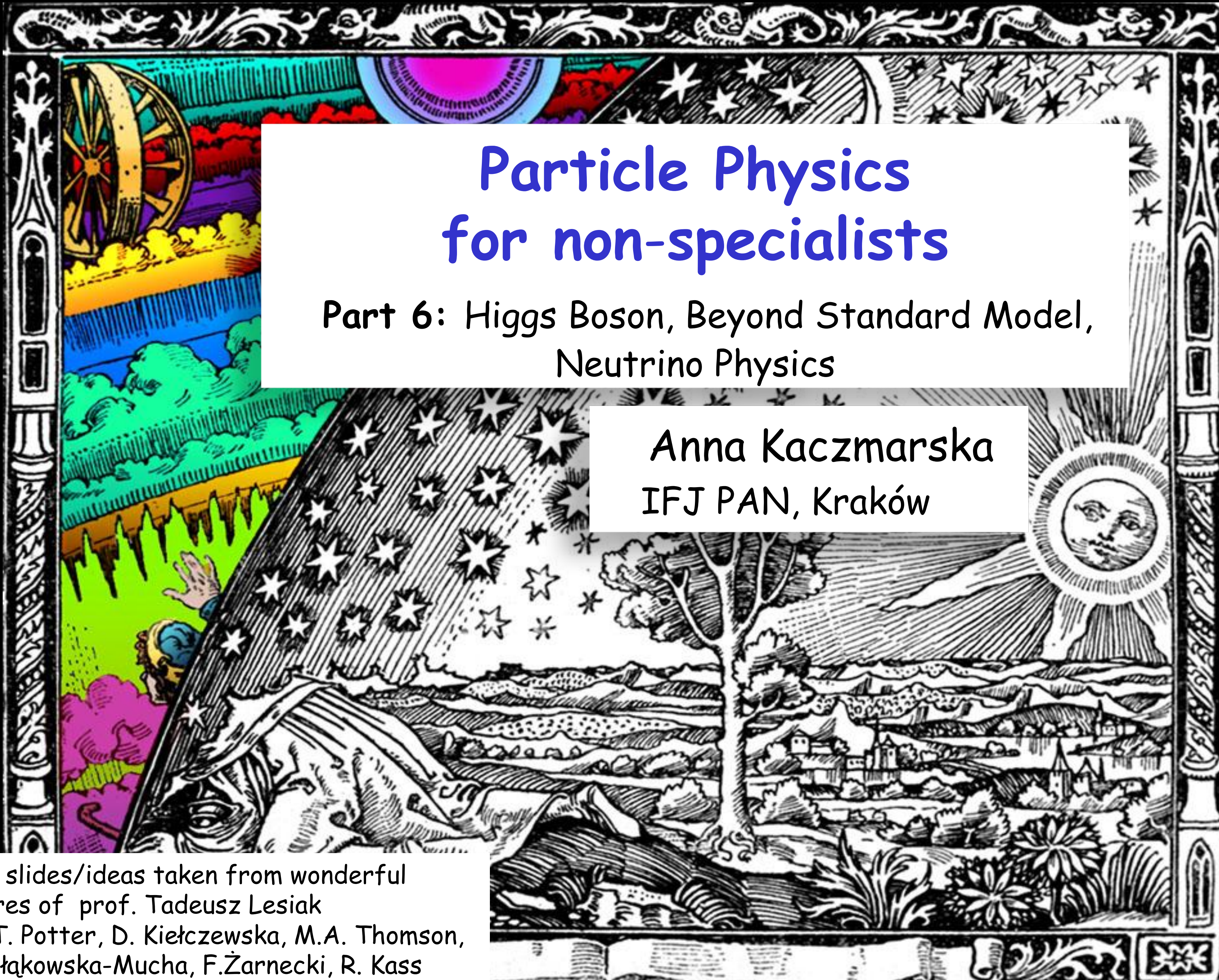


Particle Physics for non-specialists

Part 6: Higgs Boson, Beyond Standard Model, Neutrino Physics

Anna Kaczmarska
IFJ PAN, Kraków

Some slides/ideas taken from wonderful lectures of prof. Tadeusz Lesiak and T. Potter, D. Kiełczewska, M.A. Thomson, A. Obłąkowska-Mucha, F.Żarnecki, R. Kass

Content of the course

- **The Particle Physics for non-specialists course** consists of 6 lectures (2x45′)
  - I. Concepts and history, basic terms
  - II. Accelerators
  - III. Detectors
  - IV. Symmetries, the quark model, Feynman diagrams, QED
  - V. e-p scattering, QCD, Weak and Electroweak Interactions
  - VI. **Higgs Boson, Beyond Standard Model, Neutrino Physics**

- Slides will be available on indico
  - **https://indico.ifj.edu.pl/event/285/**
- **Literature**
  - Perkins *Introduction to High Energy Physics*
  - Griffits *Introduction to Elementary Particles*
  - Martin, Shaw *Particle Physics*
  - Halzen & Martin: *Quarks & Leptons: an Introductory Course in Modern Particle Physics*
  - Particle Data Group: "Review of Particle Physics" [http://pdg.lbl.gov]

- The (mini-)exam
  - written form, short answers to questions (from the list - to be provided earlier)

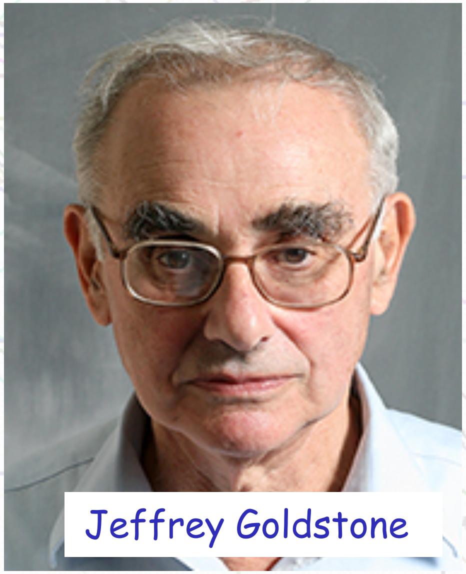
Problems with the mass

- In gauge field theories, **the gauge bosons should be massless** (mass term not gauge invariant!)
  - OK for QED and QCD, but not for W and Z!

- So the question started to be asked: could the symmetry breaking that gives rise to vector boson masses be spontaneous symmetry breaking?

- Such an effect was known in superconductivity
- Yoichiro Nambu (1960) suggested a similar mechanism could give masses to elementary particles
  - But… spontaneous breaking of a continuous symmetry implies the existence of **massless spin-0 so called Nambu-Goldstone bosons** - none of which had ever been seen!
  - Weinberg & Salam & Goldstone (1962): "In a manifestly Lorentz-invariant quantum field theory, if there is a continuous symmetry under which the Lagrangian is invariant, then *either* the vacuum state is also invariant *or* there must exist spinless particles of zero mass."
  - How this can be avoided ?
- Weinberg: *'Nothing will come of nothing; speak again!'* (King Lear)

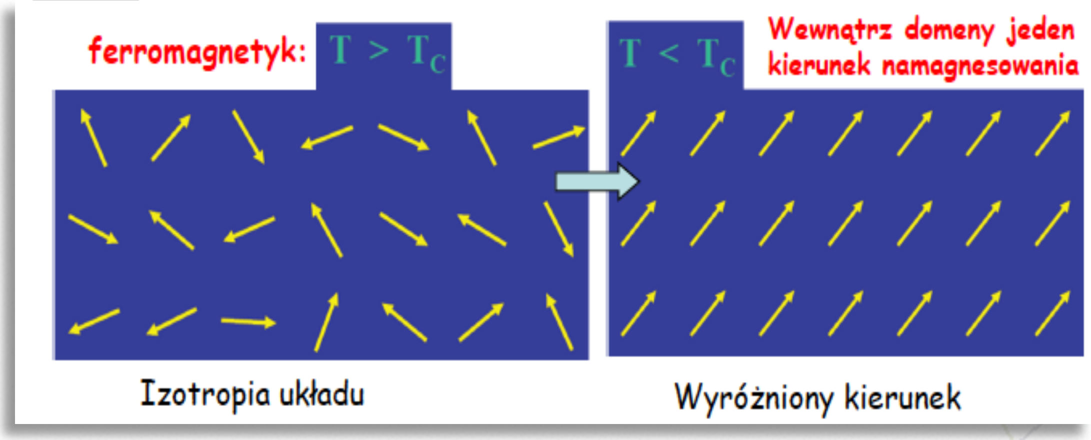
Yoichiro Nambu
The Nobel Prize in Physics 2008



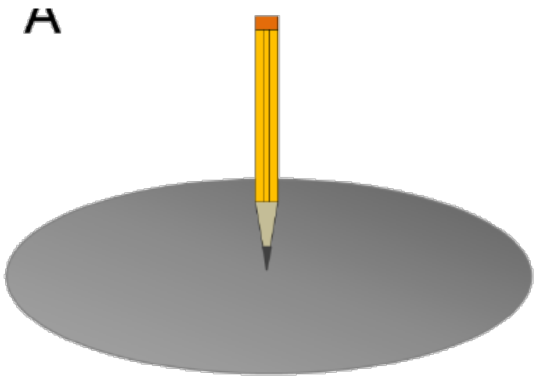
Jeffrey Goldstone

Symmetry-breaking without breaking the symmetry

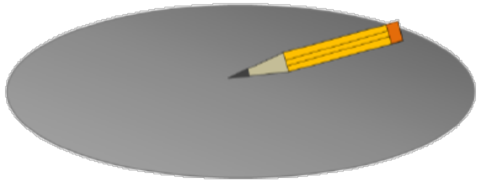
- Spontaneous breaking of symmetry occurs when the ground state or vacuum state does not share the symmetry of the underlying theory
- It is ubiquitous in condensed matter physics
- Often there is a high-temperature symmetric phase, and a critical temperature below which the symmetry is spontaneously broken
  - crystallization of a liquid breaks rotational symmetry
  - Curie-point transition in a ferromagnet



- The rotational symmetry of the pencil around its axis implies that the pencil is equally likely to fall in any direction.



- However, perform the experiment once, and the pencil must fall in some direction.

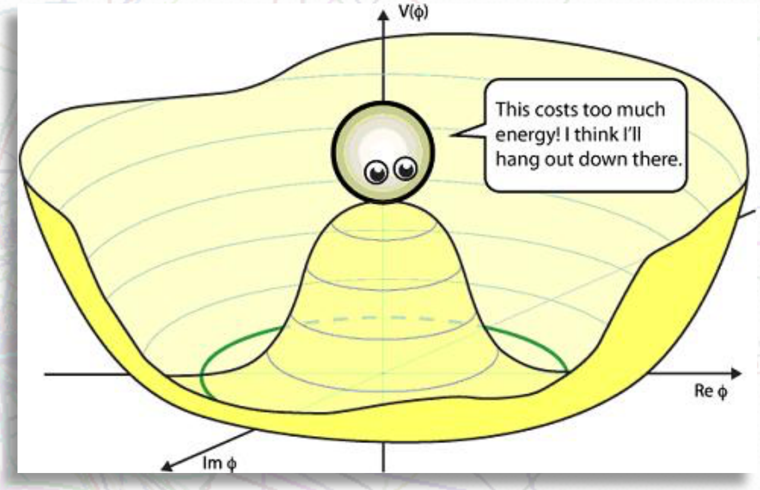


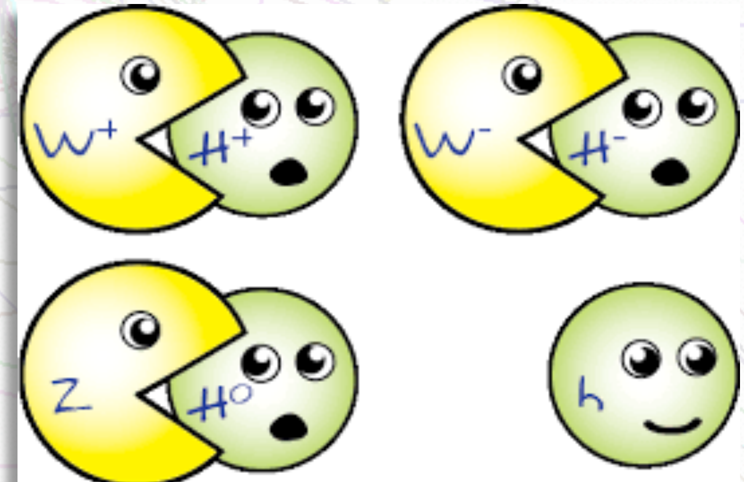
- The resulting state of the pencil breaks the rotational symmetry, **although the rotational symmetry of the laws that govern the falling pencil remain intact.**

The Englert-Brout-Higgs-Guralnik-Hagen-Kibble Mechanism

- Solution was found by three groups
  - Englert & Brout (1964), Higgs (1964), Guralnik, Hagen & Kibble (1964)
  - gauge theories are not like other field theories: masslessness of Nambu–Goldstone bosons and gauge bosons 'cancels out', combining to create massive gauge bosons

- Postulate the existence of a spinless quantum field with 'sombrero' potential -> the **Higgs field**
- The physical laws which govern the Higgs field respect the symmetry that require massless W^+, W^- and Z bosons
- The symmetric point of the Higgs field is of higher energy than the vacuum state => in the vacuum, the Higgs field breaks the symmetry like the fallen pencil
- In EW theory we need doublet of complex scalar Higgs fields (== 4 components of Higgs field)
- 3 massless Goldstone bosons are generated from 3 components of Higgs field and are "eaten" to give masses to the $W^\pm$ and Z gauge bosons
- The remaining component of the complex Higgs doublet becomes the Higgs boson - a new fundamental scalar particle
- The mechanism also gives mass to the Higgs particle and fermions that couple to the Higgs field





Idea - the Higgs Field

Empty space filled with invisible "force" – the Higgs field

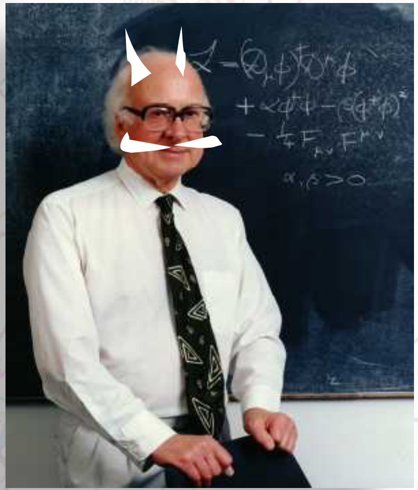
The Higgs field clusters around the particle – gives mass

And Higgs particle itself as excitation of the Higgs field:

The Higgs boson

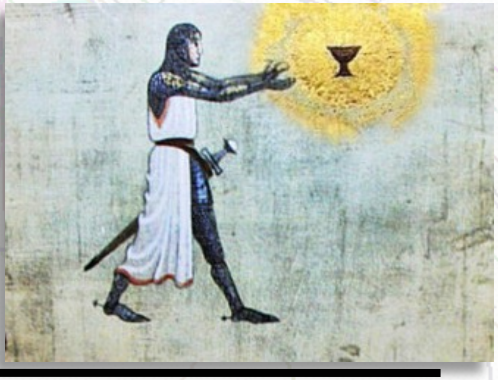
- The Higgs field fills all of space and has no external source
- The Higgs boson is an elementary excitation of the field. It must be a scalar particle.
- Some particles – including the Higgs boson itself – interact more frequently than the others; it means they are more massive.
- Photons, gluons, neutrinos do not interact at all; they are massless.
- Masses are controlled by free parameters called Yukawa Couplings (the strength of the coupling to the Higgs field)

- The Higgs Boson has a mass, but the **mass is not predicted** by the theory - we had to find it **experimentally**!



