Feebly Interacting Particles (and where to find them)

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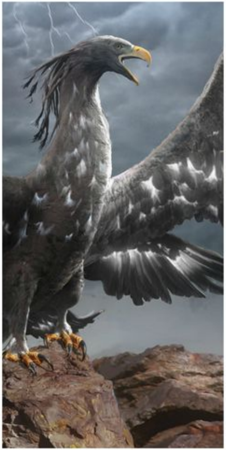
Feebly interacting particles and where to find them



Dark photon

Heavy neutral lepton

Dark scalar

. . . your favourite beast here. . .

Some overviews of the subject

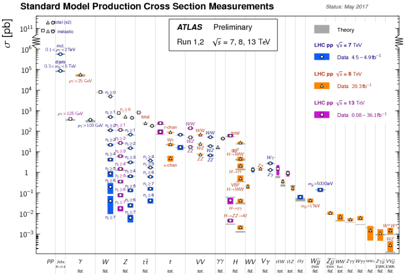
Hundreds of pages plus references therein!

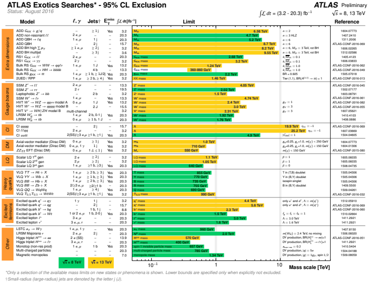
- *"Physics Beyond Colliders at CERN Beyond the Standard Model Working Group Report"* [1901.09966]
- *"Physics Briefing Book : Input for the European Strategy for Particle Physics Update 2020"* [1910.11775]
- *"A facility to Search for Hidden Particles at the CERN SPS: the SHiP physics case"* [1504.04855]
- *"FASER's Physics Reach for Long-Lived Particles"* [1811.12522]
- "Physics case" papers of other proposed experiments

Outline

1. Particle physics today: where do we stand
2. Status of the Standard Model
3. Beyond the Standard Model
4. Portals
5. Intensity Frontier experiments
6. Several Intensity Frontier experiments
7. SHiP experiment

Particle physics today





ATLAS collaboration (2018)

ATLAS collaboration (2016)

Testable . . .

. . . and falsifiable

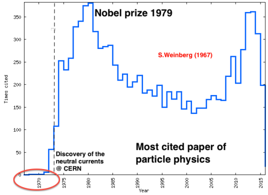
Reasons to expect new particles

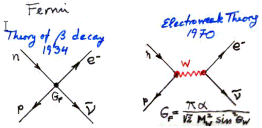
1. They have been predicted based on our current understanding (*e.g.* Higgs boson)
2. There are some **observed phenomena** that are not explained by existing particles but can be explained by hypothetical ones
3. Existing theory loses predictive power at some energies

   For some scientists there is another *raison d'être*

4. A dimensionless parameter in a theory is **very small** for no apparent reason

   I will comment on it later





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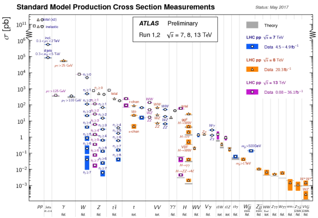
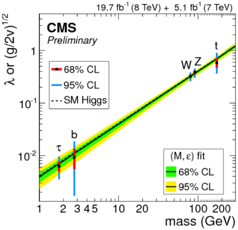
Predictions confirmed

- ✓ All crucial predictions, including new particles are confirmed experimentally. Higgs boson was last such particle!
- ? **Self-consistent:** the correct description of physics in one situation does not lead to an inconsistency in other situations.
- **Complete:** describes all the observed phenomena





Mathematical consistency

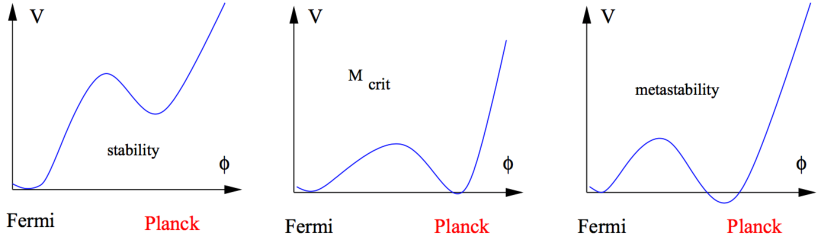
✓ Yes, our theory is mathematically consistent: does not give absurd predictions

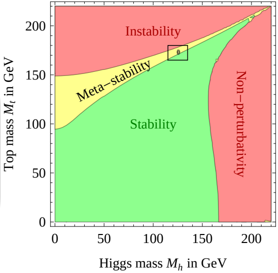
- Examples of "absurd predictions": negative probabilities, total probability exceeding 1, etc.
- This is both a good new and a bad news: mathematical inconsistency/paradox often tells us where to look for answers.

Exercise 1: *In Fermi theory estimate the cross-section of $e+\nu \to e+\nu$ process on dimensional grounds $\sigma \propto G_F^2 E_{cm}^2$*
Compare this behaviour with the **Froissart bound***:* $\sigma \propto \log^2(E_{c.m.})$

Exercise 2: *Repeat the same dimensional analysis assuming a massive mediator of weak interactions with mass M_W and coupling g_W. Argue that the cross-section decreases as high c.m. energies*

Free energy of the world

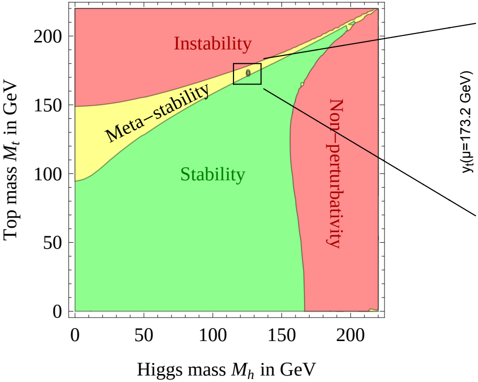


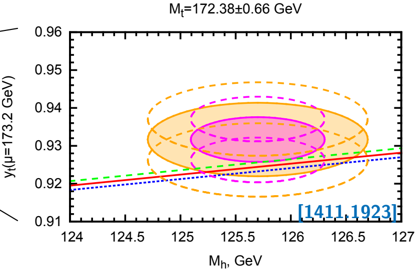


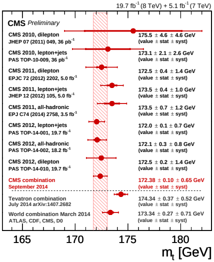
(Near) critical world

The masses of two heaviest particles (Higgs boson and top-quark) have "**conspired**" to very special values

Criticality of the world







"It is expected that the difference between the MC mass definition and the formal pole mass of the top quark is up to the order of 1 GeV" (from *First combination of Tevatron and LHC measurements of the top-quark mass* **[1403.4427]**

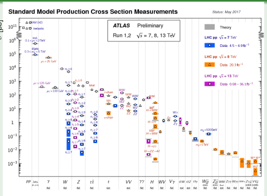
Bezrukov et al. "Higgs boson mass and new physics" [1205.2893]

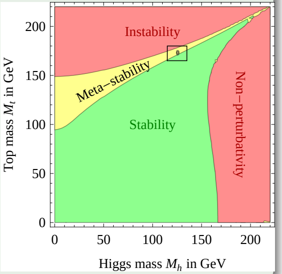
Degrassi et al. [1205.6497], **Buttazzo et al. [1307.3536]**

Standard Model does not describe all observed phenomena

Reasons to expect new particles

1. ~~They have been predicted based on our current understanding~~
2. ~~Existing theory loses predictive power at some energies~~
3. There are some **observed phenomena** that are not explained by existing particles (**What**-questions)
4. There are some peculiarities of the structure of the Standard Model that **may** indicate the presence of new particles (**Why**-questions)





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Do we have definite theoretical predictions?

