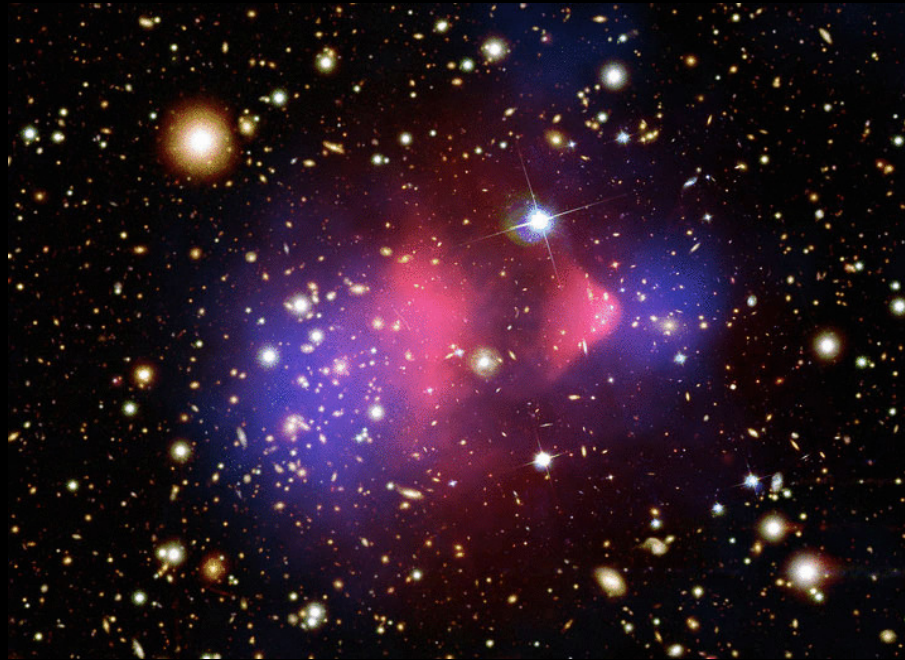


The Standard Model and Beyond

Hooman Davoudiasl

HET Group, Brookhaven National Laboratory



SULI Lecture, Physics Department, BNL

June 15, 2021

...I am induced by many reasons to suspect that they [phenomena of nature] may all depend upon certain forces by which the particles of bodies, by some causes hitherto unknown, are either mutually impelled towards each other, and cohere in regular figures, or are repelled and recede from each other; which forces being unknown, philosophers have hitherto attempted the search of nature in vain; but I hope the principles here laid down will afford some light either to this or some truer method of philosophy.

Sir Isaac Newton (1643-1727)

(Preface to Principia)

$$\hbar \approx 1.05 \times 10^{-34} \text{ J s} \quad ; \quad c \approx 3.0 \times 10^8 \text{ m/s}$$

$\hbar = c = 1$ in what follows

Mass and Energy measured in eV

Length \leftrightarrow 1/Mass

GeV (Giga eV) = 10^9 eV

proton mass \approx 1 GeV

TeV (Tera eV) = 10^{12} eV

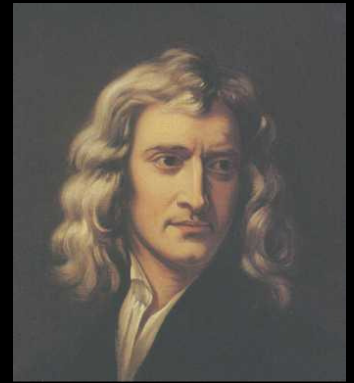
Everyday life:

Gravity and Electromagnetism (EM)



Falling Apple: Gravity

Well-described by Newtonian gravity



State of the Art: General relativity (GR)

- Spacetime curved by matter/energy.

Sun

- Gravitational Force → Geodesic.

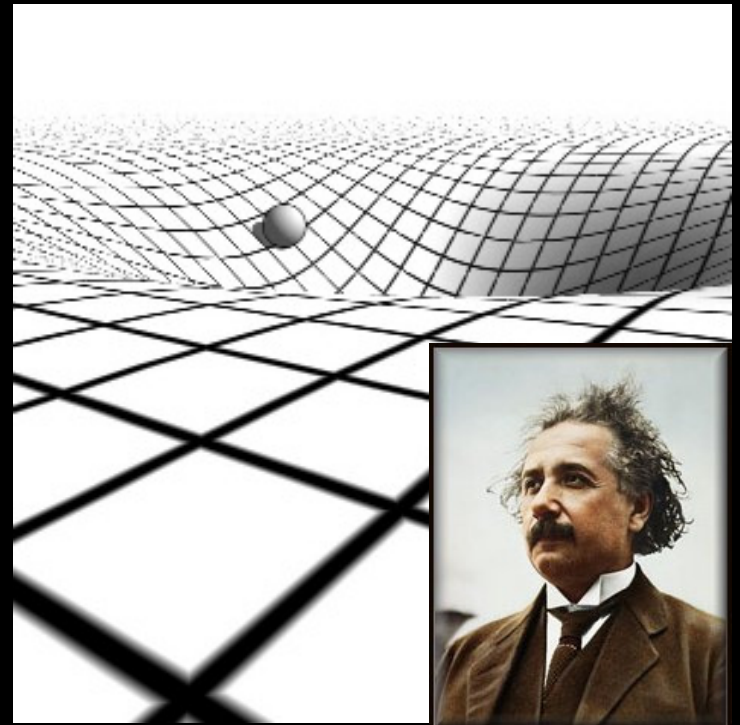
Earth's Orbit

- Basis of modern cosmology.

Einstein's equations:

Curvature $\mathcal{G}_{\mu\nu} = 8\pi G_N \mathcal{T}_{\mu\nu}$ Energy Distribution

G_N Newton's constant, $\mu, \nu = 0, 1, 2, 3$ (spacetime).



★ *Detection of Gravitational Waves* ★

- Directly confirmed a long-standing (~ 100 year) GR prediction
- Manifestation of the dynamical nature of spacetime



(SXS Project)

- Outstanding experimental achievement: measured strain (distance variation) $\sim 10^{-21}$! (highly sophisticated laser interferometry)
- 2017 Nobel Prize in Physics: Barish, Thorne, and Weiss



Shadow of M87*, Event Horizon Telescope

Mass: ~ 6.5 Billion Solar Masses ; Distance: ~ 55 Million Light Years

Results released April 10, 2019

Apple on the ground: Quantum Mechanics and EM

- Atoms in apple and ground: Electron *cloud* interactions stop the fall.
 - Pauli's exclusion principle for electrons; EM: repulsion.
- Atom: Nucleus (p and n) and electrons; Quantum Mechanics.
- Nuclear forces: weak and strong, not everyday, microscopic.
- Weak and EM forces \rightarrow Unified Electroweak Theory.

Summed up in the Standard Model of particle physics.



