Dark matter searches with Long Lived Particles

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Why Long-Lived-Particles (LLPs)?

Motivation for LLP

LLPs?

- LLPs ($\tau \sim$ ns, $c\tau \sim$ cm) : essential part of SM $\Rightarrow$ Reason to believe for them to be in BSM

Dark-matter as LLPs?

- Models of WIMP DM $\rightarrow$ Null results to date in indirect detection (ID), direct detection (DD), and missing energy searches
  - WIMP DM $\rightarrow$ Severely constrained regions of parameter space
  - Broader investigation into possible signals of particle dark matter

Lifetime of a particle

Decay rates

- Large collection : *decaying particles* at time t : $N(t)$.
- *Decay rate* Γ : *probability per unit time* $\rightarrow$ *given particle disintegrate*
- Rate : particles *decrease*

$$\frac{dN}{dt} = -\Gamma N \Rightarrow N(t) = N(0)\, e^{-\Gamma t}$$

- Mean lifetime $\rightarrow$ reciprocal of the decay rate

$$\tau = \frac{1}{\Gamma}$$

- Reality : most particles $\rightarrow$ decay by several different routes.
  - *Total decay rate* $\rightarrow$ sum of individual rates and so is their *lifetimes*

$$\Gamma_{\text{tot}} = \sum_{k=1}^{n} \Gamma_k \Rightarrow \tau = \frac{1}{\Gamma_{\text{tot}}}$$

- Branching ratios for k'th decay mode : $\dfrac{\Gamma_k}{\Gamma_{\text{tot}}}$

Parameters that make particles Long Lived

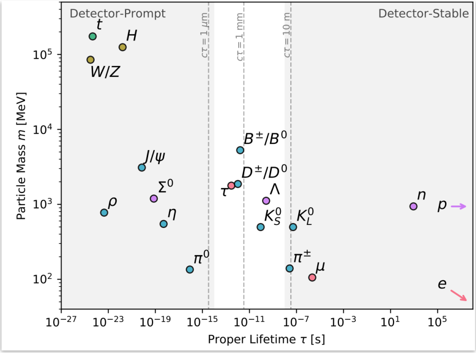
$$\Gamma_f = 2\pi \underbrace{|T_f|^2}_{\propto\, \alpha} \underbrace{\rho(E_f)}_{\sim\, \text{mass}}$$

$$\tau = \left(\sum \Gamma_f\right)^{-1}$$

Coupling constant
- Particle decay rate : strong force > electromagnetic or weak

Density of states
- Symmetries : Small DOS → a longer lifetime
- General trend : High mass particles → smaller lifetimes

Scale suppression
- Decay : suppressed by scale of the physical system mediating decay



$$\Gamma \sim y^2 \left(\frac{m}{M}\right)^n m$$

small coupling

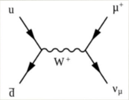
Set by symmetry structure, typically n ≥ 4

$m \ll M$

hierarchy of scales

Example 1 : Charged pion (Small coupling constant)

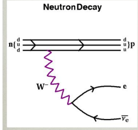
$\pi^+ \to \mu^+ \nu_\mu$



- Quark flavour conserved by all but weak interactions
- Decay highly off-shell:

$$\Gamma_{\pi^+} \sim g_W^2 \left(\frac{M_\pi}{M_W}\right)^4 M_\pi$$

Example 2 : Neutron (Phase space suppression)



- Isospin ensures that proton and neutron are nearly degenerate
- Decay highly off-shell:

$$\Gamma_{\pi^+} \sim g_W^2 \left(\frac{M_n - M_p}{M_W}\right)^4 (M_n - M_p)$$

Multiple DM theories predicting LLPs

		Small coupling	Small phase space	Scale suppression
SUSY	GMSB			✓
	AMSB		✓	
	Split-SUSY			✓
	RPV	✓		
NN	Twin Higgs	✓		
	Quirky Little Higgs	✓		
	Folded SUSY		✓	
DM	Freeze-in	✓		
	Asymmetric			✓
	Co-annihilation		✓	
Portals	Singlet Scalars	✓		
	ALPs			✓
	Dark Photons	✓		
	Heavy Neutrinos			✓

