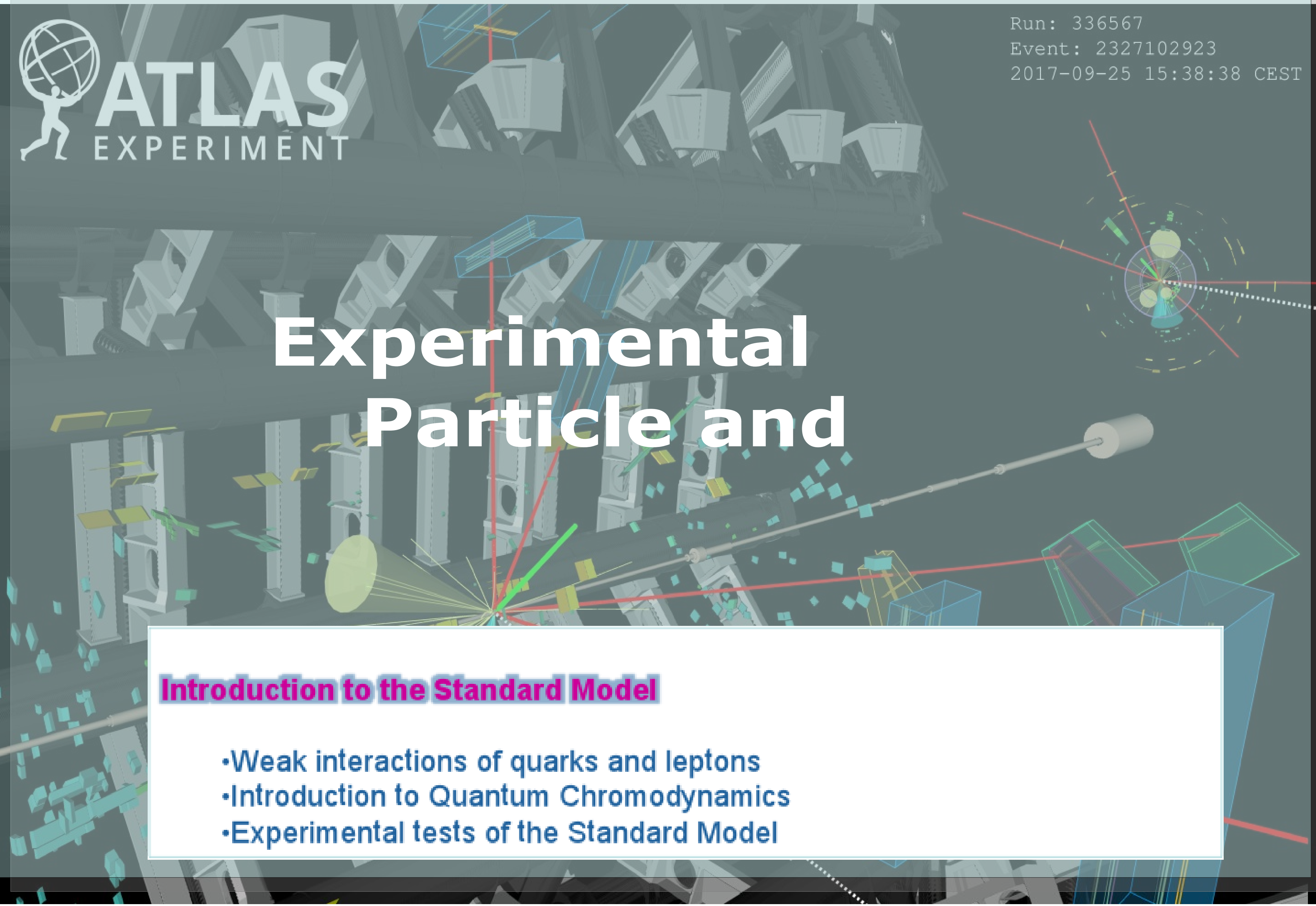


Experimental Particle and

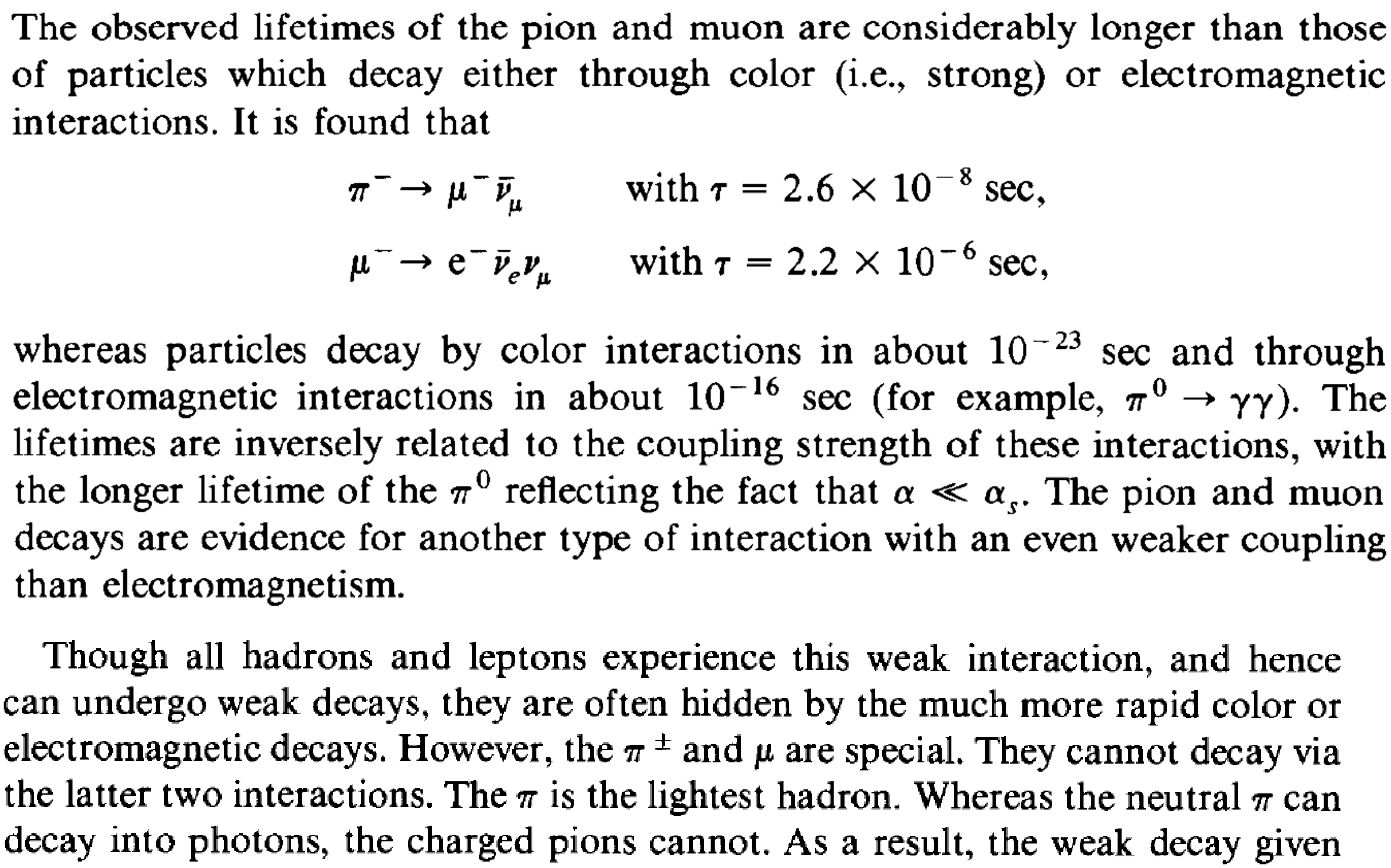
Introduction to the Standard Model

- Weak interactions of quarks and leptons
- Introduction to Quantum Chromodynamics
- Experimental tests of the Standard Model

The (electro)weak interactions

- 1896: radioactivity observed by Bequerel
- 1920/1930: beta-decay doesn’t seem to conserve energy/momentum and angular momentum
- 1930: Pauli suggests the existence of a neutral, light, spin ½ particle (neutrino)
- 1956: Lee & Yang point out that there is no experimental evidence for parity conservation in weak interactions
- 1957: Wu et al observe parity violation in beta-decay
- 1960: V-A theory (Feynman, Gell-Man and others)
- 1967/68: Glashow-Weinberg-Salam model
- 1973: weak neutral currents observed
- 1982: weak bosons (Z,W) discovered
- >1989: electroweak precision testes (LEP, SLC, Tevatron)

The weak interactions



The observed lifetimes of the pion and muon are considerably longer than those of particles which decay either through color (i.e., strong) or electromagnetic interactions. It is found that

$$\pi^- \to \mu^- \bar{\nu}_\mu \qquad \text{with } \tau = 2.6 \times 10^{-8} \text{ sec,}$$

$$\mu^- \to e^- \bar{\nu}_e \nu_\mu \qquad \text{with } \tau = 2.2 \times 10^{-6} \text{ sec,}$$

whereas particles decay by color interactions in about 10^{-23} sec and through electromagnetic interactions in about 10^{-16} sec (for example, $\pi^0 \to \gamma\gamma$). The lifetimes are inversely related to the coupling strength of these interactions, with the longer lifetime of the π^0 reflecting the fact that $\alpha \ll \alpha_s$. The pion and muon decays are evidence for another type of interaction with an even weaker coupling than electromagnetism.

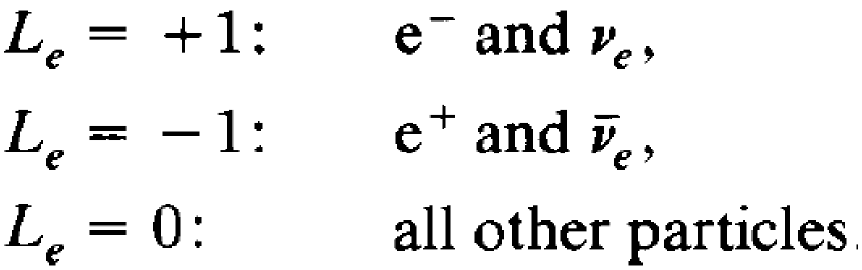
Though all hadrons and leptons experience this weak interaction, and hence can undergo weak decays, they are often hidden by the much more rapid color or electromagnetic decays. However, the $\pi^\pm$ and μ are special. They cannot decay via the latter two interactions. The π is the lightest hadron. Whereas the neutral π can decay into photons, the charged pions cannot. As a result, the weak decay given

- What about $\mu \to e\gamma$?

The weak interactions

- The fact that $\mu \to e\gamma$ is not observed suggests the existence of conserved additive quantum numbers:

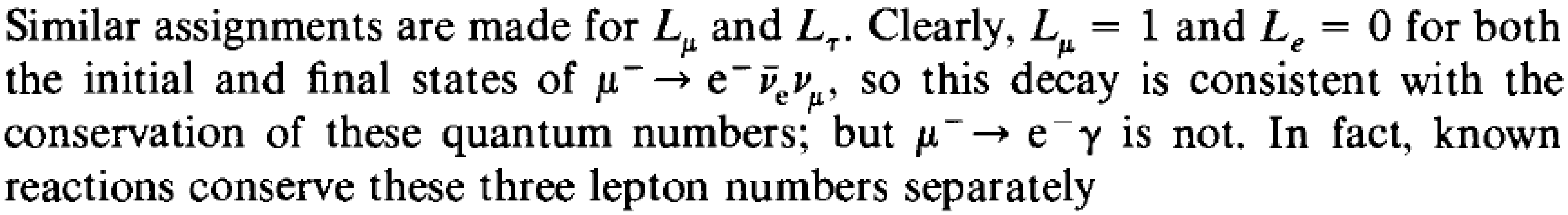
the lepton numbers



$L_e = +1$: e^- and ν_e,

$L_e = -1$: e^+ and $\bar{\nu}_e$,

$L_e = 0$: all other particles.



Similar assignments are made for L_μ and L_τ. Clearly, $L_\mu = 1$ and $L_e = 0$ for both the initial and final states of $\mu^- \to e^- \bar{\nu}_e \nu_\mu$, so this decay is consistent with the conservation of these quantum numbers; but $\mu^- \to e^- \gamma$ is not. In fact, known reactions conserve these three lepton numbers separately

- Notice that the given examples of weak processes involve **neutrinos**: electrically neutral and (almost) massless particles which can only interact by the weak interaction

The weak interactions

The weak interaction is also responsible for the β-decay of atomic nuclei, which involves the transformation of a proton to a neutron (or vice versa). Examples involving the emission of an $e^+\nu_e$ lepton pair are

$$^{10}\mathrm{C} \to {}^{10}\mathrm{B}^* + e^+ + \nu_e,$$

$$^{14}\mathrm{O} \to {}^{14}\mathrm{N}^* + e^+ + \nu_e.$$

Here, one of the protons in the nucleus transforms into a neutron via

$$p \to n e^+ \nu_e.$$

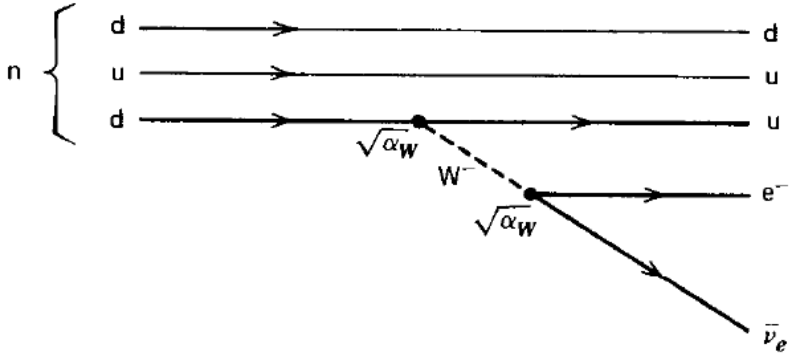
For free protons, this is energetically impossible (check the particle masses), but the crossed reaction, the β-decay process

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

is allowed and is the reason for the neutron's instability (mean life 920 sec). Without the weak interaction, the neutron would be as stable as the proton, which has a lifetime in excess of 10^{30} years.

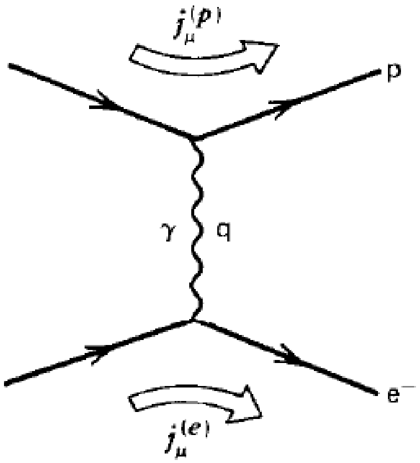
$$p = uud$$

$$n = udd$$



The weak interactions

- In 1932 **Fermi** proposes a theory inspired by the electromagnetic interaction to explain the beta-decay
  - Electromagnetic electron-proton scattering:



$$\mathcal{M} = (e\bar{u}_p\gamma^\mu u_p)\left(\frac{-1}{q^2}\right)(-e\bar{u}_e\gamma_\mu u_e)$$

$$e j_\mu^{em} \equiv j_\mu^{fi}(0) = -e\bar{u}_f\gamma_\mu u_i$$

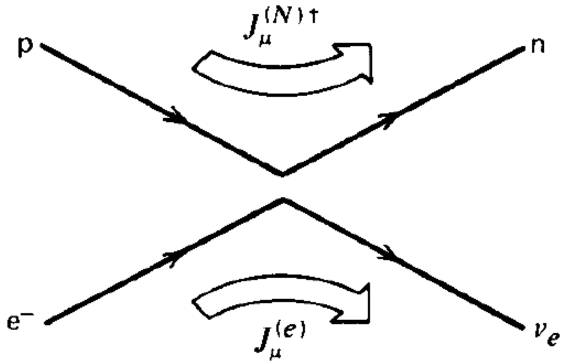
$$\mathcal{M} = -\frac{e^2}{q^2}(j_\mu^{em})_p(j^{em\mu})_e$$

  - Consider the beta-decay process $\mathrm{p} \rightarrow \mathrm{n}e^+\nu_e$

crossing: $\mathrm{p}e^- \rightarrow \mathrm{n}\nu_e$

$$\boxed{\mathcal{M} = G(\bar{u}_n\gamma^\mu u_p)(\bar{u}_{\nu_e}\gamma_\mu u_e)}$$

G is called the Fermi constant



The weak interactions

Parity violation

The parity of pion from: $\pi d \to nn$

1) we can determine the internal parity of the pion by studying pion capture by a deuteron: $\pi + d \to n + n$

2) Pion Spin: 0

Deuteron Spin: 1
(internal) Parity:
+1

Neutron Spin: ½

3) pion captured by the deuteron from a 1S state (*l* **= 0**)

$\Rightarrow$ Total Angular Momentum of the Initial State, *j=1*

4) The parity of initial state: $(-1)^\ell P_\pi P_d = (-1)^0 P_\pi P_d = P_\pi$

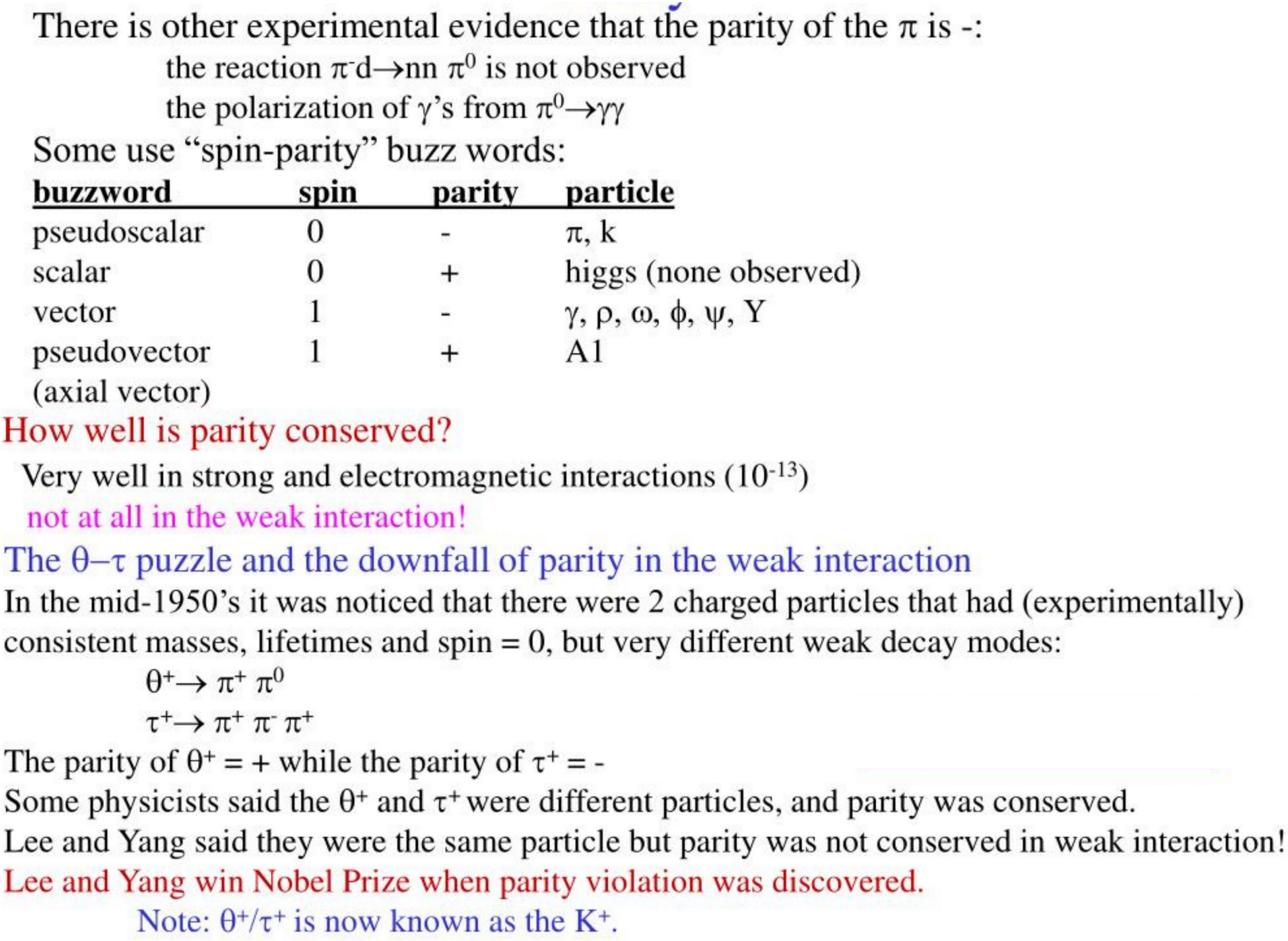
5) The parity of final state: $P_n P_n (-1)^\ell = (-1)^\ell \Rightarrow \boxed{P_\pi = (-1)^\ell}$

6) States for the (n,n) system: ${}^1S_0\,,\ {}^3P_{0,1,2}\,,\ {}^1D_2\,,\ {}^3F_{2,3,4}\ldots$

the one with *j=1* is: ${}^3P_1$ (*l=1*) $\Rightarrow \boxed{P_\pi = -1}$

The weak interactions

Parity violation



There is other experimental evidence that the parity of the π is -:

the reaction $\pi^- d \to nn\ \pi^0$ is not observed

the polarization of γ's from $\pi^0 \to \gamma\gamma$

Some use "spin-parity" buzz words:

buzzword	**spin**	**parity**	**particle**
pseudoscalar	0	-	π, k
scalar	0	+	higgs (none observed)
vector	1	-	γ, ρ, ω, ϕ, ψ, Y
pseudovector (axial vector)	1	+	A1

How well is parity conserved?

Very well in strong and electromagnetic interactions (10^{-13})

not at all in the weak interaction!

The θ–τ puzzle and the downfall of parity in the weak interaction

In the mid-1950's it was noticed that there were 2 charged particles that had (experimentally) consistent masses, lifetimes and spin = 0, but very different weak decay modes:

$$\theta^+ \to \pi^+ \pi^0$$

$$\tau^+ \to \pi^+ \pi^- \pi^+$$

The parity of θ^+ = + while the parity of τ^+ = -

Some physicists said the θ^+ and τ^+ were different particles, and parity was conserved.

Lee and Yang said they were the same particle but parity was not conserved in weak interaction!

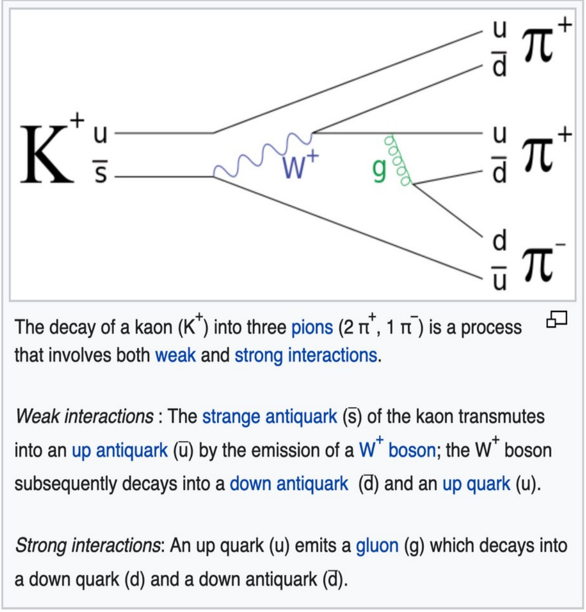
Lee and Yang win Nobel Prize when parity violation was discovered.

Note: θ^+/τ^+ is now known as the K^+.

The weak interactions

Parity violation

Kaons (Strange particles)



The decay of a kaon (K^+) into three pions ($2\,\pi^+$, $1\,\pi^-$) is a process that involves both weak and strong interactions.

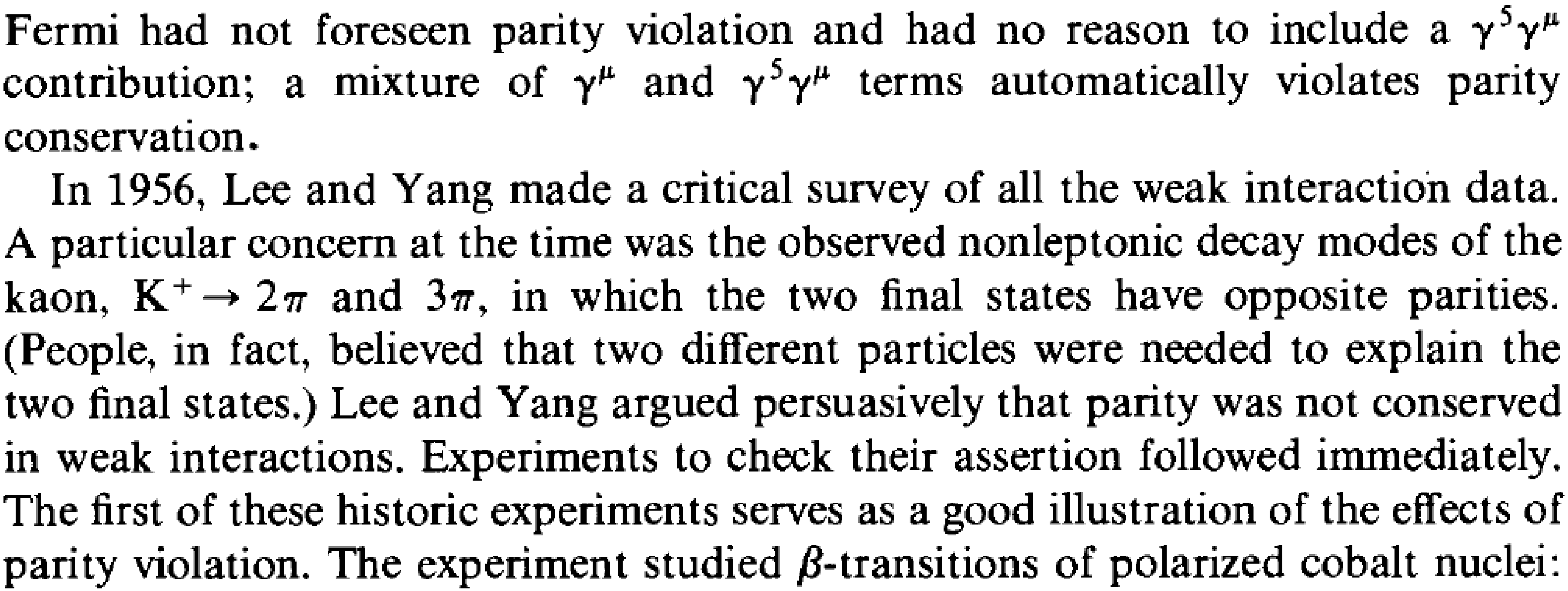
Weak interactions : The strange antiquark ($\bar{s}$) of the kaon transmutes into an up antiquark ($\bar{u}$) by the emission of a W^+ boson; the W^+ boson subsequently decays into a down antiquark ($\bar{d}$) and an up quark (u).

