The Window to the Terascale

Jesse Thaler (UC Berkeley)

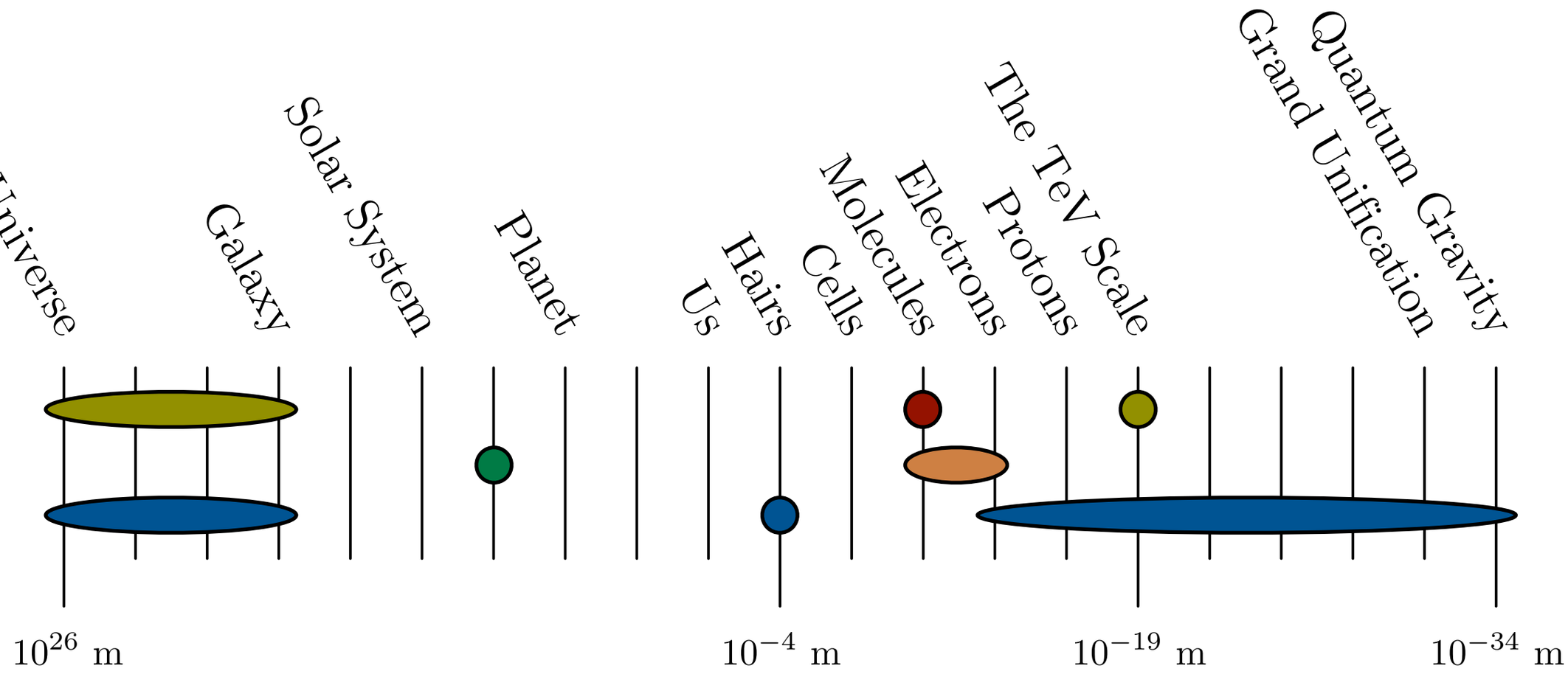
Welcome to Aspen!

The Window to the ~~Terascale~~ TeV Scale

$$\hbar = c = 1 \qquad \mathrm{eV} = 1?$$

Far more important than the particles we discover at the LHC are the principles that govern electroweak physics.

The Universe is a Big Place



← Satellites Accelerators →

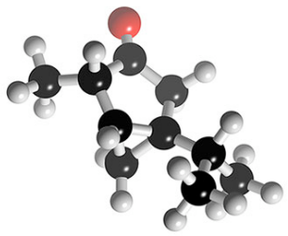
Single Molecule Biophysics	●	Jan. 4 – Jan. 10, 2009
Themes in Condensed Matter	●	Jan. 11 – Jan. 17, 2009
The Dark Sector	●	Jan. 25 – Feb. 1, 2009
Magnetars	●	Feb. 1 – Feb. 7, 2009
Year of the Ox	●	Feb. 8– Feb. 14, 2009

Fundamental Physics

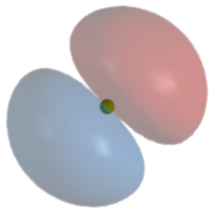
Daß ich erkenne, was die Welt
Im Innersten zusammenhält.

— Goethe, *Faust*

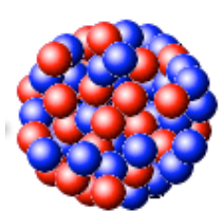
c. 2008: "Innersten" = 10^{-19} m (10^{-9} smaller than Bohr radius of Hydrogen)



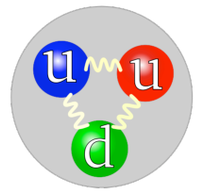
molecule



atom (10^{-10} m)



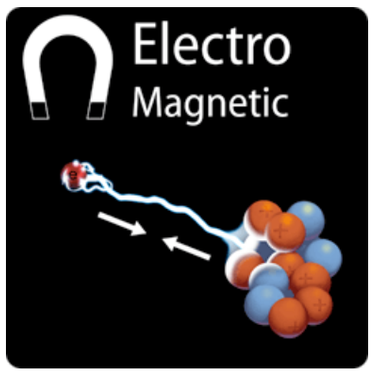
nucleus

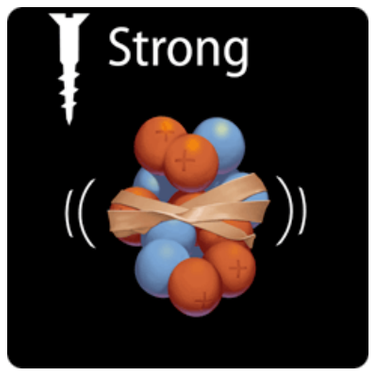


proton (10^{-16} m)

quark

c. 2008: "Innersten" = 4 forces + 12 fermions + Higgs





Collisions!

