

OPEN QUESTIONS IN THEORETICAL PHYSICS

DANIEL STOLARSKI



TAU to CERN October 5, 2015

OPEN QUESTIONS IN THEORETICAL PHYSICS PARTICLE

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SOME OPEN QUESTIONS IN THEORETICAL PHYSICS PARTICLE

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DISCOVERY!



THE STANDARD MODEL

Very simple theory:

Explains results of nearly all experiments.

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i\bar{\psi} \not{D} \psi + h.c. + \chi_i Y_{ij} \chi_j \phi + h.c.$$

	I	II	III	
Quarks	2.4 MeV $\frac{2}{3}$ $\frac{1}{2}$ u up	1.27 GeV $\frac{2}{3}$ $\frac{1}{2}$ c charm	171.2 GeV $\frac{2}{3}$ $\frac{1}{2}$ t top	0 0 1 γ photon
	4.8 MeV $-\frac{1}{3}$ $\frac{1}{2}$ d down	104 MeV $-\frac{1}{3}$ $\frac{1}{2}$ s strange	4.2 GeV $-\frac{1}{3}$ $\frac{1}{2}$ b bottom	0 0 1 g gluon
Leptons	<2.2 eV 0 $\frac{1}{2}$ ν_e electron neutrino	<0.17 MeV 0 $\frac{1}{2}$ ν_μ muon neutrino	<15.5 MeV 0 $\frac{1}{2}$ ν_τ tau neutrino	91.2 GeV 0 1 Z⁰ weak force
	0.511 MeV -1 $\frac{1}{2}$ e electron	105.7 MeV -1 $\frac{1}{2}$ μ muon	1.777 GeV -1 $\frac{1}{2}$ τ tau	80.4 GeV ±1 1 W[±] weak force

Bosons (Forces)

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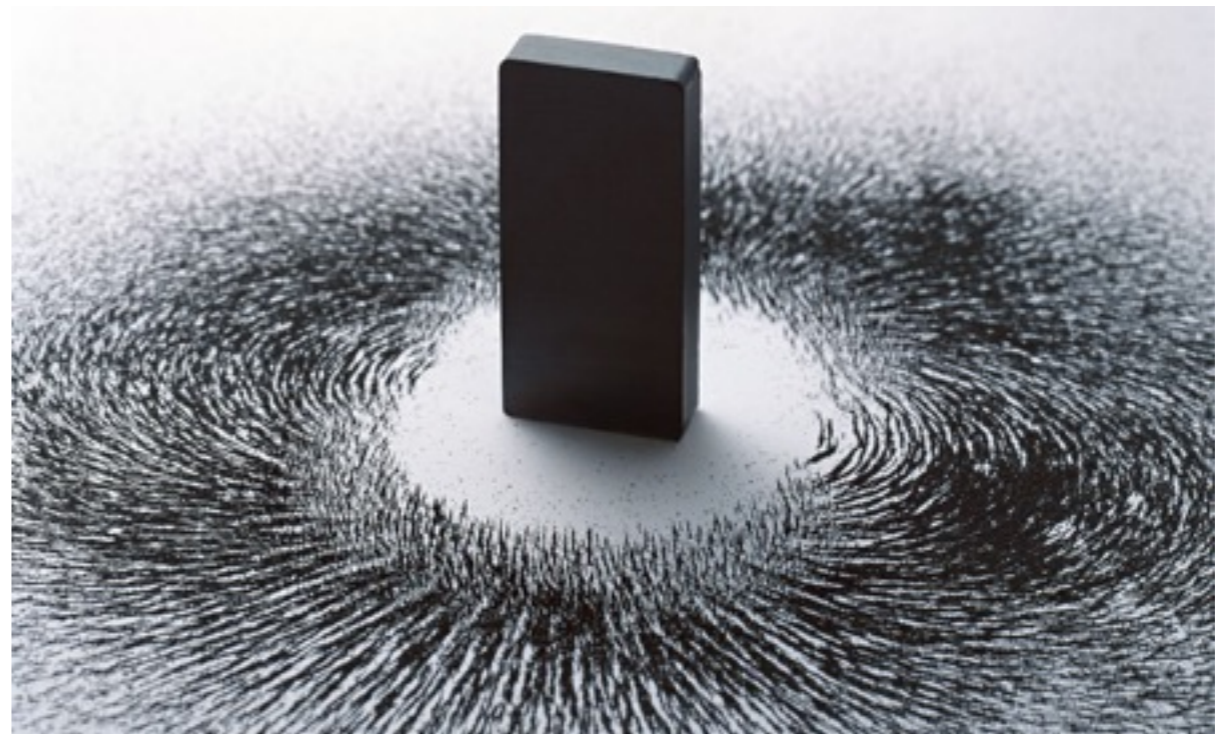
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				Bosons (Forces)
Leptons				

THE STANDARD MODEL

Periodic Table of the Elements

1 1IA 11A																	18 VIII A 8A		
1 H Hydrogen 1.0079			2 IIA 2A											13 IIIA 3A	14 IVA 4A	15 VA 5A	16 VIA 6A	17 VIIA 7A	2 He Helium 4.00260
3 Li Lithium 6.941	4 Be Beryllium 9.01218											5 B Boron 10.811	6 C Carbon 12.011	7 N Nitrogen 14.00674	8 O Oxygen 15.9994	9 F Fluorine 18.998403	10 Ne Neon 20.1797		
11 Na Sodium 22.989768	12 Mg Magnesium 24.305	3 IIIB 3B	4 IVB 4B	5 VB 5B	6 VIB 6B	7 VIIB 7B	8 VIII 8	9 VIII 8	10 VIII 8	11 IB 1B	12 IIB 2B	13 Al Aluminum 26.981539	14 Si Silicon 28.0855	15 P Phosphorus 30.973762	16 S Sulfur 32.066	17 Cl Chlorine 35.4527	18 Ar Argon 39.948		
19 K Potassium 39.0983	20 Ca Calcium 40.078	21 Sc Scandium 44.95591	22 Ti Titanium 47.88	23 V Vanadium 50.9415	24 Cr Chromium 51.9961	25 Mn Manganese 54.938	26 Fe Iron 55.847	27 Co Cobalt 58.9332	28 Ni Nickel 58.6934	29 Cu Copper 63.546	30 Zn Zinc 65.39	31 Ga Gallium 69.732	32 Ge Germanium 72.64	33 As Arsenic 74.92159	34 Se Selenium 78.96	35 Br Bromine 79.904	36 Kr Krypton 83.80		
37 Rb Rubidium 85.4678	38 Sr Strontium 87.62	39 Y Yttrium 88.90585	40 Zr Zirconium 91.224	41 Nb Niobium 92.90638	42 Mo Molybdenum 95.94	43 Tc Technetium 98.9072	44 Ru Ruthenium 101.07	45 Rh Rhodium 102.9055	46 Pd Palladium 106.42	47 Ag Silver 107.8682	48 Cd Cadmium 112.411	49 In Indium 114.818	50 Sn Tin 118.71	51 Sb Antimony 121.760	52 Te Tellurium 127.6	53 I Iodine 126.90447	54 Xe Xenon 131.29		
55 Cs Cesium 132.90543	56 Ba Barium 137.327	57-71 Lanthanide Series	72 Hf Hafnium 178.49	73 Ta Tantalum 180.9479	74 W Tungsten 183.85	75 Re Rhenium 186.207	76 Os Osmium 190.23	77 Ir Iridium 192.22	78 Pt Platinum 195.08	79 Au Gold 196.9665	80 Hg Mercury 200.59	81 Tl Thallium 204.3833	82 Pb Lead 207.2	83 Bi Bismuth 208.98037	84 Po Polonium [208.9824]	85 At Astatine 209.9871	86 Rn Radon 222.0176		
87 Fr Francium 223.0197	88 Ra Radium 226.0254	89-103 Actinide Series	104 Rf Rutherfordium [261]	105 Db Dubnium [262]	106 Sg Seaborgium [266]	107 Bh Bohrium [264]	108 Hs Hassium [269]	109 Mt Meitnerium [268]	110 Ds Darmstadtium [269]	111 Rg Roentgenium [272]	112 Cn Copernicium [277]	113 Uut Ununtrium unknown	114 Uuq Ununquadium [289]	115 Uup Ununpentium unknown	116 Uuh Ununhexium [296]	117 Uus Ununseptium unknown	118 Uuo Ununoctium unknown		
		57 La Lanthanum 138.9055	58 Ce Cerium 140.115	59 Pr Praseodymium 140.90765	60 Nd Neodymium 144.24	61 Pm Promethium 144.9127	62 Sm Samarium 150.36	63 Eu Europium 151.9655	64 Gd Gadolinium 157.25	65 Tb Terbium 158.92534	66 Dy Dysprosium 162.50	67 Ho Holmium 164.93032	68 Er Erbium 167.26	69 Tm Thulium 168.93421	70 Yb Ytterbium 173.04	71 Lu Lutetium 174.967			
		89 Ac Actinium 227.0278	90 Th Thorium 232.0381	91 Pa Protactinium 231.03588	92 U Uranium 238.0289	93 Np Neptunium 237.0482	94 Pu Plutonium 244.0642	95 Am Americium 243.0614	96 Cm Curium 247.0703	97 Bk Berkelium 247.0703	98 Cf Californium 251.0796	99 Es Einsteinium [254]	100 Fm Fermium 257.0951	101 Md Mendelevium 258.1	102 No Nobelium 259.1009	103 Lr Lawrencium [262]			

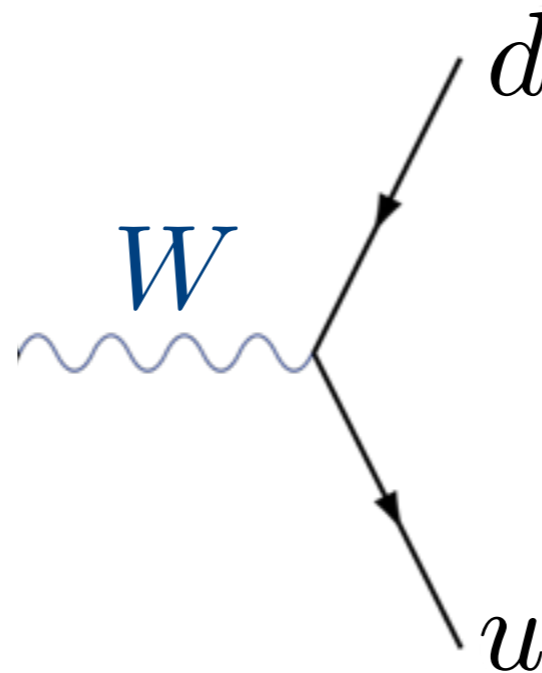
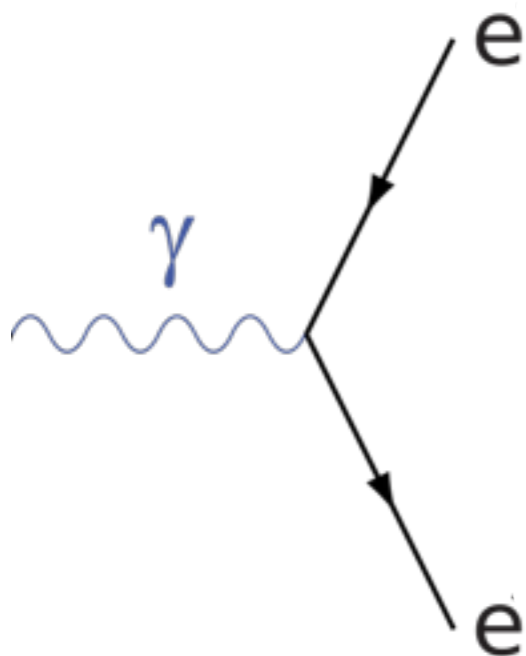
THE STANDARD MODEL



GAUGE SYMMETRIES

Gauge symmetry dictates all interactions:

$$SU(3)_c \times SU(2)_L \times U(1)_Y$$



Masses for fermions and gauge bosons forbidden.

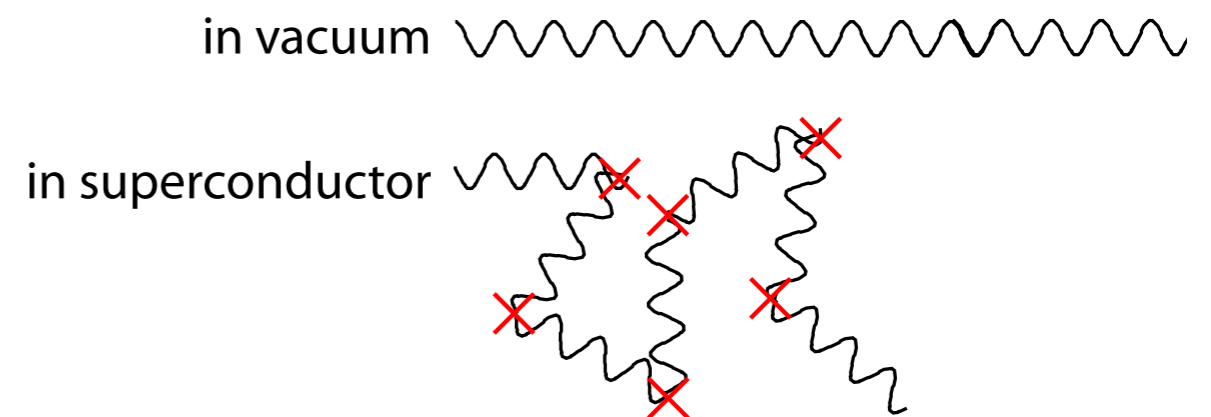
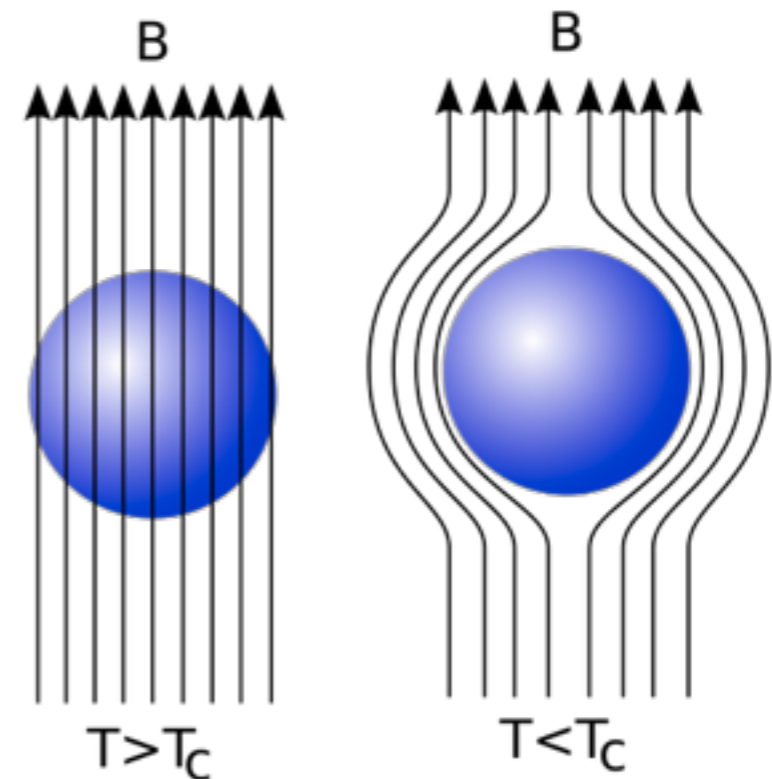
Inconsistent with observation.

SUPERCONDUCTOR

Magnetic fields are expelled: Meissner effect.

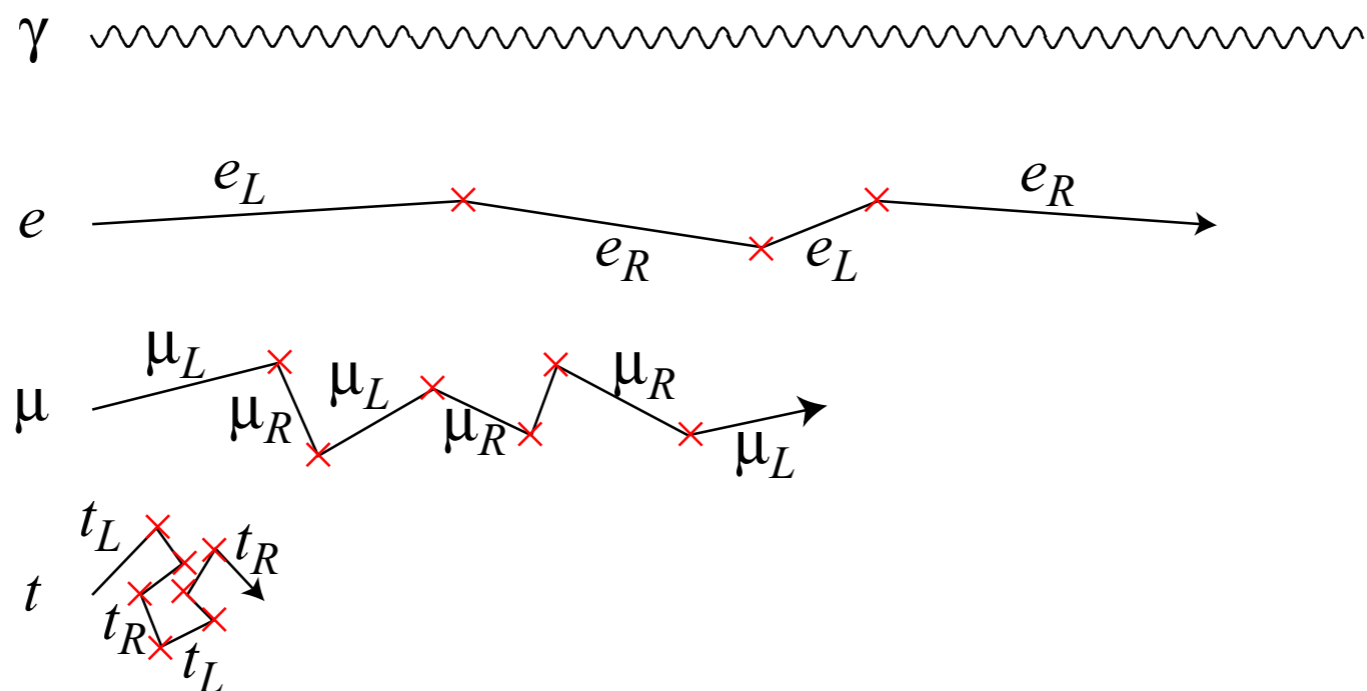
In a superconductor, electrons pairs condense and give mass to the photon.

Charged object fills space not allowing photon to propagate.



HIGGS MECHANISM

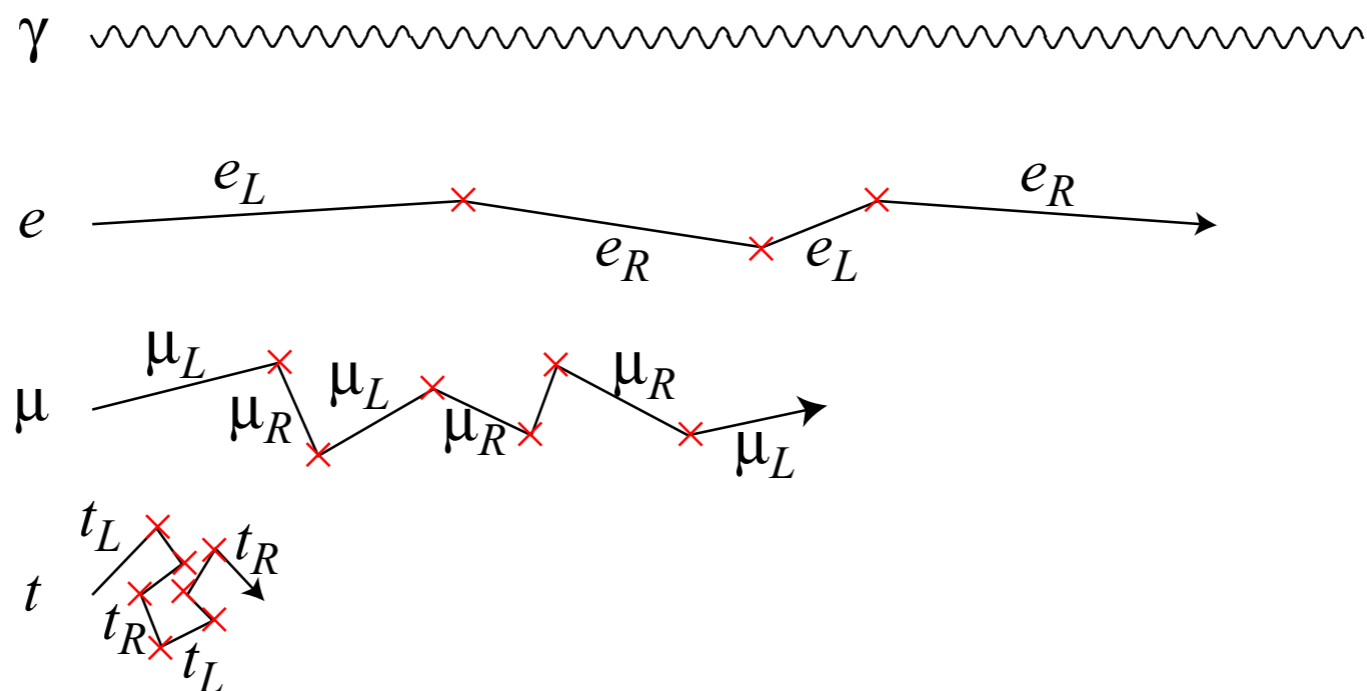
Entire universe is a superconductor, condensate of something that talks to fermions, W, Z but not photon.



