SHiP
Search for Hidden Particles

SHiP's view of the target system

- Portal to Hidden Sectors! -

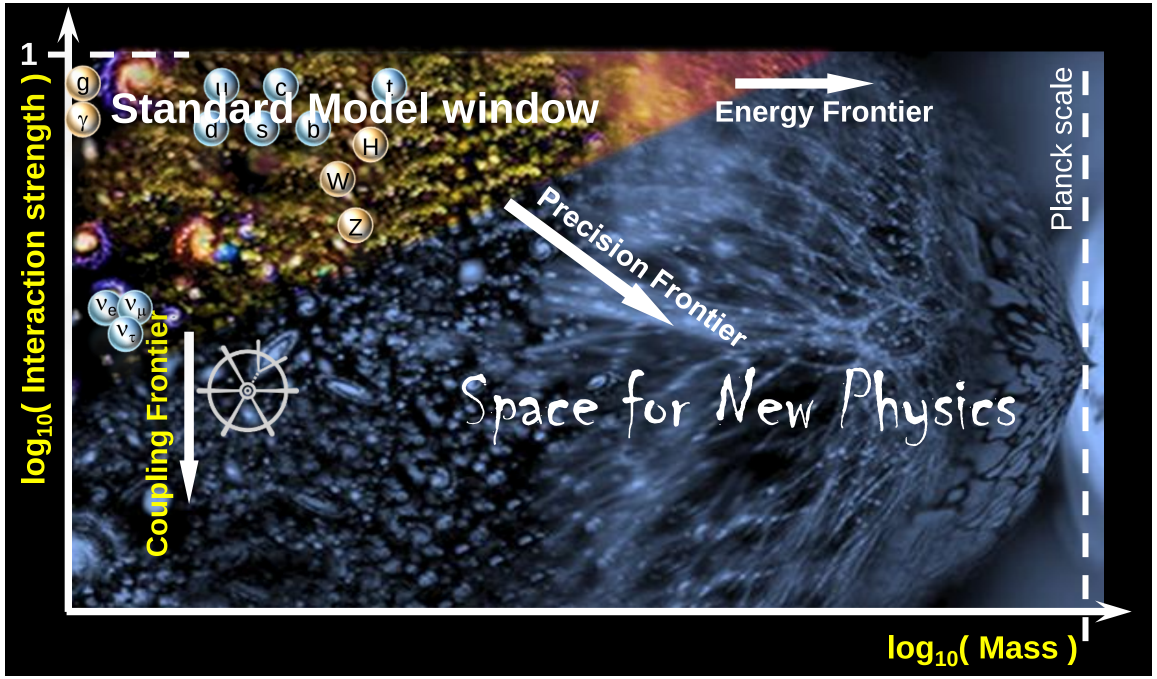
Topics covered

- Physics motivation and complementarity
- Physics programme with link to role of target system (define beam dump/fixed target)
- Target and target complex requirements and overall performance of experiments
- Physics qualifiers
- Operational scenario with beam requirements
- Sources of operational issues, failures and adverse experimental conditions
- Exchange of monitoring information

Physics scope

- Outstanding *observed features* that SM does not resolve, and with no experimental hints / guidance so far!
  - Precision cosmology: Evidence for dark matter is overwhelming
  - Neutrino oscillation: Mass hints to new potentially weak fields
  - Baryon flavour precision: Absence of explanation for matter-antimatter asymmetry

- ***New Physics*** should either be very heavy *OR* interact very feebly to have escaped detection!



"Coupling Frontier" : Any Particles engaging in Feeble Interactions (FIPs) with the SM particles

➔ Sharing the Universe already with feebly coupled, not-understood neighbours…!