- In early 80s it started to assume a key importance as the only missing piece of the SM jigsaw
  - SM worked so well that the boson had to be present

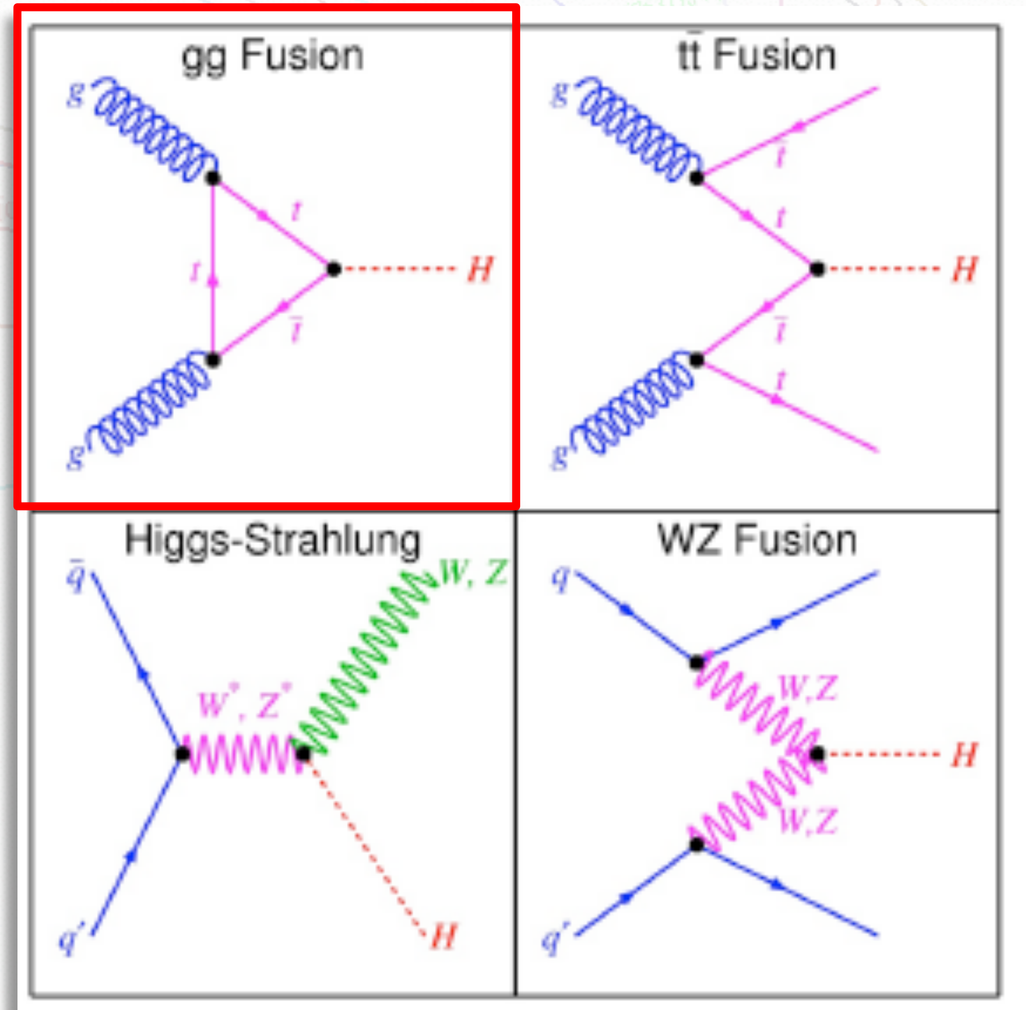
- But it required collider energetic enough to produce it. Time to design a higher energy collider and continue the search
- Finding the Higgs was one of the main objectives of the LHC

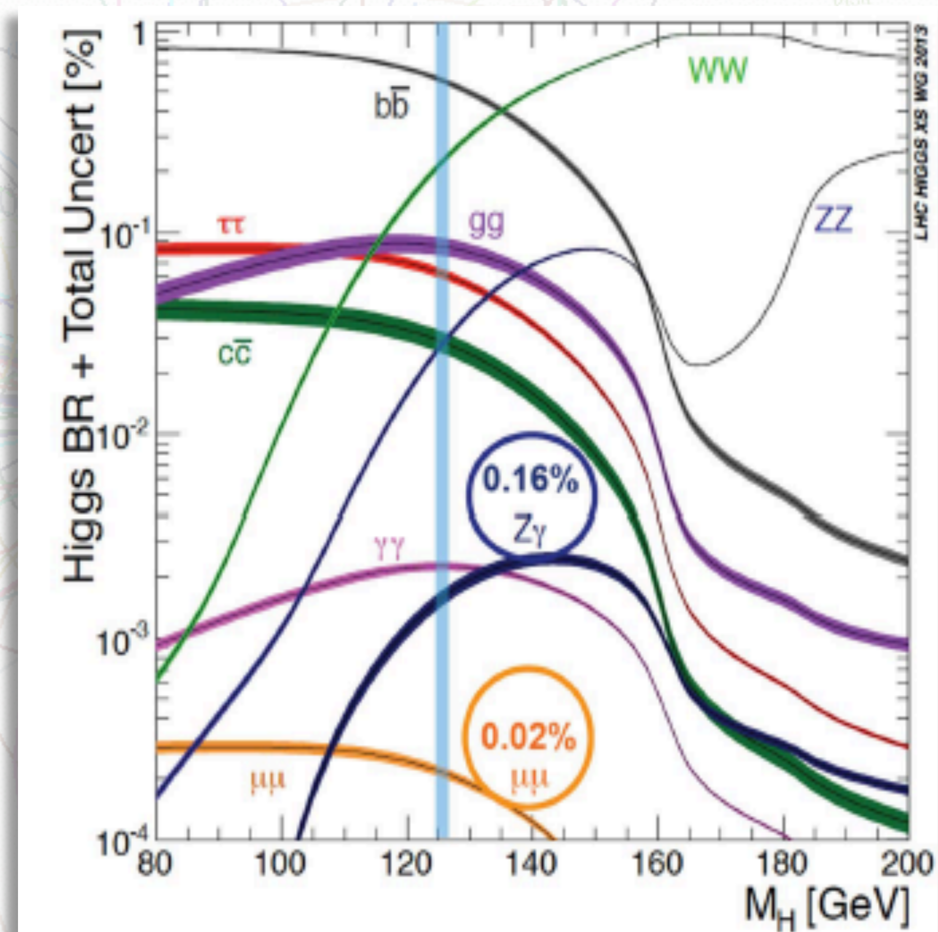


Production and Decay of a Higgs Boson at the LHC

Production (gg Fusion dominant)

Higgs coupling proportional to mass ⇒ Higgs generally decays to heaviest particles possible





"I think we have it"

The Discovery of the Higgs boson by the ATLAS and CMS experiments announced on July 4, 2012

ELSEVIER

Physics Letters B

Volume 716, Issue 1, 17 September 2012, Pages 1–29

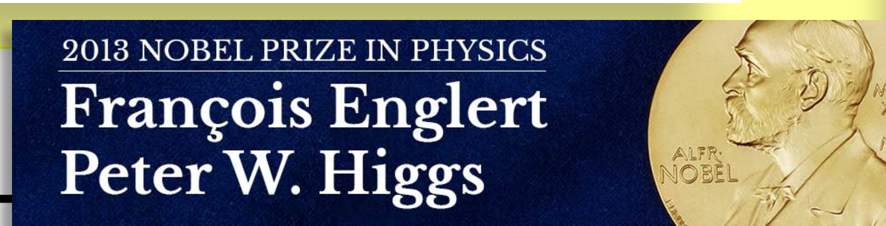
Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC ☆

ELSEVIER

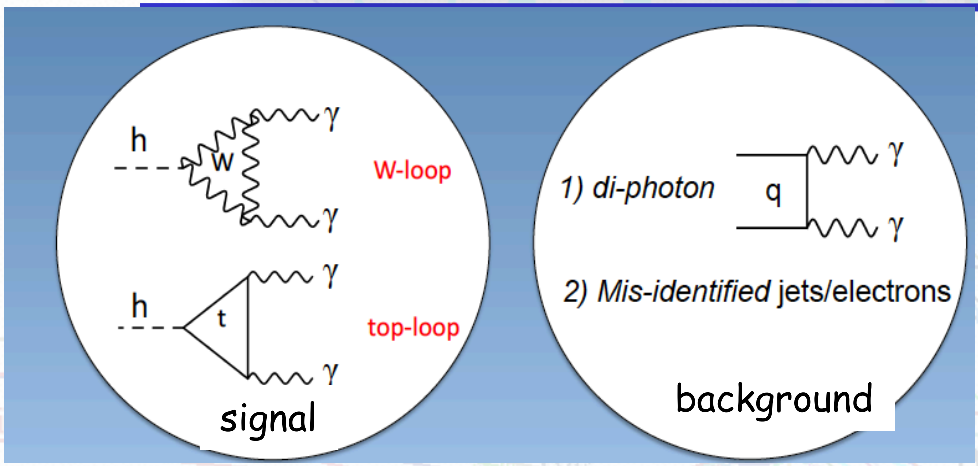
Physics Letters B

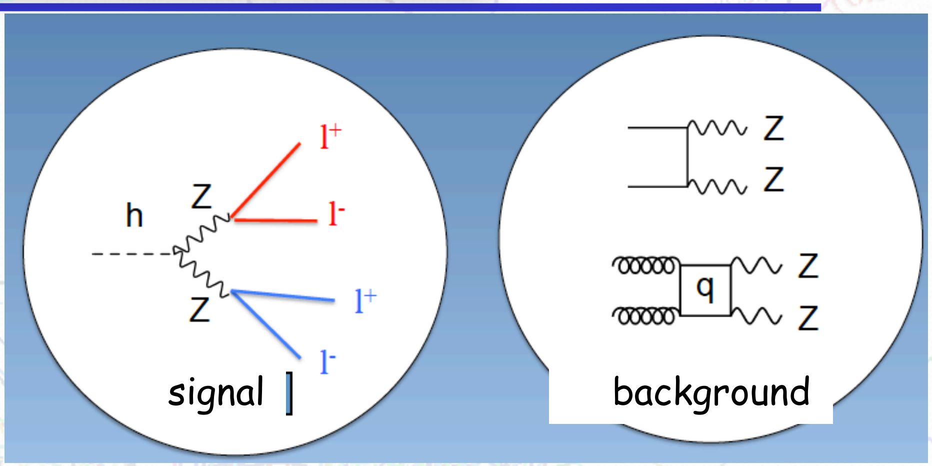
Volume 716, Issue 1, 17 September 2012, Pages 30–61

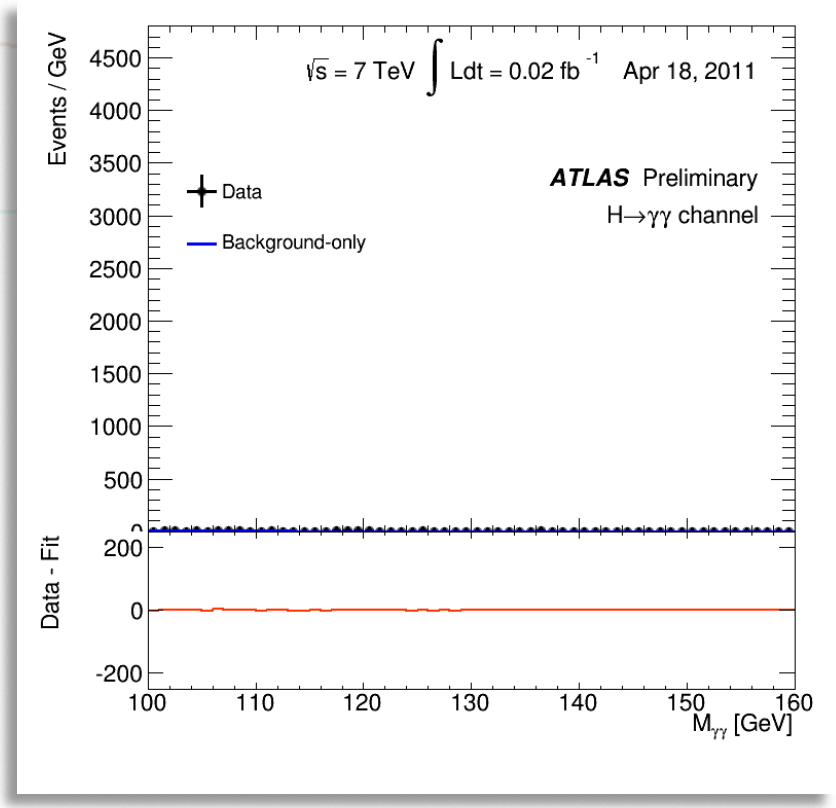
Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC ☆

