Long Lived Particles at colliders and beyond.

Felix Kling
Rencontres de Blois 2021

Why Long-Lived Particles?

We have good reasons to think that there is new physics beyond the SM
(dark matter, hierarchy problem, inflation, neutrino masses, baryogenesis ...)

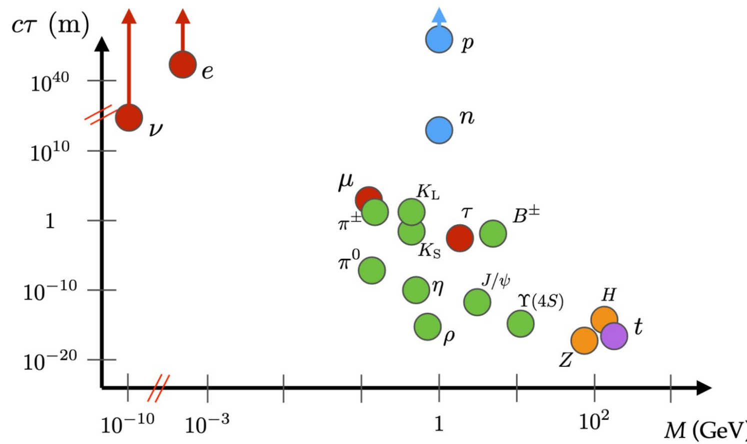
No evidence for new particles with conventional search strategies.

Maybe we have been looking in the wrong place:
"lighting new lampposts" and "leave no stone unturned"

SM as inspiration:
many particles are long-lived

↓

search for new long-lived particles
(LLPs) as sign of BSM physics



Resources.

Long-Lived Particles at the Energy Frontier:
The MATHUSLA Physics Case

1806.07396

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EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

CERN-PBC-REPORT-2018-007

1901.09966

Physics Beyond Colliders at CERN
Beyond the Standard Model Working Group Report

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Collider Searches for Long-Lived Particles
Beyond the Standard Model

1810.12602

Lawrence Lee[1], Christian Ohm[2,3], Abner Soffer[4], Tien-Tien Yu[5,6]

Searching for long-lived particles beyond the Standard Model at the Large Hadron Collider

1903.04497

March 6, 2019

Particles beyond the Standard Model (SM) can generically have lifetimes that are long compared to SM particles at the weak scale. When produced at experiments such as the Large Hadron Collider (LHC) at CERN, these long-lived particles (LLPs) can decay far from the interaction vertex of the primary proton-proton collision. Such LLP signatures are distinct from those of promptly decaying particles that are targeted by the majority of searches for new physics at the LHC, often

Theory Motivation

SM - SUSY - DM

Signatures & Experiments

LHC - Dedicated Experiments - Deam Dumps - Astronomy

LLPs in the SM.

Scale Suppression

example: muon

$$\Gamma \sim g^4 \frac{m_\mu^5}{m_W^4}$$

mass hierarchies

heavy off-shell mediator

EFT with large cutoff scale

Small Couplings

example: B-meson

$$\Gamma \sim g^4 \frac{m_B^5}{m_W^4} |V_{cb}|^2$$

loop suppression

very weak coupled physics

Phase Space

example: neutron

$$\Gamma \sim \left(\frac{m_n - m_p}{m_W}\right)^4 m_e g^4$$

compressed spectra

softly broken or approximate symmetry

These features appear in many BSM models

LLPs in SUSY.

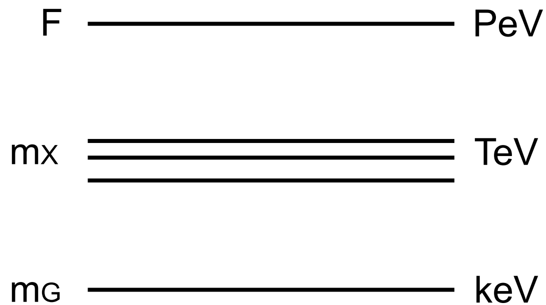
Scale Suppression: Gauge Mediated SUSY Breaking

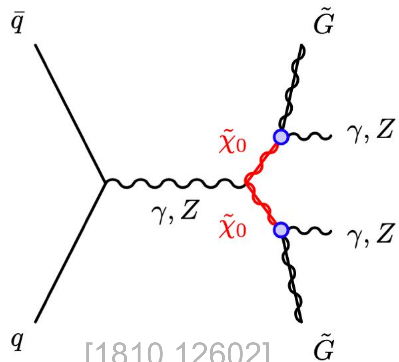
scale of SUSY breaking
$F \sim \text{PeV}$

graviton typically LSP
$m_G \sim F^2/M_{pl} \sim \text{keV}$

NLSP long-lived
$\Gamma(X \rightarrow G + SM) \sim m_X^5/F^4$

$c\tau \sim 1\text{m}$ for $m_X \sim 100$ GeV





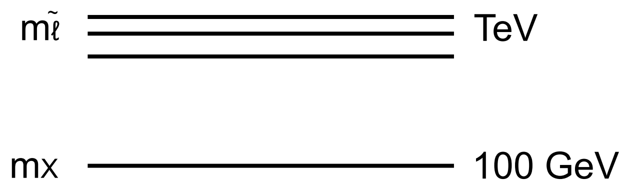
[1810.12602]

LLPs in SUSY.

Small Couplings: RPV SUSY

additional terms in superpotential:

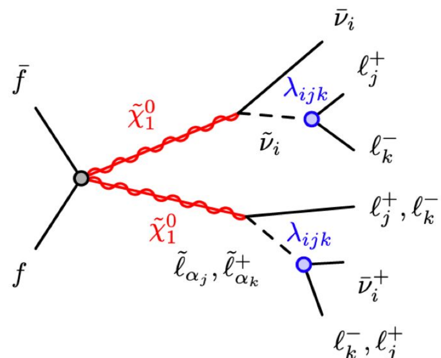
$$W_{\rm RPV} = \mu_i L_i H_u + \frac{1}{2}\lambda_{ijk} L_i L_j \bar{e}_k + \lambda'_{ijk} L_i Q_j \bar{d}_k + \frac{1}{2}\lambda''_{ijk} \bar{u}_i \bar{d}_j \bar{d}_k,$$



couplings need to be small to avoid proton decay, flavor violation ...

LSP long-lived:
$\Gamma(\chi^0 \to \ell\ell\nu) \sim \lambda^2\, m_\chi^5 / m_{\tilde\ell}^4$

$c\tau \sim 1\text{m}$ for $\lambda \sim 10^{-4}$ $m_\chi \sim 100$ GeV, $m_{\tilde\ell} \sim$ TeV



[1810.12602]

LLPs in SUSY.