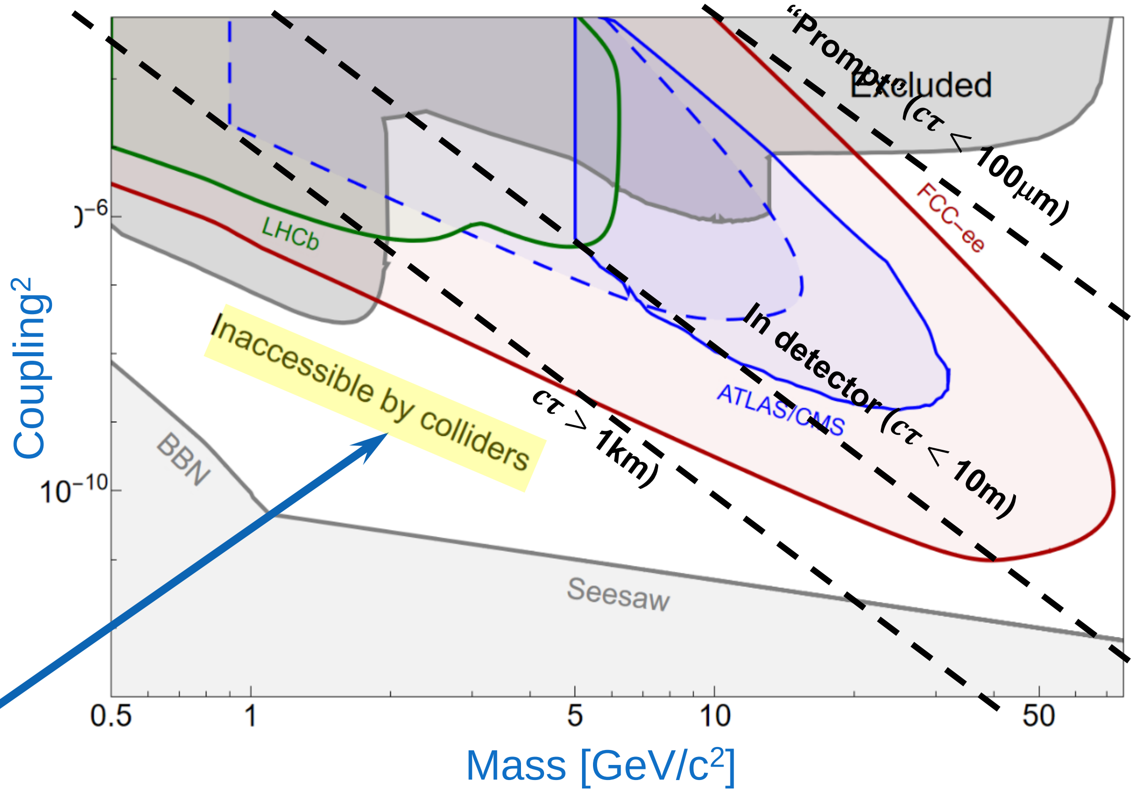
Standard Model mass scale is particularly interesting to explore… – we know for sure it exists!....

Exploration of *Coupling Frontier*

We can produce and do *direct generic* search for FIPs at accelerators !

➔ We need (very) large production of γ, q/g, c, b, W, Z, H !

E.g. Heavy Neutral Leptons



Similar behaviour $\tau_{FIP} \propto \frac{1}{\epsilon^{x}_{FIP} m^{y}_{FIP}}$ for all types of FIPs

➔ **SPS accelerator** energy and intensity unique to explore *Light Dark Matter and associated mediators, and ν mass generation* in region that can *only* be explored by beam-dump experiment

➔ BDF/SHiP experiment's raison d'être

SHiP's physics foundation

➔ BDF luminosity with the **long high-A/Z target and 4x10^{19} protons on target per year**

- ➔ BDF@SPS $\mathcal{L}_{int}[year^{-1}]$ = **>4 x 10^{45} cm^{-2}**
- ➔ HL-LHC $\mathcal{L}_{int}[year^{-1}]$ = **10^{42} cm^{-2}**

➔ BDF/SHiP ***annually*** access to yields inside detector acceptance:

- ~ 2×10^{17} charmed hadrons (>10 times the yield at HL-LHC)
- ~ 2×10^{12} beauty hadrons
- ~ 2×10^{15} tau leptons
- $\mathcal{O}(10^{20})$ photons above 100 MeV

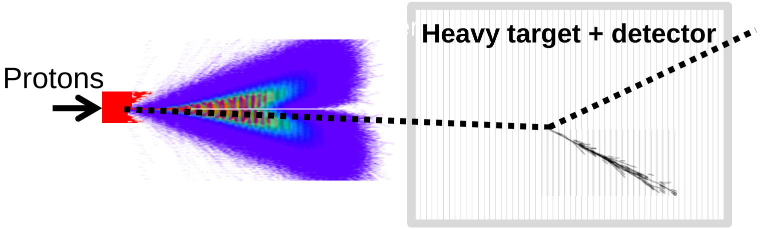
Direct New Physics searches For Hidden Sector and LDM