Anderson, 1963

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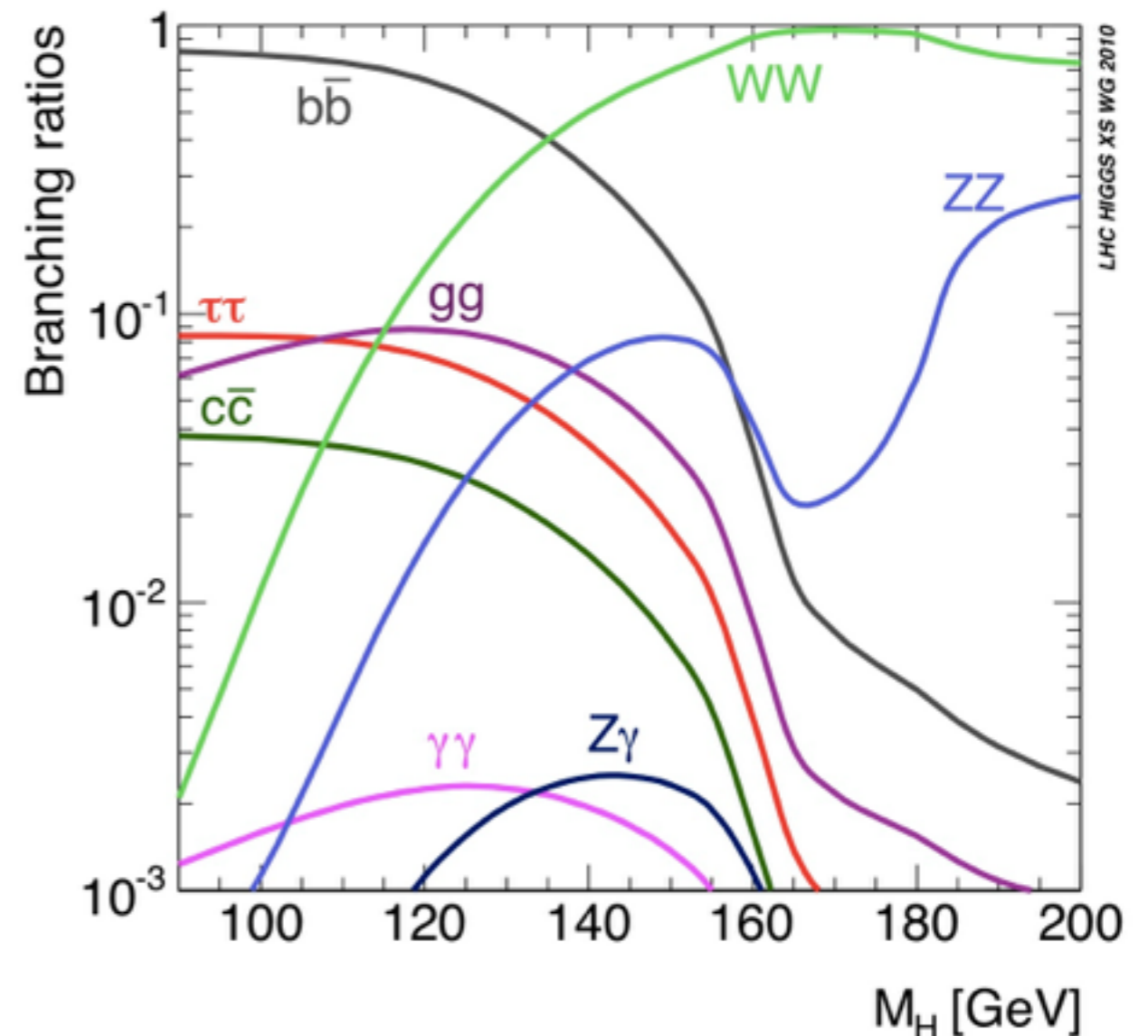
One model is an elementary scalar field proposed by Brout, Englert, Higgs and others.

HIGGS BOSON?

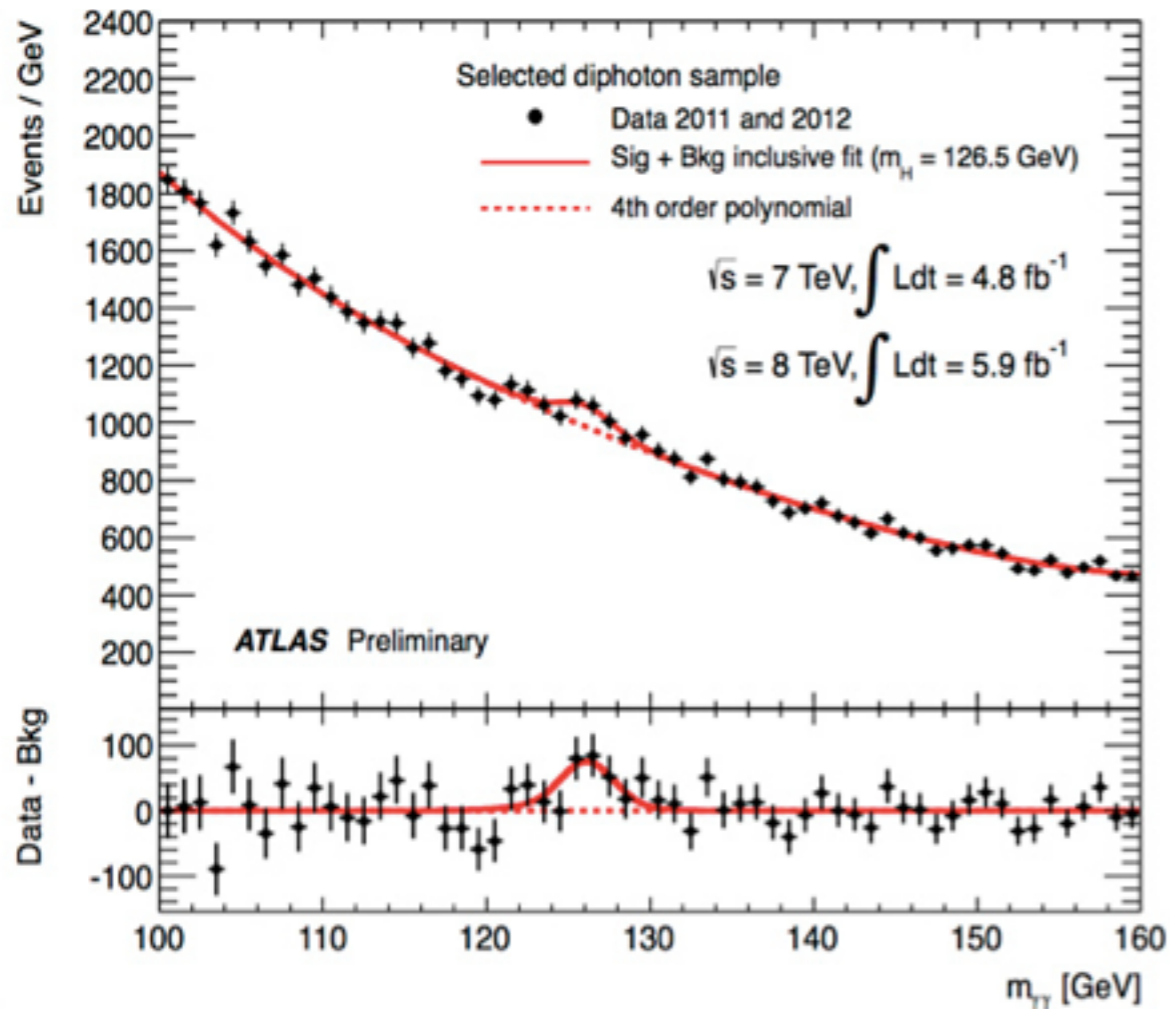
Simple model by Higgs et. al. predicts new particle.

All properties of particle dictated by symmetry.

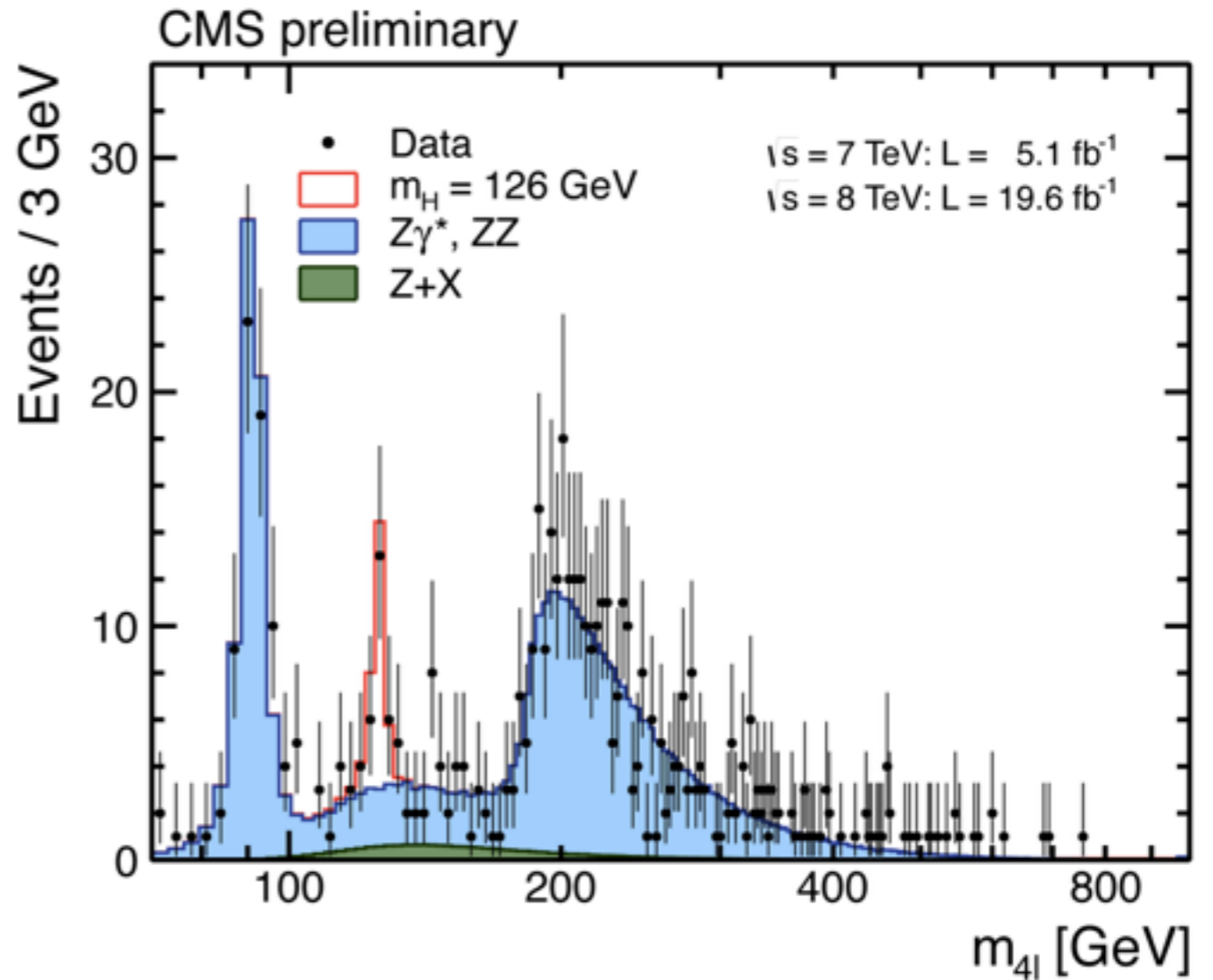
Know exactly how to find it...if it exists.



A NEW PARTICLE



$$h \rightarrow \gamma\gamma$$



$$h \rightarrow 4e/4\mu/2e2\mu$$

**IS IT THE
HIGGS?**

DISCOVERY MODES

$$h \rightarrow \gamma\gamma$$

$$h \rightarrow 4e/4\mu/2e2\mu$$

All final states are light!

Higgs is supposed to be responsible for mass...

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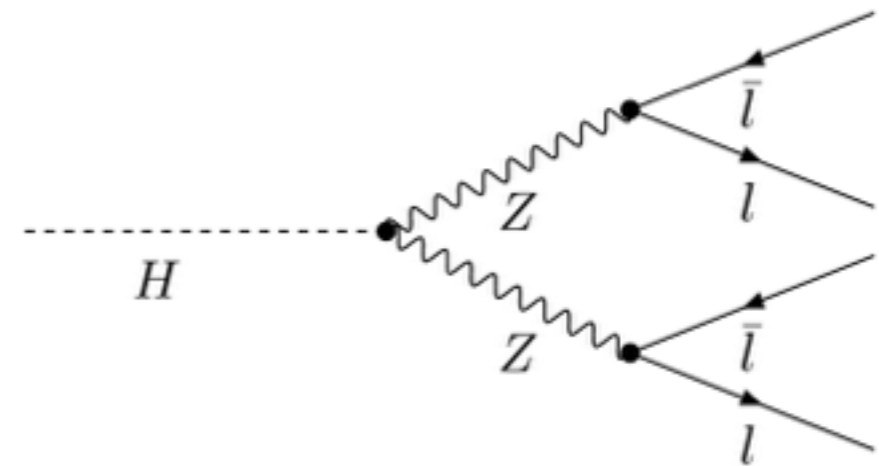
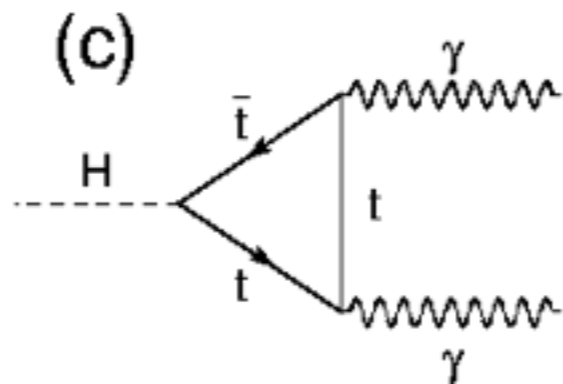
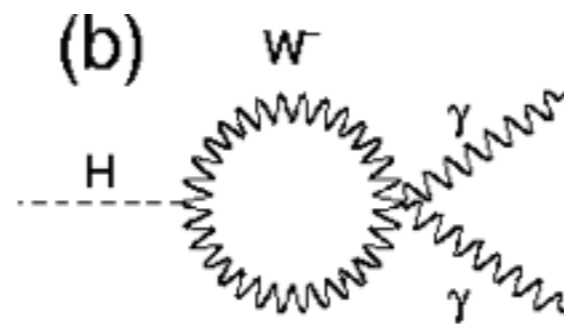
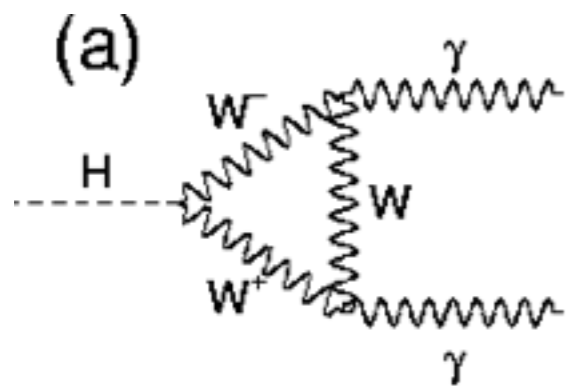
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Quantum mechanics: can have virtual particle creation.

DISCOVERY MODES

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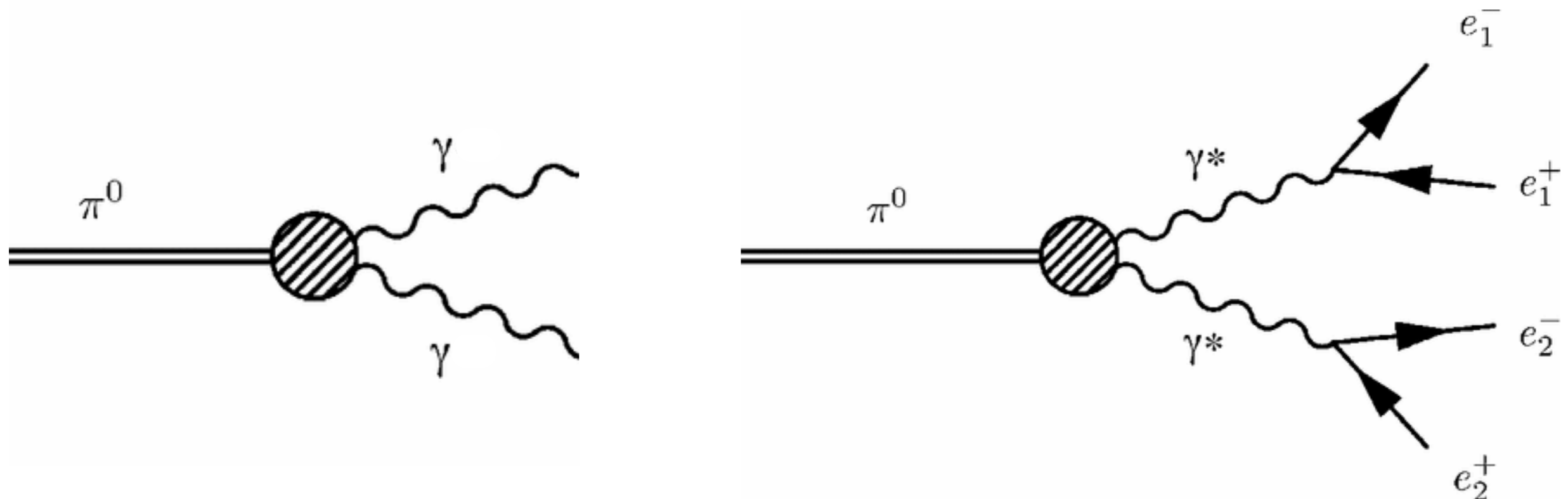
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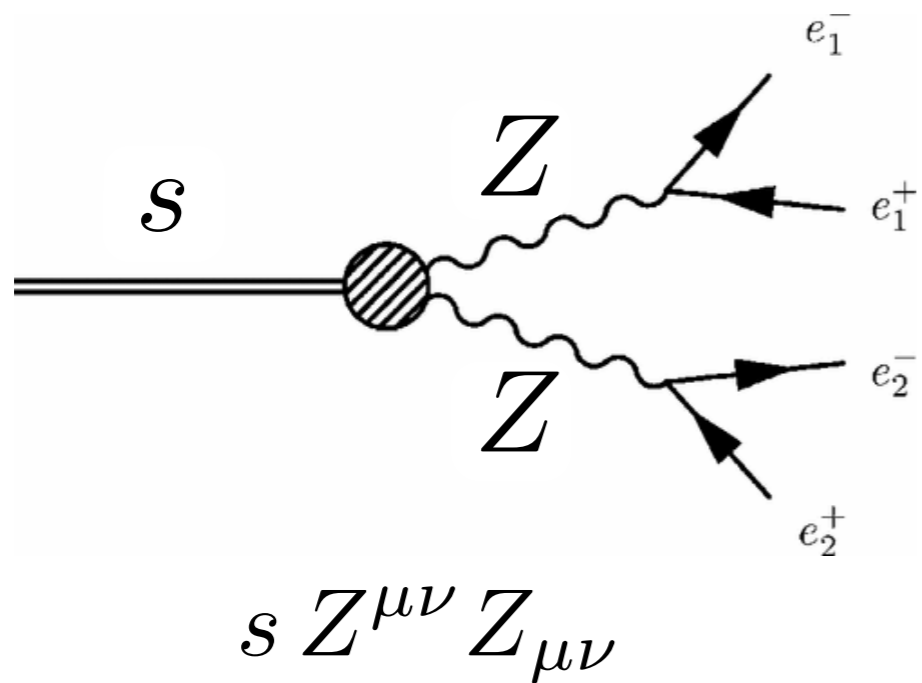
IS IT THE HIGGS?

Consistent with the Higgs, but could also be something else.

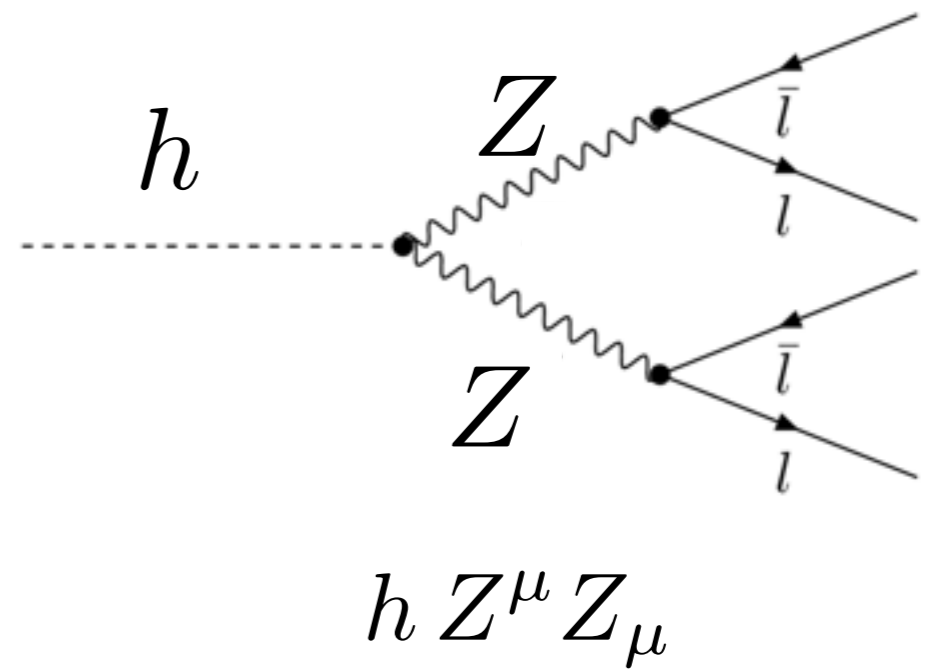
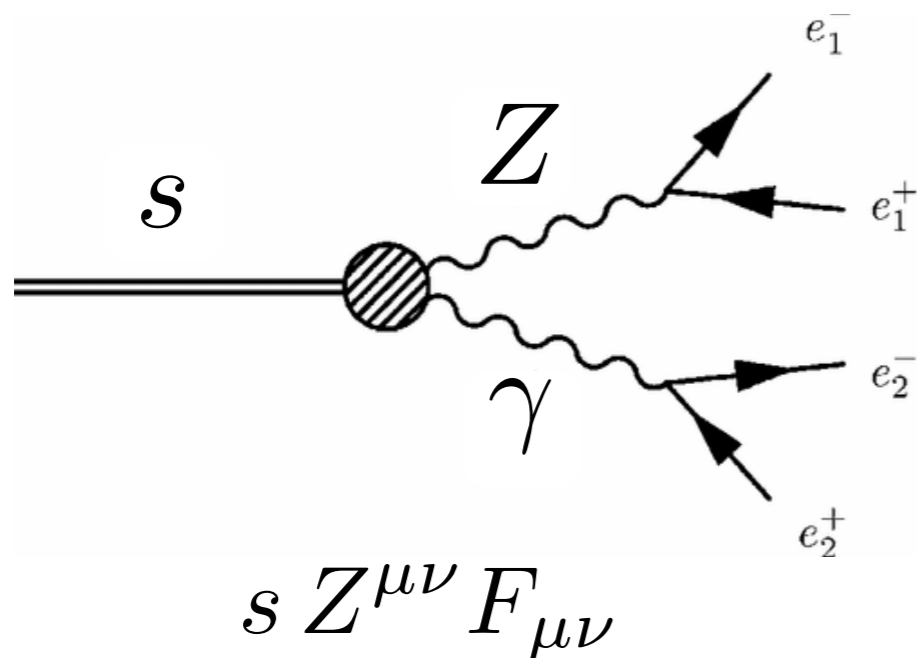
Neutral pion decays to two photons *and* four electrons, but its not a universe-wide superconductor.