The Standard Model (SM):

Most precise description of microscopic physics

- **Gauge symmetry:** $SU(3)$ (strong) \times $SU(2) \times U(1)$ (electroweak)

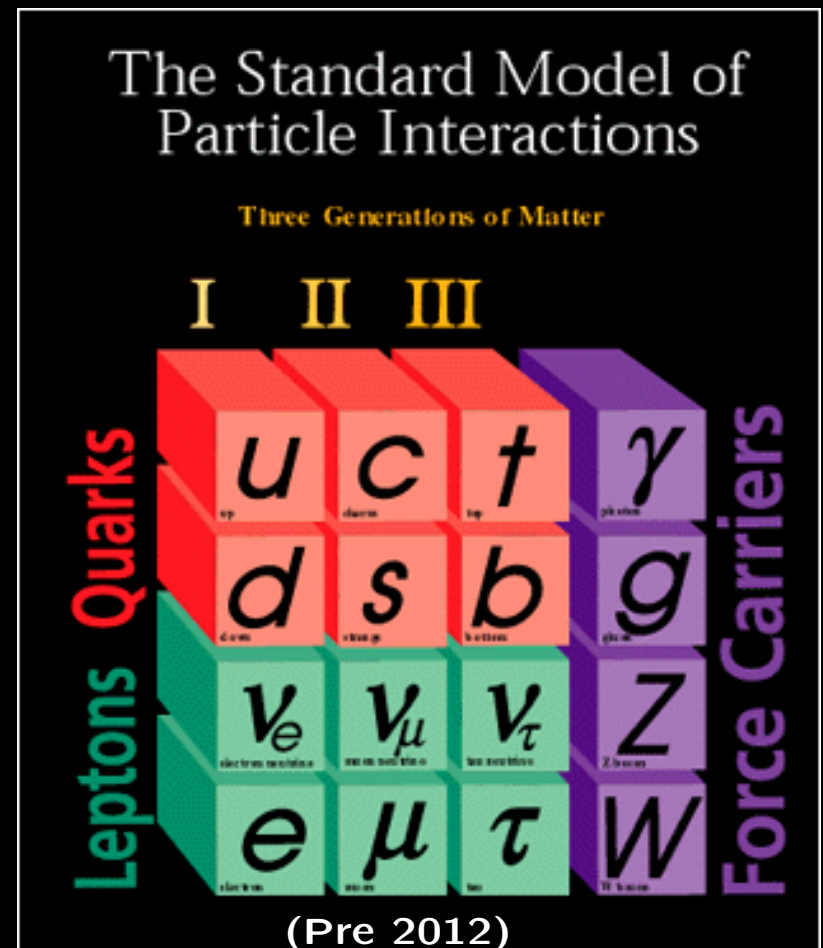
- **Elementary fermions, spin-1/2***

Quarks (+2/3, -1/3): Strong interactions

Leptons (0, -1): No strong interactions

- **Gauge Fields, spin-1**

Force mediators, generalized photons

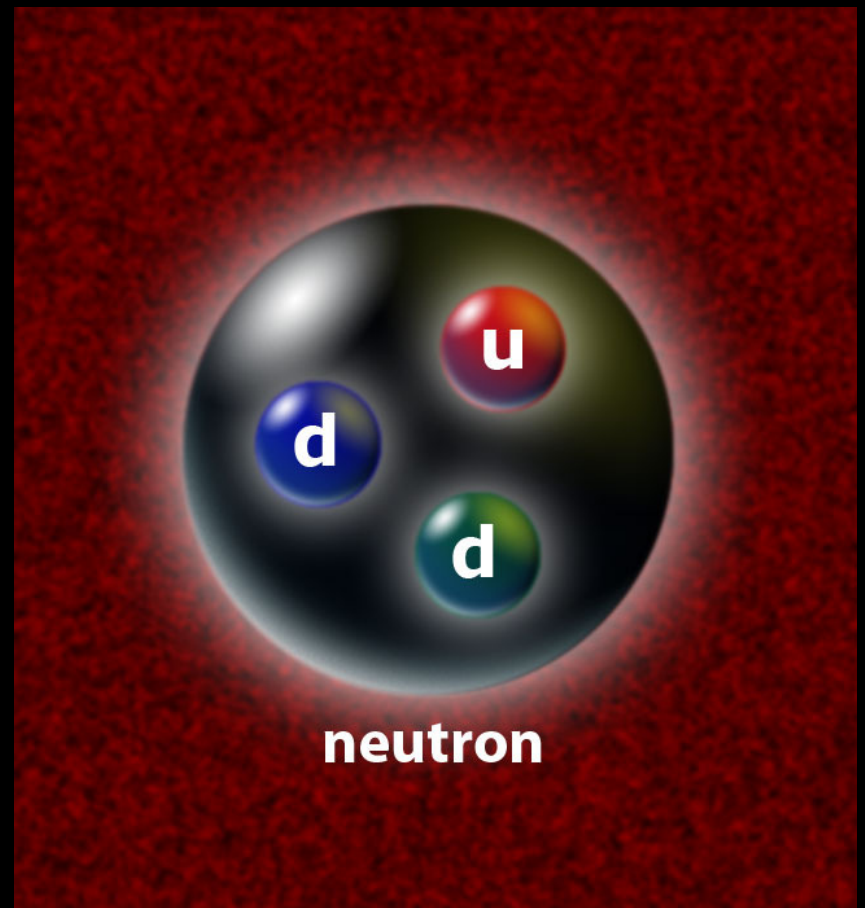
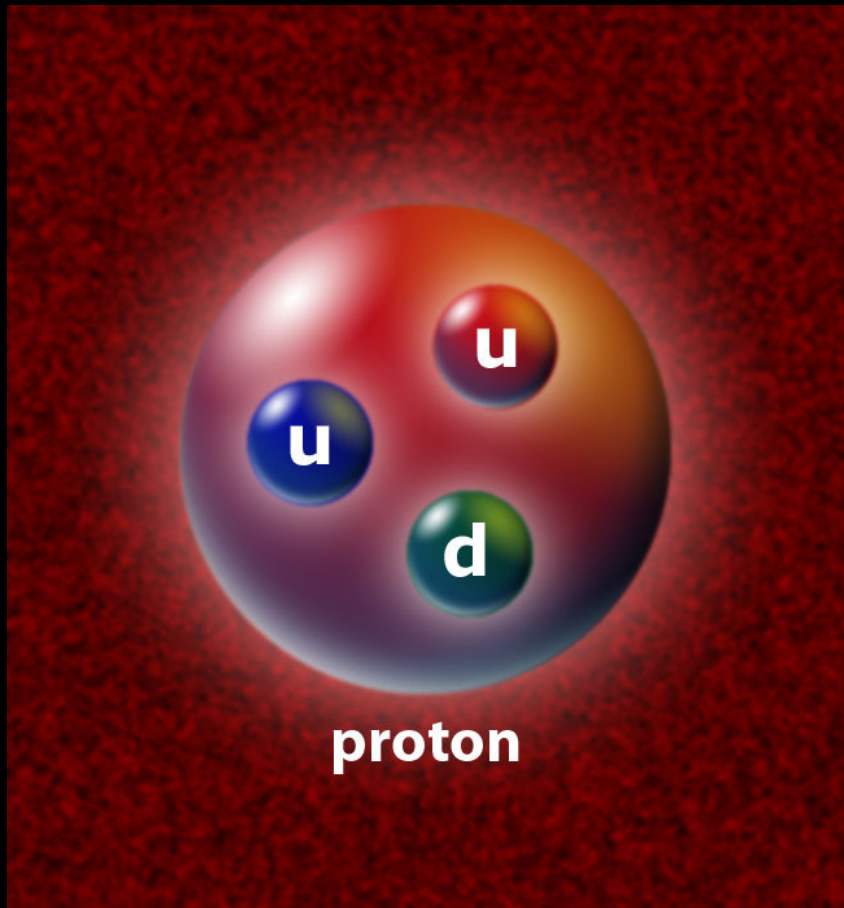


* Spin: intrinsic angular momentum (quantum mechanics)

Strong Interactions [$SU(3)$ (QCD)]:

QCD: Quantum Chromodynamics

- Short-ranged, confined to nuclear distances $\sim 10^{-15}$ m
- Gluons (g) bind quarks into **hadrons** (*hadros*: Greek for “bulky”):
 p , n , π^0 ($\bar{q}q$), . . .

