Beyond the Standard Model

Christophe Roland

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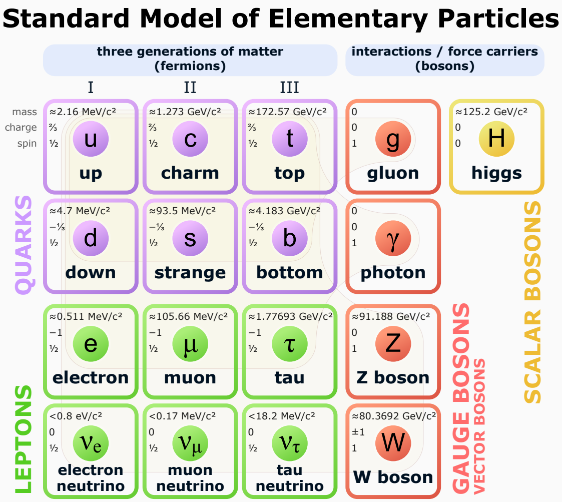
Introduction: The Standard Model

- The Standard Model is the theoretical bedrock of modern particle physics.
- Maybe the most successful theory in the whole history of physics.
- Yet, we know that the Standard Model is not the final story. We know that the Standard Model is a low energy approximation of a more fundamental theory, yet to be discovered.



Some problems with the Standard Model

- Does not include gravity! In fact, formulating a rigorous, experimentally testable, UV complete quantum theory of gravity is a huge challenge, one of the most difficult problem of modern physics.
- Explain neither dark matter nor dark energy (about 95% of the energy content of the Universe!).
- Does not provide a fully unified picture of the strong and electroweak interactions.
- Does not explain how do neutrinos acquire their masses.
- Many free parameters and unexplained patterns: Why three generations ? Why the Yukawa couplings with the Higgs have the value they have and no other ? Why is the Higgs mass so "unnaturally" small ?

Feynman on the Standard Model

Feynman:

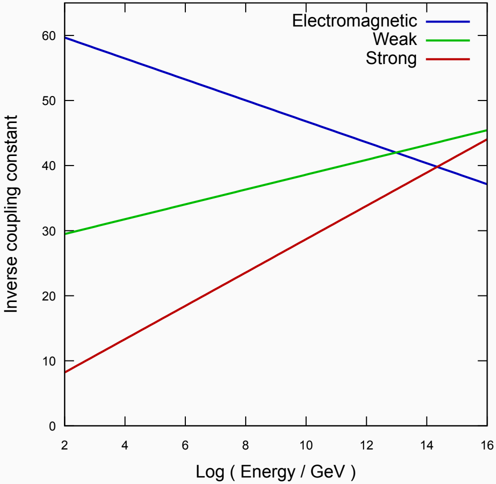
Strong interactions, weak interactions, and electromagnetic... The theories are linked because they seem to have similar characteristics.... Where does it go together? Only if you add some stuff that we don't know.

There isn't any theory today that has $SU(3) \times SU(2) \times U(1)$ *- whatever the hell it is - that we know is right, that has any experimental check.... Now, these guys are trying to put all this together. They're trying to. But they haven't. Okay?*

- The Standard is not a fully unified theory. In particular, the electroweak theory and quantum chromodynamics are not yet integrated into a more unified theory.

Grand Unification

- One evidence that we are in right track in trying to find a unified theory: the running coupling constants of the three fundamental interactions of the Standard Model more or less converge to the "Grand Unification Scale" at around 10^{16} GeV.
- This "unified interaction" is (presumably) itself unified with gravity at around the Planck scale: 10^{19} GeV.
- LHC is operating at an energy of about $\approx 10^4$ GeV!



