ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

New physics without new energy scale

Mikhail Shaposhnikov

2011 CHIPP Annual Plenary Meeting

Outline

- “No new scale” paradigm
- “No new scale” cosmology and phenomenology
- Summary: “No new scale” predictions

“No new scale” paradigm

The Standard Model cannot accommodate a number of cosmological observations (dark matter, dark energy, baryon asymmetry, inflation) and discoveries in neutrino physics, it also has a number of “fine tuning” problems from theory side.

Our strategy

- Select the most important problems to solve (may be subjective).
- Use Ockham’s razor principle: *“Frustra fit per plura quod potest fieri per pauciora”* or ”entities must not be multiplied beyond necessity”. For particle physics: entities = new hypothetical particles and new scales different from Fermi and Planck scales.

SM problems and possible solutions

Hierarchy problem: stability of the Higgs mass against radiative corrections

Possible solutions:

- Compensation of divergent diagrams by new particles at TeV scale (supersymmetry, composite Higgs boson). Consequence: new physics at LHC

SM problems and possible solutions

- New symmetry – exact, but spontaneously broken scale invariance. Higgs mass is kept small in the same way as photon mass is kept zero by gauge invariance. Consequences: validity of the SM all the way up to the Planck scale, nothing but the Higgs at LHC in the mass interval $m_{\min} < m_H < m_{\max}$

  $$m_{\min} = [129.5 \pm 2\ (exp) \pm 2\ (theor)]\ \mathrm{GeV}$$

  $$m_{\max} \simeq 175\ \mathrm{GeV}$$

  Existence of massless particle – dilaton, which can play the role of Dark Energy.

  Asymptotic safety prediction: $m_H = m_{\min}$.

SM problems and possible solutions

The universe is flat, homogeneous and isotropic with high accuracy. It contained in the past small density fluctuations that lead to structure formation

Possible solution: inflation.

The inflaton (scalar particle inflating the universe) is

- new particle with the mass of the order of 10^{13} GeV and minimal coupling to gravity

Alternative

- SM Higgs boson with non-minimal coupling to gravity

SM problems and possible solutions

Neutrino masses and oscillations

Possible solutions:

- See-saw mechanism: existence of several superheavy ($M \sim 10^{10}$ GeV) neutral leptons. Direct experimental consequences: none, as the mass is too large to be accessed

Alternative

- Existence of new leptonic flavours with masses similar to those of known quarks and leptons. Experimental consequence: possibility of direct experimental search

SM problems and possible solutions

Dark matter

Possible solutions:

- WIMPS with masses of the order of 100 GeV and roughly electroweak cross-sections (e.g. SUSY neutralino). Consequences: new particles at LHC, success of WIMP searches

Alternative

- Super-WIMPS with masses in keV region. Natural possibility: new neutral leptonic flavour with mass of few keV. Consequences: no DM candidates at LHC, failure of WIMP searches. Possibility of search through radiative processes $N \to \nu\gamma$ which leads to existence of narrow X-ray line in direction of DM concentrations.

SM problems and possible solutions

Baryon asymmetry of the Universe

Possible solutions:

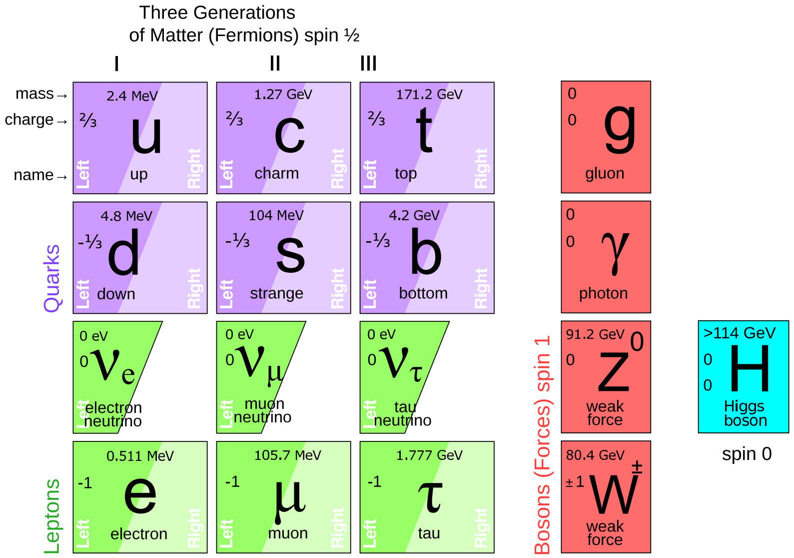
- Baryogenesis due to new physics above the electroweak scale. Potential consequences: new particles at LHC (for electroweak baryogenesis)

