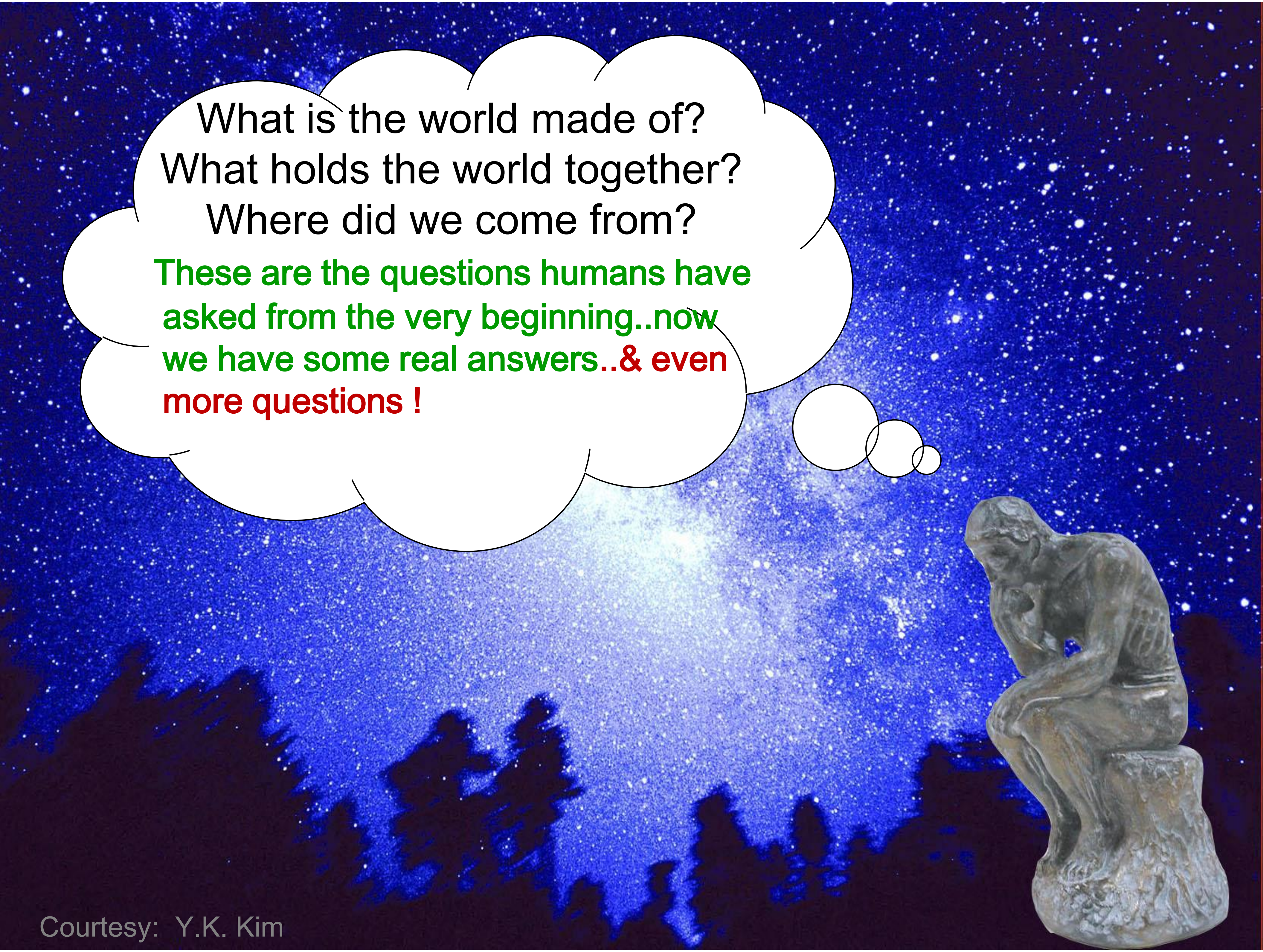
Theoretical High Energy Physics

SLAC NATIONAL ACCELERATOR LABORATORY

Tom Rizzo 6/23/2010

Theoretical High Energy Physics

THE REVOLUTION IS HERE !

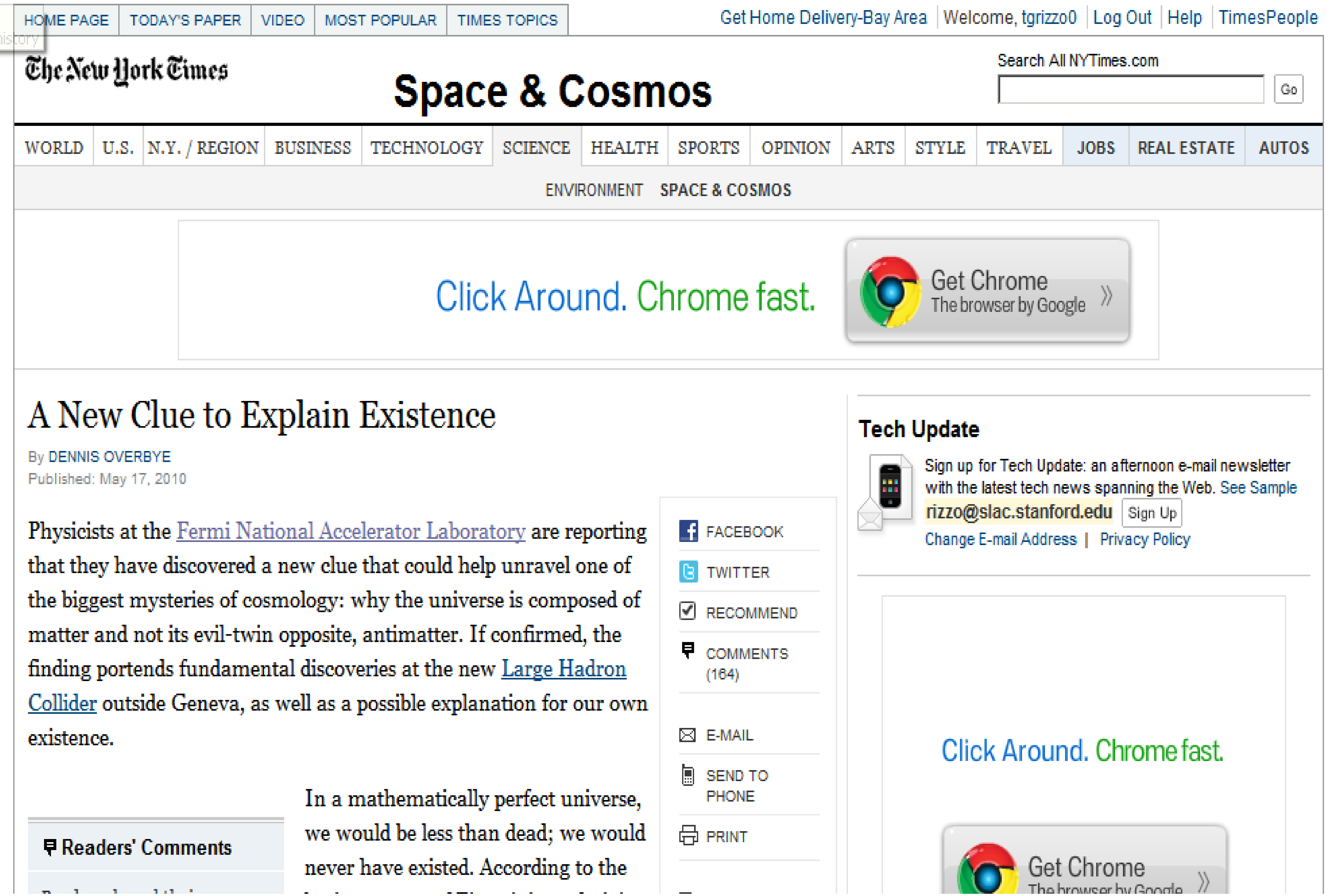


What is the world made of?
What holds the world together?
Where did we come from?

These are the questions humans have asked from the very beginning..now we have some real answers..& even more questions !

Courtesy: Y.K. Kim

Questions like these capture ‘universal’ interest….



A New Clue to Explain Existence

By DENNIS OVERBYE
Published: May 17, 2010

Physicists at the Fermi National Accelerator Laboratory are reporting that they have discovered a new clue that could help unravel one of the biggest mysteries of cosmology: why the universe is composed of matter and not its evil-twin opposite, antimatter. If confirmed, the finding portends fundamental discoveries at the new Large Hadron Collider outside Geneva, as well as a possible explanation for our own existence.

In a mathematically perfect universe, we would be less than dead; we would never have existed. According to the

Tech Update

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rizzo@slac.stanford.edu

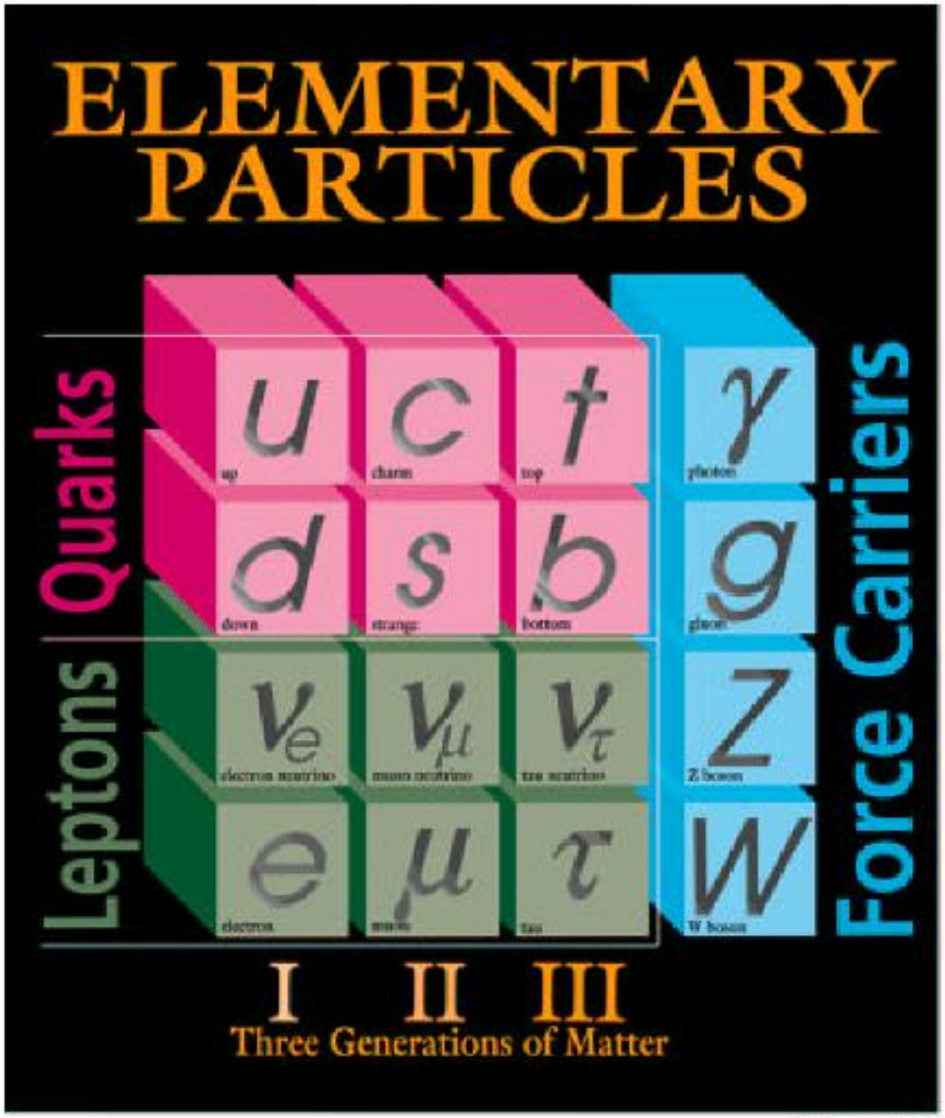
The purpose of High Energy (= Particle) Physics is to discover & understand the basic components of matter and their various interactions at the most fundamental level.   More generally, we want the answers to the following questions:

1. What are the fundamental laws of nature?
2. What is the composition of the universe?
3. How did the universe get to be as it is?

→ Here we immediately see the overlap between HEP and astrophysics/cosmology

One of the great scientific triumphs of the past century is the development of the 'Standard Model' (SM) which, together with General Relativity, describes all of the matter & interactions that we see around us (and in all of the laboratories on Earth) on scales as small as 10^{-17} cm and as large as 10^{23} cm.

The Standard Model describes the strong nuclear force, the weak nuclear force, and electromagnetism (light, electricity, magnetism…) while General Relativity describes gravity.



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Quarks & leptons are spin-1/2 *fermions* making up all of the matter we know (proton ~ uud, neutron ~udd). They come in 3 'generations' or copies for some *unknown* reason .

The strong force is 'carried' by gluons, the weak force by $W^\pm$ & Z bosons and electromagnetism by the photon ; all are spin-1 *bosons.* Gravity is carried by gravitons which have spin-2.

The Forces result from ‘Gauge Symmetries’:

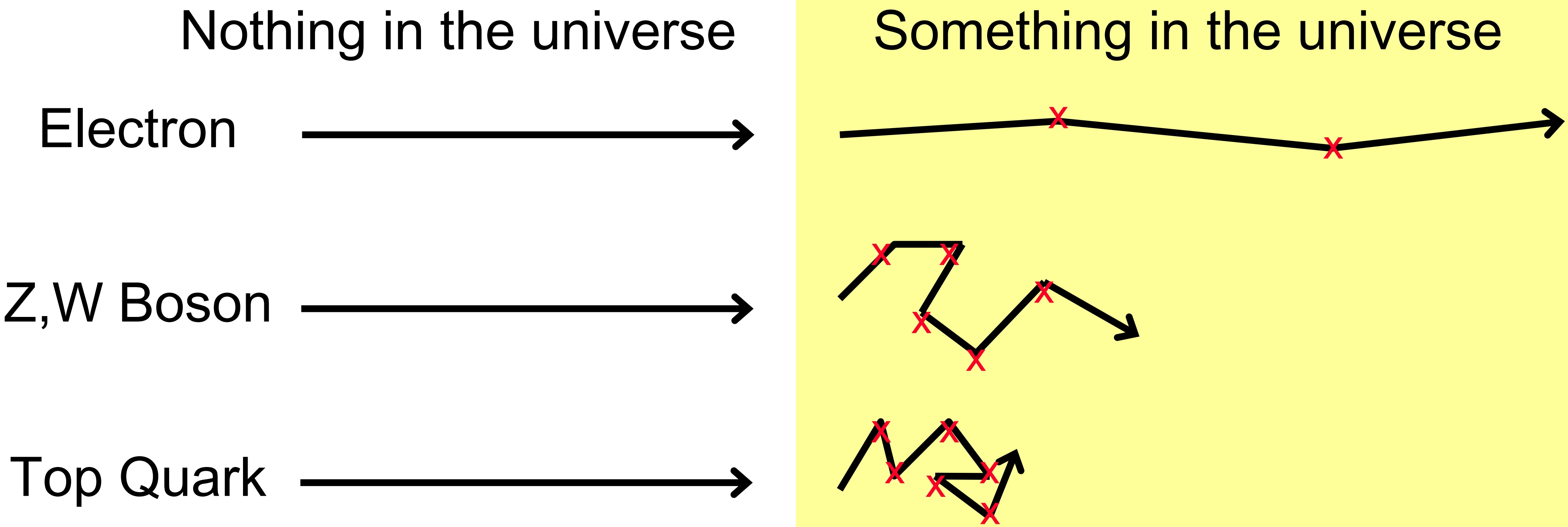
$$\underbrace{SU(3)_C}_{\text{QCD}} \times \underbrace{SU(2)_L \times U(1)_Y}_{\text{Electroweak}} \rightarrow \text{‘Spontaneously Broken’ to QED}$$

Gauge invariance requires massless force carriers like the γ & forces of infinite range, $\sim 1/r^2$. But the weak force is short ranged, $\sim e^{-mr}/r^2$, & the W/Z bosons are massive requiring a ‘breaking’ of the gauge symmetry by some mechanism. In the SM this is done by the hypothetical, spin-0 *Higgs boson*.

While all the gauge bosons, quarks & leptons of the SM have been observed experimentally, the Higgs has not yet been seen in any experiments….

Origin of Mass:

Something in the universe gives mass to particles



Nothing in the universe

Something in the universe

Electron

Z,W Boson

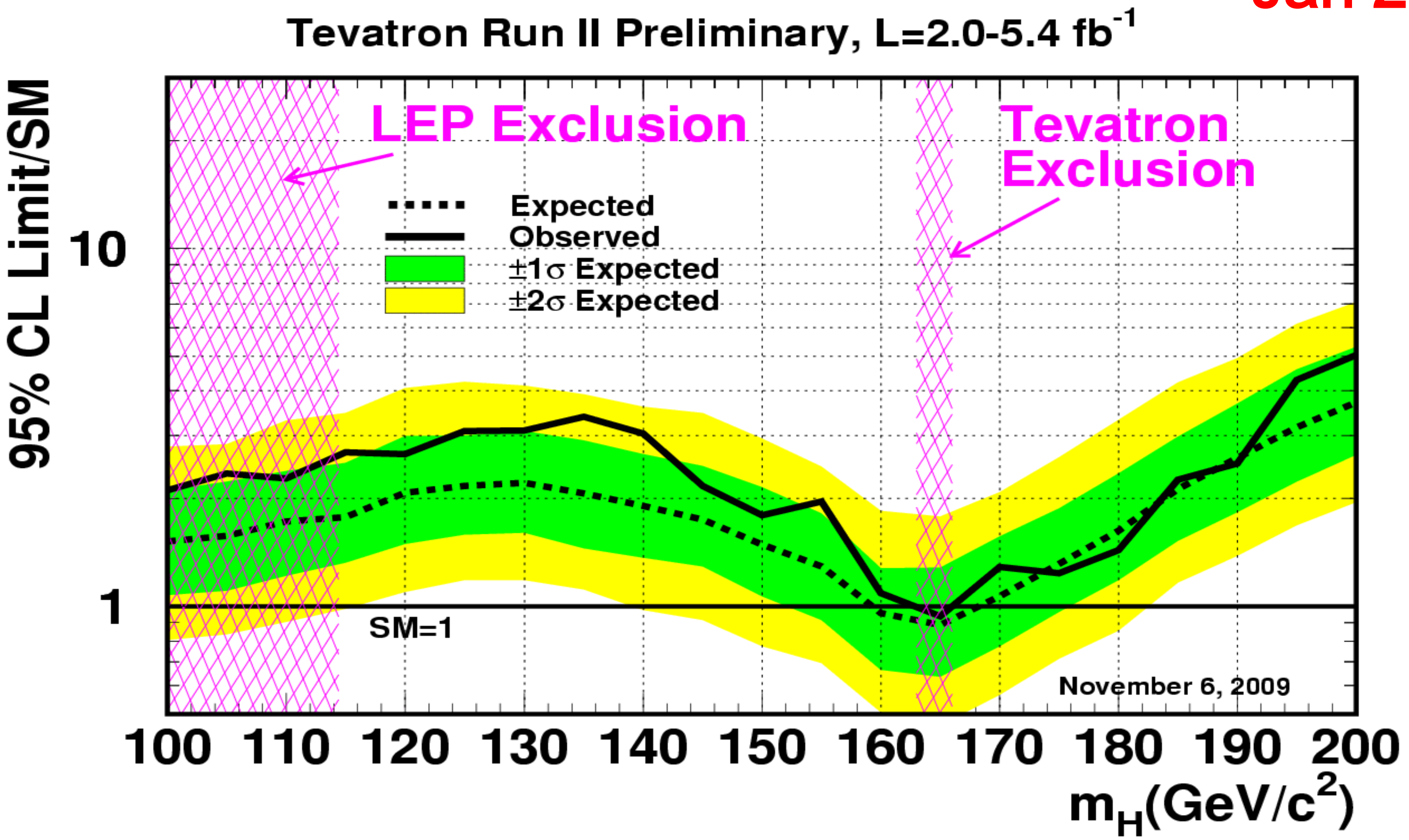
Top Quark

But where is the Higgs??