- Large number of neutrinos *detected* with 3t-W ν detector target:
  $3500\ \nu_\tau + \bar{\nu}_\tau$ *per year*, and $2\times10^5\ \nu_e + \bar{\nu}_e$ / $7\times10^5\ \nu_\mu + \bar{\nu}_\mu$

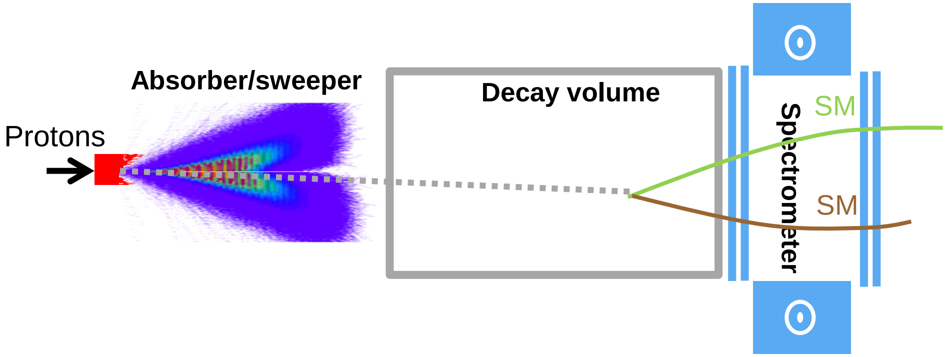
Standard Model measurements and BSM with neutrinos

➔ SHiP employs dual-technique detector

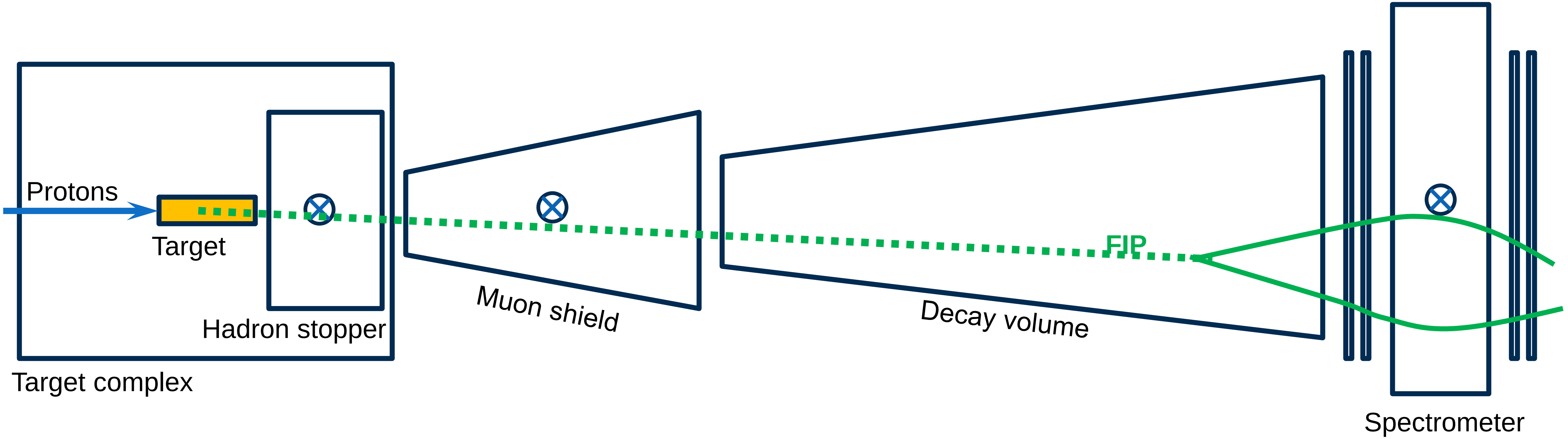
Scattering off atomic electrons and nuclei



