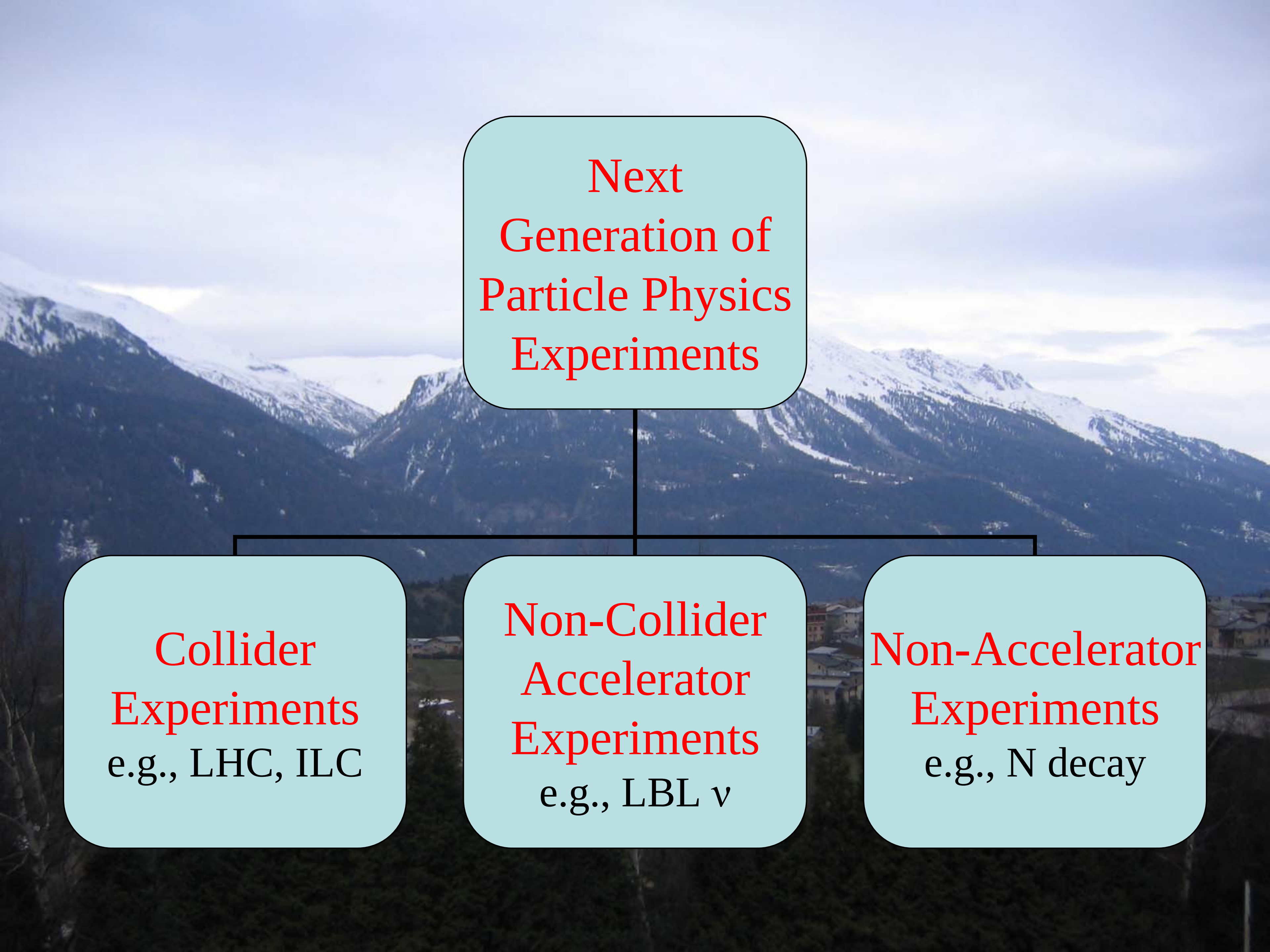
Physics Motivations

for the

Next Generation of Nucleon Decay and Neutrino Detectors

NNN05, Aussois,

John Ellis, April 7th 2004


Next Generation of Particle Physics Experiments
Collider Experiments
e.g., LHC, ILC
Non-Collider Accelerator Experiments
e.g., LBL ν
Non-Accelerator Experiments
e.g., N decay

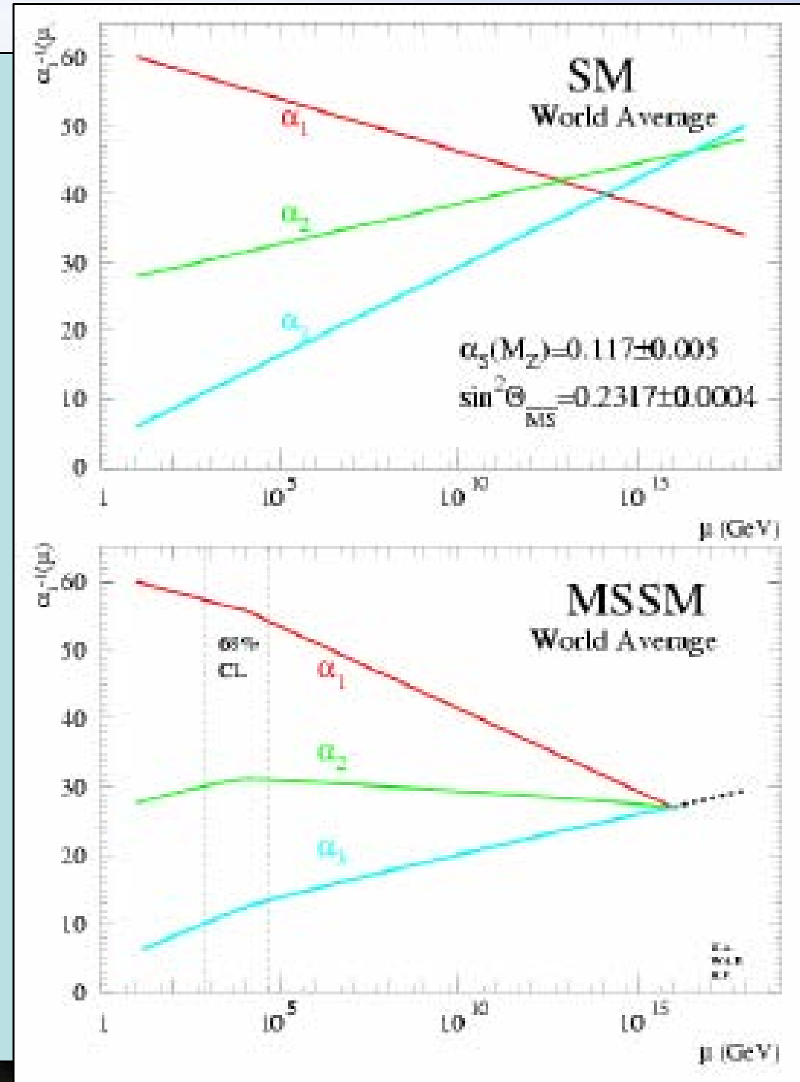
Ironies of History

- Fame often comes in unexpected ways
- True both of accelerators and non-accelerator experiments
- Bevatron: antiproton → resonances
- SPS: fixed-target → collider: W, Z
- Kamiokande & Super-Kamiokande:

  Nucleon decay → SN 1987a, ν oscillations

Baryon Decay

- Still very much on the theoretical agenda
- Grand Unification hinted by accelerator data on gauge couplings, supersymmetry
- Supported by ν physics
- Baryon decay is the guts of GUTs



Traditional GUT Models

- Only group of rank 4 with suitable complex representations 10 + 5*: SU(5)
- Only suitable group of rank 5 is: SO(10)
- Each generation in irreducible

$$16 = 10 + 5^* + 1 \text{ of } SU(5)$$

- Next step is rank 6: E_6 has suitable complex

$$27 = 16 + 10 + 1 \text{ of } SO(10)$$

Appears in String theory

Suitable for right-handed neutrino

Baryon Decay in Minimal SU(5)

- Exchanges of new X, Y bosons:

$$(\epsilon_{ijk} u_{R_k} \gamma_\mu u_{L_j}) \quad \frac{g_X^2}{8m_X^2} \quad (2e_R \gamma^\mu d_{L_i} + e_L \gamma^\mu d_{R_i})$$

$$(\epsilon_{ijk} u_{R_k} \gamma_\mu d_{L_j}) \quad \frac{g_Y^2}{8m_X^2} \quad (\nu_L \gamma^\mu d_{R_i}) , \qquad G_X \equiv \frac{g_X^2}{8m_X^2} \simeq G_Y \equiv \frac{g_Y^2}{8m_Y^2} .$$

- Proton decay rate $\Gamma_B = c G_X^2 m_p^5$ lifetime: $\tau_p = \frac{1}{c} \frac{m_X^4}{m_p^5}$
- Preferred modes: $p \to e^+\pi^0 , \quad e^+\omega , \quad \bar{\nu}\pi^+ , \quad \mu^+ K^0 , \quad \ldots$
  $n \to e^+\pi^- , \quad e^+\rho^- , \quad \bar{\nu}\pi^0 , \quad \ldots$
- Estimate of X, Y masses: $m_X \simeq (1 \text{ to } 2) \times 10^{15} \times \Lambda_{QCD}$
- Lifetime too short:

$\tau(p \to e^+\pi^0) \simeq 2 \times 10^{31\pm1} \times \left(\frac{\Lambda_{QCD}}{400 \text{ MeV}} \right)^4 \quad y$ exp’t: $\tau(p \to e^+\pi^0) > 1.6 \times 10^{33} \quad y$

Proton Decay in Supersymmetric SU(5)

- Increase in GUT scale:

$$m_X \simeq 10^{16}\ \mathrm{GeV}$$

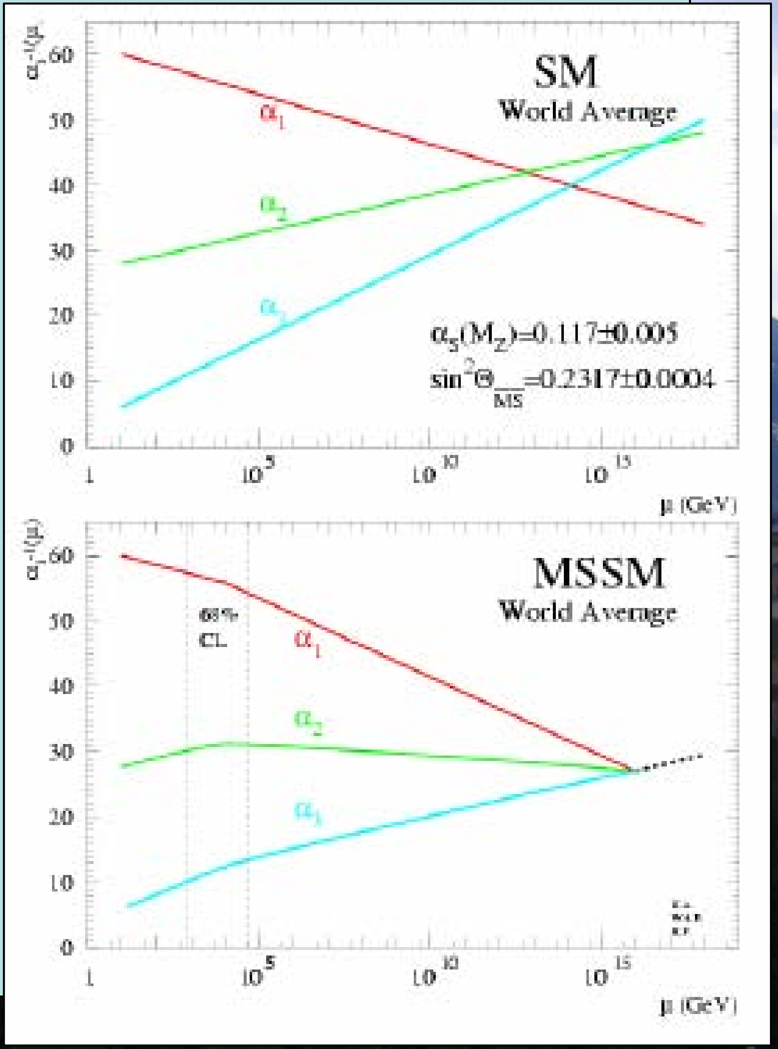
- X, Y exchanges OK
- Beware GUT Higgsinos:

$$G_X \to \mathcal{O}\left(\frac{\lambda^2 g^2}{16\pi^2}\right)\frac{1}{m_{\tilde{H}_3}\tilde{m}}$$

- Preferred decay modes:

$$p \to \bar{\nu}K^+\ ,\quad n \to \bar{\nu}K^0\ ,\quad \ldots$$

- Lifetime too short?
- Suppressed in some models



Stringy GUTs?

