Physics at Neutrino Factories

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ICHEP 2000
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Outline of talk

Introduction & Basic assumptions
Neutrino factory ideas and parameters
Oscillation physics
Other neutrino physics
Other Physics
Summary & conclusions

NUFACT'00, Monterey, May 22-26
> 150 participants
FNAL Physics Study FN - 692
CERN Yellow Report 99-02

WORK OF MANY PEOPLE*

* THANKS TO NIGEL SMITH

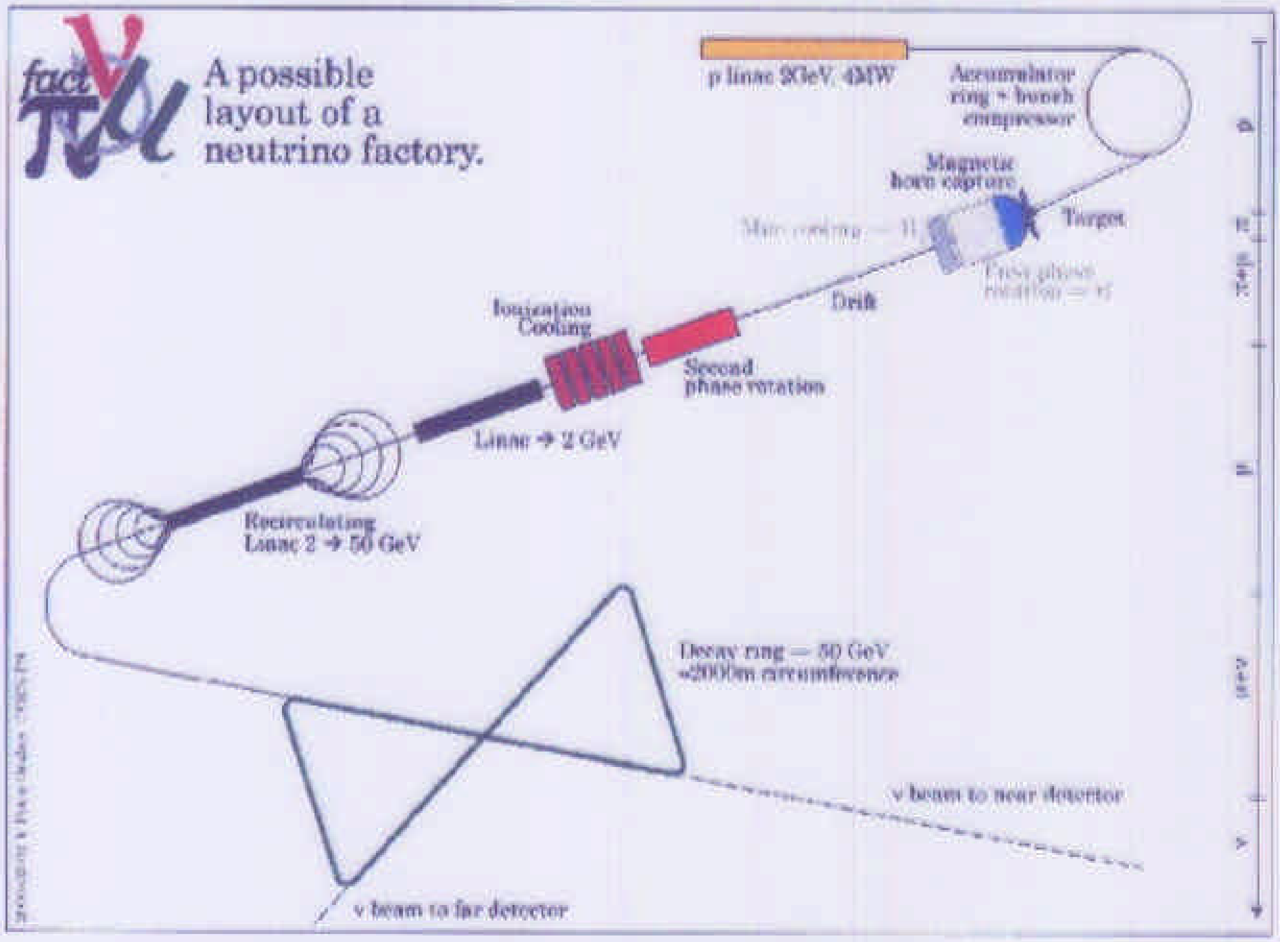
Introduction

- ⇨ **Strong interest in neutrino factories**
  - Driven initially by muon collider ideas
    - first proposed in 1960's
    - needs enormous muon cooling
      (>10^6 reduction in emittance)
  - Increasing emphasis on neutrino factory
    - less cooling required
    - Strong independent scientific case
      Neutrino oscillations
    - 'Demonstrator' for muon colliders
      3 stage scenario
        - neutrino factory
        - Higgs factory
        - Multi-TeV muon collider
- ⇨ **Basic assumptions**
  - A neutrino factory is needed *somewhere*
    - Location & orientation fixed by mixing parameters
      e.g.

