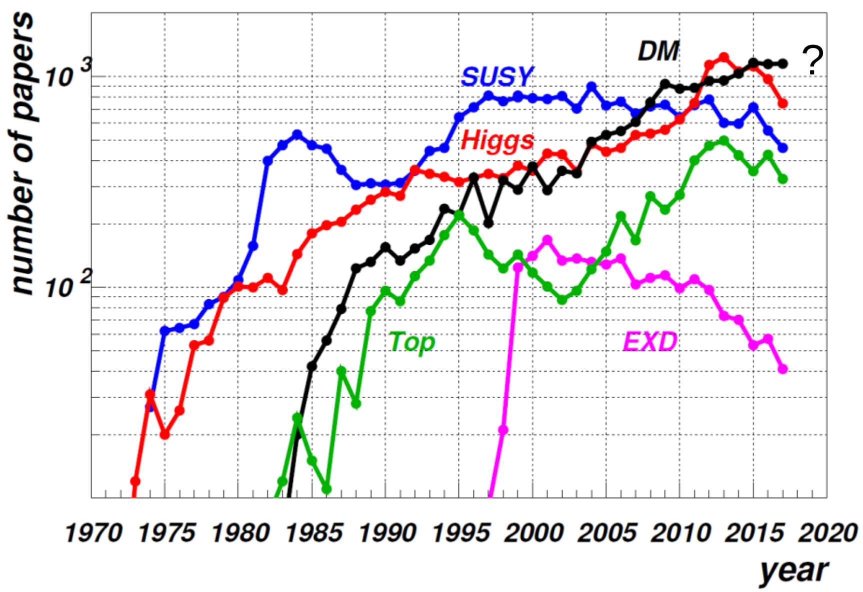
Search for Hidden Particles

Richard Jacobsson



A. Belyaev, Southhampton University & RAL

A more complete seminar, BE/OP quarantine lectures:
https://indico.cern.ch/event/891907/

Hidden/Dark Sector?

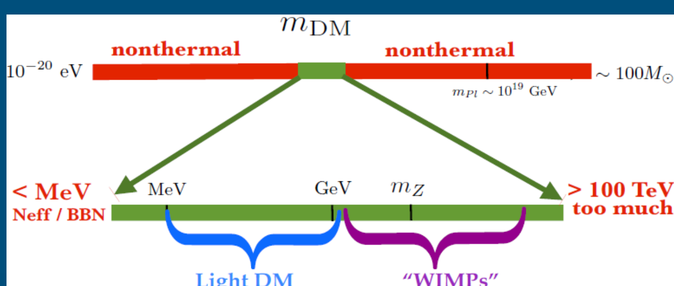
- 7% of LHC+HL-LHC data recorded - no unambiguous sign of NP
  - ➔ New physics (particles) should either be very
    - ➔ heavy if interactions have $\mathcal{O}$(SM strength) (e.g. SUSY, Technicolour)
    - ➔ or light, and be very feebly coupled

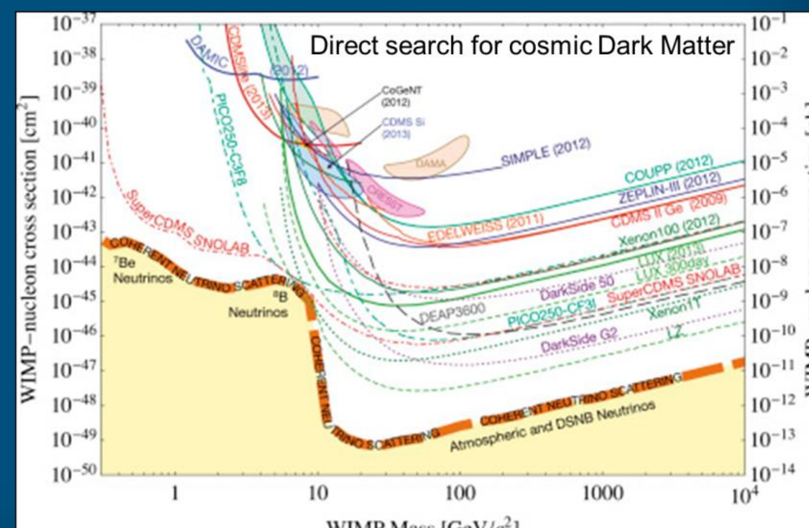
$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \sum_{d>4} \frac{c_n^{(d)}}{\Lambda^{d-4}} \mathcal{O}^{(d)}$$

- Hidden Sector : Any Particles engaging in Feebly (or no) Interactions (FIPs) with the SM particles
  - Fair (<u>but not necessary</u>) 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!)





Experimental guidance?

Limited theoretical guidance on the Higgs boson initially…

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

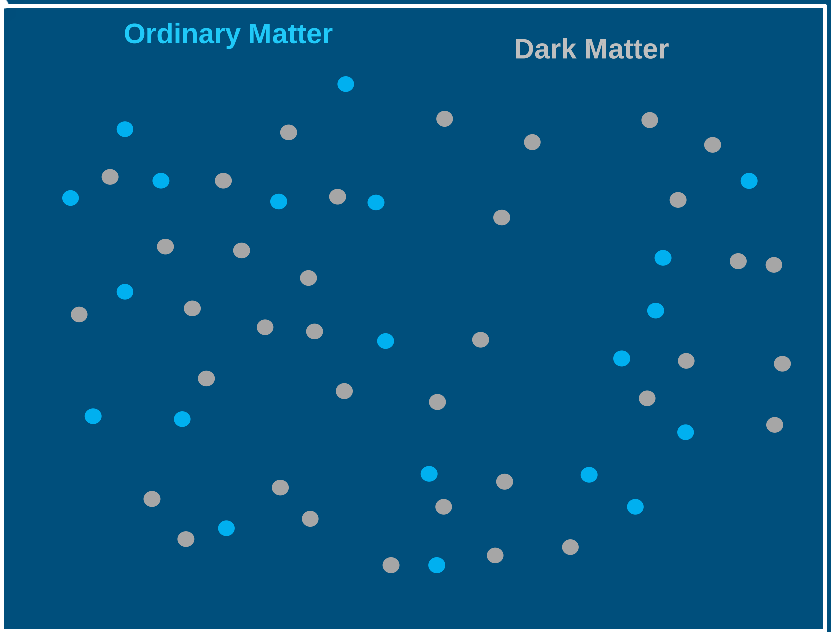
334 *J. Ellis et al. / Higgs boson*

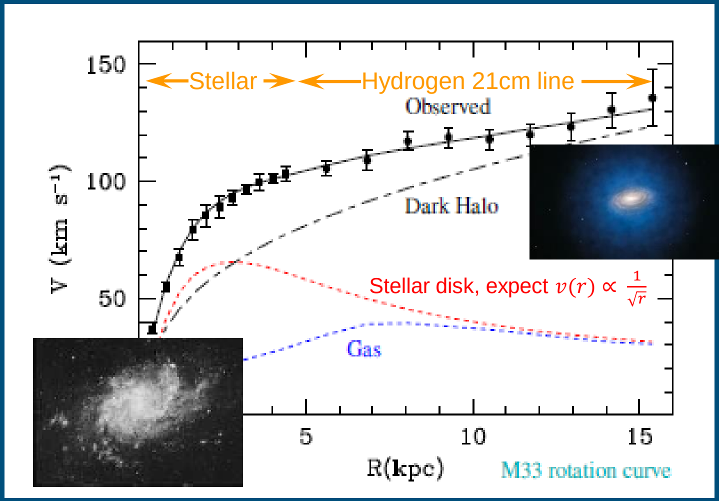
We should perhaps finish with an apology and a caution. We apologize to experimentalists for having no idea what is the mass of the Higgs boson, unlike the case with charm [3,4] and for not being sure of its couplings to other particles, except that they are probably all very small. For these reasons 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

