SHiP

Search for **Hi**dden **P**articles

J. Chauveau

LPNHE IN2P3/CNRS and UPMC Paris 6

French-Ukrainian Workshop on the instrumentation developments for high energy physics

LAL Orsay

October 6-8, 2017

What is SHiP ?

- Direct **S**earch for **Hi**dden **P**articles at the CERN SPS
- A General Purpose Experiment to exploit a new Beam Dump Facility at the CERN SPS
- Prepared by a Collaboration of

  16 countries, CERN & JINR

  49 institutes, 5 associate institutes,

  With LAL, LPNHE and TSNUK Kyiv
- Aim : data taking in Run-4 of the LHC

> - *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/*

Outline

- Motivation
- Physics case
- Design of the experiment
- Evolutions
- Opportunities
- Perspectives

Motivation

SHiP
Search for Hidden Particles

- New Physics Beyond the Standard Model
  - Neutrino masses and oscillations
  - Dark matter
  - The antimatter problem
  - Cosmology connection (inflation, dark energy)
- No obvious mass scale
  - No signal at TeV yet
  - ➢ Search lower mass weaker coupling particles

Motivation

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A hidden Sector ??

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A hidden Sector ??

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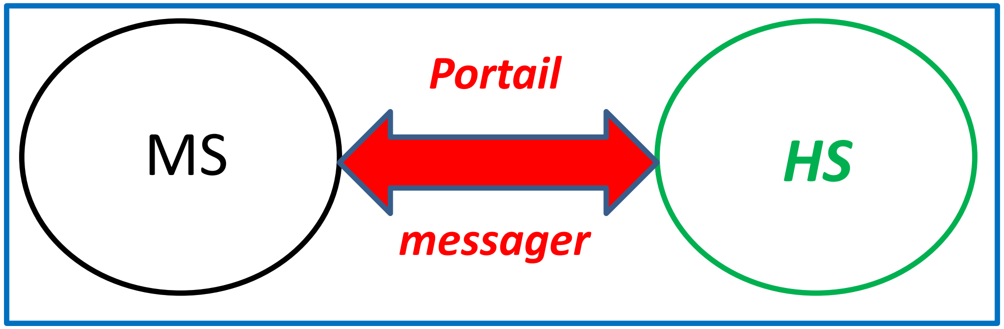
Beam Dump at the SPS

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.**
- If the messengers are **light**,

  a **direct detection** is possible
  - ➢ Via ***decay*** or ***scattering***.



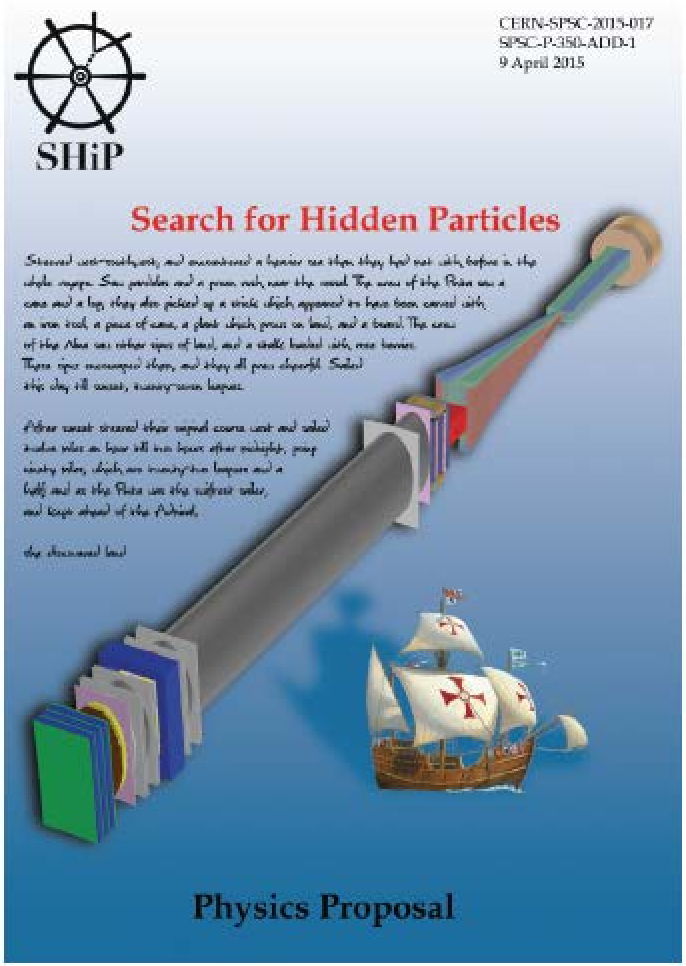
SHiP Physics Paper: 1504.04855

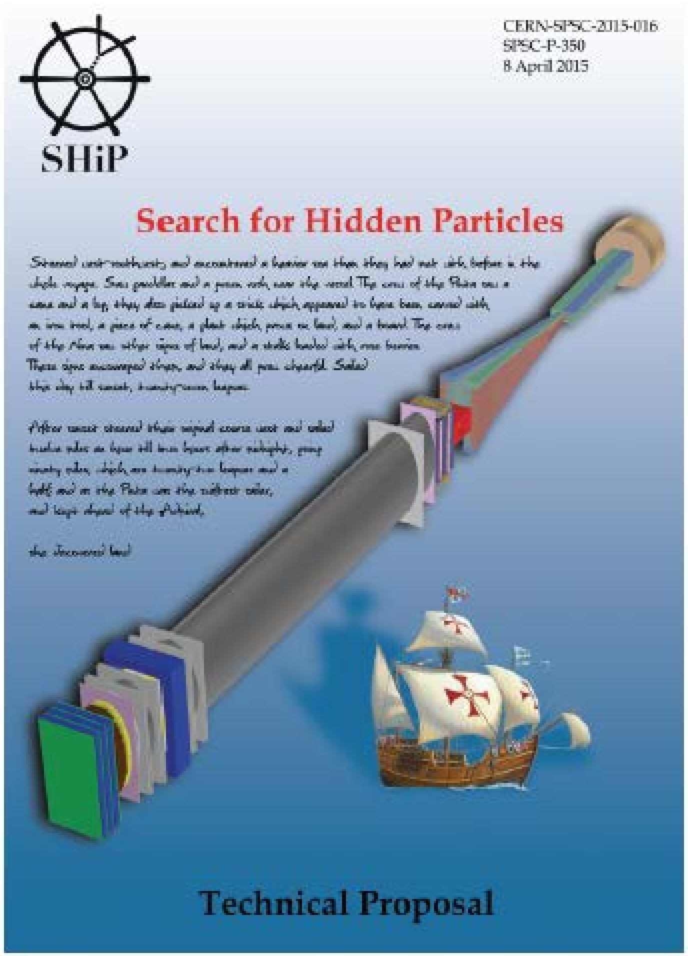
- Very feeble interactions
  - ➢ **A source with high intensity**
  - ➢ **They easily traverse matter**
  - ➢ **They are long-lived**
  - ➢ **Very rare events**

→ **BeamDump**

→ **« 0-background »**

SHiP a proton beam dump experiment





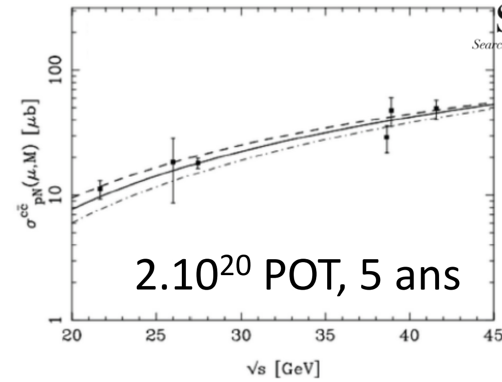
→ S. Alekhin et al., Rep. Prog. Phys. **79** 124201 (2016).

Requirements (Decay)

- Heavy flavor
- N with high P_T

P+A → D or B X, D or B→ **N** l (X)

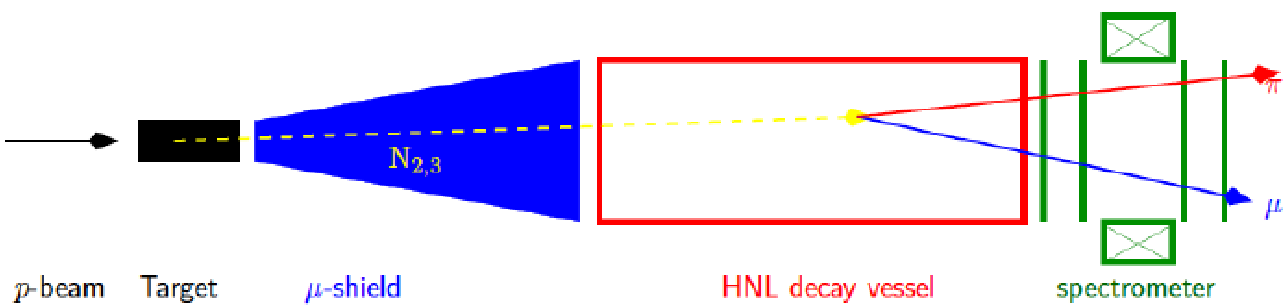
N → 2/3-body



✓ *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



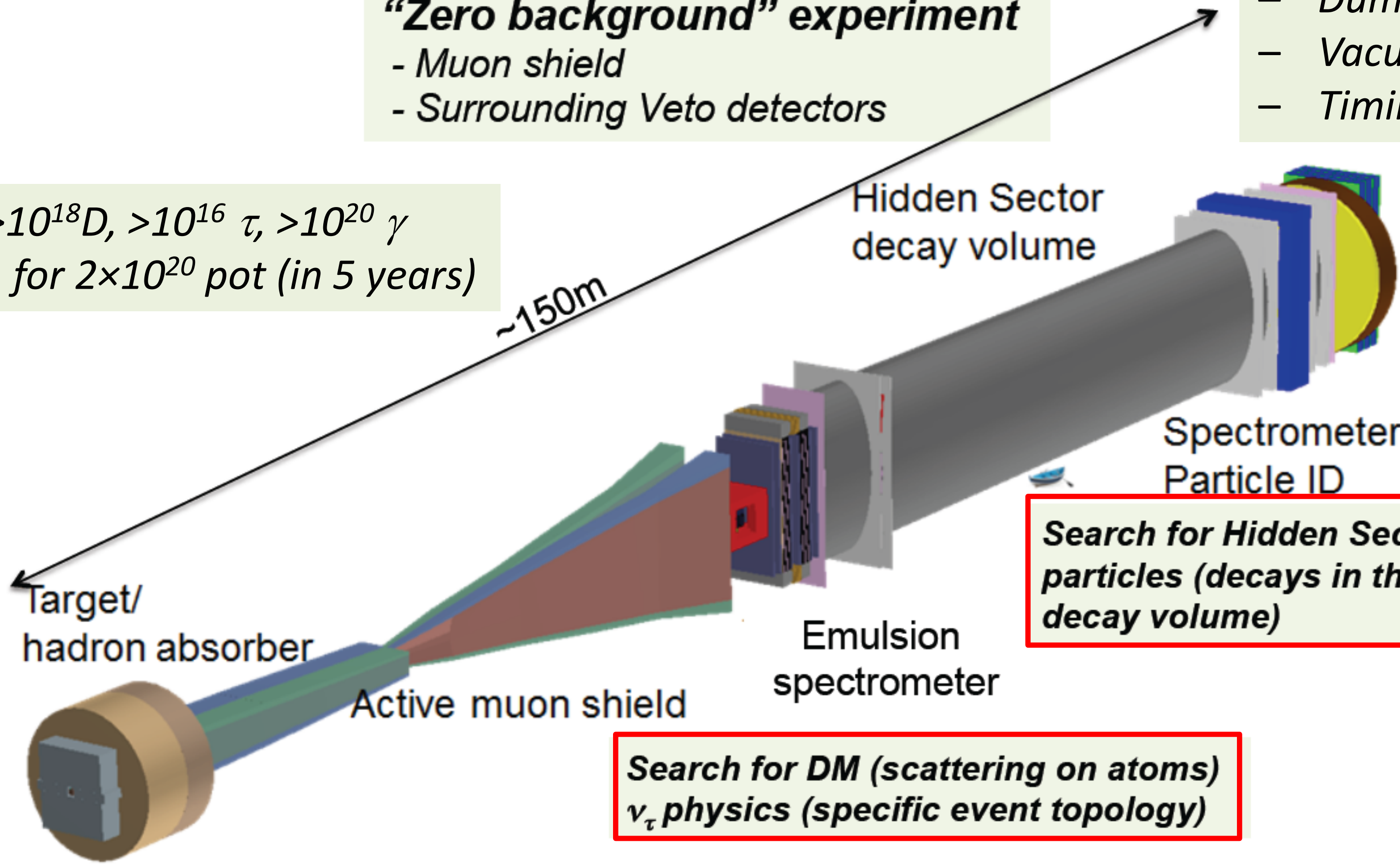
The SHiP experiment at SPS
(as implemented in Geant4 for TP)