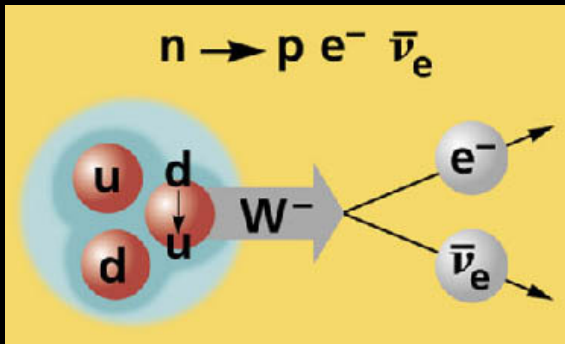


Electroweak Interactions [$SU(2)_L \times U(1)_Y$]:

- Spontaneously broken to EM

\Rightarrow Massive W^\pm (80.4 GeV/ c^2), Z^0 (91.2 GeV/ c^2)

Short-ranged: $\Delta x \sim c \Delta t \sim c \times \frac{\hbar}{mc^2} \sim 10^{-18}$ m (energy-time uncertainty)



Q: Why are there stable neutrons in atomic nuclei?

- EM: $U(1)_{EM}$ (QED)

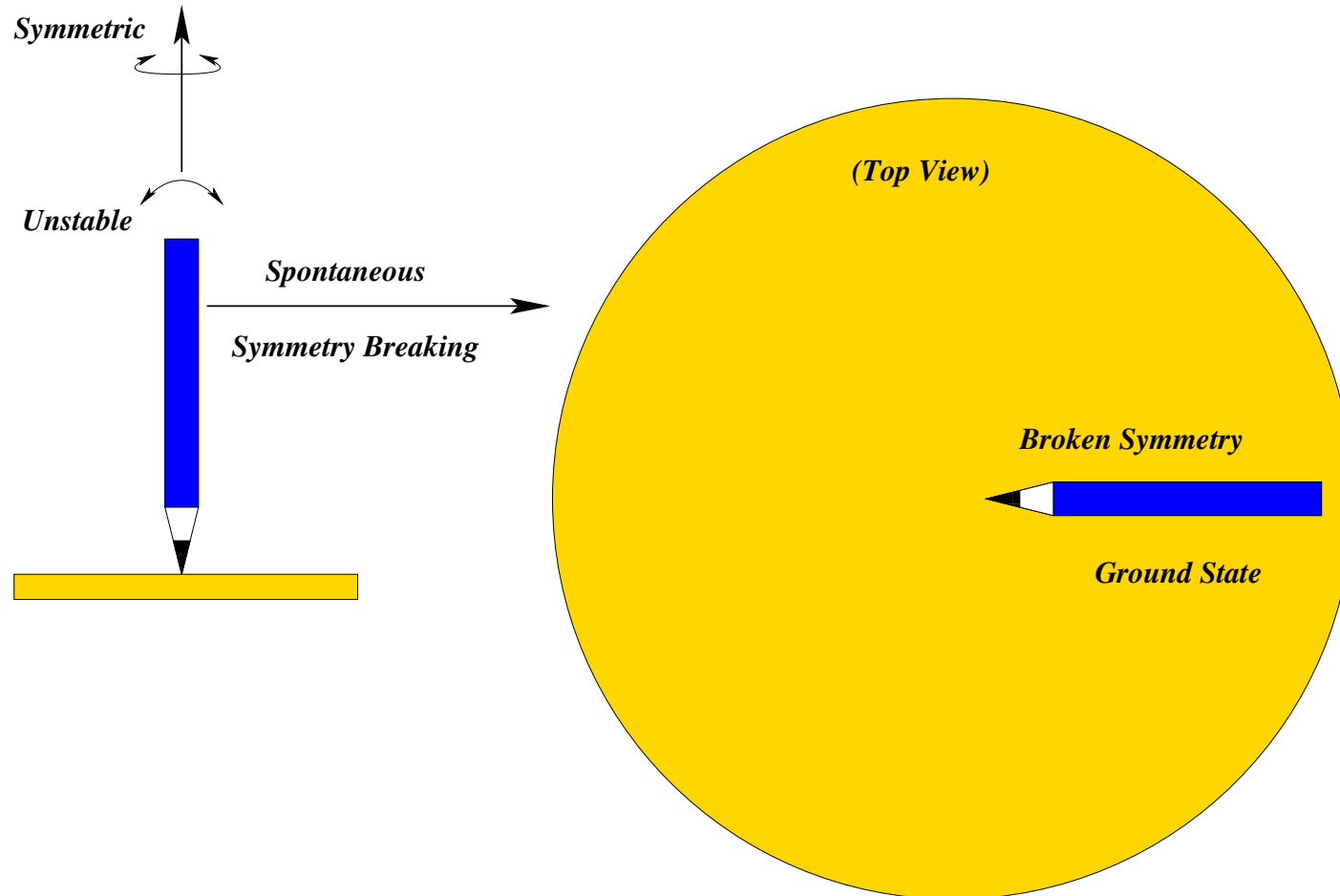
Massless photon, γ , long-ranged



Tabletop Spontaneous Symmetry Breaking

A pencil, standing on its tip: unstable, falls to its “ground state”.

- Underlying theory: rotationally symmetric, no preferred direction.
- The pencil **spontaneously** picks an orientation, breaks the symmetry.



What breaks electroweak symmetry?

A key question probed at the LHC (pp collider) at CERN



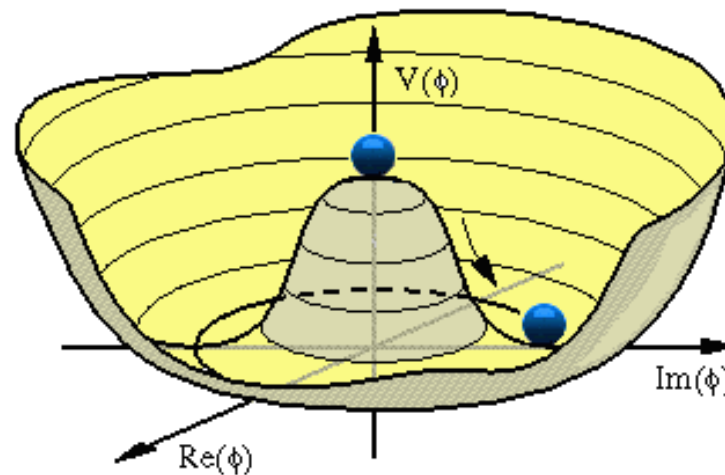
Beam energy: 2×7000 GeV (design)

2×6500 GeV Run finished in 2018 (to resume in 2022)

