ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

Particle Physics and Cosmology

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New Trends in Particle Physics,
Quantum Gravity & Cosmology

Outline

Lecture 2

- The current scene: LHC and ΛCDM
- Vacuum meta(?) stability
- Minimal physics for inflation: Higgs as an inflaton

Lecture 3

- Minimal physics for neutrino masses
- Baryogenesis
- Dark Matter
- Conclusions

Baryon asymmetry and dark matter

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- Ockham’s razor in action, 2 step logic:

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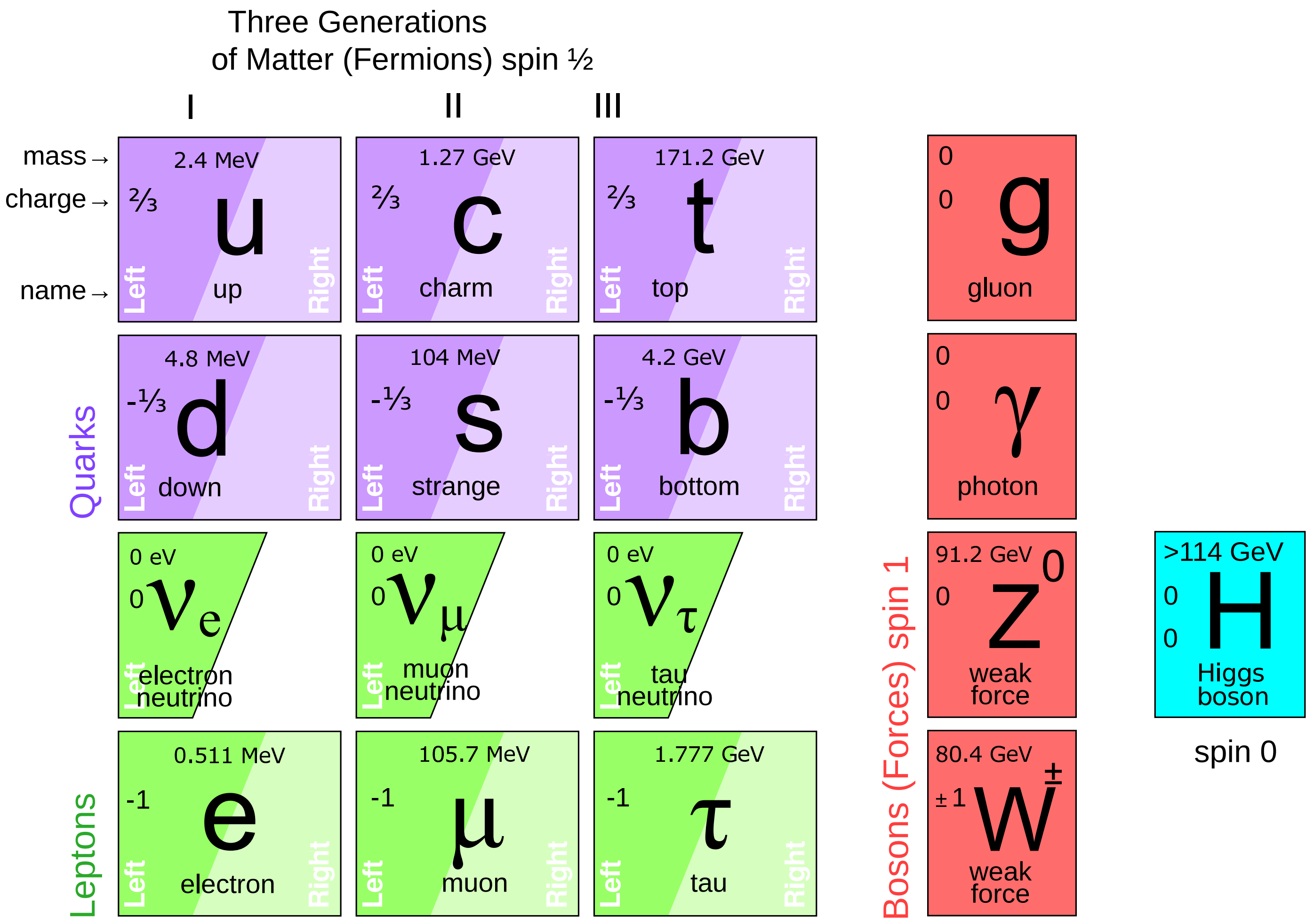
Baryon asymmetry and dark matter

- Ockham’s razor in action, 2 step logic:
- To explain neutrino masses we better have right-handed neutrinos
- Let’s use them for baryogenesis and dark matter!

the SM



Three Generations
of Matter (Fermions) spin ½

mass →
charge →
name →

	I	II	III
Quarks	2.4 MeV ⅔ u up Left Right	1.27 GeV ⅔ c charm Left Right	171.2 GeV ⅔ t top Left Right
	4.8 MeV -⅓ d down Left Right	104 MeV -⅓ s strange Left Right	4.2 GeV -⅓ b bottom Left Right
	0 eV 0 ν_e electron neutrino Left	0 eV 0 ν_μ muon neutrino Left	0 eV 0 ν_τ tau neutrino Left
Leptons	0.511 MeV -1 e electron Left Right	105.7 MeV -1 μ muon Left Right	1.777 GeV -1 τ tau Left Right

Bosons (Forces) spin 1

0 0 g gluon
0 0 γ photon
91.2 GeV 0 Z^0 weak force
80.4 GeV ±1 $W^\pm$ weak force

>114 GeV 0 0 H Higgs boson

spin 0

The missing piece: sterile neutrinos

Most general renormalizable (see-saw) Lagrangian

$$L_{see-saw} = L_{SM} + \bar{N}_I i\partial_\mu \gamma^\mu N_I - F_{\alpha I}\, \bar{L}_\alpha N_I \Phi - \frac{M_I}{2}\, \bar{N}_I^c N_I + h.c.,$$

Assumption: all Yukawa couplings with different leptonic generations are allowed.

$I \leq \mathcal{N}$ - number of new particles - HNLs - cannot be fixed by the symmetries of the theory.

Let us play with $\mathcal{N}$ to see if having some number of HNLs is good for something

- $\mathcal{N} = 1$: Only one of the active neutrinos gets a mass

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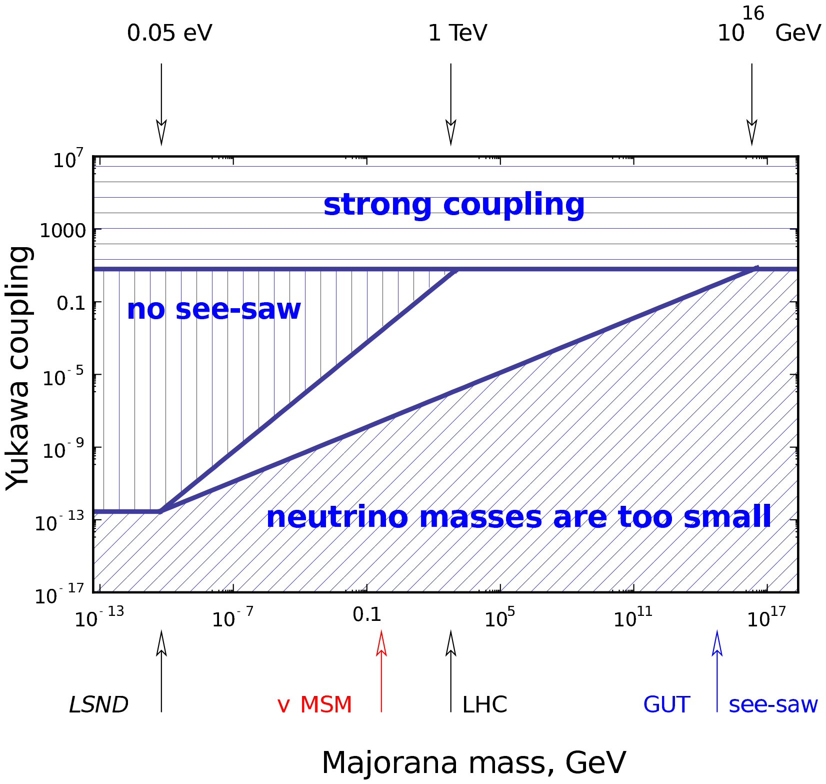
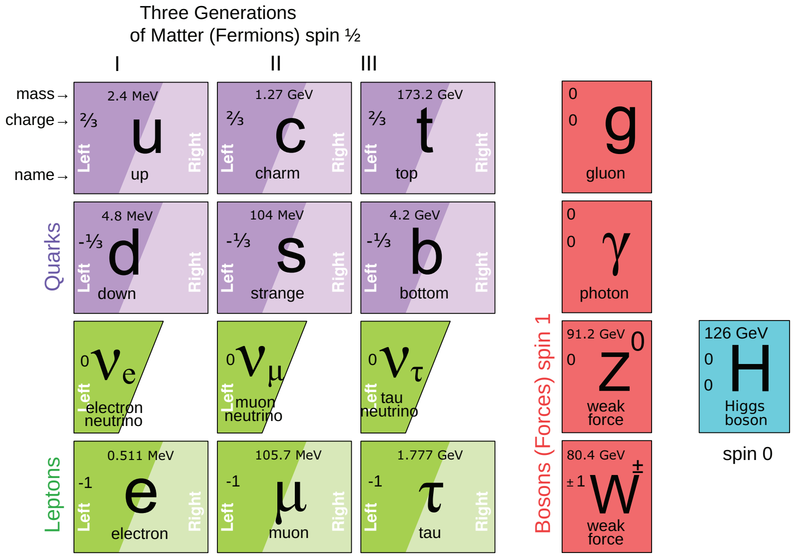
- $\mathcal{N} > \mathbf{3}$: Now you can do many things, depending on your taste - extra relativistic degrees of freedom in cosmology, neutrino anomalies, dark matter, different scenarios for baryogenesis, and different combinations of the above.

