

Introduction to SHiP and Activities at IJCLab

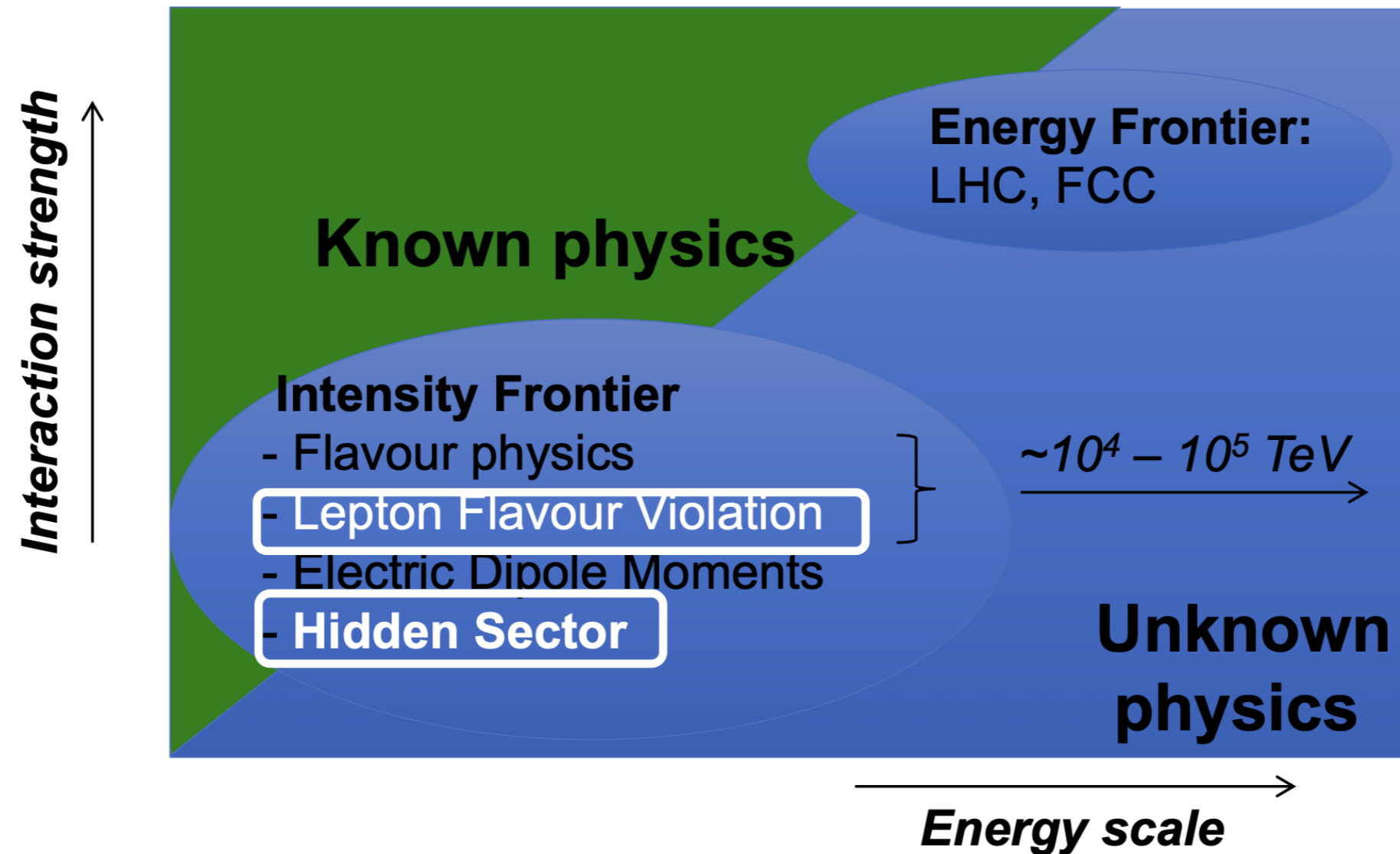
Roman Pöschl

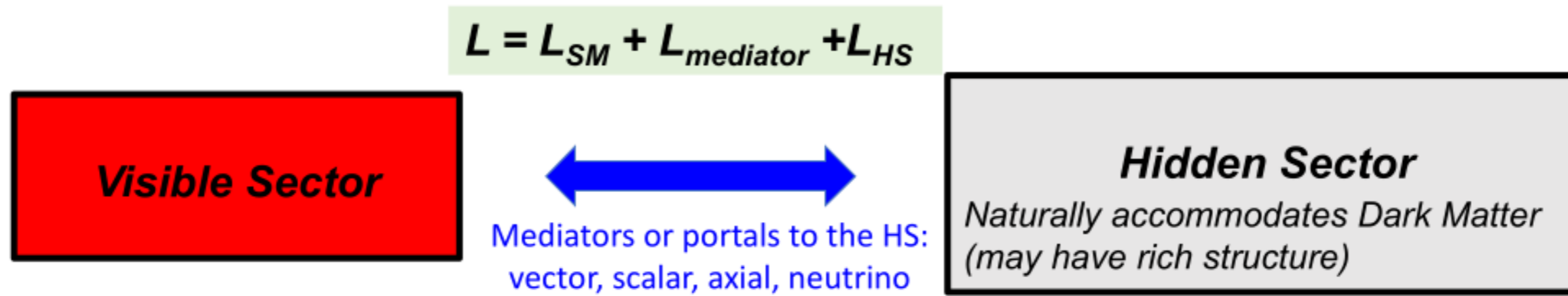


Dark Matter Day 2026 IJCLab

Disclaimer: I am still in a learning phase,
Will focus on topics relevant for Work at IJCLab
Many slides “stolen”
from Andrei Golutvin and Matei Climescu
Further material from (nice)
Master Thesis by Elias Svensson (Chalmers University)
See also: SHiP input to EPPSU (2504.06692)
SHiP Physics Case (1504.04855)
Sensitivity of SHiP to Dark Matter (2010.11057)

- Higgs discovery made the SM complete
- Standard Model is a great theory but does not represent the full picture
- New Physics should exist but we have no definitive predictions on the masses and coupling constants of NP particles





- ✓ *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*
 - *May decay to various final states*

Portal models	Final states
HNL Vector, scalar, axion portals	$l^+\pi^-, l^+K^-, l^+\rho^-$ l^+l^-
HNL Axion portal	$l^+l^-\nu$ $\gamma\gamma$

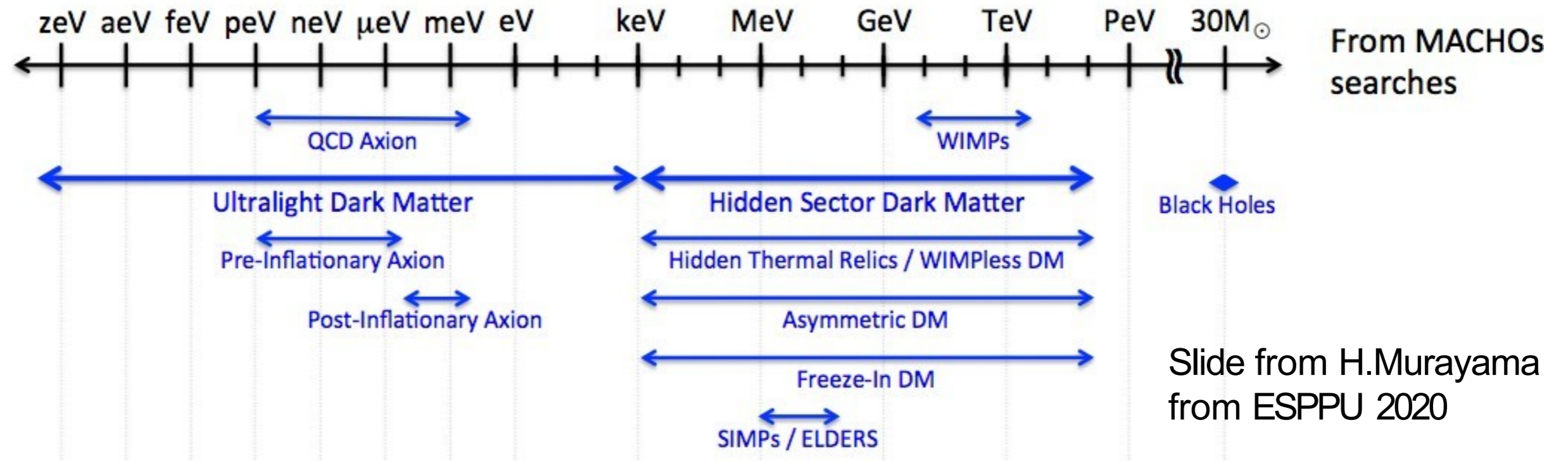
Full reconstruction and PID are essential to minimize model dependence

Experimental challenge is background suppression



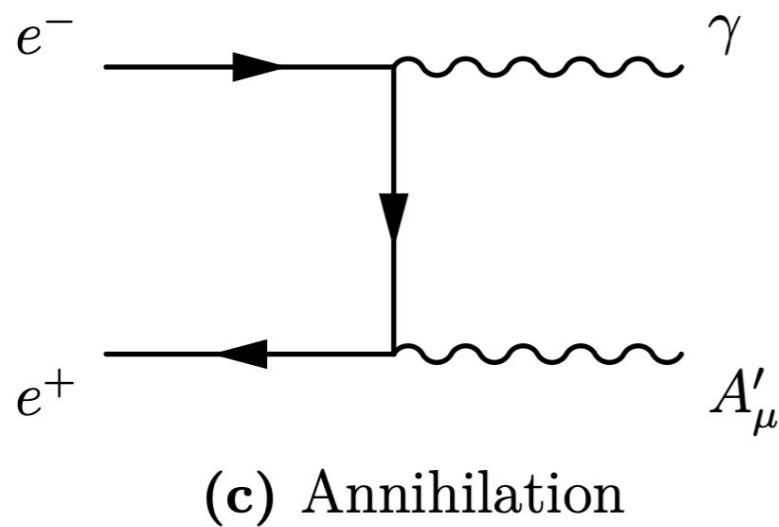
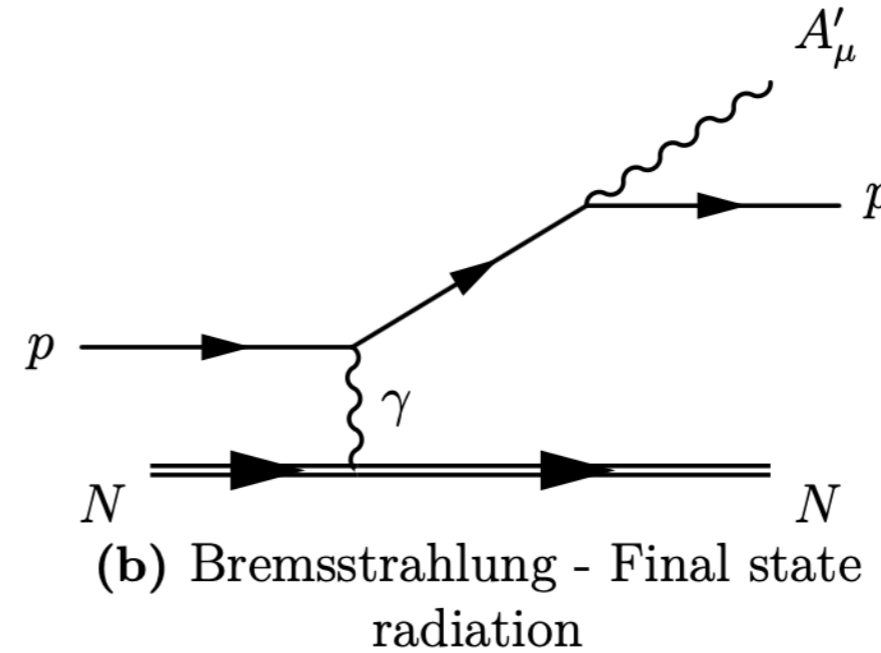
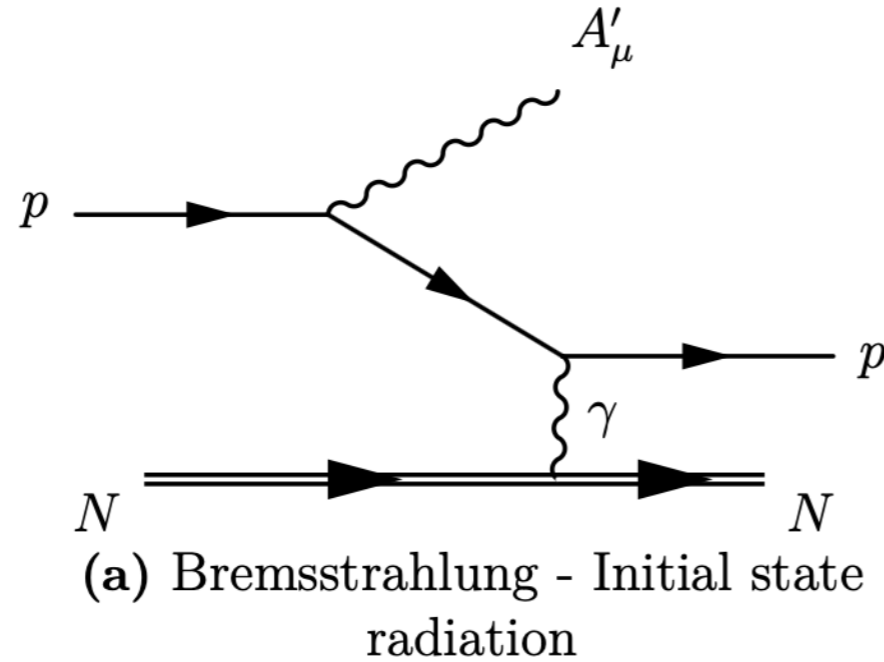
Dark Matter Candidates: Very little clue on mass scales

Too small mass
 ⇒ won't "fit"
 in a galaxy!

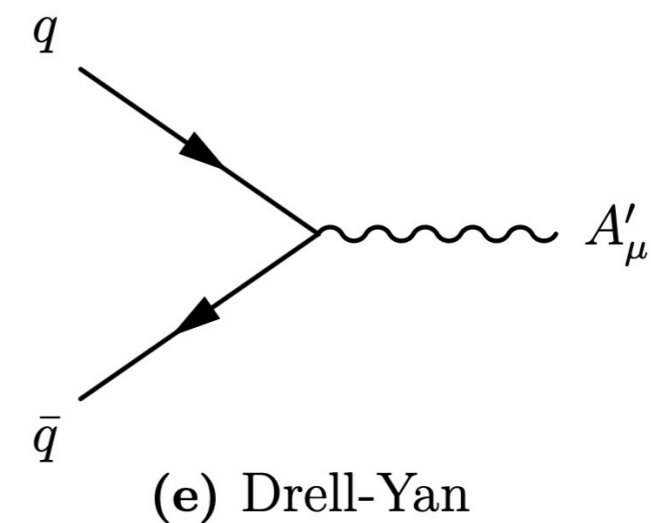
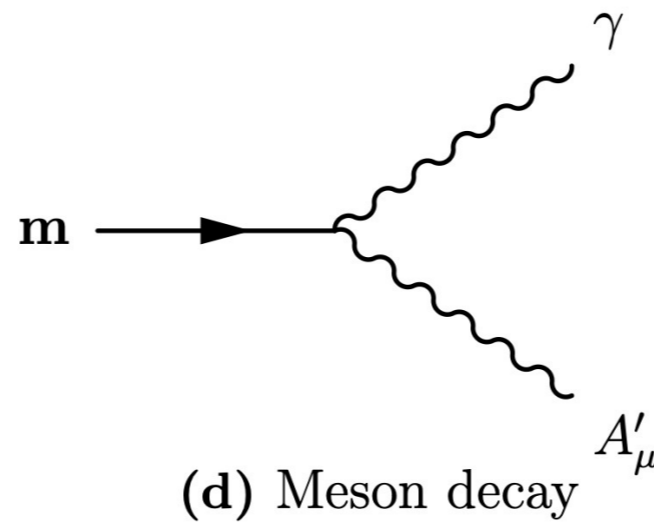


Slide from H.Murayama from ESPPU 2020

The prediction for the mass scale of Dark Matter particles spans from 10⁻²² eV (ALPs) to 10²⁰ GeV (Wimpzillas, Q-balls)



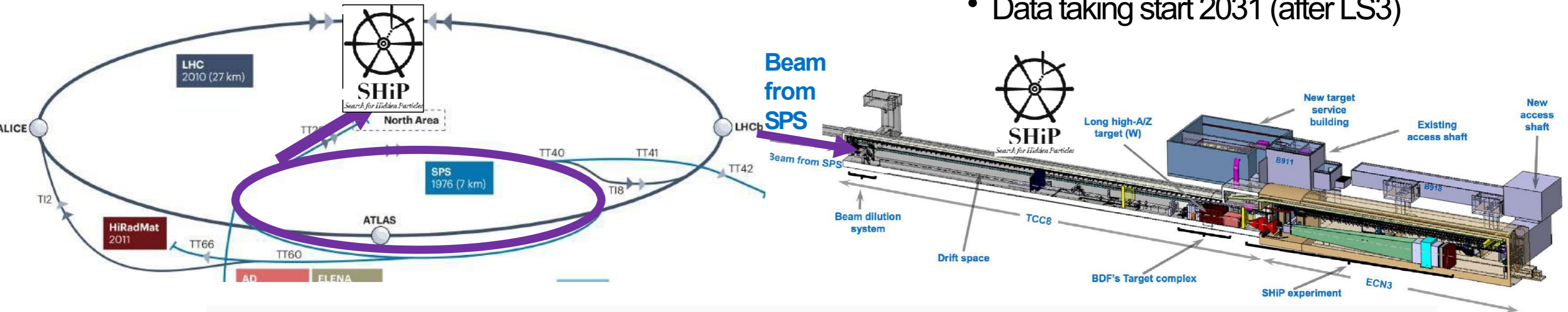
Irrelevant at SHiP



Subdominant at SHiP

- Idea for “Search for Hidden Particles” experiment formulated in 2013
- SHiP is an approved CERN experiment since 2024
 - “Approved” means that CERN agreed to refurbish the Beam Dump Facility in the ECN3 experimental hall