Circumference (km): 26.659

Electroweak Symmetry Breaking in SM

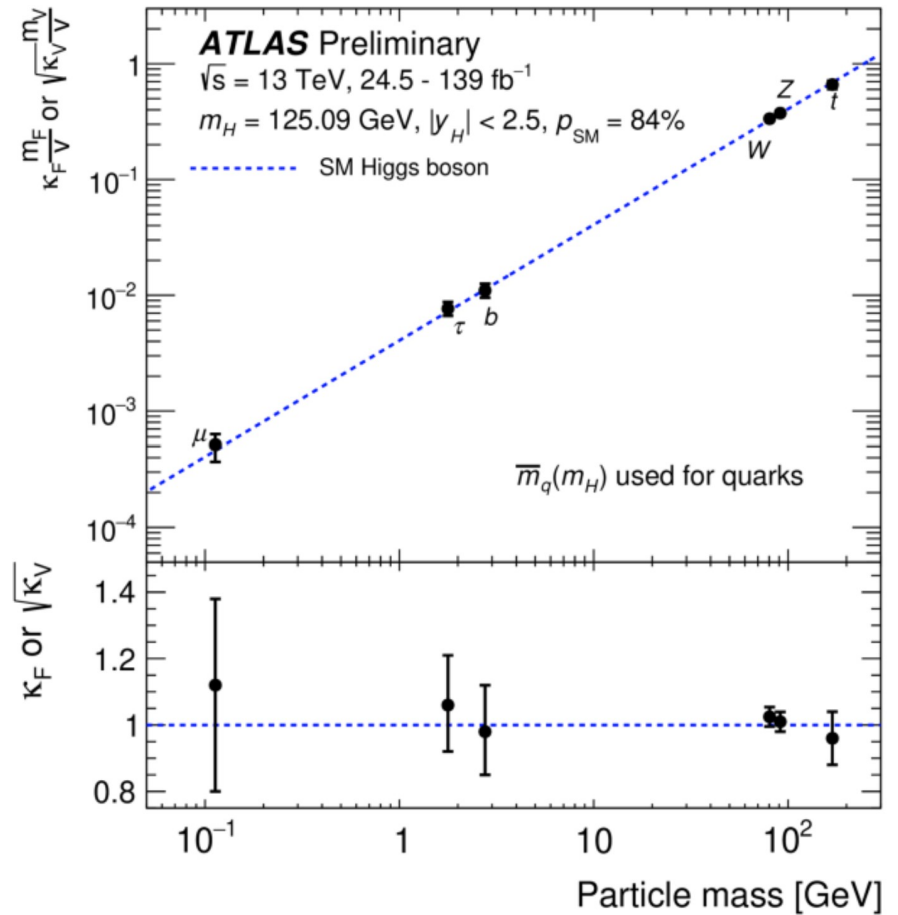
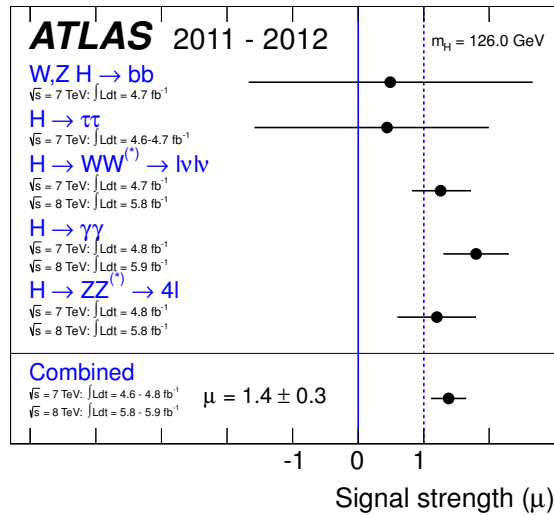
- Higgs (H) boson condensation $\langle H \rangle \neq 0$.
- Elementary particle masses from interactions with $\langle H \rangle \neq 0$:
 - $m_W, m_Z, m_{\text{fermion}} \propto \langle H \rangle$
 - Fermion flavor: $m_t/m_u \sim 10^5!$ (Why?)
- $m_\nu = 0$ (Strongly disfavored by data!)



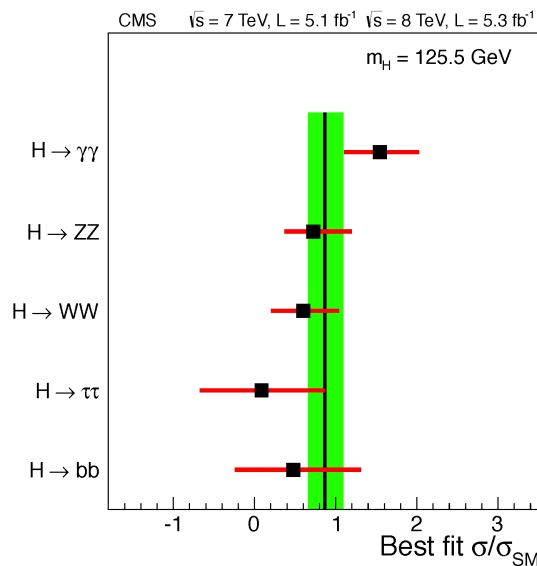
Q: How much of the “visible” mass in Universe is from Higgs?

July 4th, 2012, discovery announced at CERN

Scalar (spin-0) H boson discovered at ~ 125 GeV



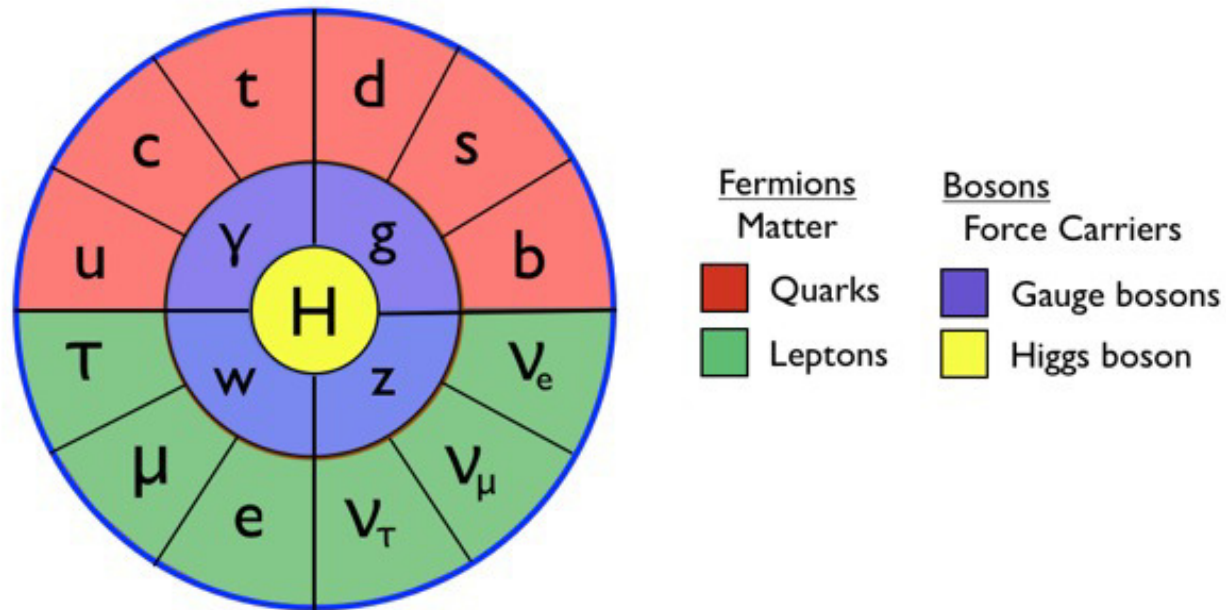
(Image: ATLAS Collaboration/CERN)



Early Run 1: ~ 10 fb $^{-1}$

Q: What is significant about having the muon in the plot?

SM + GR \Rightarrow Great Success!



Particles of the Standard Model

Nearly all* measurements in agreement with SM+GR.

* Except, for example, potential hints from muon $g - 2$ (more later), some B meson (bound state of b quark with a light quark) decays,...

SM: An Incomplete Description of Nature

- **Theoretical Hints**

Why is gravity so weak?

Why is the neutron electric dipole moment so small?

...

- **Experimental Evidence**

Non-zero neutrino masses, dark matter, ...

Conceptual Mystery: Why is gravity so weak?

