ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

The SHiP experiments, LLPs and the intensity frontier

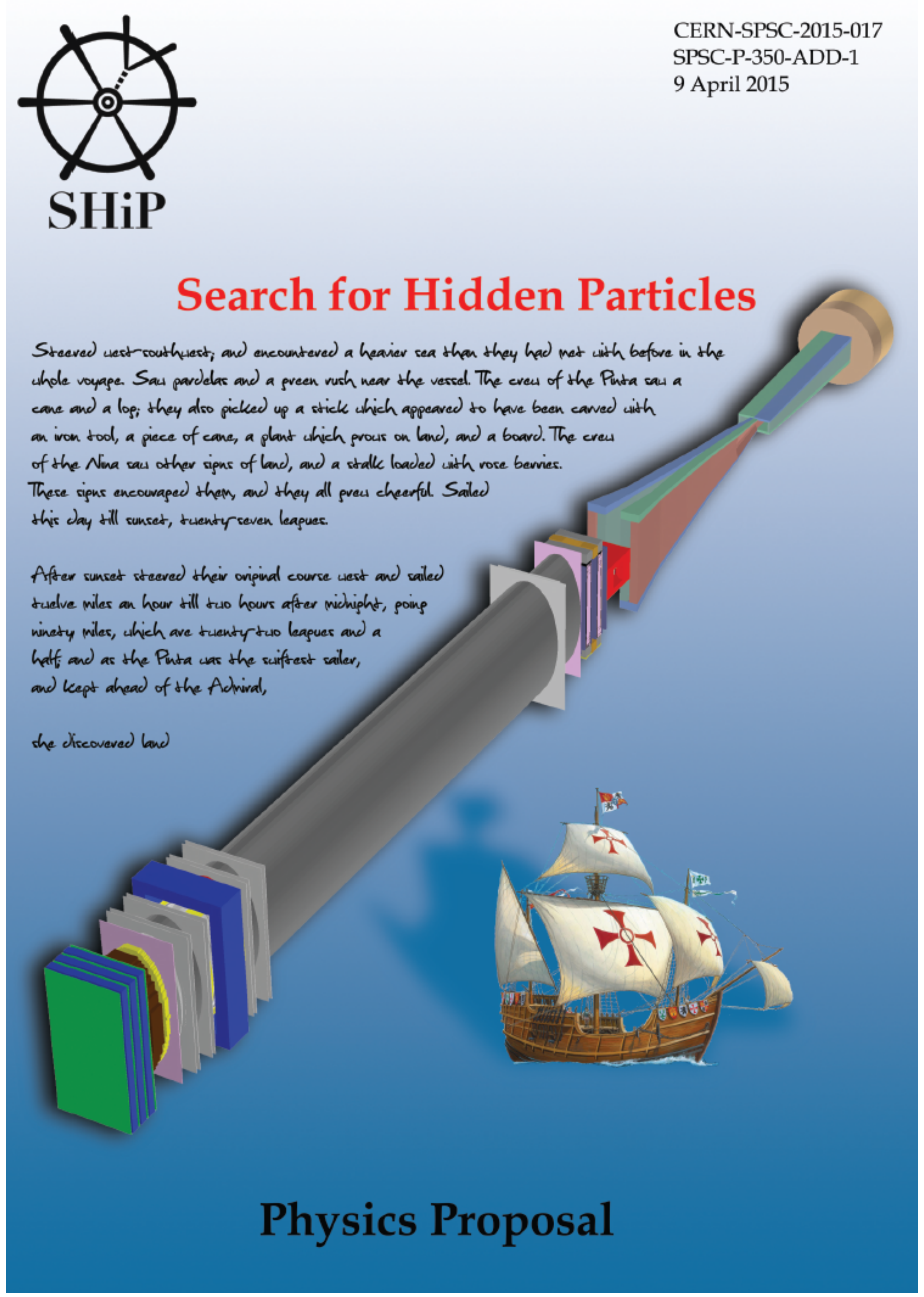
Federico Leo Redi (EPFL) - on behalf of the SHiP Collaboration

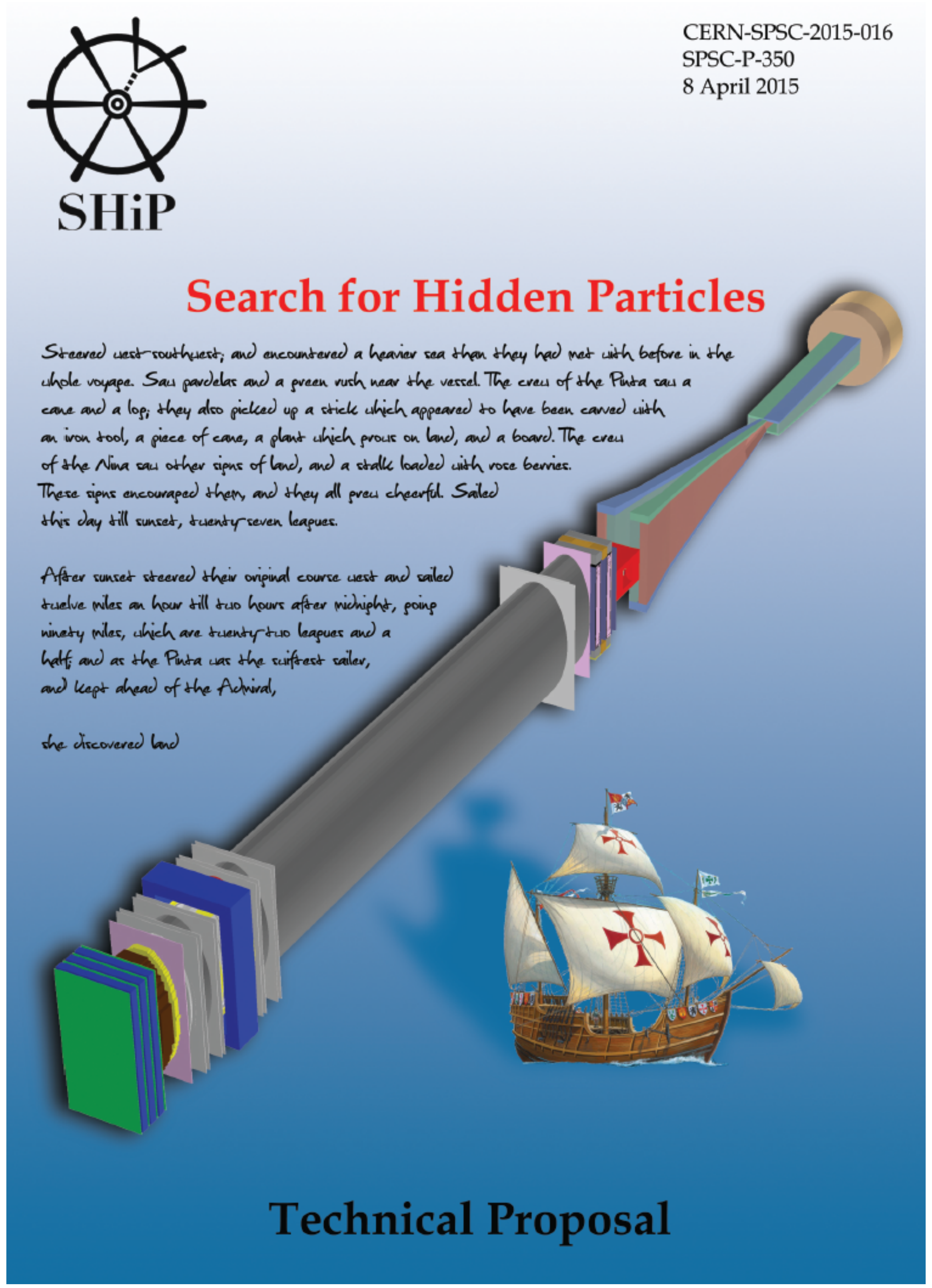
SHiP
Search for Hidden Particles

SHiP / Public documents

- The technical proposal (250 physicists, 46 institutes, 16 countries) submitted to CERN in Apr 2015 (arXiv:1504.04956)

- Physics Paper (85 physicists, 65 institutes) Accepted for publication in Review on Progress in Physics (arXiv:1504.04855)

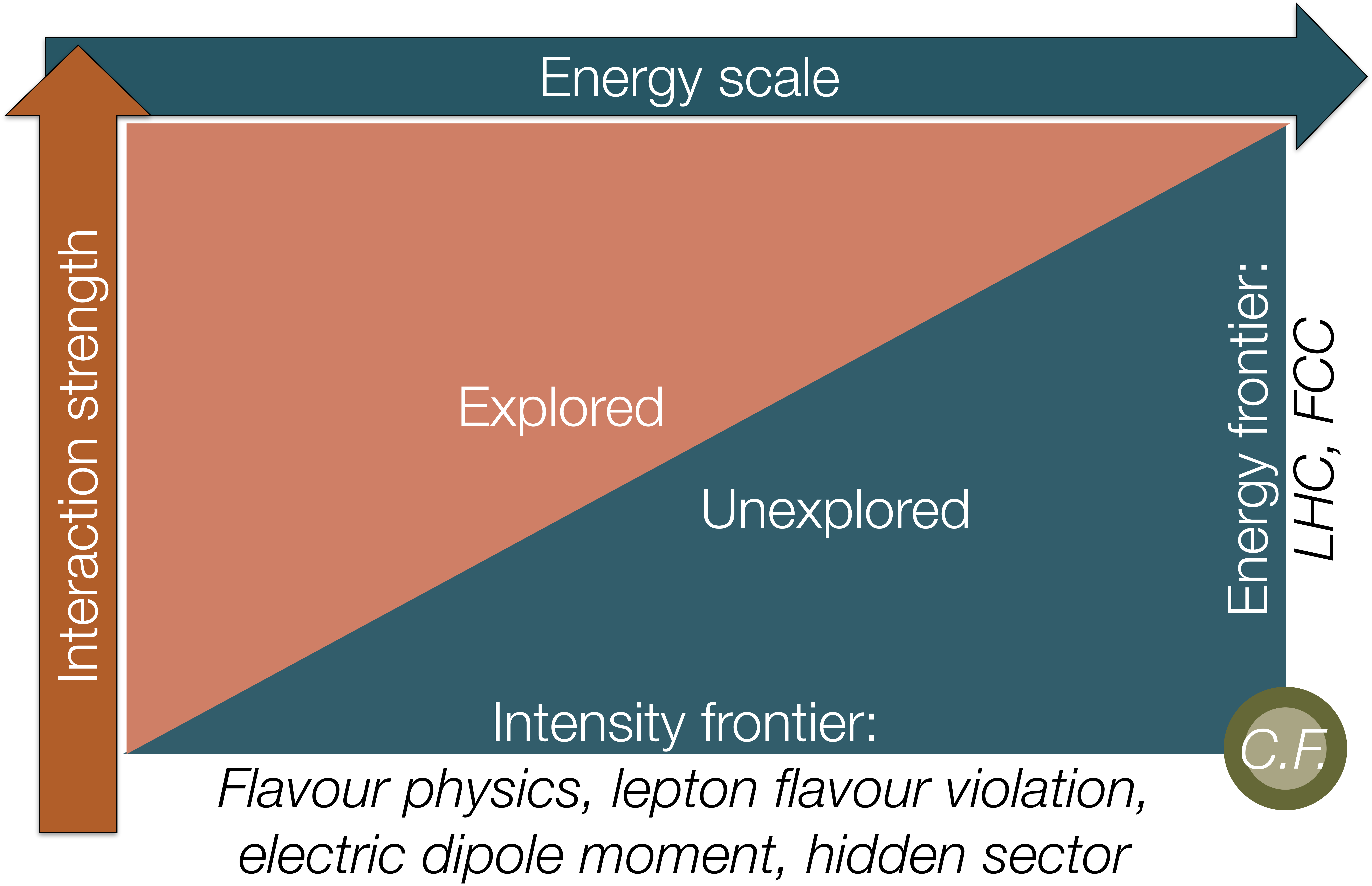




SHiP / Collaboration

Introduction / 1

- Naturalness does not seem to be a guiding principle of Nature
- There are some anomalies in flavour physics which (if true) seem again to point out that our theory prejudice was wrong
- We should therefore not forget that we have a 2D problem (Mass VS Coupling)
- Low coupling → Long Lived

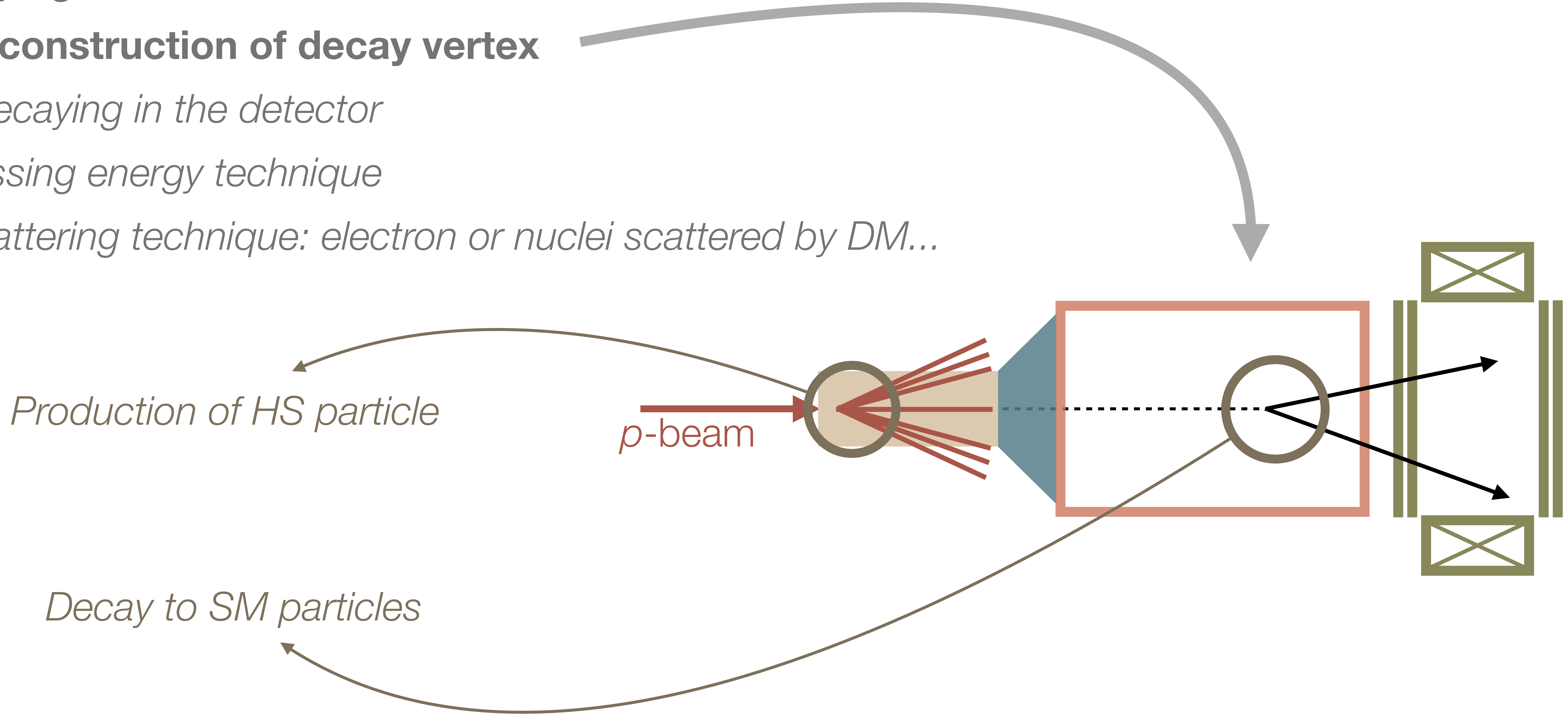


Exploring the dark sector / 1

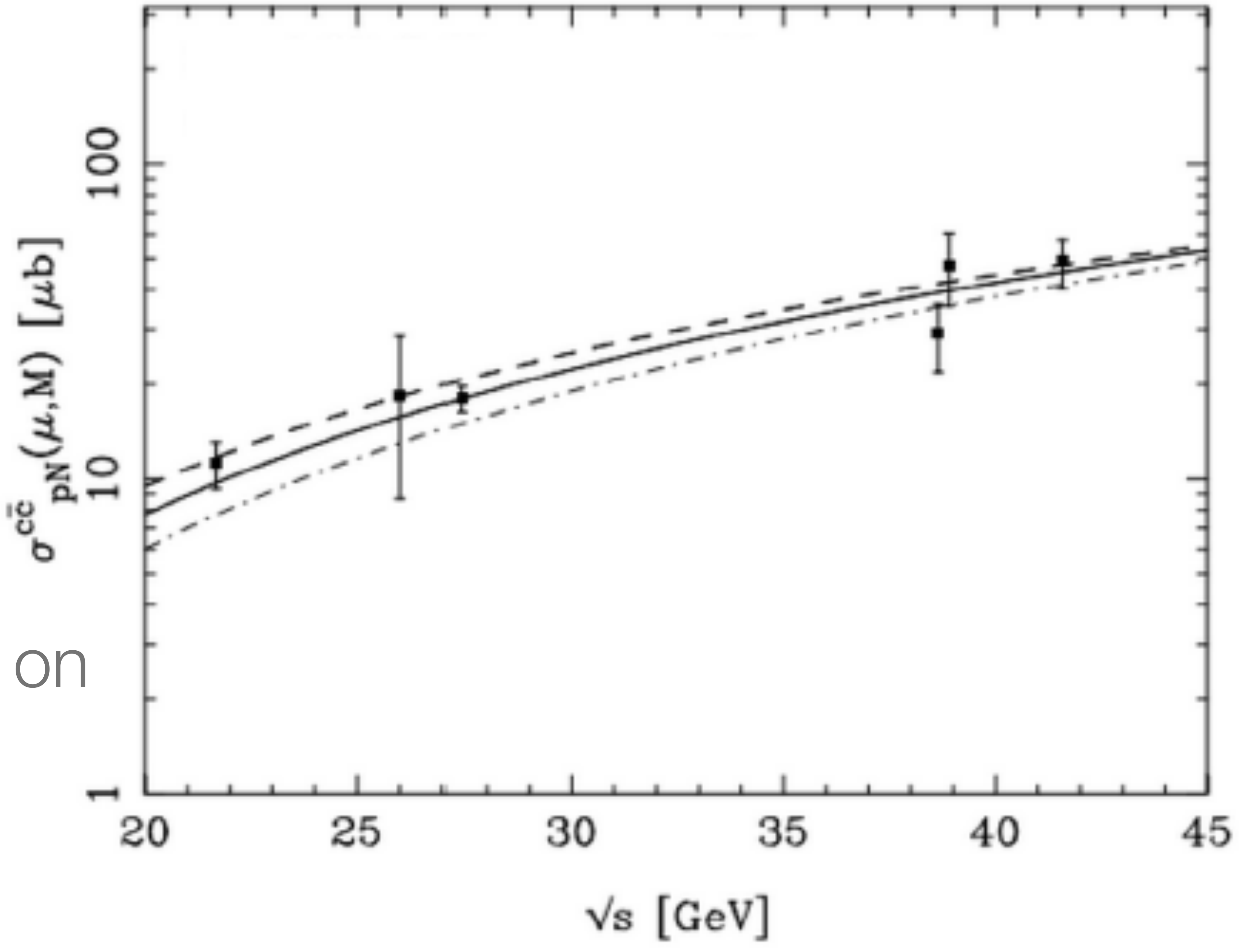
- In the dark sector: $\boldsymbol{L = L_{SM} + L_{mediator} + L_{HS}}$
  - **HS** production and decay rates are strongly suppressed relative to SM
    Production branching ratios $O(10^{-10})$
    Long-lived objects
    Interact very weakly with matter
- Experimental challenge is **background suppression**
- **Full reconstruction and PID are essential to minimise model dependence**
- **Two** strategies of searching for mediators at accelerators:
- *Decaying in the detector*
  - *Reconstruction of decay vertex*
- *Not decaying in the detector*
  - *Missing energy technique*
  - *Scattering technique: electron or nuclei scattered by DM...*

Exploring the dark sector / 2

- **Decaying in the detector**
  - **Reconstruction of decay vertex**
- *Not decaying in the detector*
  - *Missing energy technique*
  - *Scattering technique: electron or nuclei scattered by DM...*



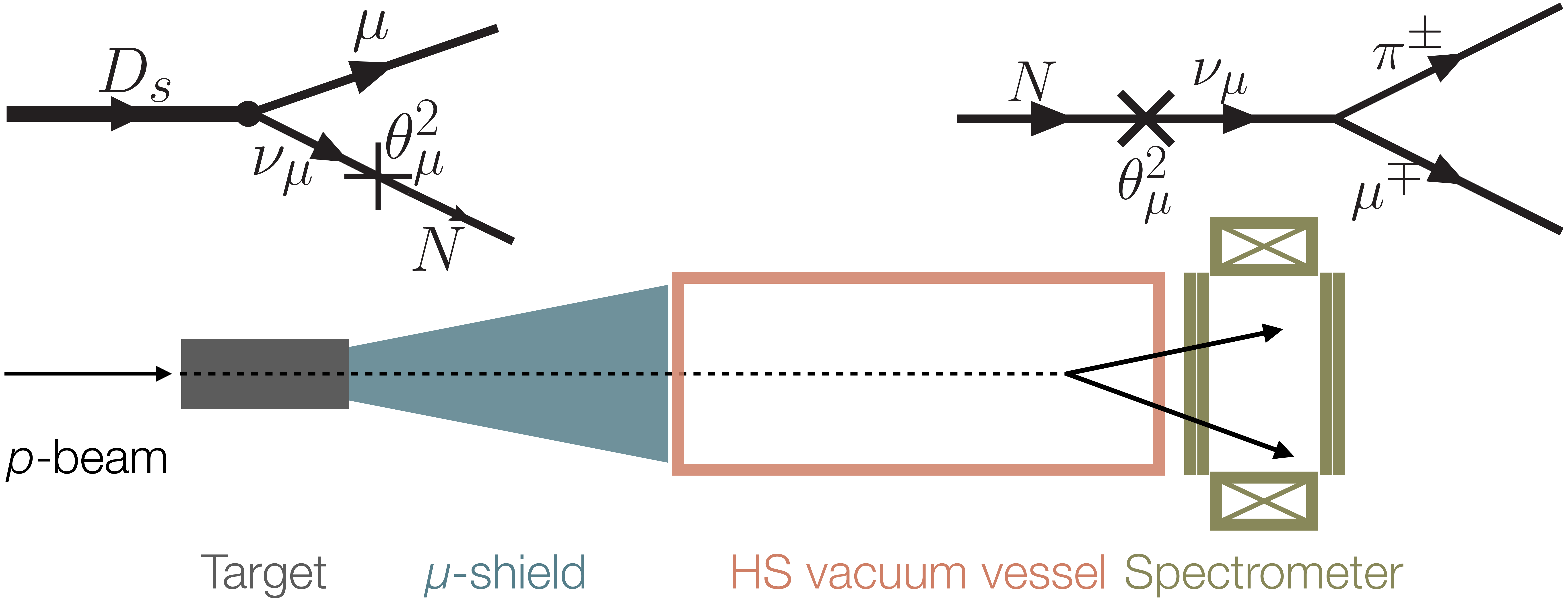
Decaying dark sector candidates / 1



- **Experimental requirements**:
  - Particle beam with maximal intensity
  - Search for HS particles in Heavy Flavour decays
    - Charm (and beauty) cross-sections strongly dependent on the beam energy.
    - At CERN SPS:
      σ(pp→ssbar X)/σ(pp→X) ~ 0.15
      σ(pp→ccbar X)/σ(pp→X) ~ 2.0 x 10^{-3}
      σ(pp→bbbar X)/σ(pp→X) ~ 1.6 x 10^{-7}
- HS produced in charm and beauty decays have **significant p_T**
- *Detector must be placed close to the target to maximise geometrical acceptance.*
  Effective (and "short") muon shield is the key element to reduce muon-induced backgrounds
- *Long decay volume and large geometrical acceptance of the spectrometer are essential to maximise detection efficiency...*

Decaying dark sector candidates / 2

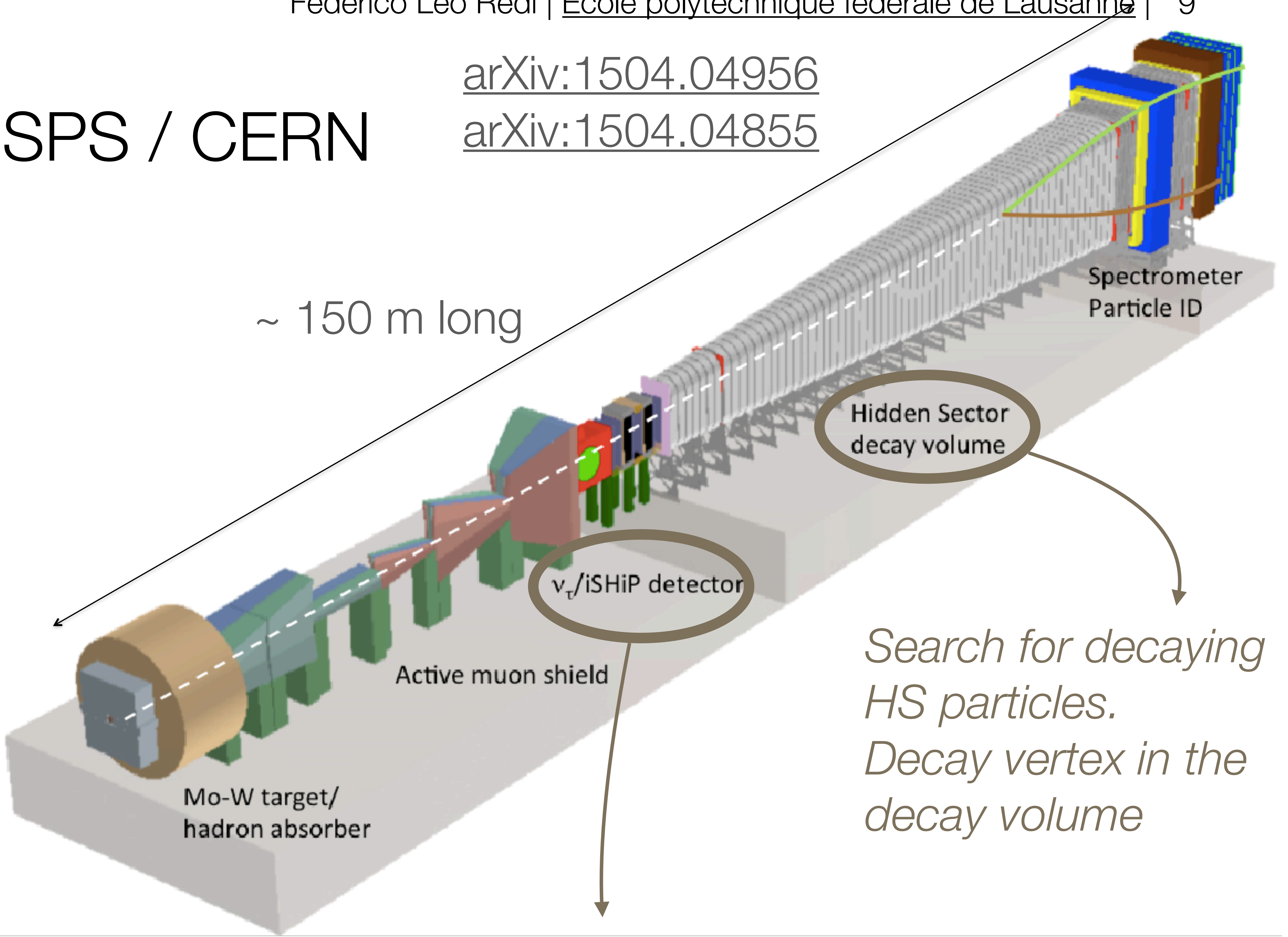
- Detector must be placed **close to the target** to maximise geometrical acceptance. Effective (and "short") **muon shield** is the **key element** to reduce muon-induced backgrounds
- **Long decay volume** and **large geometrical acceptance** of the spectrometer are essential to maximise detection efficiency



arXiv:1504.04956
arXiv:1504.04855

SHiP Beam Dump Facility at SPS / CERN

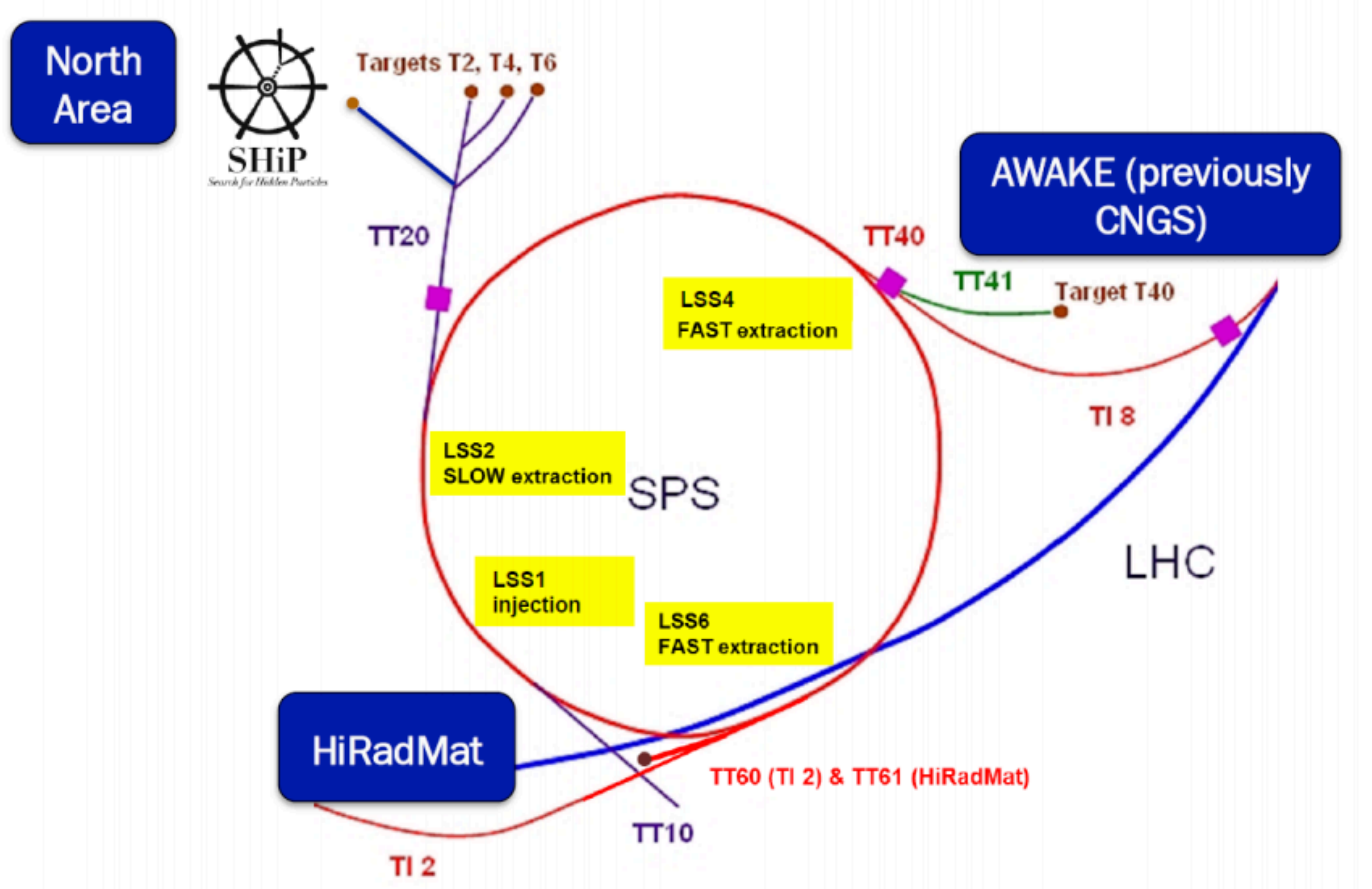
- Numbers:
  $>10^{18}$ D,
  $>10^{16}$ τ,
  $>10^{20}$ γ
  for **2×10^{20} pot (in 5 years)**
- ***Zero background*** experiment
  Heavy target
  Muon shield
  Surrounding Veto detectors
  Timing and PID detectors, etc.
- Multipurpose layout: near and far detector (**new**)

