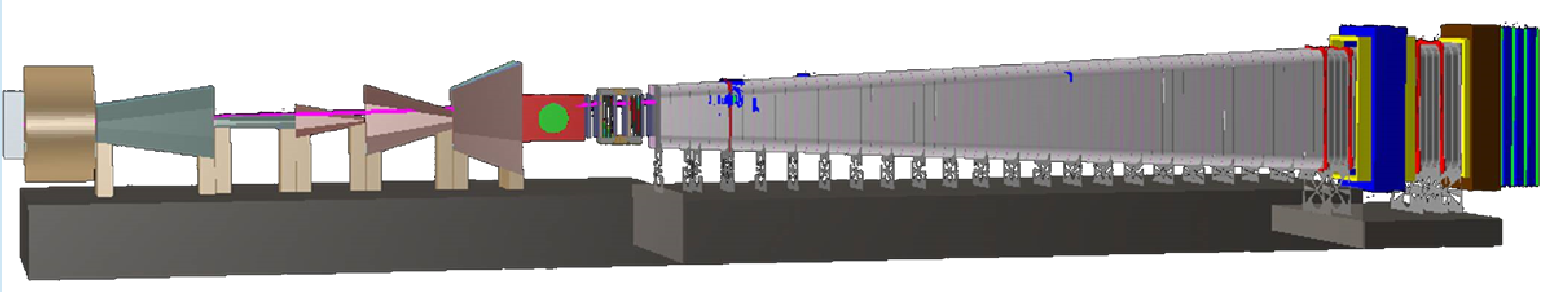
Search for Hidden Particles (SHiP): an experimental proposal at the SPS

ship.web.cern.ch/ship

Mario Campanelli (UCL)

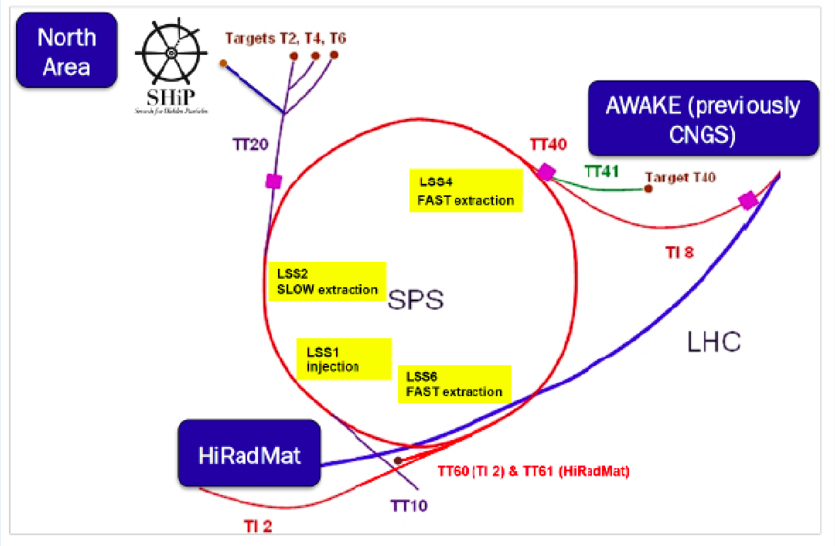


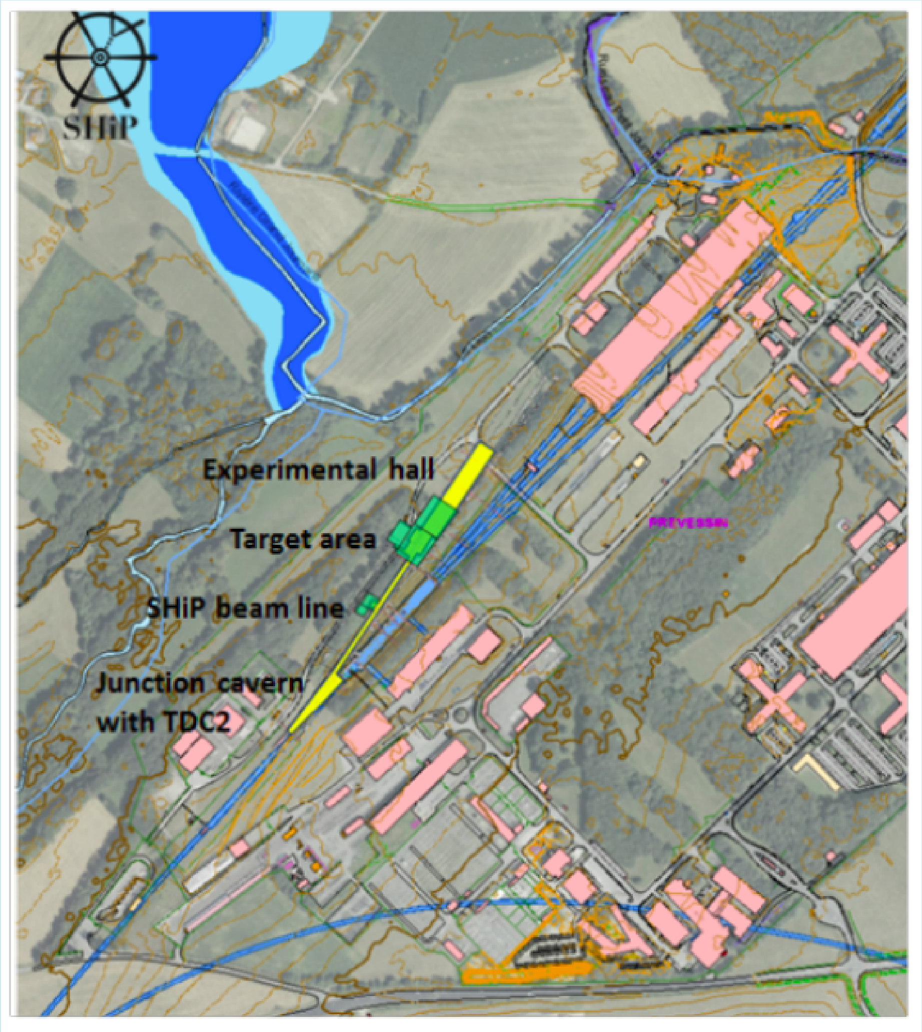
SHiP facility

400 GeV beam from SPS on a beam dump

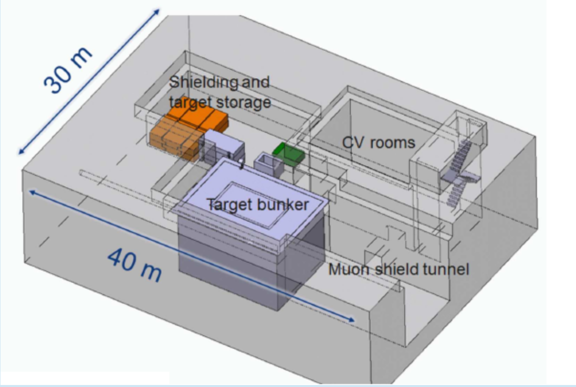
4E13 protons per spill in slow extraction

→ 2E20 in 5 years



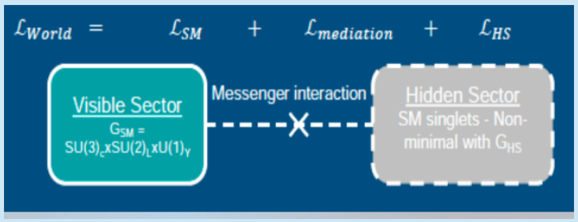


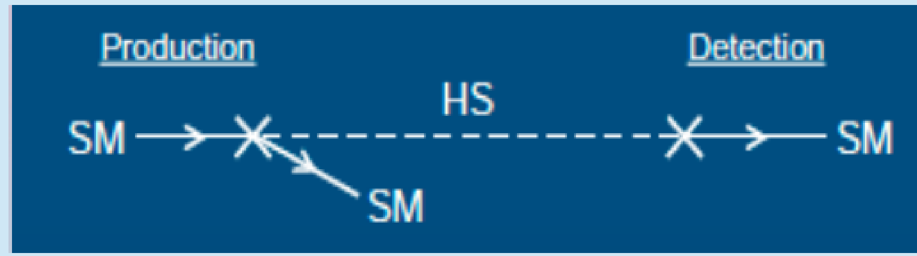
Use TT20 area (same as NA62, Compass, test-beams), requires new beam line and dedicated shielded target and detector areas



The "hidden sector" approach to new physics

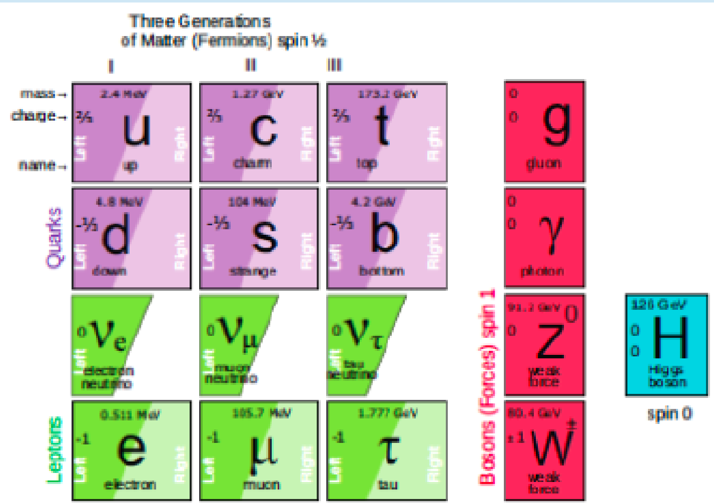
- Searches for new particles at the LHC so far unsuccessful, maybe new physics has a very small coupling?
- If an additional, weakly interacting, term to the Lagrangian could lead to particles very difficult to observe, but contributing to dark matter.