Strong interactions: An up quark (u) emits a gluon (g) which decays into a down quark (d) and a down antiquark ($\bar{d}$).

Properties of kaons

Particle name	Particle symbol	Antiparticle symbol	Quark content	Rest mass (MeV/c^2)	I^G	J^{PC}	S	C	B'	Mean lifetime (s)
Kaon[1]	K^+	K^-	$u\bar{s}$	493.677 ±0.016	½	0^-	1	0	0	$(1.2380 \pm 0.0021) \times 10^{-8}$
Kaon[2]	K^0	$\bar{K}^0$	$d\bar{s}$	497.611 ±0.013	½	0^-	1	0	0	[§]
K-Short[3]	K^0_S	Self	$\frac{d\bar{s}-s\bar{d}}{\sqrt{2}}$ [†]	497.611 ±0.013[‡]	½	0^-	[*]	0	0	$(8.954 \pm 0.004) \times 10^{-11}$
K-Long[4]	K^0_L	Self	$\frac{d\bar{s}+s\bar{d}}{\sqrt{2}}$ [†]	497.611 ±0.013[‡]	½	0^-	[*]	0	0	$(5.116 \pm 0.021) \times 10^{-8}$

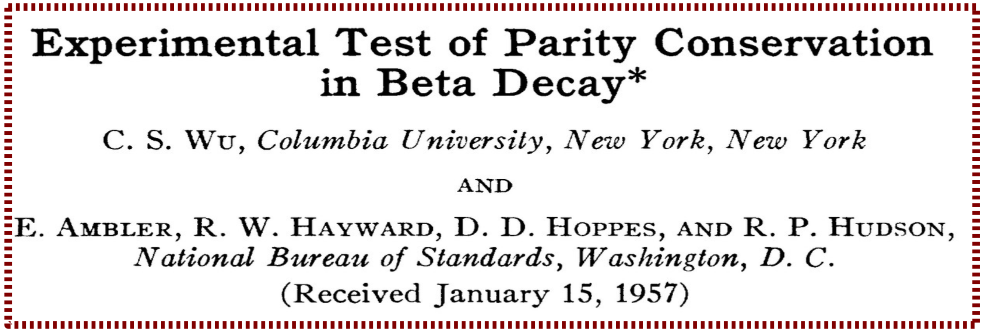
Parity in the weak interactions



Fermi had not foreseen parity violation and had no reason to include a $\gamma^5\gamma^\mu$ contribution; a mixture of γ^μ and $\gamma^5\gamma^\mu$ terms automatically violates parity conservation.

In 1956, Lee and Yang made a critical survey of all the weak interaction data. A particular concern at the time was the observed nonleptonic decay modes of the kaon, $K^+ \to 2\pi$ and 3π, in which the two final states have opposite parities. (People, in fact, believed that two different particles were needed to explain the two final states.) Lee and Yang argued persuasively that parity was not conserved in weak interactions. Experiments to check their assertion followed immediately. The first of these historic experiments serves as a good illustration of the effects of parity violation. The experiment studied β-transitions of polarized cobalt nuclei:

$$^{60}\text{Co} \to {}^{60}\text{Ni}^* + e^- + \bar{\nu}_e .$$



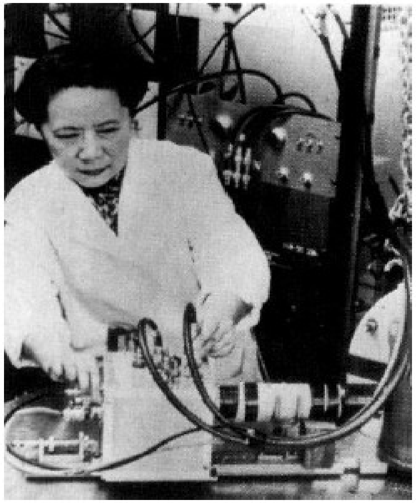
Experimental Test of Parity Conservation in Beta Decay*

C. S. Wu, *Columbia University, New York, New York*

AND

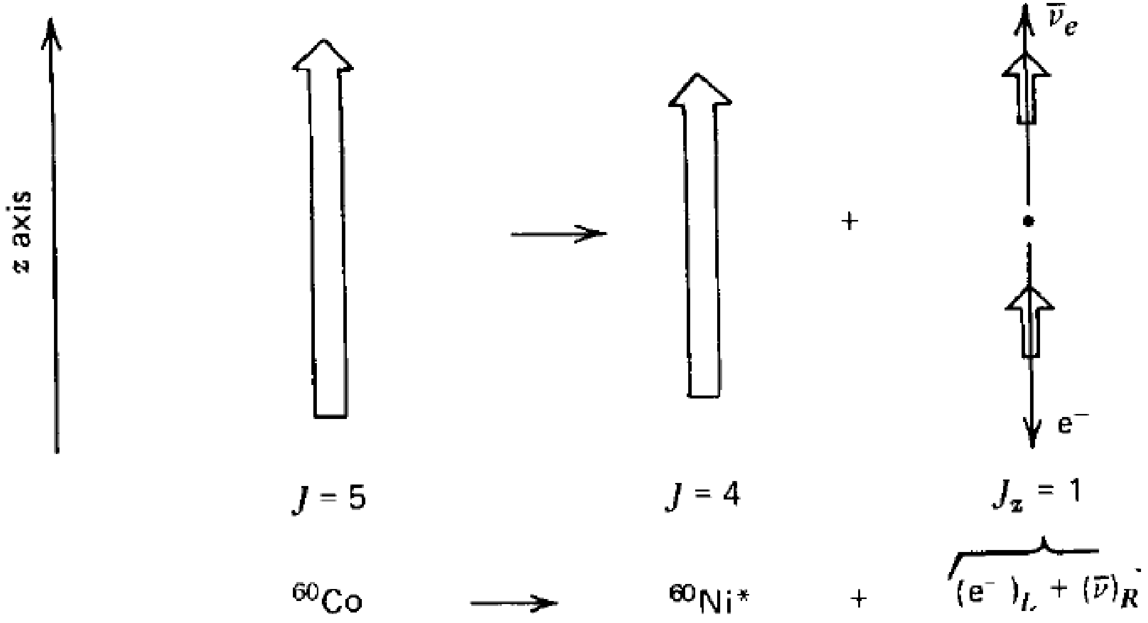
E. Ambler, R. W. Hayward, D. D. Hoppes, and R. P. Hudson,
National Bureau of Standards, Washington, D. C.
(Received January 15, 1957)

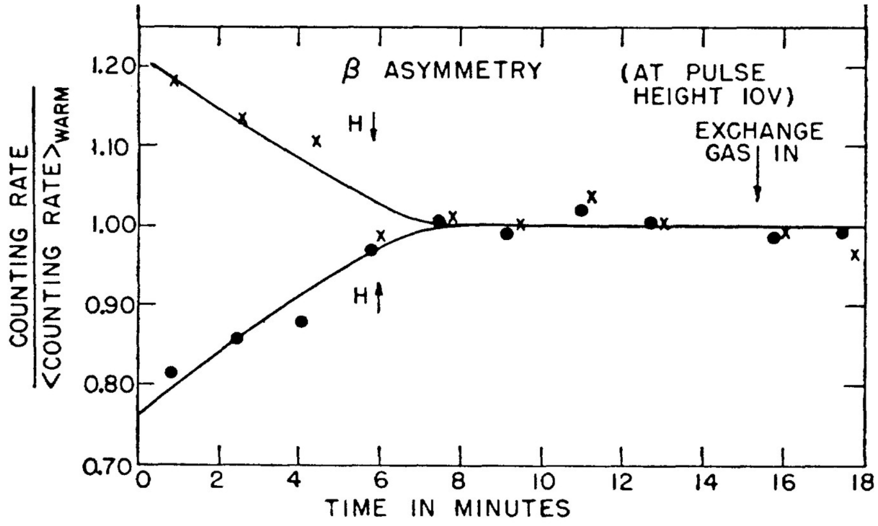
Phys. Rev. 105, 1413–1415 (1957)



Parity in the weak interactions

The nuclear spins in a sample of ^{60}Co were aligned by an external magnetic field, and an asymmetry in the direction of the emitted electrons was observed. The asymmetry was found to change sign upon reversal of the magnetic field such that electrons prefer to be emitted in a direction opposite to that of the nuclear spin.

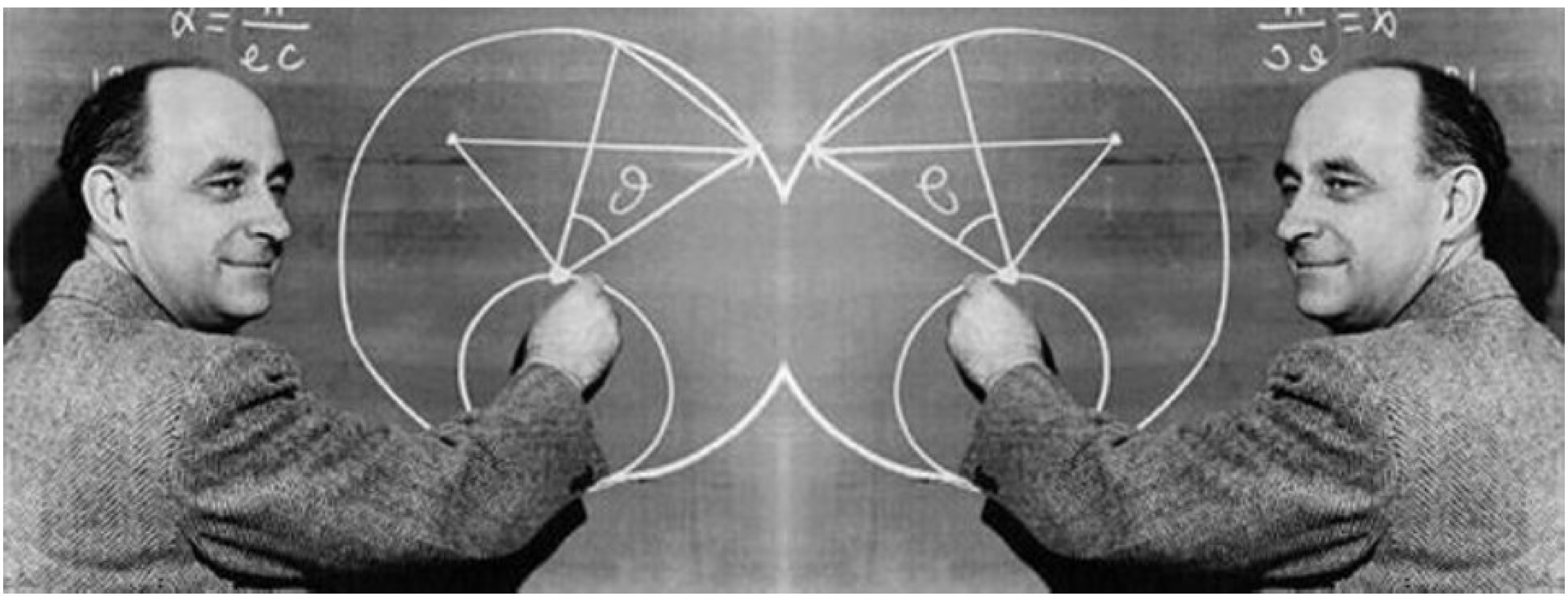




The observed correlation between the nuclear spin and the electron momentum is explained if the required $J_z = 1$ state is formed by a **right-handed antineutrino and a left-handed electron**

Parity in the weak interactions

Enrico Fermi



- Nature favors one side of the mirror!
  - No right-handed neutrinos (left-handed antineutrinos) are observed!

Parity in the weak interactions

- The cumulative evidence of many experiments is that only right-handed antineutrinos and left-handed neutrinos are involved in weak interactions
- The absence of the “mirror image” states is a clear violation of parity invariance
- Charge conjugation (*C*) invariance is also violated, since *C* transforms a left neutrino state into a left antineutrino state

$$\Gamma(\pi^+ \to \mu^+ \nu_L) \neq \Gamma(\pi^+ \to \mu^+ \nu_R) = 0 \qquad \text{P violation,}$$

$$\Gamma(\pi^+ \to \mu^+ \nu_L) \neq \Gamma(\pi^- \to \mu^- \bar{\nu}_L) = 0 \qquad \text{C violation,}$$

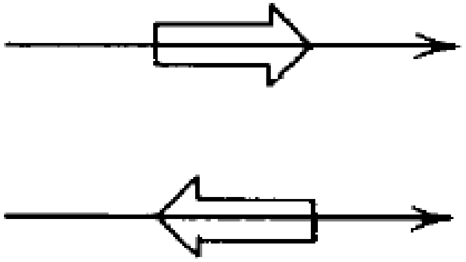
- What about *CP* invariance?...

Helicity and zero-mass fermions

- The "spin" component in the direction of motion, $\frac{1}{2}\boldsymbol{\sigma}\cdot\hat{\mathbf{p}}$, is a "good" quantum number and can be used to label the solutions. We call this quantum number the *helicity* of the state.

- The possible eigenvalues λ of the helicity operator $\frac{1}{2}\boldsymbol{\sigma}\cdot\hat{\mathbf{p}}$ are

$$\lambda = \begin{cases} +\frac{1}{2} & \text{positive helicity,} \\ -\frac{1}{2} & \text{negative helicity.} \end{cases}$$



- Dirac equation, $\boxed{H\psi = (\boldsymbol{\alpha}\cdot\mathbf{p} + \beta m)\psi}$

  note that β is not involved in the case of zero-mass particles and that we need only satisfy $\alpha_i\alpha_j + \alpha_j\alpha_i = 2\delta_{ij}$, $\quad \alpha_i = \alpha_i^\dagger$

  These relations can be realized by the 2×2 Pauli matrices

Helicity and zero-mass fermions

- take $\alpha_i = -\boldsymbol{\sigma}_i$ and $\alpha_i = \boldsymbol{\sigma}_i$, and the massless Dirac equation divides into two *decoupled* equations for two-component spinors $\chi(\mathbf{p})$ and $\phi(\mathbf{p})$:

$$E\chi = -\boldsymbol{\sigma}\cdot\mathbf{p}\,\chi,$$

$$E\phi = +\boldsymbol{\sigma}\cdot\mathbf{p}\,\phi.$$

- Each equation is based on the relativistic energy–momentum relation,

$$E^2 = \mathbf{p}^2$$

and so has one positive and one negative energy solution.

- The positive energy solution has $E = |\mathbf{p}|$ and so satisfies

$$\boldsymbol{\sigma}\cdot\hat{\mathbf{p}}\,\chi = -\chi.$$

That is, χ describes a left-handed neutrino (helicity $\lambda = -\frac{1}{2}$)

Helicity and zero-mass fermions

- consider a neutrino solution with energy $-E$ and momentum $-\mathbf{p}$

$$\boldsymbol{\sigma}\cdot(-\hat{\mathbf{p}})\chi = \chi$$

→ positive helicity, and hence describes a right-handed antineutrino ($\lambda = +\frac{1}{2}$) of energy E and momentum $\mathbf{p}$

- $E\chi = -\boldsymbol{\sigma}\cdot\mathbf{p}\,\chi$ describes ν_L and $\bar{\nu}_R$

- Such a wave equation was first proposed by Weyl in 1929 but was rejected because of noninvariance under the parity operation

$$\nu_L \rightarrow \nu_R$$

→ this is no longer an objection as weak interactions do not respect parity conservation

P_L and P_R operators

$$P_R \equiv \tfrac{1}{2}(1+\gamma^5), \qquad P_L \equiv \tfrac{1}{2}(1-\gamma^5)$$

have the appropriate properties to be (right- and left-hand) projection operators, that is,

$$P_i^2 = P_i, \qquad P_L + P_R = 1, \qquad P_R P_L = 0.$$

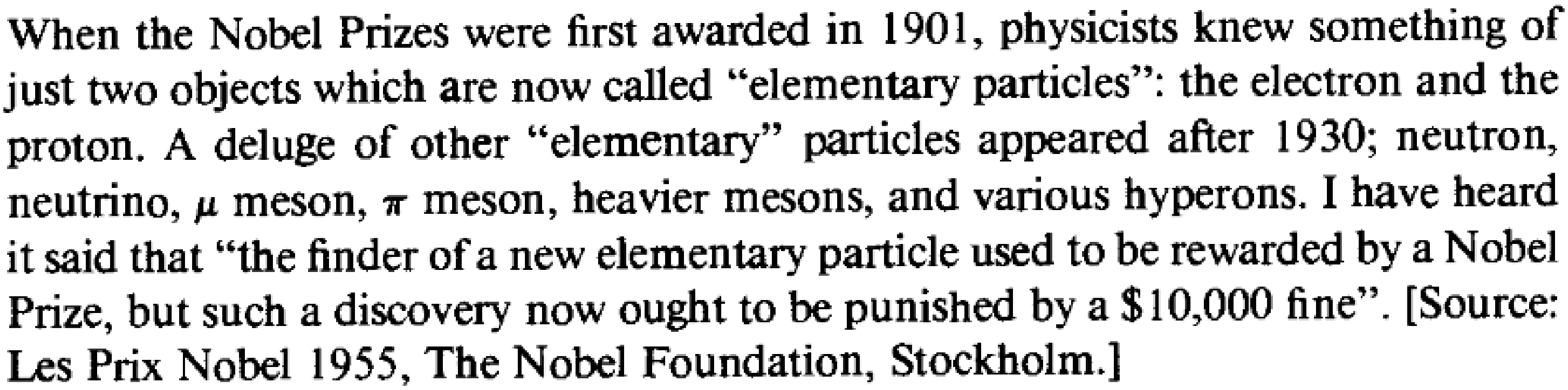
Particles	Antiparticles
$u_L = \tfrac{1}{2}(1-\gamma^5)u$	$v_L = \tfrac{1}{2}(1+\gamma^5)v$
$u_R = \tfrac{1}{2}(1+\gamma^5)u$	$v_R = \tfrac{1}{2}(1-\gamma^5)v$
$\bar{u}_L = \bar{u}\tfrac{1}{2}(1+\gamma^5)$	$\bar{v}_L = \bar{v}\tfrac{1}{2}(1-\gamma^5)$
$\bar{u}_R = \bar{u}\tfrac{1}{2}(1-\gamma^5)$	$\bar{v}_R = \bar{v}\tfrac{1}{2}(1+\gamma^5)$

R and L correspond to helicity $+1$ and -1 if $m = 0$, and *approximately* so if $E \gg mc^2$.

$$u = \left(\frac{1-\gamma^5}{2}\right)u + \left(\frac{1+\gamma^5}{2}\right)u = u_L + u_R$$

1950's: more and more particles discovered

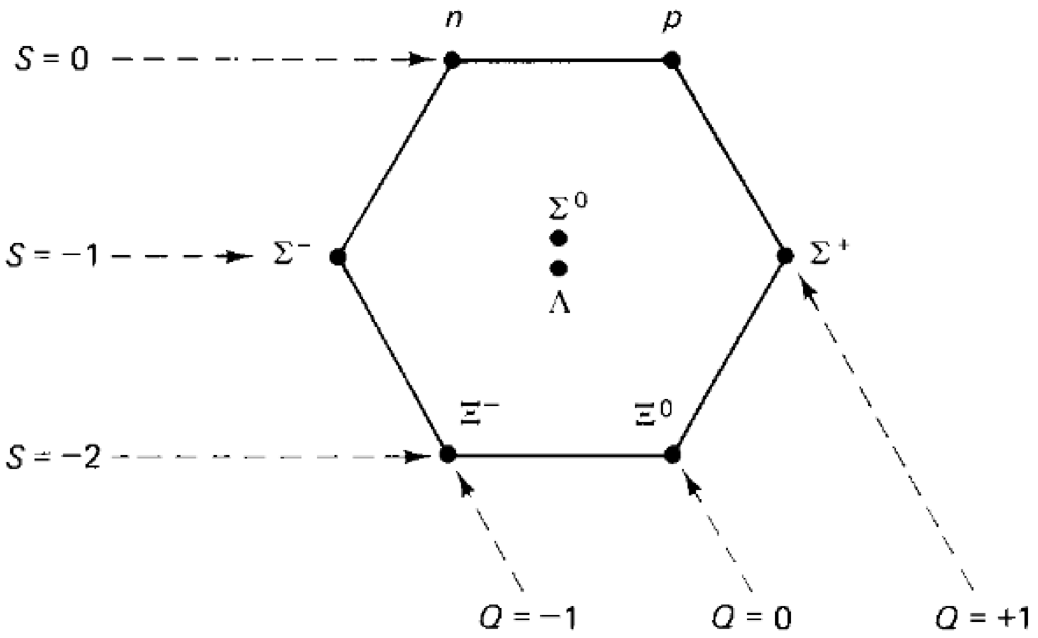
- Willis Lamb Nobel lecture in 1955:



When the Nobel Prizes were first awarded in 1901, physicists knew something of just two objects which are now called "elementary particles": the electron and the proton. A deluge of other "elementary" particles appeared after 1930; neutron, neutrino, μ meson, π meson, heavier mesons, and various hyperons. I have heard it said that "the finder of a new elementary particle used to be rewarded by a Nobel Prize, but such a discovery now ought to be punished by a $10,000 fine". [Source: Les Prix Nobel 1955, The Nobel Foundation, Stockholm.]

The Eightfold Way (1961-1964)

The Mendeleev of elementary particle physics was Murray Gell-Mann, who introduced the so-called *Eightfold Way* in 1961.[21] (Essentially the same scheme was proposed independently by Ne'eman.) The Eightfold Way arranged the baryons and mesons into weird geometrical patterns, according to their charge and strangeness. The eight lightest baryons fit into a hexagonal array, with two particles at the center:

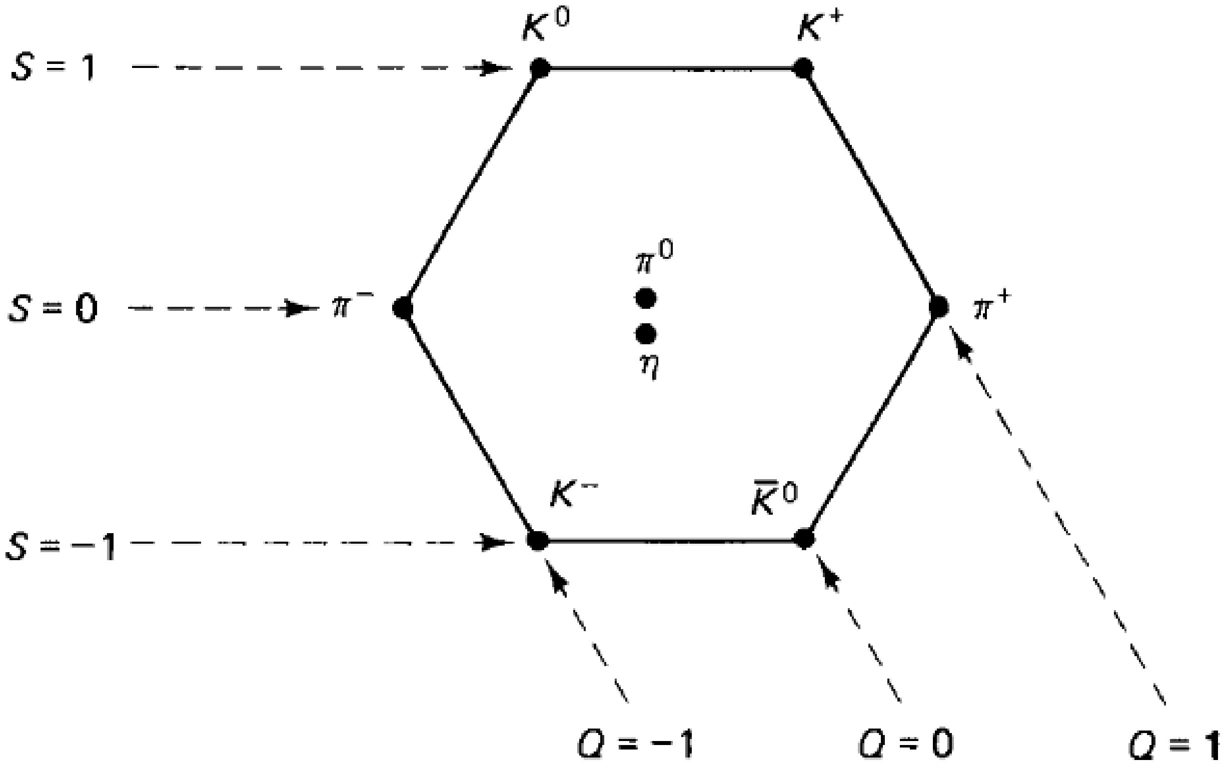


The Baryon Octet

There is some arbitrariness in the assignment of strangeness numbers, obviously. We could just as well have given $S = +1$ to the Σ's and the Λ, and $S = -1$ to K^+ and K^0; in fact, in retrospect it would have been a little nicer that way. [In exactly the same sense, Benjamin Franklin's original convention for

The Eightfold Way (1961-1964)