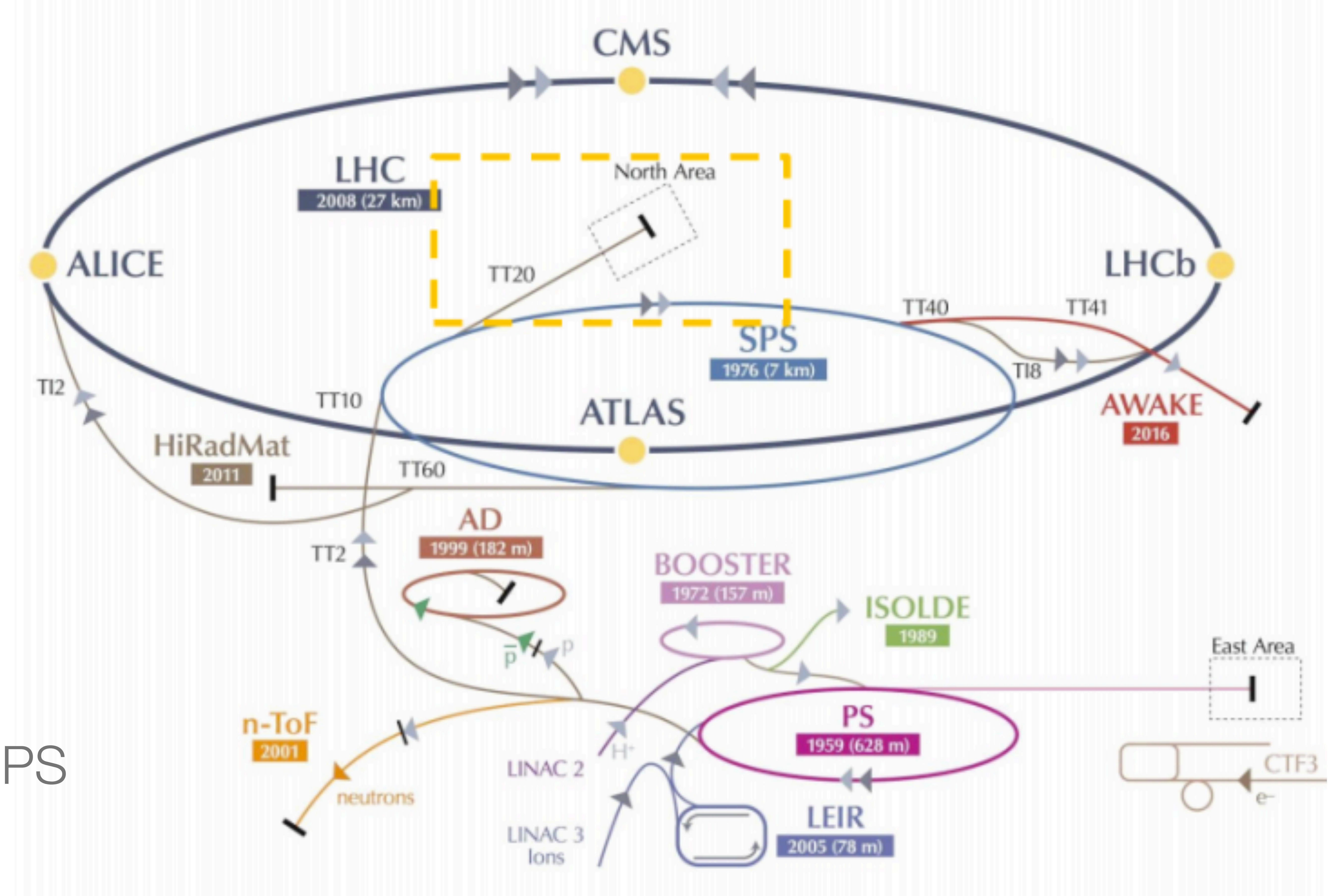


Search for decaying HS particles. Decay vertex in the decay volume

Search for HS (scattering on atoms) and ν physics. Specific event topology in emulsion. Background reducible to a manageable level

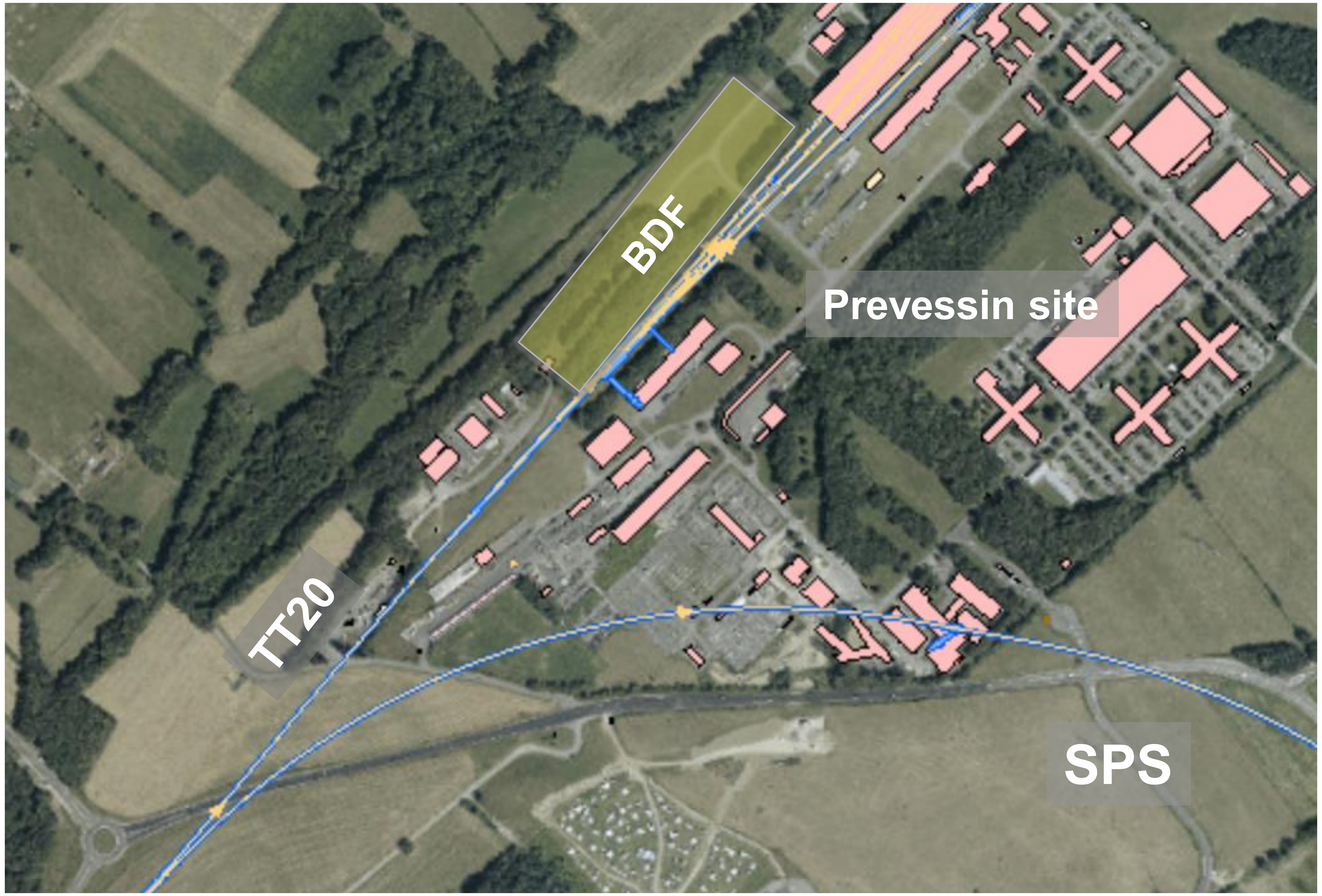
SHiP / Beam line





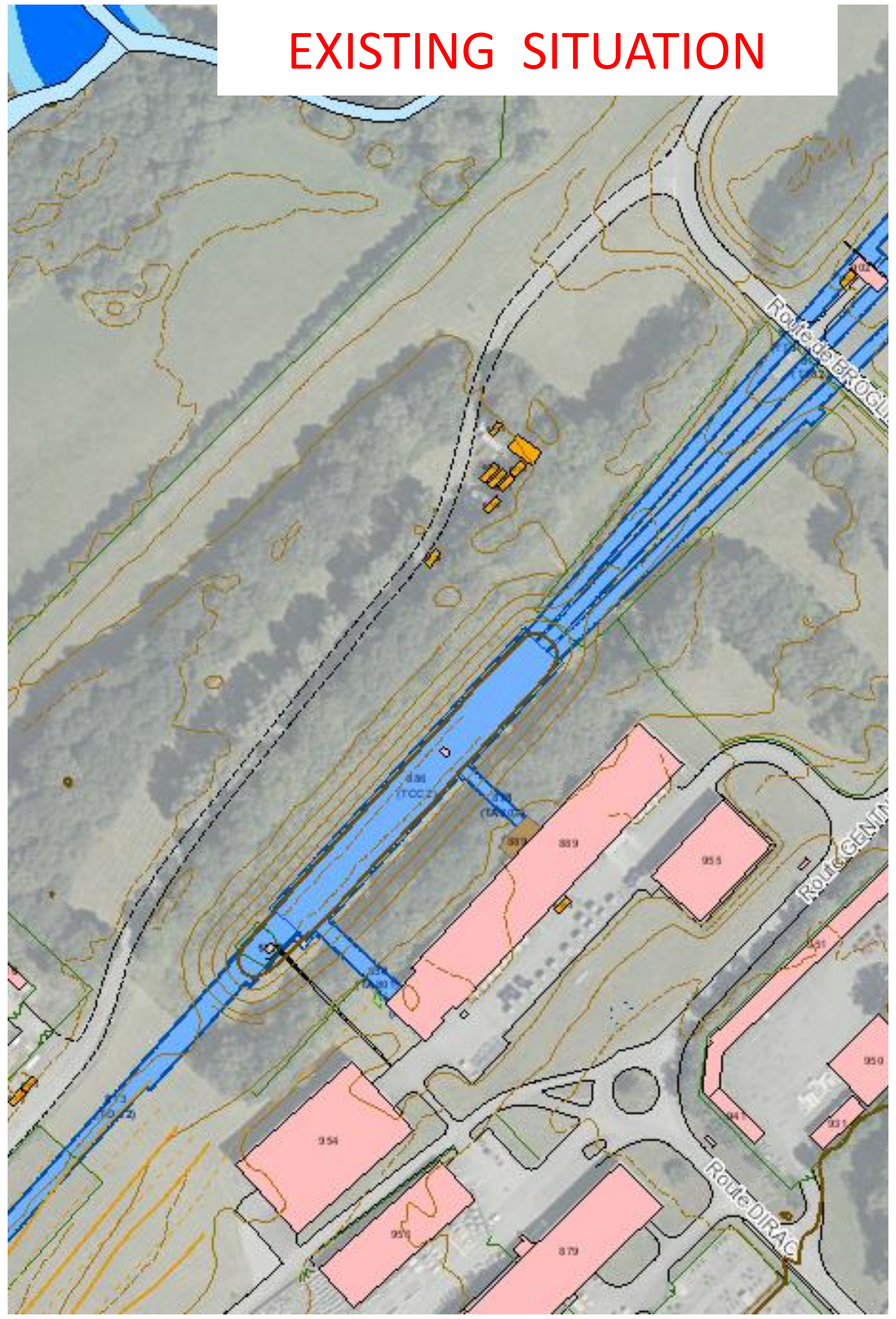
- New beam line in the north area at SPS
- Proton beam SPS@400GeV
- Possible to deliver 5x1020 PoT in ~5 years
- Operation in parallel with LHC and other beam lines at SPS
- LHC tunnel near interaction points, or on the surface, was considered BUT SPS beam is best for low mass HNL production, plus need zero background, need a magnet!

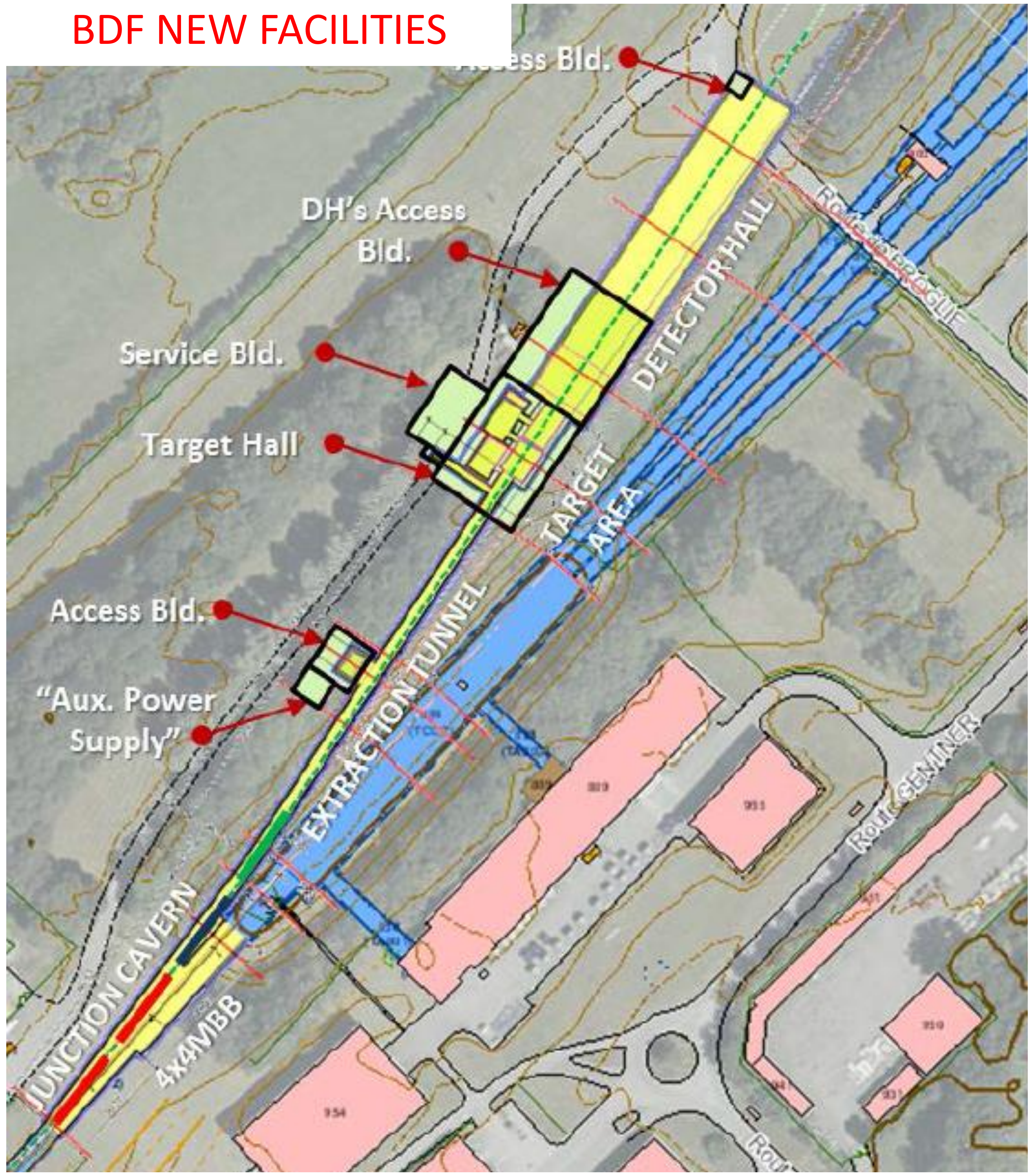
SHiP / Beam dump facility

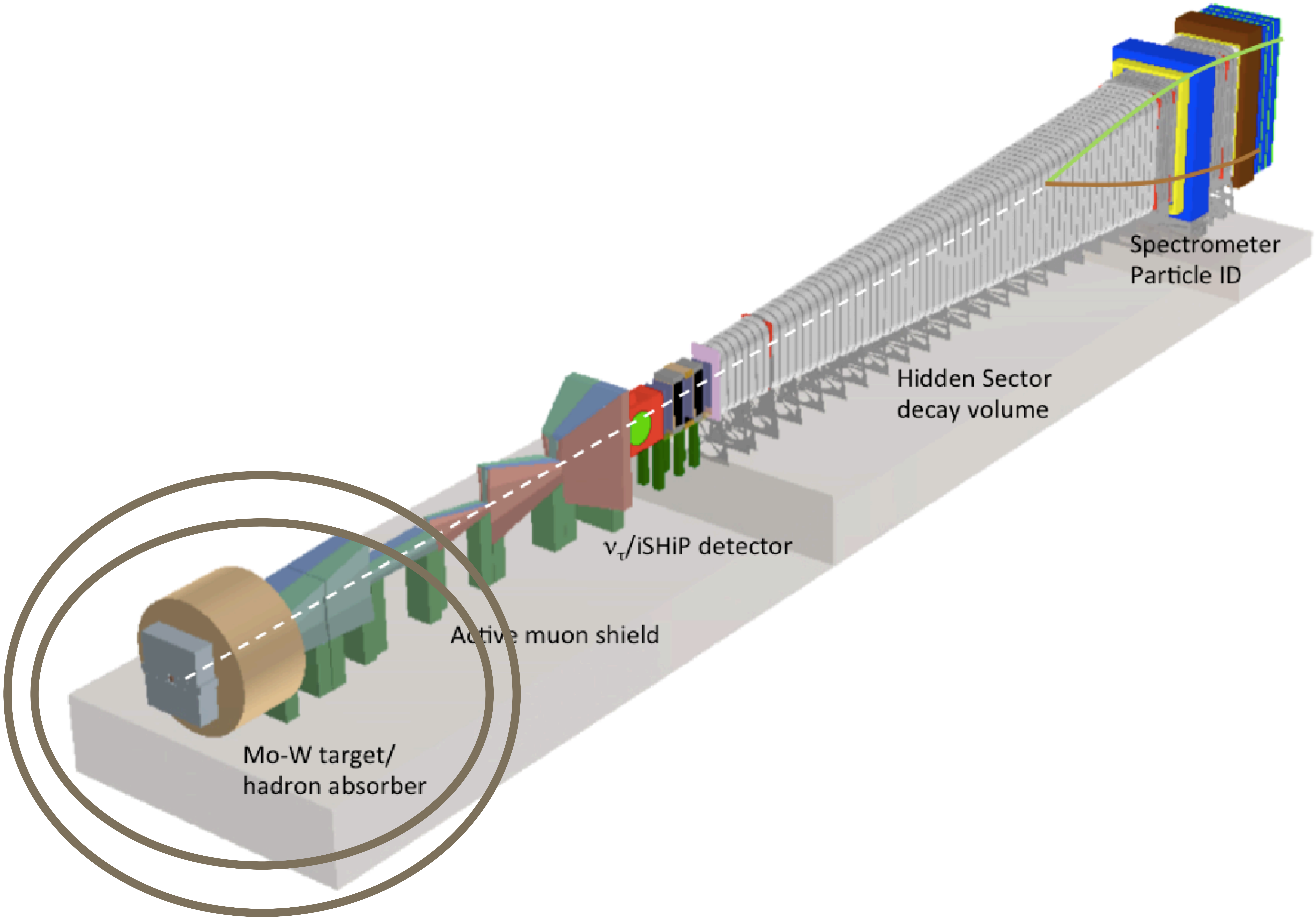


SHiP / Beam dump facility

- Extraction line on target
- Beam dilution on target
- Target/Dump at facility
- Target design
- Target complex
  (Radiation Protection challenges)
- R&D approved for 2017 to 2019

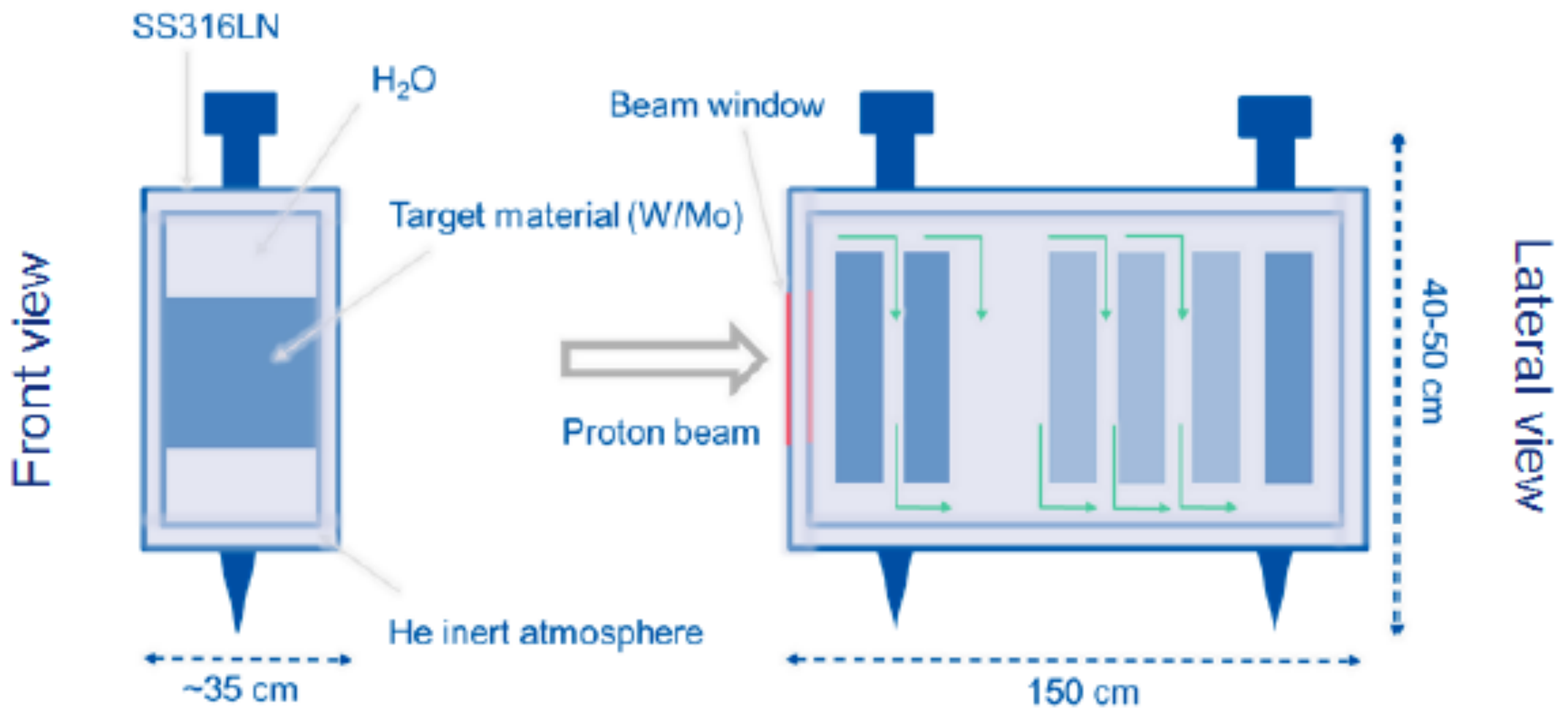


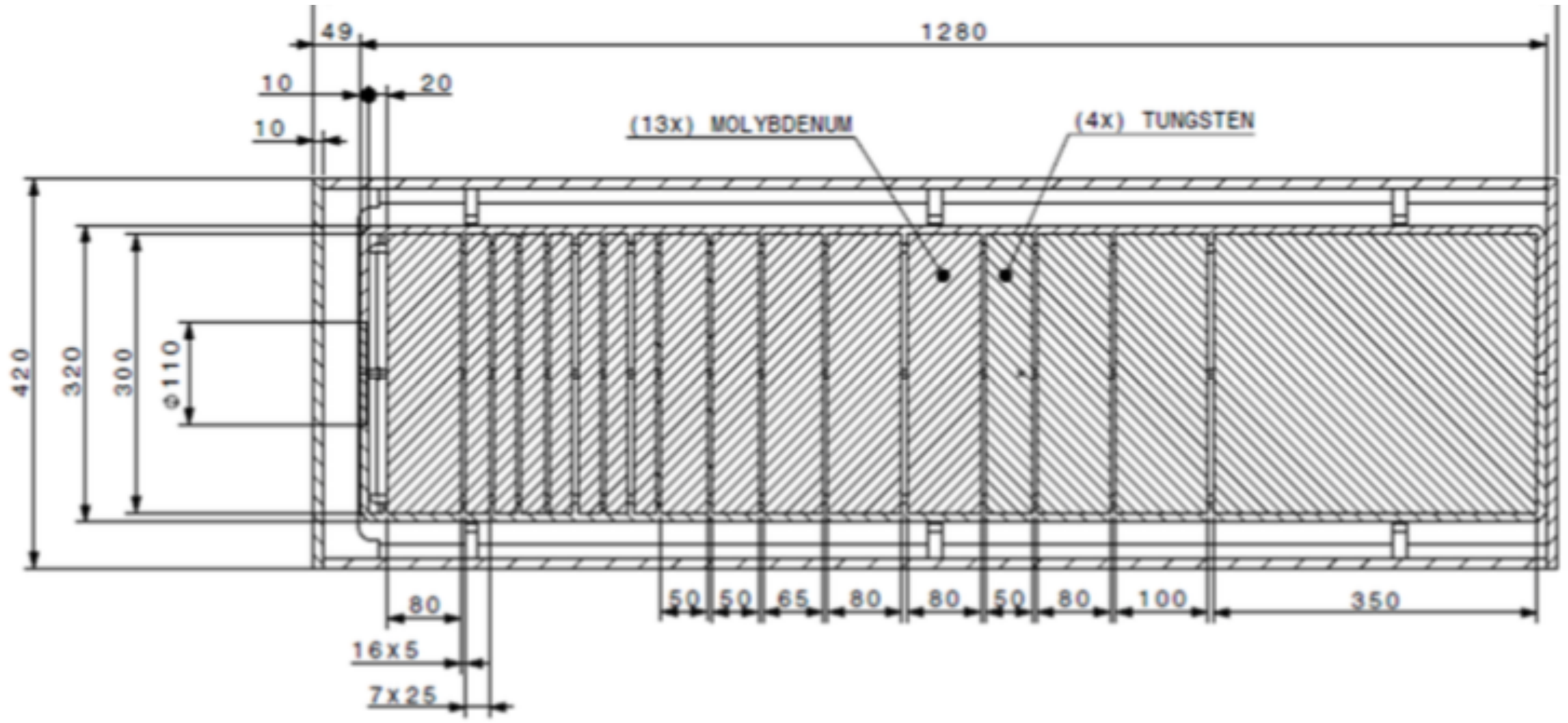


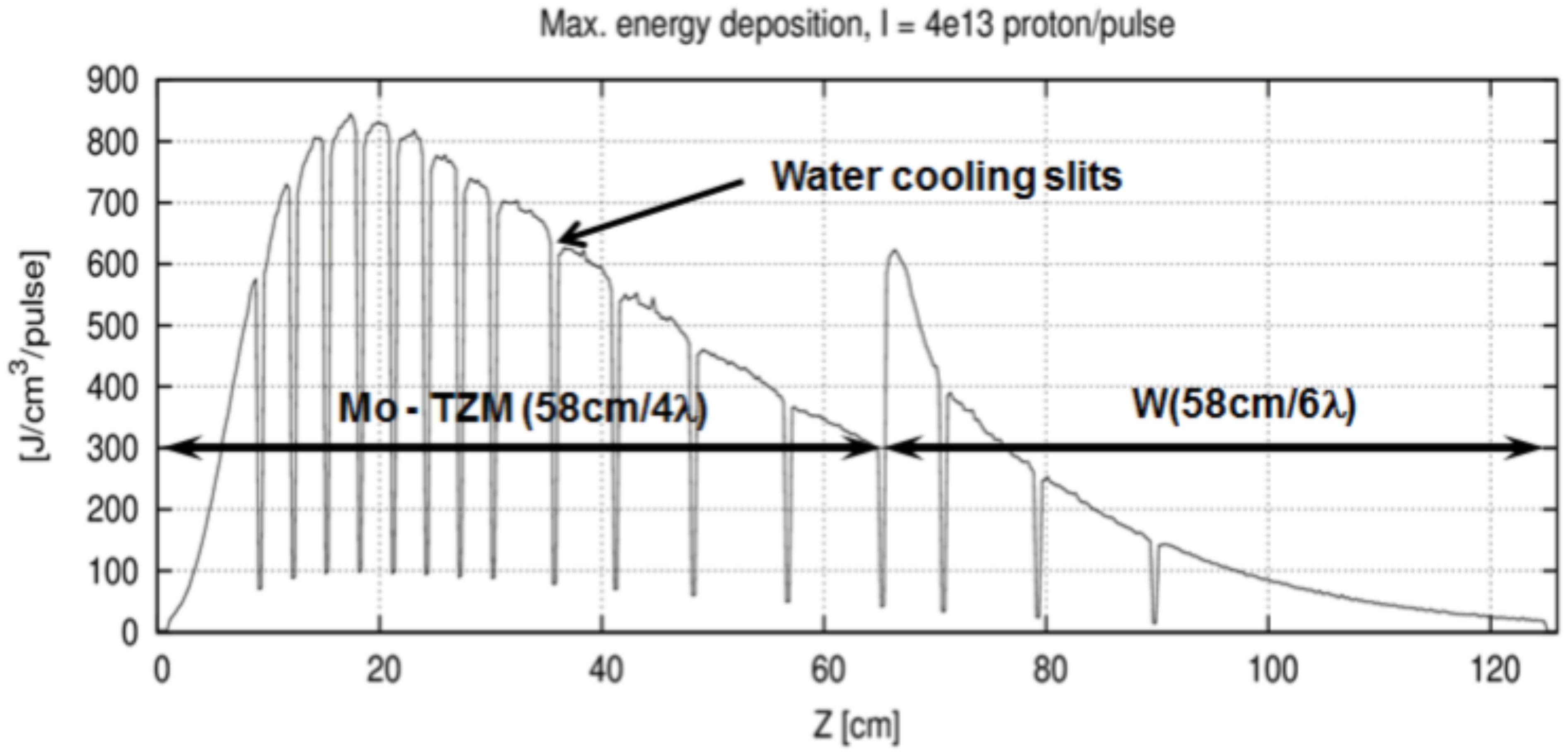

Spectrometer
Particle ID
Hidden Sector
decay volume
ν_τ/iSHiP detector
Active muon shield
Mo-W target/
hadron absorber