We know that new particles exist

- Neutrino masses and oscillations

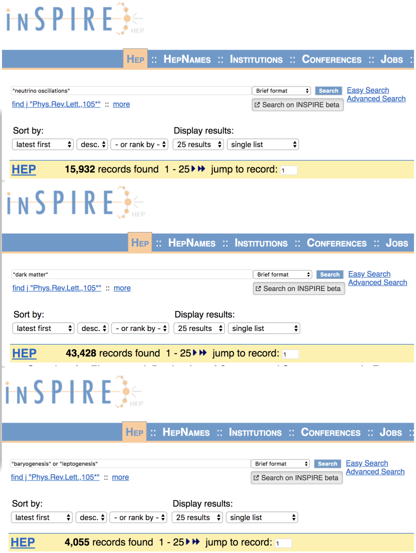
  Scale of new physics:
  from 10^{-9} GeV to 10^{15} GeV

- Dark matter

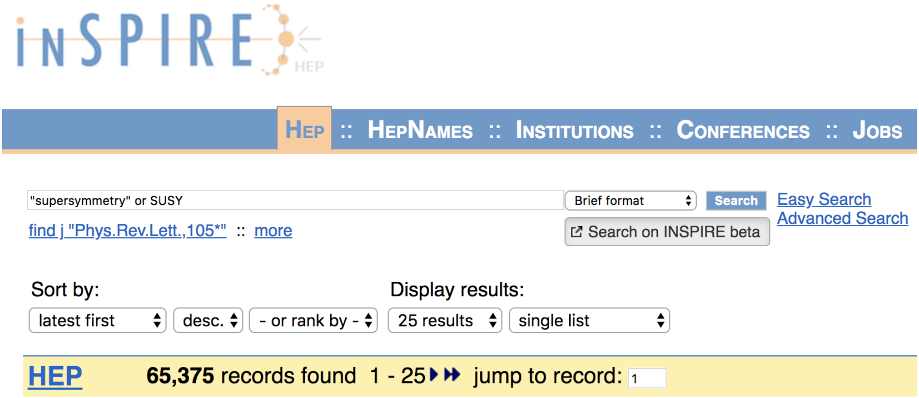
  Scale of new physics:
  from 10^{-30} GeV to 10^{64} GeV

- Baryon asymmetry of the Universe

  Scale of new physics:
  from 10^{-3} GeV to 10^{15} GeV

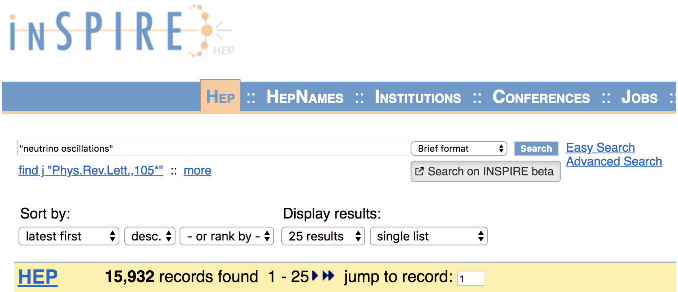


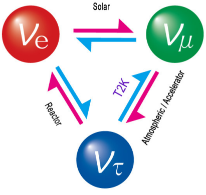
Majority in physics is not always right



BSM problem I: Neutrino oscillations

What makes neutrinos disappear and then re-appear in a different form? Why they have mass?





Neutrino oscillation between three generations

- Predicted by **Pontekorvko 1957** soon after the kaon oscillation story (why - because neutrinos are **neutral**)
- Predicted **before** ν_μ and ν_τ were known to exist
- Observed in the 1960s as solar neutrino deficit
- Verified by many possible experiments both in **appearance** and **disappearance**

BSM problem I: Neutrino oscillations

What makes neutrinos disappear and then re-appear in a different form? Why they have mass?

- Oscillations are mis-alignment between charge (or **flavour**) and mass eigenstates:

$$|\nu_\alpha(t)\rangle = \sum_{i=1}^{n} U^*_{\alpha i}\,|\nu_i(t)\rangle \tag{1}$$

- Here $U_{\alpha i}$ is a matrix, mixing flavour (labelled α) and mass (labelled i) states
- It is known as **PMNS** (Pontecorvo-Maki-Nakagawa-Sakata) matrix
- You get for "mass eigenstates"

$$|\nu_i(t)\rangle = e^{-\frac{iE_i t}{\hbar}}\,|\nu_i(0)\rangle \tag{2}$$

with $E_i = \sqrt{p^2c^2 + m_i^2c^4}$.

- We are used to the fact that the same quantum mechanical state propagates and interacts. This does not have to be the case, as we see

Exercise 3: *Demonstrate that oscillations imply that neutrinos have mass*

Exercise 4: *What conservation law prohibits oscillation of neutrons into their anti-particles?*

Quantum mechanical cartoon of oscillations

Exercise 5:

- *Consider the massive neutrino states (eigen-states of a propagation Hamiltonian $|1\rangle$ with energy E_1 and $|2\rangle$ with energy E_2)*
- *At $t = 0$ there a* **charge** *eigen-state $|\nu_e\rangle$ ("electron neutrino") is produced. It is a superposition*

$$|\nu_e\rangle = \cos\theta\,|1\rangle + \sin\theta\,|2\rangle \tag{3}$$

- *Its orthogonal superposition is "muon neutrino" $|\nu_\mu\rangle = -\sin\theta\,|1\rangle + \cos\theta\,|2\rangle$ where θ is some parameter (no oscillations means $\theta = 0$)*
- *Then at time $t > 0$*

$$|\psi(t)\rangle = e^{-iE_1 t}\cos\theta\,|1\rangle + \sin\theta\,|2\rangle\,e^{-iE_2 t} \tag{4}$$

- *Therefore there is a* **non-zero probability** *to detect an orthogonal state $|\nu_\mu\rangle$ at time $t > 0$:*

$$P(t) = \left|\langle\nu_\mu|\psi(t)\rangle\right|^2$$
$$= \cos^2\theta\sin^2\theta\left|e^{-iE_1 t} - e^{-iE_2 t}\right|^2 = \sin^2(2\theta)\sin^2\left(\frac{\Delta E t}{2}\right) \tag{5}$$

- *Maximum $P(\nu_e \to \nu_\mu) = \sin^2(2\theta)$ (equals to 1 for $\theta = \frac{\pi}{2}$)*

Mass vs. charge eigenstates in quark sector

Exercise 6: *Another (familiar) example of oscillations is that of neutral flavour mesons: $K^0 \leftrightarrow \bar{K}^0$ where $|K^0\rangle = |d\bar{s}\rangle \neq |\bar{K}^0\rangle = |\bar{d}s\rangle$ (and similarly $D^0 \leftrightarrow \bar{D}^0$, $B^0 \leftrightarrow \bar{B}^0$). This time the mis-alignment is between "strong" and "weak" eigenstates*

- *Strong interactions are diagonal in the flavour basis and therefore in QCD* **flavour** *is a conserved quantum number*

$$\mathscr{L}_{QCD} = -\frac{1}{2}\mathrm{Tr}(G_{\mu\nu}G^{\mu\nu}) + \bar{u}\not{D}u + \bar{d}\not{D}d + \bar{s}\not{D}s + \cdots + \mathscr{L}_{mass} \tag{6}$$

- *Because of this fact lightest mesons of each flavour ($\pi^{\pm}$, $K^{\pm}$, D, B are very* **long-lived** *(as compared to strong interaction rates)*
- *Lagrangian (6) had quark mass matrix in the diagonal form:*

$$\mathscr{L}_{mass} = \begin{pmatrix} \bar{u} \\ \bar{d} \\ \vdots \\ \bar{t} \end{pmatrix} \begin{pmatrix} m_u & 0 & \cdots & 0 \\ 0 & m_d & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & m_t \end{pmatrix} \begin{pmatrix} u \\ d \\ \vdots \\ t \end{pmatrix} \tag{7}$$

Mass vs. charge eigenstates in quark sector

- *. . . but* **weak interaction charge states** *non-diagonal*

$$\mathscr{L}_{Weak\ \ int} = g \begin{pmatrix} \bar{u} \\ \bar{c} \\ \bar{t} \end{pmatrix} \underbrace{\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}}_{CKM\ matrix} \gamma^{\mu}(1-\gamma_5) W_{\mu} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

- *One can* **diagonalize** *weak interaction states:*

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} \equiv \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix} \tag{8}$$

- *In the new basis (u, d', s', c, b', t) weak interactions are diagonal (i.e. W boson interacts with $\bar{u}d'$ with $\bar{c}s'$, with $\bar{t}b'$ but never with other combinations*
- *QCD kinetic term remains diagonal in "primed" basis:*

$$\bar{d}\not{D}d \to \bar{d}'\not{D}d' \tag{9}$$

Mass vs. charge eigenstates in quark sector

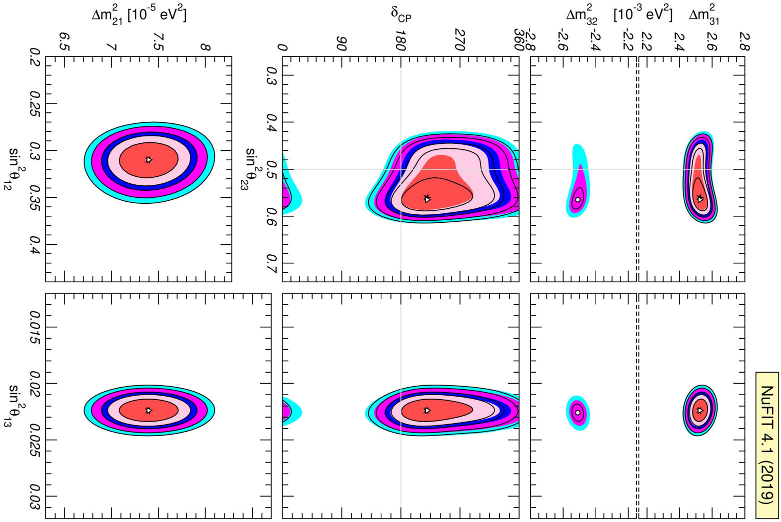
- *. . .* **but** *mass matrix becomes non-diagonal:*

$$\mathscr{L}_{mass.\ weak\ basis} = \begin{pmatrix} \bar{u} \\ \bar{d}' \\ \bar{s}' \\ \vdots \\ \bar{t} \end{pmatrix} \begin{pmatrix} \text{Non-diagonal} \\ \text{quark mass} \\ \text{matrix} \end{pmatrix} \begin{pmatrix} u \\ d' \\ s' \\ \vdots \\ t \end{pmatrix} \tag{10}$$

