Dark sectors: high intensity and LHC experiments

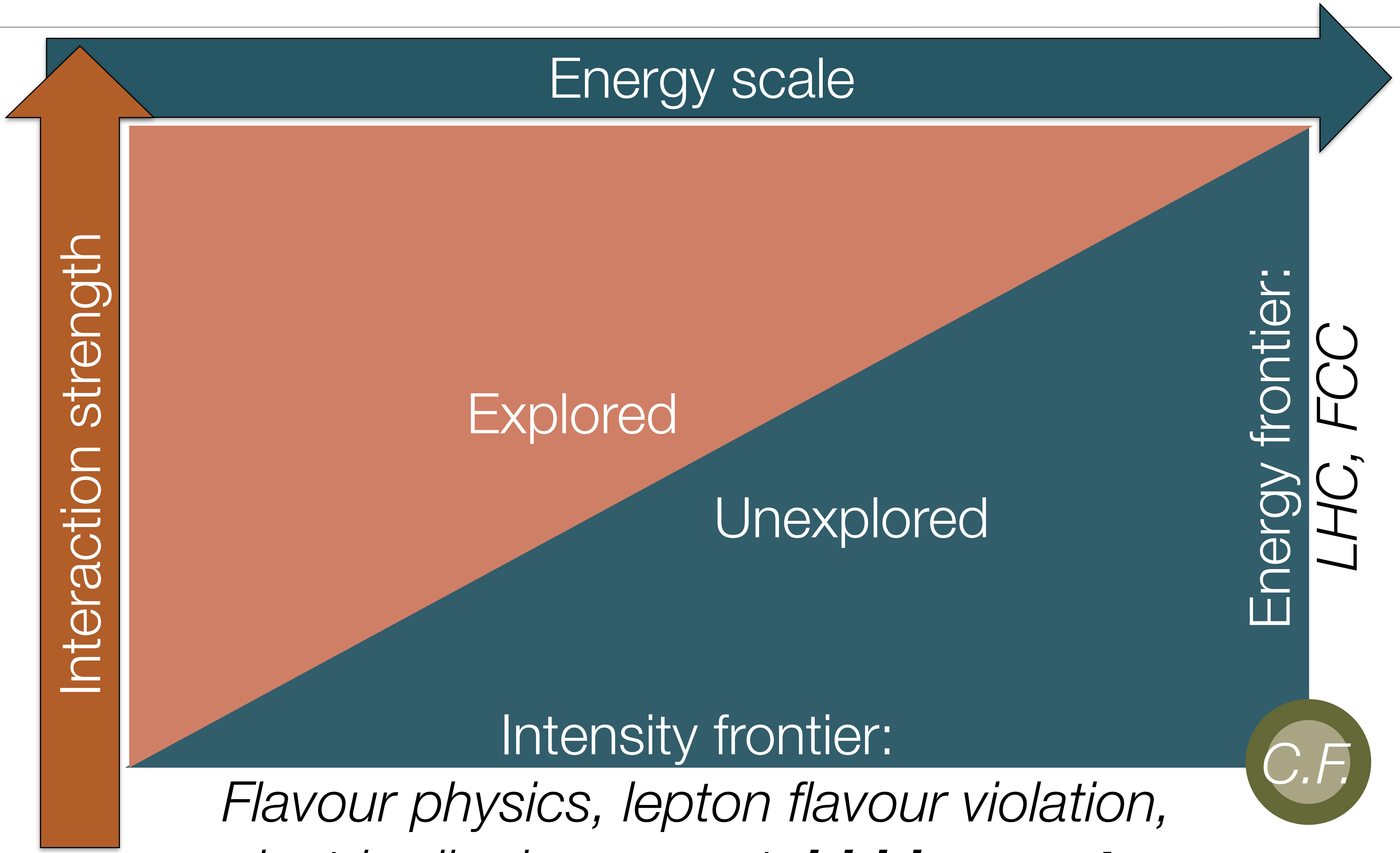
Searching for new physics at the intensity frontier

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

SHiP
Search for Hidden Particles

LHCb

Introduction / 1

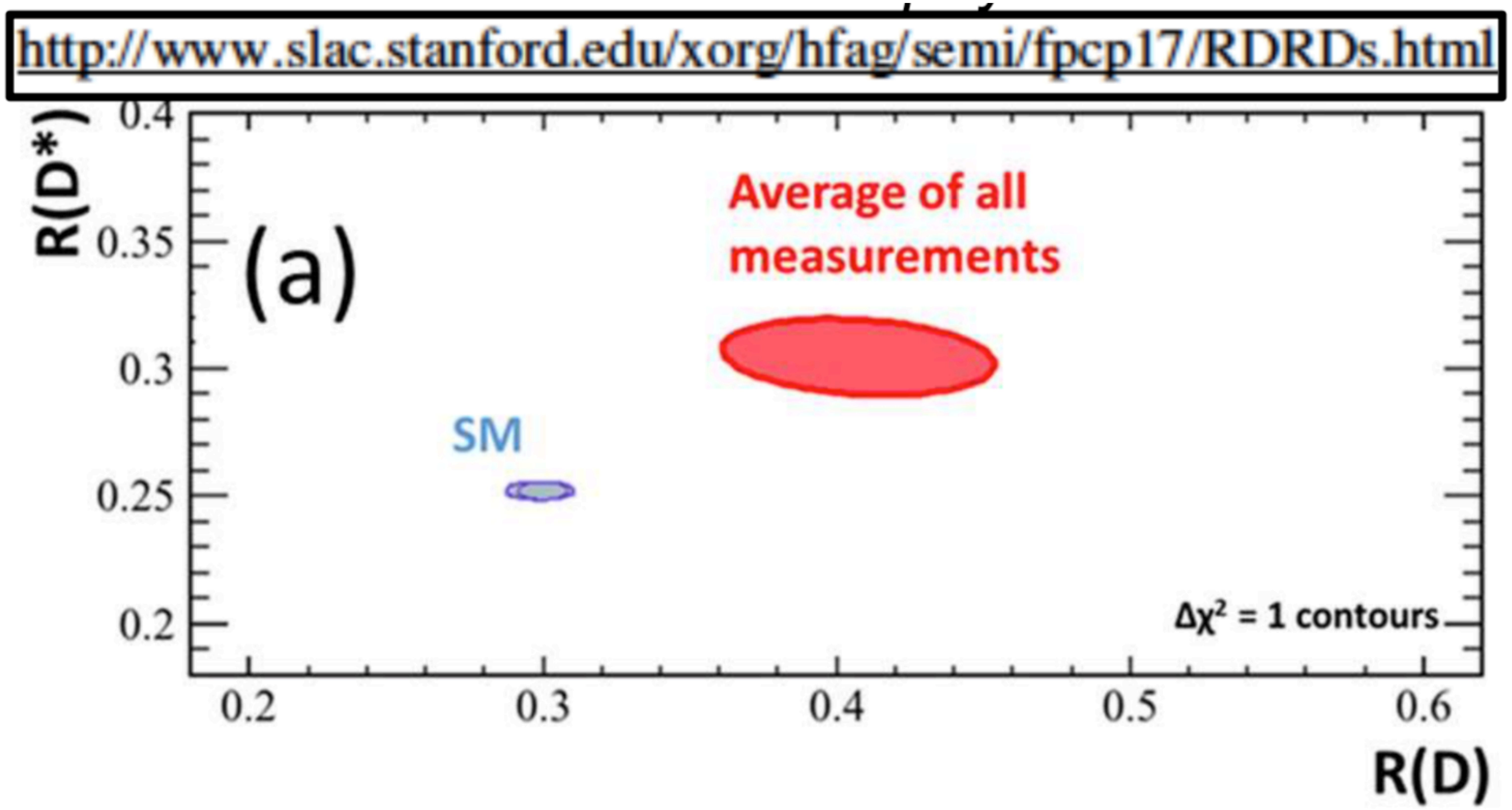


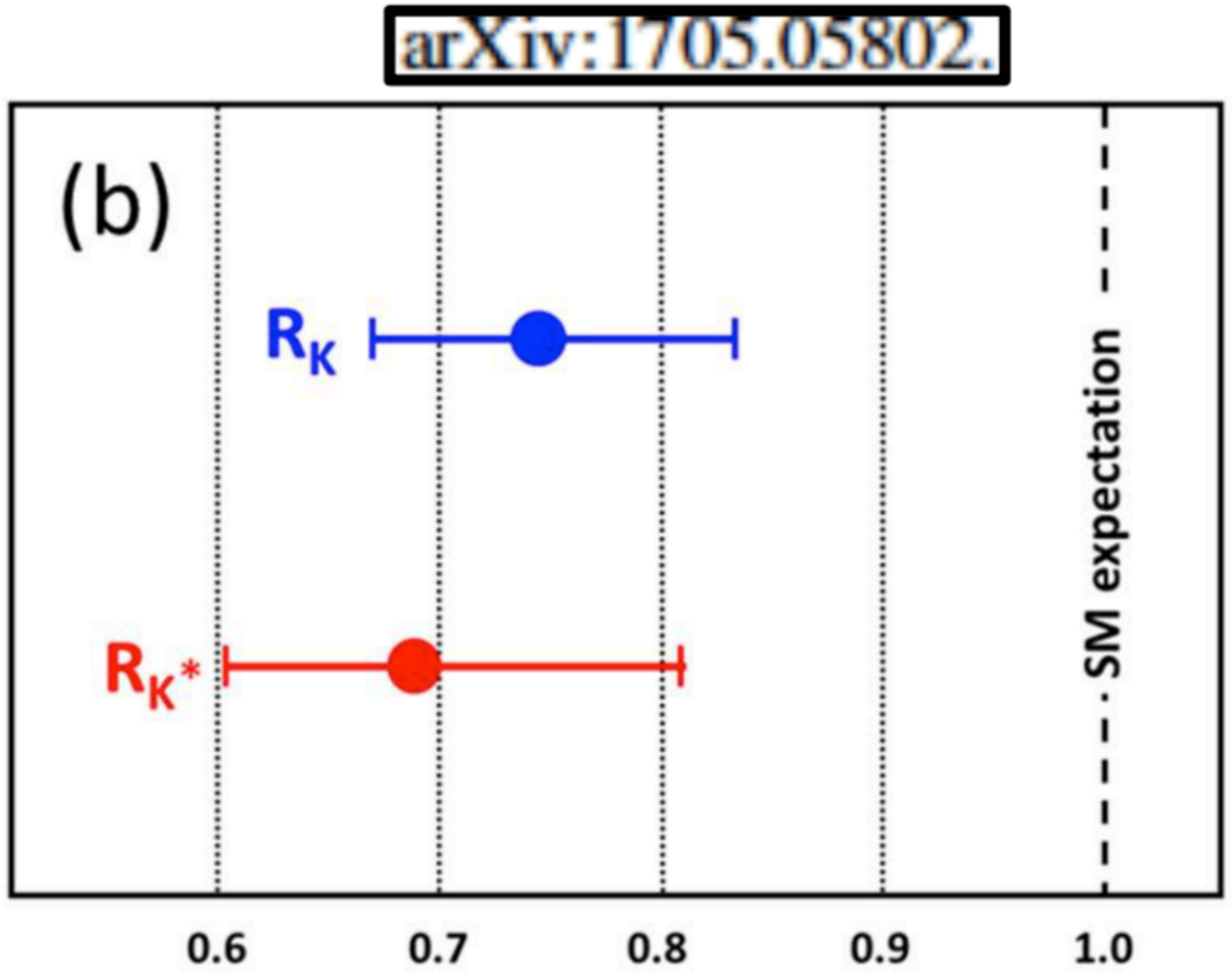
Flavour physics, lepton flavour violation, electric dipole moment, ***hidden sector***

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** and **lepton flavour violation** in τ.
- **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 $b \to s e^+e^-$ / $b \to s\mu^+\mu^-$ decays
    - **Clear evidence of BSM** physics if substantiated with further studies (possibly by **BELLE II**)

Landscape today / 2





See previous talks in the morning!

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
- 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

- 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**
- **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

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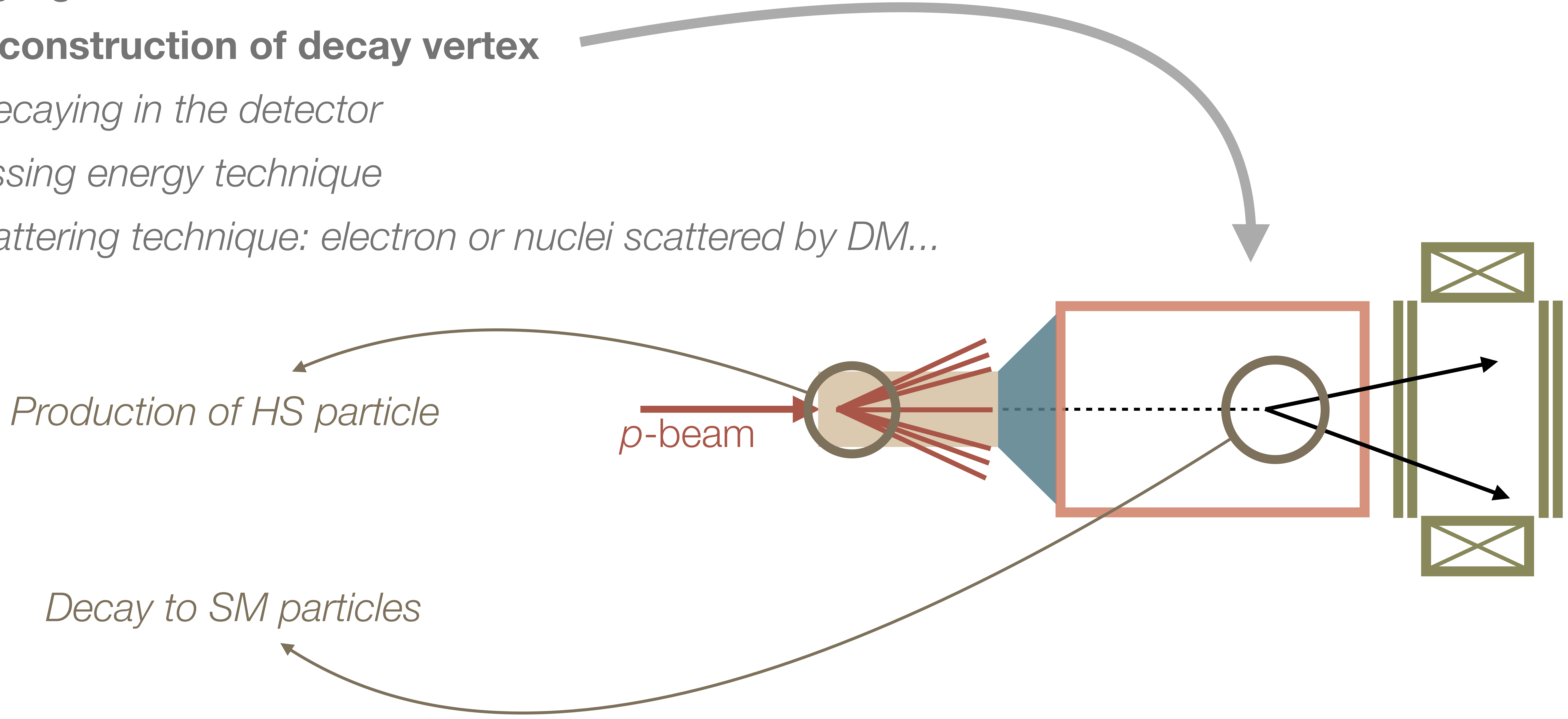

Exploring the dark sector / 3

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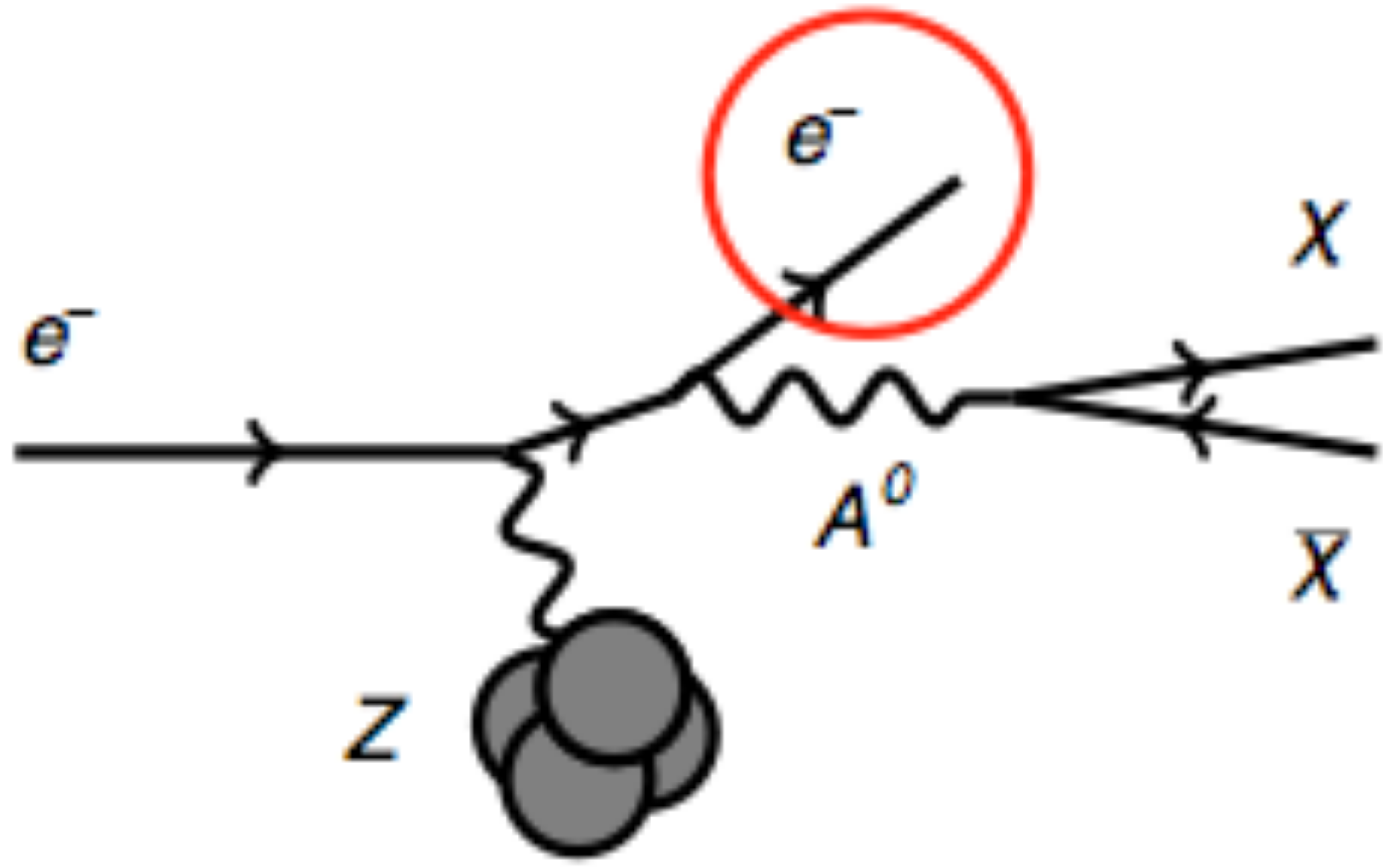
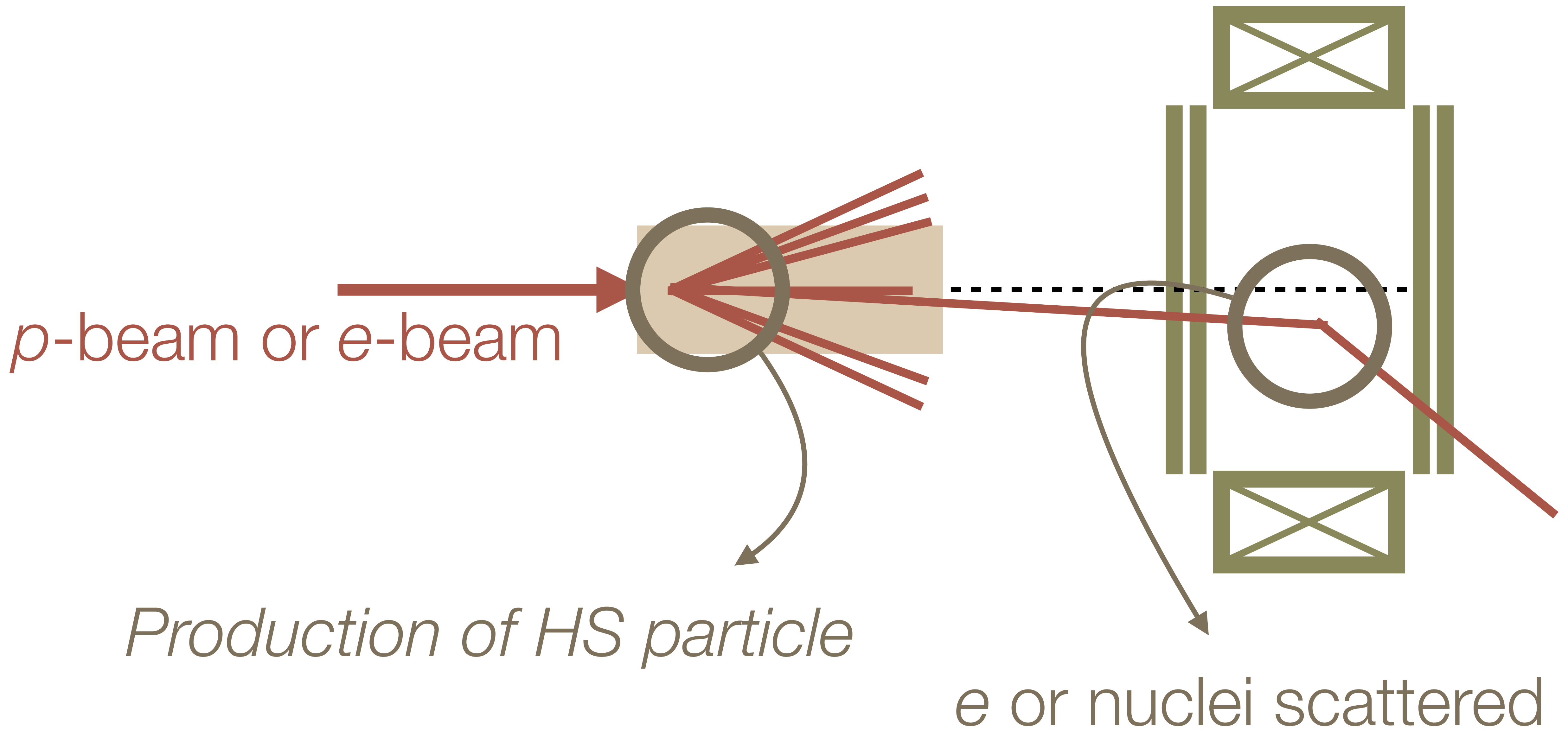
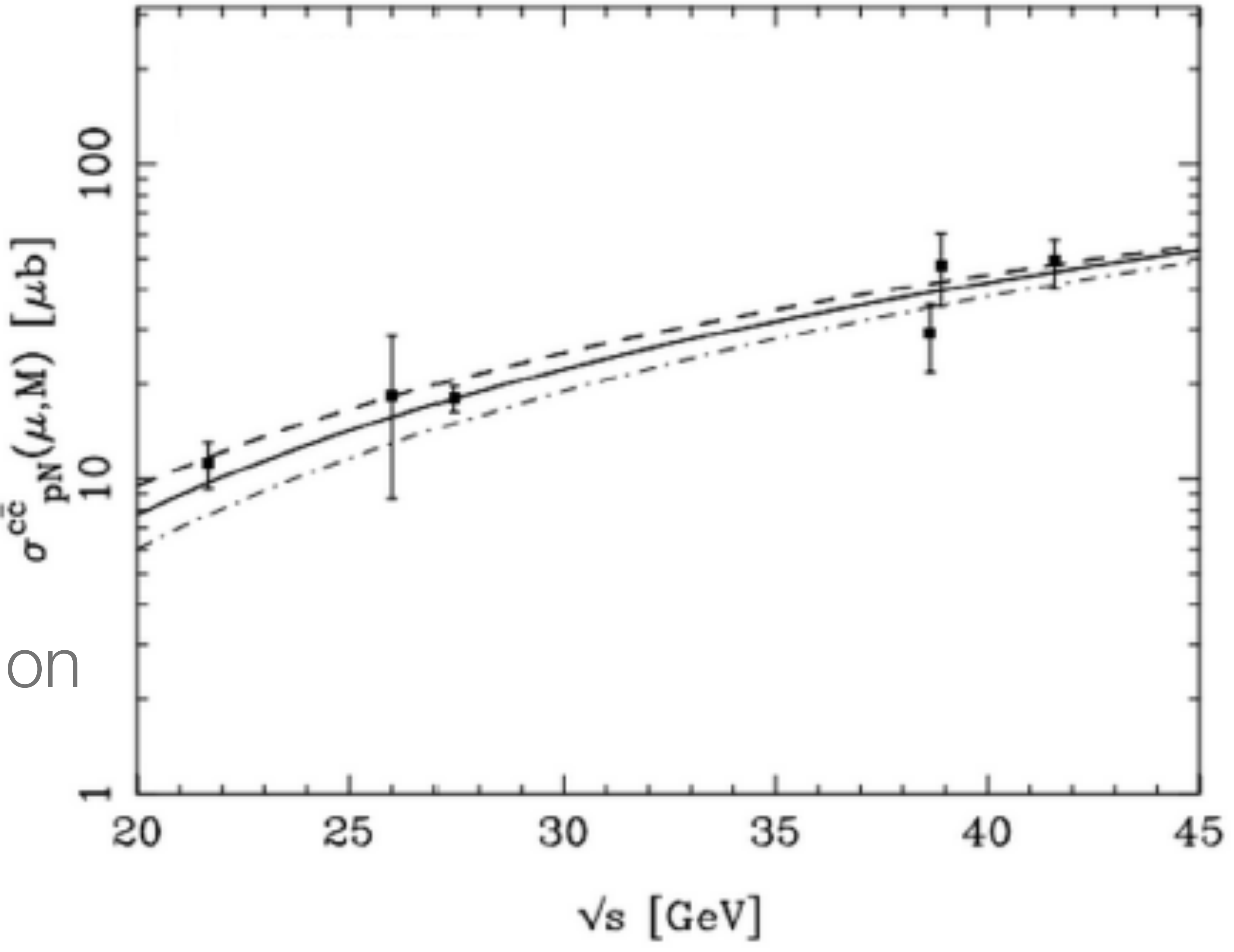




