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PAC eleven

DISCOVERIES AT PARTICLE COLLIDERS

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

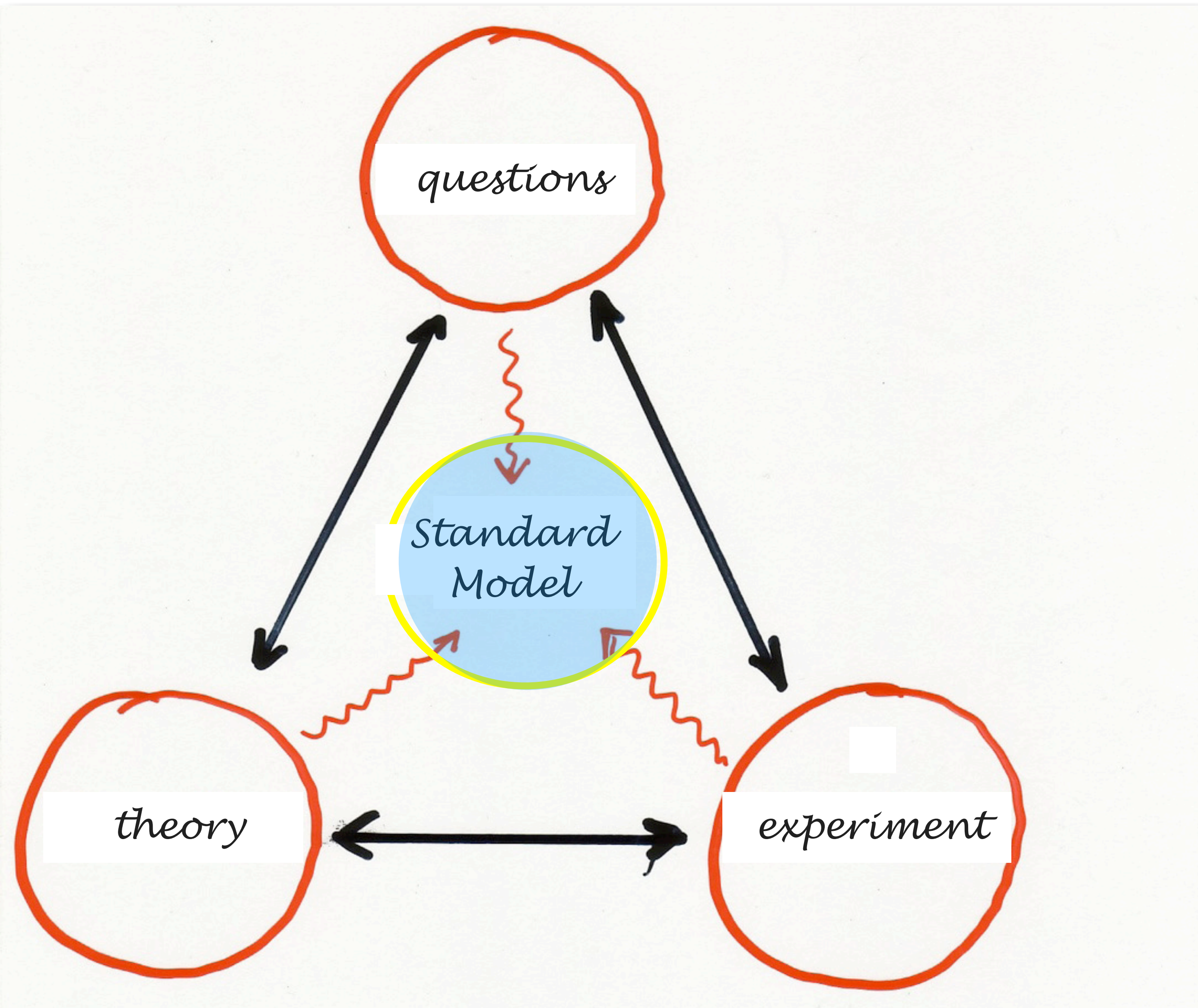
JACOBO KONIGSBERG, U. FLORIDA

What we've dared ask...

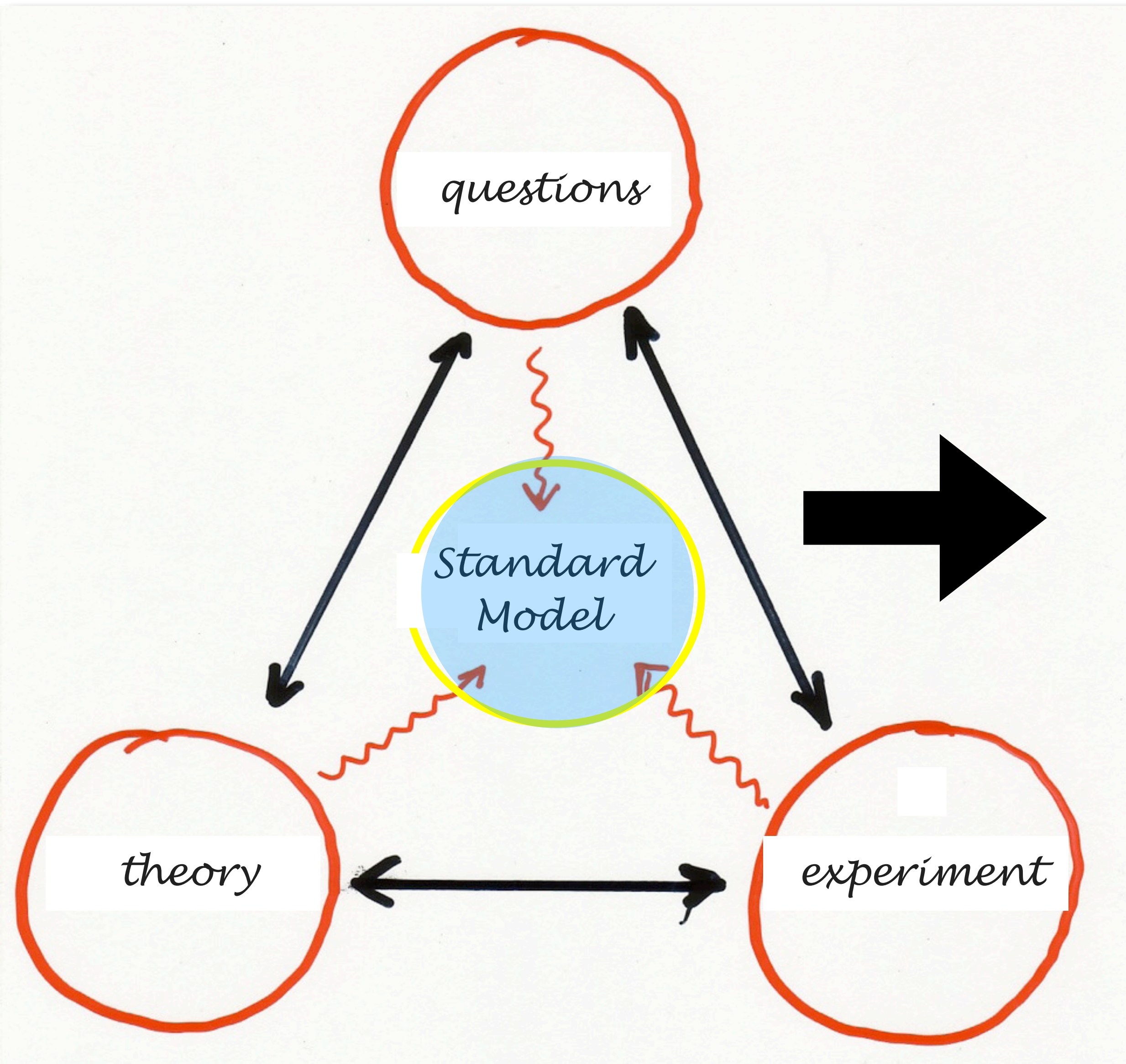
...and attempted to answer

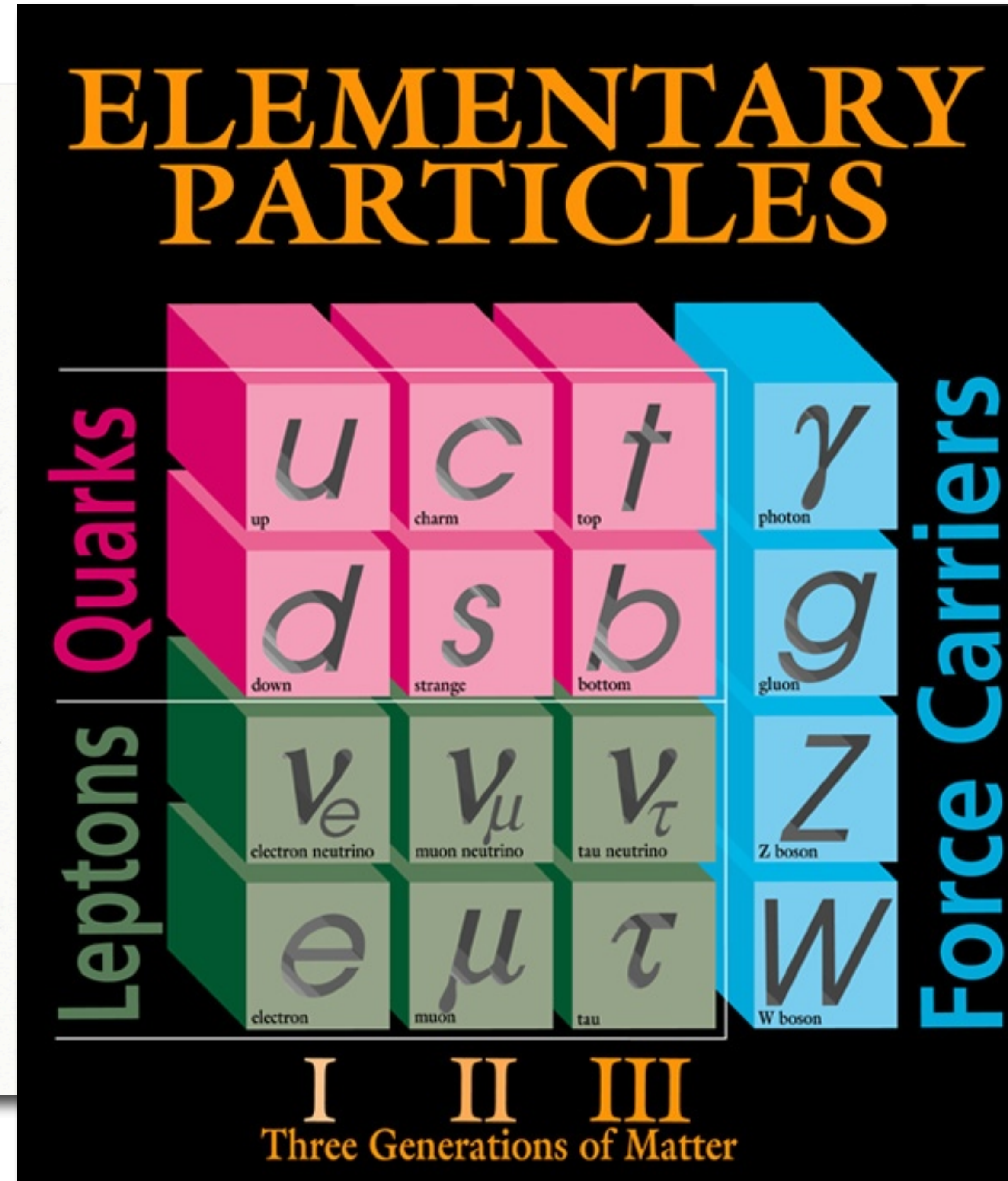
- How does Nature behave at its most fundamental level ?
- What are the elementary building blocks of all matter ?
- How do they interact with each other ?
- How is this connected to the evolution of the Universe ?
- Can all this be described simply ?

Some remarkable answers



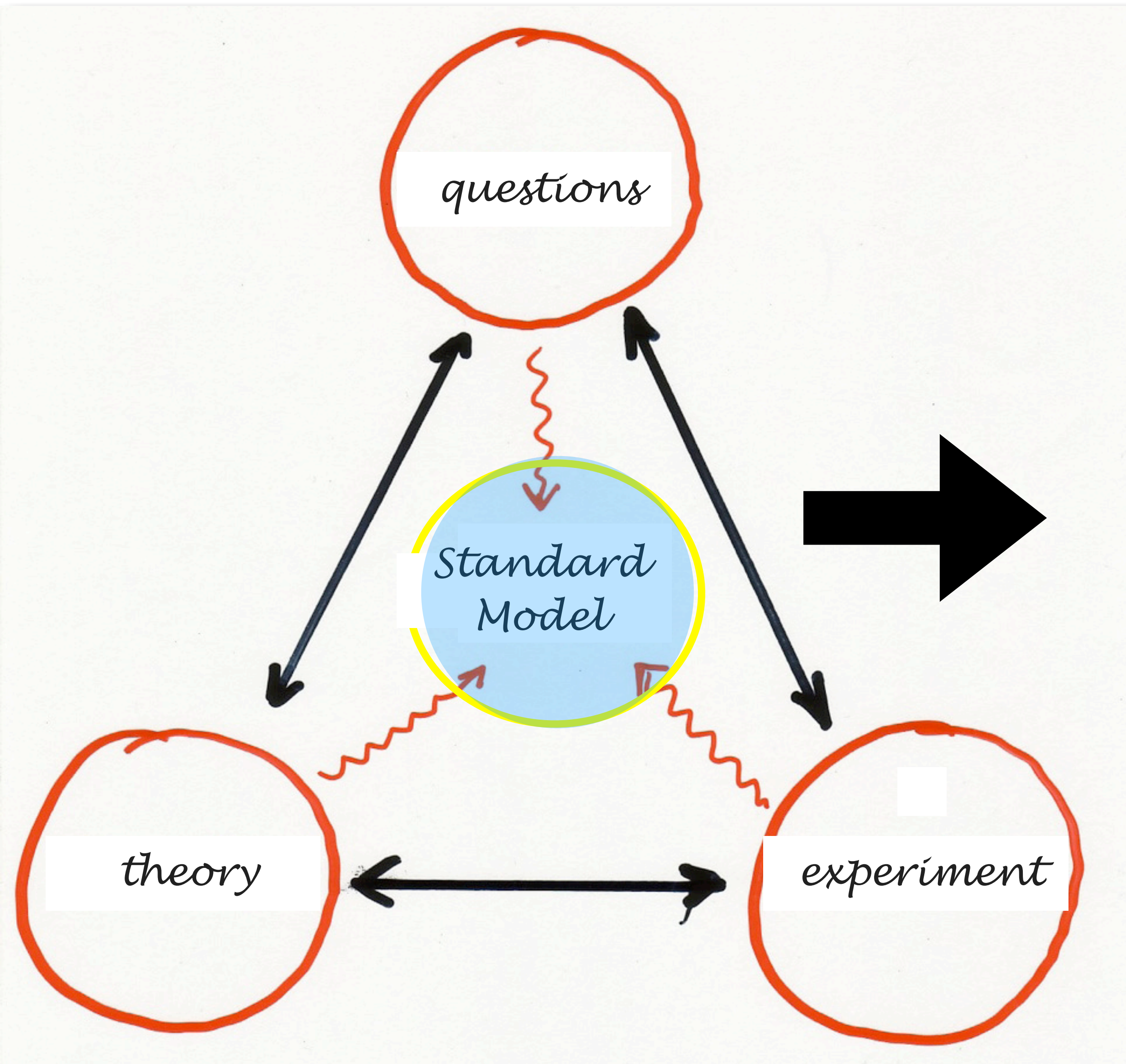
Some remarkable answers





anti-particles too !

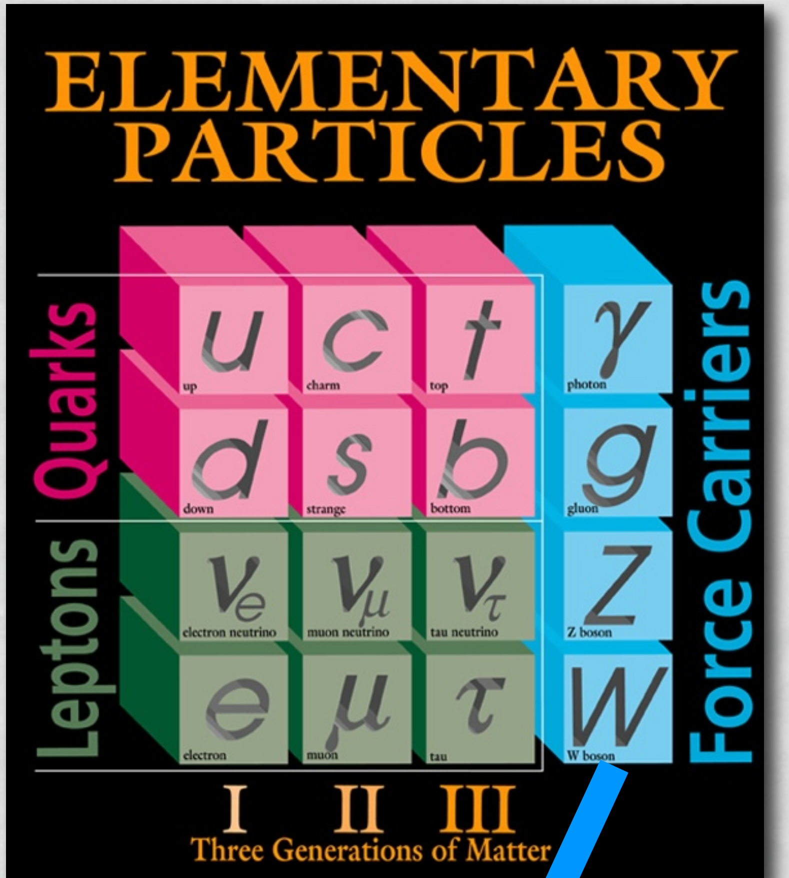
Some remarkable answers

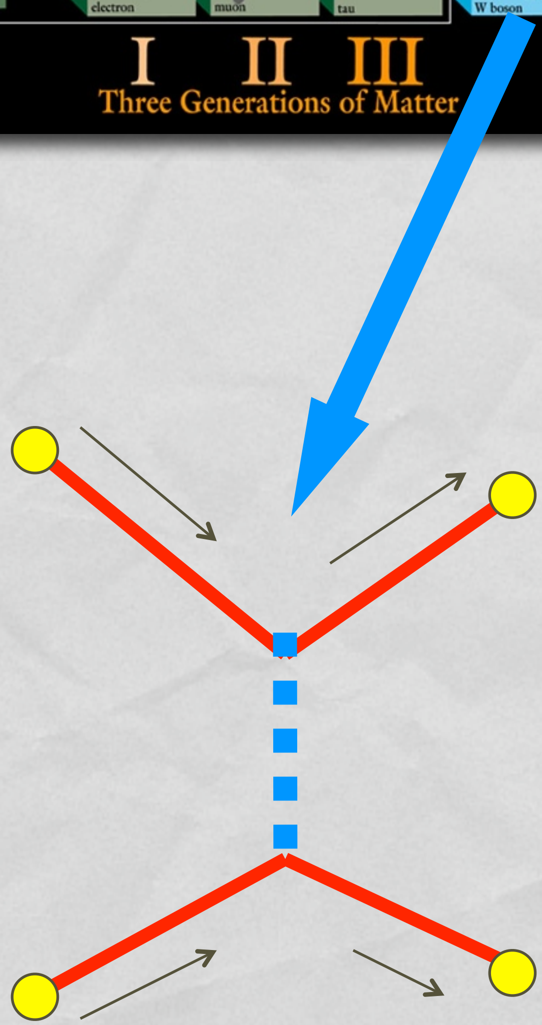


Discovered in:

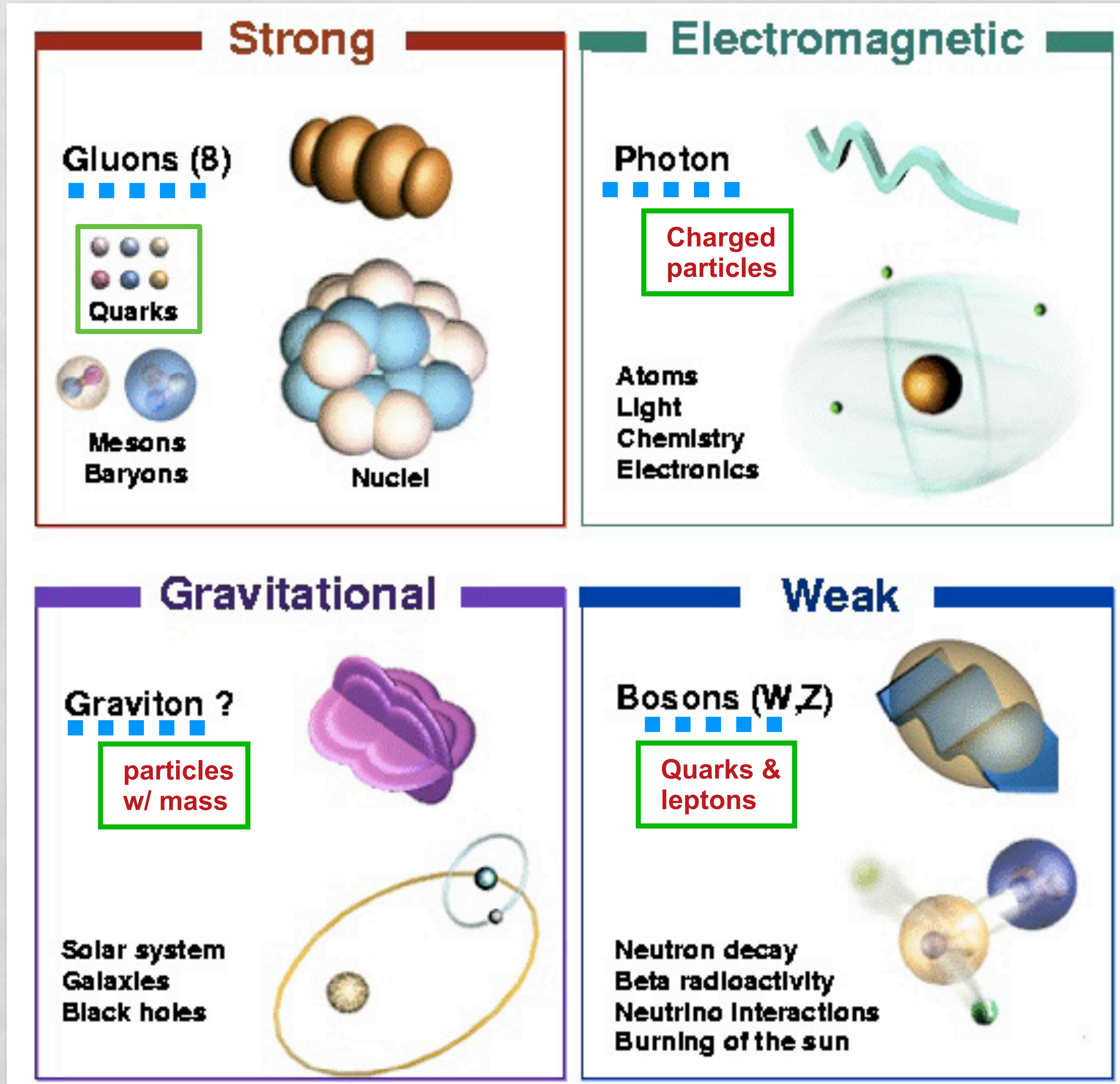
- Radioactivity
- Cosmic Rays
- Accelerators

Fundamental Interactions (forces)



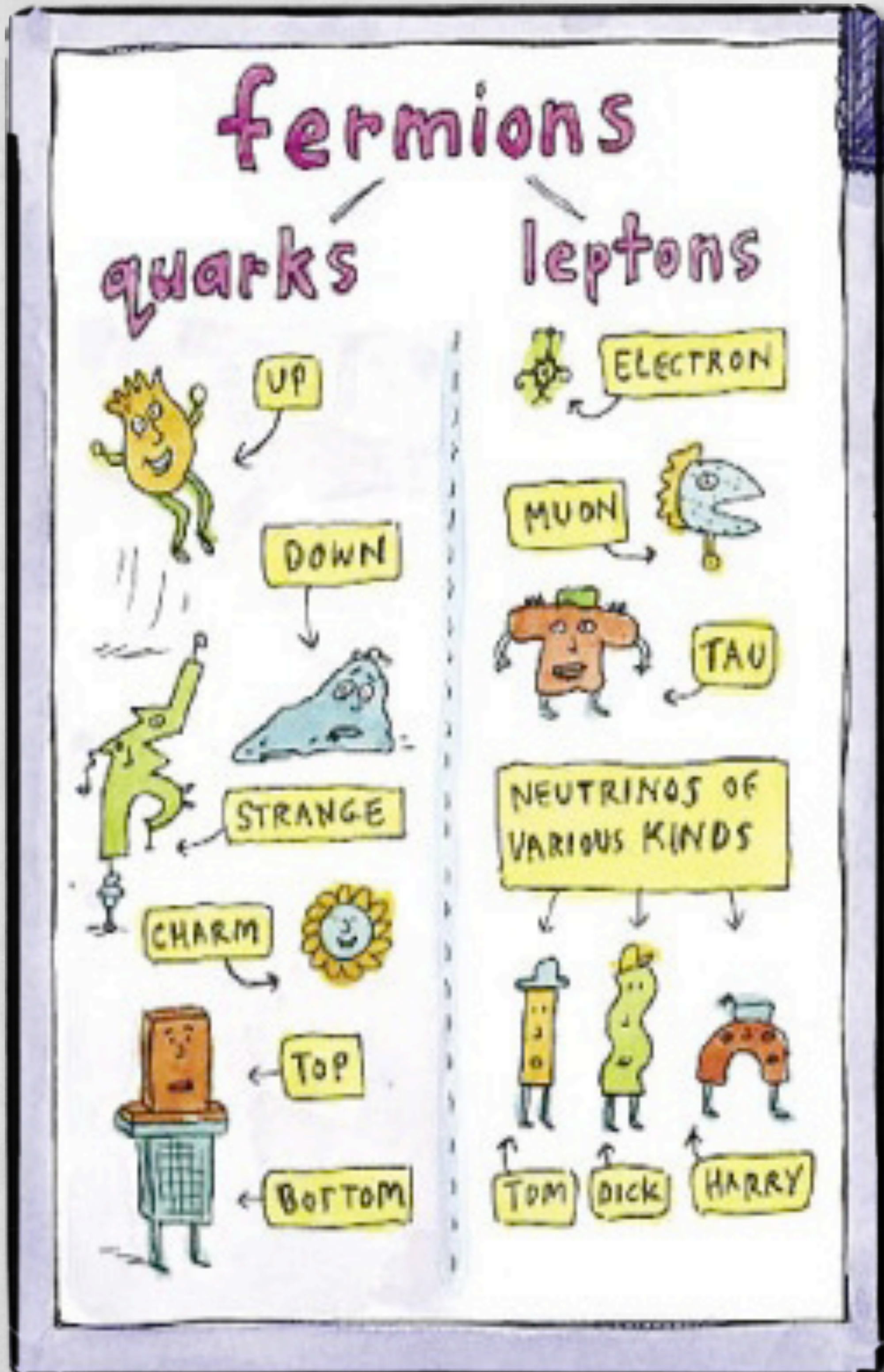


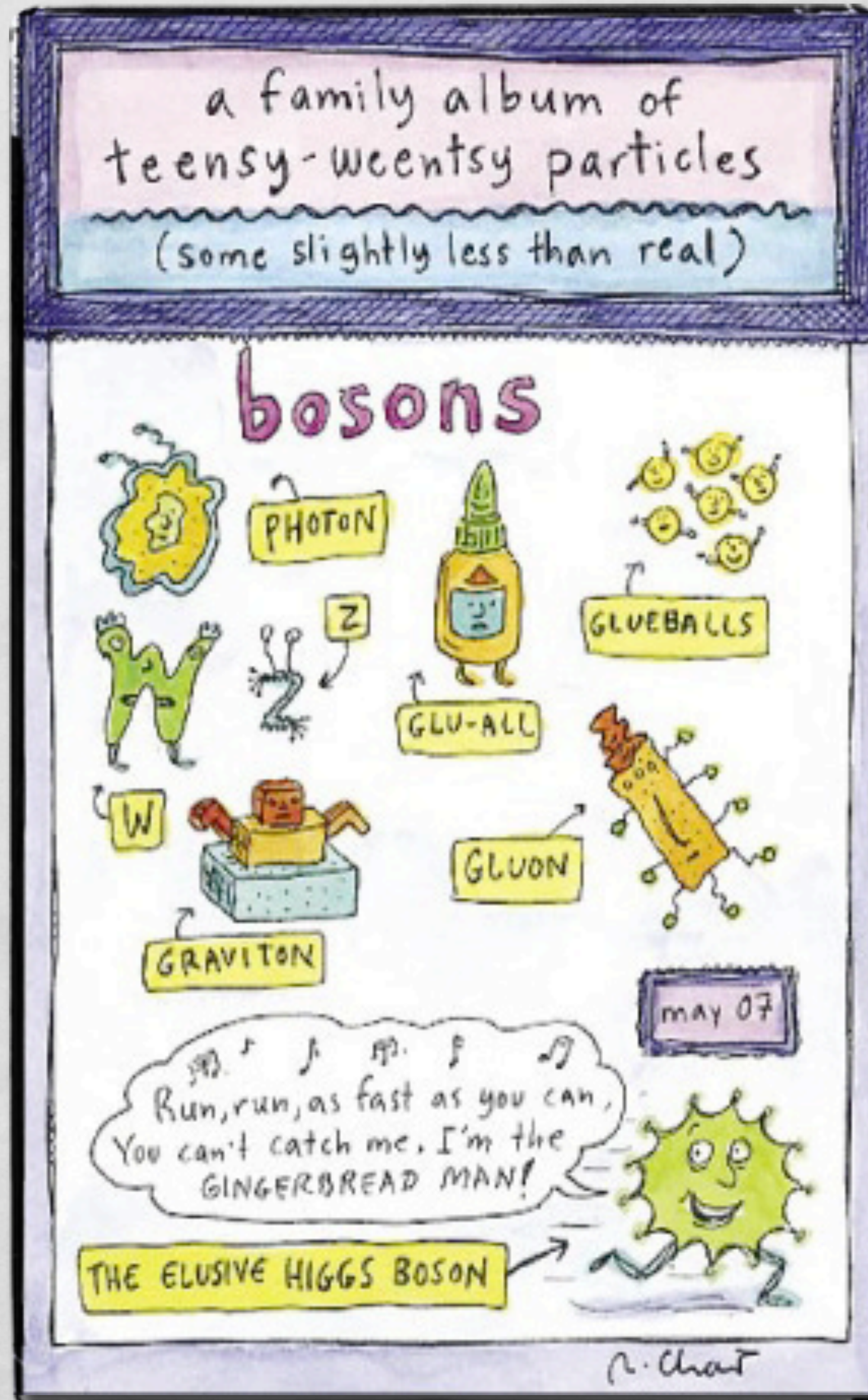
Feynman diagrams



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

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

Here,

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

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

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

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

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

and

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

where

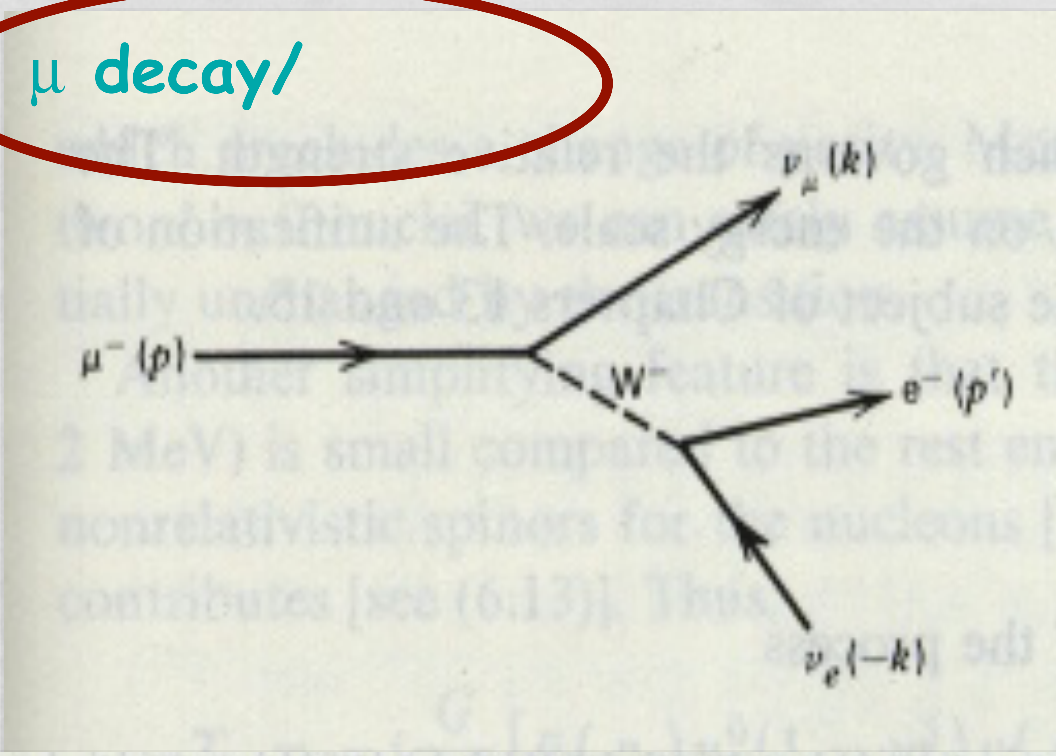
$$\begin{aligned} J^{\mu a}_{(3)} &= \bar{u}^i \gamma^\mu T^a_{(3)} u^i + \bar{d}^i \gamma^\mu T^a_{(3)} d^i \\ J^\mu_{W^+} &= \frac{1}{\sqrt{2}}\left(\bar{\nu}^i_{\rm L}\gamma^\mu e^i_{\rm L} + V^{ij}\bar{u}^i_{\rm L}\gamma^\mu d^j_{\rm L}\right) \\ J^\mu_{W^-} &= (J^\mu_{W^+})^* \\ J^\mu_Z &= \frac{1}{\cos\theta_W}\left[\frac{1}{2}\bar{\nu}^i_{\rm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

XXXXL

"Elementary" calculations

Relativistic Quantum Field Theory

μ decay/



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

initial state — final state

force carrier

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

Standard Model of

FUNDAMENTAL PARTICLES AND INTERACTIONS

The Standard Model summarizes the current knowledge in Particle P... (quantum chromodynamics or QCD) and the unified theory of weak and electromagnetic interactions (electroweak). G... 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^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

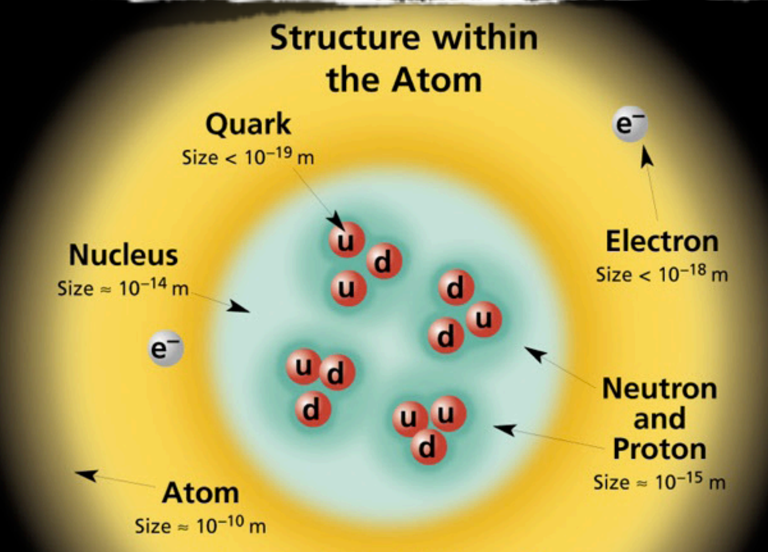
Quarks spin = 1/2

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.



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^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.

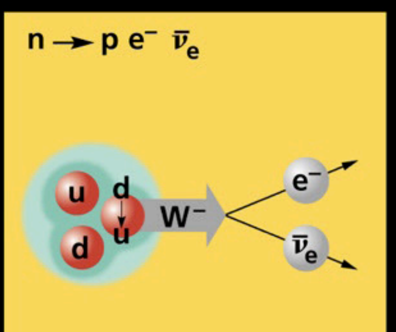
Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
π^+	pion	$u\bar{d}$	+1	0.140	0
K^-	kaon	$s\bar{u}$	–1	0.494	0
ρ^+	rho	$u\bar{d}$	+1	0.770	1
B^0	B-zero	$d\bar{b}$	0	5.279	0
η_c	eta-c	$c\bar{c}$	0	2 .980	0

Matter and Antimatter

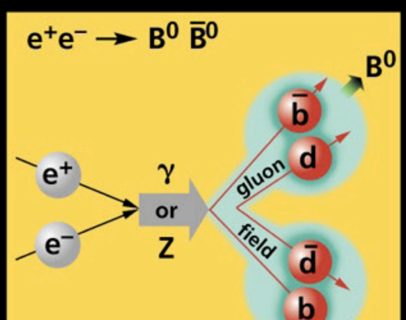
For every particle type there is a corresponding antiparticle type, denoted by a bar over the particle symbol (unless + or – charge is shown). Particle and antiparticle have identical mass and spin but opposite charges. Some electrically neutral bosons (e.g., Z^0, γ, and $\eta_c = c\bar{c}$, but not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

Figures

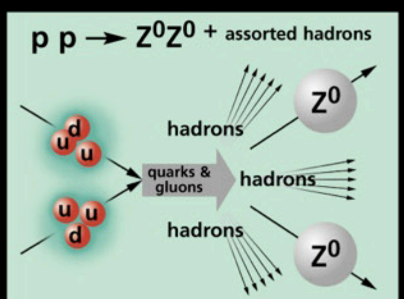
These diagrams are an artist's conception of physical processes. They are ***not*** exact and have ***no*** meaningful scale. Green shaded areas represent the cloud of gluons or the gluon field, and red lines the quark paths.



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-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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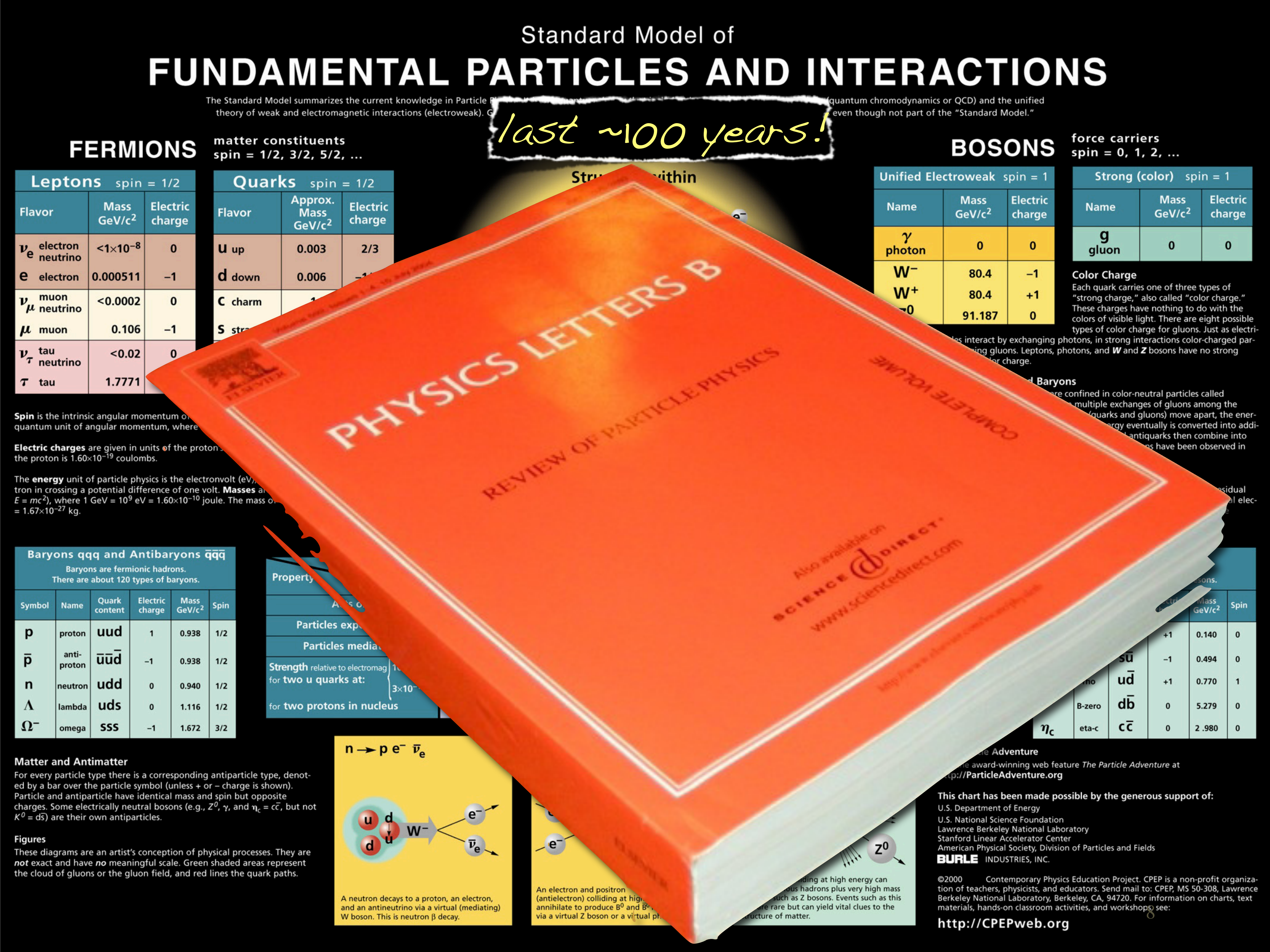
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FUNDAMENTAL PARTICLES AND INTERACTIONS
last ~100 years!
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Electric charge
electron neutrino
electron
muon neutrino
muon
tau neutrino
tau
<1×10⁻⁸
0.000511
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0.106
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c charm
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Unified Electroweak spin = 1
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REVIEW OF PARTICLE PHYSICS
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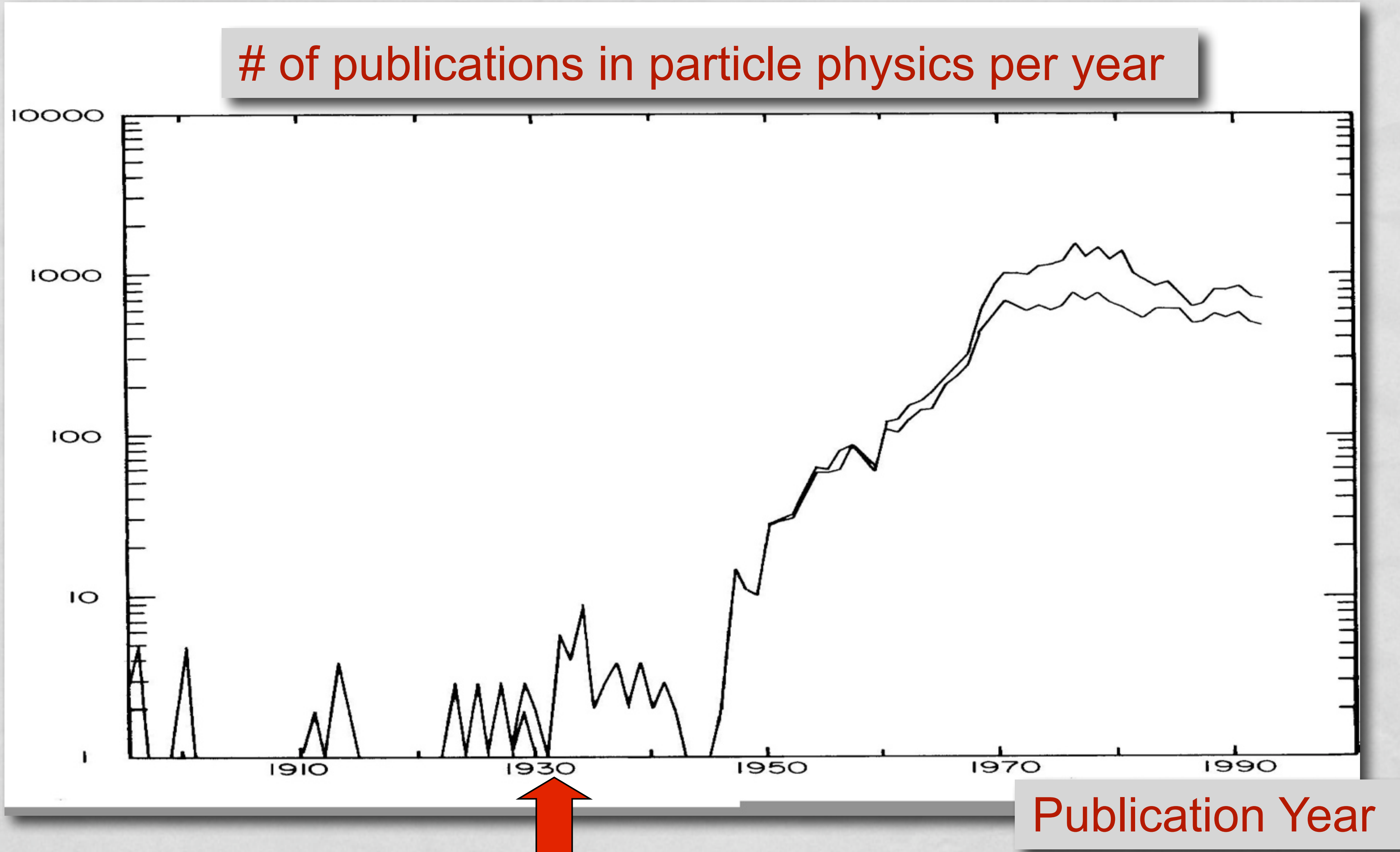
The Role of Particle Accelerators



The advent of the era of accelerators: a "game changer" - as they say...

E. Lawrence

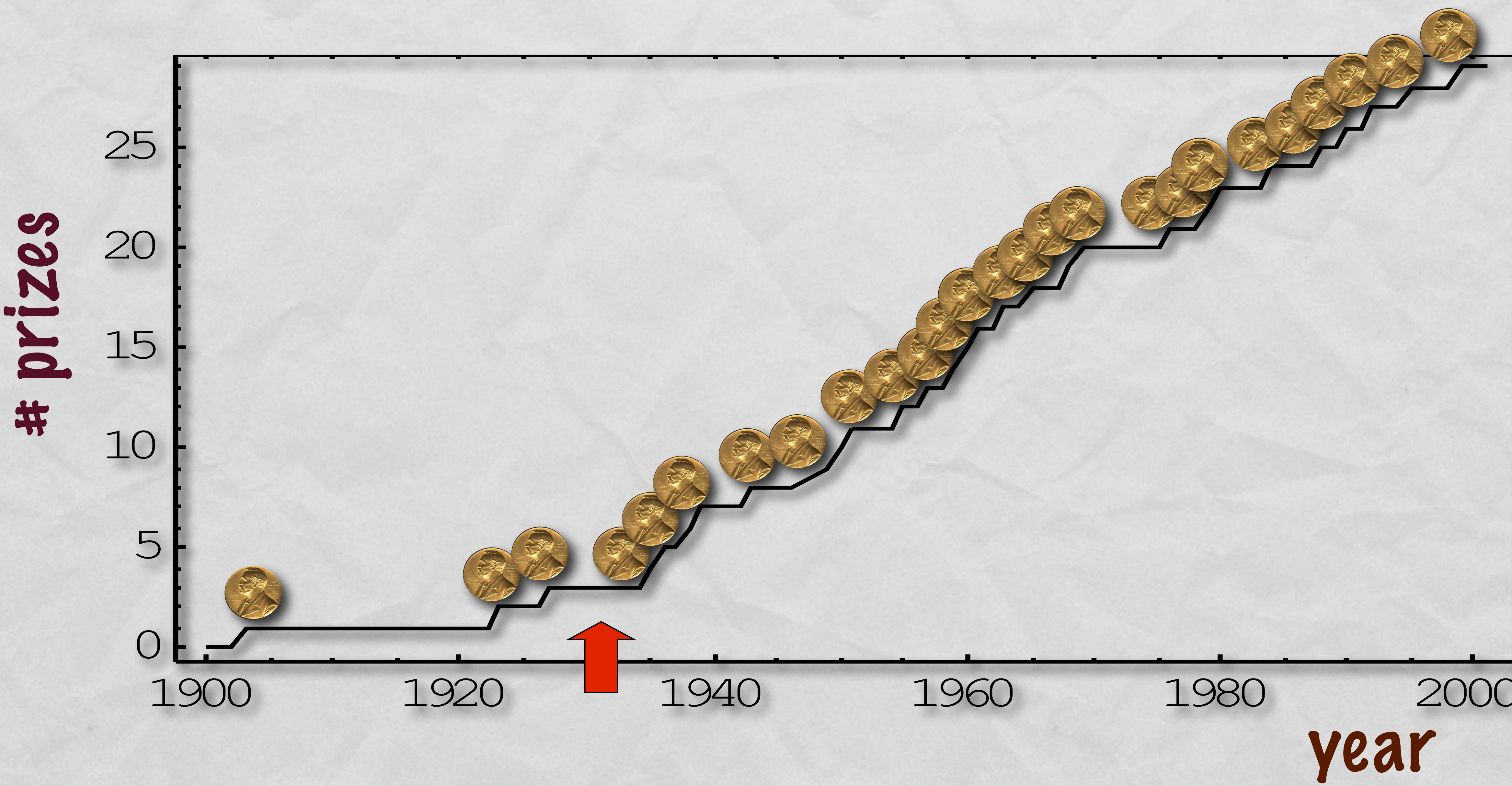
John Cockcroft

R. Van de Graaff

and collaborators,
and many others...