$$P(Osc) \approx \sin^2(2\theta)\sin^2\left(1.27\,\Delta m^2\,\frac{L}{E}\right)$$

    - Other science parasitic
  - Sensitivity at fixed fluence $\propto E_\mu$
    - High energy muon storage ring (≈ 50GeV)
  - Cost ≈ A + B E_μ
    - Low energy muon storage ring » τ threshold (≈ 20GeV)

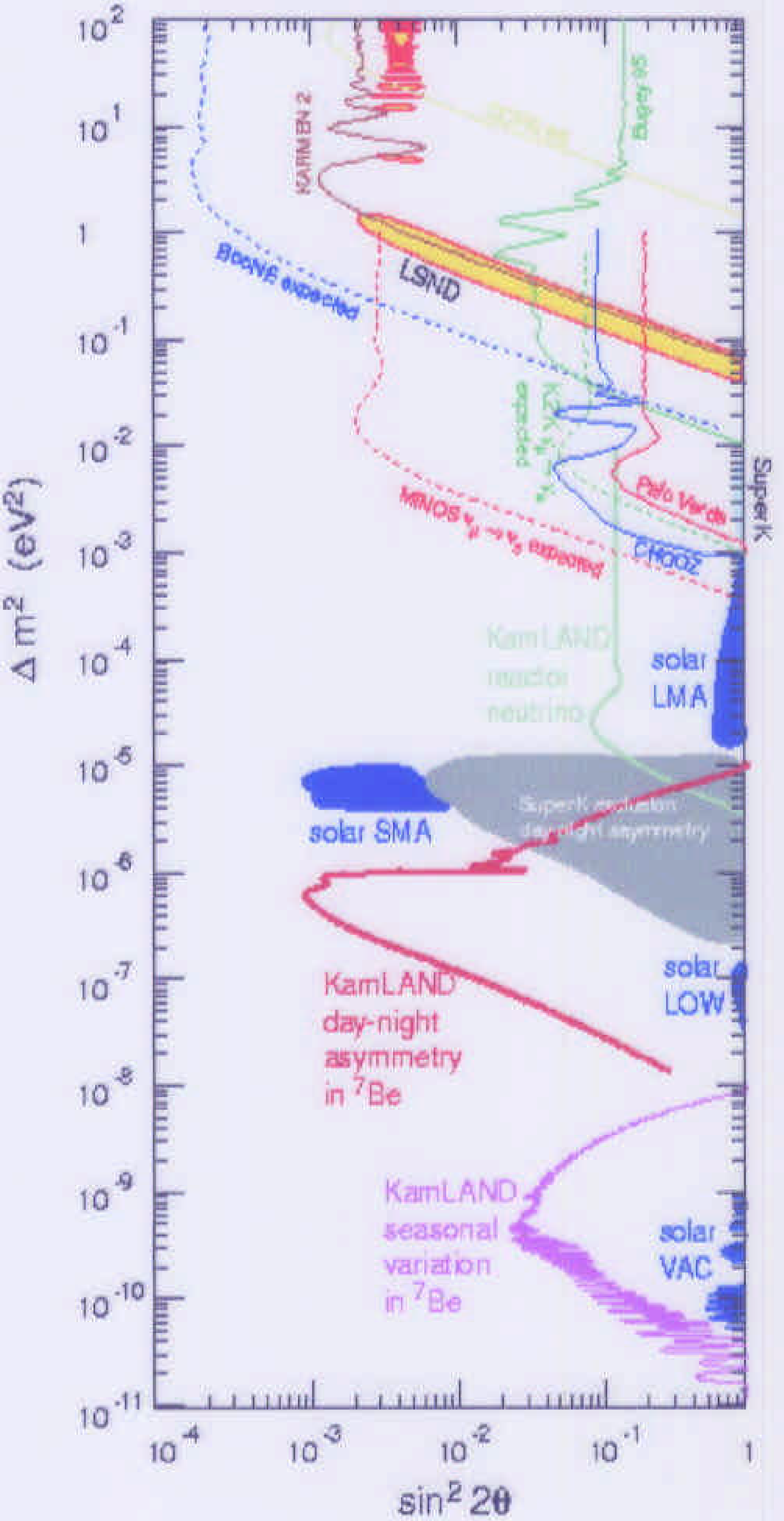
The Neutrino Factory



⇨ Basic features of a neutrino factory

- **High intensity proton source**
  - 2-50GeV, 100-1Hz
- **High power target**
  - 4MW (liquid metal, moving solid, ...)
- **Pion capture & decay channel, muon capture**
  - solenoid
- **Cooling**
  - phase rotation, ionisation
- **Acceleration**
- **Storage**
  - Aim: ~10^{21} muon decays/year
  - E_{μ} 20-50 GeV

