SHiP, a new beam dump facility at the SPS

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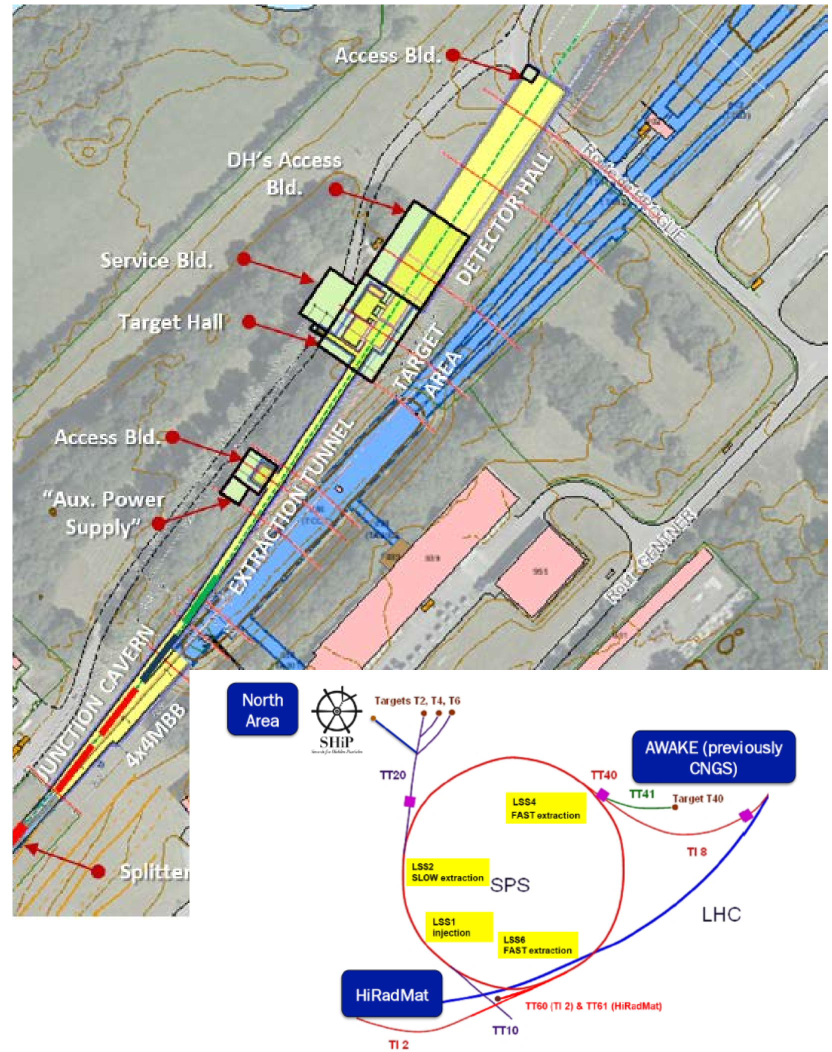
LPNHE

GDR InF CERN 02 Feb 2018

What is SHiP ?

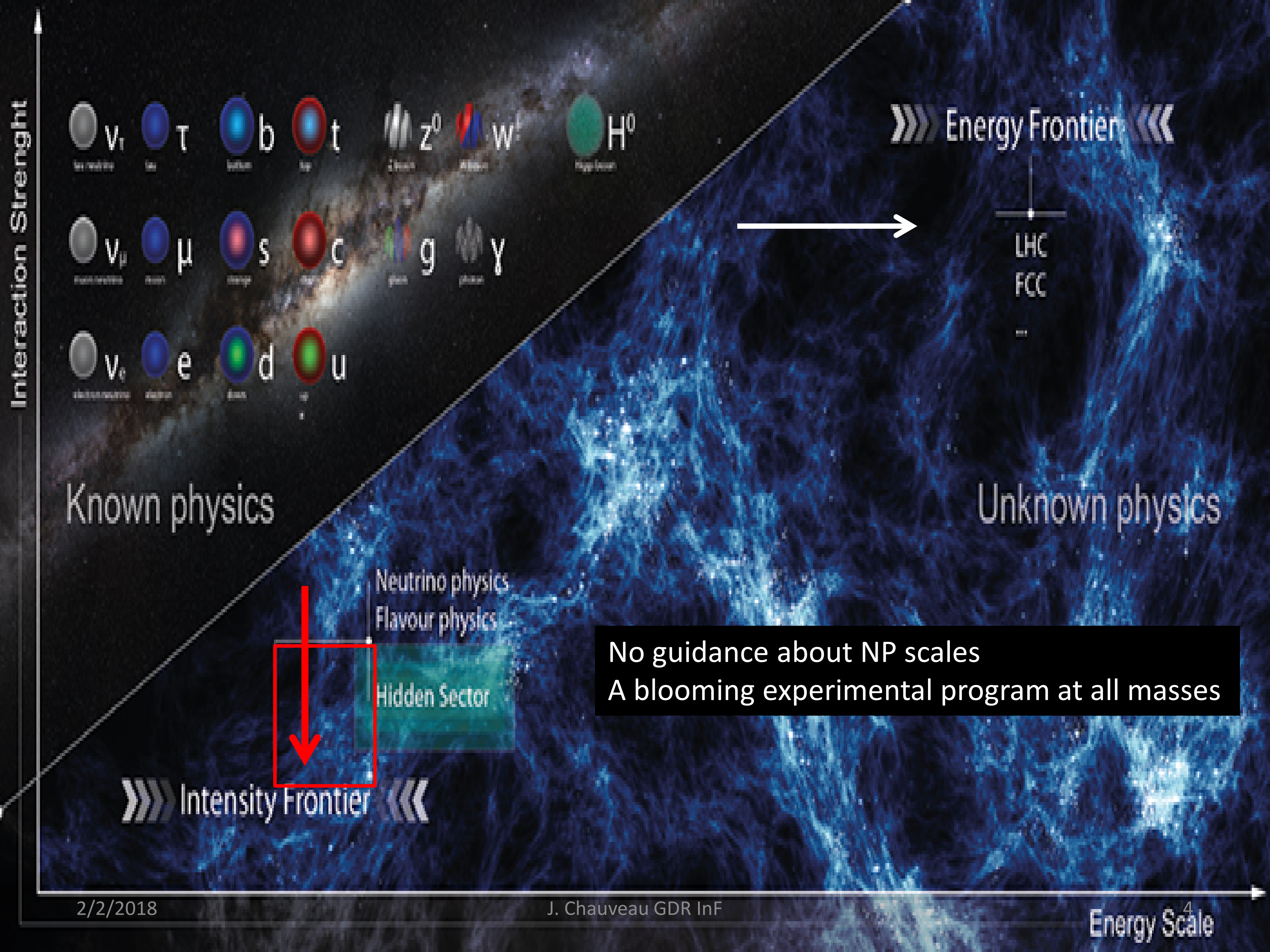
- Direct **S**earch for **Hi**dden **P**articles at the CERN SPS
- A General Purpose Experiment to exploit at the CERN SPS a new Beam Dump Facility
- A Collaboration of
  16 countries, CERN & JINR
  49 institutes, 5 associate institutes
- Aim : data taking in Run-4 of the LHC



Technical Proposal ArXiv 1505.04956 + CERN-SPSC-2015-040
Physics Proposal S. Alekhin_2016_Rep._Prog._Phys._79_124201

Motivation

- Physics beyond the standard model
- The best prospects for MeV-GeV mass are at the SPS
  - Luminosity
  - Protons available
- Past experience
- Well suited to HEP labs (e.g. in France)

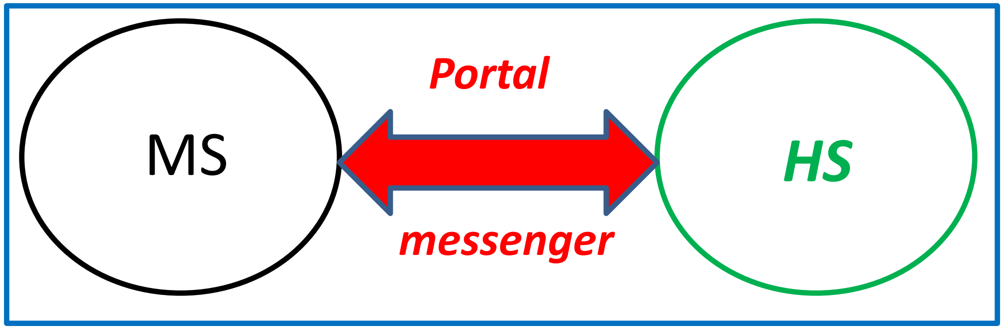

Interaction Strenght
ν τ b t Z0 W H0
ν μ s c g γ
ν e d u
Energy Frontier
LHC
FCC
...
Known physics
Unknown physics
Neutrino physics
Flavour physics
Hidden Sector
Intensity Frontier
No guidance about NP scales
A blooming experimental program at all masses
Energy Scale

Outline

- Physics case, in search for a hidden sector
- Experimental methods
- SHiP history and prospects
- A new beam dump facility at the SPS
- The decay detector, dSHiP
- The interaction detector iSHip (νSHiP)
- Possible further use of the facility τSHiP,…
- Outlook

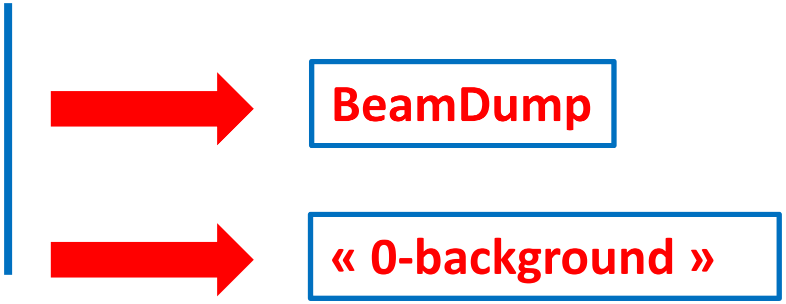
Hidden Sector

- A New Physics beyond the Standard Model must be there,
  - **At what scale ?**
- To discover it, look for the messengers (portals) of new interactions between the SM fields and the hidden fields.
- Possible portals:
  - **Neutrino, Vector, Scalar, Axial.**



SHiP Physics Paper: 1504.04855

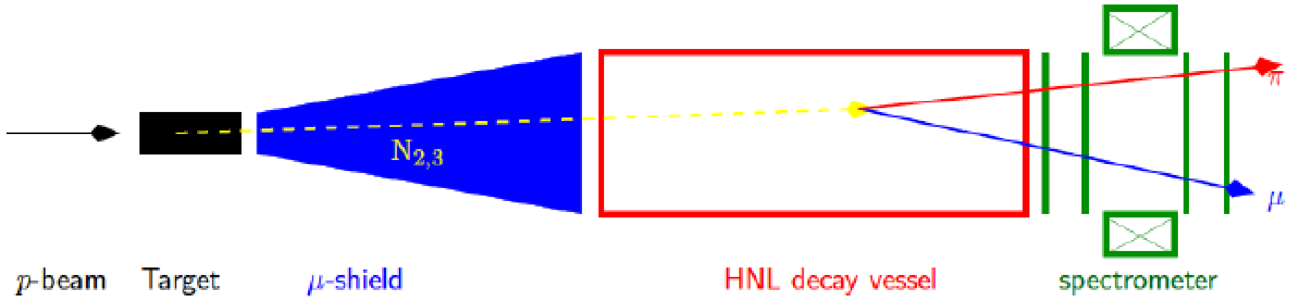
- If the messengers are **light**,
  a **direct detection** is possible
  - Via ***decay*** or ***scattering***.
- Very feeble interactions
  - **A source with high intensity**
  - **They easily traverse matter**
  - **They are long-lived**
  - **Very rare events**

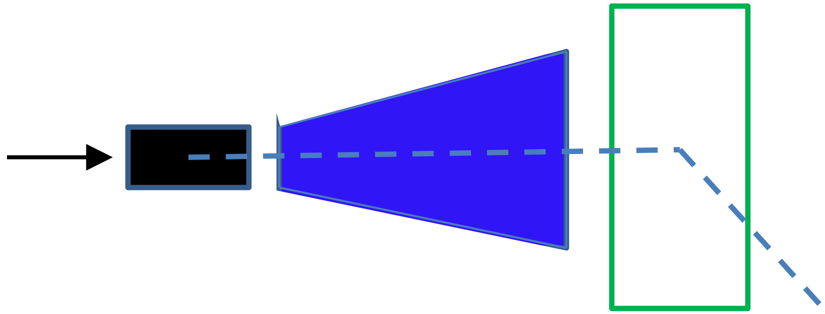


Hidden Sector Portals

- Neutrino (HNL), νMSM
- Vector (U boson, dark photon)
- Scalar (extended Higgs sector)
- Axion-like particles ALP
- Others (SUSY,…)

Decay and interaction experiments



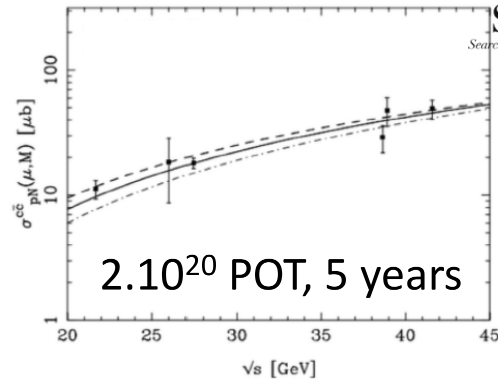


Requirements (Decay)

- Heavy flavor
- N with high P_T

P+A → D or B X, D or B→ **N** l (X)

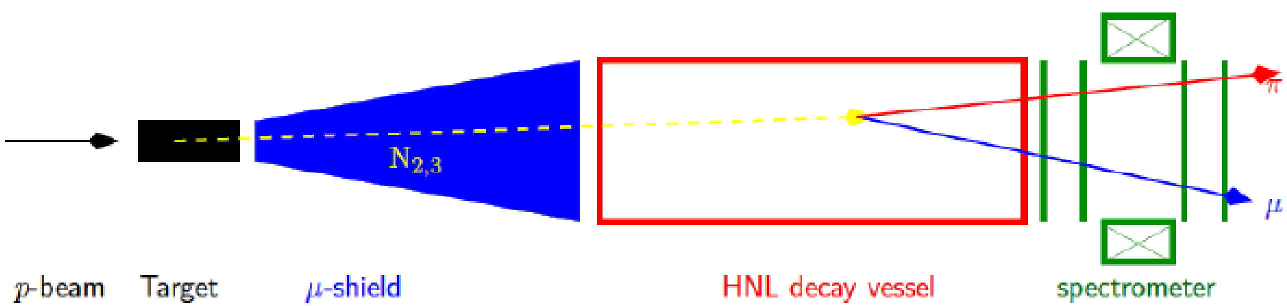
N → 2/3-body



✓ *Decays:*

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	$\pi^{0}\pi^{0}$

- Decay vessel close to target
- Muon shield as short as possible



The SHiP experiment at SPS

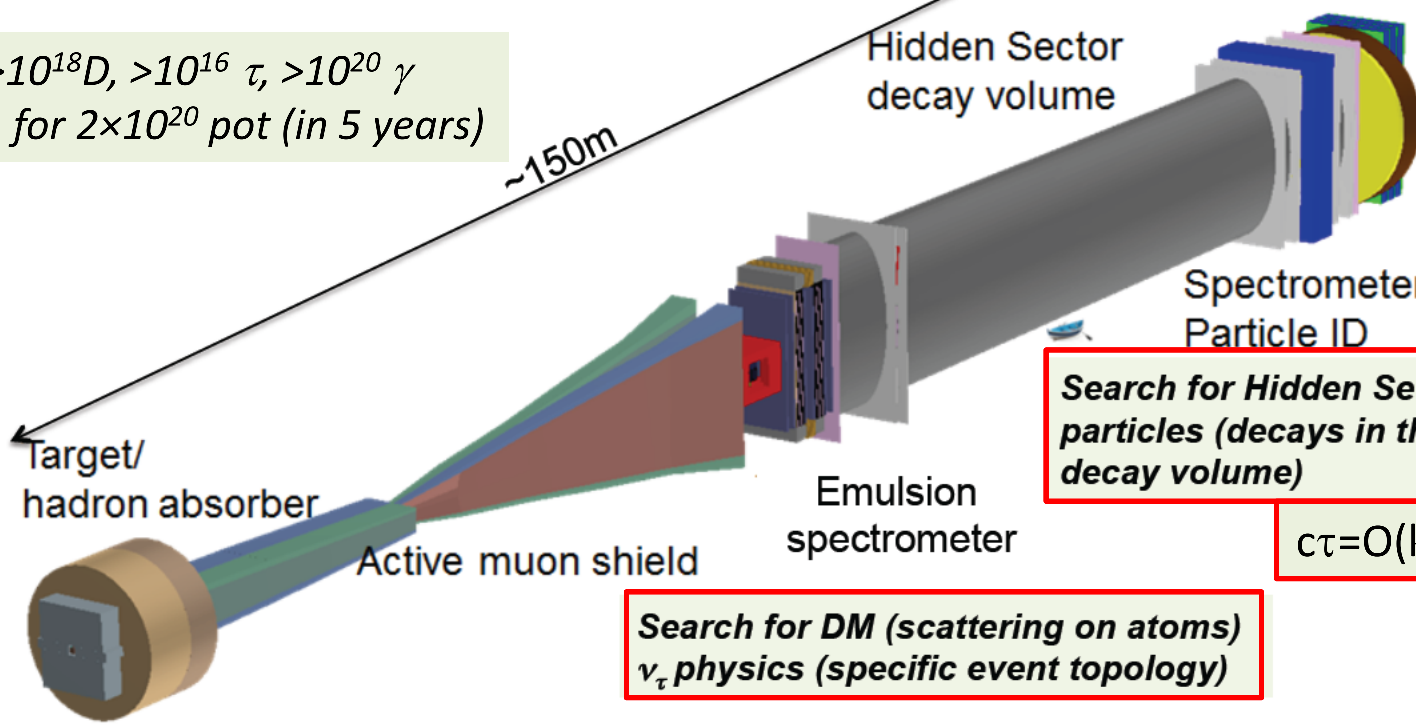
(as implemented in Geant4 for TP)

SHiP Technical Proposal:
1504.04956

"Zero background" experiment
- *Muon shield*
- *Surrounding Veto detectors*

- *Dump*
- *Vacuum*
- *Timing, PID*

>10^{18}D, >10^{16} τ, >10^{20} γ for 2×10^{20} pot (in 5 years)



Search for Hidden Sector particles (decays in the decay volume)

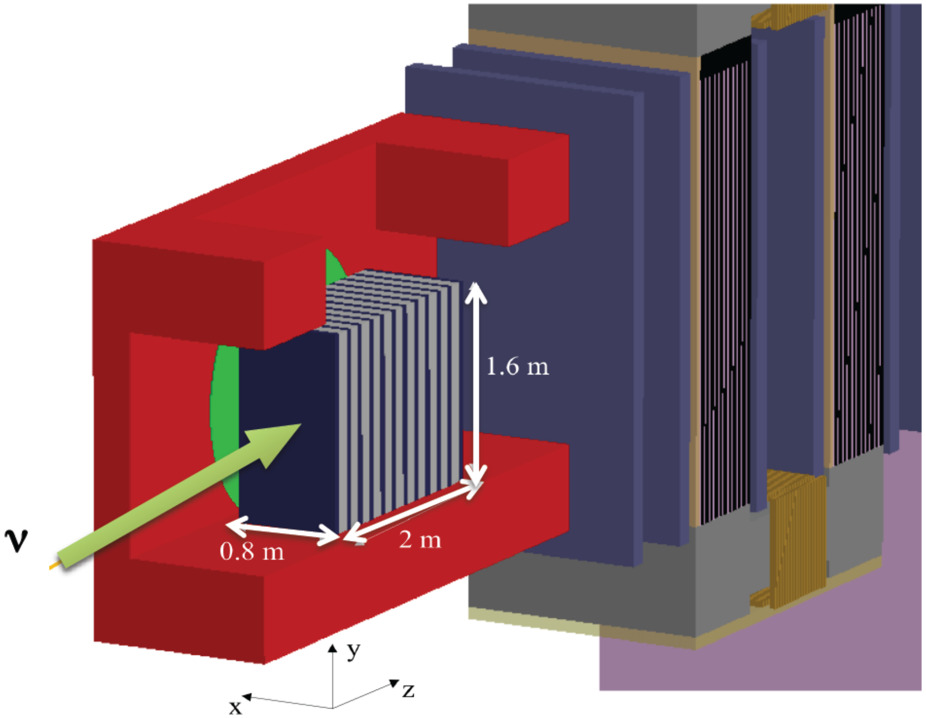
$c\tau$=O(km)

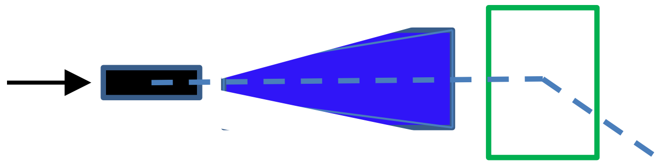
Search for DM (scattering on atoms)
ν_τ physics (specific event topology)

4

Requirements (Interaction)

The ν_τ detector in the Technical Proposal





- Observe τ decays (1mm path) with high resolution
  - ➢ Emulsions
- Electronic detection of tau decay prongs (timestamp, tracking to muon spectrometer)
  - ➢ Target Tracker
- Dipole magnet
  - ➢ measure charges
- Muon spectrometer