IS IT THE HIGGS?



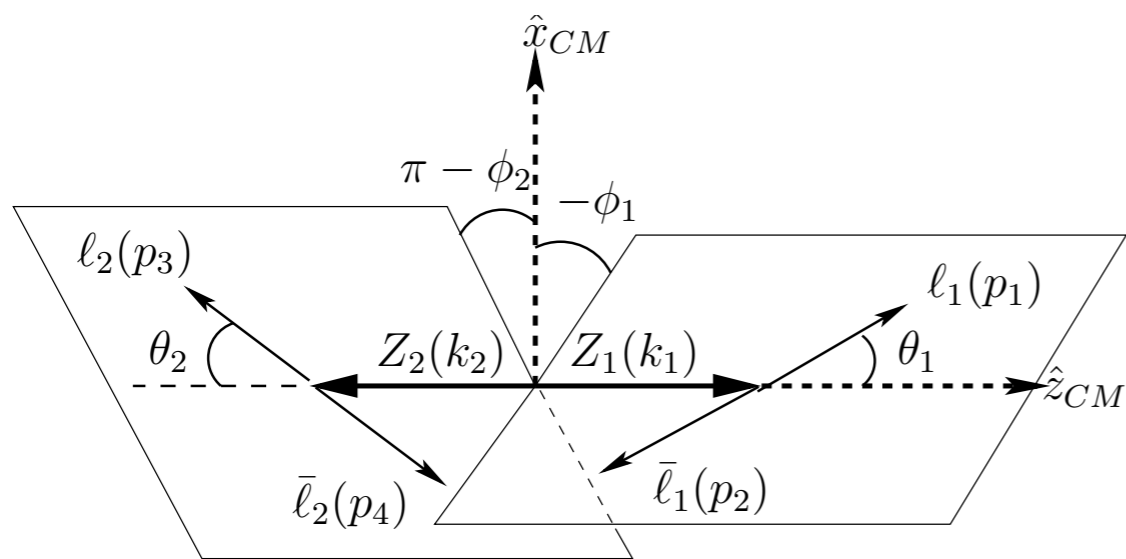
OR



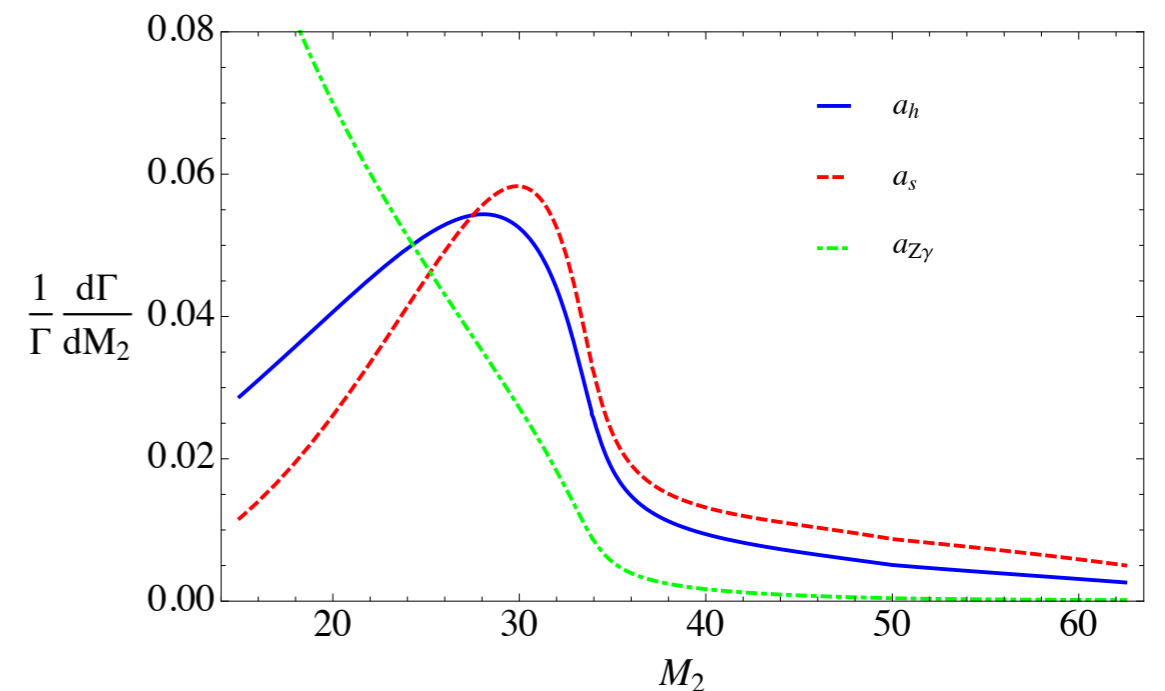
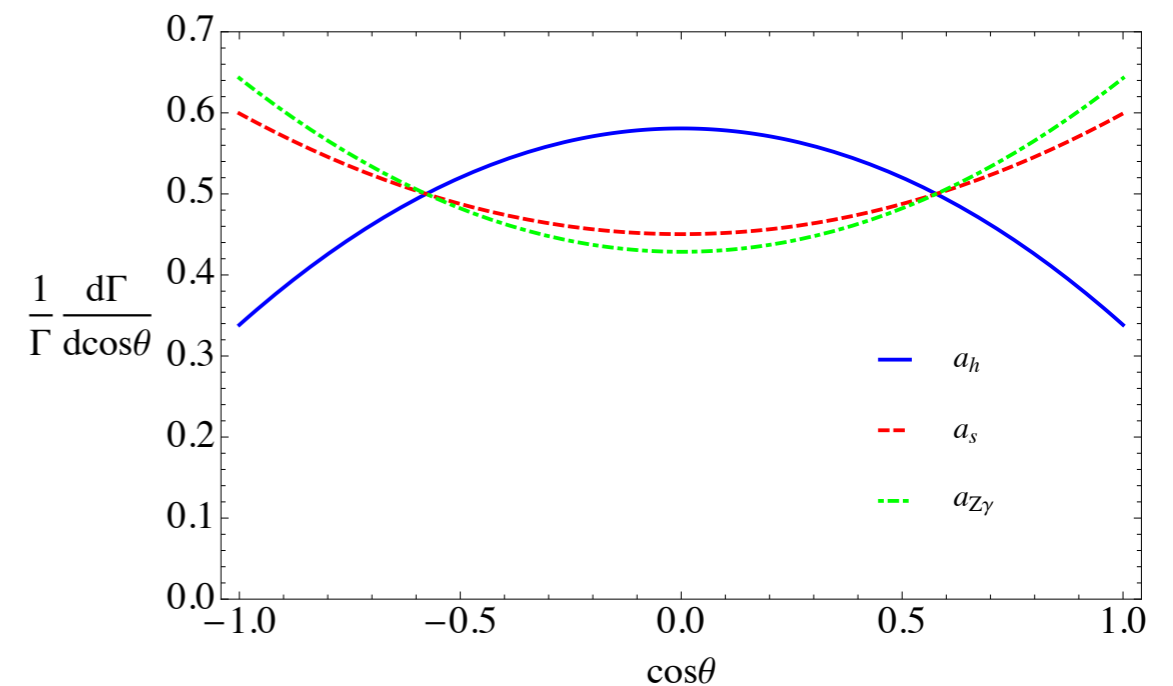
KINEMATIC DISTRIBUTIONS

Study $h \rightarrow 4e/4\mu/2e2\mu$

Each event is characterized by five different variables.



DS, R. Vega-Morales, Phys.Rev.D.86, 117504 (2012) [arXiv:1208.4840].

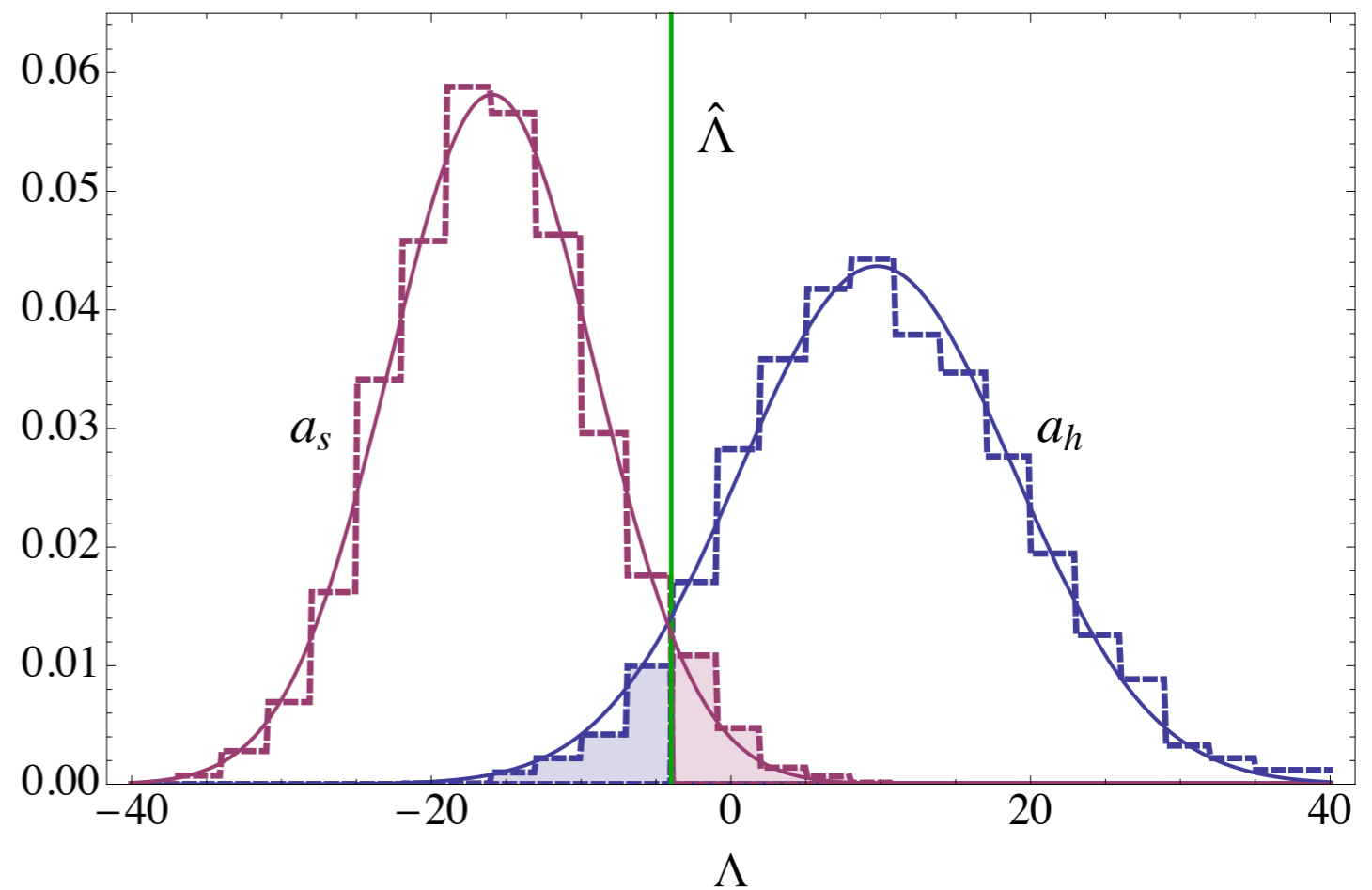


STATISTICAL DISCRIMINATION

Can construct test to distinguish different hypotheses.

DS, R. Vega-Morales,
Phys.Rev.D.86, 117504 (2012)
[arXiv:1208.4840].

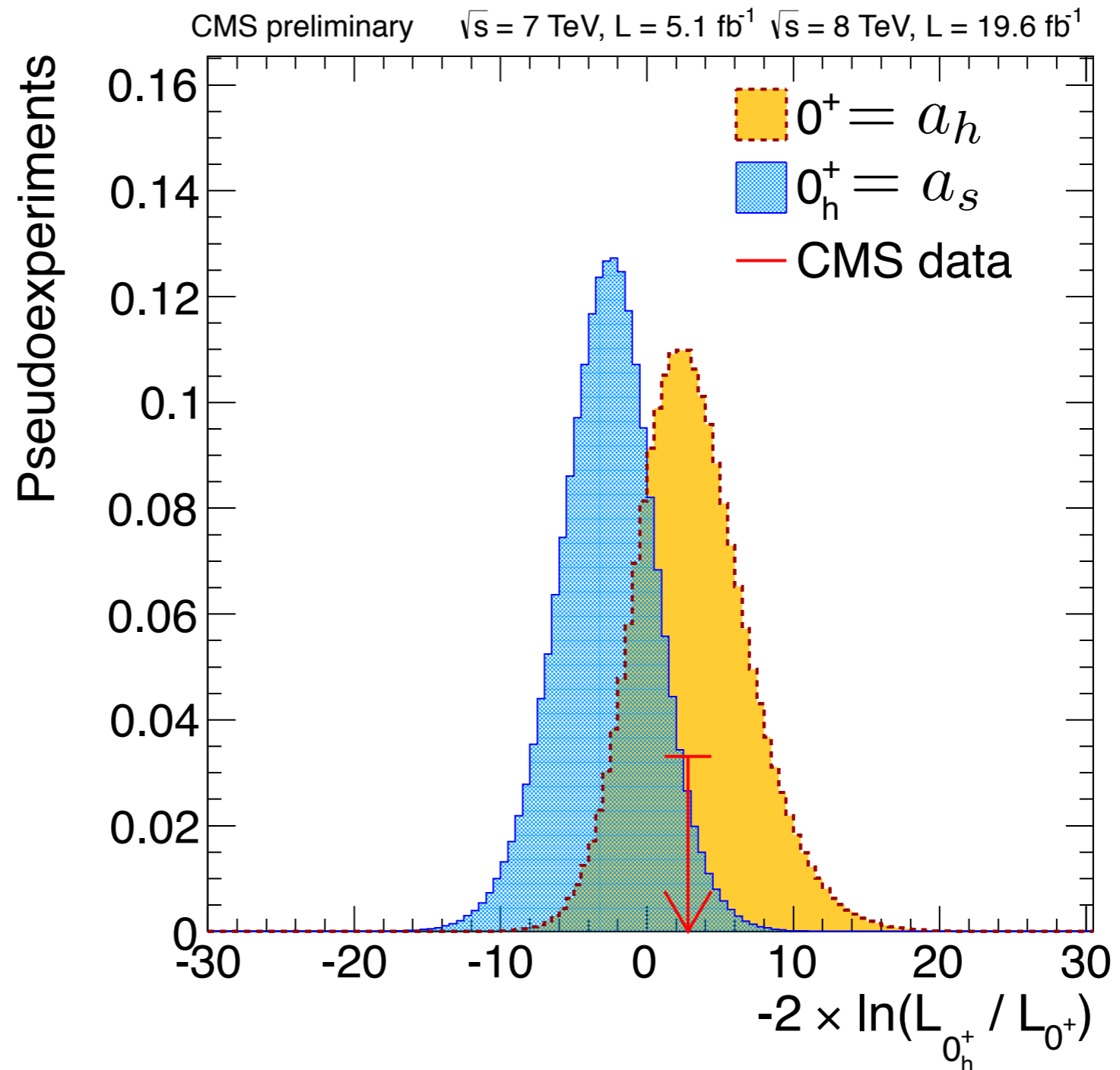
Example for 50 events:



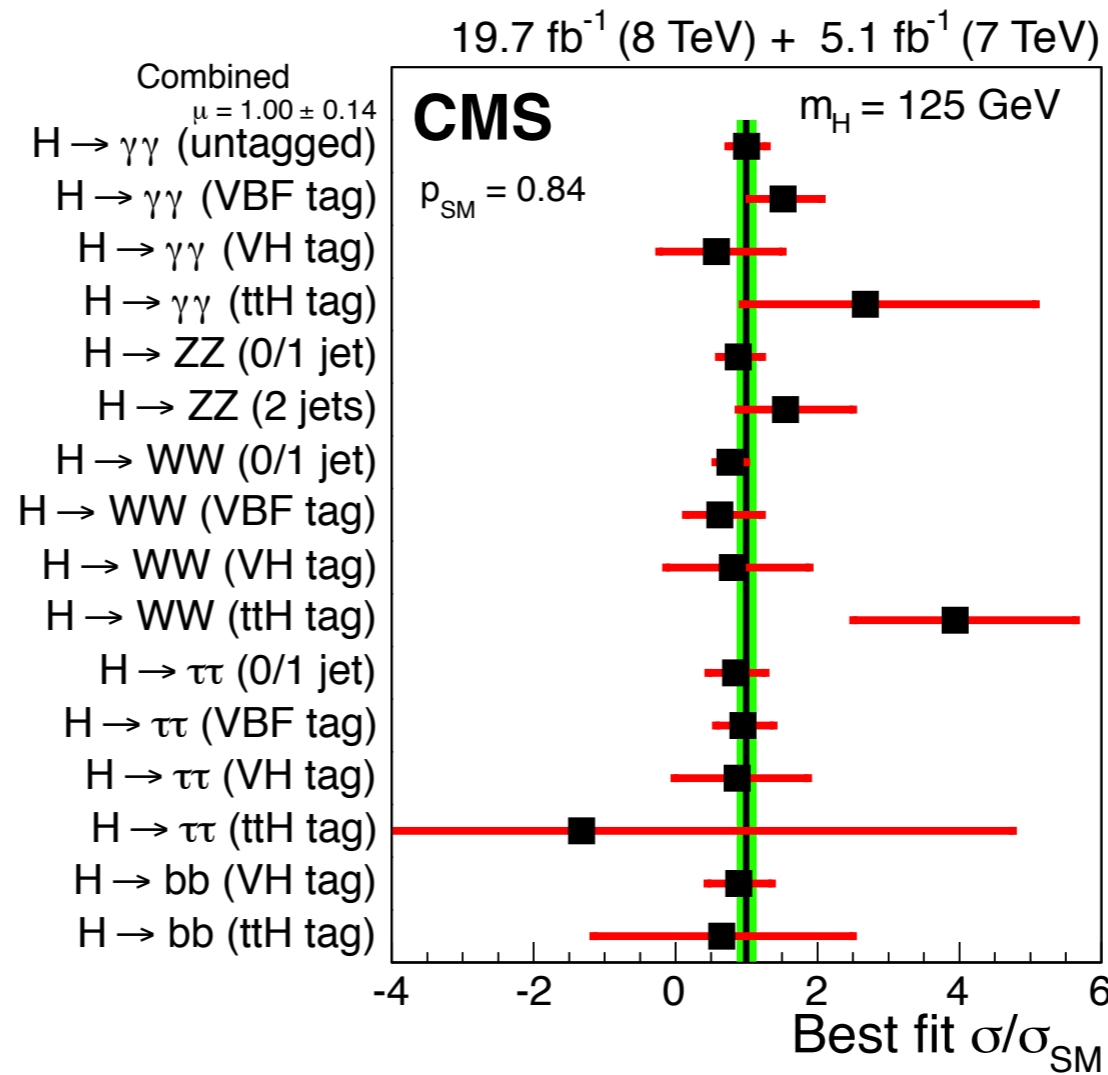
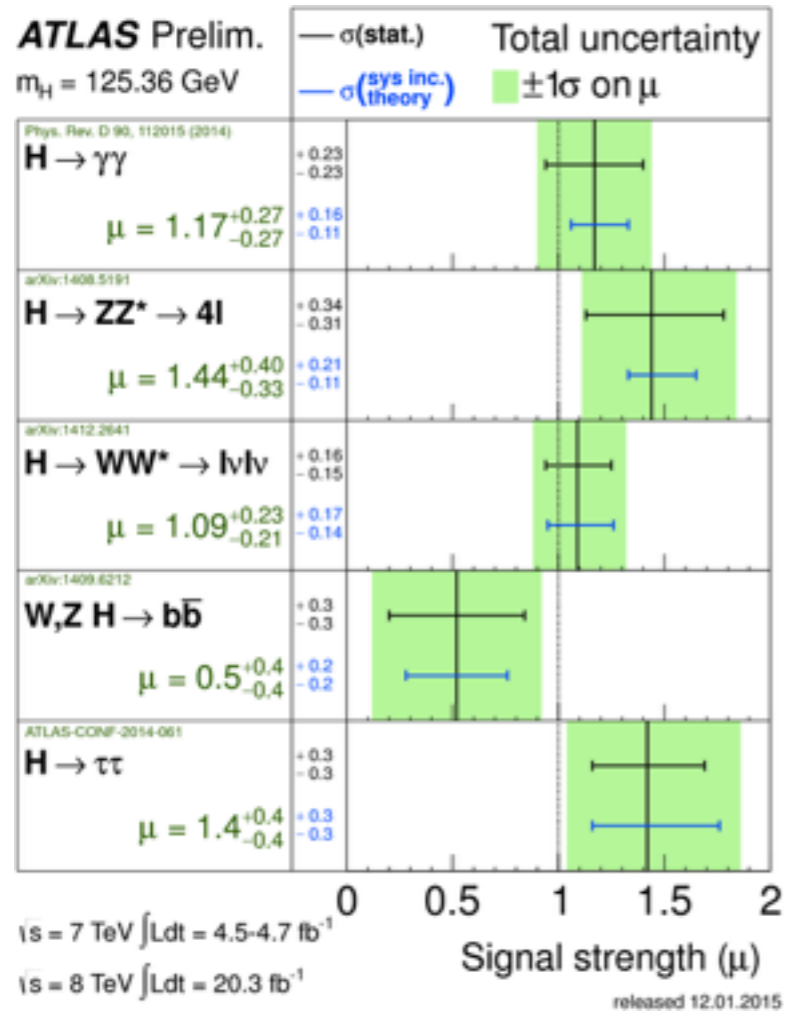
$$\Lambda = 2 \log[\mathcal{L}(a_1) / \mathcal{L}(a_2)]$$