CERN Accelerator Complex



- 6×10^{20} protons in 15 years
- Data taking start 2031 (after LS3)

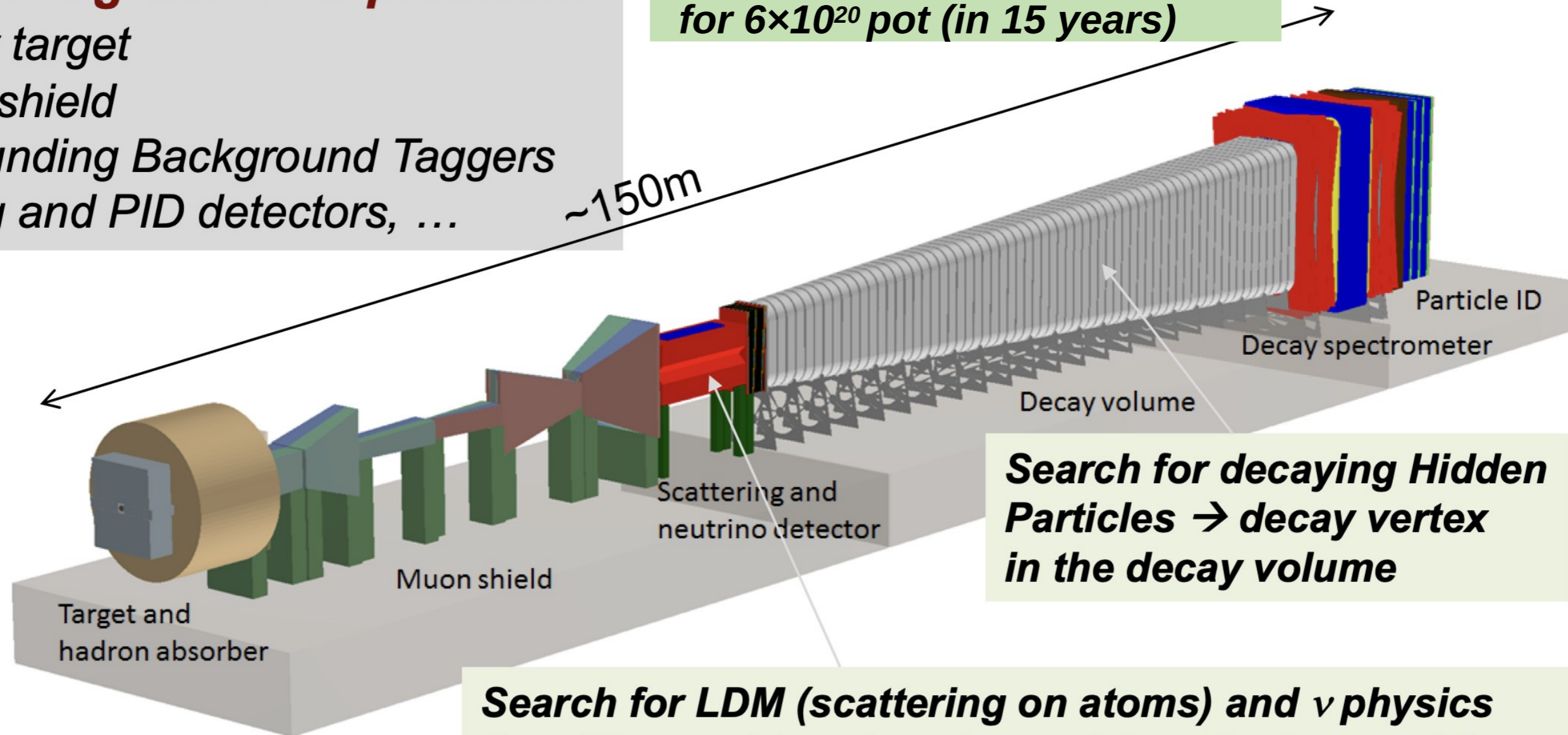
Accelerator schedule	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	
LHC	Run 3		LS3					Run 4		LS4			
SPS (North Area)													
BDF / SHiP	Design and prototyping		Production / Construction / Installation									Operation	Complete detector / consolidation
Milestones BDF	TDR studies		PRR						CwB				
Milestones SHiP	★	TDR studies		PRR				CwB	CwB				

★ Approval for TDR
 Facility TDR submission
 Experiment TDRs submission
 Start of detector installation
 Facility commissioning
 Experiment commissioning & start of data taking

“Zero background” experiment

- Heavy target
- Muon shield
- Surrounding Background Taggers
- Timing and PID detectors, ...

$>10^{18} D$, $>10^{16} \tau$, $>5 \times 10^{15} \nu_\tau$
 for 6×10^{20} pot (in 15 years)



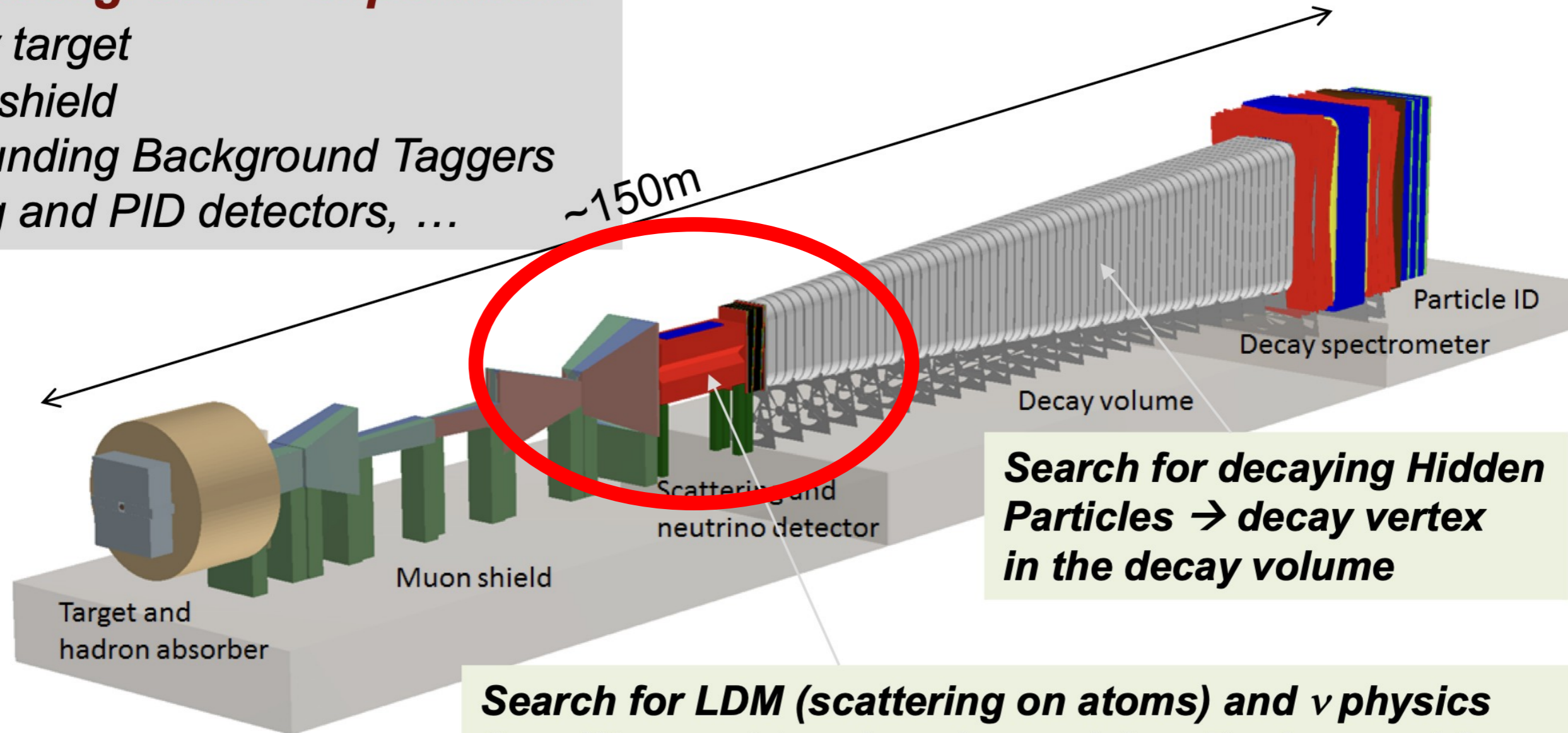
Search for decaying Hidden Particles → decay vertex in the decay volume

Search for LDM (scattering on atoms) and ν physics
Specific event topology in emulsion. Background from neutrino interaction for LDM searches can be reduced to a manageable level

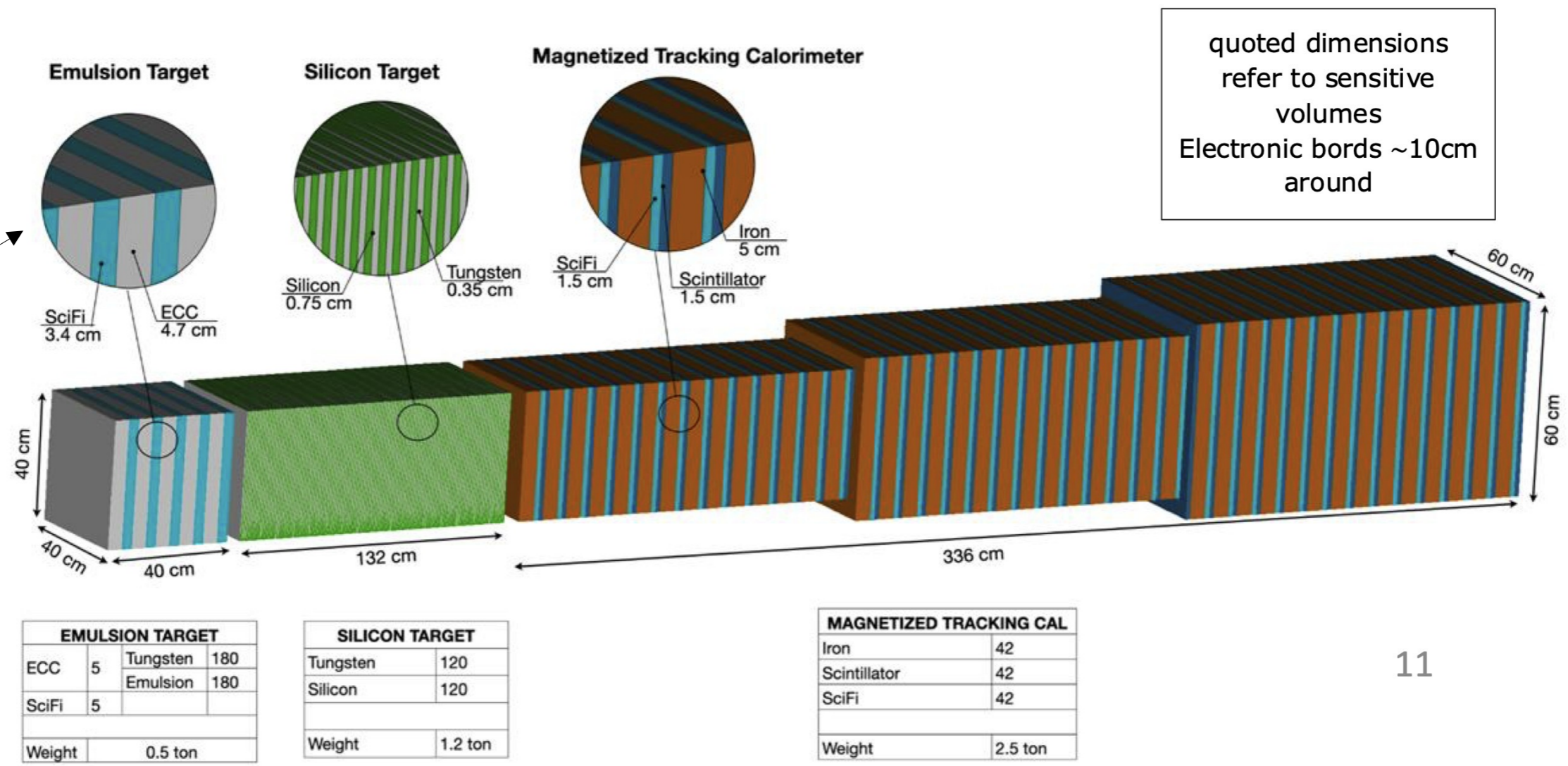
Andrei Golutvin
 SHiP Spokesperson

“Zero background” experiment

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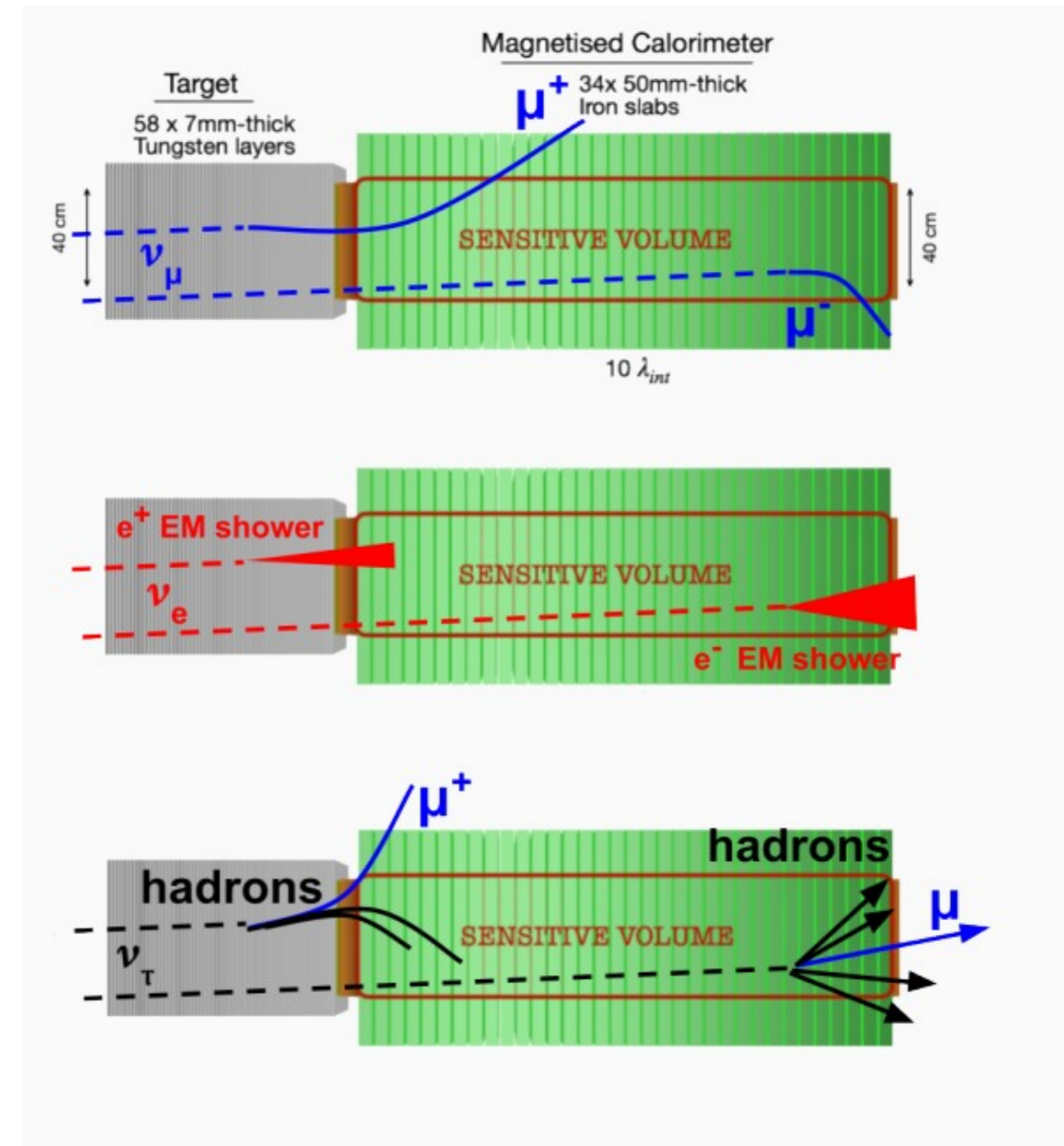
Discarded
"too slow"

11

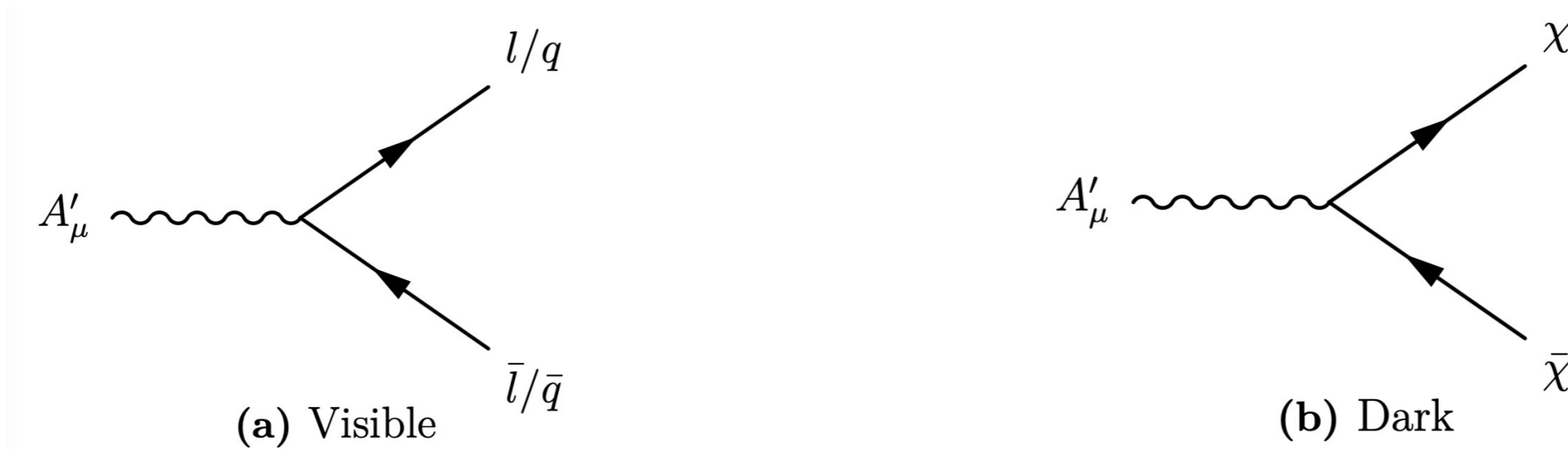
- "Currently" SND is composed of two types of detectors
 - Silicon Target with W as absorber and silicon strips (100 um x 40 cm arranged in xy) detectors as sensitive material
 - Magnetised Tracking Detector with scintillating tiles (5x5 cm²) supported by LHCb like scintillating fibre detectors
- Room for another technology?