Decaying dark sector candidates / 1



- **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:
      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

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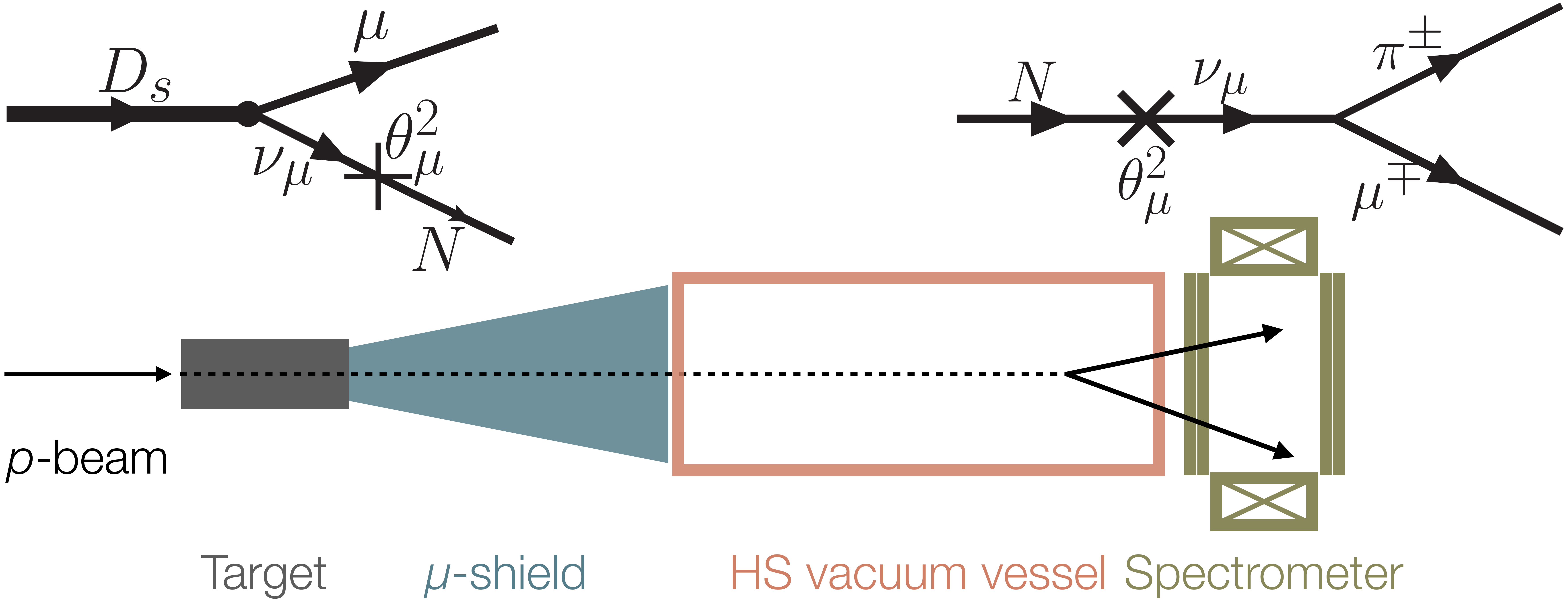
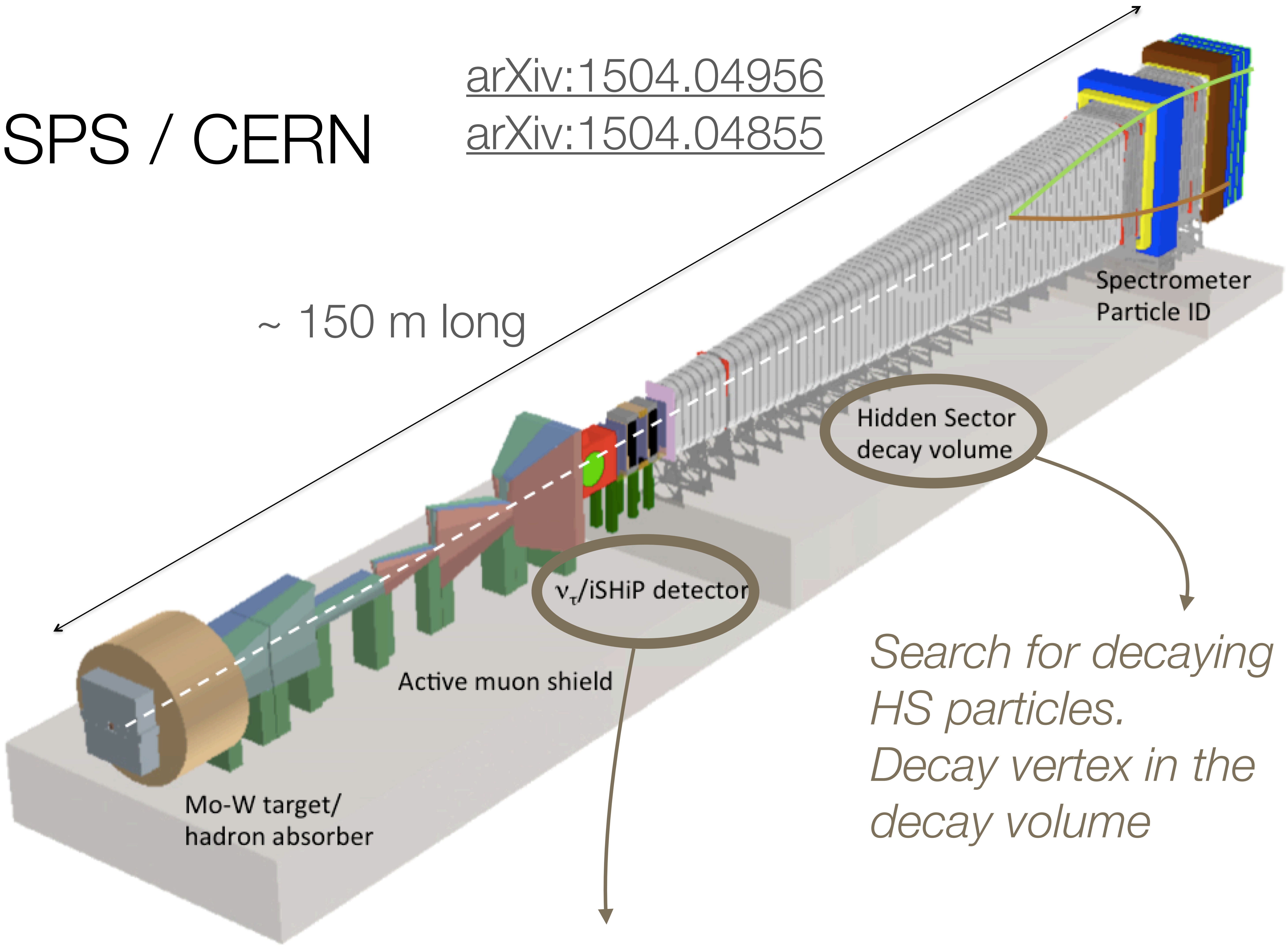


SHiP Beam Dump Facility at SPS / CERN

arXiv:1504.04956
arXiv:1504.04855

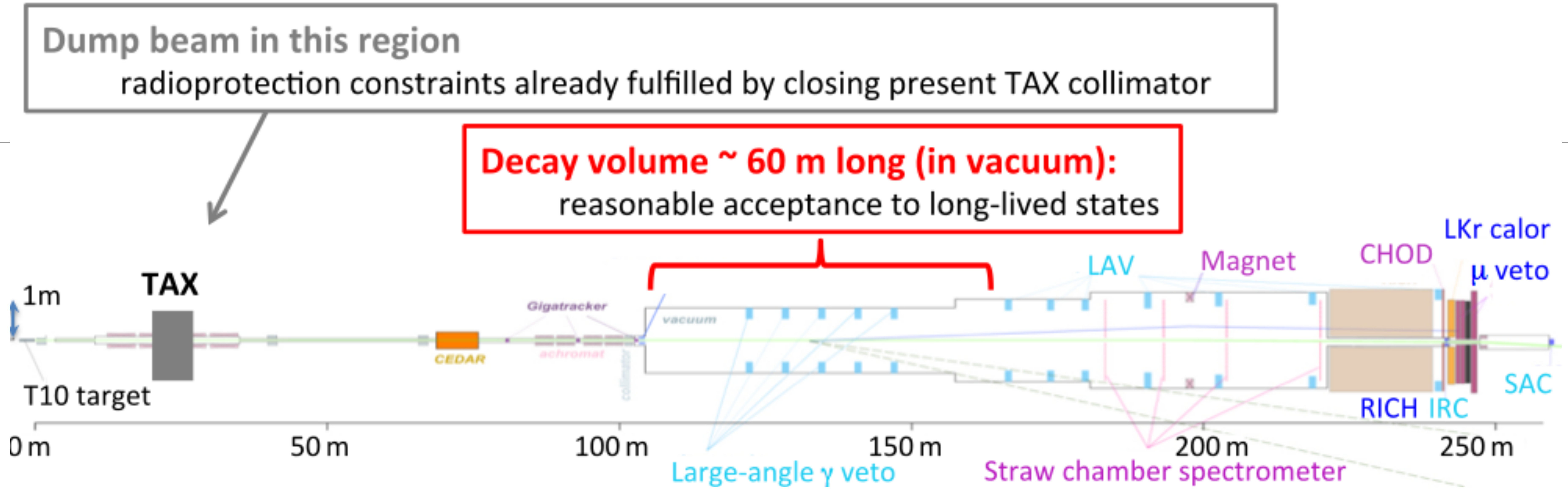
- Numbers:
  $>10^{18}$ D,
  $>10^{16}$ τ,
  $>10^{20}$ γ
  for **2×10^{20} pot (in 5 years)**
- "***Zero background***" experiment
  Heavy target
  Muon shield
  Surrounding Veto detectors
  Timing and PID detectors, etc.
- Multipurpose layout: near and far detector (**new**)



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

NA62+

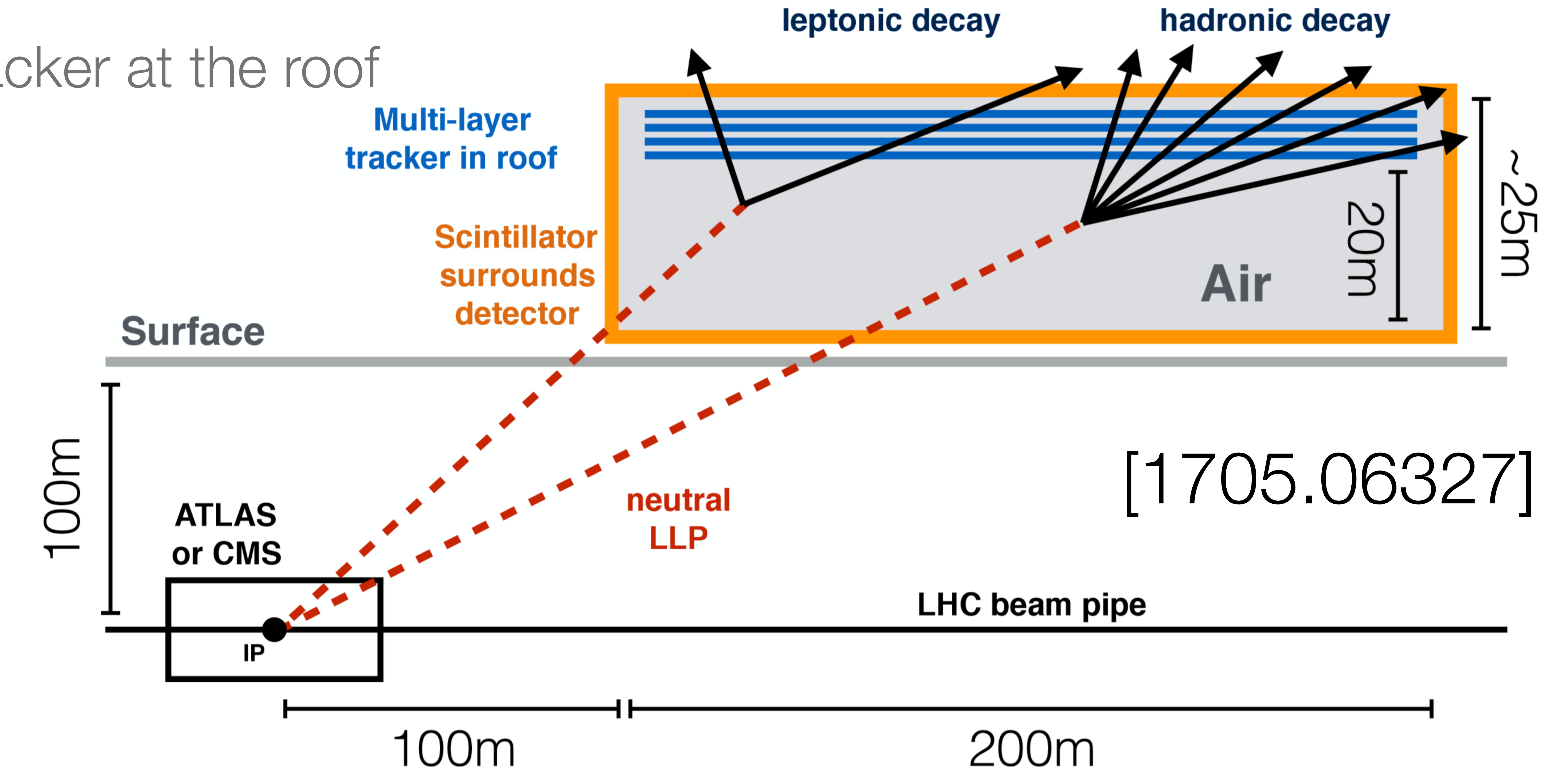


- NA62 **currently collecting** data at SPS to study kaon physics ($K+ \to \pi+\nu\nu$)
- Will start exploring a part of SHiP physics programme in **2020**
  - NA62+ will run in a beam dump mode at the beam intensity ~1e12 POT/sec on spill
    - **~1e18 POT/nominal year** ~80 days
    - while the large 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

MATHUSLA

Thanks to: Kyrylo Bondarenko, Maksym Ovchynnikov, Alexey Boyarsky (Leiden) Oleg Ruchayskiy (NBI)

- Large area, surface detector, above and displaced an LHC *pp* IP (either ATLAS or CMS)
- Dedicated to detection of **ultra** long-lived particles
- Decay area with total volume V ~ 20 m·100 m·100 m ≃ 2x1e5 m3
- The rock as passive wall + multi-layer tracker at the roof
- $N(B)_{SHiP}$ ~ 6e13; $N(B)_{MATHUSLA}$ ~ 6e12
- $N(D)_{SHiP}$ ~ 6e17; $N(D)_{MATHUSLA}$ ~ 5e14
- pseudo-rapidity coverage must be **carefully taken into account**
- Similarly must be performed for **background estimation**