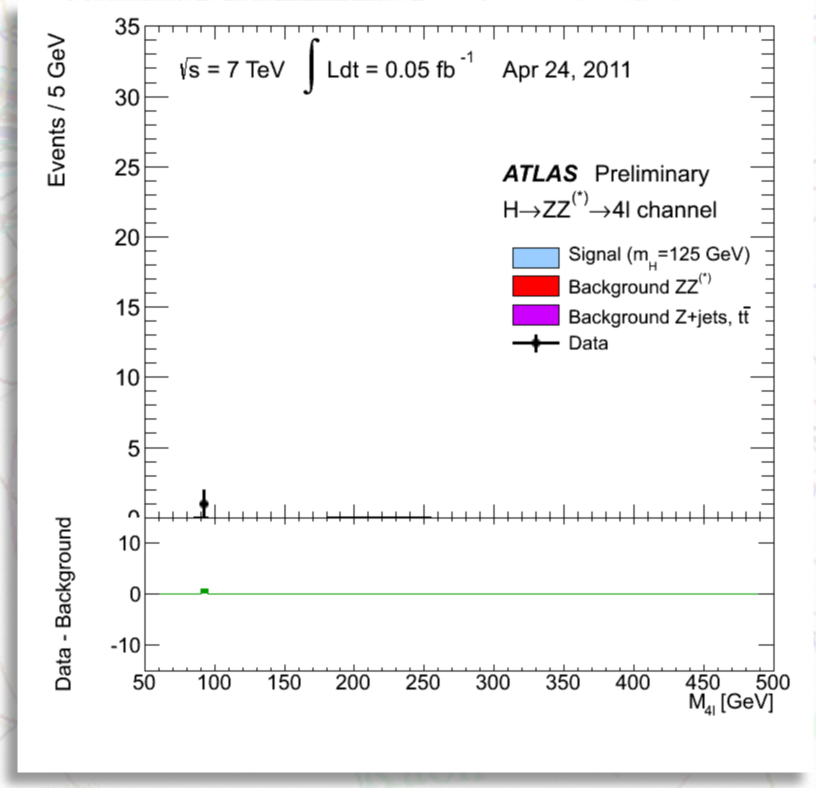


Two "cleanest" channels



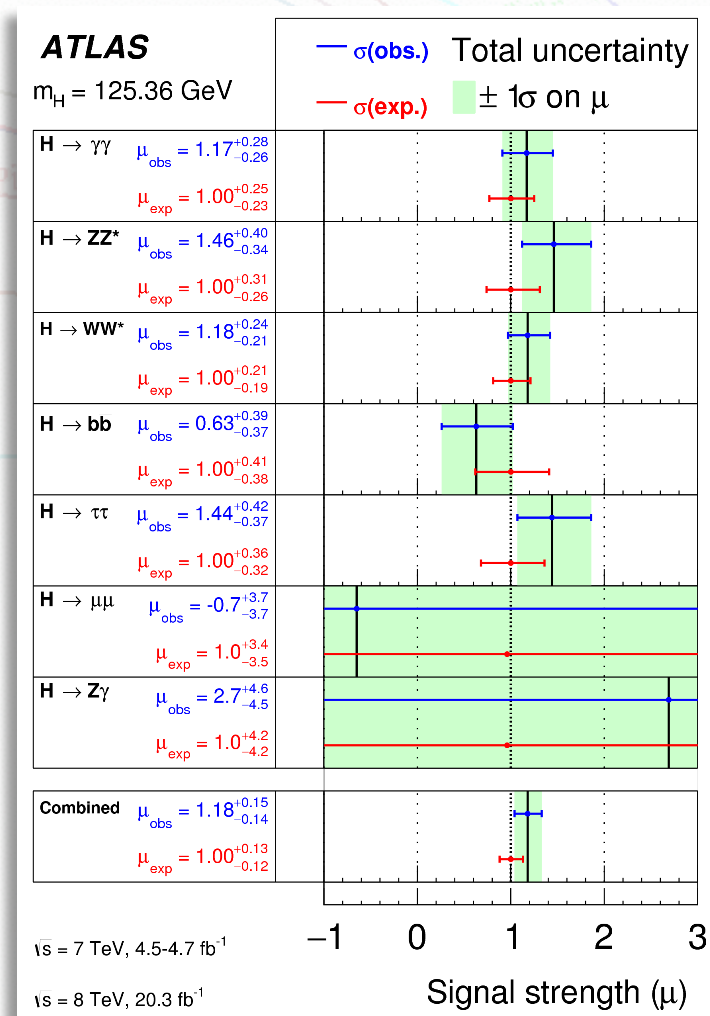




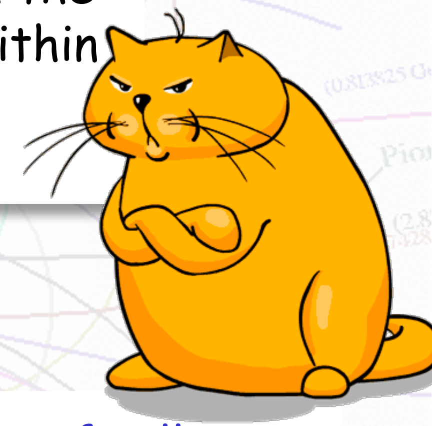


But is this SM Higgs boson?

2019 -> we can see also decays : H -> W^+W^-, H->bb-bar, H->$\tau^+\tau^-$



- So far the observations are consistent with the observed particle being the Standard Model Higgs boson
- The particle decays into at least some of the predicted channels
- Also production rates, BRs, spin-parity (0^+) etc. for the observed channels match the predictions by the Standard Model within the experimental uncertainties



The discovery of the Higgs boson finally completes the Standard Model of particle physics.

Is this the end of particle physics?

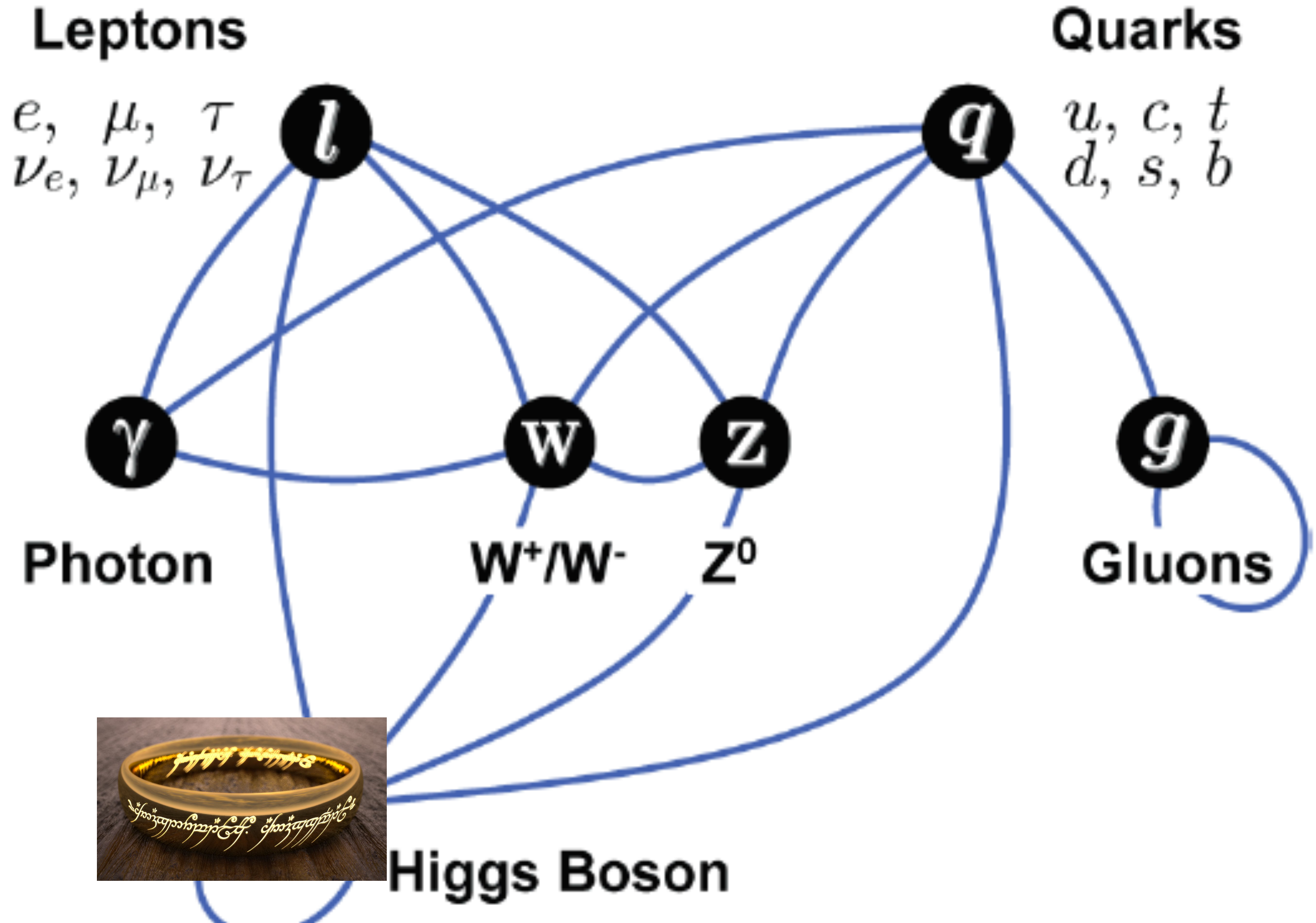
Definitely No!

There are many outstanding questions still to be answered.

The Standrad Model is the combination of the Gauge groups

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

including the Higgs Mechansism



Gravity is described separately by General Relativity

Problems of the Standard Model

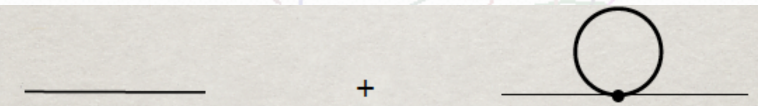
- The Standard Model successfully describes all existing particle physics data (though question marks over the neutrino sector)

- But: many (too many? At least 19…) input parameters:
  - Quark and lepton masses
  - Quark charge
  - Couplings
  - Quark (+ neutrino) generation mixing – VCKM etc.
- And: many unanswered questions:
  - Why so many free parameters?
  - Why only 3 generations of quarks and leptons?
  - Why is the neutrino mass so small and the top quark mass so large?
  - Why are the charges of the p and e identical?
  - What is responsible for the observed matter-antimatter asymmetry?
  - How can we include gravity?
  - Etc.

Is there anything beyond the Standard Model?

Why Supersymmetry is Super? – Fine Tuning

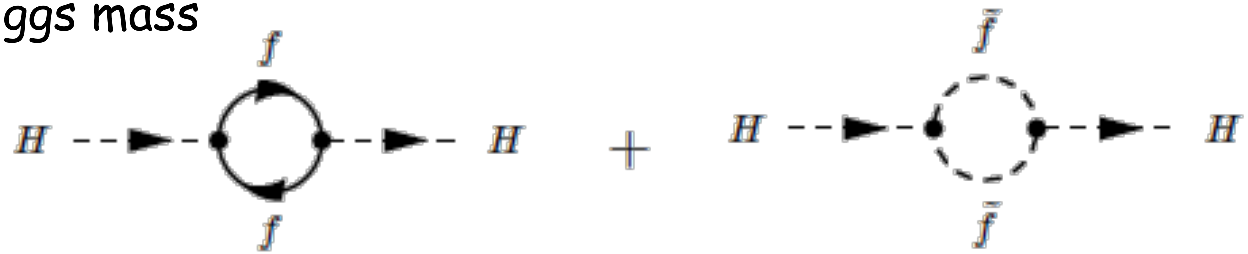
- Scalar quantum fields (like Higgs boson) get corrections terms to their masses which are sensitive to physics at arbitrarily high energies
- Quadratically divergent loop contributions to the Higgs mass drive the Higgs mass to unacceptably large values unless the tree level mass parameter is finely tuned to cancel the large quantum corrections.