- ν_μ : straightforward, nothing come in and a track comes out, tell apart parity using muon bending
- ν_e : more challenging, nothing come in and an electromagnetic shower takes place inside of your detector. Parity is complex to identify.
- ν_τ : challenging as τ s have many possible decays, look for nothing coming in and a vertex associated to multiple tracks. Parity obtained by looking at charge of everything through the bending.

In particular τ -decay may (will) benefit from Full kinematic reconstruction

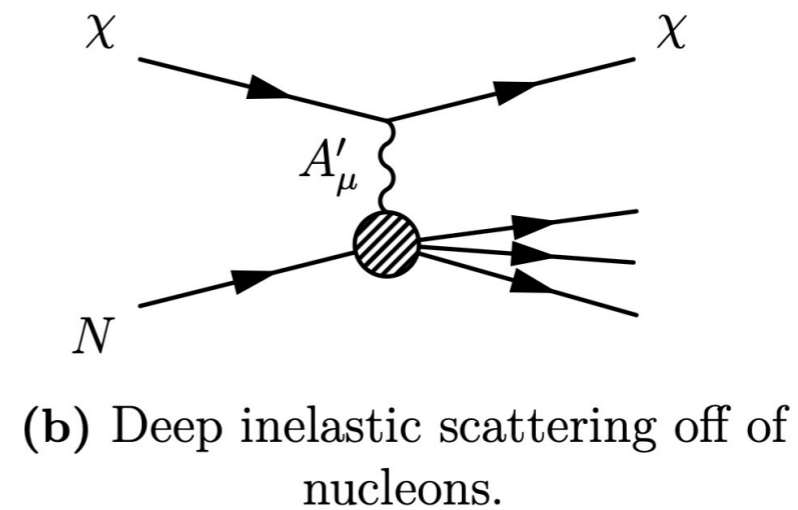
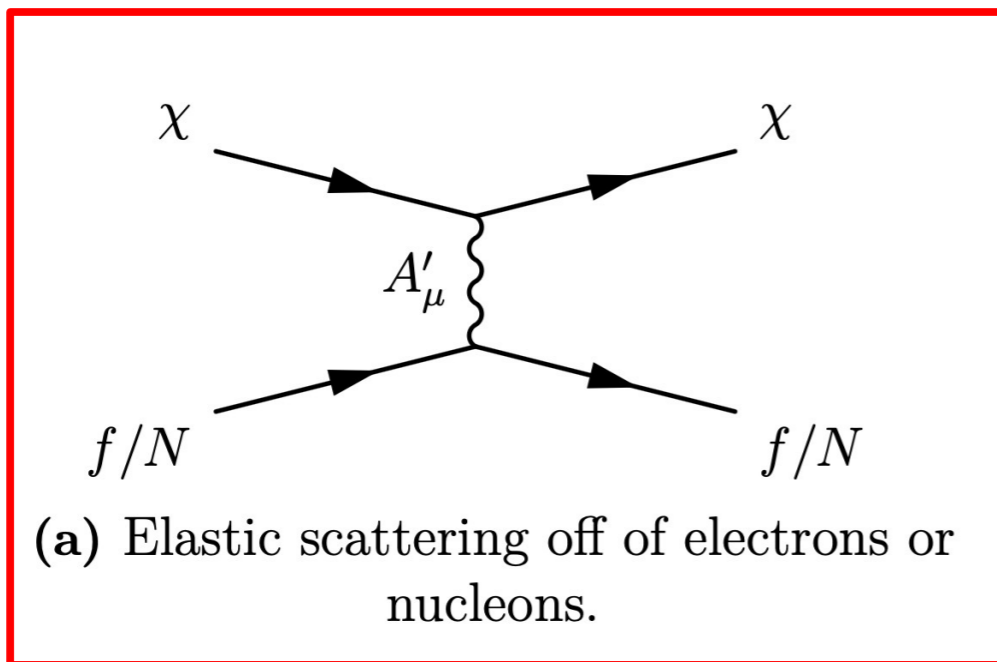


Decay of Dark Photon

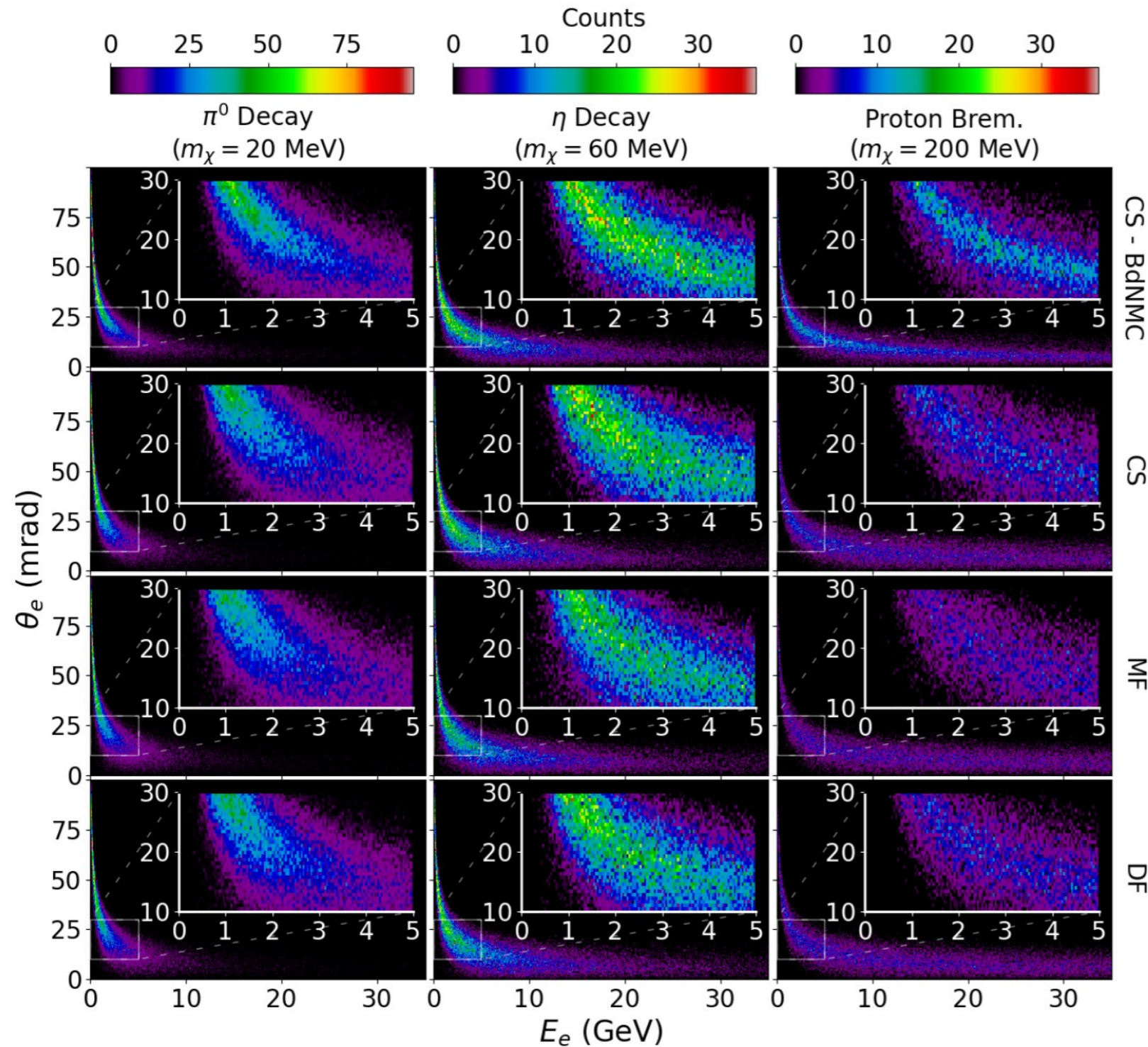


Dominates if:
 $M_{A'} > 2M_\chi$

Scattering of Dark Particles



Highest
 Sensitivity!
 ->
 Requires
 granular
 calorimeter

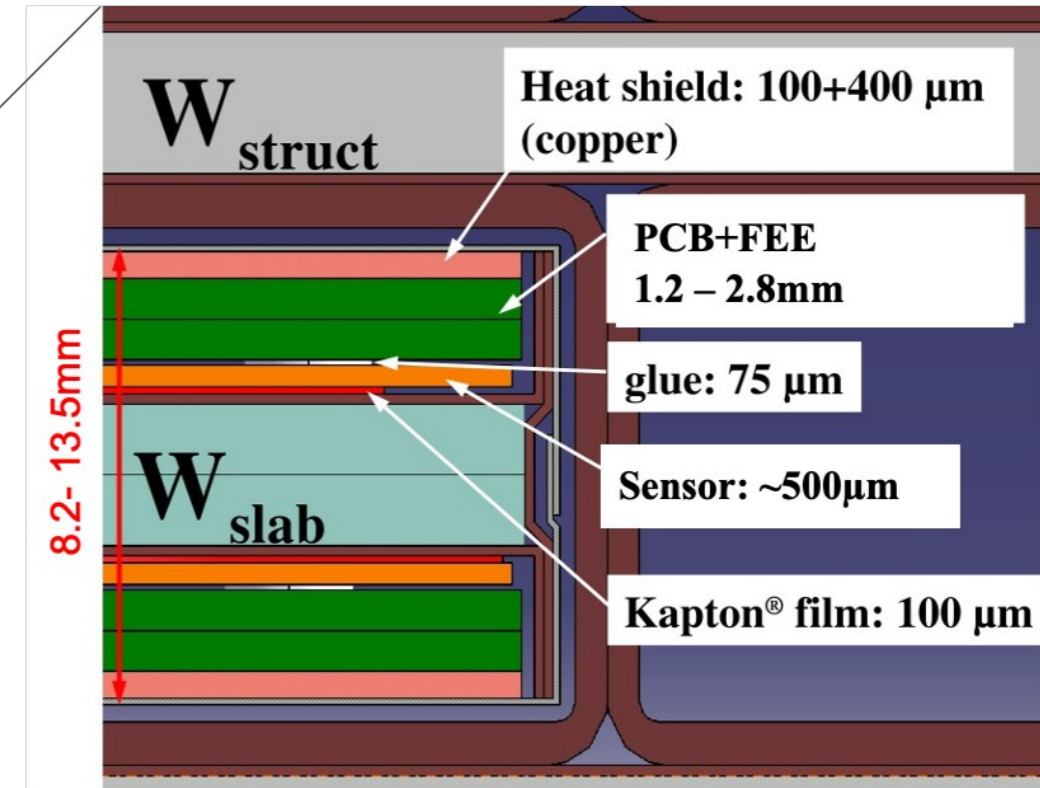
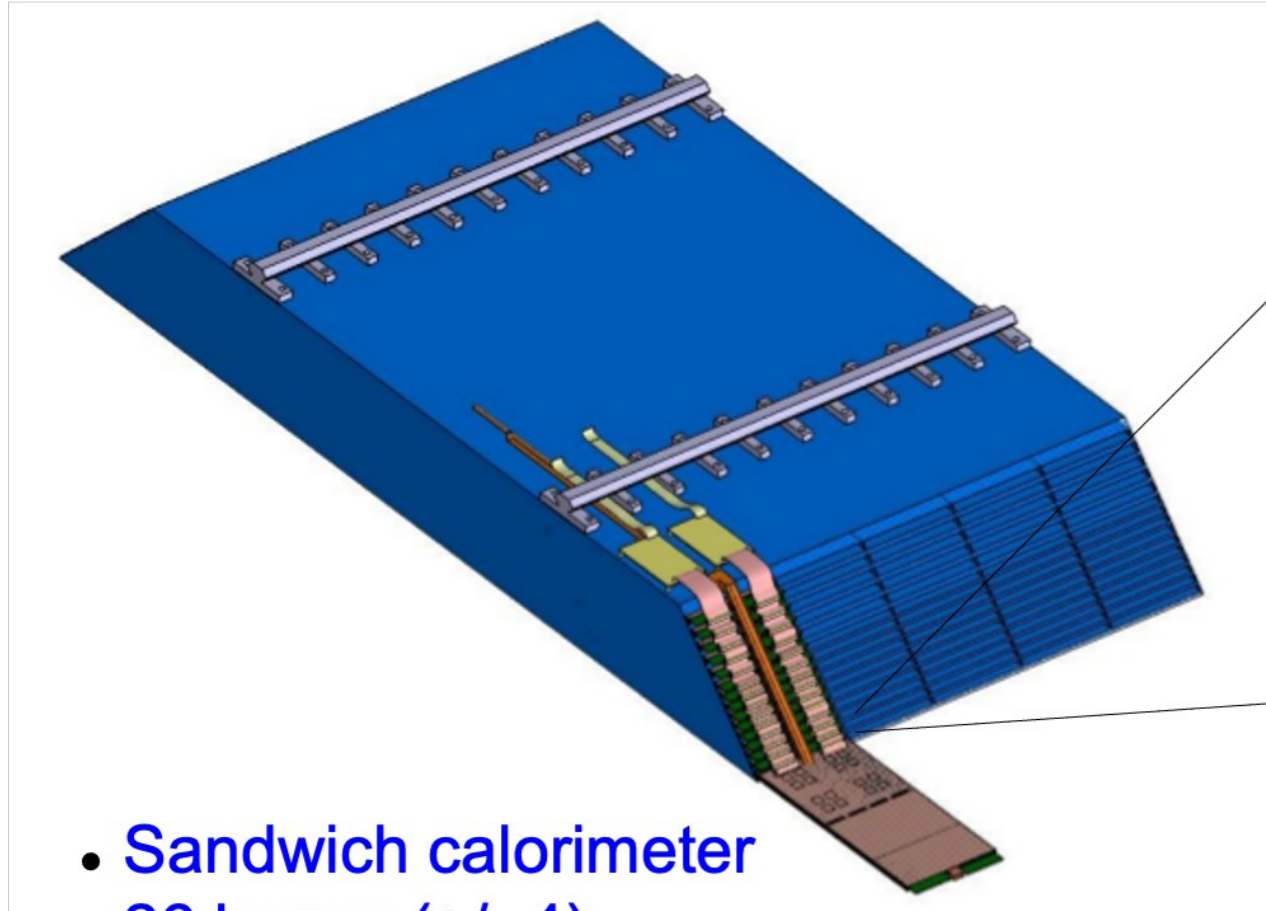


- Energies of scattered electrons $\sim 1-5$ GeV
- Scattering angle 10-20 mrad
- Excellent parameter space for SiPad Detector

CS = Complex Scalar
 MF = Majorana Fermion
 MD = Dirac Fermion
 BdNMC = BdNMC Generator
 else Maddump

Master Thesis by Elias Svensson (Chalmers University)

Ecal alveolar structure



- Sandwich calorimeter
- 26 layers (+/- 4)
- Thickness: $\sim 20\text{cm}$, $24 X_0/1\lambda_1$
- Pixel size $\sim 5 \times 5 \text{ mm}^2$
- Expected elm. energy resolution $15\text{-}20\%/\sqrt{E}$

- Overall height of a layer w/o absorber $\sim 3.5\text{mm}$
 - Glue might be rather 100-200 μm
 - PCB + FEE $< 2.8\text{mm}$
 - Layer housing would add
 - Typically thin carbon frames in case of SHiP

