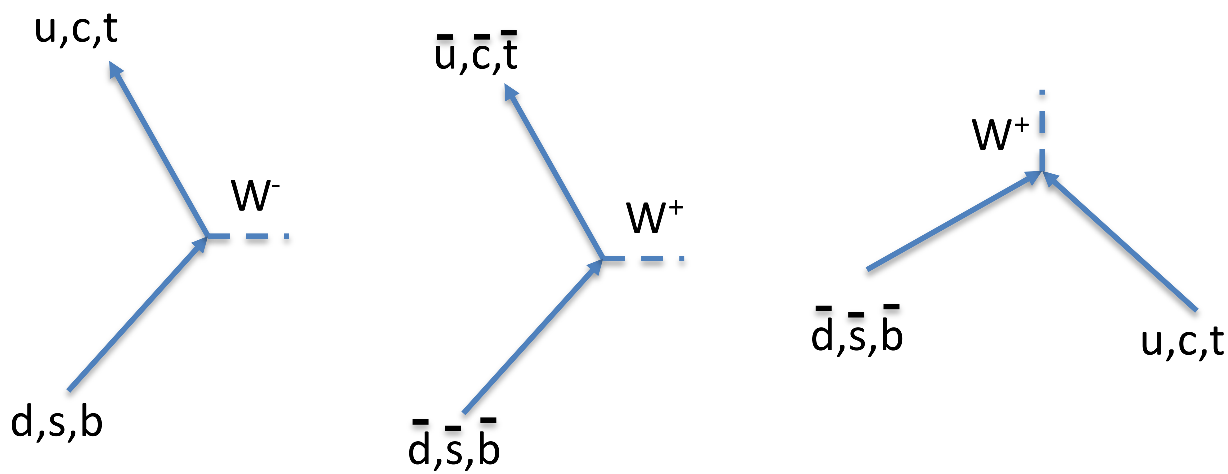
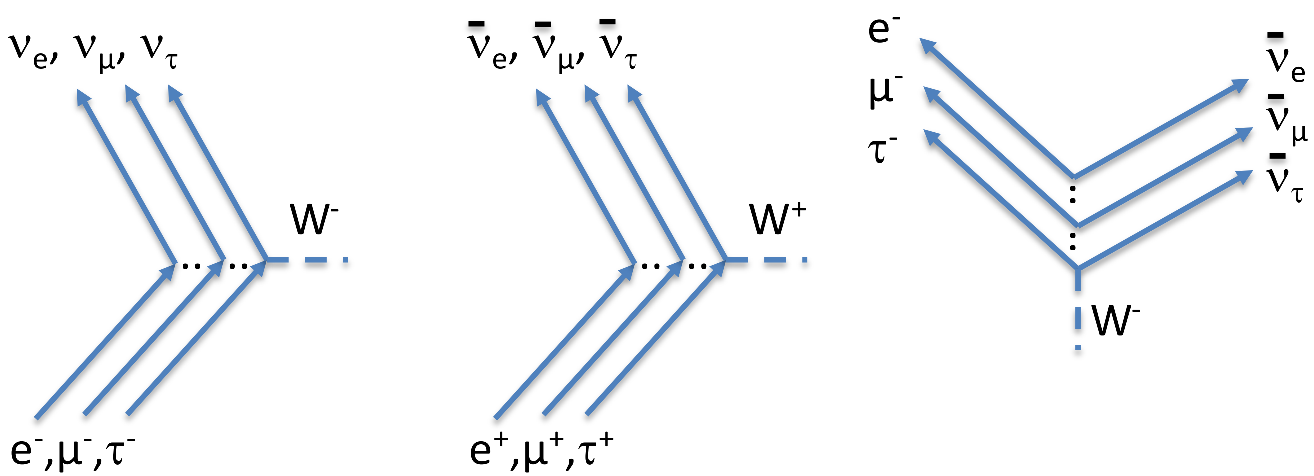
Weak Interactions

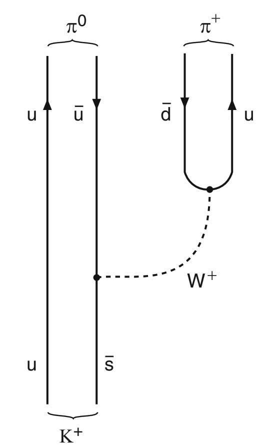


or reverse with opposite charge W



Example Reactions:

- $n \to p + e^- + \bar{\nu}_e$
- $\Lambda \to \pi^- + p$
- anti-n decay
- pp -> D, beta+ decay
- $\overline{\nu}_e + p \to n + e^+$
- $\pi^- \to \mu^- + \bar{\nu}_\mu$
- $\mu^- \to e^- + \nu_\mu + \bar{\nu}_e$
- $\tau^- \to \pi^- + \nu_\tau$.



More about the Weak Interaction:

- Reminder: $\mathcal{M}_{fi} \;\propto\; g \cdot \dfrac{1}{Q^2c^2 + M_W^2c^4} \cdot g$ $\qquad \dfrac{G_F}{\sqrt{2}} = \dfrac{\pi\,\alpha}{2} \cdot \dfrac{g^2}{e^2} \cdot \dfrac{(\hbar c)^3}{M_W^2 c^4}$
- Violates Parity (V-A structure)
  – For hadrons: Have separate couplings G_V = G_F, G_A
- Quark mixing: Mass eigenstates ≠ participants in the weak interaction: (Cabibbo angle)

$$|\,\mathrm{d}'\,\rangle = \cos\theta_C\,|\,\mathrm{d}\,\rangle + \sin\theta_C\,|\,\mathrm{s}\,\rangle$$
$$|\,\mathrm{s}'\,\rangle = \cos\theta_C\,|\,\mathrm{s}\,\rangle - \sin\theta_C\,|\,\mathrm{d}\,\rangle\ ,$$