Oscillation Physics



From Fermilab Report FB 693

Oscillation Physics

$$P(\nu_\alpha \Rightarrow \nu_\beta) = P_{CP=+1}(\nu_\alpha \Rightarrow \nu_\beta) + P_{CP=-1}(\nu_\alpha \Rightarrow \nu_\beta)$$

$$P_{CP=+1}(\nu_\alpha \Rightarrow \nu_\beta) = \delta_{\alpha\beta} - 4\sum_{i>j} \mathrm{Re}(U_{\alpha i}U^*_{\beta i}U^*_{\alpha j}U_{\beta j})\sin^2\left(\frac{\Delta m^2_{ij}L}{4E}\right)$$

$$P_{CP=-1}(\nu_\alpha \Rightarrow \nu_\beta) = 2\sum_{i>j} \mathrm{Im}(U_{\alpha i}U^*_{\beta i}U^*_{\alpha j}U_{\beta j})\sin\left(\frac{\Delta m^2_{ij}L}{2E}\right)$$

U: Maki-Nagawa-Sakata (MNS) neutrino mixing matrix

For three generations of neutrinos, there are 7 parameters

- **2 independent Δm**
- **3 mixing angles $\theta_{12}, \theta_{23}, \theta_{13}$**
- **1 T-violating phase δ**
- **1 absolute mass scale**

A neutrino factory in principle can make 12 measurements e→e e→μ e→τ

charge conjugate $\mu \Rightarrow e$; $\mu \Rightarrow \mu$; $\mu \Rightarrow \tau$

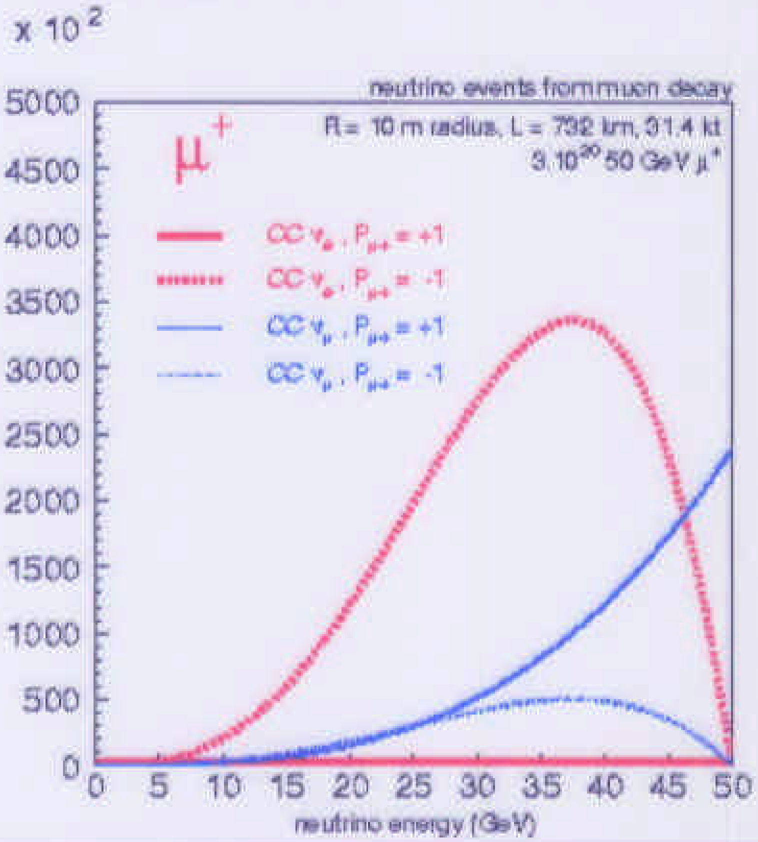
and

Measure all except absolute mass scale!