- First: compactify $E_8 \times E_8$ heterotic string on complex 'Calabi-Yau' manifold:

  Gauge group = subgroup of E_6

  No Higgses to break GUT group
- Second: replace manifold by fermions

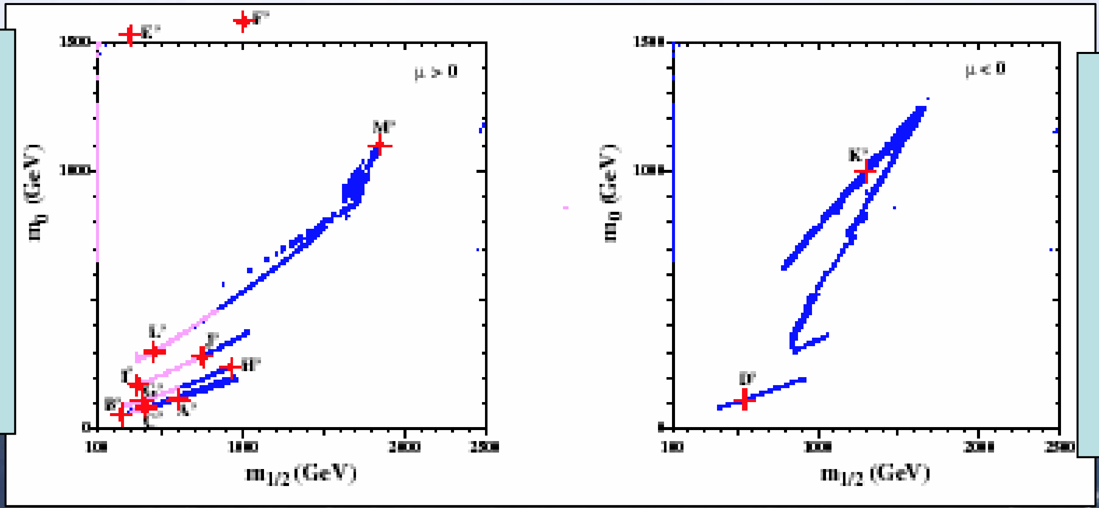
  still no GUT Higgses
- Can construct pseudo-GUT: 'flipped' SU(5) × U(1):

  $e \leftrightarrow \nu, u \leftrightarrow d$
- Does not need large GUT Higgs representations

Antoniadis, JE, Hagelin, Nanopoulos

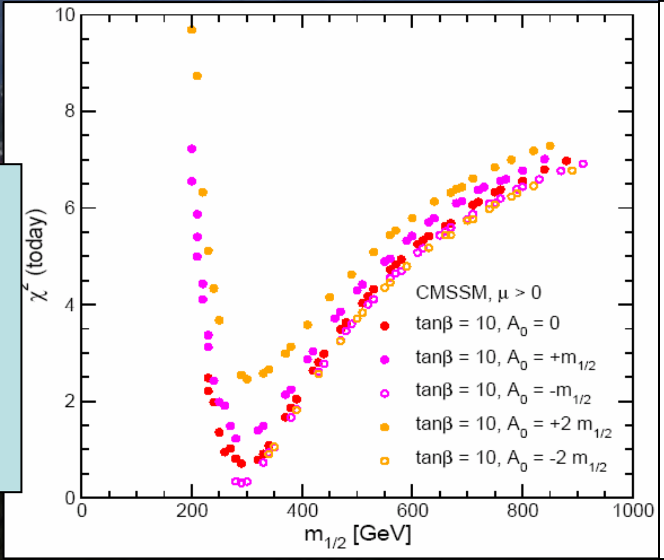
Supersymmetric Parameter Space

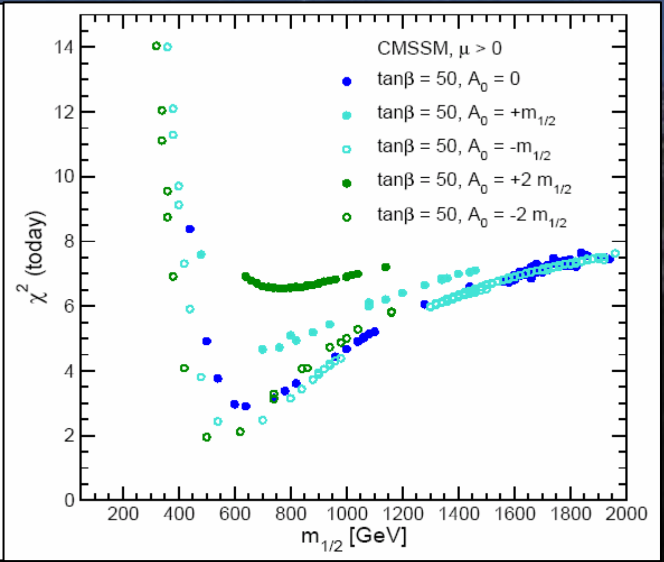
Lines in susy space allowed by accelerators, cosmology



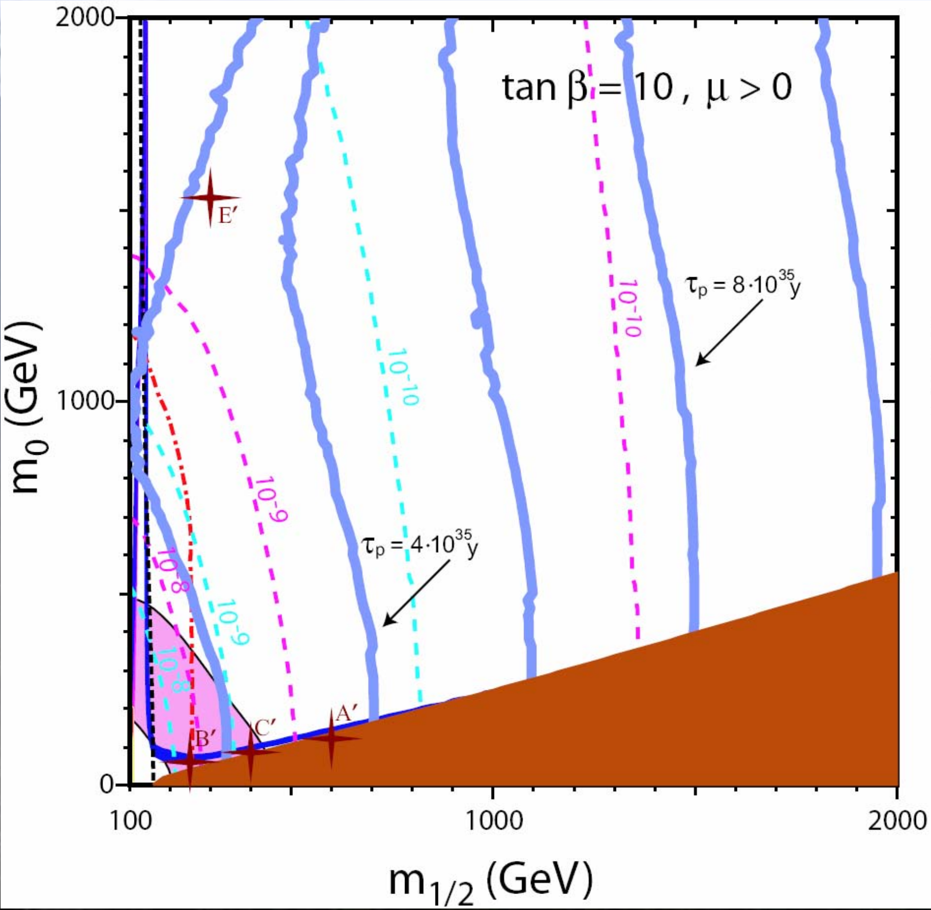
Specific benchmark points along cosmological lines

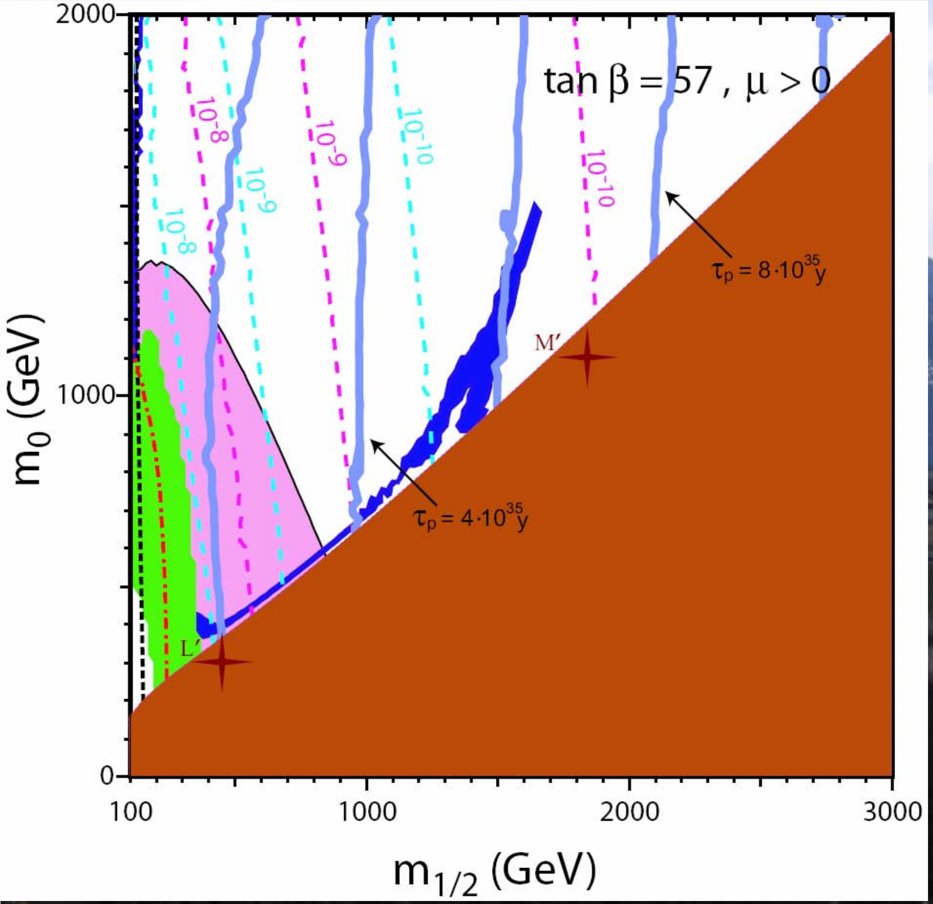
Global fits to present data: $m_{1/2}$ dependence for tan β = 10, 50





Proton Lifetime in Flipped SU(5) × U(1)

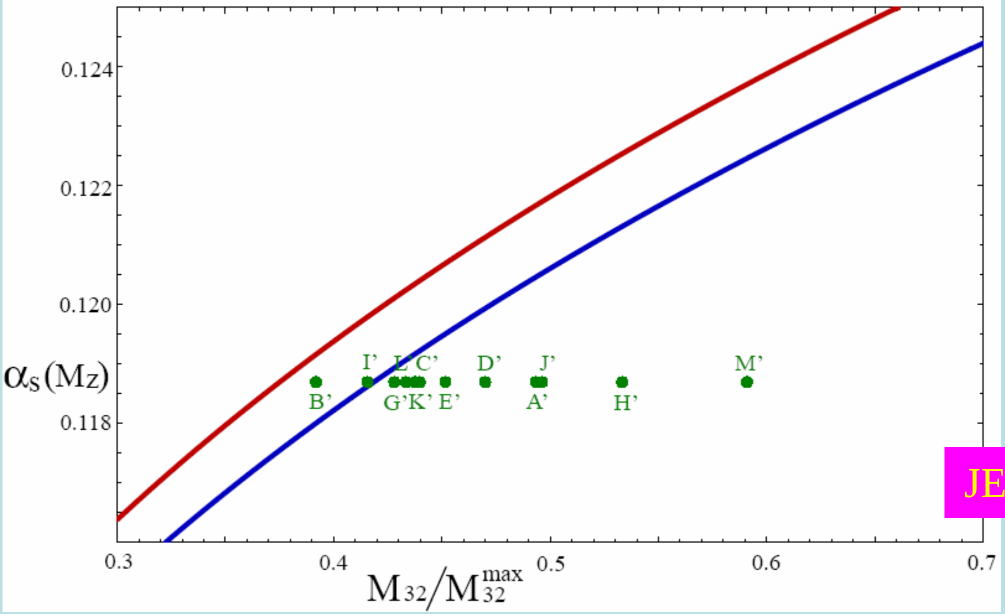




JE + Nanopoulos + Walker

Proton Decay in 'Flipped' SU(5) × U(1)