Visible decay to SM particles



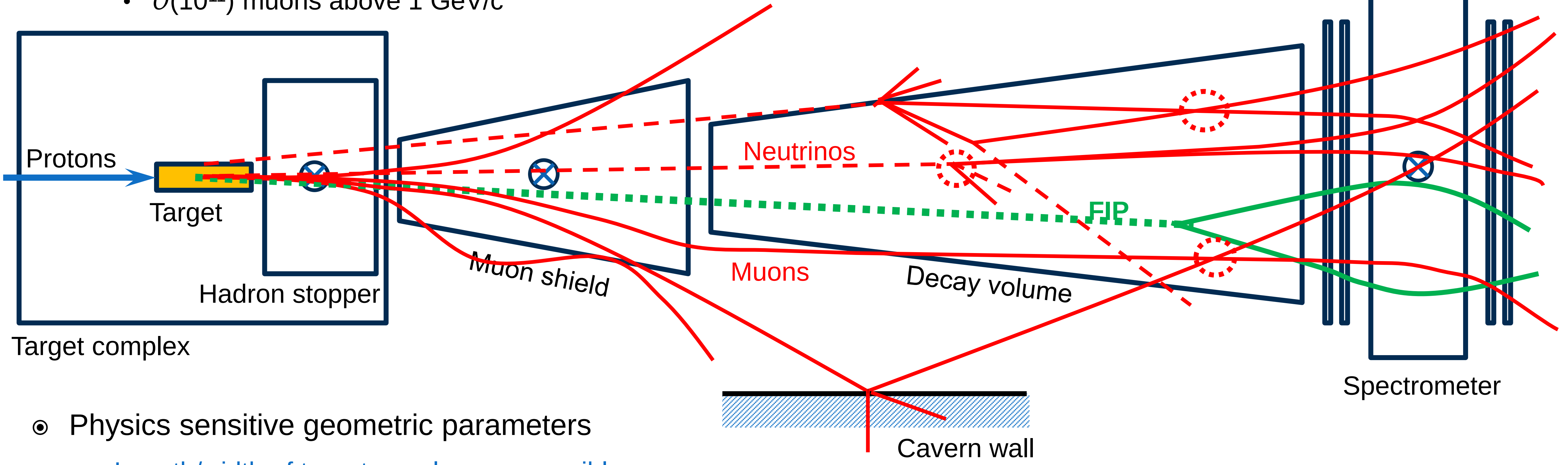
Signatures and background



Signatures and background

Per spill of 4x10^{13} protons (x 15x10^{6} spills...)

- 1.5 ×10^{12} neutrinos and anti-neutrinos through SHiP's fiducial volume
- $\mathcal{O}(10^{11})$ muons above 1 GeV/c



- Physics sensitive geometric parameters
  - Length/width of target – as long as possible
  - Distance between target and mgnetised hadron stopper – as short as possible (partly solved by tungsten/copper plug)
  - Length of hadron stopper (strength of field >1.5T) – as short as possible
  - Length of muon shield – "~as short as possible"

➔ Too short or too long is also not good…..

A note on requirements ☺

Optimisation of experimental performance and associated requirements?

➔ Experimental performance ≡ Reachable discovery/exclusion region in mass-coupling phase space

“Signal/background” $\propto f($ [operational parameters], [experimental geometry], [technology], [complexity], [cost] $)$

... And that also depends on the model and the experimental technique !....

...The dependencies are correlated (non-orthogonal axes!)

…The function has many degenerate optima but with different steepness wrt to a given parameter !