Alternative

- Baryogenesis due to new neutral leptonic flavours with masses in the region from 140 MeV up to few GeV. Experimental consequence: possibility of direct experimental search

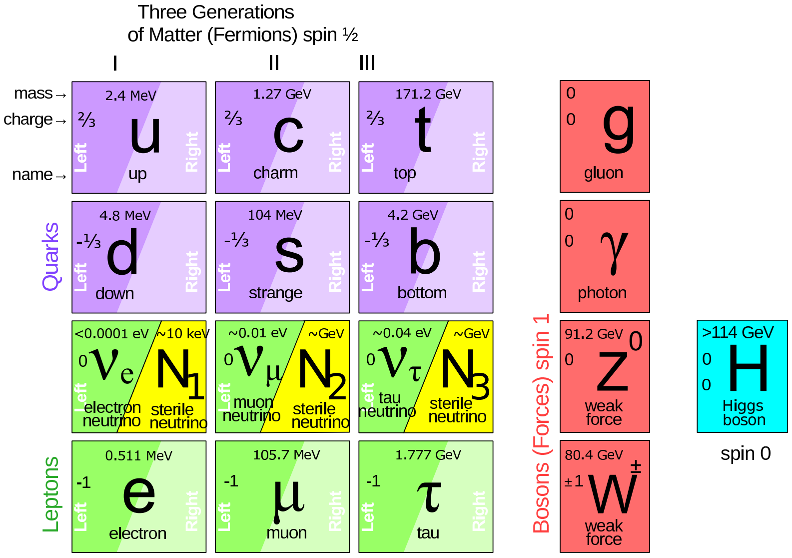
“No new scale” cosmology and phenomenology

Realisation: νMSM



Three Generations of Matter (Fermions) spin ½

	I	II	III	Bosons (Forces) spin 1	
mass→ charge→ name→ (Quarks)	2.4 MeV ⅔ u up	1.27 GeV ⅔ c charm	171.2 GeV ⅔ t top	0 0 g gluon	
Quarks	4.8 MeV -⅓ d down	104 MeV -⅓ s strange	4.2 GeV -⅓ b bottom	0 0 γ photon	
Leptons	0 eV 0 ν_e electron neutrino	0 eV 0 ν_μ muon neutrino	0 eV 0 ν_τ tau neutrino	91.2 GeV 0 Z^0 weak force	>114 GeV 0 0 H Higgs boson
Leptons	0.511 MeV -1 e electron	105.7 MeV -1 μ muon	1.777 GeV -1 τ tau	80.4 GeV ±1 $W^\pm$ weak force	spin 0



Three Generations of Matter (Fermions) spin ½

	I	II	III	Bosons (Forces) spin 1	
mass→ charge→ name→ (Quarks)	2.4 MeV ⅔ u up	1.27 GeV ⅔ c charm	171.2 GeV ⅔ t top	0 0 g gluon	
Quarks	4.8 MeV -⅓ d down	104 MeV -⅓ s strange	4.2 GeV -⅓ b bottom	0 0 γ photon	
Leptons	<0.0001 eV 0 ν_e electron neutrino ~10 keV N_1 sterile neutrino	~0.01 eV 0 ν_μ muon neutrino ~GeV N_2 sterile neutrino	~0.04 eV 0 ν_τ tau neutrino ~GeV N_3 sterile neutrino	91.2 GeV 0 Z^0 weak force	>114 GeV 0 0 H Higgs boson
Leptons	0.511 MeV -1 e electron	105.7 MeV -1 μ muon	1.777 GeV -1 τ tau	80.4 GeV ±1 $W^\pm$ weak force	spin 0