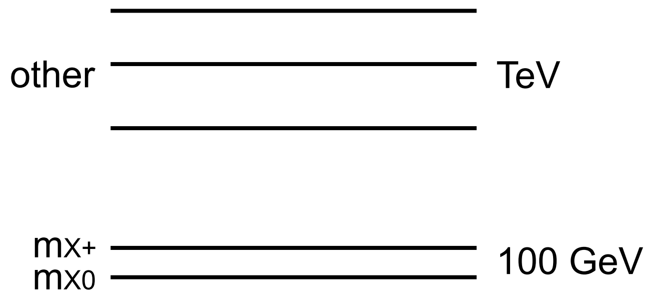
Phase Space: Anomaly Mediated SUSY Breaking

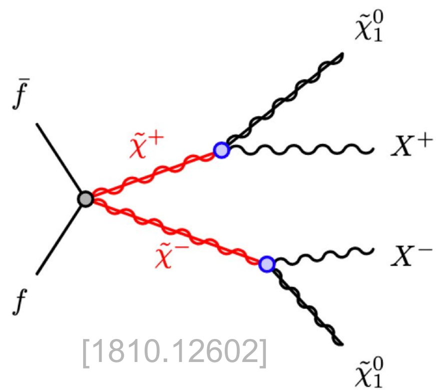
Wino is LSP

small chargino/neutralino
mass difference
$\Delta m \sim m_W^4/\mu^3 \sim 100\text{MeV}$
for $\mu \sim$TeV

chargino long-lived:
$\Gamma(X^+ \rightarrow X^0 + \text{SM}) \sim \Delta m^3/m^2$

$c\tau \sim 1\text{m}$ for $m_X \sim 100\text{GeV}$





[1810.12602]

LLPS in DM and Portals.

Scale Suppression: Heavy Neutral Lepton Portal

add right-handed neutrinos to SM:

$$\mathcal{L}_N = i\,\overline{\nu_{Ri}}\,\partial\!\!\!/\,\nu_{Ri} - \underbrace{f_{\alpha i}}_{m}\overline{L}_\alpha \tilde{H}\nu_{Ri} - \underbrace{\frac{M_i}{2}}_{M}\overline{\nu_{Ri}}^{c}\nu_{Ri} + \text{h.c.}$$

diagonalize mass matrix: $\theta \sim m/M$

$\nu = \nu_L - \theta\, \nu_R$ with $m_\nu \sim m^2/M$ and $N = \nu_R + \theta\, \nu_L$ with $m_N \sim M$

couplings of N to W,Z suppressed by $\theta \sim m/M$

N is long-lived:

$\Gamma(N \to \ell\ell\nu) \sim \theta^2\, m_N^5 / m_W^4$

$c\tau \sim 1\text{m}$ for $m_N \sim 10$ GeV , $\theta \sim 10^{-5}$

LLPS in DM and Portals.

Small Coupling: Dark Photon Portal

Simple Example: Light Dark Matter charged under U(1)

$$\mathcal{L} \supset -\frac{\epsilon}{2} F^{\mu\nu} F'_{\mu\nu} - \frac{1}{2} m^2_{A'} A'^2 - m^2_{\chi} \chi^2 - i g_D A' \chi^2$$

if mA'< 2mX: A' can only decay to SM and becomes long-lived

$\Gamma(A' \to ee) \sim \varepsilon^2 m_{A'}$

$c\tau \sim 10$cm for $\varepsilon \sim 10^{-5}$ and $m_{A'} \sim 100$ MeV

LLPS in DM and Portals.

Scale Suppression: Inelastic Dark Matter and Co-Annihilation

Weyl fermions η,ξ with opposite charge under $U(1)_D$

$$-\mathcal{L} \supset m_D\, \eta\, \xi + \frac{1}{2} m_M \left(\eta^2 + \xi^2\right) + \text{h.c.}$$

conserves $U(1)_D$

breaks $U(1)_D$

if $m_D >> m_M$: two almost degenerate pseudo-Dirac fermions X_1 and X_2
with mass mX ~ mD and small mass splitting Δ ~ 2mM

$$\chi_1 \simeq \frac{i}{\sqrt{2}}(\eta - \xi)\ ,\ \chi_2 \simeq \frac{1}{\sqrt{2}}(\eta + \xi)$$

non-diagonal coupling: $\mathscr{L} \supset i e_D\, A'_\mu\, \bar{\chi}_1 \gamma^\mu \chi_2$

X_2 is long-lived
$\Gamma(X_2 \to X_1 \ell\ell) \sim \varepsilon^2\, \Delta^5 / m_{A'}^4$
$c\tau \sim 1$m for m~10GeV, Δ~0.05, $\varepsilon \sim 10^{-2}$

Theory Motivations.