- *Based on this write a diagram of* $K^0 \leftrightarrow \bar{K}^0$ *oscillations*

Neutrino oscillations in numbers

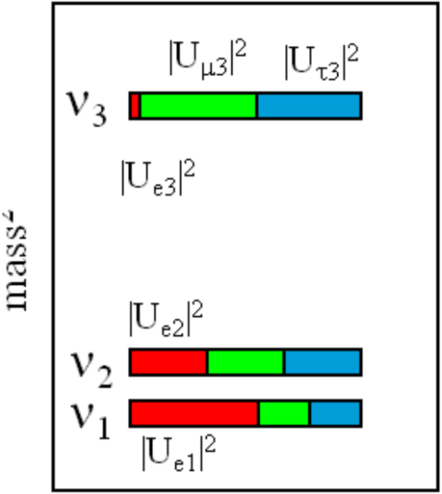
http://www.nu-fit.org



We will mostly refer to $m_{atm} = \sqrt{|\Delta m_{3i}|^2}$ that gives an idea of the overall neutrino mass scale

Relation between mass and flavour (phenomenology)

From 1609.02386



Flavour composition of the mass eigenstates

- The mass states are shown by boxes
- Each box contains mixture of different flavors (color parts)
- Areas of colored parts give probabilities to find the corresponding flavor neutrino in a given mass state, if the area of the box is 1

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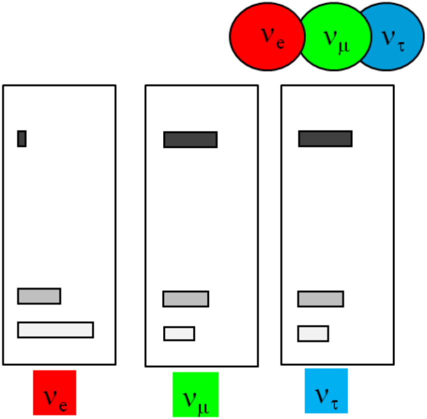


Mass composition of the flavour states (example is shown for normal ordering)

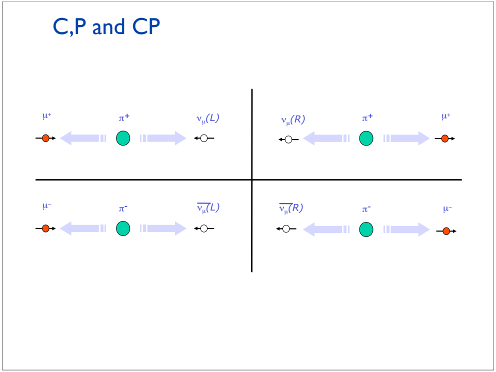
- The gray-black boxes correspond to the mass states in a given flavor state
- Relative areas of the boxes give probabilities to find the corresponding mass state in a given flavor state

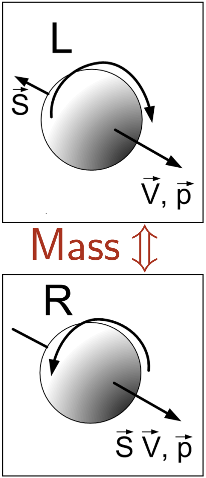
How to write a mass for neutrino

- A theory of massive neutrinos should be ...

$$\mathscr{L} = i\bar{\nu}_L \gamma^\mu \partial_\mu \nu_L - \bar{\nu}_R M \nu_L + \text{h.c}$$

- ... but we do not know "particle" ν_R !





Illustrations from G. Raven, "CP violation", CERN S

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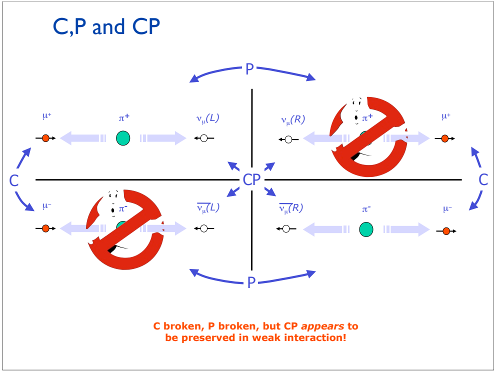
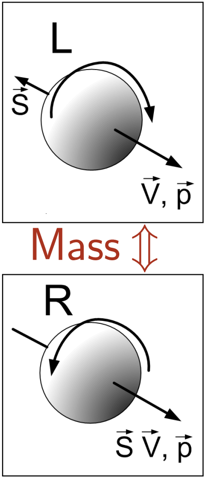




Illustrations from G. Raven, "CP violation", CERN S

New particle?

- Have we just predicted a new particle?

$\boxed{\text{No!}}$

- All we predicted was a new spin state of an already existing particle
- This state is **not produced** in interactions and can only be populated in scatterings with probability $\propto (m_\nu/E)^n$
- Cross-section of neutrinos grows with energy (recall $\sigma \propto G_F^2 E_{c.m.}^2$) and therefore the probability to populate this state is tiny

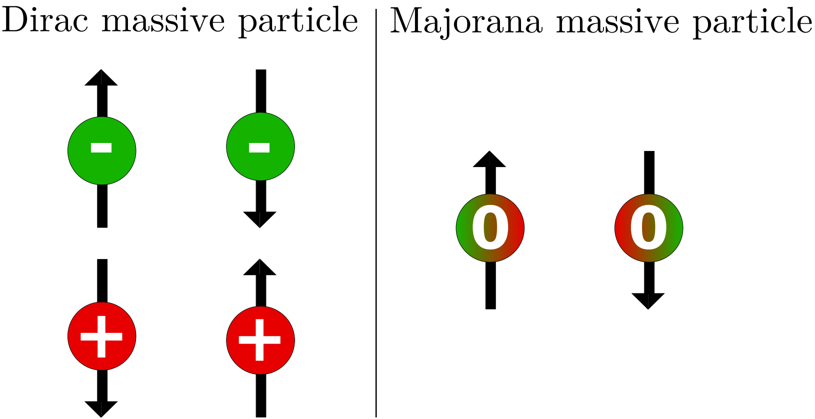
Majorana representation

See e.g. **hep-ph/0605172** or **1412.3320**

Exercise 7:

- *Ettori Majorana noticed that there is a* **totally imaginary representation of γ matrices**: $\boxed{(\gamma^\mu)^* = -\gamma^\mu}$. *Find this representation explicitly!*
- *Therefore the Dirac equation* $\left(i\gamma^\mu\partial_\mu - m\right)\chi = 0$ *admits* **real solutions** $\boxed{\chi^* = \chi}$ – **Majorana fermion**
- *Such fermion has* **2 degrees of freedom**
- *Such fermion can carry* **no U(1) charges**
- *Write a Lagrangian for Majorana fermion*

Dirac vs. Majorana fermion



4 degrees of freedom

2 degrees of freedom

From 1601.07512

Neutrino Majorana mass

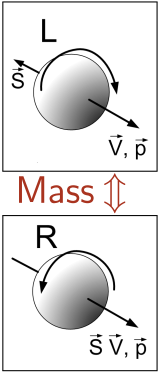
- For particle that carries no U(1) charge one can write a Majorana mass term
- The only neutral particle in the Standard model is **neutrino**

$$\mathscr{L}_{\text{Majorana}} = -\frac{1}{2}\,\bar{\nu}\,M_M\,\nu^c + \text{h.c.} \qquad (11)$$

couples neutrino ν and its anti-particle ν^c.

- One can construct a Majorana spinor:

$$\chi = \frac{\nu + \nu^c}{\sqrt{2}}$$



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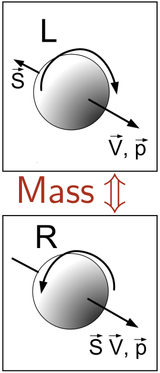

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☹ So where is the "neutrino mass puzzle"?