Figure: Table of theories predicting LLPs[1]

Freeze-in DM (FIMPs)

- Decay responsible → DM accumulation

$$\underbrace{A}_{\text{Thermal eq. in Early universe}} \longrightarrow \underbrace{\chi}_{\text{DM particle}} + \underbrace{B_{\text{SM}}}_{\text{SM particle}}$$

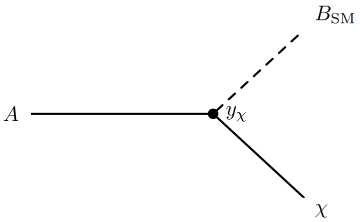


Figure: Toy diagram of a freeze-in scenario

- Feeble coupling constant y_χ → Making χ thermally decoupled from the plasma
- This *feebleness* ⇒ **long lifetime** of A

Freeze-in DM : Decay rate

- **Relic abundance** of χ is related to the A decay width Γ_A by

$$\underbrace{\Omega_\chi h^2}_{\text{Cosmo. den. of}\chi} = \frac{10^{27}}{g_*^{\frac{3}{2}}} \frac{m_1 \Gamma_A}{m_2^2}$$

  g_* is the number of relativistic degrees of freedom at temperatures $T \approx m_2$ (around the A mass)
- In the SM $g_*\,(100 \text{ GeV}) \simeq 100$ and $g_*\,(100 \text{ MeV}) \simeq 10$
- Assuming $\chi \rightarrow$ all DM today i.e. $\Omega_\chi h^2 = 0.11 \rightarrow$ *inverse decay width* of A as

$$\Gamma^{-1}\,(A \rightarrow \chi + B_{\text{SM}}) \sim \left(\frac{m_1}{100\mathrm{GeV}}\right)\left(\frac{200\mathrm{GeV}}{m_2}\right)^2\left(\frac{100}{g_*\,(m_2)}\right)^{3/2} \times 10^6 \ \mathrm{ns} \sim 0.01 \text{ secs}$$

Co-annihiliating DM

- **DM relic abundance** $\rightarrow$ *annihilation between two different species*
- f : SM particle, ψ : BSM LLP, χ : DM particle
- Long lifetime $\rightarrow$ set by a *suppressed phase space*

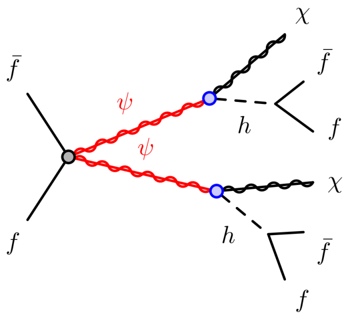
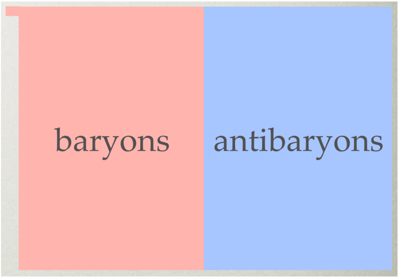


Figure: Feynman diagram for a co-annihilation scenario[1]

Asymmetric DM

- DM particle $\neq$ own antiparticle : relic dark matter density $\rightarrow$ particle-antiparticle asymmetry (Like the Baryon asymmetry)
  - DM production $\rightarrow$ non-thermally (out-of-equilibrium process)
- Easiest scenario for DM production using asymmetry
  - Early universe : Particle species $\psi \rightarrow m_\psi > m_\chi$ with an abundance $\Omega_\psi \rightarrow$ decays to χ

$$\Omega_\chi \simeq \Omega_\psi \frac{m_\chi}{m_\psi}$$



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Signature of "Long-lived particles" at Collider experiments