DATA

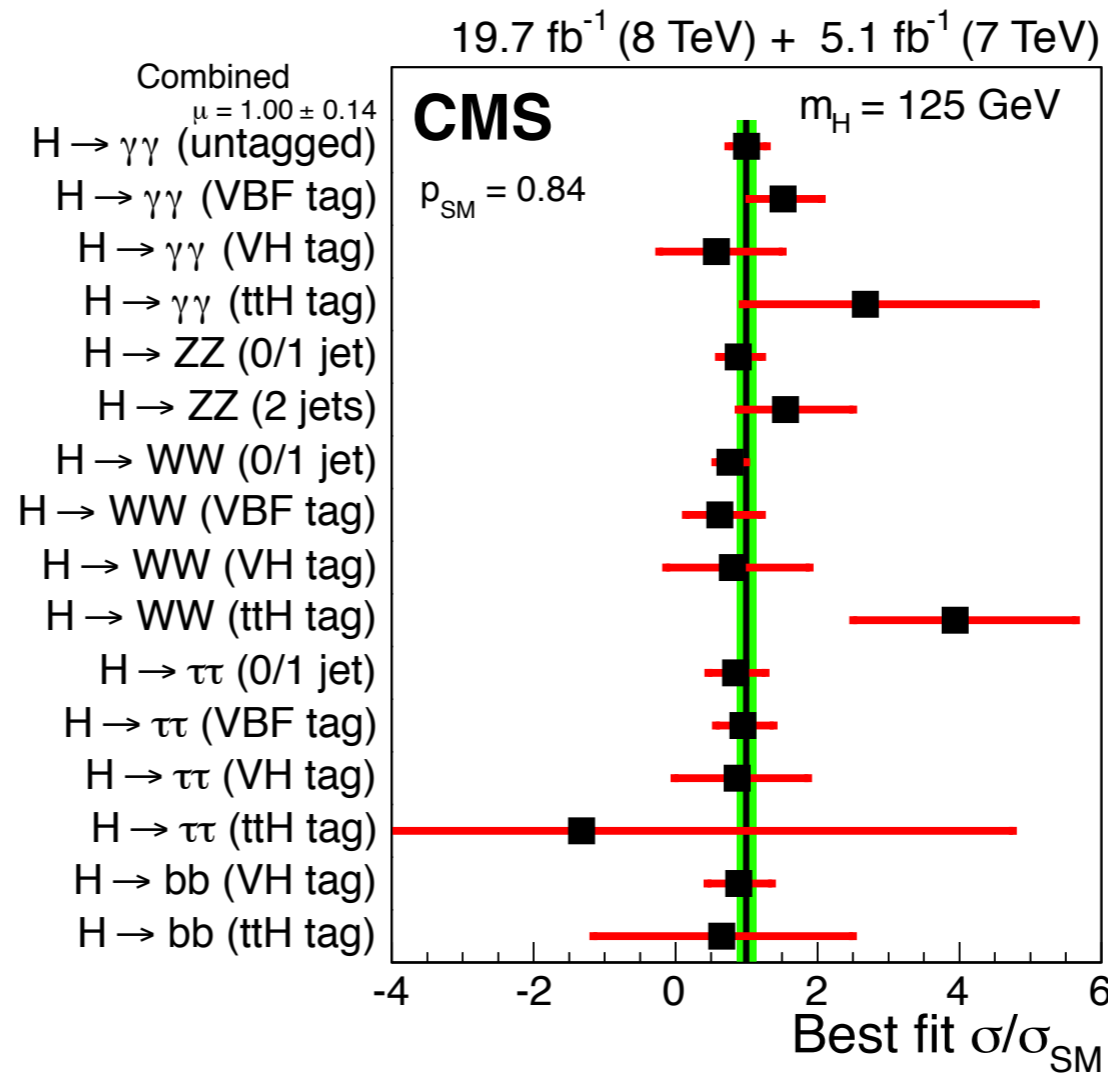
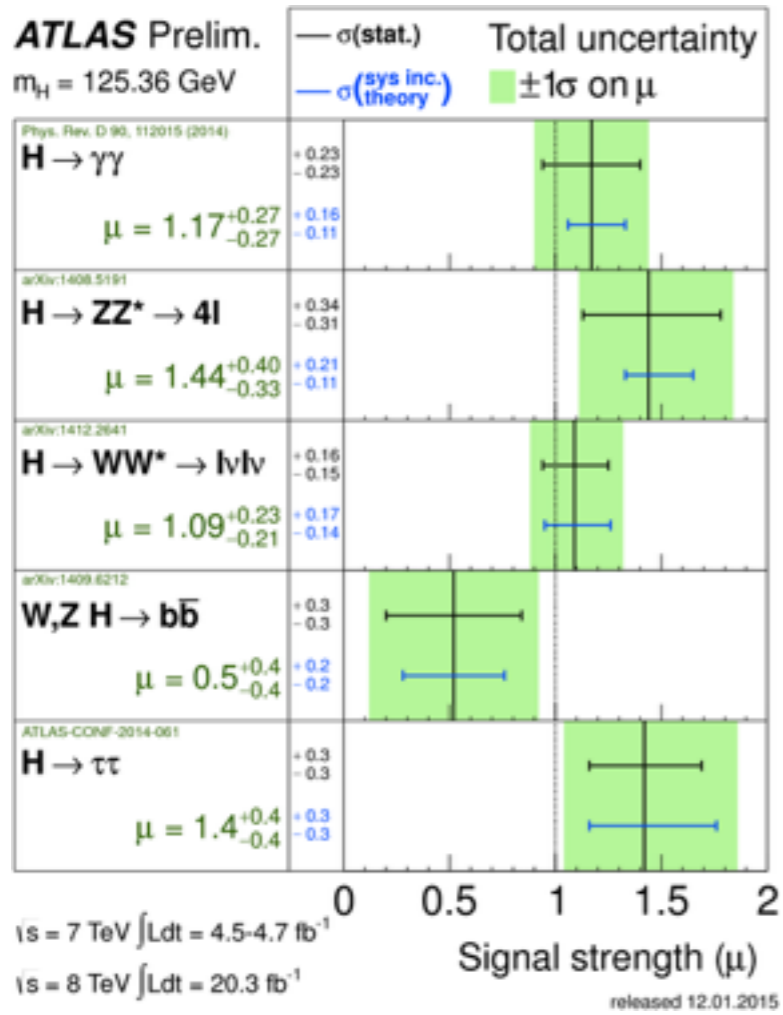
Evidence for the Higgs:



DATA



DATA



ARE WE DONE?

All Standard Model parameters are now known.
Are we just left with measuring them more precisely?

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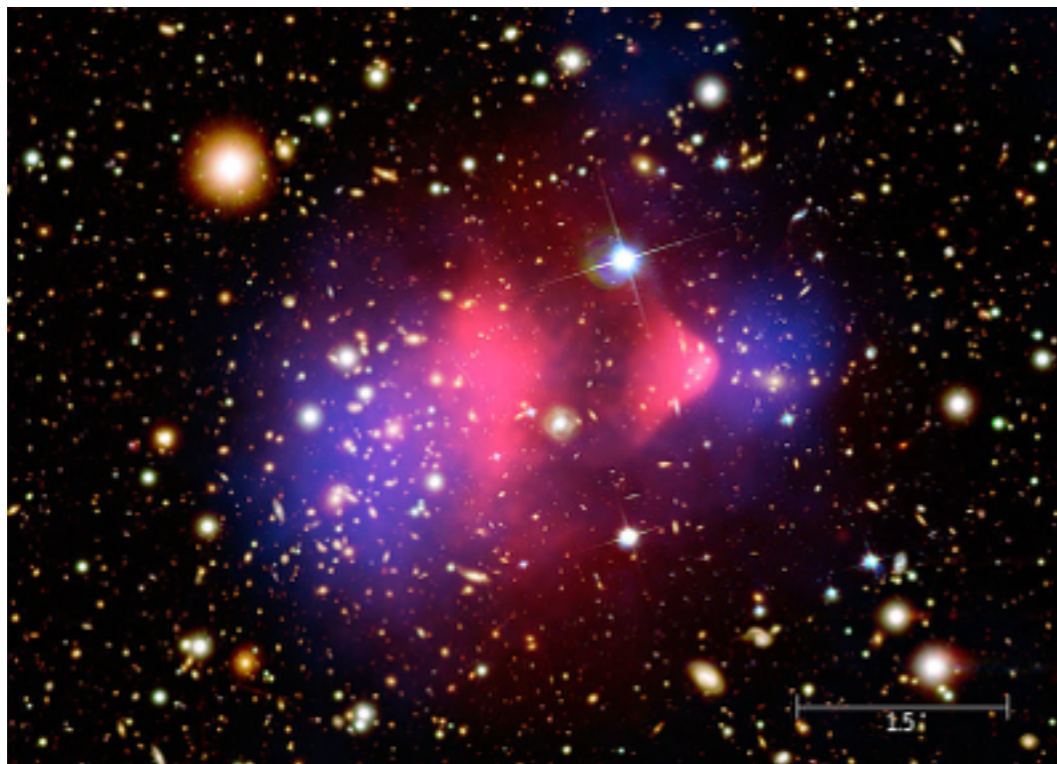
NO! The SM cannot explain:

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NO! The SM cannot explain:

- Dark Matter

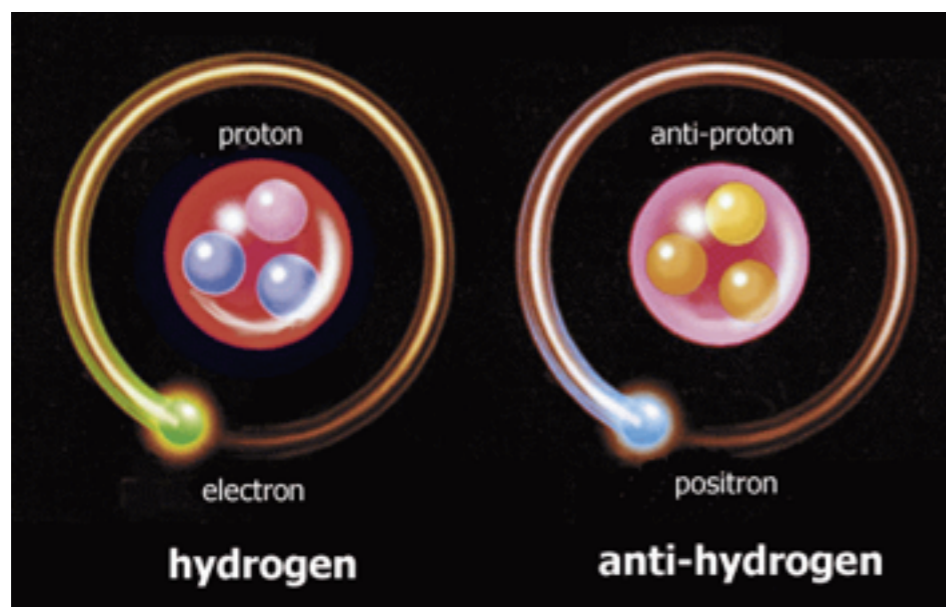


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- Neutrino mass
- Inflation
- Unification of forces

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NO! The SM cannot explain:

- Dark Matter
- Matter antimatter asymmetry of the universe
- Neutrino mass
- Inflation
- Unification of forces
- Unknown unknowns?

THE HIERARCHY PROBLEM

WHY IS GRAVITY SO WEAK?

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WHY IS GRAVITY SO WEAK?

Dinky little magnet
can overcome force of
entire earth!



PUZZLE



Balance: \$74



PUZZLE



Balance: \$74



$\$52 + \22

PUZZLE



Balance: \$74

\$107 - \$33

PUZZLE



Balance: \$74

\$913 - \$839

PUZZLE

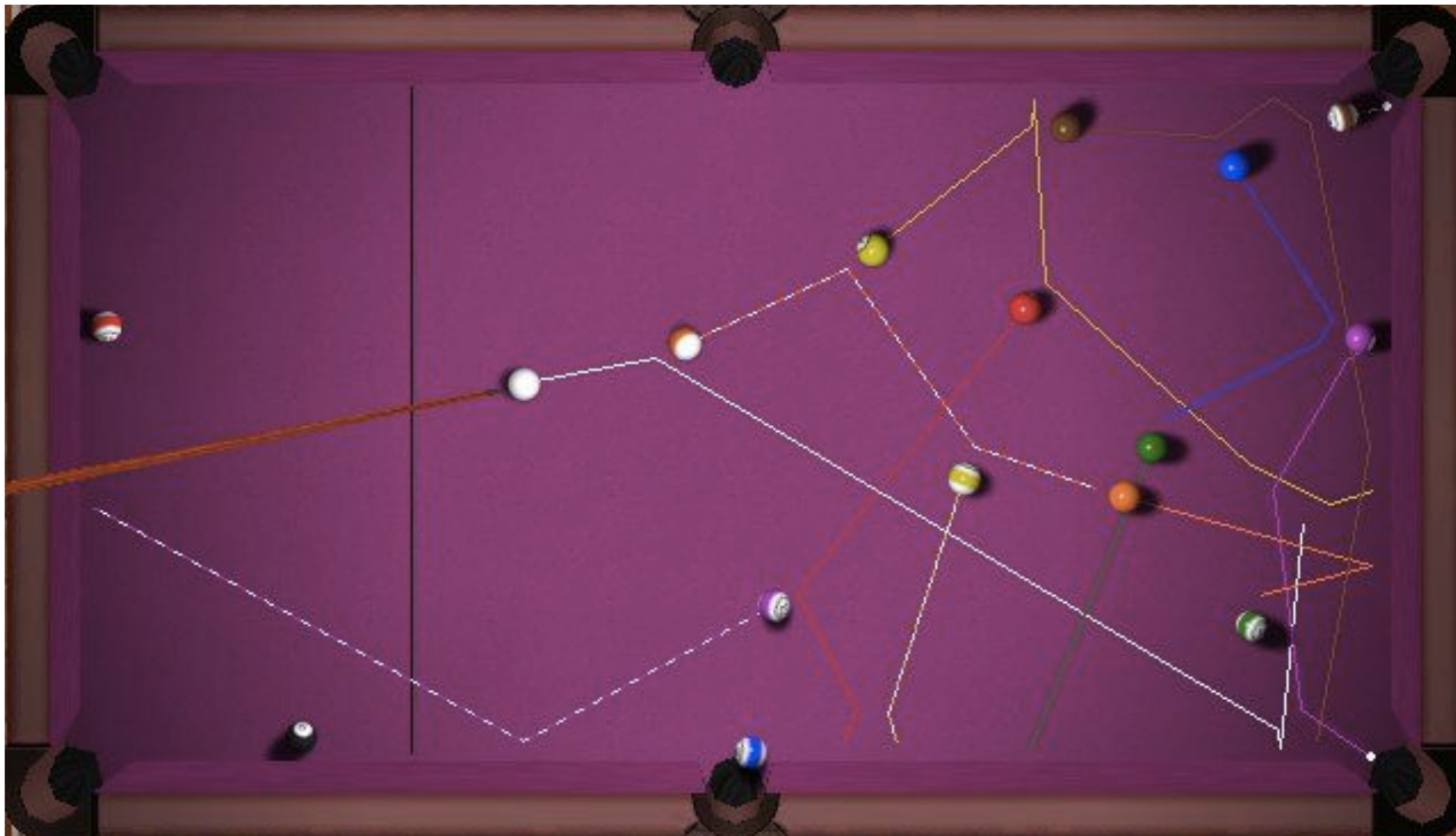


Balance: \$74

$\$829,375,293 - \$829,375,219$

DECOUPLING

We can calculate everything in this picture.



DECOUPLING

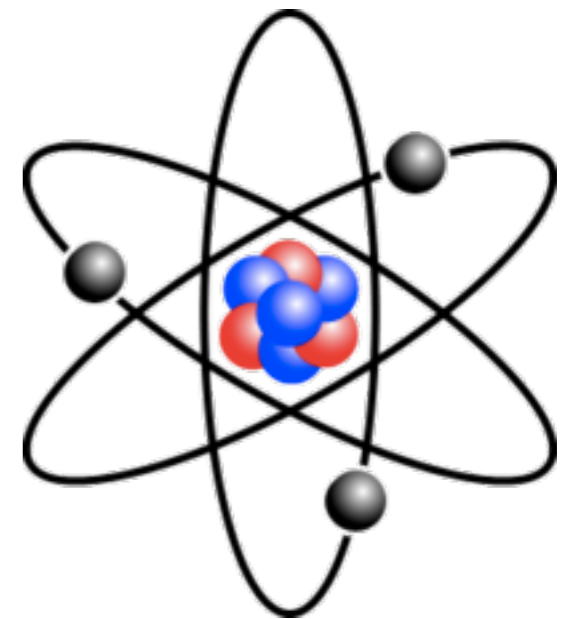
Do we have to worry about vibration of atoms in the ball? Rotation of the earth?

No...physics of different length scales decouple.

Size of effect

$$\left(\frac{R_{\text{atom}}}{R_{\text{ball}}} \right)$$

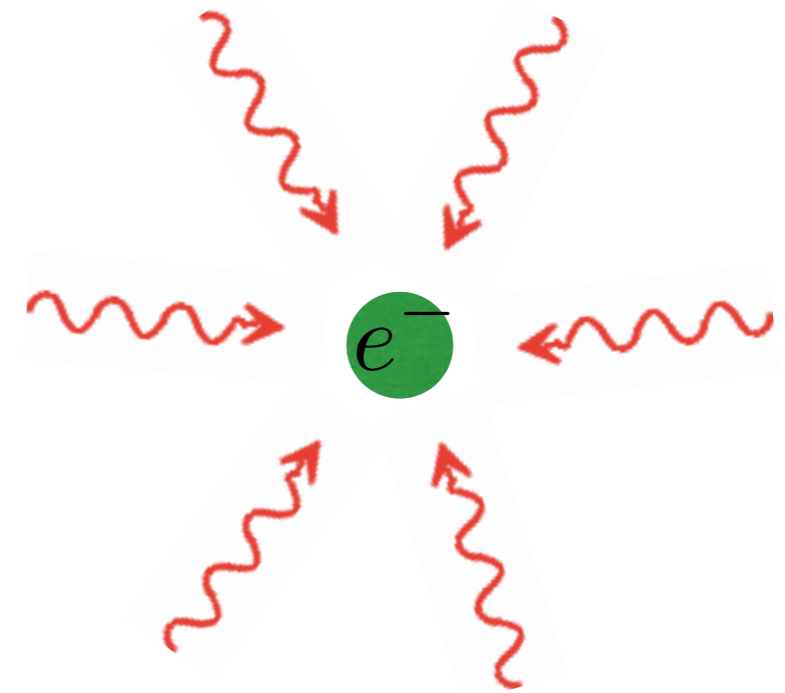
$$\left(\frac{R_{\text{ball}}}{R_{\text{earth}}} \right)$$



HISTORICAL ANALOGY

Electron has classical self energy.

$$E_{\text{self}} \sim \frac{1}{4\pi\epsilon_0} \frac{e^2}{r_e}$$

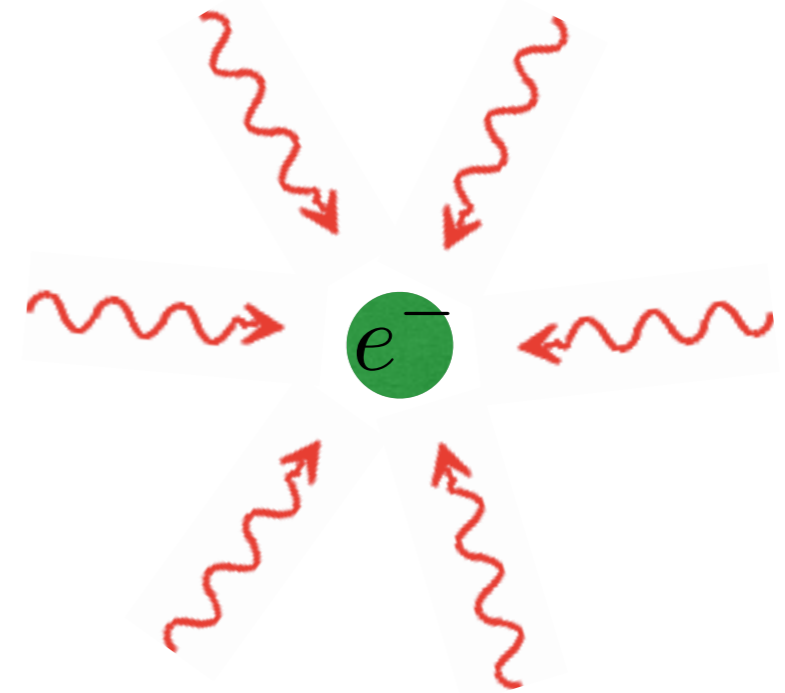


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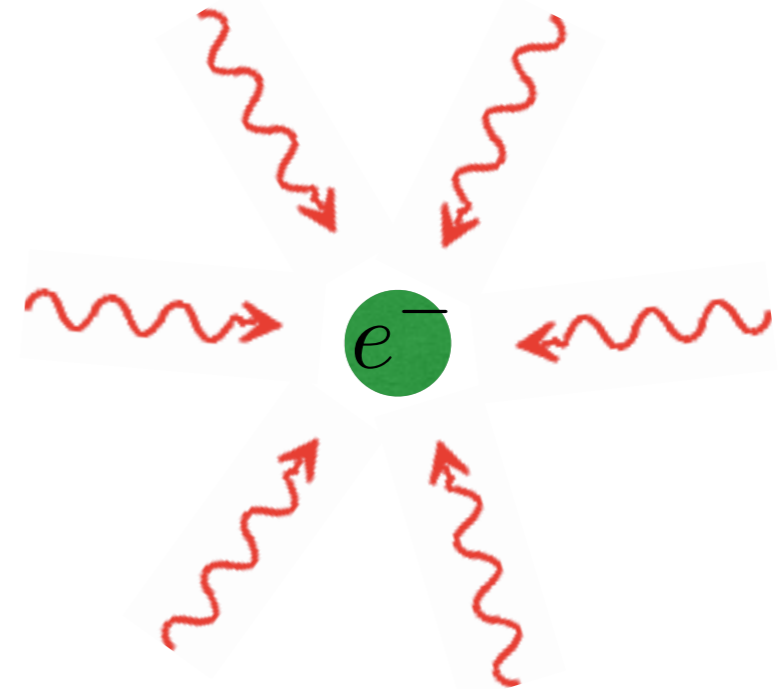


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Problem for $r < 4$ fm, well above current maximum size.

Energy (mass) is sensitive to short distance (high energy).

