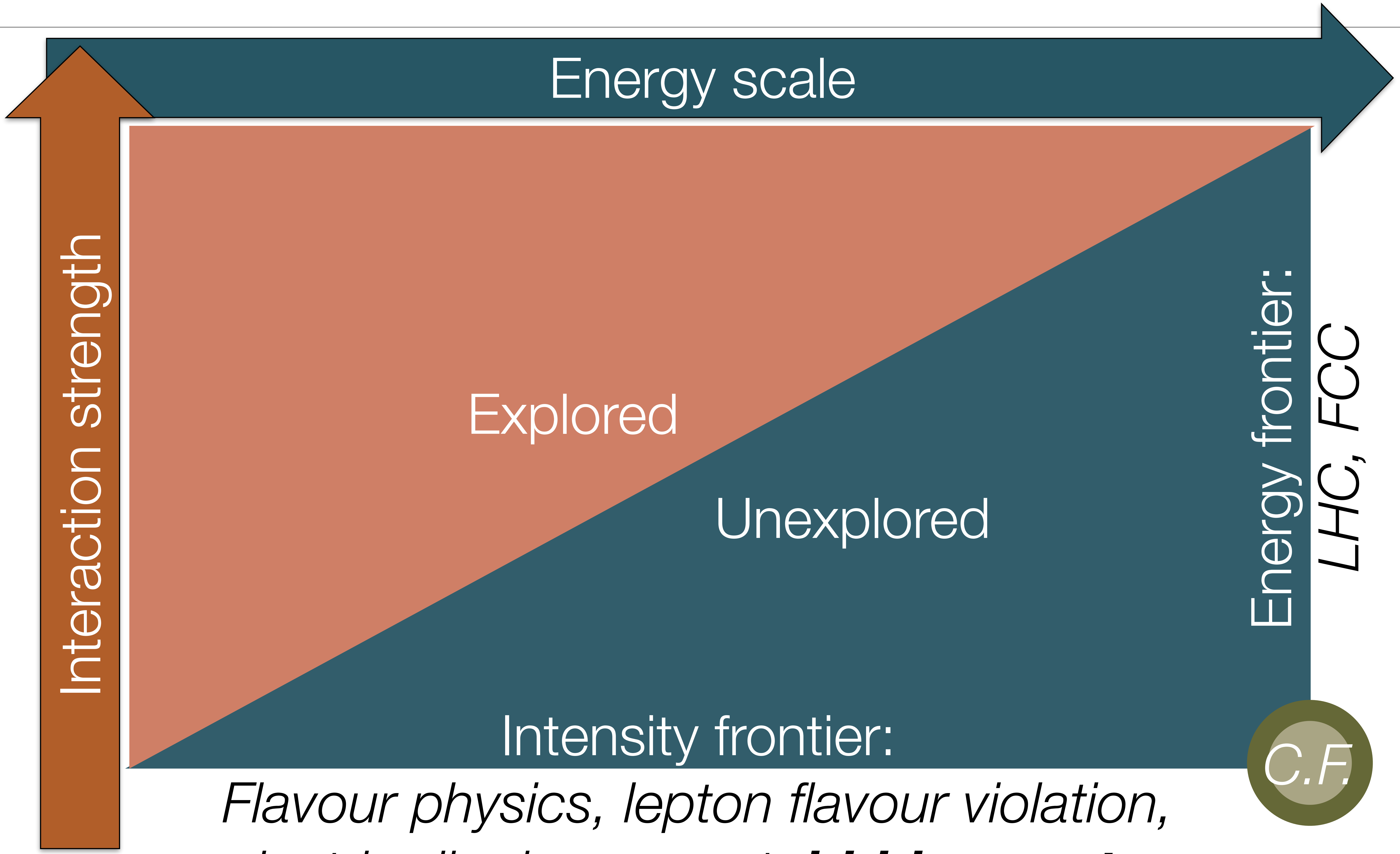
The SHiP experiment

Federico Leo Redi on behalf of the SHiP collaboration

WIN2019 - Bari, Italia

Introduction / 1



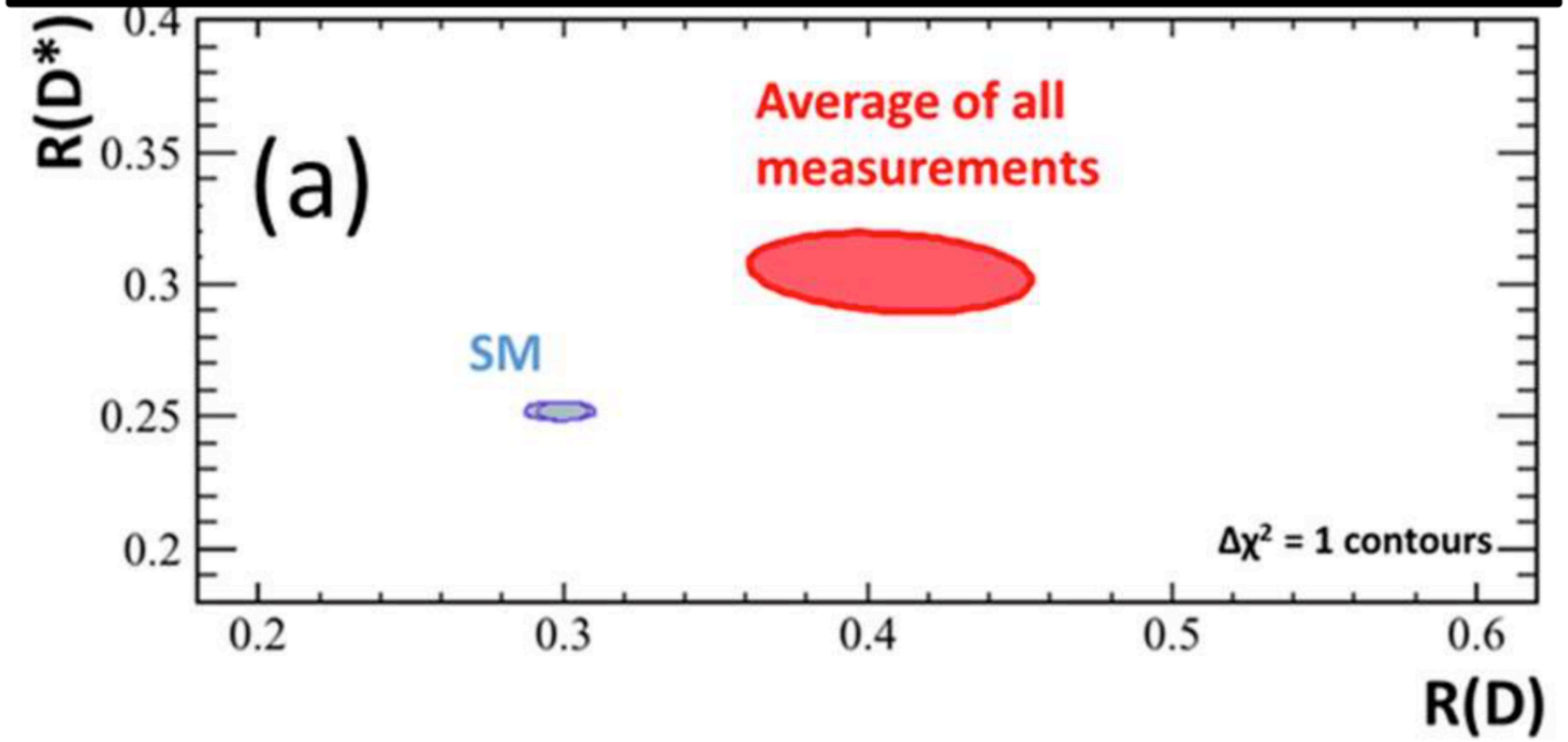
Flavour physics, lepton flavour violation,
electric dipole moment, ***hidden sector***

Landscape today / 1

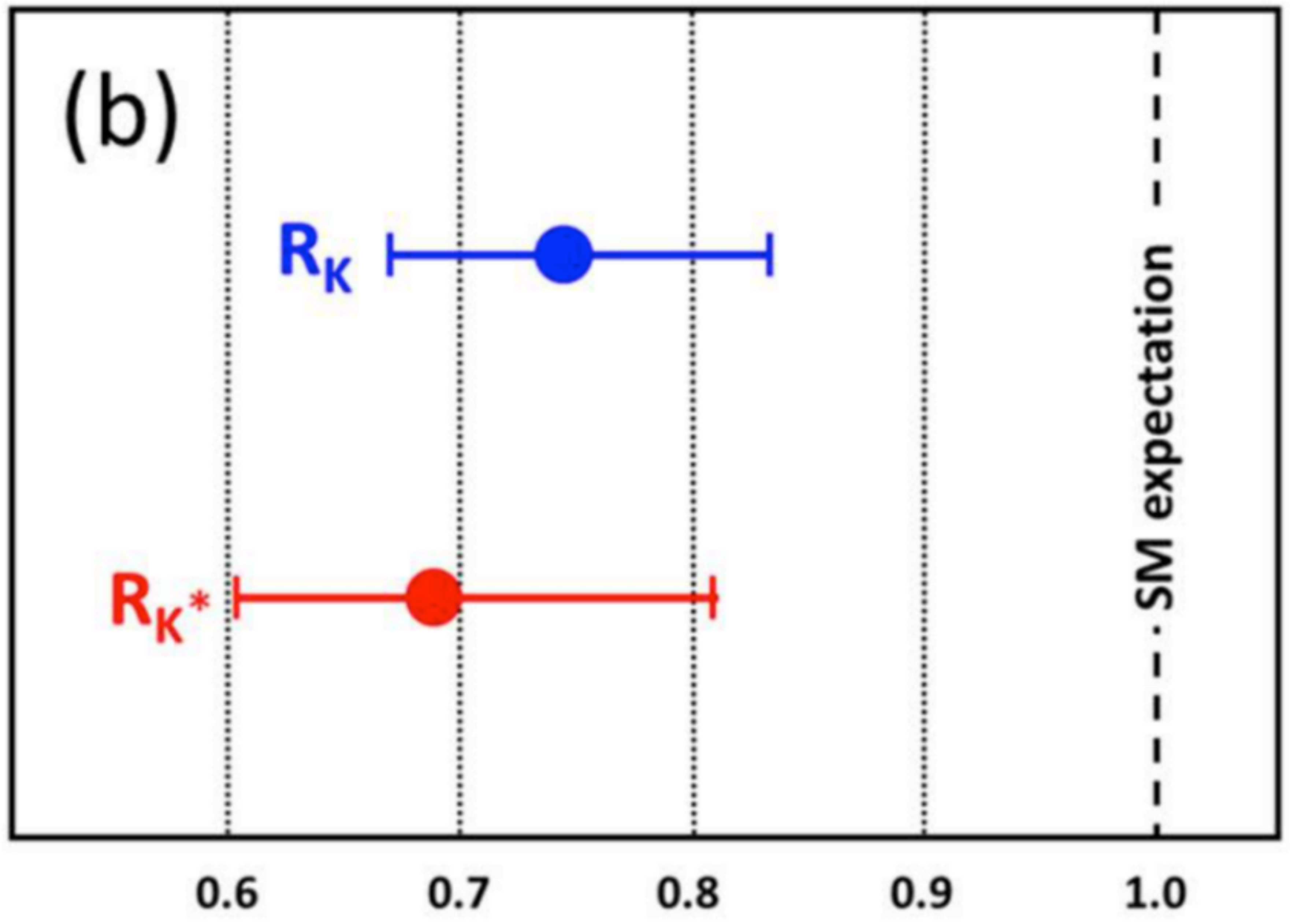
- The Intensity frontier is a **broad** and **diverse**, yet **connected**, set of science opportunities: heavy quarks, charged leptons, hidden sectors, neutrinos, nucleons and atoms, proton decay, etc...
- In this talk, I will concentrate on **dark sectors**...
- **Landscape**: LHC results in brief:
  - 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

http://www.slac.stanford.edu/xorg/hfag/semi/fpcp17/RDRDs.html



arXiv:1705.05802.



Landscape today / 3

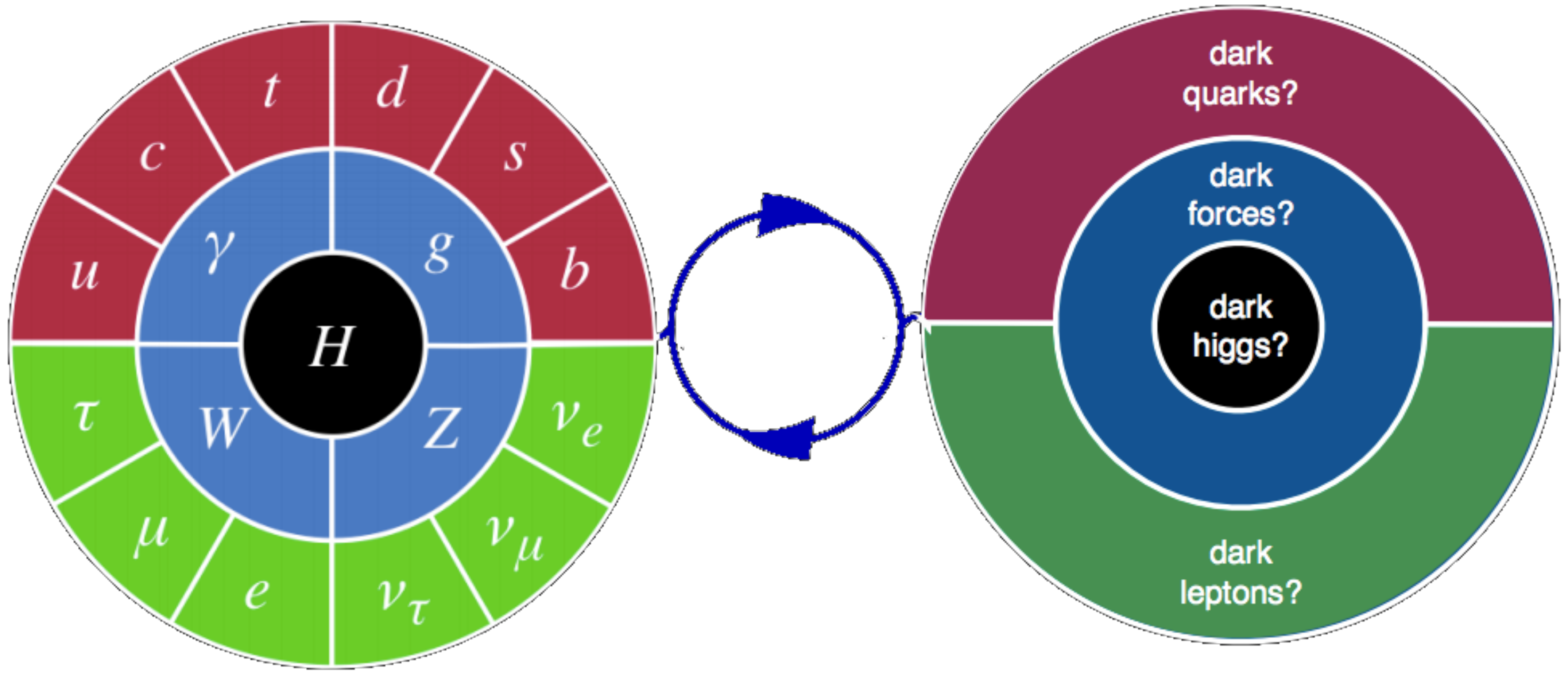
- Therefore, from LHC hints, **strong motivation to search** for
  - Light Dark Matter (**LDM**)
    Portals to Hidden Sector (**HS**) (dark photons, dark scalars)
    Axion Like Particles (**ALP**)
    Heavy Neutral Leptons (**HNL**)
    LFV τ decays

We need a general-purpose setup!

- 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**, ...)

