Mauro Mezzetto,
Istituto Nazionale di Fisica Nucleare, Sezione di Padova

“ Future Long Baseline Neutrino Experiments"

- Physics Case.
- Super Beams
- Beta Beams
- Neutrino factory
- Comparisons and Conclusions

Standard Model of

FUNDAMENTAL PARTICLES AND INTERACTIONS

The Standard Model is a quantum theory that summarizes our current knowledge of the physics of fundamental particles and fundamental interactions (interactions are manifested by forces and by decay rates of unstable particles).

FERMIONS

matter constituents
spin = 1/2, 3/2, 5/2, ...

Leptons spin =1/2

Flavor	Mass GeV/c^2	Electric charge
ν_L lightest neutrino*	$(0-0.13)\times10^{-9}$	0
e electron	0.000511	−1
ν_M middle neutrino*	$(0.009-0.13)\times10^{-9}$	0
μ muon	0.106	−1
ν_H heaviest neutrino*	$(0.04-0.14)\times10^{-9}$	0
τ tau	1.777	−1

Quarks spin =1/2

Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.002	2/3
d down	0.005	−1/3
c charm	1.3	2/3
s strange	0.1	−1/3
t top	173	2/3
b bottom	4.2	−1/3

*See the neutrino paragraph below.

Spin is the intrinsic angular momentum of particles. Spin is given in units of $\hbar$, which is the quantum unit of angular momentum where $\hbar = h/2\pi = 6.58\times10^{-25}$ GeV s $=1.05\times10^{-34}$ J s.

Electric charges are given in units of the proton's charge. In SI units the electric charge of the proton is 1.60×10^{-19} coulombs.

The energy unit of particle physics is the electronvolt (eV), the energy gained by one electron in crossing a potential difference of one volt. **Masses** are given in GeV/c^2 (remember $E = mc^2$) where 1 GeV $= 10^9$ eV $=1.60\times10^{-10}$ joule. The mass of the proton is 0.938 GeV/c^2 $= 1.67\times10^{-27}$ kg.

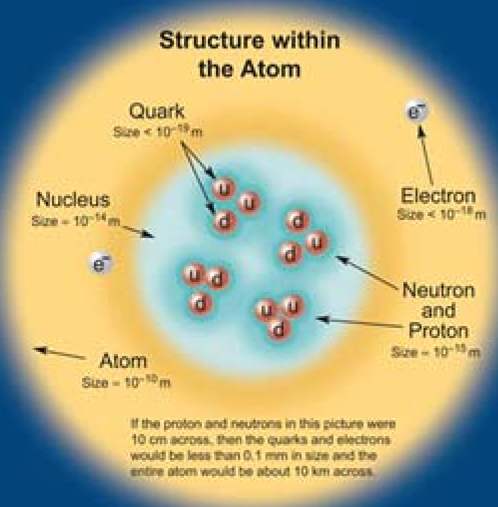
Neutrinos

Neutrinos are produced in the sun, supernovae, reactors, accelerator collisions, and many other processes. Any produced neutrino can be described as one of three neutrino flavor states ν_e, ν_μ, or ν_τ, labelled by the type of charged lepton associated with its production. Each is a defined quantum mixture of the three definite mass neutrinos ν_L, ν_M, and ν_H for which currently allowed mass ranges are shown in the table. Further exploration of the properties of neutrinos may yield powerful clues to puzzles about matter and antimatter and the evolution of stars and galaxy structures.

Matter and Antimatter

For every particle type there is a corresponding antiparticle type, denoted by a bar over the particle symbol (unless + or – charge is shown). Particle and antiparticle have identical mass and spin but opposite charges. Some electrically neutral bosons (e.g., Z^0, γ, and $\eta_c = c\bar{c}$ but not $K^0 = d\bar{s}$) are their own antiparticles.

Structure within the Atom



If the proton and neutrons in this picture were 10 cm across, then the quarks and electrons would be less than 0.1 mm in size and the entire atom would be about 10 km across.

BOSONS

force carriers
spin = 0, 1, 2, ...

Unified Electroweak spin = 1

Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W^-	80.39	−1
W^+ W bosons	80.39	+1
Z^0 Z boson	91.188	0

Strong (color) spin =1

Name	Mass GeV/c^2	Electric charge
g gluon	0	0

Color Charge

Only quarks and gluons carry "strong charge" (also called "color charge") and can have strong interactions. Each quark carries three types of color charge. These charges have nothing to do with the colors of visible light. Just as electrically-charged particles interact by exchanging photons, in strong interactions, color-charged particles interact by exchanging gluons.

Quarks Confined in Mesons and Baryons

Quarks and gluons cannot be isolated – they are confined in color-neutral particles called **hadrons**. This confinement (binding) results from multiple exchanges of gluons among the color-charged constituents. As color-charged particles (quarks and gluons) move apart, the energy in the color-force field between them increases. This energy eventually is converted into additional quark-antiquark pairs. The quarks and antiquarks then combine into hadrons; these are the particles seen to emerge.

Two types of hadrons have been observed in nature **mesons** $q\bar{q}$ and **baryons** qqq. Among the many types of baryons observed are the proton (uud), antiproton ($\bar{u}\bar{u}\bar{d}$), neutron (udd), lambda Λ (uds), and omega Ω^- (sss). Quark charges add in such a way as to make the proton have charge 1 and the neutron charge 0. Among the many types of mesons are the pion π^+ ($u\bar{d}$), kaon K^- ($s\bar{u}$), B^0 ($d\bar{b}$), and η_c ($c\bar{c}$). Their charges are +1, −1, 0, 0 respectively.

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Property	Gravitational Interaction	Weak Interaction	Electromagnetic Interaction	Strong Interaction
		(Electroweak)		
Acts on:	Mass – Energy	Flavor	Electric Charge	Color Charge
Particles experiencing:	All	Quarks, Leptons	Electrically Charged	Quarks, Gluons
Particles mediating:	Graviton (not yet observed)	W^+ W^- Z^0	γ	Gluons
Strength at 10^{-18} m	10^{-41}	0.8	1	25
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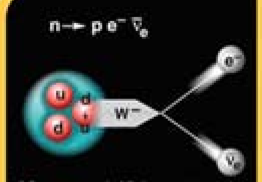
Particle Processes

These diagrams are an artist's conception. Blue-green shaded areas represent the cloud of gluons.



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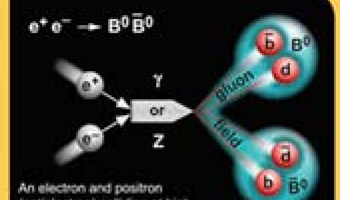

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Unsolved Mysteries

Driven by new puzzles in our understanding of the physical world, particle physicists are following paths to new wonders and startling discoveries. Experiments may even find extra dimensions of space, mini-black holes, and/or evidence of string theory.

Universe Accelerating?

The expansion of the universe appears to be accelerating. Is this due to Einstein's Cosmological Constant? If not, will experiments reveal a new force of nature or even extra (hidden) dimensions of space?

Why No Antimatter?

Matter and antimatter were created in the Big Bang. Why do we now see only matter except for the tiny amounts of antimatter that we make in the lab and observe in cosmic rays?

Dark Matter?

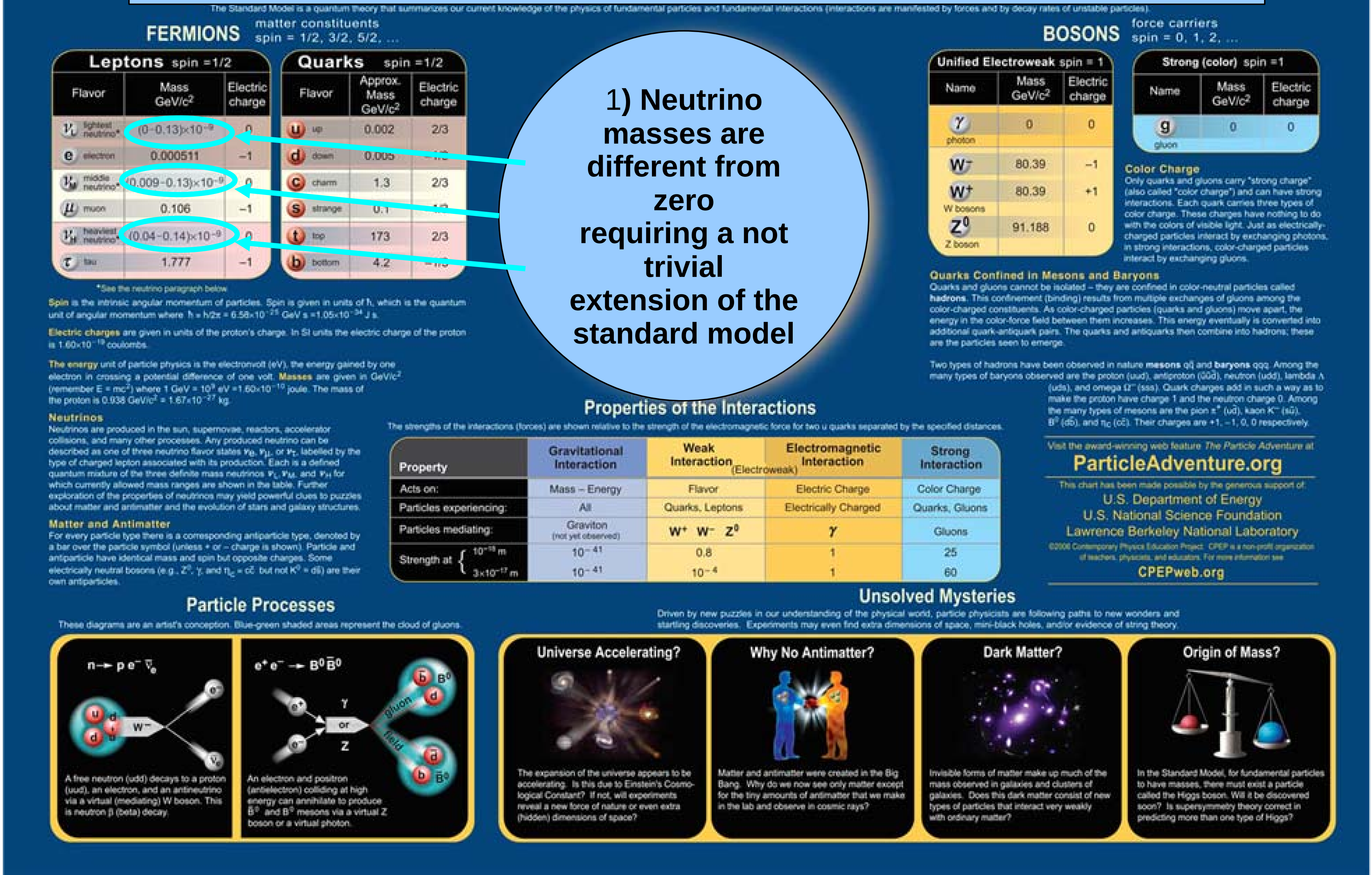
Invisible forms of matter make up much of the mass observed in galaxies and clusters of galaxies. Does this dark matter consist of new types of particles that interact very weakly with ordinary matter?

Origin of Mass?

In the Standard Model, for fundamental particles to have masses, there must exist a particle called the Higgs boson. Will it be discovered soon? Is supersymmetry theory correct in predicting more than one type of Higgs?