Force between e and p in an atom: $\frac{F(\text{Grav})}{F(\text{EM})} \sim 10^{-40}!$

Gravity: the weakest known interaction

Newton's Constant: $G_N = 6.67 \times 10^{-11} \text{ m}^3\text{kg}^{-1}\text{s}^{-2}$

Gravity scale: Planck mass

$$M_P \equiv (\hbar c / G_N)^{1/2} \approx 10^{19} \text{ GeV} \sim (10^{-35} \text{ m})^{-1} !$$

(mass \leftrightarrow 1/length; uncertainty)

$$M_P \gg m_W$$

$$\hbar = c = 1.$$

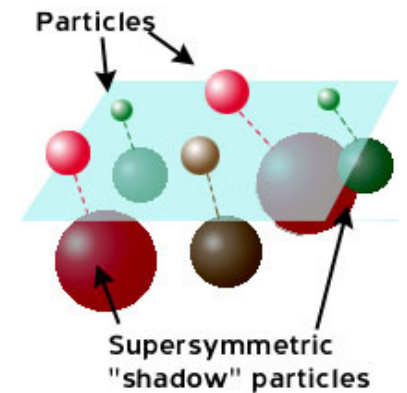
Hierarchy and New Physics Near m_H

- Strong Interactions near m_H

- Composite Higgs (analogue of a QCD hadron)
- Extra dimensions (lowering the fundamental mass scale of gravity by diluting it in compact extra dimensions)

- Supersymmetry: Fermions \leftrightarrow Bosons.

- Quantum effects on $\langle H \rangle$ cancel



- *So far, no firm evidence at LHC for new physics near $m_H \approx 125$ GeV*
- *New physics elusive, or perhaps "naturalness" not the right guide*

Strong Empirical Evidence for Beyond SM

- **Neutrino Flavor Oscillations**

- Solar, atmospheric, and terrestrial data:

$$m_\nu \lesssim 10^{-6} m_e$$

- Simple extension: right-handed* neutrinos ν_R

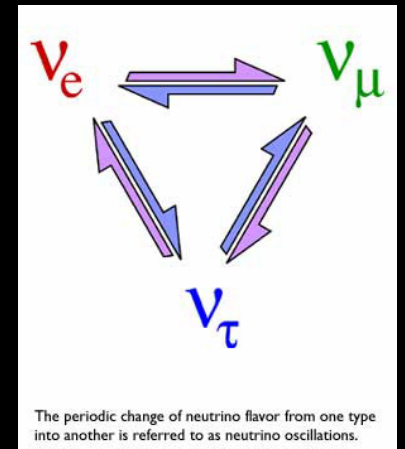
* Spin and momentum aligned

- Typically, difficult to test:

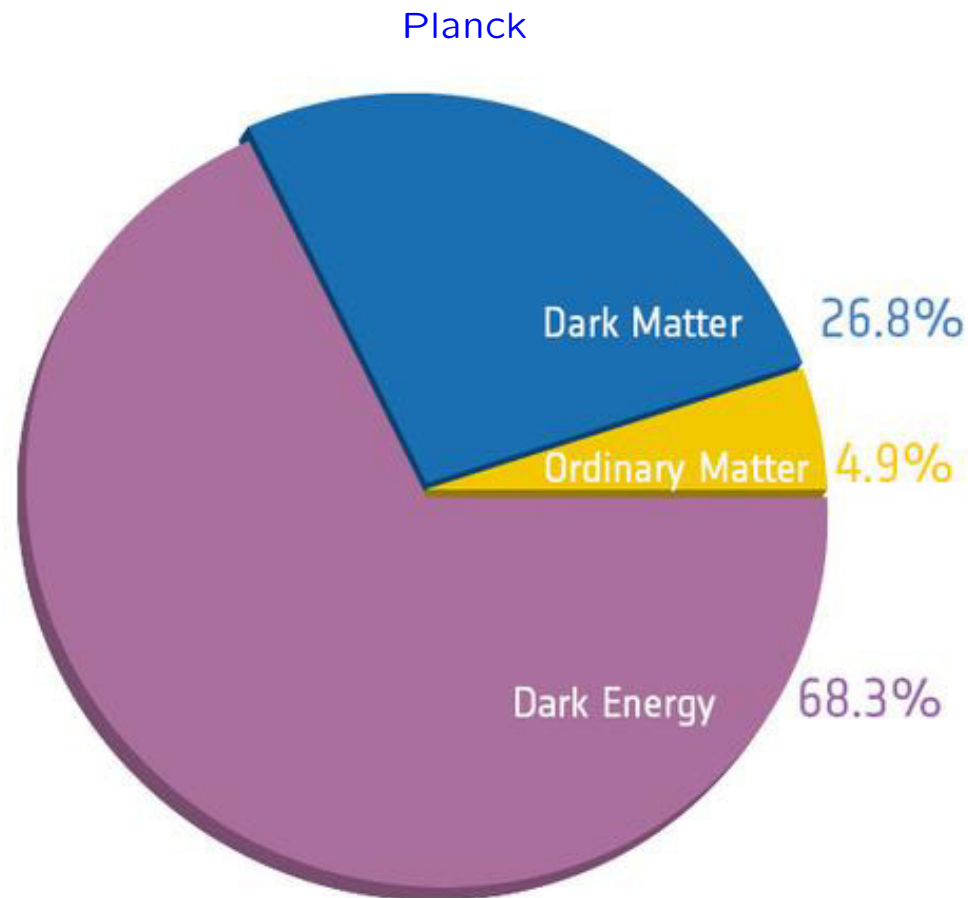
- ν_R very massive or else negligible coupling to SM

- **Cosmology**

- Dark Matter: neutral, cosmologically stable



Cosmos: 95% unknown!



Cosmic acceleration (dark energy):

Could be vacuum energy (cosmological constant); no dynamics

Visible (Everyday) Matter

PERIODIC TABLE
Atomic Properties of the Elements

National Institute of Standards and Technology
Technology Administration, U.S. Department of Commerce

Frequently used fundamental physical constants
For the most accurate values of these and other constants, visit physics.nist.gov/constants
1 second = 9 192 631 770 periods of radiation corresponding to the transition between the two hyperfine levels of the ground state of ^{133}Cs

speed of light in vacuum c 299 792 458 m s⁻¹ (exact)
Planck constant h 6.626 069 3 × 10⁻³⁴ J s
elementary charge e 1.602 176 634 × 10⁻¹⁹ C
electron mass m_e 9.109 383 56 × 10⁻³¹ kg
proton mass m_p 1.672 621 63 × 10⁻²⁷ kg
fine-structure constant α 1/137.036
Rydberg constant R_∞ 10 973 732 m⁻¹
 $R_\infty c$ 3.289 842 × 10¹⁵ Hz
 $R_\infty h c$ 13.605 693 eV
Boltzmann constant k 1.380 658 × 10⁻²³ J K⁻¹