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)



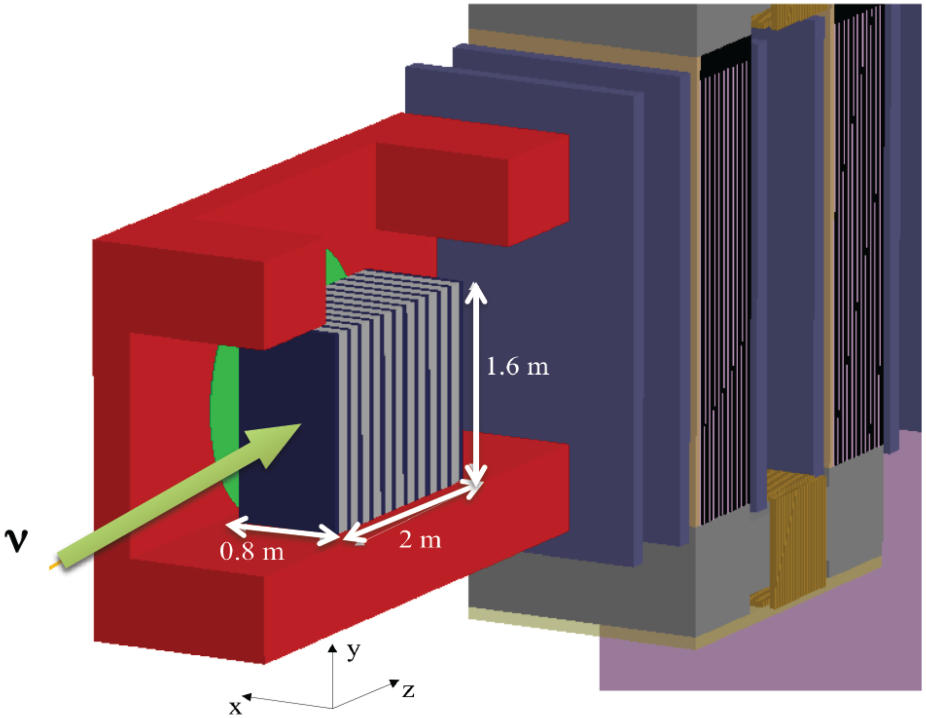
Search for Hidden Sector particles (decays in the decay volume)

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

Beyond Collider Physics, CERN 4

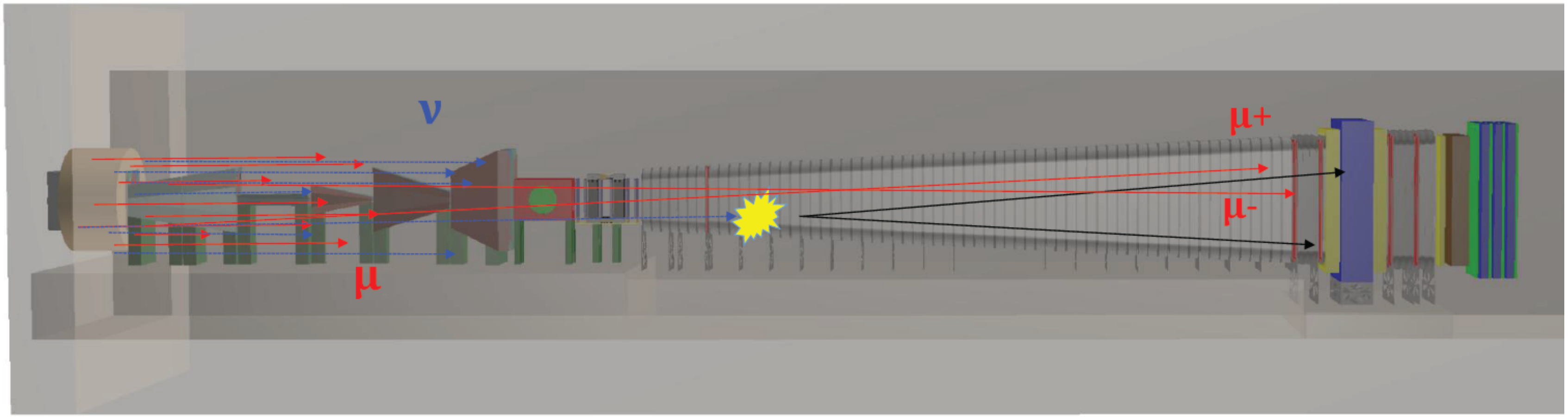
Requirements (Interaction)

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

….Background, background, background…..



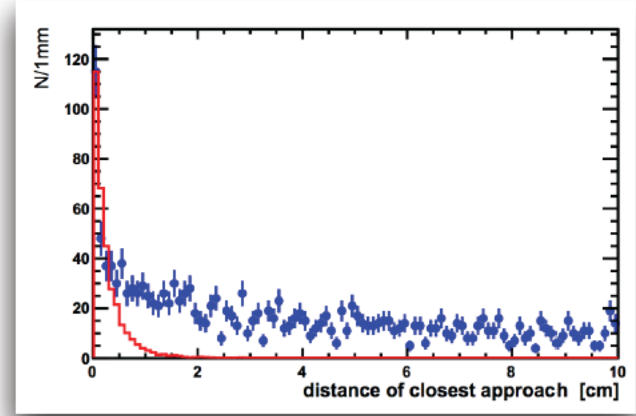
Two types of background expected:

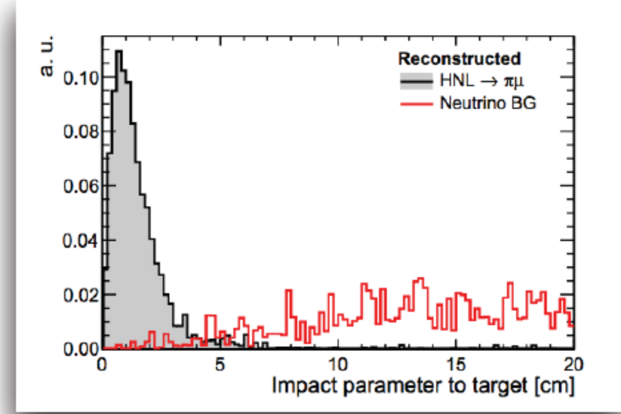
1) neutrino and muon inelastic interactions with the detector material, namely with the decay vessel;
- ⟶ mostly in-time tracks, not pointing backwards to the target;
- ⟶ main detectors to reduce this background: VETO detectors (surrounding background tagger, Upstream Veto)

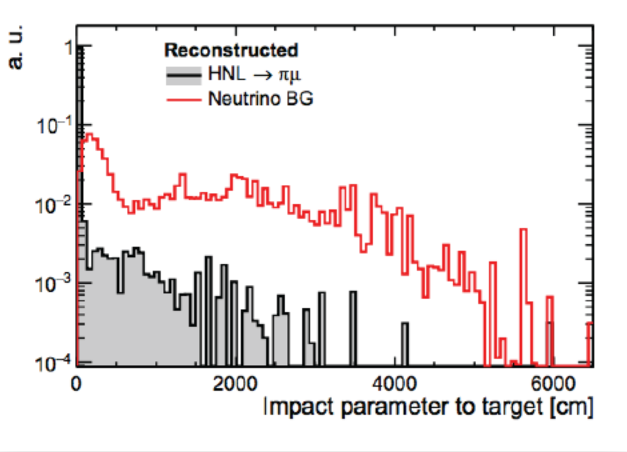
2) muon combinatorial background:
- ⟶ mostly out-of-time tracks, not pointing backwards to the target
- ⟶ main detectors to reduce this background: Timing Detector (and muon system with timing capabilities)

G. Lanfranchi at the LPNHE workshop October 11, 2017

Kinematic Selection







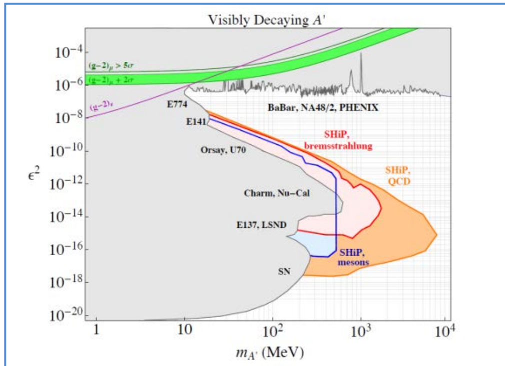
Very simple selection reduces the bkg to only a few in 5 years:

- Fiducial volume
- DOCA
- IP wrt target
- Vetos

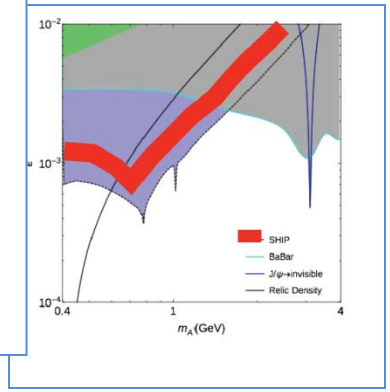
Realistic to reach 0.1 expected bkg events for exclusive channels we have been studying so far