What neutrino oscillations tell us about this picture?

1) Neutrino masses are different from zero requiring a not trivial extension of the standard model



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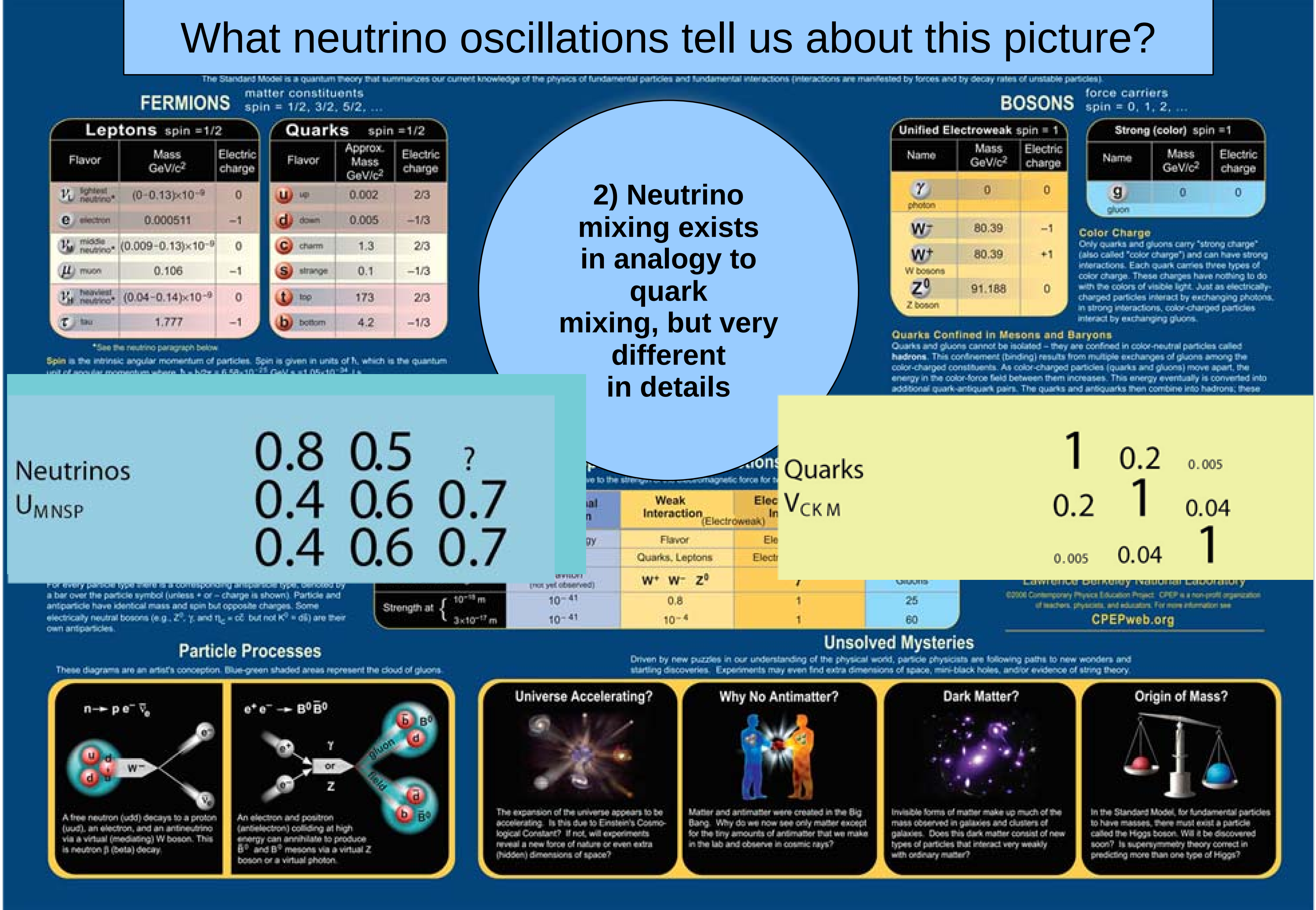

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2) Neutrino mixing exists in analogy to quark mixing, but very different in details

Neutrinos
U_{MNSP}

$$\begin{matrix} 0.8 & 0.5 & ? \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{matrix}$$

Quarks
V_{CKM}

$$\begin{matrix} 1 & 0.2 & 0.005 \\ 0.2 & 1 & 0.04 \\ 0.005 & 0.04 & 1 \end{matrix}$$

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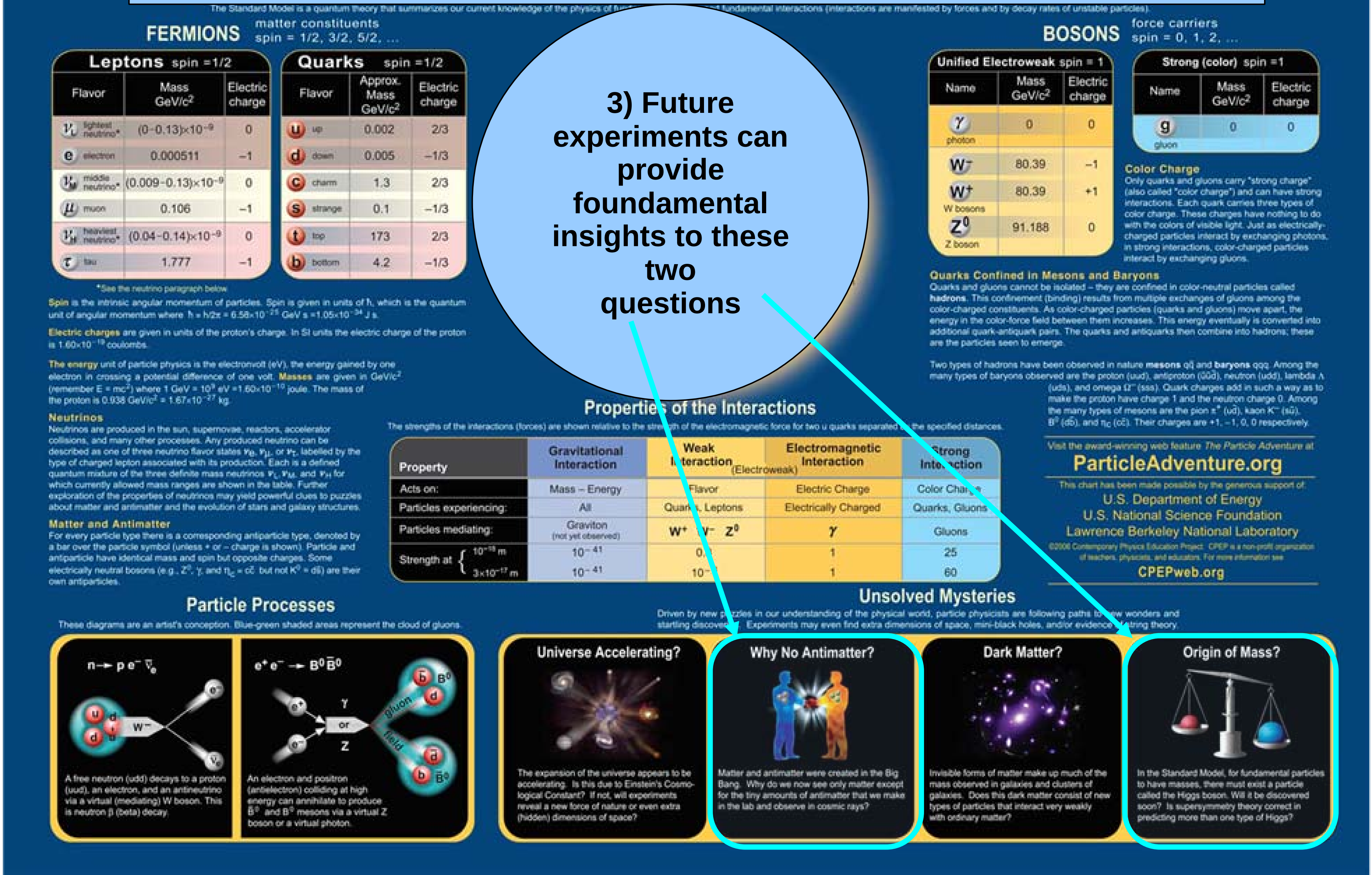

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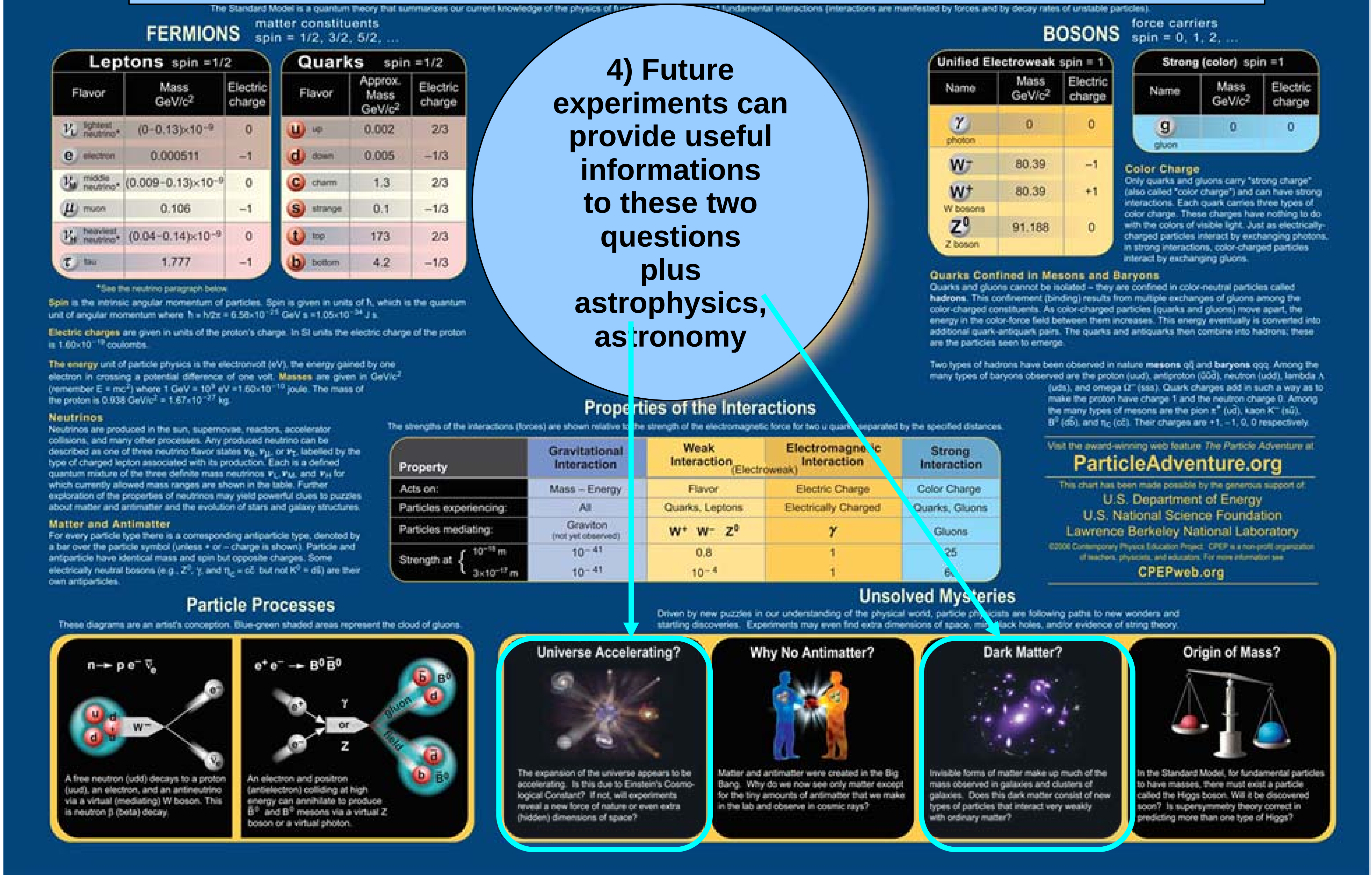

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ν_M middle neutrino*	$(0.009-0.13)\times10^{-9}$	0
μ muon	0.106	−1
ν_H heaviest neutrino*	$(0.04-0.14)\times10^{-9}$	0
τ tau	1.777	−1

Quarks spin =1/2

Flavor	Approx. Mass GeV/c²	Electric charge
u up	0.002	2/3
d down	0.005	−1/3
c charm	1.3	2/3
s strange	0.1	−1/3
t top	173	2/3
b bottom	4.2	−1/3

*See the neutrino paragraph below

Spin is the intrinsic angular momentum of particles. Spin is given in units of ħ, which is the quantum unit of angular momentum where $\hbar = h/2\pi = 6.58\times10^{-25}$ GeV s $=1.05\times10^{-34}$ J s.

