Physics with an Intense Proton Source

Proton Driver Workshop

FNAL

John Ellis, Oct. 7th 2004

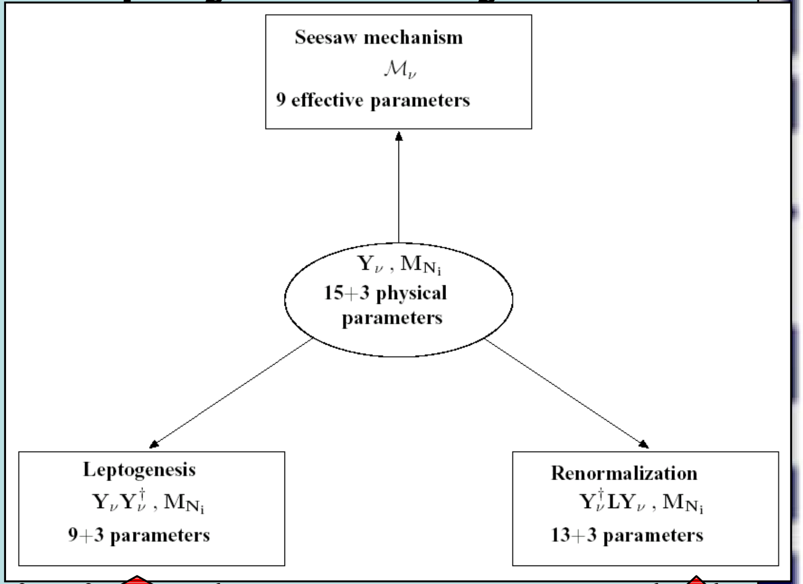
… a manifesto

The High-Intensity Frontier

- Exploration and understanding
  - Novel phenomena
  - Rare processes
  - High statistics
- Active option in front-line physics: factories for
  - Z, B, τ/Charm, K, antiproton, anti-Hydrogen
- Proton driver → new opportunities for
  - ν, muon, kaon, nuclear physics

Neutrino Physics

- ν oscillations first evidence for physics beyond the Standard Model
- Still unknown parameters:
  - mixing angle Θ_{13}
  - CP-violating phase δ
  - Sign of Δm^2



- Many other parameters in minimal seesaw model
  - Total of 18: responsible for leptogenesis?
- Some accessible in rare muon processes

Ideas about ν masses and mixing

Higher-order Higgs effect: $\frac{(H.L)(H.L)}{M} \rightarrow m_\nu \sim \frac{<0|H|0>^2}{M}$

Underlying Lagrangian with $\nu_R \equiv N$: $\mathcal{L} = N_i^c (M_{\nu_D})_{ij} L_j + \frac{1}{2} N^c{}_i (M_{\nu_R})_{ij} N_j^c + h.c.$

Seesaw mass matrix: $\mathcal{M} = \begin{pmatrix} 0 & M_{\nu_D} \\ M_{\nu_D}^T & M_{\nu_R} \end{pmatrix}$

18 parameters

ν mixing matrix:

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{13}s_{23}e^{i\delta} & c_{12}c_{23} - s_{12}s_{13}s_{23}e^{i\delta} & c_{13}s_{23} \\ s_{12}s_{23} - c_{12}s_{13}c_{23}e^{i\delta} & -c_{12}s_{23} - s_{12}s_{13}c_{23}e^{i\delta} & c_{13}c_{23} \end{pmatrix}$$

Fluxes from Different ν Facilities

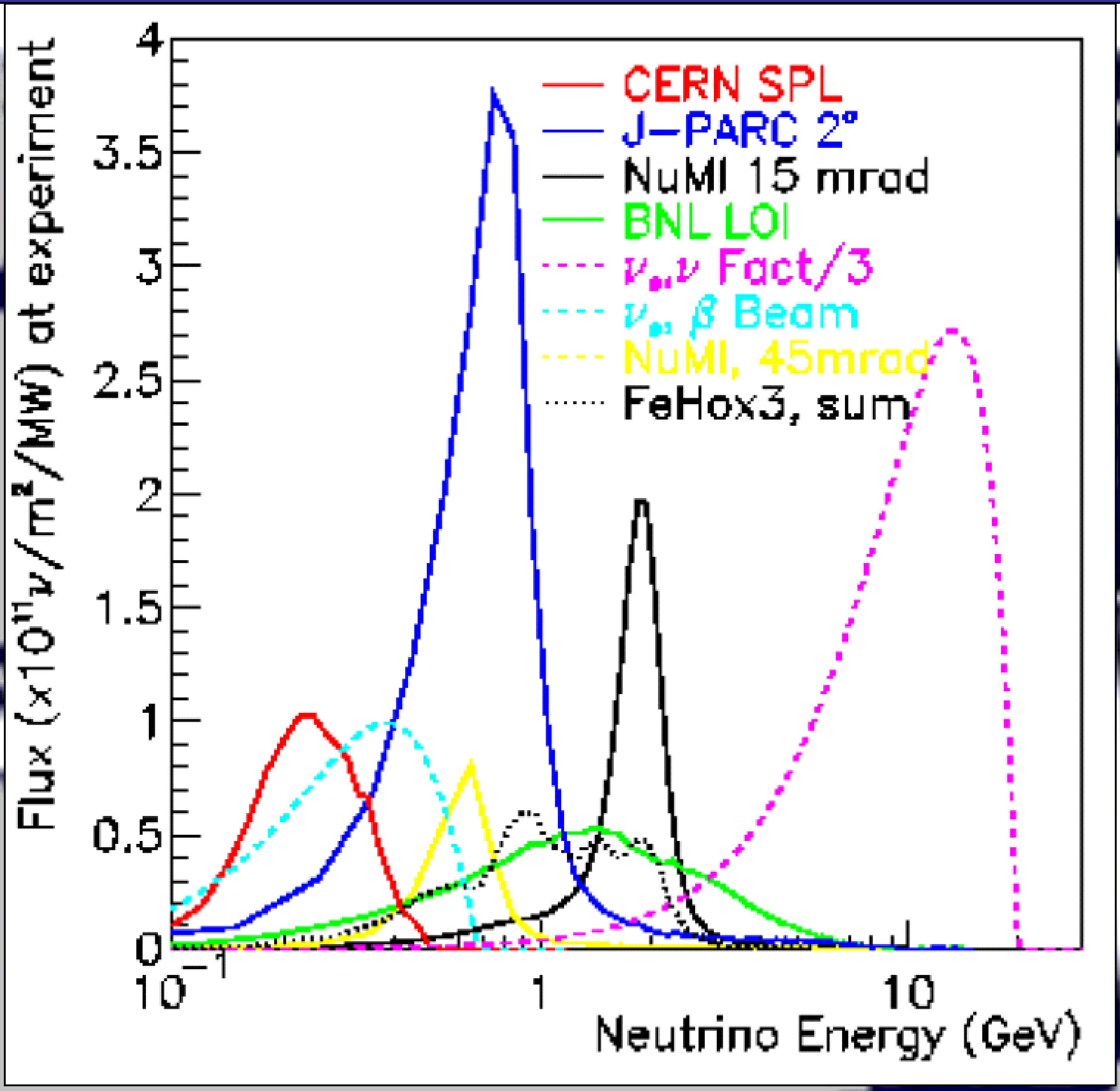
NuMI

J-PARC

Superbeam

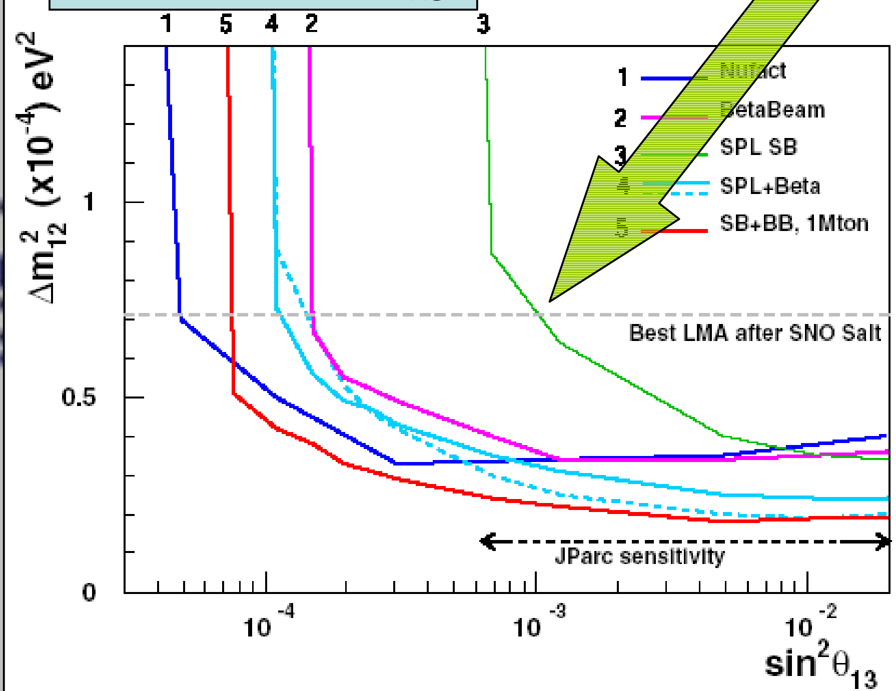
β beam

ν factory

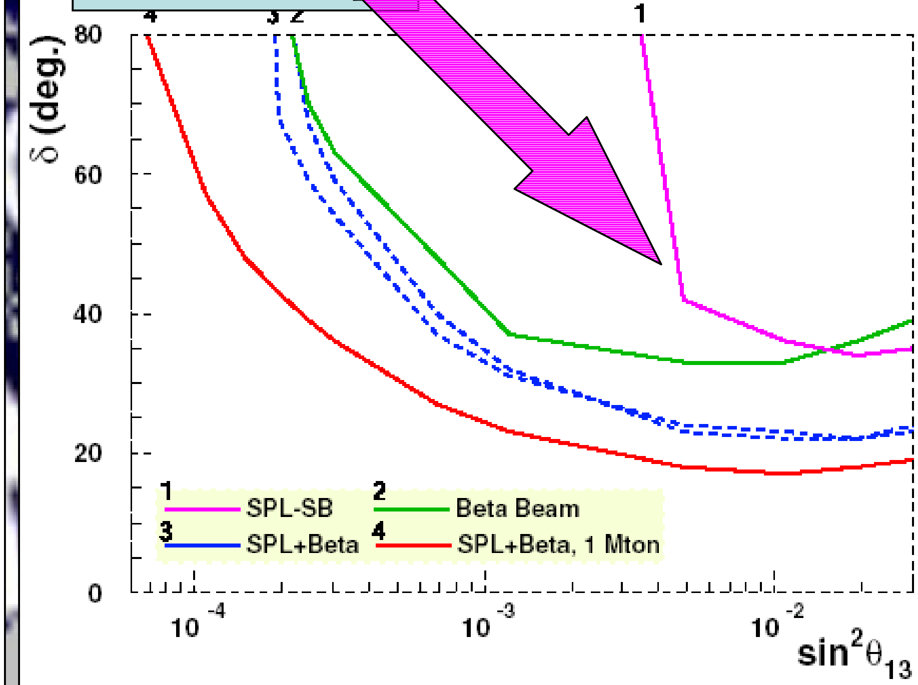


Sensitivities of Super & β Beams

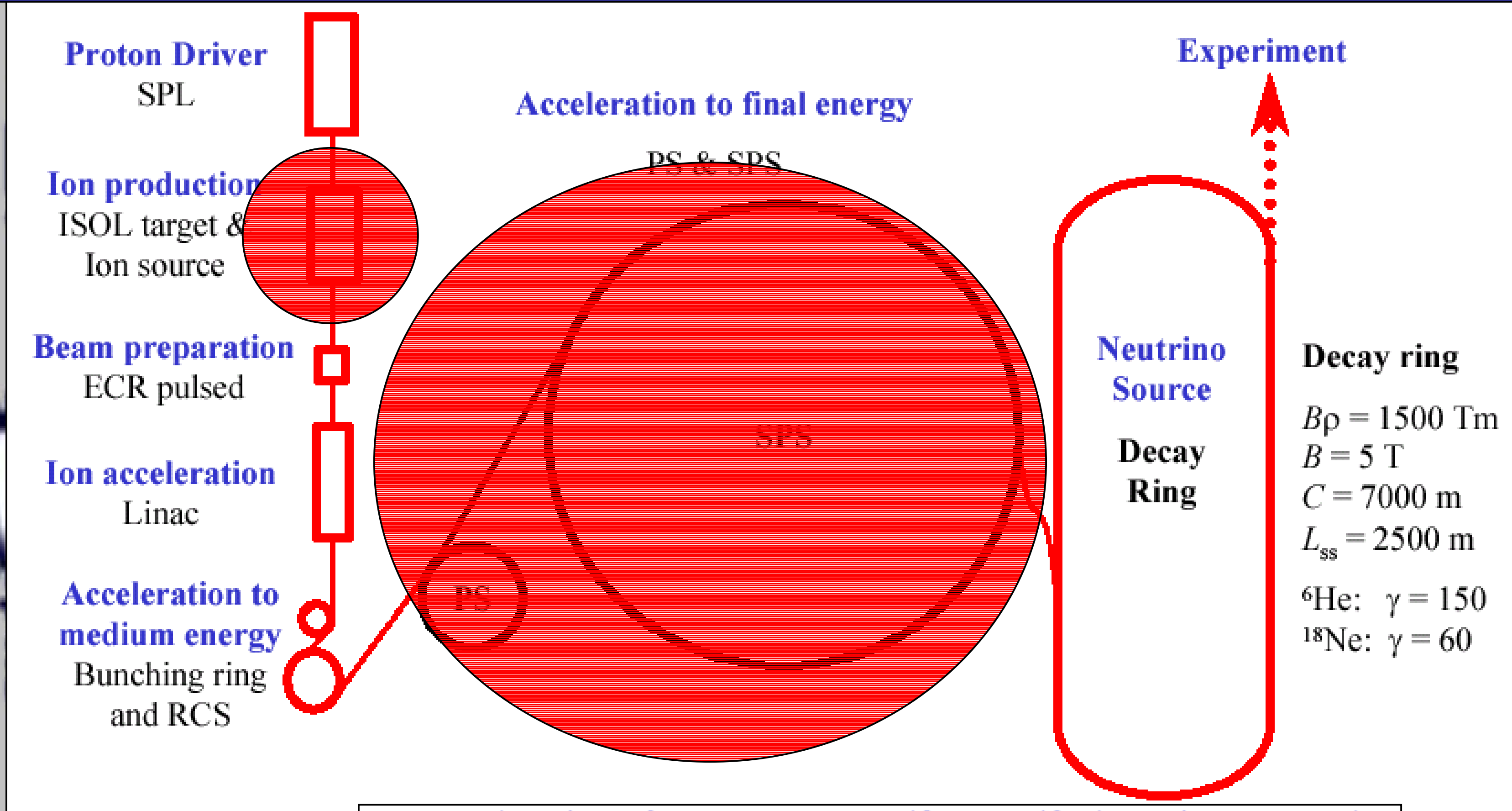
To Δm^2 vs □$_{13}$



To δ vs □$_{13}$



Schematic Layout of β Beam @ CERN



Intensity objectives

^{6}Helium^{2+}

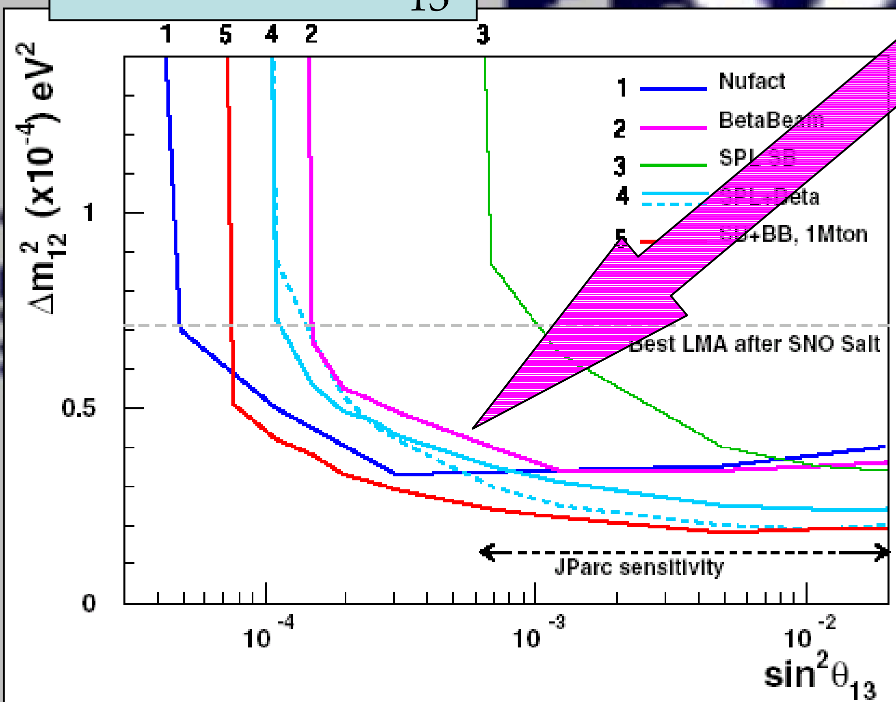
- In Decay ring: 1.0×10^{14} ions
- Energy: 139 GeV/u
- Rel. gamma: 150
- Rigidity: 1500 Tm

^{18}Neon^{10+} (single target)