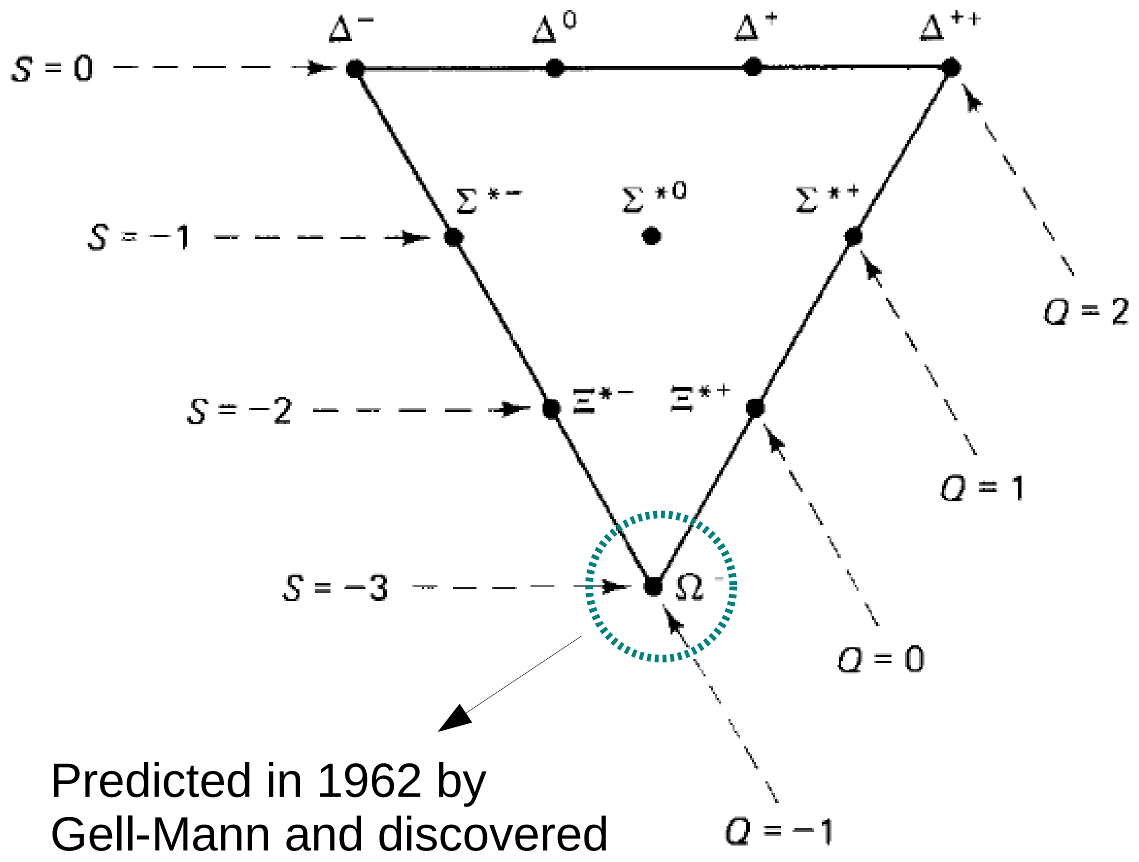
The eight lightest mesons fill a similar hexagonal pattern, forming the *(pseudo-scalar) meson octet:*



The Meson Octet

The Eightfold Way (1961-1964)

Hexagons were not the only figures allowed by the Eightfold Way; there was also, for example, a triangular array, incorporating 10 heavier baryons—the *baryon decuplet:*

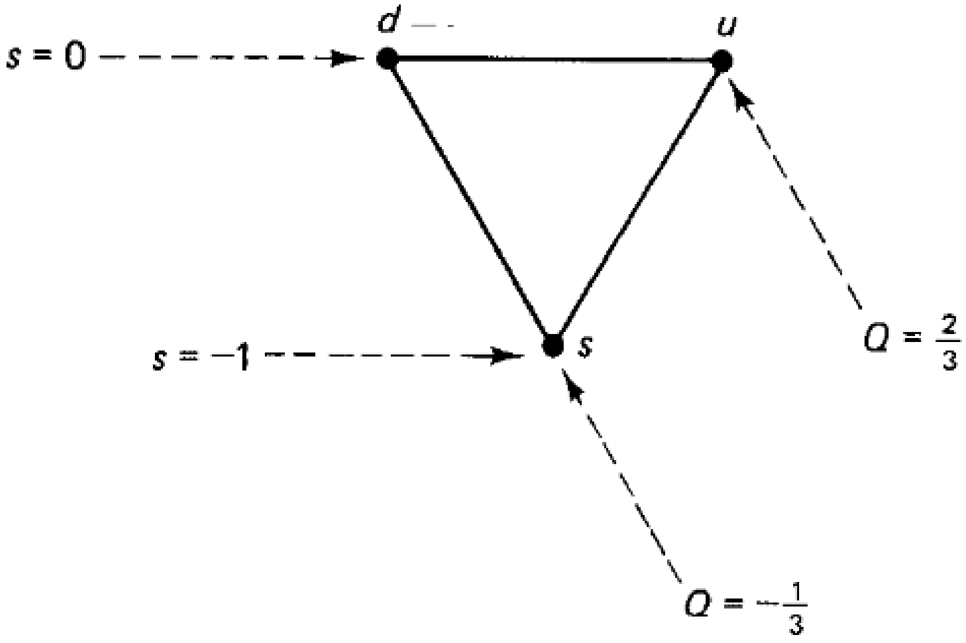


The Baryon Decuplet

Predicted in 1962 by
Gell-Mann and discovered
In 1964

The quark model (1964)

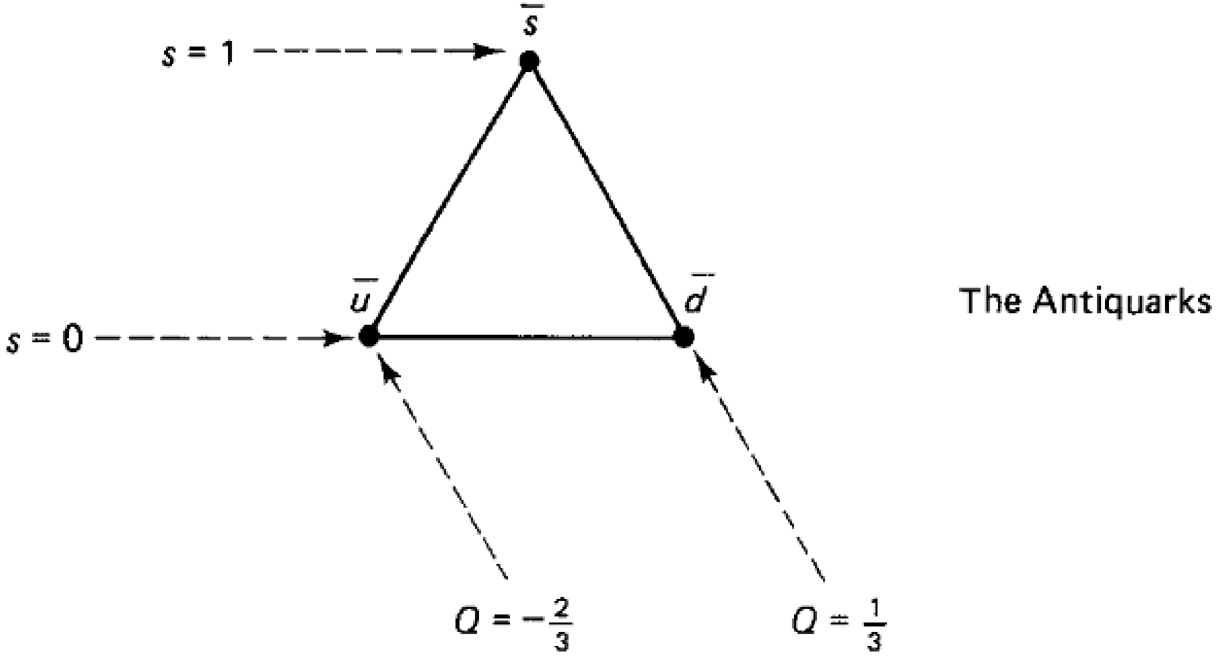
But the very success of the Eightfold Way begs the question: *Why* do the hadrons fit into these curious patterns? The Periodic Table had to wait many years for quantum mechanics and the Pauli exclusion principle to provide its explanation. An understanding of the Eightfold Way, however, came already in 1964, when Gell-Mann and Zweig independently proposed that all hadrons are in fact composed of even more elementary constituents, which Gell-Mann called *quarks*.[24] The quarks come in three types (or "flavors"), forming a triangular "Eightfold-Way" pattern:



The Quarks

The quark model (1964)

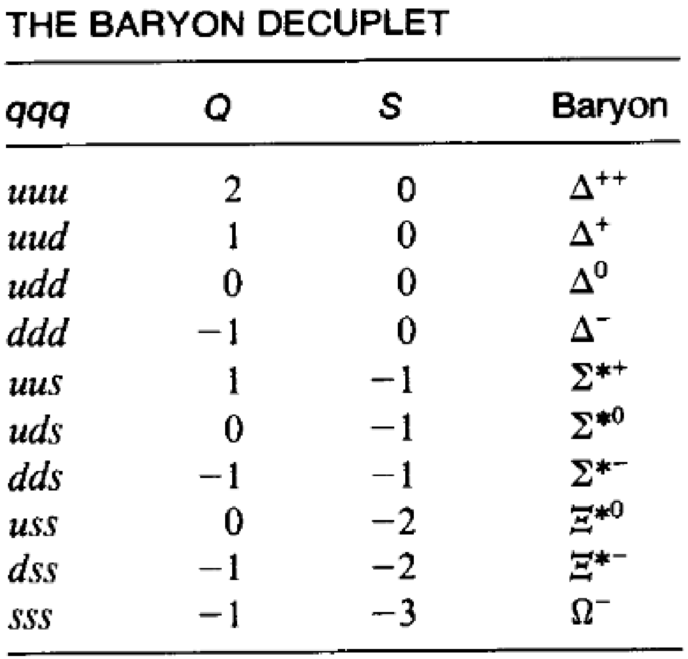
The *u* (for "up") quark carries a charge of $\frac{2}{3}$ and a strangeness of zero; the *d* ("down") quark carries a charge of $-\frac{1}{3}$ and $S = 0$; the *s* (originally "sideways", but now more commonly "strange") quark has $Q = -\frac{1}{3}$ and $S = -1$. To each quark (q) there corresponds an *anti*quark ($\bar{q}$), with the opposite charge and strangeness:



The quark model asserts that

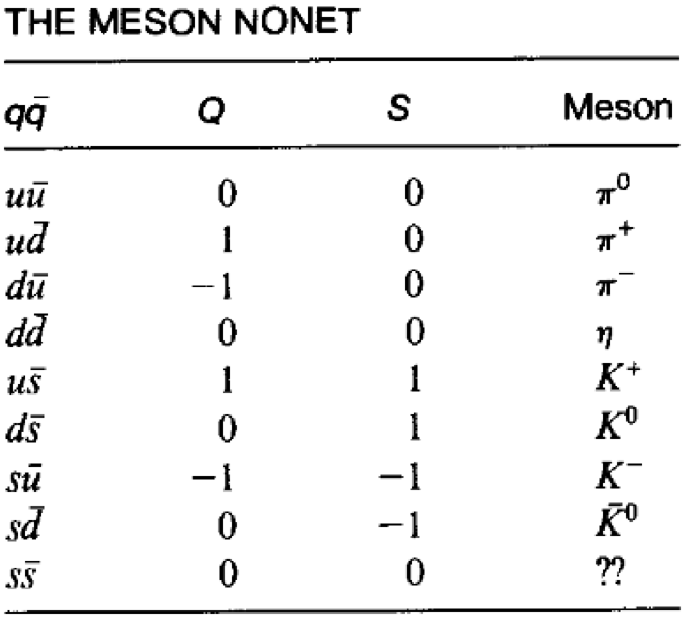
1. Every baryon is composed of three quarks (and every *anti*baryon is composed of three *anti*quarks).
2. Every meson is composed of a quark and an antiquark.

The quark model (1964)



THE BARYON DECUPLET

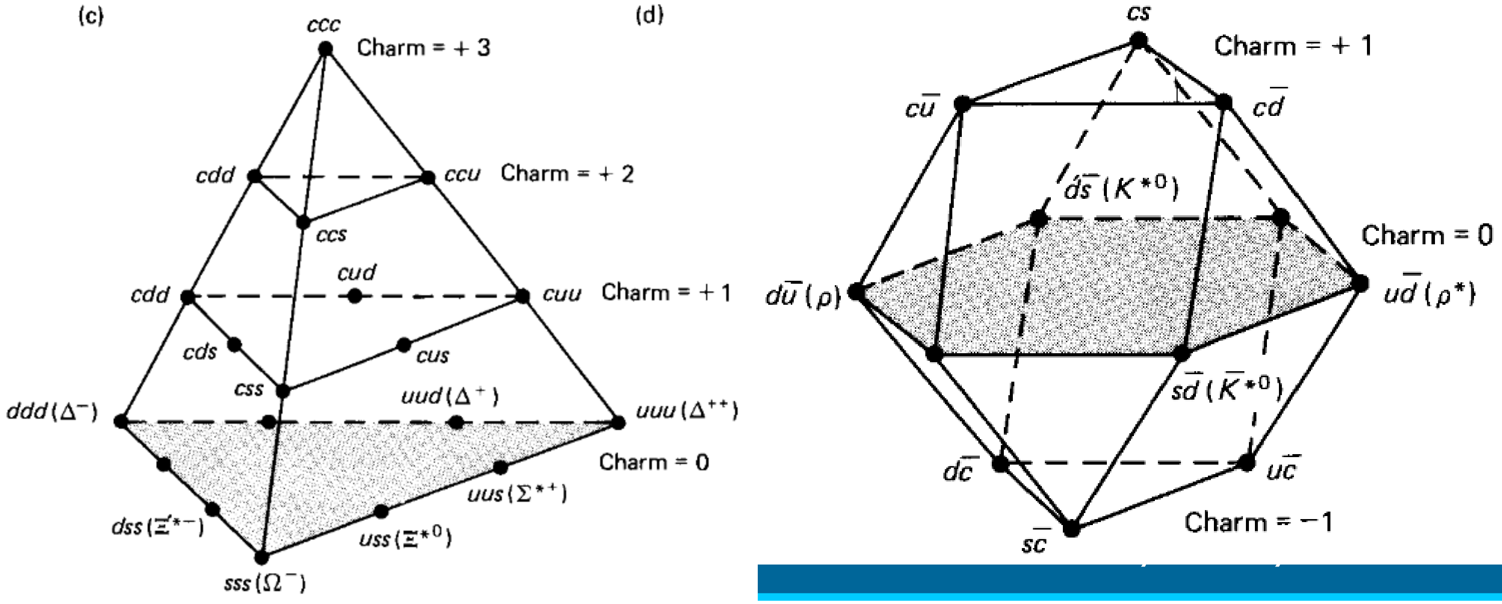
qqq	Q	S	Baryon
uuu	2	0	Δ^{++}
uud	1	0	Δ^{+}
udd	0	0	Δ^{0}
ddd	-1	0	Δ^{-}
uus	1	-1	Σ^{*+}
uds	0	-1	Σ^{*0}
dds	-1	-1	Σ^{*-}
uss	0	-2	Ξ^{*0}
dss	-1	-2	Ξ^{*-}
sss	-1	-3	Ω^{-}



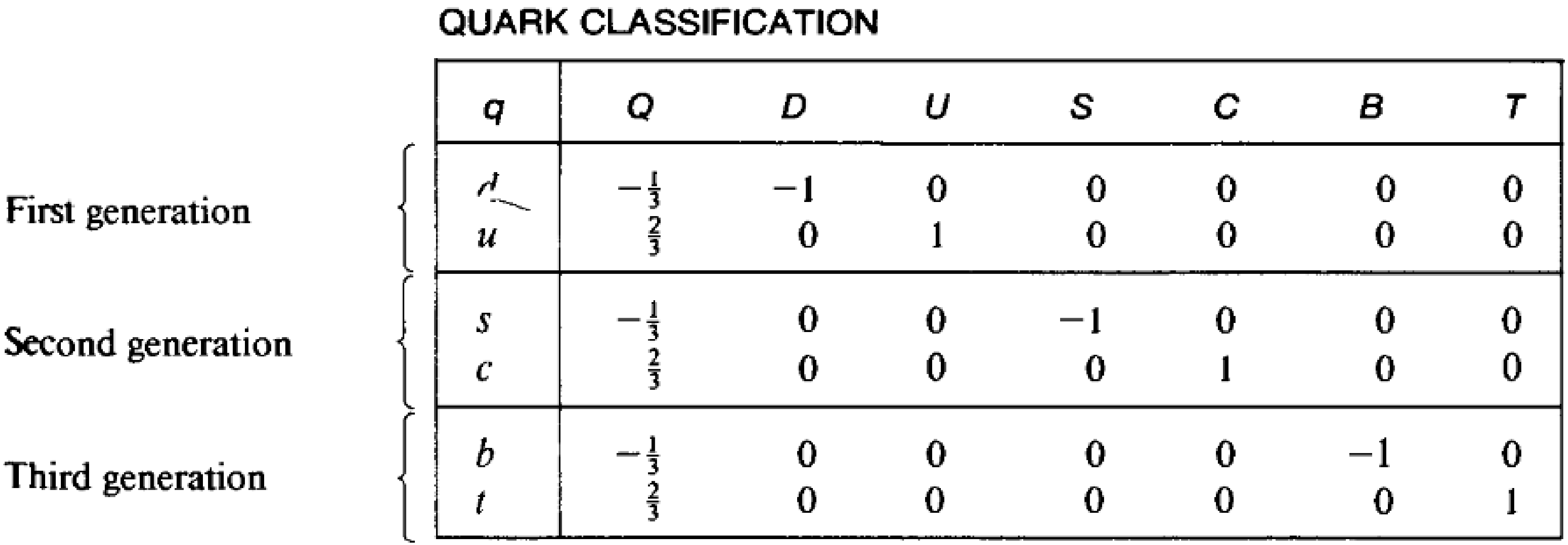
THE MESON NONET

$q\bar{q}$	Q	S	Meson
$u\bar{u}$	0	0	π^0
$u\bar{d}$	1	0	π^+
$d\bar{u}$	-1	0	π^-
$d\bar{d}$	0	0	η
$u\bar{s}$	1	1	K^+
$d\bar{s}$	0	1	K^0
$s\bar{u}$	-1	-1	K^-
$s\bar{d}$	0	-1	$\bar{K}^0$
$s\bar{s}$	0	0	??

With 4 quarks, we can build supermultiplets:



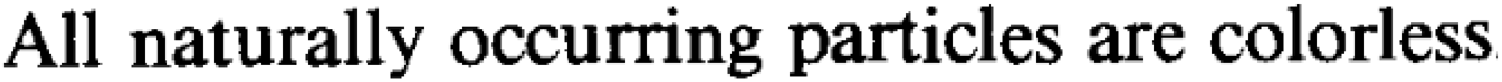
The quark model (1964)



QUARK CLASSIFICATION

	q	Q	D	U	S	C	B	T
First generation	d	$-\frac{1}{3}$	-1	0	0	0	0	0
	u	$\frac{2}{3}$	0	1	0	0	0	0
Second generation	s	$-\frac{1}{3}$	0	0	-1	0	0	0
	c	$\frac{2}{3}$	0	0	0	1	0	0
Third generation	b	$-\frac{1}{3}$	0	0	0	0	-1	0
	t	$\frac{2}{3}$	0	0	0	0	0	1

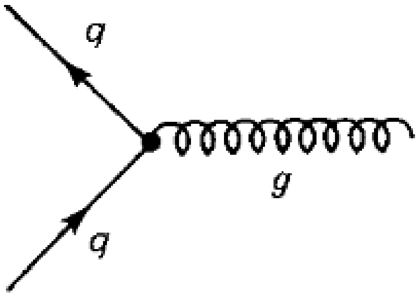
Each quark have 3 different colors: red, green, blue



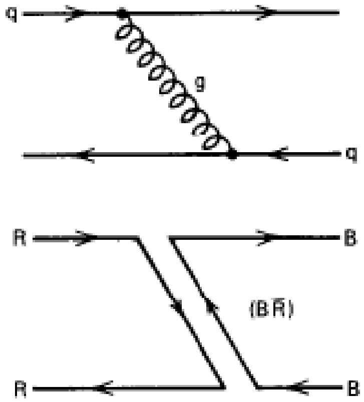
All naturally occurring particles are colorless

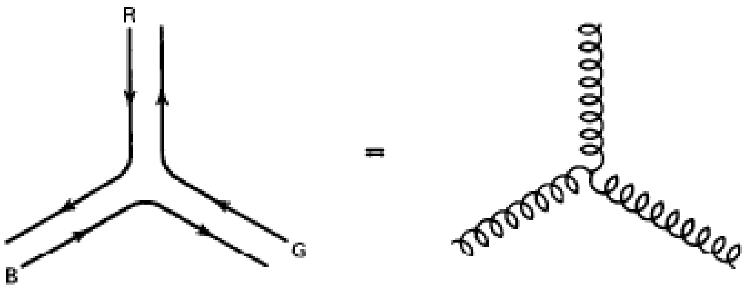
Quantum Chromodynamics (QCD)

In chromodynamics *color* plays the role of charge, and the fundamental process (analogous to $e^- \to e^- + \gamma$) is quark → quark-plus-gluon (since leptons do not carry color, they do not participate in the strong interactions):



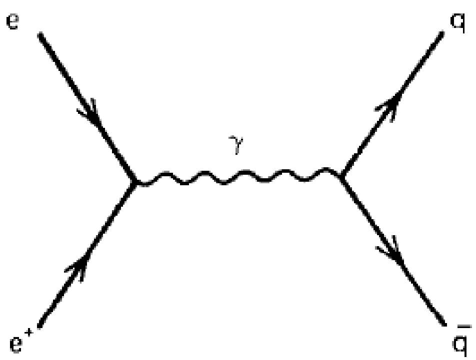
- Quarks carry color as well as electric charge
- Color is exchanged by eight bicolored gluons
- Color interactions are assumed to be a copy of electromagnetic interactions with the change
- The gluo $\sqrt{\alpha} \to \sqrt{\alpha_s}$ ssless and have spin 1
- Gluons carry color themselves, so they can interact with other gluons

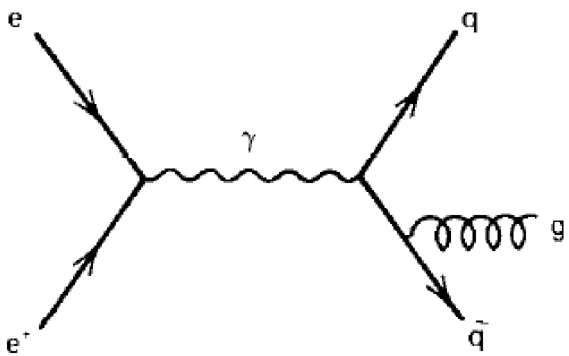


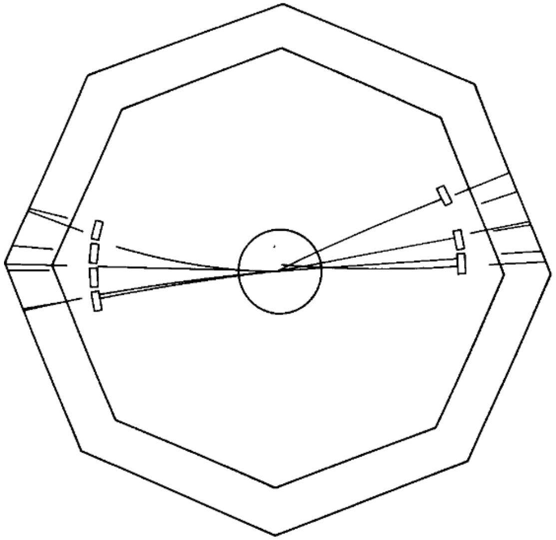


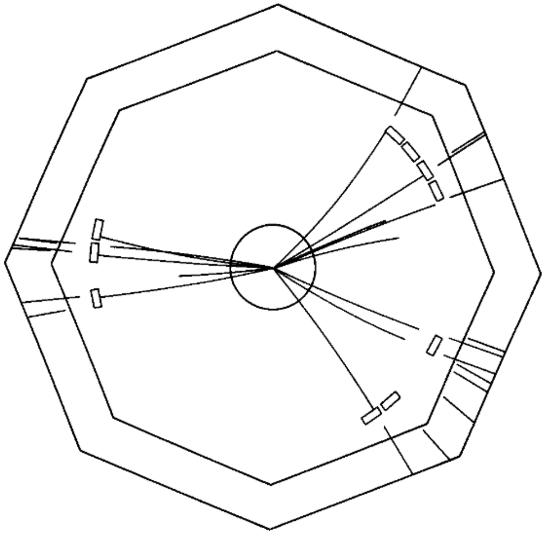
Quantum Chromodynamics (QCD)

e^-e^+ Annihilation into Hadrons: $e^-e^+ \to q\bar{q}$









Quantum Chromodynamics (QCD)

e^-e^+ Annihilation into Hadrons: $e^-e^+ \rightarrow q\bar{q}$

$$\sigma(e^-e^+ \rightarrow \mu^-\mu^+) = \frac{4\pi\alpha^2}{3Q^2} \qquad s = Q^2 = 4E_b^2$$

$$\sigma(e^-e^+ \rightarrow q\bar{q}) = 3e_q^2\sigma(e^-e^+ \rightarrow \mu^-\mu^+)$$

where we have taken account of the fractional charge of the quark, e_q

$$\begin{aligned}\sigma(e^-e^+ \rightarrow \text{hadrons}) &= \sum_q \sigma(e^-e^+ \rightarrow q\bar{q}) \\ &= 3\sum_q e_q^2\sigma(e^-e^+ \rightarrow \mu^-\mu^+)\end{aligned}$$

$$\boxed{R \equiv \frac{\sigma(e^-e^+ \rightarrow \text{hadrons})}{\sigma(e^-e^+ \rightarrow \mu^-\mu^+)} = 3\sum_q e_q^2.}$$

