Some principles for the Hidden Sector explorer

Two possibilities for Beyond Standard Model with light particles

1. Wider theory exist at new high energy scale (SUSY, extra dim., etc) with degrees of freedom that stay relevant at low energies. Particles may be intrinsically light or be light by dynamic effects
2. SM + Hidden Sector with light messengers is all there is up to Planck scale – no new visible scale
3. or both…

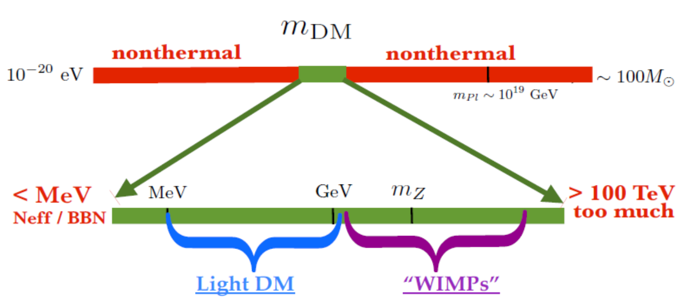
Hidden/Dark Sector?

- 7% of LHC+HL-LHC data recorded - no unambiguous sign of NP
  - ➔ New physics (particles) should either be very
    - ➔ heavy if interactions have $\mathcal{O}$(SM strength) (e.g. SUSY, Technicolour)
    - ➔ or light (or heavy…), and be very feebly coupled

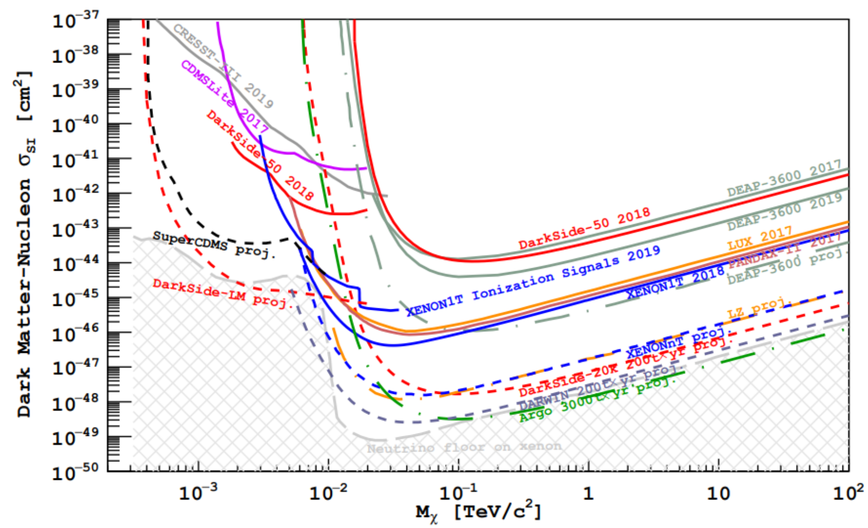
- Hidden Sector : Any Particles engaging in Feebly (or no) Interactions (FIPs) with the SM particles
  - Fair (but not necessary) starting point: *Dark Matter*

- Many reasons MeV – GeV region is particularly interesting….
  1. We know this mass scale exists !...
  2. Absence of hints for new particles at higher energies
  3. Possibility of thermal DM
  4. Cosmologically interesting and powerful constraints
  5. Largely unexplored territory
  6. And because we can!

     (…test many reasonable theoretical models!)

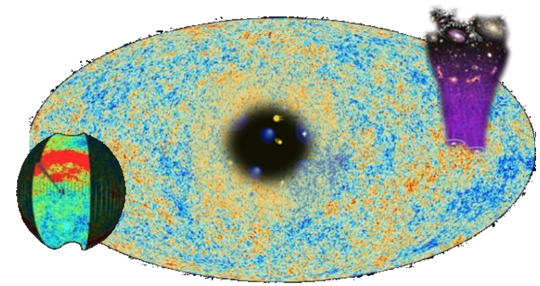


Direct searches for cosmic DM

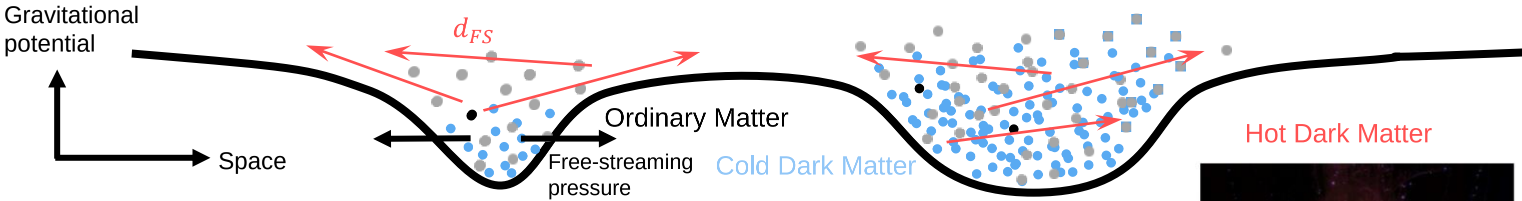


arXiv:1910.11775

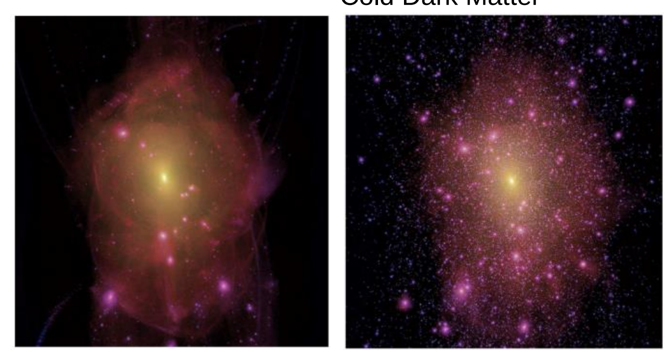
E.g. Structure formation and Dark Matter



- At CMB $\delta\rho/\rho \sim 10^{-5}$
  - ➔ $\delta\rho/\rho$ grow with ~scale a during matter domination
  - ➔ $a_{today}/a_{dec} = 1 + z_{dec} \sim 10^3$
  - ➔ Not enough!
- DM can contribute in two ways:
  - Increasing mass density (increasing Jeans' scale for gravitational collapse $\propto \sqrt{T/m\rho}$)
  - Damping clustering of (too) small structures due to free-streaming $d_{FS} \propto v/\sqrt{\rho}$



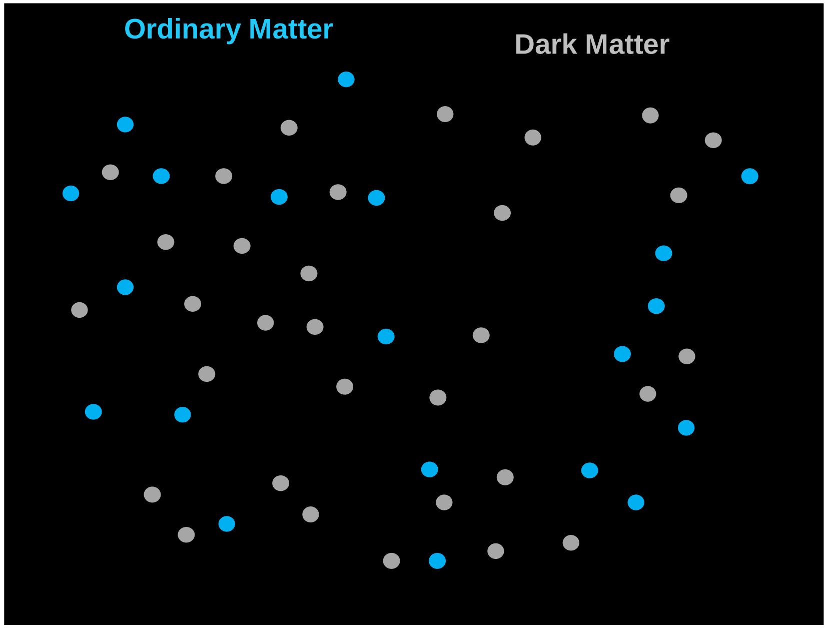
Hot Dark Matter Cold Dark Matter



- DM could produce a drop-off in the power spectrum of structures as a function of the scale
  - Wash out of structures with sizes in the range $10^6 – 10^8$ solar masses
  - How to measure?
    - Structures of $<10^8$ solar masses are very unlikely to have formed stars!

Multi-million dollar question

A sample of space and matter



$$\mathcal{L} = i\bar{\psi}\gamma^{\mu}\partial_{\mu}\psi - m\bar{\psi}\psi -$$

Free fermion

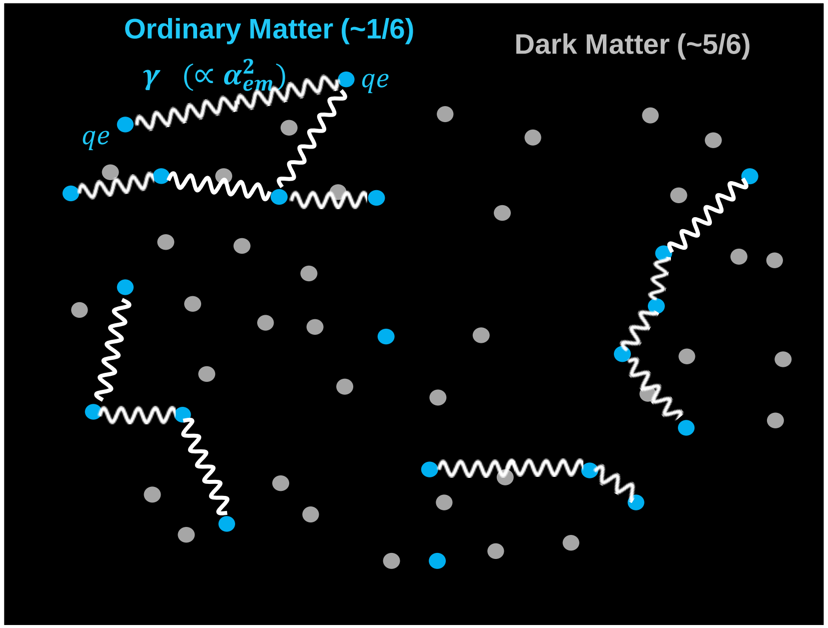
Fermion mass

DM mass

Free DM

$$+ i\bar{\chi}\gamma^{\mu}\partial_{\mu}\chi - m\bar{\chi}\chi -$$

Multi-million dollar question



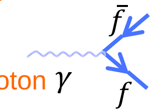
$$\mathcal{L} = i\bar{\psi}\gamma^{\mu}\partial_{\mu}\psi - m\bar{\psi}\psi - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} + e\bar{\psi}\gamma^{\mu}A_{\mu}\psi$$

Free fermion

Fermion mass

Free photon

Interaction fermion-photon

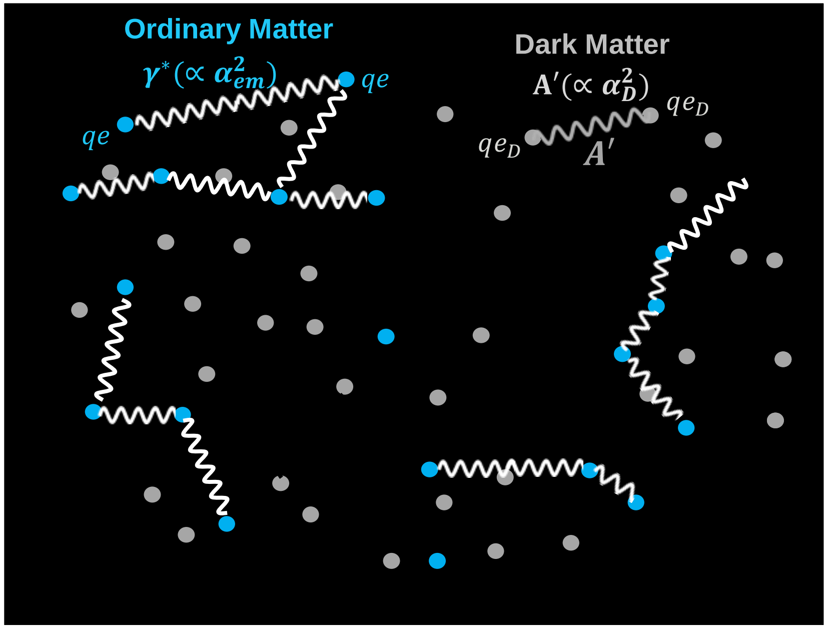


$$+ i\bar{\chi}\gamma^{\mu}\partial_{\mu}\chi - m\bar{\chi}\chi -$$

Free DM

DM mass

Multi-million dollar question



$$\mathcal{L} = i\bar{\psi}\gamma^\mu\partial_\mu\psi - m\bar{\psi}\psi - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} + e\bar{\psi}\gamma^\mu A_\mu\psi$$