c. 2008: "Innersten" = 10^{-19} m = 1.9 TeV @ Tevatron (10^{-7} Joule)

$$E = \frac{hc}{\lambda}$$

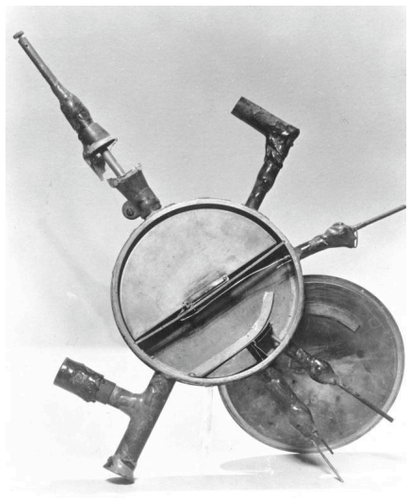
(variant of Heisenberg uncertainty: $\Delta p \approx \hbar/\Delta x$)

Experimental Basis for Modern Particle Physics

Fixed Target:

$$m_{\rm inv} \simeq \sqrt{2p_z m}$$

1931 (10^{-6} TeV)



Colliding Beams:

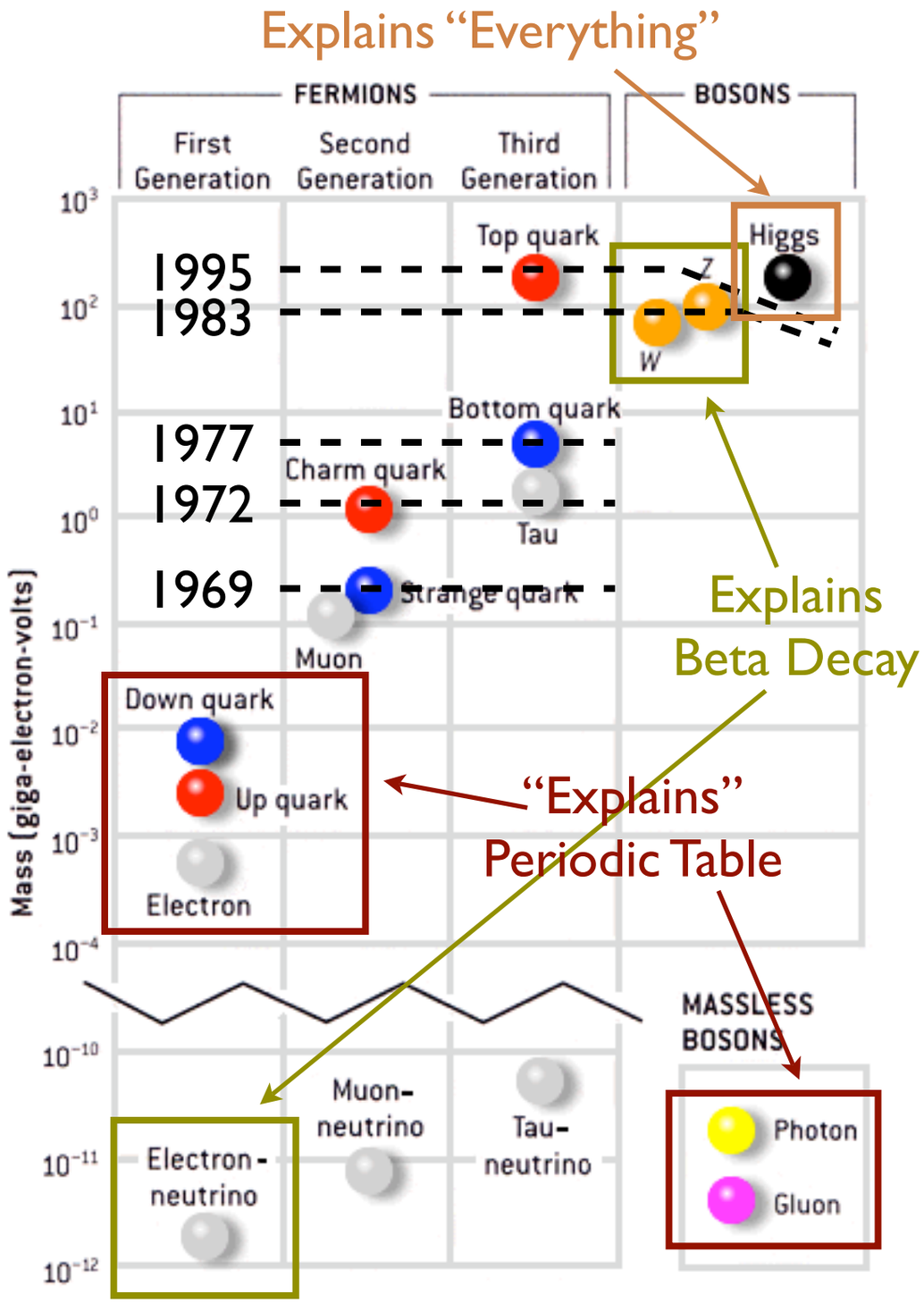
$$m_{\rm inv} \simeq 2p_z$$

2008 (1.9 TeV)

Colliding beams maximize bang/buck:

Tevatron-equivalent fixed target experiment would encircle the globe.

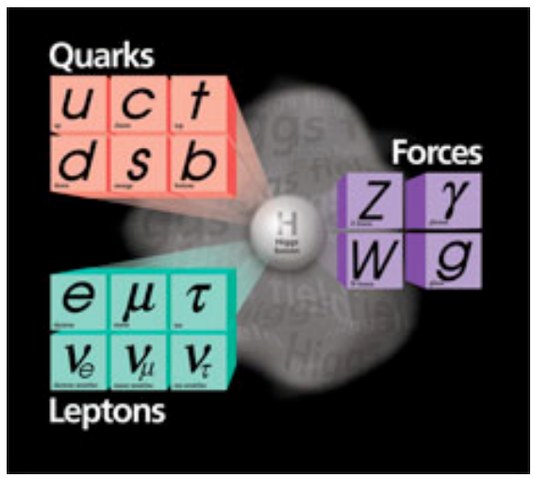
The Standard Model

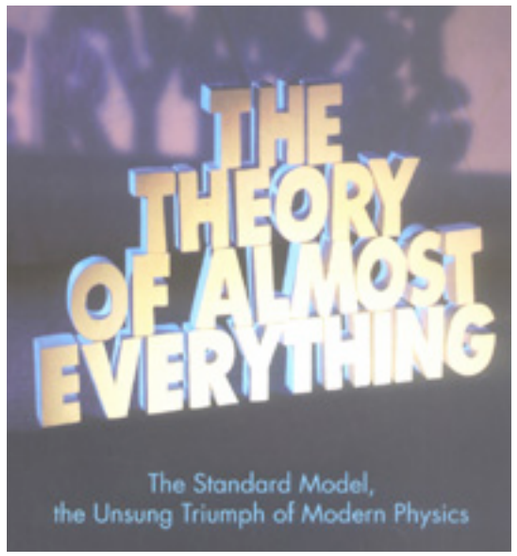


c. 2008: "Innersten"
= 4 forces + 12 fermions + Higgs

$$E = mc^2$$ ("Particles from Vacuum")

1995 (Tevatron = 1.9 TeV):
top quark = 0.17 TeV/c^2
≈ Gold atom ($97\ e^-$, $97\ p^+$, $118\ n$)





Visible Universe
Milky Way
Solar System
Earth
This way to...