Electric charges are given in units of the proton's charge. In SI units the electric charge of the proton is 1.60×10^{-19} coulombs.

The energy unit of particle physics is the electronvolt (eV), the energy gained by one electron in crossing a potential difference of one volt. **Masses** are given in GeV/c² (remember $E = mc^2$) where 1 GeV $= 10^9$ eV $=1.60\times10^{-10}$ joule. The mass of the proton is 0.938 GeV/c² $= 1.67\times10^{-27}$ kg.

Neutrinos
Neutrinos are produced in the sun, supernovae, reactors, accelerator collisions, and many other processes. Any produced neutrino can be described as one of three neutrino flavor states ν_e, ν_μ, or ν_τ, labelled by the type of charged lepton associated with its production. Each is a defined quantum mixture of the three definite mass neutrinos ν_L, ν_M, and ν_H for which currently allowed mass ranges are shown in the table. Further exploration of the properties of neutrinos may yield powerful clues to puzzles about matter and antimatter and the evolution of stars and galaxy structures.

Matter and Antimatter
For every particle type there is a corresponding antiparticle type, denoted by a bar over the particle symbol (unless + or − charge is shown). Particle and antiparticle have identical mass and spin but opposite charges. Some electrically neutral bosons (e.g., Z^0, γ, and $\eta_c = c\bar{c}$ but not $K^0 = d\bar{s}$) are their own antiparticles.

BOSONS

force carriers
spin = 0, 1, 2, ...

Unified Electroweak spin = 1

Name	Mass GeV/c²	Electric charge
γ photon	0	0
W^-	80.39	−1
W^+ W bosons	80.39	+1
Z^0 Z boson	91.188	0

Strong (color) spin =1

Name	Mass GeV/c²	Electric charge
g gluon	0	0

Color Charge
Only quarks and gluons carry "strong charge" (also called "color charge") and can have strong interactions. Each quark carries three types of color charge. These charges have nothing to do with the colors of visible light. Just as electrically-charged particles interact by exchanging photons, in strong interactions, color-charged particles interact by exchanging gluons.

Quarks Confined in Mesons and Baryons
Quarks and gluons cannot be isolated – they are confined in color-neutral particles called **hadrons**. This confinement (binding) results from multiple exchanges of gluons among the color-charged constituents. As color-charged particles (quarks and gluons) move apart, the energy in the color-force field between them increases. This energy eventually is converted into additional quark-antiquark pairs. The quarks and antiquarks then combine into hadrons; these are the particles seen to emerge.

Two types of hadrons have been observed in nature **mesons** $q\bar{q}$ and **baryons** qqq. Among the many types of baryons observed are the proton (uud), antiproton ($\bar{u}\bar{u}\bar{d}$), neutron (udd), lambda Λ (uds), and omega Ω^- (sss). Quark charges add in such a way as to make the proton have charge 1 and the neutron charge 0. Among the many types of mesons are the pion π^+ ($u\bar{d}$), kaon K^- ($s\bar{u}$), B^0 ($d\bar{b}$), and η_c ($c\bar{c}$). Their charges are +1, −1, 0, 0 respectively.

Visit the award-winning web feature *The Particle Adventure* at

ParticleAdventure.org

This chart has been made possible by the generous support of:
U.S. Department of Energy
U.S. National Science Foundation
Lawrence Berkeley National Laboratory

CPEPweb.org

Properties of the Interactions

The strengths of the interactions (forces) are shown relative to the strength of the electromagnetic force for two u quarks separated by the specified distances.

Property	Gravitational Interaction	Weak Interaction (Electroweak)	Electromagnetic Interaction	Strong Interaction
Acts on:	Mass – Energy	Flavor	Electric Charge	Color Charge
Particles experiencing:	All	Quarks, Leptons	Electrically Charged	Quarks, Gluons
Particles mediating:	Graviton (not yet observed)	W^+ W^- Z^0	γ	Gluons
Strength at 10^{-18} m	10^{-41}	0.8	1	25
Strength at 3×10^{-17} m	10^{-41}	10^{-4}	1	6

Particle Processes

These diagrams are an artist's conception. Blue-green shaded areas represent the cloud of gluons.

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

A free neutron (udd) decays to a proton (uud), an electron, and an antineutrino via a virtual (mediating) W boson. This is neutron β (beta) decay.

$e^+ e^- \rightarrow B^0 \bar{B}^0$

An electron and positron (antielectron) colliding at high energy can annihilate to produce $\bar{B}^0$ and B^0 mesons via a virtual Z boson or a virtual photon.

Unsolved Mysteries

Driven by new puzzles in our understanding of the physical world, particle physicists are following paths to new wonders and startling discoveries. Experiments may even find extra dimensions of space, mini black holes, and/or evidence of string theory.

Universe Accelerating?
The expansion of the universe appears to be accelerating. Is this due to Einstein's Cosmological Constant? If not, will experiments reveal a new force of nature or even extra (hidden) dimensions of space?

Why No Antimatter?
Matter and antimatter were created in the Big Bang. Why do we now see only matter except for the tiny amounts of antimatter that we make in the lab and observe in cosmic rays?

Dark Matter?
Invisible forms of matter make up much of the mass observed in galaxies and clusters of galaxies. Does this dark matter consist of new types of particles that interact very weakly with ordinary matter?

Origin of Mass?
In the Standard Model, for fundamental particles to have masses, there must exist a particle called the Higgs boson. Will it be discovered soon? Is supersymmetry theory correct in predicting more than one type of Higgs?

Shopping list for future experiments

δm^2_{12} ☑

SOLARS+KAMLAND
$\delta m^2_{12} = (7.9 \text{ +/- } 0.7)\ 10^{-5}\ eV^2$

θ_{12} ☑

SOLARS+KAMLAND
$\sin^2(2\theta_{12}) = 0.82\text{+/-}0.055$

Addressed by a SuperBeam/Nufact experiment

δm^2_{23} $_{23}$ ☑

ATMOSPHERICS
$\delta m^2 = (2.4 \text{ +/- } 0.4)\ 10^{-3}\ eV^2$

θ_{23} ☑

ATMOSPHERICS
$\sin^2(2\theta_{23}) > 0.95$

θ_{13} ☐

CHOOZ LIMIT
$\sin^2 2\theta_{13} < 14^0$

LSND/Steriles ☑?

δ_{CP} ☐

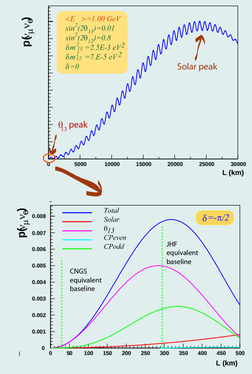
Mass hierarchy ☐

Σm_ν ☐

BETA DECAY END POINT
$\Sigma m_\nu < 6.6$ eV

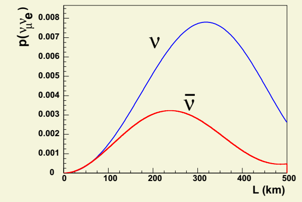
Dirac/Majorana ☐

Sub leading $\nu_\mu - \nu_e$ oscillations



$$
\begin{aligned}
p(\nu_\mu \to \nu_e) = {} & 4c_{13}^2 s_{13}^2 s_{23}^2 \sin^2 \frac{\Delta m_{13}^2 L}{4E} \times \left[1 \pm \frac{2a}{\Delta m_{13}^2}(1-2s_{13}^2)\right] && \theta_{13}\ \text{dri} \\
& + 8c_{13}^2 s_{12} s_{13} s_{23} (c_{12}c_{23}\cos\delta - s_{12}s_{13}s_{23}) \cos\frac{\Delta m_{23}^2 L}{4E} \sin\frac{\Delta m_{13}^2 L}{4E} \sin\frac{\Delta m_{12}^2 L}{4E} && \text{CPev} \\
& \mp 8c_{13}^2 c_{12} c_{23} s_{12} s_{13} s_{23} \sin\delta \sin\frac{\Delta m_{23}^2 L}{4E} \sin\frac{\Delta m_{13}^2 L}{4E} \sin\frac{\Delta m_{12}^2 L}{4E} && \text{CPodd} \\
& + 4s_{12}^2 c_{13}^2 \{c_{13}^2 c_{23}^2 + s_{12}^2 s_{23}^2 s_{13}^2 - 2c_{12}c_{23}s_{12}s_{23}s_{13}\cos\delta\} \sin\frac{\Delta m_{12}^2 L}{4E} && \text{solar driven} \\
& \mp 8c_{12}^2 s_{13}^2 s_{23}^2 \cos\frac{\Delta m_{23}^2 L}{4E} \sin\frac{\Delta m_{13}^2 L}{4E} \frac{aL}{4E}(1-2s_{13}^2) && \text{matter effect (CP odd)}
\end{aligned}
$$

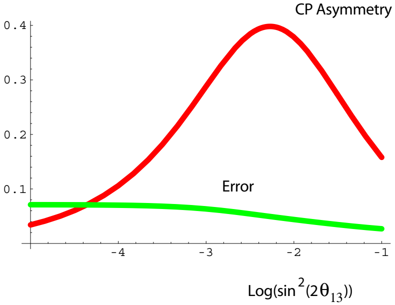
θ_{13} discovery requires a signal ($\propto \sin^2 2\theta_{13}$) greater than the solar driven probability



Leptonic CP discovery requires $A_{CP} = \frac{P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e)}{P(\nu_\mu \to \nu_e) + P(\bar{\nu}_\mu \to \bar{\nu}_e)} \neq 0$

Measuring Leptonic CP violation

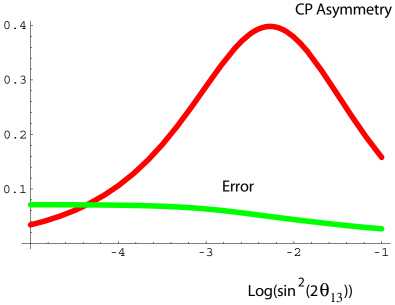
$$A_{CP} = \frac{P(\nu_\mu \to \nu_e) - P(\overline{\nu}_\mu \to \overline{\nu}_e)}{P(\nu_\mu \to \nu_e) + P(\overline{\nu}_\mu \to \overline{\nu}_e)}$$



LCPV asymmetry at the first oscillation maximum, $\delta = 1$, Error curve: dependence of the statistical+systematic (2%) computed for a beta beam the fixed energy $E_\nu = 0.4$ GeV, $L = 130$ km.