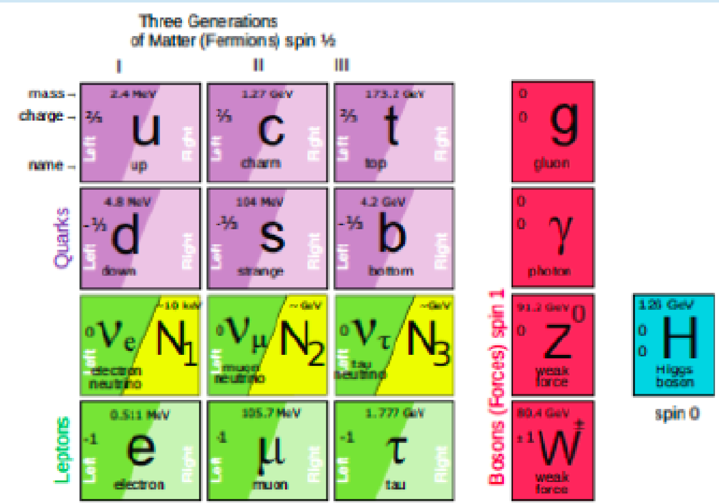




The νMSSM

T.Asaka, M.Shaposhnikov, PL B620 (2005) 17
M.Shaposhnikov Nucl. Phys. B763 (2007) 49





Particle content of SM made symmetric by adding 3 HNL: N_1, N_2, N_3

With $M(N_1)$ ~ few KeV, it is a good DM candidate (or DM can be generated outside of this model through decay of inflaton)

With $M(N_2, N_3)$ ~ GeV, could explain Barion Asymmetry of Universe (via leptogenesis), and generate neutrino masses through see-saw.

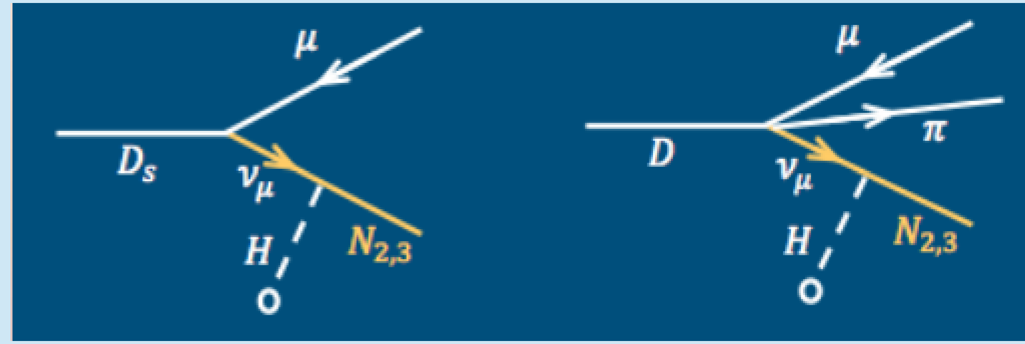
HNL production and decay modes

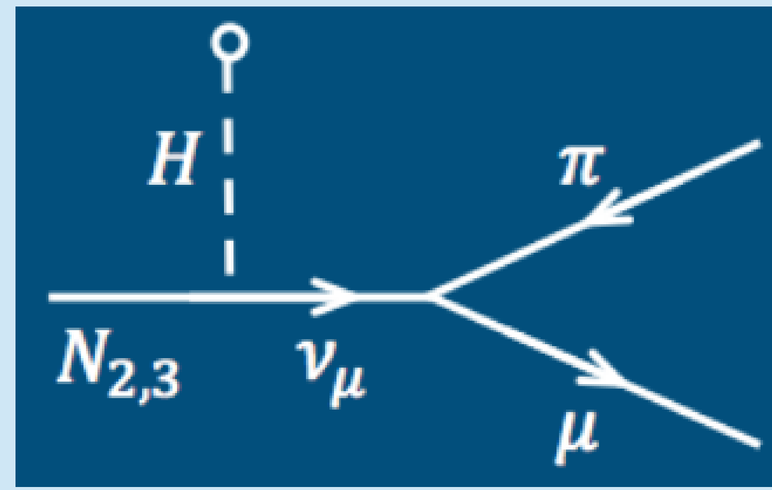
Interaction with Higgs vev leads to mixing with active neutrinos, resulting in a bahaviour similar to oscillation to the HNL and back into a virtual neutrino, that

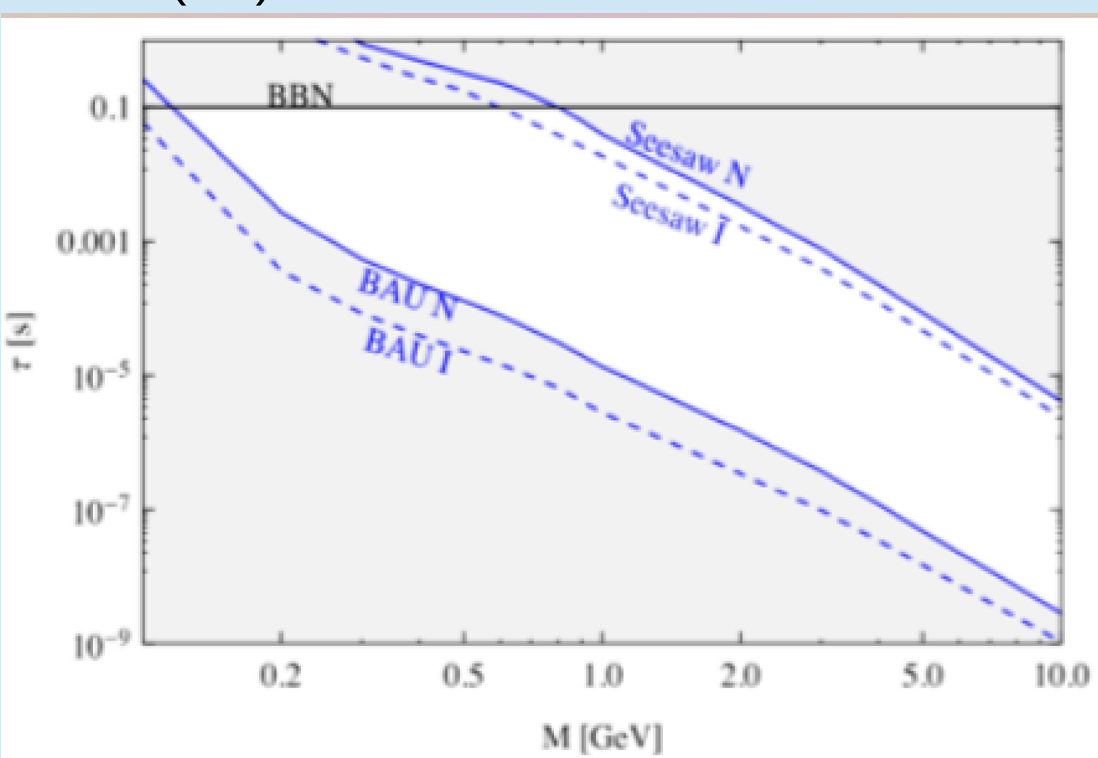
produces a muon and a W (→ hadrons, eg pions)

Exact branching fractions depend n flavor mixing

Due to small couplings, ms lifetimes, decay paths O(km)