Multi-million dollar question

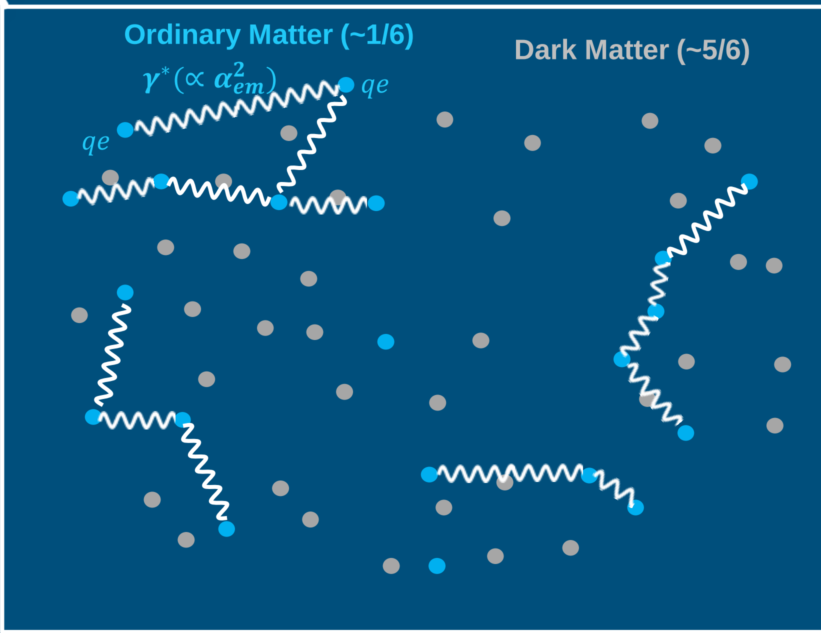
A sample of space

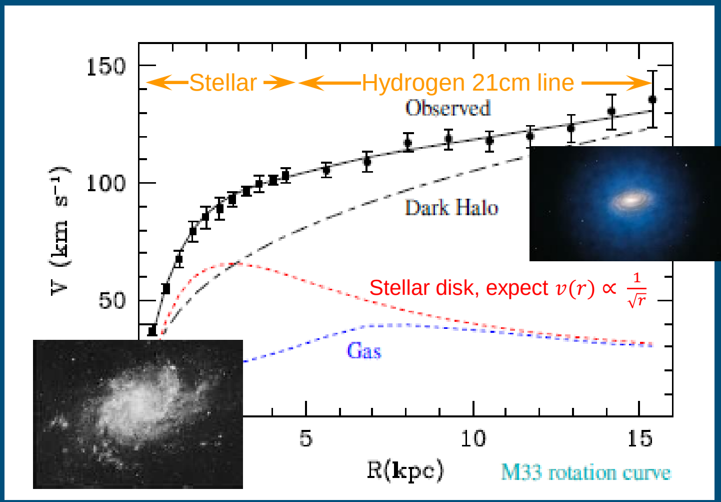




Multi-million dollar question

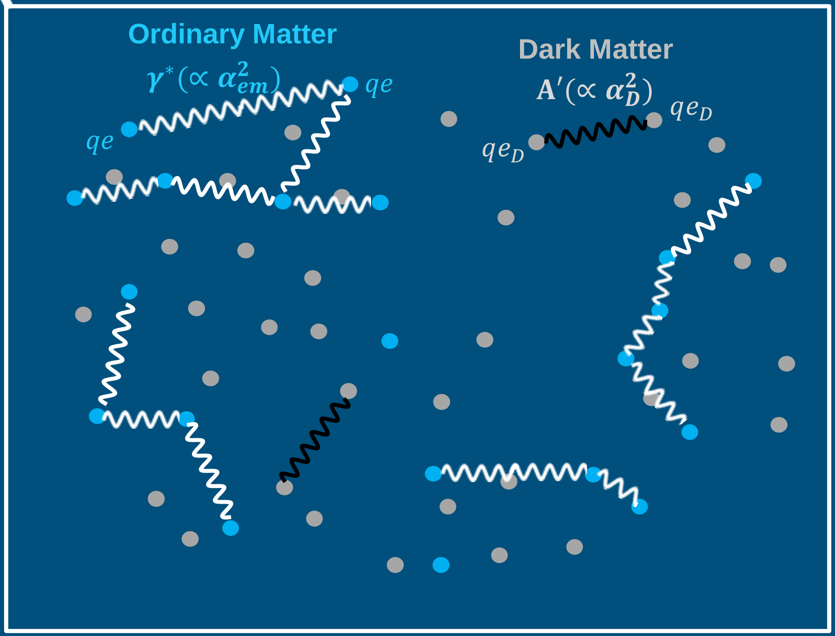
A sample of space and matter

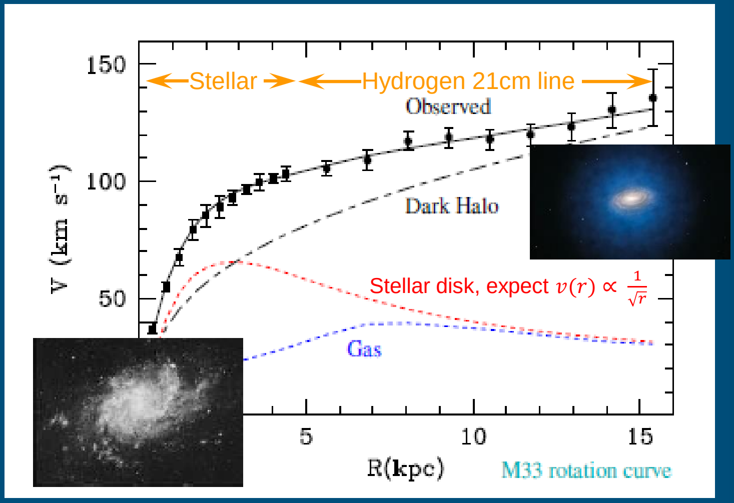




Multi-million dollar question

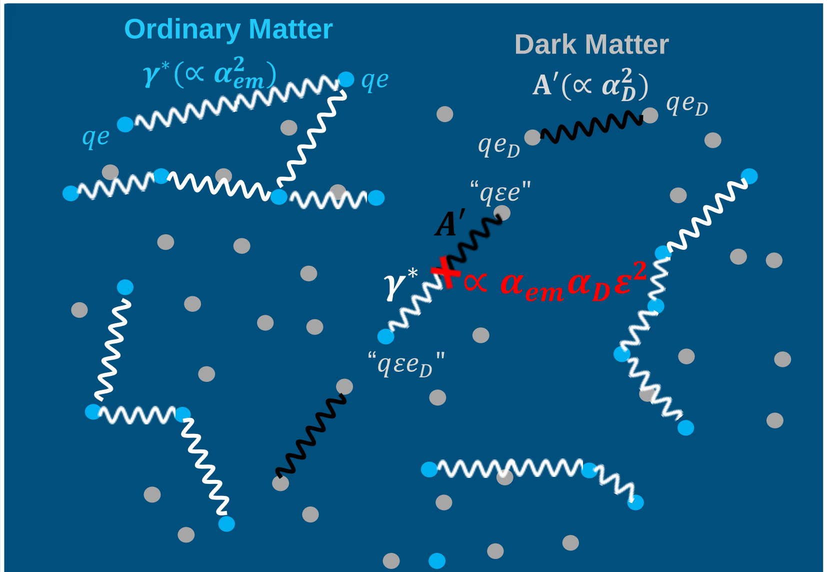
A sample of space



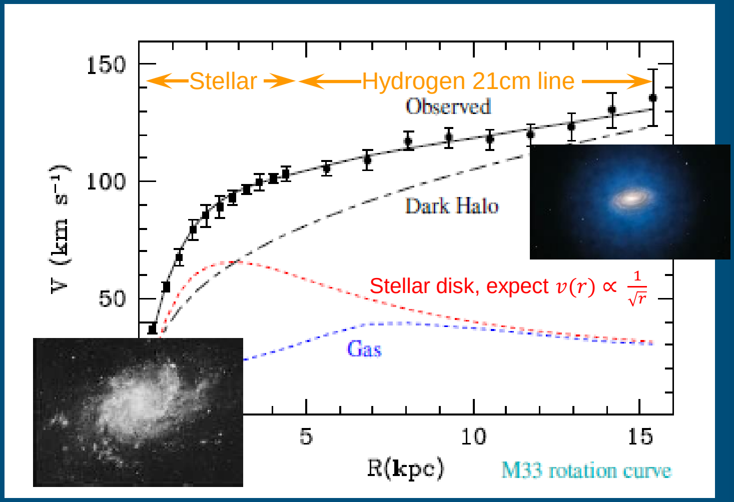


Multi-million dollar question

A sample of space

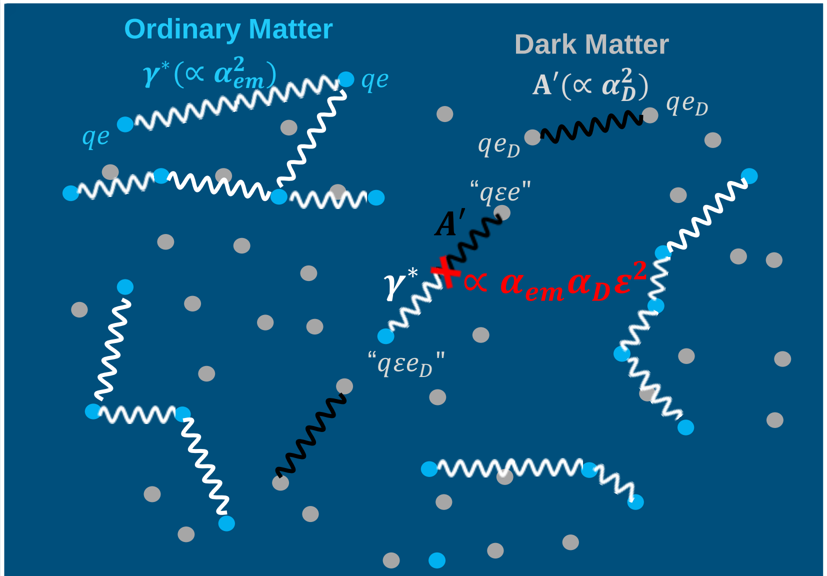


DM self-interaction and boson-dark boson mixing

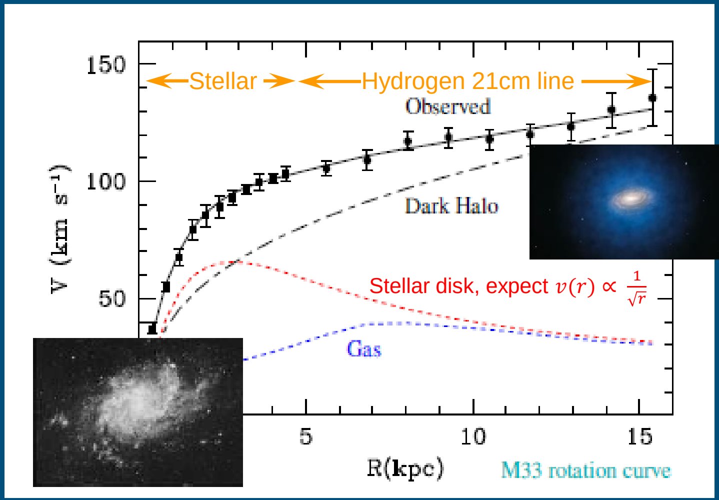


Multi-million dollar question

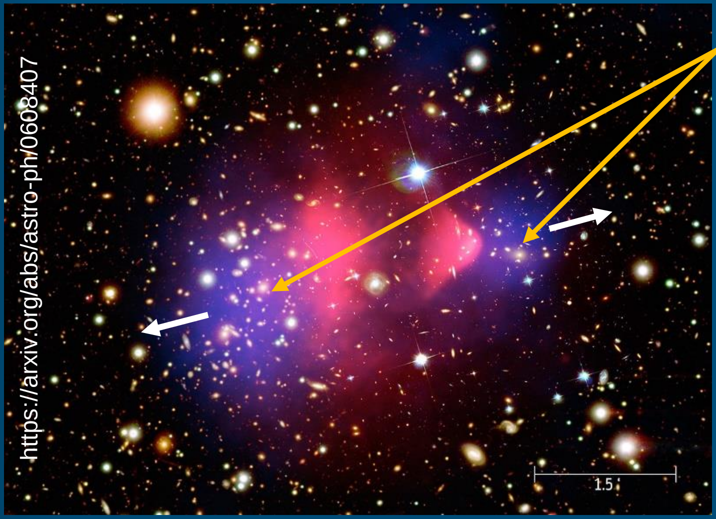
A sample of space



DM self-interaction and boson-dark boson mixing



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 (1-2% of mass) seemingly undisturbed

➔Almost(?) collisionless

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

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

Standard model of a feebly interacting 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:
    - Lagrangian equation of motion + wave function + relativity + quantization + fields + symmetries ↔ conservation + renormalizability, …
    - Lagrangian $\mathcal{L} \equiv [Kinetic\ terms] - [Potential\ energy] \overset{SM}{\Longrightarrow} [Freemoving\ particles] - [Interactions]$
    - Dark states must be neutral under Standard Model

➔ Dark Photons, Dark Scalars, Heavy Neutral Leptons, Axion-Like Particles, fermionic/scalar DM

…. 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, …

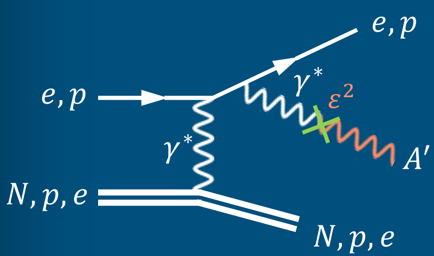
➔ A lot of theoretical work still to be done, not so many models on the market yet

➔ A lot of experimental work still to be done on cosmology and astrophysics

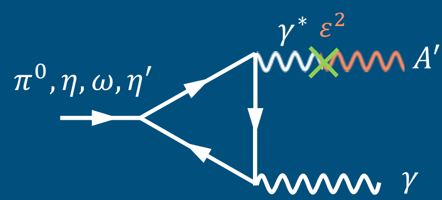
- Also some SUper-SYmmetric "portals" etc
  - Sgoldstino, Neutralino in R-Parity Violating SUSY, Hidden Photinos, axinos and saxions….

Production

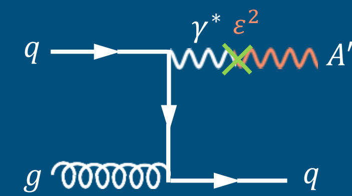
Dark photons: need loads of photons!



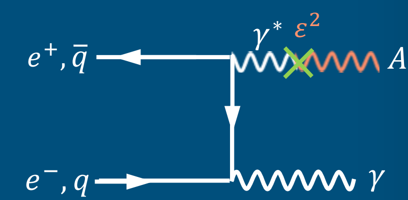
Bremsstrahlung



Light neutral meson decays



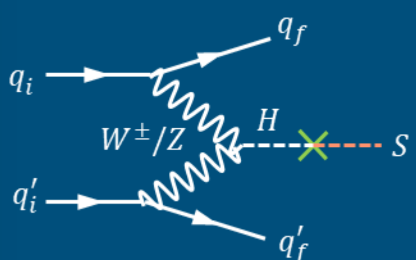
Quark/gluon scattering

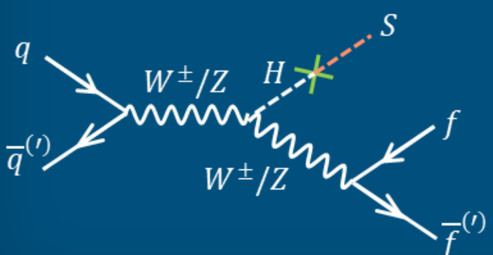


Annihilation

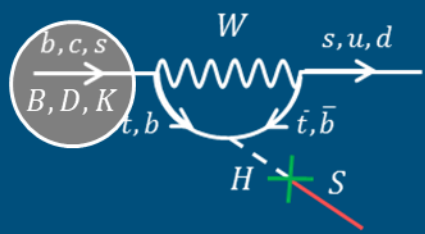
Dark Scalars: Loads of Higgses (real or virtual)!

pp colliders



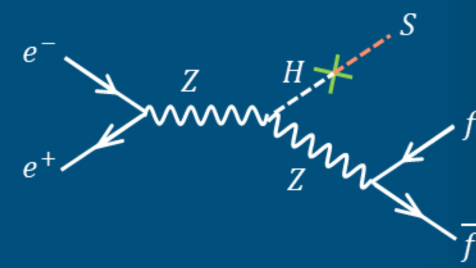


pp colliders or p beam dumps



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

Higgs factory

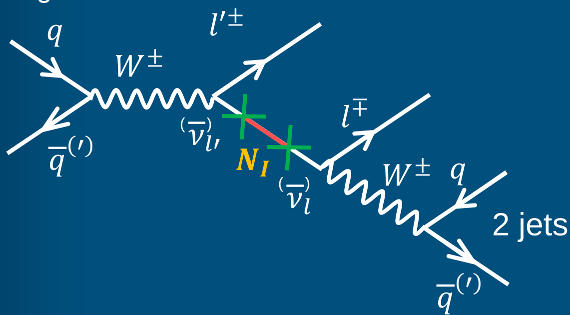


Production

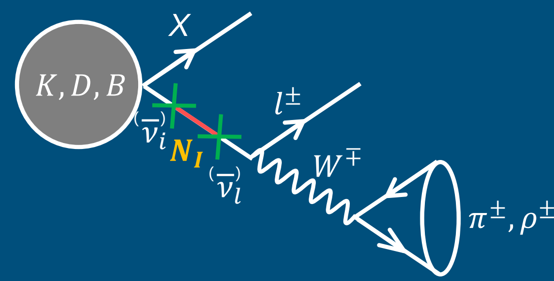
- Heavy Neutral Leptons: loads of neutrinos!

pp colliders

E.g.