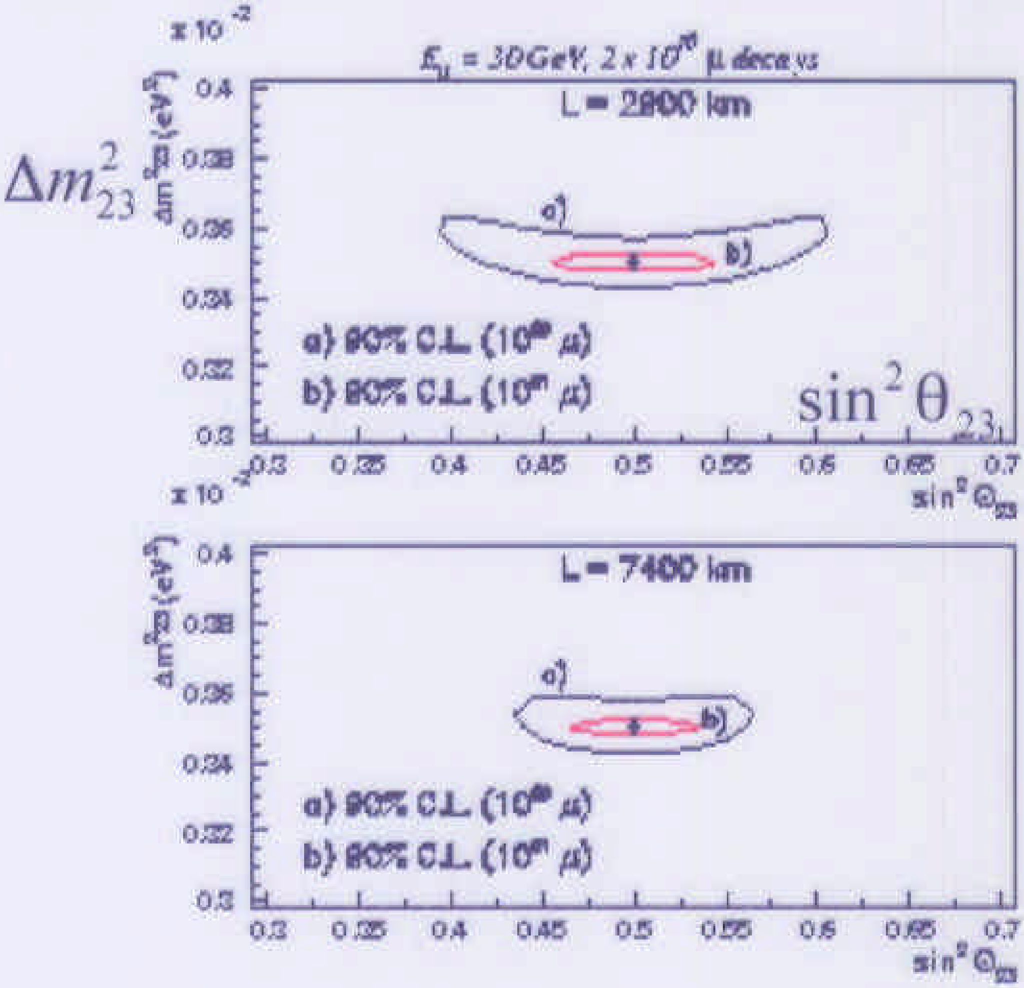
Notes:h

1. **Charge tag of lepton defines initial neutrino flavour**
2. **T (CP) violation needs flavour changing interaction**

Energy Spectrum



Blondel et al
CERN-EP-2000-053



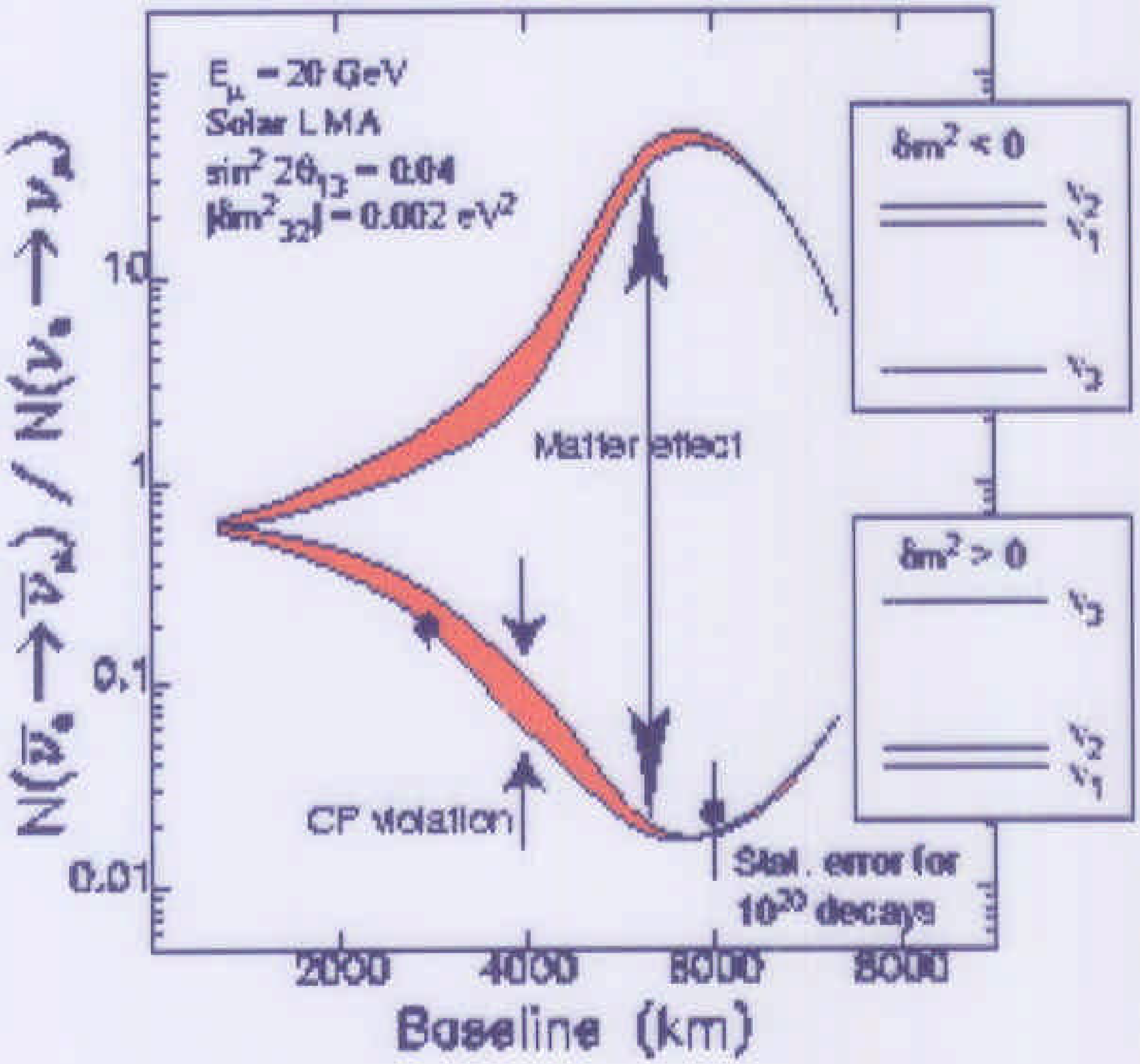
Example:

Simulated ν_μ disappearance experiment.