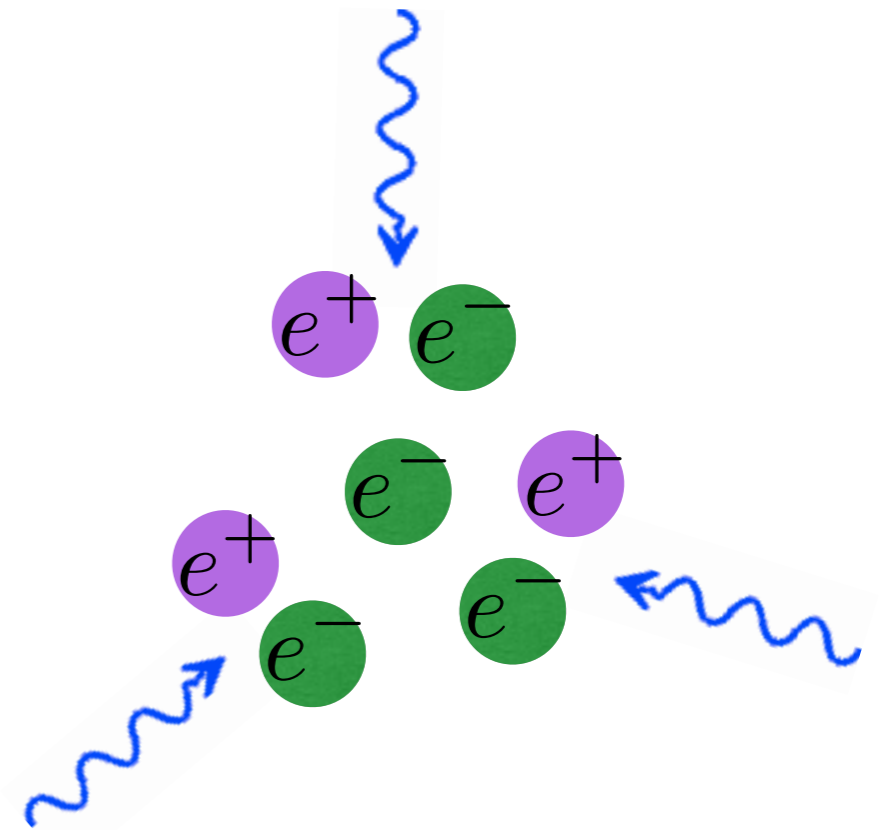
HISTORICAL ANALOGY

At high energy, start to see electron-positron pairs.

$$E_{\text{self}} \sim \frac{e^2}{4\pi\epsilon_0} \frac{m_e c}{\hbar} \log \left(\frac{m_e c r_e}{\hbar} \right)$$

Only log-sensitive to actual radius.

New particle (positron) comes in and saves separation of scales.

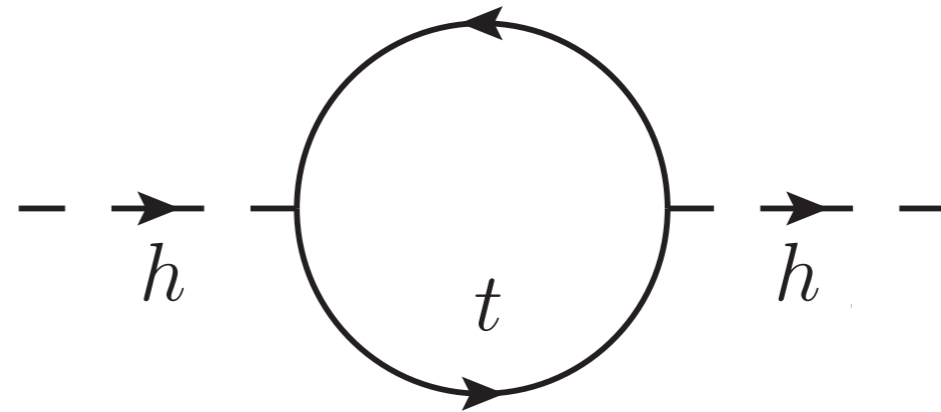


HIGGS SELF ENERGY

Higgs self-energy sensitive to high energy scale.

$$E_{\text{self}} \sim \frac{y}{2\pi} \Lambda$$

High energy scale

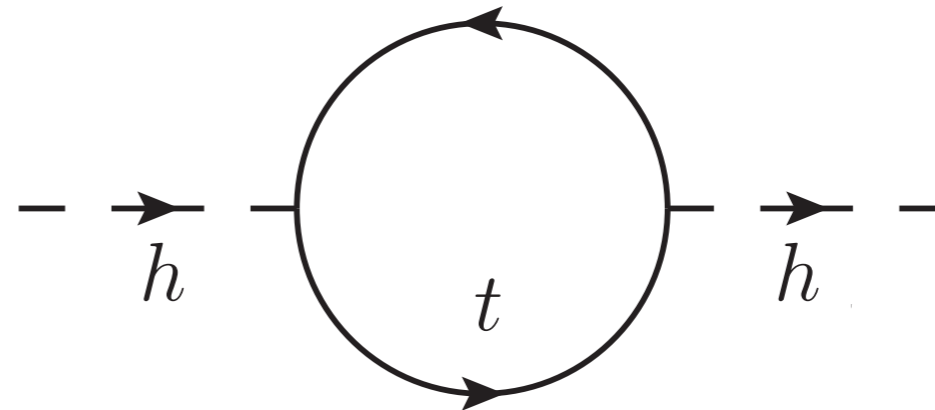


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High energy scale



$$\begin{aligned} & 15,270,932,974,520,497,610,934,762,105,716 \\ - & \underline{15,270,932,974,520,497,610,934,762,105,714} \end{aligned}$$

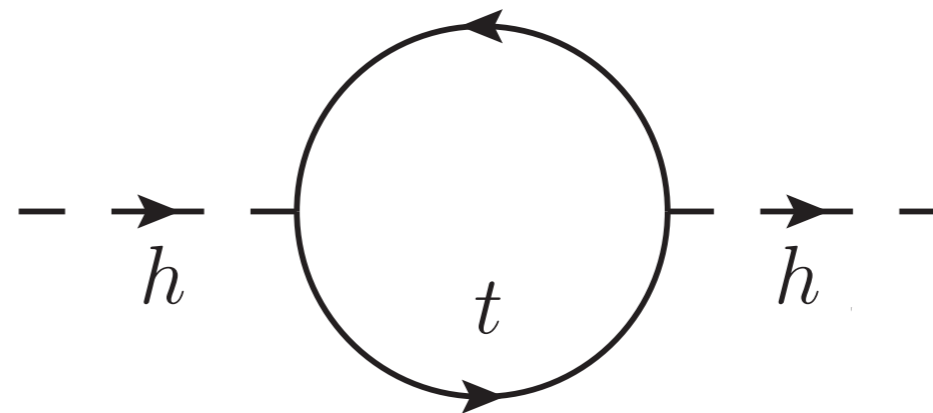
2

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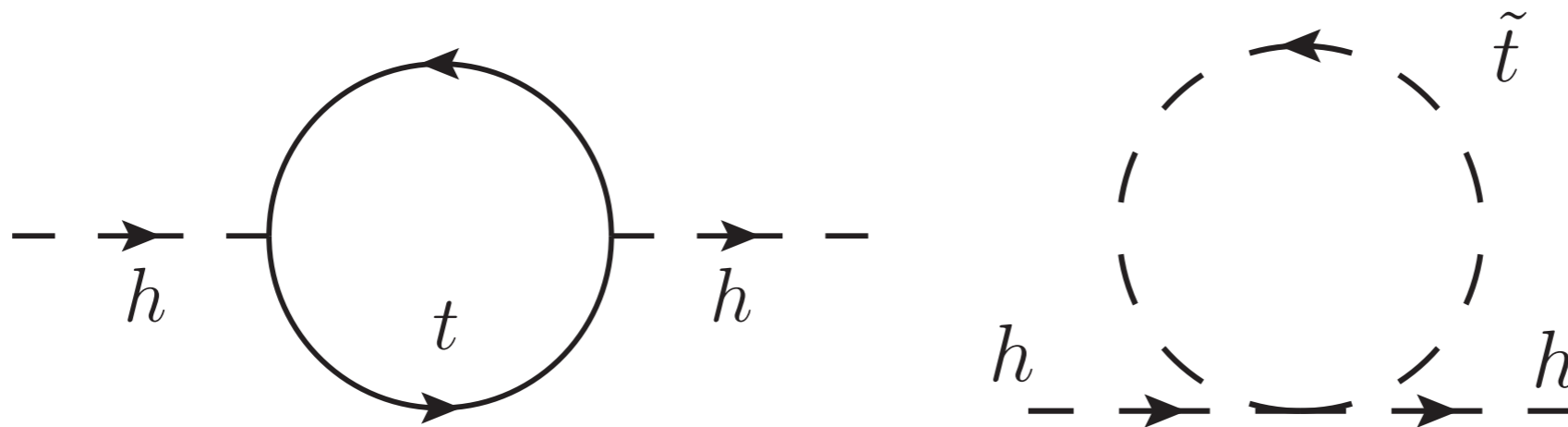
$$\begin{array}{r} 15,270,932,974,520,497,610,934,762,105,716 \\ - 15,270,932,974,520,497,610,934,762,105,714 \\ \hline \end{array}$$

2

Standard Model violates decoupling principle:
hierarchy problem.

CANCELLATION

Adding new particles can cancel sensitivity (to a log).



$$E_{\text{self}} \sim \frac{y}{2\pi} m_t \log(\Lambda/m_t)$$

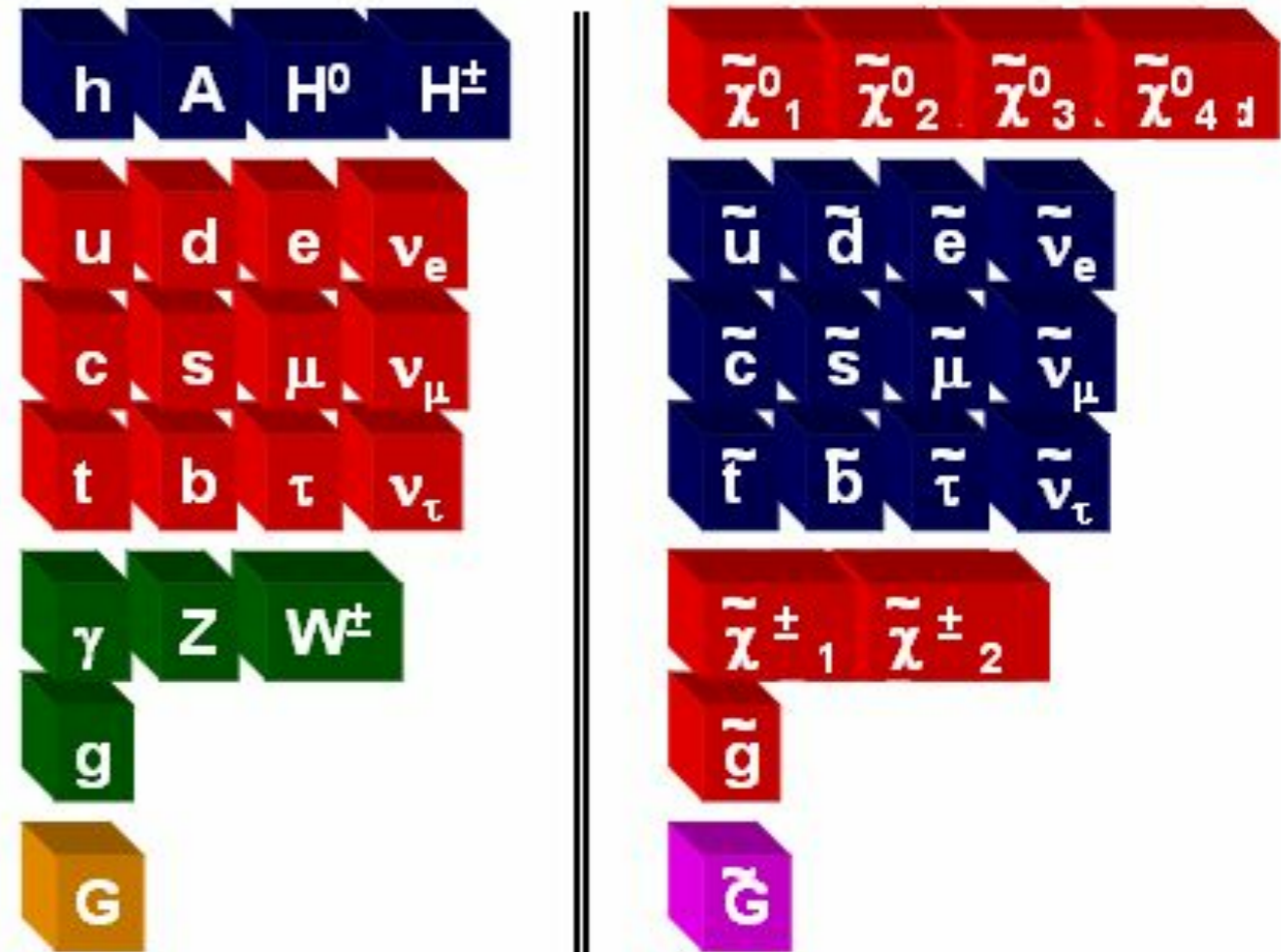
Particle has to have same gauge quantum numbers and coupling to the Higgs.

SUPERSYMMETRY

New spacetime symmetry:

Can help with dark matter and unification of forces.

Double particle content: many potential signatures.

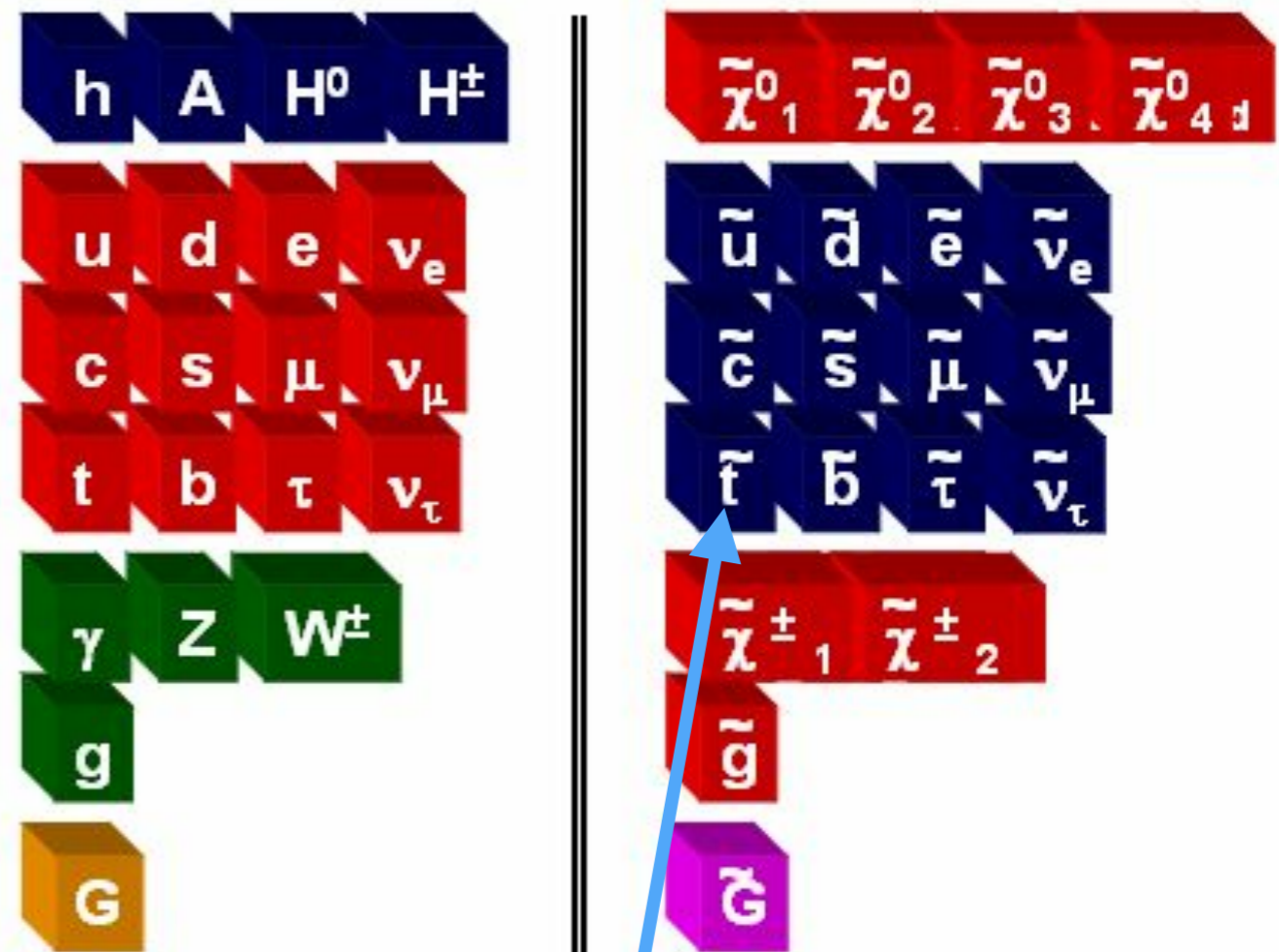


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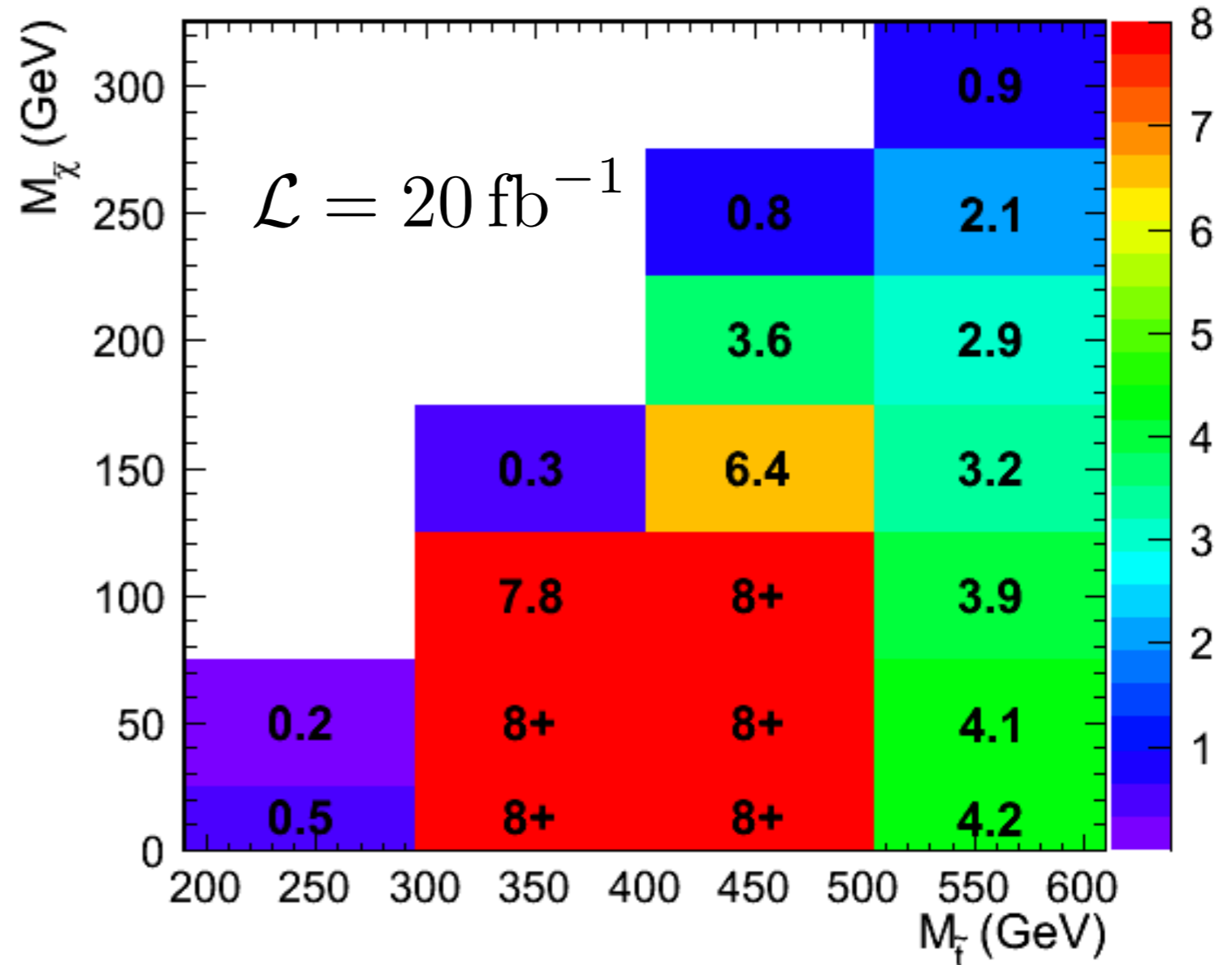