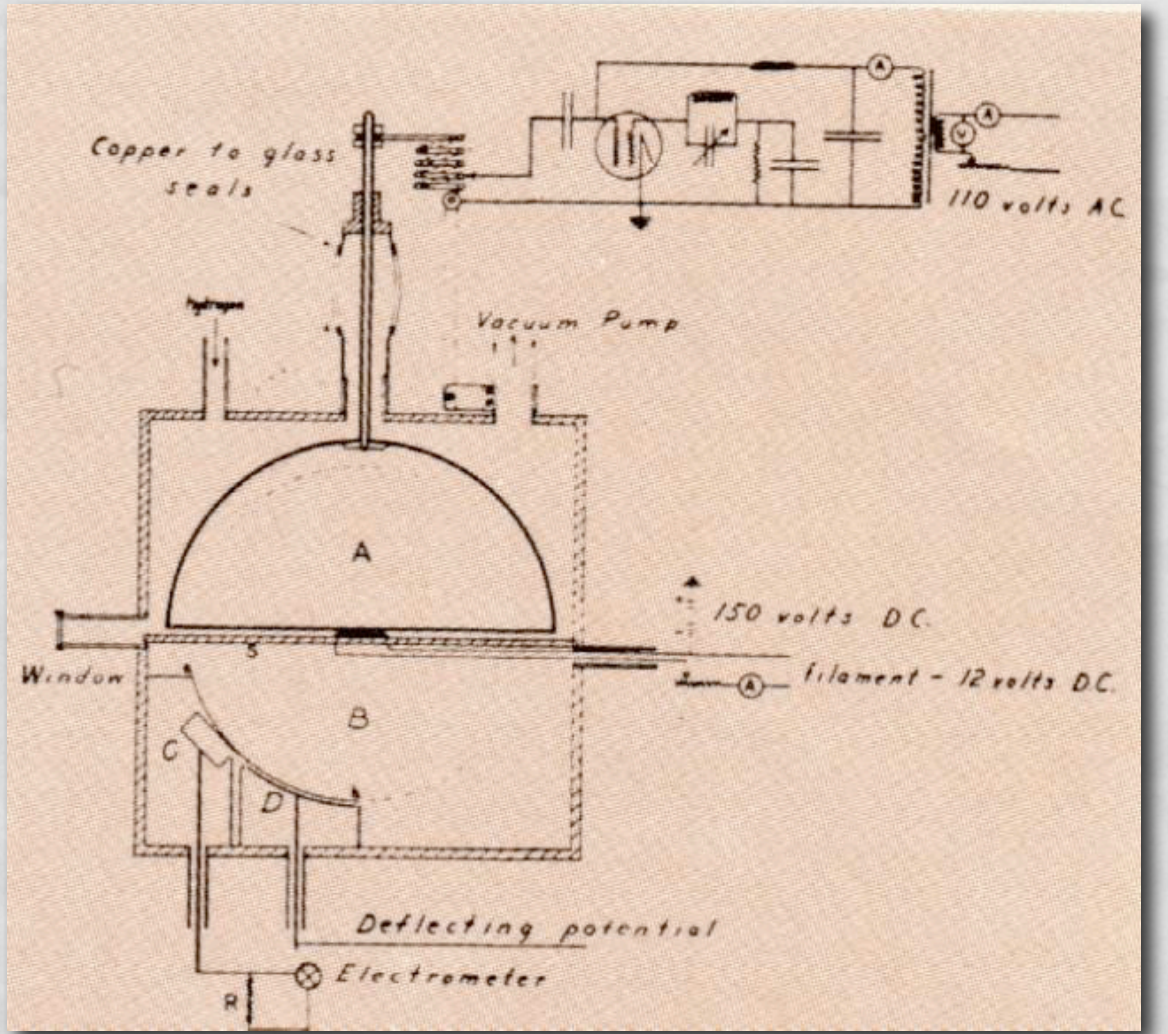
Some recognition

- 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

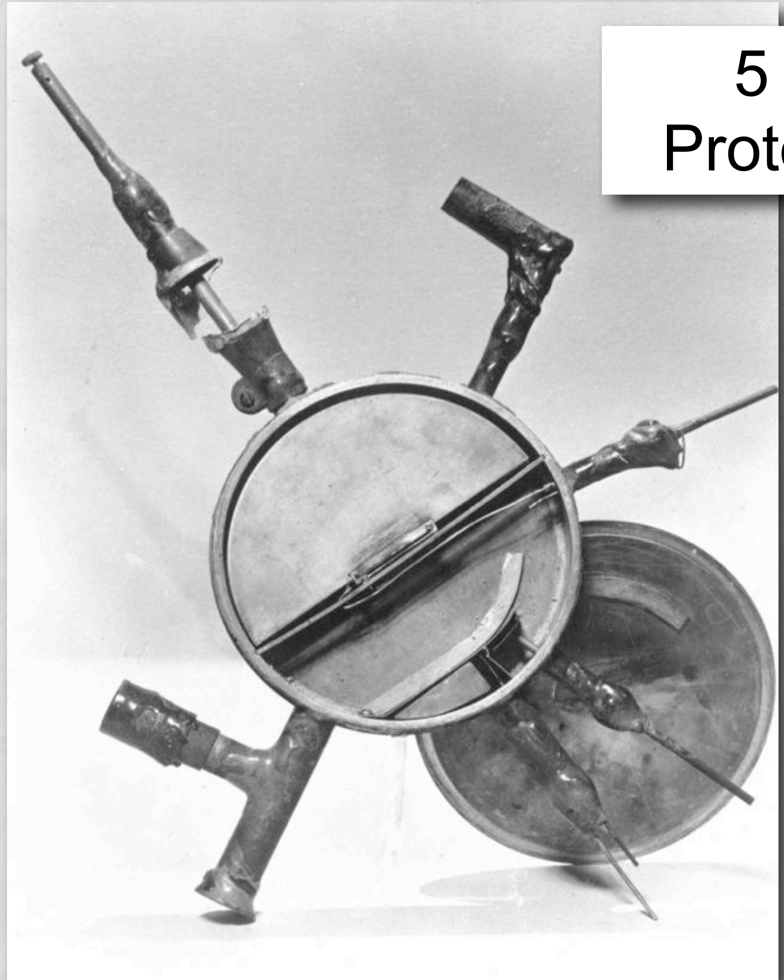


The First Cyclotron

E. Lawrence



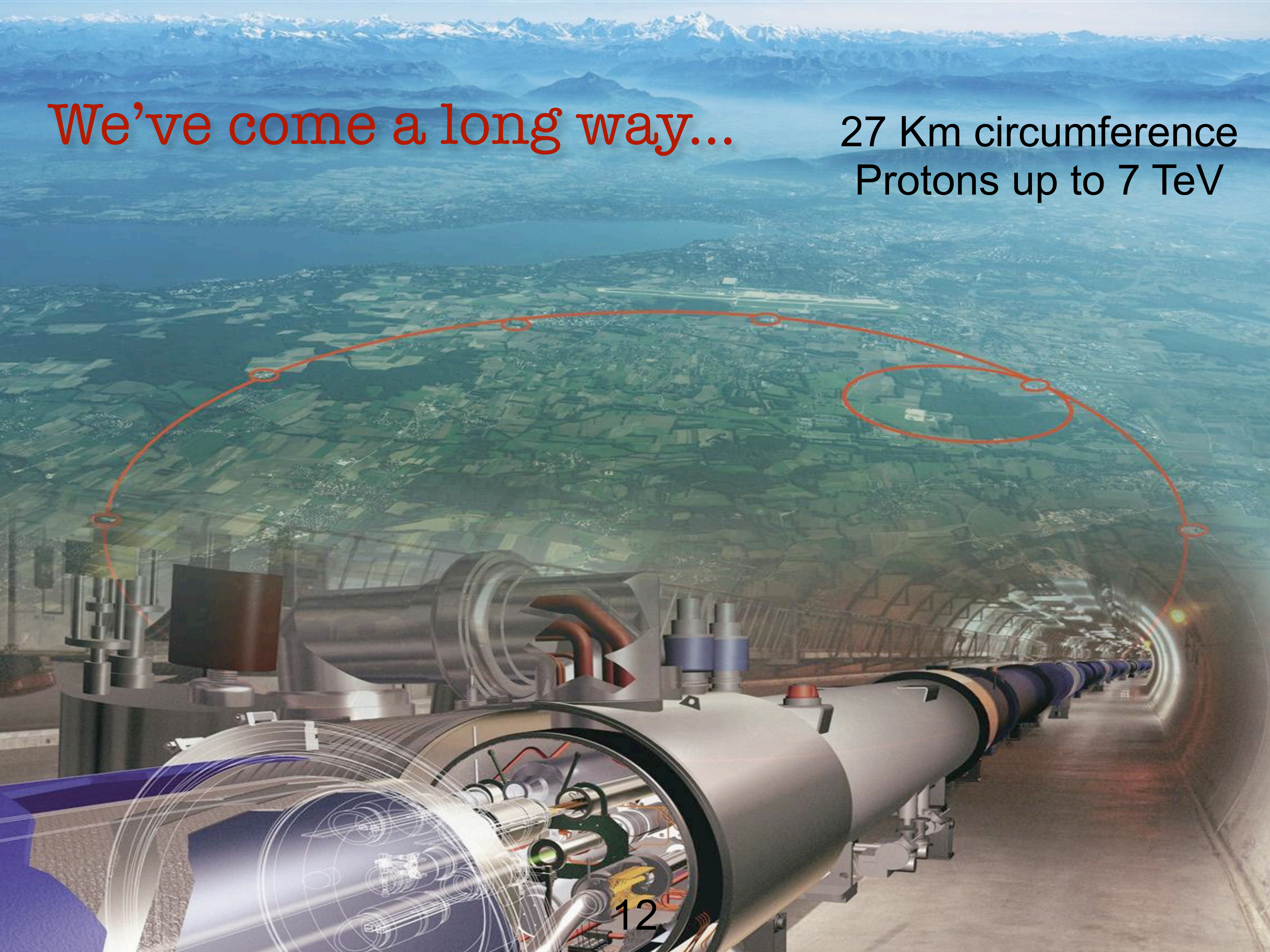
First successful cyclotron constructed by Lawrence and M. S. Livingston - 1930



5 in. diameter
Protons @ 80 KeV

We've come a long way...

27 Km circumference
Protons up to 7 TeV



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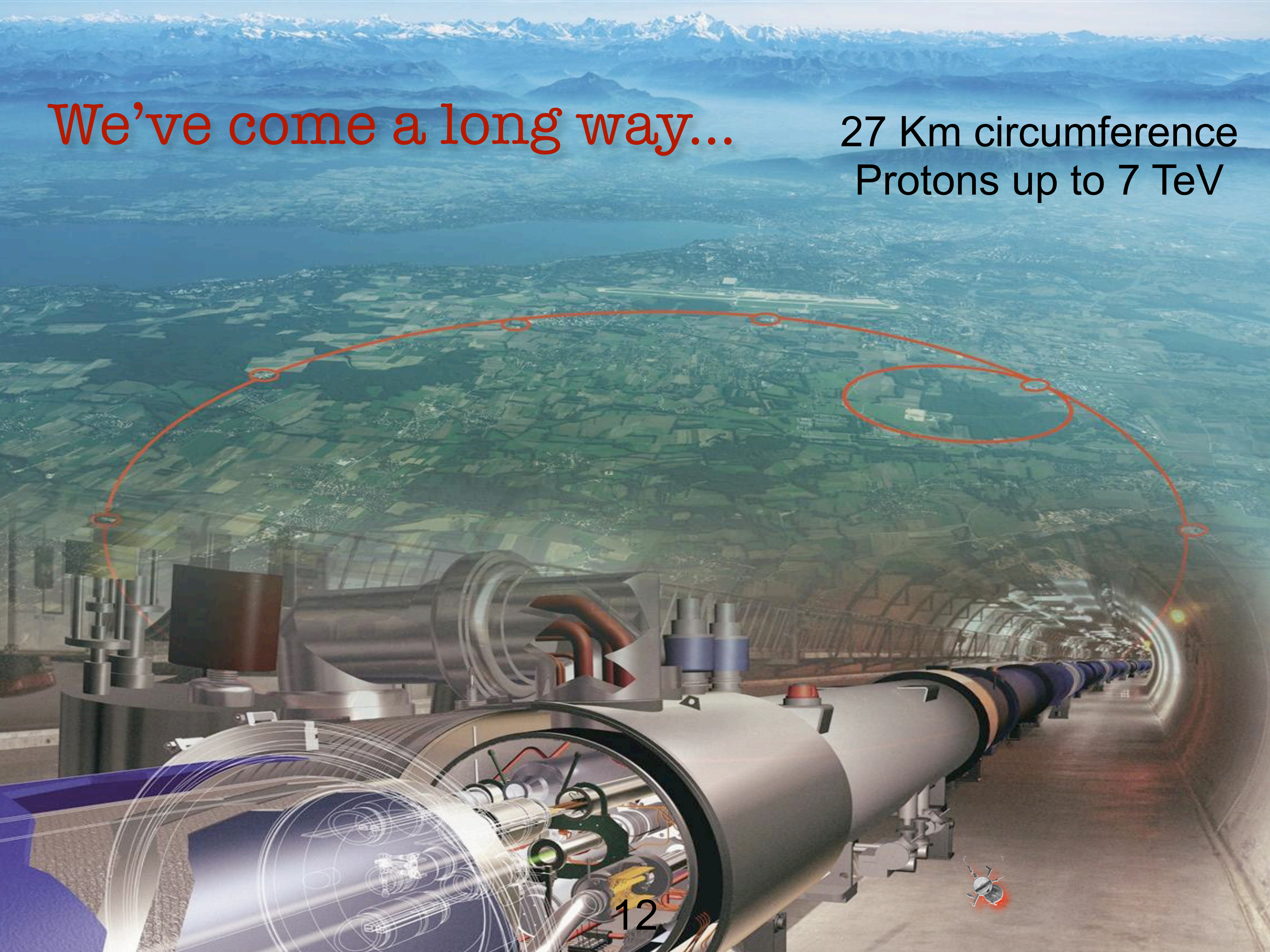
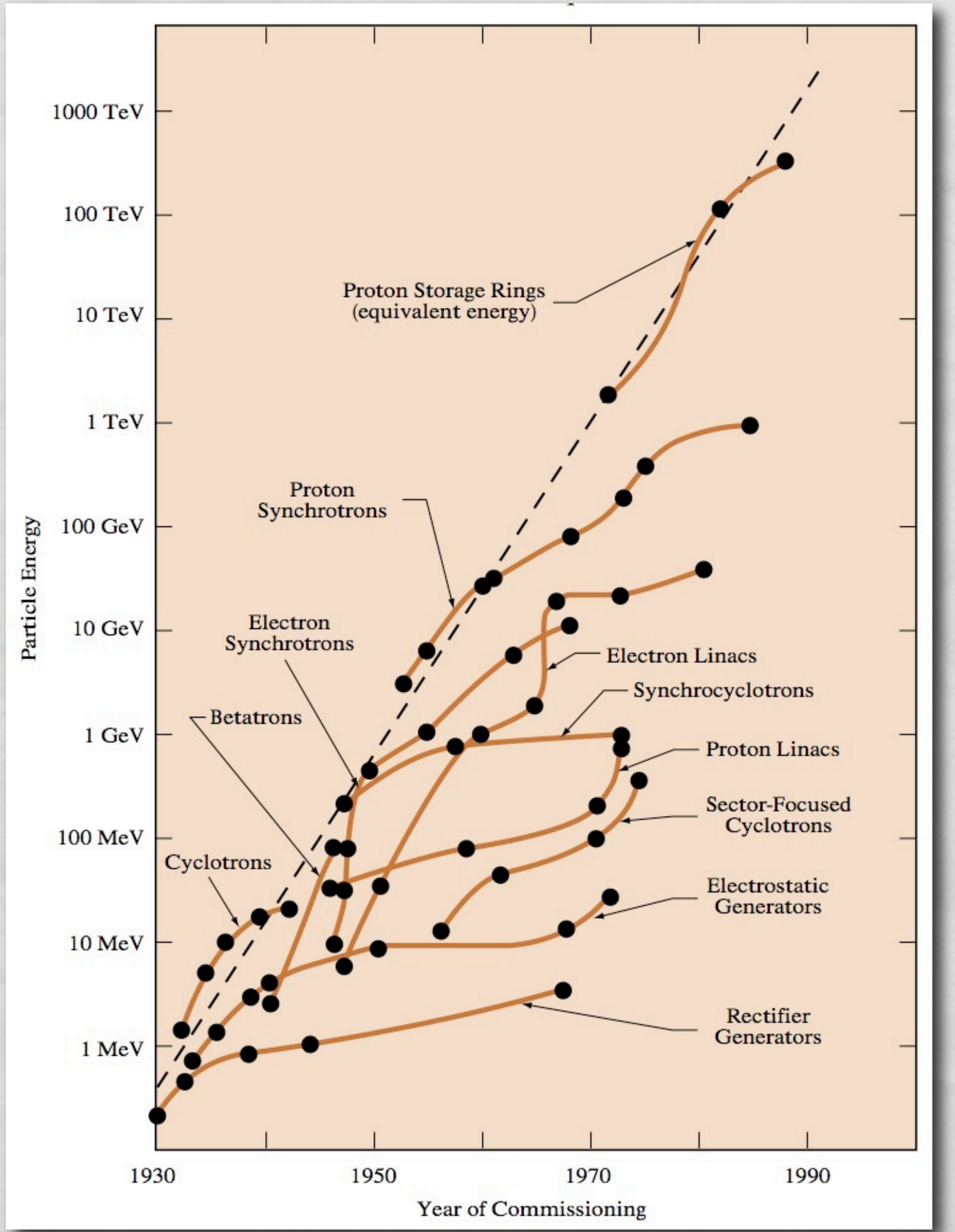


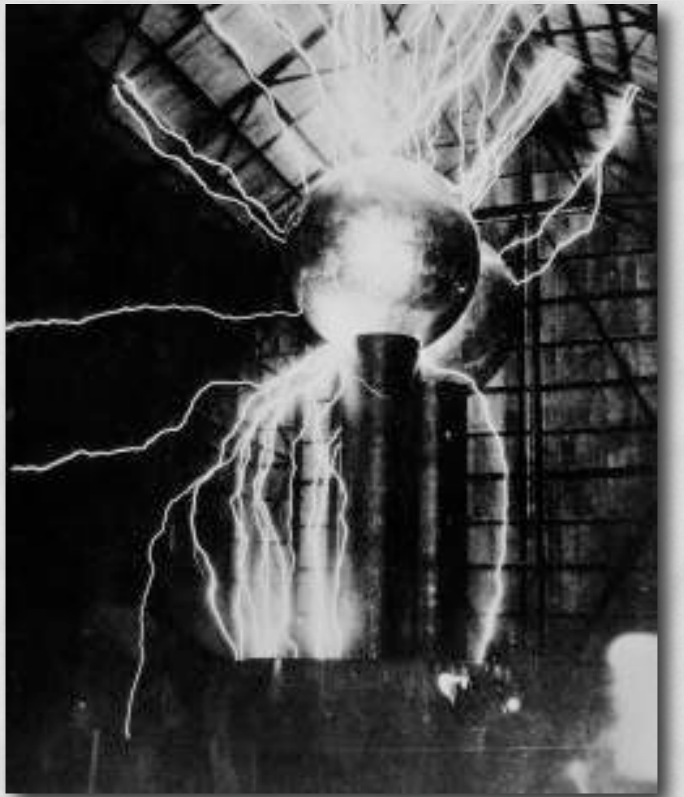
"E-volution" of Particle Accelerators

Particle Energy

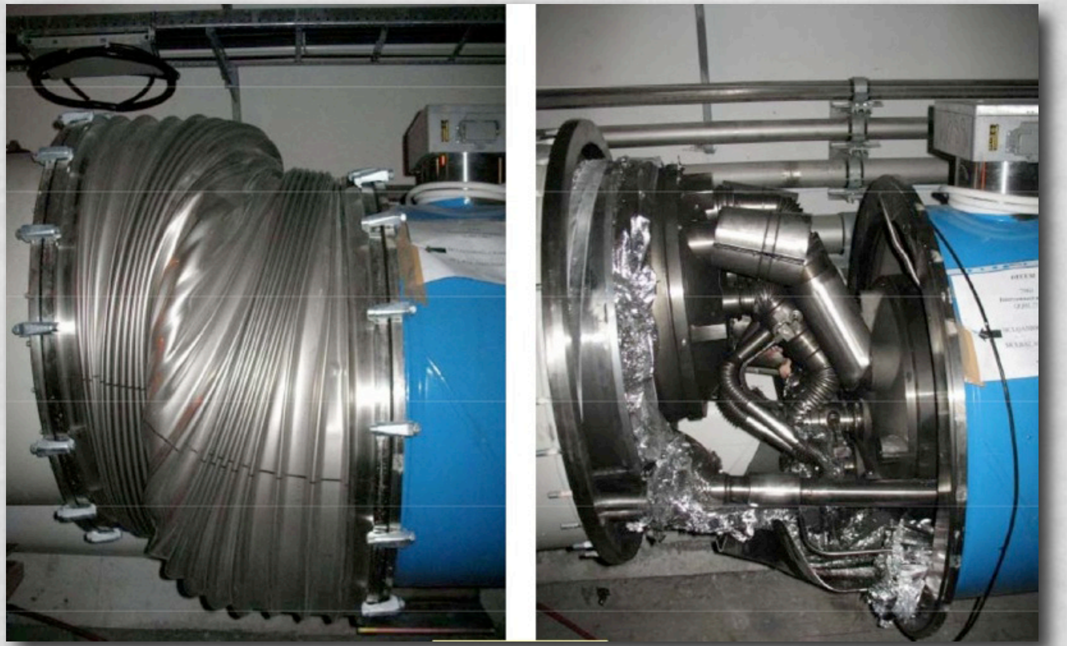


Year

Not necessarilly smoothly !

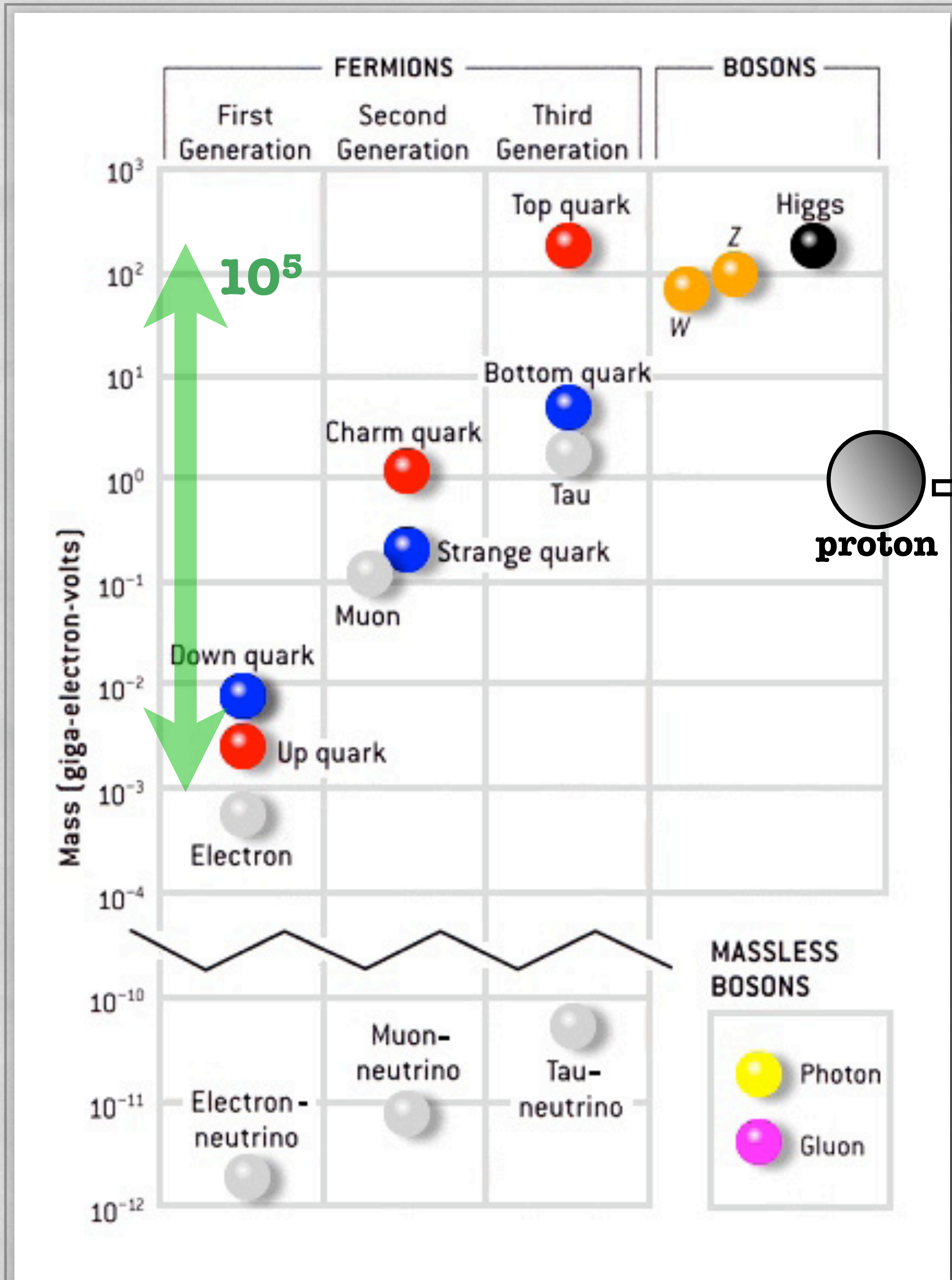


Early particle accelerators, like MIT's Van de Graaff machine, had difficulty containing the high voltages required.



LHC Sept 2008

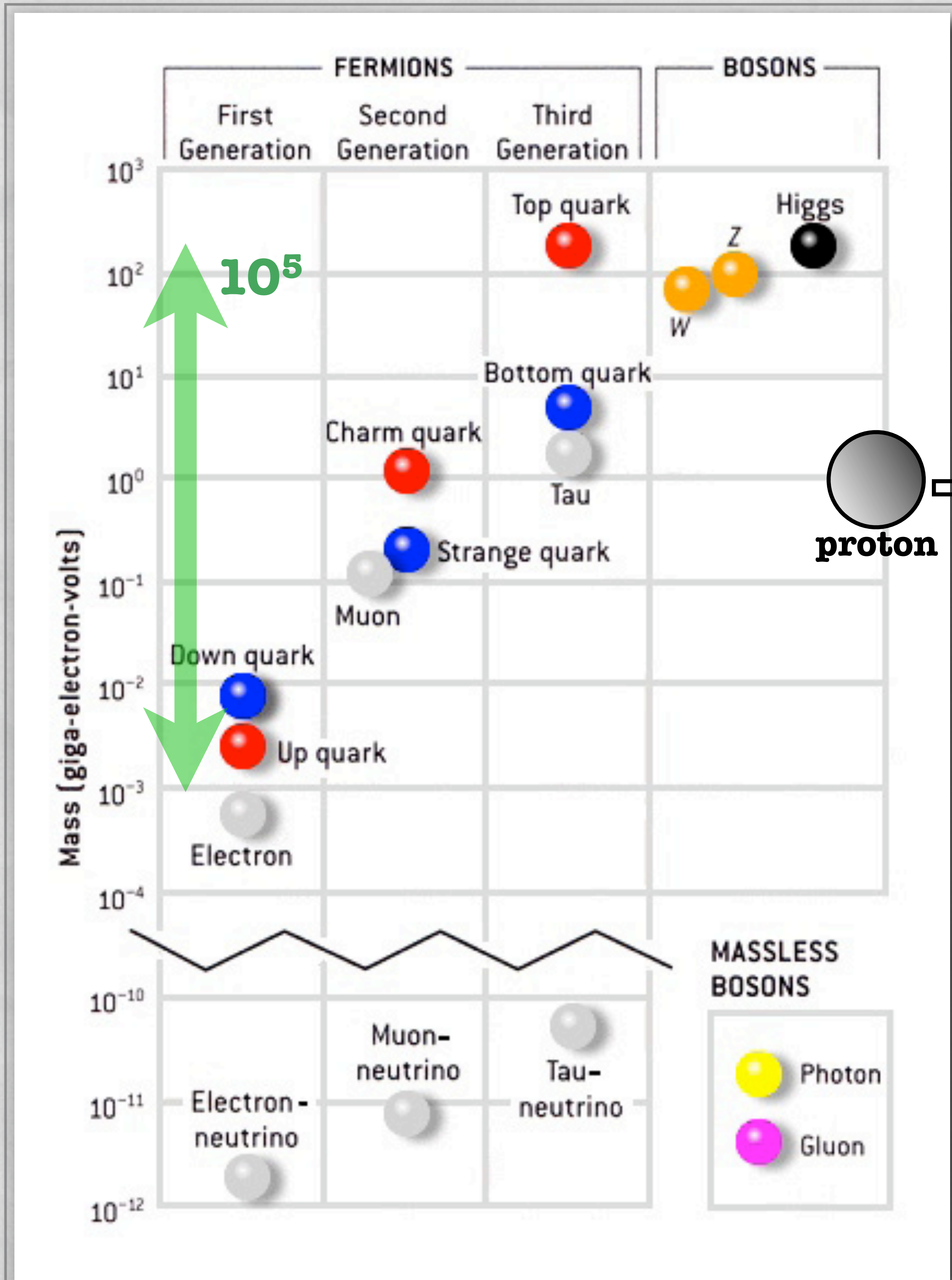
BUT major puzzles: particle masses

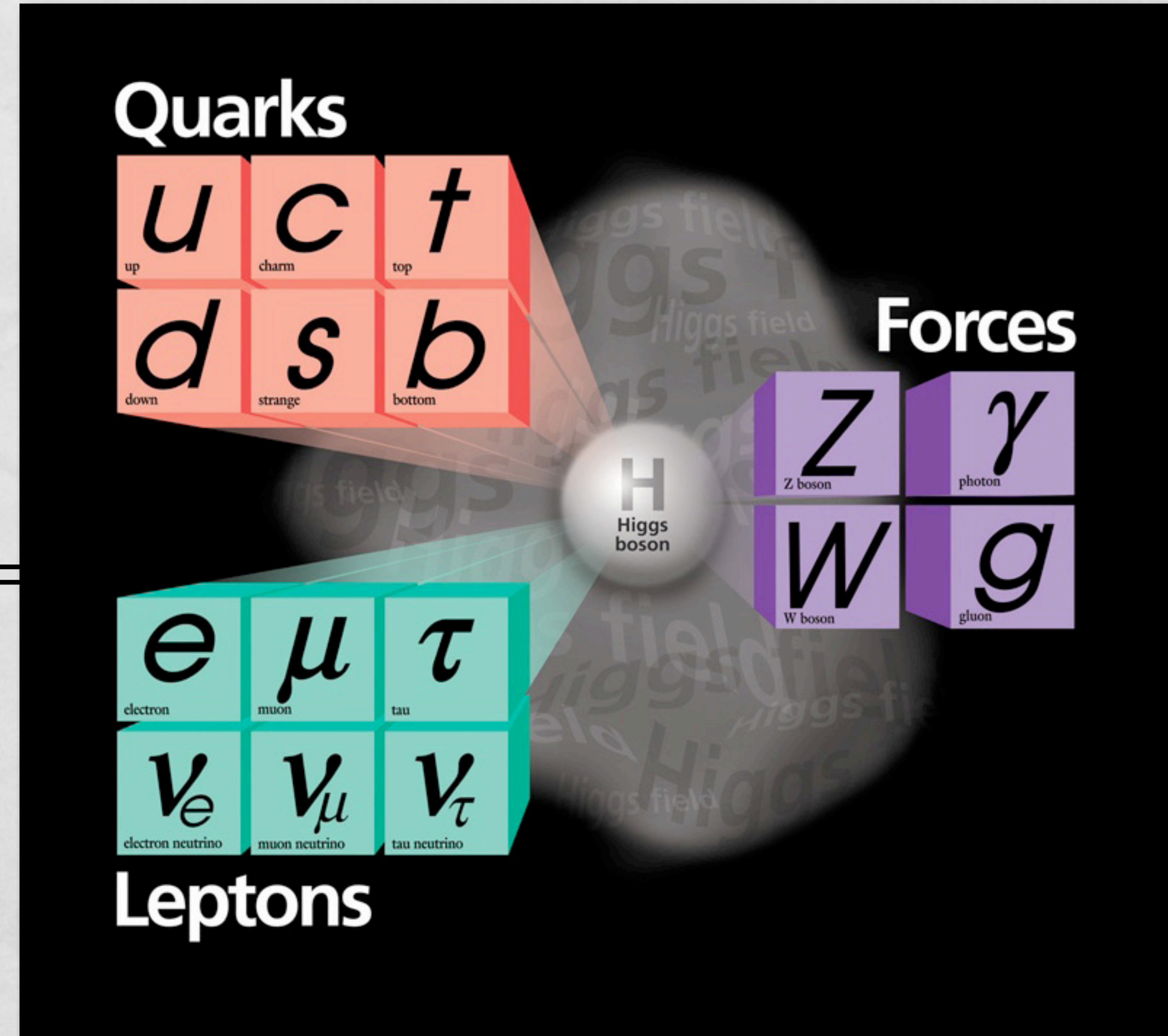


- 5 orders of magnitude span for quarks
- Top quark as heavy as a gold atom
- Neutrinos nearly massless
- Force carriers have either zero or very larger masses

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

BUT major puzzles: particle masses





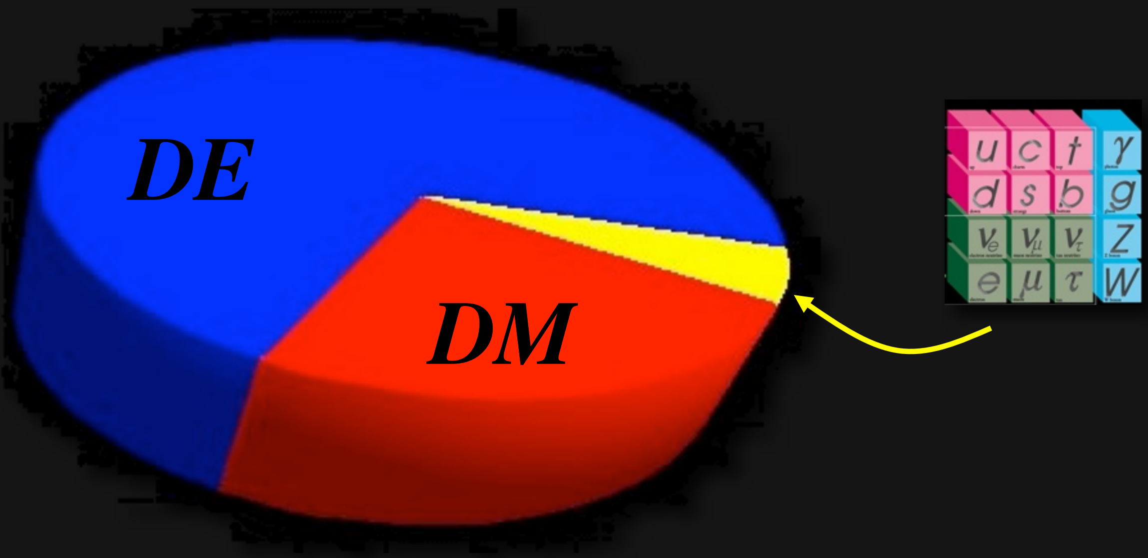
"The Higgs"

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 !

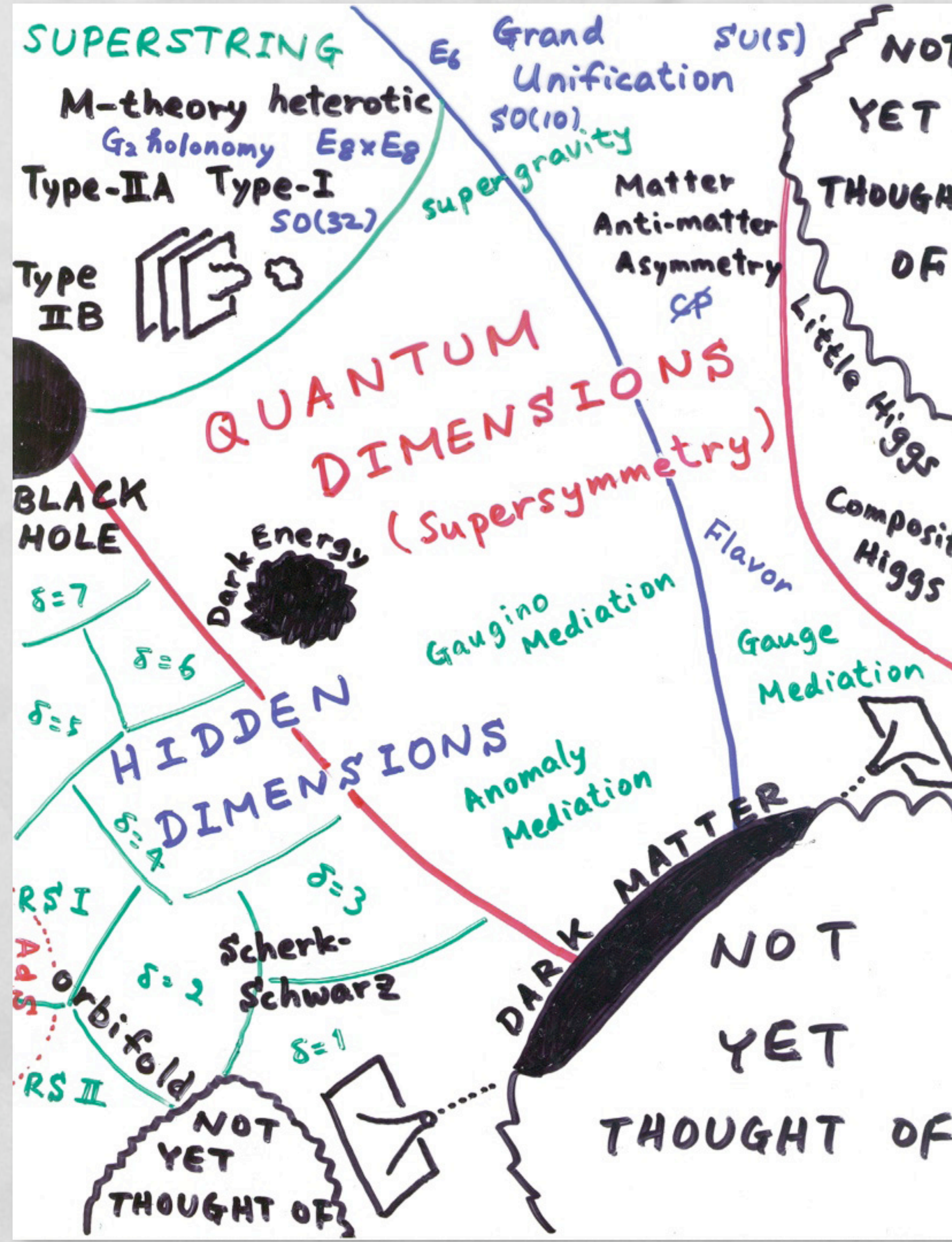
A whole new set of deep questions

- ☐ 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
- ...



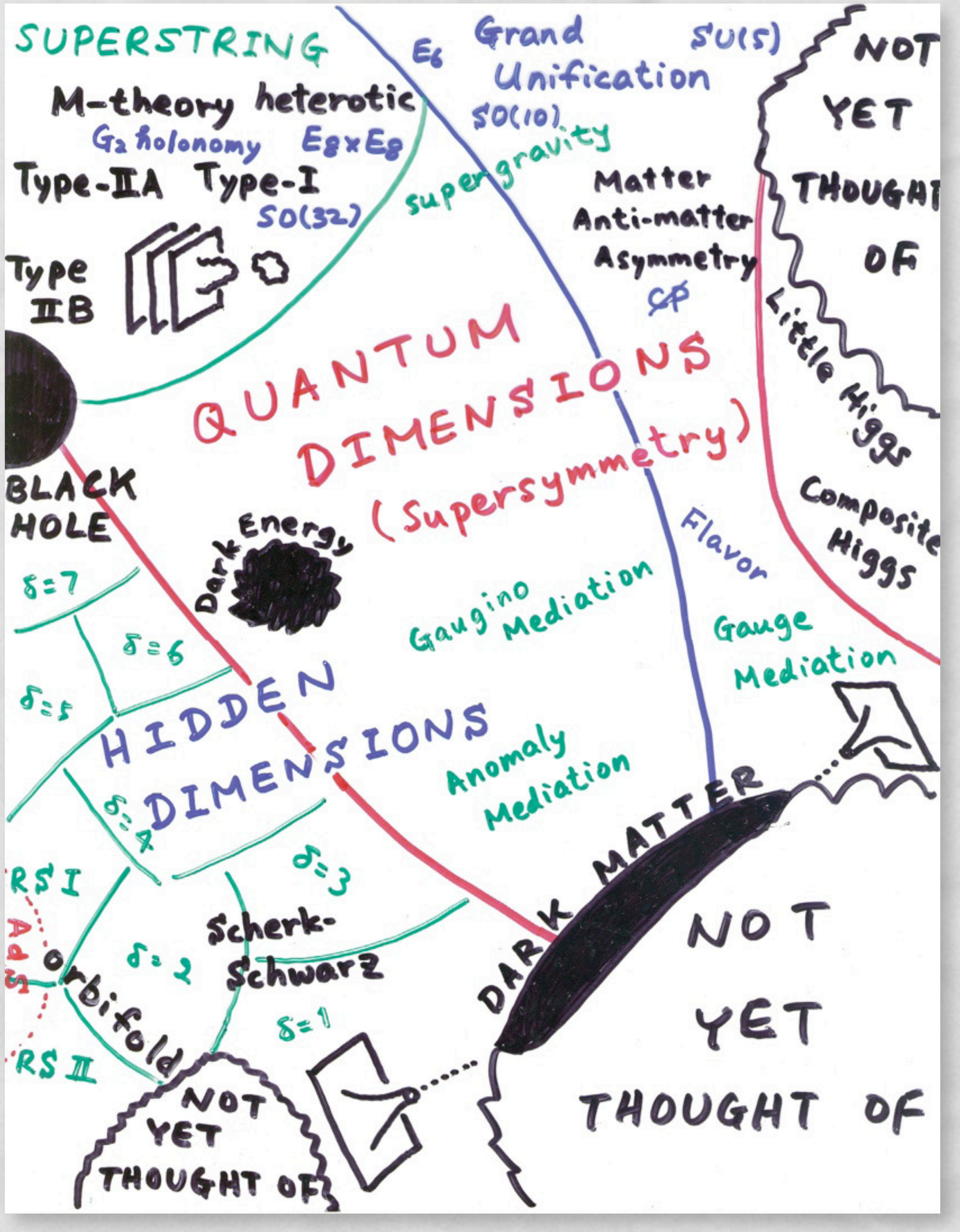
- All of which predict **new particles to be discovered**

Theorists at work

[hesitate to say "to the rescue"]

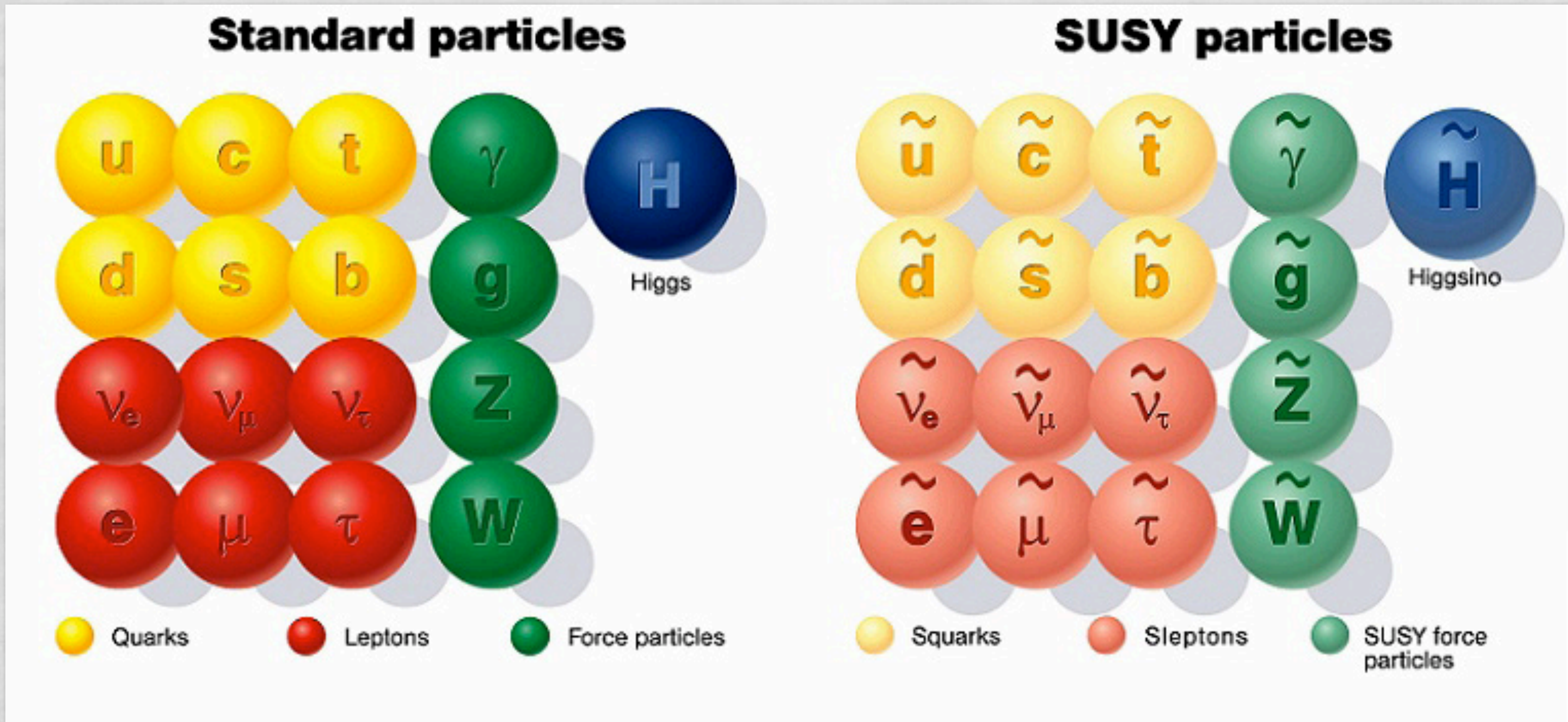
- Strings
- Supersymmetry
- Extended gauge theories
- Multi-Higgs, Little Higgs, Higgs-less
- Technicolor, topcolor
- Compositeness
- Extra dimensions
- Hidden Valleys
- ...

