New Horizons in Particle Physics with the SHiP experiment

(SHiP stands for the **S**earch for **Hi**dden **P**articles)

Andrey Golutvin

Imperial College London

CERN

SHiP

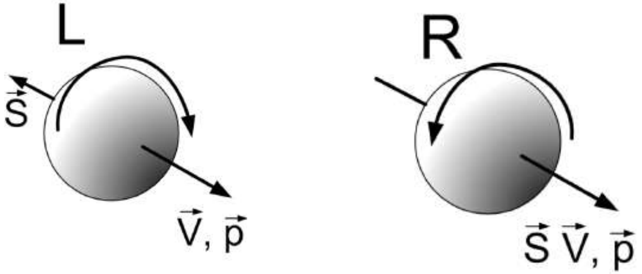
Search for Hidden Particles

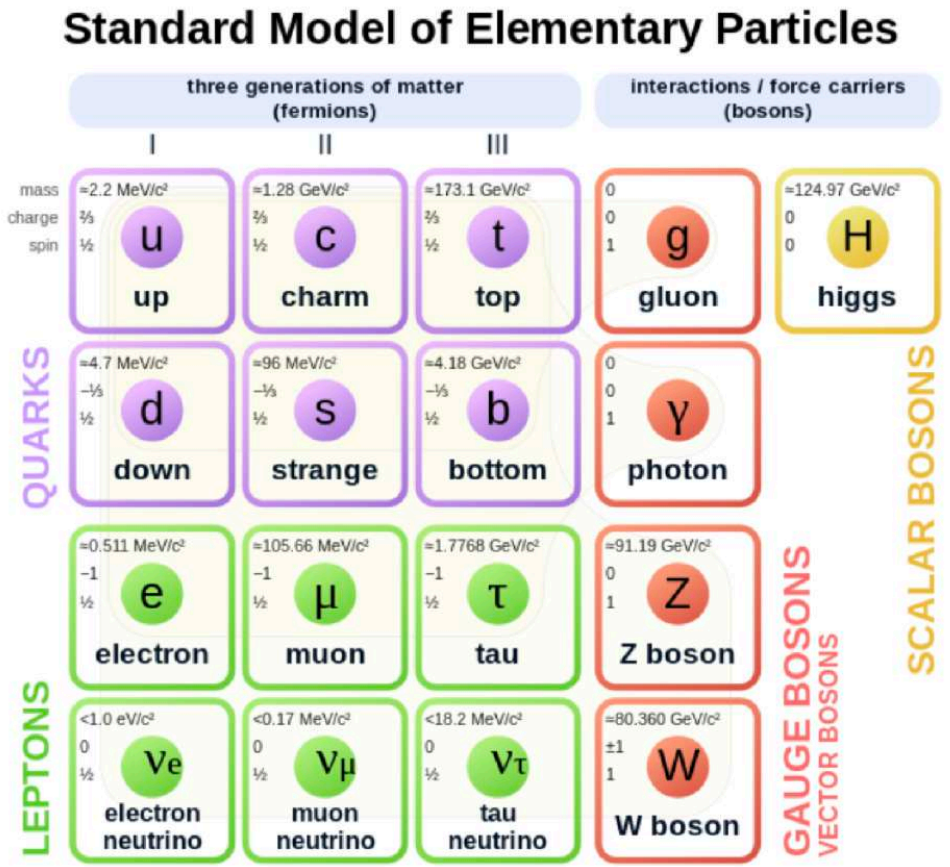
Particle physics

- Described by the Standard Model (SM) invented in 1967 and completed with the discovery of Higgs 45 years later at LHC, in 2012
- SM can describe interactions of all known elementary particles at very small and very large energies up to Planck scale 10^{19} GeV, 15 orders of magnitude larger than LHC energy
- SM is consistent with almost all experiments in particle physics but not in our Universe

What SM is made of ?

- **Three generations** of matter constituents
  & corresponding anti-matter constituents
- Force carriers
  - EM interactions - photon
  - Weak interactions – $W^{+,-}$, Z^0
  - Strong interactions – gluons
  - How to unify with gravity?
- Matter and field particles are distinguished by Spin
  - Matter is made of fermions (s=1/2)
  - Forces are carried by bosons (s=0,1)
  - Can be left- or right-handed





Why do we need three generations ?

- Open question at the time when SM was formulated

- Understanding was driven by the symmetries, which always played a big role in physics

Translations in R^3	Momentum
Rotations in R^3	Angular momentum
Time translations	Energy

$\Downarrow \quad \Rightarrow \quad \Uparrow$

invariance
conservation

Why do we need three generations ?

- Open question at the time when SM was formulated

- Understanding was driven by the symmetries, which always played a big role in physics and in particle physics (discrete symmetries)
- Examples:

  - C – charge conjugation: $e^+ \leftrightarrow e^-$ or $u \leftrightarrow \bar{u}$

  - P – parity transformation: $\vec{x} \leftrightarrow -\vec{x}$, $\vec{v} \leftrightarrow -\vec{v}$ but $\vec{s} \leftrightarrow \vec{s}$
- C- and P– are conserved in electromagnetic and strong interactions

  but broken in weak interactions

Nobel Prize:

T.D.Lee, C.N.Yang, 1956

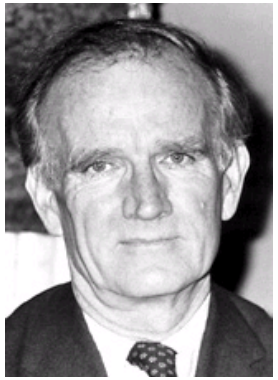
C.S.Wu, 1957

Why do we need three generations ?

- It was believed that the combined CP-symmetry is exact
  → anti-particles look like particles in the mirror
- Discovery of CP-violation in 1964 by Cronin, Fitch, Christenson, Turlay in neutral K meson decays:

$$K^0 \to \pi^- e^+ \nu_e, \quad \bar{K}^0 \to \pi^+ e^- \bar{\nu}_e$$

  There is a tiny difference between particles and anti-particles: ~10^{-3} more positrons than electrons
- Symmetry between matter and anti-matter (CP) is slightly broken



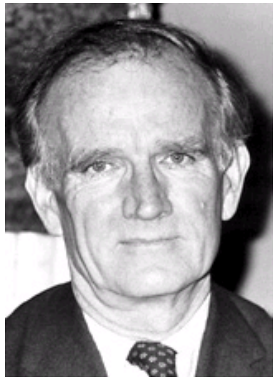
Nobel prize:
J.Cronin, V.Fitch, 1964

Why do we need three generations ?

- It was believed that the combined CP-symmetry is exact
  → anti-particles look like particles in the mirror
- Discovery of CP-violation in 1964 by Cronin, Fitch, Christenson, Turlay in neutral K meson decays:

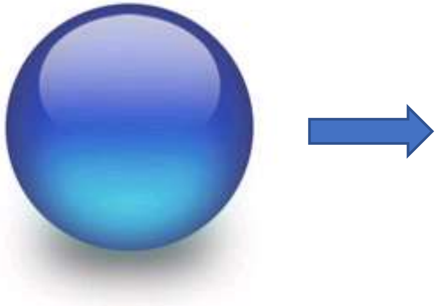
$$K^0 \to \pi^- e^+ \nu_e, \quad \bar{K}^0 \to \pi^+ e^- \bar{\nu}_e$$

There is a tiny difference between particles and anti-particles: ~10^{-3} more positrons than electrons

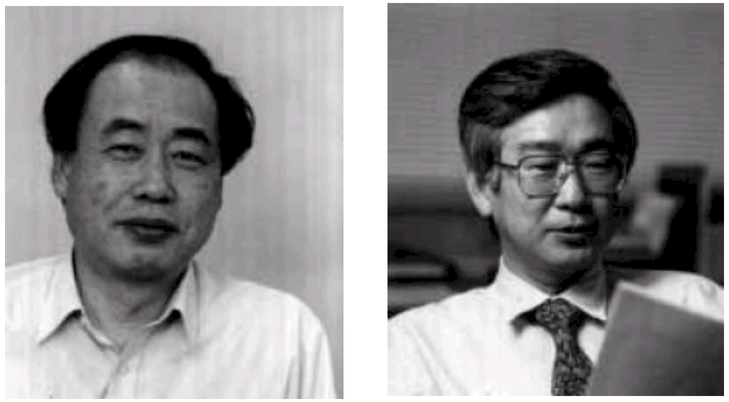



Nobel prize:
J.Cronin, V.Fitch, 1964

- Symmetry between matter and anti-matter (CP) is slightly broken



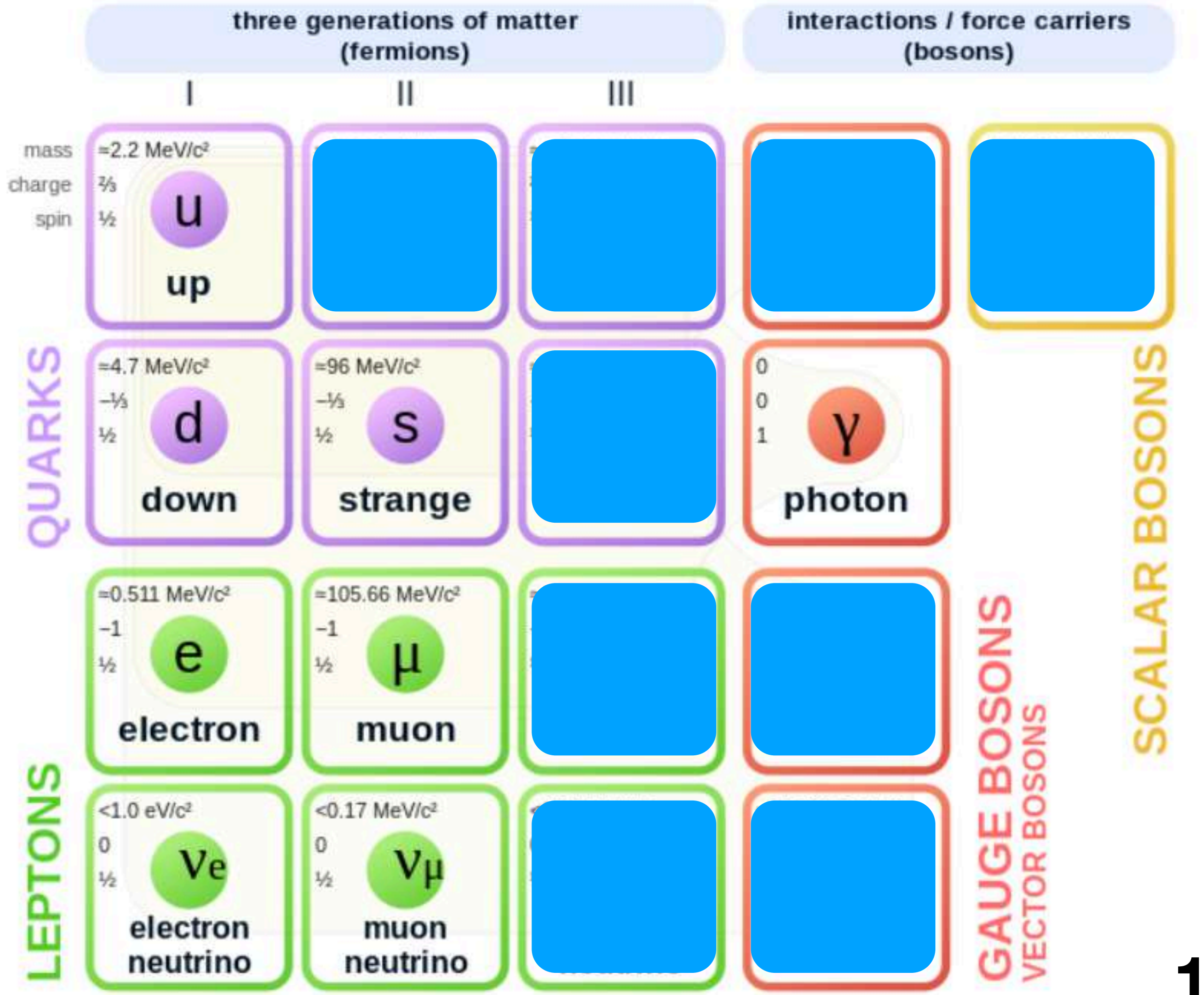
Why do we need three generations ?



Nobel prize:
M.Kobayashi, T.Maskawa, 1974

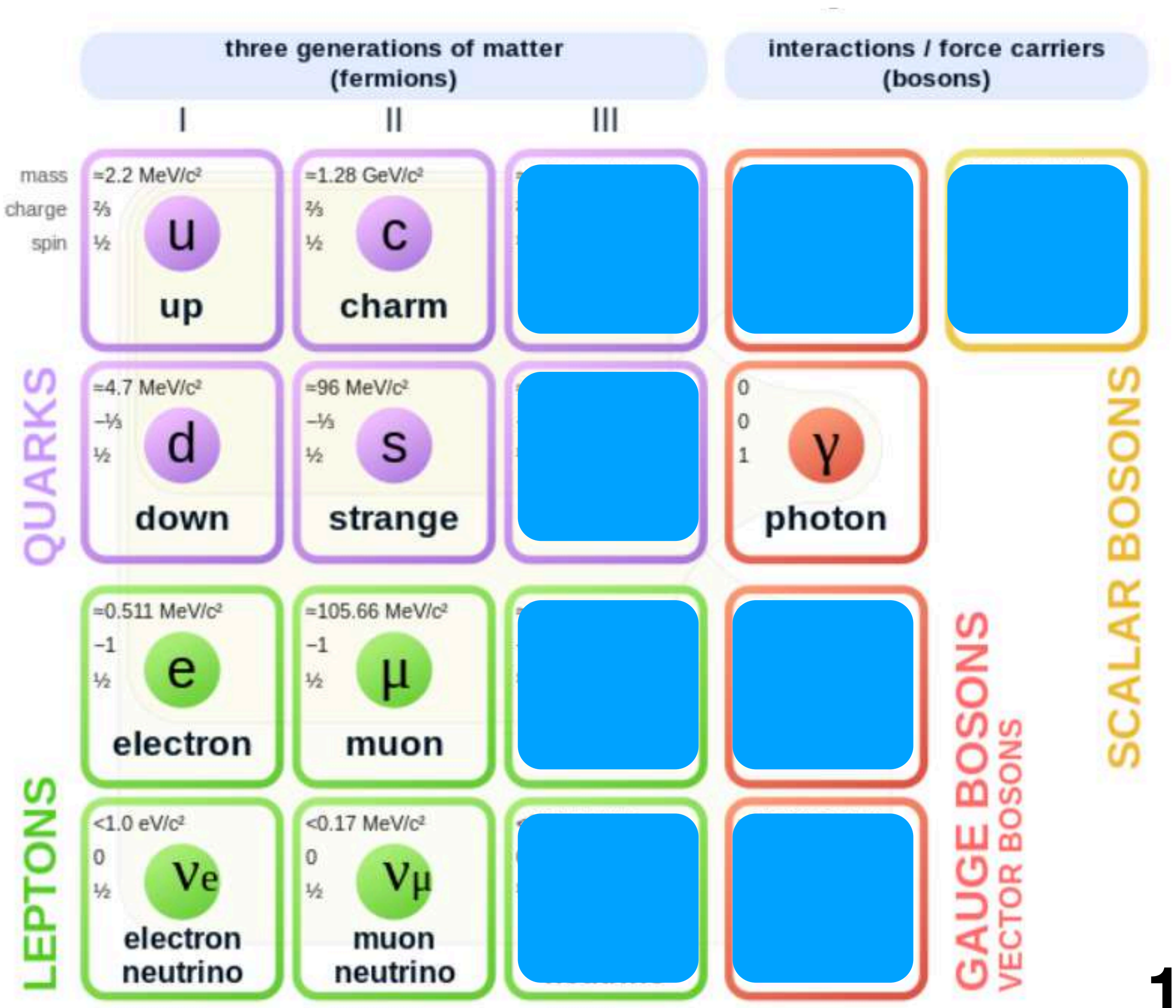
- *M. Kobayashi, T.Maskawa* proposed theoretical mechanism for CP-violation in the SM in 1974.
  It works only if number of generations $\geq$ 3
- Experiments with Z^0 bosons at LEP (CERN) and SLC (SLAC) in 1991 have proven that there are exactly three generations of fermions, *i.e.* minimum required number in SM