Towards the CDS, SHiP reoptimization

- Calendar
- The Beam Dump Facility
- The active muon shield
- The dSHiP
- The ν/iSHiP
- Preparatory experiments

Cost (TP) and schedule (today)

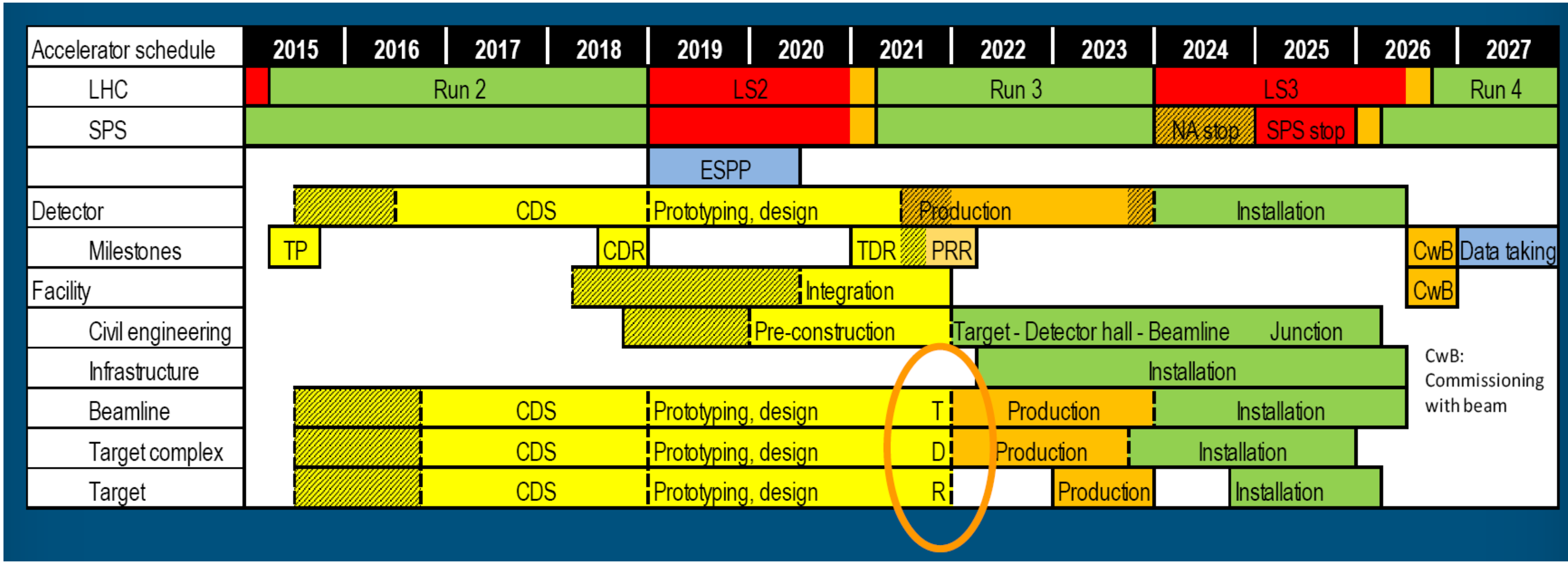
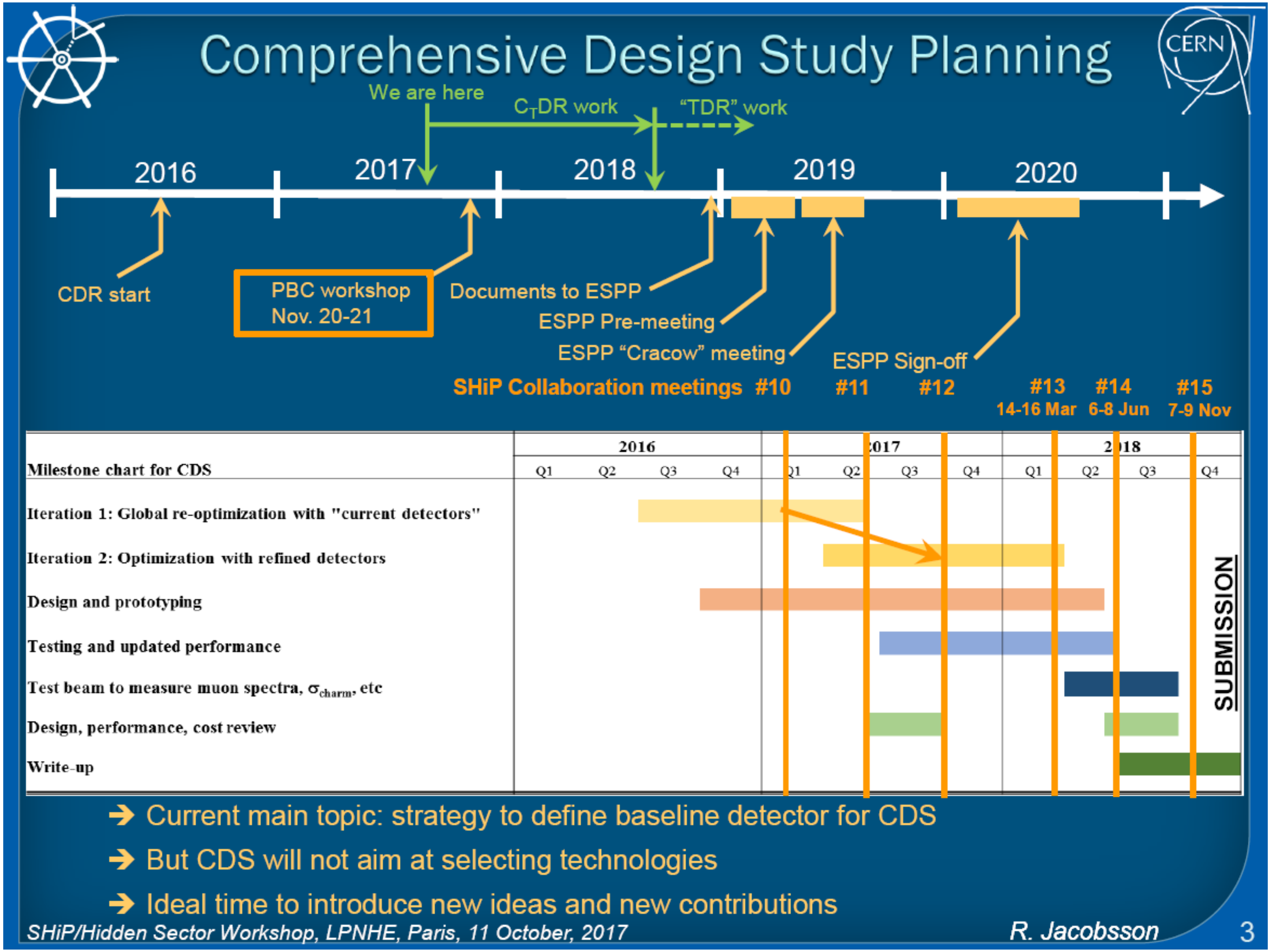
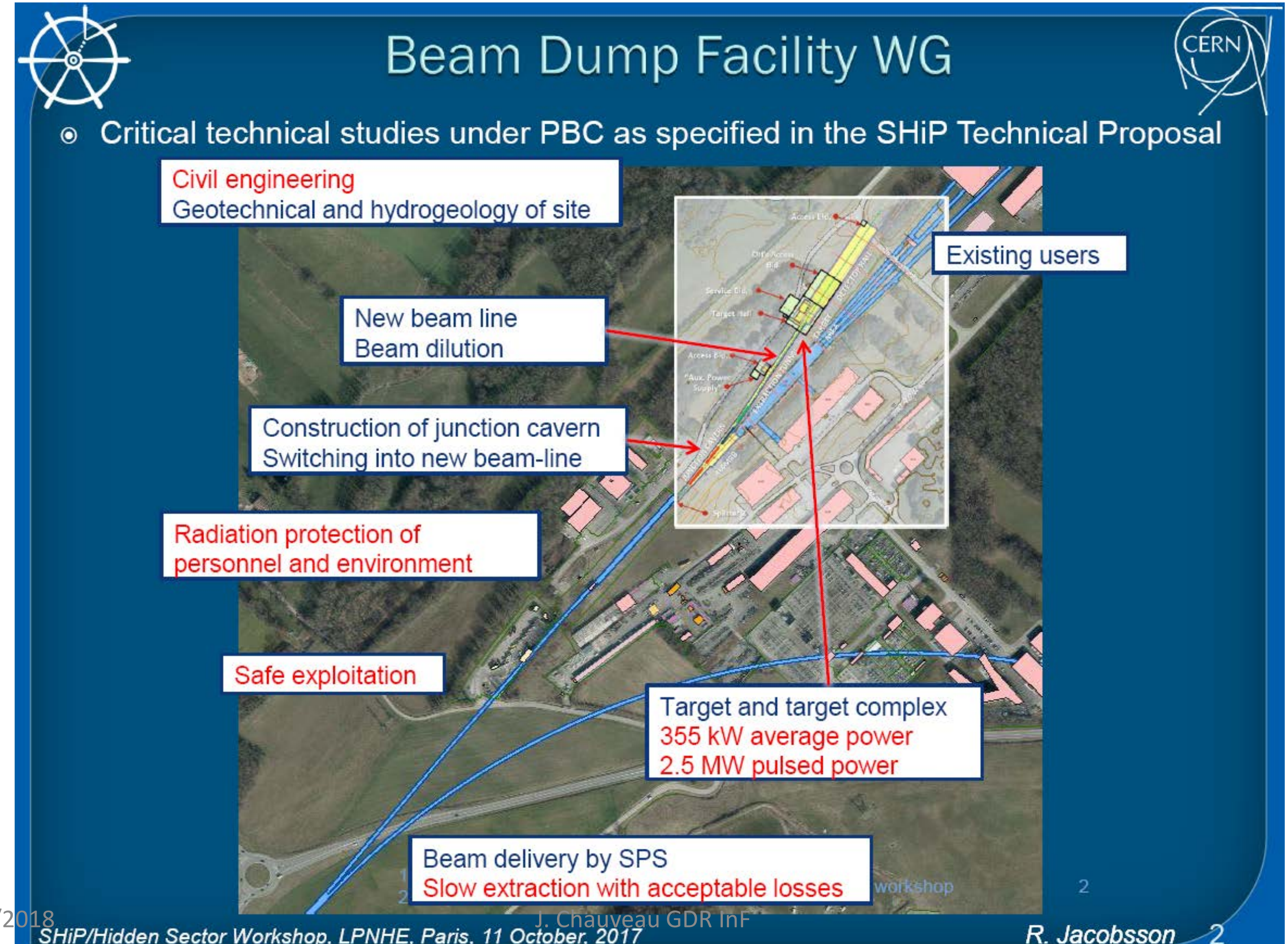


Table 6.3: Breakdown of the cost of the SHiP detectors.

Item	Cost (MCHF)	
Tau neutrino detector		**11.6**
Active neutrino target	6.8	
Fibre tracker	2.5	
Muon magnetic spectrometer	2.3	
Hidden Sector detector		**46.8**
HS vacuum vessel	11.7	
Surround background tagger	2.1	
Upstream veto tagger	0.1	
Straw veto tagger	0.8	
Spectrometer straw tracker	6.4	
Spectrometer magnet	5.3	
Spectrometer timing detector	0.5	
Electromagnetic calorimeter	10.2	
Hadronic calorimeter	4.8	
Muon detector	2.5	
Muon iron filter	2.3	
Computing and online system		**0.2**
Total detectors		**58.7**
Facility		**135.8**
Grand total		**194.5**


Comprehensive Design Study Planning
CERN
We are here
C$_T$DR work
"TDR" work
2016
2017
2018
2019
2020
CDR start
PBC workshop
Nov. 20-21
Documents to ESPP
ESPP Pre-meeting
ESPP "Cracow" meeting
ESPP Sign-off
SHiP Collaboration meetings #10
#11
#12
#13
14-16 Mar
#14
6-8 Jun
#15
7-9 Nov
Milestone chart for CDS
2016
2017
2018
Q1 Q2 Q3 Q4 Q1 Q2 Q3 Q4 Q1 Q2 Q3 Q4
Iteration 1: Global re-optimization with "current detectors"
Iteration 2: Optimization with refined detectors
Design and prototyping
Testing and updated performance
Test beam to measure muon spectra, σ$_{charm}$, etc
Design, performance, cost review
Write-up
SUBMISSION
➔ Current main topic: strategy to define baseline detector for CDS
➔ But CDS will not aim at selecting technologies
➔ Ideal time to introduce new ideas and new contributions
SHiP/Hidden Sector Workshop, LPNHE, Paris, 11 October, 2017
R. Jacobsson
3

Beam Dump Facility



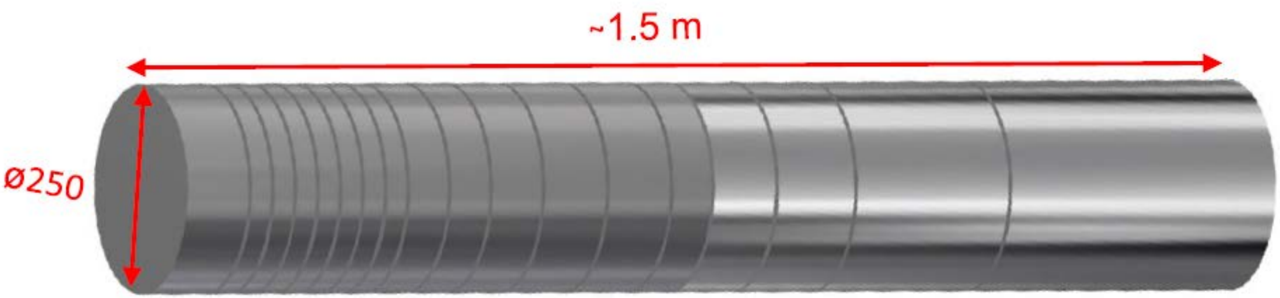
Beam Dump Facility

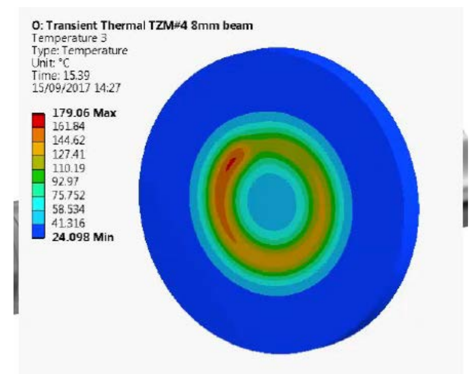
Huge effort by CERN/SHiP

Within the PBC workshop

Funded in the 2018 MTP

Beam extraction, Target, Absorber





TZM 4λ

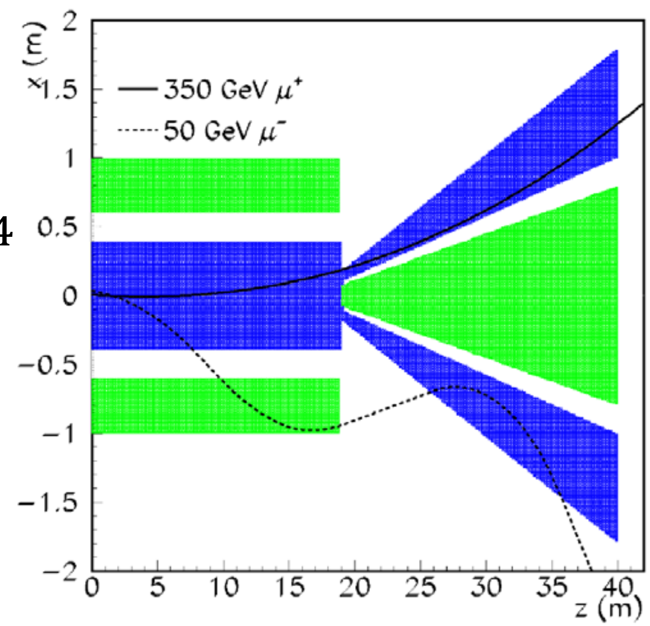
W 6 λ

4×10^{13} protons, 1s spill, 7s cycle
10 interaction lengths target
4.5 m iron absorber, magnetized

Power 355 kW(av), 2.5 MW (pk)
➢ Dilute beam
Pulsed beam option?

Muon Filter

- $4 \times 10^{13}\ p.o.t$ during a one second spill,
- $\sim 10^{11}$ muons/s mainly from meson decays. *Too high a background*!
- Must reduce the muon flux by at least 10^4 while keeping the detector as close to the target as possible.
- Cannot be done realistically with passive shielding.



- Devise an active filter using a series of magnets to deflect the muons out of the acceptance of the spectrometer.
- Proof of principle L~30 m

A. Akmete et al 2017 JINST 12 P05011.

- Currently optimized using machine learning methods.

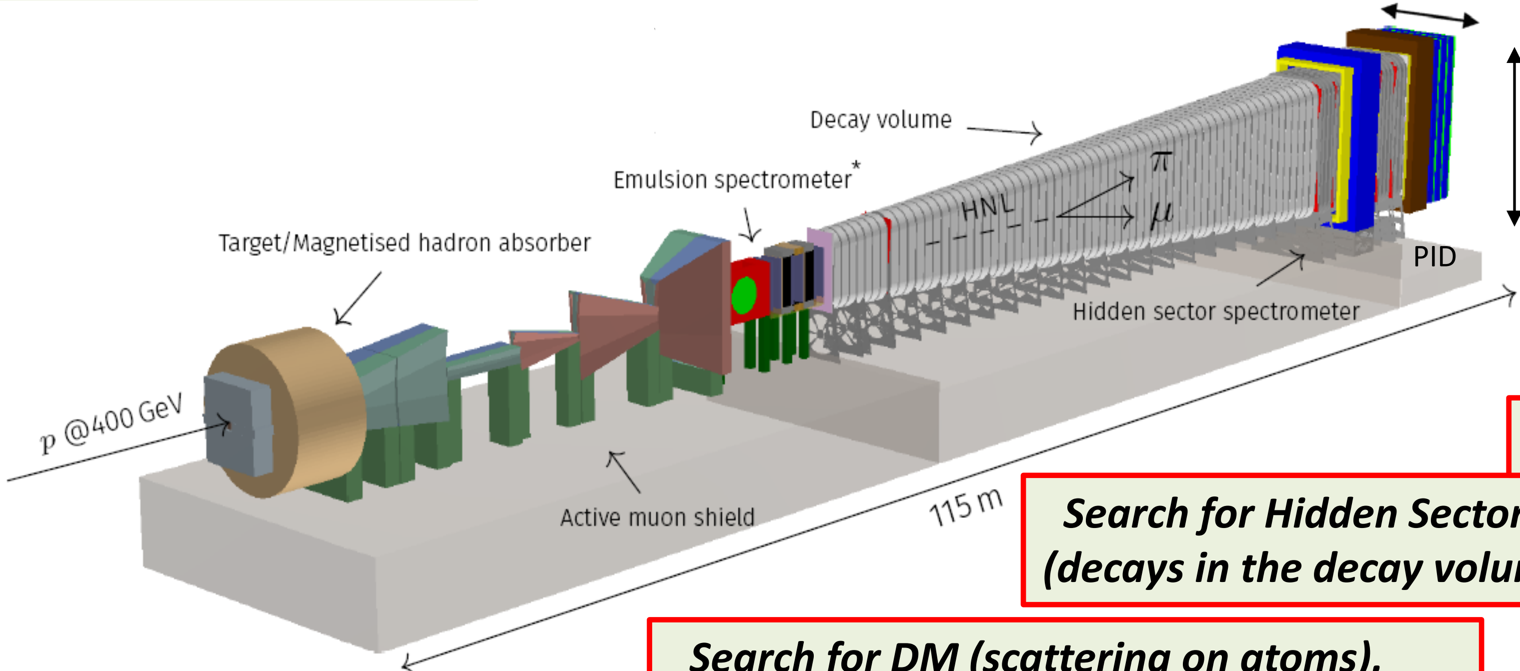
Reoptimization of the SHiP experiment

SHiP
Search for Hidden Particles

$>10^{18}$D, $>10^{16}$ τ, $>10^{20}$ γ
for 2×10^{20} pot (in 5 years)

« Zero-background experiment »

- *Dump*
- *Muon Shield*
- *Surrounding Veto detectors*
- *Vacuum*
- *Timing, PID*



$c\tau$=O(km)

Search for Hidden Sector particles (decays in the decay volume) dSHiP

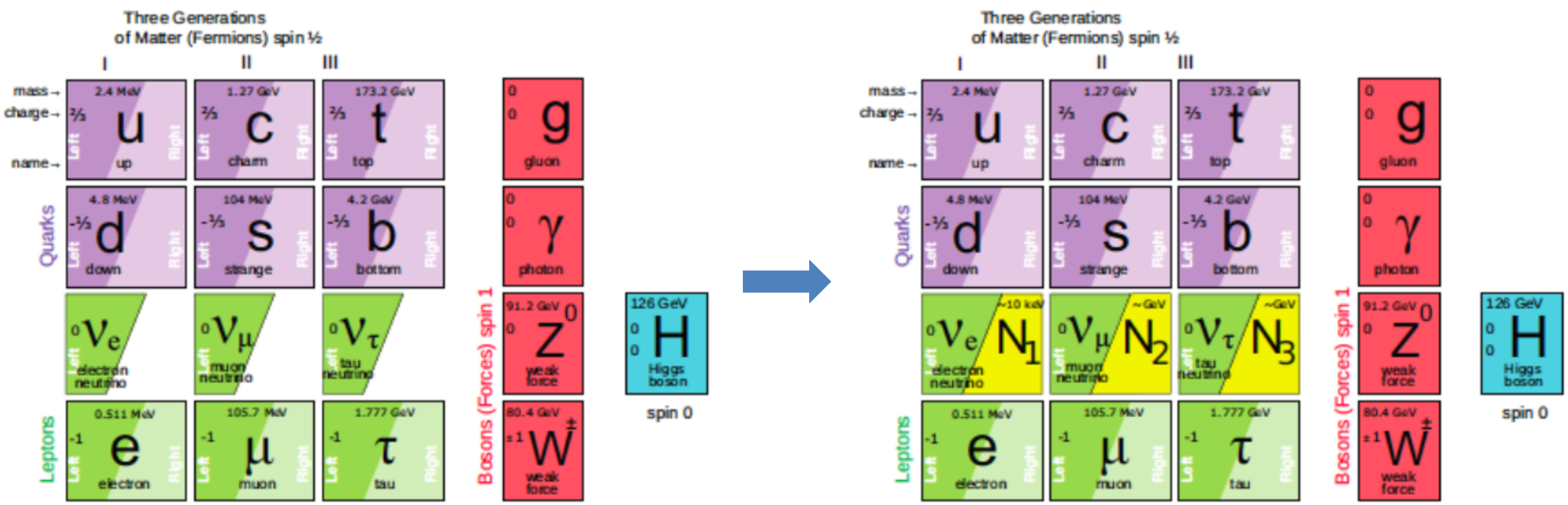
Search for DM (scattering on atoms), ν_τ physics (specific event topology) iSHiP

dSHiP

- Evolution of the detector design
  - closer to the target
  - pyramidal
- Use a neutrino portal model, the νMSM, to support the description of the design.
- Emphasize features needed by the ALP channel (calorimetry).
- Show physics reach of the unevolved detector, while working on an update this summer.