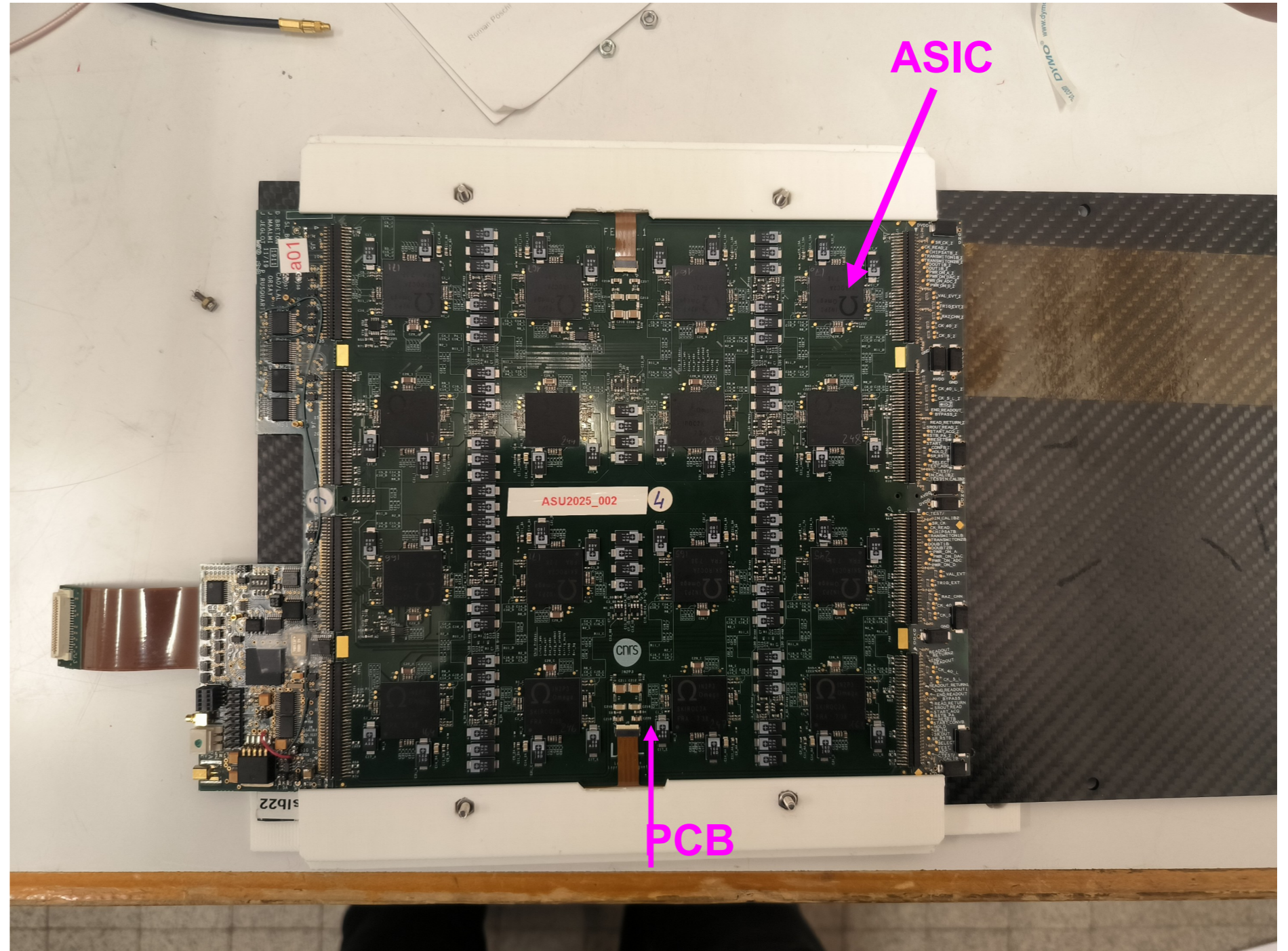
Current Active Signal Unit (ASU)



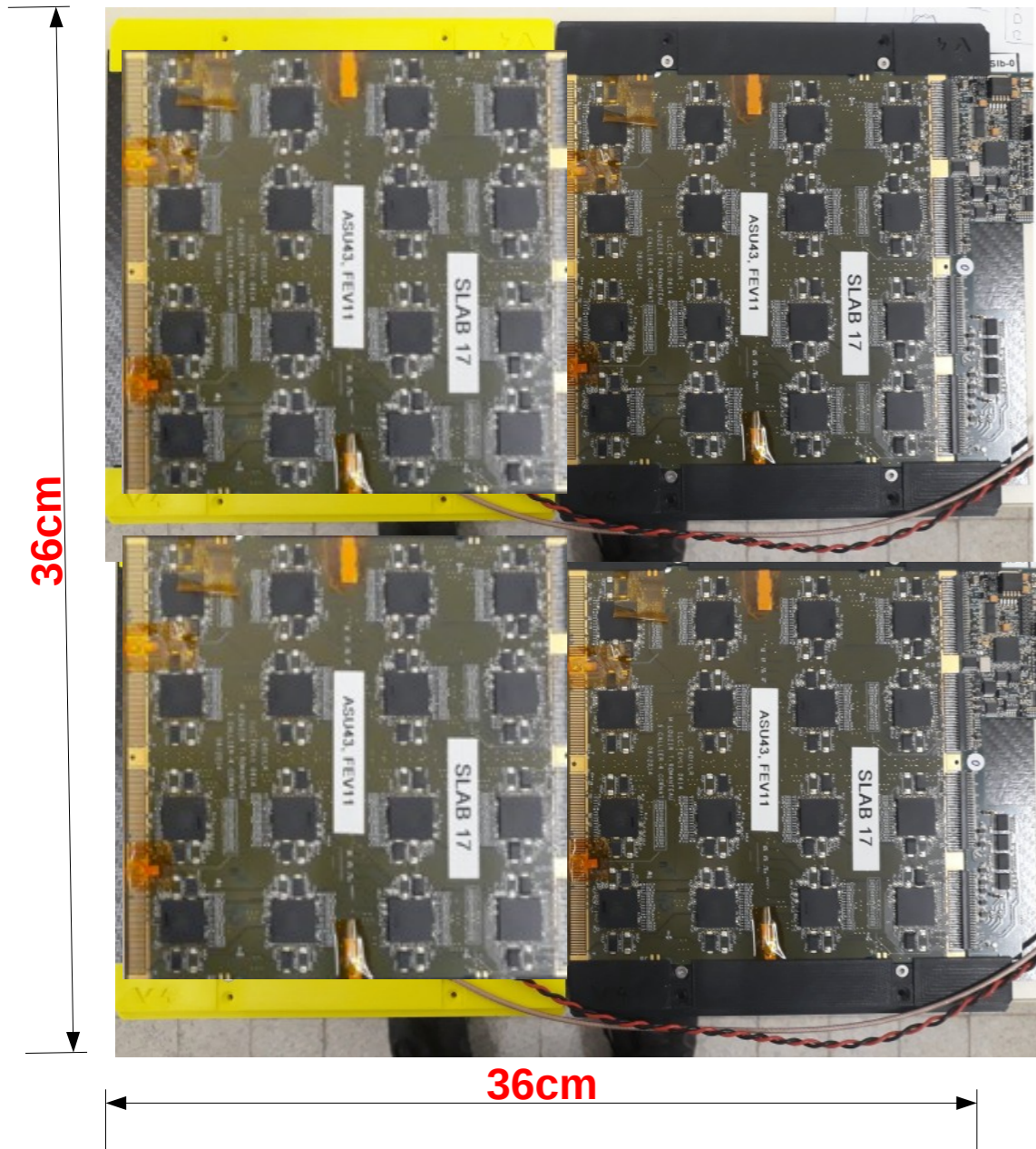
Pad size 5.5x5.5 mm²

An ASU is composed of:

- 16 ASICs
- 1 PCB
- 4 Si sensors



A Silicon Pad (SiPad) Layer for SHiP



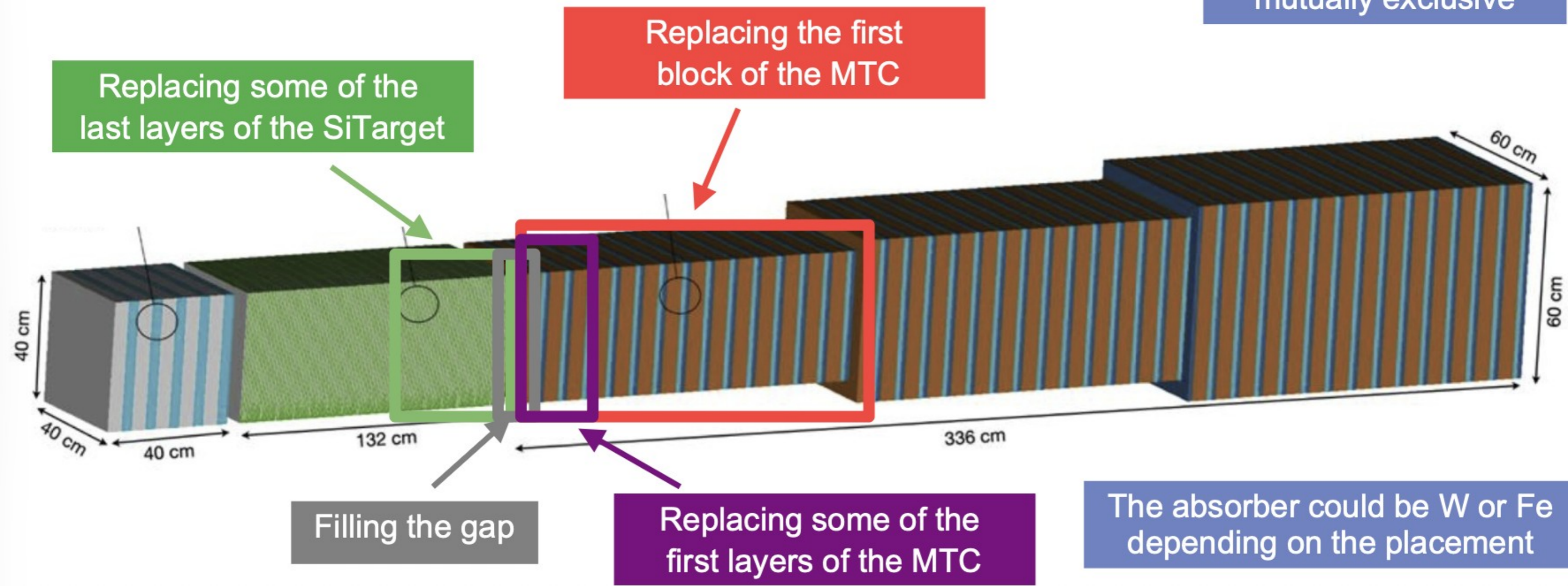
- Should be straightforward to arrange SiW ECAL ASUs
 - Modularity inherent to detector design
 - N.B.: 18x18 cm² is not a canonical number but many tools are or will be developed for this size
- 2 Chains of 2 ASUs/layer
- Engineering support at IJCLab!
 - Mechanics and Electronics Department

Better drawing next time, promised

A SiPad Detector for SND?

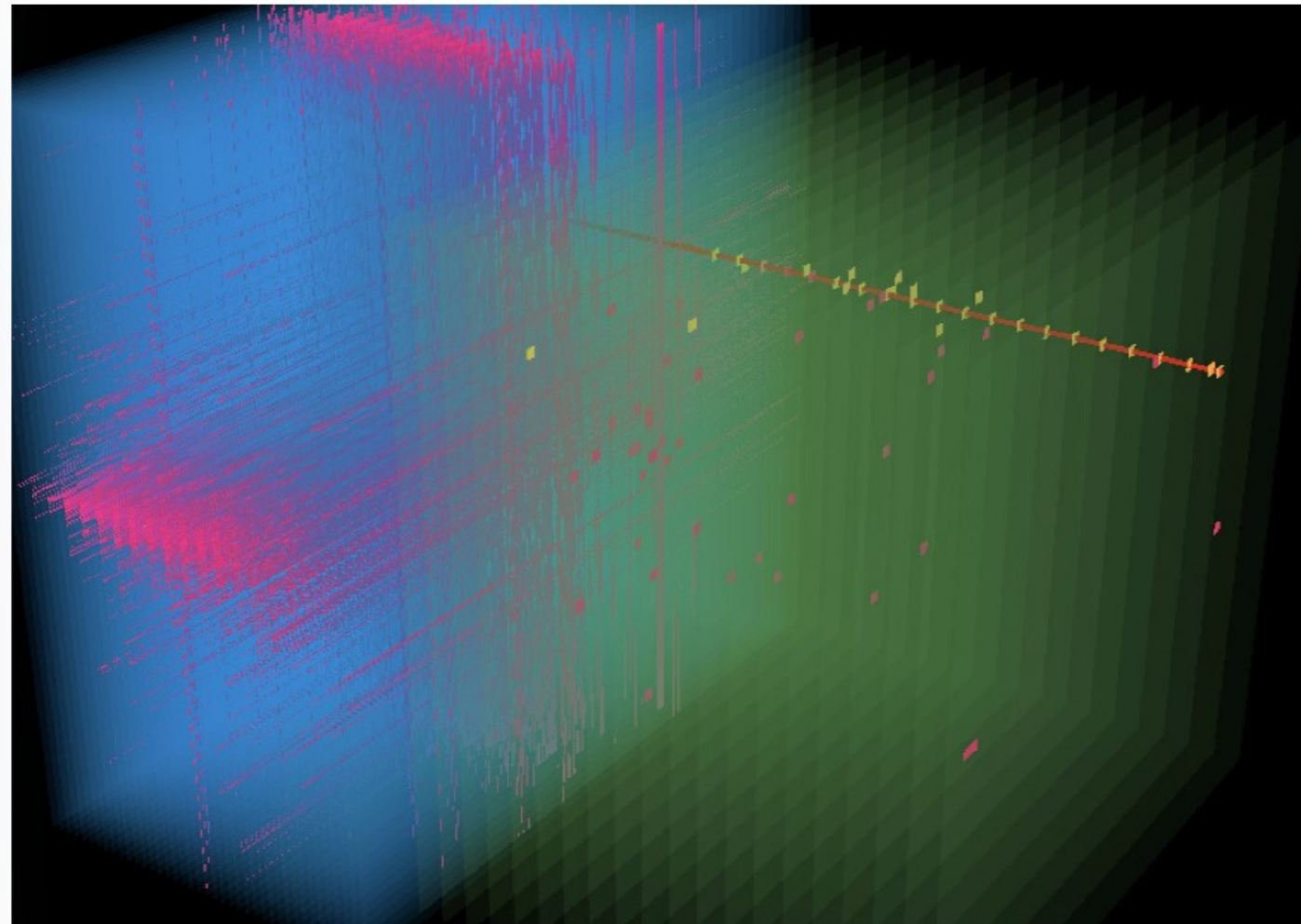
Where would it fit?

