Long-Lived and Feebly Interacting Particles

José Francisco Zurita

Muon Collider Physics and Detector Workshop, Zoom, 02.06.2021

Outline

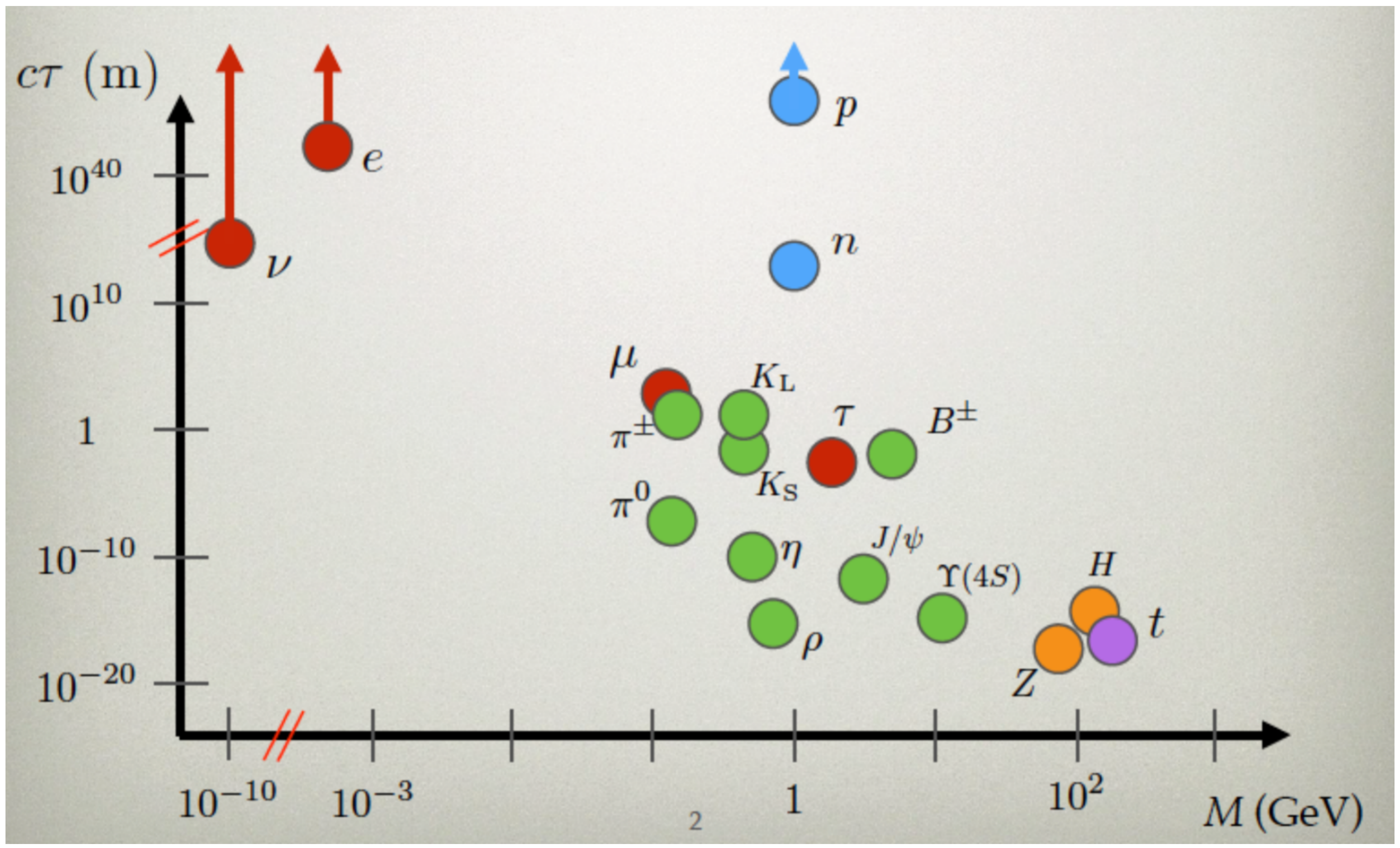
- Long-Lived Particles (LLPs)
  & Feebly-Interactive Particles (FIPs)
  (what, why, how?)
- LLPs in action:
  Disappearing tracks @ Muon Collider
- Lessons learned

Long-Lived Particles (LLPs)

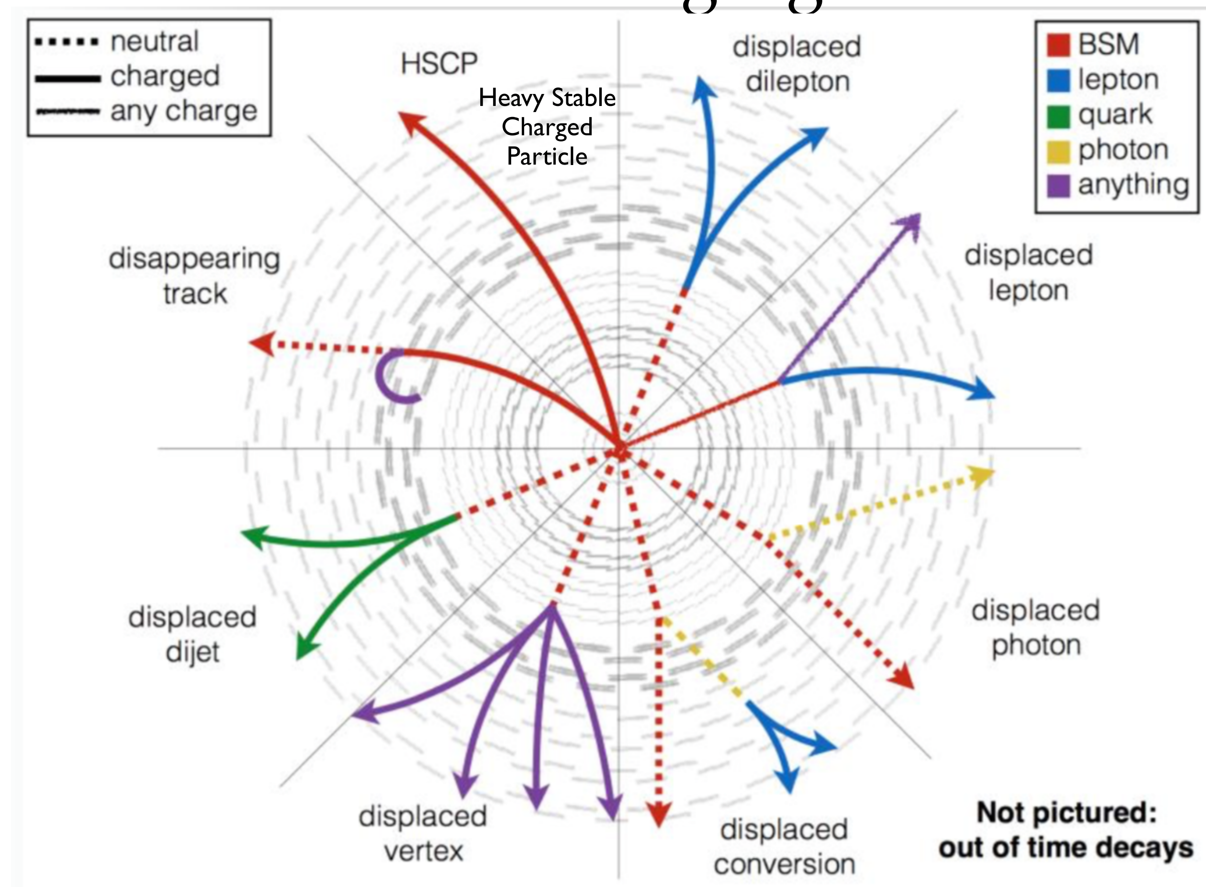
Long-Lived Particles (LLPs)

- LLPs: New Particles with macroscopic lifetimes (τ~ns, cτ~cm), theoretically well motivated.

Exist in the SM!



A lot of interesting signatures!



large cτ, small Γ

- Large mass hierarchies
- Compressed spectra
- Small couplings

EW Baryogenesis
Dark Matter
Hierarchy Problem
Neutrino Masses

BSM Models: Supersymmetry, dark QCD, RH neutrinos , Neutral Naturalness, Higgs Portal, Z′ Portal, Hidden Valleys, …

LLP signatures-> arXiv:1903.04497 ; LLP theory motivations-> arXiv 1806.07396

LLP-Genesis (Lessons from the [B]SM)

3 mechanisms to get large cτ / small Γ

$$\left(\frac{c\tau}{\mathrm{mm}}\right) = 1.98 \times 10^{-16} \left(\frac{\mathrm{GeV}}{\Gamma}\right)$$

1) Large mass hierarchies/off-shell mediator: heavy E scale

muon

$$c\tau(\mu \to e\nu) = \frac{1.2 \text{ fm}}{g_X^4}\left(\frac{m_e}{m_\mu}\right)^4\left(\frac{1 \text{ TeV}}{m_\mu}\right) \sim 1 \text{ cm}$$

- $m_e = 10\mathrm{GeV}, \mathrm{m}_\mu = 100 \text{ GeV}, \mathrm{g}_\mathrm{X}^4 = 10^{-7}$ RH neutrinos
- $m_e = 10 \text{ GeV}, \mathrm{m}_\mu = 1 \text{ TeV}, \mathrm{g}_\mathrm{X}^4 = 10^{-3}$ Hidden Valleys

2) Compressed spectra: Object reconstruction, thresholds

neutron

$$c\tau(n \to pe\nu) \sim \frac{1.2 \text{ fm}}{g_X^4}\left(\frac{m_p}{m_n - m_p}\right)^4\left(\frac{1 \text{ TeV}}{m_n - m_p}\right) \sim 1 \text{ cm}$$

SUSY

$m_n = 101 \text{ GeV}, \mathrm{m_p} = 100 \text{ GeV}, \mathrm{g}_\mathrm{X}^4 = 10^{-2}$

3) Tiny coupling: Low rates

Z′ / dark photon

$$c\tau(Z \to \nu\nu) \sim \frac{0.02 \text{ fm}}{g_Z^4}\left(\frac{1 \text{ TeV}}{m_Z}\right) \sim 1 \text{ cm}$$

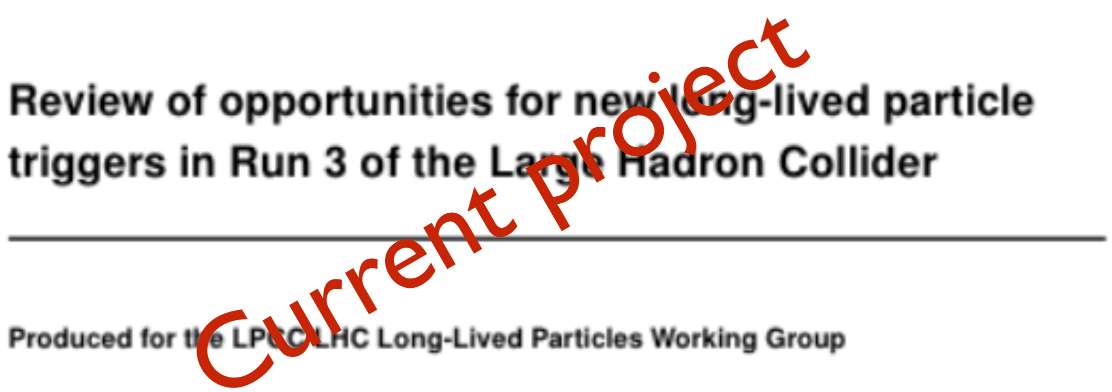
$m_Z = 1 \text{ GeV}, \ \mathrm{g}_\mathrm{Z}^2 = 10^{-12}$ $\mathrm{Z_D}$ models

LLP WG & Community

The ***LLP Working Group*** (within LHC Physics Centre, kicked-off May 2020) aims at facilitating communication between the LHC experiments and TH, providing recommendations for benchmark models and result presentations, development/validation of tools, discussing new search directions based on TH/EXP input.