Exploring the dark sector / 1

M. Williams



- In the dark sector: $\boldsymbol{L = L_{SM} + L_{mediator} + L_{HS}}$
  - Hidden Sector decay rates into SM final states is suppressed
  - Branching ratios of $O(10^{-10})$
  - Long-lived objects
  - Interact very weakly with matter
- Experimental challenge is **background suppression**
- **Full reconstruction**, **low pT** triggering, and **PID** are essential to minimise model dependence
  - **Two** strategies of searching for mediators at accelerators:
  - ***Direct search (signal proportional to <coupling>^{4})***
    - *Scattering technique: electron or nuclei scattered by DM…*
    - *Reconstruction of decay vertex*
  - ***Indirect search (signal proportional to <coupling>^{2})***
    - *Missing energy technique*

Exploring the dark sector / 2

- ***Direct search (signal proportional to <coupling>^{4})***
  - ***Scattering technique: electron or nuclei scattered by DM***
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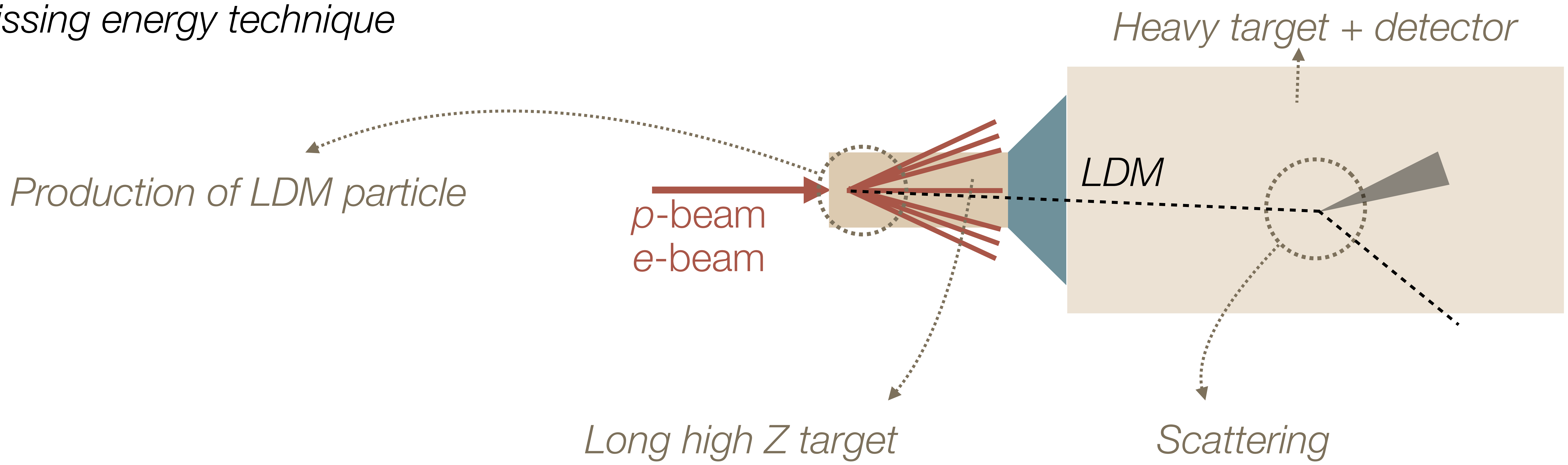

Exploring the dark sector / 3

- ***Direct search (signal proportional to <coupling>^{4})***
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  - ***Reconstruction of decay vertex***
- ***Indirect search (signal proportional to <coupling>^{2})***
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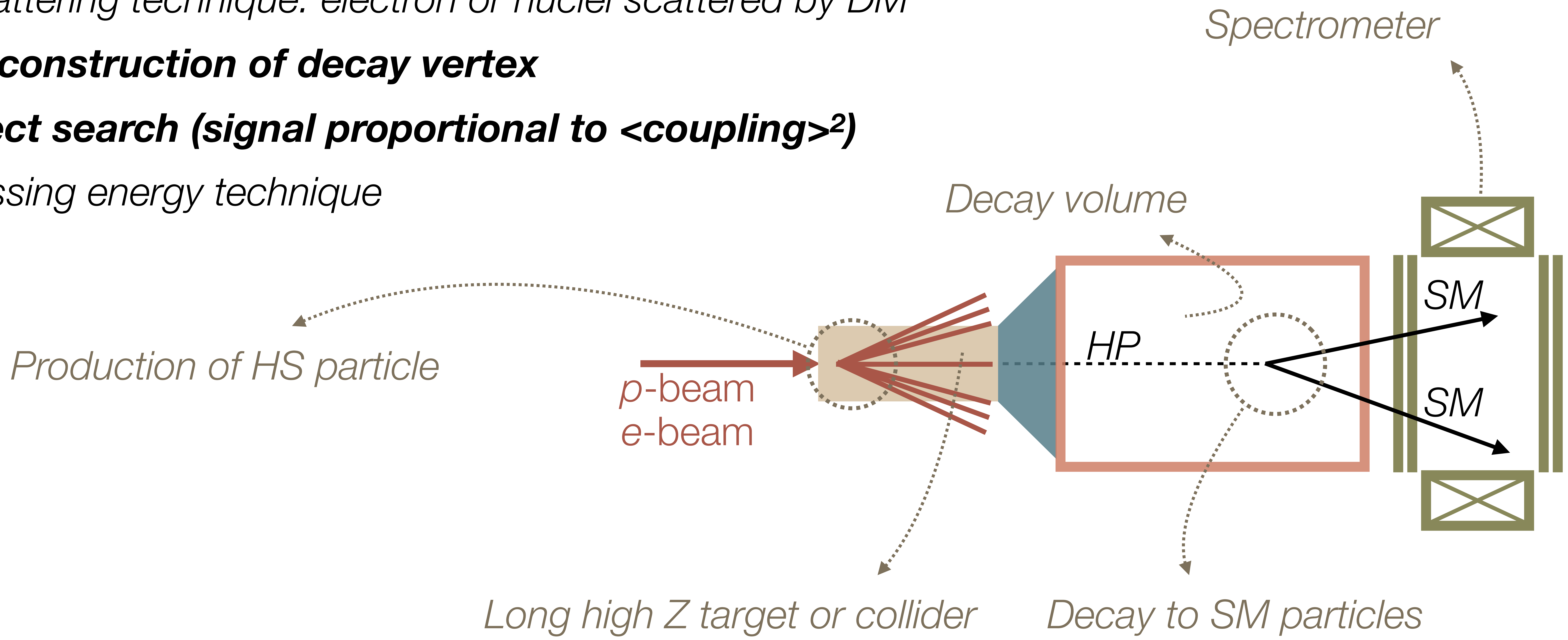

Exploring the dark sector / 4

- ***Direct search (signal proportional to <coupling>^{4})***
  - *Scattering technique: electron or nuclei scattered by DM*
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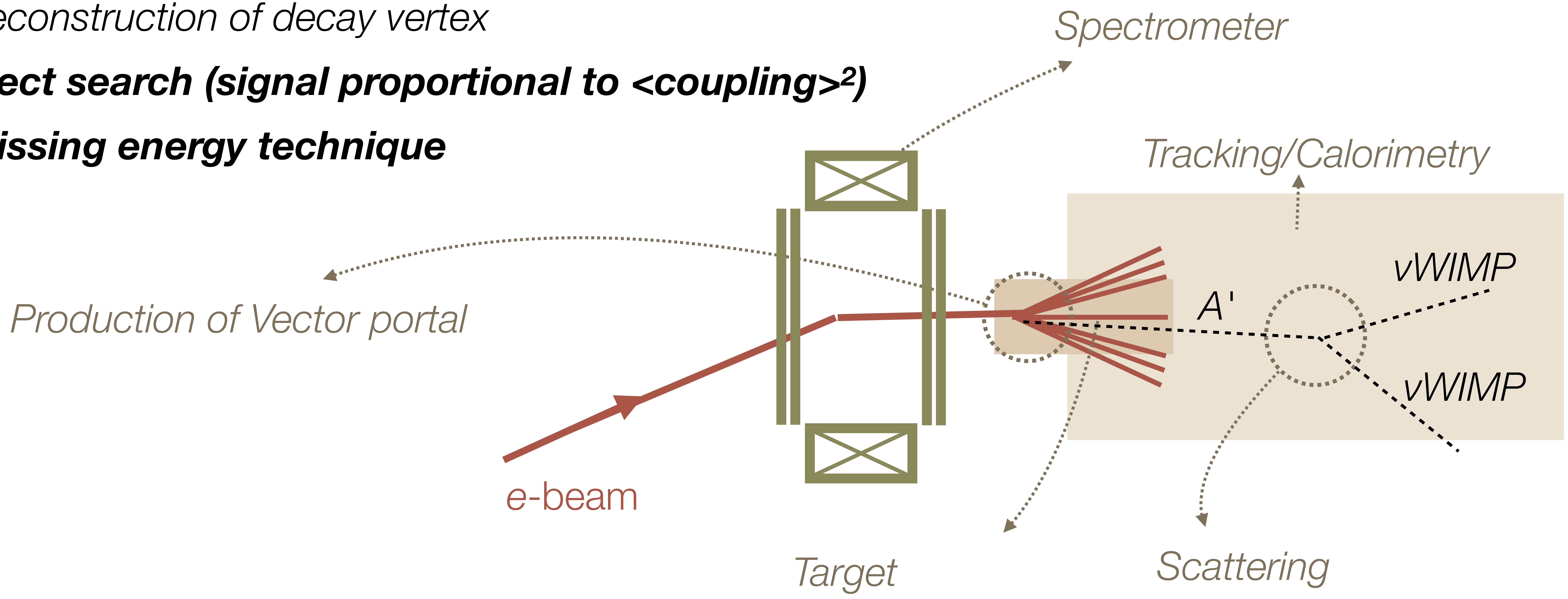
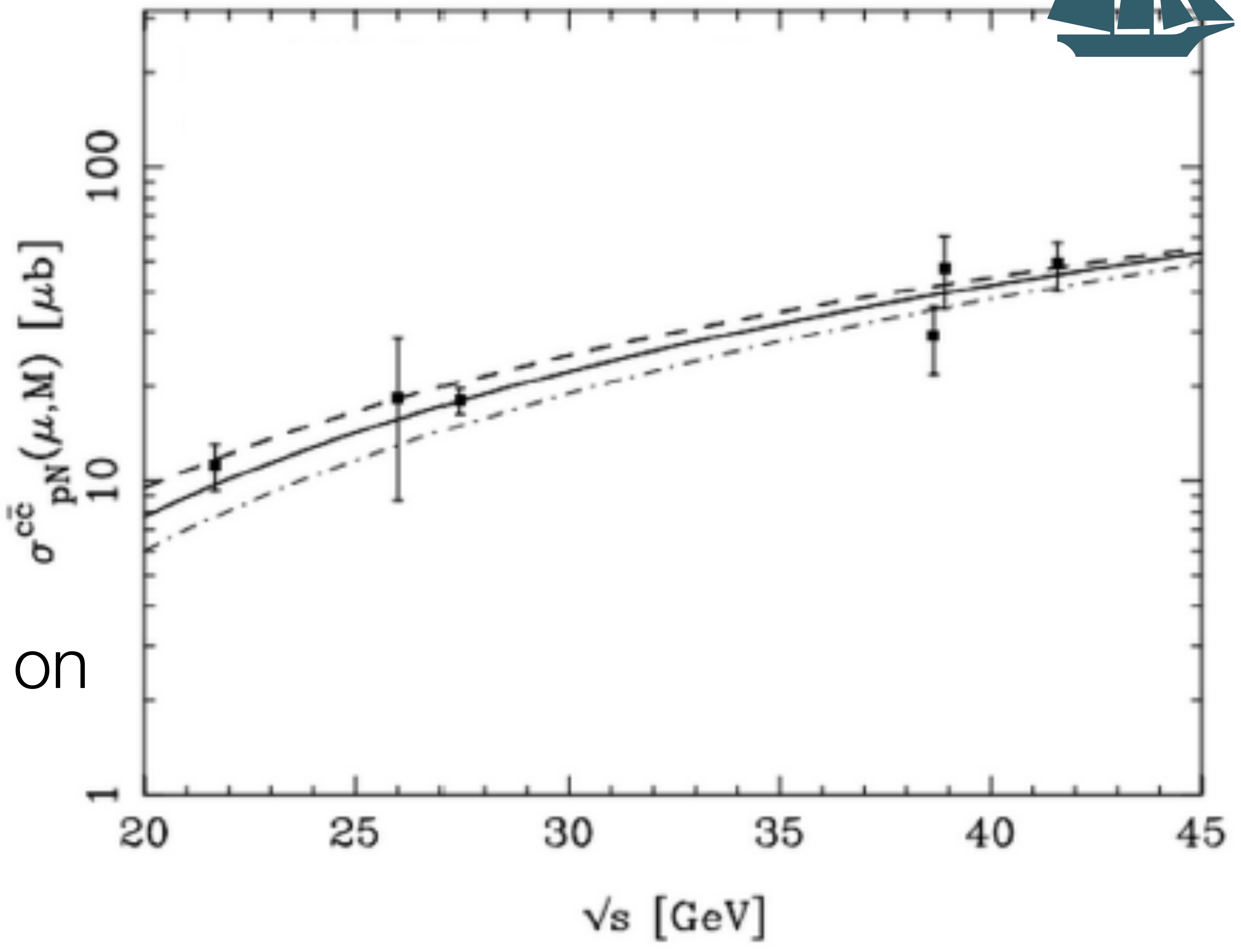


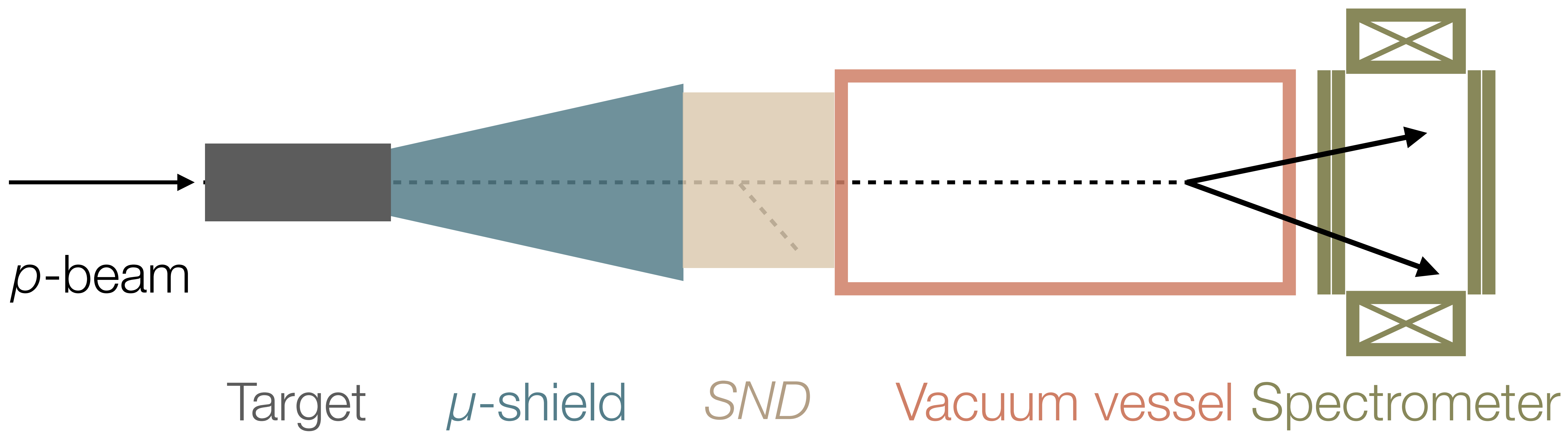
Decaying dark sector candidates / 1



- **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:
      $\sigma(pp \to s\bar{s}\,X)/\sigma(pp \to X) \sim 0.15$
      $\sigma(pp \to c\bar{c}\,X)/\sigma(pp \to X) \sim 2.0 \times 10^{-3}$
      $\sigma(pp \to b\bar{b}\,X)/\sigma(pp \to X) \sim 1.6 \times 10^{-7}$
- 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...*

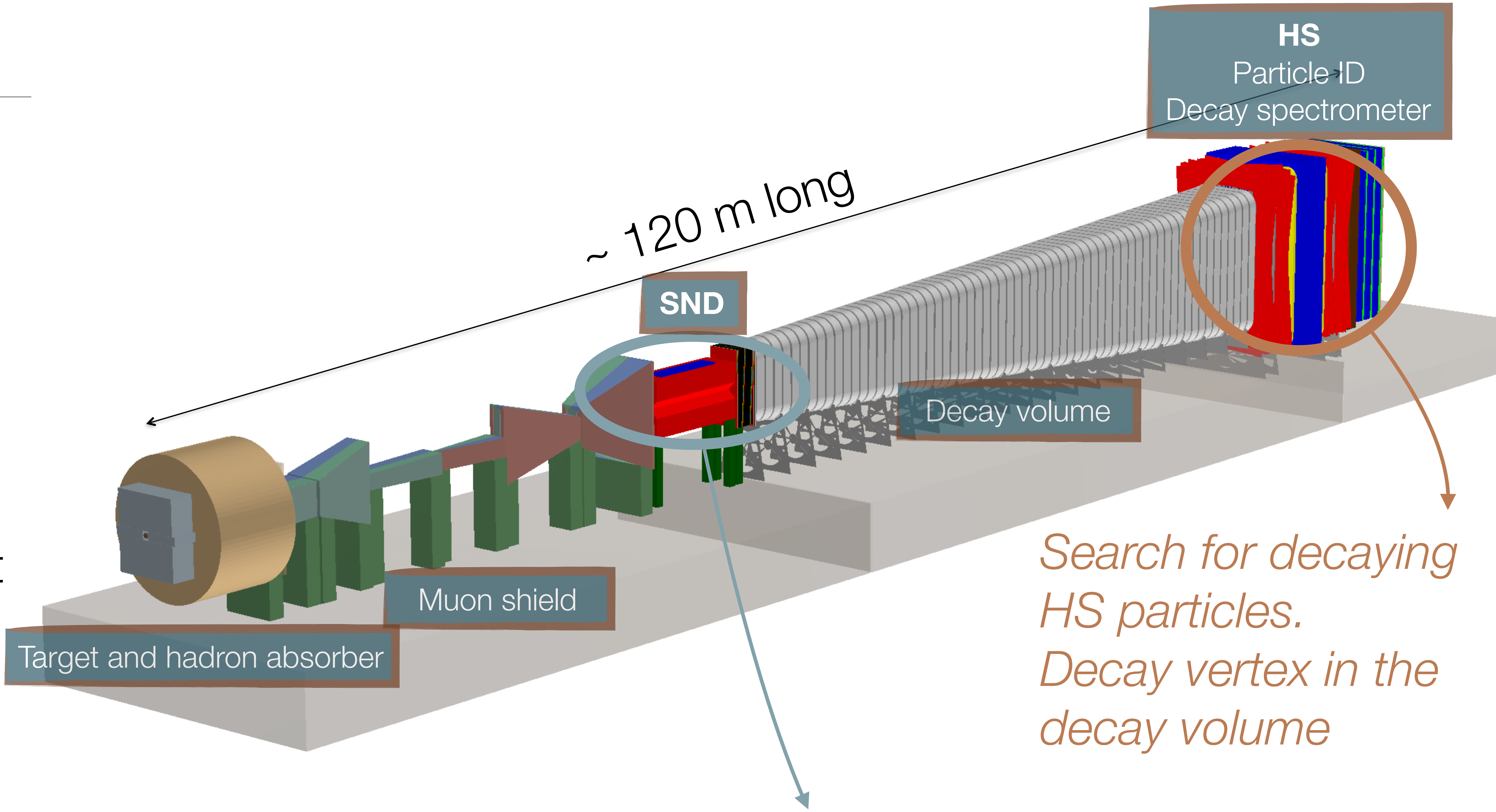
Decaying dark sector candidates / 2

- 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
- **Zero** background means 2 candidates are a discovery
- Mass, charge, flavour information available at observation allow to narrow down physics models



SHiP / 1

- Numbers:
  $>10^{18}$ D, $>10^{16}$ τ, $>10^{21}$ γ
  for **2×10^{20} pot (in 5 years)**
- **Dual detector** system:
  HS detector
  SND detector
- "***Zero background***" experiment
  Heavy target
  Muon shield
  Surrounding Veto detectors
  Timing and PID detectors, etc.