Most important for naturalness

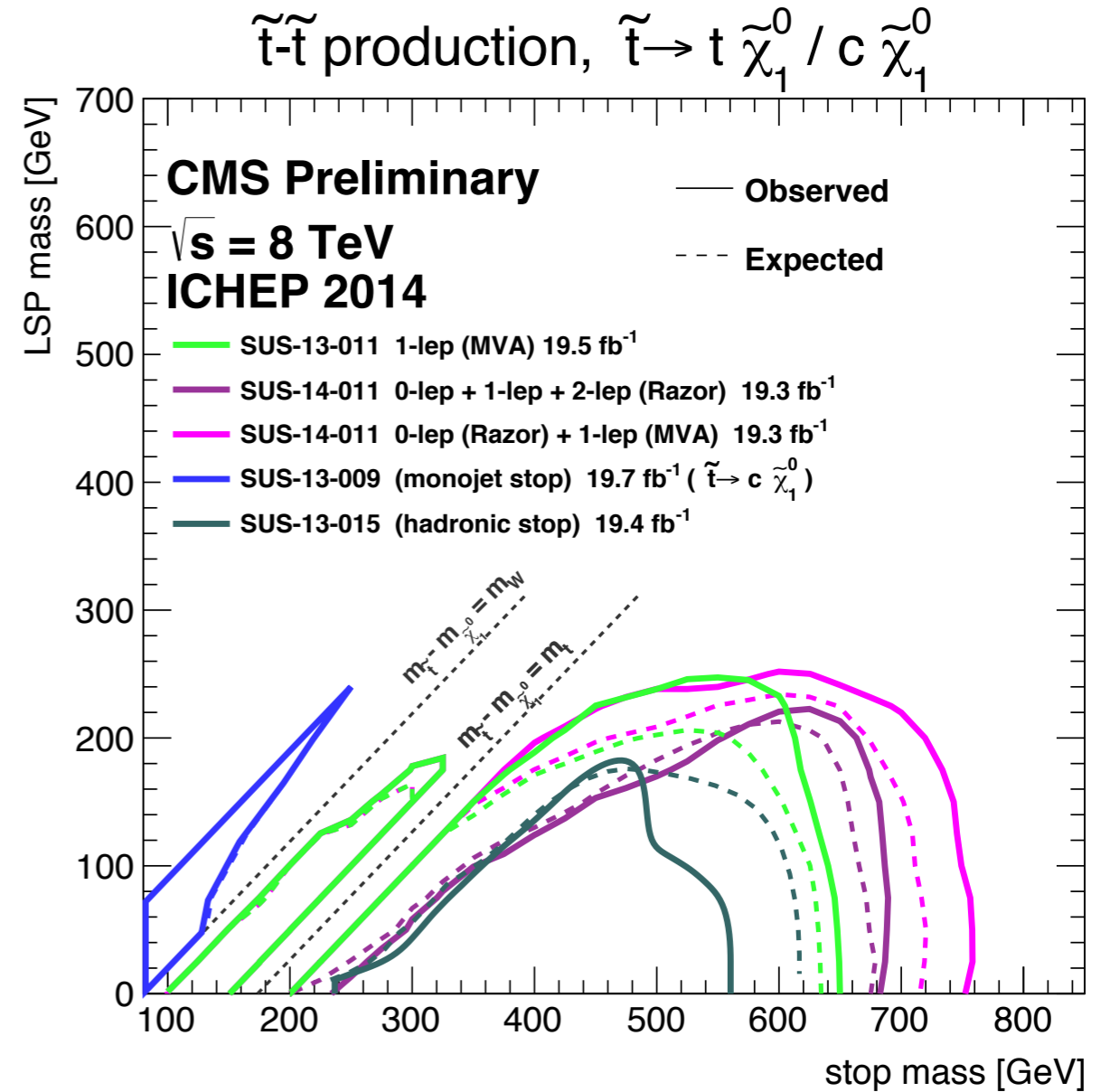
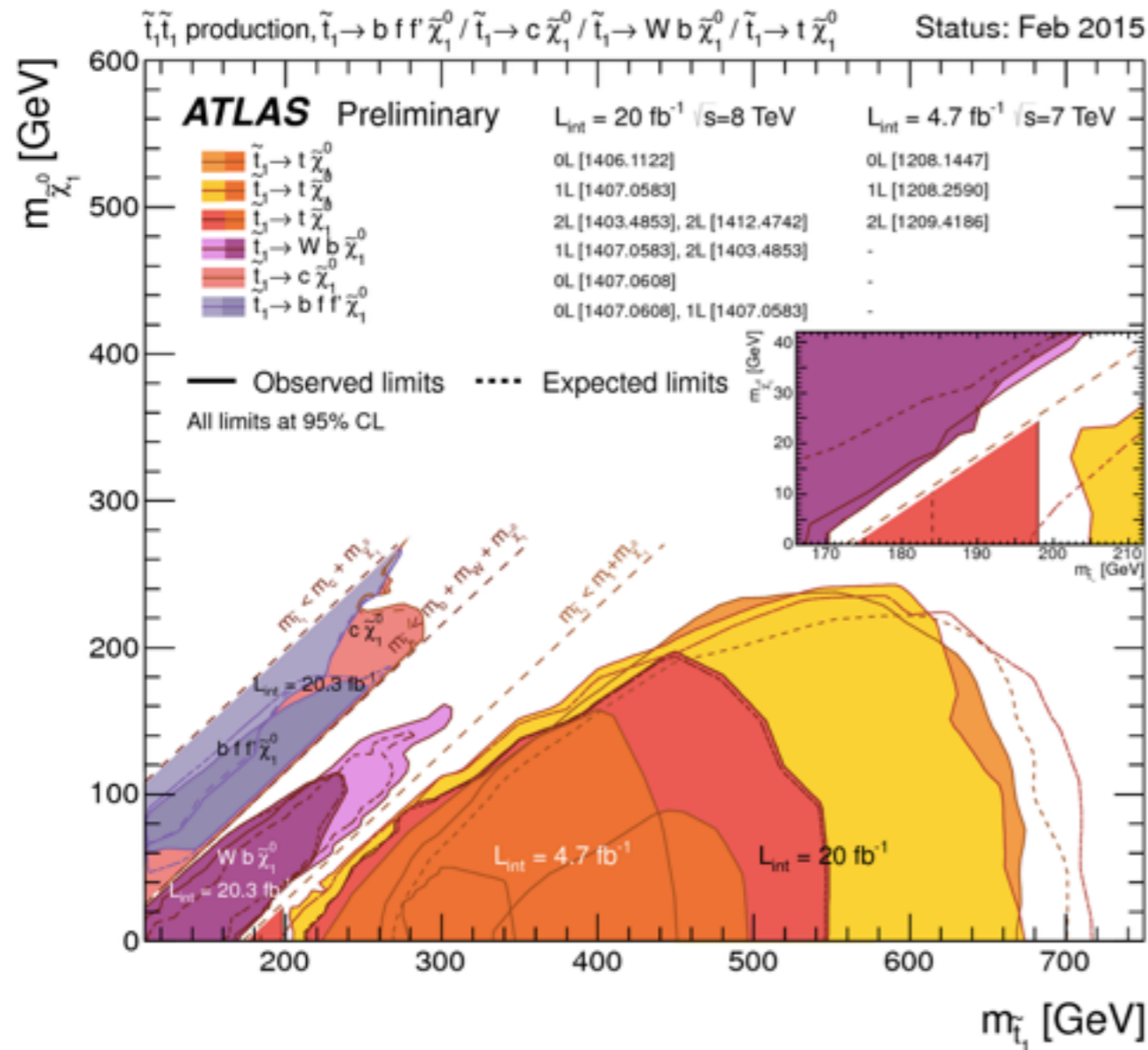
DIRECT SEARCHES

Proposed novel way
to search for stops.

D. Kaplan, K. Rehermann,
DS, JHEP 1207 (2012) 119
[arXiv:1205.5816].



NO DISCOVERY



No discovery, but our method placed strong bounds.

**DARK
MATTER**

ROTATION OF GALAXIES

How fast do stars rotate around center of a galaxy?



ROTATION OF GALAXIES

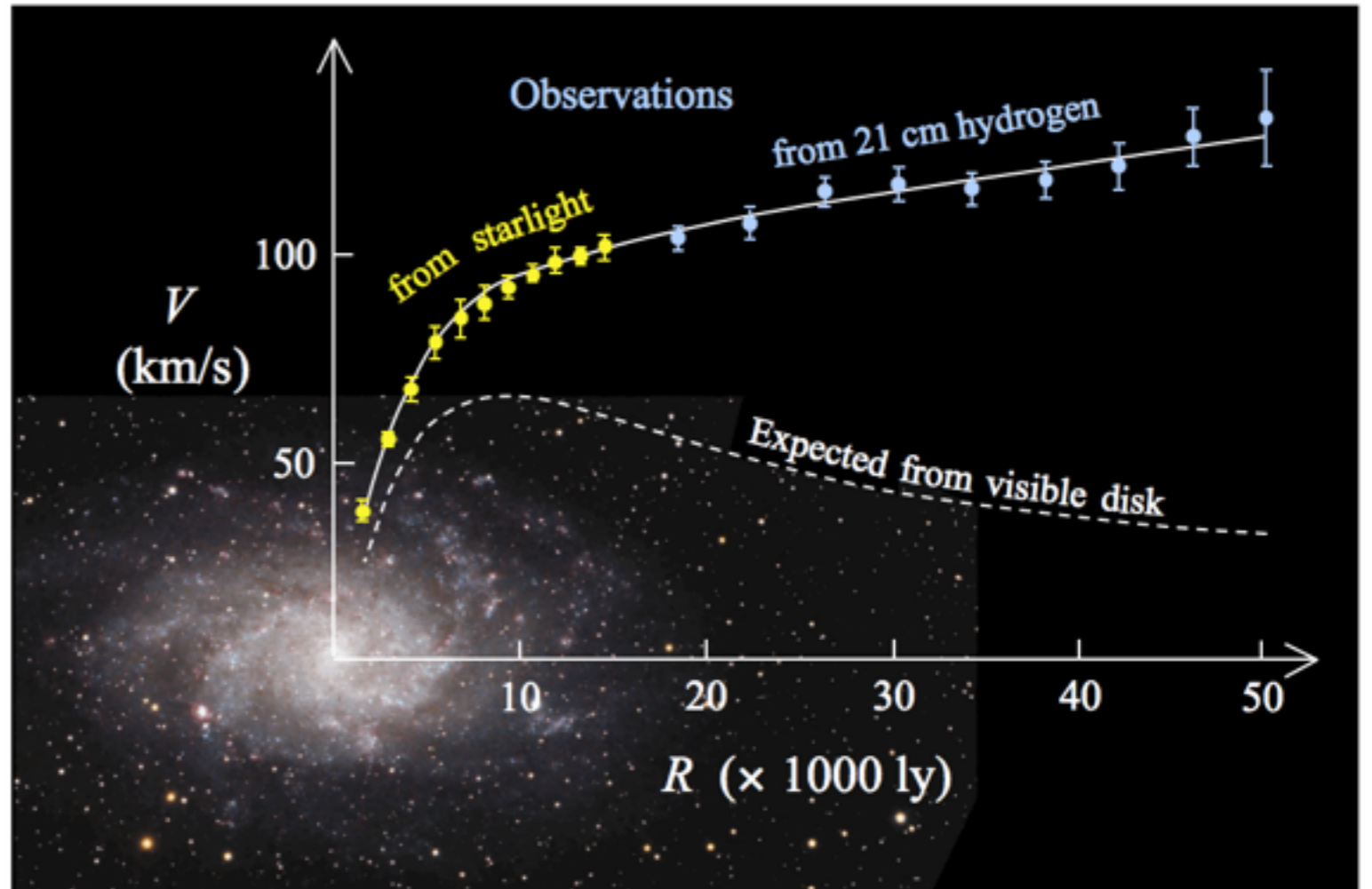
Too fast!



Zwicky '33

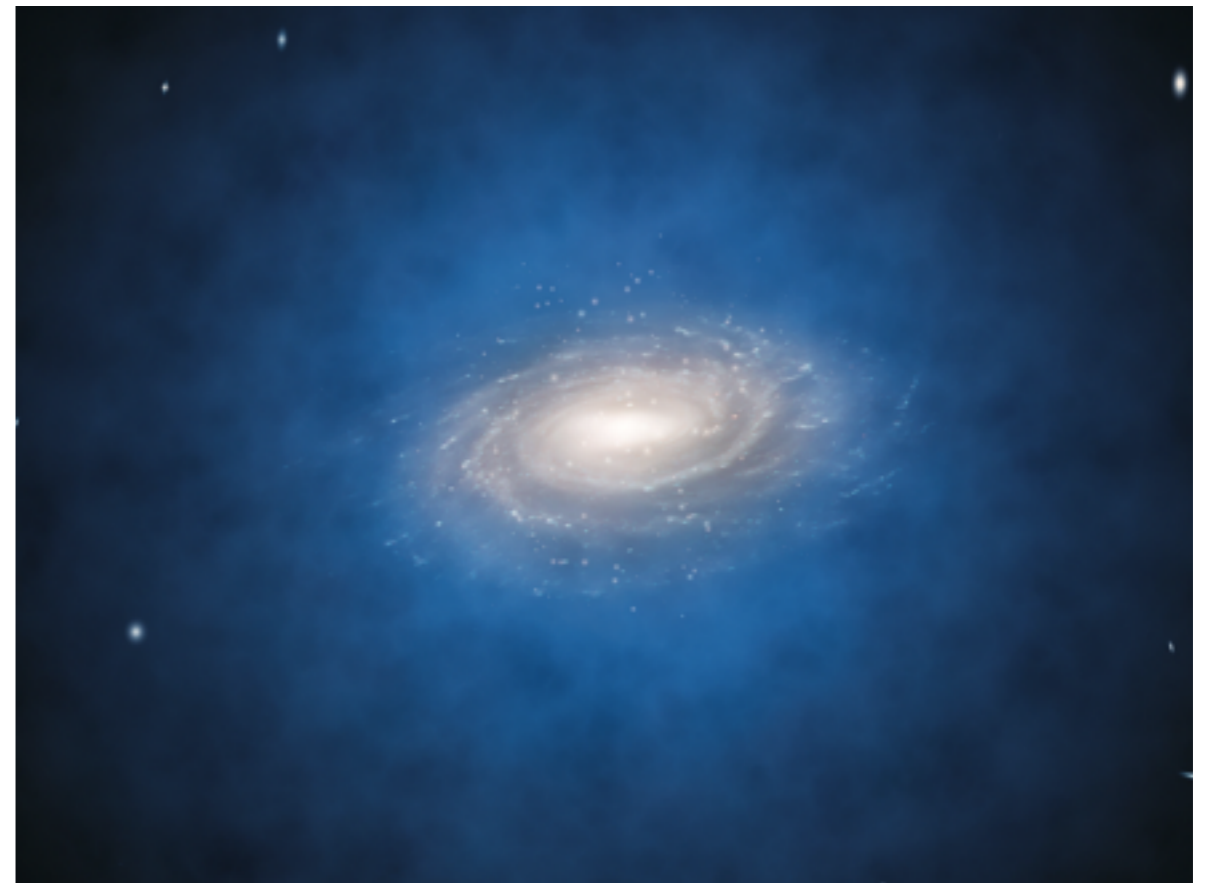


Rubin '70



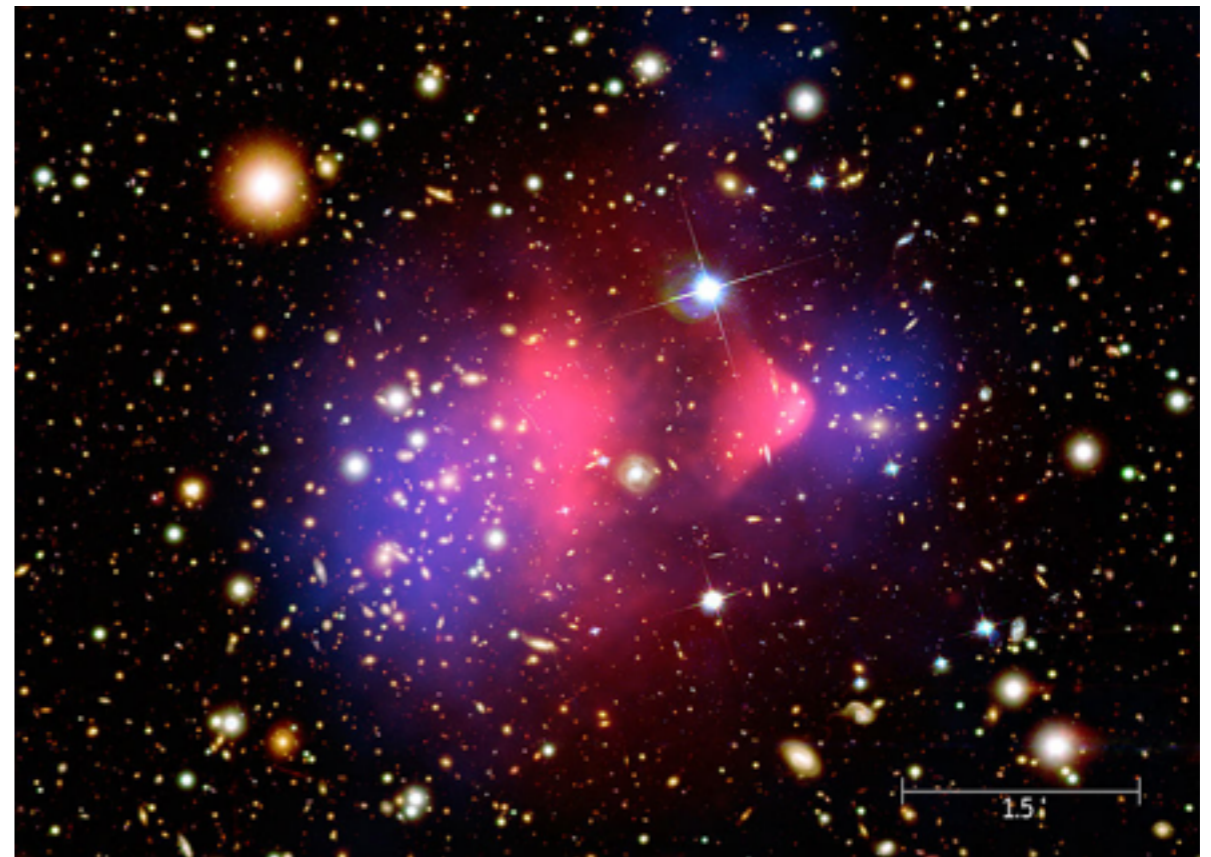
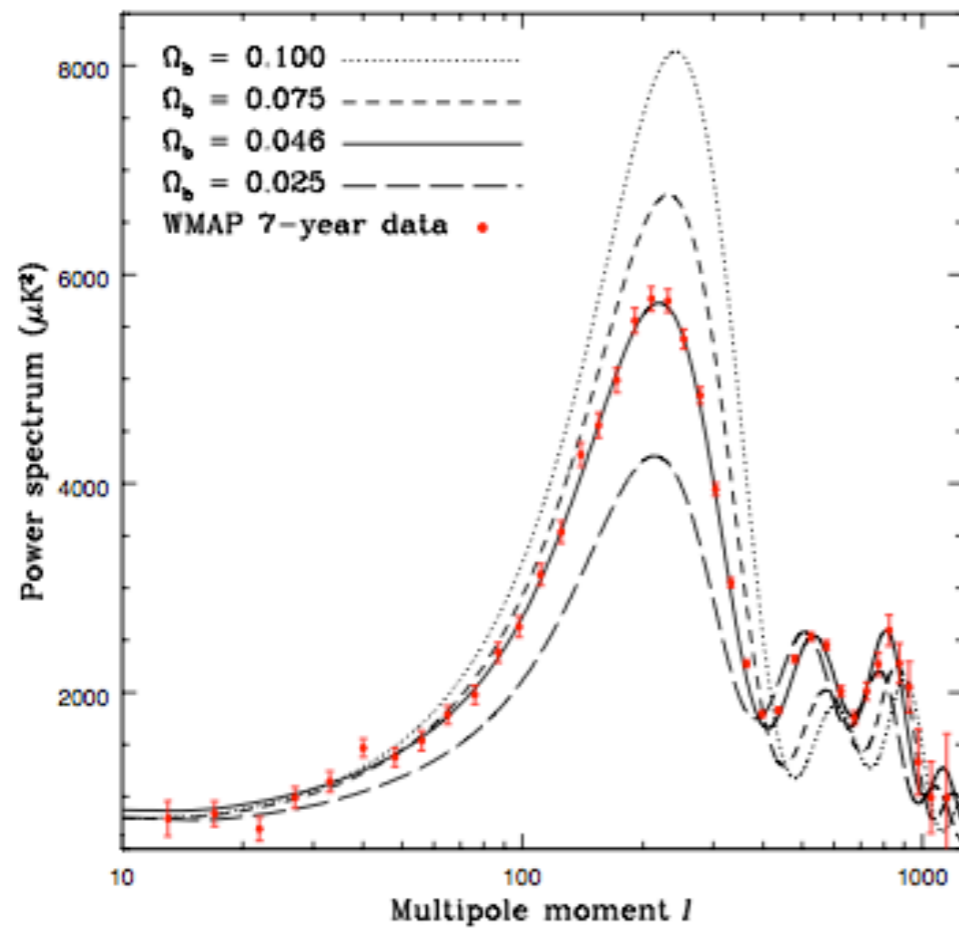
DARK MATTER

Galaxy surrounded by other matter whose gravity holds stars in.



DARK MATTER

Lots of evidence for dark matter now.



WHAT IS IT?

What do we know about
dark matter?

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- Dark (no electric charge).

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(not neutron-like).

WHAT IS IT?

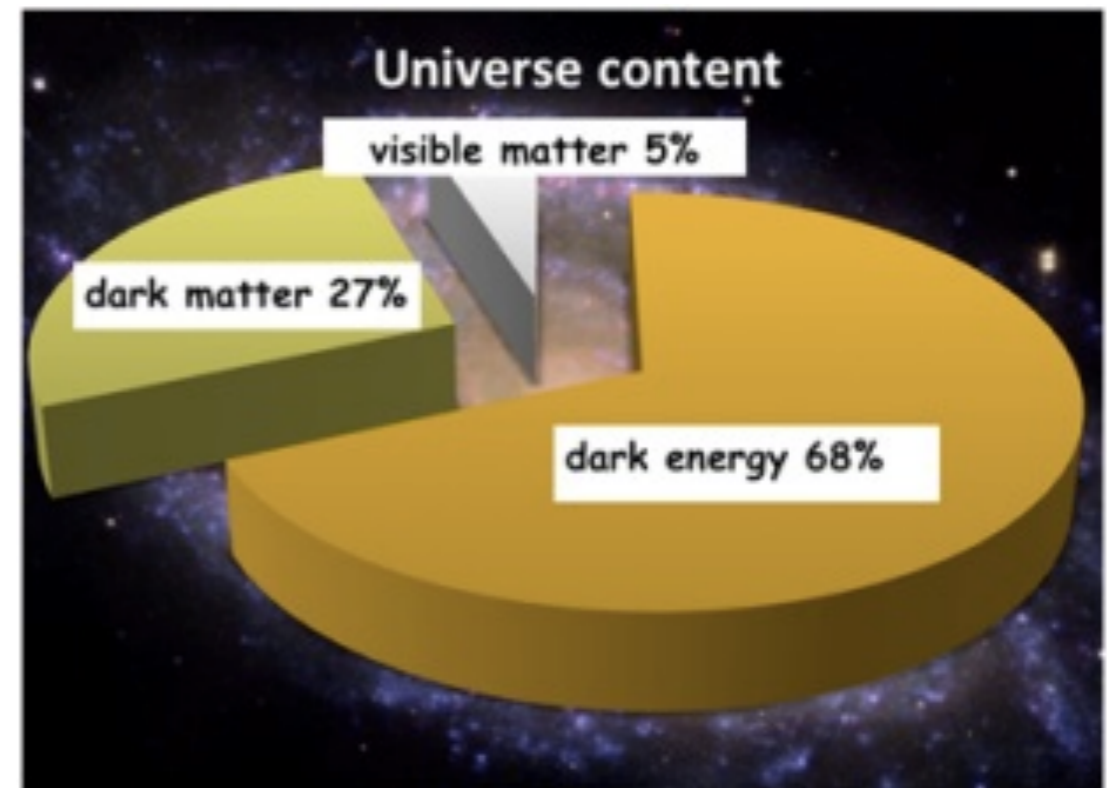
What do we know about dark matter?