Experimental proof of SM



1973

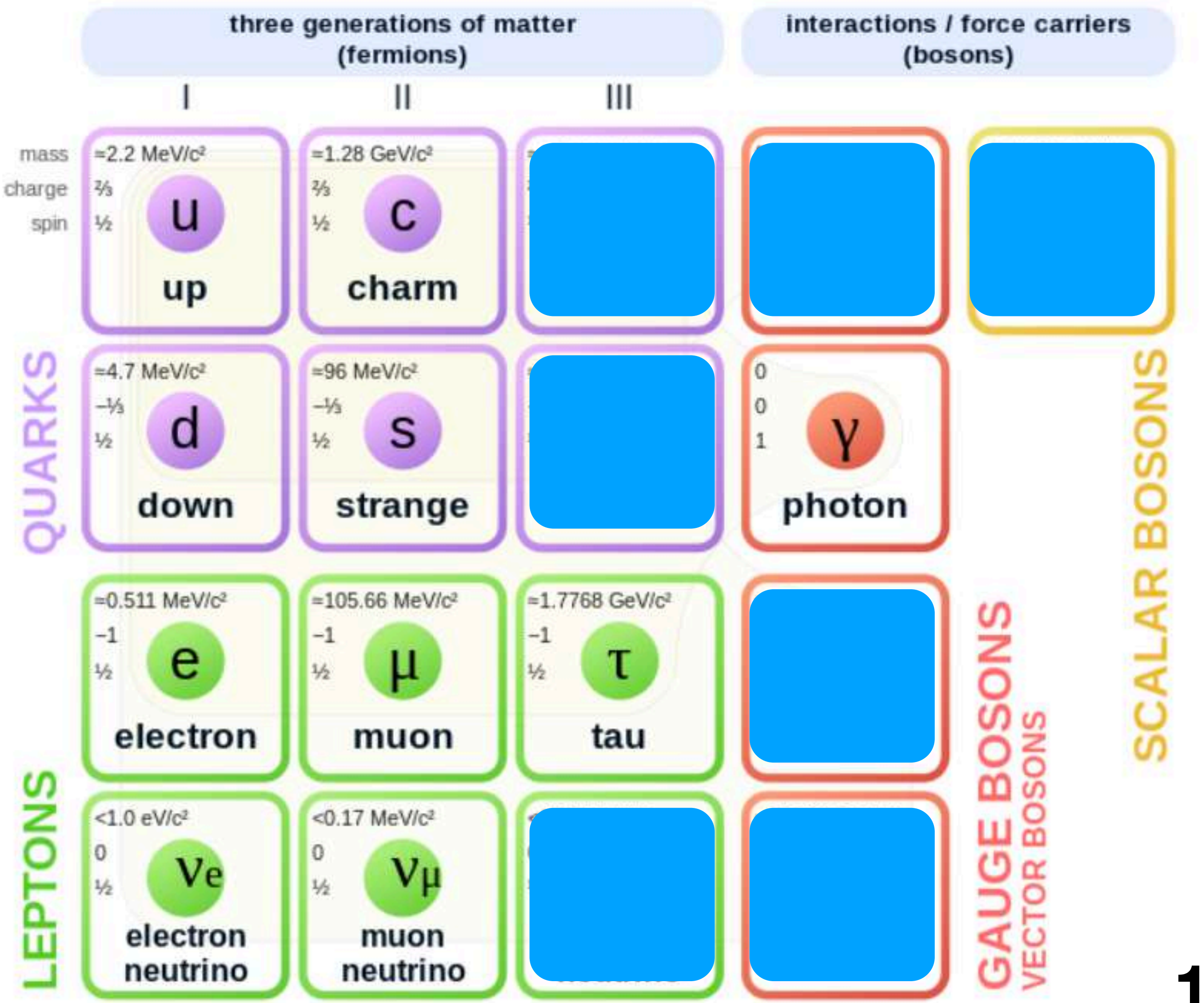
Experimental proof of SM



1974


Nobel prize:
Samuel Ting, Burton Richter

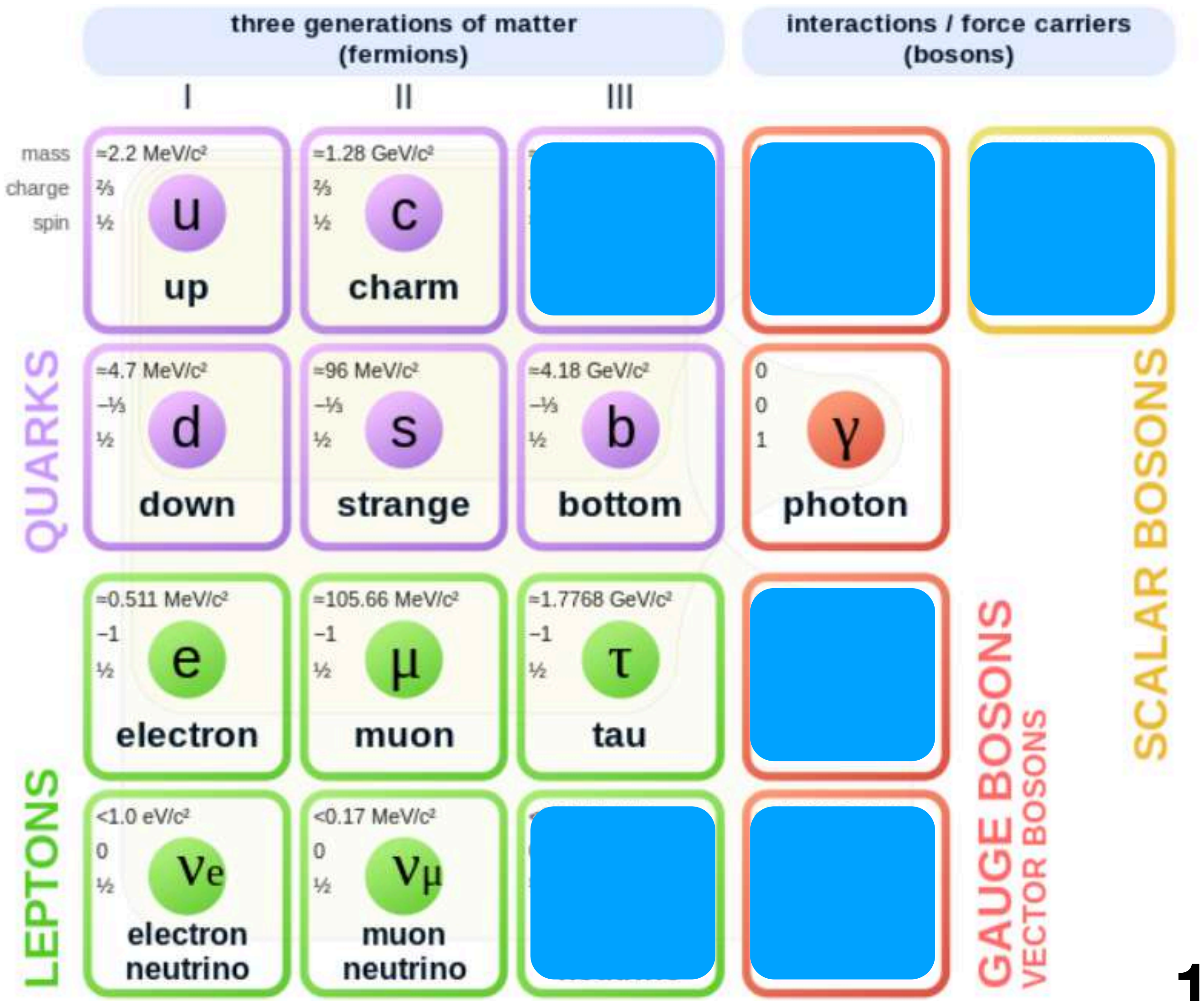
Experimental proof of SM



Nobel prize:
Martin Perl

1975

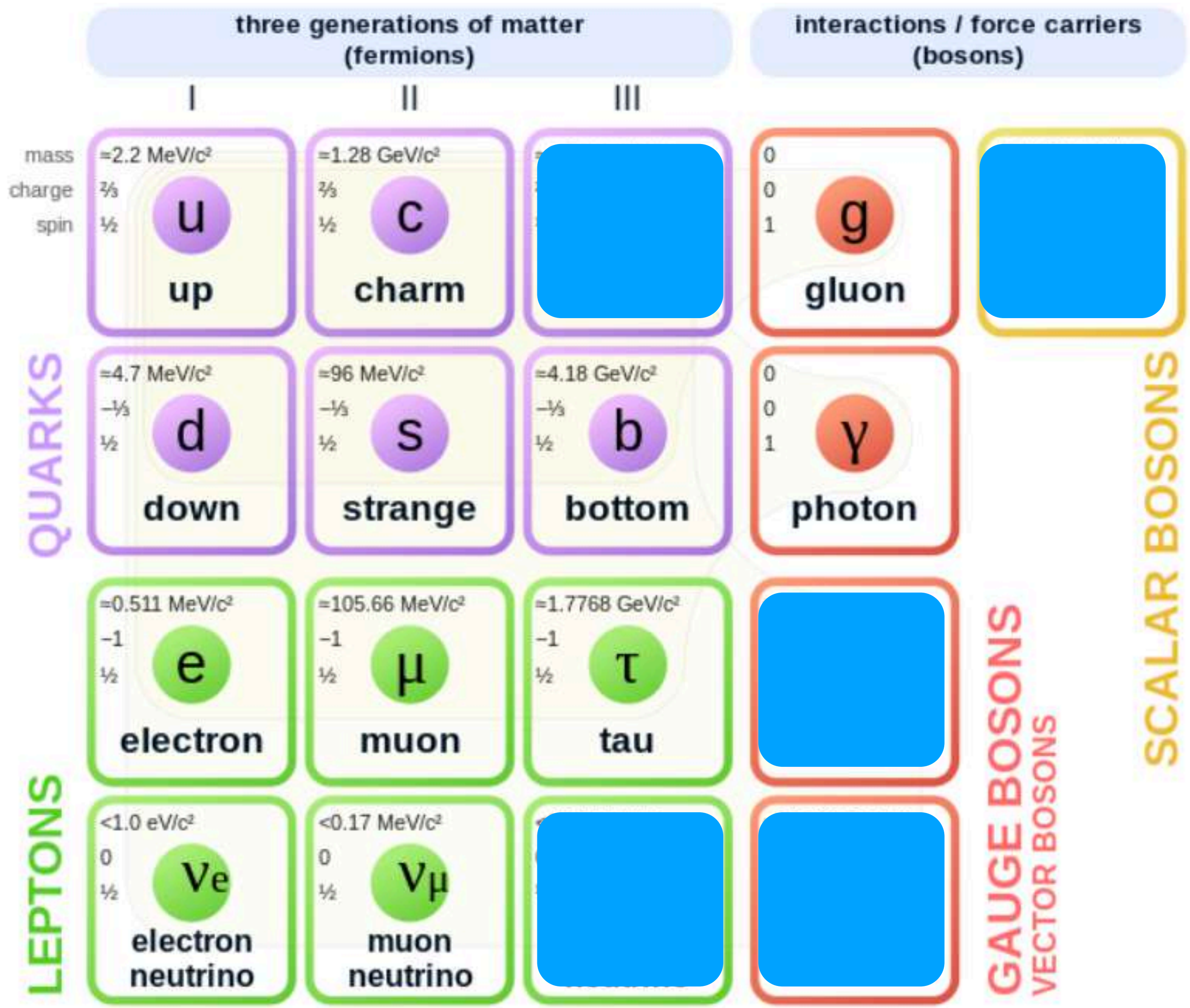
Experimental proof of SM



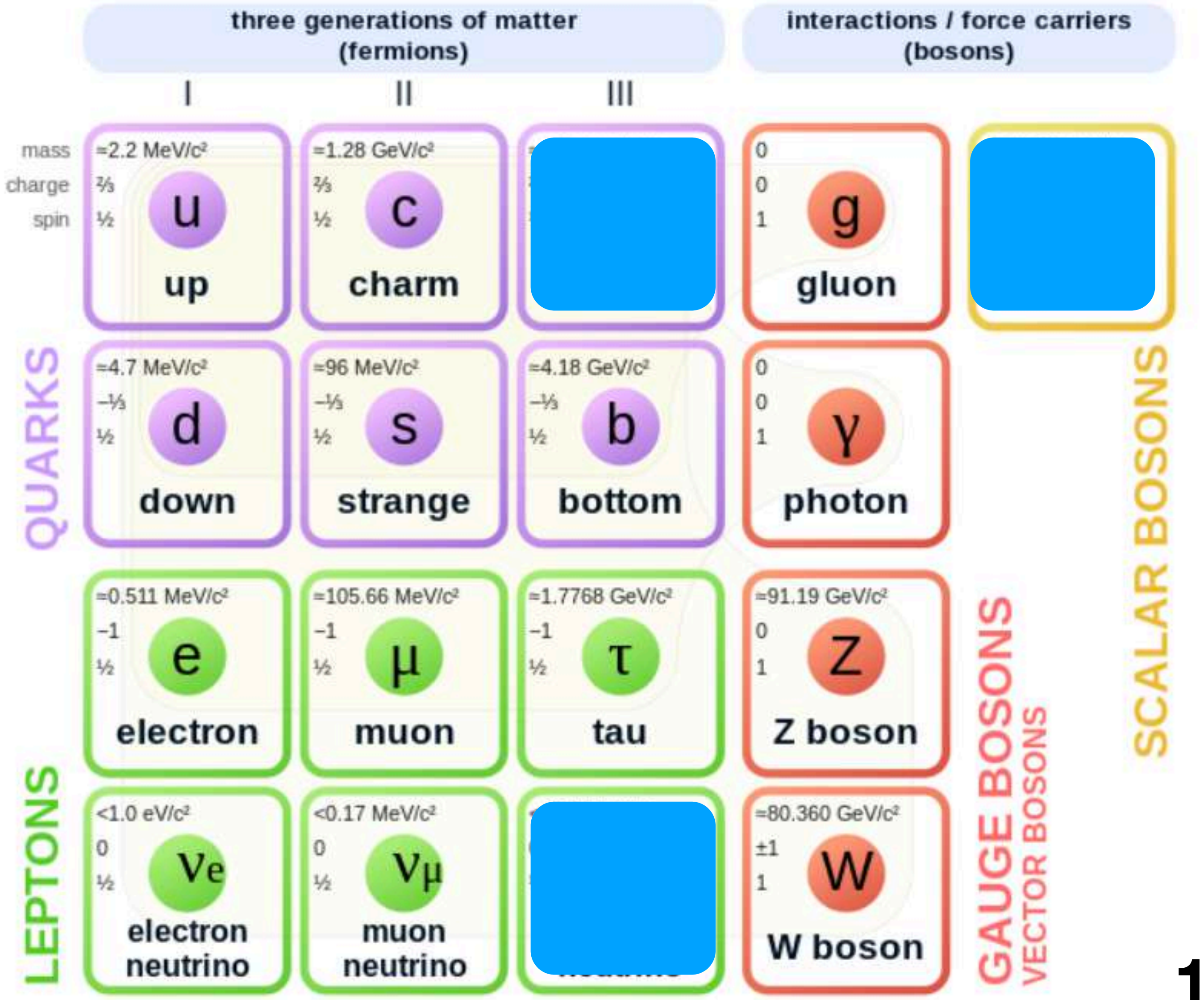
Nobel prize:
Leon Lederman

1977

Experimental proof of SM

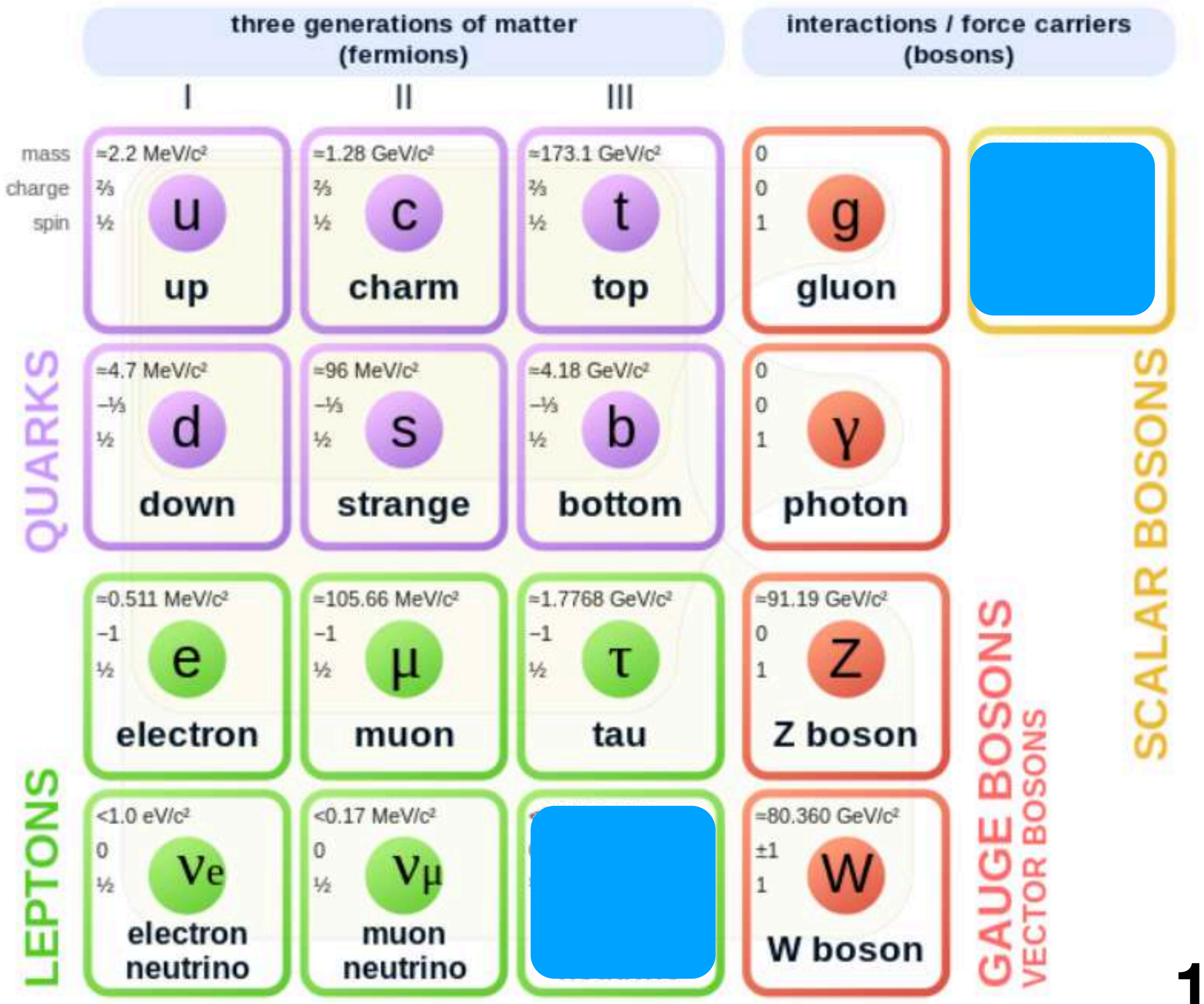


Experimental proof of SM



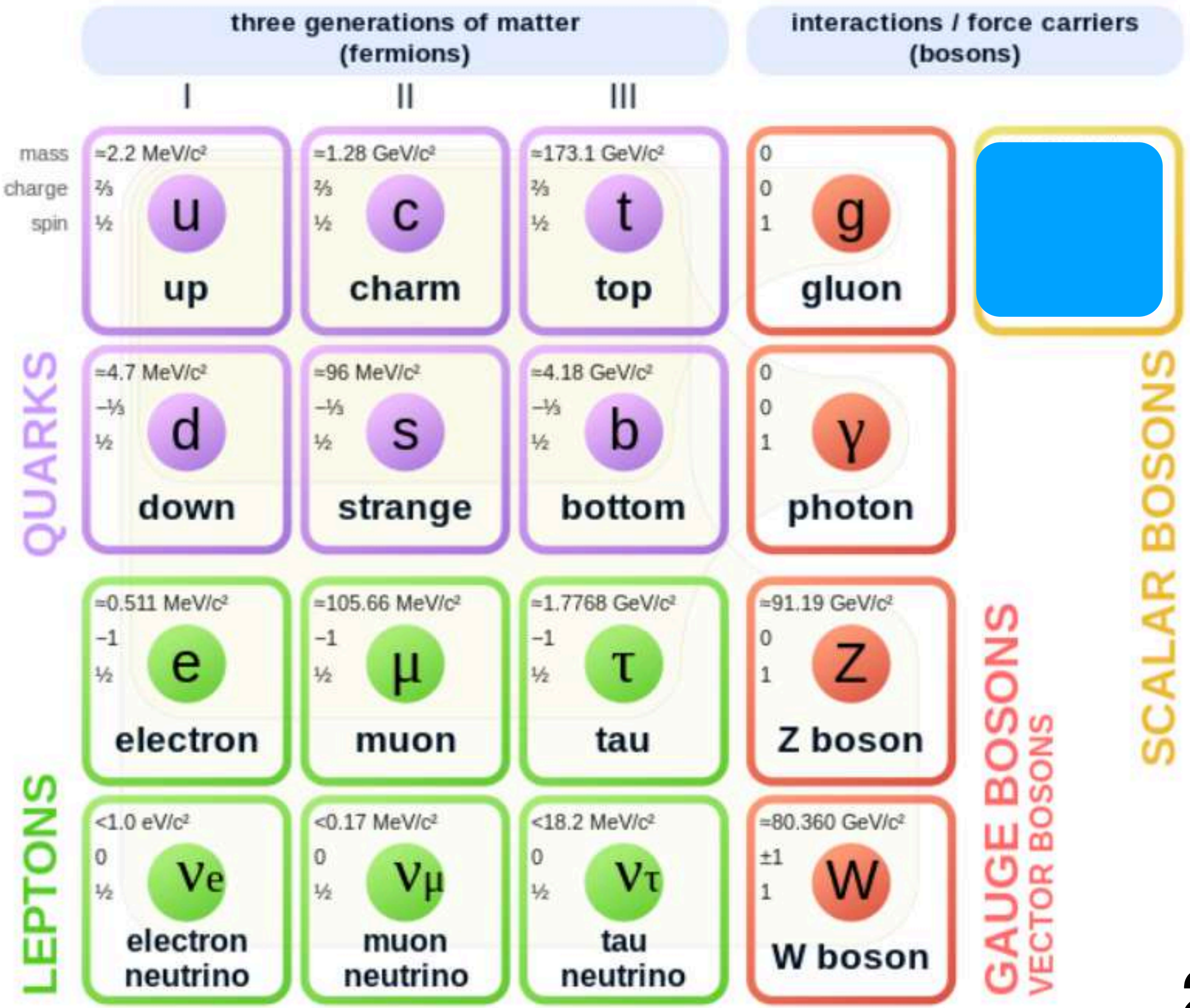
1983

Experimental proof of SM



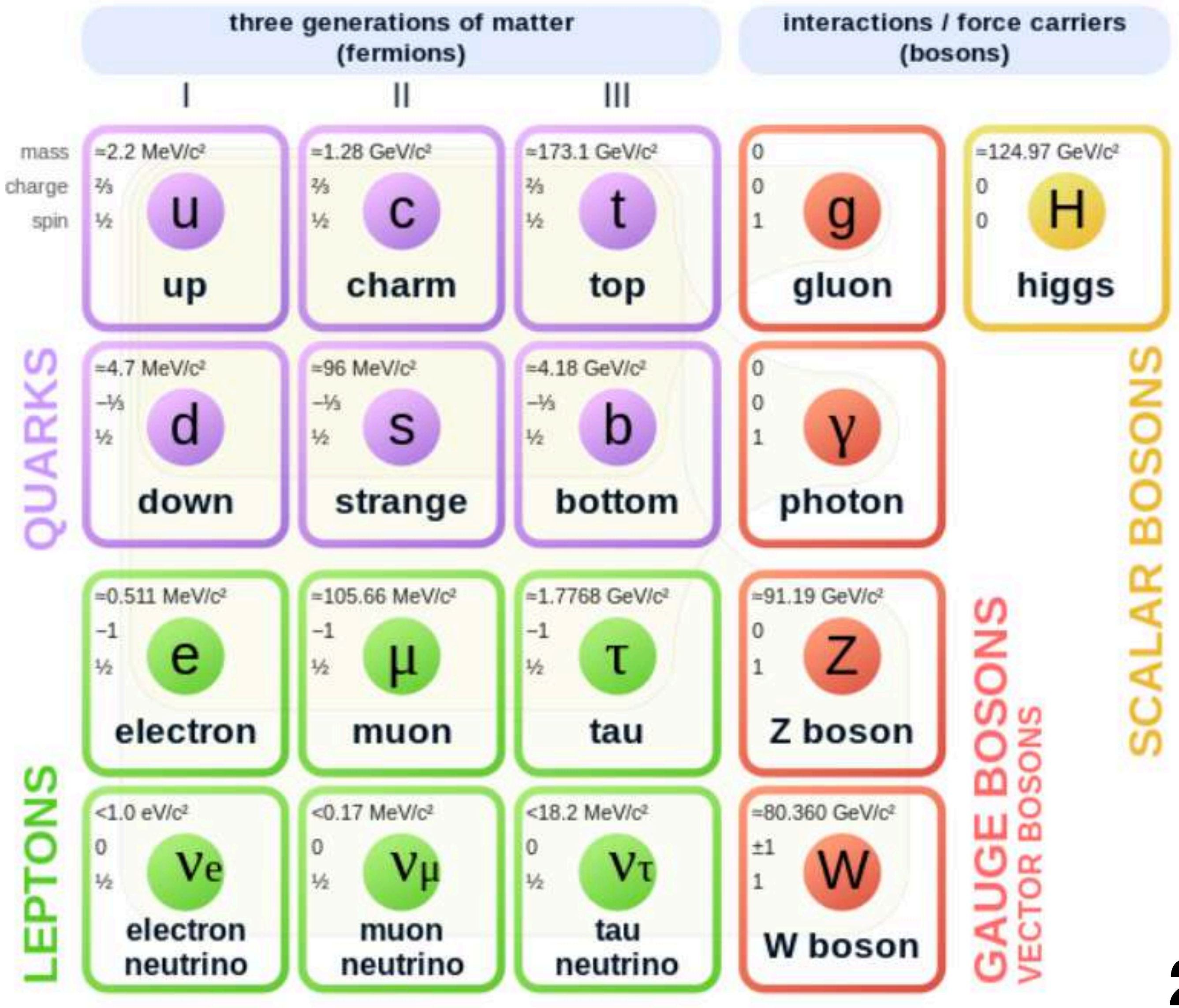
1995

Experimental proof of SM



2000

Experimental proof of SM

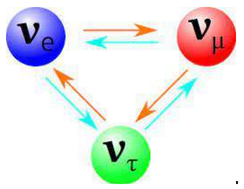


2012

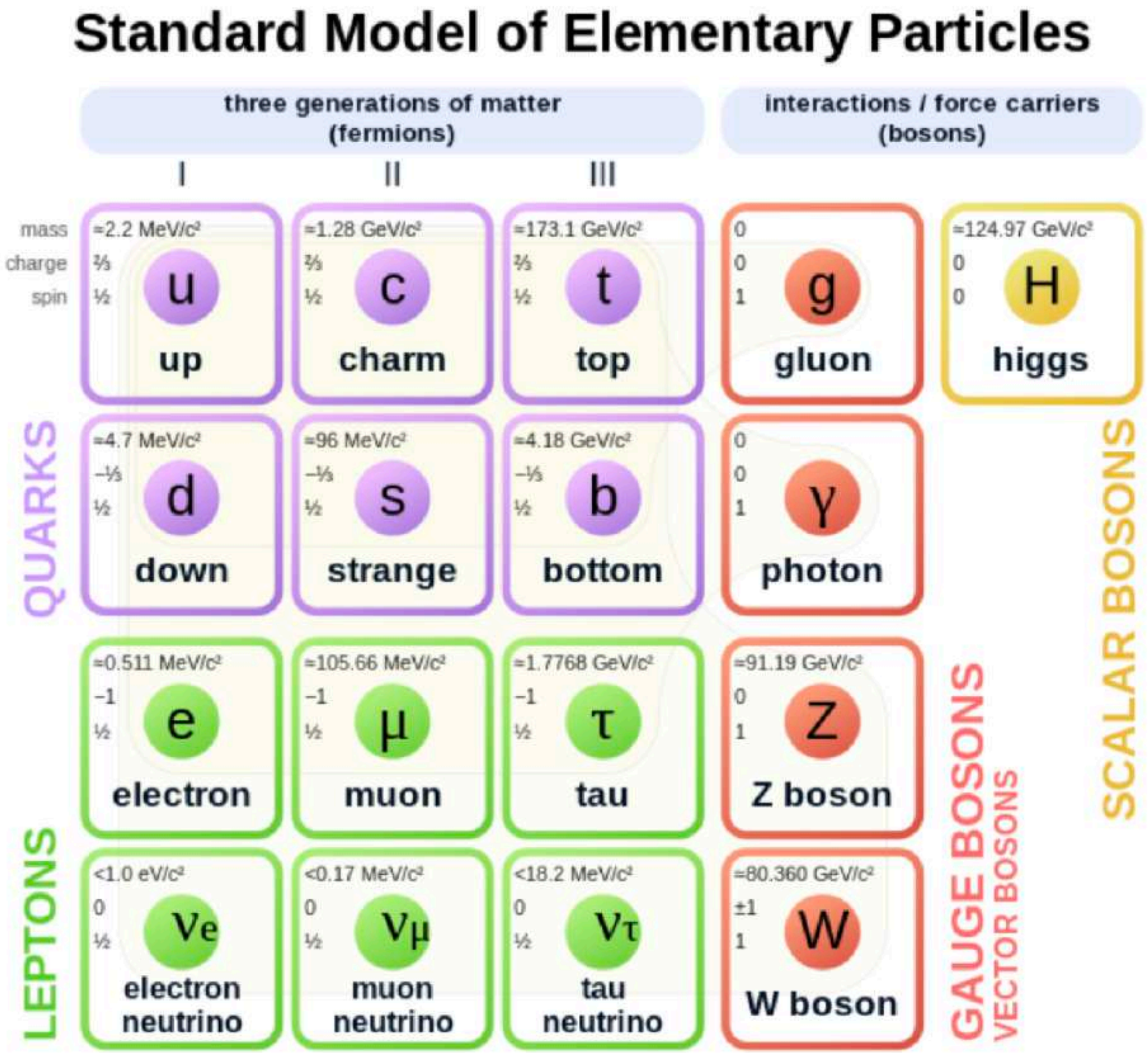