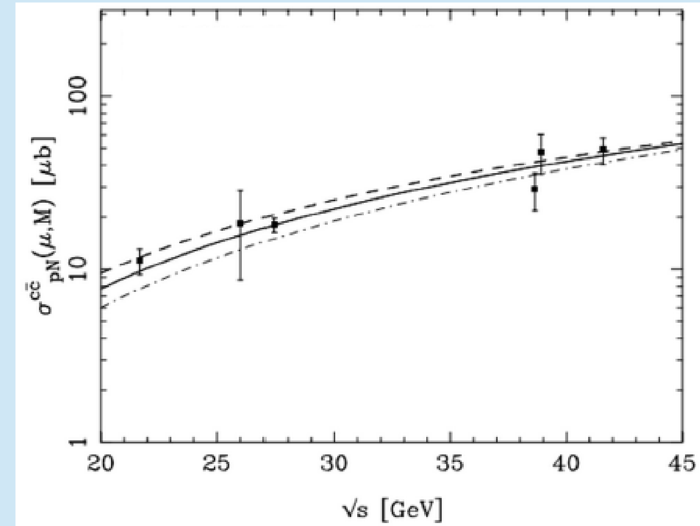


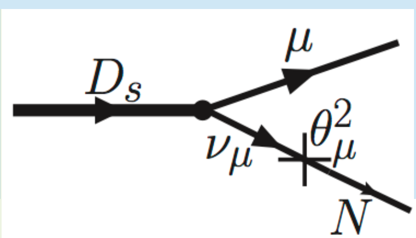
Decay mode	Branching ratio
$N_{2,3} \rightarrow \mu, e + \pi$	0.1 – 50 %
$N_{2,3} \rightarrow \mu^- / e^- + \rho^+$	0.5 - 20%
$N_{2,3} \rightarrow \nu + \mu + e$	1 – 10%

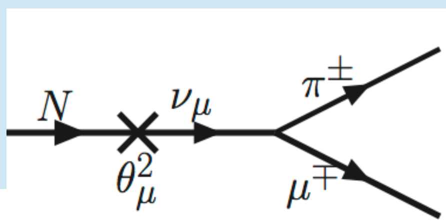
General experimental requirements
to search for HS at beam dump experiment

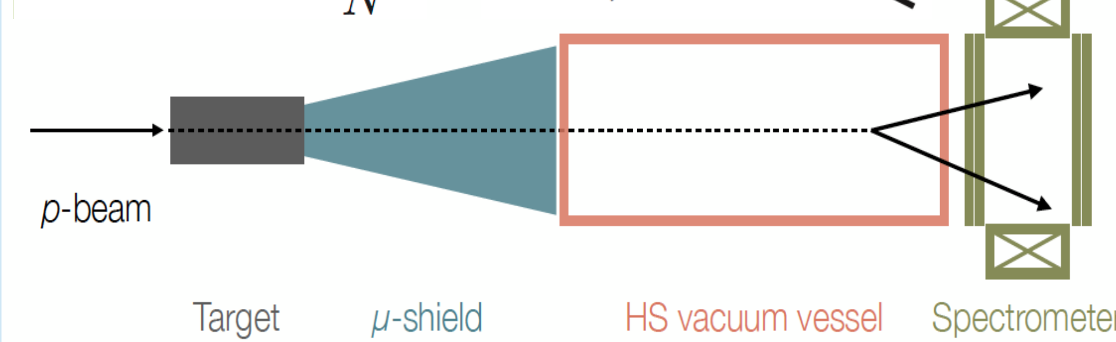
- ✓ *Search for HS particles in Heavy Flavour decays*
  Charm (and beauty) cross-sections strongly depend on the beam energy

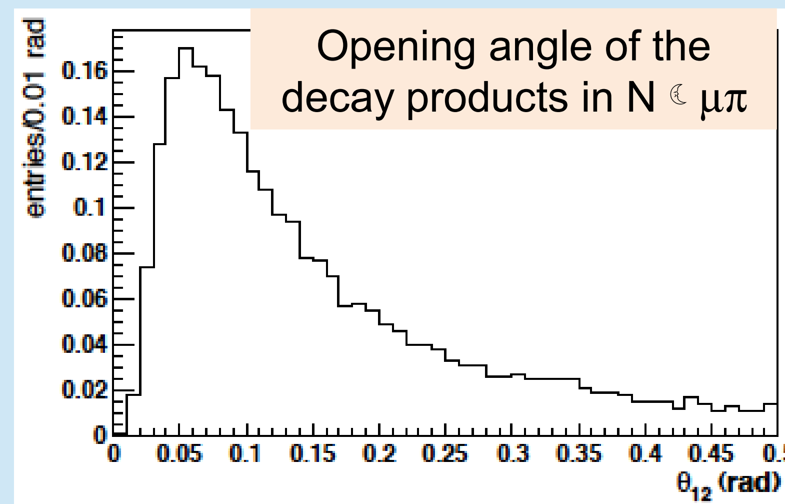
- ✓ *HS produced in charm and beauty decays have significant P_T*











Detector must be placed close to the target to maximize geometrical acceptance. Effective (and "short") muon shield is the key element to reduce muon-induced backgrounds

The SHiP experiment at SPS

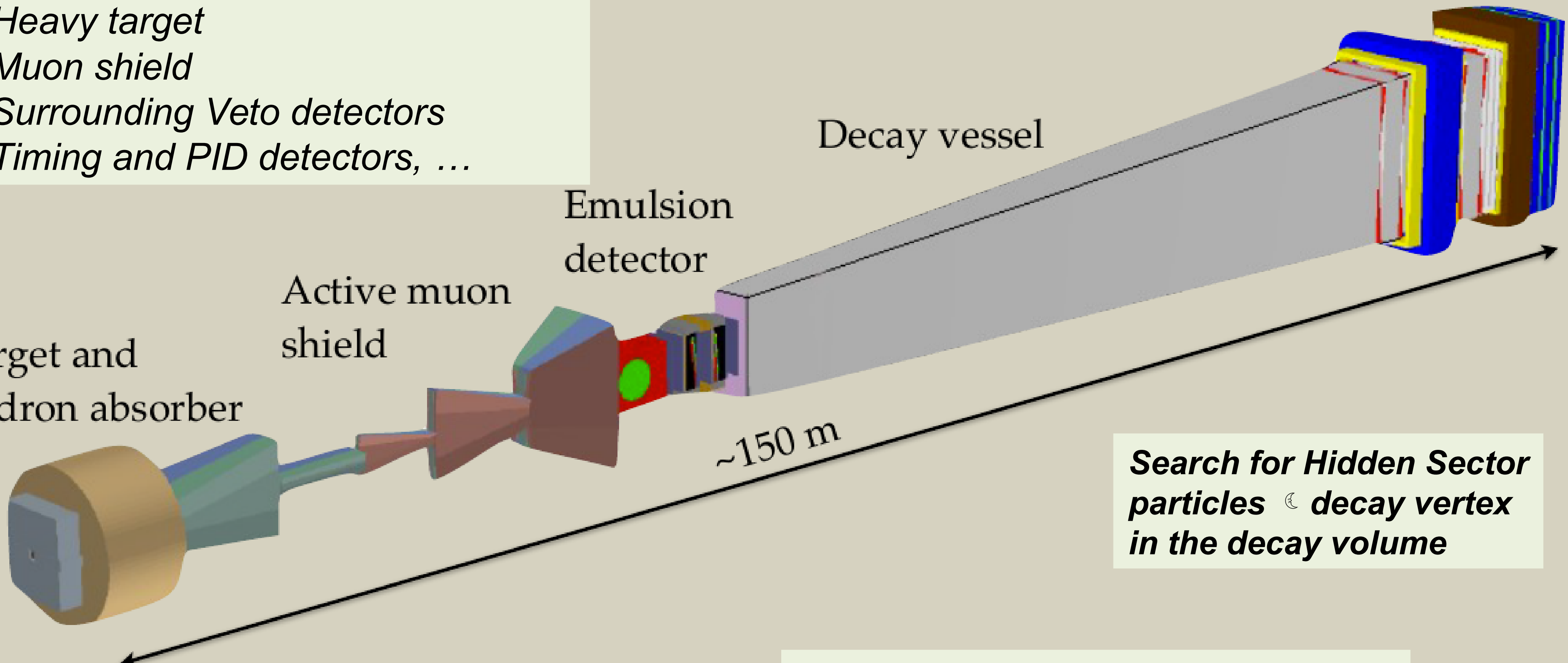
(to search for HS particles with O(10 GeV) masses)

SHiP Technical Proposal: 1504.04956

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

"Zero background" experiment

- *Heavy target*
- *Muon shield*
- *Surrounding Veto detectors*
- *Timing and PID detectors, …*