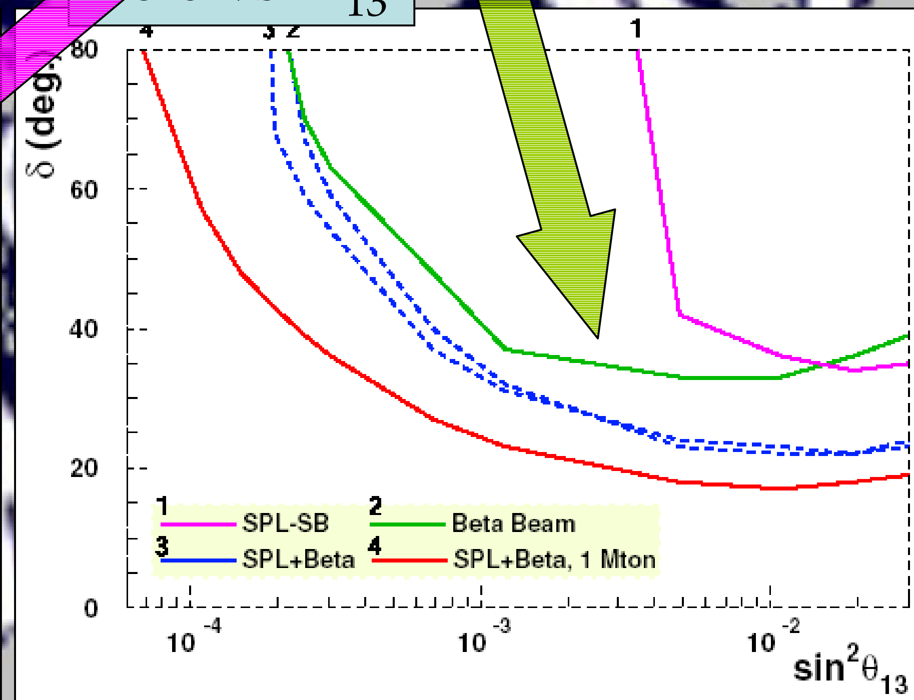
- In decay ring: 4.5×10^{12} ions
- Energy: 55 GeV/u
- Rel. gamma: 60
- Rigidity: 335 Tm

Sensitivities of Super & β Beams

To Δm^2 vs □$_{13}$

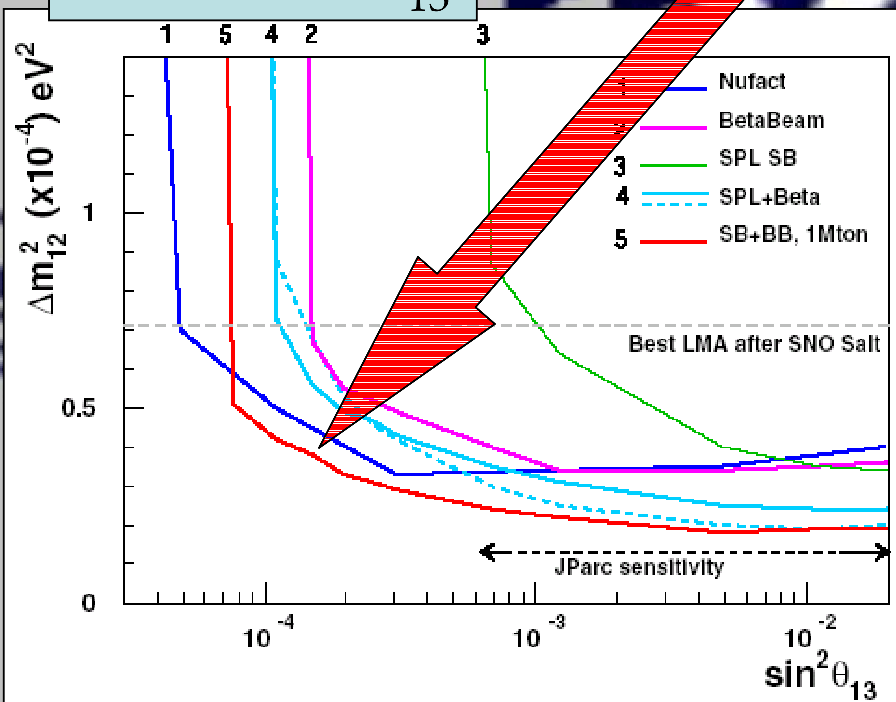


To δ vs □$_{13}$

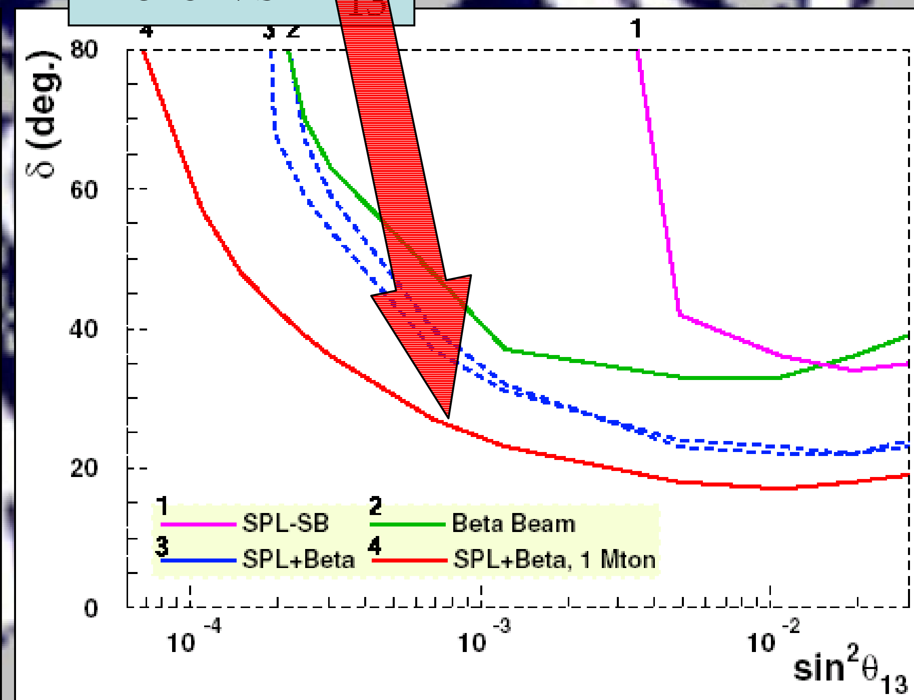


Sensitivities of Super & β Beams

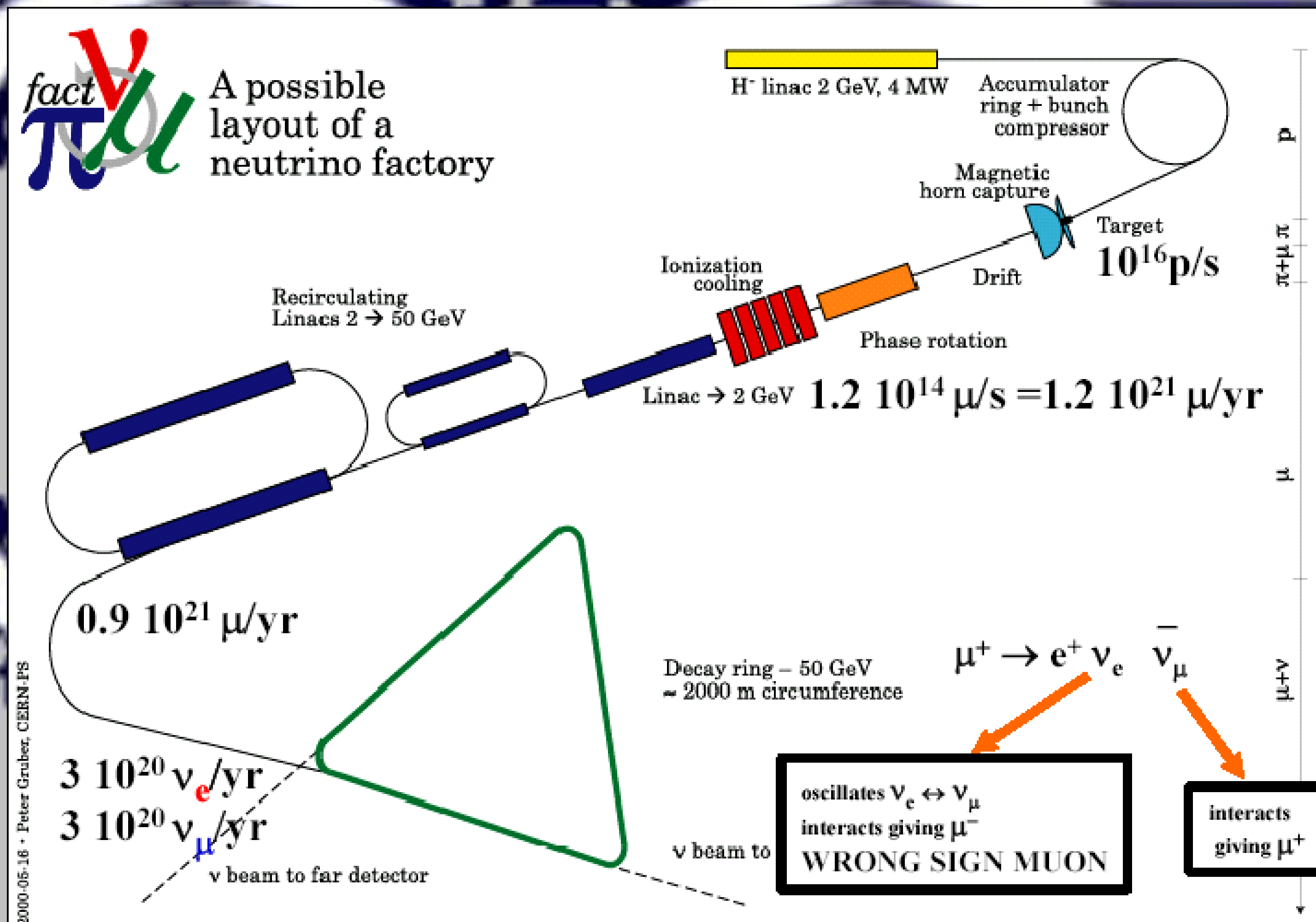
To Δm^2 vs □$_{13}$



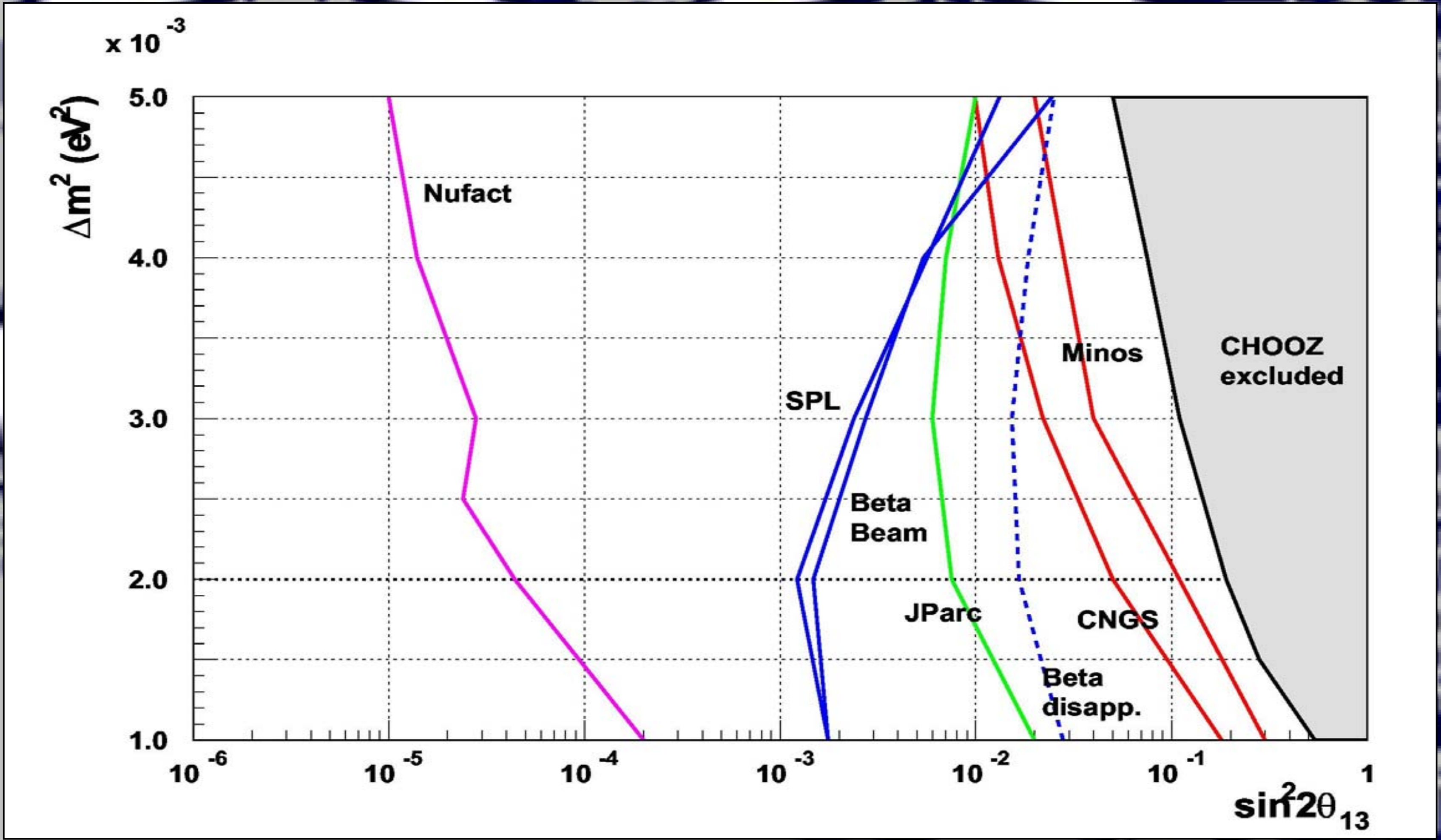
To δ vs □$_{13}$



Schematic Layout of ν Factory

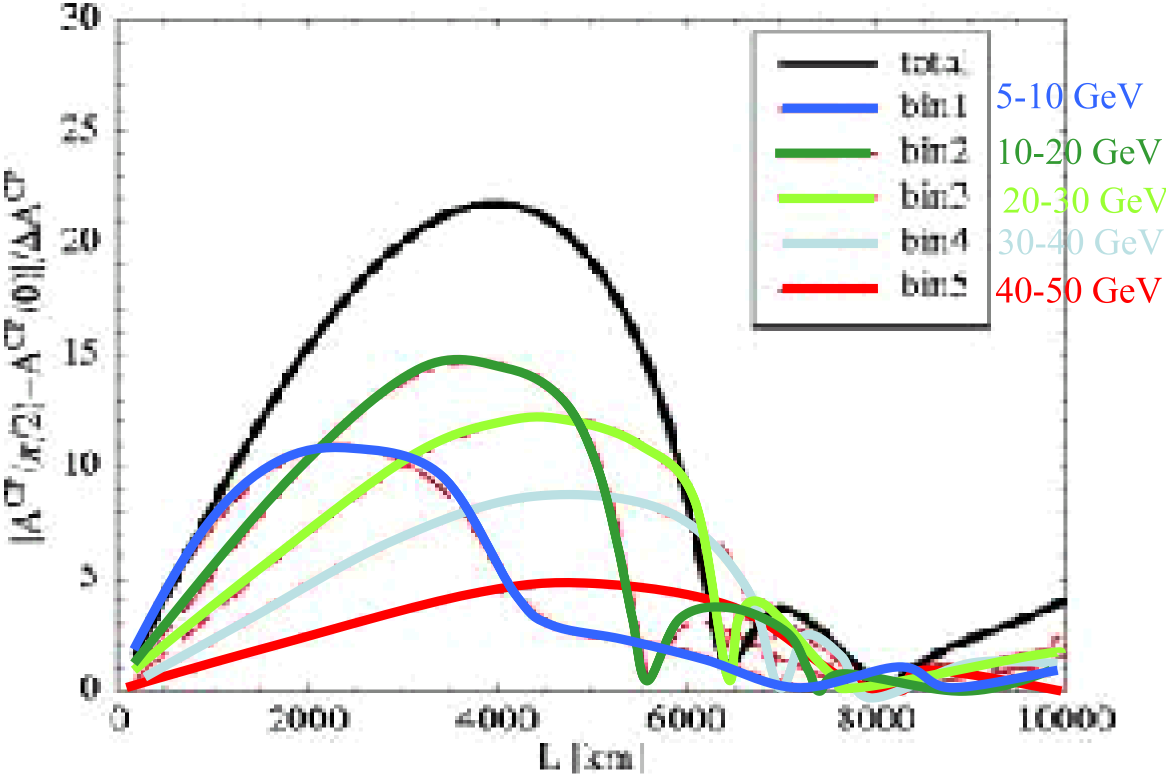


Sensitivities to θ_{13}



Neutrino Factory Sensitivity: CP-Violating Phase δ

Signal vs distance



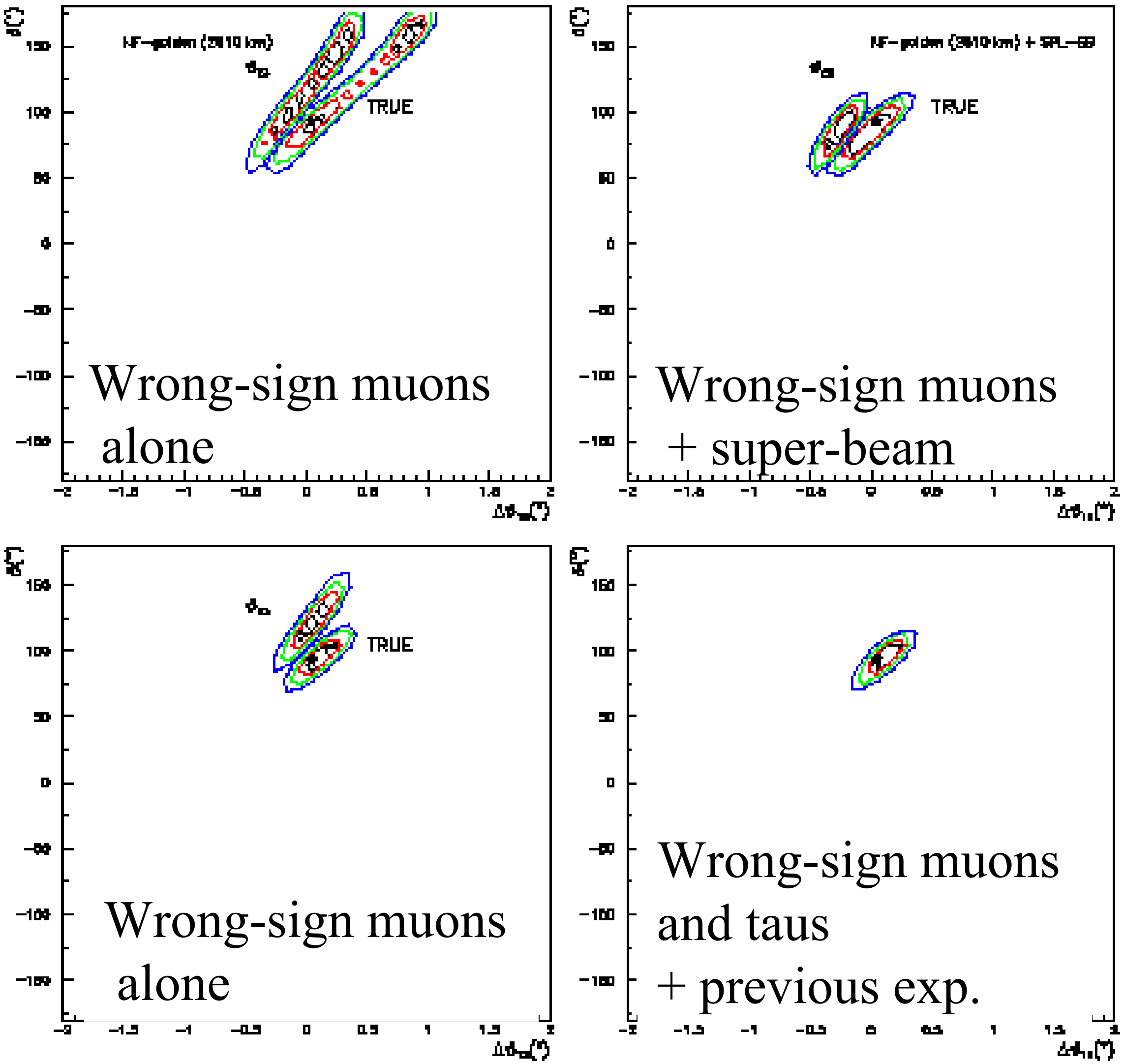
40 kton detector & 50 GeV ν factory: 5 yrs 10^{21}m /yr

In fact, 20-30 GeV is enough!