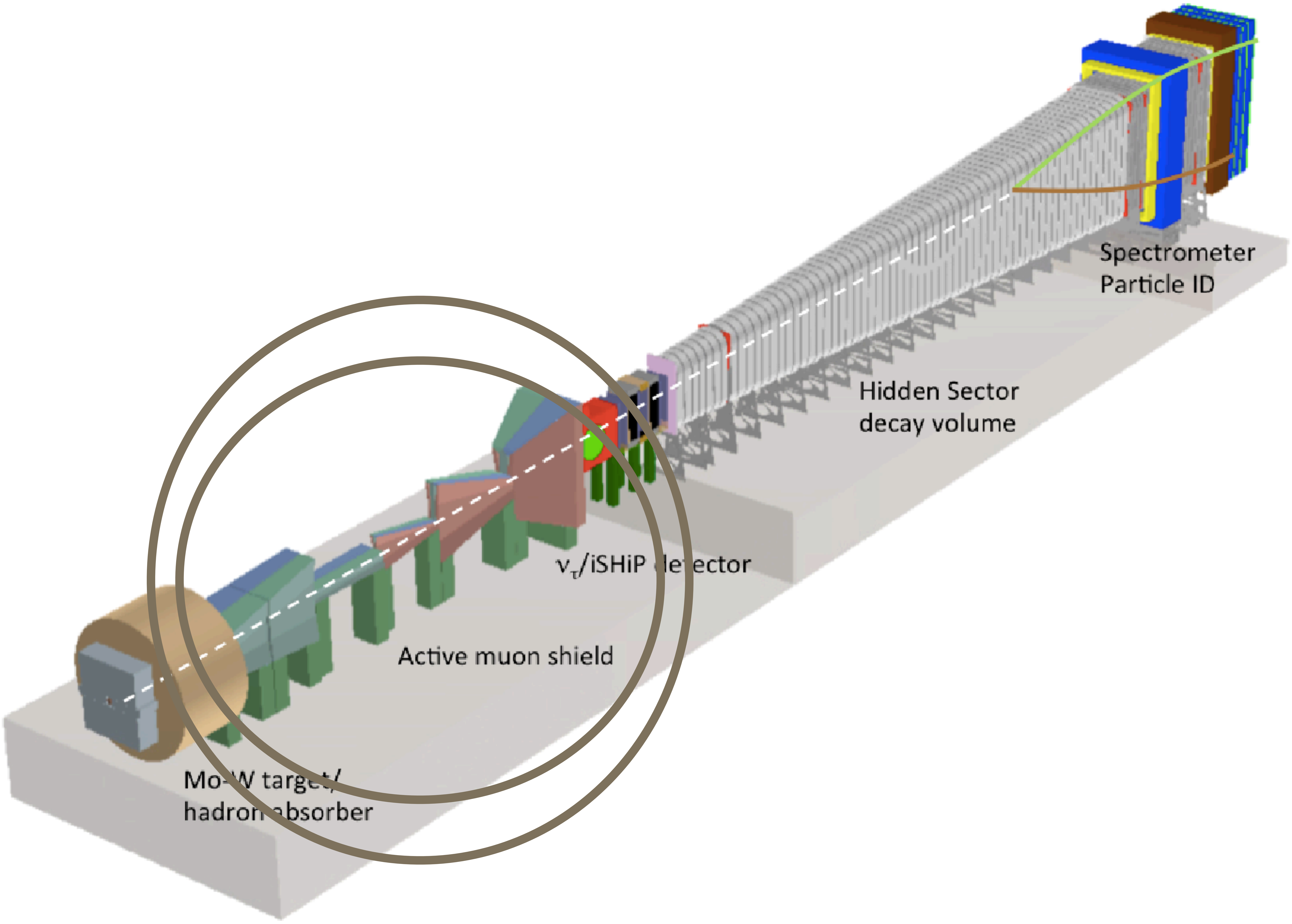
SHiP / Target

- High intensity proton beam: 4*1013 p+/pulse, 4*1019 POT/year, 355 kW average beam power (CNGS ~500 kW)
- Slow extraction (~1 sec. flat top)
- O(400 GeV) optimal beam momentum
- Minimal impact on running the North Area program
- Dense target/dump to maximise production & stop π and K before decay into μν
- Layers of Titanium/Zirconium/Molibdenum for 4λint in the core of the beam followed by Layers of pure W





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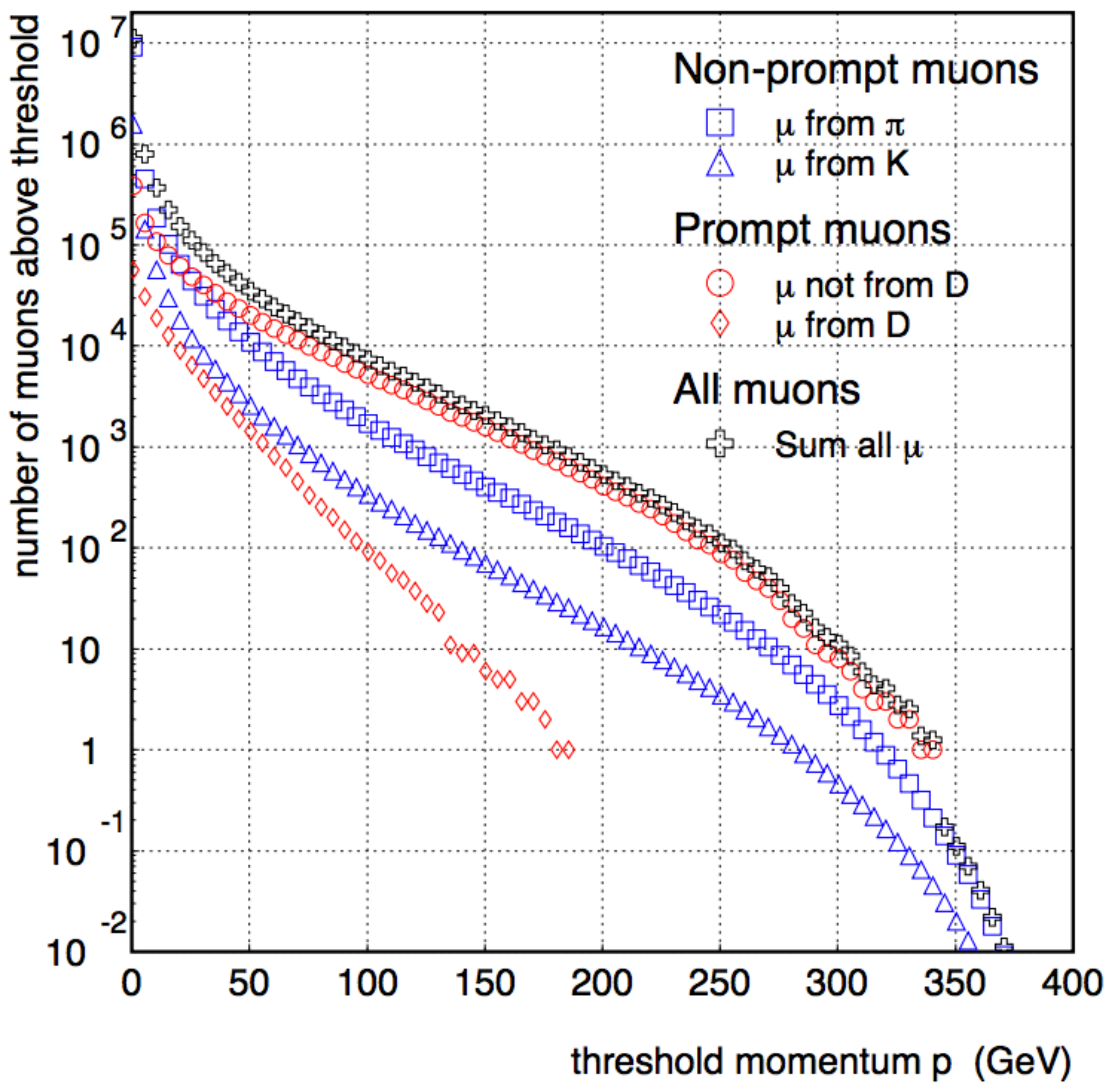
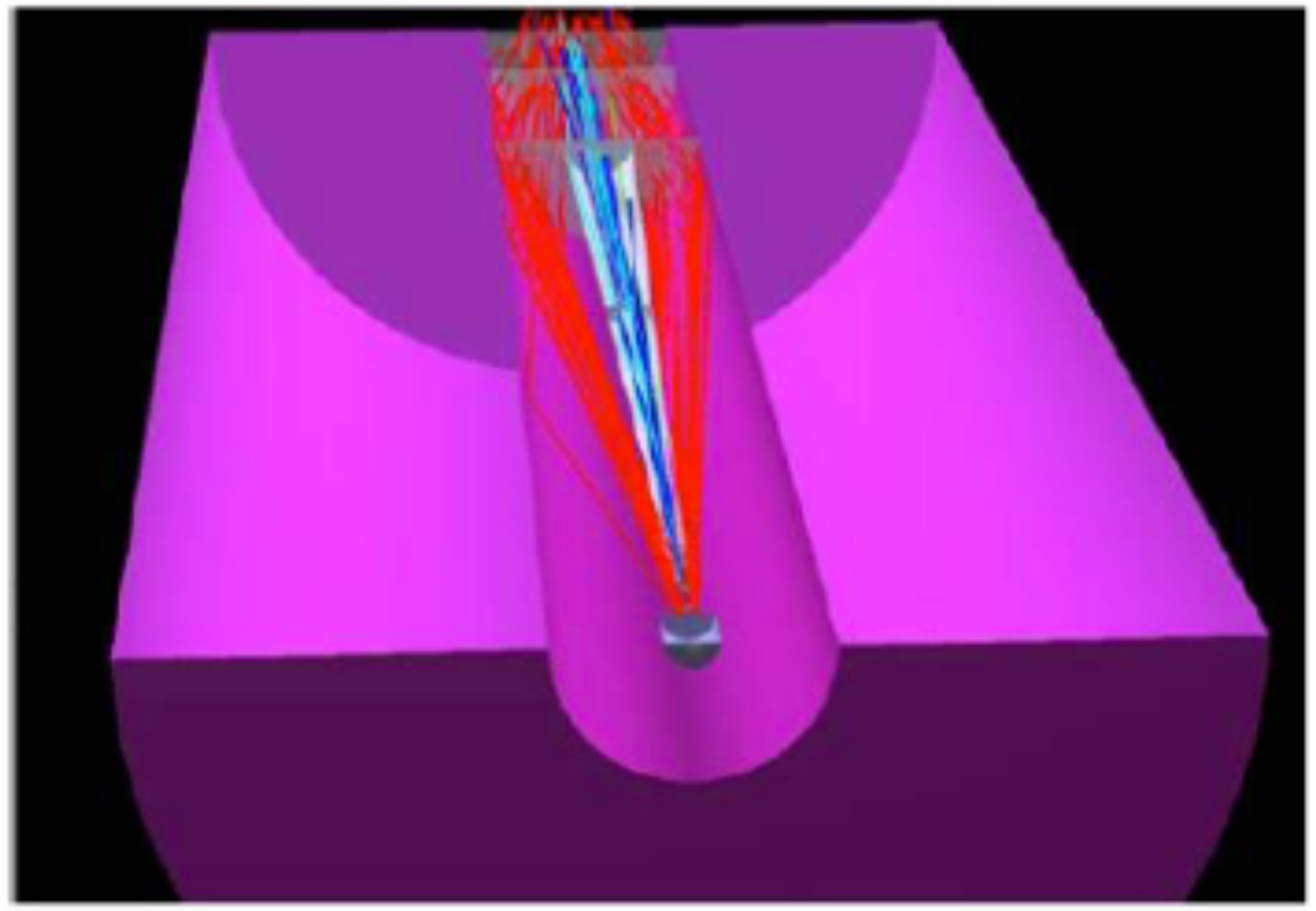
SHiP / Muon target / 1



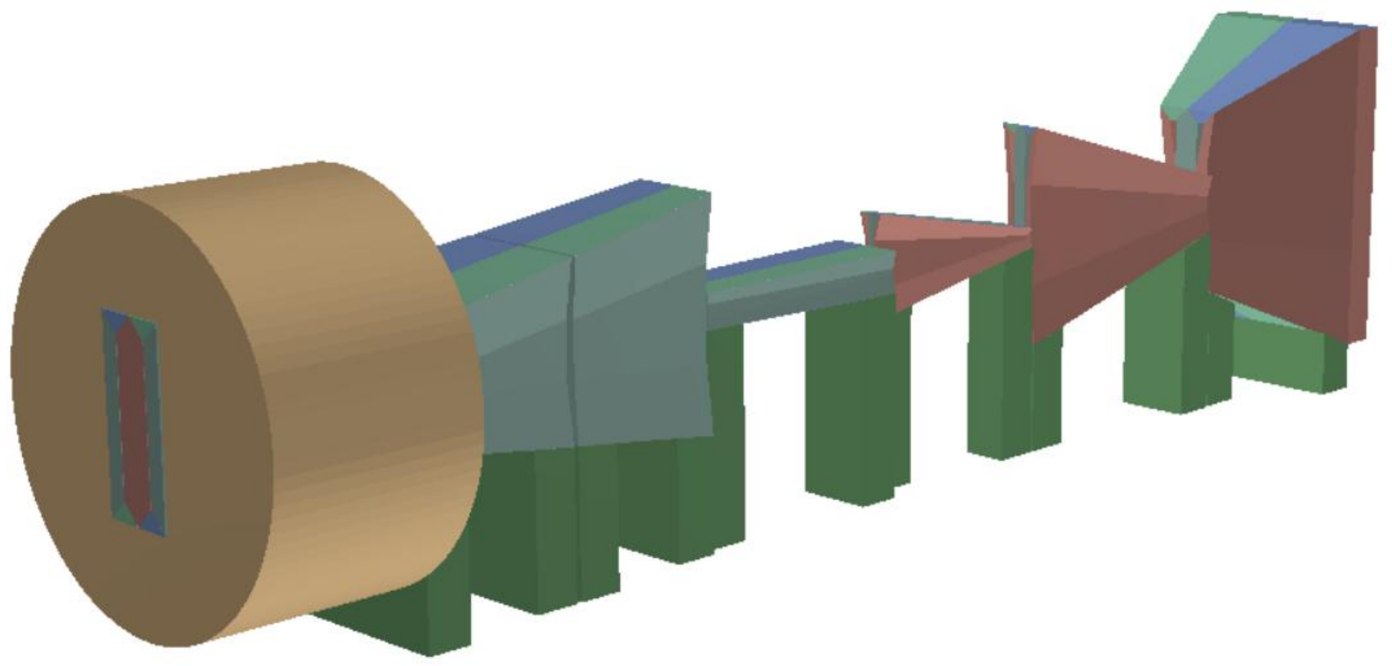


- Distribute the bkg over a long spill: $4\text{x}10^{13}$ PoT/1.3 seconds
- Sweeping magnet
- Decay volume to be far away from the walls

- Heavy target stops hadrons before they decay. After the target and the hadron absorber only muons survive
- Muons come mainly from η, η' and ω (High energy muons)

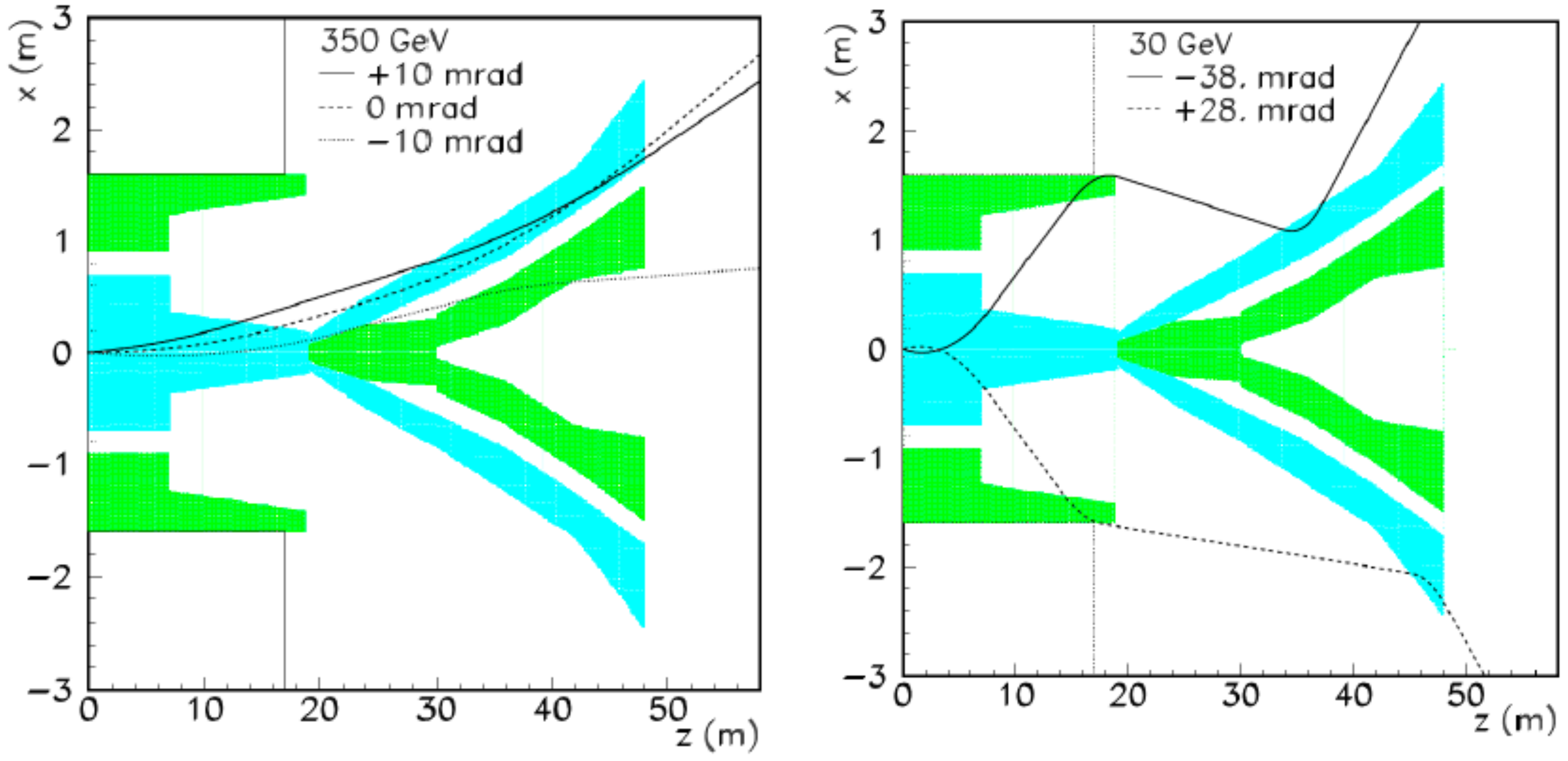
SHiP / Muon target / 2

- ✓ *Muon flux limit driven by emulsion based neutrino detector and HS background*
- ✓ *Active muon shield based entirely on magnet sweeper with a total field integral B_y = 86.4 Tm*
  Realistic design of sweeper magnets in progress
  Challenges: flux leakage, constant field profile, modeling magnet shape

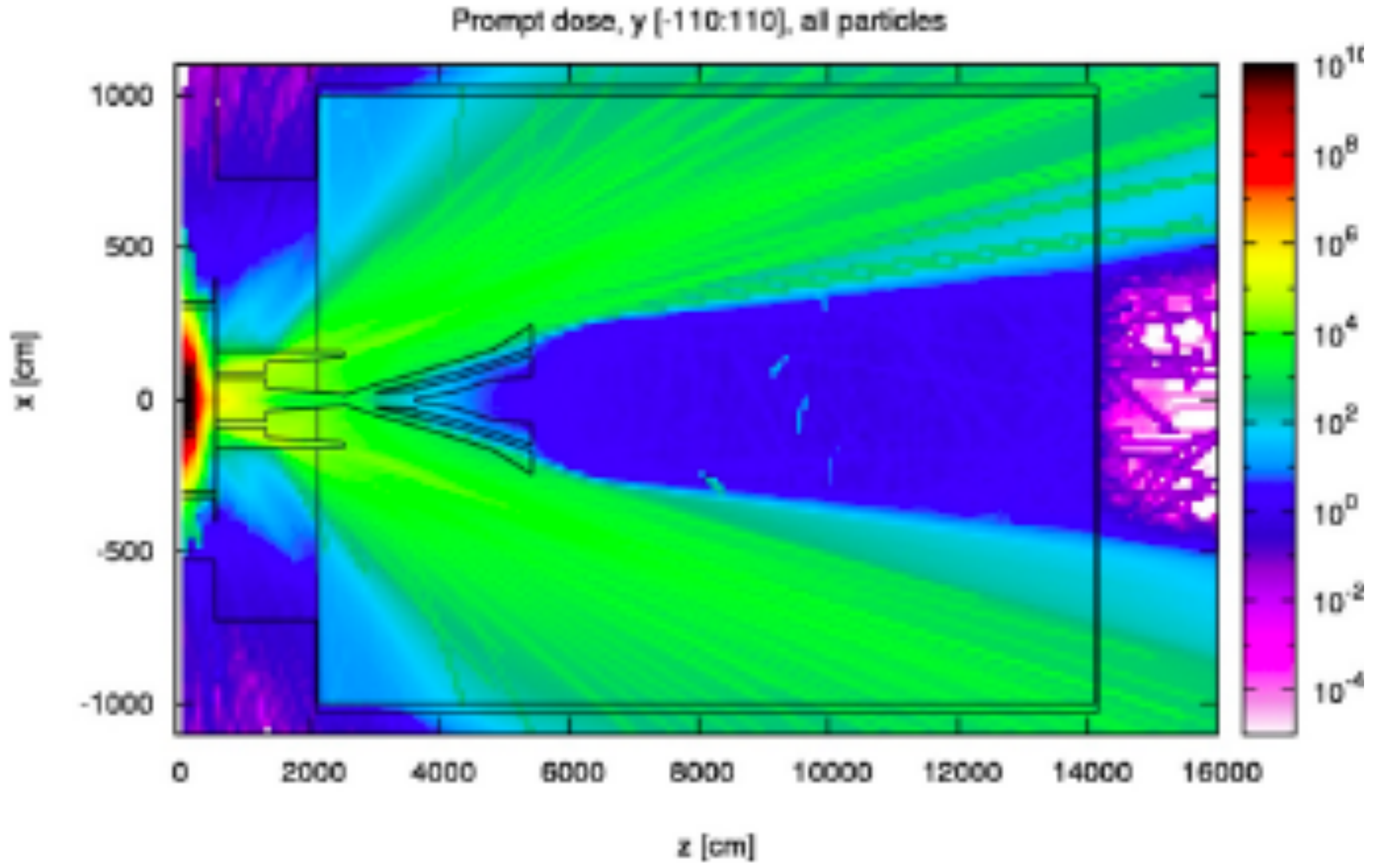


- Flux below emulsion saturation limit
- Small induced bkg in the HS spectrometer

Magnetic sweeper field



Dose rate in the SHiP hall



SHiP / Muon target / 3

The active muon shield in the SHiP experiment
JINST 12 P05011 2017

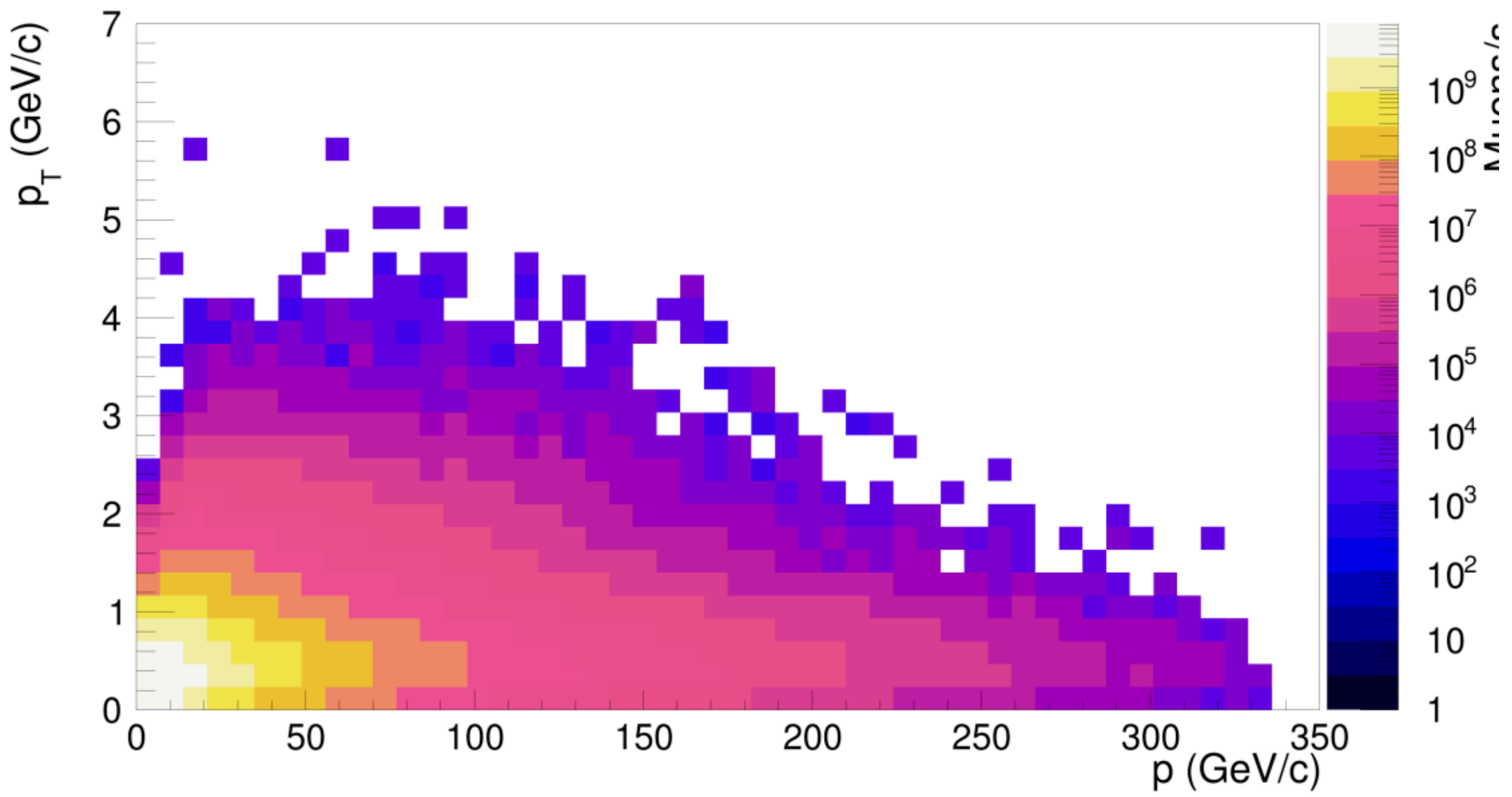


Figure 1. Transverse momentum versus momentum distribution of muons, as generated by Pythia [5, 7].