10^4 m

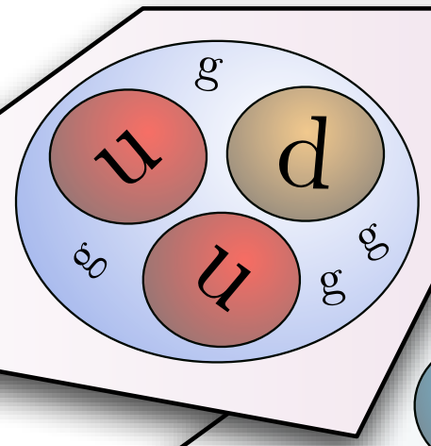
10^2 m

1 m

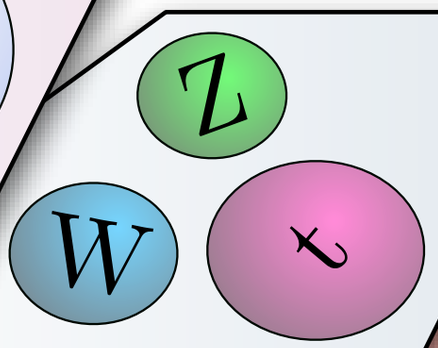
Cells
Molecules
...

10^{-16} m

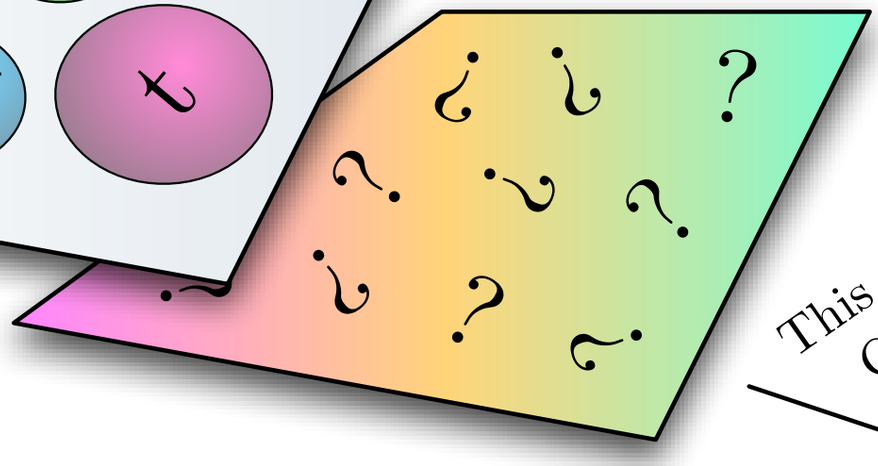
Atoms
Nuclei
...



10^{-18} m



10^{-20} m



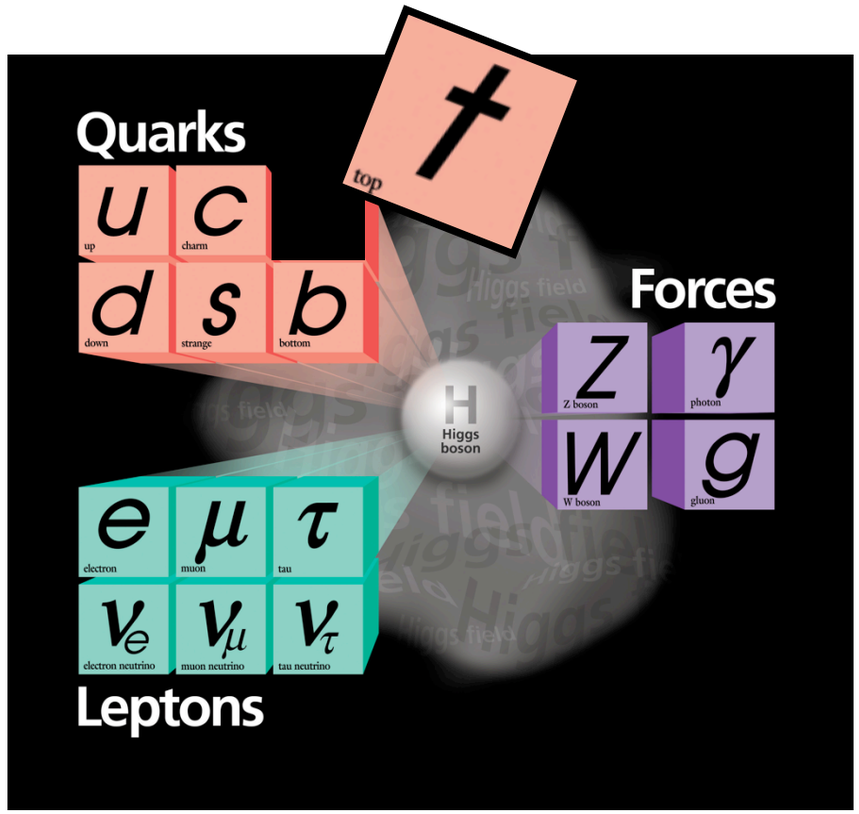
This way to...
Grand Unification?
Quantum Gravity?