We believe it’s a Higgs Field

A particle which couples proportionally to mass

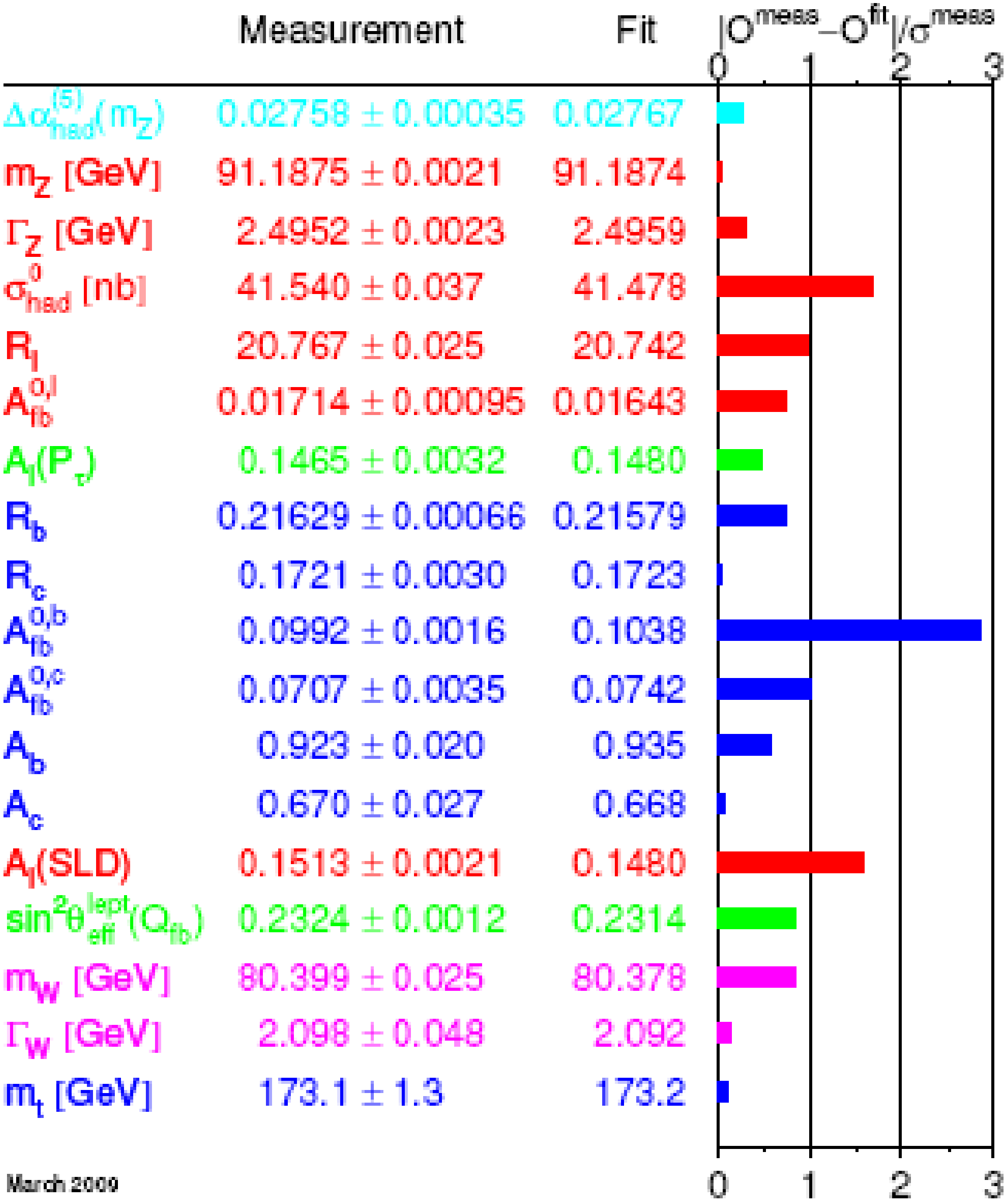
Jan 2010



SM Sensitivity: 159-169 GeV/c^2!

SM Exclusion: 162-166 GeV/c^2!

T. Aaltonen *et al.*, (CDF and DØ Collaborations), Phys. Rev. Lett. **104**, 061802 (2010).



	Measurement	Fit
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02758 ± 0.00035	0.02767
m_Z [GeV]	91.1875 ± 0.0021	91.1874
Γ_Z [GeV]	2.4952 ± 0.0023	2.4959
σ_{had}^{0} [nb]	41.540 ± 0.037	41.478
R_l	20.767 ± 0.025	20.742
$A_{fb}^{0,l}$	0.01714 ± 0.00095	0.01643
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1480
R_b	0.21629 ± 0.00066	0.21579
R_c	0.1721 ± 0.0030	0.1723
$A_{fb}^{0,b}$	0.0992 ± 0.0016	0.1038
$A_{fb}^{0,c}$	0.0707 ± 0.0035	0.0742
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1480
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.399 ± 0.025	80.378
Γ_W [GeV]	2.098 ± 0.048	2.092
m_t [GeV]	173.1 ± 1.3	173.2

March 2009

The SM picture has been precisely tested in many ways & over many years generally to the level of ~ 0.1% & in some cases to 1 part in 10^{15} !

Though there are a few ‘tiny’ discrepancies, it works so well & in so many places that it has been turned into a wall poster…

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/c²	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

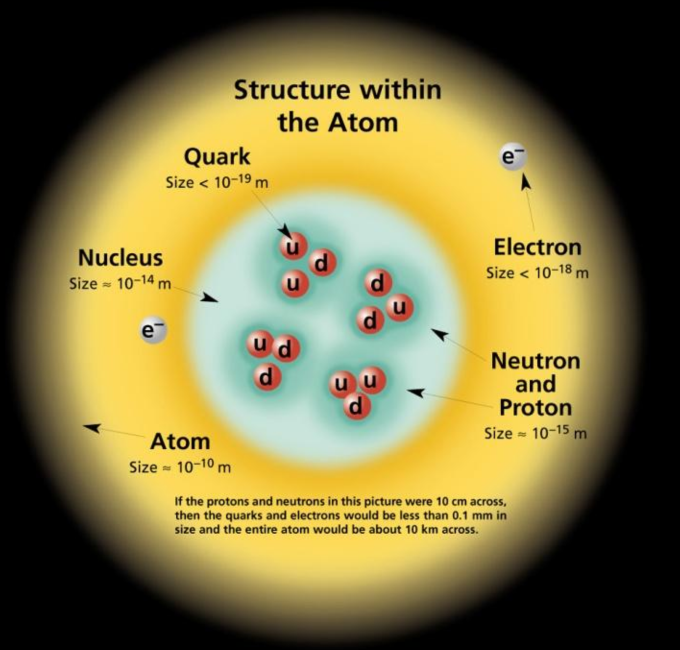
Quarks spin = 1/2

Flavor	Approx. Mass GeV/c²	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 $= 1.05\text{x}10^{-34}$ 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/c²	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/c²	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/c²	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

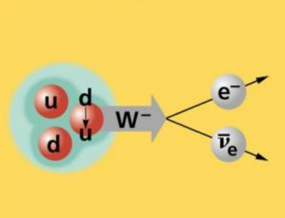
Matter and Antimatter

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

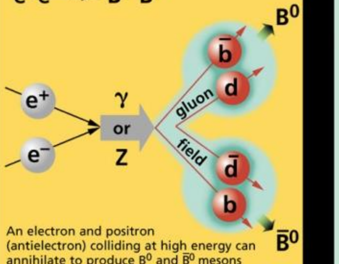
These diagrams are an artist's conception of physical processes. They are ***not*** exact and have ***no*** meaningful scale. Green shaded areas represent the cloud of gluons or the gluon field, and red lines the quark paths.

$n \rightarrow p\, e^-\, \bar{\nu}_e$



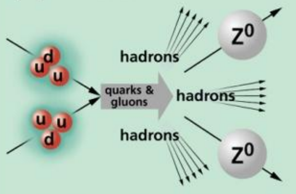
A neutron decays to a proton, an electron, and an antineutrino via a virtual (mediating) W boson. This is neutron β decay.

$e^+e^- \rightarrow B^0\, \bar{B}^0$



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.

$p\, p \rightarrow Z^0 Z^0$ + assorted hadrons



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.

Mesons $q\bar{q}$

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

Symbol	Name	Quark content	Electric charge	Mass GeV/c²	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

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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Lawrence Berkeley National Laboratory
Stanford Linear Accelerator Center
American Physical Society, Division of Particles and Fields
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http://CPEPweb.org

Despite its many successes the SM is incomplete & leaves MANY questions *unanswered:*

1. Are there undiscovered principles of nature: New symmetries, new physical laws?

2. How can we solve the mysteries of dark energy and dark matter? Can we make dark matter in a laboratory on Earth?

3. Why are there 4 space-time dimensions? Are there extra dimensions of space? Can we see them?

4. Do all the forces become unified? Why do the SM parameters take on the particular values that they do?

5. Why is the EW scale at ~100 GeV & not, e.g., at the (Planck) scale of gravity ~10 ^{19} GeV?

6. Why are there so many kinds of particles? Why are there three generations of quarks & leptons with such diverse masses?

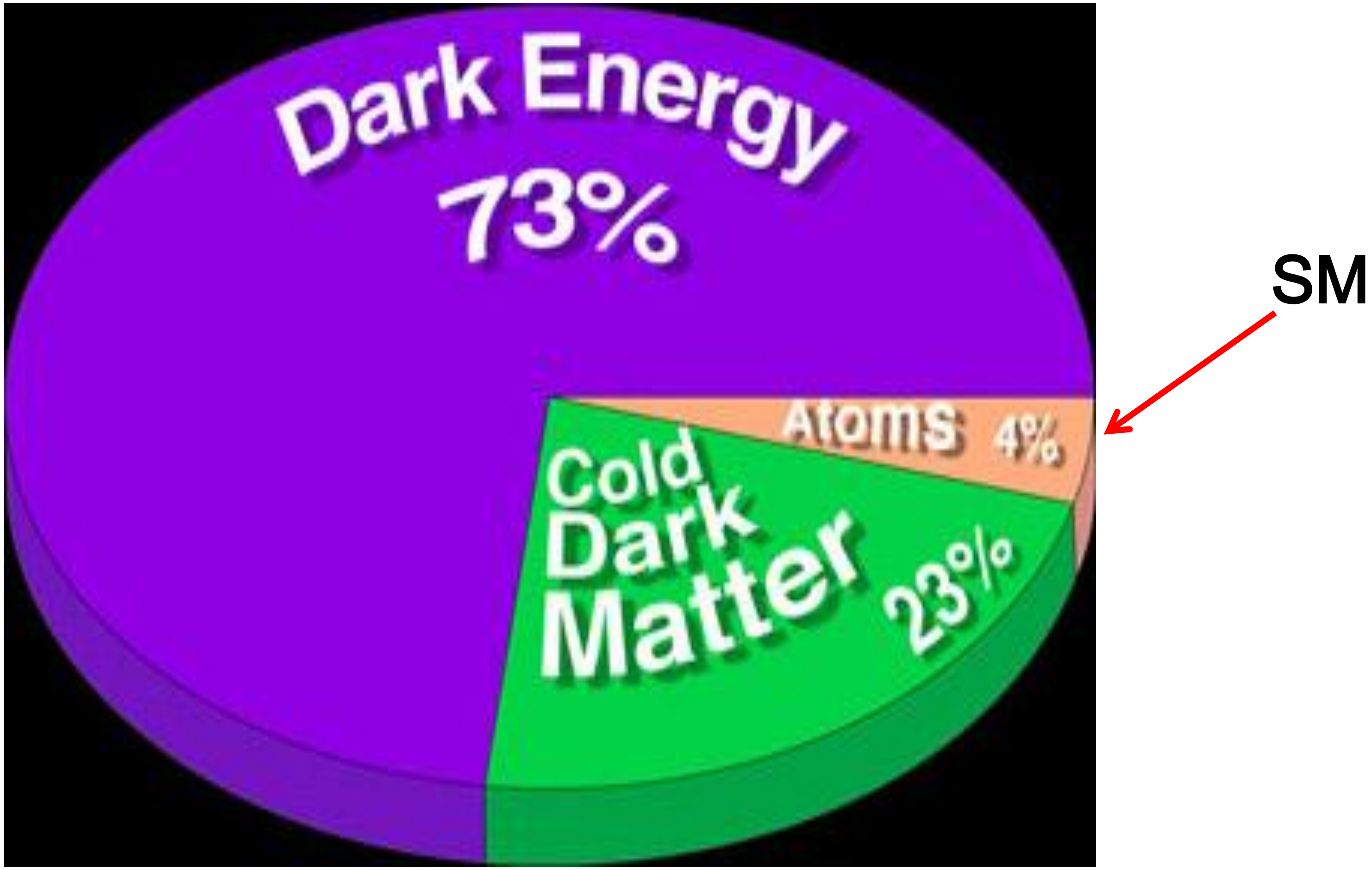
7. What are the neutrino masses & mixings telling us?

8. How did the universe come to be? Why is gravity so much weaker than the other forces? How do we incorporate GR into this SM picture? Is GR the correct theory of gravity?

9. Why is there only matter; what happened to the antimatter?

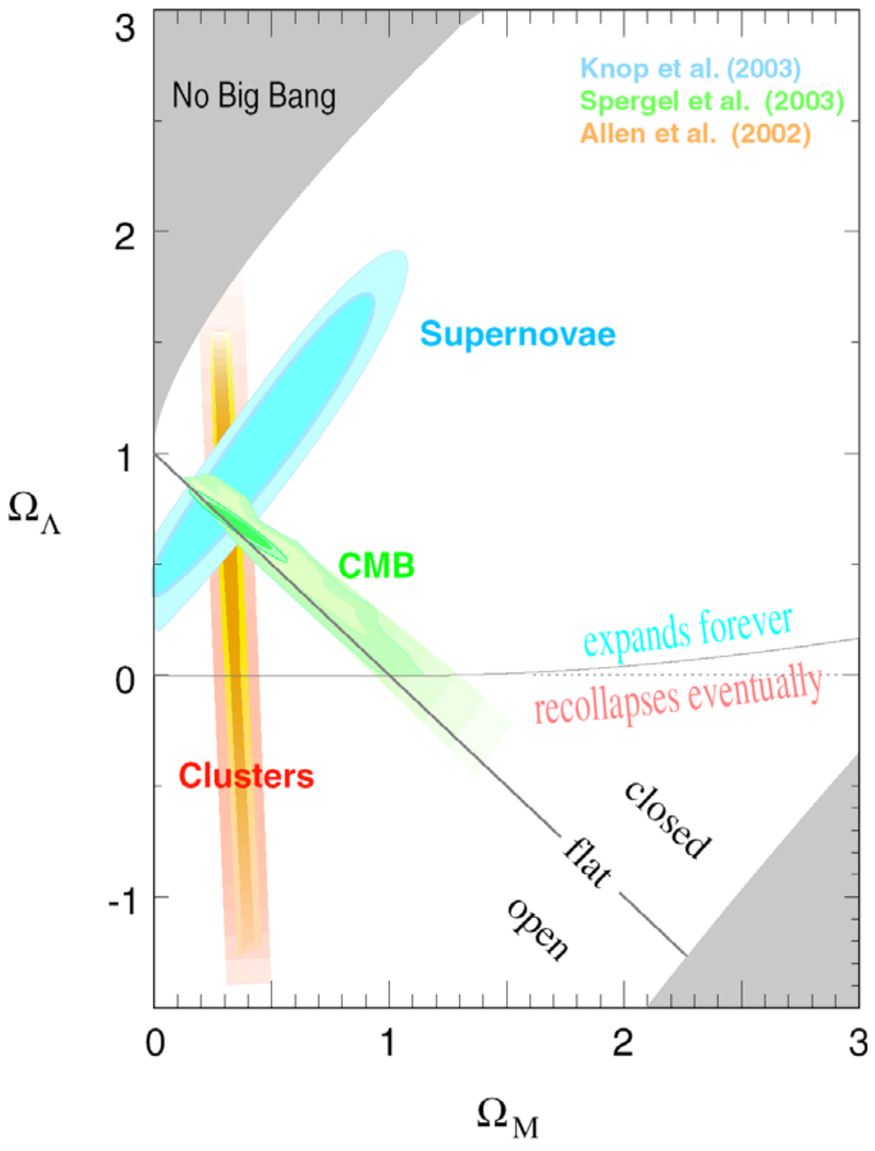
10. ……

One can add many other questions to this list…let's talk about a few of them..



A combination of a number of astrophysical measurements tell us that most of the universe is made up of stuff that is not part of the SM as well as electromagnetically ‘invisible’…. what is it????

EVIDENCE FOR DARK MATTER



- Ultimate Copernican Revolution!
- There is now **overwhelming & precise** data showing that normal matter is not dominant in the Universe:

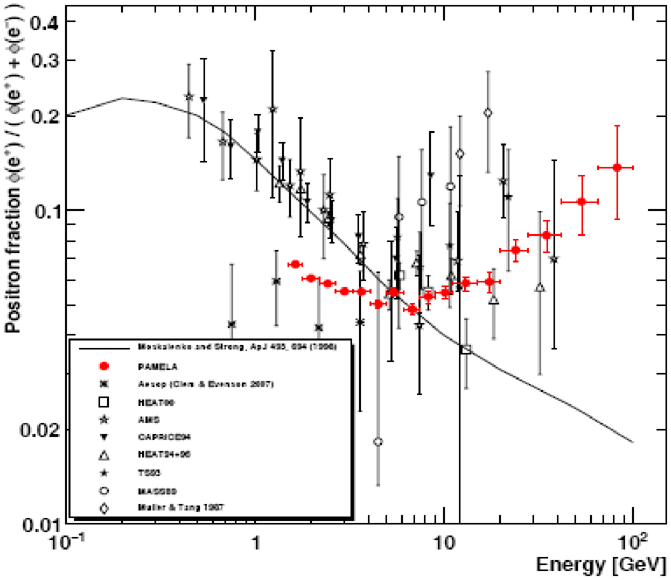
  Dark Matter: 22.5%   0.7%

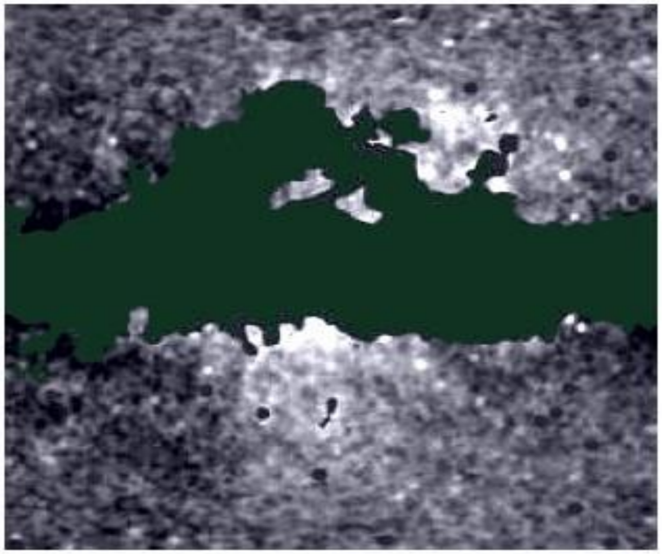
  Dark Energy: 72.8% ± 1.5%

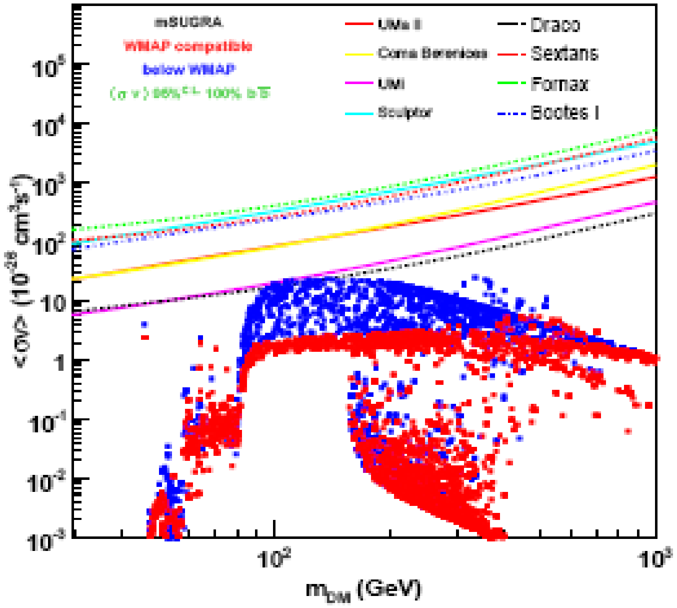
  Normal Matter: 4.6% ± 0.1%

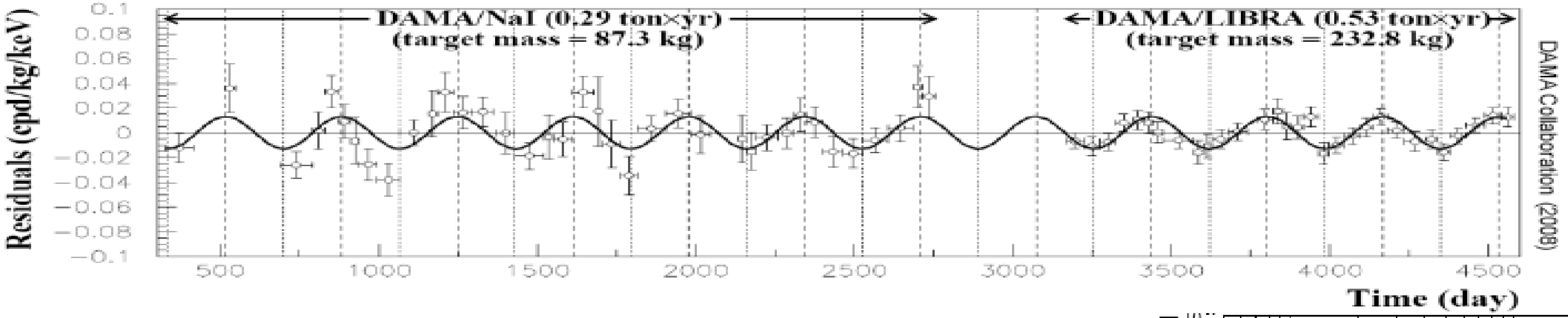
  Neutrinos: Σm_ν <0.58 eV

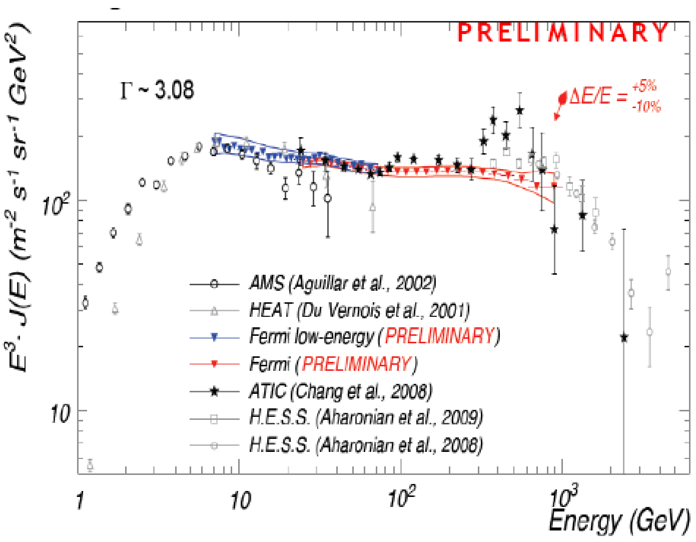
- To date, all evidence is from dark matter's gravitational effects. We would like to detect it in other ways to learn more about it.