- Similar modes to conventional SU(5): different branching ratios, no Higgsino exchange
- SU(3) and SU(2) unify below usual GUT scale

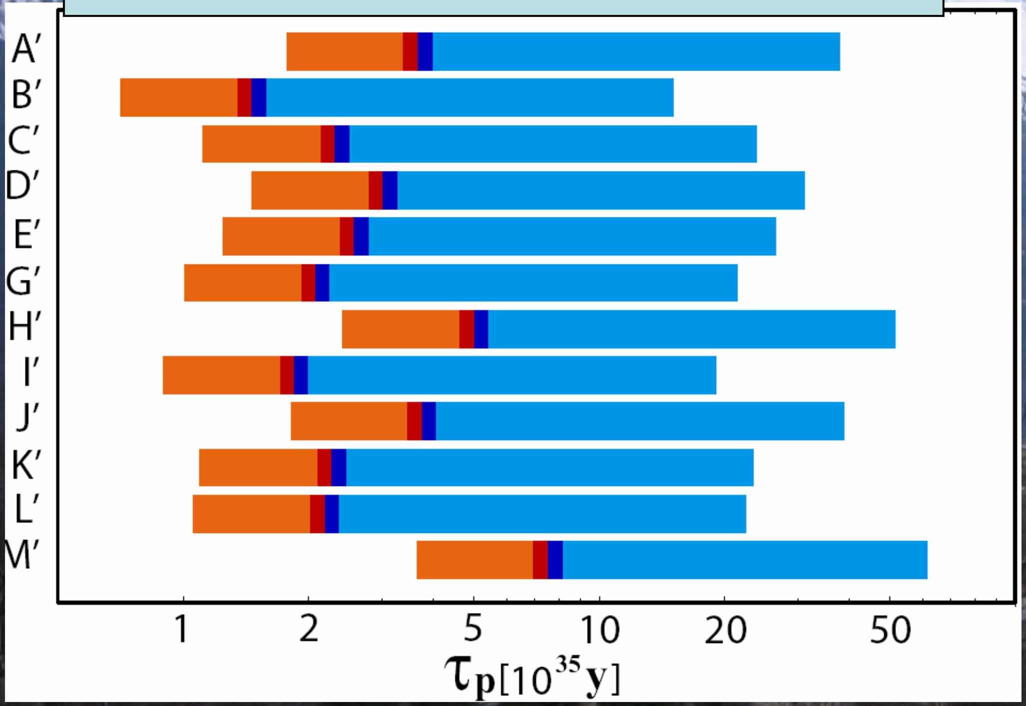


JE + Nanopoulos + Walker

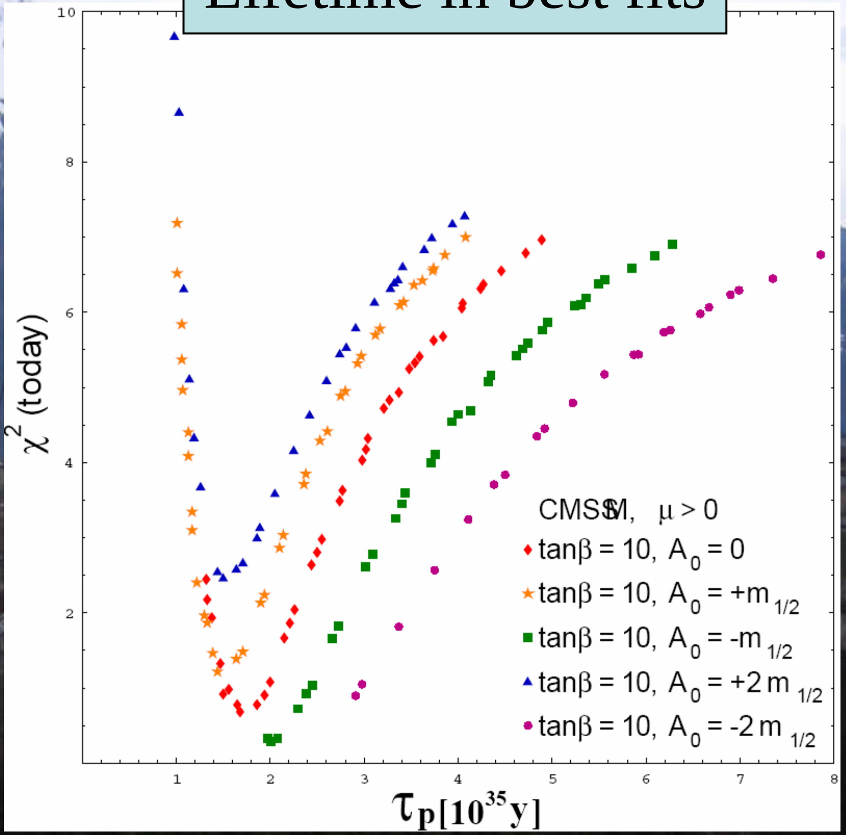
- Enhanced rate in strongly-coupled M theory

Lifetime accessible to Experiment?

Lifetime in benchmark scenarios



Lifetime in best fits



JE + Nanopoulos + Walker

The High-Proton-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

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 $\nu_R \equiv N$:

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

18 parameters

Seesaw mass matrix:

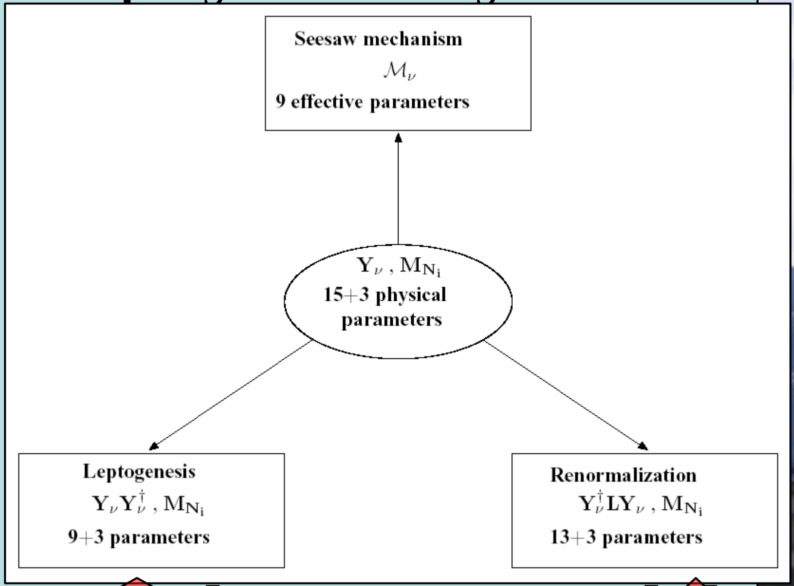
$$\mathcal{M} = \begin{pmatrix} 0 & M_{\nu_D} \\ M_{\nu_D}^T & M_{\nu_R} \end{pmatrix}$$

ν mixing matrix:

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

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

Agenda for Future ν Experiments

- Confirm or reject LSND

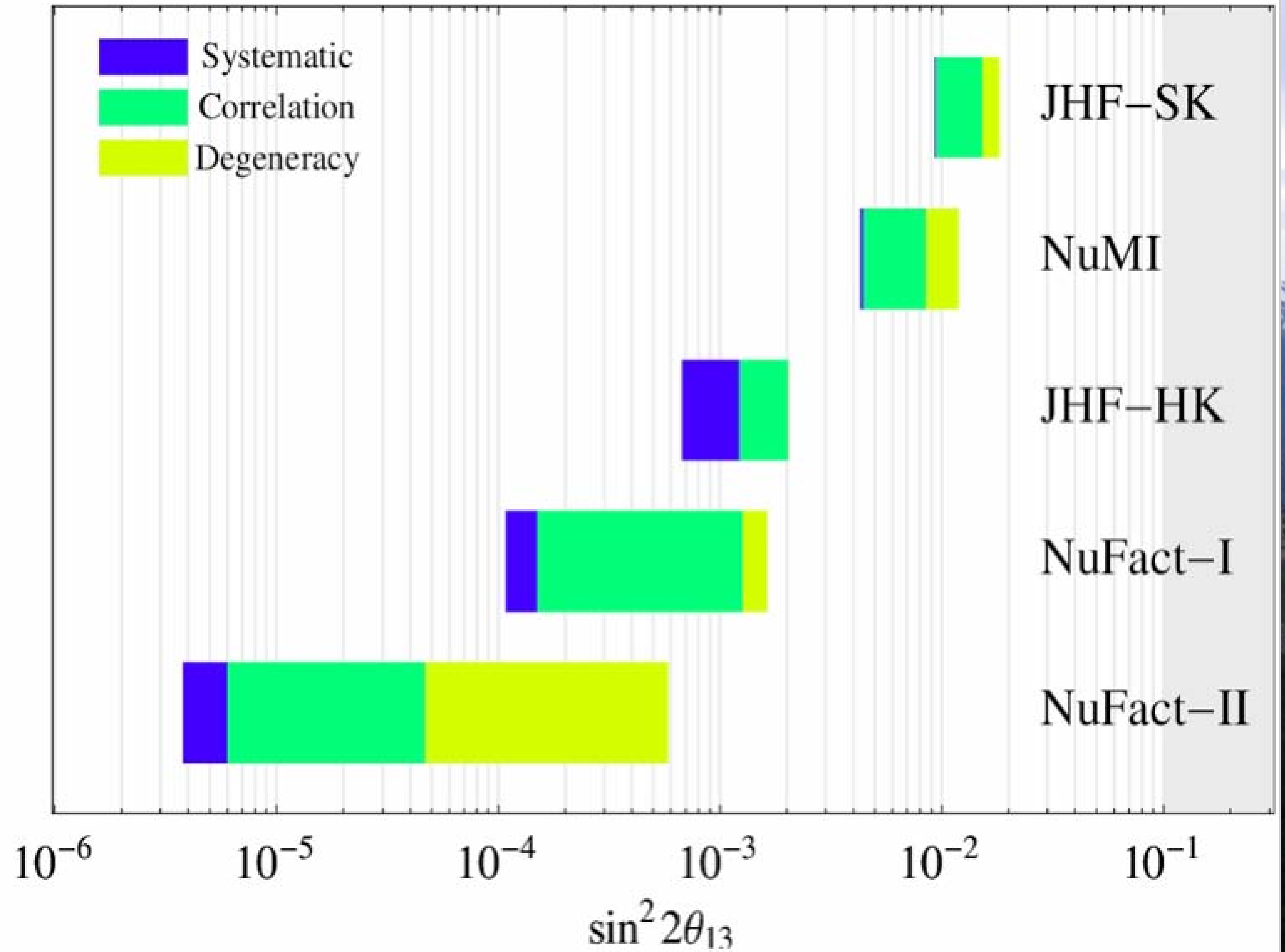
  (In progress: MiniBoone)
- Measure θ_{13}

  (In preparation: MINOS, Reactors, JHF....)
- Detect ν_τ in $\nu_\mu \rightarrow \nu_\tau$