Measuring Leptonic CP violation

$$A_{CP} = \frac{P(\nu_\mu \to \nu_e) - P(\overline{\nu}_\mu \to \overline{\nu}_e)}{P(\nu_\mu \to \nu_e) + P(\overline{\nu}_\mu \to \overline{\nu}_e)}$$

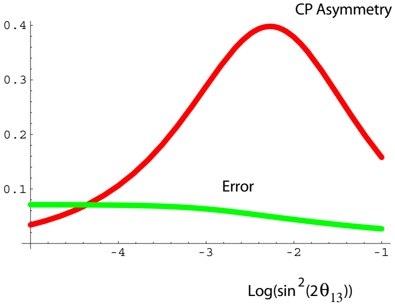


LCPV asymmetry at the first oscillation maximum, $\delta = 1$, Error curve: dependence of the statistical+systematic (2%) computed for a beta beam the fixed energy $E_\nu = 0.4$ GeV, $L = 130$ km.

- **The detection of such asymmetry is an evidence of Leptonic CP violation only in absence of competitive processes (i.e. matter effects, see following slides) ⇒ "short" Long Baseline experiments**

Measuring Leptonic CP violation

$$A_{CP} = \frac{P(\nu_\mu \to \nu_e) - P(\overline{\nu}_\mu \to \overline{\nu}_e)}{P(\nu_\mu \to \nu_e) + P(\overline{\nu}_\mu \to \overline{\nu}_e)}$$



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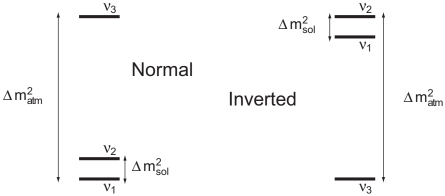
- **The detection of such asymmetry is an evidence of Leptonic CP violation only in absence of competitive processes (i.e. matter effects, see following slides) ⇒ "short" Long Baseline experiments**
- Statistics and systematics play different roles at different values of $\theta_{13} \Rightarrow$ impossible to optimize the experiment without a prior knowledge of θ_{13}
- Contrary to the common belief, the highest values of θ_{13} are not the easiest condition for LCPV discovery

Measuring mass hierarchy

An internal degree of freedom of neutrino masses is the sign of Δm^2_{31}: $\mathrm{sign}(\Delta m^2_{23})$.



This parameter decides how mass eigenstates are coupled to flavor eigenstates with important consequencies to direct neutrino mass and double beta decay experiments.

Neutrino Oscillations in Matter

$$P_{\theta_{13}} = \sin^2(2\theta_{13})\sin\theta_{23}{}^2\sin^2((\hat{A}-1)\hat{\Delta})/(\hat{A}-1)^2;$$
$$p_{\sin\delta} = \alpha\sin(2\theta_{13})\zeta\sin\delta\sin(L\hat{\Delta})\sin(\hat{A}\hat{\Delta})\sin((1-\hat{A})\hat{\Delta})/((1-\hat{A})\hat{A});$$
$$p_{\cos\delta} = \alpha\sin(2\theta_{13})\zeta\cos\delta\cos\hat{\Delta}\sin(\hat{A}\hat{\Delta})\sin(1-\hat{A}\hat{\Delta})/((1-\hat{A})\hat{A});$$
$$p_{\mathrm{solar}} = \alpha^2\cos\theta_{23}{}^2\sin^2 2\theta_{12}\sin^2(\hat{A}\hat{\Delta})/\hat{A}^2;$$

$\alpha = \mathrm{Abs}(\Delta m^2_{21}/\Delta m^2_{31})$; $\hat{\Delta} = \frac{L\Delta m^2_{31}}{4E}$ $\zeta = \cos\theta_{13}\ \sin 2\theta_{12}\sin 2\theta_{23}$
$\boldsymbol{\hat{A} = \pm a/\Delta m^2_{31}}$; $a = 7.6\cdot 10^{-5}\rho\cdot E_\nu(GeV)$ $\quad\rho = \text{matter density }(\mathrm{g\,cm^{-3}})$
The $\hat{A}$ term changes sign with $\mathrm{sign}(\Delta m^2_{23})$

Matter effects require long "long baselines"

Neutrino Oscillations in Matter

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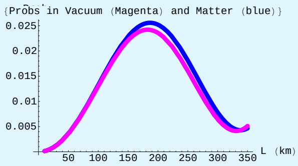
Matter effects require long "long baselines"

$E_\nu = 0.35\mathrm{GeV}$ $L \simeq 130$ km



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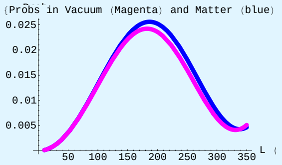
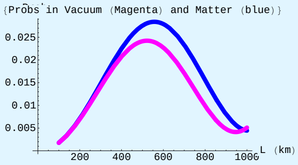
Matter effects require long "long baselines"

$E_\nu = 0.35\mathrm{GeV}$ $L \simeq 130$ km **$E_\nu = 1\mathrm{GeV}$ $L \simeq 500$ km**





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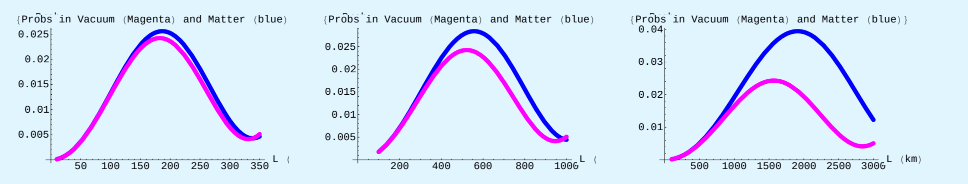
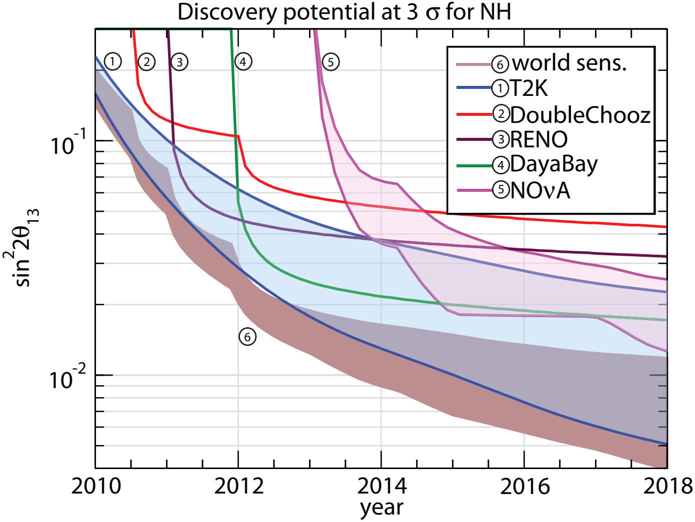
Matter effects require long "long baselines"

$E_\nu = 0.35\mathrm{GeV}$ $L \simeq 130$ km $E_\nu = 1\mathrm{GeV}$ $L \simeq 500$ km $E_\nu = 3\mathrm{GeV}$ $L \simeq 1500$ km

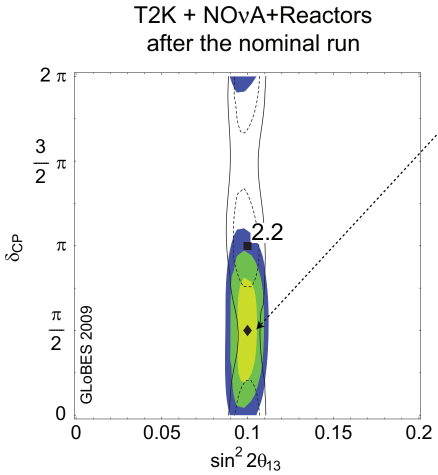


Status after this generation of LBL experiments: θ_{13}

From M.M. and T. Schwetz, arXiv:1003.5800

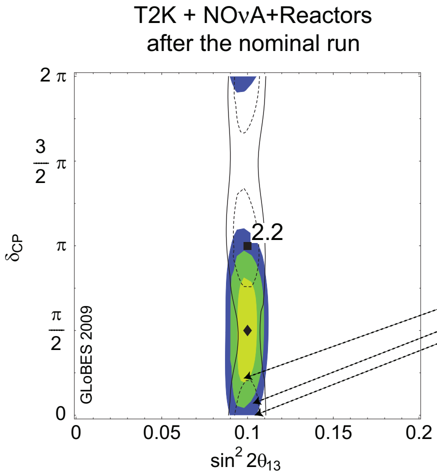


Status after this generation of LBL experiments: CPV



1) Choose a test point, this is the most favorable: max δ_{CP} and max θ_{13}

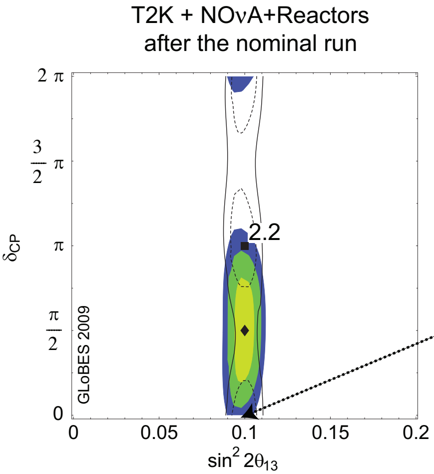
Status after this generation of LBL experiments: CPV



1) Choose a test point, this is the most favorable: max δ_{CP} and max θ_{13}

2) Fit to the expected sensitivity of the experiments: 1σ, 2σ, 3σ

Status after this generation of LBL experiments: CPV



1) Choose a test point, this is the most favorable: max δ_{CP} and max θ_{13}

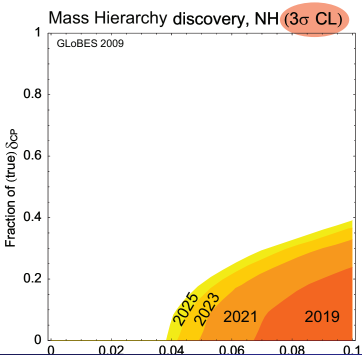
2) Fit to the expected sensitivity of the experiments: 1σ, 2σ, 3σ

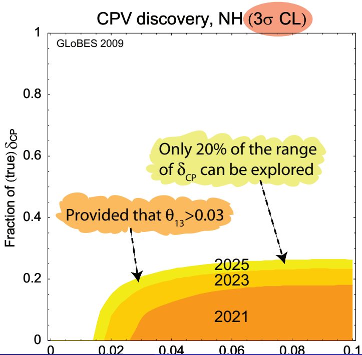
3) Null CP is compatible with data already at 2σ

Status after this generation of LBL experiments

From P. Huber et al., JHEP 0911:044,2009.