Free fermion — Fermion mass — Free photon — Interaction fermion-photon

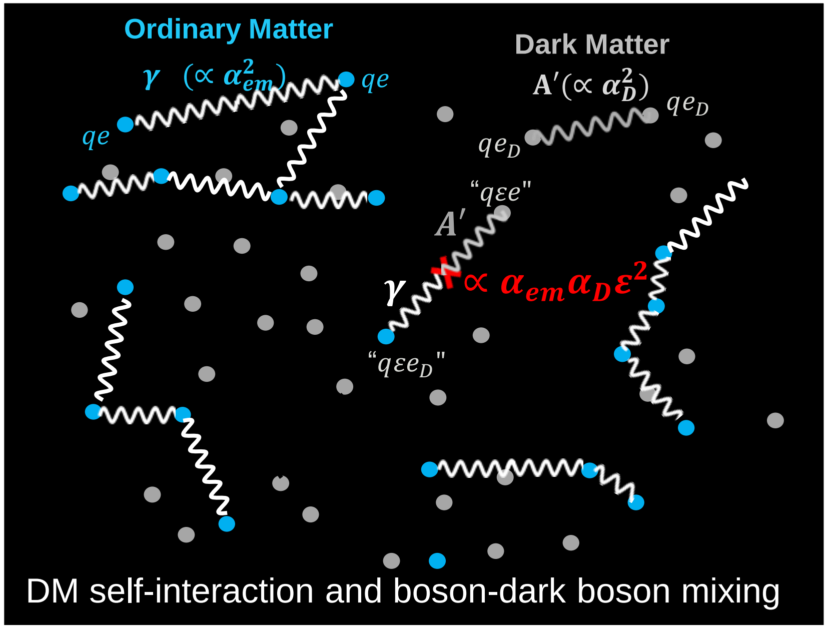
$$+ i\bar{\chi}\gamma^\mu\partial_\mu\chi - m\bar{\chi}\chi - \frac{1}{4}V_{\mu\nu}V^{\mu\nu} + \epsilon\bar{\chi}\gamma^\mu A'_\mu\chi + \cdots$$

Free DM — DM mass — Free dark photon — Interaction dark fermion – dark photon, DM self-interaction…

Dark electric charge
Coupling extremely weak

Multi-million dollar question - SIDM

A sample of space



$$\mathcal{L} = i\bar{\psi}\gamma^\mu\partial_\mu\psi - m\bar{\psi}\psi - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} + e\bar{\psi}\gamma^\mu A_\mu\psi$$

Free fermion — Fermion mass — Free photon — Interaction fermion-photon

$$+ i\bar{\chi}\gamma^\mu\partial_\mu\chi - m\bar{\chi}\chi - \frac{1}{4}V_{\mu\nu}V^{\mu\nu} + \epsilon\bar{\chi}\gamma^\mu A'_\mu\chi + \cdots$$

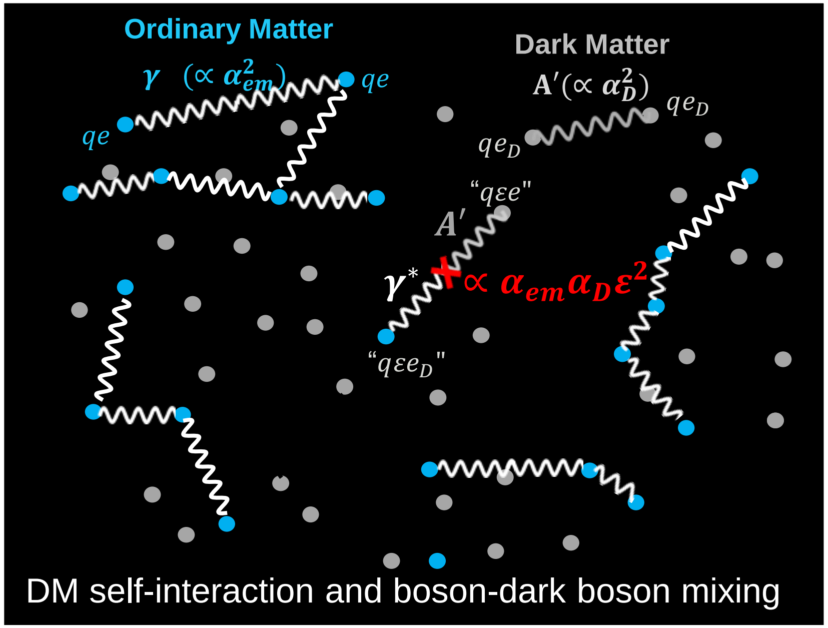
Free DM — DM mass — Free dark photon — Interaction dark fermion – dark photon DM self-interaction…

$$-\frac{1}{4}\varepsilon F_{\mu\nu}V^{\mu\nu}$$

Kinetic mixing between ordinary photon and dark photon!
"Vector portal"
→ Coupling extremely week

Multi-million dollar question – SIDM?

A sample of space



$$\mathcal{L} = i\bar{\psi}\gamma^\mu\partial_\mu\psi - m\bar{\psi}\psi - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} + e\bar{\psi}\gamma^\mu A_\mu\psi$$

Free fermion; Fermion mass; Free photon; Interaction fermion-photon

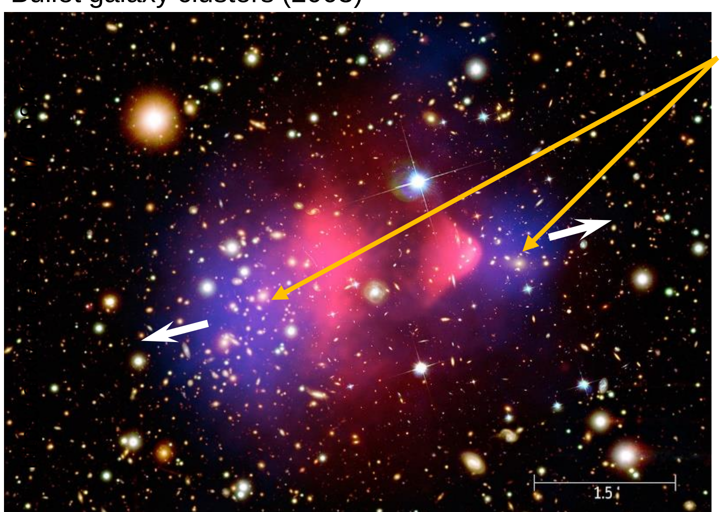
$$+ i\bar{\chi}\gamma^\mu\partial_\mu\chi - m\bar{\chi}\chi - \frac{1}{4}V_{\mu\nu}V^{\mu\nu} + \epsilon\bar{\chi}\gamma^\mu A'_\mu\chi + \cdots$$

Free DM; DM mass; Free dark photon; Interaction dark fermion – dark photon DM self-interaction…

$$-\frac{1}{4}\varepsilon F_{\mu\nu}V^{\mu\nu}$$

Kinetic mixing between ordinary photon and dark photon!
"Vector portal"
→ Coupling extremely week

Bullet galaxy clusters (2003)



Collision between two galaxy clusters

- In red, X-ray emitting plasma = dominant baryonic mass (5-15%)
- In blue, reconstruction of total mass distribution from lensing
  →Trace out Dark Matter distribution

Dark Matter remains around galaxy clusters seemingly undisturbed

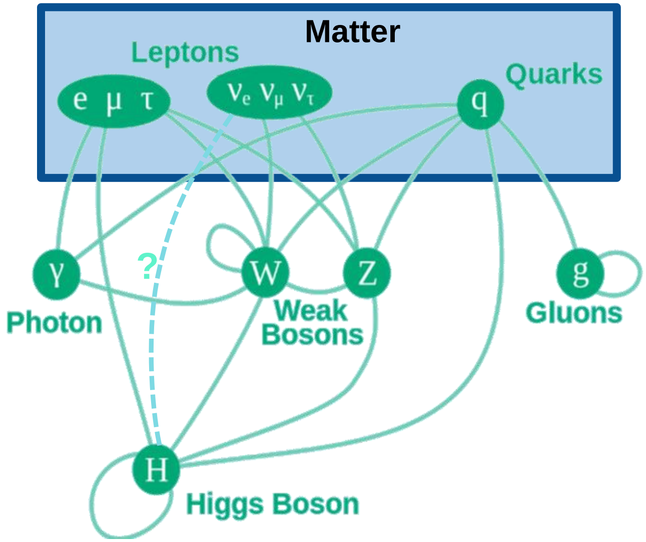
→Almost(?) collisionless

→Dark Matter is, *or is just about*, non-self-interacting $\sigma/m \lesssim 1 cm^2 g^{-1}$

→Currently we observe >70 colliding galaxy clusters (arXiv:1610.05327)

"Standard model" of Hidden Sector

- Standard Model has taught us successful formalism to implement particles, interaction and mediators
  - SM not only successful, we discovered what it predicted
  - Gives us plausible tools to implement Dark Sector with well-defined phenomenology:



Options for "portals"

➔ fermionic/scalar DM

➔ Dark Photons

➔ Dark Scalars

➔ Heavy Neutral Leptons

➔ Axion-Like Particles

….

A model should be used to teach us something!

- Dynamics of Hidden Sector may drive dynamics and 'anomalies' of Visible Sector!

➔ Neutrino oscillations and mass, baryon asymmetry, Higgs mass, Dark Matter (abundance, distribution and "behavior"), structure formation, inflation, …

- Also some SUper-SYmmetric DM candidates and "portals" etc
  - Sgoldstino, Neutralino in R-Parity Violating SUSY, Hidden Photinos, axinos and saxions….

Search guidelines are not always so clear…

Weinberg (1967)

VOLUME 19, NUMBER 21 PHYSICAL REVIEW LETTERS 20 NOVEMBER 1967

[11] In obtaining the expression (11) the mass difference between the charged and neutral has been ignored.

[12] M. Ademollo and R. Gatto, Nuovo Cimento 44A, 282 (1966); see also J. Pasupathy and R. E. Marshak, Phys. Rev. Letters 17, 888 (1966).

[13] The predicted ratio [eq. (12)] from the current algebra is slightly larger than that (0.23%) obtained from the ρ-dominance model of Ref. 2. This seems to be true also in the other case of the ratio $\Gamma(\eta\to\pi^+\pi^-\gamma)/\Gamma(\gamma\gamma)$ calculated in Refs. 12 and 14.

[14] L. M. Brown and P. Singer, Phys. Rev. Letters 8, 460 (1962).

A MODEL OF LEPTONS*

Steven Weinberg†
Laboratory for Nuclear Science and Physics Department,
Massachusetts Institute of Technology, Cambridge, Massachusetts
(Received 17 October 1967)

Leptons interact only with photons, and with the intermediate bosons that presumably mediate weak interactions. What could be more natural than to unite[1] these spin-one bosons into a multiplet of gauge fields? Standing in

and on a right-handed singlet

$$R \equiv [\tfrac{1}{2}(1-\gamma_5)]e. \quad (2)$$

The largest group that leaves invariant the kine-

⋮

The coupling of φ_1 to muons is stronger by a factor M_μ/M_e, but still very weak. Note also that (14) gives g and g' larger than e, so (16) tells us that $M_W > 40$ BeV, while (12) gives $M_Z > M_W$ and $M_Z > 80$ BeV.

The only unequivocal new predictions made

If $g \gg e$ then $g \gg g'$, and this is just the usual e-ν scattering matrix element times an extra factor $\frac{3}{2}$. If $g \simeq e$ then $g \ll g'$, and the vector interaction is multiplied by a factor $-\frac{1}{2}$ rather than $\frac{3}{2}$. Of course our model has too many arbitrary features for these predictions to be

1265

taken very seriously, but it is worth keeping in mind that the standard calculation[8] of the electron-neutrino cross section may well be wrong.

mi, Z. Physik 88, 161 (1934). A model similar to ours was discussed by S. Glashow, Nucl. Phys. 22, 579 (1961); the chief difference is that Glashow introduces symmetry-breaking terms into the Lagrangian, and

1973: Discovery of neutral currents at CERN

1979: Nobel price Glashow, Salam, Weinberg

...

Nucl. Phys. B106 (1976)

A PHENOMENOLOGICAL PROFILE OF THE HIGGS BOSON

John ELLIS, Mary K. GAILLARD * and D.V. NANOPOULOS **
CERN, Geneva

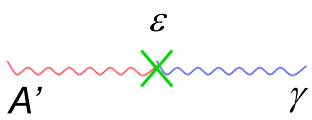
Received 7 November 1975

We should perhaps finish with an apology and a caution. We apologize to experimentalists for having no idea what is the mass of the Higgs boson, unlike the case with charm [3,4] and for not being sure of its couplings to other particles, except that they are probably all very small. For these reasons we do not want to encourage big experimental searches for the Higgs boson, but we do feel that people performing experiments vulnerable to the Higgs boson should know how it may turn up.