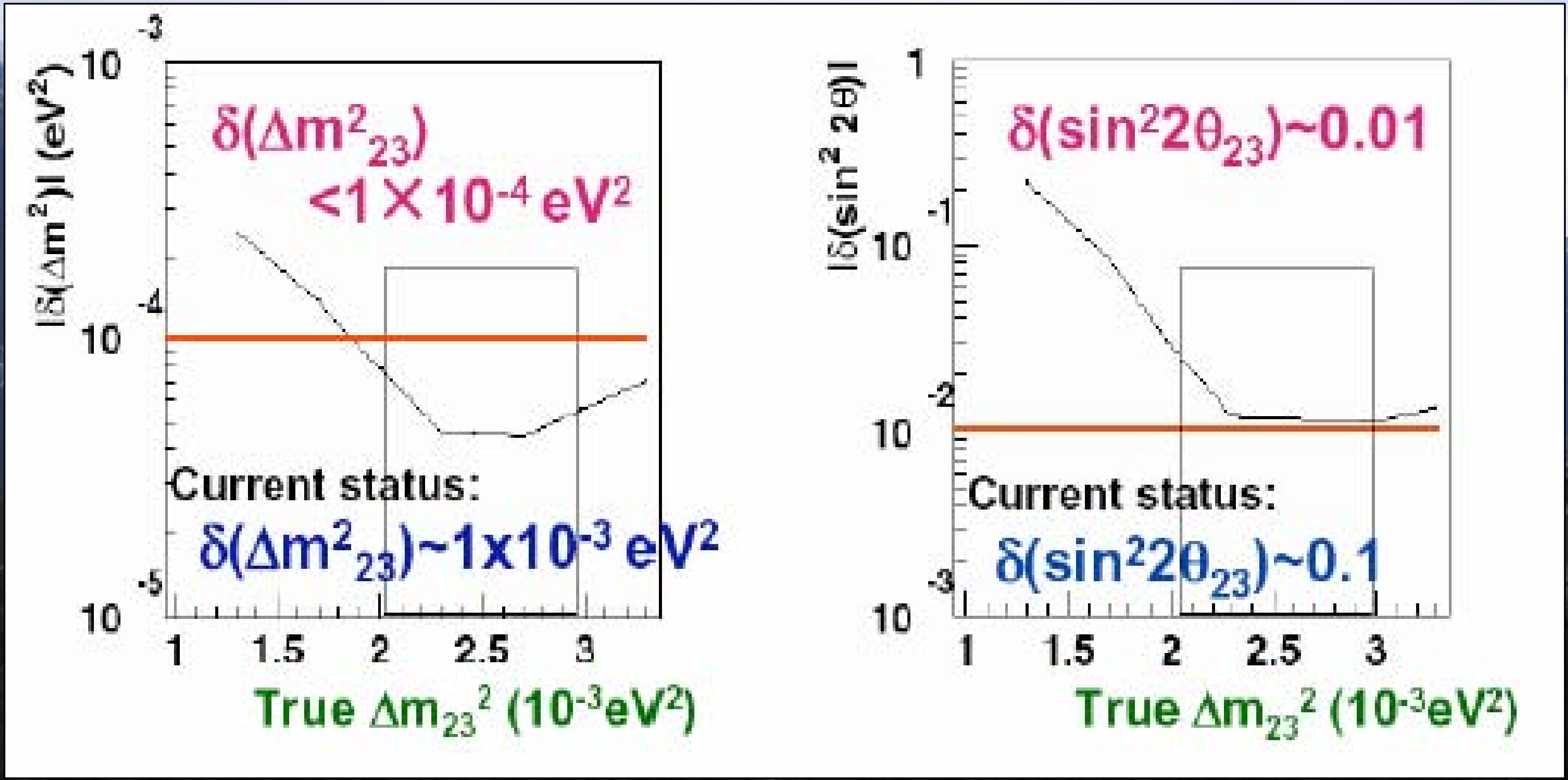
  (In preparation: Opera, Icarus)
- How close to maximal is θ_{23}?

  (In preparation: JHF, …)
- Determine sign of Δm_{23}^2
- Search for CP violation
- Improve sensitivity to $0\nu\beta\beta$
- Search for other lepton mixing/CP-violating parameters

Sensitivity to $\sin^2 2\theta_{13}$



T2K Sensitivity to 23 Mixing



ν Oscillation Facilities @ CERN

- CNGS:

  ν from SPS: τ production

- Superbeam?

  intense ν beam from SPL

- β beam?

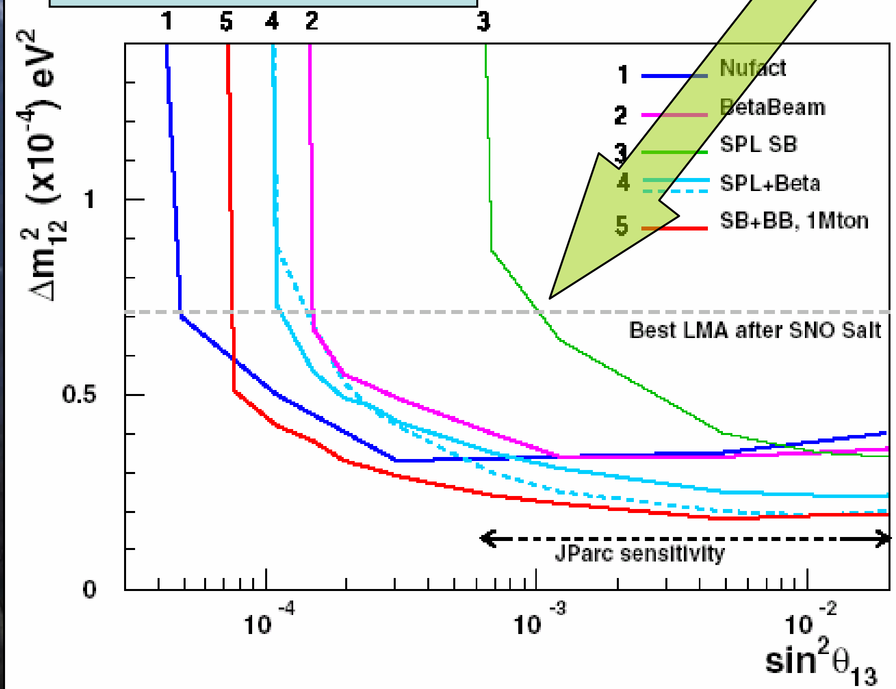
  signed electron (anti) ν beams from heavy ions

- ν factory?

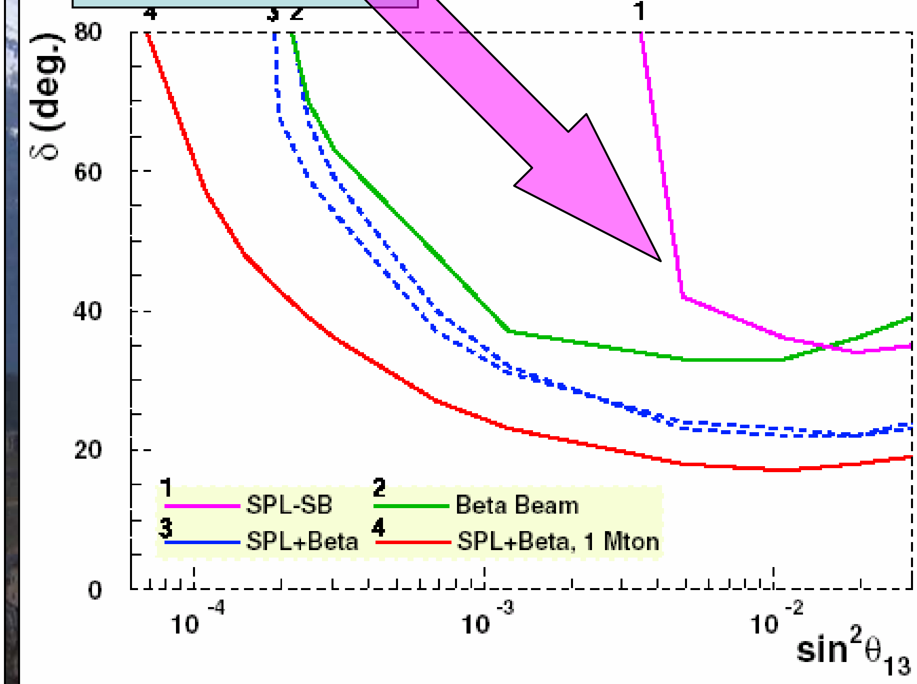
  muon and electron (anti) ν beams from μ decay

Sensitivities of Super & β Beams

To Δm^2 vs ϑ_{13}



To δ vs ϑ_{13}



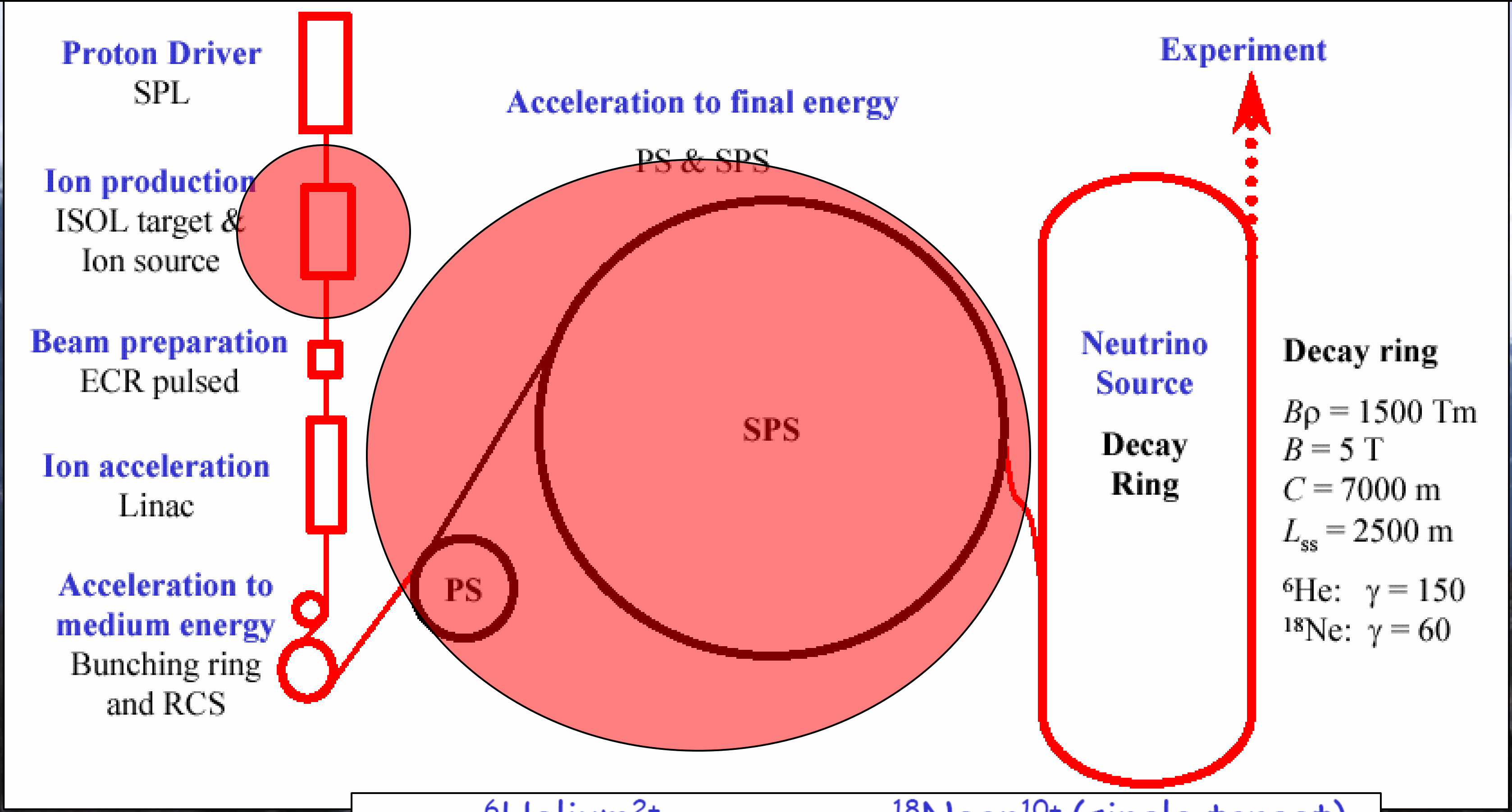
Optimization of Proton Beam Energy

E_{proton} GeV	2.2	3.5	4.5	6.5
Non-oscill. ν_μ	36917	60969	73202	78024
Oscillated ν_e	43	60	64	61
Intrinsic Beam ν_e	165	222	242	288
Background π^0, μ/e mis.	70	105	127	148
Significance $S/(N \quad)^{1/2}$	1.88	2.16	2.17	1.87