Bueno, Campanelli & Rubbia

Example of Neutrino Factory CP-violation study

Wrong-Sign Muon Measurements



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Scaling Law / Figure of Merit

Muon energy × Muon Intensity × Detector Mass

$$E_\mu \times I_\mu \times M$$

Sensitivity to Oscillation parameters

Examples: E_μ=50GeV

Whisnant

L	Δm^2_{32}	$s^2 2\theta_{23}$	$s^2 2\theta_{13}$
~700km	12%	17%	0.003
~3000km	4.90%	1.80%	0.0004
~7000km	1.40%	0.64%	0.002

'Michelin' ratings

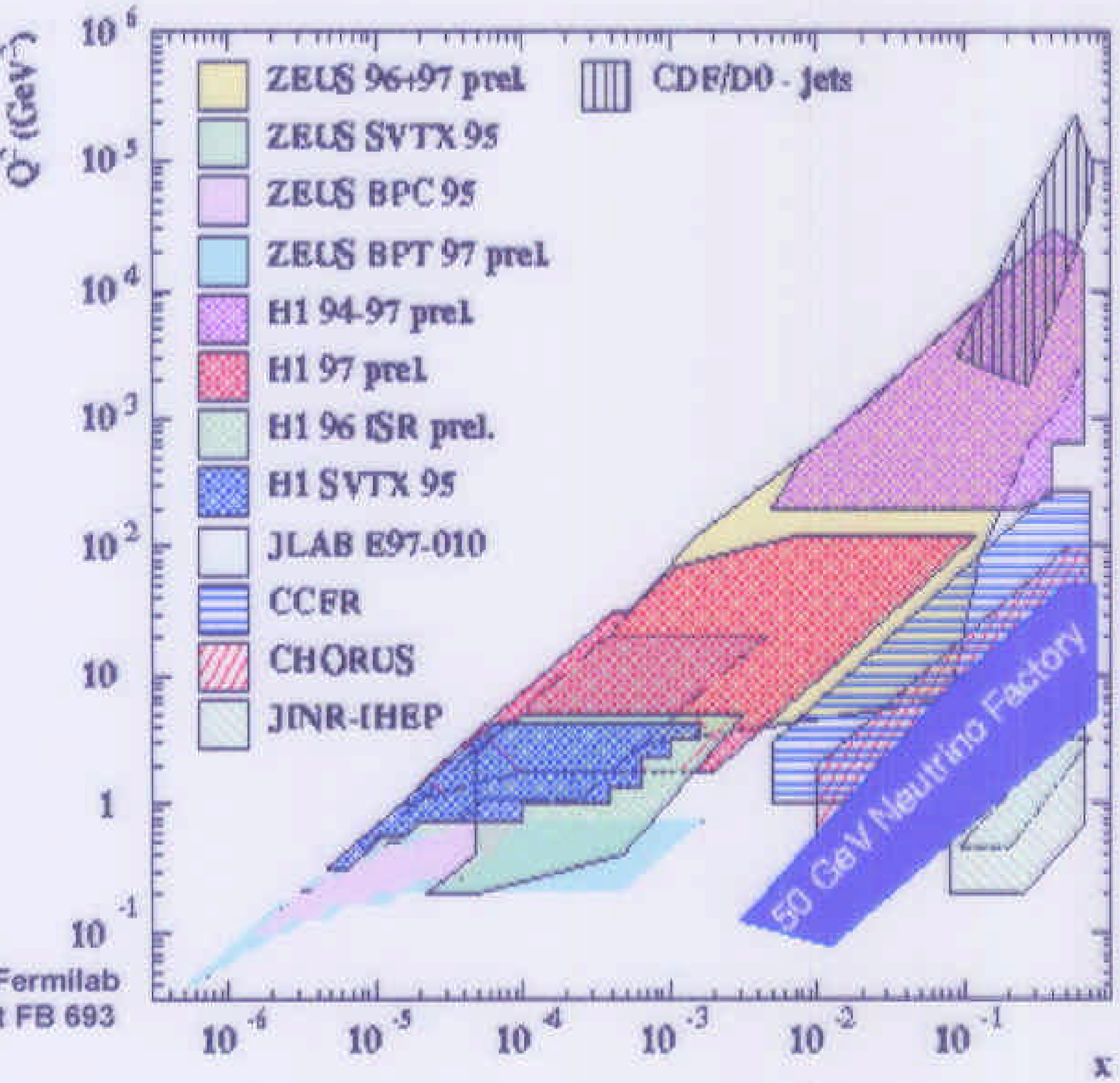
'Subjective'