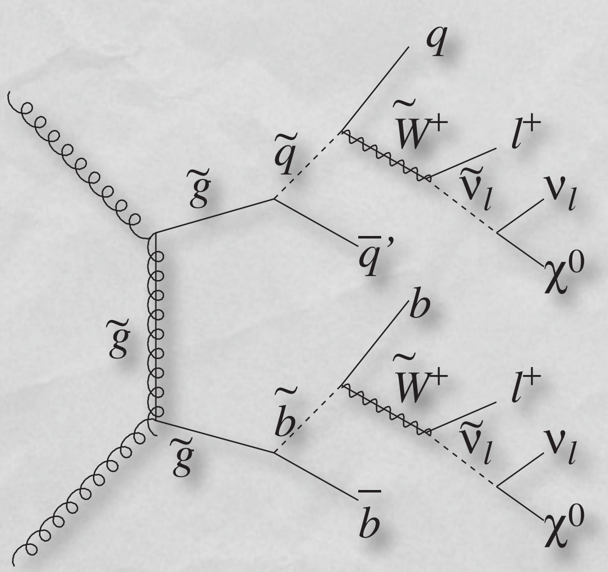
None of which may be true!



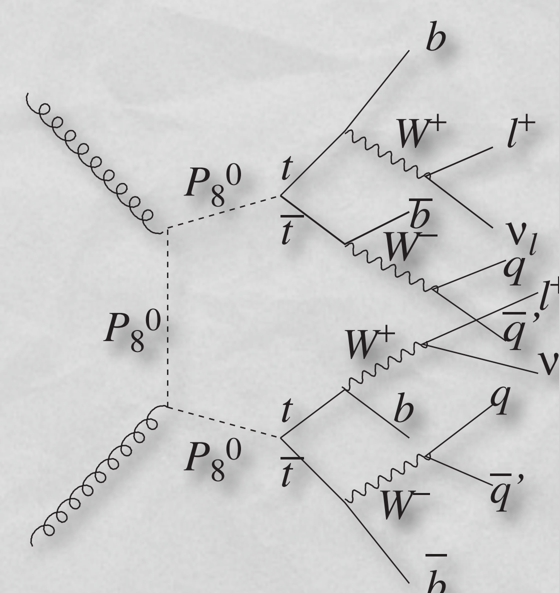
- All of which predict **new particles to be discovered**

Ex: SuperSymmetry



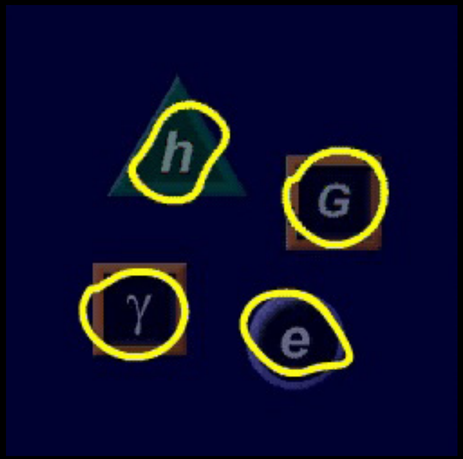


Double the fun !



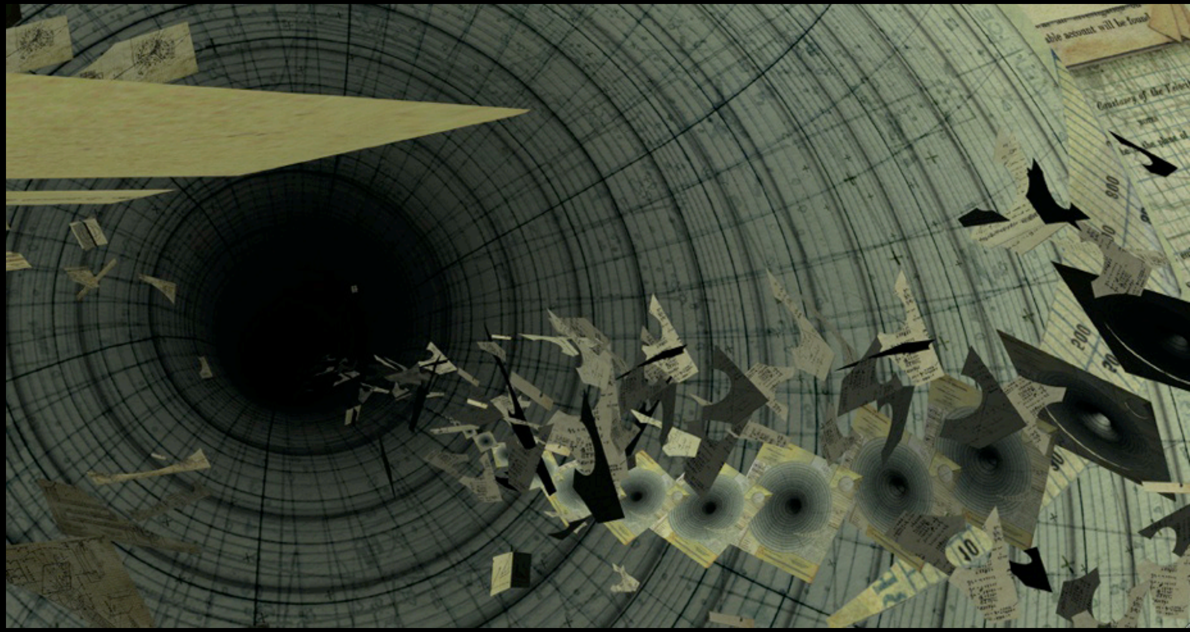
Ex: SuperStrings

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

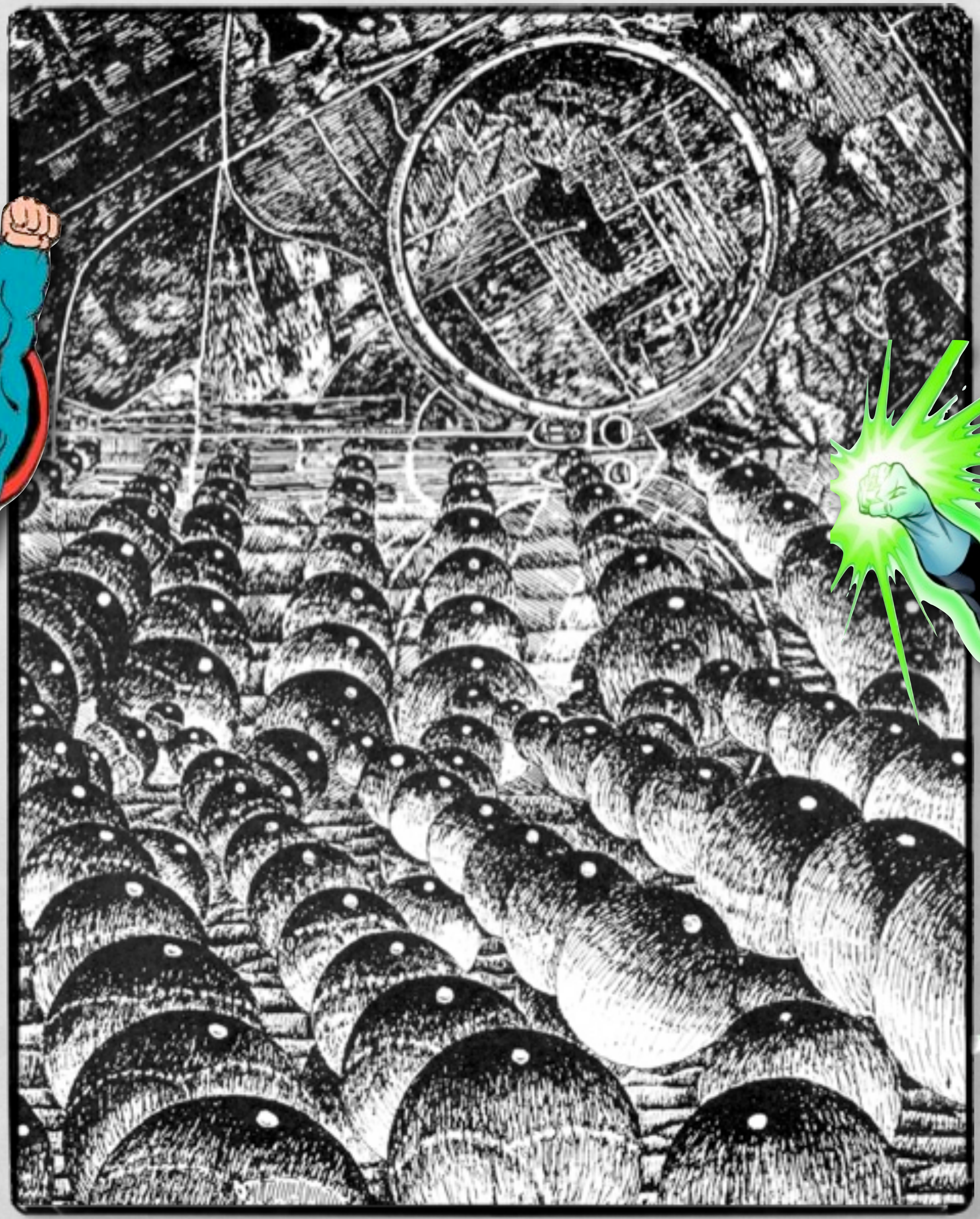


Potential to explain much (all ?)

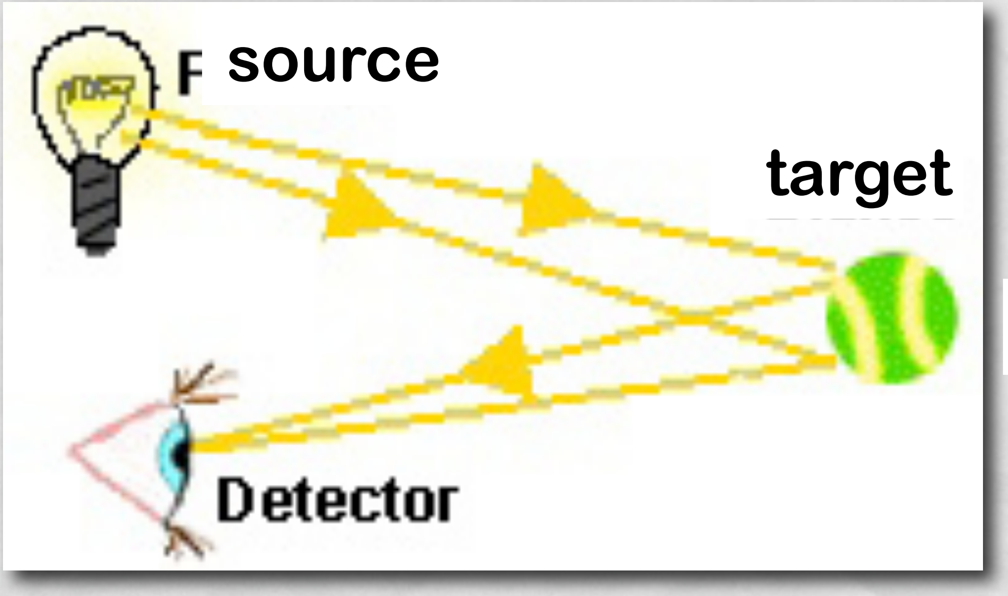
- Particle spectrum
- A single interaction
- Implies SUSY and Extra Dimensions
- contains other objects "branes"
  could even explain gravity
- Has evolved into "M-theory"
  But… the equations have many solutions
  corresponding to different Universes
  The challenge is to find the solution to our Universe…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



Adventures in Collider-land

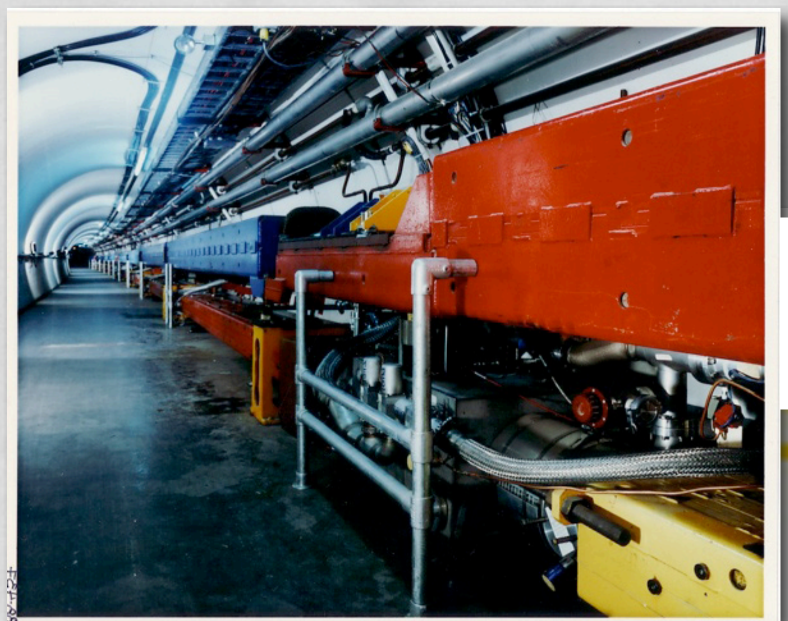


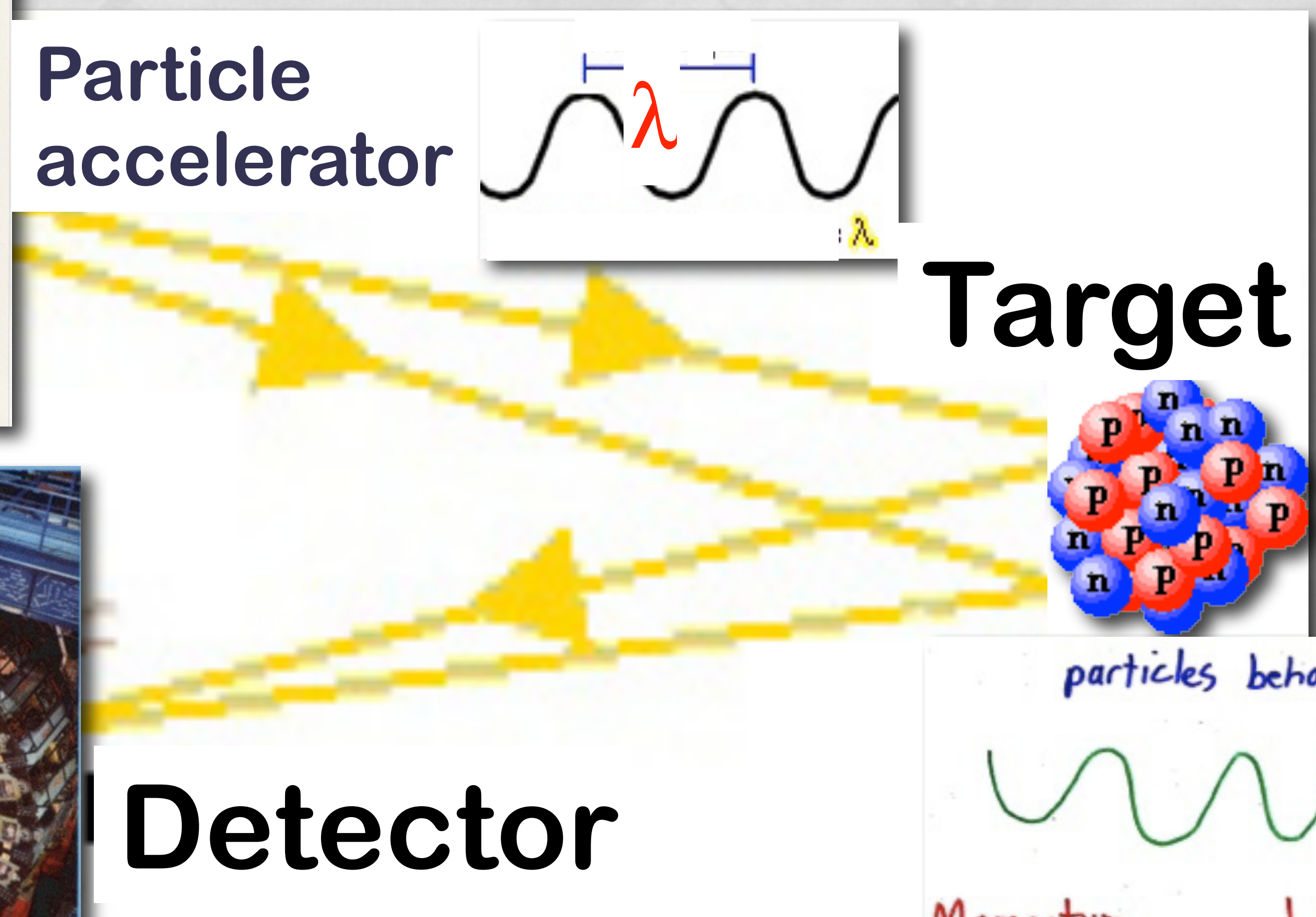
Accelerators are discovery machines !

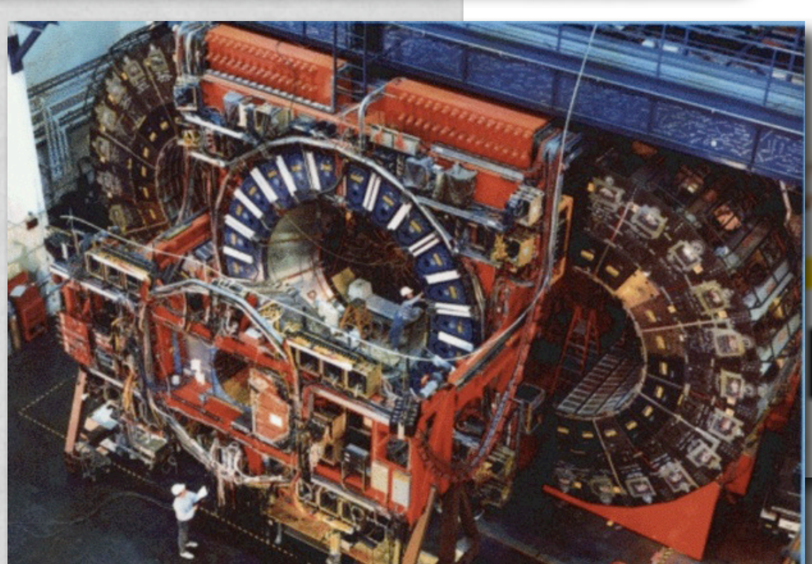


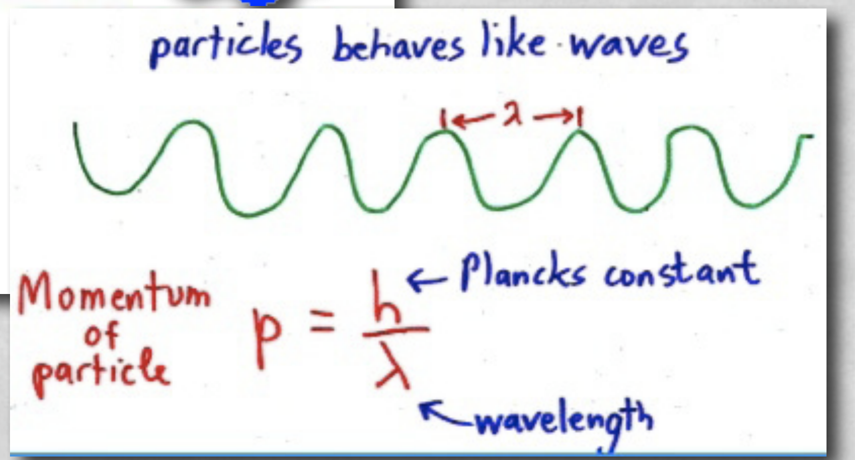
This is how we normally see

This is how we extend our senses !









Colliders

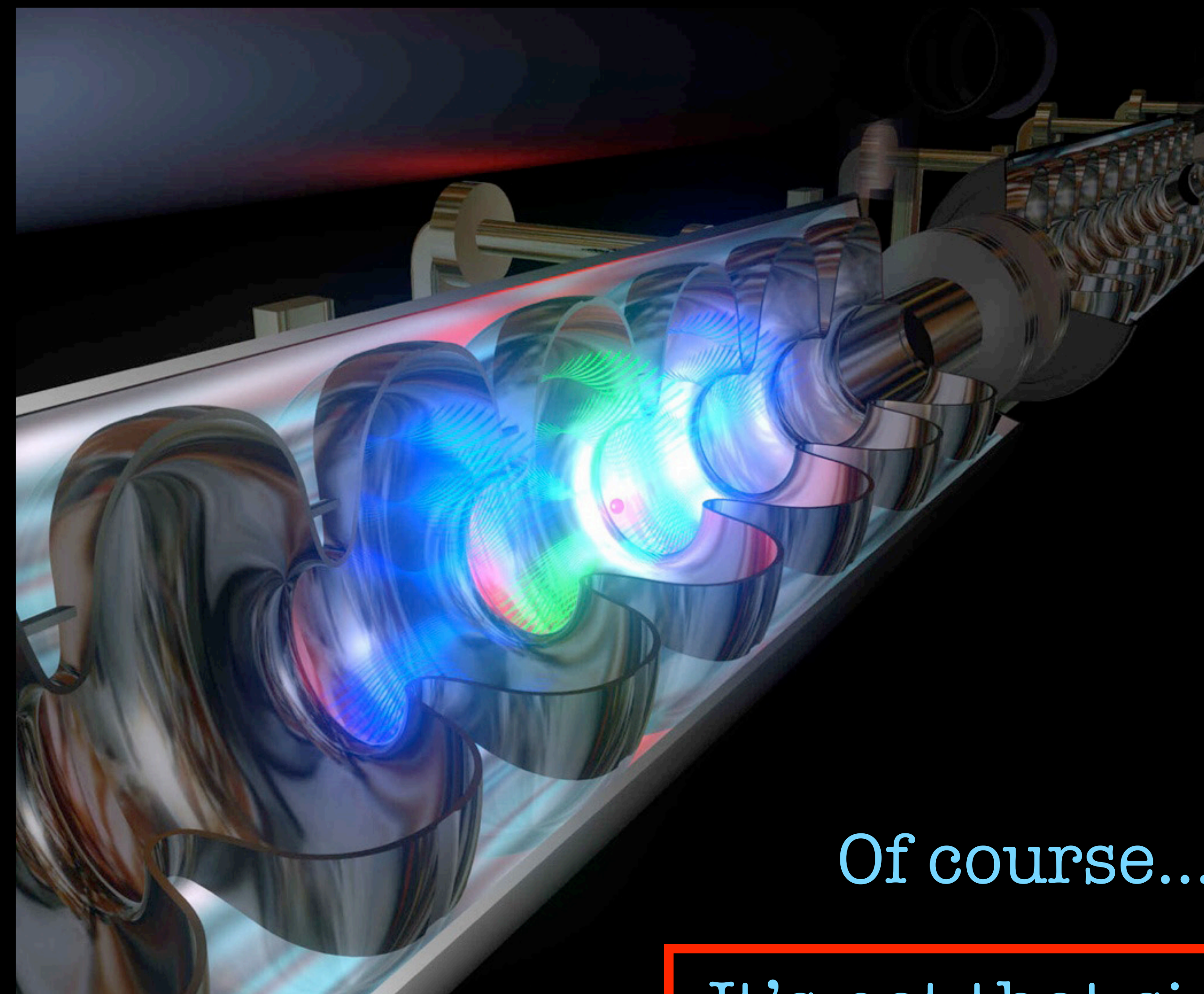
A simple idea:

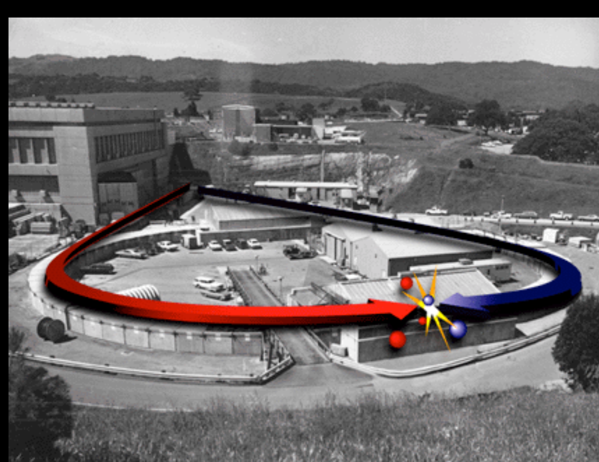
* Accelerate charged particles in an electric field

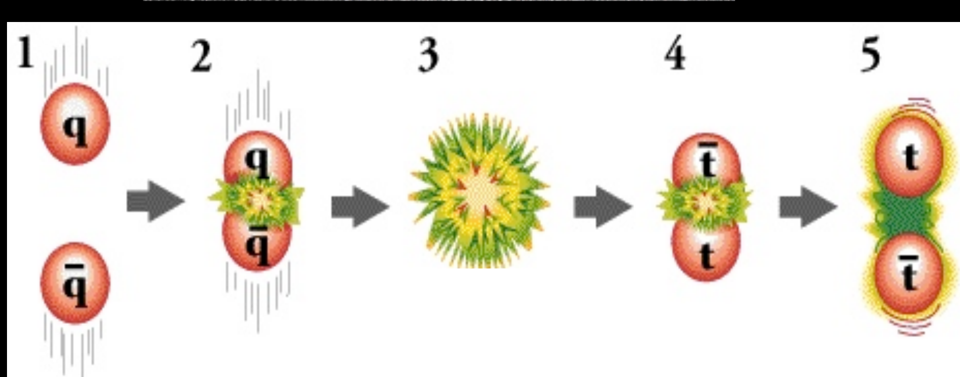
* Keep them in orbit using magnets

* Collide them against each other or a target

* See what comes out…





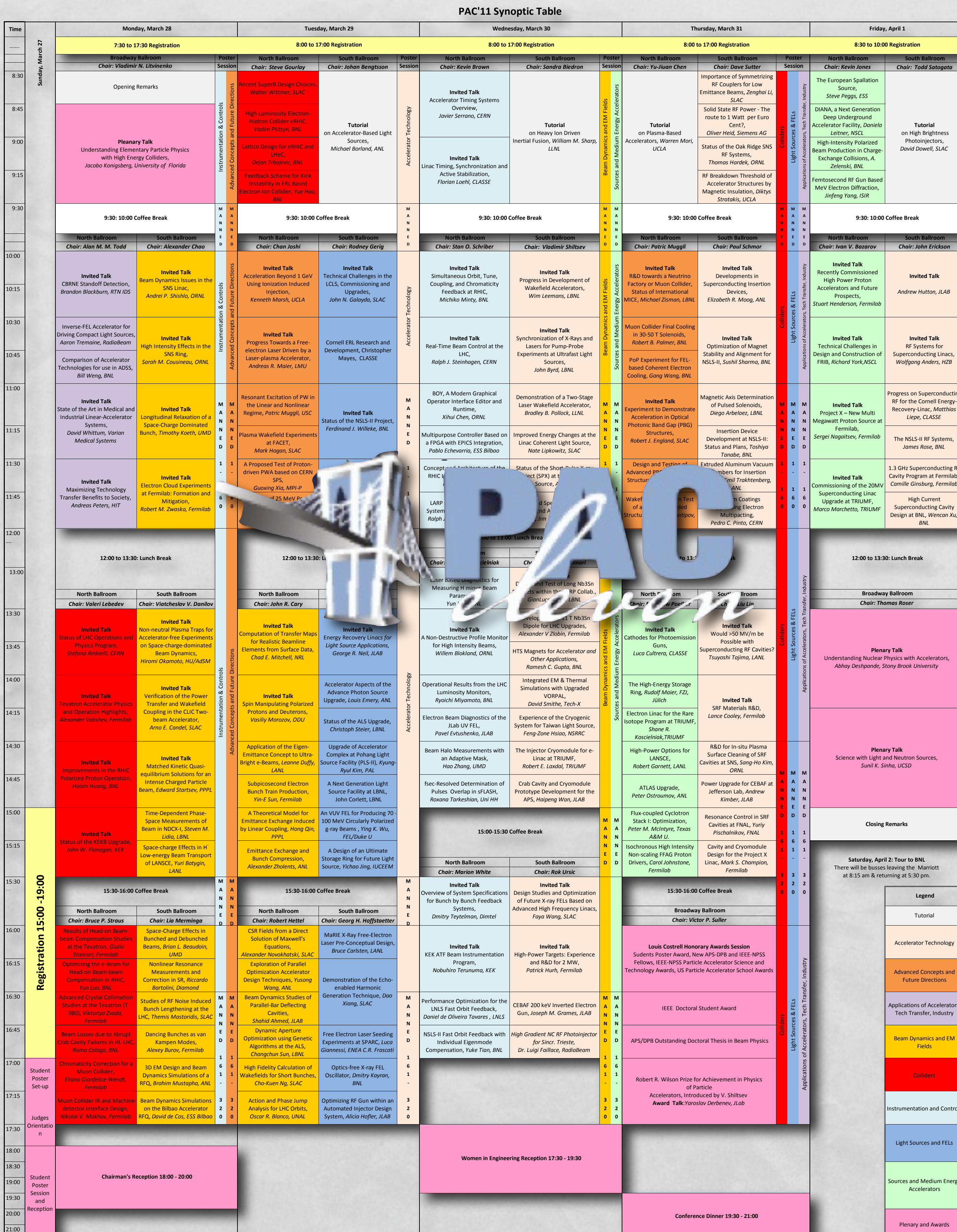


Of course…

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

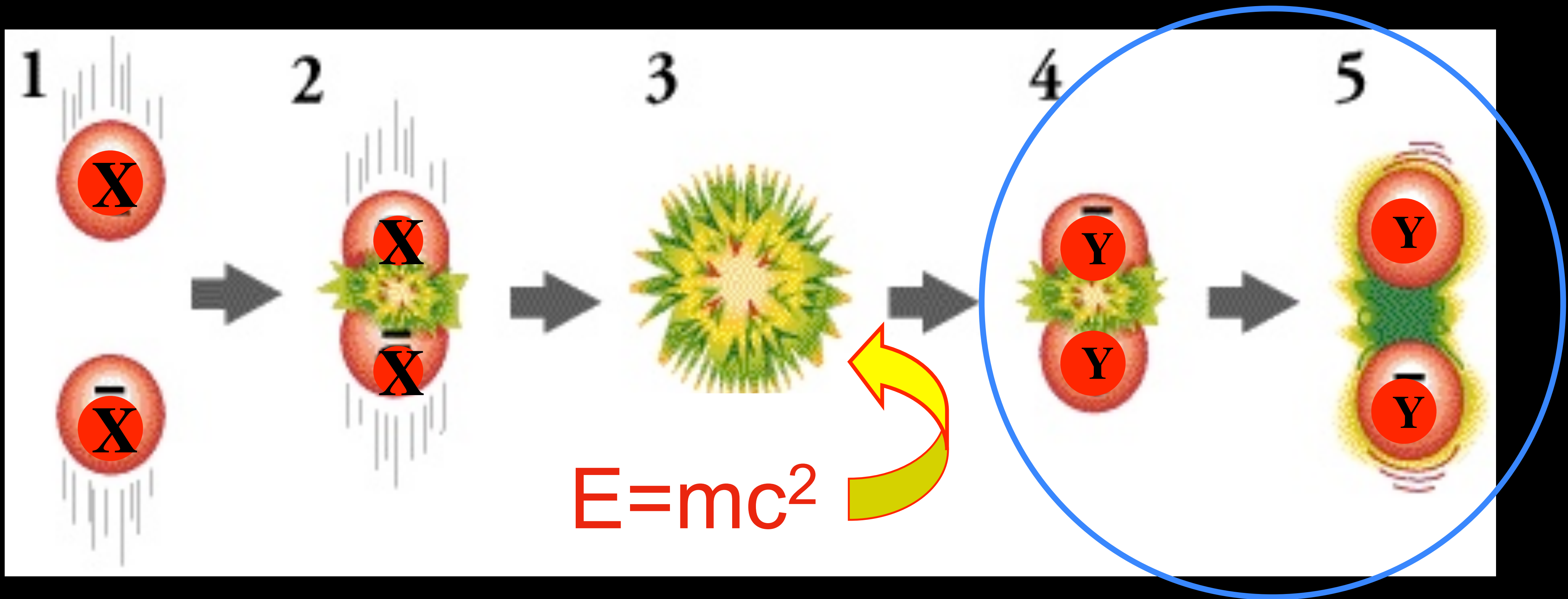
1 TeV = 10^{12} eV

Here is the evidence:



At the collision point

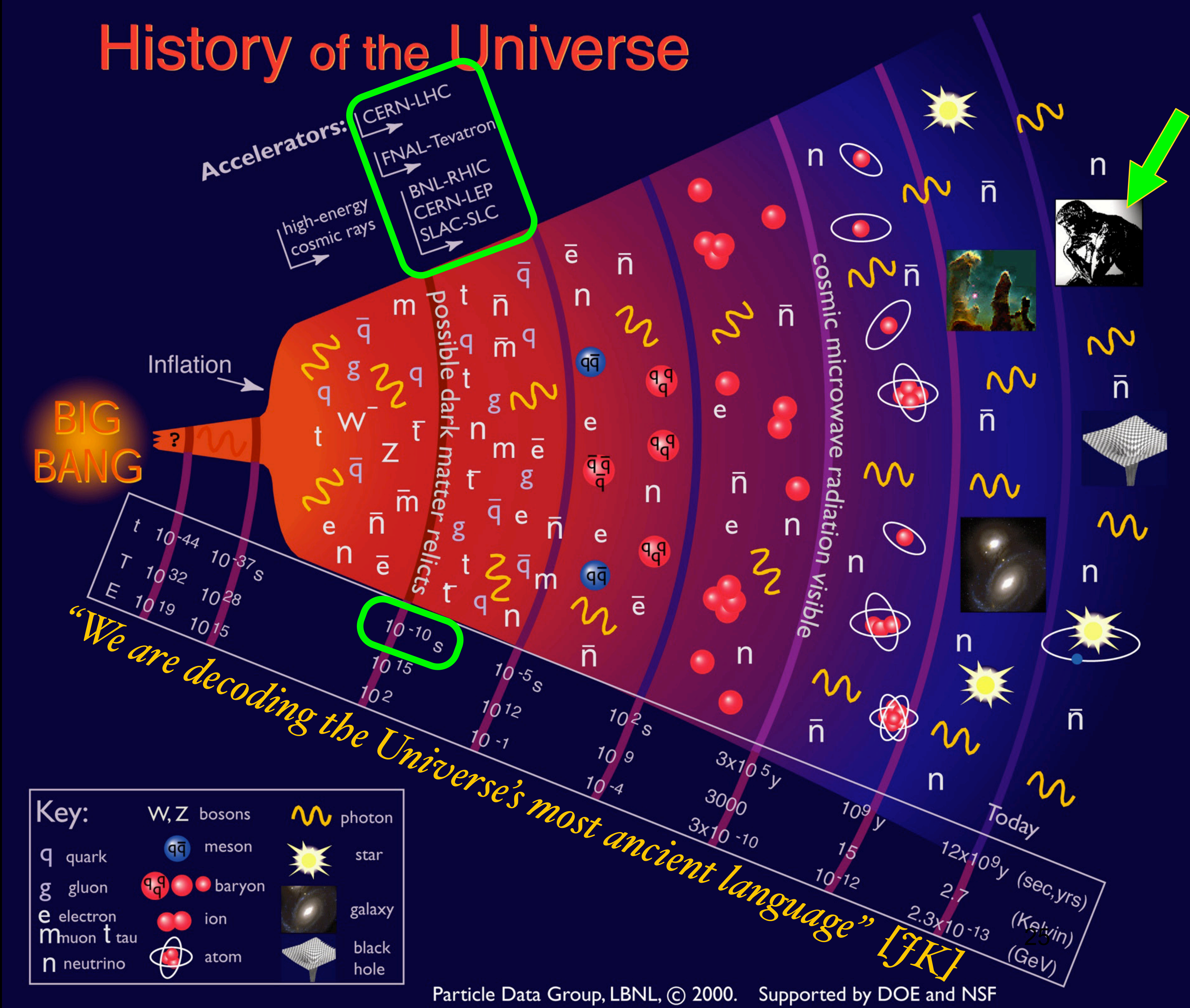
Discoveries !



More energy ==> produce more massive particles

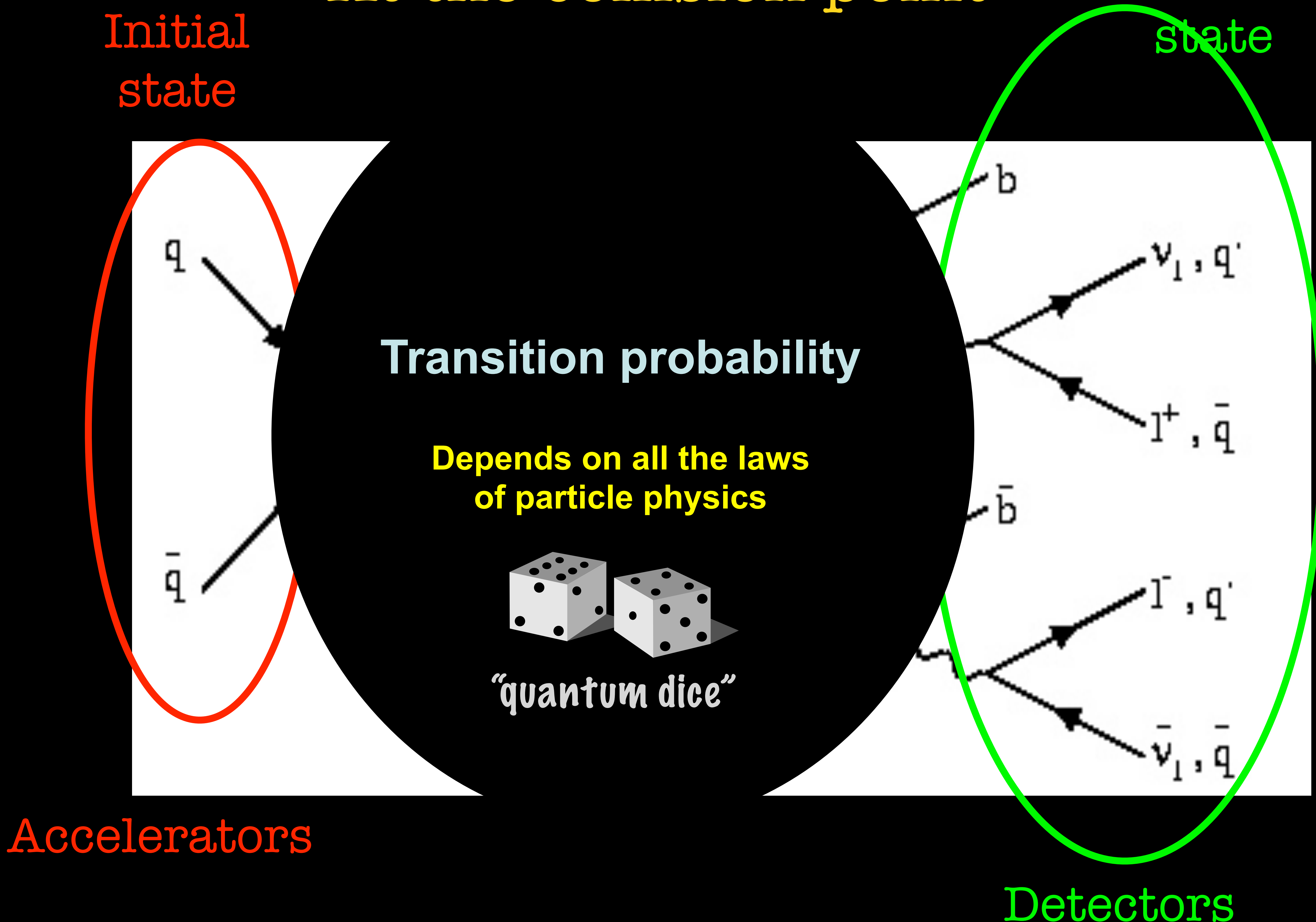
More energy ==> look in more detail

More energy ==> go back further in time !

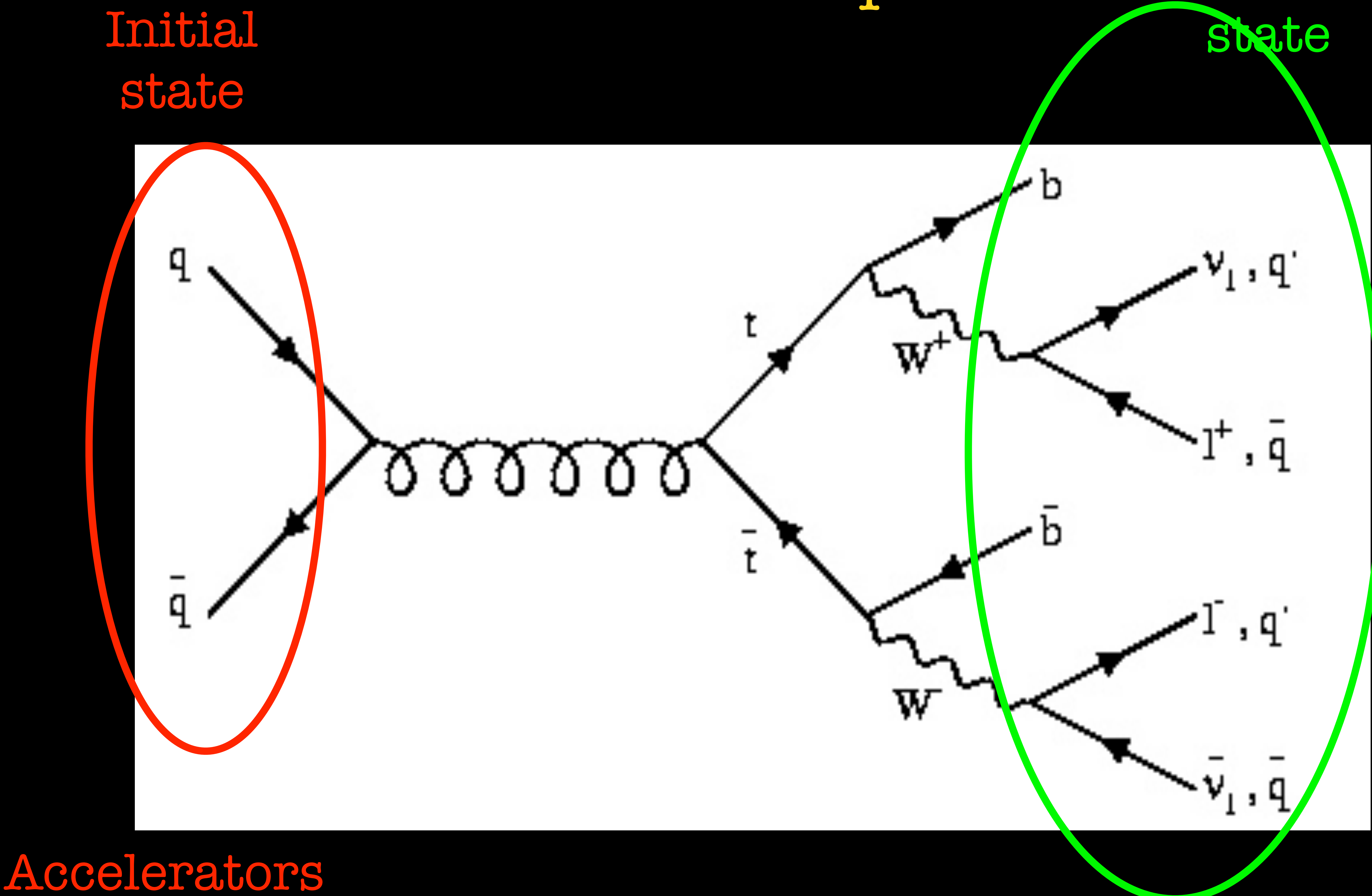


History of the Universe
Accelerators:
CERN-LHC
FNAL-Tevatron
BNL-RHIC
CERN-LEP
SLAC-SLC
high-energy cosmic rays
Inflation
BIG BANG
possible dark matter relicts
cosmic microwave radiation visible
t 10^-44 10^-37 s
T 10^32 10^28
E 10^19 10^15
10^-10 s
10^15
10^2
10^-5 s
10^12
10^-1
10^2 s
10^9
10^-4
3x10^5 y
3000
3x10^-10
10^9 y
15
10^-12
Today
12x10^9 y (sec,yrs)
2.7 (Kelvin)
2.3x10^-13 (GeV)
Key:
W, Z bosons
photon
q quark
meson
star
g gluon
baryon
e electron
galaxy
ion
m muon t tau
n neutrino
atom
black hole
Particle Data Group, LBNL, © 2000. Supported by DOE and NSF
"We are decoding the Universe's most ancient language" [JK]

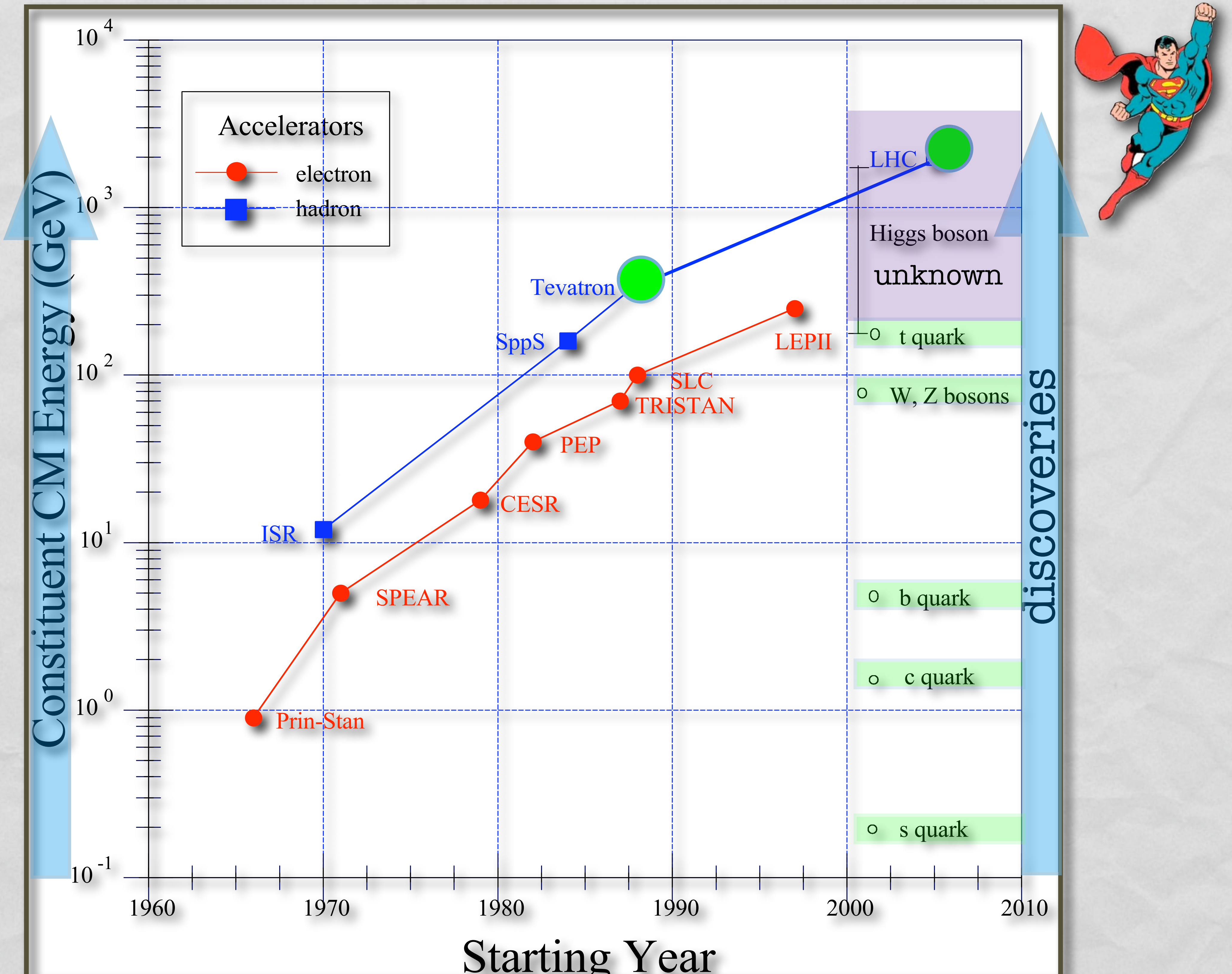
At the collision point



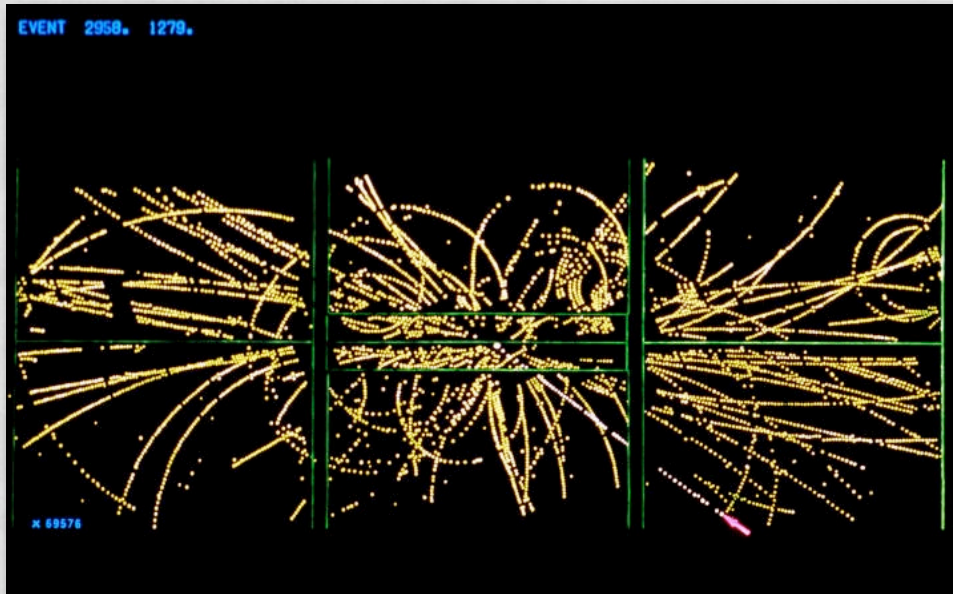
At the collision point



Energy ==> Discoveries



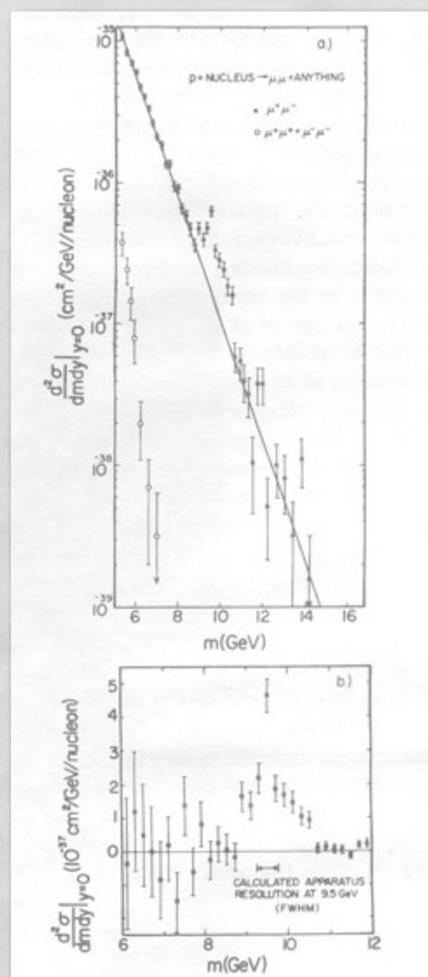
Some Good Old Particle Discoveries at Accelerators