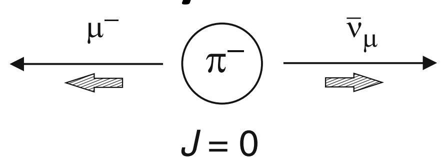
$$\sin\theta_C \approx 0.22\ , \qquad \text{and} \qquad \cos\theta_C \approx 0.98$$

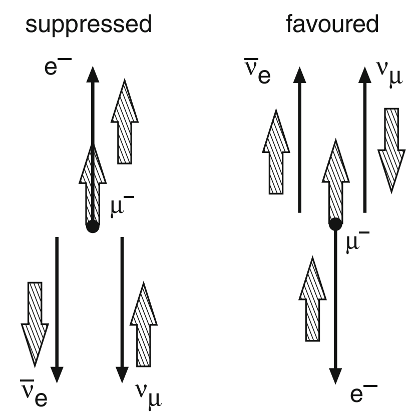
- Cabibbo-Kobayashi-Maskawa matrix:

$$\begin{pmatrix} |\,\mathrm{d}'\,\rangle \\ |\,\mathrm{s}'\,\rangle \\ |\,\mathrm{b}'\,\rangle \end{pmatrix} = \begin{pmatrix} V_{\mathrm{ud}} & V_{\mathrm{us}} & V_{\mathrm{ub}} \\ V_{\mathrm{cd}} & V_{\mathrm{cs}} & V_{\mathrm{cb}} \\ V_{\mathrm{td}} & V_{\mathrm{ts}} & V_{\mathrm{tb}} \end{pmatrix} \cdot \begin{pmatrix} |\,\mathrm{d}\,\rangle \\ |\,\mathrm{s}\,\rangle \\ |\,\mathrm{b}\,\rangle \end{pmatrix} \qquad \left(\ \left|V_{ij}\right|\ \right) = \begin{pmatrix} 0.974 & 0.225 & 0.003 \\ 0.225 & 0.973 & 0.041 \\ 0.008 & 0.040 & 0.999 \end{pmatrix}$$

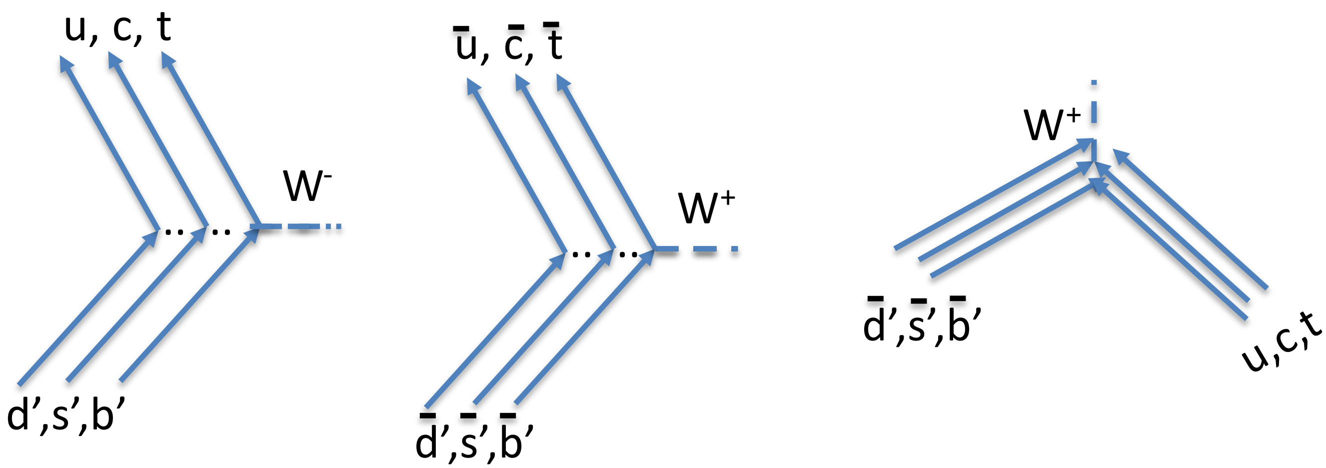
Parity Violation

- Maximal in the weak interaction!
- W's couple only to "left-handed" particles
- Explains preference for μ in π decay