Scale Suppression

mass hierarchies

heavy offshell mediator

EFT with large cutoff scale

SM: muon

SUSY: GMSB

DM: HNLs

Small Couplings

loop suppression

very weak coupled physics

SM: B-meson

SUSY: RPV

DM: Dark Photon

Phase Space

compressed spectra

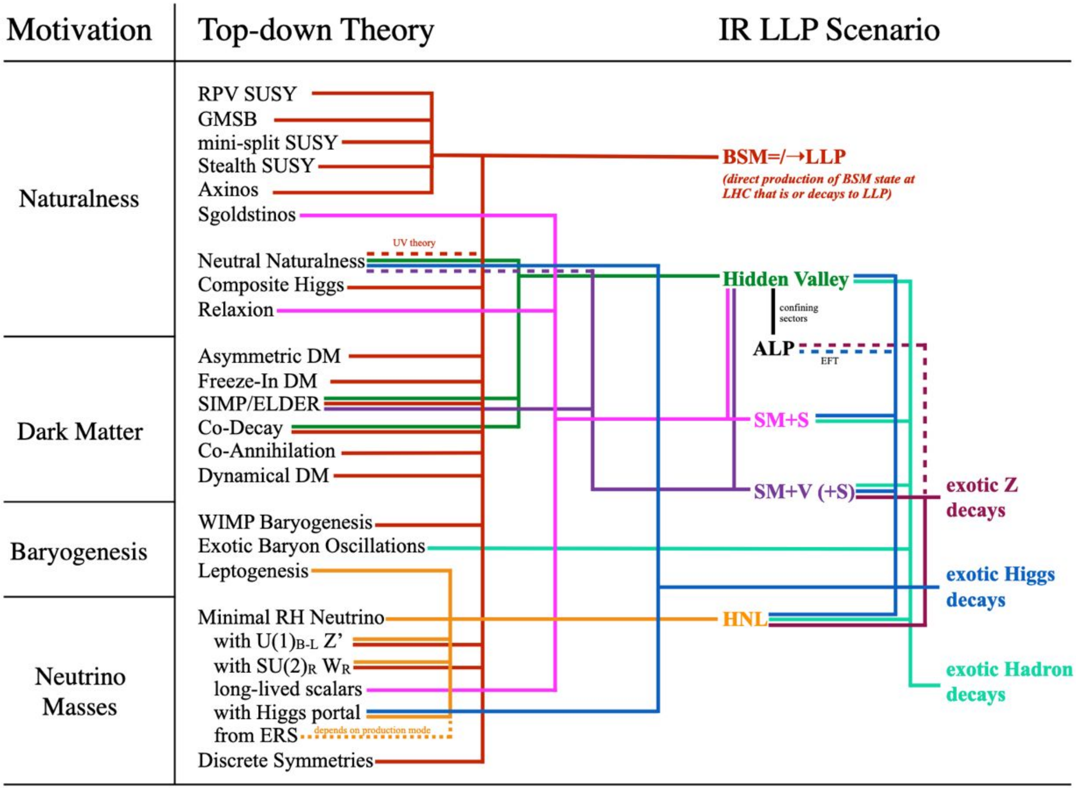
softly broken or approximate symmetry

SM: neutron

SUSY: AMSB

DM: IDM

Theory Motivation.



The MATHUSLA Physics Case: [1806.07396]

Theory Motivation

SM - SUSY - DM

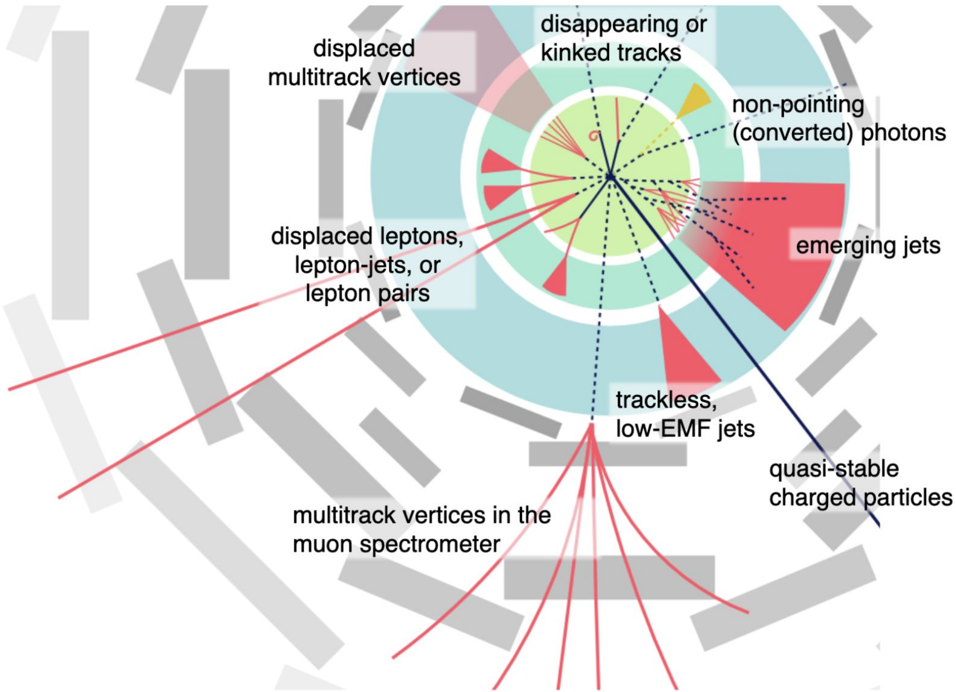
Signatures & Experiments

LHC - Dedicated Experiments - Deam Dumps - Astronomy

Main LHC Detectors.

variety of different signatures

Searching for LLPs beyond the SM at the LHC: 1903.04497



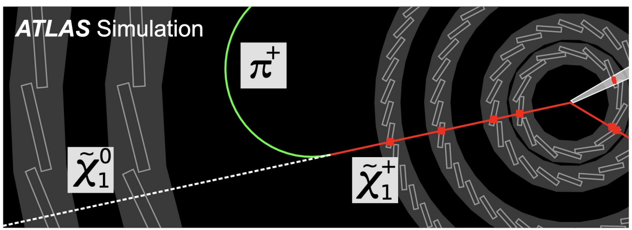
→ see Stefano Passaggio's and Margaret Lutz's talk

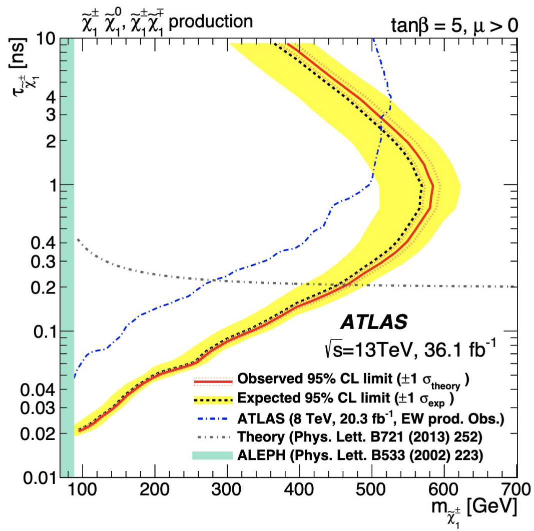
Main LHC Detectors.

Signature: Disappearing Tracks

$X^+ \to X^0 + \pi^+$ with almost degenerate mass spectrum

pion has low momentum and is not reconstructed





[ATLAS 1712.02118]

Main LHC Detectors.

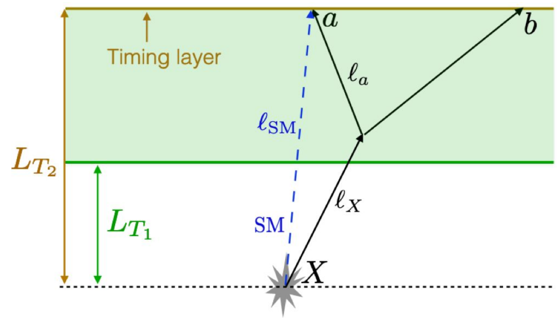
Signature: Delayed Jets

delayed signal due to
slow moving heavy particle
longer trajectory

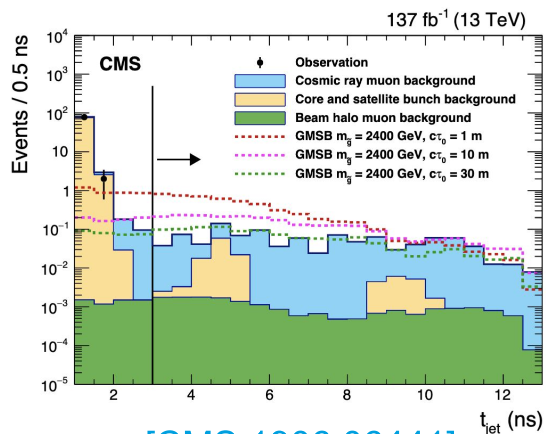
use detector upgrades for delayed searches:
30ps resolution, mainly for pile up

ATLAS high granularity timing layer
CMS HGCAL with timing

additional timing layers?
timing for triggers?