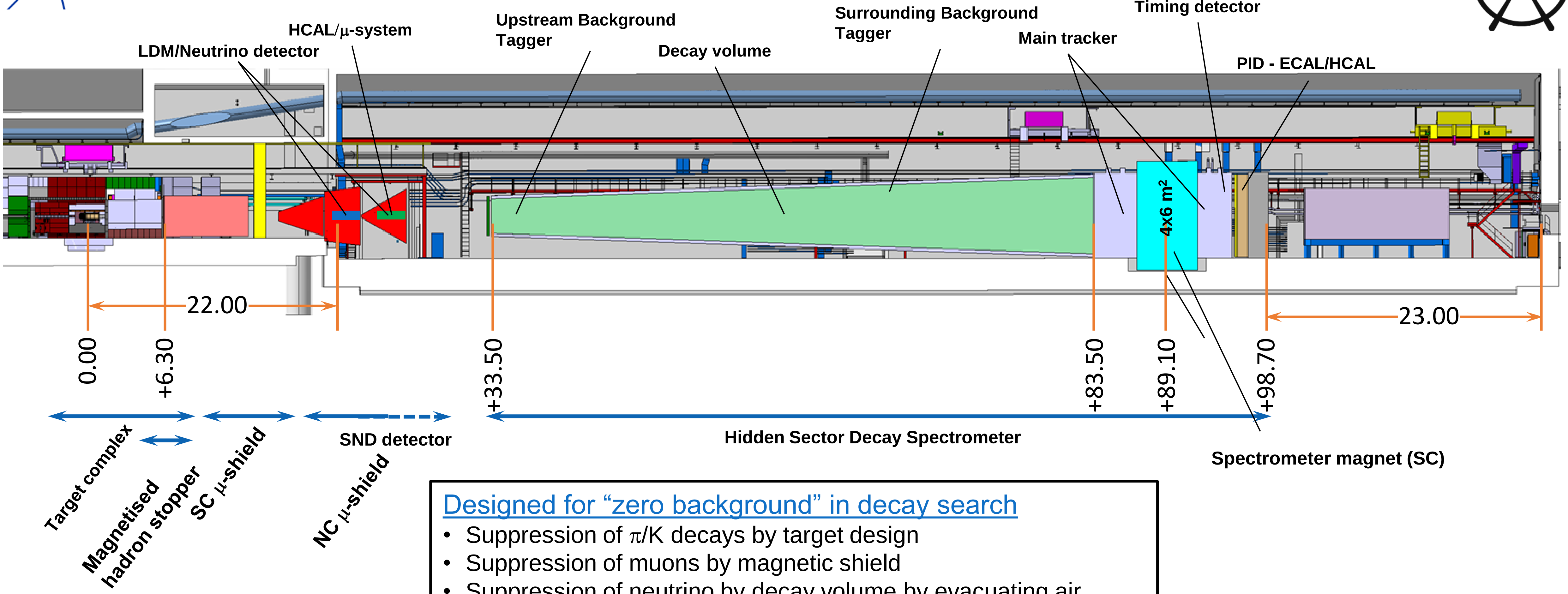
➔ Requirements in terms of **limits do** exist but they can be very costly not just in money but real ultimate physics

➔ Testing a new condition is usually time consuming or wishy-washy…

➔ We want to be as “generic and tolerant as possible” to deal with the uncertainty of the unknown !

➔ No, this is not a poor apology, welcome to Alice in the Wonderland !...

SHiP detector in more detail



Designed for "zero background" in decay search

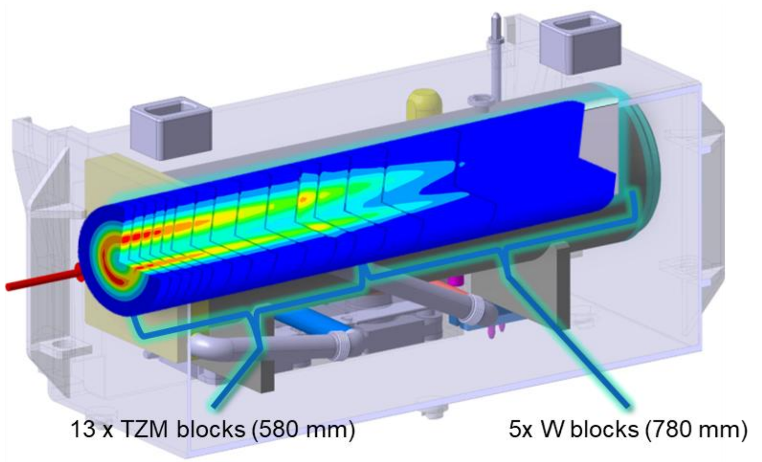
- Suppression of π/K decays by target design
- Suppression of muons by magnetic shield
- Suppression of neutrino by decay volume by evacuating air
- Background taggers
- Momentum and decay vertex information } by main tracker
- Impact parameter at target } by main tracker
- Coincidence timing