Neutrino Majorana mass

- Neutrino carries no electric charge, but it is **not** neutral
- . . . neutrino is part of the SU(2) doublet $\boxed{L = \begin{pmatrix} \nu_e \\ e \end{pmatrix}}$
- . . . and carries **hypercharge** $Y_L = -1$
- What we call **neutrino** is actually $\boxed{\nu = (L \cdot \tilde{H})}$ (where $\tilde{H}_a = \varepsilon_{ab} H_b^*$)
- Therefore neutrino Majorana mass term is

$$\text{Neutrino Majorana mass} = \frac{\boldsymbol{c}(\bar{L} \cdot \tilde{H}^\dagger)(L^c \cdot \tilde{H})}{\boldsymbol{\Lambda}}$$

- Notice that this operator violates **lepton number**
- Assuming $\boldsymbol{c} \sim \mathscr{O}(1)$ one gets

$$\boldsymbol{\Lambda} \sim \frac{v^2}{m_{\text{atm}}} \sim 10^{15}\ \text{GeV}$$

- This is **Weinberg operator** or "dimension-5 operator"

Neutrino oscillations and conservation laws

- Lepton sector: 3 conserved quantities **lepton flavour number**

Particle	L_e	L_μ	L_τ	L_{tot}
e^-	1	0	0	1
ν_e	1	0	0	1
μ^-	0	1	0	1
ν_μ	0	1	0	1
τ^-	0	0	1	1
ν_τ	0	0	1	1

Prohibited decays based on these conservation laws

- $\mu \to e\gamma$
- $\mu \to e\bar{e}e$
- $\tau \to \mu\bar{\mu}\mu$

Exercise 8: *What conservation law makes stable electron? Proton? What decay modes would be available for these particles if the corresponding conservation laws were gone?*

- Neutrino oscillations violate L_e, L_μ, L_τ **but preserve total lepton number**
- Weinberg operator (neutrino Majorana mass) violates the **total lepton number**

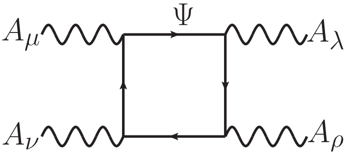
$$\frac{(\bar{L}\cdot\tilde{H}^\dagger)(L^c\cdot\tilde{H})}{\Lambda}$$

- This has not yet been confirmed experimentally!

Neutrino masses and effective field theory

- Usually one expects that some "heavy" particles mediated Weinberg operator (or similar) and that at energies $E \sim \Lambda$ new particles should appear
- Example, at energies $E < m_e$ light-on-light scattering is mediated by virtual fermions, leading to **Heisenber-Euler Lagrangian**

$$\mathscr{L}_{H-E} = \frac{1}{\Lambda^4}\Big((\vec{E}^2 - \vec{B}^2)^2 + 7(\vec{E}\cdot\vec{B})^2\Big)$$



where the scale Λ is proportional to the mass of the particle, running in the loops

$$\boxed{\Lambda^4 = \frac{m_e^4}{2\alpha^2}}$$

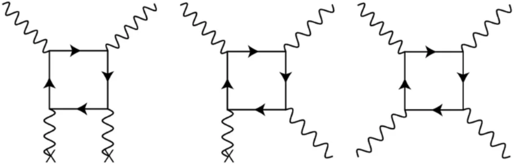
- All heavy particles contribute – if one can measure the effects of such terms precisely, one can deduce the presence of new heavy states

Exercise 9:

a) Count mass dimension of $(\bar{L}\cdot\tilde{H}^\dagger)(L^c\cdot\tilde{H})$ and convince yourself that Λ in Weinberg's operator has the dimension of mass

b) Count mass dimension of the Heisenberg-Euler term $(\vec{E}^2 - \vec{B}^2)^2$ and $(\vec{E}\cdot\vec{B})^2$

Light-by-light scattering



nature physics

Article | Open Access | Published: 14 August 2017

Evidence for light-by-light scattering in heavy-ion collisions with the ATLAS detector at the LHC

ATLAS Collaboration

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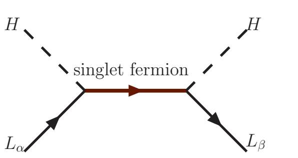
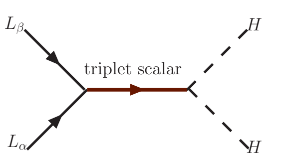
Seesaw mechanisms

There are many ways to "resolve" the Weinberg's operator, *i.e.* to couple left fermion SU(2) doublets L and the Higgs SU(2) doublet H



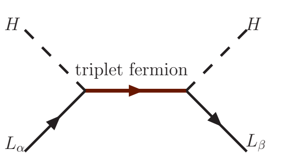
Type I see-saw

extra singlet fermion



Type II see-saw

extra SU(2) triplet scalar with hypercharge 1



Type III see-saw

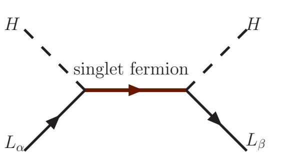
extra SU(2) triplet fermion with hypercharge 0

- Other models include: "loop mediated neutrino masses", split-seesaw, etc.

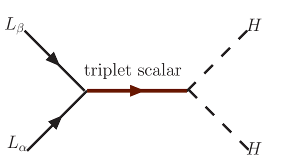
Strumia & Vissani "Neutrino masses and mixings and..." [hep-ph/0606054v3]

Scale of new particles?

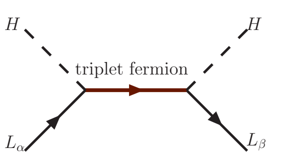
Neutrino oscillations imply new particles



Type I see-saw
extra singlet fermion



Type II see-saw
extra SU(2) triplet scalar



Type III see-saw
extra SU(2) triplet fermion

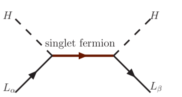
- Operator of dimension > 4 implies new particles
- Naively the masses of these new particles are

$$M_{\text{new states}} \lesssim \Lambda = \frac{v^2}{m_{\text{atm}}}$$

where $v = \langle H \rangle$ – Higgs VEV

Type I seesaw mechanism

- Assume one extra fermion N
- It couples to the "neutrino" combination $\nu = (\tilde{H}\cdot L)$
- This combination is $SU(3)\times SU(2)\times U(1)$ gauge singlet
- **N carries no Standard Model gauge charges!**



$$\mathscr{L}_{\text{Seesaw Type I}} = \mathscr{L}_{\text{SM}} + i\bar{N}\partial N + F\bar{N}(\tilde{H}\cdot L) + \mathscr{L}_{\text{Majorana}}(N) \tag{12}$$

- Majorana mass term $\mathscr{L}_{\text{Majorana}}(N) = \frac{1}{2}\bar{N}\boldsymbol{M}N^c + \text{h.c}$ is possible for N
- In terms of ν and N we get ($m_{\text{Dirac}} = F\nu$ – Dirac mass)

$$\mathscr{L}_{\text{Seesaw Type I}} = \mathscr{L}_{\text{SM}} + i\bar{N}\partial N + \frac{1}{2}\begin{pmatrix}\bar{\nu}\\ \bar{N}^c\end{pmatrix}\begin{pmatrix}0 & m_{\text{Dirac}}\\ m_{\text{Dirac}} & \boldsymbol{M}\end{pmatrix}\begin{pmatrix}\nu^c\\ N\end{pmatrix} \tag{13}$$

Type I seesaw mechanism

Particle content

- If $M \gg m_{\text{Dirac}}$ this theory describes two particles:
  - Light **neutrino** with mass $\boxed{m_\nu \simeq m_{\text{Dirac}} \dfrac{m_{\text{Dirac}}}{M}}$ — **seesaw formula**
  - Heavier particle with mass $\approx M$
- Neutrinos are light because $m_{\text{Dirac}} \ll M$
- Mixture between states ν and N (difference between weak eigenstate ν and massive state $\tilde{\nu}$) is parametrized by **active-sterile mixing angle**

$$\boxed{\sin U \approx U = \frac{m_{\text{Dirac}}}{M} \ll 1} \tag{14}$$

Type I seesaw mechanism

We call this new particle

"Sterile neutrino" or "heavy neutral lepton" or **HNL**

also "Majorana fermion", "heavy Majorana neutrino", "right-handed neutrino", etc.