Physics proposal plots

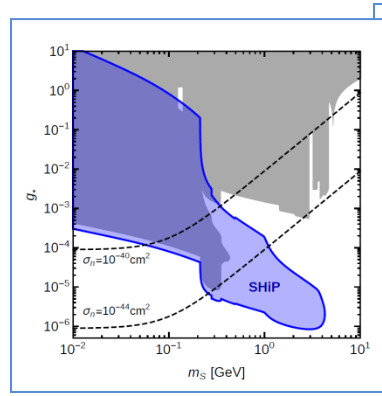
Dark photon



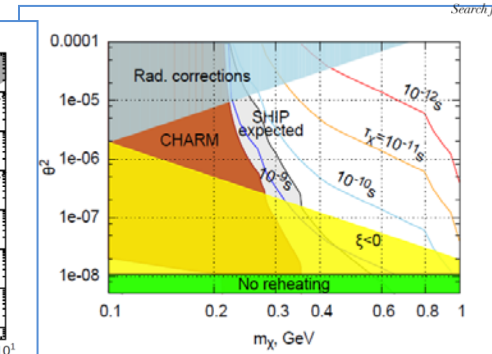
A'→χχ



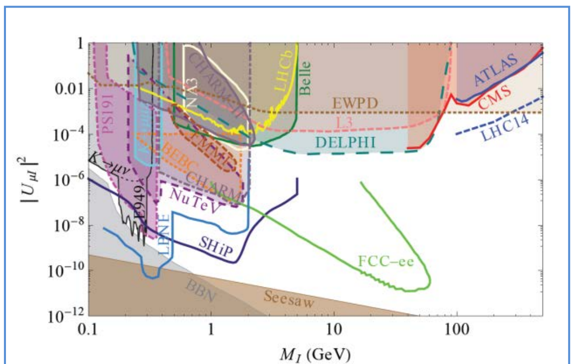
Scalar



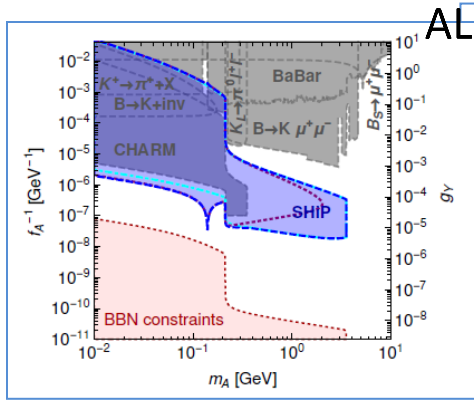
inflaton

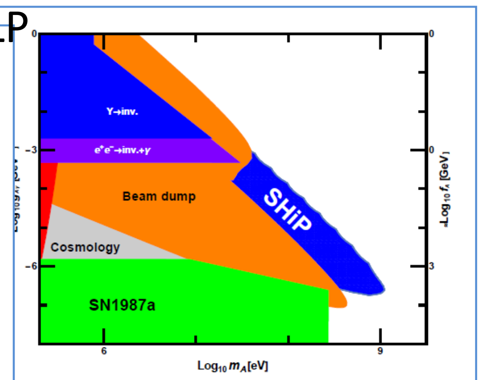


HNL

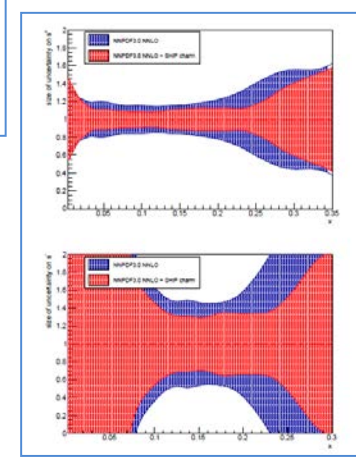


ALP

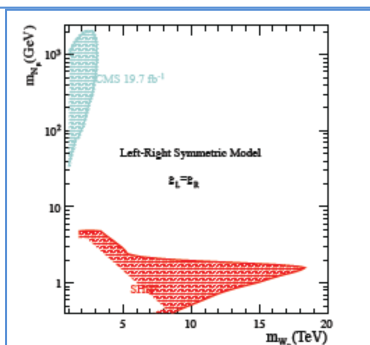




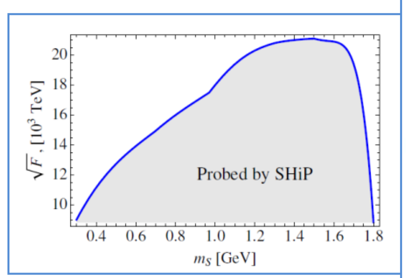
ν_τ DIS

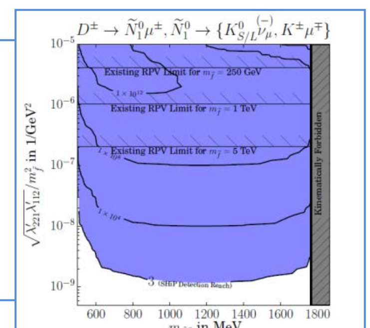


L/R



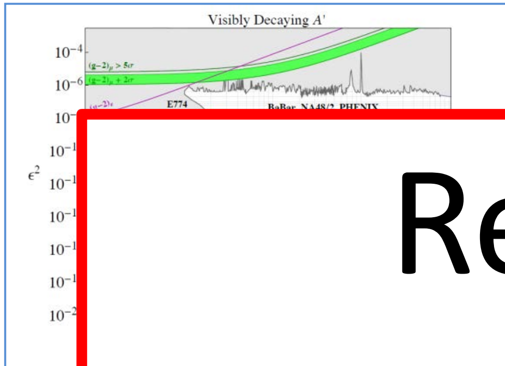
SUSY



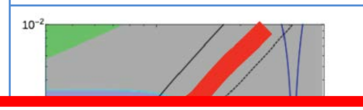


Physics proposal plots

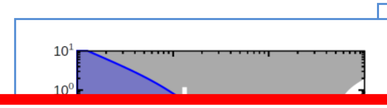
Dark photon



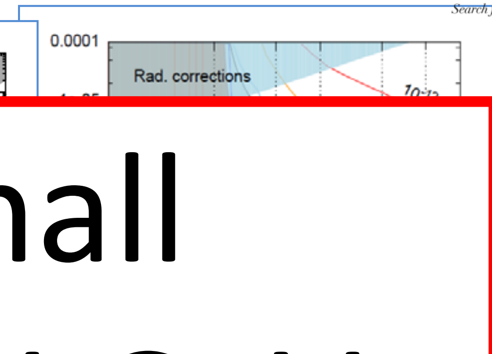
A'→χχ



Scalar

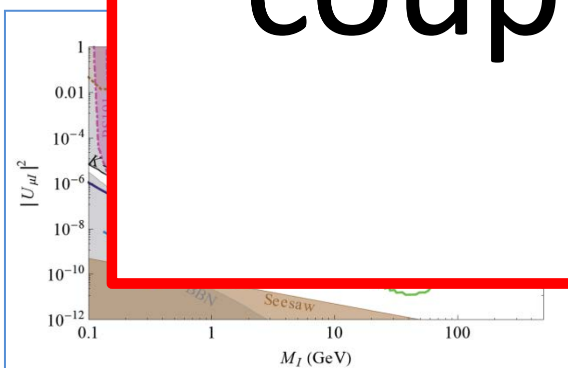


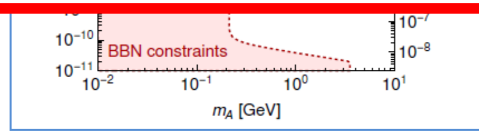
inflaton

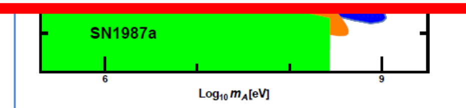


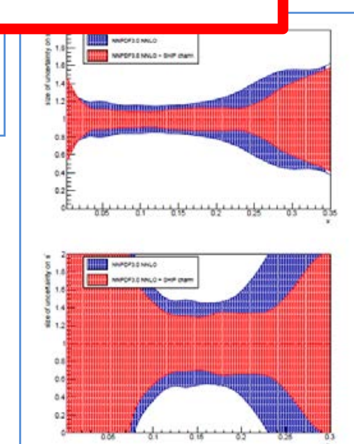
Reach very small couplings in MeV-GeV mass range

HNL

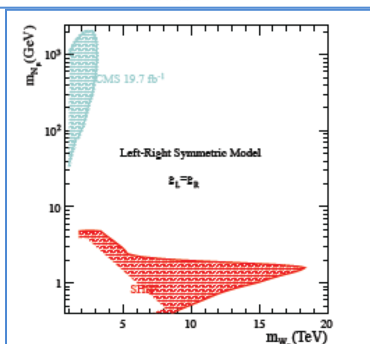




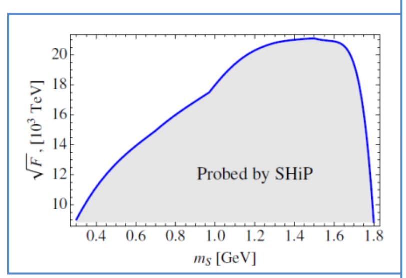


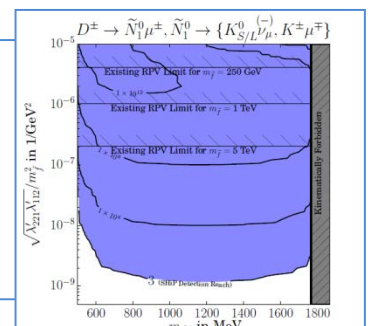


L/R



SUSY





Cost (TP) and schedule (today)

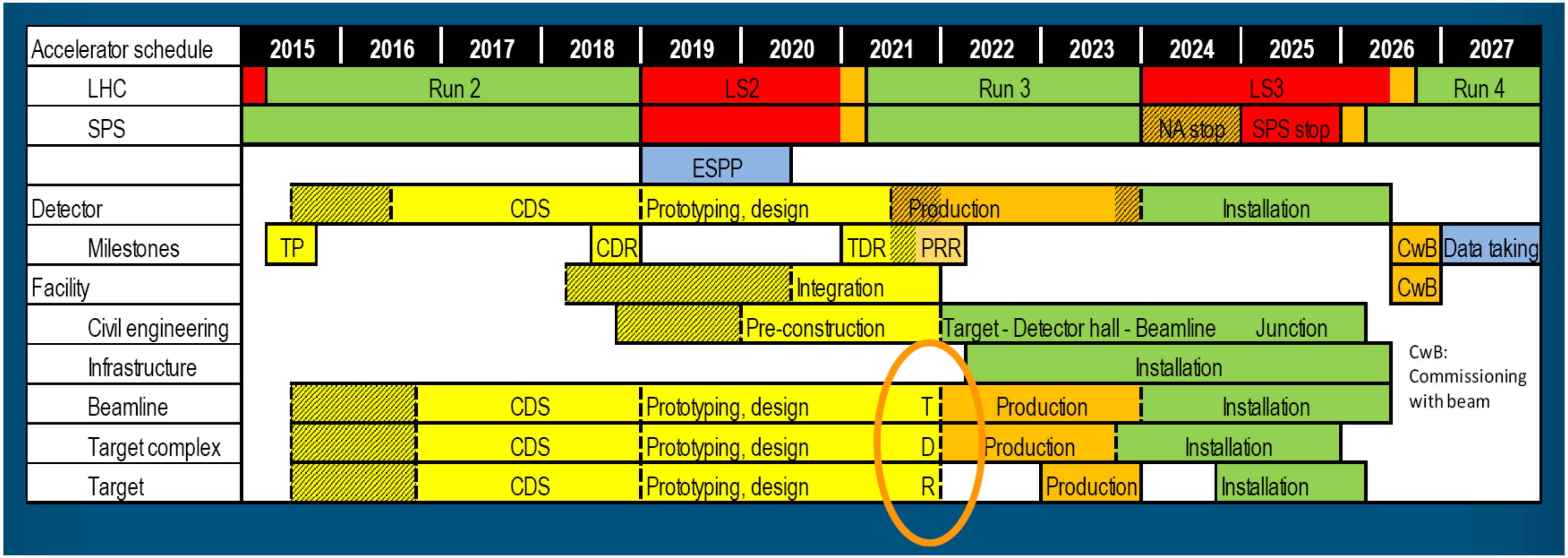
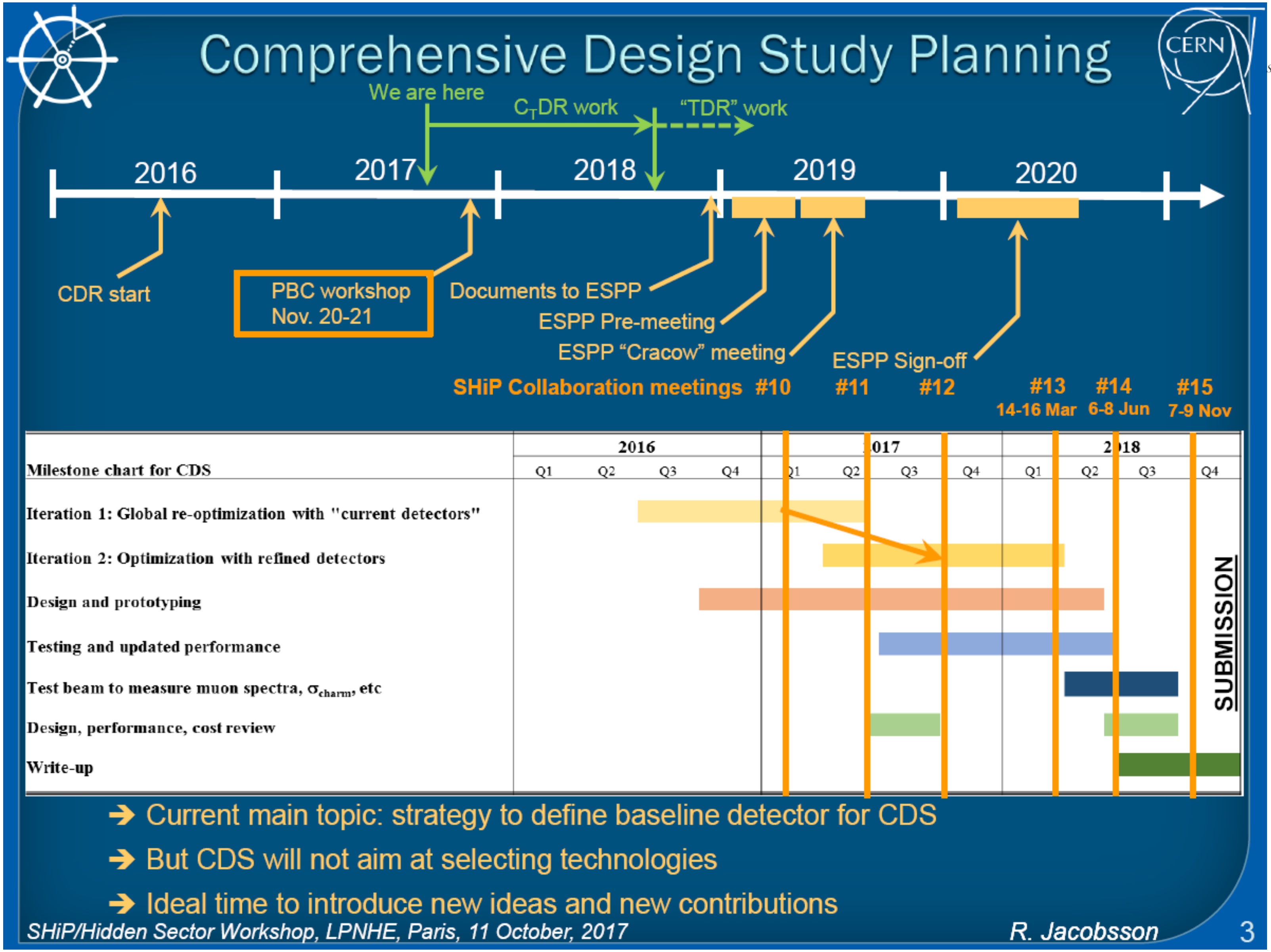


