SHiP - Search for Hidden Particles.

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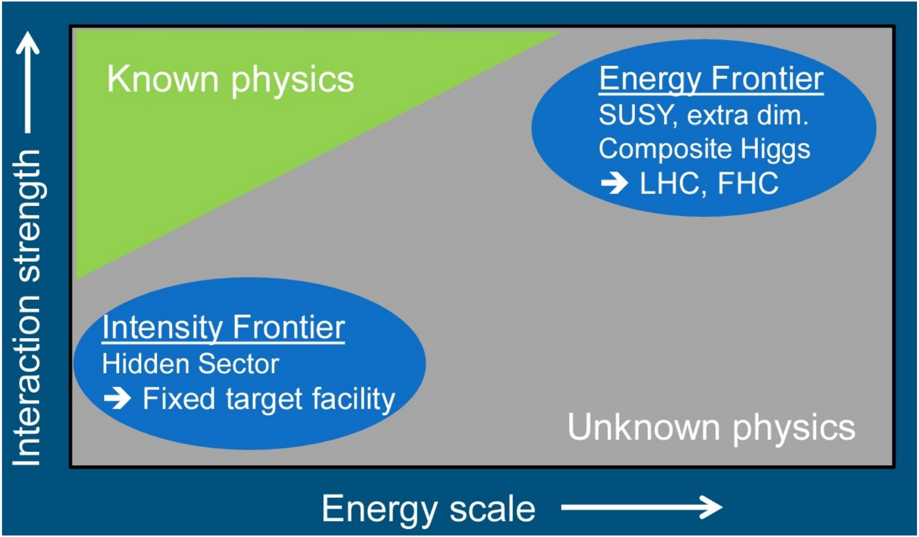
BSM problems

We observe a number of phenomena that require some extension of the Standard Model:

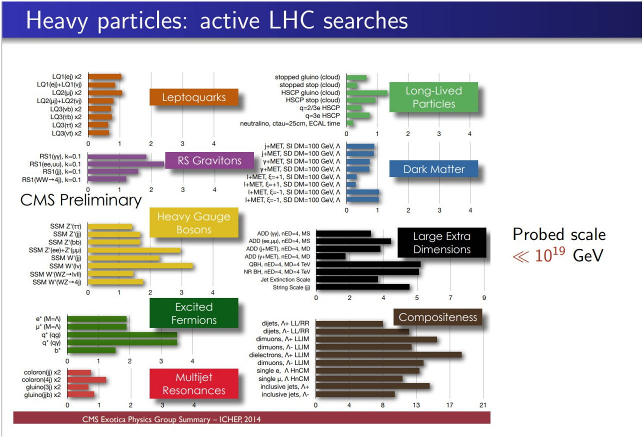
1. Dark matter
2. Neutrino masses and oscillations
3. Baryon assymetry of the Universe

Frontier in particle physics



Energy frontier

- Experiments at LHC can directly probe energy frontier: search for particles that are heavy



Probed scale $\ll 10^{19}$ GeV

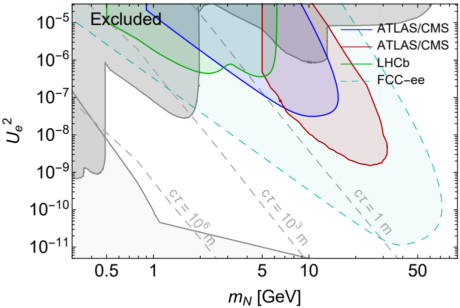
Intensity frontier

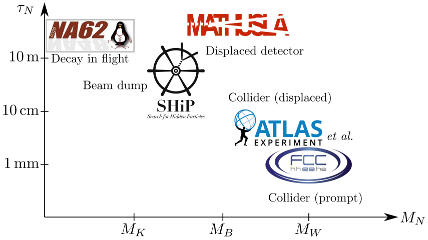
- We may have not observed new particles not because they are too heavy but too feebly coupled to the SM – new physics is suppressed by small dimensionless parameter
- Portals: simple classification of low-energeric parts of NP:
  1. Scalar portal
  $$\mathcal{L}_S = c_1 H^\dagger H S + c_2 H^\dagger H S^2, \tag{1}$$
  2. Fermion portal (HNLs)
  $$\mathcal{L}_N = F_{N\alpha} \bar{N}^c \sigma_2 H^* L_\alpha + \text{h.c.}, \tag{2}$$
  3. Vector portal (dark photons)
  $$\mathcal{L}_V = -\frac{\epsilon}{2} V_{\mu\nu} B^{\mu\nu}, \tag{3}$$
  4. Axion (not renormalizable but phenomenologically attractive) portal
  $$\mathcal{L}_a = \frac{a}{f_a} B_{\mu\nu} \tilde{B}^{\mu\nu} \tag{4}$$