$$\int d^4k \frac{1}{k^2 - m^2} \approx g\Lambda^2$$

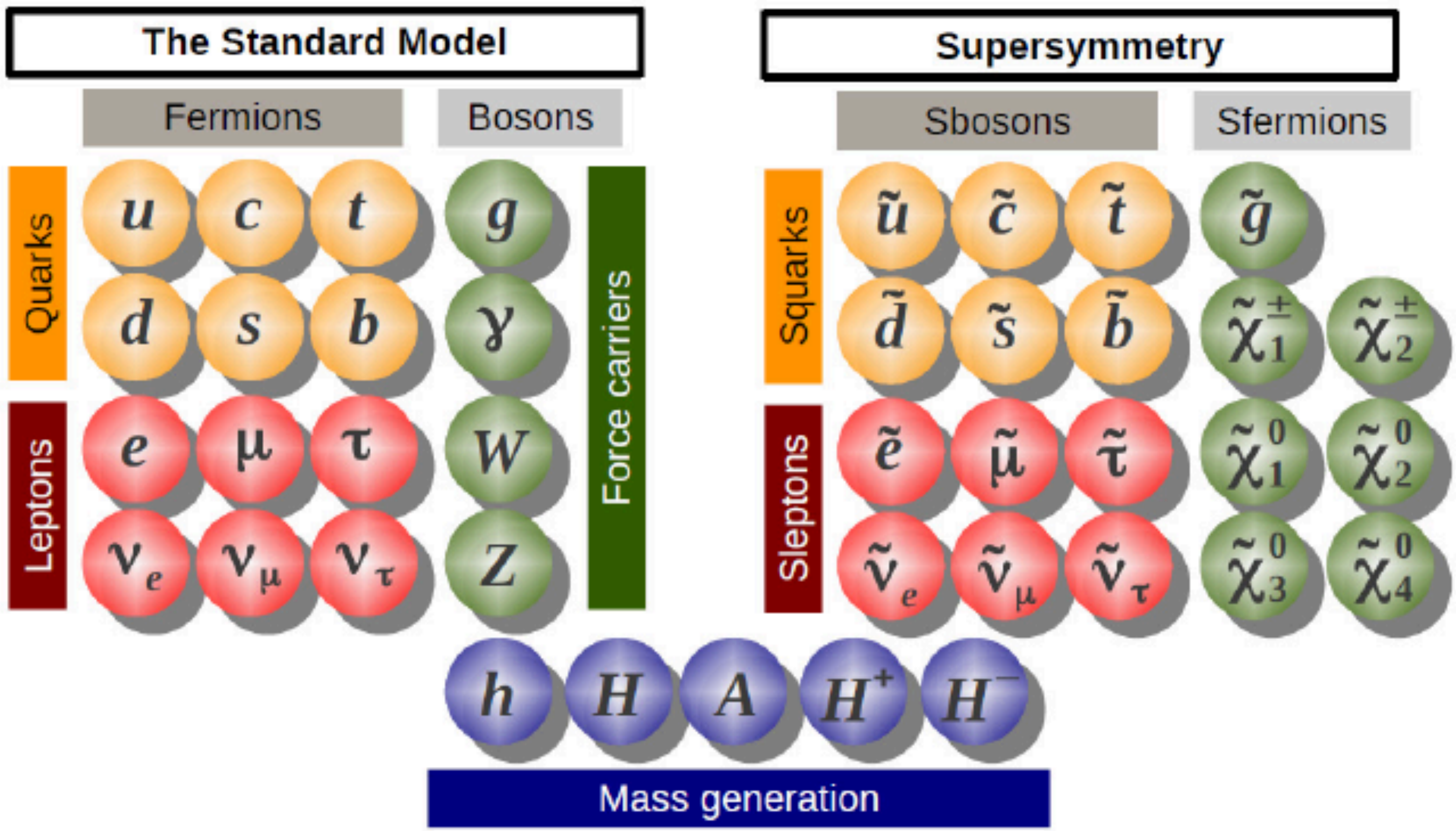
$$m^2_{\text{phys}} = m^2_{\text{bare}} + g\Lambda^2 << \Lambda^2$$

- Attractive solution: introduce a new symmetry, "supersymmetry" which links fermions and bosons
- Each fermion has a boson partner, and vice versa, with the same couplings. Boson and fermion loops contribute with opposite sign, giving a natural cancellation in their effect on the Higgs mass



- Must be a broken symmetry, because we clearly don't see bosons and fermions of the same mass
- However, this doubles the particle content of the model, and introduces lots of new unknown parameters

Supersymmetric Family



$$\mathrm{SM:}\quad W^{\pm},\ W^{0},\ B \xrightarrow{\text{mixing}} W^{\pm},\ Z,\ \gamma$$

$$\mathrm{SUSY:}\quad \tilde{H}_u^0,\ \tilde{H}_d^0,\ \tilde{W}^0,\ \tilde{B}^0 \xrightarrow{\text{mixing}} \tilde{\chi}_1^0,\ \tilde{\chi}_2^0,\ \tilde{\chi}_3^0,\ \tilde{\chi}_4^0$$

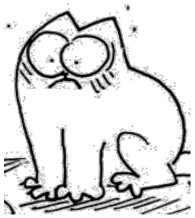
neutralinos

$$\tilde{H}_u^+,\ \tilde{H}_d^-,\ \tilde{W}^+,\ \tilde{W}^- \xrightarrow{\text{mixing}} \tilde{\chi}_1^{\pm},\ \tilde{\chi}_2^{\pm}$$

charginos

Why Supersymmetry is Super? – Dark Matter

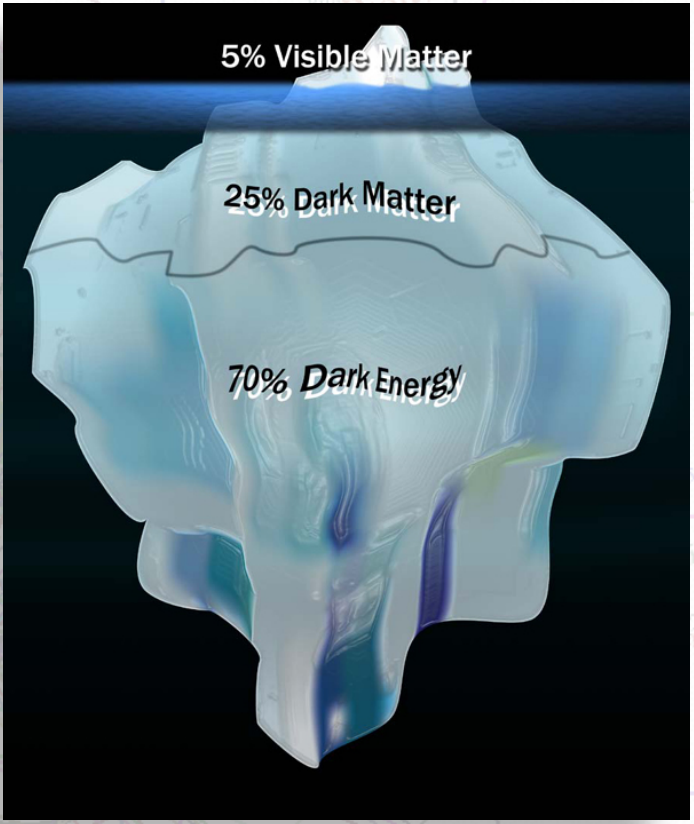
- Astronomy says:
  - Ordinary matter (~5%)
    – the only thing we knew until recently
  - Dark matter (~25%)
    – does not emit light, but seen with gravity
  - Dark energy (~70%)
    – do not know what it is; explain accelerated expansion



- New quantum number => R-parity

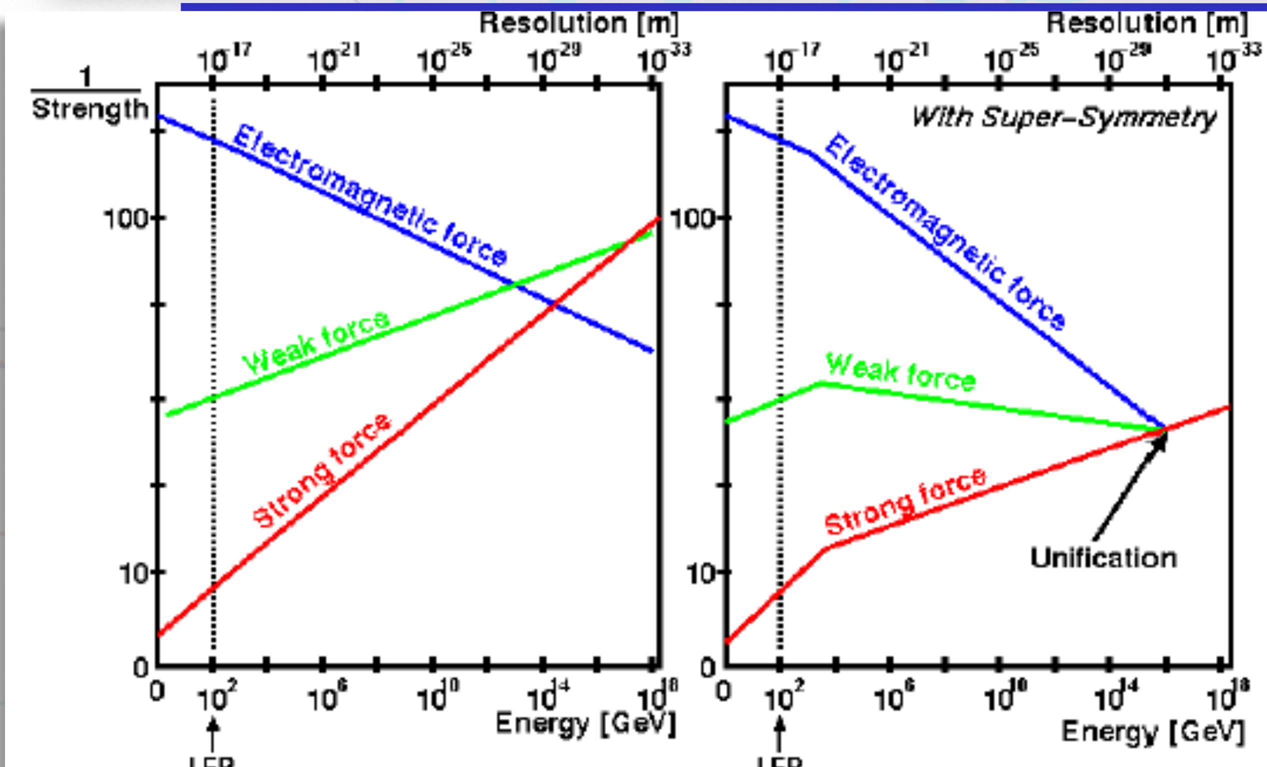
$$R_p = (-1)^{3(B-L)+2S} \qquad \text{S: Spin}$$

- SM particles R=+1
- SUSY particles R=-1
- Multiplicative number
- Two important consequences if R-parity is preserved:
  - Superpartners are pair-produced
  - Lightest superpartner is stable (LSP)
  - Proton is stable (in general SUSY allows for non conservation of L and B)

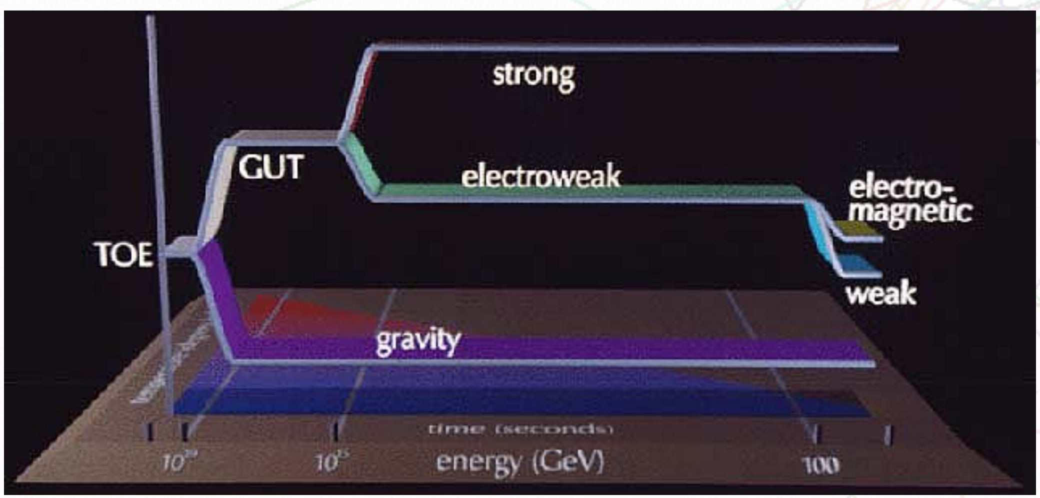


- LSP is good candidate for Dark Matter particle
  - neutralino (mix of fotino, zino and higgsino)
  - Very hard to detect!