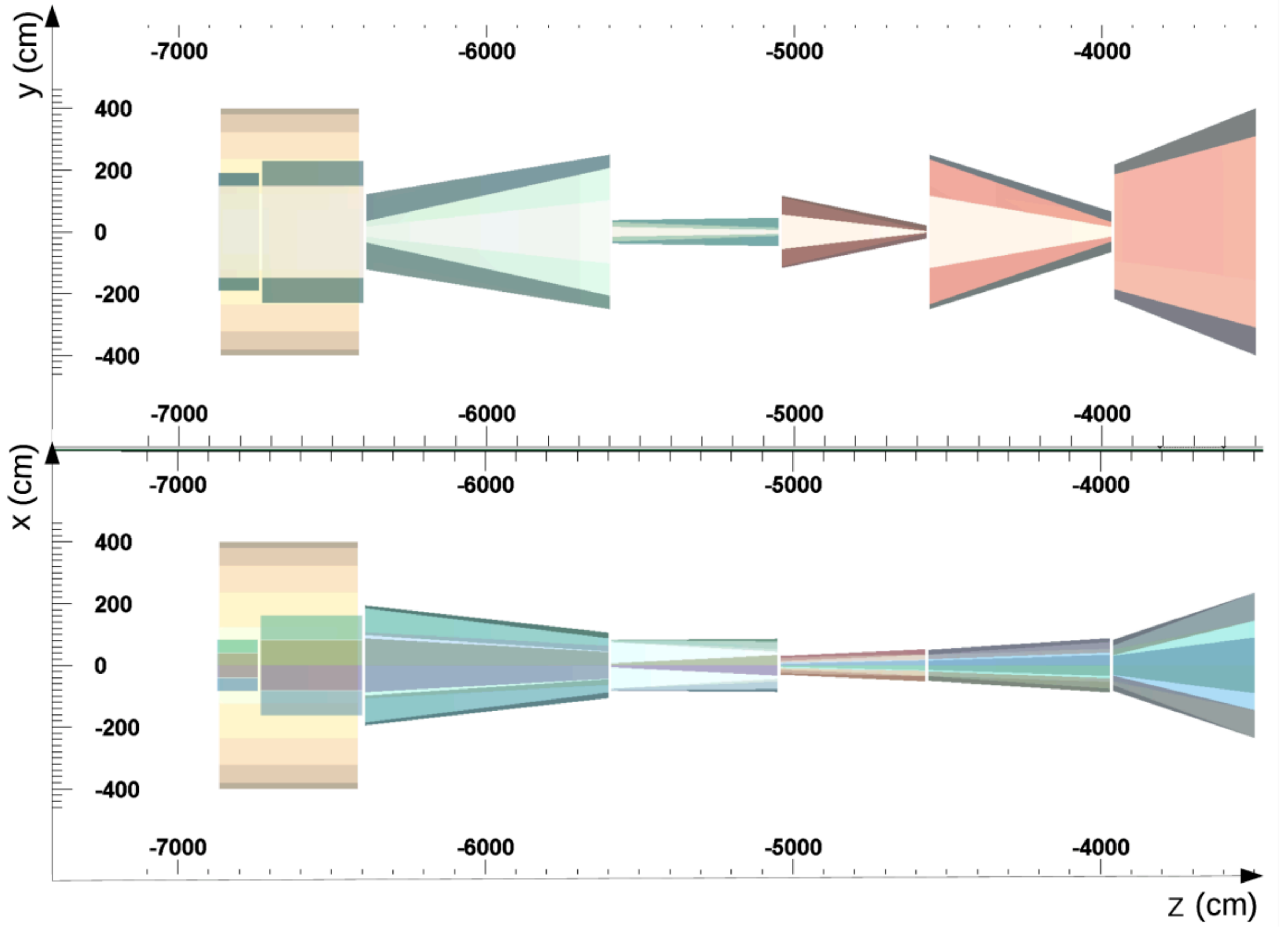


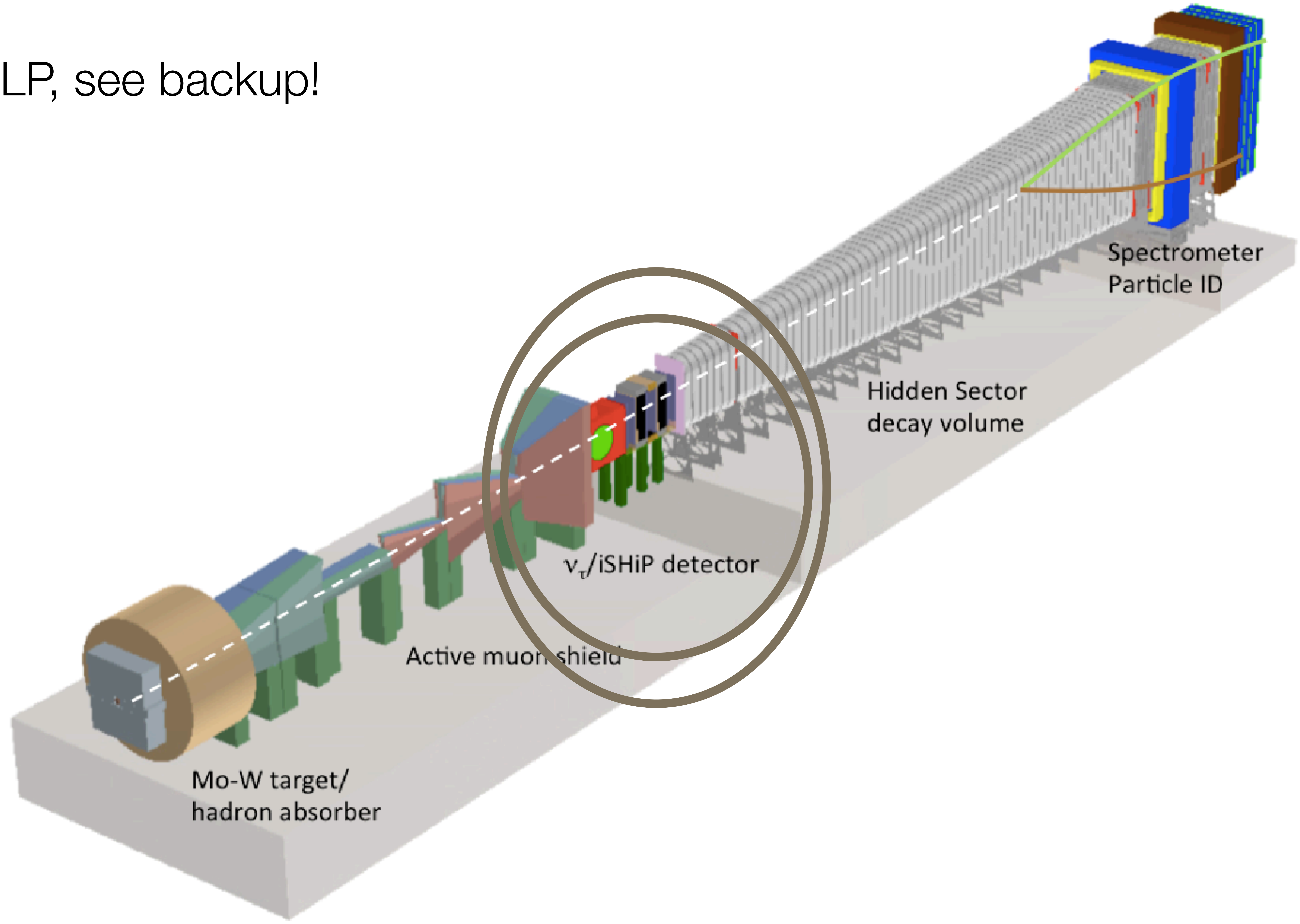
Figure 4. Geometric view of the optimized muon shield, showing at the top, the *z*-*y* plane view, and at the bottom, the *z*-*x* plane view. SHiP defines the origin of the coordinate system to be in the center of the decay vessel. Color shading is used to enhance the contrast between different magnetic field orientations.

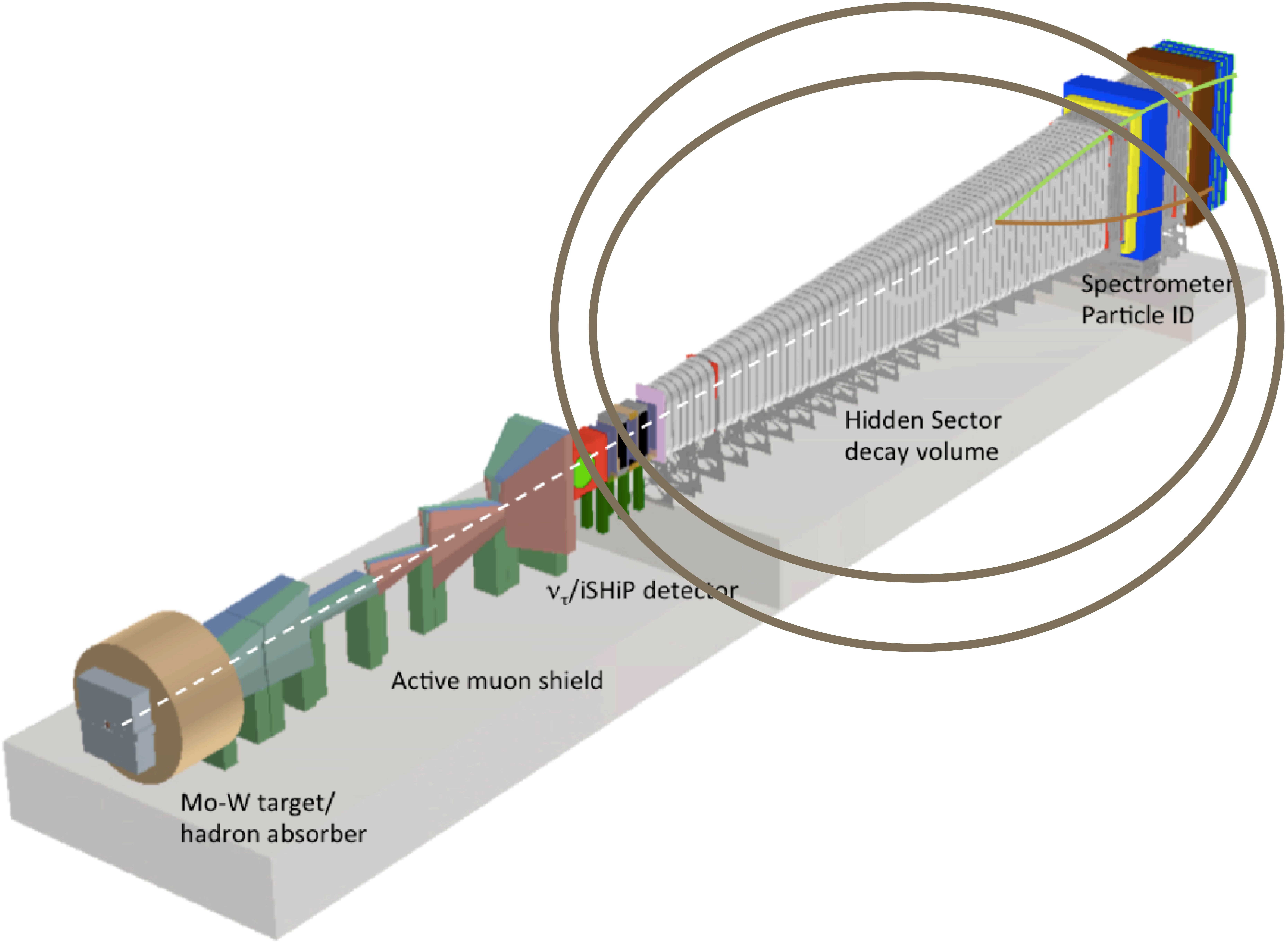
Running the simulation with material

- ~$3\text{x}10^9$ muons/spill with magnets off
- With the magnet on $3\text{x}10^5$ muons/spill
- ~$6.5\text{x}10^4$ muons/spill with p>3GeV

Opimization of the muon shield includes muon rate, weight (1.850 Tons) and length (34 meters)

Not LLP, see backup!

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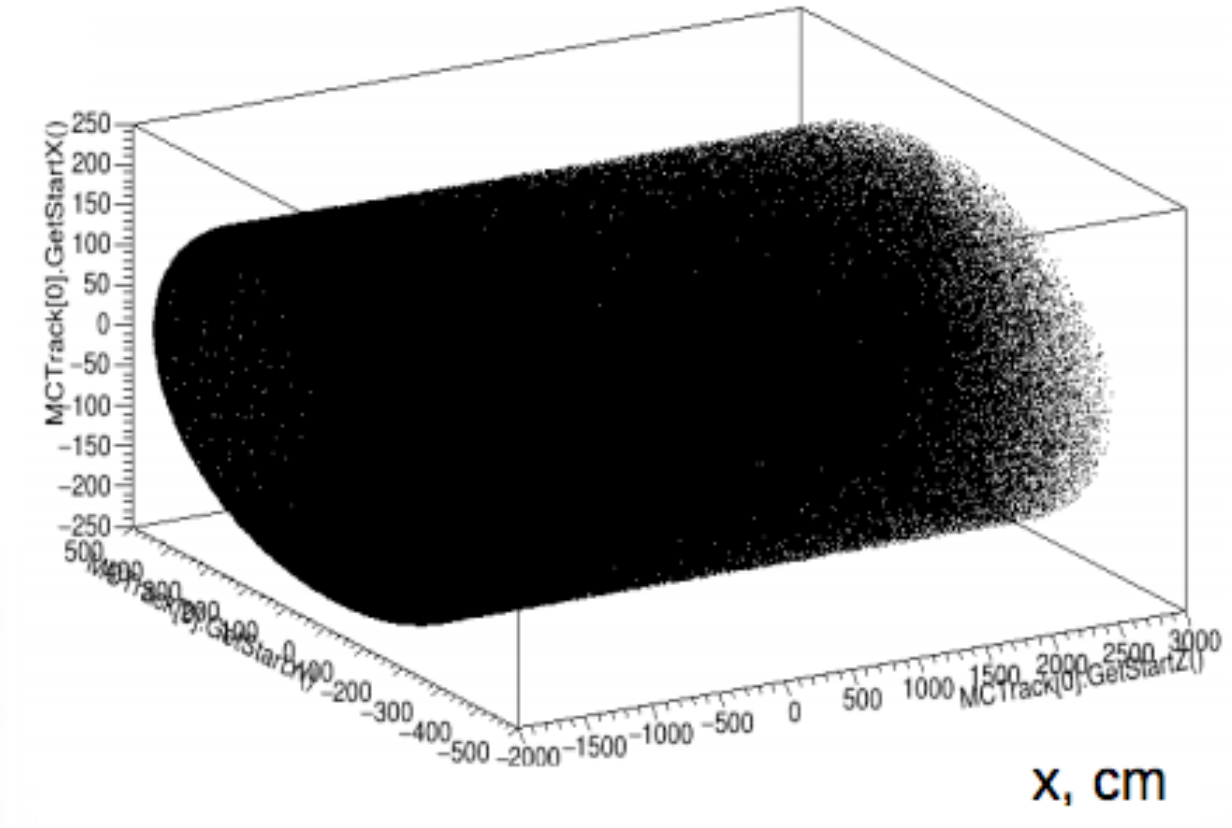
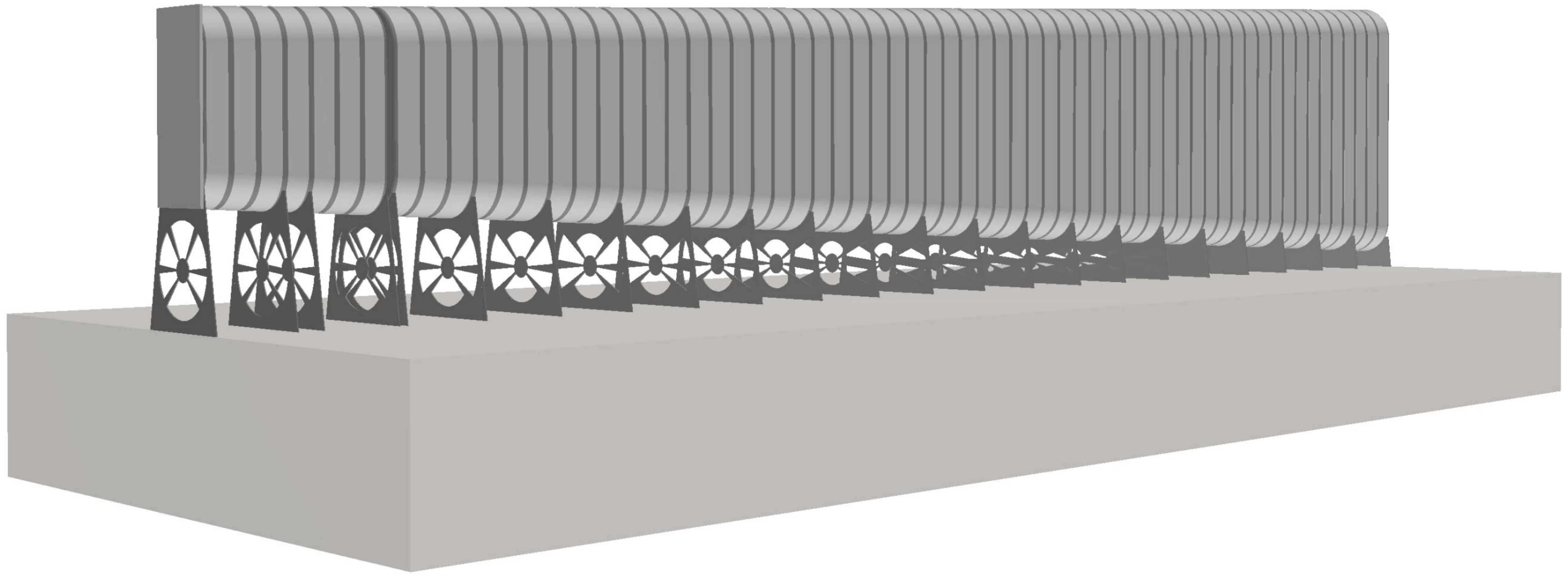
Vacuum vessel

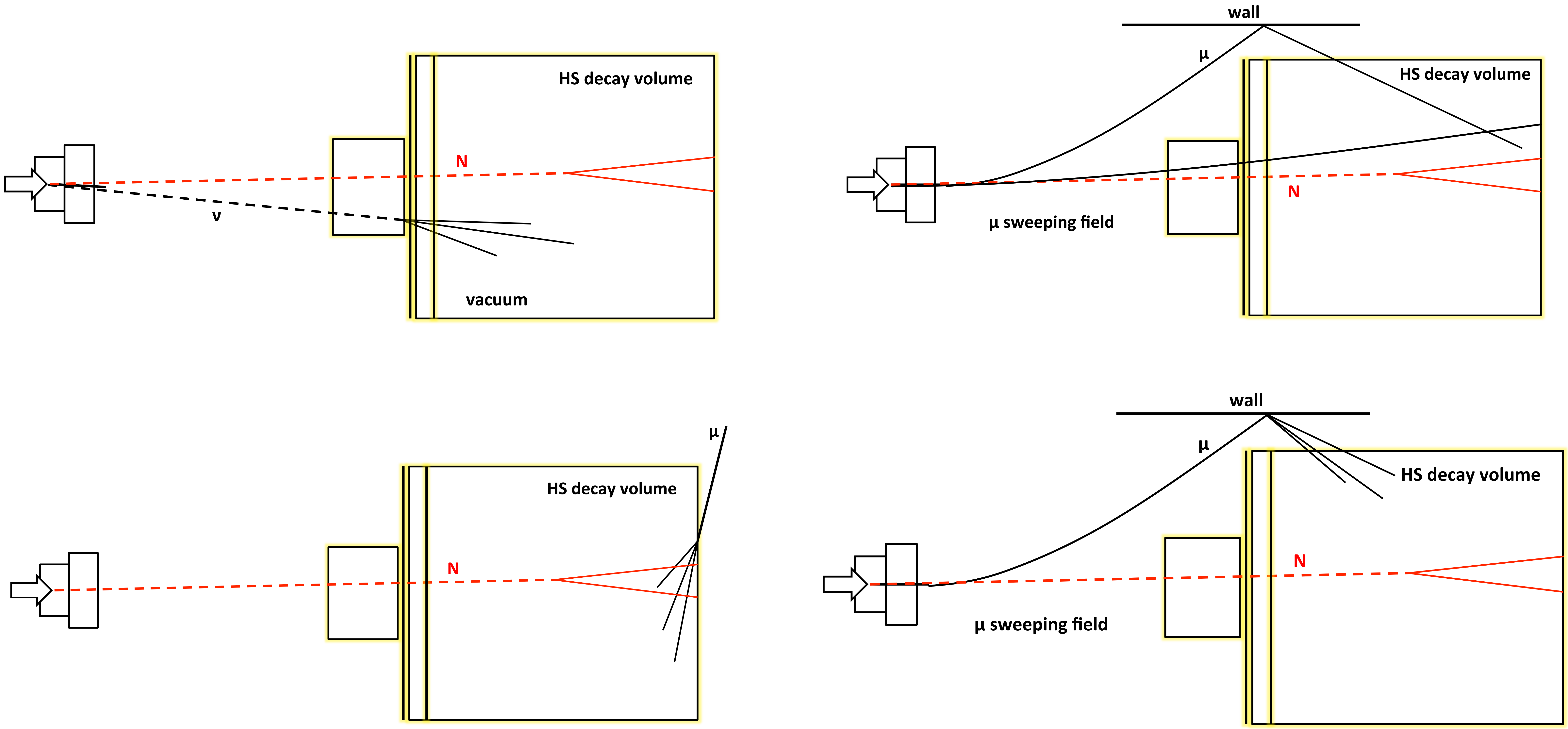


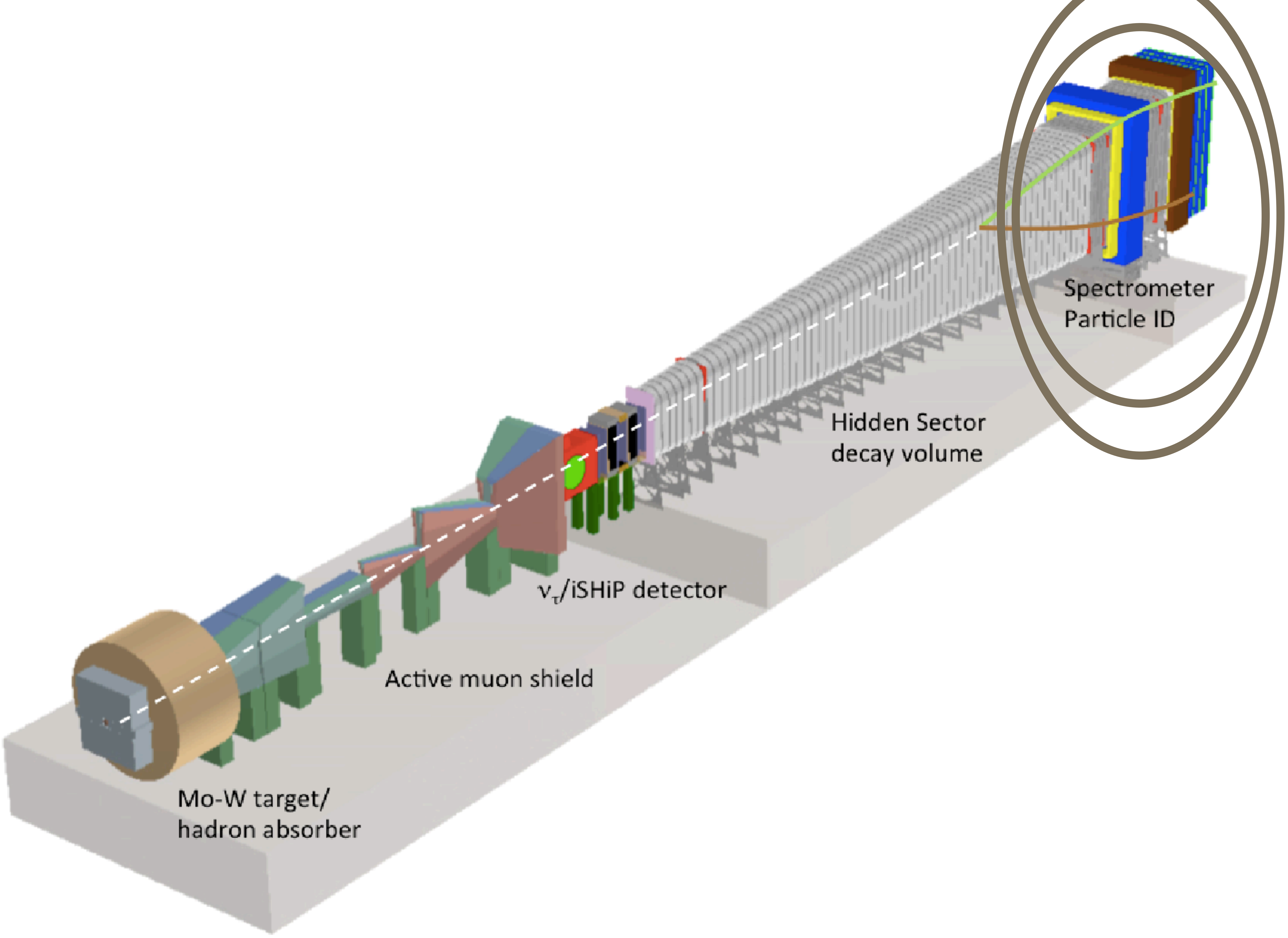


- The fiducial volume cannot be filled with air at atmospheric pressure
- This would mean about 100K neutrino interaction in the experiment
- Of this about 300 would survive a loose offline selection
- Therefore Plan to have a vacuum vessel with 10-3 Atm
- Use of pyramidal frustum shape to maximise the acceptance
- Surrounding background tagger made of liquid scintillators: total weight of ~ 480 t

Vacuum vessel dominant backgrounds

- Main sources do not include K0 background since this type of background has been proven to be under control

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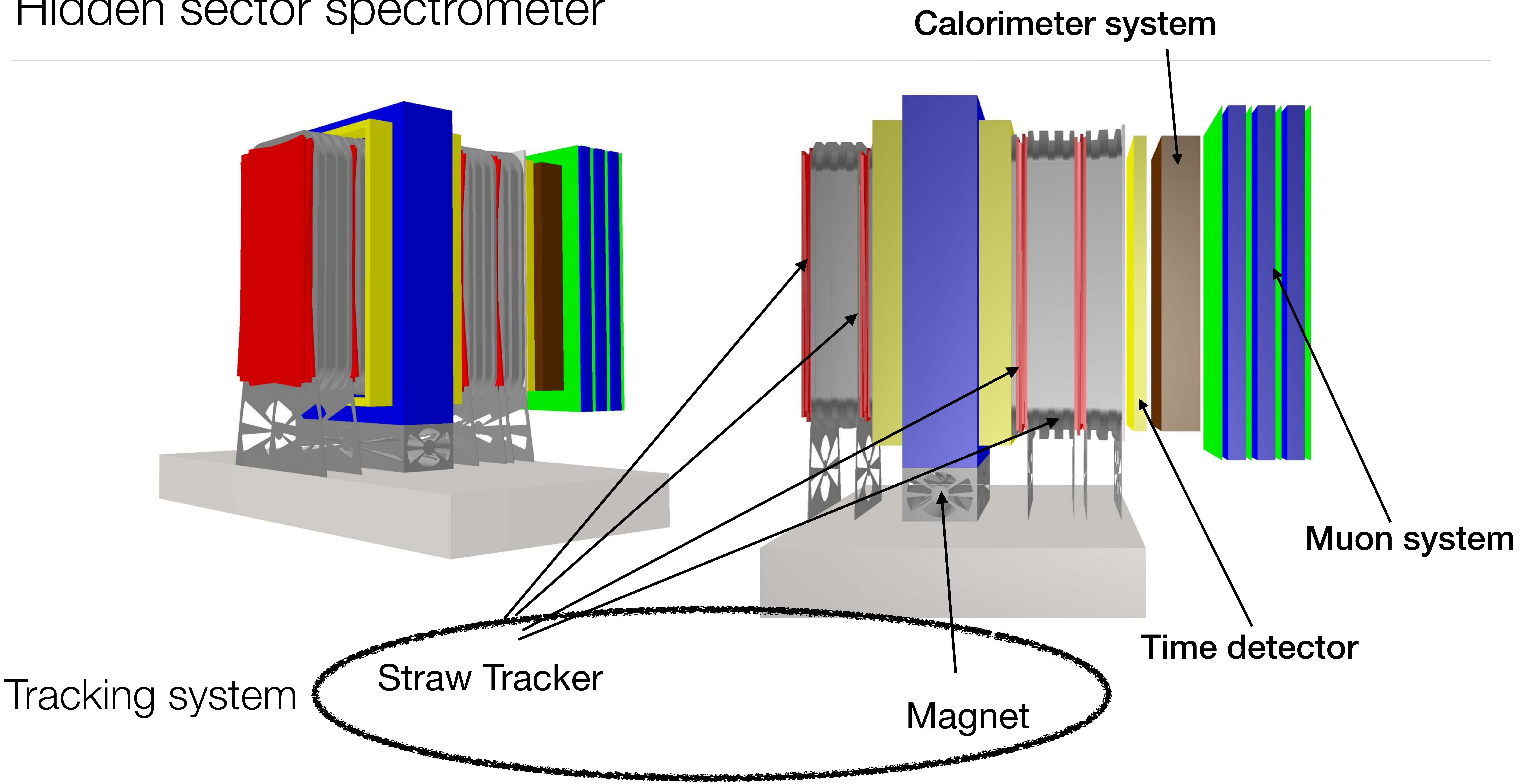
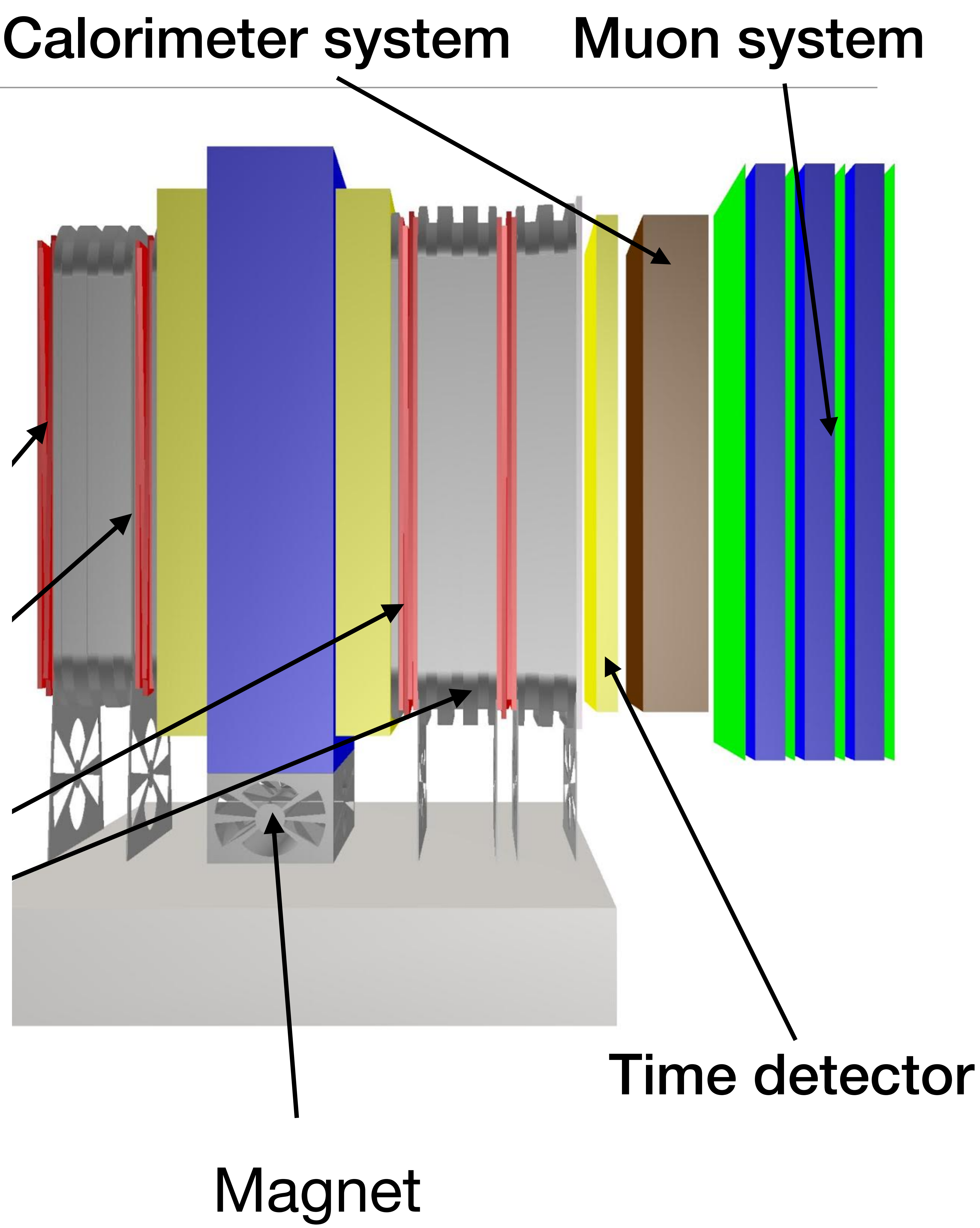
Hidden sector spectrometer