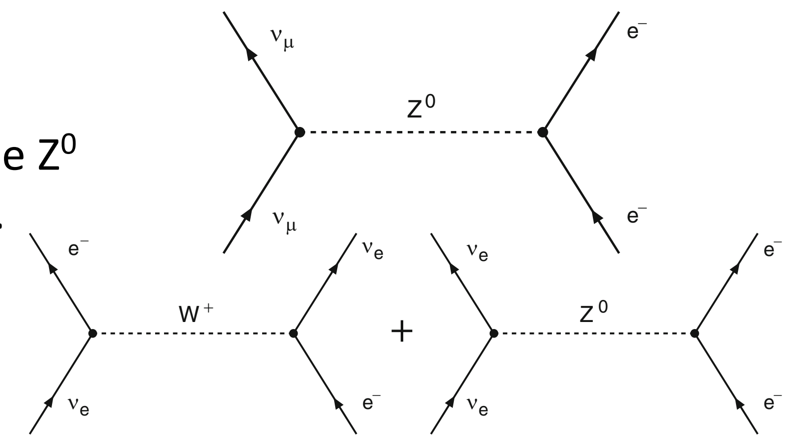
Weak Interactions with Weak Eigenstates

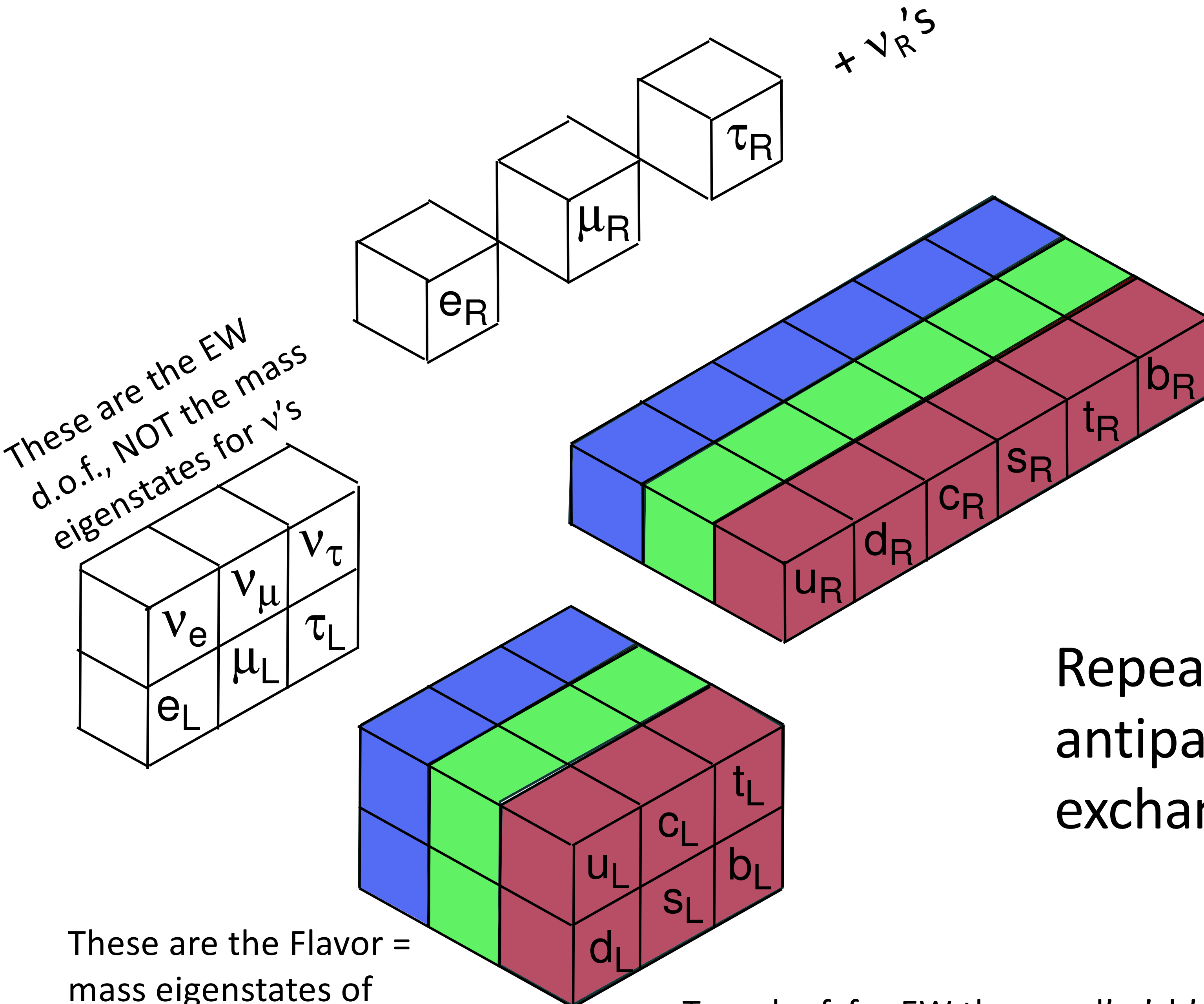


or reverse with opposite charge W

Why don’t the Lepton States mix?
THEY DO! But we cannot observe the mass eigenstates of the neutrinos. See later…

Why is there no W^0?
THERE IS! However, in “real life” we instead observe the Z^0 which is slightly more massive than the W’s. see later…