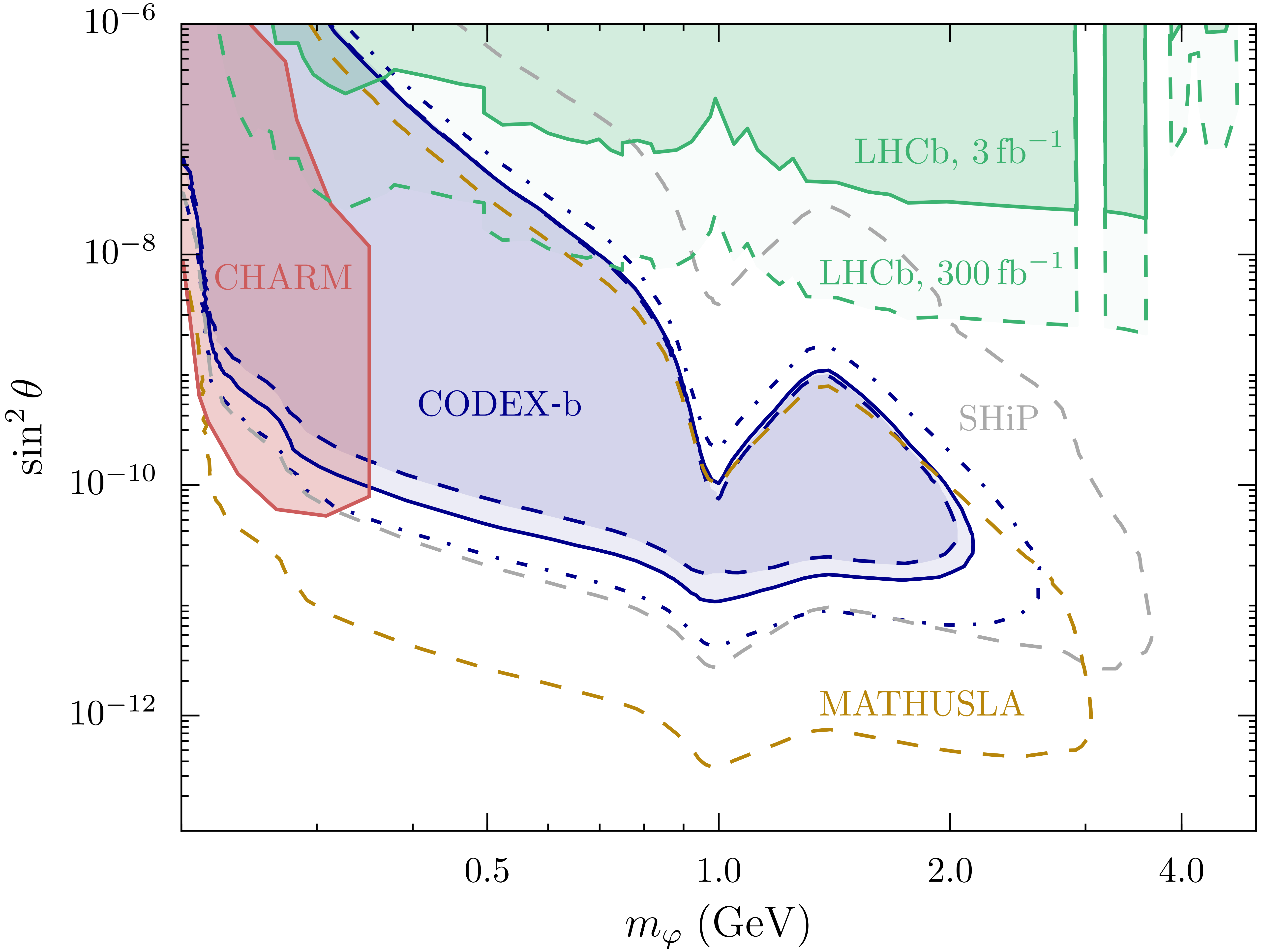


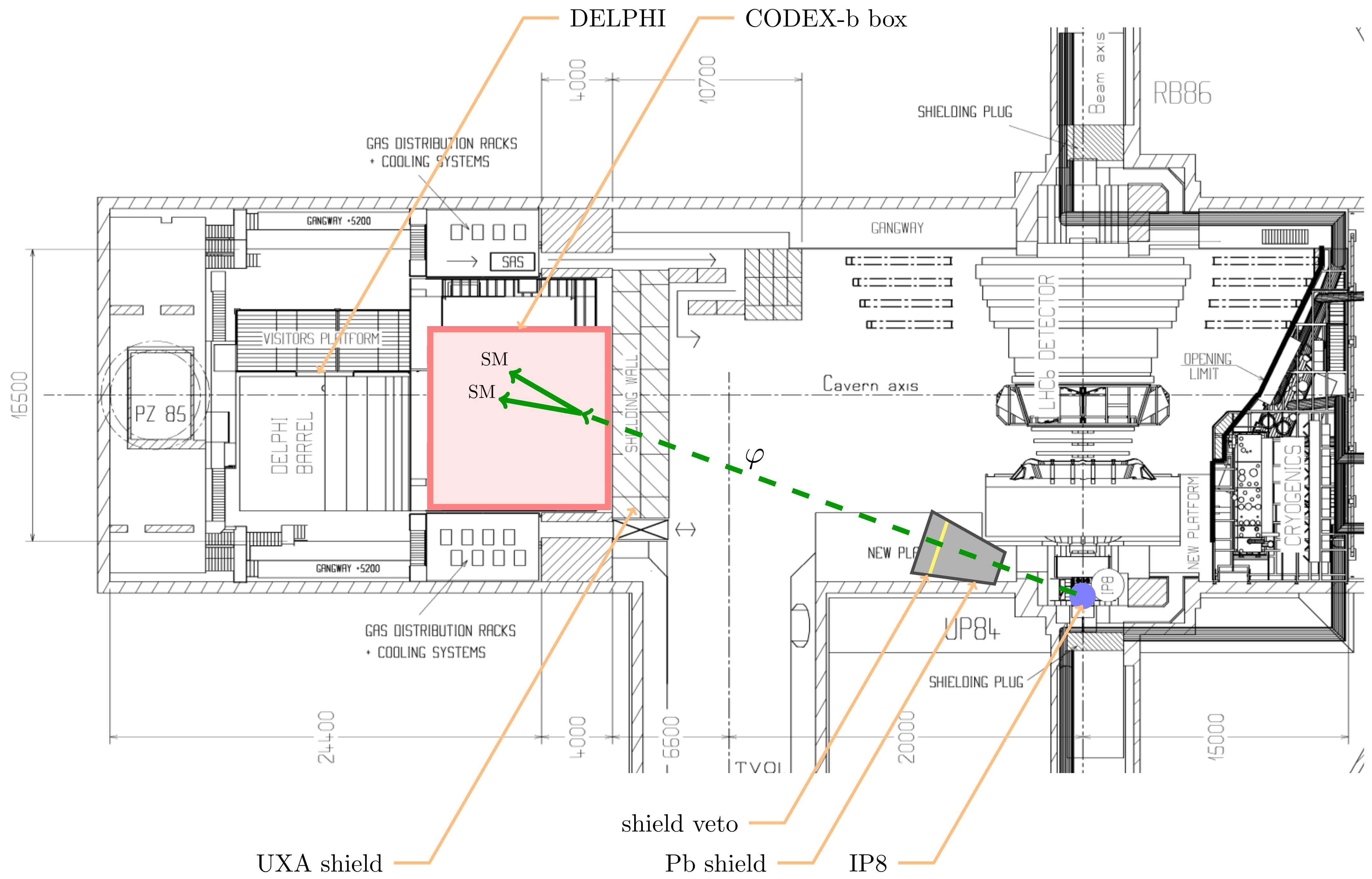
[1705.06327]

CODEX-b

[1708.0939] V. Gligorov, S. Knapen, M. Papucci, & D. Robinson

- Complementary to other detectors





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:

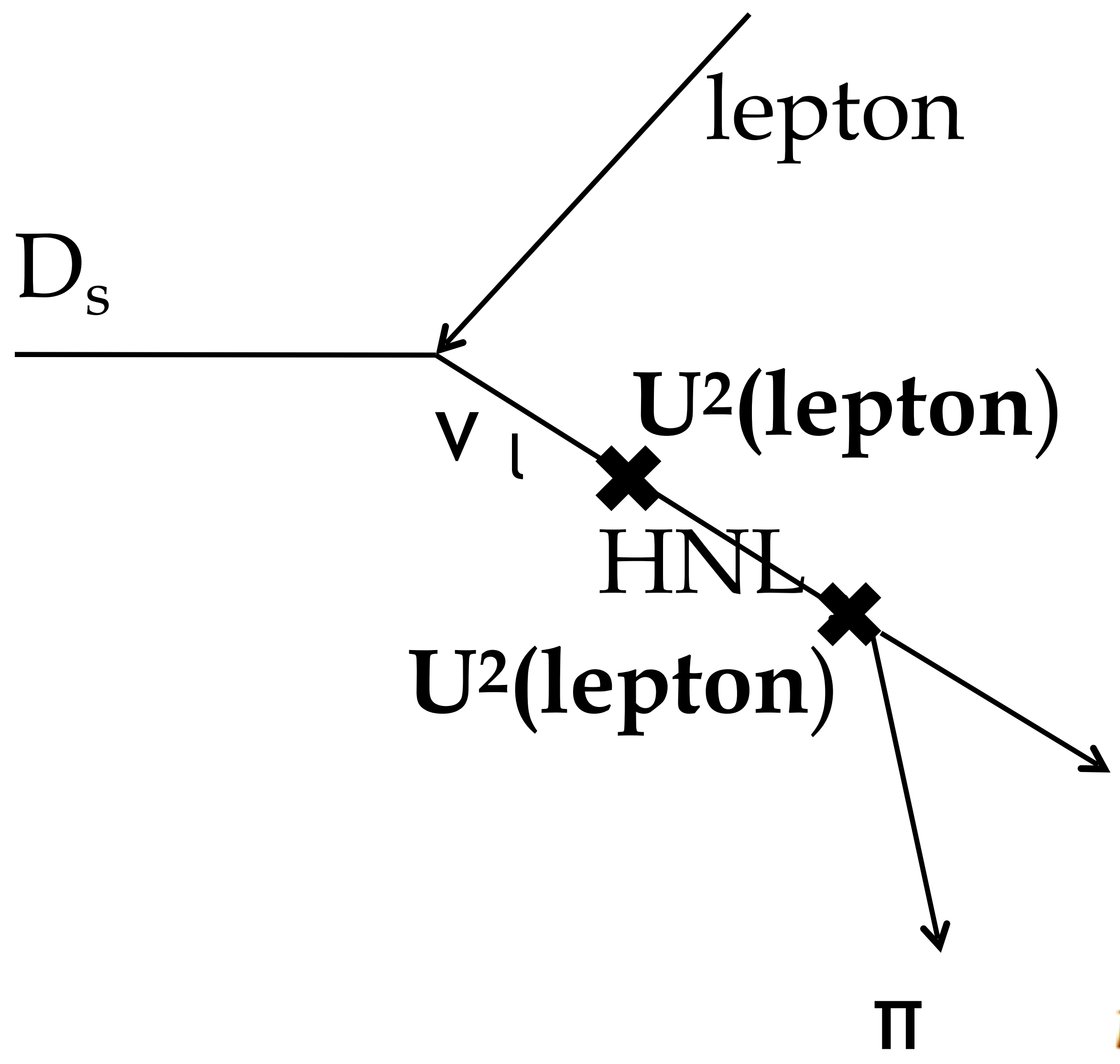
$N \to H^0 \nu$, with $H^0 = \pi^0, \rho^0, \eta, \eta'$

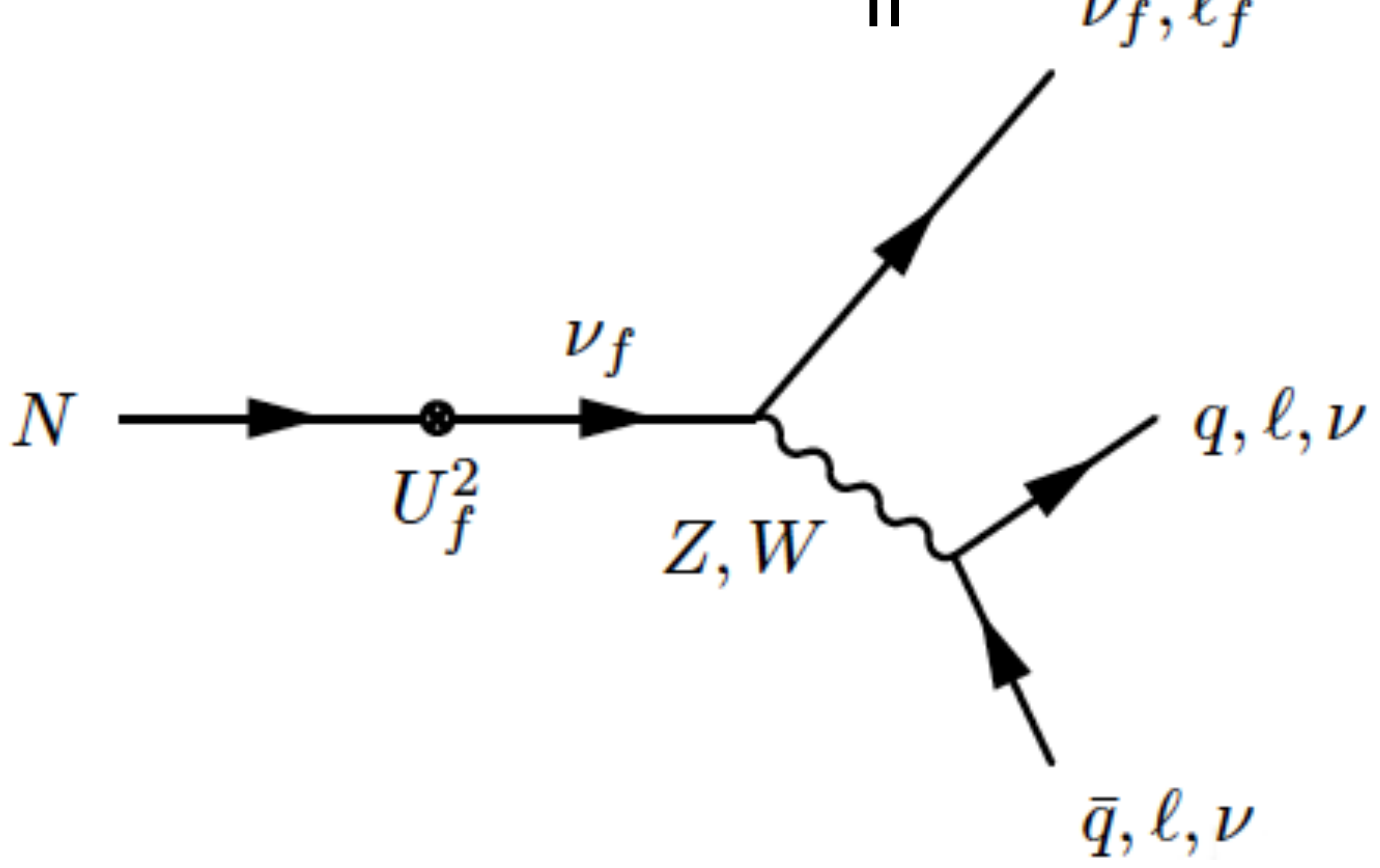
$N \to H^\pm \ell^\mp$, with $H = \pi, \rho$

$N \to 3\nu$

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

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

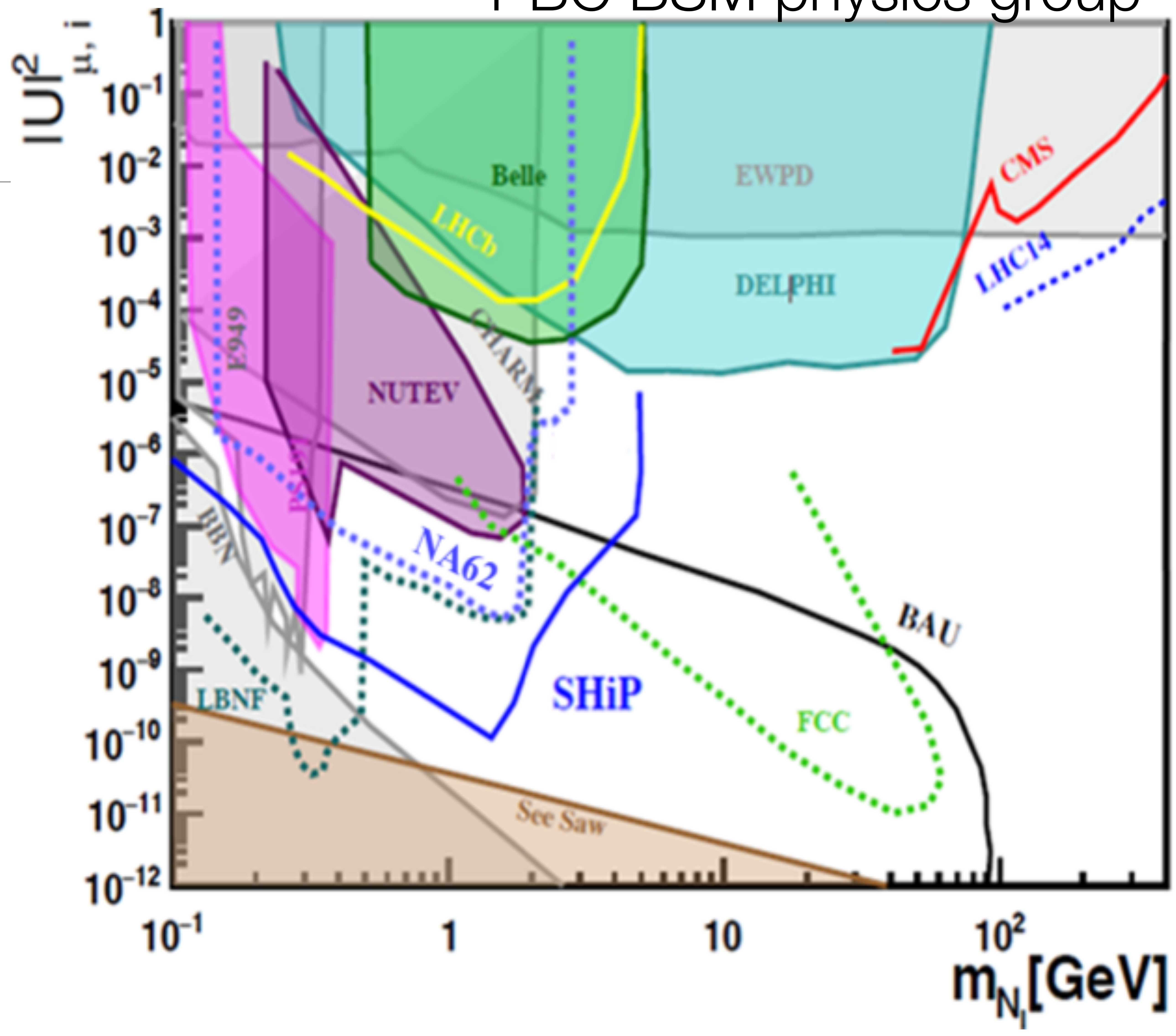




Neutrino portal / sensitivities

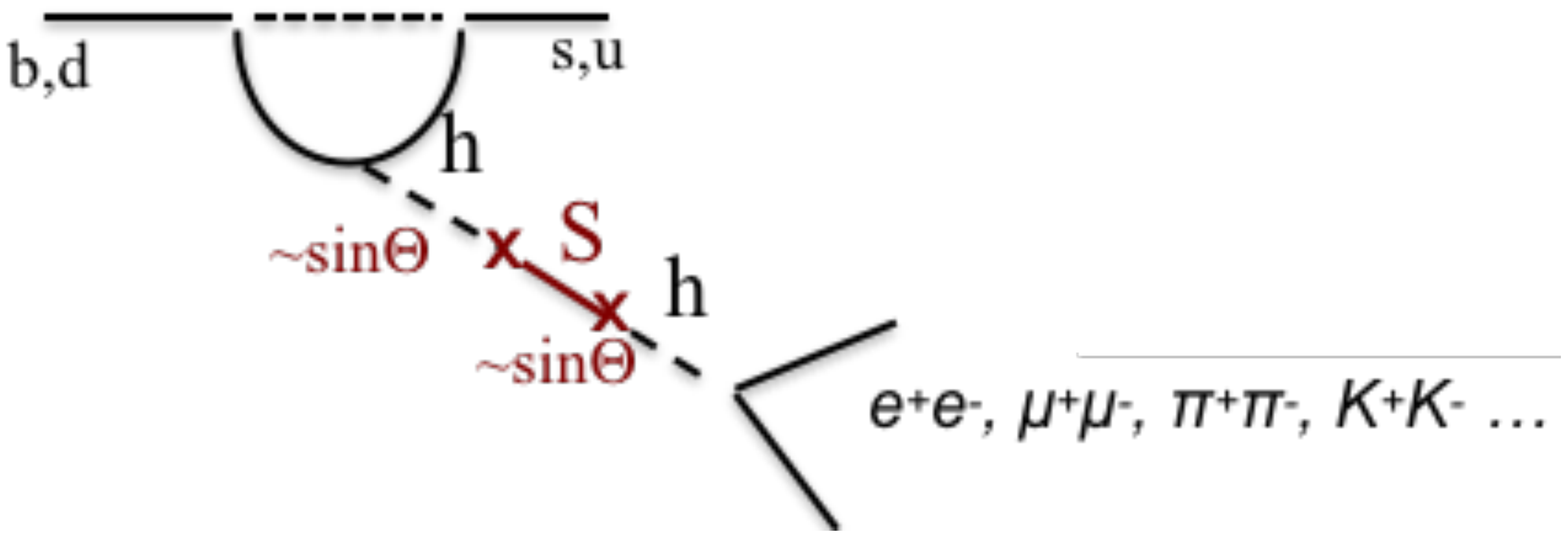
- **M(HNL)< M(b)**:
  LHCb, Belle2
  - SHiP will have much better sensitivity
- **M(b)<M(HNL)<M(Z)**:
  FCC in e+e- mode
  - (improvements are also expected from ATLAS / CMS)
- **M(HNL)>M(Z)**:
  Prerogative of ATLAS/CMS @ HL LHC
- SHiP sensitivity covers large area of parameter space below B mass moving down towards ultimate see-saw limit

PBC BSM physics group



Scalar portal / sensitivities

- **Dark Scalar** particles can couple to the Higgs i[r]
  transition in K and B decays:



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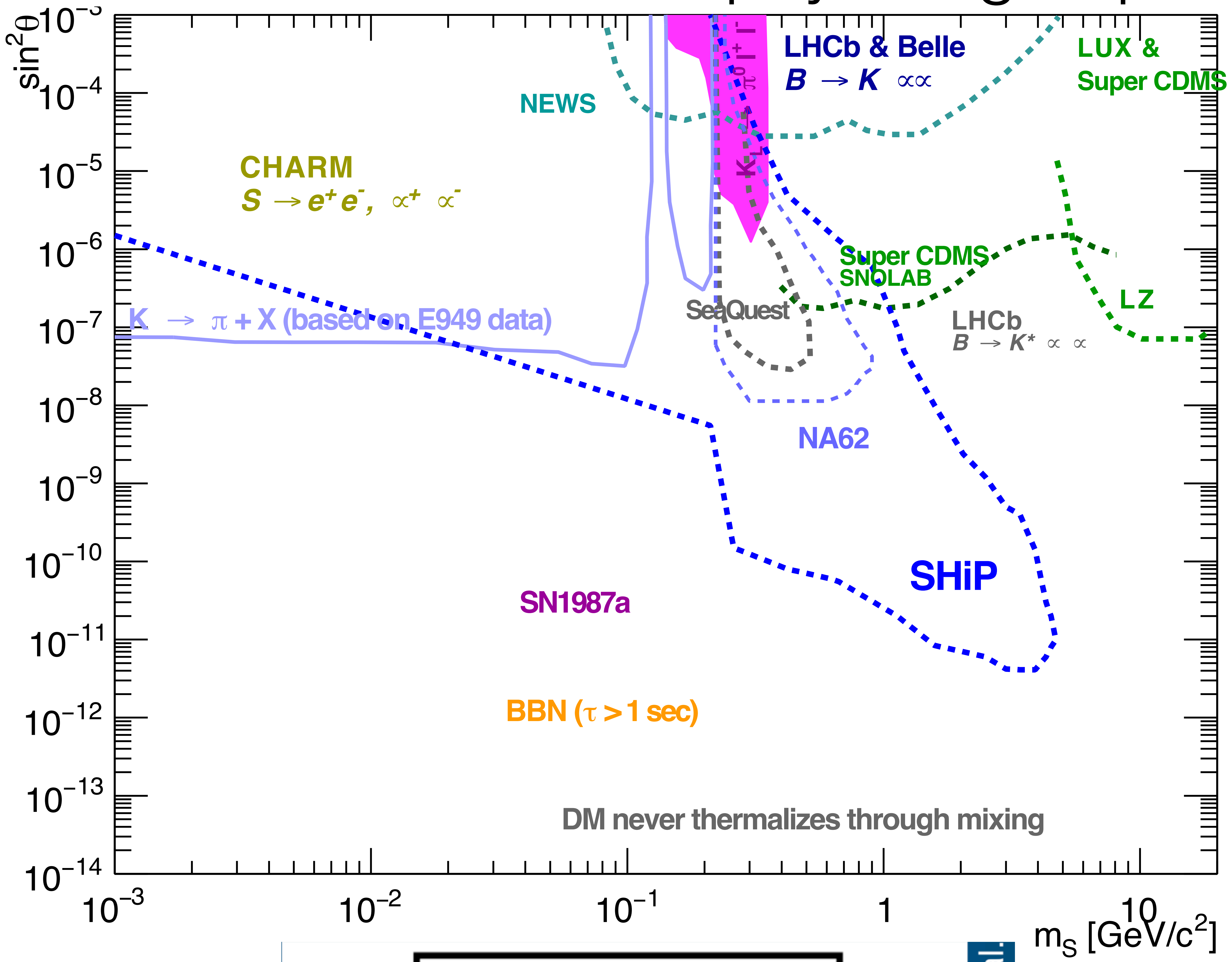
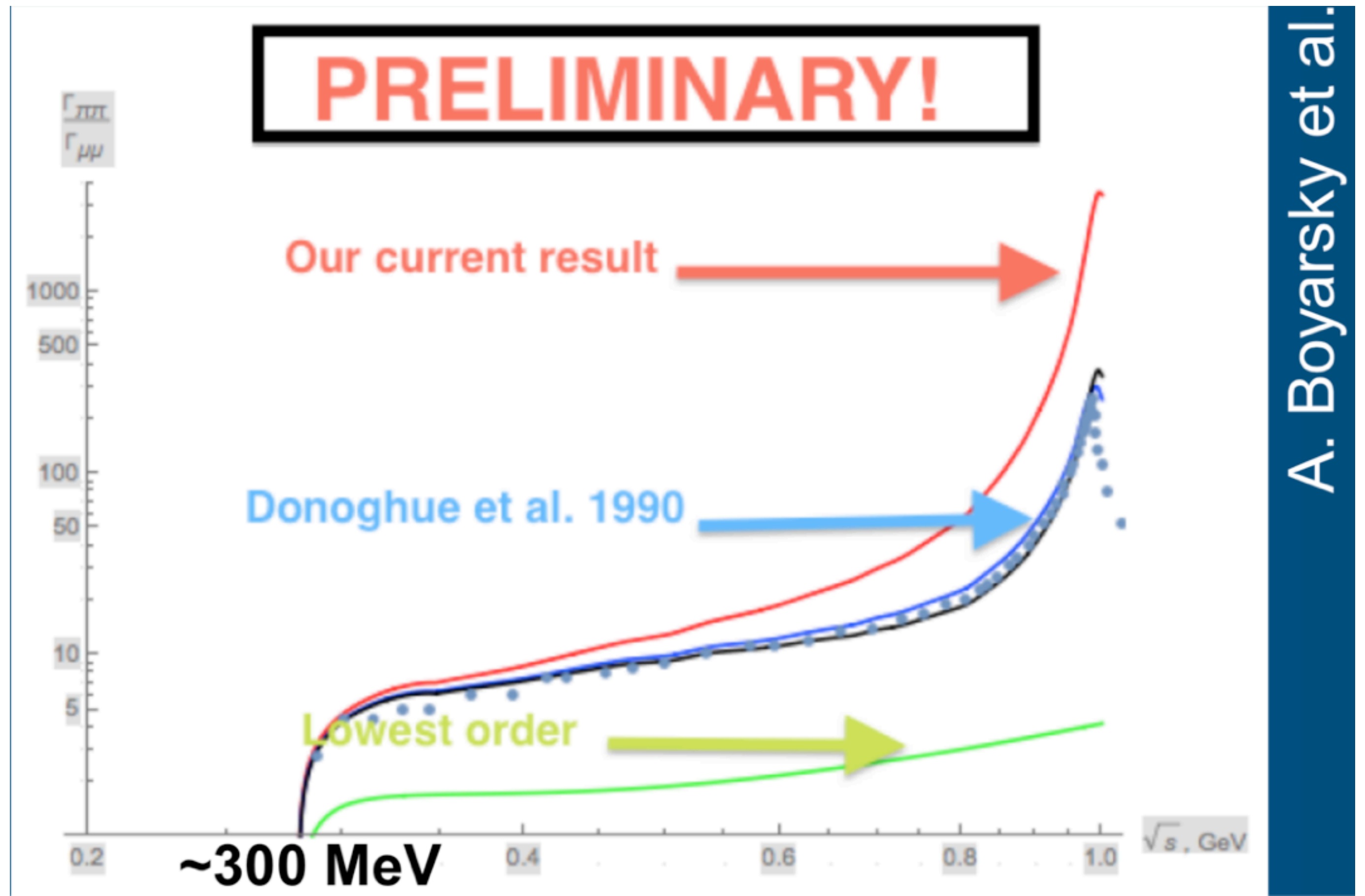
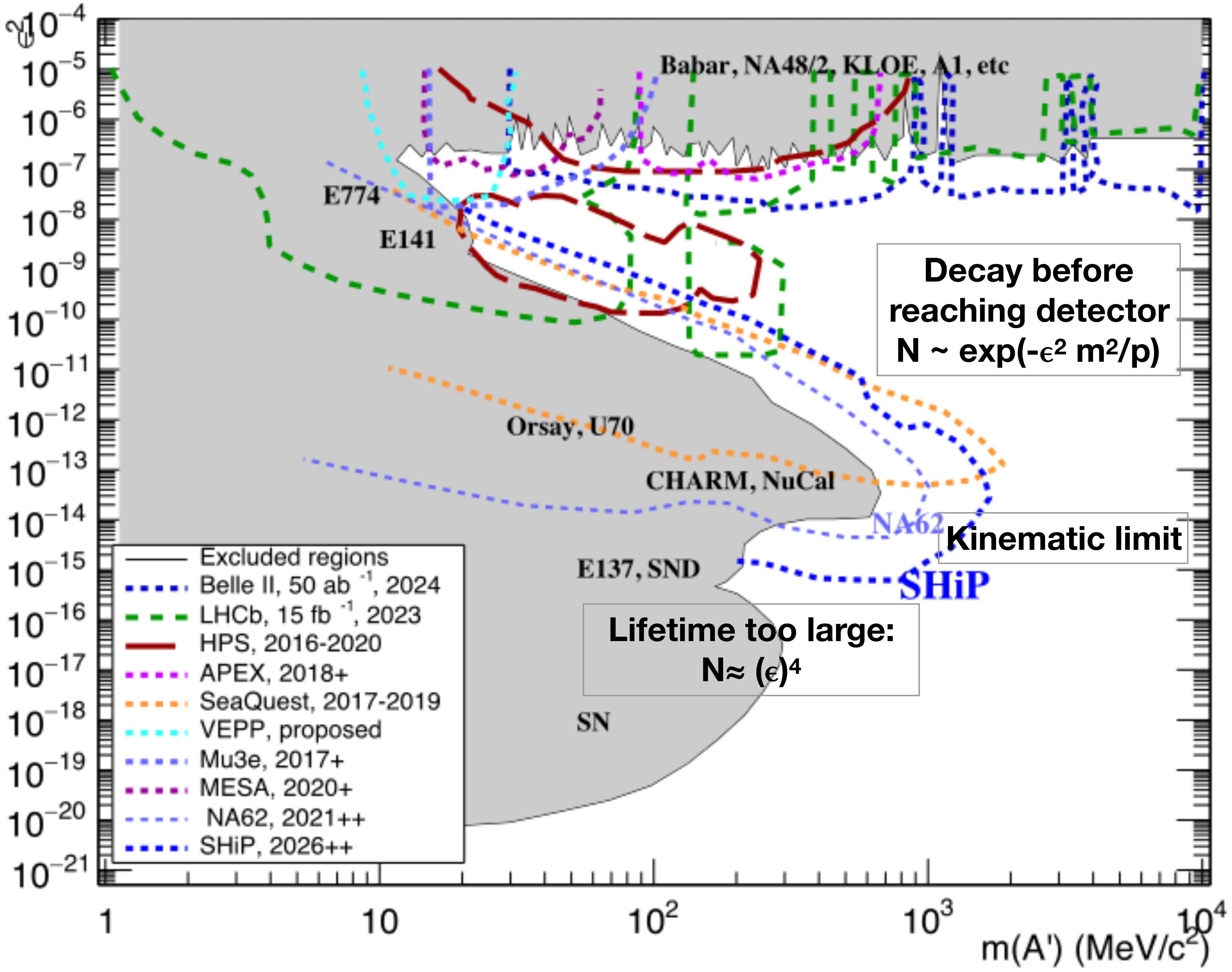


- Issue with simulation:
  - Scalar has been implemented in full simulation but **uncertainty on hadronic** BR($S \to \pi\pi, KK$)
  - Lowest order calculation used in many works Difference may be **a factor 50x**



Vector portal / sensitivities

- **Production**
  - Mesons decay, e.g. $\pi 0 \to \gamma$ 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
- *LHCb also has leading role...*
- *At low m(A'), more coming in the next slides from NA64...*



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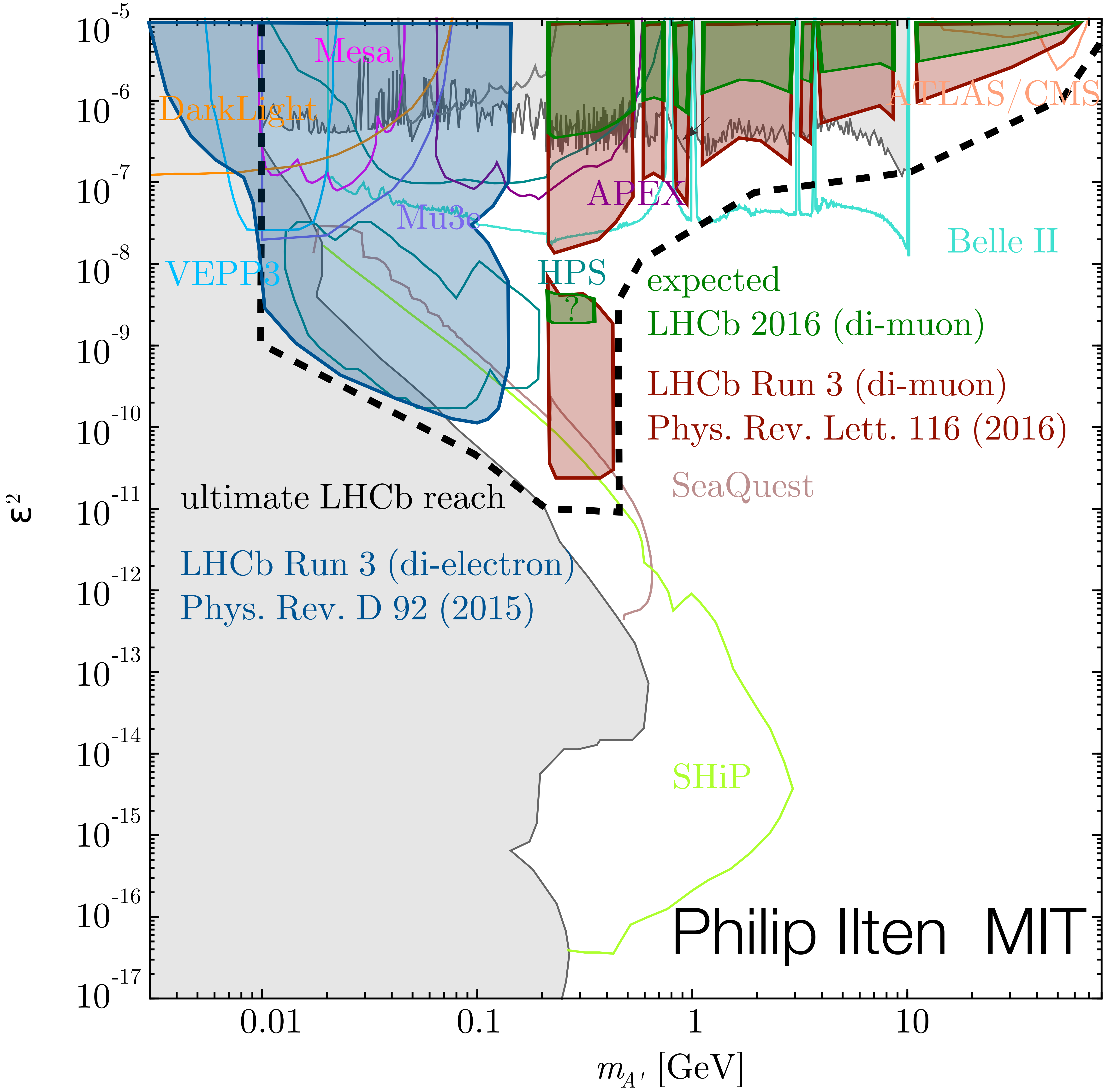
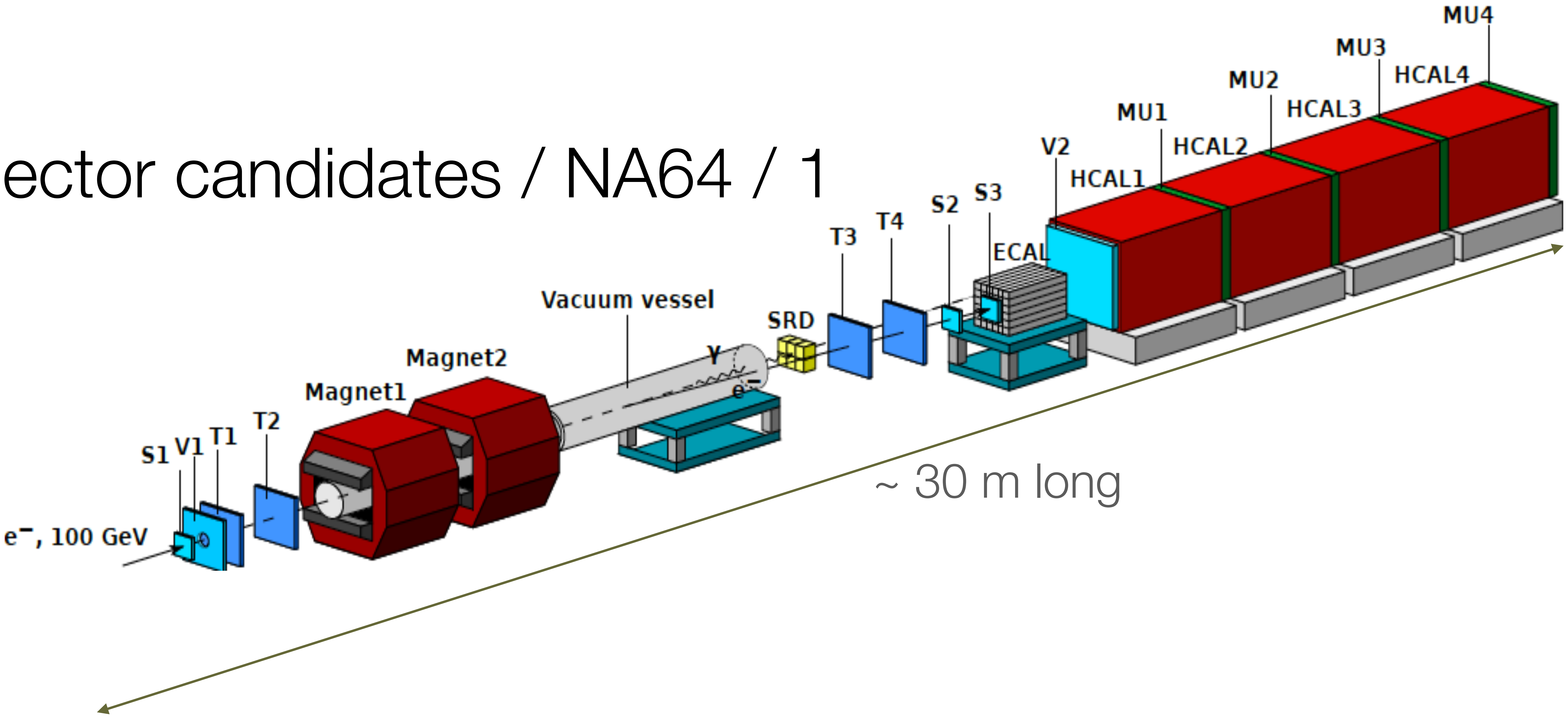


Not decaying dark sector candidates / NA64 / 1



- 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)

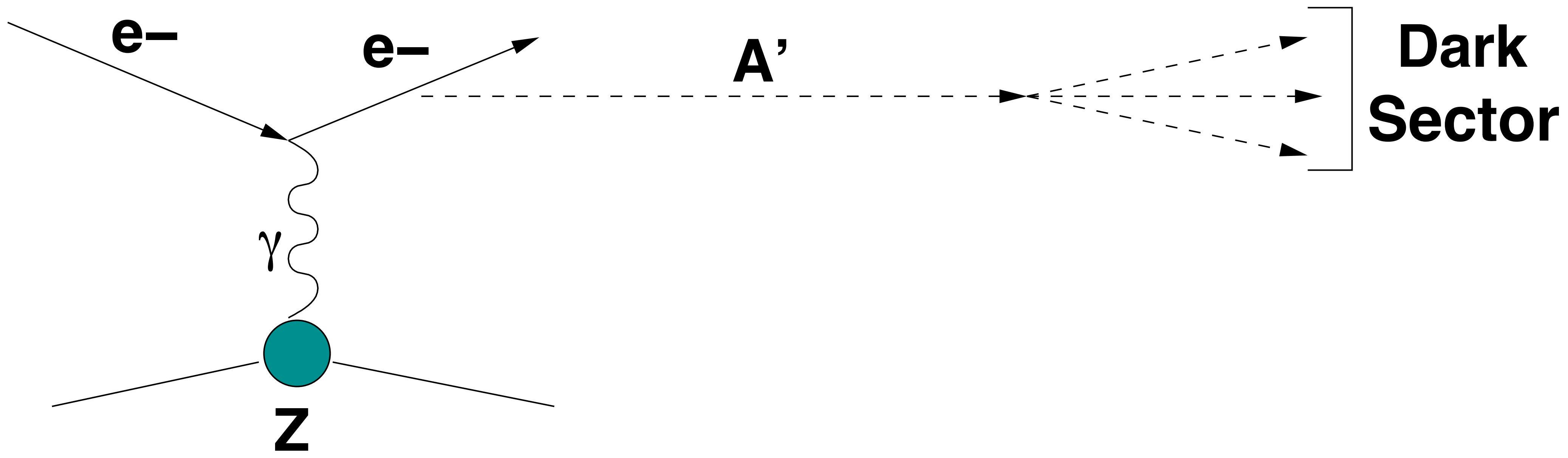
- Key features
  - SPS 100 GeV electron beam
  - Magnetic spectrometer (trackers (**ETHZ**) + bending dipole)→momentum reconstruction of primary particle
  - Synchrotron radiation detector (**ETHZ**) → primary electron identification
  - Electromagnetic calorimeter (**active beam dump**)
  - Hadronic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

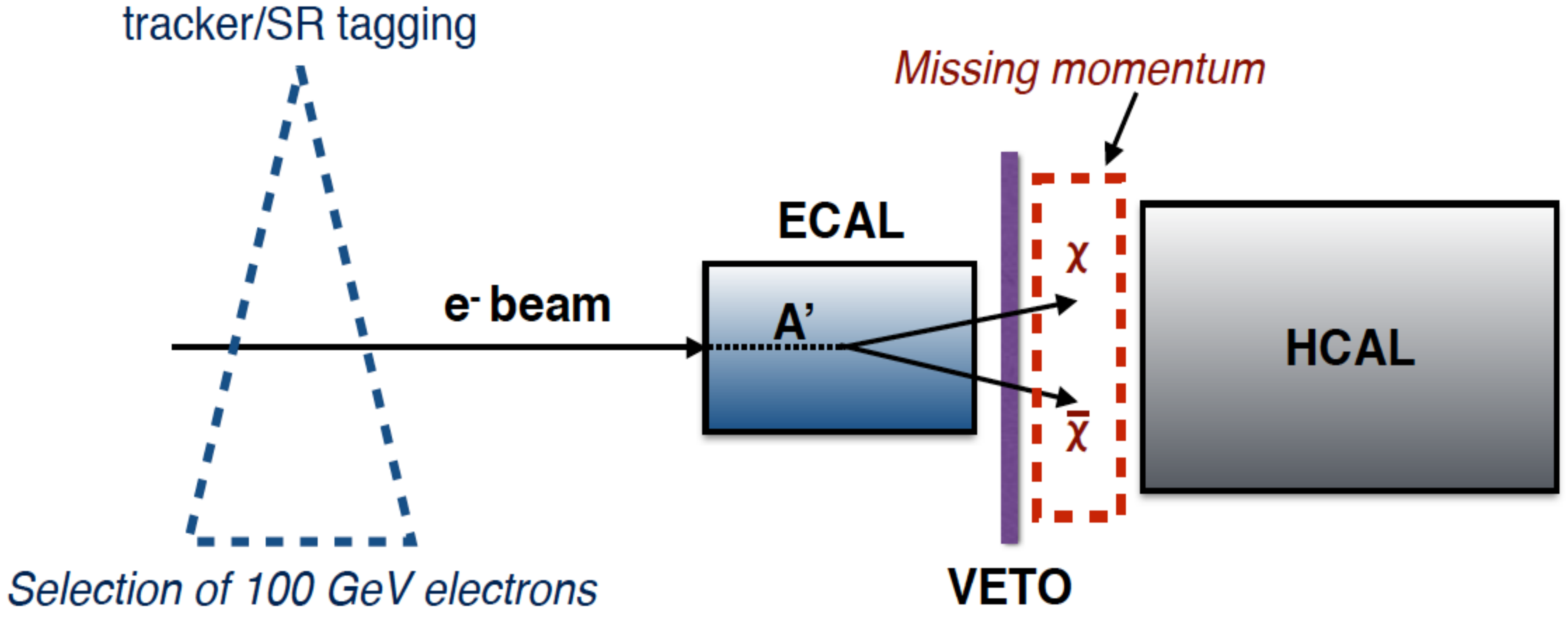
E. Depero (ETHZ) et al., NIMA866 (2017) 196-201 (Synchrotron radiation detector)