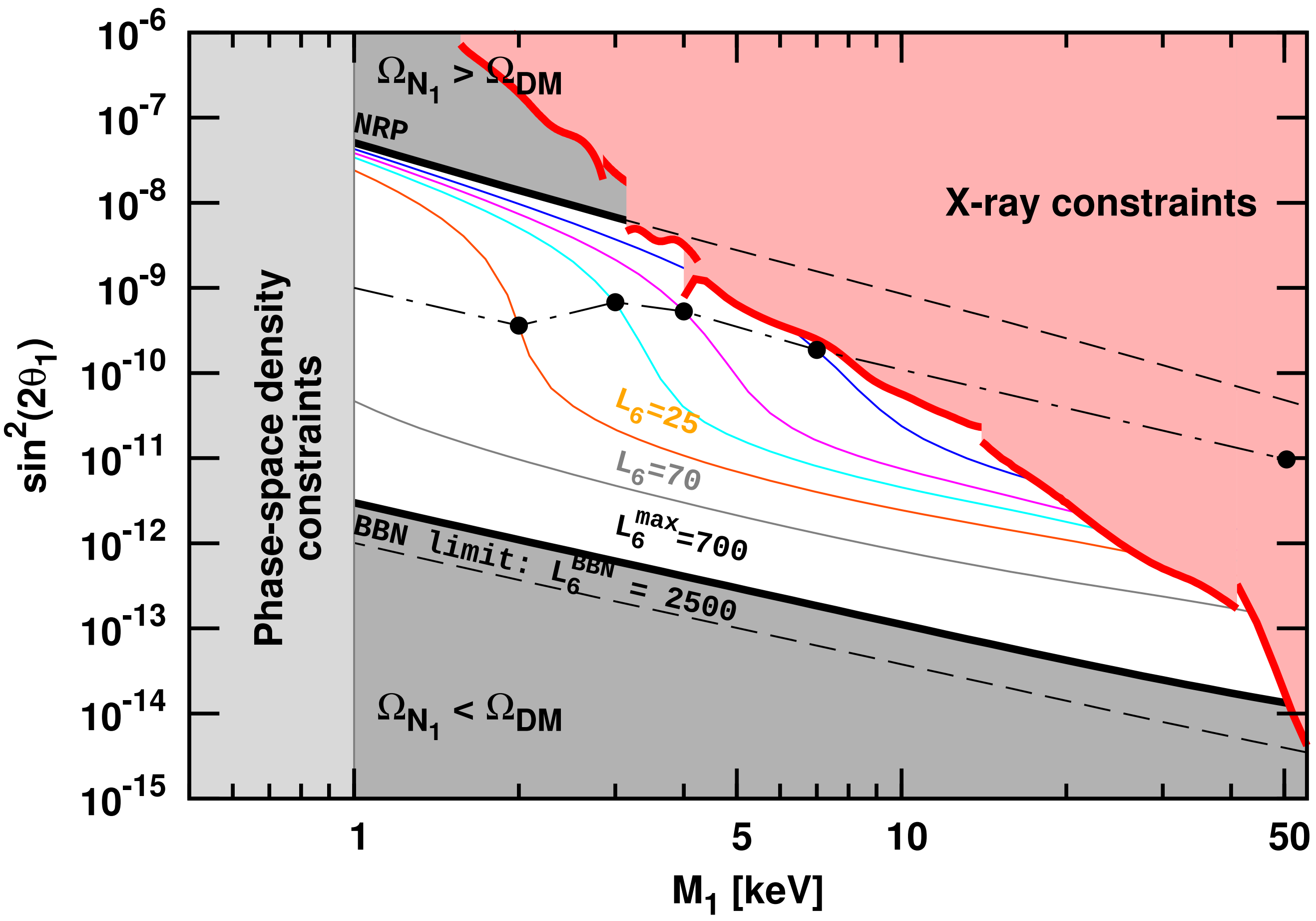
Role of N_e with mass in keV region: dark matter

Role of N_μ, N_τ with mass in 100 MeV – GeV region: “give” masses to neutrinos and produce baryon asymmetry of the Universe

Role of the Higgs: give masses to quarks, leptons, Z and W and inflate the Universe.

Constraints on DM sterile neutrino, N_1

- Production. $\boldsymbol{N_1}$ are created in the early Universe in reactions $\boldsymbol{l\bar{l} \to \nu N_1, \quad q\bar{q} \to \nu N_1}$ etc. We should get correct DM abundance.
- Structure formation. If $\boldsymbol{N_1}$ is too light it may have considerable free streaming length and erase fluctuations on small scales. This can be checked by the study of Lyman-$\boldsymbol{\alpha}$ forest spectra of distant quasars and structure of dwarf galaxies.
- X-rays. $\boldsymbol{N_1}$ decays radiatively, $\boldsymbol{N_1 \to \gamma\nu}$, producing a narrow line which can be detected by X-ray telescopes (such as Chandra or XMM-Newton). This line has not been seen yet.



Important: DM sterile neutrino production requires the presence of large, $\Delta L/L > 2 \times 10^{-3}$ lepton asymmetry at temperature $T \sim 100$ MeV. It can only be produced in the νMSM.