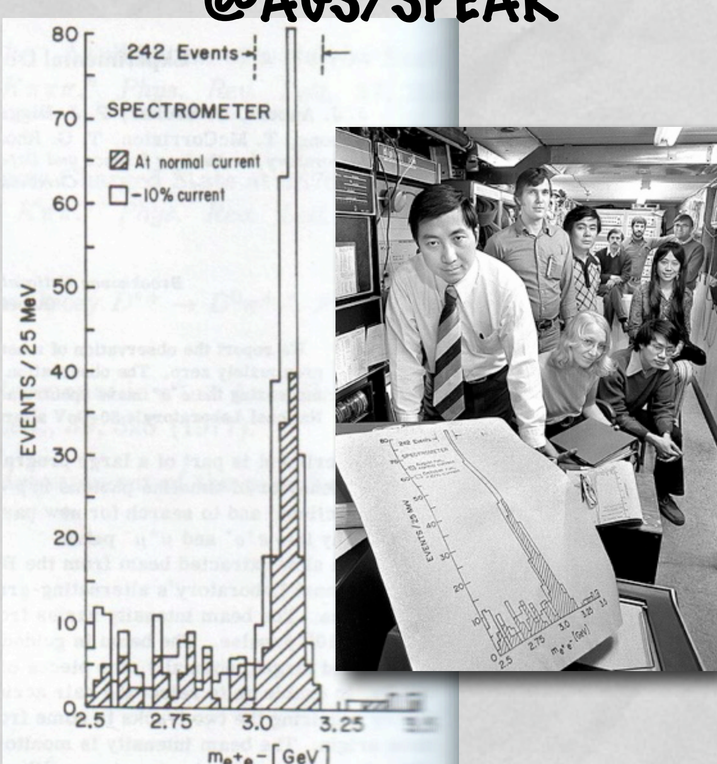
W-boson 1983
@SPS-CERN

The Top 1995
@Tevatron

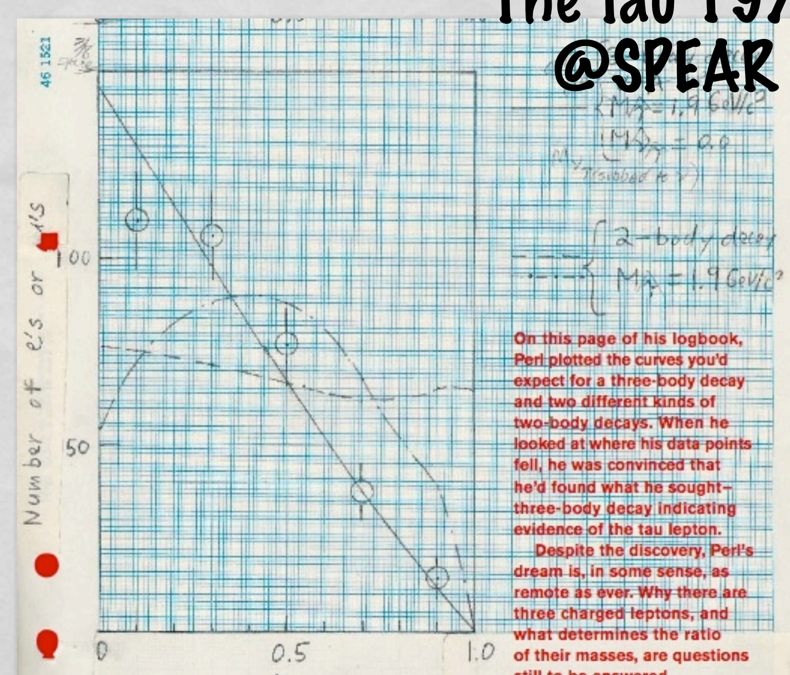
Bottom (upsilon) 1978
@FNAL



Charm (J/psi) 1974
@AGS/SPEAR



The Tau 1975
@SPEAR



FOCUS ON

Fermilab's Tevatron

Proton-antiproton collider

Ecm = 1.96 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

Ecm = 7=>14 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

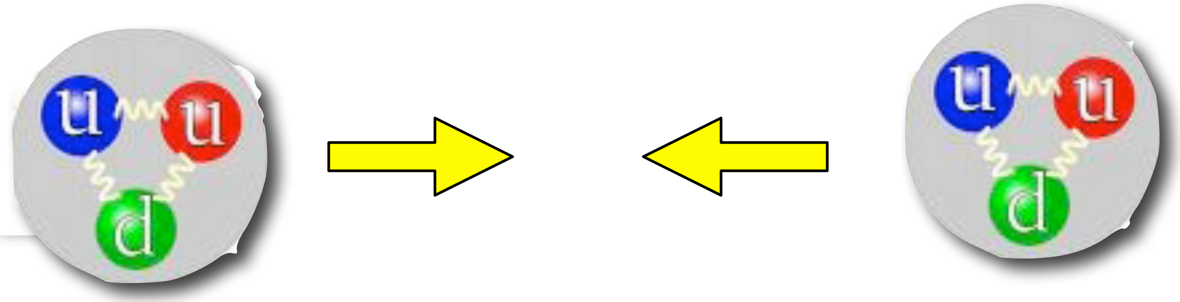
LARP

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	275×10^{9}	115×10^{9}
pBar/bunch	80×10^{9}	-
Stored beam energy	1.6 + .5 MJ	366+366 MJ*
Peak luminosity	4×10^{32} $cm^{-2}s^{-1}$	1.0×10^{34} $cm^{-2}s^{-1}$
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)

$$1.0\times10^{34}\ cm^{-2}s^{-1} \sim 50\ fb^{-1}/yr$$

*2.1 MJ ≡ "stick of dynamite" ⇒ very scary numbers

Hadron Collisions

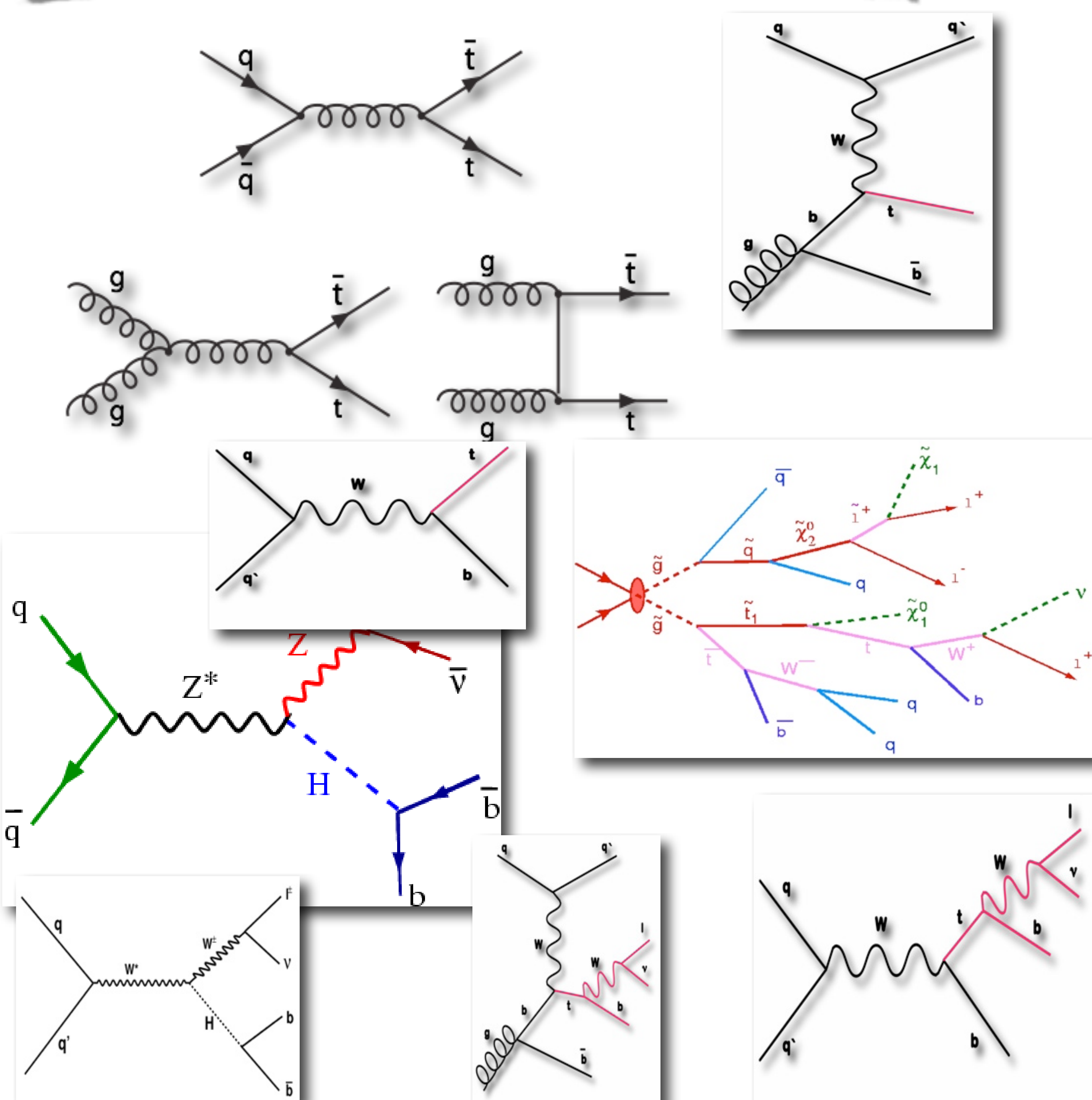


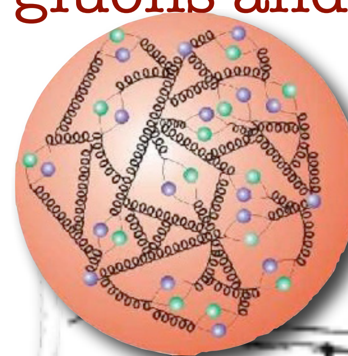
protons are 3-quark baryons

hadrons = composite particles:

- mesons = made of a quark & antiquark
- baryons = made of 3 quarks
- also gluons and more stuff

Collisions are between "partons"

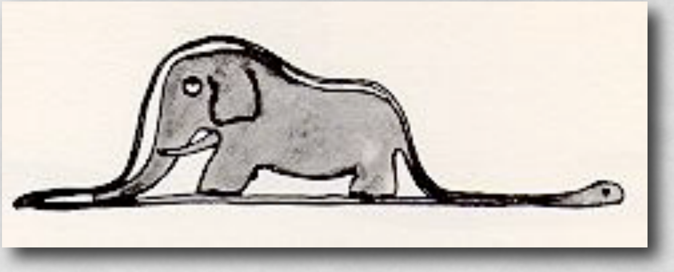


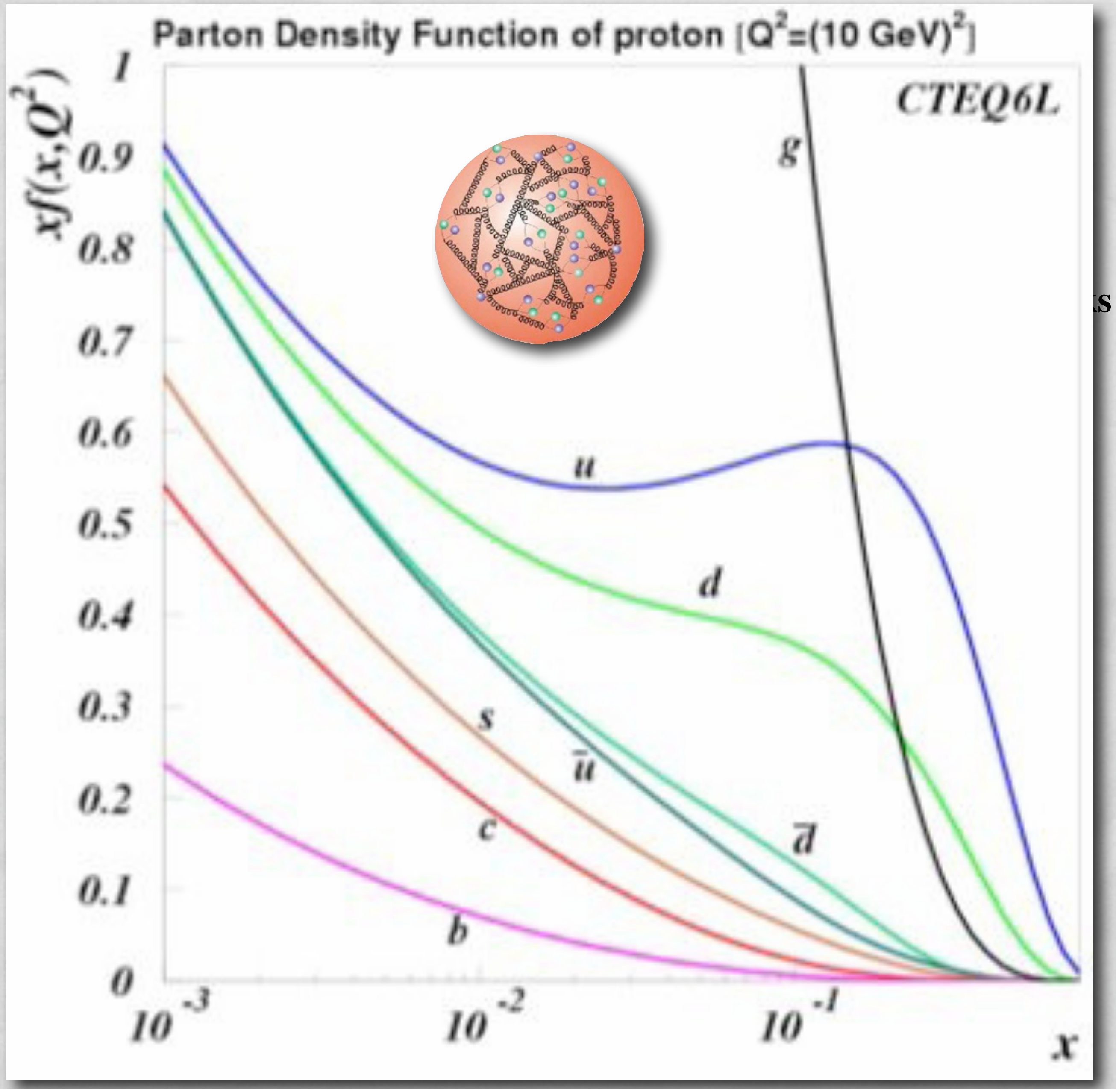


Colliders

"Particles, particles, particles"

Life in a proton





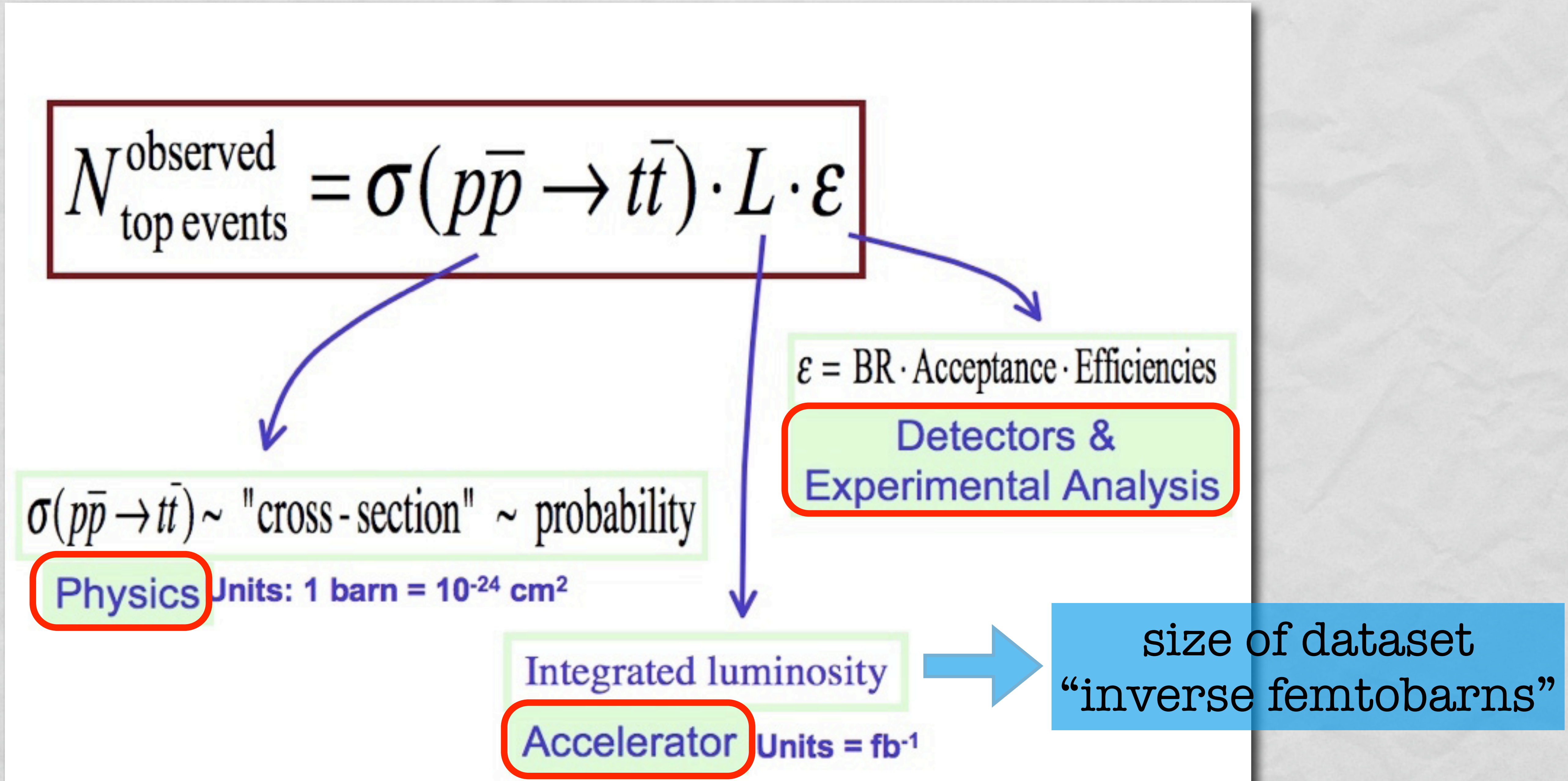
X = fraction of proton momentum taken by each parton

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

How many can we find of each?

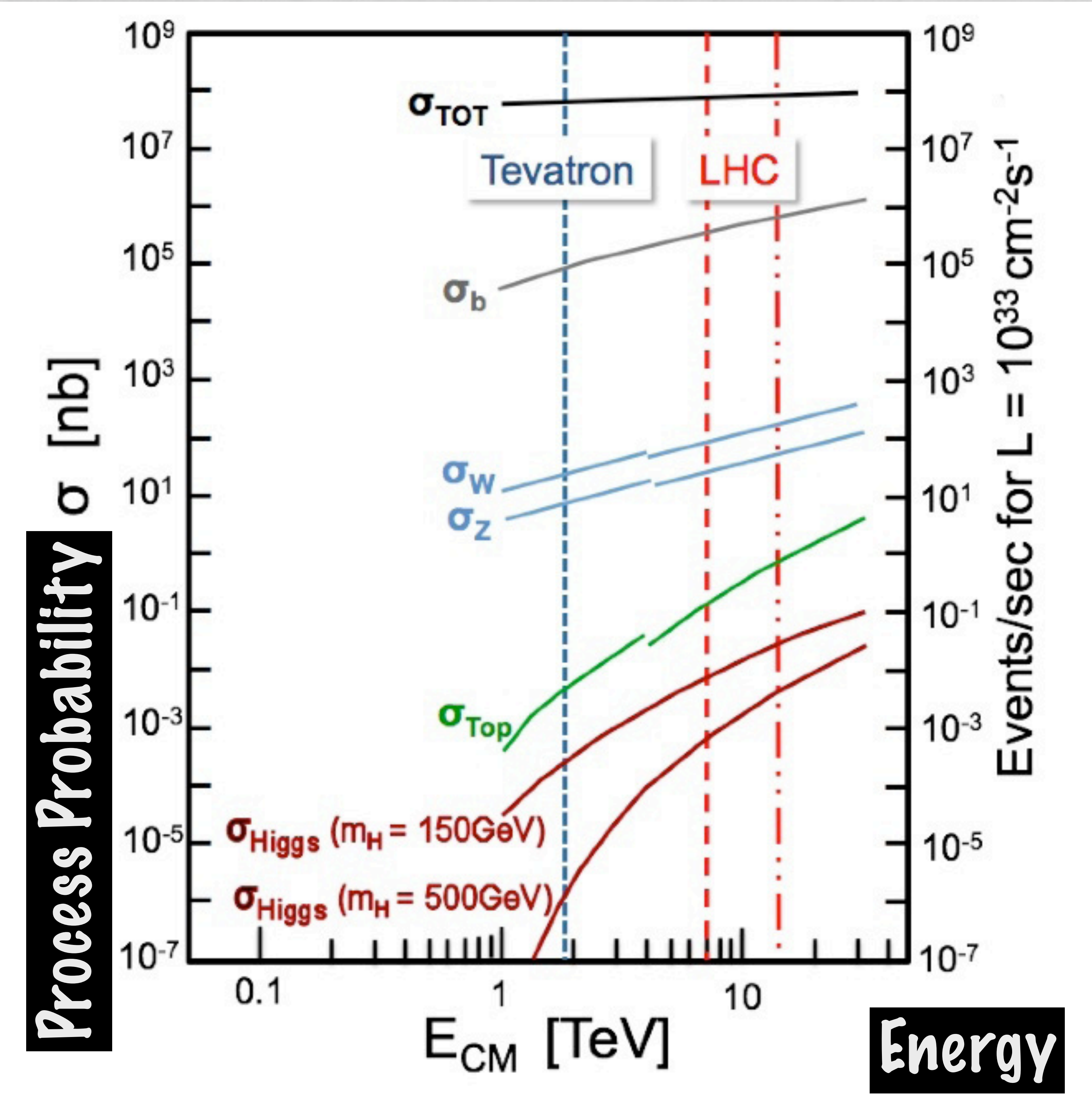


$$L = \int \mathcal{L} \times dt$$

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

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

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

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

Luminosity is paramount

$$L = \frac{f_{rev} n_b N_b^2}{4\pi\sigma^2} R_\phi$$

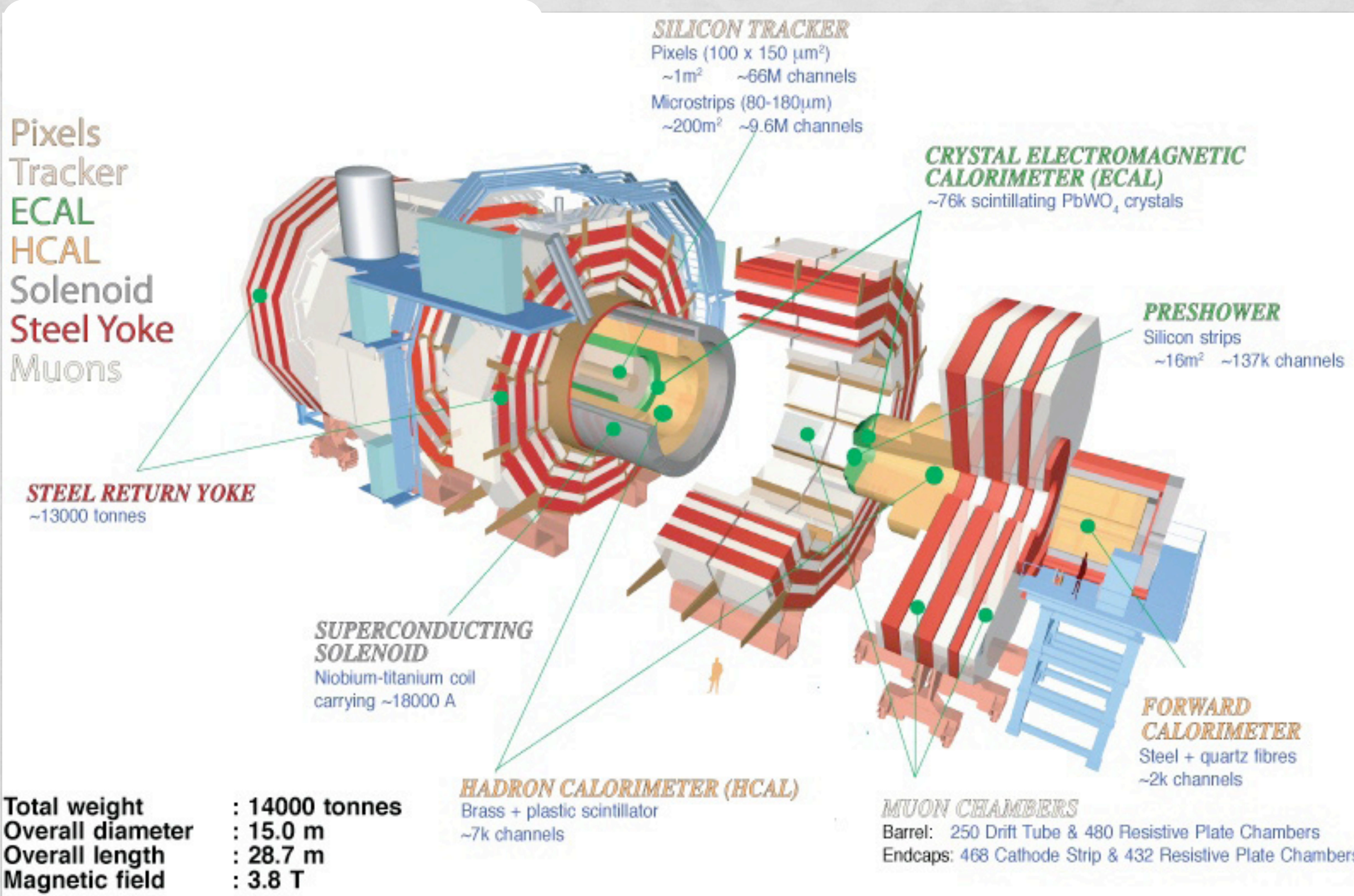
- Revolution frequency
- Number of bunches
- Bunch population
- Transverse beam size
- Geometric factor, related to crossing angle.

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

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
ε_n	Normalized emittance	Injector chain
β^*	Beta function value at Interaction Point (IP)	Interaction region focusing system
F	Reduction factor due to crossing angle	Beam separation schemes

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

And nothing wrong with having awesome detectors



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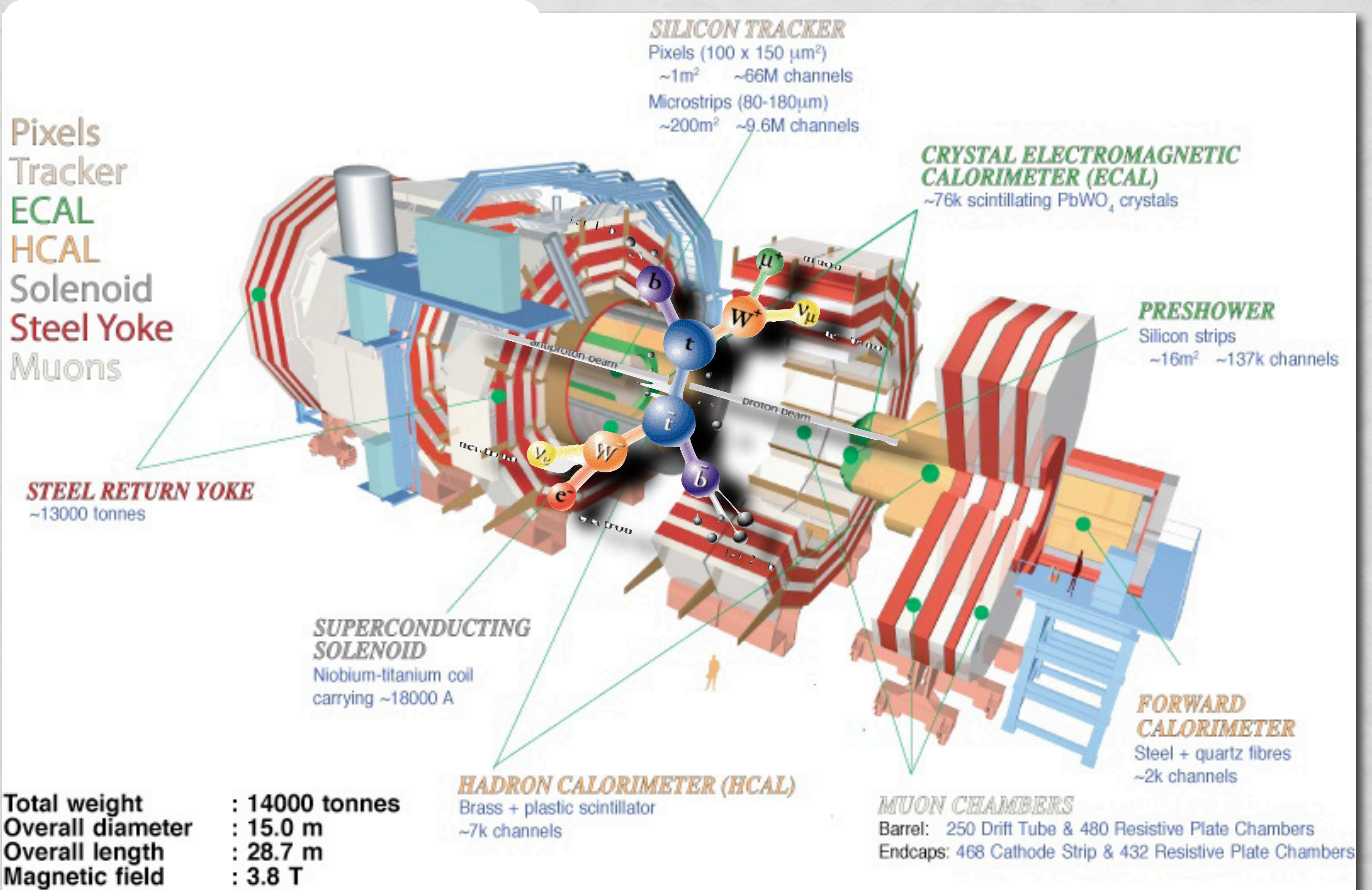
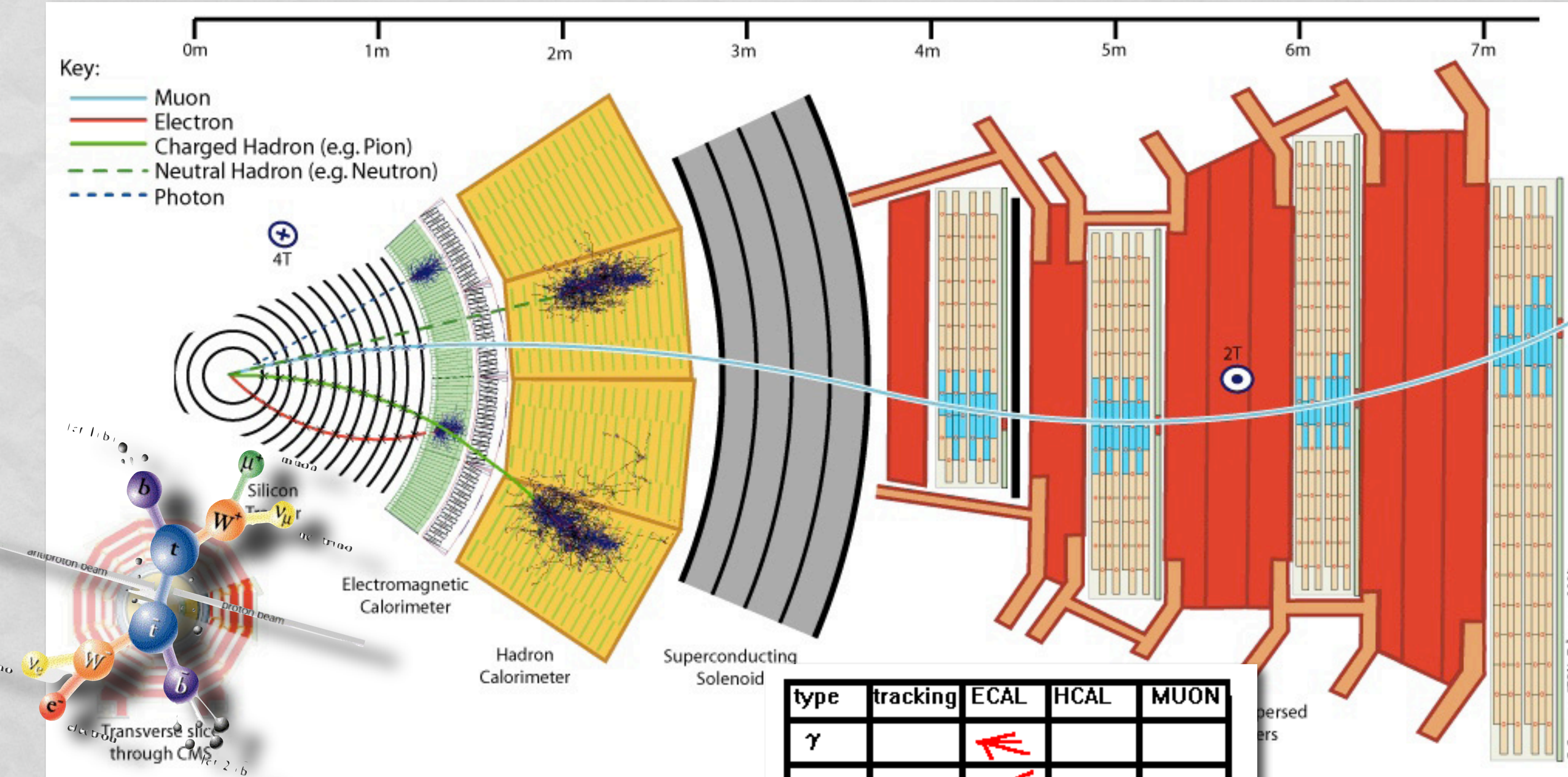
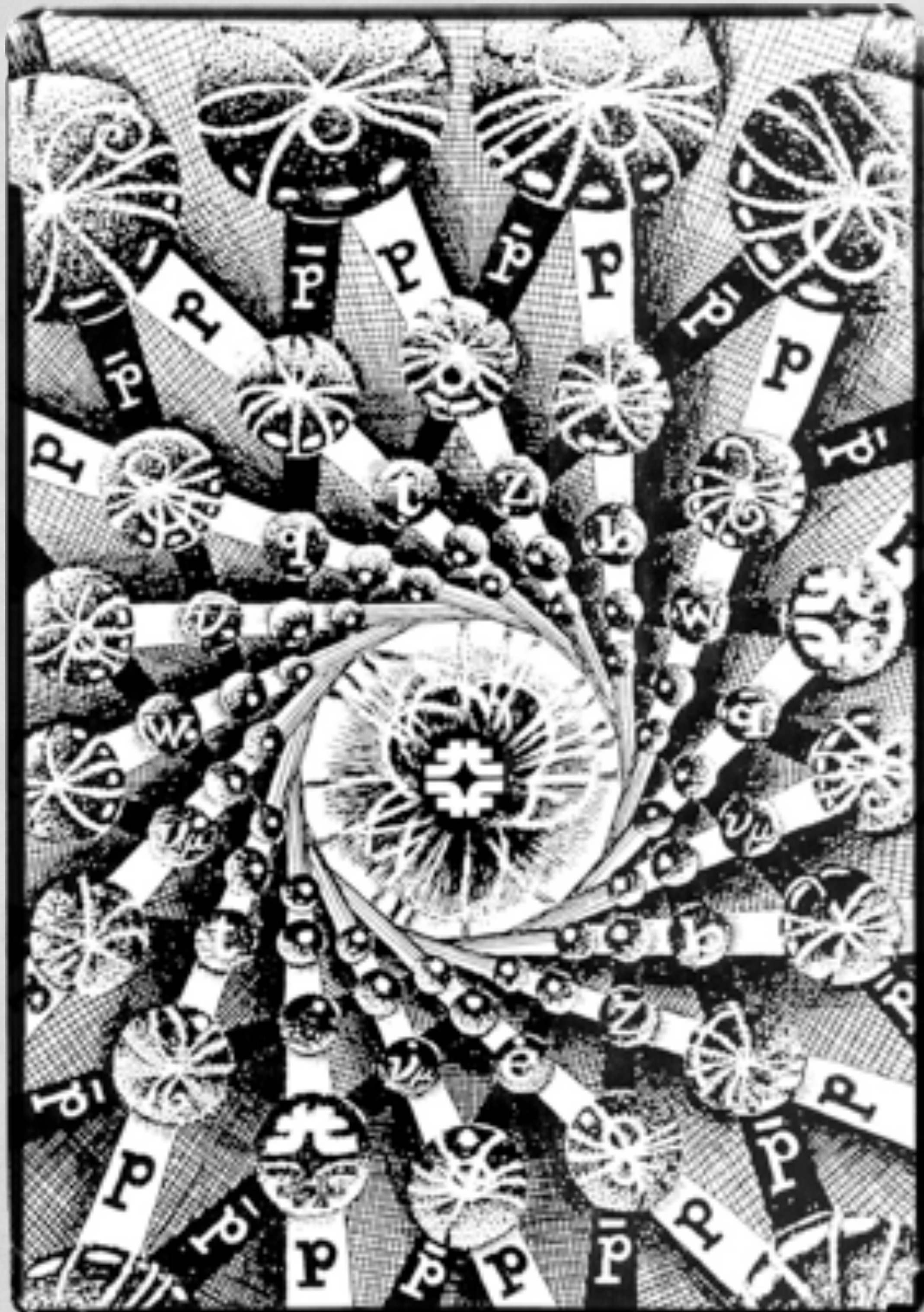


To catch and measure it all...



type	tracking	ECAL	HCAL	MUON
γ				
e				
μ				
Jet				
Et miss				

The Tevatron: A Storied Odyssey

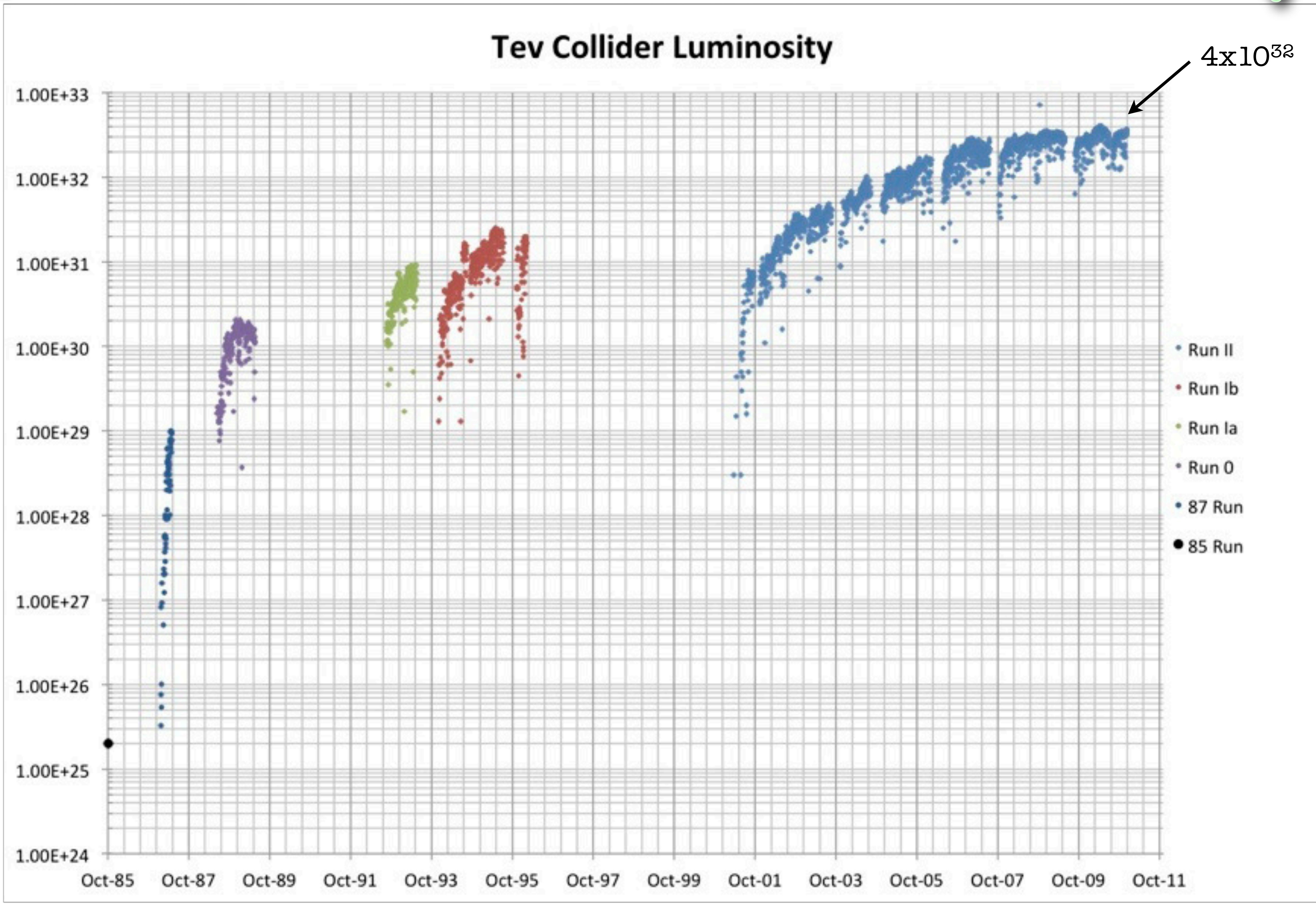


- Discoveries
  - New elementary particles
  - New composite particles
  - Rare SM processes
  - Subtle behavior
- New research areas
- Precision measurements
- Tests for New Physics
- Hunting down the Higgs

October 2010: 25th Anniversary of the first collisions !