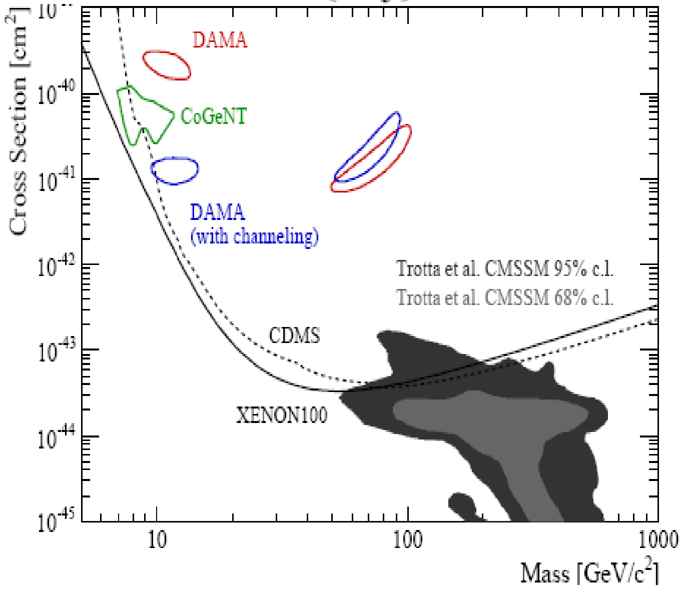


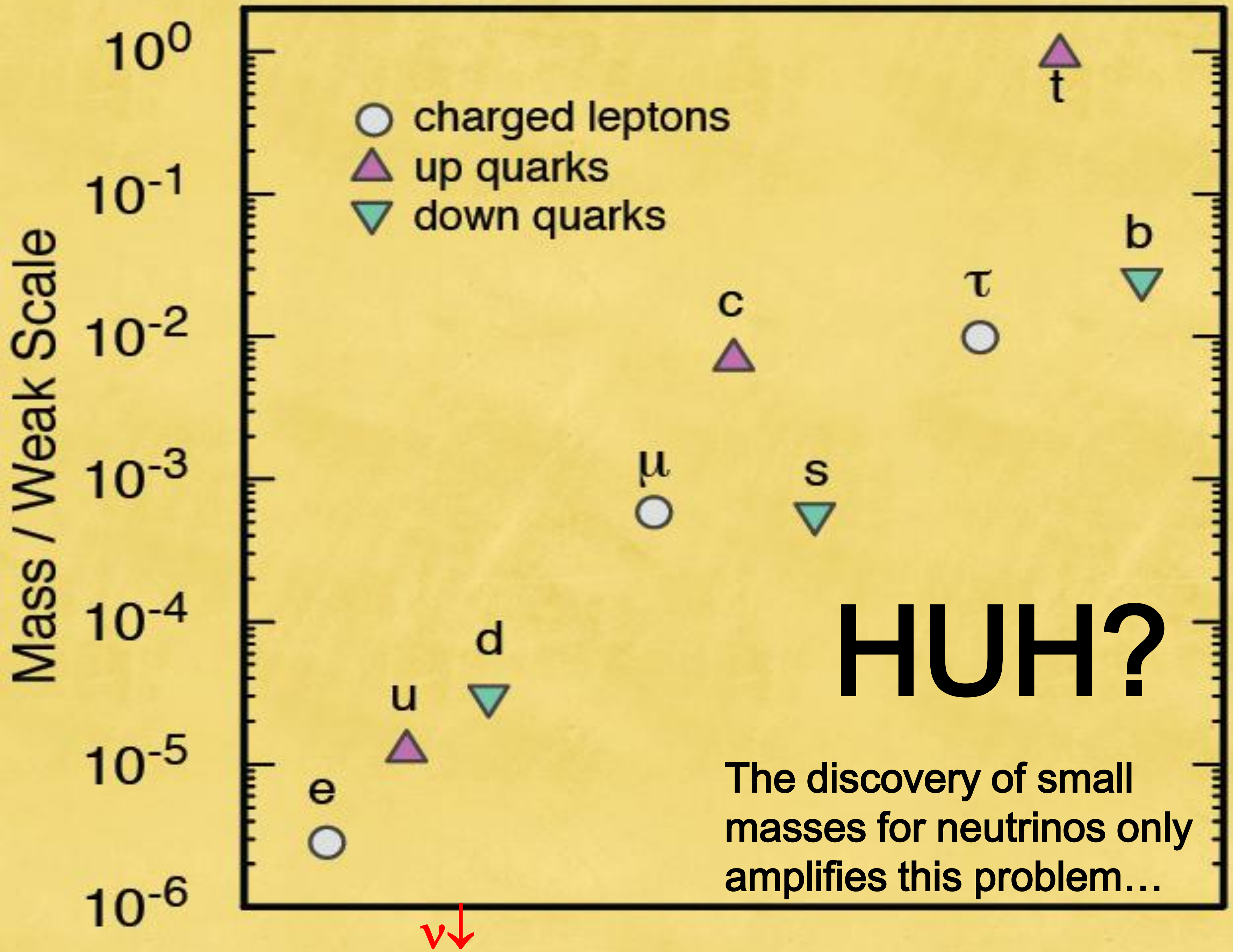






Searches for Dark Matter

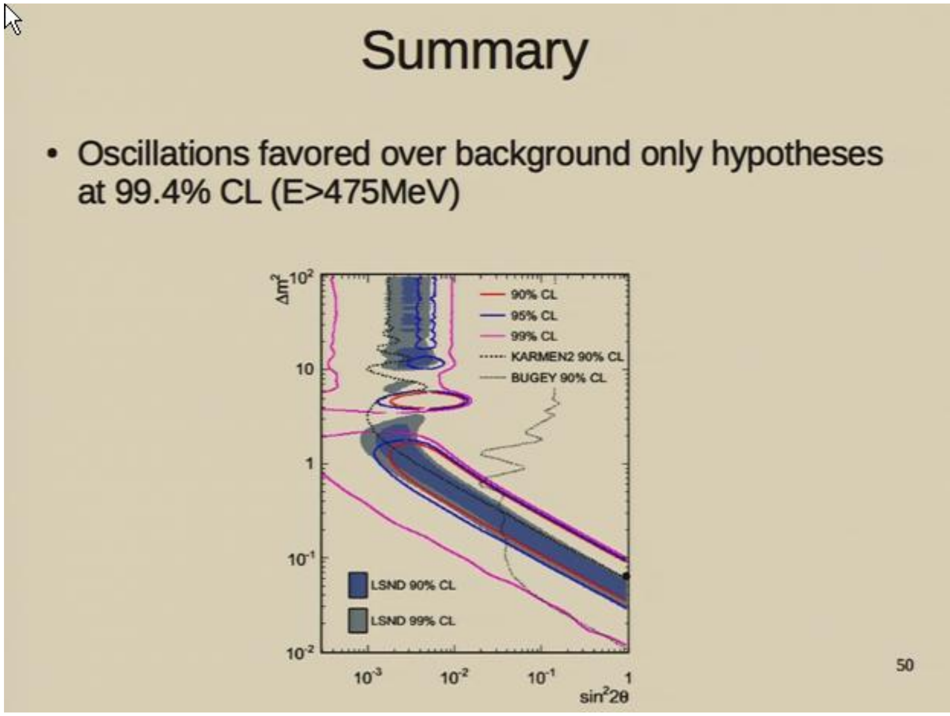




HUH?

The discovery of small masses for neutrinos only amplifies this problem…

..& just LAST WEEK we heard evidence that there may be new (sterile) neutrinos, that neutrinos can violate CP & possibly even CPT!!!!

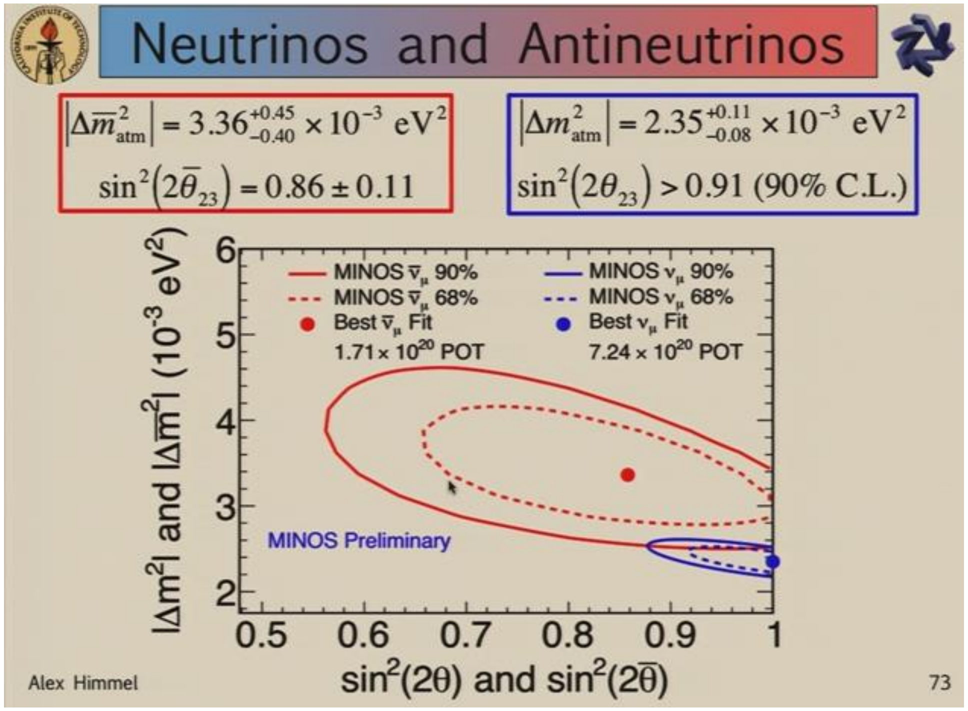


Summary

- Oscillations favored over background only hypotheses at 99.4% CL (E>475MeV)

50

MiniBooNe



Neutrinos and Antineutrinos

$\left|\Delta\overline{m}^2_{\text{atm}}\right| = 3.36^{+0.45}_{-0.40}\times10^{-3}\ \text{eV}^2$

$\sin^2\left(2\overline{\theta}_{23}\right) = 0.86\pm0.11$

$\left|\Delta m^2_{\text{atm}}\right| = 2.35^{+0.11}_{-0.08}\times10^{-3}\ \text{eV}^2$

$\sin^2\left(2\theta_{23}\right) > 0.91\ (90\%\ \text{C.L.})$

Alex Himmel

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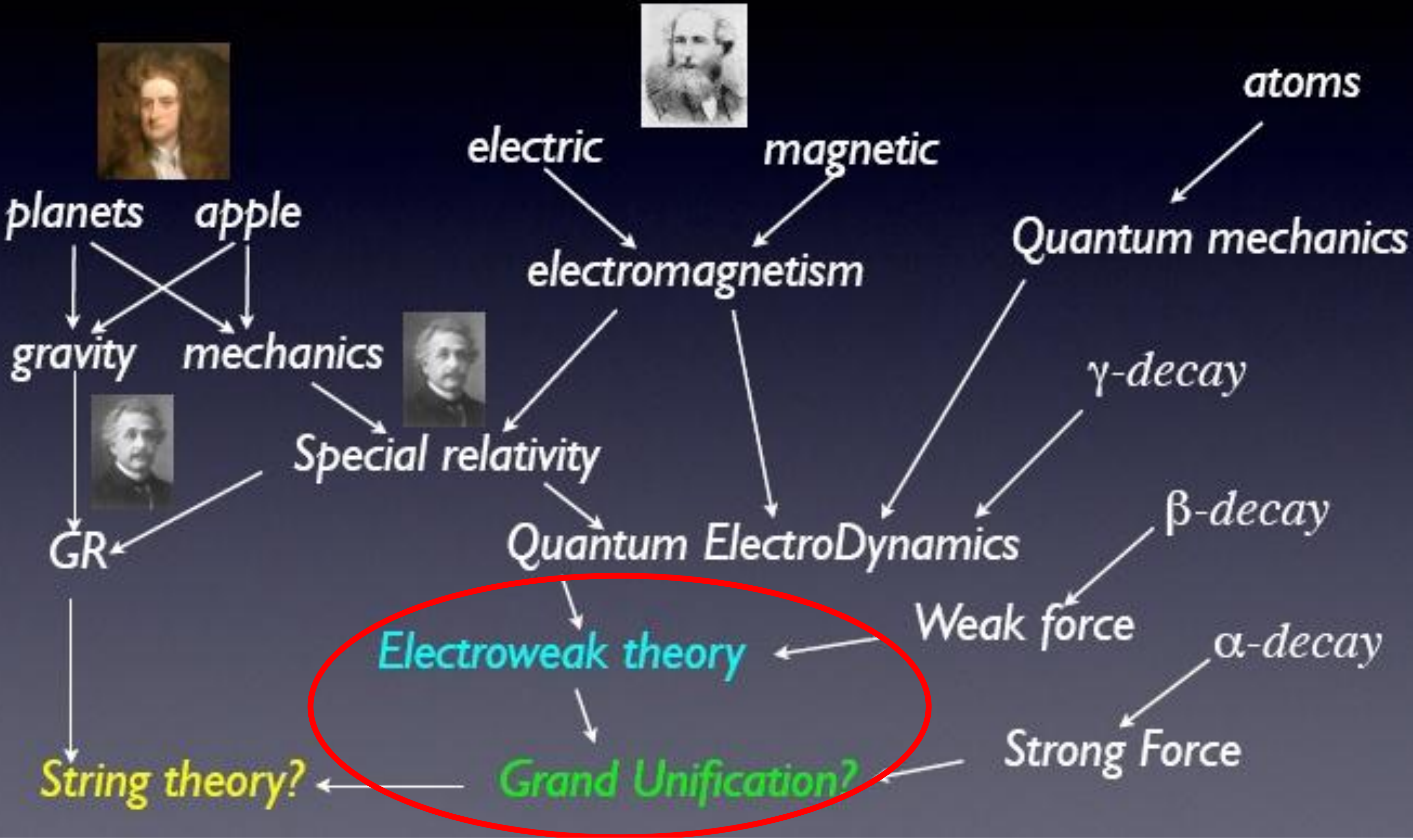
MINOS

History of Unification



electric

magnetic

atoms

planets apple

electromagnetism

Quantum mechanics

gravity mechanics

γ-decay

Special relativity

β-decay

GR

Quantum ElectroDynamics

Weak force

Electroweak theory

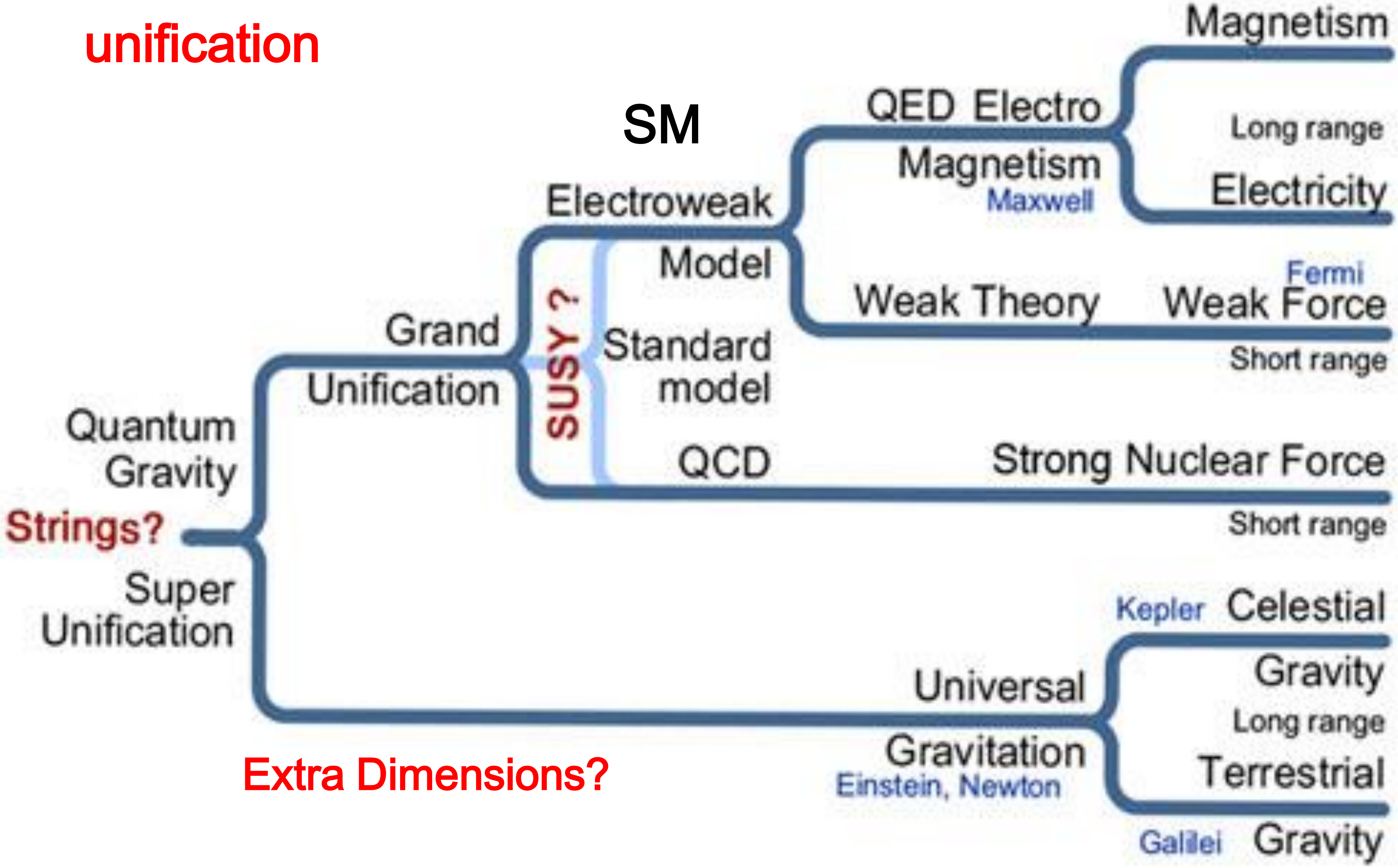
α-decay

Strong Force

String theory?

Grand Unification?

Another view of unification



The Hierarchy Problem

Energy (GeV)

10^{19} Planck=Gravity

10^{16} GUT

desert

Collider Energies → 10^{3} Weak

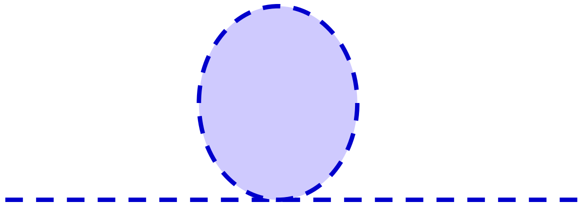
All of known physics

10^{-18} Solar System Gravity

Quantum Corrections:

→Drags the Weak Scale to M_{Planck}

$\delta m_H^2 \sim$



$\sim M_{Pl}^2$

It is more 'natural' for the weak scale to be near the Planck scale than ~1 TeV

To address these and other questions many theorists have been very busy over the last 3 decades constructing models of new physics which are various possible extensions of the SM.