The need for new (BSM) physics

- Standard Model (SM) of particle physics consistent with results of almost all experiments

- BUT – three big observational challenges:
    - Neutrinos have non-zero masses and oscillate



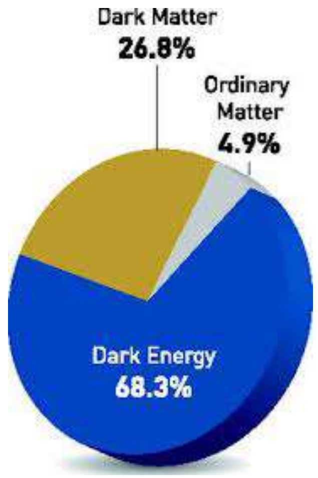
    - The Universe contains Dark Matter
    - There is a matter-antimatter asymmetry in the Universe

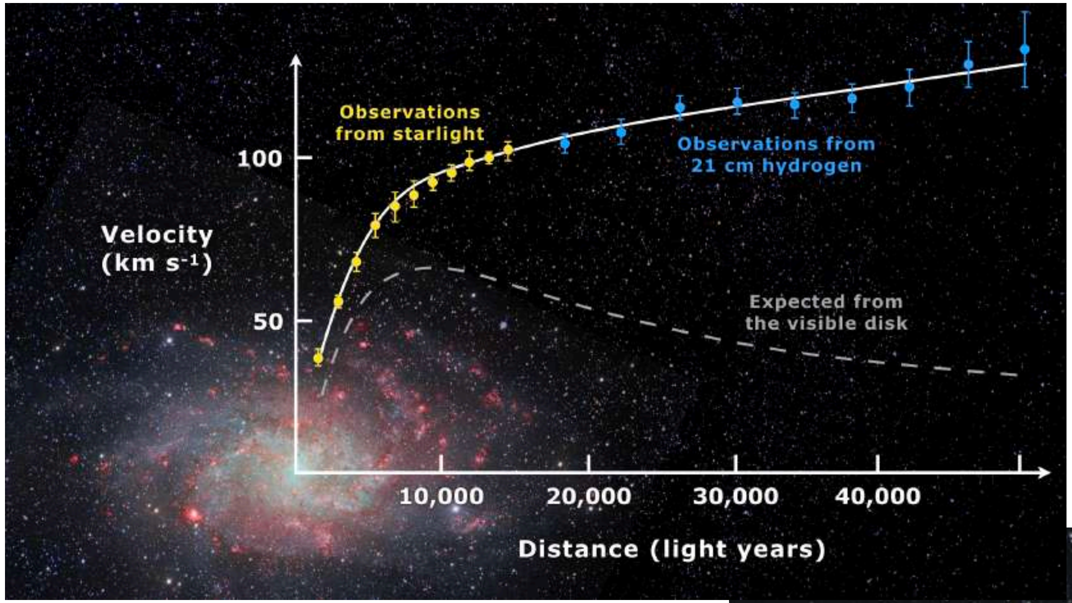


Particle physics & Cosmology

- Experiments in particle physics study small distances $\leq$ Fermi ~ 10^{-13} cm
- Cosmology considers large distances, parsec ~ 10^{18} cm
- Both domains in physics overlap and strongly influence each other in the early Universe when it was hot and dense → interactions between elementary particles played a decisive role in its evolution