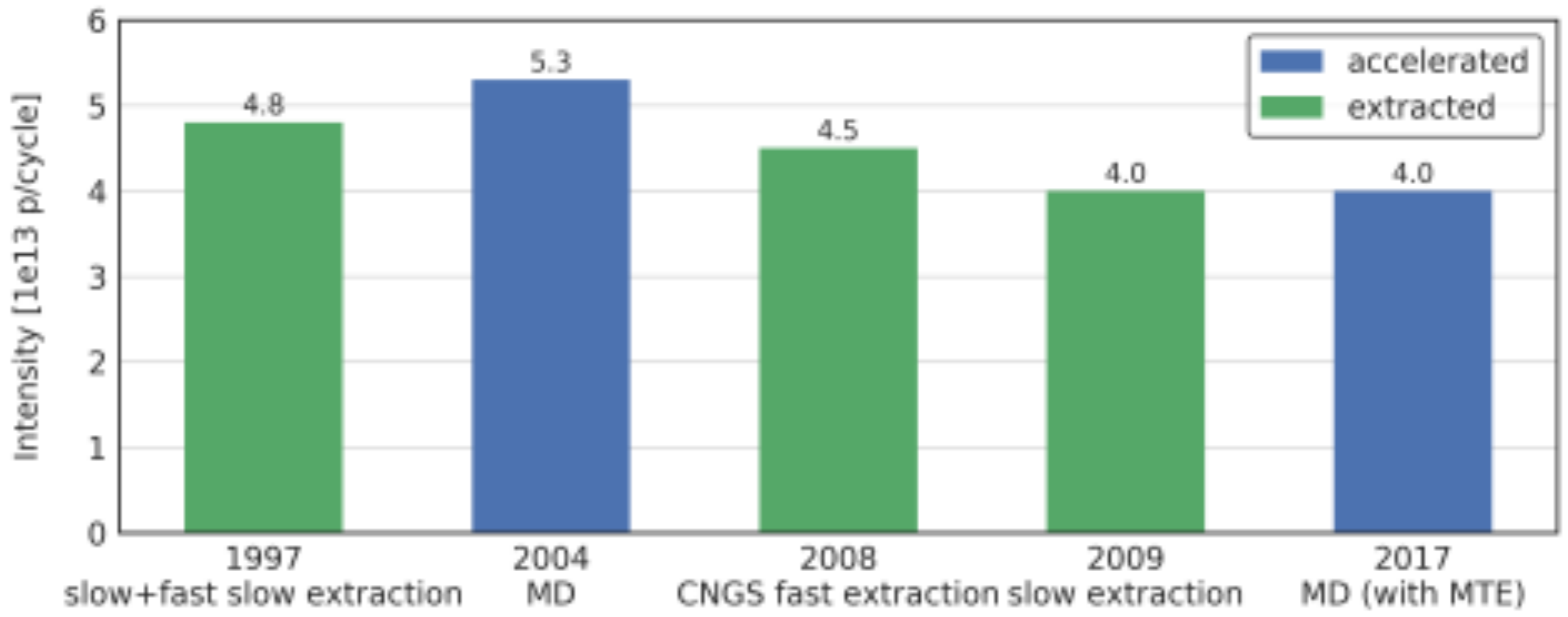
Search for decaying HS particles. Decay vertex in the decay volume

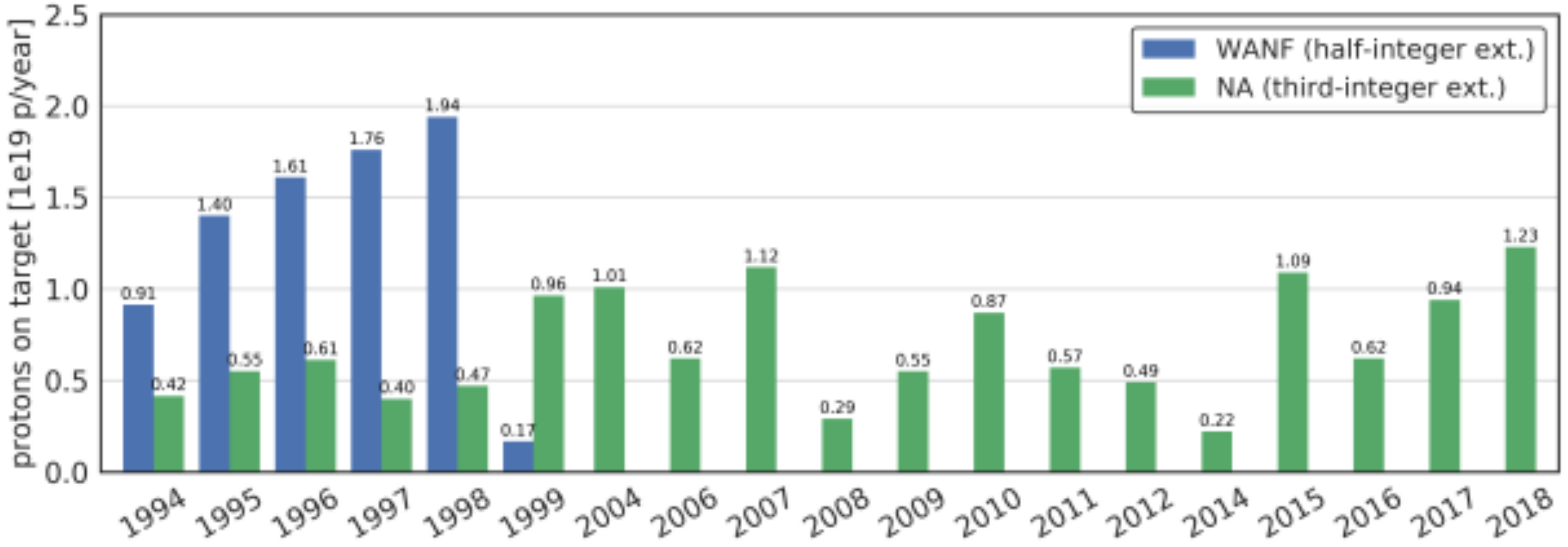
Search for DM (scattering on atoms) and ν physics. Specific event topology in emulsion. Background reducible to a manageable level

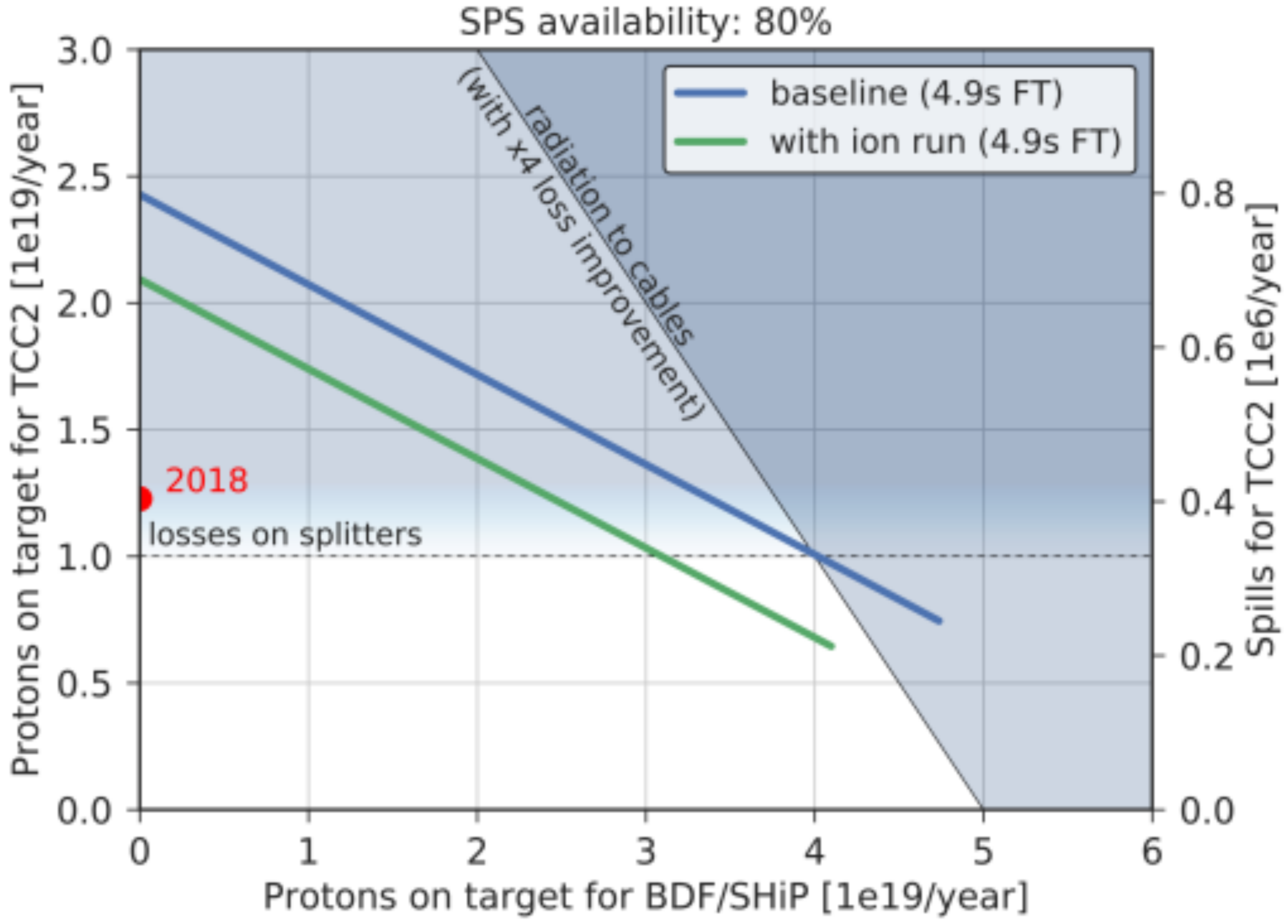
Models	Final states
Neutrino portal, SUSY neutralino	$\ell^\pm\pi^\mp, \ell^\pm K^\mp, \ell^\pm\rho^\mp, \quad \rho^\pm \to \pi^\pm\pi^0$
Vector, scalar, axion portals, SUSY sgoldstino	$\ell^+\ell^-$
Vector, scalar, axion portals, SUSY sgoldstino	$\pi^+\pi^-, K^+K^-$
Neutrino portal ,SUSY neutralino,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

SHiP / 2

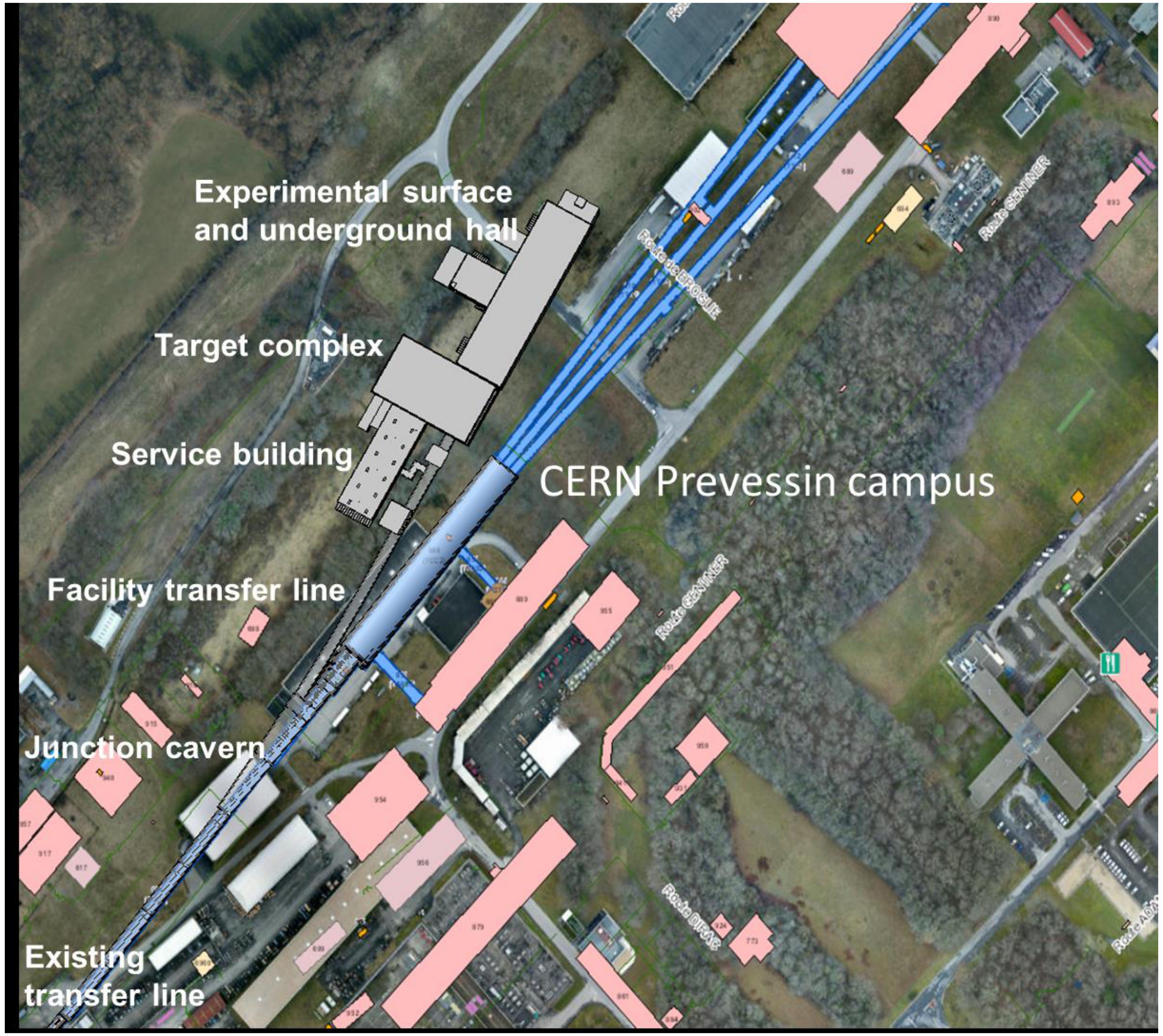
- SHiP assumes **current capacity of SPS**, slowly extracted 1s spills with 4×10^{13} p / 7.2s
- **Slow extraction** of $(4 + 1) \times 10^{19}$ p/year requires reduction of losses by factor four
- Factor of three was achieved in MDs in 2018 (**Flat Top** of 4.9 s)