How to find DM sterile neutrino

Boyarsky et al: Flux from DM decay $N_1 \to \nu\gamma$:

$$F_{\rm dm} = \frac{\Gamma_{\rm rad} M_{\rm dm}^{\rm fov}}{8\pi D_L^2} \approx \frac{\Gamma_{\rm rad}\Omega_{\rm fov}}{8\pi} I, \quad I = \int_{\text{line of sight}} \rho_{\rm dm}(r)dr$$

(Valid for small redshifts $z \ll 1$, and small fields of view $\Omega_{\rm fov} \ll 1$)

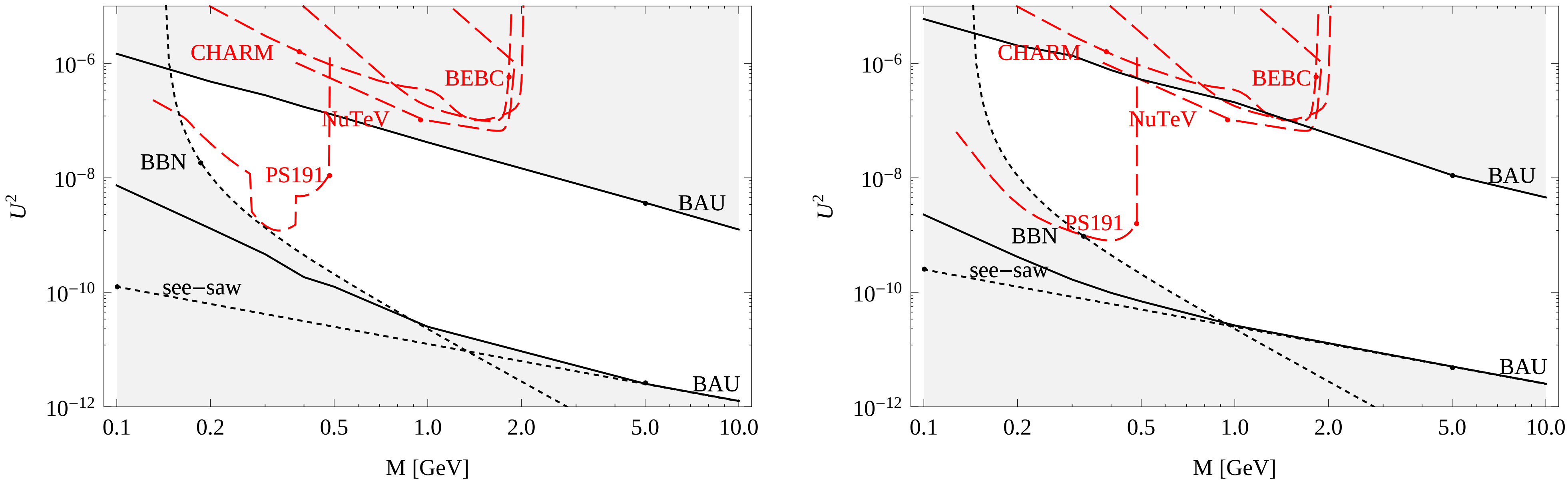
Strategy: Use X-ray telescopes (such as Chandra and XMM Newton) to look for a narrow γ line against astrophysical background. Choose astrophysical objects for which:

- The value of line of sight DM density integral I is maximal
- The X-ray background is minimal

Result: Look at Milky Way and dwarf satellite galaxies

Constraints on BAU sterile neutrinos $N_{2,3}$

- BAU generation requires out of equilibrium: mixing angle of $\boldsymbol{N_{2,3}}$ to active neutrinos cannot be too large
- Neutrino masses. Mixing angle of $\boldsymbol{N_{2,3}}$ to active neutrinos cannot be too small
- BBN. Decays of $\boldsymbol{N_{2,3}}$ must not spoil Big Bang Nucleosynthesis
- Experiment. $\boldsymbol{N_{2,3}}$ have not been seen yet.



Constraints on U^2 coming from the baryon asymmetry of the Universe (solid lines), from the see-saw formula (dotted line) and from the big bang nucleosynthesis (dotted line). Experimental searched regions are in red - dashed lines. Left panel - normal hierarchy, right panel - inverted hierarchy. Gorbunov, M.S., Canetti

Experimental signatures 1

Challenge - from baryon asymmetry: $\theta^2 \lesssim 5 \times 10^{-7} \left(\frac{\mathrm{GeV}}{M}\right)$

- Peak from 2-body decay and missing energy signal from 3-body decays of K, D and B mesons (sensitivity θ^2)

  Example:

  $$K^+ \to \mu^+ N, \quad M_N^2 = (p_K - p_\mu)^2 \neq 0$$

  Similar for charm and beauty.