Supersymmetry

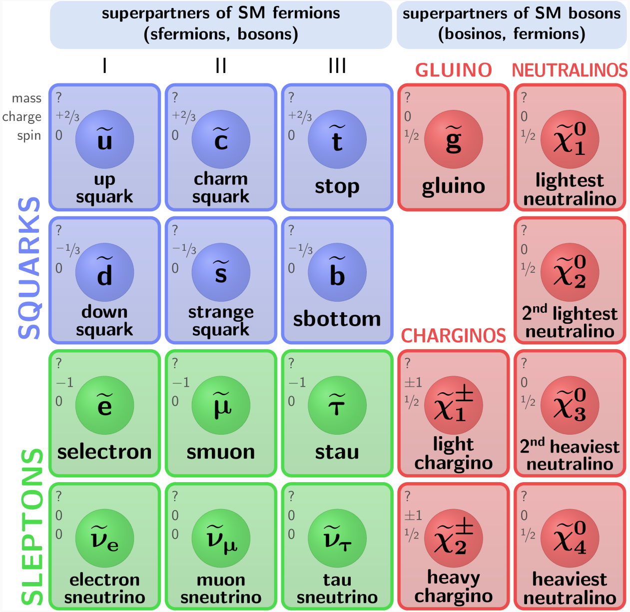
- Coleman-Mandula Theorem: spacetime and internal symmetries can only combine in a trivial way.
- One famous loophole: Supersymmetry !
- Introduces a new symmetry between fermions and bosons. Could explain dark matter!
- Introduces super-Lie algebra with a Lie superbracket $[,]$ such that we have:

$$[x, y] = -(-1)^{|x||y|}[y, x] \tag{1}$$

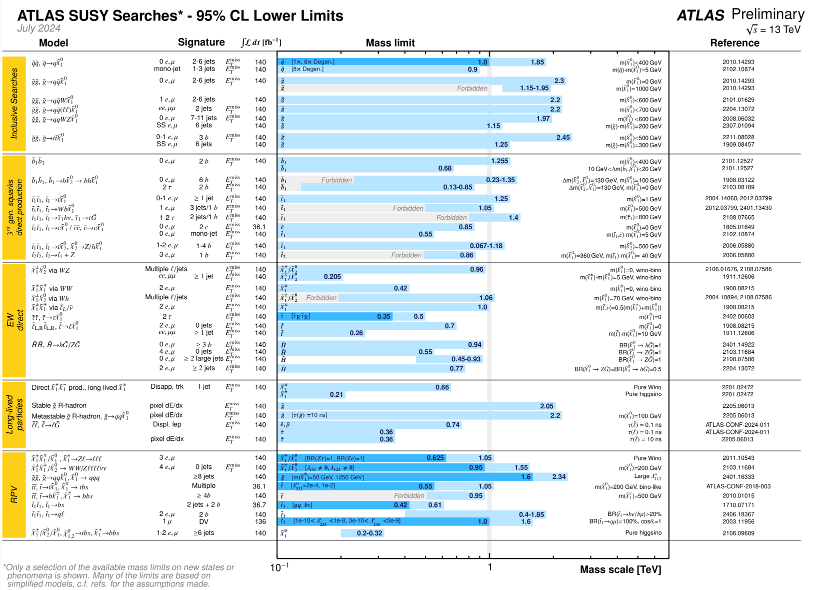
$$(-1)^{|x||z|}[x, [y, z]] + (-1)^{|y||x|}[y, [z, x]] + (-1)^{|z||y|}[z, [x, y]] = 0 \tag{2}$$

- Could solve the hierarchy problem, without the need for fine-tuning.
- Help to build grand unification models, and with quantum gravity (supergravity).

Supersymmetry

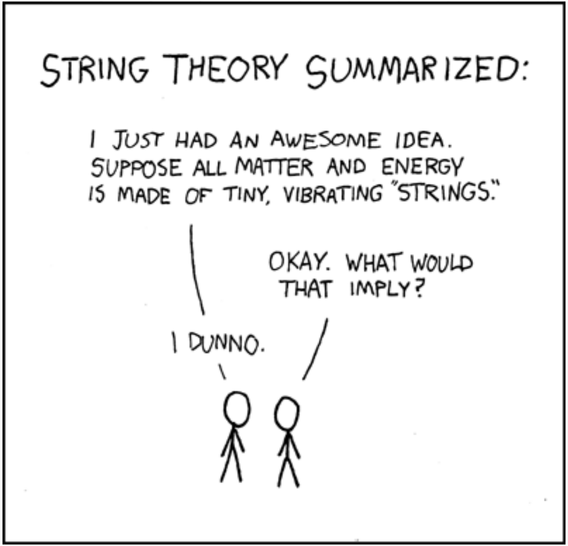


No EWK scale SUSY ?