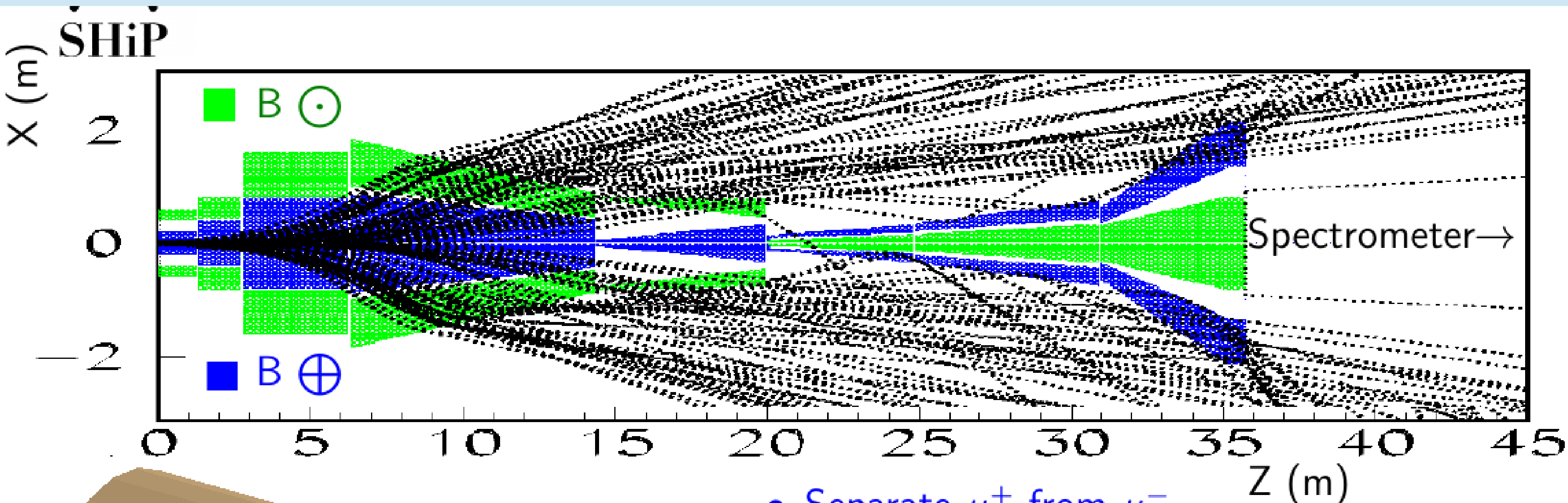


Search for Hidden Sector particles ☾ decay vertex in the decay volume

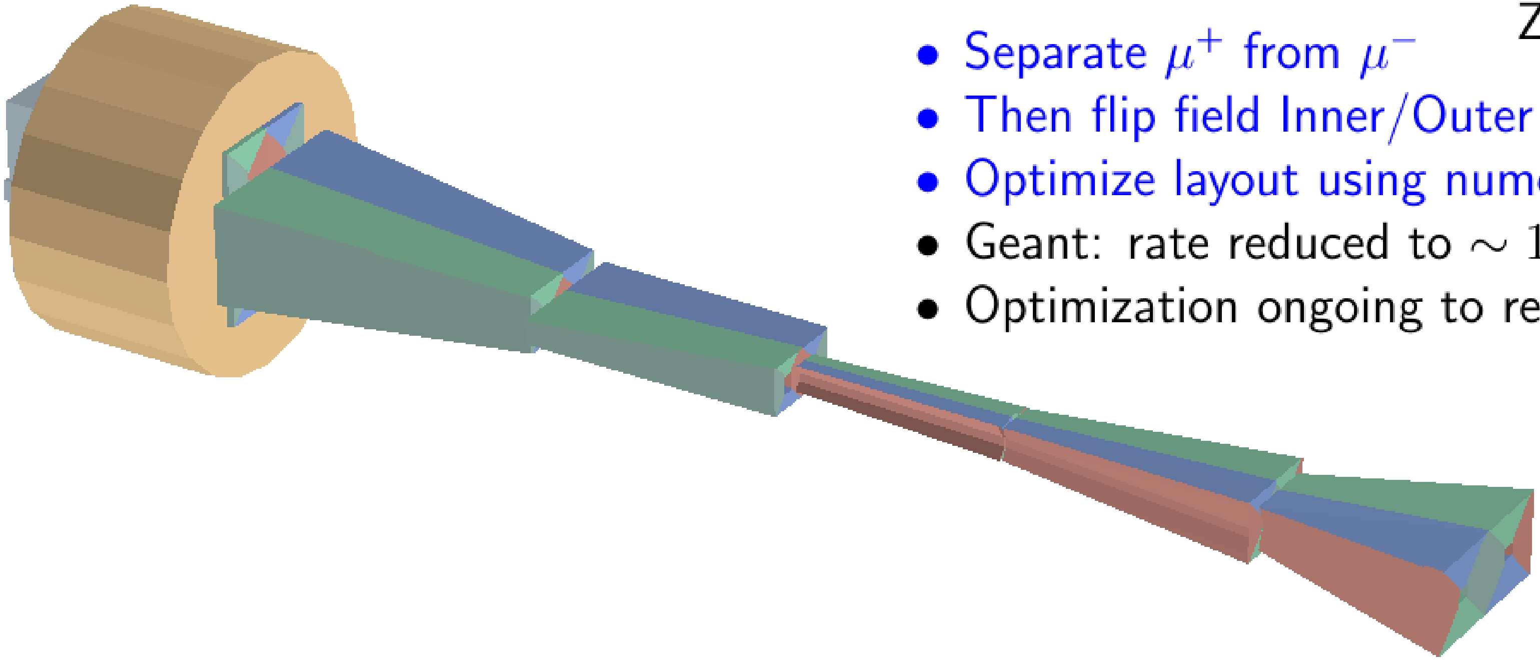
Search for DM (scattering on atoms)
Specific event topology in emulsion
Background from neutrino interaction can be reduced to a manageable level

Active muon shield

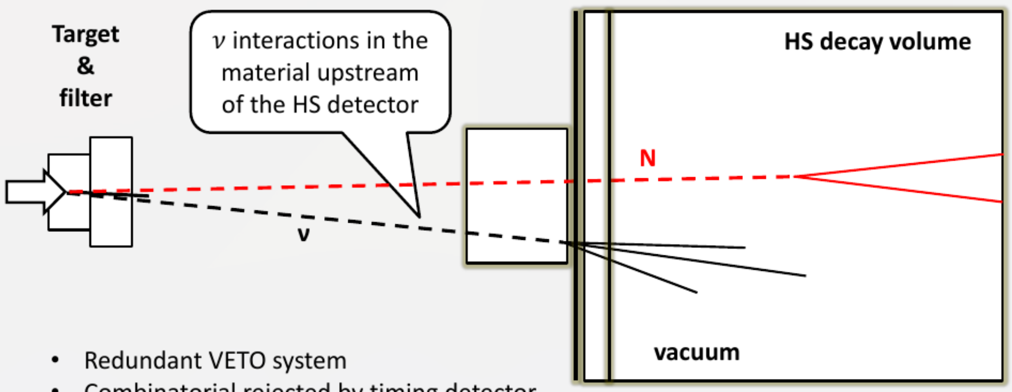
Journal of Instrumentation, 12 (May 2017)



- Separate μ^+ from μ^-
- Then flip field Inner/Outer
- Optimize layout using numerical minimization
- Geant: rate reduced to $\sim 10^5$ μ/s.
- Optimization ongoing to reduce rate even further.

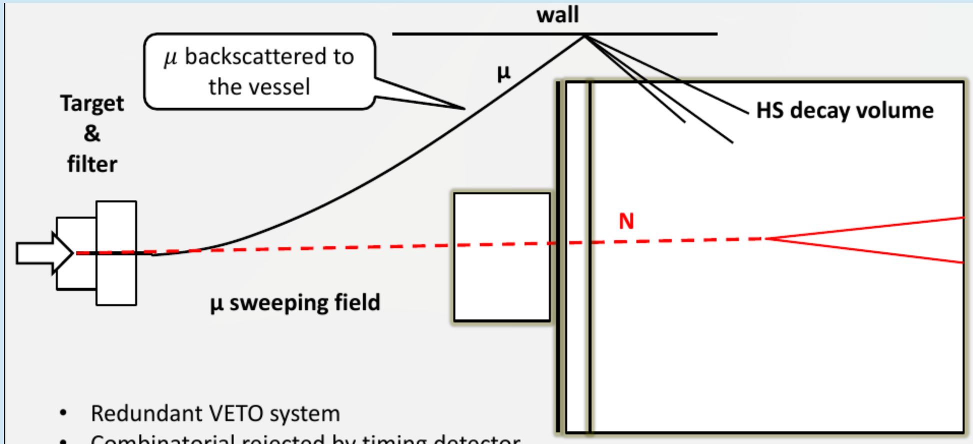


Background rejection for HNL searches



- Redundant VETO system
- Combinatorial rejected by timing detector
- Impact parameter to the target
- 75% selection efficiency for signal