  - $M_N < M_K$: NA62
  - $M_K < M_N < M_D$: charm and τ factories
  - $M_N < M_B$: B-factories (planned luminosity is not enough to get into cosmologically interesting region)

Experimental signatures 2

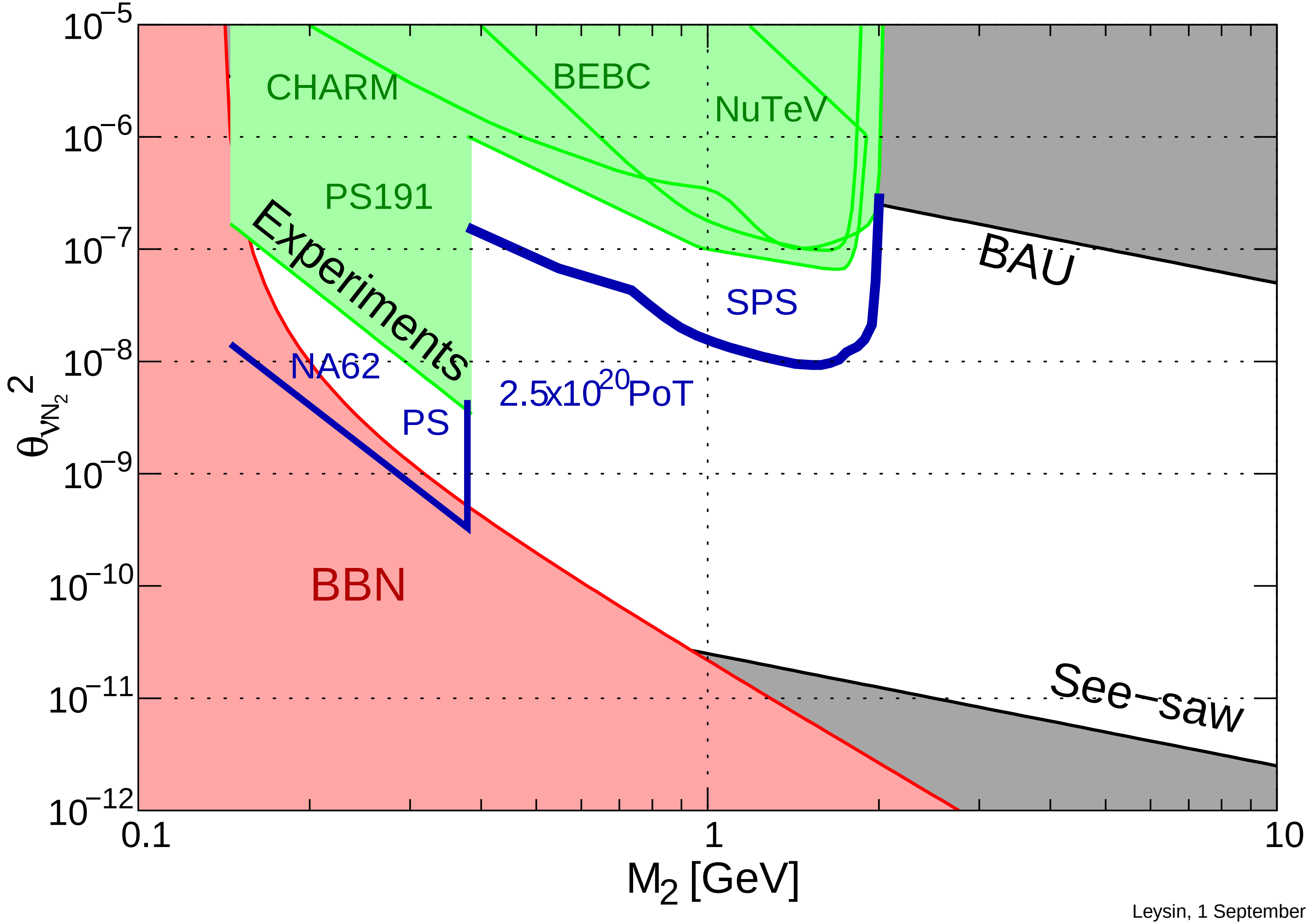
- Two charged tracks from a common vertex, decay processes $N \to \mu^+\mu^-\nu$, etc. (sensitivity $\theta^4 = \theta^2 \times \theta^2$)

  First step: proton beam dump, creation of N in decays of $K,\ D$ or B mesons: θ^2

  Second step: search for decays of N in a near detector, to collect all Ns: θ^2

  - $M_N < M_K$: Any intense source of K-mesons (e.g. from proton targets of PS.)
  - $M_N < M_D$: Best option: SPS beam + near detector
  - $M_N < M_B$: Project X (?) + near detector
  - $M_N > M_B$: extremely difficult

CERN SPS is the best existing machine to uncover new physics below the electroweak scale. Sensitivity is proportional to total delivered protons on target. Incorporate to LAGUNA?