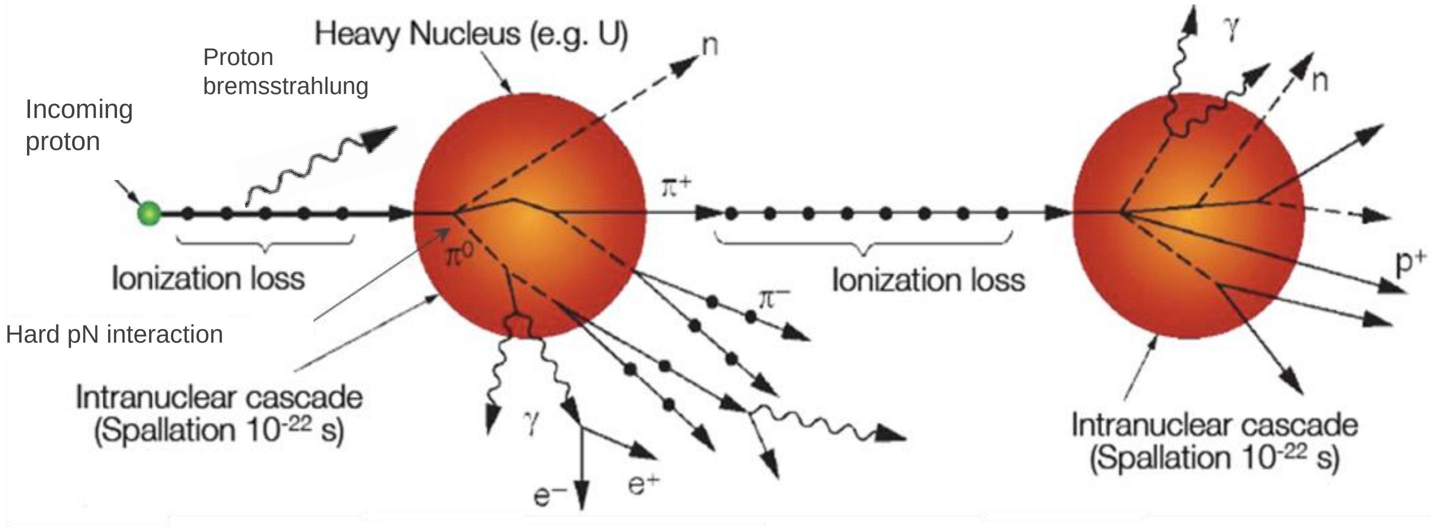
- Invariant mass } Not currently used in background suppression
- Particle identification } Not currently used in background suppression

Physics FoM of the target

- <u>Target design for signal/background optimisation:</u>
  - *“induce hard interactions of all protons and secondaries in the densest possible medium”:*
  - Very thick → use full beam and secondary interactions (12λ)
  - High-A/Z → maximise production cross-sections
  - Short λ → stop pions/kaons before decay

➔ **Beam dump or fixed target? Both!**





Physics FoM of the target

- <u>Signal</u>
  - Proton DIS — $\sigma_{pN} \propto \sigma_{pp} A^{2/3}$
  - Electromagnetic processes — $\sigma_{QN} \propto \sigma_{Qp} Z^2$

- <u>Background (μ, ν from π, K, and neutrons)</u>
  - π, K decay: $c\tau\gamma(\pi)$=7.8γ m, $c\tau\gamma(K)$=3.7γ m

    $$N_{dec}(x) = N_0 e^{-x/\gamma\tau}$$

    $$N_{int}(x) = N_0 e^{-x/\lambda_{int}}$$

  - Hadronic interaction $$\lambda_{int}(\pi) = \frac{1}{n\sigma_{inel}} = \frac{A}{\sigma_{\pi p} A^{2/3} N_a \rho} \propto A^{1/3}$$
  - (Electromagnetic) $$X_0 \propto \frac{A}{Z^2}$$
  - Muon shield will suppress muon flux by six orders of magnitude
  - Neutrino background suppressed by helium in decay volume

- Hadron shower containment
  - $t_{max}[\lambda_{int}] \approx 0.2\, ln(400\ GeV) + 0.7 \sim 1.9\lambda_{int}$
  - **95% long. containment:** $L_{95} \approx t_{max} + 2.5(400\ GeV)^{1/3} = 20.3\ \lambda_{int}$
  - **95% radial containment:** $R_{95} \approx \lambda_{int} + 2\sigma_{beam} + r_{sweep}$