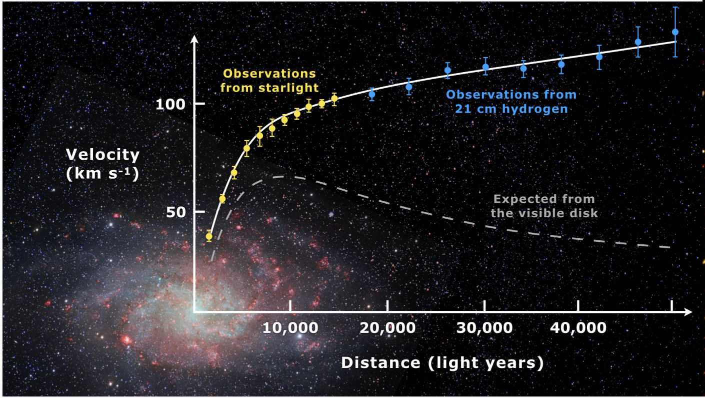


Quantum gravity

- Several candidates exist: string theory, loop quantum gravity, Causal dynamical triangulation, super-krampouz algebraic geometrodynamics quantum gravity, ...
- Very difficult to test experimentally ! Most theories make prediction at very high energy scale ($\approx$ Planck scale).
- Some research done at the LHC nonetheless: massive gravitons, micro black holes, extra-dimensions, ...



Dark Matter



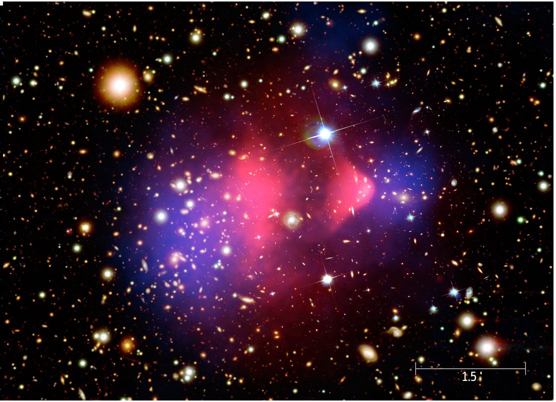
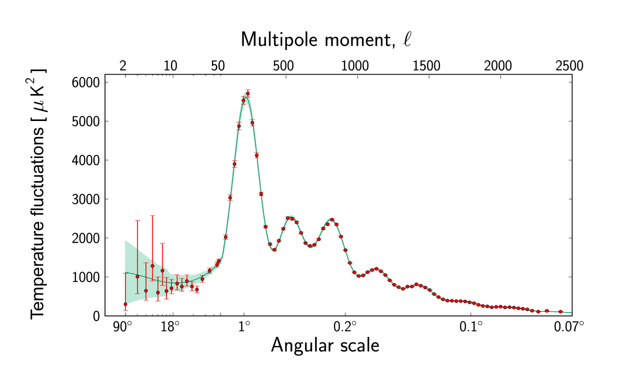
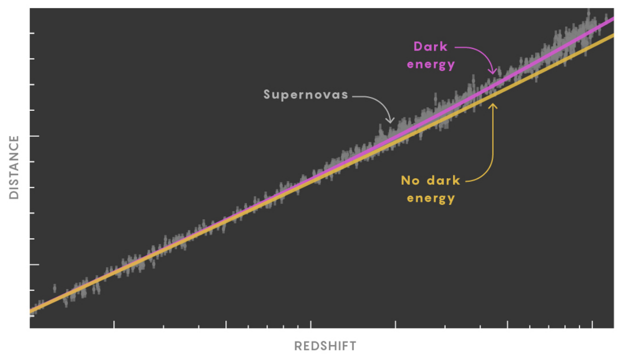


Illustration on the left from Wikipedia

- Strong evidence of dark matter! Left: rotation curve of M31 compared with expectation with no Dark Matter, right: Bullet Cluster. In blue is the mass distribution inferred by gravitational lensing, in pink the X-ray-emitting gas and the rest is in visible light.