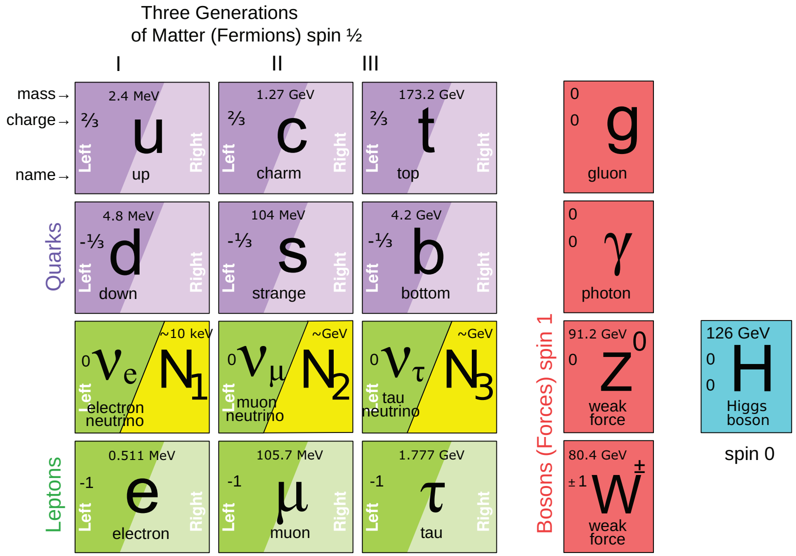
New mass scale and Yukawas

$$Y^2 = Trace[F^\dagger F]$$



$\mathcal{N} = 3$ with $M_I < M_W$: the νMSM





N = Heavy Neutral Lepton - HNL

Role of N_1 with mass in keV region: dark matter

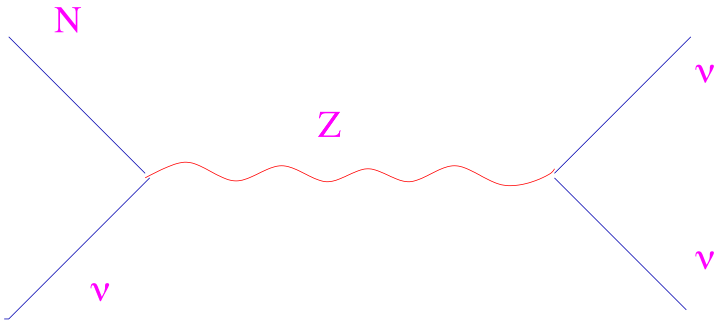
Role of $N_2,\ N_3$ with mass in 100 MeV – GeV region: “give” masses to neutrinos and produce baryon asymmetry of the Universe

What should be the properties of $N_{1,2,3}$ in the minimal setup - no any type of new physics between the Fermi and Planck scales ?

How to search for them experimentally?

DM candidate: the lightest Majorana ν, N_1

Yukawa couplings are small → sterile N can be very stable.



Main decay mode: $N \to 3\nu$.

For one flavour:

$$\tau_{N_1} = 5\times10^{26}\,\text{sec}\left(\frac{1\text{keV}}{M_1}\right)^5\left(\frac{10^{-8}}{\Theta^2}\right)$$

$$\Theta = \frac{m_D}{M_I}$$

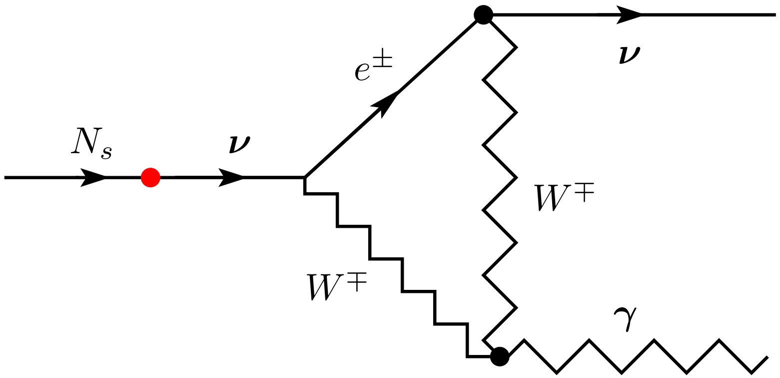
Dark Matter candidate: N_1

DM particle is not stable. Main decay mode $N_1 \to 3\nu$ is not observable.

Subdominant radiative decay channel: $N \to \nu\gamma$.

Photon energy:

$$E_\gamma = \frac{M}{2}$$



Radiative decay width:

$$\Gamma_{\rm rad} = \frac{9\,\alpha_{\rm EM}\,G_F^2}{256 \cdot 4\pi^4}\,\sin^2(2\theta)\,M_s^5$$

Dark Matter production

Cosmological production of sterile neutrinos

Sterile neutrino never equilibrates, since their interactions are very weak

$$\Omega_N h^2 \sim 0.1 \sum_I \sum_{\alpha=e,\mu,\tau} \left(\frac{|\Theta_{\alpha I}|^2}{10^{-8}}\right)\left(\frac{M_I}{1\ \mathrm{keV}}\right)^2 .$$

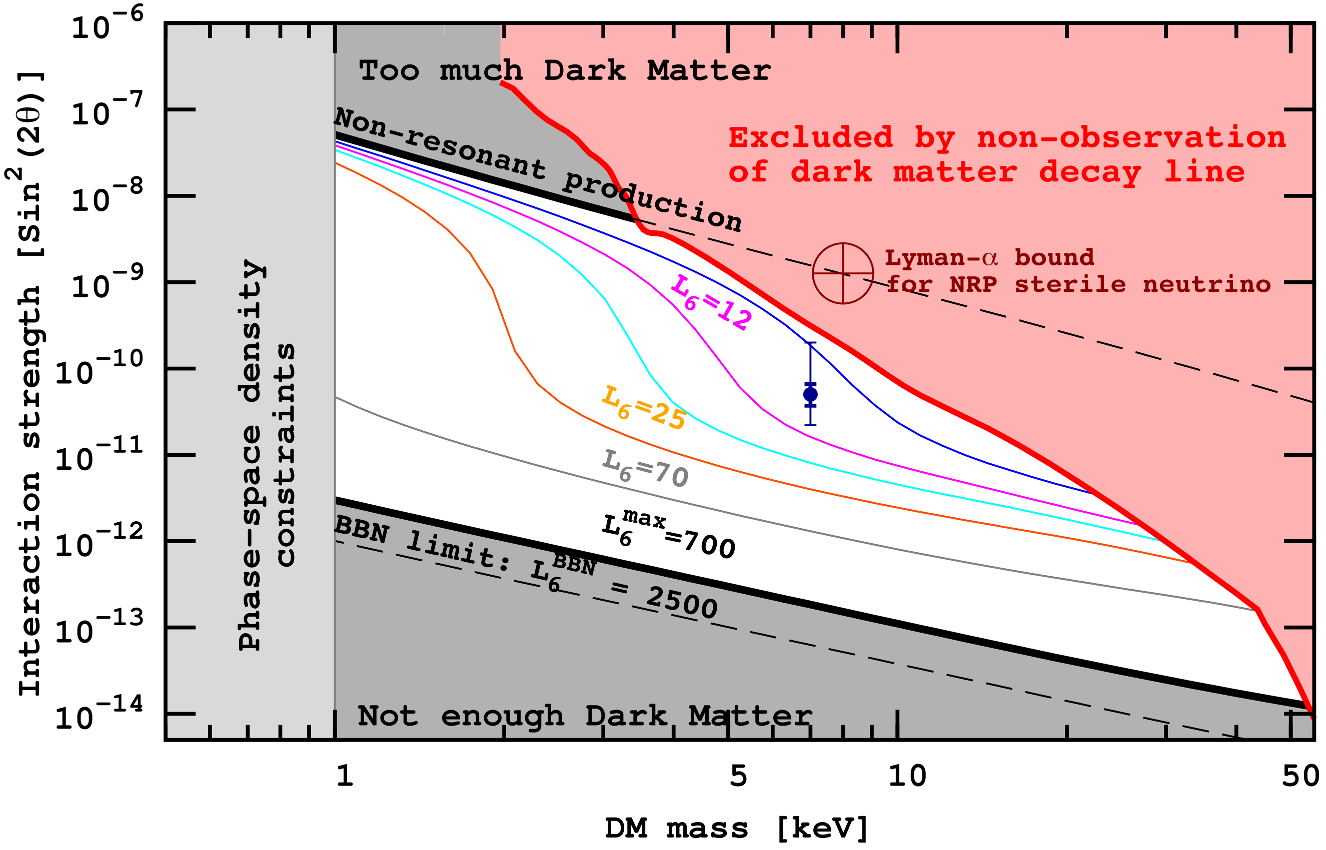
Production temperature $\sim 130 \left(\frac{M_I}{1\ \mathrm{keV}}\right)^{1/3}$ MeV

Production rate depends on Yukawa couplings and on lepton asymmetry.

Note: DM sterile neutrino does not contribute to the number of relativistic species! Perfect agreement with Planck measurements.

Constraints on DM sterile neutrino N_1

- Stability. N_1 must have a lifetime larger than that of the Universe
- Production. N_1 are created in the early Universe in reactions $l\bar{l} \to \nu N_1, \quad q\bar{q} \to \nu N_1$ etc. We should get correct DM abundance
- Structure formation. If 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-α forest spectra of distant quasars and structure of dwarf galaxies
- X-rays. N_1 decays radiatively, $N_1 \to \gamma\nu$, producing a narrow line which can be detected by X-ray telescopes (such as Chandra or XMM-Newton).

