

Long-lived particles

Lecture 2: how to search for long-lived particles

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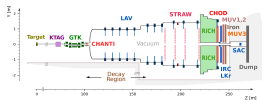
1 Experiments and signatures

2 Signal-event estimation

3 Conclusions

Various terrestrial experiments for LLP searches

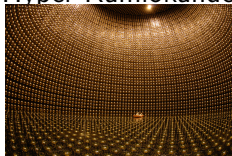
- **Beam dumps:** PS191, NA62, SHiP, DUNE, ...
- **Colliders:** LEP, BABAR, Belle II, LHC, ...
- **LHC far detectors:** FASER(2), MoEDAL-MAPP1(2), MATHUSLA, CODEX-b, ...
- **Neutrino detectors:** Super-Kamiokande, Hyper-Kamiokande, ...
- ...



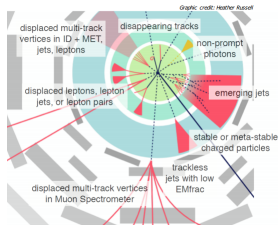
NA62



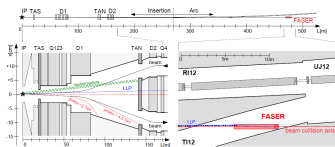
SHiP
Search for Hidden Particles



Super-K



ATLAS/CMS

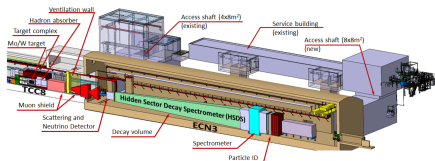


FASER

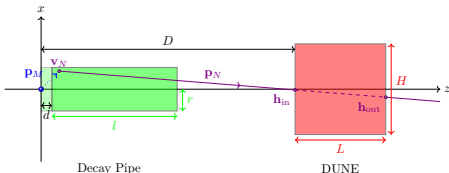


Belle II

Proton beam-dump experiments



SHiP

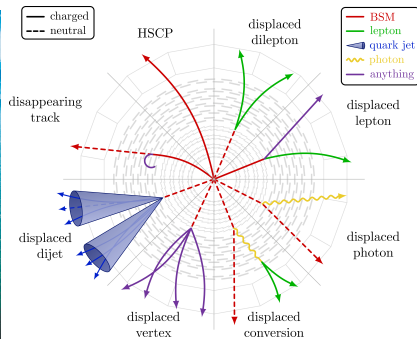
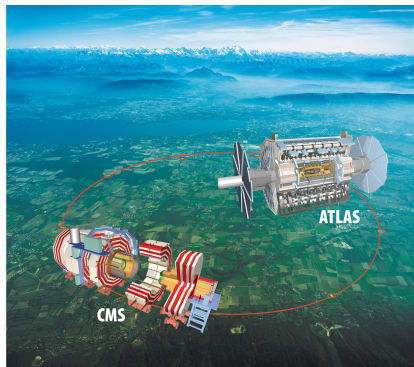


DUNE-ND

Experiment	POT/year	No. of years	E_p [GeV]	\sqrt{s} [GeV]	D [m]	L [m]
SHiP	4×10^{19}	15	400	27.4	33	50
DUNE-ND	1.1×10^{21}	10	120	15.0	574	6.4

- SHiP to start data collection in 2031, DUNE (?)

ATLAS and CMS



Sketch by J. Antonelli

- Symmetric pp collisions at $\sqrt{s} = 13\text{--}14$ TeV
- HL-LHC to have collected 3000 fb^{-1} int. lumi around 2041.

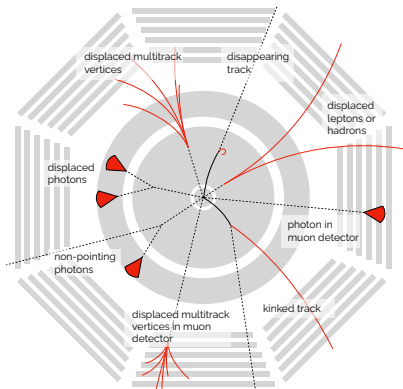
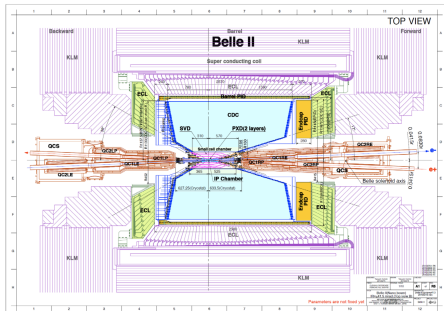
Meson production at the HL-LHC, DUNE, and SHiP