Why Supersymmetry is Super? - Unification of Interactions



- In the Standard Model, the interaction strengths are not quite unified at very high energy
- Add SUSY, the running of the couplings is modified, because sparticle loops contribute as well as particle loops
- Details depend on the version of SUSY, but in general unification much improved



However, no sign of supersymmetry yet…

ATLAS SUSY Searches* - 95% CL Lower Limits

October 2019

ATLAS Preliminary

$\sqrt{s}$ = 13 TeV

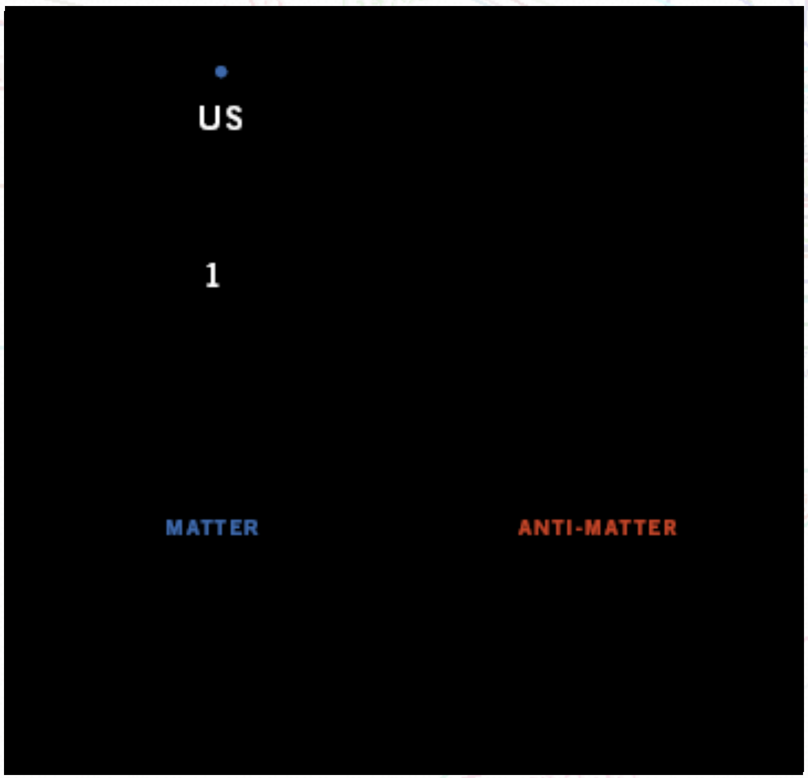
	Model	Signature			$\int \mathcal{L}\, dt$ [fb^{-1}]	Mass limit		Reference
Inclusive Searches	$\tilde{q}\tilde{q}, \tilde{q}\to q\tilde{\chi}^0_1$	0 e,μ	2-6 jets	E_T^{miss}	139	$\tilde{q}$ [10× Degen.] 1.9	m($\tilde{\chi}^0_1$)<400 GeV	ATLAS-CONF-2019-040
		mono-jet	1-3 jets	E_T^{miss}	36.1	$\tilde{q}$ [1×, 8× Degen.] 0.43 0.71	m($\tilde{q}$)-m($\tilde{\chi}^0_1$)=5 GeV	1711.03301
	$\tilde{g}\tilde{g}, \tilde{g}\to q\bar{q}\tilde{\chi}^0_1$	0 e,μ	2-6 jets	E_T^{miss}	139	$\tilde{g}$ 2.35	m($\tilde{\chi}^0_1$)=0 GeV	ATLAS-CONF-2019-040
						$\tilde{g}$ Forbidden 1.15-1.95	m($\tilde{\chi}^0_1$)=1000 GeV	ATLAS-CONF-2019-040
	$\tilde{g}\tilde{g}, \tilde{g}\to q\bar{q}(\ell\ell)\tilde{\chi}^0_1$	3 e,μ	4 jets		36.1	$\tilde{g}$ 1.85	m($\tilde{\chi}^0_1$)<800 GeV	1706.03731
		$ee,\mu\mu$	2 jets	E_T^{miss}	36.1	$\tilde{g}$ 1.2	m($\tilde{g}$)-m($\tilde{\chi}^0_1$)=50 GeV	1805.11381
	$\tilde{g}\tilde{g}, \tilde{g}\to qqWZ\tilde{\chi}^0_1$	0 e,μ	7-11 jets	E_T^{miss}	36.1	$\tilde{g}$ 1.8	m($\tilde{\chi}^0_1$) <400 GeV	1708.02794
		SS e,μ	6 jets		139	$\tilde{g}$ 1.15	m($\tilde{g}$)-m($\tilde{\chi}^0_1$)=200 GeV	1909.08457
	$\tilde{g}\tilde{g}, \tilde{g}\to t\bar{t}\tilde{\chi}^0_1$	0-1 e,μ	3 b	E_T^{miss}	79.8	$\tilde{g}$ 2.25	m($\tilde{\chi}^0_1$)<200 GeV	ATLAS-CONF-2018-041
		SS e,μ	6 jets		139	$\tilde{g}$ 1.25	m($\tilde{g}$)-m($\tilde{\chi}^0_1$)=300 GeV	ATLAS-CONF-2019-015
3rd gen. squarks direct production	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1\to b\tilde{\chi}^0_1/t\tilde{\chi}^\pm_1$		Multiple		36.1	$\tilde{b}_1$ Forbidden 0.9	m($\tilde{\chi}^0_1$)=300 GeV, BR($b\tilde{\chi}^0_1$)=1	1708.09266, 1711.03301
			Multiple		36.1	$\tilde{b}_1$ Forbidden 0.58-0.82	m($\tilde{\chi}^0_1$)=300 GeV, BR($b\tilde{\chi}^0_1$)=BR($t\tilde{\chi}^\pm_1$)=0.5	1708.09266
			Multiple		139	$\tilde{b}_1$ Forbidden 0.74	m($\tilde{\chi}^0_1$)=200 GeV, m($\tilde{\chi}^\pm_1$)=300 GeV, BR($t\tilde{\chi}^\pm_1$)=1	ATLAS-CONF-2019-015
	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1\to b\tilde{\chi}^0_2 \to bh\tilde{\chi}^0_1$	0 e,μ	6 b	E_T^{miss}	139	$\tilde{b}_1$ Forbidden 0.23-1.35	Δm($\tilde{\chi}^0_2,\tilde{\chi}^0_1$)=130 GeV, m($\tilde{\chi}^0_1$)=100 GeV	1908.03122
						$\tilde{b}_1$ 0.23-0.48	Δm($\tilde{\chi}^0_2,\tilde{\chi}^0_1$)=130 GeV, m($\tilde{\chi}^0_1$)=0 GeV	1908.03122
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to Wb\tilde{\chi}^0_1$ or $t\tilde{\chi}^0_1$	0-2 e,μ	0-2 jets/1-2 b	E_T^{miss}	36.1	$\tilde{t}_1$ 1.0	m($\tilde{\chi}^0_1$)=1 GeV	1506.08616, 1709.04183, 1711.11520
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to Wb\tilde{\chi}^0_1$	1 e,μ	3 jets/1 b	E_T^{miss}	139	$\tilde{t}_1$ 0.44-0.59	m($\tilde{\chi}^0_1$)=400 GeV	ATLAS-CONF-2019-017
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to\tilde{\tau}_1 b\nu, \tilde{\tau}_1\to\tau\tilde{G}$	1 τ + 1 e,μ,τ	2 jets/1 b	E_T^{miss}	36.1	$\tilde{t}_1$ 1.16	m($\tilde{\tau}_1$)=800 GeV	1803.10178
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to c\tilde{\chi}^0_1$ / $\tilde{c}\tilde{c}, \tilde{c}\to c\tilde{\chi}^0_1$	0 e,μ	2 c	E_T^{miss}	36.1	$\tilde{c}$ 0.85	m($\tilde{\chi}^0_1$)=0 GeV	1805.01649
						$\tilde{t}_1$ 0.46	m($\tilde{t}_1,\tilde{c}$)-m($\tilde{\chi}^0_1$)=50 GeV	1805.01649
		0 e,μ	mono-jet	E_T^{miss}	36.1	$\tilde{t}_1$ 0.43	m($\tilde{t}_1,\tilde{c}$)-m($\tilde{\chi}^0_1$)=5 GeV	1711.03301
	$\tilde{t}_2\tilde{t}_2, \tilde{t}_2\to\tilde{t}_1 + h$	1-2 e,μ	4 b	E_T^{miss}	36.1	$\tilde{t}_2$ 0.32-0.88	m($\tilde{\chi}^0_1$)=0 GeV, m($\tilde{t}_1$)-m($\tilde{\chi}^0_1$)= 180 GeV	1706.03986
	$\tilde{t}_2\tilde{t}_2, \tilde{t}_2\to\tilde{t}_1 + Z$	3 e,μ	1 b	E_T^{miss}	139	$\tilde{t}_2$ Forbidden 0.86	m($\tilde{\chi}^0_1$)=360 GeV, m($\tilde{t}_1$)-m($\tilde{\chi}^0_1$)= 40 GeV	ATLAS-CONF-2019-016
EW direct	$\tilde{\chi}^\pm_1\tilde{\chi}^0_2$ via WZ	2-3 e,μ		E_T^{miss}	36.1	$\tilde{\chi}^\pm_1/\tilde{\chi}^0_2$ 0.6	m($\tilde{\chi}^0_1$)=0	1403.5294, 1806.02293
		$ee,\mu\mu$	≥ 1	E_T^{miss}	139	$\tilde{\chi}^\pm_1/\tilde{\chi}^0_2$ 0.205	m($\tilde{\chi}^\pm_1$)-m($\tilde{\chi}^0_1$)=5 GeV	ATLAS-CONF-2019-014
	$\tilde{\chi}^\pm_1\tilde{\chi}^\mp_1$ via WW	2 e,μ		E_T^{miss}	139	$\tilde{\chi}^\pm_1$ 0.42	m($\tilde{\chi}^0_1$)=0	1908.08215
	$\tilde{\chi}^\pm_1\tilde{\chi}^0_2$ via Wh	0-1 e,μ	2 b/2 γ	E_T^{miss}	139	$\tilde{\chi}^\pm_1/\tilde{\chi}^0_2$ Forbidden 0.74	m($\tilde{\chi}^0_1$)=70 GeV	ATLAS-CONF-2019-019, 1909.09226
	$\tilde{\chi}^\pm_1\tilde{\chi}^\mp_1$ via $\tilde{\ell}_L/\tilde{\nu}$	2 e,μ		E_T^{miss}	139	$\tilde{\chi}^\pm_1$ 1.0	m($\tilde{\ell},\tilde{\nu}$)=0.5(m($\tilde{\chi}^\pm_1$)+m($\tilde{\chi}^0_1$))	ATLAS-CONF-2019-008
	$\tilde{\tau}\tilde{\tau}, \tilde{\tau}\to\tau\tilde{\chi}^0_1$	2 τ		E_T^{miss}	139	$\tilde{\tau}$ [$\tilde{\tau}_L, \tilde{\tau}_{R,L}$] 0.16-0.3 0.12-0.39	m($\tilde{\chi}^0_1$)=0	ATLAS-CONF-2019-018
	$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}, \tilde{\ell}\to\ell\tilde{\chi}^0_1$	2 e,μ	0 jets	E_T^{miss}	139	$\tilde{\ell}$ 0.7	m($\tilde{\chi}^0_1$)=0	ATLAS-CONF-2019-008
		2 e,μ	≥ 1	E_T^{miss}	139	$\tilde{\ell}$ 0.256	m($\tilde{\ell}$)-m($\tilde{\chi}^0_1$)=10 GeV	ATLAS-CONF-2019-014
	$\tilde{H}\tilde{H}, \tilde{H}\to h\tilde{G}/Z\tilde{G}$	0 e,μ	≥ 3 b	E_T^{miss}	36.1	$\tilde{H}$ 0.13-0.23 0.29-0.88	BR($\tilde{\chi}^0_1 \to h\tilde{G}$)=1	1806.04030
		4 e,μ	0 jets	E_T^{miss}	36.1	$\tilde{H}$ 0.3	BR($\tilde{\chi}^0_1 \to Z\tilde{G}$)=1	1804.03602
Long-lived particles	Direct $\tilde{\chi}^+_1\tilde{\chi}^-_1$ prod., long-lived $\tilde{\chi}^\pm_1$	Disapp. trk	1 jet	E_T^{miss}	36.1	$\tilde{\chi}^\pm_1$ 0.46	Pure Wino	1712.02118
						$\tilde{\chi}^\pm_1$ 0.15	Pure Higgsino	ATL-PHYS-PUB-2017-019
	Stable $\tilde{g}$ R-hadron		Multiple		36.1	$\tilde{g}$ 2.0		1902.01636,1808.04095
	Metastable $\tilde{g}$ R-hadron, $\tilde{g}\to qq\tilde{\chi}^0_1$		Multiple		36.1	$\tilde{g}$ [$\tau(\tilde{g})$ =10 ns, 0.2 ns] 2.05 2.4	m($\tilde{\chi}^0_1$)=100 GeV	1710.04901,1808.04095
RPV	LFV $pp\to\tilde{\nu}_\tau + X, \tilde{\nu}_\tau\to e\mu/e\tau/\mu\tau$	$e\mu,e\tau,\mu\tau$			3.2	$\tilde{\nu}_\tau$ 1.9	λ'_{311}=0.11, $\lambda_{132/133/233}$=0.07	1607.08079
	$\tilde{\chi}^\pm_1\tilde{\chi}^\mp_1/\tilde{\chi}^0_2 \to WW/Z\ell\ell\ell\ell\nu\nu$	4 e,μ	0 jets	E_T^{miss}	36.1	$\tilde{\chi}^\pm_1/\tilde{\chi}^0_2$ [$\lambda_{i33} \neq 0, \lambda_{12k} \neq 0$] 0.82 1.33	m($\tilde{\chi}^0_1$)=100 GeV	1804.03602
	$\tilde{g}\tilde{g}, \tilde{g}\to qq\tilde{\chi}^0_1, \tilde{\chi}^0_1 \to qqq$		4-5 large-R jets		36.1	$\tilde{g}$ [m($\tilde{\chi}^0_1$)=200 GeV, 1100 GeV] 1.3 1.9	Large λ''_{112}	1804.03568
			Multiple		36.1	$\tilde{g}$ [λ''_{112}=2e-4, 2e-5] 1.05 2.0	m($\tilde{\chi}^0_1$)=200 GeV, bino-like	ATLAS-CONF-2018-003
	$\tilde{t}\tilde{t}, \tilde{t}\to t\tilde{\chi}^0_1, \tilde{\chi}^0_1 \to tbs$		Multiple		36.1	$\tilde{g}$ [λ''_{323}=2e-4, 1e-2] 0.55 1.05	m($\tilde{\chi}^0_1$)=200 GeV, bino-like	ATLAS-CONF-2018-003
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to bs$		2 jets + 2 b		36.7	$\tilde{t}_1$ [qq, bs] 0.42 0.61		1710.07171
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to q\ell$	2 e,μ	2 b		36.1	$\tilde{t}_1$ 0.4-1.45	BR($\tilde{t}_1\to be/b\mu$)>20%	1710.05544
		1 μ	DV		136	$\tilde{t}_1$ [1e-10< λ'_{23k} <1e-8, 3e-10< λ'_{23k} <3e-9] 1.0 1.6	BR($\tilde{t}_1\to q\mu$)=100%, cosθ_t=1	ATLAS-CONF-2019-006

10^{-1} 1 Mass scale [TeV]

*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.

Where is antimatter?