These options are not mutually exclusive

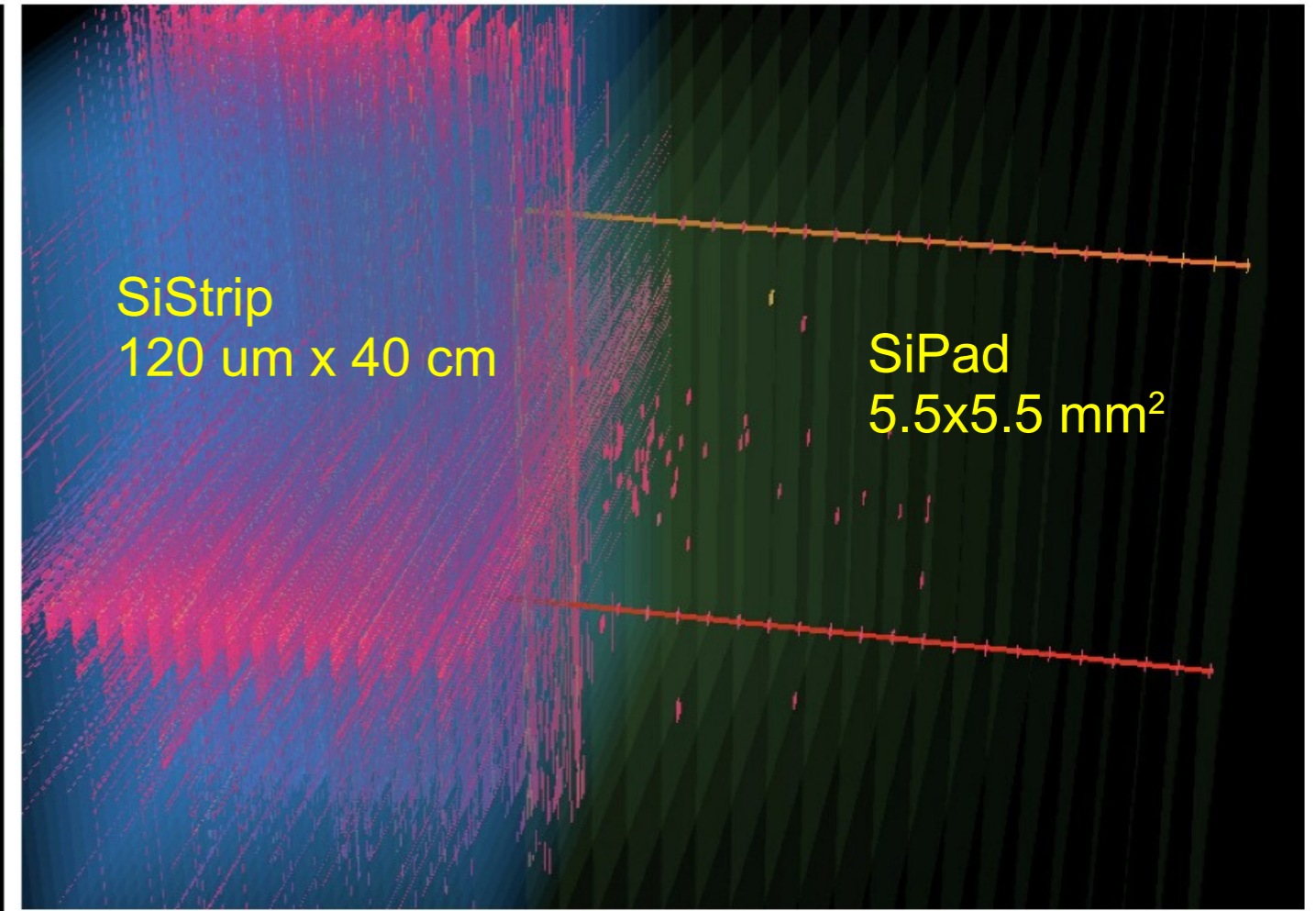


Filling the gap

Optimisation about to start

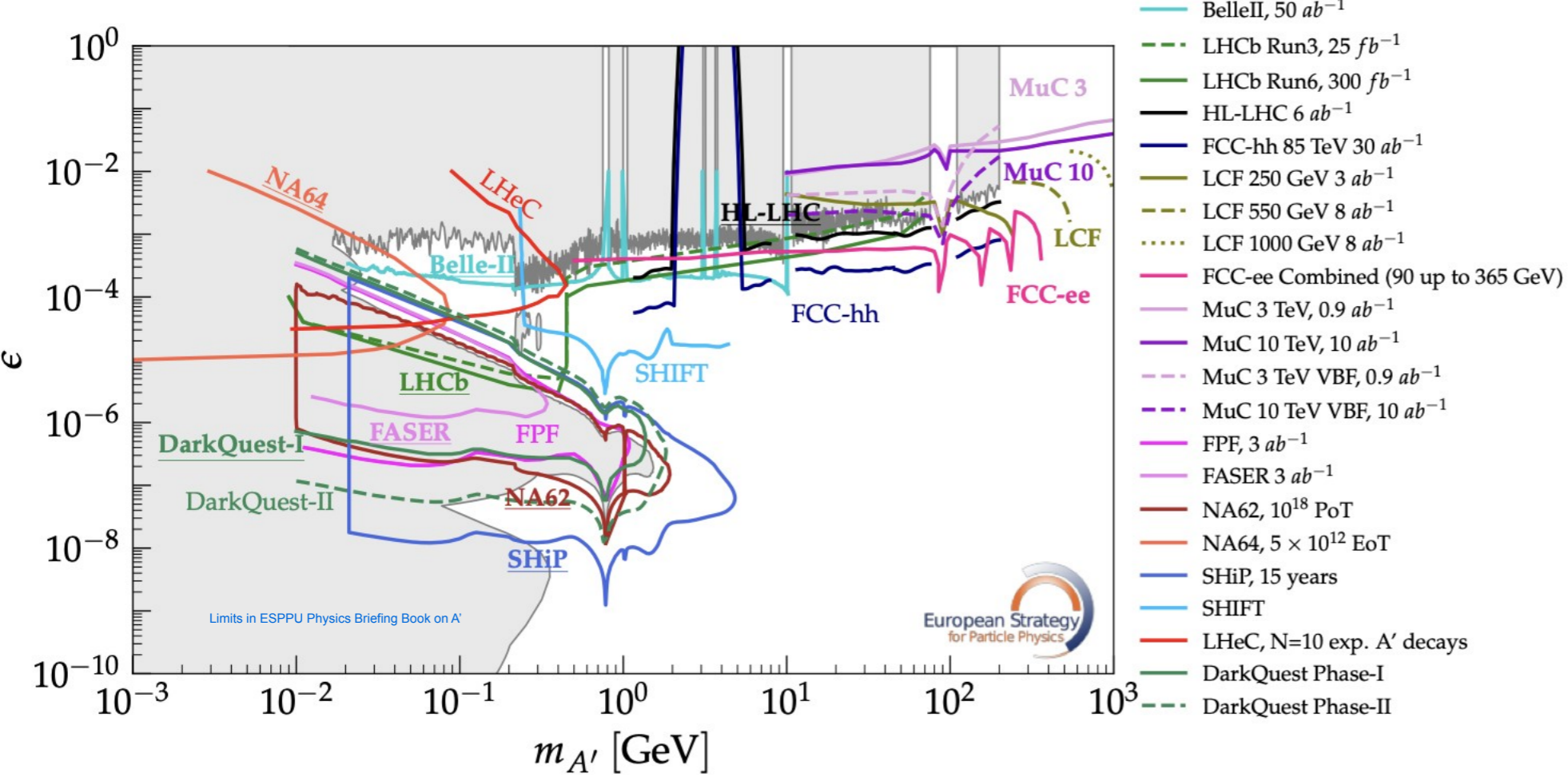


$1 \mu^- 1 e^-$

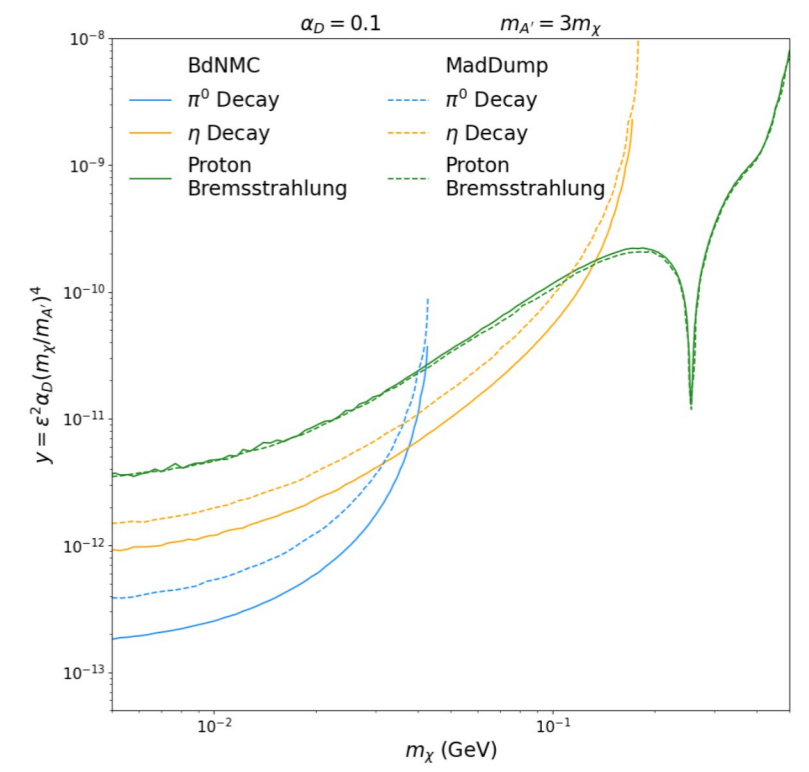


$2 \mu^- 1 e^-$

- (Outstanding) Work in progress by Postdoc Jesus Marquez
 - Implementation of SiPad and SiStrip Detectors
 - Next step scintillating tiles and SciFi of MTC

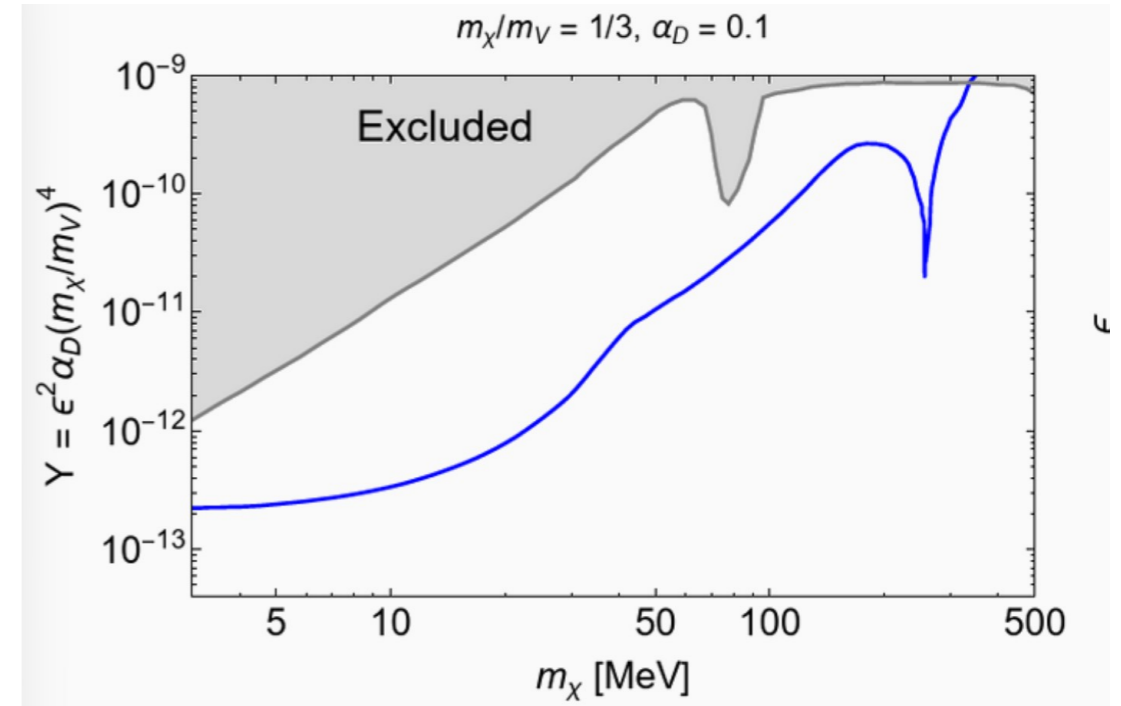


Contributions to Dark Photon Limits (E.Svensson)



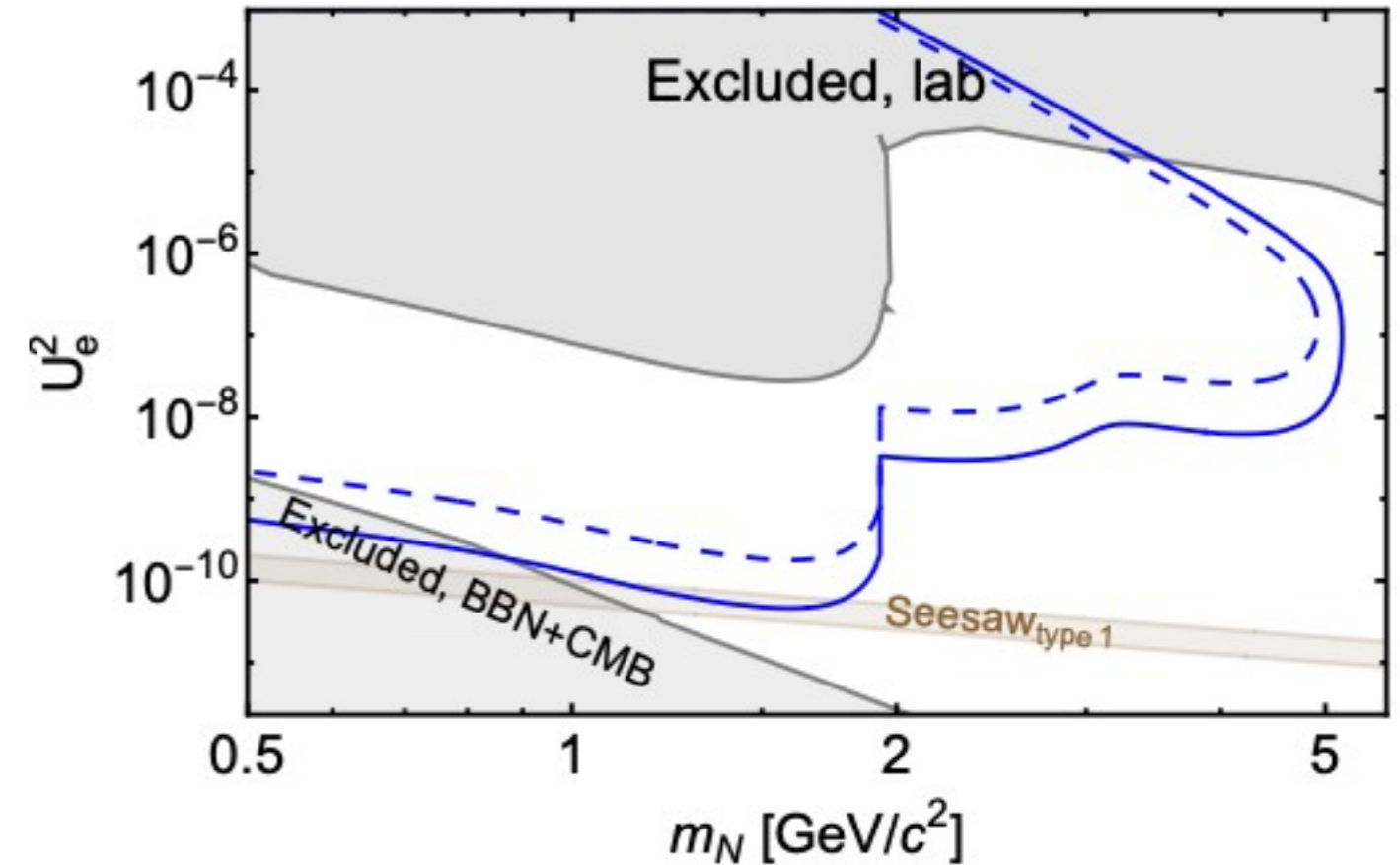
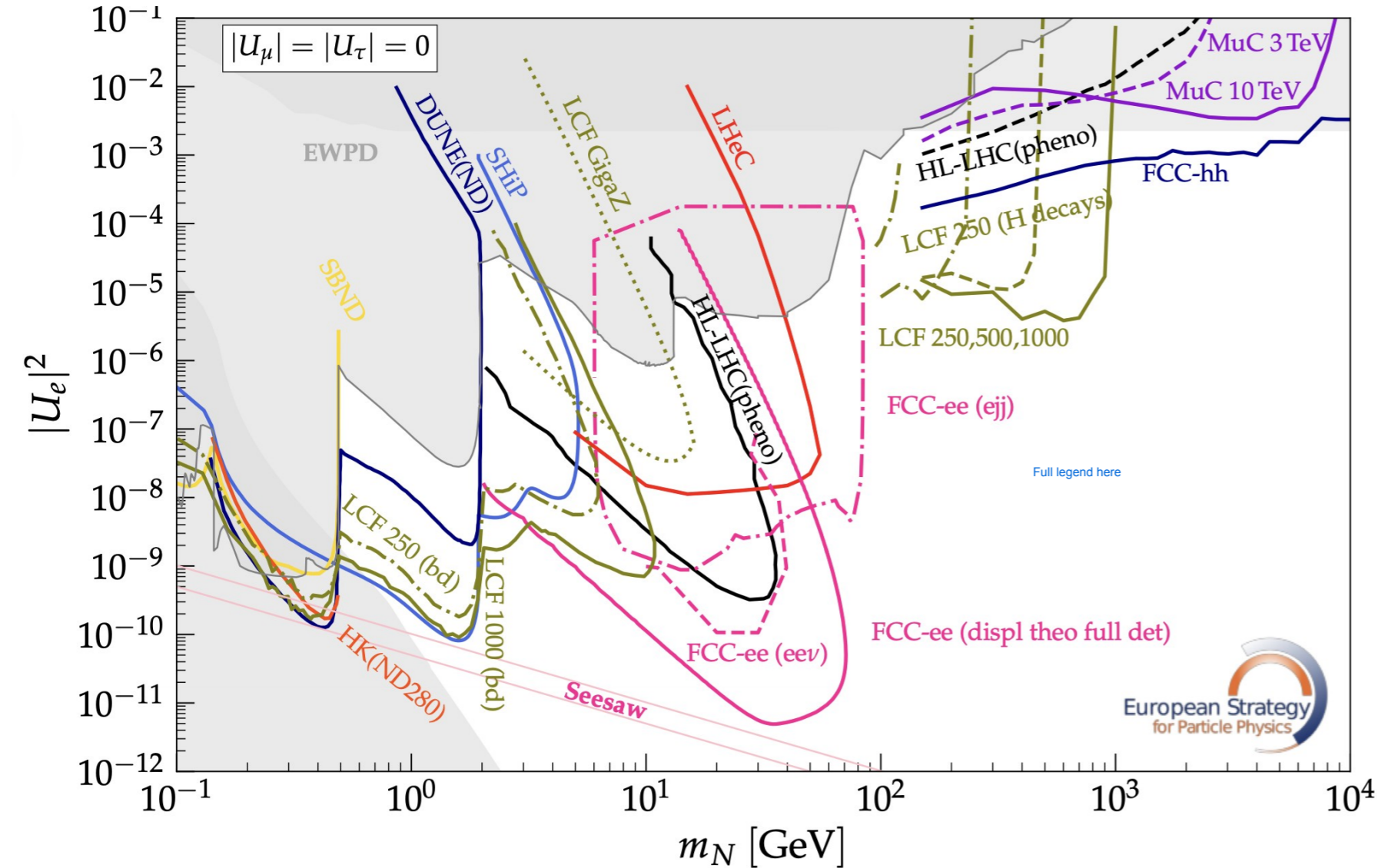
Limits on chi by SHiP (M. Climescu at Queen Mary)

- SHiP sensitive to Dark Photons and Dark Matter Fermions in regime up to 5 GeV
- SHiP will dominate the phase space of (kinematically allowed) dark photon masses



Future limits as in ESPPU Briefing Book

Zoom into SHiP (2504.06692v1)