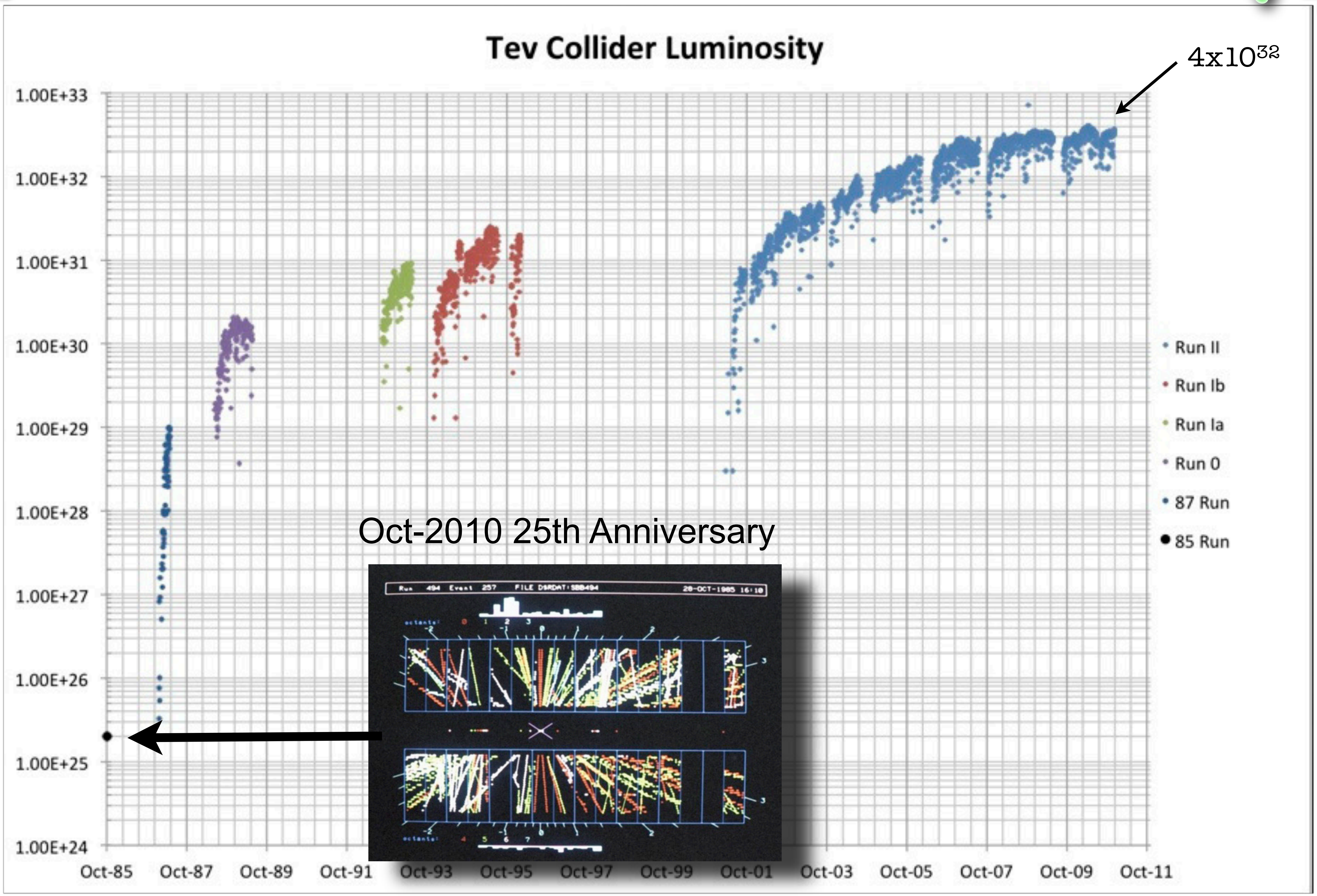
25 year Luminosity Evolution

A 7 orders of magnitude tour de force



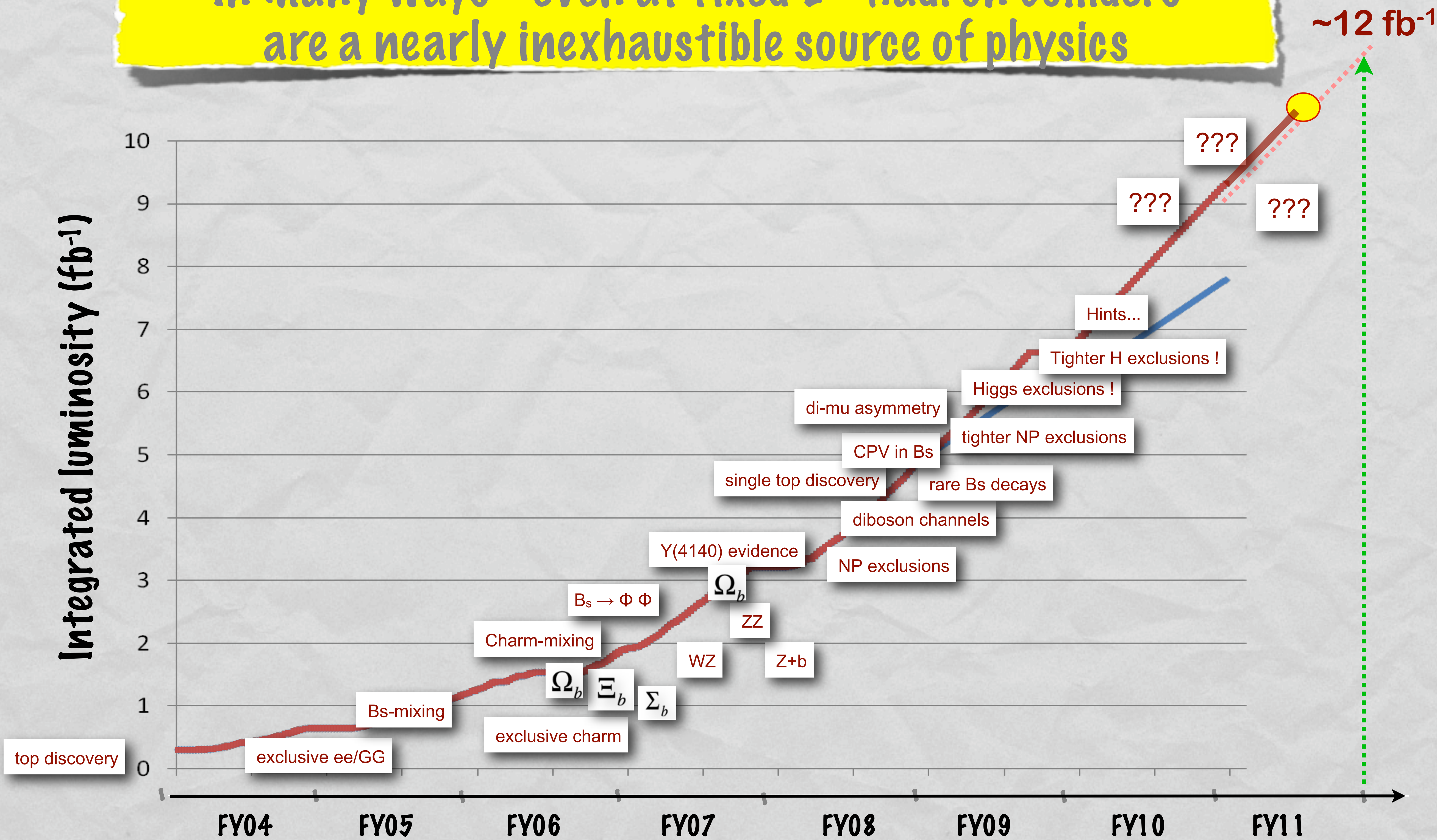
25 year Luminosity Evolution

A 7 orders of magnitude tour de force

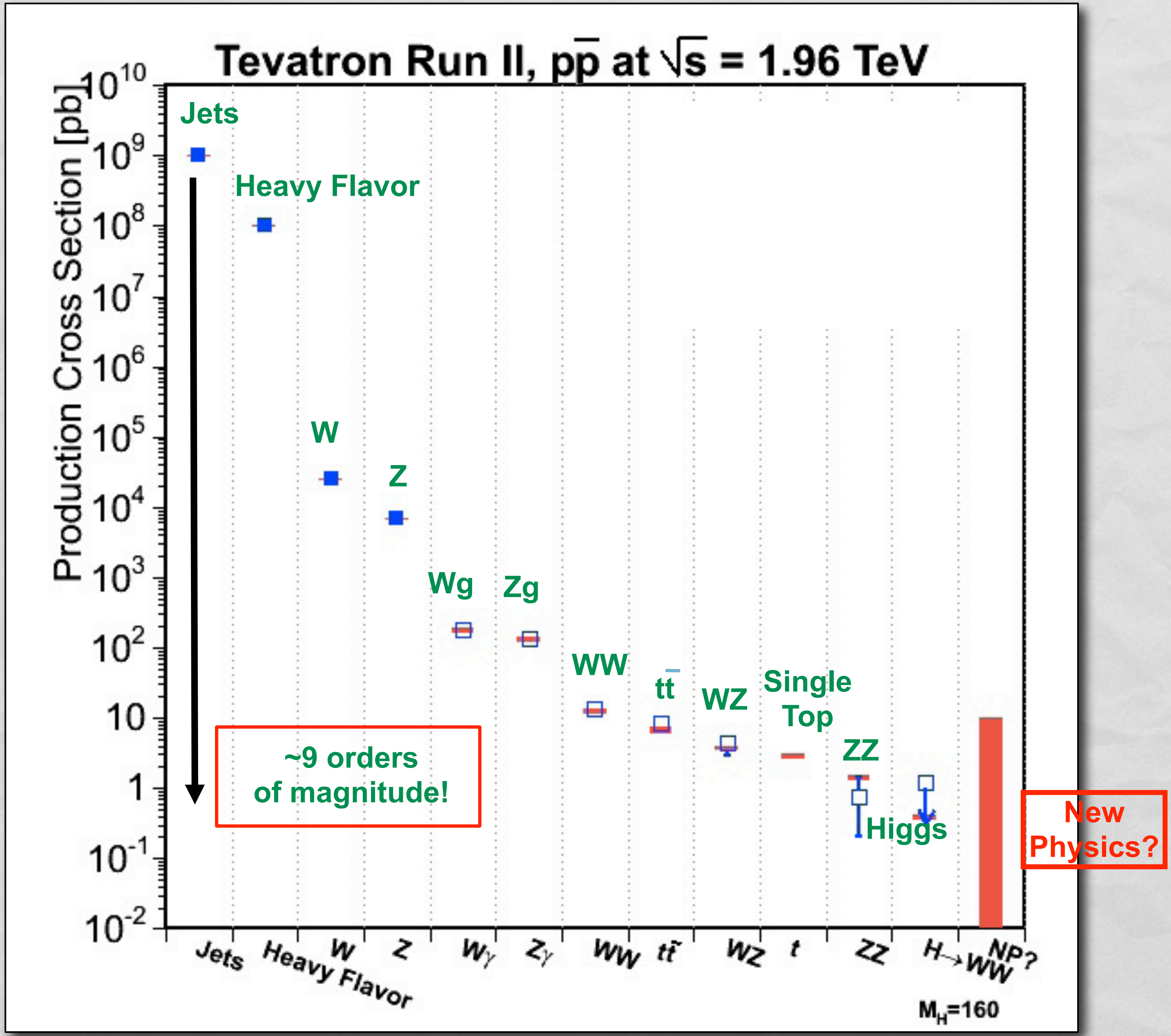


A Luminosity Story

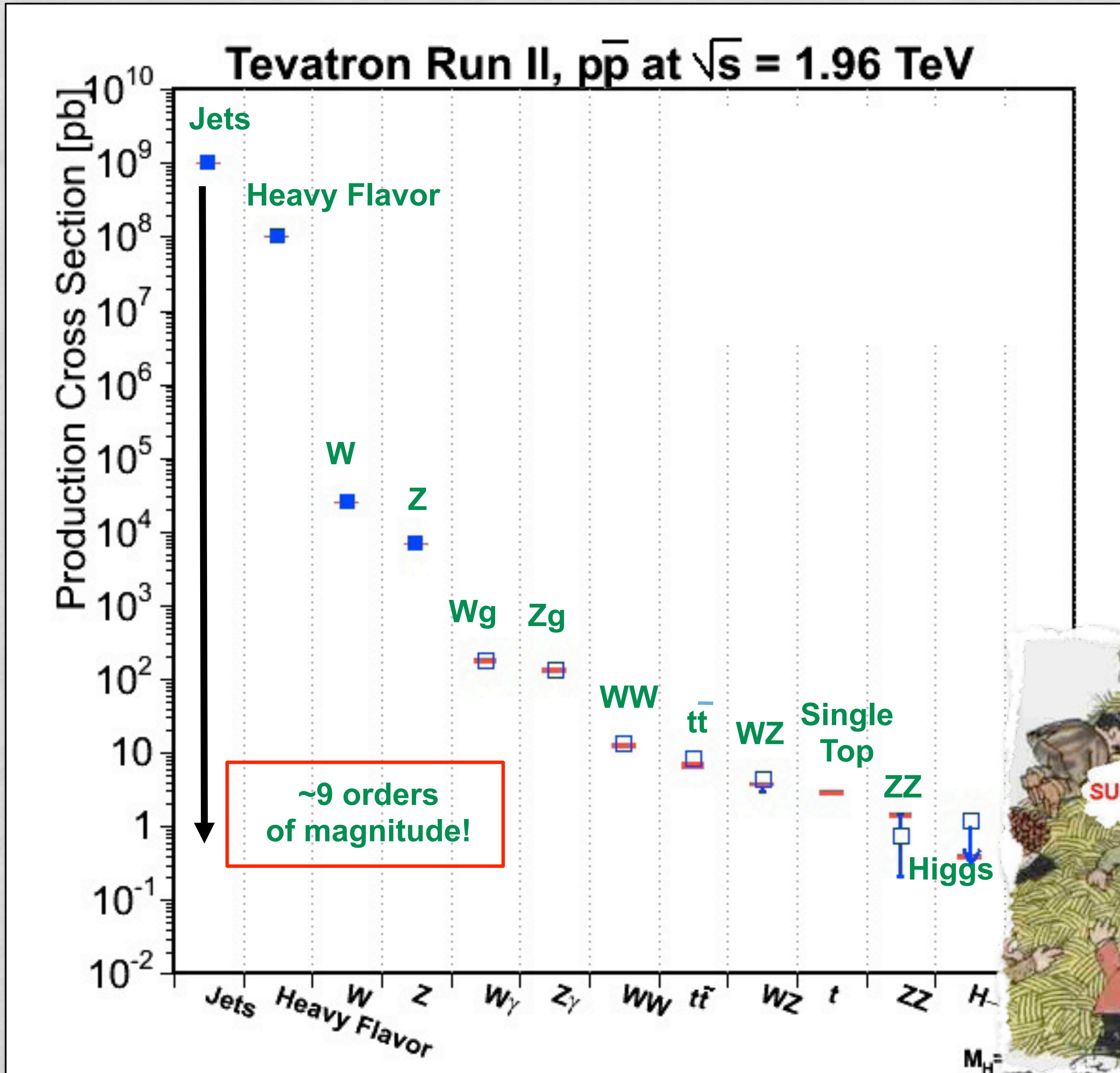
In many ways - even at fixed E - hadron colliders are a nearly inexhaustible source of physics



Digging…


Tevatron Run II, $p\bar{p}$ at $\sqrt{s}$ = 1.96 TeV
Production Cross Section [pb]
10^{10}
10^{9}
10^{8}
10^{7}
10^{6}
10^{5}
10^{4}
10^{3}
10^{2}
10
1
10^{-1}
10^{-2}
Jets
Heavy Flavor
W
Z
Wg
Zg
WW
$t\bar{t}$
WZ
Single Top
ZZ
Higgs
~9 orders of magnitude!
New Physics?
Jets
Heavy Flavor
W
Z
$W\gamma$
$Z\gamma$
WW
$t\bar{t}$
WZ
t
ZZ
$H \to WW$
NP?
M_H=160

Digging...



Tevatron Run II, p$\bar{p}$ at $\sqrt{s}$ = 1.96 TeV
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10^{-2}
Jets
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W
Z
Wg
Zg
WW
t$\bar{t}$
WZ
Single Top
ZZ
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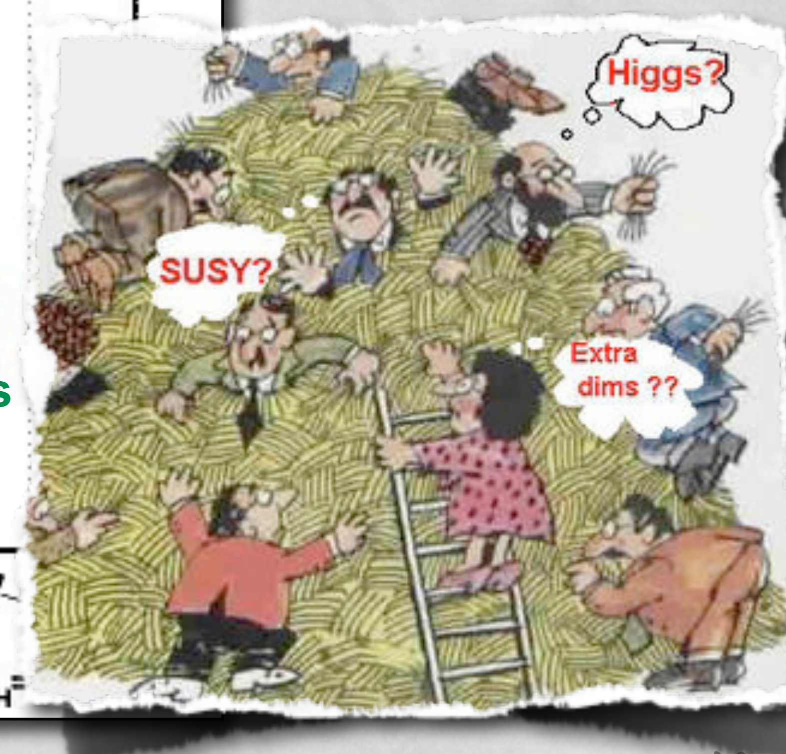
~9 orders of magnitude!
Jets
Heavy Flavor
W
Z
Wγ
Zγ
WW
t$\bar{t}$
WZ
t
ZZ



Higgs?
SUSY?
Extra dims ??

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)

Discoveries on the Horizon?

arXiv.org > hep-ex > arXiv:1005.2757

High Energy Physics - Experiment

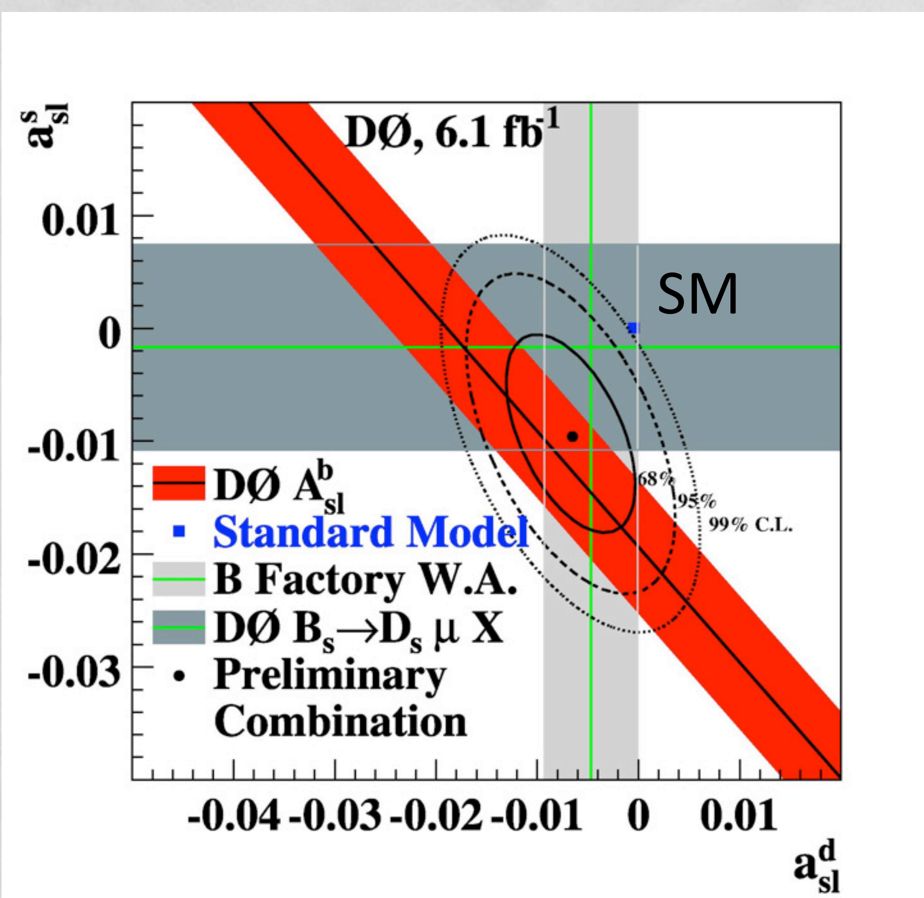
Evidence for an anomalous like-sign dimuon charge asymmetry

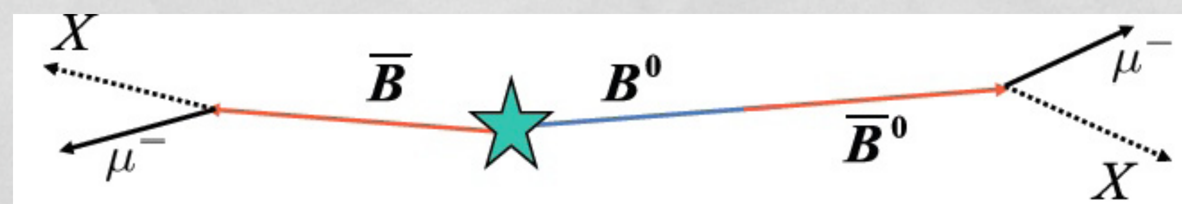
The D0 Collaboration: V.M. Abazov, et al

(Submitted on 16 May 2010)

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





$$A_{sl}^b \equiv \frac{N_b^{++} - N_b^{--}}{N_b^{++} + N_b^{--}}$$

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-tbar production asymmetry and its rapidity and mass dependence. The measurements are performed with 5.3 fb^{-1} of p-pbar 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-tbar rest frame, and are consistent with CP conservation under interchange of t and tbar. In the t-tbar rest frame, the asymmetry increases with the t-tbar rapidity difference, \Delta(y), and with the invariant mass M_{t-tbar} of the t-tbar 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-tbar}. For M_{t-tbar} > 450 GeV/c^2, the parton-level asymmetry in the t-tbar rest frame is A^{t-tbar} = 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
FEBR
VIEW CURRE

Interesting effect at the Tevatron hints at new physics

March 18, 2011 | 9:00 am

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

...ron Collider may be on the verge of ... according to mounting evidence from ... Tevatron.

... not the Higgs.

... of new physics through the study of a ... discovered at the Tevatron, the top ...

... anti-particles, anti-top quarks, are ... s at the Tevatron, detectors note the ... Theory predicts that the particles will ... over the other, traveling that way about ...

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

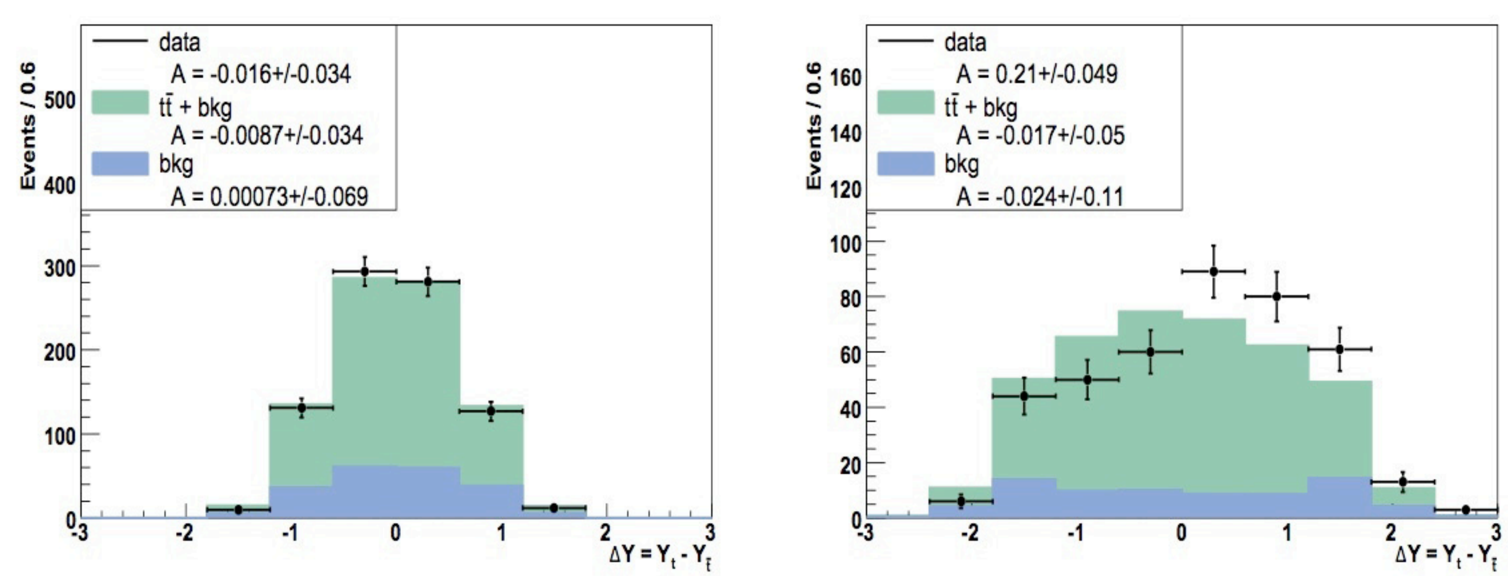
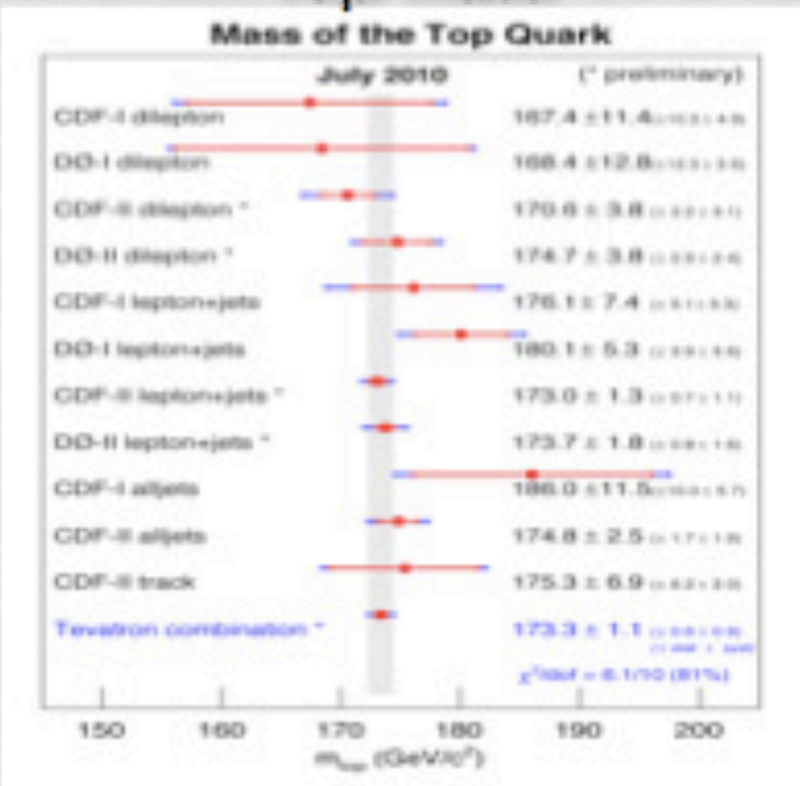
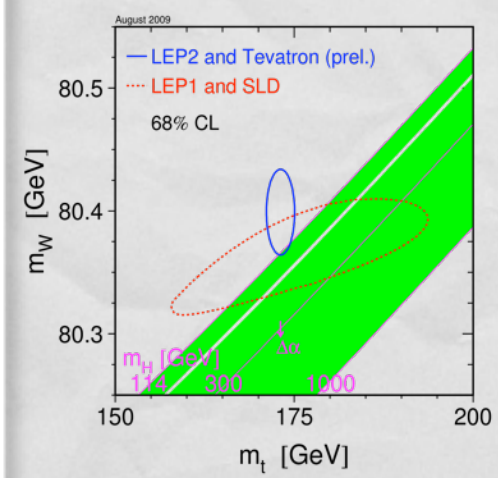


FIG. 12: Top: The distribution of Δy at low mass (left) and high mass (right).

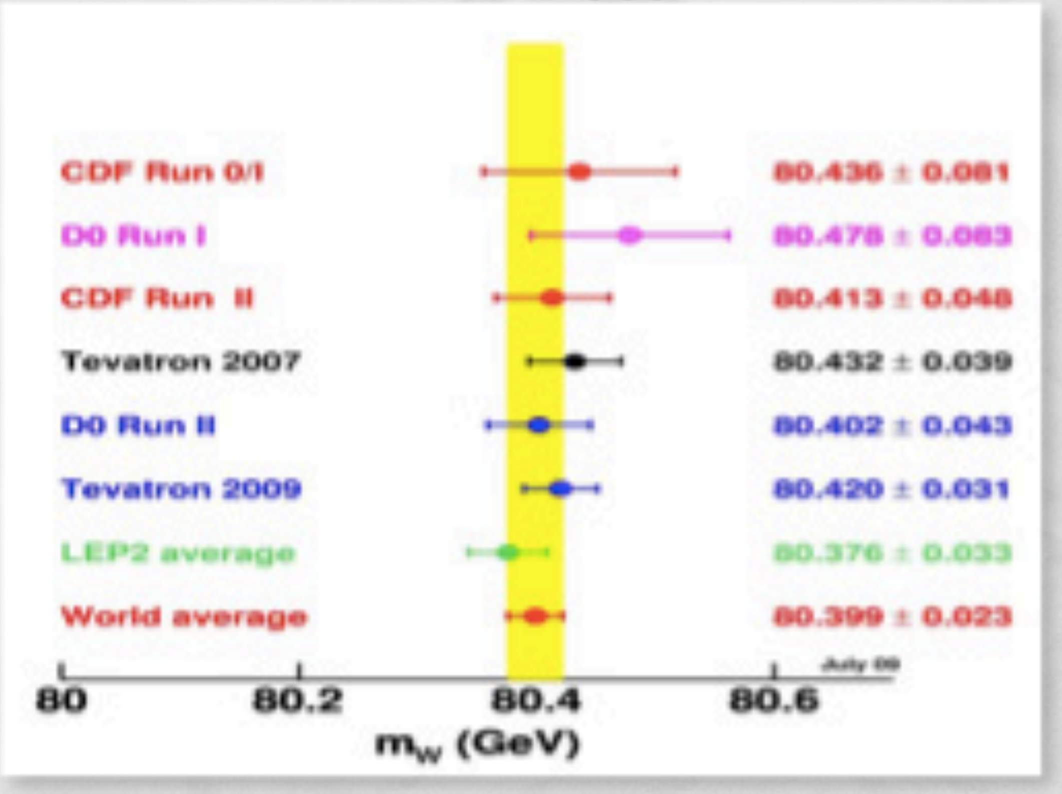
Legacy measurements

Top mass



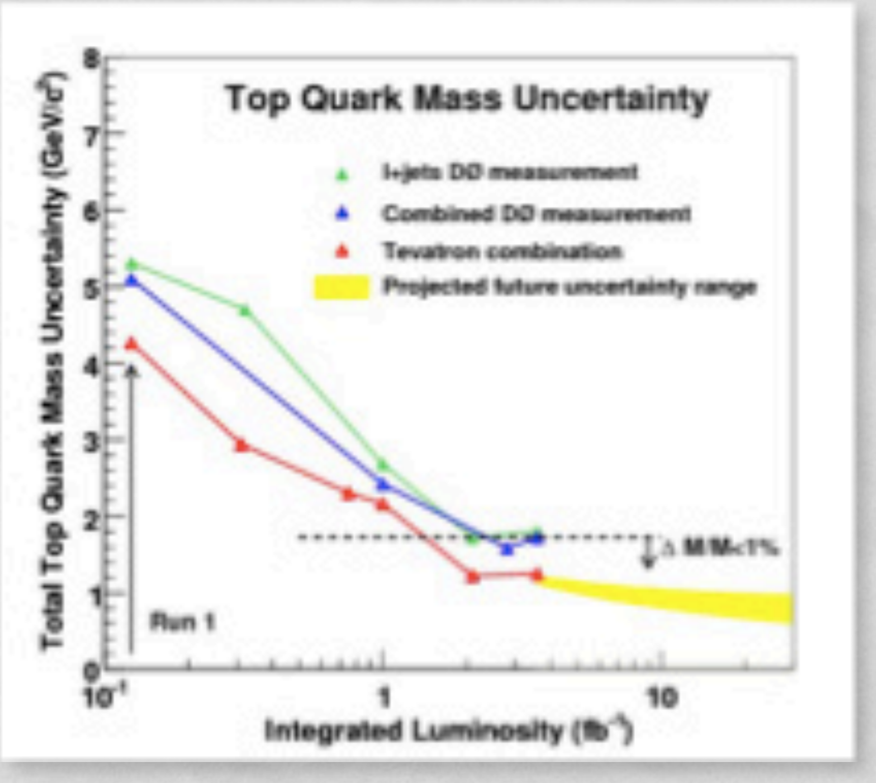


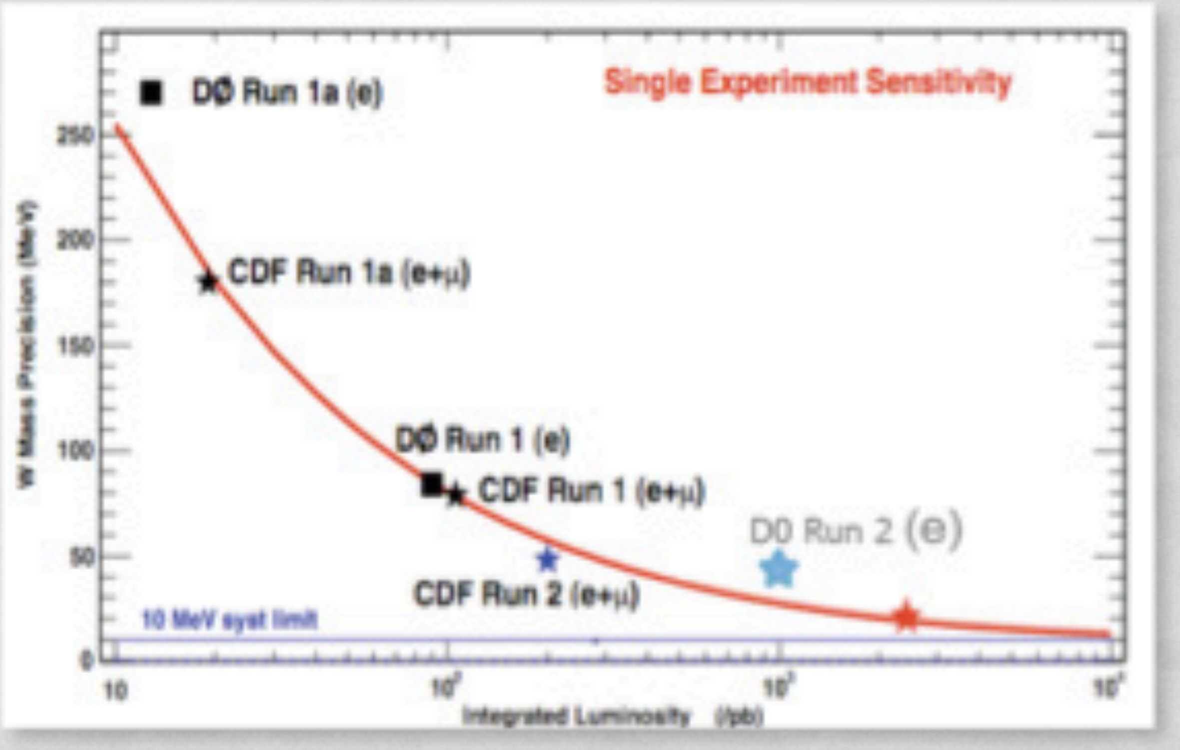
W mass



Current Tevatron precision: 0.7%

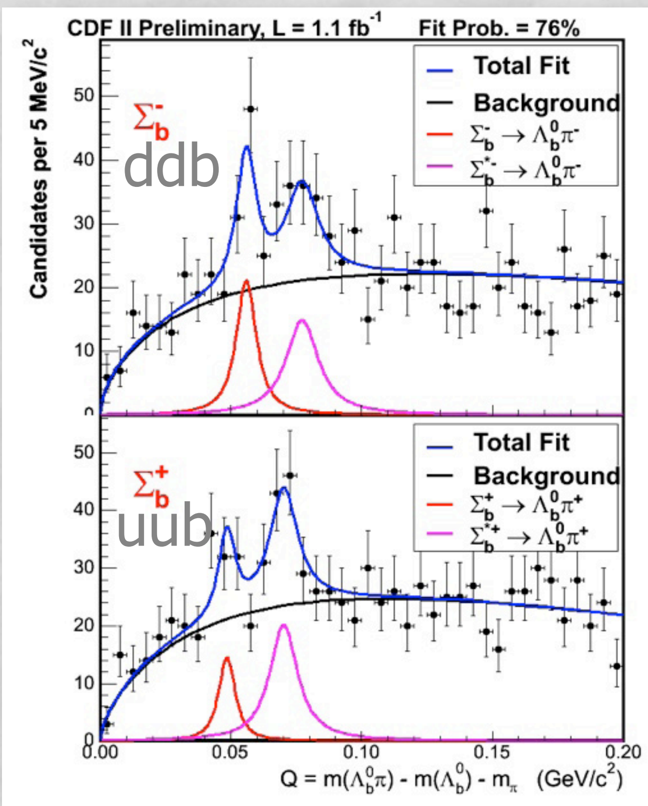
Current Tevatron precision: 0.04%





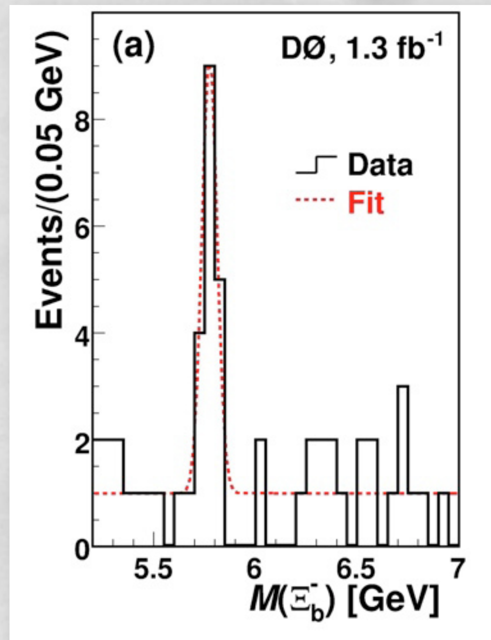
Observation of new heavy baryons

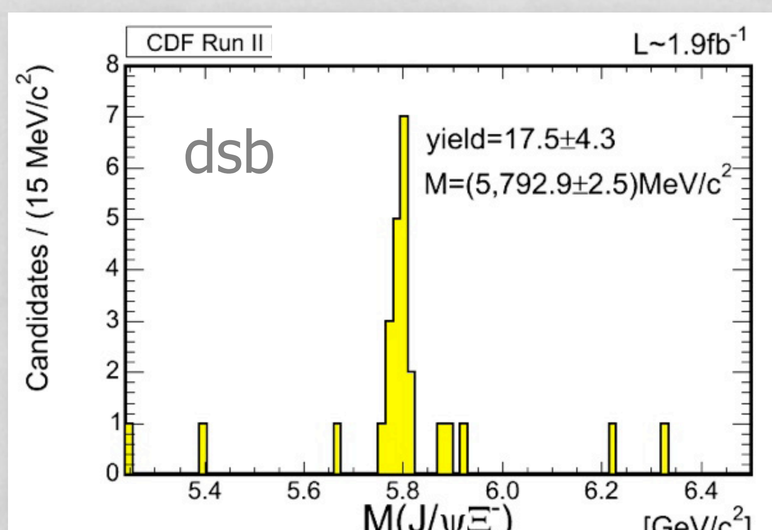
Σ_b



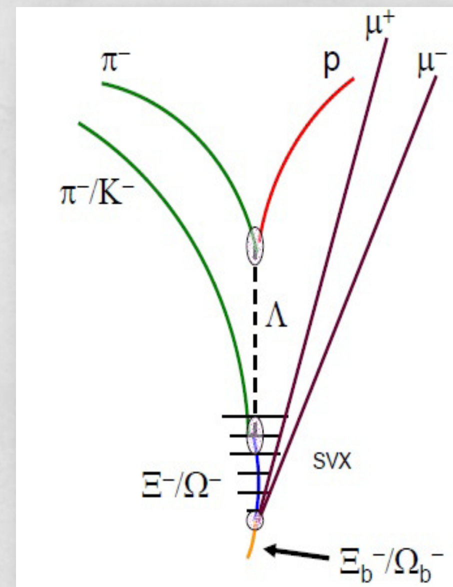
2006

Ξ_b

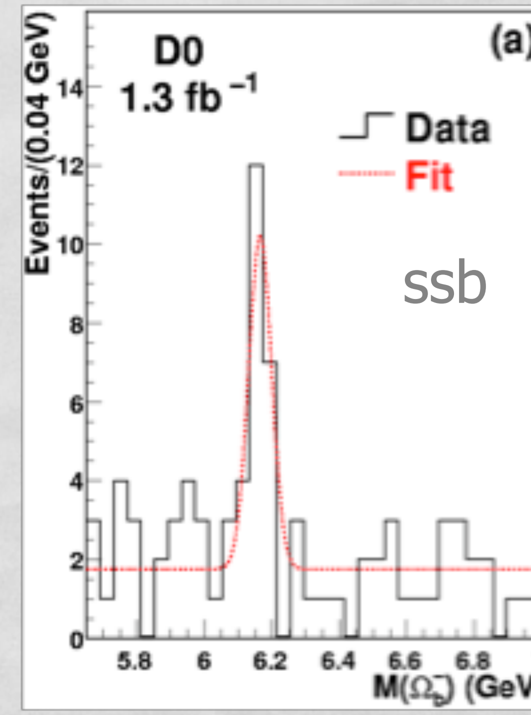


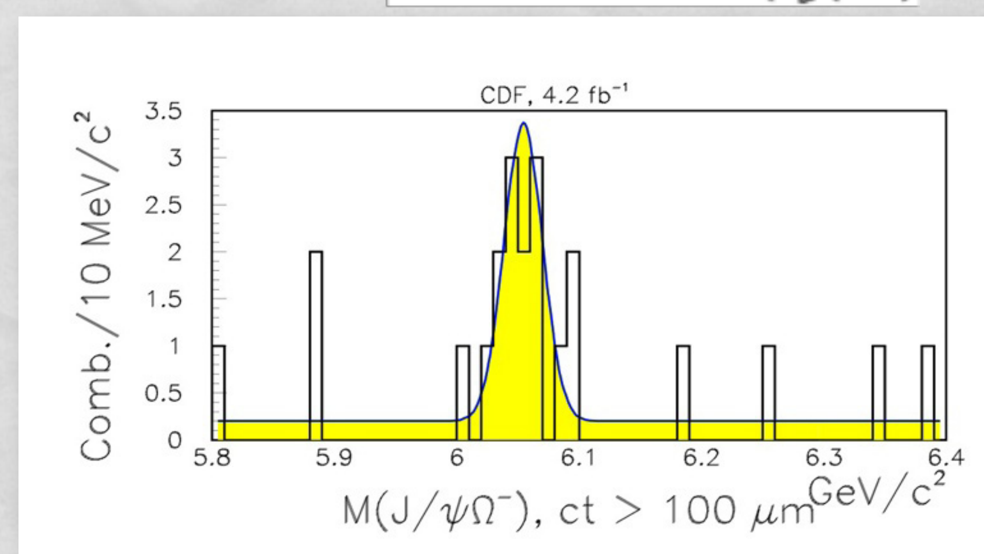


2007



Ω_b





2008/2009

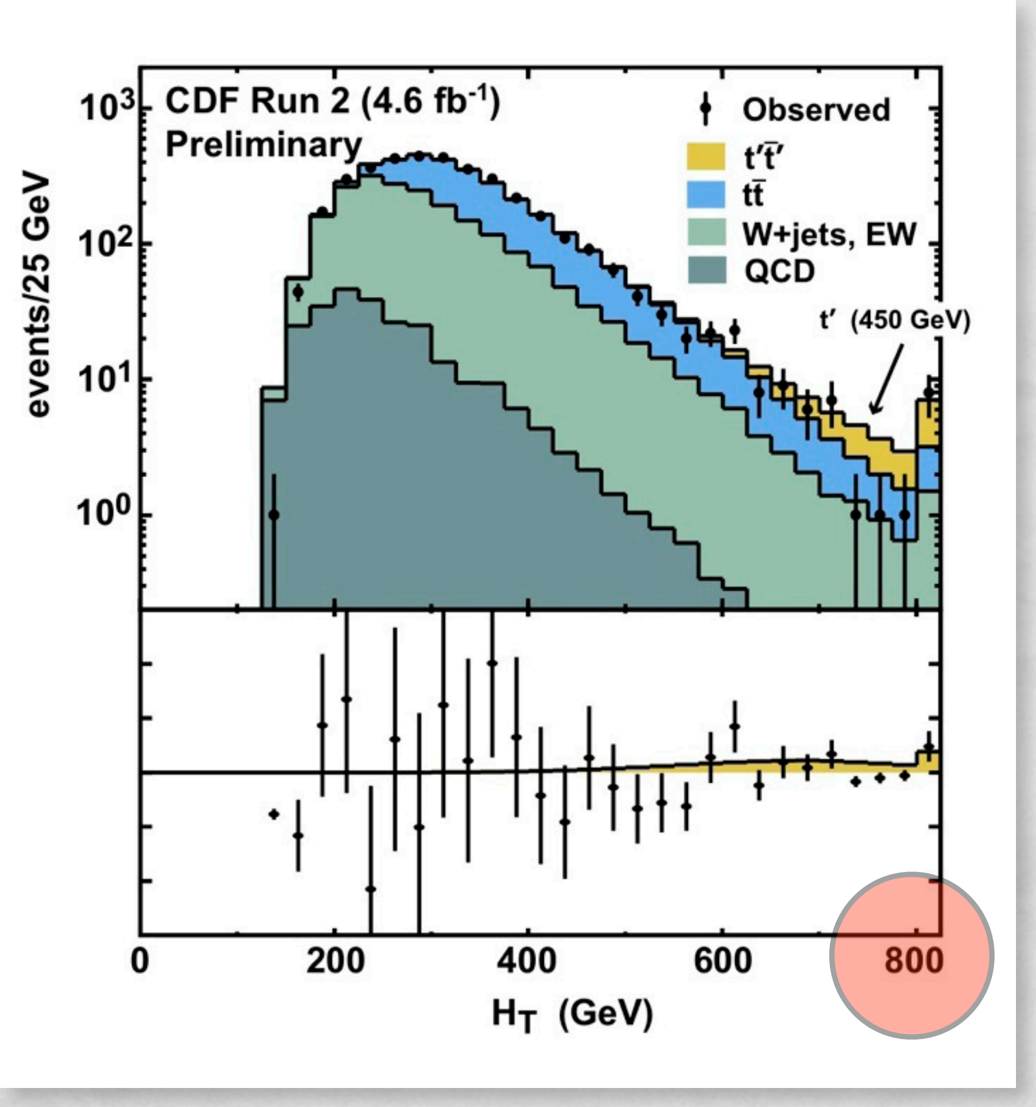
Searches for new particles

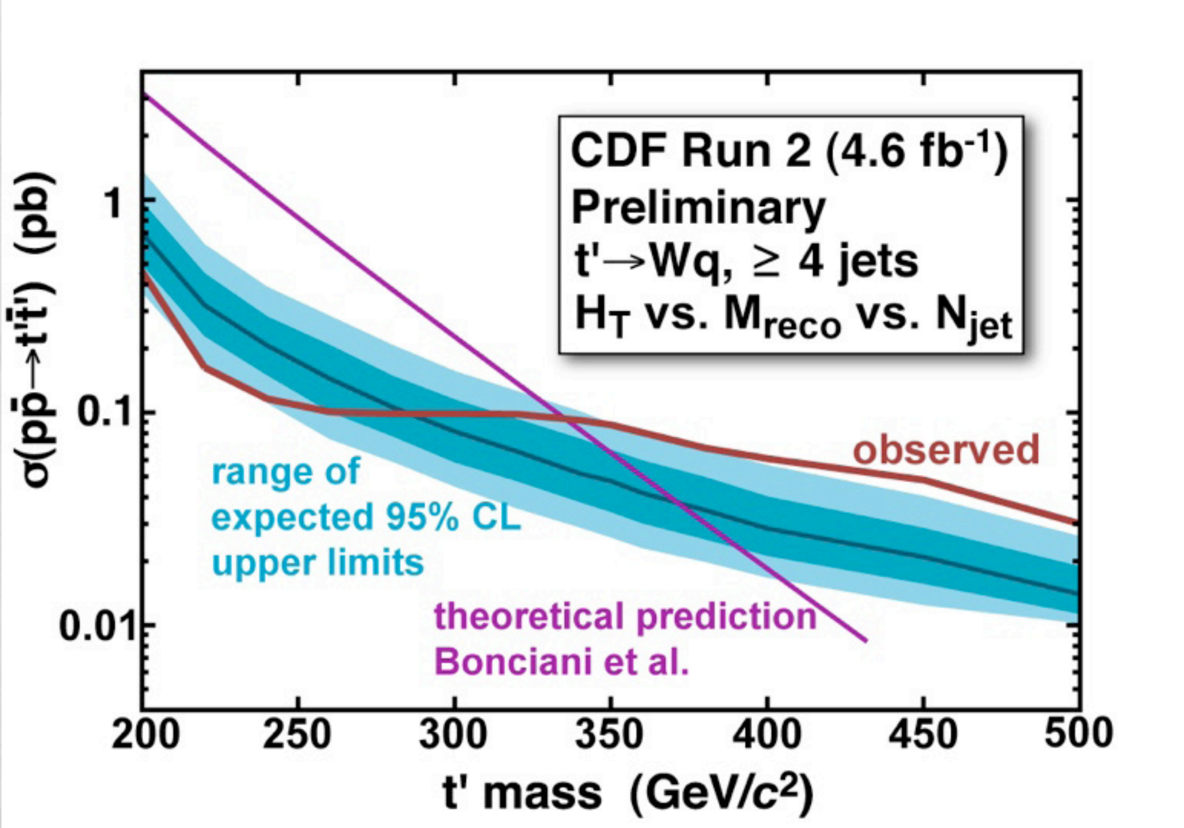
- SUSY pushed up in energy
  - charginos/neutralinos > O(200) GeV
  - squarks > O(400) GeV
    (all gluino masses)
  - gluinos > O(300) GeV
    (all squark masses)
  - stop, sbottom > O(250) GeV