Convenors: James Beacham, Sascha Mehlhase (ATLAS), Juliette Alimena, Albert de Roeck (CMS), Federico Leo Redi, Carlos Vázquez Sierra (LHCb), James Pinfold (MoEDAL), Dave Casper (FASER), Nishita Desai, José Zurita (Theory)

https://lpcc.web.cern.ch/lhc-llp-wg

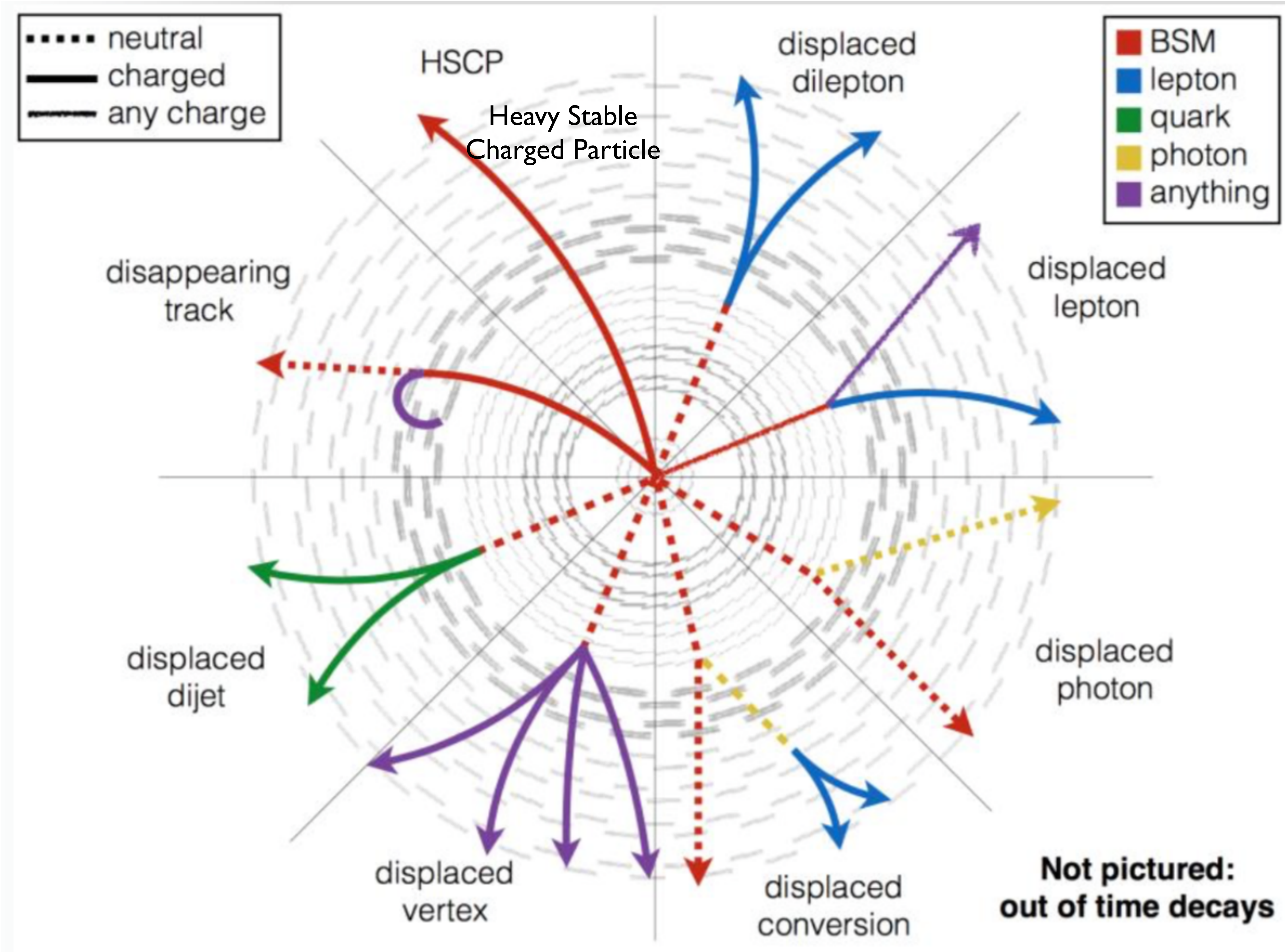


We also contacted other WGs (we met with DMWG!) and have other projects under consideration.

The ***LLP Community*** is a group of scientists interested in the exploration of long-lived signatures at colliders (not only LHC!) and beyond, operating since 2016. It organises two yearly workshops where new results are presented, and topics of relevance are discussed in an informal atmosphere.
Most of these discussions summarised in LLP@LHC White Paper, arXiv 1903.04497 *J.Phys.G* 47 (2020) 9, 090501.
Large community effort (21 editors, 201 signatories imply a broad range of topics).
Ongoing work on several topics (pushing forward the LLP frontiers!)

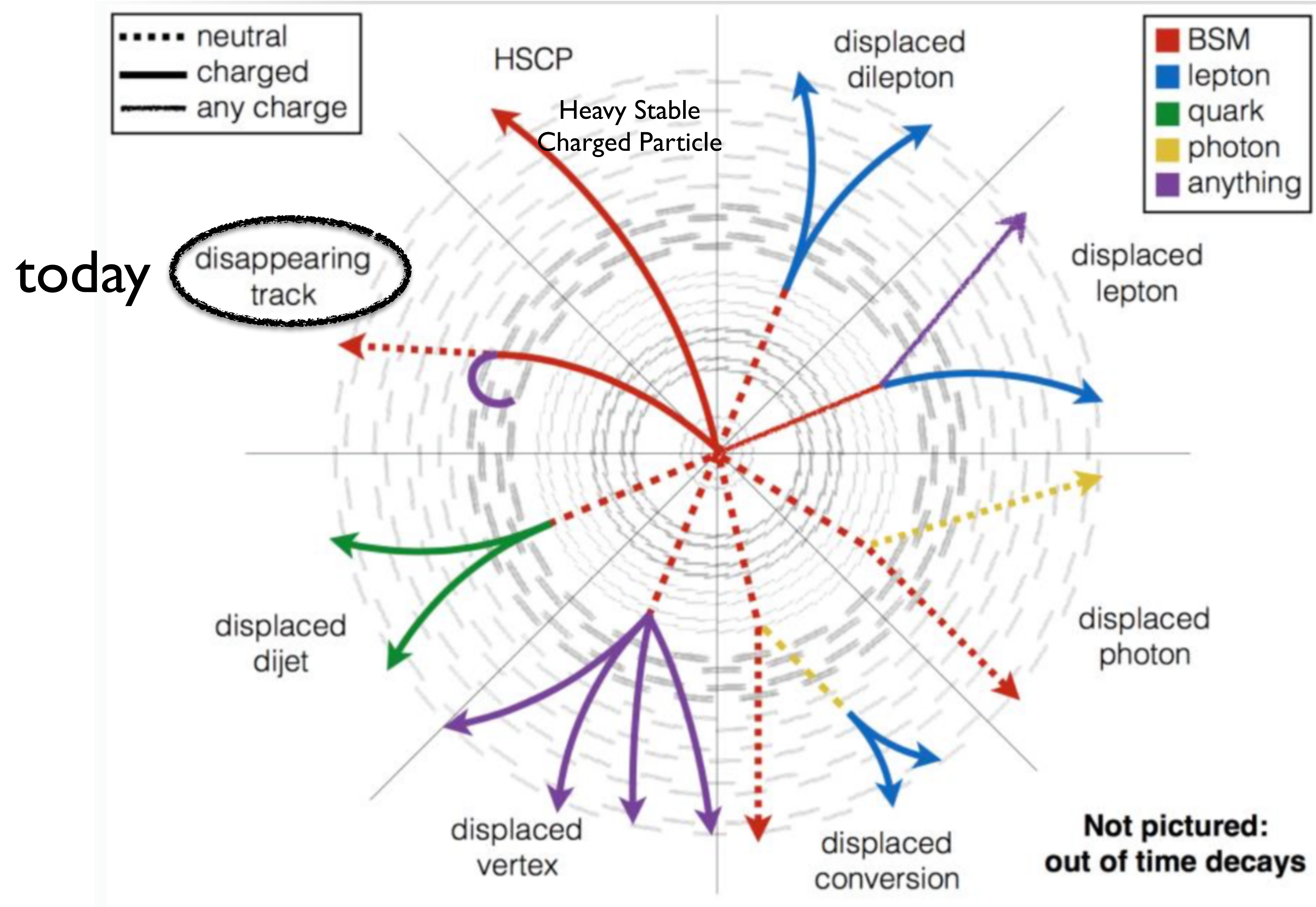
https://longlivedparticles.web.cern.ch

LLP >>>> DVs!



+ dark showers: emerging jets (1502.05409), semi visible jets (1503.00009), SUEPs (1612.00850), …

LLP >>>> DVs!



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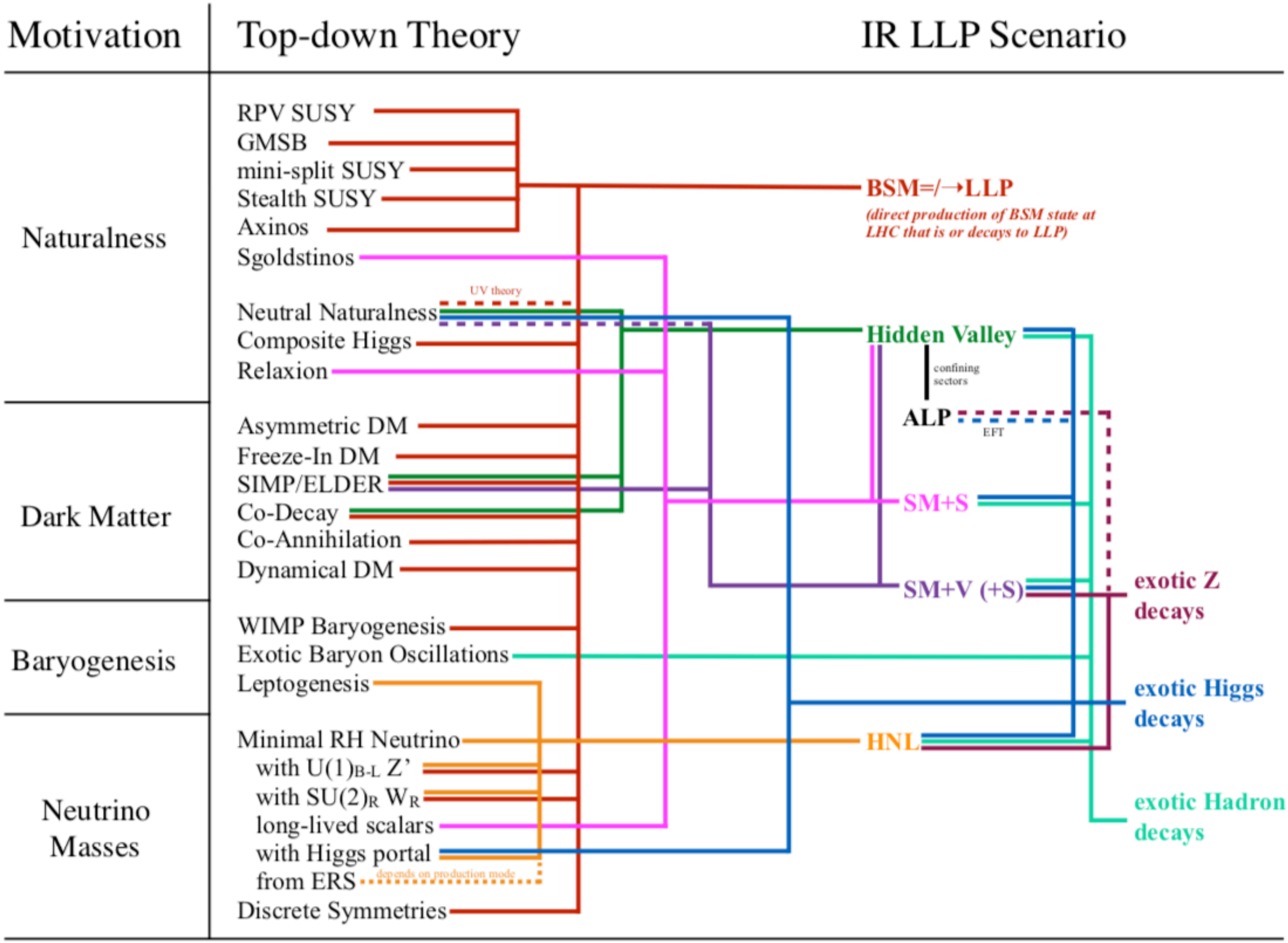
LLP Theory Chart



Curtin et al, arXiv 1806.07396, *Rept.Prog.Phys.* 82 (2019) 11, 116201

Challenges in LLP-Realm

Problem: original LHC detectors not built with LLPs as main target (except LHCb)

a) *Triggers*: Existing menu not optimal for LLPs: LLP WG already into this!