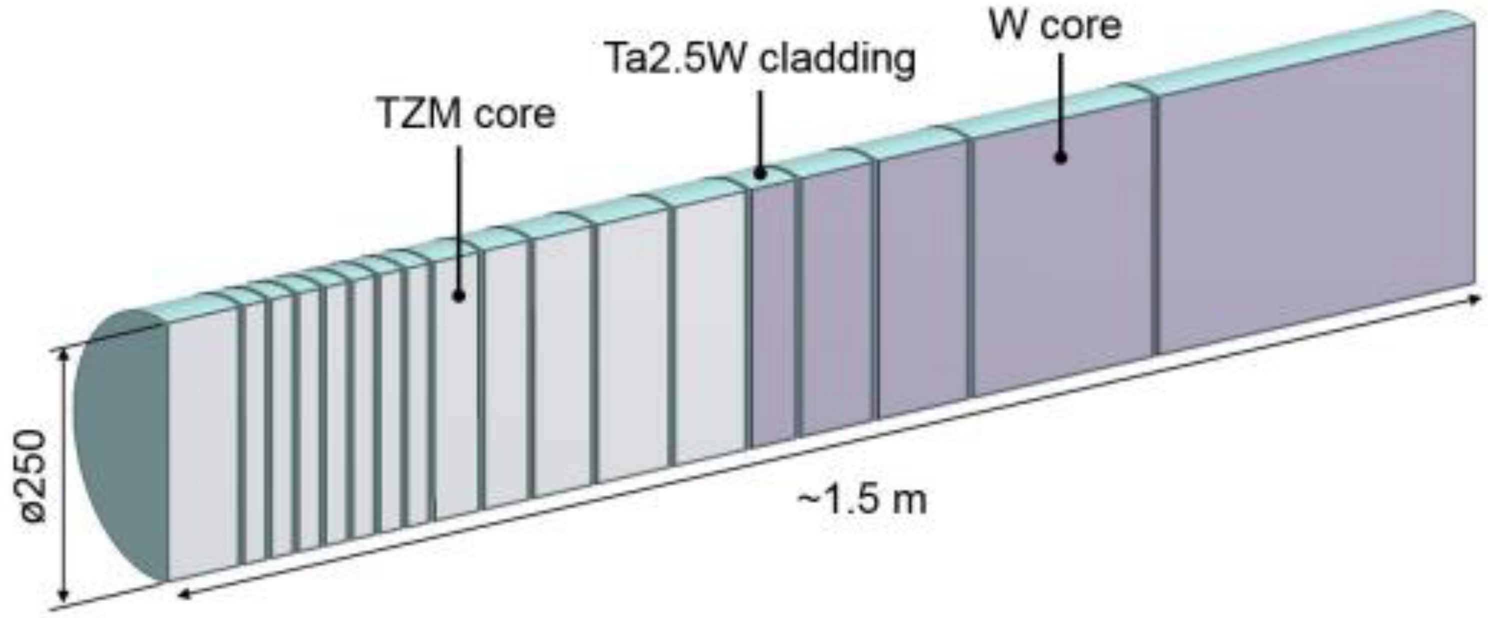




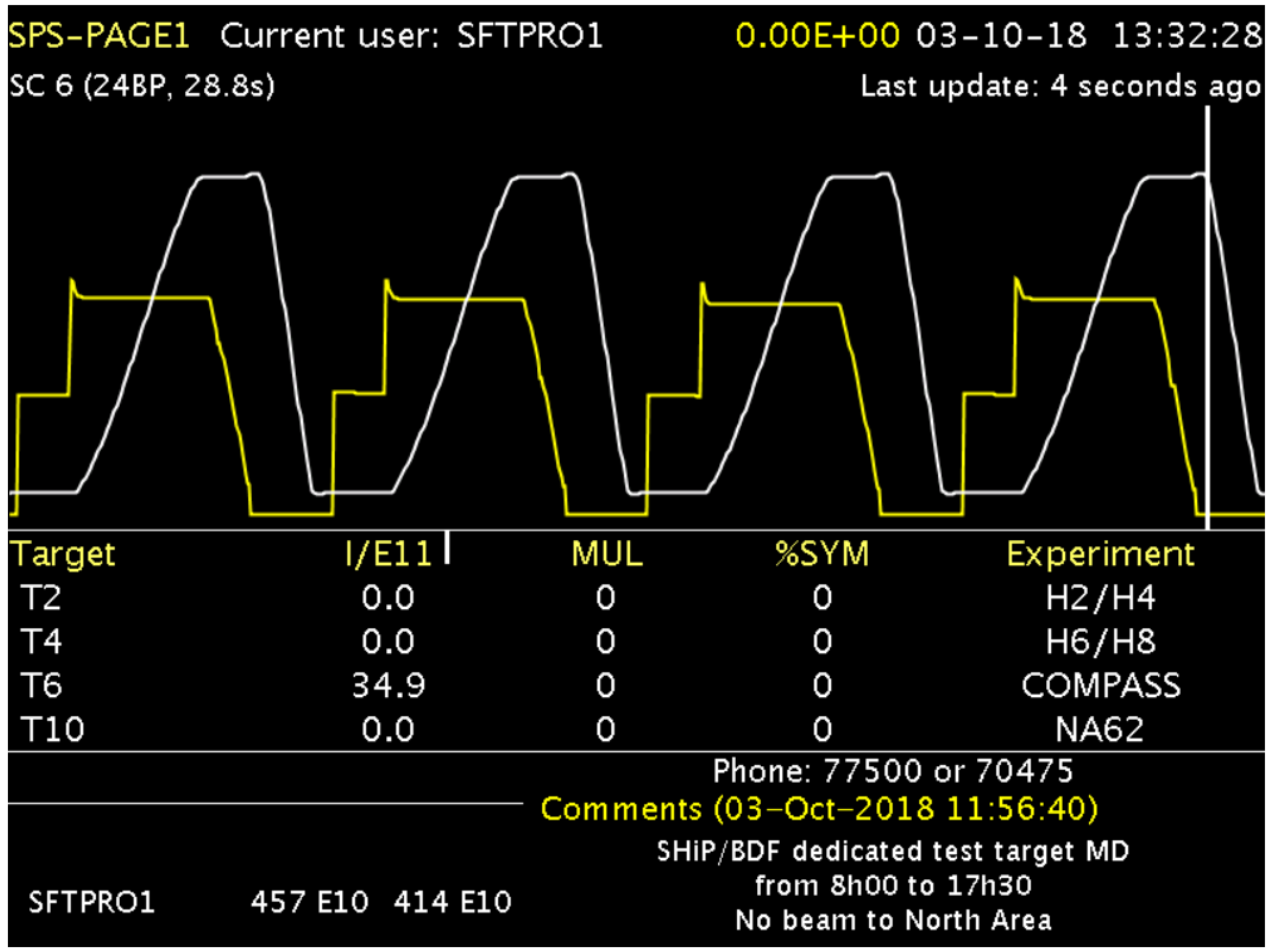
SHiP / 3



Experimental surface
and underground hall
Target complex
Service building
Facility transfer line
Junction cavern
Existing
transfer line
CERN Prevessin campus



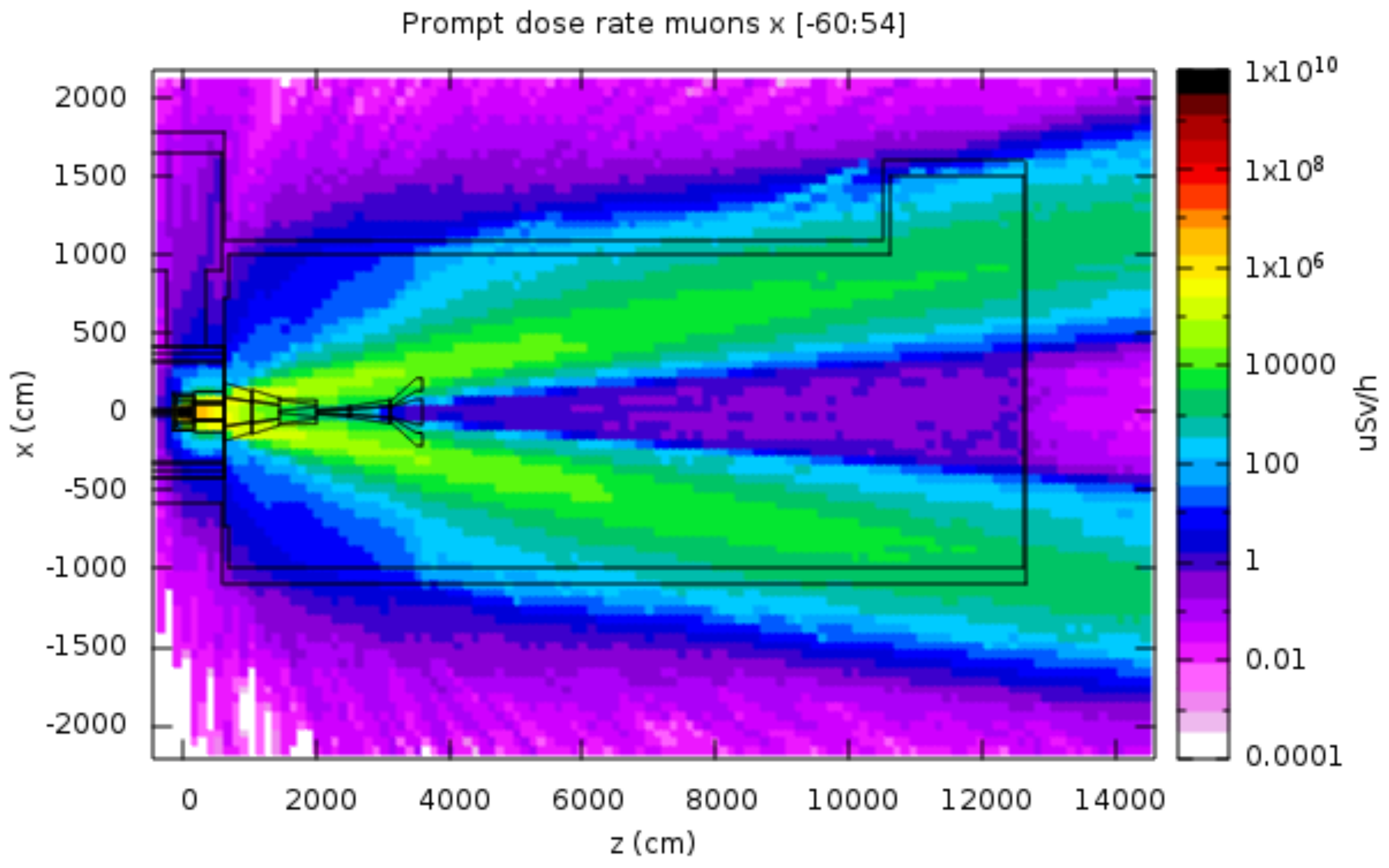
W core
Ta2.5W cladding
TZM core
ø250
~1.5 m

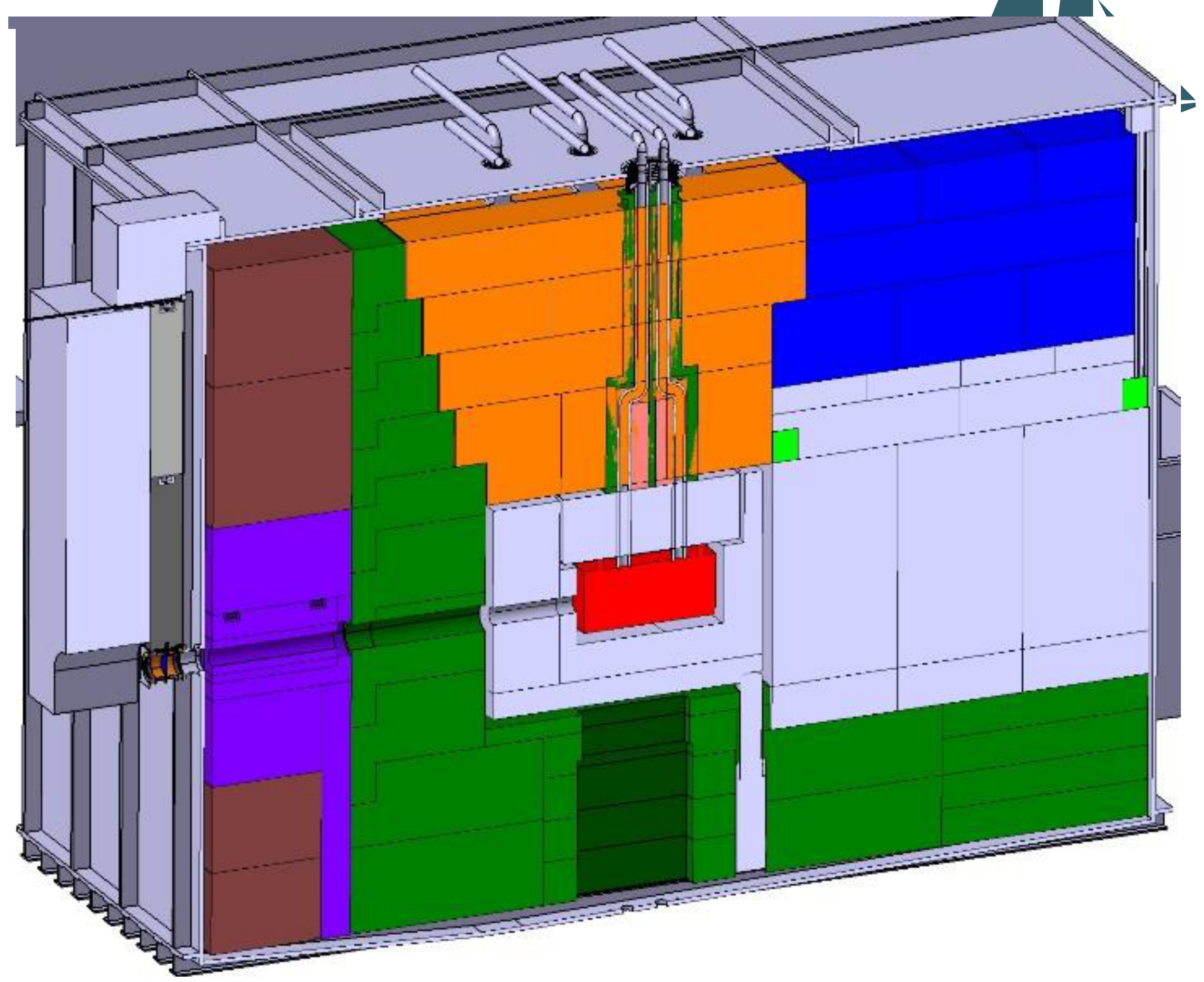


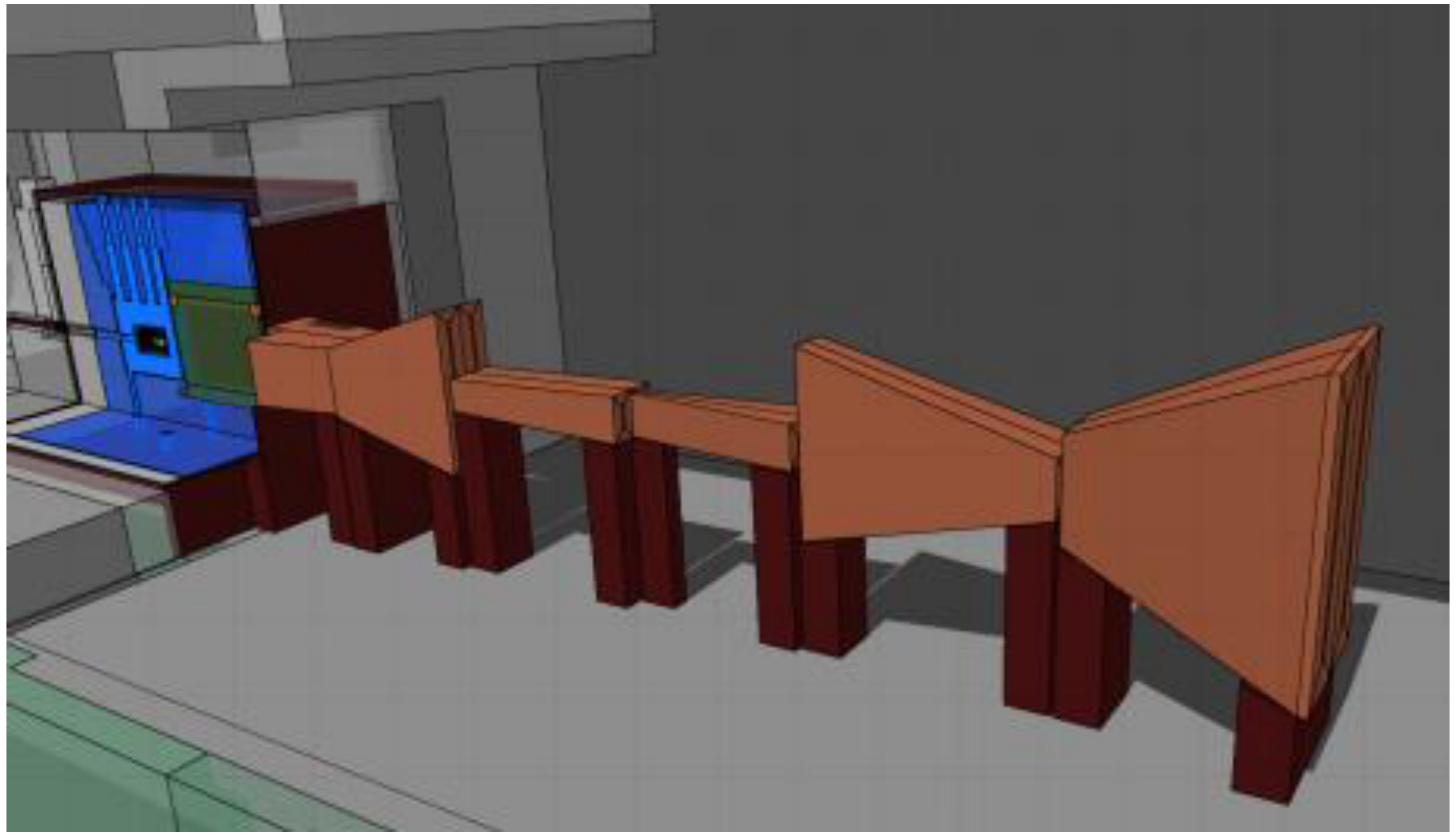
SPS-PAGE1 Current user: SFTPRO1 0.00E+00 03-10-18 13:32:28
SC 6 (24BP, 28.8s) Last update: 4 seconds ago
Target I/E11 MUL %SYM Experiment
T2 0.0 0 0 H2/H4
T4 0.0 0 0 H6/H8
T6 34.9 0 0 COMPASS
T10 0.0 0 0 NA62
Phone: 77500 or 70475
Comments (03-Oct-2018 11:56:40)
SHiP/BDF dedicated test target MD
from 8h00 to 17h30
No beam to North Area
SFTPRO1 457 E10 414 E10