W: A=184, Z=74, λ_{int}=9.9cm, $\lambda_{int}(\pi)$=11.3cm
Mo: A= 96, Z=42, λ_{int}=15.2cm, $\lambda_{int}(\pi)$=18.0cm
Cu: A= 64, Z=29, λ_{int}=15.3cm, $\lambda_{int}(\pi)$=18.5cm
H_2O: λ_{int}=83.3cm, $\lambda_{int}(\pi)$=115.6cm

(Design guidelines)

- No simple metric but different target configurations can be quite easily compared for fast exploration
- Guidelines:
  - Highest density
  - Shower containment for hadronic component is important up to a radius where π/K decays "miss detector"
  - Cooling gaps are less critical as long as negligible contribution to combined interaction length of π/K
  - Sufficiently long and dense before hadron stopper to stop protons, pions, kaons
  - Beam spot size and sweep radius, see later
- Use FLUKA for checking performance of different options
  - p, π, K, μ, n $(x, y, x, \bar{p})$ to check rates and hadronic shower containment at scoring plane after hadron stopper

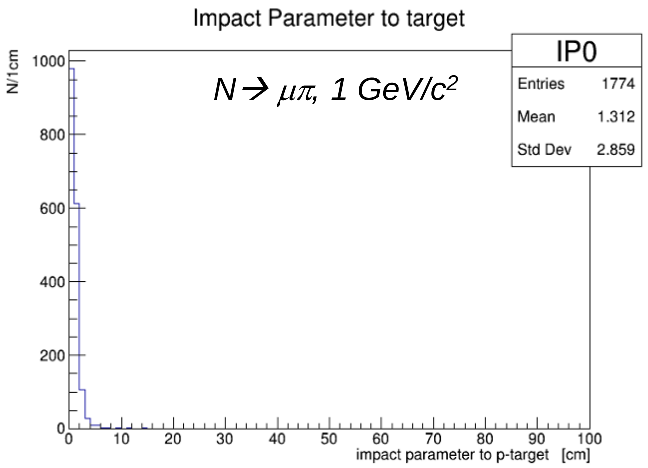
Operational scenario with beam requirements

- Annual proton yield expected on target
  - *Physics programme relies on 4x10^{19} protons on target per year for up to 15 years of operation and <1 event background!*
  - ➔ 4-5 x10^{13} protons on target over 1s spills/7s
  - ➔ ~10^{6} spills per year
  - ➔ Up to 3.2 MJ /1s spill , up to 450 kW average beam power

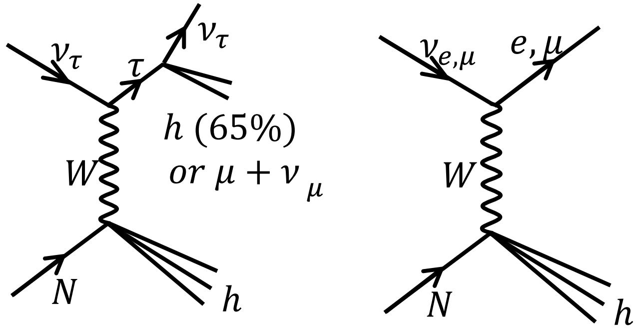
- Joint target/experiment optimization of *nominal* beam parameters
  - Beam sweep on target with 50mm radius (angle w.r.t. beam axis ~0.5 mrad)
  - Beam spot σ ~8-16mm (second order effect)
  - Stability of beam centre axis and sweep <1σ
  - ➔ Parameters driven by aperture of muon shield and use of impact parameter at target for background discrimination

- Regular (few per year) (re-)commissioning/calibration run
  - Low intensity <5x10^{11} with no sweep and nominal beam spot
  - ➔ Motivated by alignment run with measurement of reconstruction performance

