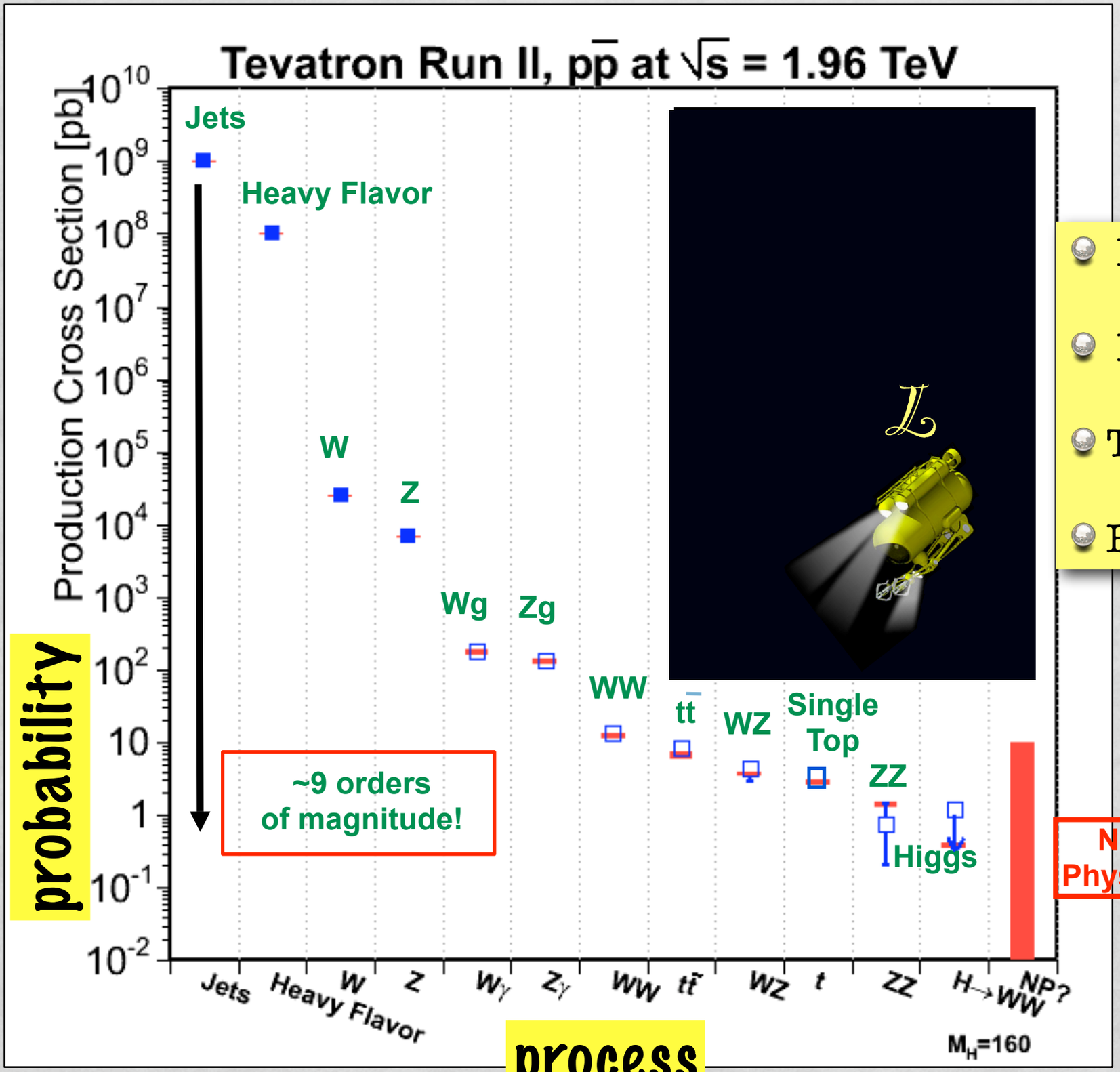
$$L = \int \mathscr{L} \cdot dt$$

$\mathscr{L}$ = instantaneous luminosity [beam intensity]
Units = 10^{32} cm^{-2}s^{-1}

The Tevatron: A Luminosity Story $\mathcal{L}$

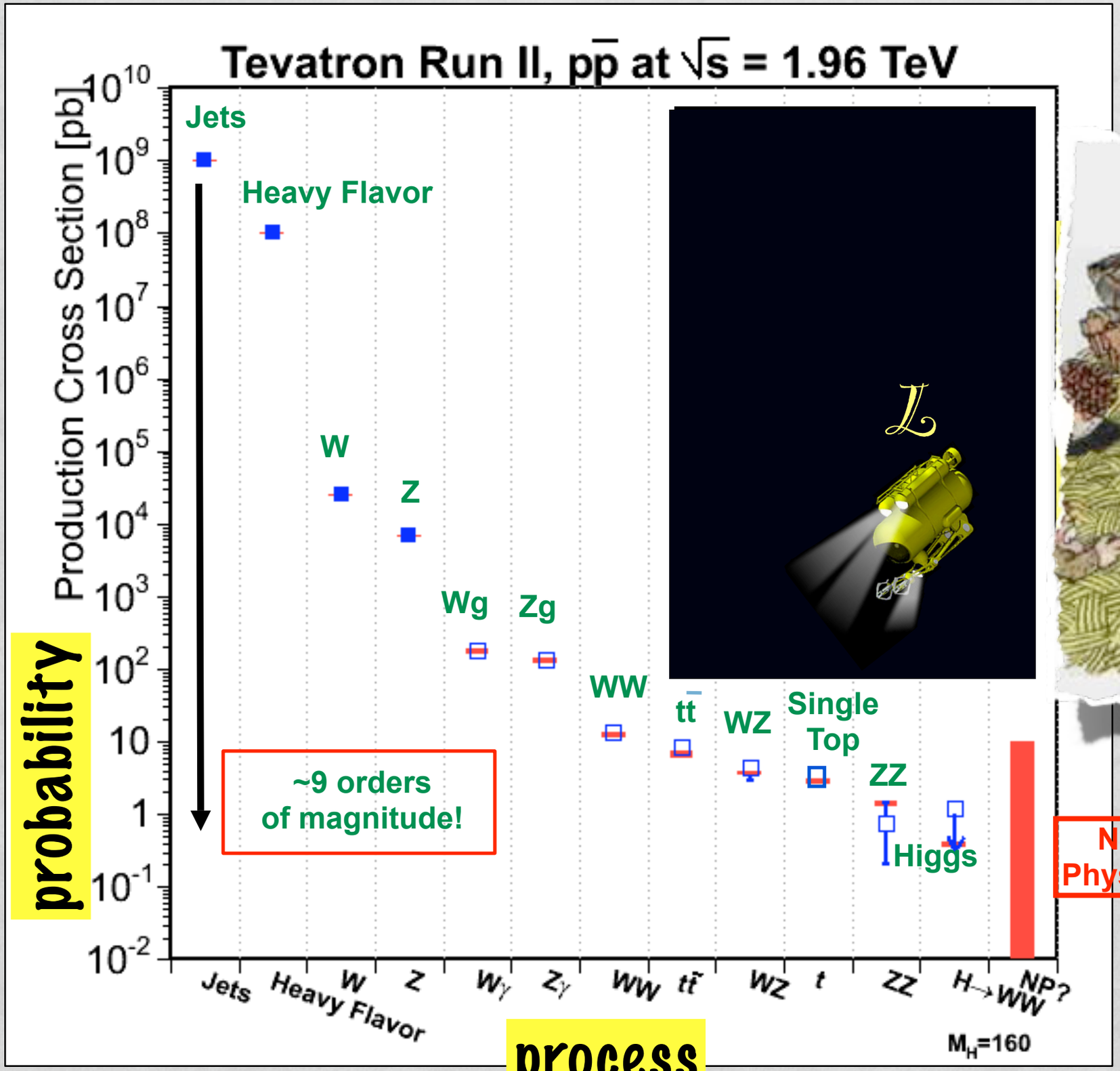


The Tevatron: A Luminosity Story $\mathcal{L}$

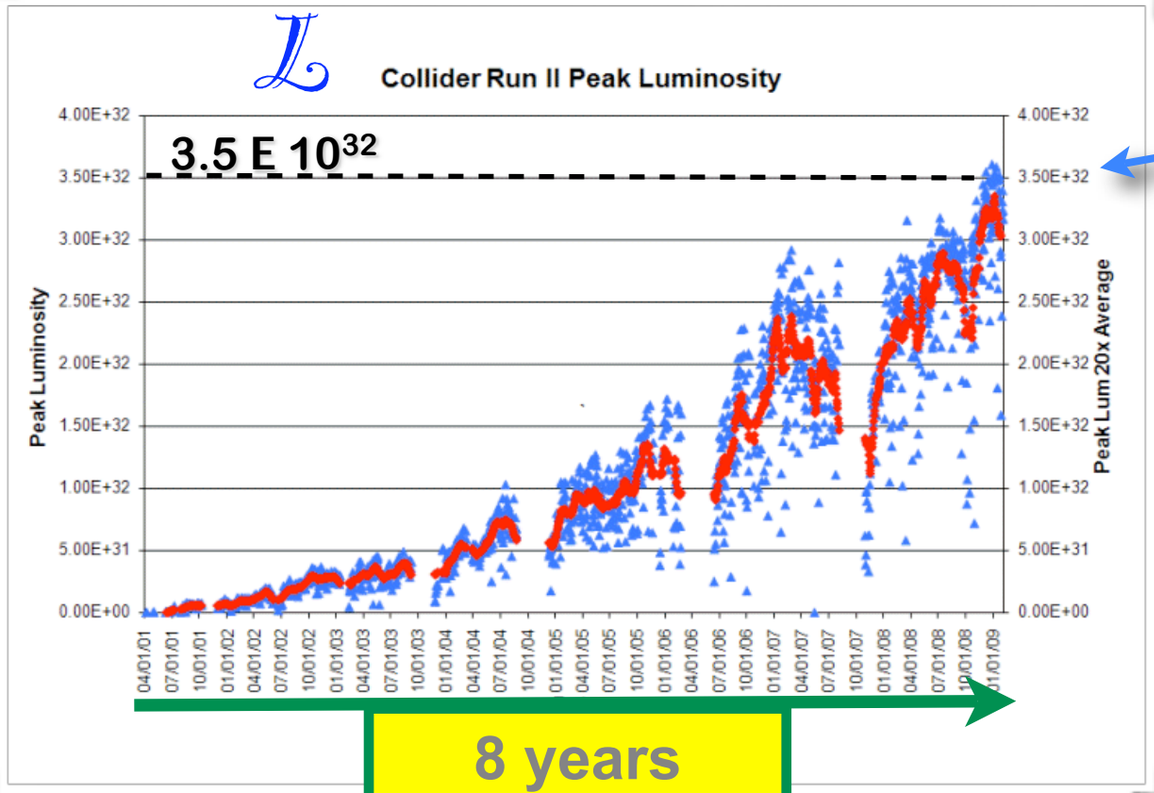


- Discoveries
- Increase precision
- Test for New Physics
- Reach "Higgs depth"