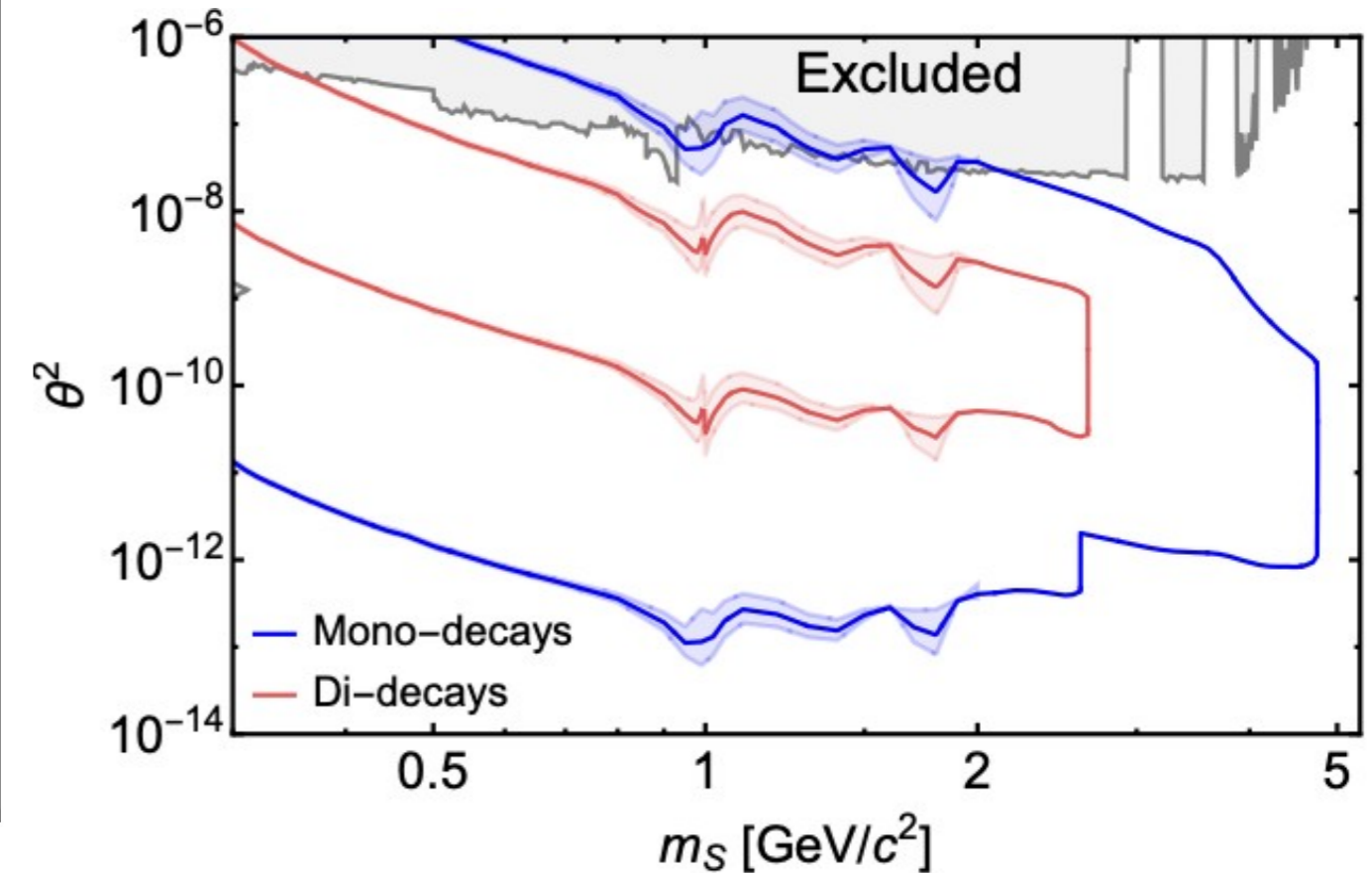
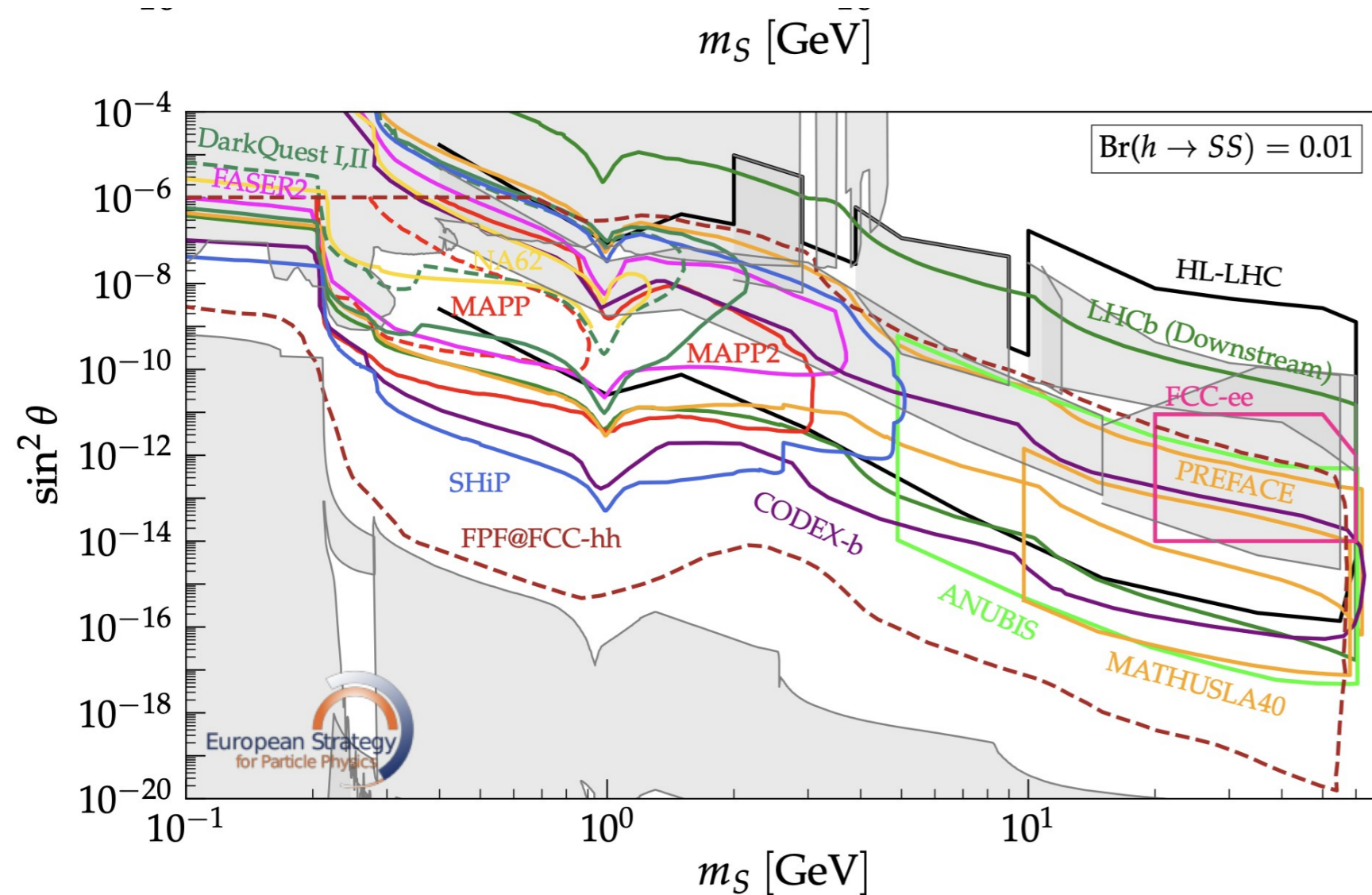


- SHiP sensitive to light scalars up to 5 GeV
 - Among projects studied by ESPPU SHiP and DUNE are the only approved experiments
- Reality until maybe the middle of the 2050's
- Allow me to also point out the remarkable phase space covered by a LCF

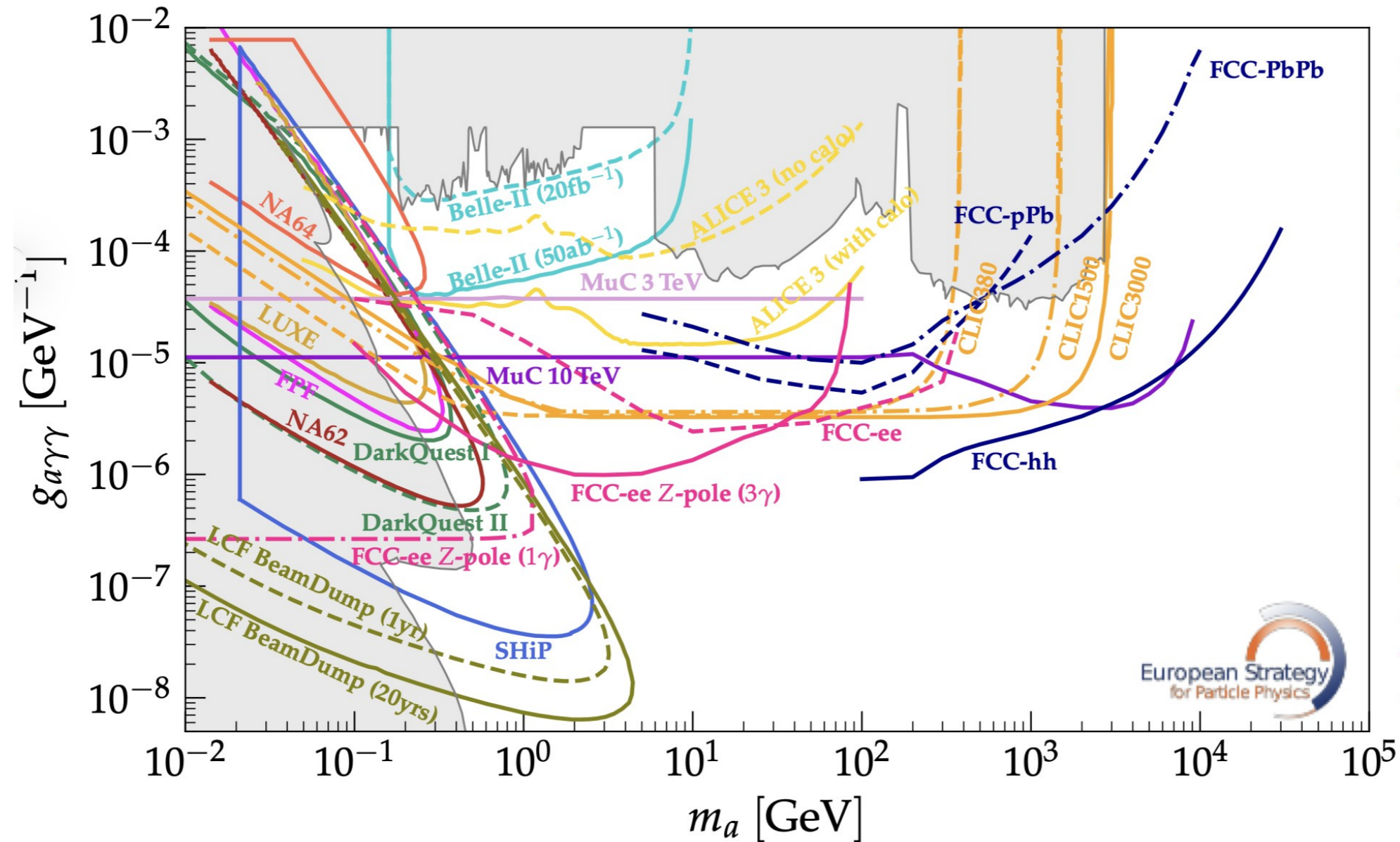
See backup for details on HNL@SHiP

Future limits as in ESPPU Briefing Book

Zoom into SHiP (2504.06692v1)



- SHiP sensitive to light scalars up to 5 GeV
- Significant increase reach if both scalars in pair production can be fully reconstructed!
- Mono-decays vs. Di-decays



- Below 5 GeV SHiP would/will dominate the landscape for decades
- Would only be topped by LCF beam dump facility

- SHiP will be beam dump facility at CERN ECN3 using CERN's 400 GeV SPS Proton beam
- SHiP is supposed to become world leading facility for Hidden Sector Searches in range ~ 100 MeV – 5(10) GeV
 - For many portals SHiP will dominate landscape for decades to come
- SiPad ECAL is an option for the instrumentation of the Scattering and Neutrino Detector
 - Sensitivity to Dark Matter Production and Neutrino Physics
 - Detector optimisation for SHiP starts now!
 - In our case how many Ecal layers and where it's best to place them?
- In parallel hardware development
- SHiP is IJCLab project since Spring 2026
 - Other institutes showed interest to join
 - **What about you?**
 - SiW ECAL prototype under construction as credible demonstrator for Higgs factories and SHiP
- Synergies with other similar experiments (that may take data before SHiP)!?
 - LUXE, Lohengrin, EBES

Backup

Calorimetry in SHiP

Two types of calorimeters:

- Neutrino physics and search for LDM scattering:

- LDM and $\nu_e \rightarrow \text{Si/W}$

- ν_μ and $\nu_\tau \rightarrow$ **Magnetised Tracking Calorimeter (MTC)**

Both are integrated to the muon shield

- Searches for FIPs and PID

- Sampling ECAL with pointing capabilities (e.g. $\text{ALP} \rightarrow \gamma\gamma$)

- HCAL to discriminate between muons and hadrons in wide momentum range

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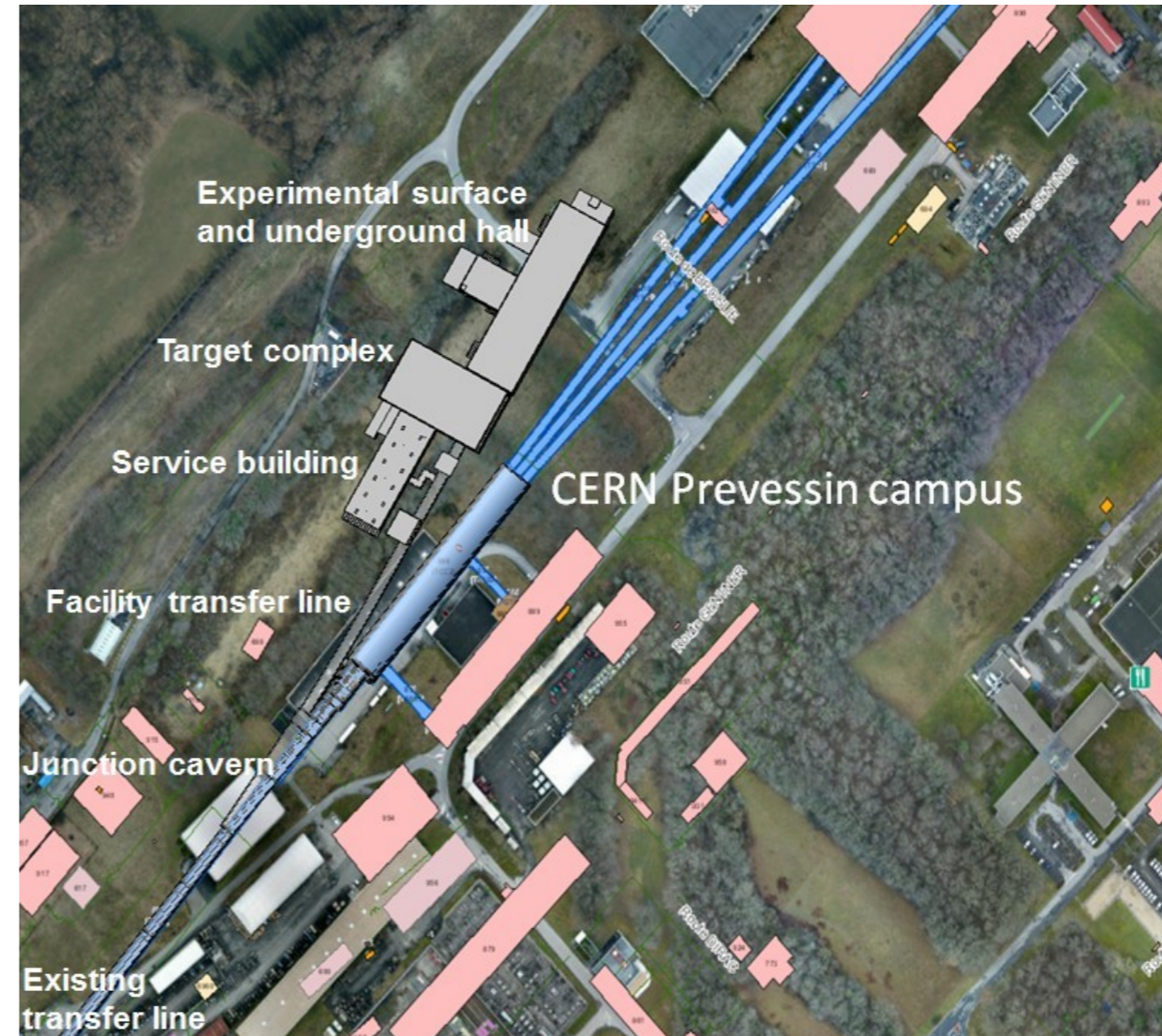
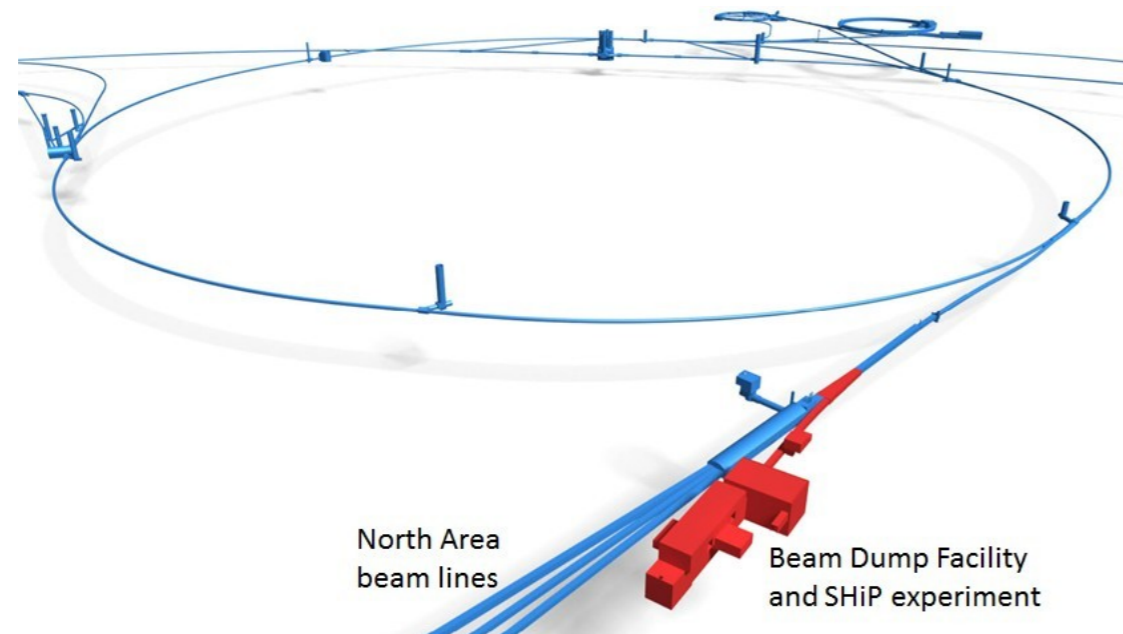
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Location at CERN

New 400 GeV proton beam line branched off the splitter section of the SPS transfer line to the North Area