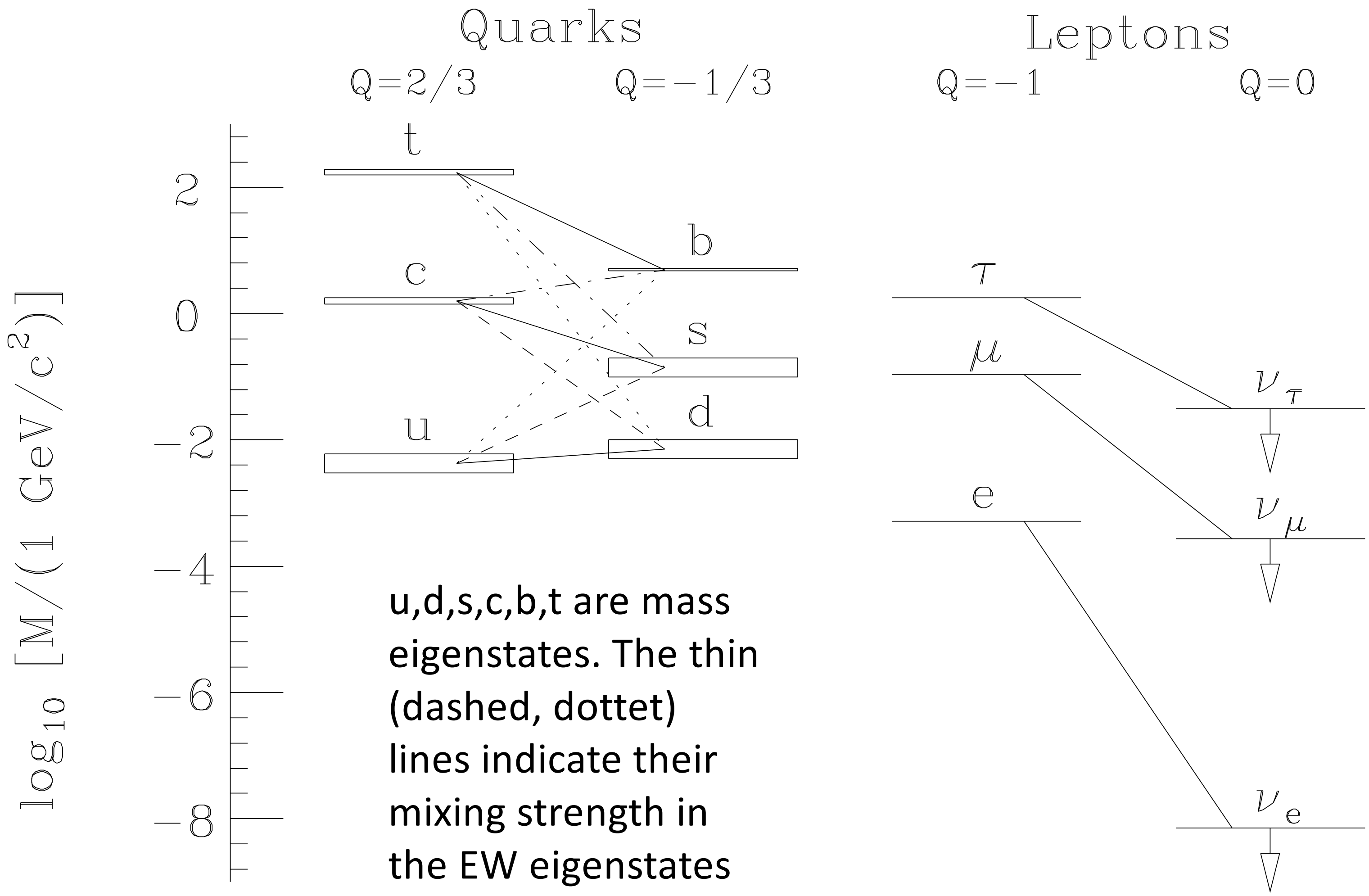




Repeat with antiparticles but exchange R vs. L

These are the Flavor = mass eigenstates of the quarks

True d.o.f. for EW theory: d′, s′, b′



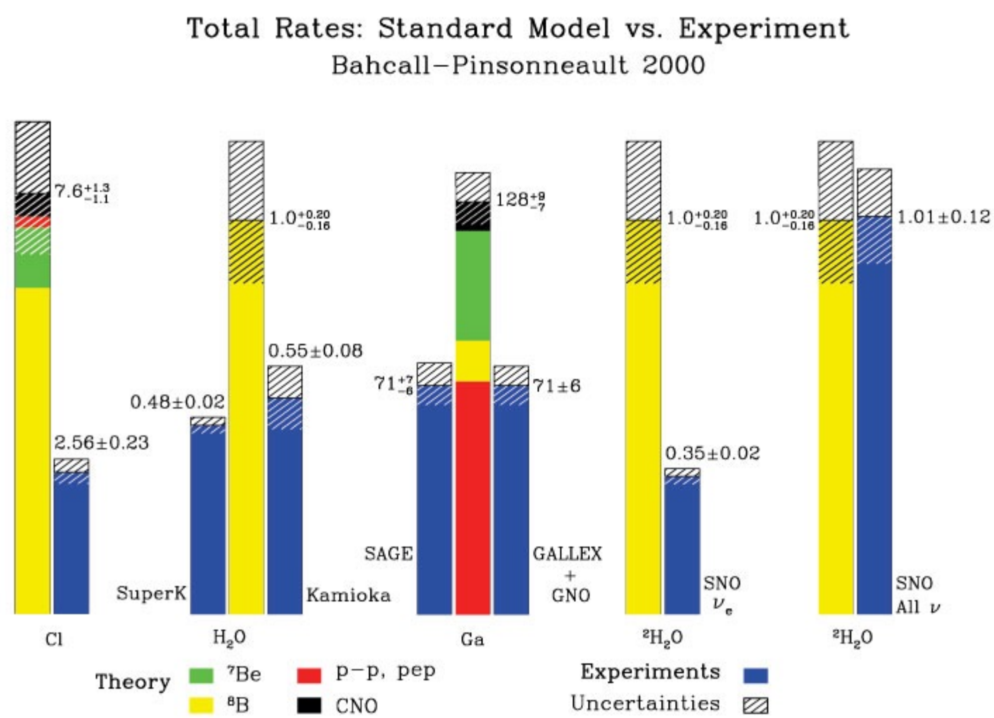
u,d,s,c,b,t are mass eigenstates. The thin (dashed, dottet) lines indicate their mixing strength in the EW eigenstates d',s' and b'

The neutrinos are the EW eigenstates. They are NOT mass eigenstates.

Neutrinos DISAPPEAR!

- Originally discovered by Ray Davis: there are too few neutrinos coming from the sun

- Original experiment in Homestead Mine (Cl): Only 1/3 of expected flux
- Confirmed by Sage, Gallex, Super-K, SNO, …
- Confirmed with reactors: Bugey, Chooz, KamLand,… and accelerator neutrinos (T2K, NOνA,…)
- Also found disappearance of μ-neutrinos in atmosphere: Super-K.