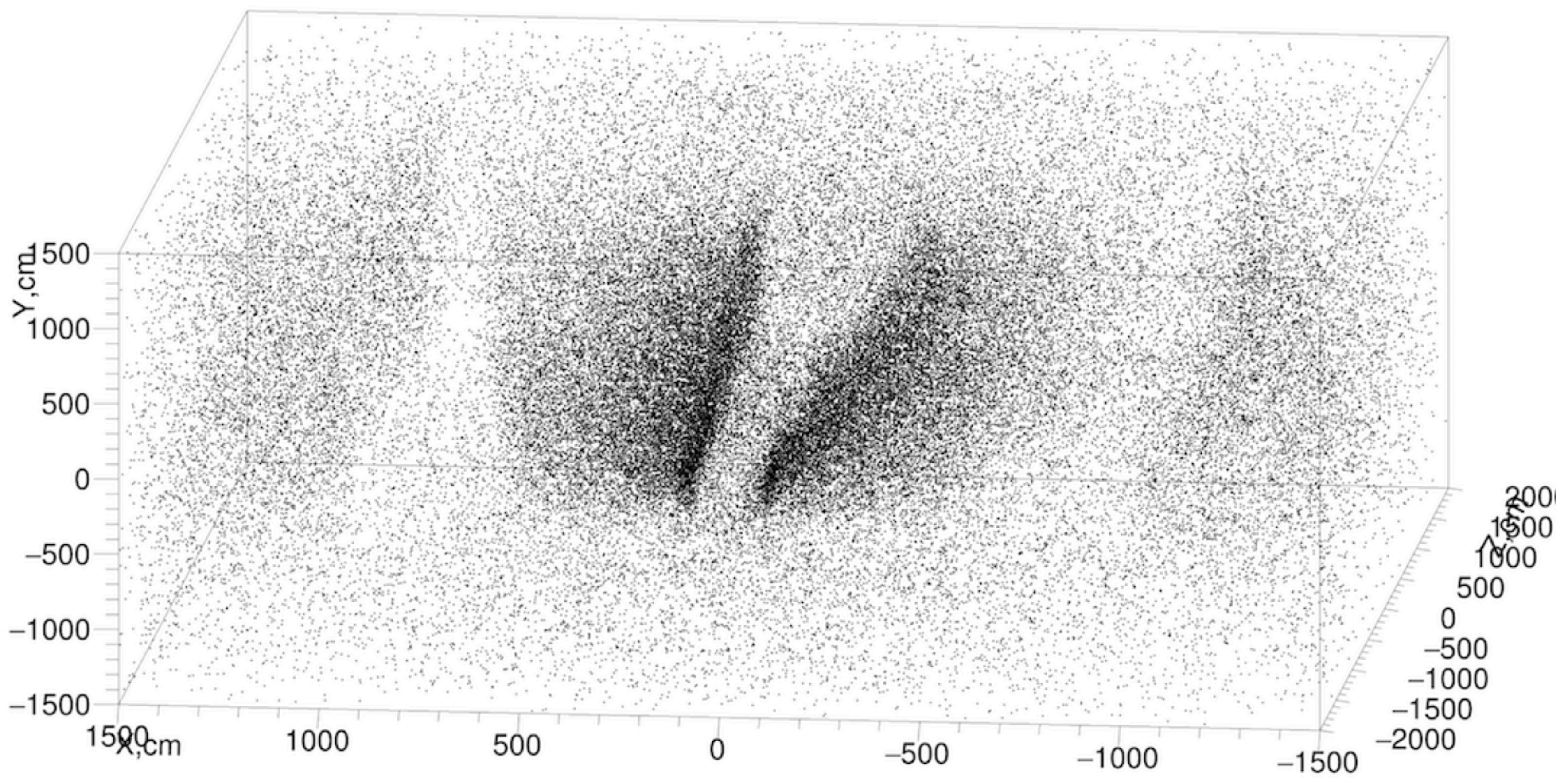


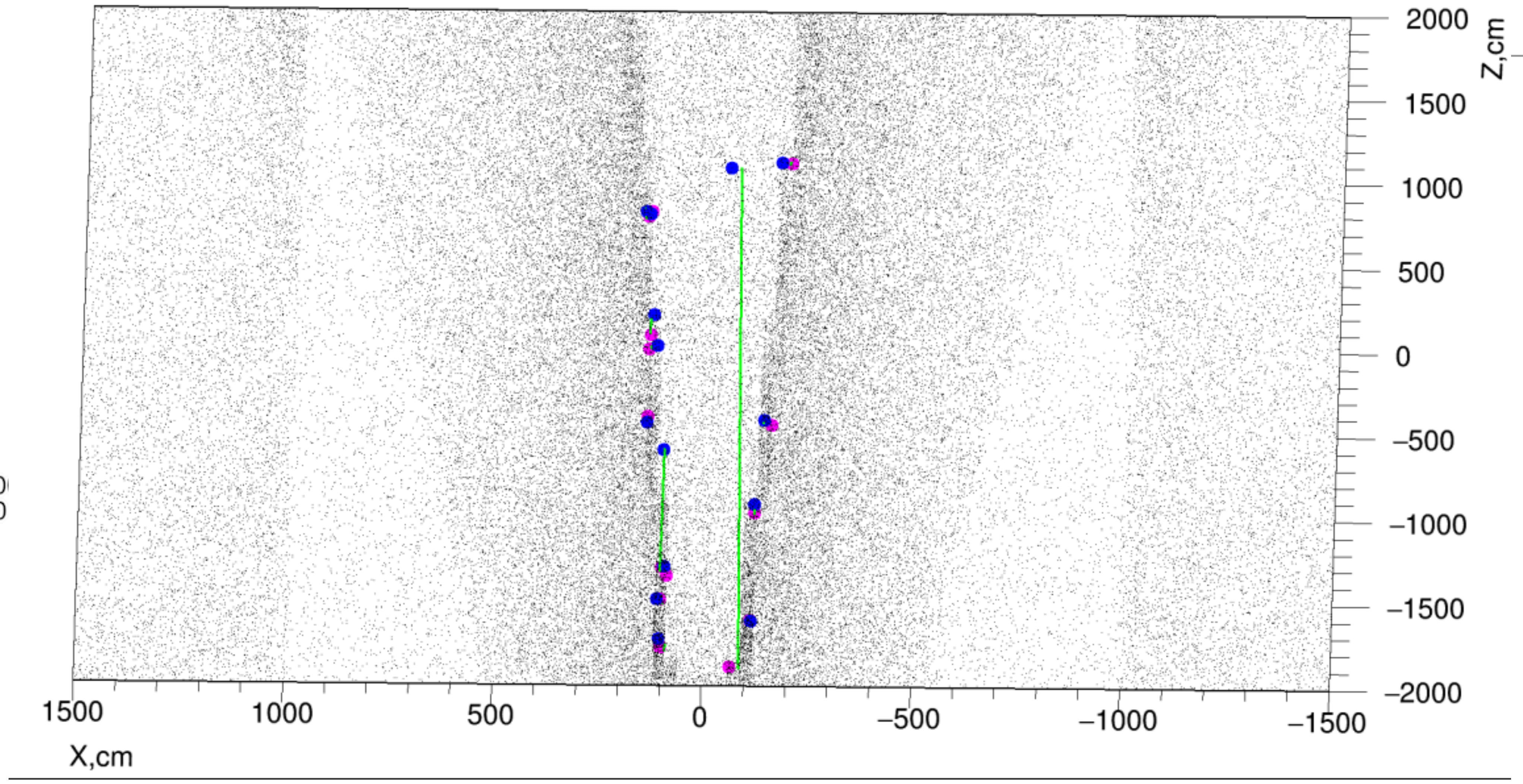
Hidden sector spectrometer

- Straw tracker: resolution of 120 μm per straw and is very light
- Magnet with vacuum vessel: 5m length
- Time detector: Plastic or SciFi read out by SiPM, <100 ps is achievable, test beam this July will test timing in SciFi
- Calorimeter system: ECAL + HCAL
- Muon system: 4 stations, 1000 t of iron



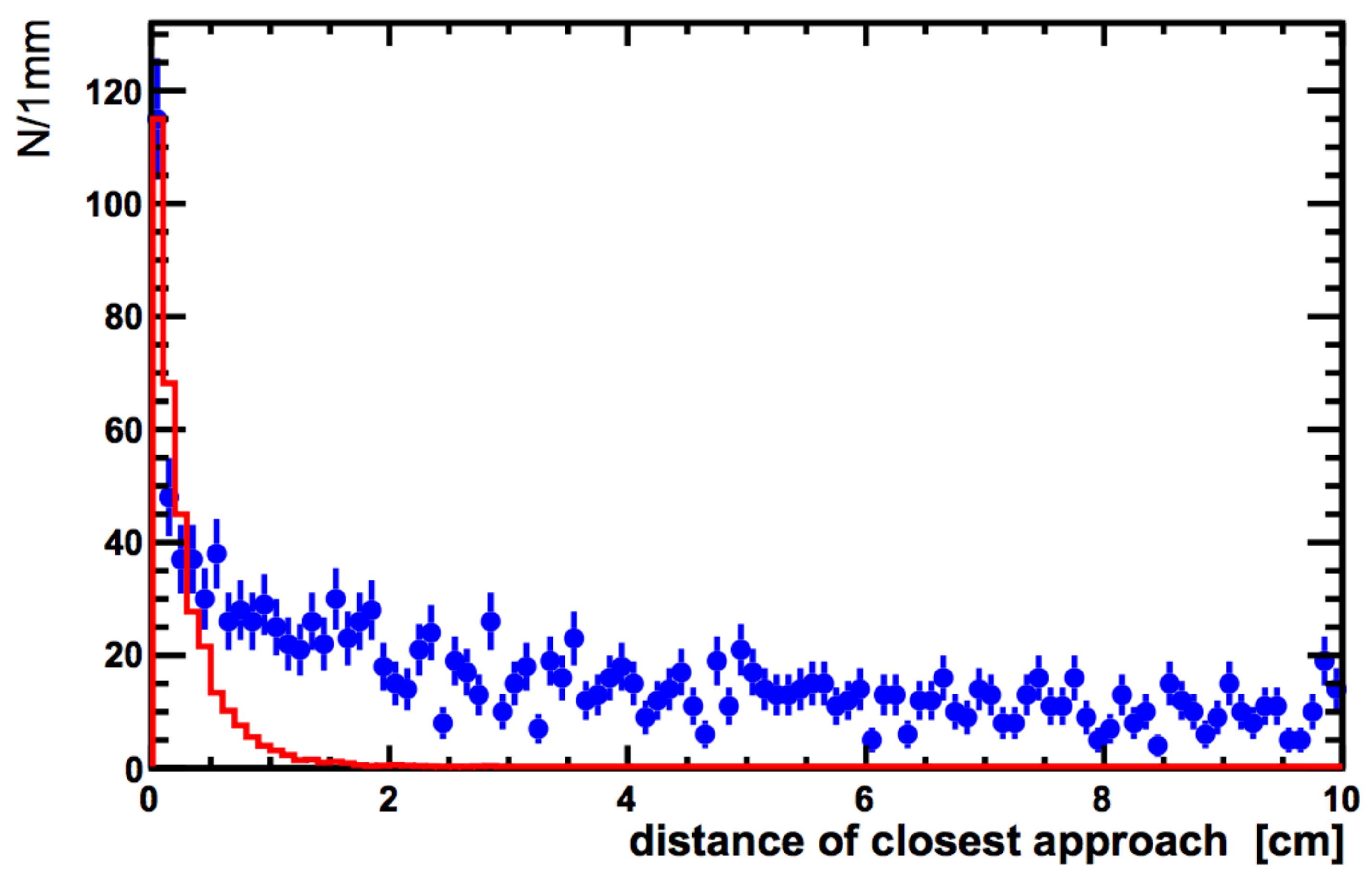
Backgrounds / 1

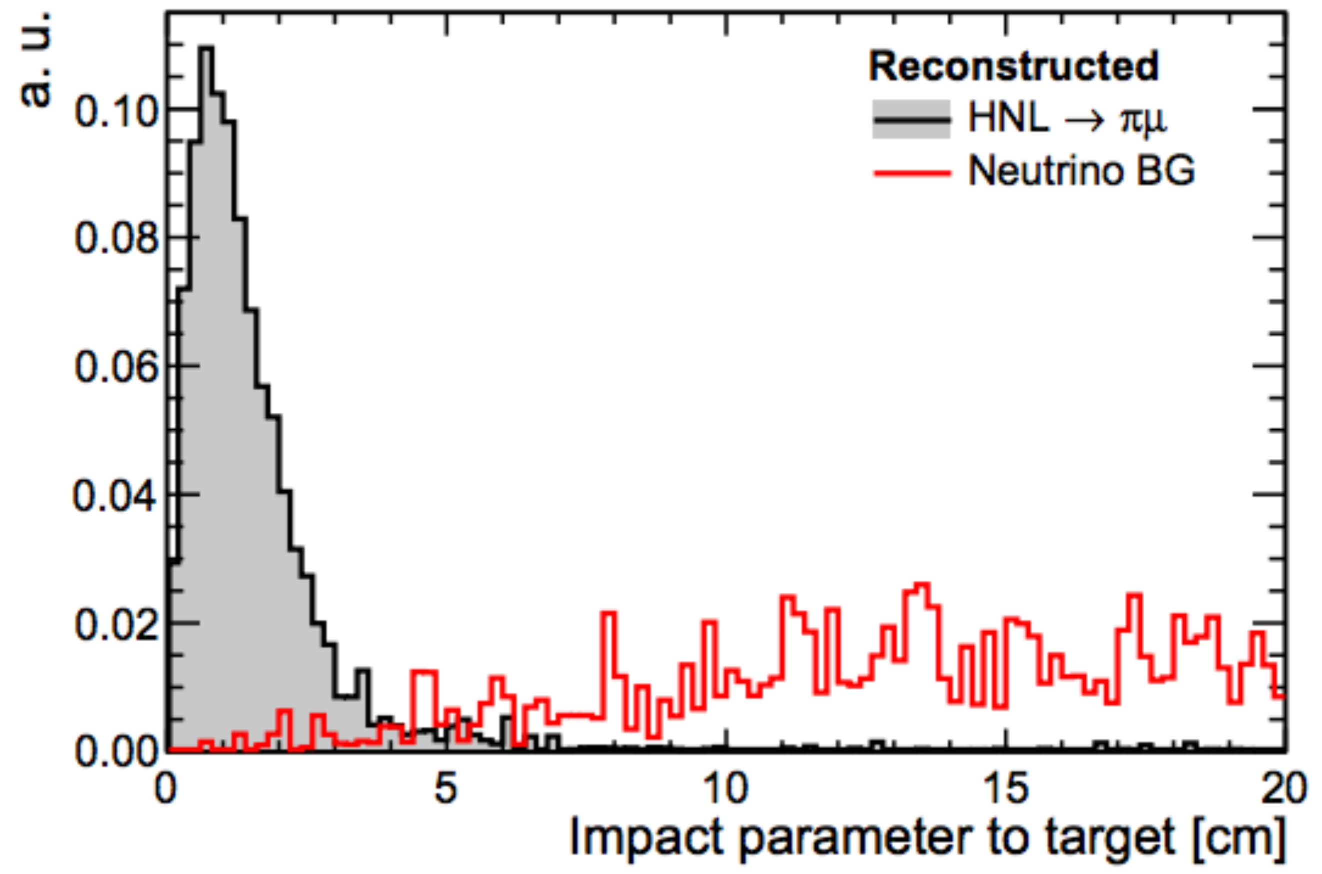


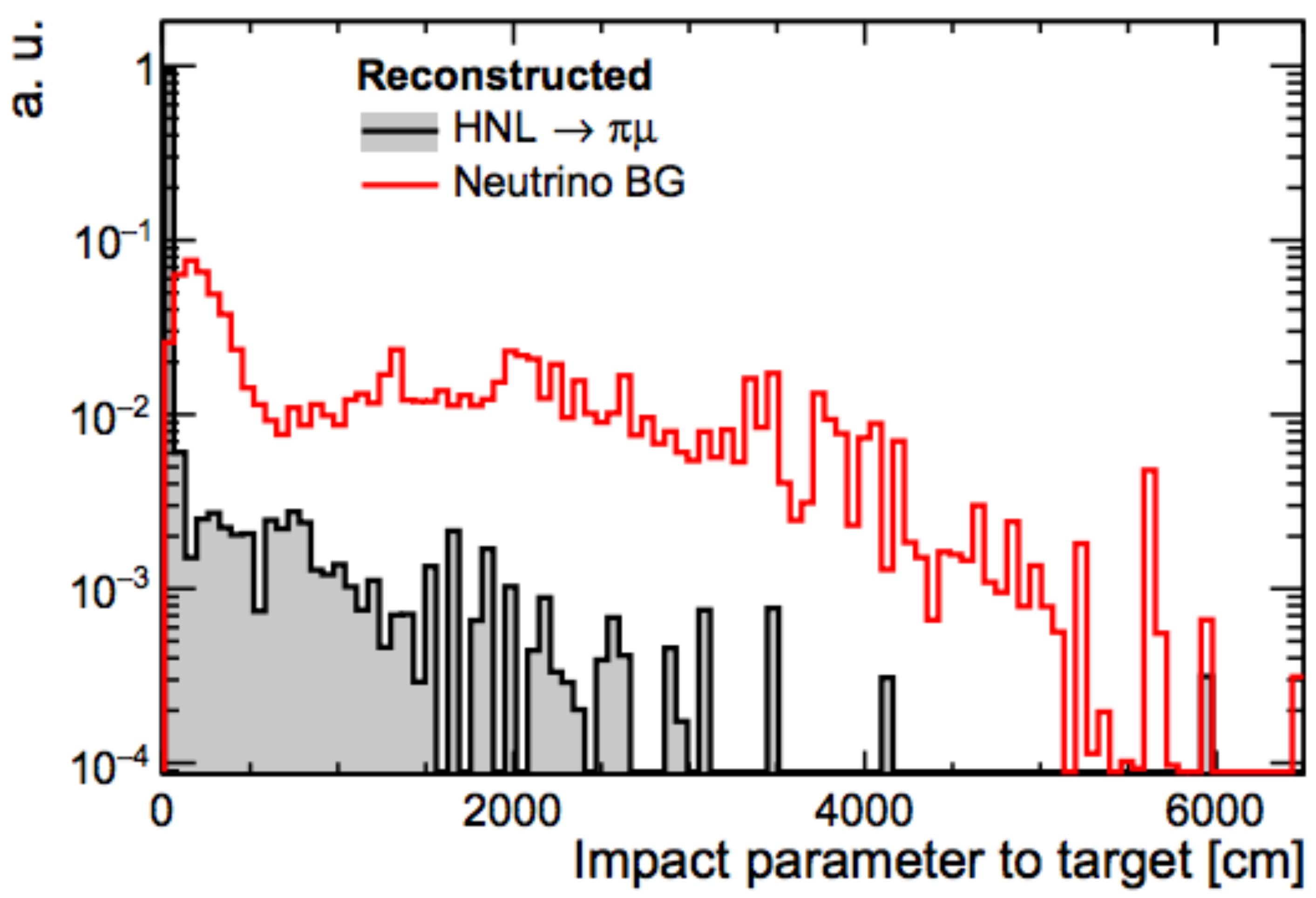


- Using the expected rate of muons (with sweeping magnets) the main background consists of neutrino inelastic, **including background from K0**,
  - Reduced rate of inelastic muons, efficiently killed by vets
  - Cosmic muons killed by veto (+ bad pointing)
  - Combinatorial muons killed by timing
- Generating about 5 years of SHiP data taking estimate compatible with 0 bkg events
- Preparing a large simulation corresponding to 10x 5 years of SHiP

Backgrounds / 2







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 all channels we have been studying

Neutrino portal / kinematic

- HNL can be produced in decays of heavy flavours to ordinary neutrinos through kinetic mixing, ~ U2
  - $D \to K \ell N$
  - $D_s \to \ell N$
  - $D_s \to \tau \nu_\tau$ followed by $\tau \to \mu \nu N$ or $\tau \to \pi N$
  - $B \to \ell N$
  - $B \to D \ell N$
  - $B_s \to D_s \ell N$
- Then HNL decay again to SM particles through mixing (~U2) with a SM neutrino. This (now massive) neutrino can decay to a large amount of final states:

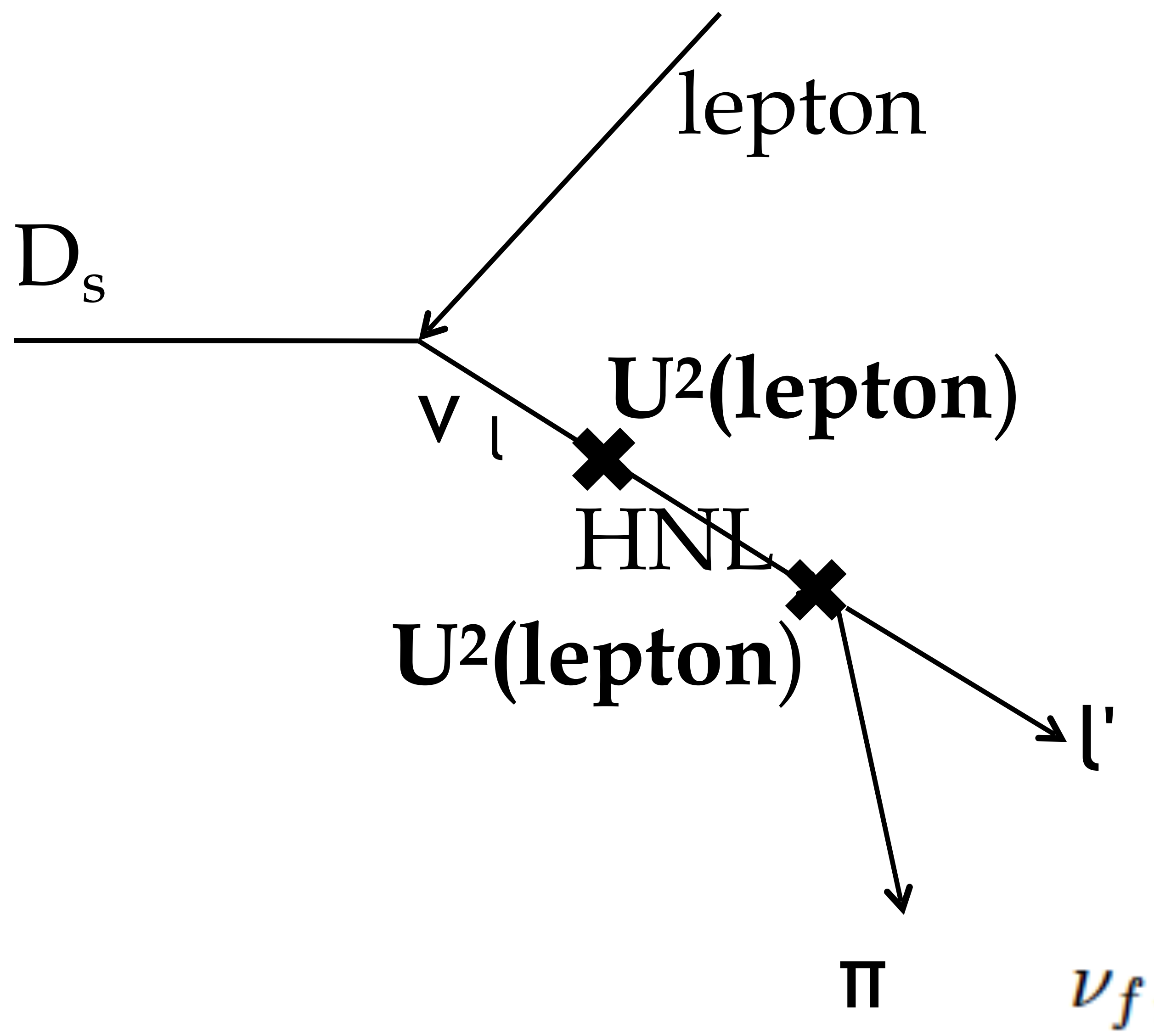
$N \to H^0 \nu$, with $H^0 = \pi^0, \rho^0, \eta, \eta'$

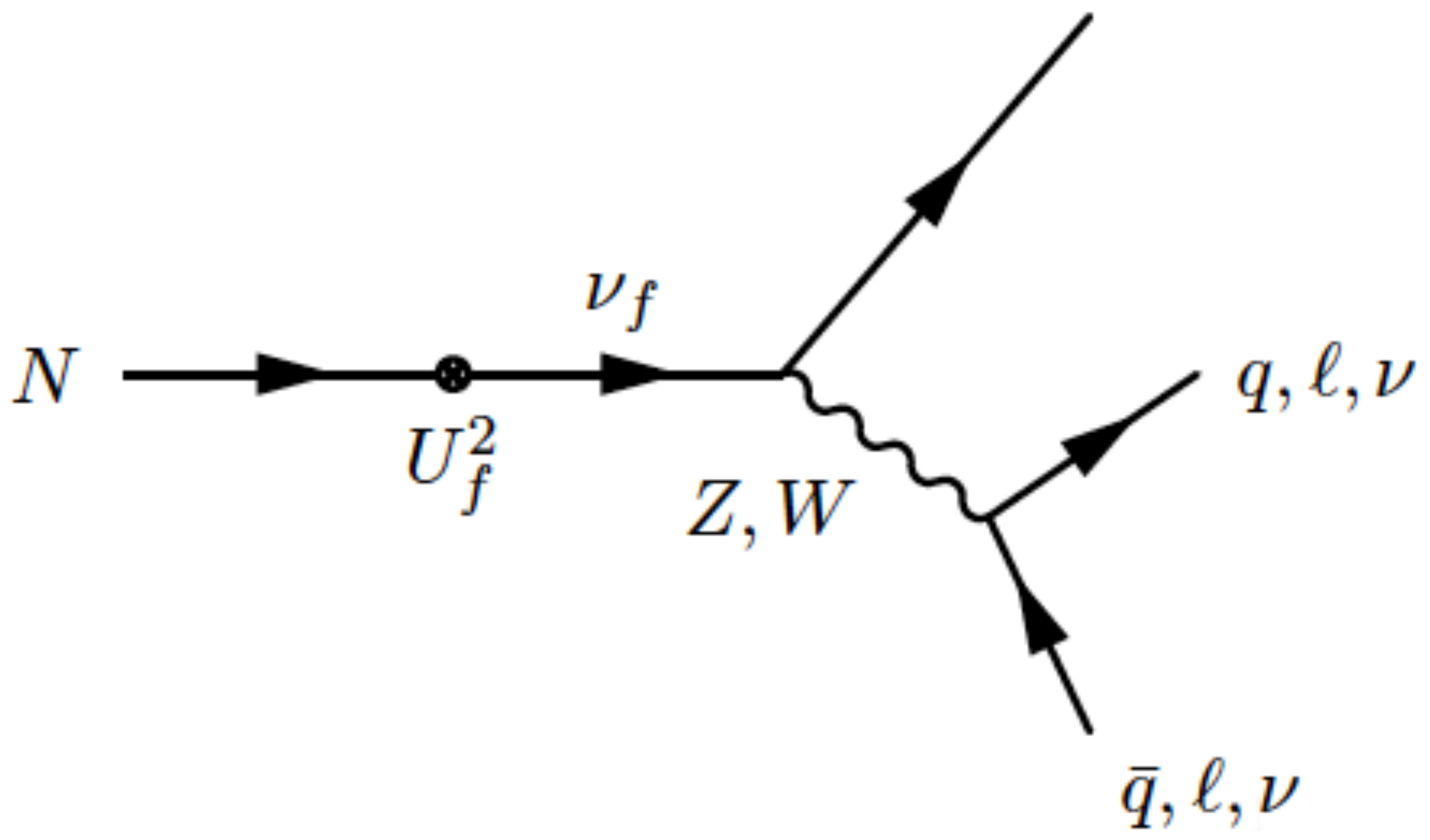
$N \to H^\pm \ell^\mp$, with $H = \pi, \rho$