Best distance is 2500-3500 km

e.g. Fermilab or BNL -> West Coast or …

Resolving Ambiguities with ν Factory

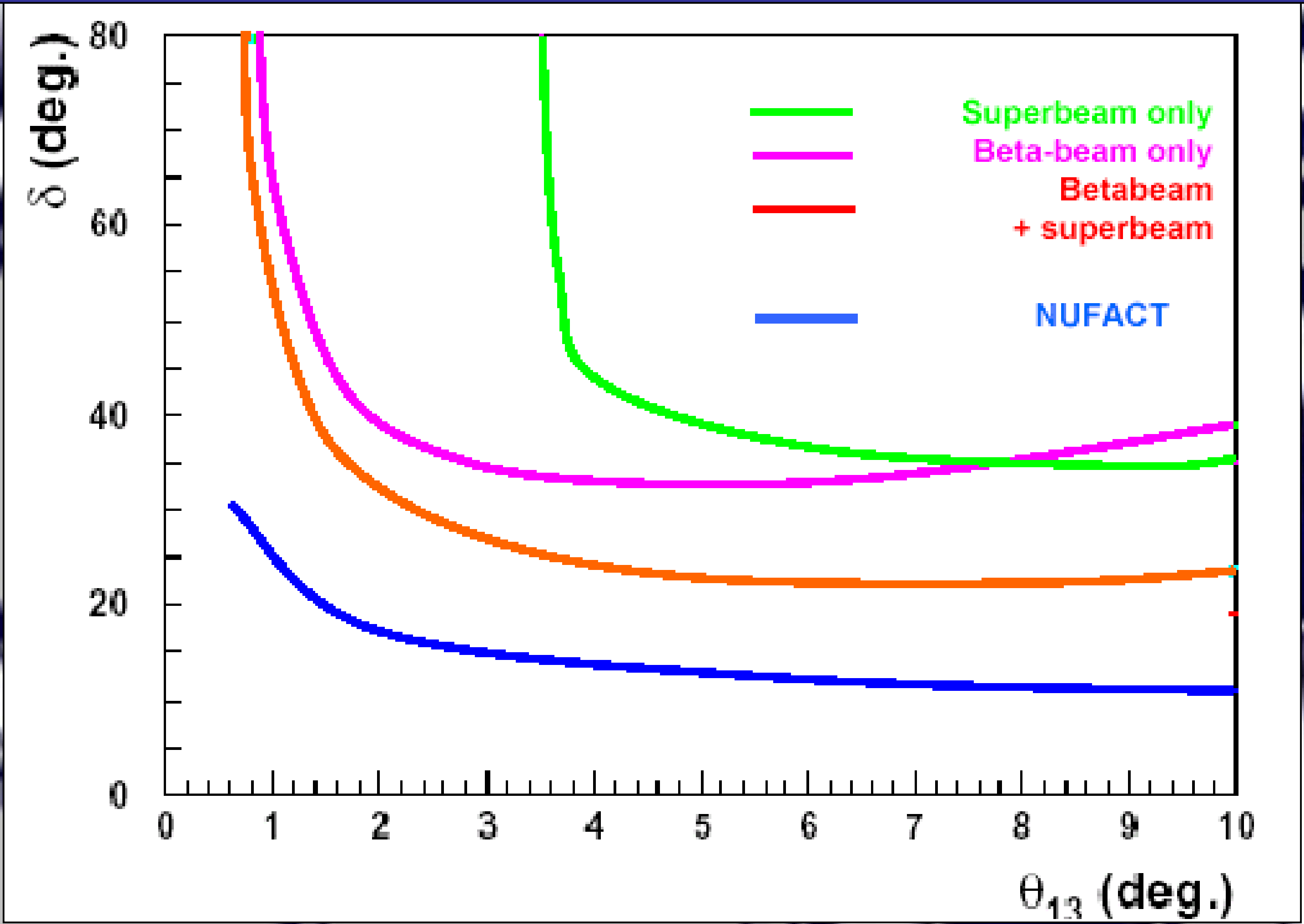


Getting to ultimate precision means combining data from several channels:

- Wrong-sign muons
- $\nu_e \rightarrow \nu_\tau$
- Conventional Beams

hep-ph/0310014

Three-σ Sensitivities of Various Options



Neutrinos as Probes of Standard Model

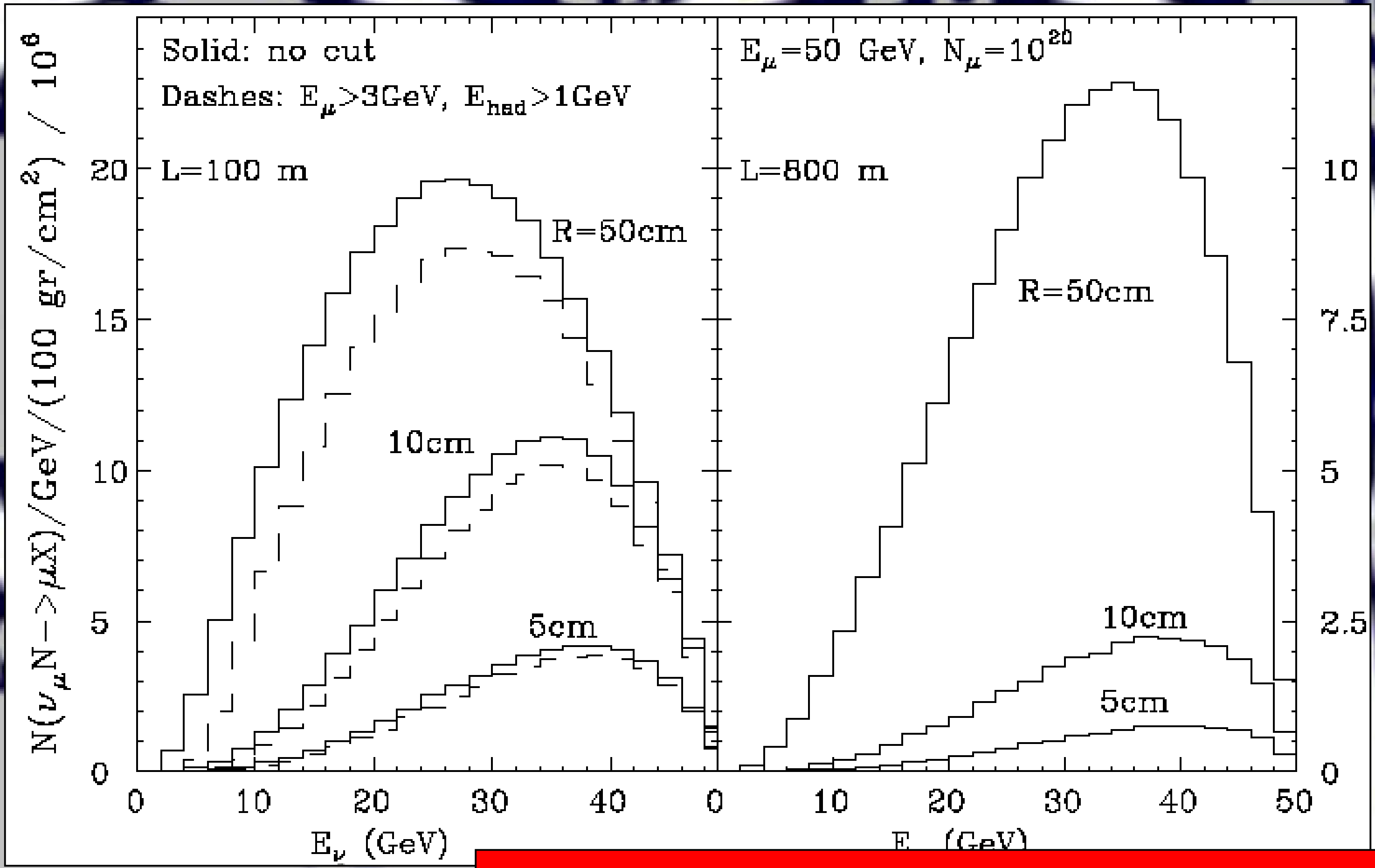
- Enormous interaction rates in nearby detector
- Extraction of α_s, $\sin^2 \theta_W$
- Quark and antiquark densities

  Polarized and unpolarized

  e.g., strange quarks
- Charm production
- Polarization of Λ baryons

  also probe of strange polarization

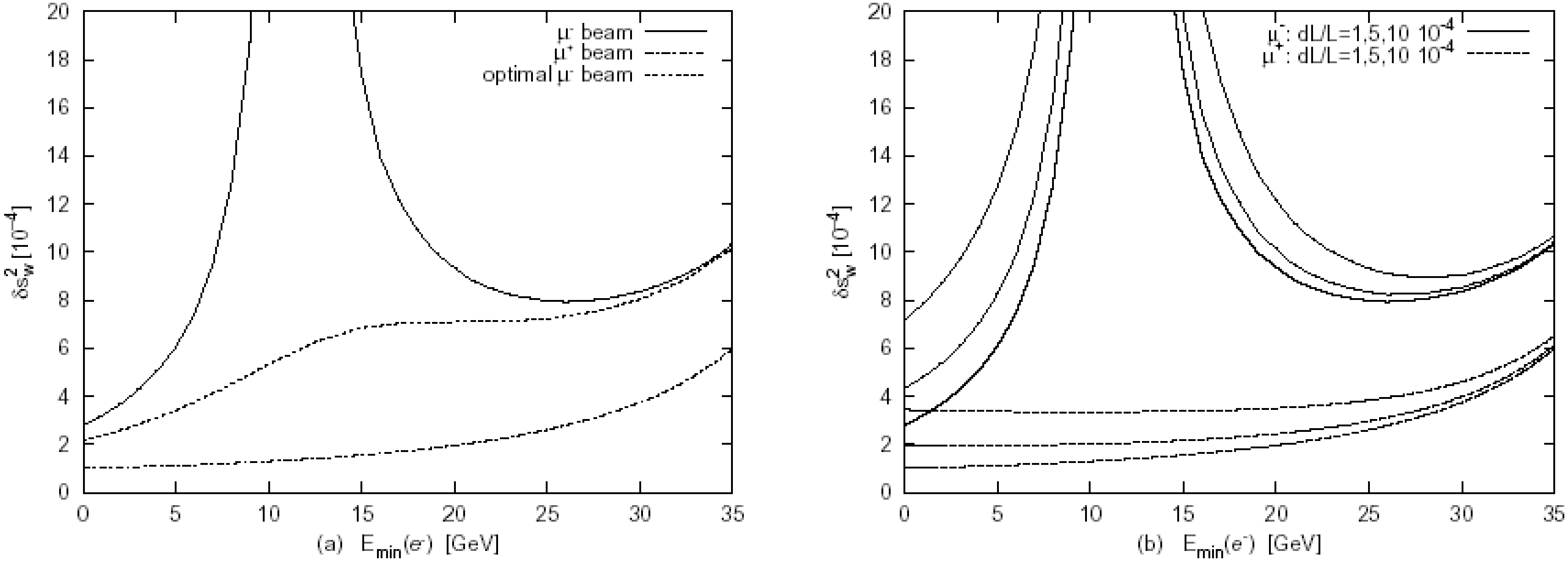
Event Rates in Nearby Detector



Millions of events – even in small detector

Potential Accuracy for $\sin^2\theta_W$

UNCERTAINTIES AT THE ν FACTORY: $(\times 10^{-4})$



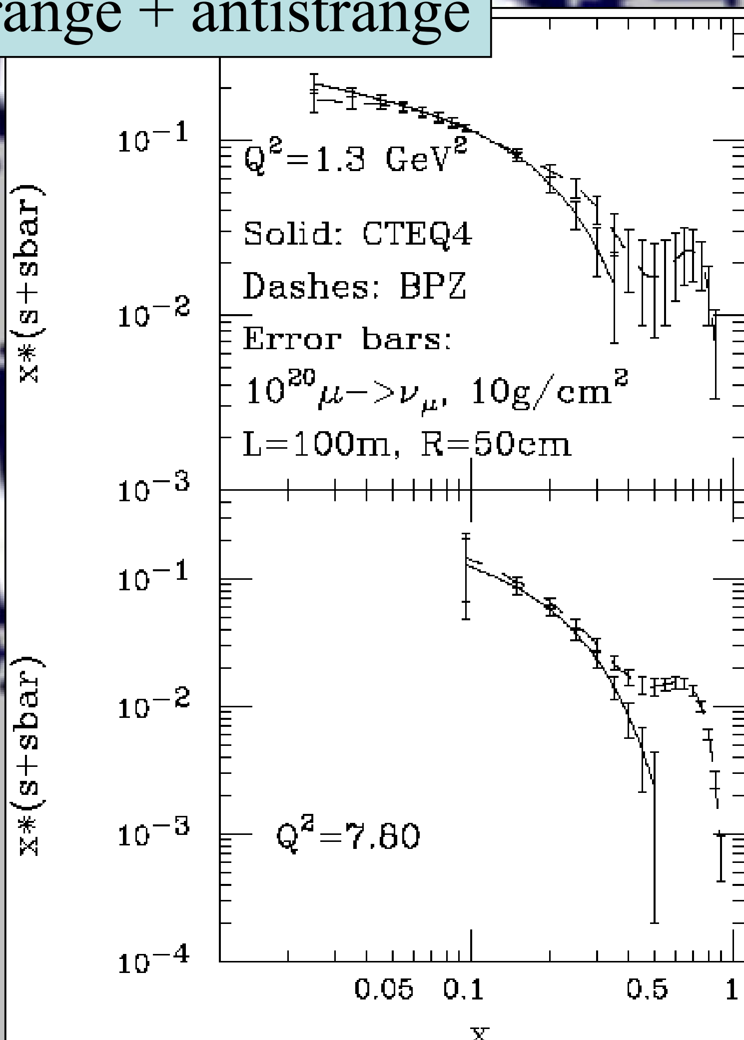
STAT. UNCERTAINTY

SYST. LUMI. UNCERTAINTY

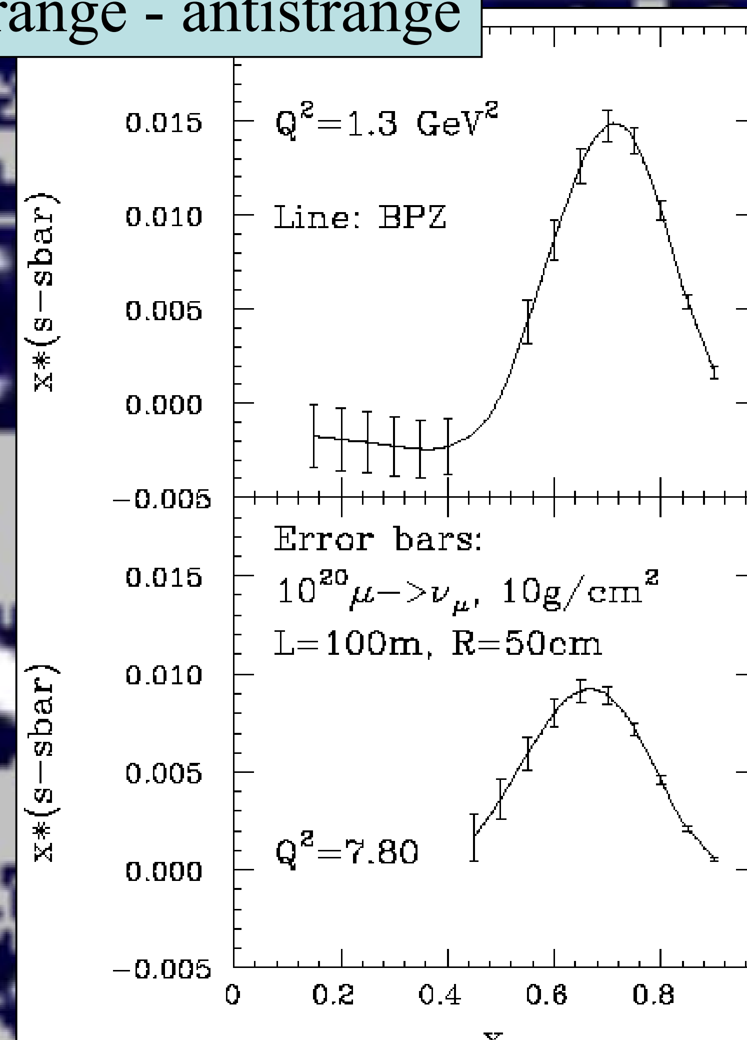
- SIGNAL: FORWARD e TRACK WITH NO HADRONS, $E > E_{min}$
- BACKGROUND: QUASIELASTIC $\nu - p$ SCATTERING, REMOVE WITH p_T CUT