Exercise 10: *Diagonalize the mass term (13) via rotation by the angle U. Find the* **mass eignestates** $\boldsymbol{\nu}$ *and* $\boldsymbol{N}$

$$\begin{aligned} \boldsymbol{\nu} &= \cos U\, \nu - \sin U\, N^c \approx \quad \nu - U \times N^c \\ \boldsymbol{N} &= \sin U\, \nu^c + \cos U\, N \approx \quad N + U \times \nu^c \end{aligned} \tag{15}$$

assuming $U \ll 1$ and neglecting $\mathscr{O}(U^2)$ terms where the **mixing angle** *U is defined via*

$$U \simeq \frac{m_{Dirac}}{\boldsymbol{M}} \tag{16}$$

Both $\boldsymbol{\nu}$ and $\boldsymbol{N}$ have Majorana mass terms:

$$\mathscr{L}_{Seesaw\ Type\ I} = \mathscr{L}_{SM} + i\bar{\boldsymbol{N}}\partial\!\!\!/\boldsymbol{N} + \frac{1}{2}\bar{\boldsymbol{\nu}} m_\nu \boldsymbol{\nu}^c + \frac{1}{2}\bar{\boldsymbol{N}} M_N \boldsymbol{N}^c \tag{17}$$

where

$$m_\nu \simeq \frac{(m_{Dirac})^2}{\boldsymbol{M}} \quad \text{and} \quad M_N \simeq \boldsymbol{M}$$

Other HNL varieties

HNL varieties

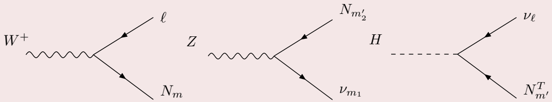
- Type-III seesaw **Foot et al. Z. Phys. C44 (1989)**
- Inverse seesaw **(Mohapatra PRL 56 (1986); Mohapatra & Valle PRD34 (1986))**
- Radiative seesaw **Pilaftsis Z. Phys. C55 (1992)**

Interactions with new gauge bosons/scalars

- Left-right symmetric models **Pati & Salam (1974); Mohapatra & Pati (1975); Mohapatra & Senjanovic (1981)**
- HNLs will carry charge w.r.t. $U(1)_{B-L}$ – can be produced via off-shell $B-L$ boson (couples to protons) **See e.g. Mohapatra & Marshak (1980); del Aguila & Aguilar-Saavedra [0705.4117]; Huitu et al. [0803.2799]; Batell et al. [1604.06099]**
- Majorana mass of HNL can be generated via coupling with a new singlet scalar S **(Shaposhnikov & Tkachev (2006); Shoemaker et al. (2010))** $\boldsymbol{M}\bar{N}^c N \to f_N S \bar{N}^c N$ where S develops vev

Interactions of HNLs

Interactions



$$\mathscr{L}_{int} = \frac{g}{\sqrt{2}} W^+_\mu \overline{N^c}\, U^*\, \gamma^\mu (1-\gamma_5)\ell^-_\alpha + \frac{g}{2\cos\theta_W} Z_\mu \overline{N^c}\, U^*\, \gamma^\mu (1-\gamma_5)\nu + \dots \quad (18)$$

- In every process where neutrino appears and where kinematics allows we expect an HNL with probability $\propto |U|^2$. For example,

$$\Gamma(W^+ \to \mu^+ + N) = |U_\mu|^2\, \Gamma(W^+ \to \mu^+ + \nu_\mu) \quad (19)$$

Feebly interacting HNLs

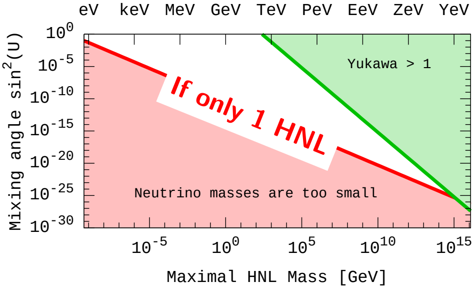
- HNLs are thus interacting "weaker-than-neutrinos" (by a factor $|U_\alpha|^2$). However, these particles can be detected via other means, thanks to their larger mass [1805.08567]

- Naive seesaw formula tells us

$$\boxed{U^2 \sim \frac{m_{\text{atm}}}{M} \sim 10^{-12}\frac{100\,\text{GeV}}{M}} \tag{20}$$

- Fortunately, we need **more than 1 HNL** to explain both Δm^2_{atm} and Δm^2_{sun}
- All neutrino experiments would allow to determine

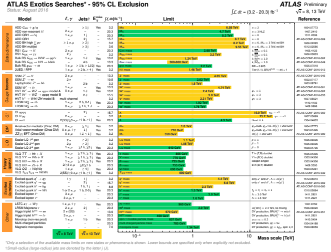
  7 out of 11 parameters (2HNL)
  9 out of 18 parameters (3HNL)

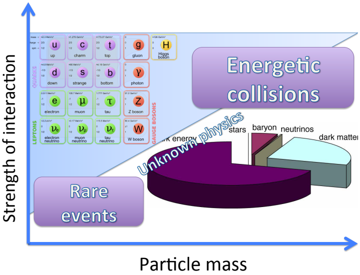


Seesaw formula (20) provides a **bottom line for values of the coupling**

Feebly interacting particles

- Particles with the masses up to $\mathcal{O}(TeV)$ and weak-scale interaction with the Standard Model should have showed up at the LHC by now
- Therefore any particles lighter than that should be "weaker-than-weak" interacting in order to avoid detection
- Community is adopting the term **feebly interacting particles** or **FIPs** to denote these kinds of particles





HNLs and other beyond-Standard-Model puzzles

Mass of heavy neutral leptons?

- ☹ No information from neutrino oscillations
- What can other BSM phenomena tell us about HNL properties?

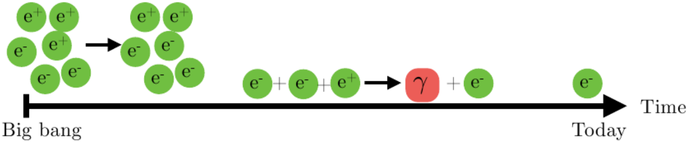
Cosmology

- Dark matter
- Matter-antimatter asymmetry of the Universe

Baryon asymmetry of the Universe

what had created tiny matter-antimatter disbalance in the early Universe?

- Particle physics applied to the whole Universe was very successful in explanation of primordial abundance of elements, prediction of CMB, etc.

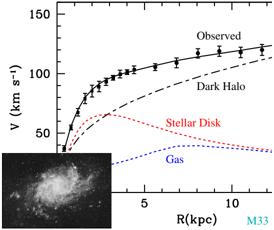


- Since Dirac we know: physics is symmetric w.r.t. particles $\leftrightarrow$ antiparticles
- Thermal equilibrium "does not remember" its history
- **Sakharov conditions:** violation of Baryon number; violation of CP; deviation from thermal equilibrium
- Even neutrinos are in equilibrium in the dense primordial plasma; there is no phase transition in the Standard Model with the current Higgs mass

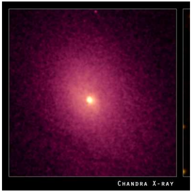
$\Rightarrow$ **we need new feebly interacting particles**

Dark matter

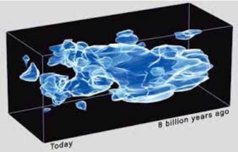
What is the most prevalent kind of matter in our Universe?



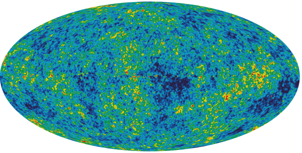
Expected: $v(R) \propto \frac{1}{\sqrt{R}}$
Observed: $v(R) \approx \text{const}$



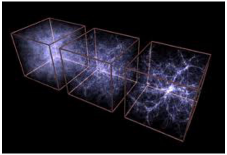
Expected: $\text{mass}_{\text{cluster}} = \sum \text{mass}_{\text{galaxies}}$
Observed: 10^2 times more mass confining ionized gas



Lensing signal (direct mass measurement) **confirms** other observations



Jeans instability turned tiny density fluctuations into all visible structures



Neutrinos (the only neutral, stable particles)cannot be dark matter

$\Rightarrow$ **need new particle**!

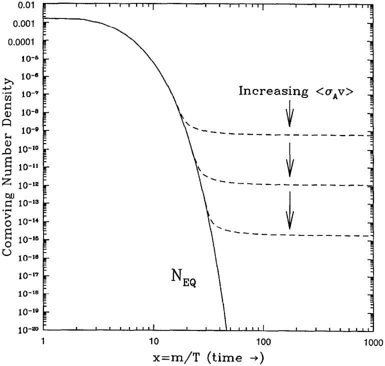
Feebly interacting particles and dark matter

Cosmological mass bound on weakly interacting particles

- Original idea of Weakly Interacting Massive Particles (**WIMP** dark matter) goes back to 1977
- **Lee & Weinberg (Phys. Rev. Lett. 1977)**
  "Cosmological lower bound on heavy-neutrino masses"
- **Vysotskii, Dolgov, Zel'dovich (JETP Lett. 1977)**
  "Cosmological limits on the masses of neutral leptons"

- Assume a new **weakly** interacting stable particle (called "heavy neutrino" in the original paper)
- These particles were in **thermal equilibrium** in the early Universe
- They keep the equilibrium number density via annihilation $\chi + \bar{\chi} \leftrightarrow \mathrm{SM} + \mathrm{SM}$
- As Universe expands — DM density drops and annihilation rate decreases
- At some moment **annihilation rate** is not enough to maintain the equilibrium number density $\Rightarrow$ **freeze out**
- WIMP "remembers" density of the Universe at the time of **freeze-out**

WIMP freeze out



- The weaker you interact the larger is your number density

$$\Omega_\chi h^2 \sim \frac{3\cdot 10^{-27}\,\mathrm{cm}^3/\mathrm{sec}}{\langle \sigma_{ann} v\rangle} \qquad (21)$$

- Annihilation cross-section depends on the interaction strength and on the number of final states

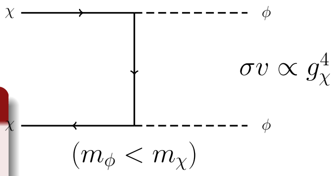
$$\langle \sigma_{ann} v\rangle \sim G_F^2 \; m_\chi^2 \; N_{\mathrm{channels}} \qquad (22)$$

For mass $m_\chi \sim \mathscr{O}(1)$ GeV annihilation into the SM channels leads to a **too small** cross-section $\Rightarrow$ **too large** DM abundance

Lee & Weinberg took G_F as an interaction strength and got the lower bound $m_\chi > 5$ GeV

Light WIMP $\Rightarrow$ extra light states

- Light DM requires more **light** states to annihilate into (scalars, vectors, ...)