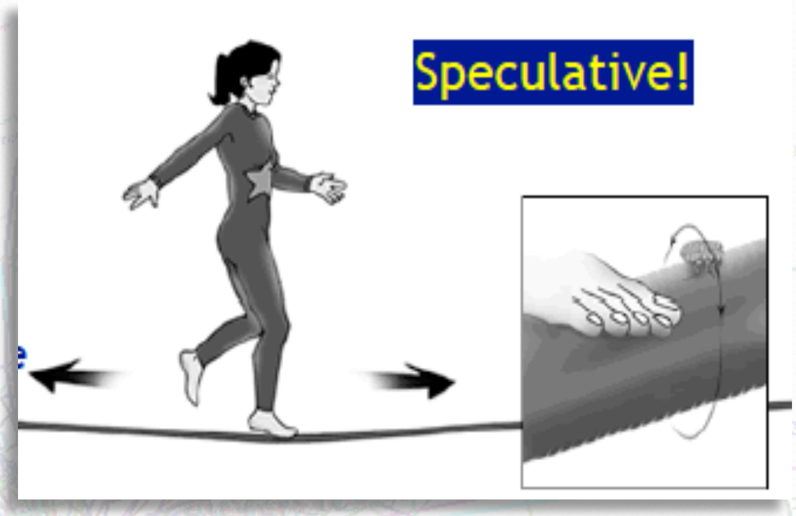
- We exist because there is no antimatter around us



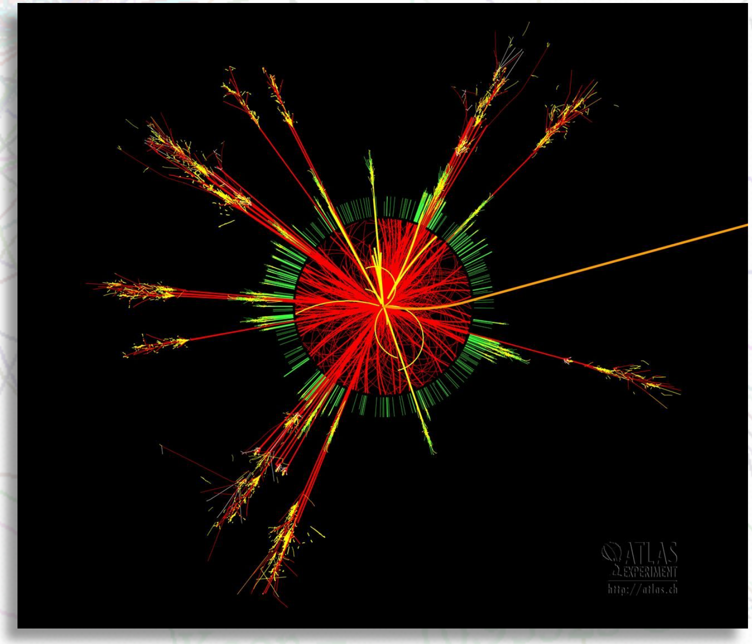
- The Big Bang should have created equal amounts of matter and antimatter in the early universe.
- If matter and antimatter are created and destroyed together, it seems the universe should contain nothing but leftover energy
- Nevertheless, a tiny portion of matter – about one particle per billion – managed to survive. This is what we see today.
- The laws of nature do not apply equally to matter and antimatter!
  - CP violation we observe in kaons and B mesons systems seem to be not enough…
  - There has to be New Physics to explain that asymmetry!

Extra Dimensions

- The ultimate unification of the forces should include gravity (TOE)
- But gravity very much weaker than other forces
- Many ideas proposed to explain this
  - e.g. Extra Dimensions
- Most particles (and us) can only travel in the regular 3 space + 1 time dimensions
- Gravitions - the bosons which propagate gravity - can travel in the extra dimensions
- The real gravitational constant is larger than the effective one we see
- They have to be small extra dimensions, otherwise we'd have seen them already
- If the dimensions are big enough we might see their effects at the LHC!



- Mini black hole production at the LHC would be an observable consequence of extra space-time dimensions
- Black hole will decay very quickly ($\sim 10^{-26}$ s) via Hawking radiation: particles emitted isotopically

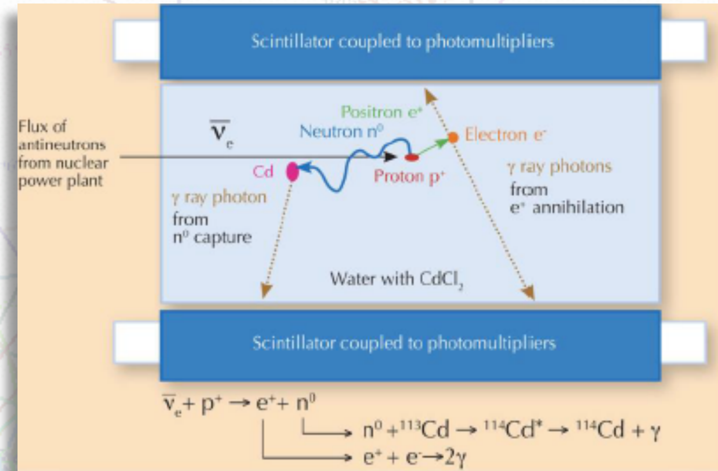


I have done a terrible thing:
I have postulated a particle
that cannot be detected.

Wolfgang Pauli (1930)

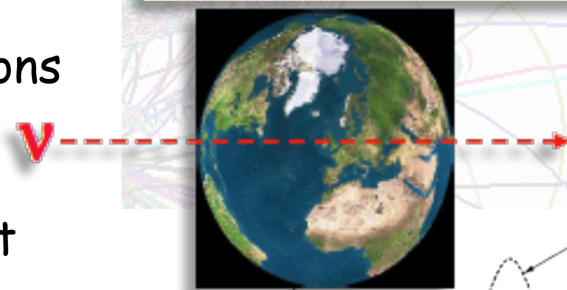
Neutrinos – short reminder

- Neutrinos are known to us since 1930 => β-decay
- It took 26 years to detect this particle
  - Cowan and Reines put a detector close to the reactor and observed the inverse beta decay (few events/hour)

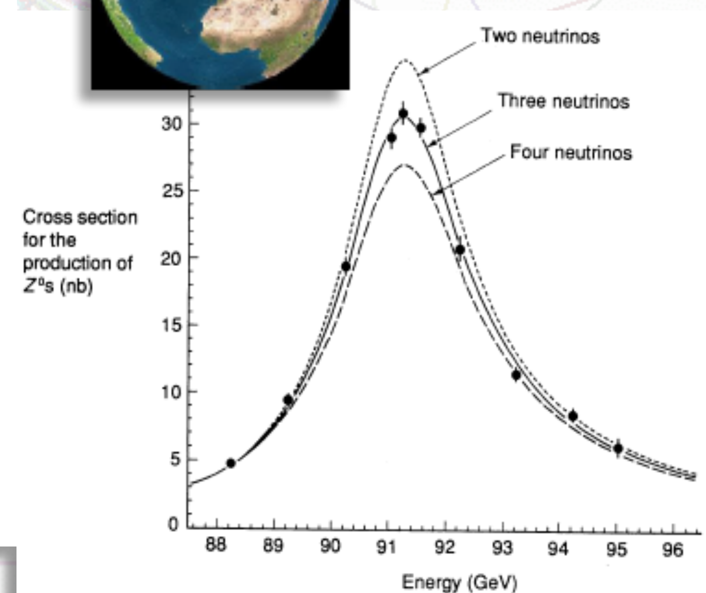


Neutrinos in the Standard Model

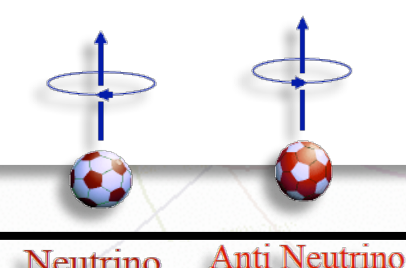
- Massless, chargeless leptons => only weak interactions
- Cross section for neutrino interaction in matter is incredibly small. For energy of the order of 1 MeV average free path in matter (!) of the order of light years !!!



- We need very strong sources and very large detectors to study neutrinos...
- Only 3 ν generations: experimentally verified from Z^0 width measured at LEP (for ν masses <45 GeV/c²)
- ν_e (1956), ν_μ (1962), ν_τ (2001)



- Neutrinos are Left-Handed



Neutrino sources

Natural sources:

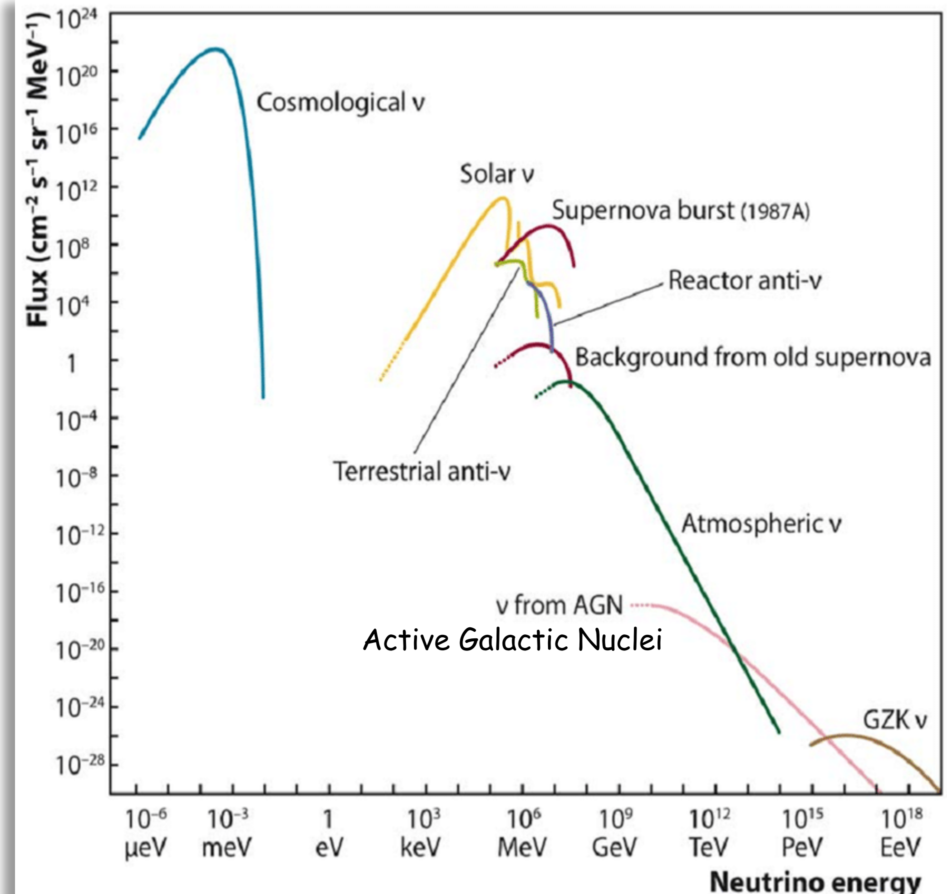
- Atmospheric neutrinos
- Solar neutrinos
- Supernova neutrinos
- Cosmological neutrinos
    - as the universe expanded and cooled, neutrinos decoupled from matter (like cosmic microwave background)
- Geo-neutrinos
    - Radioactivity at the core of the earth

Artificial sources

- Accelerator neutrinos
    - proton beams interacting with dense target produce secondary pions and kaons. Muon neutrinos are produced in:

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$
$$K^+ \rightarrow \mu^+ + \nu_\mu$$

    - By focusing produced pions and kaons prior to their decay, we can obtain high energy neutrino (or anti-neutrino) beams...

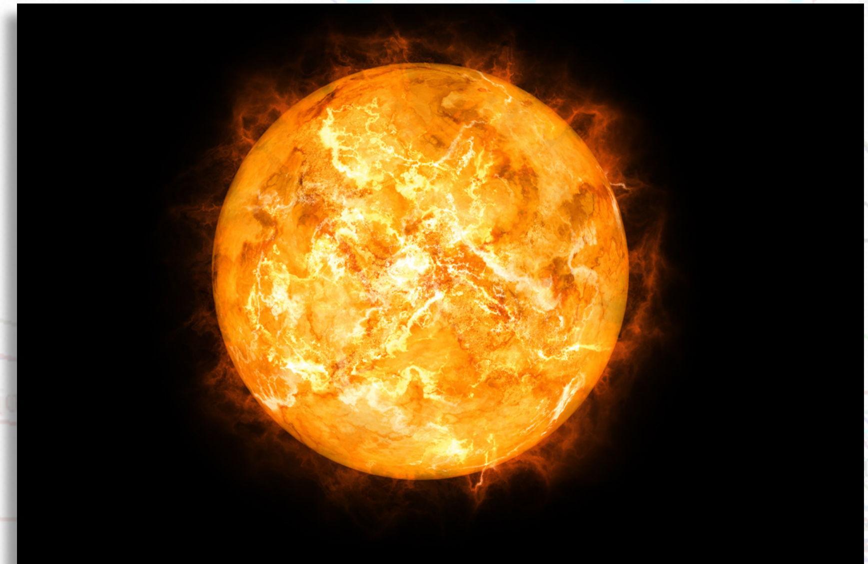


- Reactor neutrinos

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

    - 100% anti-ν_e source, high fluxes (6×10^{20} ν/s), ~ 200 MeV

Solar Neutrinos



$$p + p \rightarrow D + e^+ + \nu_e \ (E_\nu \leq 0.42\ MeV) \quad \textbf{(pp)}$$

$$p + e^- + p \rightarrow D + \nu_e \ (E_\nu \approx 1.44\ MeV) \quad \textbf{(pep)}$$