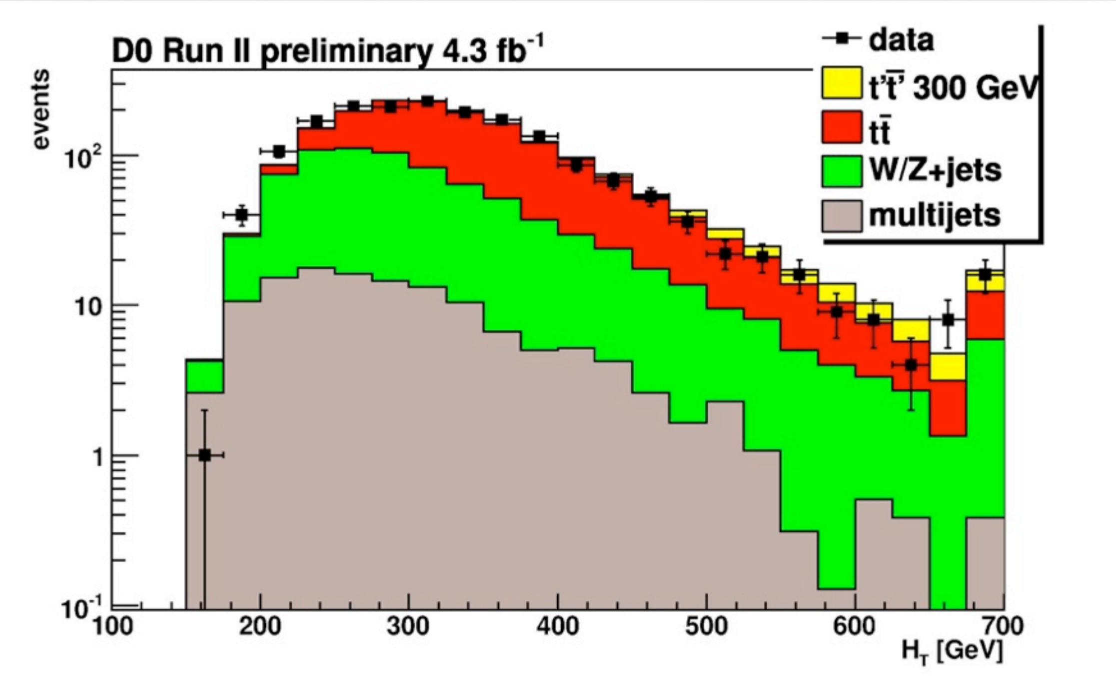
- Other models and new generation particles also up
  - b' and t' > O(400) GeV
  - W' and Z' > O(800) GeV

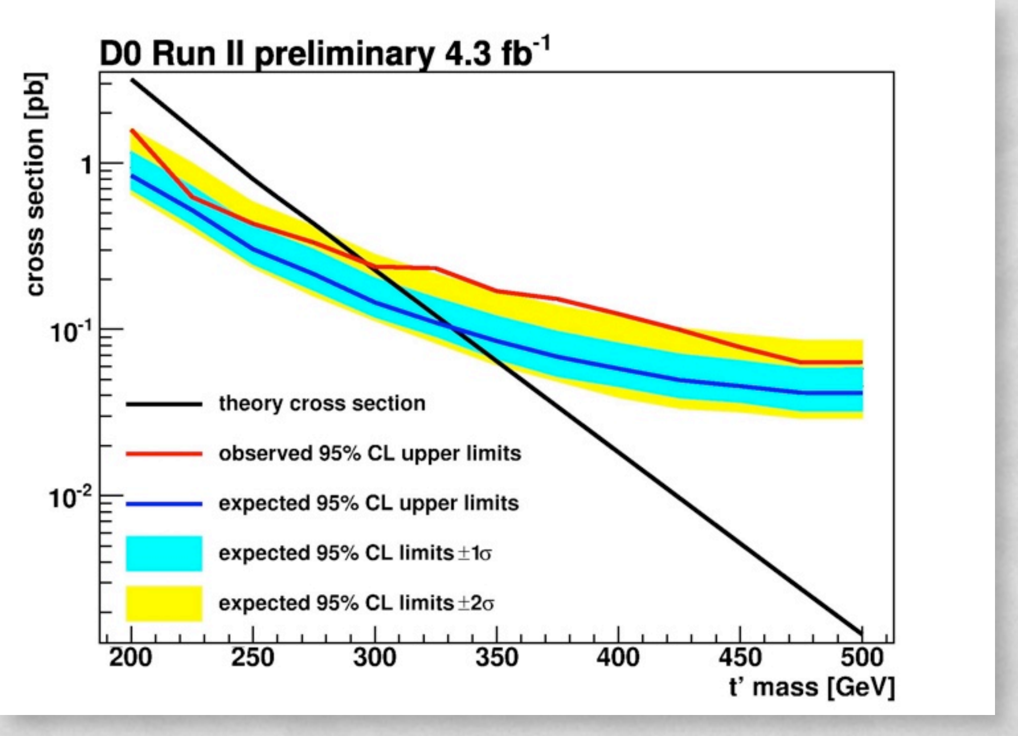
tt samples - keep an eye on:

t-prime search

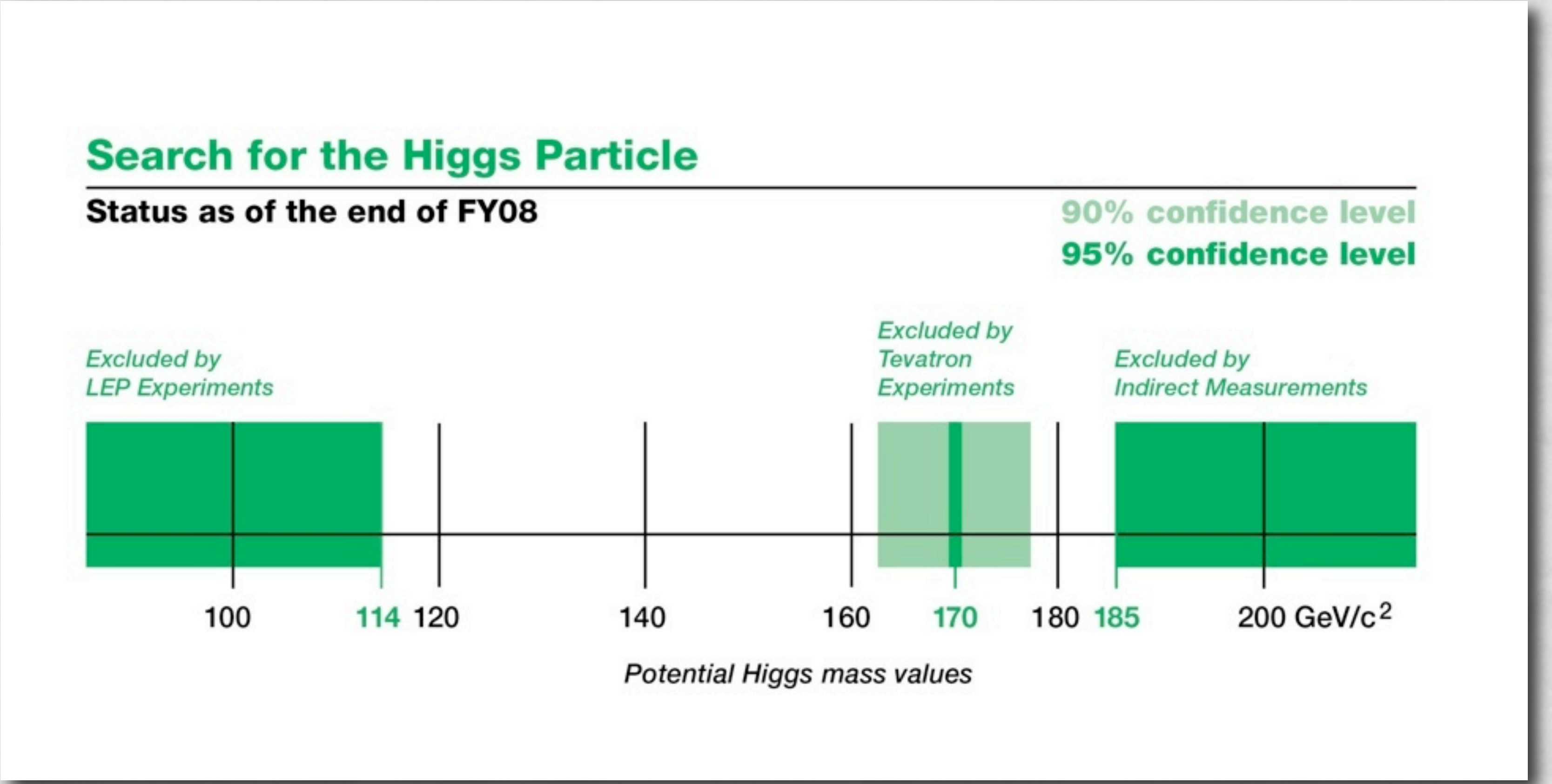




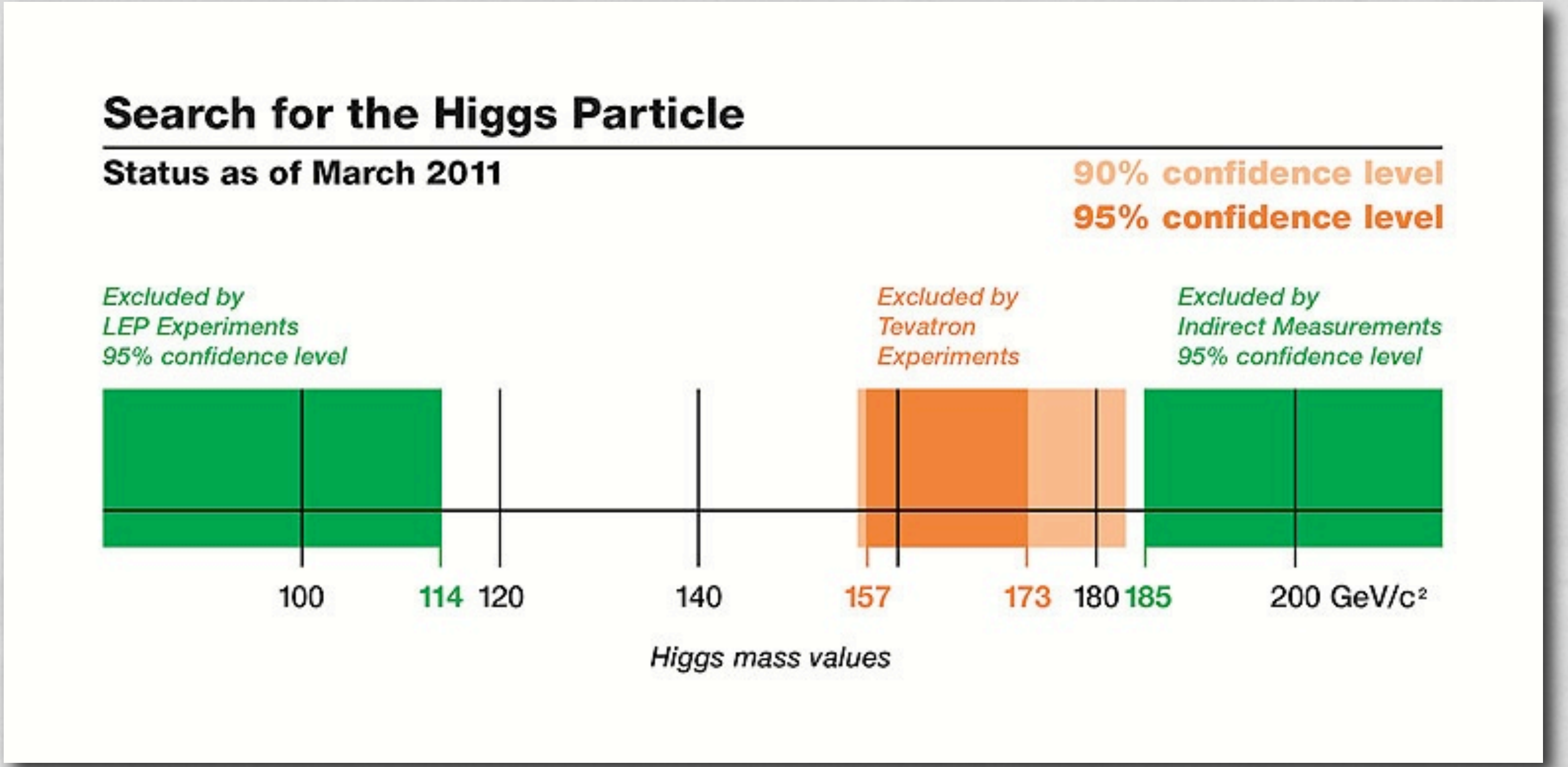




The Higgs Hunt



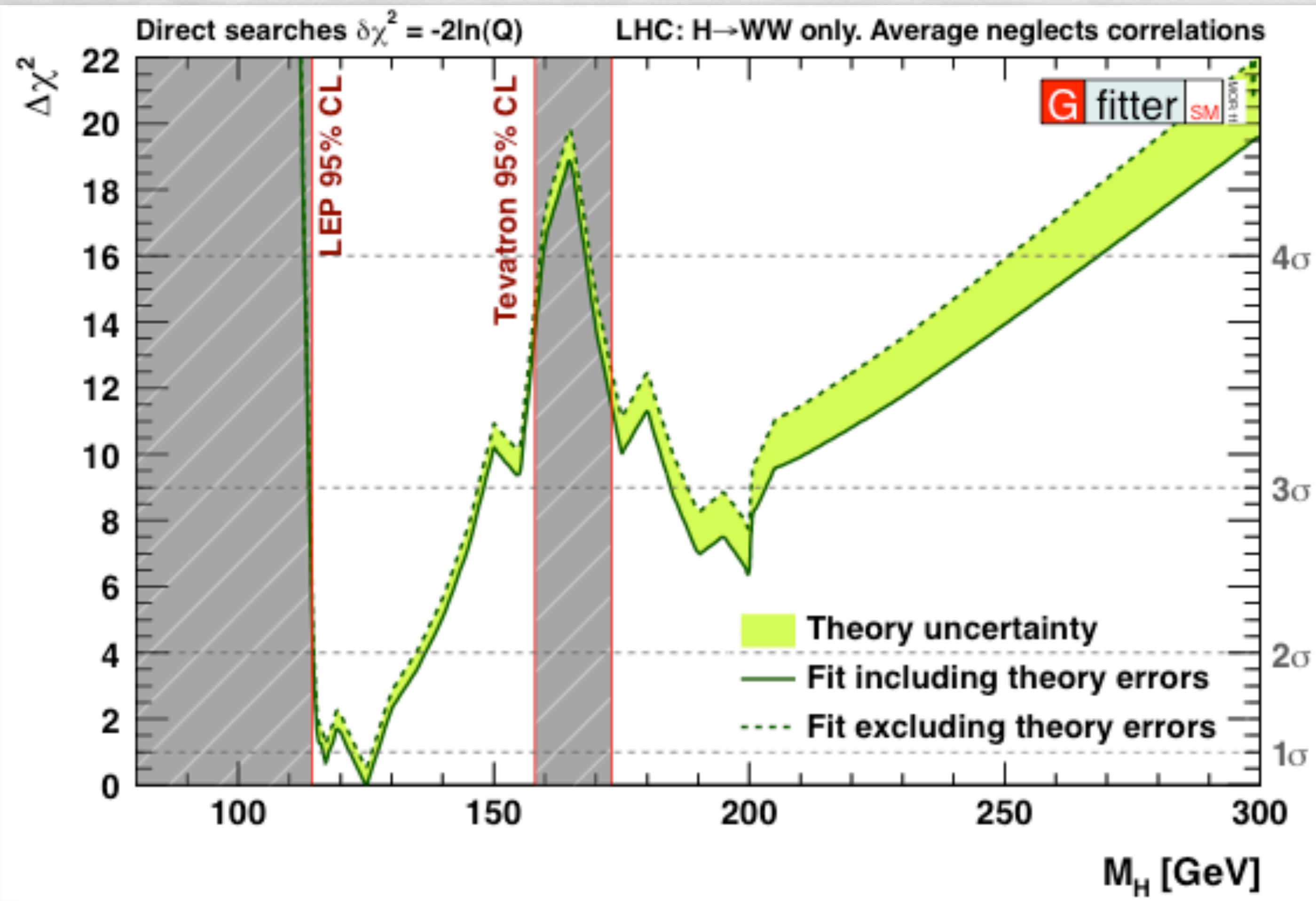
2008

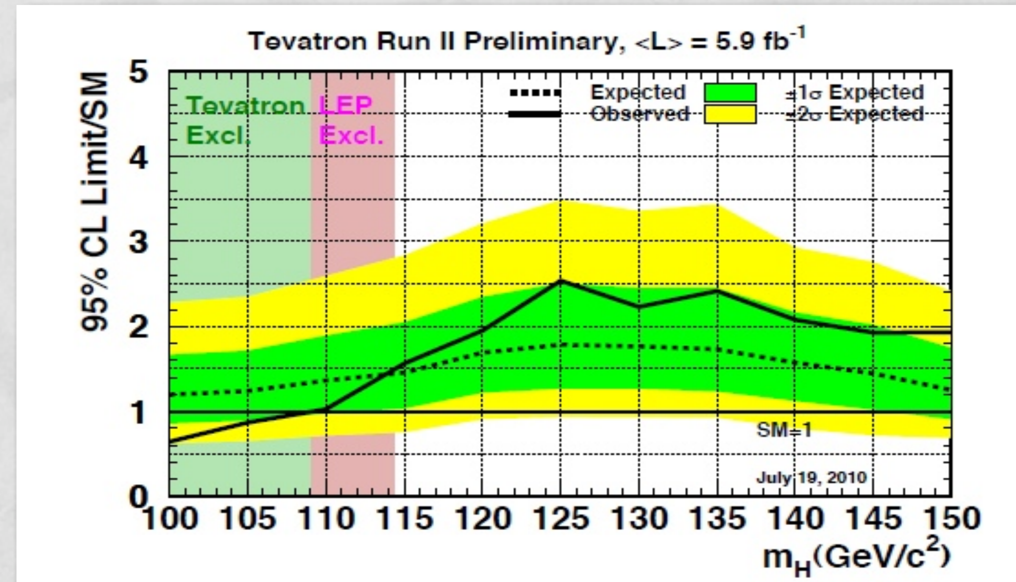


2 yrs later

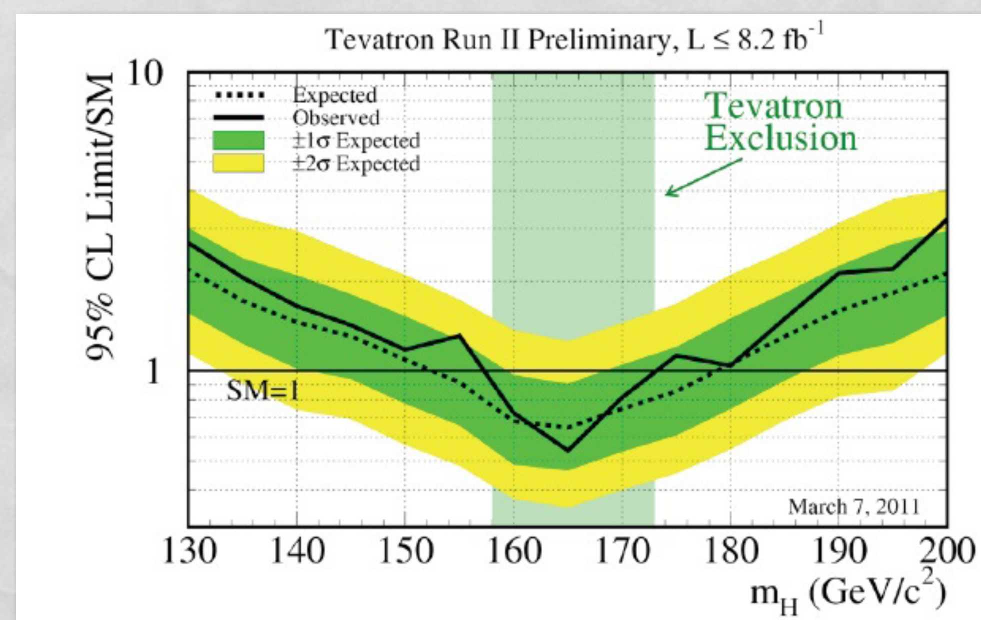
The Higgs Hunt

~Inv. probability vs Higgs Mass





"low" mass



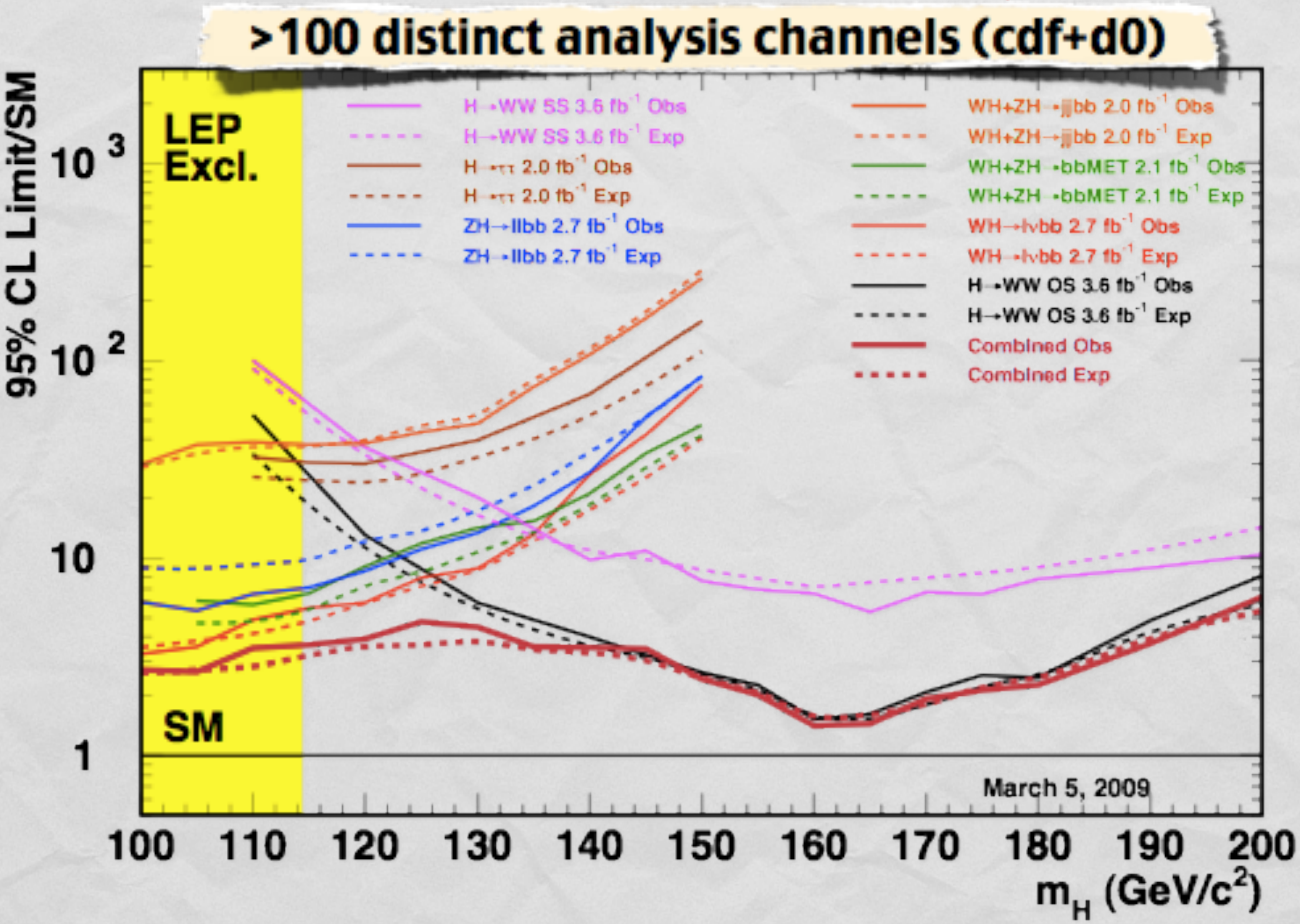
"high" mass

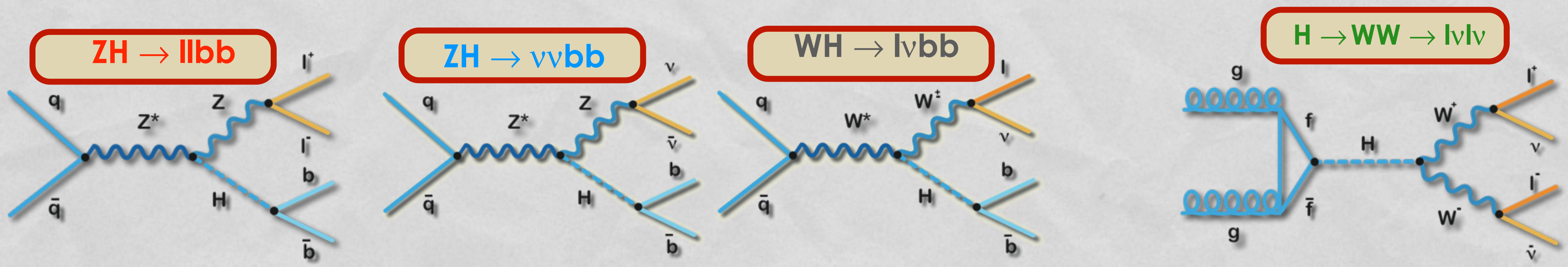
Most probable value:

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

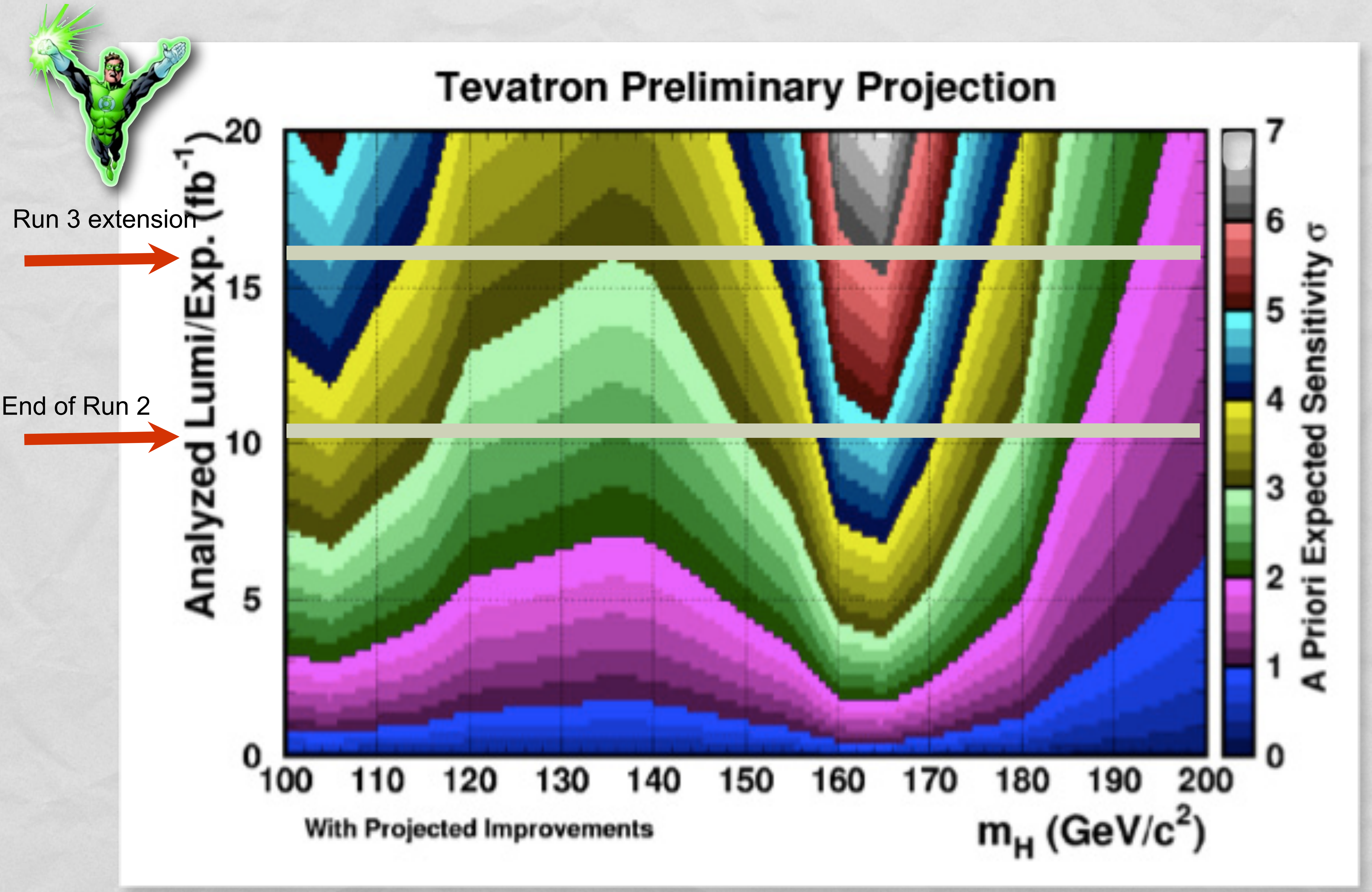
2-std. dev. interval ~ [114,145]

The Higgs search: a monumental effort





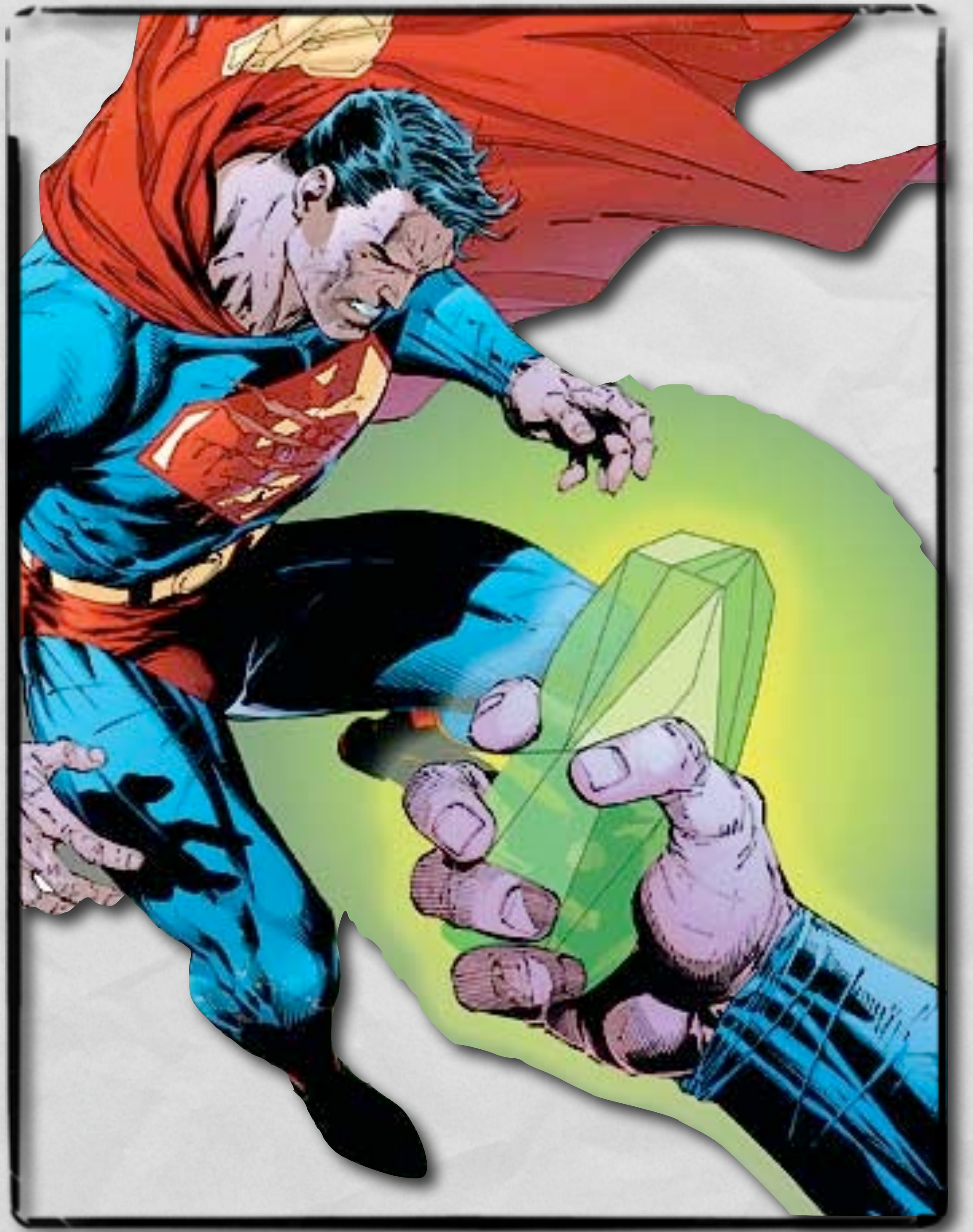
Higgs reach with more Luminosity

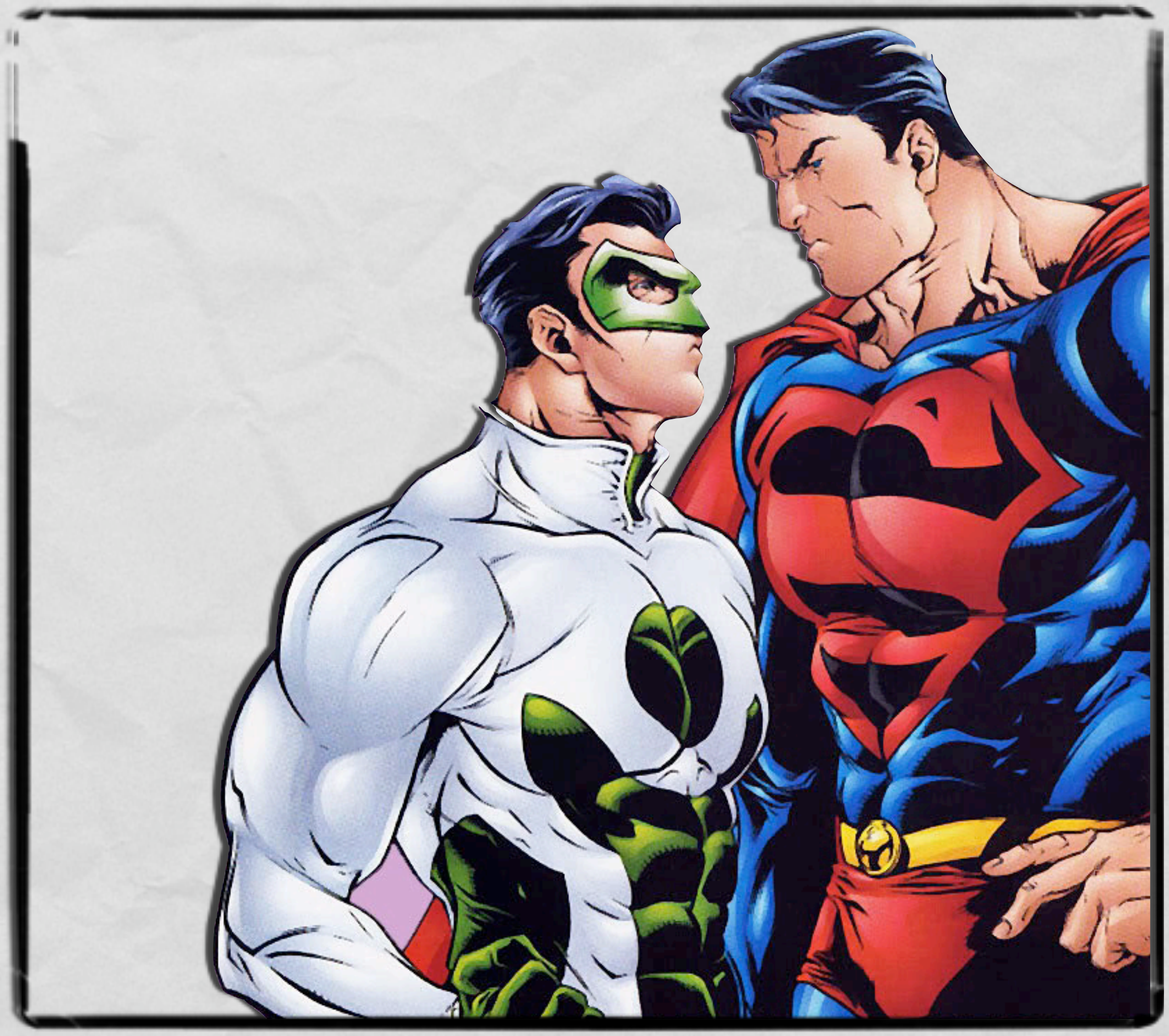


With 10 fb^{-1} analyzed > 95% CL sensitivity is possible for all allowed SM masses !

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 for~~ find new physics at the TeV scale
- Identify the particle(s) that make the Dark Matter in the Universe

Also:

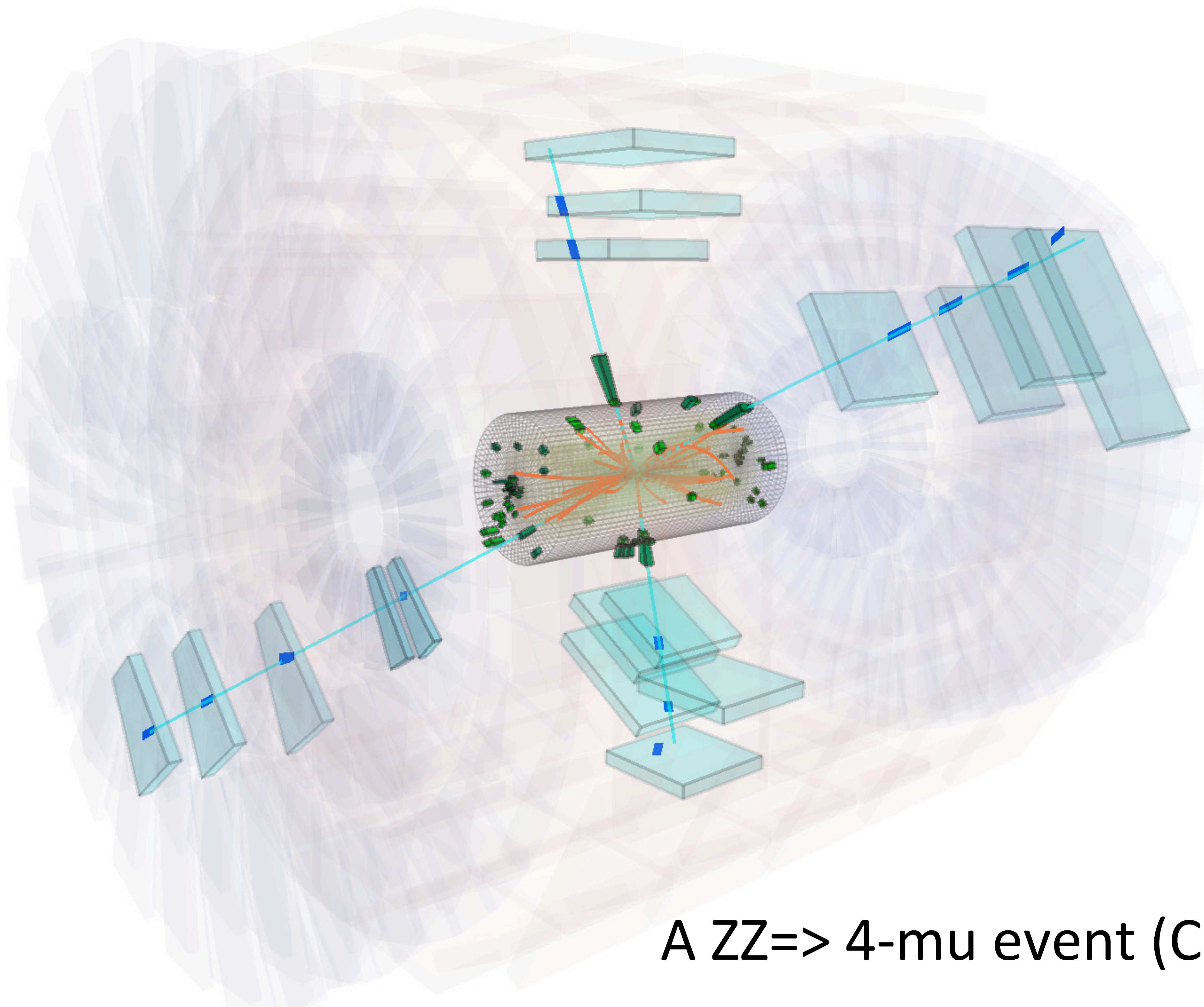
- LHCb: precision B physics (CKM matrix and CP violation)
- ALICE: Heavy ion collisions & QCD phase diagram

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

The future of particle physics rests on the LHC

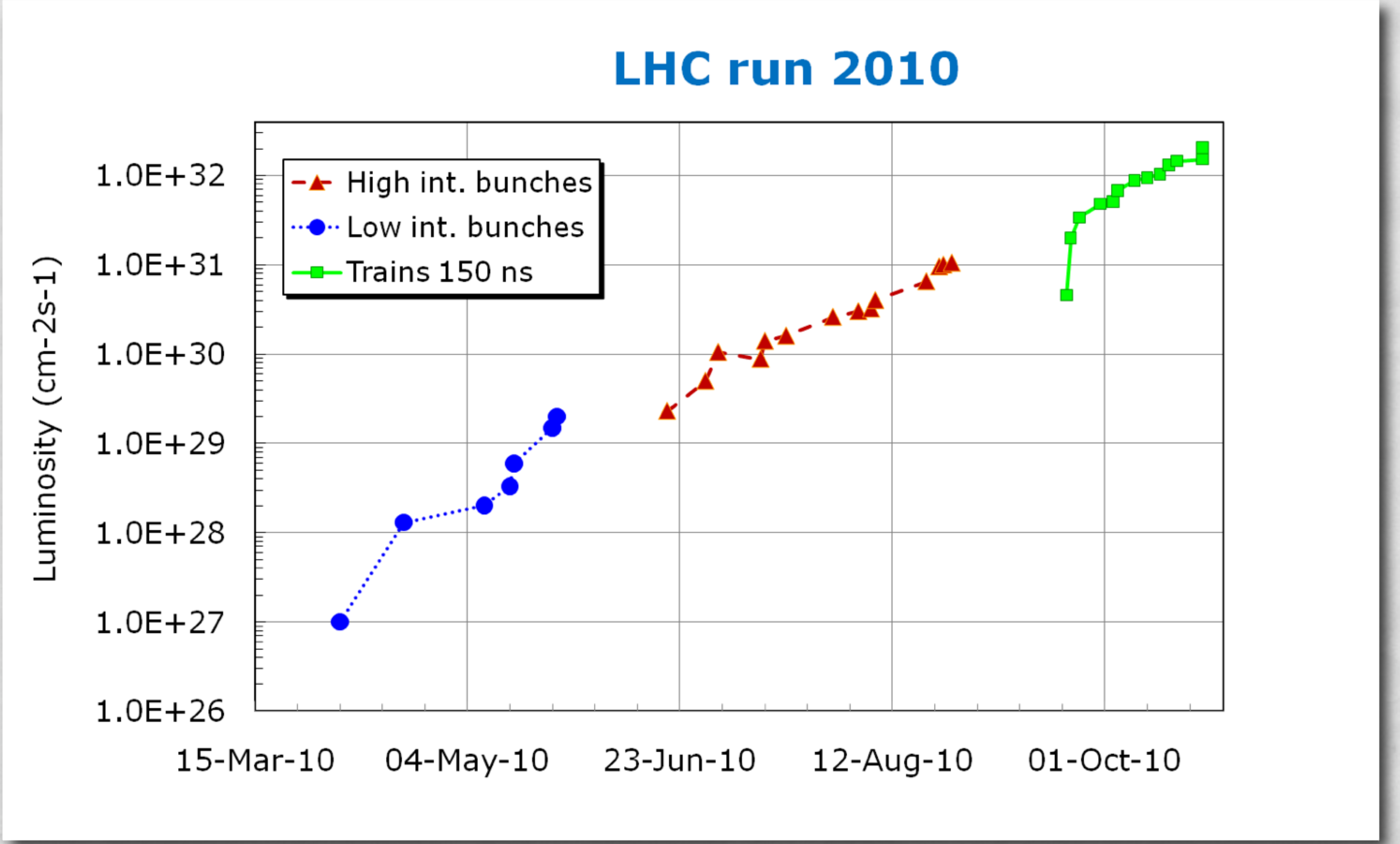
The LHC (with the luminosity upgrade) has the potential to last for 15-20 years

They sure have nice event displays !



A ZZ=> 4-mu event (CMS)

LHC's 2010 Run



CM Energy @ 7 TeV

Integrated luminosity ~48 pb^{-1}

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.

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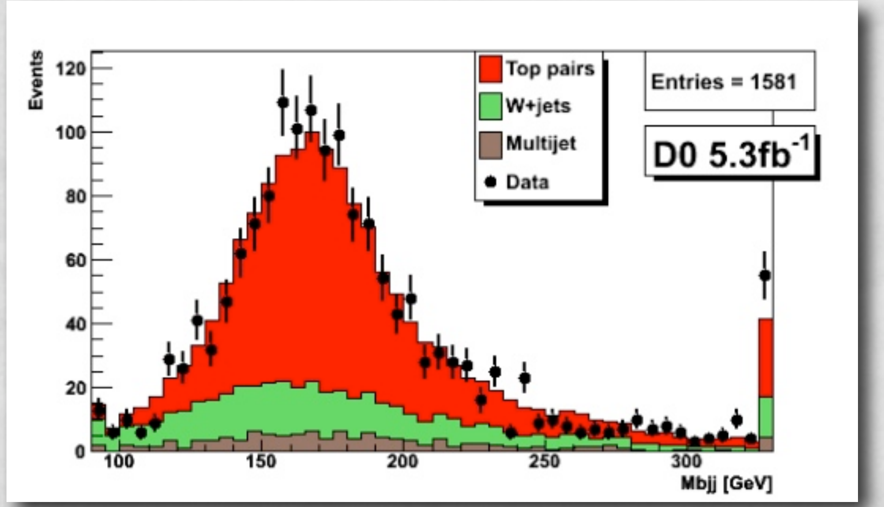
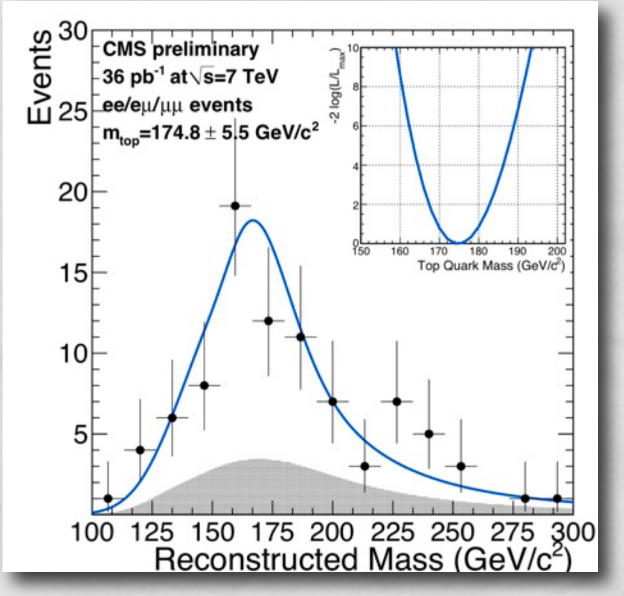
- Slew of new results presented at Winter Conf.
- It is wonderful to see results from these two colliders, together.
- And from the rest of the particle physics experiments as well !