$N \to 3\nu$

$N \to \ell_i^\pm \ell_j^\mp \nu_j$

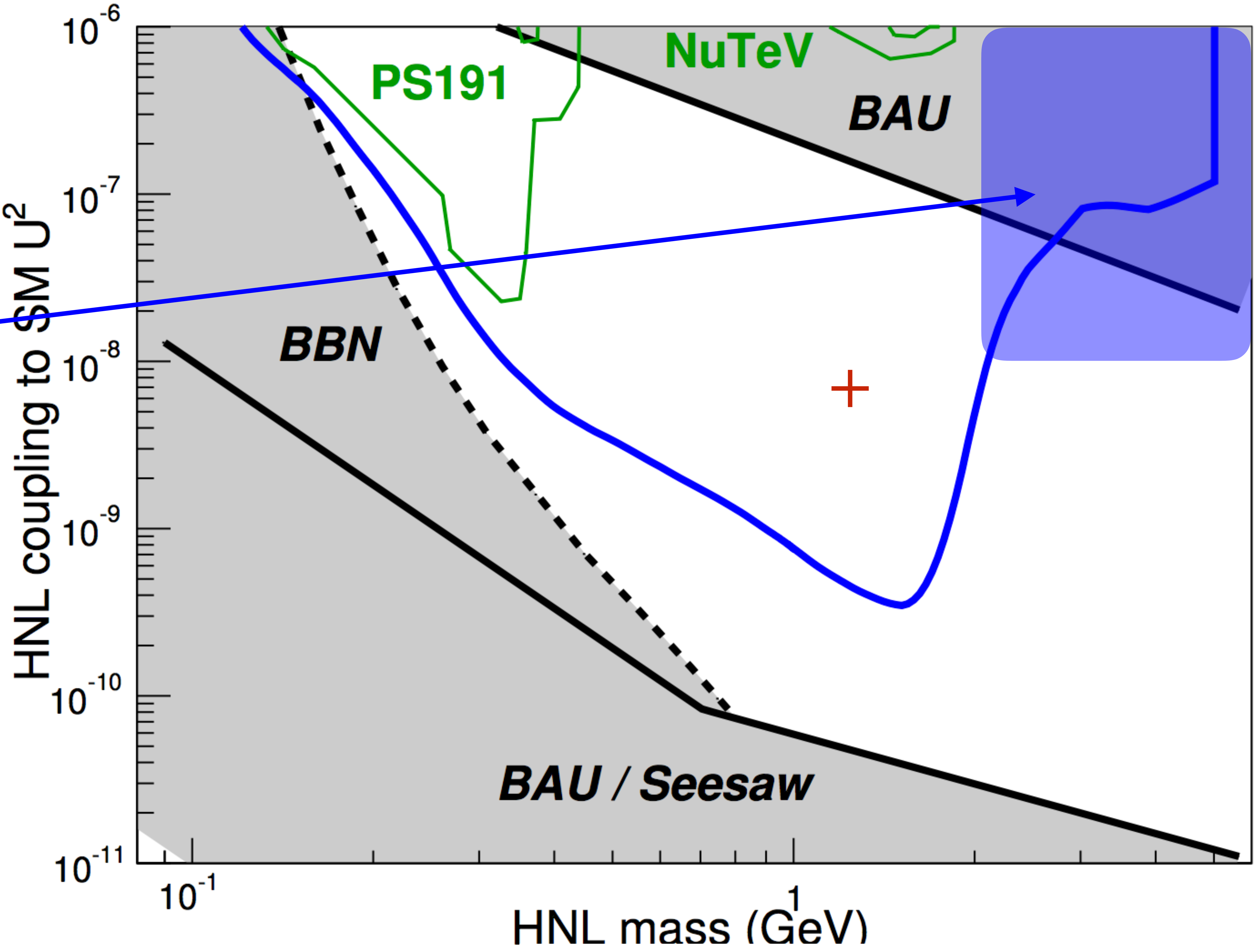
$N \to \nu_i \ell_j^\pm \ell_j^\mp$

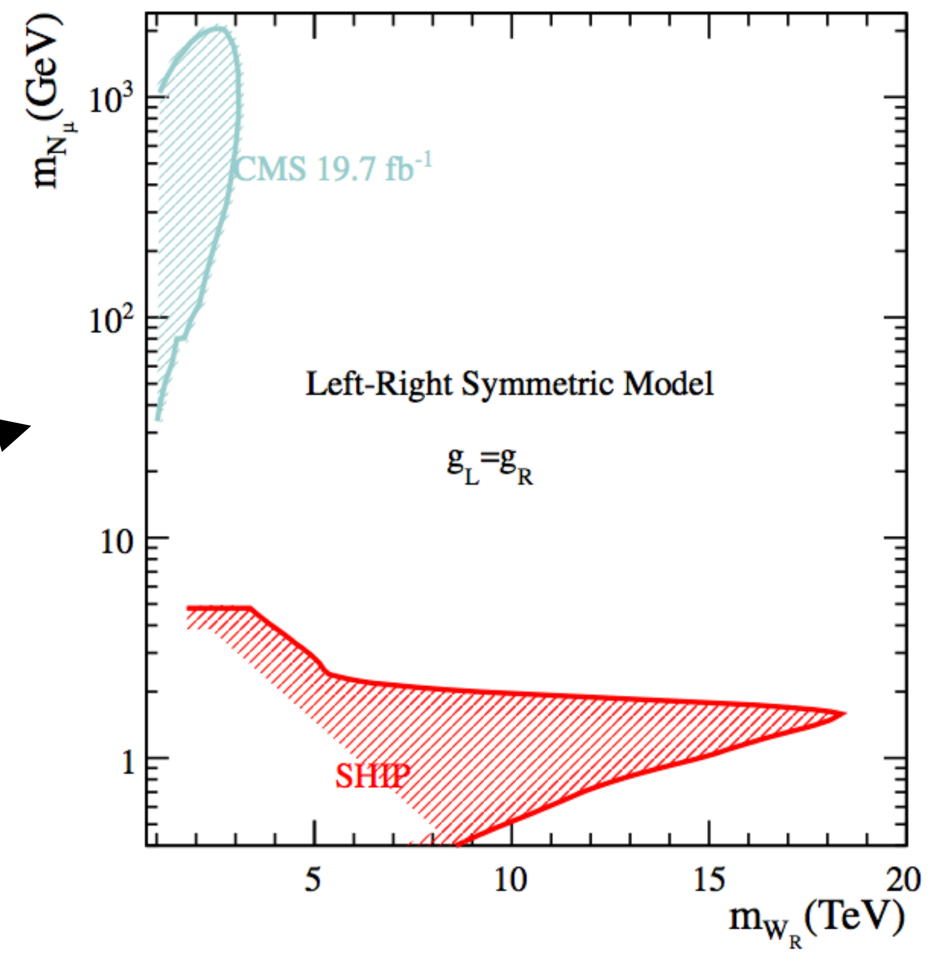




Neutrino portal / sensitivities

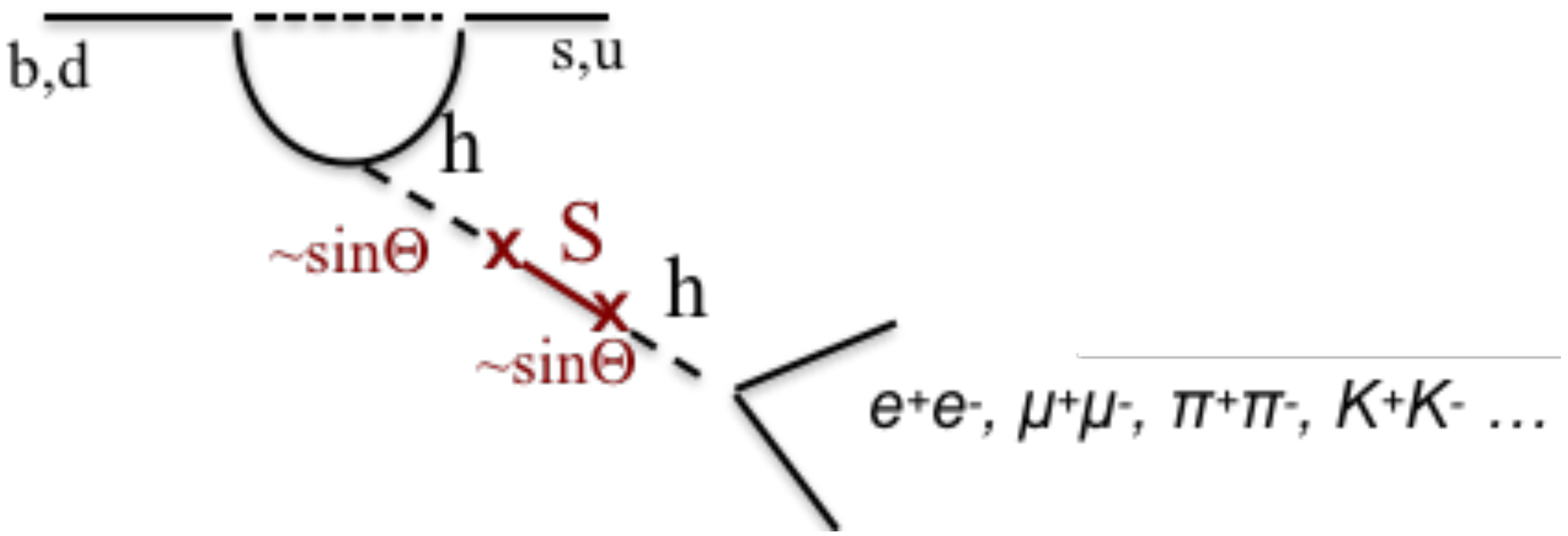
- **Updated sensitivity (improved and extended to Bc mass contribution will be reported at the PBC) [Boyarsky & Ruchayskiy]**
- **M(HNL)< M(b)**: LHCb, Belle2
  - SHiP will have much better sensitivity
- **M(b)<M(HNL)<M(Z)**: FCC in e+e- mode
  - (improvements are also expected from ATLAS / CMS)
- **M(HNL)>M(Z)**: Prerogative of ATLAS/CMS @ HL LHC
- **E.g. :** U2=10-8 and M=1GeV (~50 times lower than the present limit) SHiP will see **more than 1000 fully reconstructed events**, i.e. SHiP would discover sterile neutrinos in less than a week of running! The result can be reinterpreted for instance in the context of the Left-right symmetric model



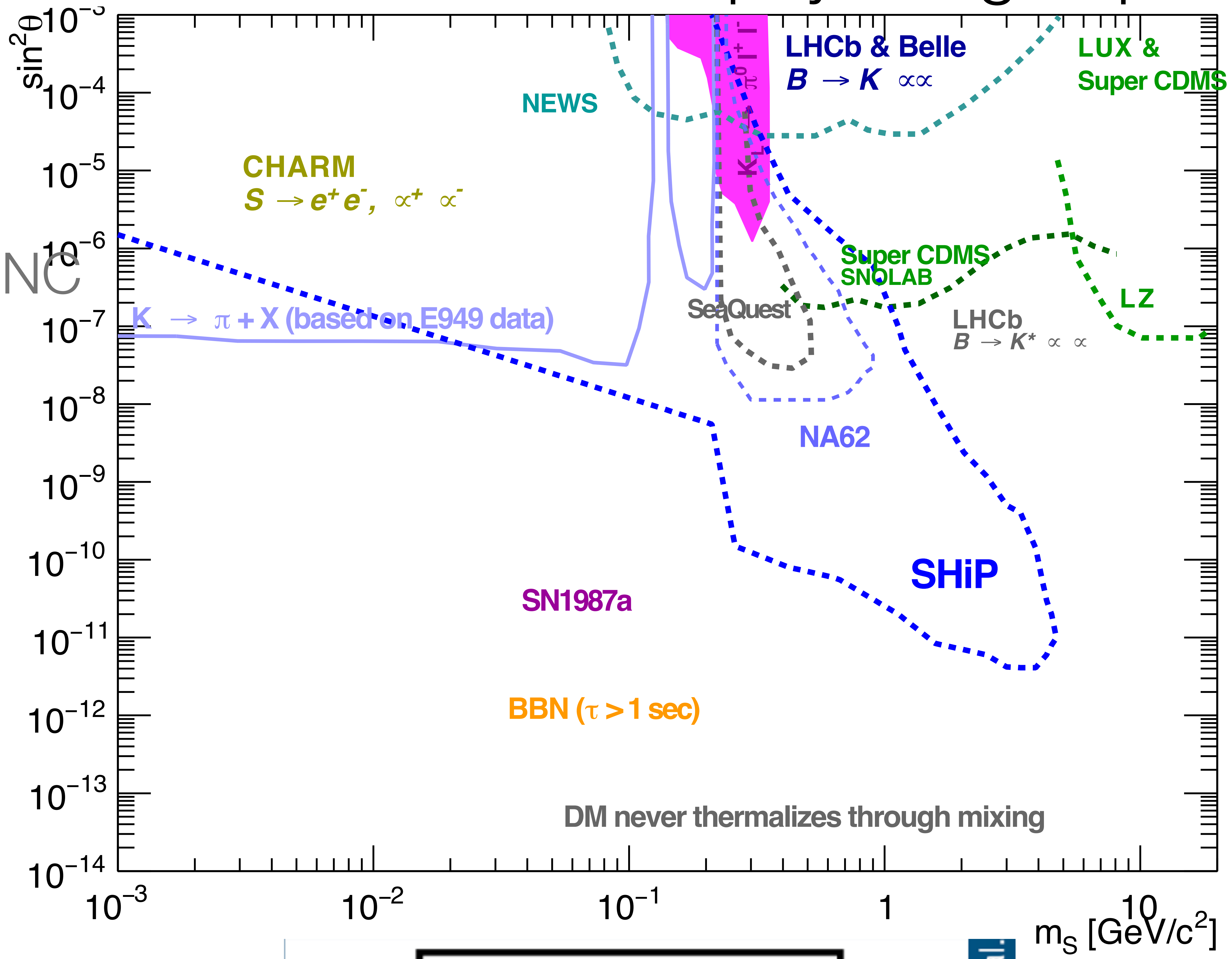


Scalar portal / sensitivities

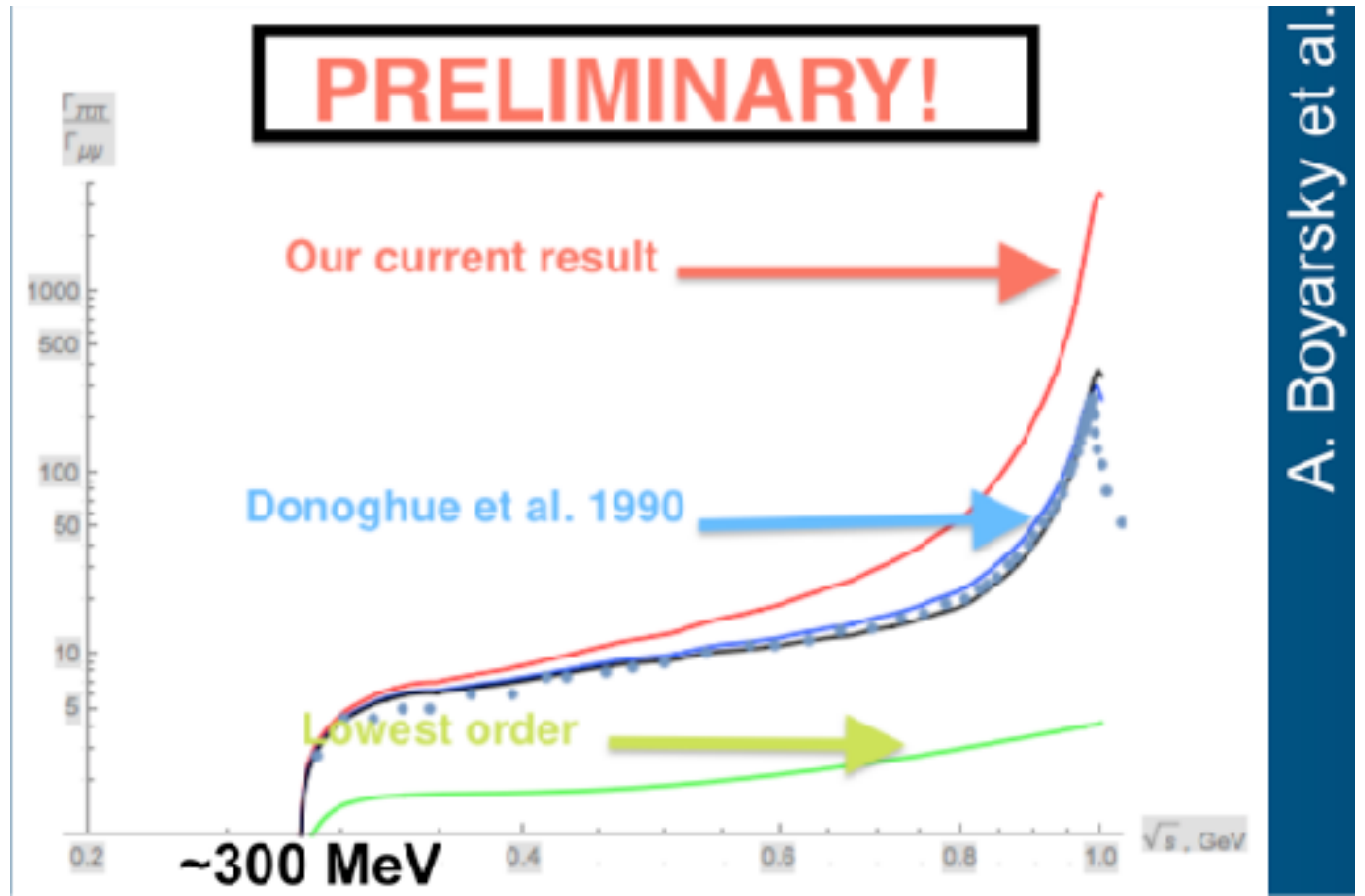
- **Dark Scalar** particles can couple to the Higgs in FCNC transition in K and B decays:



PBC BSM physics group



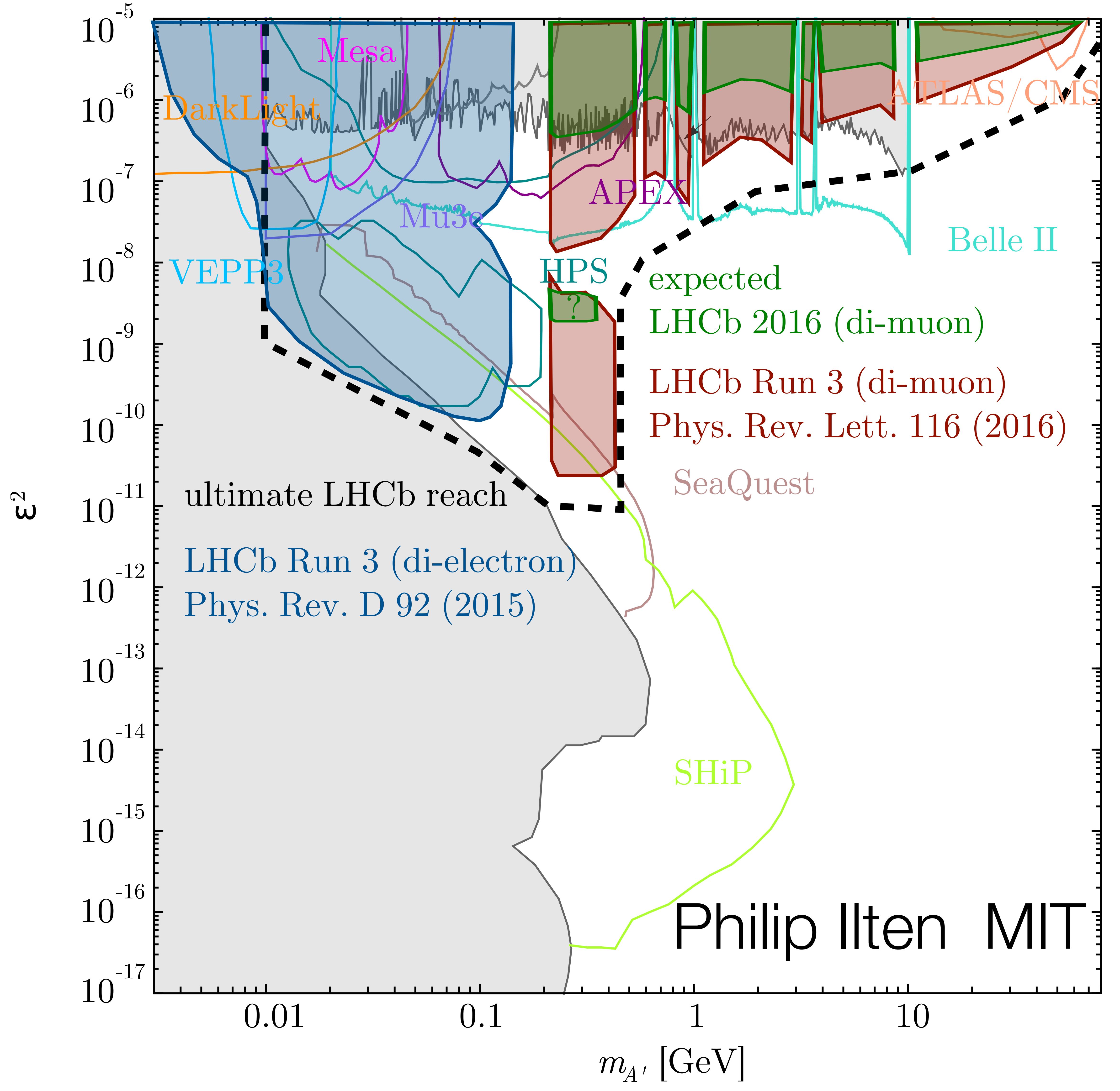
- Issue with simulation:
  - Scalar has been implemented in full simulation but **uncertainty on hadronic** BR($S \to \pi\pi, KK$)
  - Lowest order calculation used in many works Difference may be **a factor 50x**



PBC BSM physics group

Vector portal / sensitivities

- **Production**
  - Mesons decay, e.g. π0→γ V(~ε2)
  - p bremsstrahlung on target nuclei, pp→ppV
  - largest MV in direct QCD production but large theoretical uncertainties.
- **Decay**
  - into a pair of SM particles: e+e-, μ+μ–, π+π+, KK, ηη, ττ, DD, …
- EM showers are not taken into account as source of DP



Physics signals

Signature	Physics	Backgrounds
$\pi^-\mu^+$,$K^-\mu^+$	HNL,NEU	RDM, $K_L^0 \to \pi^-\mu^+\nu_\mu$
$\pi^-\pi^0\mu^+$	HNL($\to \rho^-\mu^+$)	$K_L^0 \to \pi^-\mu^+\nu_\mu(+\pi^0)$, $K_L^0 \to \pi^-\pi^+\pi^0$
π^-e^+,K^-e^+	HNL, NEU	$K_L^0 \to \pi^-e^+\nu_e$
$\pi^-\pi^0e^+$	HNL($\to \rho^-e^+$)	$K_L^0 \to \pi^-e^+\nu_e$, $K_L^0 \to \pi^-\pi^+\pi^0$
μ^-e^++p^{miss}	HNL,Higgs Portal (HP)($\to \tau\tau$)	$K_L^0 \to \pi^-\mu^+\nu_\mu$, $K_L^0 \to \pi^-e^+\nu_e$
$\mu^-\mu^+$+p^{miss}	HNL,HP($\to \tau\tau$)	RDM, $K_L^0 \to \pi^-\mu^+\nu_\mu$
$\mu^-\mu^+$	DP,PNGB,HP	RDM, $K_L^0 \to \pi^-\mu^+\nu_\mu$
$\mu^-\mu^+\gamma$	Chern-Simons	$K_L^0 \to \pi^-\pi^+\pi^0$, $K_L^0 \to \pi^-\mu^+\nu_\mu(+\pi^0)$
e^-e^++p^{miss}	HNL,HP	$K_L^0 \to \pi^-e^+\nu_e$
e^-e^+	DP,PNGB,HP	$K_L^0 \to \pi^-e^+\nu_e$
$\pi^-\pi^+$	DP,PNGB,HP	$K_L^0 \to \pi^-\mu^+\nu_\mu$, $K_L^0 \to \pi^-e^+\nu_e$, $K_L^0 \to \pi^-\pi^+\pi^0$,$K_L^0 \to \pi^-\pi^+$
$\pi^-\pi^+$+p^{miss}	DP,PNGB, HP($\to \tau\tau$), HSU,HNL($\to \rho^0\nu$)	$K_L^0 \to \pi^-\mu^+\nu_\mu$, $K_L^0 \to \pi^-e^+\nu_e$, $K_L^0 \to \pi^-\pi^+\pi^0$, $K_L^0 \to \pi^-\pi^+$,$K_S^0 \to \pi^-\pi^+$,$\Lambda \to p\pi$
K^+K^-	DP,PNGB, HP	$K_L^0 \to \pi^-\mu^+\nu_\mu$, $K_L^0 \to \pi^-e^+\nu_e K_L^0 \to \pi^-\pi^+\pi^0$, $K_L^0 \to \pi^-\pi^+$,$K_S^0 \to \pi^-\pi^+$,$\Lambda \to p\pi$
$\pi^+\pi^-\pi^0$	DP,PNGB,HP, HNL($\eta\nu$)	$K_L^0 \to \pi^-\pi^+\pi^0$
$\pi^+\pi^-\pi^0\pi^0$	DP,PNGB,HP	$K_L^0 \to \pi^-\pi^+\pi^0(+\pi^0)$
$\pi^+\pi^-\pi^0\pi^0\pi^0$	PNGB($\to \pi\pi\eta$)	–
$\pi^+\pi^-\gamma\gamma$	PNGB($\to \pi\pi\eta$)	$K_L^0 \to \pi^-\pi^+\pi^0$
$\pi^+\pi^-\pi^+\pi^-$	DP,PNGB,HP	–
$\pi^+\pi^-\mu^+\mu^-$	Hidden Susy (HSU)	–
$\pi^+\pi^-e^+e^-$	Hidden Susy	–
$\mu^+\mu^-\mu^+\mu^-$	Hidden Susy	–
$\mu^+\mu^-e^+e^-$	Hidden Susy	–

HNL=Heavy Neutral Lepton, NEU=neutralino

DP=Dark Photon, PNGB=Pseudo-Nambu Goldston Boson

Background: RDM=random di-muons from the target

Conclusions

- The days of "guaranteed" discoveries or of no-lose theorems in particle physics are over, at least for the time being ....
- .... but the big questions of our field remain wild open (hierarchy problem, flavour, neutrinos, DM, BAU, ...)
- This simply implies that, more than for the past 30 years, future HEP's progress is to be driven by experimental exploration, possibly renouncing/reviewing deeply rooted theoretical bias

Michelangelo Mangano

Conclusions

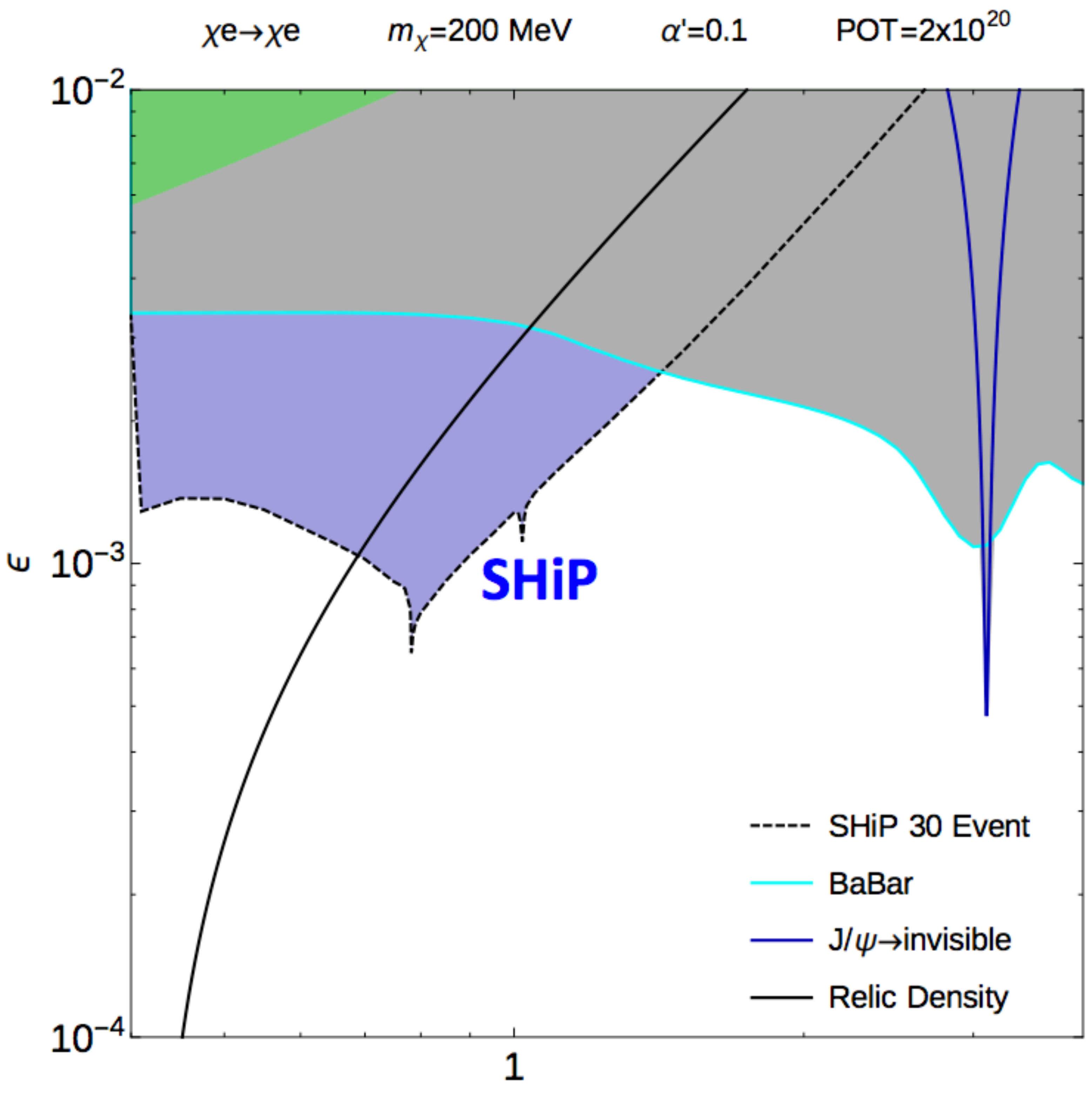
- Theoretical bias?
  - **Long lived particles**
- Progress driven by experimental exploration?
  - CERN is ideal place to search for Dark Sector at high energy and high intensity **SPS** beams. Two complementary strategies can be explored
    - Direct observation of the decay vertex
    - Indirect detection via scattering on atoms
  - **SHiP** experiment at SPS has:
    - **Intense beam** 400GeV@SPS with 2x1020 PoT in 5 years
    - **Heavy target** to maximise the signal (from direct production and heavy mesons) and minimise the bkg (muon and neutrino induced)
    - **Muon sweepers**, Vacuum Vessel and series of vetos
    - **Emulsion Spectrometer** and HS spectrometer
  - **Background** is demonstrated to be at **negligible level** (<<1) in 5 years within the fiducial volume
    - If we have **one** event isolated in the vacuum vessel and pointing back to the target it is **evidence**.
    - If we have **two** sitting at the same mass is a **discovery**.
    - **We have redundancy to make sure signal is signal.**

Thanks

Federico Leo Redi

Emulsion spectrometer detector

- SHiP also maximises the flux of $\nu\tau$ wrt to the other neutrino flavours
- Scenario: only 9 fully reconstructed $\nu\tau$ at present and anti-$\nu\tau$ never observed directly
- If Light-DM particles (M~GeV) are produced in the target, via the decay of a hidden sector mediator, we can look for the interaction of the LDM particles with the ESD
- If DM lighter than WIMPS, not LLP, direct detection will loose sensitivity
  - SHiP is capable of indirect detection via electron and nuclear recoil in ESD
- Main background is ν_e scattering: use kinematics
- Inelastic is suppressed by vetoing vertices with extra particles



	Φ	<E> (GeV)
ν_μ	1.7×10^6	29
ν_e	2.5×10^5	46
ν_τ	7.6×10^3	59
Anti-ν_μ	6.7×10^5	28
Anti-ν_e	9.0×10^4	46
Anti-ν_τ	3.9×10^3	58