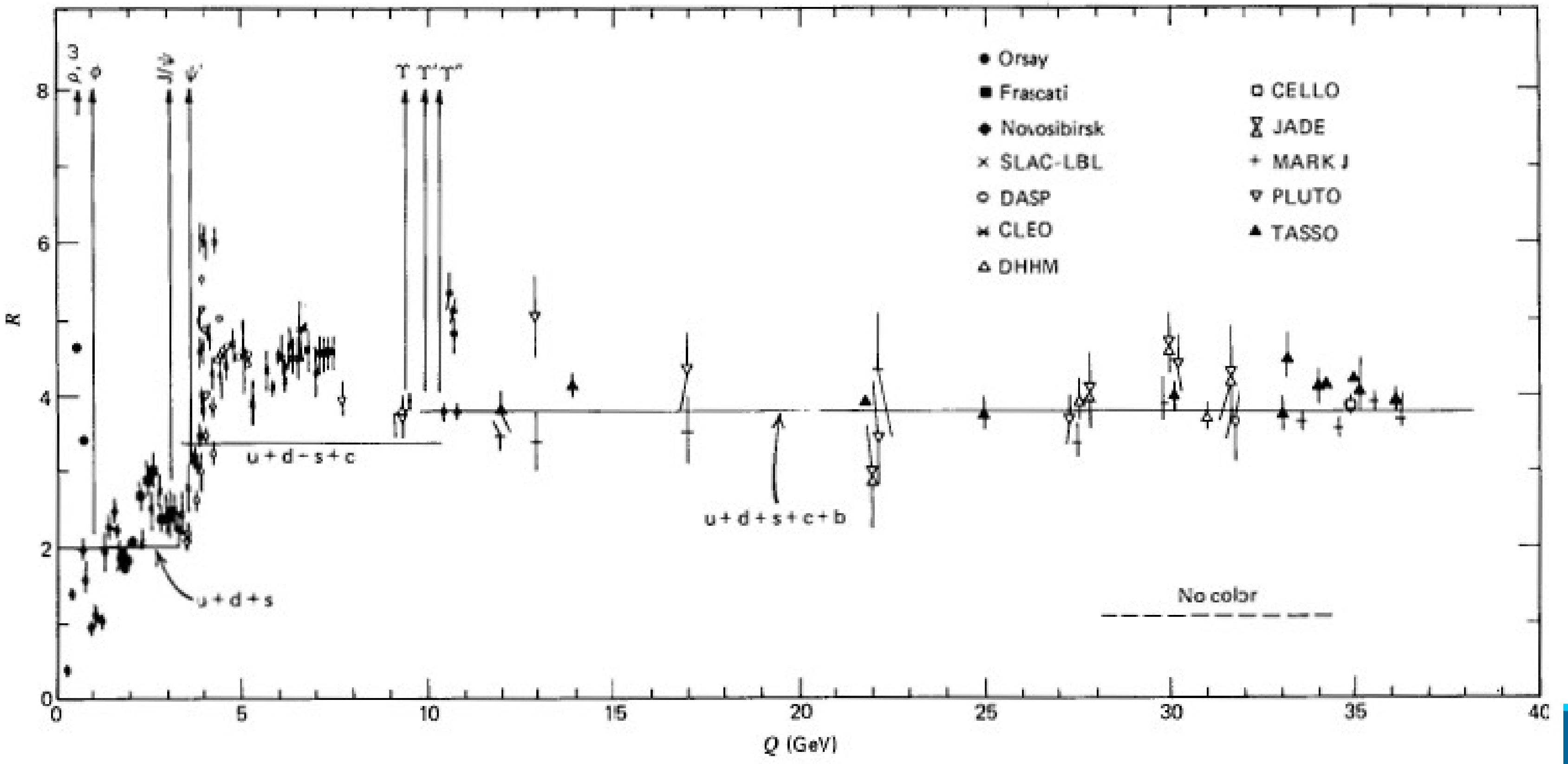
Quantum Chromodynamics (QCD)

e^-e^+ Annihilation into Hadrons: $e^-e^+ \to q\bar{q}$

$$R = 3\left[\left(\tfrac{2}{3}\right)^2 + \left(\tfrac{1}{3}\right)^2 + \left(\tfrac{1}{3}\right)^2\right] = 2 \qquad \text{for u, d, s,}$$

$$= 2 + 3\left(\tfrac{2}{3}\right)^2 = \tfrac{10}{3} \qquad \text{for u, d, s, c,}$$

$$= \tfrac{10}{3} + 3\left(\tfrac{1}{3}\right)^2 = \tfrac{11}{3} \qquad \text{for u, d, s, c, b.}$$

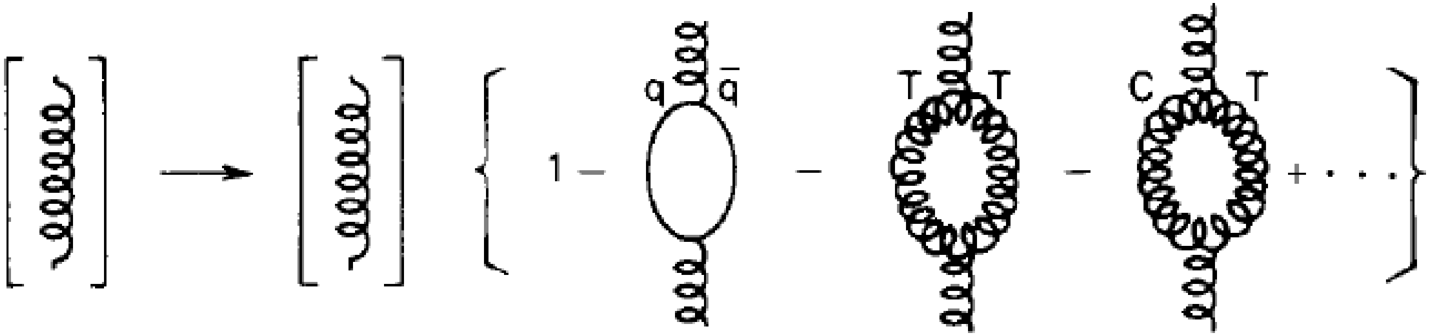


Quantum Chromodynamics (QCD)

- The previous results for *R* are based on the leading order calculation and change when interpreted in the context of QCD:

$$R = 3\sum_q e_q^2\left(1 + \frac{\alpha_s(Q^2)}{\pi}\right)$$

Running Coupling Constant for QCD



$$\boxed{\alpha_s(Q^2) = \frac{12\pi}{(33 - 2n_f)\log(Q^2/\Lambda^2)}.}$$

Experimental tests of the Standard Model

Motivation for Precision Measurements

- The electroweak gauge sector of the standard model is constrained by three precisely known parameters
  - $\alpha_{EM}(M_Z) = 1 / 127.918(18)$
  - $G_F = 1.16637\ (1) \times 10^{-5}\ \mathrm{GeV}^{-2}$

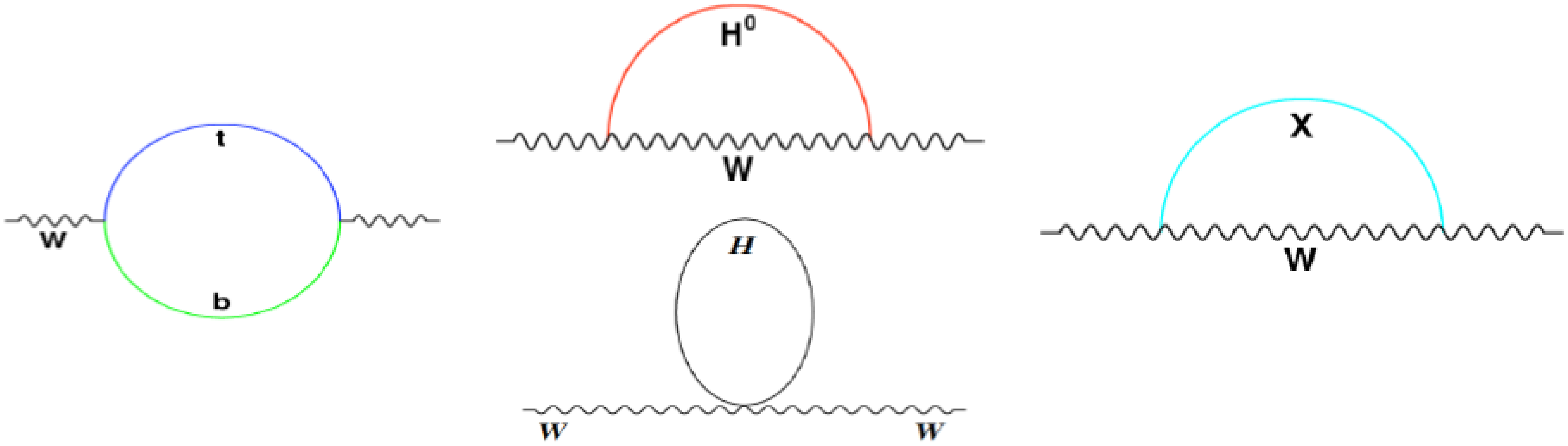
    $M_Z = 91.1876\ (21)\ \mathrm{GeV}$
- At tree-level, these parameters are related to other electroweak observables, *e.g.* M_W
  - $M_W{}^2 = \pi\alpha_{EM} / \sqrt{2}G_F \sin^2\vartheta_W$
    - Where ϑ_W is the weak mixing angle, defined by (in the on-shell scheme)

      $\cos\vartheta_W = M_W/M_Z$

Experimental tests of the Standard Model

Motivation for Precision Measurements

- Radiative corrections due to heavy quark and Higgs loops and exotica



Motivate the introduction of the ρ parameter: $M_W^2 = \rho\, [M_W(\text{tree})]^2$

with the predictions $(\rho\text{-}1) \sim M_{top}^2$ and $(\rho\text{-}1) \sim \ln M_H$

$$\rho_0 \equiv \frac{M_W^2}{M_Z^2\, \hat{c}_Z^2\, \hat{\rho}}$$

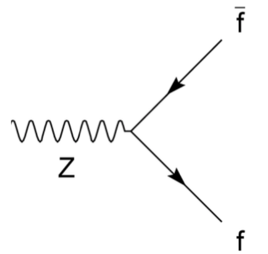
$$\rho_0 = 1.0008^{+0.0017}_{-0.0007}$$

- In conjunction with M_{top}, the W boson mass constrains the mass of the Higgs boson, and possibly new particles beyond the standard model

Predictive Power of the SM

Tree level relations for $Z \to f\bar{f}$

$$g^{(0)}_{V,f} \equiv g^{(0)}_{L,f} + g^{(0)}_{R,f} = I^f_3 - 2Q^f \sin^2\theta_W$$
$$g^{(0)}_{A,f} \equiv g^{(0)}_{L,f} - g^{(0)}_{R,f} = I^f_3$$



$$i\bar{f}\gamma^\mu\left(g_{V,f} - g_{A,f}\gamma_5\right) f Z_\mu$$

- Unification connects the electromagnetic and the weak couplings
- M_W can be expressed in terms of M_Z and G_F

Radiative corrections

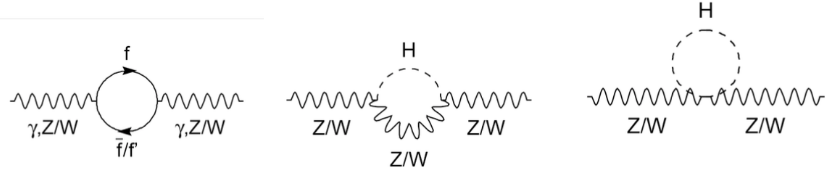
- Parametrisation through electroweak form factors ρ, κ, Δr
- Effective couplings at the Z-pole
- ρ, κ, Δr depend nearly quadratically on m_t and logarithmically on M_H

$$\sin^2\theta^f_{\text{eff}} = \kappa^f_Z \sin^2\theta_W$$

$$g_{V,f} = \sqrt{\rho^f_Z}\left(I^f_3 - 2Q^f \sin^2\theta^f_{\text{eff}}\right)$$

$$g_{A,f} = \sqrt{\rho^f_Z}\, I^f_3$$

$$M^2_W = \frac{M^2_Z}{2}\left(1 + \sqrt{1 - \frac{\sqrt{8}\pi\alpha(1+\Delta r)}{G_F M^2_Z}}\right)$$

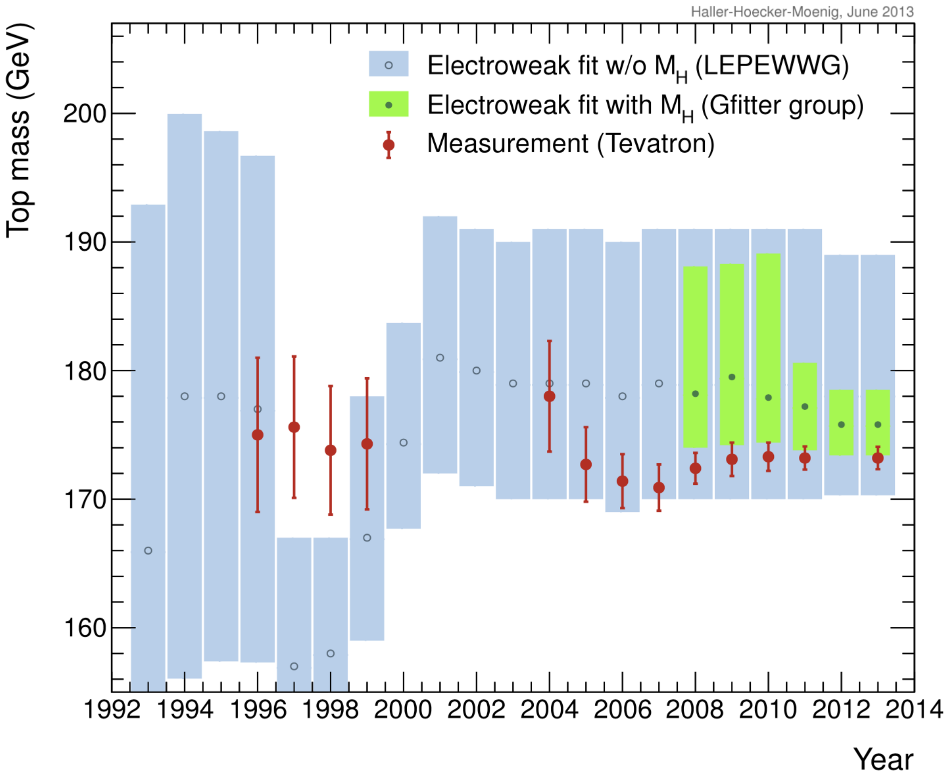


Experimental tests of the Standard Model

Electroweak Fits

A long tradition

- Huge amount of pioneering work to precisely understand loop corrections
- Observables known at least in two-loop order, sometimes higher orders available
- Precision measurements crucial, after the LEP/SLC era results from Tevatron and LHC become available

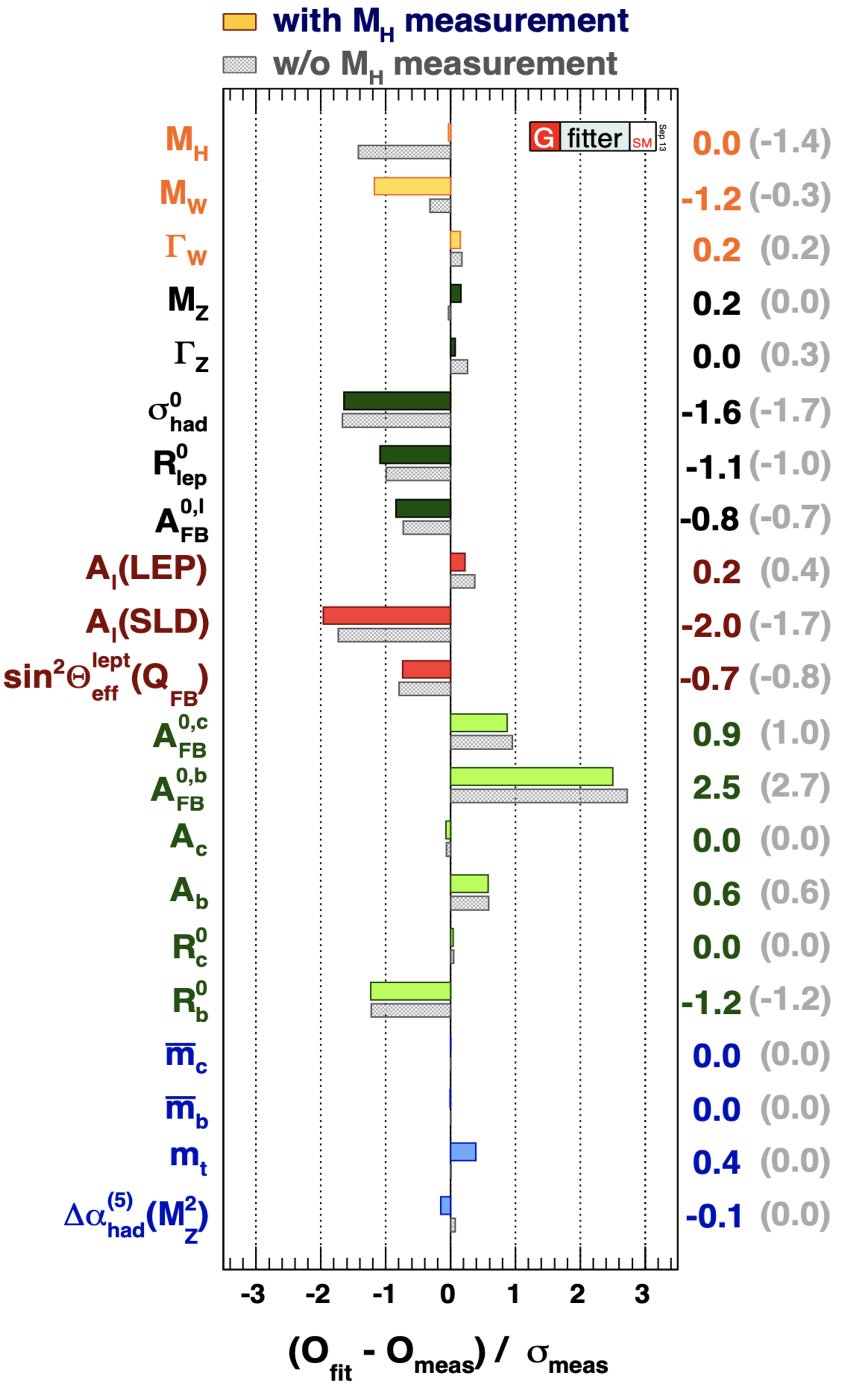


- Top mass predictions from loop effects available since ~1990
  - LEPEWWG fits since 1993
- The EW fit has always been able to predict the top mass correctly

Global Fit: Results

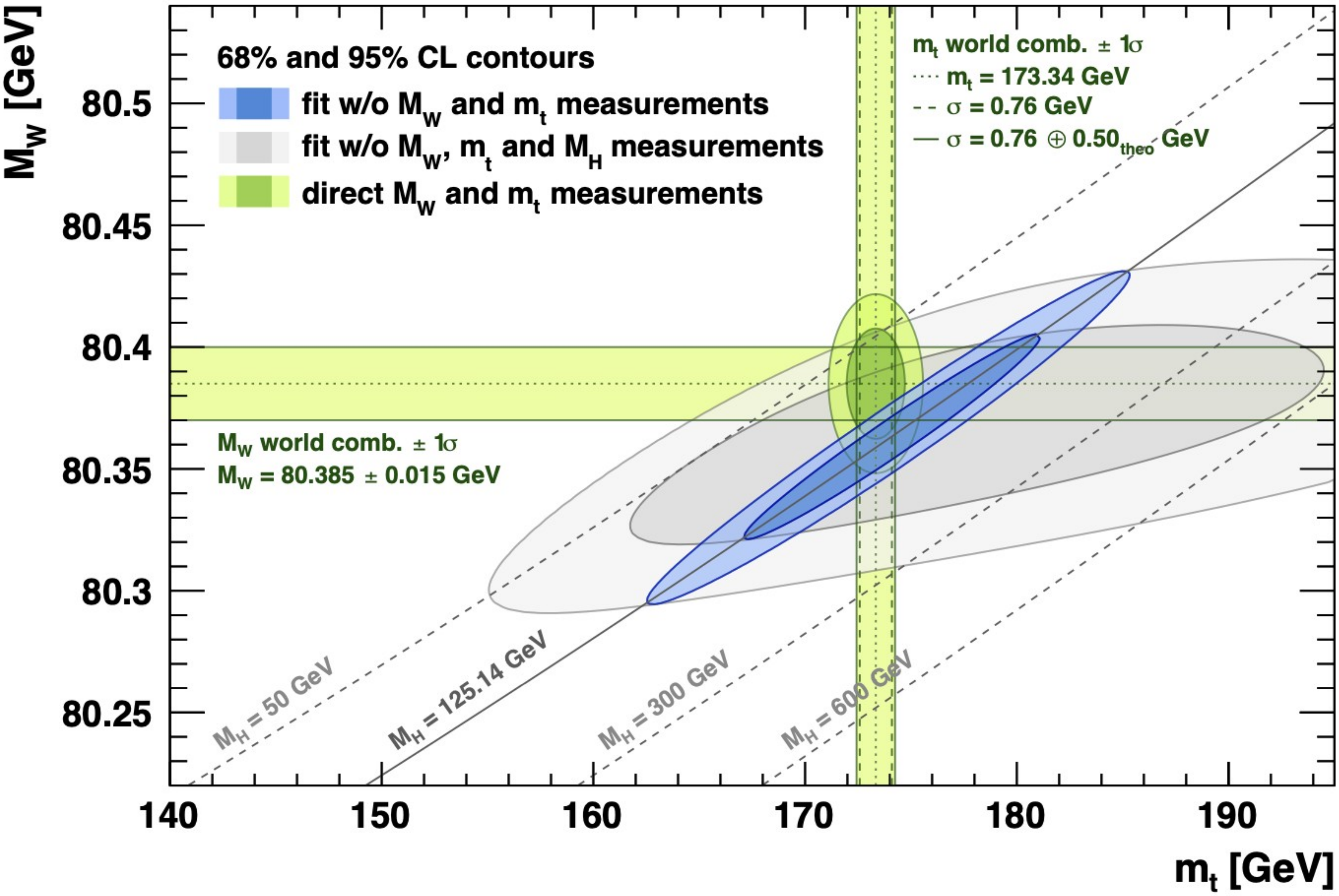
Pull values after the fit

- No pull value exceeds deviations of more than 3σ (consistency of SM)
- Small values for $M_H, A_c, R^0{}_c, m_c$ and m_b indicate that their input accuracies exceed the fit requirements
- Largest deviations in the b-sector: $A^{0,b}{}_{FB}$ with 2.5σ (small dependence on M_H)
- $R^0{}_b$ using one-loop calculation: 0.8σ
- inclusion of M_H: largest effect on M_W prediction shifted by ~13 MeV

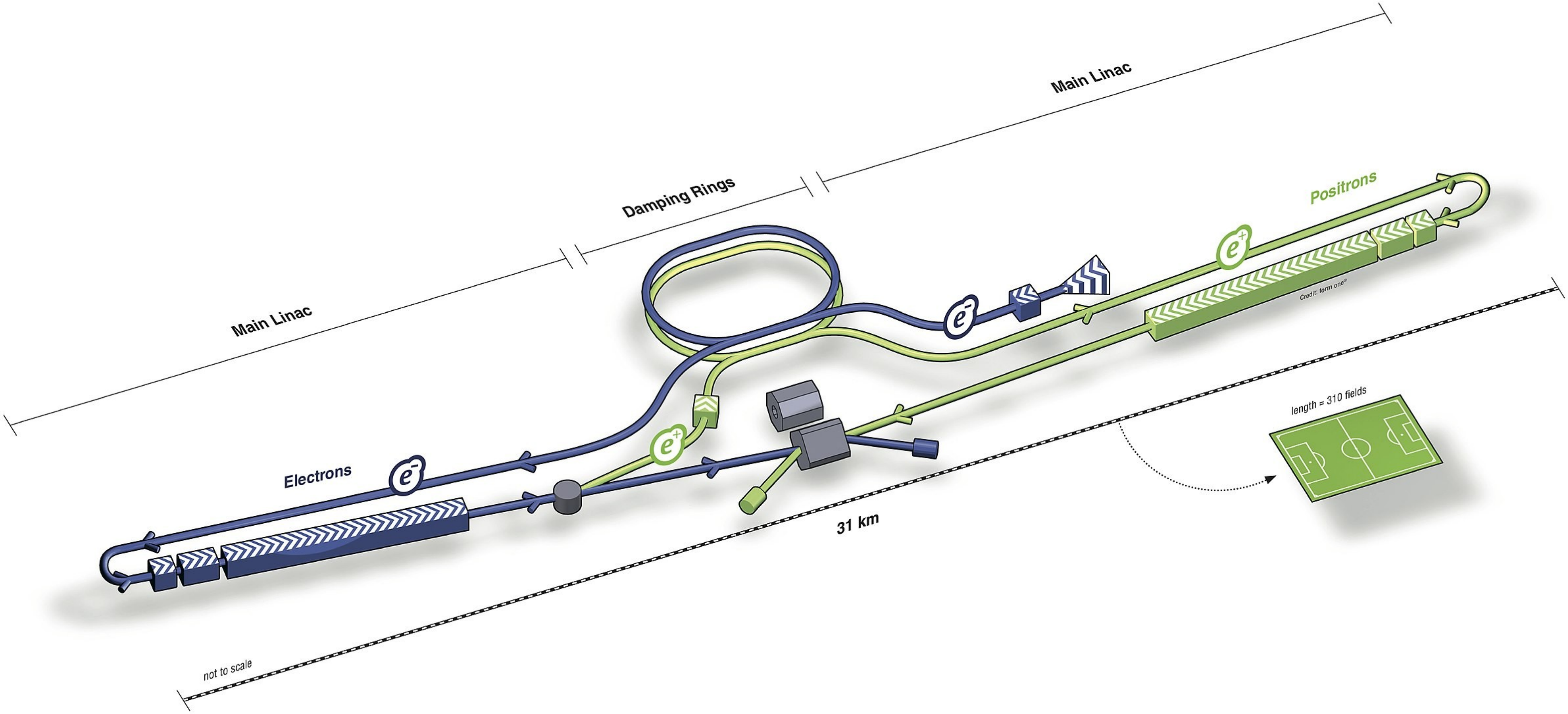


Plot inspired by Eberhardt et al. [arXiv:1209.1101]