Solids
 Liquids
 Gases
 Artificially Prepared

1 1A 1 H Hydrogen 1.00794 1.008 1.00784	2 2A 2 He Helium 4.002602 4.002602 4.002602											13 3A 13 Al Aluminum 26.981538 26.981538 26.981538	14 4A 14 Si Silicon 28.0855 28.0855 28.0855	15 5A 15 P Phosphorus 30.973761 30.973761 30.973761	16 6A 16 S Sulfur 32.065 32.065 32.065	17 7A 17 Cl Chlorine 35.453 35.453 35.453	18 8A 18 Ar Argon 39.948 39.948 39.948
3 3A 3 Li Lithium 6.941 6.941 6.941	4 4A 4 Be Beryllium 9.012182 9.012182 9.012182											5 5A 5 B Boron 10.811 10.811 10.811	6 6A 6 C Carbon 12.0107 12.0107 12.0107	7 7A 7 N Nitrogen 14.0064 14.0064 14.0064	8 8A 8 O Oxygen 15.999032 15.999032 15.999032	9 9A 9 F Fluorine 18.9984032 18.9984032 18.9984032	10 10A 10 Ne Neon 20.1797 20.1797 20.1797
11 1A 11 Na Sodium 22.989769 22.989769 22.989769	12 2A 12 Mg Magnesium 24.3050 24.3050 24.3050											13 3A 13 Al Aluminum 26.981538 26.981538 26.981538	14 4A 14 Si Silicon 28.0855 28.0855 28.0855	15 5A 15 P Phosphorus 30.973761 30.973761 30.973761	16 6A 16 S Sulfur 32.065 32.065 32.065	17 7A 17 Cl Chlorine 35.453 35.453 35.453	18 8A 18 Ar Argon 39.948 39.948 39.948
19 1A 19 K Potassium 39.0983 39.0983 39.0983	20 2A 20 Ca Calcium 40.078 40.078 40.078	21 3B 21 Sc Scandium 44.955910 44.955910 44.955910	22 4B 22 Ti Titanium 47.867 47.867 47.867	23 5B 23 V Vanadium 50.9415 50.9415 50.9415	24 6B 24 Cr Chromium 51.9961 51.9961 51.9961	25 7B 25 Mn Manganese 54.938045 54.938045 54.938045	26 8B 26 Fe Iron 55.845 55.845 55.845	27 9B 27 Co Cobalt 58.933200 58.933200 58.933200	28 10B 28 Ni Nickel 58.6934 58.6934 58.6934	29 11B 29 Cu Copper 63.546 63.546 63.546	30 12B 30 Zn Zinc 65.409 65.409 65.409	31 13B 31 Ga Gallium 69.723 69.723 69.723	32 14B 32 Ge Germanium 72.64 72.64 72.64	33 15B 33 As Arsenic 74.9216 74.9216 74.9216	34 16B 34 Se Selenium 78.96 78.96 78.96	35 17B 35 Br Bromine 79.904 79.904 79.904	36 18B 36 Kr Krypton 83.798 83.798 83.798
37 1A 37 Rb Rubidium 85.4678 85.4678 85.4678	38 2A 38 Sr Strontium 87.62 87.62 87.62	39 3B 39 Y Yttrium 88.90585 88.90585 88.90585	40 4B 40 Zr Zirconium 91.224 91.224 91.224	41 5B 41 Nb Niobium 92.90638 92.90638 92.90638	42 6B 42 Mo Molybdenum 95.94 95.94 95.94	43 7B 43 Tc Technetium (98) (98) (98)	44 8B 44 Ru Ruthenium 101.07 101.07 101.07	45 9B 45 Rh Rhodium 102.90550 102.90550 102.90550	46 10B 46 Pd Palladium 106.42 106.42 106.42	47 11B 47 Ag Silver 107.8682 107.8682 107.8682	48 12B 48 Cd Cadmium 112.411 112.411 112.411	49 13B 49 In Indium 114.818 114.818 114.818	50 14B 50 Sn Tin 118.710 118.710 118.710	51 15B 51 Sb Antimony 121.757 121.757 121.757	52 16B 52 Te Tellurium 127.60 127.60 127.60	53 17B 53 I Iodine 126.90447 126.90447 126.90447	54 18B 54 Xe Xenon 131.29 131.29 131.29
55 1A 55 Cs Cesium 132.90545 132.90545 132.90545	56 2A 56 Ba Barium 137.327 137.327 137.327	57 3B 57 La Lanthanum 138.905 138.905 138.905	58 4B 58 Ce Cerium 140.12 140.12 140.12	59 5B 59 Pr Praseodymium 140.90765 140.90765 140.90765	60 6B 60 Nd Neodymium 144.24 144.24 144.24	61 7B 61 Pm Promethium (145) (145) (145)	62 8B 62 Sm Samarium 150.36 150.36 150.36	63 9B 63 Eu Europium 151.964 151.964 151.964	64 10B 64 Gd Gadolinium 157.25 157.25 157.25	65 11B 65 Tb Terbium 158.92534 158.92534 158.92534	66 12B 66 Dy Dysprosium 162.500 162.500 162.500	67 13B 67 Ho Holmium 164.93032 164.93032 164.93032	68 14B 68 Er Erbium 167.259 167.259 167.259	69 15B 69 Tm Thulium 168.93402 168.93402 168.93402	70 16B 70 Yb Ytterbium 173.04 173.04 173.04	71 17B 71 Lu Lutetium 174.967 174.967 174.967	
87 1A 87 Fr Francium (223) (223) (223)	88 2A 88 Ra Radium (226) (226) (226)	89 3B 89 Ac Actinium (227) (227) (227)	90 4B 90 Th Thorium 232.0381 232.0381 232.0381	91 5B 91 Pa Protactinium 231.03688 231.03688 231.03688	92 6B 92 U Uranium 238.02891 238.02891 238.02891	93 7B 93 Np Neptunium (237) (237) (237)	94 8B 94 Pu Plutonium (244) (244) (244)	95 9B 95 Am Americium (243) (243) (243)	96 10B 96 Cm Curium (247) (247) (247)	97 11B 97 Bk Berkelium (247) (247) (247)	98 12B 98 Cf Californium (251) (251) (251)	99 13B 99 Es Einsteinium (252) (252) (252)	100 14B 100 Fm Fermium (257) (257) (257)	101 15B 101 Md Mendelevium (258) (258) (258)	102 16B 102 No Nobelium (259) (259) (259)	103 17B 103 Lr Lawrencium (262) (262) (262)	

Based upon ^{12}C . () indicates the mass number of the most stable isotope. For a description of the data, visit physics.nist.gov/data NIST SP 966 (September 2003)

- ~ 5% of energy budget
- Baryonic: protons, neutrons
- Asymmetric: $\Delta B \neq 0$ (negligible anti-matter today)

Generation of Baryon Asymmetry

- Requires Sakharov's conditions for *baryogenesis*:
 - (i) Baryon number violation
 - (ii) C and CP violation (distinguishing particles from anti-particles)
 - (iii) Departure from equilibrium
- Conditions absent [(iii)] or not at sufficient levels [(ii)] in the SM
- ΔB small, $n_B/n_\gamma \sim 10^{-9}$, but still too big to explain!

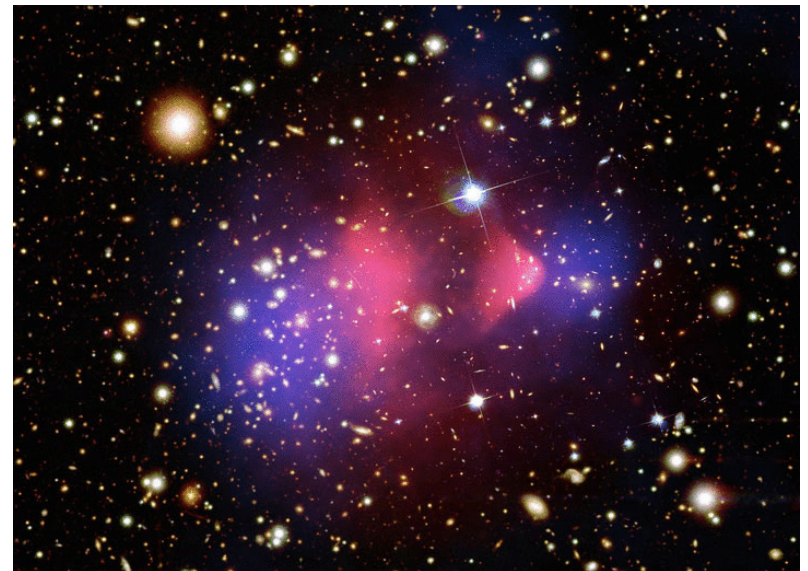
⇒ **New Physics**

Dark matter (DM)

- $\sim 27\%$ of energy density
- Robust evidence from cosmology and astrophysics
 - CMB, BBN, rotation curves of galaxies, lensing, Bullet Cluster, ...
- **Unknown origin**
 - Feeble interactions with atoms and photons
 - Self-interactions not strong ($\sigma \lesssim 1$ barn)
 - Not explained in SM

Strongly motivates new physics

So far, evidence limited to gravity effects



How do you look for something of unknown nature?