Target and μ shielding / 1

- Critical to reduce **muon flux** and **neutrino interaction**:
  - Magnetisation of hadron stopper
  - **Active** muon shield
  - Decay volume under vacuum
- Redundant rejection of residual background:
  - **Background taggers**
  - Momentum and vertex information
  - Impact parameter at target
  - Coincidence timing
  - Invariant mass
  - Particle identification
- *Aim for **zero background***

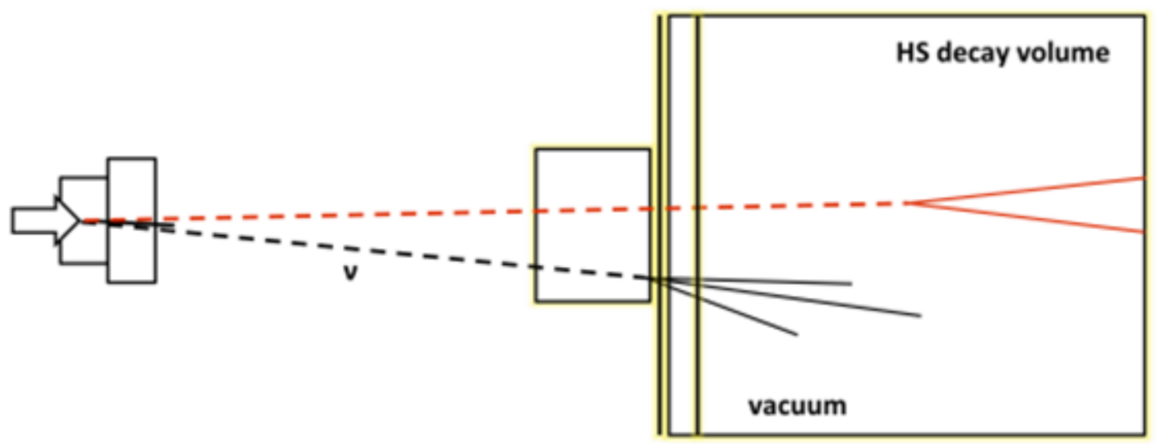




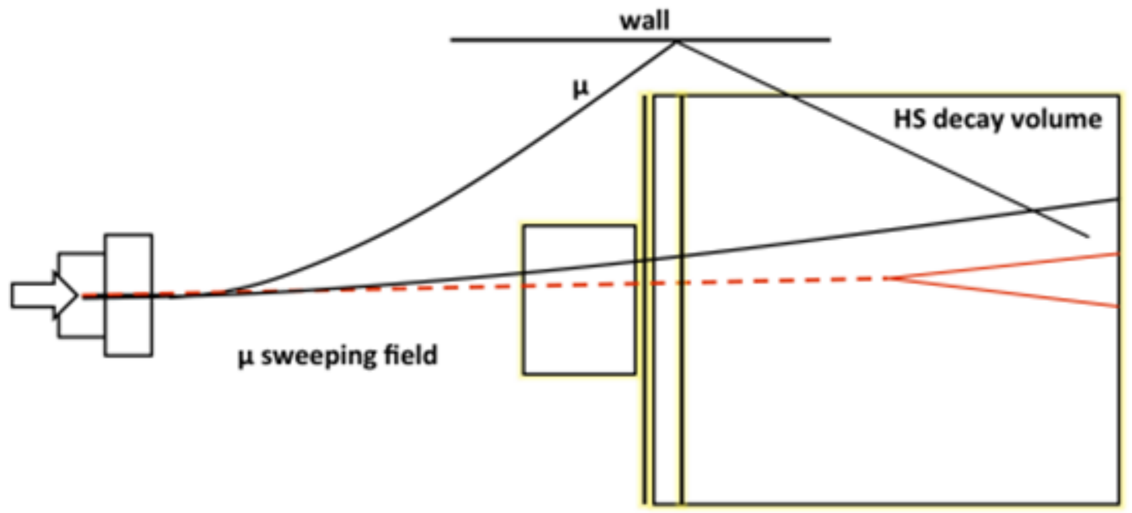


Background free? / 1

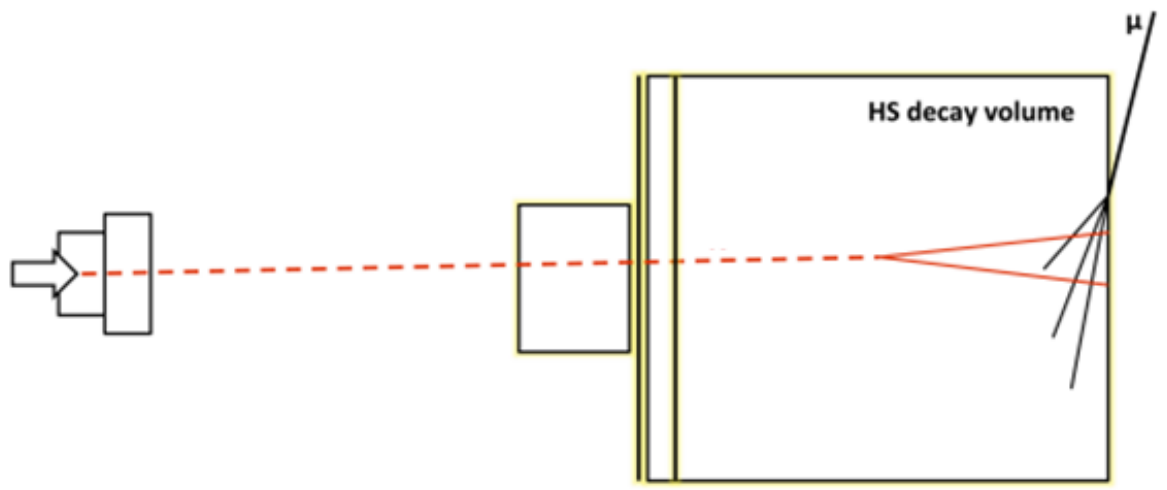
- **Muon combinatorial** (5 yrs): < 10–2 @ 90%CL
- **Muon inelastic** (5 yrs): < 6×10^{-4} @ 90%CL
- **ν interactions** (10 yrs): ν-air: < 10–2; ν-mat: = 0 @90%CL