Experimental tests of the Standard Model



International Linear Collider



Credit: form one®

Experimental tests of the Standard Model

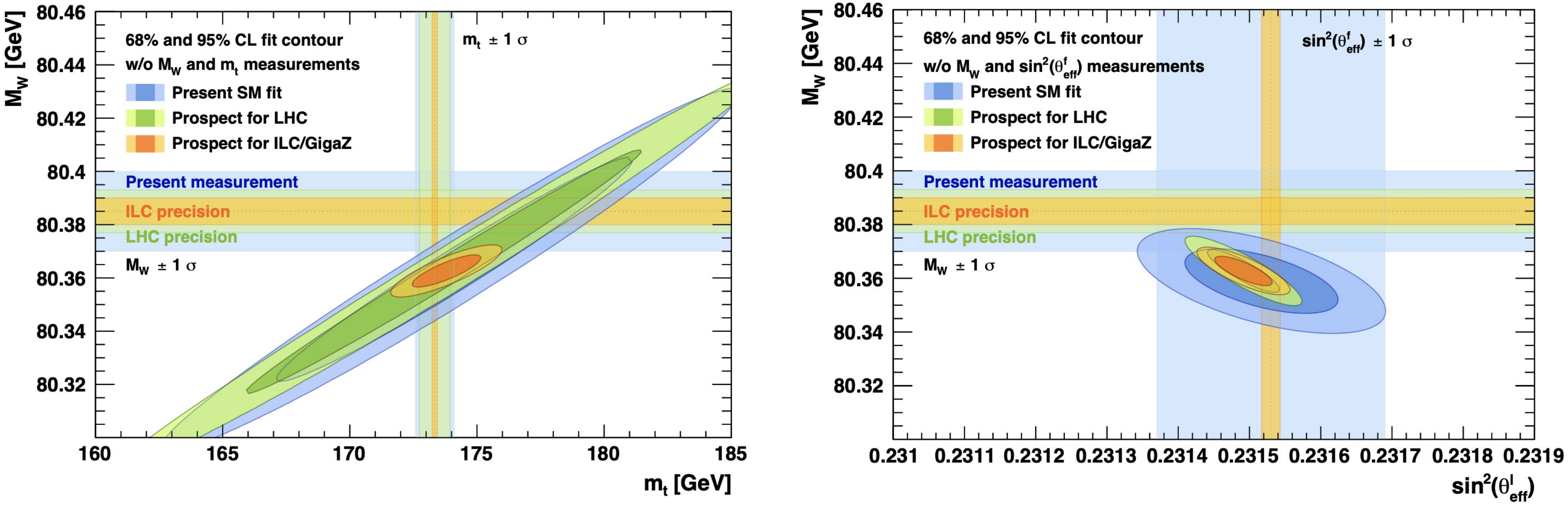
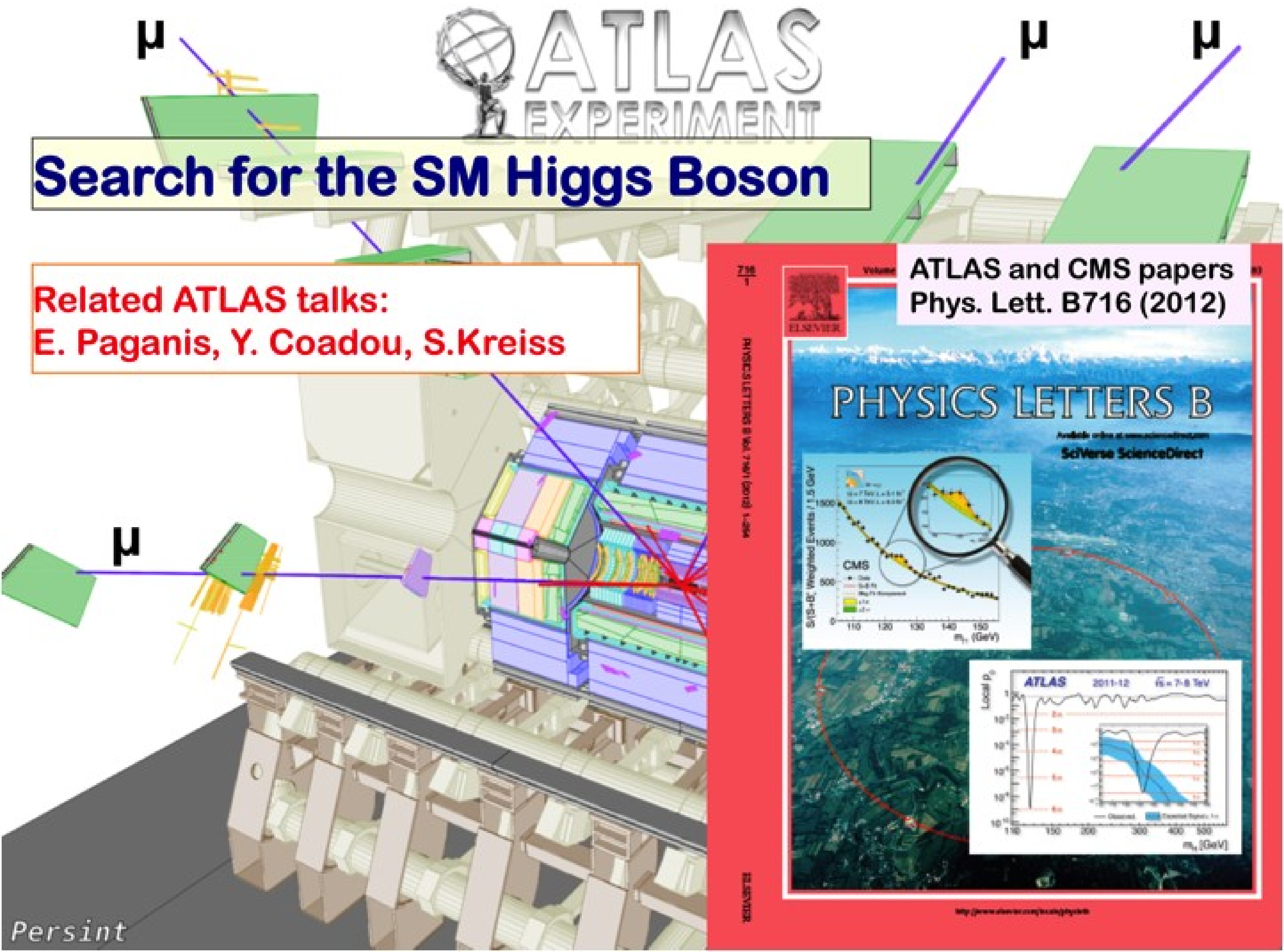


Figure 6: Fit constraints for the present and extrapolated future scenarios compared to the direct measurements for the observable pairs M_W versus m_t (top) and M_W versus $\sin^2\theta^\ell_{\rm eff}$ (bottom). The direct measurements are not included as input measurements in the fits. For the future scenarios the central values of the other input measurements are adjusted to reproduce the SM with $M_H \simeq 125$ GeV. The horizontal and vertical bands indicate in blue today's precision of the direct measurements, and in light green and orange the extrapolated precisions for the LHC and ILC/GigaZ, respectively. The ellipses receive significant contributions from the theoretical uncertainties parametrised by $\delta_{\rm theo} M_W$ and $\delta_{\rm theo} \sin^2\theta^f_{\rm eff}$. For better visibility the measurement ellipses corresponding to two degrees of freedom are not drawn.



Search for the SM Higgs Boson

Related ATLAS talks:
E. Paganis, Y. Coadou, S.Kreiss

ATLAS and CMS papers
Phys. Lett. B716 (2012)

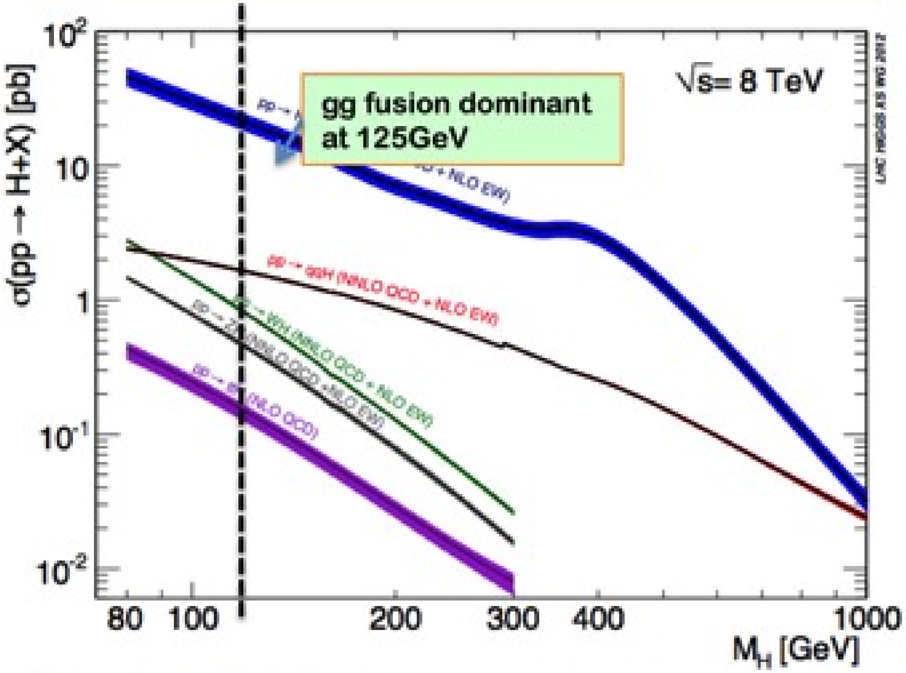
Higgs production and decay rates at √s =8 TeV

Gluon Fusion
pp→H

Vector Boson Fusion:
pp→qqH

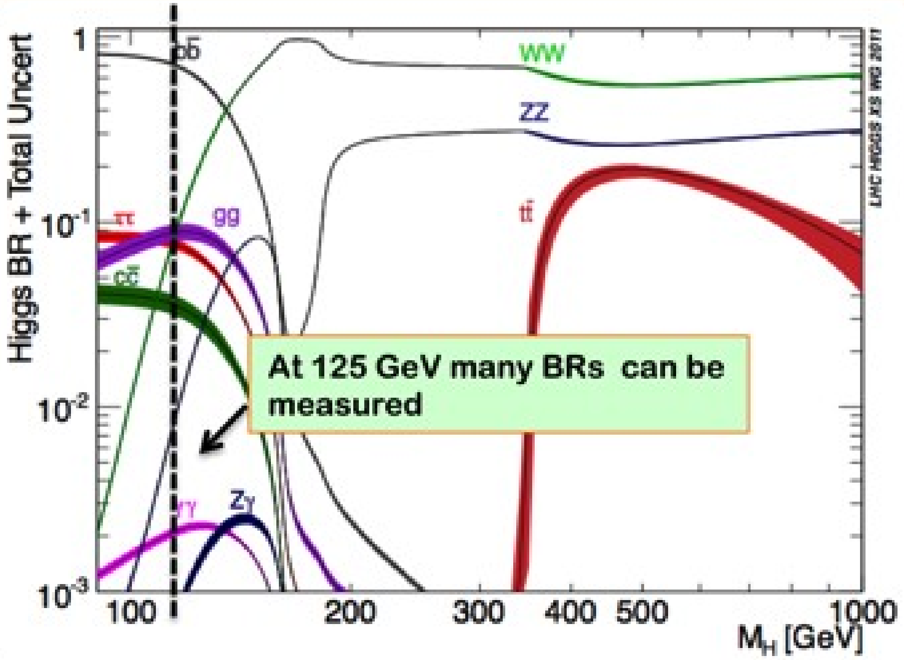
Associated Production:
pp→ WH, ZH, ttH

Higgs production cross-section vs MH



gg fusion dominant at 125GeV

Higgs decay channels: BRs depend on Higgs mass



At 125 GeV many BRs can be measured

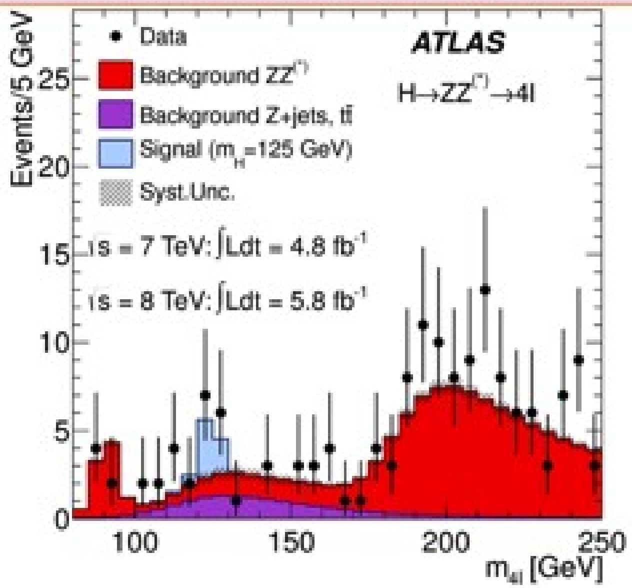
√s=7 → 8 TeV: Higgs cross-section increases by ~ 1.3 for m_H ~ 125 GeV

$H \rightarrow ZZ^{(*)} \rightarrow 4l$ (l=e,μ) search

The golden channel – very few events but S/B ~1!

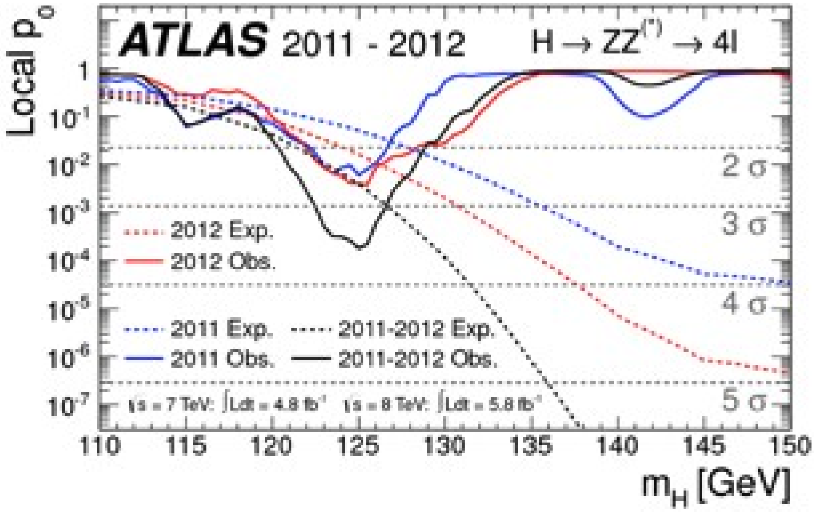
- Select four isolated leptons
- Main backgrounds:
  - Irreducible bkg: continuum ZZ*
  - Reducible bkg (low mass): Z+bbar,Z+ light jets, ttbar with two leptons from b-jets or q-jets
- Key-points:
  - Very high lepton reco/ID efficiency needed: down to low p_T and largest possible coverage
  - Excellent mass resolution
    - improved by using Z-constraint on leading lepton pair

Reconstructed 4l mass spectrum after all selections

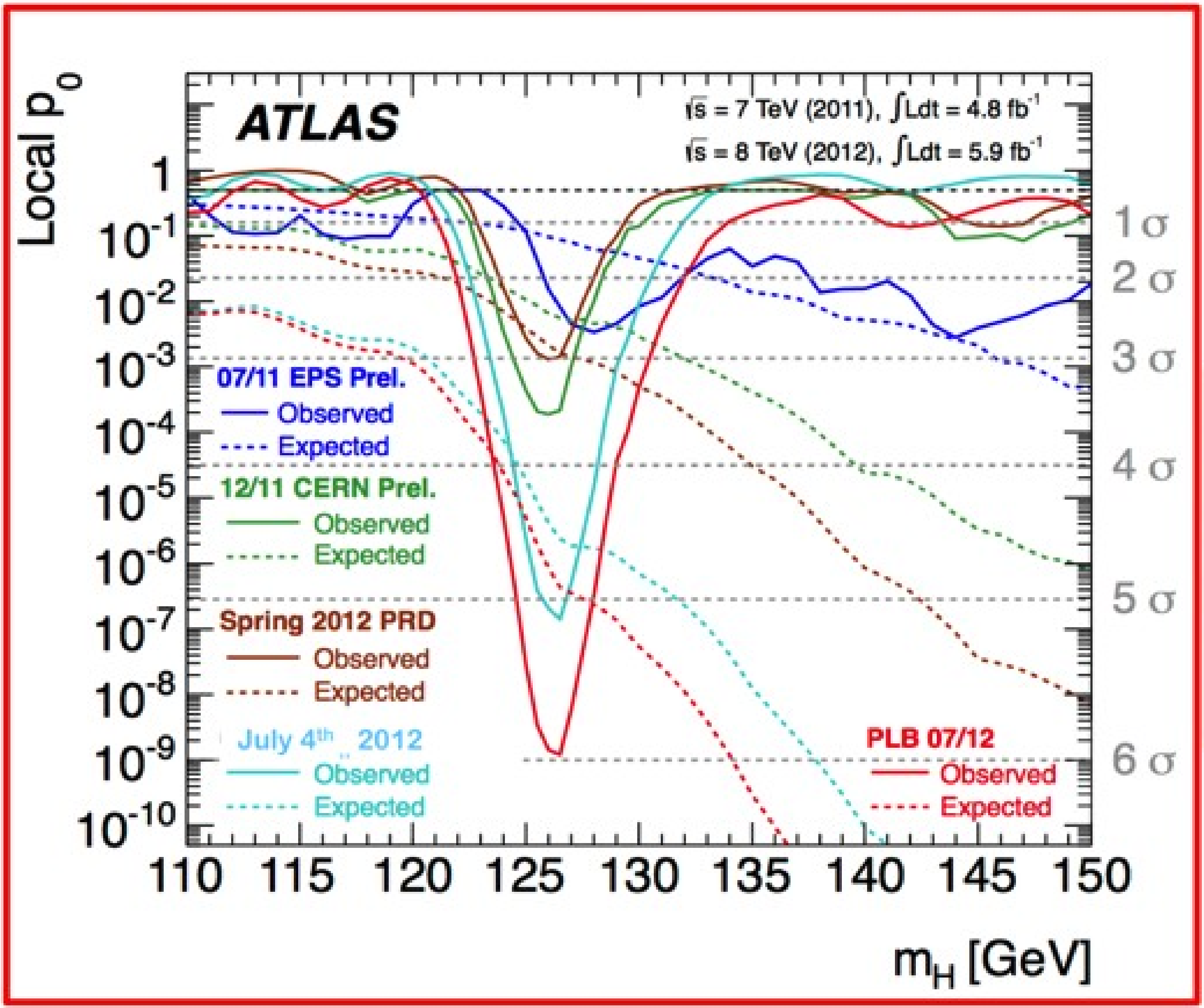


Most significant deviation from background-only hypothesis at m_H=125 GeV.

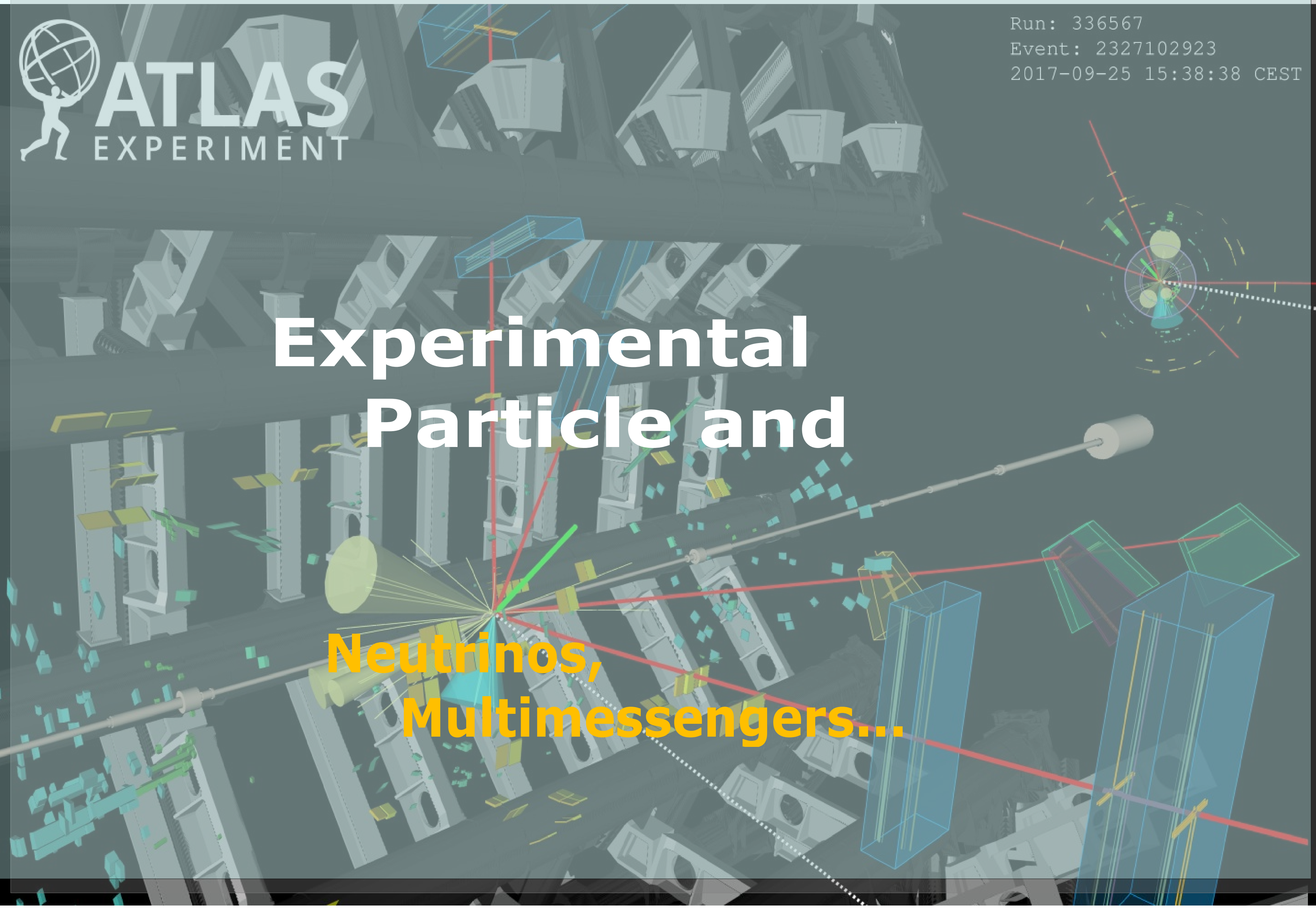
- **Local p_0-value corresponding to 3.6 σ (2.7 σ expected)**
- **Both, 2011 and 2012 data contribute to excess in the same mass range.**



Evolution of the excess with time



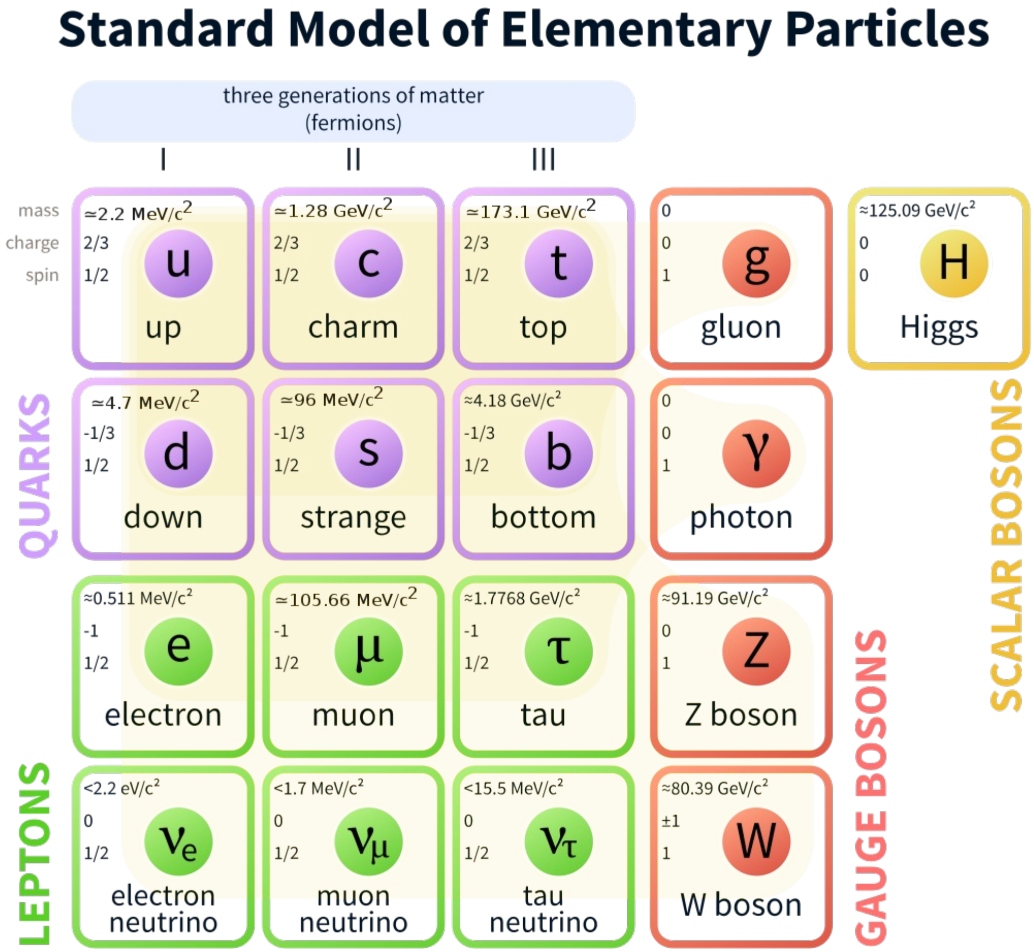
Significance increase from 4th July to the PLB from including H→ WW* search for 2012 data (from 5.2 to 5.9 σ)



Experimental Particle and

Neutrinos, Multimessengers...