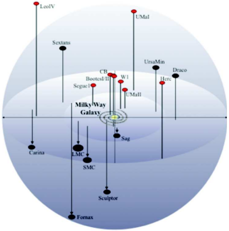


Detection of An Unidentified Emission Line in the Stacked X-ray spectrum of Galaxy Clusters. E. Bulbul, M. Markevitch, A. Foster, R. K. Smith, M. Loewenstein, S. W. Randall. e-Print: arXiv:1402.2301

An unidentified line in X-ray spectra of the Andromeda galaxy and Perseus galaxy cluster. A. Boyarsky , O. Ruchayskiy, D. Iakubovskyi, J. Franse. e-Print: arXiv:1402.4119

Dwarf spheroidal galaxies – smallest DM-dominated objects known

- Dwarf spheroidals are "*galaxies inside our Galaxy*"
- These are ancient galaxies "swallowed" by the Milky Way
- Dwarf spheroidal galaxies are too light and compact to confine X-ray emitting gas ($k_B T \sim G_N \frac{\text{Mass}}{\text{Size}}$)

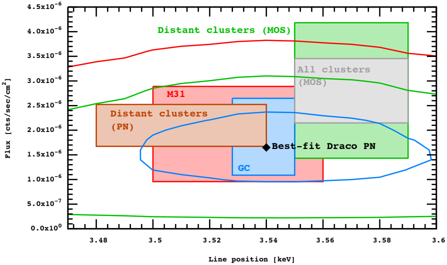


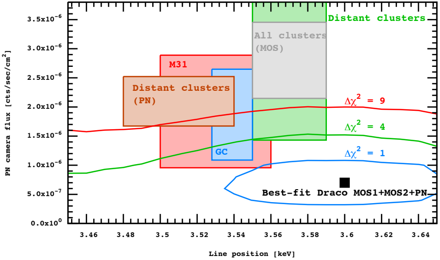
- The best target (balance between mass and distance) for the current satellite – dwarf galaxy in the constellation of Draco – **Draco dSph galaxy**
- XMM-Newton's time allocation committee granted us 1.4 Mega-seconds (10% of the annual observational budget)

PI: A. Boyarsky

Analysis of Draco dSph

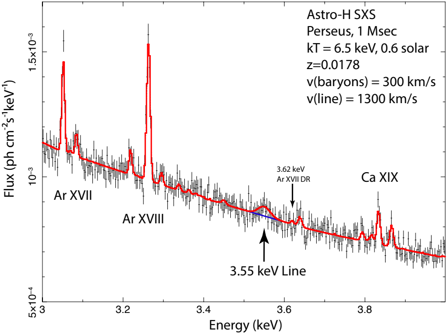
- The line is detected in the spectrum of Draco dSph with low (2σ) significance
- Line flux/position are consistent with previous observations
- There is a shift in position ($\sim 1\sigma$) between two XMM-Newton detectors (which happens for weak lines)
- The data is consistent with DM interpretation for lifetime $\tau > (7{-}9) \times 10^{27}$ sec
- Compared to [1512.01239] we do data processing differently and use a more sophisticated background model.





Next step: Astro-H

- Astro-H – new generation X-ray spectrometer with a superb spectral resolution
- Should be launched February 17 2016
- Calibration phase – about 1 year
- First observational/calibration target – Perseus galaxy cluster



- Will be able to confirm the presence of the 3.5 keV line in Perseus and distinguish it from atomic element lines (Potassium, Chlorium, etc.)

Baryon asymmetry

Sakharov conditions:

- Baryon number violation - OK due co complex vacuum structure in the SM and chiral anomaly
- CP-violation - OK due to new complex phases in Yukawa couplings
- Deviations from thermal equilibrium - OK as HNL are out of thermal equilibrium for $T > \mathcal{O}(100)$ GeV

Anomalous fermion number non-conservation

- Vacuum structure in gauge theories
- Sphalerons
- Anomaly and fermionic level crossing
- Rate of baryon number non-conservation

Non-trivial vacuum structure in gauge theories

Simplest example: Abelian Higgs model in 1+1 dimensions

$$L = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + |D_\mu \phi|^2 - U(\phi) \ ,$$

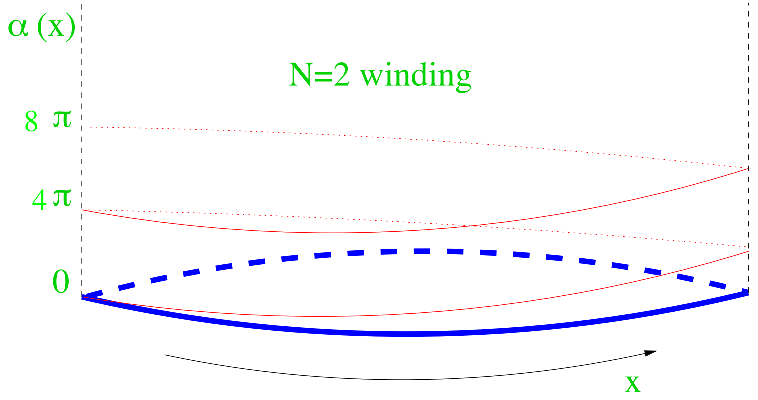
$$D_\mu = \partial_\mu - i g A_\mu \ , \quad U(\phi) = \lambda \left(|\phi|^2 - c^2\right)^2$$

Vacuum state: $|\phi|^2 = c^2$.

Topology: best discussed when the space is compact:

$$\text{spacetime}_d = \mathcal{S}_{d-1} \times T \ ,$$

1d space: $\mathcal{S}_{d-1}$ is a circle S_1.



Examples of non-trivial phases:

$$\alpha_N(x) = \frac{2\pi N x}{L},$$

N-integer, degree of mapping of $S_1 \to U(1)$.

Winding number of the Higgs field.

If the Higgs field is non-zero everywhere in space, its phase is uniquely defined:

$$\exp(2i\alpha(x)) = \frac{\phi}{\phi^*}.$$

It gives of mapping of the spatial circle onto the group U(1).

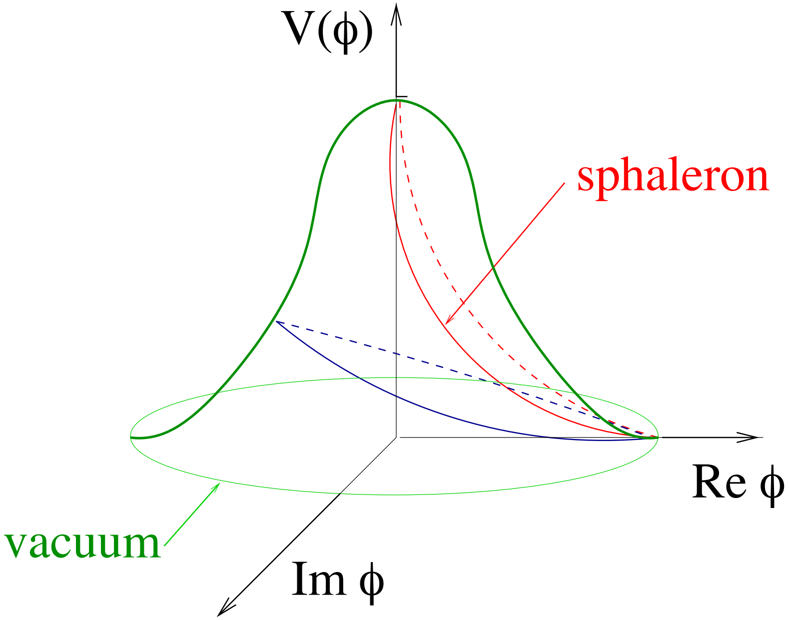
Consequences:

- Periodicity of the phase space of the theory: N-vacua states
  $\phi = e^{i\alpha_N(x)} c$
- Existence of sphalerons describing real-time transitions between different N-vacua

Energy barrier and sphalerons

What is the energy barrier between different topological vacua?

Loops in configuration space: set of static configuration of the Higgs and gauge fields depending on some parameter τ, interpolating between the vacua with topological numbers 0 and 1.



Non-contractible loop: the process of pulling on the loop lying on the potential profile for $|\phi| < c$ on the potential hill

The minimal barrier height: the minimax procedure

$$E_B = min_{paths} max_{\tau} E(\tau),$$

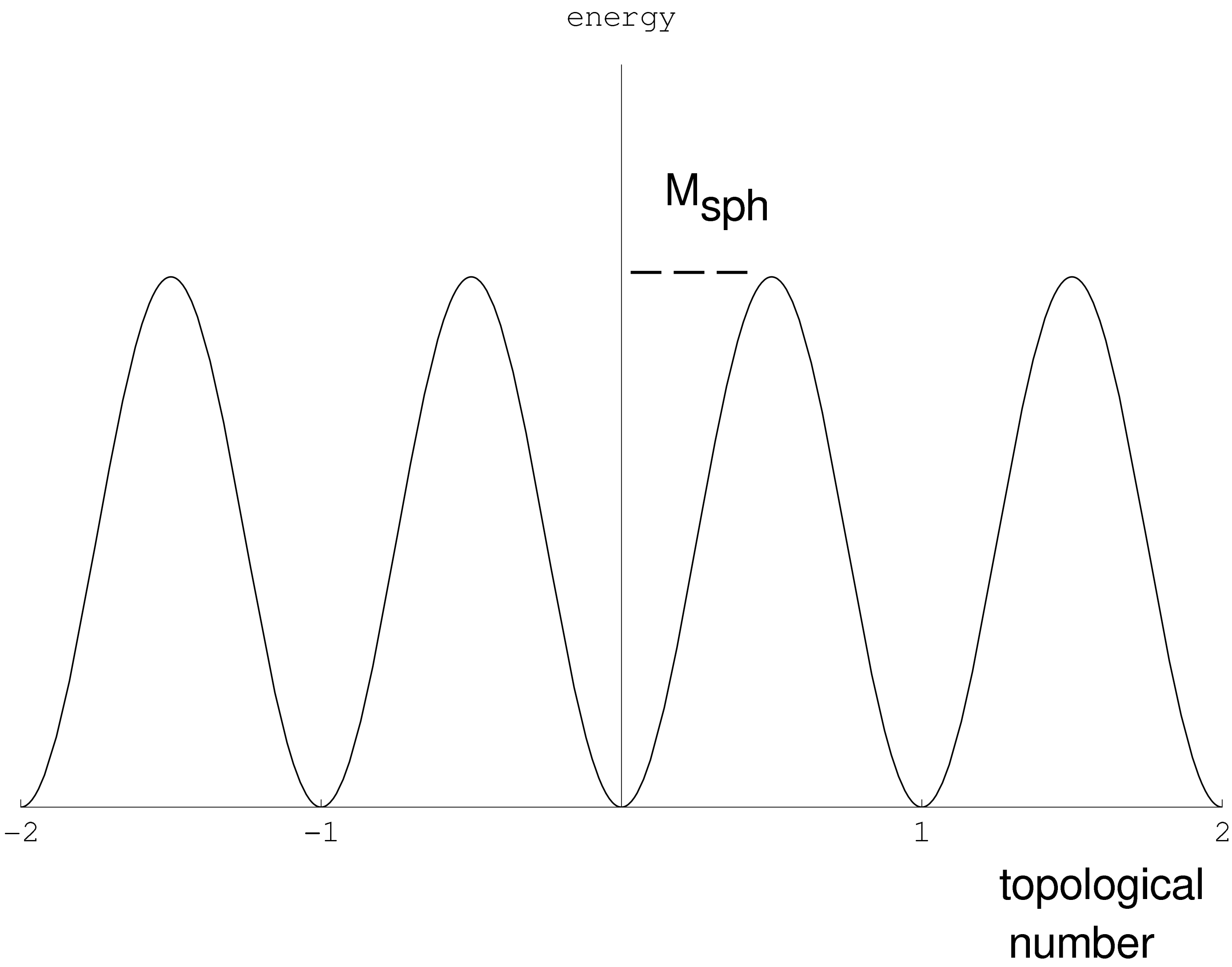
$E(\tau)$ – the static energy.