Examples:

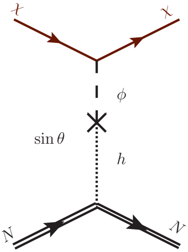
- Light scalar ϕ (scalar portal mediator)

$$\mathscr{L}_{\text{DM}-\phi} = \bar{\chi}\left(g_\chi + \gamma_5 g'_\chi\right)\phi\chi$$

- Light vector portal A_μ

$$\mathscr{L}_{\text{DM}-A'} = \bar{\chi}\gamma^\mu A'_\mu\left(g_\chi + \gamma_5 g'_\chi\right)\chi$$

- χ – dark matter particle, heavier than (dark) scalar or vector

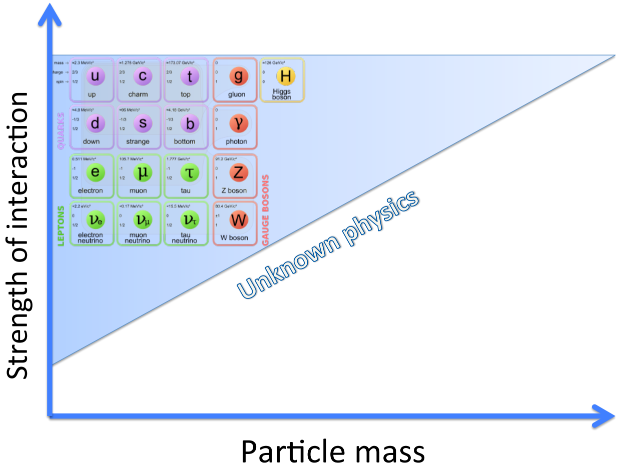


Why haven't we seen them yet?

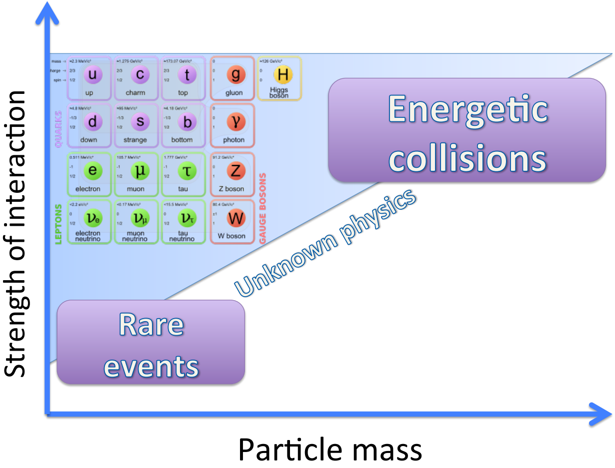
- We did not **produce** them yet
  - $E = mc^2$ therefore you need $E_{c.m.} > Mc^2$ to produce a new particle with the mass M
  - LHC runs 1–2 were about pushing this "energy frontier"

- We did not produce **enough** of them
  - Efficiency of the detector, background of other particles can prevent new particles to be seen
  - HL-LHC is about reaching sufficient precision ("precision frontier")
- We produced enough of them but did not **detect** their presence
  - Particles can be very weakly interacting and fly through our detectors unnoticed
  - To discover them we need high-intensity beams of particles ("Intensity Frontier")

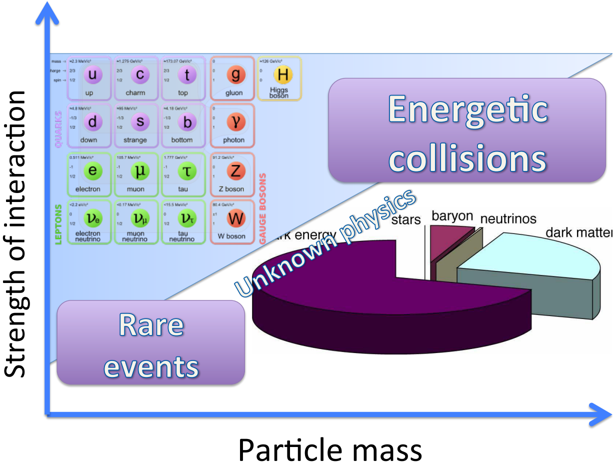
New particles?



New particles?



New particles?



Outline

1. Particle physics today: where do we stand
2. Status of the Standard Model
3. Beyond the Standard Model
4. Portals
5. Intensity Frontier experiments
6. Several Intensity Frontier experiments
7. SHiP experiment

New feebly interacting particles via portals

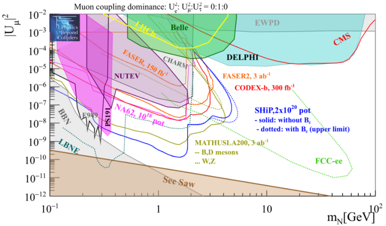
See refs in "*SHiP Physics Case*" [1504.04855]. PBC report [1901.09966]

Neutrino portal

new particles are gauge-singlet fermions coupled to a singlet fermion operators $(\bar{L} \cdot \tilde{H})$ couple to new neutral singlet fermions N

$$\mathscr{L}_{\text{Neutrino portal}} = F_{\alpha I}(\bar{L}_\alpha \cdot \tilde{\Phi})N$$

neutrino masses and HNLs; different scenarios of baryogenesis with HNLs; models with 2 and 3 HNLs; HNLs in cosmology, . . .



New feebly interacting particles via portals

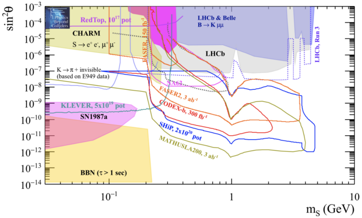
See refs in "*SHiP Physics Case*" [1504.04855]. PBC report [1901.09966]

Scalar portal

new particles are neutral singlet scalars, S that couples the Higgs field:

$$\mathscr{L}_{\text{Scalar portal}} = (\lambda S^2 + gS)(H^\dagger H)$$

Higgs as a portal to Dark Matter; Hidden Valleys; Exotic Higgs decays; Twin Higgs models; NMSSM; 2HDM; light inflaton; ...



New feebly interacting particles via portals

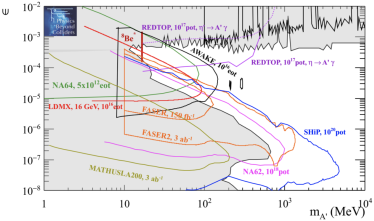
See refs in "*SHiP Physics Case*" [1504.04855]. PBC report [1901.09966]

Vector portal

new particles are Abelian fields, A'_μ with the field strength $F'_{\mu\nu}$, that couple to the hypercharge field $F_Y^{\mu\nu}$ via

$$\mathscr{L}_{\text{Vector portal}} = \varepsilon F'_{\mu\nu} F_Y^{\mu\nu}$$

Anomaly-free gauge groups (B-L, $L_\mu - L_\tau$ etc); Portals with anomaly that can be cancelled at the weak scale (e.g. B, or L separately). Other anomalous U(1)'s; Stuckelberg portals; Light DM; ...