Measuring Strange Partons

Strange + antistrange

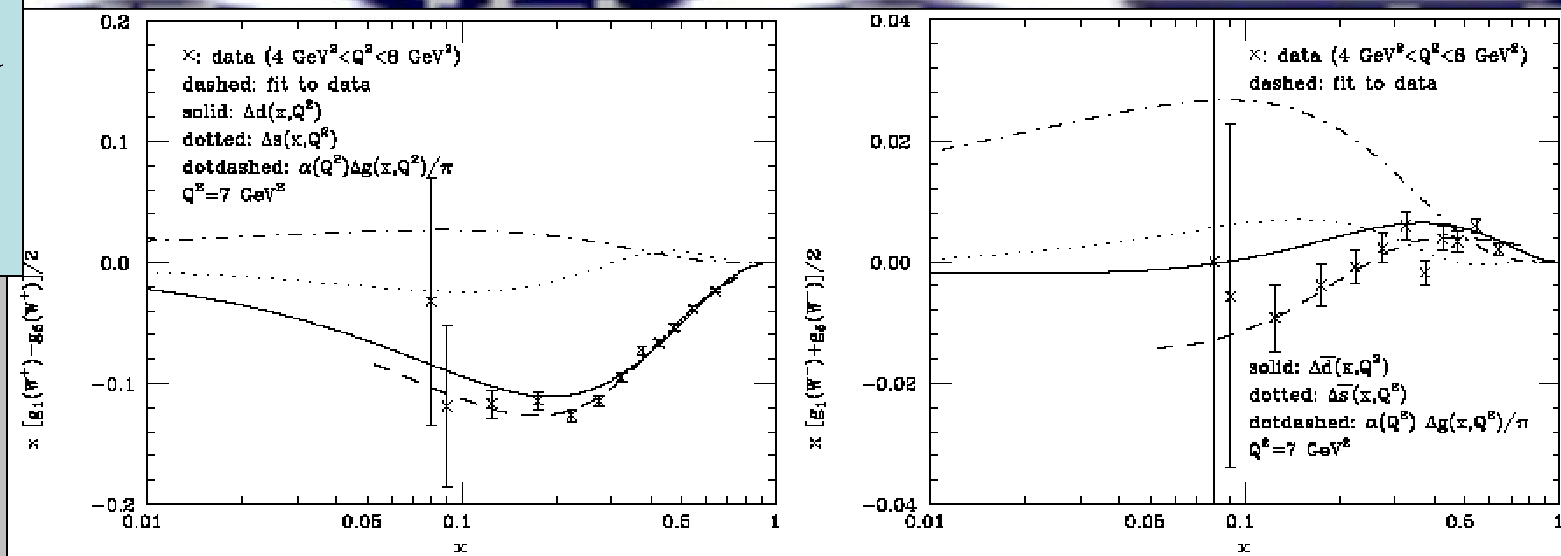


Strange - antistrange

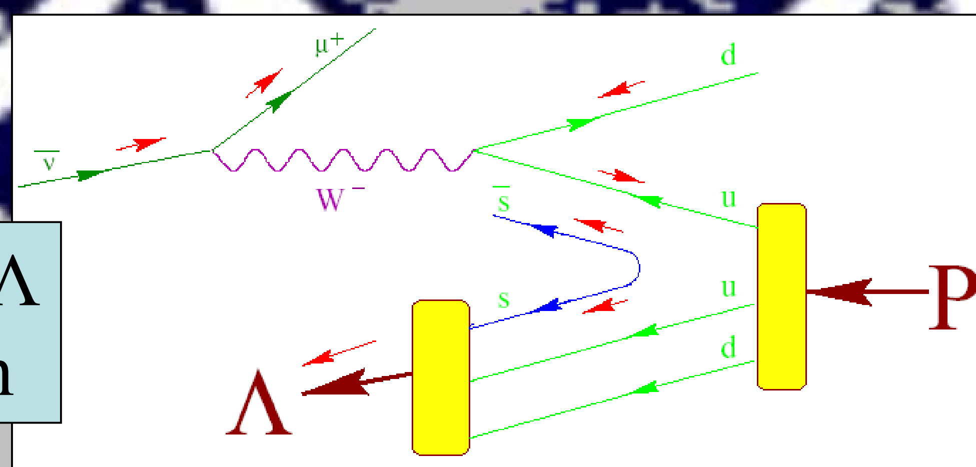


Handles on Strange Polarization

Polarized Structure functions



Final-state Λ Polarization



Muon Physics

- Proton source produces many muons
- Rare μ decays

  μ → e γ, μ → eee,

  μ A → e A

  Expected in susy seesaw model: probe unknown parameters

$$BR(\mu \to e\gamma) < 1.2 \times 10^{-11}$$
$$BR(\mu^+ \to e^+e^+e^-) < 1.0 \times 10^{-12}$$
$$R(\mu^- Ti \to e^- Ti) < 6.1 \times 10^{-13}$$

- Dipole moments:

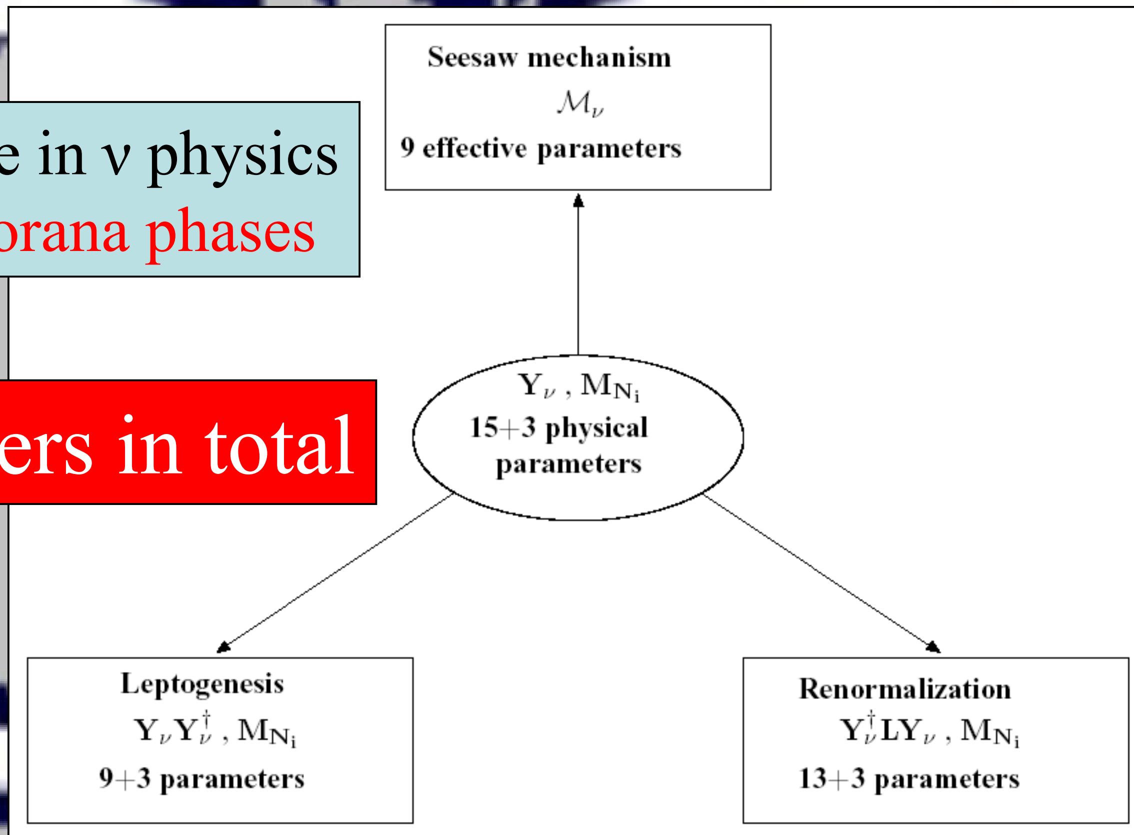
  $g_\mu - 2$, electric dipole moment, CPT tests
- Nuclear, condensed-matter physics:

  (radioactive) μ-ic atoms, muonium, μ-ic Hydrogen

Measuring Seesaw Parameters

9 measurable in ν physics

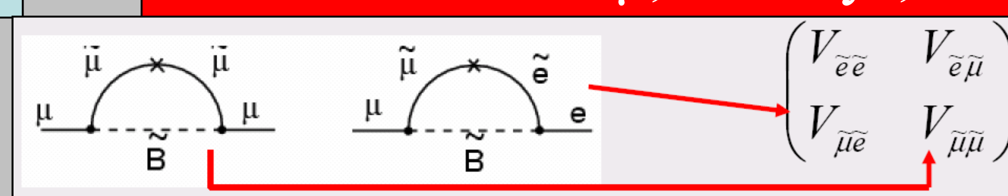
m_i, θ_{ij}, Majorana phases



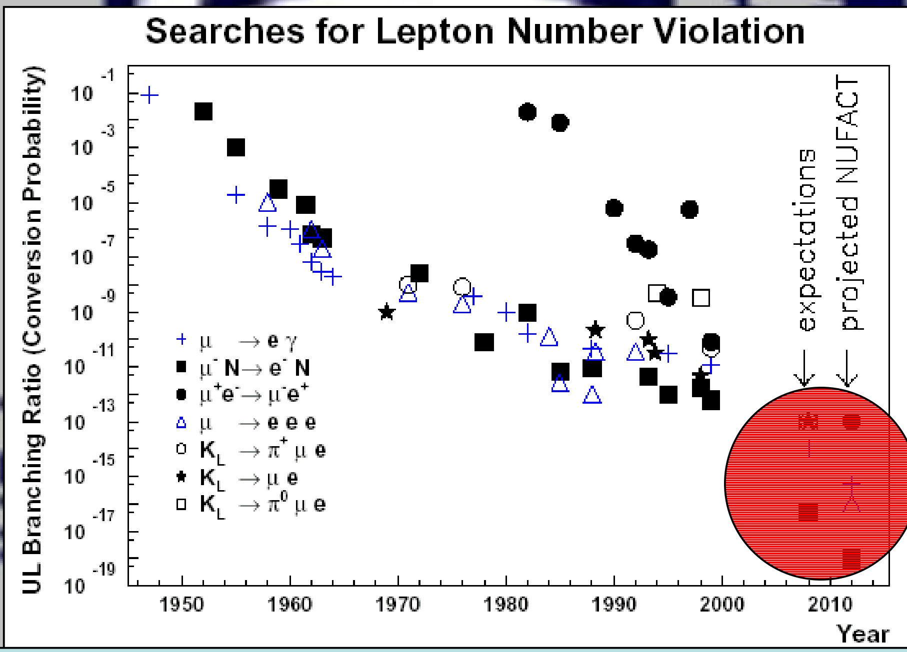
18 parameters in total

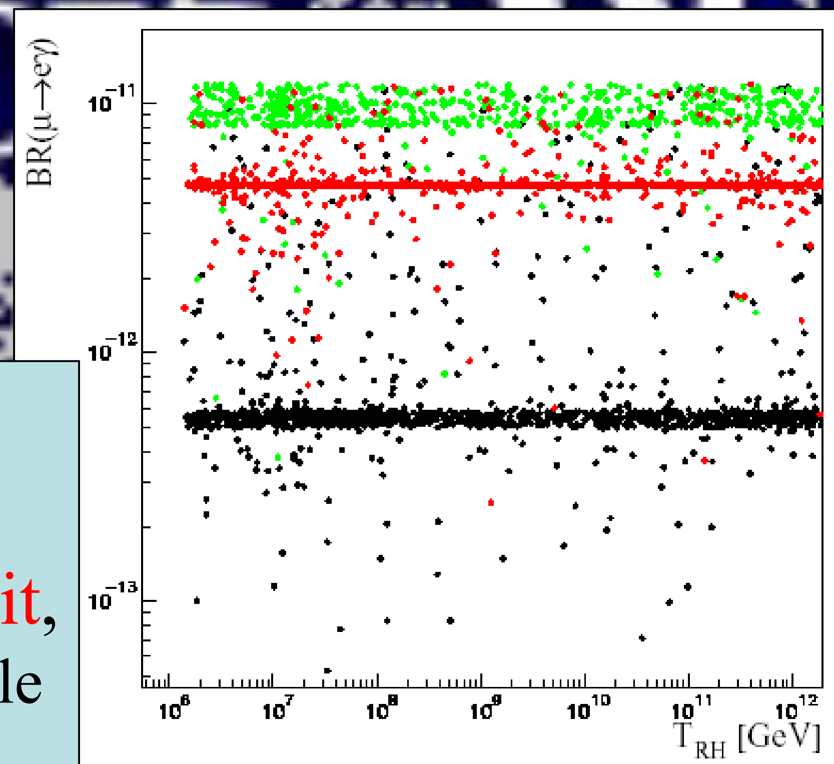
12 Generate baryon asymmetry?

16 measurable in μ, τ decays, …



μ → eγ in Supersymmetric Seesaw

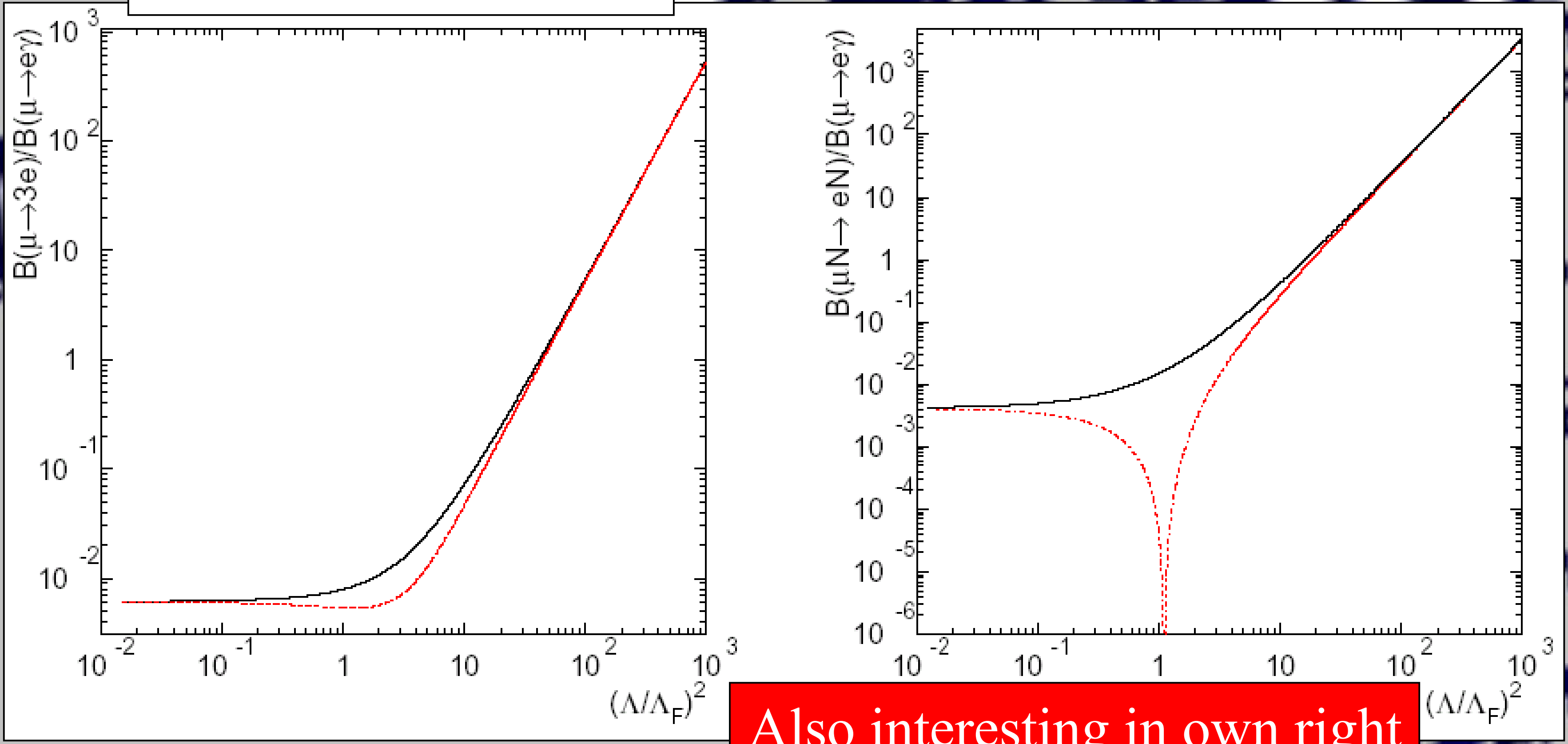




Many models predict
μ → eγ
close to present experimental limit,
e.g., model where sneutrino responsible
for inflation, baryogenesis

New Interactions: $\mu \rightarrow e\gamma$ vs $\mu \rightarrow eee$, $\mu A \rightarrow eA$