Configuration for which the minimax procedure is saturated : the sphaleron:

$$\phi_{sph} = i\exp(i\pi x/L)\frac{c}{\sqrt{2}} th \frac{M_H x}{2}$$

Important properties of sphaleron:

- unstable solution to the classical static equations of motion
- exactly one negative mode
- scalar field is equal to zero at the center of the sphaleron
- change of the winding number of the scalar field occurs precisely at sphaleron



The dependence of the energy on N_{CS}

$$E(\tau) = E_{sph}|\sin^3 \pi\tau|, \quad E_{sph} = \frac{\sqrt{8\lambda}}{3}c^3$$

Dirac vacuum

Vector-like theory - quantum electrodynamics

$L = L_{bosonic} + \bar{\psi} D \psi - m \bar{\psi} \psi,$

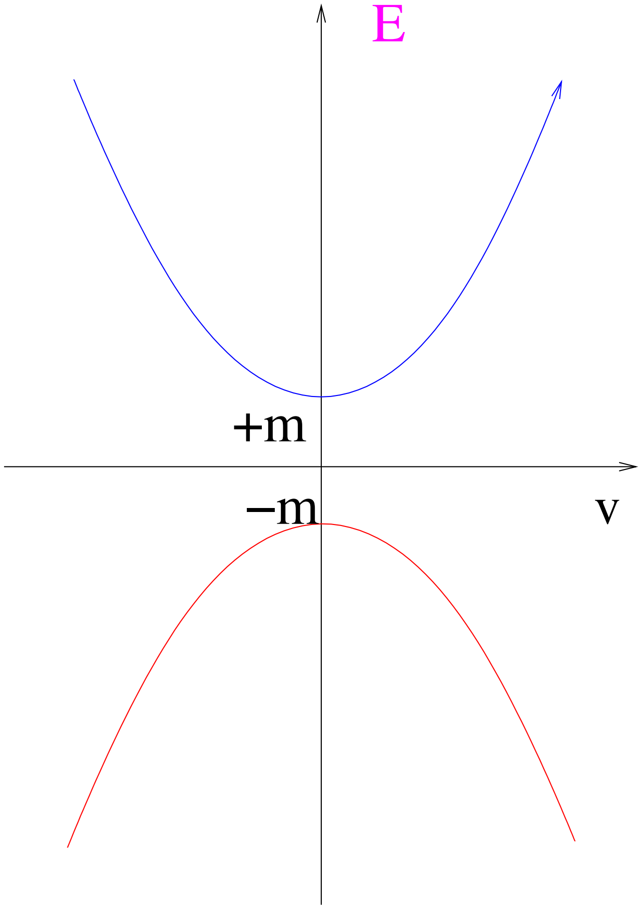
$D = i\gamma^{\mu}(\partial_{\mu} - ieA_{\mu})$

Dirac equation:$(D - m)\psi = 0$

Relativistic energies of particles from Dirac equation:

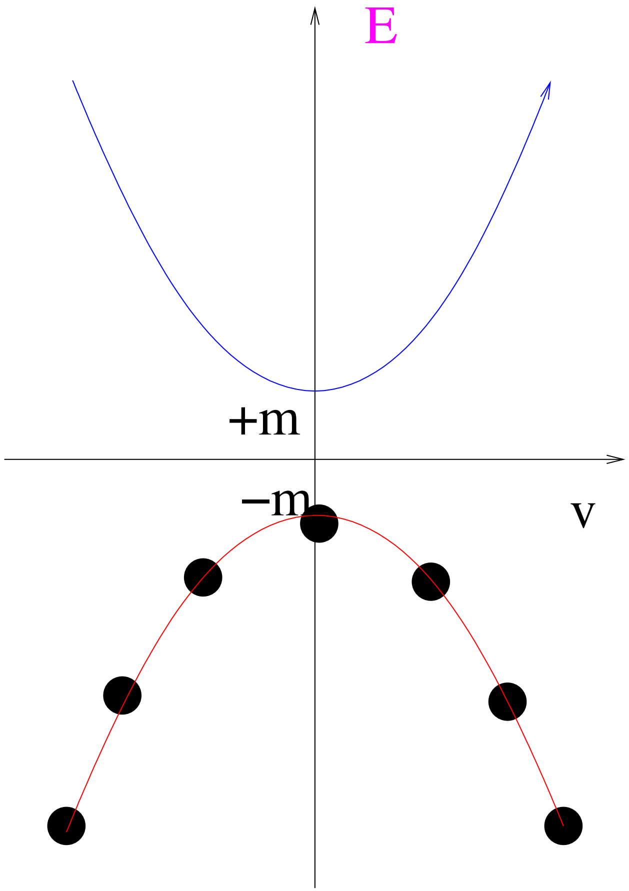
$$E = \pm \frac{m}{\sqrt{1 - v^2}}$$

Positive and negative energies...

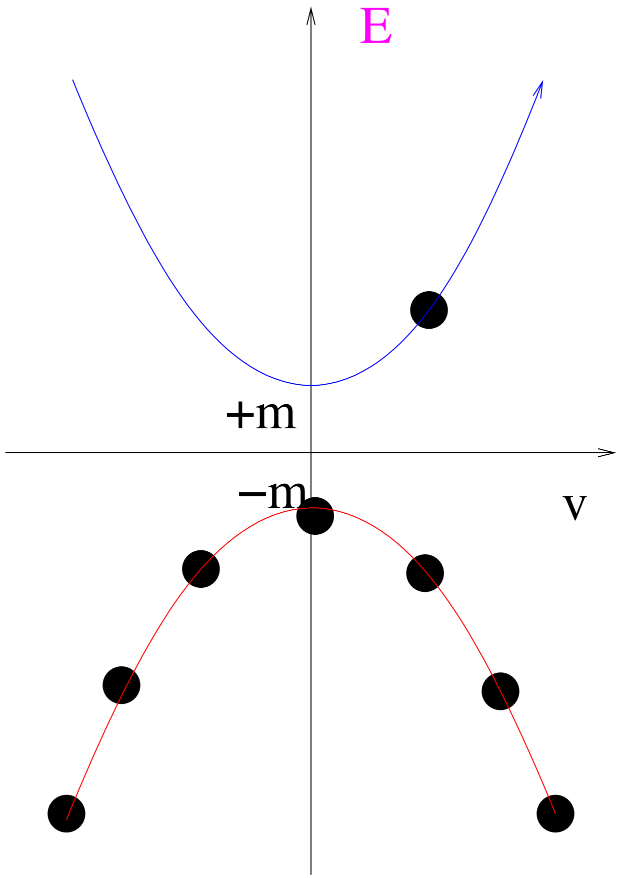


Dirac proposal: Let us fill all negative energy levels by electrons and call this state a vacuum. Then it is stable due to the Pauli principle!

Pauli principle: no more than one fermion for a quantum state.

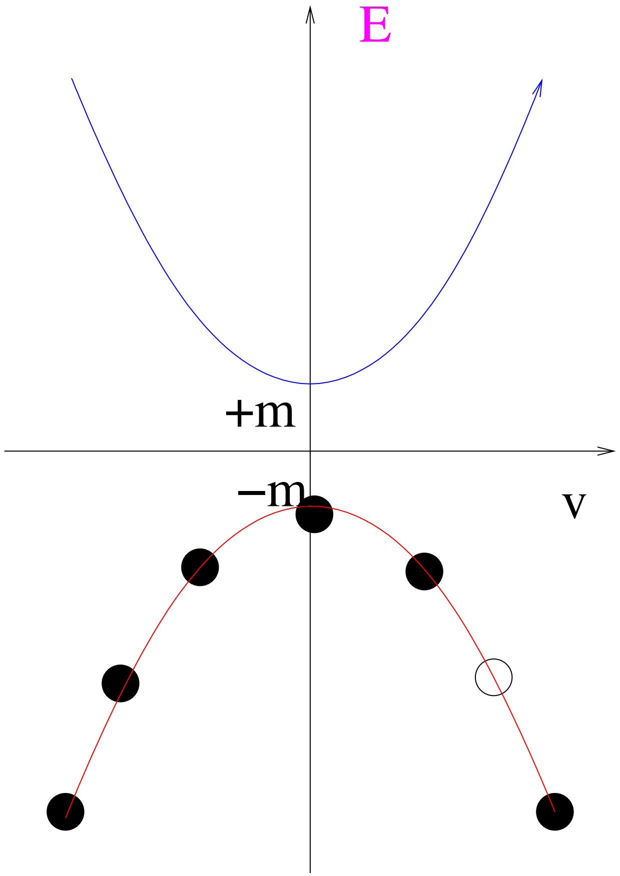


vacuum

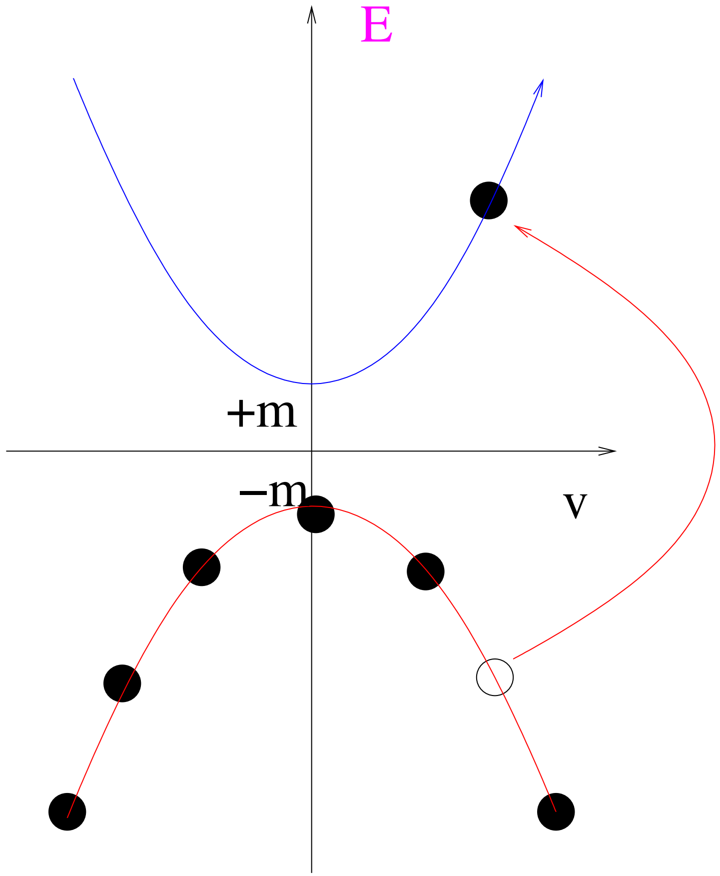


particle

Holes in the Dirac vacuum (sea) are particles with positive energies and positive electric charge



antiparticle



pair creation

Chiral gauge theory

$$L = L_{bosonic} + \bar{\psi}_1 D\psi_1 + \bar{\psi}_2 D\psi_2,$$

ψ_i – chiral (left-handed) fermions

$$D\psi_i = i\gamma^\mu(\partial_\mu - ie_i A_\mu(1+\gamma_5))\psi_i, \;\; e_1 = -e_2 = e$$