Detecting Dark-matter

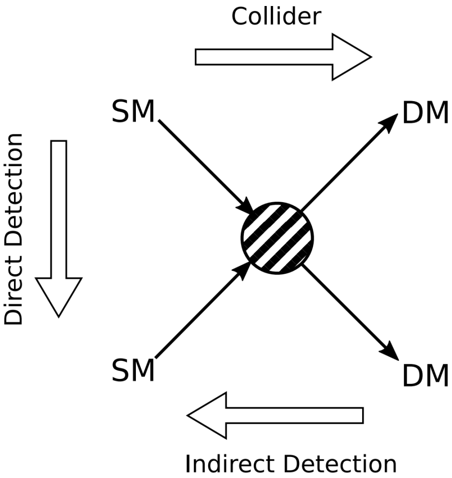

Figure: [3]

Kinematics in a detector

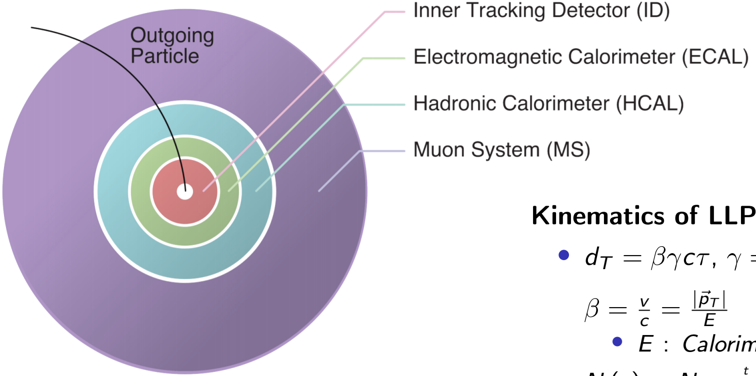

Figure: Not to scale transverse schematic of a typical collider [1]

Kinematics of LLPs [1]

- $d_T = \beta\gamma c\tau$, $\gamma = \frac{E}{m} = \frac{1}{\sqrt{1-\beta^2}}$, $\beta = \frac{v}{c} = \frac{|\vec{p}_T|}{E}$
  - E : *Calorimeter*, $|\vec{p}_T|$: *Track bend*
- $N(t) = N_0 e^{-\frac{t}{\tau}}$
- $P_{\text{dec}} = \frac{1}{4\pi}\int_{\Delta\Omega} d\Omega \int_{L_1}^{L_2} \frac{1}{d} e^{-\frac{L}{d}}$

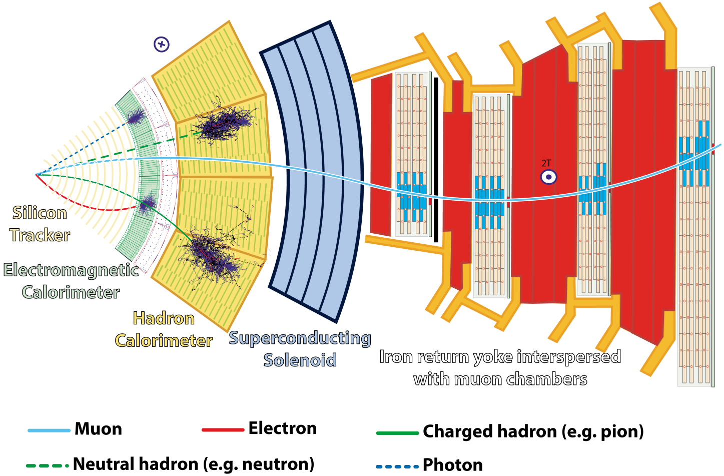

Figure: Cross section of a collider[4]

- Particles produce → region of ionization → solid-state / gaseous detectors → *hits.*
  - Fit into trajectory → *track* → Get charge / momentum