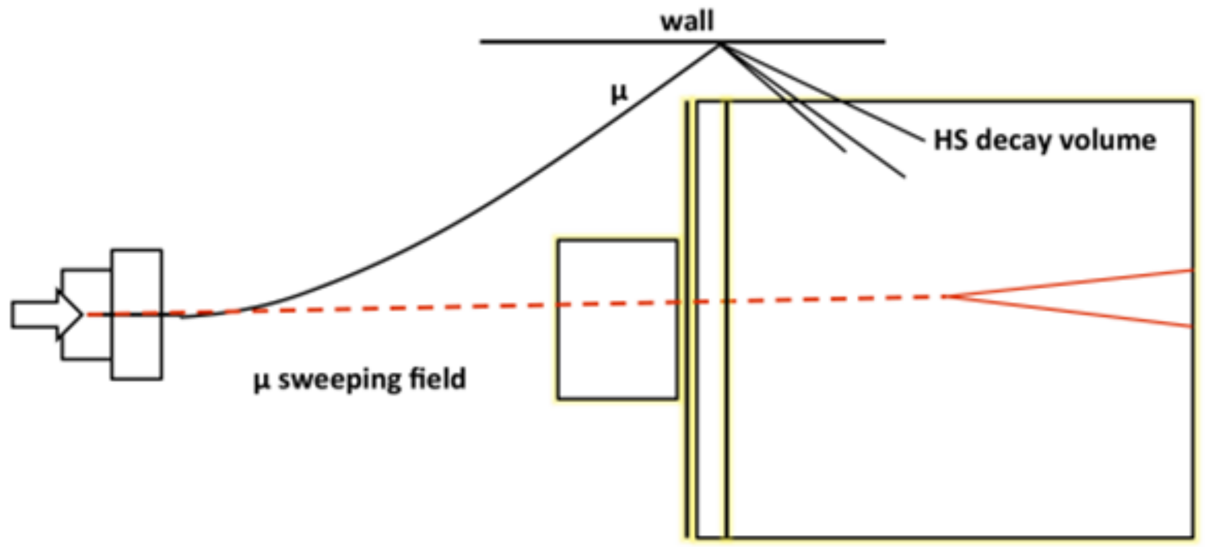
Neutrino interactions



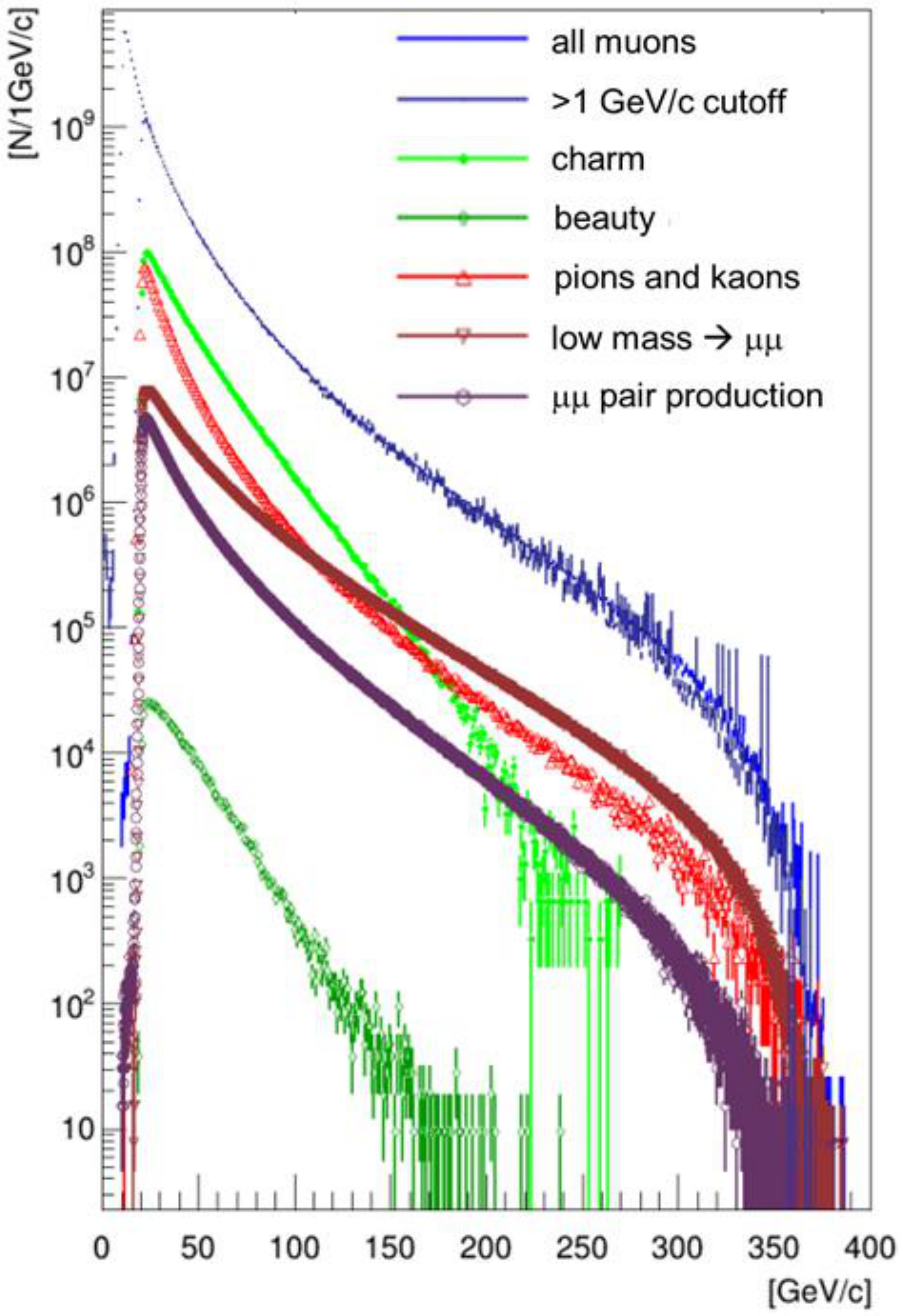
Muon combinatorial



Cosmic muons

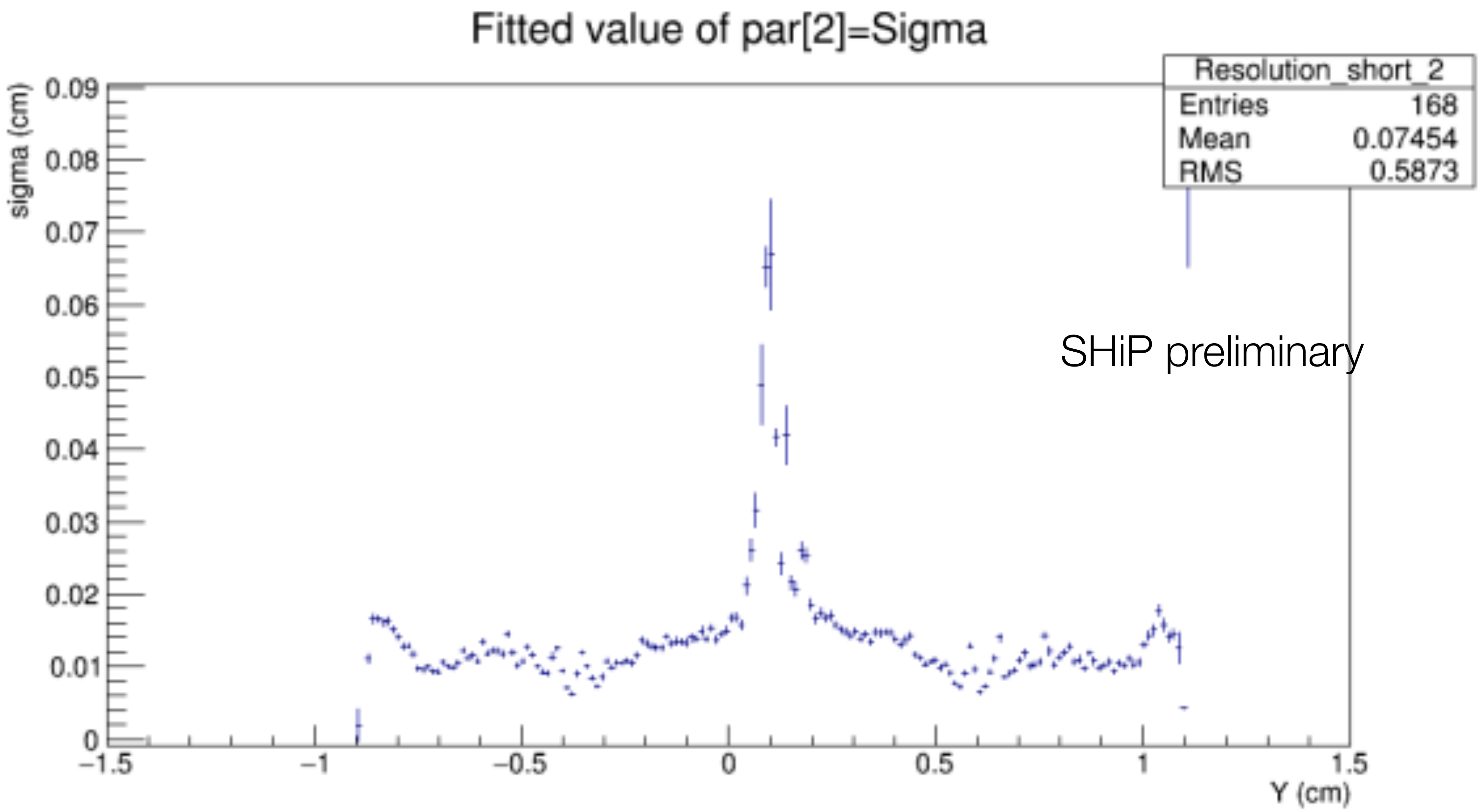


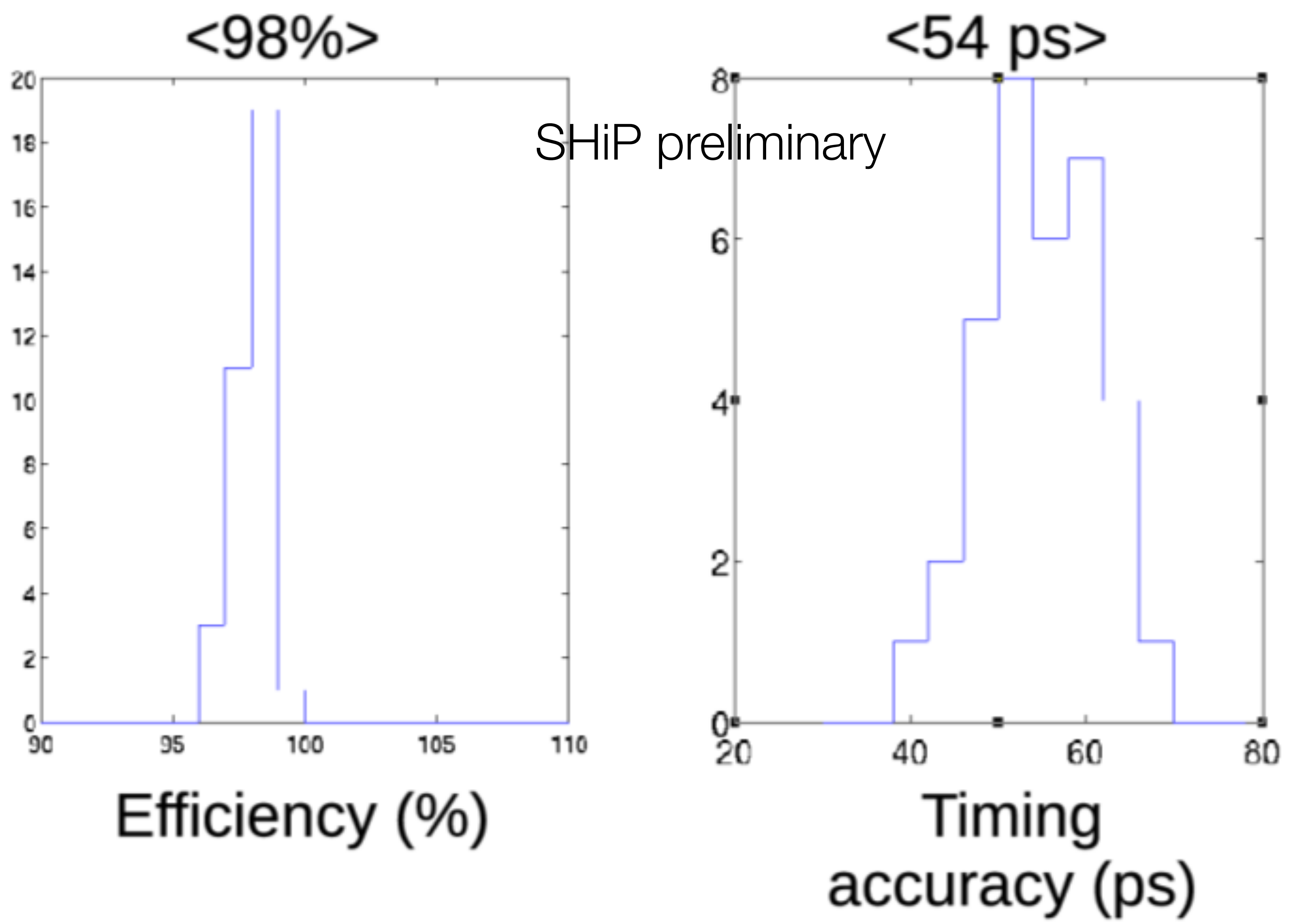
Deep inelastic



HS decay spectrometer / 1

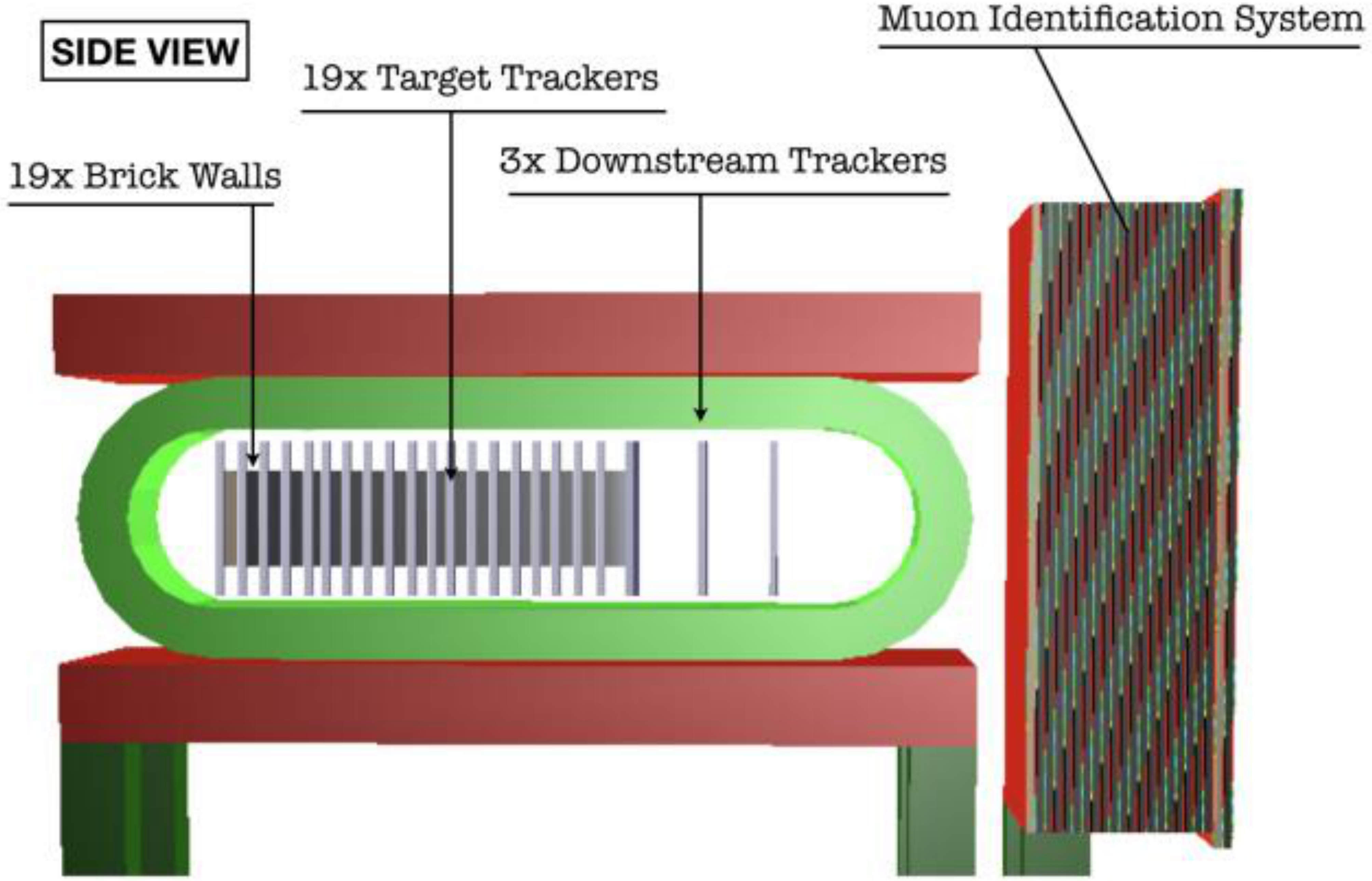
- Fiducial **rectangular aperture** 5x10 m^2
- **Straw tracker**: test beam confirms 120 μm hit resolution with hit efficiency >99%
- **Timing detector** (scint. bars + large SiPMs, σt 60 ps)
- **ECAL with tracking** (SplitCal, $\sigma\theta \approx$ few mrad): e/γ identification, π^0 reconstruction, photon directionality for ALP→γγ
- **μ detector** (scintillating tiles + SiPMs): μ/π separation ($\varepsilon_\mu > 95\%$, $p_\mu \in$ [5-100] GeV), timing to contribute to reject combinatorial background





Scattering and Neutrino Detector / 1

- Studying **interactions of ν_τ, charm production** induced by neutrinos etc, and normalisation of **HS yields**
- Searching for **Light Dark Matter** through scattering against atomic electrons
- Detector based on re-development of **Opera** concepts
- Magnet allows distinguishing between neutrino and **anti-neutrino** interactions
- Equivalent of 10 tonnes lead target @ 40 m is 450 tonnes liqAr @120 m
- Momentum of hadrons measured by **Emulsion** Spectrometers in each brick wall
- Momentum of **muons** by Downstream Trackers

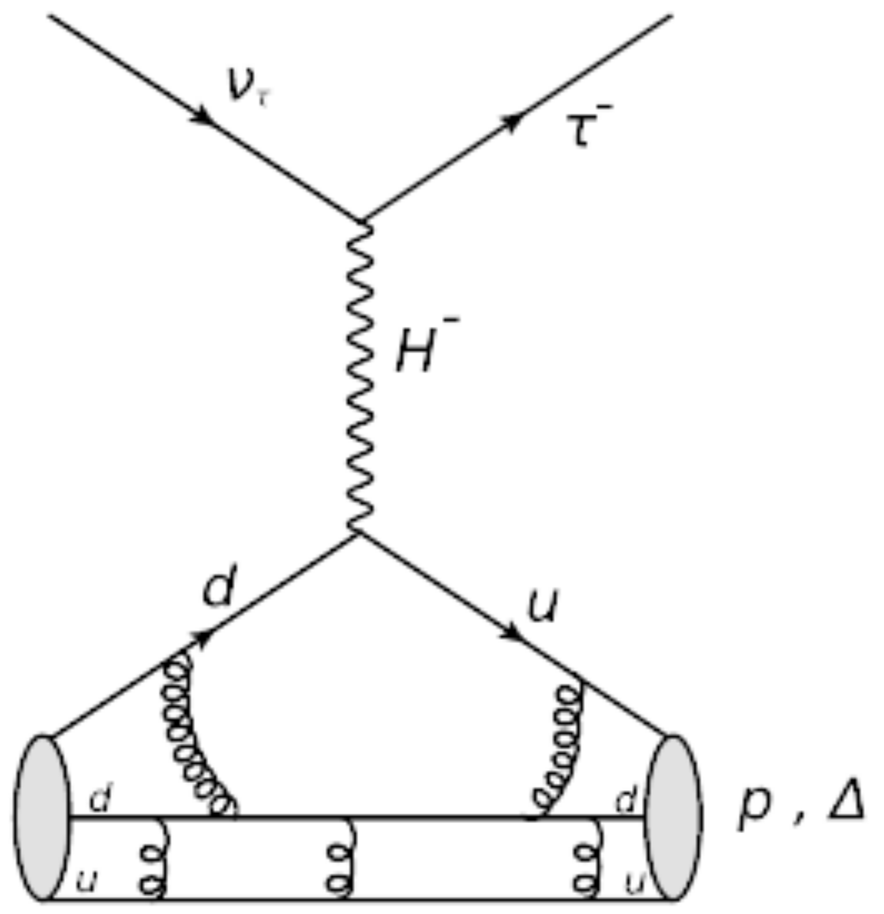


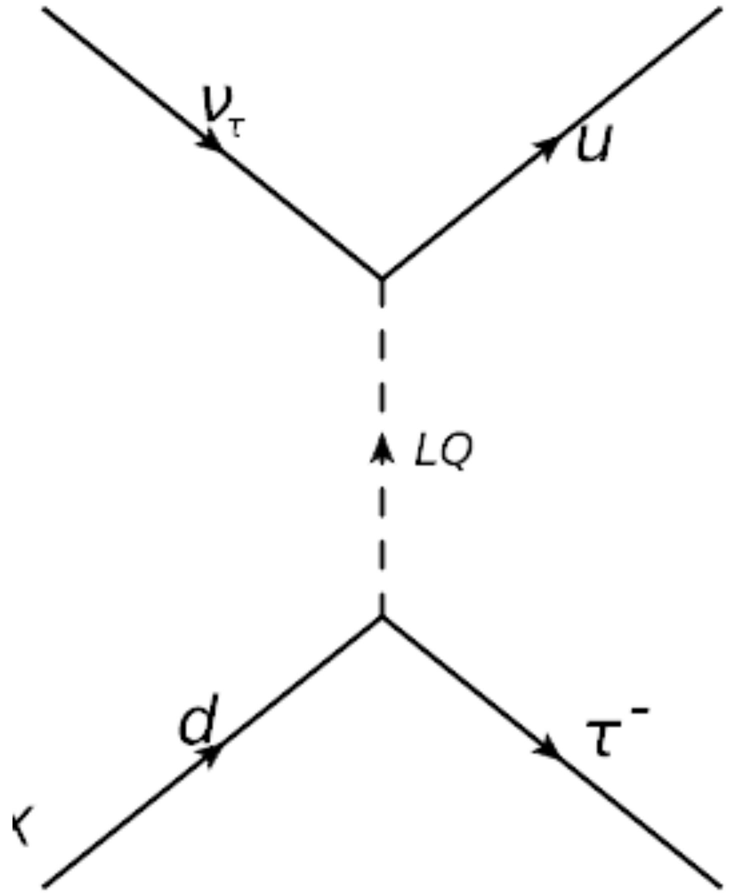
	<E>[GeV]	CC DIS interactions
N_{ν_e}	59	1.1×10^6
N_{ν_μ}	42	2.7×10^6
N_{ν_τ}	52	3.2×10^4
$N_{\overline{\nu}_e}$	46	2.6×10^5
$N_{\overline{\nu}_\mu}$	36	6.0×10^5
$N_{\overline{\nu}_\tau}$	70	2.1×10^4