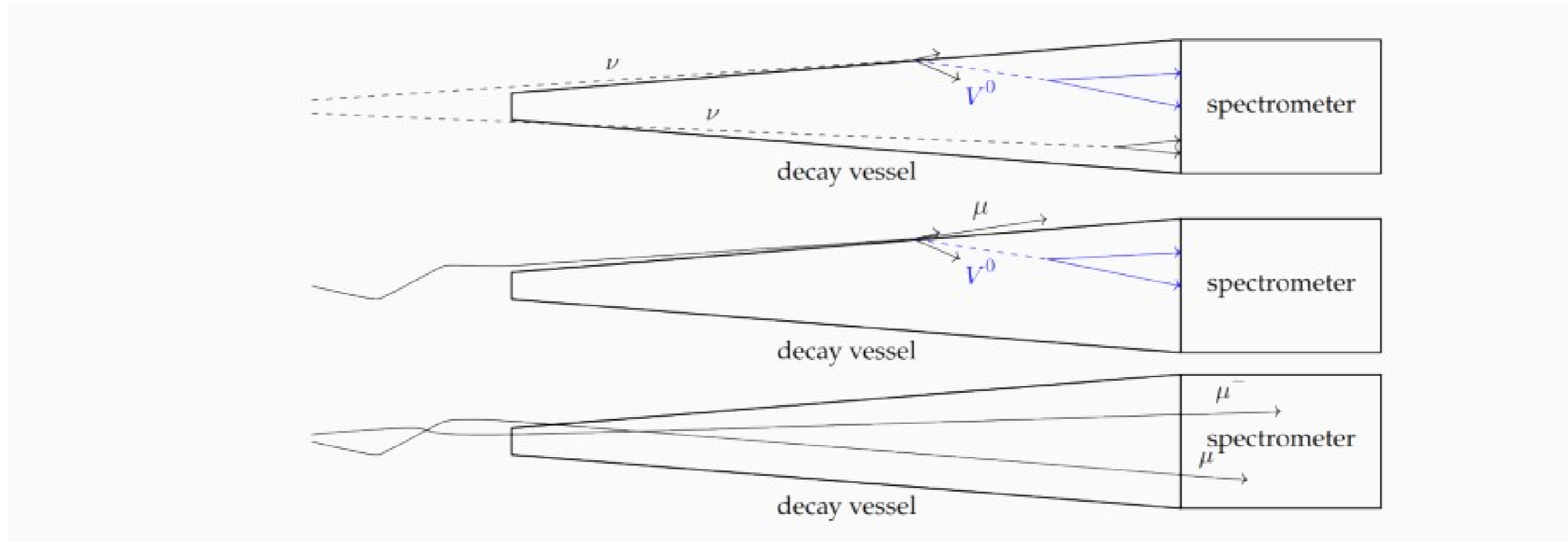


Proton yield and beam delivery

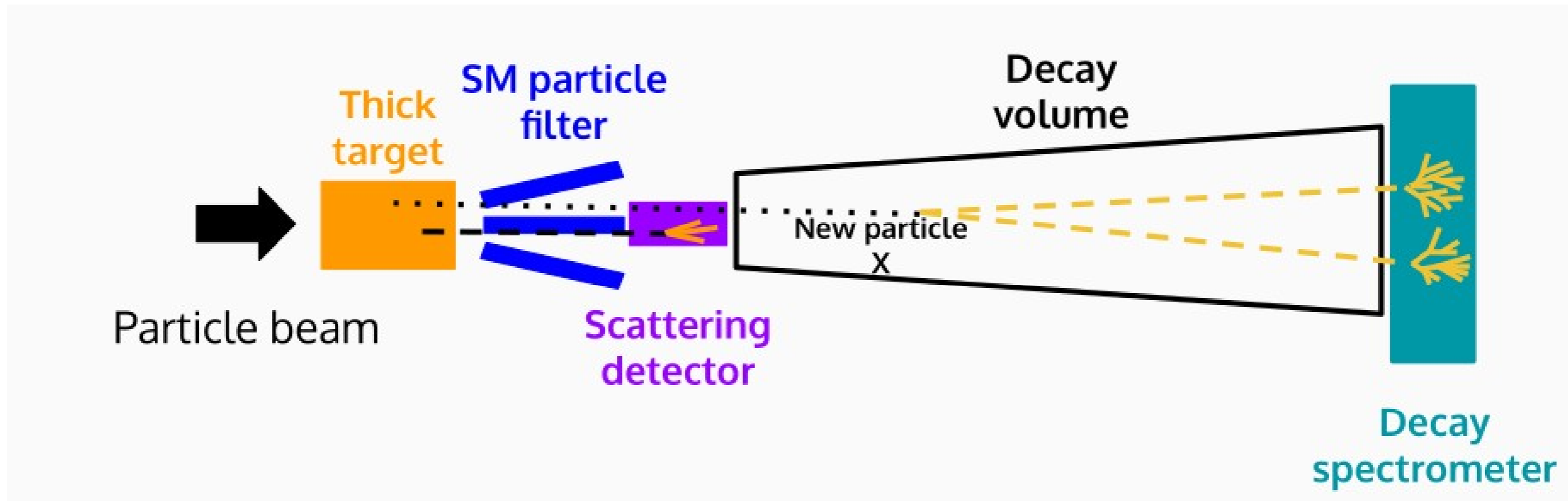
- Nominal beam intensity 4×10^{13} pot per spill
- Baseline scenario: annual yield of 4×10^{19} pot to the BDF, and 10^{19} pot to the other experiments in the North Area, while respecting HL-LHC requirements
- SHiP sensitivities assume 5×10^{20} pot in five years of nominal operation

The Main “Enemy” - Background

- A set of background taggers will be used to allow SHiP to reach its 0-background goal
 - the Upstream background tagger
 - the Surround background tagger
- 3 backgrounds are significant: neutrino background, muon DIS background and muon combinatorial

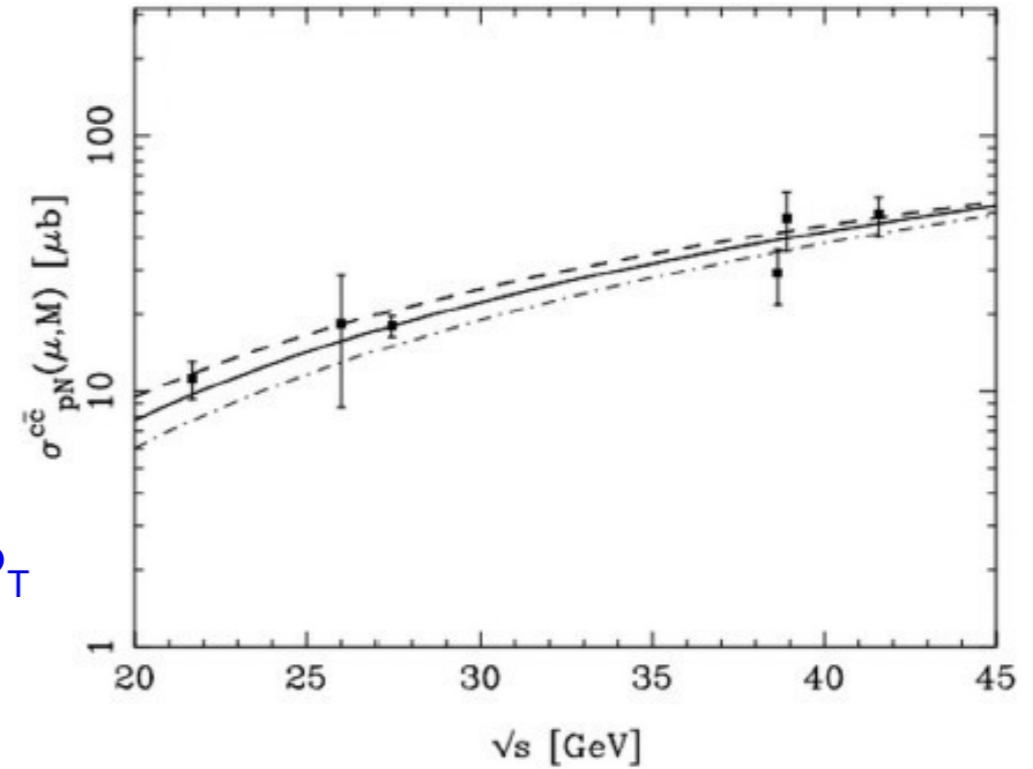


- A high intensity particle beam is needed
 - Search for rare events → particular attention to be given to background suppression
- A long baseline is needed
 - Give space for FIPs to decay
- Presence of high-precision scattering detectors and decay spectrometers
 - Allow observation of faint events

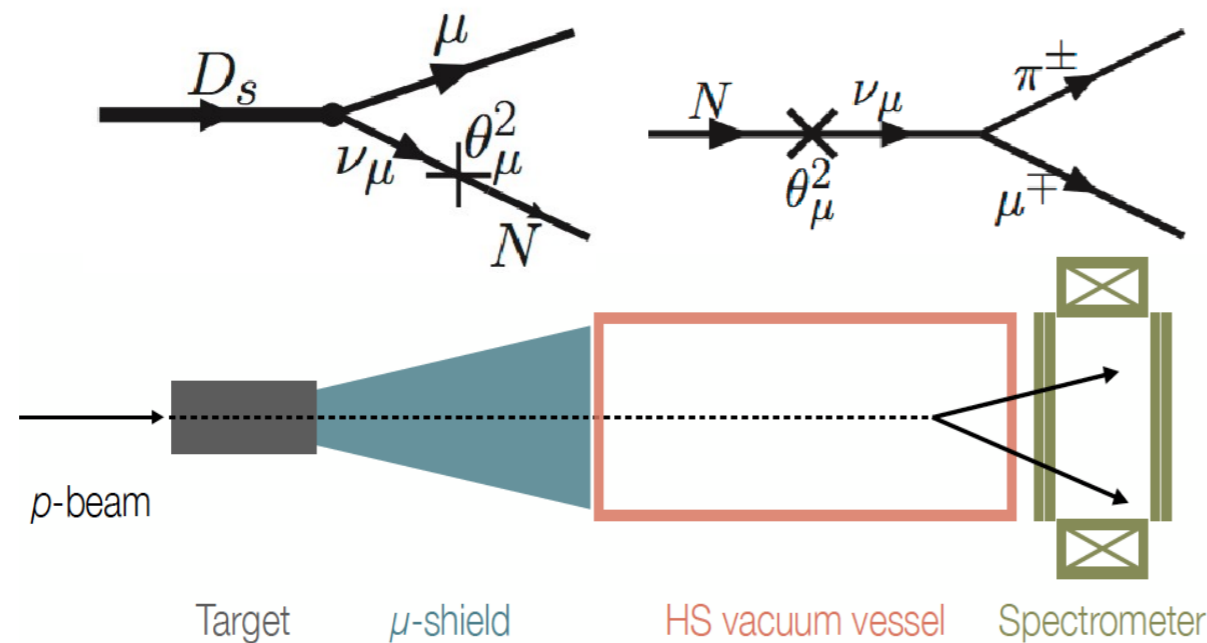


Particle beam with maximal intensity
 Search for HS particles in Heavy Flavour decays
 Charm (and beauty) cross-sections strongly depend
 on the beam energy.

At CERN SPS: $\sigma(pp \rightarrow s\bar{s} + X) \sim 0.15$
 $\sigma(pp \rightarrow c\bar{c} + X) \sim 2 \times 10^{-3}$
 $\sigma(pp \rightarrow b\bar{b} + X) \sim 1.6 \times 10^{-7}$

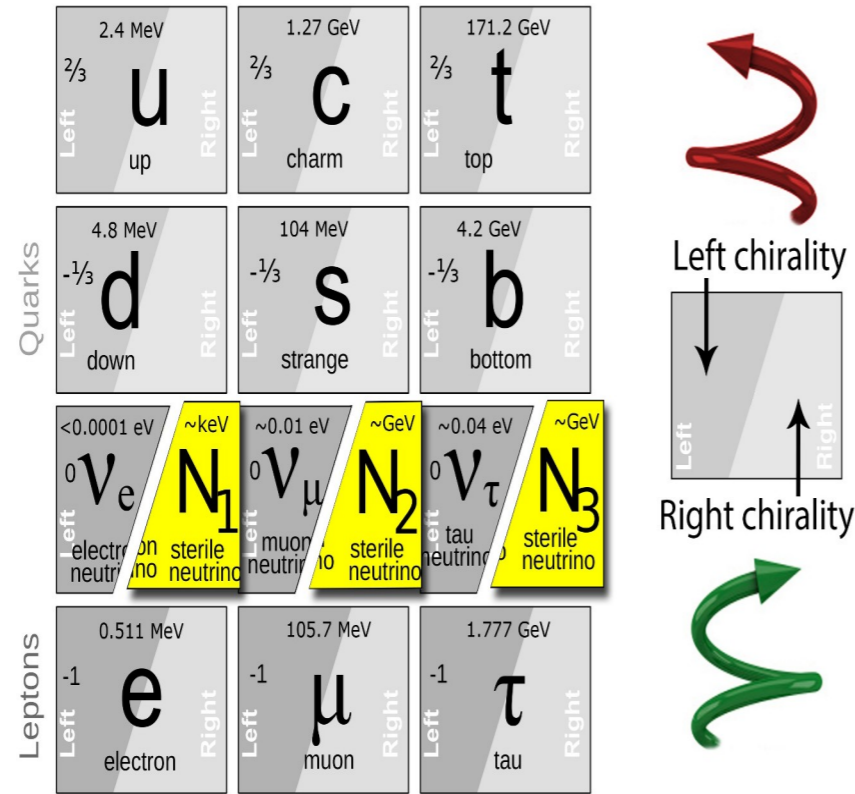


HS produced in charm and beauty decays have significant P_T



Long decay volume and large
 geometrical acceptance of the
 spectrometer are essential to
 maximize detection efficiency

*Detector must be placed close to the target to maximize geometrical acceptance
 Effective (and “short”) muon shield is essential to reduce muon-induced
 backgrounds*



Neutrino oscillations: particles N_2, N_3

Baryon asymmetry: same particles N_2, N_3

Masses $\geq O(100 \text{ MeV})$

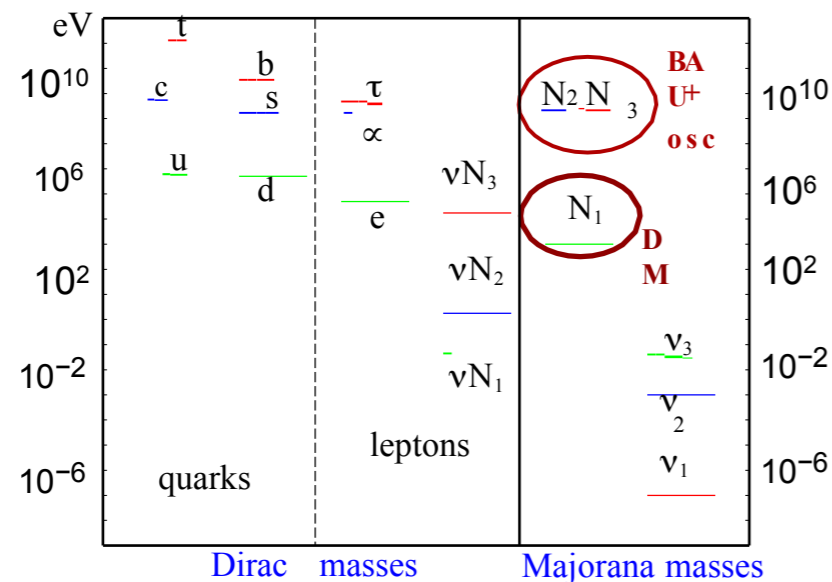
Dark matter: particle N_1

mass $1 - 50 \text{ keV}$

Inflation: Higgs field coupled to gravity

Inflationary parameters for

$M_{\text{Higgs}} \sim 126 \text{ GeV}$ in perfect agreement with observations



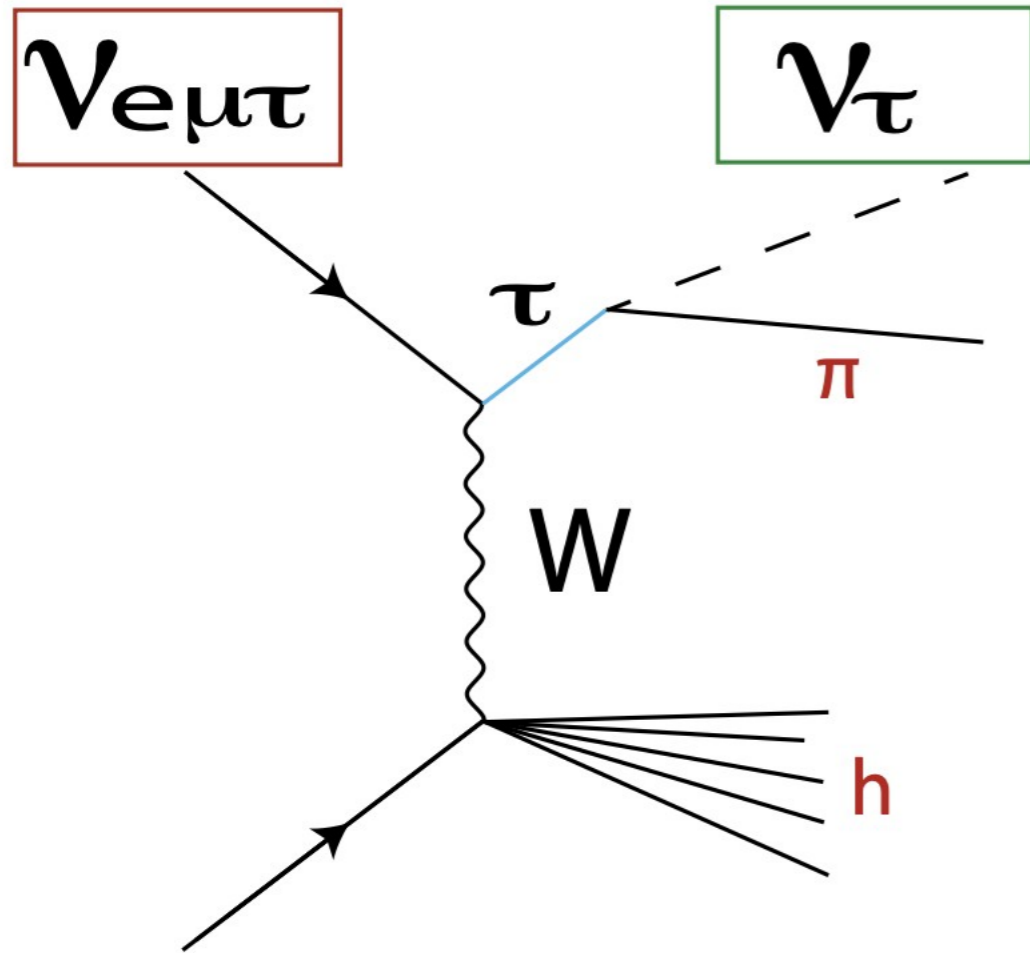
Neutrino Minimal Standard Model (ν MSM)

Masses of right-handed neutrinos as of other order of masses of other leptons

Yukawas as those of electron or smaller

Review: Boyarsky, Ruchayskiy, Shaposhnikov Ann.