→ Upgrades!

b) *Analysis Strategies*: Within experiments, a lot of creativity is needed!

c) *Reinterpretation*: Use search based on model X to set constraints on model Y. Particularly difficult since i) there is no standard definition of LLP objects, and ii) LLP backgrounds are often not possible to simulate with Monte Carlo.

d) *New signatures*: *dark showers* (emerging jets, semi-visible jets, dark jets, etc) Important ongoing activities in LLP Community & Snowmass.

e) *New Experiments*: Place external detectors to catch all LLPs produced at LHC.

- FASER is an official LHC experiment (proposed Aug 2017, approved Mar 2019).
- SND@LHC (forward direction, approved March 12th 2021).
- Other proposals updating EoI, TDRs (MATHUSLA, Codex-B, ANUBIS, MilliQan, …).
- Proposal to build a Forward Physics Facility (FPF).

Feebly-Interacting Particles (FIPs)

Portals into New Physics

- How to couple light degrees of freedom to the SM while being consistent with all possible constraints (e.g: LEP, Tevatron, EDMs, LHC, flavor…)?

- Idea: add new particle feebly coupled to the SM via a portal term.
  FIPs= Feebly Interacting Particles

$$\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_{portal} + \mathcal{L}_{\mathcal{NP}}$$

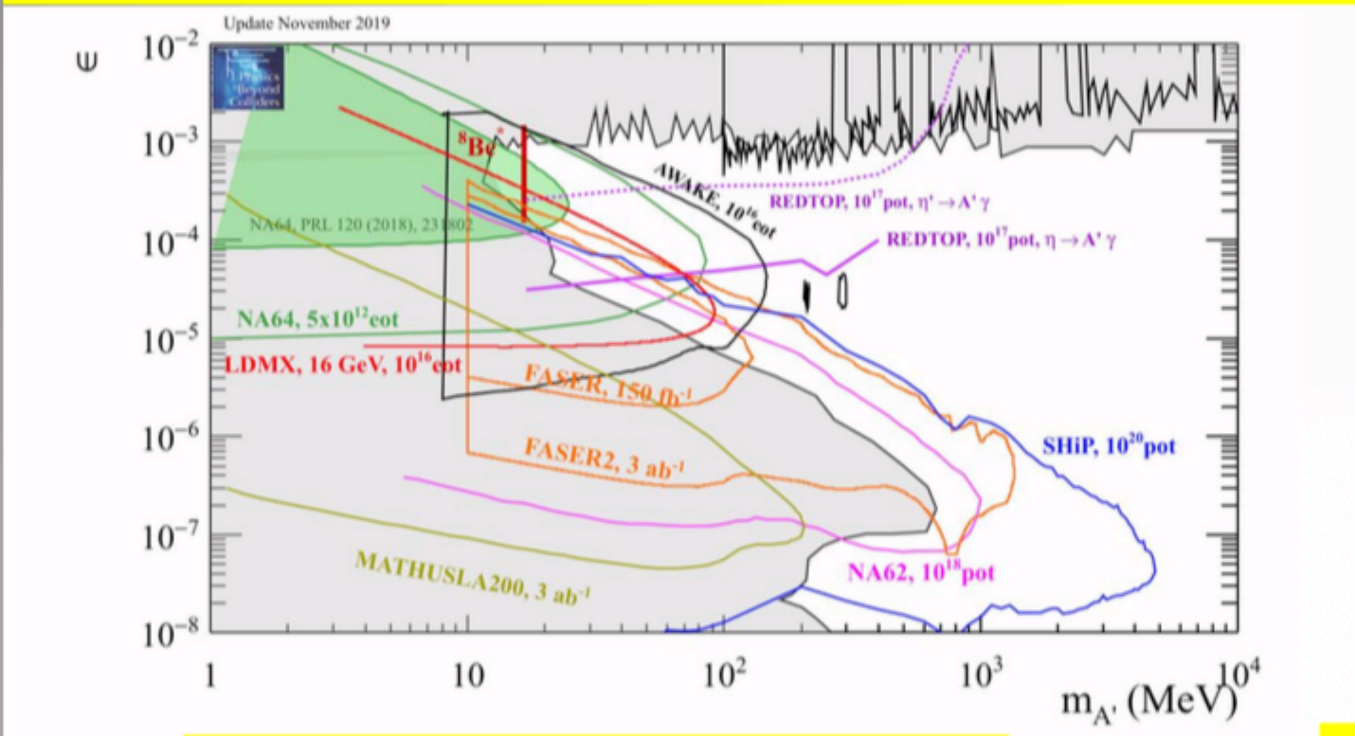
→ Encodes interaction of SM fields and new particles

Field	Lagrangian	Phenomenology
Scalar S:	$\mathcal{L}_S \supset \mu S H^\dagger H + \lambda S^2 H^\dagger H$	Exotic Higgs decays
Vector A′:	$\mathcal{L}_{A'_\mu} \supset \epsilon F'_{\mu\nu} B_{\mu\nu}$	Dark photon/Z′
Fermion N:	$\mathcal{L}_N \supset y_{ai}(L_a H) N^i$	HNL (ν masses)
Pseudoscalar	$\mathcal{L}_a \supset a \left(\frac{F_{\mu\nu}\widetilde{F}^{\mu\nu}}{4f_\gamma} + \frac{G_{\mu\nu}\widetilde{G}^{\mu\nu}}{4f_g} \right) + \frac{\partial^\mu a}{f_f} \bar{f}_i \gamma^\mu \gamma^5 f^i$	ALPs

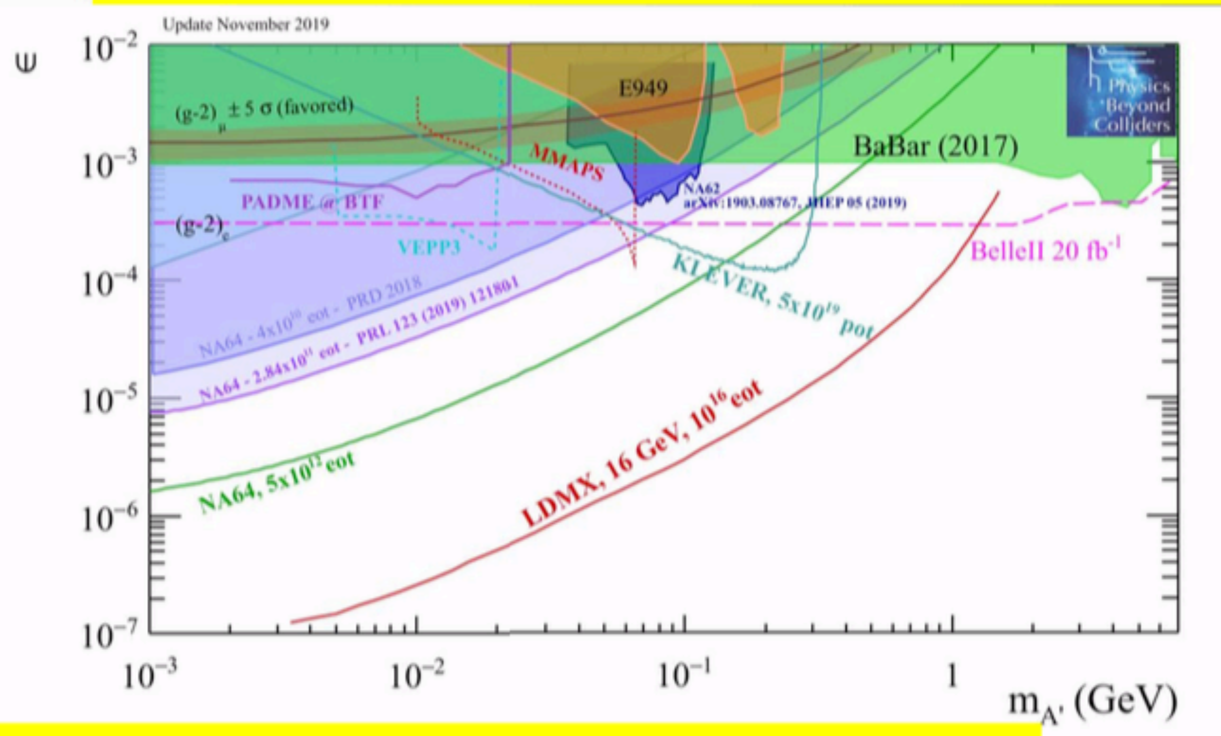
Physics Beyond Colliders Report, Beacham et al, 1901.09966
FIPs 2020 Workshop Report, Agrawal et al, 2102.12143

Results for portal models

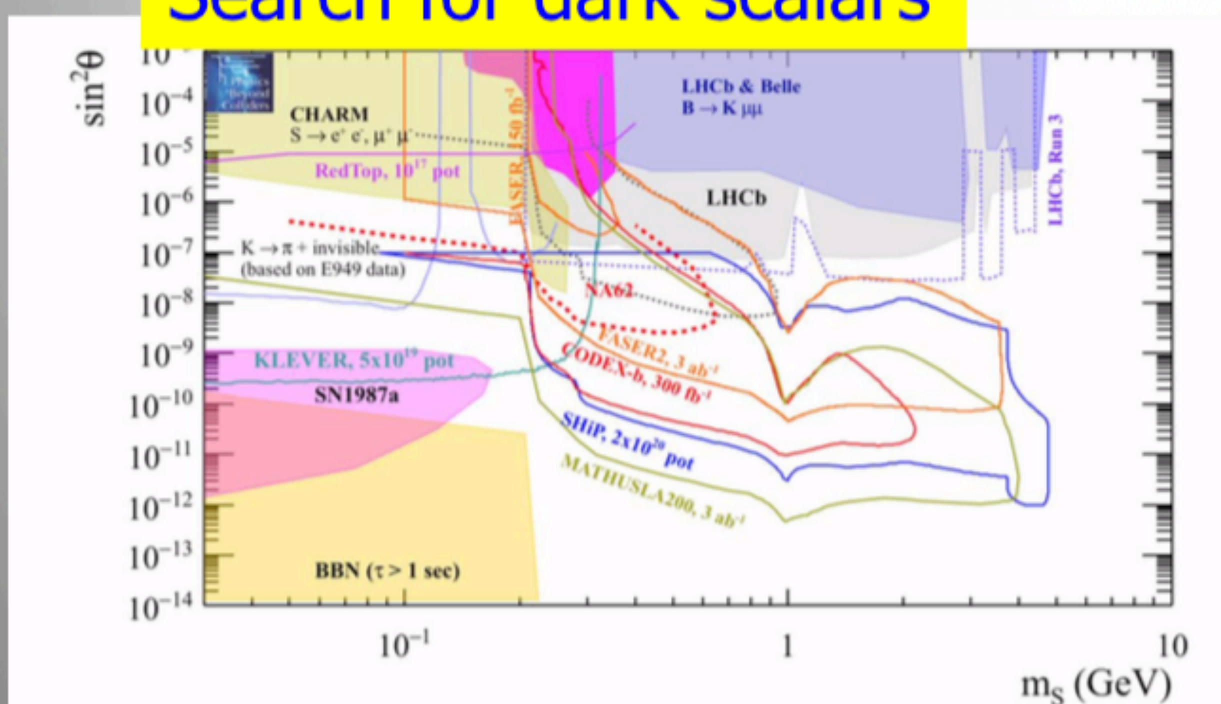
Search for dark photons (visible mode)