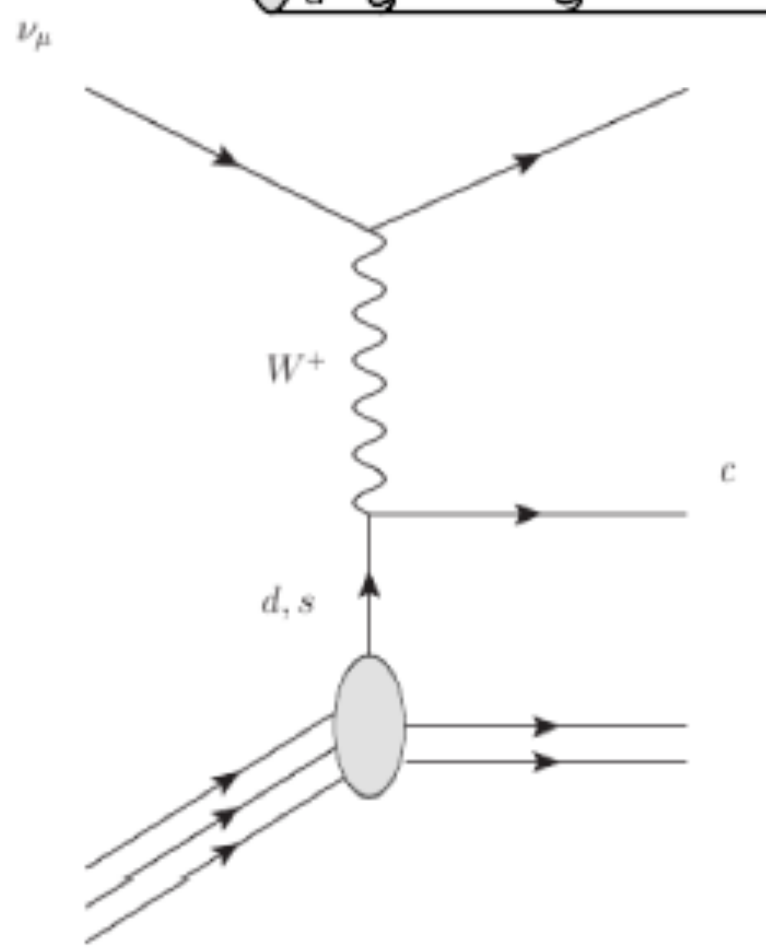
Prospects: SM physics / 1

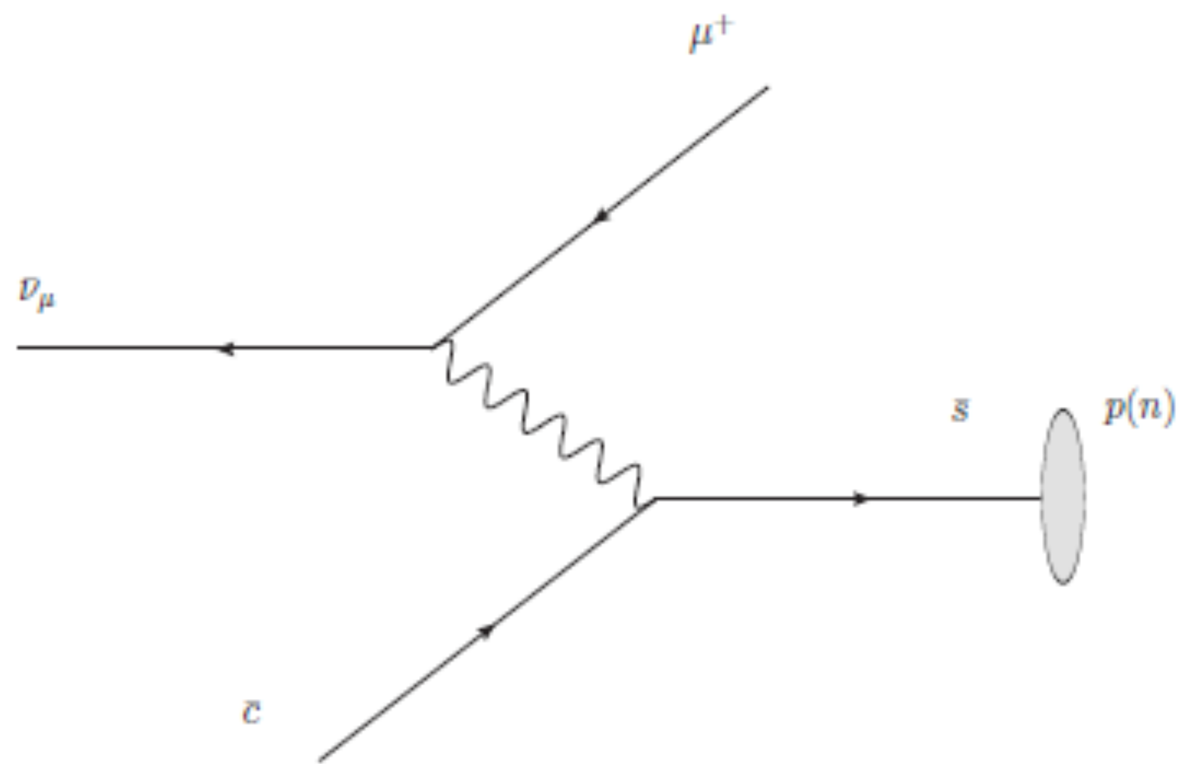
$$\frac{d^2\sigma^{\nu(\overline{\nu})}}{dxdy} = \frac{G_F^2 M E_\nu}{\pi(1+Q^2/M_W^2)^2}\Bigg((y^2 x + \frac{m_\tau^2 y}{2E_\nu M})F_1 + \left[(1-\frac{m_\tau^2}{4E_\nu^2}) - (1+\frac{Mx}{2E_\nu})\right] F_2 \pm \left[xy(1-\frac{y}{2}) - \frac{m_\tau^2 y}{4E_\nu M}\right] F_3 + \frac{m_\tau^2(m_\tau^2+Q^2)}{4E_\nu^2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

- **First observation of anti-ν_τ interaction**
- Measurement of **anti-ν_τ** and **ν_τ** cross-section
  - Allow extraction of **F4** and **F5** structure functions from charged current neutrino-nucleon **DIS**. Test beyond SM
- **ν_τ magnetic momentum**
- **ν_e cross-section at high energies**
- Testing strange quark content of nucleon through **charm production**
- Normalisation of **hidden particle search**