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Designing an experiment (very schematic)

Need a lot of particles that do not decay strongly

- Muons can produce light particles in their decays
- Hadrons – only the lightest carriers of the flavour charge (strangeness, charm, beauty) are useful
- Pions? ($\pi \to e + \bar{\nu}_e$, $\pi \to \mu + \bar{\nu}_\mu$) – Yes! Below 140 MeV
- Kaons? ($K \to e + \bar{\nu}_e$, $K \to \mu + \bar{\nu}_\mu$) – Yes! Below 490 MeV
- D-mesons ($D^+ = |c\bar{d}\rangle$, $D_s^+ = |c\bar{s}\rangle$, $D^0 = |c\bar{u}\rangle$) – Yes! Below 1.8 GeV
- B-mesons – ...
- Intermediate vector bosons (W and Z)
- Higgs bosons

Exercise 11: *Using Particle Data Group website* `http://pdglive.lbl.gov`*, compare lifetime of* π^+ *with decays of* ρ^+ *mesons (both have the same quark content* $|u\bar{d}\rangle$*)*

Exercise 12: *Identify the lightest mesons containing* s *(*c*,* b*) quarks and convince yourself that they are indeed very "long-lived" by strong interaction scales*

Designing an experiment (very schematic)

- Once we've produced a beam of new particles, we detect their decays (in a dedicated decay vessel or otherwise)

$$N_{events} = N_{produced} \times P_{decay} \tag{23}$$

where

- $N_{produced}$ – number of produced FIPs whose trajectories cross decay volume
- P_{decay} is the probability for a FIP to detect inside the decay volume
- ...this should be multiplied by the fraction of such decays that can be **reconstructed**

- See **[1902.06240]** where all the necessary details are discussed

I do not discuss here electron beam-dump experiments (although some of them have high discovery potential for models like dark photons)

Discover new particles

Dependence on parameters

- Feebly interacting particles are easily **long-lived** (LLPs)
- Indeed

$$\frac{1}{\tau_{decay}} = \Gamma_{decay} \propto \varepsilon^2 g^a \left(\frac{M}{\Lambda}\right)^b M = \frac{g^a}{\Lambda^b}\ \varepsilon^2\ M^{b+1} \qquad (24)$$

we scan over ε^2 and M

- For example, decay width of HNL is similar to muon decay width:

$$\Gamma_{HNL} \propto |U|^2 \frac{G_F^2 M_N^5}{192\pi^3} \qquad (25)$$

where $|U|^2 \ll 1$ determines how feeble is the interaction

Exercise 13: *Identify ε, Λ and g in Eq. (25). Notice that "naive" scale of new physics would be $\Lambda/\sqrt{|U|^2}$ which does not correspond to the mass of the particle in question*

- Decay of a "dark scalar" is similar to that of a light higgs decay, suppressed by $\theta \ll 1$

Discover new particles

Dependence on experimental design

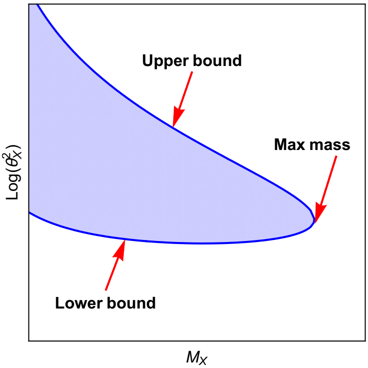
- Feebly interacting particles are easily **long-lived** (LLPs)
- Typical sensitivity region is cigar-shaped
- Number of events inside the shaded region

$$N_{events} = N_{produced} \times P_{decay}$$

- **Lower boundary** – too few decays in the decay volume:

$$P_{decay} \sim \frac{L_{det}}{c\tau_{decay}\gamma} \qquad (26)$$

– large detectors (L_{det}) allow to probe wider parameter space



Discover new particles

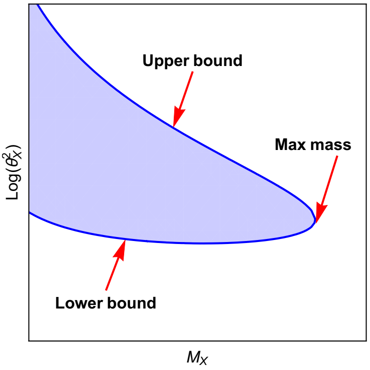
Dependence on experimental design

- **Upper boundary** – decay too fast, do not reach the decay vessel

$$P_{decay} \propto e^{-\frac{L_{to-det}}{c\tau_{decay}\gamma}} \qquad (27)$$

where distance between FIP production and decay vessel L_{to-det} as well as **distribution** in γ-factors, etc play the main role

- Maximal mass – intersection of the above or kinematics
- Most of these things can be estimated analytically [1902.06240]



Optimizing production

- To increase $N_{produced}$ one can increase **geometric acceptance** – fraction of all produced FIPs that fly through the fiducial decay volume $\Rightarrow$ larger solid angle of the detector
- Also: increase the number of parent particles
  - Mesons (10^{17} D-mesons at SHiP; 10^{14} B-mesons)
  - W-bosons ($\mathcal{O}(10^{12})$ at the end of HL LHC run)
  - Higgs bosons ($\mathcal{O}(10^{8})$ at the end of HL LHC run)
- Want to increase $\boxed{N_{PoT}}$ – high intensity proton beam
- Want to increase $\boxed{X_{q\bar{q}}}$ – high energy beam

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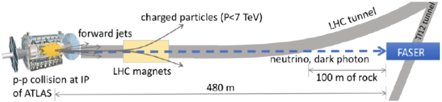
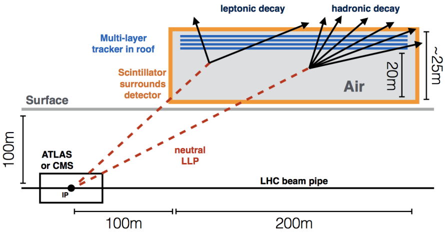
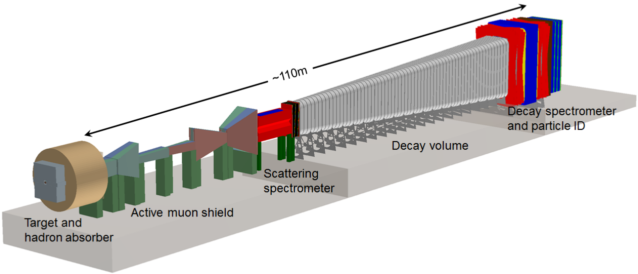
What we are discussing today

See PBC report [1901.09966] or *"Physics Briefing Book : Input for the European Strategy for Particle Physics Update 2020"* [1910.11775]







- FASER: ATLAS
- MATHUSLA: CMS or ATLAS
- Codex-b: LHCb
- SHiP: SPS
- NA62++: SPS
- ...(actually, many more)

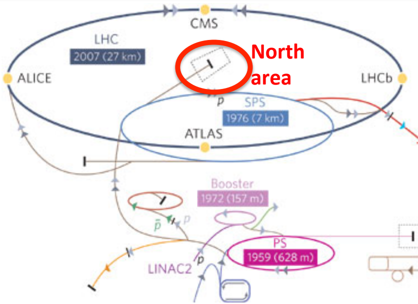
Outline

1. Particle physics today: where do we stand
2. Status of the Standard Model
3. Beyond the Standard Model
4. Portals
5. Intensity Frontier experiments
6. Several Intensity Frontier experiments
7. SHiP experiment

Super Proton Synchrotron (SPS)

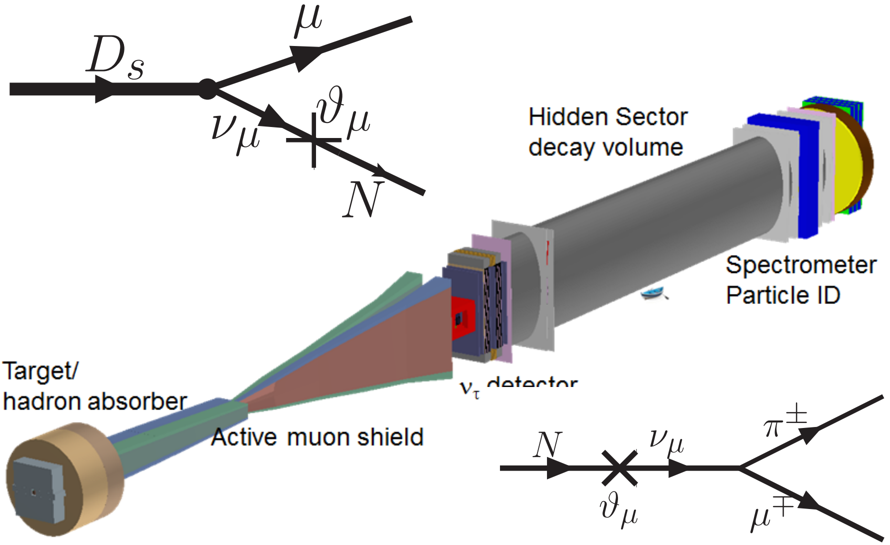
$$N_{D-\text{mesons}} = 2 \times \boxed{X_{c\bar{c}}} \times \boxed{N_{PoT}}$$

- High energy proton beam – 400 GeV
- 4×10^{19} PoT (protons on target per year). 2×10^{20} PoT over 5 years
- Beam intensity: 4×10^{13} protons/sec
- Produces a lot of c-quarks: $X_{c\bar{c}} \sim 10^{-3}$