[Liu, Liu, Wang 1805.05957]



[CMS 1906.06441]

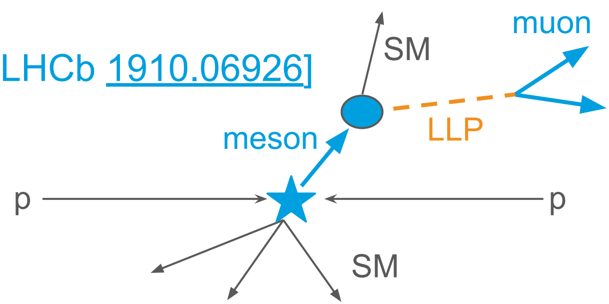
Main LHC Detectors.

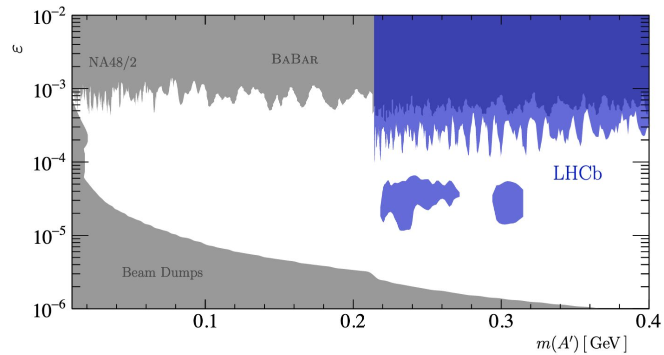
Signature: Displaced Vertex

charged tracks emerging in empty space some distance away from primary collision

performed by ATLAS, CMS, LHCb

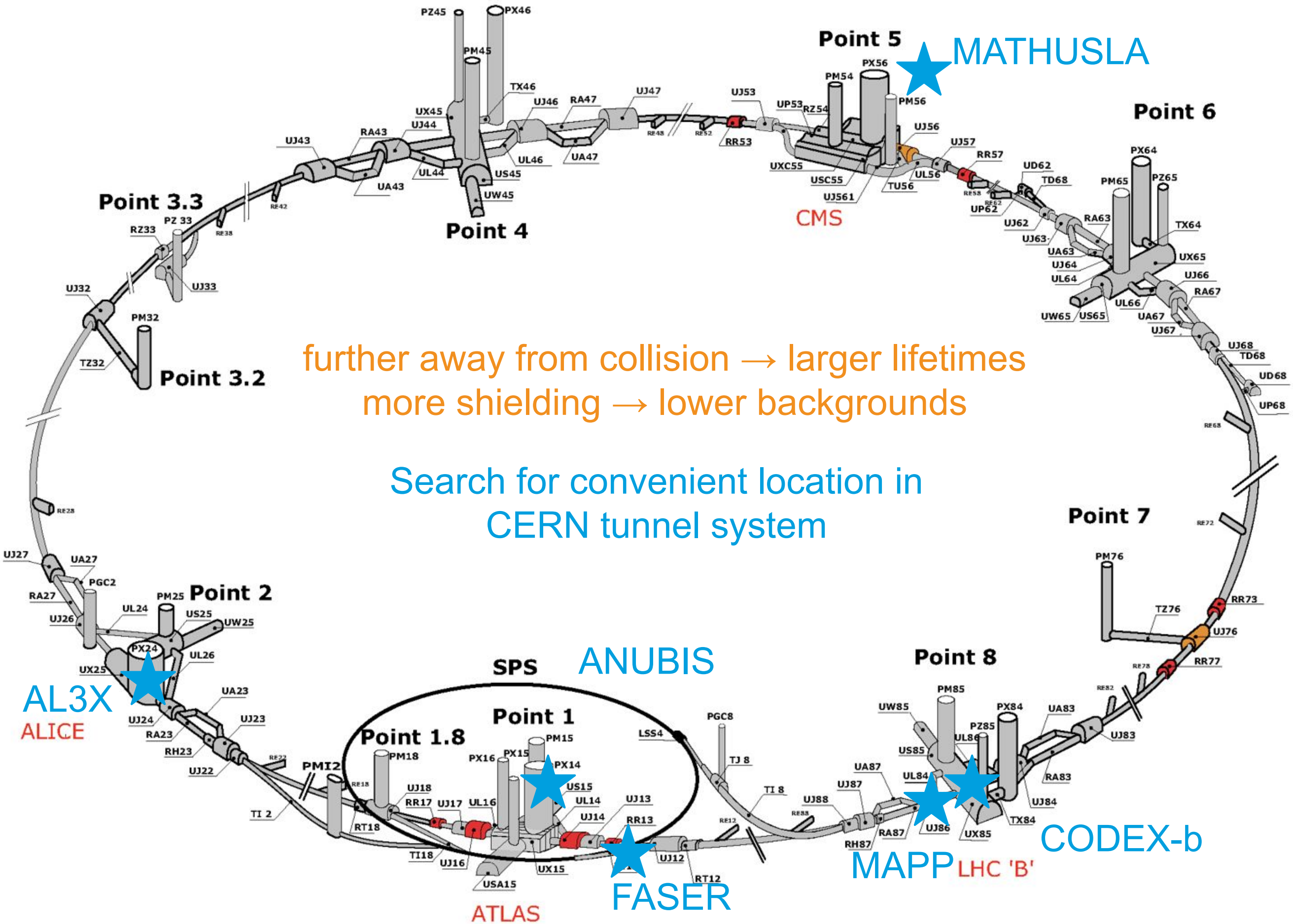
[LHCb 1910.06926]





also at other colliders, for example Belle 2:
→ see Sascha Dreyer's talk

Dedicated Far Detectors.



further away from collision → larger lifetimes
more shielding → lower backgrounds

Search for convenient location in
CERN tunnel system

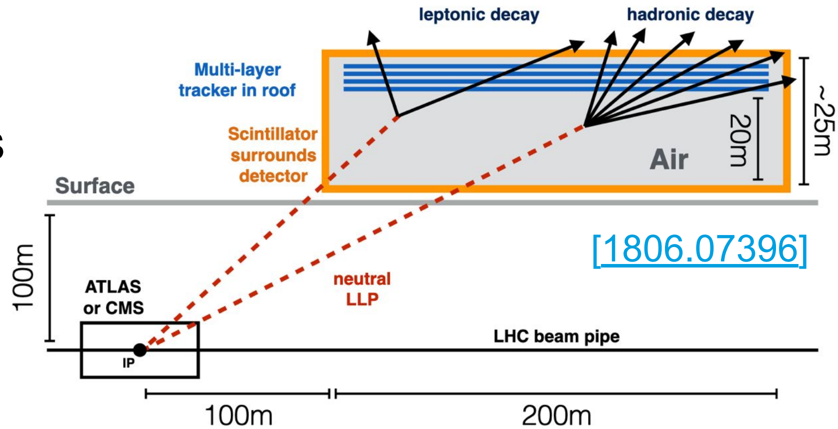
Dedicated Far Detectors.