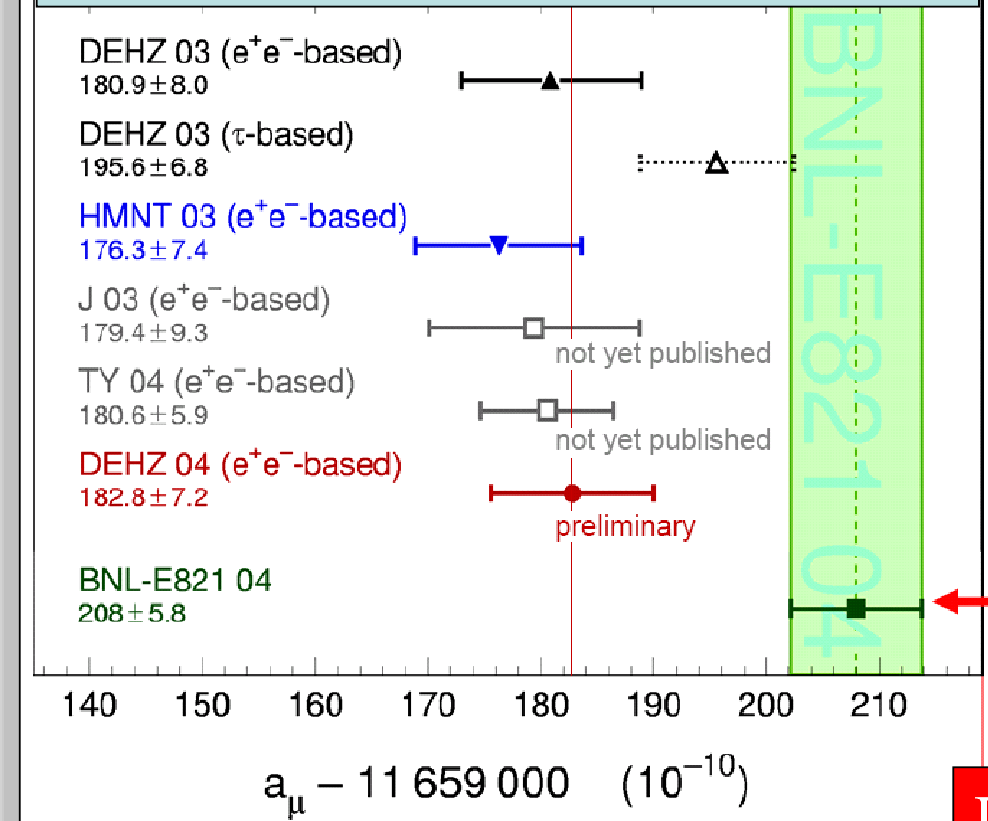
$$\frac{B(\mu \to 3e)}{B(\mu \to e\gamma)} = \frac{1}{12(4\pi)^2}\left(\frac{\Lambda}{\Lambda_F}\right)^4$$



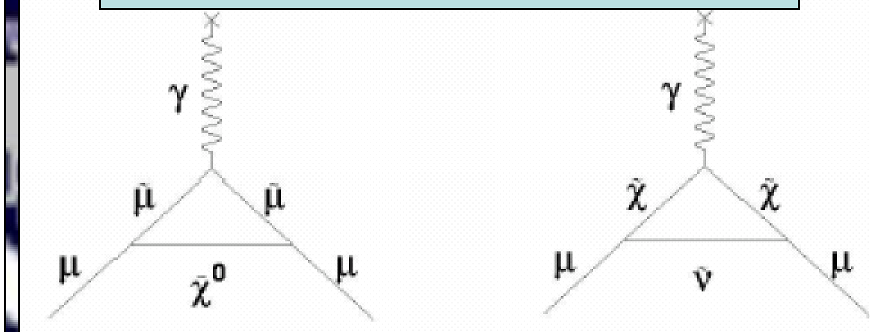
Also interesting in own right

Anomalous Magnetic Moment

'Consensus' on discrepancy with Standard Model, based on e^+e^- data



'Natural' supersymmetric interpretation

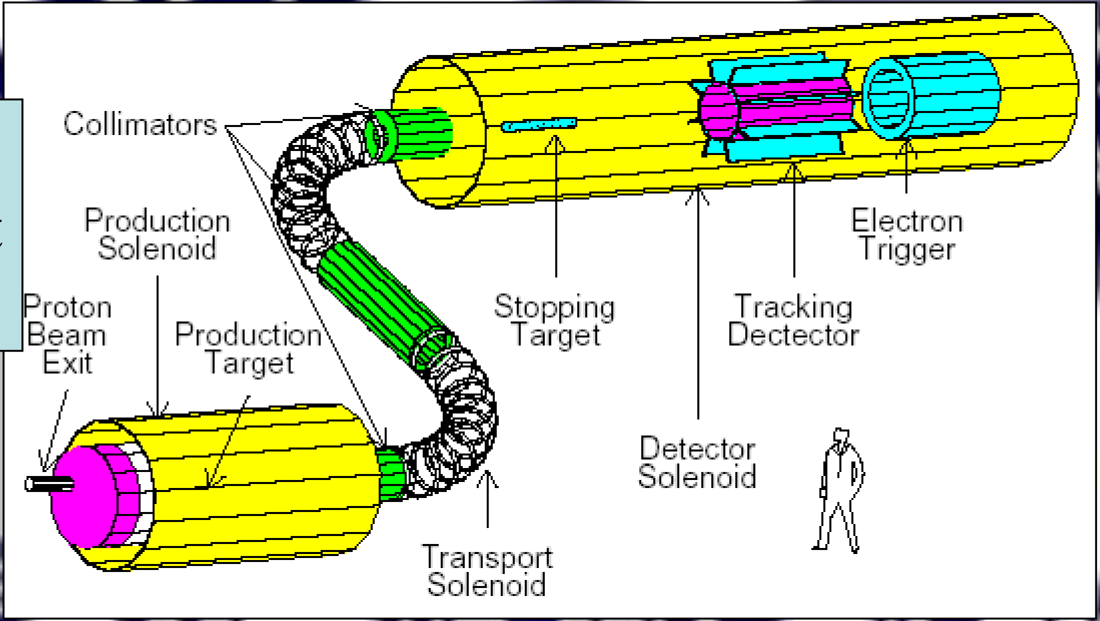


$$\Delta a_{\mu}^{SUSY} \approx 1.1\,\mathrm{ppm} \times \left(\frac{100\ GeV}{\tilde{m}}\right)^2 \tan\beta$$

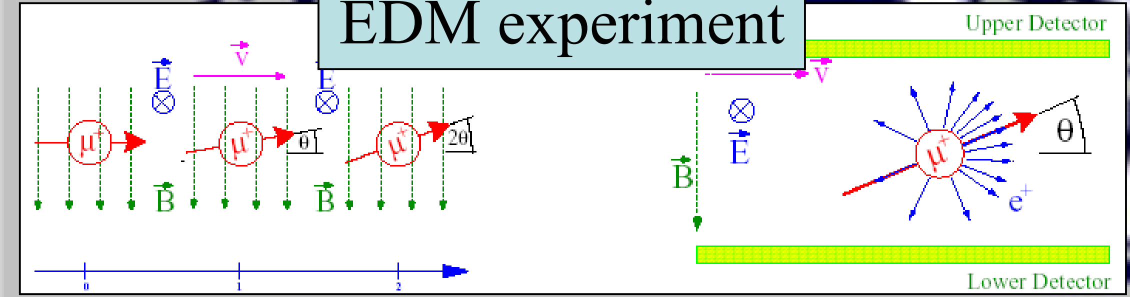
Deserves a follow-up experiment

Other Experiments: μA → eA, EDM

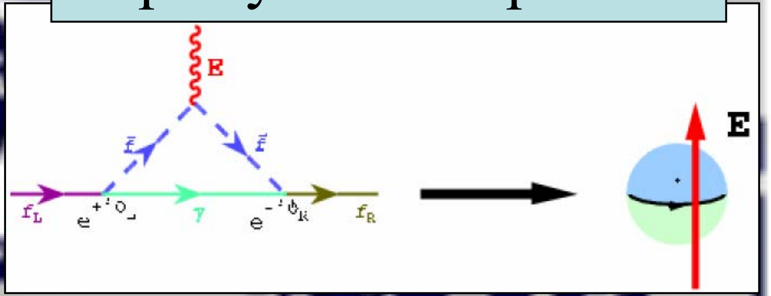
Planned layout of MECO experiment for μA → eA



Principle of EDM experiment



Supersymmetric phases?



Muon Colliders?

- Extrapolate μ cooling technology
- Light Higgs Factory?

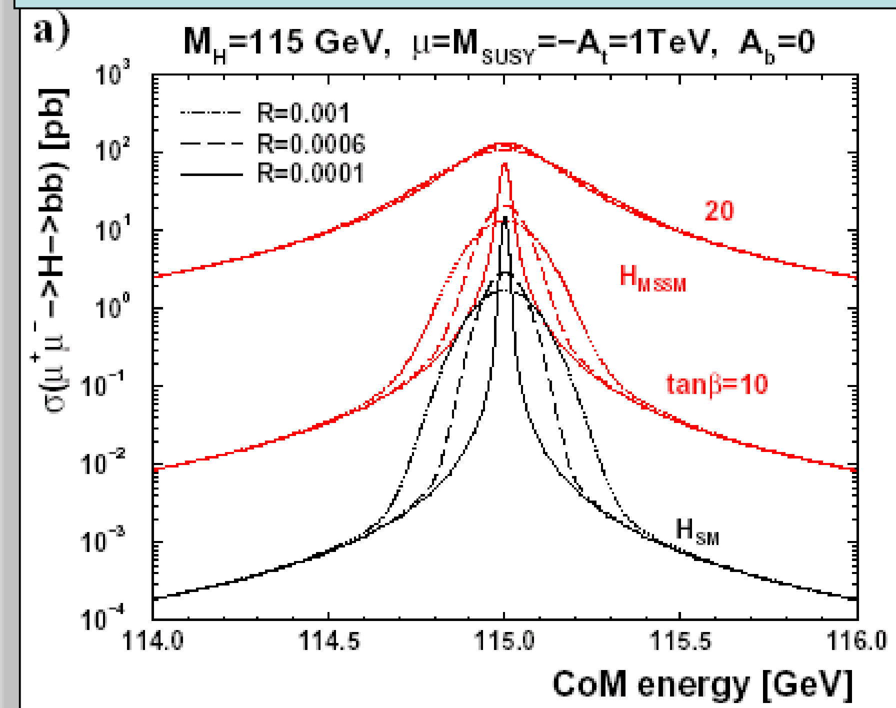
  Standard Model vs supersymmetry?
- Factory for heavier supersymmetric Higgses?

  New probes of CP violation?
- High-energy frontier?

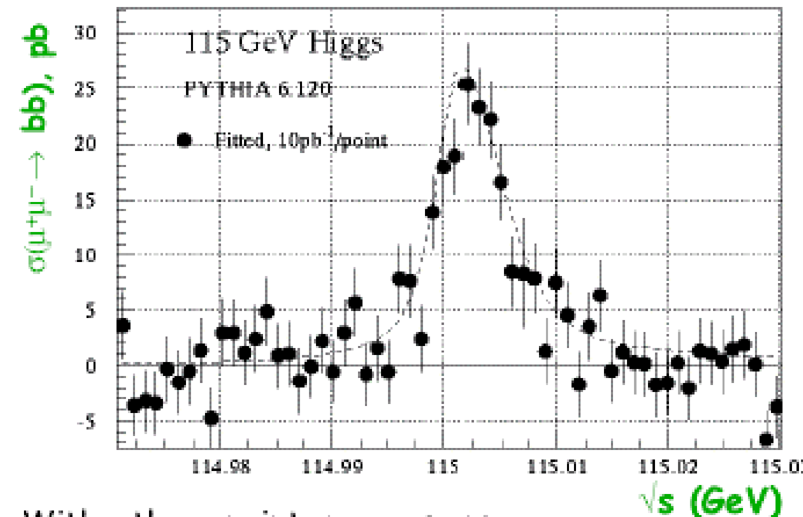
  Alternative to CLIC for multi-TeV lepton collisions?

Higgs Studies @ First Muon Collider

Detailed measurements
of light Higgs boson:
Standard Model vs supersymmetry



With an irrealistic 10 pb^{-1} / MeV scan:



With a three-point energy scan:

Observable	With 100 pb^{-1}	With 2.5 fb^{-1}
Mass	± 0.1 MeV/c^2	± 0.05 MeV/c^2
Width	± 0.5 MeV	± 0.1 MeV
σ_{peak}	± 1 pb	± 0.2 pb

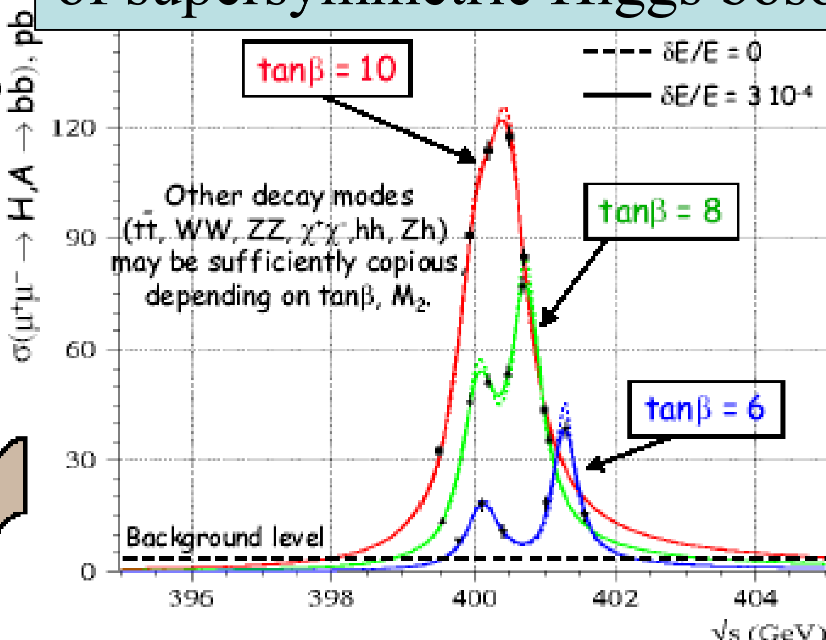
Statistics limited !

Still to be tried:

A scan in $\delta E/E$

Higgs @ Second Muon Collider

Detailed measurements of supersymmetric Higgs bosons

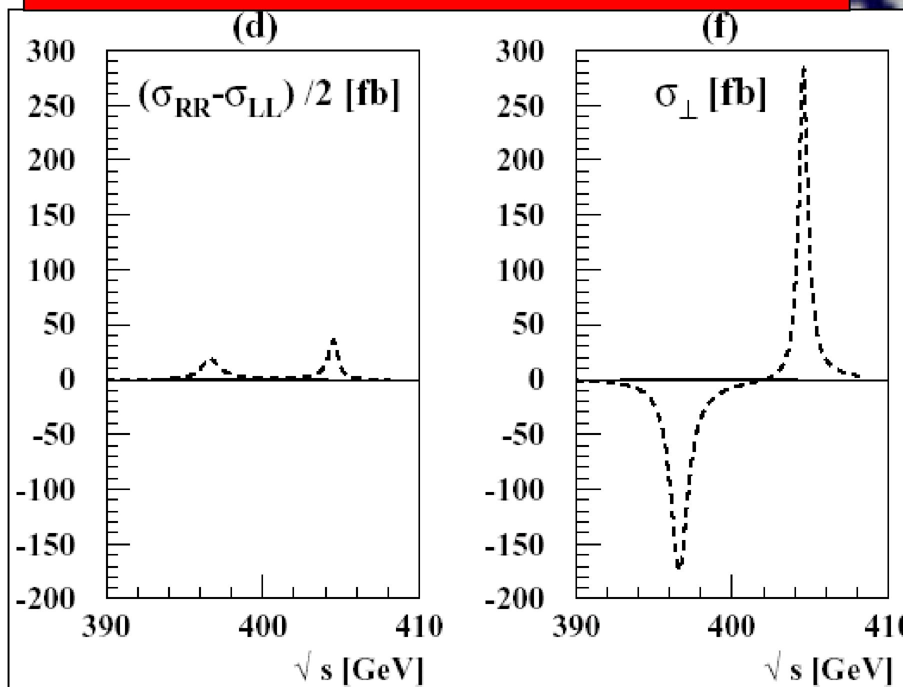


- Determine m_H, m_A, and tanβ to an excellent accuracy;
- Fit for e.g., stop masses (m_{SUSY}) and mixing (A_t, μ).
- Start precision tests of the MSSM and of SUSY breaking through rad. corr. to masses and widths;

(to be done)

(≡ LEP for standard model and EWSB)

Unique probe of CP violation?