Intensity frontier at LHC/FCC

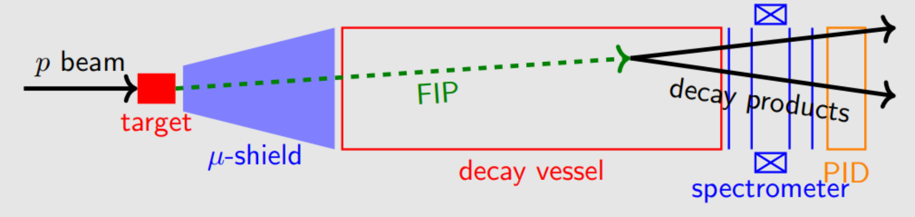
- Feebly interacting particles (FIPs) — large intensity of the experiments
- LHC during high luminosity phase and FCC will collect large integrated luminosity – can probe intensity frontier below ~ 100 GeV
- Also, FIPs lifetime $\sim 1/m^n_{\text{FIP}}$ ($n = 1 - 5$, depending on portal), so light ~ 1 GeV FIPs may have macroscopic decay length and escape the detectors

- LHC/FCC are not suitable for probing NP at GeV scale

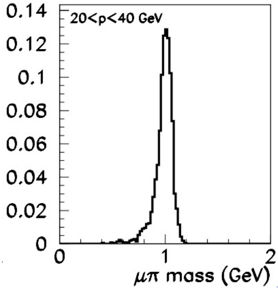




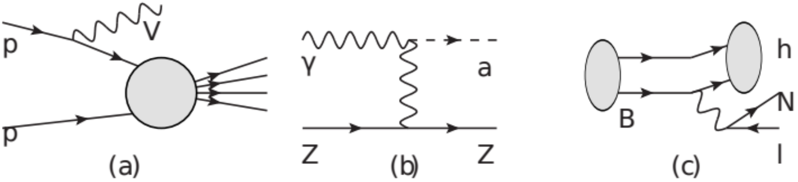
Intensity frontier: BDF



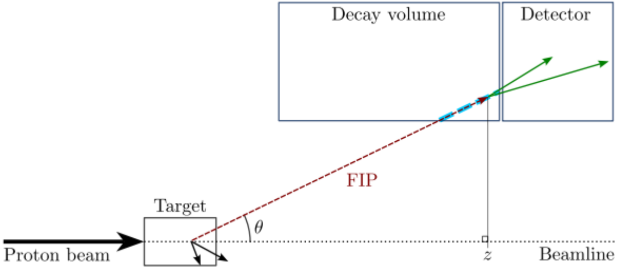
1. BDF experiments may search for all new particles regardless of their nature
2. BDF experiments may measure the properties of new particles - mass, spin, their being portal particles or particles from more complicated models
3. $\rightarrow$ potentially we can not only find FIPs, but also **probe their connection to BSM problems**!