Experiment: MATHUSLA

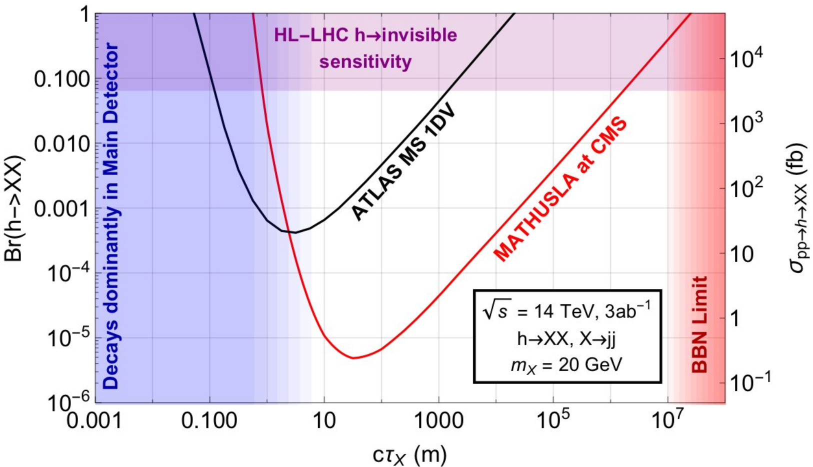
proposed surface detector near CMS

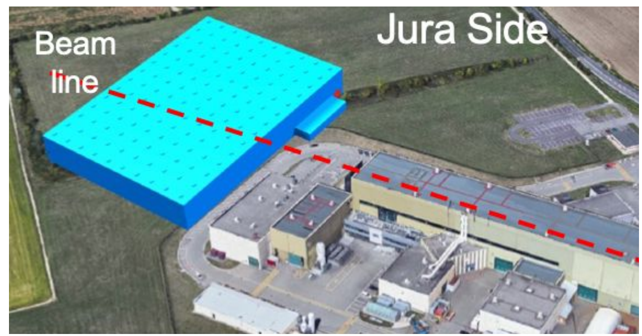
[Idea 1606.06298]

mathusla-experiment.web.cern.ch



[1806.07396]

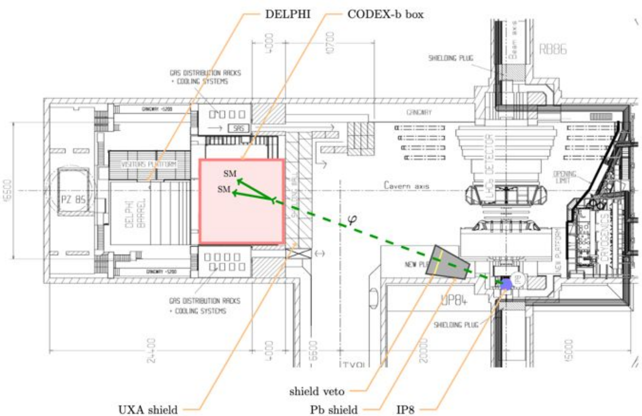




Dedicated Far Detectors.

Experiment: CODEX-b

located in LHCb cavern

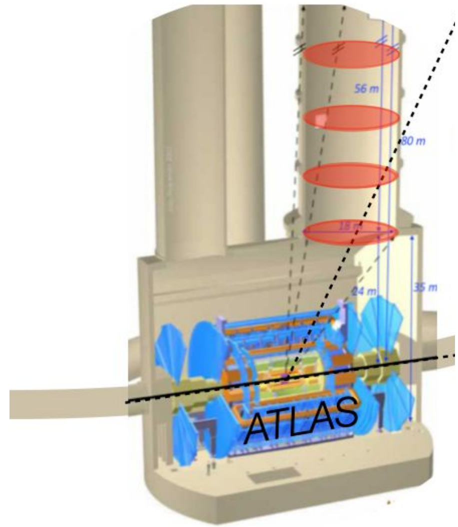


[Idea: 1708.09395]

[CODEX-b EOI 1911.00481]

Experiment: ANUBIS

located in ATLAS service shaft



[Idea 1909.13022]

hep.phy.cam.ac.uk/ANUBIS

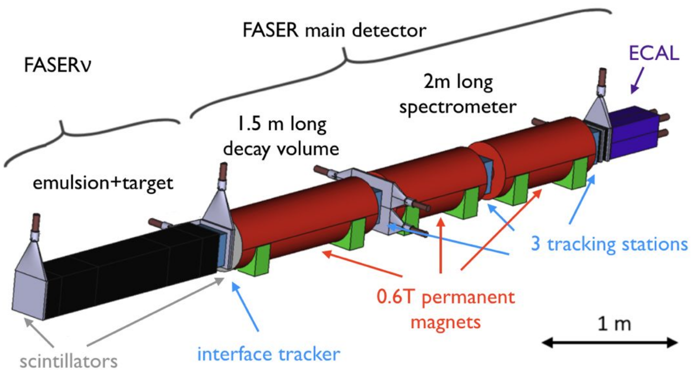
Dedicated Far Detectors.

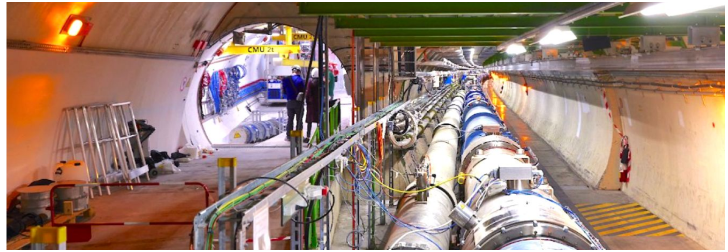
Experiment: FASER

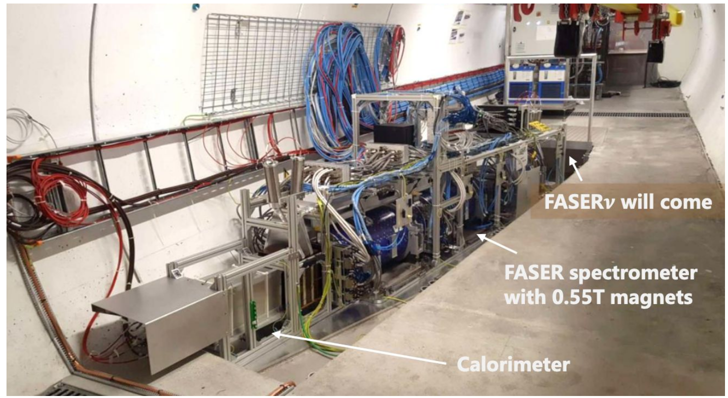
light LLPs produced in the forward direction

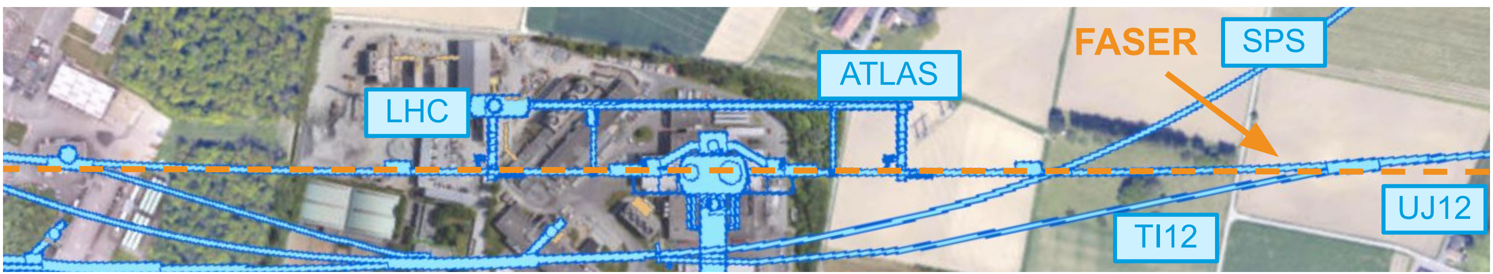
successfully installed in March 2021

faser.web.cern.ch



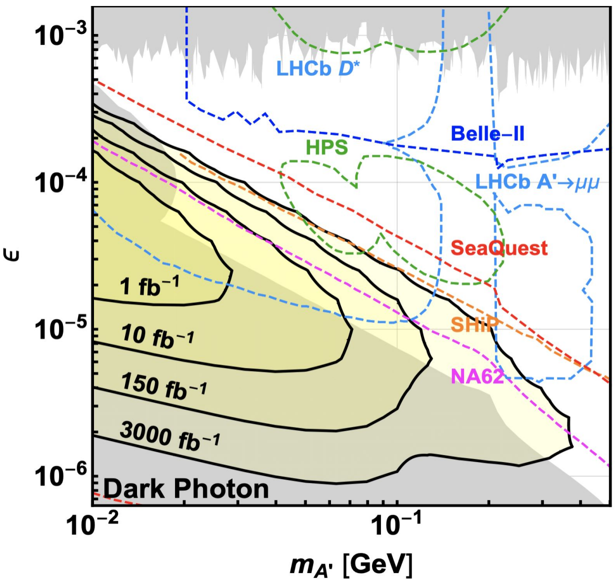






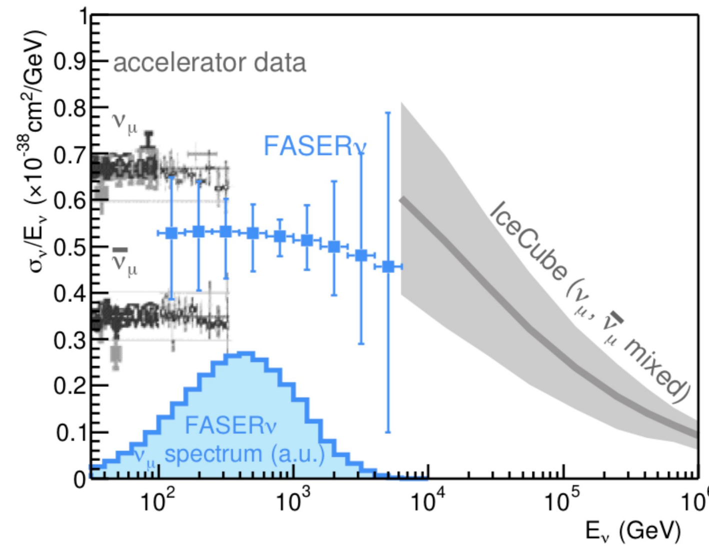
Dedicated Far Detectors.

LLP searches



[FASER 1811.12522]

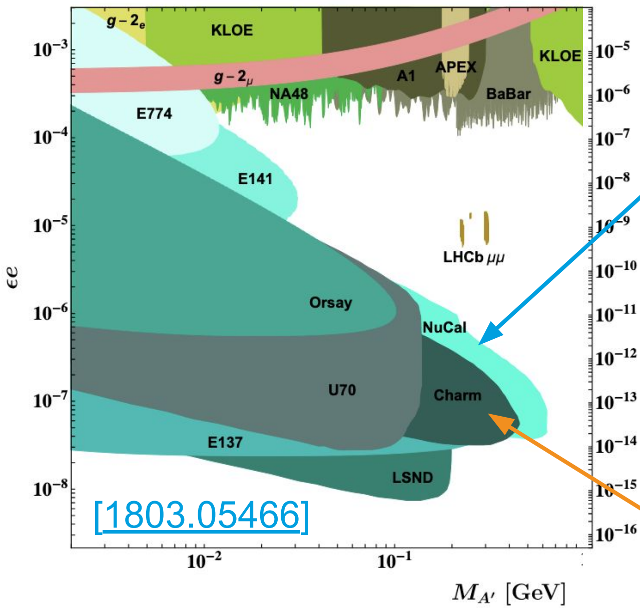
LHC Neutrinos



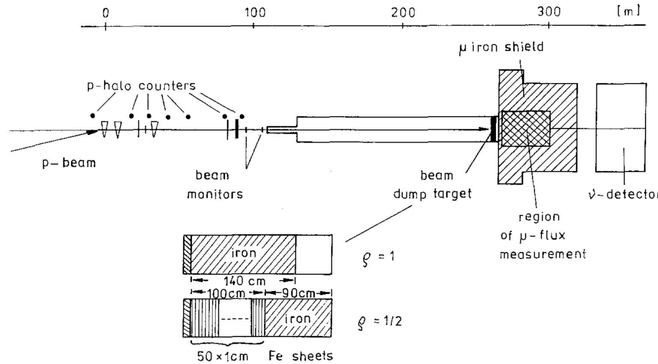
[FASER 1908.02310]

→ see Laurie Nevay's talk

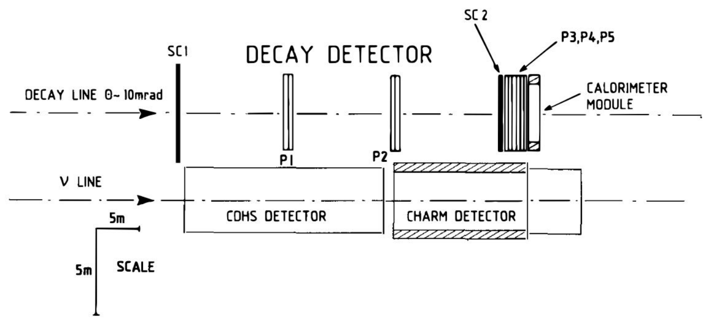
Beam Dumps.