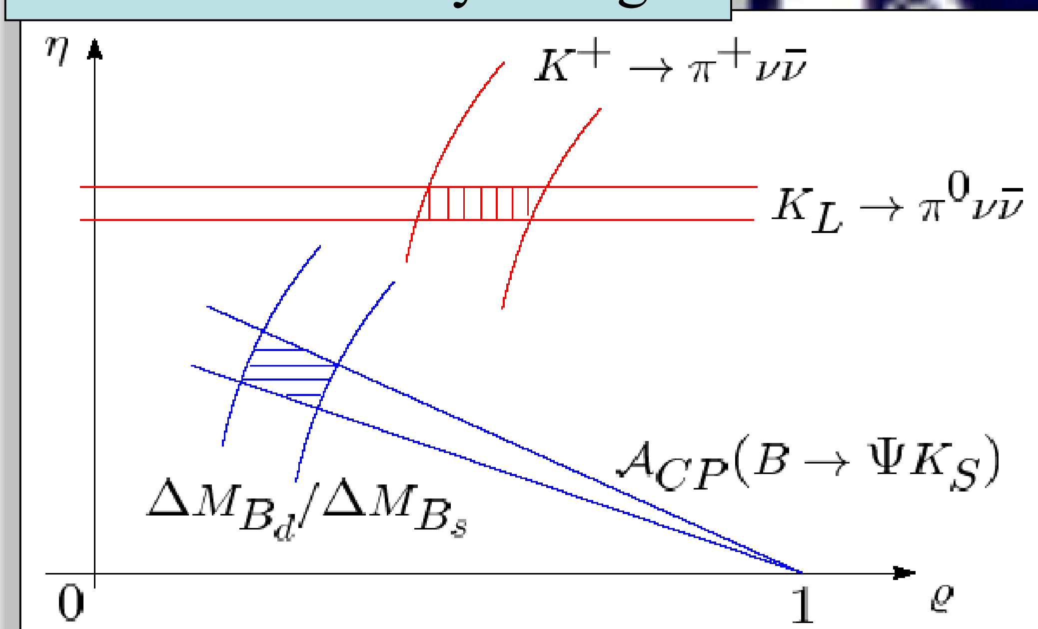


Rare K Decays

Many kaons produced if high-energy source or booster ring

K → πνν:

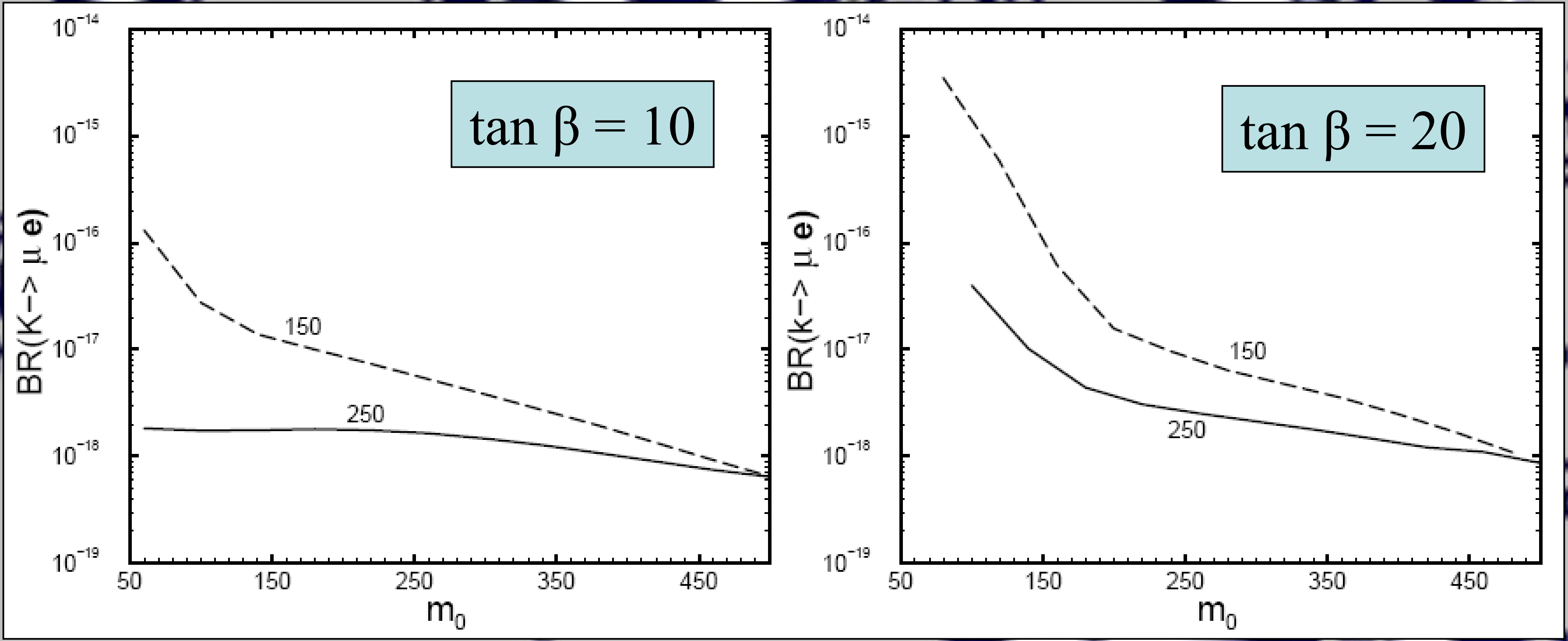
Alternative window on CKM unitarity triangle



Possible window on physics beyond SM

Decay mode	BR limit (90% CL)
$K^+ \to \pi^+\mu^+e^-$	2.8×10^{-11}
$K^+ \to \pi^+\mu^-e^+$	5.2×10^{-10}
$K^+ \to \pi^-e^+e^+$	6.4×10^{-10}
$K^+ \to \pi^-\mu^+\mu^+$	3.0×10^{-9}
$K^+ \to \pi^-\mu^+e^+$	5.0×10^{-10}
$K_L \to \mu e$	4.7×10^{-12}
$K_L \to \mu\mu ee$	4.12×10^{-11}
$K_L \to \pi^0\mu e$	6.2×10^{-9}

Example: K → μe in Minimal Supersymmetric Seesaw Model

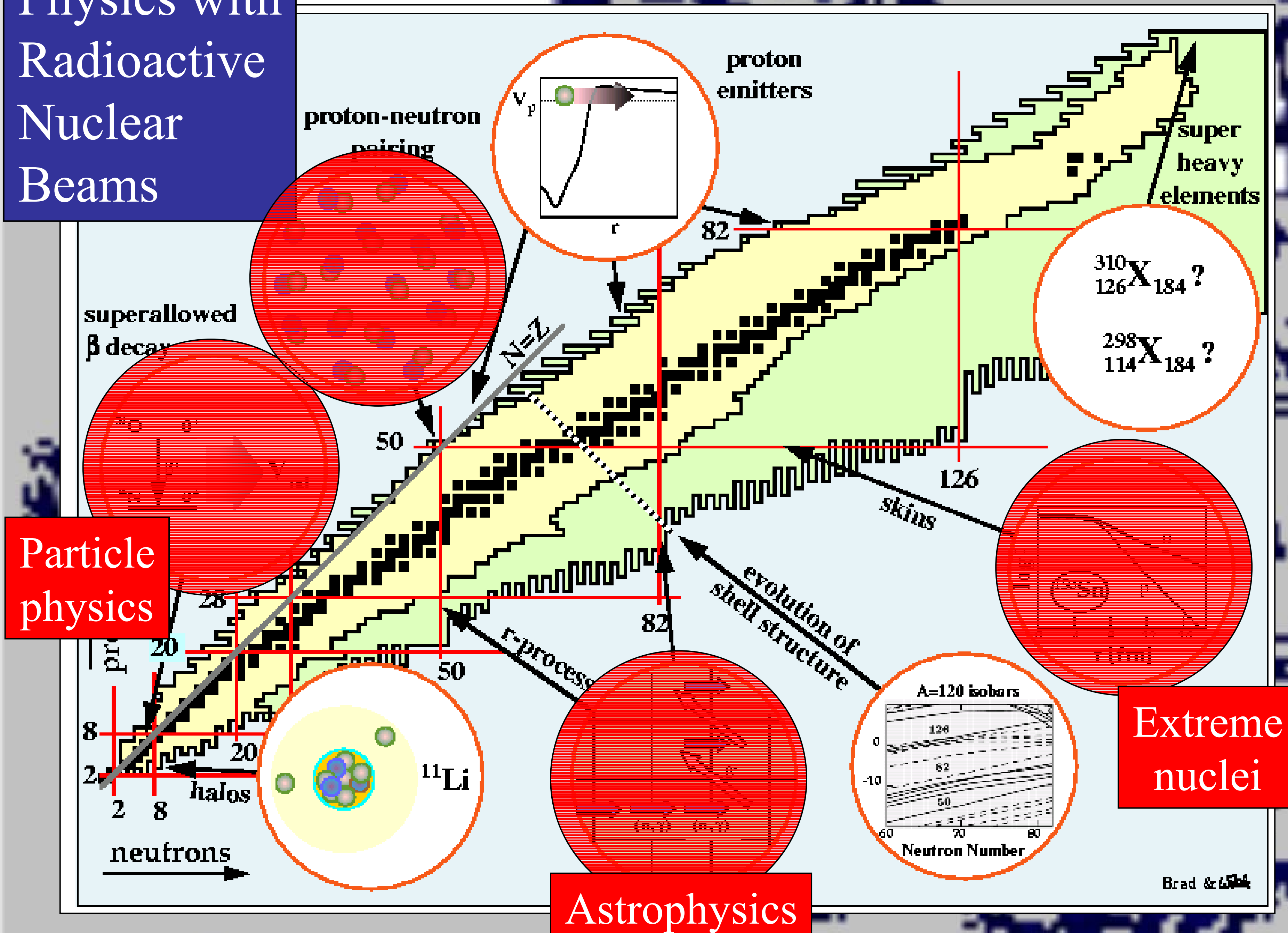


… also examples in R-violating supersymmetry, T-odd $p_T(\mu)$ in $K_{\mu 3}$ decays, …

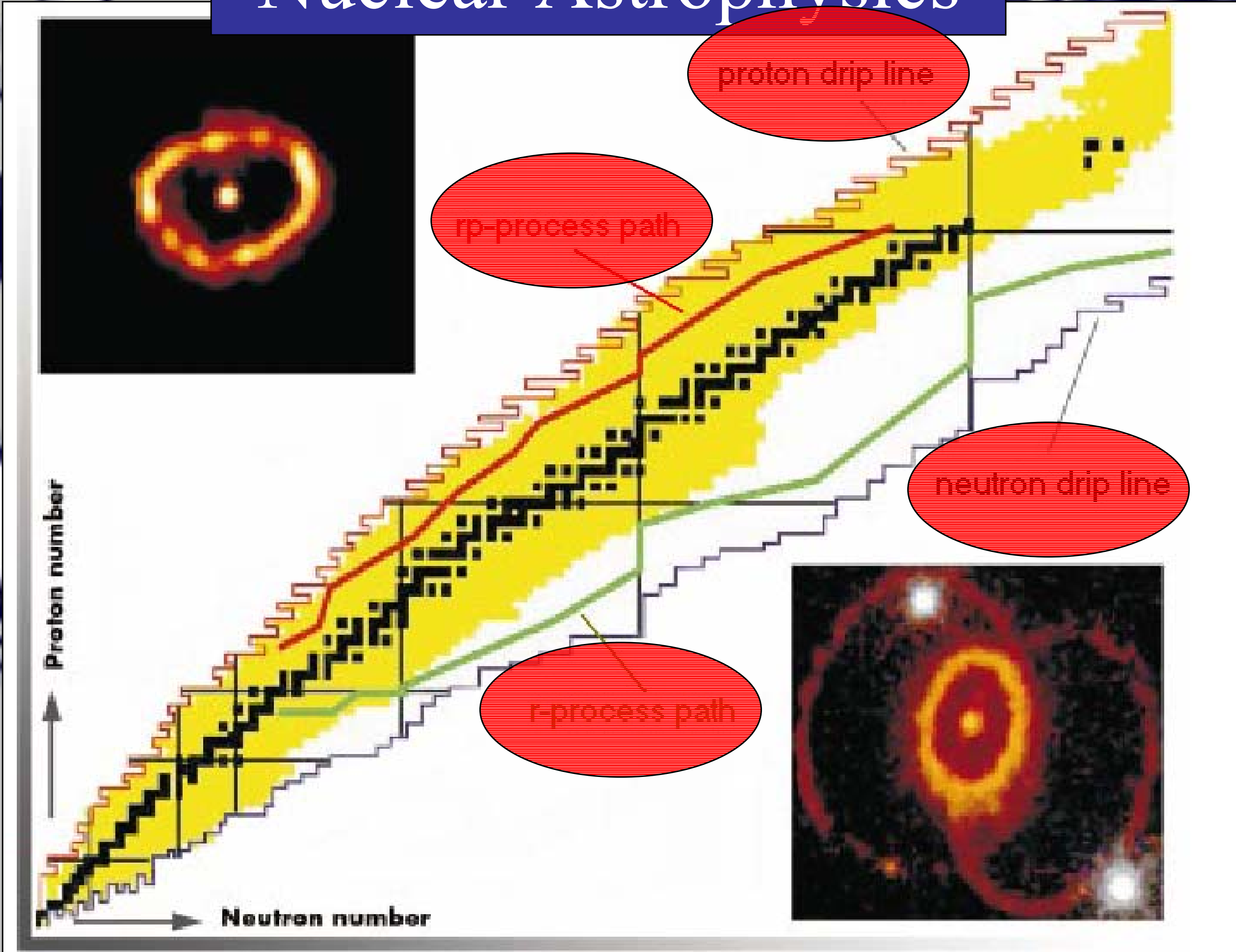
Isotope Source for Nuclear Physics

- The limits of nuclear existence:
  neutron & proton drip lines,
  superheavy elements,
  extreme nucleonic matter
- Nuclear astrophysics:
  rp-process, r-process
- Probes of Standard Model:
  CKM, P, T, CP
- Materials science:
  radioactive spies, curing chemical blindness,
  positron annihilation studies,
  applications to biomedicine, etc.

Physics with Radioactive Nuclear Beams



Nuclear Astrophysics



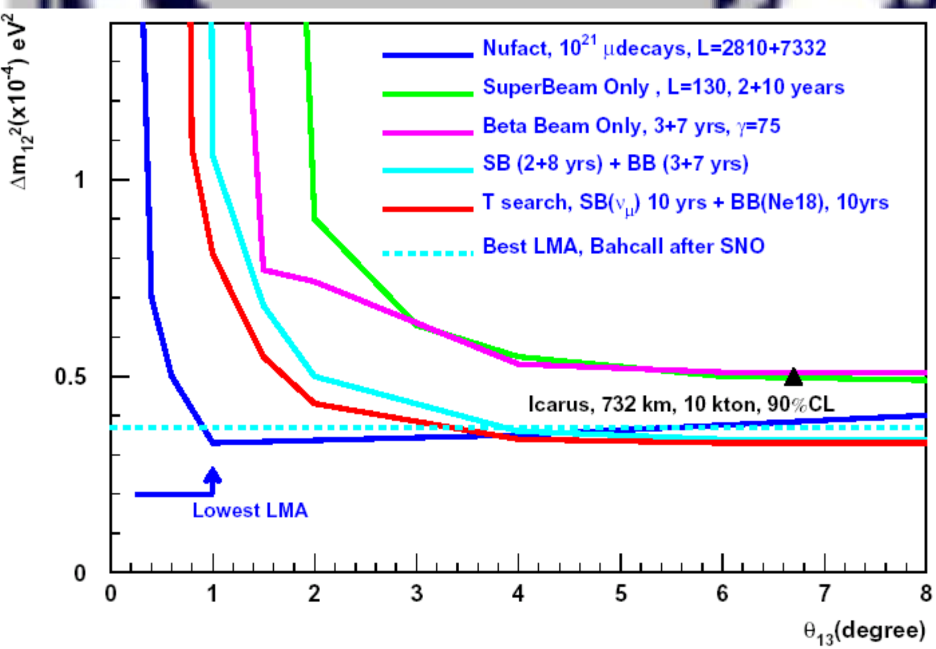
Physics with a Proton Driver

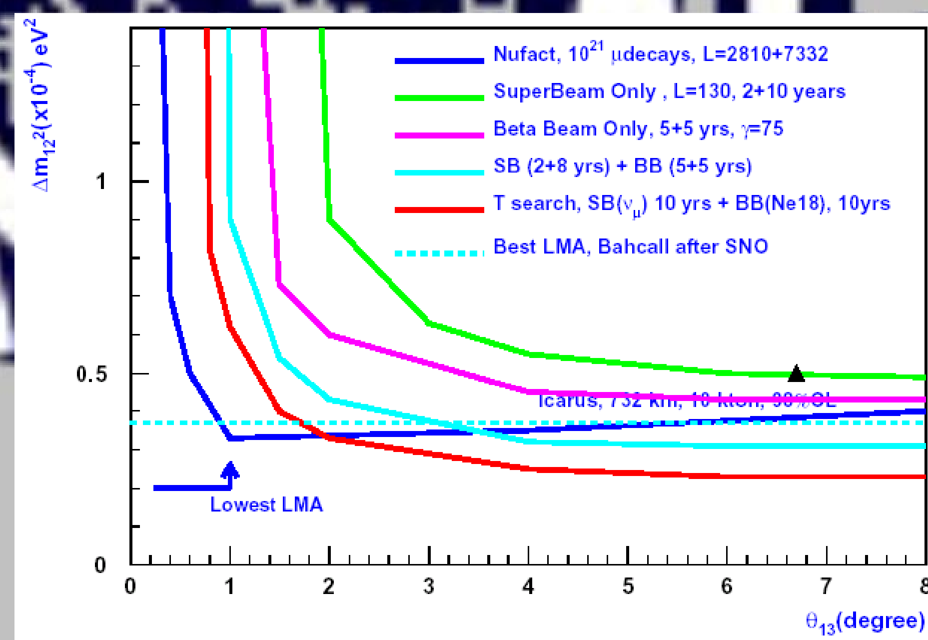
- Long-range programme in ν physics:
  superbeam, β beam, ν factory
- Complementary programme in μ physics:
  rare μ decays, μ properties, μ colliders?
- Next-generation facility for nuclear physics
  also tests of SM, nuclear astrophysics
- Synergy with FNAL programme?
  host laboratory for ILC?