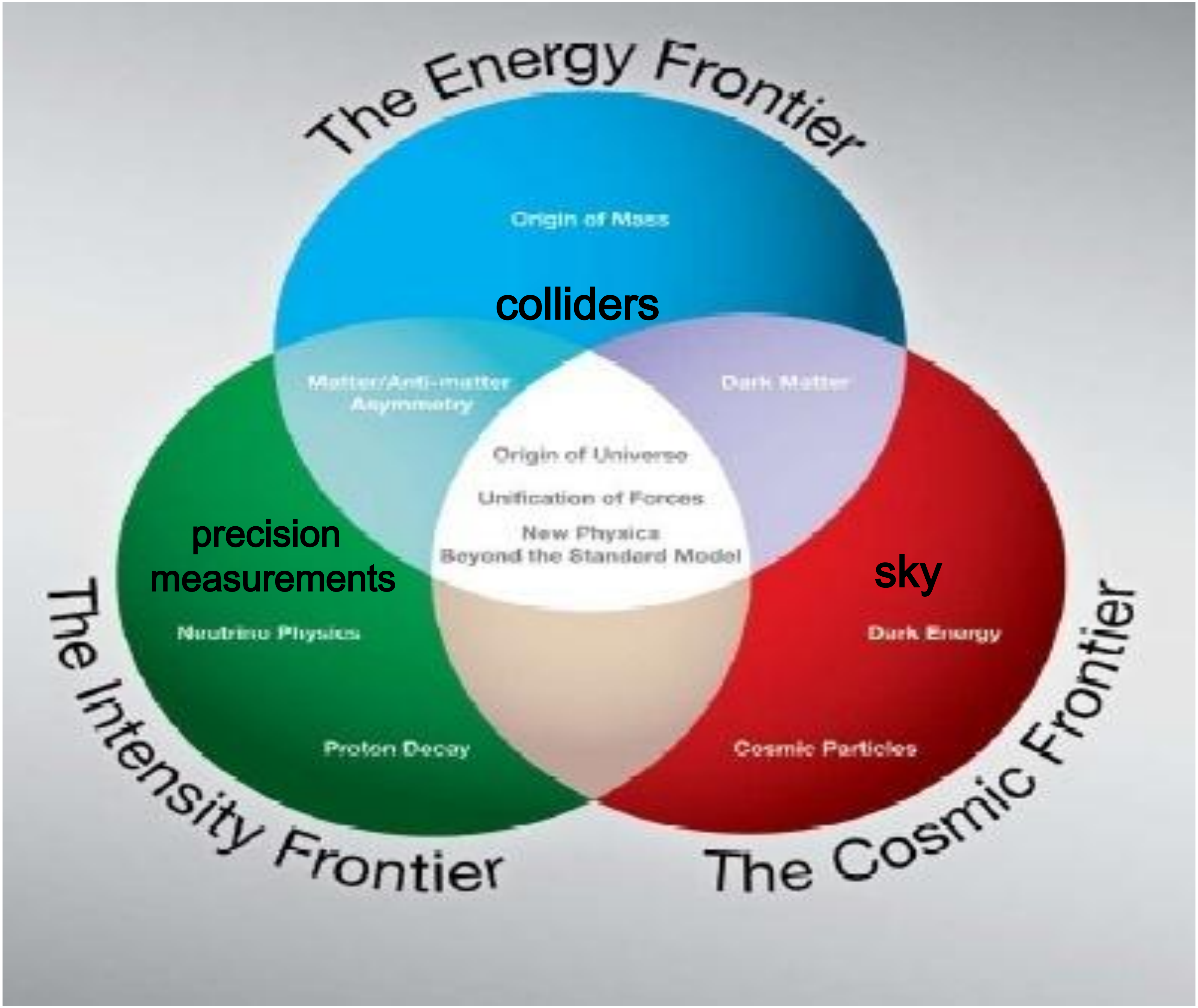
There are some very good reasons to think that at least some of the answers to the above questions await us at the TeV energy scale..which is now being opened up by new experiments

How do we look for new physics at higher energies???

There are 3 ways to find new physics beyond the SM:

(i) Make it directly at a collider like the LHC or Tevatron **
(ii) Look for subtle new physics modifications to SM processes
(iii) Look to the sky …**

** I will focus on these possibilities below



colliders

precision measurements

sky

This is a Special Time in Particle Physics

- Urgent Questions

  Provocative discoveries have led to important questions

- Connections

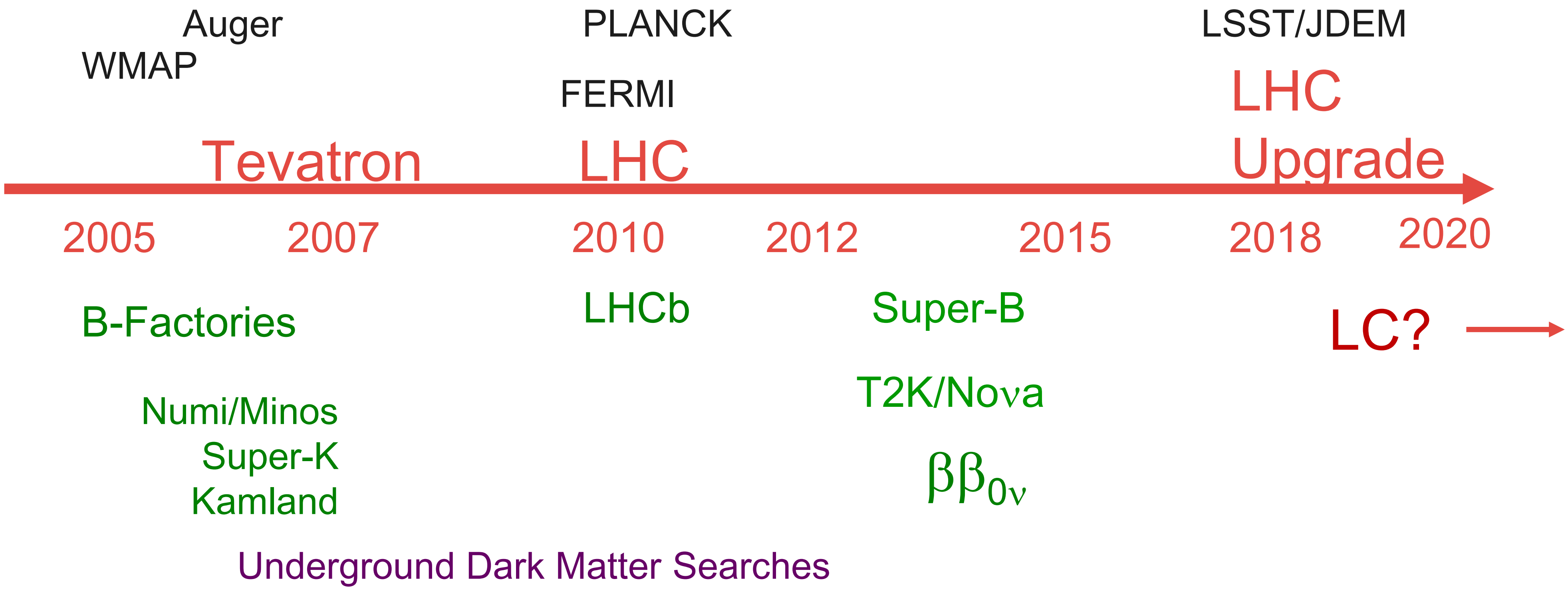
  Questions seem to be related in fundamental, yet mysterious, ways & link high energy and astrophysics

- Tools

  We have the experimental tools, technologies, and strategies to tackle these questions coming on-line!

We are witnessing a Scientific Revolution in the Making!

Science Timeline: The Tools



Auger
WMAP
PLANCK
FERMI
LSST/JDEM

Tevatron
LHC
LHC Upgrade

2005
2007
2010
2012
2015
2018
2020

B-Factories
LHCb
Super-B
LC?

Numi/Minos
Super-K
Kamland

T2K/Noνa

$\beta\beta_{0\nu}$

Underground Dark Matter Searches

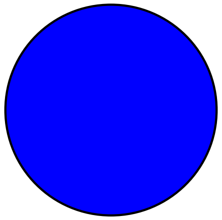
Accelerators are Powerful Microscopes

They make high energy particle beams that allow us see small things : $E \sim 1/x$

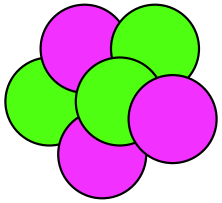
$1\ \text{MeV} \sim (2 \times 10^{-11}\ \text{cm})^{-1}$

$1\ \text{GeV} \sim (2 \times 10^{-14}\ \text{cm})^{-1}$

→ $1\ \text{TeV} \sim (2 \times 10^{-17}\ \text{cm})^{-1}$

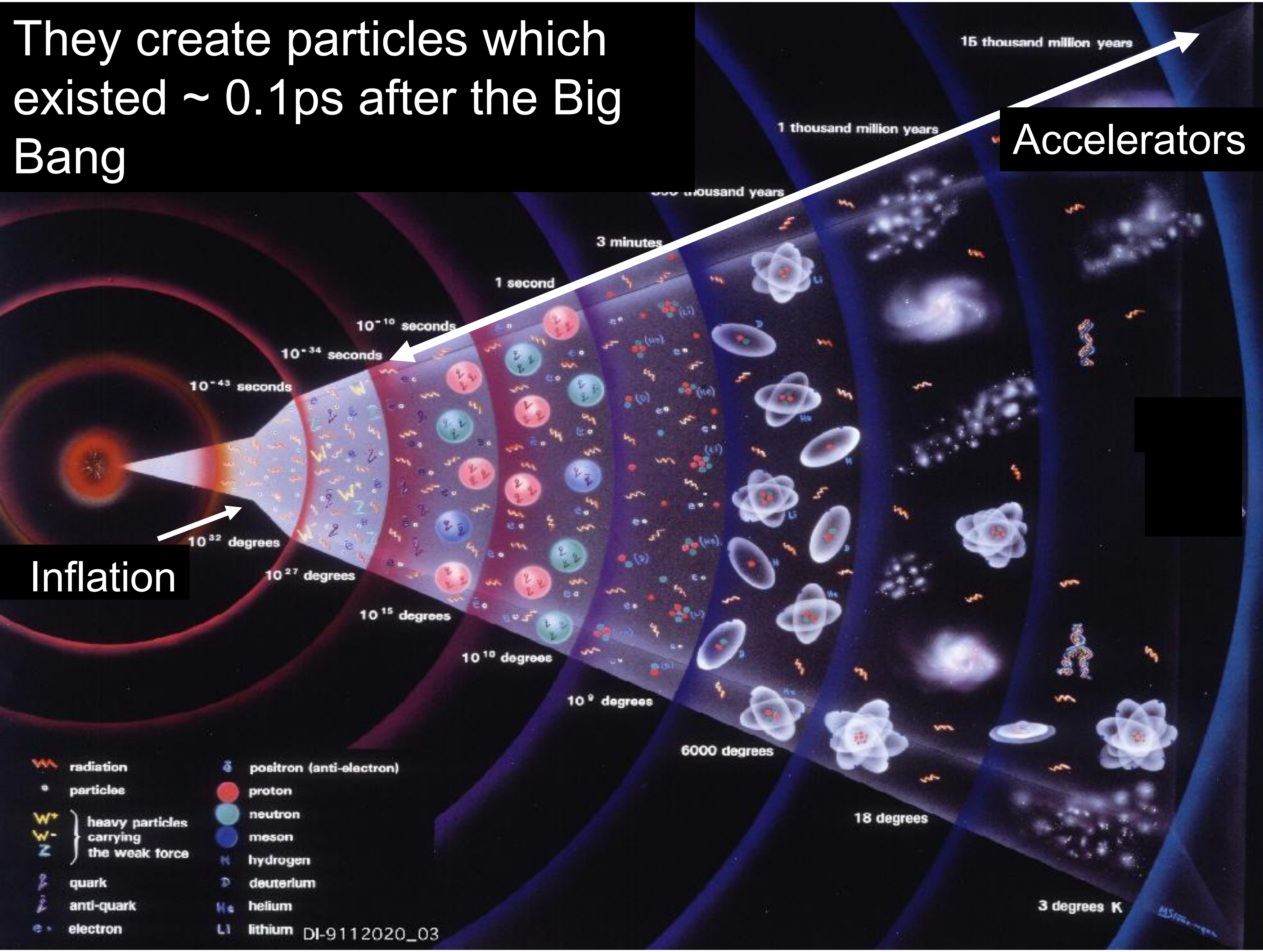


seen by low energy beam
(poorer resolution)



seen by high energy beam
(better resolution)

They create particles which existed ~ 0.1ps after the Big Bang



Accelerators

Inflation

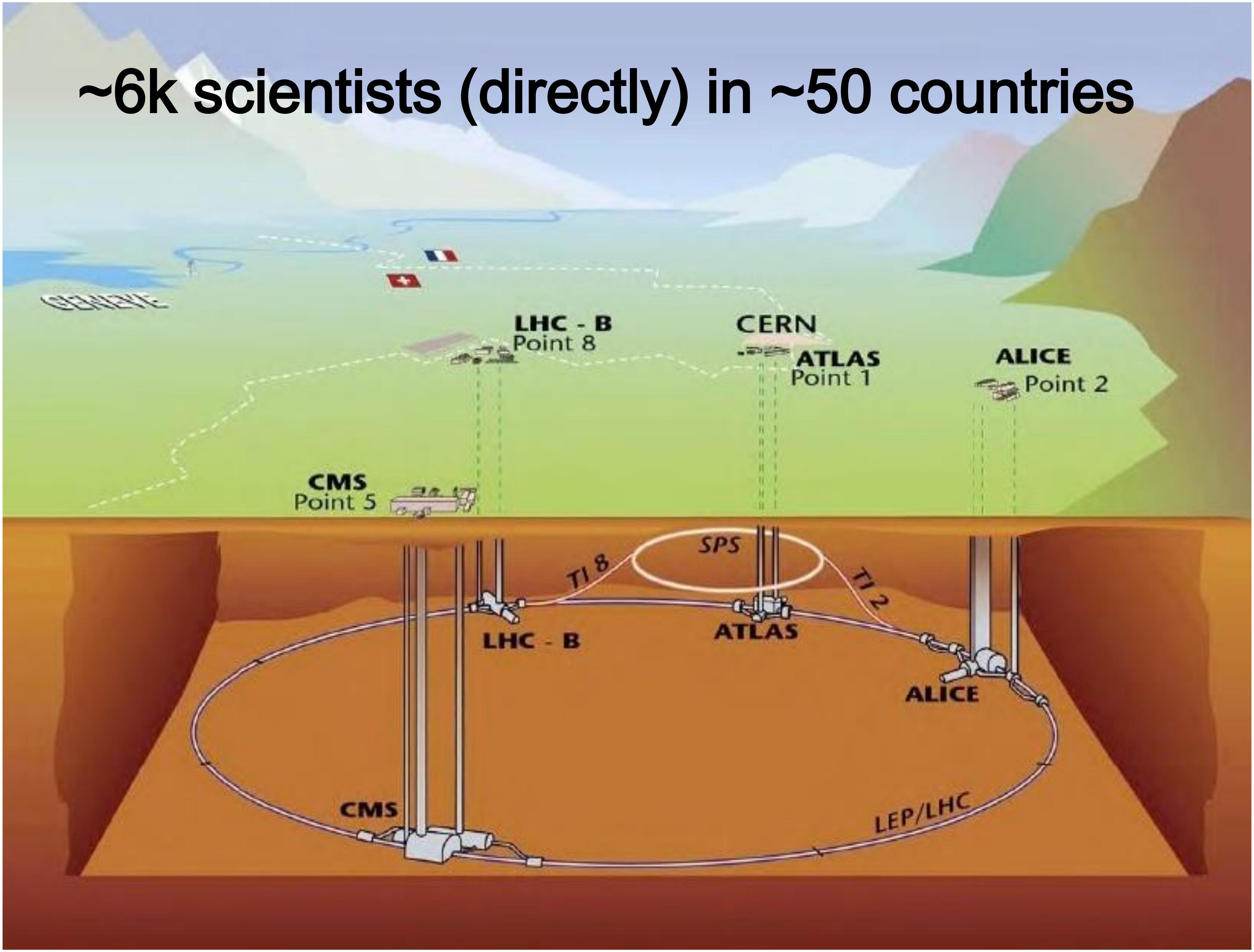
[redacted]

Colliders can allow us to produce new, previously unknown heavy particles by converting the energy of the colliding particles, such as protons at the LHC, into mass via E=mc^2

There is no substitute for directly producing & observing new physics!

Depending on their interactions, the LHC should be able to produce new particles with masses as large as a few TeV – more than 15x heavier than the top quark ..

~6k scientists (directly) in ~50 countries

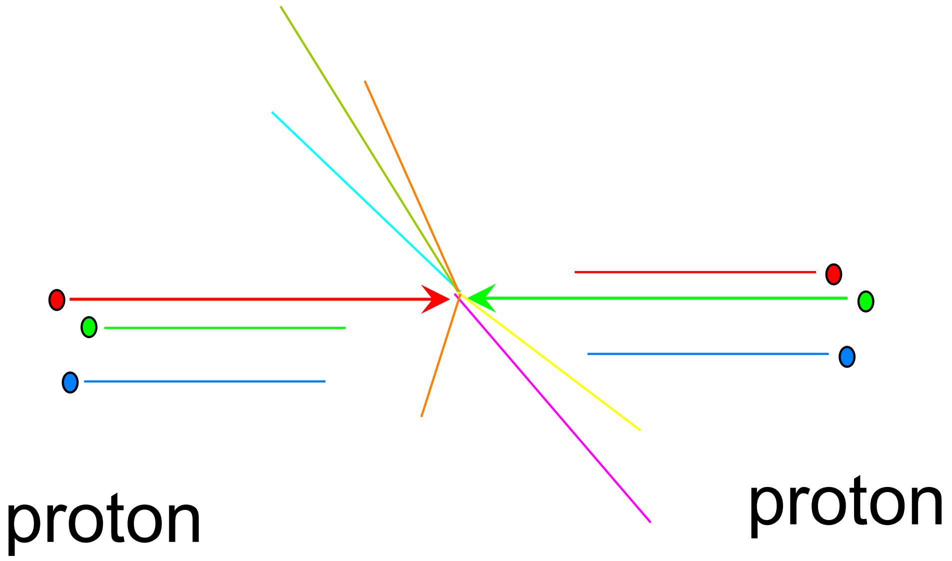


CMS

ATLAS superimposed to the 5 floors of building 40

ATLAS

The LHC: pp collisions @ 7-14 TeV



Hard scattering occurs between two proton's constituents - quarks & gluons

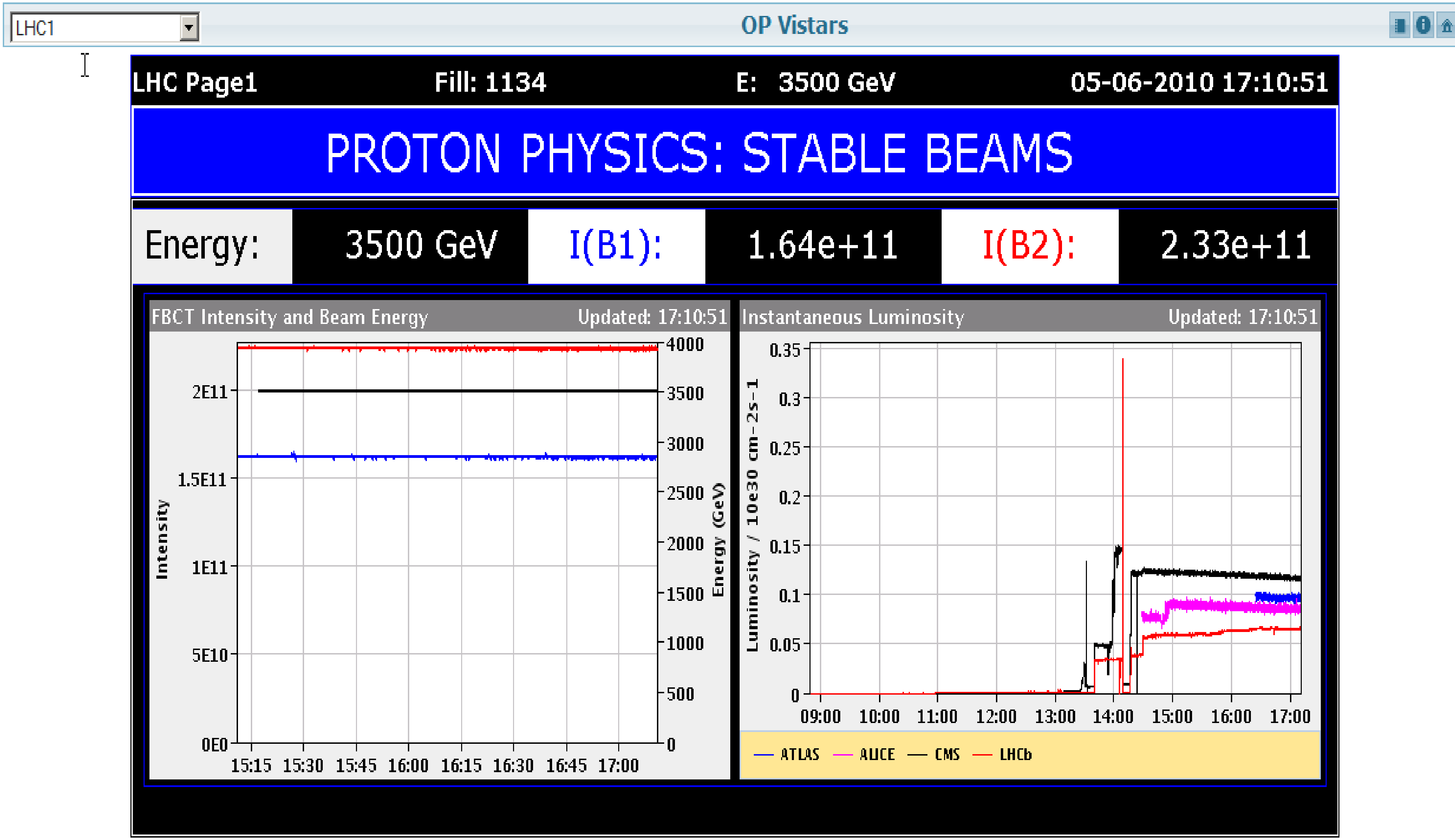
E_{scatt} ~ 1/10 E_{CoM} ~ 1-2 TeV

Current LHC Schedule:

- 1st Physics run: 2010-11, 1 fb^{-1} at 7 TeV -> rediscover SM + ??
- Down in 2012 for 'safety' upgrade
- Physics runs 2013 and onwards at ~14 TeV →100 fb^{-1}

pp Collisions:

- Broad energy reach
- Large event rate
- Complex environment
- Don't know initial state



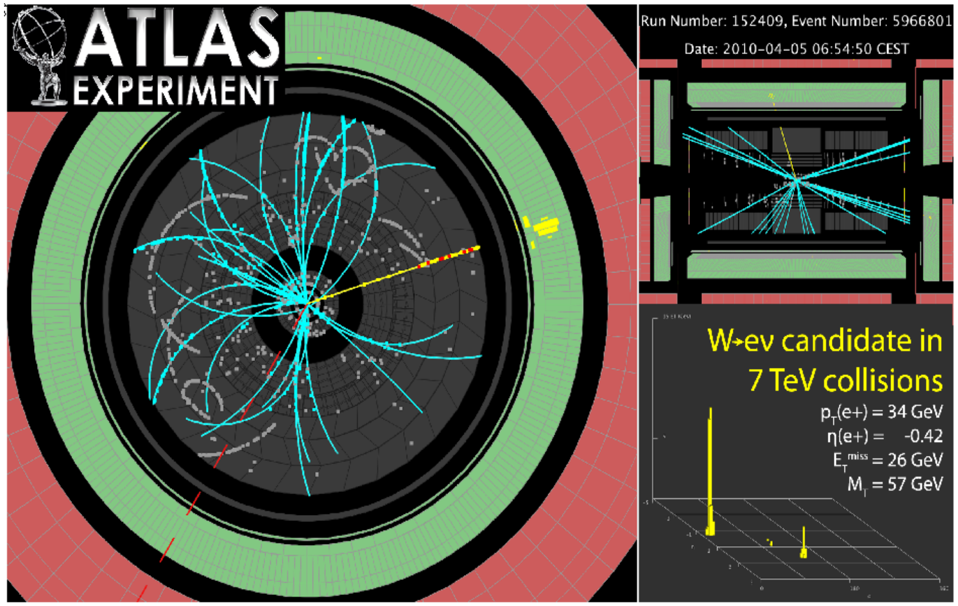
LHC1

OP Vistars

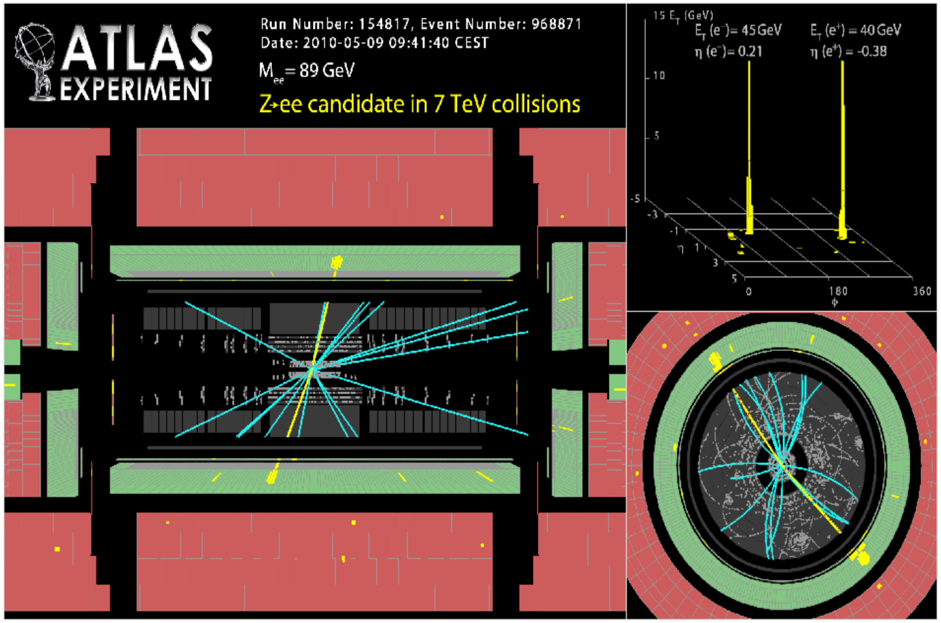
LHC Page1 Fill: 1134 E: 3500 GeV 05-06-2010 17:10:51

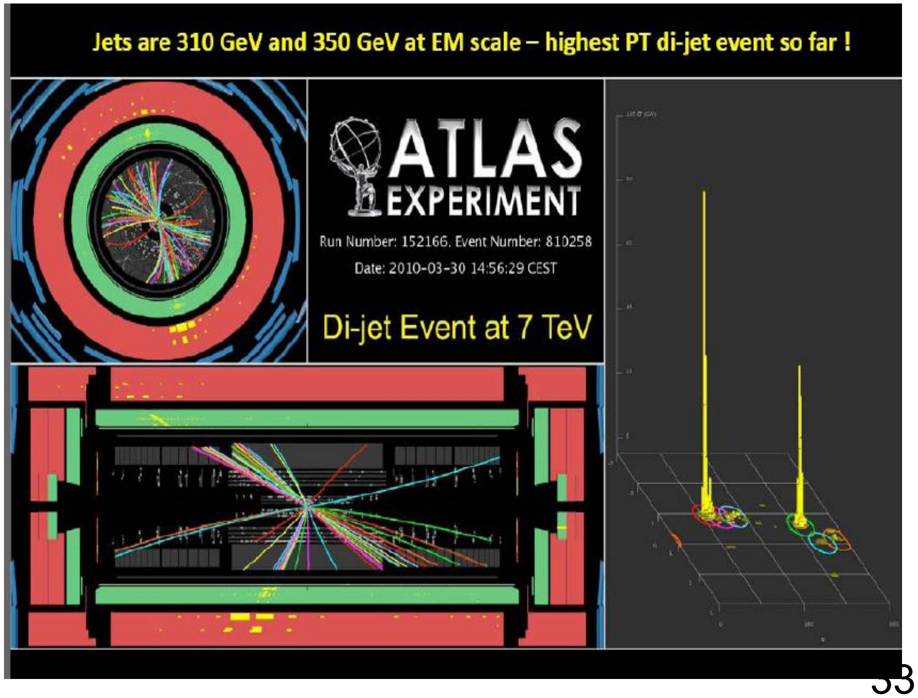
PROTON PHYSICS: STABLE BEAMS

Energy:	3500 GeV	I(B1):	1.64e+11	I(B2):	2.33e+11



The LHC is already testing QCD in new energy regimes and has 'rediscovered' the W & Z bosons of the SM by running at 7 TeV ! Seeing the top quark is next…& then??



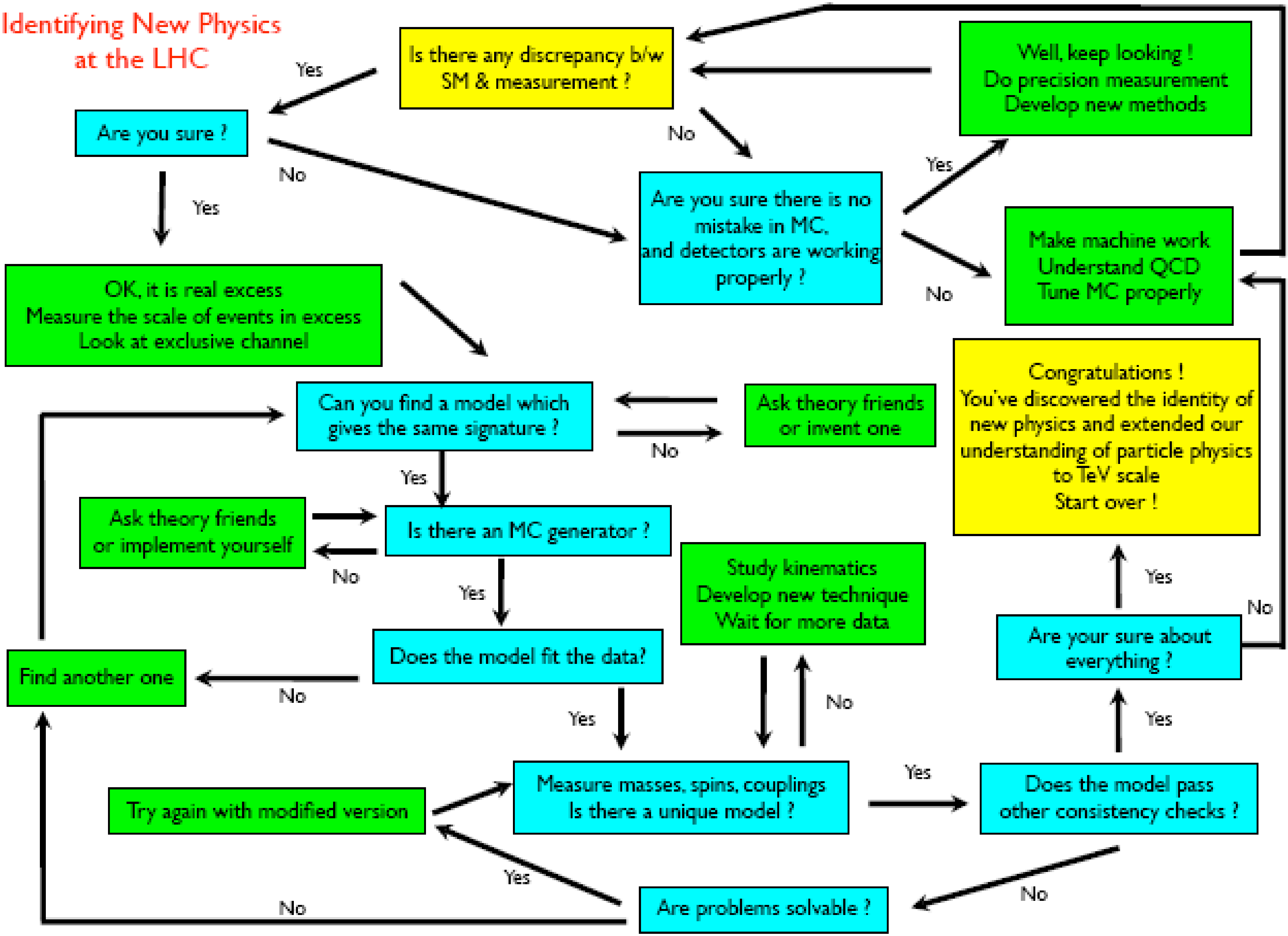


BUT if new particles are produced in a collider experiment how will we know? Almost all of the time these new states are *unstable* & decay rapidly back to some set of ordinary SM particles seen in the detectors. There will just be more of them than the SM predicts - perhaps distributed in a different way kinematically. How much more? How different?

To see a SIGNAL (S) for the production of new particles, we need to precisely understand the production properties of the SM BACKGROUND (B) in addition to being able to precisely calculate the production characteristics of the new particles that we're looking for. →STATISTICS!

Of course, some new particles may be more easily seen than others…let's look at a few examples:

Identifying New Physics at the LHC



Is there any discrepancy b/w SM & measurement ?

Yes

Are you sure ?

No

No

Yes

Well, keep looking !
Do precision measurement
Develop new methods

Yes

Are you sure there is no mistake in MC, and detectors are working properly ?

No

Make machine work
Understand QCD
Tune MC properly

OK, it is real excess
Measure the scale of events in excess
Look at exclusive channel

Can you find a model which gives the same signature ?

No

Ask theory friends or invent one

Congratulations !
You've discovered the identity of new physics and extended our understanding of particle physics to TeV scale
Start over !

Yes

Ask theory friends or implement yourself

Is there an MC generator ?

No

Yes

Study kinematics
Develop new technique
Wait for more data

Yes

No

Does the model fit the data?

Are your sure about everything ?

Find another one

No

Yes

No

Yes

Try again with modified version

Measure masses, spins, couplings
Is there a unique model ?

Yes

Does the model pass other consistency checks ?

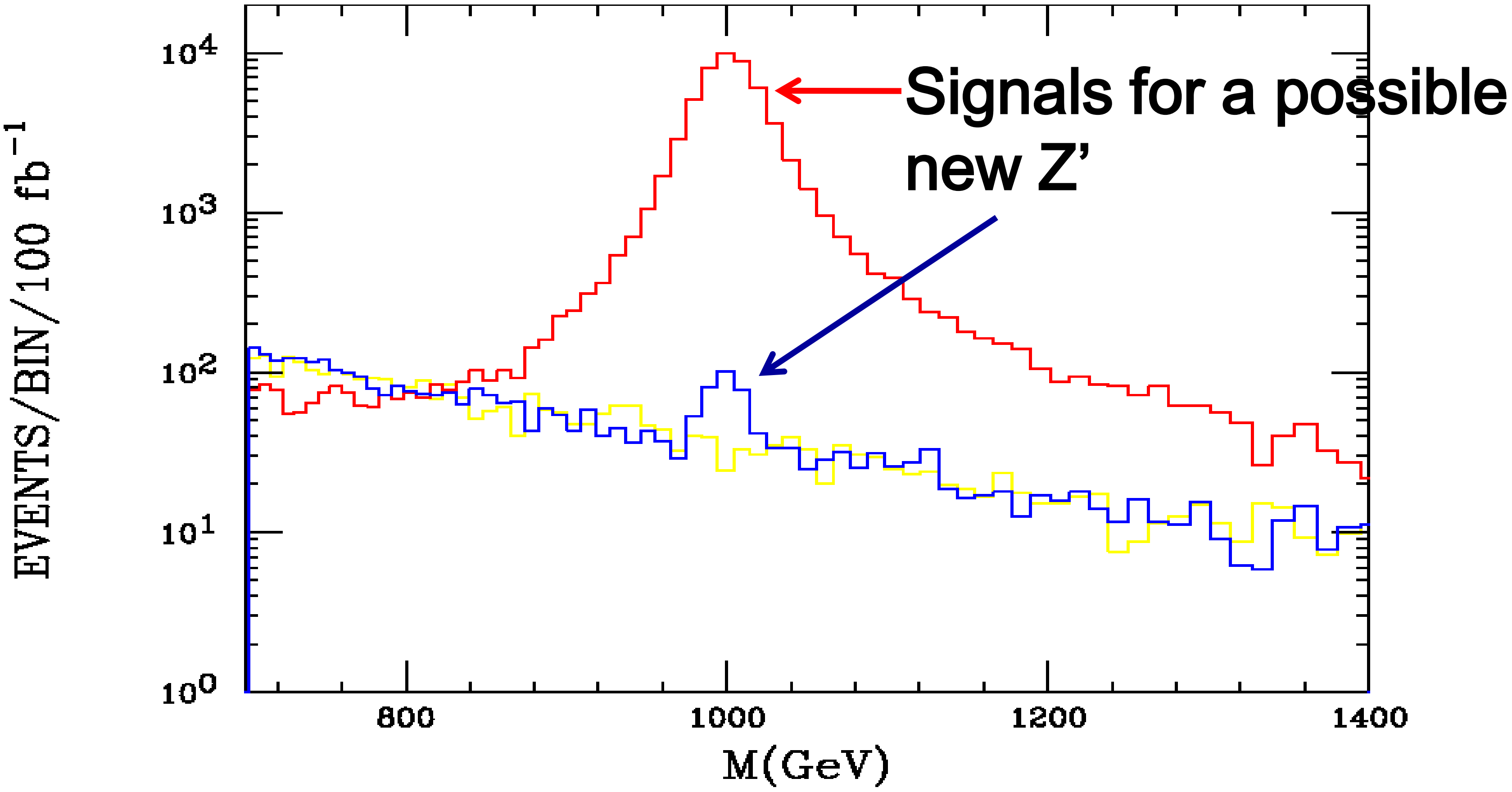
Yes

No

No

Are problems solvable ?

pp→ e^+e^- + anything at the LHC

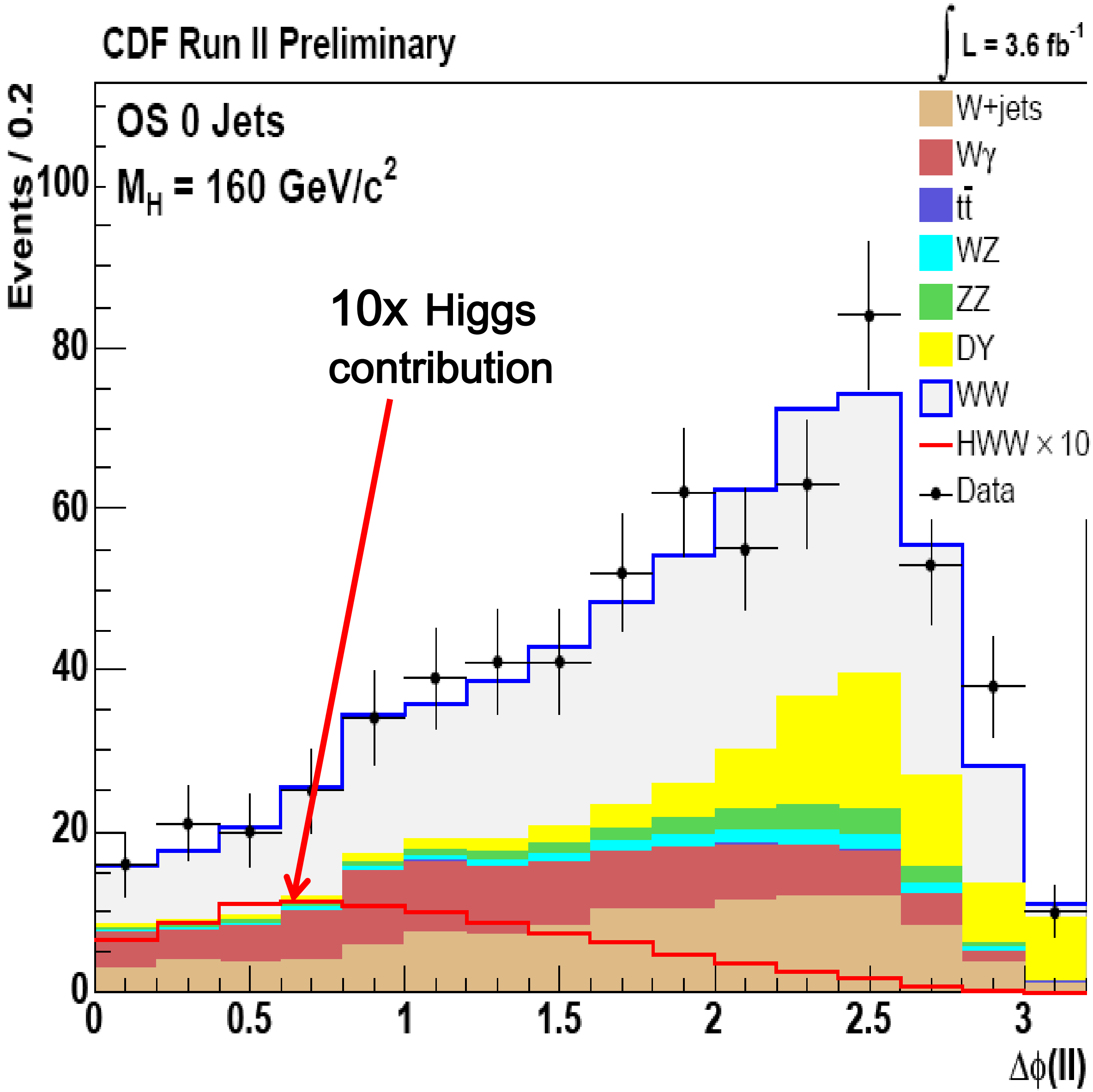


Signals for a possible new Z'

Yellow = SM background as a function of the binned invariant mass of the two leptons showing statistical fluctuations

Clearly the red case is very visible while the blue one is not..a small **change** in background might obscure it…so knowing the background **very precisely** would be very important in this case.