20% Increase in significance at higher energy: 3.5 or 4.5 GeV

Campagne + Cazes

Schematic Layout of β Beam @ CERN

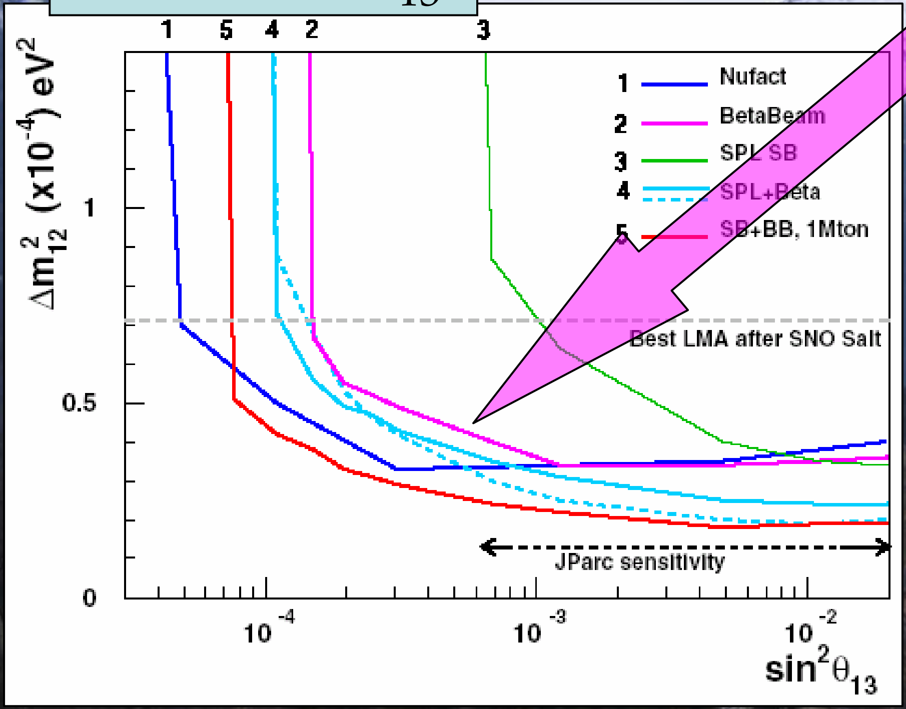


Intensity objectives

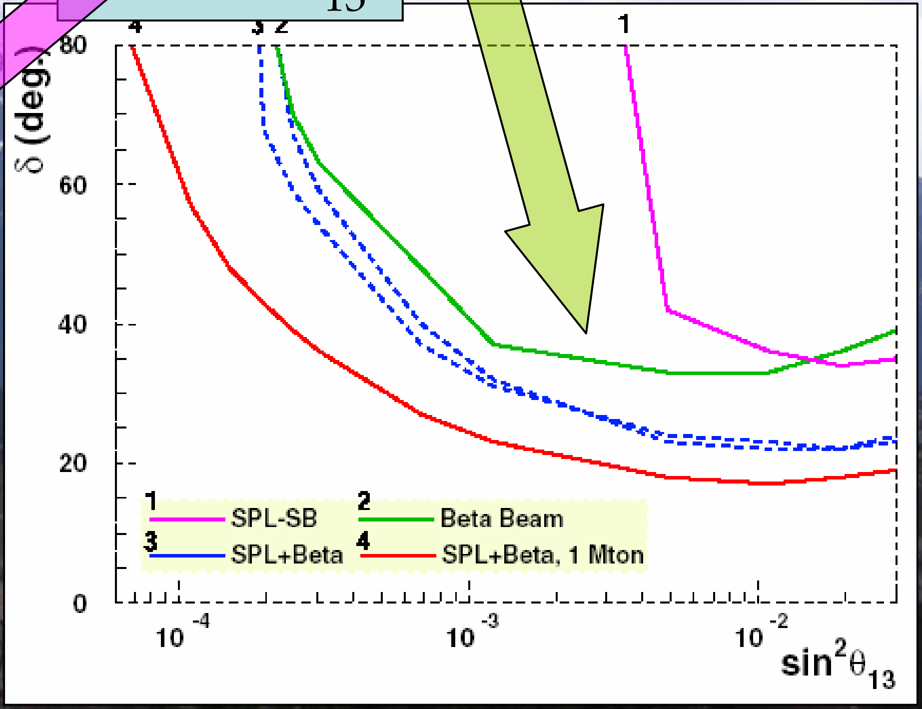
^{6}Helium^{2+}	^{18}Neon^{10+} (single target)
- In Decay ring: 1.0×10^{14} ions	- In decay ring: 4.5×10^{12} ions
- Energy: 139 GeV/u	- Energy: 55 GeV/u
- Rel. gamma: 150	- Rel. gamma: 60
- Rigidity: 1500 Tm	- Rigidity: 335 Tm

Sensitivities of Super & β Beams

To Δm^2 vs ϑ_{13}

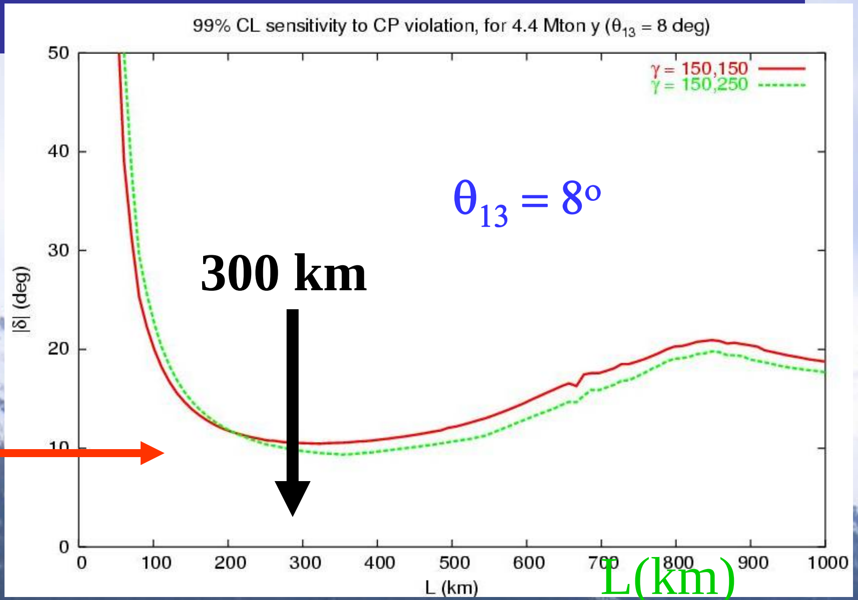


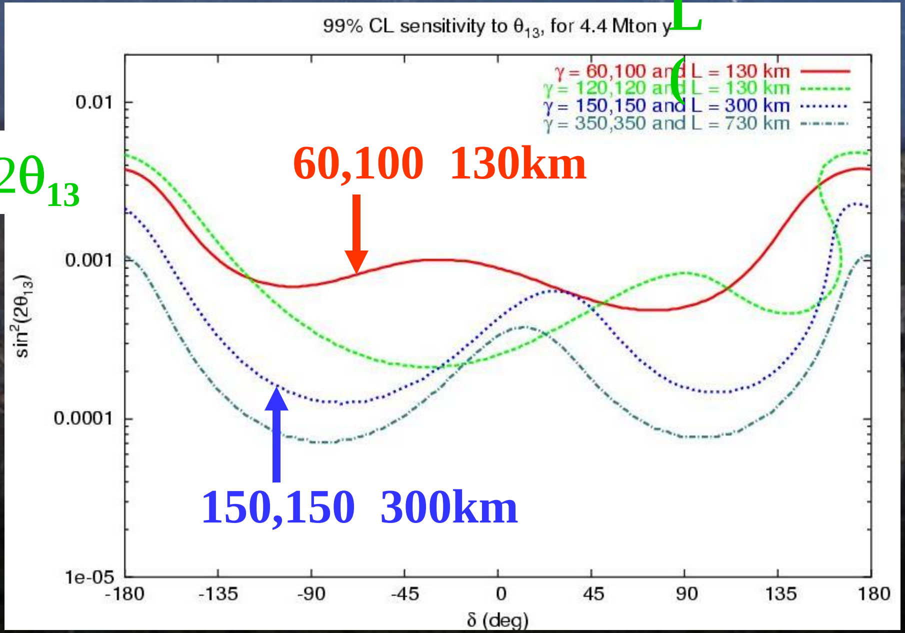
To δ vs ϑ_{13}



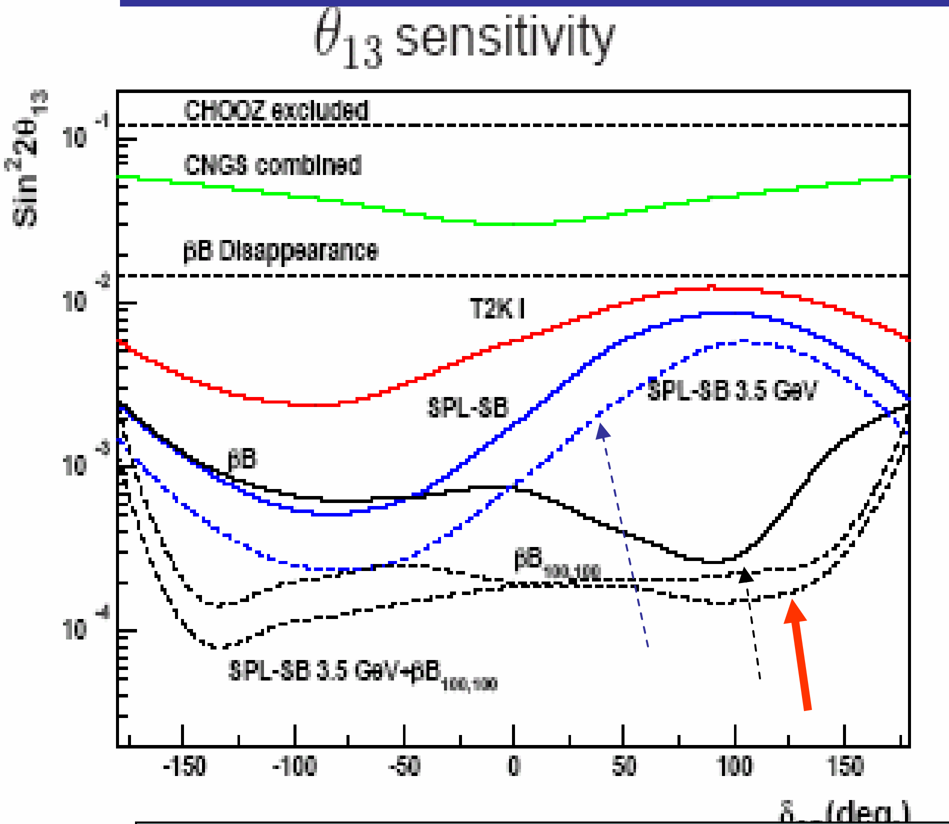
Fix γ at Maximum SPS Value: 150.

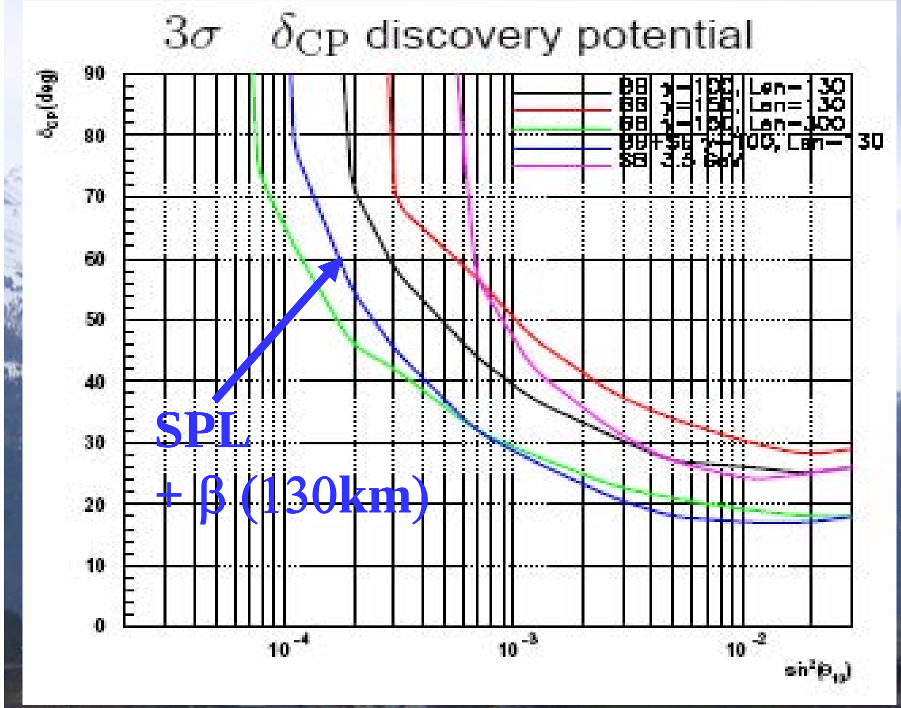
- For this γ the optimum distance is
  300 km
- The 99% CL δ reach can be improved
  from 15° to 10°.
- The θ_{13} sensitivity can also be improved substantially
- But no laboratory at this distance!