Prediction of sensitivity including a fully optimized global run (antineutrinos in T2K and NOνA) and full upgrade of the accelerators: 1.6 MW at J-PARC and 2.4 MW at FNAL (Project-X)


Mass Hierarchy discovery, NH (3σ CL)


CPV discovery, NH (3σ CL)

Only 20% of the range of δ_{CP} can be explored

Provided that $\theta_{13}>0.03$

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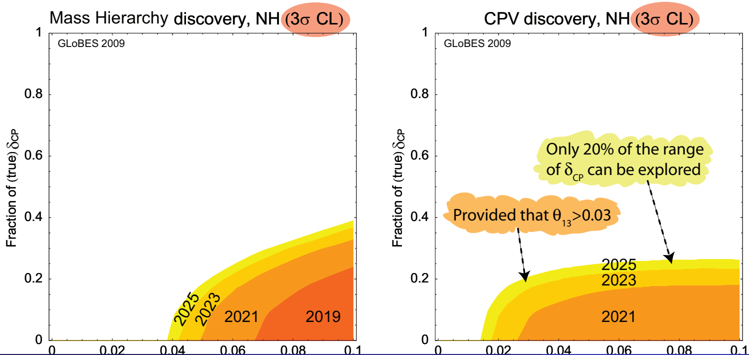


Mass Hierarchy discovery, NH (3σ CL)

CPV discovery, NH (3σ CL)

Only 20% of the range of δ_{CP} can be explored

Provided that θ_{13}>0.03

Laguna, EU Design Study FP7

(See JCAP, 2007, 0711, 011)

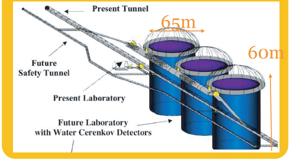
A coordinated European effort aimed towards conceptual designs for European large underground detectors including feasibility studies for site excavation and cost boundaries.
Three detection techniques investigated:

- Water Cerenkov imaging (**Memphys**) , ∼ 500 kton, with synergy with HK (Japan) and Dusel (USA).
- Liquid argon time-projection chamber (**Glacier**) , ∼ 100 kton. Technology pioneered in Europe by the ICARUS R&D programme, at present ongoing R&D in USA and Japan, too.
- Liquid scintillator (**Glacier**) , ∼ 50 kton connected to Borexino R&D programme.

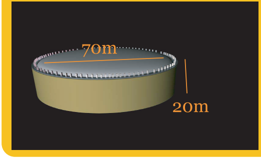
Physics case (non accelerator physics)

- Proton decay
- Super Nova neutrinos
- Relic Super Nova neutrinos
- Solar and Atmospheric neutrinos

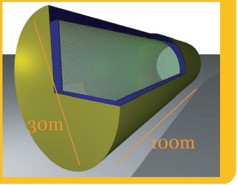
MEMPHYS



GLACIER



LENA

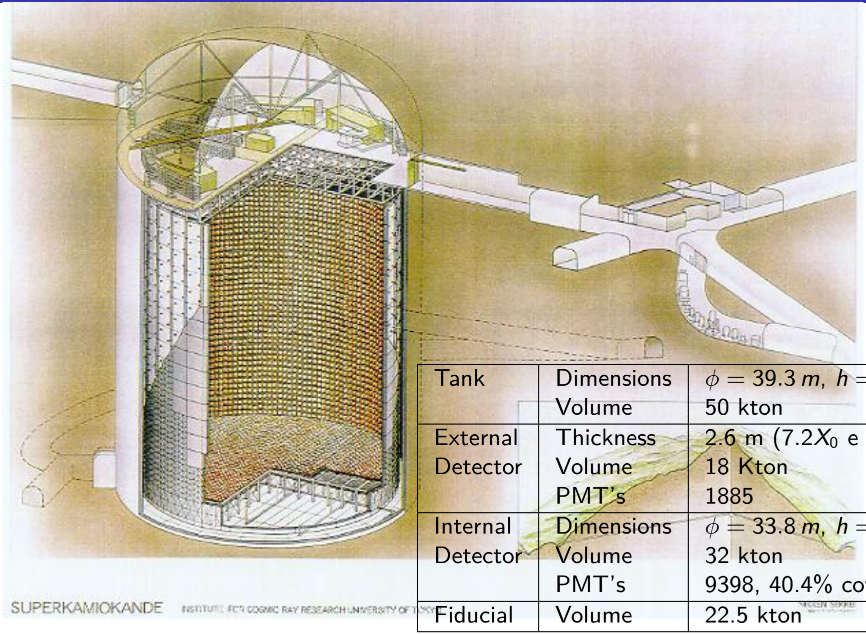


The SuperBeam way

Upgrade existing or future accelerators to several MW power and build WC detectors 10 × Super Kamiokande or 300 × Icarus

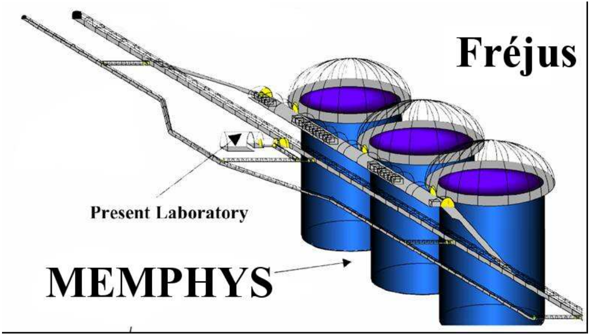
- **Japan.**
  J-Parc: 0.75 ⇒ 2 MW + Super Kamiokande ⇒ Hyper Kamiokande (500 kton fiducial: 20 × bigger)
- **USA.**
  FNAL: Project X to a 3 × 100 kton water Cherenkov detectors (or $3 - 6 \times$ 20kton liquid argon) at Dusel, $L \sim 1300$ km.
- **Europe**
  - 10×CNGS ⇒ off-axis CNGS fired on a 20-100 kton liquid argon detector
  - 4 MW SPL fired on 500 kton water Cherenkov (Memphys) at Frejus at 130 km
  - 2 MW PS2 fired on 100 kton liquid Argon (Glacier) at Slanic (RO) at 1570 km

SuperKamiokande detector



Tank	Dimensions Volume	$\phi = 39.3\,m,\ h = 41.4\,m$ 50 kton
External Detector	Thickness Volume PMT's	2.6 m ($7.2X_0$ e $4.3\lambda_0$) 18 Kton 1885
Internal Detector	Dimensions Volume PMT's	$\phi = 33.8\,m,\ h = 36.2\,m$ 32 kton 9398, 40.4% coverage
Fiducial	Volume	22.5 kton

The Memphys detector (hep-ex/0607026)



In the middle of the Frejus tunnel at a depth of 4800 m.w.e excavate three shafts of about 250,000 m^3 each ($\Phi = 65\,m$, full height=80 m). 440 kton fiducial volume

30% coverage by using 12“ PMT's, 81k per shaft (with the same photostatistics of SuperKamiokande with 40% coverage)

Physics scope, independently from the beam

- Proton decay
- Super Nova neutrinos
- Relic Super Nova neutrinos
- Solar and Atmospheric neutrinos
- Indirect searches of DM annihilation in the sun

SuperBeams - J-PARC phase 2 (T2HK)

Upgrade the proton driver from 0.75 MW to 4 MW

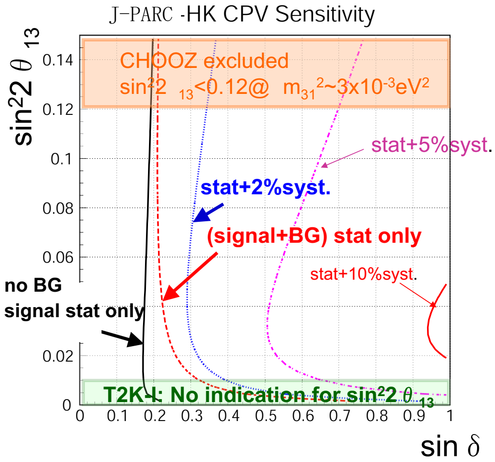
Upgrade SuperKamiokande by a factor ∼ 20 ⟹ HyperKamiokande

Both upgrades are necessary to address leptonic CP searches.

Other possibility:

displace half detector at the second oscillation maximum (T2KK) for better sensitivity on $\mathrm{sign}(\Delta m^2_{23})$and better degeneracy removal

T. Kobayashi, J.Phys.G29:1493(2003)

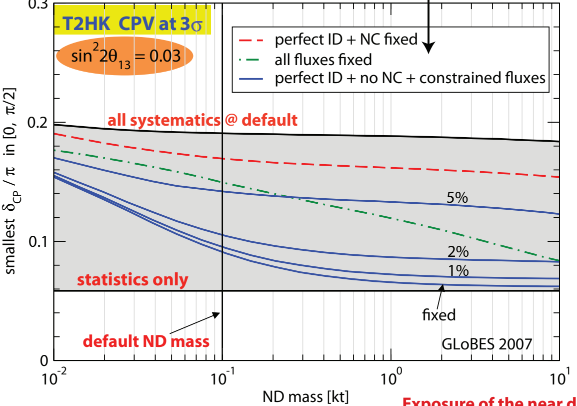


Next to statistics: systematic errors

From Huber, MM, Schwetz, JHEP 0803:021,2008

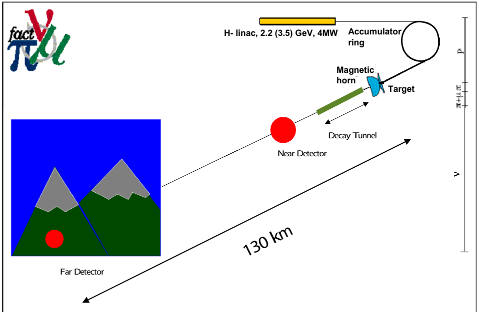
The main limiting factor for future searches of leptonic CP violation will be statistics, next the not perfect knowledge of the neutrino beam fluxes

Some hypothesis about near detector performances and ancillary data by hadroproduction experiments



Exposure of the near detector

SuperBeams - SPL ν beam at CERN



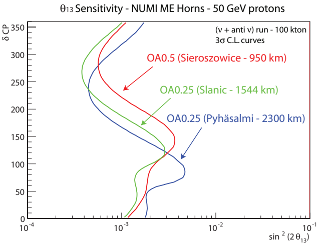
Possible Low Energy Super Beam Layout

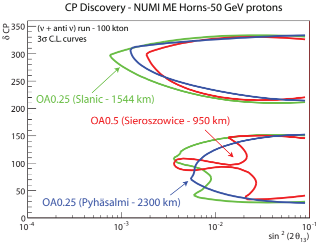
- A 3.5 GeV, 4MW Linac: the HP-SPL.
- A liquid mercury (or carbon) target capable to manage the 4 MW proton beam. R&D required.
- A conventional neutrino beam optics capable to survive to the beam power, the radiation and the mercury. Already prototyped.
- Up to here is the first stage of a neutrino factory complex.
- A sophisticated close detector to measure at 2% signal and backgrounds.
- A megaton class detector under the Frejus, L=130 km: Memphys.