Decays within the tracker

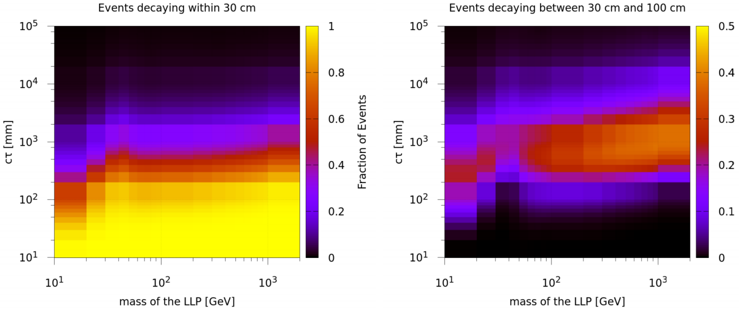

Figure: Fraction of LLPs decaying → Left : within 30 cm, Right : between 30 - 100 cm [2]

- Most theories : Predict lifetimes of LLP $>>$ 25 ns.
- Detect them in conventional subsystems $\xrightarrow{\text{due to}}$ Exponential decay probability

Direct detection : Anomalous Ionization

- CLLP $\rightarrow$ Leaves *track* in ID $\Rightarrow$Direct detection possible
  - If $m_{\text{CLLP}} > m_{\text{proton}} \rightarrow$ Produced with lower β (Compared to : Track forming SM particle)
  - Detect : Slow moving / heavily charged particle $\rightarrow$ Anomalously large $\left\langle \frac{dE}{dx} \right\rangle$
    - Bethe-Bloch formula $\left\langle \frac{dE}{dx} \right\rangle \sim -\frac{z^2}{\beta^2} \cdot \left[\ln\left(\frac{\beta^2}{(1-\beta^2)}\right) - \beta^2 + C \right]$ (Ionization energy lost per unit distance traveled)

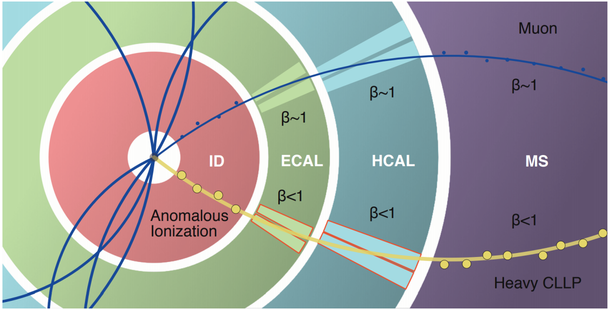

Figure: Anomalous ionization of a heavy CLLP[1]

Indirect detection I : Displaced Tracks

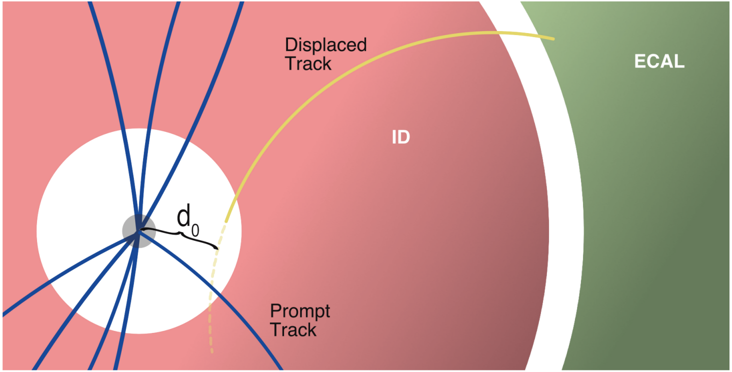

Figure: Displaced track vs Prompt track[1]

- Neutral LLP $\rightarrow$ Transverses some macroscopic distance within ID
  - Decays into charged particle/s $\rightarrow$Leaves a *displaced track* or *a displaced vertex* (next slide)