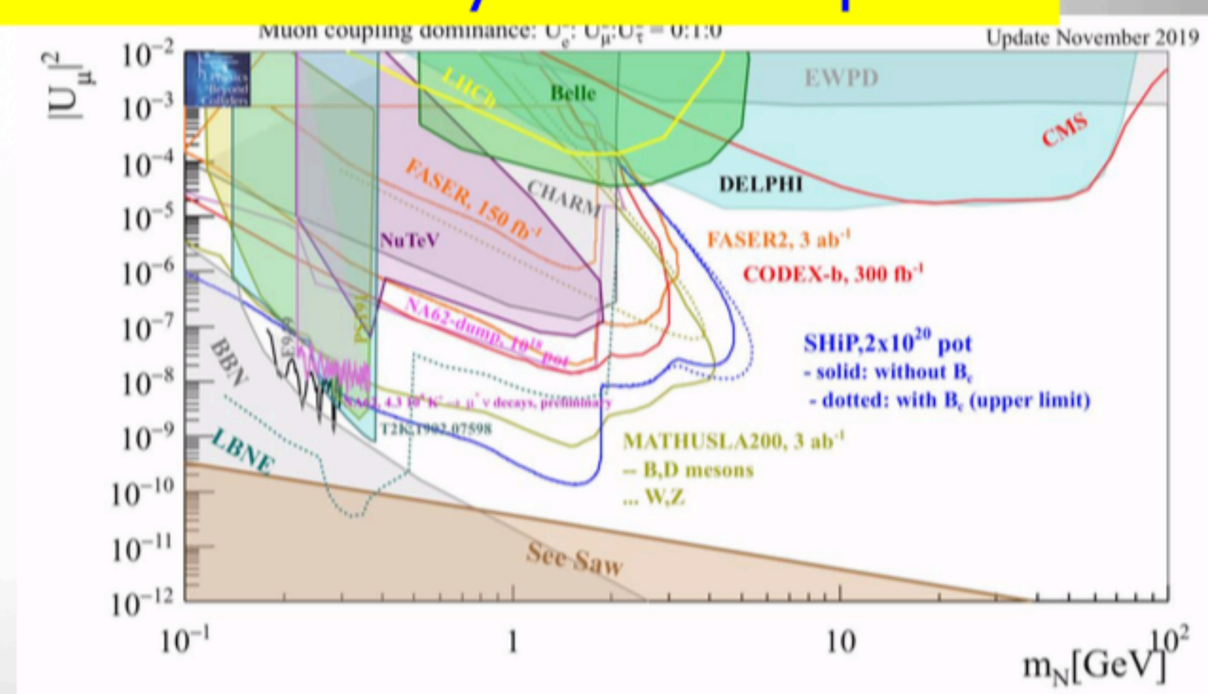
Search for dark photons (invisible)



Search for dark scalars



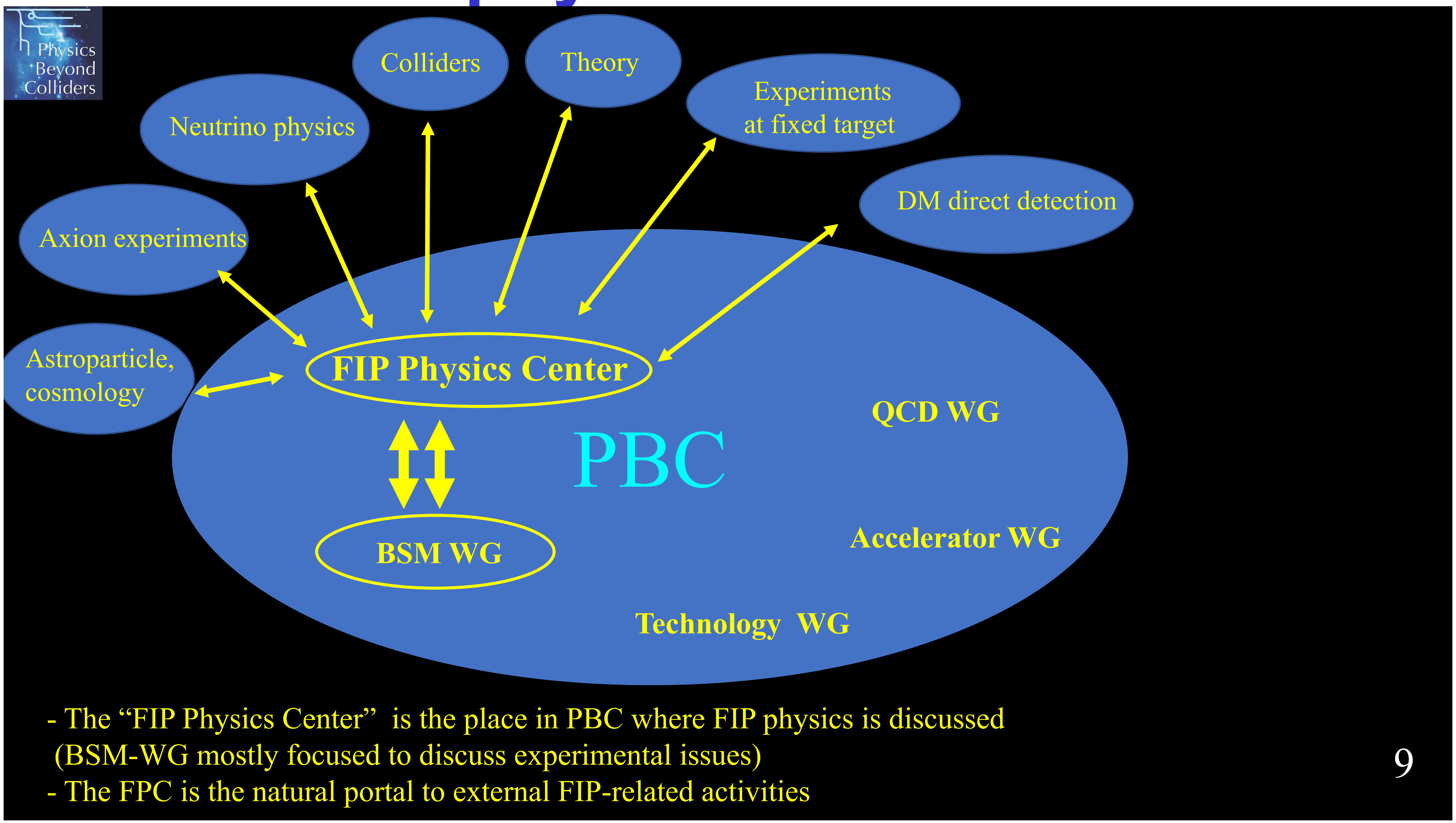
Search for heavy neutral leptons



A. de Roeck, STEALTH@LHCb 2020

Future of FIPS

FIP physics center idea



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M. Pospelov, Searching for long-lived particles at the LHC and beyond: Ninth workshop of the LLP Community

LLPs in action:
Disappearing tracks @ Muon Collider

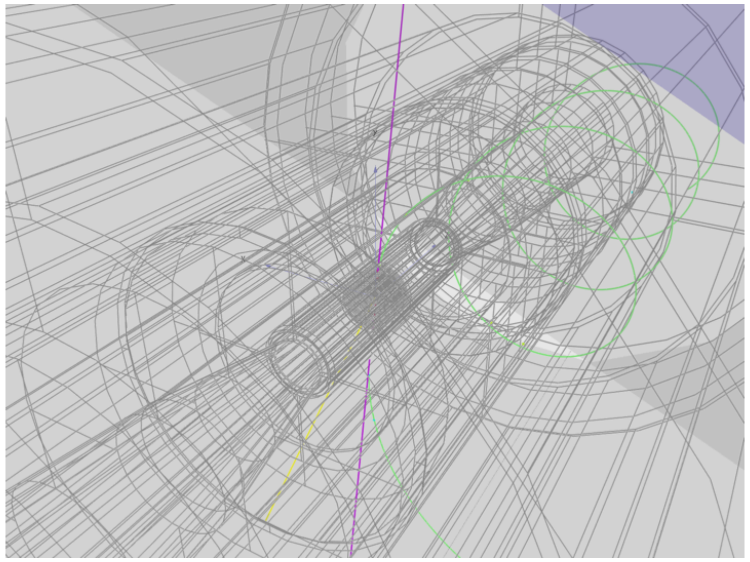
R. Capdevilla, F. Meloni, R. Simoniello, JZ, arXiv 2102.11292

LLPs@MuC

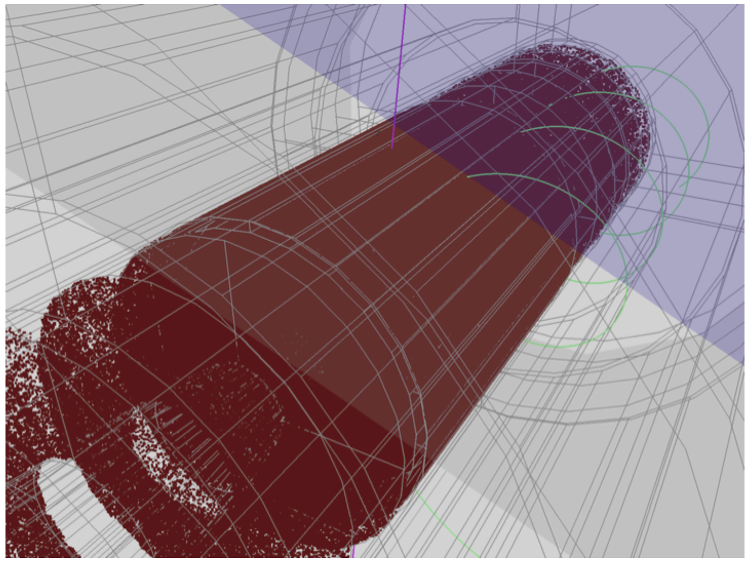
- Which advantages can a MuC give for LLPs? Folklore: "A lepton collider is clean…"

- MuC is not clean for LLPs (~4x10^5 μ/m, give or take…). Roll up the sleeves!

<u>signal event display</u>



BIB off



BIB on

Credit: F. Meloni

Pure electroweakinos

Thomas, Wells, hep-ph/9804359,
Cirelli, Formengo, Strumia, hep-ph/051209

Since EW symmetry is broken, in an EW multiplet neutral components correct their masses due to Z-loops, charged components also have W, γ-loops.

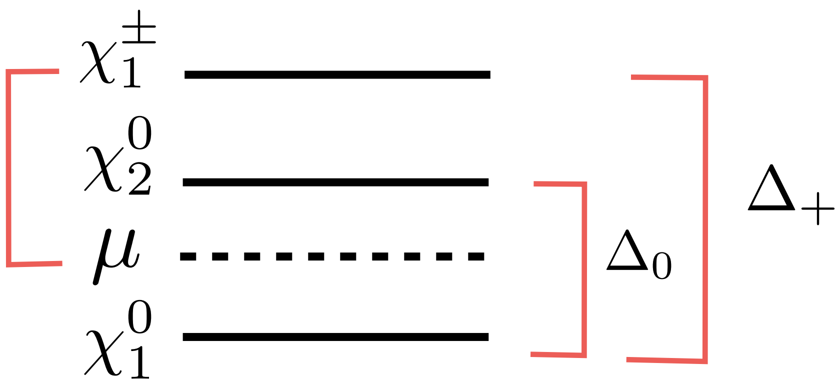
	$\Delta_{1-\mathrm{loop}}$ [MeV]	$c\tau$ [mm]
$\widetilde{H}$	335	6.7
$\widetilde{W}$	165	68

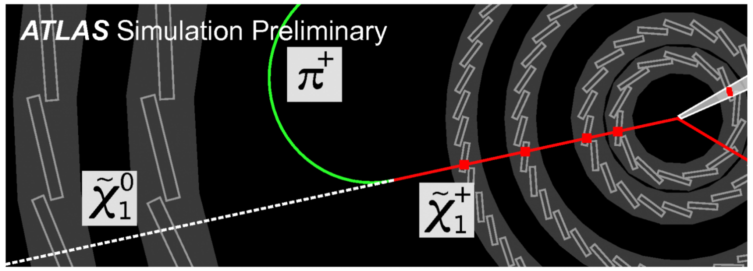
Higgsino: Expanding in $\mu/M_1, m/M_1$

BR $(\chi_1^\pm \to \pi^\pm \chi_0^{(1)}) \sim 97\%$.

$$M = \begin{pmatrix} M_1 & -mc_\beta & ms_\beta \\ -mc_\beta & 0 & \mp\mu \\ ms_\beta & \mp\mu & 0 \end{pmatrix}$$

335 MeV





$$m = m_Z s_W \approx 43.8 \text{ GeV}$$

$$\Delta_0 = \frac{192 \text{ MeV}}{(M_1/10 \text{ TeV})} + \mathcal{O}\left(\frac{|\mu|}{M_1}, \frac{m}{M_1}\right) \qquad \Delta_+ = \Delta_{1-\mathrm{loop}} + \frac{96 \text{ MeV}(1 \mp s_{2\beta})}{(M_1/10 \text{ TeV})} + \mathcal{O}\left(\frac{|\mu|}{M_1}, \frac{m}{M_1}\right)$$

Δ_0 < 100 KeV gives inelastic scattering in direct detection → M_1 < 20 PeV.