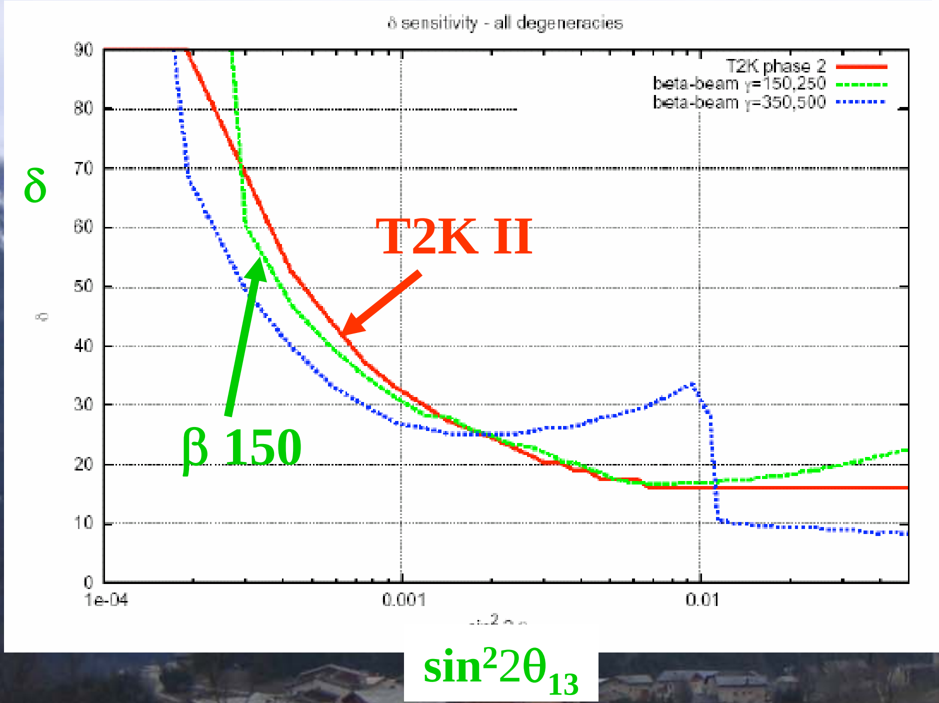
Combining SPL and β-Beams

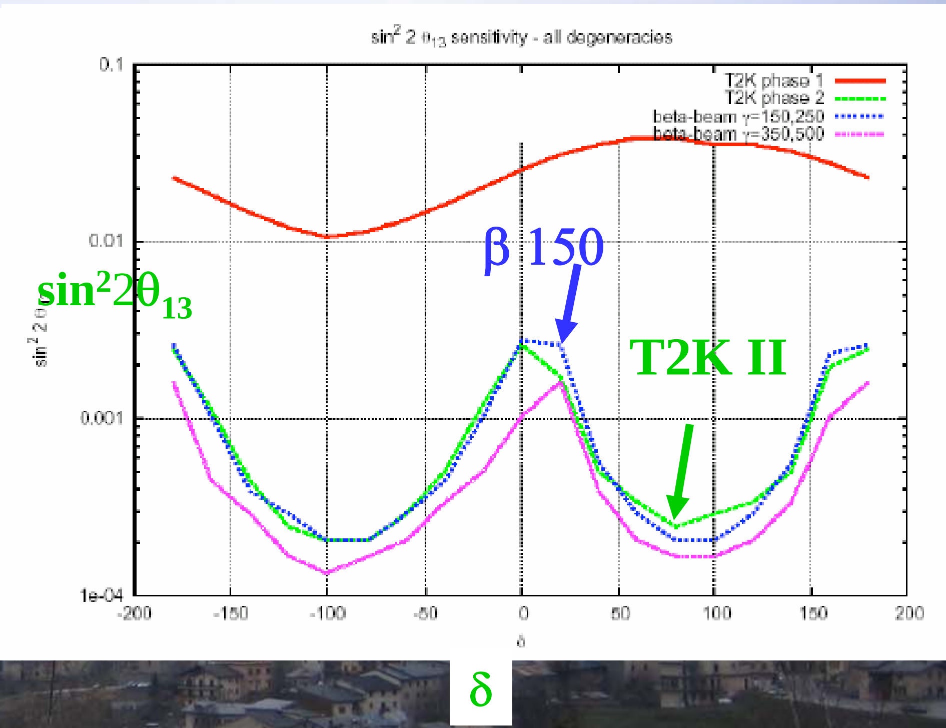




- The β-beam is more sensitive than an SPL beam.
- The β-beam only requires the SPL for 10% of its up time.
- Can therefore run an SPL beam at the SAME TIME as the β-beams.
- The combination improves over the β-beam alone.

T2K II vs β-Beam





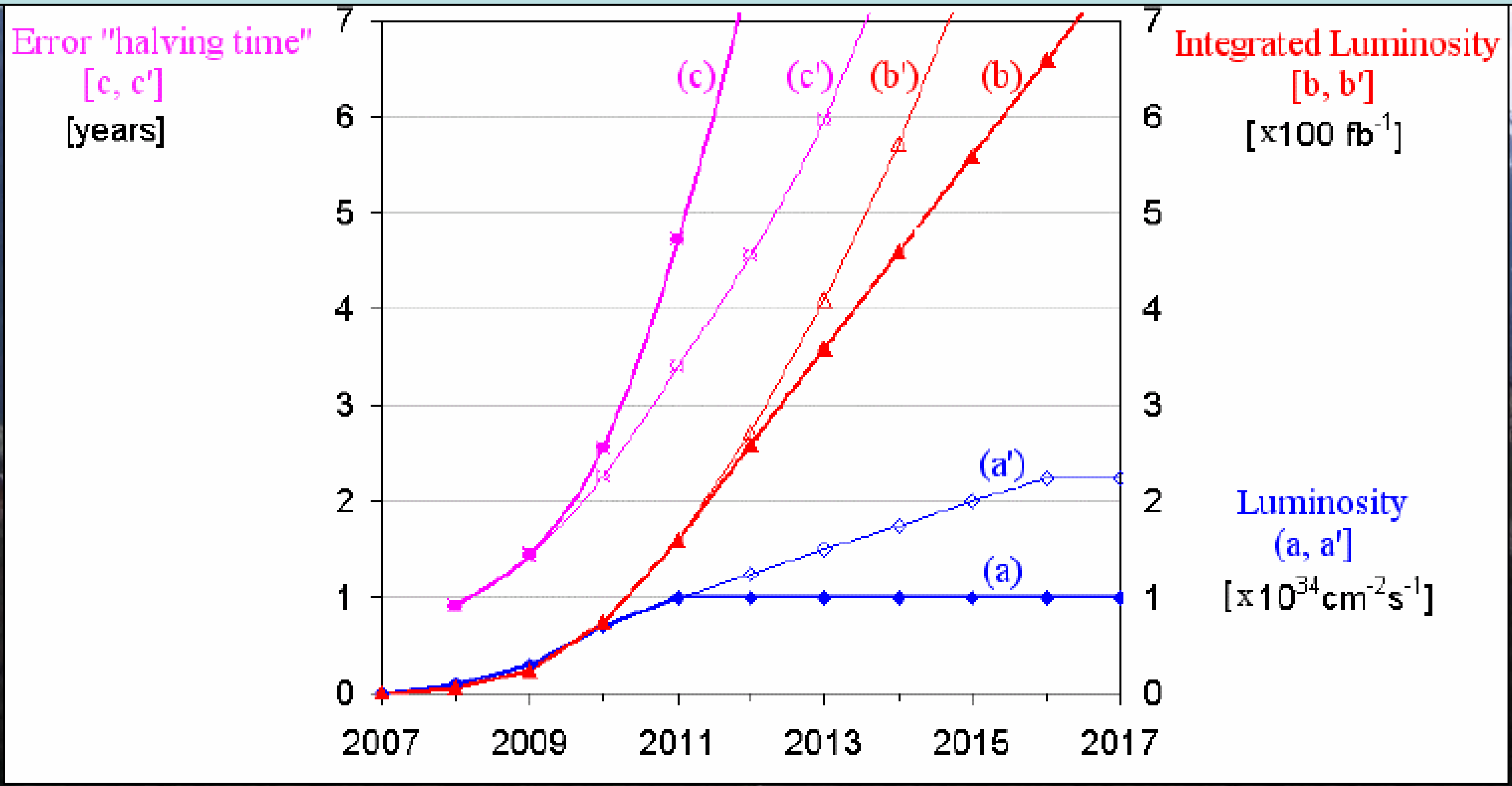
T2K Phase II and β-beam (γ = 150) have very similar CP reach and $\sin^2 2\theta_{13}$ sensitivity.

CERN Proton Driver Physics Matrix

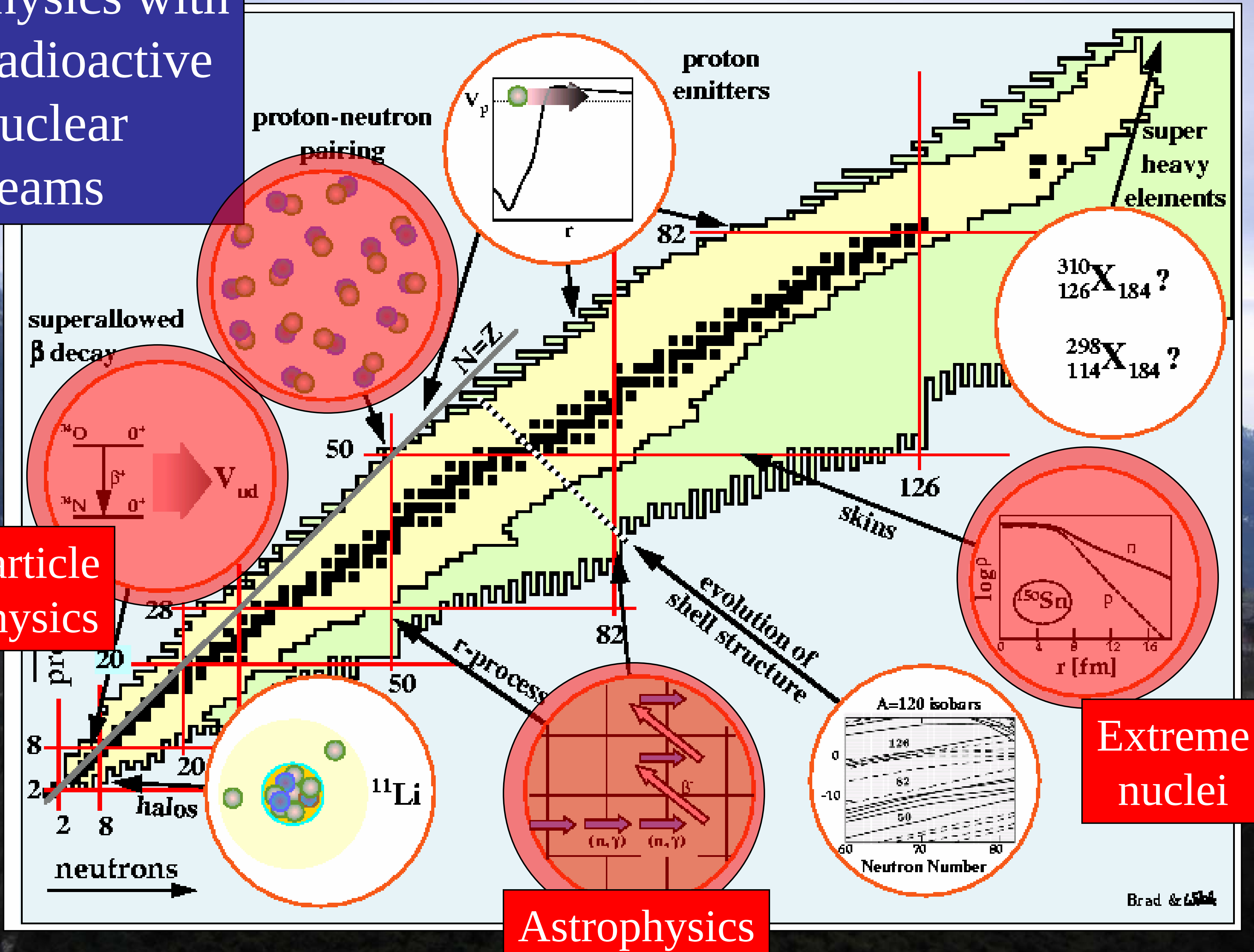
Present accelerator	Replacement accelerator	Improvement	INTEREST FOR			
			LHC upgrade	ν physics beyond CNGS	RIB beyond ISOLDE	Physics with k and μ
Linac2	Linac4	50 → 160 MeV $H^+ \rightarrow H^-$	+	0 (if alone)	0 (if alone)	0 (if alone)
PSB	2.2 GeV RCS* for HEP	1.4 → 2.2 GeV 10 → 250 kW	+	0 (if alone)	+	0 (if alone)
	2.2 GeV/mMW RCS*	1.4 → 2.2 GeV 0.01 → 4 MW	+	++ (super-beam, β-beam ?, ν factory)	+ (too short beam pulse)	0 (if alone)
	2.2 GeV/50 Hz SPL*	1.4 → 2.2 GeV 0.01 → 4 MW	+	+++ (super-beam, β-beam, ν factory)	+++	0 (if alone)
PS	SC PS*/** for HEP	26 → 50 GeV Intensity x 2	++	0 (if alone)	0	+
	5 Hz RCS*/**	26 → 50 GeV 0.1 → 4 MW	++	++ (ν factory)	0	+++
SPS	1 TeV SC SPS*/**	0.45 → 1 TeV Intensity x 2	+++	?	0	+++