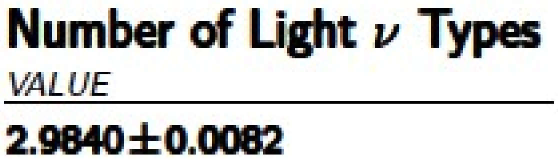
Neutrino and the New Physics



Standard Model of Elementary Particles

three generations of matter (fermions)

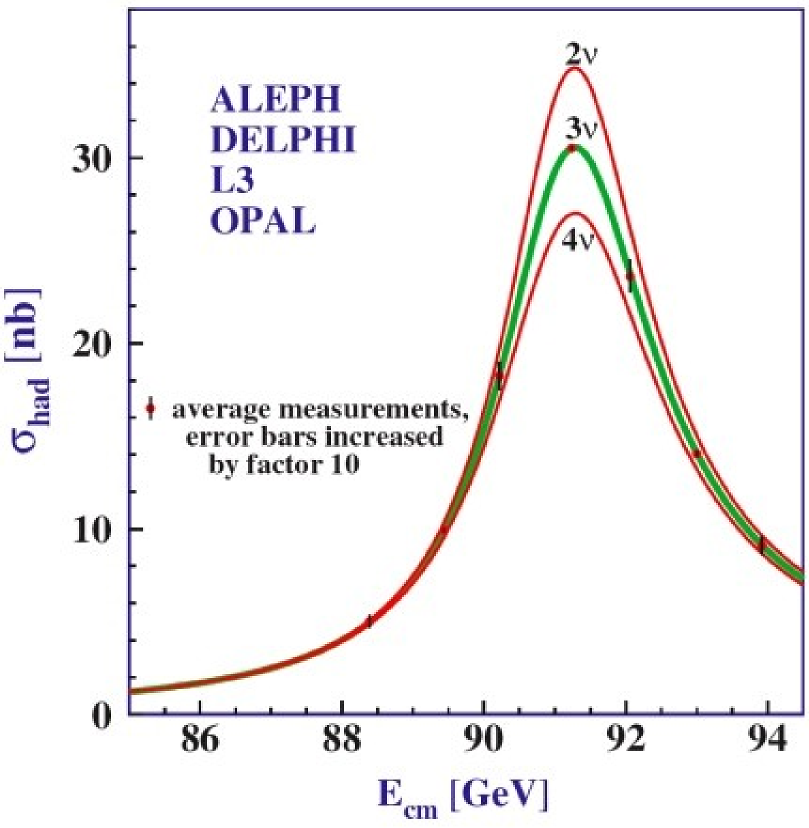
	I	II	III		
mass charge spin	≃2.2 MeV/c^2 2/3 1/2 u up	≃1.28 GeV/c^2 2/3 1/2 c charm	≃173.1 GeV/c^2 2/3 1/2 t top	0 0 1 g gluon	≃125.09 GeV/c^2 0 0 H Higgs
QUARKS	≃4.7 MeV/c^2 -1/3 1/2 d down	≃96 MeV/c^2 -1/3 1/2 s strange	≃4.18 GeV/c^2 -1/3 1/2 b bottom	0 0 1 γ photon	SCALAR BOSONS
	≃0.511 MeV/c^2 -1 1/2 e electron	≃105.66 MeV/c^2 -1 1/2 μ muon	≃1.7768 GeV/c^2 -1 1/2 τ tau	≃91.19 GeV/c^2 0 1 Z Z boson	
LEPTONS	<2.2 eV/c^2 0 1/2 ν_e electron neutrino	<1.7 MeV/c^2 0 1/2 ν_μ muon neutrino	<15.5 MeV/c^2 0 1/2 ν_τ tau neutrino	≃80.39 GeV/c^2 ±1 1 W W boson	
				GAUGE BOSONS	



Number of Light ν Types

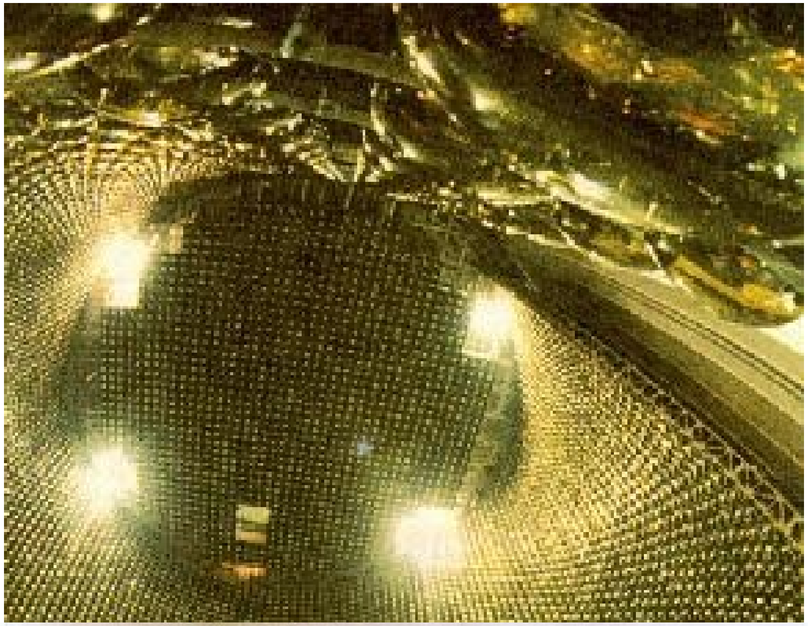
VALUE

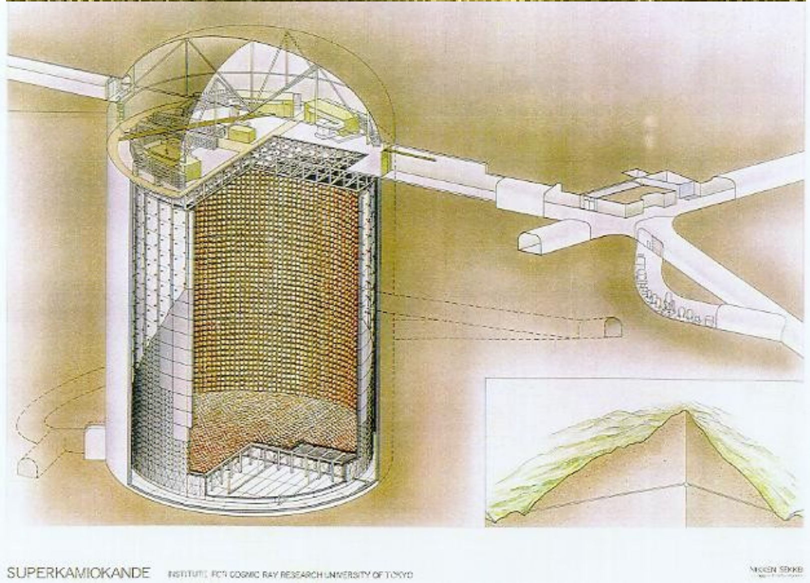
2.9840±0.0082

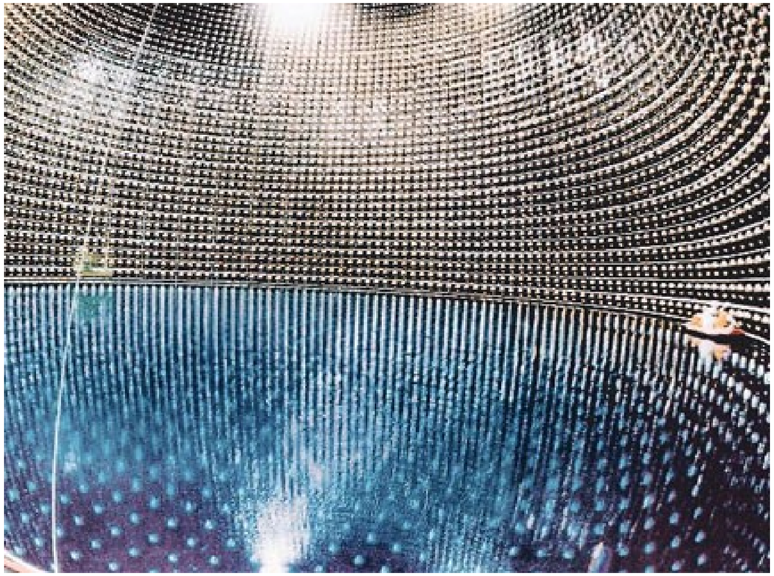


Super-Kamiokande

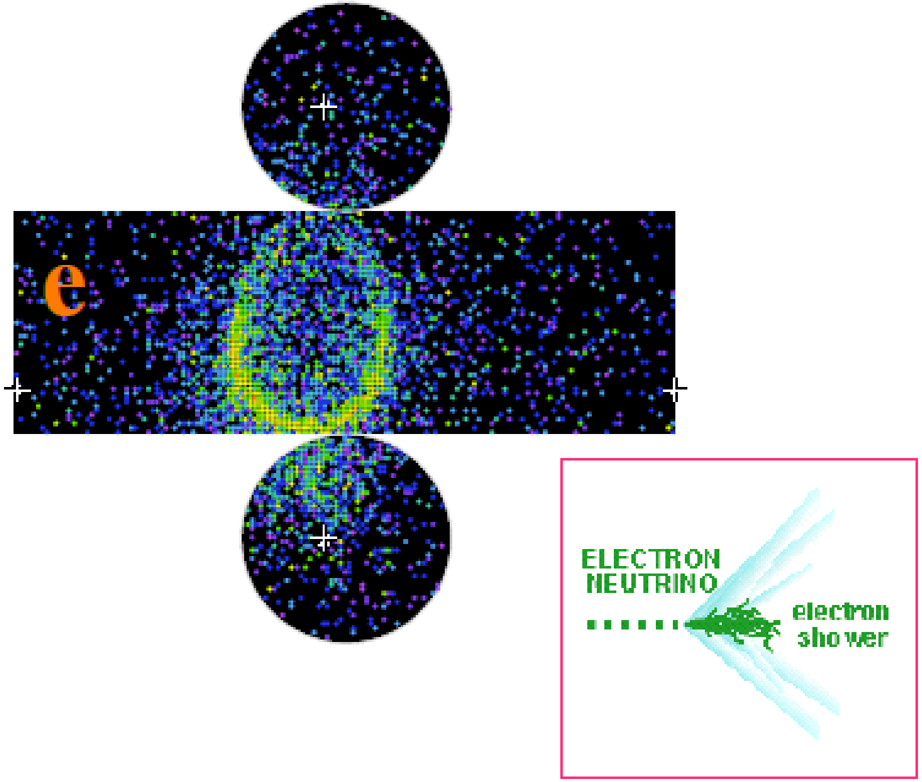
11 stores high
1,000 meters underground
50,000 tons of water
22,500 tons fiducial volume
11,200 photomultipliers
0.5 meter photomultiplier diameter
(old copper and zinc mine)

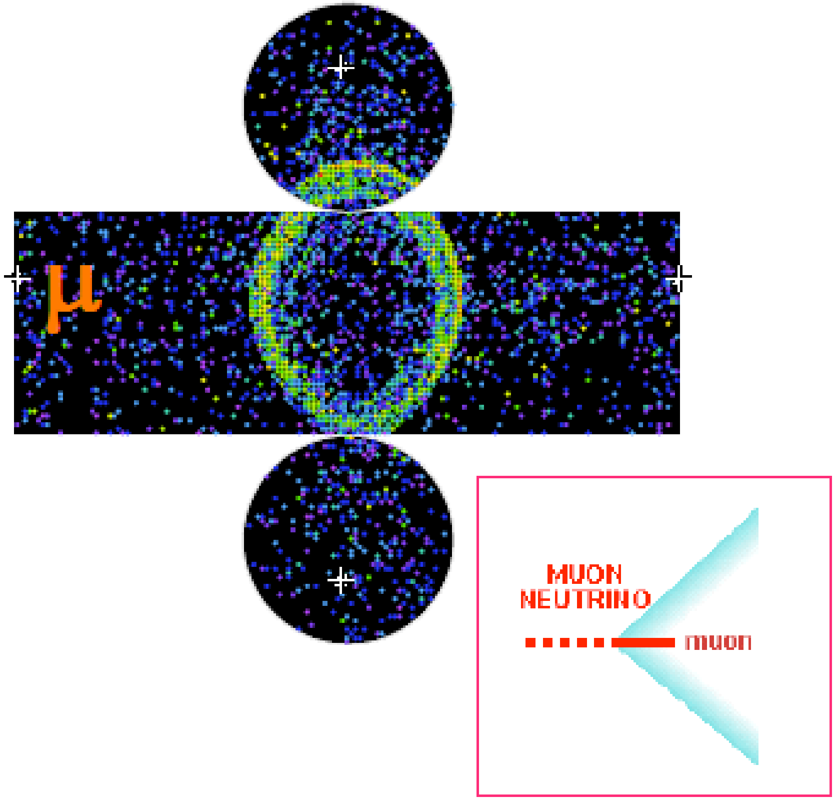






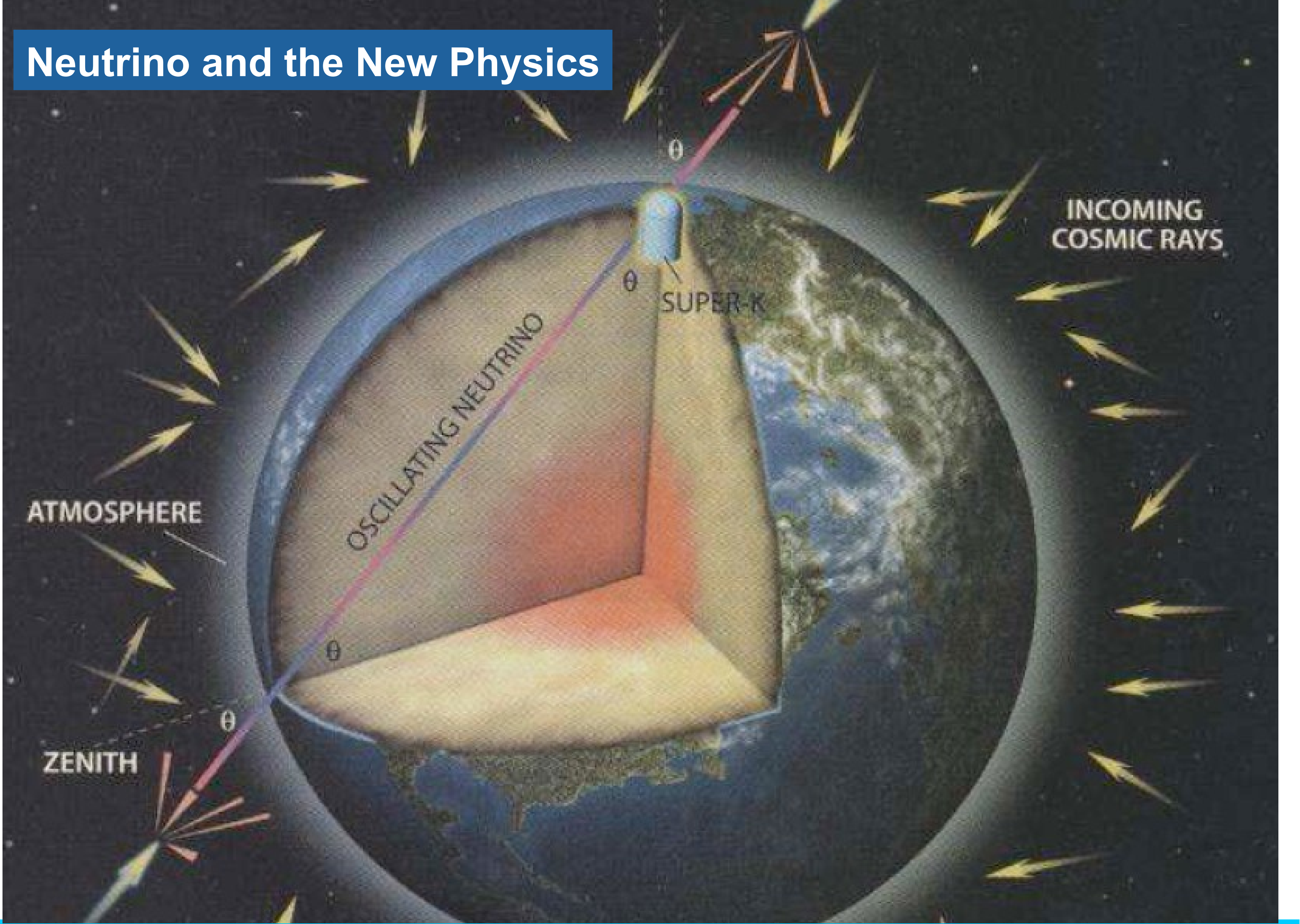
Electron and Muon Identification



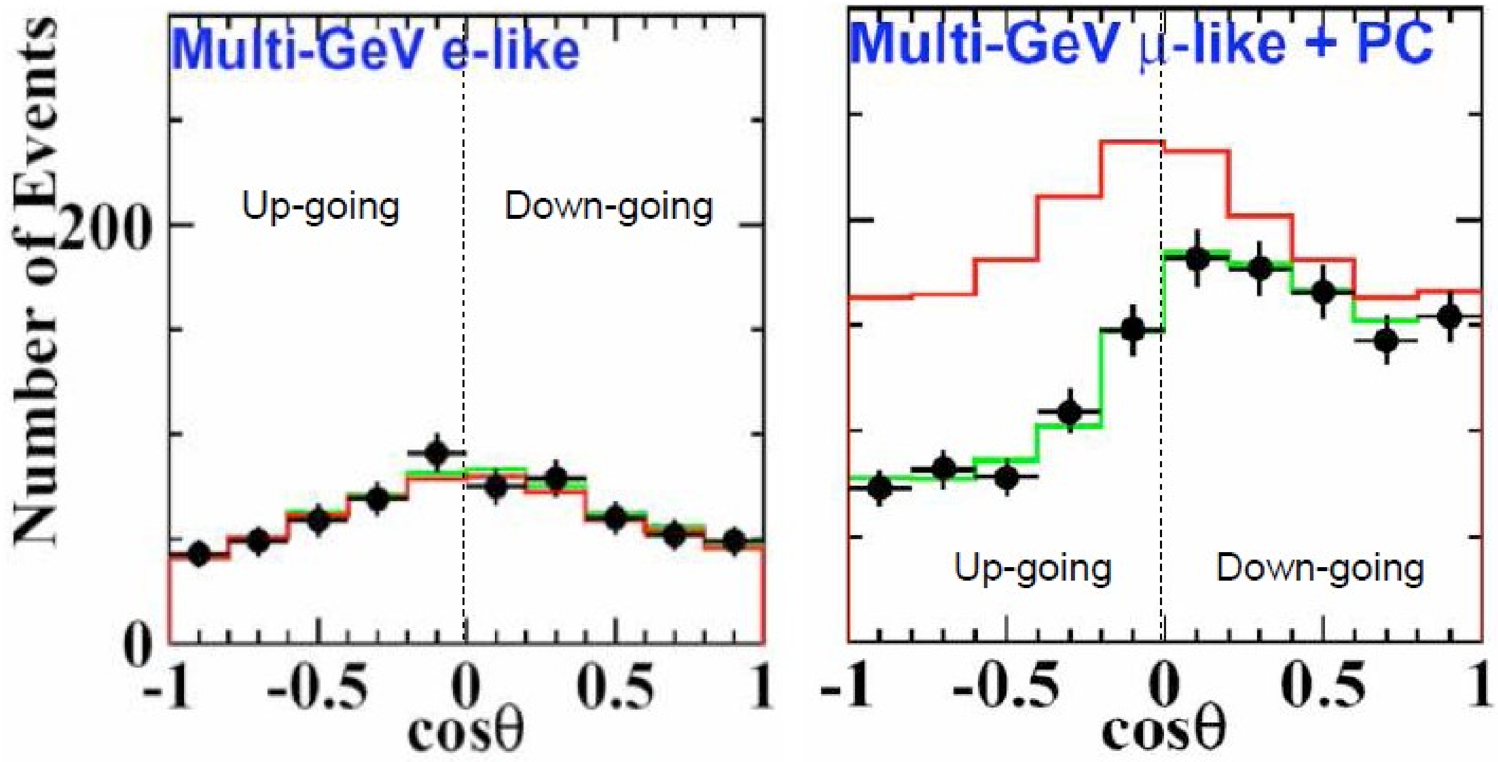


Electron ring is fuzzier than muon ring. Electron produces shower of gammas, electrons and positrons. Gammas don't produce Cherenkov light. Electrons and positrons do. In the shower each of them flies at a little bit different angle and each of them makes its own weak Cherenkov ring. All those rings added together produce the observed fuzzy ring. This difference in sharpness of muon and electron rings is used to identify muons and electrons in Super-Kamiokande.

Neutrino and the New Physics



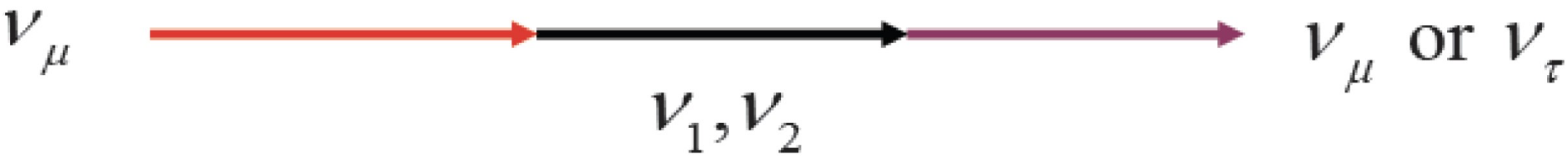
Zenith angle Distribution



Half of the ν_μ are lost!

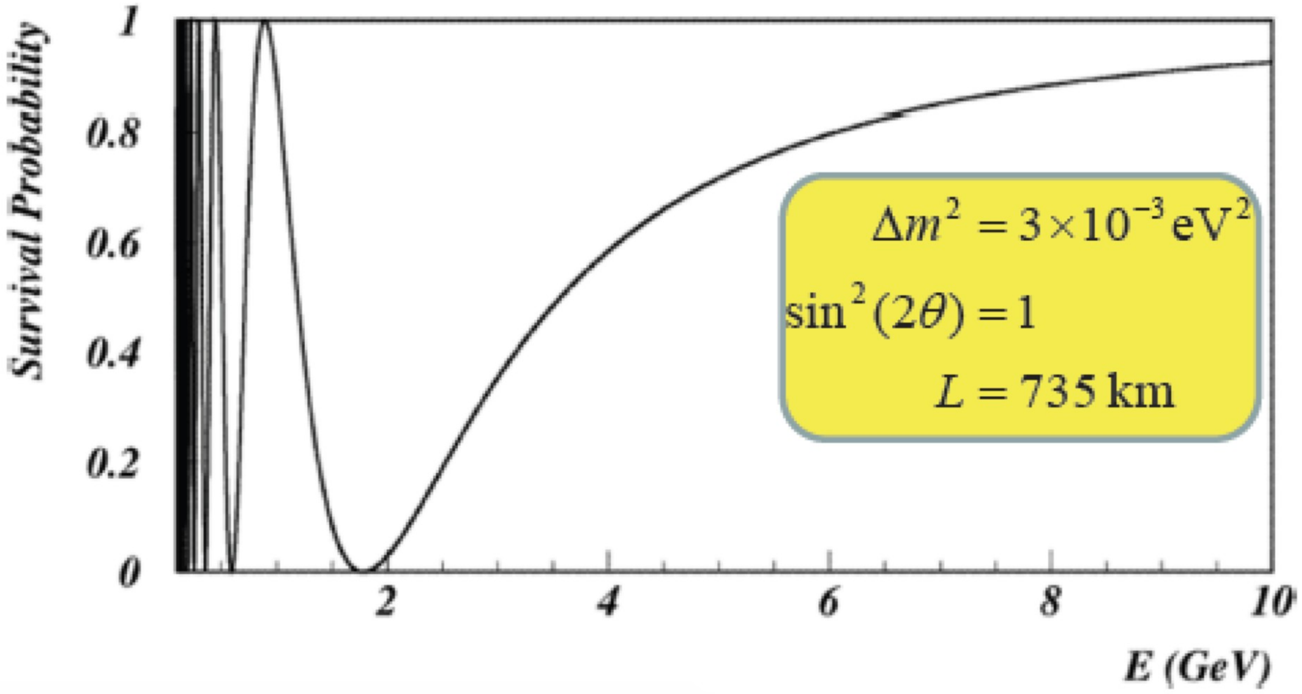
19

Neutrino and the New Physics



$$\begin{pmatrix} \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix} \qquad P(\nu_\mu \to \nu_\tau) = \sin^2(2\theta)\sin^2\left(\frac{1.27\Delta m^2 L}{E_\nu}\right)$$

- Measure prob.
  - Survival
  - Appearance
- Result
  - Mixing angle
  - Mass differences



Pontecorvo-Maki-Nakagawa-Sakata Matrix

unitary matrix

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

by defn $|U_{e1}|^2 > |U_{e2}|^2 > |U_{e3}|^2$

$$U_{PMNS} = U_{23}(\theta_{23}, 0)\; U_{13}(\theta_{13}, \delta)\; U_{12}(\theta_{12}, 0)$$

$$= \begin{pmatrix} 1 & & \\ & c_{23} & s_{23} \\ & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & & s_{13}e^{-i\delta} \\ & 1 & \\ -s_{13}e^{+i\delta} & & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & \\ -s_{12} & c_{12} & \\ & & 1 \end{pmatrix}$$

$$s_{ij} = \sin\theta_{ij},\; c_{ij} = \cos\theta_{ij} \qquad \times\, \mathrm{diag}(1,\; e^{i\frac{\alpha_{21}}{2}},\; e^{i\frac{\alpha_{31}}{2}})$$

$$\begin{pmatrix} c_{13}c_{12} & c_{13}s_{12} & s_{13}e^{-i\delta} \\ -c_{23}s_{12} - s_{13}s_{23}c_{12}e^{i\delta} & c_{23}c_{12} - s_{13}s_{23}s_{12}e^{i\delta} & c_{13}s_{23} \\ s_{23}s_{12} - s_{13}c_{23}c_{12}e^{i\delta} & -s_{23}c_{12} - s_{13}c_{23}s_{12}e^{i\delta} & c_{13}c_{23} \end{pmatrix}$$

Few, selected topics

Some open questions in neutrino astrophysics

- Why we do not have a “neutrino map”?
- Correlation with UHECRs and Neutrinos
- About **Galactic** sources
- Detecting **extragalactic** sources

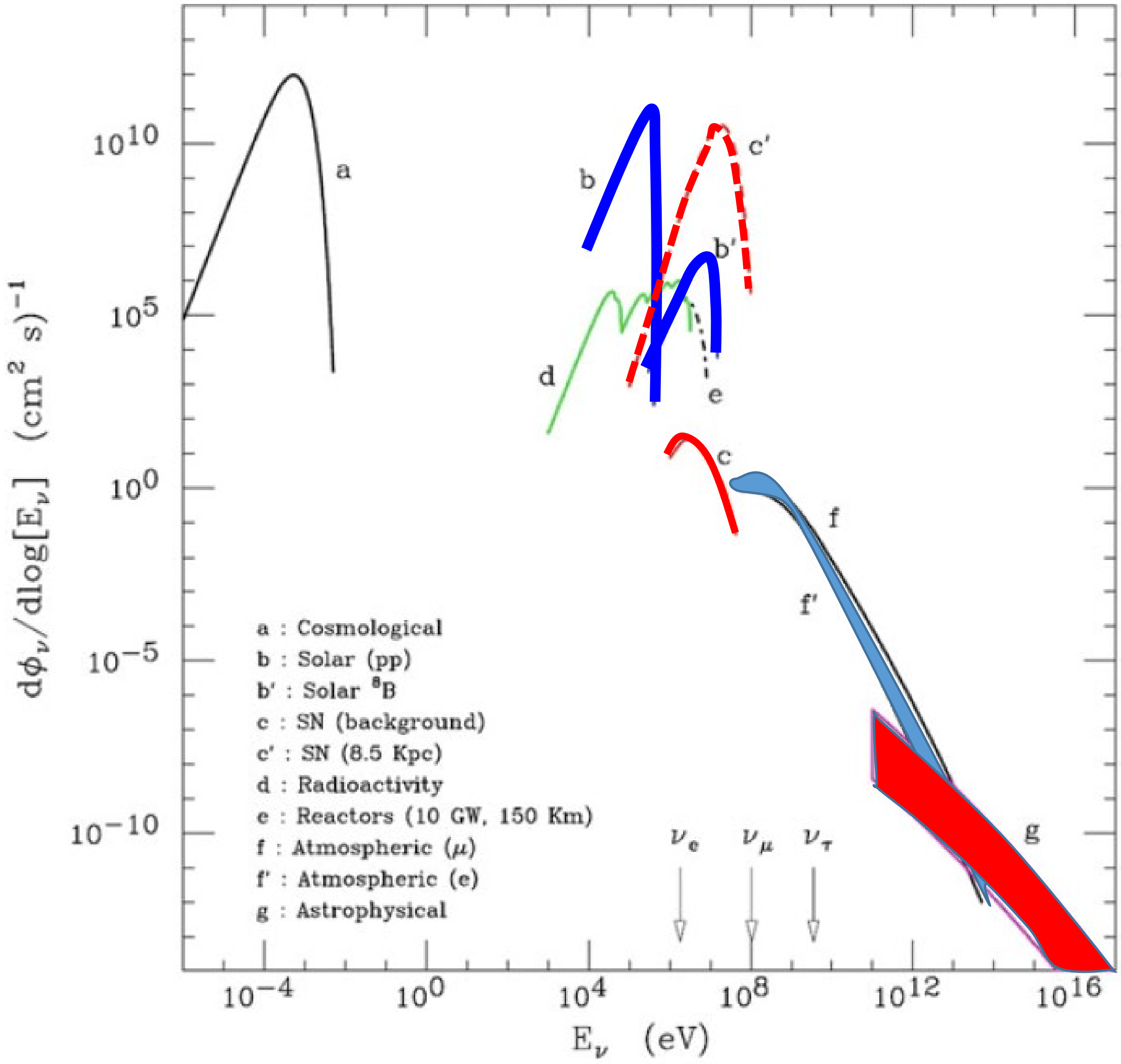
Extragalactic objects

- Gamma-ray bursts and consequences
- Fast Radio Bursts

The multimessenger role of Gravitational waves

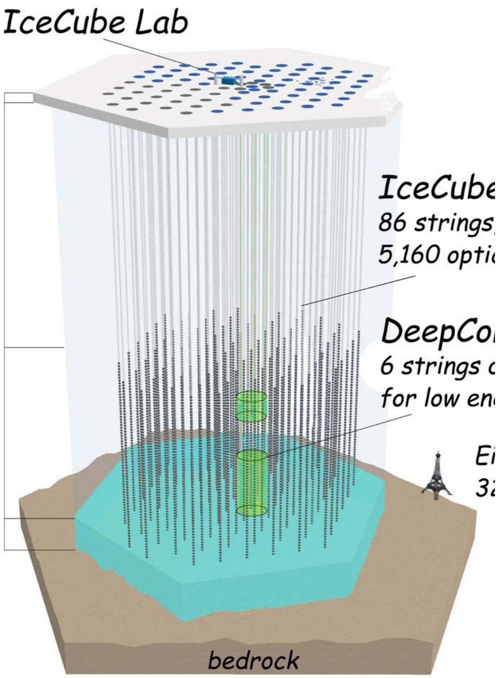
- Importance for **particle physics**
- Importance for **cosmology**
- Importance for **astrophysics**