After selections:
≤ 0.1 bkg / 5 y



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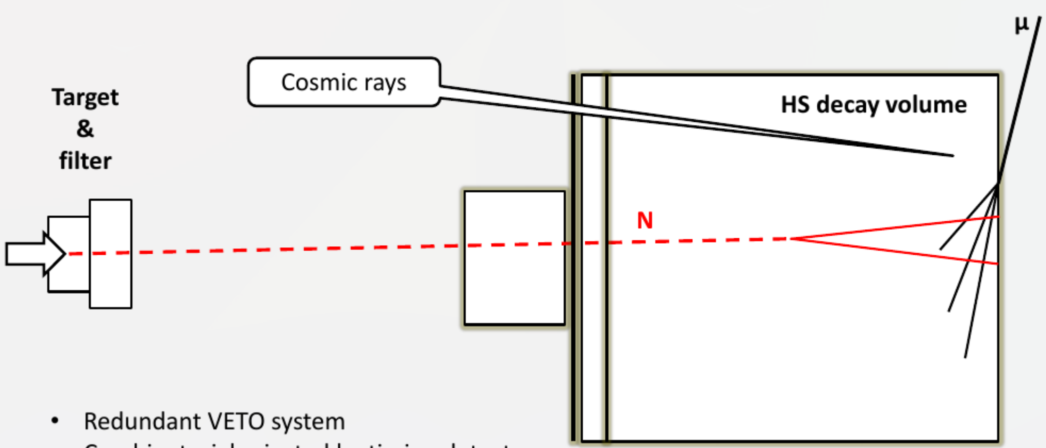

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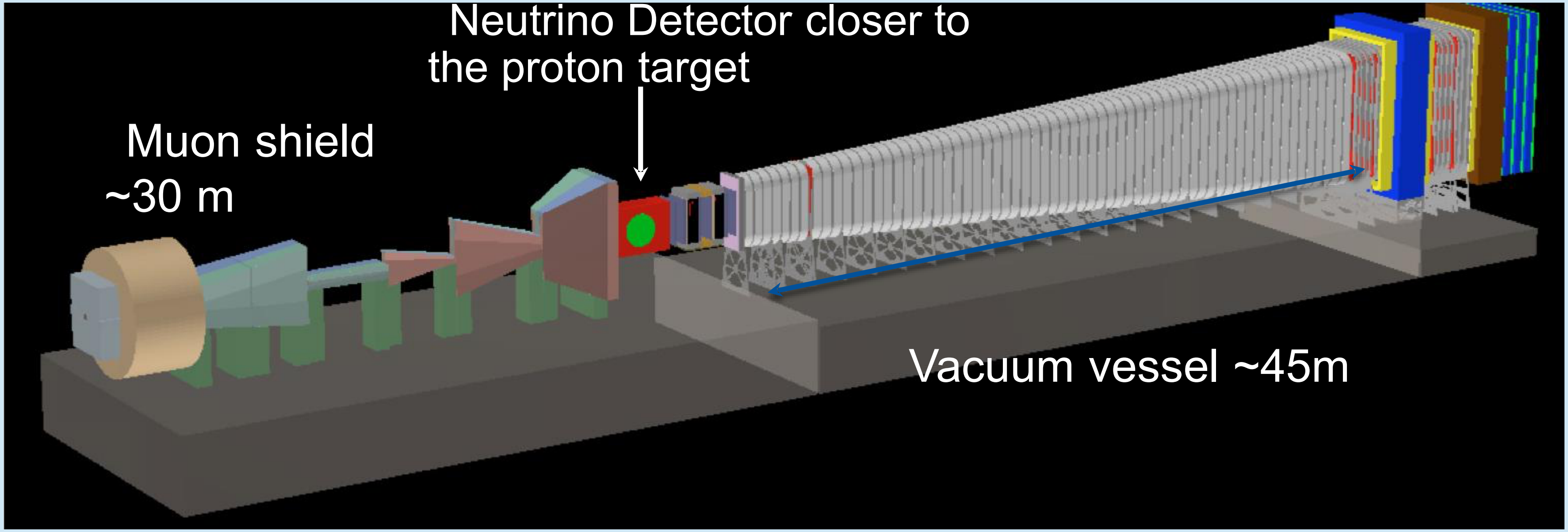
Background source	Stat. weight	Expected background (UL 90% CL)
ν**-induced**		
$2.0 < p < 4.0$ GeV/c	1.4	1.6
$4.0 < p < 10.0$ GeV/c	2.5	0.9
$p > 10$ GeV/c	3.0	0.8
$\overline{\nu}$**-induced**		
$2.0 < p < 4.0$ GeV/c	2.4	1.0
$4.0 < p < 10.0$ GeV/c	2.8	0.8
$p > 10$ GeV/c	6.8	0.3
Muon inelastic	0.5	4.6
Muon combinatorial	–	<0.1
Cosmics		
$p < 100$ GeV/c	2.0	1.2
$p > 100$ GeV/c	1600	0.002

Main goals of the SHiP optimization for the CDS

- ✓ *Further optimization of the target*
- ✓ *Configuration of the muon shield, including magnetization of the hadron stopper (**MC to be validated with data**)*
- ✓ *Shape, dimension and evacuation of the decay volume*



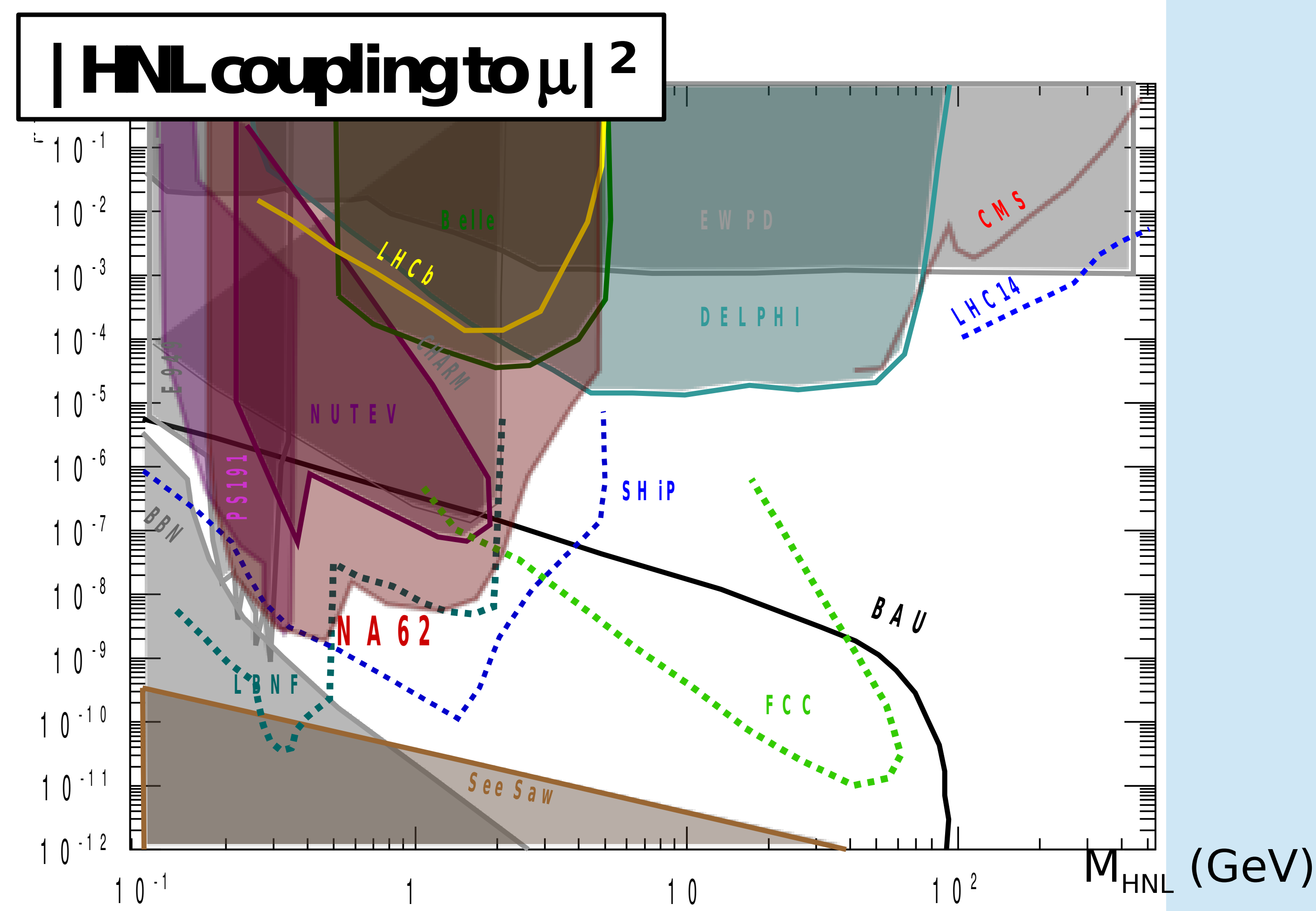
- ✓ *Optimization of the emulsion detector to search for LDM*
- ✓ *Optimization of physics performance for various sub-detectors*
- ✓ *Revisit detector technologies, including new sub-detectors, to further consolidate background rejection and extend PID*

Updated background estimates and signal sensitivities, and cost

- ✓ *Contribution from the secondary interactions in the target improves signal yield by ~50% (**to be validated with data)***