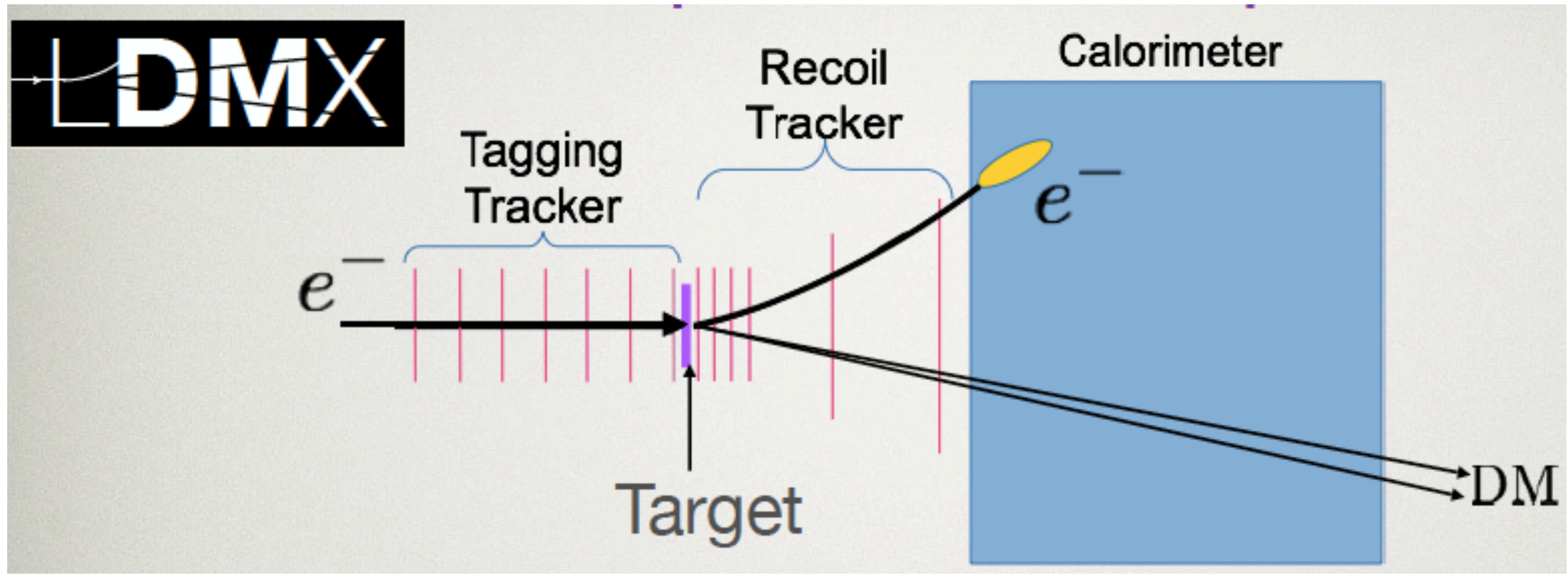
D. Banerjee (ETHZ) et al., NIMA881 (2018) 72-81 (Multiplexed micromegas tracker)

Not decaying dark sector candidates / NA64 / 2

- Dark photon production and decay: through kinetic mixing of a Bremsstrahlung photon in the ECAL
- The Dark photon would **escape** then the setup undetected through a new vector boson (dark photon) A’
- Dark Photon signature:
  Tagged 100 GeV electron
  Missing energy in the ECAL (threshold<50 GeV)
  no activity in VETO and HCAL
- Similar idea exploited by LDMX at SLAC
  - Deep highly segmented CALO rejects events with visible particles

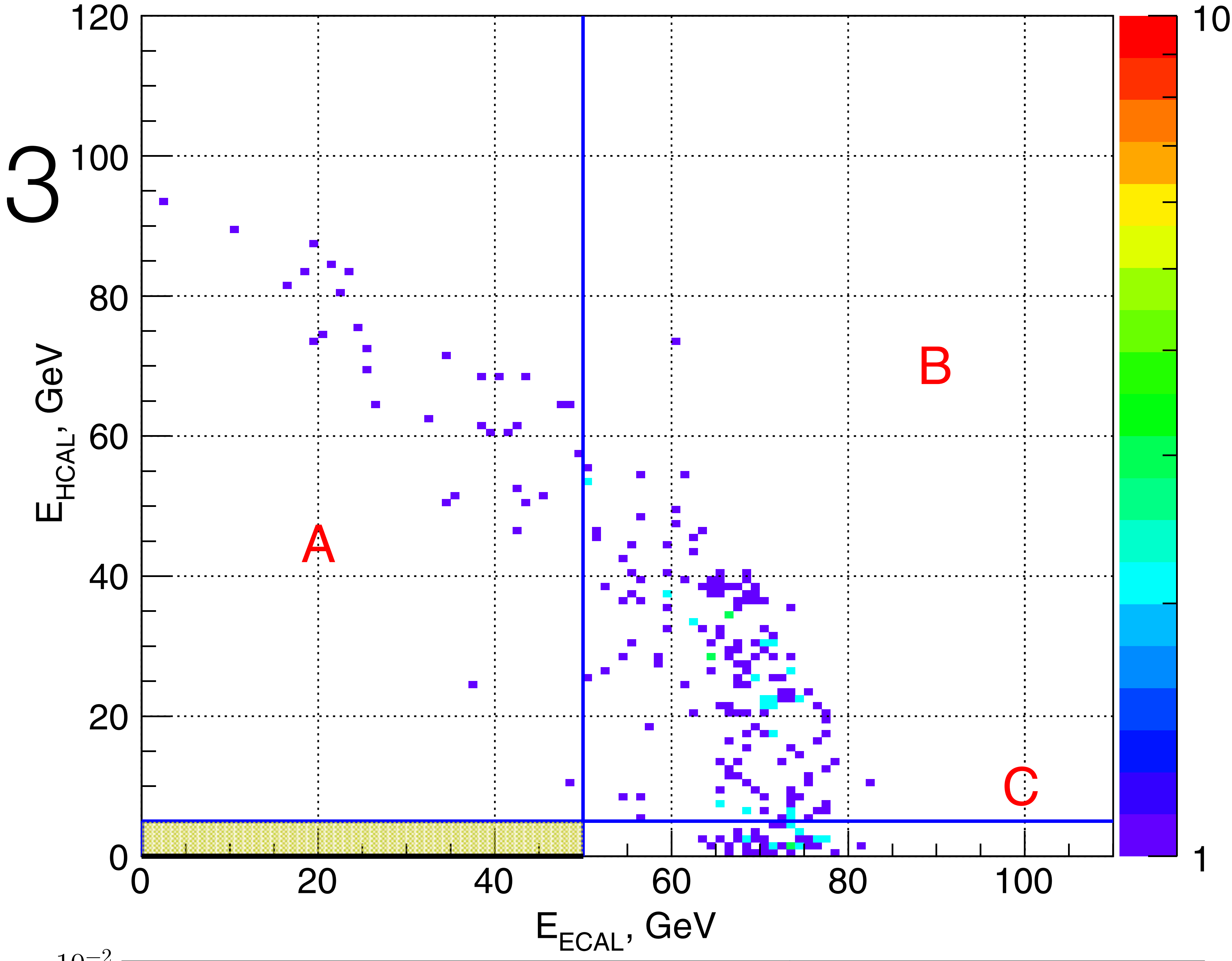


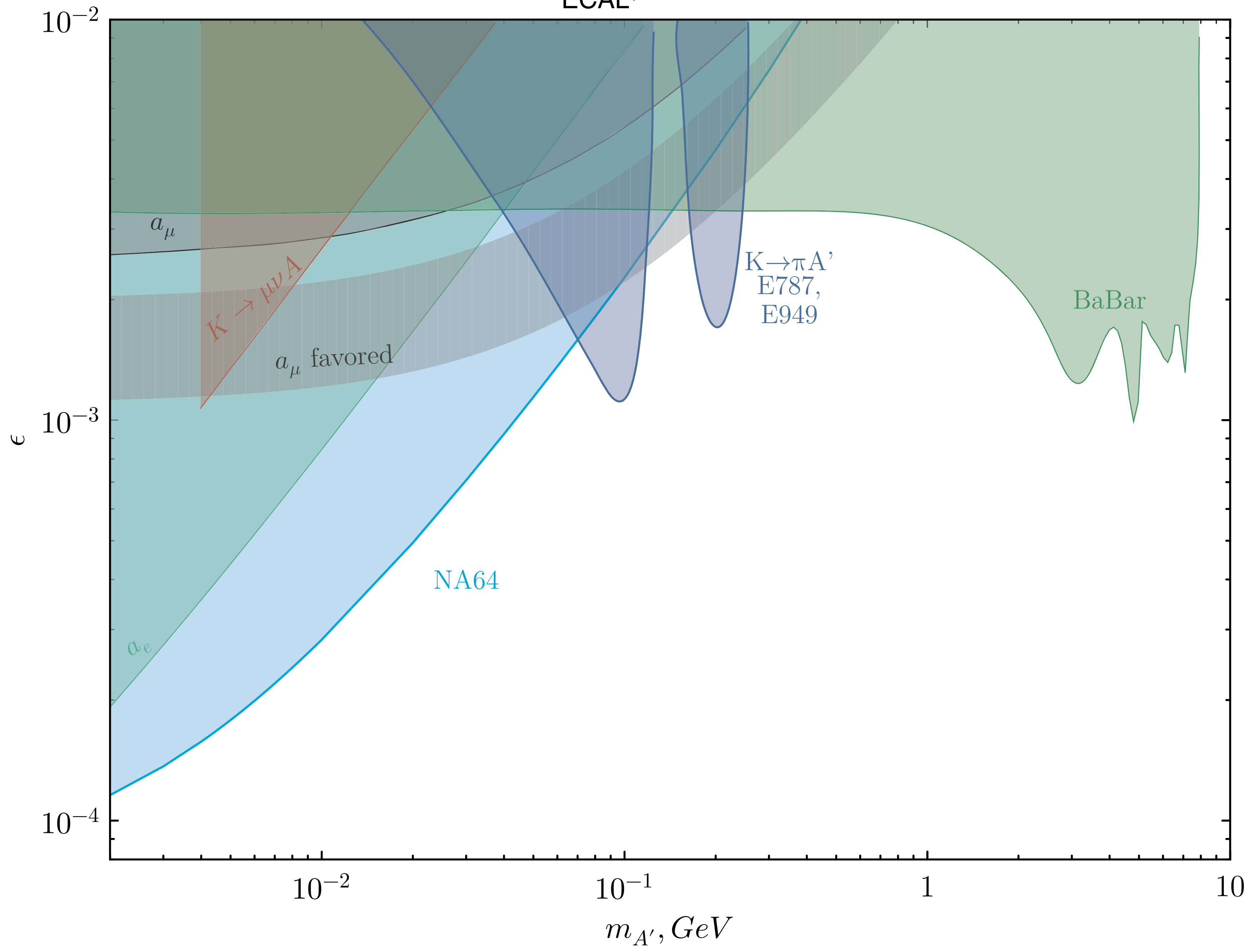




Not decaying dark sector candidates / NA64 / 3

- 2016 beam time (**2 weeks** in July 2016 !):
- 2.75 x 1e9 electrons on target with beam intensity of 1.4 x 1e6 *e*- / 4.8 s spill with a 1.5 cm (FWHM) diameter beam (Compared to LDMX: Multi GeV ultra low (1-5/bunch) *e*-beam 1-200 MHz bunch spacing)
- No event observed in the signal region:
  - exclusion of **most of the g-2** muon favoured region
- Signal region: E_{ECAL}< 50 GeV and E_{HCAL}< 1 GeV
- Neat result in **PRL**:
  NA64 collaboration, Phys. Rev. Lett. 118, 011802 (2017)
  (now g-2 fully excluded by BaBar)
- *And prospects... down to the relic*





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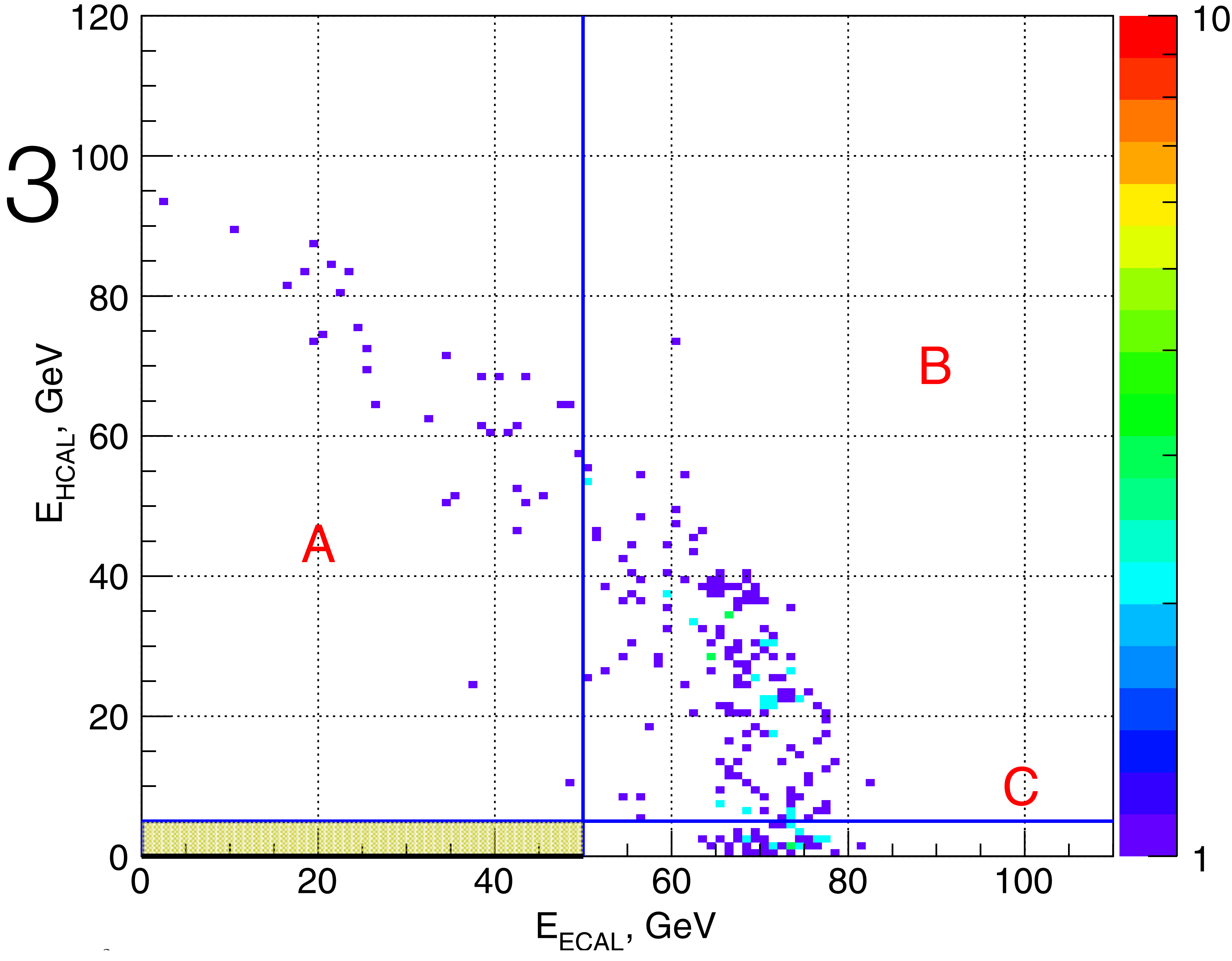
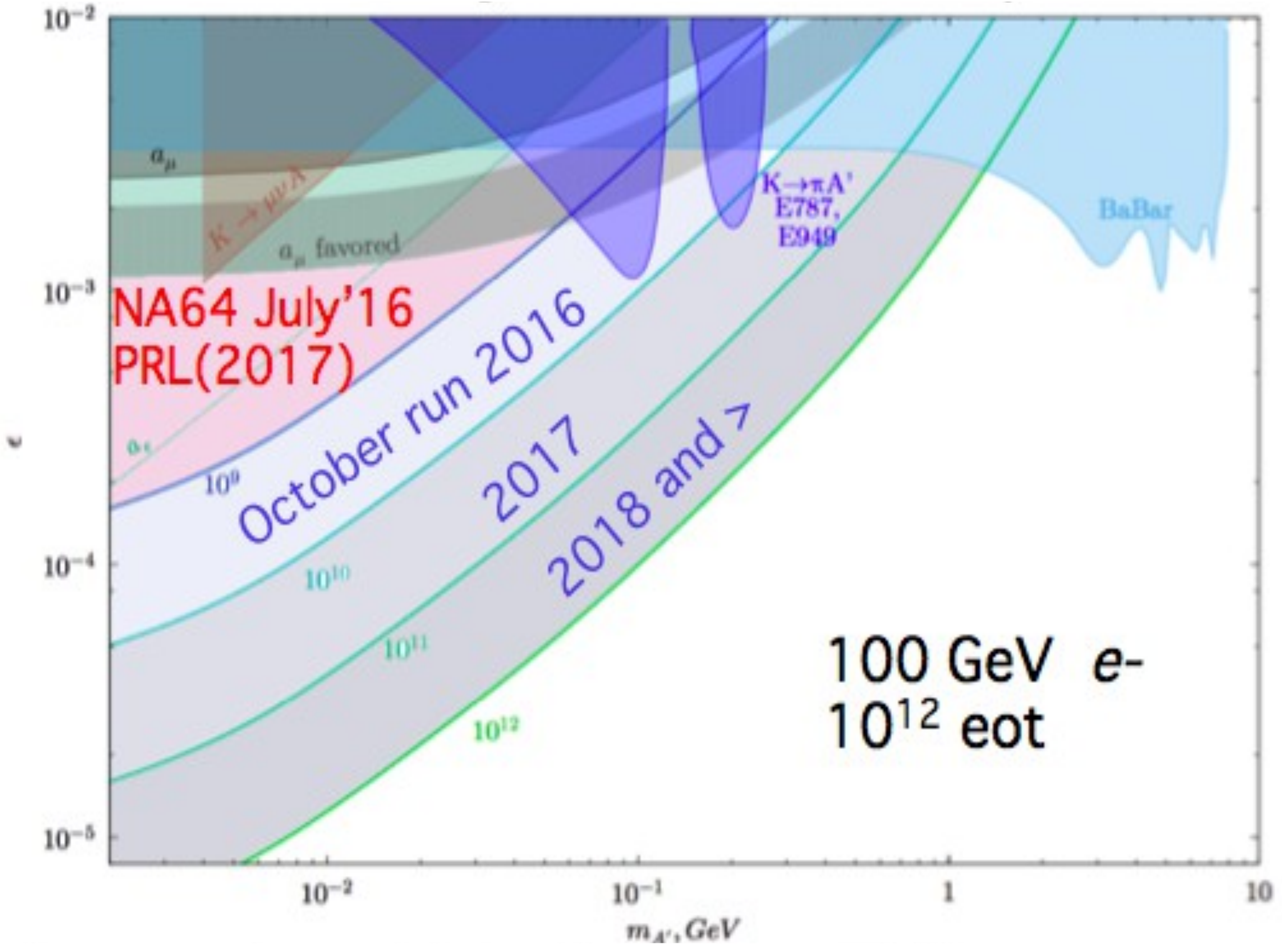
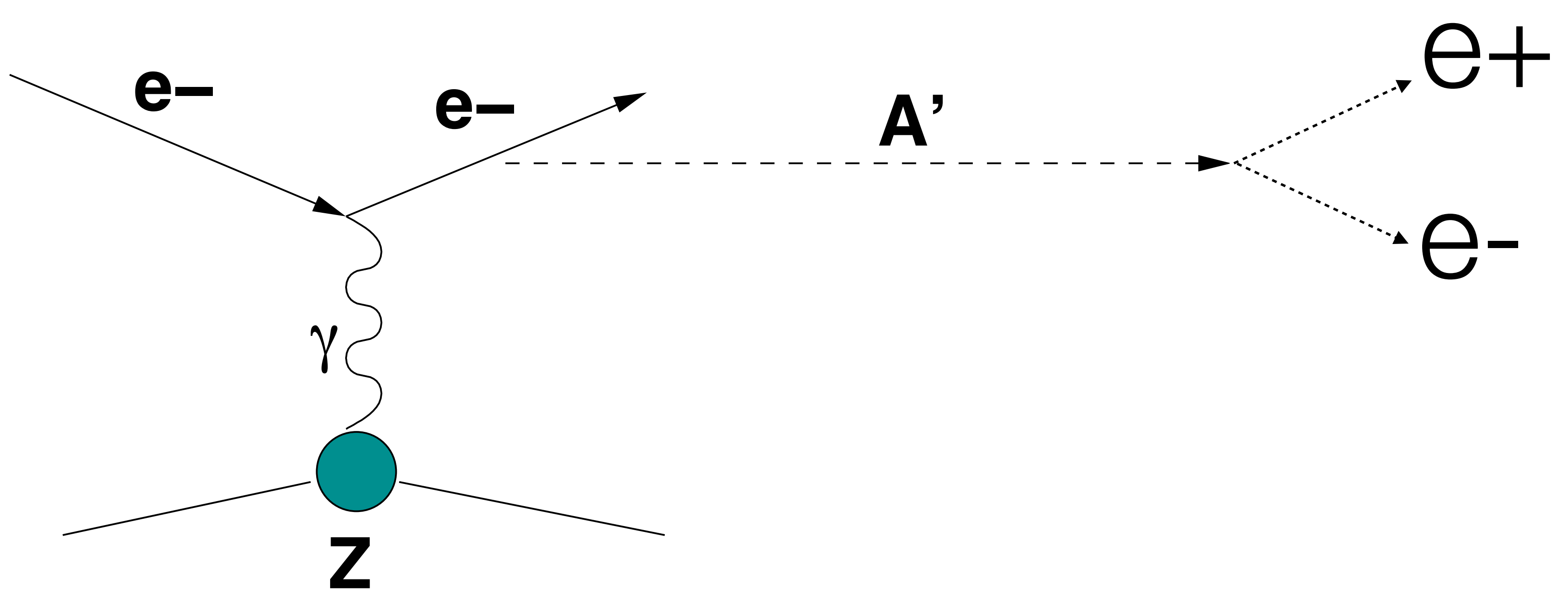
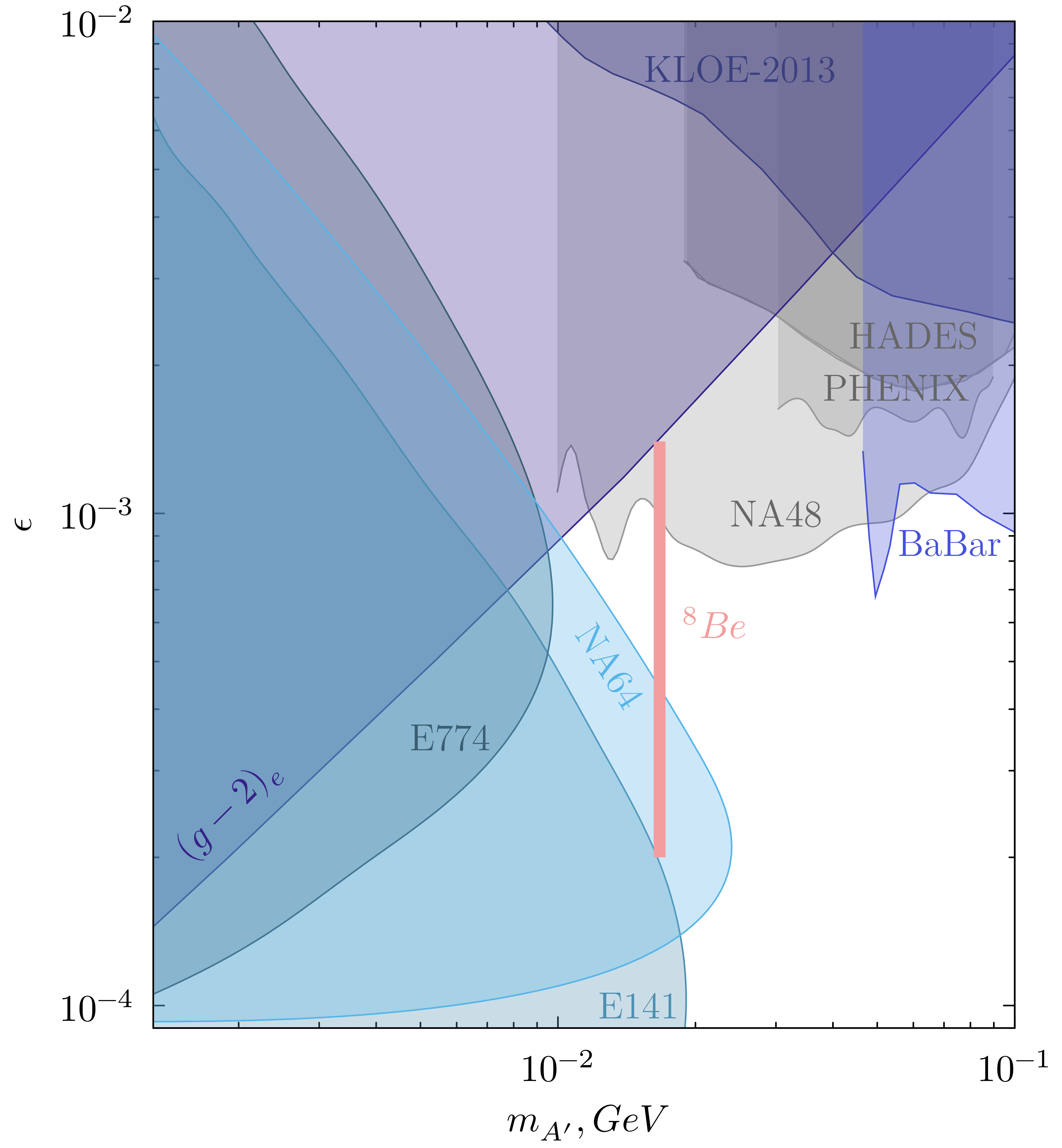