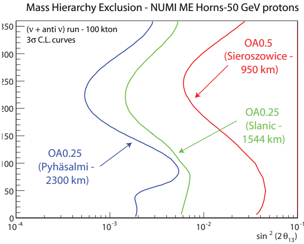
PS2 Super Beams

A. Rubbia: arXiv.1003.1921

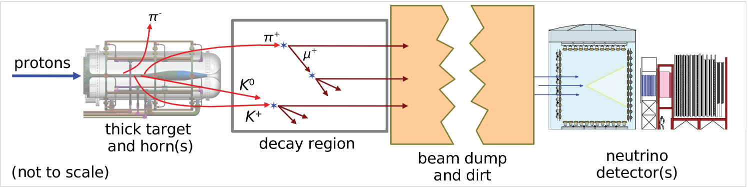
Assume 2 MW from a 50 GeV PS2.
An on-axis wide band neutrino beam.
Three possible sites: Sieroszowice at 950 km, Slanic at 1544 km or Pyhasalmi at 2300 km.
A 100 kton liquid argon detector capable of measuring neutrino oscillations at both the first and second oscillation maxima with optimal perfromance on reconstruction of neutrino energy and background rejection.


θ13 Sensitivity - NUMI ME Horns - 50 GeV protons


CP Discovery - NUMI ME Horns-50 GeV protons


Mass Hierarchy Exclusion - NUMI ME Horns-50 GeV protons

Conventional neutrino beams are going to hit their ultimate limitations.



In a **conventional neutrino beam**, neutrinos are produced SECONDARY particle decays (mostly pions and kaons).
Given the short life time of the pions ($2.6 \cdot 10^{-8}$s), they can only be focused (and charge selected) by means of magnetic horns. Then they are let to decay in a decay tunnel, short enough to prevent most of the muon decays.

- Besides the main component (ν_μ) at least 3 other neutrino flavors are present ($\overline{\nu}_\mu$, ν_e, $\overline{\nu}_e$), generated by wrong sign pions, kaons and muon decays. $\nu_e$contamination is a background for θ_{13} and δ, $\overline{\nu}_\mu$contamination dilutes any CP asymmetry.
- Hard to predict the details of the neutrino beam starting from the primary proton beam, the problems being on the secondary particle production side.

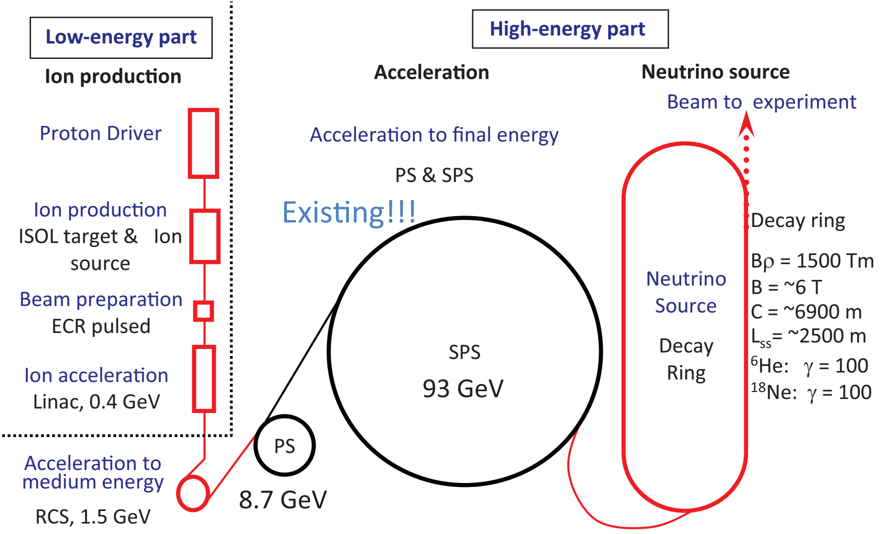
All these limitations are overcome if secondary particles become primary

Collect, focus and accelerate the neutrino parents at a given energy. This is impossible within the pion lifetime, but can be tempted within the muon lifetime **(Neutrino Factories)** or within some radioactive ion lifetime **(Beta Beams)**:

- Just one flavor in the beam
- Energy shape defined by just two parameters: the endpoint energy of the beta decay and the γ of the parent ion.
- Flux normalization given by the number of ions circulating in the decay ring.
- Beam divergence given by γ.

Beta Beam (P. Zucchelli: Phys. Lett. B532:166, 2002)

M. Lindroos M. Mezzetto, “Beta Beams”, Imperial College Press, 2009



Decay ring

$B\rho$ = 1500 Tm

B = ~6 T

C = ~6900 m

L_{ss}= ~2500 m

^{6}He: γ = 100

^{18}Ne: γ = 100

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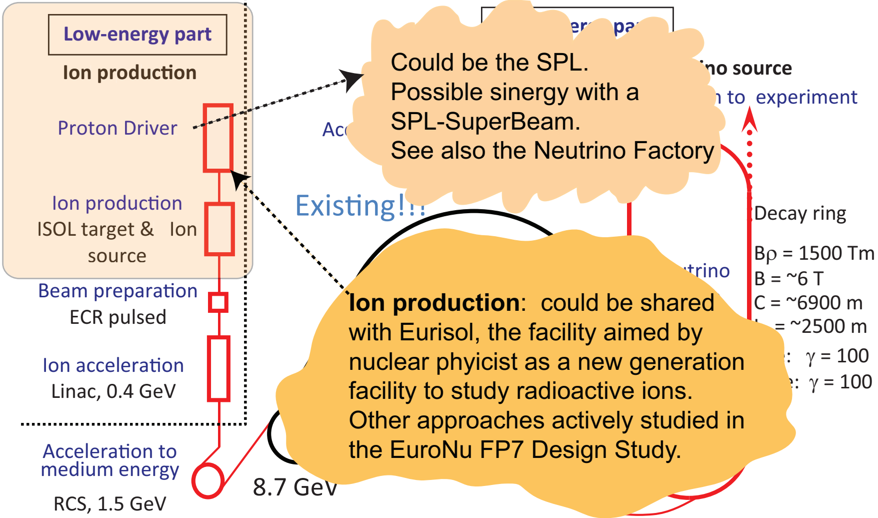


Low-energy part

Ion production

Proton Driver

Ion production
ISOL target & Ion source

Beam preparation
ECR pulsed

Ion acceleration
Linac, 0.4 GeV

Acceleration to medium energy
RCS, 1.5 GeV

8.7 GeV

Existing!!!

Ac

er pa

no source

to experiment

trino

Decay ring

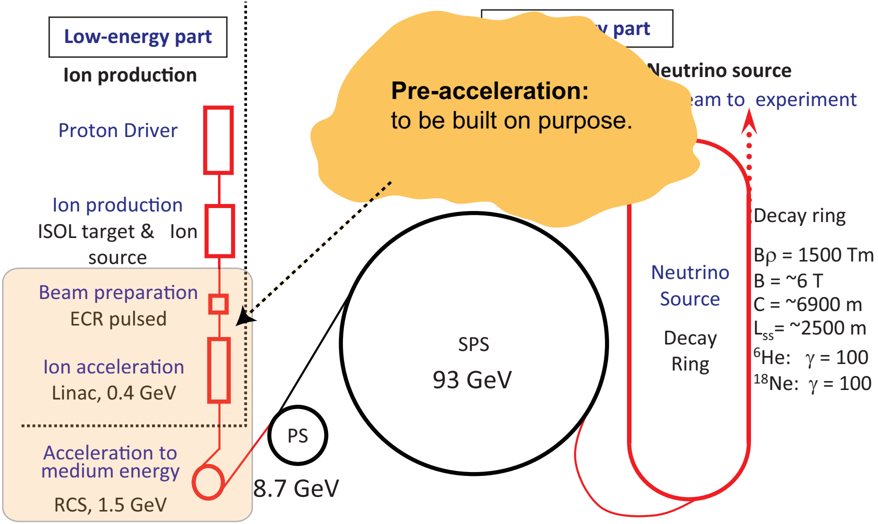
Bρ = 1500 Tm
B = ~6 T
C = ~6900 m
= ~2500 m
: γ = 100
: γ = 100

Could be the SPL.
Possible sinergy with a SPL-SuperBeam.
See also the Neutrino Factory

Ion production: could be shared with Eurisol, the facility aimed by nuclear phyicist as a new generation facility to study radioactive ions. Other approaches actively studied in the EuroNu FP7 Design Study.

Beta Beam (P. Zucchelli: Phys. Lett. B532:166, 2002)

M. Lindroos M. Mezzetto, “Beta Beams”, Imperial College Press, 2009



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Acceleration to medium energy
RCS, 1.5 GeV

PS
8.7 GeV

SPS
93 GeV

Pre-acceleration:
to be built on purpose.

y part

Neutrino source

am to experiment

Neutrino Source
Decay Ring

Decay ring

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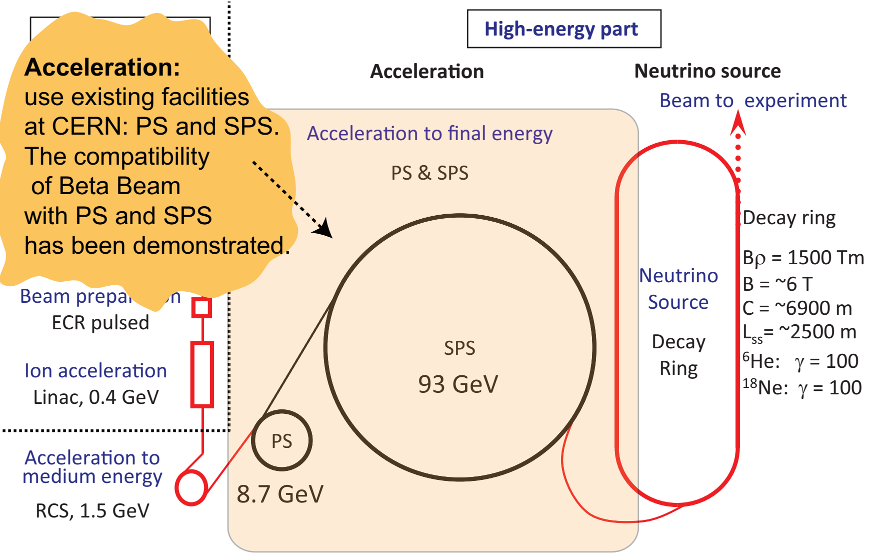

Acceleration:
use existing facilities
at CERN: PS and SPS.
The compatibility
of Beta Beam
with PS and SPS
has been demonstrated.