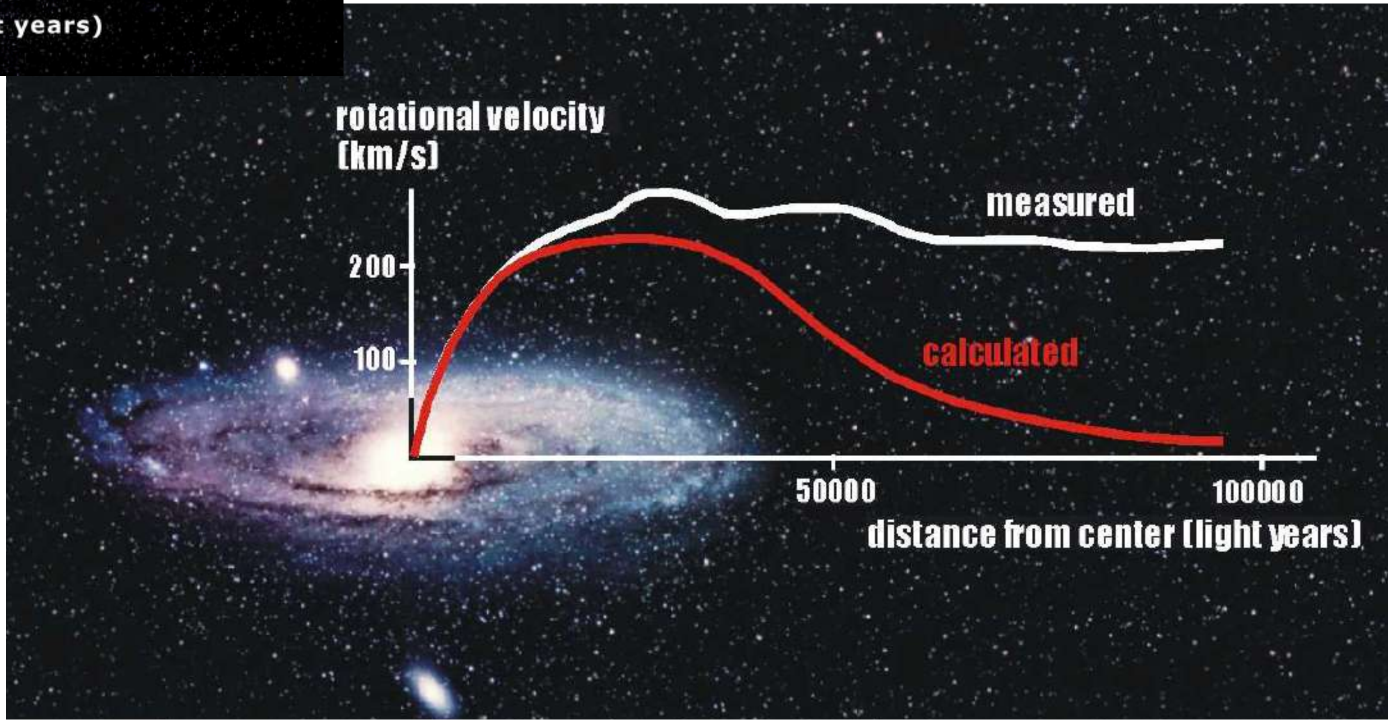
Dark Matter



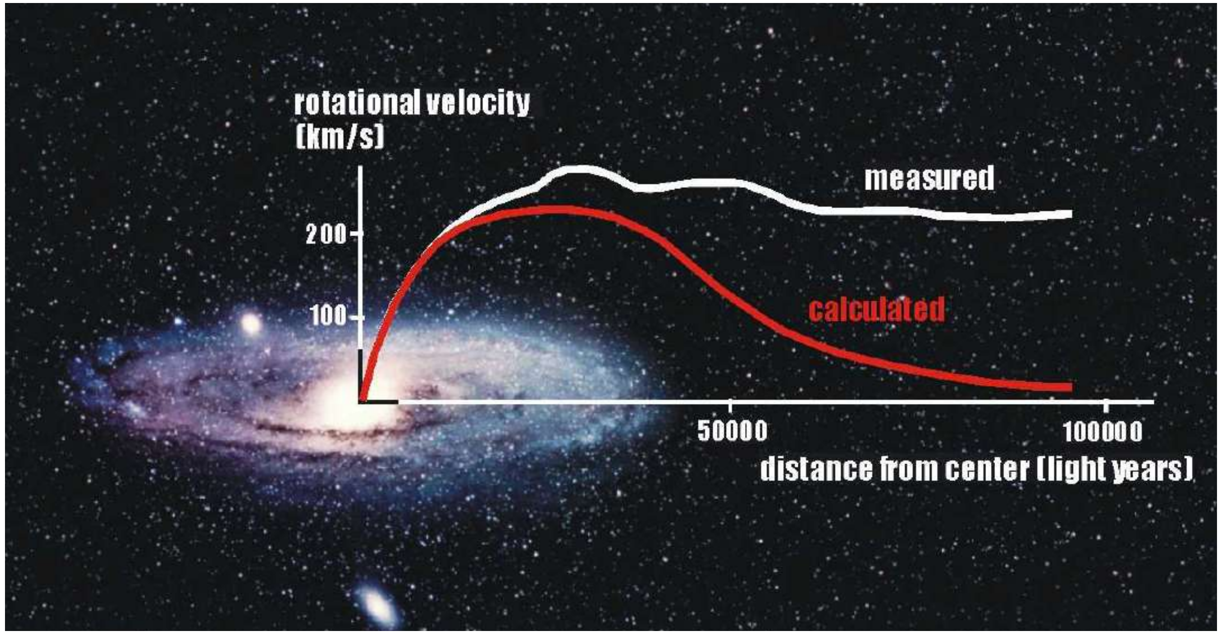


Rotation curve of spiral galaxy Messier 33 (yellow and blue points with error bars), and a predicted one from distribution of the visible matter (gray line).[1]
Corbelli, E.; Salucci, P. (2000-01-15) "The extended rotation curve and the dark matter halo of M33". *Monthly Notices of the Royal Astronomical Society*.

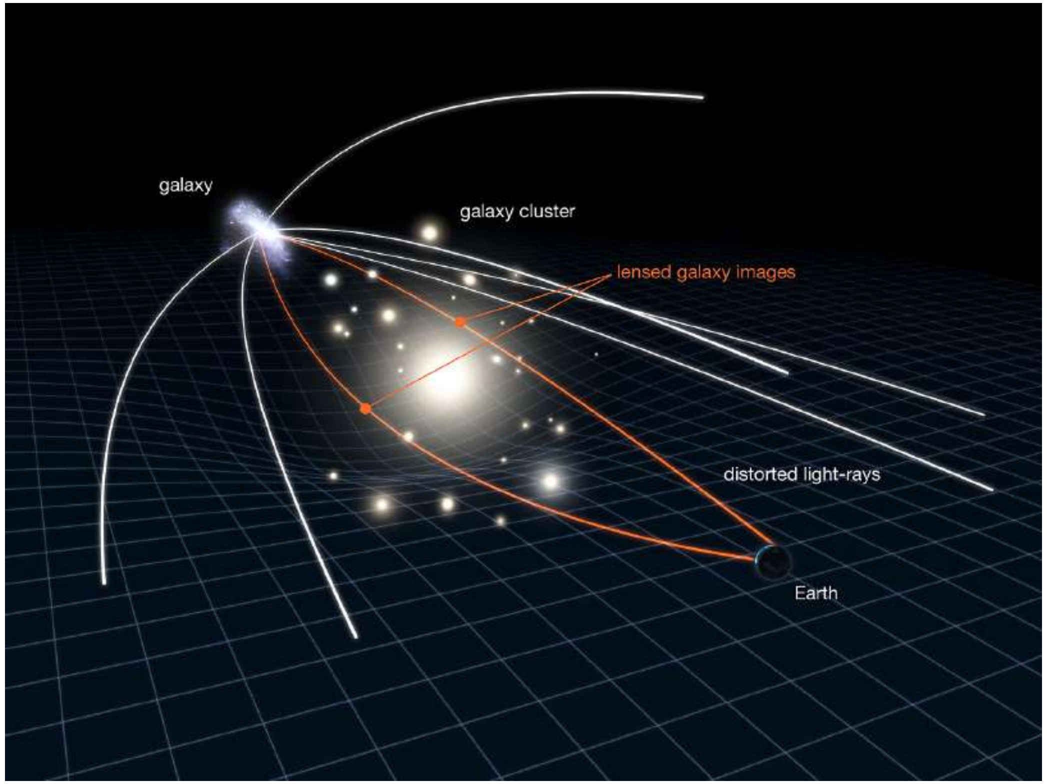
Galaxies rotate faster than expected for the visible matter alone



Dark Matter

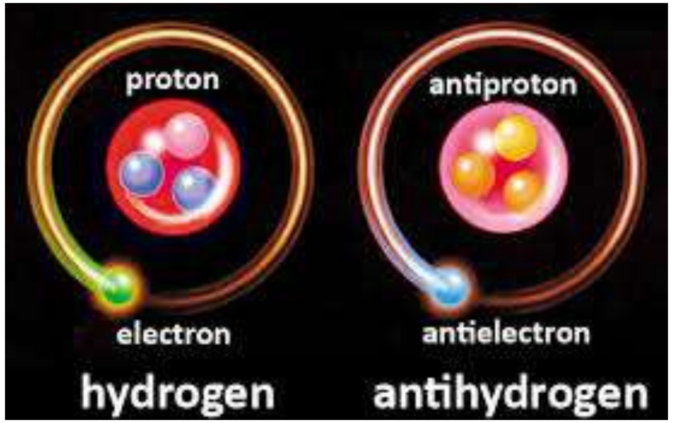


- Rotational velocity of galaxies
  - Galaxies rotate faster than expected for the visible matter alone

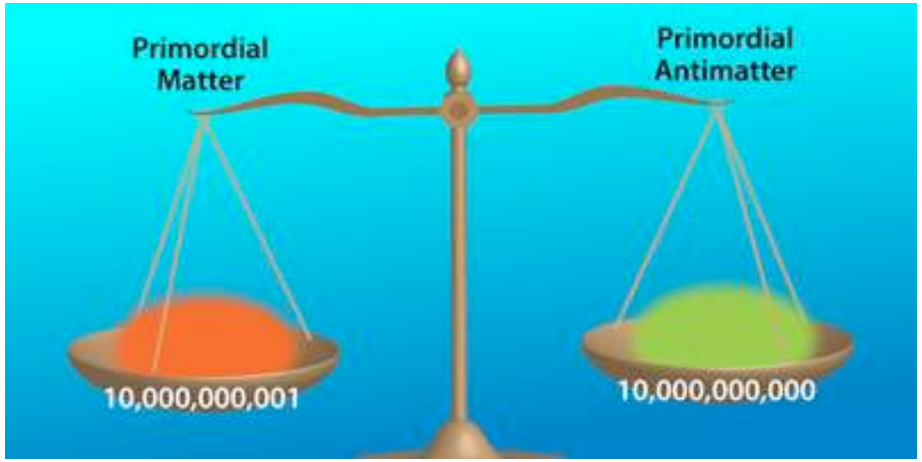


- Gravitational lensing
  - Bending of light around massive objects
  - Astronomers can study distant galaxies otherwise unseen

Baryon Asymmetry of the Universe



- Big Bang relation between the temperature T and the age t of the Universe: $(t / \text{sec}) \sim (\text{MeV} / T)^2$
  In the early Universe, $t \sim 10^{-6}$ sec and $T > 10^{13}\text{K} \cong m_p c^2$
  reactions like $\gamma + \gamma \rightarrow e^+e^-$, $p\bar{p}$ were possible and we had nearly equal amount of matter and anti-matter
- Now everything annihilated to photons (corresponding to T=2.73K)
- Today we have $N_\gamma = (410 \pm 5)$ photons / cm^3
  $N_B = (0.25 \pm 0.01)$ nucleon / m^3
  So, $N_B / N_\gamma = (6.1 \pm 0.2) \times 10^{-10}$
  $\rightarrow (N_B - N_{\bar{B}}) / (N_B + N_{\bar{B}}) = 10^{-10}$

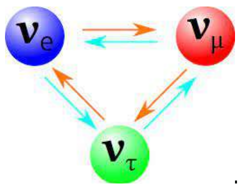


Very small asymmetry at the early moments led to gigantic effect: no anti-matter left

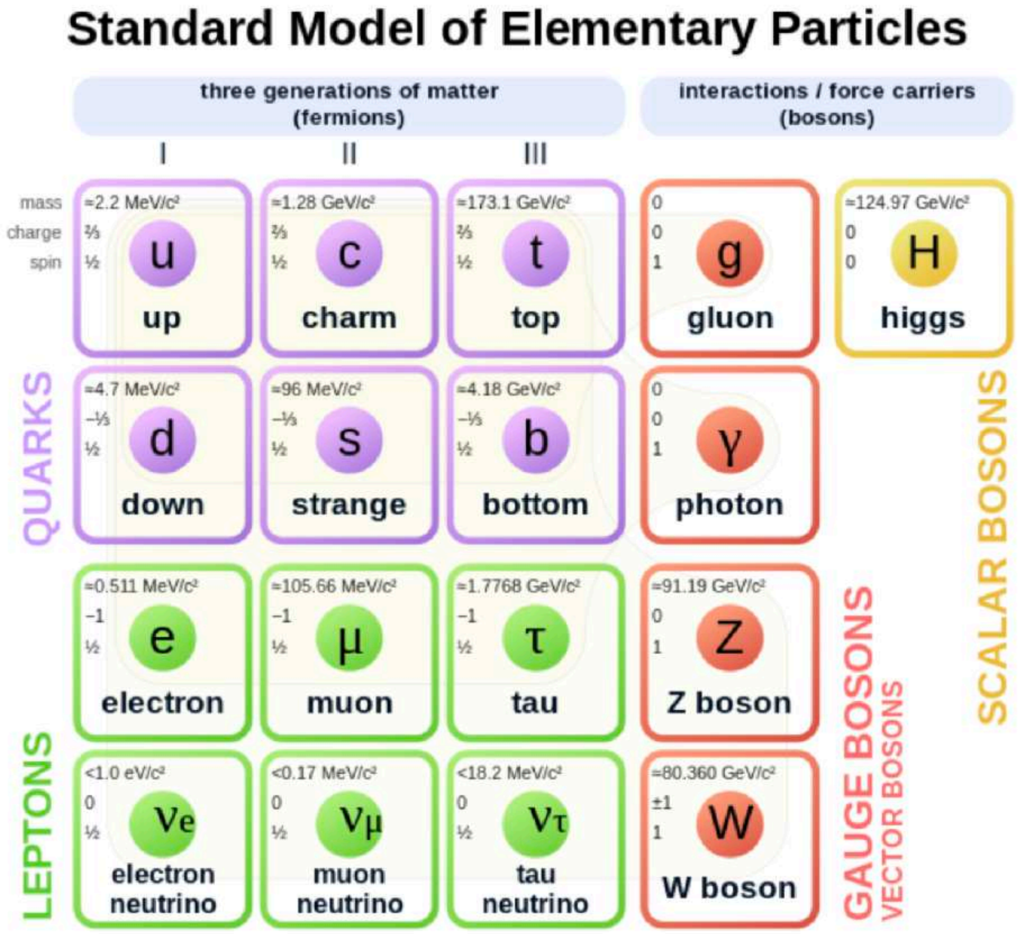
The need for new (BSM) physics

- Standard Model (SM) of particle physics consistent with results of almost all experiments

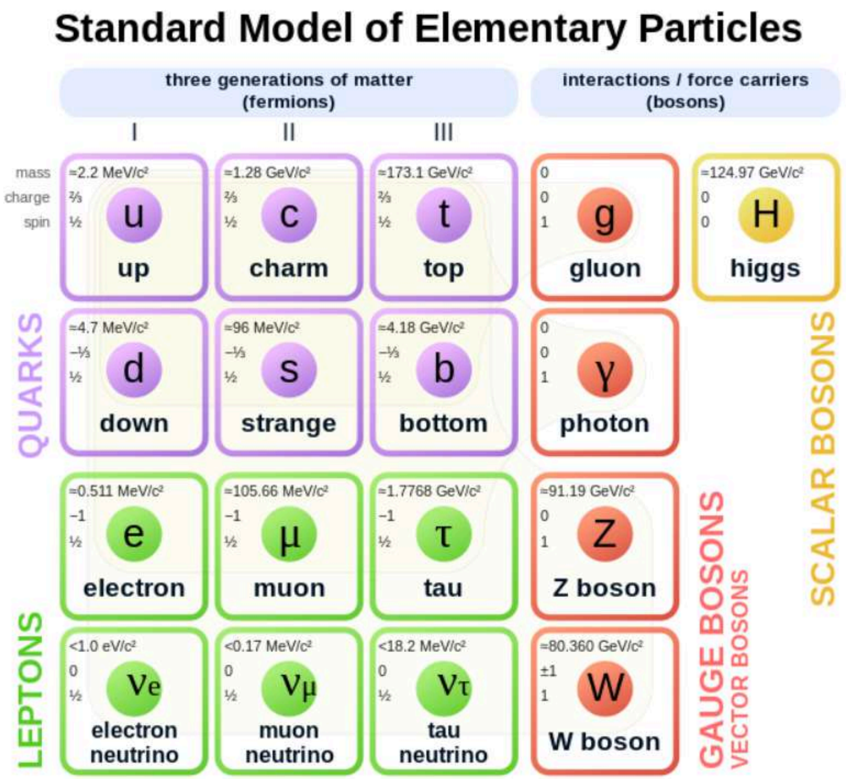
- BUT – three big observational challenges:
  - Neutrinos have non-zero masses and oscillate
  - The Universe contains Dark Matter
  - There is a matter-antimatter asymmetry