Two currents conserved on classical level: electric current:

$$J_\mu^{em} = \bar{\psi}_1\gamma_\mu\psi_1 - \bar{\psi}_2\gamma_\mu\psi_2$$

and fermionic number current:

$$J_\mu^F = \bar{\psi}_1\gamma_\mu\psi_1 + \bar{\psi}_2\gamma_\mu\psi_2$$

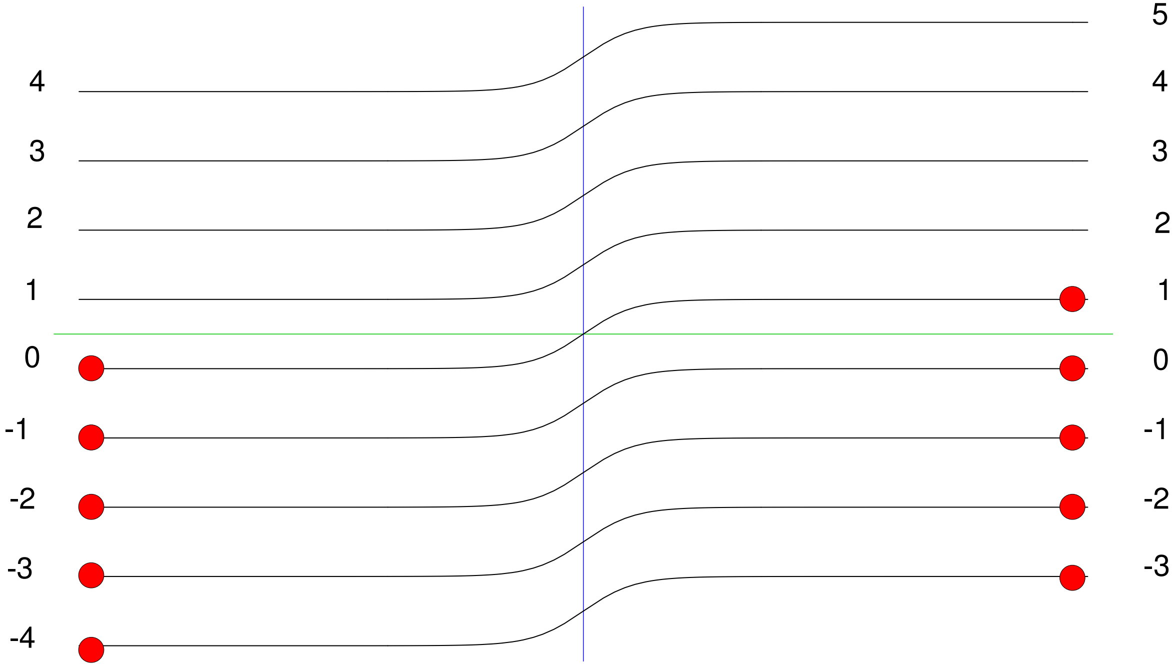
Fermionic level crossing

Again : (1+1) theory in a box of size L, periodic boundary conditions. Fermionic spectrum in the background of constant gauge field A_1 ($A_0 = 0, \;\; \partial A_1 = 0$):

$$E_k = \pm|k| - eA_1, \qquad k = 2\pi n/L$$

The fermionic energy levels have the same structure for any two gauge fields $A_1^{(1)}$ and $A_1^{(2)}$ connected by large gauge transformation Ω_n, since $A_1^{(1)} - A_1^{(2)} = 2\pi n/eL$.

Adiabatic change from, A_1=0 non-zero $A_1 = 2\pi/eL$:



The number of created fermions is given by

$$n_F = \frac{e}{2\pi} A_1 L = N_{CS}(A_1) = \int \frac{e}{2\pi} \epsilon_{\mu\nu} F_{\mu\nu},$$

Rate of baryon number non-conservation

System with one degree of freedom:

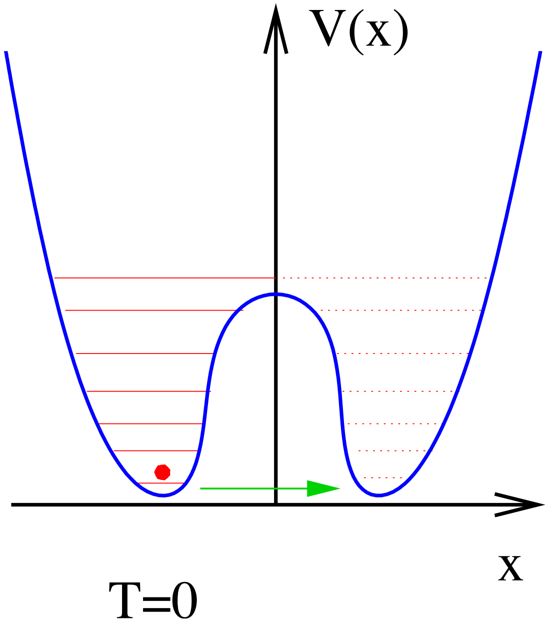
$$H = \frac{p^2}{2m} + U(x).$$

$T = 0$:

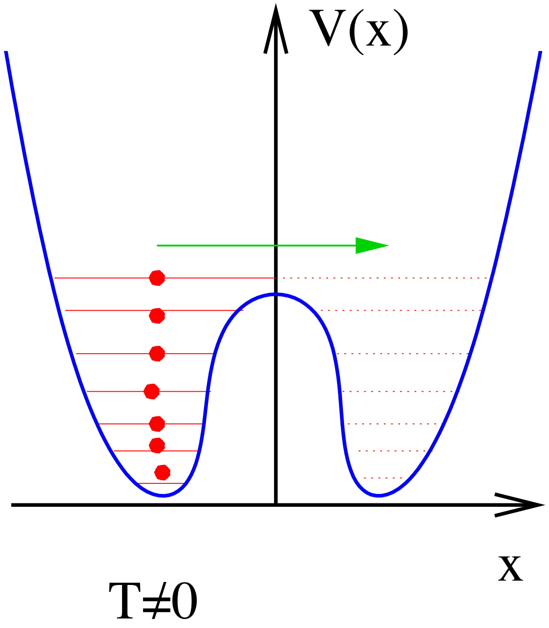
The probability of tunneling in the semiclassical WKB approximation

$$P \sim exp(-2S_0)$$

$$S_0 = \int_{-x_0}^{x_0} \sqrt{2mU(x)}.$$



$T \neq 0$:



Rate

$$P = \frac{\omega_0}{2\pi} \exp(-U_0/T),$$

U_0 – height of the barrier

ω_0 – curvature of the potential near the origin.

in (1+1):

$$\Gamma = \left[\frac{3E_{sph}}{\pi T}\right]^{\frac{1}{2}} \frac{\sqrt{M_H^3 M_W}}{4\pi} 2^{\frac{2M_W}{M_H} - \frac{3}{4}} \exp\left(-\frac{E_{sph}}{T}\right)$$

Selection rules for EW theory

There are 12 fermionic doublets:

$(\nu_e, e),\ (\nu_\mu, \mu),\ (\nu_\tau, \tau)$

$(u\ \ , d),\ (c\ \ , s),\ (t\ \ , b)$

$(u\ \ , d),\ (c\ \ , s),\ (t\ \ , b)$

$(u\ \ , d),\ (c\ \ , s),\ (t\ \ , b)$

Take one fermion from every fermionic doublet to have B-non-conservation: $bosons \leftrightarrow bosons + 9q + 3l$,

Proton is stable but deuteron decays:

$$D = pn \rightarrow \bar{n}\ e^+\bar{\nu}_\mu\bar{\nu}_\tau$$

EW theory: rate at $T < T_c$.

Rate in (3+1)

$$\Gamma = \frac{T^4 \omega_-}{M_W(T)} \left(\frac{\alpha_W}{4\pi}\right)^4 N_{tr} N_{rot} \left(\frac{2M_W(T)}{\alpha_W T}\right)^7 \exp\left(-\frac{E_{sph}(T)}{T}\right) \kappa$$

zero mode normalizations: $N_{tr} \simeq 26, \; N_{rot} \simeq 5.3\ 10^3$

κ – determinant of non-zero modes

$E_{sph}(T) = 2M_W(T)/\alpha_W B(\lambda/\alpha_W)$– effective sphaleron mass accounting for the temperature evolution of the Higgs vev.

EW theory: rate at $T > T_c$.

Consider pure classical gauge theory.

Statistical sum:

$$\exp\left(-\frac{1}{g_W^2 T}\int d^3x[E^2+H^2]\right)$$

Make all dimensionful variables dimensionless with the use of the scale $g_W^2 T$.

Rate per unit time and unit volume: GeV ^{4}

$$\Downarrow$$

$$\Gamma = A(\alpha_W T)^4$$

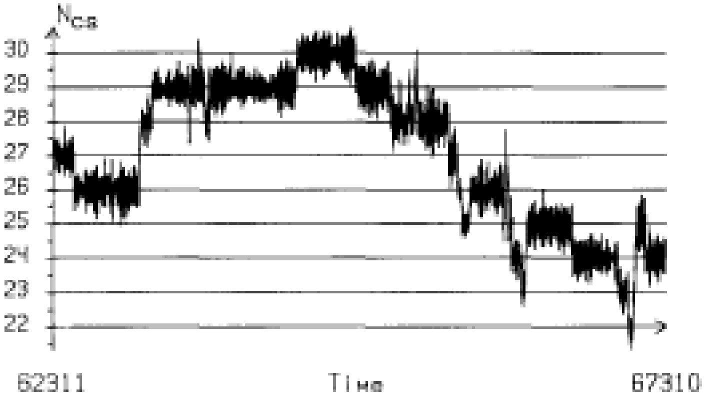
A – unknown dimensionless factor.