High-energy part

Acceleration

Neutrino source

Beam to experiment

Acceleration to final energy

PS & SPS

SPS

93 GeV

PS

8.7 GeV

Neutrino Source

Decay Ring

Decay ring

$B\rho$ = 1500 Tm
B = ~6 T
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Beam prepa n
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Ion acceleration
Linac, 0.4 GeV

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RCS, 1.5 GeV

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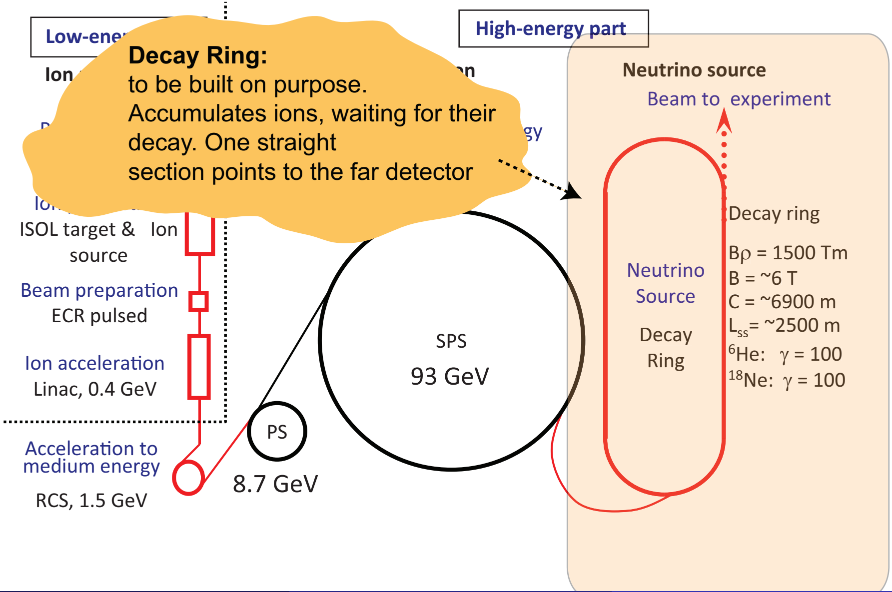

Decay Ring:
to be built on purpose.
Accumulates ions, waiting for their decay. One straight section points to the far detector

$B\rho = 1500$ Tm
$B = \sim 6$ T
$C = \sim 6900$ m
$L_{ss} = \sim 2500$ m
^{6}He: $\gamma = 100$
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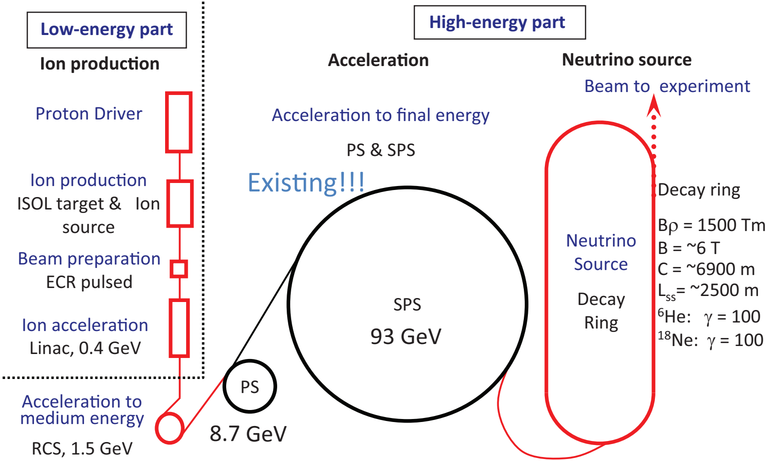

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Ion production

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ISOL target & Ion source

Beam preparation
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Linac, 0.4 GeV

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High-energy part

Acceleration

Acceleration to final energy

PS & SPS

Existing!!!

SPS
93 GeV

PS
8.7 GeV

Neutrino source

Beam to experiment

Neutrino Source

Decay Ring

Decay ring

$B\rho$ = 1500 Tm
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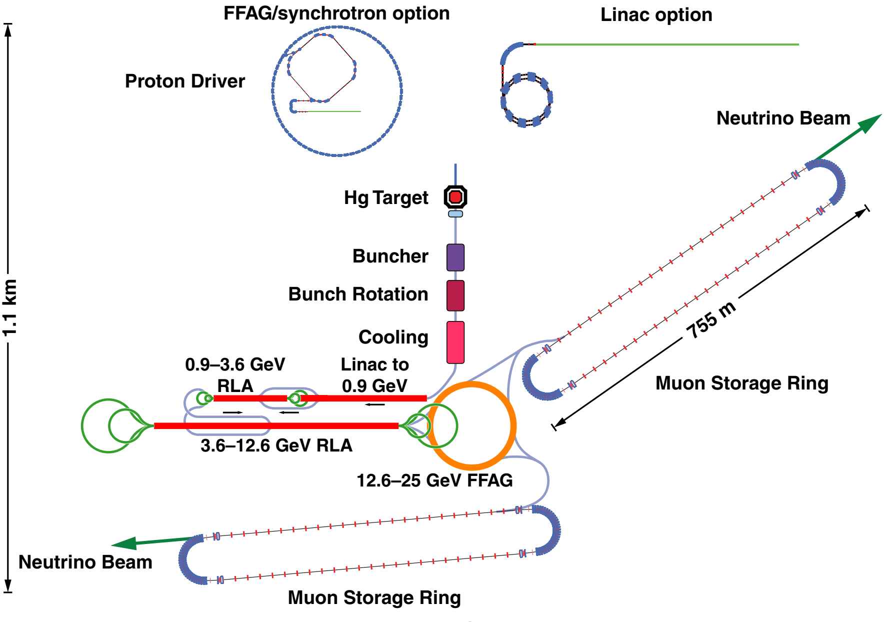
^{6}He: γ = 100
^{18}Ne: γ = 100

- $\overline{\nu}_e$ generated by He^6, 100 μA, $\Rightarrow 2.9 \cdot 10^{18}$ ion decays/straight session/year.
- ν_e generated by Ne^{18}, 100 μA, $\Rightarrow 1.1 \cdot 10^{18}$ ion decays/straight session/year.

Layout of a Neutrino Factory



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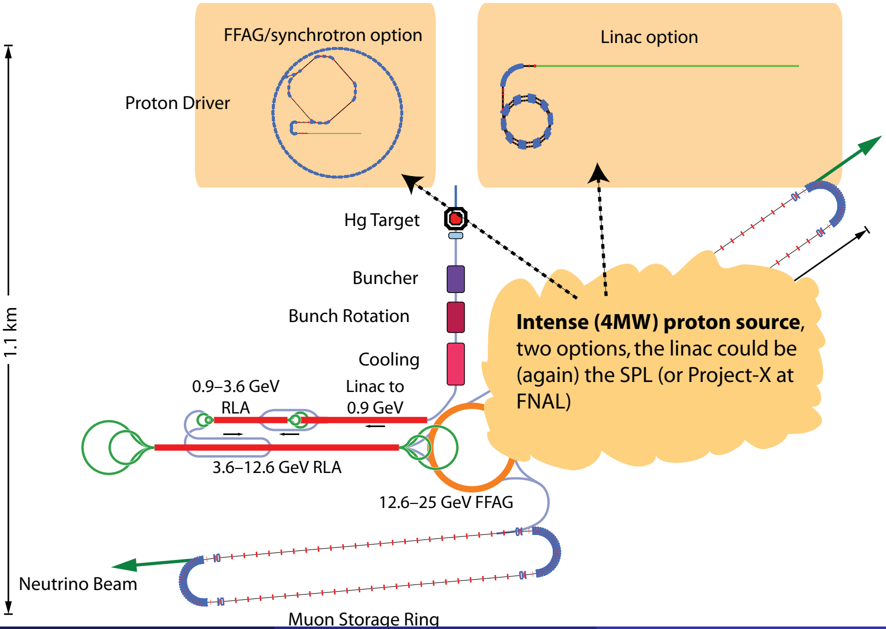
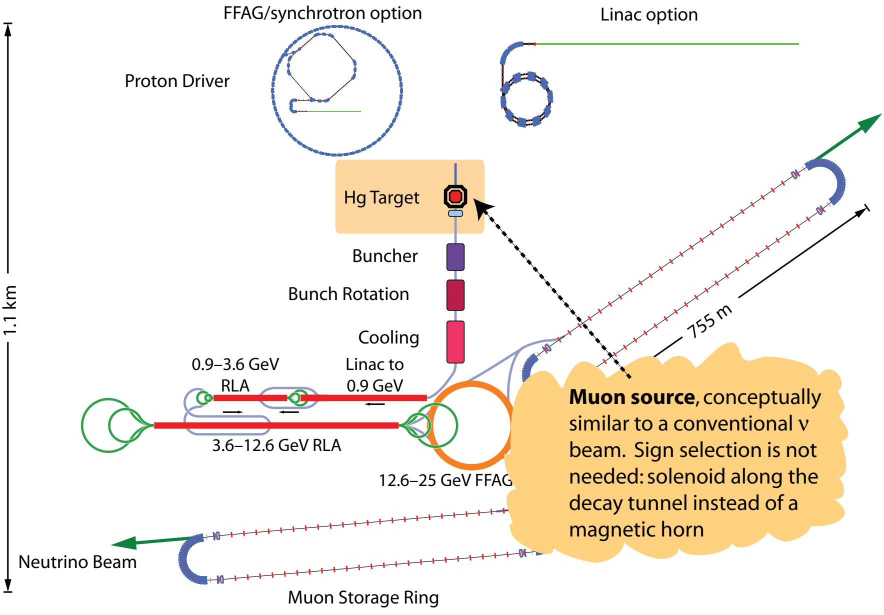


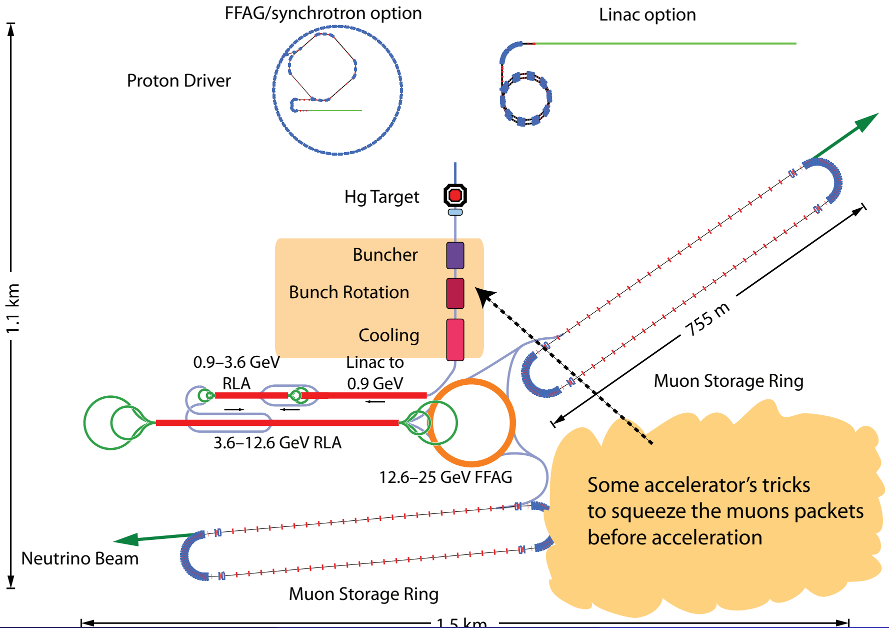
Intense (4MW) proton source, two options, the linac could be (again) the SPL (or Project-X at FNAL)