Explanation: 2 –neutrino model

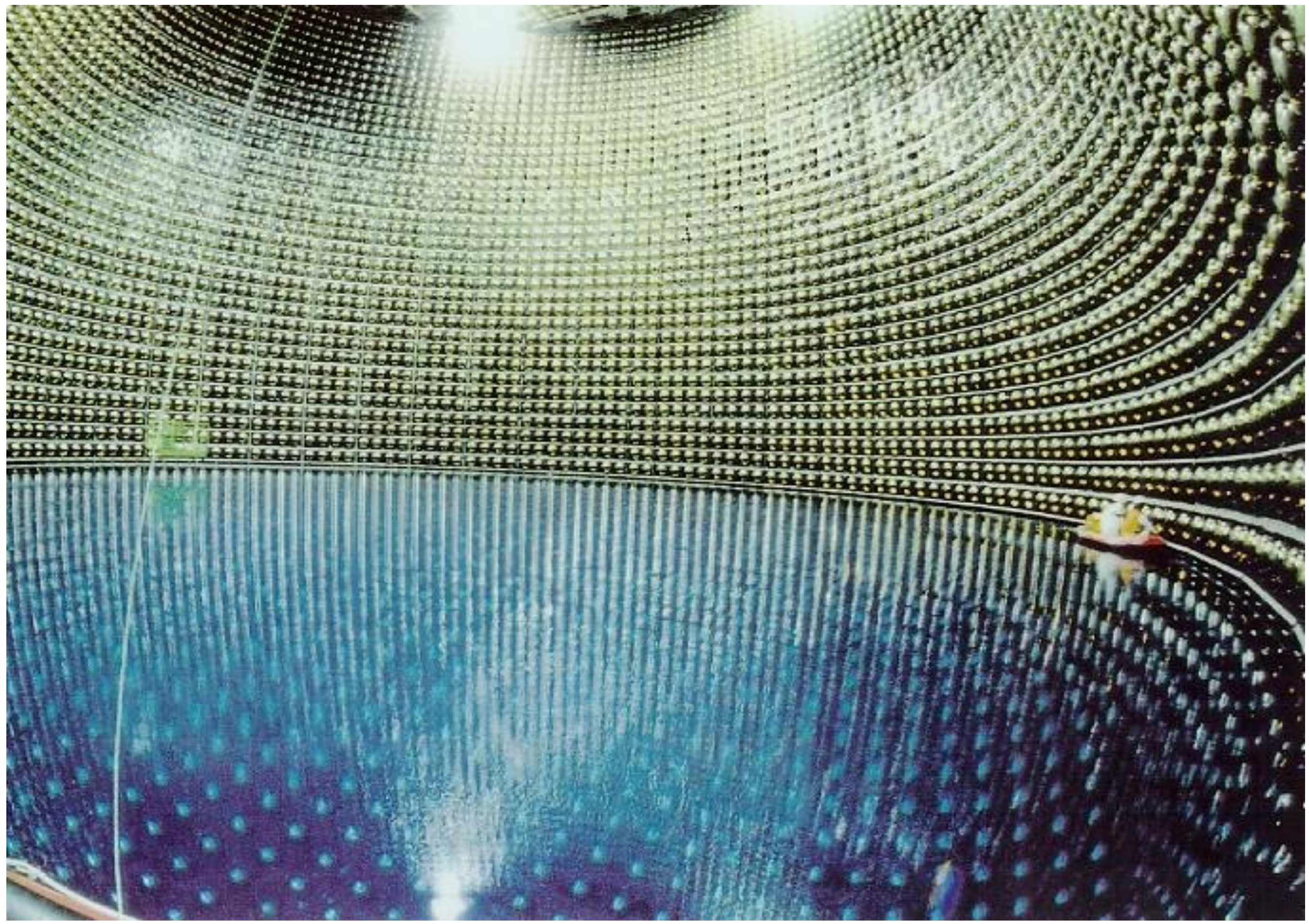
$$P_{\alpha\to\beta,\alpha\neq\beta} = \sin^2(2\theta)\,\sin^2\left(\frac{\Delta m^2 L}{4E}\right)\ \text{(natural units)}.$$

$$P_{\alpha\to\beta,\alpha\neq\beta} = \sin^2(2\theta)\,\sin^2\left(1.27\frac{\Delta m^2 L}{E}\,\frac{[\mathrm{eV}^2]\,[\mathrm{km}]}{[\mathrm{GeV}]}\right).$$

- The mass differences, Δm^2, are known to be on the order of 1×10^{-4} eV^2
- Oscillation distances, L, in modern experiments are on the order of kilometers
- Neutrino energies, E, in modern experiments are typically on order of MeV or GeV.

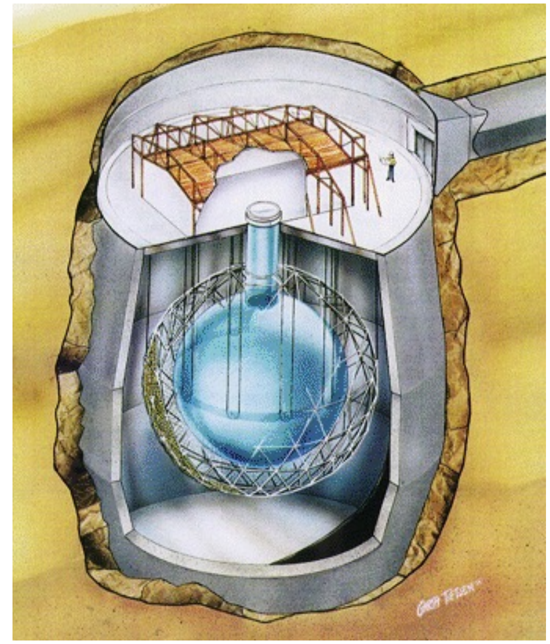
Kamiokande, Super-K

- Detect neutrinos from sun and atmospheric neutrinos
- Only 50% of solar νs
- Detection via Cherenkov Light



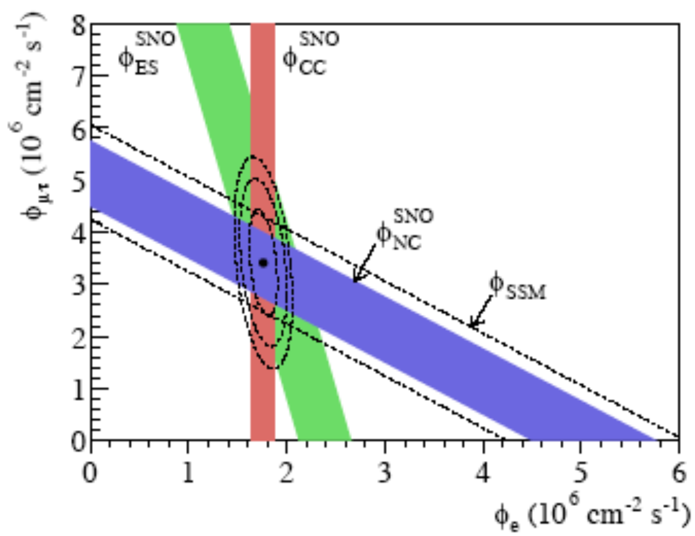
Kamioka Observatory, ICRR (Institute for Cosmic Ray Research), The University of Tokyo

SNO



- Heavy Water Cherenkov detector
- Sensitive to all 3 types of ν' s with different observables:

  $d + \nu_e \rightarrow p + p + e^-$;
  $d + \nu_\mu \rightarrow p + n + \nu_\mu$
- First unambiguous confirmation that total number of ν' s from sun is as expected - only flavor changes



The Nobel Prize in Physics 2015
Takaaki Kajita, Arthur B. McDonald

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The Nobel Prize in Physics 2015

Photo © Takaaki Kajita

Takaaki Kajita

Prize share: 1/2

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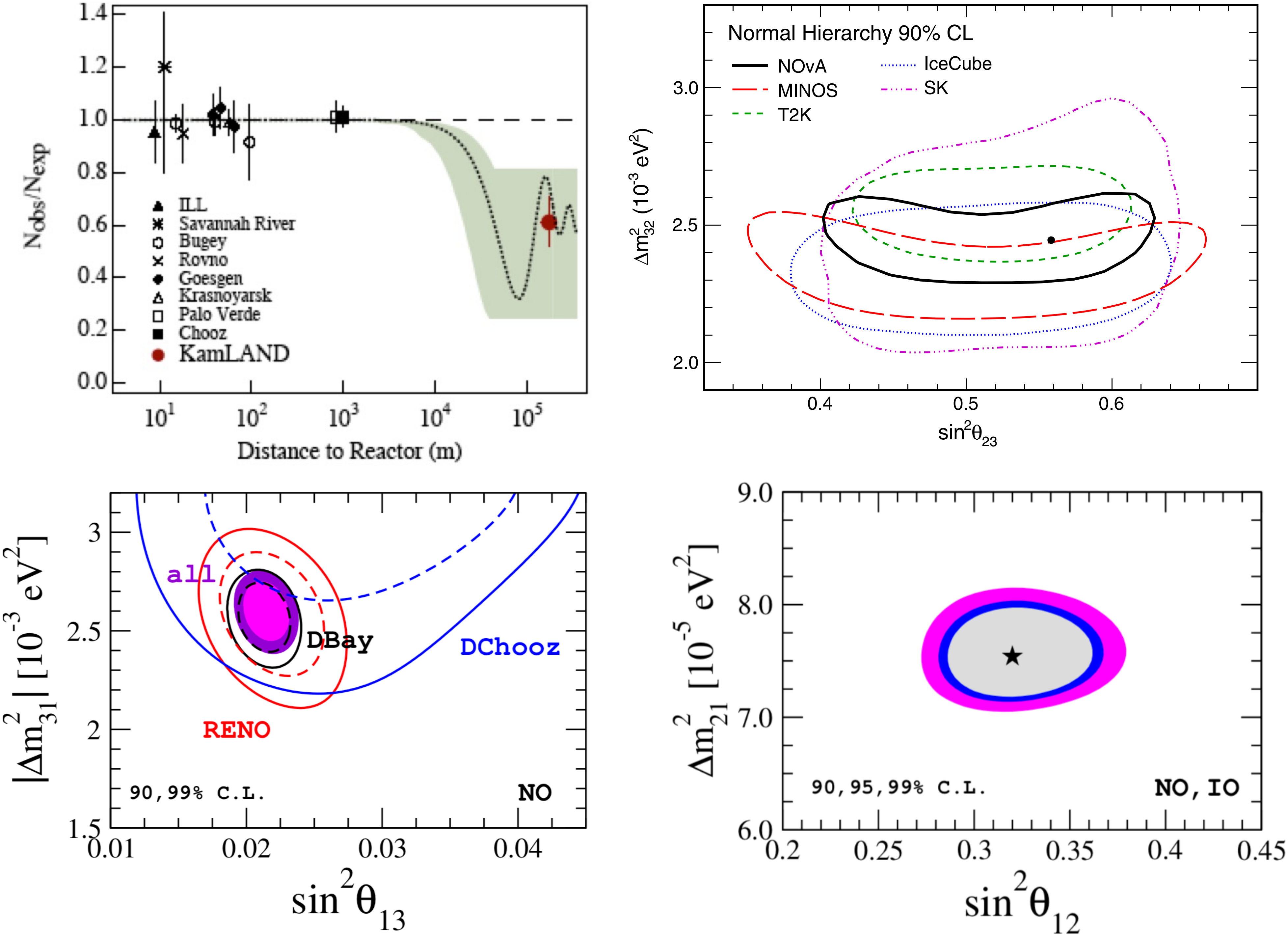
Arthur B. McDonald

Prize share: 1/2

The Nobel Prize in Physics 2015 was awarded jointly to Takaaki Kajita and Arthur B. McDonald *"for the discovery of neutrino oscillations, which shows that neutrinos have mass"*



1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
Nobs/Nexp
ILL
Savannah River
Bugey
Rovno
Goesgen
Krasnoyarsk
Palo Verde
Chooz
KamLAND
10^1
10^2
10^3
10^4
10^5
Distance to Reactor (m)
Normal Hierarchy 90% CL
NOvA
MINOS
T2K
IceCube
SK
3.0
2.5
2.0
Δm²32 (10^-3 eV²)
0.4
0.5
0.6
sin²θ23
3
2.5
2
1.5
|Δm²31| [10^-3 eV²]
all
DBay
DChooz
RENO
90,99% C.L.
NO
0.01
0.02
0.03
0.04
sin²θ13
9.0
8.0
7.0
6.0
Δm²21 [10^-5 eV²]
90,95,99% C.L.
NO,IO
0.2
0.25
0.3
0.35
0.4
0.45
sin²θ12