Dark matter and Dark energy



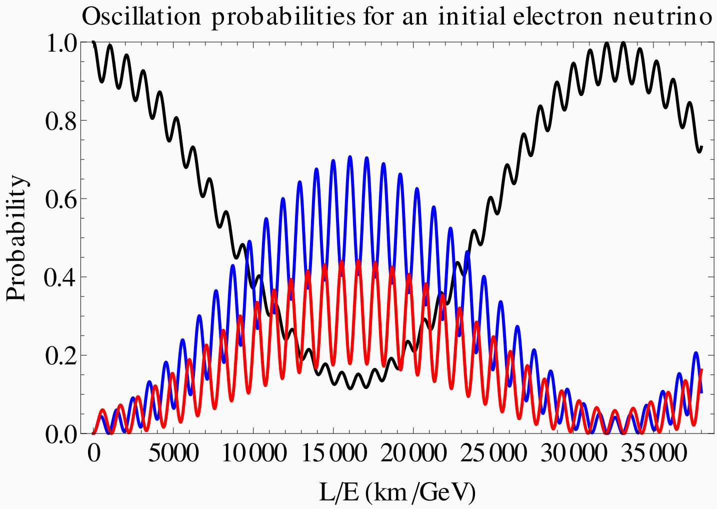


- The Cosmic Wave Background provides more evidence of the existence of dark matter. The power spectrum best fit correspond to the Λ CDM model.
- The CMB also give evidence for dark energy, which can also be seen directly by looking at the redshift of far away galaxies.

Left plot: Quanta mag.

Neutrinos

- Neutrinos oscillate between the different flavors: only possible if they have masses!
- Standard Model neutrinos are massless, how neutrinos get their masses is unknown.
- Could point to BSM physics! E.g. with the Seesaw mechanism, the (small) neutrinos masses is connected to physics at very large energy.
- You will know more about it tomorrow !



Resonance search

- How to find new particles (e.g. SUSY, dark matter, ...)
- One popular approch: trying to find new renonances !
- We basically try to find a "bump" in the data using the invariant mass distribution.
- New particles can also be found by looking at missing transverse energy, or with displaced vertices, ...

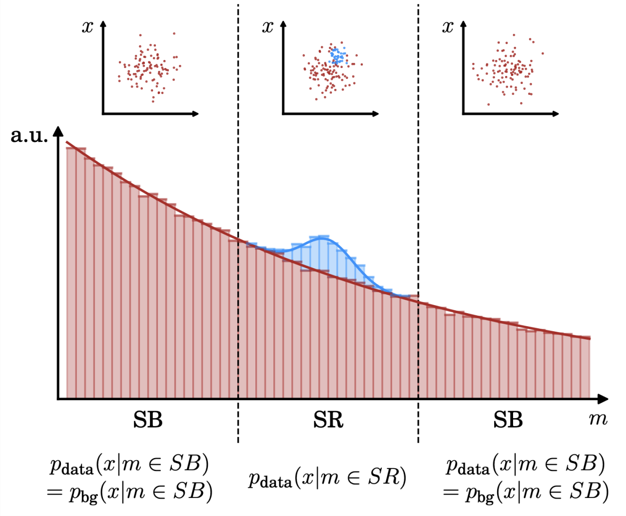
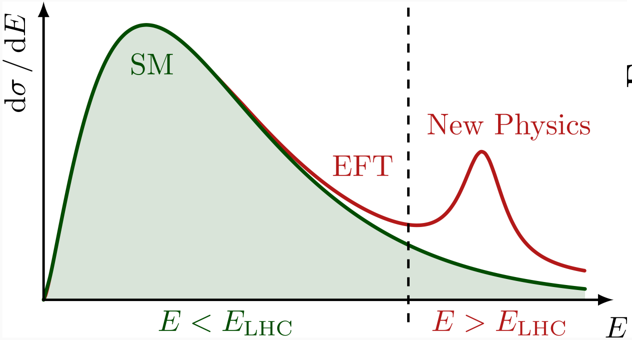
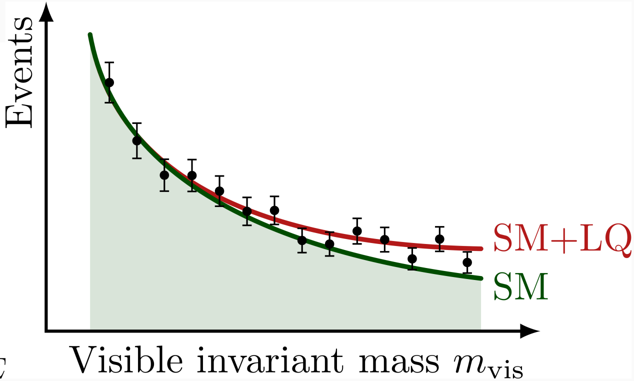


Illustration from: Classifying Anomalies THrough Outer Density Estimation

Effective field theory





- Even if a new resonance is too massive to be seen directly, if the mass is not much larger than the energy of collision, evidence for a new particle can be found.
- $\rightarrow$ effective field theory approach.