NA64 / Bonus [arXiv:1803.07748]

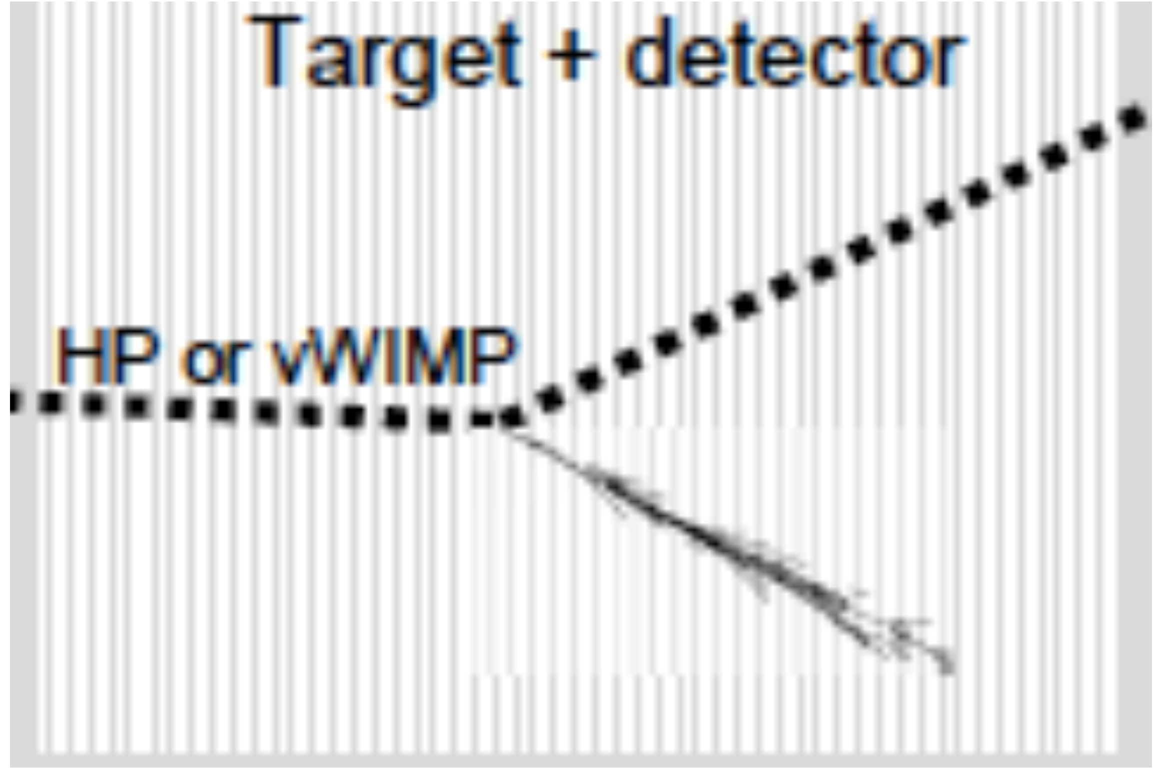
- NA64 also capable of direct searches of dark sector candidates.
- Letter submitted, first results from the NA64 experiment specifically designed for a **direct search** of the *e+e-* decays of new short-lived particles at the CERN SPS in the sub-GeV mass range.
- The reaction is $e^- + Z \to e^- + Z + A'(X);\ A'(X) \to e^+e^-$
- 2.4×1e10 EOT and 3×1e10 EOT were collected with two different targets.
- Anomalous bump in $^8\mathrm{Be}^* \to {}^8\mathrm{Be} + e^+e^-$ could be a DP candidate (emission of a light neutral vector boson, then decaying into an *e+e–* pair)
- **First world limits** on its coupling to electrons!

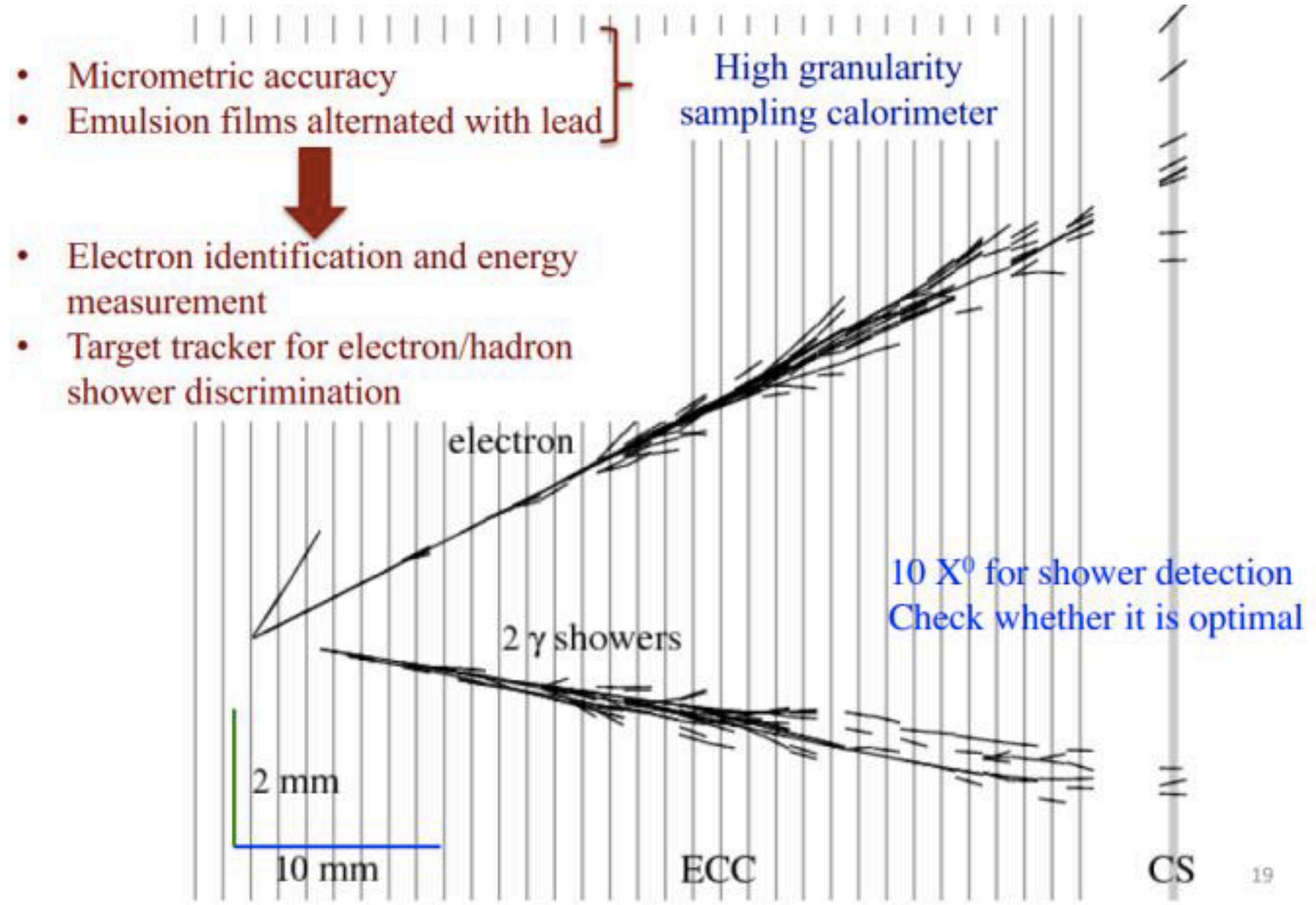




Not decaying dark sector candidates / iSHiP / 1

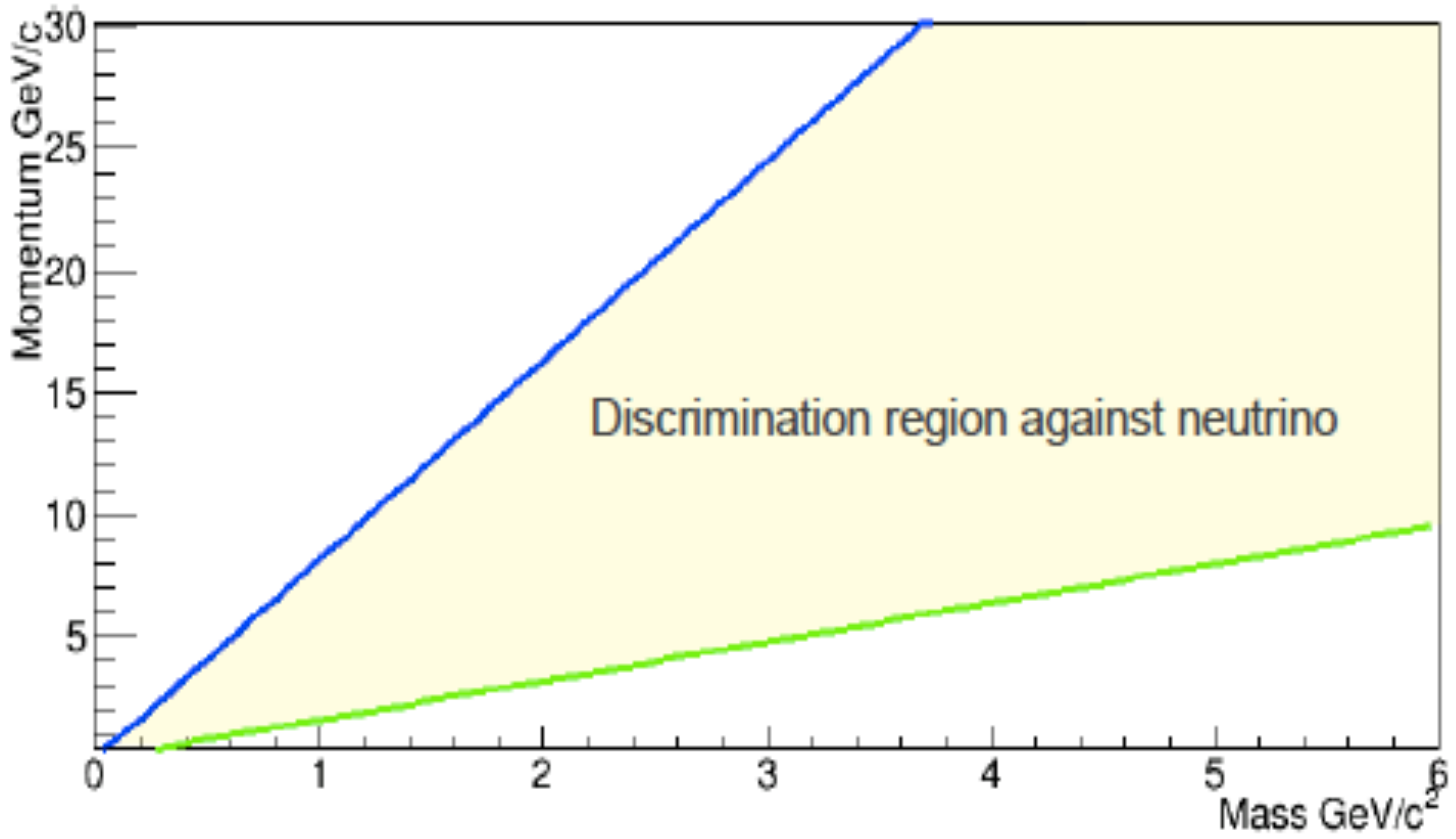
- Not decaying dark sector candidates can scatter on atoms of the dense material of the SHiP **emulsion detector** (iSHiP) giving detection signature: EM shower (or nuclei recoil)
  - Reconstruction of the EM showers in emulsion demonstrated with OPERA data
  - *Complement emulsion detector with fast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

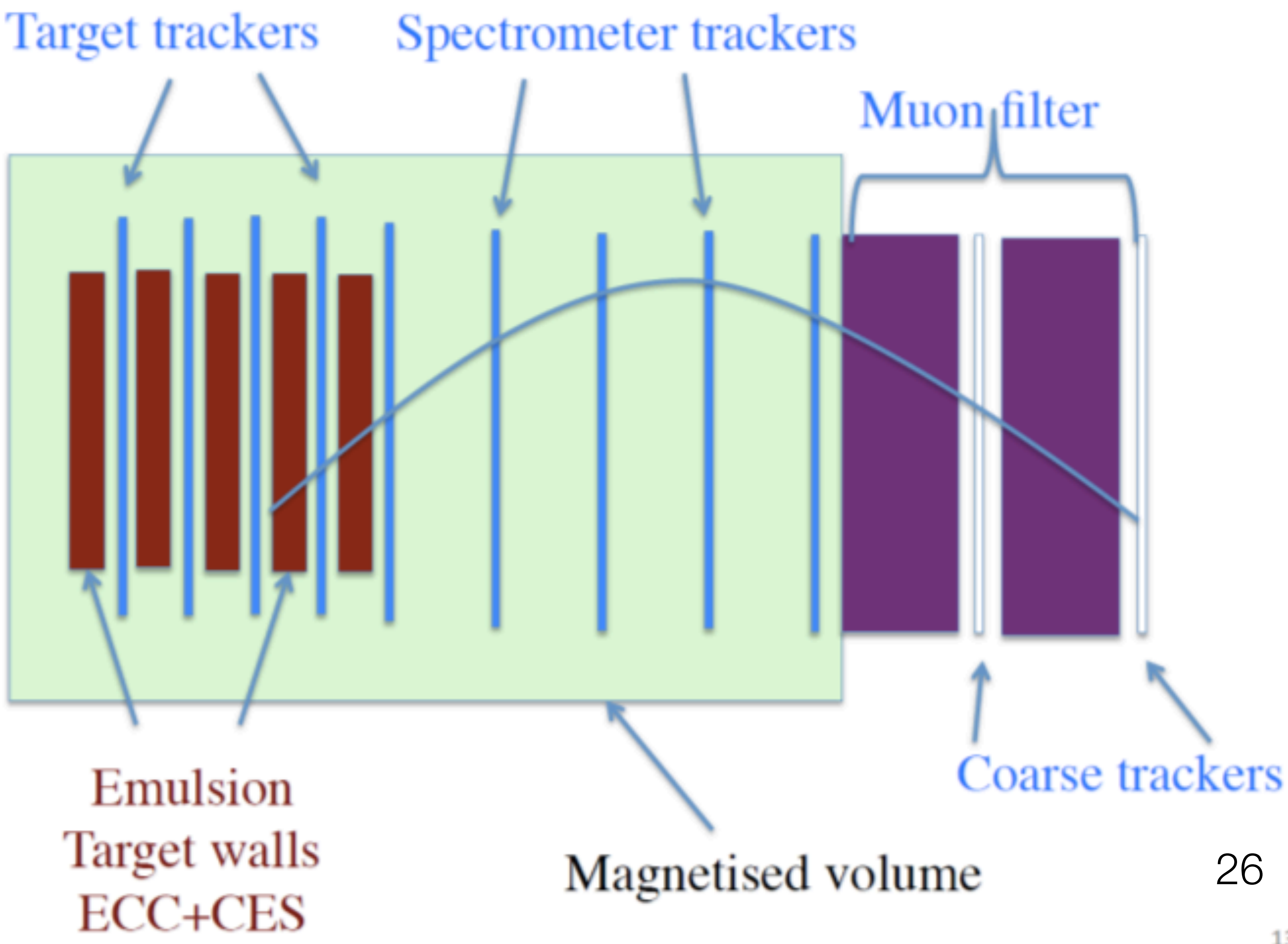




Not decaying dark sector candidates / iSHiP / 2

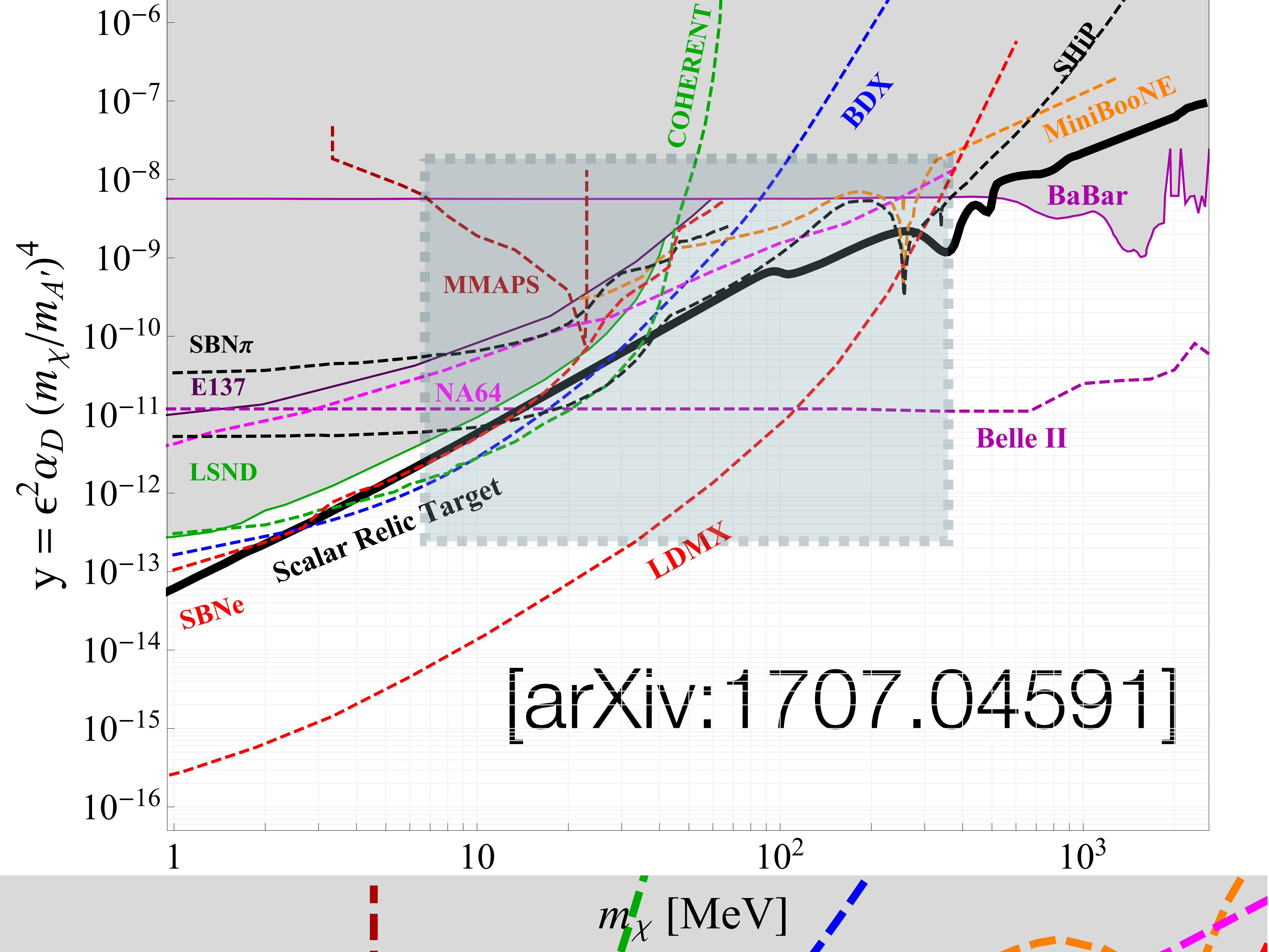
- Complement emulsion detector with fast electronic Target Tracker to improve electron reconstruction (SciFi ? → SPS test beam July 2018)
- Under study: Elimination of the neutrino background by ToF operating with the SPS bunched beam: 4σ /spacing = 1.5ns / 25ns & ~40 m distance from the target
- Requires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