Possible Upgrades of LHC

Increase luminosity – but beware of integrated radiation dose



Physics with Radioactive Nuclear Beams



Muon Physics

- Proton source produces many muons
- Rare μ decays

  $\mu \rightarrow e\,\gamma$, $\mu \rightarrow eee$,

  $\mu A \rightarrow e A$

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

  Expected in susy seesaw model: probe unknown parameters
- Dipole moments:

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

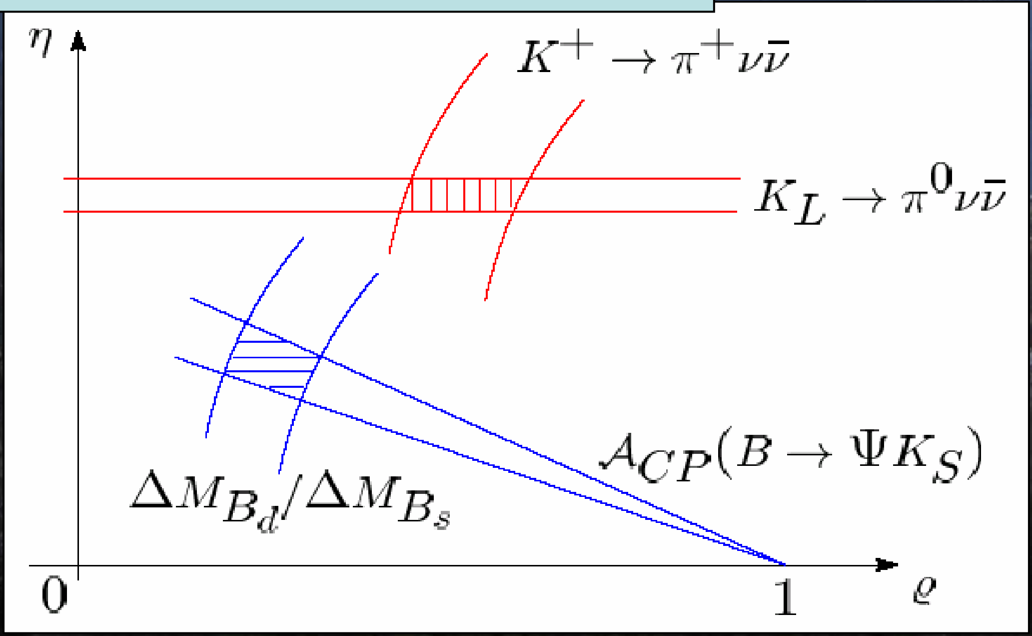
  (radioactive) μ-ic atoms, muonium, μ-ic Hydrogen

Rare K Decays

Many kaons produced if high-energy source or booster ring

$K \rightarrow \pi\nu\nu$:

Alternative window
on CKM unitarity triangle



Possible window
on physics beyond SM

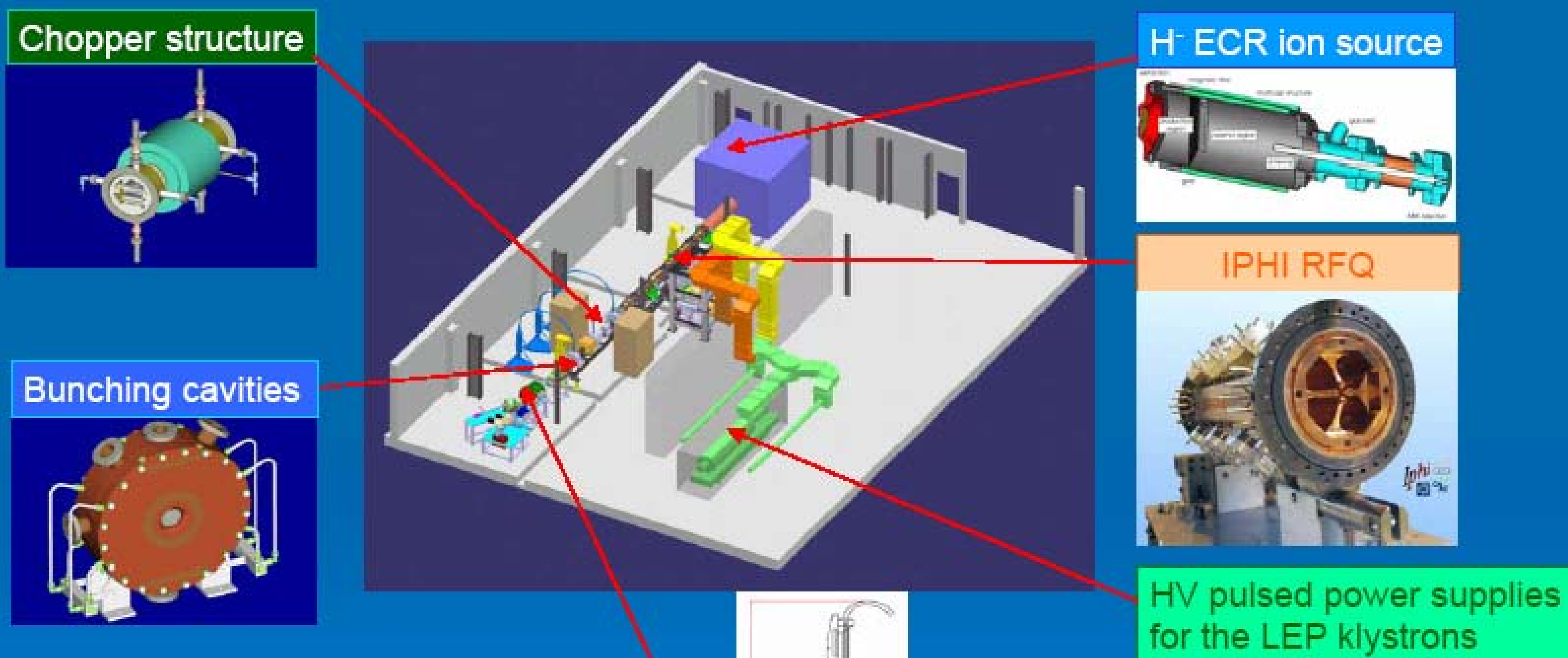
Decay mode	BR limit (90% CL)
$K^+ \to \pi^+\mu^+e^-$	2.8×10^{-11}
$K^+ \to \pi^+\mu^-e^+$	5.2×10^{-10}
$K^+ \to \pi^-e^+e^+$	6.4×10^{-10}
$K^+ \to \pi^-\mu^+\mu^+$	3.0×10^{-9}
$K^+ \to \pi^-\mu^+e^+$	5.0×10^{-10}
$K_L \to \mu e$	4.7×10^{-12}
$K_L \to \mu\mu ee$	4.12×10^{-11}
$K_L \to \pi^0\mu e$	6.2×10^{-9}

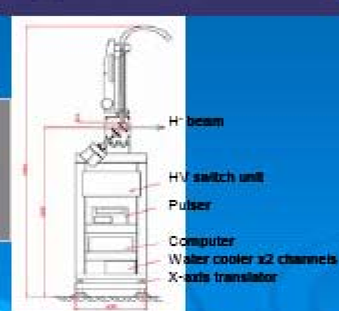
Possibilities @ CERN

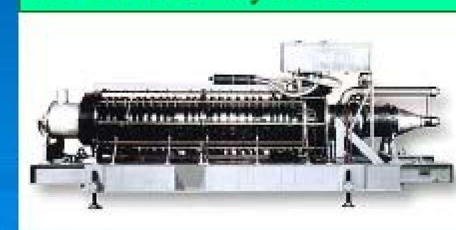
Stage 1: 3 MeV Test Facility

In construction. To be operational in 2007.

(RFQ from CEA Saclay, 3 MeV chopping line from CERN).