Indirect detection II : Displaced Vertices

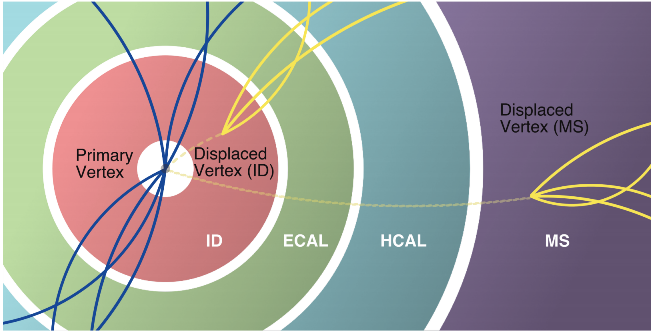

Figure: Displaced vertex vs Prompt vertex[1]

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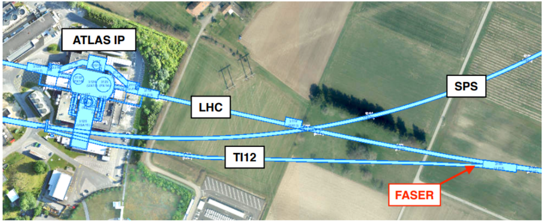
LLP specific detectors

FASER



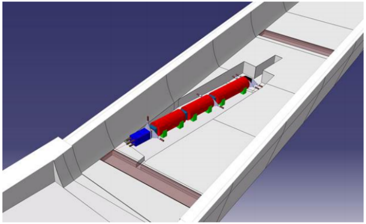


Figure: Left : Location of FASER w.r.t Atlas, Right : View of FASER in a tunnel[7]

- Goal : Detect LLPs / decay products → Transversed $\sim 150m$ (Inagurated May 2021)
- Isolation → Low SM background (Most SM background : near the ATLAS IP)
- New resolution/parameter space → LLP detection.

MATHUSLA

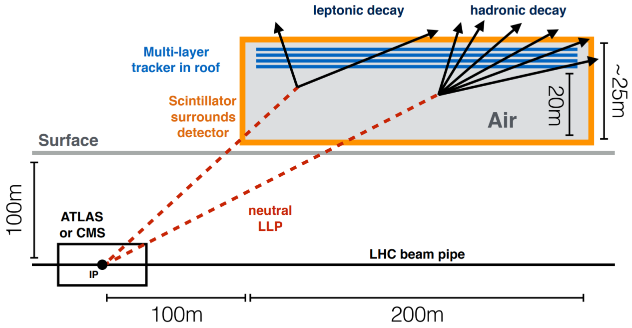


Figure: Schematic of proposed MATHUSLA detector[9]

- $200 \times 200 \times 20\,\text{m}^3$ in size, roughly 100 m above CMS/ATLAS caverns.
- Neutral LLPs : very large lifetimes produced in the collisions $\rightarrow$ decay within the volume of MATHUSLA $\rightarrow$ displaced vertices could be reconstructed

Belle II (e^+e^- collider)

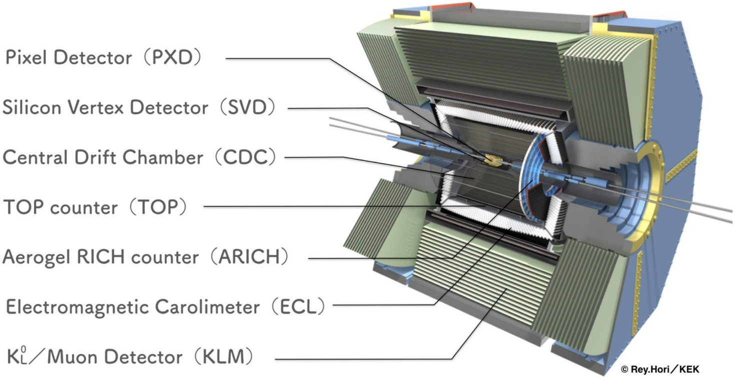


Figure: Schematic of Belle II electron-positron collider[8]