The Tevatron: A Luminosity Story $\mathcal{L}$



Run 2 Luminosity Progress



Record peak inst. luminosity

3.6 E 10^{32} cm^{-2} s^{-1}

Record luminosity/week

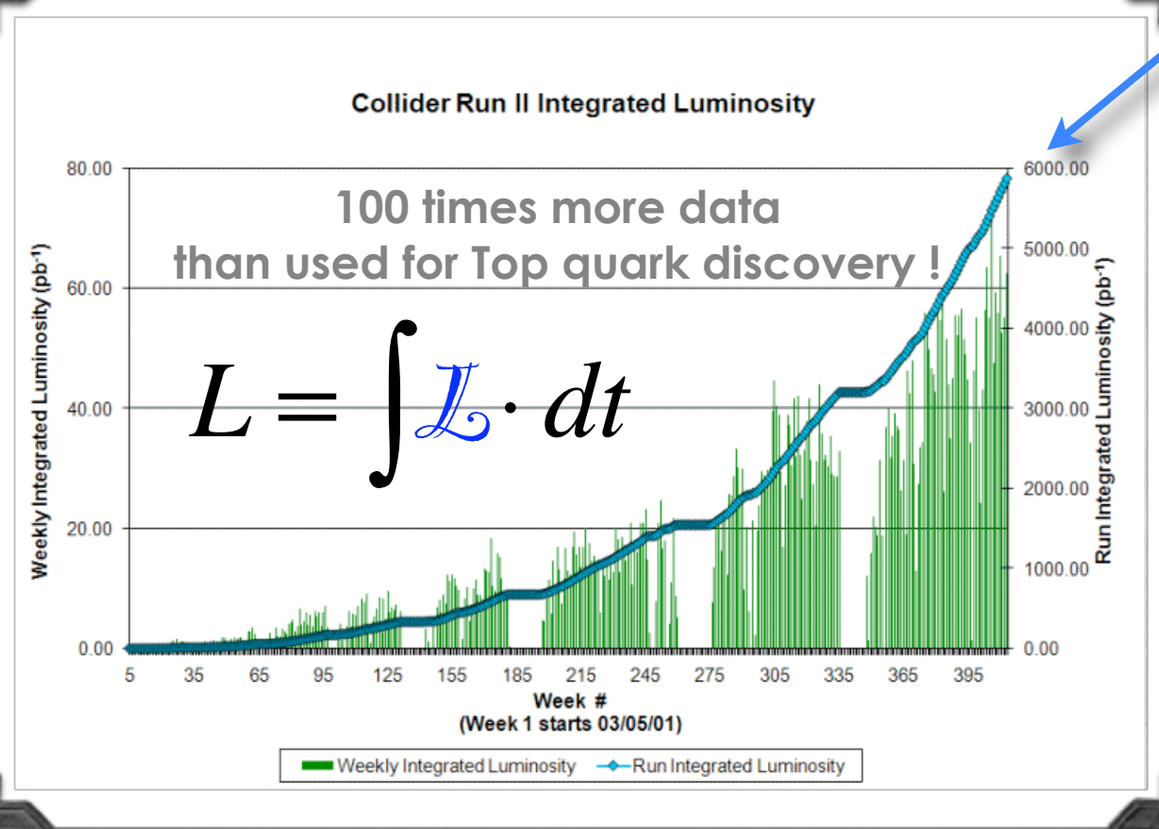
74 pb^{-1}

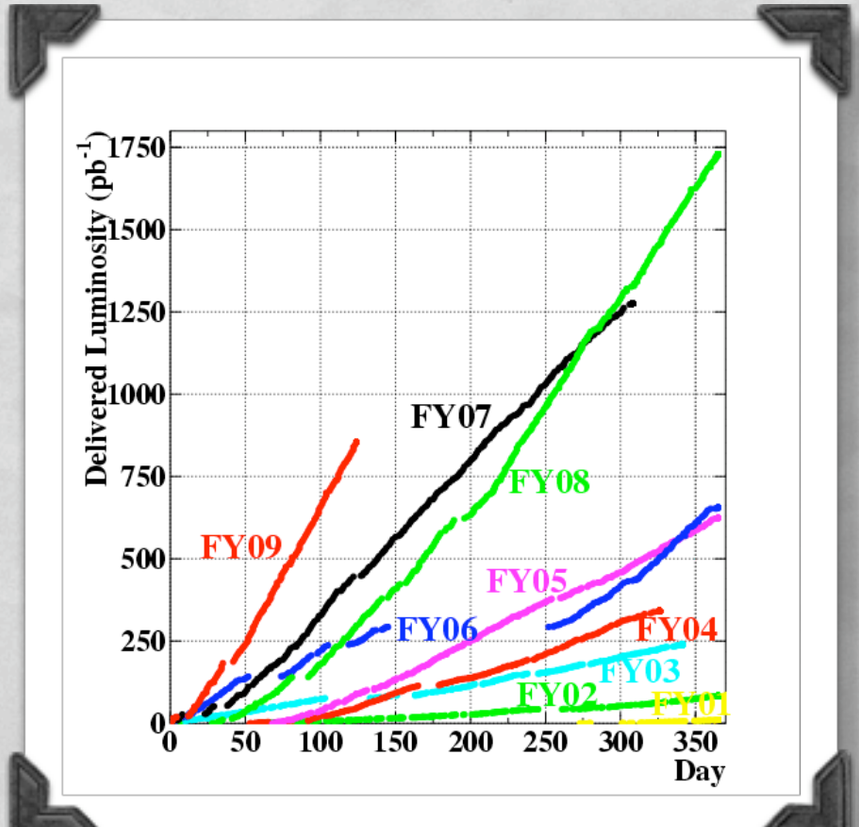
Record luminosity/month

263 pb^{-1}

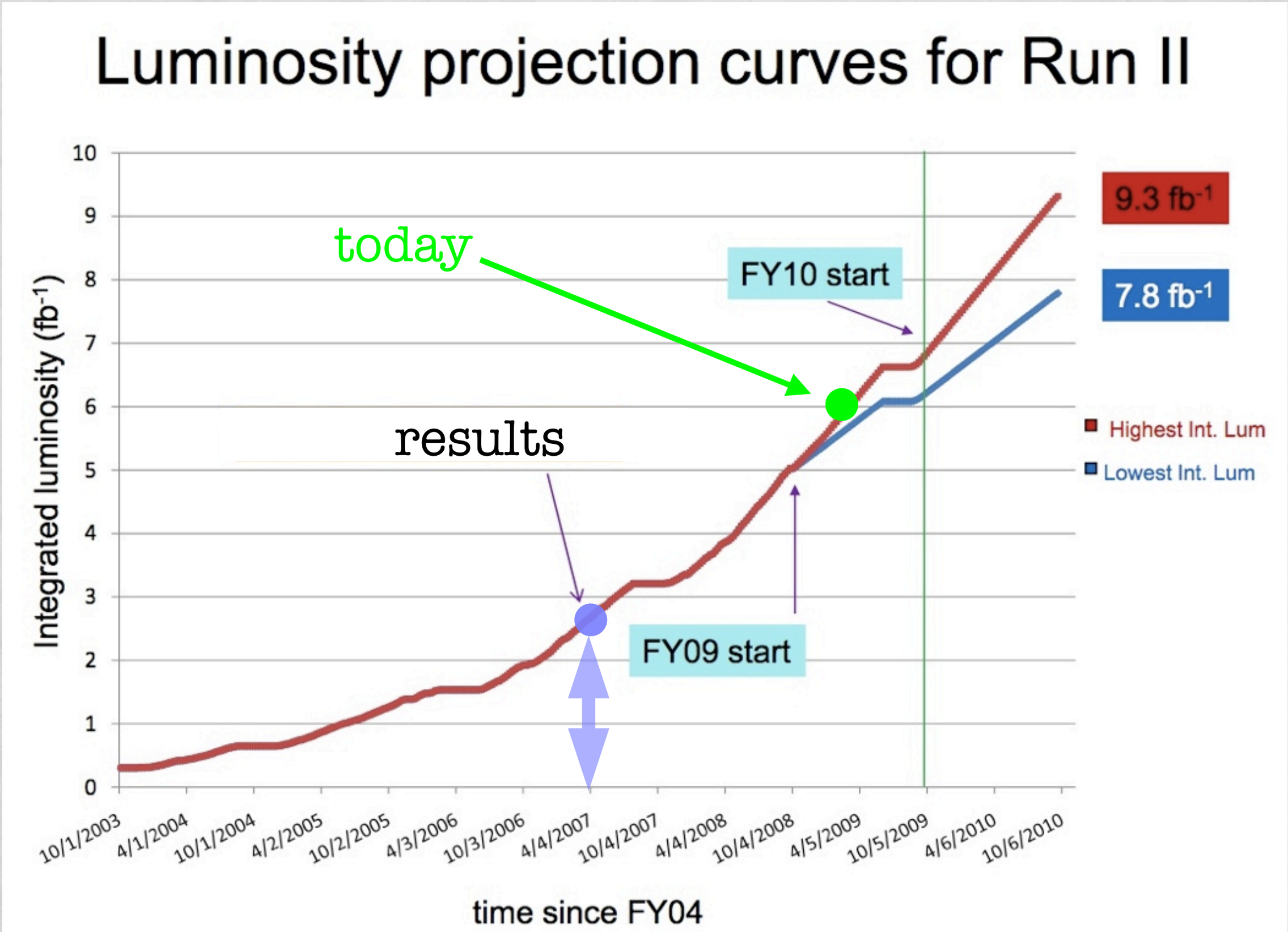
Total Luminosity delivered

6 fb^{-1}

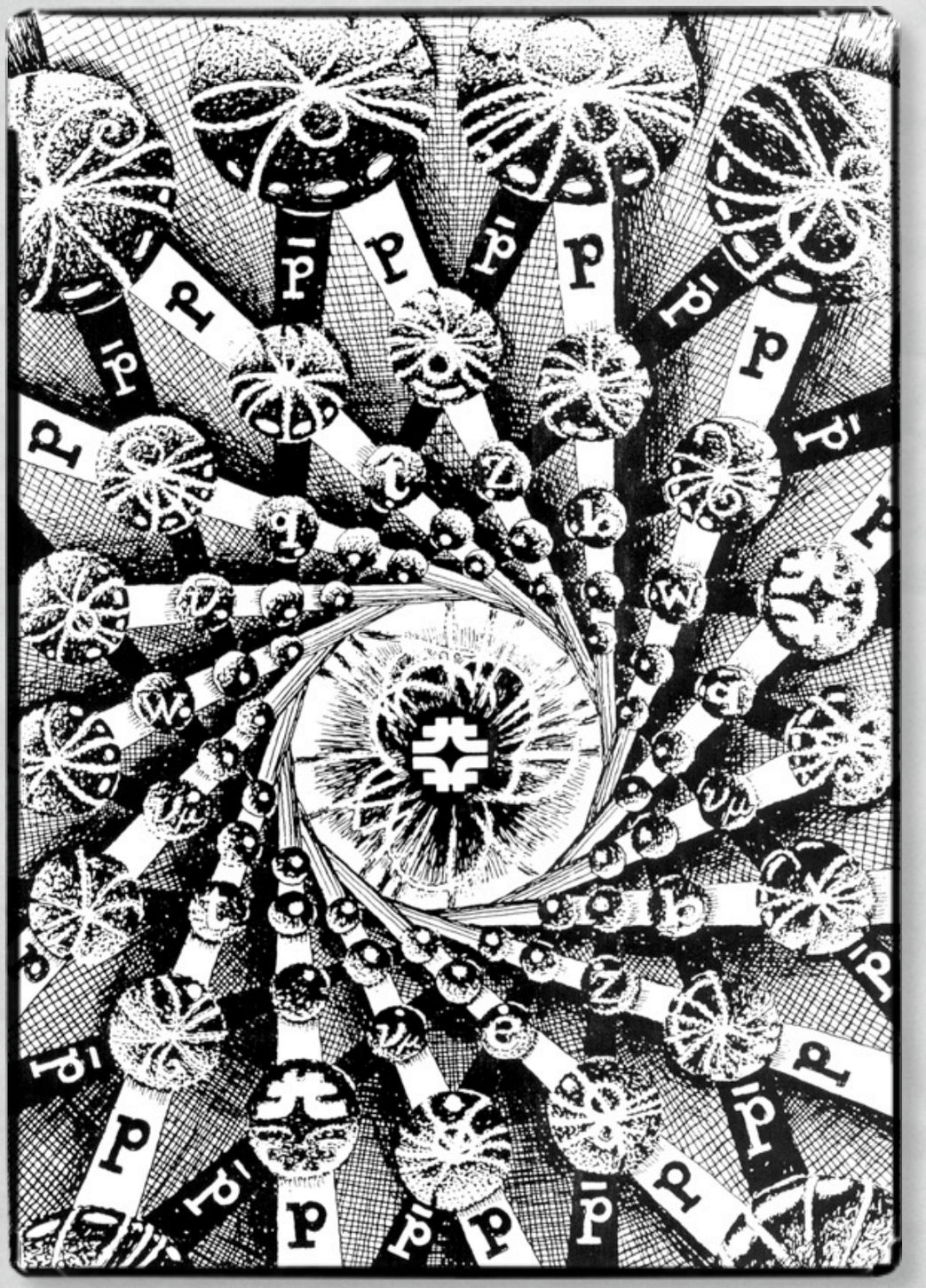




Until when ?


Luminosity projection curves for Run II
today
results
FY10 start
FY09 start
9.3 fb-1
7.8 fb-1
Highest Int. Lum
Lowest Int. Lum
Integrated luminosity (fb-1)
0
1
2
3
4
5
6
7
8
9
10
10/1/2003
4/1/2004
10/1/2004
4/2/2005
10/2/2005
4/3/2006
10/3/2006
4/4/2007
10/4/2007
4/4/2008
10/4/2008
4/5/2009
10/5/2009
4/6/2010
10/6/2010
time since FY04

Tevatron Stories



- Discoveries
  - New elementary particles
  - New and rare SM processes
  - New composite particles
  - Observation of subtle behavior
- Precision measurements of particle properties
- Cornering the unknown

http://www.fnal.gov/pub/presspass/press_releases

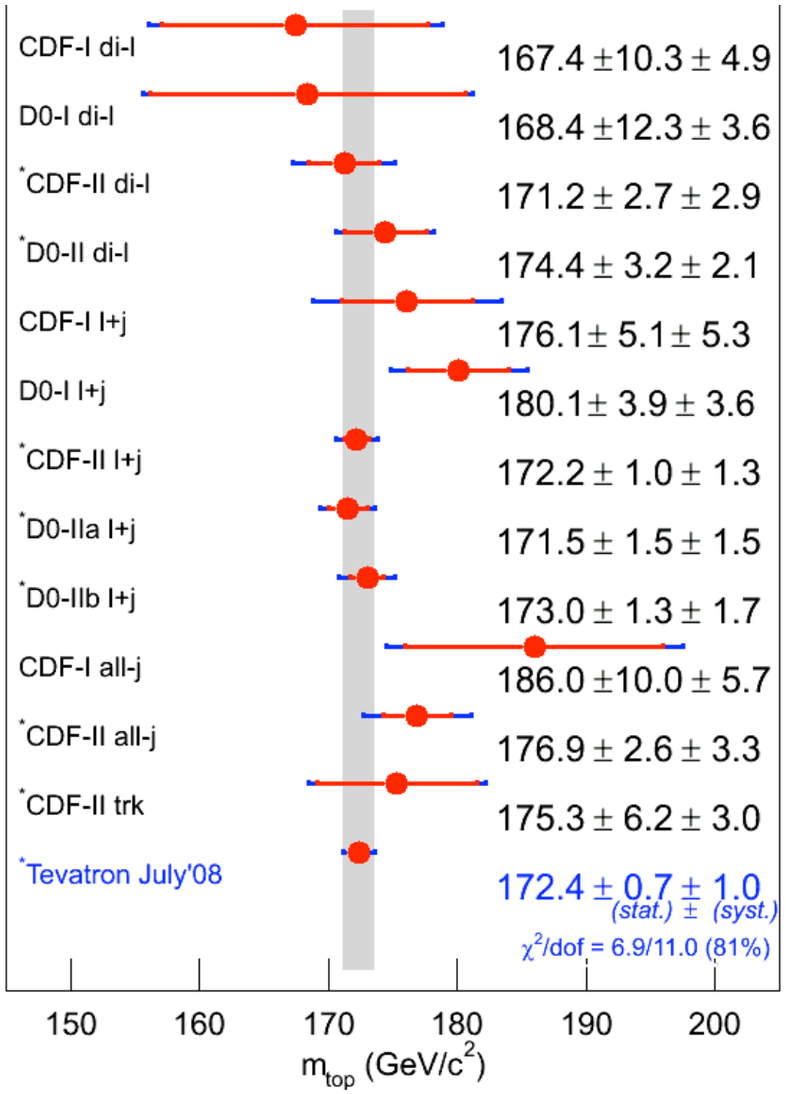
- [ ] Physicists Discover Top Quark (1995)
- [ ] CDF Results Raise Questions on Quark Structure (1996)
- [ ] Collider Run II Begins at Fermilab (2001)
- [ ] Fermilab Results Change Higgs Mass Estimate (2004)
- [ ] What Happened to the Antimatter? Fermilab's DZero Experiment Finds Clues in Quick-Change 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)

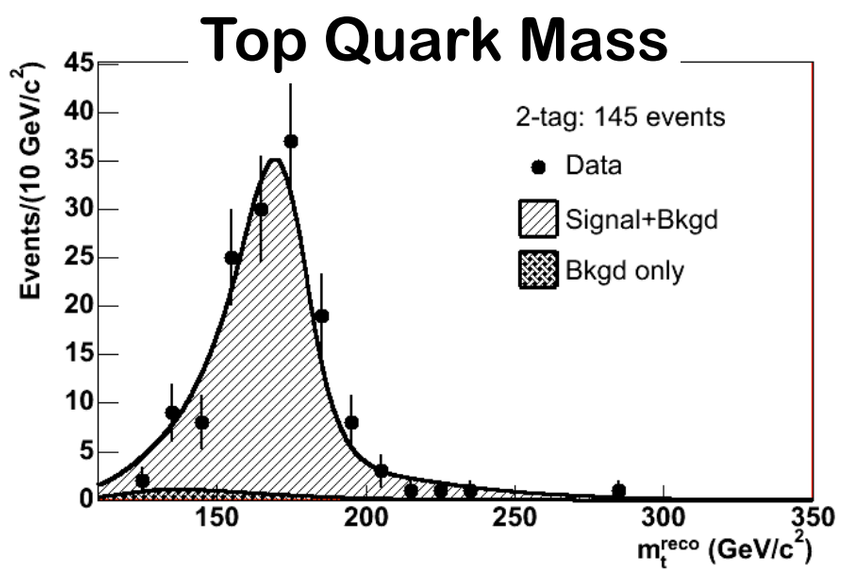
http://www.fnal.gov/pub/presspass/press_releases/

- 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)