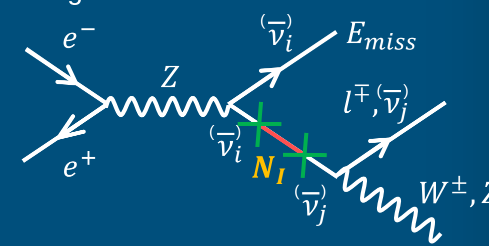


pp colliders or p beam dumps



e^+e^- colliders (W,Z)

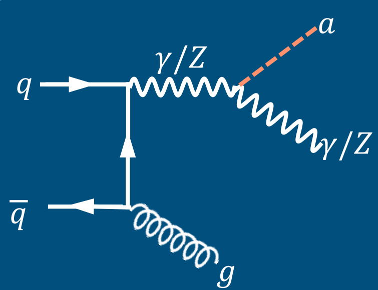
E.g.



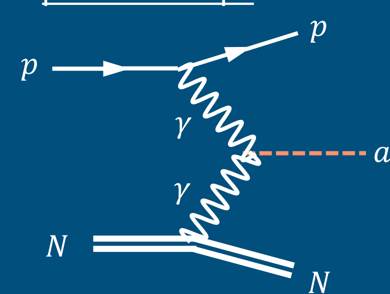
Axion-Like Particles: Couplings to photons, gluons and fermions, loads of interactions!

pp colliders

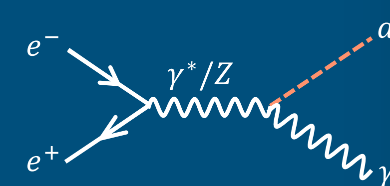
E.g.

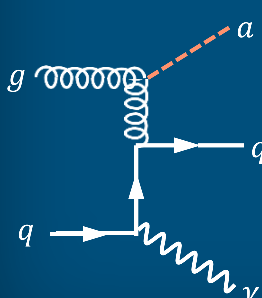


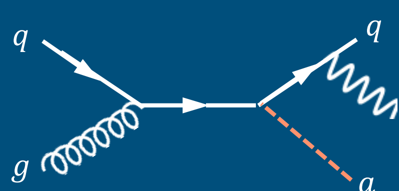
p beam dumps

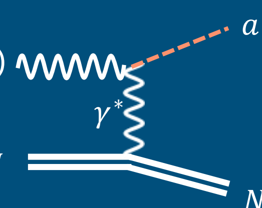


e^+e^- colliders









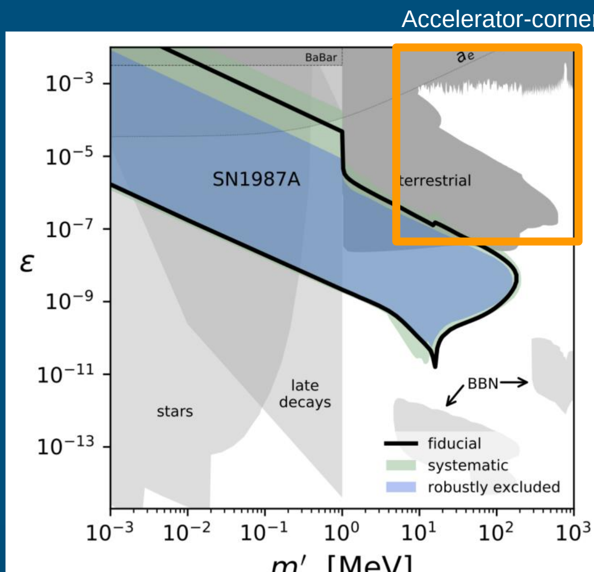
Complementarity

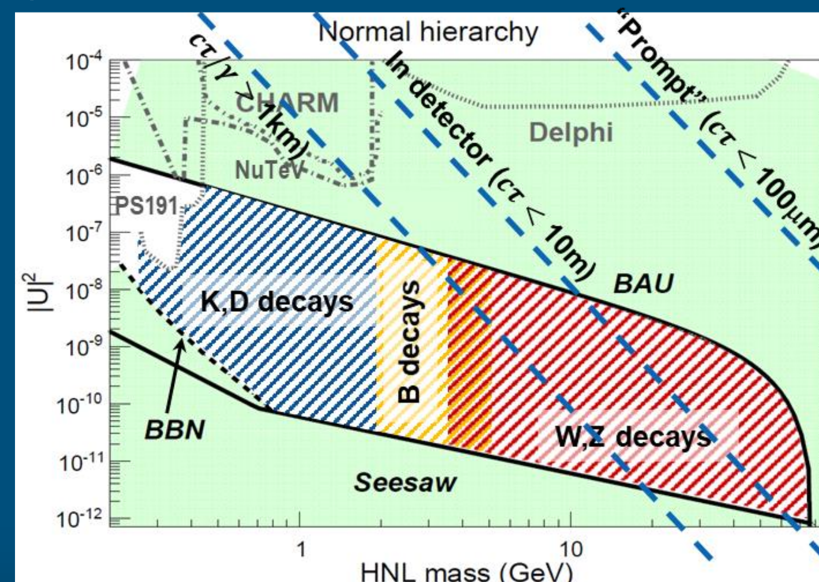
➔ New states are typically long-lived, e.g. HNL – neutrino mixing $\tau_N \sim \frac{96\pi^2 h}{|\mathcal{U}|^2 G_F^2 M_N^5}$

Complementarity between accelerator-based search methods and experimental configurations

- Classical collider detectors (ATLAS, CMS, LHCb):
  ➔ higher mass, complete geometric acceptance and short lifetimes (displaced vertex)
  ➔ …. or missing mass!
- Distant collider detectors (FASER, CODEX-b, MATHUSLA, ANUBIS):
  ➔ higher mass, *longer* lifetimes, limited geometric acceptance
- Beam dump experiments (NA62, NA64, SHiP, LDMX):
  ➔ High luminosity and geometric acceptance, lower mass, long lifetimes

➔ Verification/falsification of different techniques important





Optimisation of a proton beam dump experiment

Design for direct detection

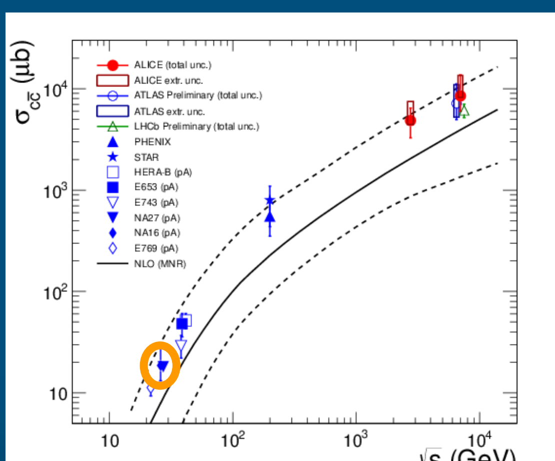
- Production branching ratios $\mathcal{O}(10^{-10})$ → <u>Largest possible number of protons</u>

  ➔ "Primary" SPS FT luminosity for a long target (e.g. 1m++ Mo, ρ_N nucleon density) with 4x10^{13} p/spill

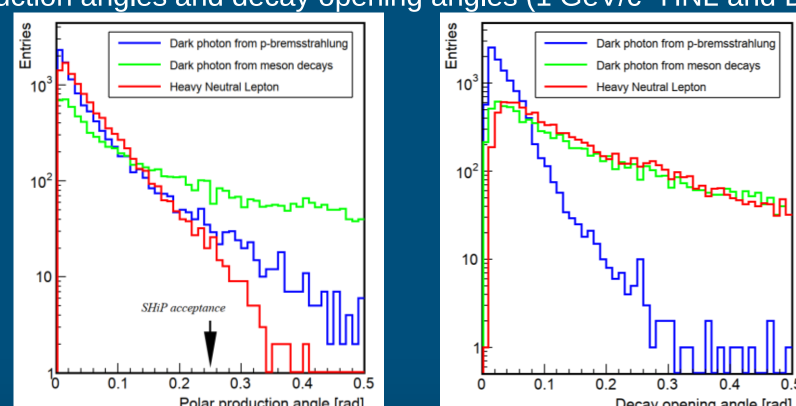
  SPS $\mathcal{L}_{int}[year^{-1}] = 10^6 s \times \int_0^{"\infty"} \Phi_0 \times \rho_N \times e^{-l/\lambda} dl = \Phi_0 \times \rho_N \times \lambda$ = <u>3.6 x 10^{45} cm^{-2}</u> (cascade not incl.)

  ➔ HL-LHC $\mathcal{L}_{int}[year^{-1}] = 10^7 s$ ×10^{35} s^{-1}cm^{-2} = <u>10^{42} cm^{-2}</u>

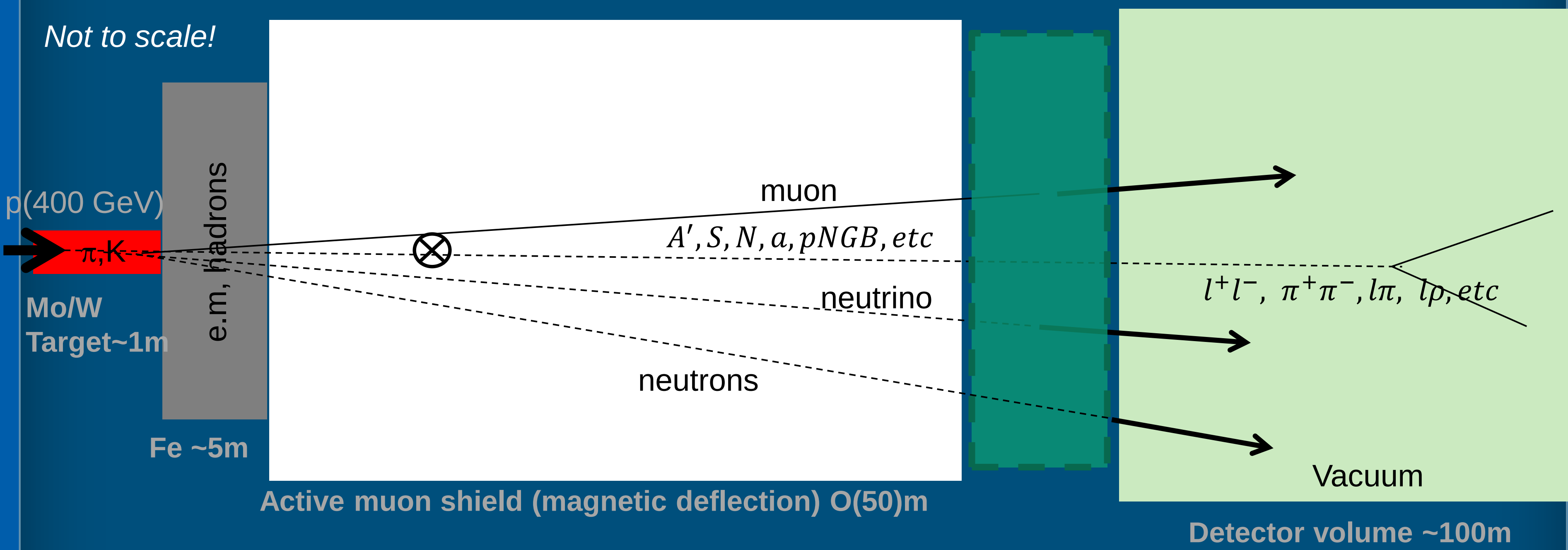
- Production in light and heavy hadron decays, photons → <u>High A and Z target</u>
- Large neutrino background → <u>Short λ target</u>
- Large muon flux → <u>Slow extraction (unique at SPS)</u>
- Hidden particles travel unperturbed through *ordinary* matter → <u>Filtering out beam induced background</u>
- Significant production angles → <u>Decay volume as close as possible</u>
- Long-lived objects → <u>Long decay volume</u>
- Detection by visible decays → <u>Full reconstruction and identification</u>
- Detection by scattering → <u>Large detector target mass</u>



Production angles and decay opening angles (1 GeV/c^2 HNL and DP)



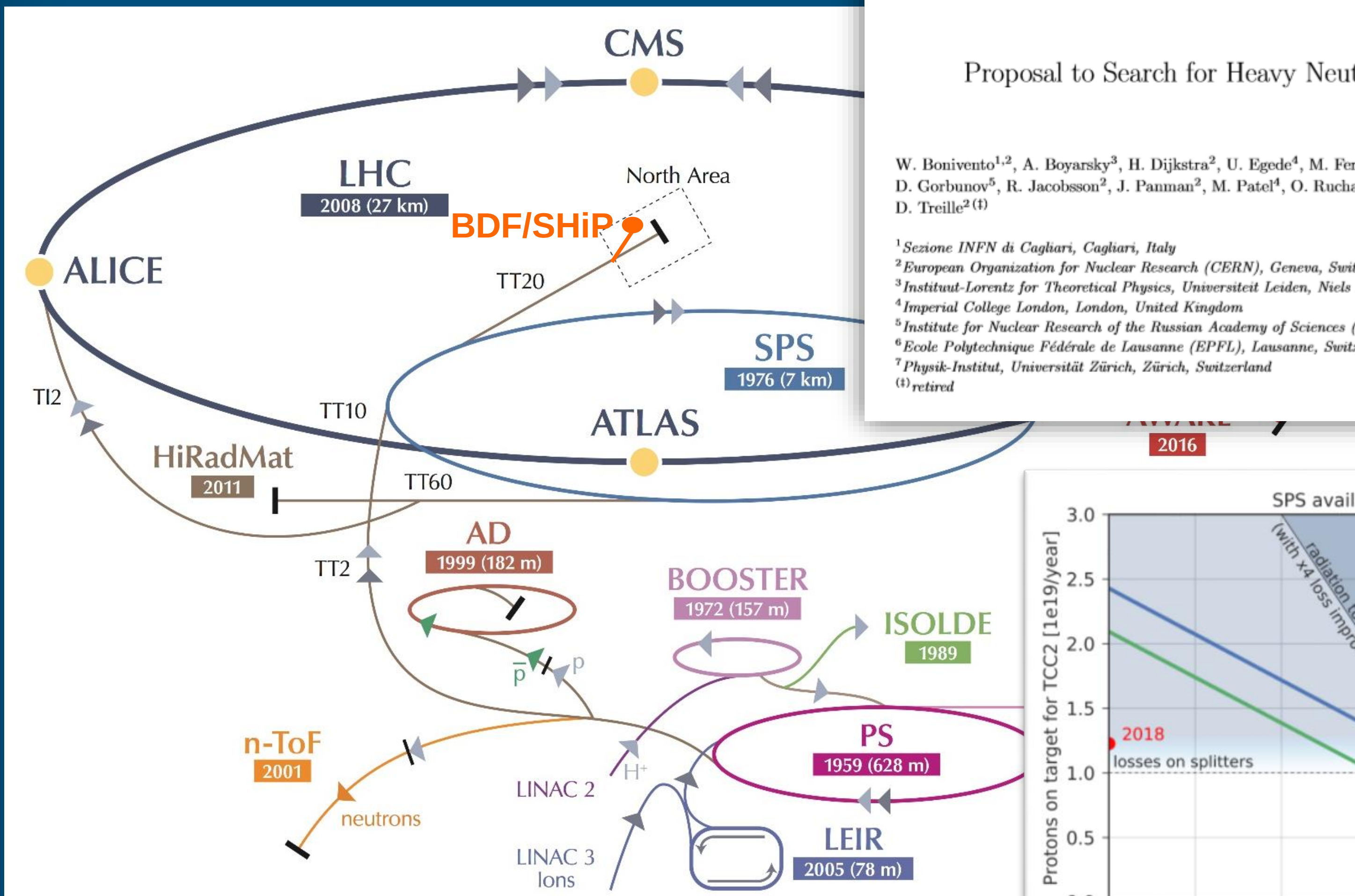
Schematically



Beam Dump Facility

- 2013 Oct: EOI with SHiP@SPS North Area, right E and 4x10^{19} p/year 'free' after CNGS
  ...following brainstorming SHiP@IP8, SHiP@LBD, SHiP@CNGS, SHiP@WANF

arXiv:1310.1762



CERN-SPSC-2013-024 / SPSC-EOI-010
October 8, 2013

Proposal to Search for Heavy Neutral Leptons at the SPS

W. Bonivento[1,2], A. Boyarsky[3], H. Dijkstra[2], U. Egede[4], M. Ferro-Luzzi[2], B. Goddard[2], A. Golutvin[4], D. Gorbunov[5], R. Jacobsson[2], J. Panman[2], M. Patel[4], O. Ruchayskiy[6], T. Ruf[2], N. Serra[7], M. Shaposhnikov[6], D. Treille[2 (‡)]

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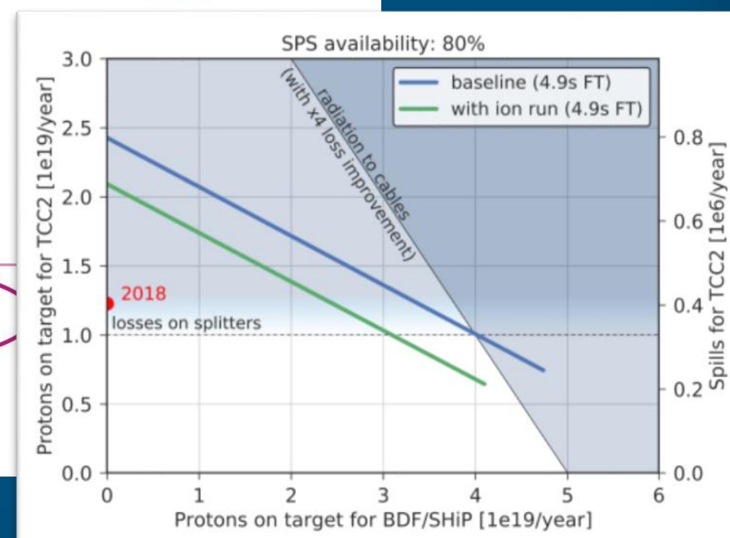
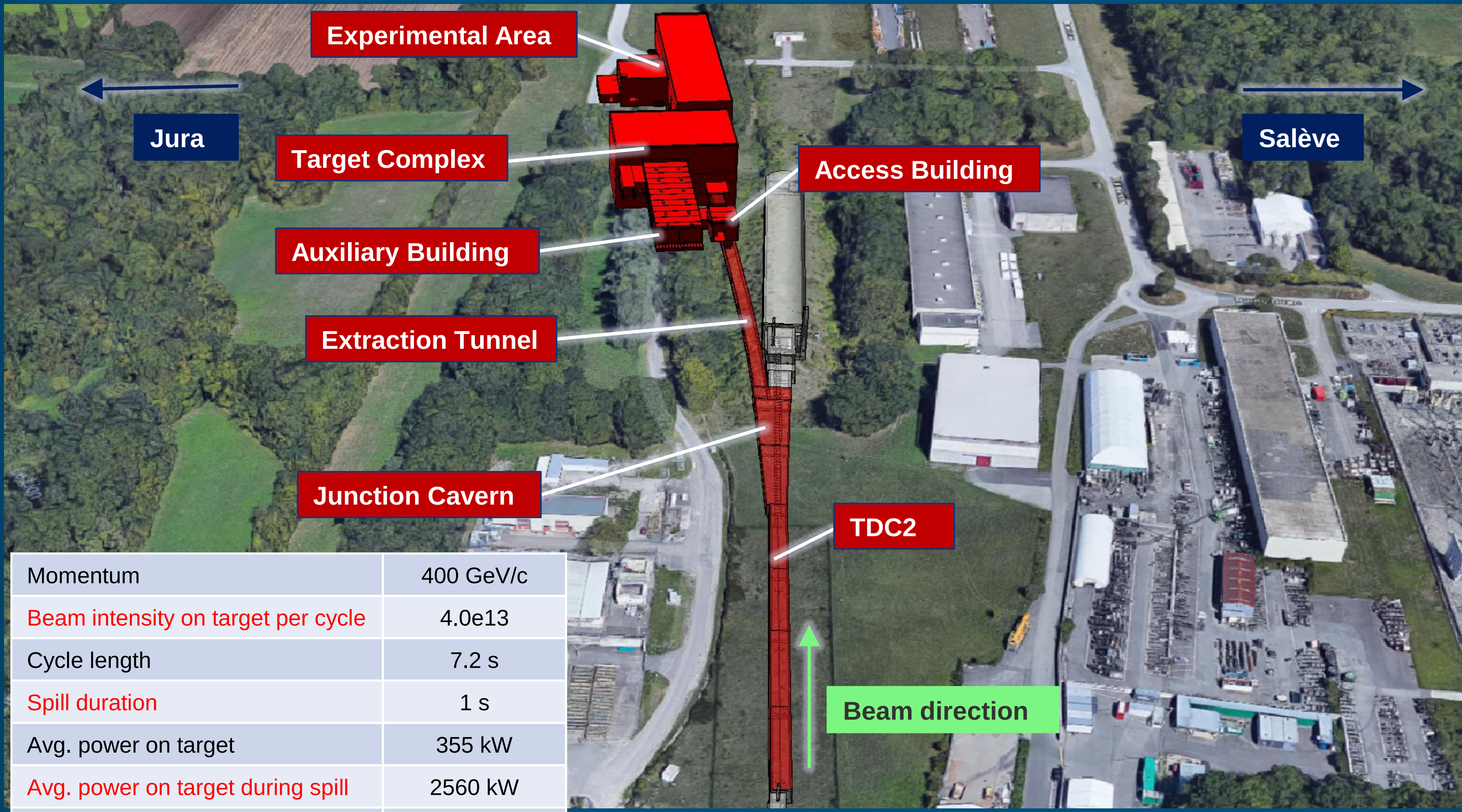
[3] *Instituut-Lorentz for Theoretical Physics, Universiteit Leiden, Niels Bohrweg 2, Leiden, The Netherlands*
[4] *Imperial College London, London, United Kingdom*
[5] *Institute for Nuclear Research of the Russian Academy of Sciences (INR RAN), Moscow, Russia*
[6] *Ecole Polytechnique Fédérale de Lausanne (EPFL), Lausanne, Switzerland*
[7] *Physik-Institut, Universität Zürich, Zürich, Switzerland*
(‡) *retired*

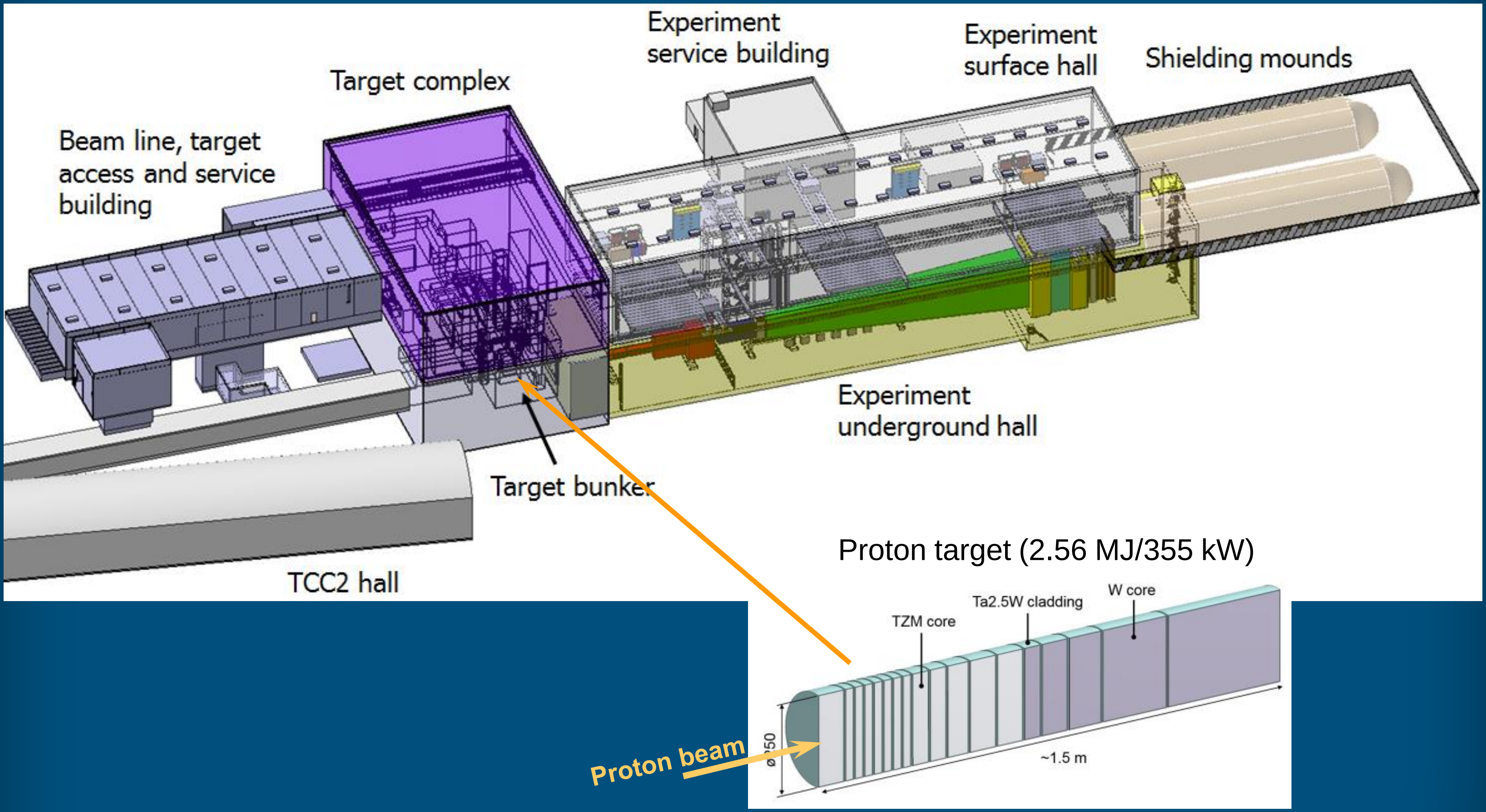


BDF/SHiP overview



Momentum	400 GeV/c
Beam intensity on target per cycle	4.0e13
Cycle length	7.2 s
Spill duration	1 s
Avg. power on target	355 kW
Avg. power on target during spill	2560 kW
Protons on target (PoT) per year	4e19
PoT in 5 years' data taking	2.0e20

SHiP@BDF


Experiment service building
Experiment surface hall
Shielding mounds
Target complex
Beam line, target access and service building
Experiment underground hall
Target bunker
TCC2 hall
Proton target (2.56 MJ/355 kW)
W core
Ta2.5W cladding
TZM core
ø250
~1.5 m
Proton beam

SHiP beam-induced background

- Aim for zero-background!

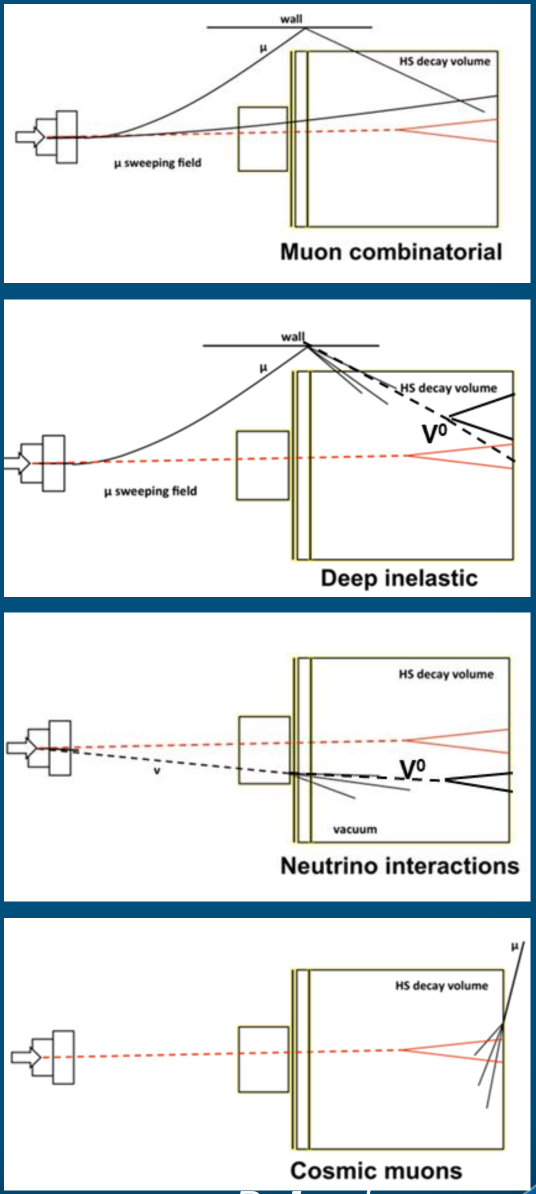
- Beam-induced background flux
  - $\mathcal{O}(10^{11})$ muons (>1 GeV/c) per spill of $4\text{x}10^{13}$ protons
  - 4.5×10^{18} neutrinos and $3\text{x}10^{18}$ anti-neutrinos in acceptance in 2×10^{20} proton on target

➔ Critical to reduce muon flux and neutrino interactions
  - Active muon shield
  - Decay volume under vacuum

➔ Redundant rejection of residual background
  - Background taggers
  - Momentum and vertex information
  - Impact parameter at target
  - Coincidence timing
  - Invariant mass
  - Particle identification

➔ Signal characterisation!

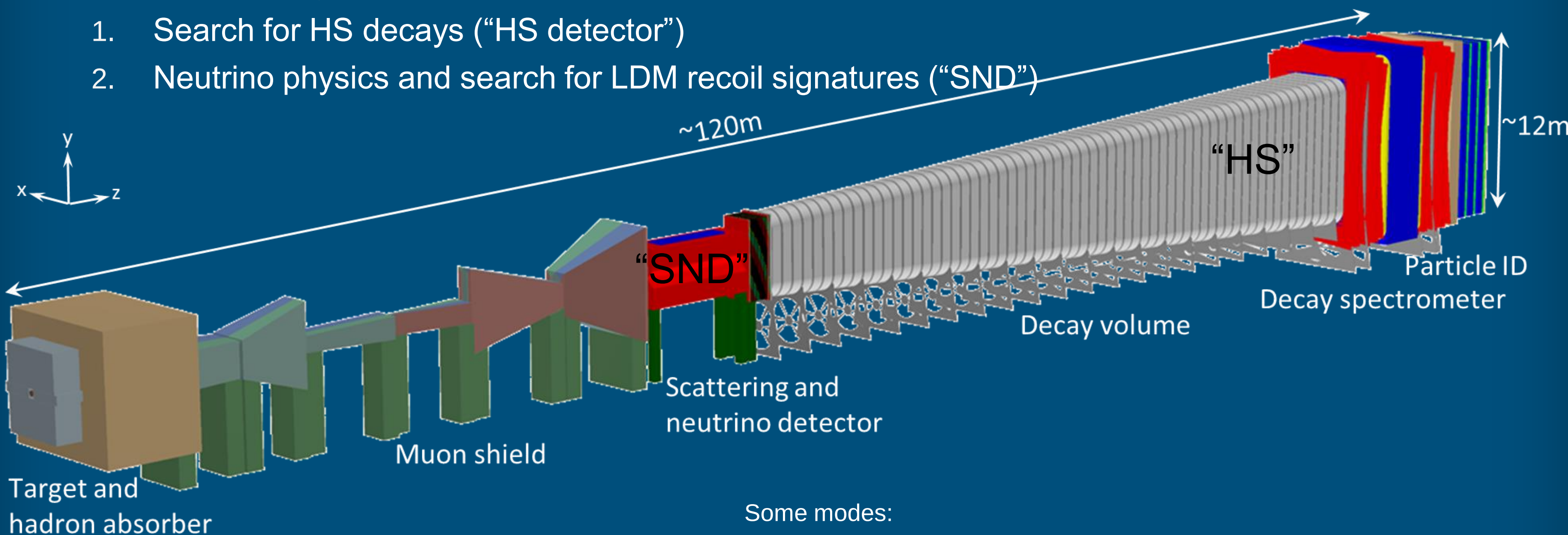
Hidden sector decay search background types



SHiP experimental setup

- Physics cased based on $2x10^{20}$ protons on target (5 years of nominal operation)
  - ➔ Signal yields from $>10^{18}$ D mesons, $>10^{16}$ τ, $>10^{21}$ photons (>100 MeV)

- Dual detector system
  1. Search for HS decays ("HS detector")
  2. Neutrino physics and search for LDM recoil signatures ("SND")



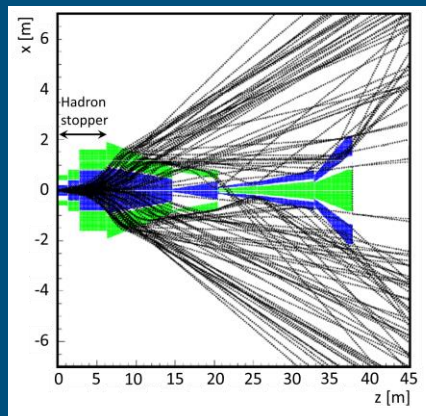
Some modes:

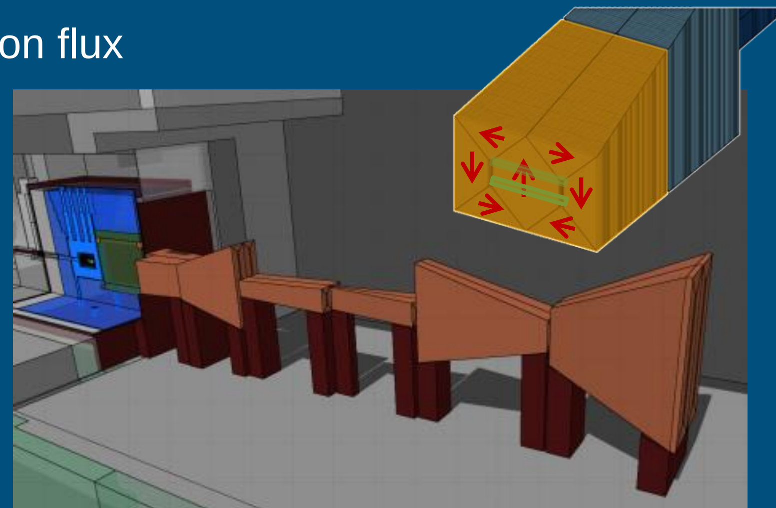
Models	Final states
Neutrino portal, SUSY neutralino	$\ell^{\pm}\pi^{\mp}, \ell^{\pm}K^{\mp}, \ell^{\pm}\rho^{\mp}, \quad \rho^{\pm} \to \pi^{\pm}\pi^{0}$
Vector, scalar, axion portals, SUSY sgoldstino	$\ell^{+}\ell^{-}$
Vector, scalar, axion portals, SUSY sgoldstino	$\pi^{+}\pi^{-}, K^{+}K^{-}$
Neutrino portal ,SUSY neutralino, axino	$\ell^{+}\ell^{-}\nu$
Axion portal, SUSY sgoldstino	$\gamma\gamma$
SUSY sgoldstino	$\pi^{0}\pi^{0}$

➔ Large-scale engineering of a precision instrument requiring accurate knowledge about background and detector efficiencies

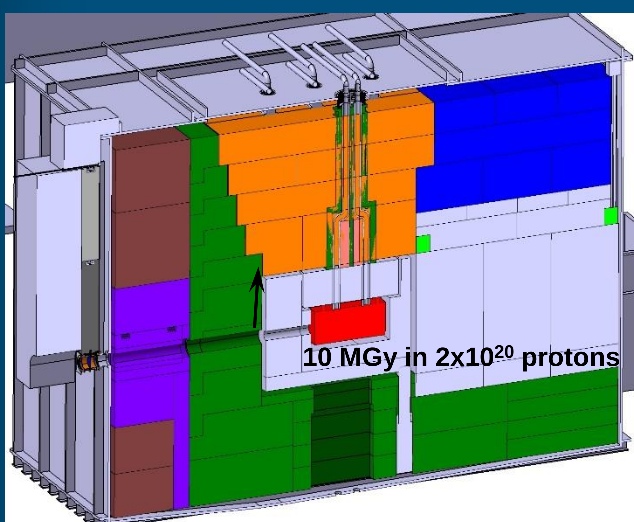
Muon shield

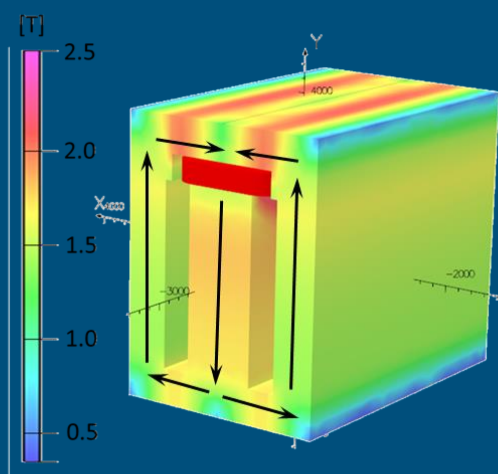
- Based on magnetic deflection of muon flux

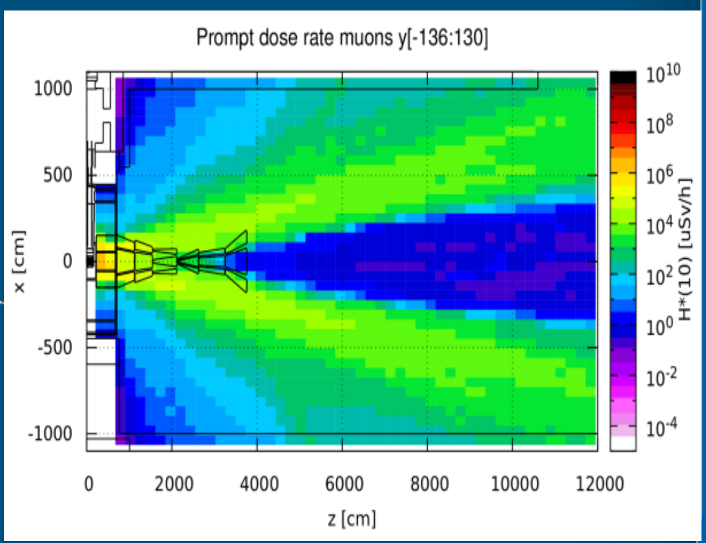




- Muon deflection starts within the target complex: magnetization of hadron stopper

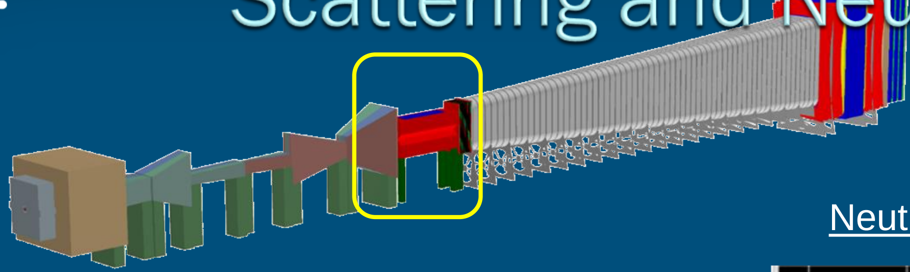




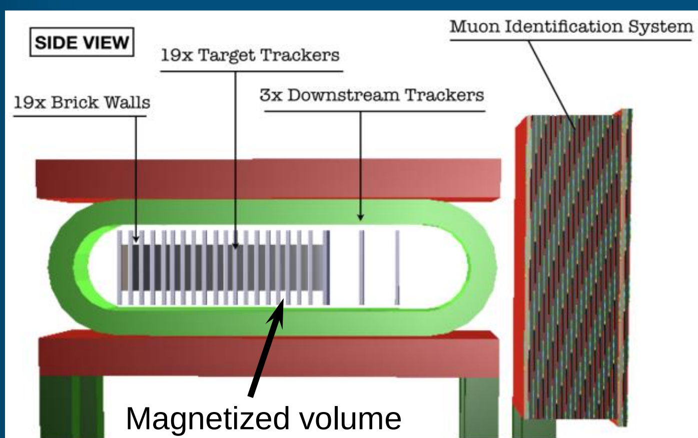


- Muon flux “bow wave” determines ultimate envelope for the fiducial volume

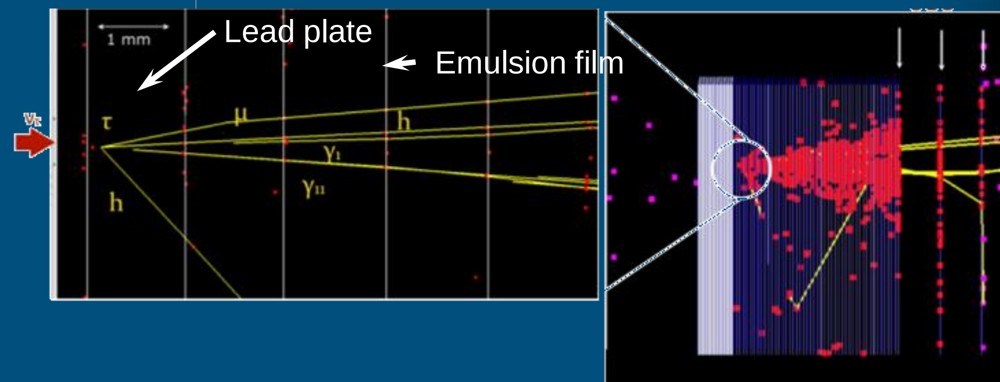
Scattering and Neutrino Detector



- Detector based on Opera concepts
- Magnet allows distinguishing between $\nu/\bar{\nu}$ interactions

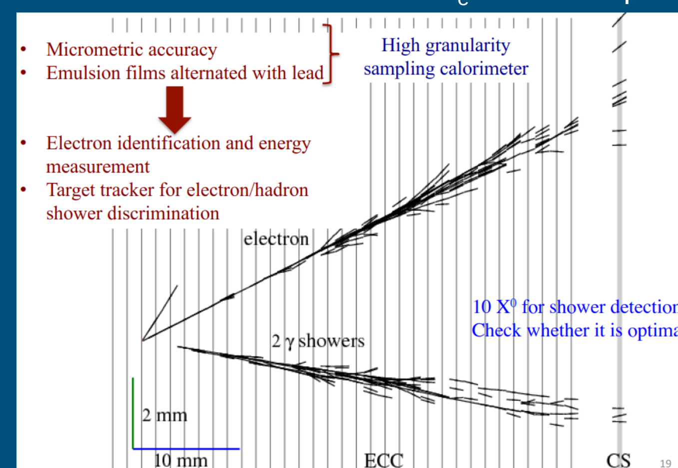


Neutrino detection



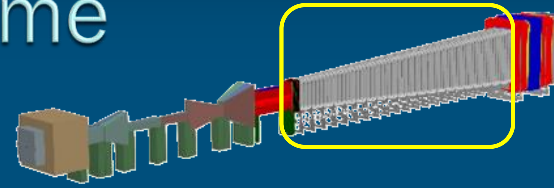
LDM detection

ν_e event in Opera

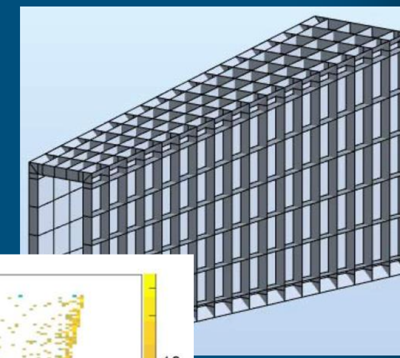


Equivalent of 10 tonnes lead target @ 40m is 450 tonnes liqAr @120m

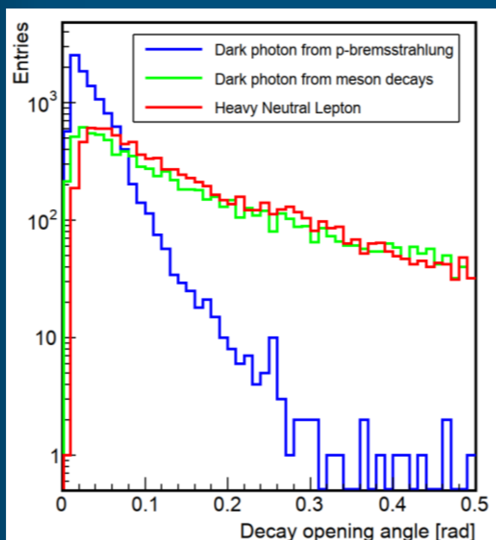
HS Decay volume



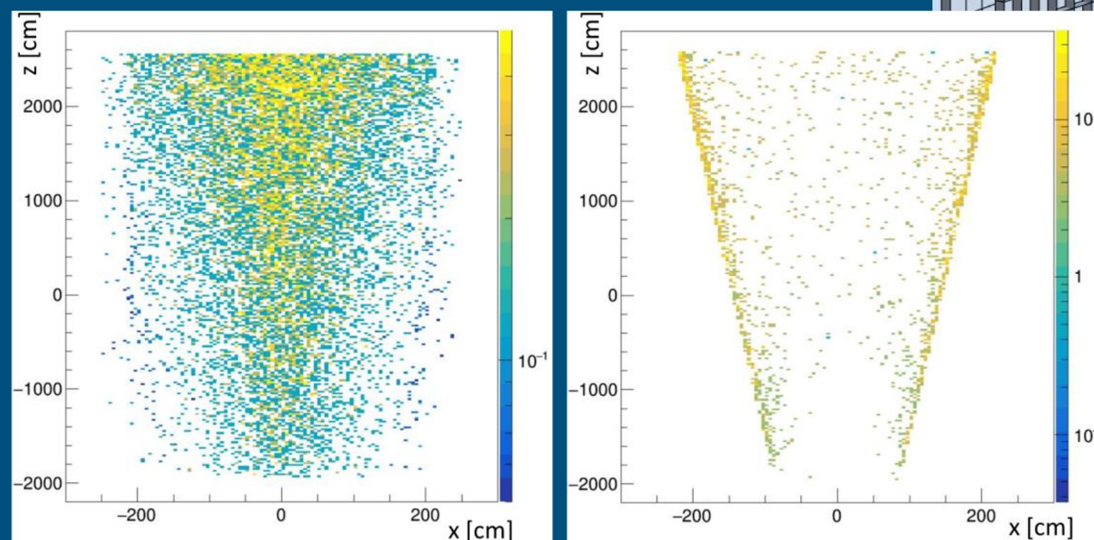
- Decay volume driven by
  - Optimization of geometry (length) with assumption of spectrometer aperture of 5 x 10 m² and taking into account decay acceptances for all signal modes
  - ➔ 50m pyramidal frustum
  - ➔ Instrumented with Surround Background Tagger