Possible DM mass scale: 10^{-22} eV $\lesssim M_{\text{DM}} \lesssim 10^{68}$ eV

(~ 90 orders of magnitude!)

Q: Why is there a lower bound ($\sim 10^{-22}$ eV)?

Searches often guided by *theoretical motivation*

- New physics to address unresolved questions in SM

Example:

- **The hierarchy** problem in SM:
 - New particles with masses $M_{\text{new}} \gtrsim M_H (\approx 125) \text{ GeV}$: supersymmetry, ...
 - Energy scale often referred to as the “weak scale” (weak interactions)
- ⇒ **Weakly Interacting Massive Particles** (WIMPs)

- SM extensions often introduce/require new symmetries

- Symmetry → Charge conservation

⇒ Stable or long-lived particles: DM candidates

WIMPs

- Thermal relic density: annihilation, freeze-out

- $\rho_{\text{WIMP}} \propto 1/\sigma_{\text{ann}}$

- $\sigma_{\text{ann}} \sim g^4/M^2$

- $g \sim g_{\text{weak}}, M \sim \text{TeV}$: roughly the right amount of DM

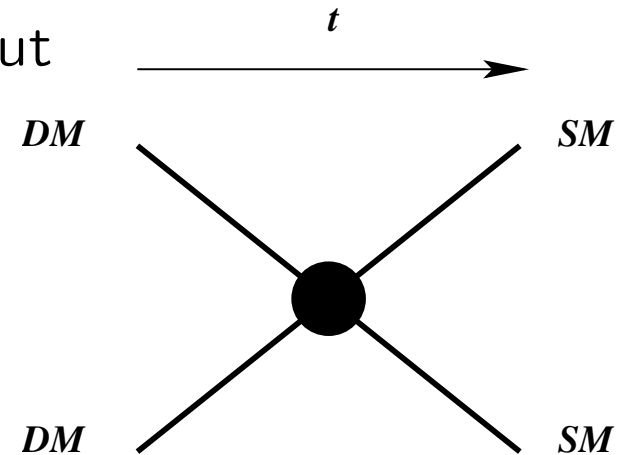
- Weak scale ($\sim \text{TeV}$) theoretically motivated

- However, g^4/M^2 may be achieved otherwise (WIMPless Miracle)

[Feng and Kumar, 2008](#)

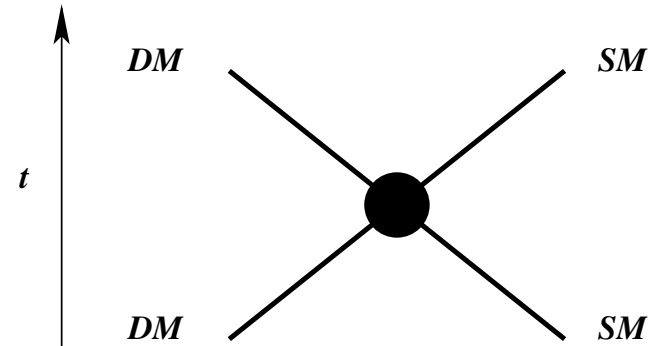
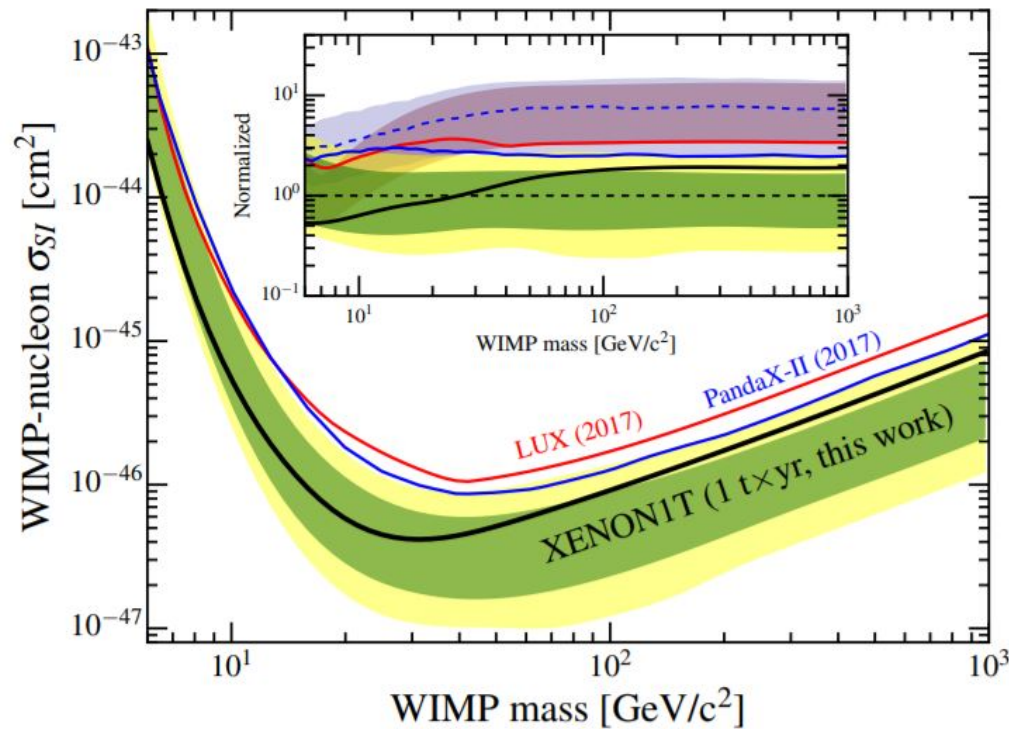
- **WIMPs: have been a main focus of DM searches**

- DAMA/LIBRA, CDMS, Xenon10, CDMSII, Xenon100, LUX, Fermi GST...



Direct WIMP DM Searches

- Recoil off atomic nuclei (electrons)

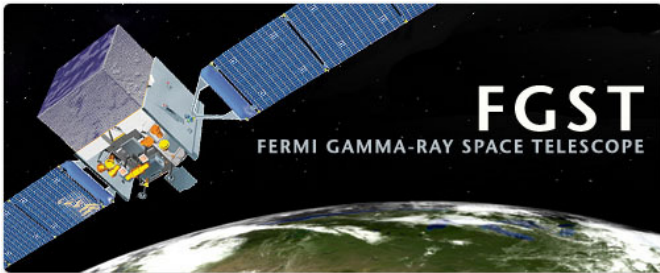


E. Aprile *et al.* [XENON Collaboration], Phys. Rev. Lett. **121**, no. 11, 111302 (2018)

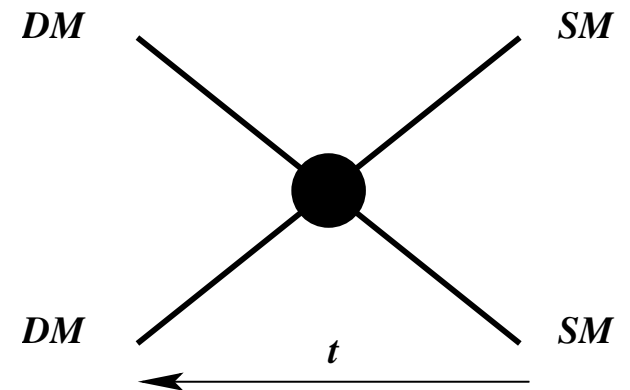
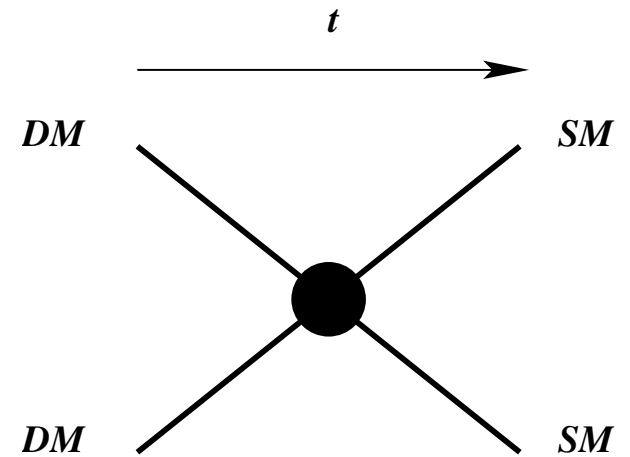
Q: Why do the constraints get weaker towards lower and higher DM masses?