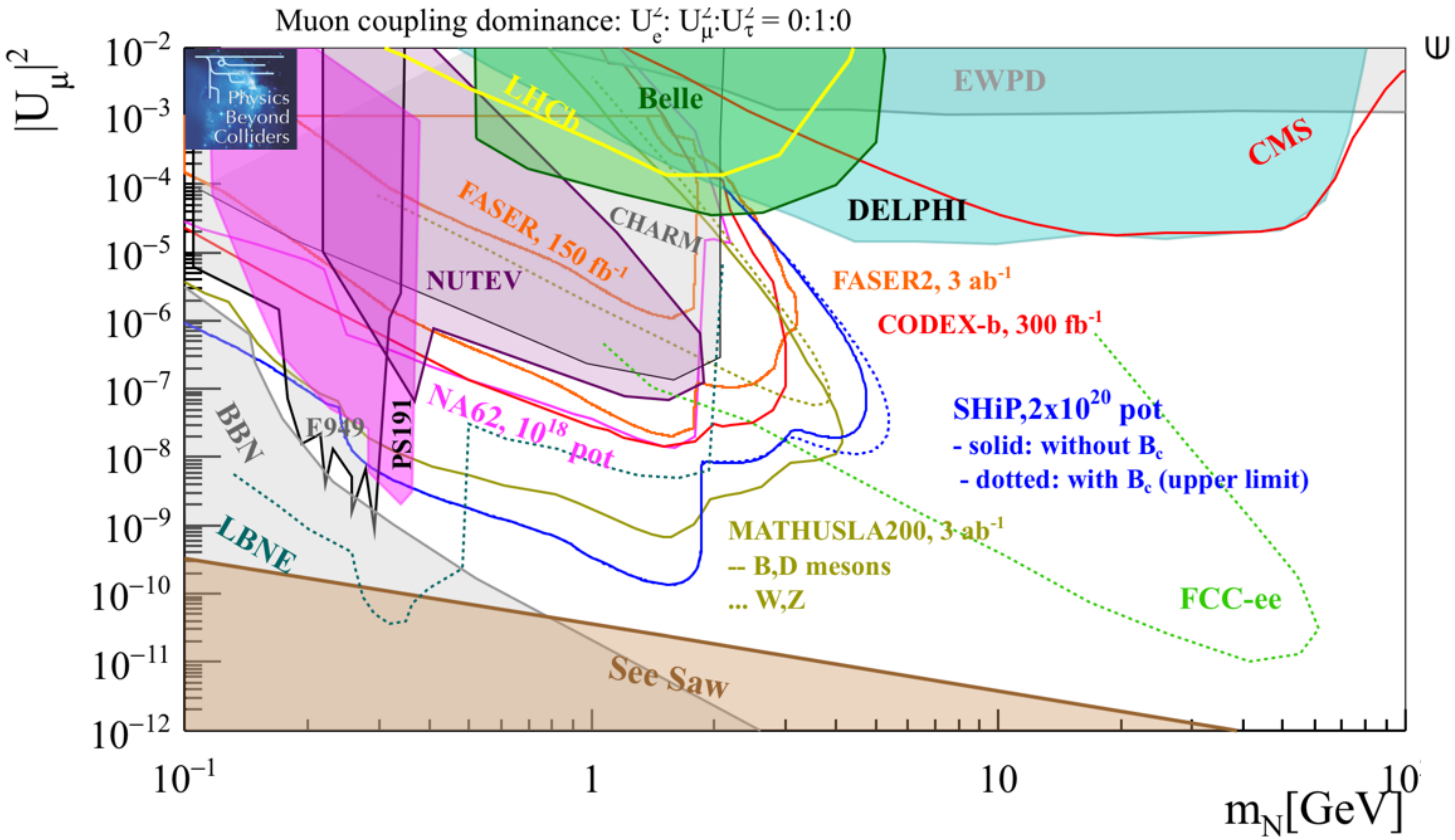


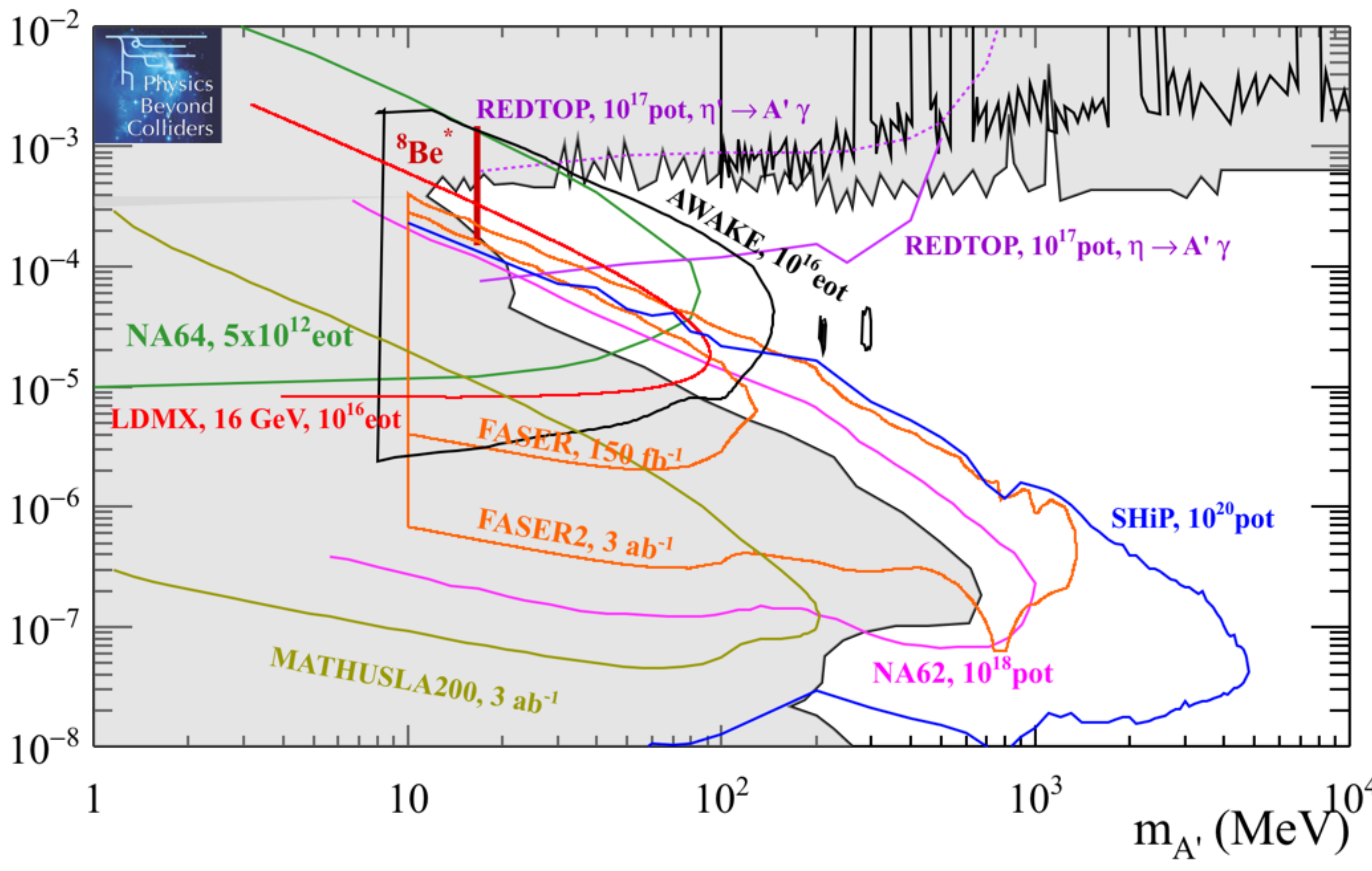






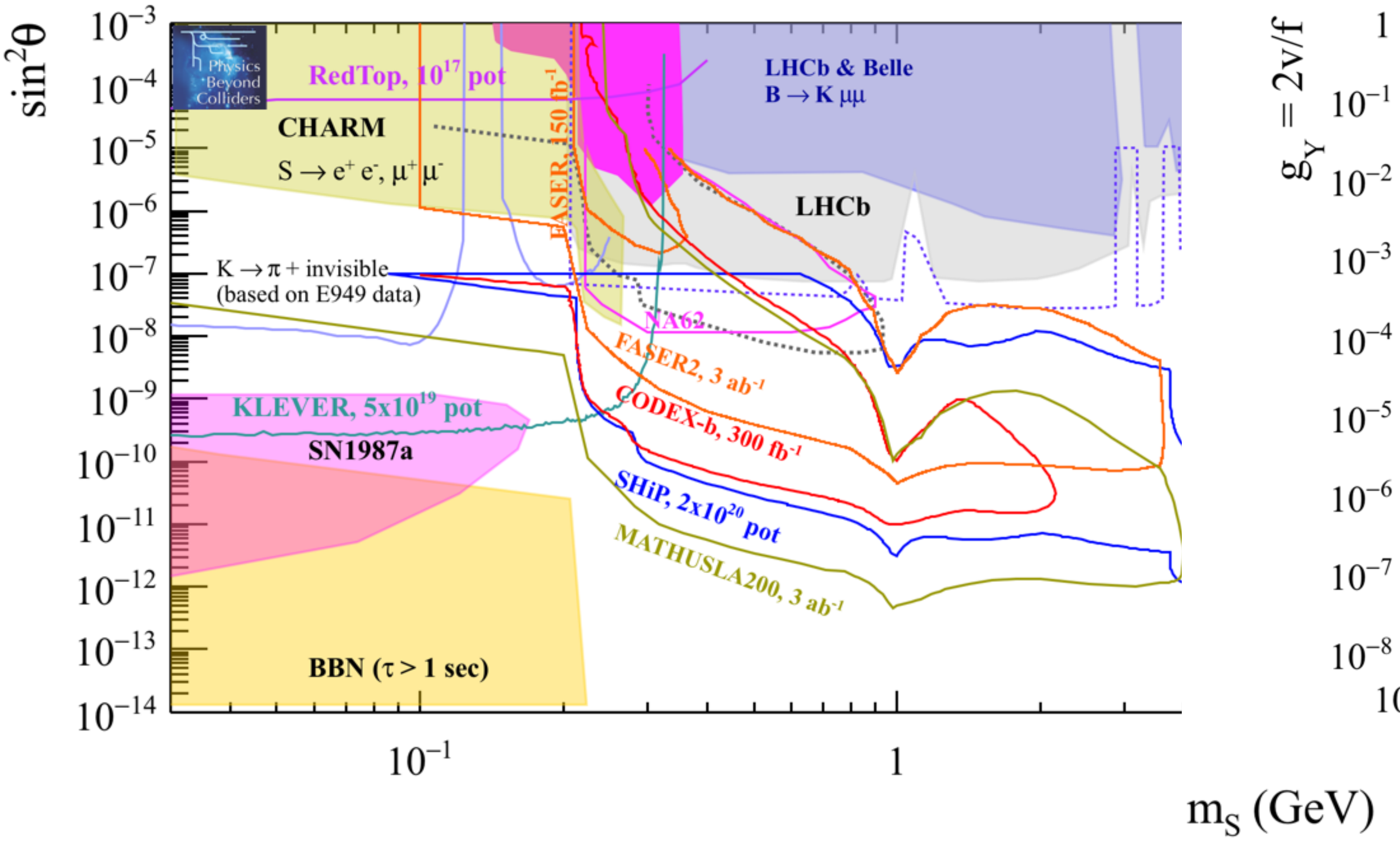
Prospects: BSM physics / 1

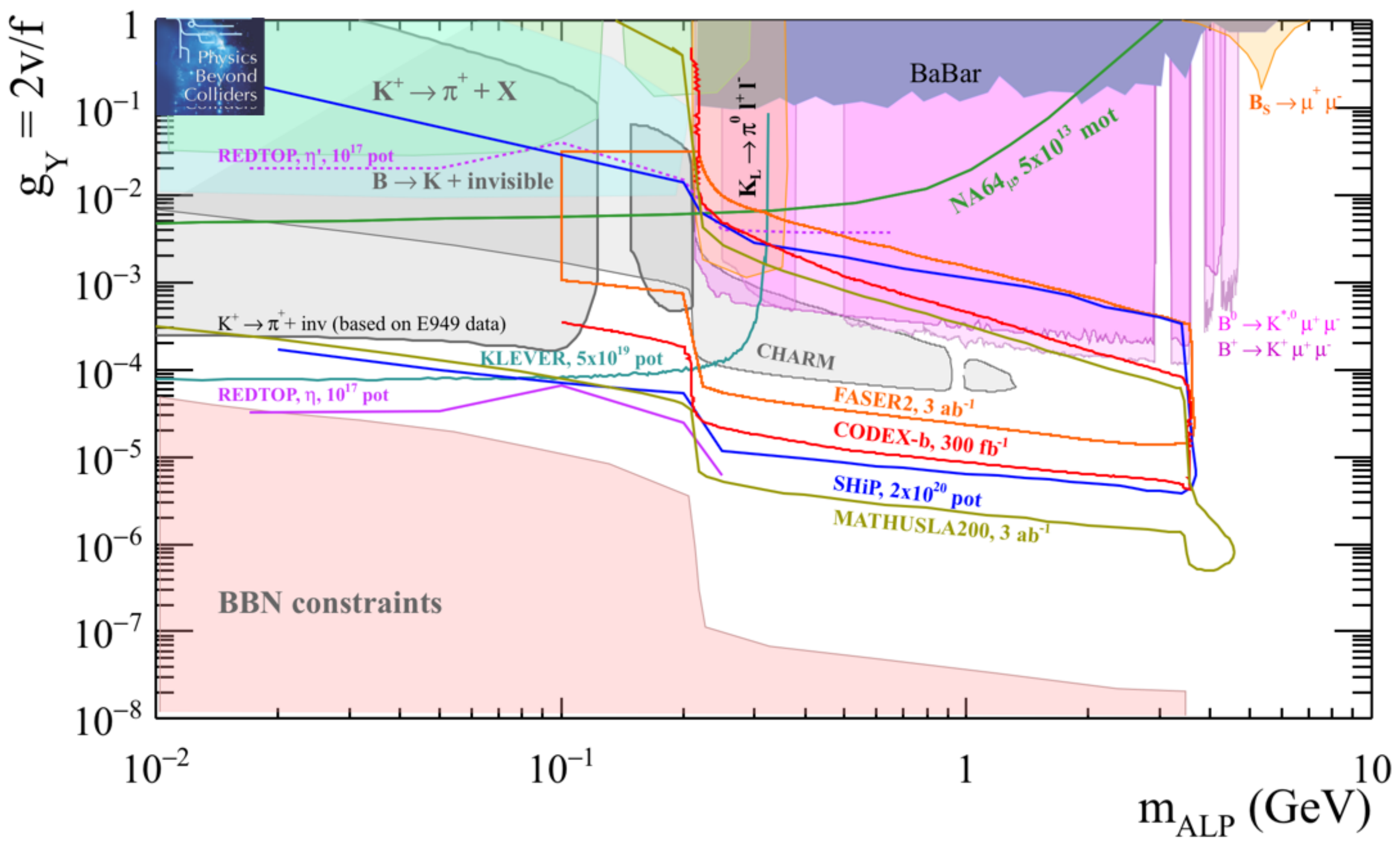


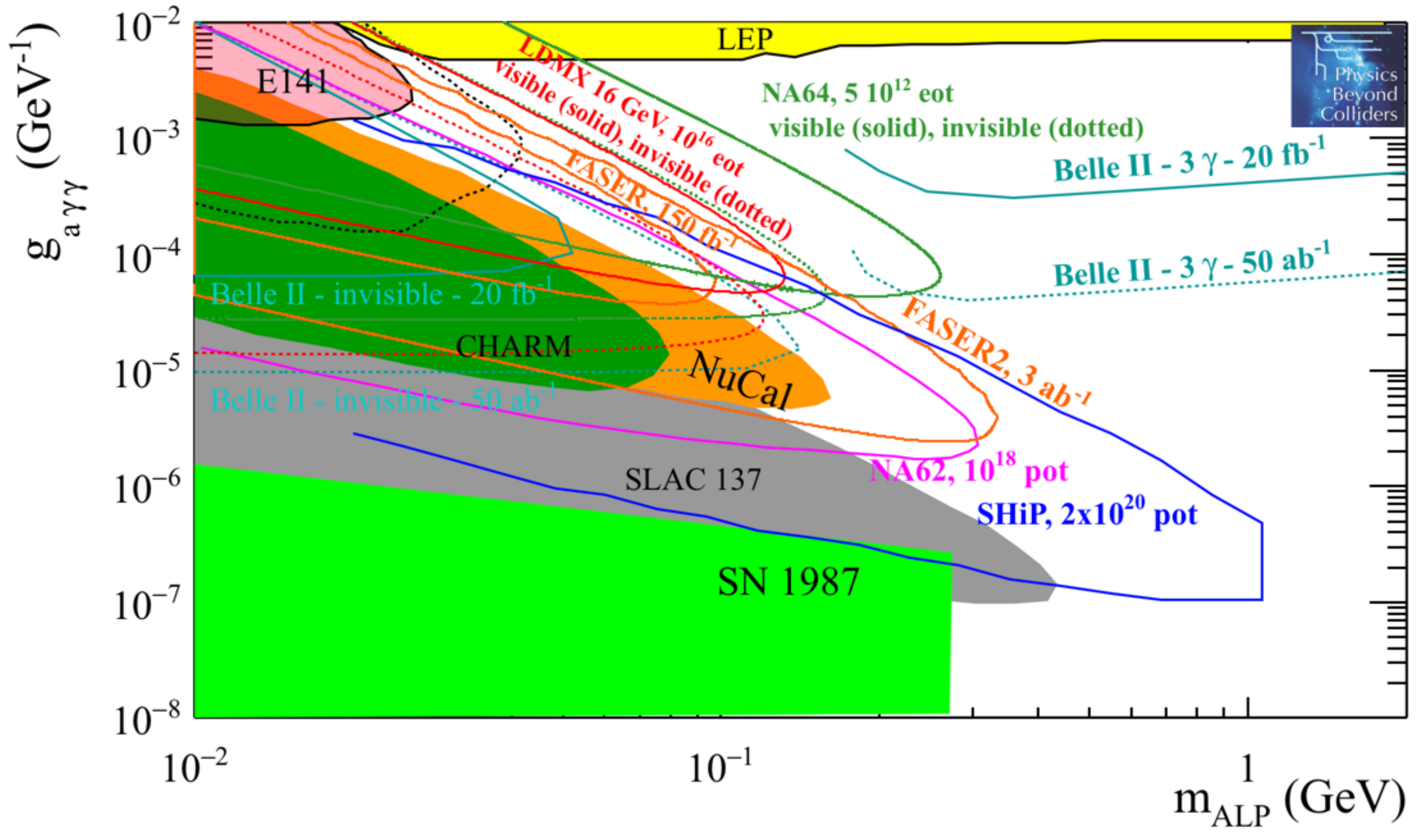


- **LHS:** HNL (heavy meson decays)
- **RHS:** Dark photon (decays + bremsstrahlung + QCD)

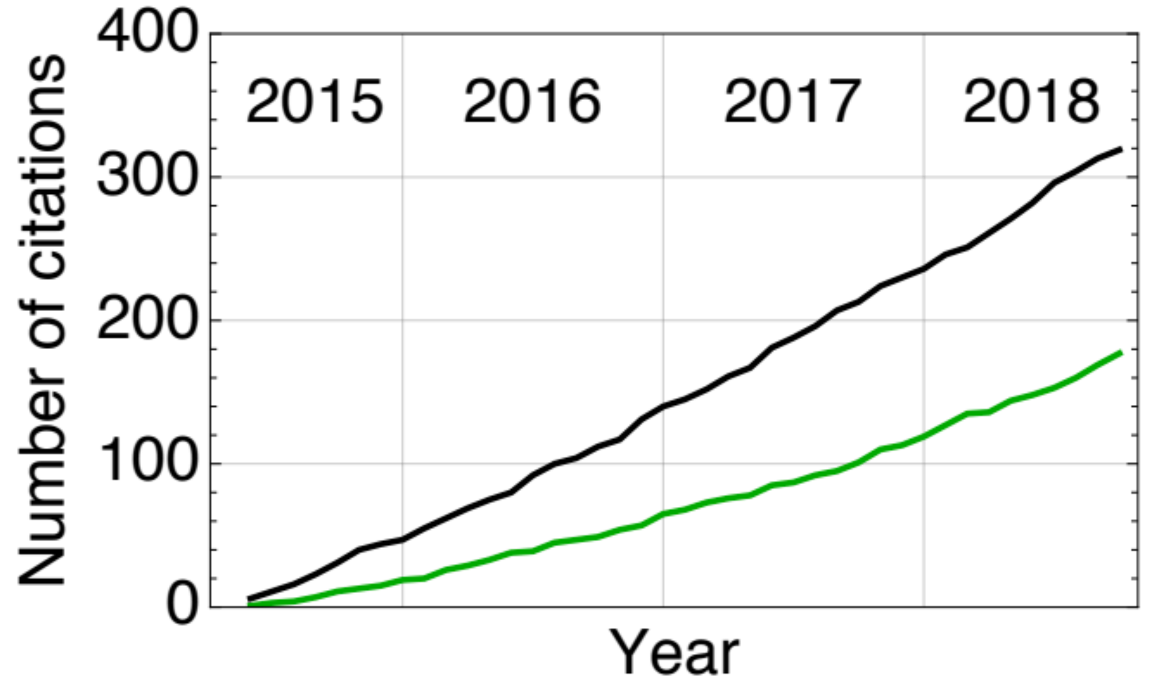
Prospects: BSM physics / 2







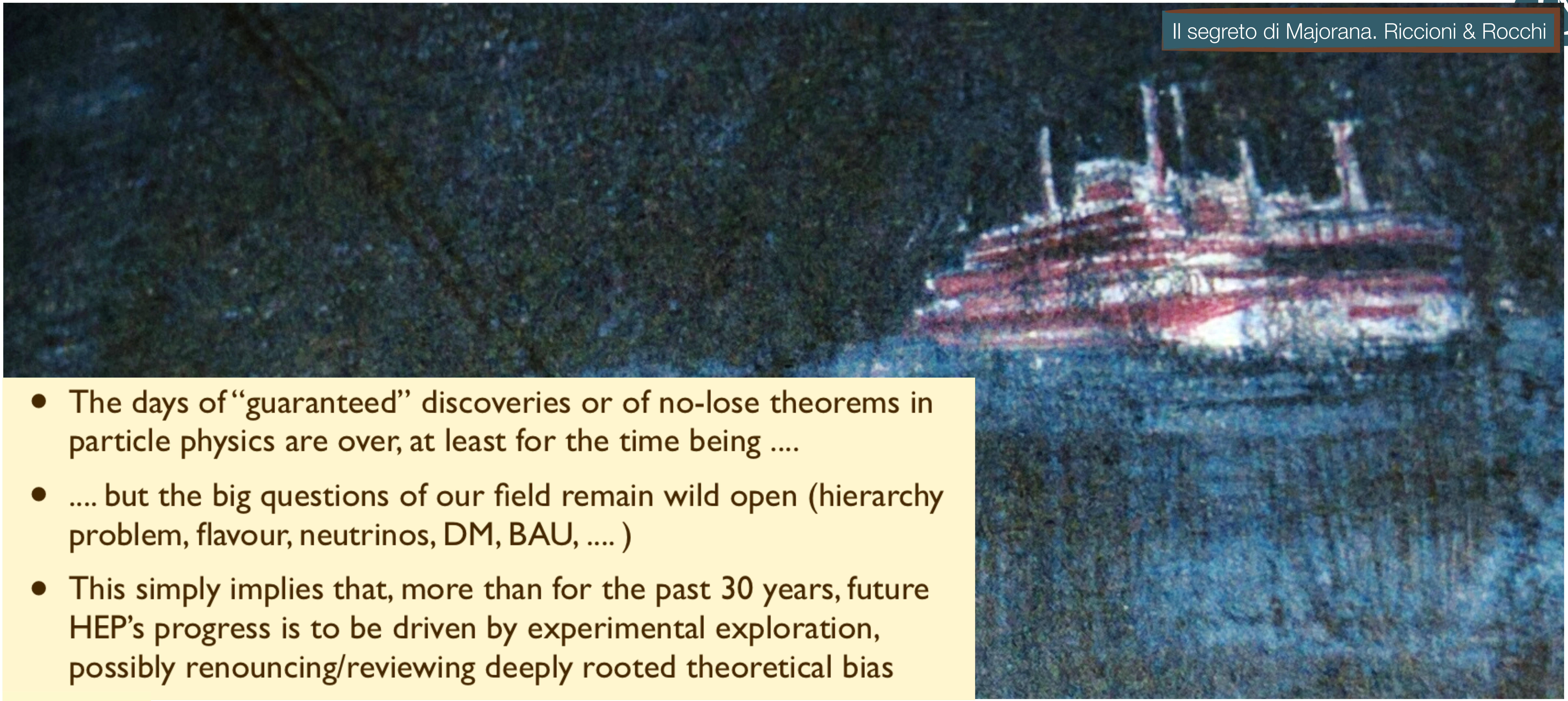
- **LHS:** scalar (K and B decays)
- **Center:** ALPs coupled to fermions
- **RHS:** ALPs coupled to photons
- Full reconstruction and PID allows identifying models and measuring parameters



Conclusions

- Expression of Interest submitted in 2013 and Collaboration formed.
- In 2015 two documents describing the **physics** and **SHiP's Technical Proposal** where published
- CDS of the experimental facility is published; SHiP's CDS by 2019
- **SHiP has evolved massively** in the last couple of years, still using unique high intensity of SPS
- SHiP is a true **background free experiment**
- Beam Dump Facility in the NA can **benefit generations of experiments to come**
- Unique opportunity for ν_τ physics, direct Dark Matter search, LFV τ, etc.

2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	203+
LS2		**RUN III**			LS3			**RUN IV**			LS4		**RUN V**	
		L = 2e33						L = 2e33; 50 fb^{-1}					300 fb^{-1}	
Design	Prototyping			Construction		Installation		**Data taking**						
CDS	ESPP	TDR	PRR					CdW						



Il segreto di Majorana. Riccioni & Rocchi

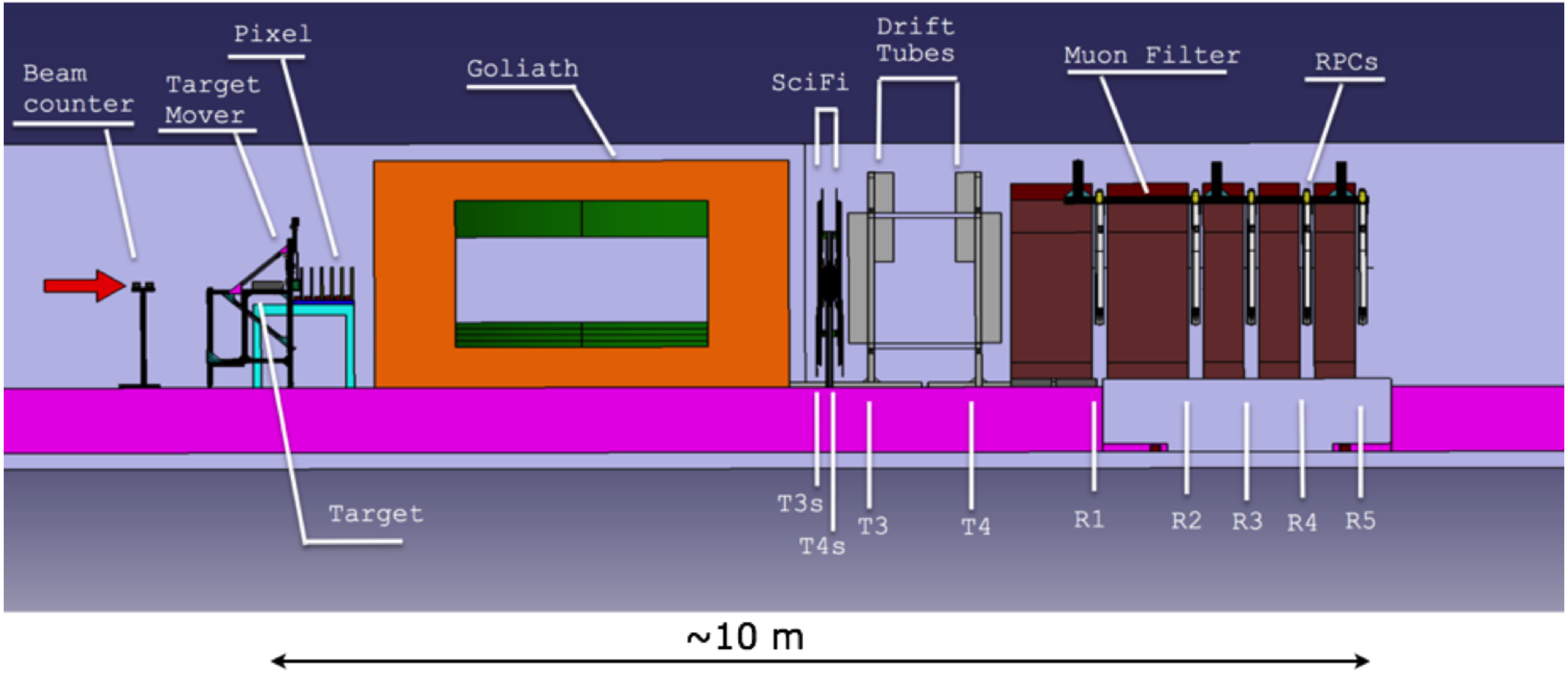
- The days of "guaranteed" discoveries or of no-lose theorems in particle physics are over, at least for the time being ....
- .... but the big questions of our field remain wild open (hierarchy problem, flavour, neutrinos, DM, BAU, ...)
- This simply implies that, more than for the past 30 years, future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

M. Mangano

Thanks

Federico Leo Redi

Test beams / 1


Pixel
Beam counter
Target Mover
Goliath
SciFi
Drift Tubes
Muon Filter
RPCs
Target
T3s
T4s
T3
T4
R1
R2
R3
R4
R5
~10 m

Comparison / 1

Experiment	**PS191**	**NuTeV**	**CHARM**	**SHiP**
Proton energy (GeV)	19.2	800	400	400
Protons on target ($\times 10^{19}$)	0.86	0.25	0.24	20
Decay volume (m^3)	360	1100	315	1780
Decay volume pressure (bar)	1 (He)	1 (He)	1 (air)	10^{-6} (air)
Distance to target (m)	128	1400	480	80-90
Off beam axis (mrad)	40	0	10	0