- Dark (no electric charge).
- No strong charge (not neutron-like).
- Cold.

WHAT IS IT?

What do we know about dark matter?

- Dark (no electric charge).
- No strong charge (not neutron-like).
- Cold.
- Much more than visible matter.



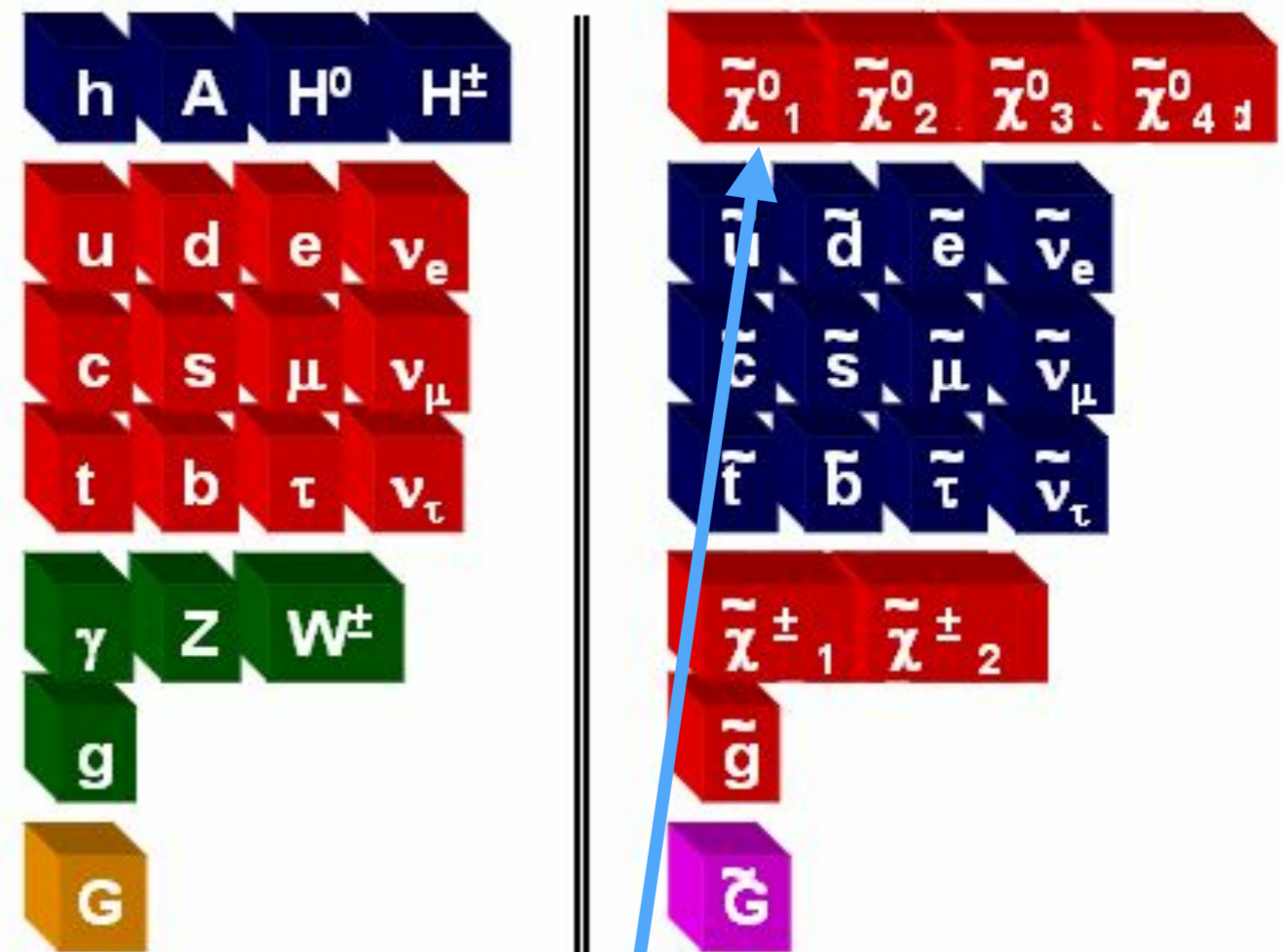
LETS BUILD A MODEL

No known particles
can be DM.

LETS BUILD A MODEL

No known particles can be DM.

Supersymmetry is interesting, and it has a candidate.



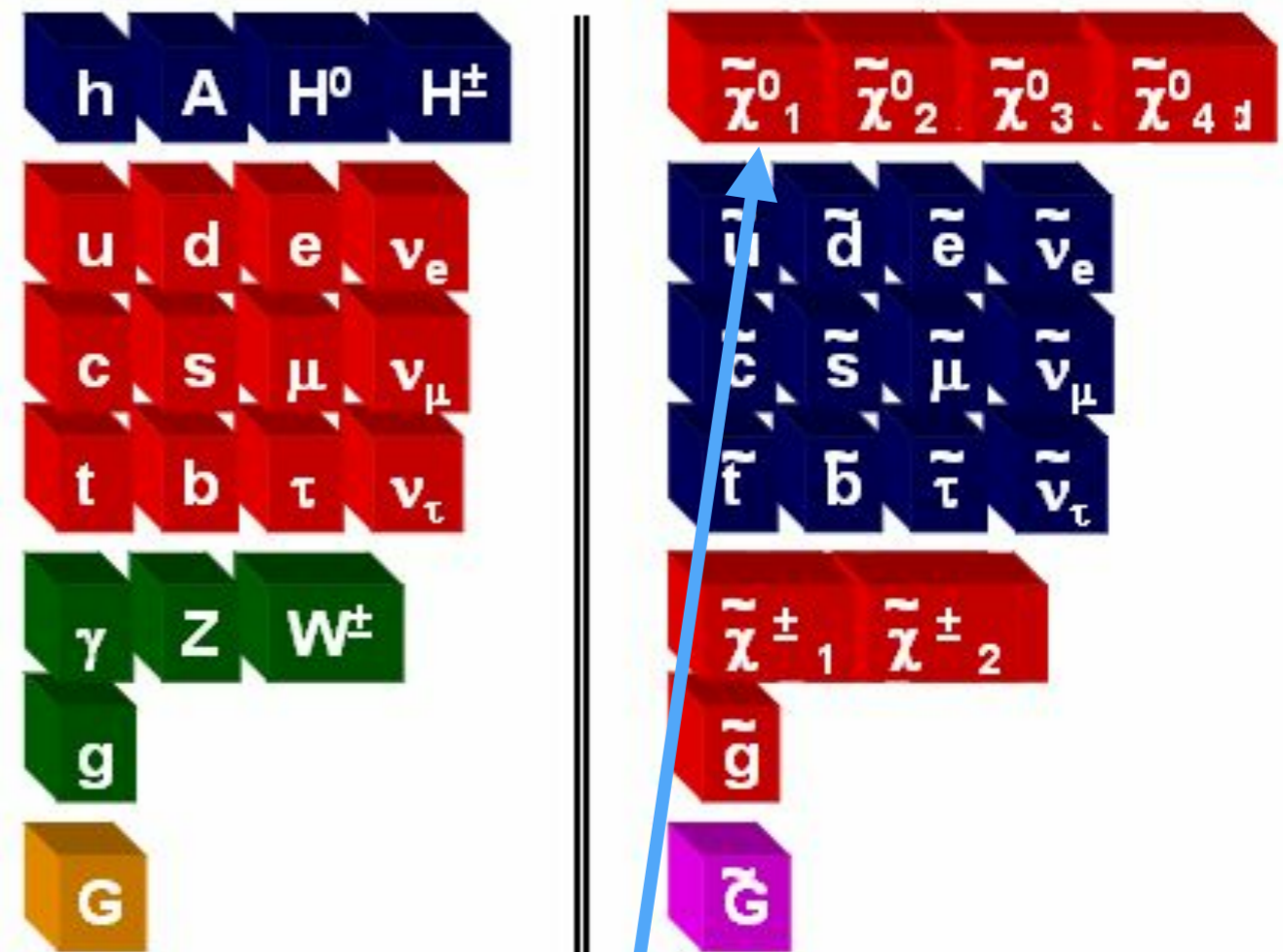
Could be dark matter.

LETS BUILD A MODEL

No known particles can be DM.

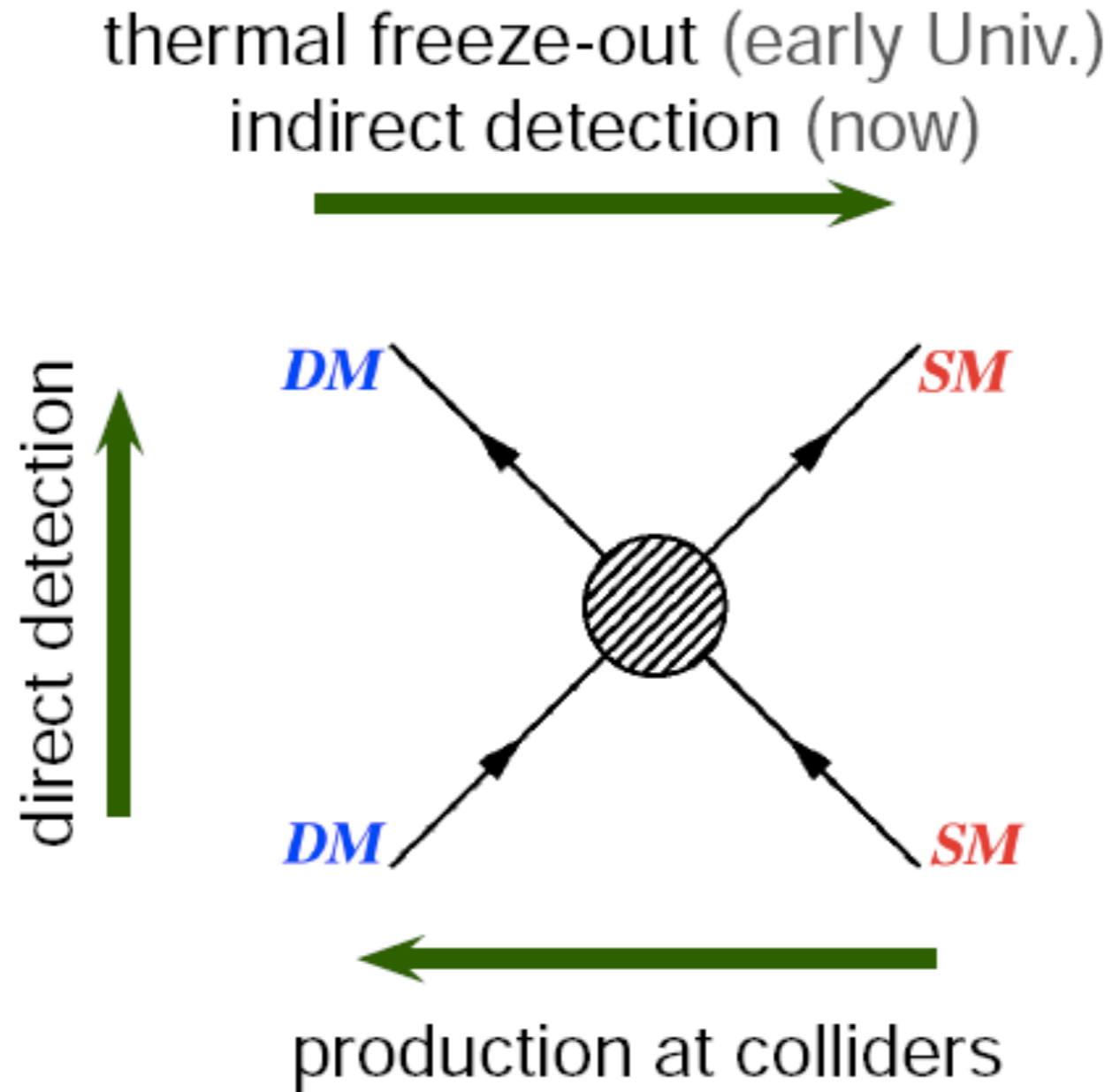
Supersymmetry is interesting, and it has a candidate.

How do we test this model?

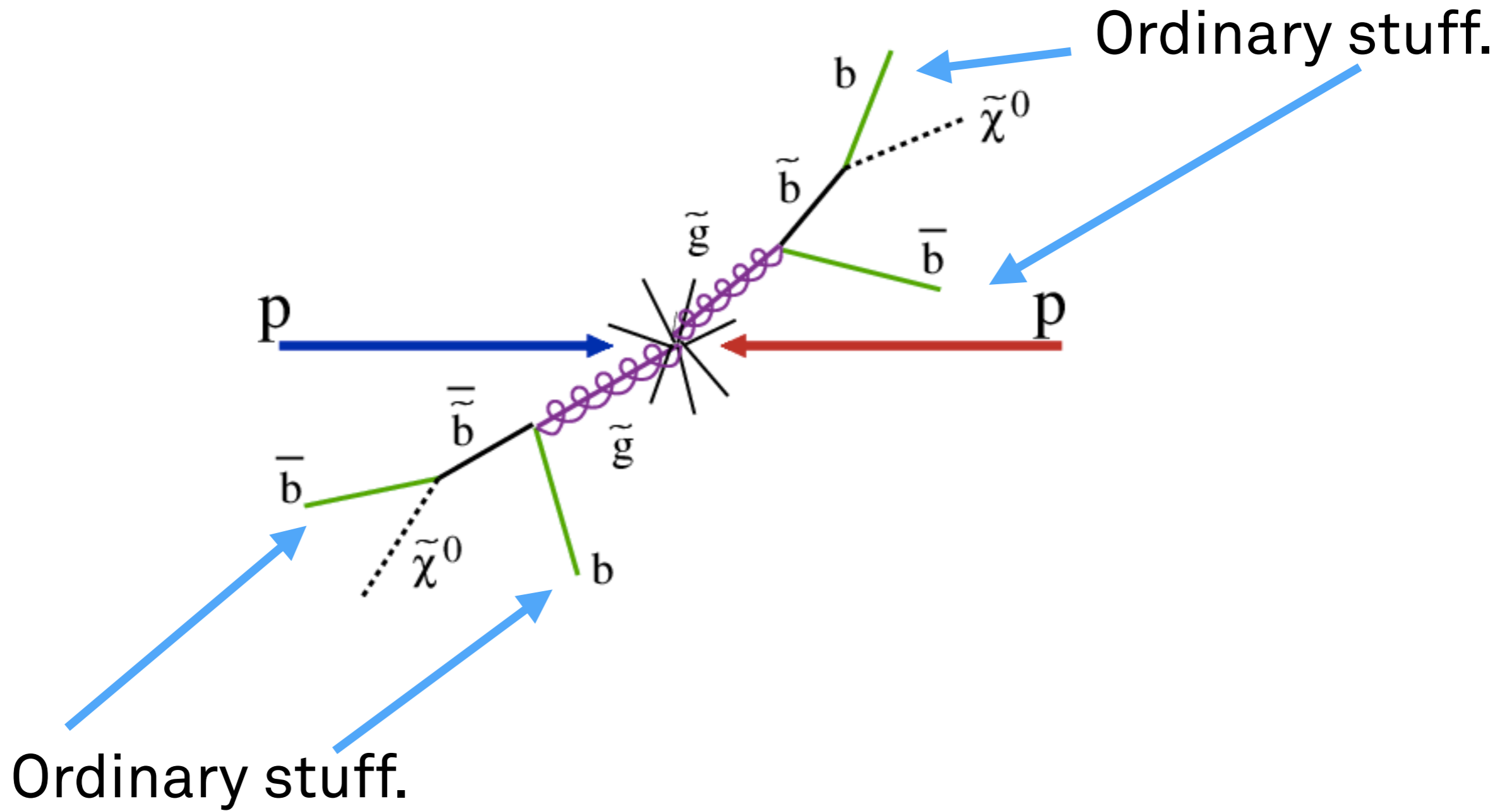


Could be dark matter.