Table 6.3: Breakdown of the cost of the SHiP detectors.

Item	Cost (MCHF)	
Tau neutrino detector		**11.6**
Active neutrino target	6.8	
Fibre tracker	2.5	
Muon magnetic spectrometer	2.3	
Total detectors		**58.7**
Facility		**135.8**
Grand total		**194.5**

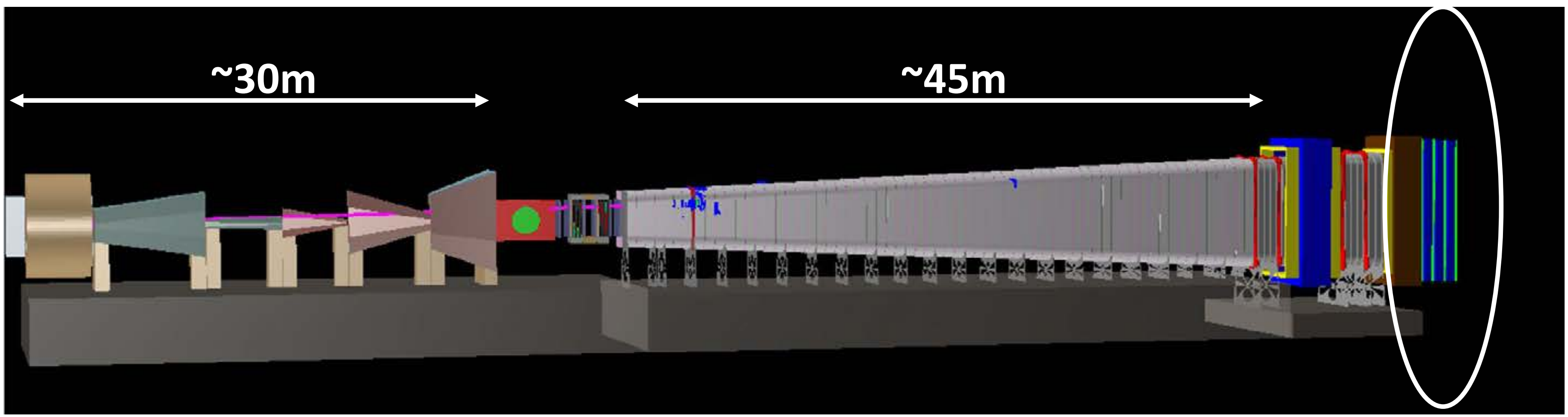
Hidden Sector detector		**46.8**
HS vacuum vessel	11.7	
Surround background tagger	2.1	
Upstream veto tagger	0.1	
Straw veto tagger	0.8	
Spectrometer straw tracker	6.4	
Spectrometer magnet	5.3	
Spectrometer timing detector	0.5	
Electromagnetic calorimeter	10.2	
Hadronic calorimeter	4.8	
Muon detector	2.5	
Muon iron filter	2.3	
Computing and online system		**0.2**



Comprehensive Design Study Planning
CERN
We are here
C_TDR 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 #15
14-16 Mar
6-8 Jun
7-9 Nov
Milestone chart for CDS
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

Evolutions, opportunities

- Enlarge physics case
- Increase acceptance, fight background
- Define/explore (alternative) technologies
- Anticipate common transverse tasks (e.g. electronics/DAQ)