Displaced vertex signatures

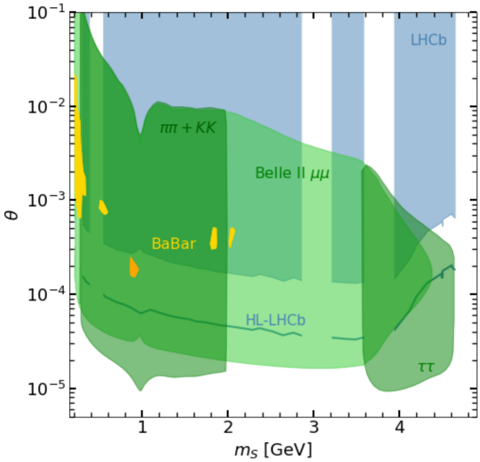
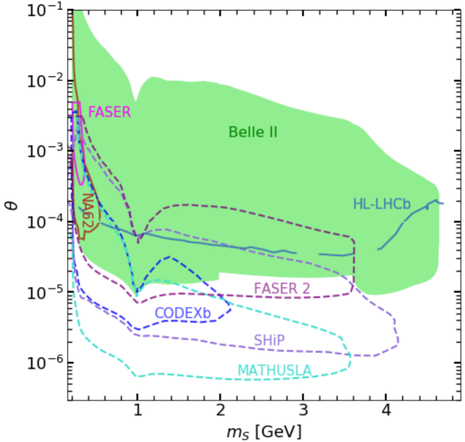


Figure: [10]

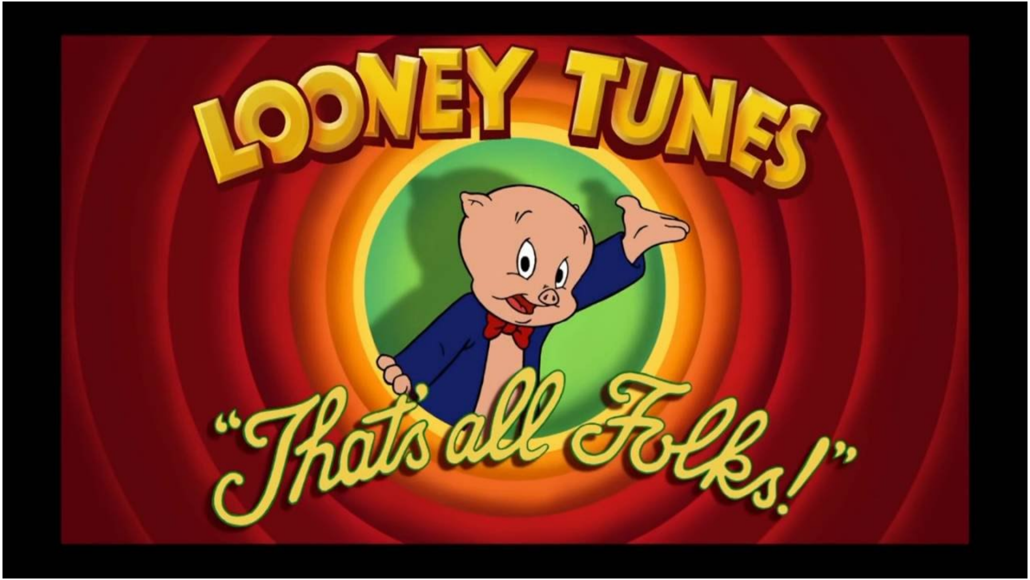


10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
θ
FASER
Belle II
NA62
HL-LHCb
FASER 2
CODEXb
SHiP
MATHUSLA
1
2
3
4
m_S [GeV]

Figure: [10]

Conclusion

- LLPs $\rightarrow$ Natural prediction by many theories.
    - LLP searches important : It is a *strong DM candidate*, also to cover entire *spectrum of DM candidates*
- Increase chances of LLP detection,
    - *Low SM backgrounds*
    - Extra detectors : *far-distance* from collision point $\rightarrow$ *decay products* get an opportunity to be detected
- Very young field : huge potential for discovering different aspects of BSM, both theoretically and experimentally


LOONEY TUNES
"That's all Folks!"

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