“No new scale” predictions

(made mostly in 2005-2007)

- **LHC physics**
  - Nothing but the Higgs with the mass in the window $M_H \in [\mathbf{129}, \mathbf{175}]\ \mathbf{GeV}$ in which the νMSM is a consistent theory below the Planck scale. Preference for the lower value of this interval.
  - No new sources of CP-violation in the hadronic sector

- **Neutrino physics**
  - Hierarchical structure of active neutrino masses with one of them smaller than $\mathcal{O}(10^{-5})$ eV.
  - Two other masses are fixed to be $m_3 = [4.8^{+0.6}_{-0.5}] \cdot 10^{-2}$ eV and $m_2 = [9.05^{+0.2}_{-0.1}] \cdot 10^{-3}$eV ($[4.7^{+0.6}_{-0.5}] \cdot 10^{-2}$eV) in the normal (inverted) hierarchy.
  - Double β decay: Majorana mass of electron neutrino is smaller than the atmospheric mass difference, $m_{ee} \leq 0.05$ eV

- **Dark matter searches.**
  - Negative result for the WIMP and axion searches.
  - The existence of a narrow X-ray line due to two-body decays of the sterile dark matter neutrino. The position and the intensity of this line are quite uncertain, with preference for a few keV energy range.
- **B-non-conservation.** No accessible proton decay or neutron-antineutron oscillations.
- **Flavour physics.** Existence of two almost degenerate weakly coupled singlet leptons with masses below M_W (with a preference for small masses $\lesssim 1$ GeV) which can be searched for in rare decays of mesons or τ-lepton and their own decays. Visible lepton number non-conservation in N decays, with CP-breaking that can allow to fix theoretically the sign and magnitude of the baryon asymmetry of the Universe.

Back up slides

Previous searches at CERN

- A. M. Cooper-Sarkar *et al.* [WA66 Collaboration] “Search For Heavy Neutrino Decays In The Bebc Beam Dump Experiment”, 1985
- J. Dorenbosch *et al.* [CHARM Collaboration] “A search for decays of heavy neutrinos in the mass range 0.5-GeV to 2.8-GeV”, 1985
- G. Bernardi *et al.*, “Search For Neutrino Decay”, 1986;
  “Further Limits On Heavy Neutrino Couplings”, 1988
- P. Astier *et al.* [NOMAD Collaboration], “Search for heavy neutrinos mixing with tau neutrinos”, 2001
- P. Achard *et al.* [L3 Collaboration], “Search for heavy neutral and charged leptons in e^+e^- annihilation at LEP”, 2001