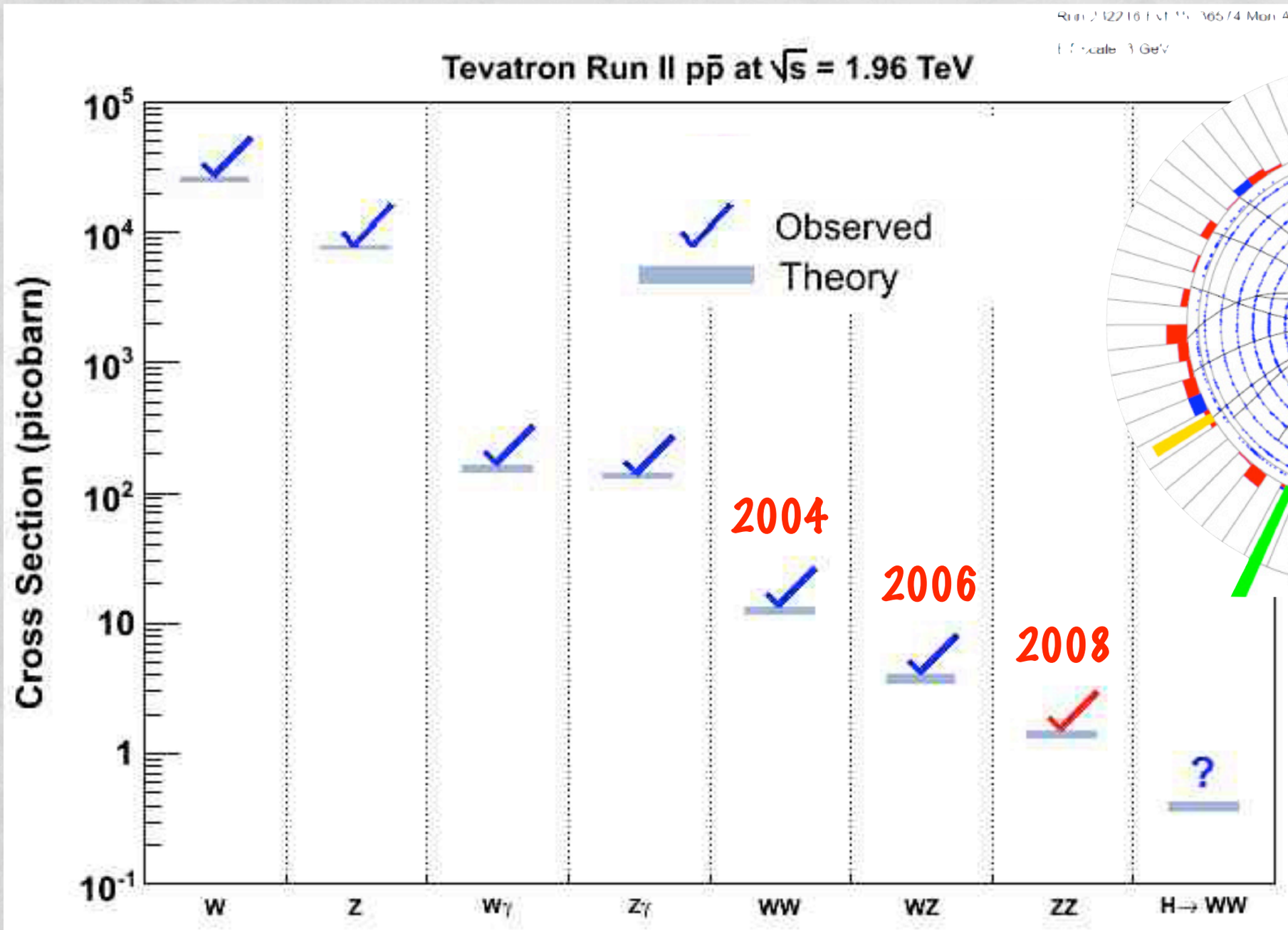
Top Quark Discovery

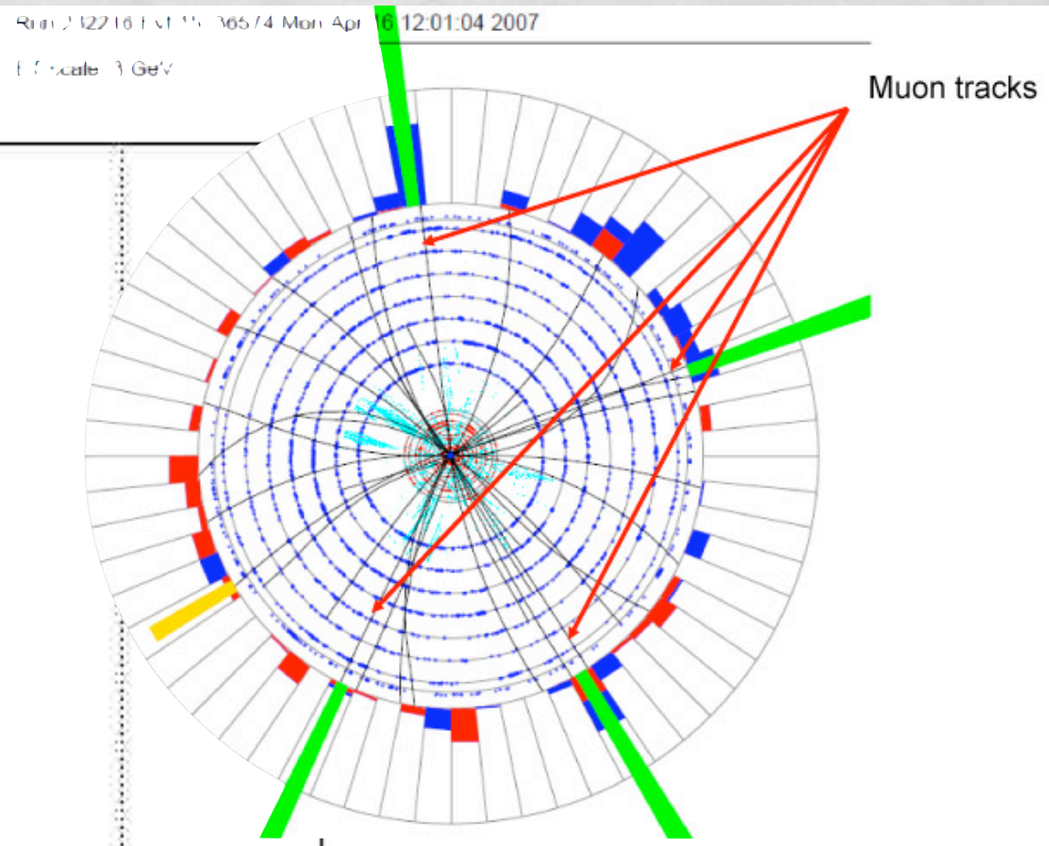
Top Quark Precision



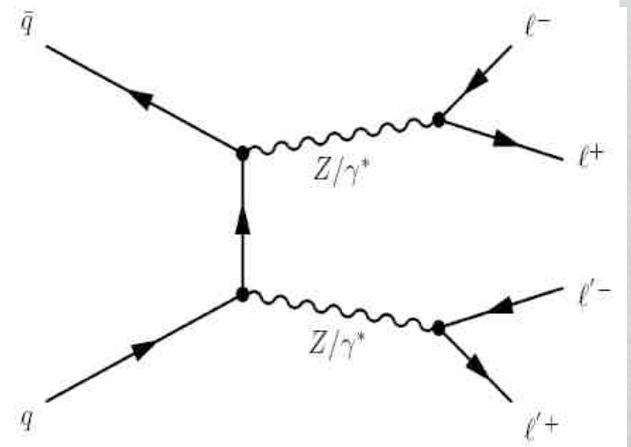


Recent Tevatron discoveries of rare Standard Model processes



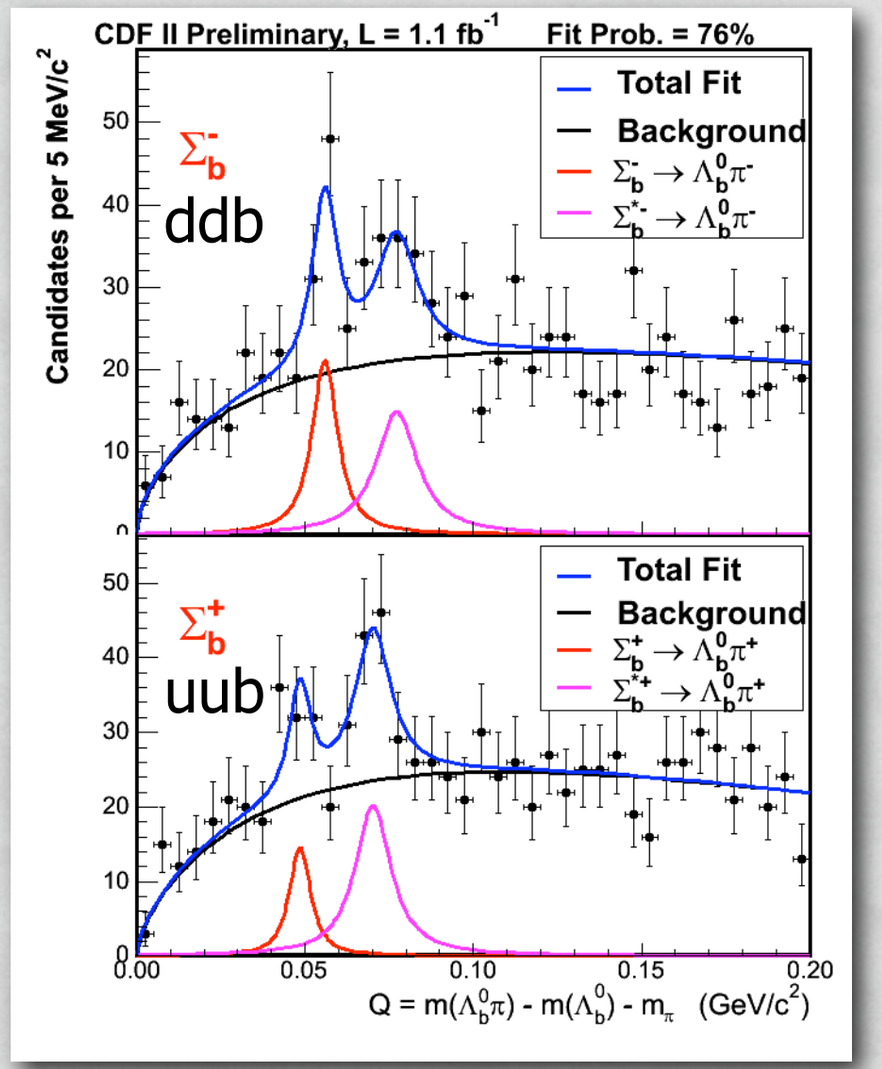


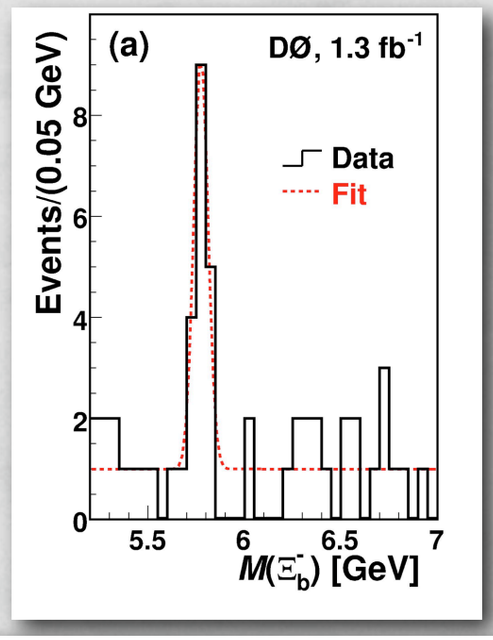
ZZ ==> mu,mu,mu,mu

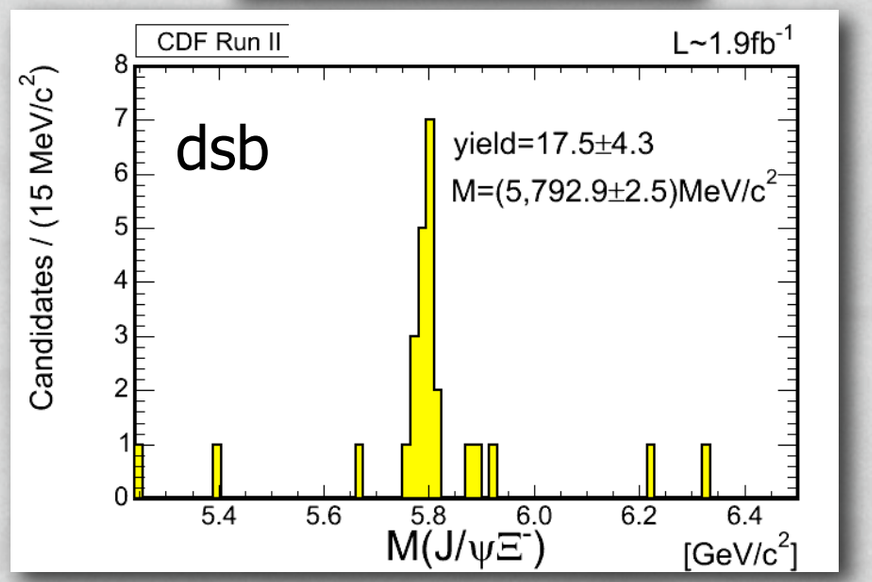


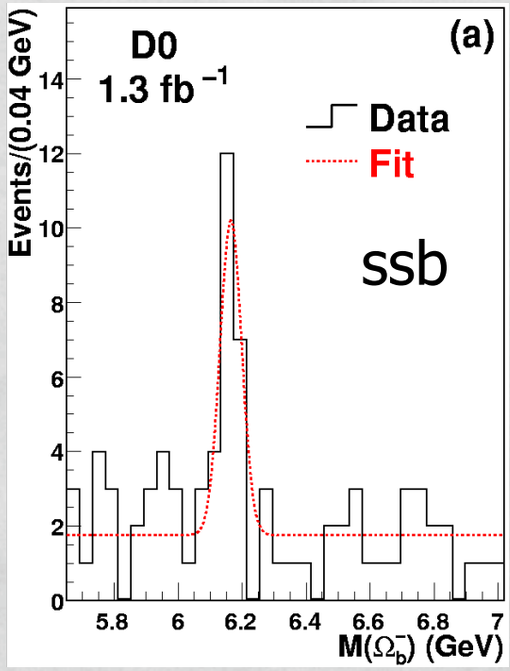
Recent Observation of new heavy baryons

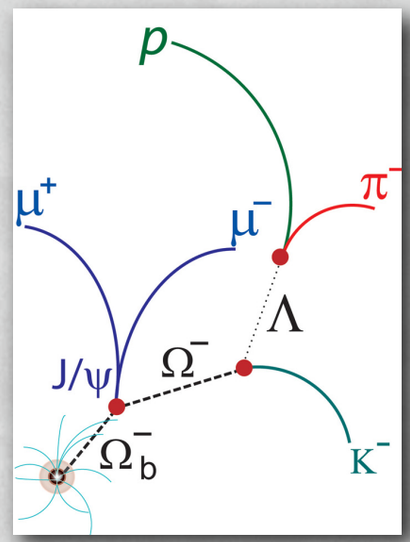
Σ_b Ξ_b Ω_b





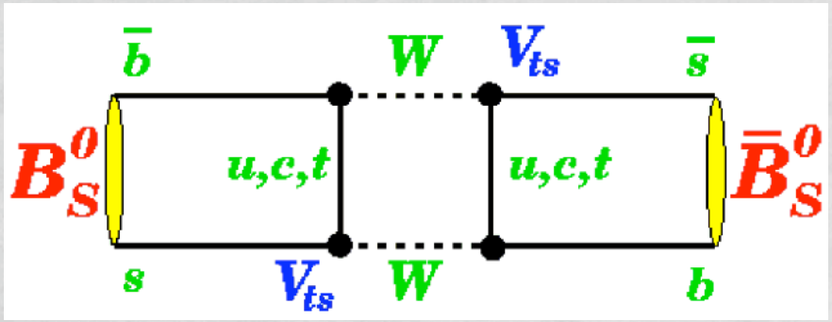




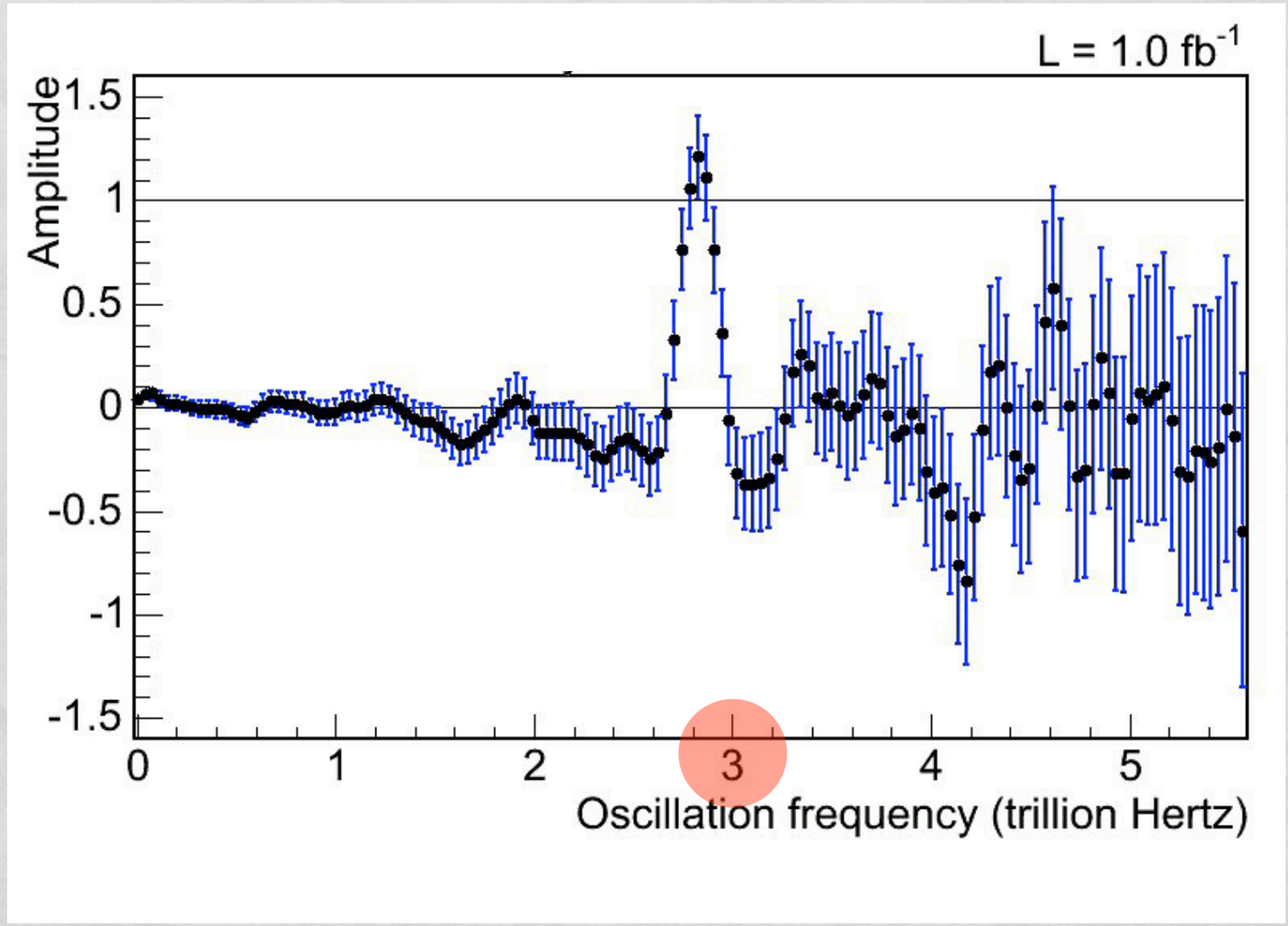


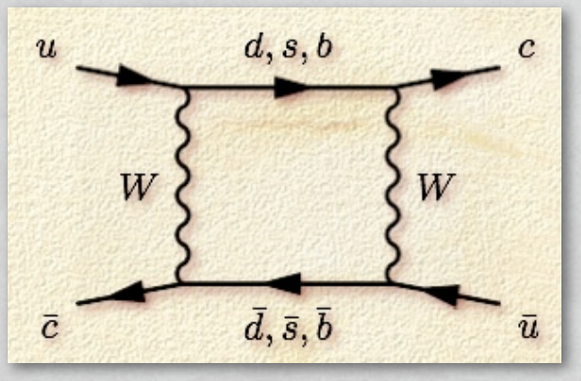
2006 2007 2008

Discovery of incredibly subtle oscillations between matter and anti-matter



$B_s^0 - \overline{B}_s^0$ mixing





$D^0 - \bar{D}^0$

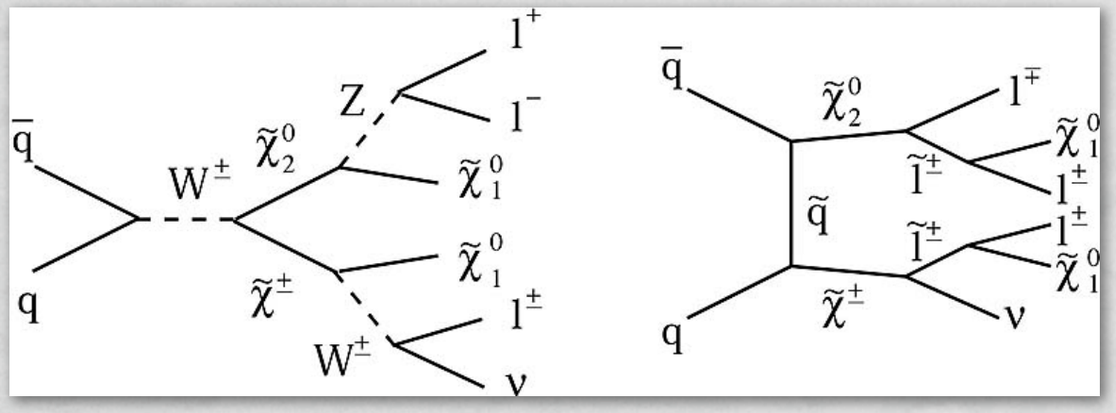
The Higgs Hunt

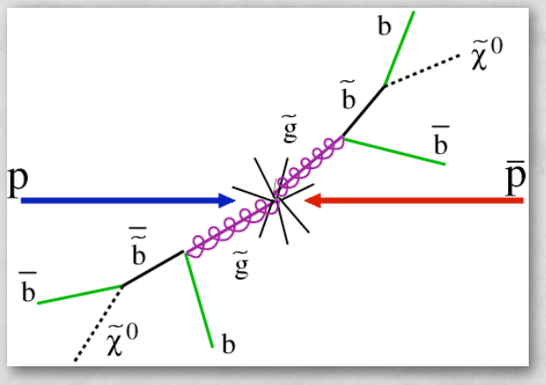
- The SM Higgs particle [if it exists] is being produced NOW at the Tevatron ! - we have enough energy
  - Just not that often & it's buried in "backgrounds"
  - It's a story of luminosity, passion, persistence and luck
  - Still, we know how to look for it - an we are closing in !