At pp colliders π⁺ gets lost in hadronic noise.
The signature is a charged track (χ^+) decaying into missing energy (χ^0): *disappearing track.*

TeV "pure" Electroweakinos: MSSM's last stand

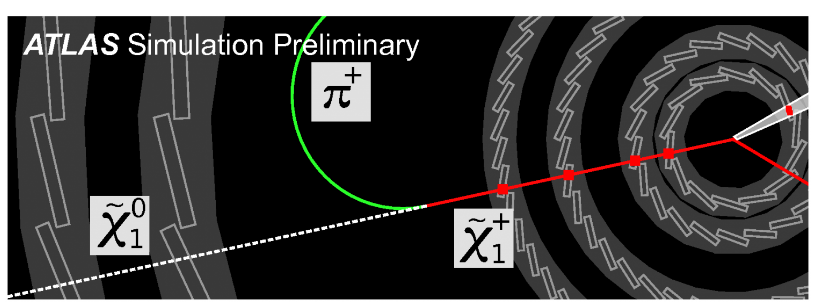
- The neutralino is the MSSM DM candidate, made out of Bino, Wino and Higgsino*.
- Relic density sets "pure" masses: $\tilde{B}$(100 GeV), $\tilde{W}$(2.7 TeV), $\tilde{H}$ (1.1 TeV).

Since EW symmetry is broken, in an EW multiplet neutral components correct their masses due to Z-loops, charged components also have W, γ-loops.

Y	c τ [mm]	Δ_+ [MeV]
0	6.6	160
1/2	68	340

At pp colliders π^+ gets <u>lost in hadronic noise</u>. The signature is a charged track (χ^+) decaying into missing energy (χ^0): *disappearing track.*

$$\chi^\pm \to \chi^0 + \pi^\pm$$

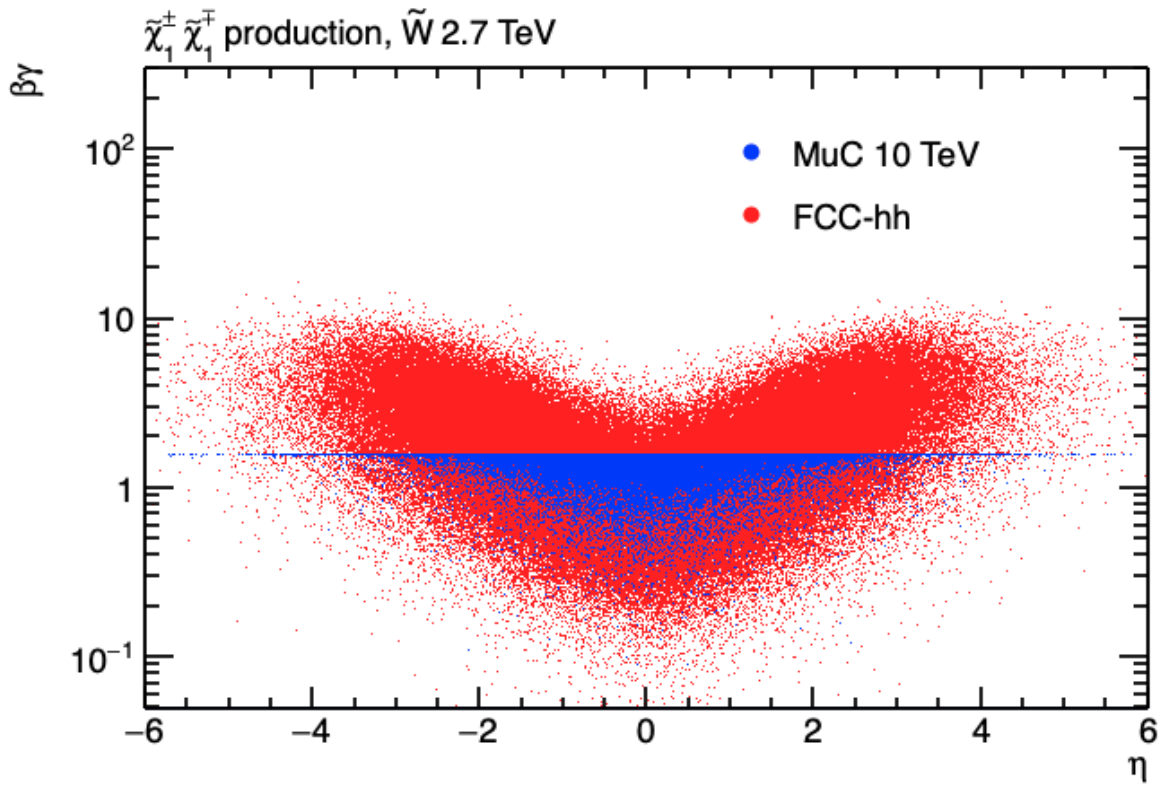


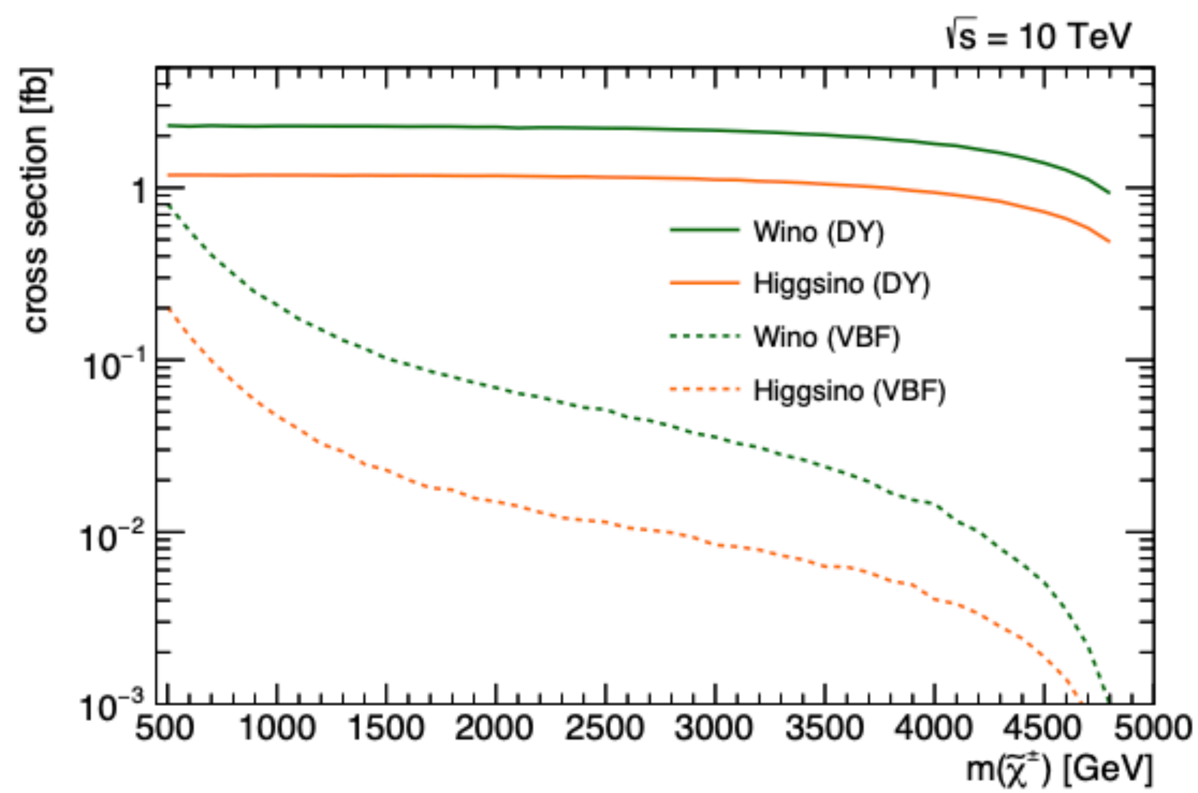
Popular benchmark: studied for several future colliders (see European Strategy Physics Briefing Book, 1910.11775)

* A pure Higgsino, EW doublet, is ruled out, because both neutral states are mass degenerate, and the Z-n1-n2 coupling is actually Z-n1-n1. Z currents with weak couplings are excluded by direct detection experiments (XENON100, LUX, etc). Some additional Bino and/or Wino component is required.

DTs@MuC

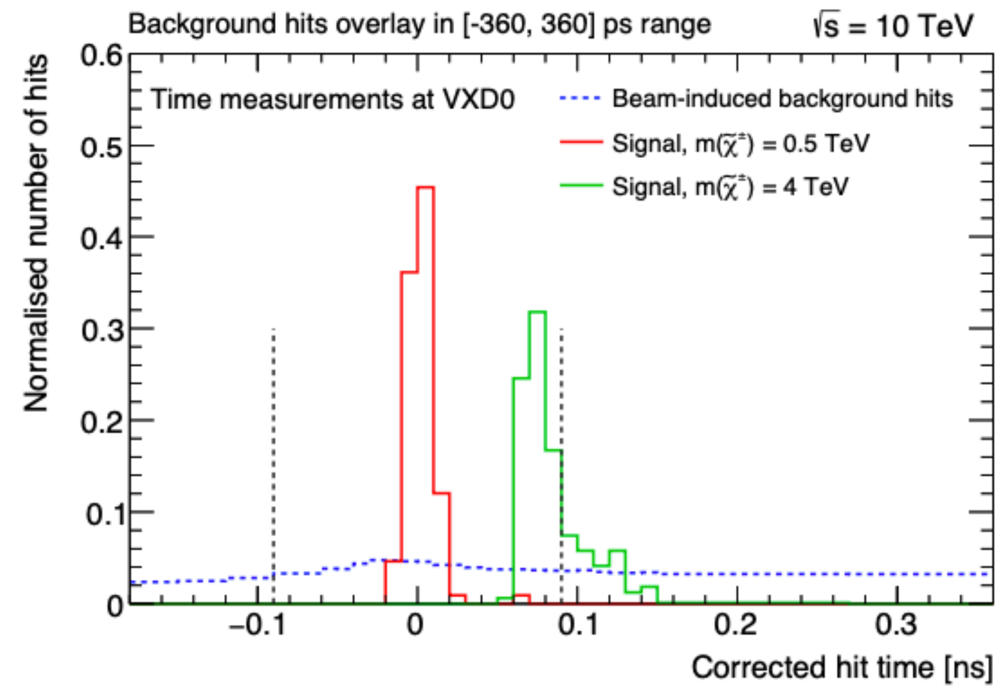
- Pair production of EWkinos is more central and less spread.
- About 10K events $\chi^{\pm}\,\chi^{\mp}$ at MuC 10 (MuC 3 has 1/10 less luminosity, 10 XS).

