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Verifiche del Modello Standard a basse energie con fasci di neutrini

Standard Model and neutrino role

- Since the '60s many experimental confirmations of the Standard Model; precision tests (LEP, high energies)
- **Neutrino relevance:**
- Neutrino played a relevant role in the past (Gargamelle, discovery of neutral currents)
- Interact only weakly ⇒ possible measure of Weinberg angle
- Neutrino masses and mixing: ⇒ need to modify Standard Model. Theories beyond the S.M.

Future search of physics beyond the S.M., 2 ways:

1) Higher energy

2) High intensity (High-intensity ν beams to study ν properties and test e.w. interactions. Low energy tests of S.M.: search for rare processes and measurements of S.M. parameters with low E and very high intensity ν beams)

Neutrino physics: present status

see for instance: PRD 67 (2003) 013006; PRD 69 (2004)013005; NPB (Proc. Suppl.)143 (2005)483; Progr. Part. Nucl. Phys. 57(2006)742 and 71; hep-ph/0606060

- Neutrino (ν) known since many years, but many of its properties are still **poorly known**
- Last years very relevant results:

– ν massive and oscillating particles. Proofs from: solar (mainly SuperKamiokande and SNO), atmospheric (SK) and reactor (KamLAND) neutrinos; accelerators (K2K)

- At least 2 Δm^2, hence 3 mass eigenstates:

$\Delta m^2_{12} := m_2^2 - m_1^2 = 7\pm1\cdot10^{-5}\ eV^2$: ν solar and from reactor (LMA solution)

$|\Delta m^2_{23}| := |m_3^2 - m_2^2| = 2.0\pm0.4\cdot10^{-3}\ eV^2$: ν atmospheric and K2K

- Maximal Mixing in the sector 2-3 : $\tan^2\theta_{23} = 1$;

combining KL and solar ν data: $\tan^2\theta_{12} = 0.45\pm0.08$

- Upper limits (from CHOOZ and Palo Verde) on mixing 1-3: $\theta_{13} < 14°$

....however

Open Problems in Neutrino Physics

- Despite the relevant recent results,

Still many open problems

- Nature of neutrino (Dirac o Majorana)

- Absolute value and hierarchy of masses (direct, inverse or quasi-degenere)

- Exact determination of mixing parameters:

  $\theta_{13}=0$ or $\theta_{13} \neq 0$

- Search for CP violation

Future of neutrino physics (from accelerators)

•1st stage: Conventional ν beams from a secondary meson beam (K2K, MINOS, CERN/G.Sasso, T2K 1st phase) and Double Chooz (reactor) ⇒ partial improvement of θ_{13} ; Not enough to study the leptonic CP violation

• 2nd stage: Superbeams (T2K 2nd phase, NOνA, CERN) ⇒

• beam luminosity increase: θ_{13} precise measurement and/or (eventual) CP violation search

- T2K (Japan, 2009) 2nd phase: ν_μ beam from JParc to SuperK (L=295 Km)
- NOνA (USA): use the beam of NuMI at FNAL, detector at about 800 Km
-CERN: possible superbeam exploiting the CERN SPL

•3rd stage (end of next decade): ν from primary beam decays

Neutrino factories: ν from decay of muons (tens of GeV) in accumulation rings ($\mu^+ \to e^+ + \bar{\nu}_\mu + \nu_e$)