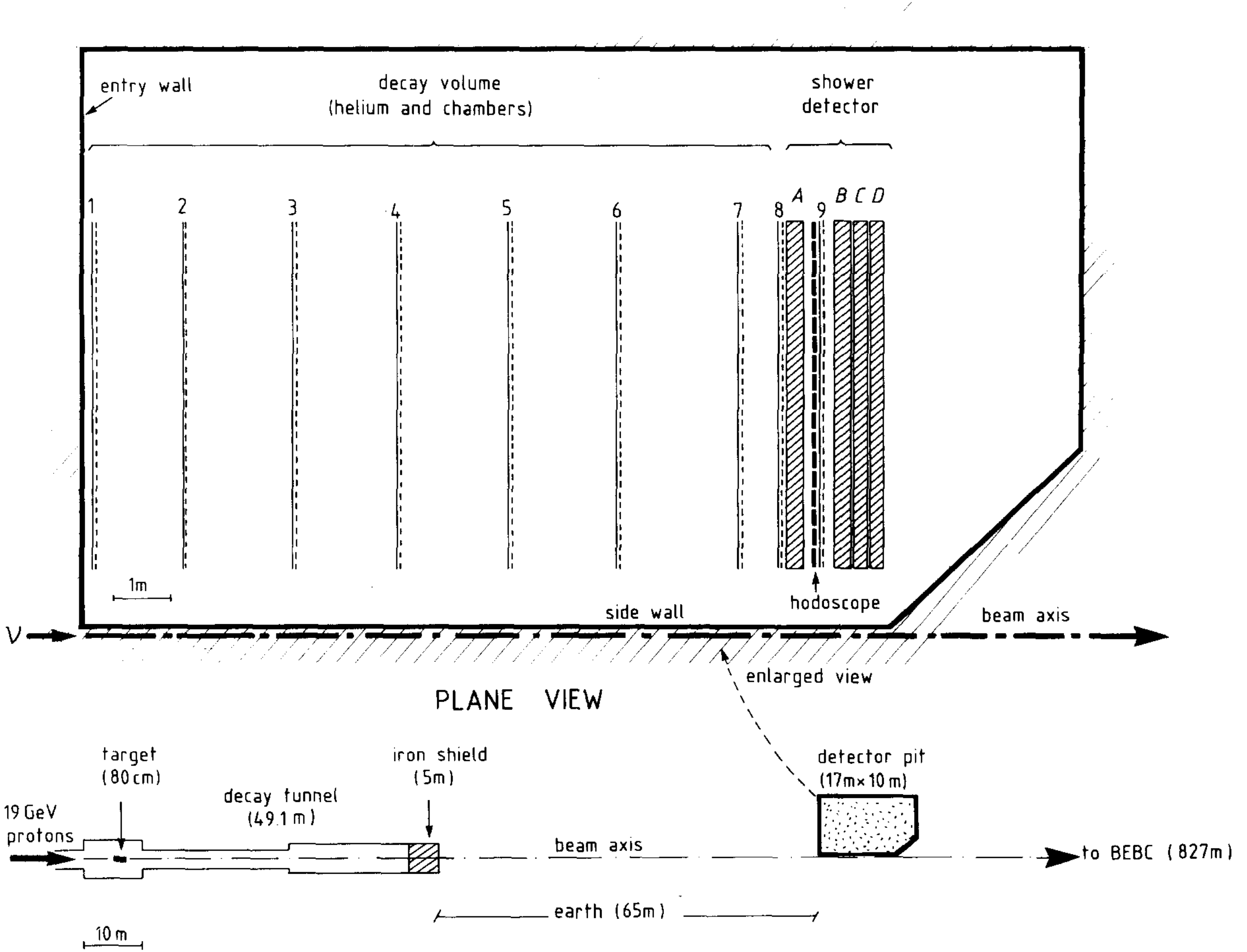
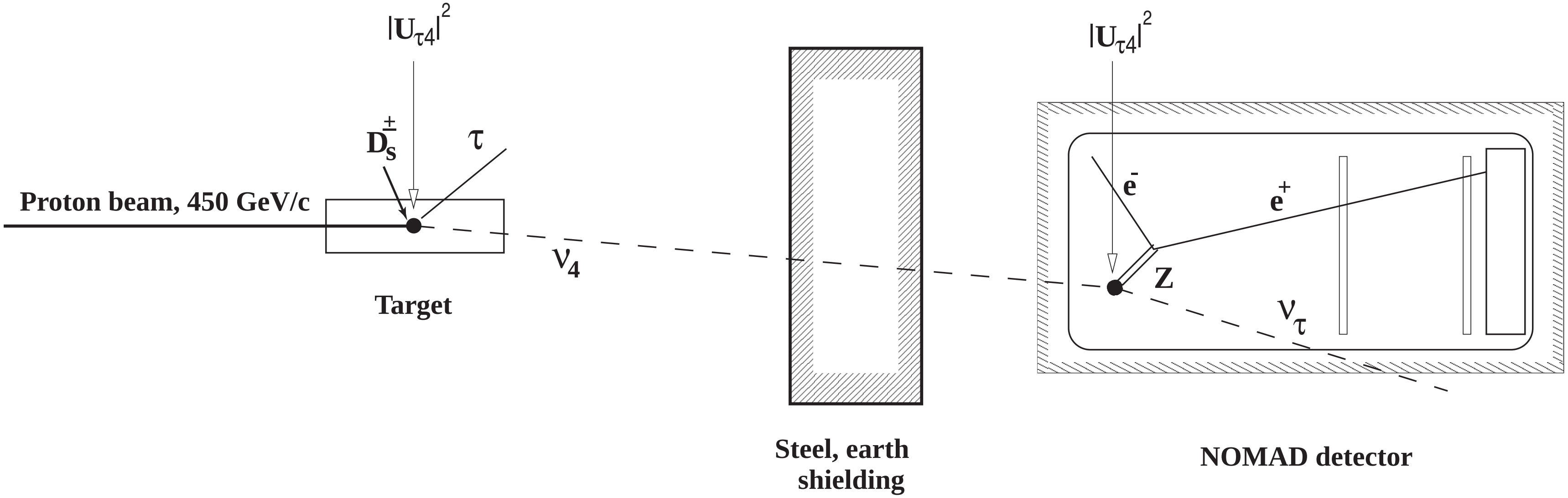


Fig. 1. Beam and layout of the detector.