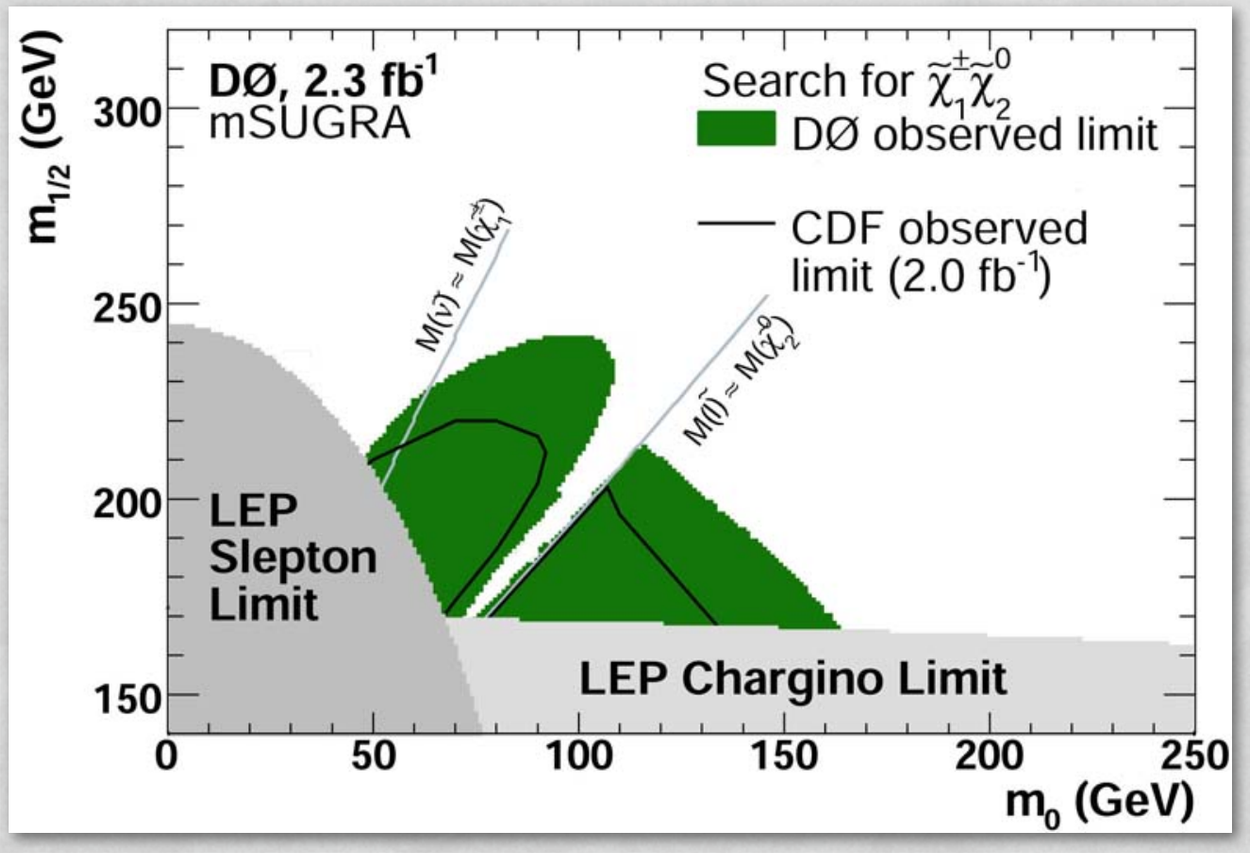
see the next presentation...

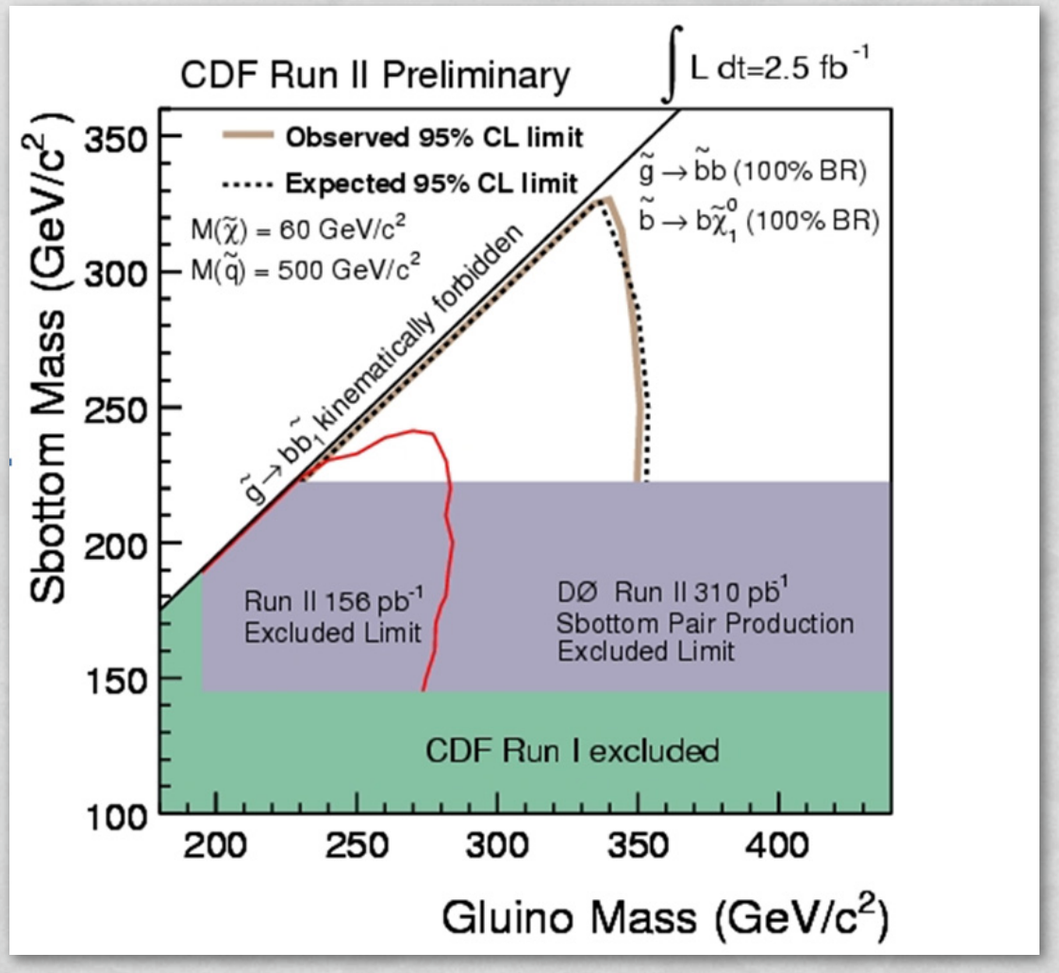
Cornering Supersymmetry

And many other theories for physics beyond the Standard Model





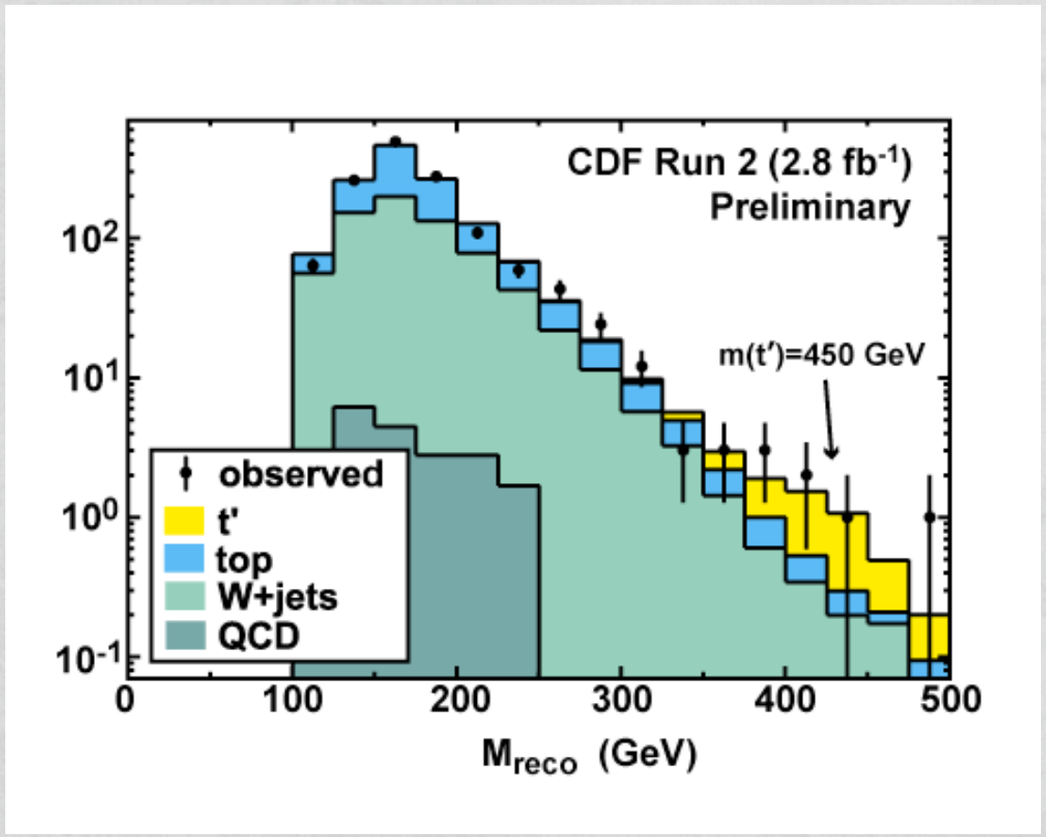




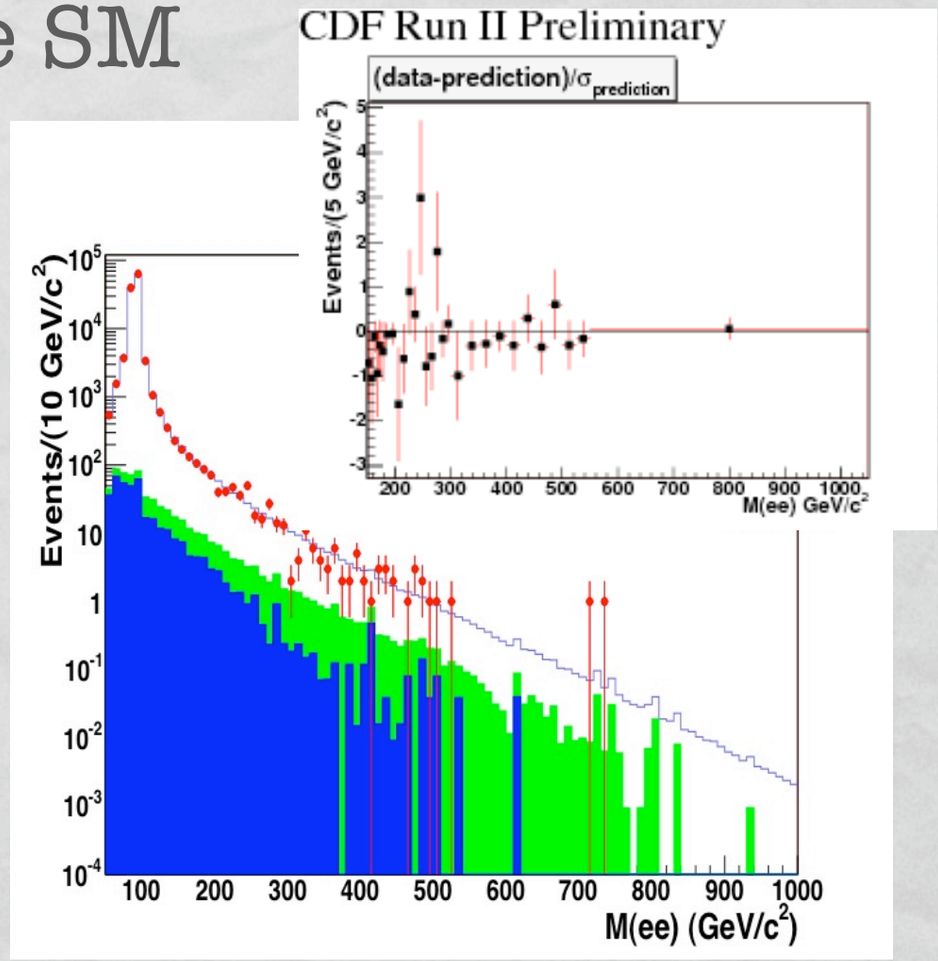
Exclude regions of SUSY masses

Discovery Watch

- Several results show discrepancies with the SM



2.5σ effects



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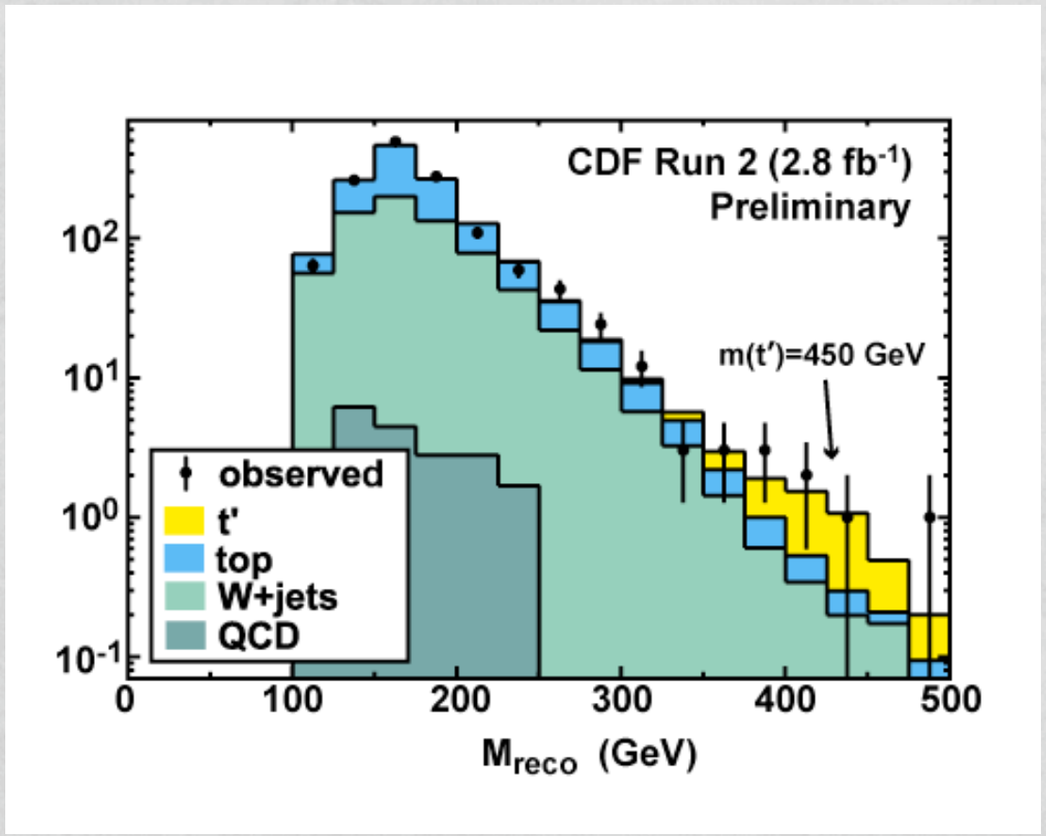
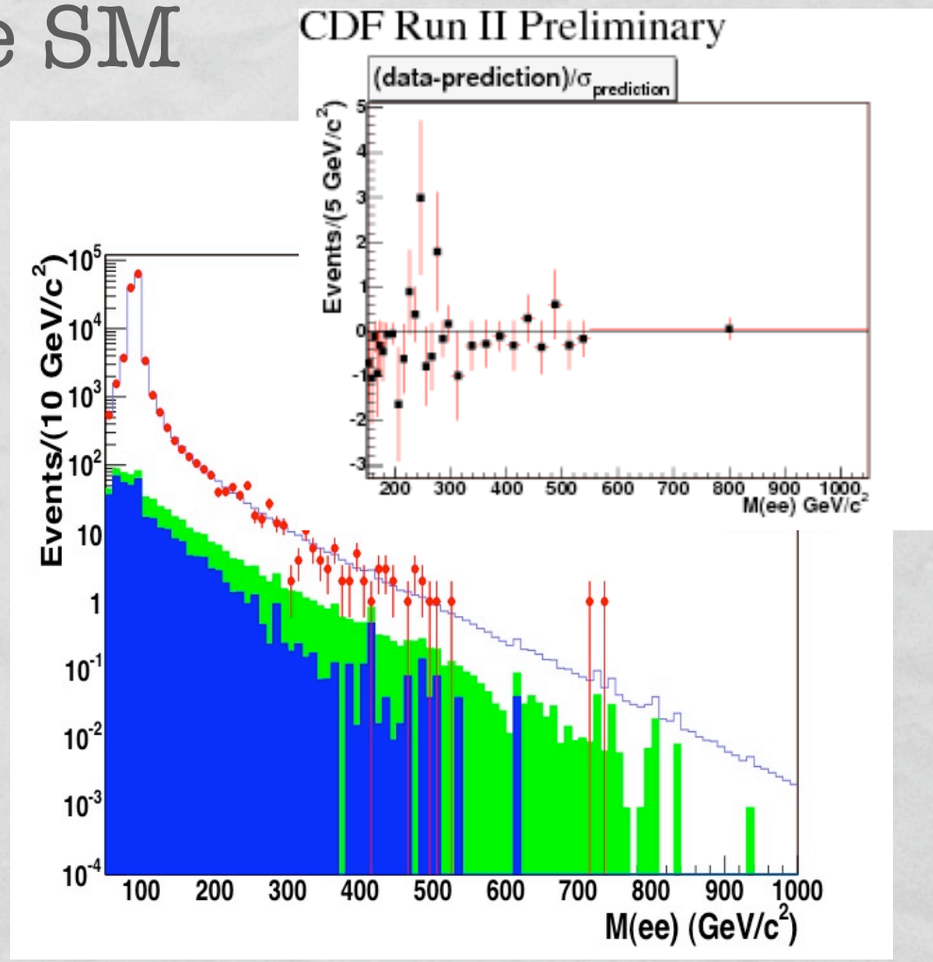
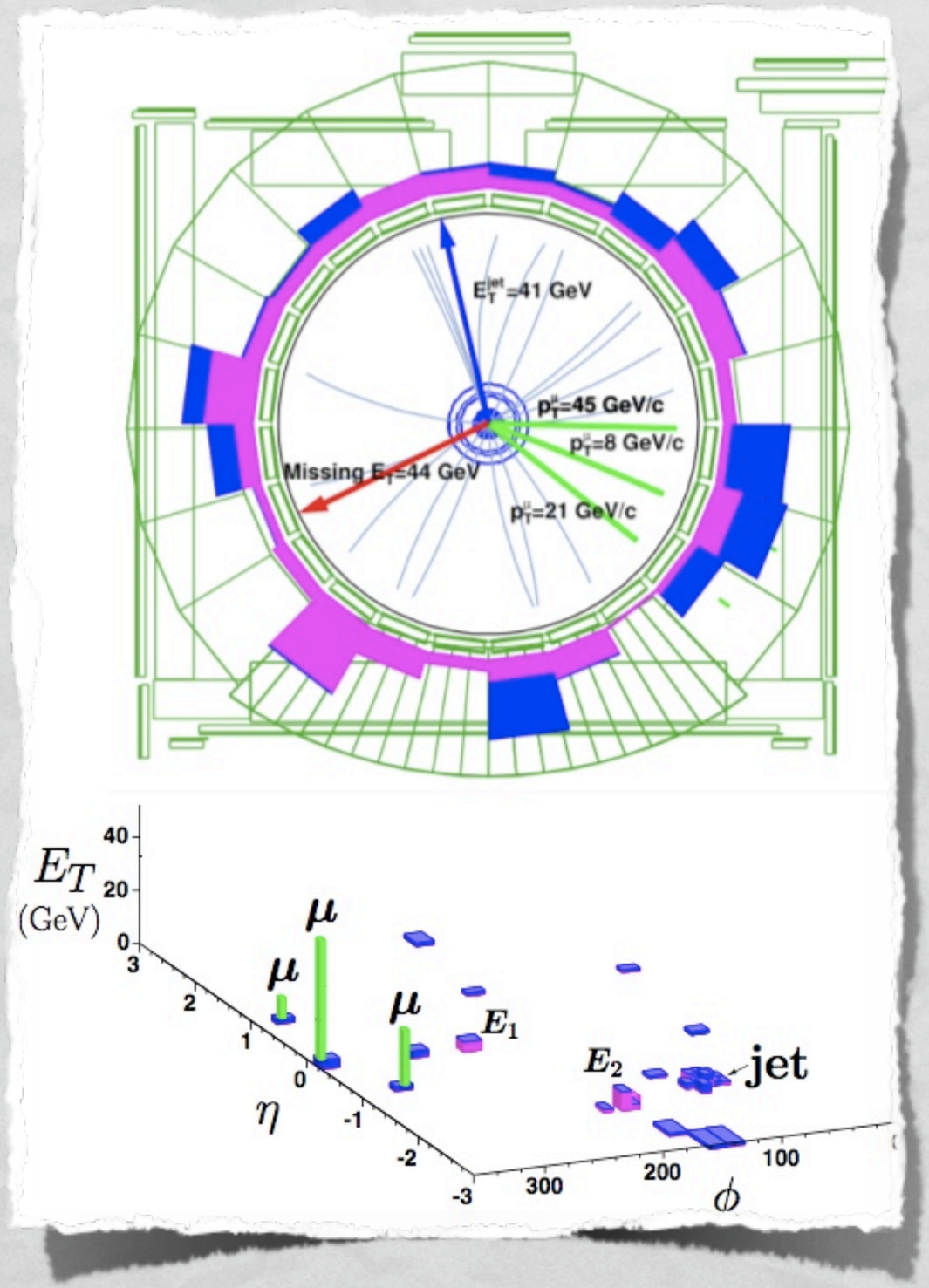