Future prospects and comparison with other facilities

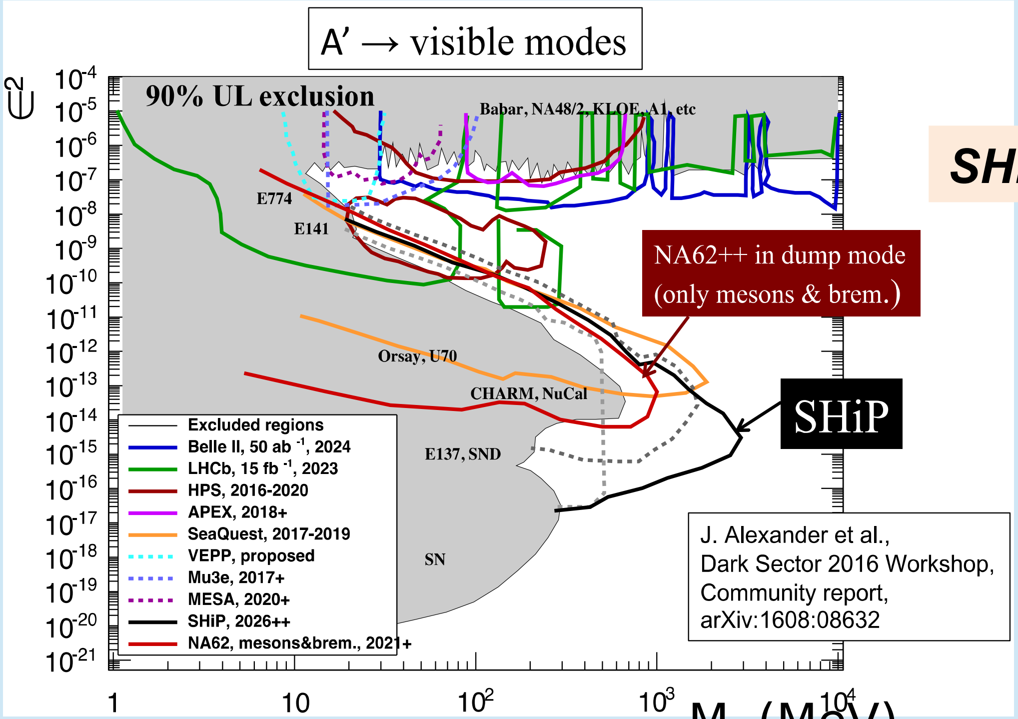
HNLs:



- ✓ $M_{HNL} < M_b$ LHCb, Belle2
  SHiP will have much better sensitivity
- ✓ $M_b < M_{HNL} < M_Z$ **FCC in e^+e^- mode** *(improvements are also expected from ATLAS / CMS)*
- ✓ $M_{HNL} > M_Z$ **Prerogative of ATLAS/CMS @ HL LHC**

SHiP will also have the best prospects for HS particles produced in heavy flavour decays, e.g. hidden scalars

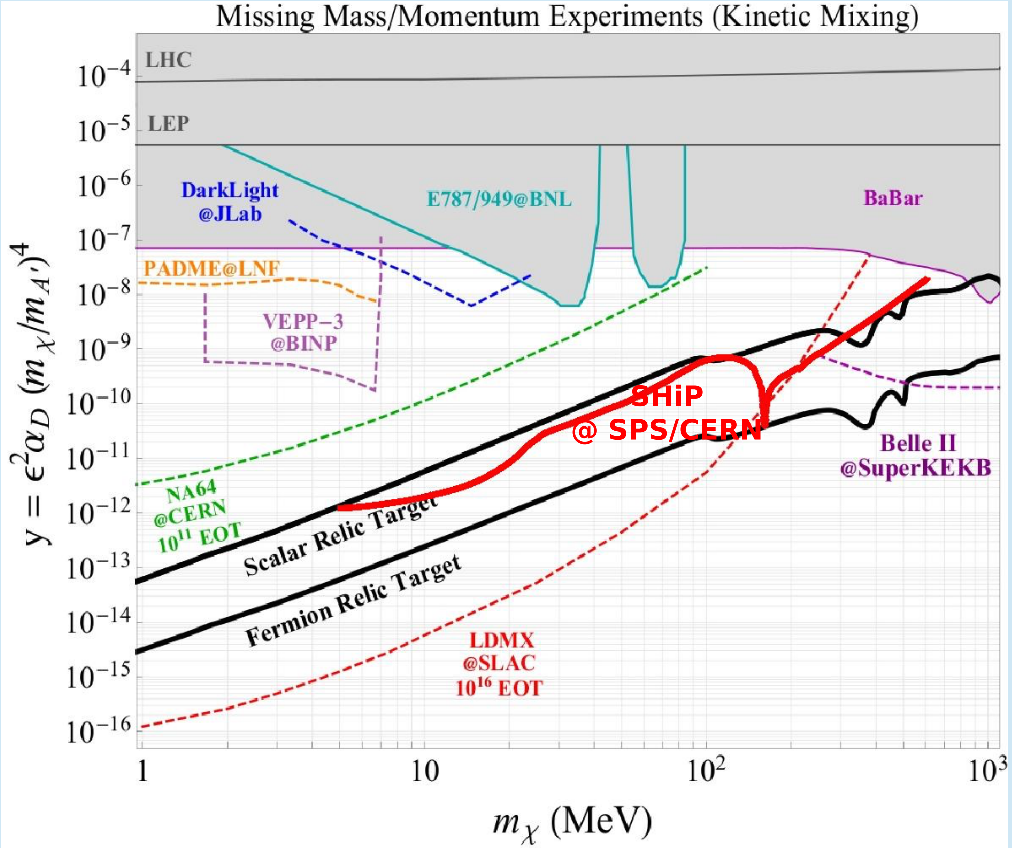
Future prospects and comparison with other facilities



Dark photons:

SHiP is unique up to O(10GeV) and $\epsilon^2 < 10^{-11}$

$M_{A'}/M_\chi=3$



Light Dark Matter

Dark sectors 2016: 1608.08632

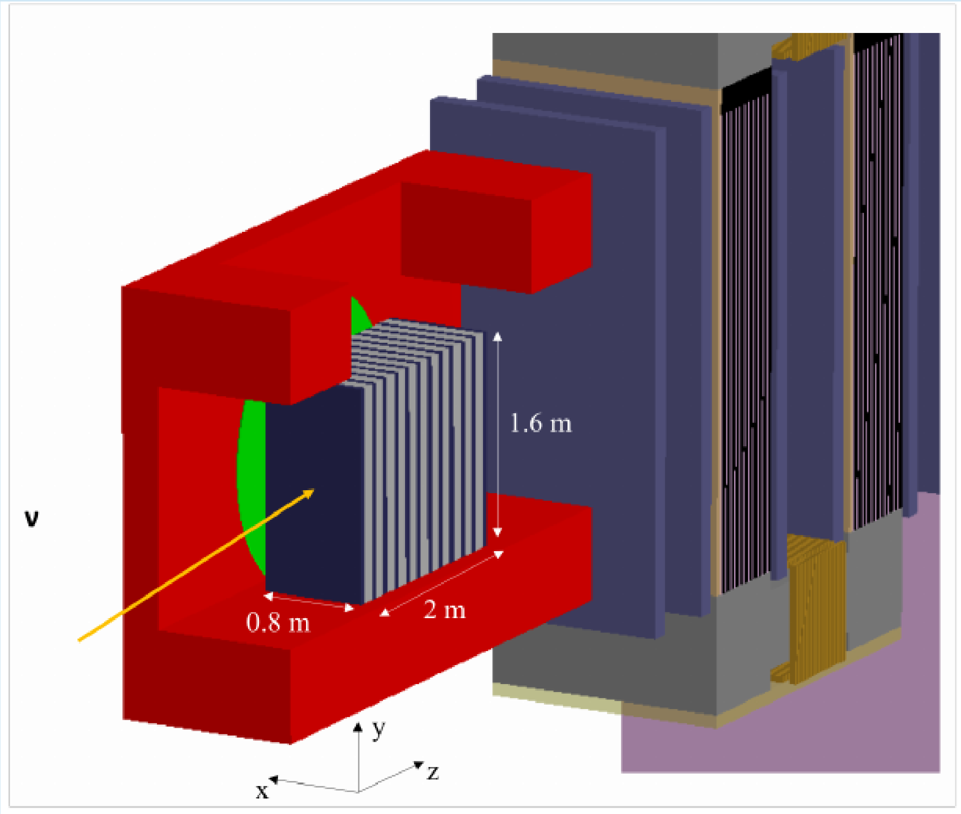
Detection via scattering

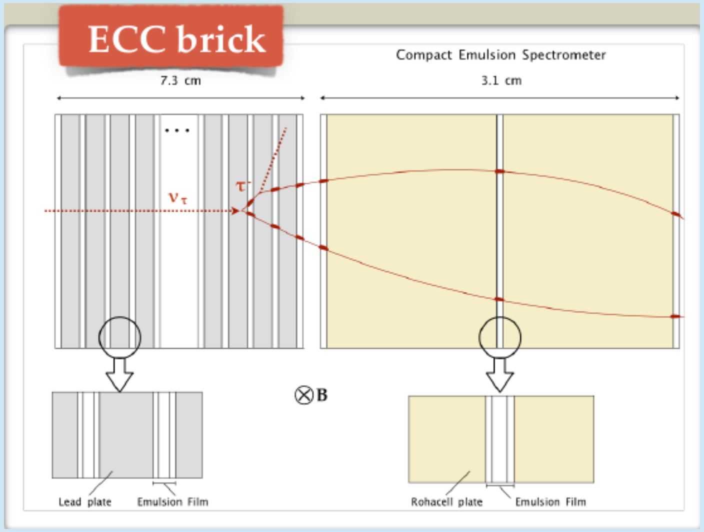
- **SHiP has unique potential for M_χ <1GeV**
- BDX in JLab may have a competitive sensitivity for M_χ <10 MeV