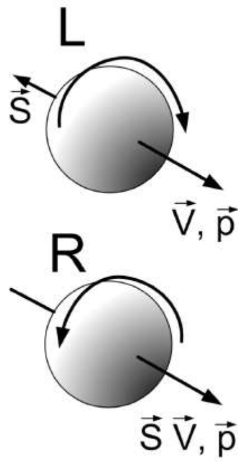


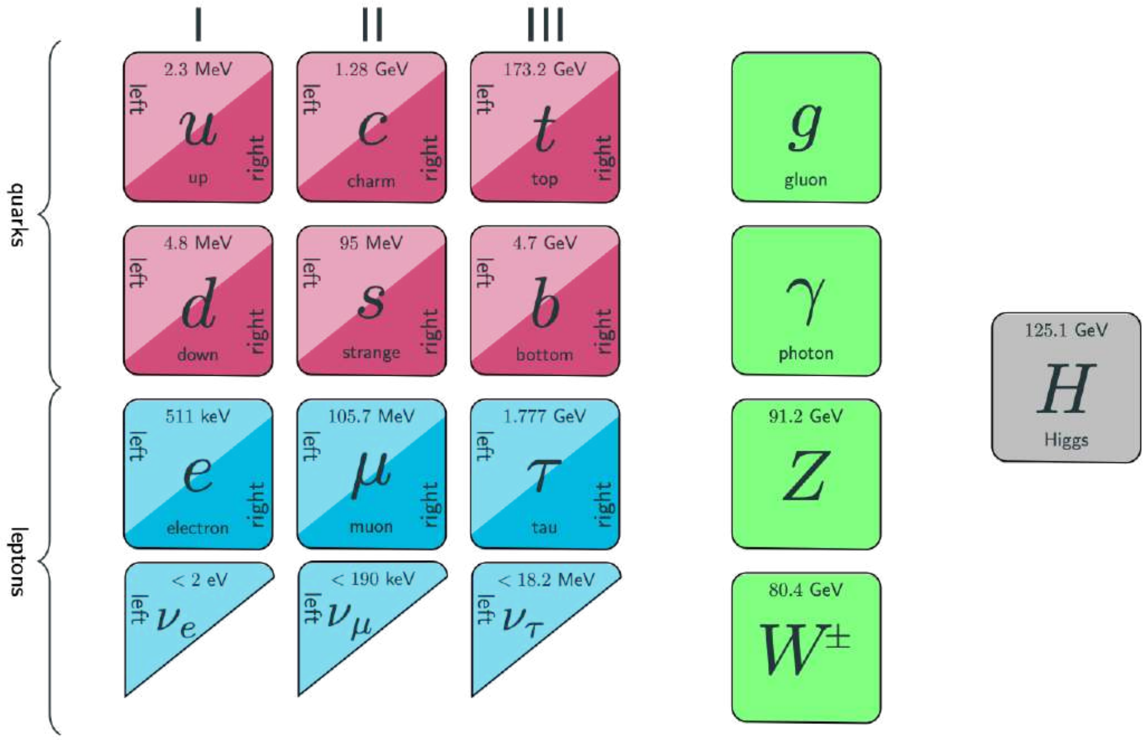
- There must be New physics but we have no theoretical guidance on its scale



What looks *strange* in the fermion sector







Neutrinos are always Left-handed and anti-neutrinos are Right-handed → maximal asymmetry between particles and anti-particles in neutrino sector

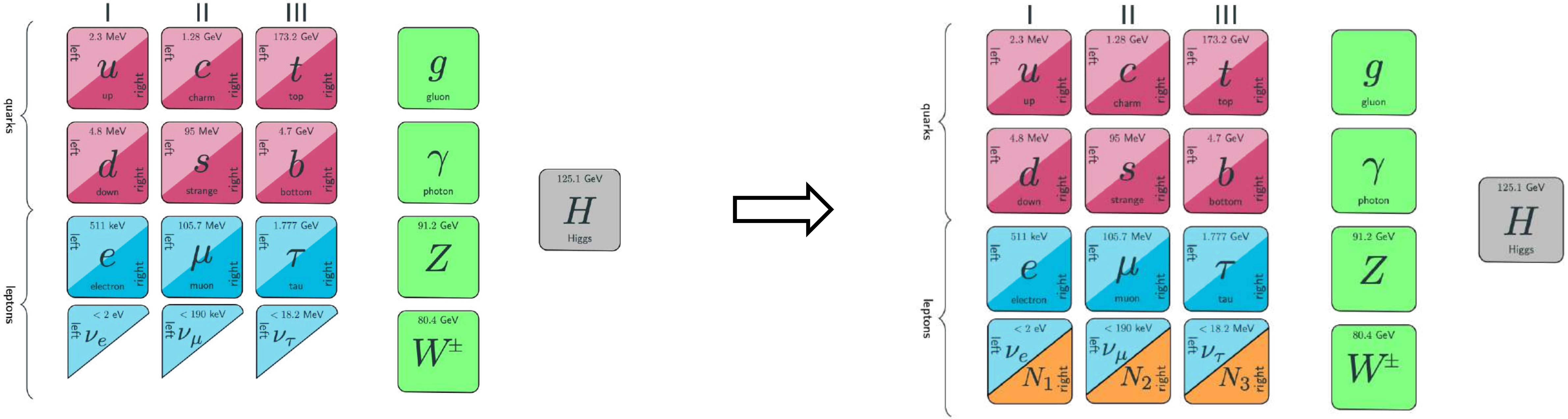
The need for new (BSM) physics

- Can one restore the symmetry in the neutrino sector by extending the generations of fundamental fermions (in a minimal way) such that the beauty of SM is preserved ?

Reminder: the 3^{rd} generation was not required by SM but was added to describe violation of symmetry between matter and anti-matter

Right-handed neutrinos

- Restore the symmetry between neutrinos and anti-neutrinos by adding three massive Right-handed neutrinos (HNL)

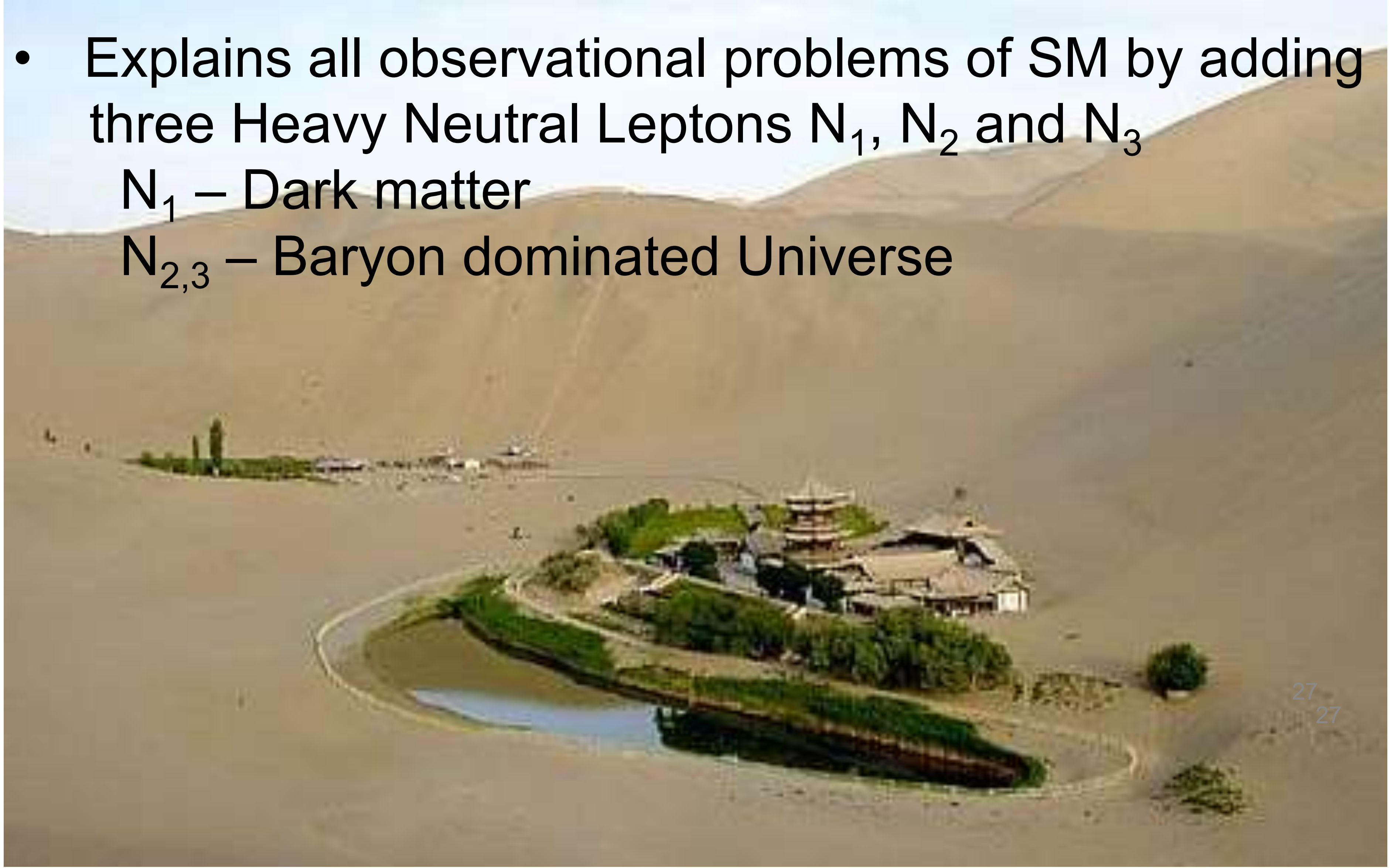


- Use Right-handed neutrinos to give masses to ordinary neutrinos via *see-saw* mechanism: $m_\nu \sim U^2 / M_N$, *where U describes interaction strength between HNL and ordinary neutrinos*

→ Hints for very large M_N or very small U

Neutrino Minimal Standard Model: νMSM

(T.Asaka, M.Shaposhnikov PL B620 (2005) 17)



- Explains all observational problems of SM by adding three Heavy Neutral Leptons N_1, N_2 and N_3

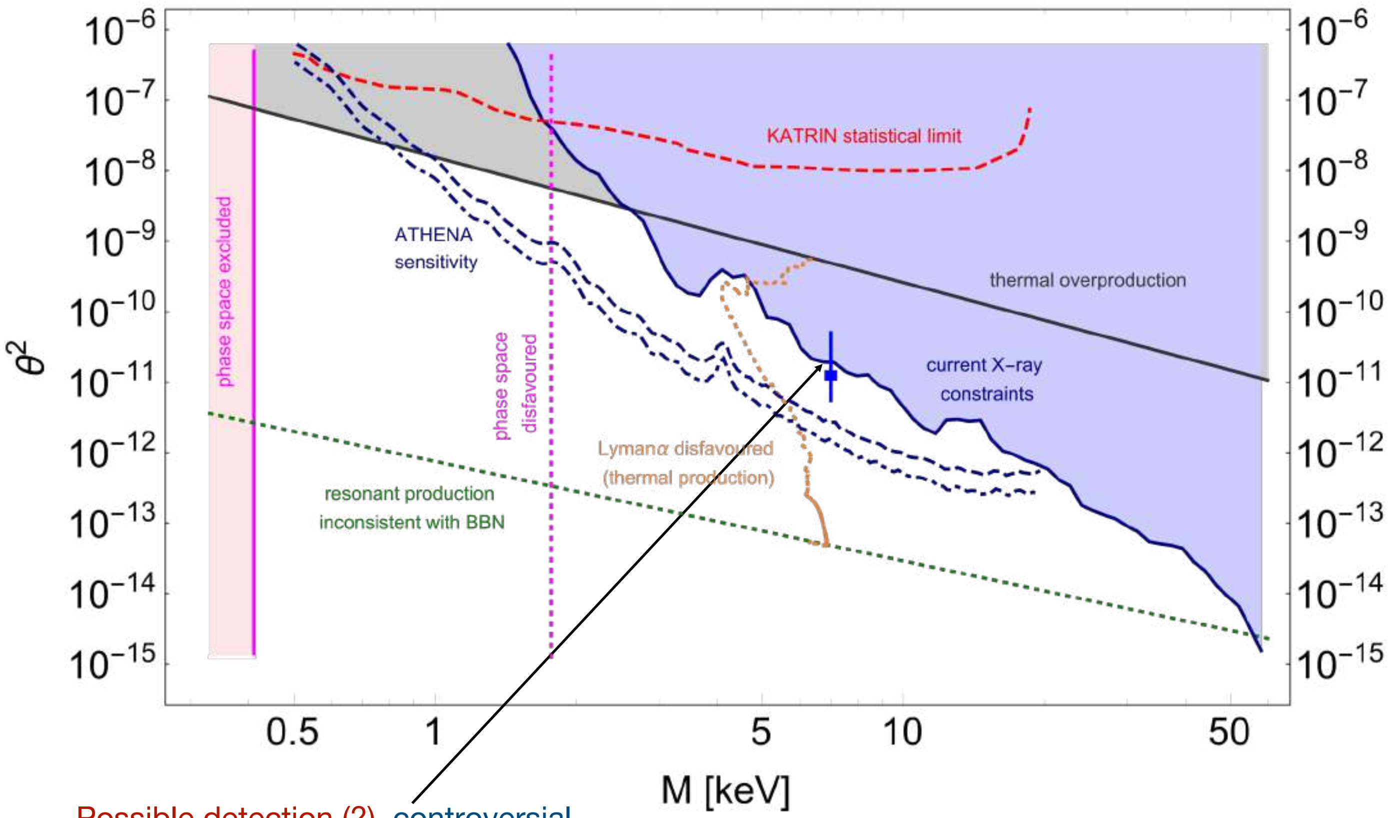
  N_1 – Dark matter

  $N_{2,3}$ – Baryon dominated Universe

27
27

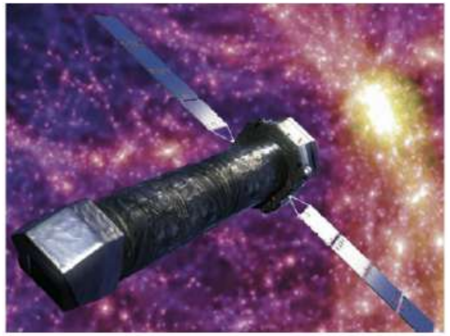
Hint for N_1 from cosmos

Available parameter space

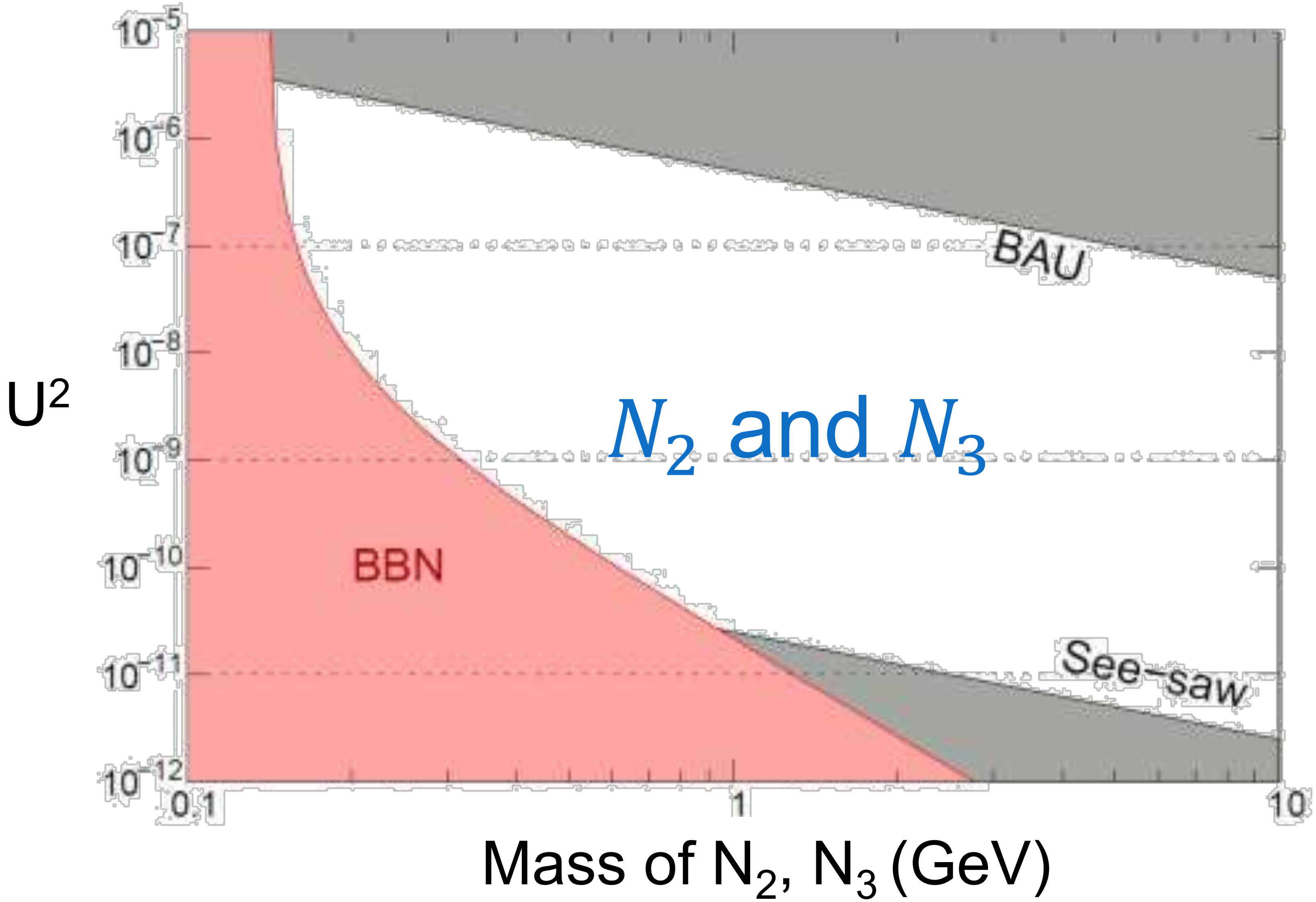


Possible detection (?), controversial
Bulbul et al; Boyarsky et al

- N_1 – light long-lived particle
  - mass in the keV-region
  - lives longer than Universe
  - can decay $N_1 \rightarrow \nu\gamma$
- Search for the photon mono-energetic line using X-ray telescopes in cosmos
- Future searches:
  - Large ESA X-ray mission Athena+ (~2030)