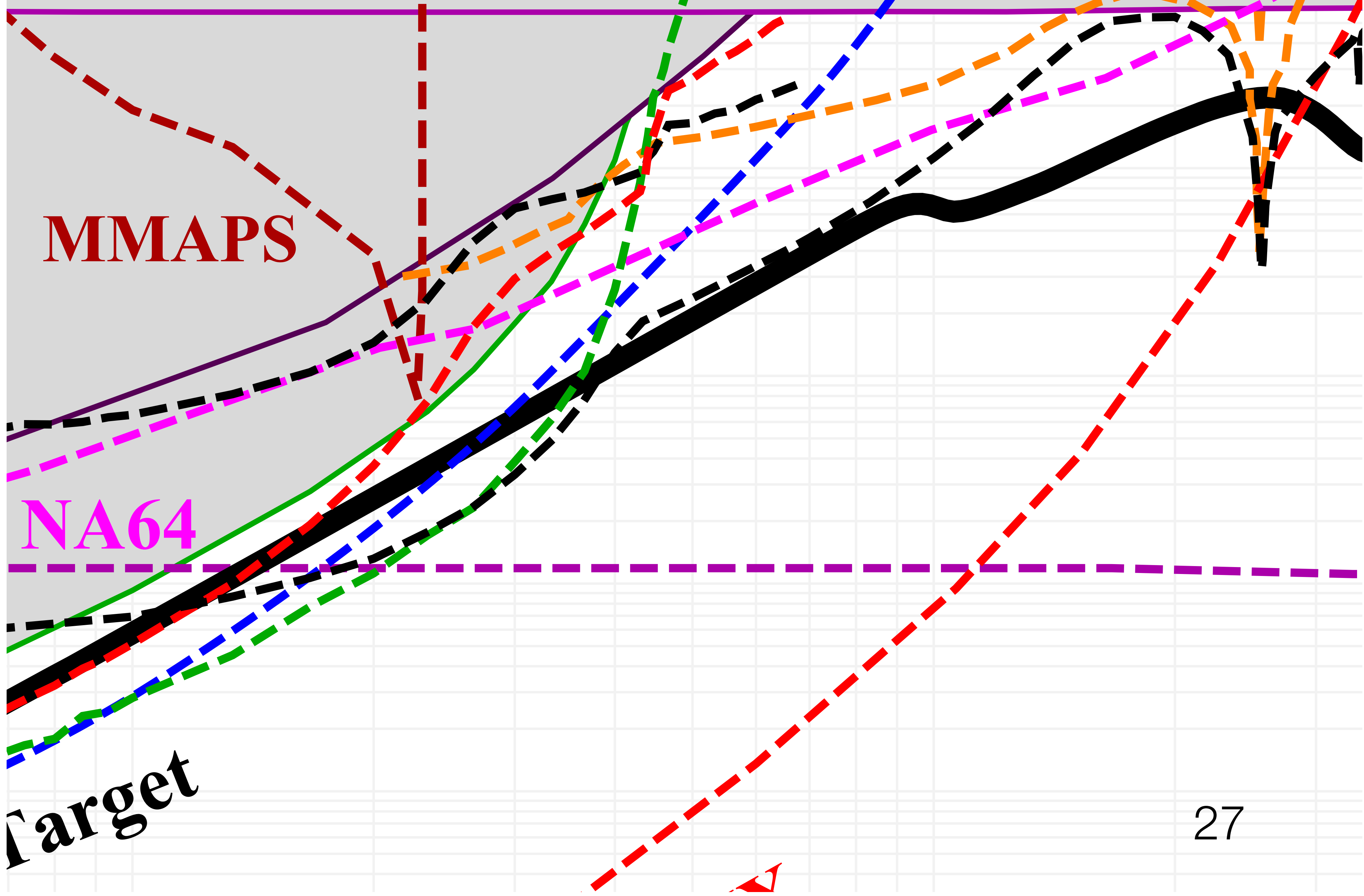




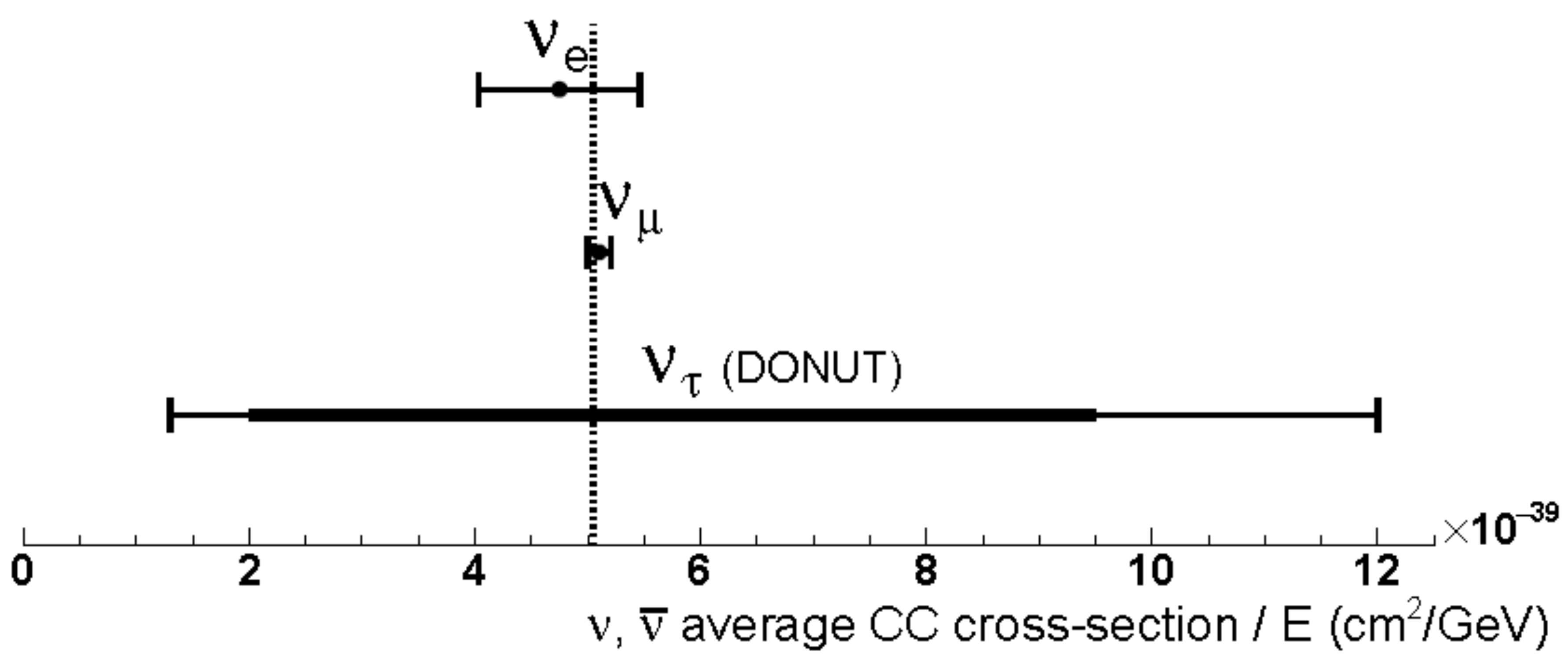
Light dark matter limits / e.g. scalar

- 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

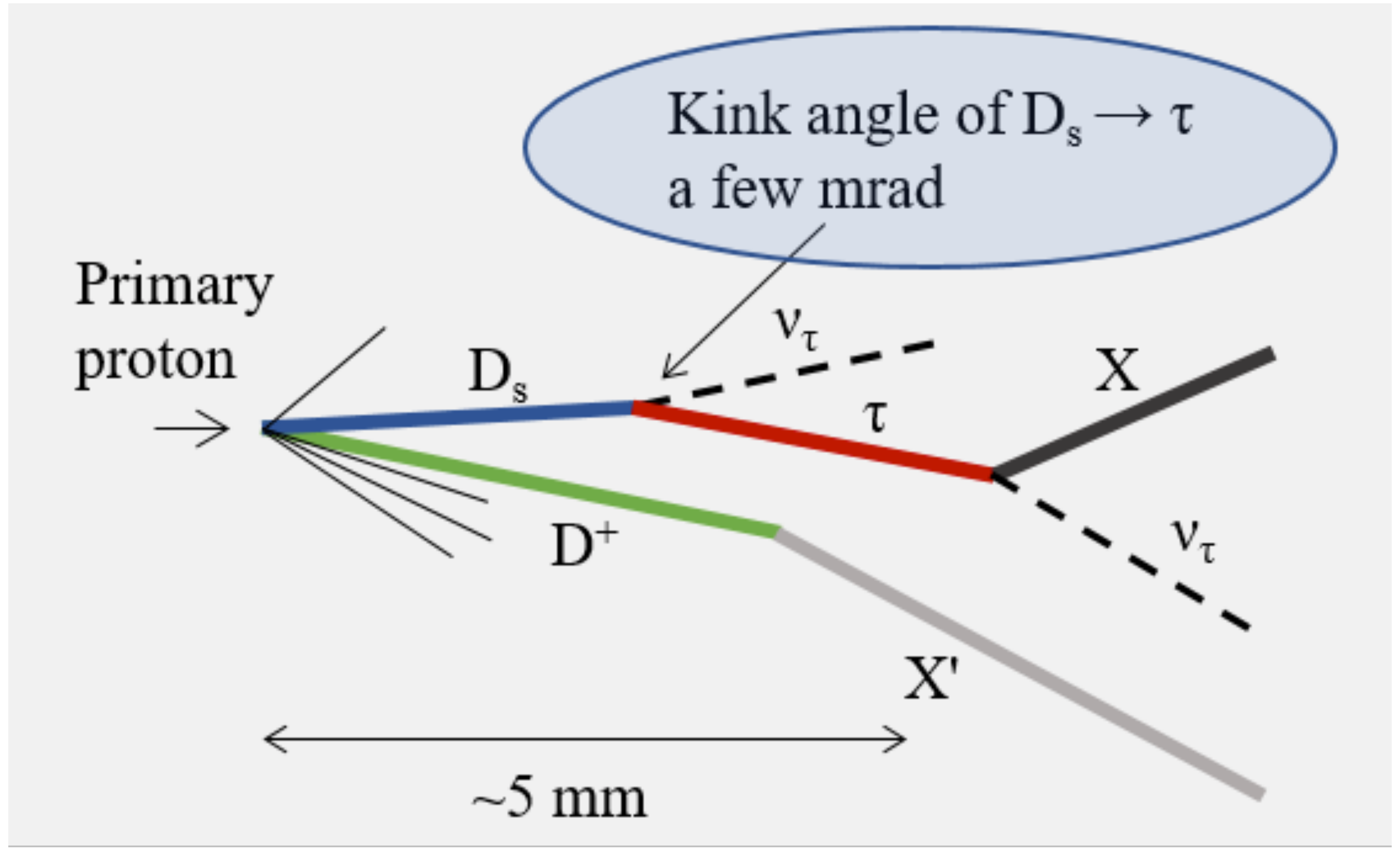




τ neutrinos



- **τ neutrinos** are the less known particles in the SM
- Large charged-current cross section uncertainty due to lack of data on Ds differential production CS
- DsTau studies τ neutrino production at SPS:
  - Directly measuring Ds→τ→X decays will provide an inclusive measurement of the Ds production rate and the decay branching ratio to τ
  - Use of emulsion technology → iSHiP
- Status is positive, beam time (2021) **recommended by SPSC**
- **Complementarity** with SHiP, expected performance in relative uncertainty for τ neutrino charged-current cross section
- 2018: down to 30 % → re-evaluate DONUT result
- 2021: **down to 10 %** → important input for future experiments



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

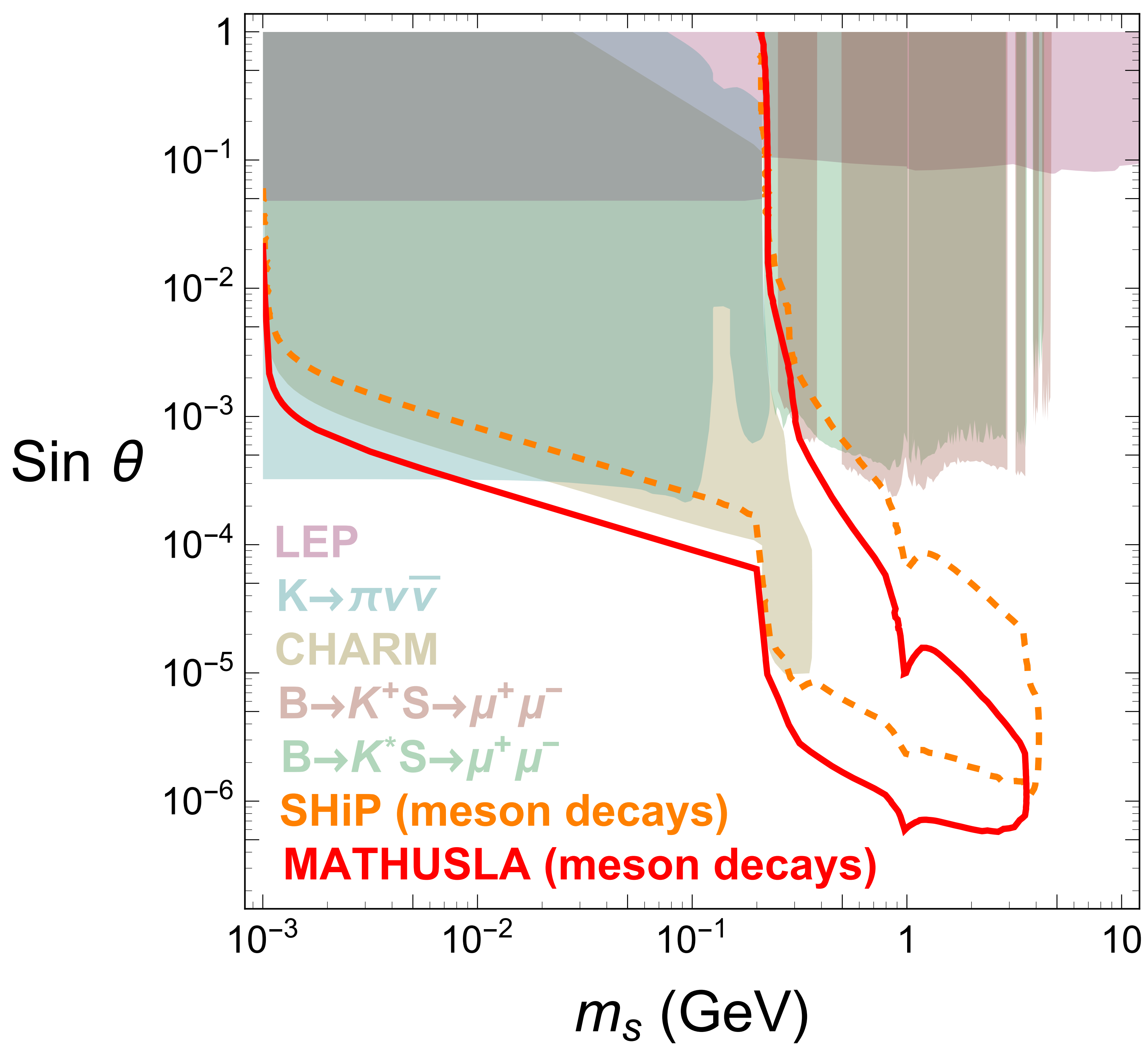
Michelangelo Mangano

- The days of guaranteed discoveries are **gone**, but the big questions remain
- Physics case to search for Dark Sectors particles is indeed **very timely**
  - No NP finding at LHC so far, but many experiments offer alternative routes
  - Great examples as **NA64** where great results can be obtained with a relatively small investment
- CERN is ideal place to search for Dark Sector at high energy and high intensity
  - SPS beams: two complementary strategies are being explored:
    - Direct observation of the decay vertex and indirect detection via scattering on atoms
- **Switzerland** is ideally placed to pursue these searches but should fight to maintain its lead

Thanks

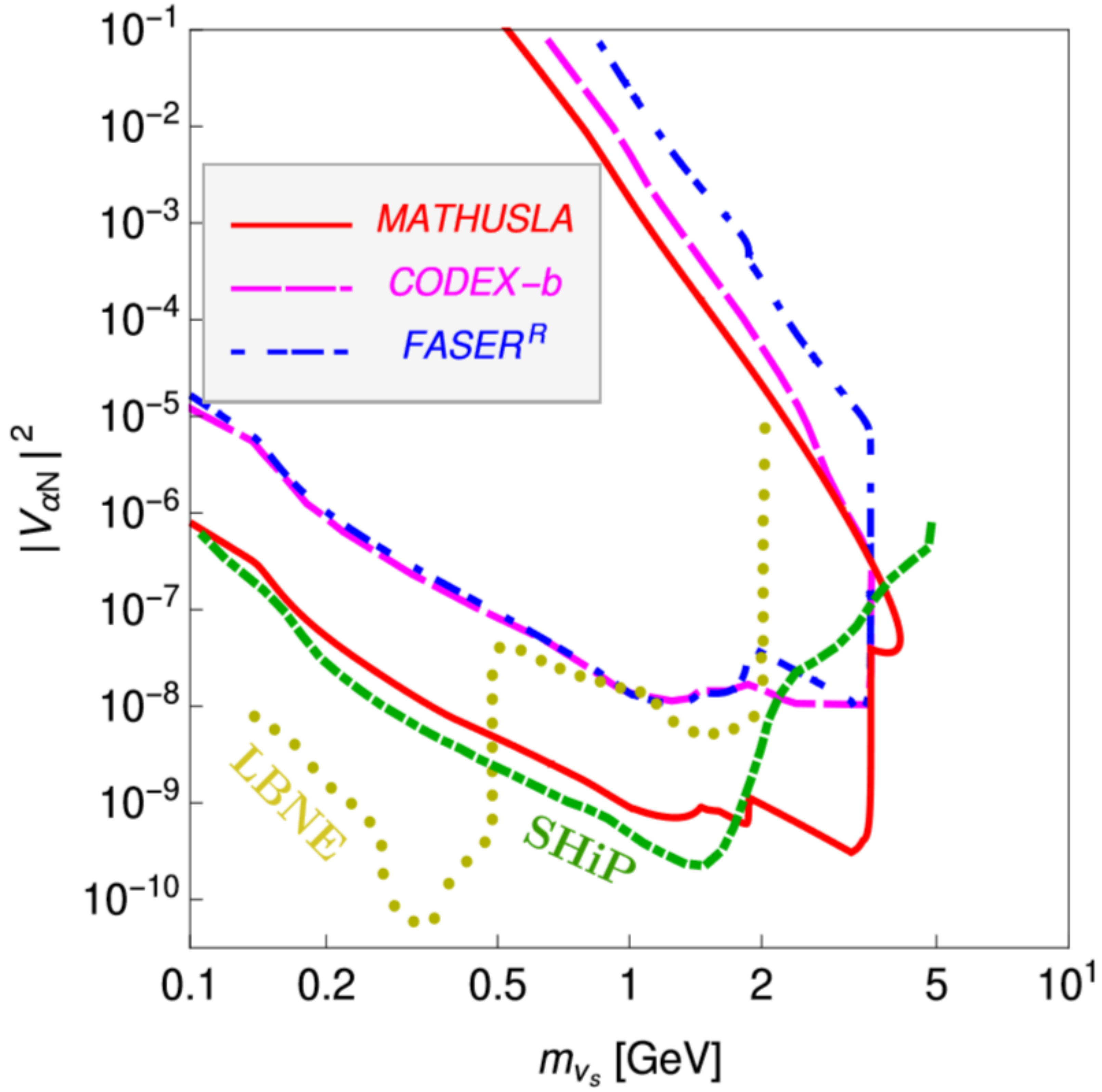
Federico Leo Redi

BKUP / MATHUSLA / expected sensitivities



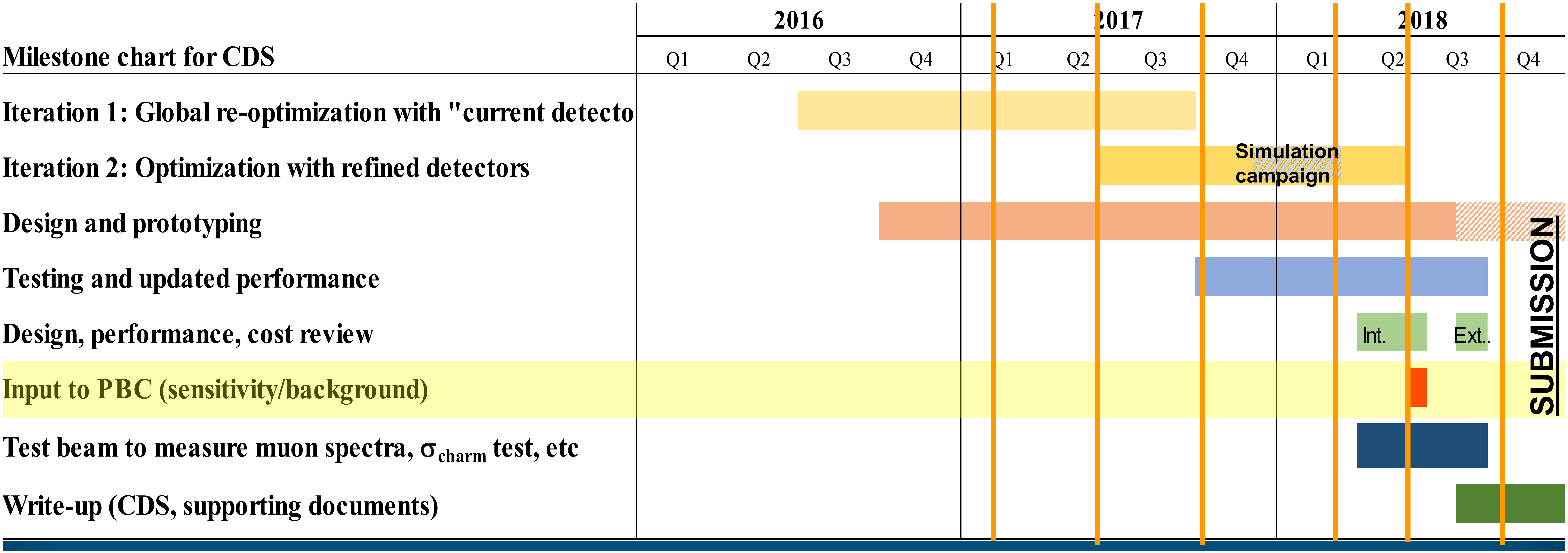
[1708.08503]