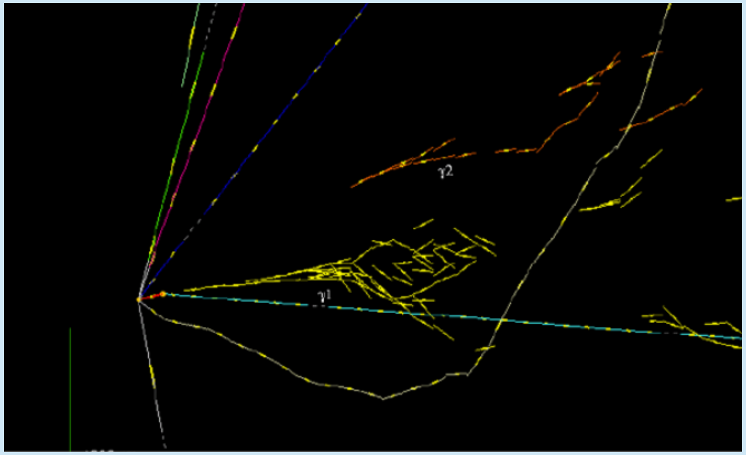
Missing mass / energy technique

- Belle II – comparable to SHiP for M_χ>0.5 GeV with 50 ab^{-1} provided that low energy mono-photon is implemented
- LDMX (under discussion at SLAC) has the best prospects for M_χ< 100 MeV Time scale is unclear.

Neutrino detector and dark matter searches





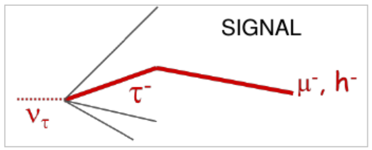


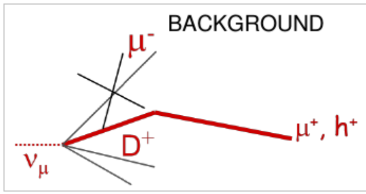
Real tau neutrino candidate from OPERA

Exploit production thousands of of tau neutrinos to study its properties and structure function

Discovery of tau-antineutrino (only missing SM particle)

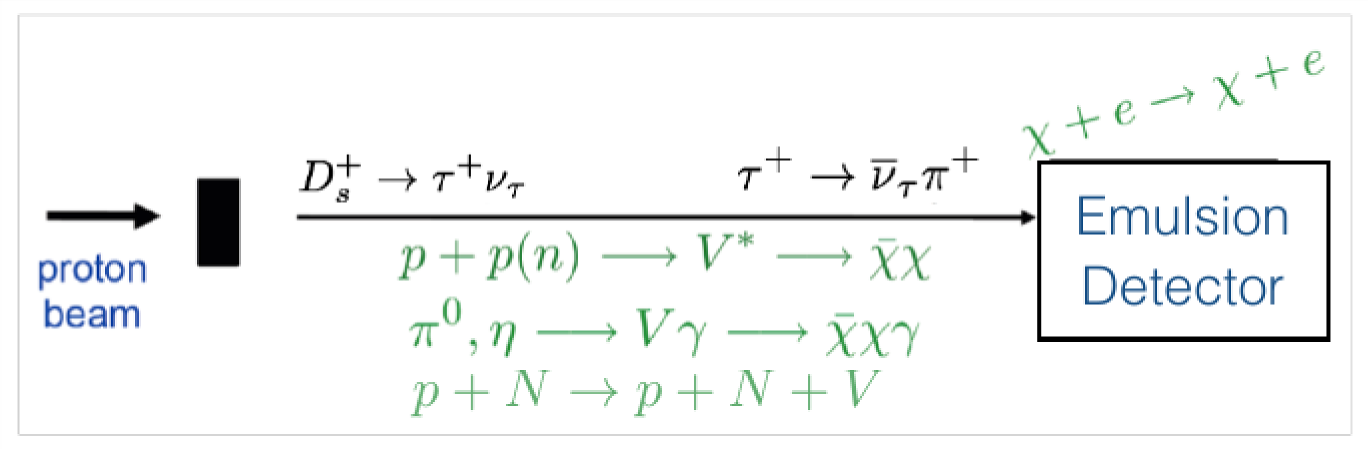
Muon spectrometer after target needed to suppress charm BG:



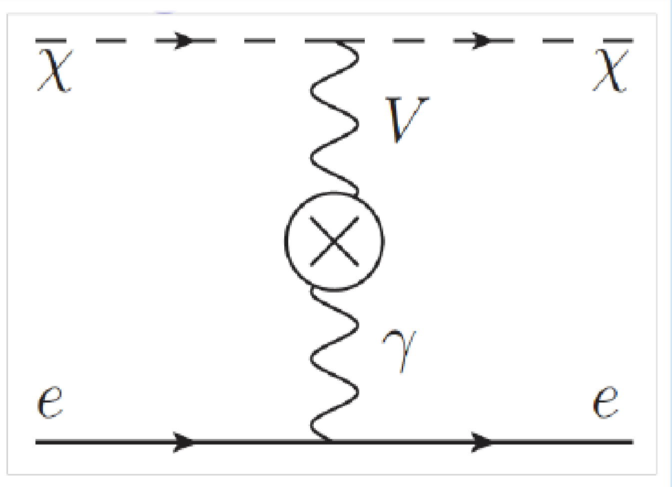


LDM production and detection

- Production:
  - Direct
  - Decay or mixing of a dark boson

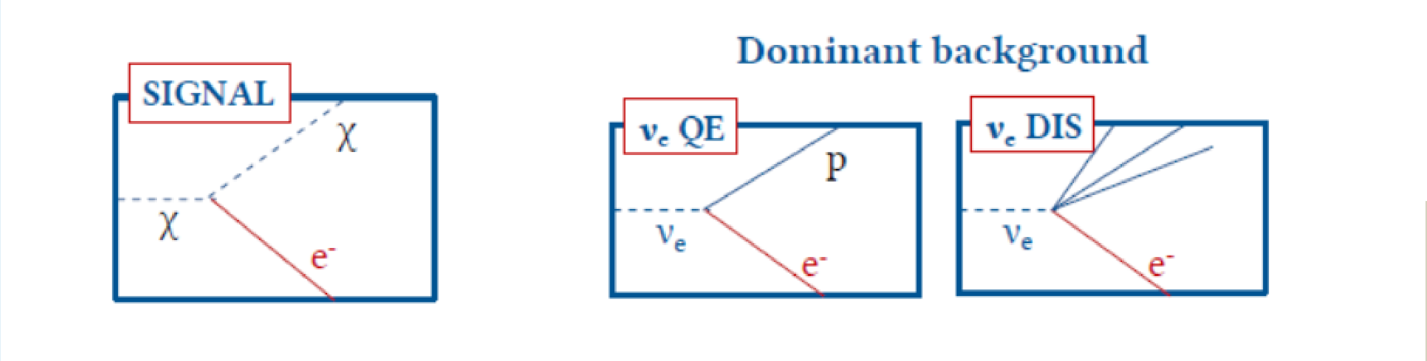


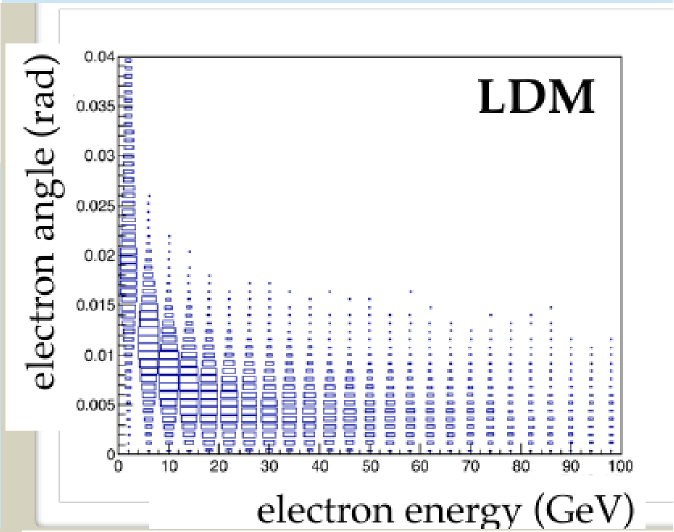
- Detection
  - Elastic scattering on electrons from atoms
  - Electrons have high energy and emitted in forward direction