2.5σ effects



- Are these just statistical fluctuations or the beginning of a beautiful friendship $\mathcal{L}$

Unusual single events



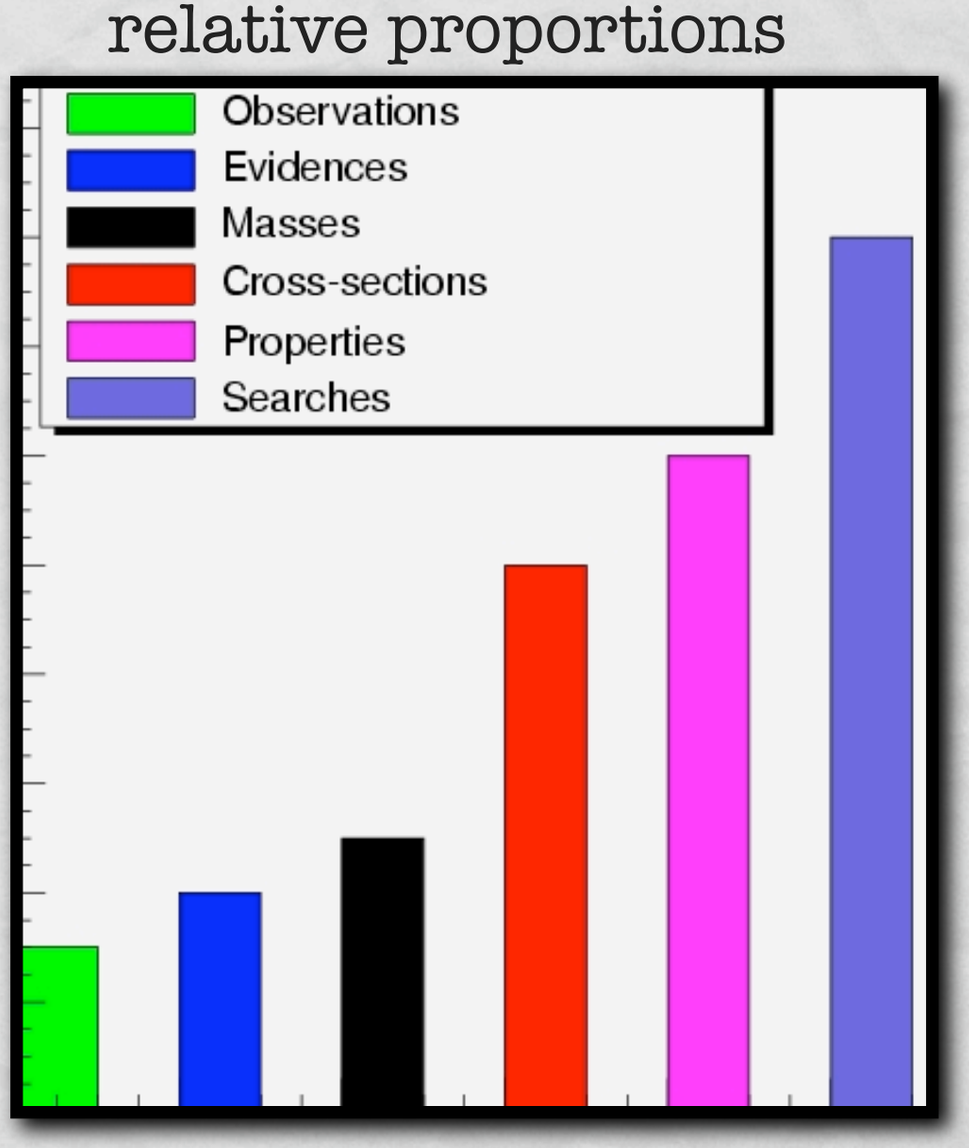
Unique tri-muon + Missing Energy + jet event

Fermilab Result of the Week

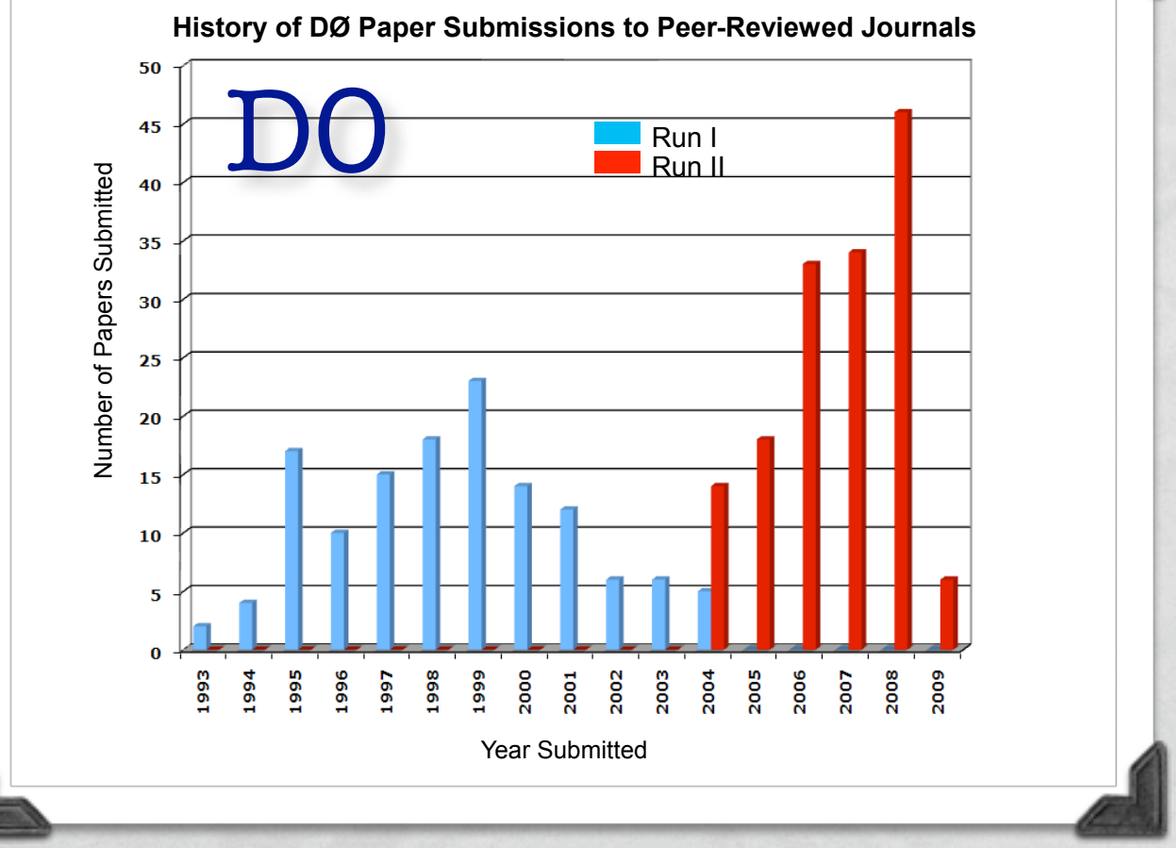
http://www.fnal.gov/pub/today/resultoftheweek/index.html

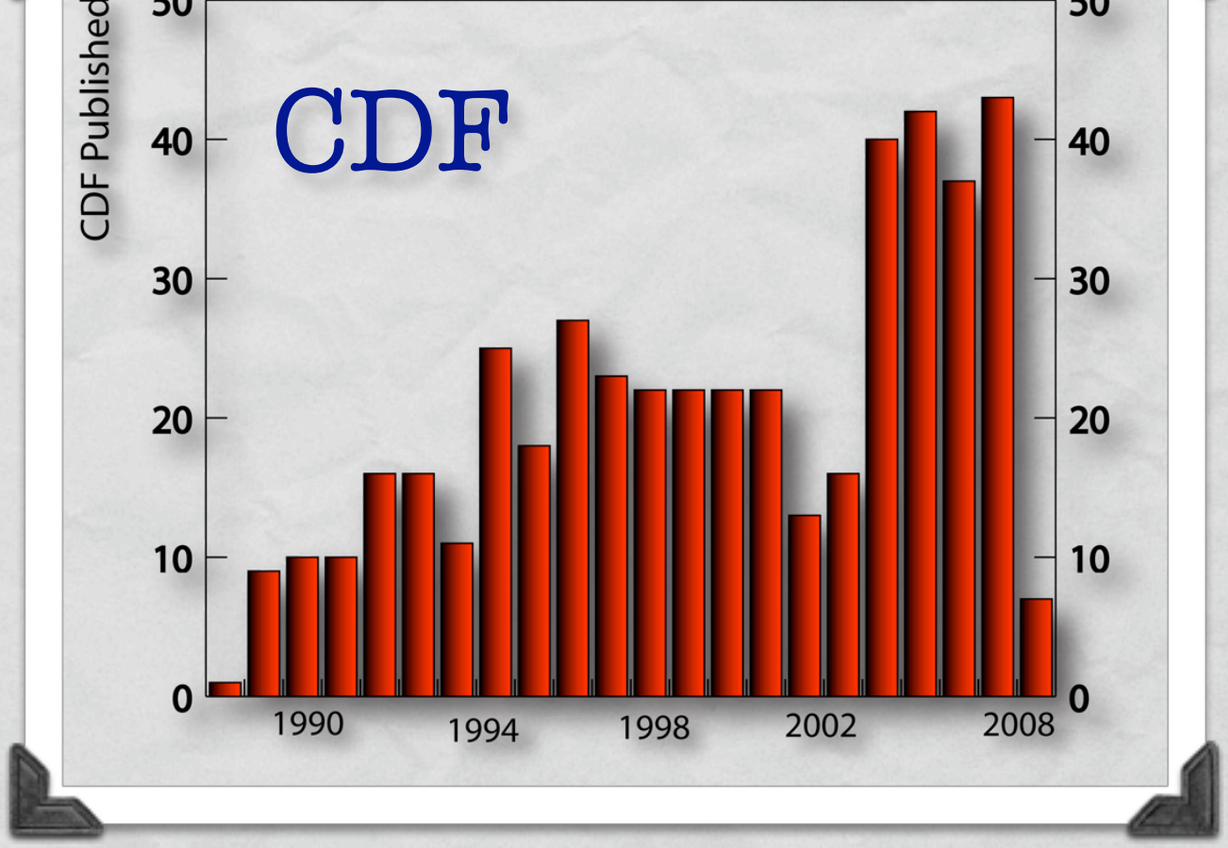
- Every thursday for the last 5 years describing a new experimental result from the Tevatron !

- Every week we decipher a little bit more of the primordial language of nature



Tevatron Physics





- Nearly 100 journal publications last year alone

Tevatron Physics

- Nearly 100 journal publications last year alone
- About 60 Ph.D's / year over the last few years
- About 3,500 physicists have participated on the CDF & Dzero experiments

And we keep on going...

Sun Jan 4 23:58:38 Shift Summary:

Another very smooth data taking. Nothing really happened except we quietly sat here for 8 hours watching luminosity to accumulate on disk.

Run 271104 running for 20.5 hours and is still running. We have so far recorded 8 pb-1 of good data, which is a new record of integrated lum for a single run.

Since we lost the large pbar stash earlier in the evening, the store 6704 will be kept "until further notice" from the RC.

Current luminosity is 56E30. We probably have a chance to update Silicon D-mode calibration soon.

End of Shift Numbers
CDF Run II

Runs	271104
Delivered Luminosity	1974.28 nb-1
Acquired Luminosity	1875.35 nb-1
Efficiency	95.0%

- mako

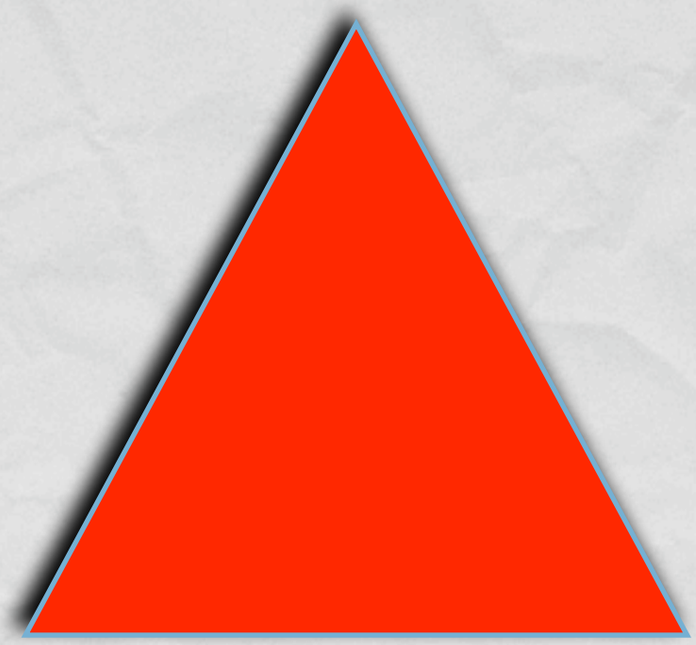
Summary and Future

- The Tevatron program has been remarkably successful
  - A Legacy of discoveries and extraordinary results
- So far only 1 to 3 fb^{-1} of data analyzed
  - This could increase by factors of 3 to 9 with data from running through 2010
- Exciting potential for future Tevatron discoveries
  - We also look forward to studying the data from the LHC and the marvels that it'll reveal - see next talks

"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?