Neutrino portal observables: *(Heavy Neutral Leptons)*

νMSM *(T.Asaka, M.Shaposhnikov PL* ***B620*** *(2005) 17)* ***explains all short comings of the SM at once by adding 3 HNL: N_1, N_2 and N_3***



N = Heavy Neutral Lepton - HNL

Role of N_1 with mass in keV region: dark matter

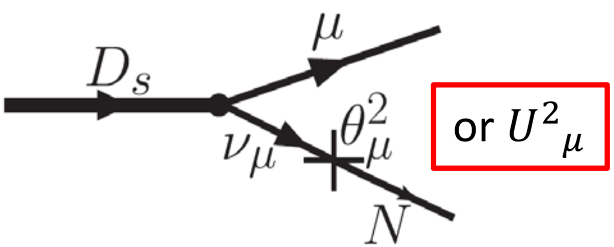
Role of N_2, N_3 with mass in 100 MeV – GeV region: "give" masses to neutrinos and produce baryon asymmetry of the Universe

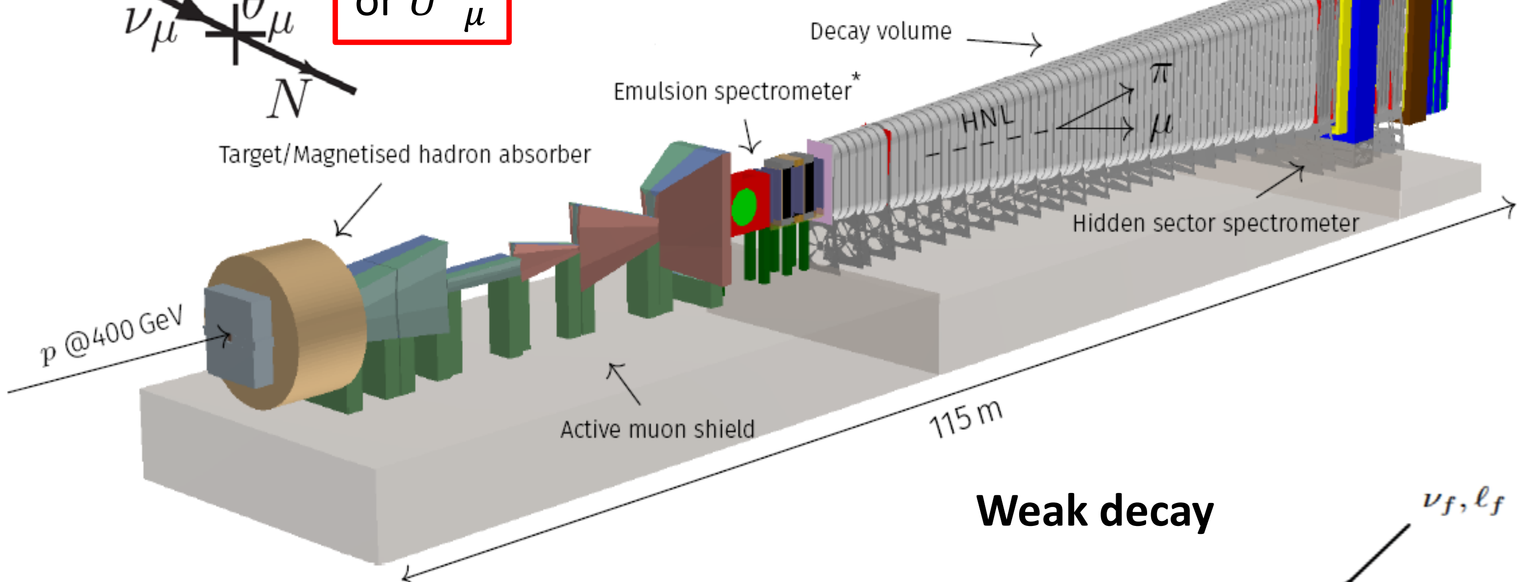
Role of the Higgs: give masses to quarks, leptons, Z and W and inflate the Universe.

HNL in dSHiP

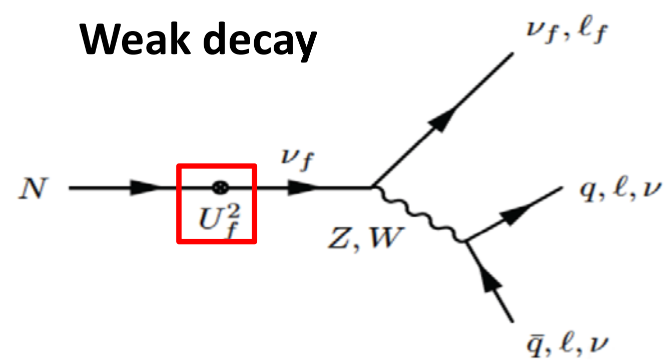
Production

(semi)leptonic heavy flavor decay



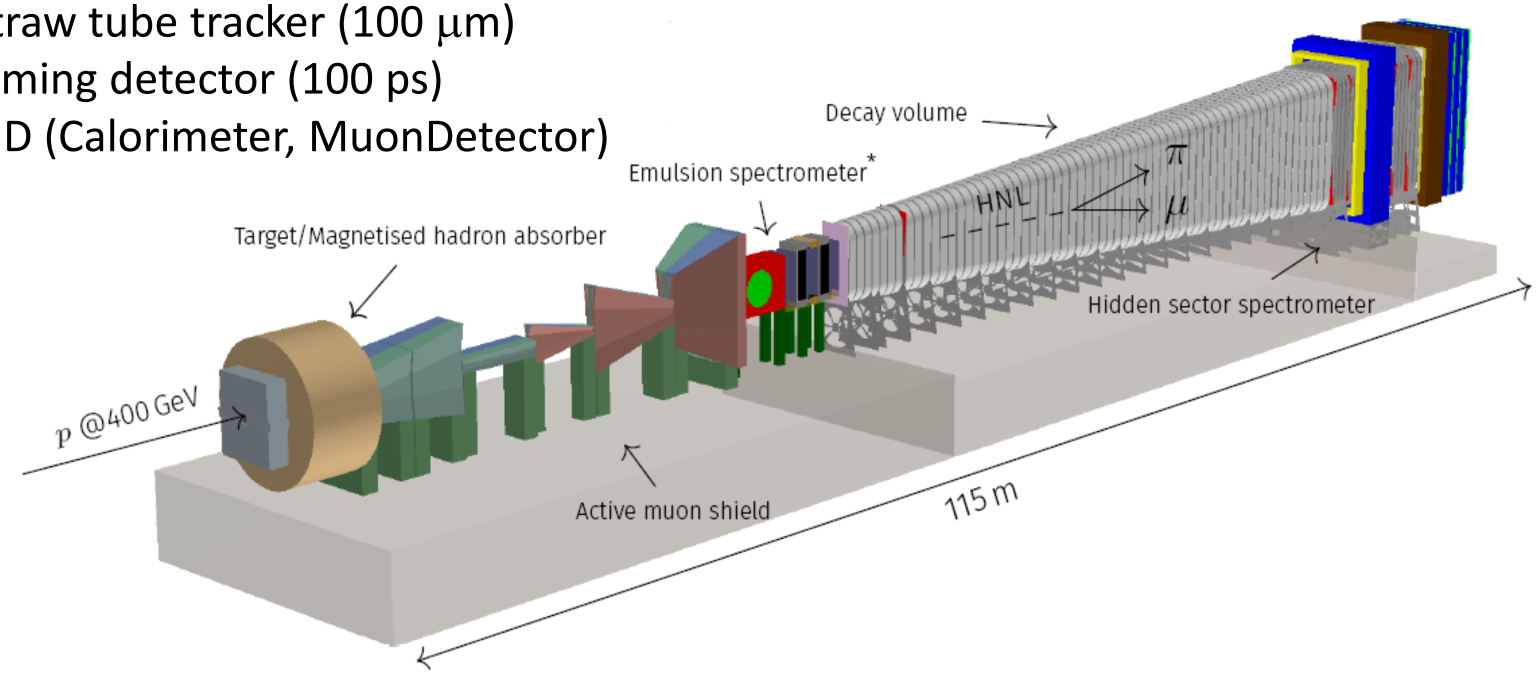


Weak decay

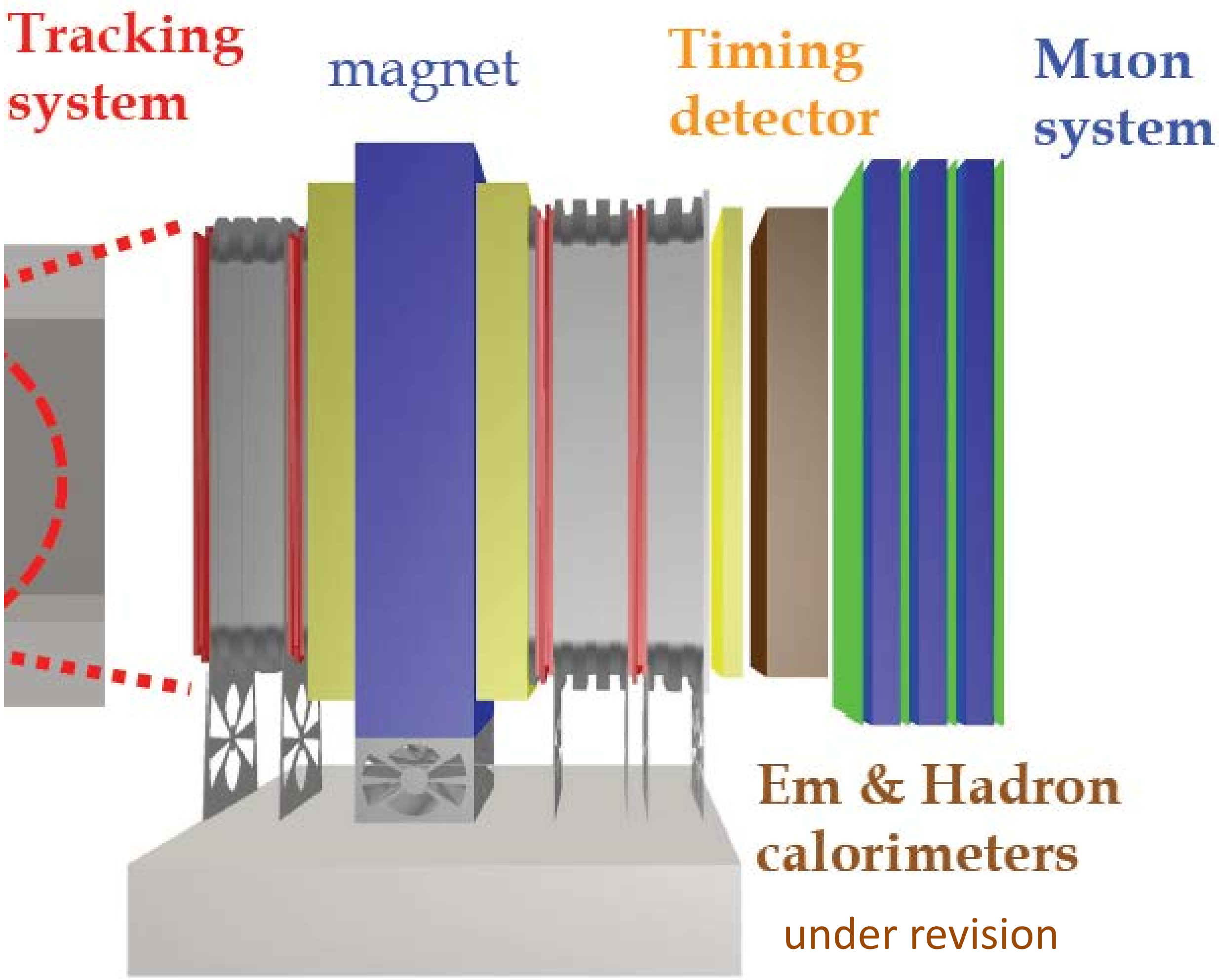


HNL in dSHiP

- Upstream, Surrounding background taggers
  - Liquid or plastic scintillator
- Vacuum vessel, p= 1 mbar
- Spectrometer
  - Straw tube tracker (100 μm)
  - Timing detector (100 ps)
  - PID (Calorimeter, MuonDetector)

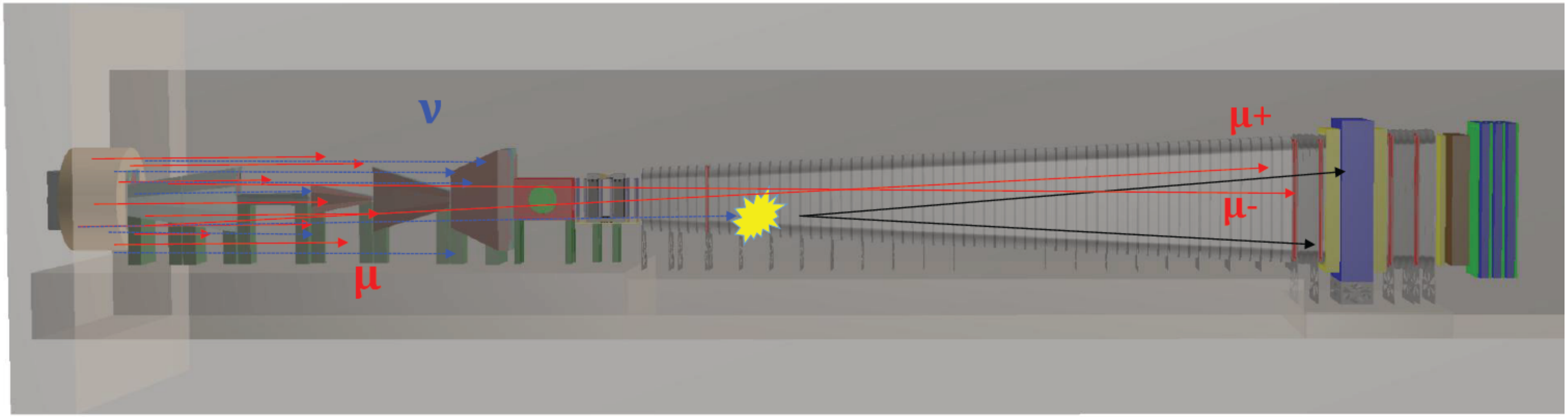


Spectrometer



under revision

….Background, background, background……



Two types of background expected:

G. Lanfranchi at the LPNHE workshop October 11, 2017

1) neutrino and muon inelastic interactions with the detector material, namely with the decay vessel;

⟶ mostly in-time tracks, not pointing backwards to the target;

⟶ main detectors to reduce this background: VETO detectors (surrounding background tagger, Upstream Veto)

2) muon combinatorial background:

⟶ mostly out-of-time tracks, not pointing backwards to the target

⟶ main detectors to reduce this background: Timing Detector (and muon system with timing capabilities)

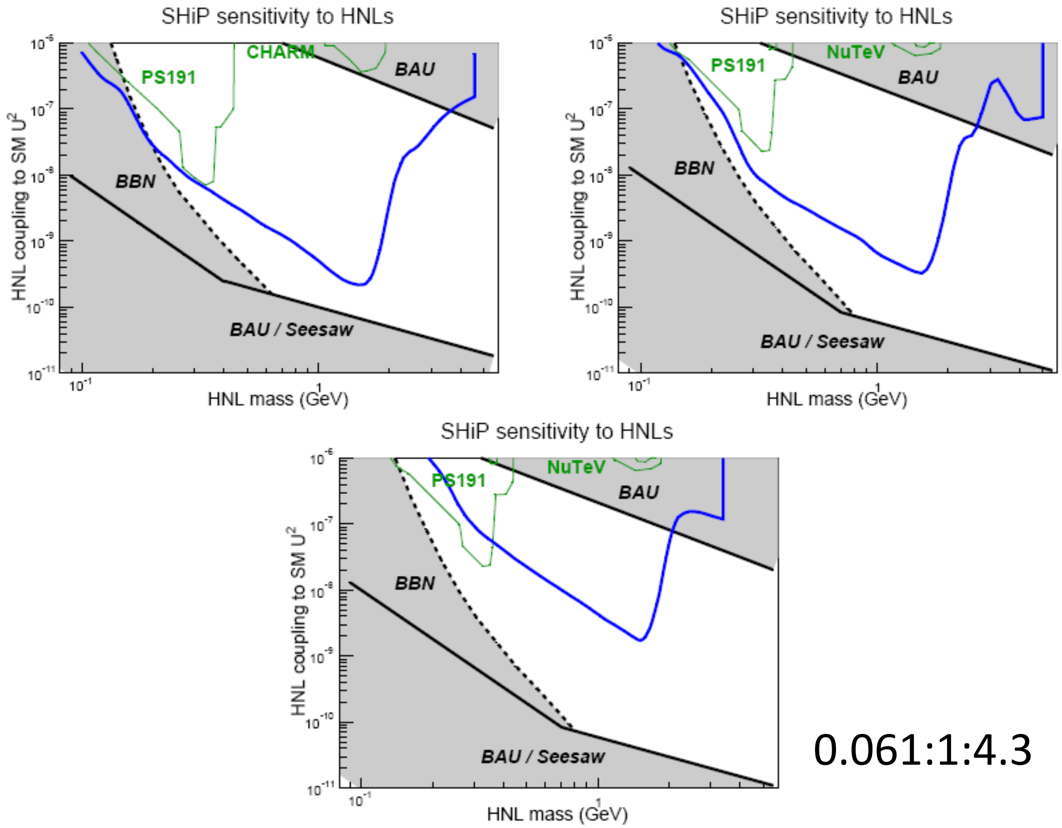
Background MC production of full SHiP exposure (5 yrs) in 2018
10 times more eventually

Sensitivity to HNL

Normal hierarchy

$U_e^2 : U_\mu^2 : U_\tau^2$

52:1:1



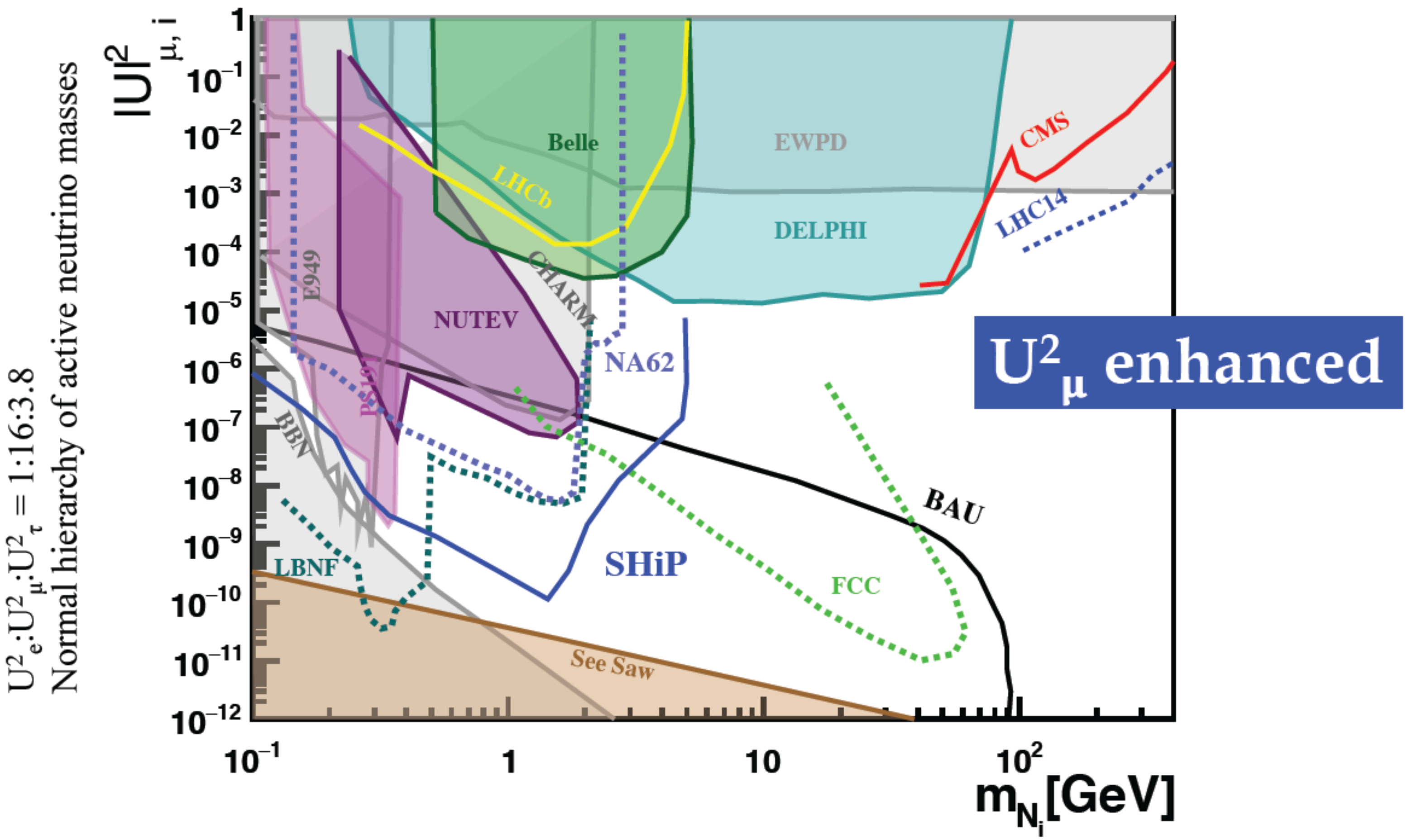
1:16:3.8

0.061:1:4.3

Figure 5.19: Sensitivity regions in the parameter space of the νMSM, for three scenarios where U_e^2, U_μ^2 and U_τ^2 dominate respectively (models I, II and III of Ref. [187]).