Electroweak Interaction
(Unification by Salam and Weinberg *et al.*)

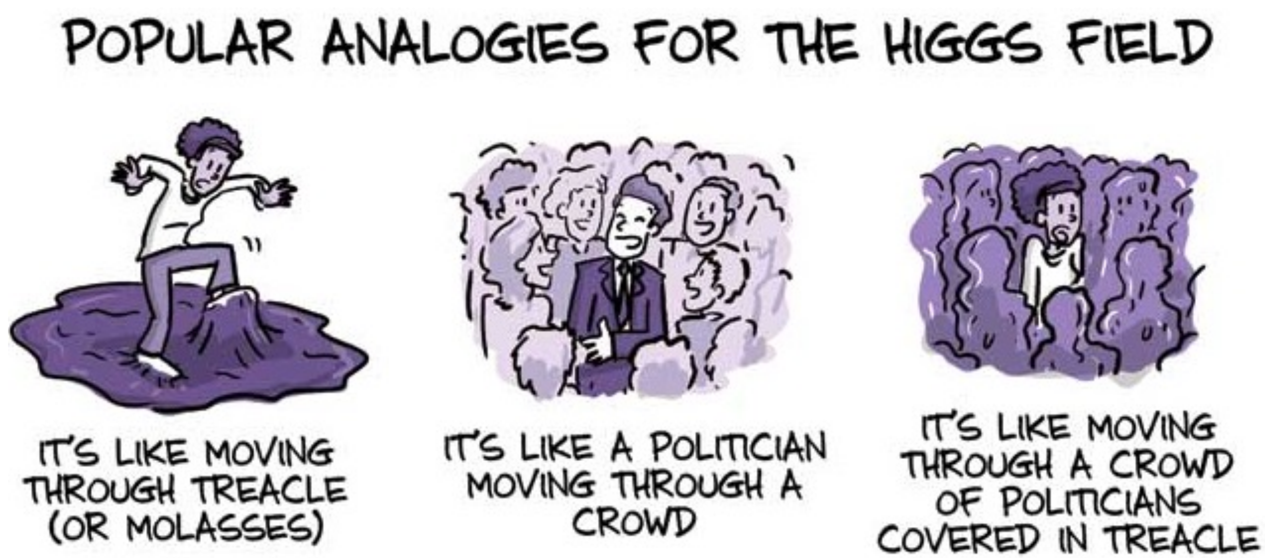
- Just like the strong and EM interaction, Weak interactions are mediated by “charges”
  - Named “Hypercharge Y” and ”Weak Isospin I”
  - W^+, W^- , W^0 and couple with strength *g* to I
  - B^0 couples with strength *g*’ to Y
  - $g \sin\theta_W = g' \cos\theta_W = e.$ $\sin^2\theta_W = 0.23113 \pm 0.00021$
- Huh? Because of their interaction with the Higgs field, some particles we actually observe are mixtures: $|\gamma\rangle = \cos\theta_W|B^0\rangle + \sin\theta_W|W^0\rangle$

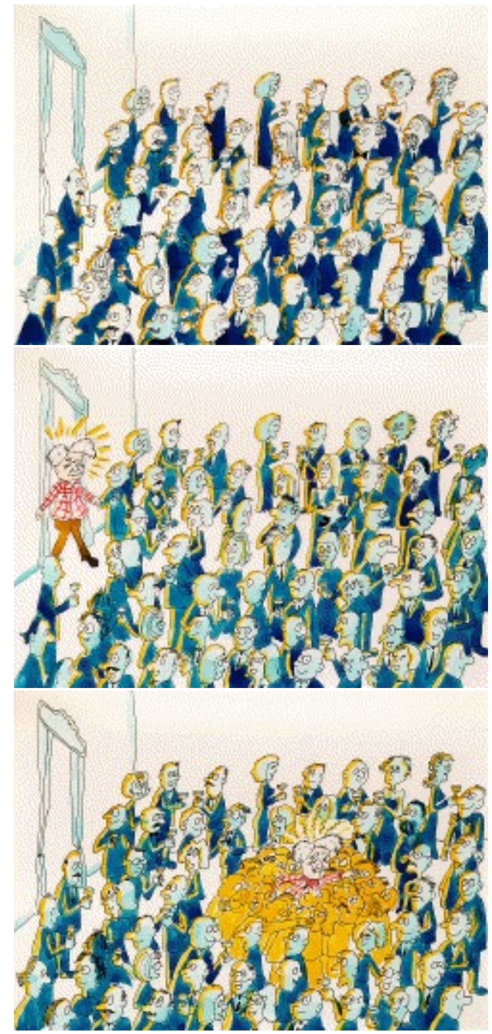
$$\frac{M_W}{M_Z} = \cos\theta_W \approx 0.88$$