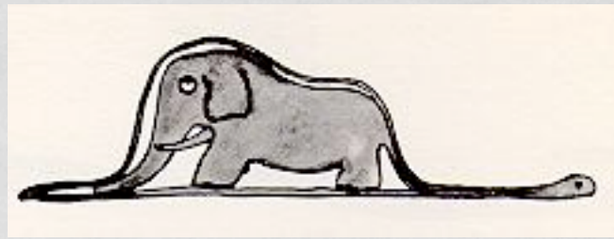
BACKUP

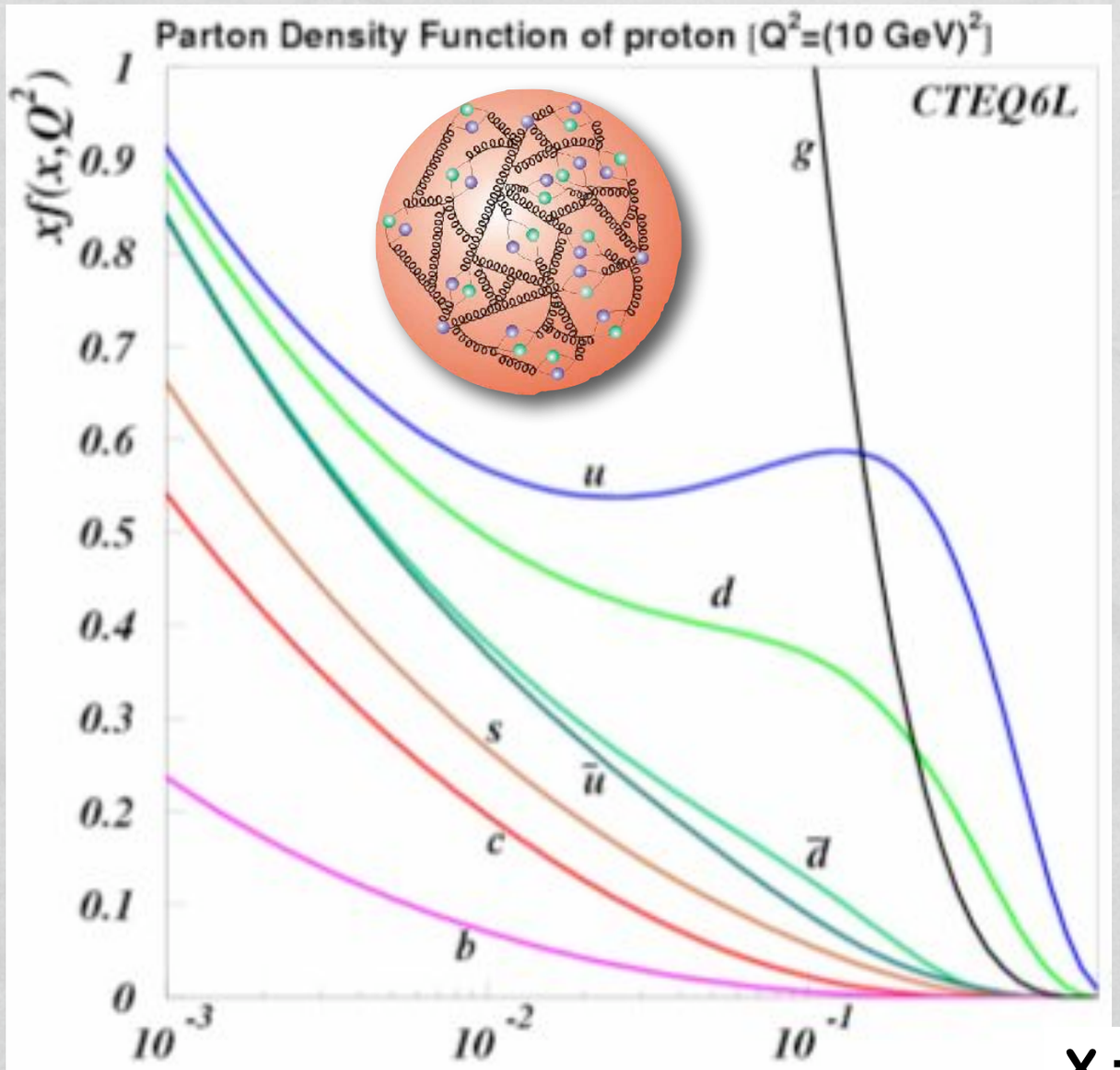


Some Links

- http://www.symmetrymagazine.org
- http://www.interactions.org
- http://particleadventure.org
- http://www.fnal.gov
- http://www.fnal.gov/pub/inquiring/matter/ww_discoveries/index.html
- history.fnal.gov
- http://history.fnal.gov/GoldenBooks/goldenbooks.html
- http://www.fnal.gov/pub/inquiring/timeline/index.html
- http://www.science.doe.gov/hep/benefits/

Life in a proton





Parton-parton collisions:

CM energy is smaller than proton-antiproton CM energy

More luminosity buys you more chances of collision at the highest-energies

Distributions change with hadron's energy...

X = fraction of proton momentum taken by the partons

Collider Beam Luminosity

The [instantaneous] luminosity formula:

$$L = \frac{3\gamma\ f_0\ B\ N_{\bar{p}} N_p}{\pi\beta^*\left(\varepsilon_p + \varepsilon_{\bar{p}}\right)} H\left(\sigma_l/\beta^*\right)$$

$$\mathbf{L} = \frac{N_p \times N_{\bar{p}} \times B \times f_0}{4\pi\sigma^2}$$

Units: # particles/cm^{2}s^{-1}

N_p = protons/bunch ($\sim 3\cdot 10^{11}$)

$N_{\bar{p}}$ = anti-protons/bunch ($\sim 4\cdot 10^{10}$)

B = number of bunches in ring (36)

ε = beam emittances

β = magnet focusing at interaction point

f_0 = $\sim$ 2 MHz (396 *n* sec bunch spacing)

$\sigma^2 \sim 3\cdot 10^{-4}$ cm^2 ($\sim$ 100 μ beam diameter)

Run 2 goal:

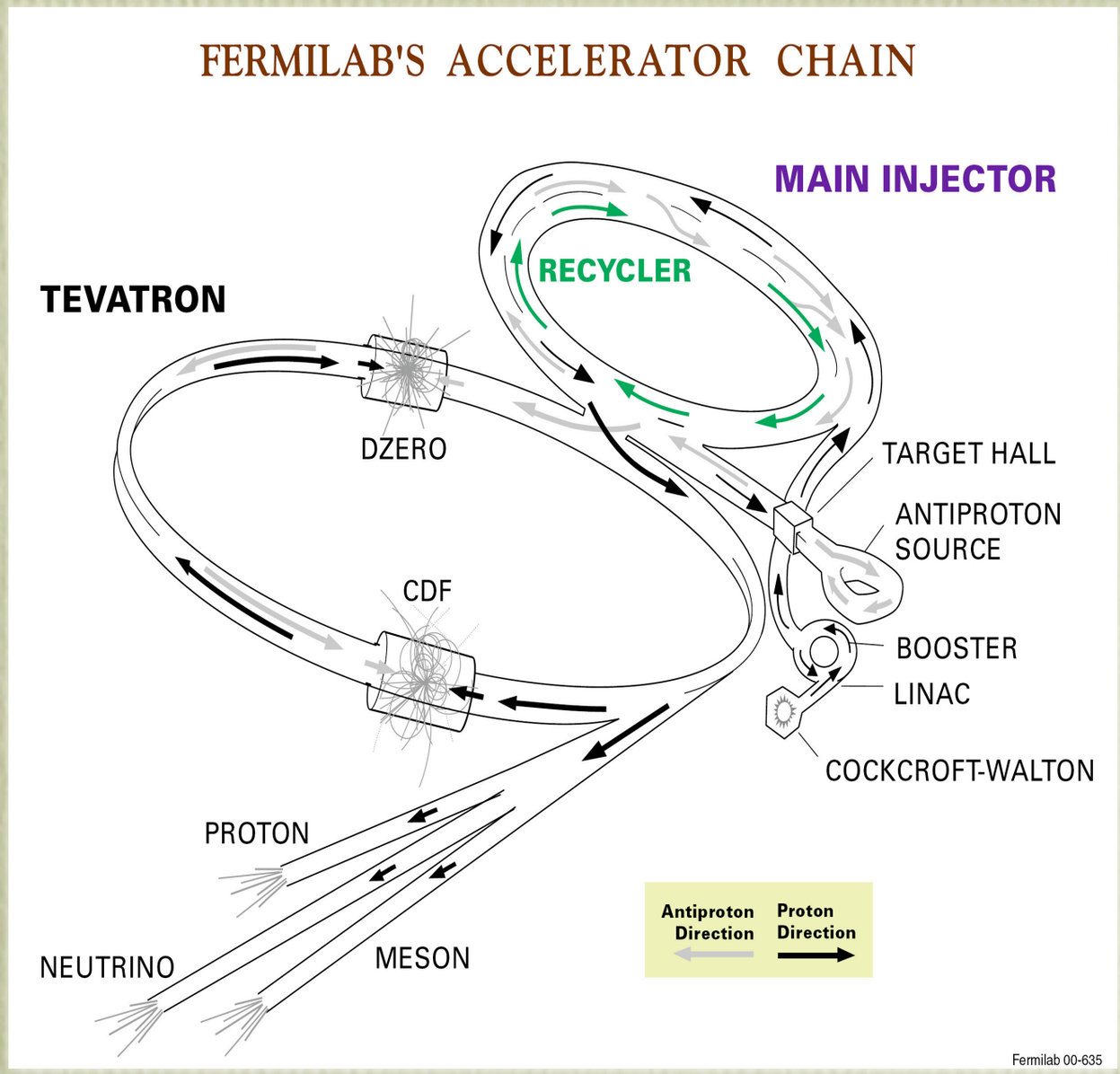
$\mathbf{L} \sim 3\text{x}10^{32}$ cm^{-2}s^{-1}

Total Lum: $L = \int \mathbf{L} \times dt$

Units: 1 barn = 10^{-24} cm^2

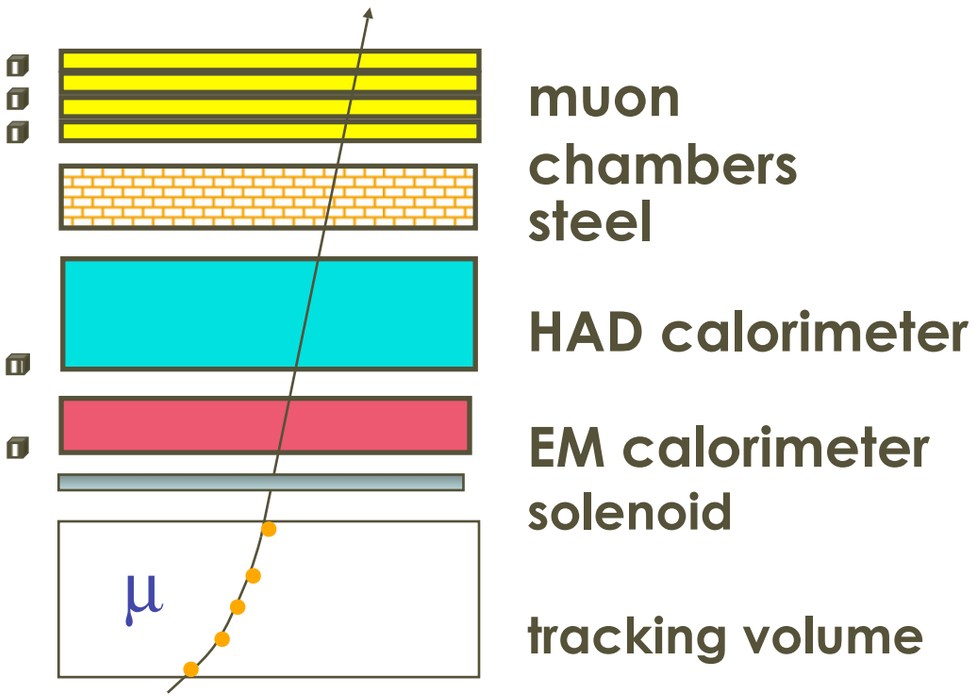
Run 2 goal: 4-8 fb^{-1}

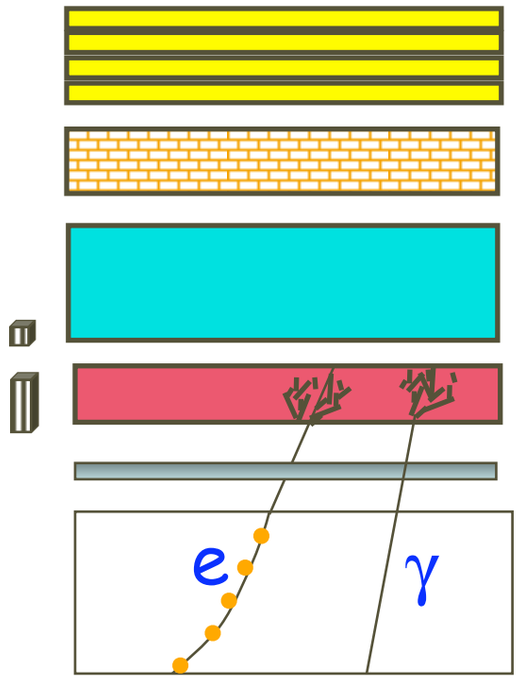
Fermilab's accelerators

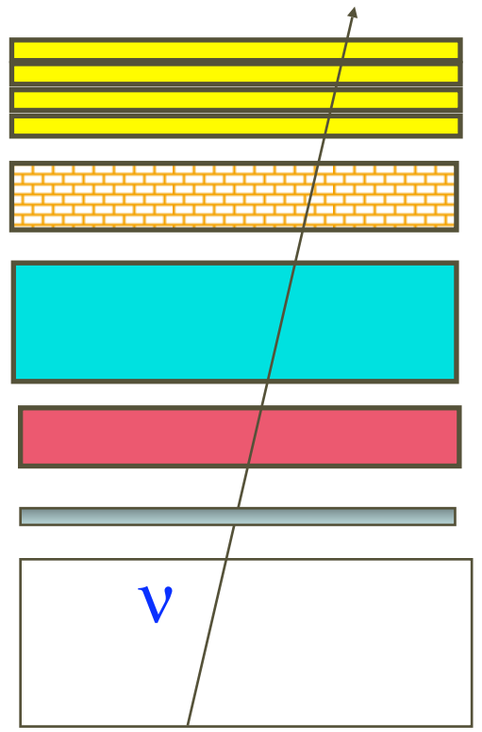


- Cockroft Walton: adds e- to H and accelerates H^- ions to 750 KeV
- Linac: H^- ions get accelerated to 400 MeV and stripped of their electrons by passing through C foils, leaving protons.
- Booster: accelerates protons to 8 GeV
- Main Injector: accelerates protons to 150 GeV
- Tevatron; protons to ~1 TeV
- Recycler: stores anti-protons