NuCal [*Z.Phys.C* 51 (1991) 341]



CHARM [*Phys.Lett.B* 128 (1983) 361]

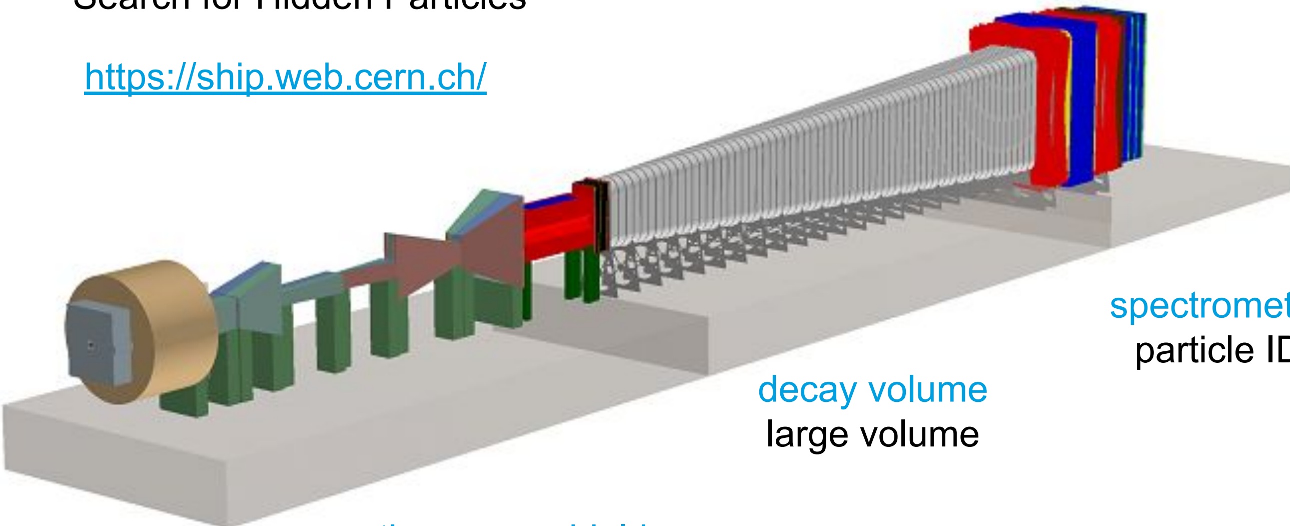


Beam Dumps.

Experiment: SHiP @ CERN

proposed dedicated experiment to
"Search for Hidden Particles"

https://ship.web.cern.ch/

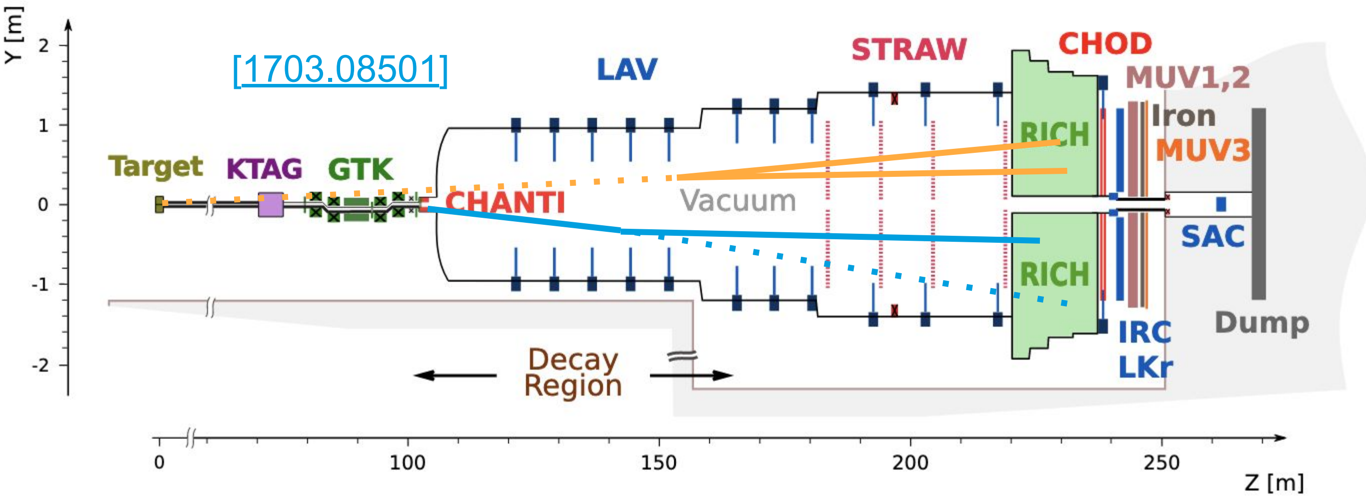


Beam Dumps.

Experiment: NA62 @ Fermilab

main goal: kaon physics, $K^+ \to \pi^+ \nu\nu$

[1703.08501]



kaon mode:
$K^+ \to \pi^+ X$

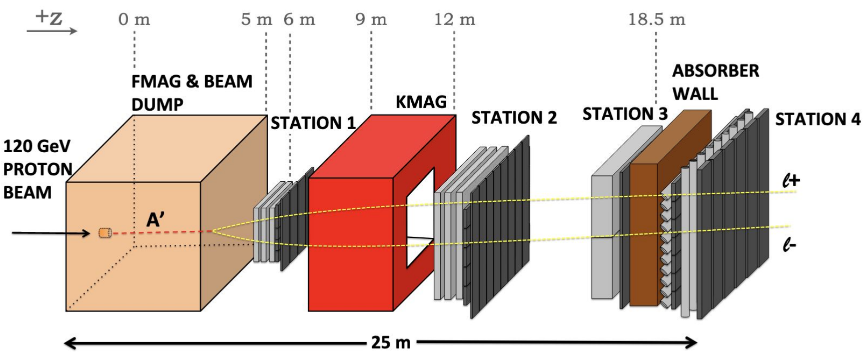
beam dump mode:
$X \to$ SM SM

Beam Dumps.