Sensitivity to HNL

Normal hierarchy



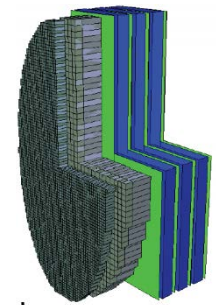
Axion-like Particles (ALPs)

- Pseudoscalars from a spontaneously broken U(1) symmetry
  scale f_a
- Generalisation of the original axion.
- Couple to
  - gauge bosons (**photons**, gluons,…) and
  - fermions.
- Production at hadron Fixed Target experiments
  - Primakoff effect ($\gamma\gamma$ fusion),
  - B and K decays.

SHiP can look for

- ALP → ll (same technique as for previous cases)
- **ALP $\rightarrow$ $\gamma\gamma$,** (f.s. unique to the ALP),
  an experimental challenge!

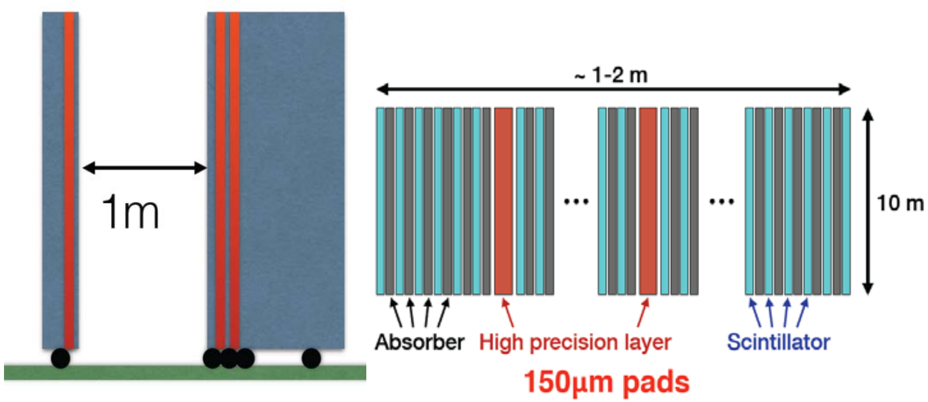
PID, timing



Evolve from the TP with a shashlik ECAL (+ HCAL) to a SplitCAL capable to track photons with mrad angular resolution.

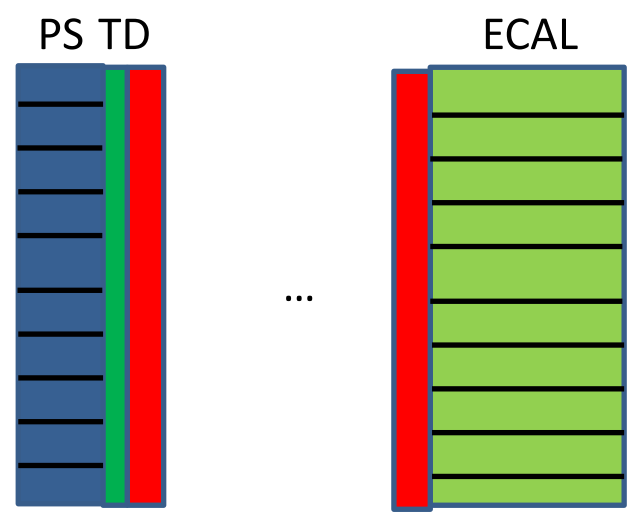
SplitCAL (Cagliari, Mainz et al)

Baseline: Pb (Fe) + scintillator sampling with 3 precision layers



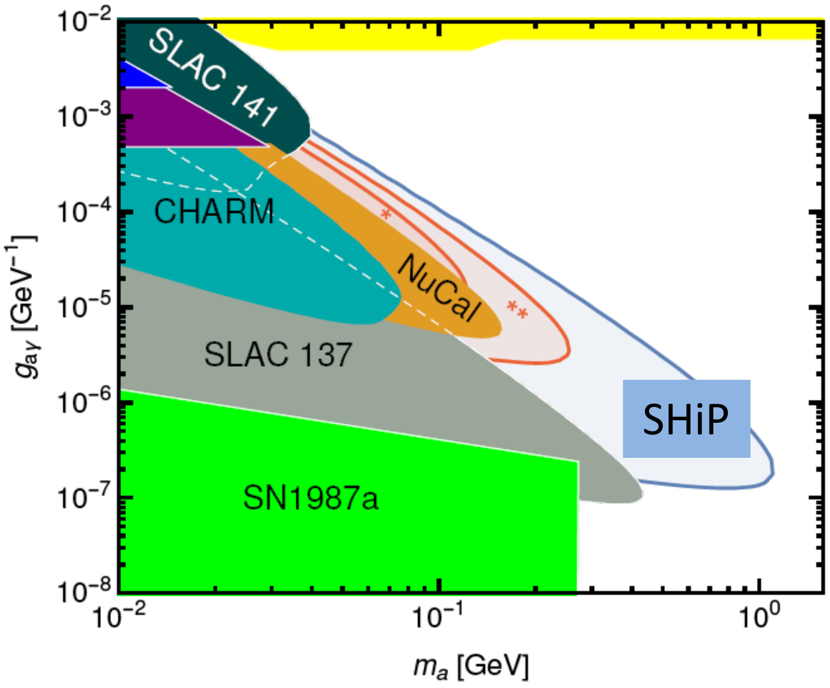
Alternate SplitCAL setup

Alternative setup: Preshower + tracking+ ECAL including (or not) timing.

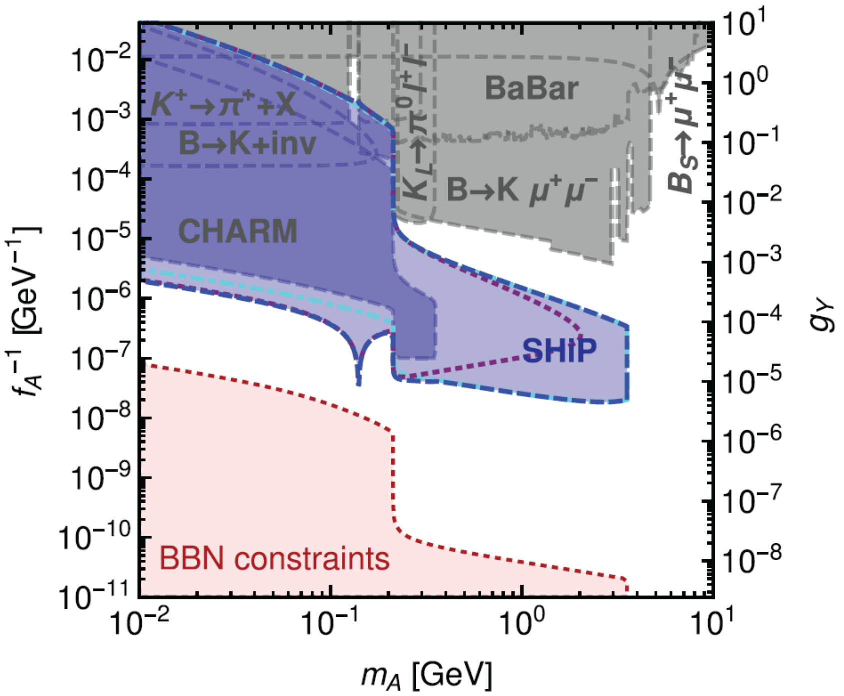


Sensitivity to ALPs

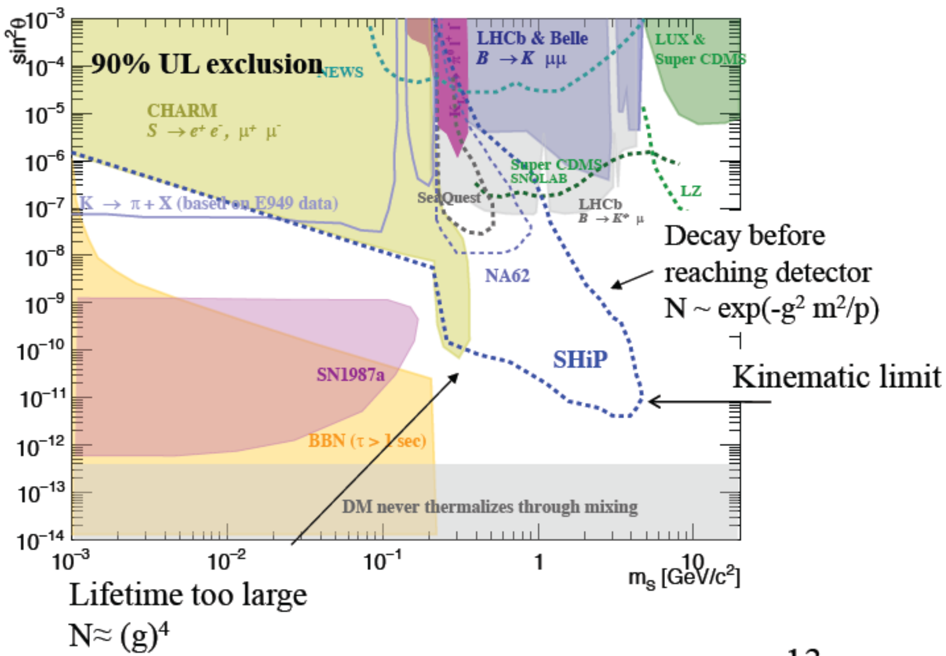
ALP → $\gamma\gamma$



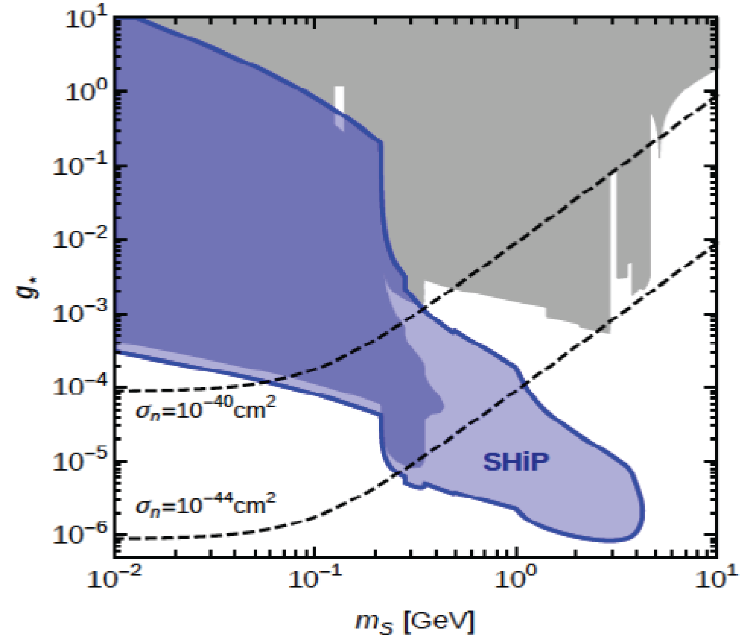
ALP → $\mu^+\mu^-$



Scalar



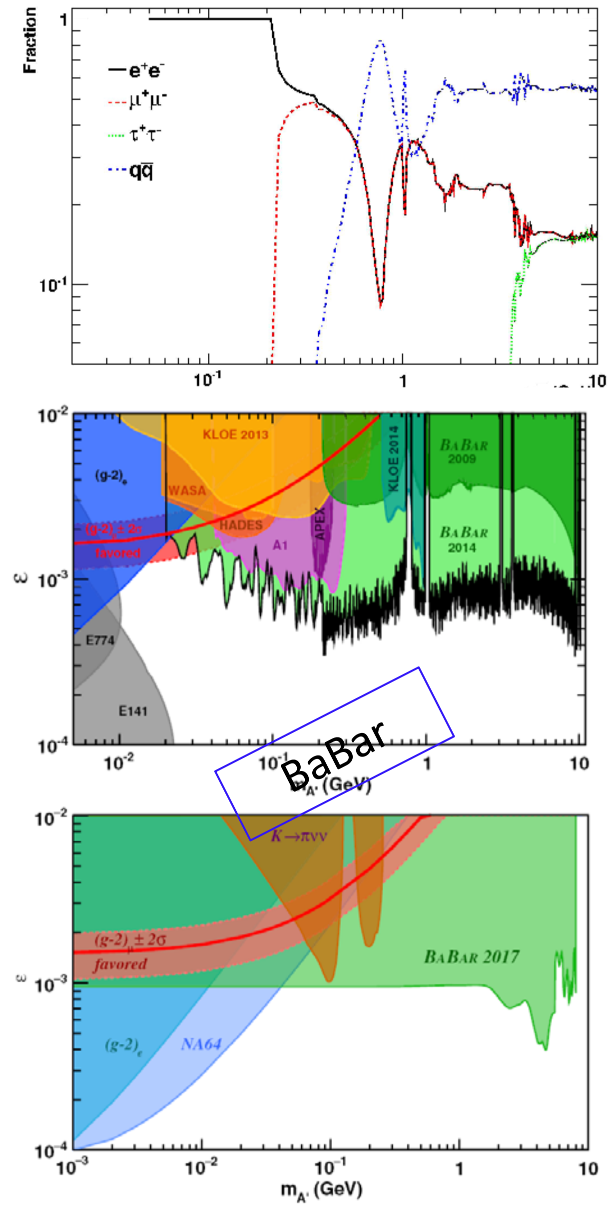
Caveat about BR(S→π+π–)



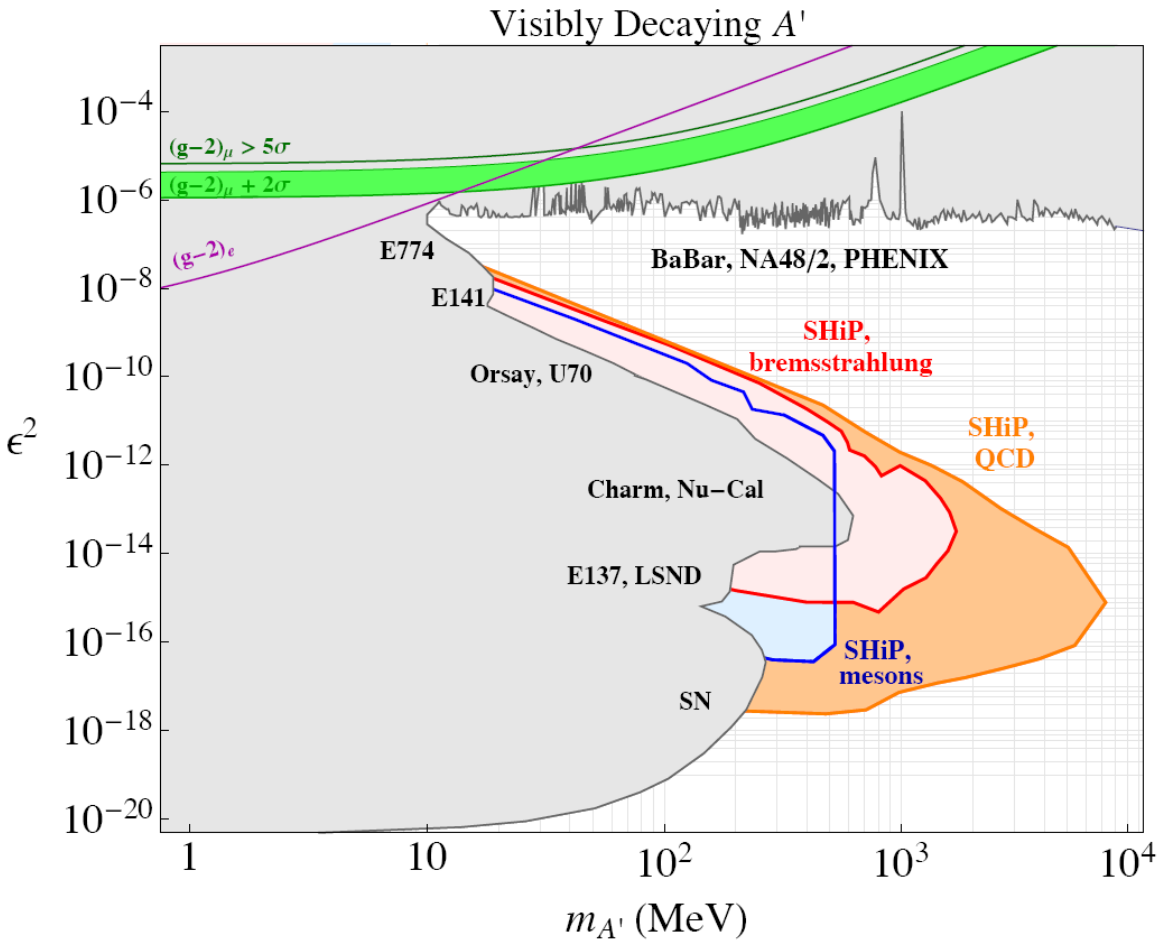
contours of constant DM nucleon cross section, assuming that S is the mediator between DM and nucleons

Dark Photon

- Gauge boson of new U(1)’ the A’,
  with MeV-GeV mass, P. Fayet PLB 95, 285(1980),…
- Kinetic mixing with γ, A’ couples to electric charge with strength εe,
- Production by brems, meson decay, direct QCD
- A’ couples to dark sector particles. Depending on its mass,
  - Visible decays — dSHiP
  - Invisible decays A’→ $\chi\chi$
- χ interact with electron or nuclei — iSHiP