Decay opening angles (1 GeV/c² HNL and DP)

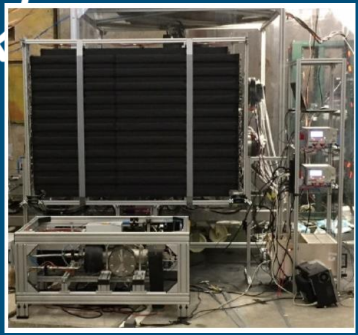


Neutrino interactions in air (left) and in vacuum vessel at 1mbar (right)



- ν interactions in fiducial volume producing signal candidates (soft selection) in 2×10^{20} p.o.t.
  - Air: 2.5×10^3 candidates with small impact parameter at target ➔ pump down to 10^{-3} bar
  - Vacuum: 1.4×10^4 candidates produced in vacuum chamber walls ➔ easily rejected

HS spectrometer

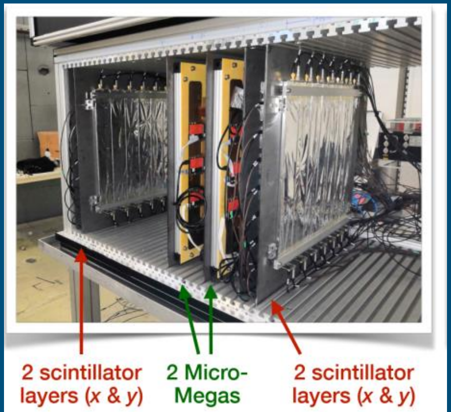


<u>Timing Detector</u>

1. Plastic scintillator +SIPM
2. MRPC

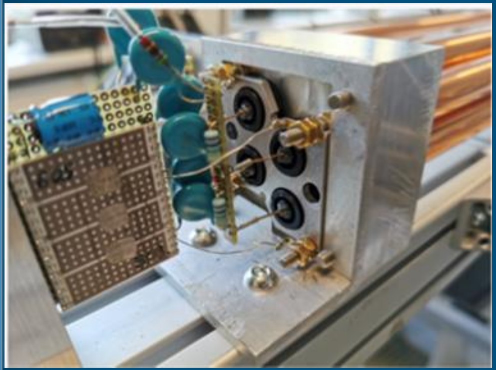
<u>ECAL/HCAL</u>

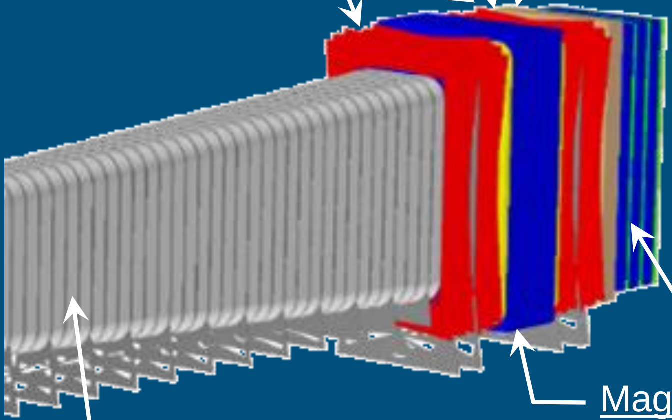
- Sandwich calorimeter w. scintillating bars+SiPM
- High-precision layers for directionality for ALP→$\gamma\gamma$



<u>Spectrometer Straw tracker</u>

Staw tubes

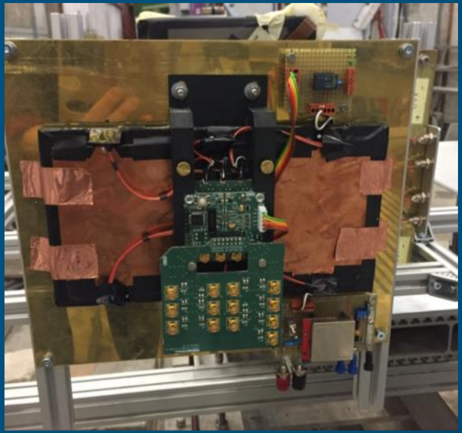




<u>MUON</u>

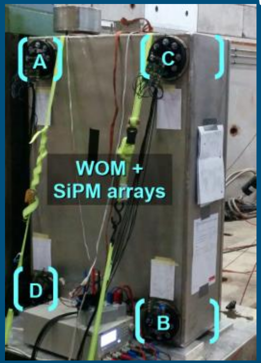
Scintillating tiles+SIPM

<u>Magnet</u>



<u>Surrounding Background Tagger</u>

Liquid scintillator + SiPM



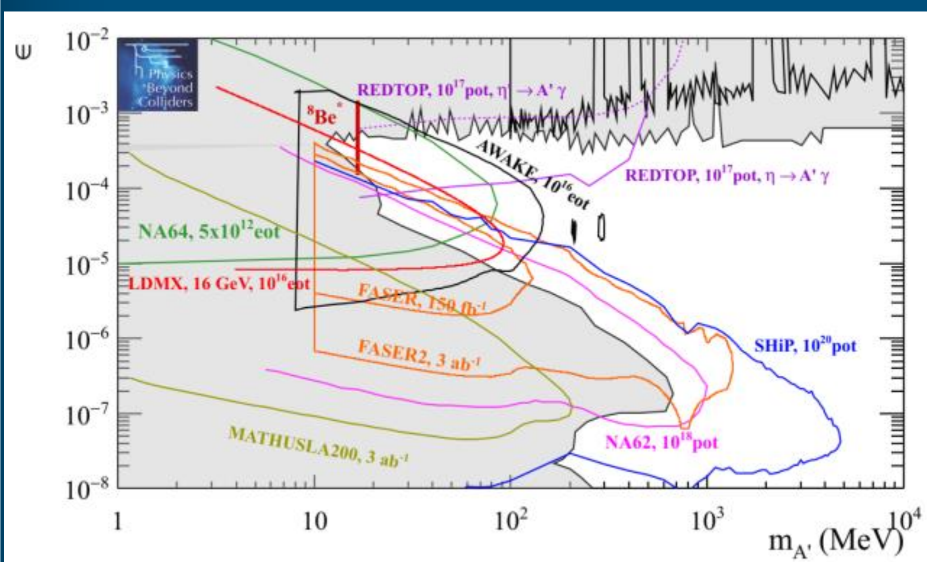
Hidden Sector sensitivities to basic benchmarks

- All plots with sensitivity to benchmark models from PBC BSM report arXiv:1901.09966
  - 90% CL exclusion limits
  - With the exception of the sensitivity to LDM (background included), all other exclusion limits consider zero background

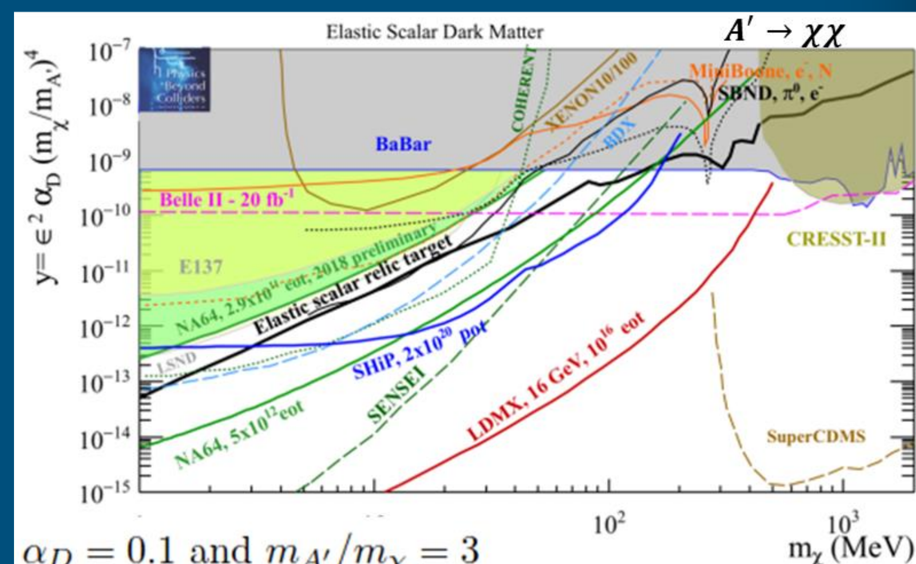
SHiP background to visible decays

Background source	Expected events
Neutrino background	< 0.1 (fully) / < 0.3 (partially)
Muon DIS (factorisation)	$< 6 \times 10^{-4}$
Muon combinatorial	4.2×10^{-2}
90% CL for 2×10^{20} protons	

Dark Photon visible decays

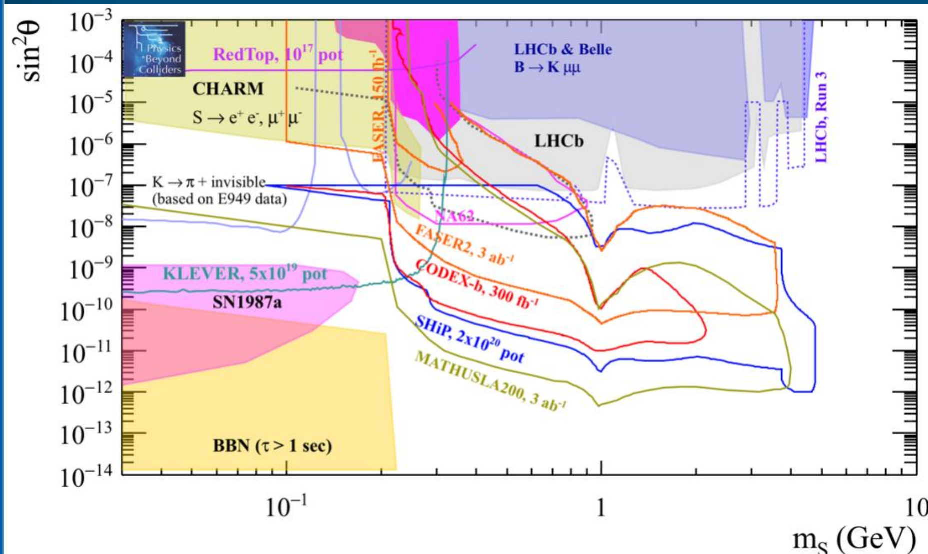


Missing energy/momentum interpreted as invisible dark photon decays to Light Dark Matter