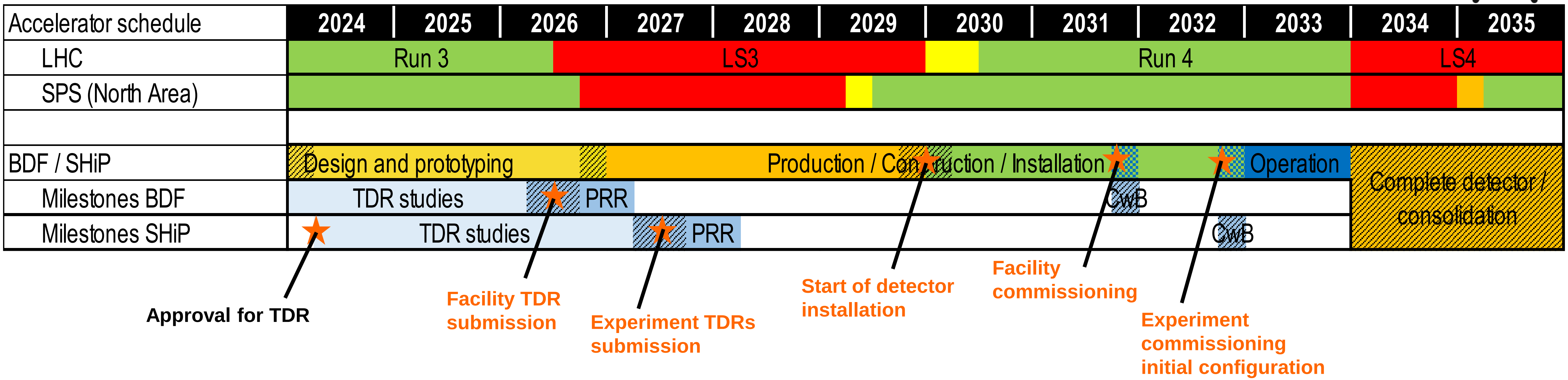
FIP decay background suppression



Tau neutrino identification



BDF/SHiP schedule



- ~3 years for detector Technical Design Reports
- Facility implementation starting in Long Shutdown 3 of CERN’s accelerator complex
- Important to start data taking ~2 year before Long Shutdown 4

→ Complete detector at the latest in LS4

→ Critical systems in full scale and full physics capability in Run 4

→ 15 years of physics exploration

Requirements and objectives in Run 4 (2)

SHiP objectives in ECN3 **with beam** for Run 4

1. Facility commissioning – 2031 Q3 (1 month)
   - Parasitic SHiP central system commissioning
   - Physics performance of beam and target systems

   } low - high intensity

2. Muon shield commissioning – 2031 Q3 / 2032 Q3
   - Performance

   } low - high intensity

3. Detector commissioning – 2032 Q3 (weeks)
   - Functional – control, readout, monitoring
   - Time/space alignment
   - Subdetector performance

   } low intensity

4. Background measurements – 2032 Q3 – 2033 Q2 (weeks)

   ➔ W/O sweep on target, muon shield off, decay volume under air
   - Rate measurements
   - Reconstruction performance (eff., res.) and rejection power
   - Tune simulation
   - Physics with background from neutrino DIS and muon DIS

   } low - mid intensity

5. Nominal physics run, reaching few(4?) x 10^{19} p/target – 2033

   } mid – high intensity

Low intensity (2031-2032)
- 5×10^{11} p/spill or less
- Spill duration >1s (FT 4.8s, 9.6s)
- Nominal beam size ~8mm
- No need for spill quality
- No need for precise beam monitoring

Mid-high intensity (2032-2033)
- $10^{12} \rightarrow 5 \times 10^{13}$ p/spill
- Spill duration 1s
- Nominal beam size
- Intensity for background measurement to be tuned

Sources of operational issues and monitoring

- Operational issues:
  - Failures - downtime
  - Adverse experimental conditions
  - ➔ Most of these are beam-induced and rather specifies the requirements on the beam requirements
- What is the longterm (physics) performance of the target?
  - Cracking, change of material properties (isotop build-up, DPA,...)
- In terms of beam-related Machine Protection, SHiP is “protected” by limits from the target itself
  - ➔ SHiP detector by construction is not sensitive to beam or target failures in terms of damage (“beam dump”)
  - ➔ SMP flag on “commissioning/calibration intensity” = intensity limit with *no beam sweep* on target
- Target related instrumentation with real-time importance to SHiP online system
  - Beam sweep (position σ~8mm) on target (300 Hz)
  - Target environmental parameters (temperatures)
  - Radiation environment around target
  - (Hadron stopper field)