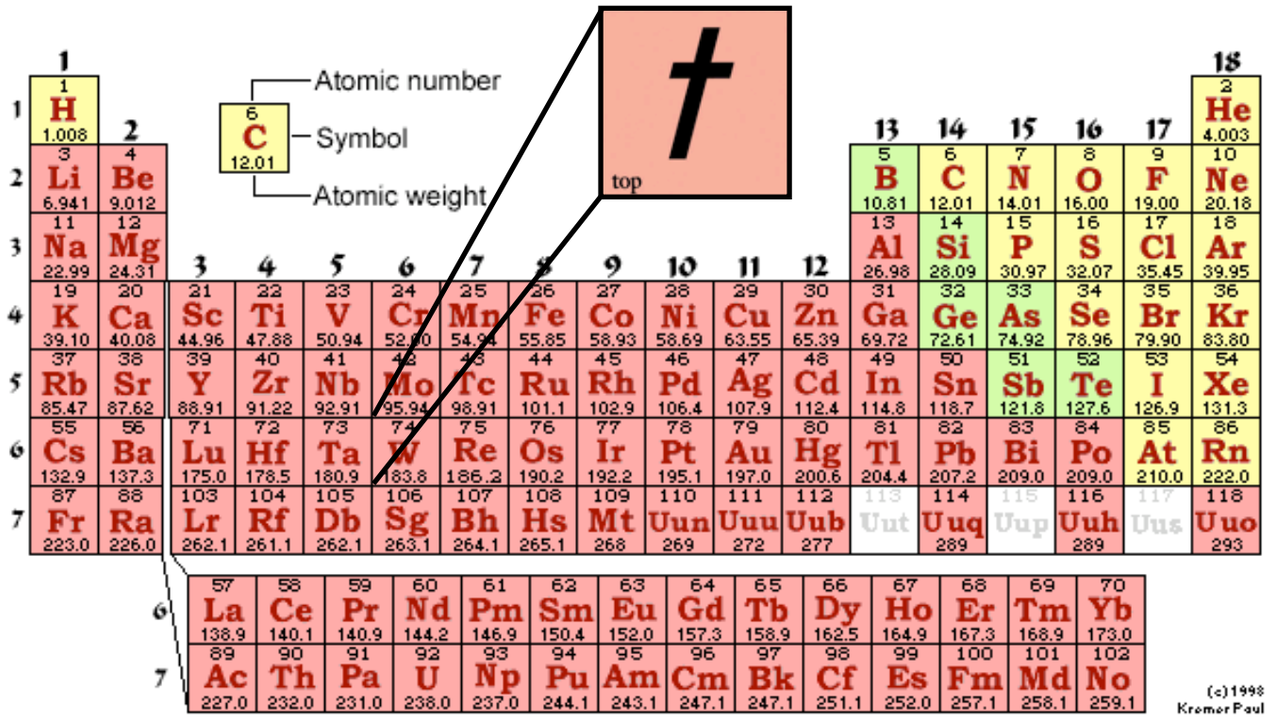
LHC:
pp @ 14 TeV

Just Матрёшка Dolls?

molecule > atom (10^{-10} m) > nucleus > proton (10^{-16} m) > quark

Subatomic Taxonomy?





Particle Physics not about Particles!

Principles!

What governs universe at long & short distances

Quantum Mechanics, Lorentz-Invariance, Locality,
Unitarity, Global Symmetries, Gauge Symmetries,
Conservation Laws, Spontaneous Symmetry Breaking...

Profound Fact: Known universe effectively described by

spin-1/2 fermions

interacting with

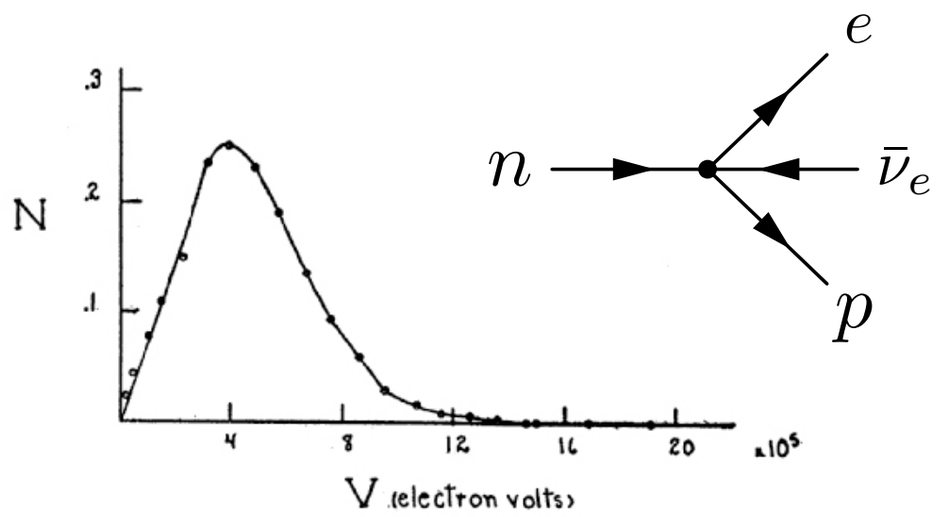
spin-2, spin-1, (and spin-0?) bosons

Particles With a Purpose

"Pauli's Neutron, Fermi's Neutrino"

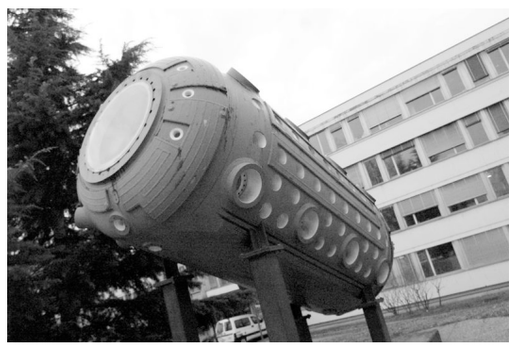
A Massless, Chargeless Particle?

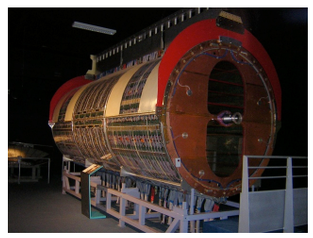
Conservation of Energy/Momentum!

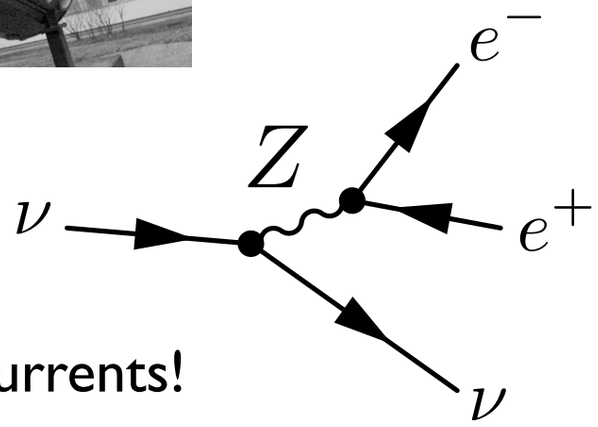


Continuous Spectrum in Beta Decay

Digging Deeper...