Interesting project – and FNAL would be a good place for it

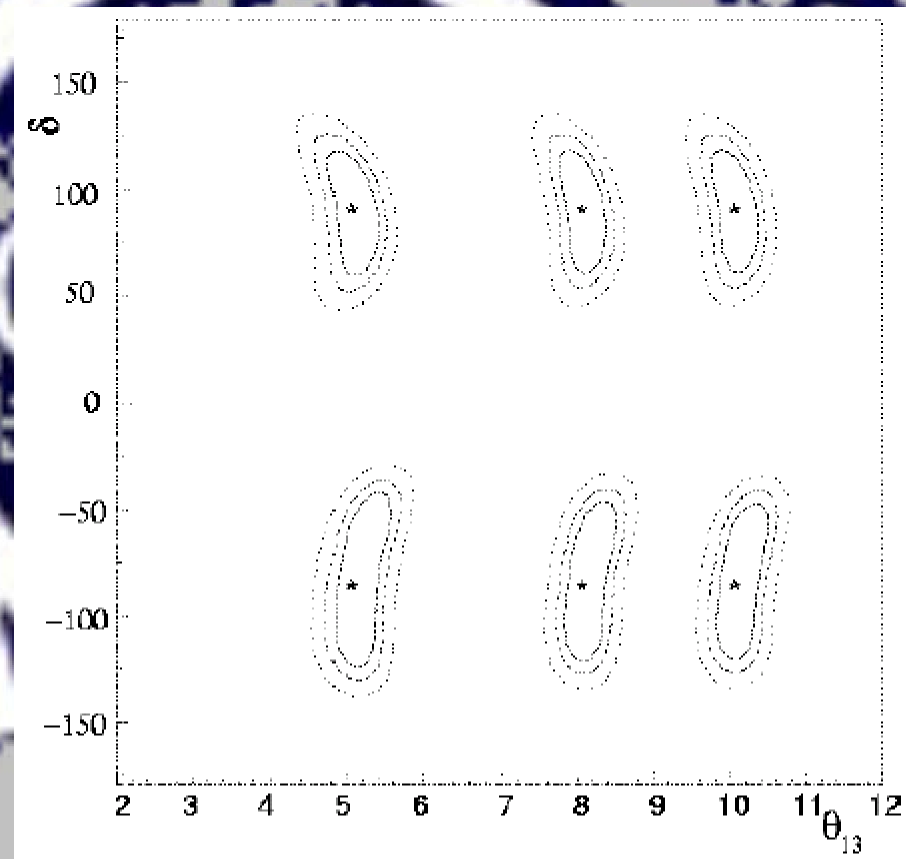
1954-2004

CERN

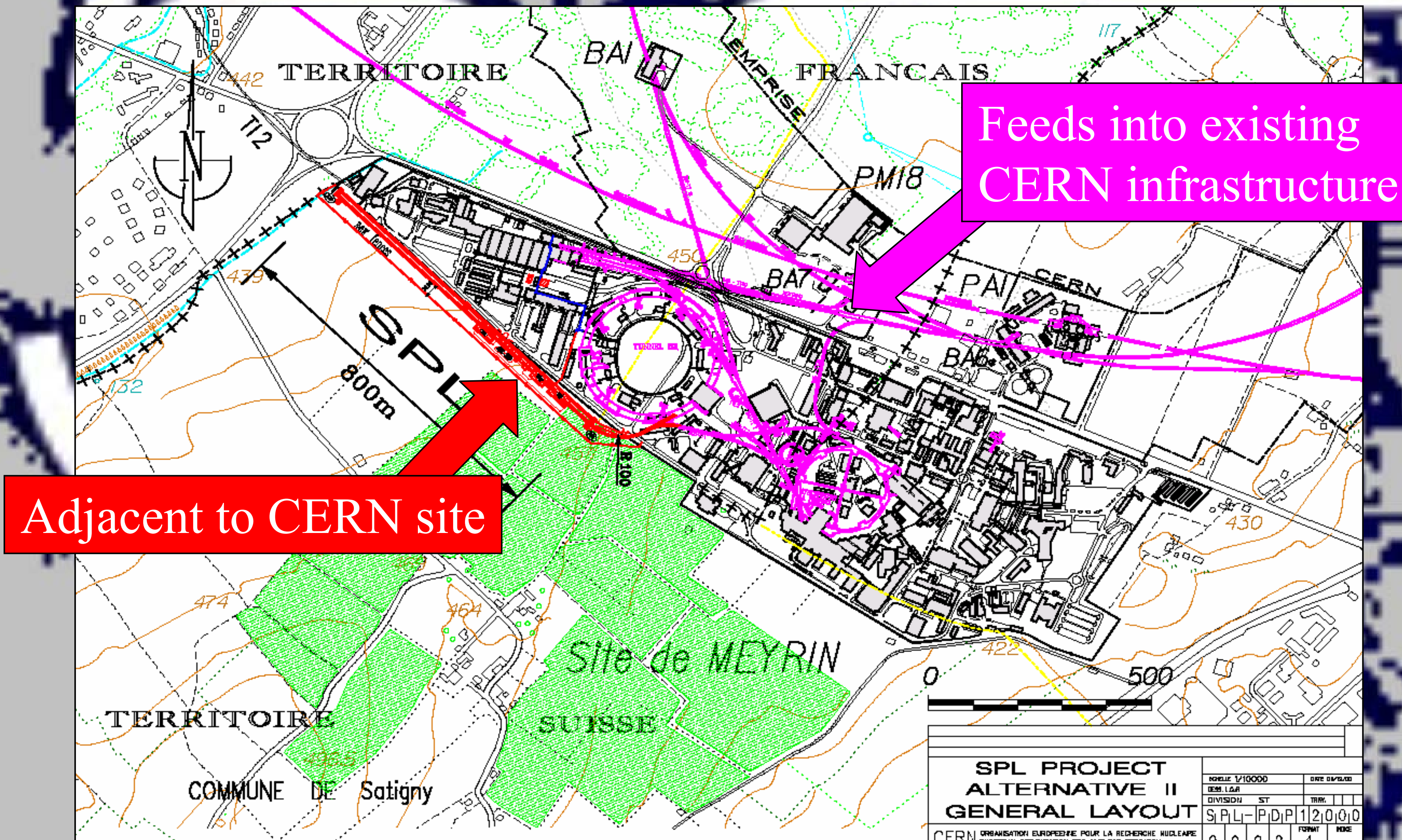




1954-2004



Possible Layout of SPL at CERN

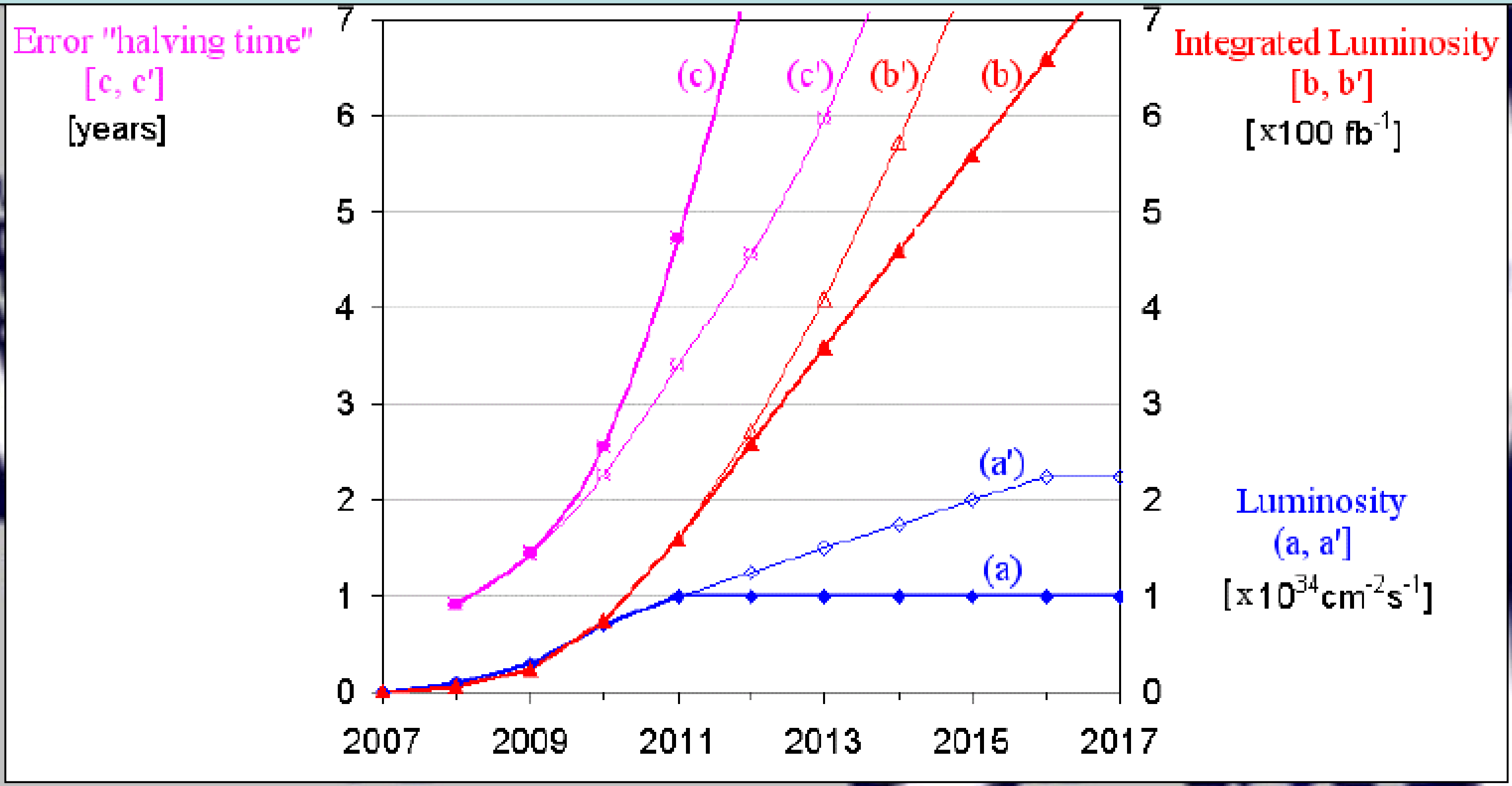


SPL @ CERN Wish List

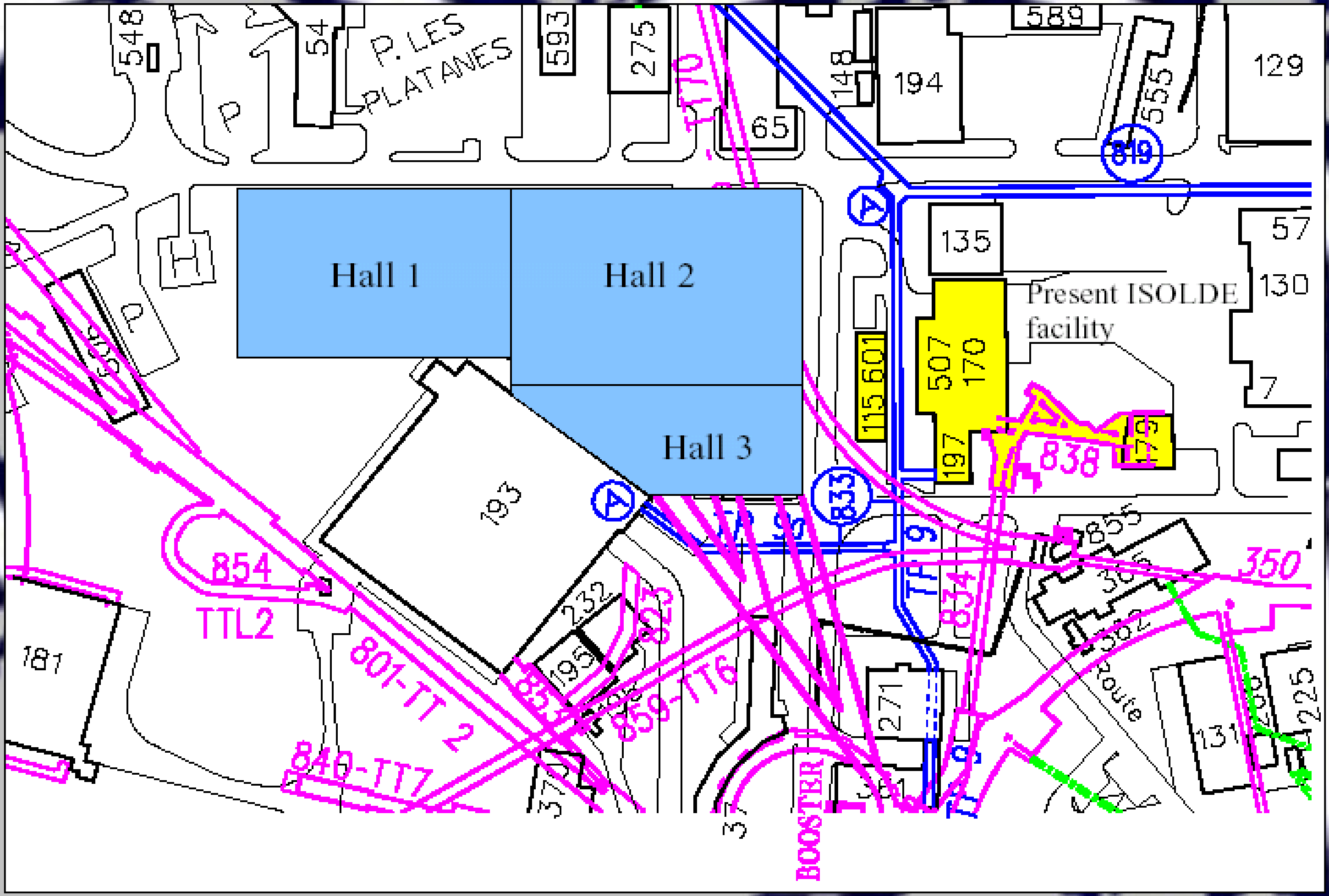
USER	CERN COMMITMENT *	USERS' WISHES	
	Short term	Medium term *[~ asap !]*	Long term *[beyond 2014]*
LHC	Planned beams	Ultimate luminosity	Luminosity upgrades
Fixed Target (COMPASS)	4.3⑨10^{5} spills/y ?	6⑨10^{5} spills/y	
CNGS	4.5⑨10^{19} p/year	Upgrade ~ ⑨ 2	
ISOLDE	1.92 µA **	Upgrade ~ ⑨ 5	
Future beams			> 2 GeV / 4 MW
EURISOL			1-2 GeV / 5 MW

Possible Upgrades of LHC

Increase luminosity – but beware of integrated radiation dose



Possible EURISOL Site @ CERN



ν Oscillation Facilities @ CERN

- CNGS:

  ν beam from SPS: τ production

- Superbeam?

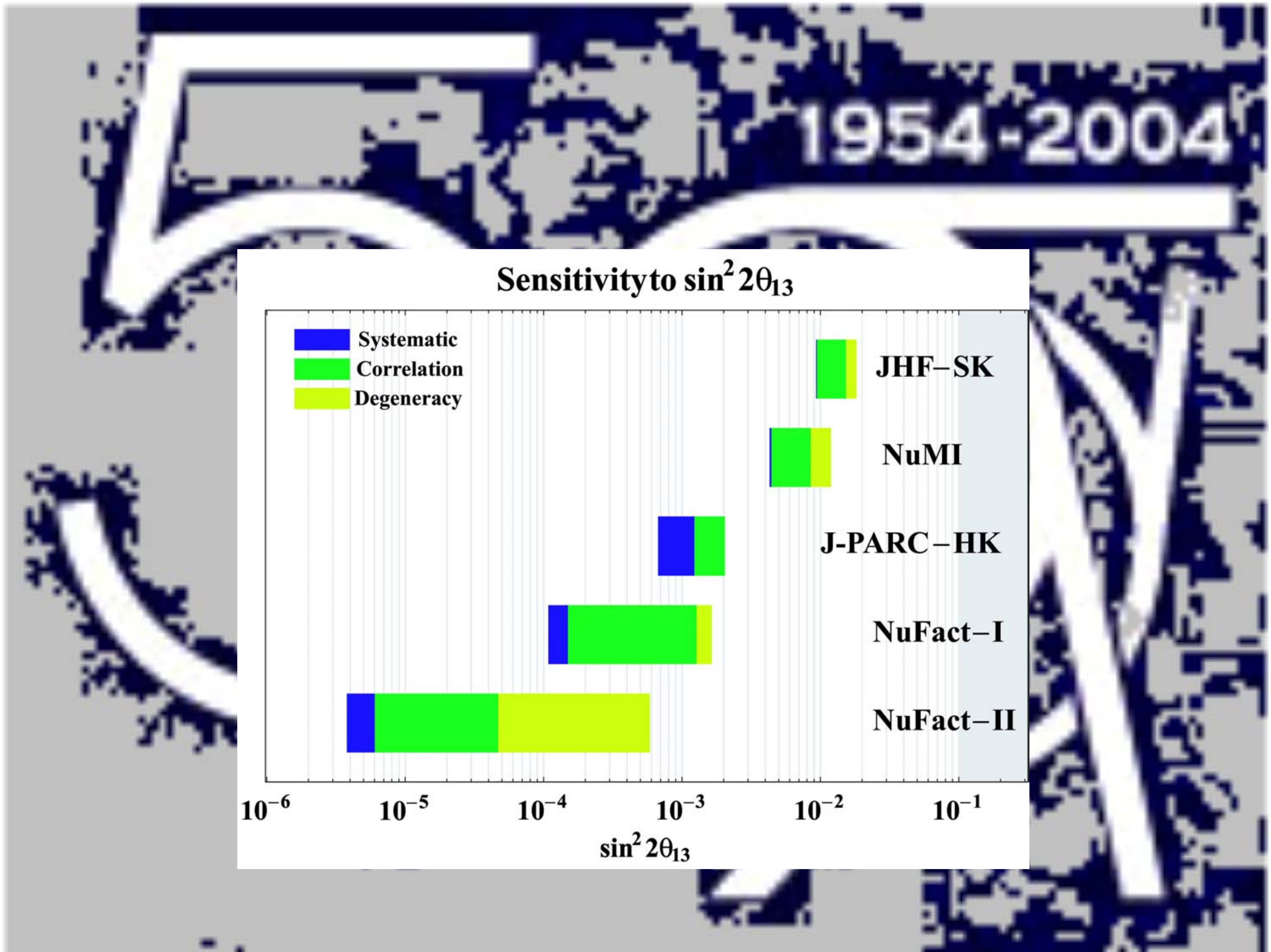
  intense ν beam from SPL

- β beam?

  signed electron (anti) ν beams from heavy ions

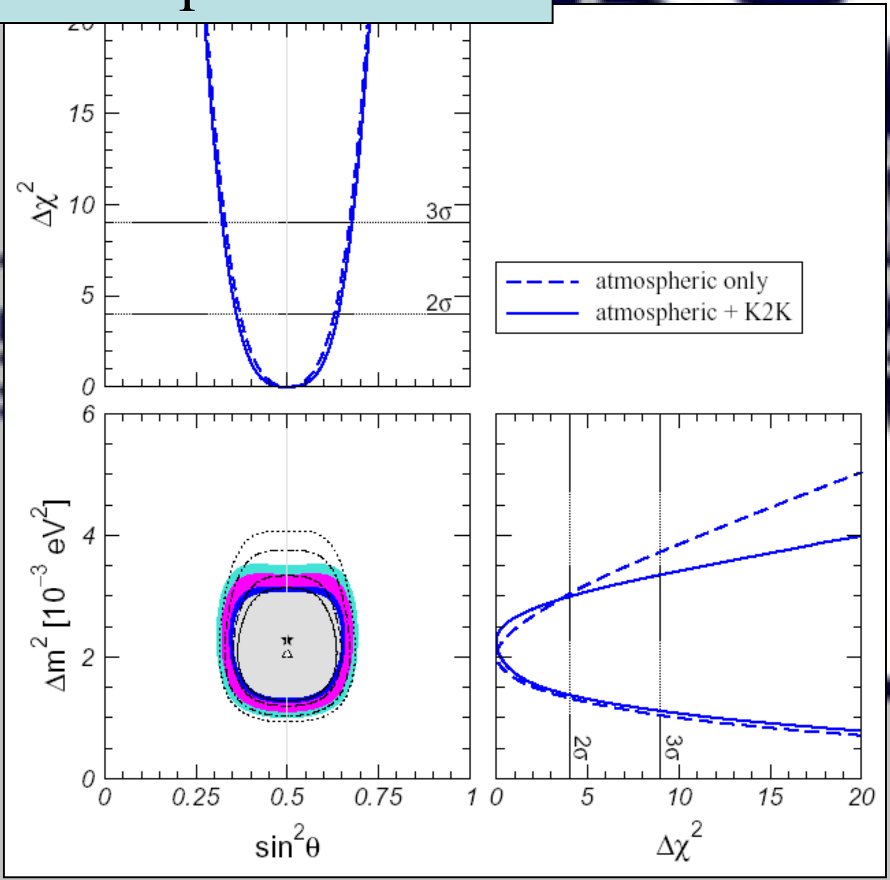
- ν factory?