L	<1000km	~3000km	>6000km
$\Delta m^2_{32}, \theta_{23}$	*	**	***
θ_{13}	***	**	**
$Sign(\Delta m^2_{32})$		**	**
CPV	*	***	

Depends upon parameters e.g. LMA & 10^{22} μ decays for CPV

Other Physics (1) - ν-DIS

- ⇨ The neutrino factory is an ideal place to measure Parton Distribution Functions (pdf's)
- ⇨ High intensity ν beams mean high statistics
  - >10^7 interactions per kg per year
  - Can use H_2 and D_2 targets
  - polarised targets
- ⇨ Clean incoming ν spectrum
  - reduce systematic errors from beam energy scale
- ⇨ Equal statistics for ν and $\bar{\nu}$
- ⇨ Naturally polarised beams



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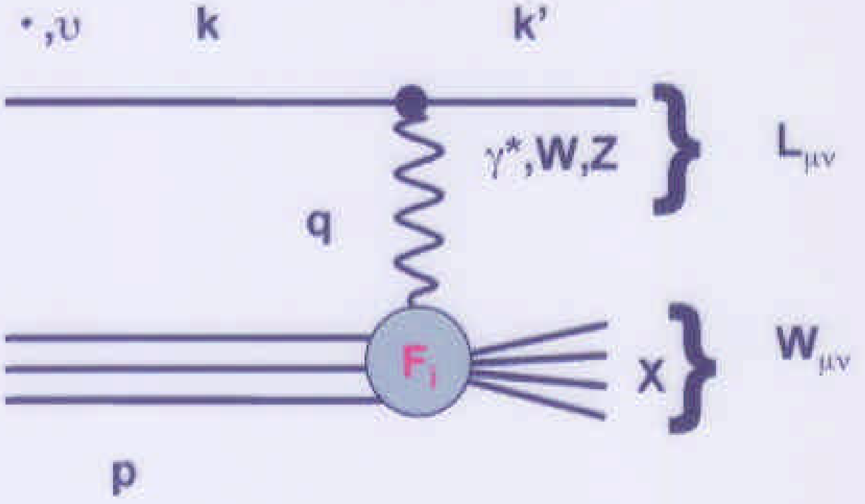
ν-DIS



Calculable

Parametrized

F_i - Structure Functions

pdfs!

$$Q^2 = -q^2 = -(k-k')^2; \quad W^2 = (q+p)^2 = Q^2 \frac{1-x}{x}$$

$$x = \frac{Q^2}{2\,p\cdot q} \quad ; \quad y = \frac{p\cdot q}{p\cdot k}$$

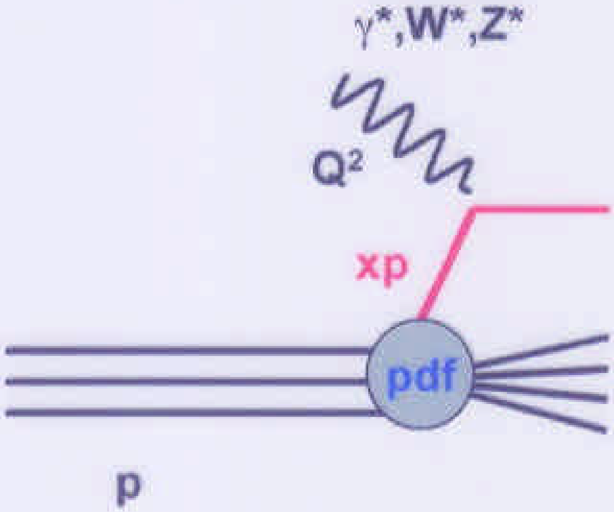
$$\frac{\partial^2\sigma^{\nu N}}{\partial x \partial y} = xy^2 F_1^{\nu}(x,Q^2) + (1-y) F_2^{\nu}(x,Q^2) - xy(1-\tfrac{1}{2}y) F_3^{\nu}(x,Q^2)$$

$$\frac{\partial^2\sigma^{\bar\nu N}}{\partial x \partial y} = xy^2 F_1^{\bar\nu}(x,Q^2) + (1-y) F_2^{\bar\nu}(x,Q^2) + xy(1-\tfrac{1}{2}y) F_3^{\bar\nu}(x,Q^2)$$

$$\frac{\partial^2\sigma^{eN}}{\partial x \partial y} = xy^2 F_1(x,Q^2) + (1-y) F_2(x,Q^2)$$