Upstream

ν_τ detector

Hidden Sector detector, esp. PID, Calorimetry

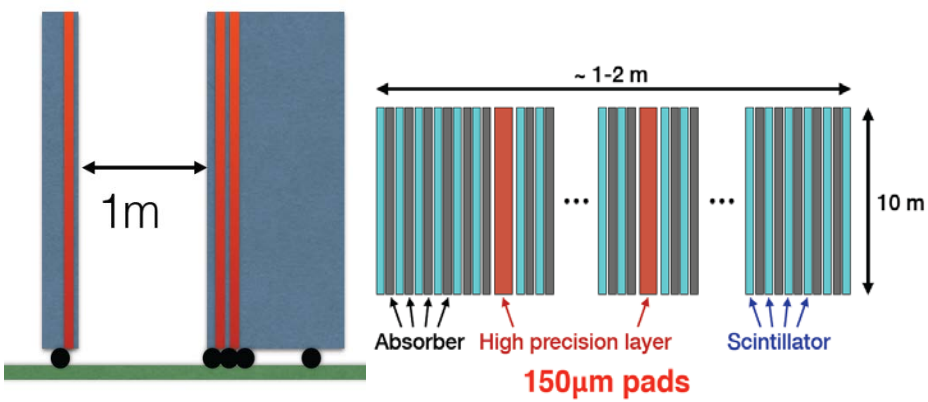
Downstream

PID, timing

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

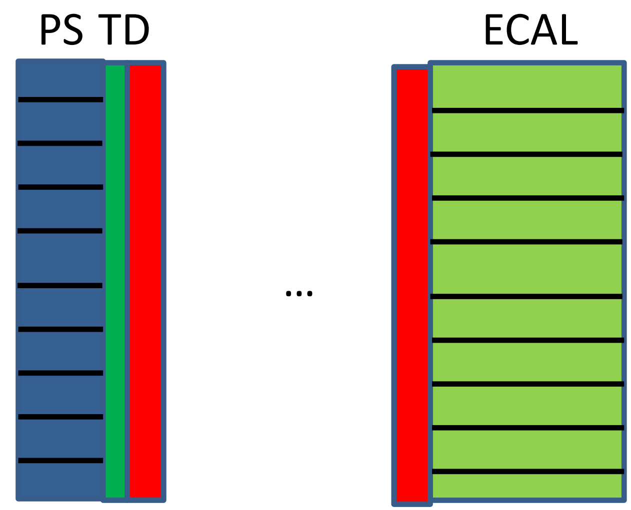
SplitCAL

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



Alternate SplitCAL setup

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



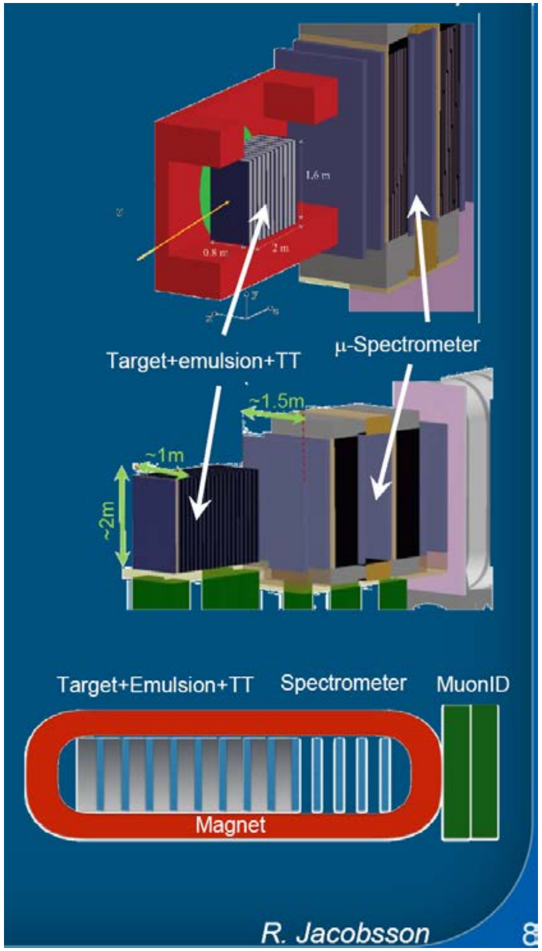
$\nu_\tau \rightarrow$ iSHiP

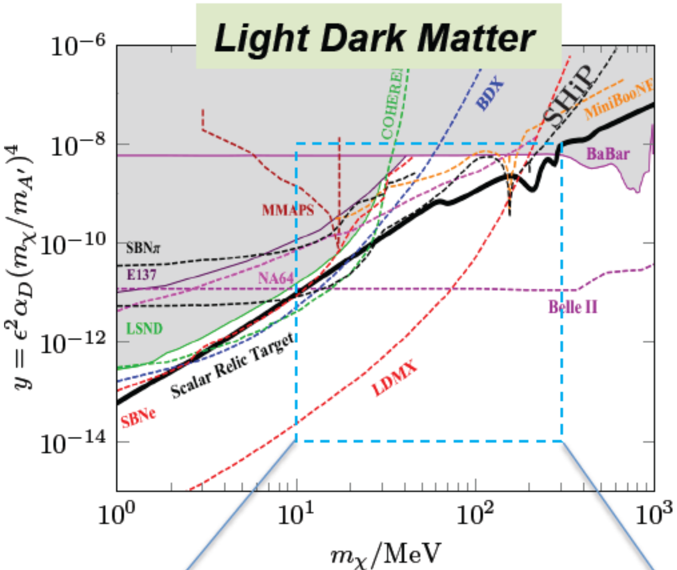
Adjusted from the TP

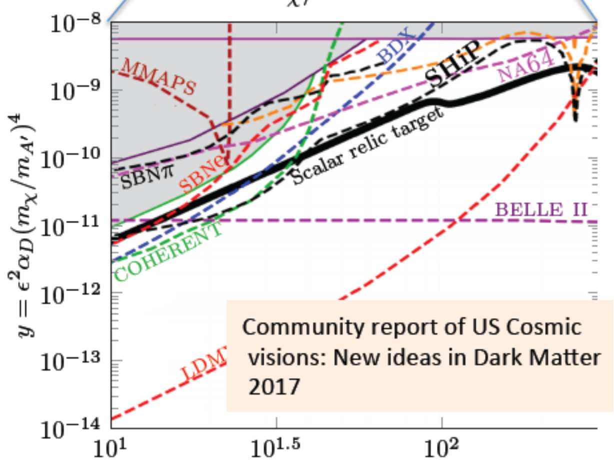
Without magnet

New design

- *calorimetric Target and TT*



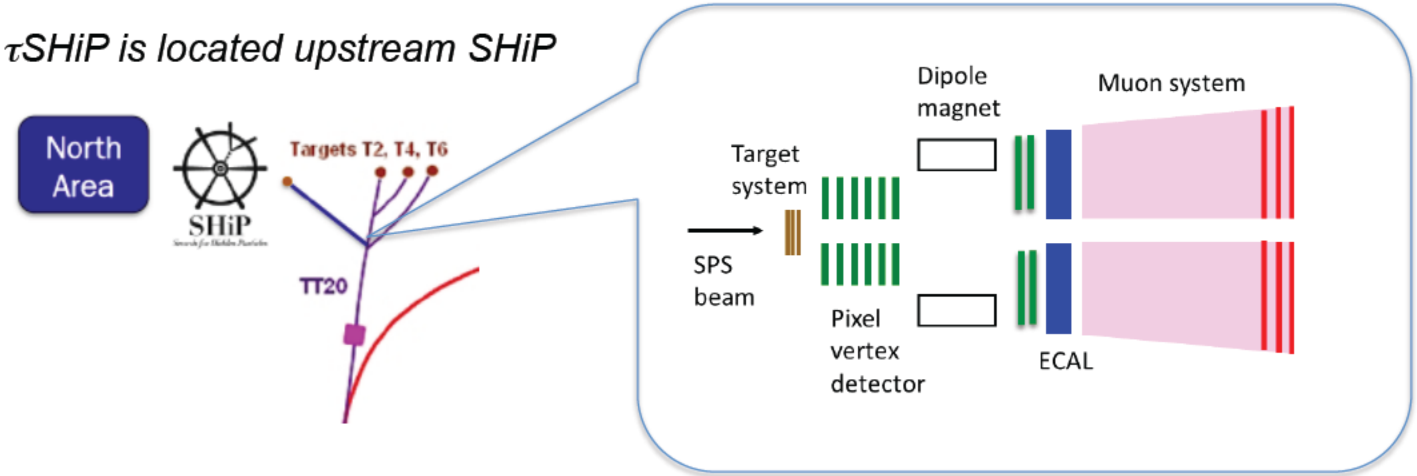




Search for $\tau \rightarrow \mu\mu\mu$ (τSHiP) at possible extension of SHiP facility

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 $\eta, \rho, \omega, \ldots$*
  - *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

Journée SHiP/Physique du secteur caché du 11/10/2017 21

A. Golutvin at the LPNHE workshop October 11, 2017

Opportunities

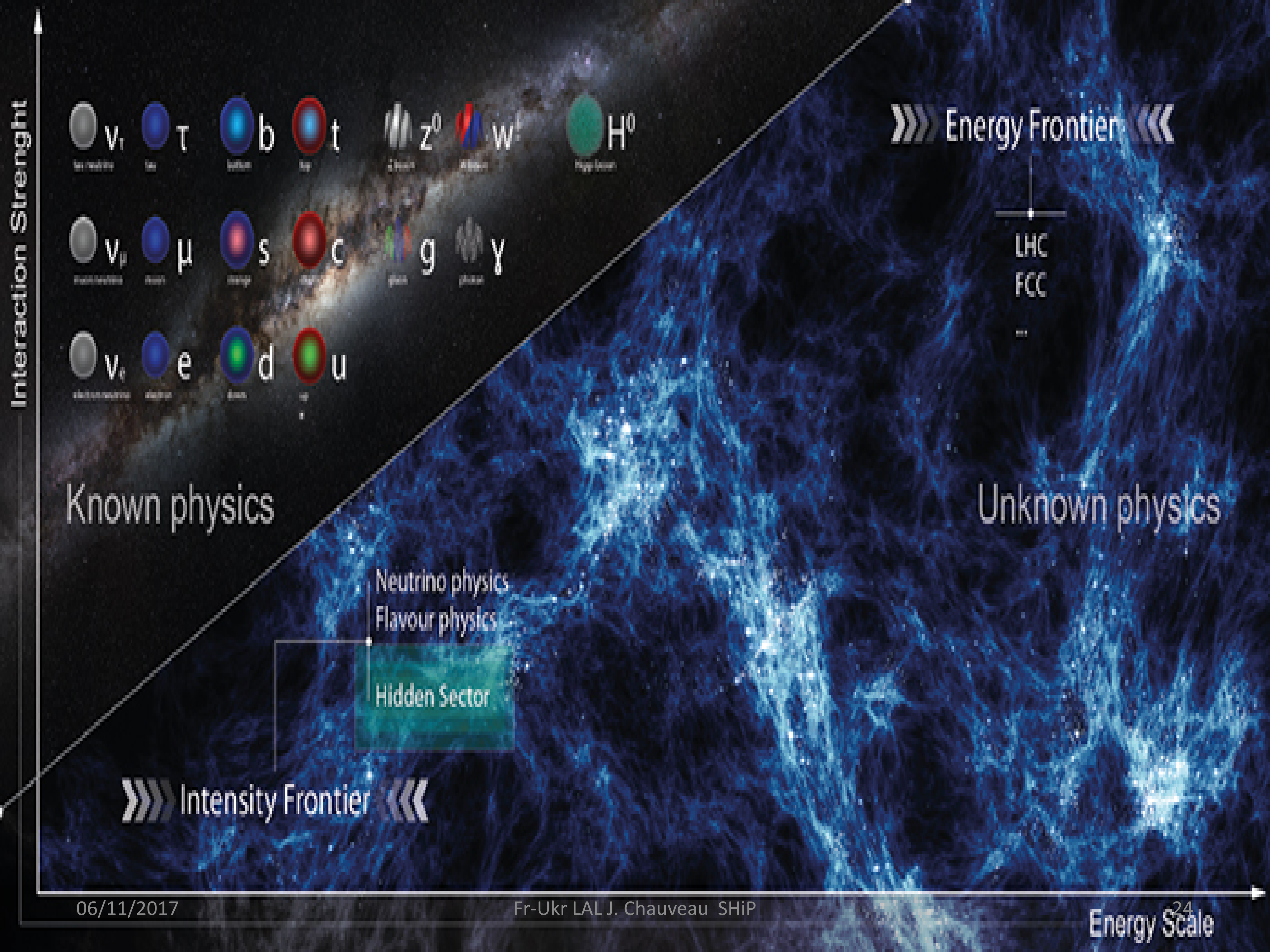
- Electronics and DAQ
  - J. Maalmi, D. Breton in charge of the coordination of the electronics.
  - 1st Electronics workshop October 25, 2017
  - Hope to see emerge federating projects in France
- Many areas to contribute
  - Subdetector design, especially PID, calorimetry
  - Measurements prepared for the TDR
    - Muon flux in 2018 test beam with SHiP target replica
    - Charm associated production in 2018-2021 to understand the cascade.
  - Substantiate pre-EOI projects
- Theory/ phenomenology (e.g. within the InF GDR).

Perspectives

- SHiP is a proton beam dump facility
- to take data 5 years starting in 2027, assuming approval $\leq$ 2020
- to reach the best sensivity for many hidden sector particles (MeV-GeV)
- with an apparatus currently being reoptimized to search for unknown neutral particle
  - decays, scattering,

  also ν_τ physics.
- The SHiP beamline is to be seen as a facility:
  - $\tau \rightarrow 3\ \mu$?..

➢ Time to join (creative period).

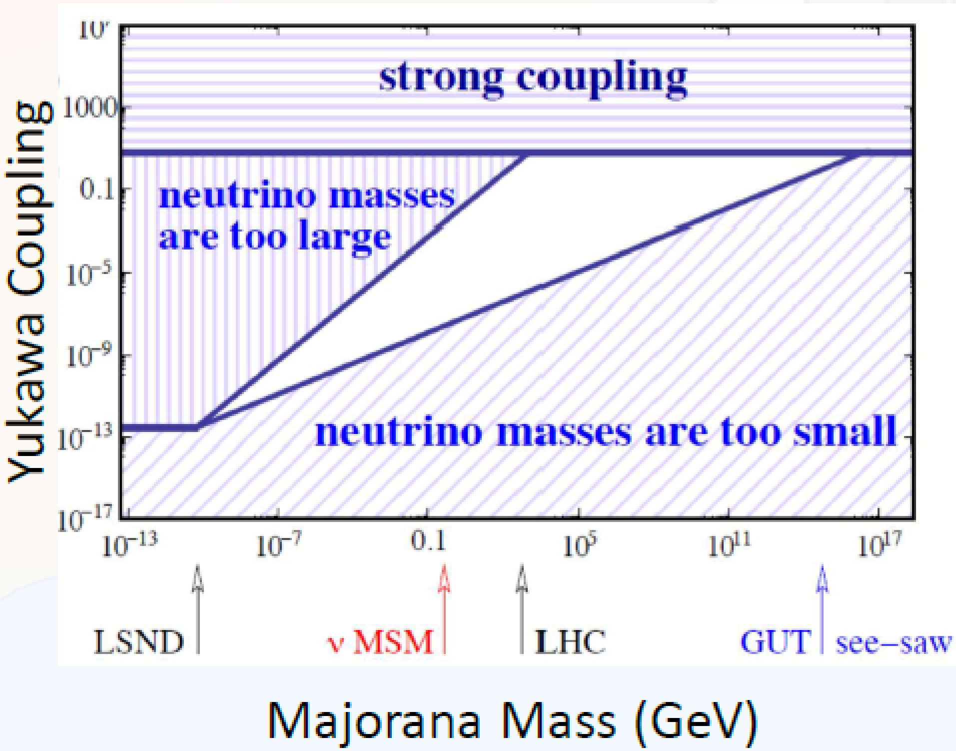

Interaction Strenght
ν_τ τ b t Z^0 W H^0
ν_μ μ s c g γ
ν_e e d u
Known physics
Energy Frontier
LHC
FCC
...
Unknown physics
Neutrino physics
Flavour physics
Hidden Sector
Intensity Frontier
Energy Scale

Extra

- 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/

Sterile neutrino masses

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



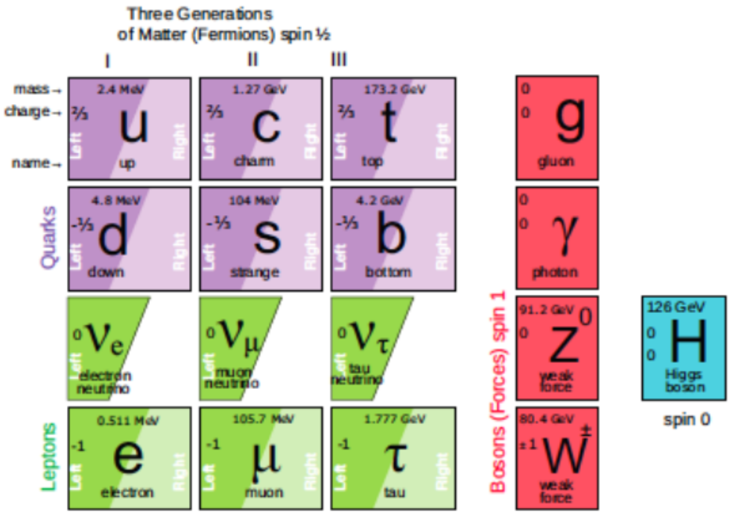
- Assuming $m_\nu = 0.1\text{eV}$
- if $Y \sim 1$ implies $M \sim 10^{14}\text{GeV}$
- if $M_N \sim 1\text{GeV}$ implies $Y_\nu \sim 10^{-7}$

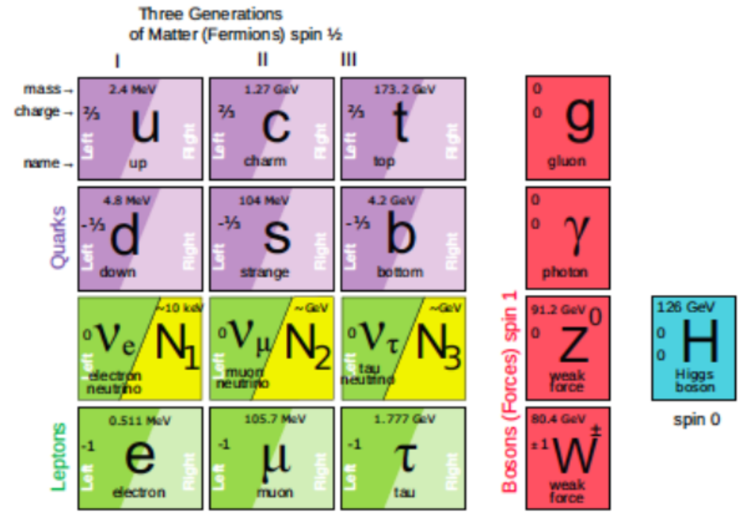
remember $Y_{top} \sim 1.$ and $Y_e \sim 10^{-6}$

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

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

$N_1 \rightarrow \nu\gamma$, seen ?