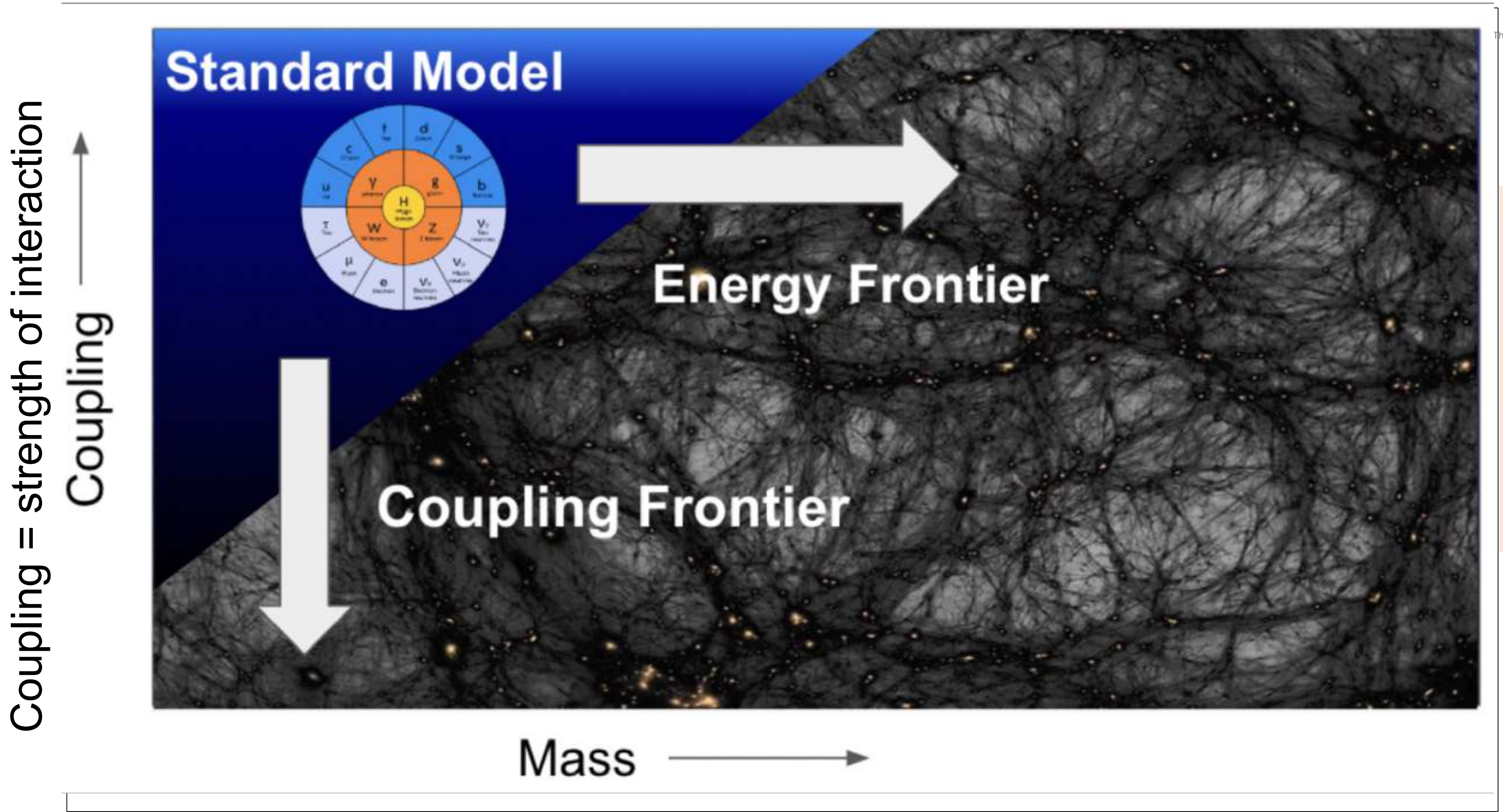
Matter anti-matter asymmetry and $N_{2,3}$ masses



Need to be verified experimentally

Search for $N_{2,3}$ at accelerators
Are we searching in the correct place?

- “Coupling Frontier”: SM particles interact with Hidden Particles ?



The image part with relationship ID rId3 was not found in the file.

New physics is either too heavy or interacts very feebly, *i.e.* much weaker than neutrino, in order to have escaped detection

Neutrino Minimal Standard Model: νMSM

(T.Asaka, M.Shaposhnikov PL B620 (2005) 17)

- Explains all observational problems of SM by adding three Heavy Neutral Leptons N_1, N_2 and N_3:
  - N_1 provides Dark matter
  - $N_{2,3}$ explain Baryon dominated Universe

Search for Hidden Particles of Nature

- Globally unique potential → CERN approval of the SHiP experiment

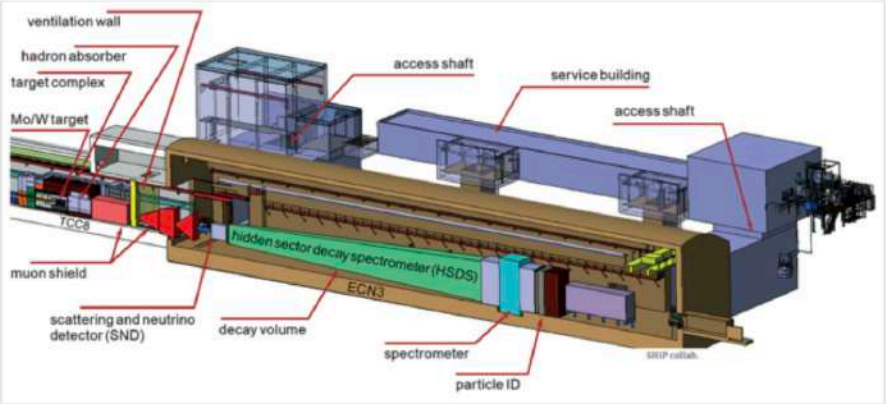
CERNCOURIER | Reporting on international high-energy physics

Physics ▾ | Technology ▾ | Community ▾ | In focus | Magazine

SEARCHES FOR NEW PHYSICS | NEWS

SHiP to chart hidden sector

3 May 2024



Full speed ahead Layout of the SHiP experiment, with the target on the left and the experiment in the ECN3 hall. Credit: SHiP collab.

In March, CERN selected a new experiment called SHiP to search for hidden particles using high-intensity proton beams from the SPS. First proposed in 2013, SHiP is scheduled to operate in the North Area's ECN3 hall from 2031, where it will enable searches for new physics at the "coupling frontier" complementary to those at high-energy and precision-flavour experiments.

Search for Hidden Particles of Nature

- Globally unique potential → CERN approval of the SHiP experiment

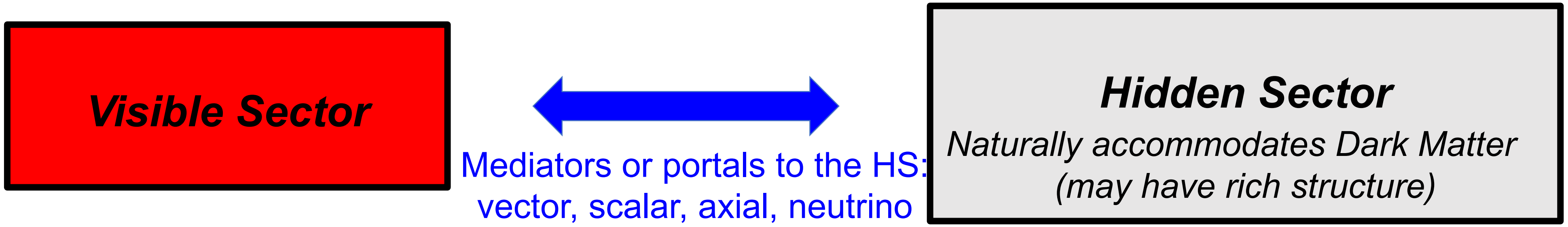
- Search for a broad range of Hidden Particles:
  - Heavy Neutral Leptons (HNLs)
  - Dark photons
  - Dark Scalar Higgs-like particles
  - Axion-like particles (ALPs)

… and make unprecedented measurements of tau neutrinos

Cern: Scientists search for mysterious ghost particles **25 March 2024**
Pallab Ghosh BBC Science correspondent

The project's ghostbuster-in-chief, Prof Andrey Golutvin of Imperial College London said that the experiment "*marks a new era in the search for hidden particles*".
"*SHiP has the unique possibility to solve several of the major problems of particle physics, and we have the prospect of discovering particles that have never been seen before*" he said.

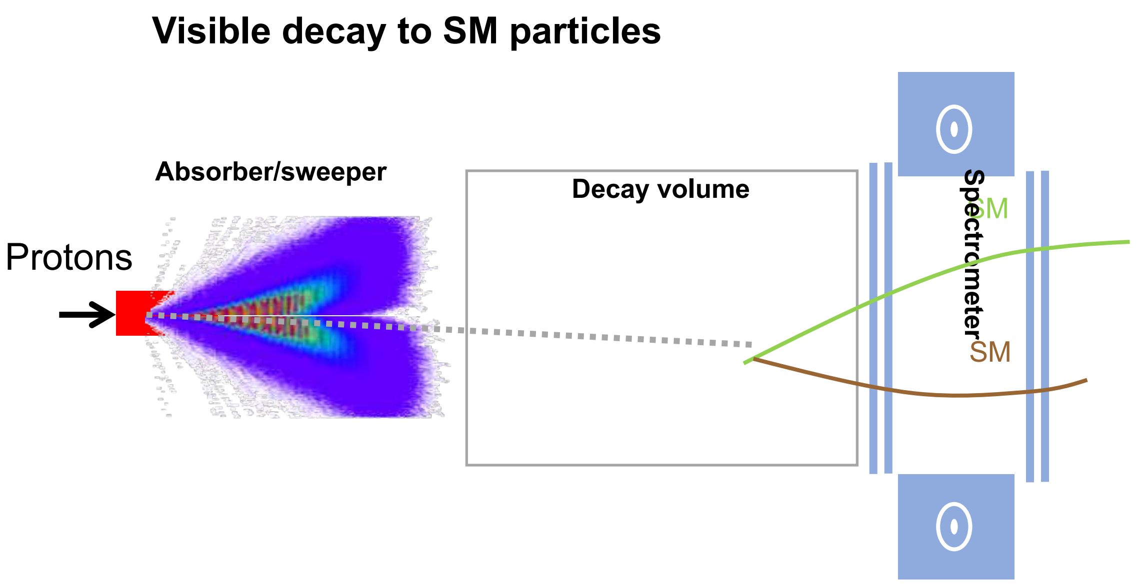
Properties of Hidden Particles

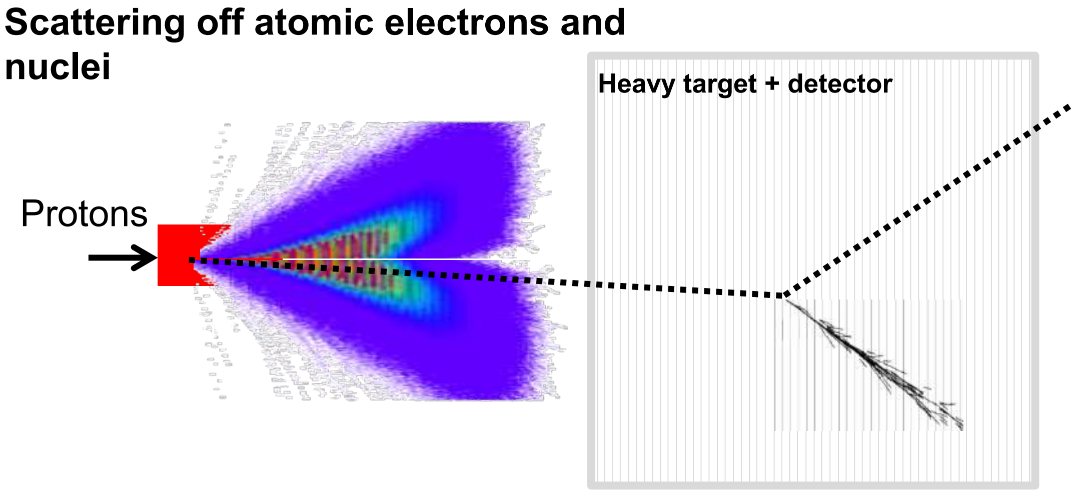


- Hidden Particle production and decay rates are strongly suppressed relative to SM
  - Production branching ratios O(10^{-10})
  - Long-lived objects
  - Interact very weakly with matter
  - May decay to various final states, e.g.

Portal models	*Final states*
HNL	$l^+\pi^-$, l^+K^-, $l^+\rho^-$
Vector, scalar, axion portals	l^+l^-
HNL	$l^+l^-\nu$
Axion portal	$\gamma\gamma$

Experimental techniques





Also suitable for neutrino interaction physics with all flavours

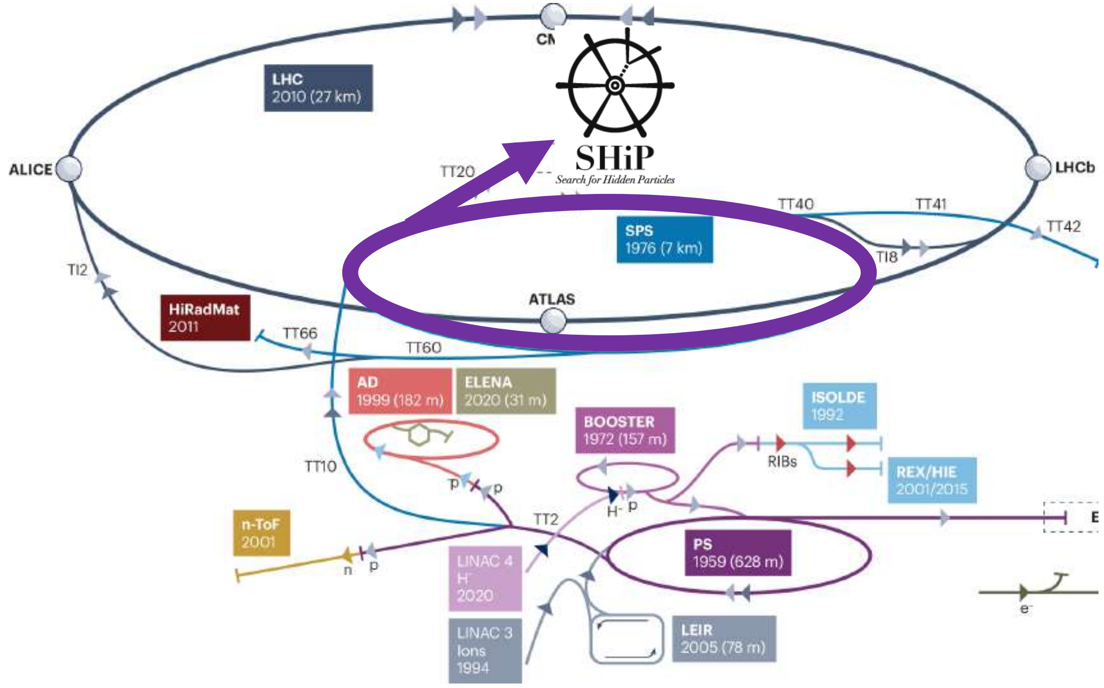
Sensitivity depends on three factors:

- Yields (protons on target)
- Detector Acceptance (lifetime & angular coverage)
- Background level
- Experimental challenge is the background suppression

What is the SHiP experiment?