➔ Hidden Sector: Room for progress in theory and expect guidance from the cosmic frontier

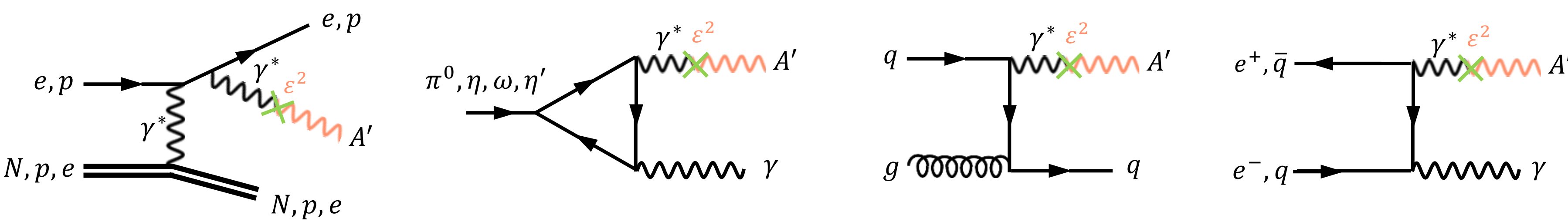
Dark photon production

- Kinetic mixing with massive dark/secluded/paraphoton *A'* : $\frac{1}{2}\varepsilon F^{SM}_{\mu\nu}F^{\mu\nu}_{HS}$



→Motivated in part by idea of "mirror world" restoring L/R symmetry, dark matter (AMS e^{+} excess), g-2 anomaly, …

Dark photons: need loads of photons!



Bremsstrahlung | Light neutral meson decays | Quark/gluon scattering | Annihilation

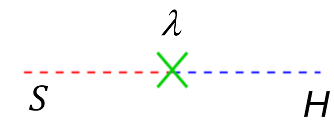
→ Proton and electron beam dumps, pp and e^+e^-colliders

→ Signature: decay or missing energy

	Physics model	Final state
HSDS	HNL, SUSY neutralino	$\ell^{\pm}\pi^{\mp}$, $\ell^{\pm}K^{\mp}$, $\ell^{\pm}\rho^{\mp}(\rho^{\mp}\to\pi^{\mp}\pi^{0})$
	DP, DS, ALP (fermion coupling), SUSY sgoldstino	$\ell^{+}\ell^{-}$
	DP, DS, ALP (gluon coupling), SUSY sgoldstino	$\pi^{+}\pi^{-}$, $K^{+}K^{-}$
	HNL, SUSY neutralino, axino	$\ell^{+}\ell^{-}\nu$
	ALP (photon coupling), SUSY sgoldstino	$\gamma\gamma$
	SUSY sgoldstino	$\pi^{0}\pi^{0}$

Dark scalar ("Higgs") production

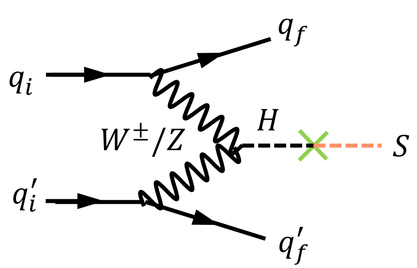
- Mass mixing with dark singlet scalar $S : (gS + \lambda S^2)H^\dagger H$

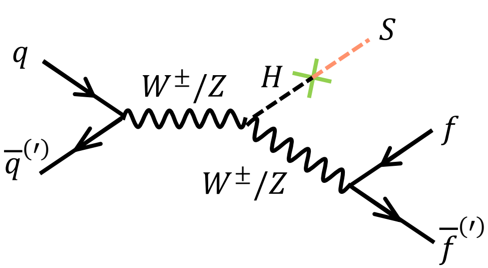


  ➔ Mass to Higgs boson and mass generation in dark sector, inflaton, dark phase transitions BAU, dark matter,…

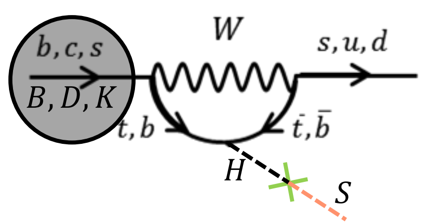
  ➔ Production of Dark Scalars: Loads of Higgses (real or virtual)!

<u>pp colliders</u>



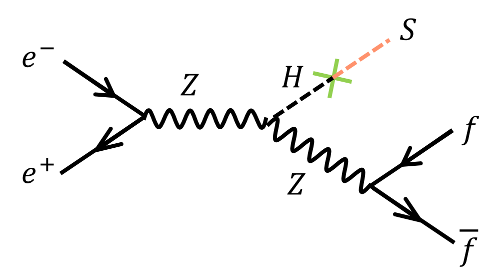


<u>pp colliders or p beam dumps</u>



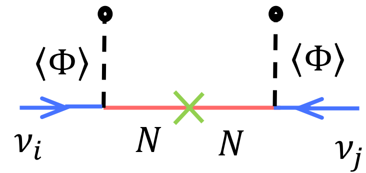
$$\Gamma(K \to \pi S) \propto (m_t^2 |V_{ts}^* V_{td}|)^2$$
$$\Gamma(D \to \pi S) \propto (m_b^2 |V_{cb}^* V_{ub}|)^2$$
$$\Gamma(B \to \pi S) \propto (m_t^2 |V_{tb}^* V_{ts}|)^2$$

<u>Higgs factory</u>



Sterile neutrino/heavy neutral lepton production

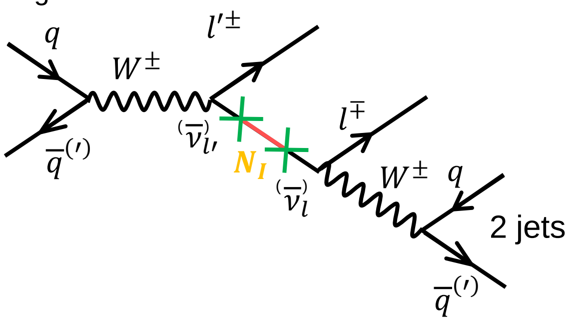
- Mixing with right-handed neutrino N (Heavy Neutral Lepton): $Y_{I\ell} H^{\dagger} \overline{N}_I L_\ell$
  - ➔ Neutrino oscillation, baryon asymmetry, dark matter



➔ Production of Heavy Neutral Leptons: loads of neutrinos!

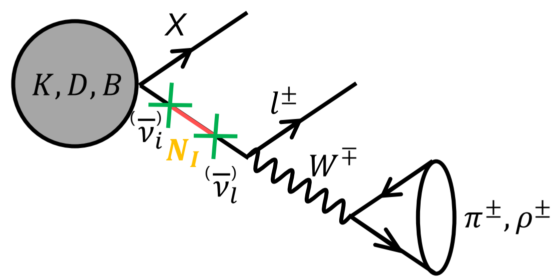
pp colliders

E.g.



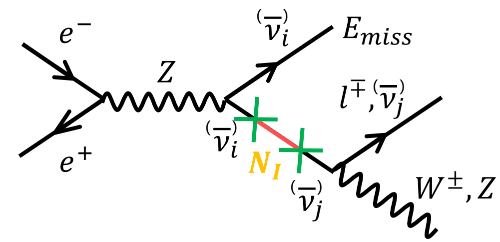
Like-sign leptons: Lepton Number Violation

pp colliders or p beam dumps



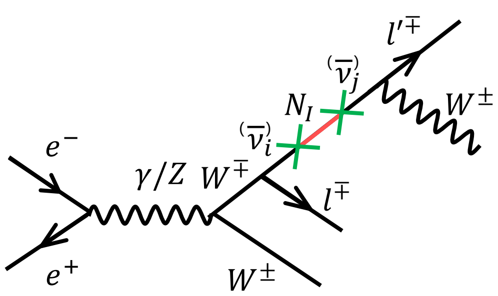
e^+e^- colliders (W,Z,H)
(also $\mu\mu$ –colliders)

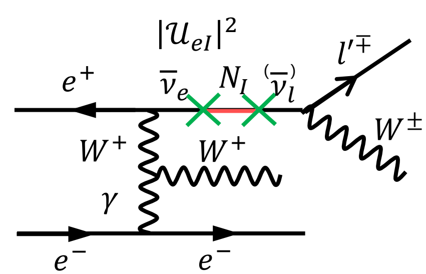
E.g. for all flavours

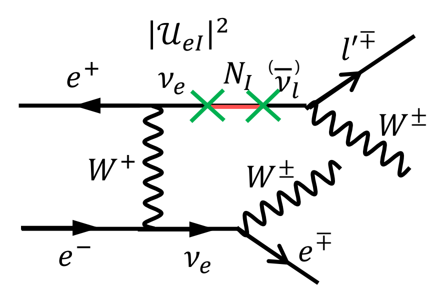


Most promising channel:
$e^+e^- \rightarrow \; N(\rightarrow l^\mp W^\pm)\, \nu_l : l^\mp + 2j + E_{miss}$

e^+e^- colliders (W,ZH) continued
(also $\mu\mu$–, $\gamma\gamma$–, $e\gamma$ –colliders)







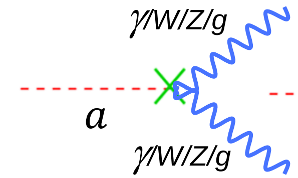
Alternative: $e^+e^- \rightarrow \; N(\rightarrow l'^\mp W^\pm) l^\mp W^\pm : dilepton + 4j$

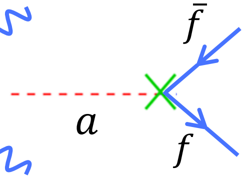
Axion-like particle production

- Mixing with Axion-Like Particles (ALPs) *a* with coupling to photons, fermions, gluons :

$$\frac{a}{F} G_{\mu\nu}\tilde{G}^{\mu\nu},\ \frac{\partial_\mu a}{F}\bar{\psi}\gamma_\mu\gamma_5\psi \text{ , etc}$$

  - Extended Higgs, SUSY breaking, dark matter, possibility of inflaton,…

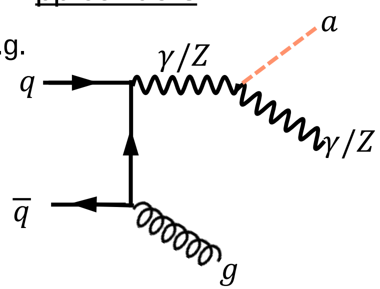


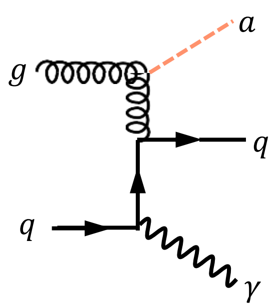


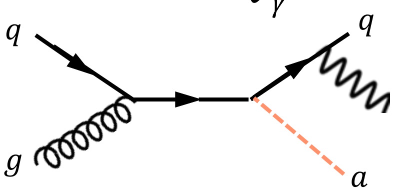
- Production of ALPs: Couplings to photons, gluons and fermions, loads of interactions!

pp colliders

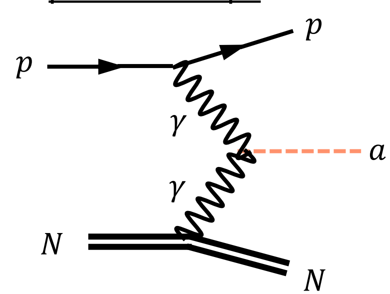
E.g.

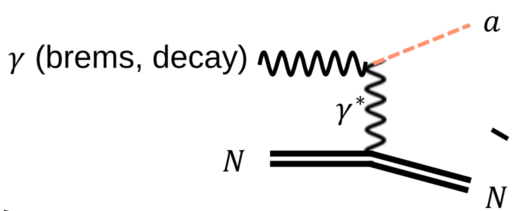




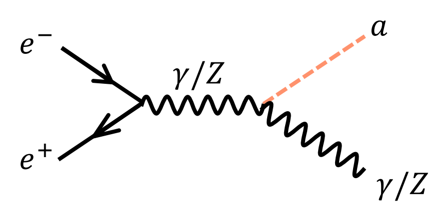


p beam dumps

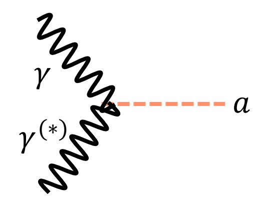




e^+e^- colliders



Gamma factory



And more...