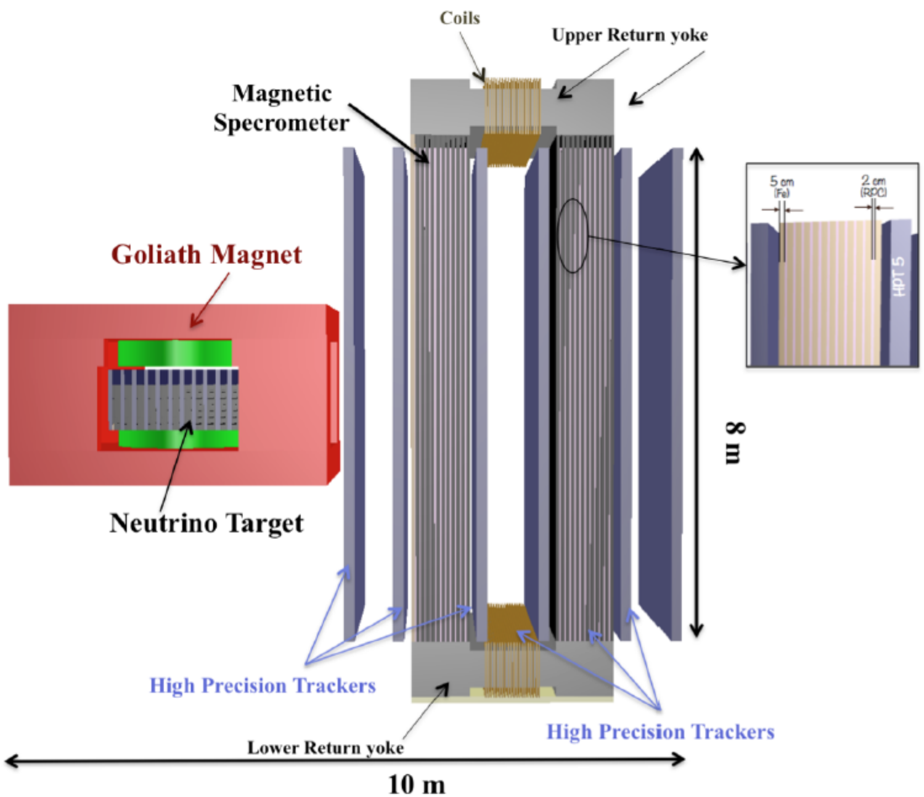


U boson/Dark Photon visible decays

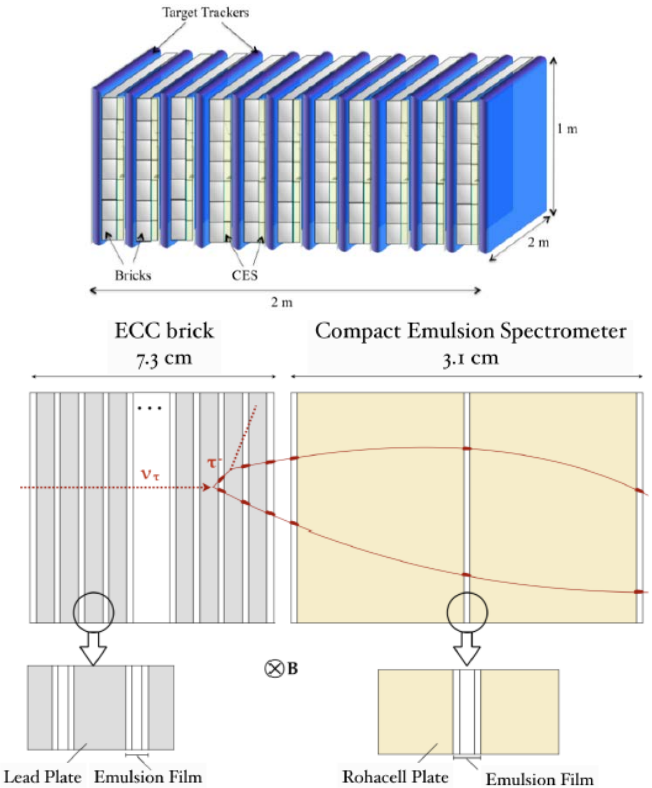


ν/iSHiP

As in the Technical Proposal

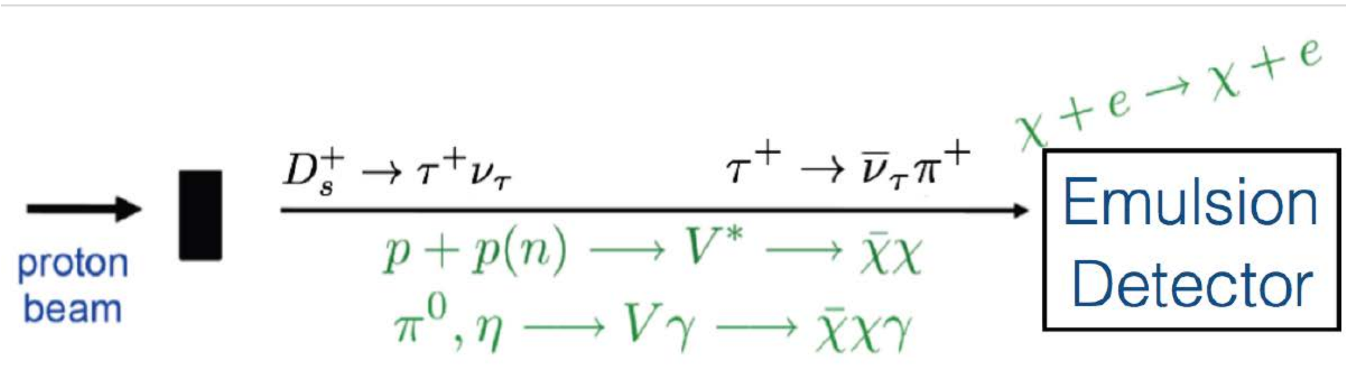


(a) *Layout of the neutrino detector.*

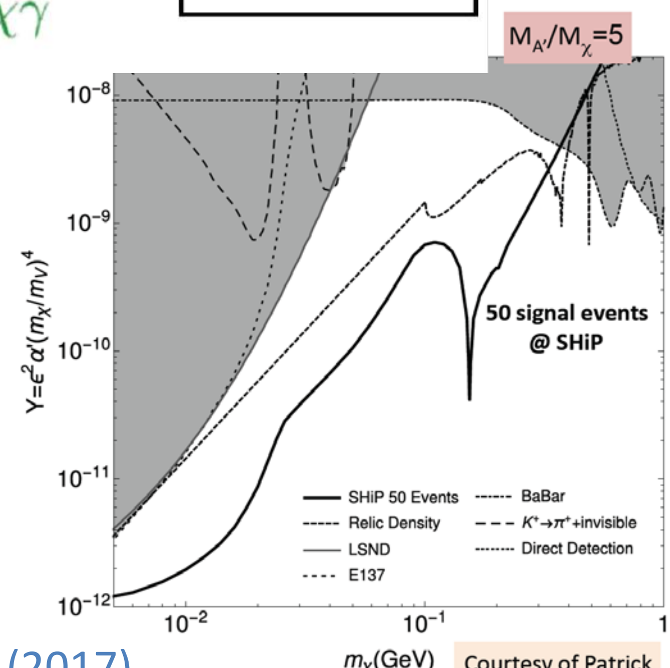


(b) *Schematic representation of the neutrino detector unitary cell.*

Accelerator-based direct (L)DM search



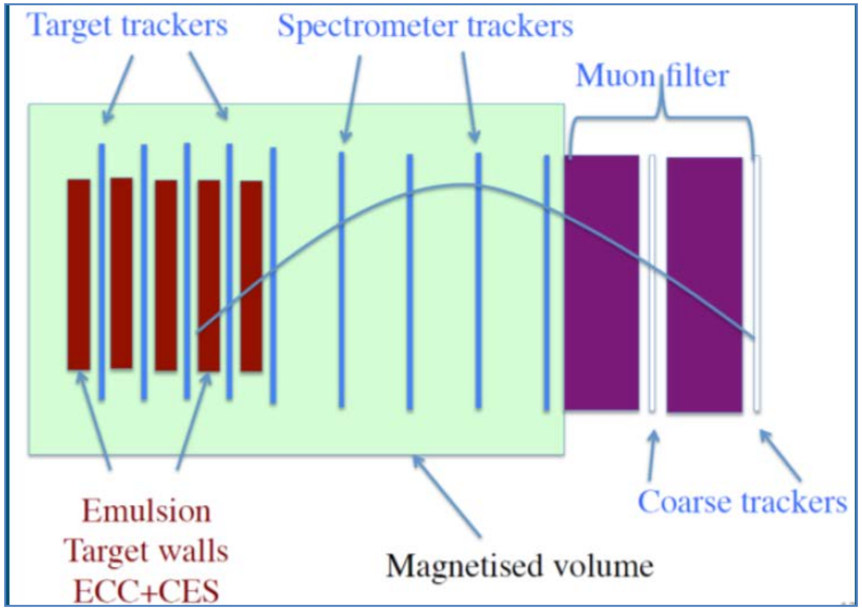
- χ could be lighter than HS mediator (e.g. V)
- ➢ V→ $\chi\chi$ allowed
- With 10^{20} photons in SHiP:
- ➢ A LDM beam downstream the dump
- Scattering experiment χe→ χe on the atoms of the SHiP detector (emulsions)
- Feasibility studies in progress (ν background)
- LDM search beyond relic density

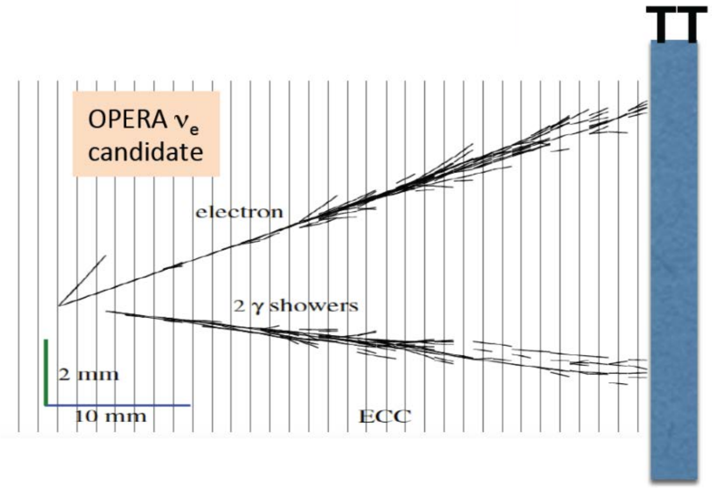


Courtesy of Patrick deNiverville

Pioneered in: de Niverville et al., Phys. Rev. D 95, 035006 (2017)
MiniBooneE: arXiv:1702.02688v1 [hep-ex]

ν/iSHiP reoptimized for LDM scattering





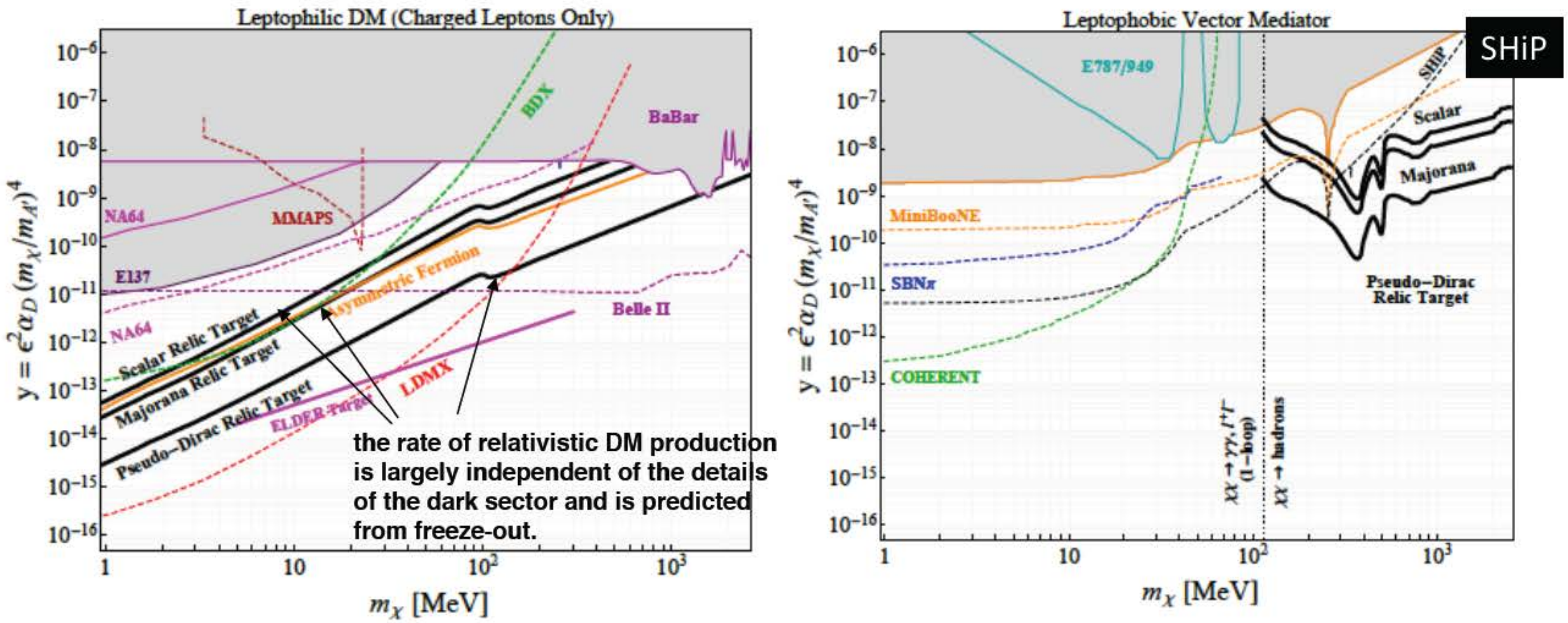
New layout under study

Possible improvements:

- Analog readout of TT to provide calorimetric information
- Optimize the distance between consecutive TT planes (currently ~10X0)
- Use a combination of TT and ECC to measure electromagnetic and hadronic showers in the event
- Timing in the TT to 0.5 ns to fight ν-background (if pulsed beam option)

LDM scattering

From arXiv: 1707.04591



- Assuming a thermal origin of the DM (e.g. freeze-out), $<\sigma v>_{annihilation}$ and $\sigma_{LDM\text{-}scatt}$ are governed by the same couplings conveniently compacted into the dimensionless parameter *y.*

➢ *Accelerator produced LDM rather than from the galactic halo wind.*

- Lepto-philic/phobic A', the latter only can be produced in SHiP.
- Work in progress

Comparison with other experiments

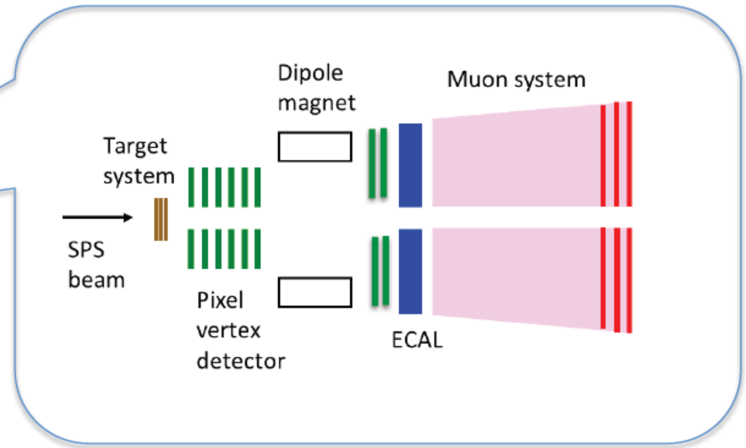
- **HNL, scalar, ALP, dark photon decays**
  - ➢ SHiP leading in the MeV-GeV ($<m_B$) range
    - Competing with NA62, SeaQuest
  - ➢ Above: FCC_ee, and ATLAS/CMS HL-LHC
- **LDM**
  - – *Scattering*
    - Best in 20-200 MeV
    - Competing with COHERENT, BDX, SBne in the US
  - – Missing mass/momentum/energy
    - ➢ not at SHiP
    - Belle-II, LDMX

τSHiP

Search for $\tau \rightarrow \mu\mu\mu$ (τSHiP) at possible extension of SHiP facility

Currently at the pre-EOI stage (see SHiP Physics Paper)

τSHiP is located upstream SHiP



- ✓ *Thin (~1mm thick) W target(s) → τ-decay vertex in the air*
- ✓ *~ 5×10^{13} τ leptons produced in 5 years*
- ✓ *Backgrounds include*
  - *Combinatorial bckg., mainly from muons produced in em decays of η, ρ, ω, …*
  - *Bckg. from various semileptonic D decays, e.g. $D^+ \rightarrow \eta\mu^+\nu$, $\eta \rightarrow \mu^+\mu^-$*
- ✓ *Estimated sensitivity: UL on BR($\tau \rightarrow 3\mu$) better than 10^{-10} (SHiP Physics Paper)*

BUT: Great improvements in detector technologies are required

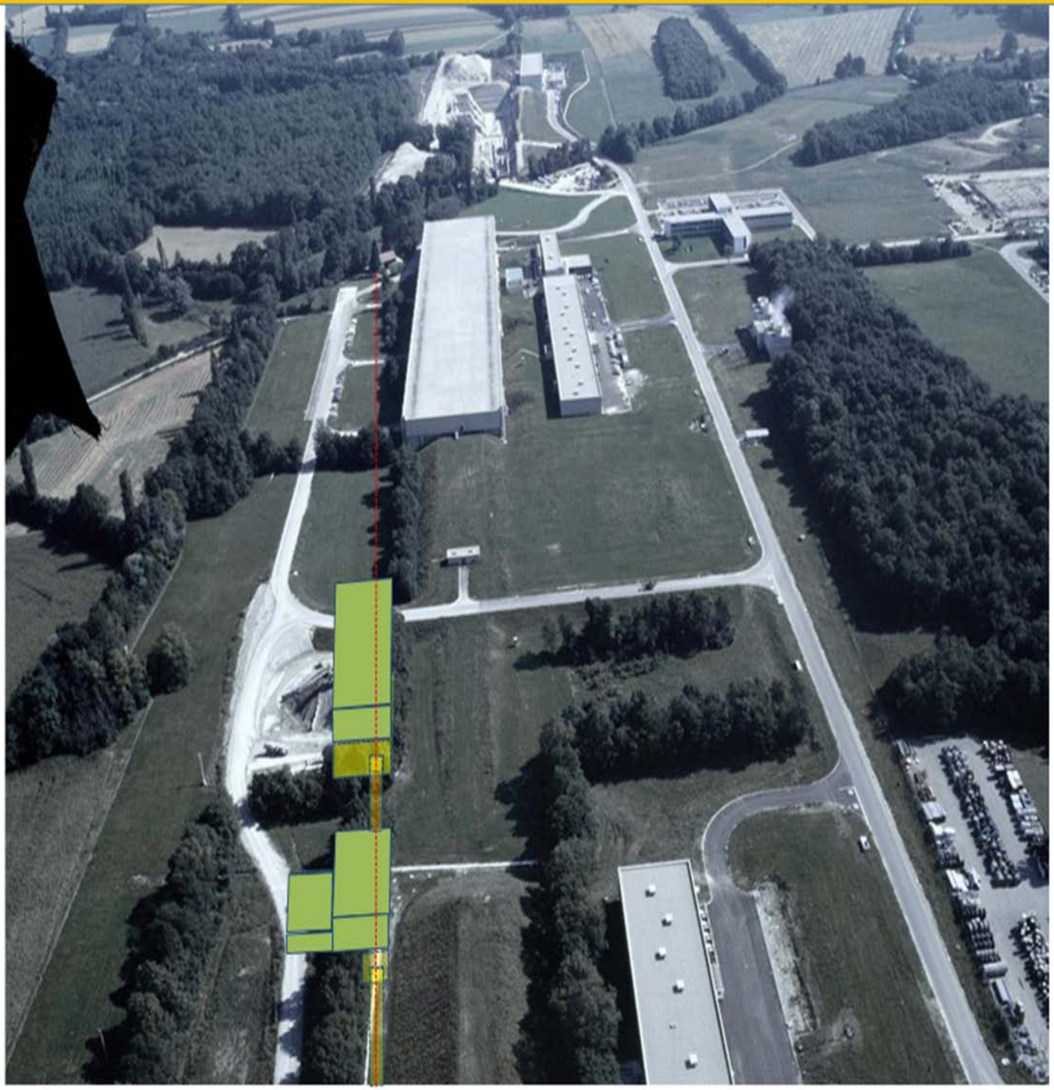
Synergy with LHCb tracking and calorimetry for future upgrades

Summary and perspectives

- SHiP a general purpose detector at the new beam dump facility at the SPS in >2026.
- A rich physics case, constantly growing.
  - Best sensitivity to decays of Hidden Sector particles compared to experiments anticipated by then.
  - Key player for the detection of the interactions of « Light Dark Matter ».
  - Guaranteed physics : ν_τ physics
- A reoptimization of the layout is underway for the CDS, input to the European Strategy. SHiP sensitivities will be revised by then.
- A major project in the review conducted within the PBC workshop.
- Detector elements are still to be defined conceptually.
- Technological choices for the TDR.
- There is room for other experiments in the facility.
- A good time to join (phenomenology, simulation, R&D).