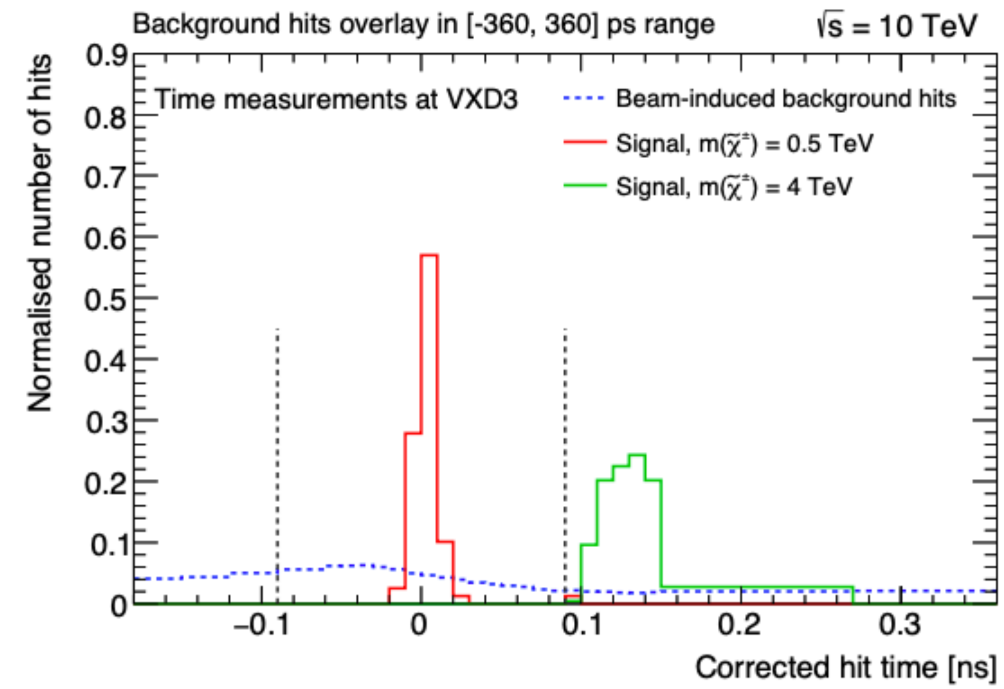




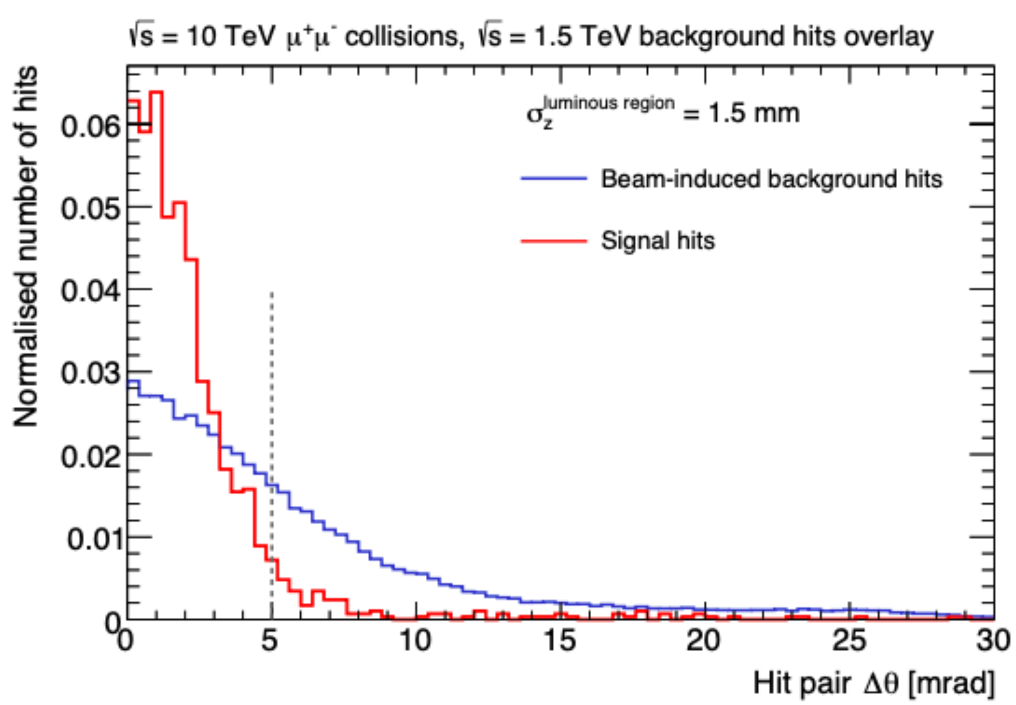
- Existing BIB simulation at 1.5 TeV CME (conservative estimate). 3 step plan:
  - #1: Reduce hits by a) timing and b) spatial correlations in double layer hits.
  - #2: Perform tracking imposing quality criteria (d0, good track fit, no holes).
  - #3: Collider analysis.

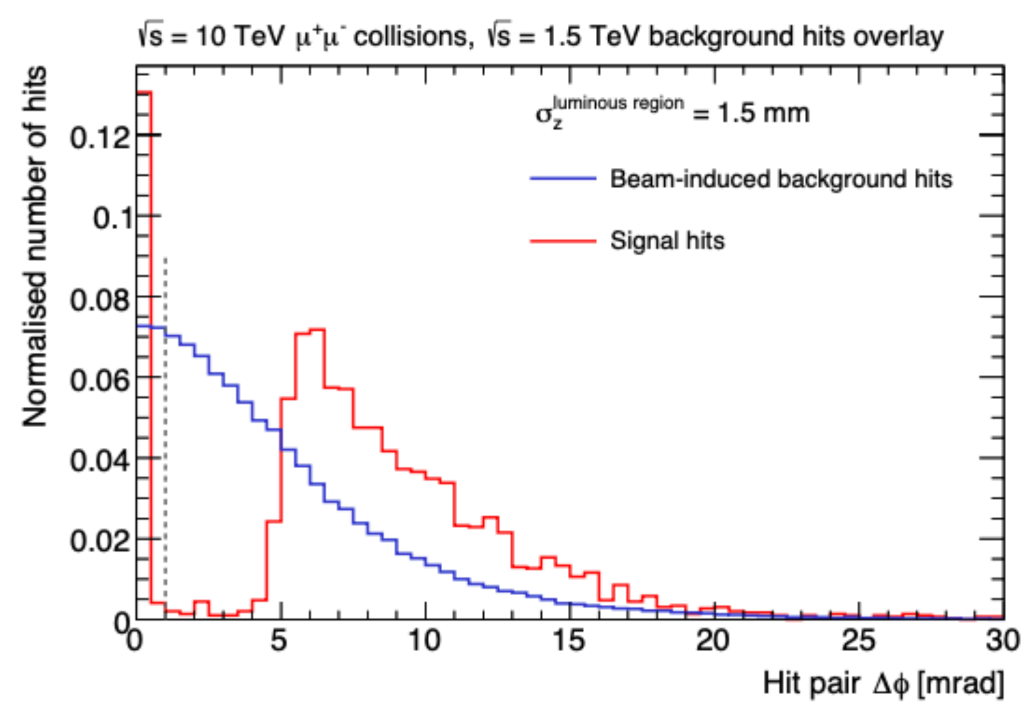
Reducing hits





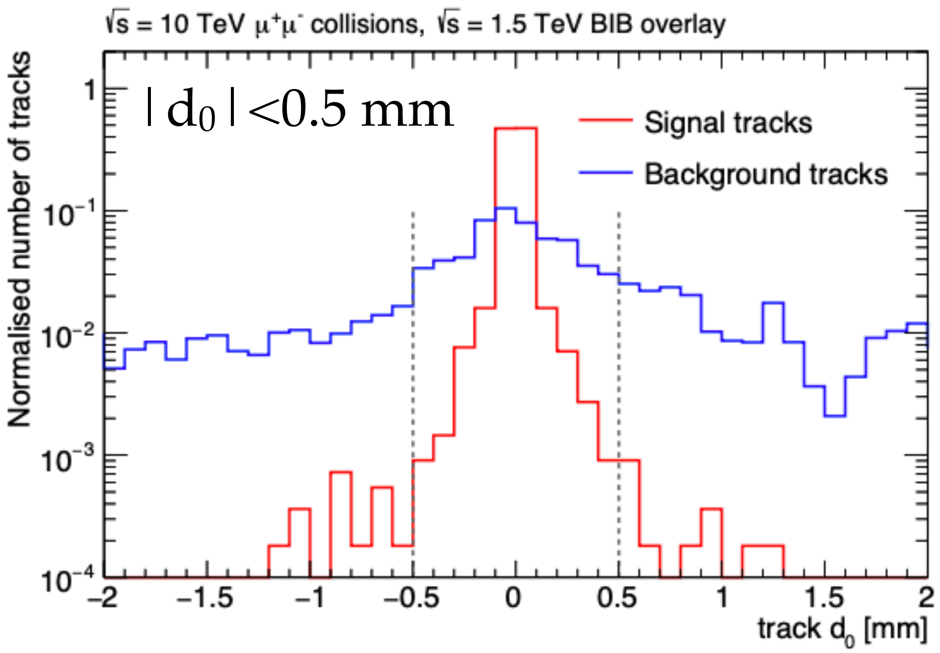
Heavy particles can get lost!