Examples with mass~$\mathcal{O}(GeV)$ and production branching ratio ~ $\mathcal{O}(10^{-10})$

➔ Light super-goldstinos [Gorbunov, 2001] "Axion- and dilaton-like"

➔ $D \rightarrow \pi X,\ X \rightarrow \pi^+\pi^-,\ \pi^0\pi^0,\ l^+l^-$

➔ R-parity violating neutralinos in SUSY [Dedes et al., 2001] "Heavy-neutrino like"

➔ $D \rightarrow l\tilde{\chi},\ \tilde{\chi} \rightarrow l^+l^-\nu$

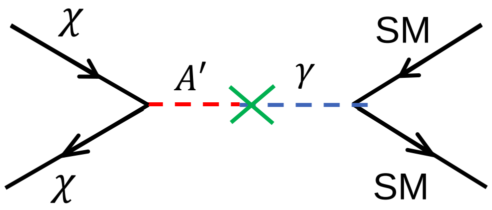
- Overlap in decay signatures!
  - Missing energy or decays:

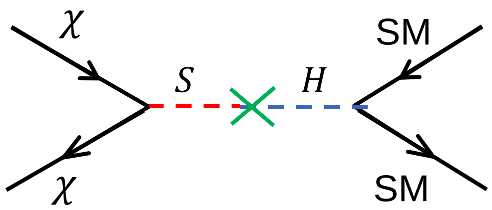
	Physics model	Final state
HSDS	HNL, SUSY neutralino	$\ell^{\pm}\pi^{\mp}$, $\ell^{\pm}K^{\mp}$, $\ell^{\pm}\rho^{\mp}(\rho^{\mp} \rightarrow \pi^{\mp}\pi^0)$
	DP, DS, ALP (fermion coupling), SUSY sgoldstino	$\ell^+\ell^-$
	DP, DS, ALP (gluon coupling), SUSY sgoldstino	$\pi^+\pi^-$, K^+K^-
	HNL, SUSY neutralino, axino	$\ell^+\ell^-\nu$
	ALP (photon coupling), SUSY sgoldstino	$\gamma\gamma$
	SUSY sgoldstino	$\pi^0\pi^0$

Also DP, DS, HNL, ALP,… to jets

(L)DM searches

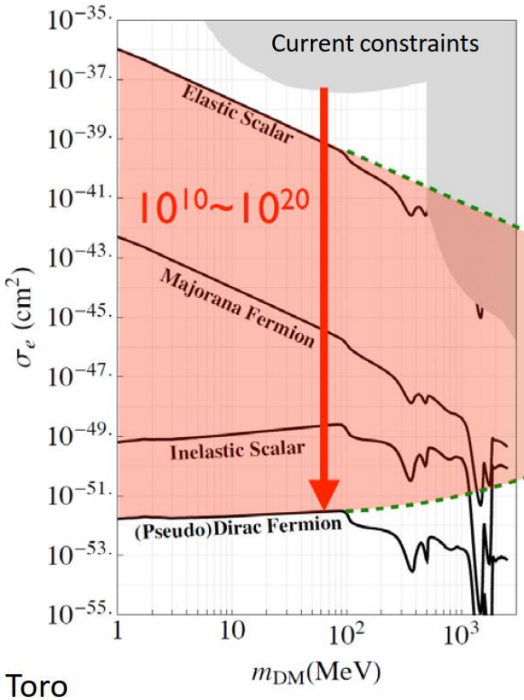
- DM search
  - Interpretation of invisible energy accompanied by SM signature (scattering, decay…) and assumption on DM-dark boson coupling



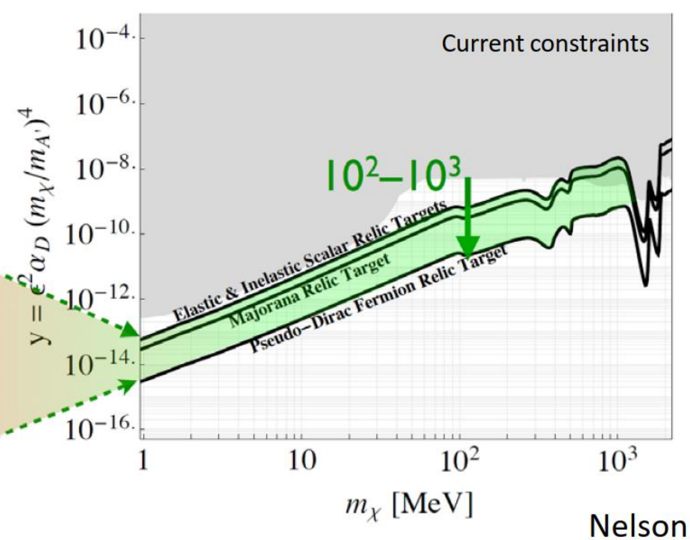


  - Scattering against atomic electrons and nuclei

<u>Detection by scattering relic DM</u>



<u>Detection by scattering accelerator-produced DM</u>



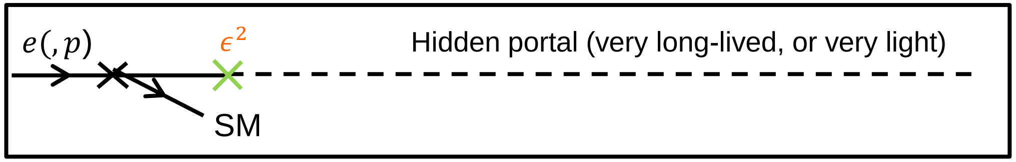
Relativistic production (high-q^2) at accelerators almost insensitive to spin and mass

Long-lived search techniques

Note : $\epsilon \ll 1$

Production | Detection

Indirect (invisible)



Escape detector
Missing energy/momentum/mass
Probability $\propto \epsilon^2$

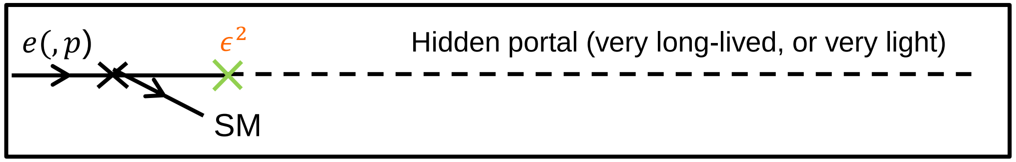
Long-lived search techniques

Note : $\epsilon \ll 1$

Production

Detection

Indirect (invisible)



Escape detector
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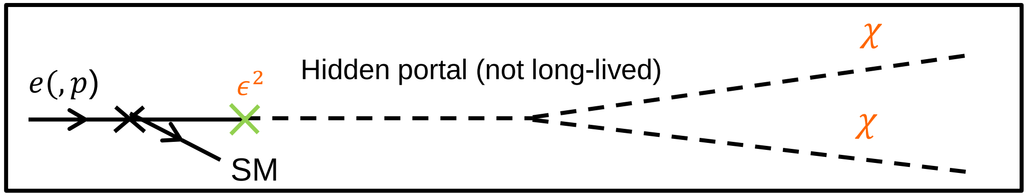


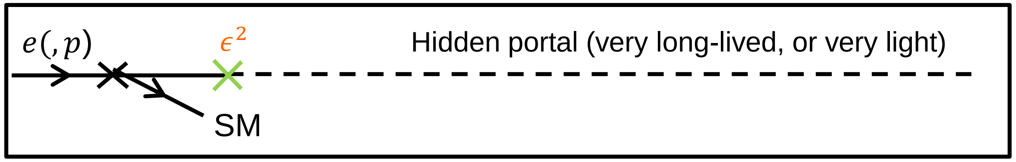
If $m_{HP} > 2m_{DM}$
Escape detector
Missing energy/momentum/mass
Probability $\propto \epsilon^2$

Long-lived search techniques

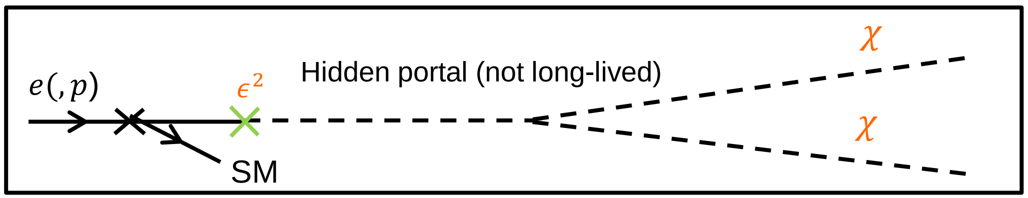
Note : $\epsilon \ll 1$

Production | Detection

Indirect



Escape detector
Missing energy/momentum/mass
Probability $\propto \epsilon^2$



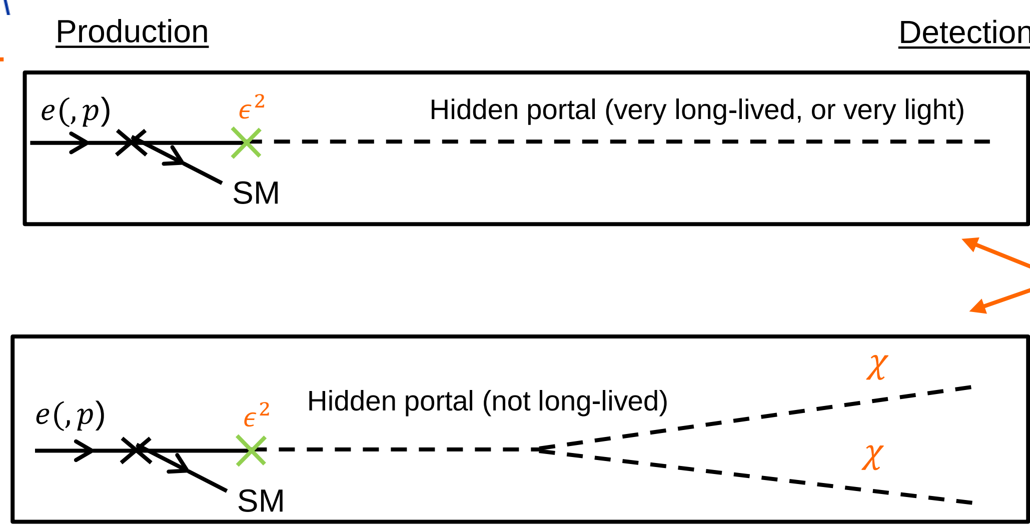
If $m_{HP} > 2m_{DM}$
Escape detector
Missing energy/momentum/mass
Probability $\propto \epsilon^2$

ATLAS
CMS
LHCb
NA64 **(++)**
LDMX
...

Long-lived search techniques

Note : $\epsilon \ll 1$

Indirect (invisible)



Escape detector
Missing energy/momentum/mass
Probability $\propto \epsilon^2$

Cannot be directly distinguished
→ Model-dependent interpretation

If $m_{HP} > 2m_{DM}$
Escape detector
Missing energy/momentum/mass
Probability $\propto \epsilon^2$

ATLAS
CMS
LHCb
NA64 (++)
LDMX

Use of electrons limits search to Dark Photon mediator (&ALPs)

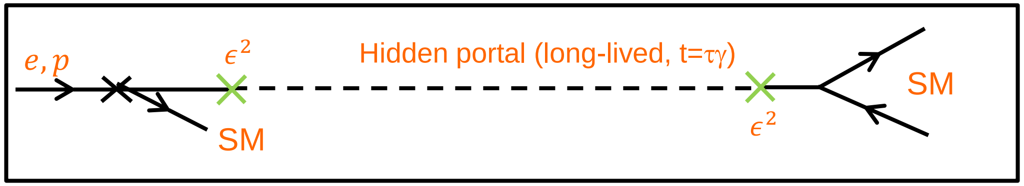
Long-lived search techniques

Production

Detection

Note : $\epsilon \ll 1$

"Direct" (indirect visible)



Decay signature ("displaced vertex)
Probability $\propto \epsilon^4$
Model independent

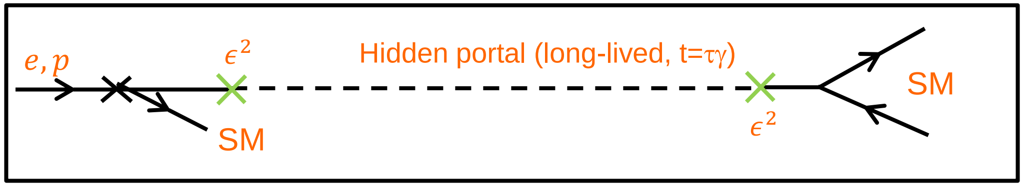
Long-lived search techniques

Production

Detection

Note : $\epsilon \ll 1$

“Direct” (indirect visible)



Decay signature (“displaced vertex)
Probability $\propto \epsilon^4$
Model independent

MATHUSLA
ANUBIS
CODEX-b

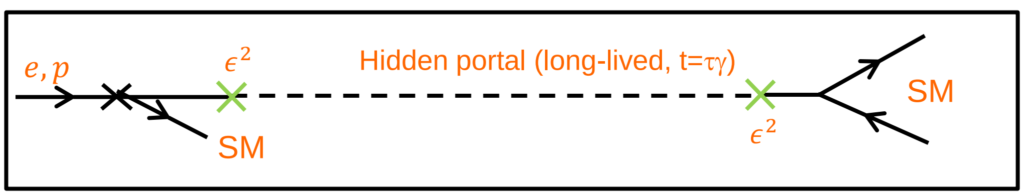
Long-lived search techniques

Production

Detection

Note : $\epsilon \ll 1$

“Direct” (indirect visible)



Decay signature (“displaced vertex)
Probability ∝ ϵ^4
Model independent
+
Reconstruction of decay: mass, PID
→ Distinguish models
→ Measurement of properties