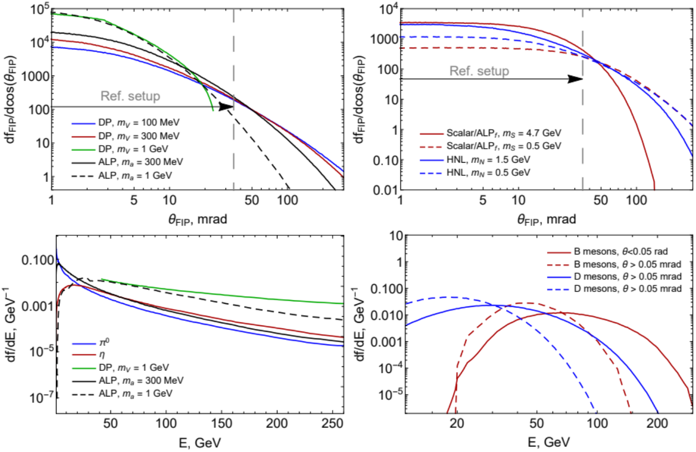
Production of FIPs



Bremsstrahlung Coherent conversion Meson decays

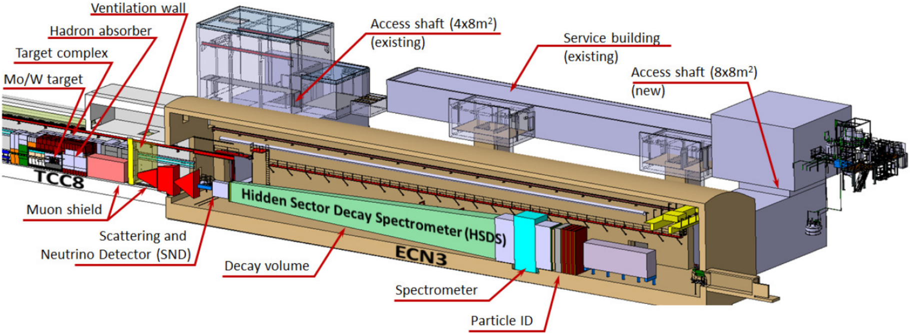


Optimized geometry

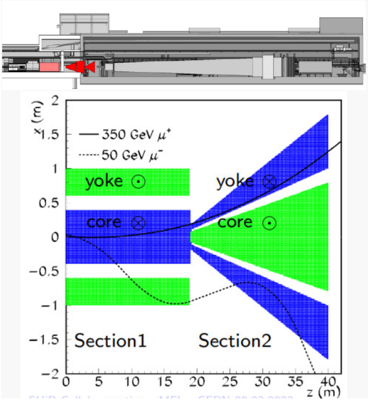


[2304.02511]

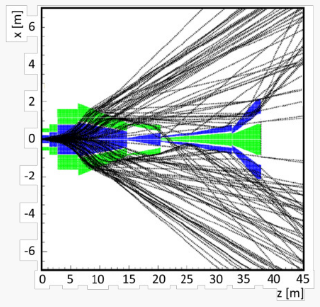
Experimental facility



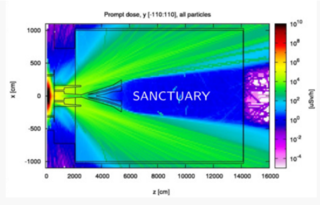
Muon shield



x (m)
350 GeV μ^+
50 GeV μ^-
yoke
core
yoke
core
Section1
Section2
z (m)

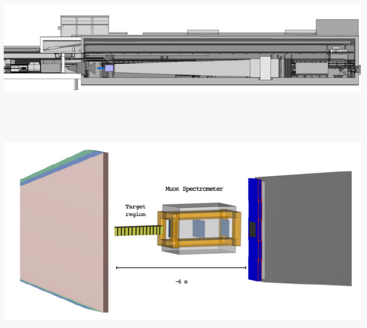


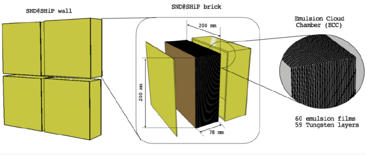
x [m]
z [m]

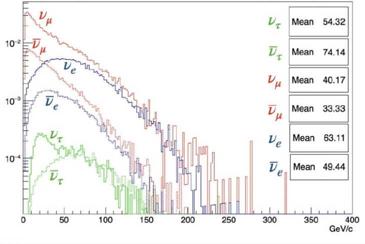


Prompt dose, y [-110:110], all particles
SANCTUARY
x [cm]
z [cm]
[uSv/h]