Effective field theory approach, anomalous coupling

- TGCs and/or QGCs could be modified by physics beyond the SM (*anomalous coupling*).
- One popular approach is the concept of Effective Field Theory (EFT): to parametrize BSM (Beyond the Standard Model) physics at low energy, one can extend the SM by adding higher dimension operators:

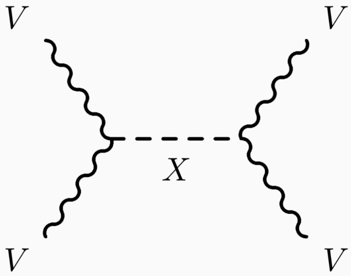
$$\mathcal{L} = \mathcal{L}_{SM} + \sum_{d>4} \sum_{i} \frac{C_i}{\Lambda^{d-4}} \mathcal{O}_i^d$$

  where $\mathcal{O}_i^d$ are the new d-dimension operators, C_i are dimensionless parameters and Λ is the new physics scale.
- Very general approach, consistent with many possible BSM scenarios ($\rightarrow$ model independence).
- Limits on dimension-6 and dimension-8 parameters can be set by studying vector bosons couplings with ATLAS and CMS: vector boson fusion/scattering, diboson and triboson production.

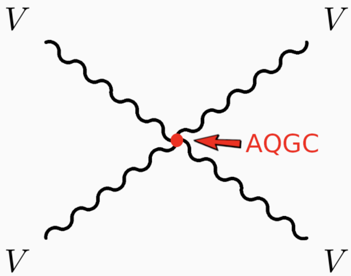
Anomalous coupling: illustration

Simple example to illustrate the idea: suppose there is a new particle X interacting with vector gauge bosons. Even if we don't have enough energy to produce it, its effect could be observed as an anomalous coupling.

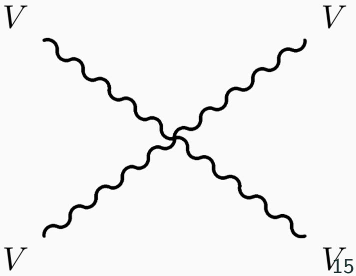
High energy:
new particle X couples with gauge bosons



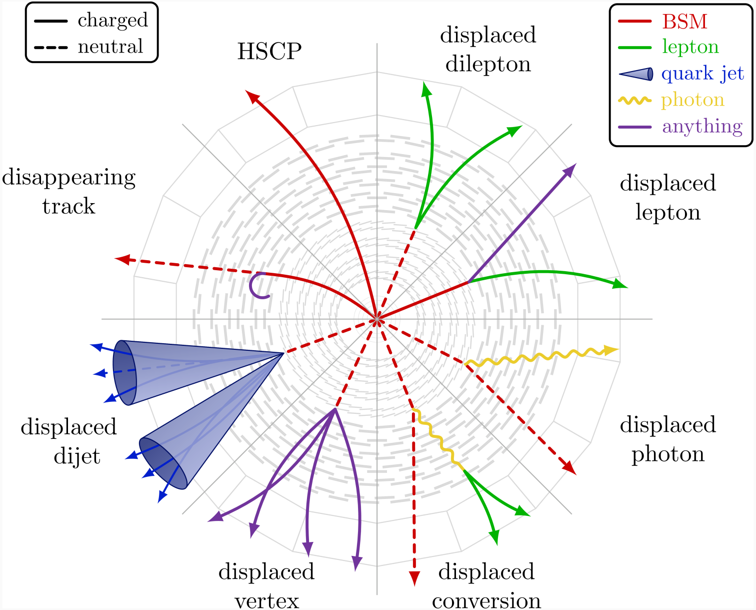
Lower energy:
at energy $\sqrt{s} << m_X$, particle X not observed directly, but affect gauge coupling