MATHUSLA
ANUBIS
CODEX-b

ATLAS
CMS
LHCb
NA62 (++)
NA64 (++)
FASER
SHiP

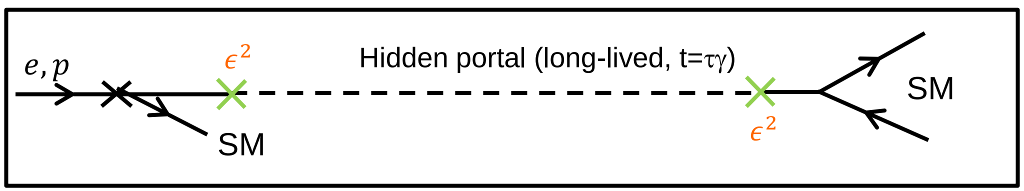
Long-lived search techniques

Note : $\epsilon \ll 1$

Production

Detection

"Direct" (indirect visible)



Decay signature ("displaced vertex)
Probability $\propto \epsilon^4$
Model independent
+
Reconstruction of decay: mass, PID
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MATHUSLA
ANUBIS
CODEX-b

ATLAS
CMS
LHCb
NA62 (++)
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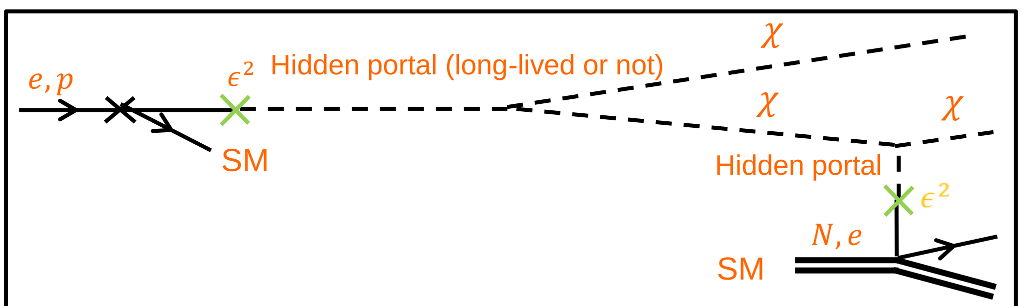


Dark matter scattering
Recoil against electron or nuclei
Probability $\propto \epsilon^4$
Model-dependent interpretation

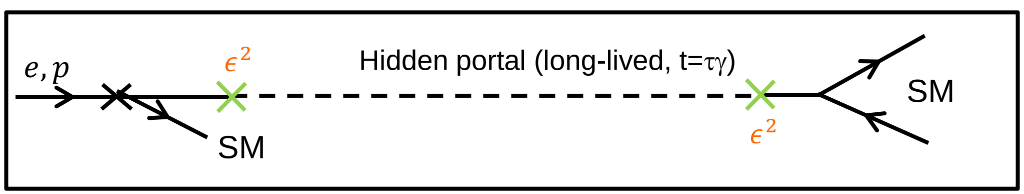
Long-lived search techniques

Note : $\epsilon \ll 1$

Production

Detection

"Direct" (indirect visible)



Decay signature ("displaced vertex)
Probability $\propto \epsilon^4$
Model independent
+
Reconstruction of decay: mass, PID
→ Distinguish models
→ Measurement of properties

MATHUSLA
ANUBIS
CODEX-b
ATLAS
CMS
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NA62 (++)
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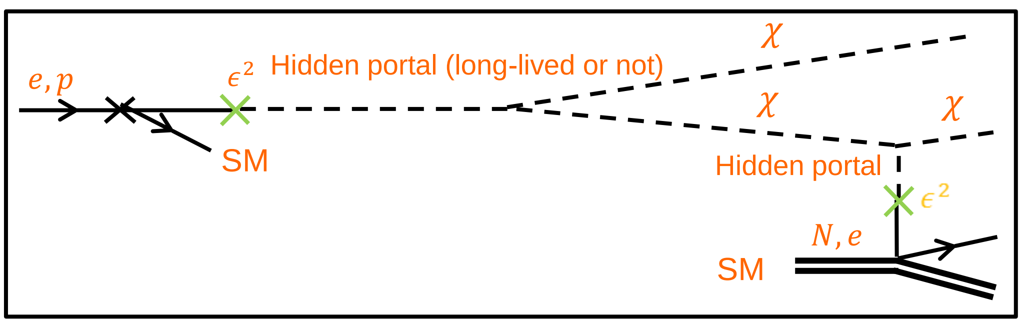
SHiP



Dark matter scattering
Recoil against electron or nuclei
Probability $\propto \epsilon^4$
Model-dependent interpretation

SHiP
SND@LHC

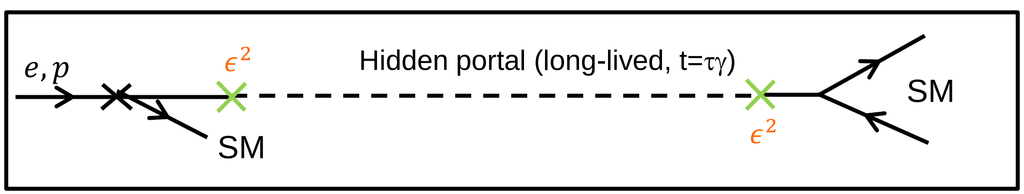
Long-lived search techniques

Note : $\epsilon \ll 1$

Production

Detection

"Direct" (indirect visible)



Decay signature ("displaced vertex)
Probability $\propto \epsilon^4$
Model independent
+
Reconstruction of decay: mass, PID
→ Distinguish models
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MATHUSLA
ANUBIS
CODEX-b
ATLAS
CMS
LHCb
NA62 (++)
NA64 (++)
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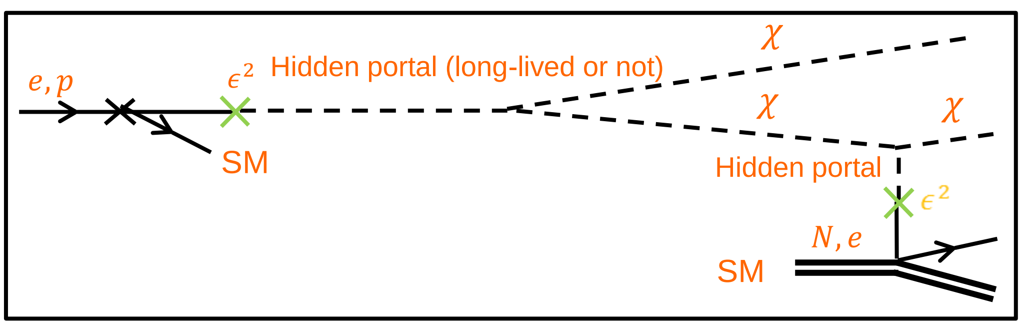
SHiP



Dark matter scattering
Recoil against electron or nuclei
Probability $\propto \epsilon^4$
Model-dependent interpretation

SHiP
SND@LHC

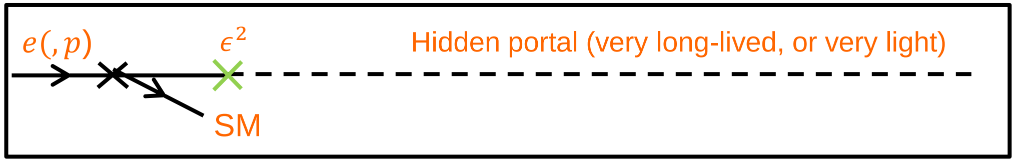
ϵ^4 dependence requires higher luminosity

Long-lived search techniques

Note : $\epsilon \ll 1$

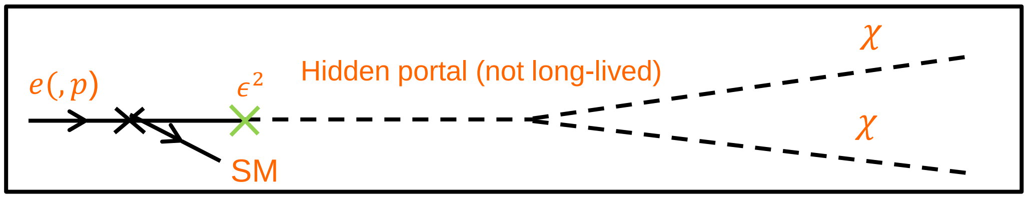
Production — Detection

Indirect (invisible)



Escape detector
Missing energy/momentum/mass
Probability $\propto \epsilon^2$

Cannot be directly distinguished
→ Model-dependent interpretation

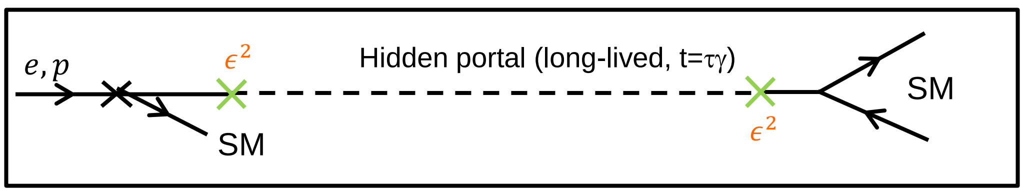


If $m_{HP} > 2m_{DM}$
Escape detector
Missing energy/momentum/mass
Probability $\propto \epsilon^2$

ATLAS
CMS
LHCb
NA64
LDMX

Use of electrons limits search to Dark Photon mediator & ALPs

"Direct" (indirect visible)



Decay signature ("displaced vertex)
Probability $\propto \epsilon^4$
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MATHUSLA
ANUBIS
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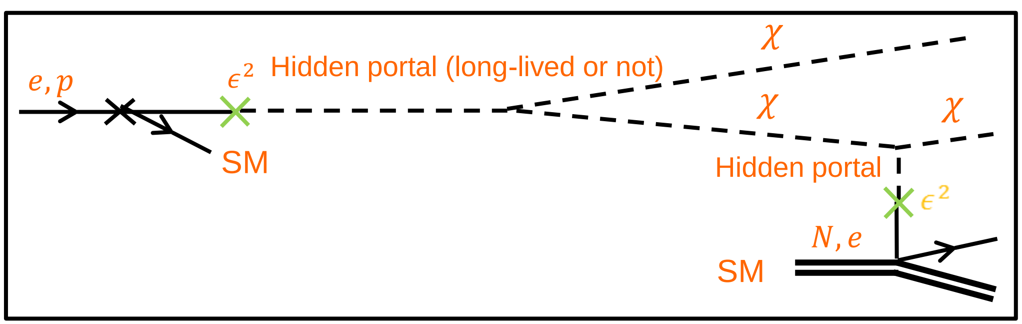


Dark matter scattering
Recoil against electron or nuclei
Probability $\propto \epsilon^4$
Model-dependent interpretation

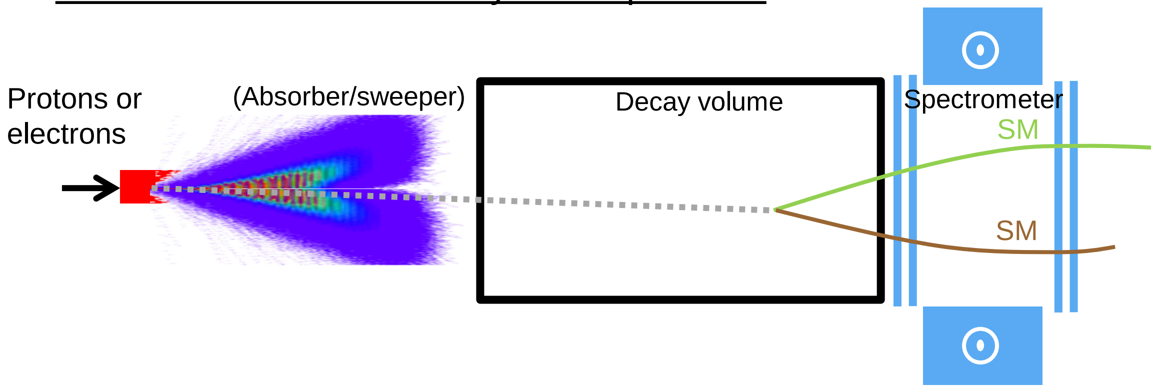
SHiP
SND@LHC

ϵ^4 dependence requires higher luminosity

➔ Background situation very different in the different techniques!