SND



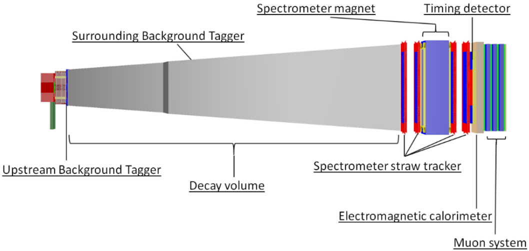


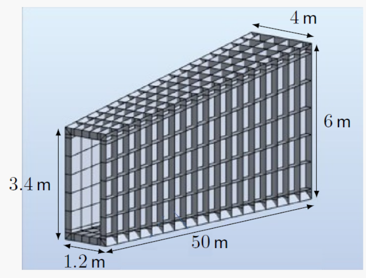


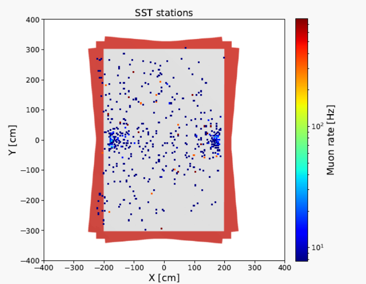
SND

- Heavy target for neutrino interactions
  - First observation of $\bar{\nu}_\tau$
  - ν_τ, $\bar{\nu}_\tau$ physics with high statistics
  - ν_τ magnetic moment
  - F4 and F5 structure functions
  - ν_e cross sections
  - ν-induced charm production
  - strange quark nucleon content
  - LFV
  - LDM via elastic scattering

Hidden sector decay volume and spectrometer



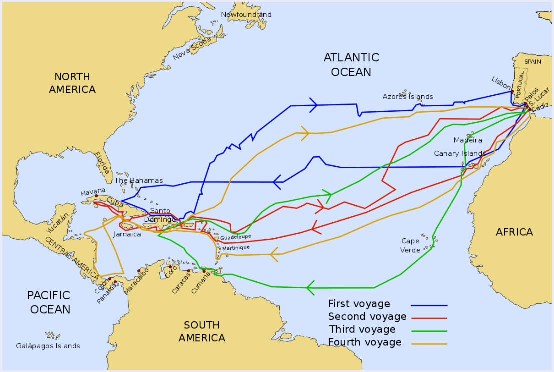




SHiP is more than just a signal discovery

SHiP is also a signal exploration machine

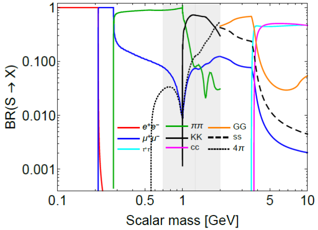
Once discovered – properties of new particles can be put to great scrutiny



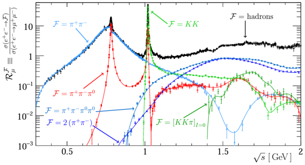
Distinguishing FIPs

Particle	Decay modes
HNL N	$l_\alpha h^\pm$ $l_\alpha l_\beta + \text{inv.}$ $h + \text{inv.}$
Scalar S	$l_\alpha \bar{l}_\alpha$, h
Vector A'	$l_\alpha \bar{l}_\alpha$, h
ALP (γ coupling) a	$\gamma\gamma$
ALP (g coupling) a	h
ALP (f coupling) a	$l_\alpha l_\alpha$, h

With tens of events, one can differentiate between various FIPs based on their decay modes



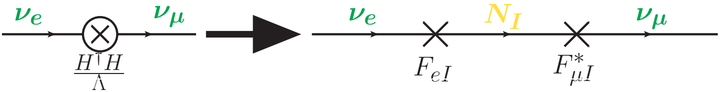
[1904.10447]



[1801.04847]

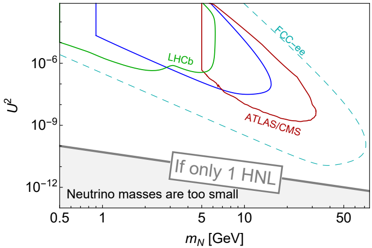
Example: Neutrino Portal and BSM problems. I

- Neutrino oscillation can be described by an effective dimension-5 operator (Weinberg operator). $\Rightarrow$ new particles (e.g. HNL) are needed:



- Naïvely, to explain neutrino oscillations HNL interacts with SM through small mixing angles $U_\alpha \sim F_\alpha / M_N$ of order

$$U^2_{\text{seesaw}} \equiv \frac{\sqrt{\Delta m^2_{\text{atm}}}}{M_N} = 5 \cdot 10^{-11} \frac{1 \text{ GeV}}{M_N} \tag{5}$$