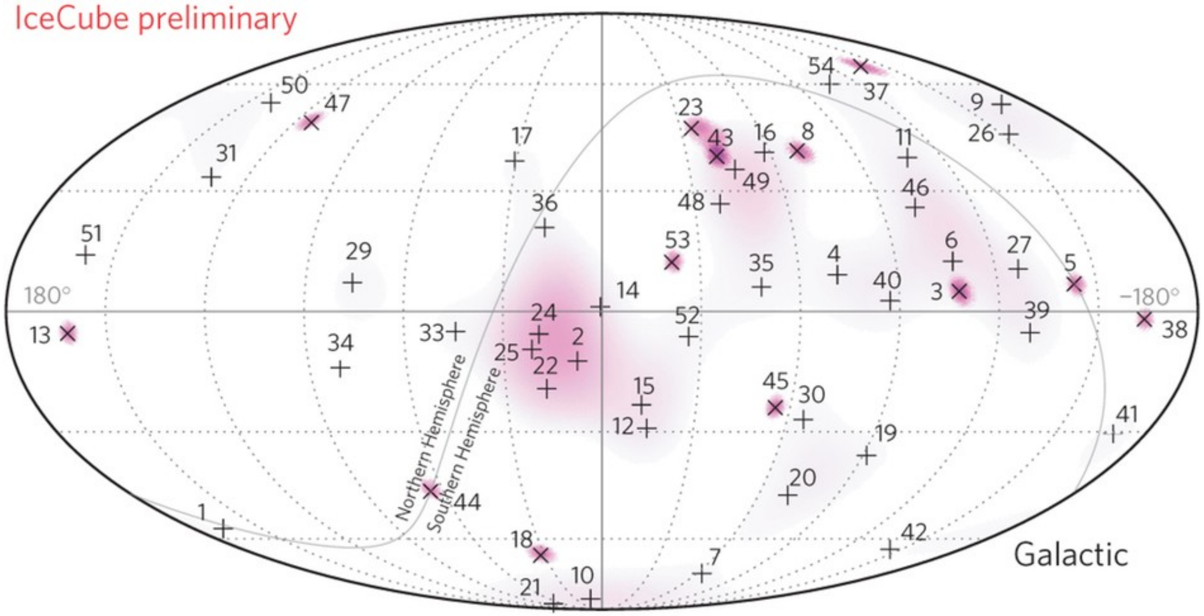
Neutrino Sources

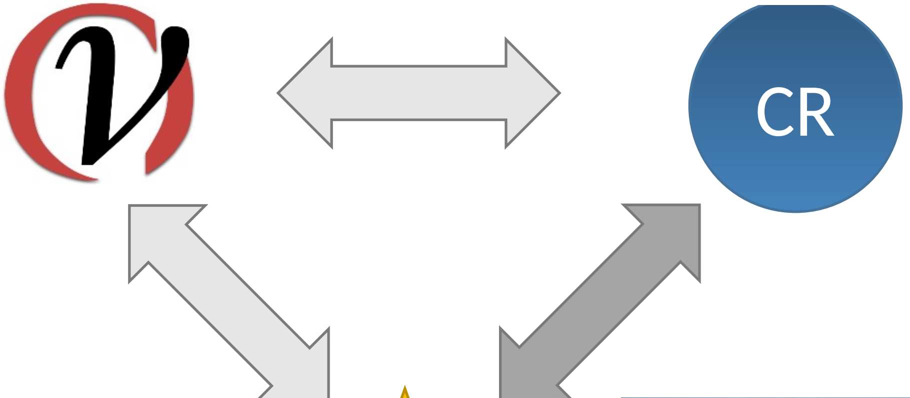


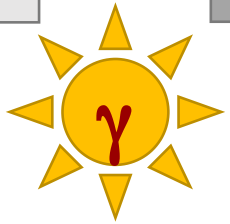
- Flux of neutrinos at the surface of the Earth.
- The three *arrows* near the *x*-axis indicate the energy thresholds for CC production of the charged lepton

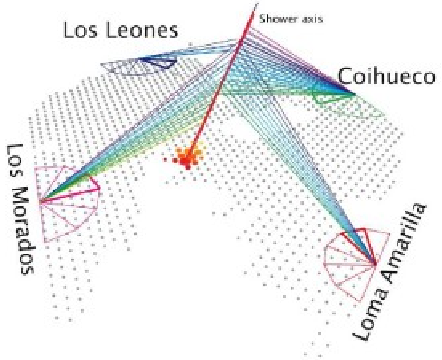
1) Open questions for neutrino astrophysics

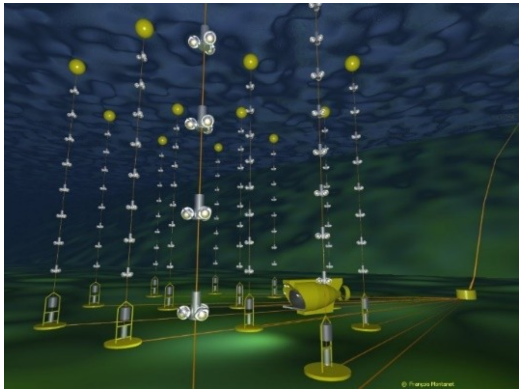












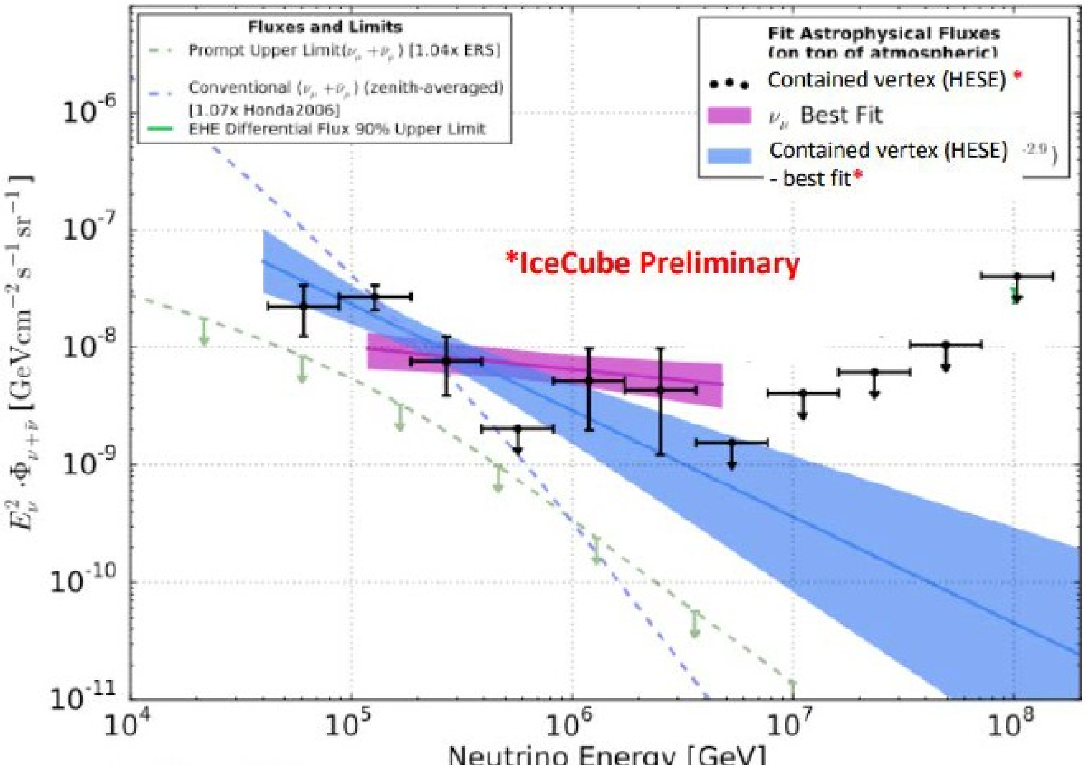
1) Open questions for neutrino astrophysics

- Origin of IceCube's HE astrophysical neutrinos?
- Evidence of galactic “TeVatron” from γ-rays (e, p or both?). But, for p and nuclei, no “LHC” o “PeVatrons” observed
- Neutrino: fundamental probe to identify **galactic** and **extragalactic** CR sources
- Disentangle astrophysical models with multimessenger observations: i.e., GRBs with GW, HEN and traditional astronomy (useful also in case of no ν observation)
- Production mechanisms of high energy cosmic particles **(jets?)**
- Study of galactic (and extragalactic?) propagation of CR, with neutrinos as tracers
- **Test the neutrino sector of the SM and BSM physics**

Detecting **cosmic** neutrinos: a threefold way

✓

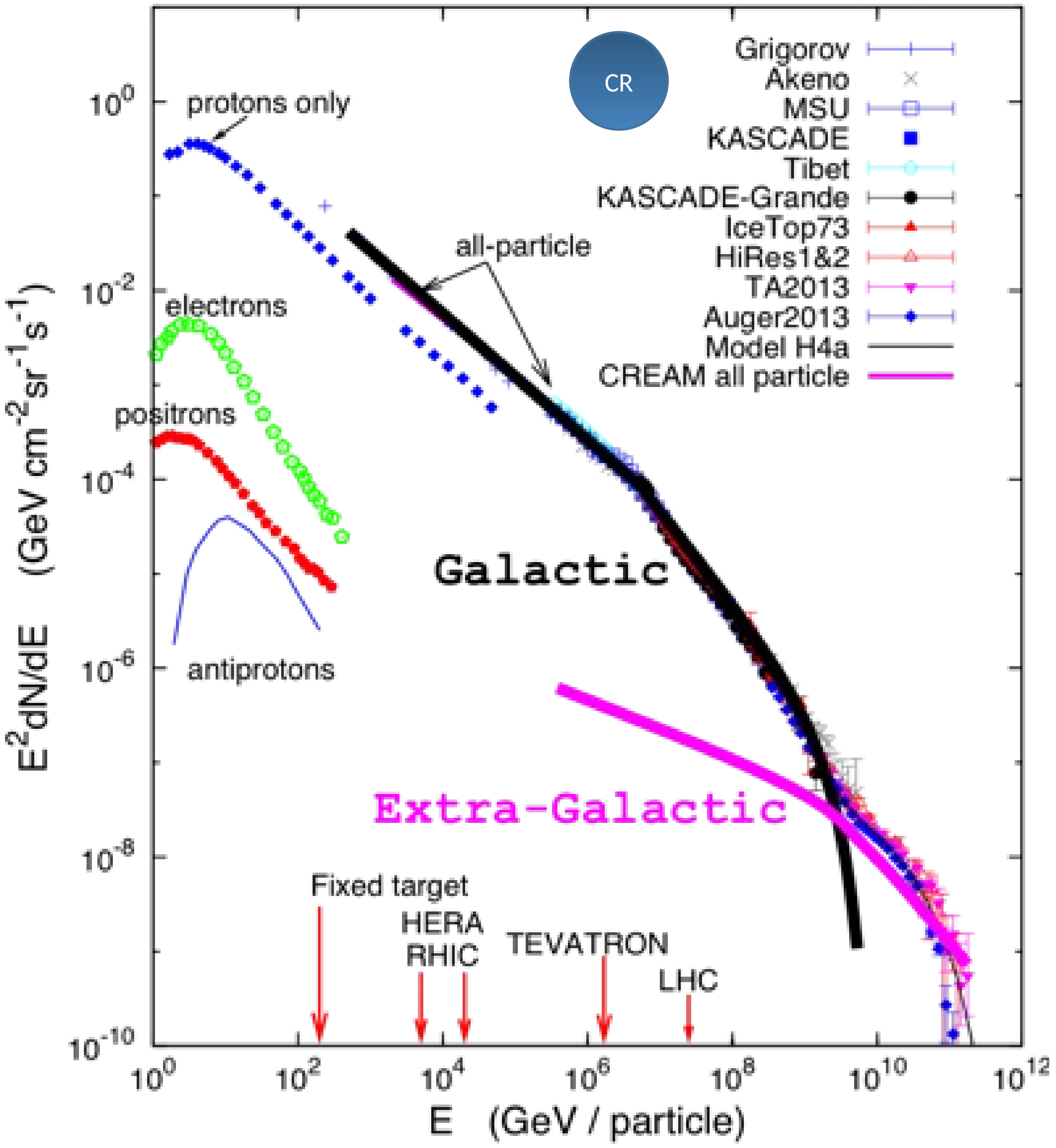
1. Excess of HE neutrinos ove the background of atmospheric events. Measurement of the **energy**

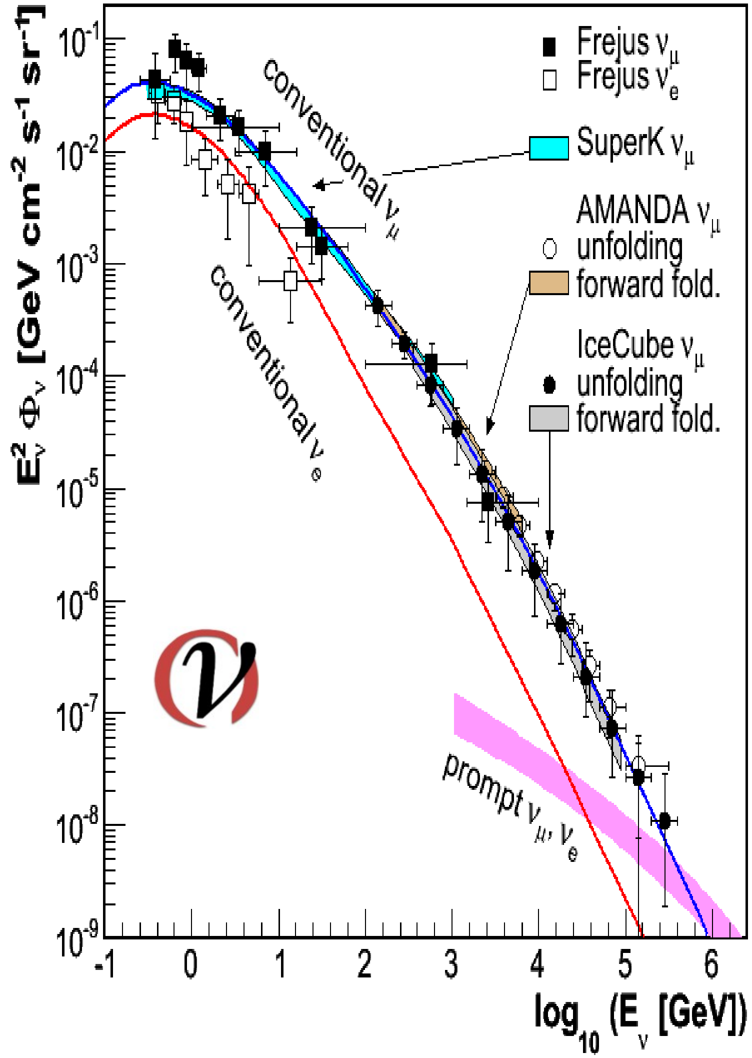


2. Point-like events, significant excess in the sky map. Measurement of the **neutrino direction**

3. Coincident event in a restricted time/direction windows with EM/γ/GW counterparts. Relaxed energy/direction measurement + **transient/ multimessenger** information

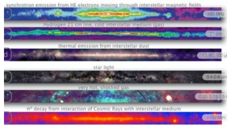
Cosmic rays and atmospheric neutrinos

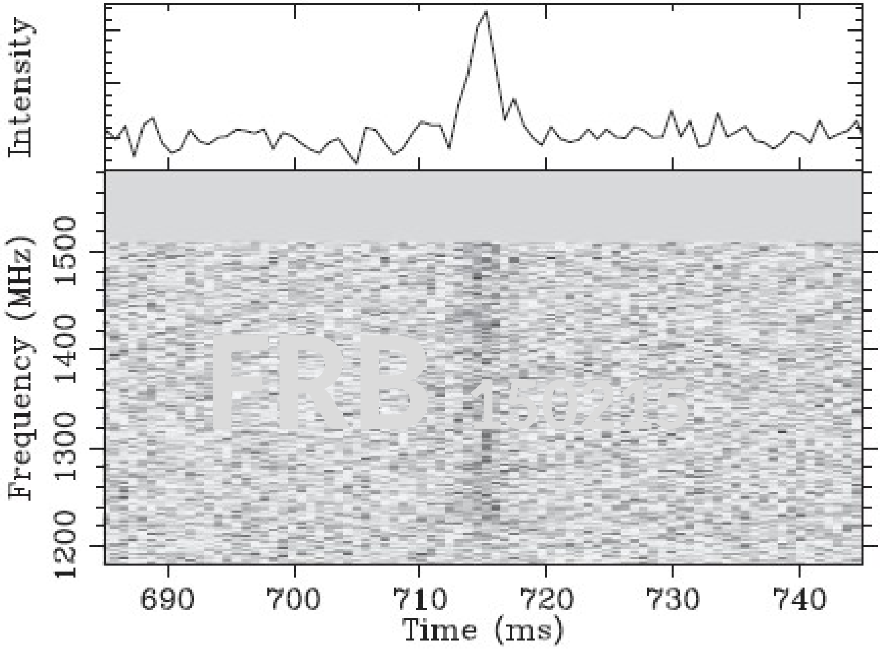


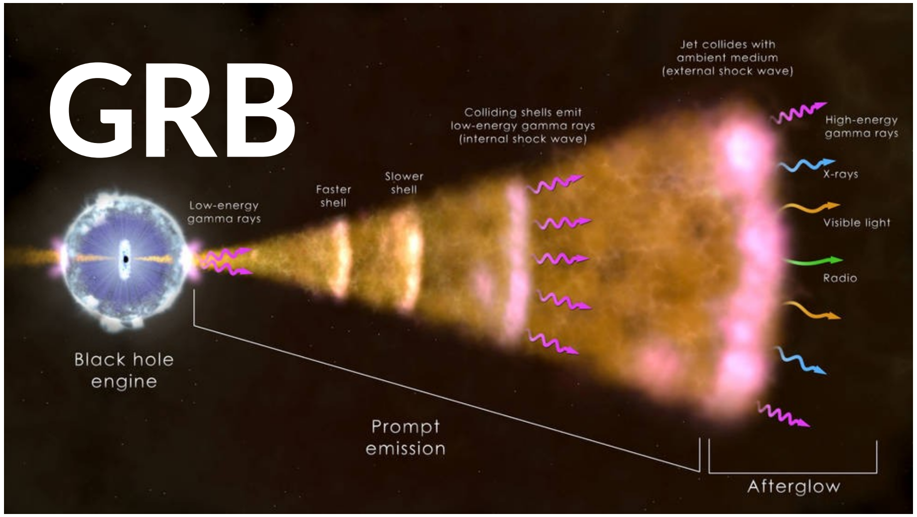


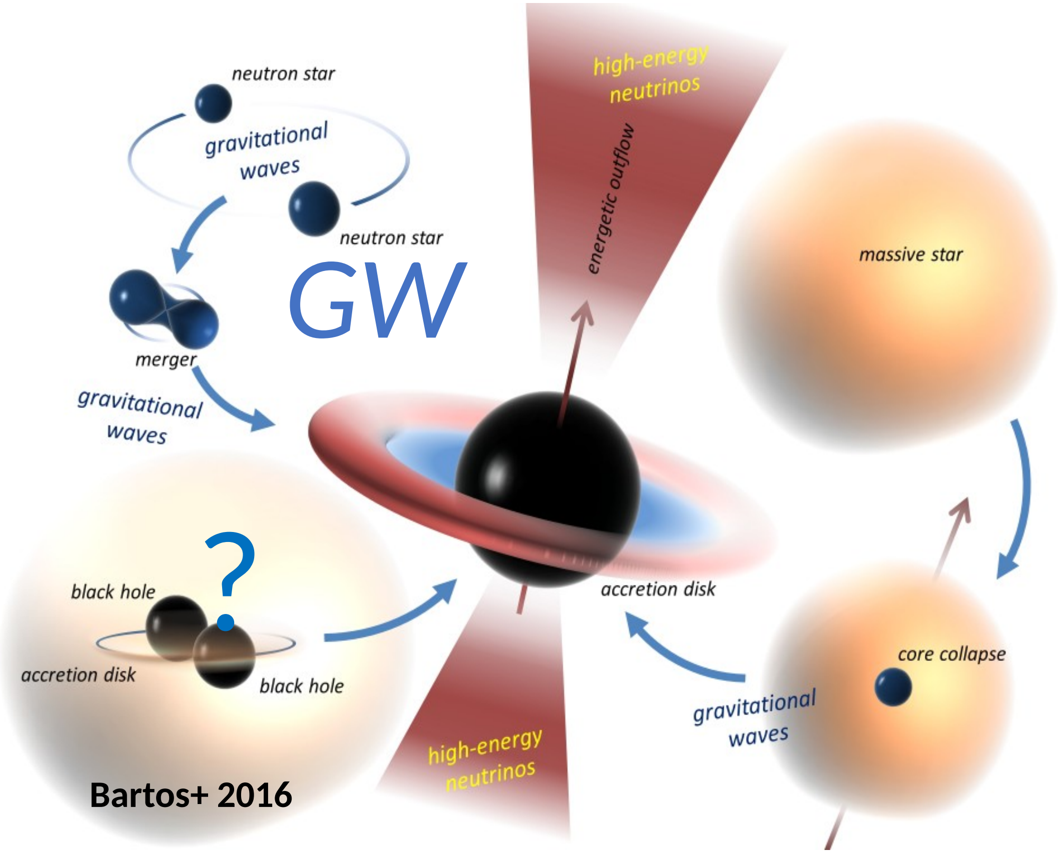
About **ExtraGalactic** sources

CR γ ν GW









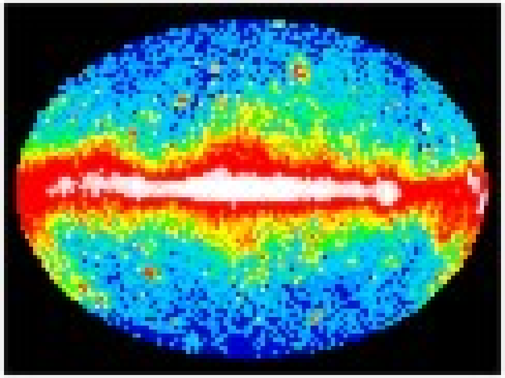
Bartos+ 2016

Gamma Ray Bursts (GRBs)

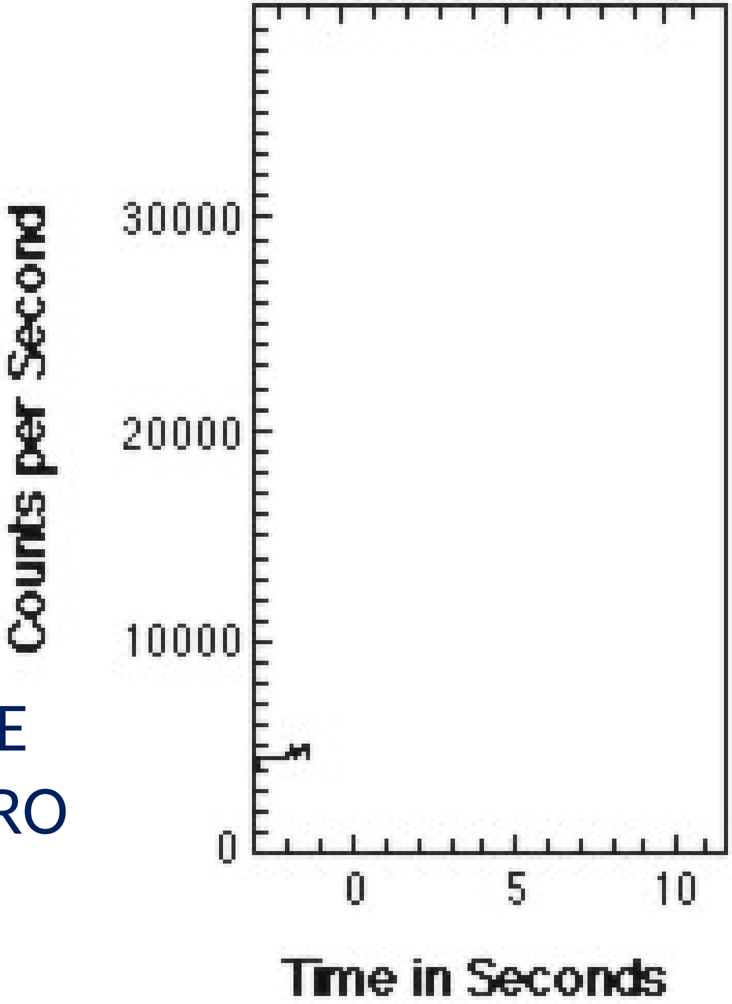
- Until ~20 y ago, GRBs were the first unknown in HE astronomy.
- They were discovered serendipitously in the late 1960s by U.S. military satellites looking for Soviet nuclear testing in violation of the atmospheric nuclear test ban treaty.