...Neutral Currents!

"Weak Gauge Bosons"

Heavy Spin-1 Resonances?

Unitarity of Scattering!
Ubiquity of Gauge Interactions!

Electroweak Symmetry Breaking

Vacuum state of universe has less symmetry than Lagrangian!

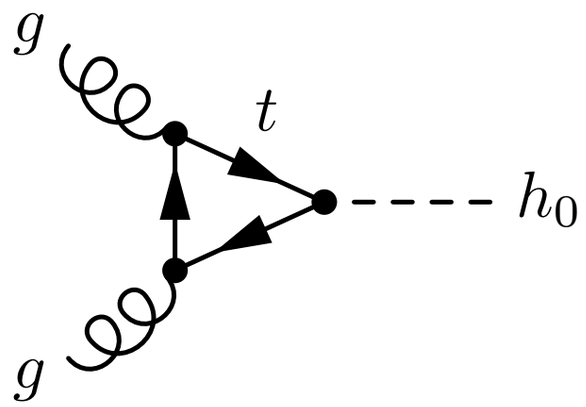
Familiar from condensed matter systems and chiral symmetry breaking in QCD

"Higgs Boson"

Fundamental Spin-0 Particle

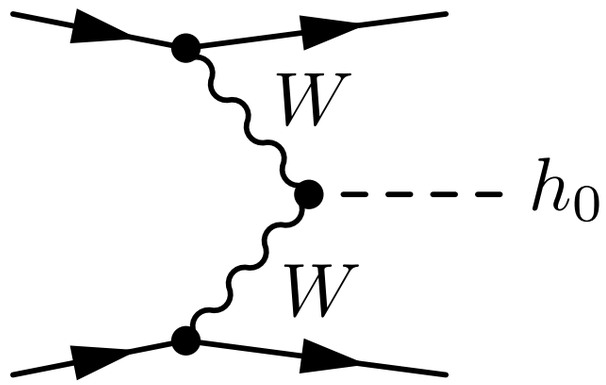
} Order parameter for symmetry breaking is fundamental field!?

Spontaneous Symmetry Breaking!



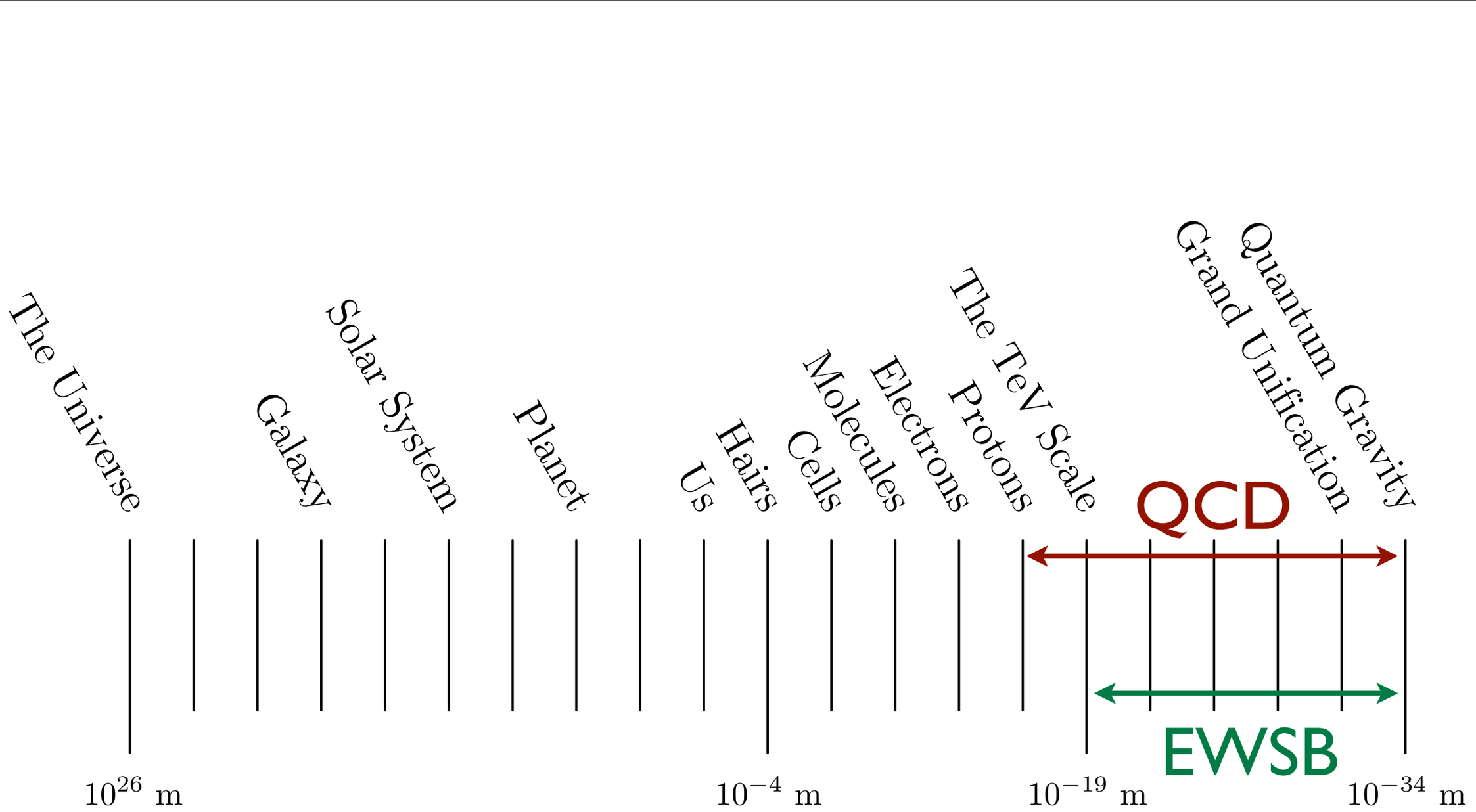
Implies Higgs vev is Origin of Fermion Masses

Unitarity Reemphasized!



Implies Higgs Unitarizes W-W Scattering!

Higgs discovery modes validate fundamental principles!