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.

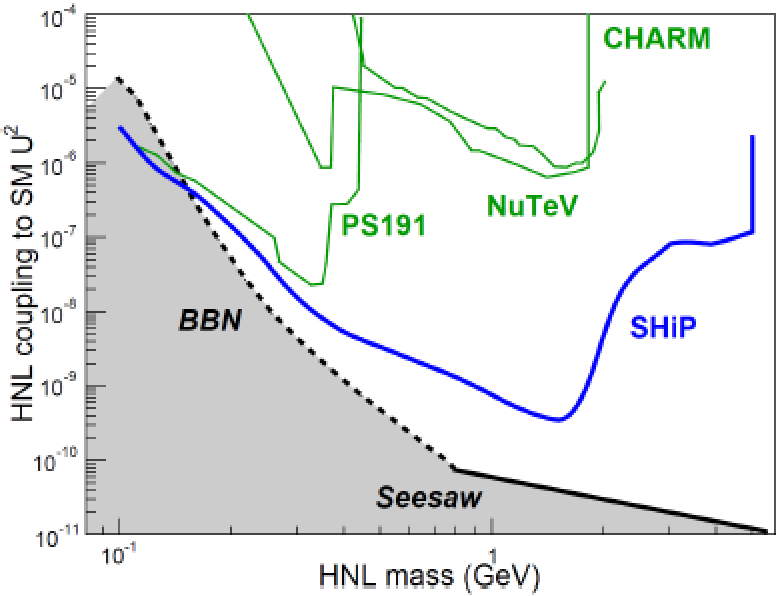
SHiP
Search for Hidden Particles

Golutvin seminar 2014

Physics Case

✓ *SHiP will directly search for weakly interacting New Physics. Will exceed the sensitivity of previous experiments by a few orders of magnitude*

For example, probe HNL couplings close to the ultimate see-saw limit



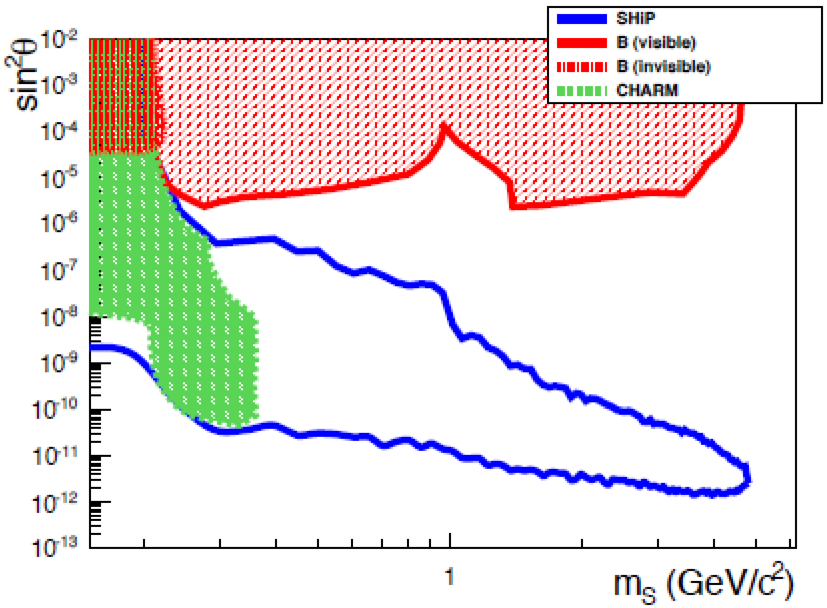


Table 2.1: Summary of the main decay modes of hidden particles in various models ($\ell = e, \mu$)

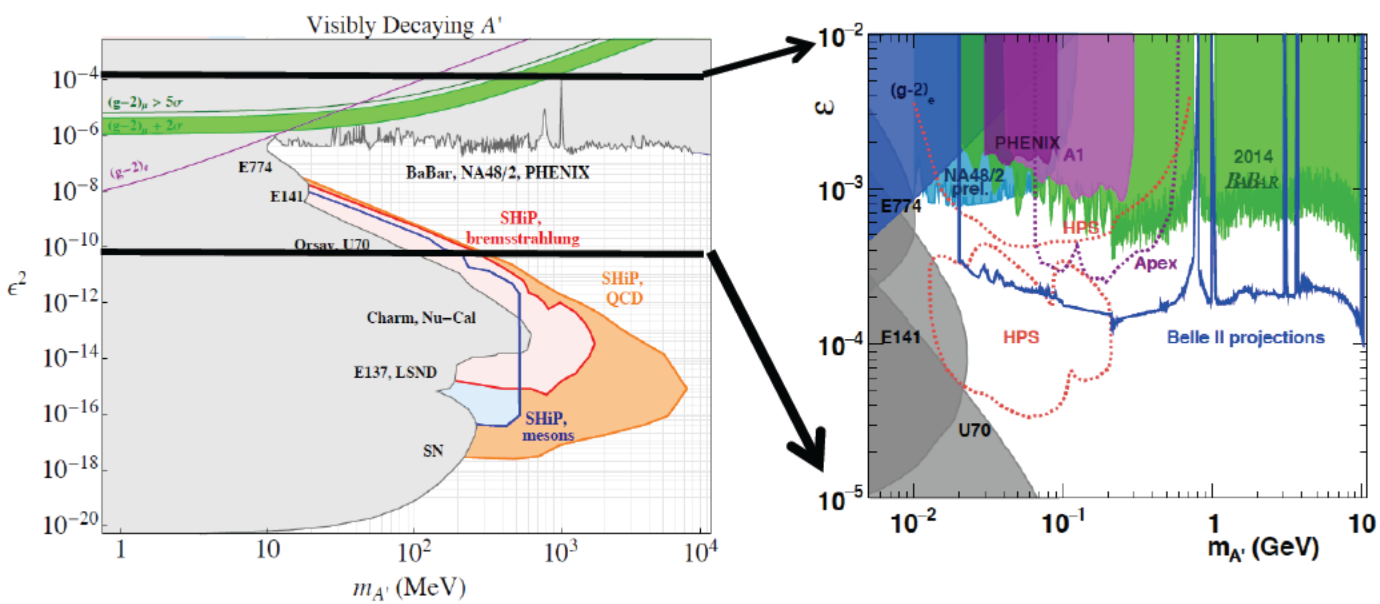
Models	Final states
Neutrino portal, SUSY neutralino	$\ell^\pm\pi^\mp, \ell^\pm K^\mp, \ell^\pm\rho^\mp$, $\rho^\pm \to \pi^\pm\pi^0$
Vector, scalar, axion portals, SUSY sgoldstino	$\ell^+\ell^-$
Vector, scalar, axion portals, SUSY sgoldstino	$\pi^+\pi^-, K^+K^-$
Neutrino portal ,SUSY neutralino, axino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

Under discussion: improve photon detection (with Preshower), and PID in general

Sensitivity to A′ → visible: SHiP vs HPS, APEX and Belle-II

SHiP

zoom



SHiP will have sensitivity in a range that cannot be covered by any current or planned experiment

Caveat: these limits are valid in the assumption that A' does not decay in dark matter

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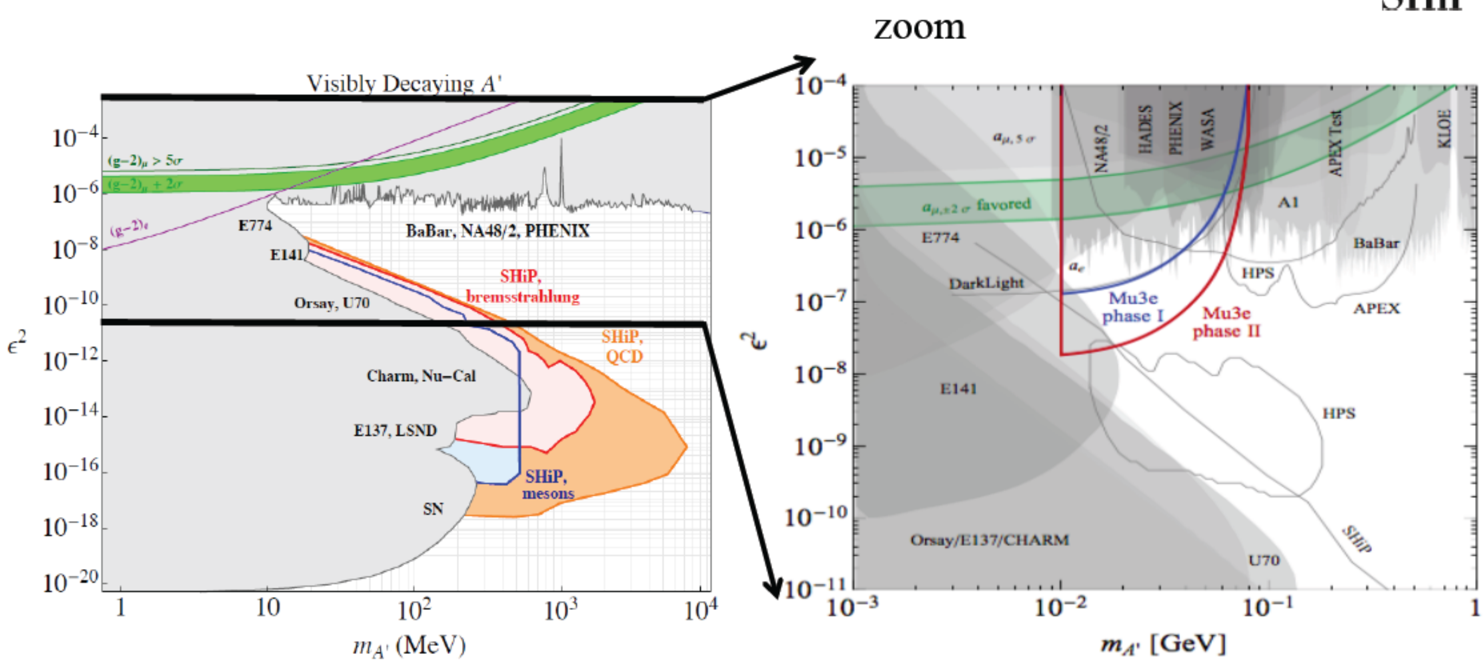
G. Lanfranchi at SLAC April workshop