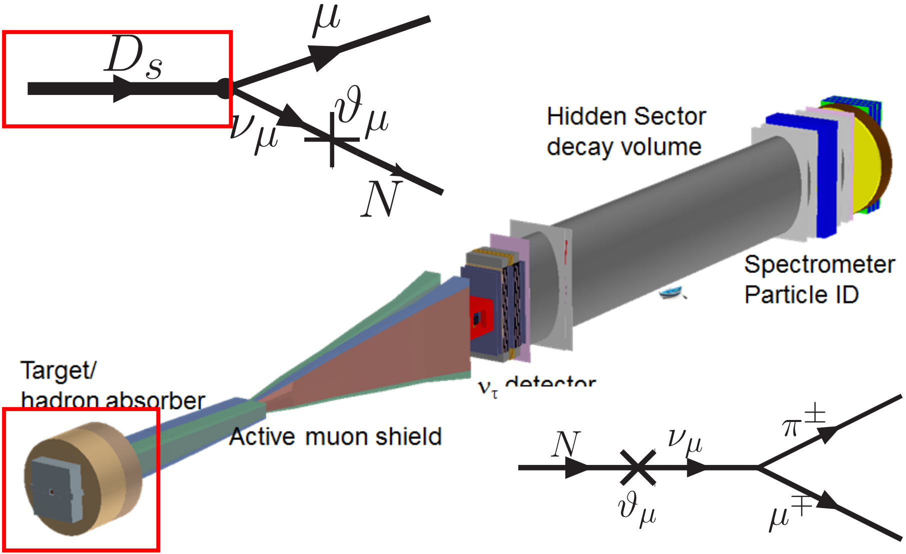
SHiP (*Search for Hidden Particles*) experiment

Step by step overview



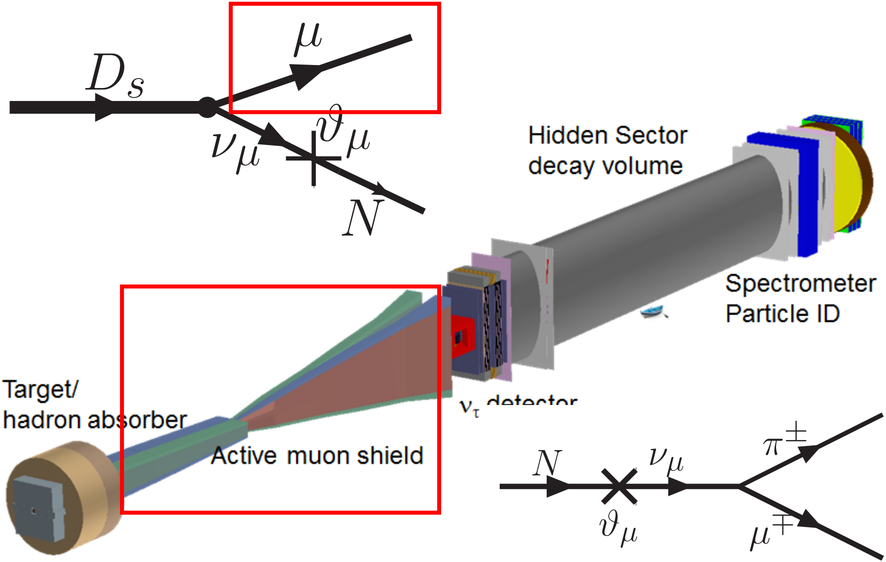
SHiP (*Search for Hidden Particles*) experiment

Step by step overview



SHiP (*Search for Hidden Particles*) experiment

Step by step overview



SHiP (*Search for Hidden Particles*) experiment

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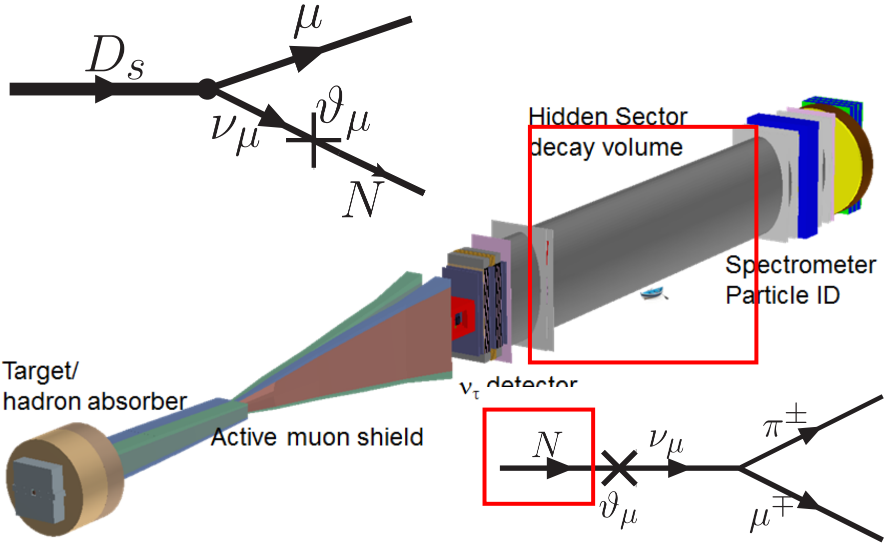

SHiP (*Search for Hidden Particles*) experiment

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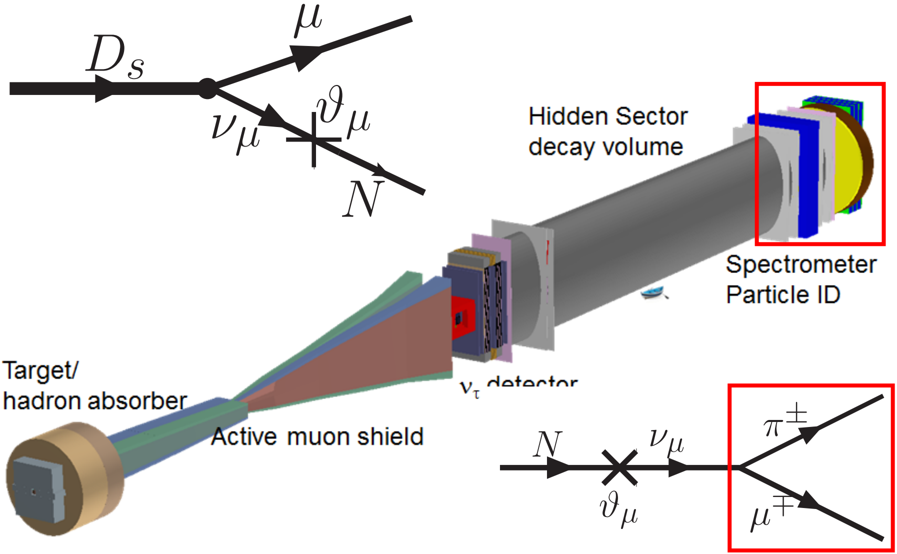


Challenges

- **Background** – many intensity frontier experiments are background free. Many but not all and knowing the background is crucial
- **PID** – can you identify particles that were produced? Are they only "charged particles", "hadrons" or something more specific
- **Mass reconstruction** – if you have a signal, what was the mass particle that decayed? If you have N signal candidate events - do they all reconstruct to the same mass?

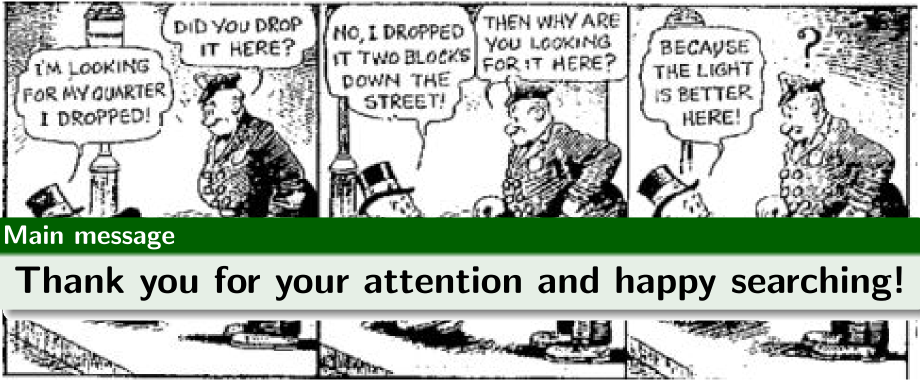
Take home messages

- All major predictions of the Standard Model have been spectacularly confirmed
- Yet, there are "beyond-the-Standard-model" puzzles of **observational** nature that lack their explanation
- Particles that are responsible for it are either too heavy (beyond the LHC reach) or too feebly interacting
- There are no theoretical predictions and therefore we need to **explore all possible options**
- **Feebly Interacting Particle**s can be searched during next LHC runs (or alongside LHC) – results within next decade

Streetlight effect

- Yes, we are "searching under the lamppost"
- But unlike that guy we have no idea where we "lost" it

Streetlight effect



Main message

Thank you for your attention and happy searching!

- Yes, we are "searching under the lamppost"
- But unlike that guy we have no idea where we "lost" it