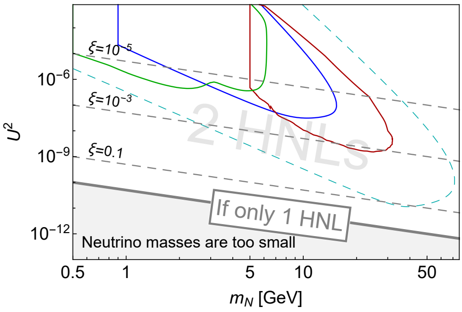


Accelerator experiments do not have enough sensitivity to probe so small mixing angles. **Does it mean that we cannot probe oscillations?**

Example: Neutrino Portal and BSM problems. II

- To explain oscillation data (two mass differences in active neutrino) at least two HNLs are needed
- In this case, mixing angle $U^2 \gg U^2_{\rm seesaw}$ can exist, but they require approximate symmetry between HNLs. The difference between HNL parameters should be:

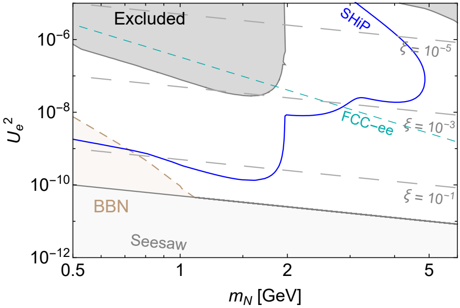
$$M_1 U_1^2 - M_2 U_2^2 \sim \sqrt{\Delta m^2_{\rm atm}} \qquad (6)$$



To quantify how fine-tuned such HNLs are, one can define the ξ-parameter

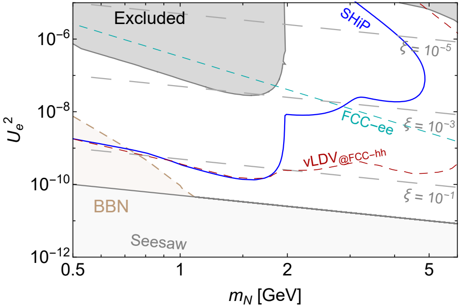
$$\xi = \frac{\sqrt{\Delta m^2_{\rm atm}}}{M_i U_i^2} = \frac{U^2_{\rm seesaw}}{U^2} \qquad (7)$$

Example: Neutrino Portal and BSM problems. III



- SHiP would allow to probe many orders of magnitude larger ξ than the past experiments, approaching to the most interesting part of the parameter space!

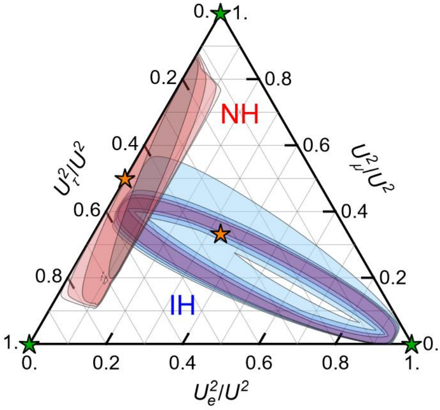
Example: Neutrino Portal and BSM problems. IV



- Above 2 GeV, the region of large ξ may be further explored with FCC-ee, FCC-hh

2. Probing neutrino oscillations I

$$\sqrt{M_I}\theta_{\alpha I} = i\left[U^{\text{PMNS}}\begin{pmatrix}\sqrt{m_1} & 0 & 0\\ 0 & \sqrt{m_2}e^{i\eta} & 0\\ 0 & 0 & \sqrt{m_3}\end{pmatrix}\times R_{2\times 3}(\omega)\right]_{\alpha I}$$



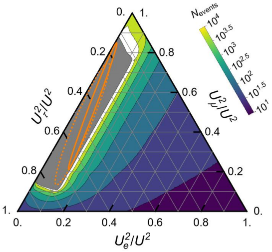
→

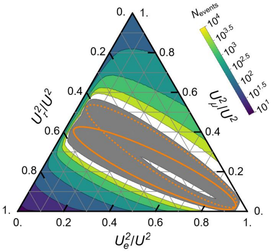
Measure flavour coupling $x_\alpha = U_\alpha^2/U^2$