Sensitivity to A′ → visible: SHiP vs Mu3e phase-I and phase-II

SHiP



SHiP will have sensitivity in a range that cannot be covered by any current or planned experiment

Caveat: these limits are valid in the assumption that A' does not decay in dark matter

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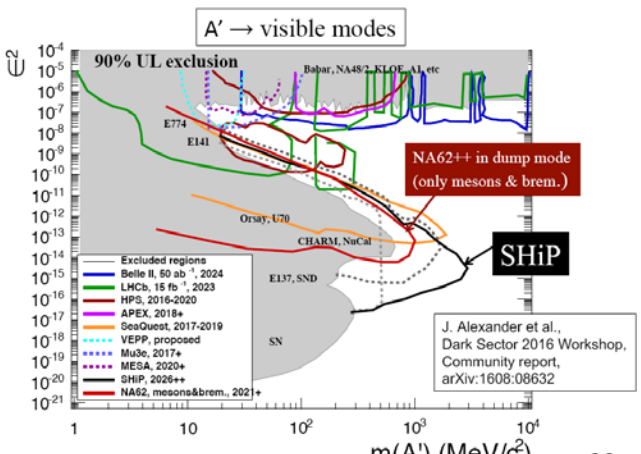
G. Lanfranchi at SLAC April workshop

Experimental landscape

SHiP
Search for Hidden Particles

Dark Photons in visible modes: past and future sensitivities



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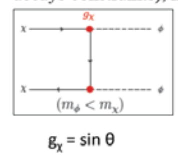
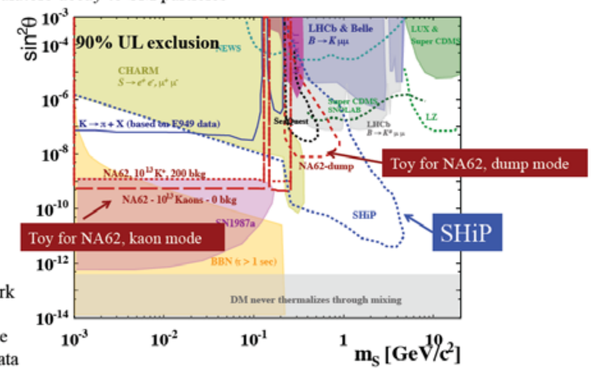
Dark Scalars in visible modes: past and future sensitivities

Secluded annihilation via mediators (only possibility compatible with CMB and rare mesons decays constraints), mediators decay to SM particles



$g_\chi = \sin\theta$

NA64 can search for Dark Scalars in the reaction : eZ → eZ S, S → invisible
Results from the 2016 data sample are being finalized.



See G. Krnjaic, arXiv:1512.04119v1, and references therein

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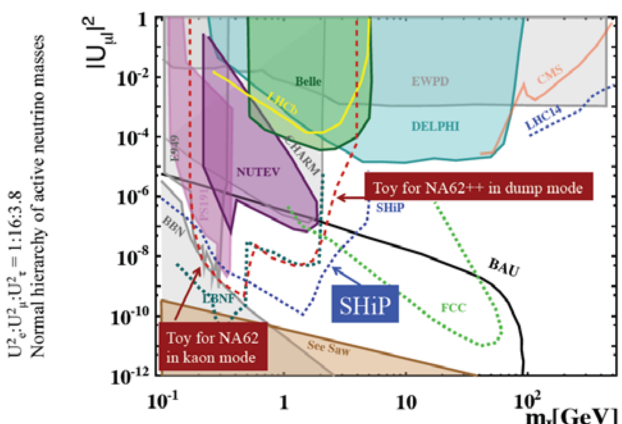
Heavy Neutral Leptons: past and future sensitivities



See A. Alekhin et al., The SHiP Physics case, arXiv:1504.04855 and references therein

NB: 1 SHiP year ~ 500 NA62 years

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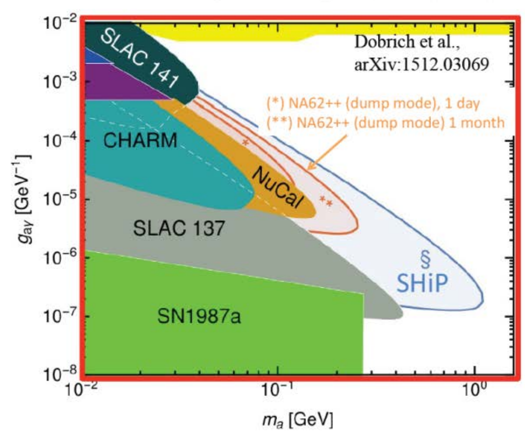
ALPS contour limit from past and future beam-dump experiments in the "high" mass region (0.1-1.0) GeV)



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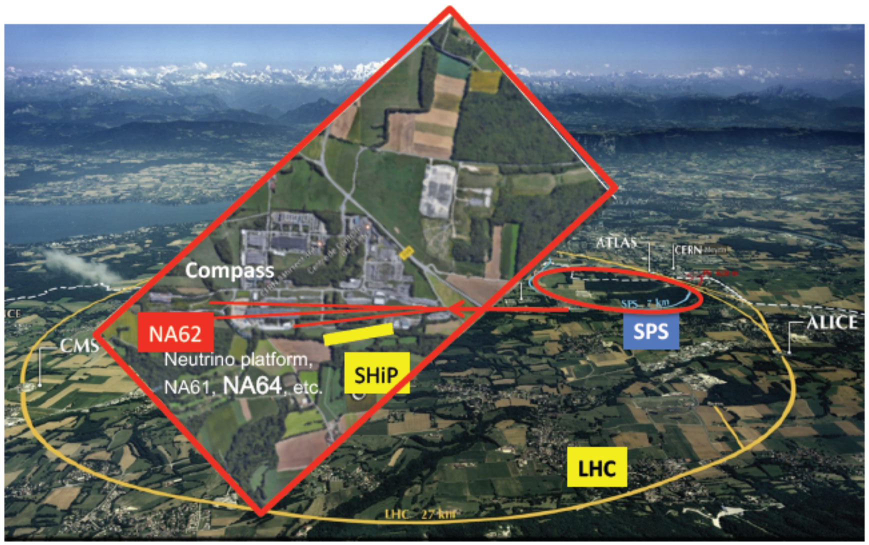
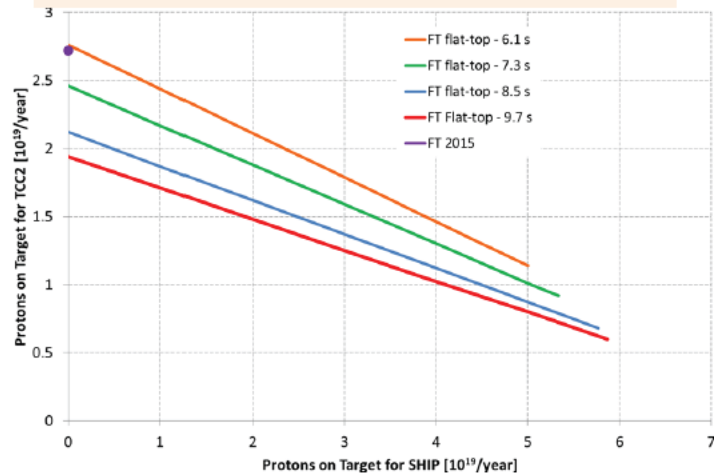
G. Lanfranchi CERN PBC 1-2 March 2017

The Fixed-target facility at the SPS: Prevessin North Area site

Very intense proton beam with highest in the world energy delivered to fixed target exp. at CERN SPS. ***The aim is to deliver with 4×10^{13} protons / spill (at slow extraction)***



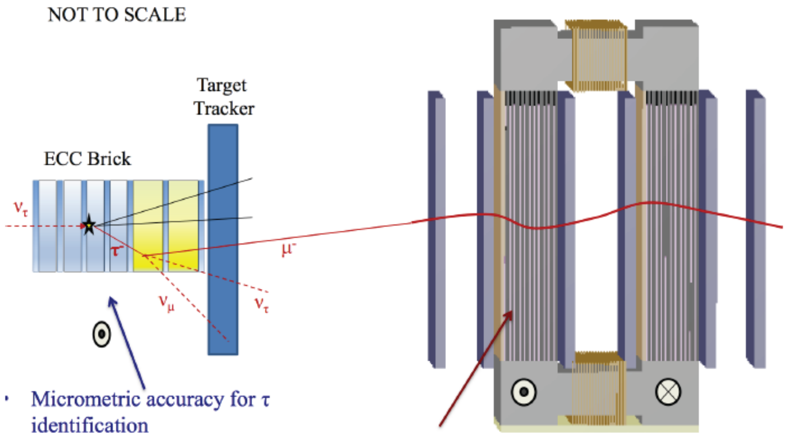
Sharing of pot between current fixed target exp. and planned Beam Dump Facility (BDF)

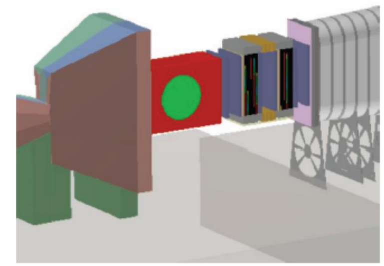


Proposed implementation is based on minimal modification to the current SPS complex

LDMA 2017 5

The ν_τ Detector (Scattering)





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

TP

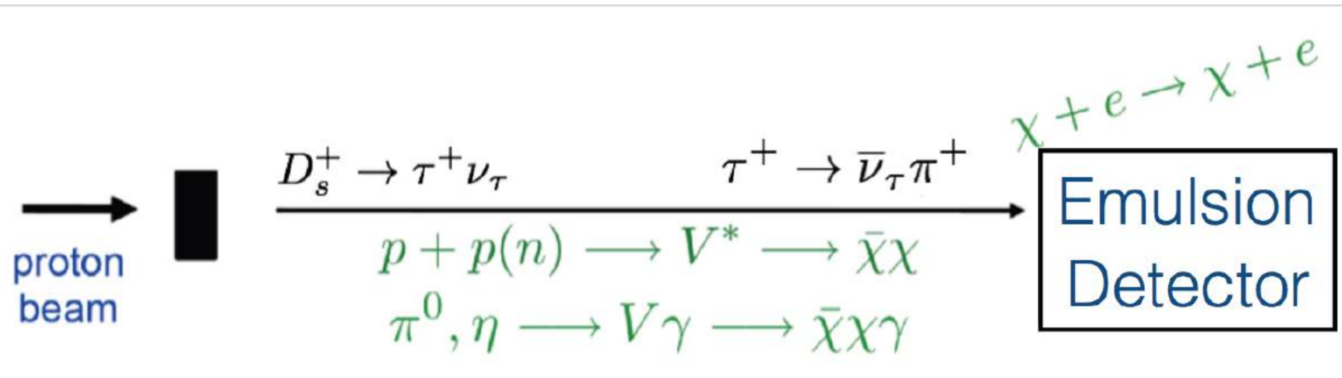
decay channel	ν_τ N^{exp}	ν_τ N^{bg}	ν_τ R	$\overline{\nu}_\tau$ N^{exp}	$\overline{\nu}_\tau$ N^{bg}	$\overline{\nu}_\tau$ R
$\tau \to \mu$	570	30	19	290	140	2
$\tau \to h$	990	80	12	500	380	1.3
$\tau \to 3h$	210	30	7	110	140	0.8
total	1770	140	13	900	660	1.4

And also,

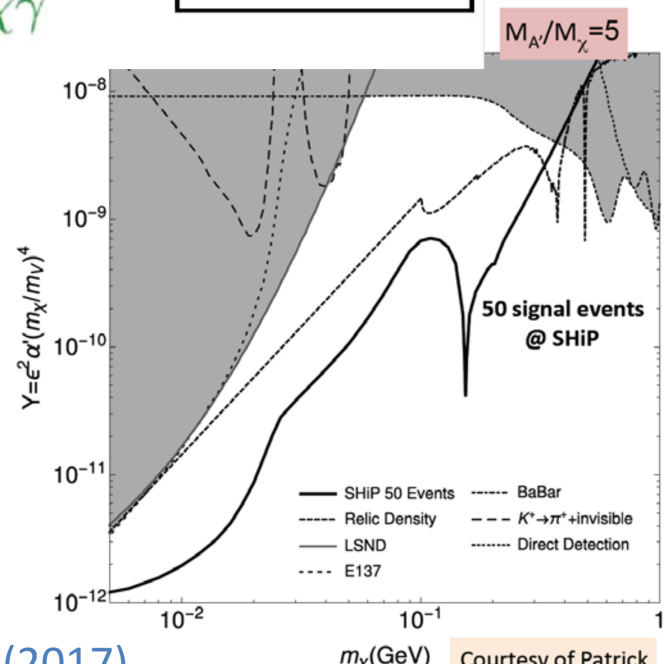
➢ Probe LFUV comparing ν_μ and ν_τ CC events ? *to be further studied*.