$N_{2,3}$ production and decays



Type on neutrino mass hierarchy - from branching ratios of $N_{2,3}$ decays to e, μ, τ.

CP asymmetry can be as large as 1% - from BAU and DM

Prediction: active neutrino masses

Asaka, Blanchet, M.S: The minimal number of sterile neutrinos, which can explain the dark matter in the Universe and neutrino oscillations, is $\mathcal{N} = 3$. Only one sterile neutrino can be the dark matter. Lightest active neutrino:

$$m_1 \le 2 \cdot 10^{-3} \text{ eV.}$$

Normal hierarchy:

$$m_2 = [9.05^{+0.2}_{-0.1}] \cdot 10^{-3}\text{eV} \simeq \sqrt{\Delta m^2_{solar}} \,,$$

$$m_3 = [4.8^{+0.6}_{-0.5}] \cdot 10^{-2}\text{eV} \simeq \sqrt{\Delta m^2_{atm}} \,,$$

Inverted hierarchy: $m_{2,3} = [4.7^{+0.6}_{-0.5}] \cdot 10^{-2}$ eV .

Prediction: neutrinoless double β decay

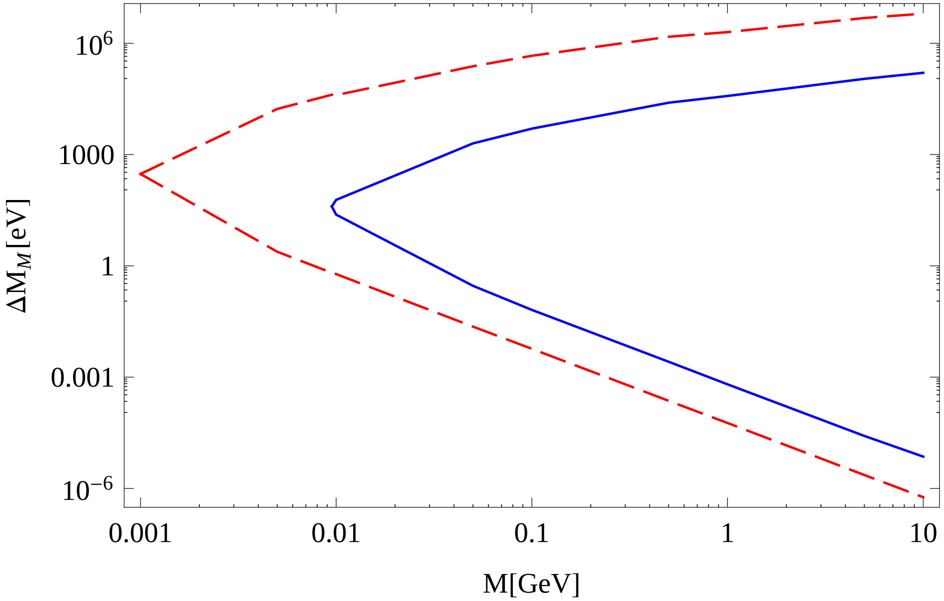
F. Bezrukov: Effective Majorana mass $m_{\beta\beta}$

Normal hierarchy: $1.3\ \mathrm{meV} < m_{\beta\beta} < 3.4\ \mathrm{meV}$

Inverted hierarchy: $13\ \mathrm{meV} < m_{\beta\beta} < 50\ \mathrm{meV}$

Knowing $m_{\beta\beta}$ experimentally will allow to fix Majorana CP-violating phases in neutrino mass matrix, provided θ_{13} and Dirac phase δ are known.

Prediction: degeneracy between N_2 and N_3



Values of $\boldsymbol{\Delta M_M}$ - $\boldsymbol{M}$ that leads to the observed baryon asymmetry for the normal hierarchy and for the inverted one. Main ‘fine tuning’ of the $\boldsymbol{\nu}$MSM.