Meson M	N_M (LHC)	N_M (DUNE)	N_M (SHiP)
K^\pm	2.38×10^{18}	5.76×10^{21}	5.7×10^{19}
K_L	1.31×10^{18}	5.76×10^{21}	5.7×10^{19}
K_S	1.31×10^{18}	5.76×10^{21}	5.7×10^{19}
D^\pm	2.04×10^{16}	2.28×10^{17}	4.2×10^{17}
D^0	3.89×10^{16}	6.95×10^{17}	1.3×10^{18}
D_s^\pm	6.62×10^{15}	9.68×10^{16}	1.8×10^{17}
B^\pm	1.46×10^{15}	4.46×10^{11}	8.1×10^{13}
B^0	1.46×10^{15}	4.46×10^{11}	8.1×10^{13}
B_s^0	2.53×10^{14}	1.11×10^{11}	2.2×10^{13}

Table 3 in [de Vries, Dreiner, Groot, Günther, ZSW 2025 \(JHEP04\(2025\)007\)](#)

- 4π solid angle
- LHC: 14 TeV, 3 ab^{-1}
- DUNE: 120 GeV, 1.1×10^{22} POTs
- SHiP: 400 GeV, 6×10^{20} POTs

- Ongoing *B*-factory experiment at the SuperKEKB collider in Japan
 - Energy-asymmetric collisions mainly at $E_{e^-} = 7 \text{ GeV}$ & $E_{e^+} = 4 \text{ GeV}$
- $\Rightarrow \sqrt{s} = 10.58 \text{ GeV}$ at $\Upsilon(4S) \rightarrow B\bar{B}$
- $\mathcal{L}_{\text{int.}} = 50 \text{ ab}^{-1} \Rightarrow N_{e^-e^+ \rightarrow \tau^-\tau^+} = 4.6 \times 10^{10}$ & $N_{B\bar{B}} = 5.5 \times 10^{10}$
 - LLP search: so far mainly using *vertex detector* and *tracker*



Comparison of the experiments

category	exp.	best prod. modes & mass	appr. or run.	forw. boost used	bgd	others
proton BDE	SHiP	D -decays	Y	Y	low/zero	
	DUNE	K -decays	Y	Y	low/zero	
LHC MDs	ATLAS/CMS	Direct prod., 10's to 100's GeV	Y	avoided	low	high pileup
LHC FDs	Transverse	B - & W -decays	partly	Y	low/zero	
	Forward	D , K , π , η , ... decays	partly			
Low- E e^+e^- col.	Belle II	B & τ decays, direct prod.	Y	N	low	low PU, no PDF \Rightarrow full recon.

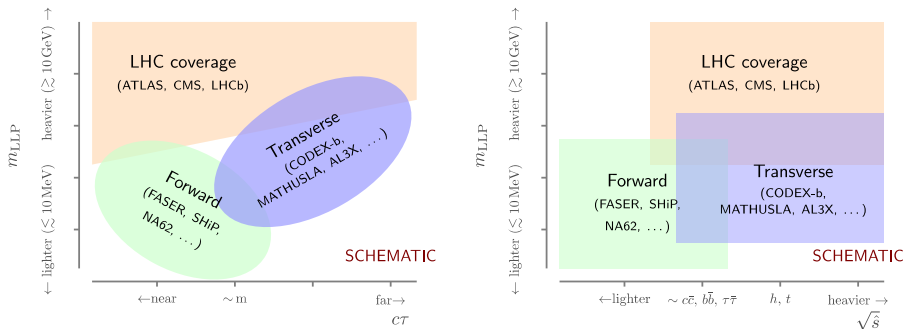


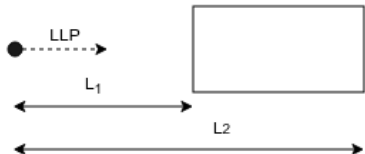
Figure 1 in [EPJC80\(2020\)12,1177 \(EOI CODEX-b\)](#)

General computation procedure

$$N_S = N_{\text{LLP}} \cdot A \cdot \epsilon$$

- N_{LLP} : production rates of the LLP

- A : acceptance $\sim e^{\frac{L_1}{\beta\gamma ct}} - e^{\frac{L_2}{\beta\gamma ct}}$
 $\sim e^{\frac{L_1}{\beta\gamma ct}} (1 - e^{\frac{L_2-L_1}{\beta\gamma ct}})$



- ϵ : detector efficiencies
- $N_B = 0 \Rightarrow N_S = 3$ for 95% C.L. exclusion limits
- $N_B \gg 1 \Rightarrow N_S = 2\sqrt{N_B}$ for 95% C.L. exclusion limits
- A and ϵ estimated with **Monte Carlo simulations**, mostly
- Tools: MadGraph5, Pythia8, FastJet3, DDC, ...

Conclusions

- Experiments to search for LLPs:
 - beam-dump experiments
 - collider main detector
 - LHC far detectors
- Detectors, geometries, CT of LLP, kinematics, production mechanisms. . .
- Computation of signal-event numbers, acceptance, detector efficiencies, backgrounds, tools. . .