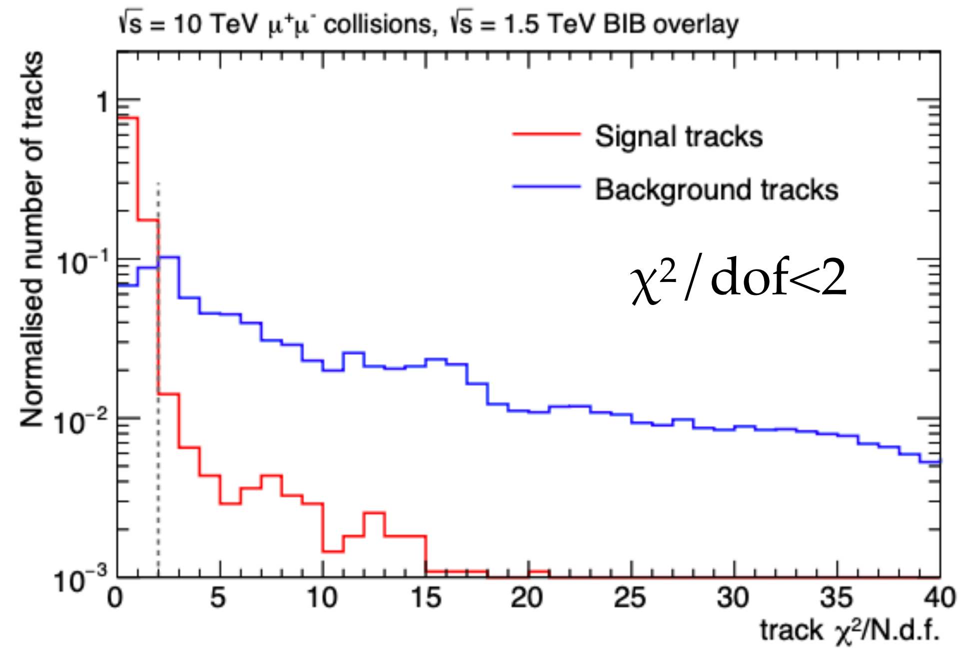


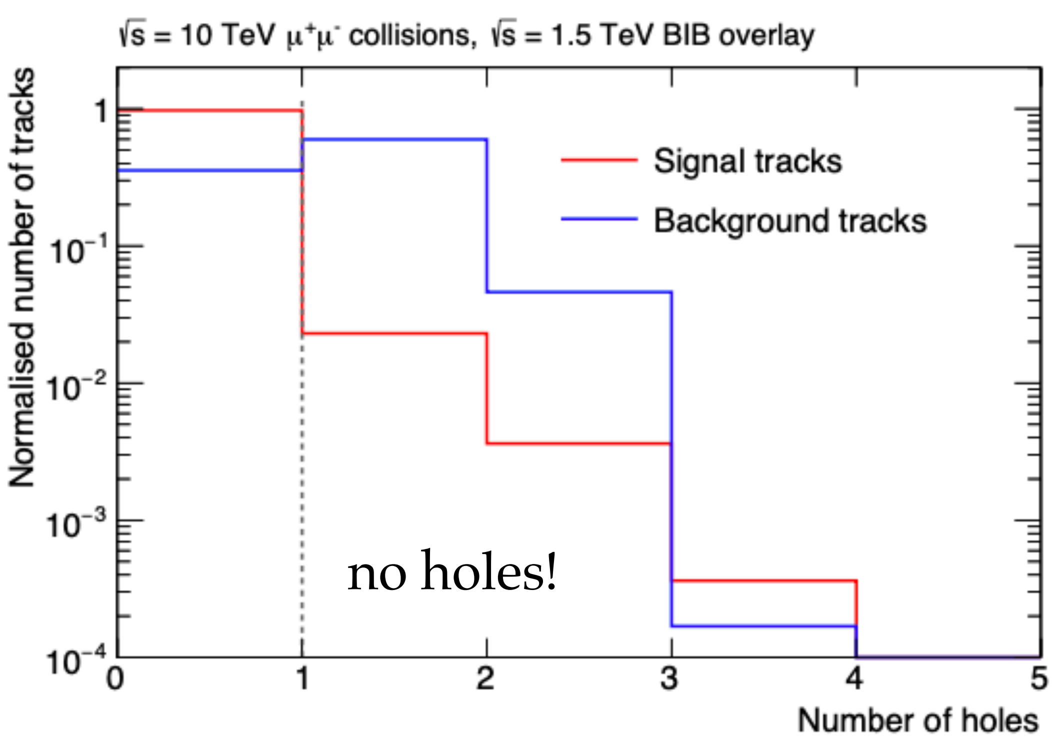


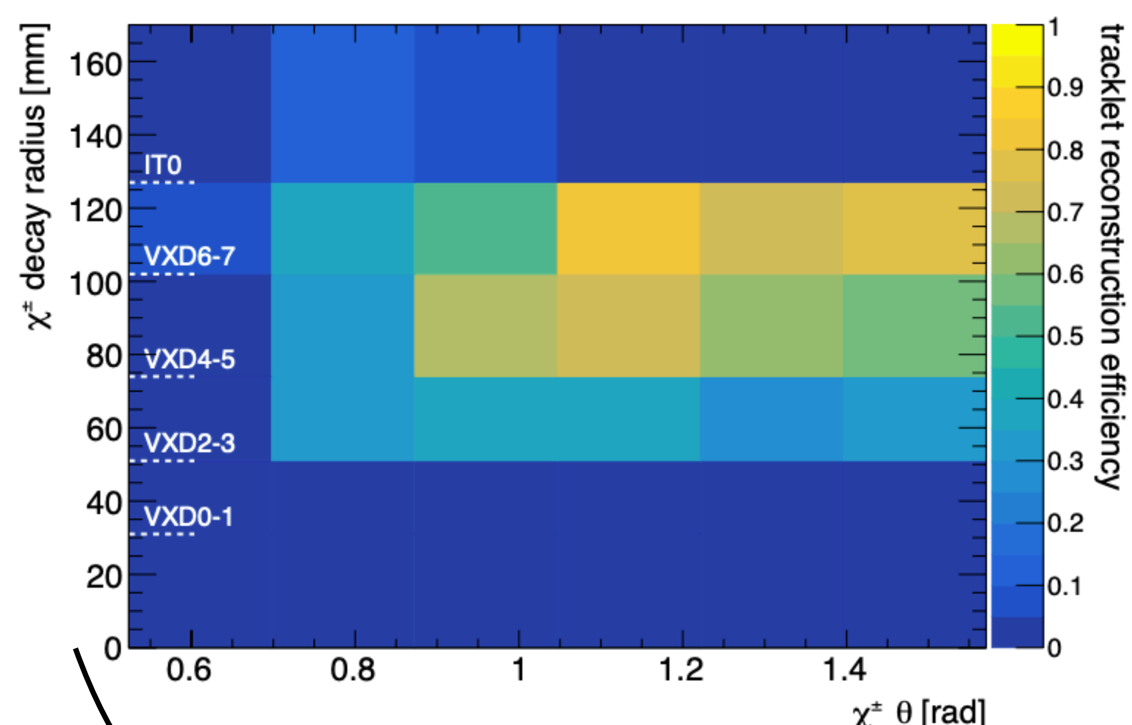
Signal hits should be aligned!

Tracking









Tracklet efficiency
(model-independent)

Collider analysis (I)

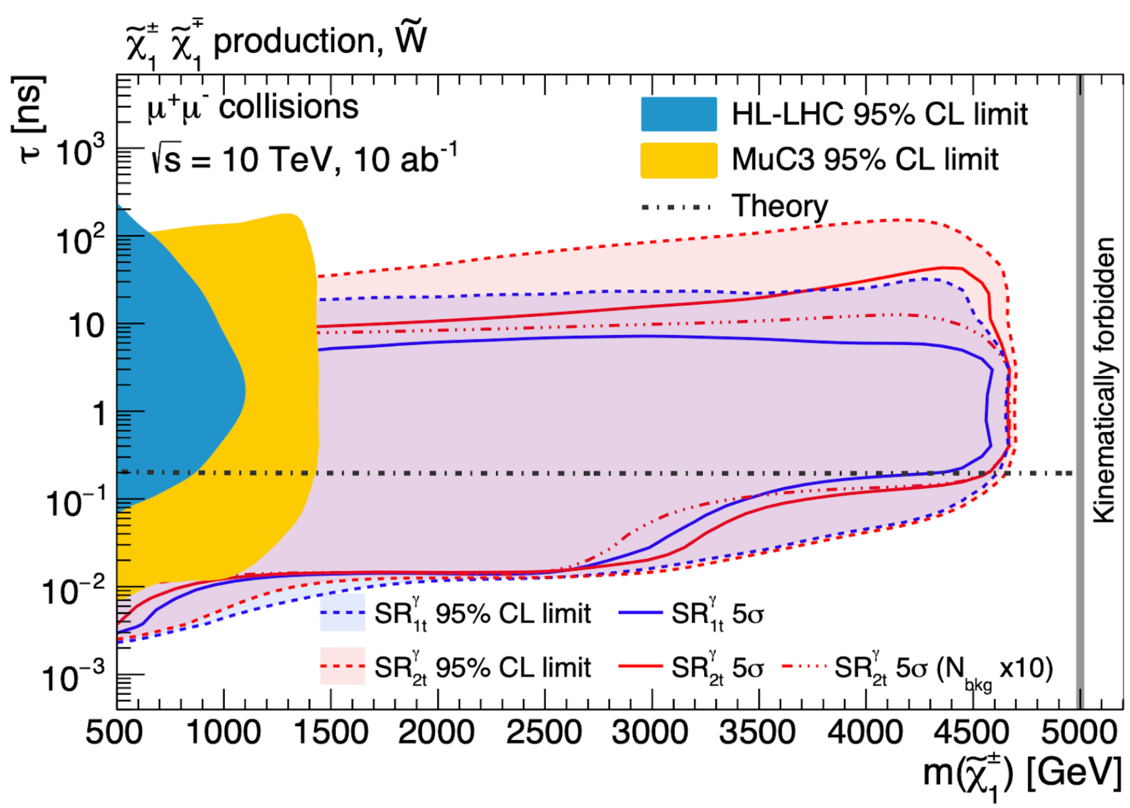
2 Signal Regions

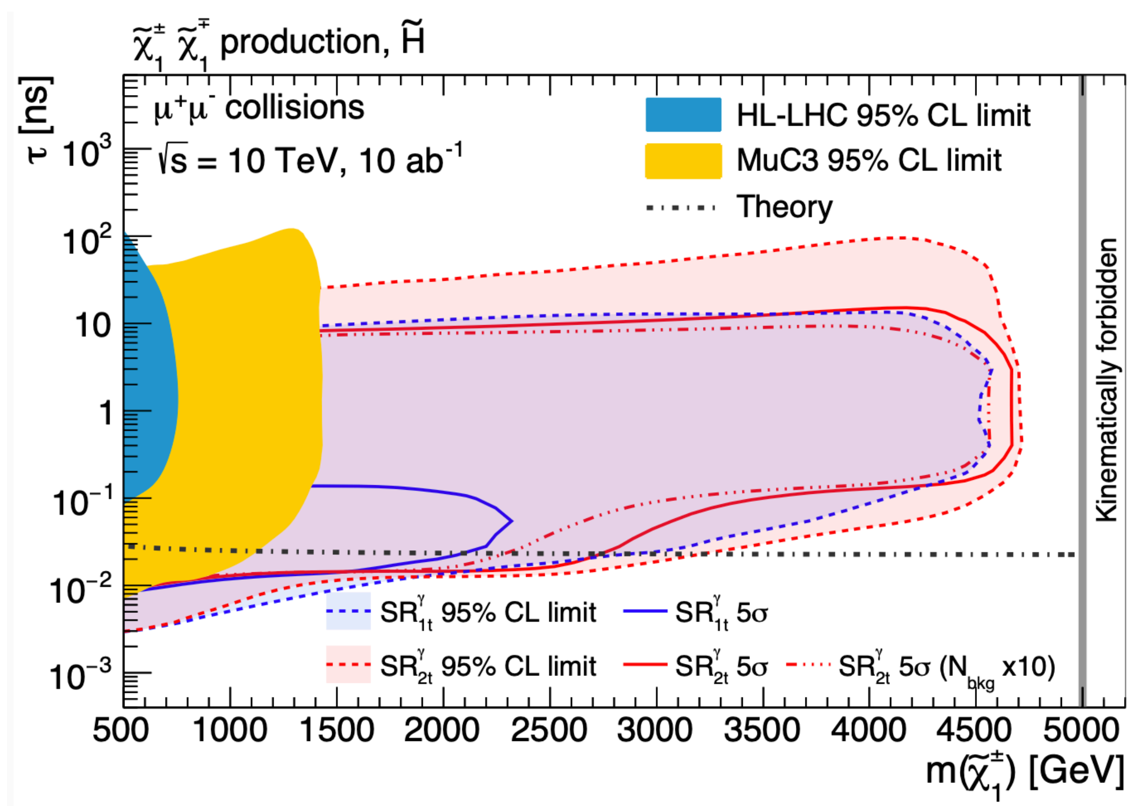
Requirement / Region	SR^{γ}_{1t}	SR^{γ}_{2t}
Vetoes	leptons and jets	
Leading tracklet p_T [GeV]	> 300	> 20
Leading tracklet θ [rad]	$[2/9\pi, 7/9\pi]$	
Subleading tracklet p_T [GeV]	-	> 10
Tracklet pair Δz [mm]	-	< 0.1
Photon energy [GeV]	> 25	> 25

	SR^{γ}_{1t}	SR^{γ}_{2t}
Total background	187.8 ± 0.6	0.16 ± 0.05
$\tilde{W}$, 2.7 TeV, $\tau = 0.2$ ns	201 ± 5	199 ± 4
$\tilde{H}$, 1.1 TeV, $\tau = 0.02$ ns	253 ± 4	170.5 ± 2.1