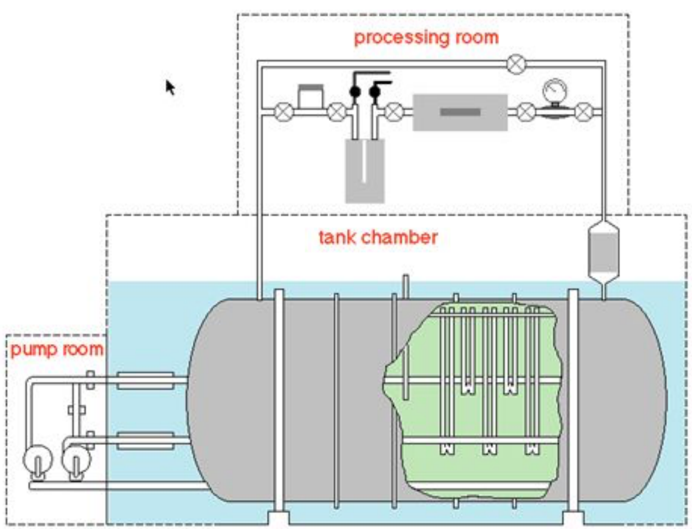
$$^8_5B \rightarrow {}^8_4Be + e^+ + \nu_e \quad \textbf{(up to 15 MeV)}$$

- Light takes about 10-100 thousand years to get out of the solar core
- Solar neutrinos take 2 s!
  - direct, real-time probe of solar processes
- Pure ν_e source 4.0×10^{10} solar neutrinos / cm^2 / sec at the earth

100,000 gallons (615 tons) of cleaning fluid (C_2Cl_4)

$$\nu_e + {}^{37}Cl \rightarrow {}^{37}Ar + e^-$$

Expect about 1.5 Ar atoms/day



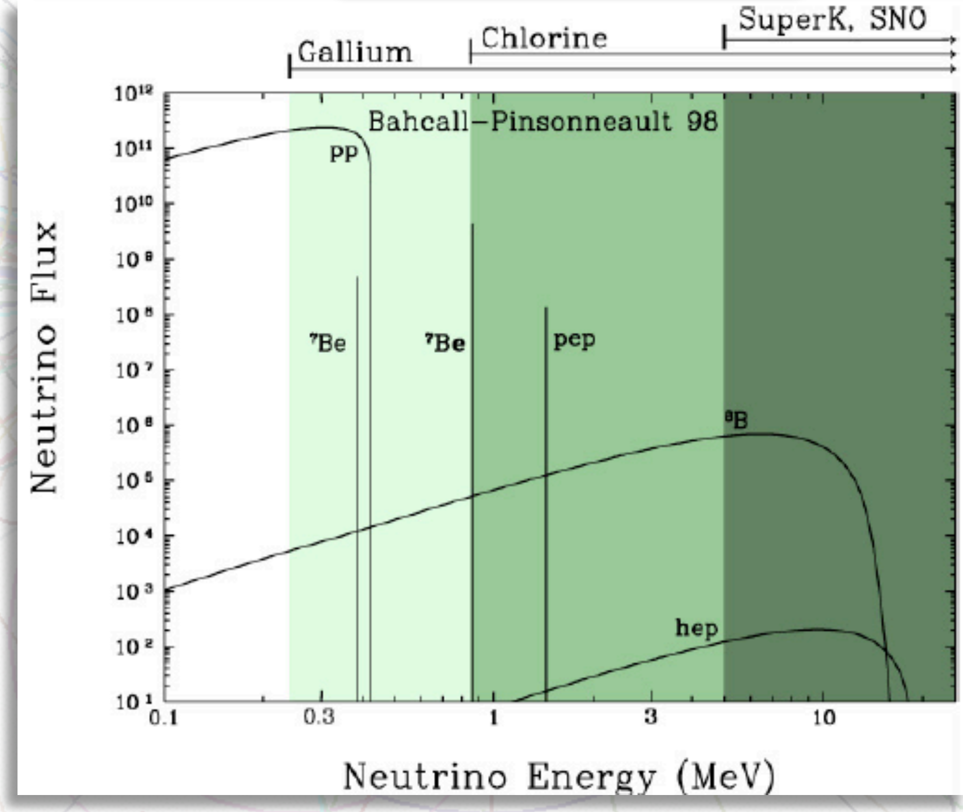
- R. Davis and J. N. Bahcall in late 1960s started developing a detector to detect the neutrinos coming from the Sun in a deep underground mine at Homestake (US)
- Huge tank of the cleansing liquid (C_2Cl_4)
- The flux measured by Davis was about one third of the theoretical prediction using Standard Solar Model!

How to detect neutrinos

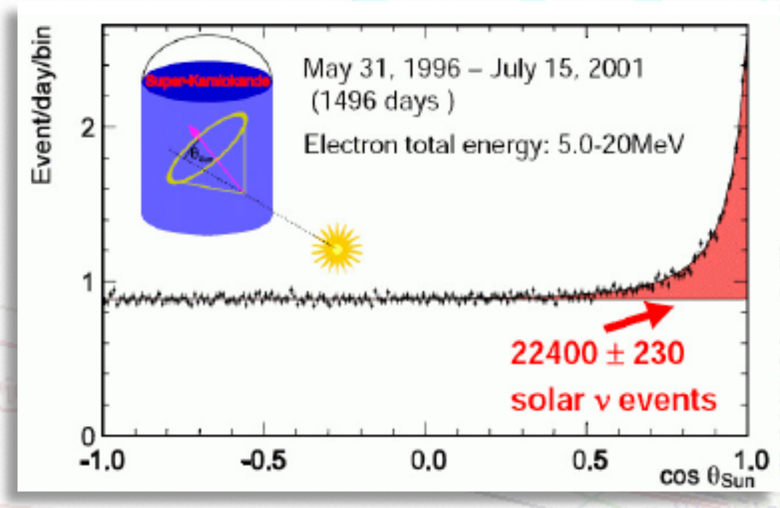
- Go underground to shield the detector from other particles
- Make your detector big
  - use large volumes of cheap materials
- Typical detection techniques:
  - water (light or heavy) – record Cherenkov light
    - Super-Kamiokande, SNO, time and direction, higher threshold
  - radiochemical (Gallium & Chlorine)
    - Gallex/GNO and Sage
    - Produced isotopes are periodically extracted and counted
    - low threshold
    - only event rates counted
    - no time information,no direction
  - liquid argon – record drifting electrons from ionization
    - ICARUS

$$\nu_e + {}^{71}Ga \rightarrow e^- + {}^{71}Ge$$

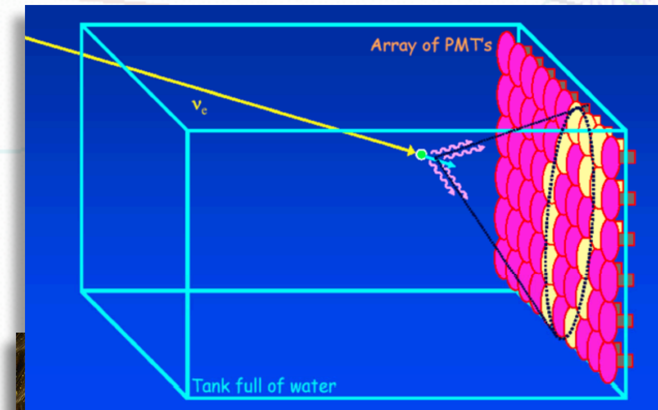
$$\nu_e + {}^{37}Cl \rightarrow e^- + {}^{37}Ar$$

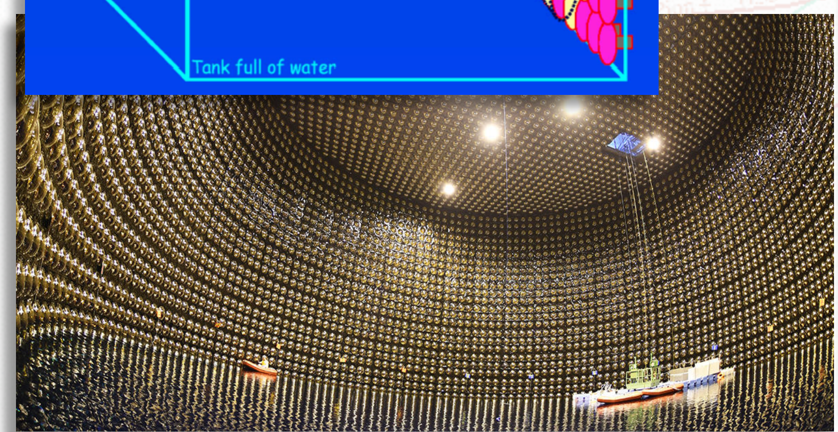


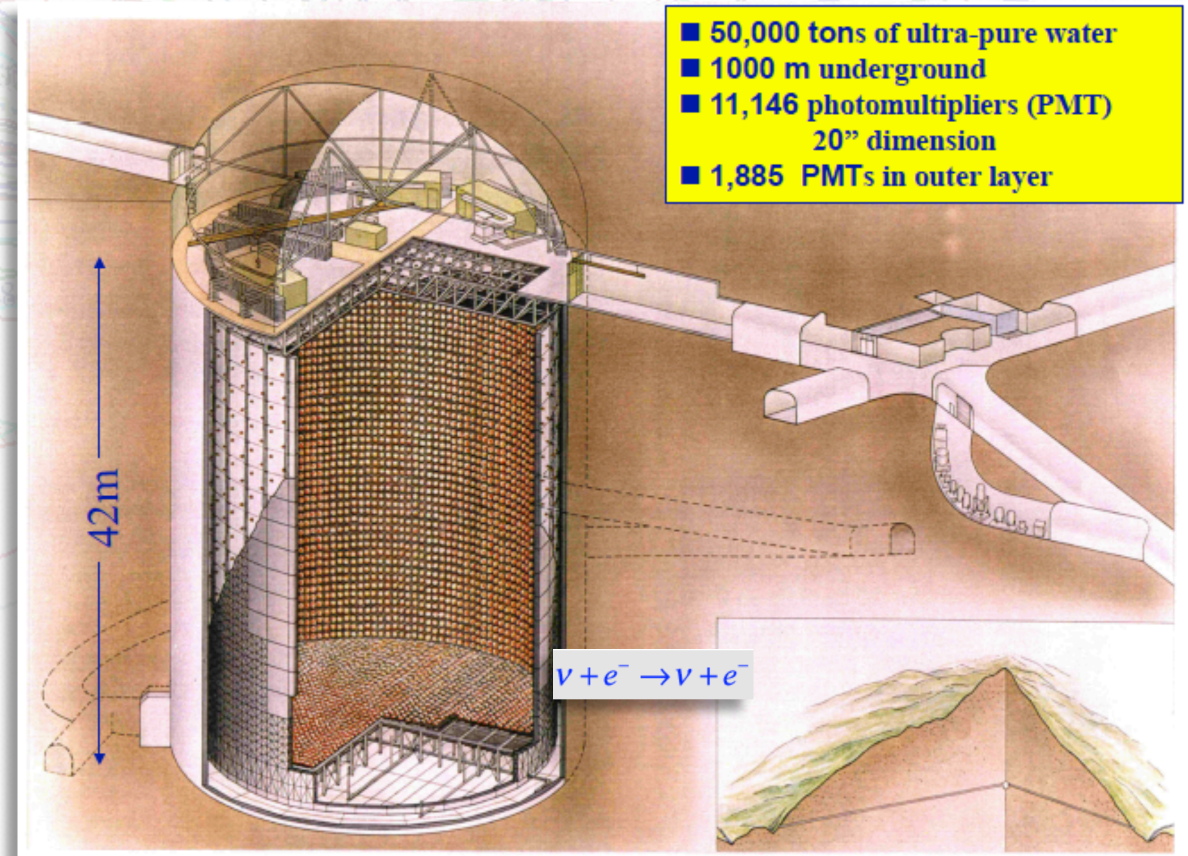
Missing solar neutrinos: Super Kamiokande



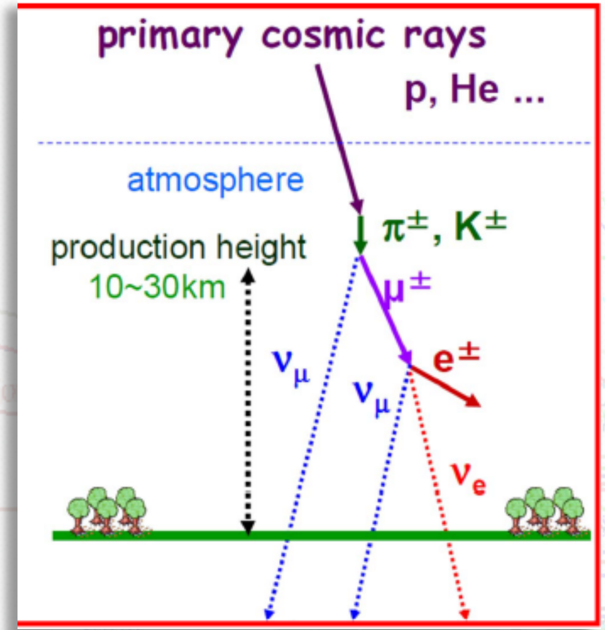
- Results of Davies confirmed by other radiochemical experiments: SAGE i GALLEX
- Deficit observed also in Super-Kamiokande – more than half of the neutrinos missing!
- Solar neutrinos clearly identified by their direction (w.r.t. Sun position)







Atmospheric neutrinos



- High energy cosmic rays (up to 10^{20} eV) interact in the upper part of the Earth's atmosphere
- Primary cosmic rays consist mainly of high energy protons and light nuclei, with energies reaching 10^{12} GeV (10^{21} eV)
- They interact with O and N nuclei in the atmosphere creating a cascade of secondary particles, most of them are pions .