$gg \rightarrow H \rightarrow W^+ W^- \rightarrow e^{\pm} \mu^{\pm}$ + neutrinos (=ME) at the Tevatron

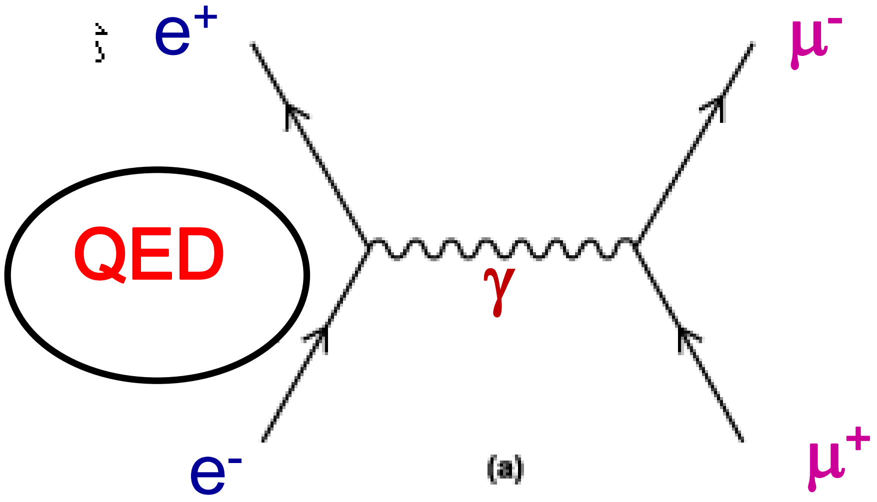


Lots of SM reactions can conspire to look like a Higgs boson which is only a tiny addition to the ordinary SM rate at the Tevatron. Unless the rates for all these processes are very well understood it will be impossible to claim that a Higgs boson has been found in this reaction…

→ Thus it is generally extremely important to be able to make precise calculations of SM processes in order to find new physics which may be hiding in the background.

This effort in the SLAC Theory group is headed by Lance Dixon

Most calculations in the SM are performed using 'Perturbation Theory' which is an expansion of cross sections in a small parameter, e.g., the fine-structure constant α in QED, using Feynman diagrams. These are pictorial representations of complex mathematical expressions which are determined by the interactions in a specific theory.

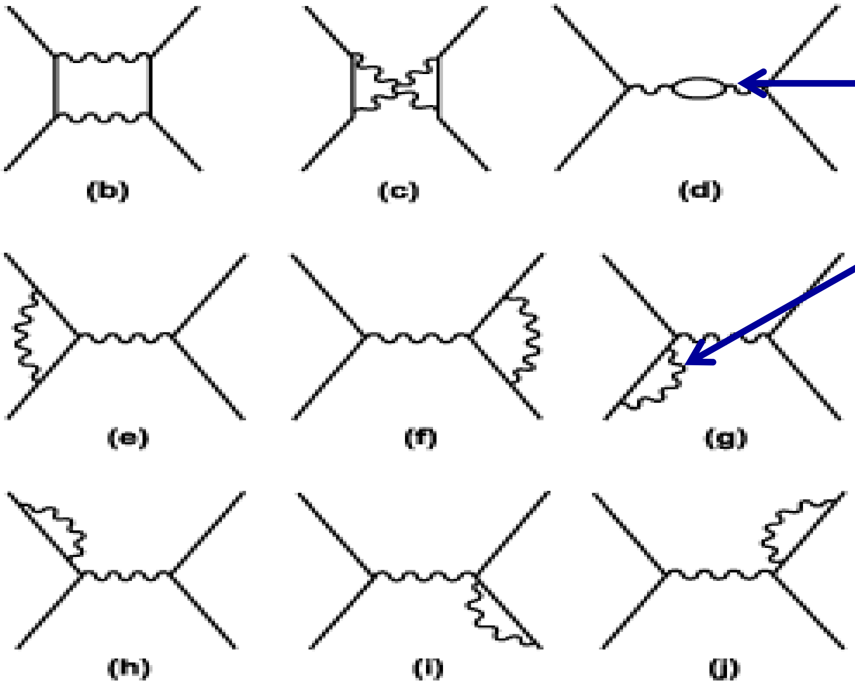


2 particles in and
→ 2 particles out

2→2

The complexity of these calculations depends upon the number of particles in the final state , e.g., 2→2 is easy involving at most a few graphs, while 2→ 8-10 may involve hundred or thousands of graphs & is VERY hard even at leading order(LO)

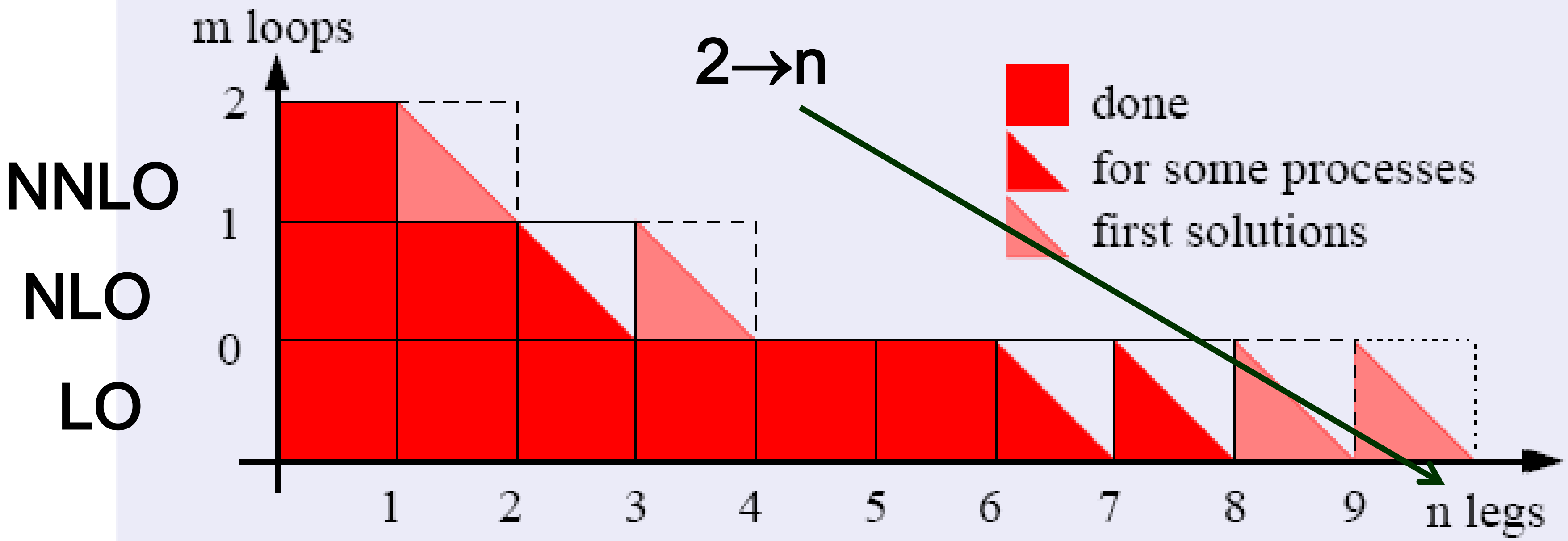
The complexity ALSO depends on the order of the calculation, e.g. , 2→2 at NLO may involve hundreds of graphs depending on the identities of the particles! This is an enormous but important effort..



'loops' occur at NLO

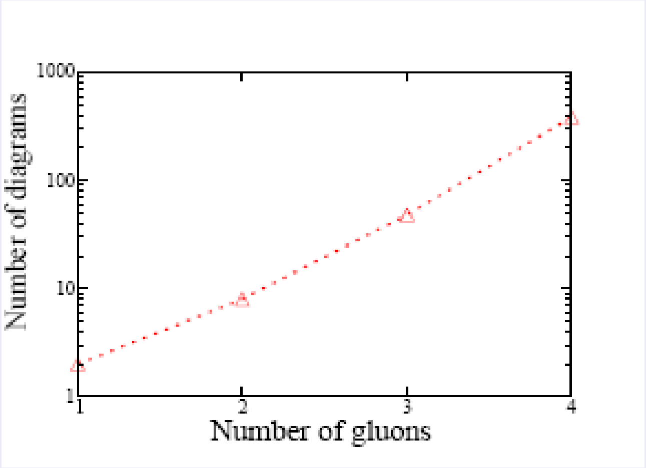
This is the same process in QED but at NLO (with a single loop).. it is STILL 2→2

Availability of exact calculations

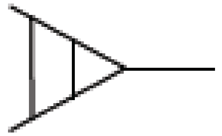


Factorial growth: $e^+e^- \to q\bar{q} + ng$

n	#diags
0	1
1	2
2	8
3	48
4	384



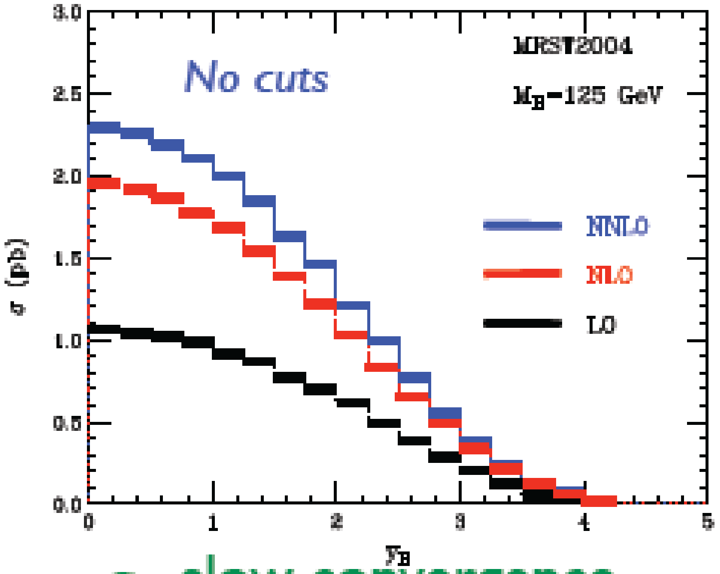
LO



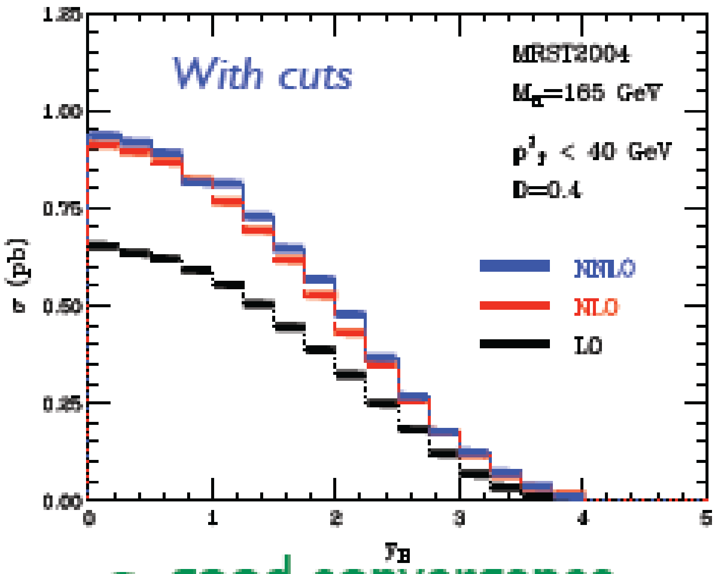
Exclusive NNLO Higgs production

First fully exclusive H→WW →2l 2ν NNLO calculation

Anastasiou, Dissertori, Stoeckli '07; also Catani, Grazzini '08



- slow convergence



- good convergence

⇒ impact of NNLO dramatically reduced by cuts

Very important to include cuts and decays in realistic studies

C. F. Berger[a], Z. Bern[b], L. J. Dixon[c], F. Febres Cordero[b],
D. Forde[c], T. Gleisberg[c], H. Ita[b], D. A. Kosower[d] and D. Maître[e]
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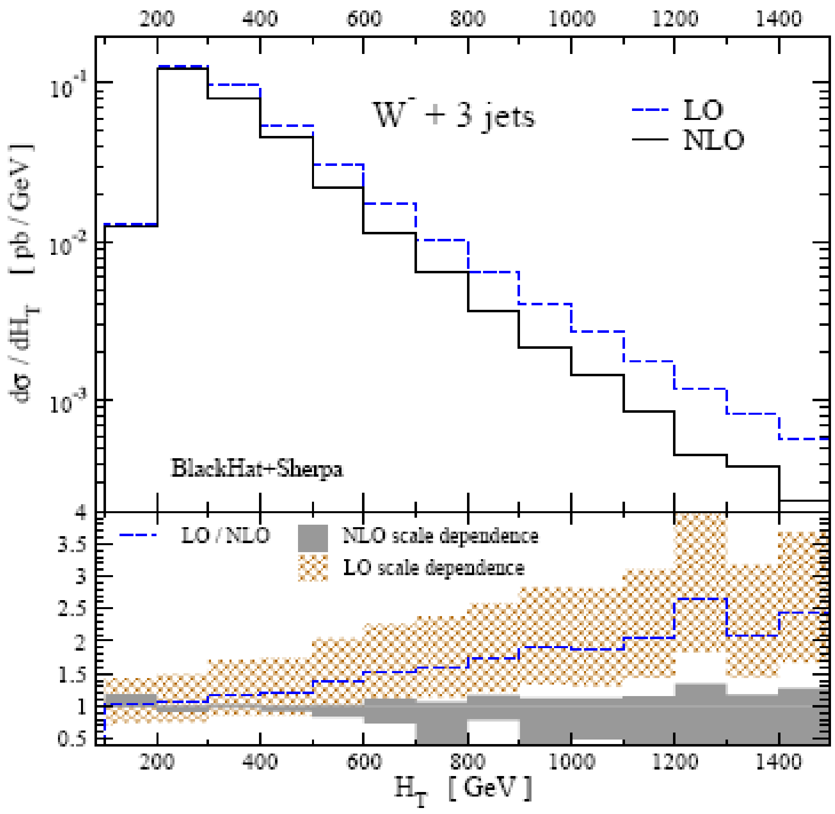
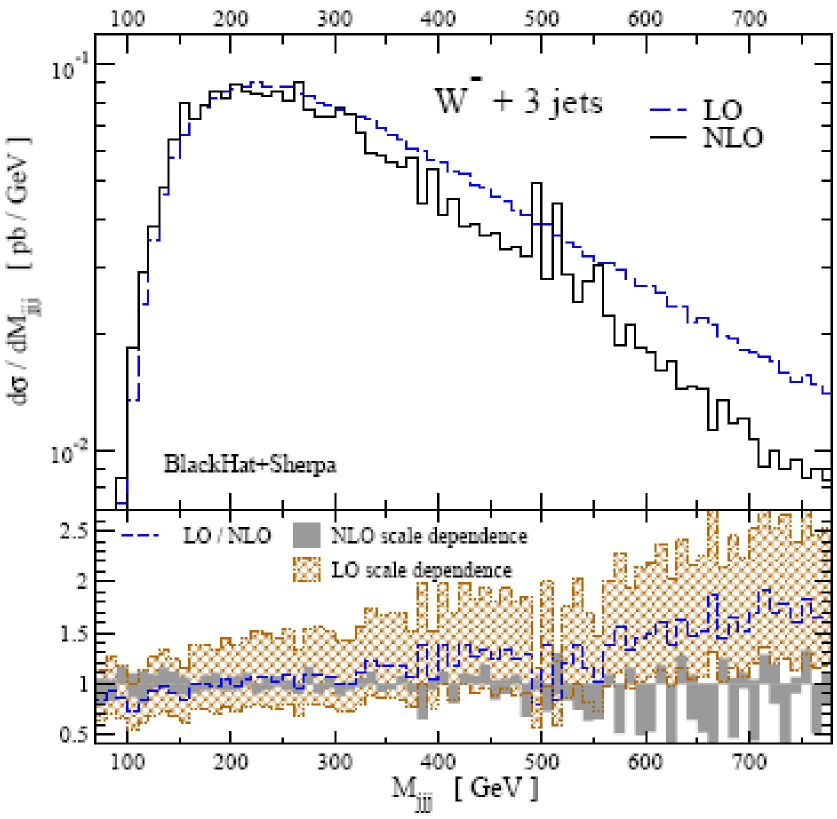
[e] *Department of Physics, University of Durham, DH1 3LE, UK*





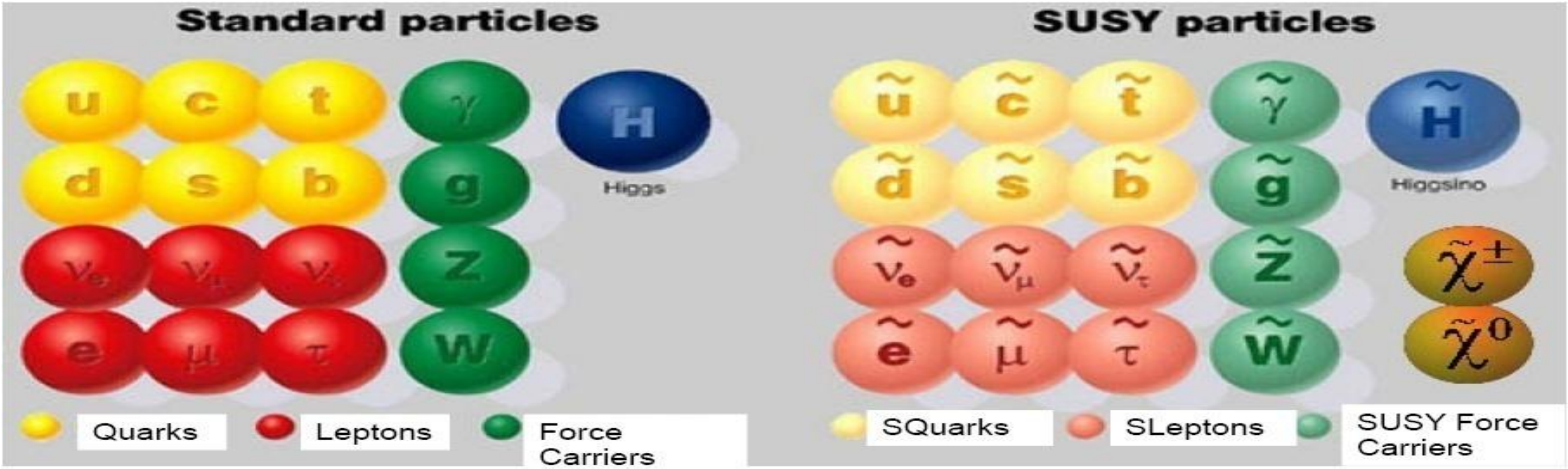
This is an important background for Higgs searches as well as for Supersymmetry, one possible new physics scenario

A large number of people in the Theory Group work on the construction of & signals for various New Physics models :