Universality of the laws of Physics



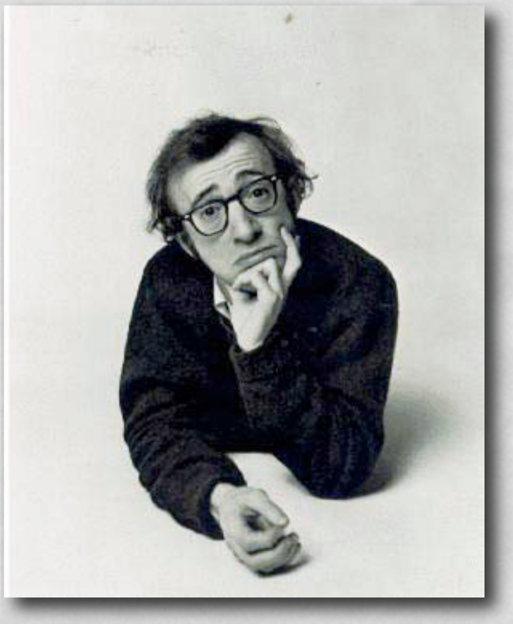
Top quarks in the US



Top quarks in Europe

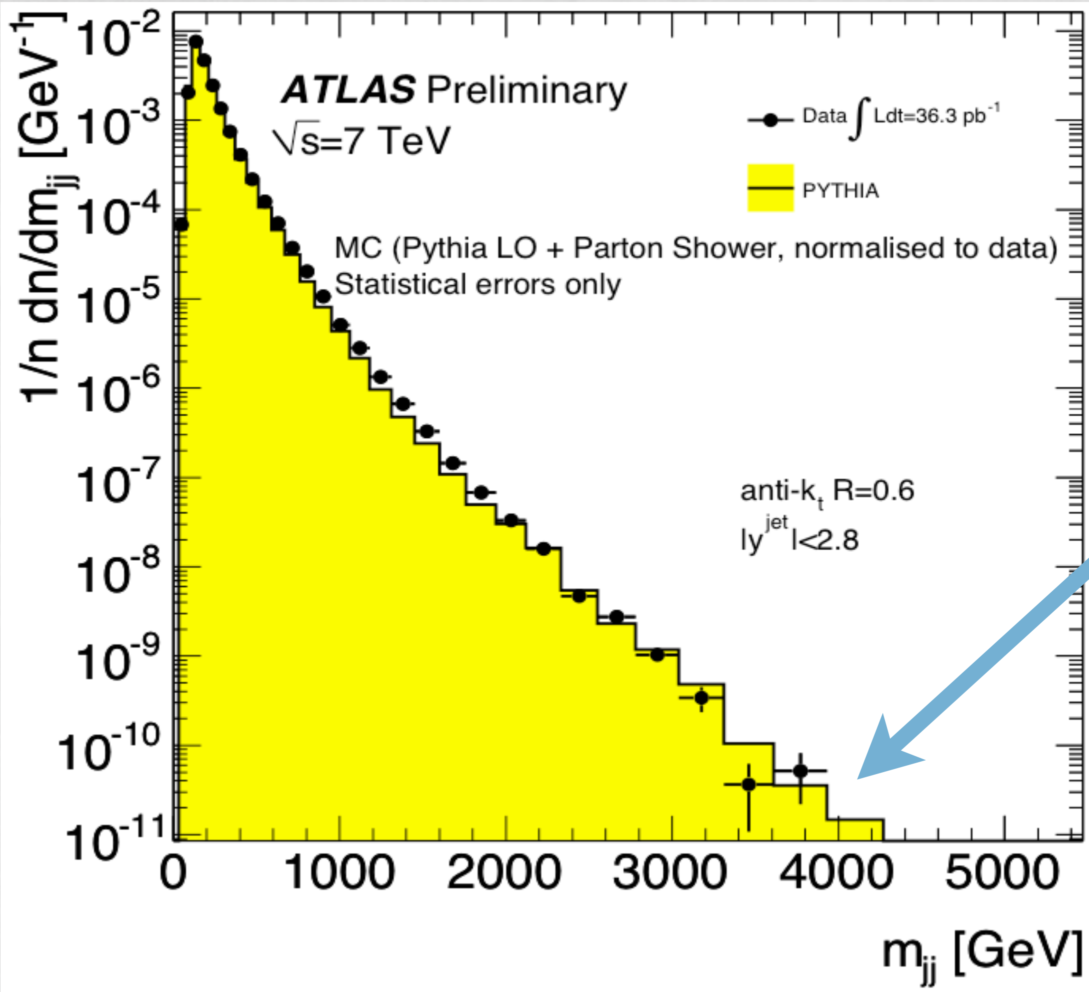
"All people know the same truth, our lives consist of how we choose to distort it."

W. Allen - Deconstructing Harry



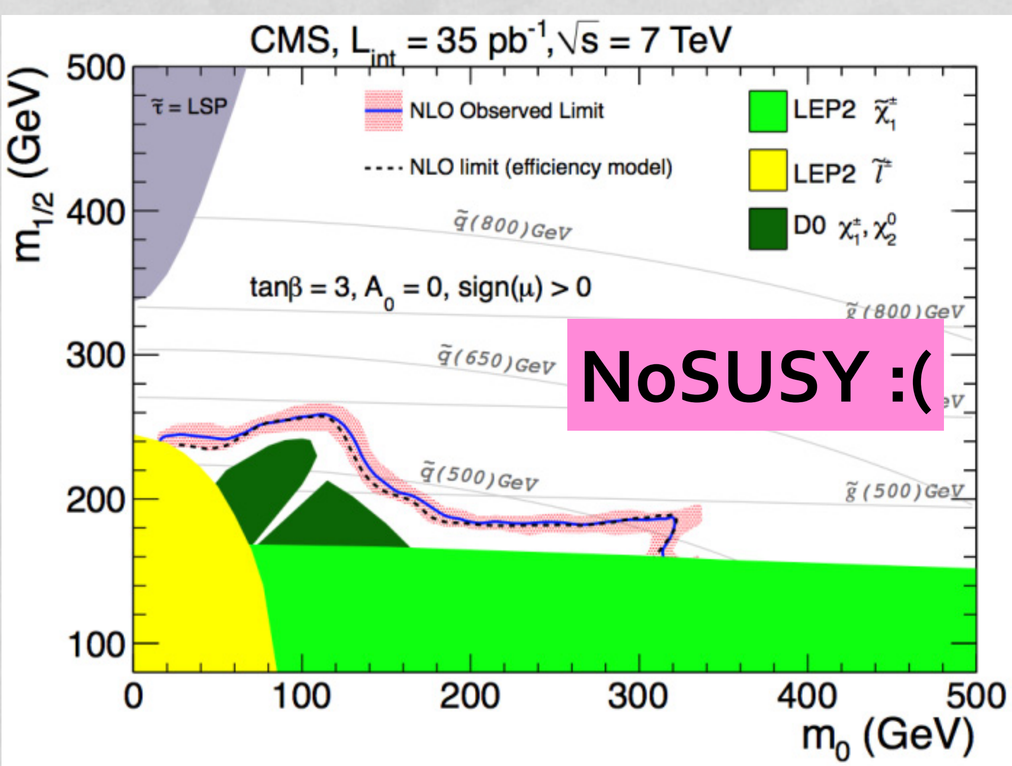
At the Terascale already !

di-jet production

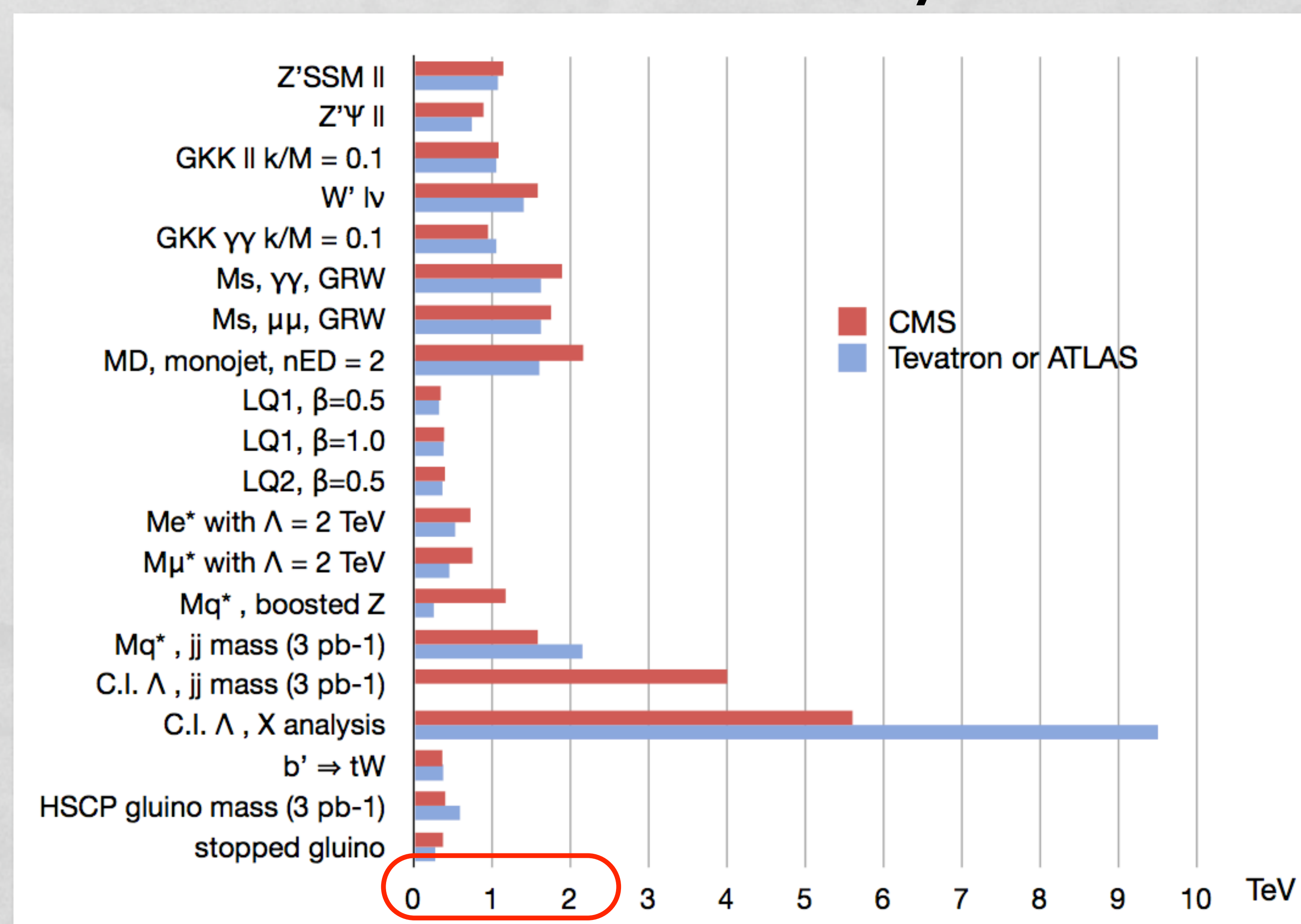


Uncharted waters

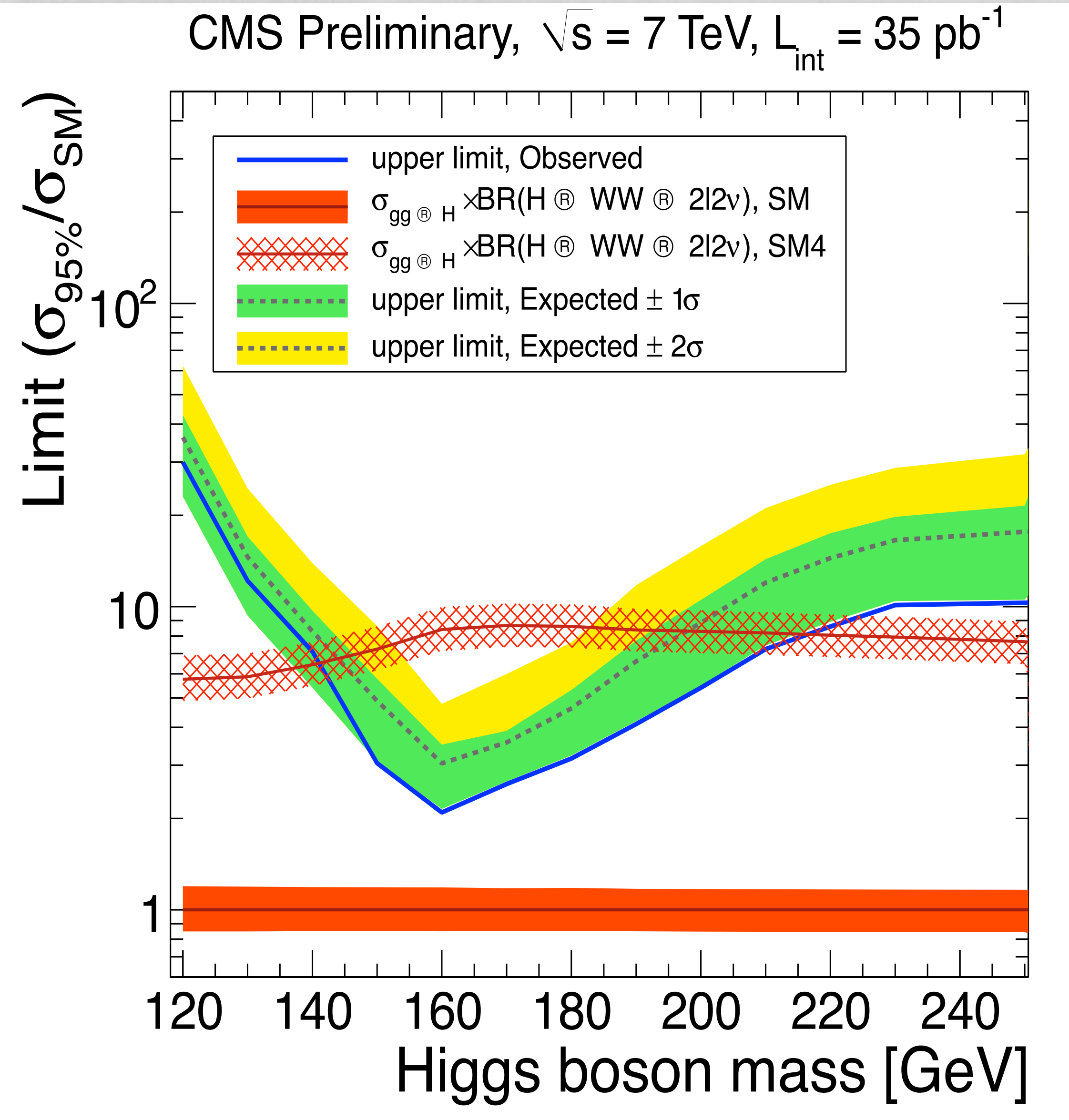
Collision CM Energy up to 4 TeV !

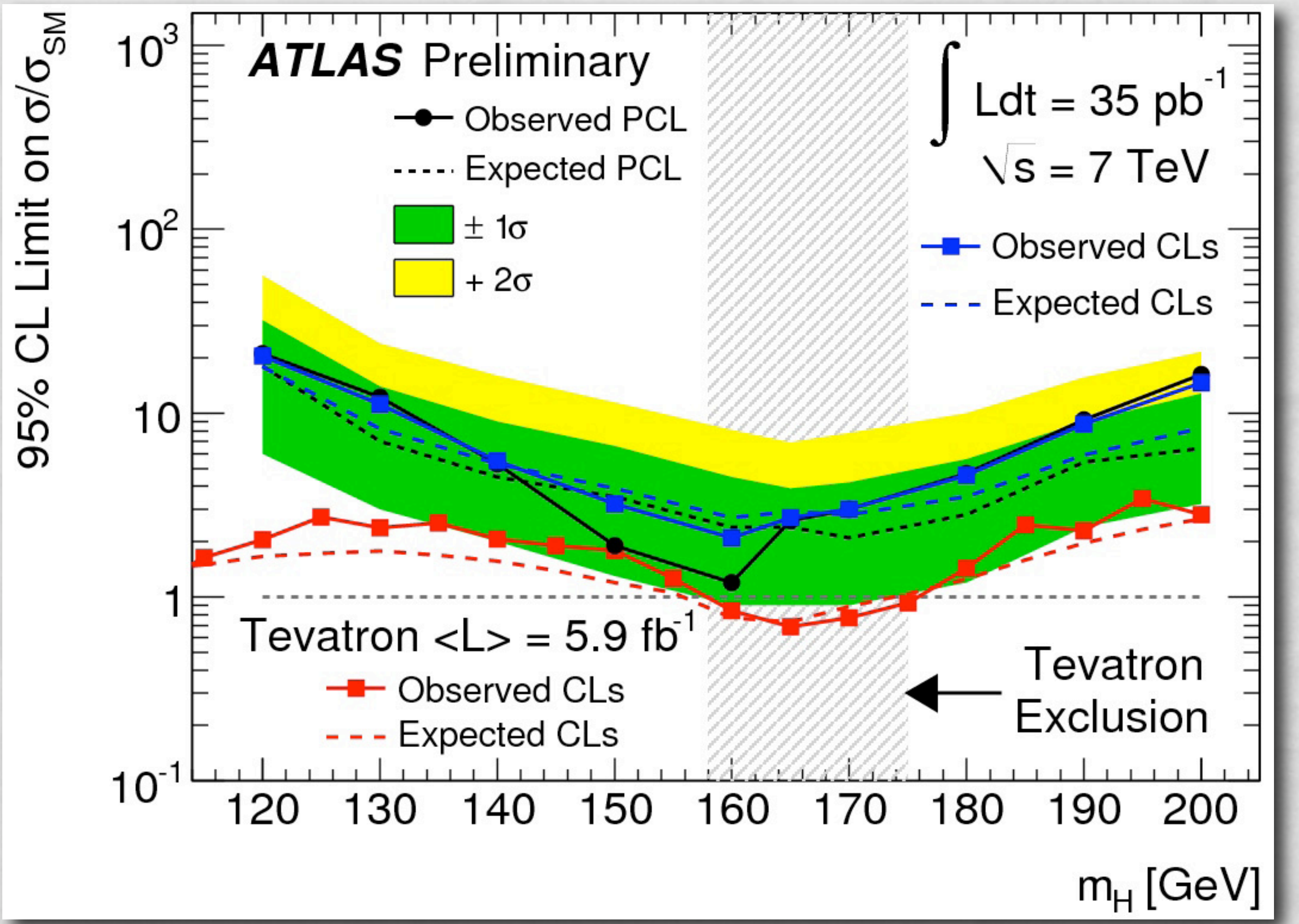


LHC Searches for New Physics-2010



LHC enters the Higgs arena: H=>WW





95 % CL Limit for M_H = 160 GeV	CMS (Bayesian)
Expected	3.0 x SM
Observed	2.1 x SM

95 % CL Limit for M_H = 160GeV	ATLAS (CL_S)
Expected	2.7 x SM
Observed	2.1 x SM

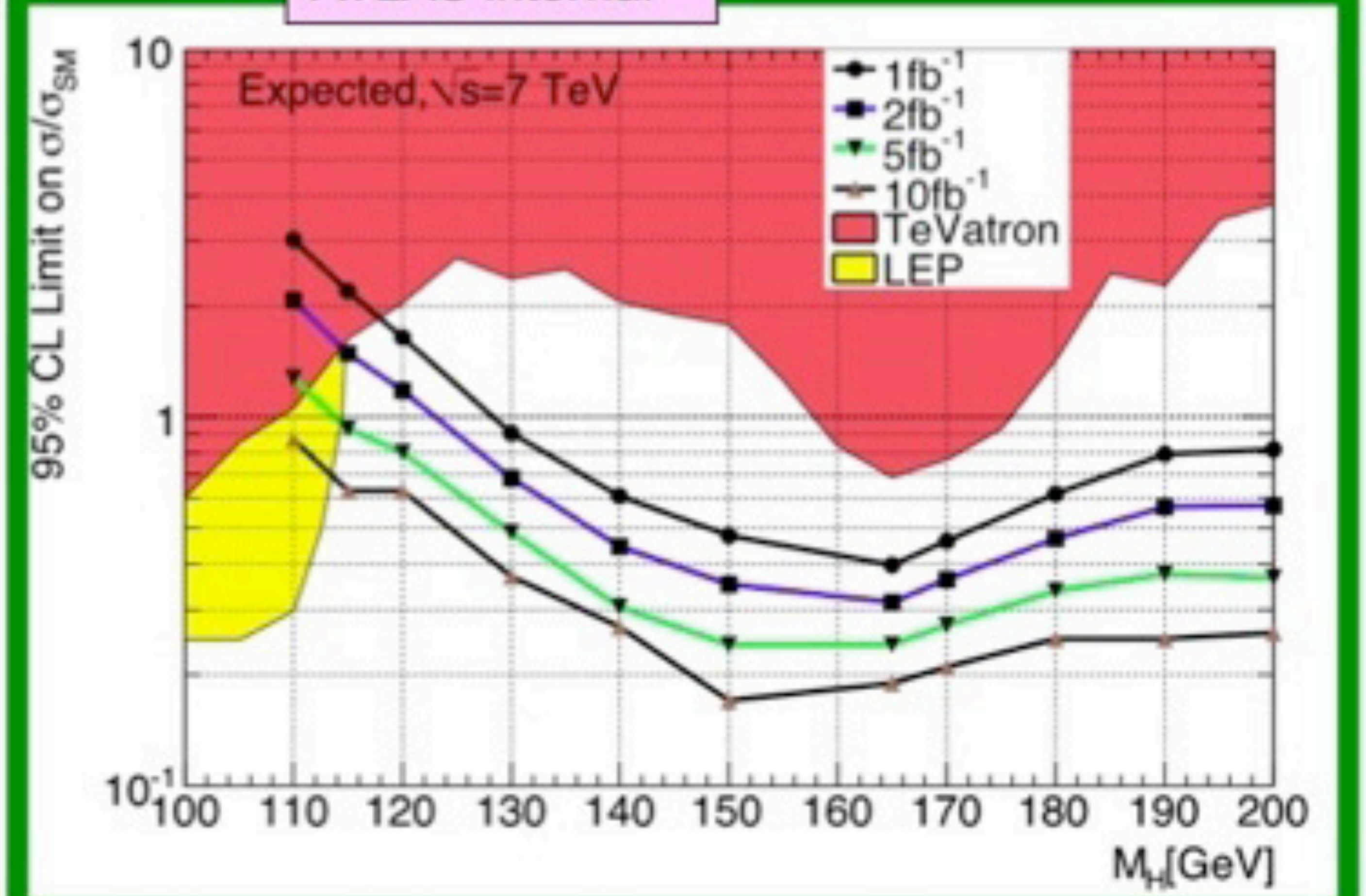
Expected Higgs mass coverage (GeV)

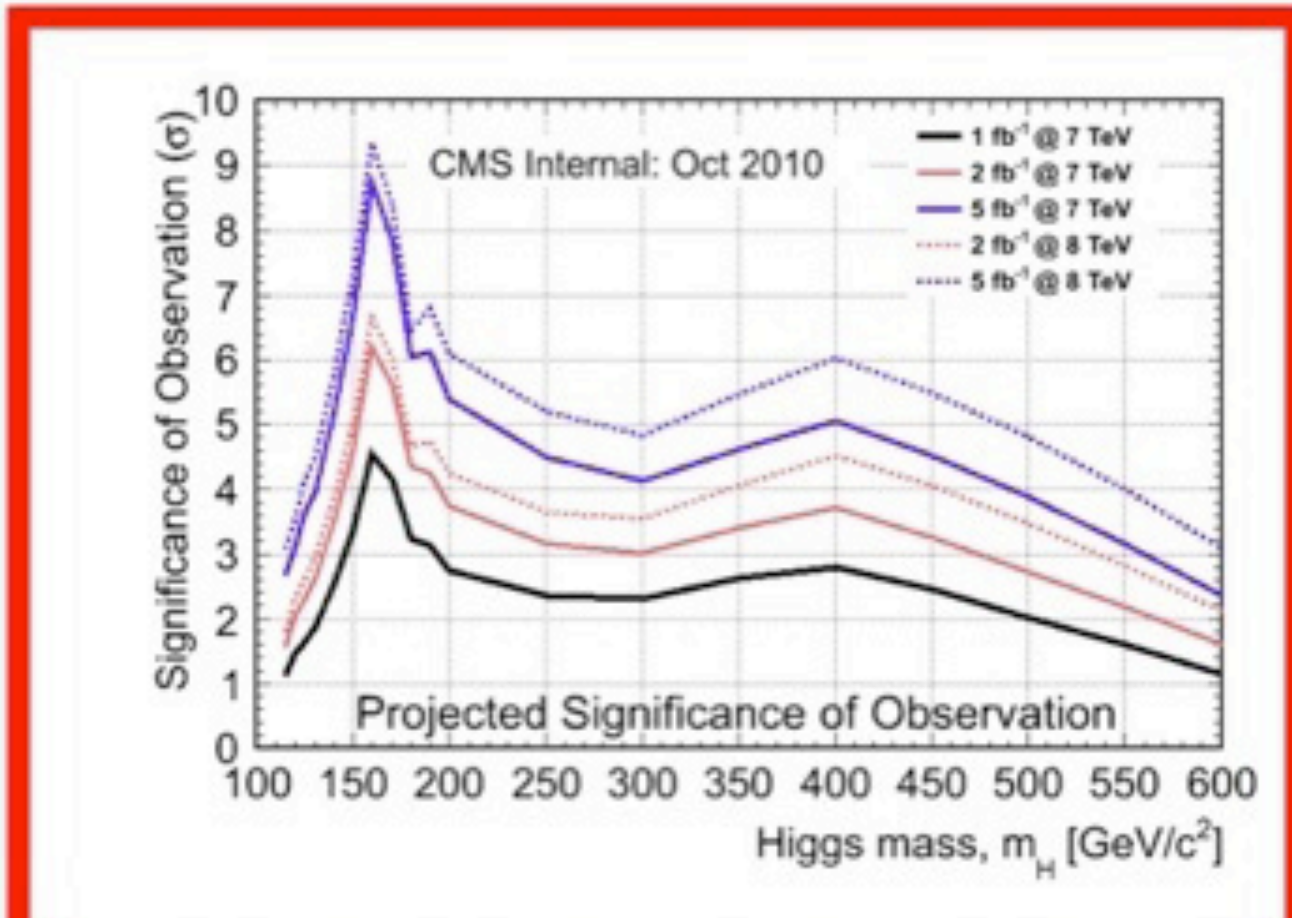
ATLAS and CMS internal and very preliminary

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

From Fabiola Gianotti

ATLAS internal





Betting on the Higgs Observation

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Transportation

Show Expired

Scientific - Higgs Boson Particle

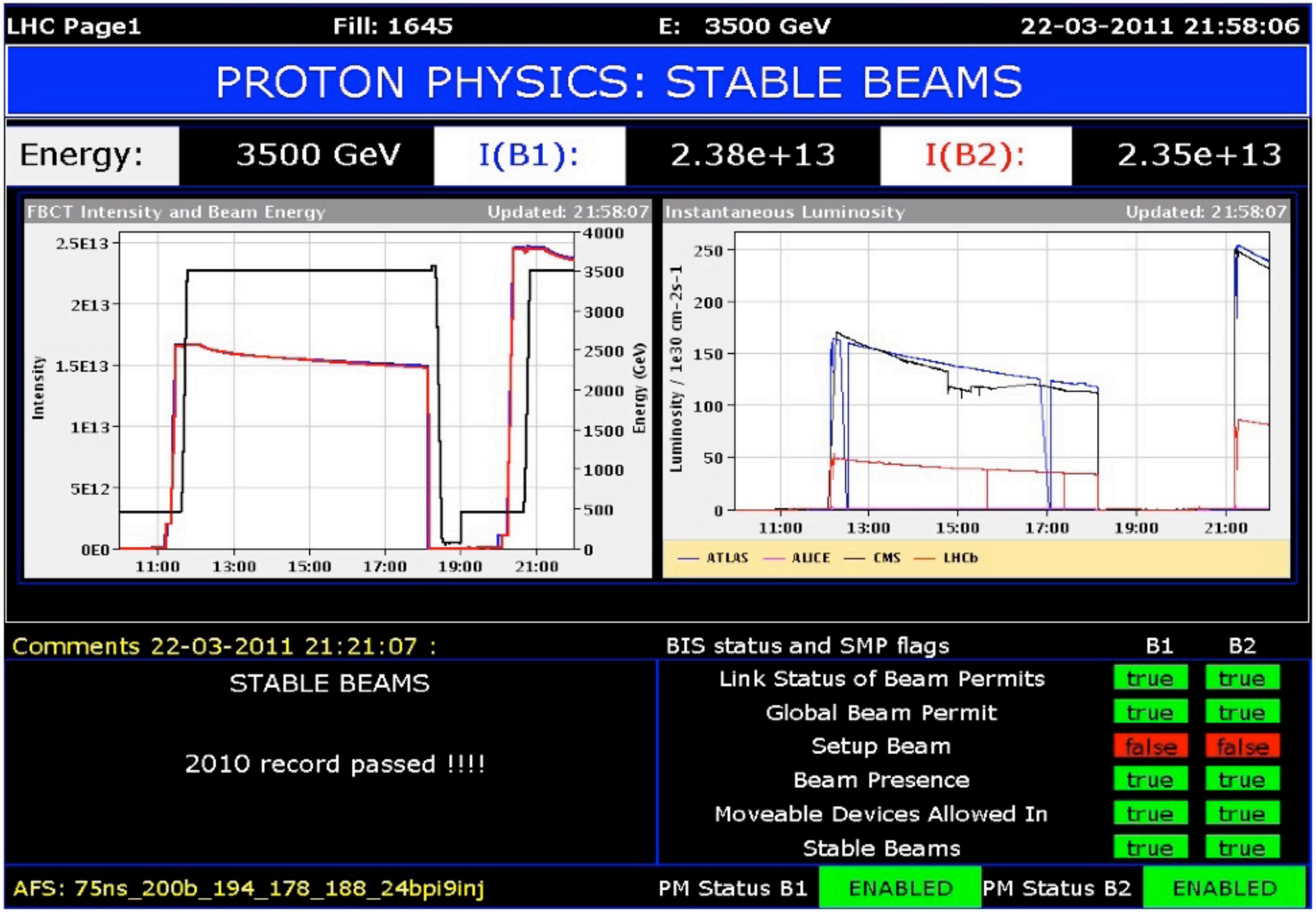
Observation of the Higgs Boson Particle

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

Mar 13 - 3:52AM GMT

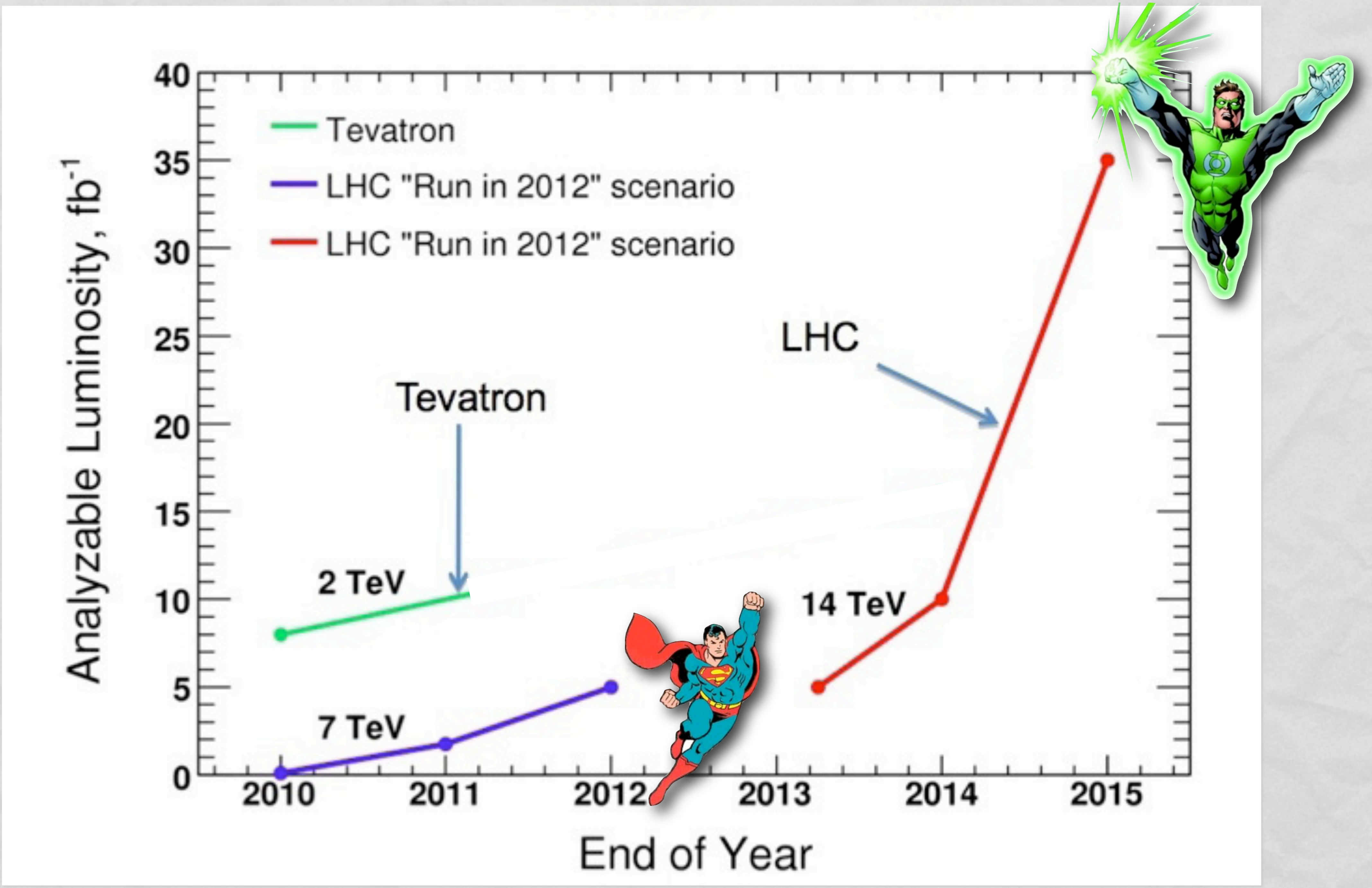
THE LHC SHOW CONTINUES !

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

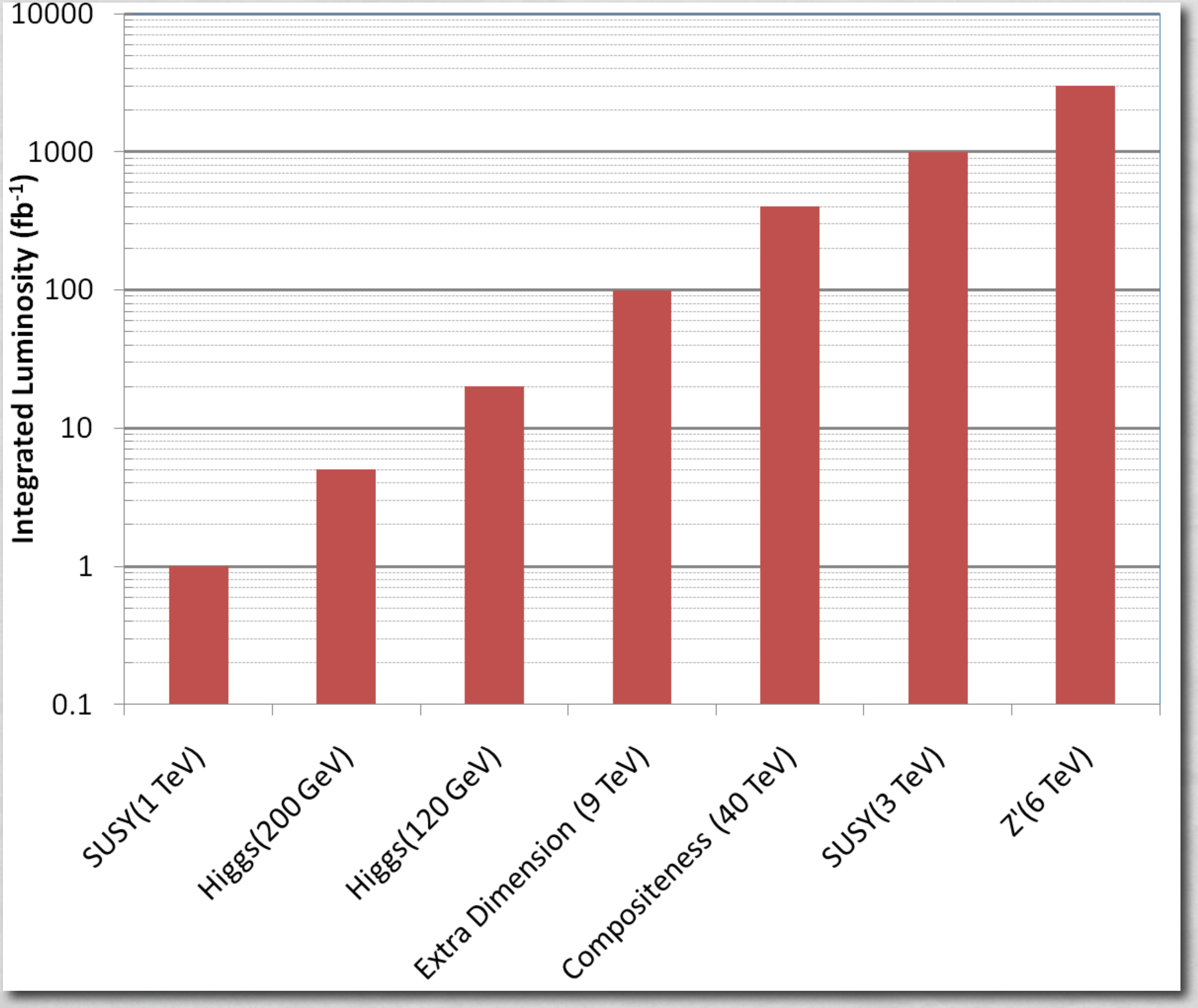


If 10^{33} achieved by the end of April $\sim 1 fb^{-1}$ before the end of June becomes a realistic goal.

The next few years



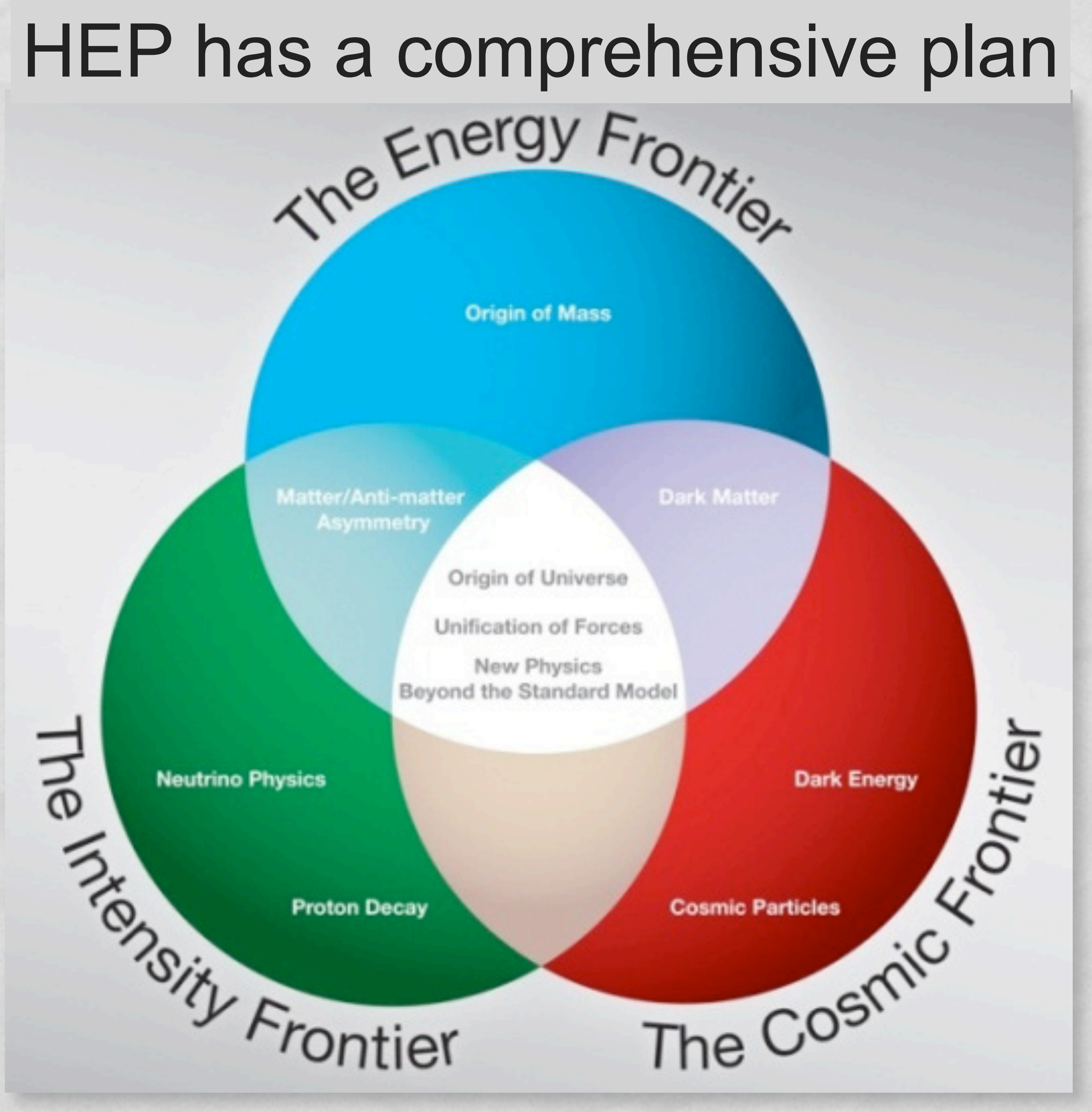
Will more reach will finally yield New Physics ?



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

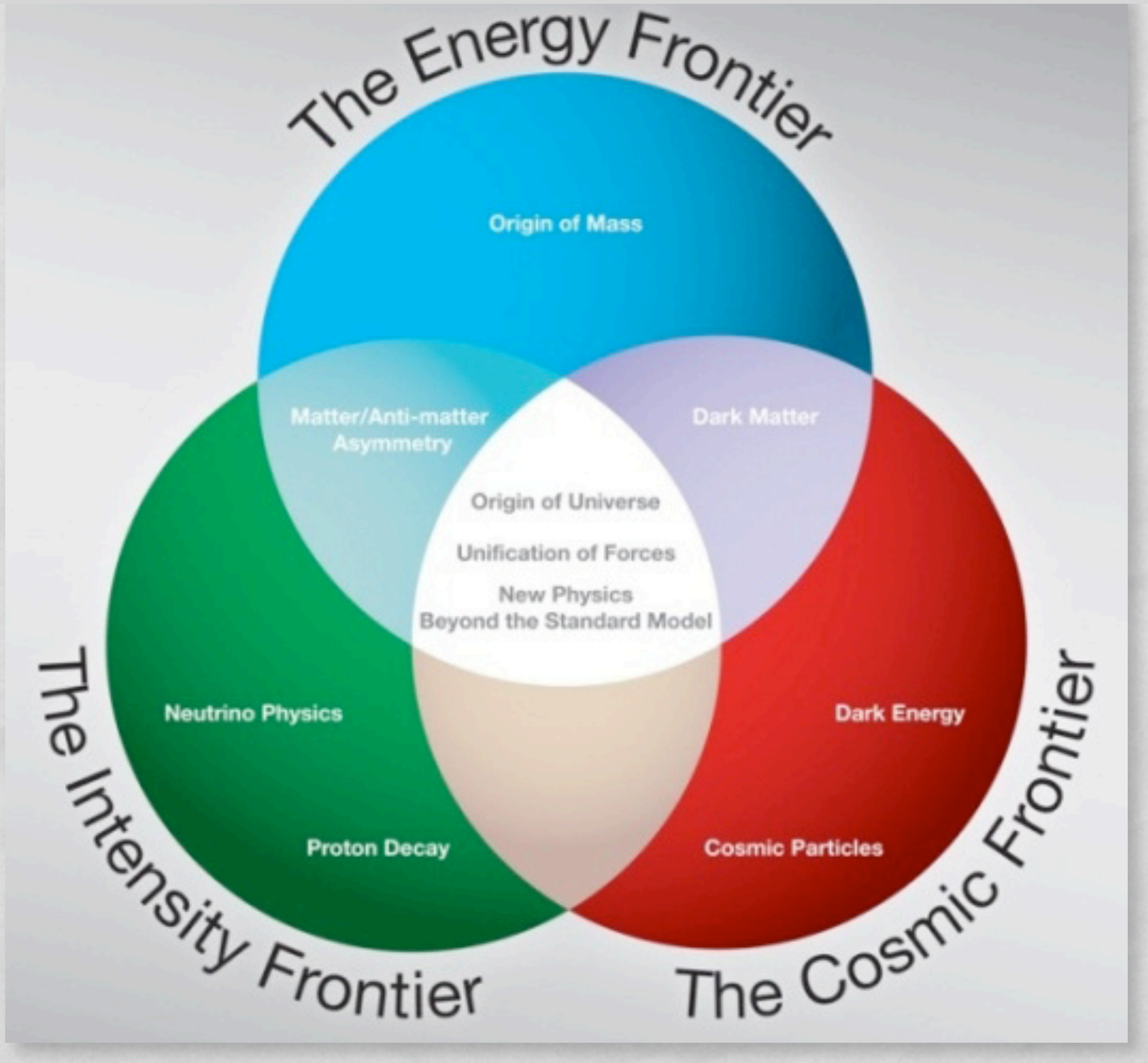


In Summary

- 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:

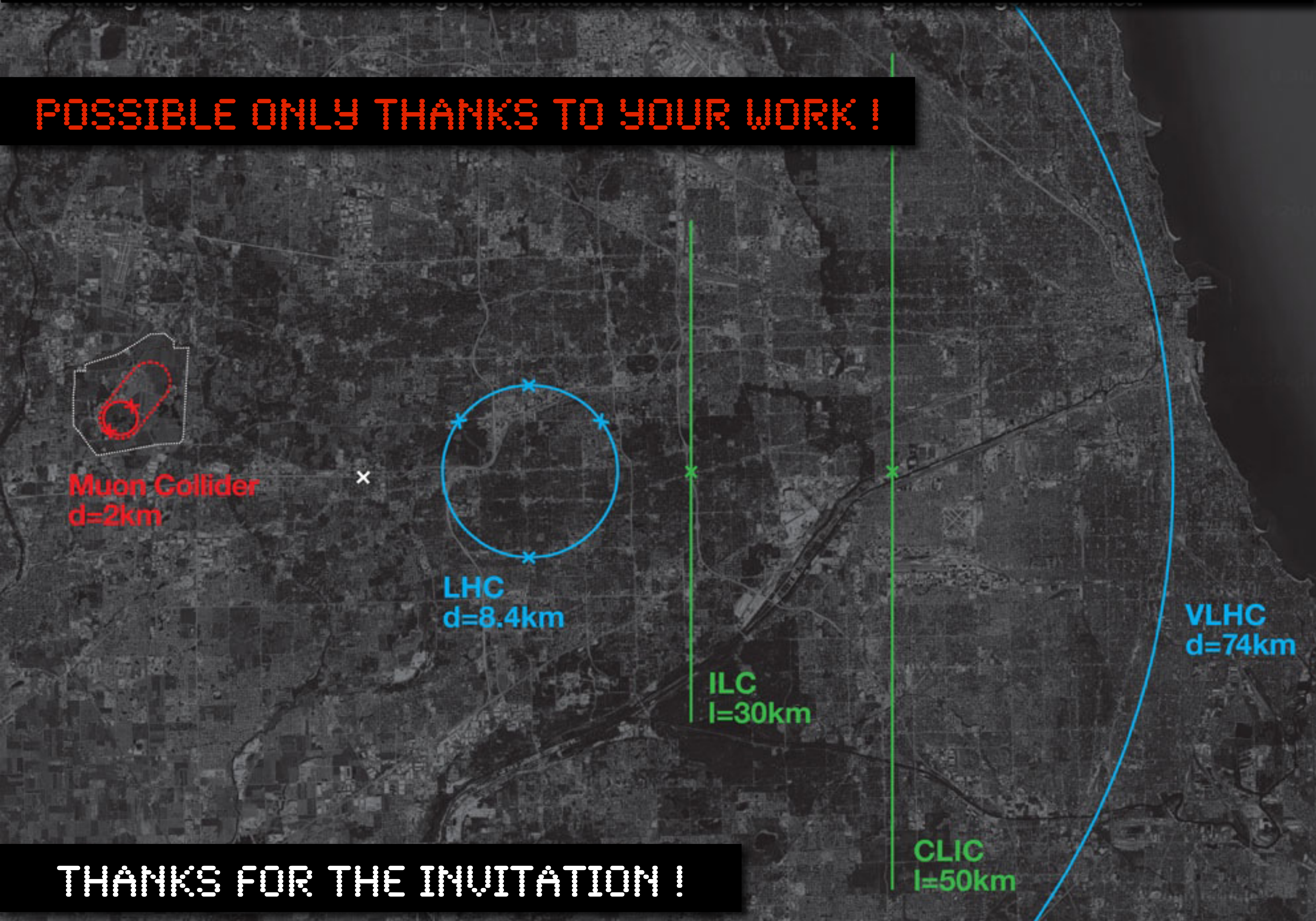
the unknown

Which should provide some fascinating answers



ANSWERS THAT WILL HELP DETERMINE THE FUTURE COLLIDERS

POSSIBLE ONLY THANKS TO YOUR WORK !



THANKS FOR THE INVITATION !