•**Neutrinos produced by:**

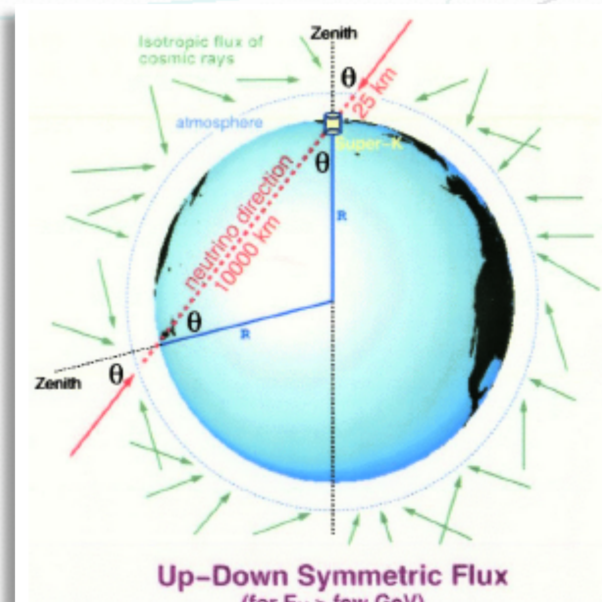
$$\pi^+ \to \mu^+ \nu_\mu \qquad \pi^- \to \mu^- \bar{\nu}_\mu$$

$$\hookrightarrow e^+ \nu_e \bar{\nu}_\mu \qquad \hookrightarrow e^- \bar{\nu}_e \nu_\mu$$

•**Flux** $\sim 1\,\mathrm{cm^{-2}sr^{-1}s^{-1}}$

•**Typical energy :** $E_\nu \sim 1\,\mathrm{GeV}$

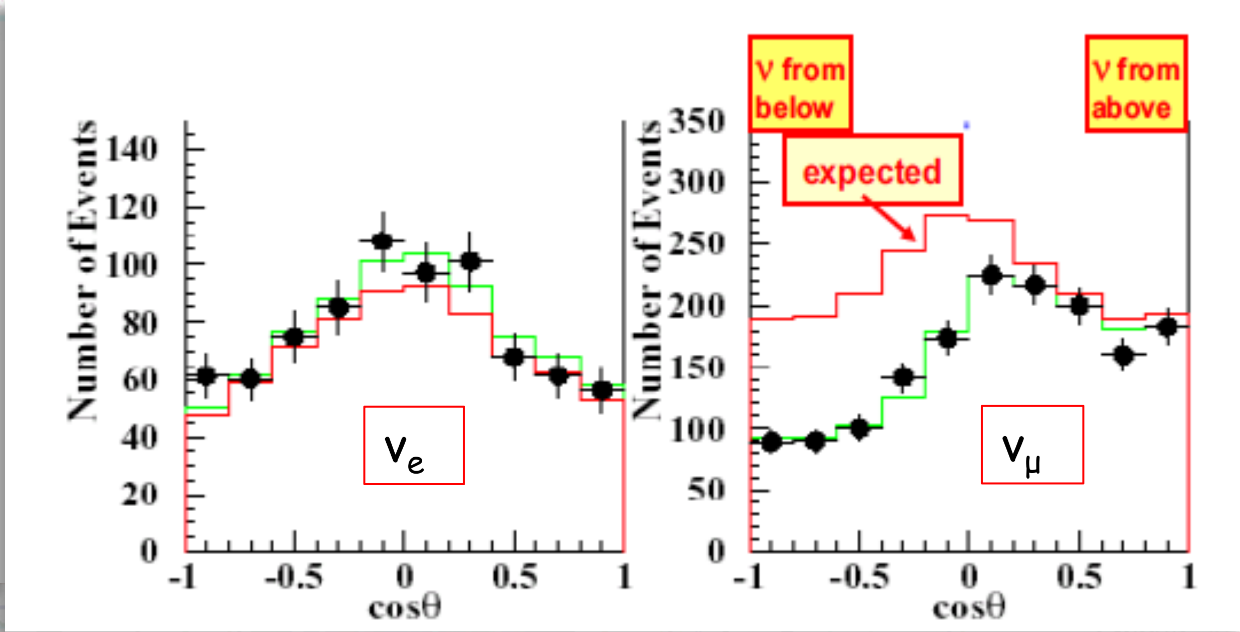
•**Expect** $\dfrac{N(\nu_\mu + \bar{\nu}_\mu)}{N(\nu_e + \bar{\nu}_e)} \approx 2$



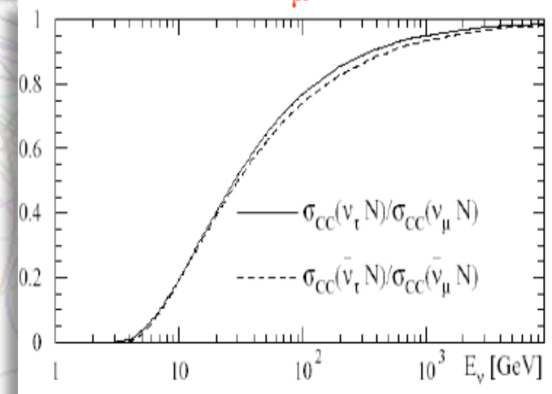
As the primary cosmic radiation is isotropic, we expect that atmospheric neutrino flux will also be isotropic !

Super Kamiokande - Atmospheric Results

- Typical energy ~1 GeV: (much greater than solar neutrinos)
- Neutrinos coming from above travel ~20 km
- Neutrinos coming from below (i.e. other side of the Earth) travel ~12800 km
- Identify ν_e and ν_μ interactions from nature of Cherenkov rings



- Similar number of ν_e going down and going up
  - in agreement with predictions
- Clear deficit of ν_μ!
- Can muon neutrino "disappear" in Earth ?!
- No! We can only explain it assuming neutrinos oscillate to tau neutrinos!
  - Predictions of oscillation model indicated by green histogram
- We cannot detect tau neutrinos
  - CC cross section for interaction (with τ) too small



$$\nu_\mu + N \to \mu^- + X$$

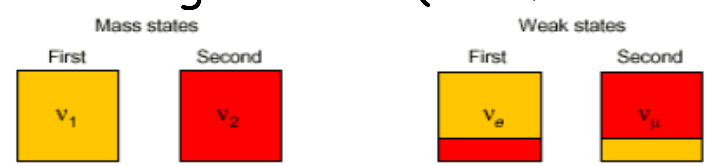
$$\nu_\tau + N \to \tau^- + X$$

Neutrino Oscillations (1)

- Neutrino oscillations were first proposed by Pontecorvo in 1967 who suggested that neutrinos change their flavour as they travel from the Sun to the Earth
- Today, the proposed mechanism of neutrino oscillation extends the SM by assuming that neutrinos do have mass

- We distinguish between two different neutrino state definitions
  - flavor eigenstates - neutrinos with defined lepton flavor as produced in weak interactions: ν_e and ν_μ
  - mass eigenstates - free neutrinos with well defined mass, as propagating in vacuum: ν_1, ν_2
- Flavor eigenstates can be described as a mixture of mass eigenstates (like for quarks):

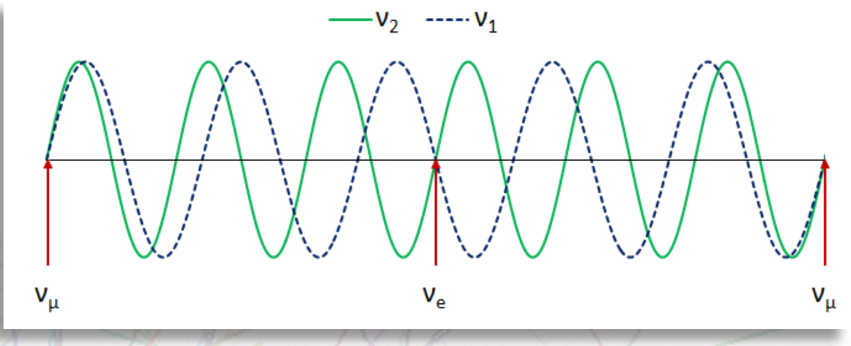
$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} \\ -\sin\theta_{12} & \cos\theta_{12} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$



- Which means that, for example, a particle which is created as ν_e has a certain probability of being observed subsequently as ν_μ or ν_τ.

Neutrino Oscillations (2)

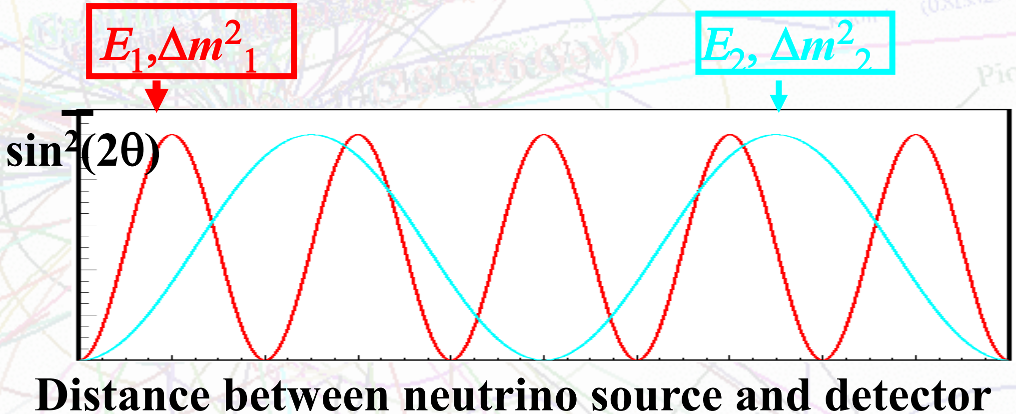
- The masses of the different neutrino mass states are not the same thus they travel at different speeds
- Thus the ratio v_1/v_2 changes during propagation



The two-flavour oscillation probability is:

$$\mathcal{P}_{\alpha\beta}(L) = \sin^2(2\theta)\sin^2\left(1.267\Delta m^2 \frac{L}{E}\right)$$

L -distance between neutrino source and detector



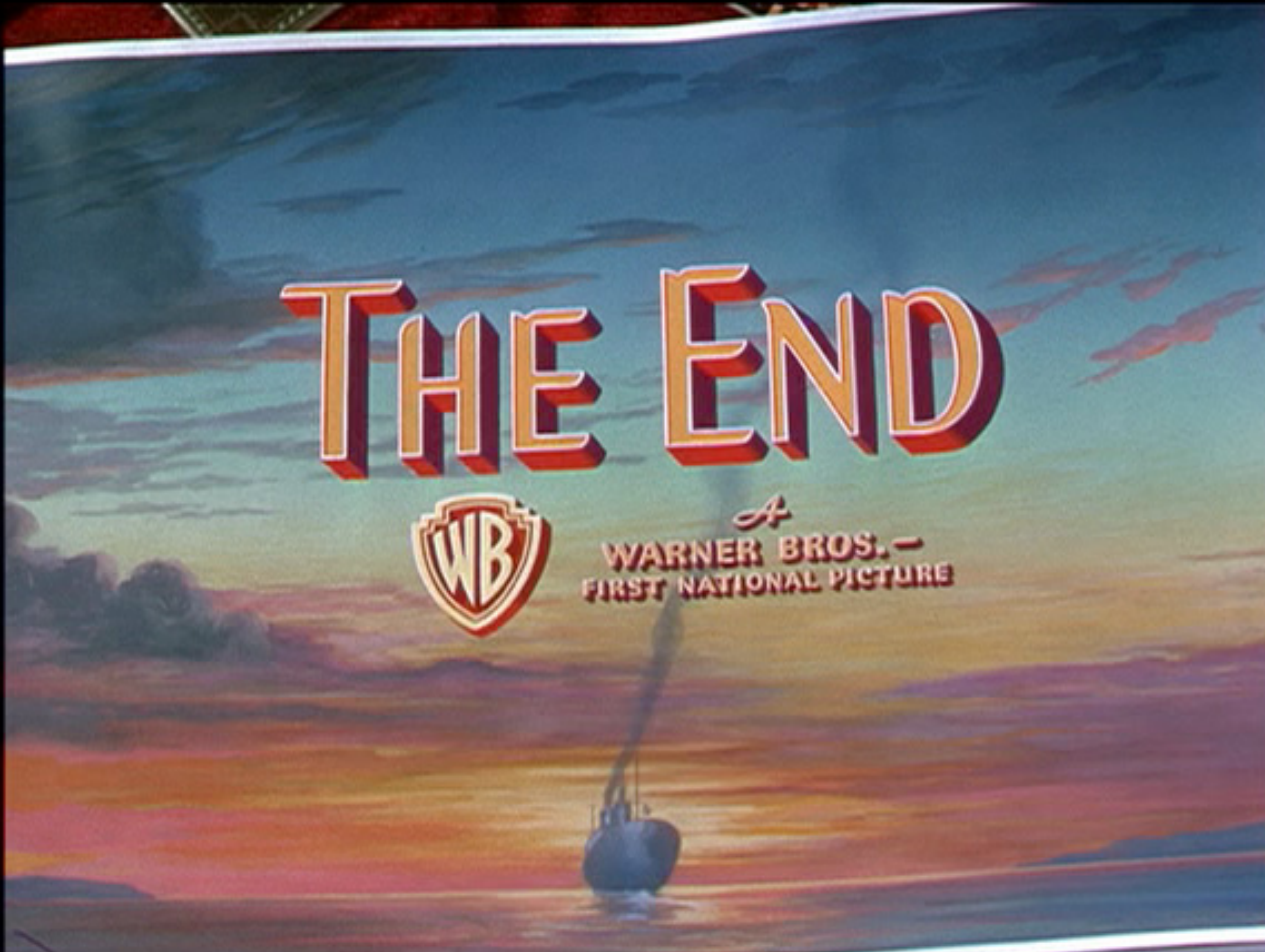
$E_1 < E_2$ and/or $\Delta m^2{}_1 > \Delta m^2{}_2$

Definition of oscillation length λ:

$$\lambda = 2.48 \frac{E}{\Delta m^2}$$

- PMNS - Pontecorvo-Maki-Nakagawa-Sakata matrix for 3 neutrino flavors (like CKM matrix for quarks)
- Experiment SNO (2001): the first clear evidence that solar neutrinos oscillations
  - total flux of all neutrino flavours measured and in agreement with prediction
- Experiment KamLAND - first direct observation of neutrino "regeneration"

Instead Summary


THE END
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