8 structure functions for each target

Parton Distribution Functions



$$F_1^{ep} = \tfrac{4}{9}(u + \bar{u}) + \tfrac{1}{9}(d + \bar{d}) + \tfrac{1}{9}(s + \bar{s}) + \tfrac{4}{9}(c + \bar{c})$$

$$F_1^{\nu p} = \bar{u} + d + s + \bar{c}$$

$$F_2 = 2xF_1$$ Callan-Gross

$$F_3^{\nu p} = [illegible] - \bar{u} + d + s - \bar{c}$$

$\nu \Leftrightarrow \bar{\nu}$; $q \Leftrightarrow \bar{q}$

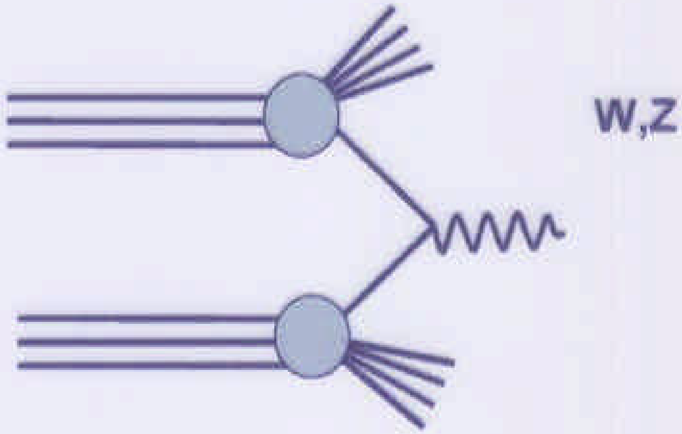
$p \Leftrightarrow n$; $u \Leftrightarrow d$

Determine *in principle* all quark & antiquark pdf's with [e],$\nu,\bar{\nu}$ on p,n targets, *except* c-$\bar{c}$

Polarised DIS - all pdfs except 'intrinsic' charm polarisation

Why?

e.g.



⇒ collider cross-sections (HERA, Tevatron, LHC)

- ~5% uncertainty on W cross-section @ LHC

  needed to predict cross-section for new processes

  ... and to control QCD backgrounds

  HERA high Q^2, CDF high P_T jets

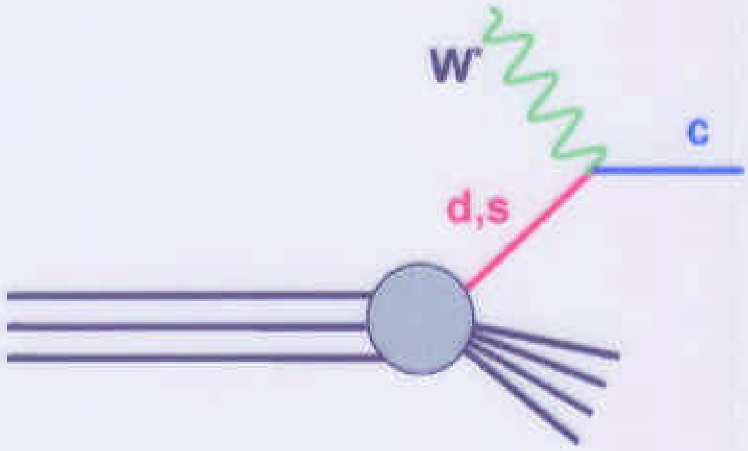
Other Physics (2) - Charm Physics

⇨ CKM matrix elements V_{cd} and V_{cs}

	V_{cd}	V_{cs}
Now errors	17%	20%
After unitarity constraint	3%	2%
neutrino factory direct	~1%	few %

Needs estimates of d(x), $d(\bar{x})$, s(x), $s(\bar{x})$

Bigi & Gibbons

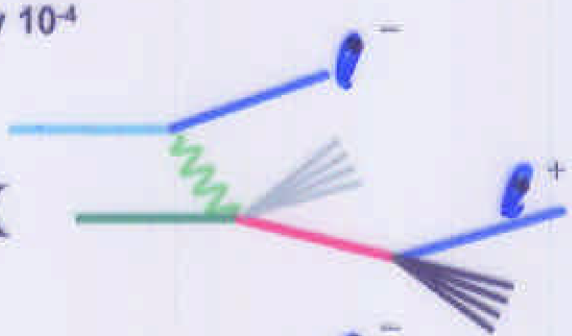


⇨ D_0 mixing

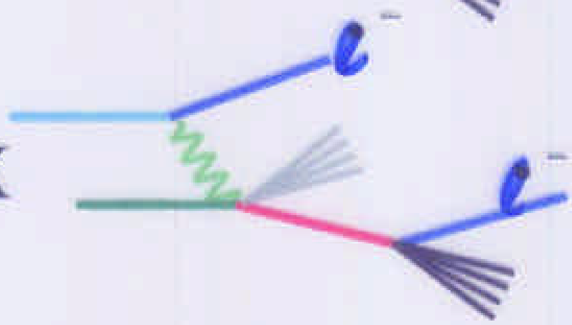
Harris, McFarland & Nelson

- New physics if measured at $>10^{-6}$ level
  - current limits few 10^{-3}
  - B-factories - eventually few 10^{-4}
- Neutrino factory?

$$\nu N \Rightarrow c\ell^- X; \quad c \Rightarrow \ell^+ X$$



$$\nu N \Rightarrow c\ell^- X; \quad \bar{c} \Rightarrow \ell^- X$$



$>10^6$ tagged events/year

Other Physics (3)