Rates for five years of nominal operation with 2×10^{20} protons on target

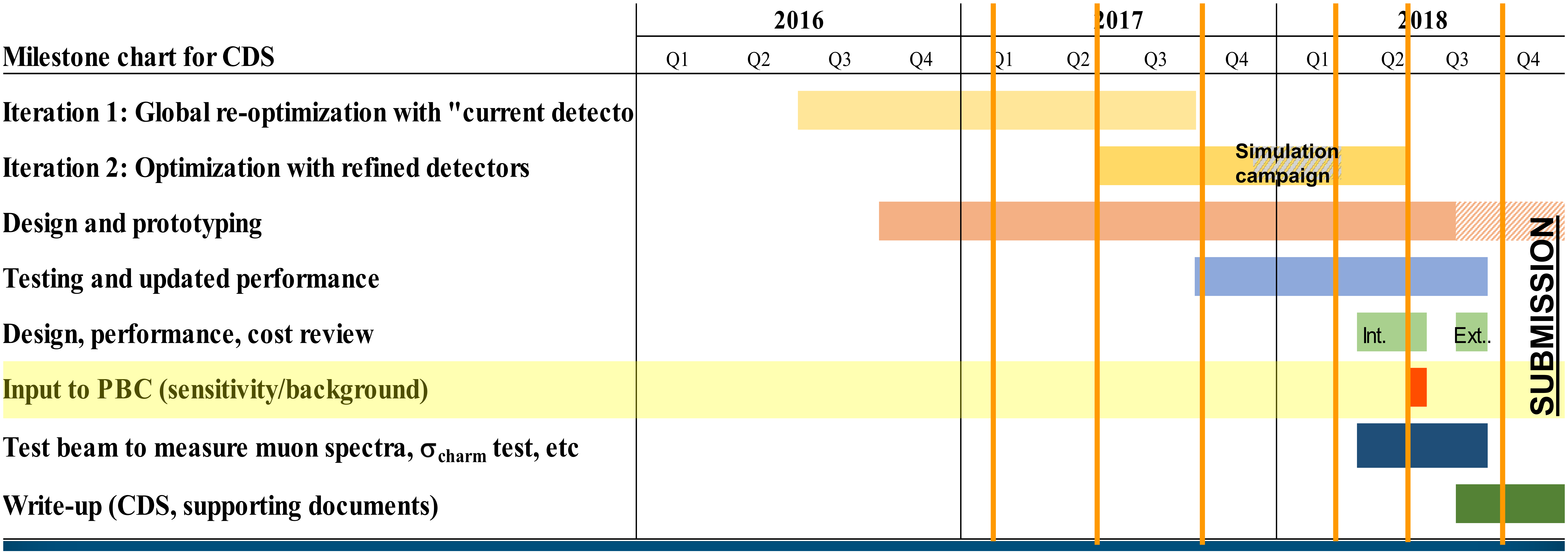
Landscape today / 1

- The Intensity frontier is a **broad** and **diverse**, yet **connected**, set of science opportunities: heavy quarks, charged leptons, hidden sectors, neutrinos, nucleons and atoms, proton decay, etc...
- In this talk, I will concentrate on **dark sectors** reach of the SHiP experiment.
- **Landscape**: LHC results in brief:
  - Direct searches for **NP** by **ATLAS** and **CMS** have not been successful so far
    - Parameter space for popular **BSM** models is **decreasing rapidly**, but only $< 5\%$ of the complete HL-LHC data set has been delivered so far
    - NP discovery **still may happen**!
  - **LHCb** reported intriguing hints for the violation of lepton flavour universality
    - In $b \to c\mu\nu$ / $b \to c\tau\nu$, and in $b \to se^+e^-$ / $b \to s\mu^+\mu^-$ decays
    - **Clear evidence of BSM** physics if substantiated with further studies (possibly by **BELLE II**)

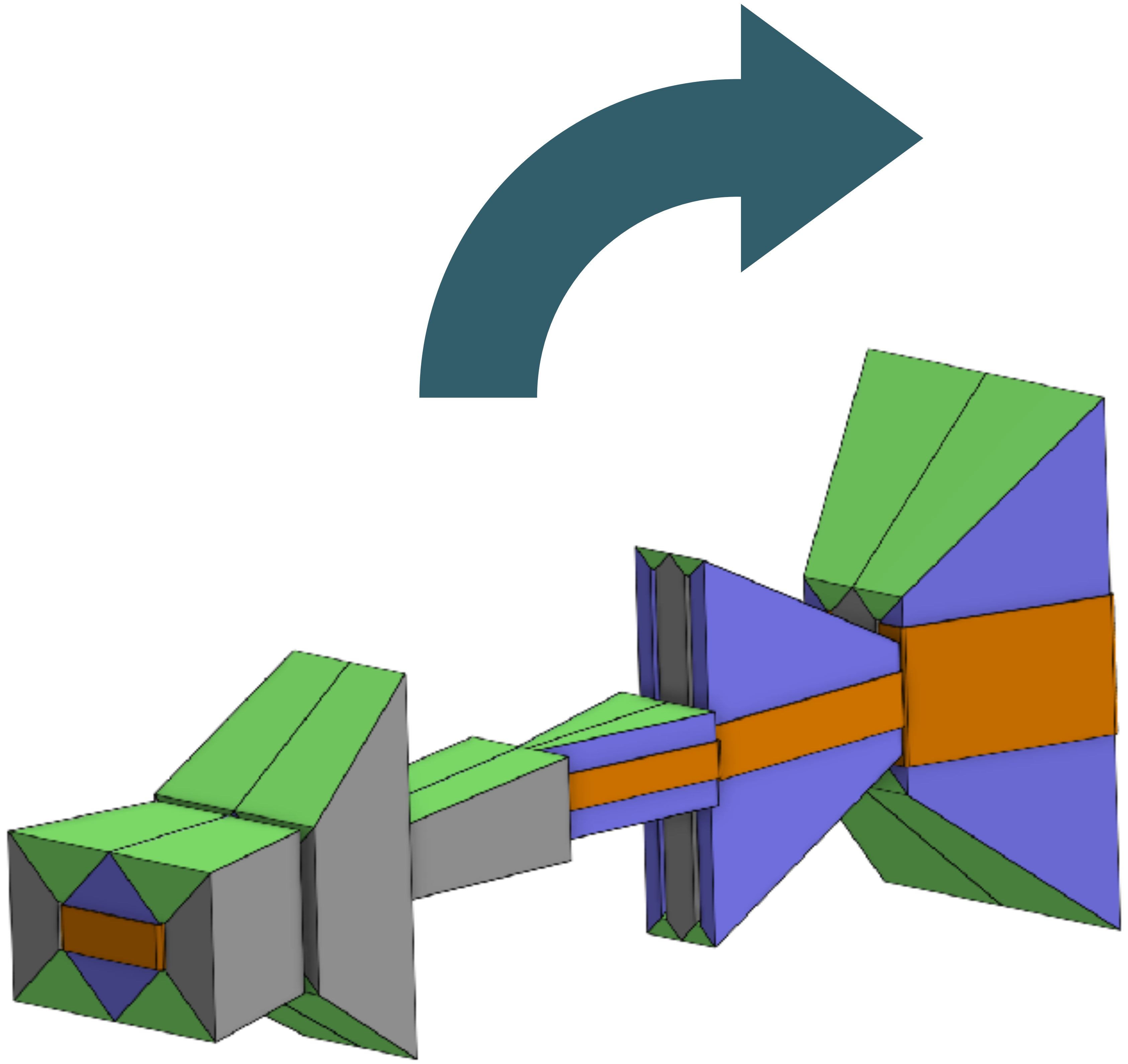
Landscape today / 2

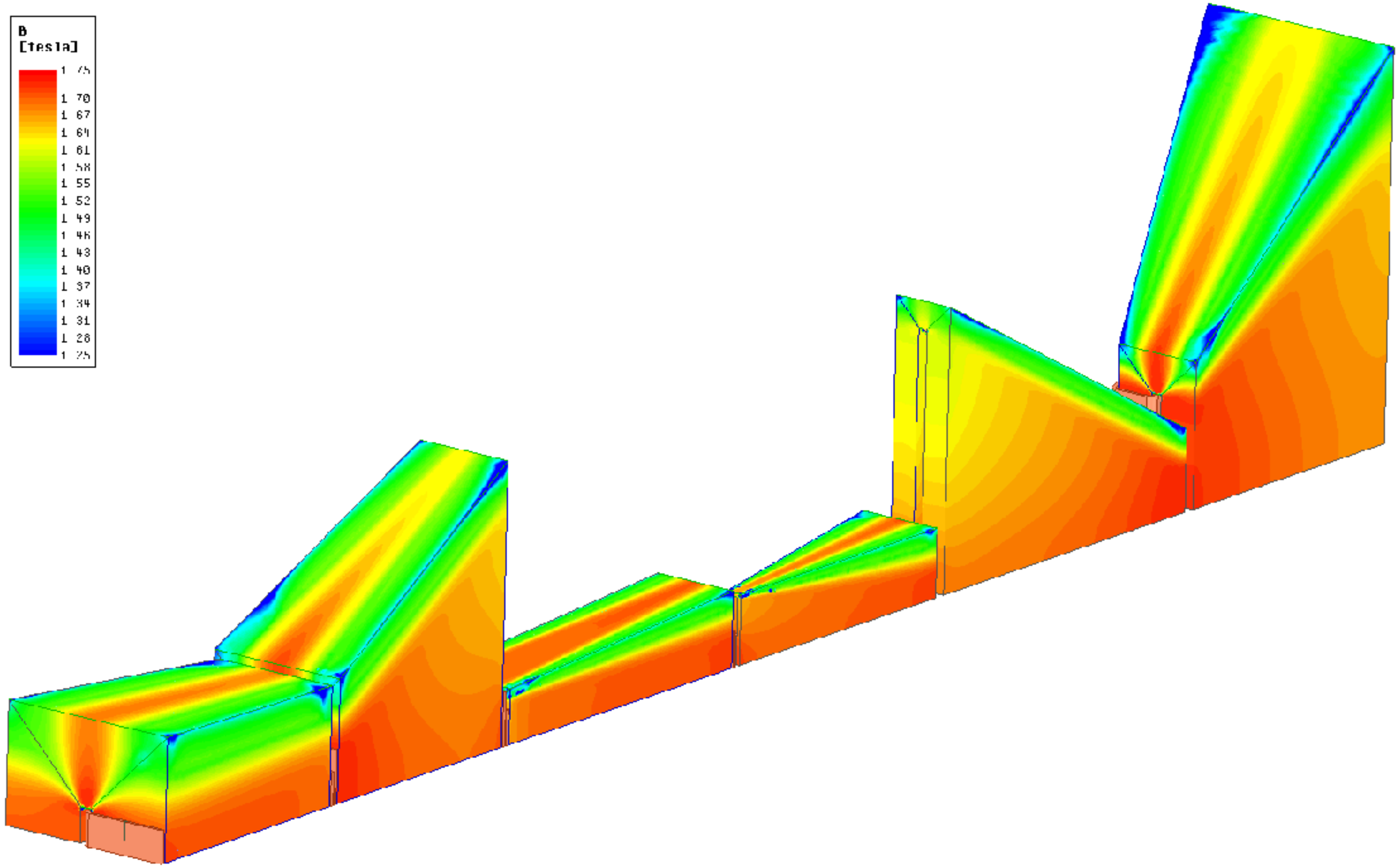
- Therefore, from LHC hints, **strong motivation to search** for
  - Light Dark Matter (**LDM**)
    Portals to Hidden Sector (**HS**) (dark photons, dark scalars)
    Axion Like Particles (**ALP**)
    Heavy Neutral Leptons (**HNL**)
    LFV τ decays
- Many theoretical models (**portal models**) predict new light particles which can be tested experimentally
  - **SHiP Physics Paper**: Rep.Progr.Phys.79(2016) 12420 – arXiv:1504.04855,
    SLAC Dark Sector Workshop 2016: Community Report – arXiv:1608.08632,
    Maryland Dark Sector Workshop 2017: Cosmic Visions – arXiv:1707.04591
- Already **active** (and continuously growing) set of experiments at intensity frontier at CERN (**NA62**, **NA64**, and ~**SHiP**),in Japan (**BELLE-2**) and in US (**LDMX**, **APEX**, **SeaQuest**, **MiniBoone**, **HPS**, ...)

SHiP so far


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 detecto
Iteration 2: Optimization with refined detectors
Simulation campaign
Design and prototyping
Testing and updated performance
Design, performance, cost review
Int.
Ext..
Input to PBC (sensitivity/background)
Test beam to measure muon spectra, σ_{charm} test, etc
Write-up (CDS, supporting documents)
SUBMISSION

SHiP / a realistic magnetic field

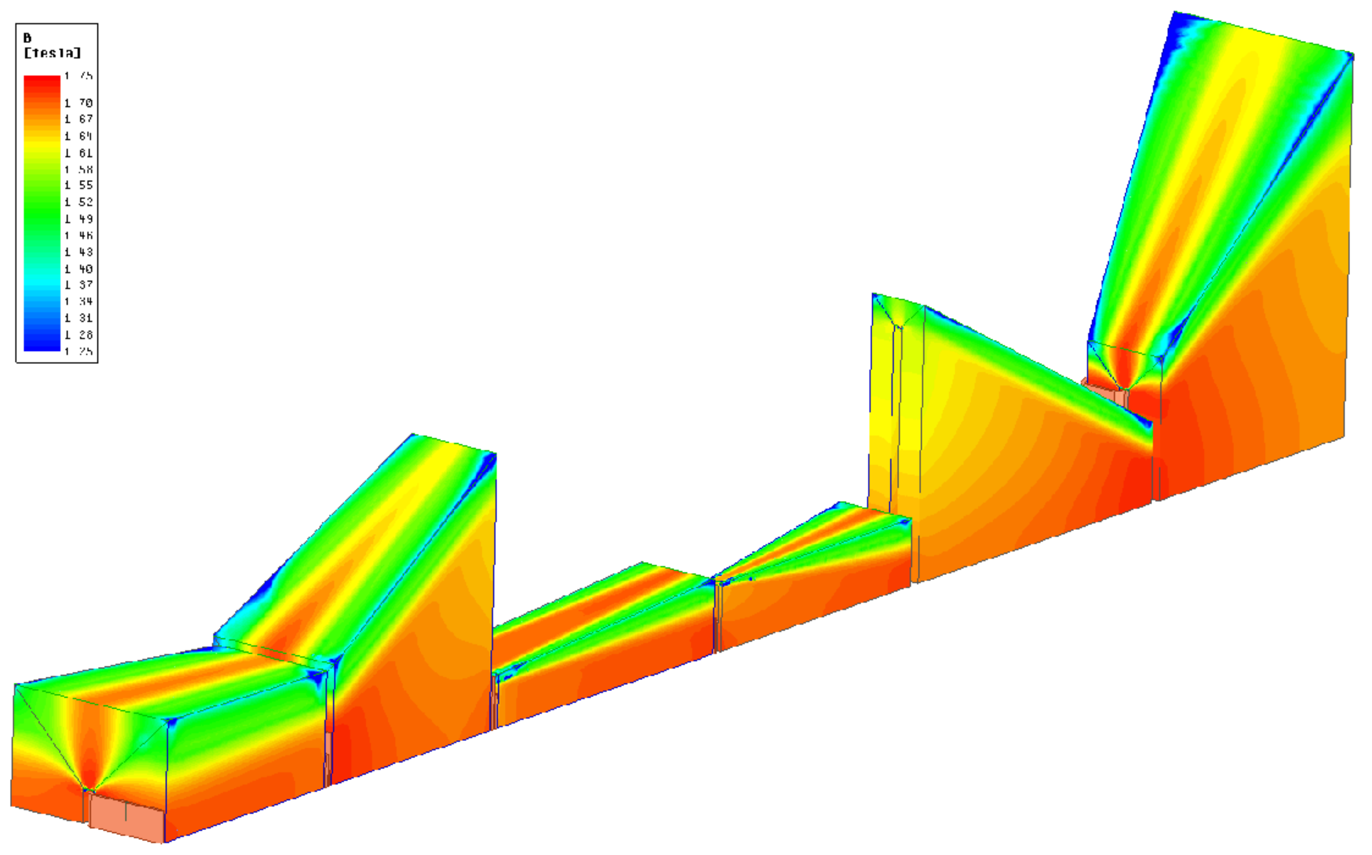


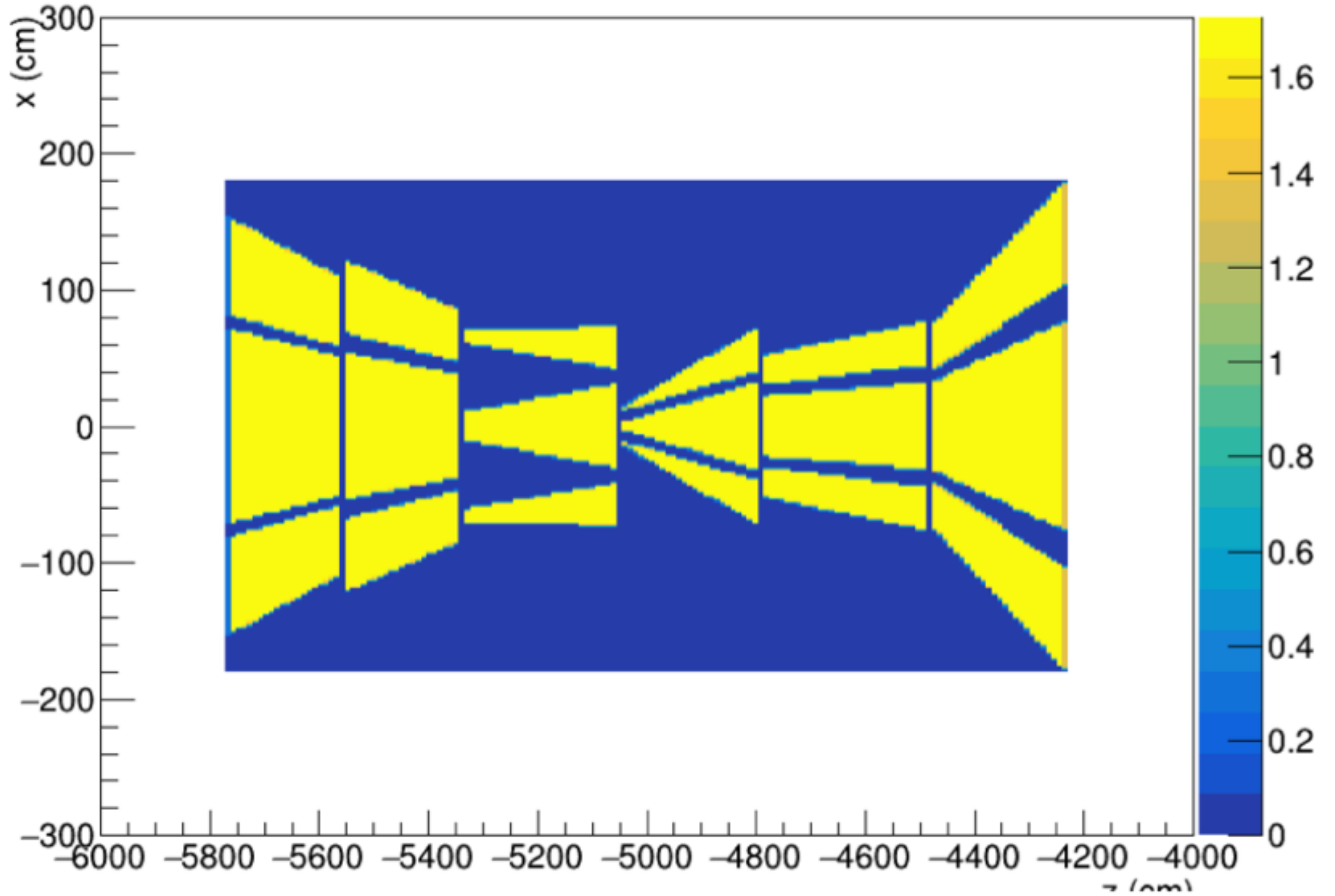


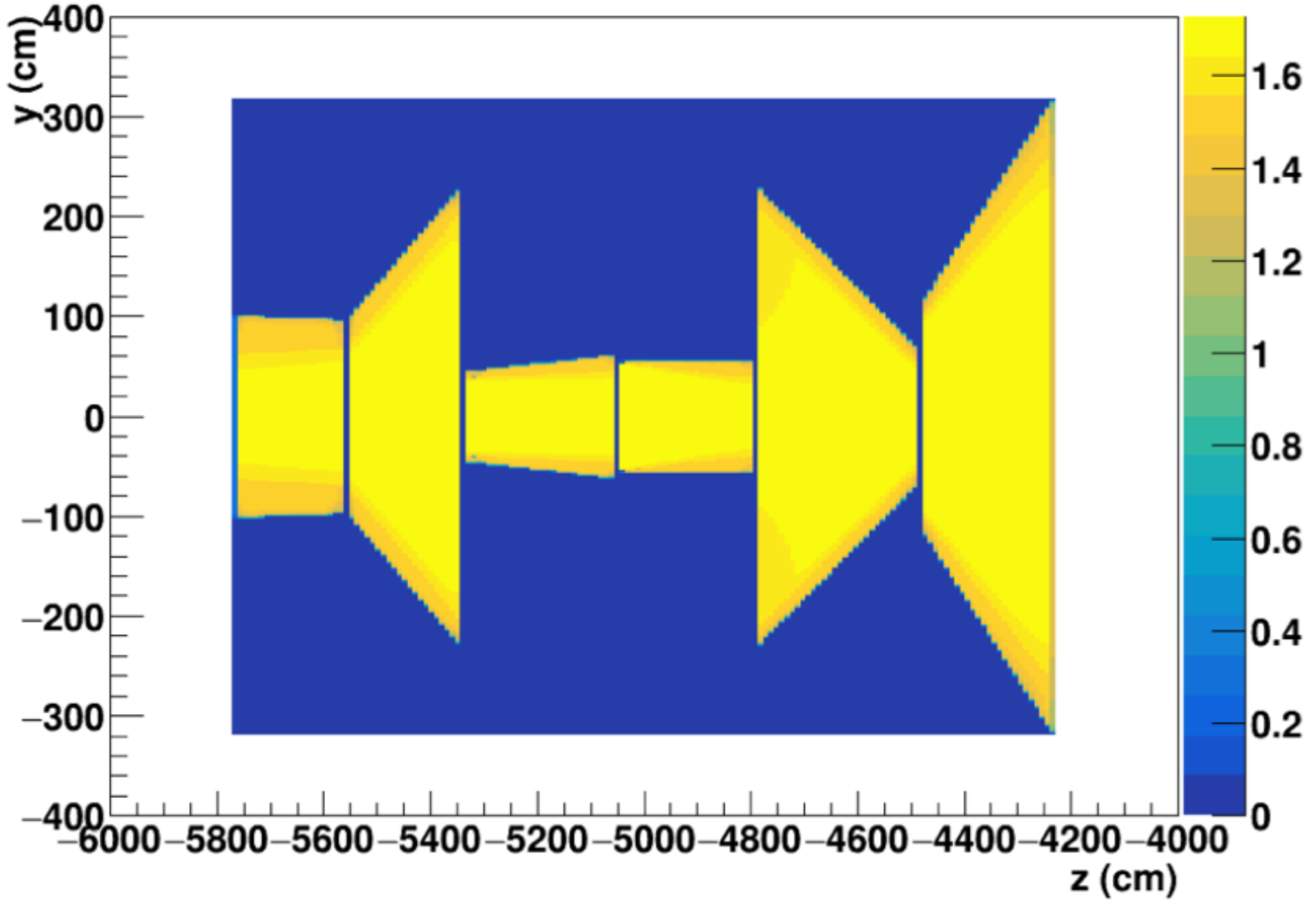
Work of F. Ratnikov (YANDEX)

Federico

SHiP / Last step, back in our simulation!

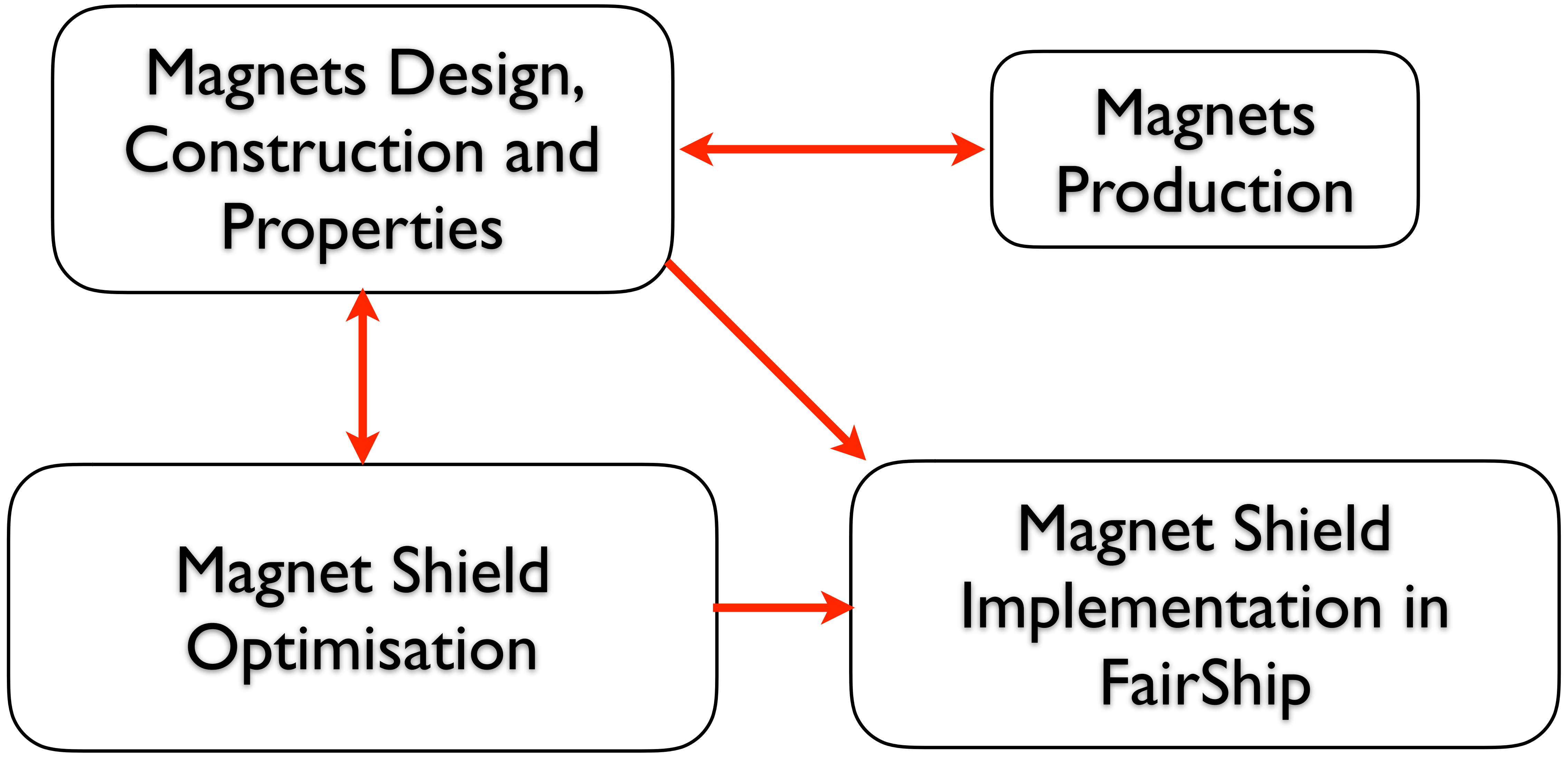






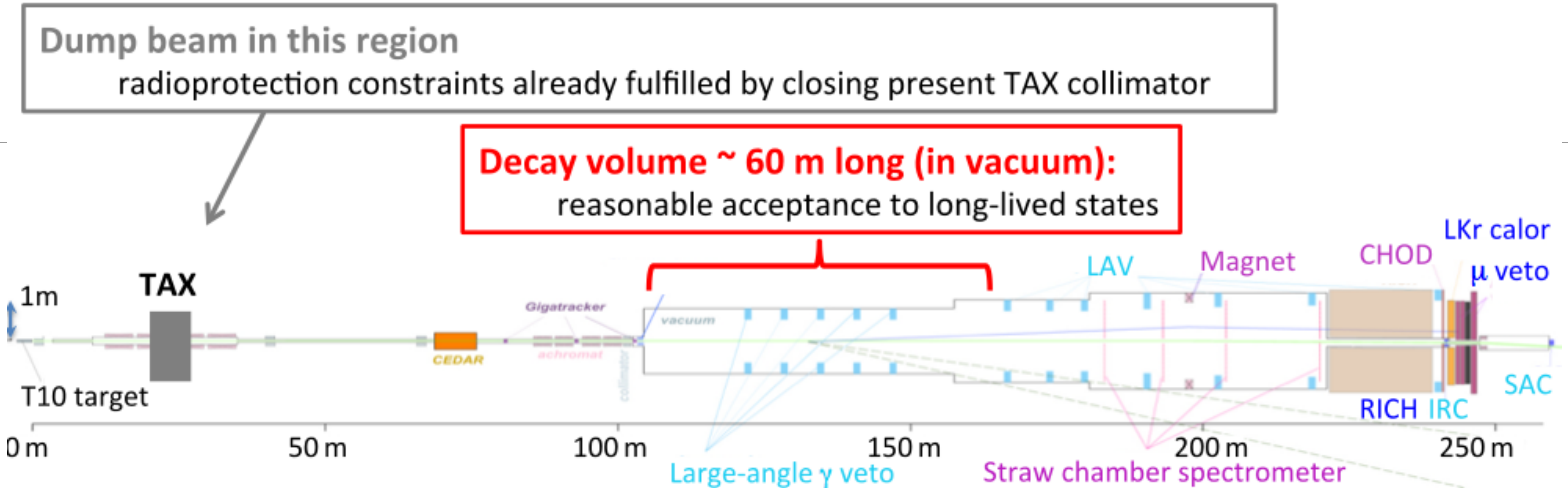
- Using a 2.5 cm map grid (positive quadrant)
- Field map is pretty close to the ideal presentation and edge effects are on distances < ~10 *cm*

SHiP / Muon shield optimisation



- The problem is extremely complex:
    1. Magnet shield optimisation per se
    2. Magnet design construction and properties (plus production)
    3. Magnet shield implementation in our simulation
- ~50 D optimisation problem of a 2.7 Gb object
- Our Ultimate goal
    - Optimal configuration at new boundary conditions within a week
    - Get performance of the given configuration within a day