Extra

Aerial view with part of the facilities foreseen



Signature	Physics	Backgrounds	Cuts
$\pi^-\mu^+, K^-\mu^+$	HNL,NEU	RDM, $K_L^0 \to \pi^-\mu^+\nu_\mu$	IP,TI,PID($\mu\pi$) P,IP,NT
$\pi^-\pi^0\mu^+$	HNL($\to \rho^-\mu^+$)	$K_L^0 \to \pi^-\mu^+\nu_\mu(+\pi^0)$, $K_L^0 \to \pi^-\pi^+\pi^0$	P,IP,NT,TI, P,IP,NT,PID($\pi\mu$)
π^-e^+, K^-e^+	HNL, NEU	$K_L^0 \to \pi^-e^+\nu_e$	P,IP,NT
$\pi^-\pi^0e^+$	HNL($\to \rho^-e^+$)	$K_L^0 \to \pi^-e^+\nu_e$, $K_L^0 \to \pi^-\pi^+\pi^0$	P,IP,NT,TI,PID(πe)
μ^-e^++MM	HNL,HP($\to \tau\tau$)	$K_L^0 \to \pi^-\mu^+\nu_\mu$, $K_L^0 \to \pi^-e^+\nu_e$	P,NT, PID($\pi\mu, \pi e$)
$\mu^-\mu^+$+MM	HNL,HP($\to \tau\tau$)	RDM, $K_L^0 \to \pi^-\mu^+\nu_\mu$	TI P,NT, PID($\pi\mu$)
$\mu^-\mu^+$	DP,PNGB,HP	RDM, $K_L^0 \to \pi^-\mu^+\nu_\mu$	TI,IP P,NT, IP, PID($\pi\mu$)
$\mu^-\mu^+\gamma$	CS	$K_L^0 \to \pi^-\pi^+\pi^0$, $K_L^0 \to \pi^-\mu^+\nu_\mu(+\pi^0)$	P,IP,NT, PID($\pi\mu$),TI,VP
e^-e^++MM	HNL,HP	$K_L^0 \to \pi^-e^+\nu_e$	P,NT, PID(πe)
e^-e^+	DP,PNGB,HP	$K_L^0 \to \pi^-e^+\nu_e$	P,IP,NT, PID(πe)
$\pi^-\pi^+$	DP,PNGB,HP	$K_L^0 \to \pi^-\mu^+\nu_\mu$, $K_L^0 \to \pi^-e^+\nu_e$ $K_L^0 \to \pi^-\pi^+\pi^0$, $K_L^0 \to \pi^-\pi^+$	P,NT, PID($\mu\pi$),IP PID($e\pi$),IP POA,IP
$\pi^-\pi^+$+MM	DP,PNGB, HP($\to \tau\tau$), HS,HNL($\to \rho^0\nu$)	$K_L^0 \to \pi^-\mu^+\nu_\mu$, $K_L^0 \to \pi^-e^+\nu_e$, $K_L^0 \to \pi^-\pi^+\pi^0$, $K_L^0 \to \pi^-\pi^+, K_S^0 \to \pi^-\pi^+, \Lambda \to p\pi$	P,NT, PID($\mu\pi$), PID($e\pi$), POA
K^+K^-	DP,PNGB, HP	$K_L^0 \to \pi^-\mu^+\nu_\mu$, $K_L^0 \to \pi^-e^+\nu_e$ $K_L^0 \to \pi^-\pi^+\pi^0$, $K_L^0 \to \pi^-\pi^+, K_S^0 \to \pi^-\pi^+, \Lambda \to p\pi$	P,NT, PID($\pi\mu, \pi e$),IP
$\pi^+\pi^-\pi^0$	DP,PNGB,HP, HNL($\eta\nu$)	$K_L^0 \to \pi^-\pi^+\pi^0$	P,IP,NT
$\pi^+\pi^-\pi^0\pi^0$	DP,PNGB,HP	$K_L^0 \to \pi^-\pi^+\pi^0(+\pi^0)$	P,IP,NT,TI
$\pi^+\pi^-\pi^0\pi^0\pi^0$	PNGB($\to \pi\pi\eta$)	–	–
$\pi^+\pi^-\gamma\gamma$	PNGB($\to \pi\pi\eta$)	$K_L^0 \to \pi^-\pi^+\pi^0$	P, IP, NT,M($\gamma\gamma$)
$\pi^+\pi^-\pi^+\pi^-$	DP,PNGB,HP	–	–
$\pi^+\pi^-\mu^+\mu^-$	HSU	–	–
$\pi^+\pi^-e^+e^-$	HSU	–	–
$\mu^+\mu^-\mu^+\mu^-$	HSU	–	–
$\mu^+\mu^-e^+e^-$	HSU	–	–

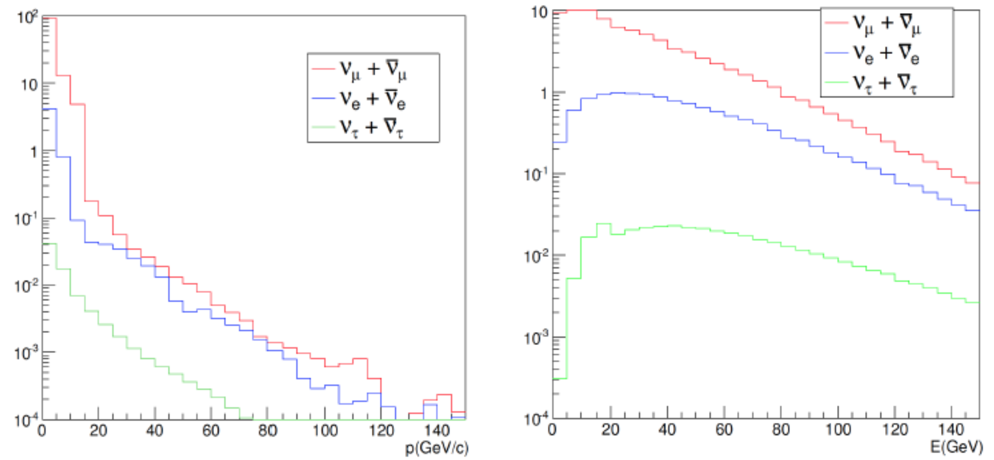
Experiment	Machine	Type	E_{beam} (GeV)	Detection	Mass range (GeV)	Sensitivity	First beam	Ref.
Future US initiatives								
BDX	CEBAF @ JLab	electron BD	2.1-11	DM scatter	$0.001 < m_\chi < 0.1$	$y \gtrsim 10^{-13}$	2019+	[211, 212]
COHERENT	SNS @ ORNL	proton BD	1	DM scatter	$m_\chi < 0.06$	$y \gtrsim 10^{-13}$	started	[213, 214]
DarkLight	LERF @ JLab	electron FT	0.17	MMass (& vis.)	$0.01 < m_{A'} < 0.08$	$\epsilon^2 \gtrsim 10^{-6}$	started	[215]
LDMX	DASEL @ SLAC	electron FT	4 (8)*	MMomentum	$m_\chi < 0.4$	$\epsilon^2 \gtrsim 10^{-14}$	2020+	[216]
MMAPS	Synchr @ Cornell	positron FT	6	MMass	$0.02 < m_{A'} < 0.075$	$\epsilon^2 \gtrsim 10^{-8}$	2020+	[217]
SBN	BNB @ FNAL	proton BD	8	DM scatter	$m_\chi < 0.4$	$y \sim 10^{-12}$	2018+	[218, 219]
SeaQuest	MI @ FNAL	proton FT	120	vis. prompt	$0.22 < m_{A'} < 9$	$\epsilon^2 \gtrsim 10^{-8}$	2017	[220]
				vis. disp.	$m_{A'} < 2$	$\epsilon^2 \sim 10^{-14} - 10^{-8}$		
Future international initiatives								
Belle II	SuperKEKB @ KEK	e^+e^- collider	~ 5.3	MMass (& vis.)	$0 < m_\chi < 10$	$\epsilon^2 \gtrsim 10^{-9}$	2018	[203]
MAGIX	MESA @ Mami	electron FT	0.105	vis.	$0.01 < m_{A'} < 0.060$	$\epsilon^2 \gtrsim 10^{-9}$	2021-2022	[205]
PADME	DAΦNE @ Frascati	positron FT	0.550	MMass	$m_{A'} < 0.024$	$\epsilon^2 \gtrsim 10^{-7}$	2018	[206, 207]
SHIP	SPS @ CERN	proton BD	400	DM scatter	$m_\chi < 0.4$	$y \gtrsim 10^{-12}$	2026+	[208, 209]
VEPP3	VEPP3 @ BINP	positron FT	0.500	MMass	$0.005 < m_{A'} < 0.022$	$\epsilon^2 \gtrsim 10^{-8}$	2019-2020	[210]
Current and completed initiatives								
APEX	CEBAF @ JLab	electron FT	1.1-4.5	vis.	$0.06 < m_{A'} < 0.55$	$\epsilon^2 \gtrsim 10^{-7}$	2018-2019	[197, 198]
BABAR	PEP-II @ SLAC	e^+e^- collider	~ 5.3	vis.	$0.02 < m_{A'} < 10$	$\epsilon^2 \gtrsim 10^{-7}$	done	[191, 229, 230]
Belle	KEKB @ KEK	e^+e^- collider	~ 5.3	vis.	$0.1 < m_{A'} < 10.5$	$\epsilon^2 \gtrsim 10^{-7}$	done	[231]
HPS	CEBAF @ JLab	electron FT	1.1-4.5	vis.	$0.015 < m_{A'} < 0.5$	$\epsilon^2 \sim 10^{-7}$**	2018-2020	[232]
NA/64	SPS @ CERN	electron FT	100	MEnergy	$m_{A'} < 1$	$\epsilon^2 \gtrsim 10^{-10}$	started	[186]
MiniBooNE	BNB @ FNAL	proton BD	8	DM scatter	$m_\chi < 0.4$	$y \gtrsim 10^{-9}$	done	[188]
TREK	K^+ beam @ J-PARC	K decays	0.240	vis.	N/A	N/A	done	[201, 202]

TABLE II: Summary table of current light DM experiments and future proposals. The sensitivities are quoted either for the kinetic mixing or the variable y, whichever is most relevant (see the text and the corresponding figures for more detailed predictions). The range quoted for experiments sensitive to both visible and invisible decays refers to the invisible case. Starting dates are subject to variations. *Legend:* beam dump (BD), fixed target (FT), dark matter scattering (DM scatter), missing mass (MMass), missing momentum (MMomentum), missing energy (MEnergy), prompt/displaced visible decays (vis). *Notes:* *LDMX beam energy is 4 GeV for phase I, and could be upgraded to 8 GeV for phase II. **Sensitivity to displaced vertices under study.

ν_τ

	<E>	Beam dump	<E>	CC DIS
N_{ν_μ}	1.4	4.4×10^{18}	29	1.7×10^{6}
N_{ν_e}	3	2.1×10^{17}	46	2.5×10^{5}
N_{ν_τ}	9	3.1×10^{15}	59	7.4×10^{3}
$N_{\overline{\nu}_\mu}$	1.5	2.8×10^{18}	28	6.7×10^{5}
$N_{\overline{\nu}_e}$	4	1.6×10^{17}	46	9.0×10^{4}
$N_{\overline{\nu}_\tau}$	8	3.1×10^{15}	58	3.7×10^{3}

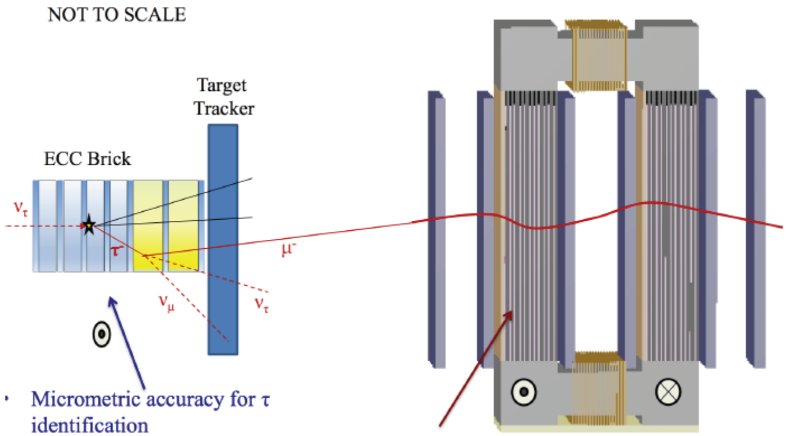
Table 2: Integrated neutrino yield for 2×10^{20} p.o.t. for the different neutrino flavors: at the beam dump (left) and CC DIS interactions (right). Energies are in GeV.

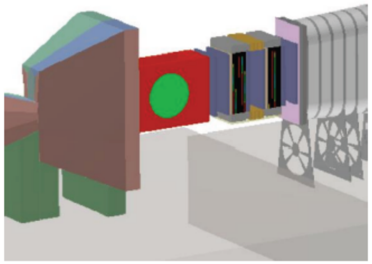


(a) *Beam dump.* (b) *CC interacting.*

Figure 5: Energy spectra of the three neutrino flavors at the beam dump (a) and of CC interactions in the neutrino target(c). The total number of neutrinos is normalized to 100.

The ν_τ Detector (Scattering)





TP

decay channel	ν_τ			$\overline{\nu}_\tau$		
	N^{exp}	N^{bg}	R	N^{exp}	N^{bg}	R
$\tau \to \mu$	570	30	19	290	140	2
$\tau \to h$	990	80	12	500	380	1.3
$\tau \to 3h$	210	30	7	110	140	0.8
total	1770	140	13	900	660	1.4

- Only 9 ν_τ events recorded to date
- $\overline{\nu}_\tau$ yet to be discovered
- ν_τ / $\overline{\nu}_\tau$ cross sections to be measured
- Charm physics with τ's
- Proton structure functions
- Large ν_e flux to measure charm production

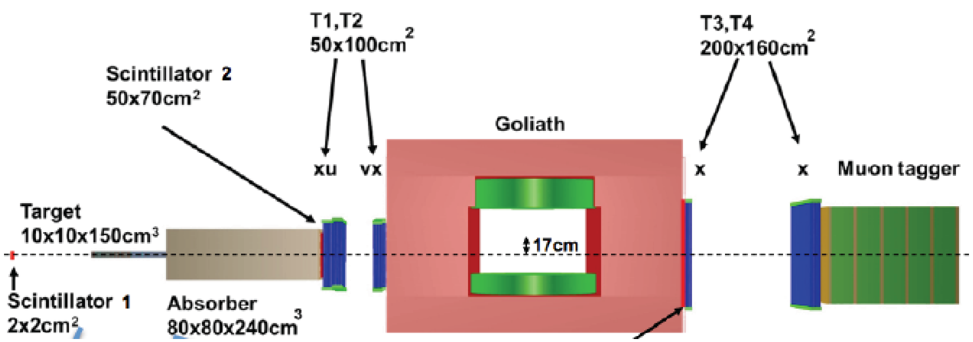
And also,

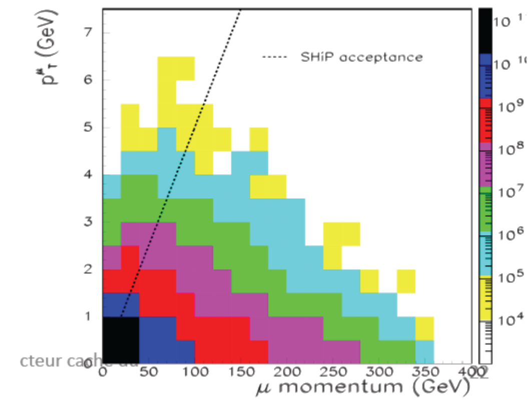
➢ Probe LFUV comparing ν_μ and ν_τ CC events ? *to be further studied*.

H. Liu, A. Rashed, A. Datta 1505.04594, Phys. Rev. D 92, 073016 (2015)

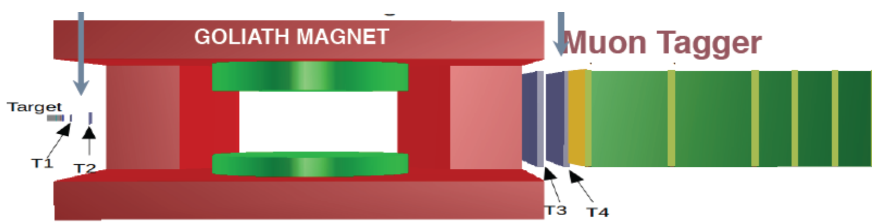
Preparatory experiments

- **2018 EoI-016 to SPSC**. Measurement of the muon flux
  - replica of SHiP target, 10^{11} p.o.t





- **2018-21 EoI-017 to SPSC** Measure charm $\frac{d^2\sigma}{dEd\vartheta}$ to validate cascade enhancement by factor 2-3.



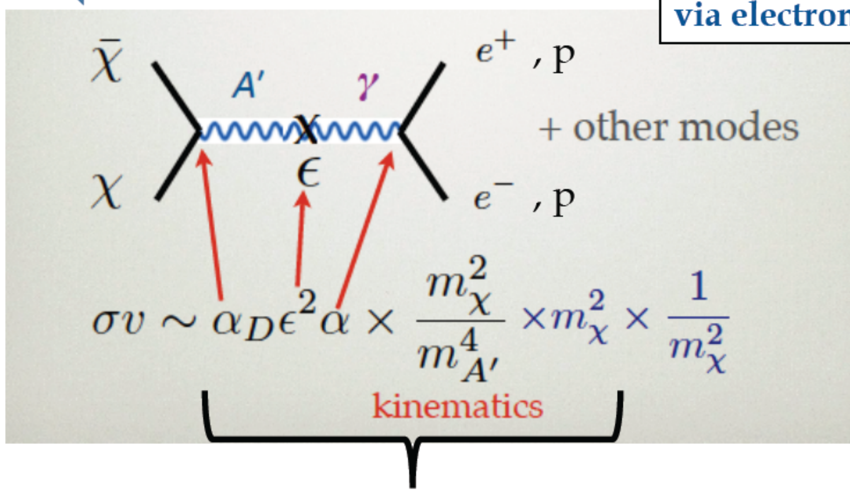
$5 \times 10^7\ p.o.t.\ or\ 1000\ charm\ pairs$

Vector Portal : connection to Light Dark Matter (and thermal origin target)

SHiP

If $m_{A'} > 2\, m_\chi$ the Dark Photon can decay also to DM with a coupling $\boldsymbol{\alpha_D}$

Production of DM at accelerators via electron or proton bremstrahlung

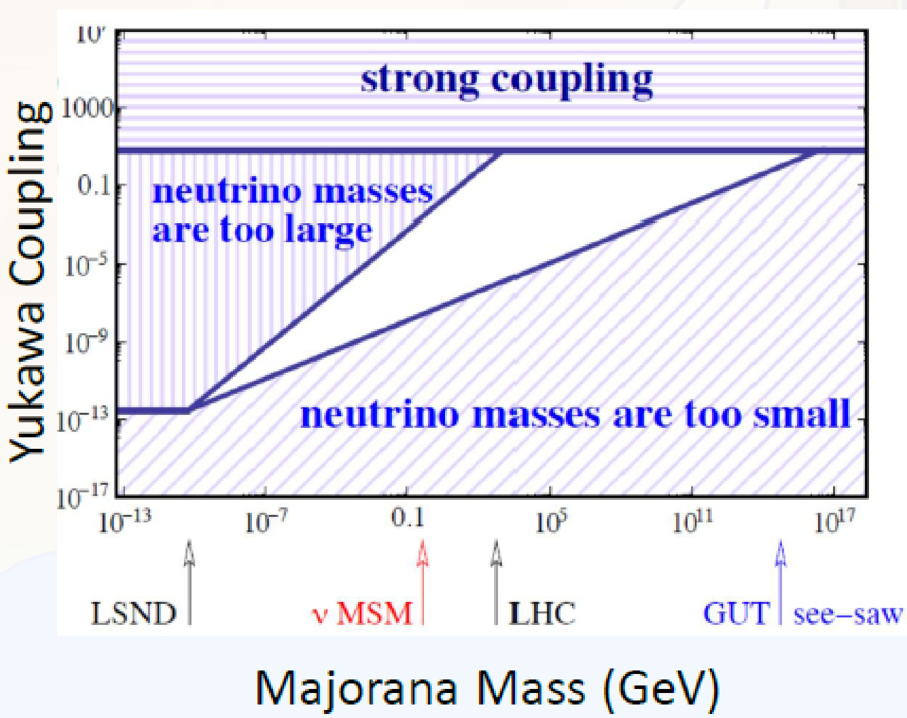


y : dimensionless parameter controlling DM cross-section

Direct DM annihilation (main process to get the thermal relic abundance) but also Direct DM scattering with e/protons

Sterile neutrino masses

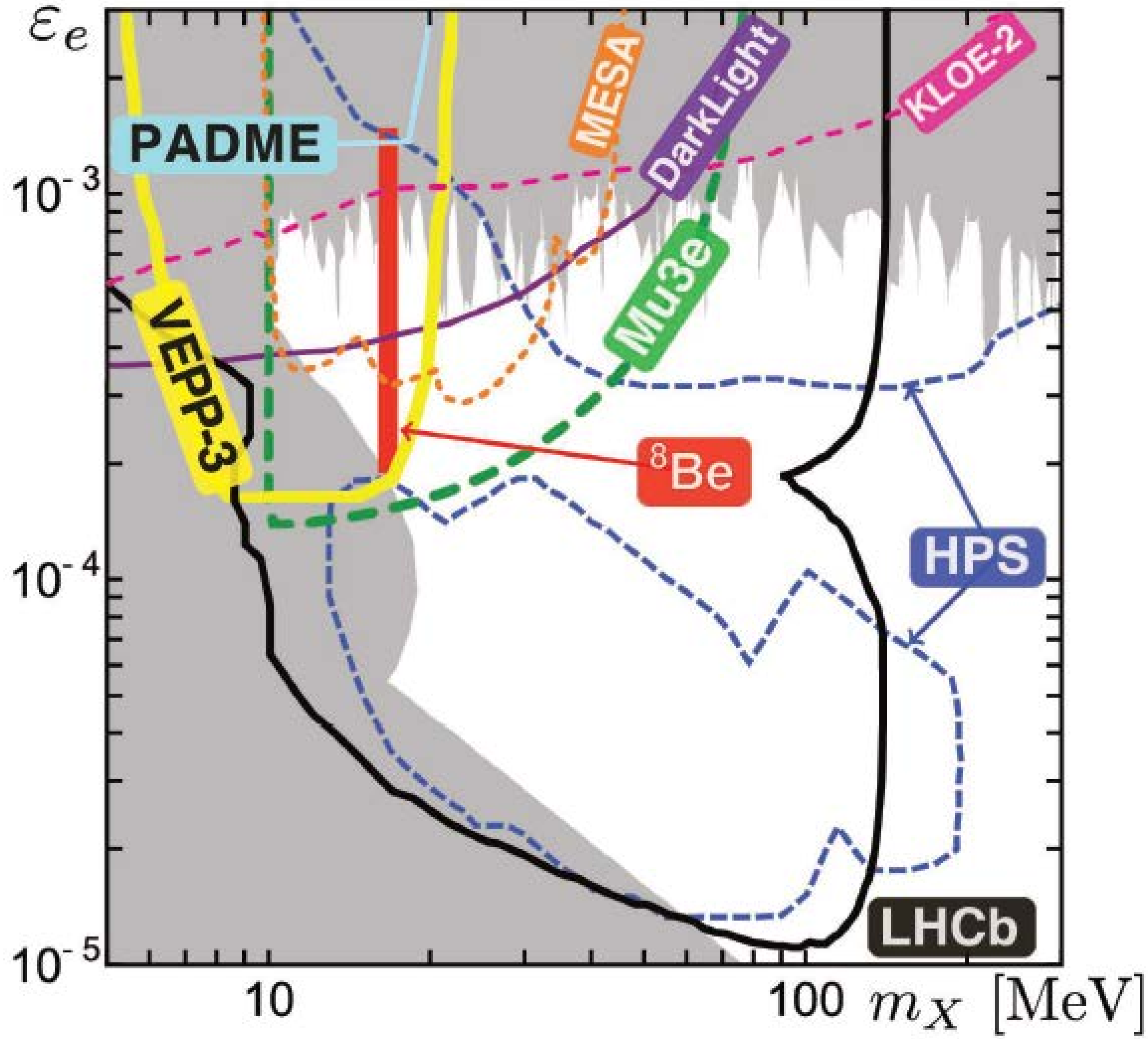
Seesaw formula $m_D \sim Y_{I\alpha} < \phi >$ and $m_\nu = \frac{m_D^2}{M}$