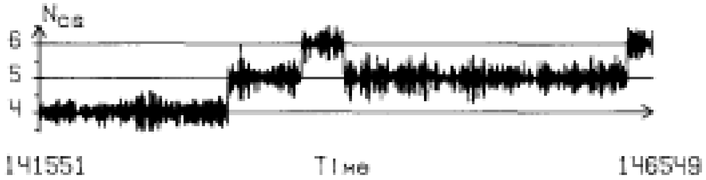
Quantum theory:

$$A \to A' \alpha_W \log(1/\alpha_W)$$

$A' \simeq 8$ can be found from real-time lattice numerical simulations

Typical time evolution of the topological number at finite temperatures derived by numerical simulations in 1+1 dimensions





Baryon asymmetry

Akhmedov, Rubakov, Smirnov; Asaka, MS

Idea - $N_{2,3}$ HNL oscillations as a source of baryon asymmetry.

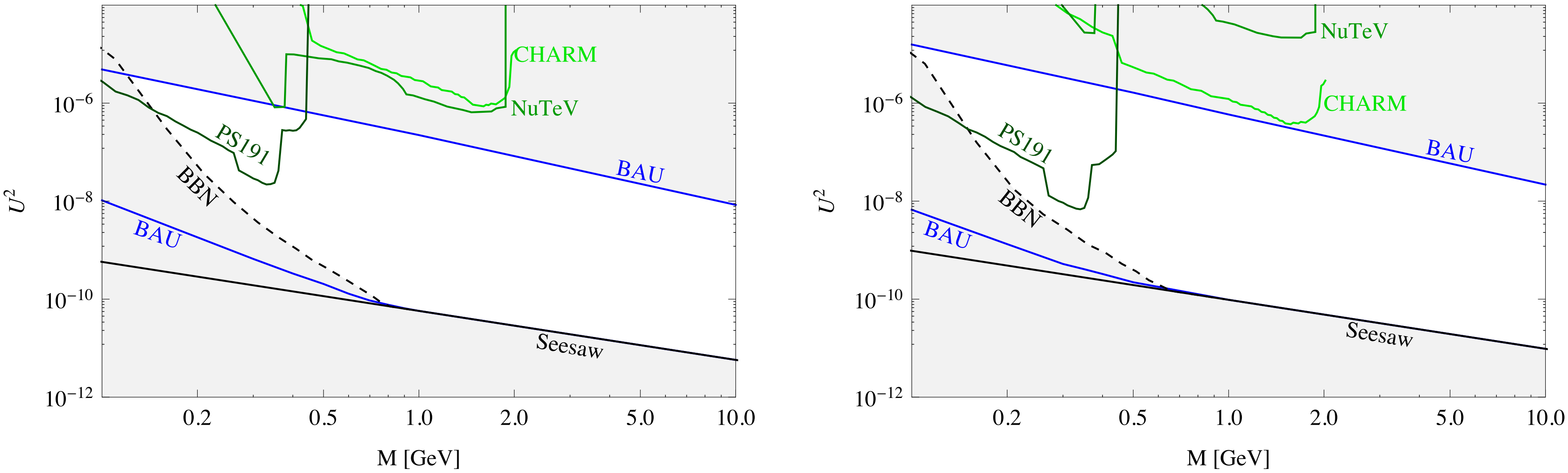
Qualitatively:

- HNL are created in the early universe and oscillate in a coherent way with CP-breaking.
- Lepton number from HNL can go to active neutrinos.
- The lepton number of active left-handed neutrinos is transferred to baryons due to equilibrium sphaleron processes.

Constraints on BAU HNL $N_{2,3}$

Baryon asymmetry generation: CP-violation in neutrino sector+singlet fermion oscillations+sphalerons

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

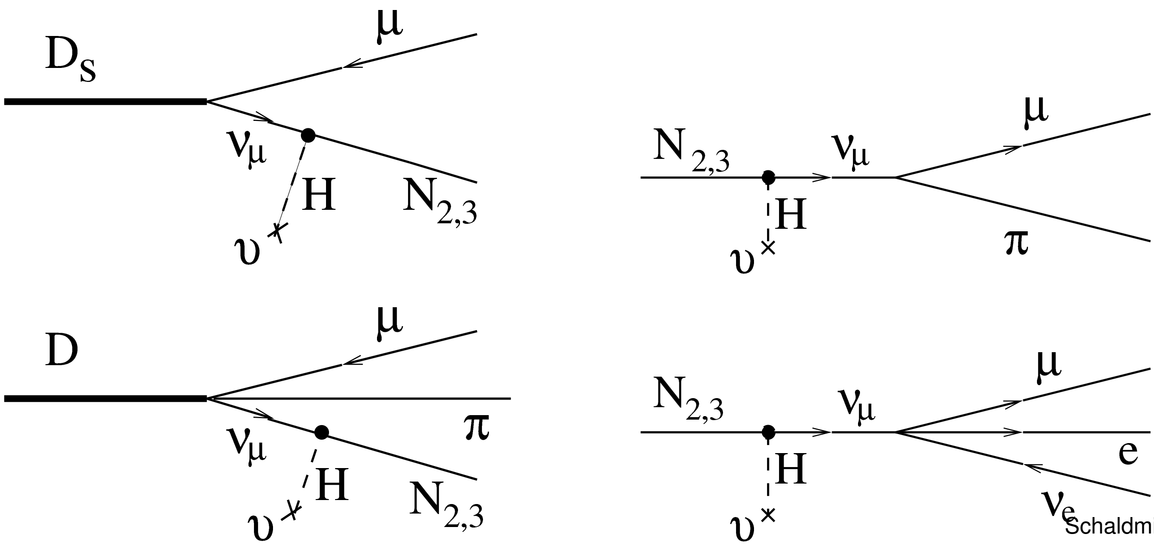


Constraints on U^2 coming from the baryon asymmetry of the Universe, from the see-saw formula, from the big bang nucleosynthesis and experimental searches. Left panel - normal hierarchy, right panel - inverted hierarchy (Canetti, Drewes, Frossard, MS).

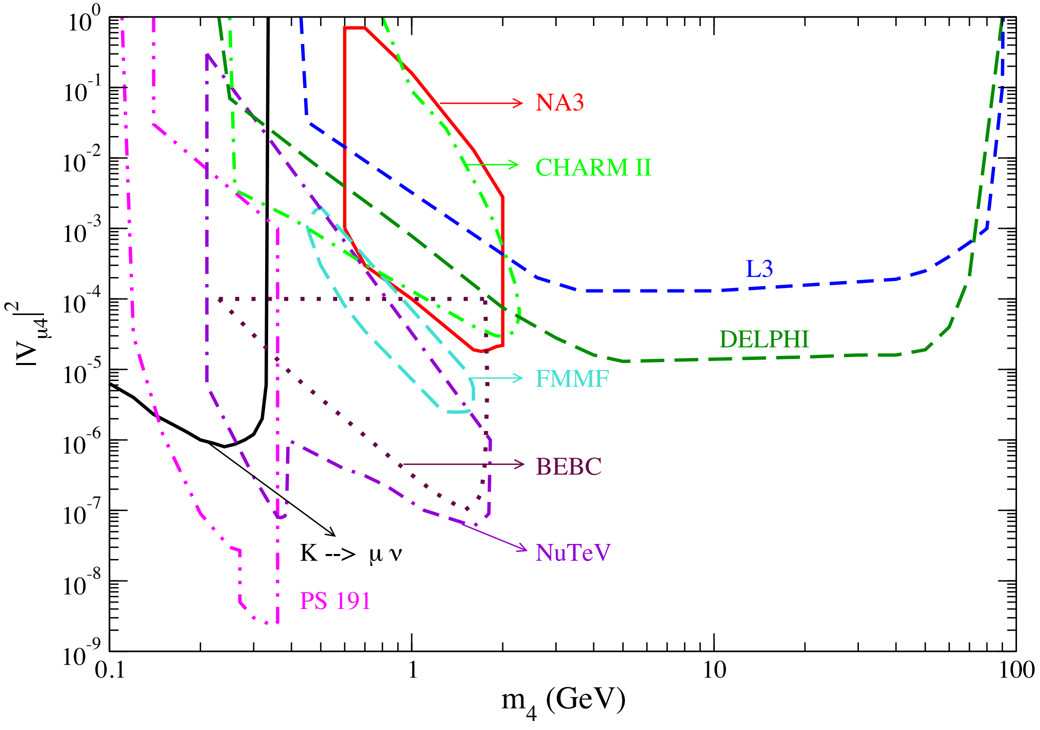
Experimental search for HNL

- Production
  - via intermediate (hadronic) state

    $p + \mathbf{target} \to \mathbf{mesons} + \ldots$, and then hadron$\to N + \ldots$.
  - via Z-boson decays: $e^+e^- \to Z \to \nu N$
- Detection
  - Subsequent decay of N to SM particles



Survey of constraints



From arXiv:0901.3589, Atre et al

How to improve the bounds or to discover light very weakly interacting HNL’s?