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

Accelerator-based direct (L)DM search



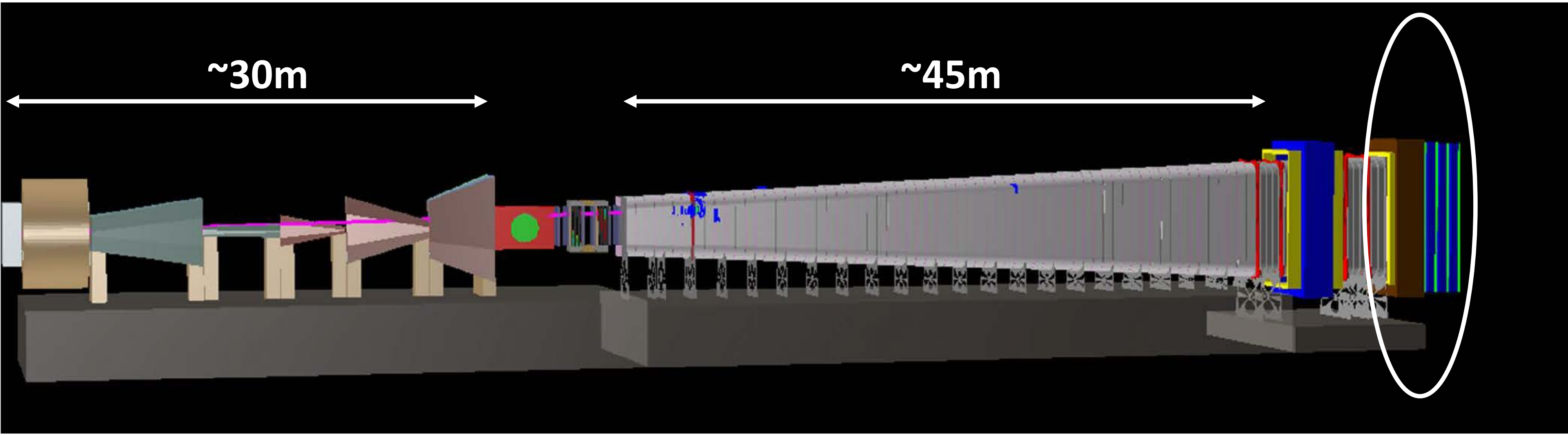
- χ could be lighter than HS mediator (e.g. V)
- ➢ V→ $\chi\chi$ allowed
- With 10^{20} photons in SHiP:
- ➢ A LDM beam downstream the dump
- Scattering experiment χe→ χe on the atoms of the SHiP detector (emulsions)
- Feasibility studies in progress (ν background)
- LDM search beyond relic density



Courtesy of Patrick deNiverville

Pioneered in: de Niverville et al., Phys. Rev. D 95, 035006 (2017)
MiniBooneE: arXiv:1702.02688v2 [hep-ex]

Detector reoptimization



- Muon shield
  The active muon shield in the SHiP experiment
  arXiv:1703.03612v2 [physics.ins-det] 2017_JINST_12_P05011
- Pyramidal shape
- ***PID, timing***
- Technology choices for the subdetectors

Towards CDS and more

- Further optimization of the target
- Muon Shield configuration
- Decay volume geometry, vacuum
- Optimization of the sub-detector performance
- Optimization of the emulsion detector iSHiP
- Massive background simulation

Some examples

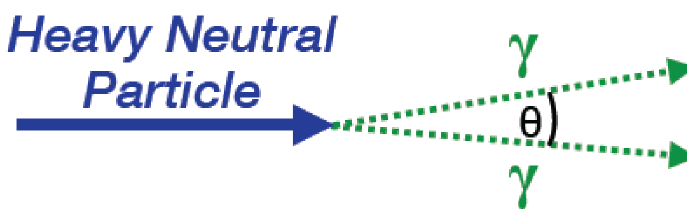
PID, timing

In the TP:

Shashlik ECAL (+HCAL)

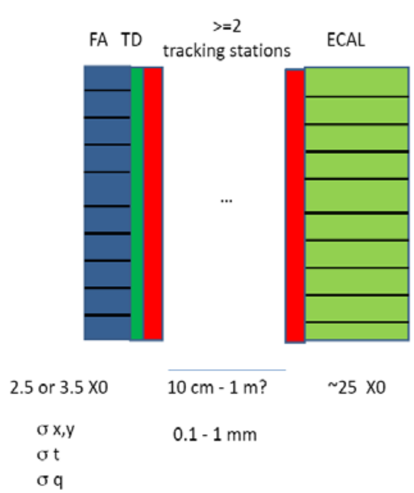
- Square cells (38.2 mm)^2.
- 22.5 X0
- $\frac{6.5\%}{\sqrt{E}} + 1\%$

But, what about:

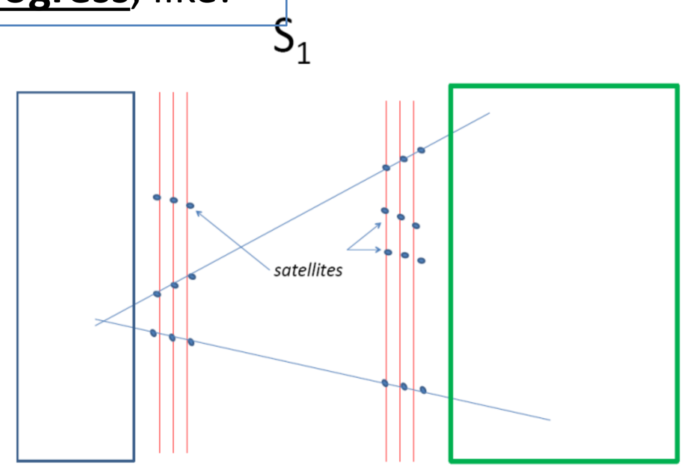


Conceptual studies in progress, like:

A possible setup with preshower (Feb 2017)



- Upstream point S_1 **via tracking**
  - Use 2 tracking stations
  - Reconstruct 3D track segments in each
  - Match them: form track candidates
  - Clean them/remove satellites using
    - energy of clusters,
    - angles
  - Vertex track candidates to determine position of the shower starting point S_1.
- Downstream point S_2
  - Use z of the shower maximum inferred from energy
  - obtain (x,y) from the lateral shower profile
  - **Which longitudinal segmentation if any?**



02/02/2017 J. Chauveau -- SHiP calorimeter 21

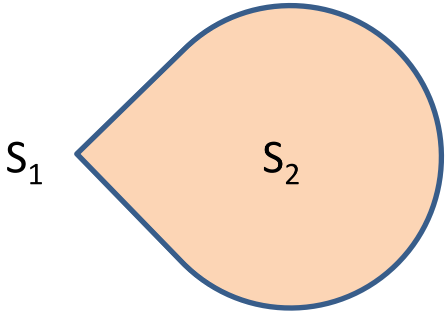
02/02/2017 J. Chauveau -- SHiP calorimeter 22

Alternate SplitCal Design

with DT, EB…

Measure 2 points (S_1, S_2) across a base L with $\sigma \sim L/1000$.

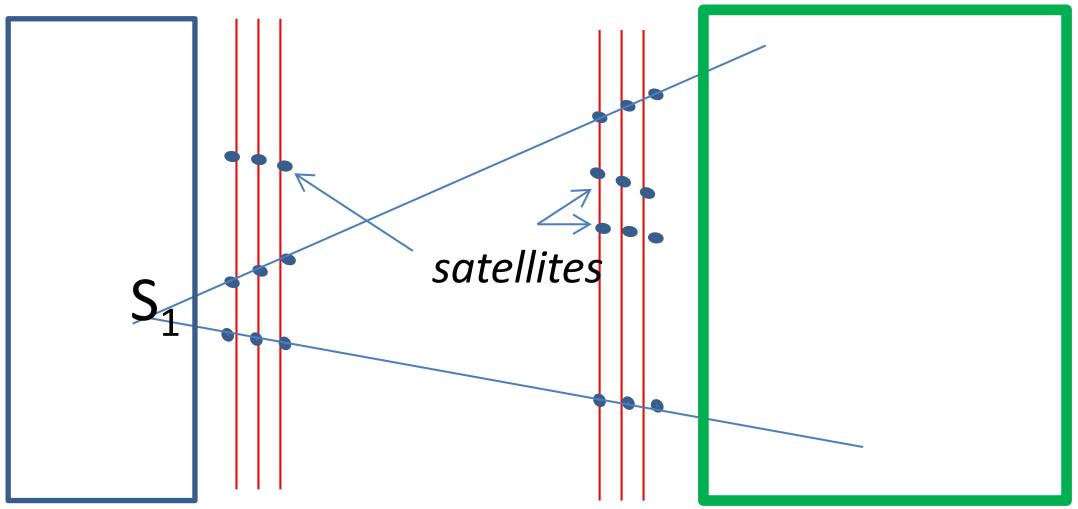
- S_1 the location of the 1st pair
- S_2 the position of the shower maximum or…
- The hard part is to measure S_1



➢ Use tracking (TPC, μM, straws?..)

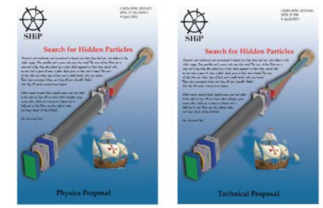
Need simulation

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

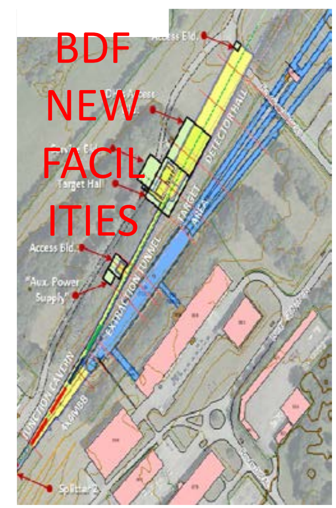


SHiP path at CERN

Not yet approved, but a leading project for the future of CERN fixed target program



- 2013-2015
  - EOI, formation of the Collaboration, T&P proposals
- 2016 SPSC/RB/ decisions by CERN management
  - ➢ **SHiP in the 2017_2021 MTP**,
  - ➢ **PBC study group** (the 3rd of F. Gianotti's 3 pillars)
    - ➢ **~5 MCHF funding for Beam Dump Facility feasibility study**
  - ➢ **CDS** (Comprehensive Design Study) report end 2018
  - ➢ Approval path in time with ESPP : **TDRs, Module-0's**
- ➢ ~ 5 years construction,
  - ➢ installation during LS3,
  - ➢ data while LHC Run4 (2027)



SHiP a recognized project in the greybook since 2016