Other Physics (3) - $\sin^2\theta_W$

⇨ precision measurements of $\sin^2\theta_W$ possible from ν-e and ν-N scattering

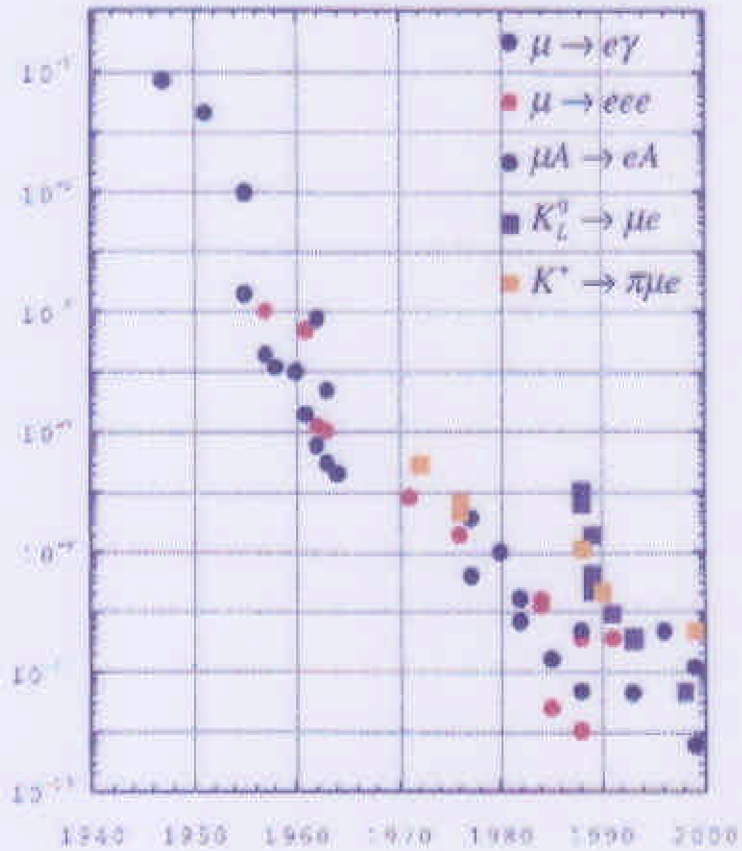
- $\delta(\sin^2\theta_W)$ ~0.0001 feasible

McFarland & Yu

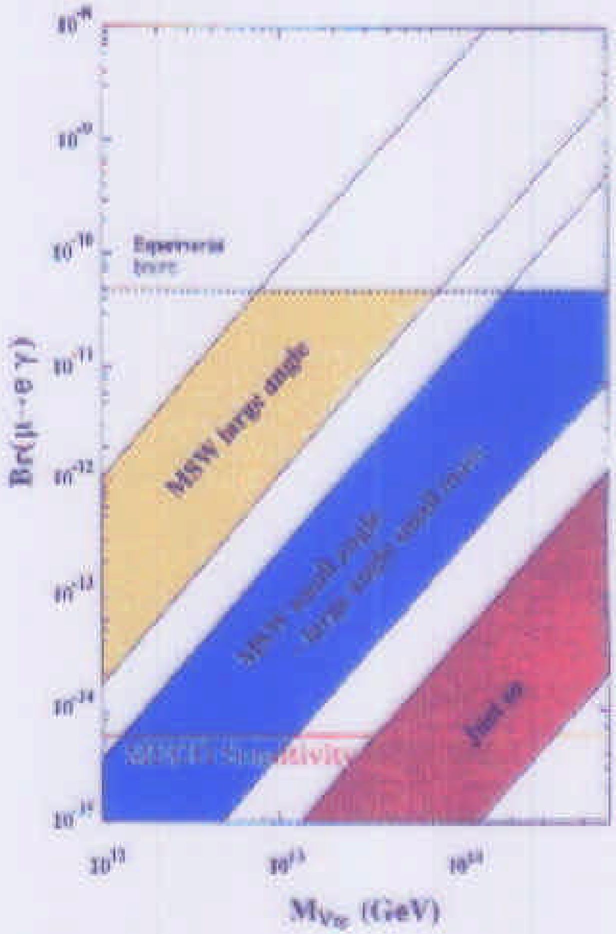
Other Physics (3) - muon physics

⇨ Rare Muon decays

- LFV in SUSY GUTS



Courtesy Y. Kuno



After Molzen

Summary & Conclusions

⇨ Growing interest in the physics potential of a neutrino factory

- Driven by neutrino oscillation physics
- Potential for CP or T Violation in the neutrino sector
  - unique for the neutrino factory
- Electron neutrino studies
  - unique for $E_{\nu_e} > m_\mu, m_\tau$
- Other physics interests
  - ν-DIS & pdf's
  - Charm physics
  - electro-weak physics
  - muon physics

⇨ ... but ...

- Significant challenges
  - proton driver
  - target, pion & muon collection
  - muon cooling & acceleration

⇨ Needs the results from the current neutrino programme before parameters can be fixed