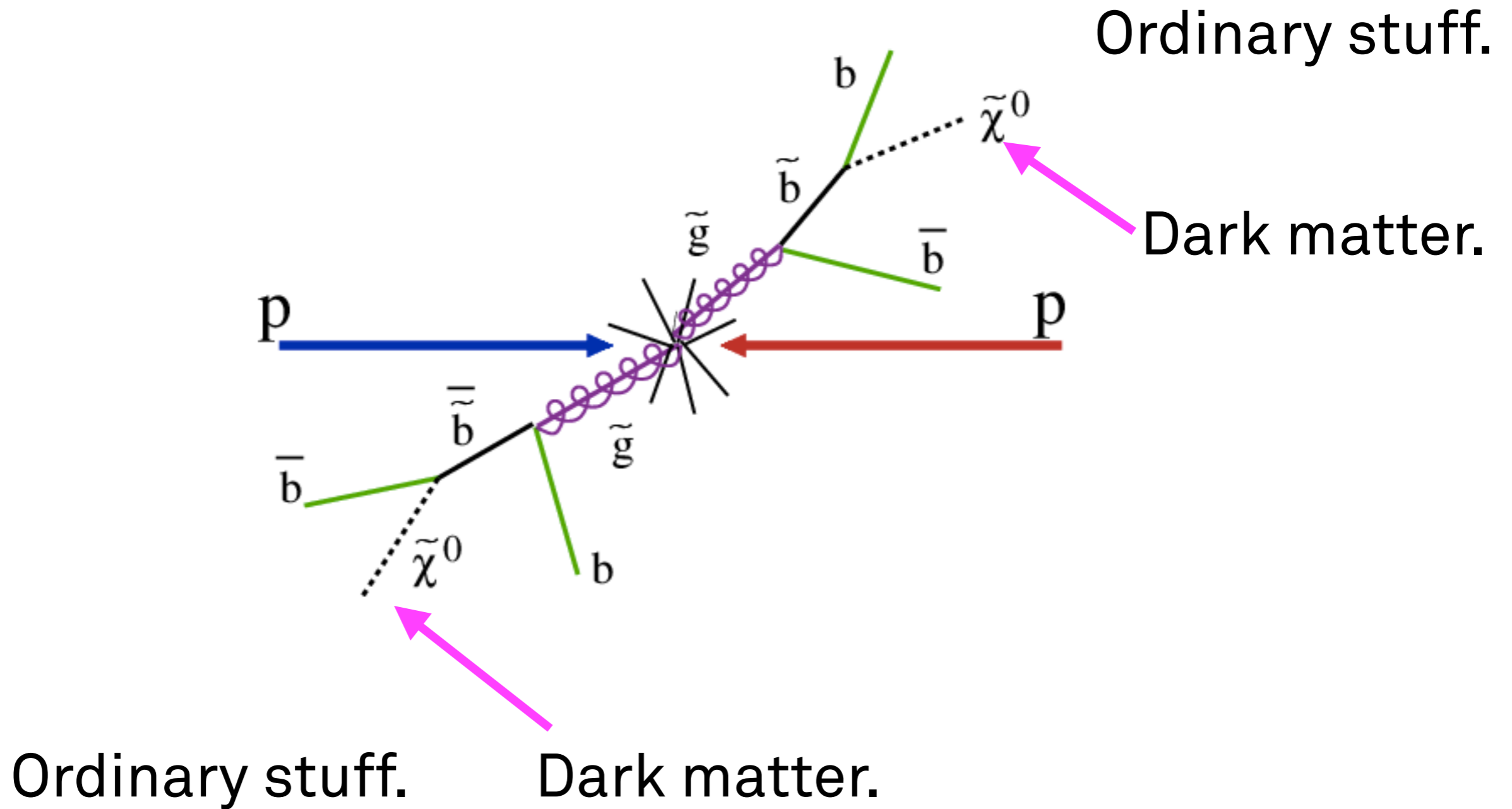
EXPERIMENTAL TESTS



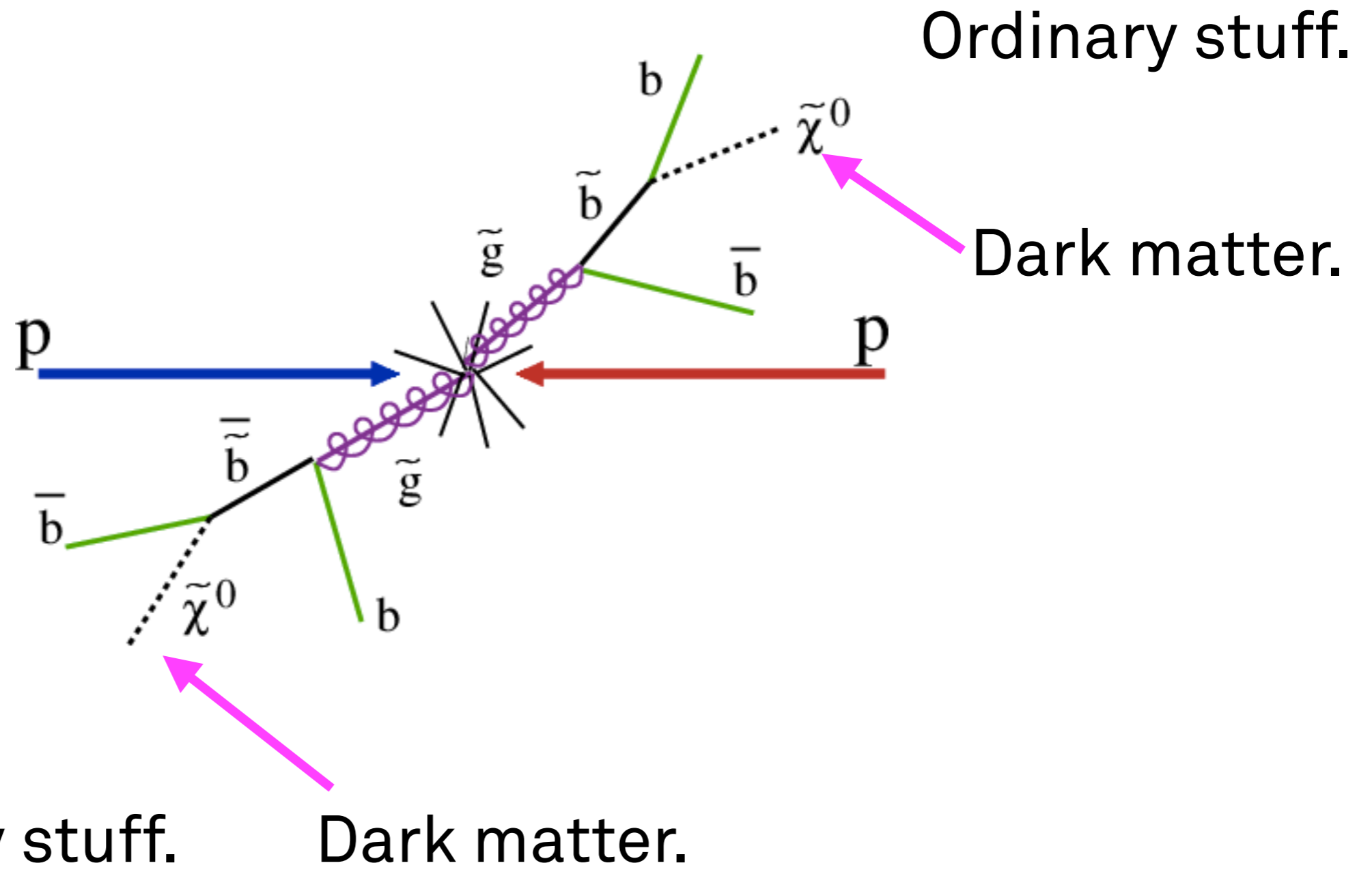
PRODUCTION AT LHC



PRODUCTION AT LHC

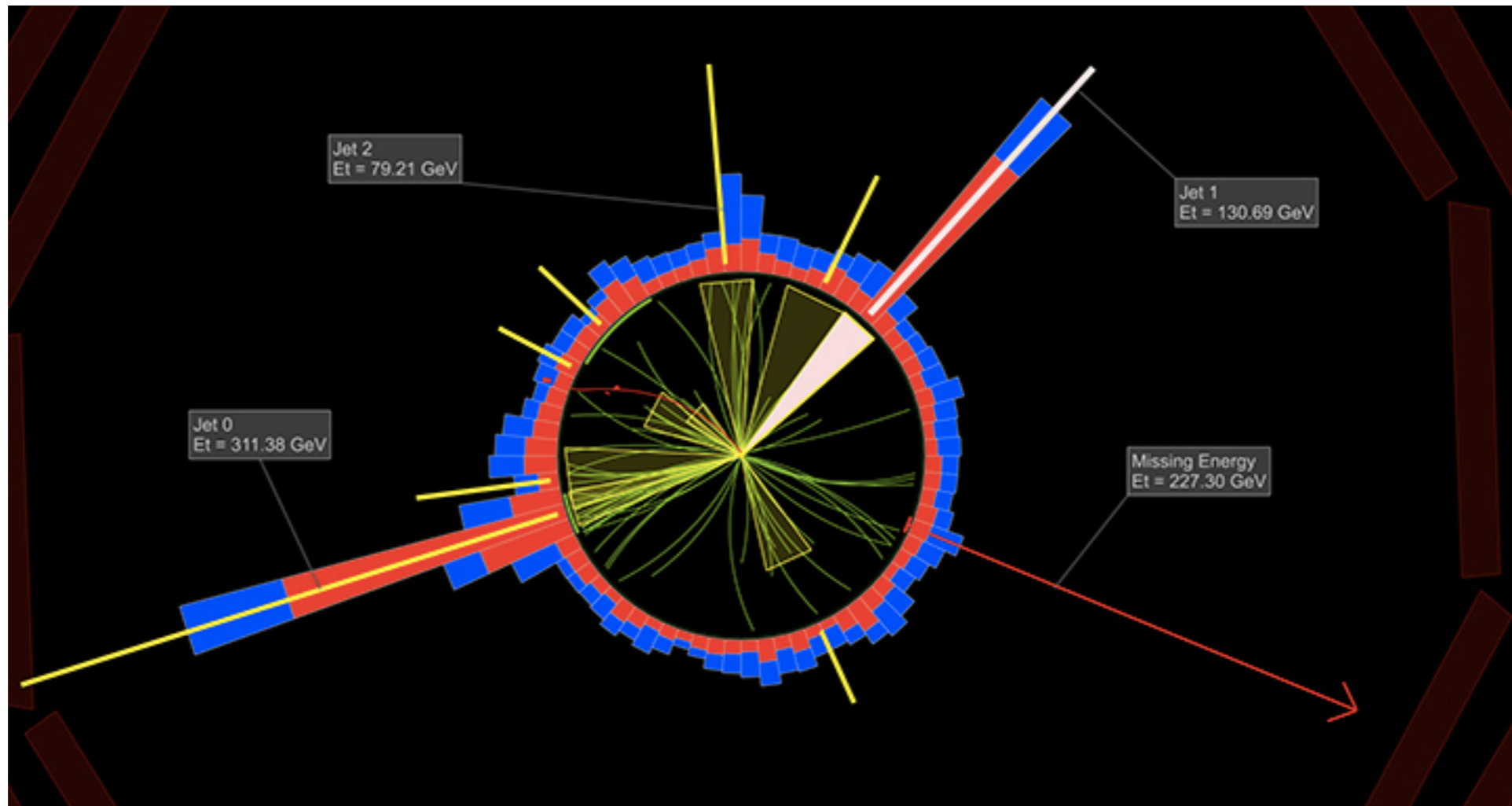


PRODUCTION AT LHC



How do you find something invisible?

MISSING ENERGY

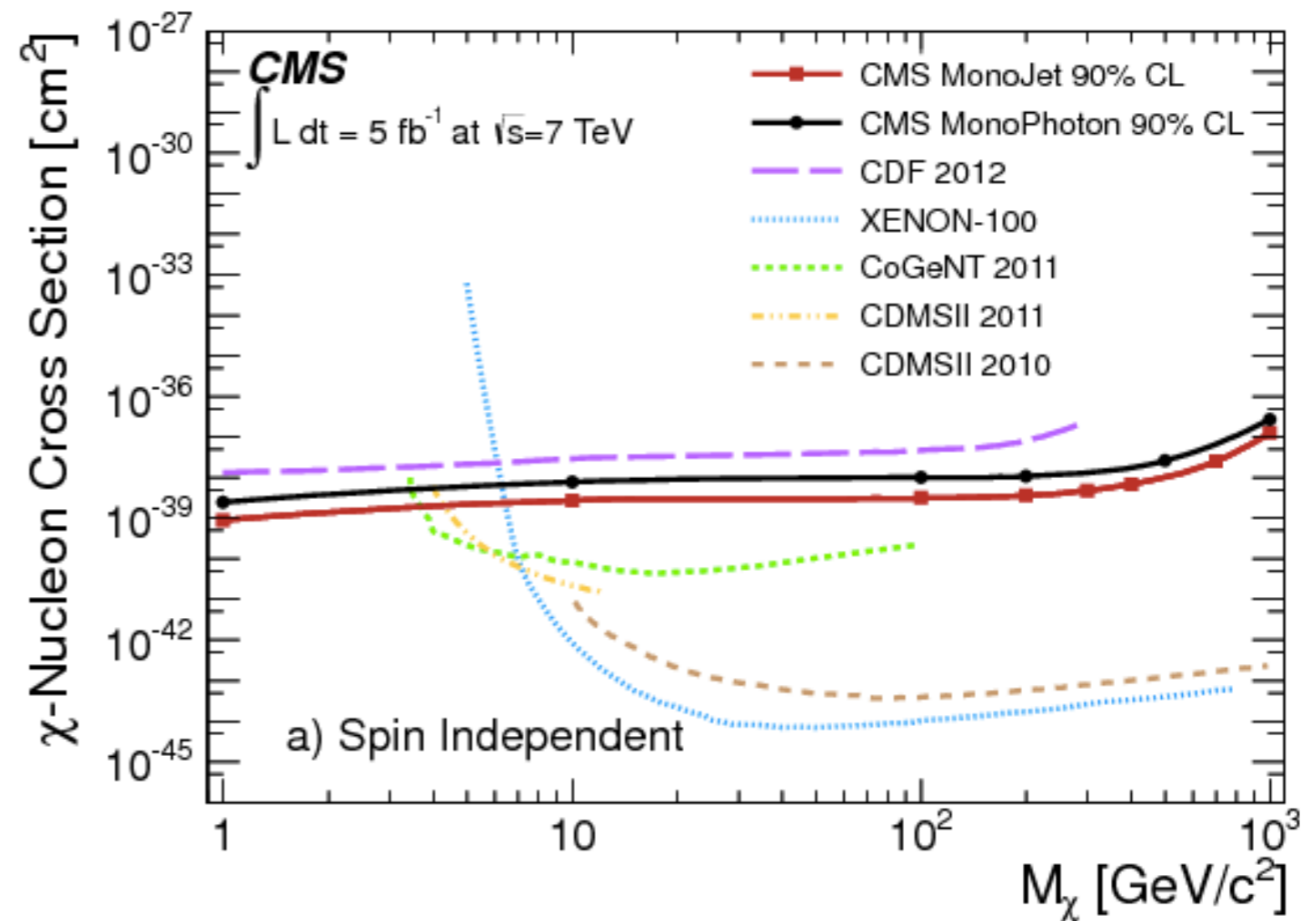


Use conservation of momentum!

DIFFERENT PROBES

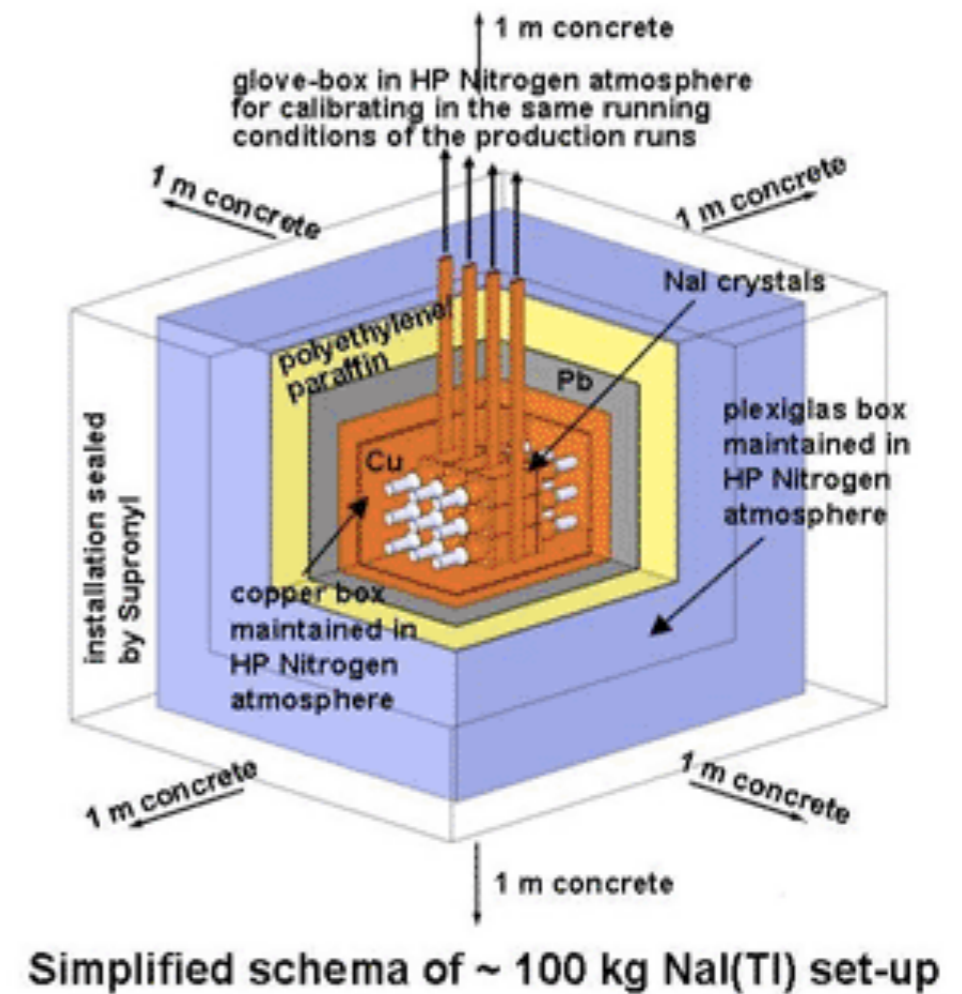
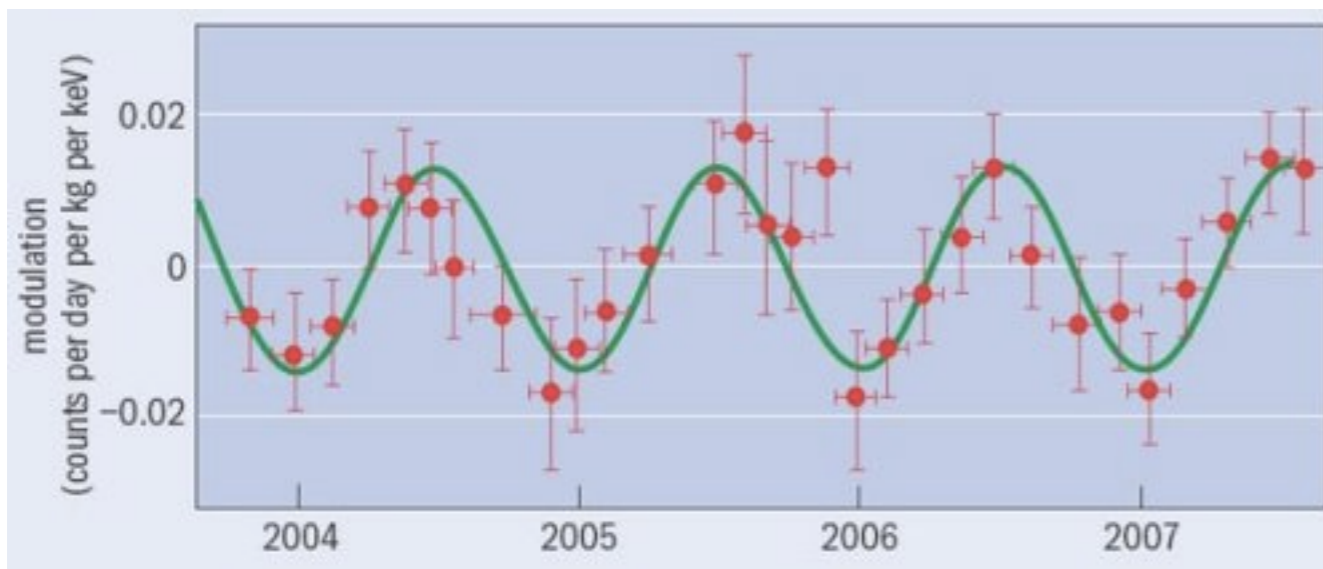
Theorists job to assess and compare different methods to probe DM.

What if there is an inconsistency?



DAMA ANOMALY

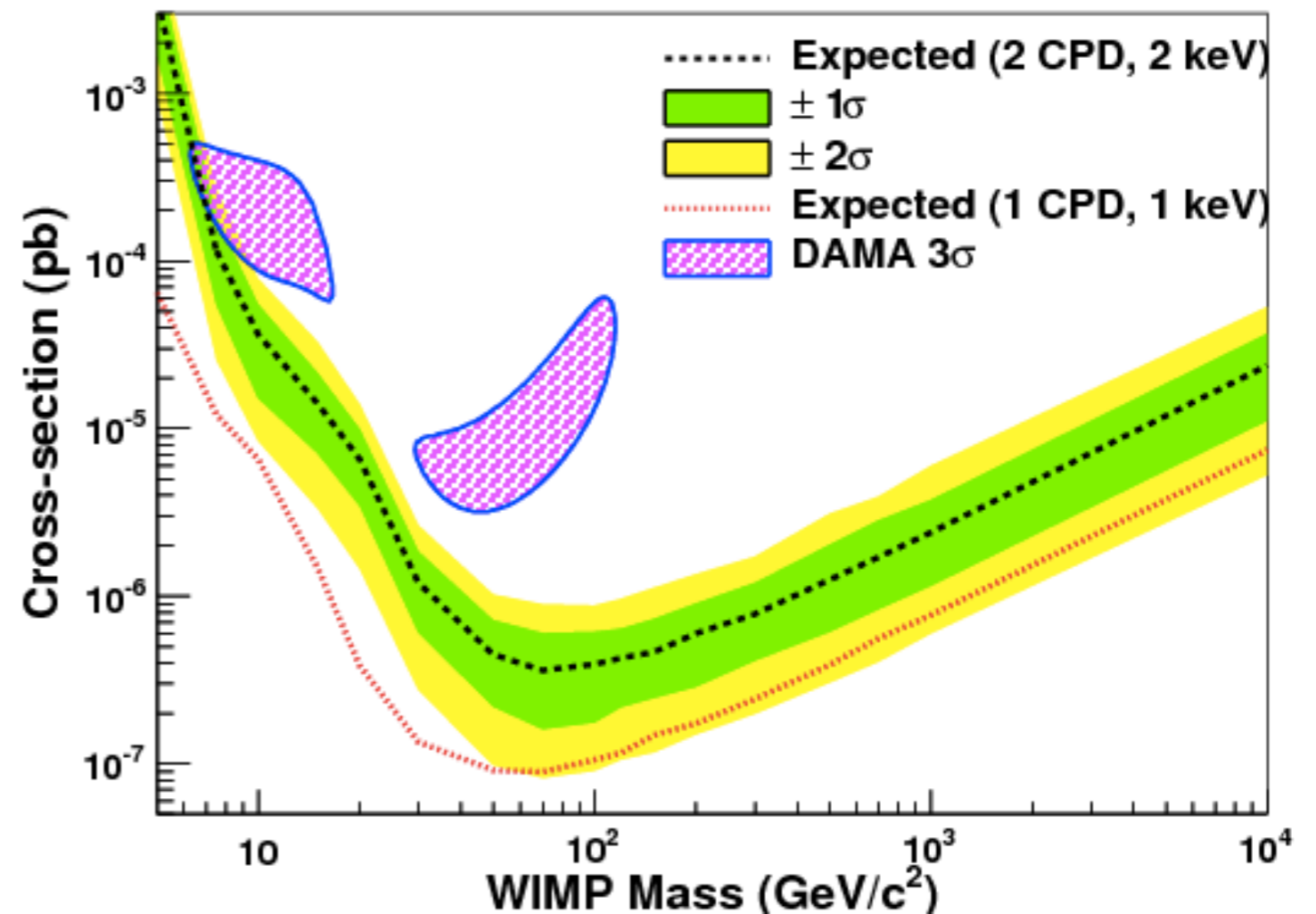
DAMA/LIBRA experiment sees signal for dark matter.



DAMA ANOMALY

Signal is completely inconsistent with many other experiments.

What if dark matter is non-standard?



THEORIES OF DARK MATTER

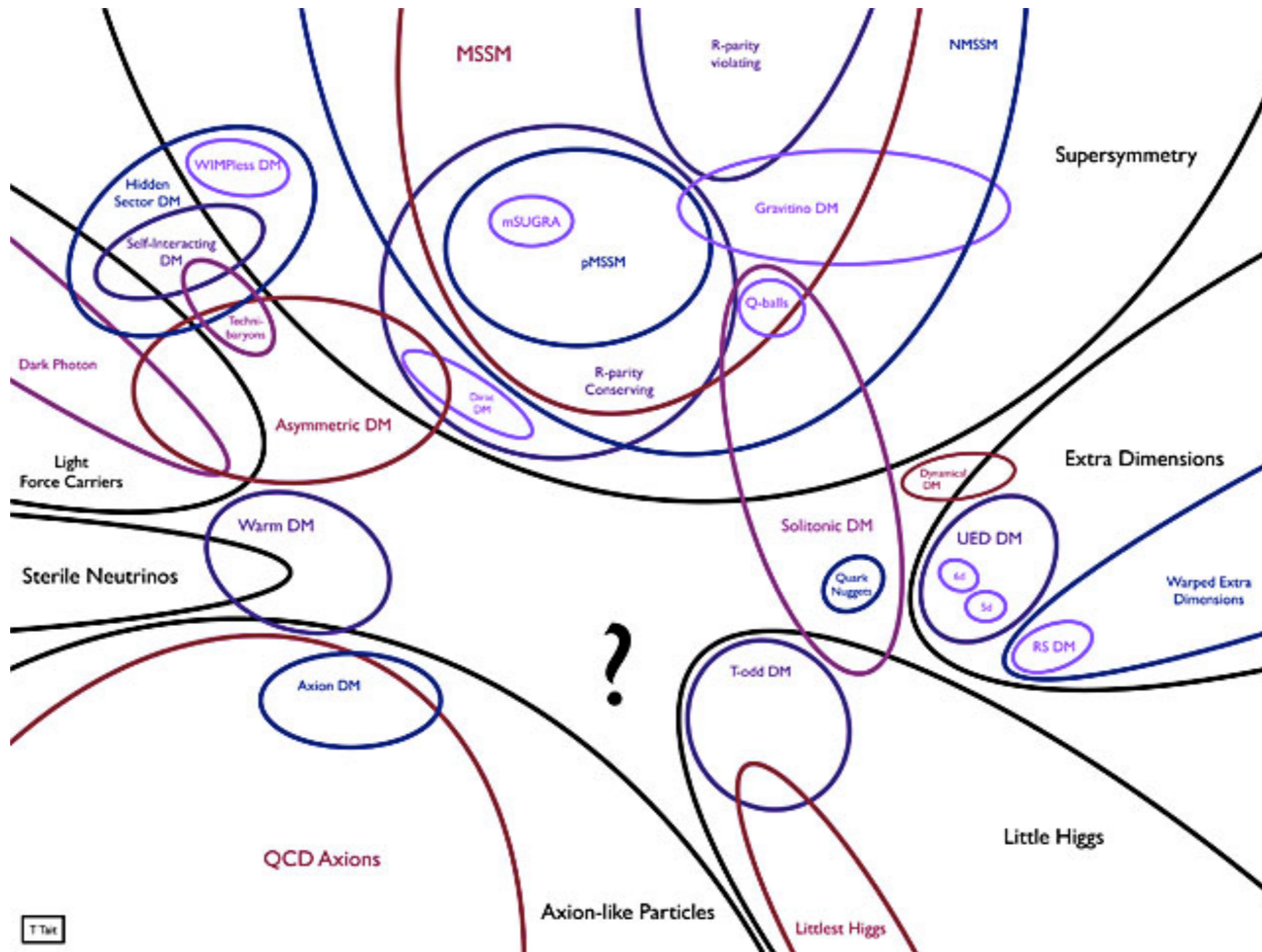


Image by
Tim Tait

**THANK
YOU**

DAMA OSCILLATION