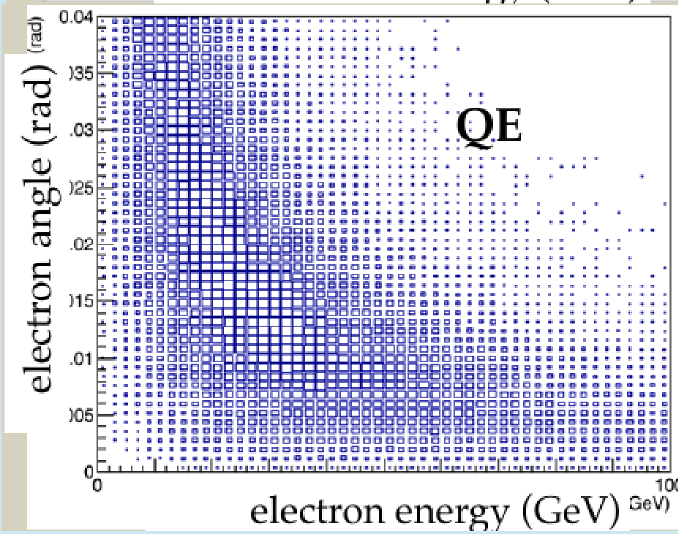


Search for Light Dark Matter

Emulsion detector will also be used to search for Dark Matter in the sub-GeV region exploiting its resolution to separate elastic scattering of DM candidates to neutrino scattering







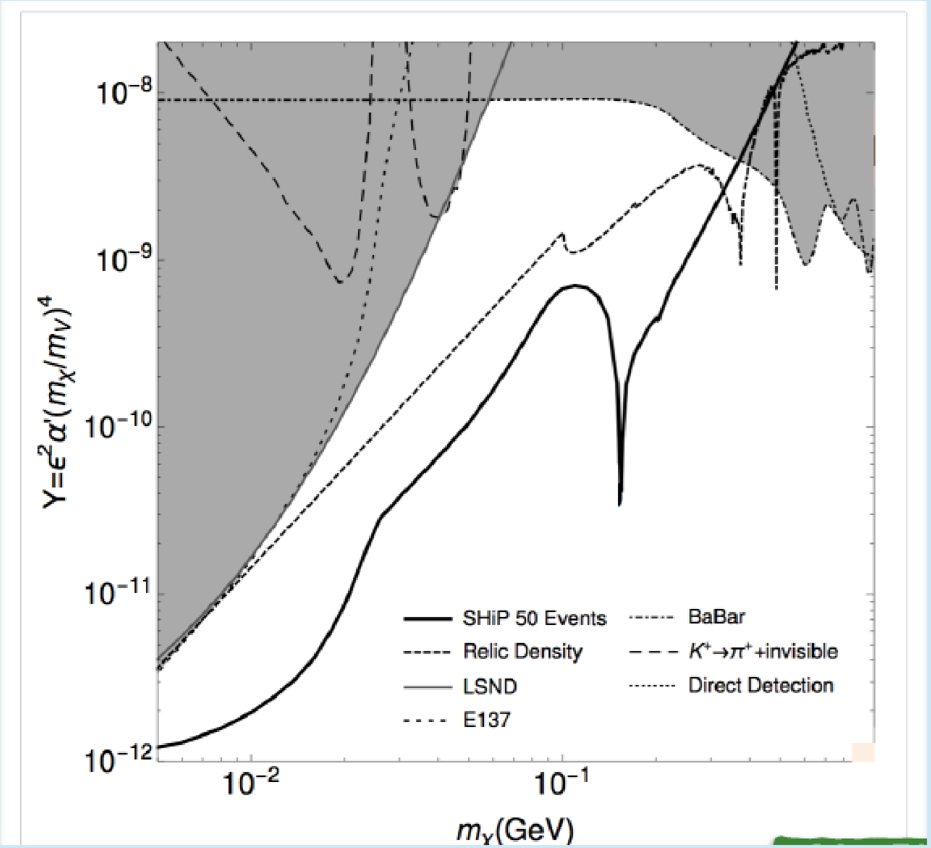
BG rejection:

- Energy-angle correlation and presence of proton rejects QE
- Presence of an hadronic jet rejects DIS

Expected BG for LDM search

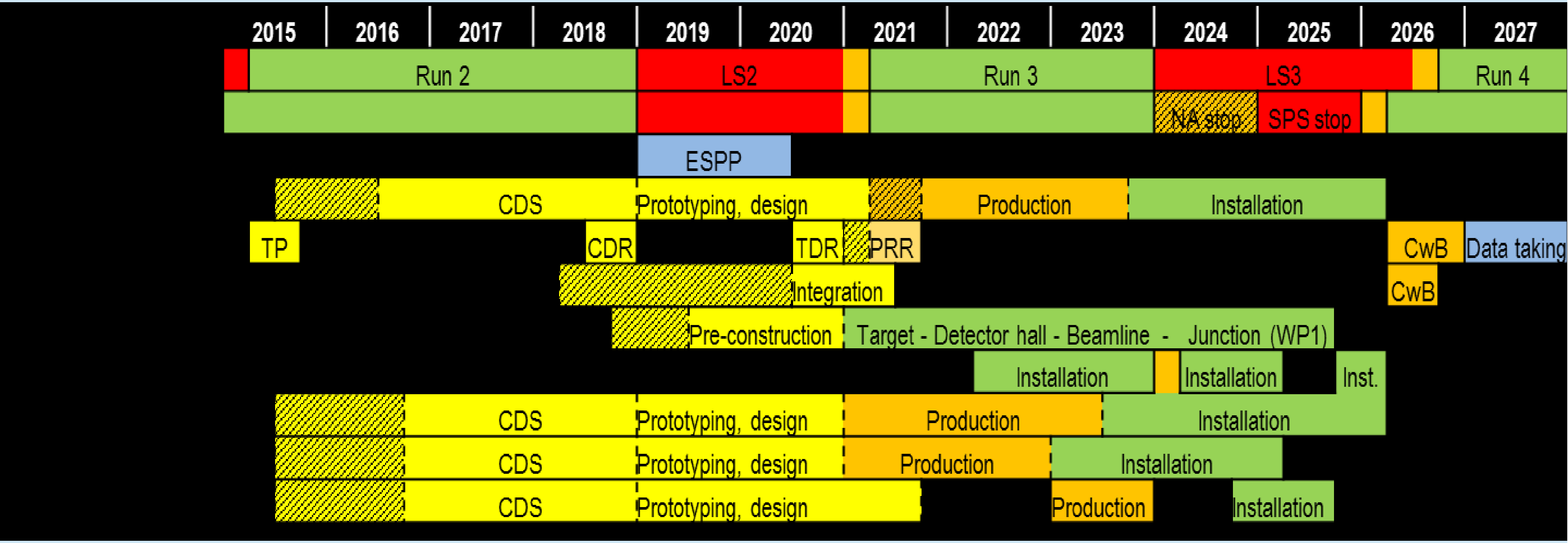
	ν_e	$\bar{\nu}_e$	ν_μ	$\bar{\nu}_\mu$	all
1) Quasi-elastic scattering	105	73			178
2) Elastic scattering on e^-	16	2	20	18	56
3) Resonant scattering	13	27			40
4) Deep inelastic scattering	3	7			10
Total	137	109	20	18	284

- 10 tons of lead
- 2x10^{20} p.o.t.
- Selection cuts applied:
- electron angle in [10,20] mrad
- electron energy < 20 GeV
- selection efficiency 50%



LDM search is not background-free; need ~ 50 events for discovery; however this is possible in a region of phase-space not excluded by previous experiments (also, plot only assumes 2.5 tons of lead)

Global SHiP schedule



- ✓ ***Planning very well aligned with***
  - *CERN scientific strategy*
  - *Update of European strategy 2019/2020*
  - *Accelerator schedule (to be followed closely)*
  - *Production Readiness Reviews (PRR) 2020Q1*
  - *Construction / production 2020*
  - *Data taking (pilot run) 2026 (start of LHC Run 4)*

- ✓ ***Main current priority: Comprehensive Design Study by 2018***
- ✓ ***Validation of MC studies with dedicated test-beams already in 2018!***

Conclusions

- Light hidden-sector particles can solve many problems of the SM, SHiP is the only dedicated detector for this physics
- The emulsion detector can do neutrino structure functions and search for light dark matter
- The SPSC asked the experiment to produce a Comprehensive Design Report, and the Research Board has favourably recommended it
- A test-beam program has been proposed, and received positive comments from the SPSC. Already in 2018 we plan to test prototypes of the muon shield and measure measure the muon flux from the SHiP target and a proof of principle of the charm cross section including cascades.