Dedicated experiments

Common features of all relatively light feebly interacting particles :

- Can be produced in decays of different mesons (π, K, charm, beauty)
- Can decay to SM particles (l^+l^-, $\gamma\gamma$, $l\pi$, etc)
- Can be long lived

Requirements to experiment:

- Produce as many mesons as you can
- Study their decays for a missing energy signal: charm or B-factories, NA62
- Search for decays of hidden sector particles - fixed target experiments
  - Have as many pot as you can, with the energy enough to produce charmed (or beauty) mesons
  - Put the detector as close to the target as possible, in order to catch all hidden particles from meson decays (to evade $1/R^2$ dilution of the flux)
  - Have the detector as large as possible to increase the probability of hidden particle decay inside the detector
  - Have the detector as empty as possible to decrease neutrino and other backgrounds

Most recent dedicated experiment - 1986, Vannucci et al

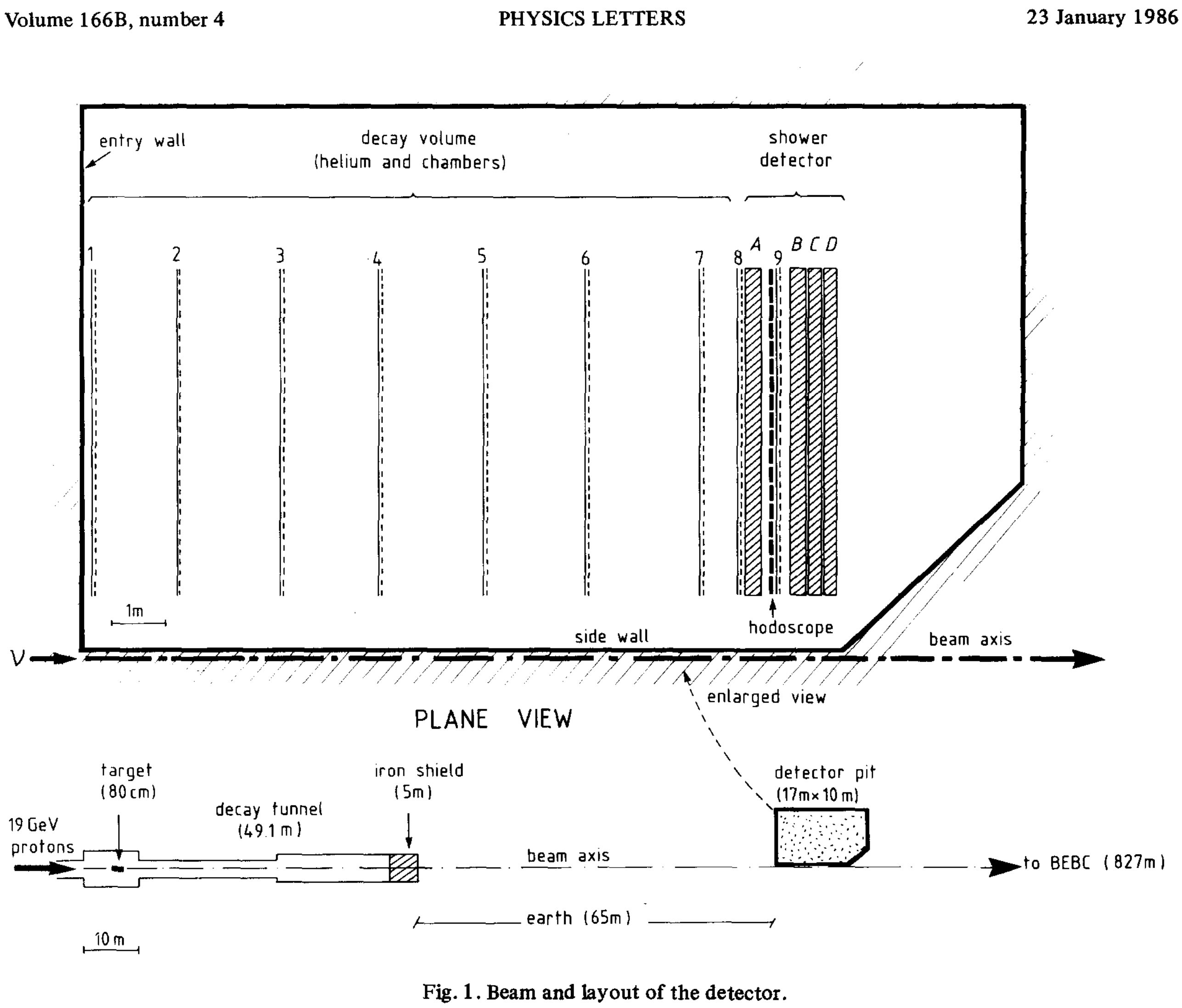

Volume 166B, number 4 PHYSICS LETTERS 23 January 1986

Fig. 1. Beam and layout of the detector.

No new particles are found with mass below K-meson, the best constraints are derived

Proposal to Search for Heavy Neutral Leptons at the SPS arXiv:1310.1762

W. Bonivento, A. Boyarsky, H. Dijkstra, U. Egede, M. Ferro-Luzzi, B. Goddard, A. Golutvin, D. Gorbunov, R. Jacobsson, J. Panman, M. Patel, O. Ruchayskiy, T. Ruf, N. Serra, M. Shaposhnikov, D. Treille

⇓

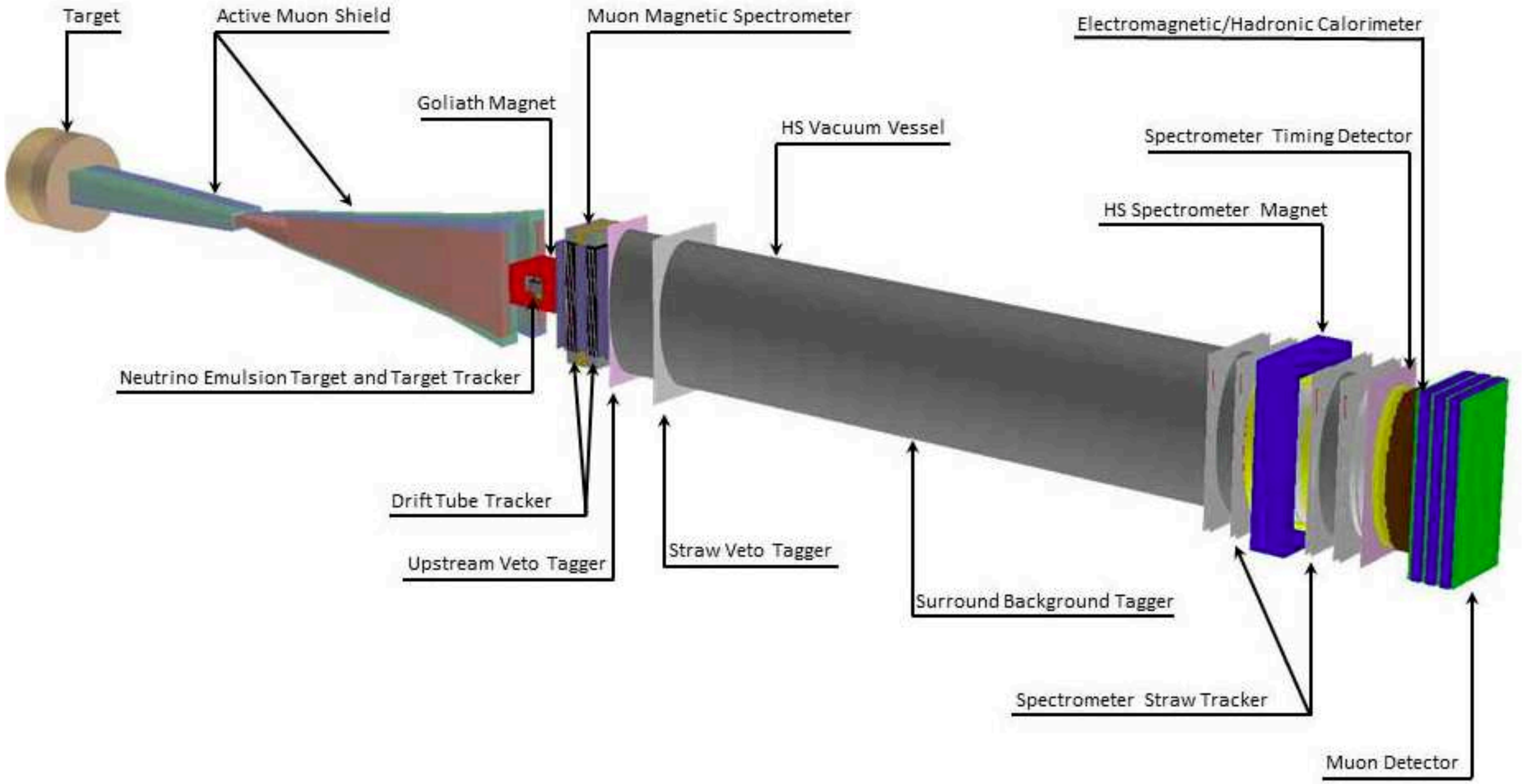
General beam dump facility: Search for Hidden Particles