- Assuming $m_\nu = 0.1\text{eV}$
- if $Y \sim 1$ implies $M \sim 10^{14}\text{GeV}$
- if $M_N \sim 1\text{GeV}$ implies $Y_\nu \sim 10^{-7}$

remember $Y_{top} \sim 1.$ and $Y_e \sim 10^{-6}$

If we want to explain the smallness of neutrino masses (in a natural way) the mass of sterile neutrinos should be at least at the GeV scale

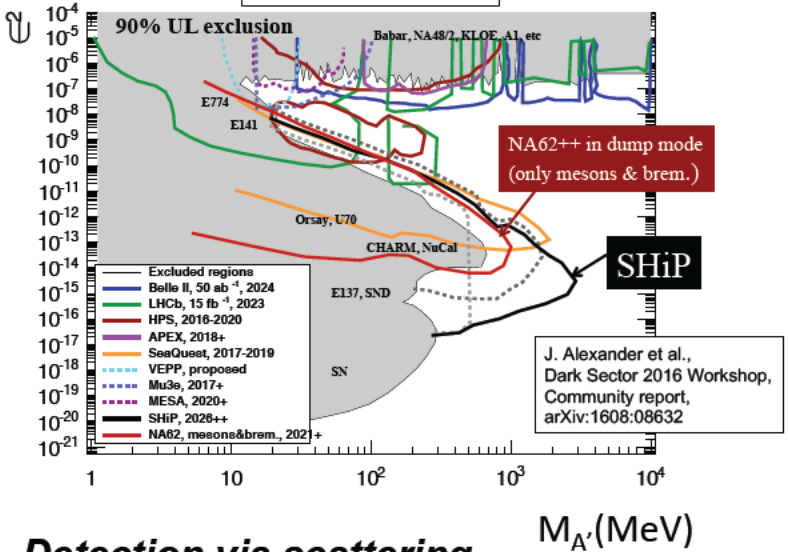


ε_e
PADME
MESA
DarkLight
KLOE-2
10^{-3}
Mu3e
VEPP-3
^{8}Be
HPS
10^{-4}
LHCb
10^{-5}
10
100
m_X [MeV]

Future prospects and comparison with other facilities

Dark photons:

A′ → visible modes



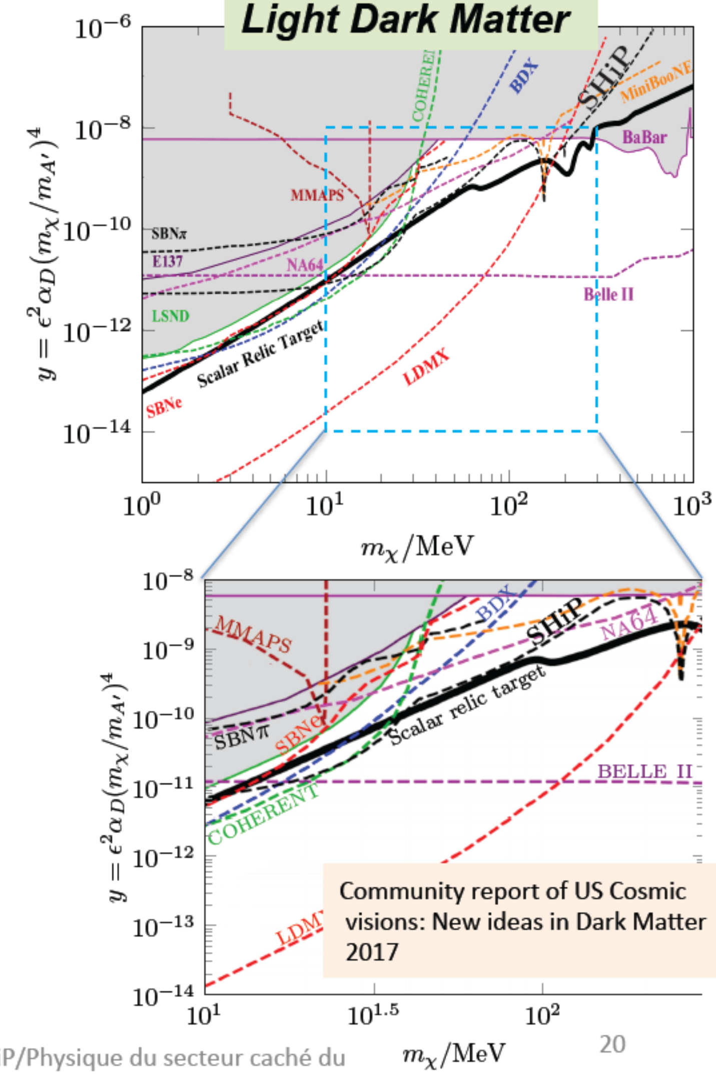
Detection via scattering

- *SHiP has the best sensitivity in 20 – 200 MeV*
  Optimization is ongoing
  COHERENT, BDX and SBNe in US

Missing mass / energy technique

- *Belle II with 50 ab⁻¹ provided that low energy mono-photon trigger works*
- *LDMX (under discussion at SLAC) has the best prospects for M_χ < 100 MeV*

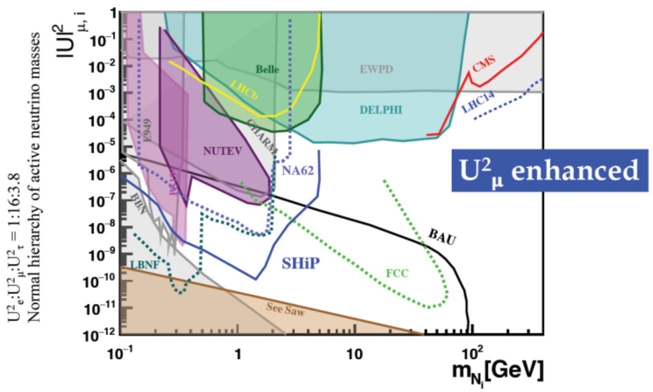
Light Dark Matter



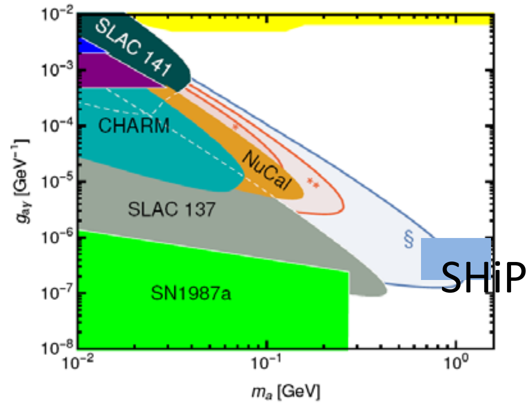
Journée SHiP/Physique du secteur caché du 11/10/2017 20

Comparison with other experiments

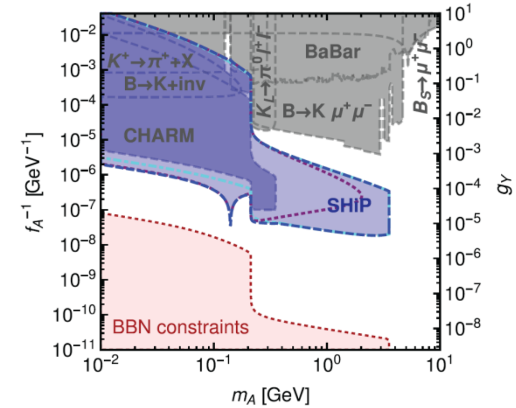
HNL



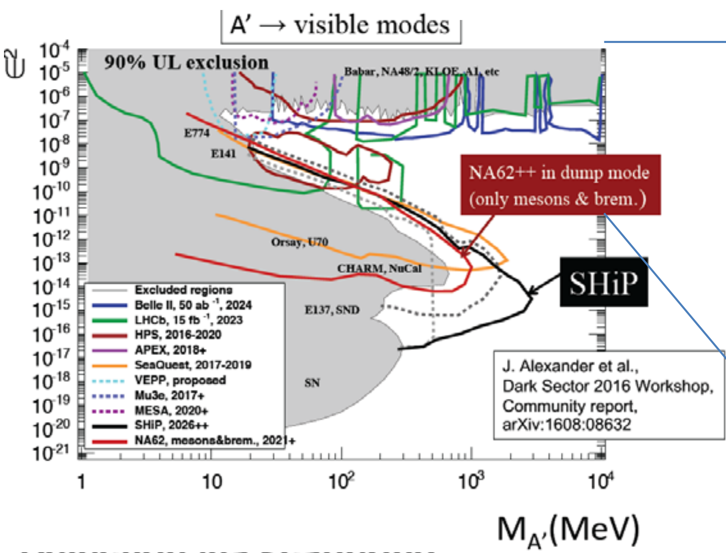
ALP → γγ

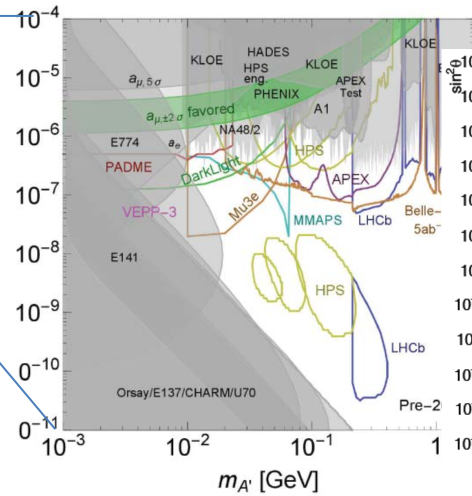


ALP → μ⁺μ⁻

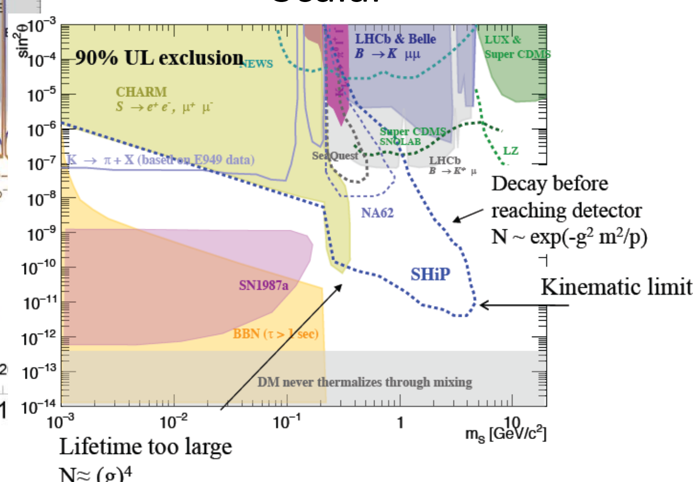


A' visible modes





Scalar



France in SHiP

- LPNHE
- LAL
  - common electronics definition
- IRFU not before 2021 μM in the TT of iSHiP
- Schedule parallel to HL-LHC projects
  - about time to seize the opportunity
- The GDR InF

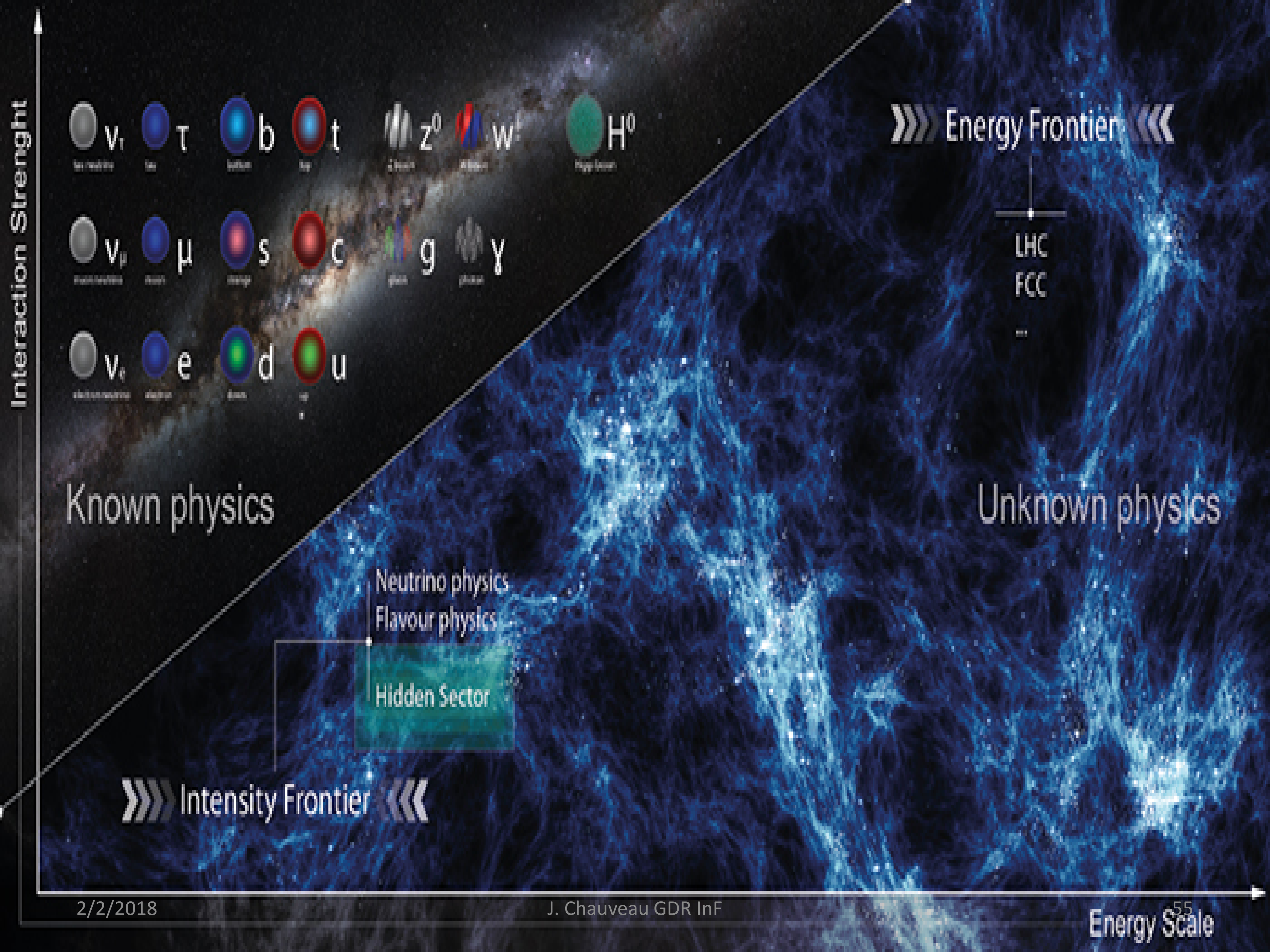
- *SHiP experiment: http://ship.web.cern.ch/ship/*
- *Journee ShiP/Physique du Secteur Cache LPNHE October 11, 2017*
- *Electronics workshop October 25, 2017*
- *Colloquium on Physics Landscape in 10 years November 9, 2017*
- *Physics beyond Colliders workshop: http://pbc.web.cern.ch/*

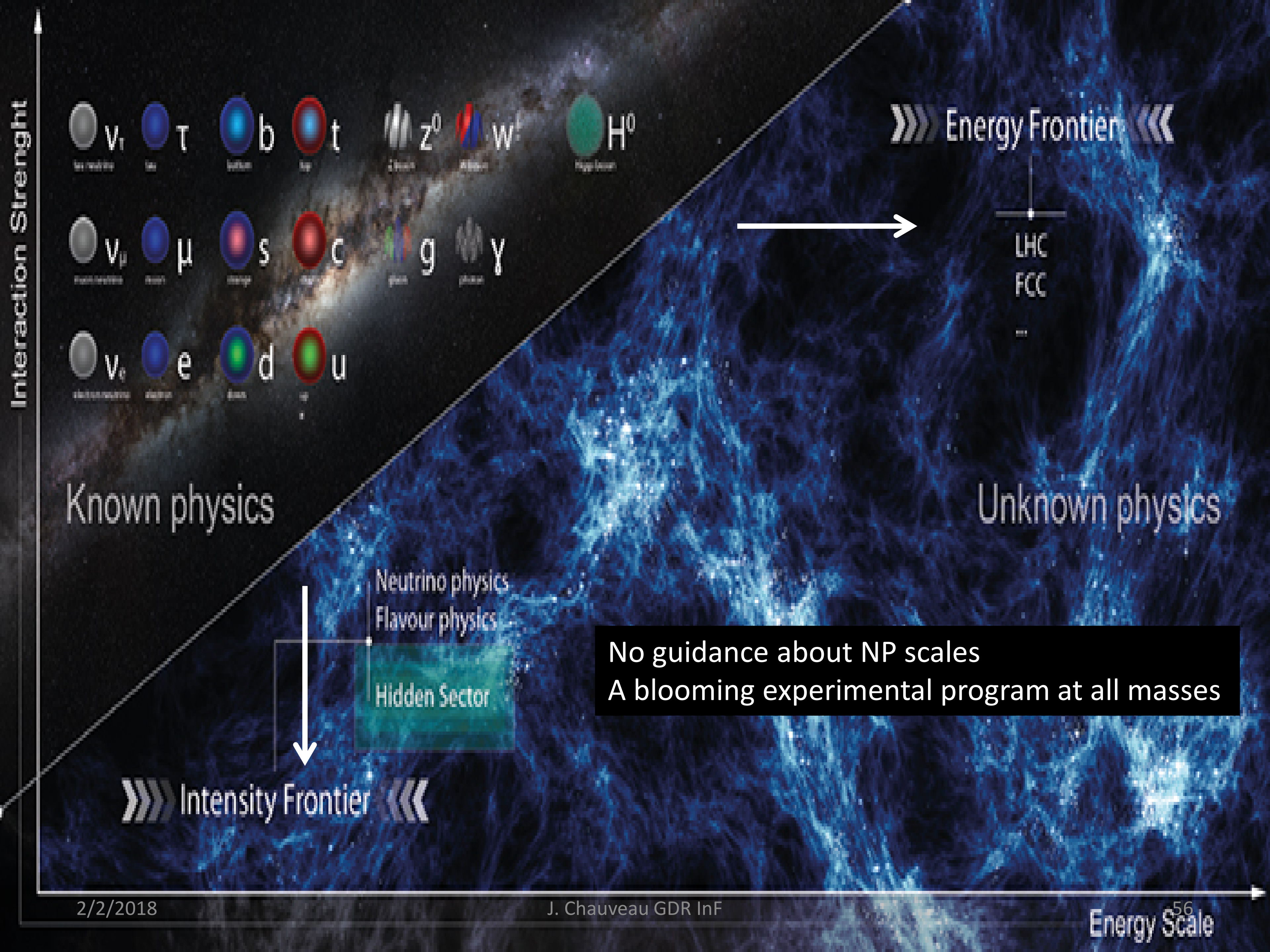
Evidence for BSM physics

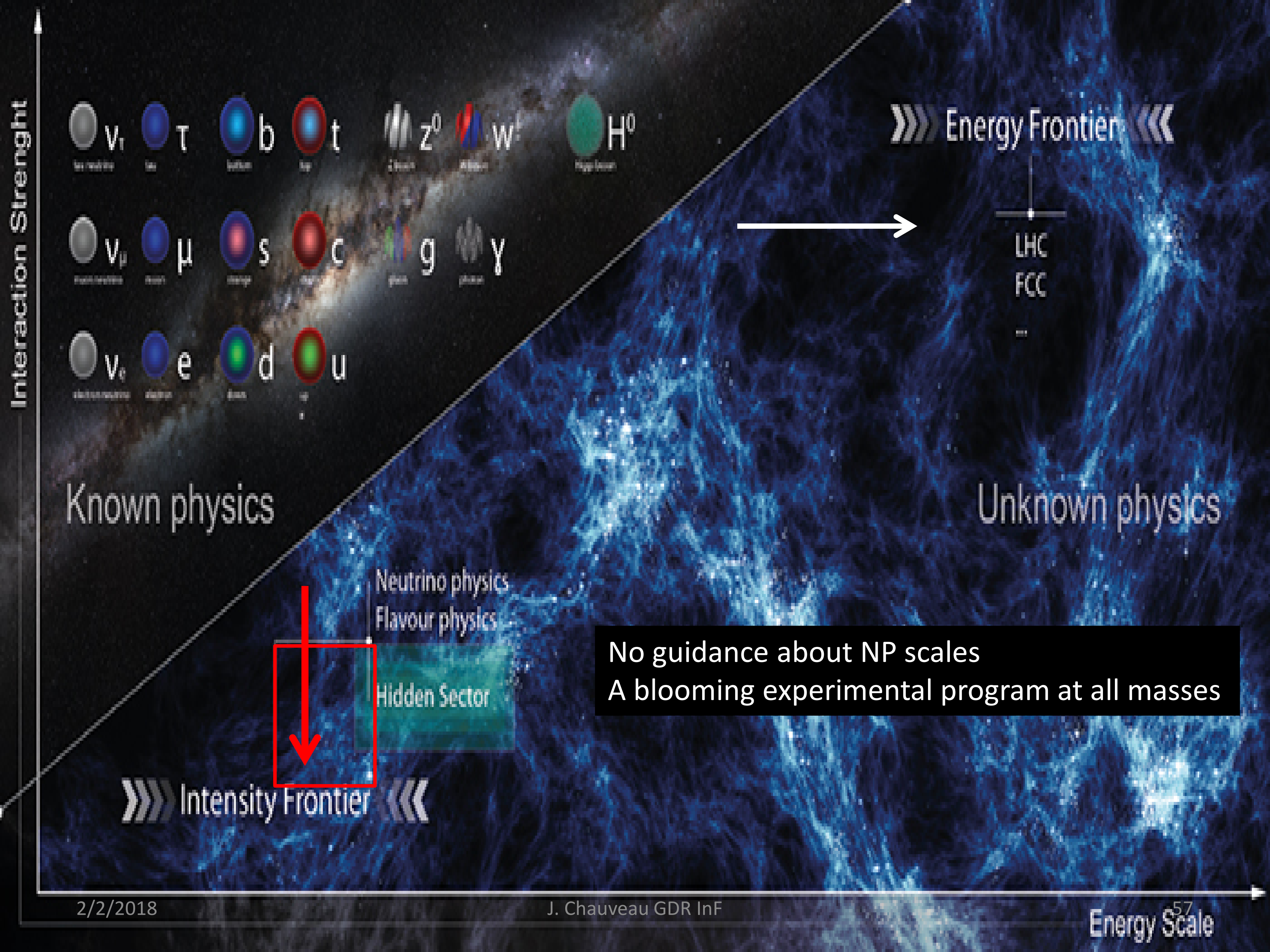
With the Higgs boson, the Standard Model (SM) is a complete framework, succesfully predictive, consistent up to the Planck scale.