Particle Detection and Identification



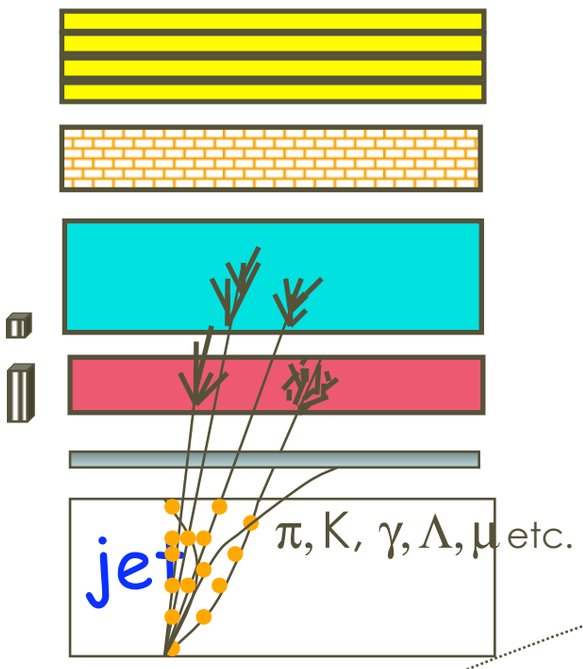


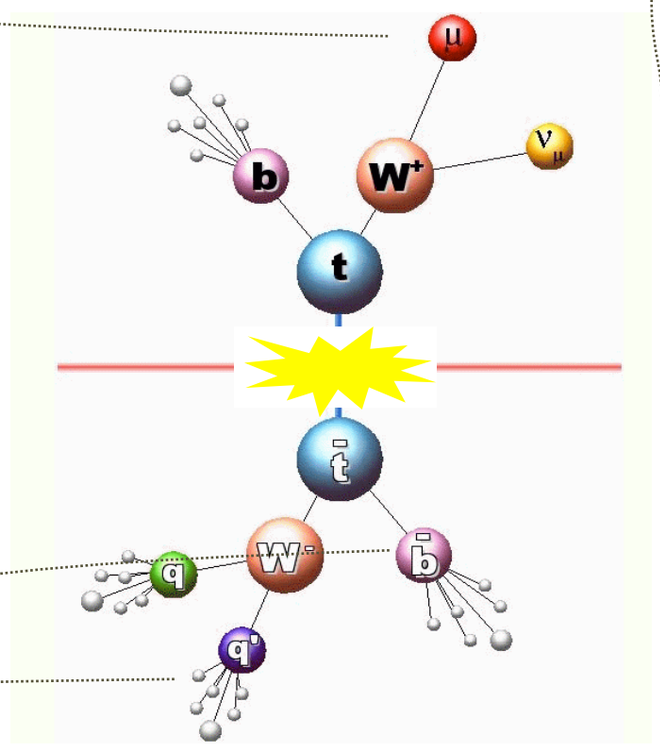


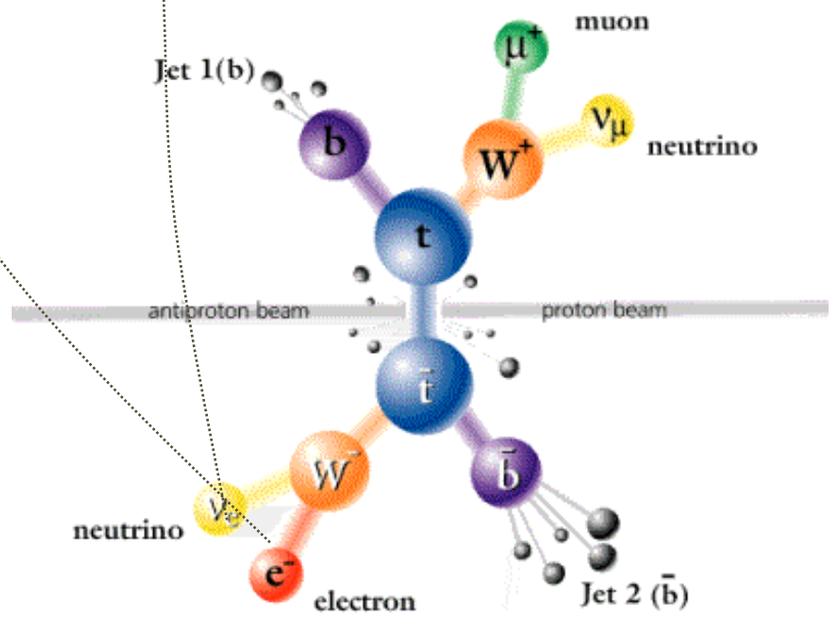
muons

electrons & photons

neutrinos

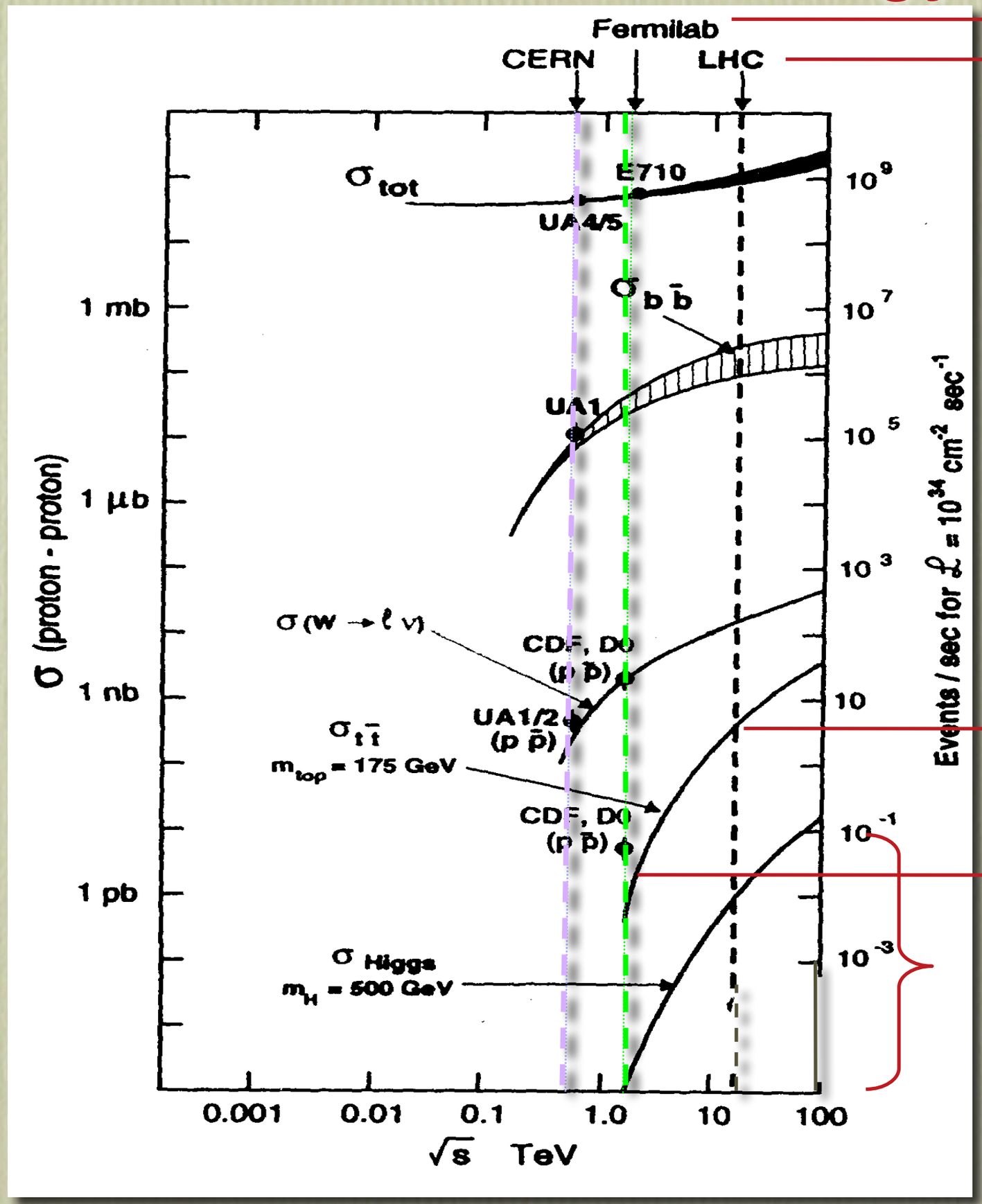




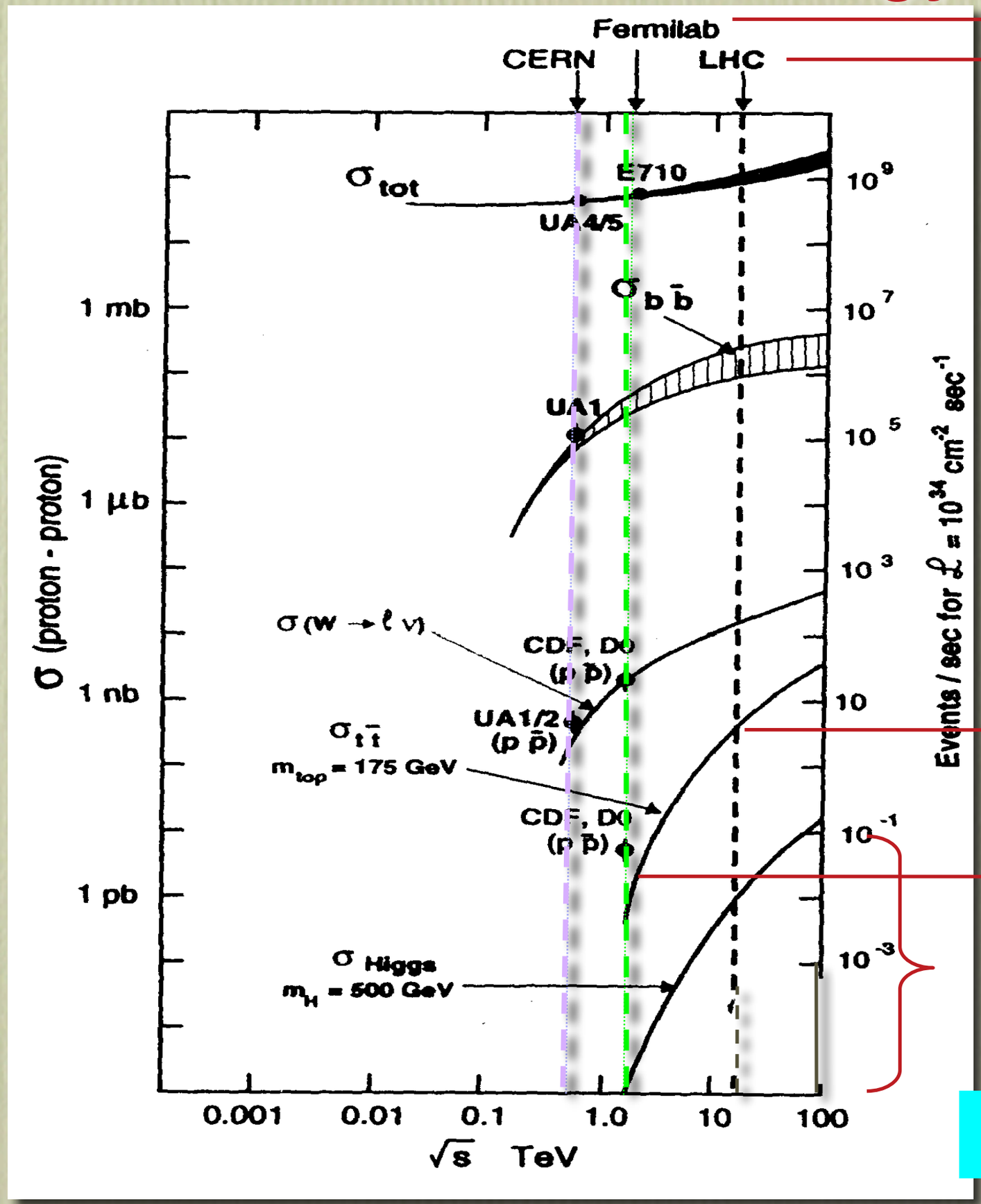


quarks & gluons

Cross sections vs energy



Cross sections vs energy



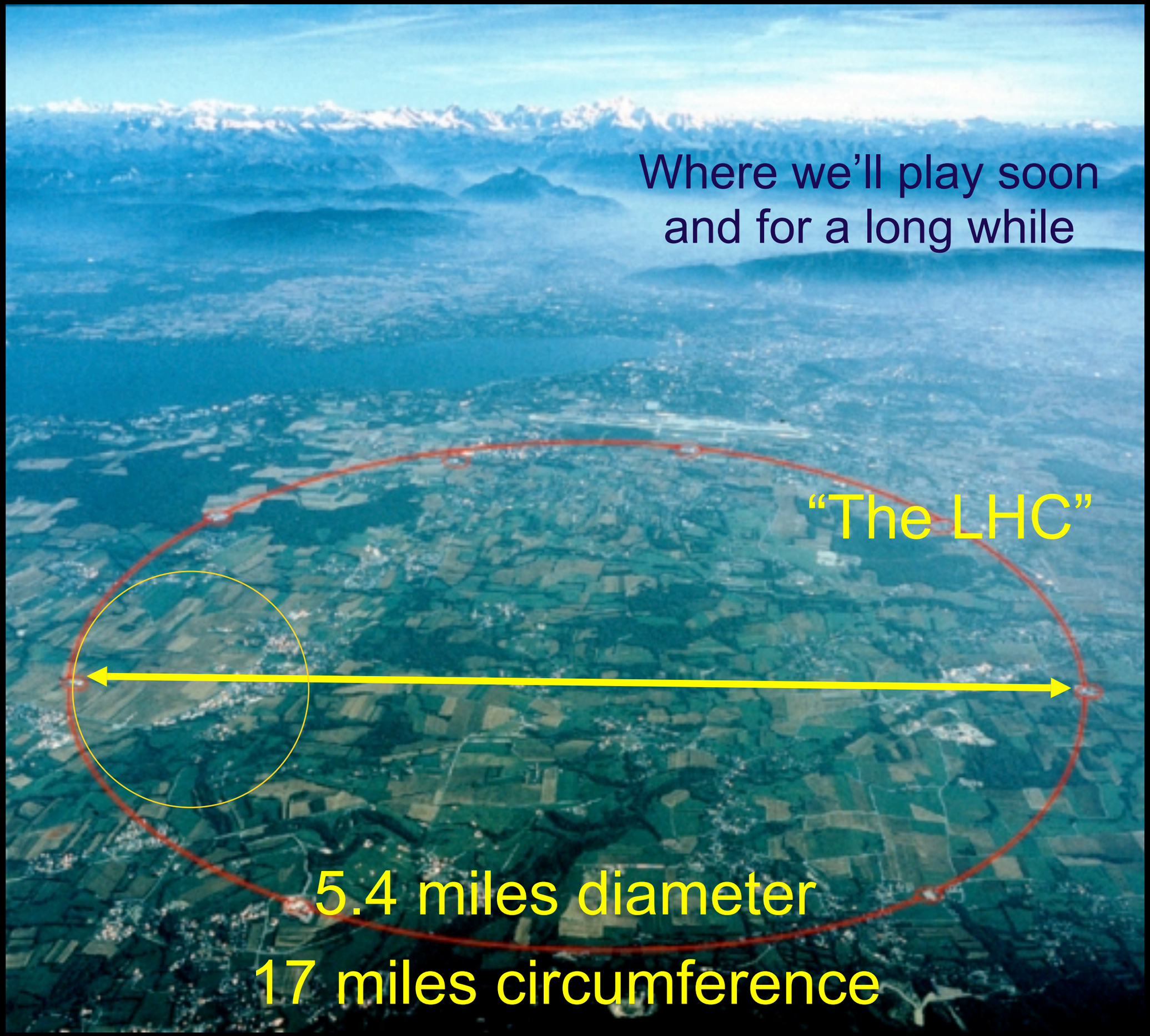
2 TeV

14 TeV

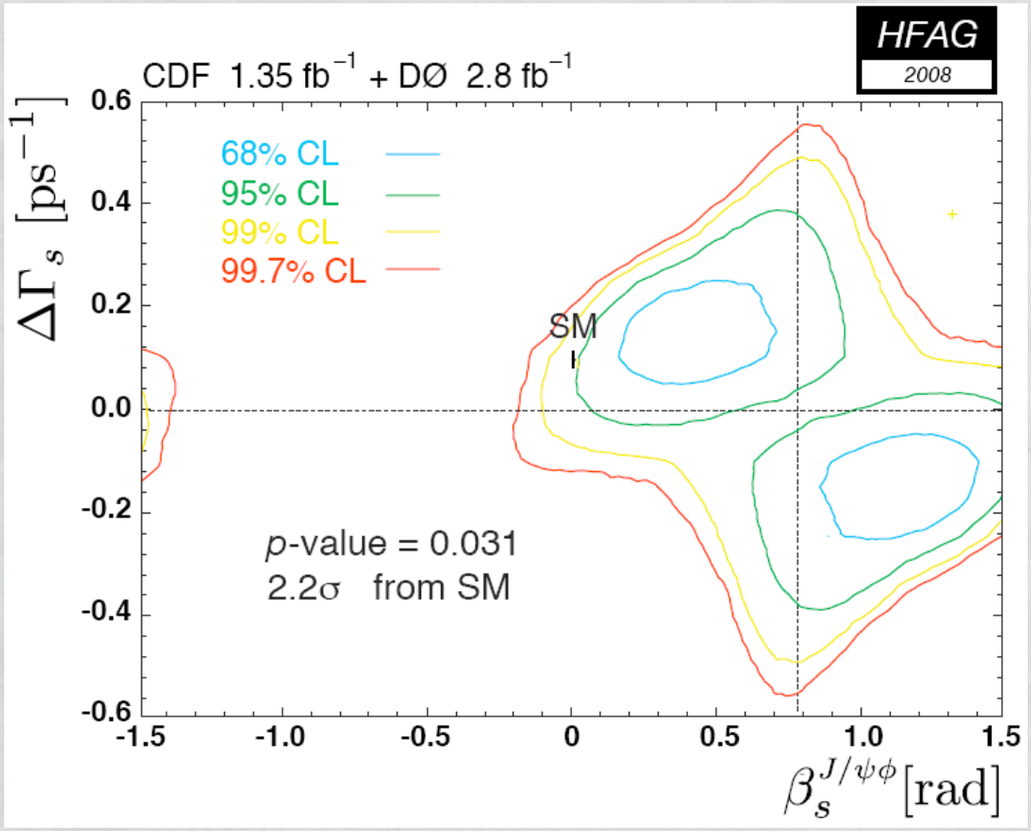
Couple of hundred times more top !

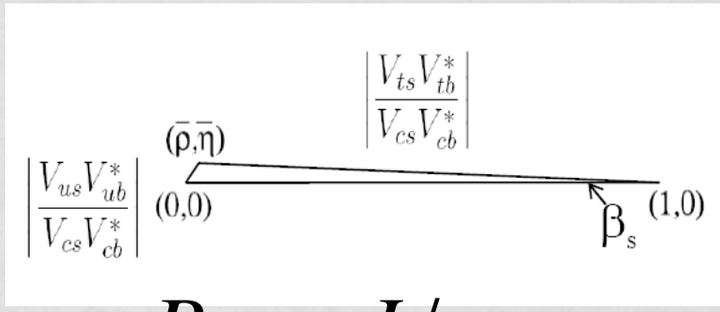
Even more Higgs !

Still buried !