Beta beams: ν beams from β decays (few GeV or lower E)

$$n \to p + e^- + \bar{\nu}_e \qquad\qquad p \to n + e^+ + \nu_e$$

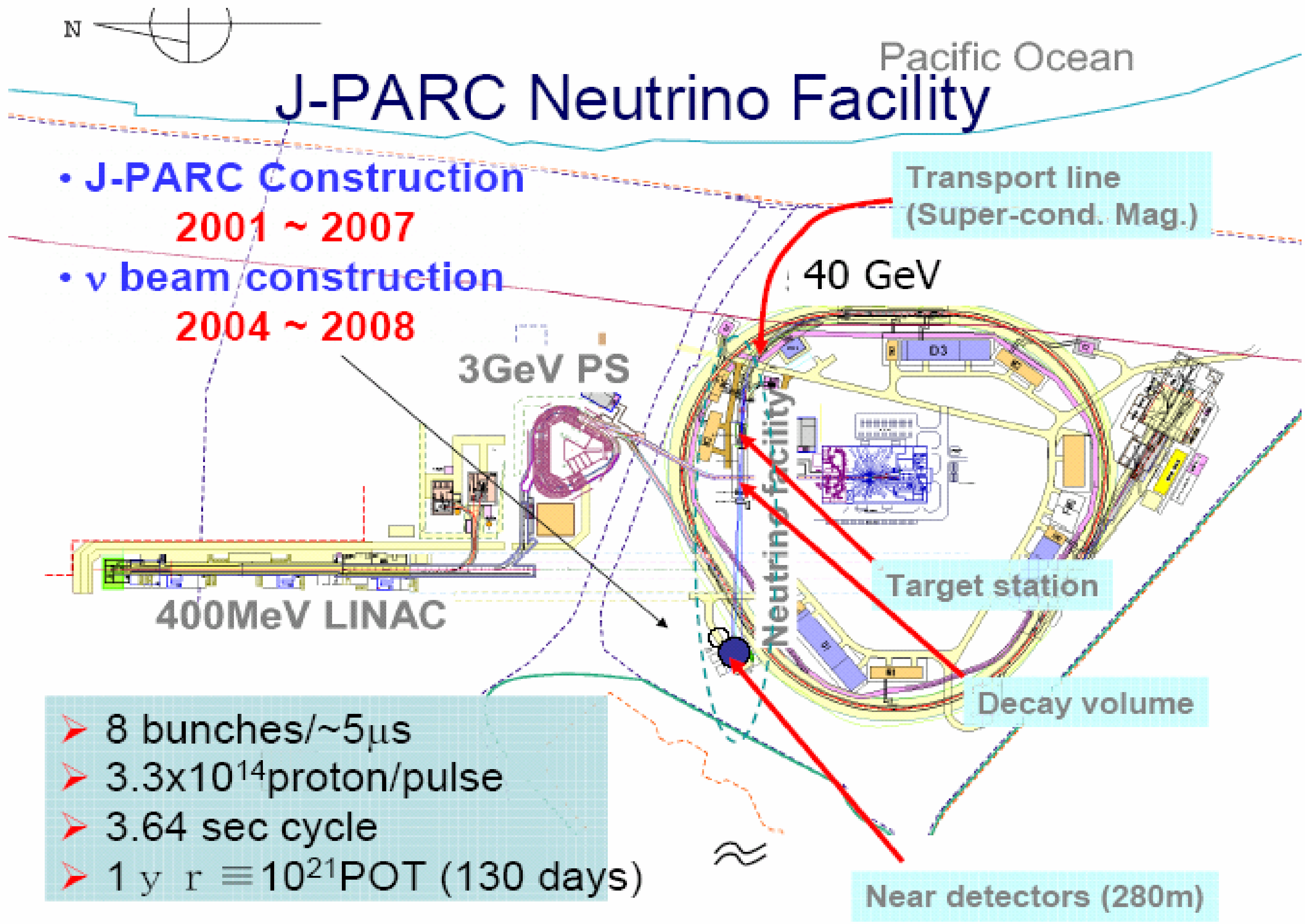
Example: ^{6}He for anti-ν beam; and ^{18}Ne for ν beams

T2K

- Neutrino beam from protosinchrotron of 50 GeV, 0.75 MW at JParc
- Off-axis beam to SuperKamiokande (L = 295 Km) .