The Universe
Galaxy
Solar System
Planet
Us
Hairs
Cells
Molecules
Electrons
Protons
The TeV Scale
Grand Unification
Quantum Gravity
QCD
EWSB
10^{26} m
10^{-4} m
10^{-19} m
10^{-34} m
Satellites
Accelerators

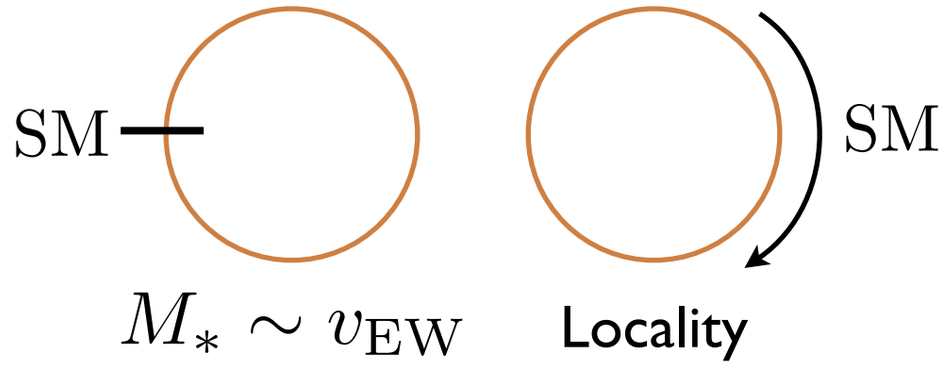
...and the Hierarchy Problem

What principles govern stability of electroweak scale?

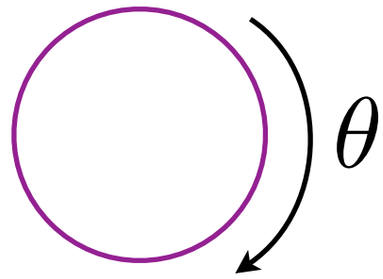
Strong Dynamics/ Compositeness?

$$\langle \psi \psi^c \rangle \to v_{\rm EW}$$
$$\langle \psi \psi^c \rangle \to H \to v_{\rm EW}$$

Higher Dimensional Structures?



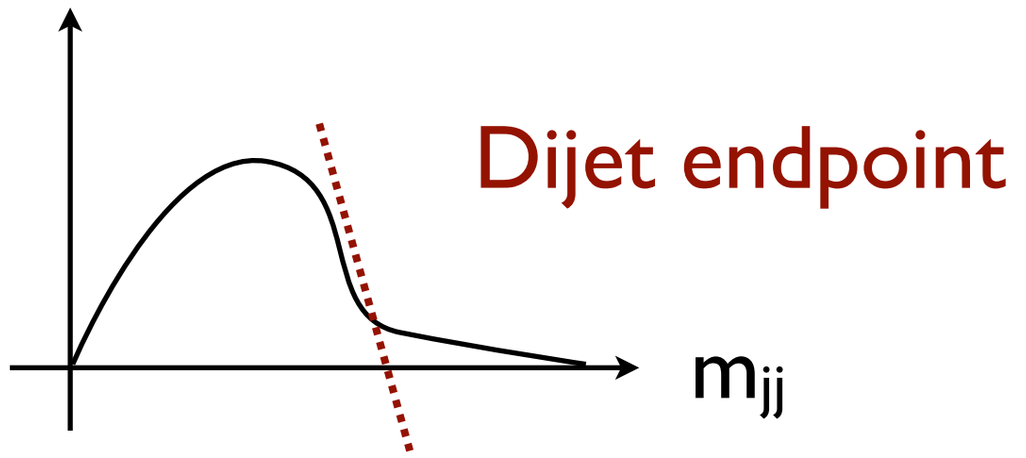
Supersymmetry?



Bosons ↔ Fermions

As profound as any other principles in fundamental physics. Well beyond simply taxonomy.

To uncover principles, have to first discover particles



X(780000+δ) & Y(220000+δ)?

Color-octet Majorana fermion?

Gluino?

SUSY solution to hierarchy problem?

Lesson from Theory

Different high energy theories can give same low energy behavior

Glashow, Salam, Weinberg Theory: 1973

Neutral Currents at Gargamelle: 1974

GSW Nobel Prize: 1979

Abbott-Fahri Model: 1981

W/Z Bosons at UA1/UA2: 1983

Rubbia,van der Meer Nobel: 1984

Precision Electroweak Favors

GSW: W/Z bosons are gauge bosons with mass from spontaneous symmetry breaking

Both predict neutral currents & Higgs-like state!

AF: W/Z bosons are composite spin-1 modes from strong dynamics (like QCD ρ meson)

Do we have enough straw-man models for SUSY?

How worried should I be of Gregoire/Katz composite "gluino"?

Lesson from the Tevatron

Large data sets needed to truly establish principles

Top quark discovered "quickly" (<100 pb^{-1} in 1995)

Single Top
W Helicity
Charge of Top
Top Width
Rare Decays

Are top and bottom really in $SU(2)_L$ doublet? $\begin{pmatrix} t \\ b \end{pmatrix}$