JoAnne Hewett, Michael Peskin, Jay Wacker & TGR

I will talk about one of them called Supersymmetry or SUSY

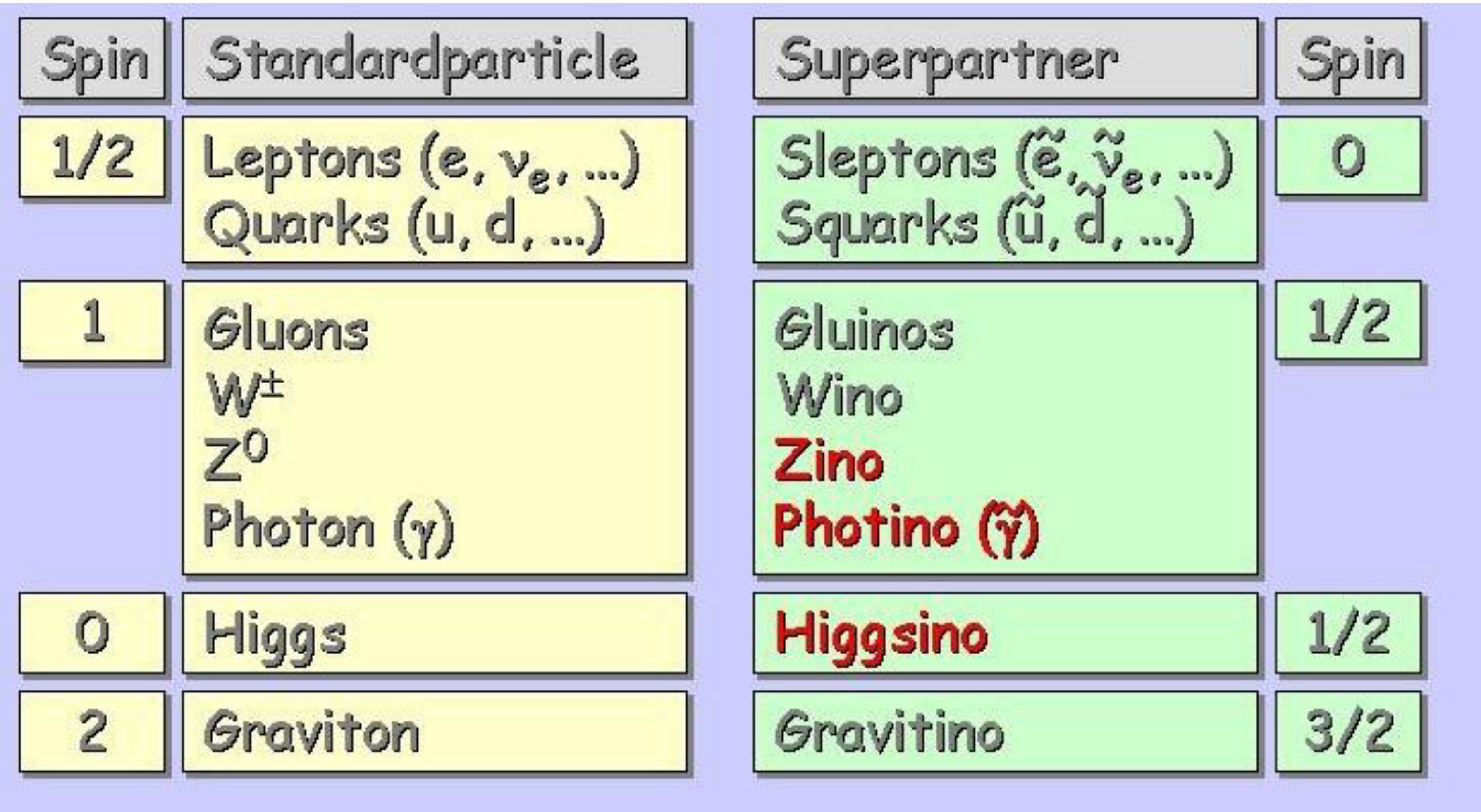
SUSY, an extension of relativity, posits that for every SM particle there is an 'identical' copy which differs from it by ½ unit of spin (with funny names) linking fermions & bosons



Symmetry between

Fermions ↔ **Bosons**

(matter) (force carrier)



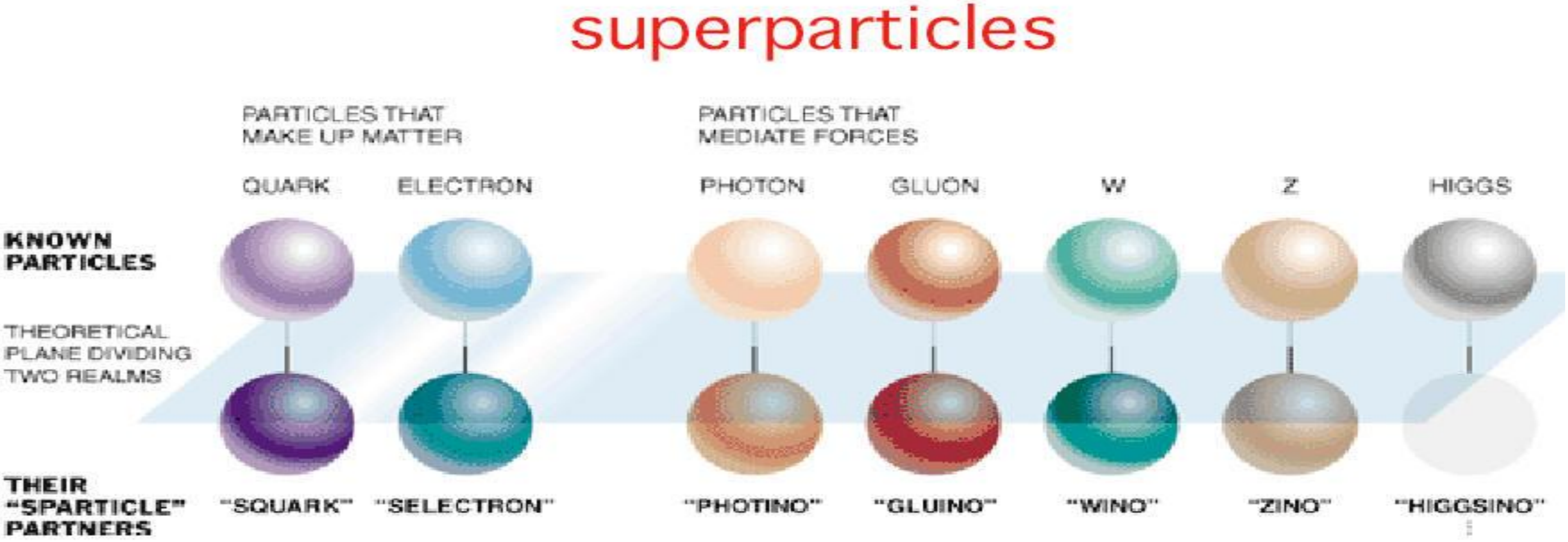
Spin	Standardparticle	Superpartner	Spin
1/2	Leptons ($e, \nu_e, \ldots$) Quarks ($u, d, \ldots$)	Sleptons ($\tilde{e}, \tilde{\nu}_e, \ldots$) Squarks ($\tilde{u}, \tilde{d}, \ldots$)	0
1	Gluons $W^\pm$ Z^0 Photon (γ)	Gluinos Wino Zino Photino ($\tilde{\gamma}$)	1/2
0	Higgs	Higgsino	1/2
2	Graviton	Gravitino	3/2

Minimal Supersymmetric Standard Model

Conserved multiplicative quantum number

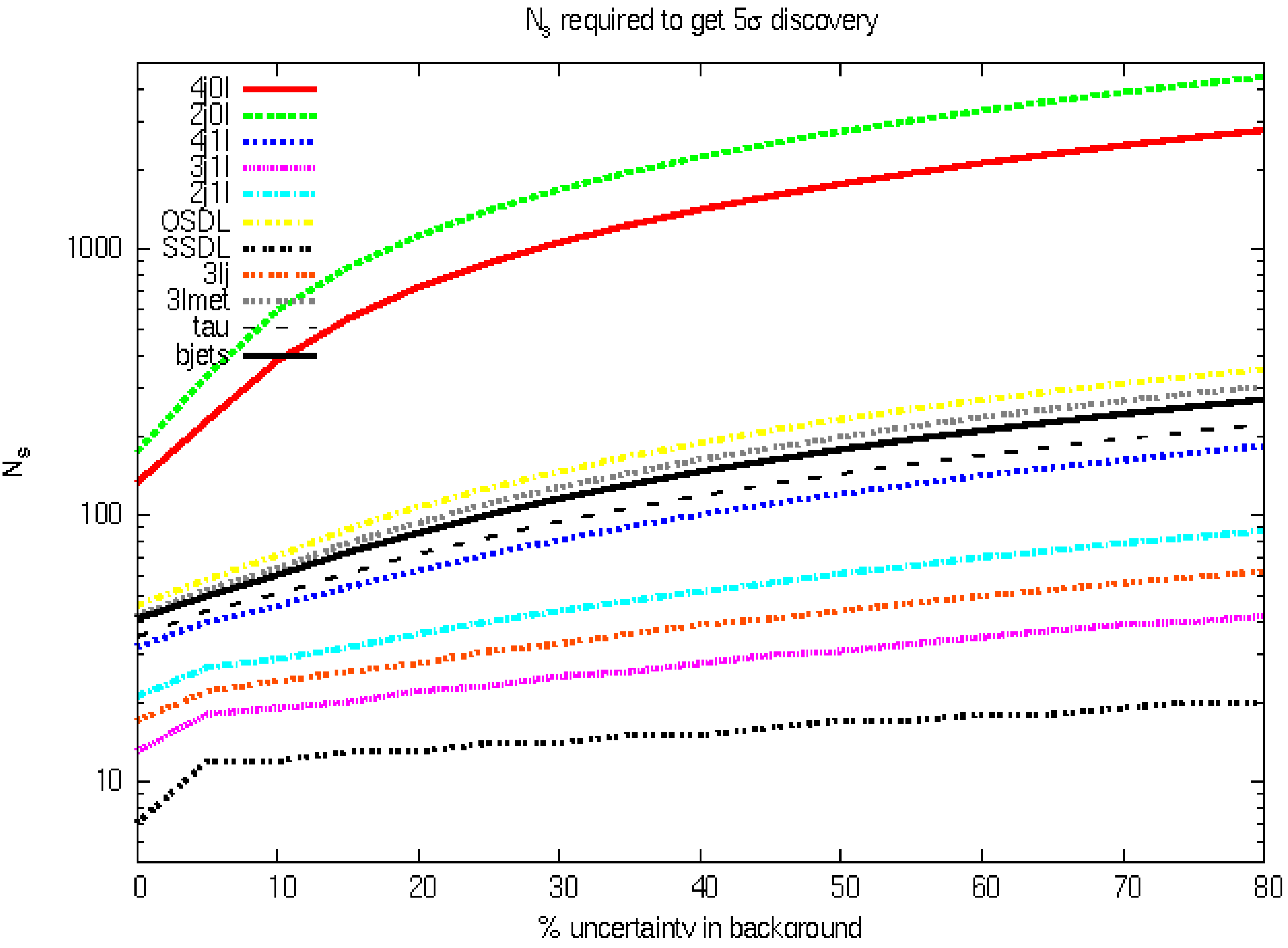
- Superpartners are produced in pairs at colliders
- Heavier Superpartners decay to the Lightest
- Lightest Superpartner is stable and may be DM

Collider signatures dependent on this assumption and on the specific model of SUSY breaking of which many exist



ATLAS 1fb $^{-1}$ Backgrounds & Target Signal Counts For Finding SUSY

ANALYSIS	BACKGROUND	S=5, δB=50%	δB=20%
4j0l	709	1759	721
2j0l	1206	2778	1129
4j1l	41.6	121	62
3j1l	7.2	44	28
2j1l	18.2	61	36
OSDL	84.7	230	108
SSDL	2.3	17	13
3l1j	12	44	28
3lm	72.5	198	94
τ	51	144	72
b	69	178	86



N_s required to get 5σ discovery
4j0l
2j0l
4j1l
3j1l
2j1l
OSDL
SSDL
3lj
3lmet
tau
bjets
N_s
10
100
1000
0
10
20
30
40
50
60
70
80
% uncertainty in background

SUSY does a lot of nice things for us :

(i) It can ‘explain’ why the TeV scale can be small compared to the gravity scale

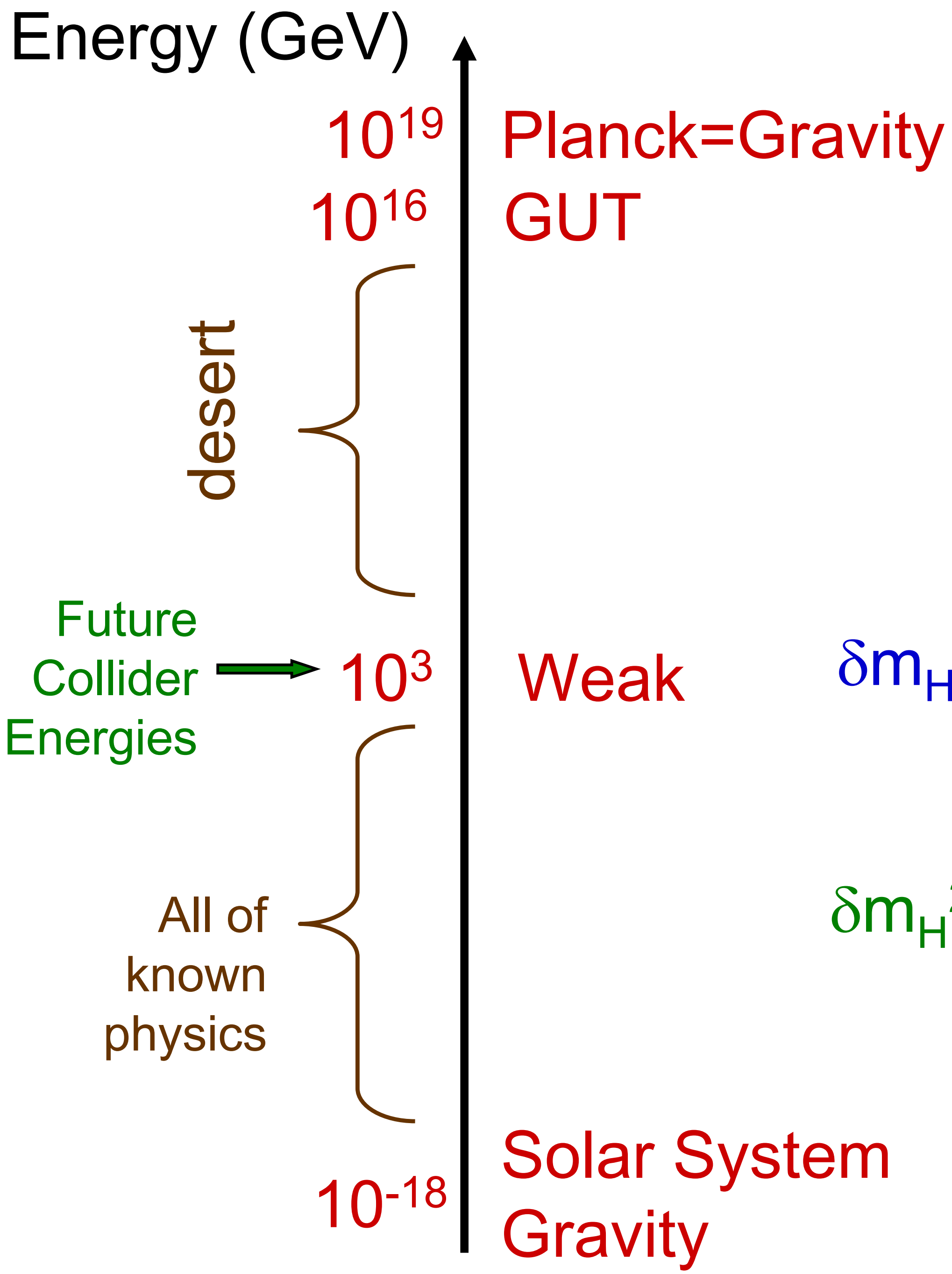
(ii) It can lead to a DM particle which comes in just the right amount

(iii) It leads to a unification of, at least, the non-gravitational forces

(iv) It can be tested in many laboratory experiments

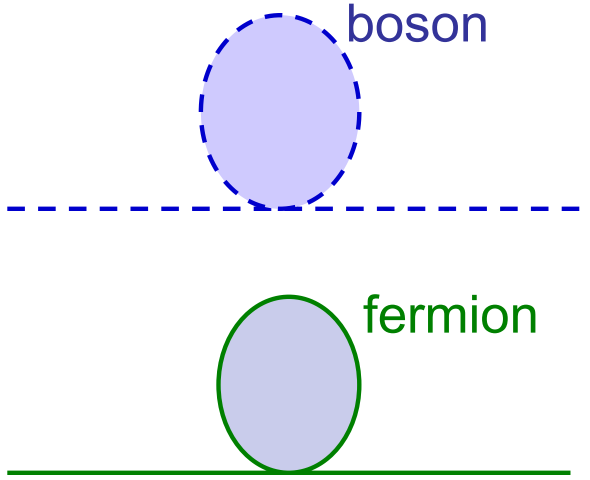
This is an interesting idea but it can’t be exactly true because, e.g., there is no spin-0 copy of the electron with the same mass .. SUSY must be a broken symmetry too.

The Hierarchy Problem: Supersymmetry



Quantum Corrections:

Higher order effects
drag Weak Scale to M_{Pl}

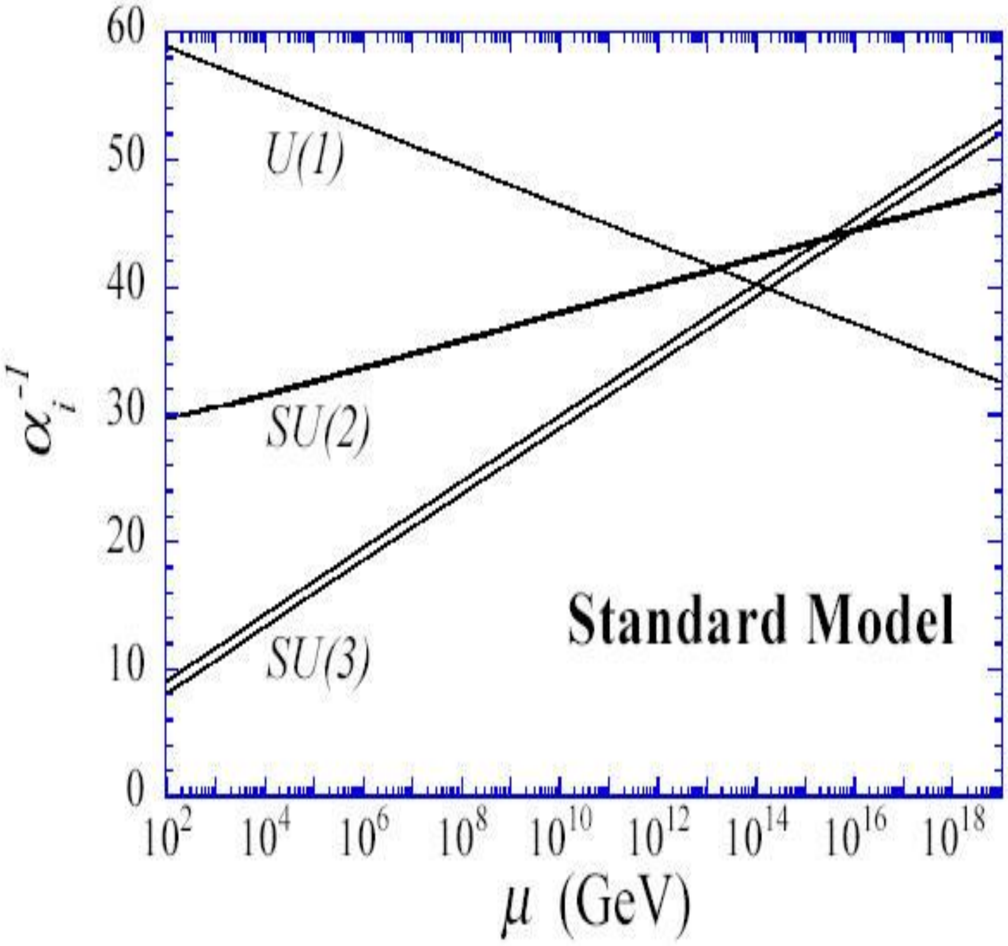


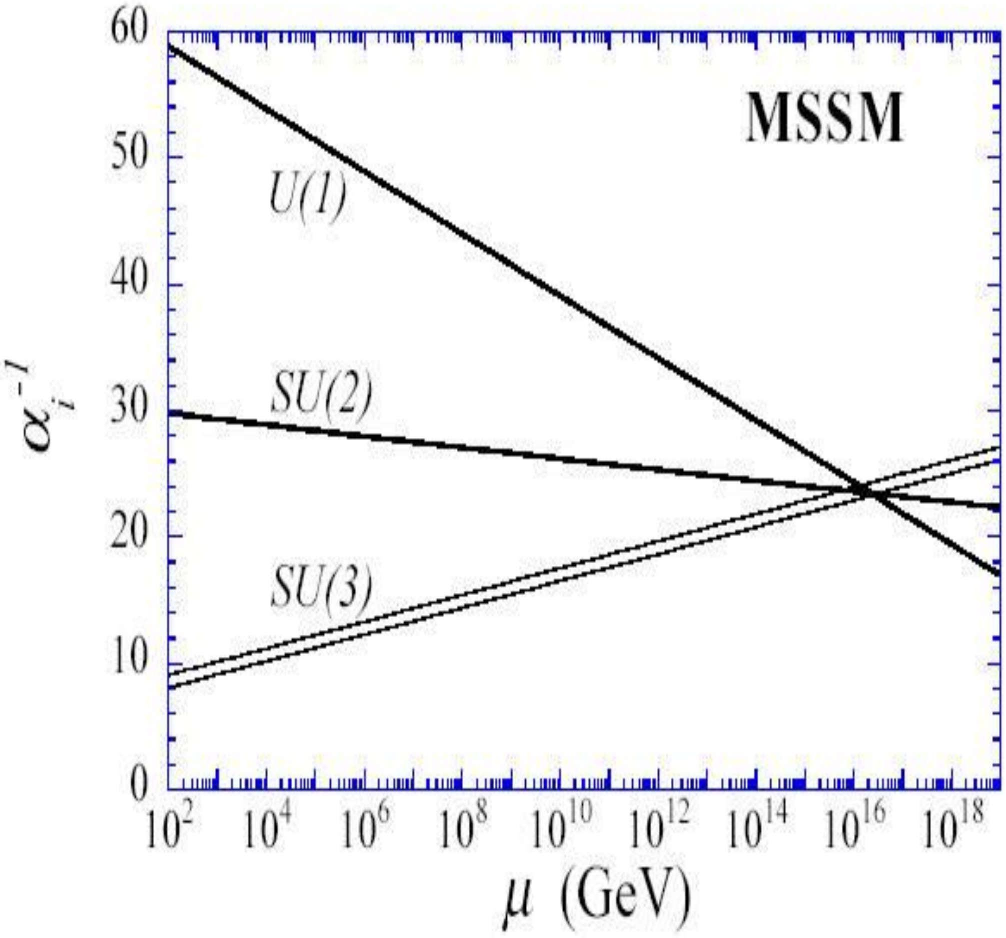
$\delta m_H^2 \sim$ $\sim M_{Pl}^2$

$\delta m_H^2 \sim$ $\sim - M_{Pl}^2$

Large effects **cancel**
order by order in
perturbation theory

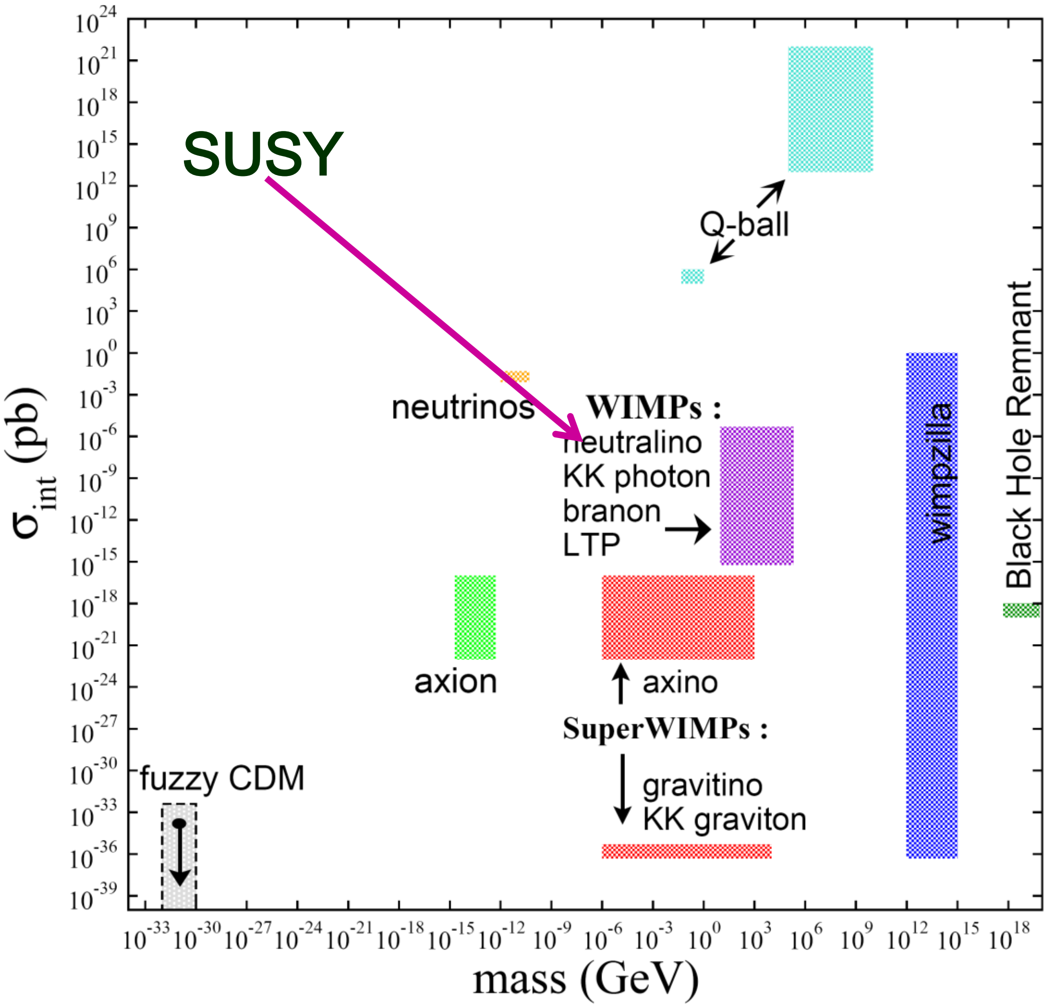
SUSY Leads to a Unification of the Forces





PARTICLE DARK MATTER CANDIDATES

- The observational constraints are no match for the creativity of theorists
- Masses and interaction strengths span many, many orders of magnitude, but not all candidates are equally motivated
- Weakly Interacting Massive Particle (WIMP)



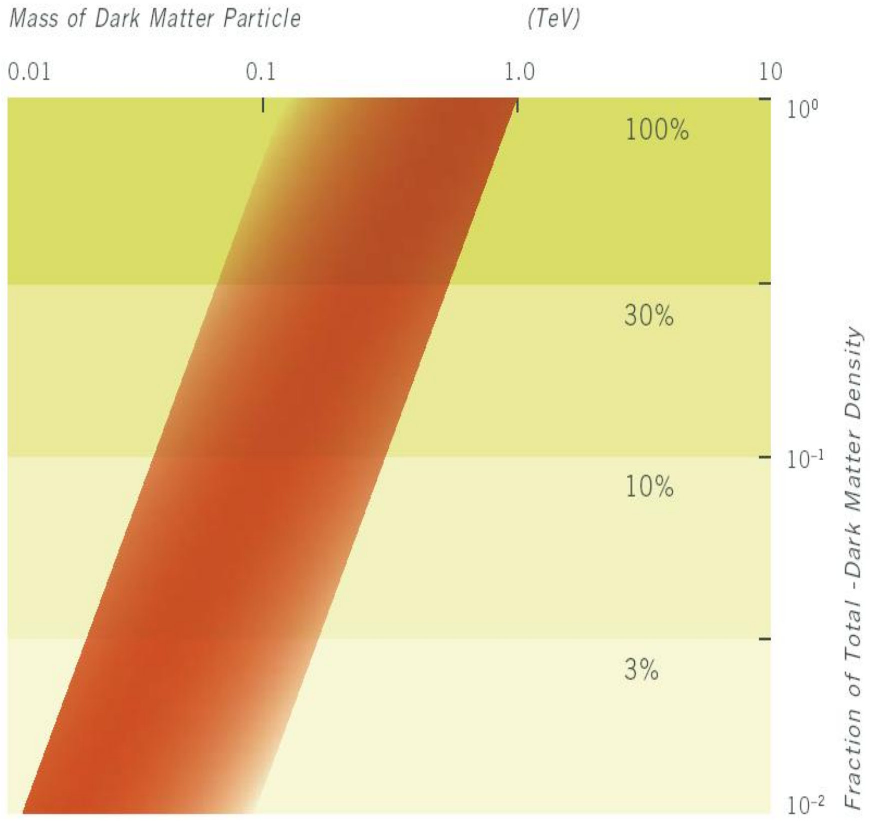
HEPAP/AAAC DMSAG Subpanel (2007)

WIMPS FROM SUPERSYMMETRY

- The amount of dark matter left over is inversely proportional to the annihilation cross section:

$$\Omega_{DM} \sim \langle\sigma_A v\rangle^{-1}$$

- The mass & couplings of the Lightest SUSY Particle (LSP) naturally lead to the right amount of DM!
- LSP is likely a mixture of photino, Zino & Higgsino



HEPAP LHC/ILC Subpanel (2006)

[band width from k = 0.5 – 2, S and P wave]

$\chi\chi \rightarrow$ photons, positrons , anti-protons…. 'in the sky' may be seen by FERMI, PAMELA & other experiments

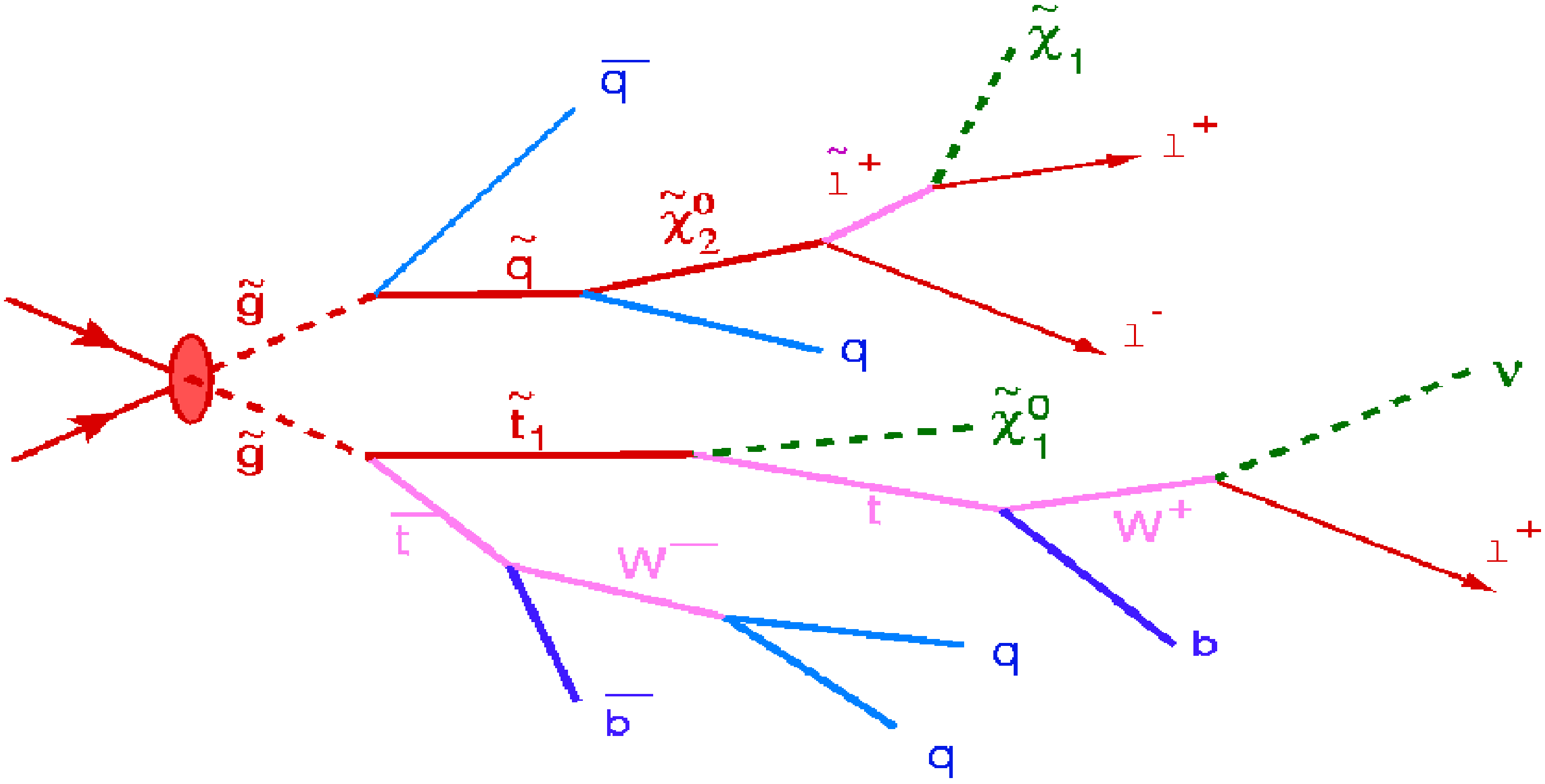
$\chi N \rightarrow \chi N$ elastic scattering may be detected on earth in deep underground experiments like, e.g., CDMS ,…

If χ really is the LSP (or some other WIMP) it may be directly produced at the LHC !

This picture can be tested in many ways….

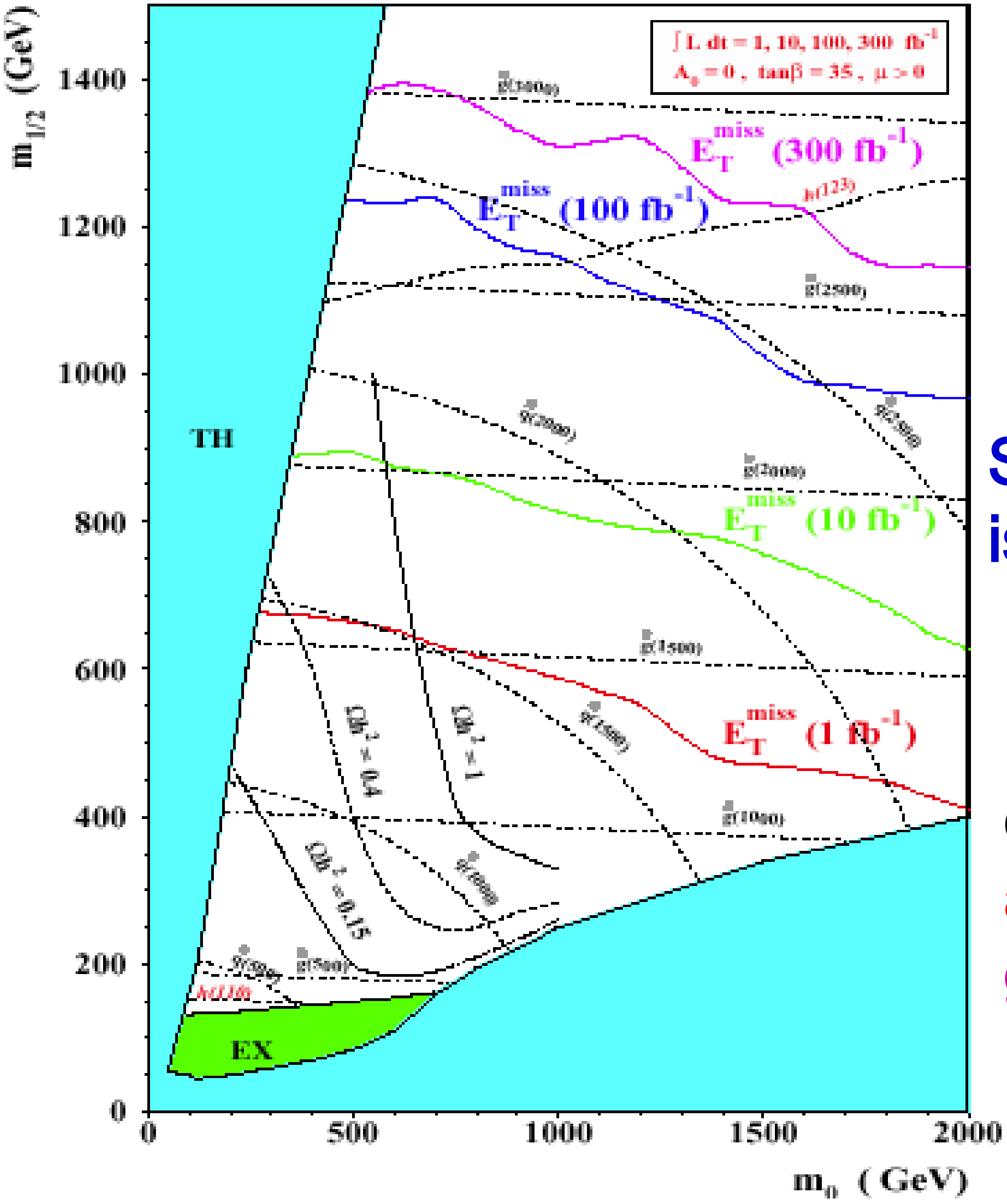
Analyses of SUSY searches at colliders have traditionally relied on the assumption of one or more specific models for how SUSY is broken: mSUGRA, GMSB, AMSB,….. which predict all the masses & interactions of the spartners in terms of only a few unknown parameters. (It's just easier !)

For example, in mSUGRA , at the LHC we may see



LHC searches are designed for specific SUSY breaking models

LHC Supersymmetry Discovery Reach

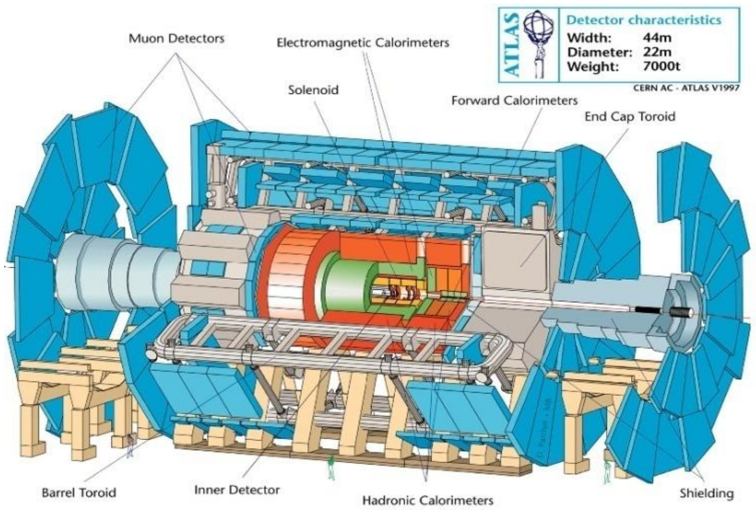


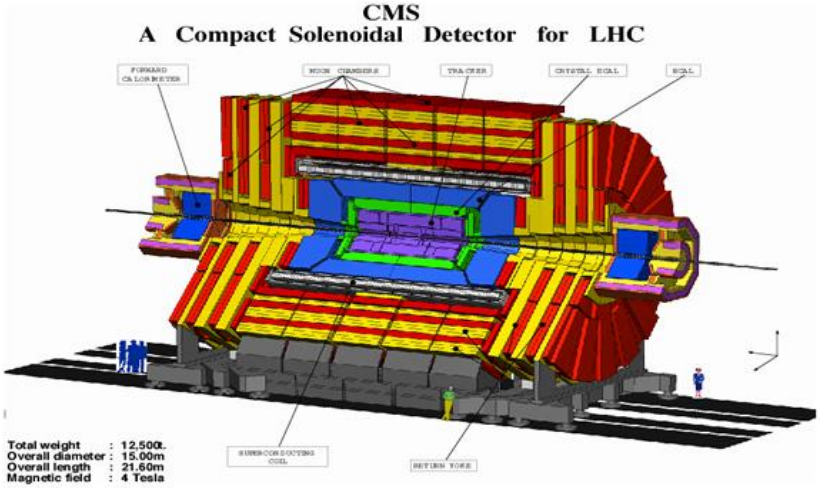
Model where gravity mediates SUSY breaking – 4 free parameters at high energies = mSUGRA

Squark and Gluino mass reach is ~ 2.5-3.0 TeV @ 300 fb^{-1}

But these & other searches depend on the SUSY breaking assumptions…can we be more general and be somewhat less prejudiced??

Supersymmetry Without Prejudice





C. F. Berger, J.A. Conley, R.C. Cotta, J. S. Gainer, J. L. Hewett , M.-P Le & TGR

We examined the signals for SUSY at the LHC without any (well, not too many) assumptions about how SUSY is broken by studying a large 19-dimesional parameter space. Such an analysis is very CPU intensive ~250 core-years & is still partially incomplete….

We found that frequently SUSY does not behave like in any of the usual well-studied SUSY breaking scenarios & may be missed at the LHC unless the existing experimental analyses are generalized.

A lot more work needs to be done by both theorists and experimenters to insure the success of the searches for all possible kinds of new physics at the LHC!

We are in a special time in HEP !

The LHC has turned on-the experiments are running & we will finally access the TeV scale so our theoretical ideas about new physics can be directly tested. The HEP community has been waiting for this for almost 30 years.

What will we find at the LHC? Higgs, SUSY, extra dimensions , black holes, something we haven't thought of yet?? I do expect we will get some important answers..but they will lead to new questions that we haven't even yet thought to ask!

In the same time frame, we will also be getting new important complementary information from both the sky & from precision measurements…

EXICITING TIMES ARE AHEAD !!