  Begins spring 2009
- Main goals:

- $\sin^2\theta_{13}$ measurement with sensitivity 20 times better than Chooz
- Measurement of Δm_{23}^2 and $\sin^2\theta_{23}$ (atmosferic parameters) at 1-2% (ν_μ disappearance)
- **search for sterile** ν (weak currents disappearance)
- Tests of Standard Model parameters: ⇒ low energy measurements, different from LEP; eventual possibility of signals of new physics


N
Pacific Ocean
J-PARC Neutrino Facility
• J-PARC Construction
2001 ~ 2007
• ν beam construction
2004 ~ 2008
3GeV PS
400MeV LINAC
40 GeV
Transport line
(Super-cond. Mag.)
Neutrino facility
Target station
Decay volume
Near detectors (280m)
D3
➢ 8 bunches/~5μs
➢ 3.3x10^14proton/pulse
➢ 3.64 sec cycle
➢ 1 yr ≡10^21POT (130 days)

n

d

Beta-Beams

PRO

- **Only 1 flavor in the beam**
- ***Well known and determined energy*** **(kinematics well known and nucleon recoil negligible)**
- **Beams well collimated and with value of (γ/E_{CM}) higher than ν factories**

Proposals:

- Cern- Frejus (L about 130 Km; ‘‘low’’ beam E)

- Higher E beams and longer baselines (Cern-G.Sasso/Canarie)

- **proposed for neutrino physics, but useful also to study Standard Model ?**

⇓

- **Analysis already available for neutrino factories**

Interesting to extend it to beta-beams

WEINBERG ANGLE

Theory of electroweak unification
Glashow-Weinberg-Salam (1967)
SU(2) x U(1) simmetry invariance
→ weak and e.m. forces *mixed*

couplings

SU(2) → g

U(1) → g'

$$\sin\vartheta_w = \frac{g'}{\sqrt{g^2 + g'^2}}$$

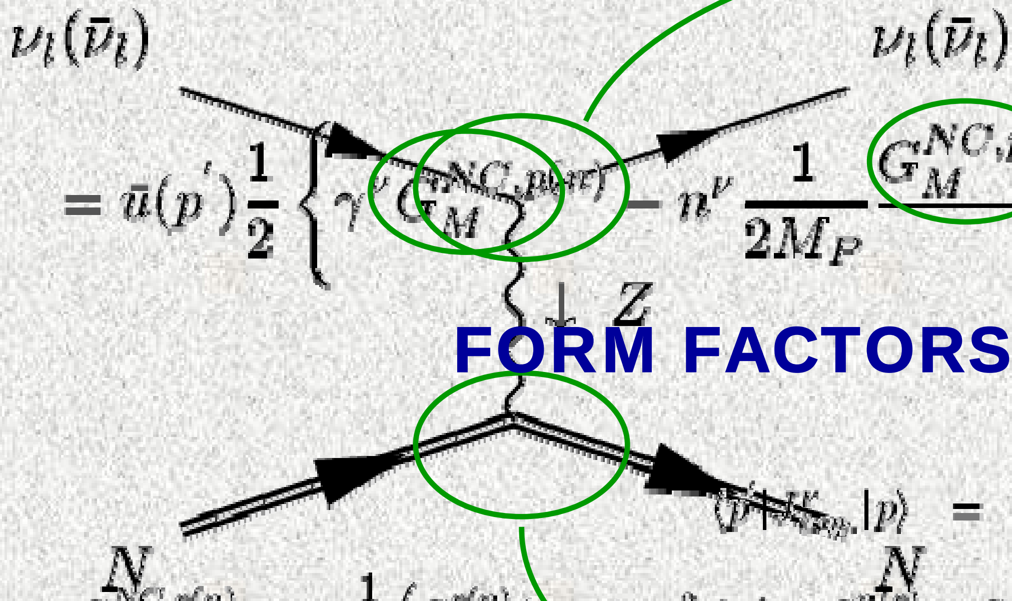
$$e = \frac{gg'}{\sqrt{g^2 + g'^2}}$$

ν-e^- elastic scattering: competitive for Weinberg angle measurement at "high energy" ν factories; at lower energies the lower cross sections compensated by high intensities.