- CERN's **SPS accelerator** will be used to fire protons on to a target

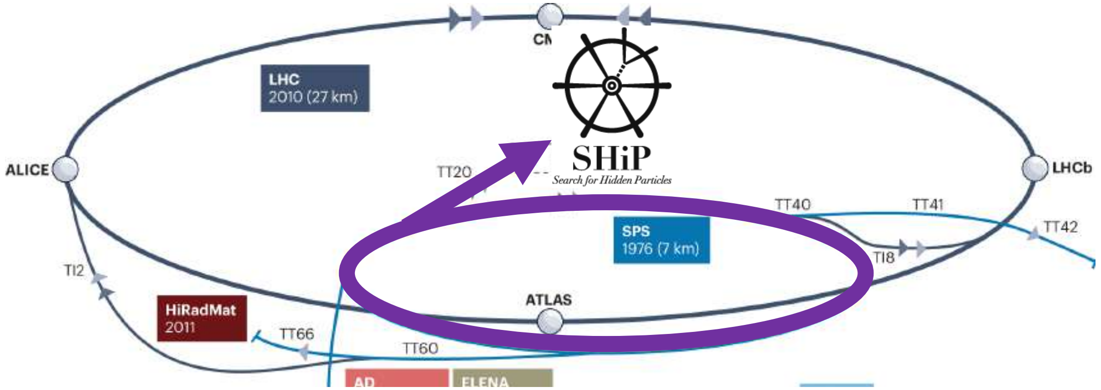
CERN accelerator complex

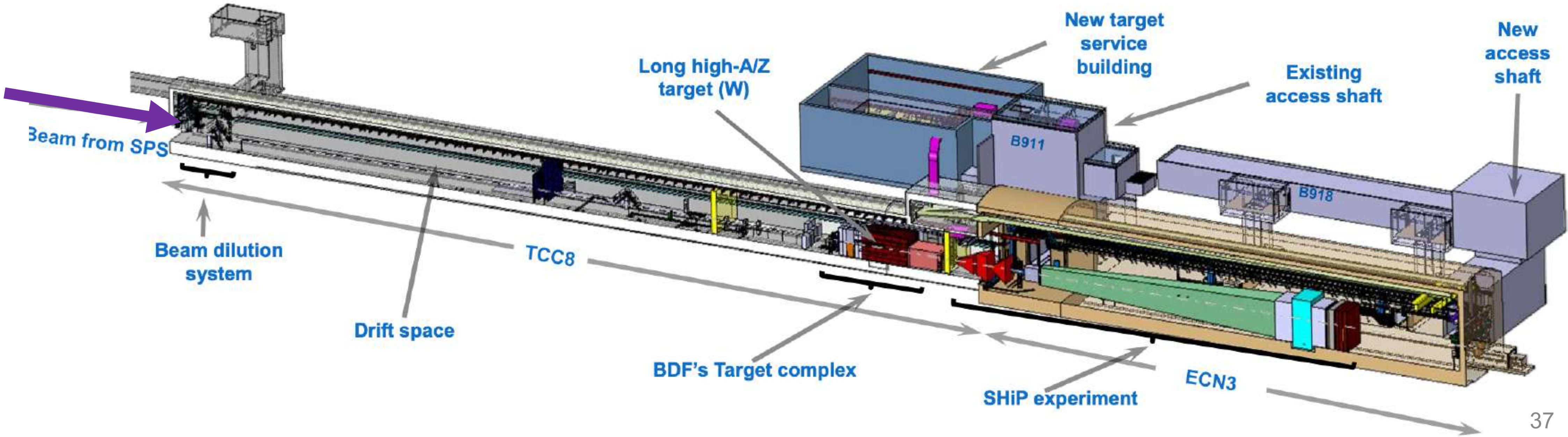


What is the SHiP experiment?

- CERN's **SPS accelerator** will be used to fire protons on to a target
  - Facility already under construction

CERN accelerator complex





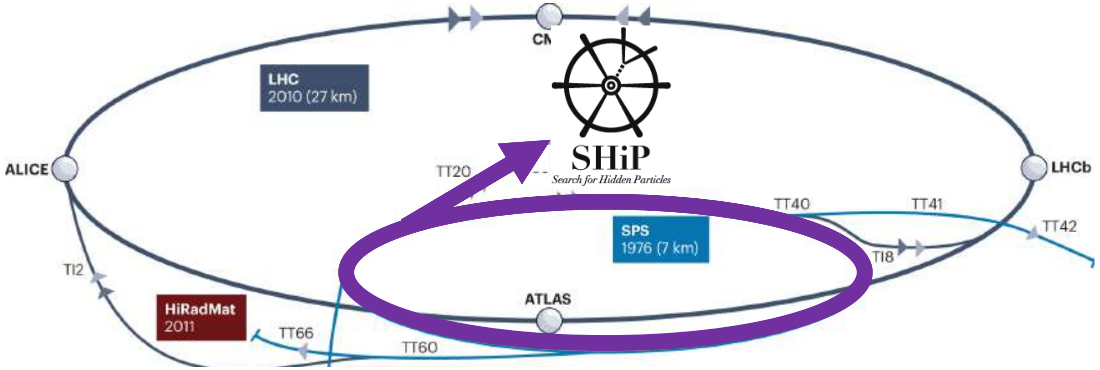
What is the SHiP experiment?

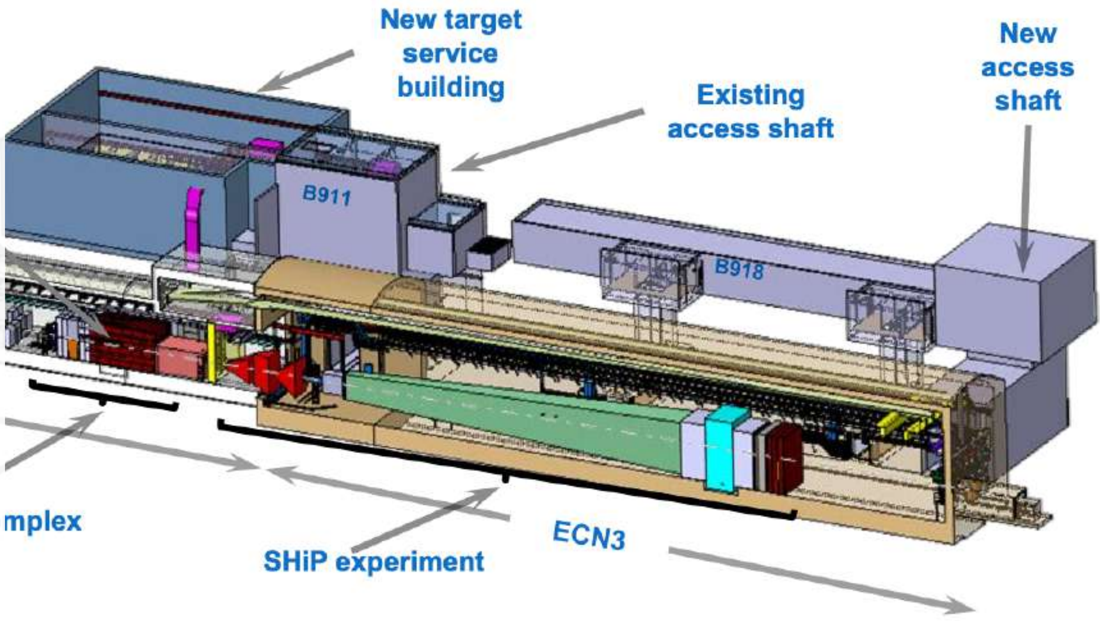
- CERN's **SPS accelerator** will be used to fire protons on to a target
  - Facility already under construction

- Collisions could generate new Hidden Particles but will also get:
  - hadrons → hadron absorber
  - muons → muon shield
  - neutrinos (irreducible) → ν **physics**

… can exploit collisions only to extent can control backgrounds

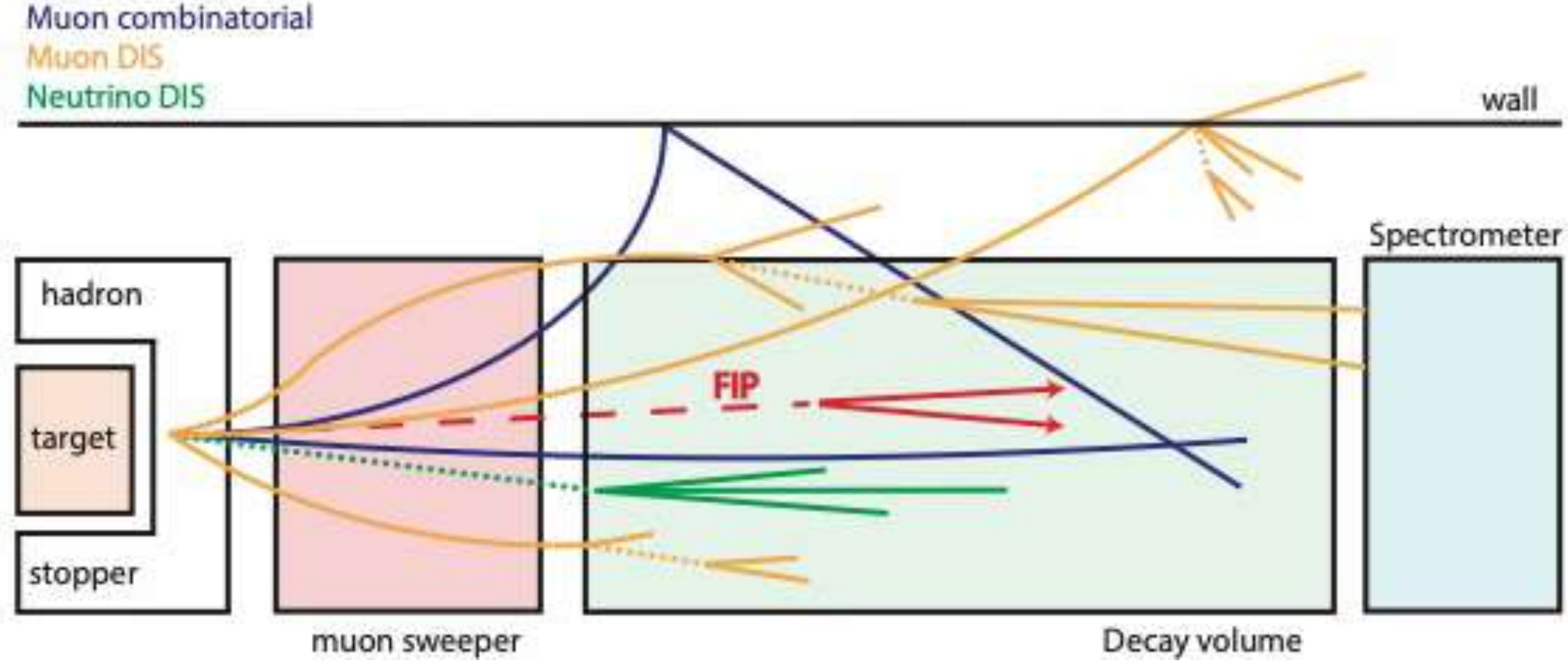
CERN accelerator complex





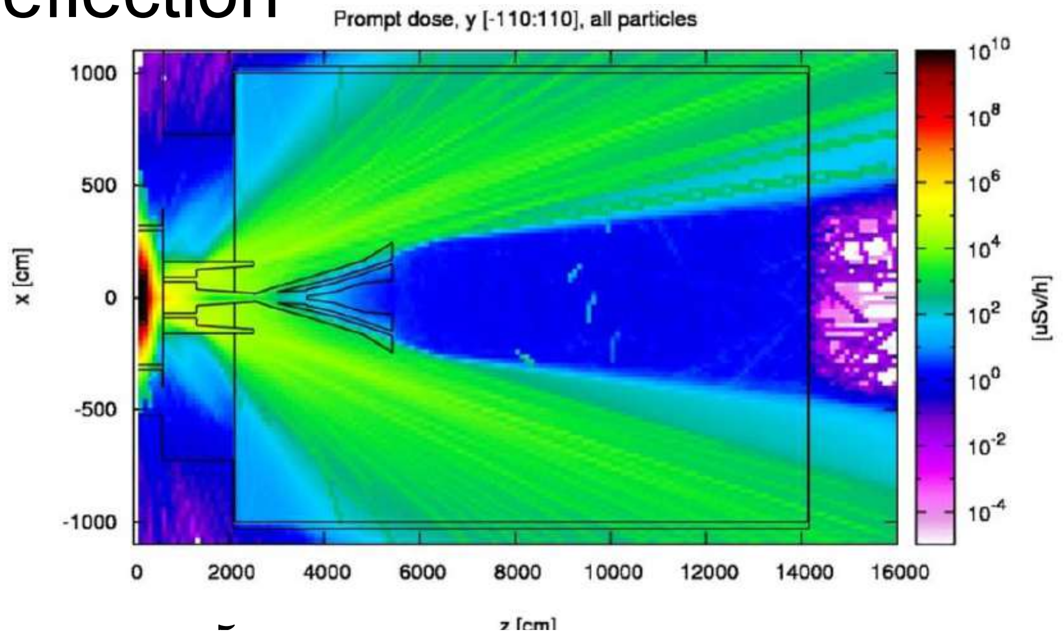
Backgrounds at SHiP

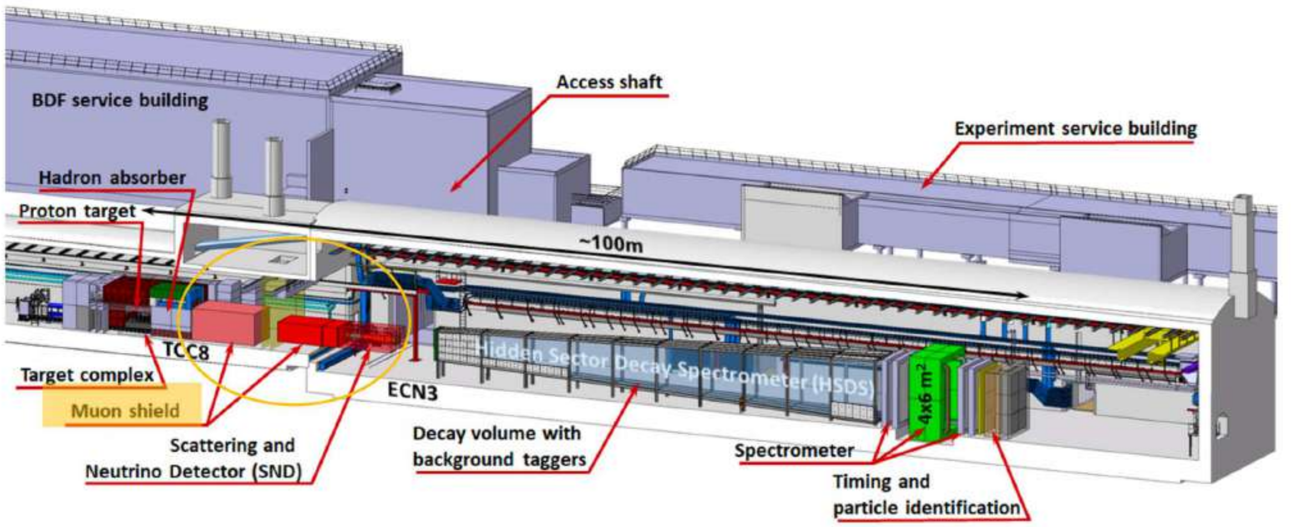
Main sources of background:

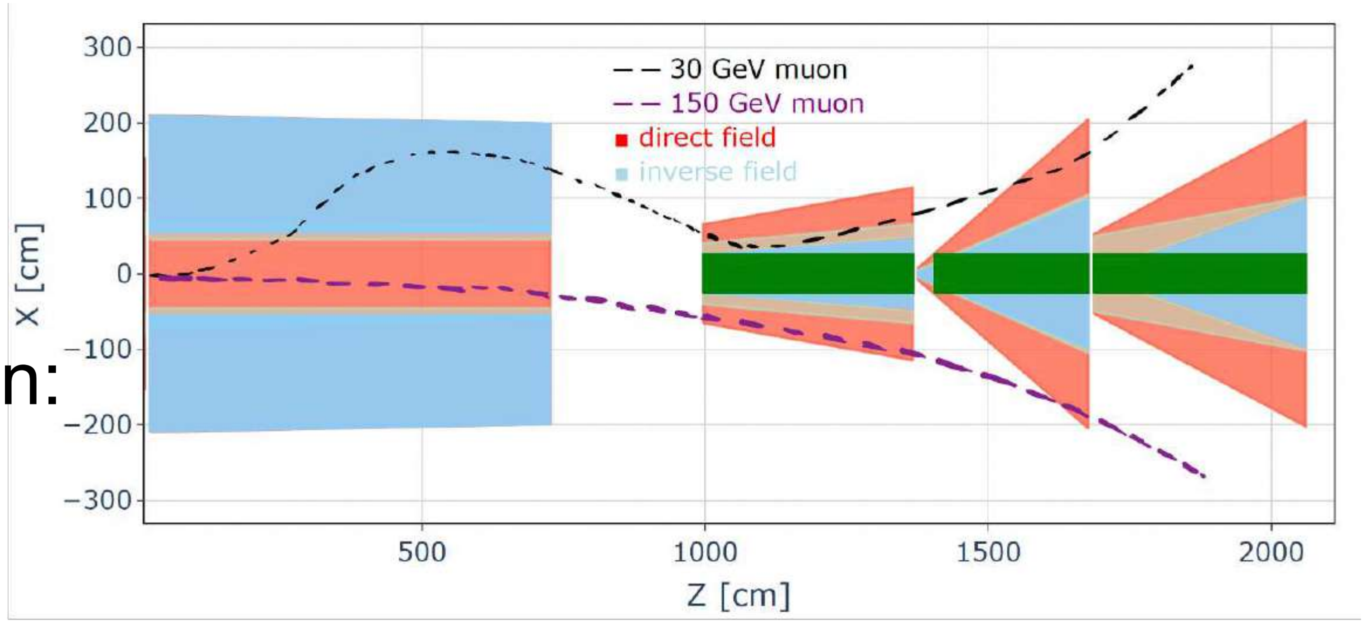


Magnetic muon shield

Reduce muon rate from 10^{10} to 10^{5} per spill (1 sec) using active deflection







Two options under consideration:

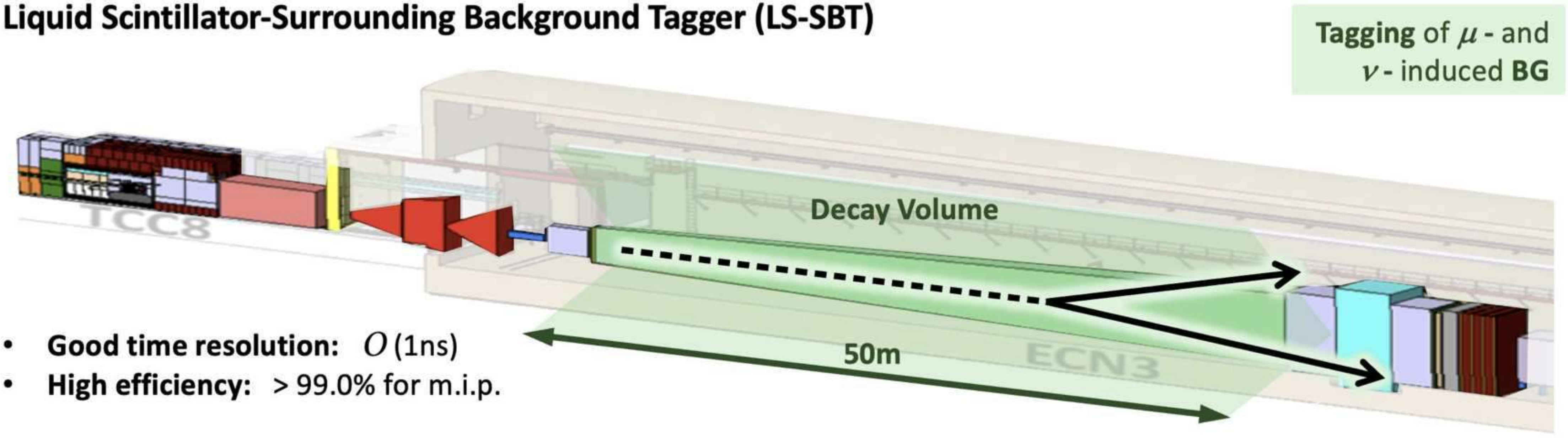
- Fully warm
- Hybrid with 1st section made of SC technology

Decay volume and background taggers

50m long frustum decay volume:

- He at atmospheric pressure
- $1.0 \times 2.7\text{m}^2$ upstream, $4\times 6\text{m}^2$ downstream

Liquid Scintillator-Surrounding Background Tagger (LS-SBT)

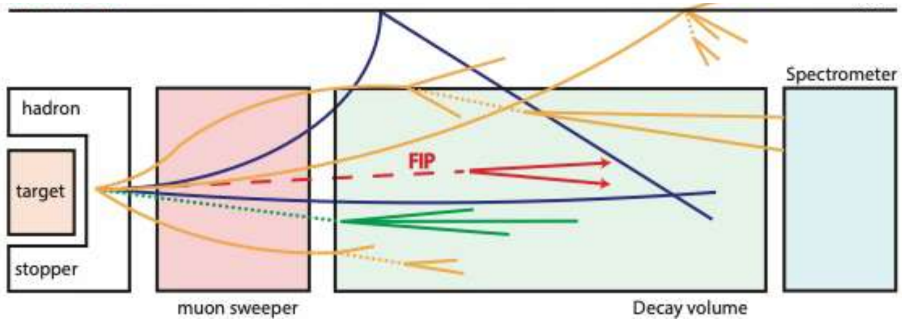


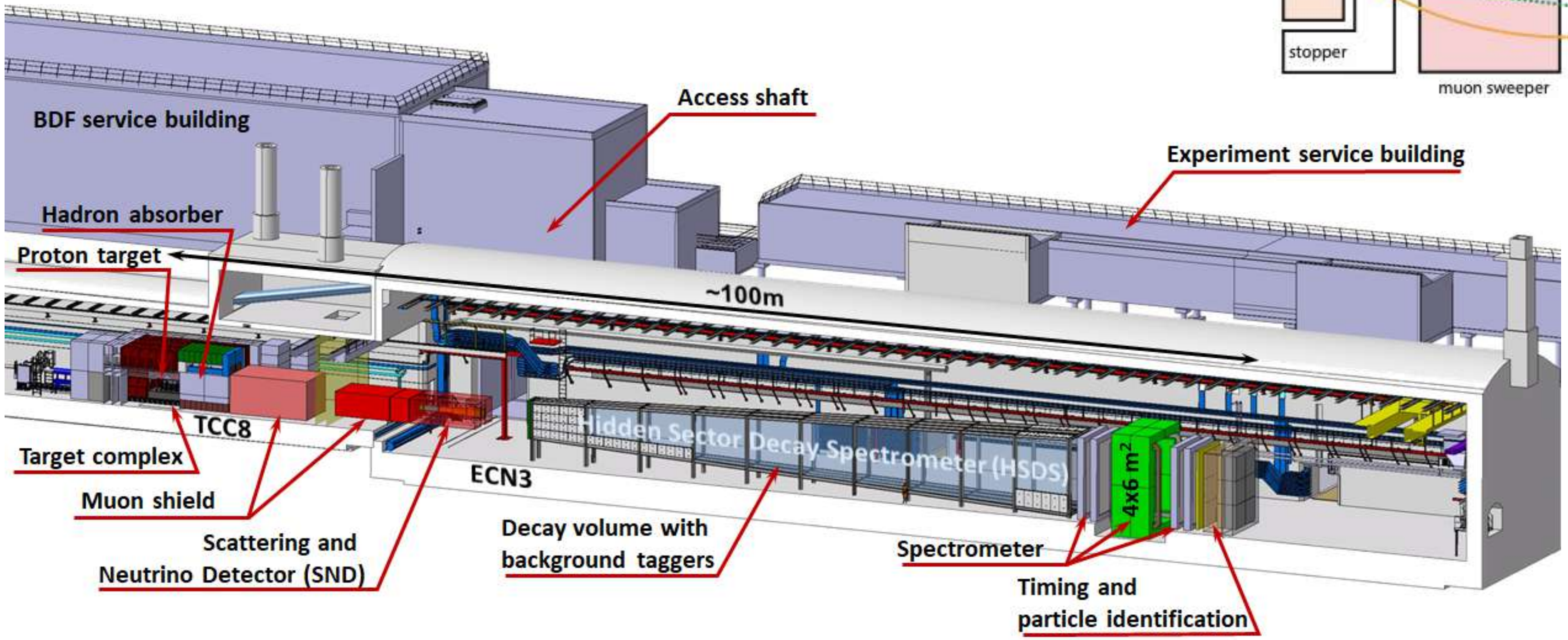
- **Good time resolution:** O (1ns)
- **High efficiency:** > 99.0% for m.i.p.

Decay volume and background taggers

50m long frustum decay volume:

- He at atmospheric pressure
- $1.0 \times 2.7\text{m}^2$ upstream, $4\times 6\text{m}^2$ downstream

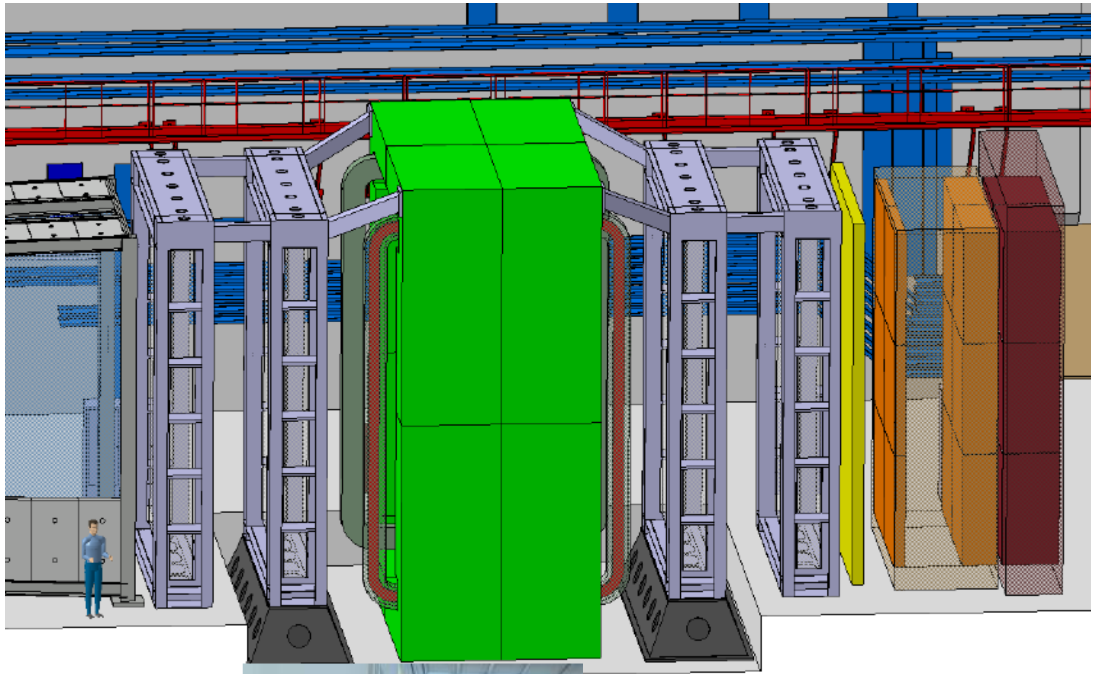




- Upstream Background Tagger to veto muons escaping muon shield
- Surrounding Background Tagger to tag muon & neutrino interactions with the surrounding infrastructure

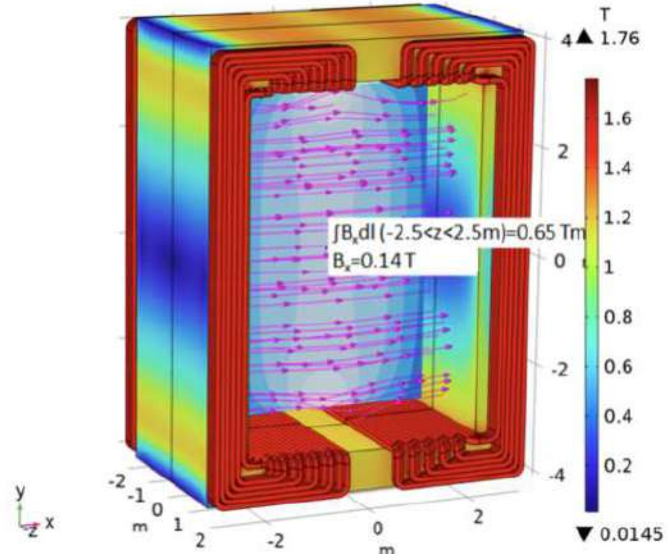
Hidden Sector Decay Spectrometer (HSDS)

- Large aperture: $4 \times 6\text{m}^2$
- Precise track reconstruction
  - Spatial resolution ~150μ
  - Large 5m-deep SC magnet: $\int Bdl = 0.65\text{Tm}$
- High hit efficiency: >99%
- High rate capability

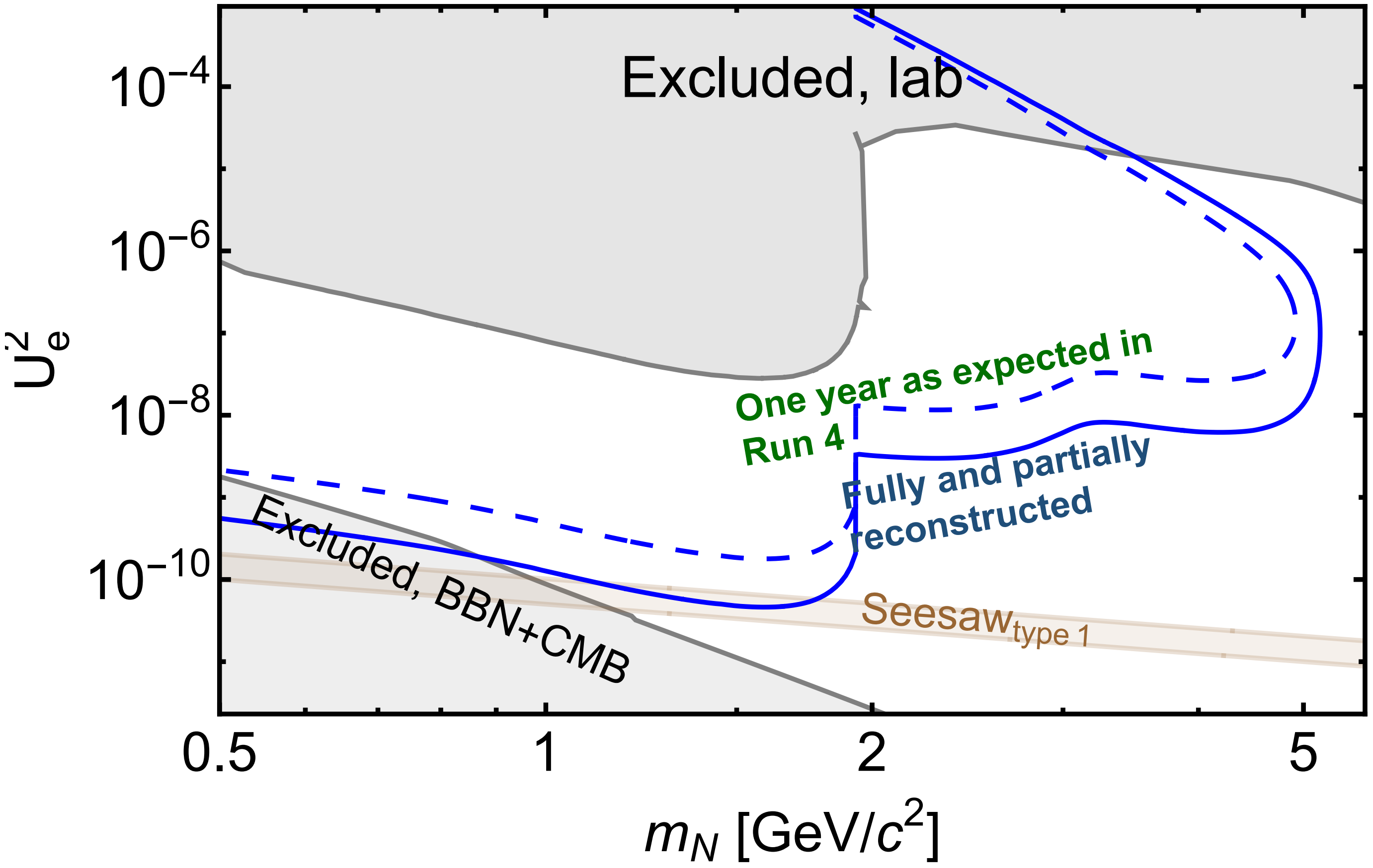


Baseline option:

- 20mm ø Mylar straw tubes ~150μ hit reconstruction
- 2×2 stations of 4 double layers at 5-10° stereo angle, 10k channels



Conclusion



- SHiP → Orders of magnitude improvement in Hidden Particle searches
  - Discovery would change the direction of the entire field
- Rich and "guarantied" physics of neutrino interactions
- We must see if there are Hidden Particles before committing to a next generation accelerator

Accelerator schedule	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035
LHC	Run 3		LS3					Run 4			LS4	
SPS (North Area)												

SHiP will start data taking in 2032