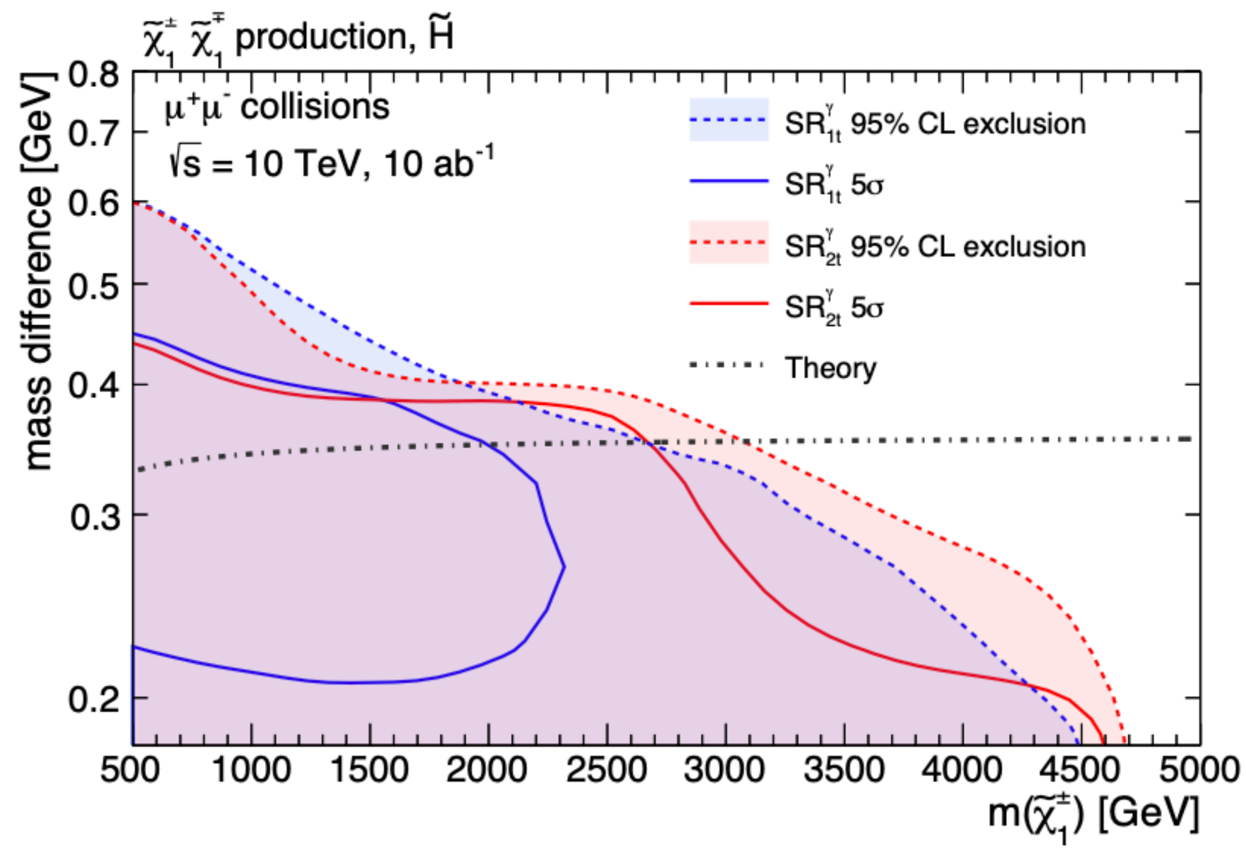
Right relic abundance

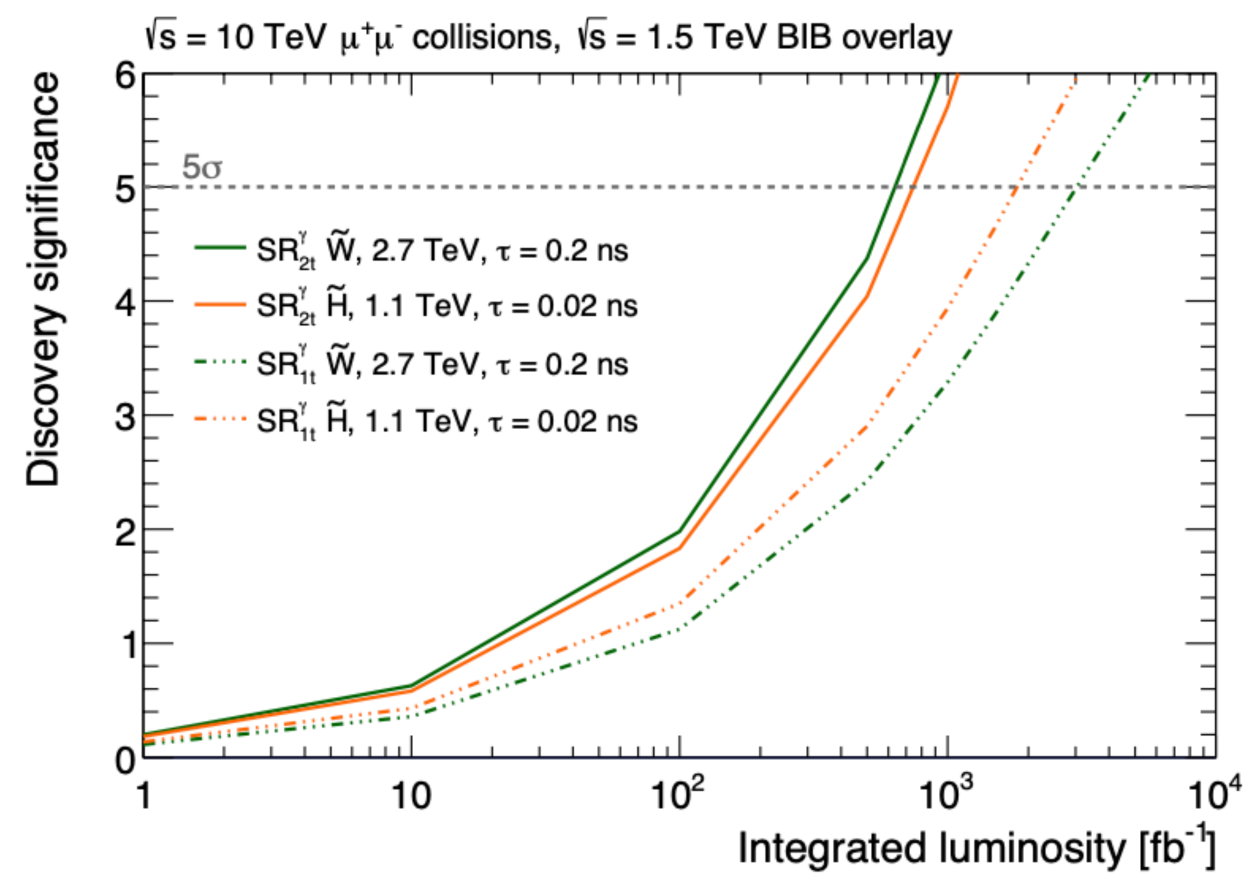
non-zero | morally 0

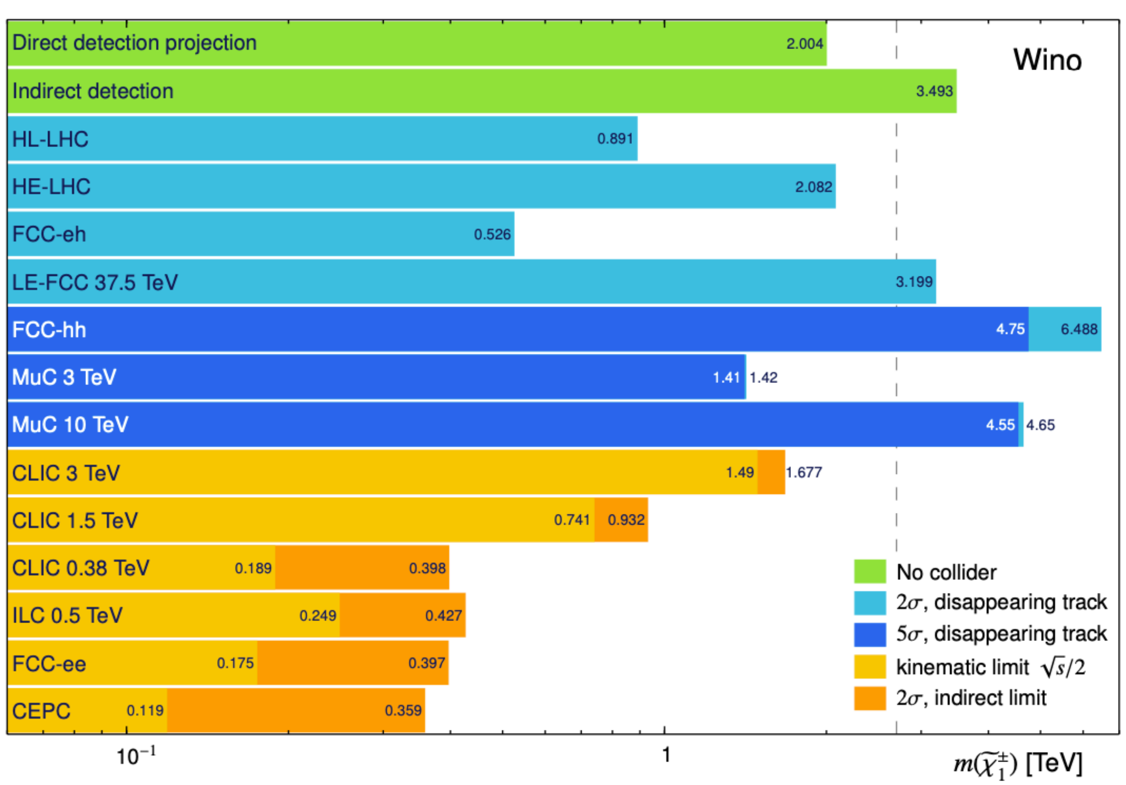


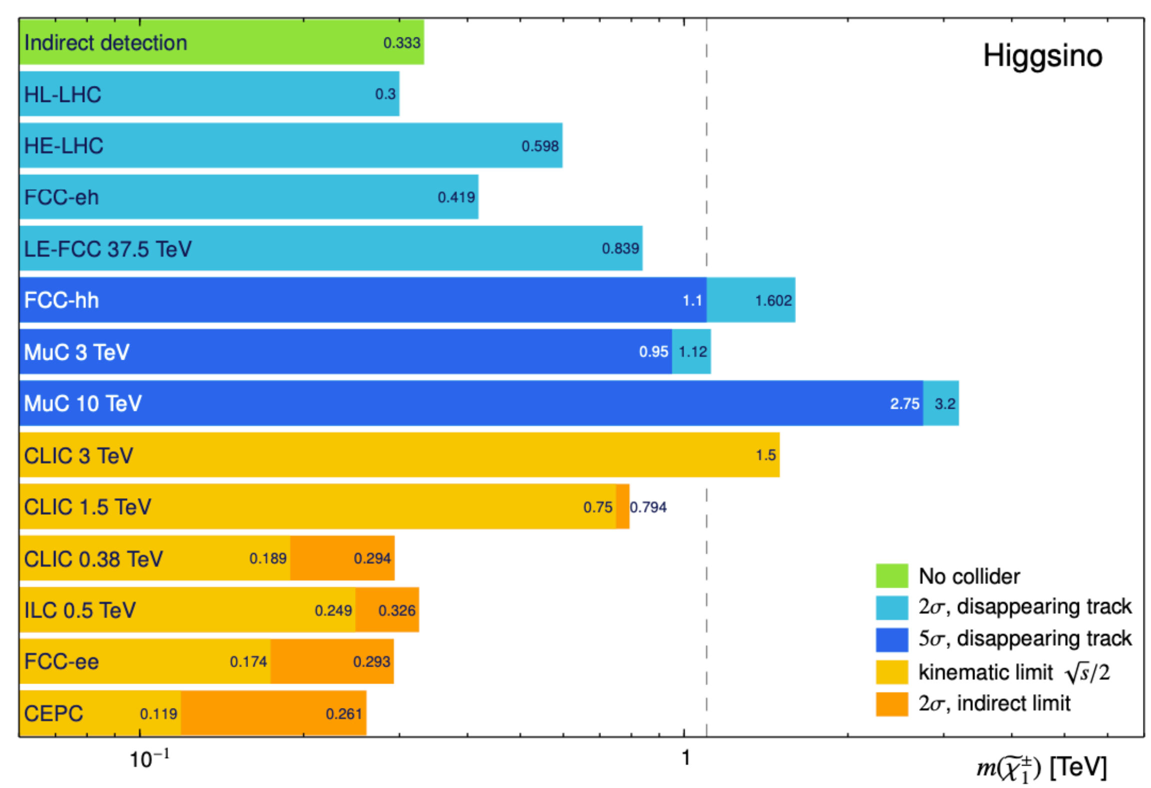


Collider analysis (II)









Lessons learned

- LLPs and FIPs are a theoretically sound BSM class of signatures which can be studied in detail at a Muon Collider (MuC).

- It would be highly desirable to have an updated Beam Induced Background (BIB) sample to verify the assumption that (fixing the "machine") the BIB decreases with energy. This is needed for a robust assessment of the MuC experimental sensitivity.

- MuC is not clean for LLP signals, but can be made clean (with some effort)

- LLP studies motivate detector improvements (mass reconstruction, soft objects, vertexing, etc)

- Other LLP signatures (DVs, HSCPs, etc) are a low hanging fruit.

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