- **LEFT**: Constraints on light Higgs- mixed scalars
- **RIGHT**: Sensitivities to HNL of different experiments
- Number of B and D is inferred for 3 invab of L collected, using eta of LHCb
- **But** number of B and D mesons, obtained in this way is **wrong**: overestimated!
- Assumed with a background free experiment
- **But** this must be backed up by robust simulation



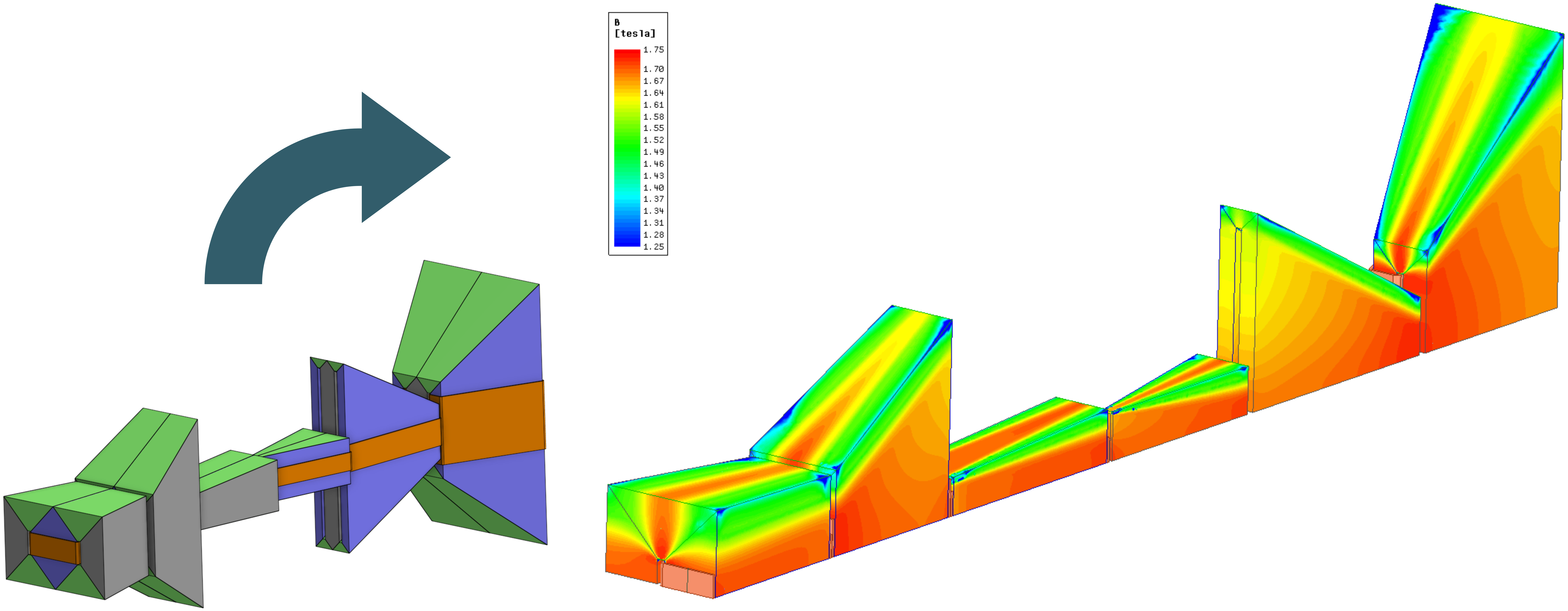
[1803.02212]

SHiP so far



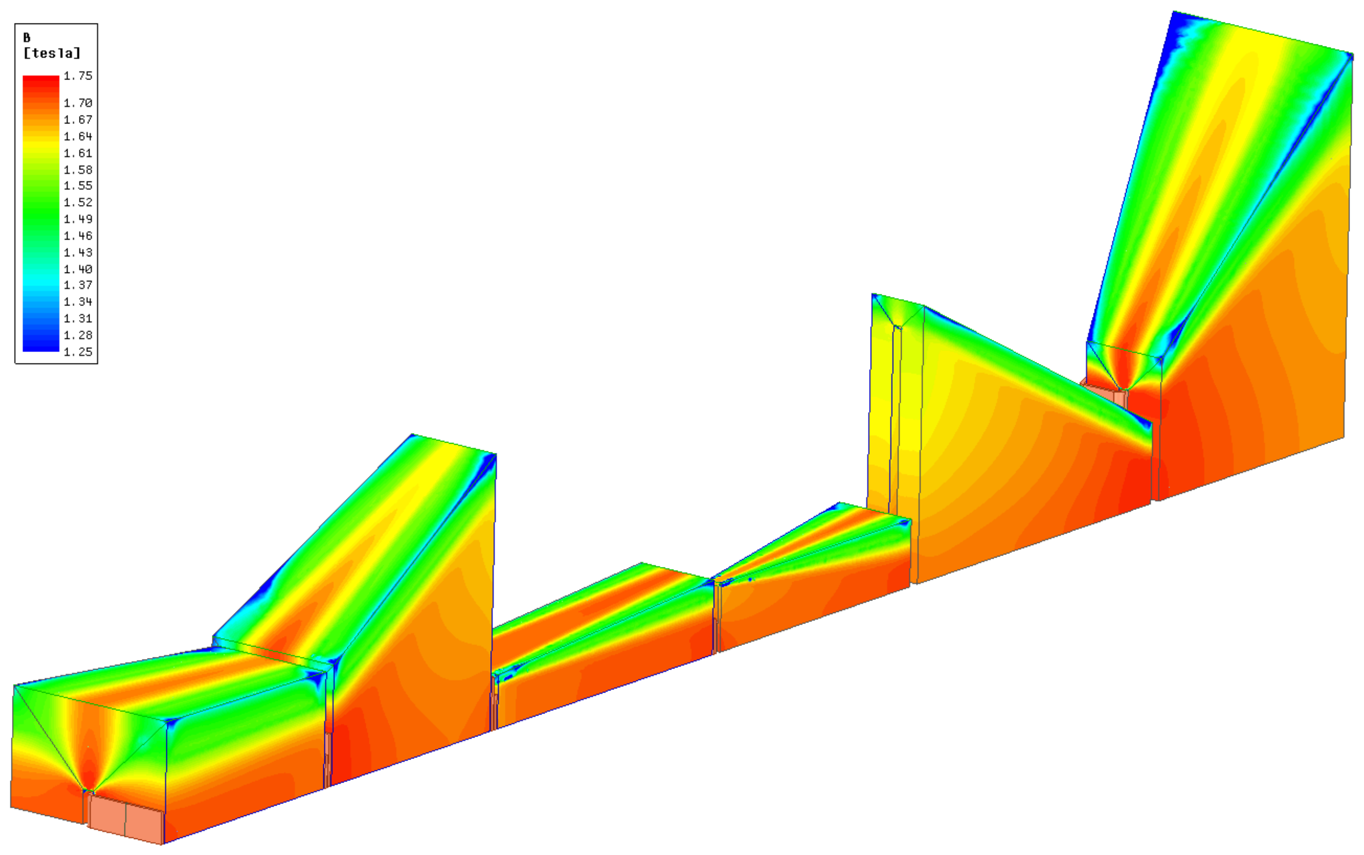
Milestone chart for CDS
2016
2017
2018
Q1
Q2
Q3
Q4
Q1
Q2
Q3
Q4
Q1
Q2
Q3
Q4
Iteration 1: Global re-optimization with "current detecto
Iteration 2: Optimization with refined detectors
Simulation campaign
Design and prototyping
Testing and updated performance
Design, performance, cost review
Int.
Ext..
Input to PBC (sensitivity/background)
Test beam to measure muon spectra, σ_{charm} test, etc
Write-up (CDS, supporting documents)
SUBMISSION

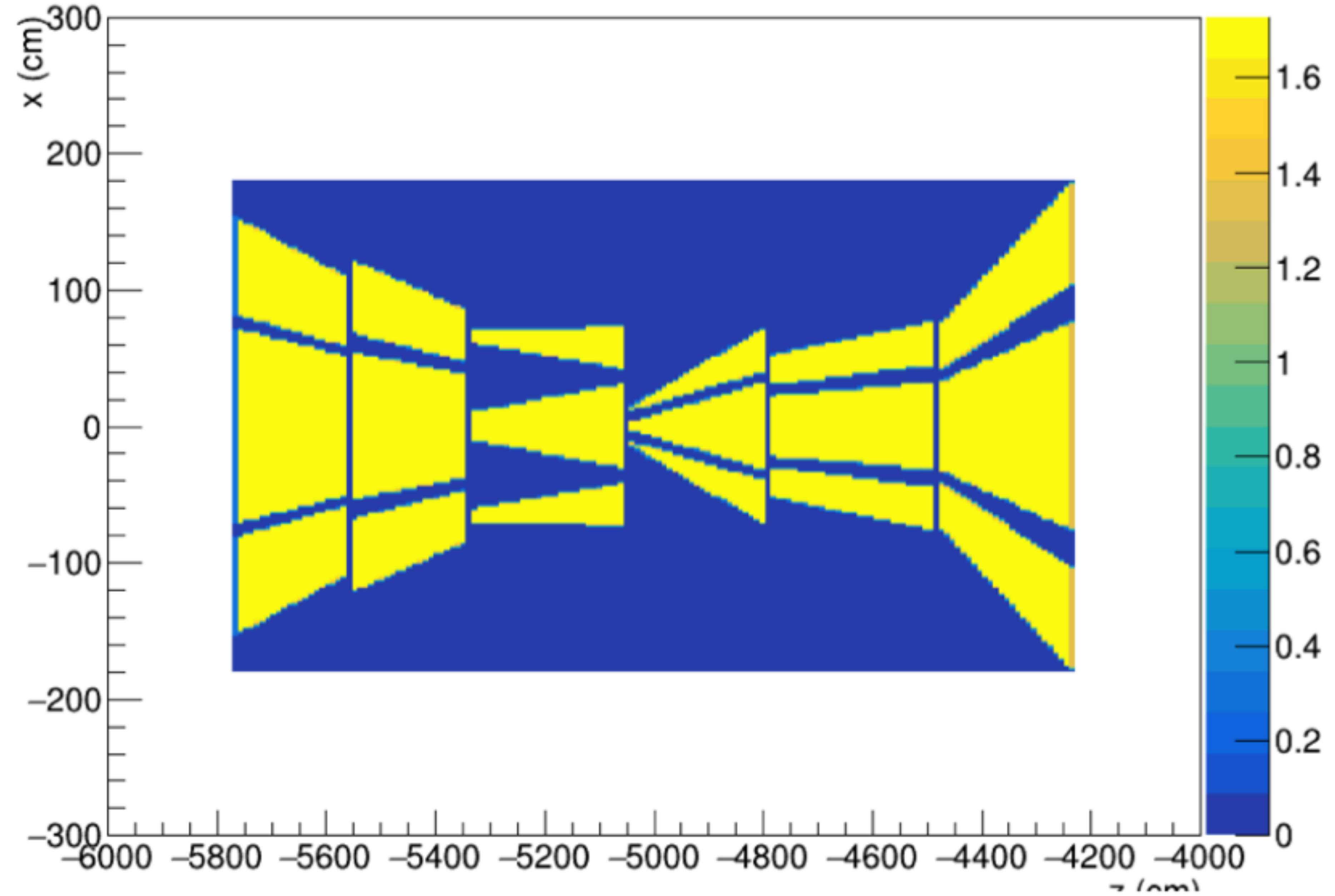
SHiP / a realistic magnetic field

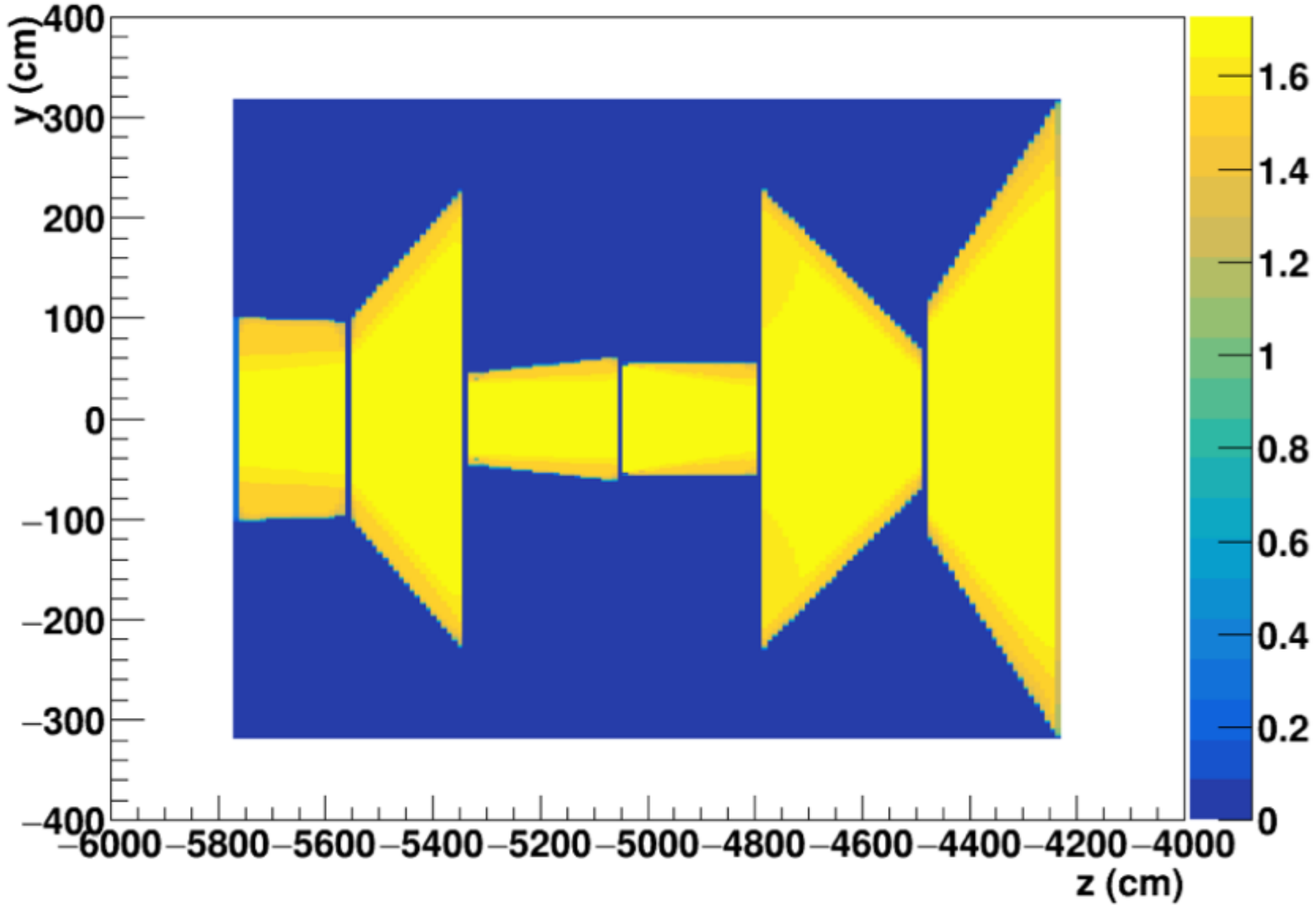


Work of F. Ratnikov (YANDEX)

SHiP / Last step, back in our simulation!

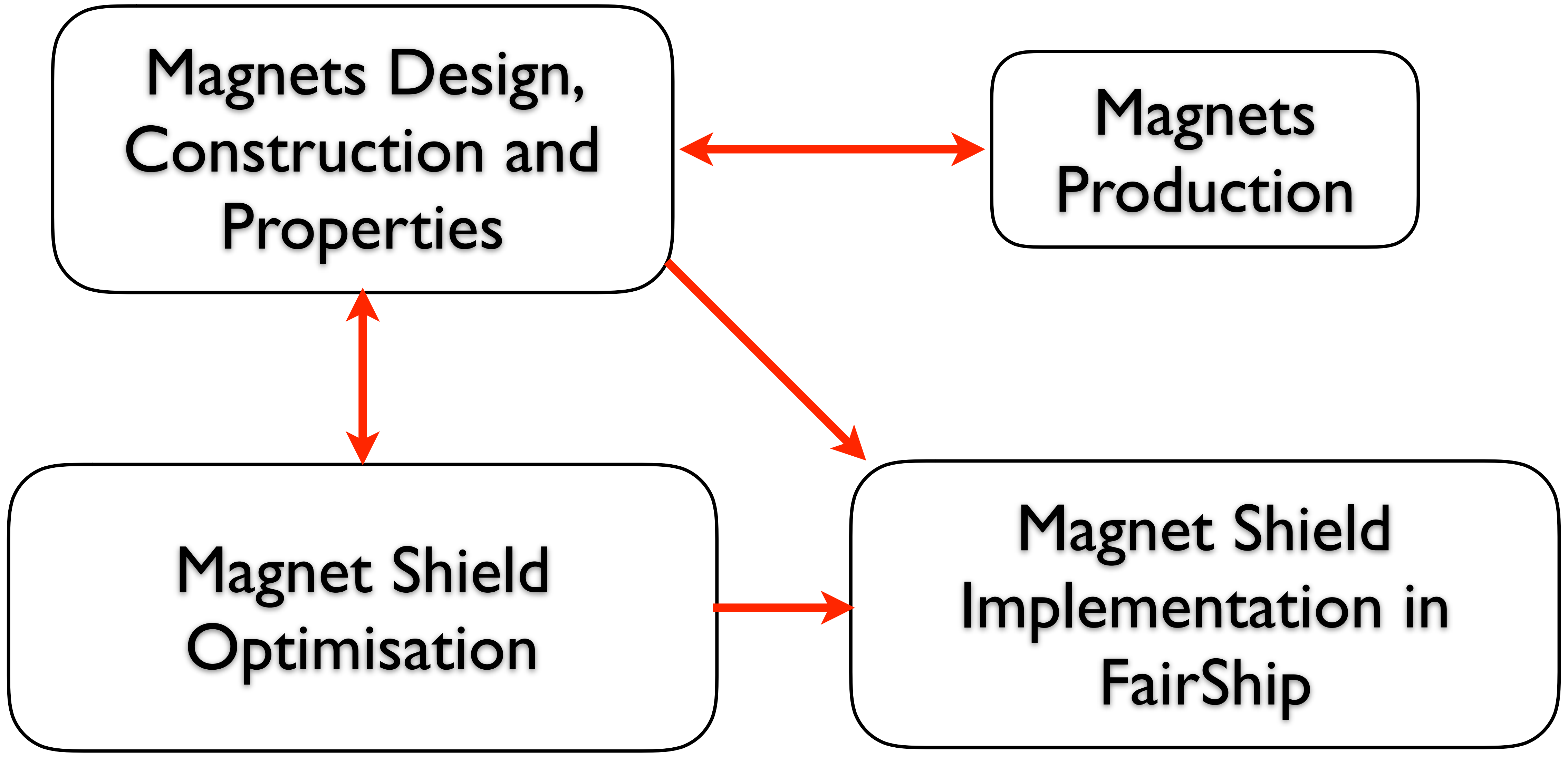






- Using a 2.5 cm map grid (positive quadrant)
- Field map is pretty close to the ideal presentation and edge effects are on distances < ~10 *cm*

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