Experiment: SeaQuest/SpinQuest @ Fermilab

main goal: contributions of antiquarks to the proton structure

possibility of LLP searches: run 2020-2022 for 2μ channel



DarkQuest:
add EMCal in
main detector
[1804.00661](https://arxiv.org/abs/1804.00661)

LongQuest:
add EMCal 10 m
behind main detector
[1908.07525](https://arxiv.org/abs/1908.07525)

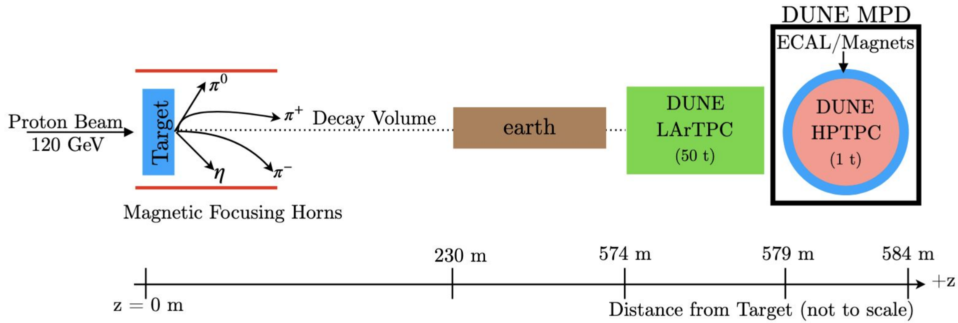
Beam Dumps.

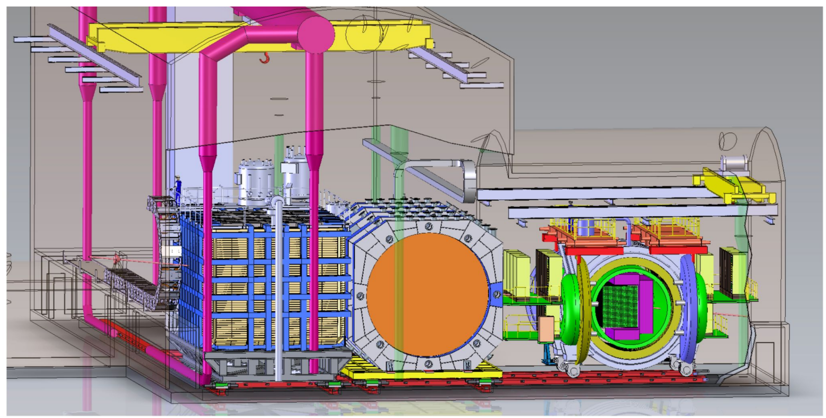
Experiment:
DUNE @ Fermilab

main goal: long baseline neutrino oscillation

DUNE near detector contains High-Pressure Gaseous Argon TPC
2103.13910

can be used for LLP searches
1912.07622





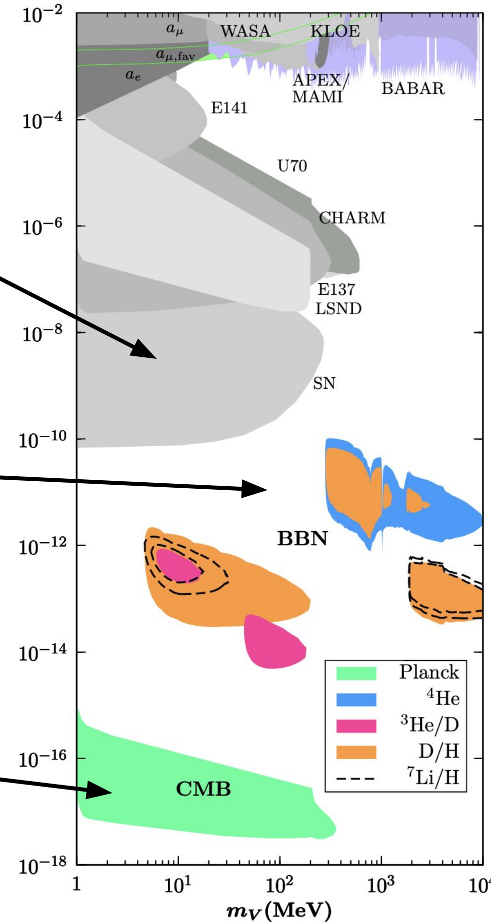
Liquid Ar	**Gas Ar**	**SAND**
Target, Vertex	Tracker, PID	Calorimeter Flux Monitor

Astronomy & Cosmology.

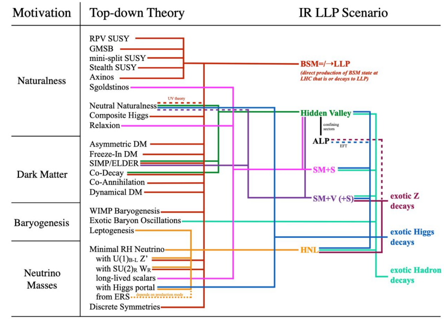
LLP with cτ~R⊙ leads to additional cooling mechanism disagreement with observed neutrino flux from SN1987
[Chang, Essig, McDermott 1611.03864]

LLP with τ≳1 would disturb light nuclei abundance: e.g. decay products break up of light nuclei, pion induced n↔p conversion
[Fradette, Pospelov, Pradler, Ritz 1407.0993]

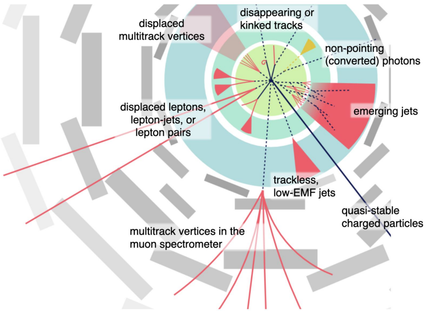
LLP with τ≳3x10^{5}yr injects energy after recombination change of ionization history incompatible with CMB
[Fradette, Pospelov, Pradler, Ritz 1407.0993]



Conclusion and Outlook

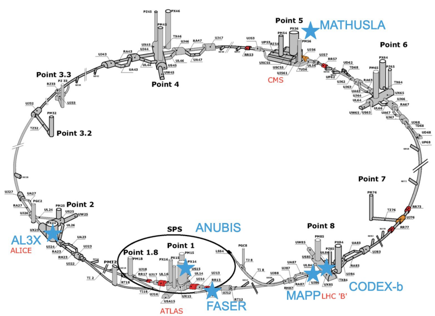


LLPs are well motivated:
they naturally appear in many BSM scenarios



variety of possible signatures:
sensitivity at many experiments

many recent developments:
dedicated experiments for LLPs



See this talk as inspiration: there is still room for new ideas.