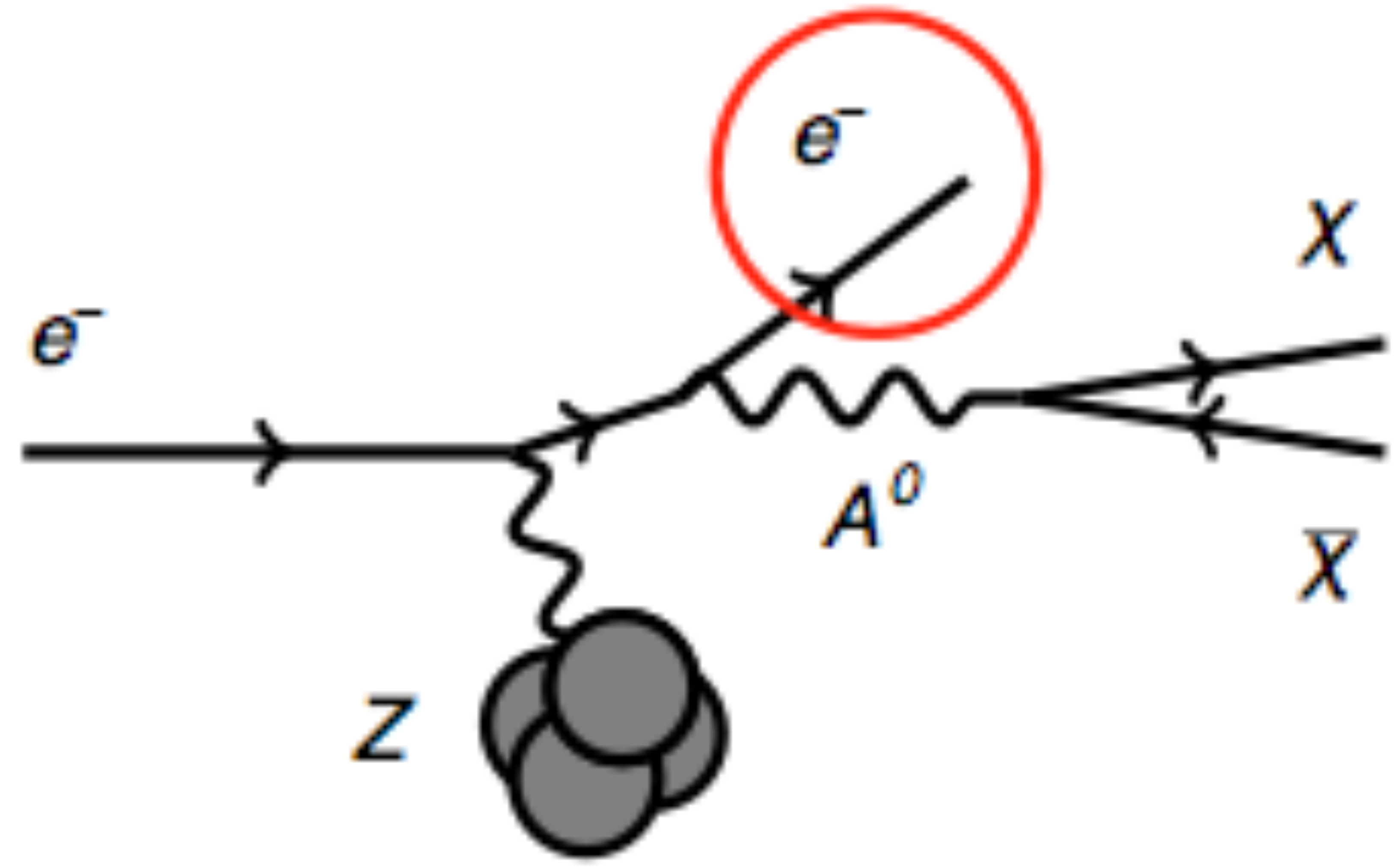
NA62+

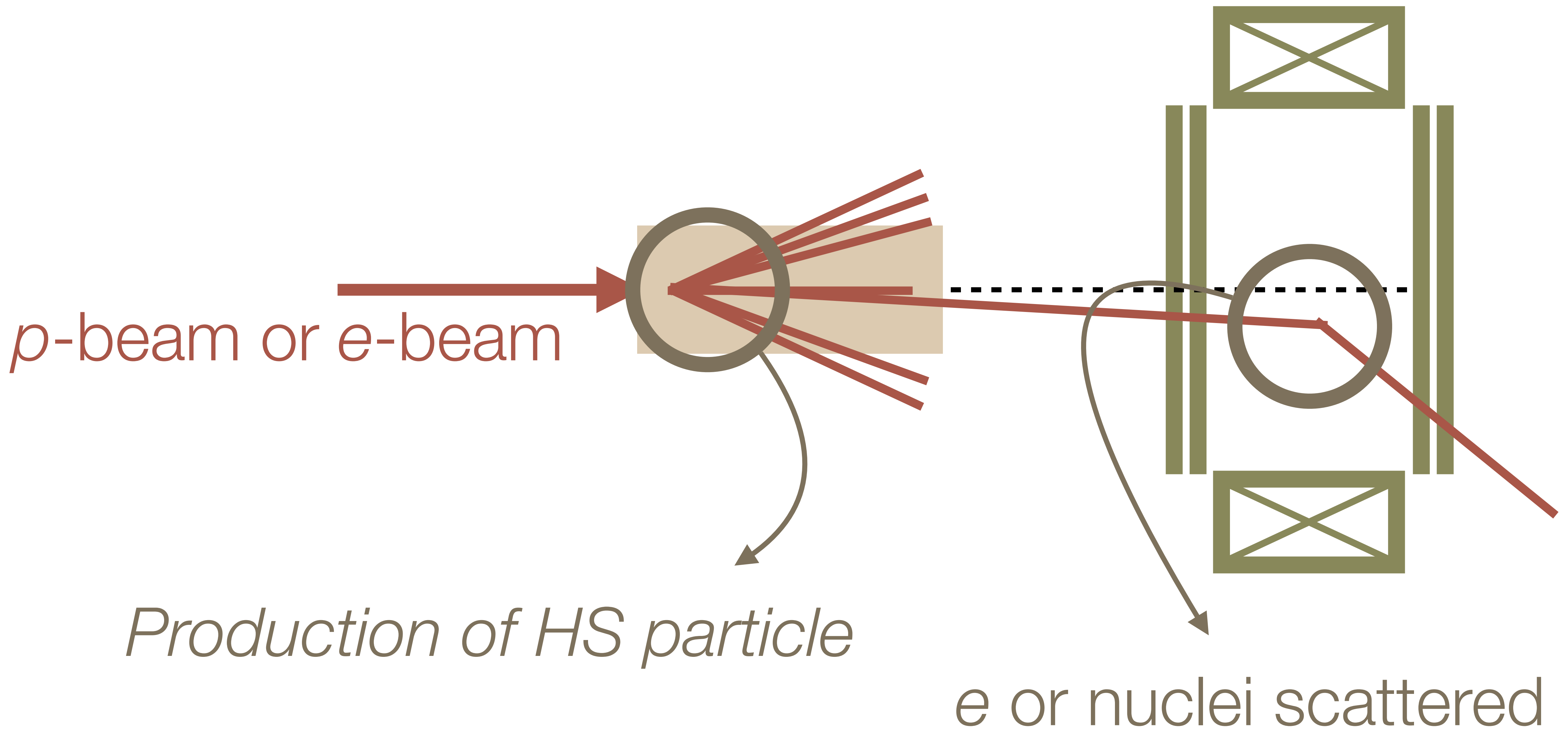


- NA62 **currently collecting** data at SPS to study kaon physics ($K^+ \rightarrow \pi^+ \nu\nu$)
- Will start exploring a part of SHiP physics programme in **2020**
  - NA62+ will run in a beam dump mode at the beam intensity ~1e12 POT/sec on spill
    - **~1e18 POT/nominal year** ~80 days
    - while the large majority (~85%) of the beam time will be dedicated to kaon physics
  - **No muon shield** and consequently high combinatorial muon background
  - But **very precise detector** may reach interesting sensitivity in exclusive decay channels

Exploring the dark sector / 3

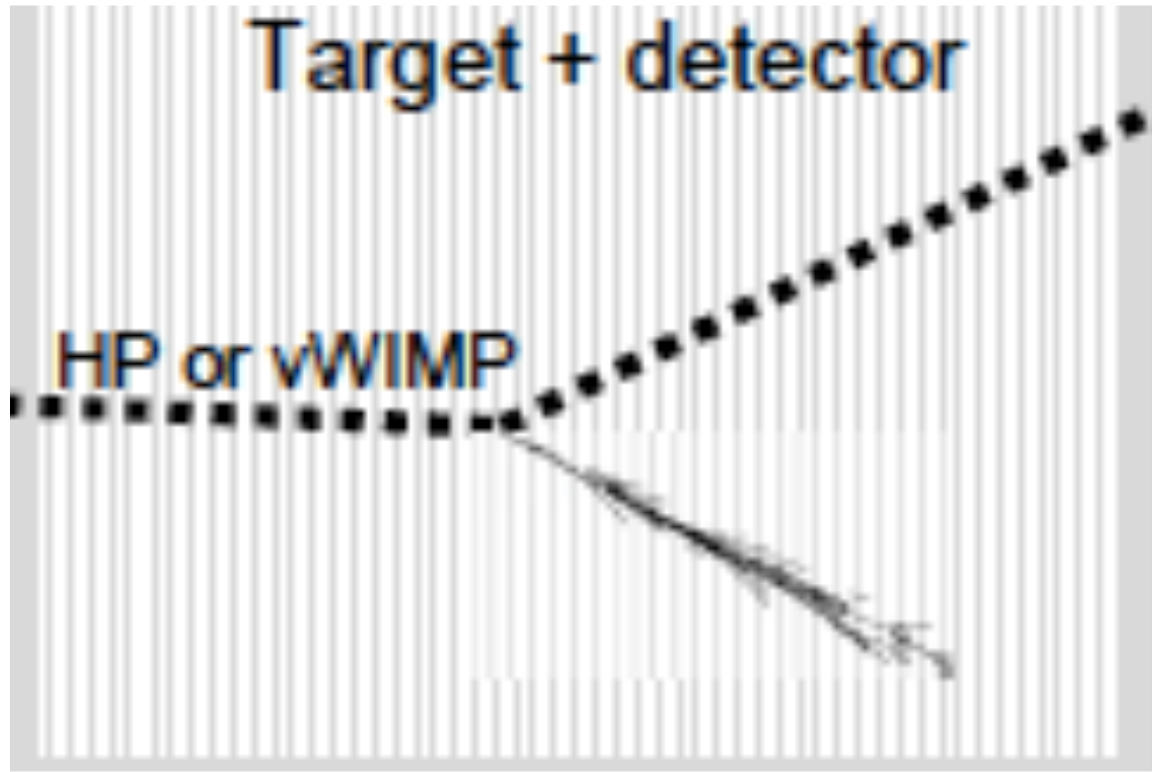
- *Decaying in the detector*
  - *Reconstruction of decay vertex*
- **Not decaying in the detector**
  - **Missing energy technique**
  - **Scattering technique: electron or nuclei scattered by DM**

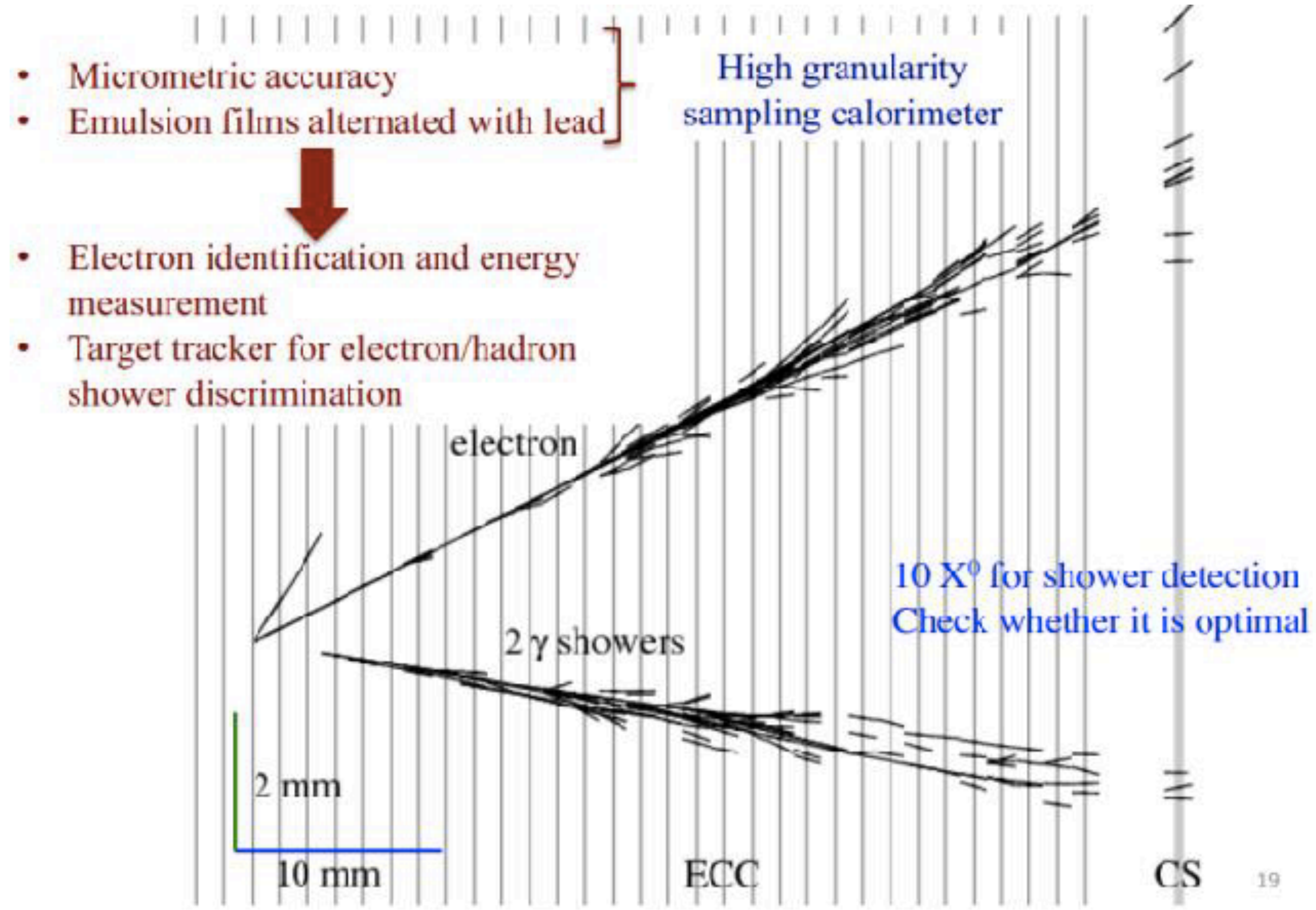




Not decaying dark sector candidates / iSHiP / 1

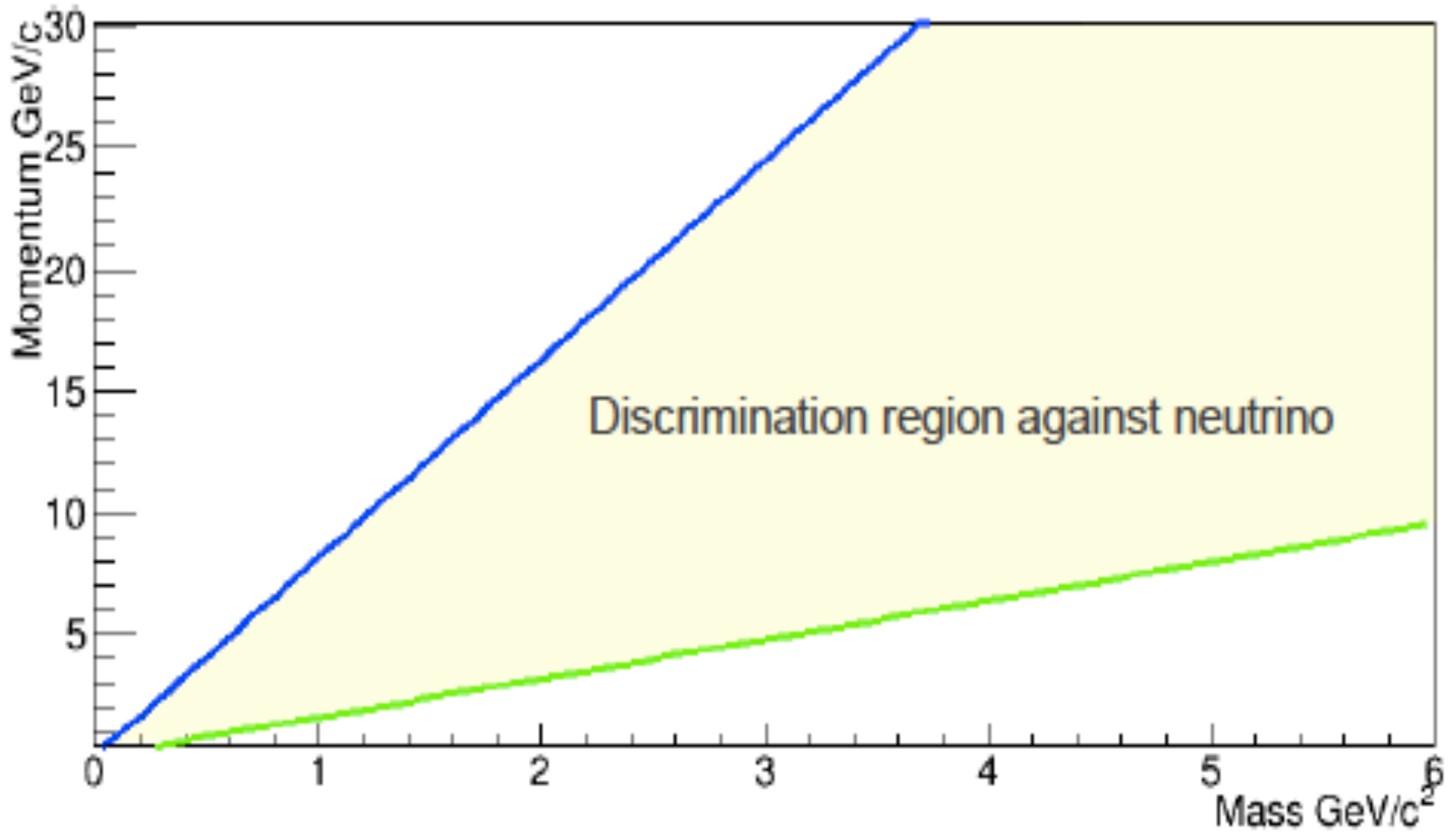
- Not decaying dark sector candidates can scatter on atoms of the dense material of the SHiP **emulsion detector** (iSHiP) giving detection signature: EM shower (or nuclei recoil)
  - Reconstruction of the EM showers in emulsion demonstrated with OPERA data
  - *Complement emulsion detector with fast electronic Target Tracker to improve electron reconstruction (SciFi ? -> SPS test beam July 2018)...*

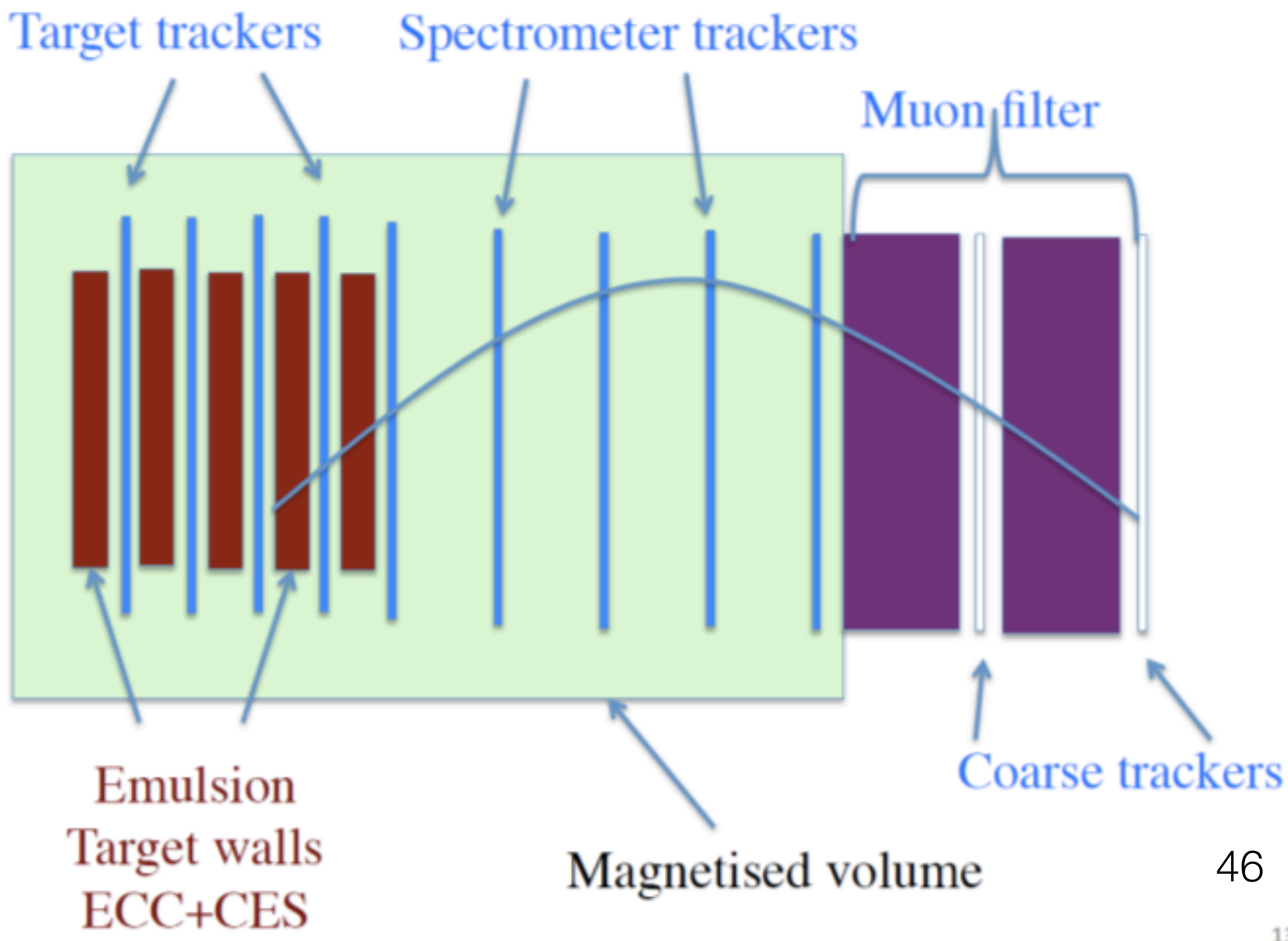




Not decaying dark sector candidates / iSHiP / 2

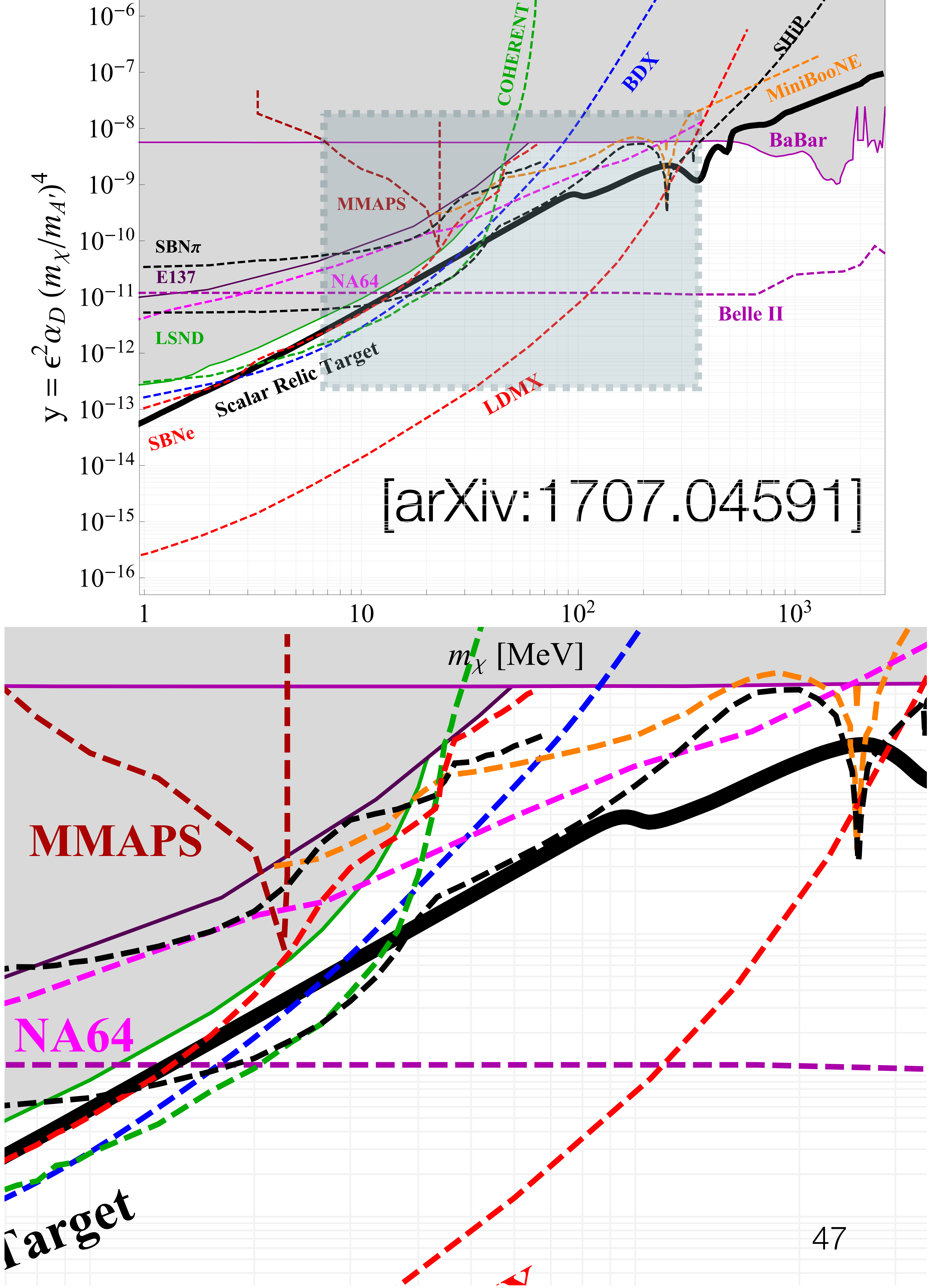
- Complement emulsion detector with fast electronic Target Tracker to improve electron reconstruction (SciFi ? → SPS test beam July 2018)
- Under study: Elimination of the neutrino background by ToF operating with the SPS bunched beam: 4σ /spacing = 1.5ns / 25ns & ~40 m distance from the target
- Requires 0.5 ns time resolution of the Target Tracker



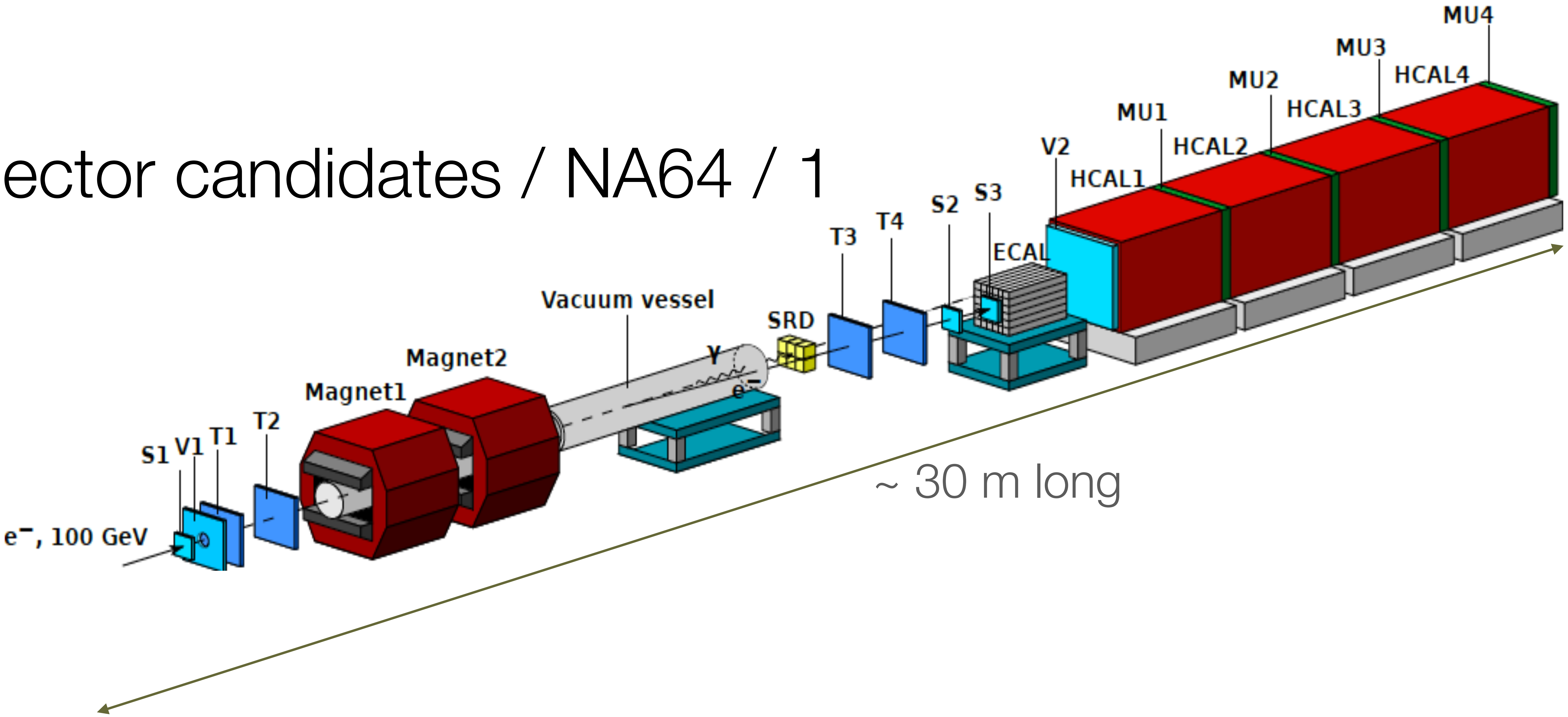


Light dark matter limits / e.g. scalar

- Missing mass/energy technique (applicable only for the models with dark photon mediator)
  - **Belle II** with 50 ab-1 provided that low energy mono-photon trigger works
  - **LDMX** (under discussion at SLAC) has the best prospects for Mχ < 100 MeV
- Detection via scattering
  - **SHiP** has the best sensitivity in 20 – 200 MeV
  - Optimisation is ongoing
  - **COHERENT**, **BDX** and **SBN** in US
- An interplay between the sensitivity, the mass of the vWIMP target and the distance from the dump



Not decaying dark sector candidates / NA64 / 1



- 47 researchers from 12 Institutes (Swiss participation 15%, ETHZ), **proposed in 2014**, first test beam in 2015 (2 weeks). Proposal (P348) was approved by CERN SPSC in March 2016 → **NA64**. In 2016 two runs of 2 and 3 weeks. In 2017 one run of 4 weeks. For 2018, **6 weeks are foreseen** (~ 4e10 EOT/week)

- Key features
  - SPS 100 GeV electron beam
  - Magnetic spectrometer (trackers (**ETHZ**) + bending dipole)→momentum reconstruction of primary particle
  - Synchrotron radiation detector (**ETHZ**) → primary electron identification
  - Electromagnetic calorimeter (**active beam dump**)
  - Hadronic calorimeter (**hermeticity**)

E. Depero (ETHZ) et al., NIMA866 (2017) 196-201 (Synchrotron radiation detector)

D. Banerjee (ETHZ) et al., NIMA881 (2018) 72-81 (Multiplexed micromegas tracker)