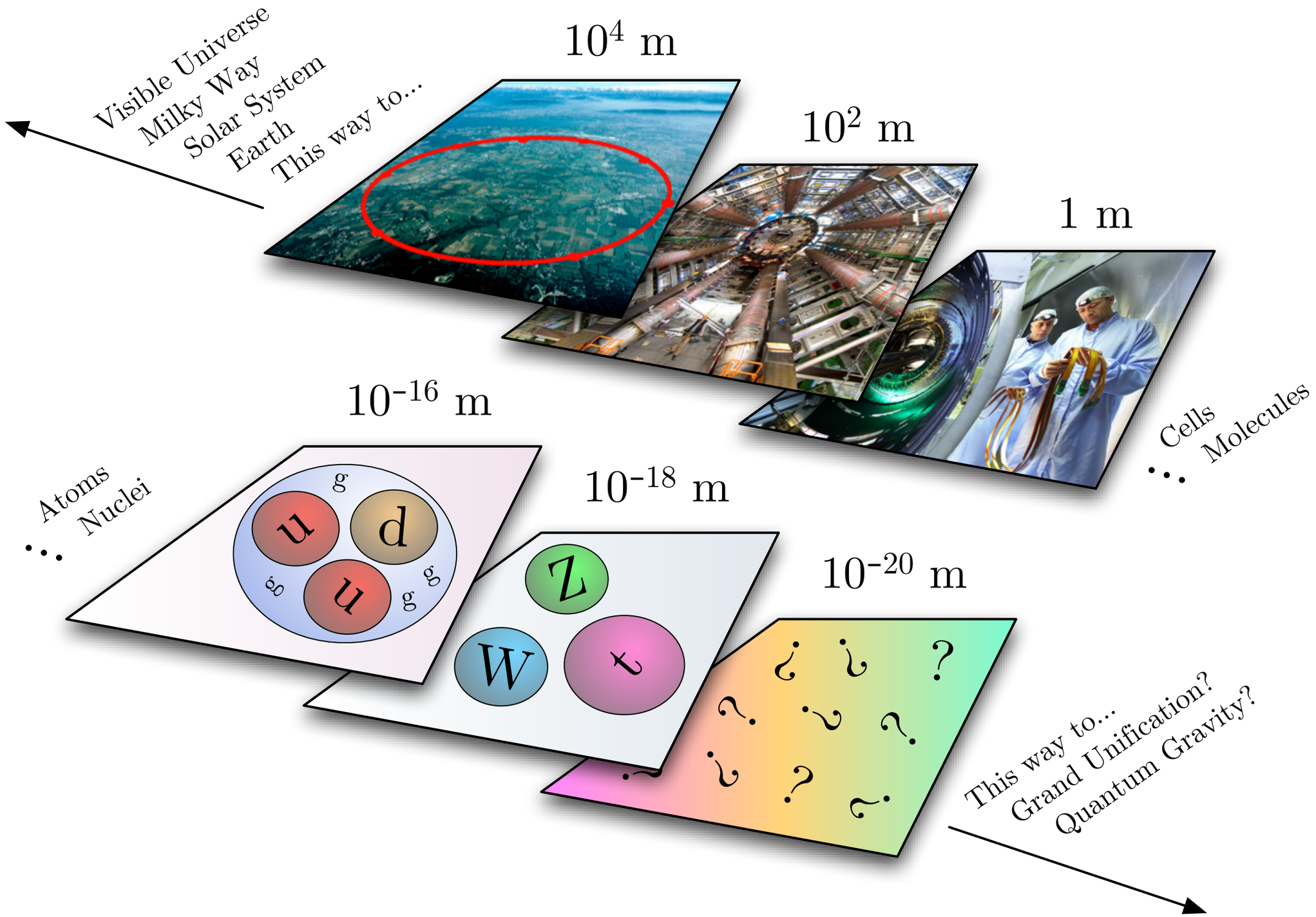
Need 1 fb^{-1} measurements

W/Z/top/Higgs properties predicted by SM

No unambiguous roadmap beyond the standard model:
Discovery @ 1 fb^{-1} → Properties @ 10 fb^{-1} →
(Preliminary) Principles @ 100 fb^{-1}??

Far more important than the particles we discover at the LHC are the principles that govern electroweak physics...

...but to uncover those principles we will need to study the detailed properties of particles and their interactions.

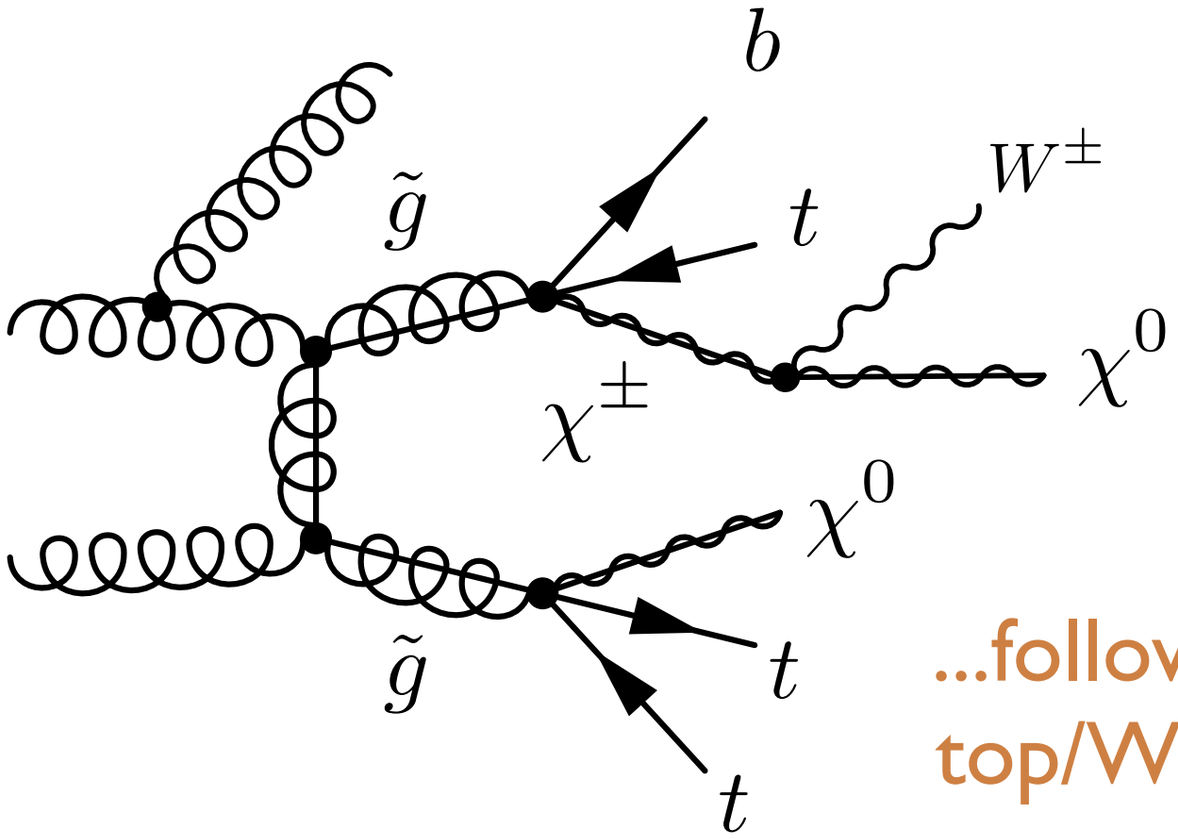


Enjoy the conference!

If I have time...

Challenge for the LHC

Predicted event topologies very complicated



...followed by top/W decay

High jet multiplicity? Isolation requirements?
ISR larger issue than at Tevatron? High luminosity pile-up?

No doubt that we'll recognize this as something new...
...will need many measurement tools to understand what this is.