For E ~M_N (quasi) elastic contributions to ν-nucleon interactions are sizable.

Neutral current scattering amplitudes

$$\langle p^{'}|J_Z^{\mu}|p\rangle = \langle p^{'}|\frac{1}{2}V_3^{\mu} - \frac{1}{4}V_s^{\mu} - \frac{1}{2}A_3^{\mu} + \frac{1}{4}A_s^{\mu} - \sin^2\vartheta_w J^{\mu}_{e.m.}|p\rangle$$



$$= \bar{u}(p^{'})\frac{1}{2}\left\{\gamma^{\nu} G_M^{NC,p(n)} - \eta^{\nu}\frac{1}{2M_P}\frac{G_M^{NC,p(n)} - G_E^{NC,p(n)}}{1+\tau} - (+) G_A^{NC}\gamma^{\nu}\gamma_5\right\}u(p)$$

$$\frac{g}{4\cos\vartheta_w}\bar{u}(k^{'})\gamma^{\mu}(1-\gamma_5)u(k)$$

FORM FACTORS introduction

$$\langle p^{'}|J^{\nu}_{e.m.}|p\rangle = \bar{u}(p^{'})\left[\gamma^{\nu}G_M(Q^2) - \eta^{\nu}\frac{1}{2M_P}\frac{G_M(Q^2) - G_E(Q^2)}{1+\tau}\right]$$

$$\langle p^{'}|A_3^{\nu}|p\rangle = \bar{u}(p^{'})\gamma^{\nu}\gamma_5\frac{G_A(Q^2)}{2}u(p)$$

$$\langle p^{'}|V_s^{\nu}|p\rangle = \bar{u}(p^{'})\left[\gamma^{\nu}G_M^s(Q^2) - \eta^{\nu}\frac{1}{2M_P}\frac{G_M^s(Q^2) - G_E^s(Q^2)}{1+\tau}\right]$$

$$\langle p^{'}|A_s^{\nu}|p\rangle = \bar{u}(p^{'})\gamma^{\nu}\gamma_5 G_A^s(Q^2)u(p)$$

$$\frac{g}{\cos\vartheta_w}\langle p^{'}|J_Z^{\mu}|p\rangle$$

$$G_M^{NC,p(n)} = \frac{1}{2}\left(G_M^{p(n)}(1-4\sin^2\vartheta_w) - G_M^{n(p)} - G_M^s\right)$$

$$G_E^{NC,p(n)} = \frac{1}{2}\left(G_E^{p(n)}(1-4\sin^2\vartheta_w) - G_E^{n(p)} - G_E^s\right)$$

$$G_A^{NC,p(n)} = \frac{1}{2}(G_A - (+)G_A^s)$$

Weinberg angle determination

- **6 cross sections:** neutrino (antineutrino) neutral currents on proton (neutron) and neutrino (antineutrino) charged currents

- Fixing the values of the electric form factors there are **6 parameters left** : Weinberg angle and 5 form factors (G^p_M, G^n_M , G^S_M , G_A , G^S_A)

- **Analytical study**:

- search for cross section combinations (ν-ν asymmetries, etc.) to isolate Weinberg angle dependence;
- "forward" approximation of form factors

We cannot ignore "strange" terms and the forward approximation is not enough

Direct analytical solution

SYSTEM of 6 equations coupled 2 by 2

•**The equation for Weinberg angle can be solved analytically in terms of measurable quantities**

$$\sin^2\vartheta_w = \frac{1}{2} + \frac{a_3 - b_2}{4b_1}$$

$$b_1 = \sqrt{\frac{Ey\,(2-y) + \sqrt{E^2y^2\,(2-y)^2 - F^2\,[2\,(1-y)+y^2]^2}}{4\alpha\,[2\,(1-y)+y^2]\,y\,(2-y)}}$$