Experimental setups

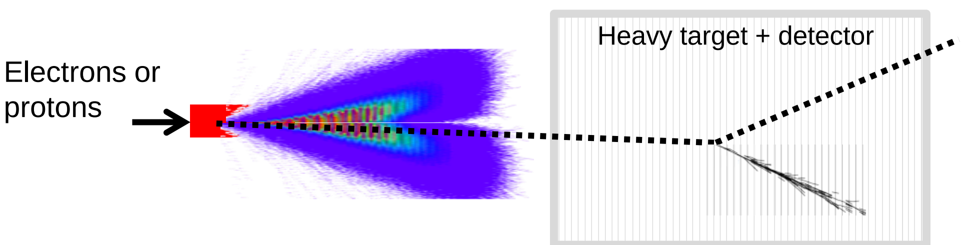
- Direct search: visible decay to SM particles



"Fixed target mode setups":
NA62++@CERN (p@400, 10^{18})
HPS, APEX, DarkLight@JLAB (e@1-10)
SHiP@CERN (p@400, 2×10^{20}),
SeaQuest@FNAL (p@120, 10^{18}–10^{20})
(LBNF@FNAL)

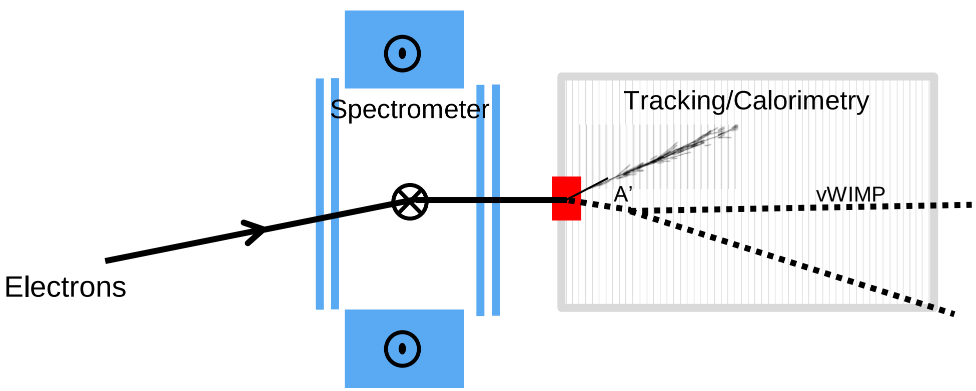
ATLAS, CMS, LHCb @LHC (no absorbers)
BELLE2@sKEKB (no absorber)
FASER@LHC
MATHUSLA@LHC (no spectrometer)

- Direct search: Scattering off atomic electrons and nuclei



"Fixed target mode setups":
BDX@JLAB (e@11, 10^{22}),
MiniBooNE@FNAL (p@8.9, 10^{20}),
SHiP@CERN (p@400, 2×10^{20})
(interest for BDX-like experiments at LNF, Mainz (MESA), SLAC, Cornell…)

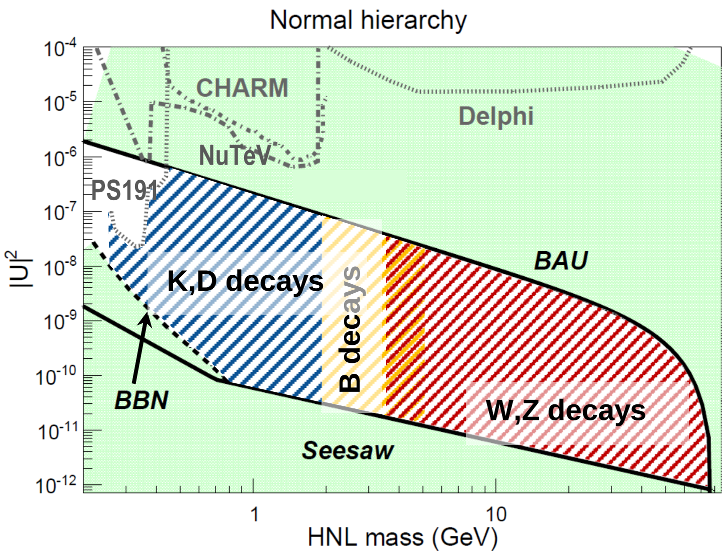
- Indirect search: Missing energy/momentum (slow extraction/electron association)

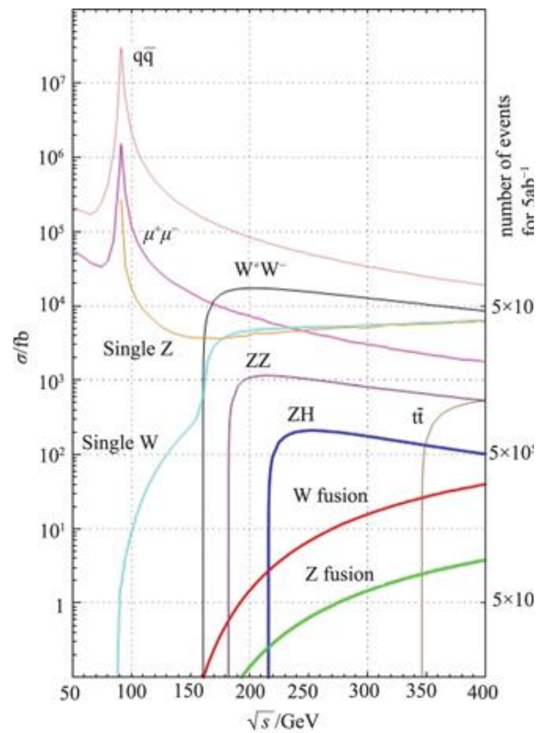


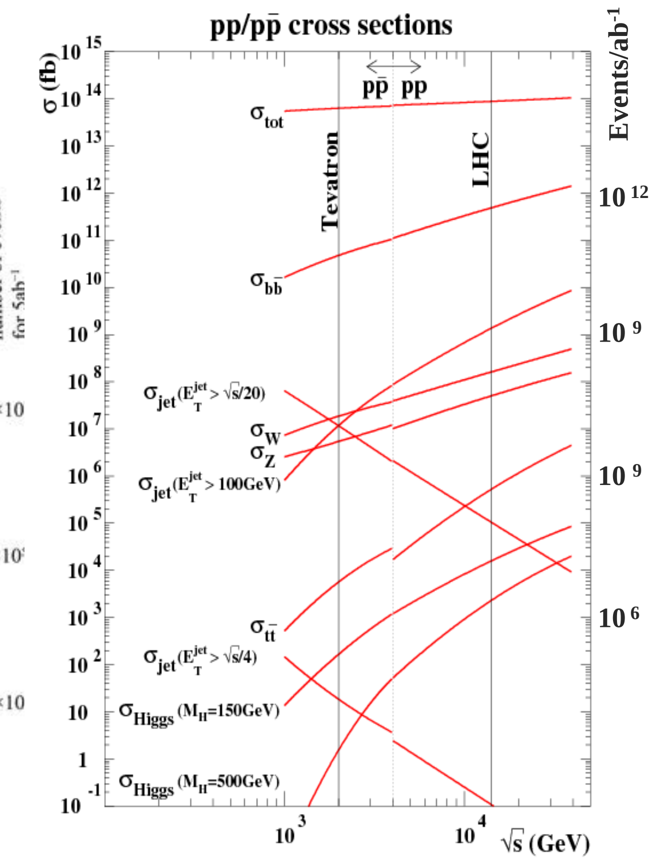
NA64/NA64++ @CERN (e@100, 10^{12})
LDMX@SLAC/CERN (e@4-8/16, 10^{14} - 10^{16})

Putting it all together

- We need massive production of $\gamma, g/q, b, W, Z, H$!
  - ➔ General purpose machines: ee, pp colliders and proton injectors for beam dumps
  - ➔ Higher energy is not the driver (cross-sections at lepton colliders, background at hadron colliders)

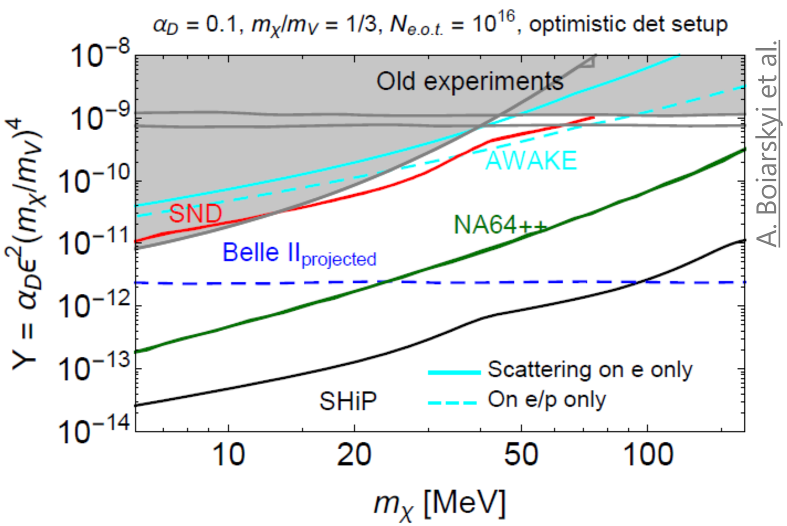


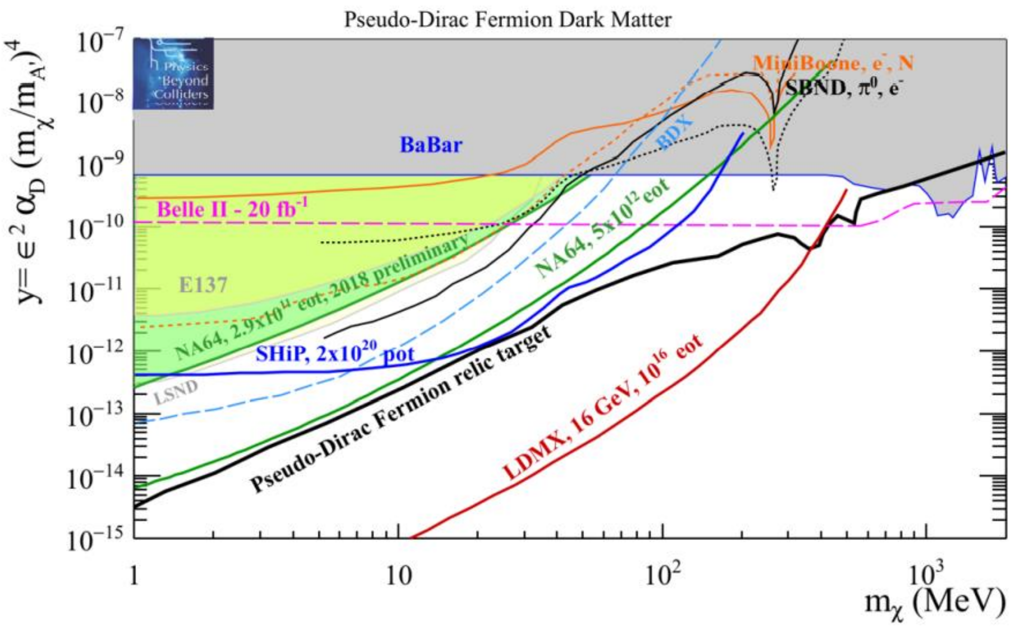




Putting it all together…

- Other machines…
  - Electron beam dumps
    - ➔Limited to dark photon/ALP(γ-coupling) coupling
    - ➔ε^2- sensitivity suffers from measuring accurately each incoming electron
    - ➔ε^4- sensitivity suffers from electron yield