Back Down to Earth

While particle physics is about the principles,
measurements are made with particles.

$$\sigma_X = \sum\!\!\!\!\!\!\int_{\{x_i\}\in X} \sigma(pp \to x_1 x_2 \cdots)$$

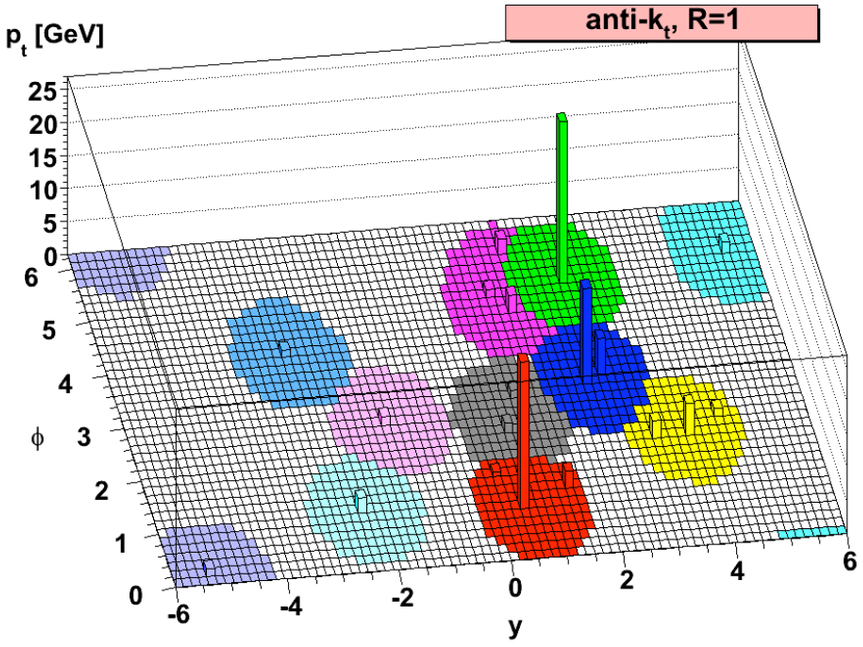
To make sense of LHC data, need X with high signal efficiency, good background rejection, and well-understood backgrounds

Two Measurement Thoughts to Discuss on the Slopes

Designer Jet Reconstruction

Advanced Data Extrapolation

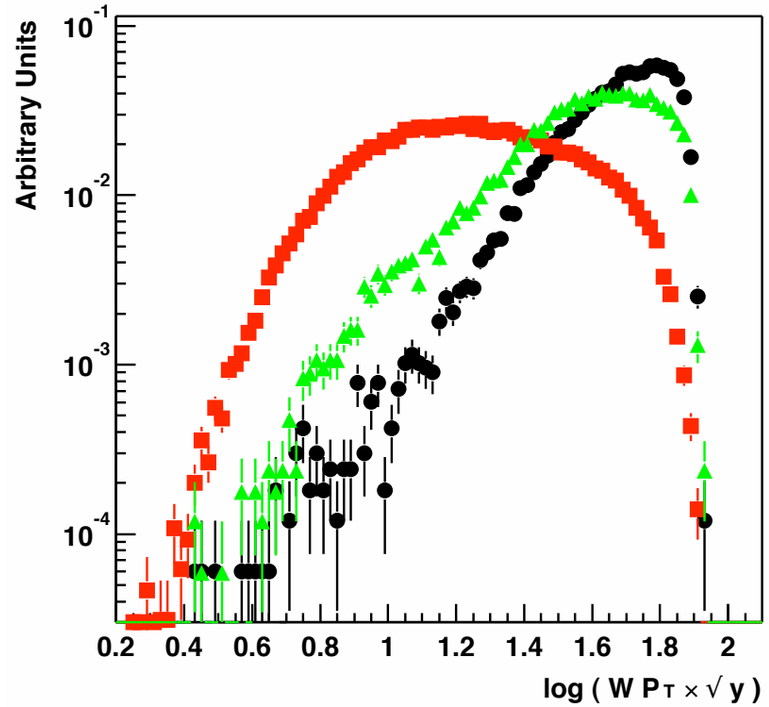
Designer Jet Reconstruction



Anti-K_T: Recursive, conical jets!

[Cacciari, Salam, Soyez]

You can make designer jets of any shape you want



Jet Substructure for Discrimination

[Butterworth, Cox, Forshaw]

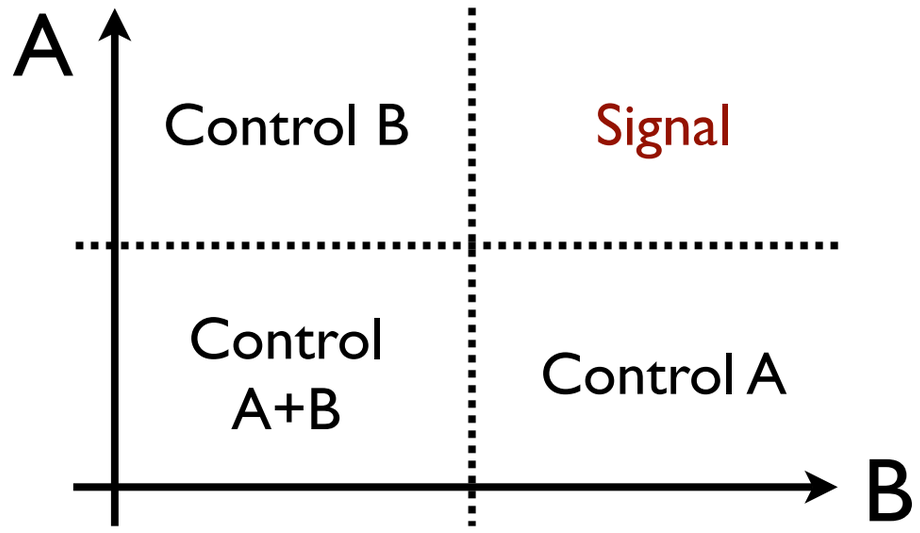
There is information in how a jet was clustered

Signal-specific (or background-rejection-specific) jet algorithms?
Design an algorithm optimized for, say, 2 TeV hadronic Z'?

Advanced Data Extrapolation

ME/PS matching and MC@NLO now standard at Tevatron.

NLO/PS merging (beyond MC@NLO) and automated NLO on the horizon.



Extrapolate Background from Data

NLO/PS requires matching of n-body calculation to (n+1)-body calculation

Background extrapolation has only been used for n-body to n-body

Can we extrapolate n-body background to (n+1)-body background using theoretical merging methods?
Want fully differential extrapolation of multijet backgrounds.