$$b_2 = \sqrt{\frac{2\,(1-y)+y^2}{\alpha y\,(2-y)}}\;\frac{B}{\sqrt{Ay\,(2-y)\,\sqrt{E^2y^2\,(2-y)^2 - B^2\,[2\,(1-y)+y^2]^2}}}$$

$$a_3 = -\sqrt{\frac{Cy\,(2-y) + \sqrt{C^2y^2\,(2-y)^2 - D^2\,[2\,(1-y)+y^2]^2}}{\alpha\,[2\,(1-y)+y^2]\,y\,(2-y)}}$$

A,B,C,D,E,F: cross section combinations;

$y = E_P / E_\nu$ kinematical variable of elastic scattering

Numerical study

•**From data analysis simultaneous fit of the values of Weinberg angle and hadronic form factors**

•In the experimental situation not possible to distinguish the neutral current on neutron → from 6 to 4 cross sections → loss of information.

•Example of analysis: fix all the other form factors to their central value and determine simultaneously **$\sin^2\theta_W$; $G^S_M(Q^2)$**

$$G_M^S(Q^2) = \frac{F_1^S Q^2 + F_2^S(0)}{(1+\tau)(1+\frac{Q^2}{M_V^2})^2} \qquad \tau = \frac{Q^2}{4M_N^2}$$

G^S_A known with bad accuracy (about 30%), but cross sections weekly dependent on G_A^S. We assume dipole form and take 1 σ variation for the forward value $G_A^S(0)$=-0,13$\pm$0.09

Experimental requirements

It is fundamental to select QE scattering from other reactions. Elastic and quasi elastic cross sections: **optimal region around 1 GeV** (ex. T2K)

- **Neutral currents must be identified:** only recoiling proton can me measured: no NC on neutron…

- **Different Q^2 bins should be investigated: kinematic reconstruction**

Main Obstacles:

- reinteractions and Fermi motions in the nucleus: reactions different from QE can mimick QE, kinematics is in general modified, additional low energy protons are produced in the nucleus

Detector alternatives

1) Water Cherenkov:

Pro: there is the possibility of assembling a very large mass (some MTon)

Con: the Cherenkov threshold prevents the detection of recoiling protons with p<1 GeV.

2) Liquid Argon TPC

Pro: in principle p down to 50 MeV can be identified.

Con: Difficult to assemble a large mass; nuclear reinteractions in Ar are more important than in water

For p > 300 MeV ⇒ $Q^2 > 0.1\ GeV^2$, about 75% of the events surviving. Measurements at near detector already competive with detector below kton (around 500 ton)

Interesting possibility mainly for superbeams

A simple example

- Using for fluxes and energy:

  $\Phi_\nu \cong 10^{16}$ (m^2/yr) ; $\Phi_{anti\text{-}\nu} \cong 5\ 10^{14}$ (m^2/yr) ; $E_\nu = 1$ GeV

- Detector : 10 ktons Liquid Ar

- Assuming in data generation $\sin^2\theta_w = 0.2312$

- From simultaneous fit of $\sin^2\theta_w$ and $G_M{}^S$, varying $G_A{}^S$, we get:

  $\sin^2\theta_w = 0.2309 \pm 0.0019$ (stat) ± 0.0024 (syst)

CONCLUSIONS

- Standard Model: tested with high accuracy and working very well up to the electroweak scale
- Useful to improve parameters knowledge at medium-low energies.
- Role of ν physics and future experiments with high intensity beams
- Neutrino (antineutrino) nucleon interaction: dependence from Weinberg angle and hadronic form factors
- Analytical study and estimate of accuracy in $\sin^2\theta_W$ determination
- Numerical analysis of the problem
- Examples: β beams and superbeams potentiality

  Measurements realistic with present Icarus technology
- Measurement at energies low with respect to LEP is interesting to verify theory consistency and/or eventual signals of physics beyond S.M.