However fundamental questions are not addressed:

- Neutrino masses and oscillations
- Baryon asymmetry in the Universe
- Dark matter
- Why no strong CP violation?
- Dark energy
- Inflation


Interaction Strenght
ν_τ τ b t Z^0 W H^0
ν_μ μ s c g γ
ν_e e d u
Known physics
Energy Frontier
LHC
FCC
...
Unknown physics
Neutrino physics
Flavour physics
Hidden Sector
Intensity Frontier
Energy Scale


Interaction Strenght
ντ τ b t Z0 W H0
νμ μ s c g γ
νe e d u
Energy Frontier
LHC
FCC
...
Known physics
Unknown physics
Neutrino physics
Flavour physics
Hidden Sector
Intensity Frontier
No guidance about NP scales
A blooming experimental program at all masses
Energy Scale



No guidance about NP scales
A blooming experimental program at all masses

History

- Path towards approval
  - 2013/10 EOI
  - 2014/12 Collaboration formed
  - 2015/04 Technical and Physics proposals
  - 2016/01&03 SPSC and RB recommendations
    - CDS (Conceptual Design Study)
    - PBC (Physics Beyond Colliders workshop)
  - European Strategy
- <=5 yr Construction
- 2026 commissionning
- 2027 data taking for 5 yrs

Cost (TP) and schedule (today)

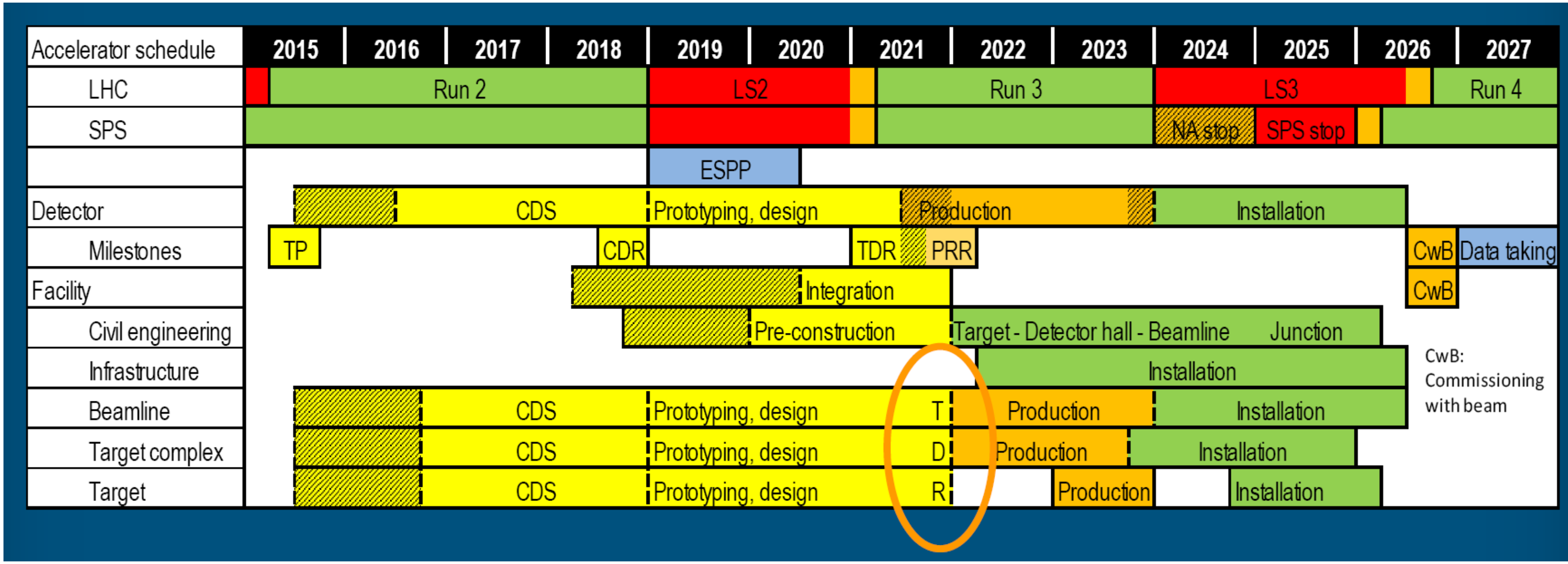


Table 6.3: Breakdown of the cost of the SHiP detectors.

Item		Cost (MCHF)
Tau neutrino detector		**11.6**
Active neutrino target	6.8	
Fibre tracker	2.5	
Muon magnetic spectrometer	2.3	
Hidden Sector detector		**46.8**
HS vacuum vessel	11.7	
Surround background tagger	2.1	
Upstream veto tagger	0.1	
Straw veto tagger	0.8	
Spectrometer straw tracker	6.4	
Spectrometer magnet	5.3	
Spectrometer timing detector	0.5	
Electromagnetic calorimeter	10.2	
Hadronic calorimeter	4.8	
Muon detector	2.5	
Muon iron filter	2.3	
Computing and online system		**0.2**
Total detectors		**58.7**
Facility		**135.8**
Grand total		**194.5**

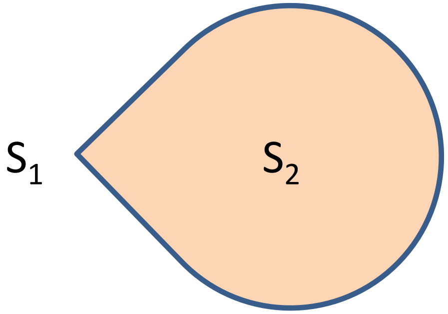
Alternate SplitCal Design

with DT, EB…

Measure 2 points (S_1, S_2) across a base *L* with σ~*L*/1000.

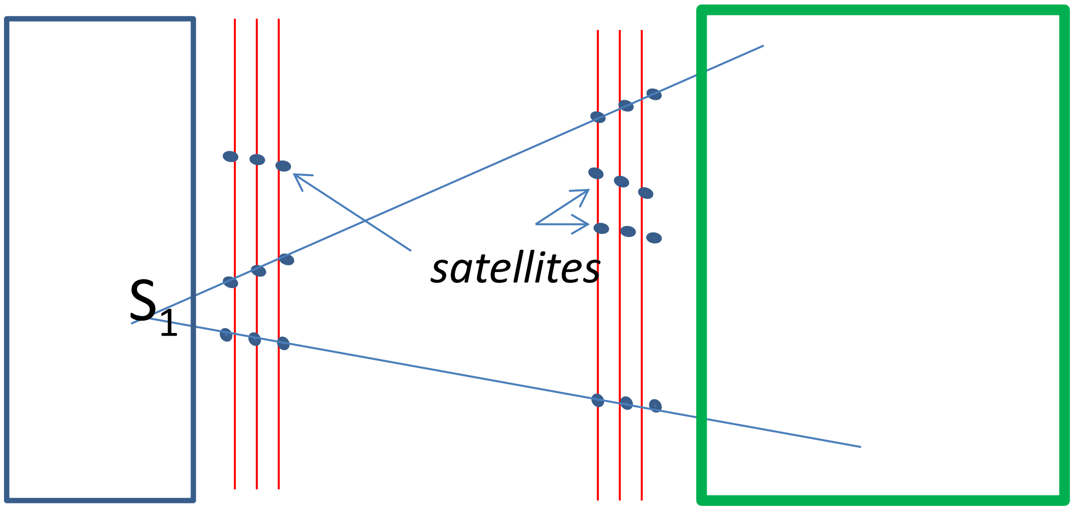
- S_1 the location of the 1st pair
- S_2 the position of the shower maximum or…
- The hard part is to measure S_1

➢ Use tracking (TPC, μM, straws?..)

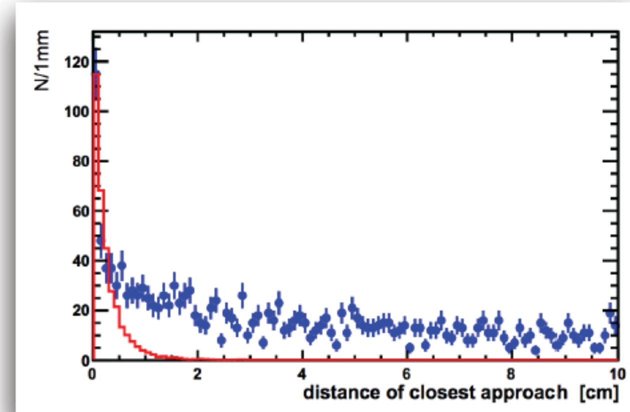


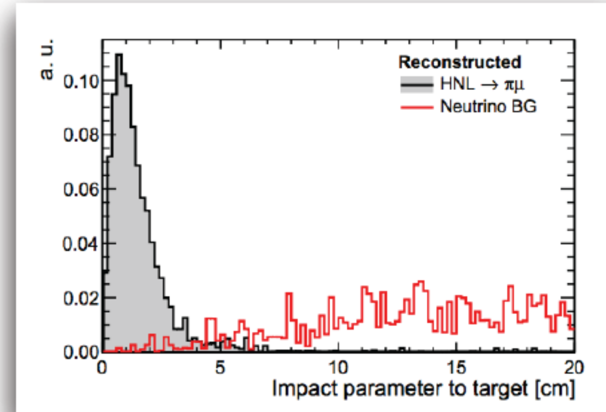
Need simulation

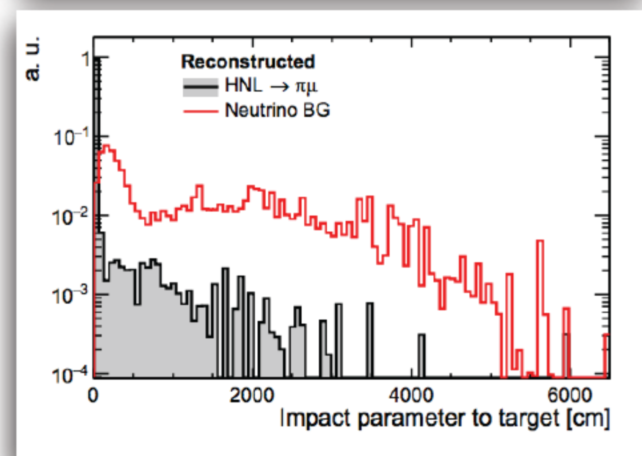
- Reconstruct 3D track candidates
- Clean them/remove satellites using
  - energy of clusters,
  - angles
- Vertex to get S_1.



Kinematic Selection







Very simple selection reduces the bkg to only a few in 5 years:

- Fiducial volume
- DOCA
- IP wrt target
- Vetos

Realistic to reach 0.1 expected bkg events for exclusive channels we have been studying so far

Signal yield

SHiP
Search for Hidden Particles

$$N(\text{p.o.t}) = 2 \cdot 10^{20}$$

$$n(HNL) = N(\text{p.o.t}) \times \chi(pp \to HNL) \times \mathcal{P}_{\text{vtx}} \times \mathcal{A}_{\text{tot}}(HNL \to \text{visible})$$

$$\chi(pp \to HNL) = 2 \sum_{q=c,b} \chi(pp \to q\bar{q}) \times \text{Br}(q \to HNL) \times U^2$$

$$U^2 = U_e^2 + U_\mu^2 + U_\tau^2$$

χ= total HNL production rate per proton interaction in Mo target

$$\chi(pp \to c\bar{c}) = 1.7 \cdot 10^{-3}$$
$$\chi(pp \to b\bar{b}) = 1.6 \cdot 10^{-7}$$

TP estimates. Expect >1.5 enhancement because of the reinteractions.

$\mathcal{P}_{\text{vtx}}$ Probability for an HNL with given mass and couplings to decay within SHiP fiducial volume

$$\mathcal{A}_{\text{tot}}(HNL \to \text{visible}) = \sum_{i=\text{visible channel}} \mathcal{BR}(HNL \to i) \times \mathcal{A}(i)$$

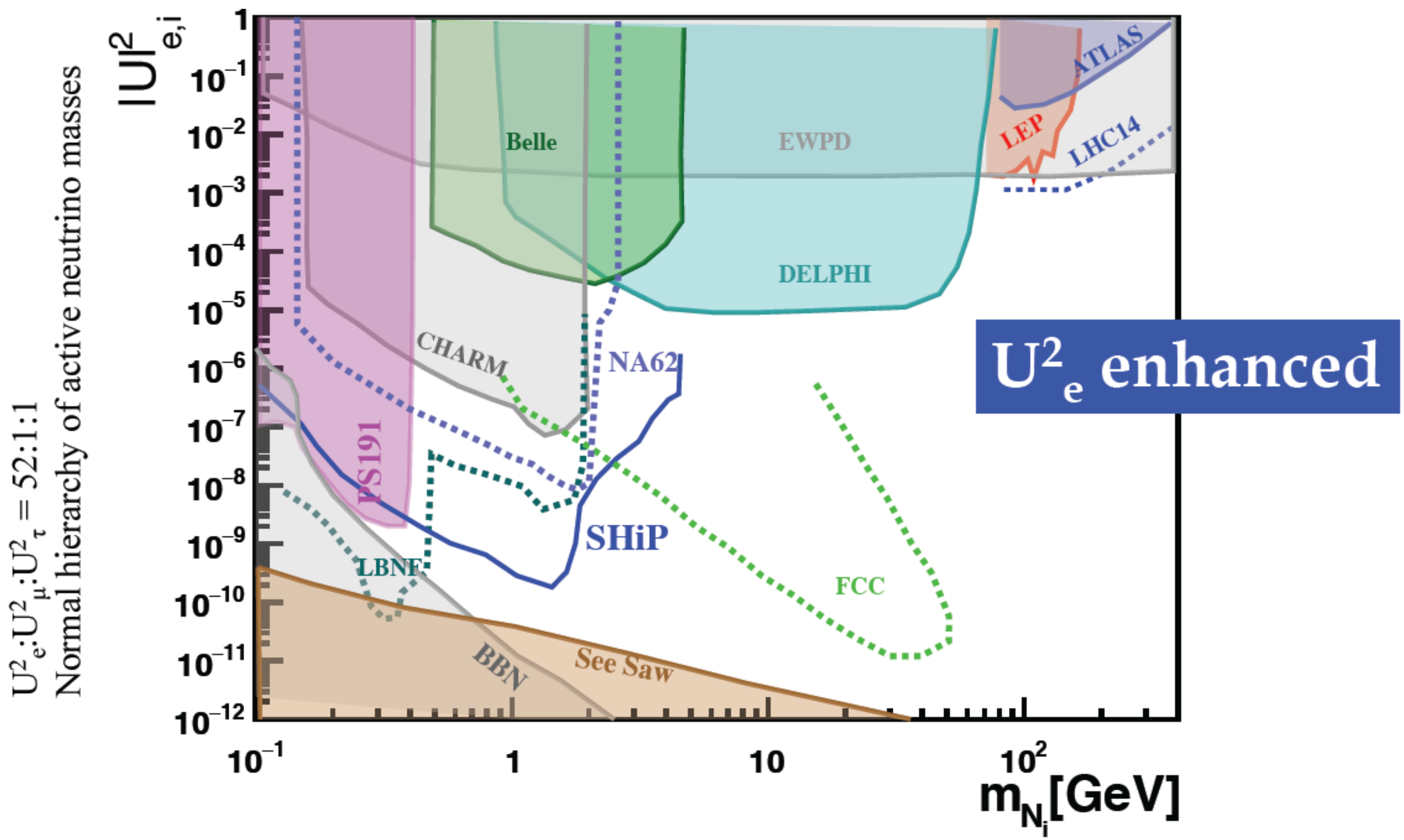
Acceptance for all final states

Typically $P_{vtx} \times A_{tot} \times \varepsilon_{selection} \sim 10^{-6} \left(\frac{U^2}{10^{-8}}\right)$ or $\sim 100 \times U^2$

Sensitivity to HNL

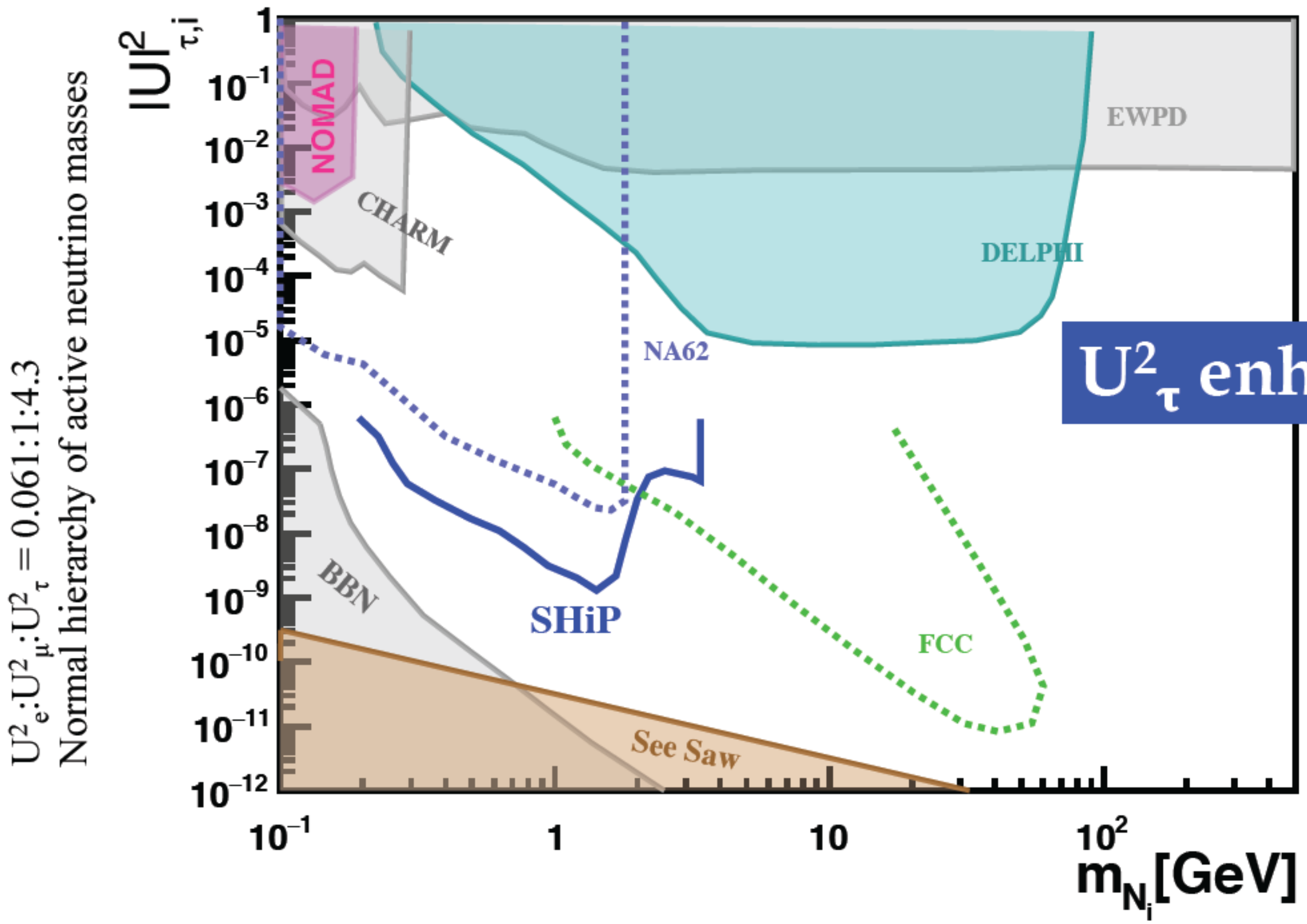
Normal hierarchy

$U_e^2 : U_\mu^2 : U_\tau^2$
52:1:1



Sensitivity to HNL

Normal hierarchy



U^2_τ enhanced