Where we'll play soon
and for a long while
"The LHC"
5.4 miles diameter
17 miles circumference

CPV phase Sin $(2\beta_s)$



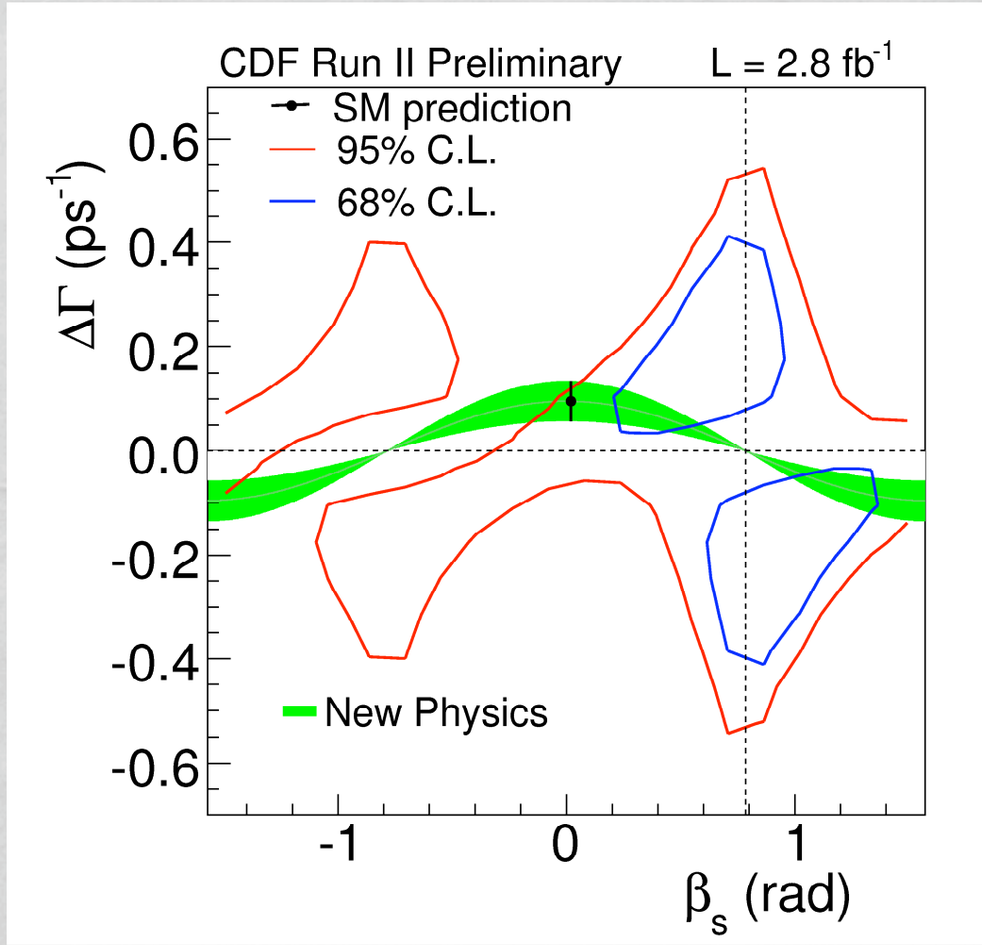


$$B_s \to J/\psi\,\varphi$$

First combination of CDF and DØ results without assumptions on strong phases: compatible at 2.2 standard deviations level with SM (p-value 0.031)

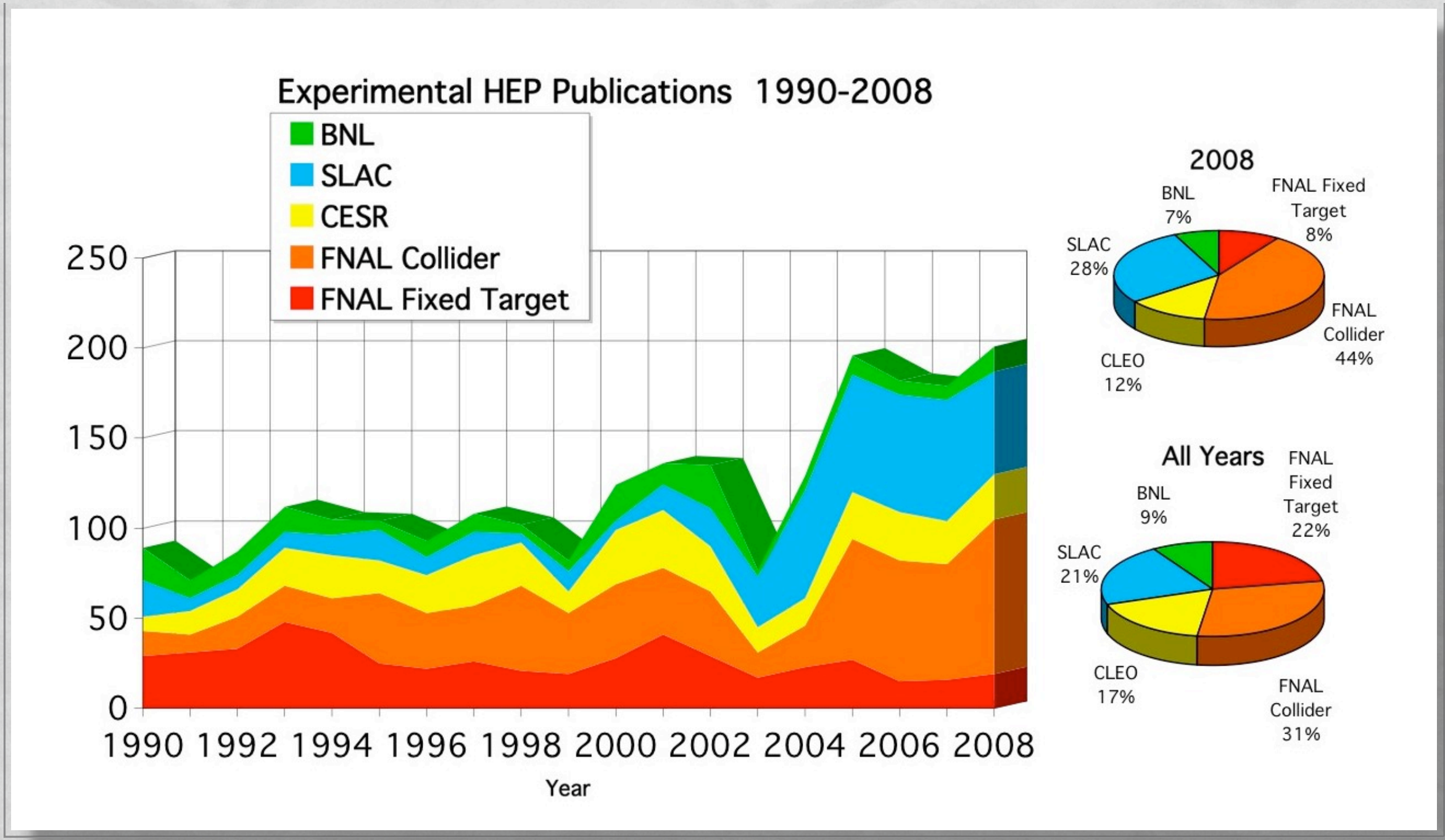
CDF: updated result with 2.8 fb^{-1} Inconsistency with SM increased (p-value from 0.15 to 0.08, corresponding to 1.8 standard deviations)

More data to come, look also in other channels (asymmetry in semileptonic decays)

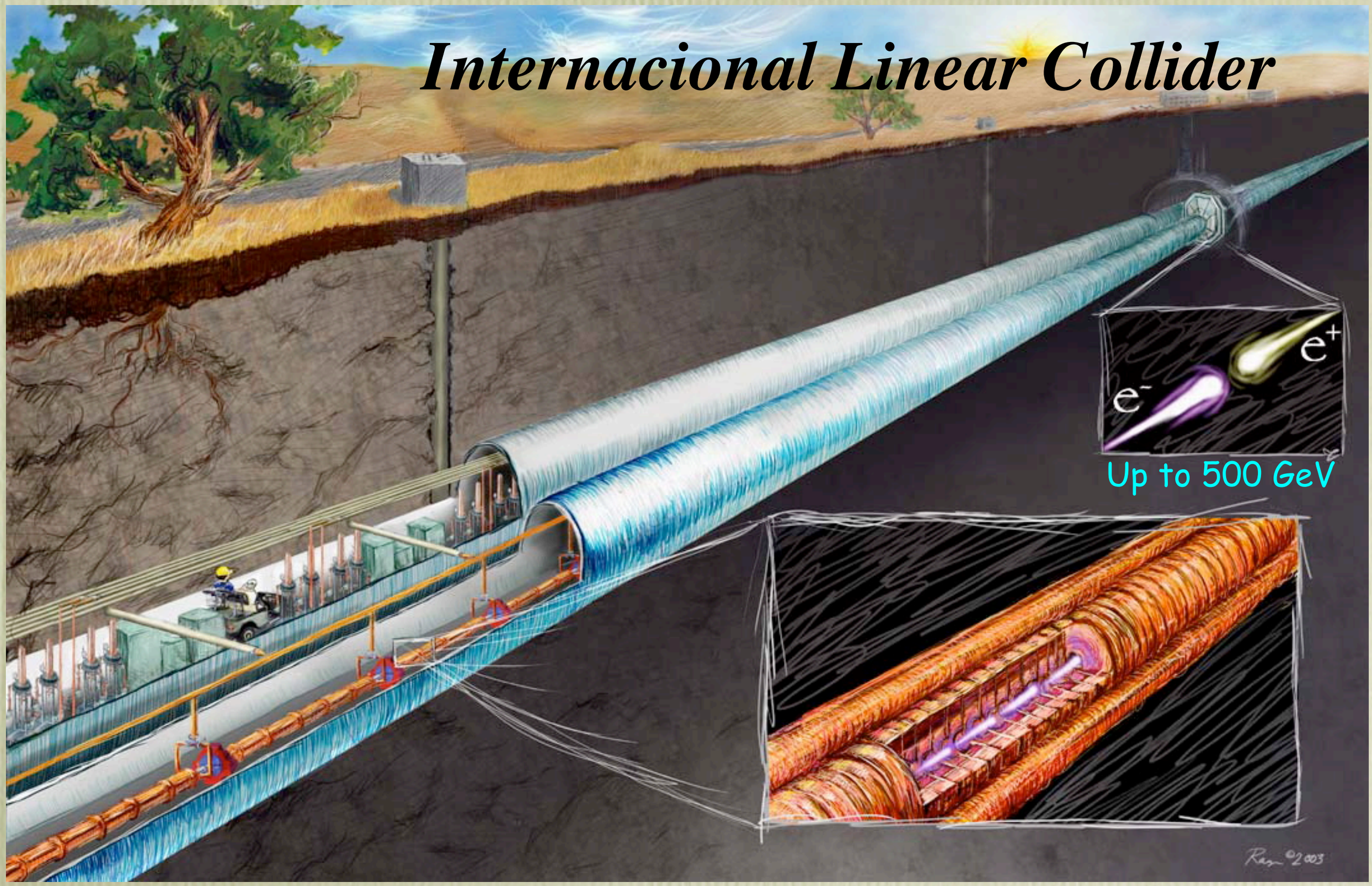


U.S. Experimental Journal Publications

- Tevatron publication at ~100/year !



New accelerators to study the New Physics



Energy Budget of the Universe

- stars
- baryon
- neutrinos
- dark matter
- dark energy

Energy Budget of the Universe

- Stars and galaxies are only ~0.5%

Energy Budget of the Universe

- Stars and galaxies are only ~0.5%
- Neutrinos are ~0.1–1.5%

stars
baryon
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- Rest of ordinary matter
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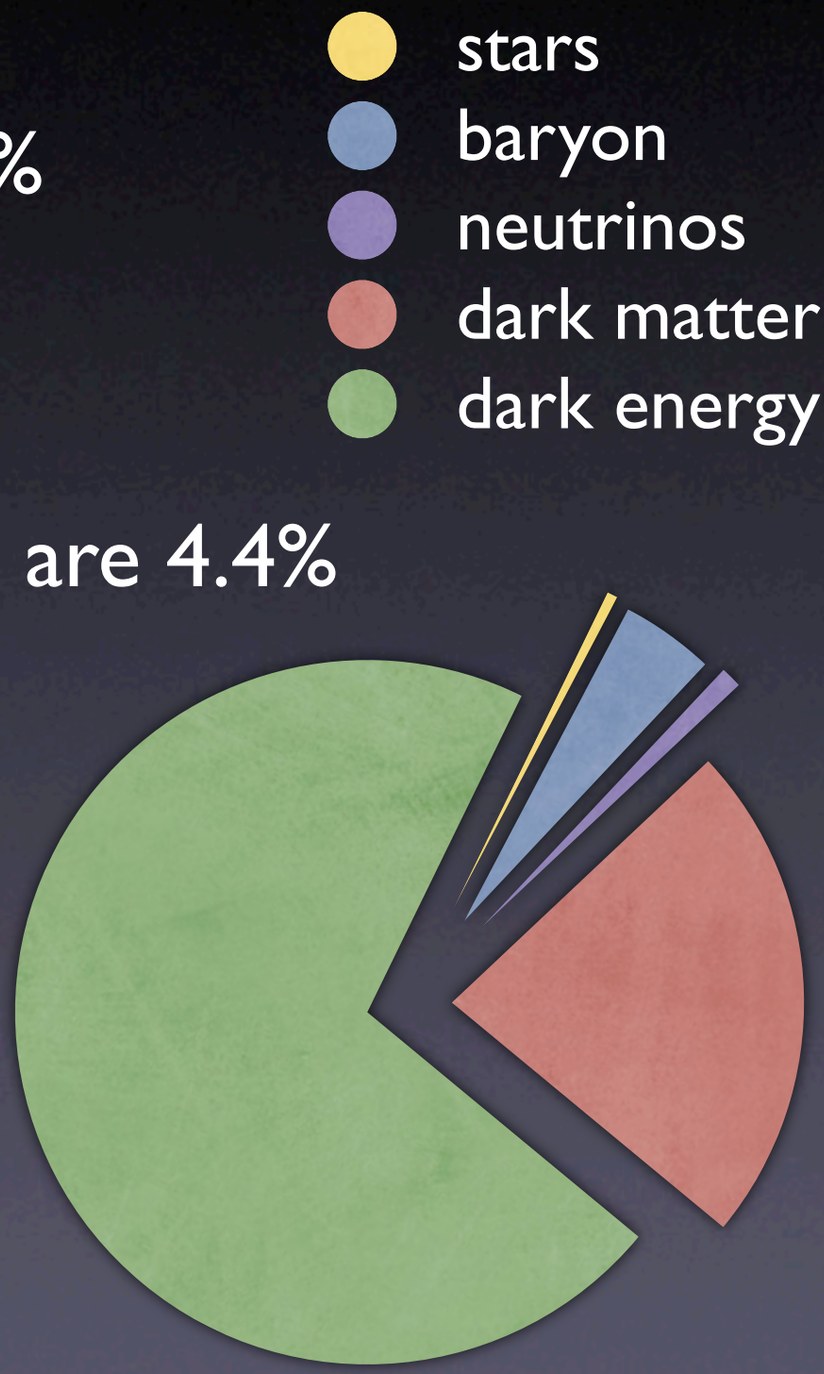
- Dark Matter 23%



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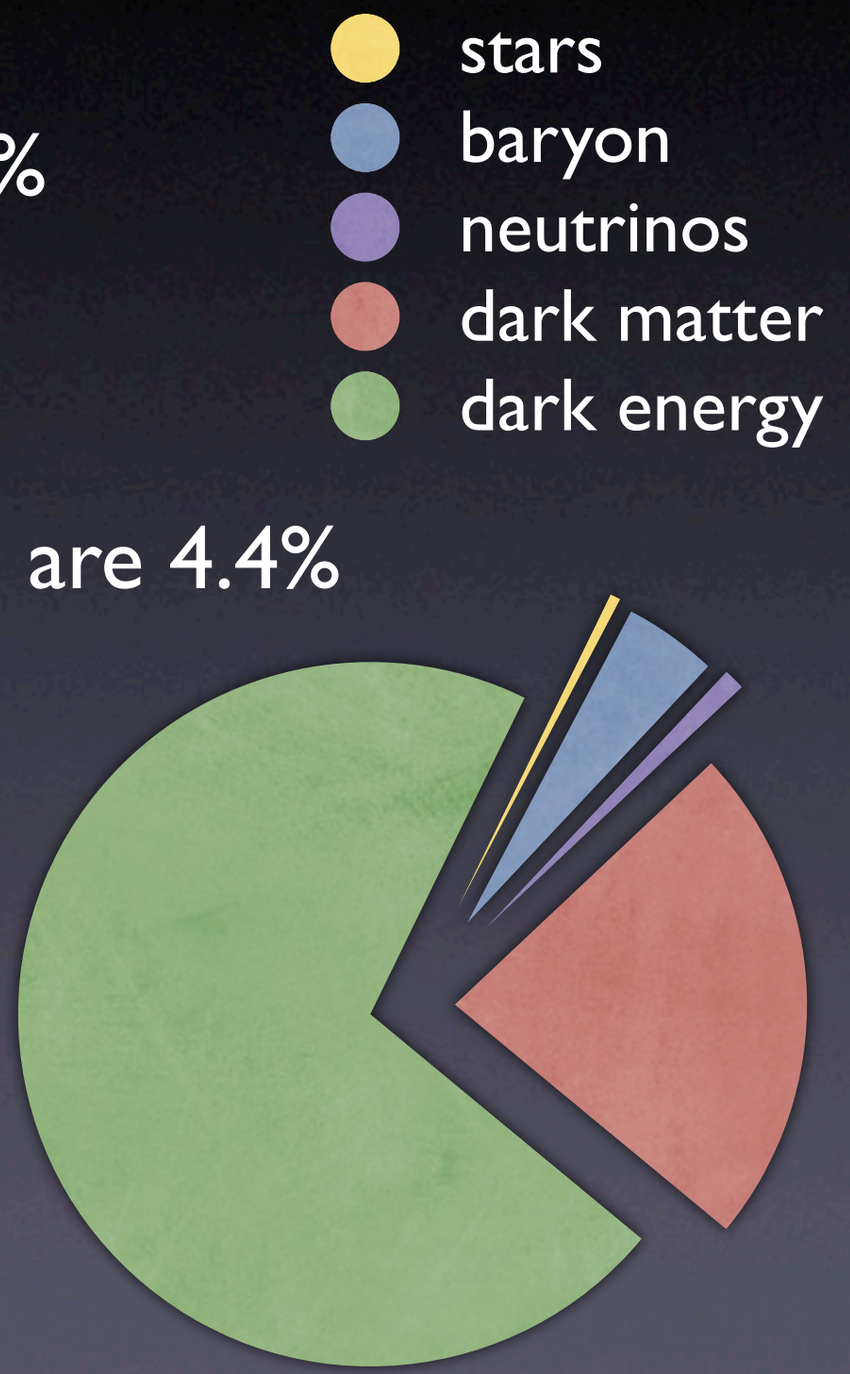
- Anti-Matter 0%



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- 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^{62}%??