$$|Z^0\rangle = -\sin\theta_W|B^0\rangle + \cos\theta_W|W^0\rangle$$

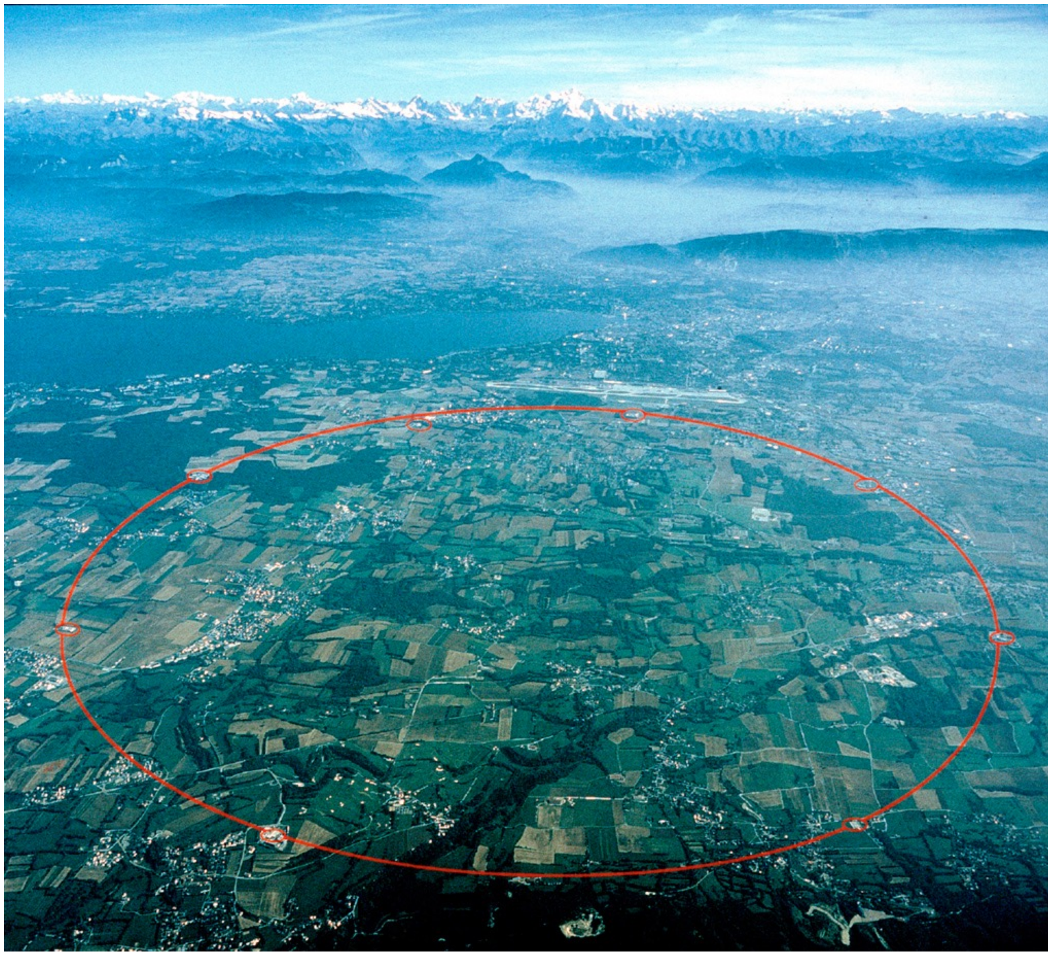
Higgs Field

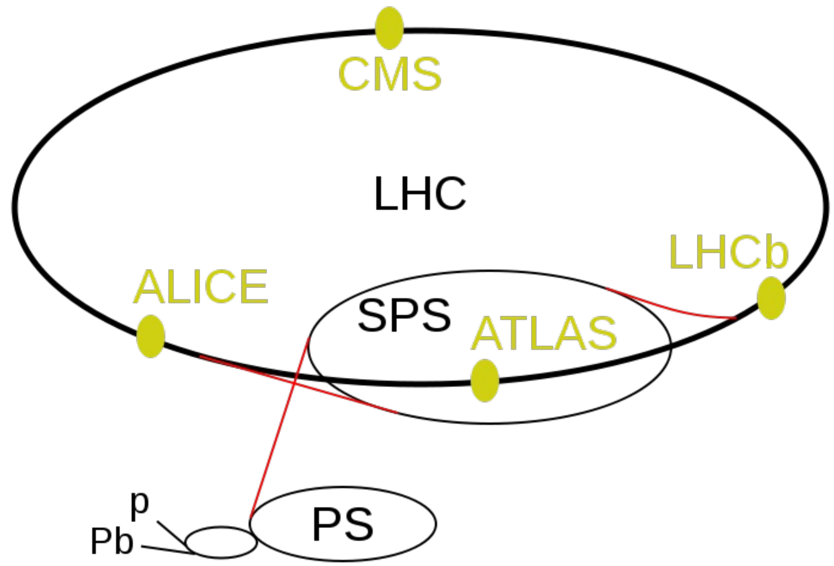
- Create “Drag” on Particles (“Molasses”)
- *) Origin of Mass
  Makes some gauge bosons very heavy (W’s, Z’s) and therefore short-range (“Weak” interaction)
- Origin of electroweak symmetry breaking
- Pointlike, Fundamental

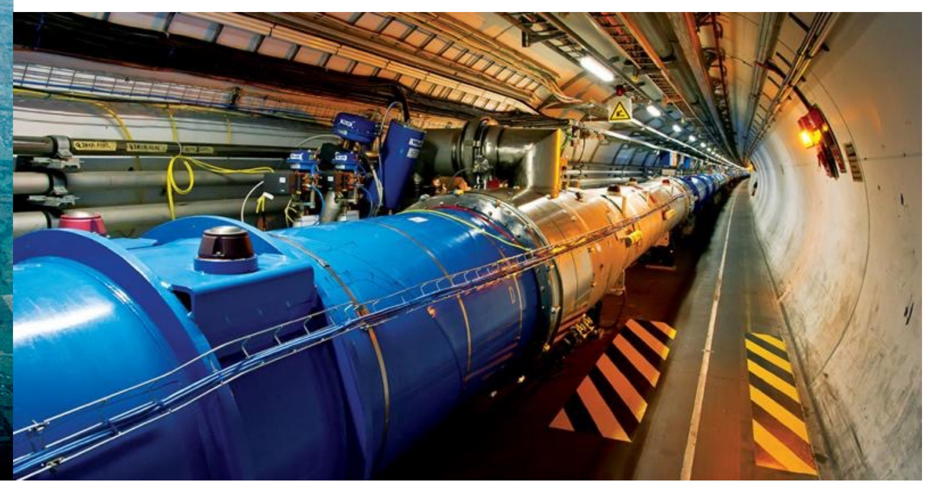




The LHC at CERN







- See also the movie “Particle Fever”

Higgs Discovery