- These satellites carried γ-ray detectors since a nuclear explosion produces γ–rays.

- **GRBs are short-lived bursts of γ–rays.**
- At least some of them are associated with a special type of Sne;
- GRBs shine hundreds of times brighter than a typical SN, making them the brightest source of γ–rays in the observable Universe.



BATSE
on CGRO

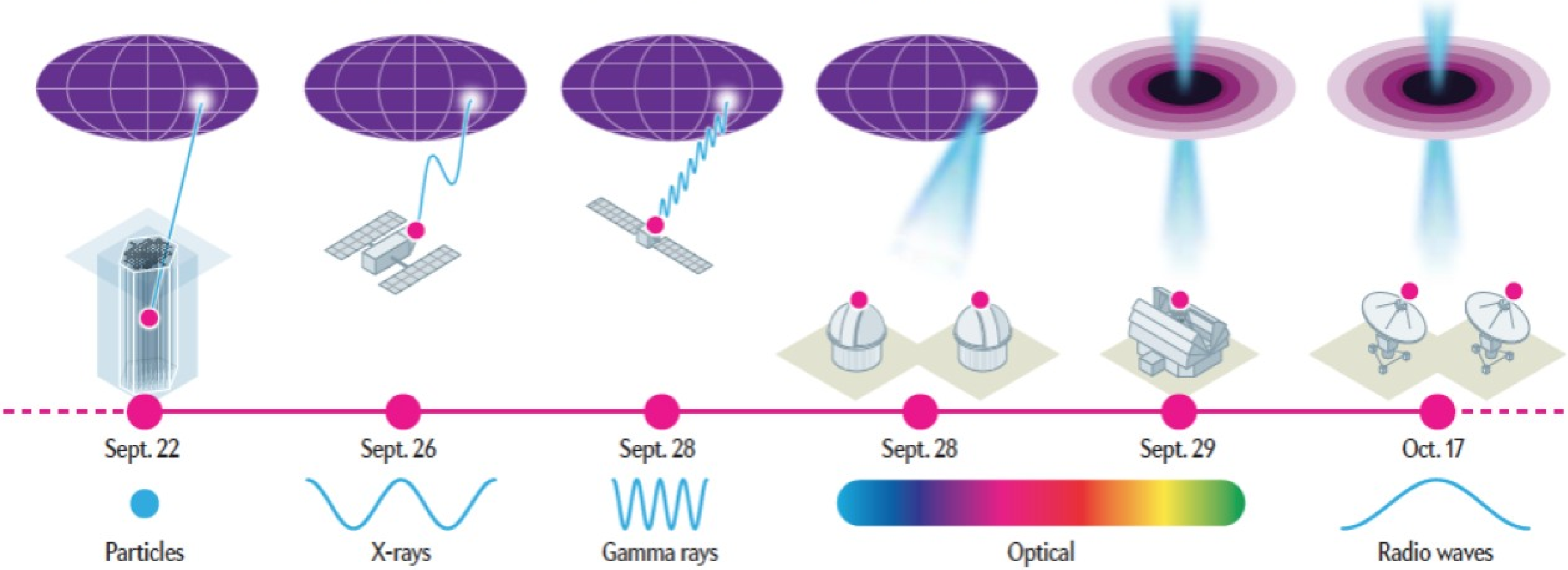


Breaking news

Many Messengers

Over three and a half weeks in 2017, astronomers observed the same celestial event—what they believe to be a flare-up from matter falling into a supermassive black hole—through multiple wavelengths of light, as well as particles called neutrinos. The combined observations offer scientists much more information about these mysterious phenomena than any measurement alone.

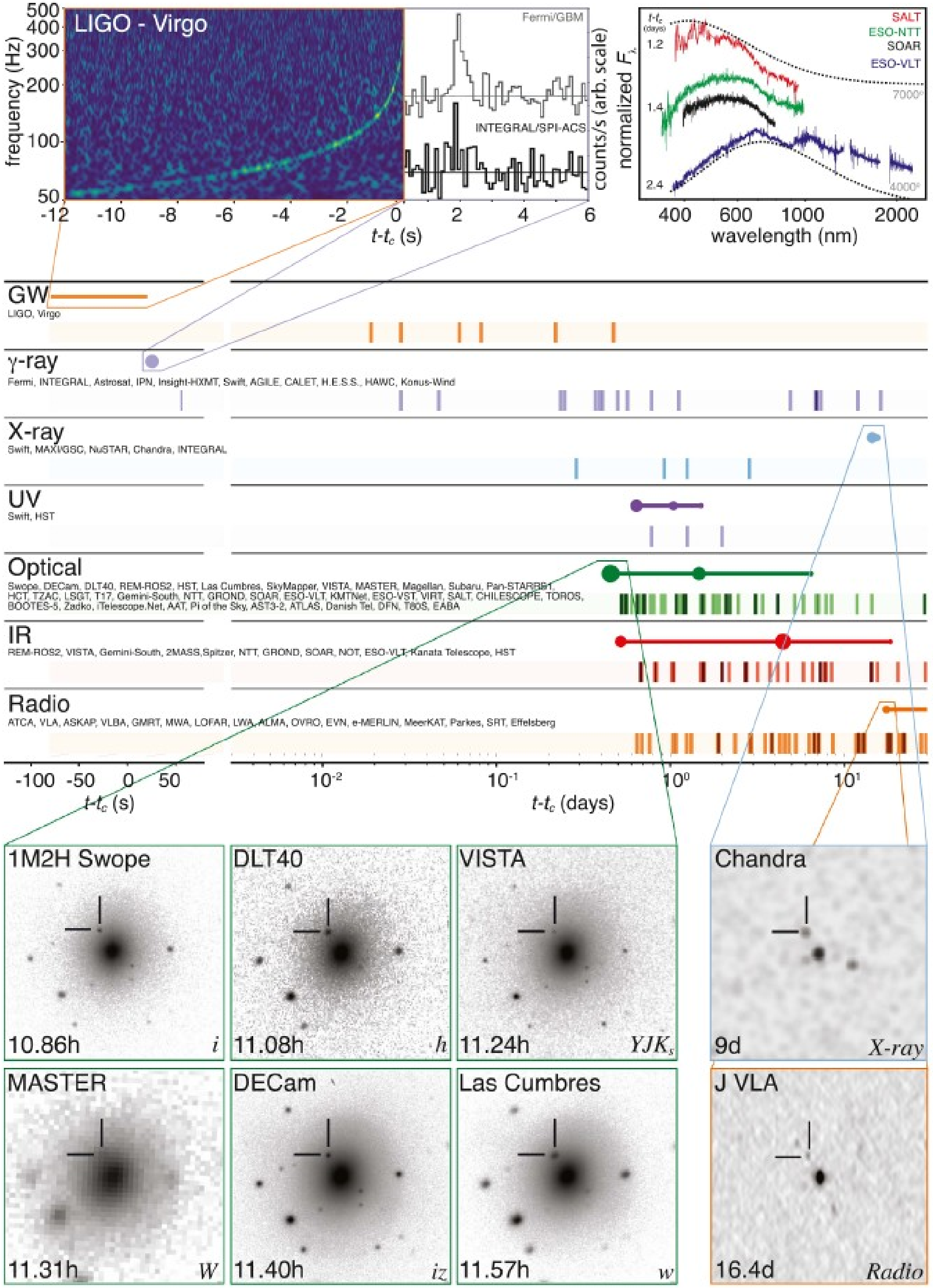
1. First, the IceCube Neutrino Observatory at the South Pole detected a high-energy neutrino and issued an alert.
2. The orbiting Swift x-ray telescope reported finding nine sources of x-rays coming from the same area of the sky as the neutrino.
3. Two days later the Fermi space telescope identified gamma rays coming from one of the same sources Swift found.
4. A network of ground-based optical telescopes called ASAS-SN announced that this source had been brightening over the past 50 days.
5. Another optical telescope found evidence that the source was a blazar—a huge black hole emitting jets as it swallowed mass.
6. The Very Large Array in New Mexico, observing in radio light, confirmed that the source of all these signals was a jet from a blazar.



(see J. Zornoza)

Finkbeiner (Scientific American)

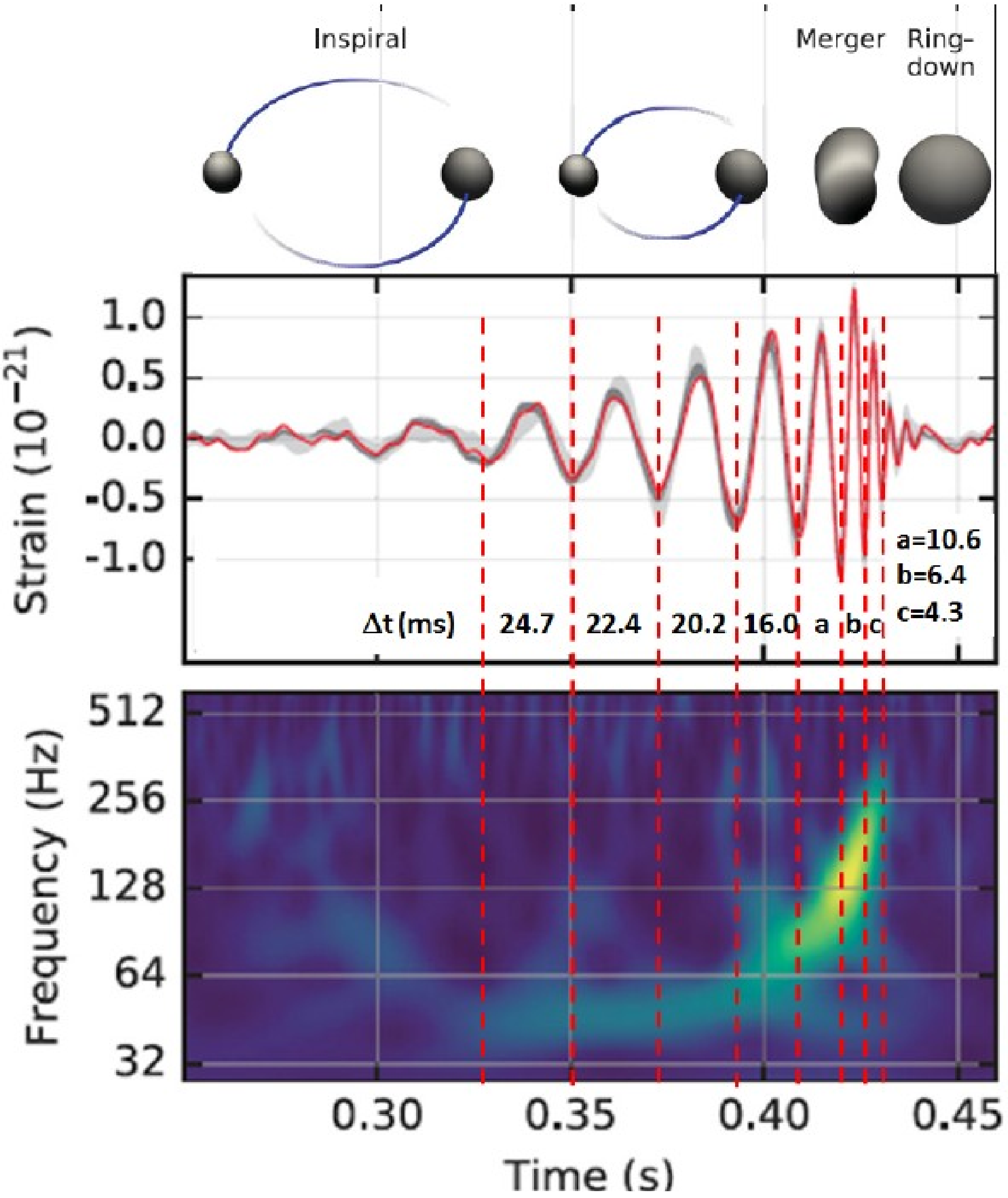
3) The multimessenger role of GWs waves



EM vs Gravitational waves

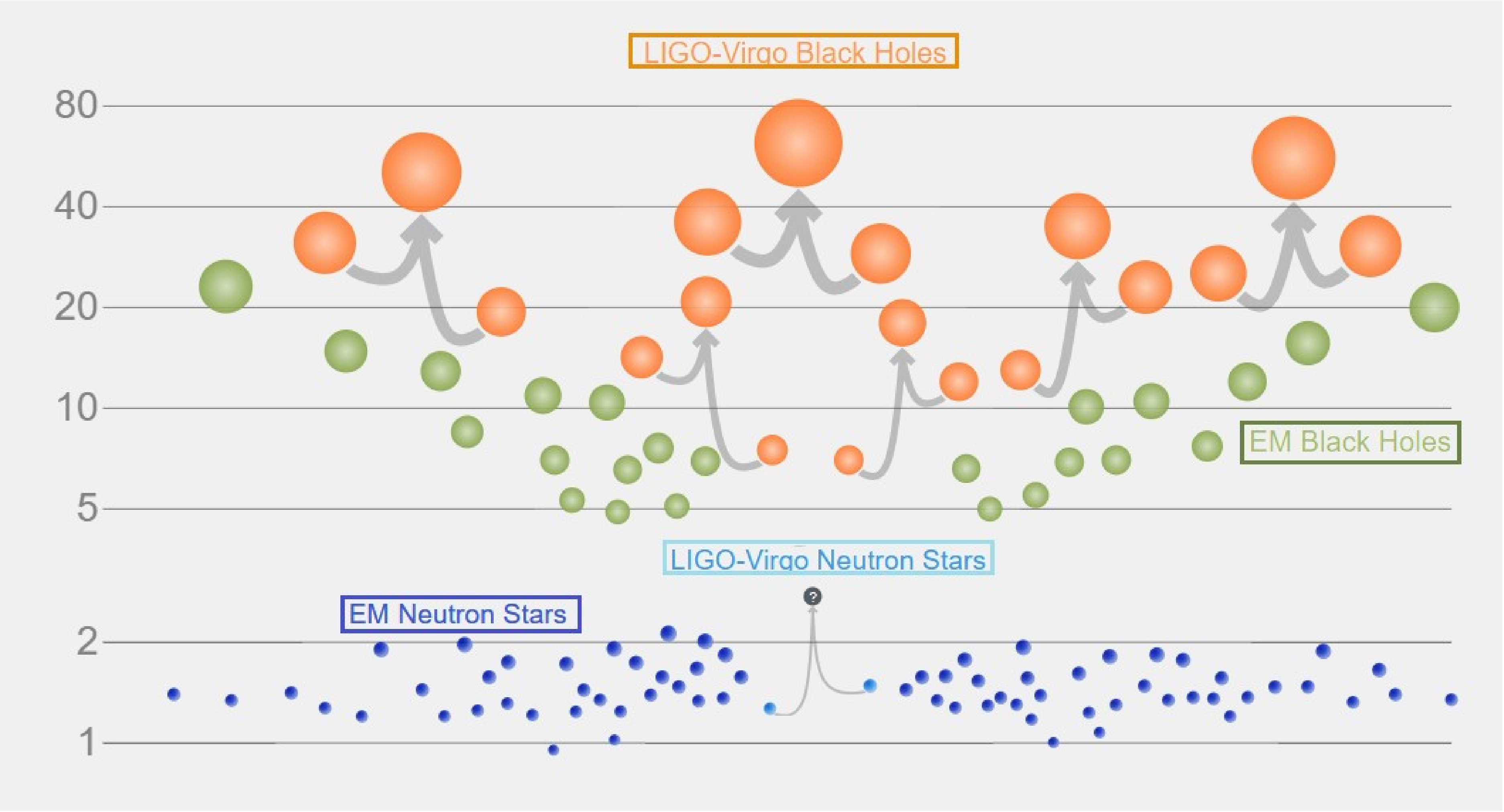
(Remember)

- The **EM radiation** emitted is an incoheren superposition from sources >> λ;
- **GW radiation** comes from systems with sizes R << λ. Hence, the signal reflects th coherent motion of extremely massive objects.
- Effect of EM radiation falls as **$1/r^2$ (intensity)**. GWs as **1/r (phase)** .
- GWs suffer a very small absorption when passing through ordinary matter.
- **Experimental methods** complementary t that developed in particle physics and traditional astronomy
- The **observables** contain direct information on **mass, distance, spin**

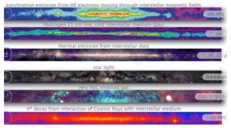


The role of Gravitational waves

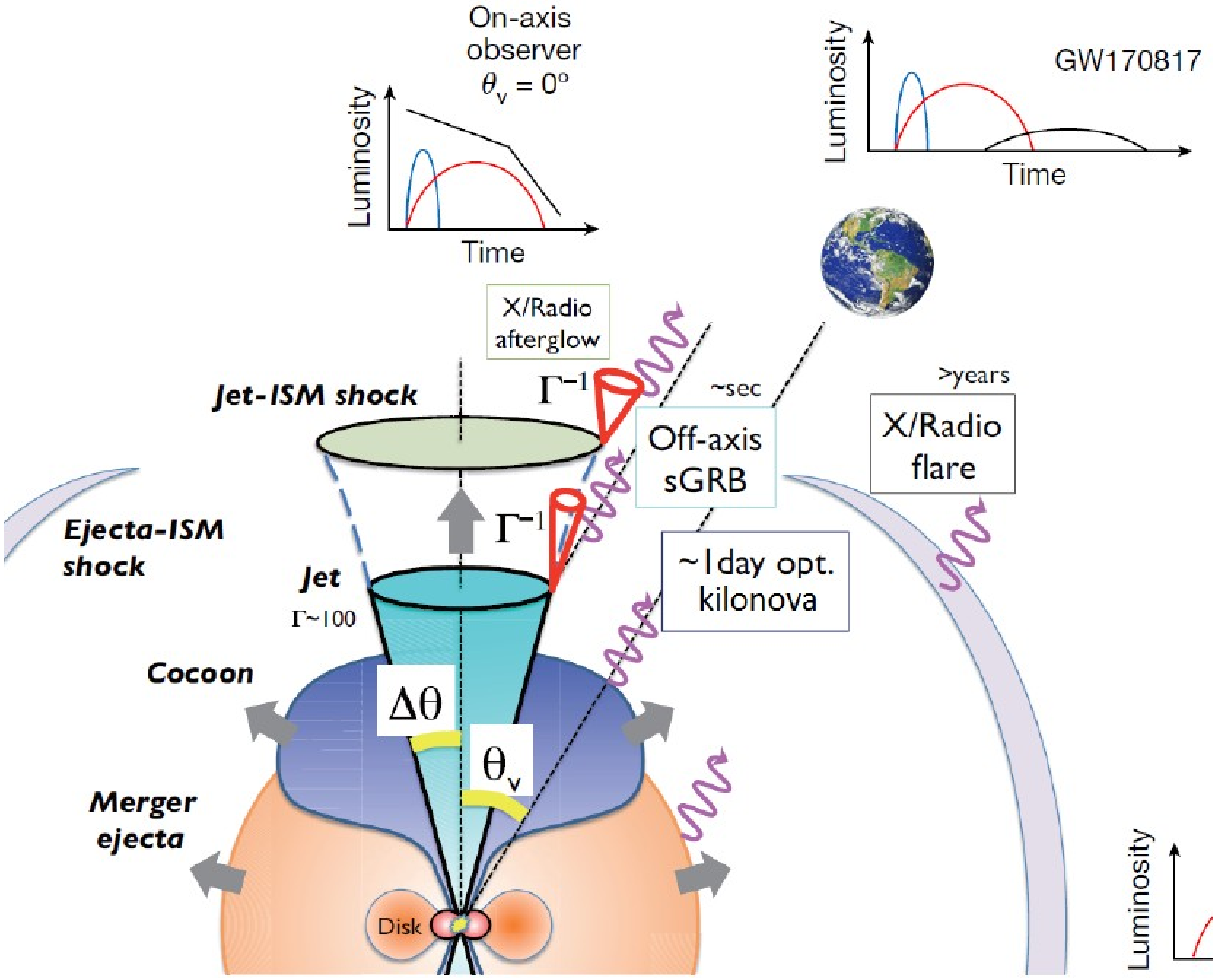
- BH+BH =



The most wanted object: NS+NS (NS+BH)

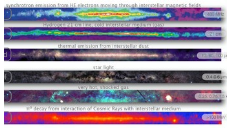


- A rich variety of phenomena in the case of NS-NS merging
- *GW* standard “sirene”
- Neutrinos
- EM counterpart
  - Fast emission (GRB)
    - Beamed emission
    - Afterglow (X-ray,…)
  - Kilonova (*)
    - Isotropic emission
    - Neutron-rich ejecta
  - Radio emission
- UHECR’s acceleration?

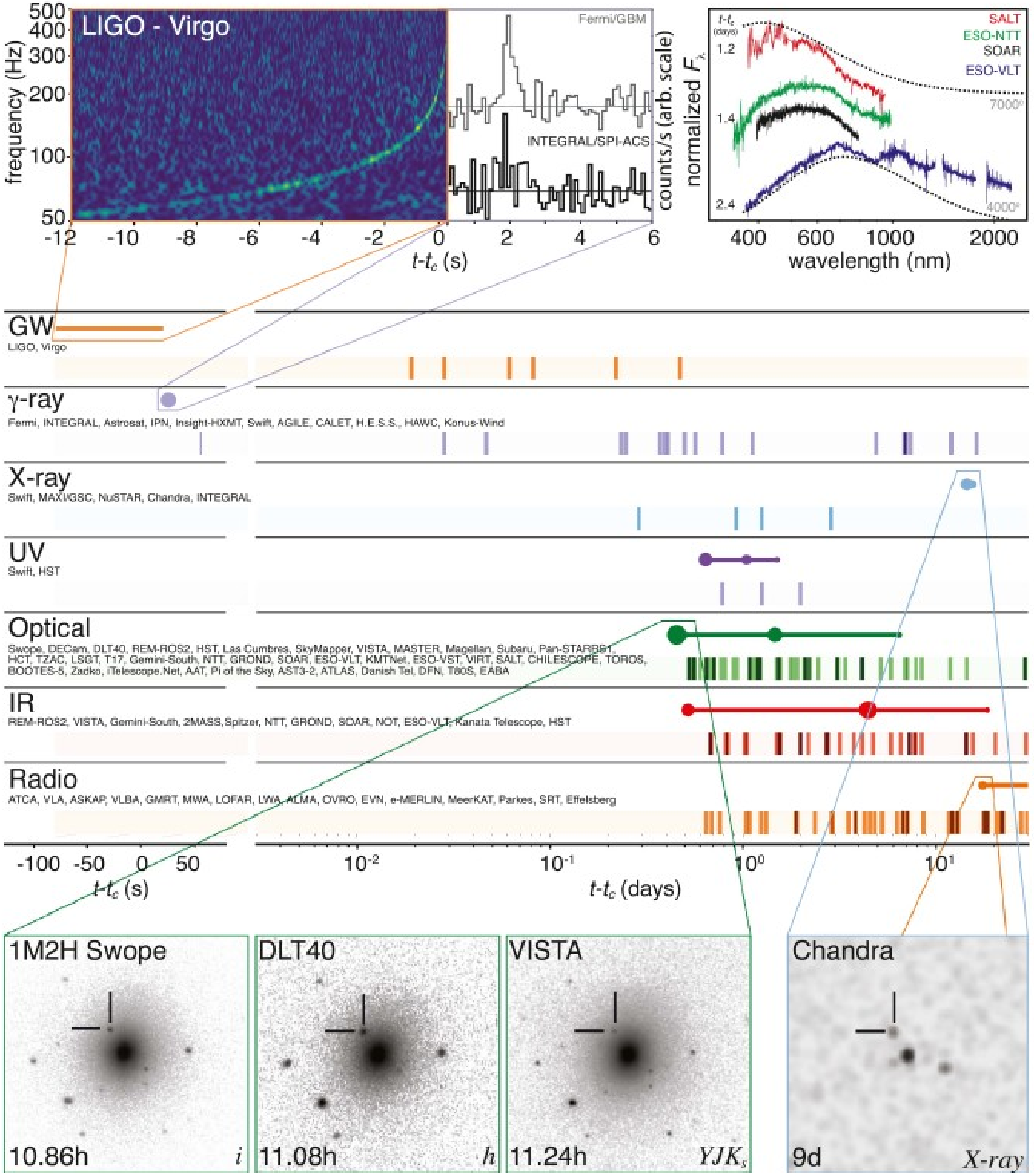


(*) By radioactive decay of heavy elements produce via r-process nucleosynthesis in the neutron-rich merger ejecta

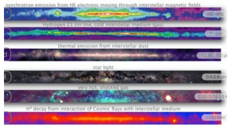
NS + NS =



- The GW signal was the input for the EM follow-up
- A simultaneous short GRB was observed by FERMI-GBM and INTEGRAL satellites. Alone, these signals are not sufficient to trigger EM position (position not known)
- The network of GW observatories can provide directionality information on the event position
- The observation of a coincident neutrino can provide directionality information as well
- In addition, ν's can provide additional info on the acceleration mechanism
- The key of the success: we know the kinematics of the merging objects, and the energy loss in GW



Conclusions



- Multi-messenger is a born field
- Combine the information from traditional astronomy, γ-rays, charged cosmic-rays, neutrinos and gravitational waves
- Use information from instruments (close) to the technology limits
- New instruments:
  - SKA (radio), Webb (IR), CTA (TeV)
  - aLIGO, adVIRGO: Astrophysics with GW signals
  - Neutrino telescopes with multi-km3 effective volumes
- Different opportunities for **particle physics**
  - Dark matter searches
  - Mass of the neutrino
  - Propagation of neutral particle (Transparency of the Universe)
  - Energy of the vacuum - axions;
  - Tests of Lorentz Invariance; Quantum gravity (space time structure of vacuum)
  - …
- **cosmology**
  - Alternative measurement of the cosmological parameters
- and **astrophysics**
  - Sources of Galactic CRs
  - Origin on cosmic neutrinos observed by IceCube
  - Origin and type of UHECRs
  - …