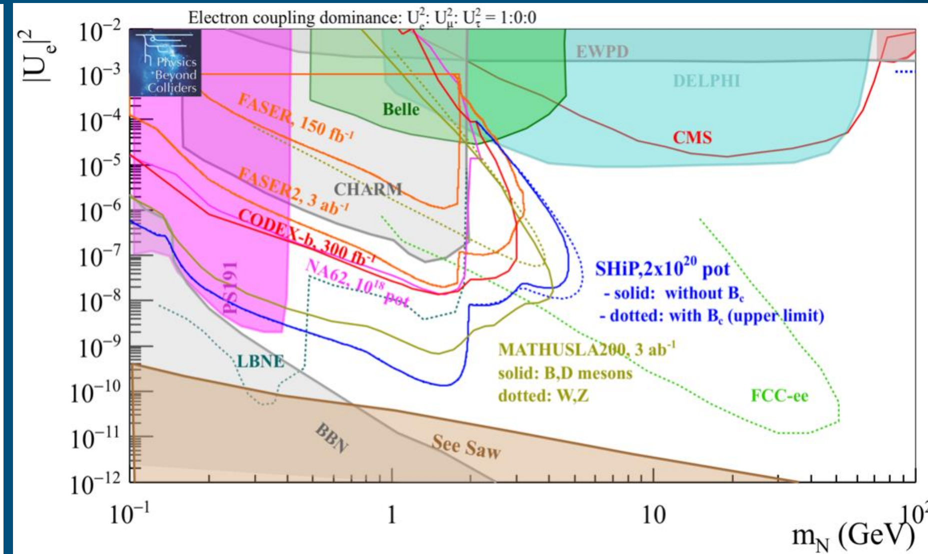


Hidden Sector sensitivities to basic benchmarks

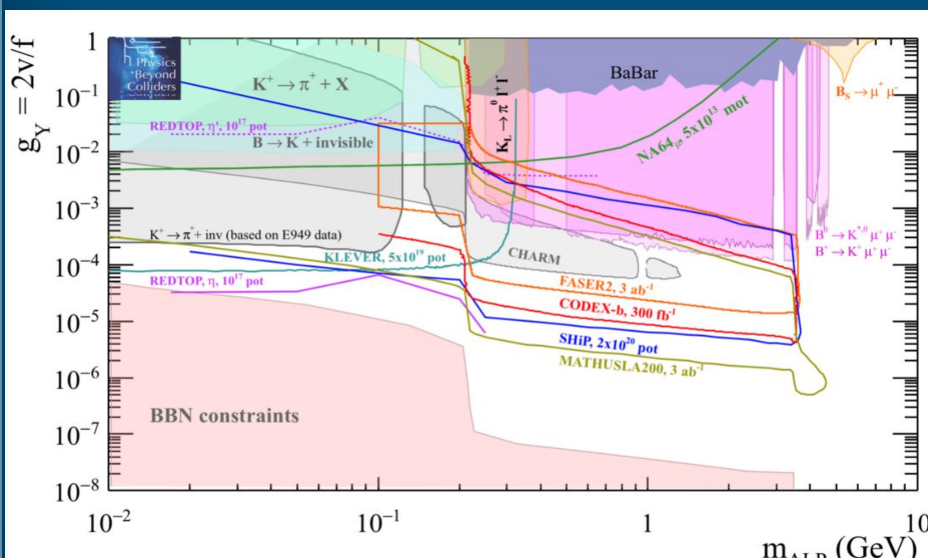
Dark Scalar visible decays



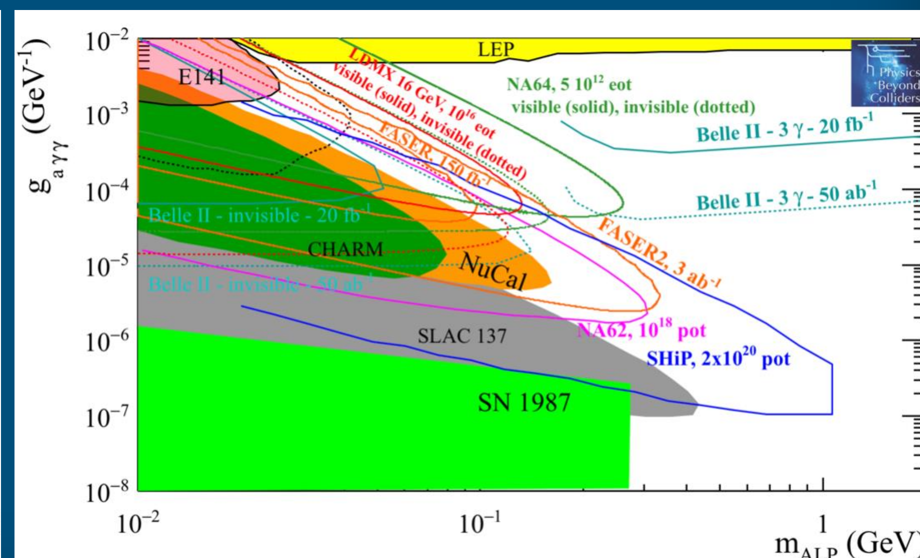
Heavy Neutral Lepton decays



ALP (fermionic coupling) visible decays



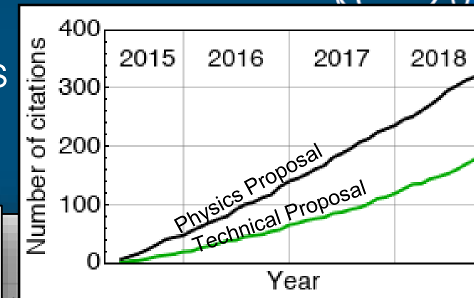
ALP (photon coupling) visible decays



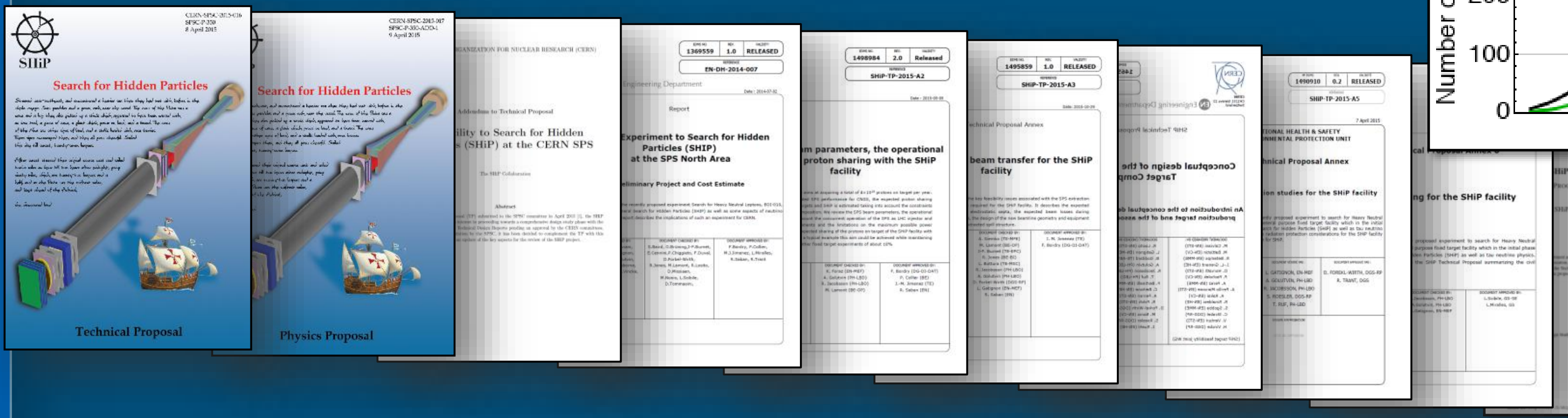
Conclusion

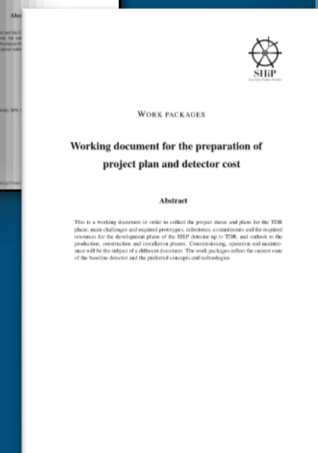
- *Bright future for Hidden/Dark Sector*
  - Very much increased interested for Hidden Sector after LHC Run 1
  - Implications of a discovery is very difficult to overestimate….
- SHiP@BDF is a mature GP platform for HS exploration
  - Set up for discovery through direct detection
  - Aiming at characterising any discovery
  - Also unique opportunity for ν_τ physics, direct Dark Matter search, LFV τ…
- Facility and physics case based on the current injector complex and SPS
- Detector R&D and design is at an advanced level
  - ➔ But many exciting developments still and many openings for new groups
- Aiming to produce TDRs by end 2023 and data taking in Run 4

SHiP history



- 2013 Oct: EOI with SHiP@SPS North Area, right E and 4x10[19] p/year 'free' after CNGS
  ...following brainstorming SHiP@IP8, SHiP@LBD, SHiP@CNGS, SHiP@WANF





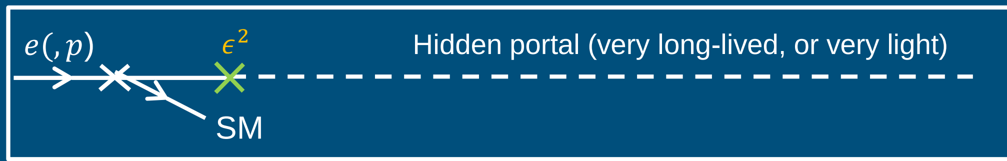
- 2014 Jan: Encouraged to form collaboration and produce TP and inter-departmental task force setup to study feasibility of proposed facility
- 2015 Apr: TP with ~700 pages by SHiP theorists, experimentalists, and CERN accelerator, engineering, and safety departments
- 2016 Jan: Recommendation by CERN SPSC to proceed to Comprehensive Design Study (CDS)
- 2016 Apr: CERN management launch of Beyond Collider Physics study group
  - SHiP experimental facility included under PBC as Beam Dump Facility
- 2018 Dec: EPPSU contribution submitted by SHiP and BDF, and submission of SHiP Progress Report
- 2019 Dec: CDS report submitted by SHiP and BDF
- SHiP Collaboration: ***330 authors, 53 + 4 Institutes, 18 countries, CERN, JINR***

Long-lived search techniques

Note : $\epsilon \ll 1$

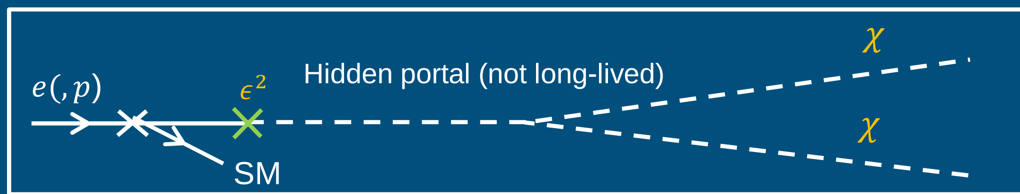
Production | Detection

Indirect



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

Cannot be directly distinguished
→ Model-dependent interpretation

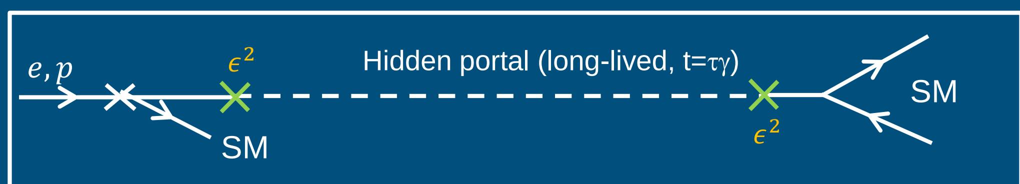


If $m_{HP} > 2m_{DM}$
Escape detector
Missing energy/momentum/mass
Probability $\propto \epsilon^2$

ATLAS
CMS
LHCb
NA64
LDMX

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

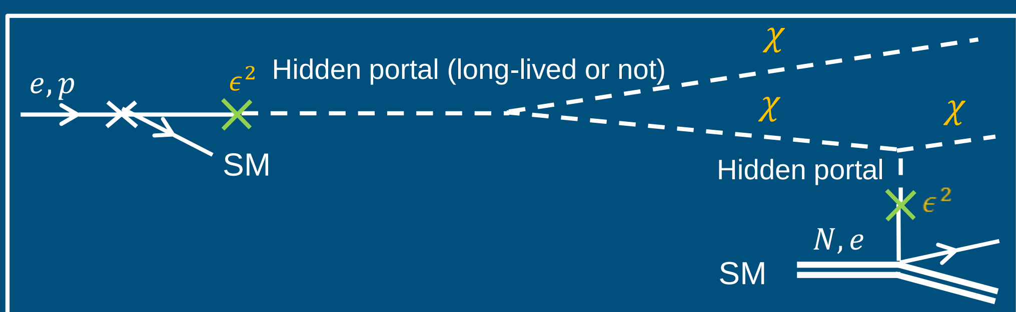
Direct



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
LHCb
NA62 (++)
NA64 (++)
FASER
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

➔ Background situation very different in the different techniques!