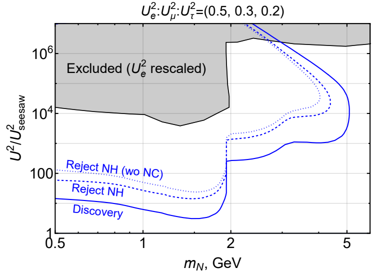
↓

Test two HNLs hypothesis

2. Probing neutrino oscillations II



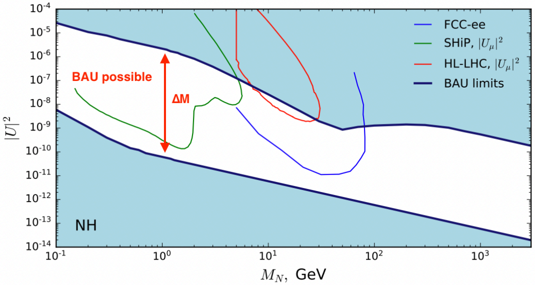




With SHiP sensitivity reach, it is possible to reject minimal 2-HNL model
[2312.00659]
[2312.05163]

3. Probing BAU

- Same HNLs that are responsible for neutrino oscillations can generate **baryon asymmetry of the Universe**
- Baryon asymmetry also demands *at least* 2 HNLs with **almost degenerate masses**:
  $\Delta M = |M_1 - M_2| \ll M_1, M_2$
  and have the same mixing angles:



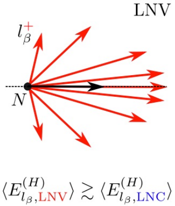
$$U_{\alpha 2}^2 = U_{\alpha 1}^2 \left[1 + O\left(\frac{\Delta M}{M_N}, \frac{U_{\text{seesaw}}^2}{U^2} \right) \right] \quad (8)$$

Can we understand that we observed such HNLs?

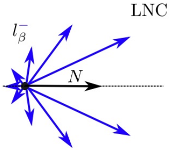
Distinguishing two HNLs?

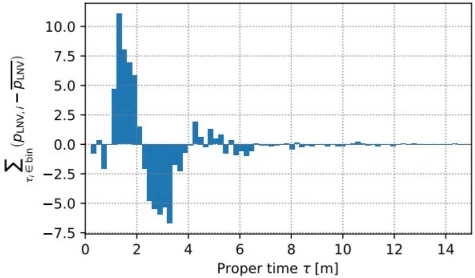
- Two HNLs with similar masses $\Rightarrow$ **HNL oscillations**
- Ratio of probability of lepton number violating (LNV) and conserving (LNC) processes:

$$\frac{P_{\rm LNV}}{P_{\rm LNC}} \sim \frac{1-\cos\Delta M\tau}{1+\cos\Delta M\tau} \qquad \tau - \text{HNL proper time} \qquad (9)$$



- Kinematics of LNV and LNC decays is statistically different

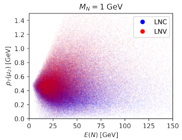




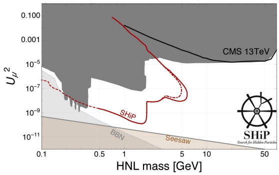
✓ SHiP can resolve HNL oscillations [1912.05520]

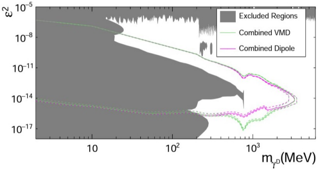
✓ Needs $\mathcal{O}(10^3)$ events – middle of the exploration region

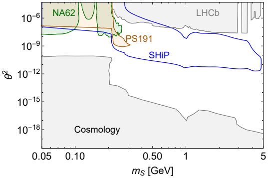
✓ Oscillation period: $2\pi/\Delta M$



SHiP: not one channel but frontier







1. SHiP can observe new physics directly
2. SHiP does not study some specific channel — it can explore the whole intensity frontier to $\sim m_B$ masses, push the constraints by orders of magnitudes for a generic model with light FIPs
3. . . . and potentially resolve the BSM problems!
   inflation, complex higgs sector, dark matter, cosmological axions. . .

Summary

- Energy frontier is quite explored already and is going to be explored even more at FCC
- Still no physics found – need to search for heavy physics in rare processes — effective operators
- Intensity frontier — not explored. A single experiment can explore the whole frontier, probing various models
- BDF can directly observe new physics particle and measure its properties
- Finally, BDF can probe connections of the new physics to BSM problems