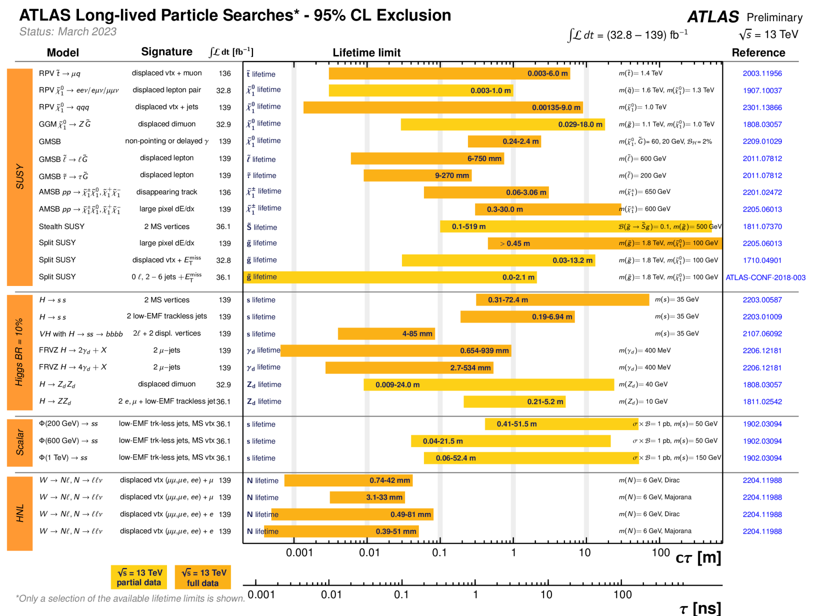
Even lower energy:
SM is recovered



Long Lived Particles Illustration: tikz



Long lived particles



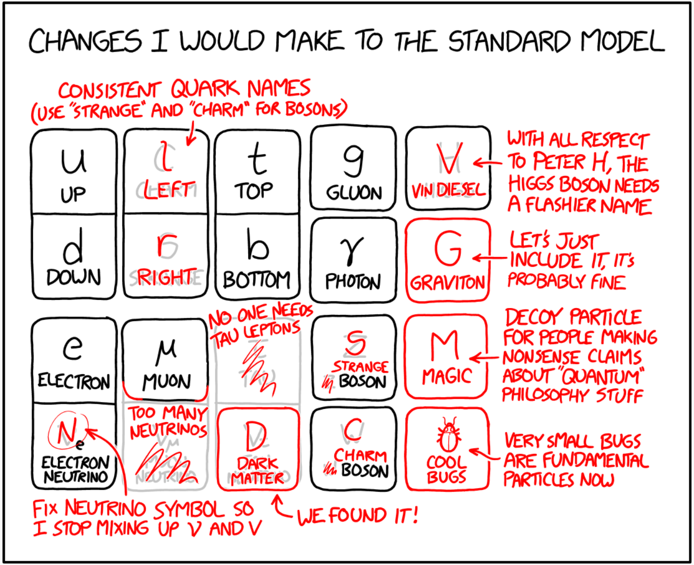
Other BSM phenomena

- New kind of particles: leptoquarks: Colored scalar or vector bosons coupling quarks directly to leptons, new heavy vector bosons (Z', W'), new scalars, krampouzinos ...
- Potential BSM sources of CP violations, strong CP problem.
- Anomalous magnetic moment of the muon: some tension compared to theoretical expectation.
- Neutron lifetime puzzle, different experimental method give different values for the neutron lifetime.
- Higgs potential shape, ...

Conclusion

- The Standard Model is nice but have many issues.
- We know experimentally that the Standard Model is wrong/incomplete: dark matter, dark energy, neutrinos masses, gravity, ...
- Search for BSM physics at CERN have been quite disappointing so far but a lot more data still need to be collected/analyzed.
- I hope you will all enjoy this session :)

Thank you :)


CHANGES I WOULD MAKE TO THE STANDARD MODEL
CONSISTENT QUARK NAMES
(USE "STRANGE" AND "CHARM" FOR BOSONS)
u
UP
l
LEFT
t
TOP
g
GLUON
V
VIN DIESEL
WITH ALL RESPECT TO PETER H, THE HIGGS BOSON NEEDS A FLASHIER NAME
d
DOWN
r
RIGHT
b
BOTTOM
γ
PHOTON
G
GRAVITON
LET'S JUST INCLUDE IT, IT'S PROBABLY FINE
e
ELECTRON
μ
MUON
NO ONE NEEDS TAU LEPTONS
S
STRANGE BOSON
M
MAGIC
DECOY PARTICLE FOR PEOPLE MAKING NONSENSE CLAIMS ABOUT "QUANTUM" PHILOSOPHY STUFF
N e
ELECTRON NEUTRINO
TOO MANY NEUTRINOS
D
DARK MATTER
C
CHARM BOSON
COOL BUGS
VERY SMALL BUGS ARE FUNDAMENTAL PARTICLES NOW
FIX NEUTRINO SYMBOL SO I STOP MIXING UP ν AND V
WE FOUND IT!