SHiP

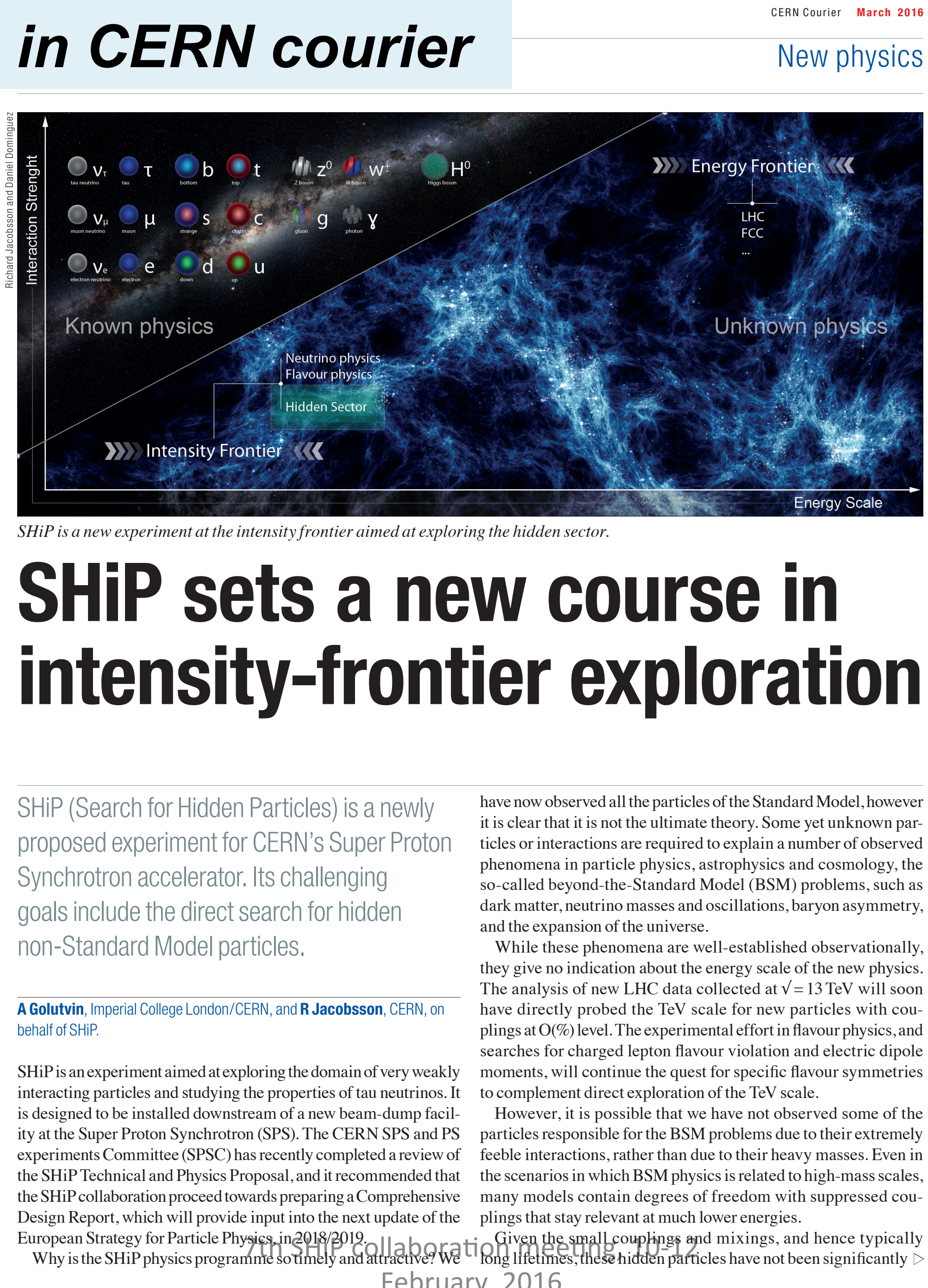
Search for Hidden Particles

SHiP is currently a collaboration of 47 institutes from 15 countries

web-site: http://ship.web.cern.ch/ship/



News: SHiP is in CERN courier



CERN Courier March 2016

New physics

SHiP is a new experiment at the intensity frontier aimed at exploring the hidden sector.

SHiP sets a new course in intensity-frontier exploration

SHiP (Search for Hidden Particles) is a newly proposed experiment for CERN's Super Proton Synchrotron accelerator. Its challenging goals include the direct search for hidden non-Standard Model particles.

A Golutvin, Imperial College London/CERN, and **R Jacobsson**, CERN, on behalf of SHiP.

SHiP is an experiment aimed at exploring the domain of very weakly interacting particles and studying the properties of tau neutrinos. It is designed to be installed downstream of a new beam-dump facility at the Super Proton Synchrotron (SPS). The CERN SPS and PS experiments Committee (SPSC) has recently completed a review of the SHiP Technical and Physics Proposal, and it recommended that the SHiP collaboration proceed towards preparing a Comprehensive Design Report, which will provide input into the next update of the European Strategy for Particle Physics in 2018/2019.

Why is the SHiP physics programme so timely and attractive? We have now observed all the particles of the Standard Model, however it is clear that it is not the ultimate theory. Some yet unknown particles or interactions are required to explain a number of observed phenomena in particle physics, astrophysics and cosmology, the so-called beyond-the-Standard Model (BSM) problems, such as dark matter, neutrino masses and oscillations, baryon asymmetry, and the expansion of the universe.

While these phenomena are well-established observationally, they give no indication about the energy scale of the new physics. The analysis of new LHC data collected at $\sqrt{} = 13$ TeV will soon have directly probed the TeV scale for new particles with couplings at O(%) level. The experimental effort in flavour physics, and searches for charged lepton flavour violation and electric dipole moments, will continue the quest for specific flavour symmetries to complement direct exploration of the TeV scale.

However, it is possible that we have not observed some of the particles responsible for the BSM problems due to their extremely feeble interactions, rather than due to their heavy masses. Even in the scenarios in which BSM physics is related to high-mass scales, many models contain degrees of freedom with suppressed couplings that stay relevant at much lower energies.

Given the small couplings and mixings, and hence typically long lifetimes, these hidden particles have not been significantly ▷

TLEP

Processes: $Z \to N\nu, \quad N \to l q \bar{q}$ (lepton + meson, lepton + 2 quark jets),

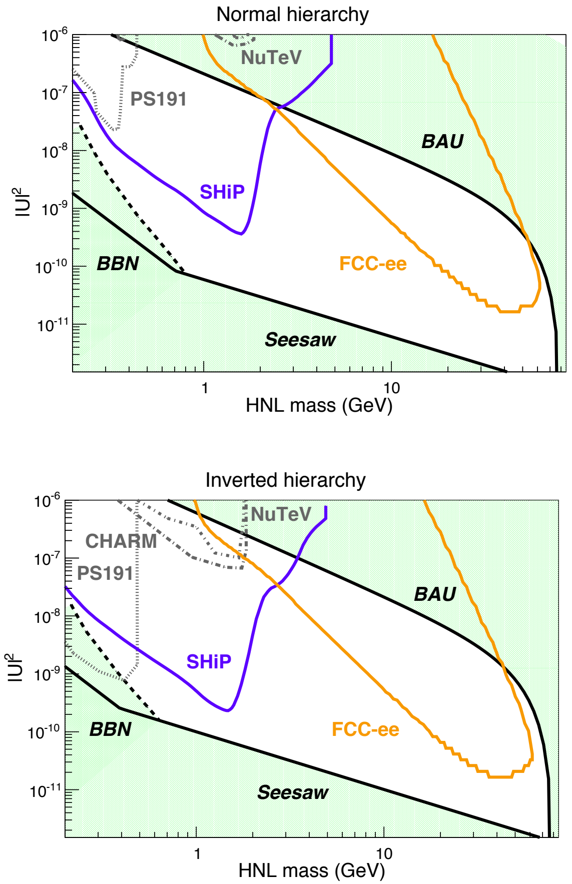
$$BR(Z \to \nu N) \simeq BR(Z \to \nu\nu) U^2, \qquad \Gamma_N \simeq \frac{G_F^2 M^5}{192\pi^3} U^2 A$$

Coefficient A counts the number of open channels, $A \sim 10$ for $M > 10$ GeV

Detector of size L:

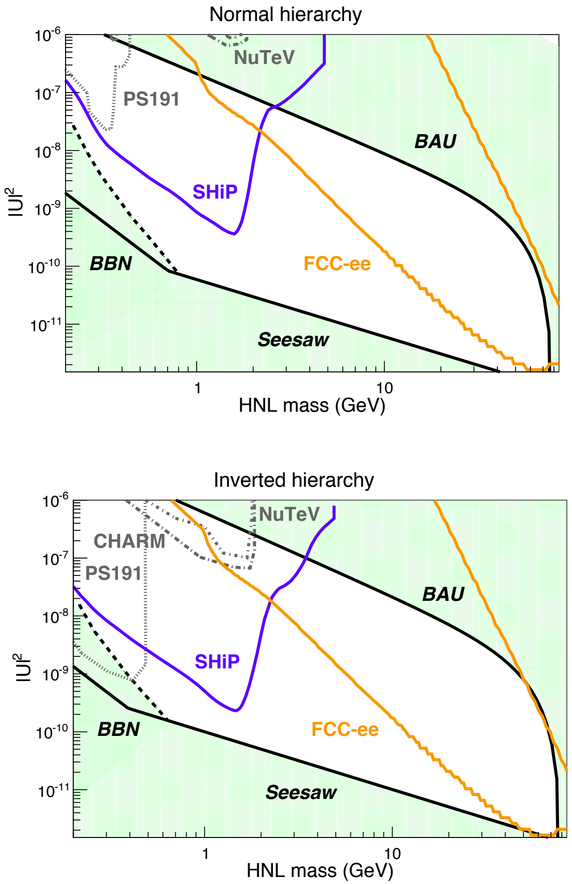
- “short lived” N: decay length < L $\Longrightarrow$ constraint on U^2 may go down to $U^2 < 10^{-10}$ as the sensitivity will grow as the number of Z-decays! This works for $M \gtrsim 20$ GeV.
- “long lived” N: decay length exceeds the size of the detector $\Longrightarrow$ constraint on U^2 may go down to $U^2 < 4 \times 10^{-8}$ as the sensitivity will grow as the square root of the number of Z-decays. This works for lighter HNL.

SHiP and FCC-ee sensitivity



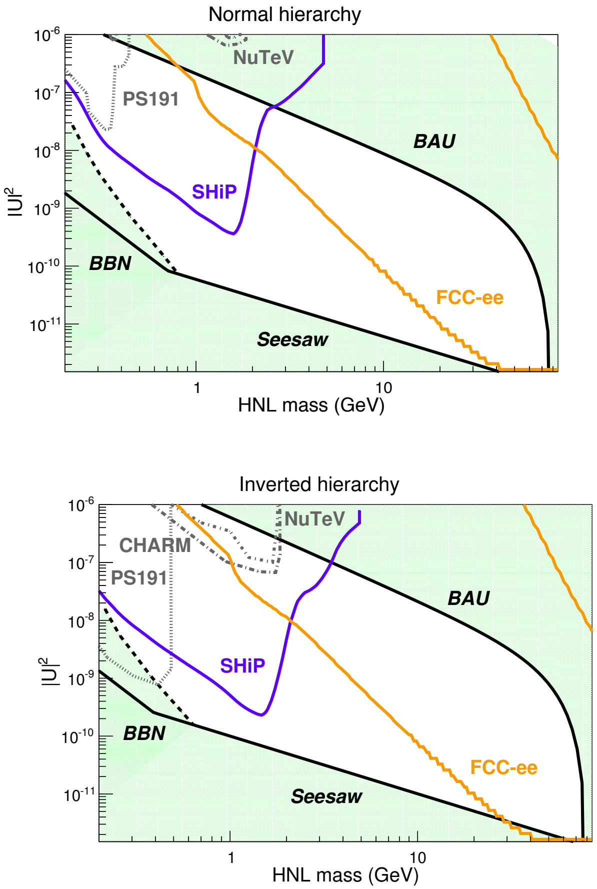
Decay length: 10-100 cm

$10^{12}\ Z^0$



10-100 cm

$10^{13}\ Z^0$



0.01-500 cm

$10^{13}\ Z^0$

Conclusions, Lecture 3

- Heavy neutral leptons can be a key to (almost all) BSM problems:
  - neutrino masses and oscillations
  - dark matter
  - baryon asymmetry of the universe
- They can be found in Space and on the Earth
  - X-ray satellites - Astro H
  - proton fixed target experiment - SHIP, $M \lesssim 2$ GeV
  - collider experiments at FCC-ee in Z-peak, $M \gtrsim 2$ GeV

Overal conclusions

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The relation between particle physics and cosmology is as strong as ever!

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The relation between particle physics and cosmology is as strong as ever!

We are waiting with impatience the results of many particle and cosmological experiments to reveal the old puzzles and bringing new ones!