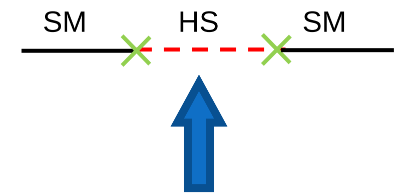


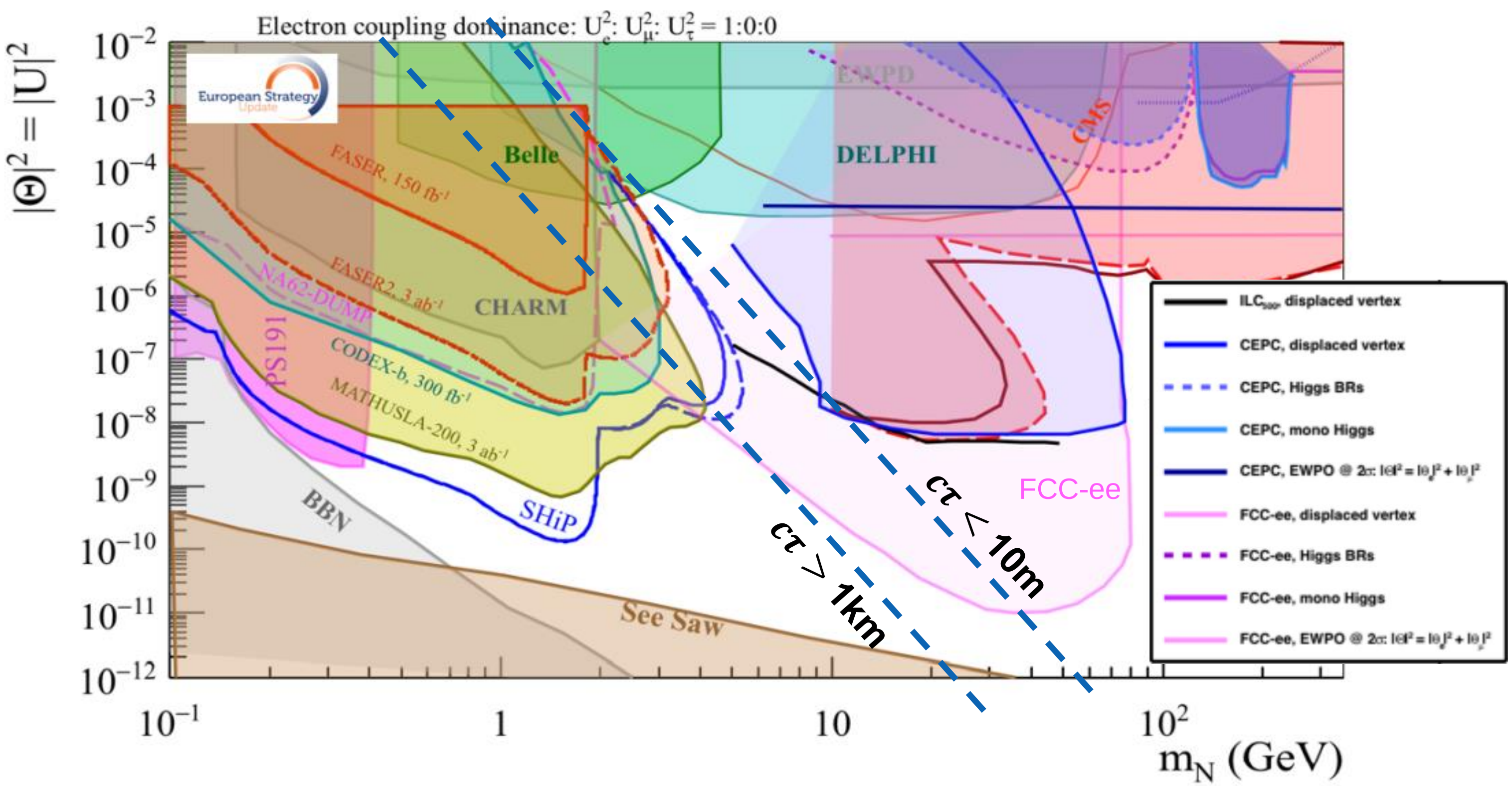
  - Muon colliders – higgs and Drell-Yann production
  - Neutrino facilities with off axis detector – lower energy (below m_K), light targets i.e. huge neutrino backgrounds…
  - Gamma factory – low mass

Caught between a rock and a hard place

- Acceptance and background are the biggest challenges!
  - Dilemma: background/pile-up versus absorbers/sweepers
  - New states are typically long-lived, e.g. HNL $\tau_N \sim \frac{96\pi^2 h}{|\mathcal{U}|^2 G_F^2 M_N^5}$

  ➔ Lifetime $\otimes\ \epsilon \times 4\pi$ challenge





Complementarity

Complementarity between accelerator-based search methods and experimental configurations

- Classical collider detectors:

➔higher particle mass, complete geometric acceptance and short lifetimes

➔Displaced vertex $100\mu m \lesssim c\tau \lesssim 10m$ or missing energy

- Distant voluminous collider detectors

➔ higher particle mass, *longer* lifetimes, limited geometric acceptance/4π and/or limited detection techniques

- Beam dump experiments

➔ High luminosity and geometric acceptance (boost), lower particle mass, long lifetimes

- E.g. SPS luminosity for a long target (e.g. 1m++ Mo/W) with 4×10^{19} pot/year
- Maximum atomic number and charge (=short X_0/λ_{int}) to increase cross-section for charm, beauty hadron and radiative processes AND reduce neutrino flux by stopping $\pi^{\pm}, K^{\pm}$

➔ Tuned to $m_K - m_b$ mass range

- SPS $\mathcal{L}_{int}[yr^{-1}] = 10^6 s \times \int_0^{"\infty"} \Phi_0 \times \rho_N \times e^{-l/\lambda} dl = \Phi_0 \times \rho_N \times \lambda$ = 3.6×10^{45} cm^{-2} (cascade not incl. ~2.6x for charm)
- HL-LHC $\mathcal{L}_{int}[yr^{-1}] = 10^7 s \times 10^{35}$ s^{-1}cm^{-2} = 10^{42} cm^{-2}

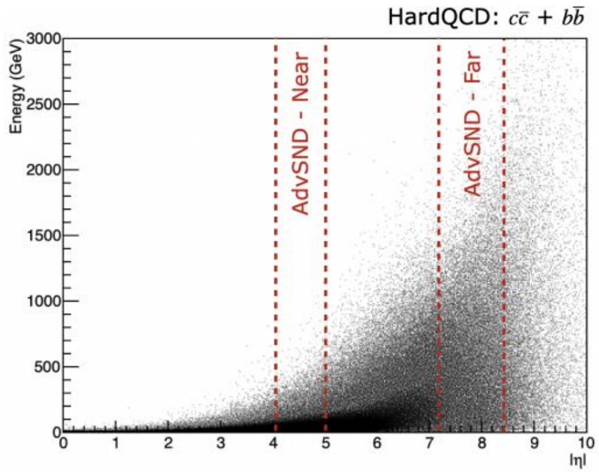
➔ LHC ($\sqrt{s}$ = 14 TeV): with 1 ab^{-1}, i.e. 3-4 years: ~ 2×10^{16} D's in 4π

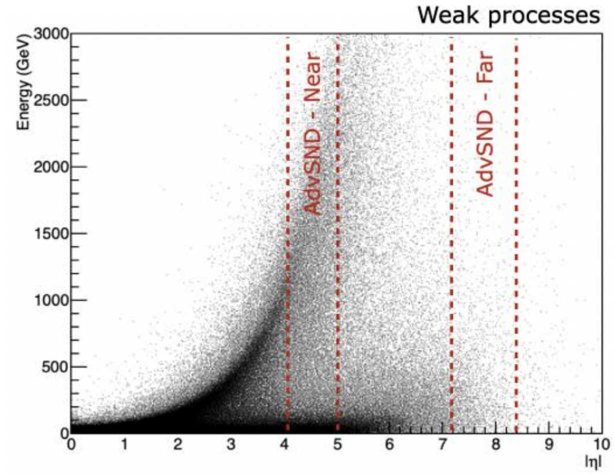
➔ SPS@400 ($\sqrt{s}$ = 27 GeV) with 2×10^{20} pot, i.e. ~5 years: ~ 2×10^{17} D's

Forward production at colliders

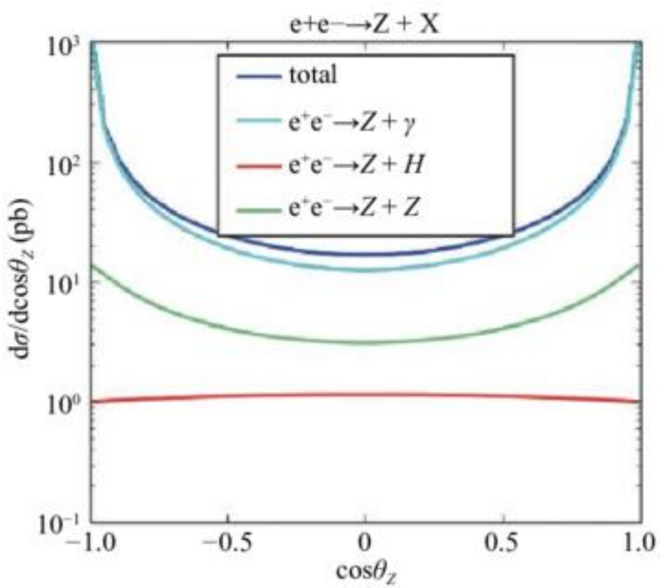
- Beam-dump style detectors at colliders (asymmetric?)

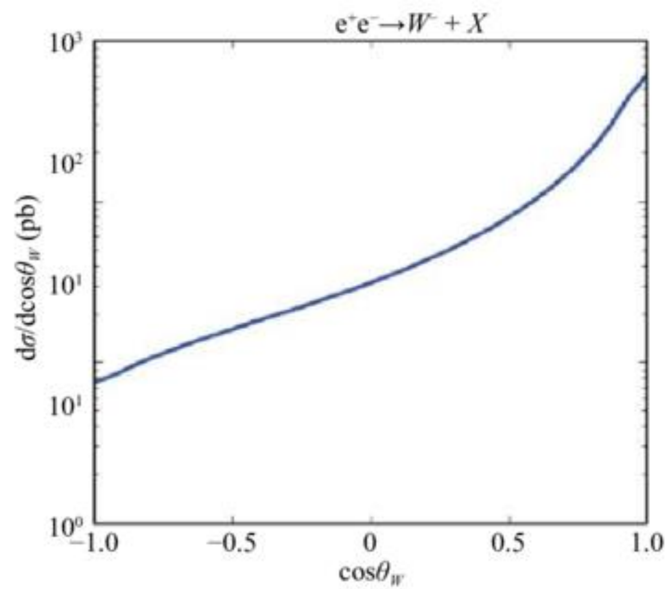
<u>pp-collider</u>



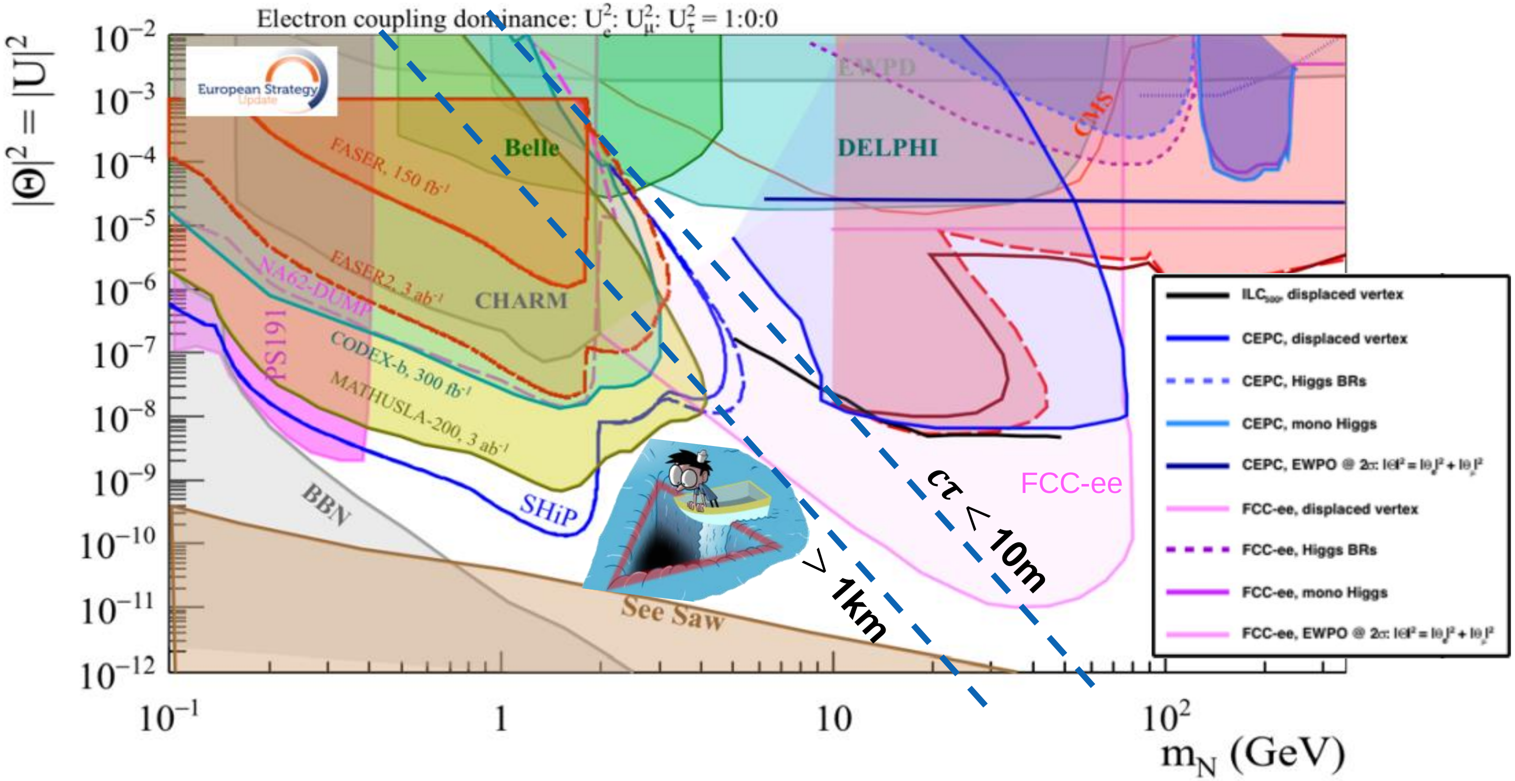


<u>e⁺e⁻-collider</u>





Hidden hidden sectors…



Bermuda triangle?

Production in B and W, Z decays with $c\tau\gamma \sim kmS$…

t-channel production from W exchange and forward large detectors a la $proton$-dump at distance from a collider IP?