  muon and electron (anti) ν beams from μ decay

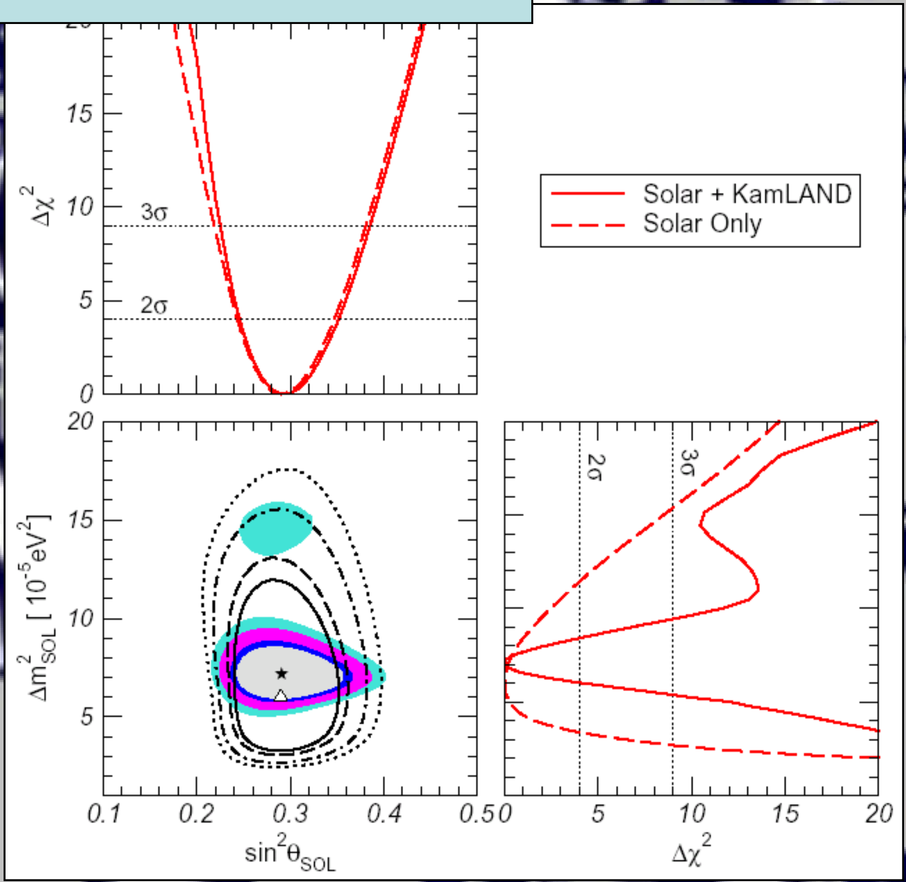

1954-2004
Sensitivity to $\sin^2 2\theta_{13}$
Systematic
Correlation
Degeneracy
JHF−SK
NuMI
J-PARC−HK
NuFact−I
NuFact−II
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
$\sin^2 2\theta_{13}$

Status of ν Oscillations

Atmospheric + K2K

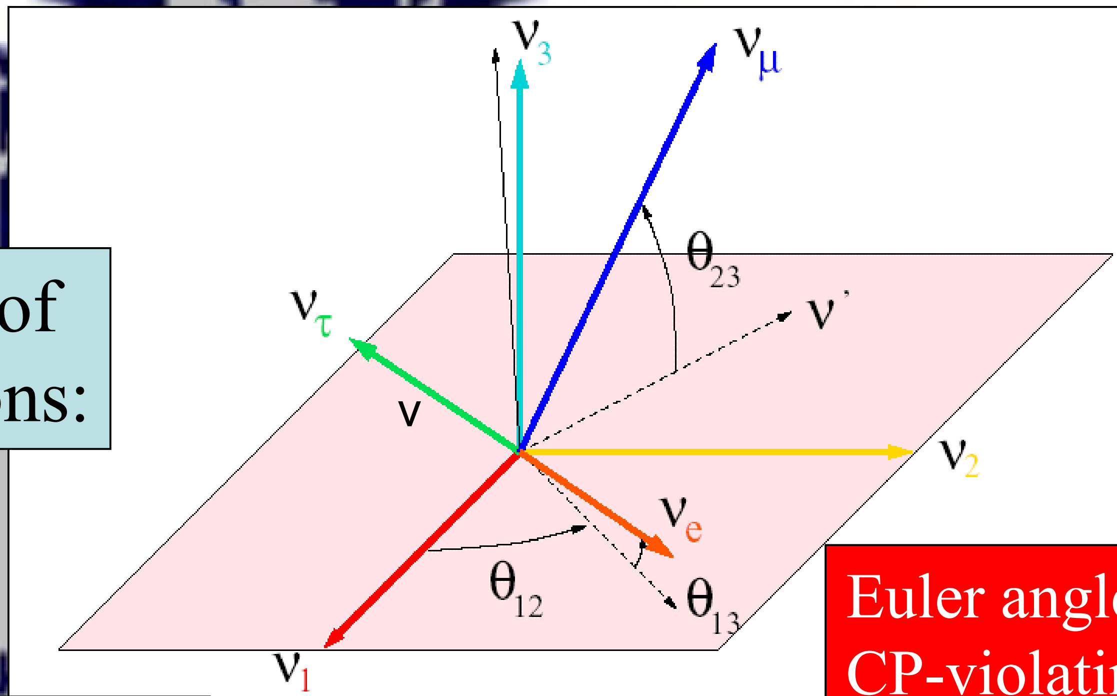


Solar + KamLAND



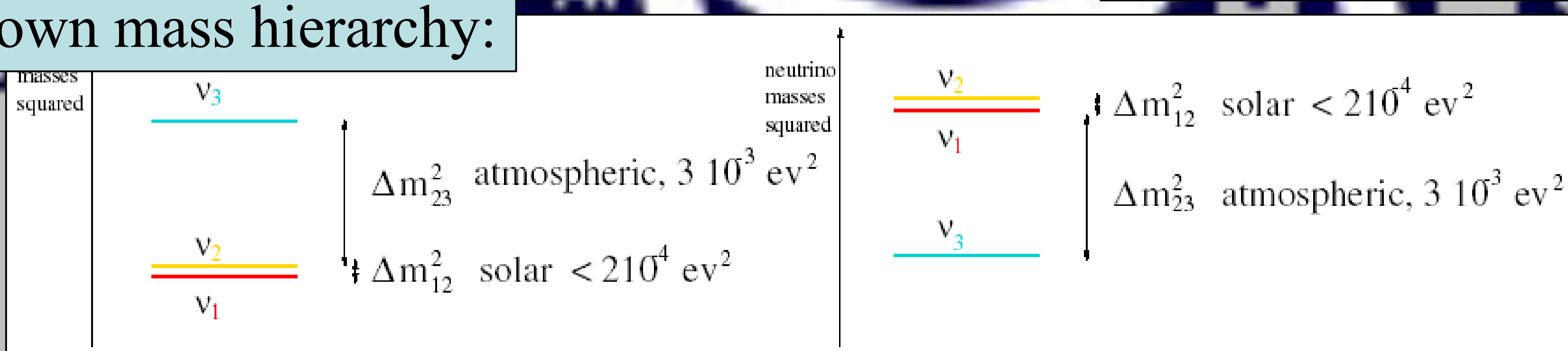
ν Oscillation Parameters

Geometry of ν oscillations:



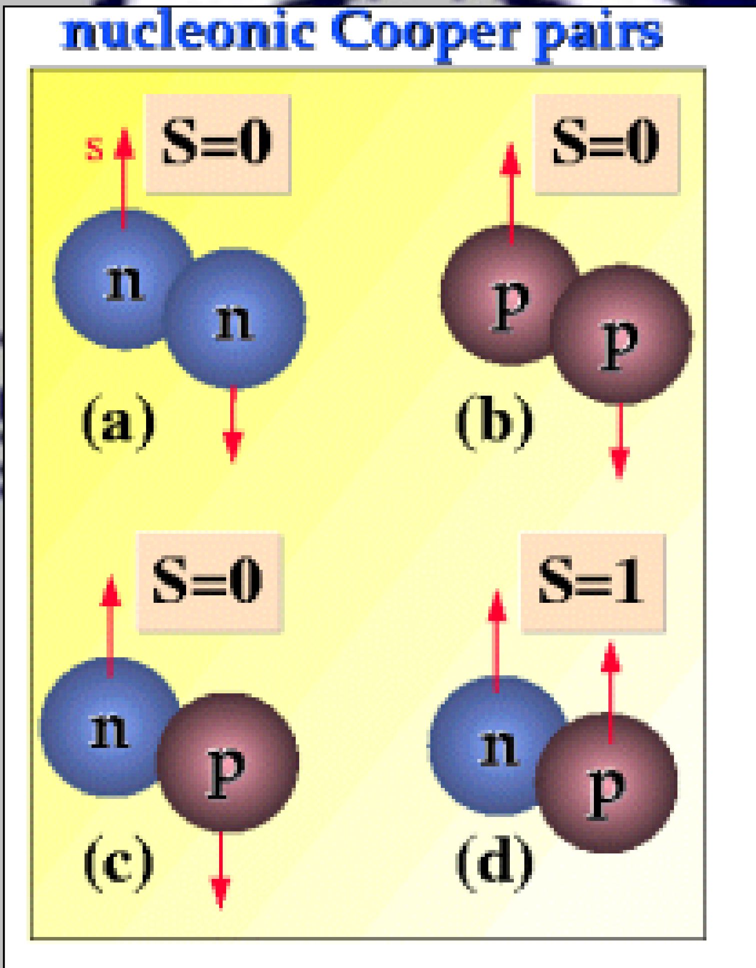
Euler angles + CP-violating phase

Unknown mass hierarchy:

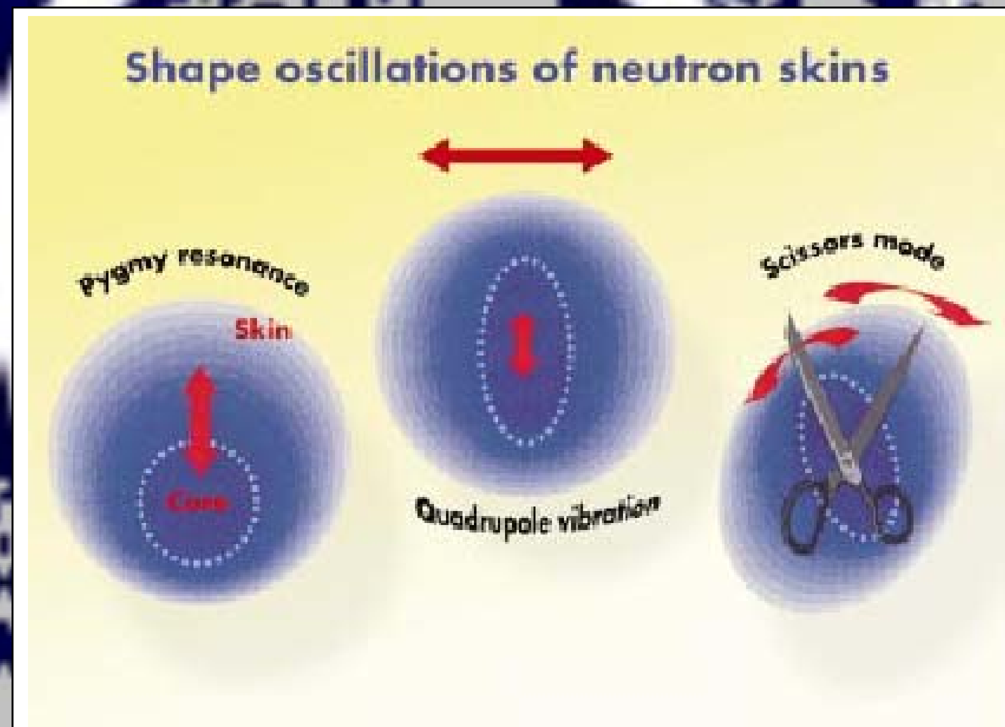


Issues in Nuclear Physics

Proton-rich nuclei



Neutron-rich nuclei



Tests of CVC hypothesis: Probe Standard Model

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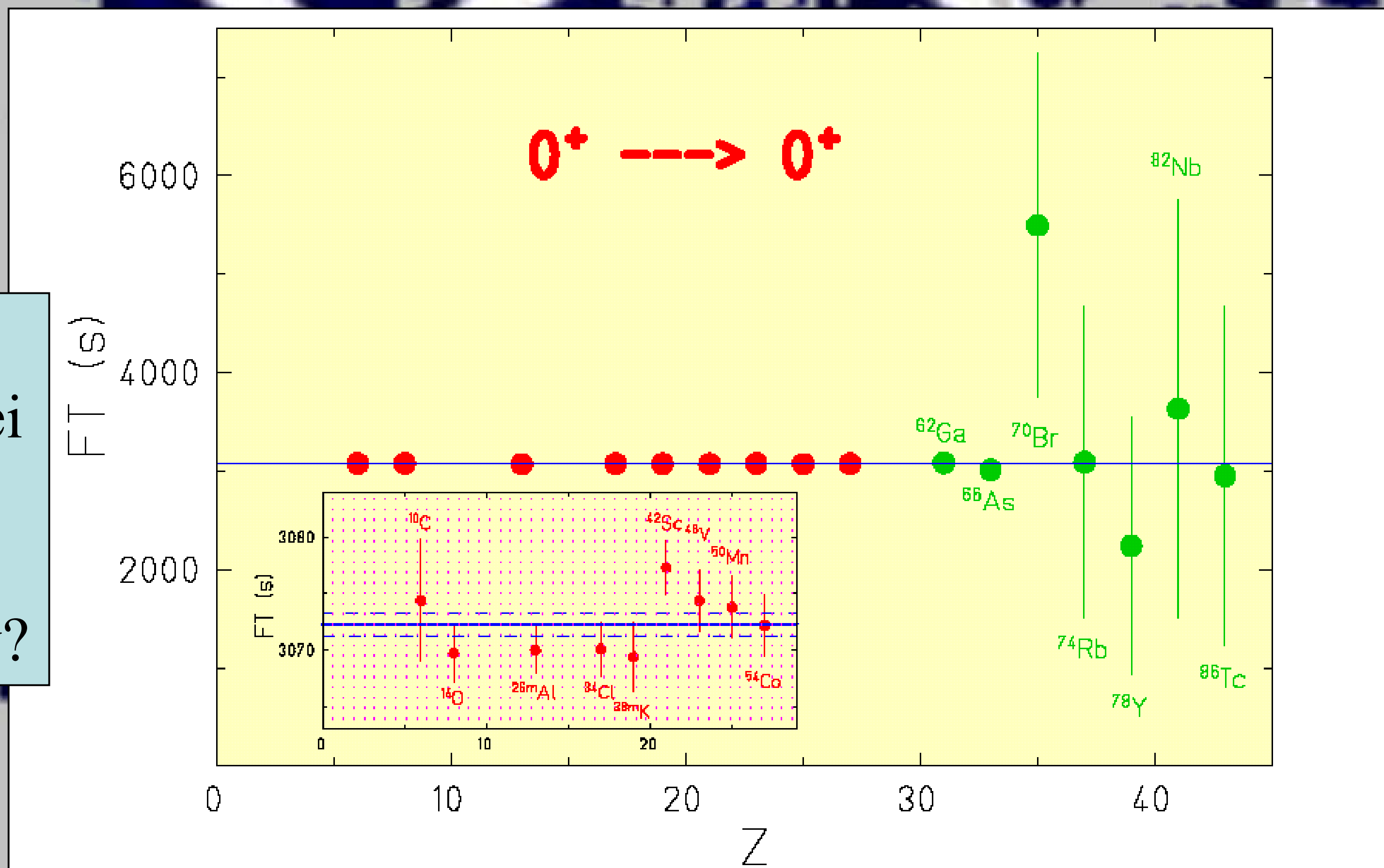

$\langle 0^+|\beta|0^+\rangle$

in *mirror* nuclei

$V_{ud}^{\;2} = G_V/G_F$

(cf μ lifetime)

CKM unitarity?

… also tests of fundamental symmetries: P, T, CP

Possible Characteristics of β Beams

Anti-ν_e from ^{6}He

Possible characteristics of a beta beam optimized for the $\overline{\nu}_e$ interaction rate.

^{6}He ion production	5×10^{13}/s every 8 s
^{6}He collection efficiency	20%
^{6}He accelerator efficiency	65%
^{6}He maximum final energy	150 GeV/nucleon
$\overline{\nu}_e$ average energy	582 MeV
Storage ring total intensity	1×10^{14} ^{6}He ions
Straight section relative length	36%
Running time/year	10^7 s
Detector distance	100 km
$\langle E \rangle / L$	5.9×10^{-3} GeV/km
$\overline{\nu}_e$ interaction rate on H_2O	69/kton/year

ν_e from ^{18}Ne

Possible characteristics of a beta beam optimized for the ν_e interaction rate.

^{18}Ne ion production	1×10^{12}/s every 4 s
^{18}Ne collection efficiency	50%
^{18}Ne accelerator efficiency	82%
^{18}Ne maximum final energy	75 GeV/nucleon
ν_e average energy	279 MeV
Storage ring total intensity	1.3×10^{13} ^{18}Ne ions
Straight section relative length	36%
Running time/year	10^7 s
Detector distance	130 km
$\langle E \rangle / L$	2.1×10^{-3} GeV/km
ν_e interaction rate on H_2O	3.1/kton/year