Layout of a Neutrino Factory



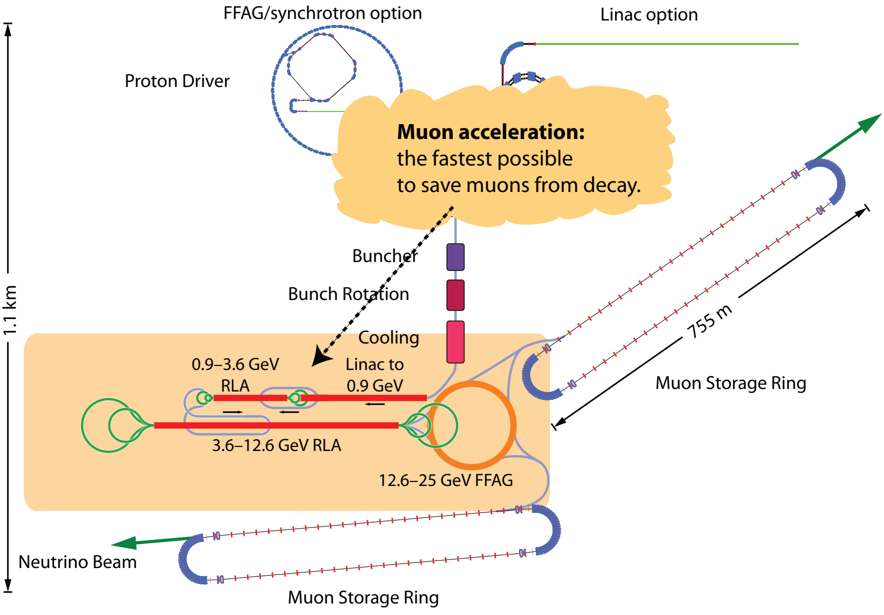
Muon source, conceptually similar to a conventional ν beam. Sign selection is not needed: solenoid along the decay tunnel instead of a magnetic horn

Layout of a Neutrino Factory



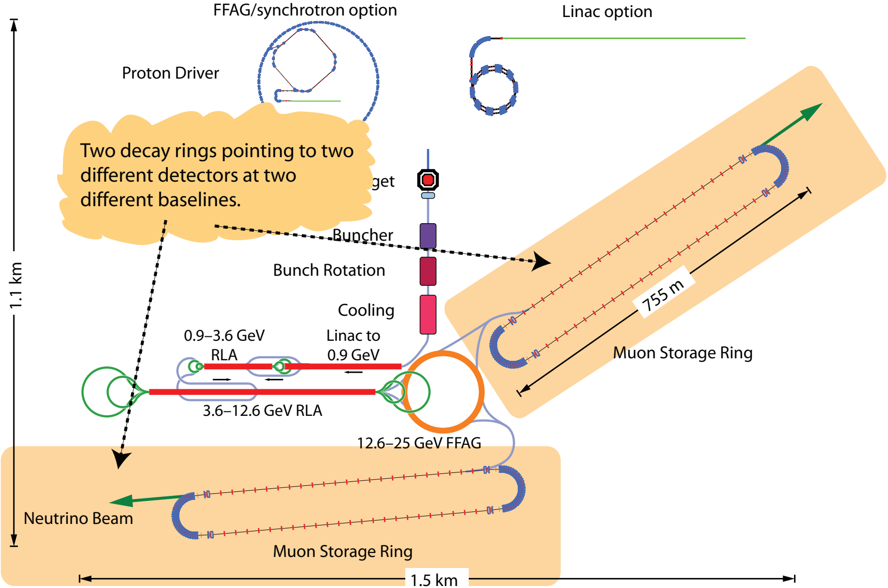
Some accelerator's tricks
to squeeze the muons packets
before acceleration

Layout of a Neutrino Factory



Muon acceleration:
the fastest possible
to save muons from decay.

Layout of a Neutrino Factory

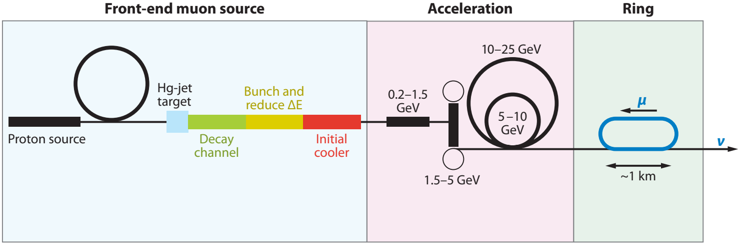


Two decay rings pointing to two different detectors at two different baselines.

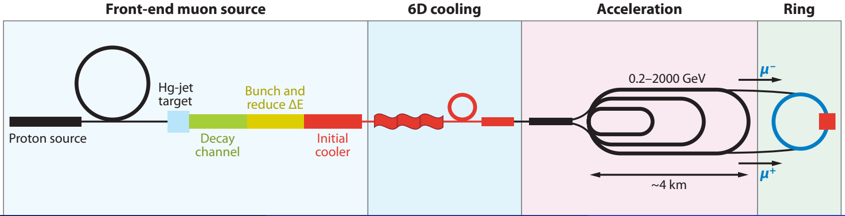
Neutrino Factory as a first stage of a Muon Collider

From S. Geer, Ann.Rev.Nucl.Part.Sci.59:347-365,2009.

Neutrino factory



Muon collider



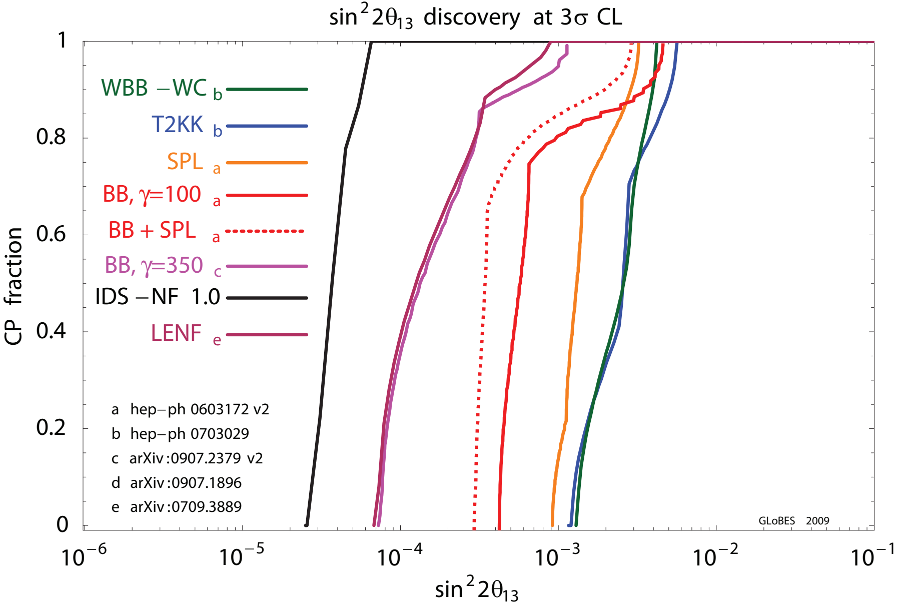
Oscillation signals at the neutrino factory

μ^- (μ^+) decay in (ν_μ, $\overline{\nu}_e$) (($\overline{\nu}_\mu$, ν_e)).

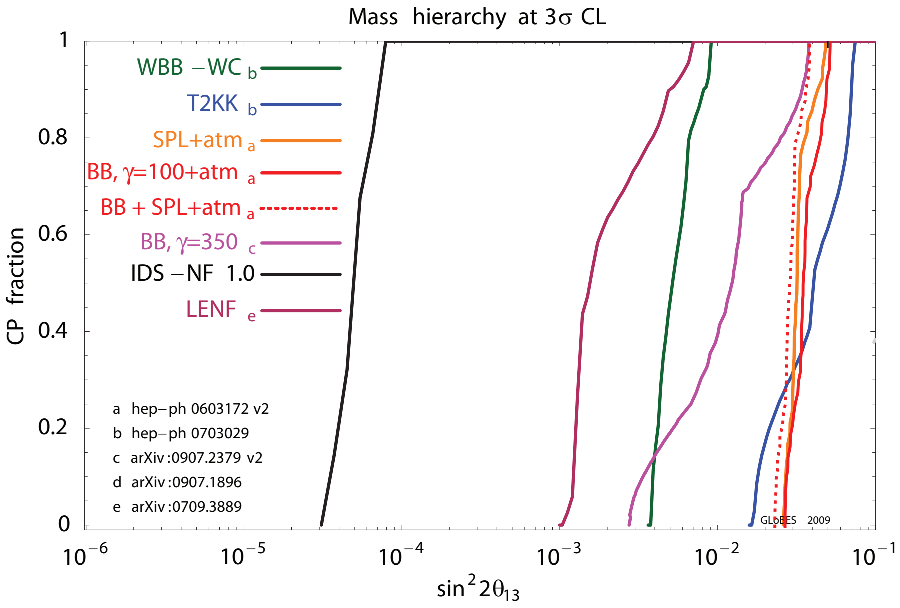
Golden channel: search for $\nu_e \rightarrow \nu_\mu$ ($\overline{\nu}_e \rightarrow \overline{\nu}_\mu$) transitions by detecting wrong sign muons.
Default detector: 40-100 kton iron magnetized calorimeter (Minos like)

Silver channel: search for $\nu_e \rightarrow \nu_\tau$ transitions by detecting ν_τ appearance.
Ideal detectors: 4× Opera or 20 Kton LAr detector.

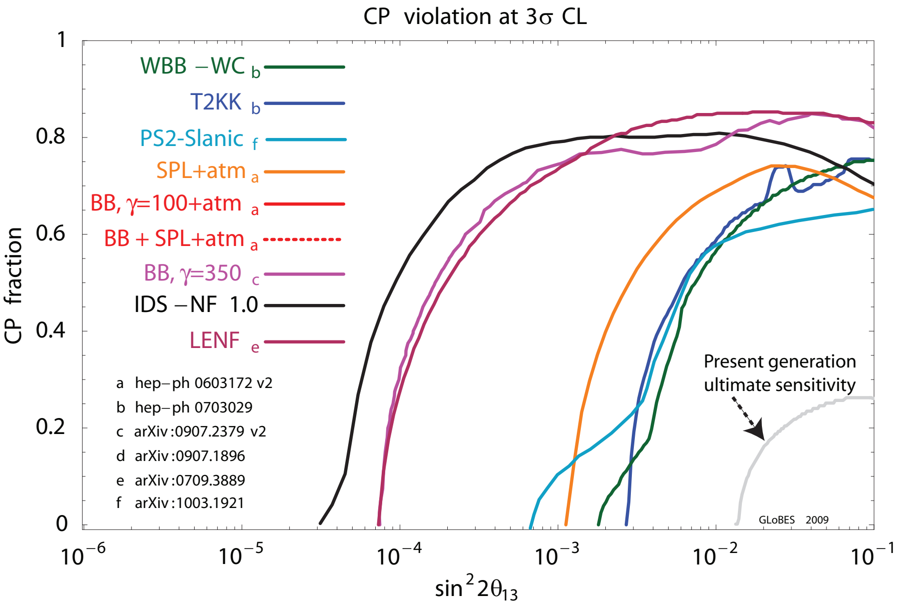
Sensitivity Comparison: θ_{13}



Sensitivity Comparison: $\mathrm{sign}(\Delta m^2_{23})$



Sensitivity Comparison: LCPV



Conclusions

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- A neutrino factory can offer the ultimate performances in neutrino oscillations and can be seen as the first stage of a muon collider.