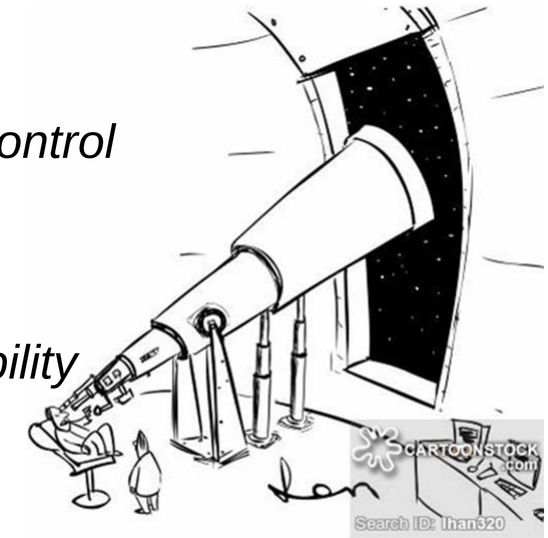
A not so little plea

Do I want to go home with an exclusion, having a doubt that I control the background… ?

or worse…

discovering something with no clue what it is and with no capability to characterise the signal…?

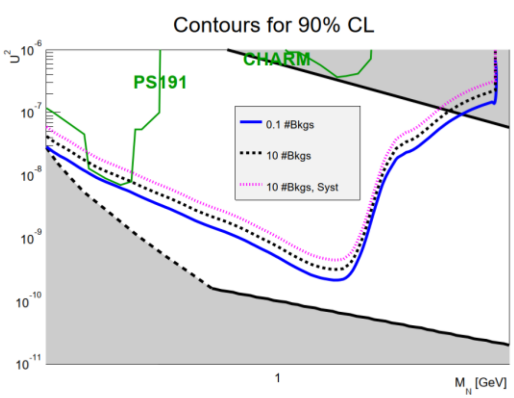
and perhaps still be worrying about my control of the background…?

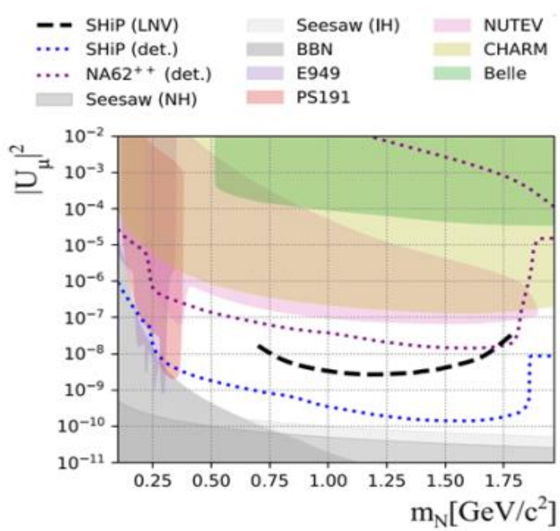


"I've either discovered dark matter, or I've left the lens cap on."

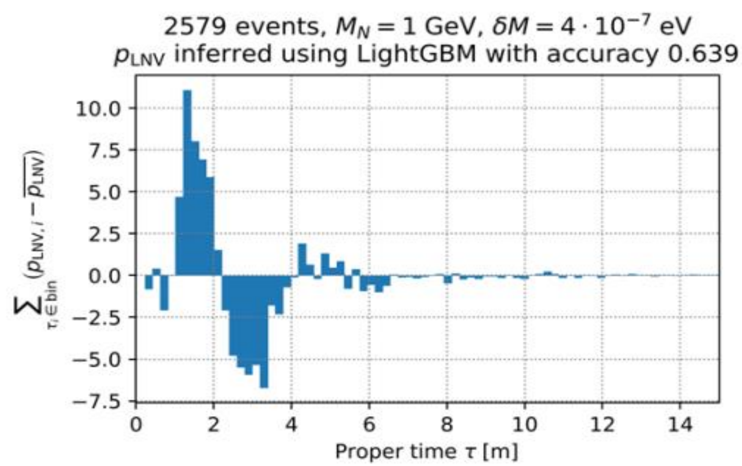
Example of model characterisation by SHiP in case of discovery

→ Sensitivity to oscillations between lepton number conserving and violating rates





arXiv:1912.05520 (2020)



Sensitivity – devil is in the background

"exclusion plots *under the assumption of zero background",* what does it mean?

- To exclude or discover (compute the significance of the observation) a hypothetical signal, the experimental data should be tested against the new physics model AND against a background only hypothesis, to see which of the two can be excluded
  - ➔ with appropriate well-understood uncertainties on the background

- Optimizing an analysis for discovery or exclusion may lead to a different setup and selection criteria
  - Optimising for discovery aim for very high signal-to-background ratio, even at the cost of acceptance and efficiency. Separating events into high signal-to-background ratios and low signal-to-background ratios classes and combining the results gives optimal sensitivity.
  - Optimising for exclusion aim at improving signal acceptance at the cost of letting in more background.

  ➔ Difference in signal/background of hadron and lepton machines

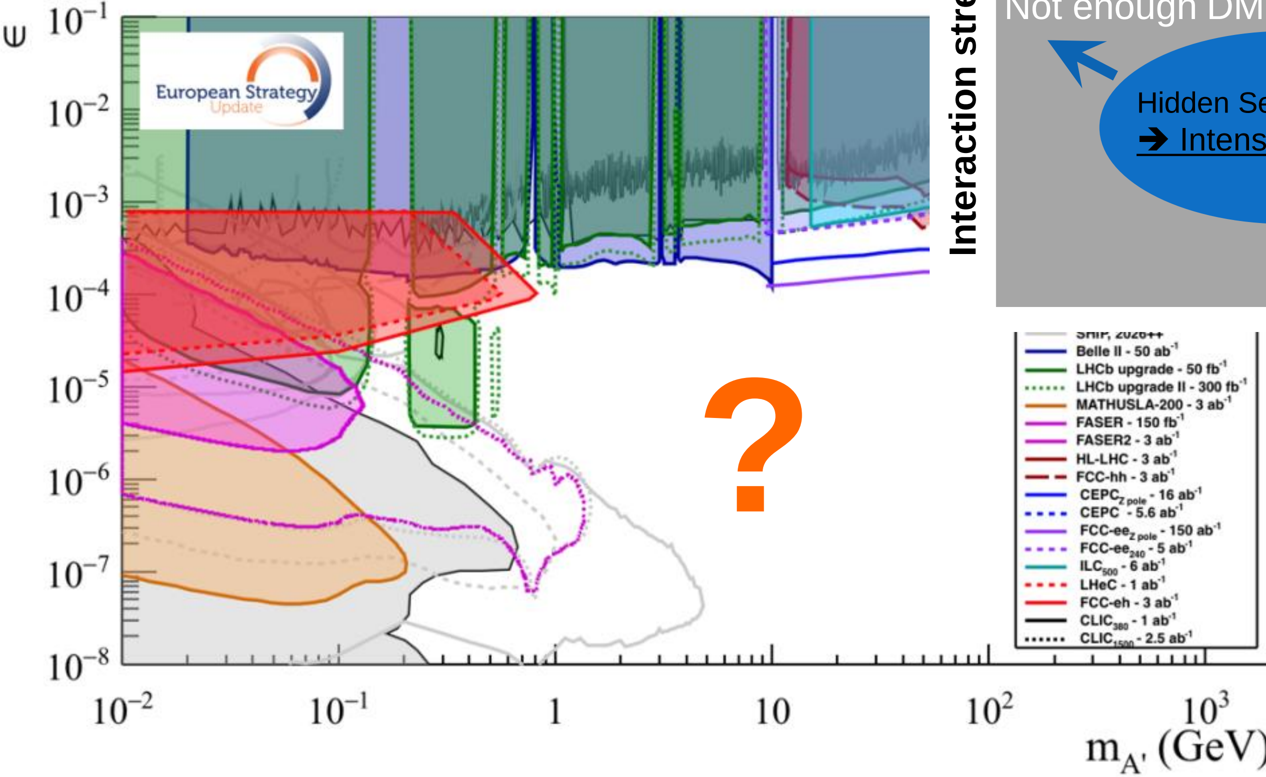
- Control of background essential
  - Binning of observables from event reconstruction: kinematics, mass, particle identification
  - Importance of control regions to constrain uncertainties on background
  - Machine Learning for optimisation relying on multiple quantities

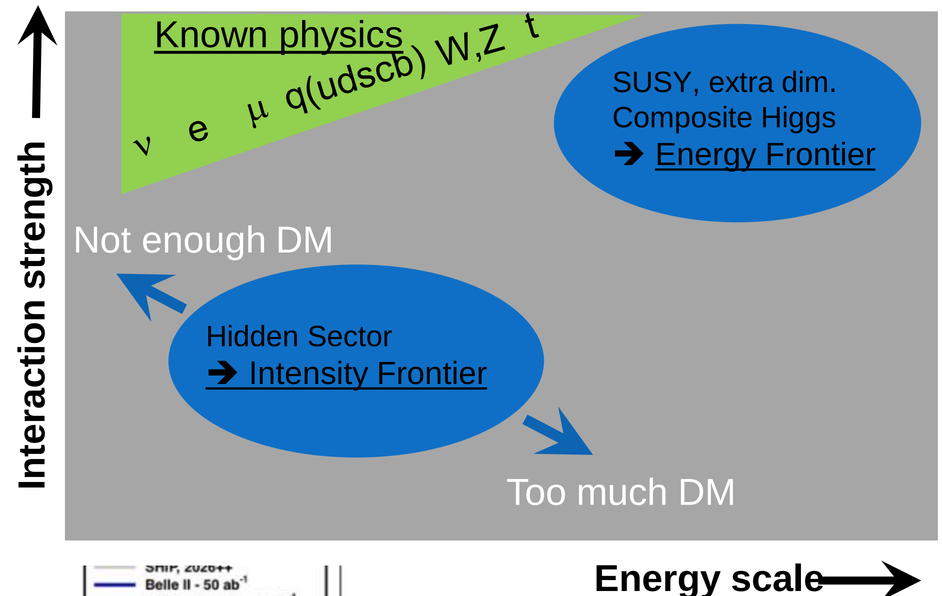
  ➔ Detailed simulations (several models for event generators and detector simulations), subsidiary measurements, full simulations… define maturity

Another plea…the log scale deception

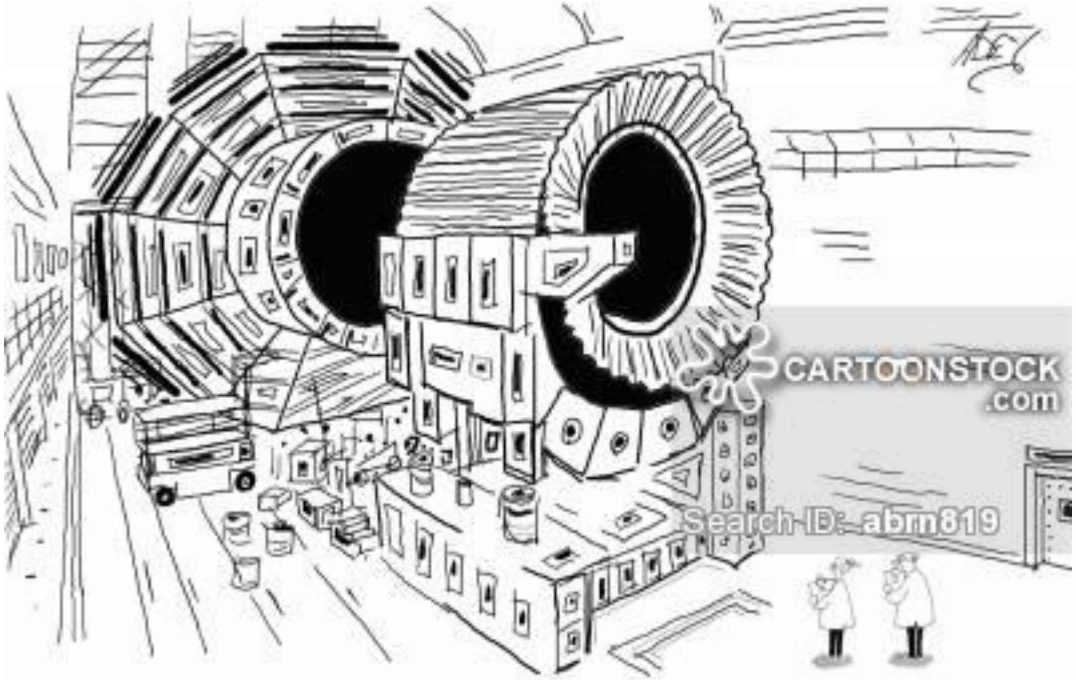
- Large number of options and huge parameter spaces
  - All parameter spaces have their "unreachable" regions, even physically attractive regions!

➔ Theoretical model building and cosmofrontier are essential guides!





Conclusion



“If all else fails - it makes a great frothy latte.”