Other avenues for WIMP search:

- Indirect searches: self-annihilation signals
 - Related to thermal relic density
 - Complicated by astrophysical backgrounds



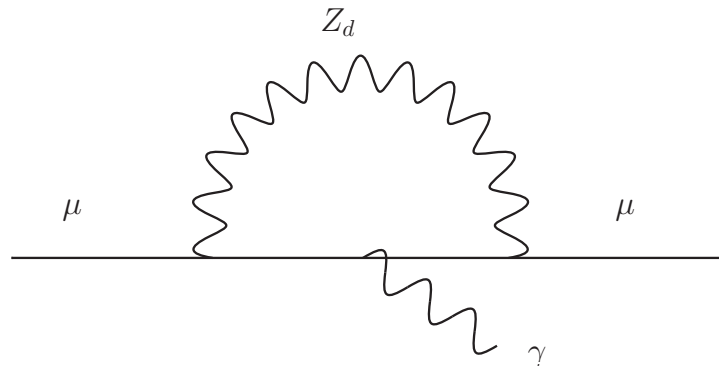
- Collider production: LHC
 - Search for missing energy in events



Dark Sectors and Dark Forces

For example: [Arkani-Hamed, Finkbeiner, Slatyer, Weiner, 2008](#)

- DM may reside in a separate sector with its own forces
 - Analogy with SM
- DM interactions with SM are indirect
- Simple example: a “dark” sector $U(1)_d$
 - Mediated by vector boson Z_d of mass m_{Z_d} coupling g_d
- $m_{Z_d} \lesssim 1$ GeV has been invoked in various contexts
 - DM interpretation of astrophysical data
 - Explaining muon $g - 2$



Muon $g - 2$

- There are some experimental hints for deviations from the SM
- A significant one is the apparent tension between SM prediction and measured muon $g - 2$

$$\vec{\mu}_l = e \frac{g}{2m_l} \vec{S} \quad (\text{Magnetic dipole moment, lepton mass } m_l, \text{ spin } \vec{S})$$

$$g = 2 \left(1 + \frac{\alpha}{2\pi} + \dots \right) \quad (\text{J. Schwinger, 1948})$$

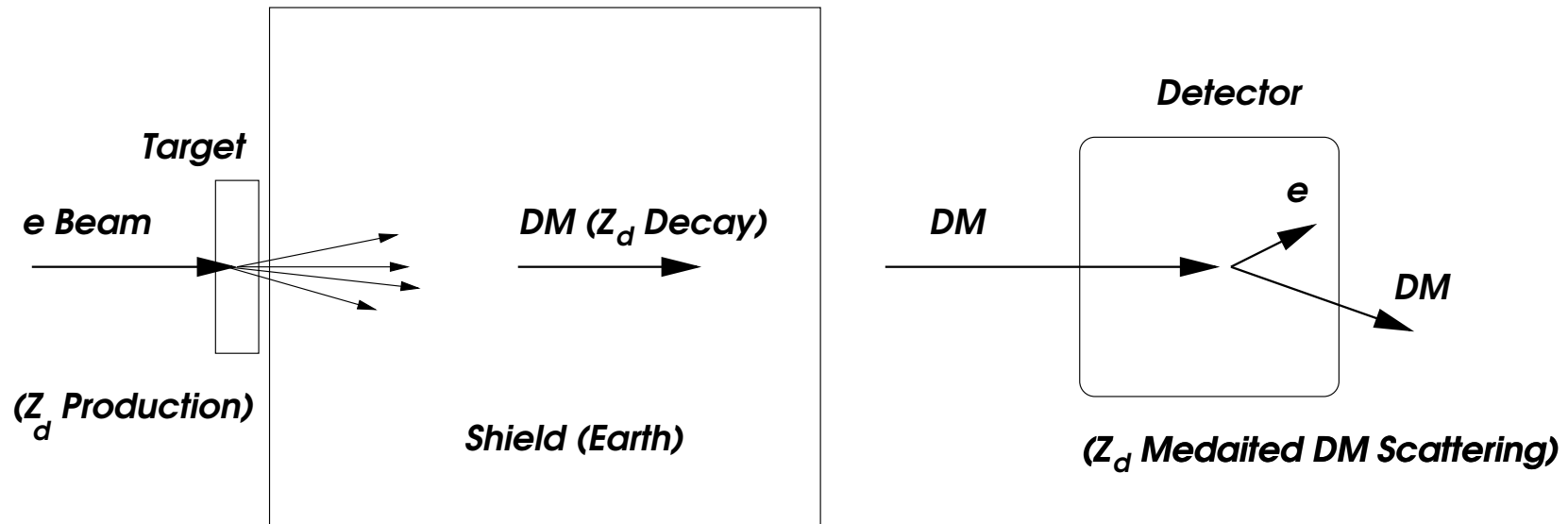
- Long-standing Brookhaven experimental results* recently confirmed by an ongoing measurement at Fermilab [Phys. Rev. Lett. 126, 141801 \(2021\)](#)

* [Phys.Rev.D73:072003,2006](#)

- A set of precision calculations suggest a 4.2σ deviation, $(251 \pm 59) \times 10^{-11}$, averaging Brookhaven and Fermilab results, but status of SM prediction is still under scrutiny
- The results could be pointing to new phenomena
- Stay tuned over the coming few years
- Upcoming lecture by W. Morse will provide many more details

Invisible Z_d and Low Mass DM Production

- Possible production and detection of *DM beams* in experiments
Batell, Pospelov, Ritz, 2009 (*p* beam); Izaguirre, Krnjaic, Schuster, Toro, 2013 (*e* beam dump)
- Interesting probe of GeV-scale DM (challenge for direct detection)



Motivated a search at Fermilab:

“Dark Matter Search in a Proton Beam Dump with MiniBooNE”

A. A. Aguilar-Arevalo *et al.* [MiniBooNE Collaboration], Phys. Rev. Lett. **118**, no. 22, 221803 (2017)

Concluding Remarks

★ Standard Model and GR successfully describe wide range of phenomena.

- Higgs boson discovered at LHC, appears to complete SM
- Some potential deviations in current data
- In particular, muon $g - 2$ could be hinting at new physics; more data and further theory investigations are needed

★ SM conceptual difficulties: hierarchy (Higgs mass “naturalness”), . . .

- No firm evidence for any new physics associated with a “natural” Higgs mass
- Perhaps still early, but new organizing principles may be needed

★ Empirical shortcomings: neutrino masses, dark matter, baryogenesis, . . .

- Neutrino mass generation: requires physics beyond SM, but typically elusive
- Dark matter: robust gravitational evidence for new physics, potentially accessible
- WIMP dark matter: Motivated by “naturalness” of m_H (under strain)
- Wide range of other possibilities for DM currently viable