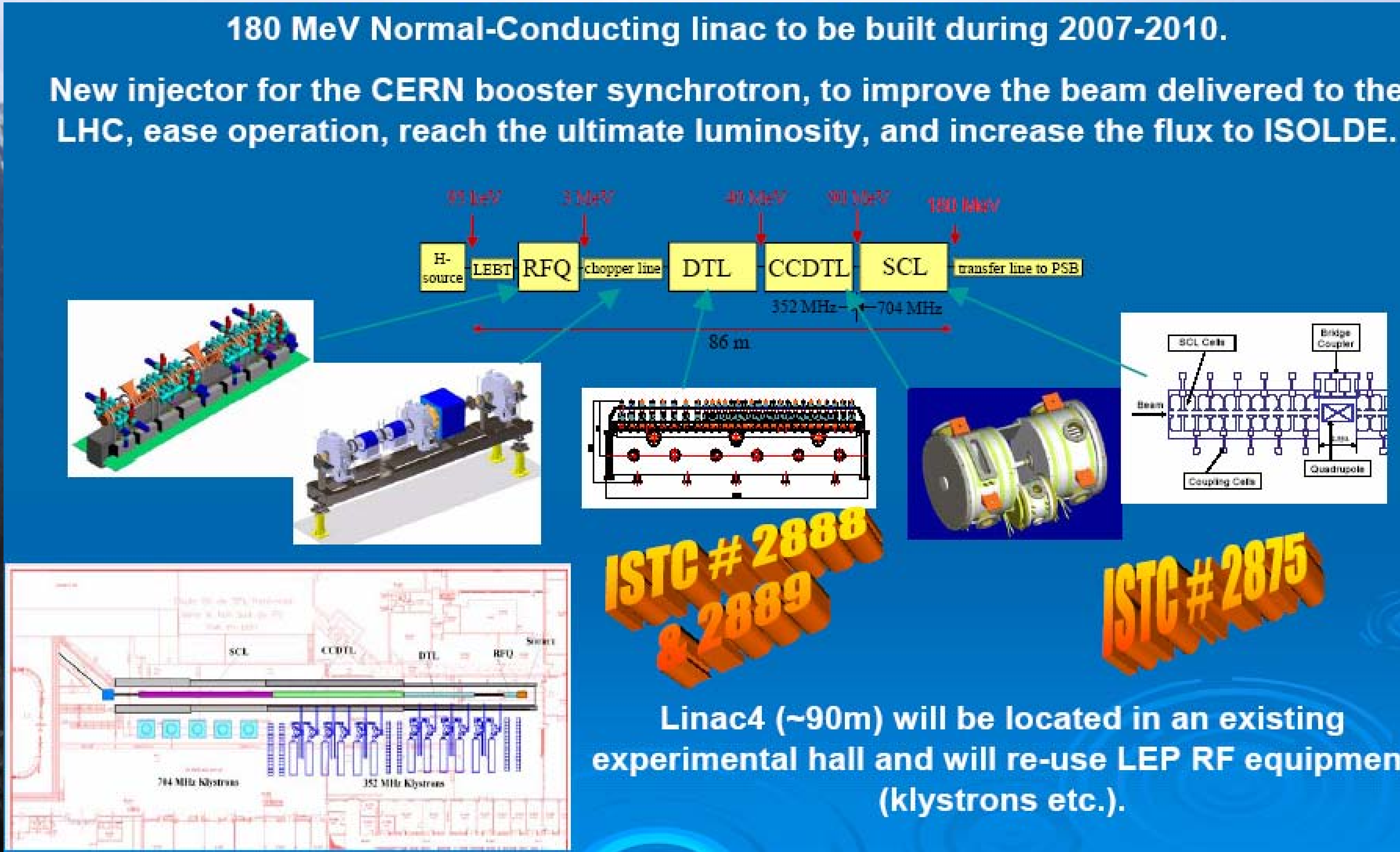




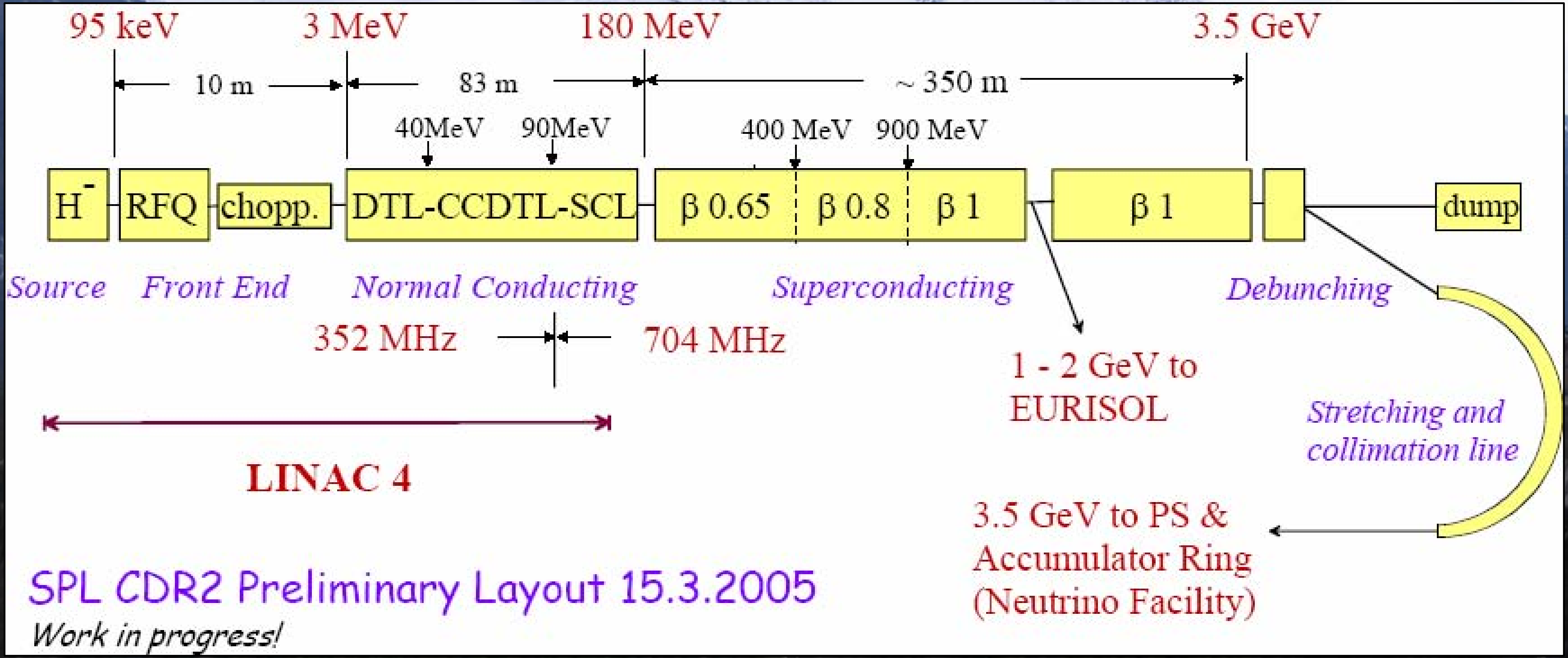


The 3 MeV test stand will become the front-end of Linac4 and SPL

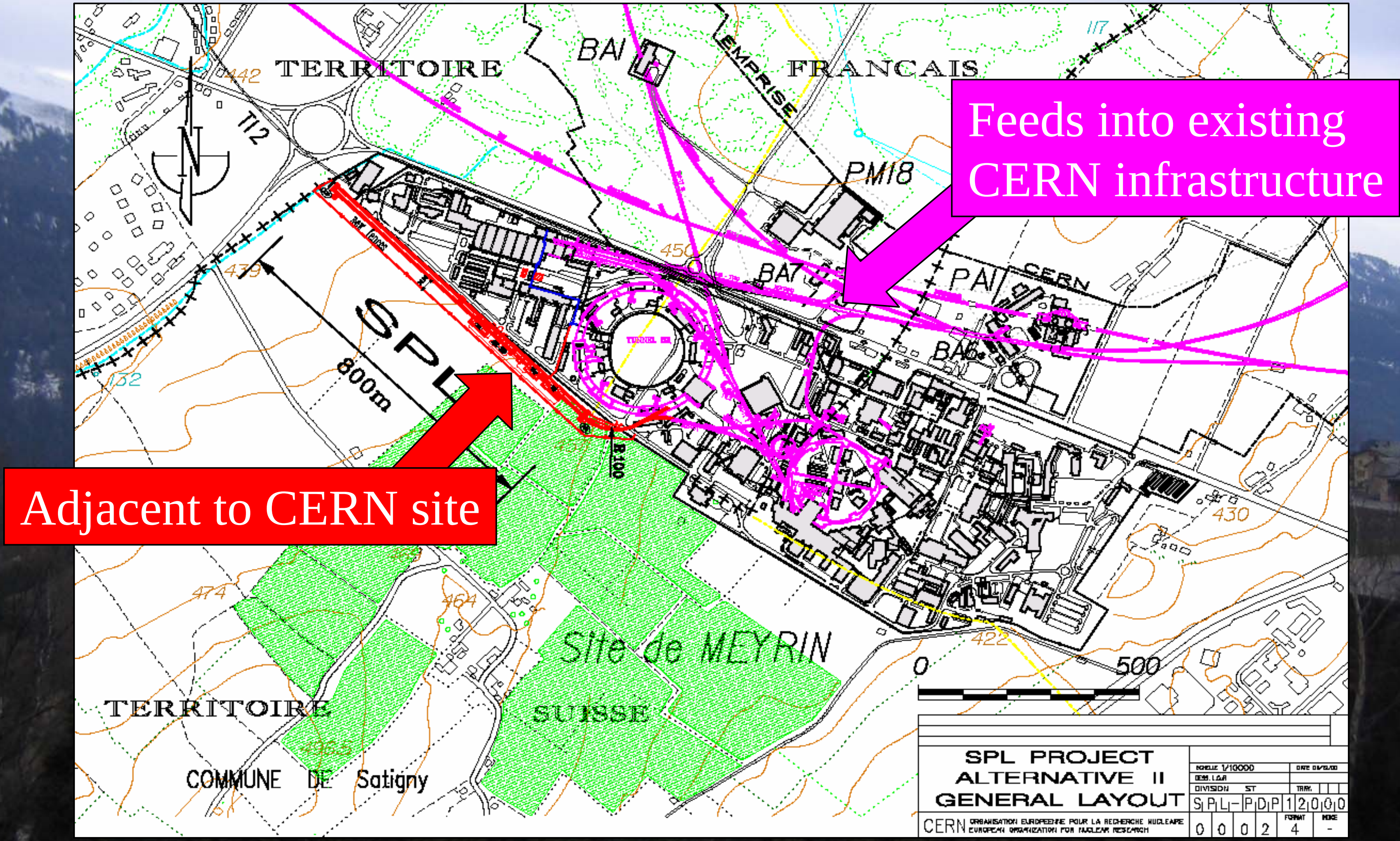
Stage 2: Linac 4



Stage 3: SPL @ 3.5 GeV



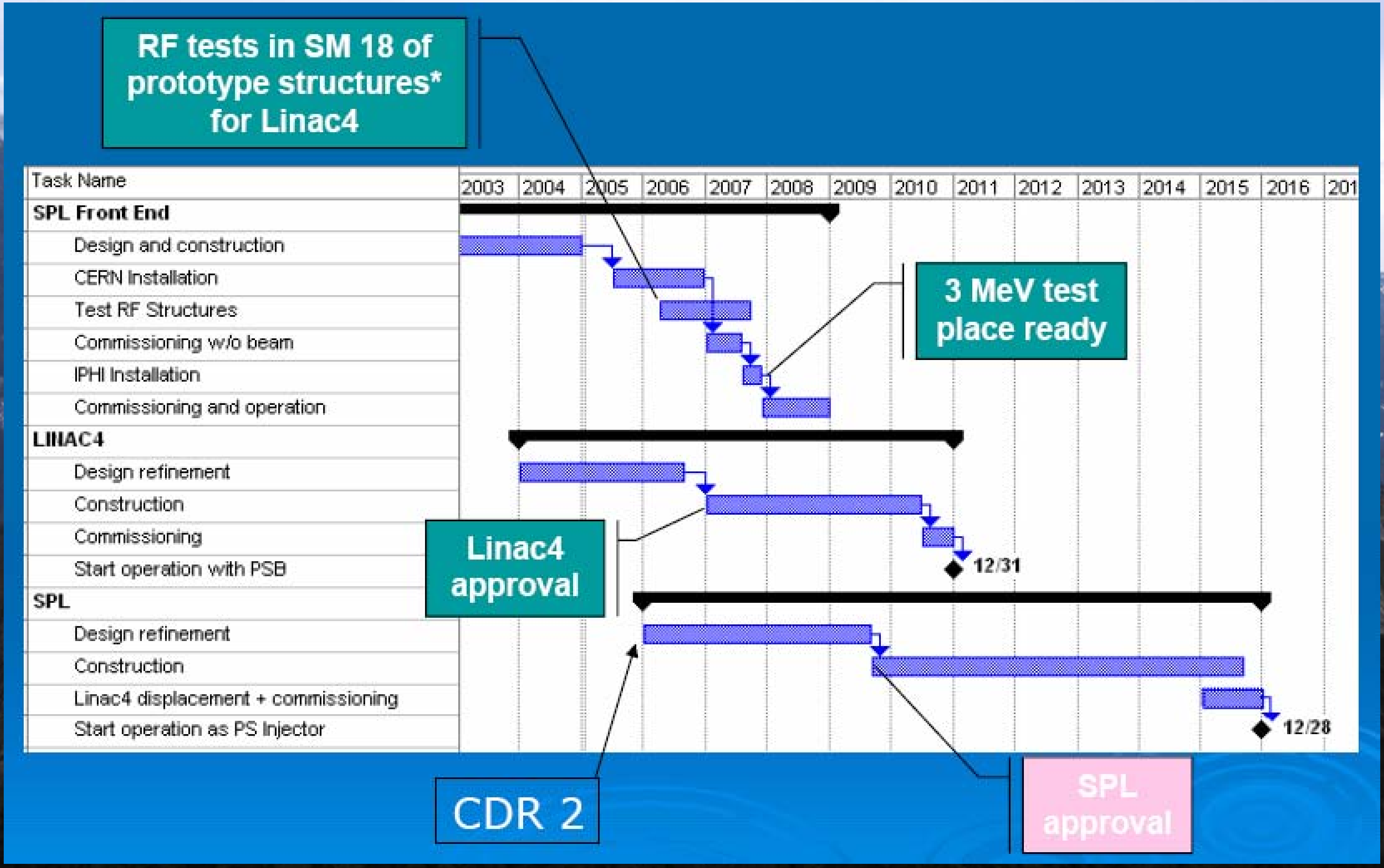
Possible Layout of SPL at CERN



CDRS2 Parameters

Ion species	H^-	
Kinetic energy	3.5	GeV
Mean current during the pulse	40 (30 ?)	mA
Mean beam power	4	MW
Pulse repetition rate	50	Hz
Pulse duration	0.57 (0.76 ?)	ms
Bunch frequency	352.2	MHz
Duty cycle during the pulse	62 (5/8)	%
rms transverse emittances	0.4	π mm mrad
Longitudinal rms emittance	0.3	π deg MeV

SPL Global Planning



Milestones for β-Beam Study

- feb 05 start of beta-beam task as a part of EURISOL design study
- end 05 confirm baseline scenario and parameter choice
- end 09 beta-beam Conceptual Design Report and cost estimate

Summary

- There is a lot of life in proton decay
- A large undergound detector would also have great opportunities in ν physics:

  Θ_{13}, δ, sign Δm^2_{23}, …
- Prospective synergies with collider physics

  Susy $\leftrightarrow$ proton decay, LHC upgrade
- NNN physics is great in its own right,

  and as complement to collider physics