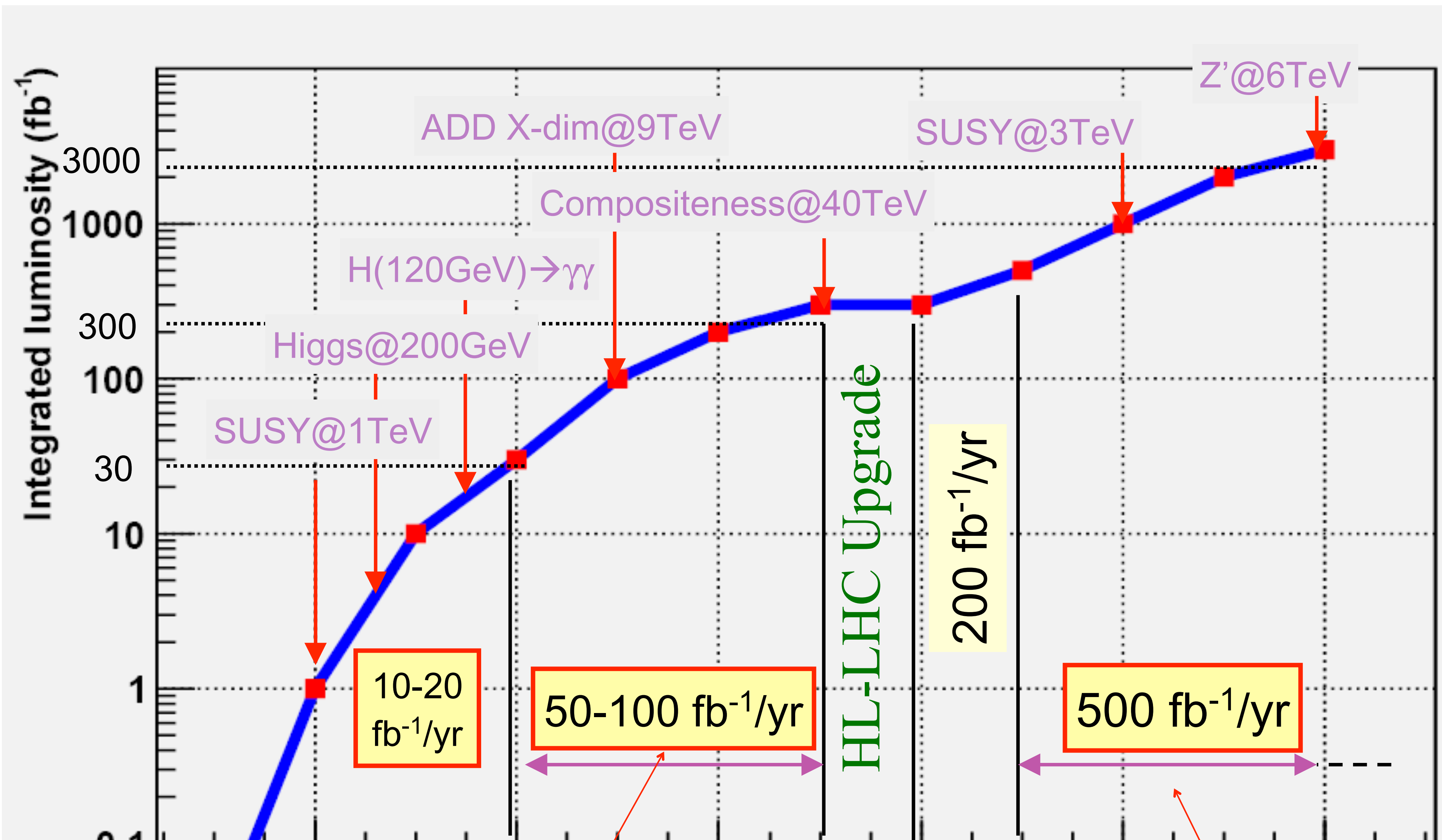
“What is a thing? The question is very old. What remains new is that it must always be asked”

- 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^{-1} by 2030.

50 x Tevatron luminosity

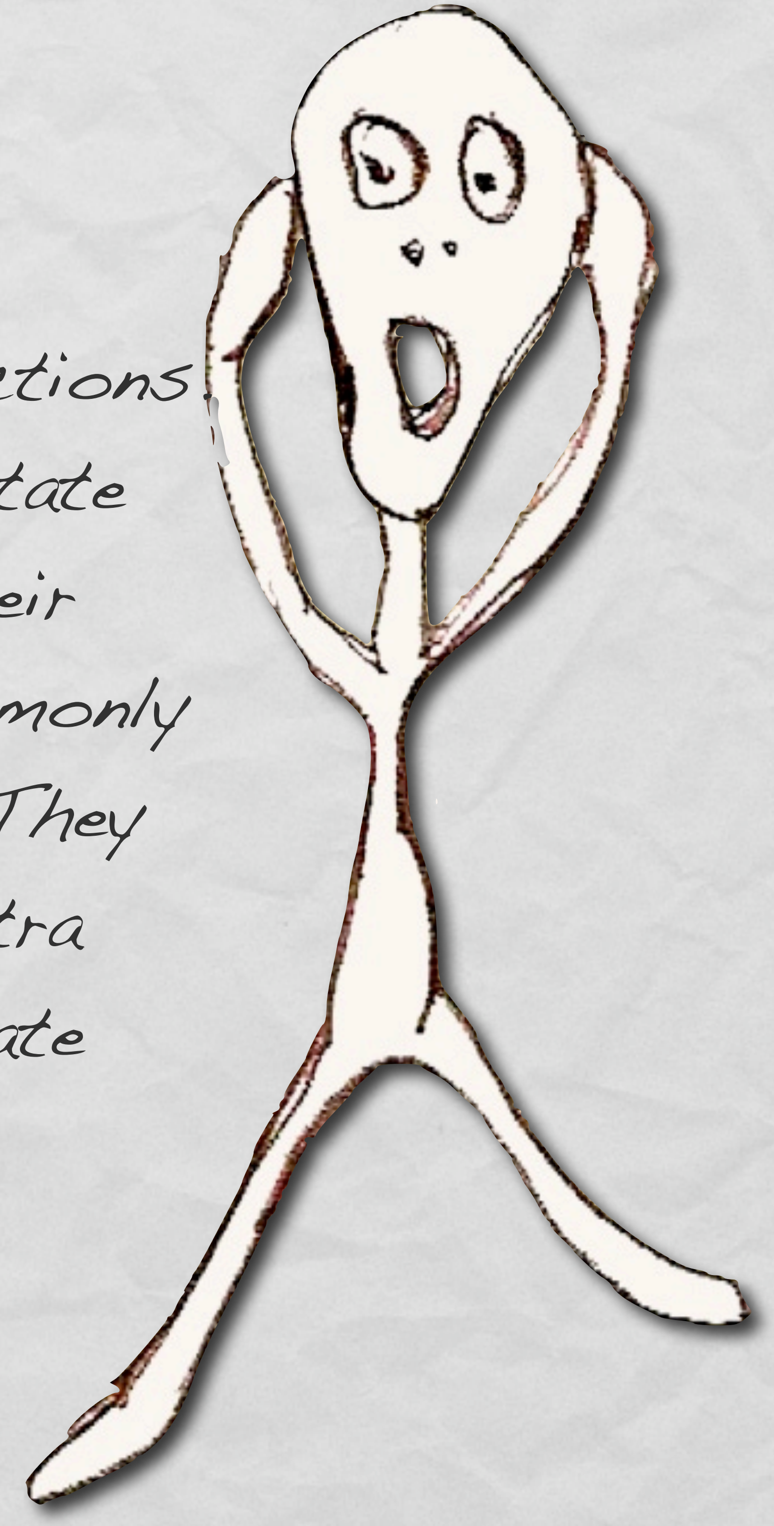
250 x Tevatron luminosity

- Lots of new challenges between now and then!

New accelerators to study the New Physics

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

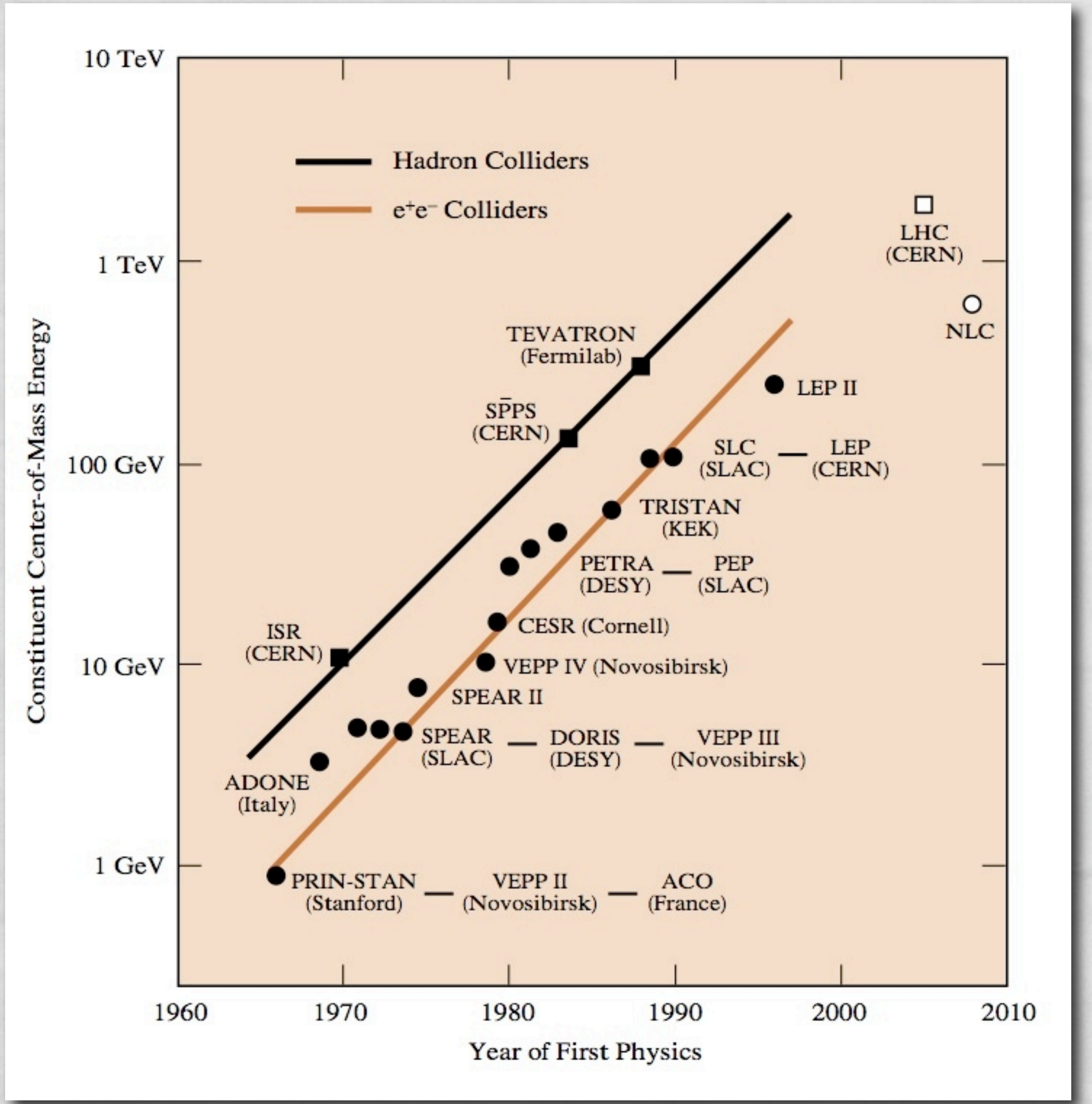
- National security
- Energy and the environment
- Medicine

Fermilab

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.

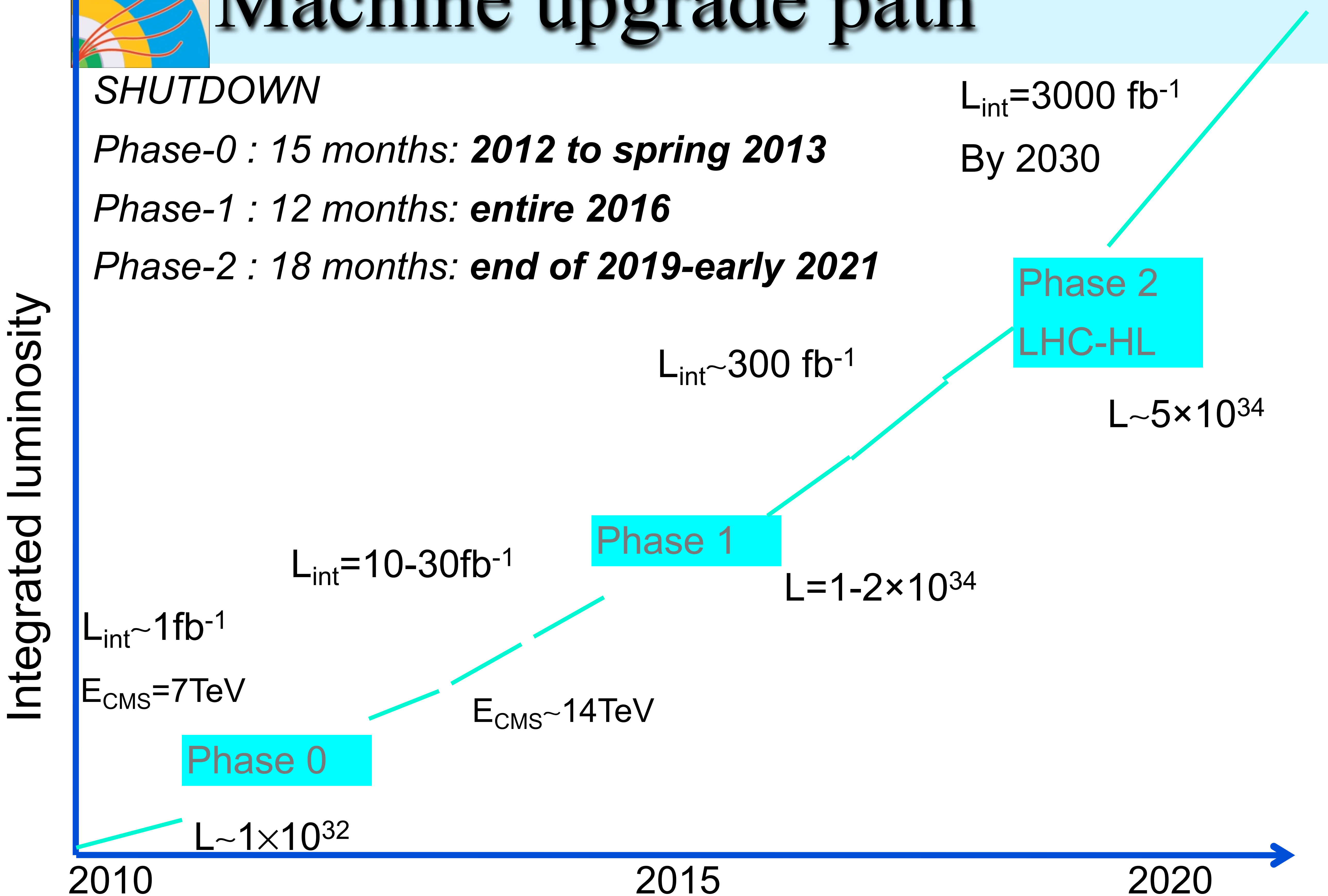
Machine upgrade path

SHUTDOWN

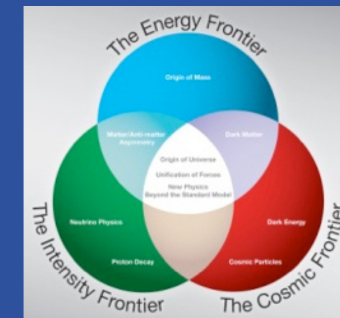
*Phase-0 : 15 months: **2012 to spring 2013***

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

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



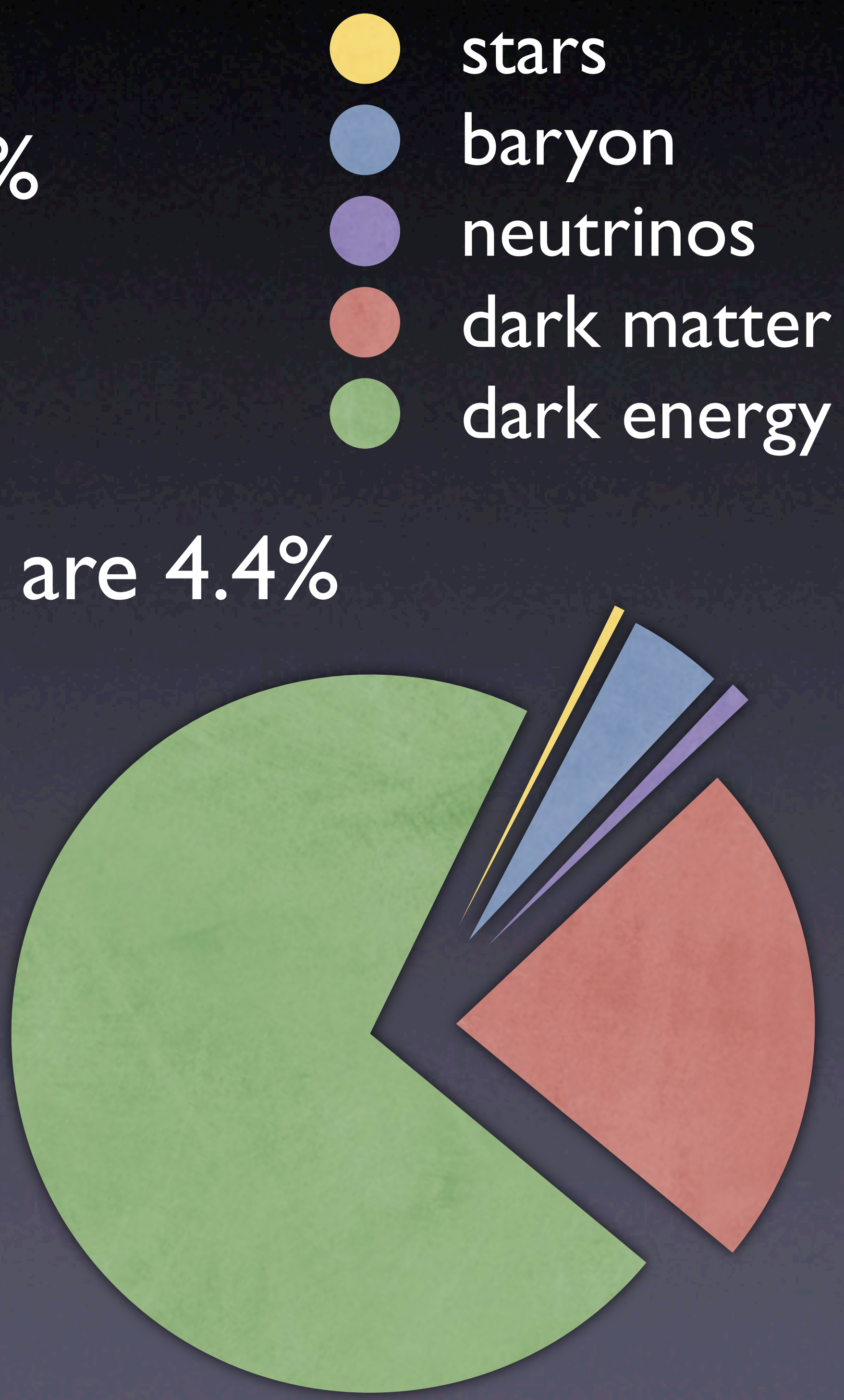
Future of Fermilab



Tevatron LHC	LHC	LHC Upgrades ILC??	LHC ILC, CLIC or Muon Collider
MINOS MiniBooNE MINERvA SeaQuest	NOvA MicroBooNE g-2? SeaQuest	LBNE Mu2e	Project X (LBNE, μ, K, nuclear, …) ν Factory ??
DM: ~10 kg DE: SDSS P. Auger	DM: ~100 kg DE: DES P. Auger Holometer?	DM: ~1 ton DE: LSST WFIRST?? BigBOSS??	DE: LSST WFIRST??

Now 2013 2016 2019 2022

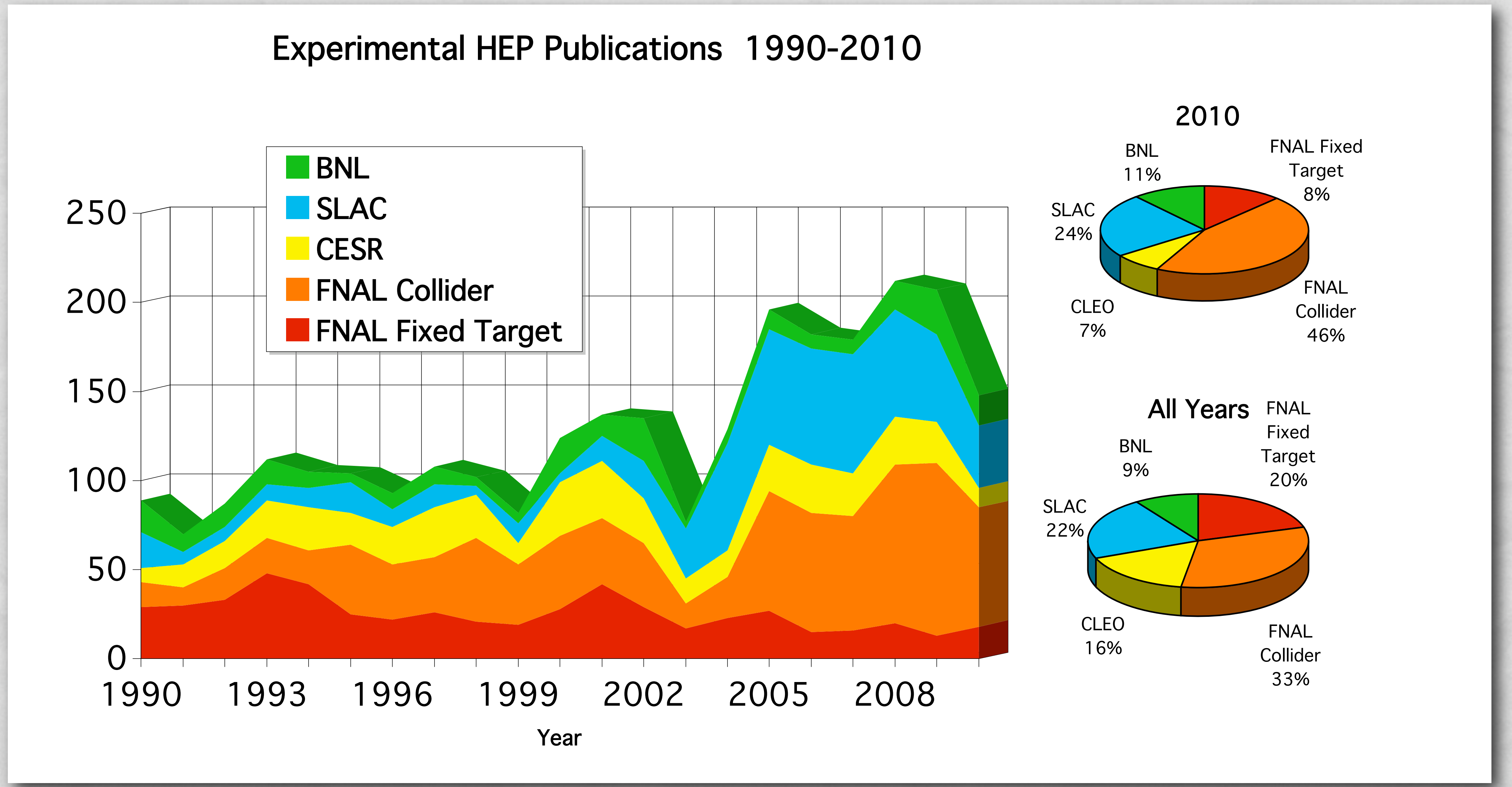
Energy Budget of the Universe



- 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^{62}%??

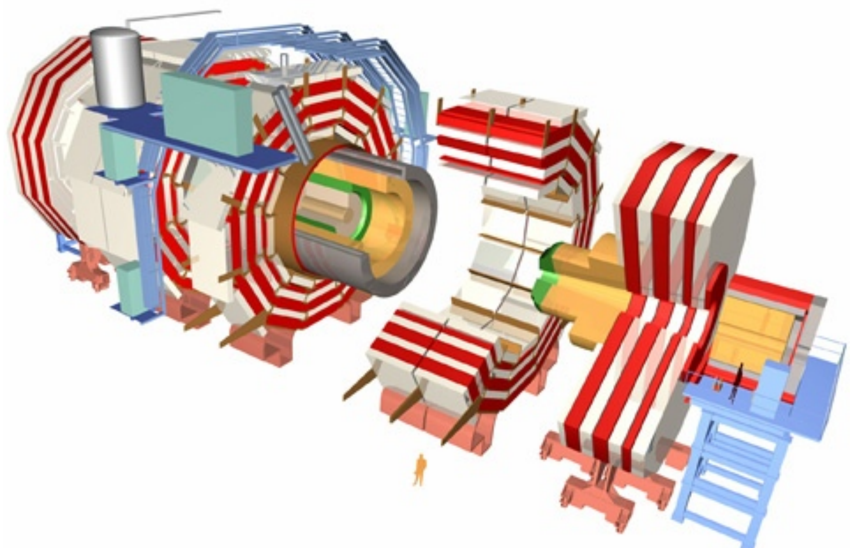
U.S. Experimental Journal Publications

- ☐ Tevatron publication at ~100/year !

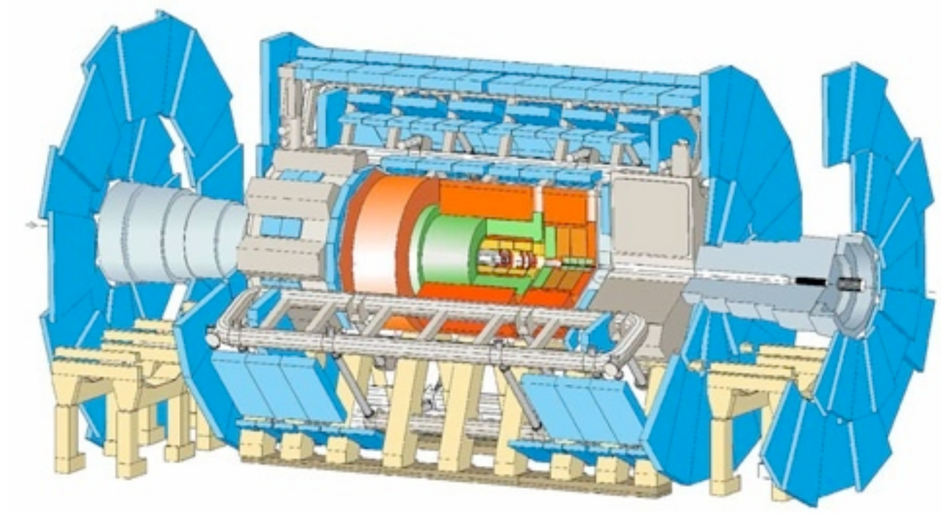


CERN Experiments

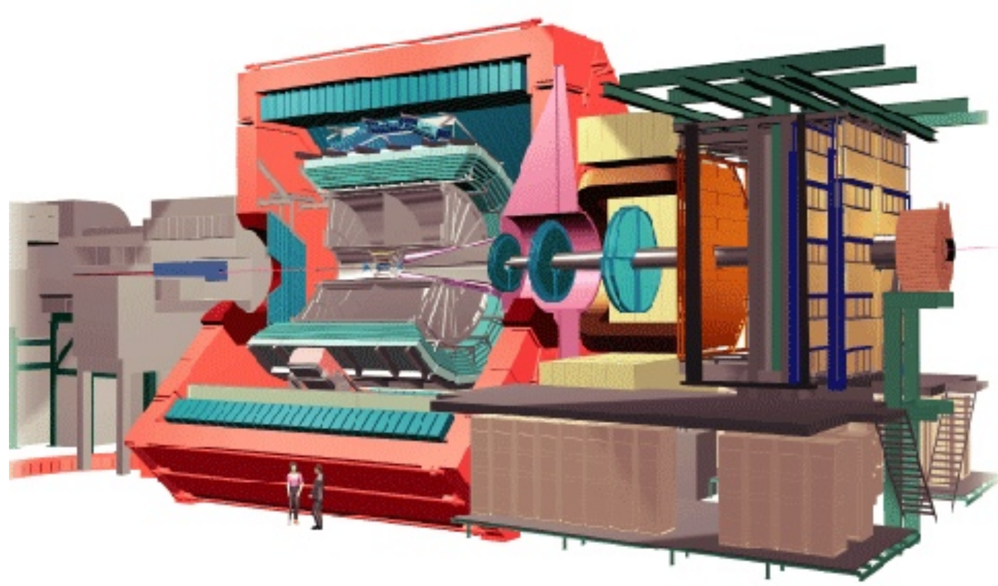
- Huge, general purpose experiments:



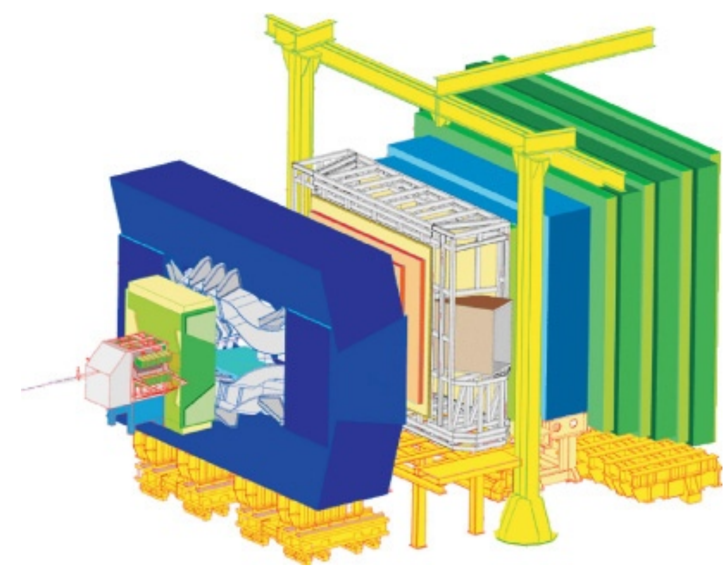
Compact Muon Solenoid (CMS)



A Toroidal LHC ApparatuS (ATLAS)

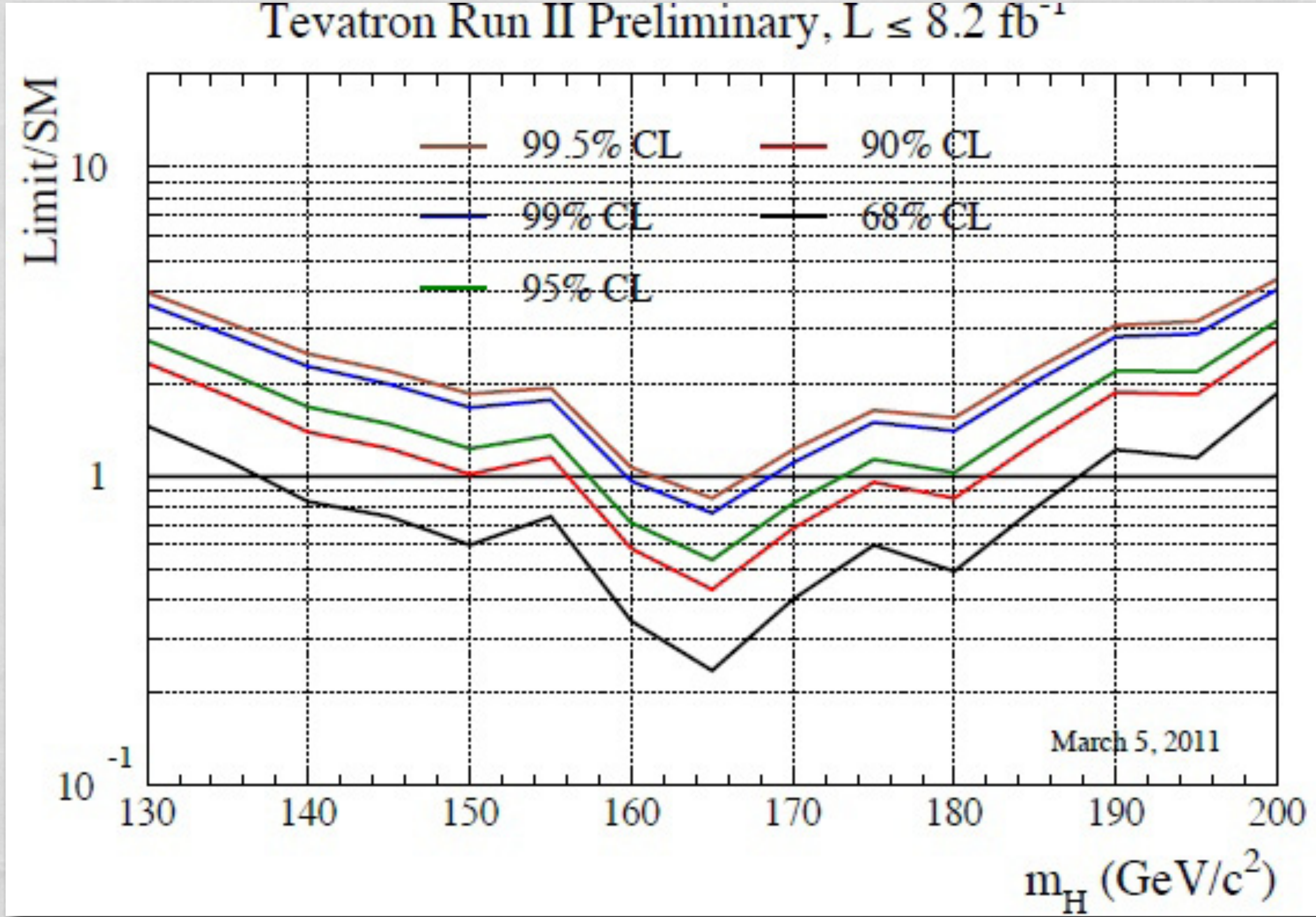


A Large Ion Collider Experiment (ALICE)



B physics at the LHC (LHCb)

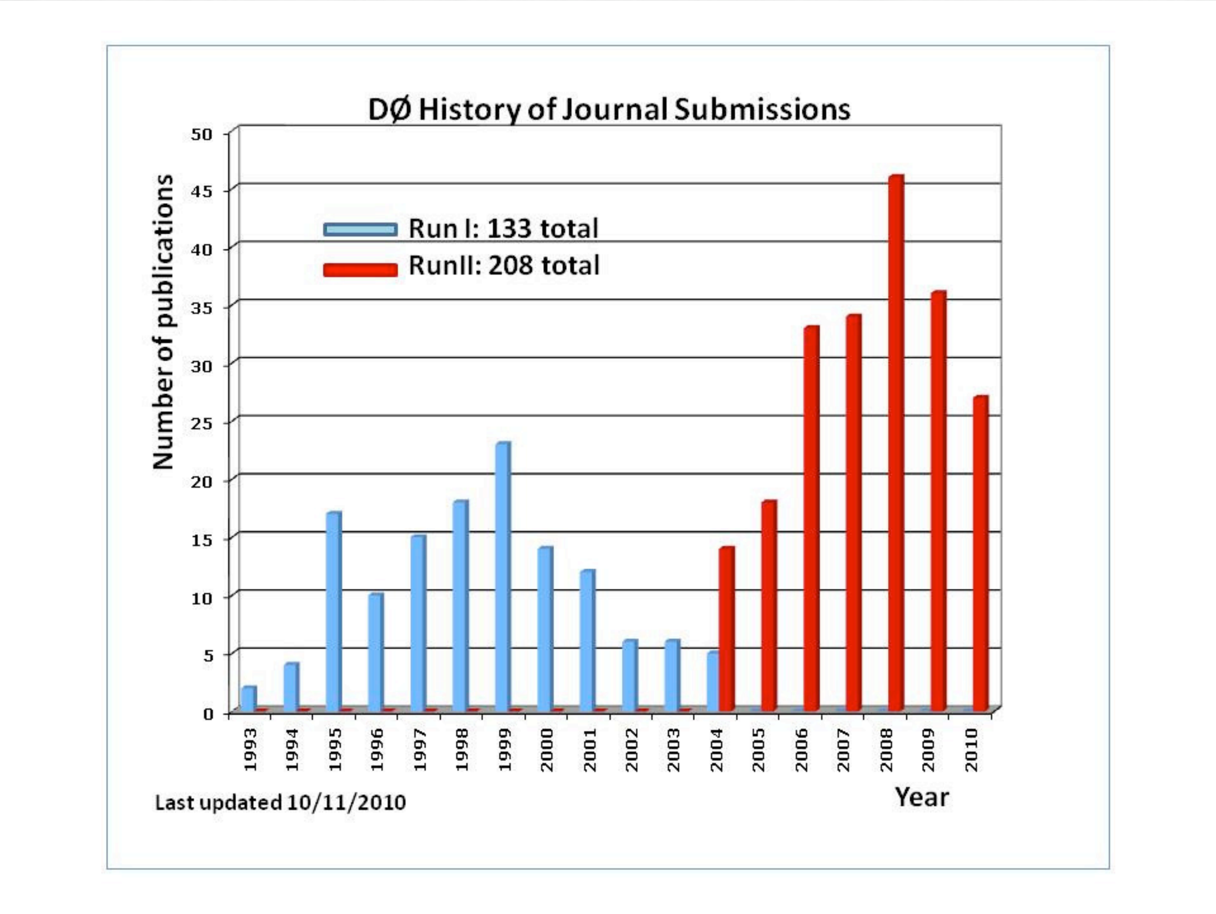
Tevatron Combination

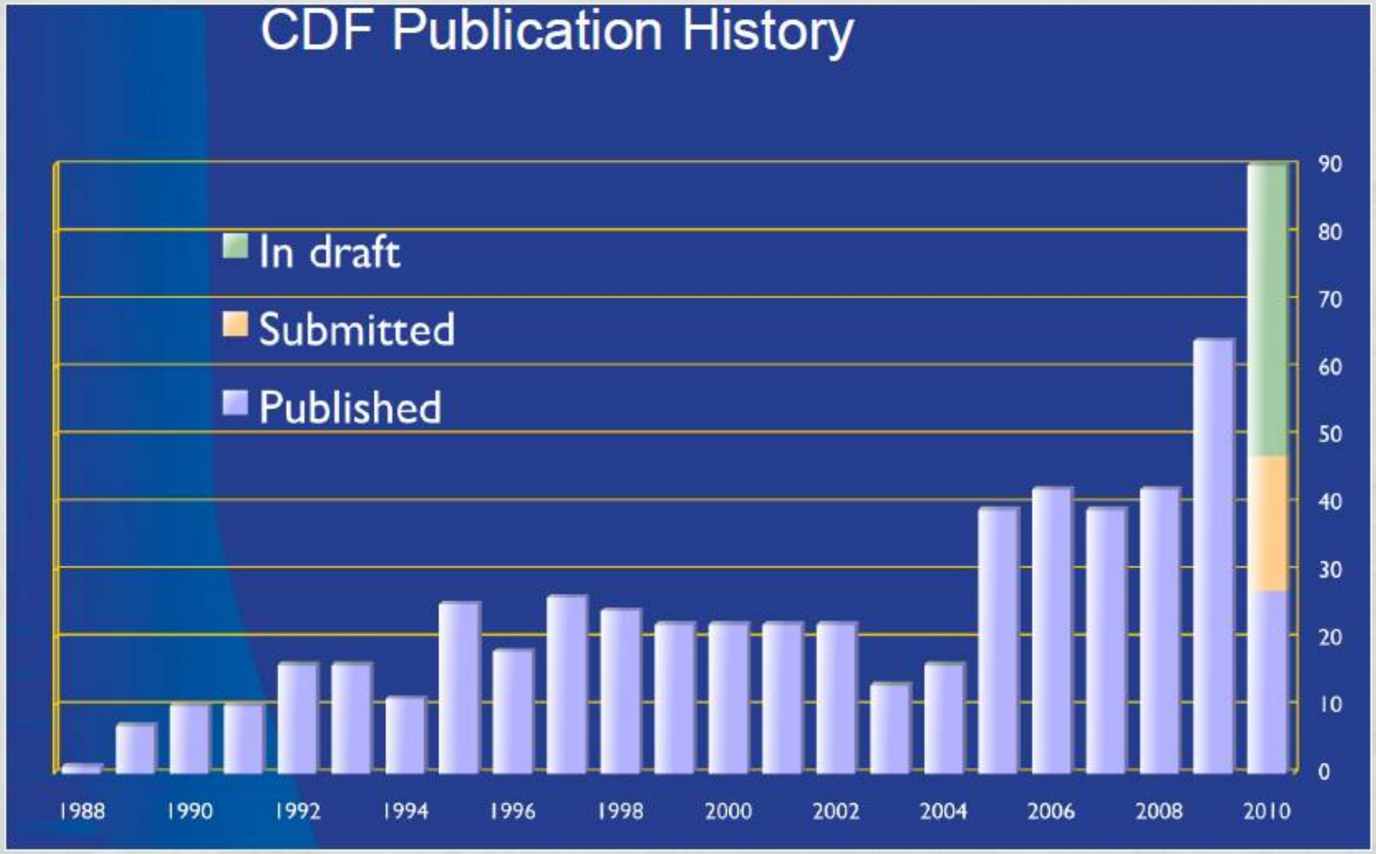


SM Higgs of 162 < m_H < 166 GeV excluded **@99.5% CL**

Tevatron Physics Output

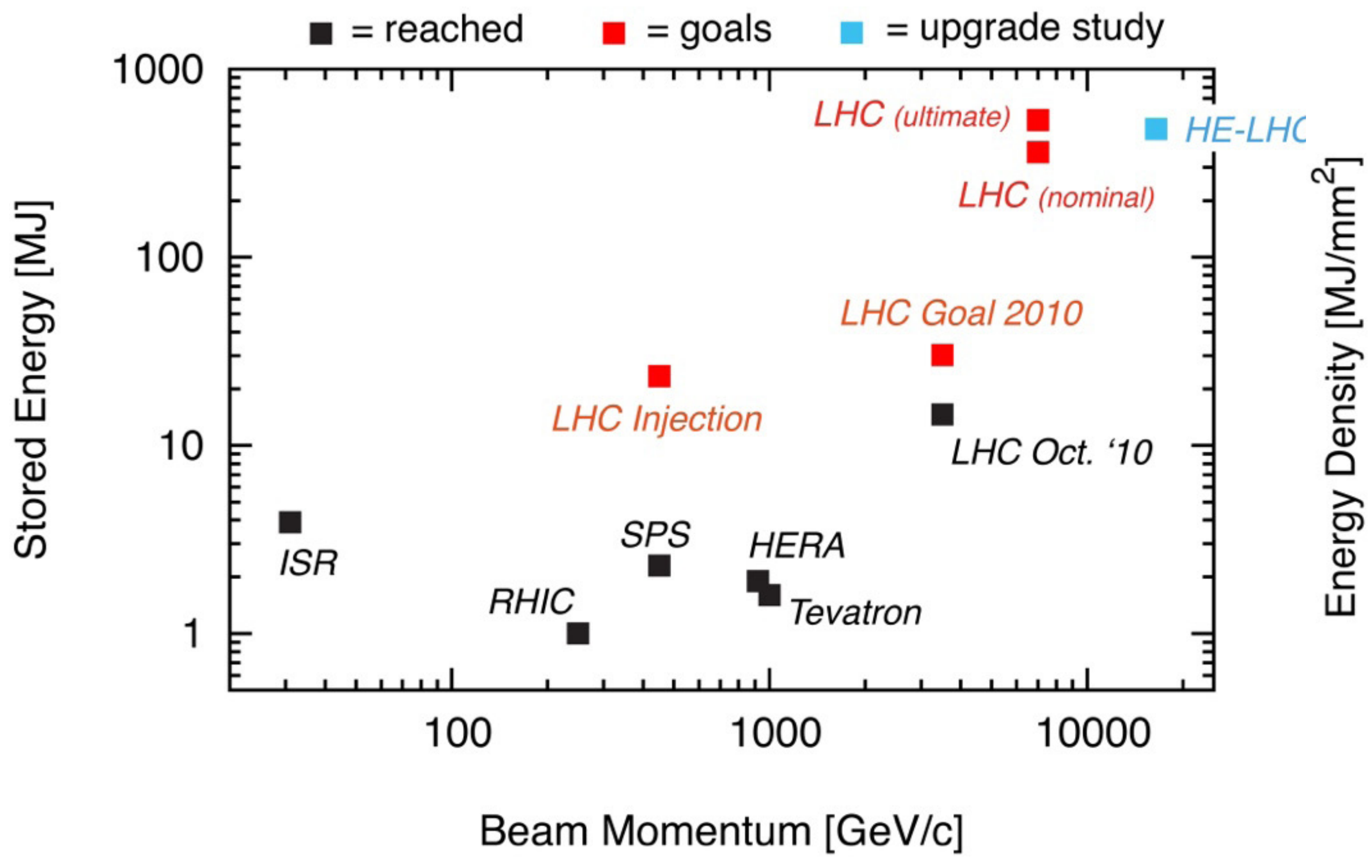
- Stable tools and well understood detectors and data

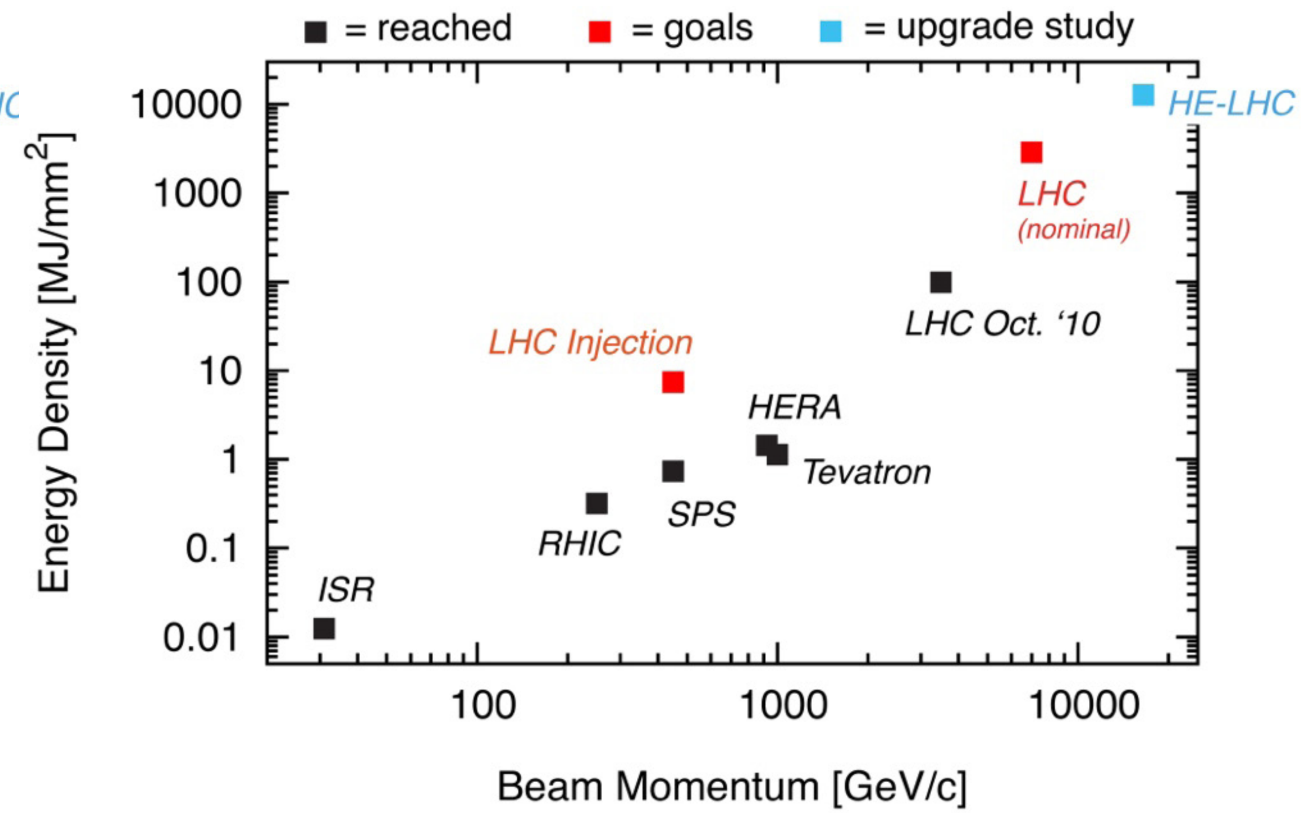




- In 2009 about 50 journal publications/experiment/yr
- About 60 Ph.D.'s / year over the last few years

Stored Energy and Energy Density





- 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