Rev. Nucl. Part. Sci. (2009), [0901.0011]



	CC DIS (W HGC)	Charm CC DIS (W HGC)	CC DIS (Fe MGTC)	Charm CC DIS (Fe MGTC)
N_{ν_e}	6.8×10^4	4.1×10^3	1.6×10^5	9.8×10^3
N_{ν_μ}	2.0×10^5	8.7×10^3	4.6×10^5	2.0×10^4
N_{ν_τ}	2.1×10^3	1.2×10^2	5.1×10^3	2.8×10^2
$N_{\bar{\nu}_e}$	1.4×10^4	7.4×10^2	3.7×10^4	1.9×10^3
$N_{\bar{\nu}_\mu}$	4.4×10^4	1.7×10^3	1.1×10^5	4.1×10^3
$N_{\bar{\nu}_\tau}$	1.5×10^3	8.6×10^1	3.8×10^3	2.1×10^2

$$\frac{d^2 \sigma^{\nu(\bar{\nu})}}{dx dy} = \frac{G_F^2 M E_\nu}{\pi (1 + Q^2/M_W^2)^2} \left\{ (y^2 x + \frac{m_\tau^2 y}{2E_\nu M}) F_1 + \right.$$

$$\left[(1 - \frac{m_\tau^2}{4E_\nu^2}) - (1 + \frac{Mx}{2E_\nu}) y \right] F_2 \pm \left[xy(1 - \frac{y}{2}) - \frac{m_\tau^2 y}{4E_\nu M} \right] F_3 +$$

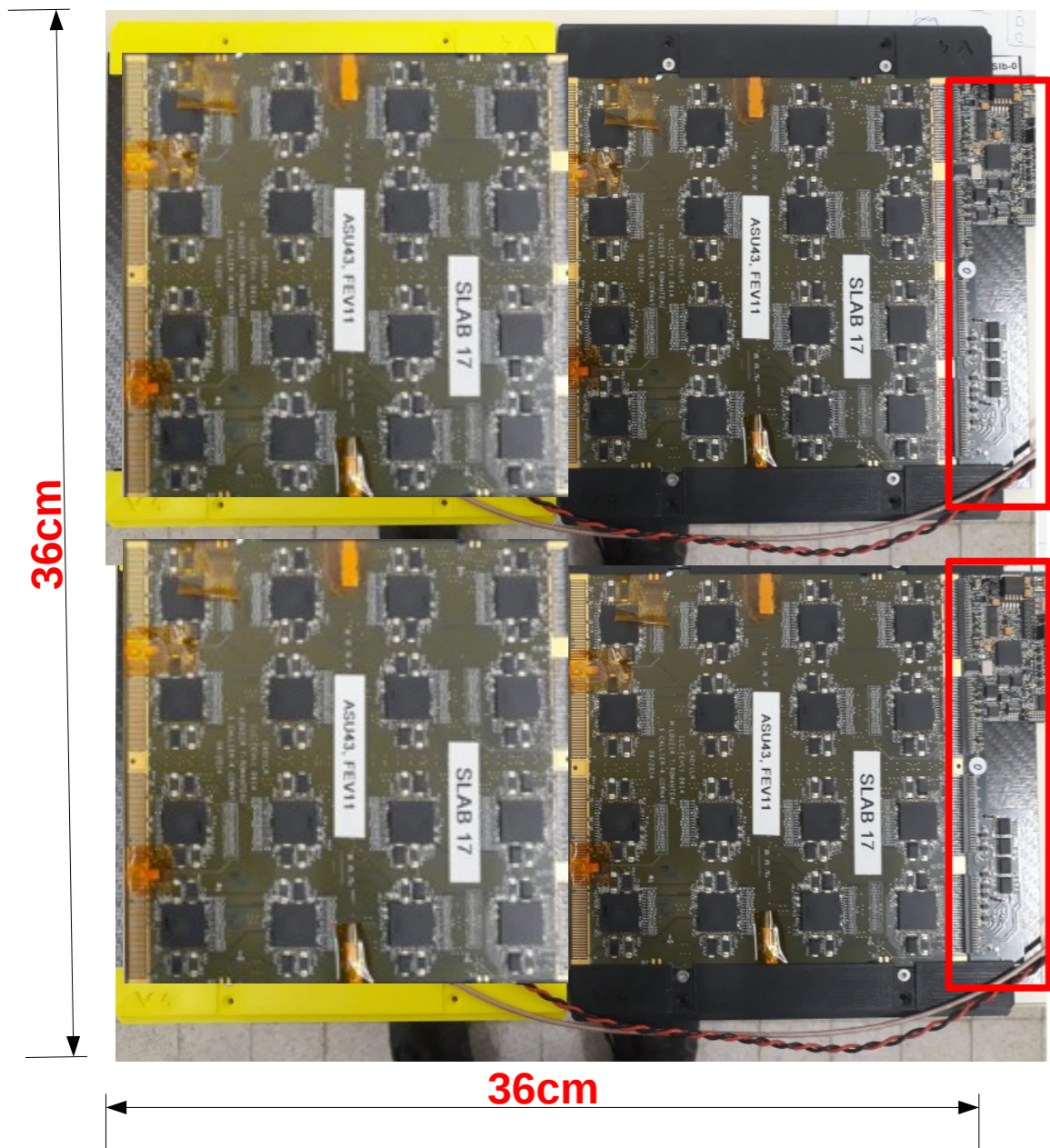
$$\left. \frac{m_\tau^2 (m_\tau^2 + Q^2)}{4E_\nu^2 M^2 x} F_4 - \frac{m_\tau^2}{E_\nu M} F_5 \right\}.$$

- A total of 26 ν_τ candidates have been observed, ever
- ν_τ has never been observed, ever
- The high neutrino flux allows for the measurement of strange quark nucleon content via charm production in ν interactions
- The tau neutrino flux allows for the determination of the never-before measured F_4 and F_5

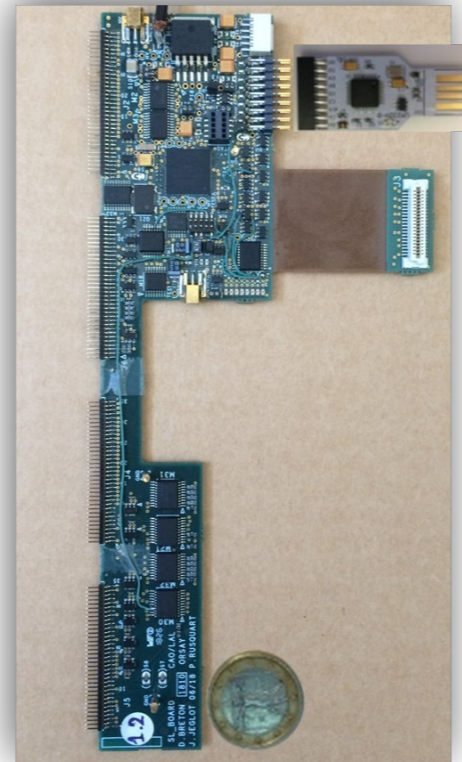
	CC DIS (W HGC)	Charm CC DIS (W HGC)	CC DIS (Fe MGTC)	Charm CC DIS (Fe MGTC)
N_{ν_e}	6.8×10^4	4.1×10^3	1.6×10^5	9.8×10^3
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N_{ν_τ}	2.1×10^3	1.2×10^2	5.1×10^3	2.8×10^2
$N_{\bar{\nu}_e}$	1.4×10^4	7.4×10^2	3.7×10^4	1.9×10^3
$N_{\bar{\nu}_\mu}$	4.4×10^4	1.7×10^3	1.1×10^5	4.1×10^3
$N_{\bar{\nu}_\tau}$	1.5×10^3	8.6×10^1	3.8×10^3	2.1×10^2

$$\frac{d^2 \sigma^{\nu(\bar{\nu})}}{dx dy} = \frac{G_F^2 M E_\nu}{\pi(1 + Q^2/M_W^2)^2} \left\{ (y^2 x + \frac{m_\tau^2 y}{2E_\nu M}) F_1 + \left[\left(1 - \frac{m_\tau^2}{4E_\nu^2}\right) - \left(1 + \frac{Mx}{2E_\nu}\right)y \right] F_2 \pm \left[xy \left(1 - \frac{y}{2}\right) - \frac{m_\tau^2 y}{4E_\nu M} \right] F_3 + \frac{m_\tau^2 (m_\tau^2 + Q^2)}{4E_\nu^2 M^2 x} F_4 - \frac{m_\tau^2}{E_\nu M} F_5 \right\}.$$

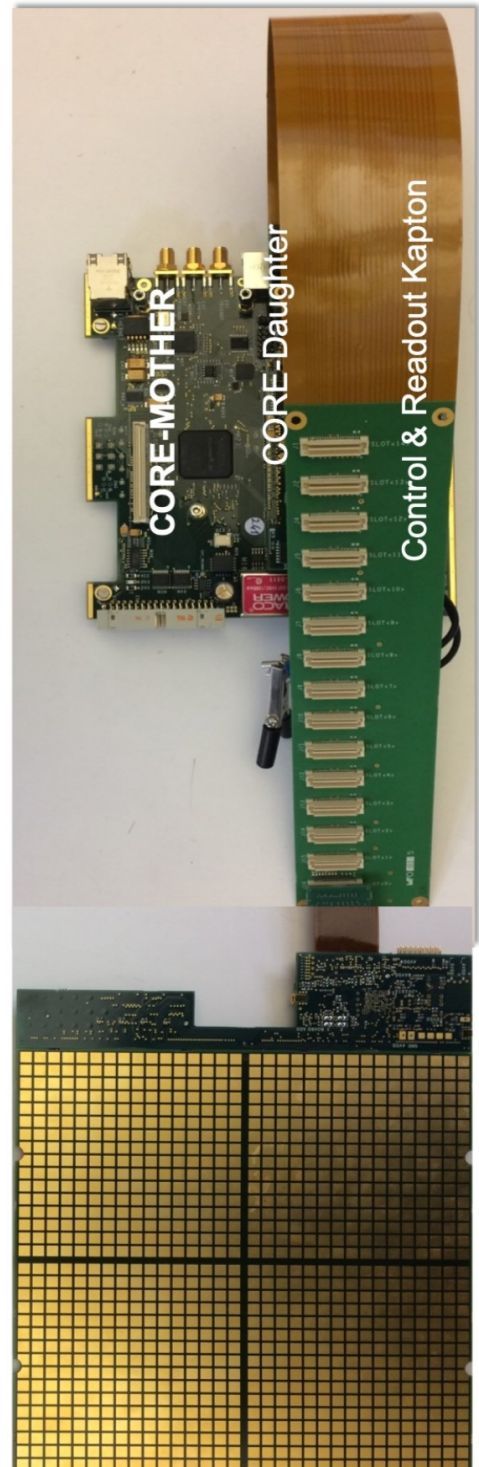
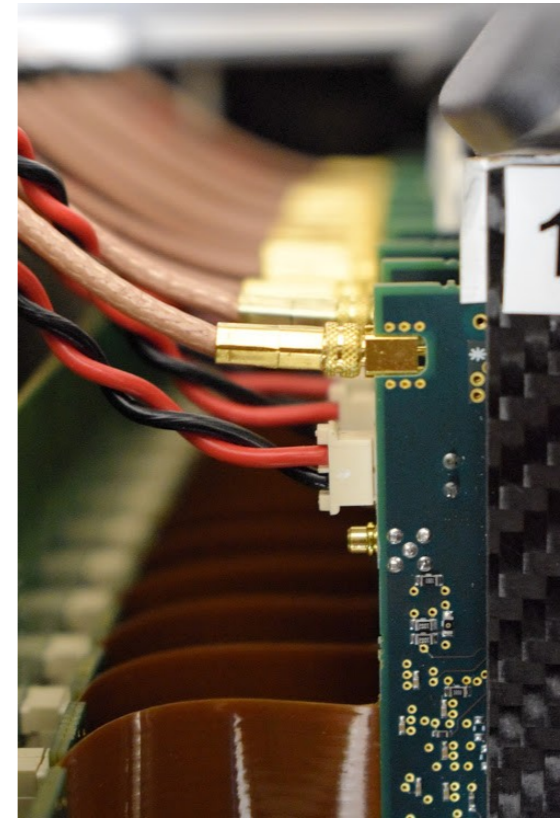
A layer for ShiP – Layer extremities



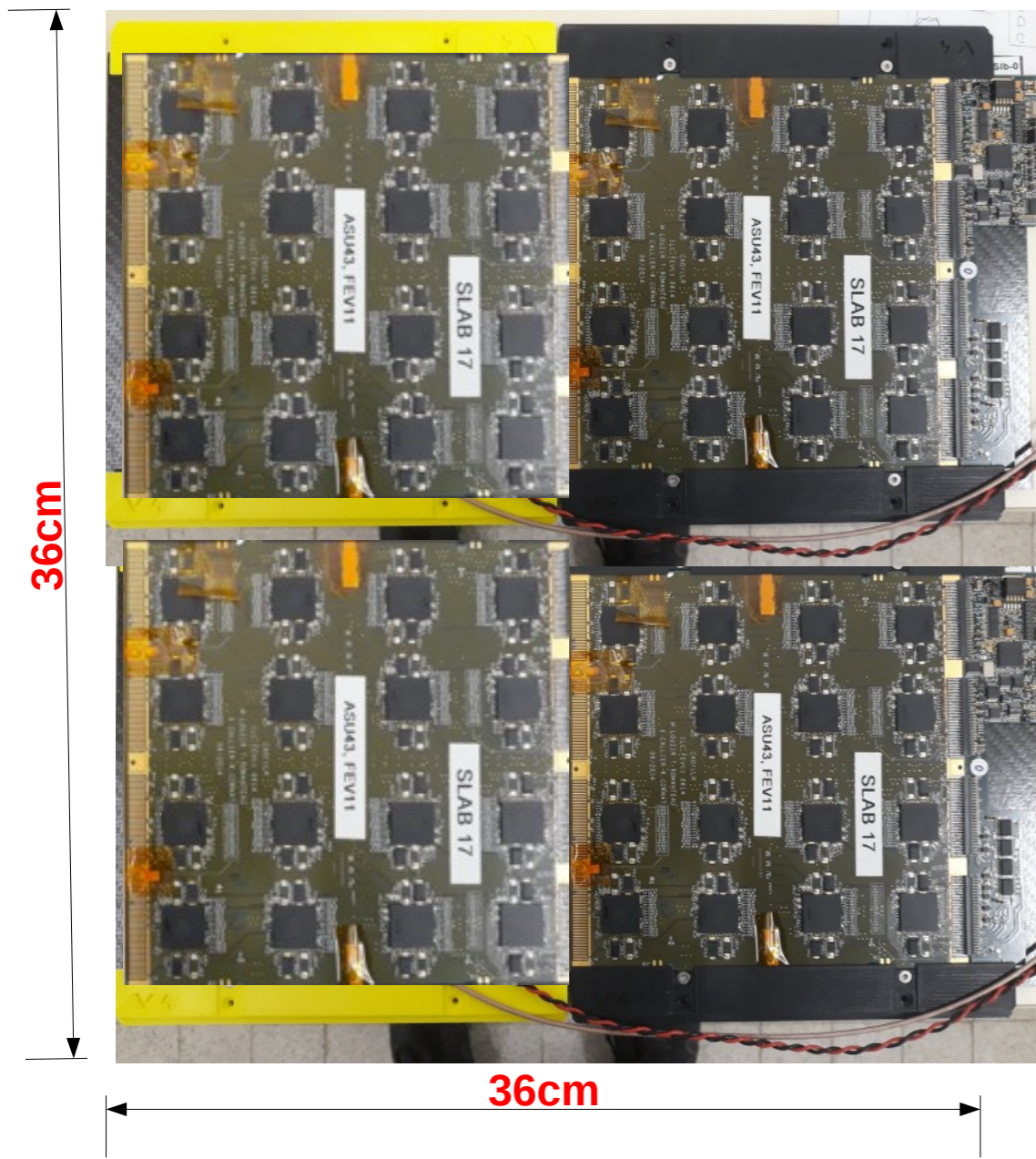
Better drawing next time, promised



SL Board



- SL Board is central piece of readout (developed by IJCLab)
- Overall dimension is 4.5x18 cm² (Designed for ILD)
- -> Would “stick out” by ~4.5 cm from actual detector volume
- Sits at the beginning of a compact digital readout chain
- Entire chain needs (of course) adaptation for SHiP
- Higher data rates
- Dimensions between sensitive layers will be different
- Different cable routing
- Detailed technical design/drawing of SND needed
- Possible active help from our side to develop it further



- **Test of demonstrator planned in 2026**
 - Stack of 15 18x18x0.5 cm³ ASUs
 - Currently under construction
 - (DRD Calo) Test beam request for SPS
 - Opportunity for SHiP members to get familiar with “our” calorimeter?

- **Development of new ASUs will start in 2026**
 - ... centered around next generation of ASICs (CALOROC)
 - Debugging of CALOROC and development of readout chain
 - Initially generic work but adaptation for SHiP will be kept in mind
 - Expect first new ASUs ~beginning of 2027
 - Provided funding
 - Strong synergies with work in DRD Calo and EU project OTELLO (if approved)

- **Mechanics**
 - Dedicated study on mechanical housing
 - Need to understand mechanical interfaces

The SHiP experiment will search for a broad range of feebly interacting particles such as:

- Light Dark Matter
- Heavy Neutral Leptons (HNLs)
- Dark photons
- Dark Scalar Higgs-like particles
- Axion-like particles (ALPs)

In addition SHiP will allow for a rich set of tests of Standard Model physics in with neutrinos

Relevant for today:

