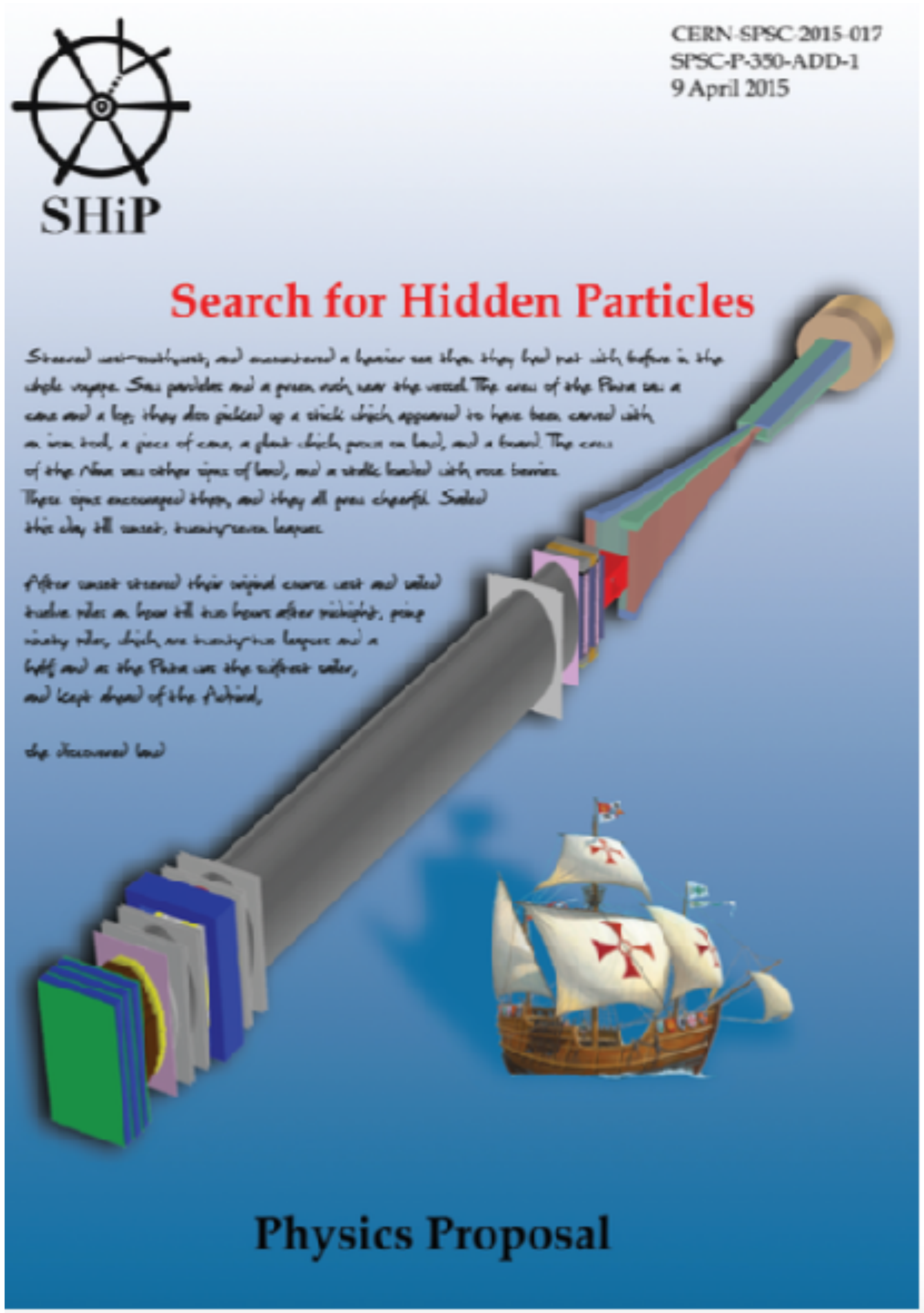
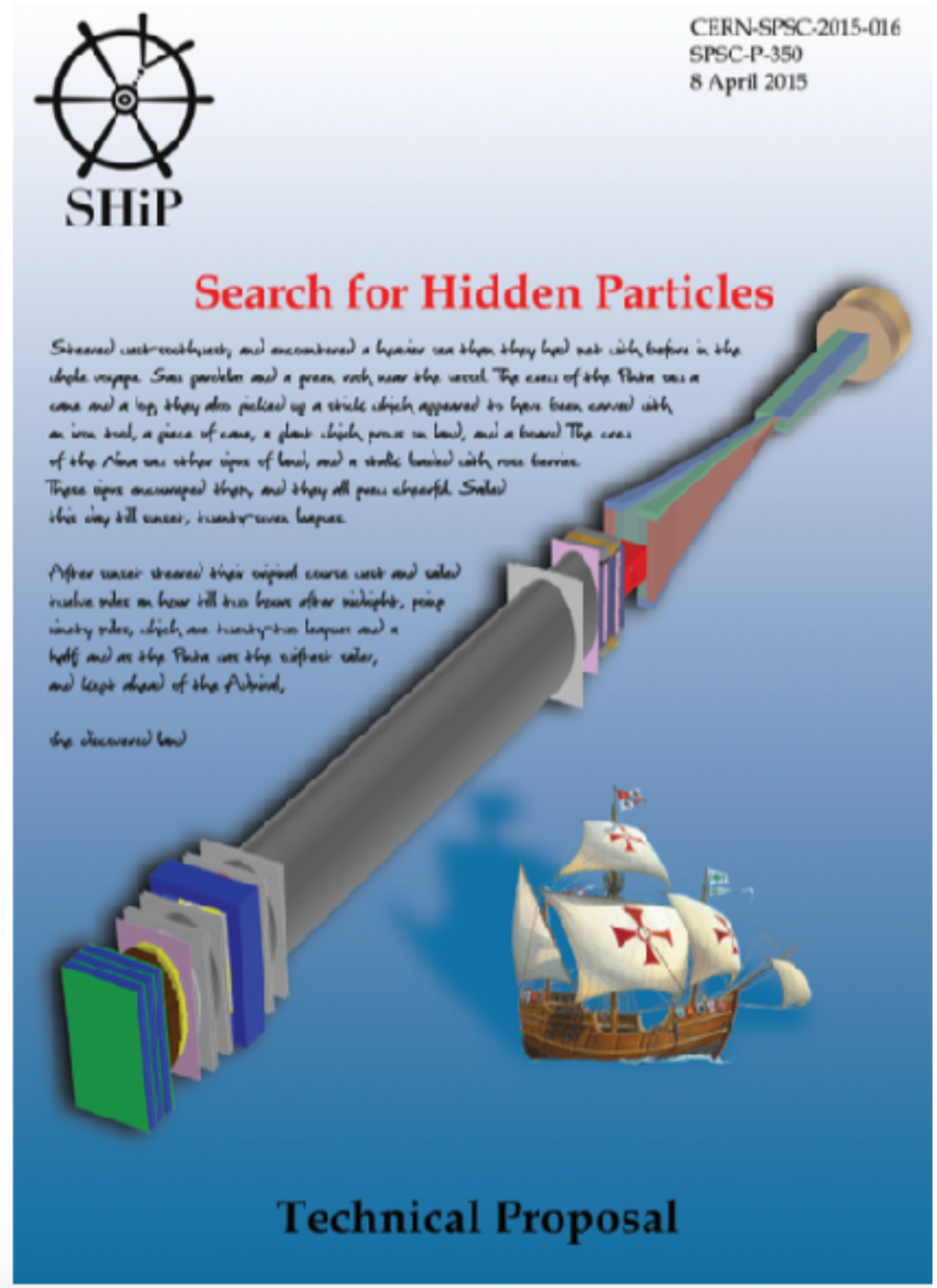
SHiP

Search for Hidden Particles

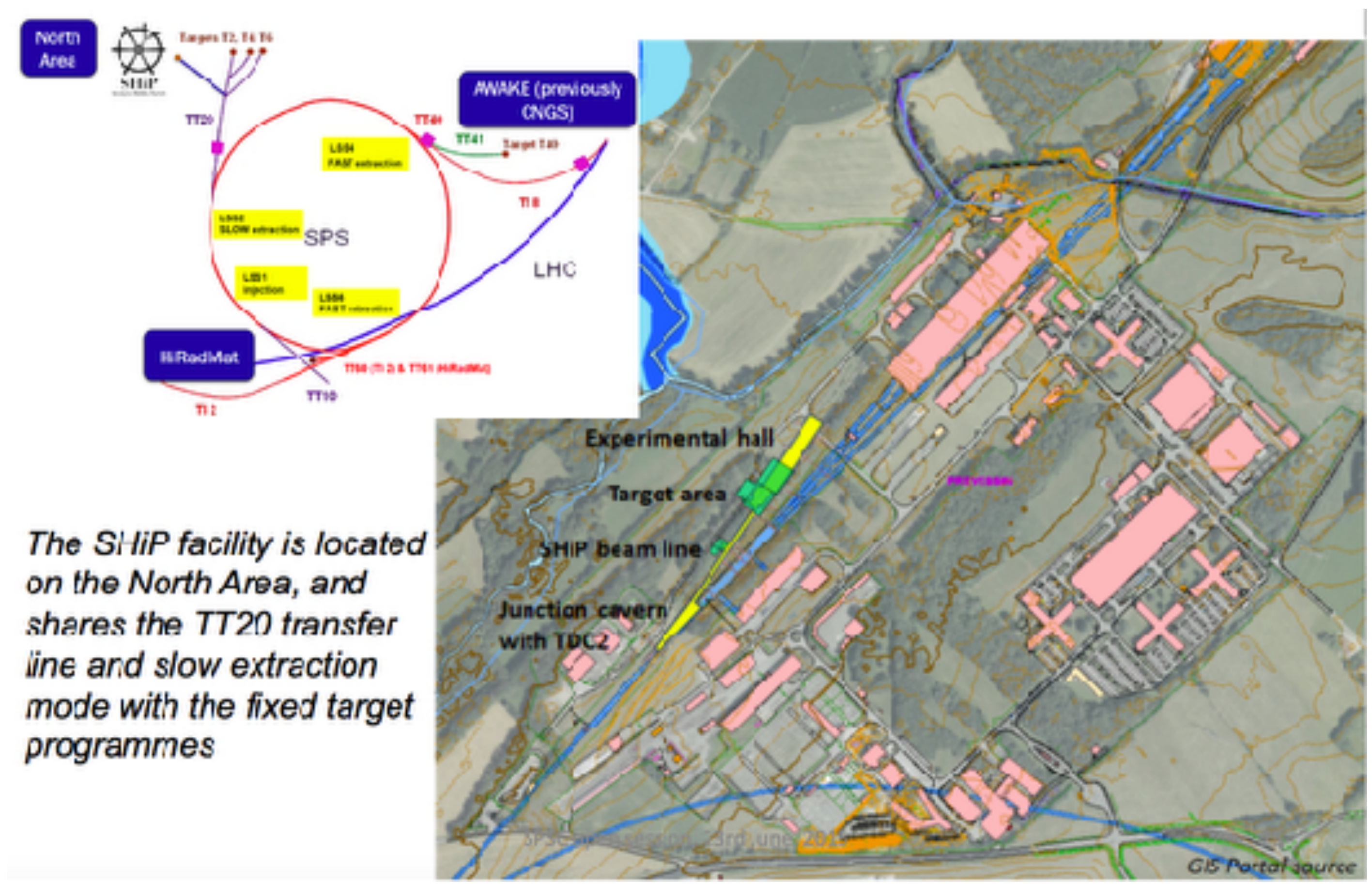
by Walter M. Bonivento


CERN-SPSC-2015-017
SPSC-P-350-ADD-1
9 April 2015
SHiP
Search for Hidden Particles
Physics Proposal


CERN-SPSC-2015-016
SPSC-P-350
8 April 2015
SHiP
Search for Hidden Particles
Technical Proposal

What is SHiP?

SHiP is a PROTON BEAM DUMP experiment proposed at CERN with the SPS p beam of 400GeV with 2×10^{20}pot/5 years



It would make good use of the full SPS intensity that, apart from the ~2fill/day of the LHC, is not exploited

PROTON BEAM DUMPS: THE PAST

Experiment	Location	approx. Date	Amount of Beam (10^{20} POT)	Beam Energy (GeV)	Target Mat.	Ref.
CHARM	CERN	1983	0.024	400	Cu	[16]
PS191	CERN	1984	0.086	19.2	Be	[17, 18]
E605	Fermilab	1986	4×10^{-7}	800	Cu	[19]
SINDRUM	SIN,PSI					
ν-Cal I	IHEP Serpukhov	1989	0.0171	70	Fe	[20–22]
LSND	LANSCE	1994-1995	813	0.798	H20, Cu	[23]
		1996-1998	882		W,Cu	
NOMAD	CERN	1996-1998	0.41	450	Be	[18, 24]
WASA	COSY	2010		0.550	LH2	[25]
HADES	GSI	2011	0.32pA*t	3.5	LH2,No,Ar+KCl	[26]
		2003-2008	6.27		Be	[27]
MiniBooNE	Fermilab	2005-2012	11.3	8.9	Be	[28]
		2013-2014	1.86		Steel	[29]

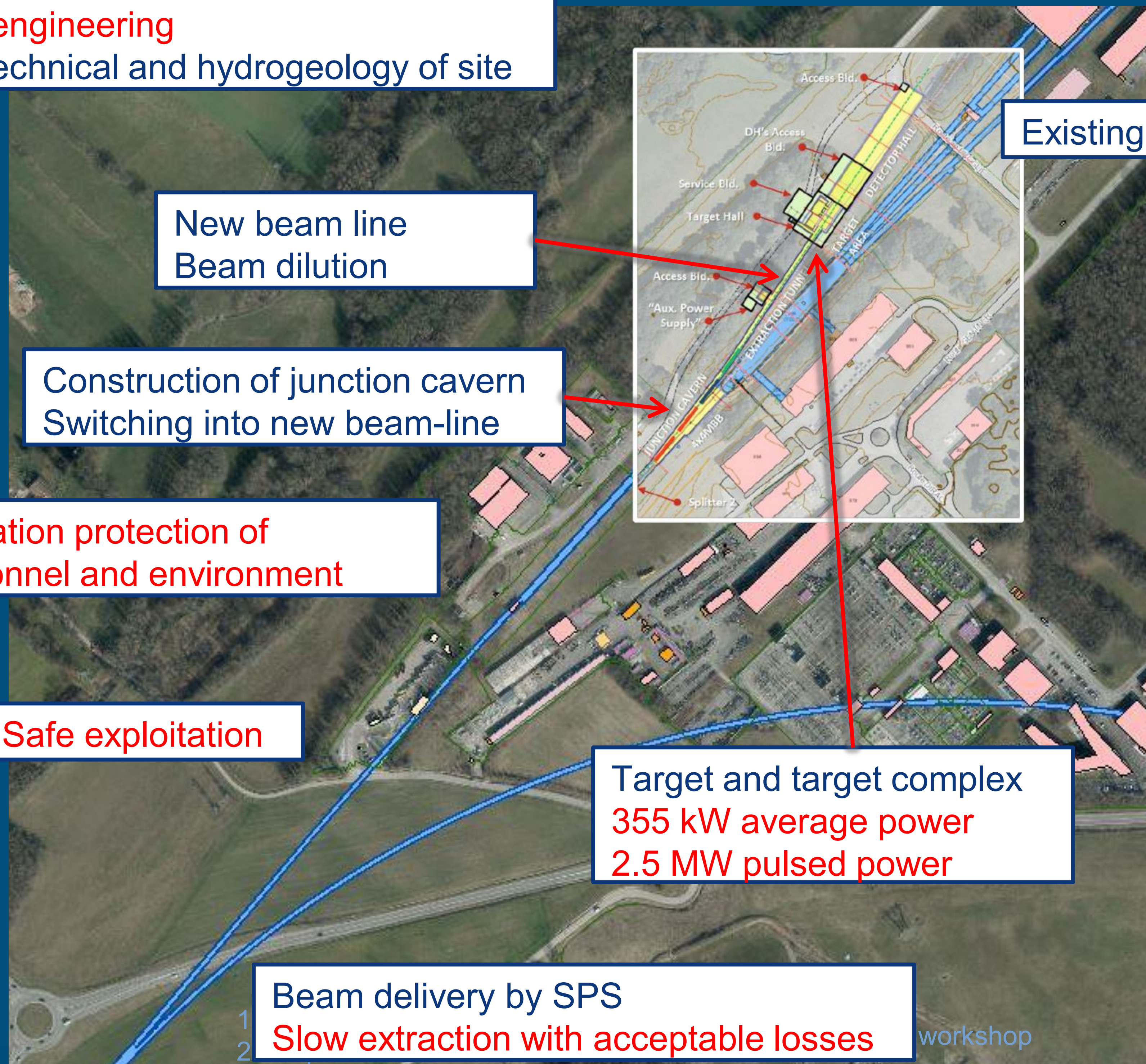
+ DONUT FNAL 3.6×10^{-3} 800 W

Figure of merit:

#(ν_τ)SHiP/DONUT=600

#(HNL)SHiP/CHARM=10k

Critical technical studies under PBC as specified in the SHiP Technical Proposal



Civil engineering
Geotechnical and hydrogeology of site

New beam line
Beam dilution

Construction of junction cavern
Switching into new beam-line

Radiation protection of personnel and environment

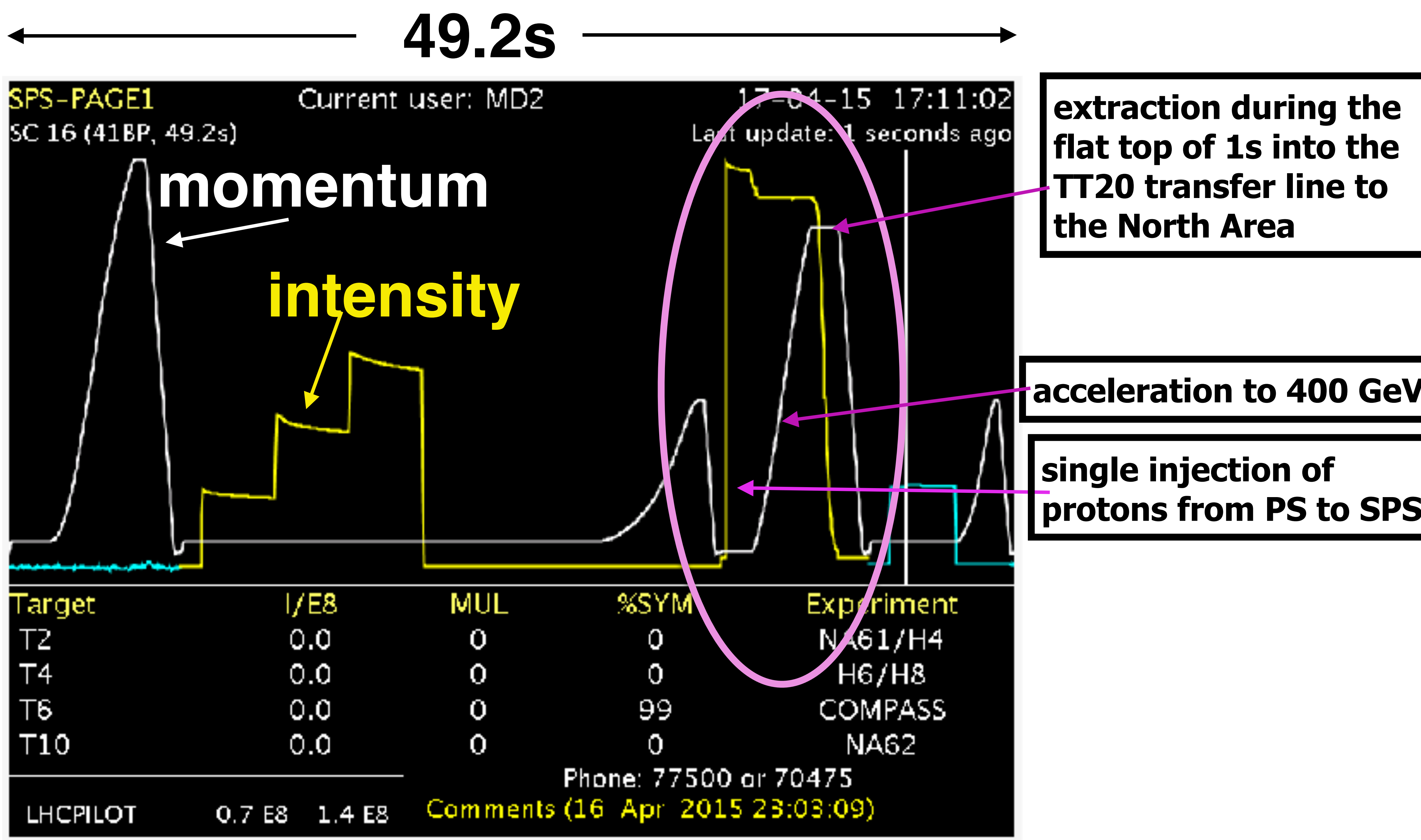
Safe exploitation

Existing users

Target and target complex
355 kW average power
2.5 MW pulsed power

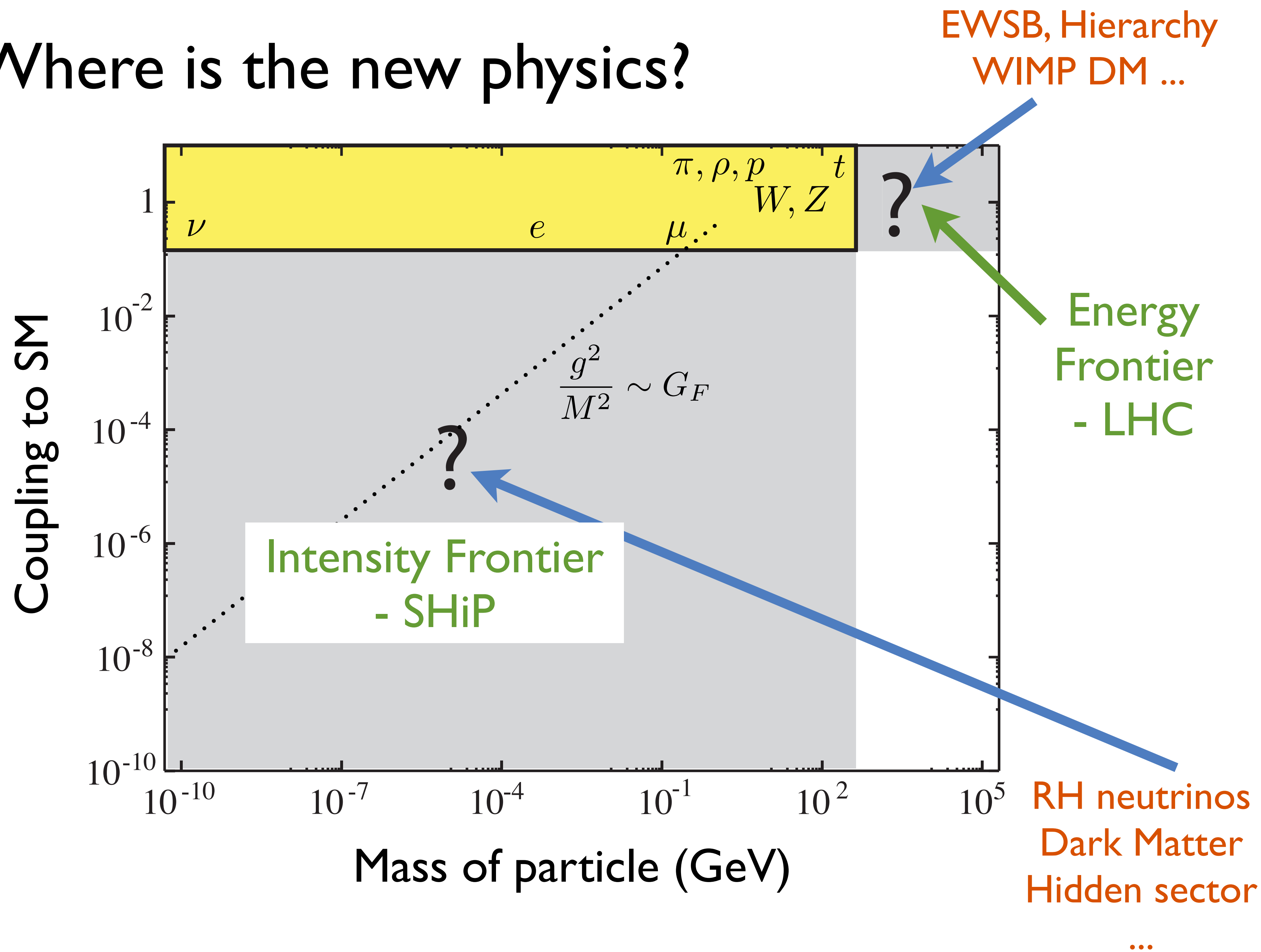
Beam delivery by SPS
Slow extraction with acceptable losses

Main new technological challenge compared to LNGS: the slow extraction of the whole SPS beam
Tested this year!



Few times 10^{12} protons/spill for a couple of hours!
The main challenge is now to go to $4x10^{13}$ protons/spill —> R&D planned

Where is the new physics?

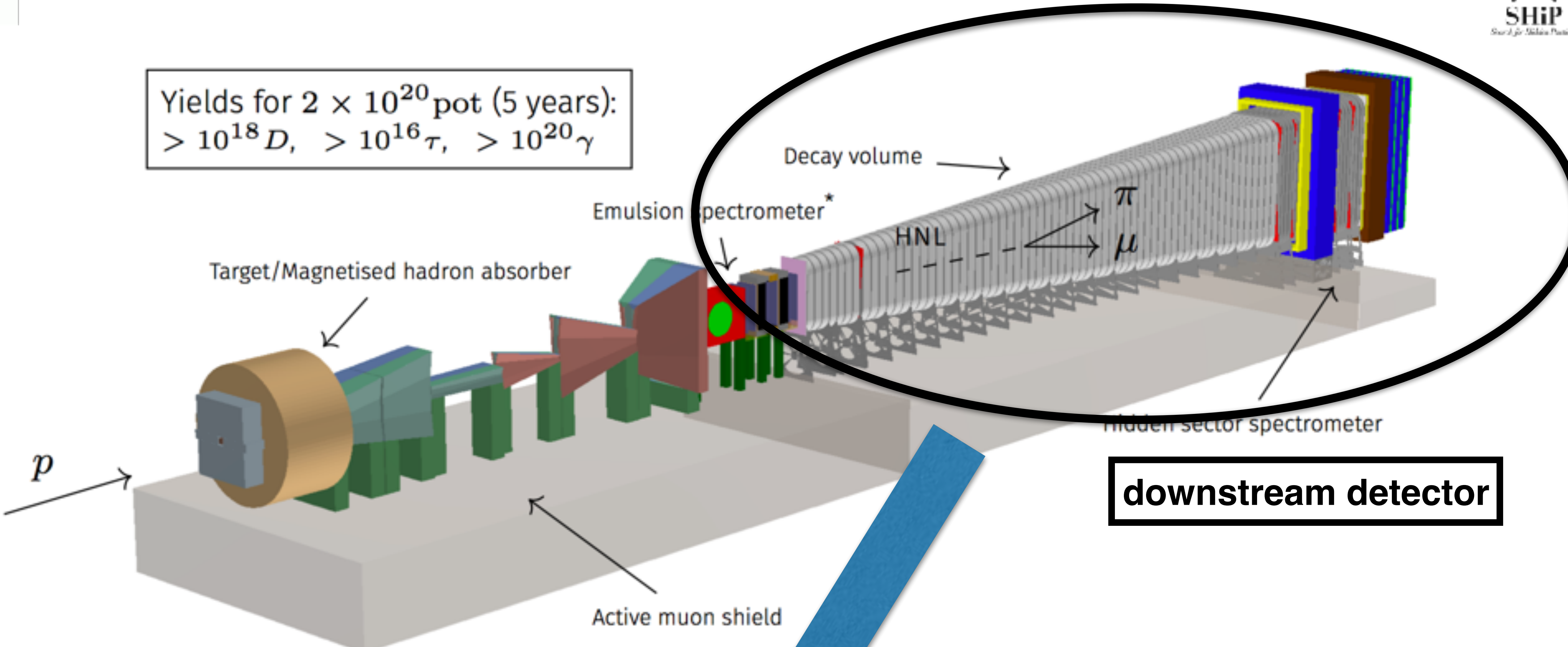


—> long lifetimes

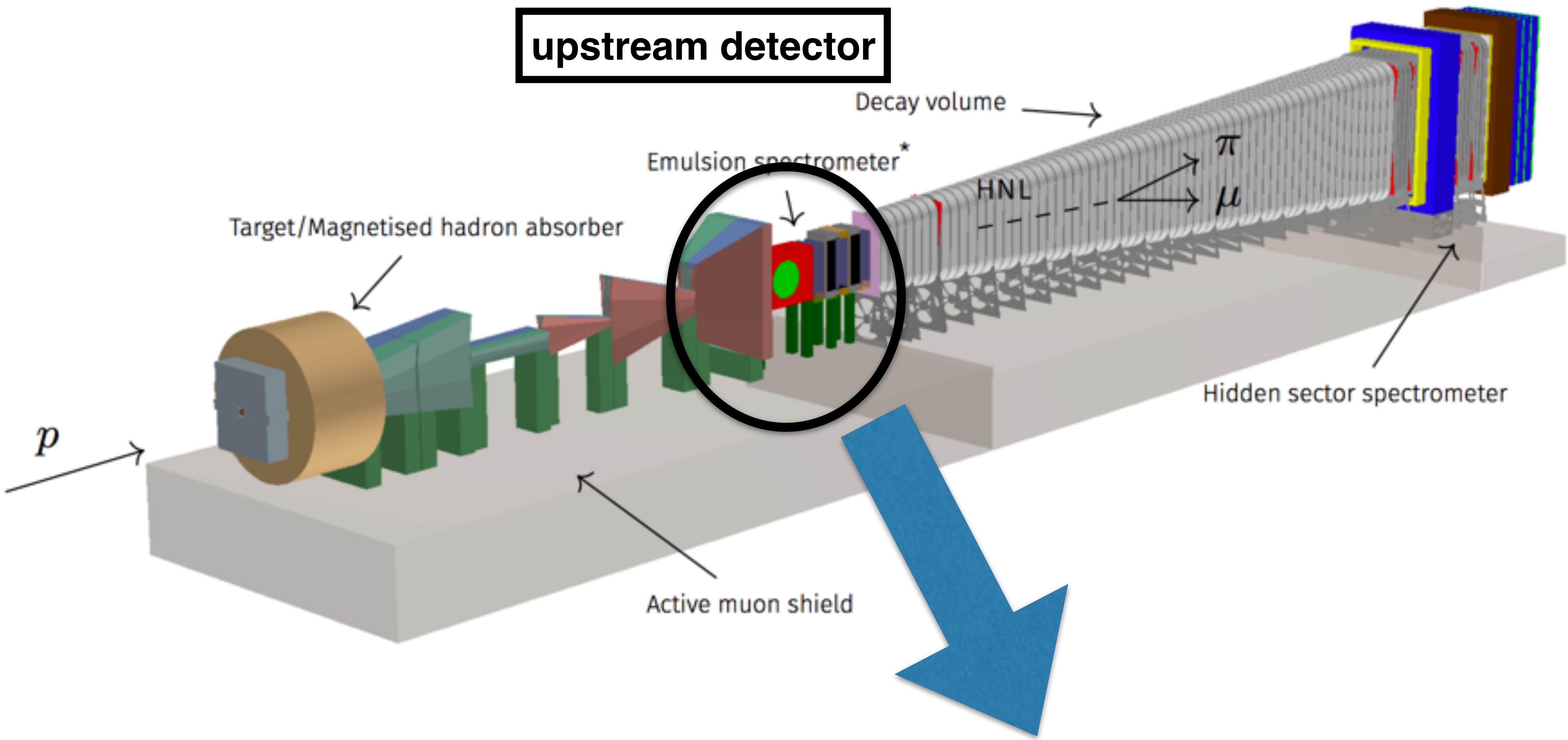
DIRECT DETECTION: long list of models that we can test in unexplored parameter domains

	Main production modes	background after selection
massive neutrinos (HNL)	c-hadron decays	0
dark photons (dark vector)	QCD	
- to SM		0
- to dark matter		≠ 0
dark scalars (dark Higgs)	b-hadron decays	0
dark pseudo-scalars (ALP, PNGB) coupling to:		
- fermions	b-hadron decays	0
- photons	Primakoff	(≠ 0)(*)
low mass SUSY	c and b hadron decays	0

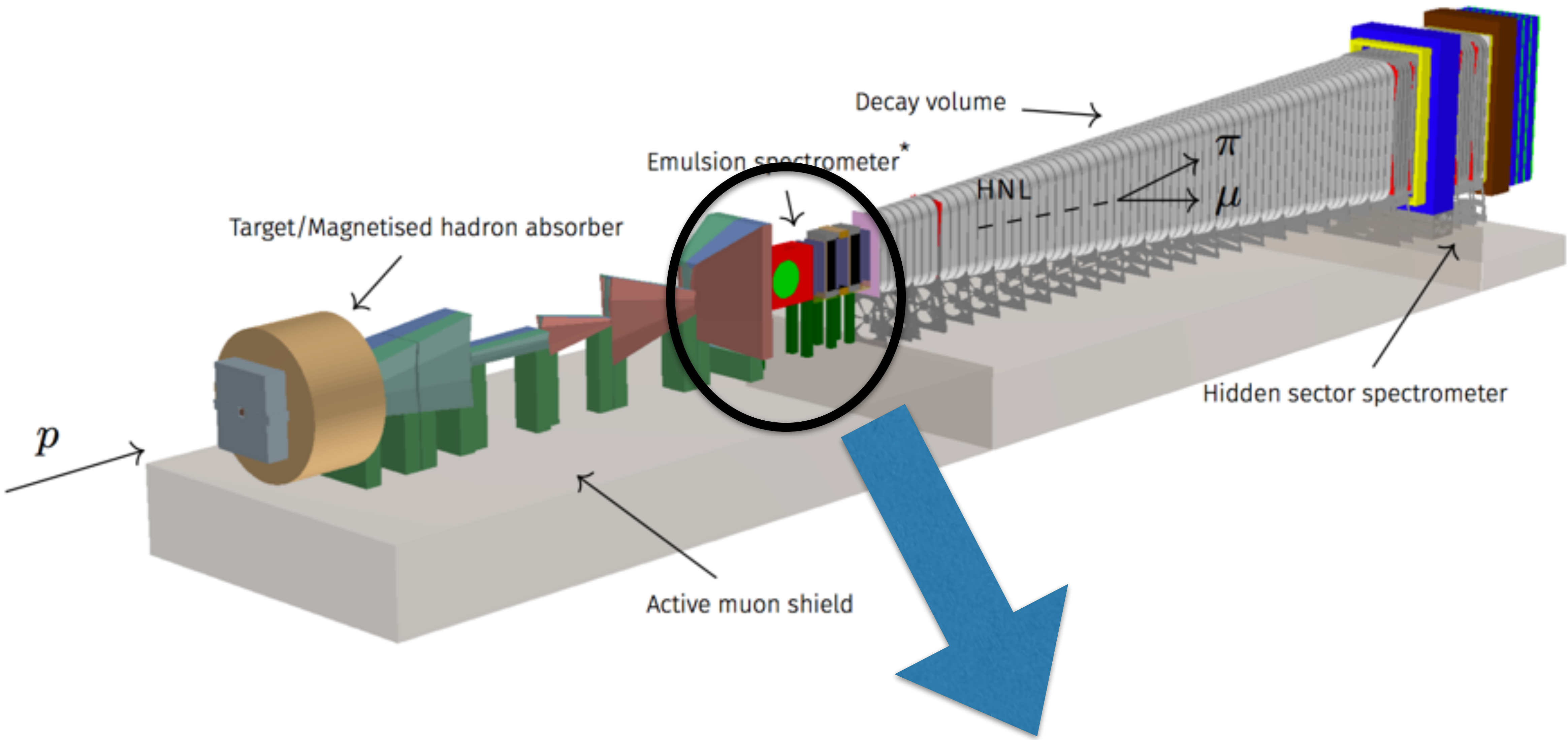
(*)under study



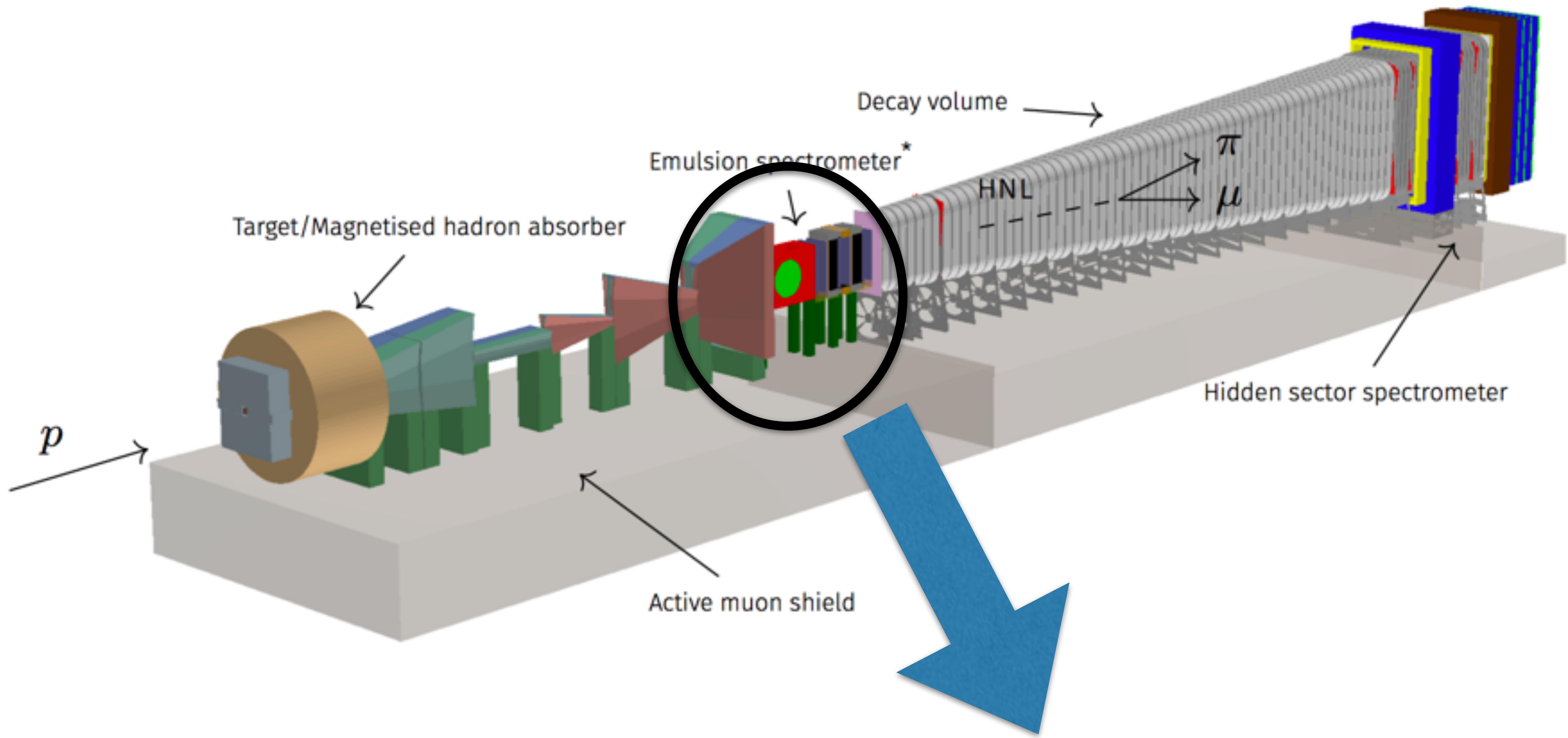
DIRECT EVIDENCE OF NP : DETECTION of long lived particles with masses below few GeV



DIRECT EVIDENCE OF NP :
DETECTION of dark matter particles with masses below few GeV



DIRECT EVIDENCE OF NP :
DETECTION of dark matter particles with masses below few GeV
+
INDIRECT EVIDENCE OF NP in ν_τ scattering: violation of lepton universality (lepto-quarks)



DIRECT EVIDENCE OF NP :
DETECTION of dark matter particles with masses below few GeV
+
INDIRECT EVIDENCE OF NP in ν scattering: violation of lepton universality (lepto-quarks)
+
new or more precise structure functions in ν scattering

Our benchmark physics

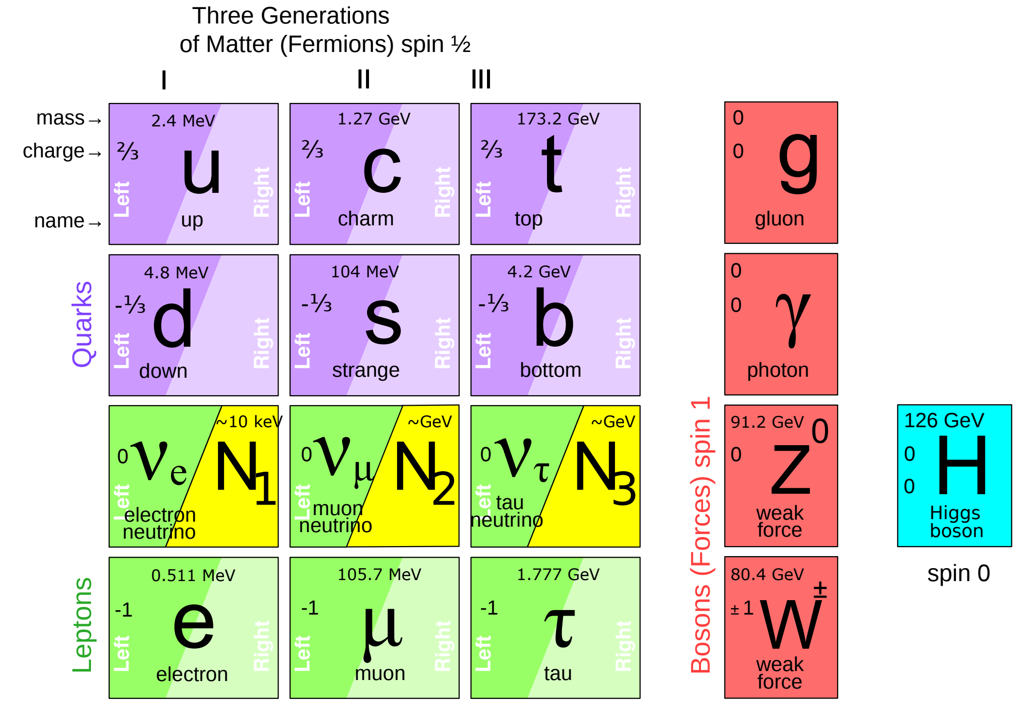
The νMSM and its fellows

3 Majorana (HNL) partners of ordinary ν, with $M_N<M_W$

In a peculiar parameter space (N_2 and N_3 almost degenerate in mass and with m=O(GeV) and N_1 decoupled with m=O(keV)), νMSM explains:

neutrino masses (see-saw), baryogenesis (via lepto-genesis) and DM (N_1)!

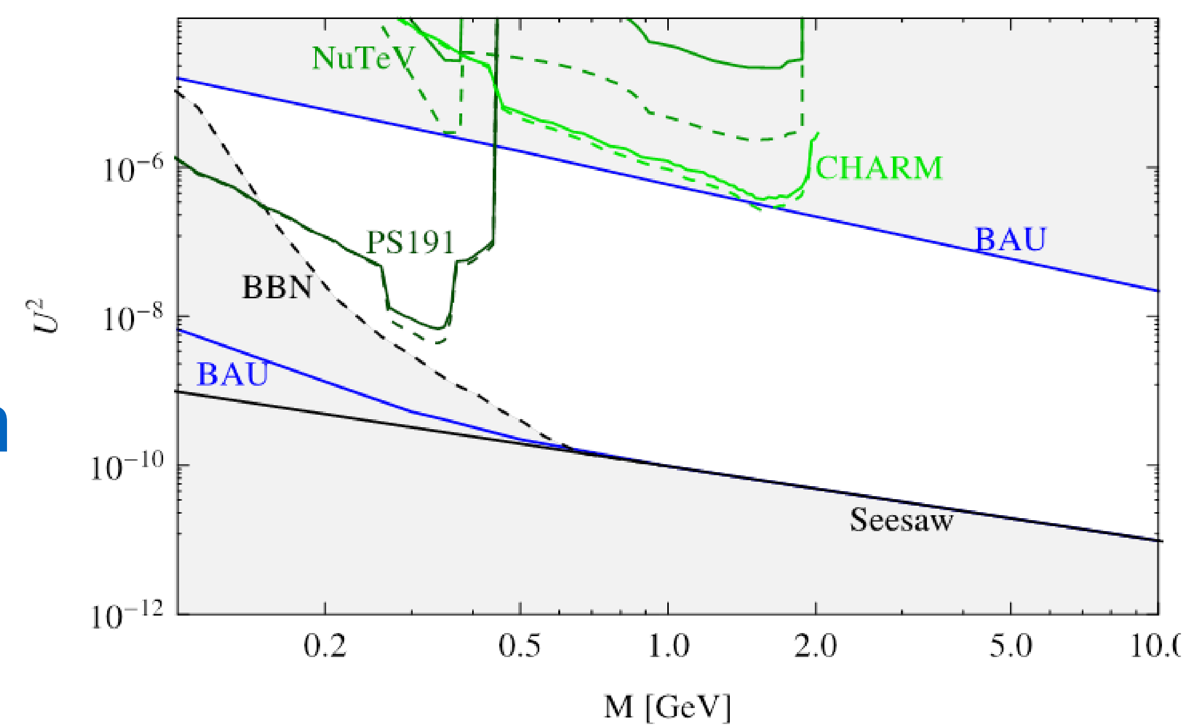
No hierarchy problem



*νMSM: T.Asaka, M.Shaposhnikov PL **B620** (2005) 17*
M.Shaposhnikov Nucl. Phys. B763 (2007) 49

$N_{2,3}$ production

inverted mass hyerarchy

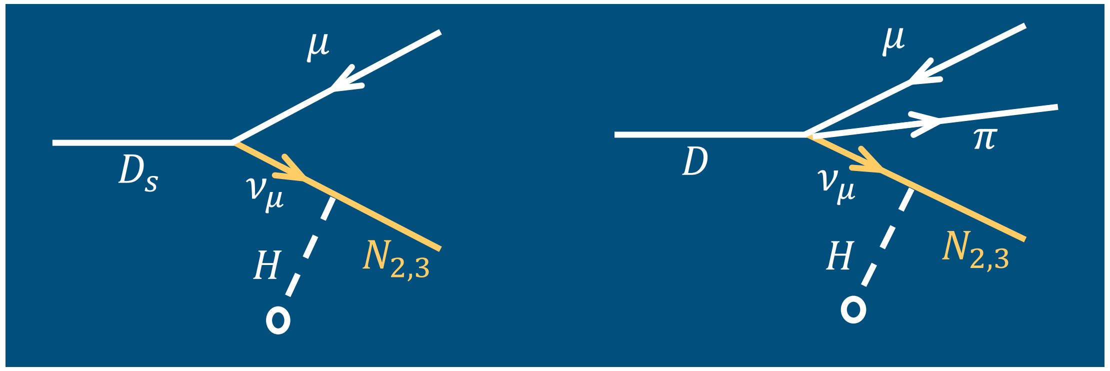


Interaction with the Higgs v.e.v. ->mixing with active neutrinos with U [2]

in the νMSM strong limitations in the parameter space (U^2,m)

a lot of HNL searches in the past but, for m>m_K, with a sensitivity not of νMSM interest

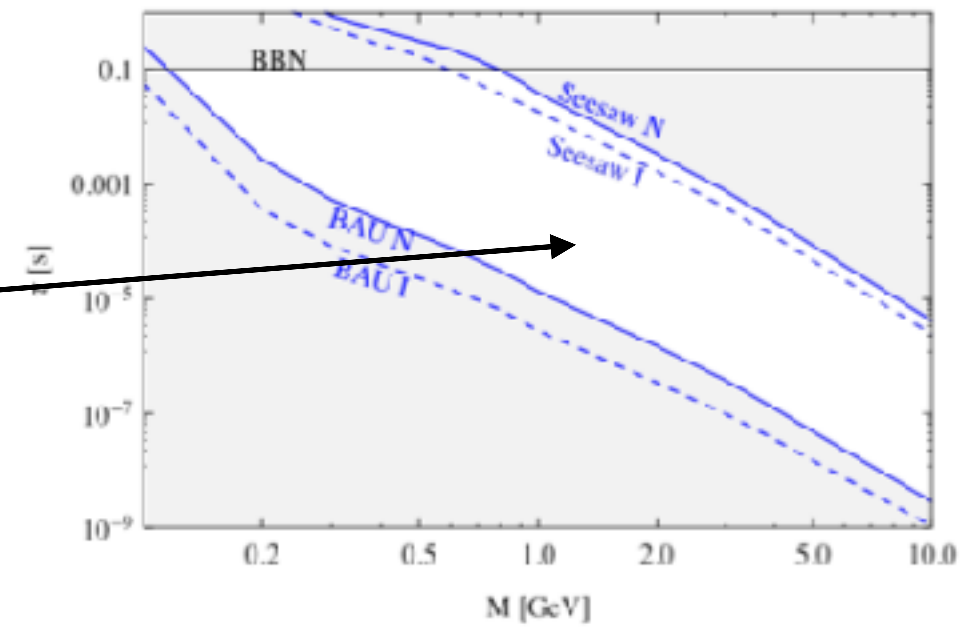
ex. meson decays —>



$N_{2,3}$ decays

very long life-time

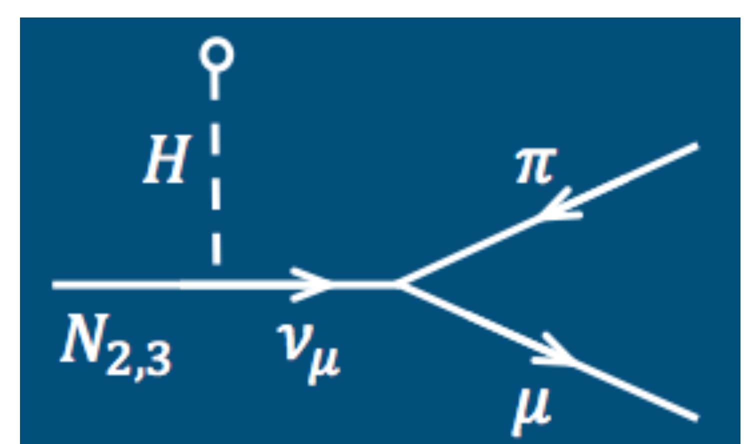
decay paths of O(km)!: for $U^2_\mu=10^{-7}$, $\tau_N=1.8\times10^{-5}$s



Various decay modes : the BR's depend on flavor mixing

Decay mode	Branching ratio
$N_{2,3} \rightarrow \mu/e + \pi$	0.1 - 50 %
$N_{2,3} \rightarrow \mu^-/e^- + \rho^+$	0.5 - 20 %
$N_{2,3} \rightarrow \nu + \mu + e$	1 - 10 %

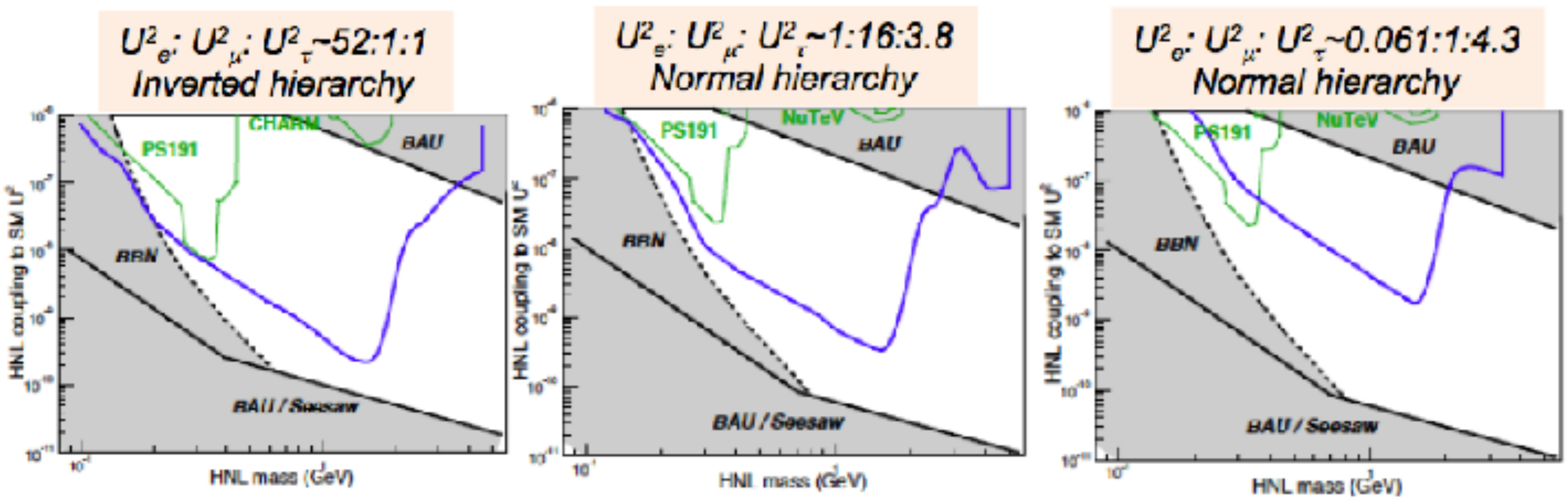
The probability that $N_{2,3}$ decays within the fiducial volume of the experiment $\propto U_\mu^2$



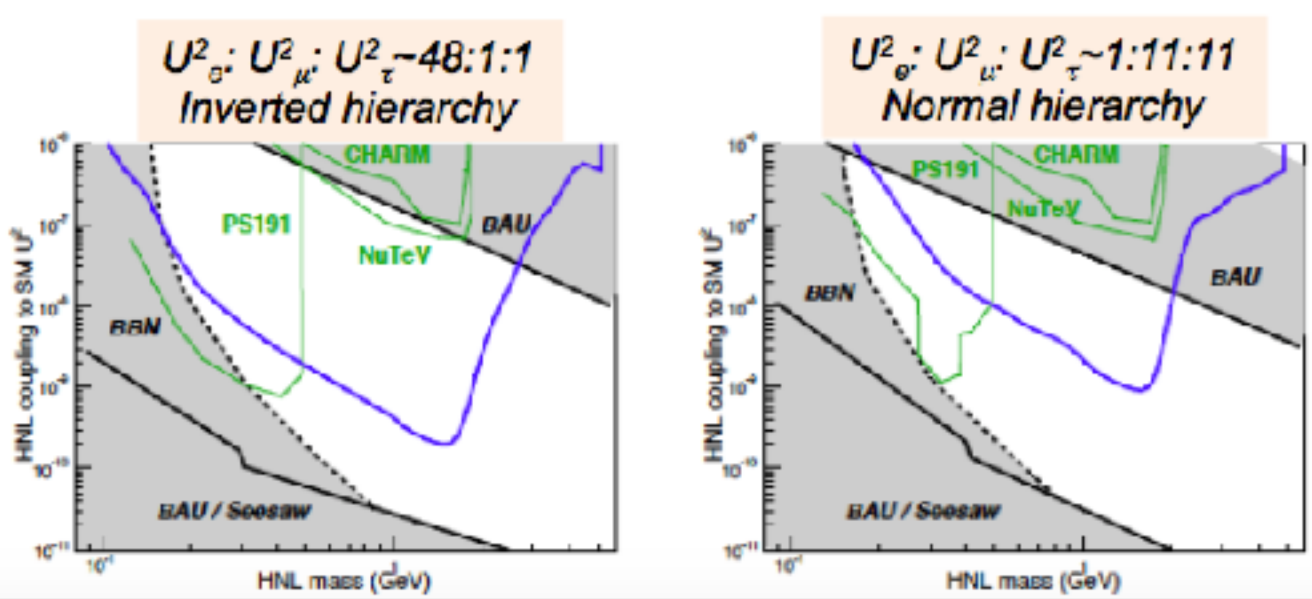
—> number of events $\propto U_\mu^4$ if N detected

SHIP sensitivity to HNL

SHIP will scan most of the cosmologically allowed (in the context of νMSM) region below the charm mass

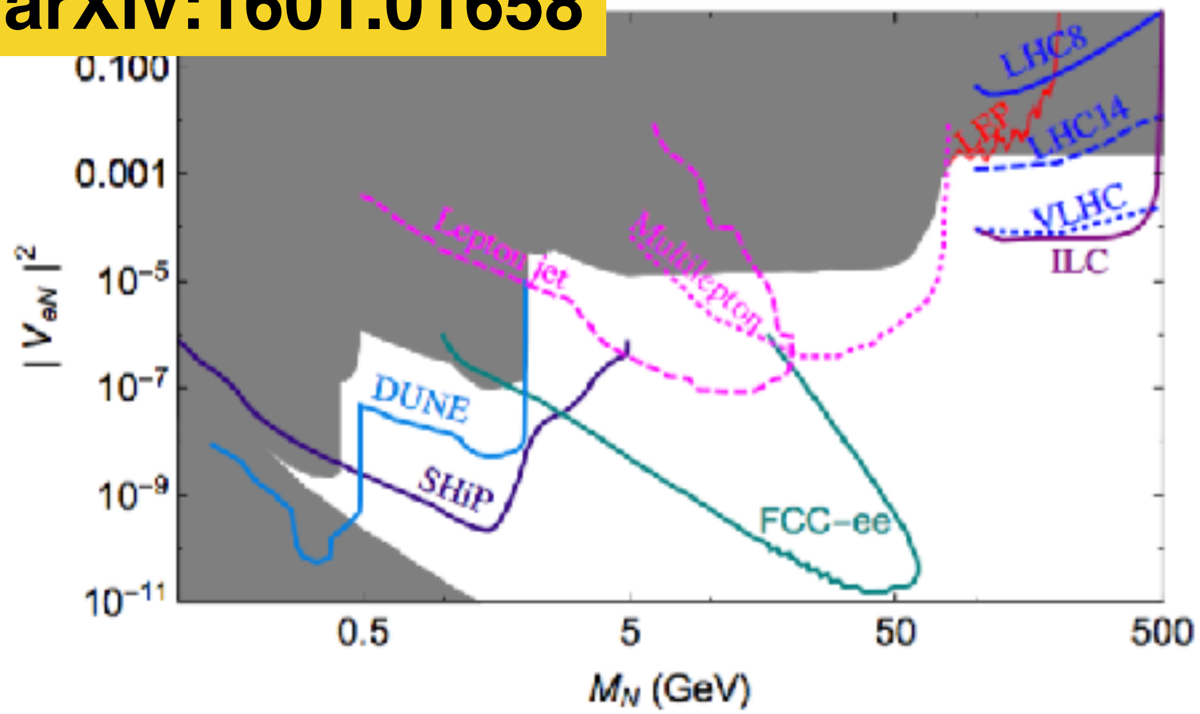


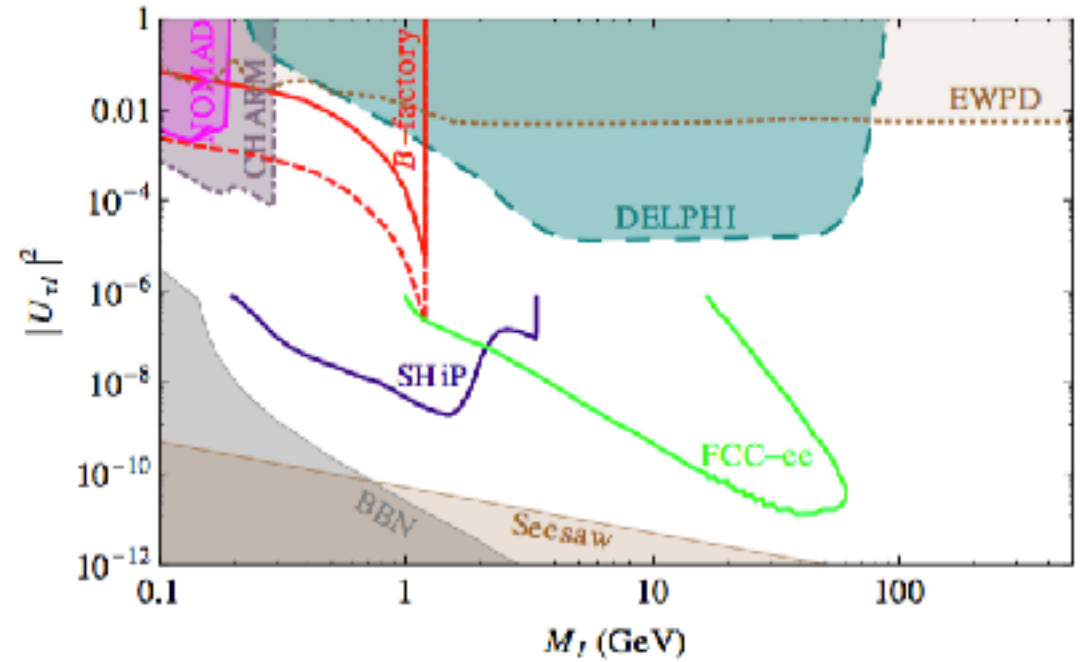
Scenarios for which baryogenesis was numerically proven

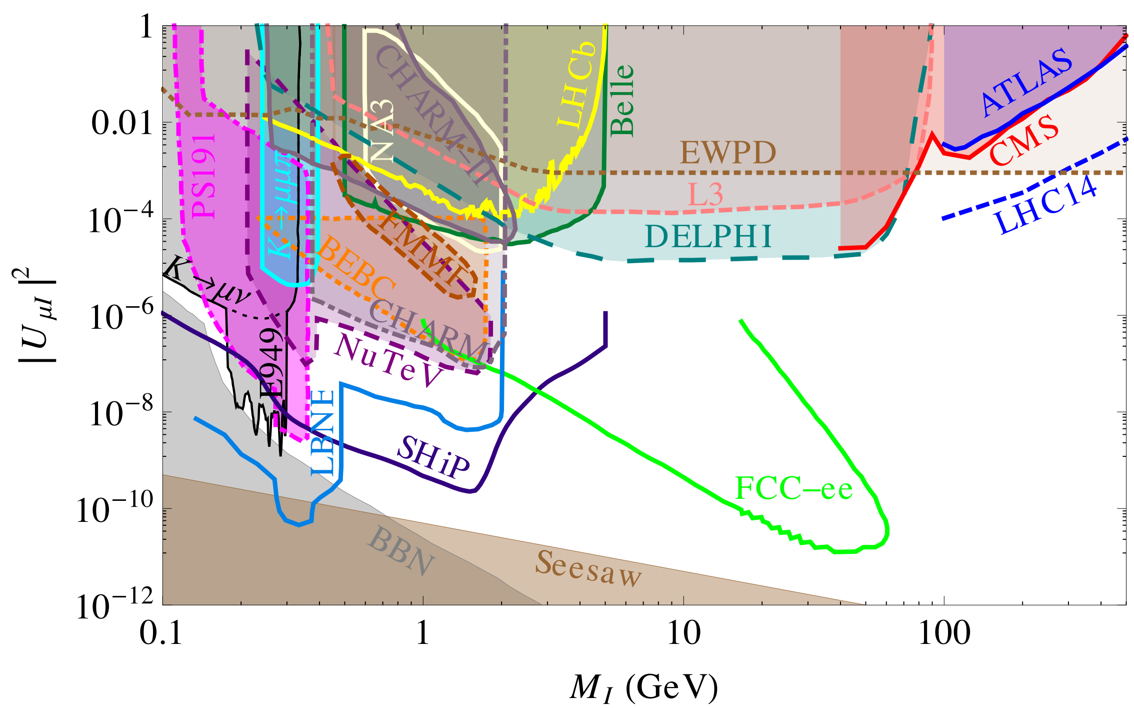


Also FCC-ee and LHC could say something

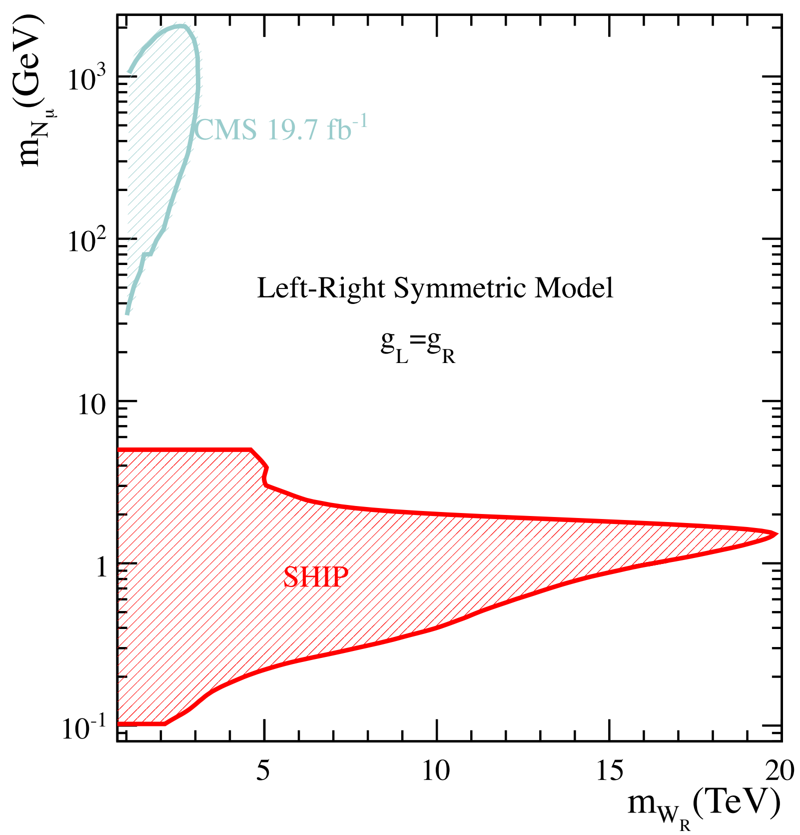
arXiv:1601.01658

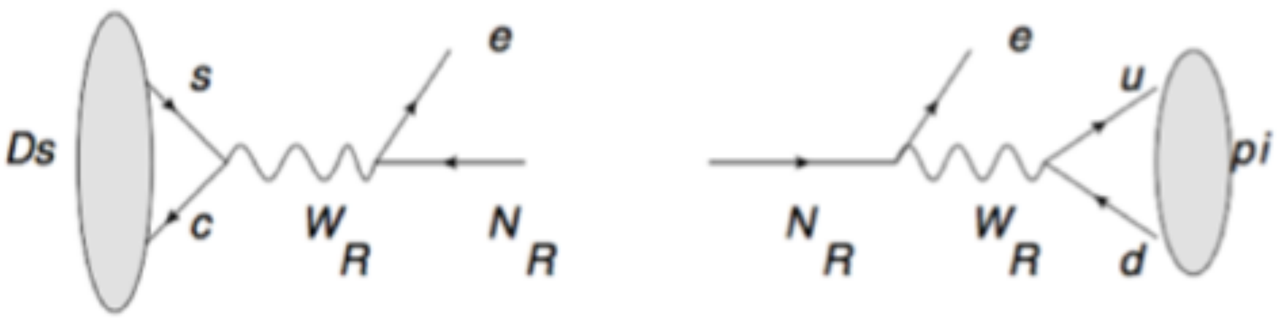




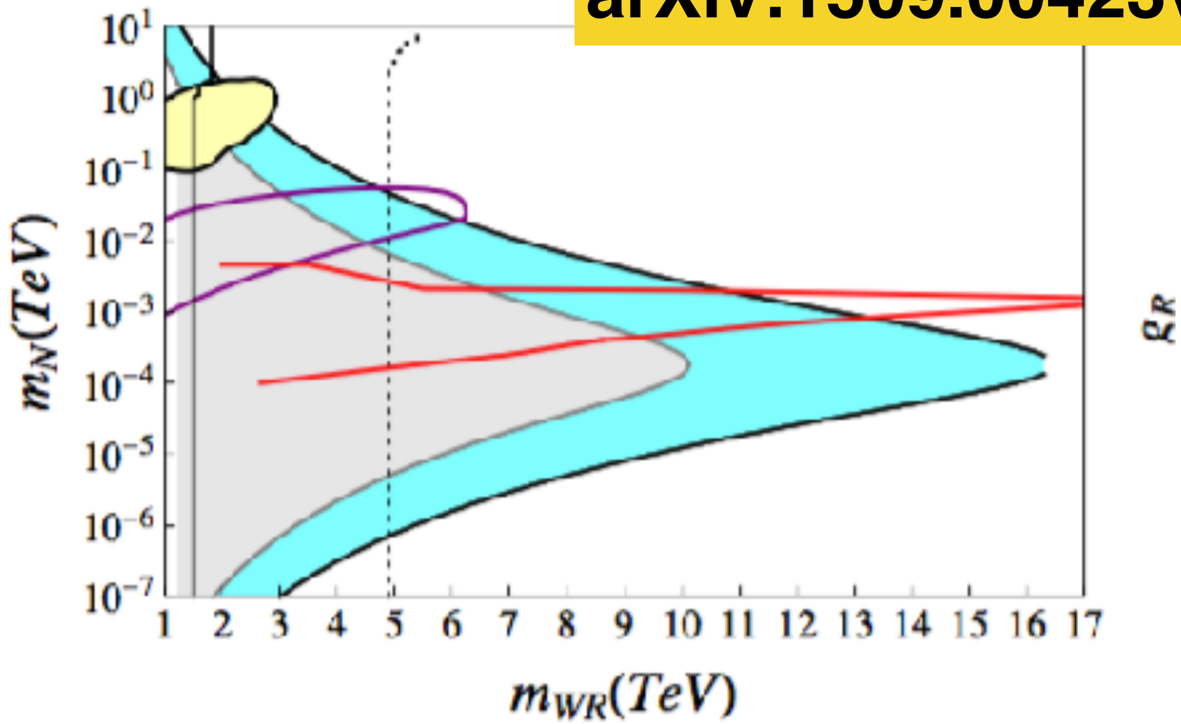


Not only νMSM for the sterile ν's (1): interpretation in the context of Left-Right symmetric model

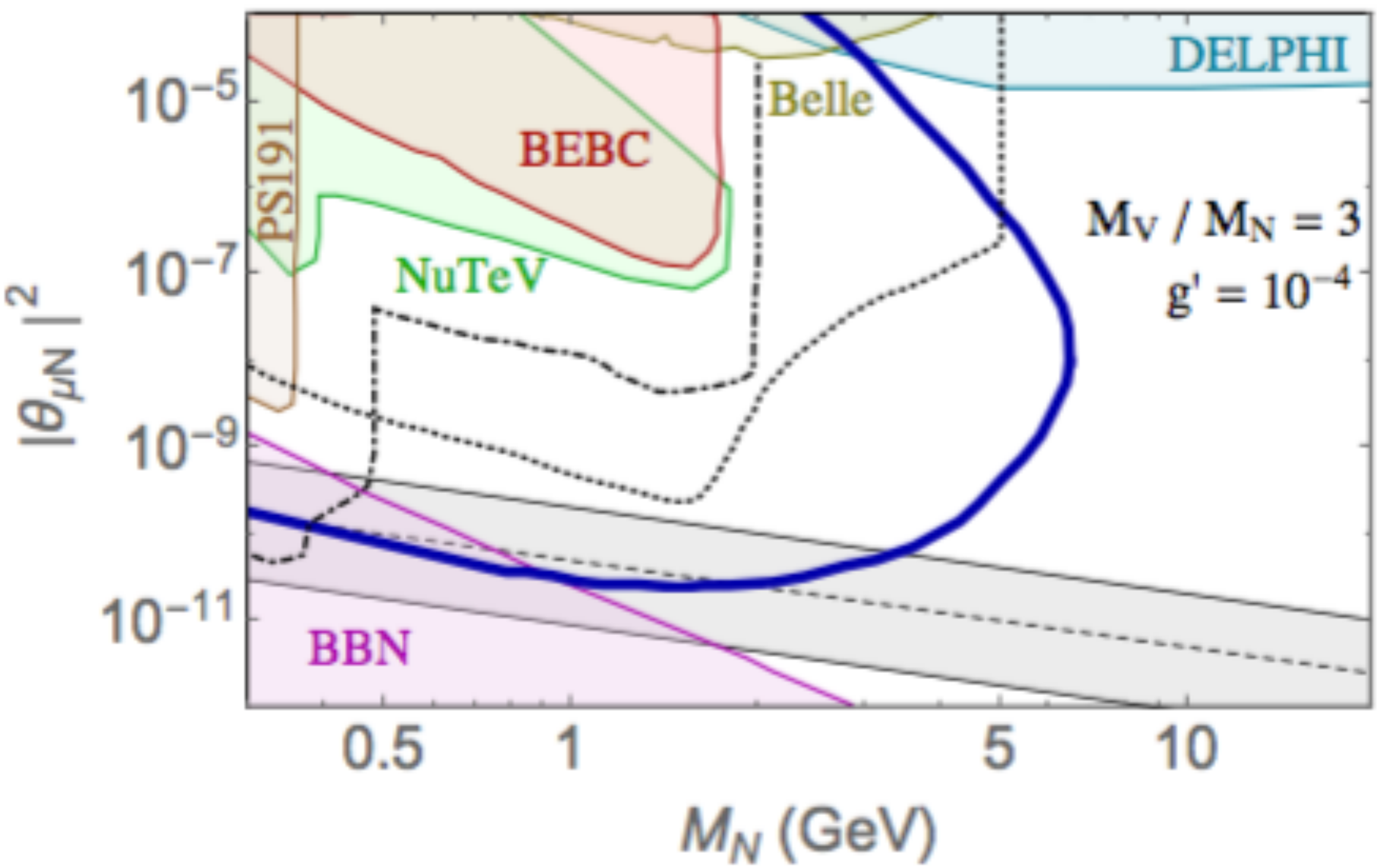


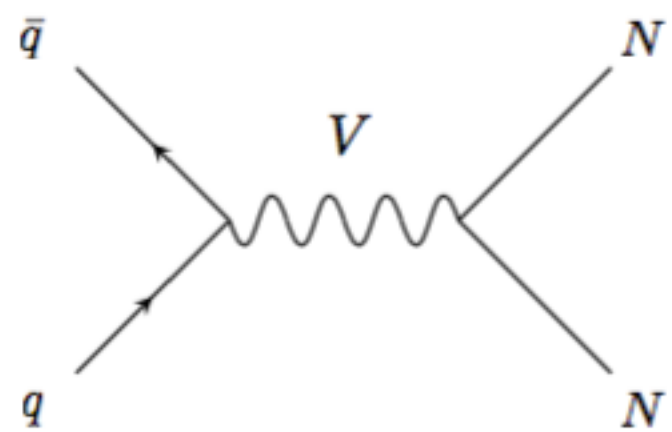


arXiv:1509.00423v1



Not only νMSM for the sterile ν's (2): enhanced sterile ν production via **new dark gauge force, e.g B-L gauge symmetry**



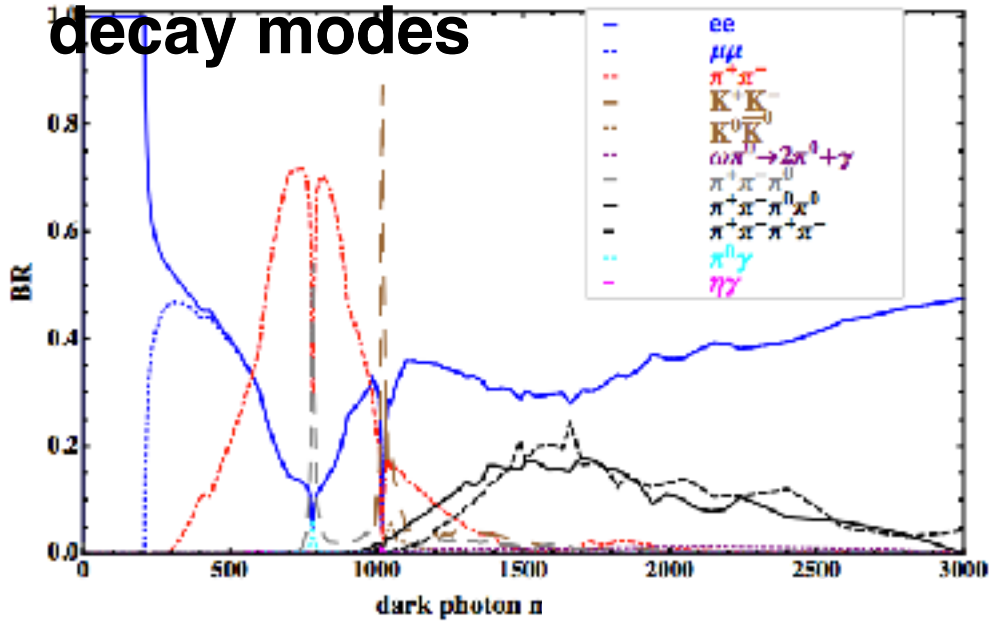


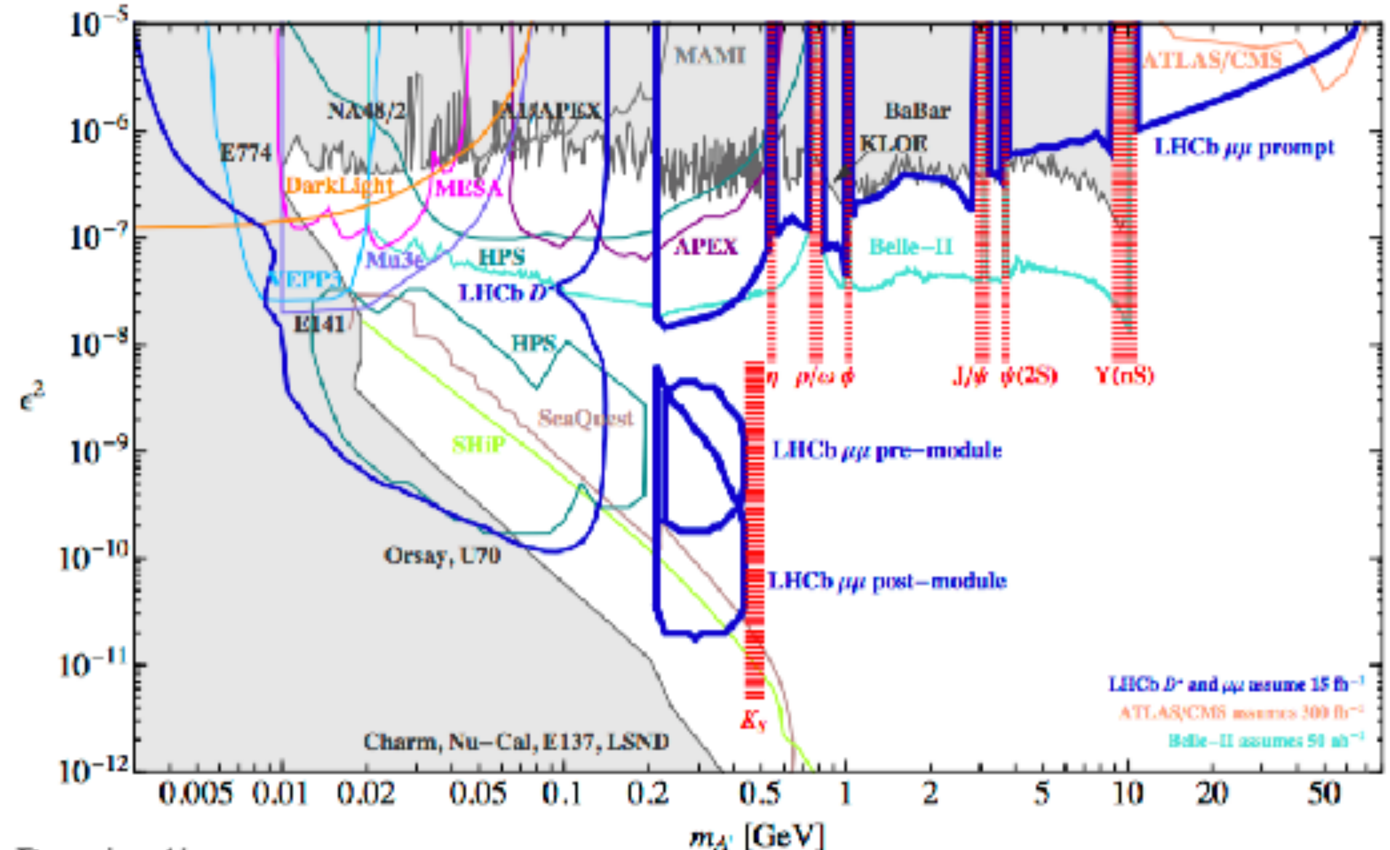
arXiv:1604.06099

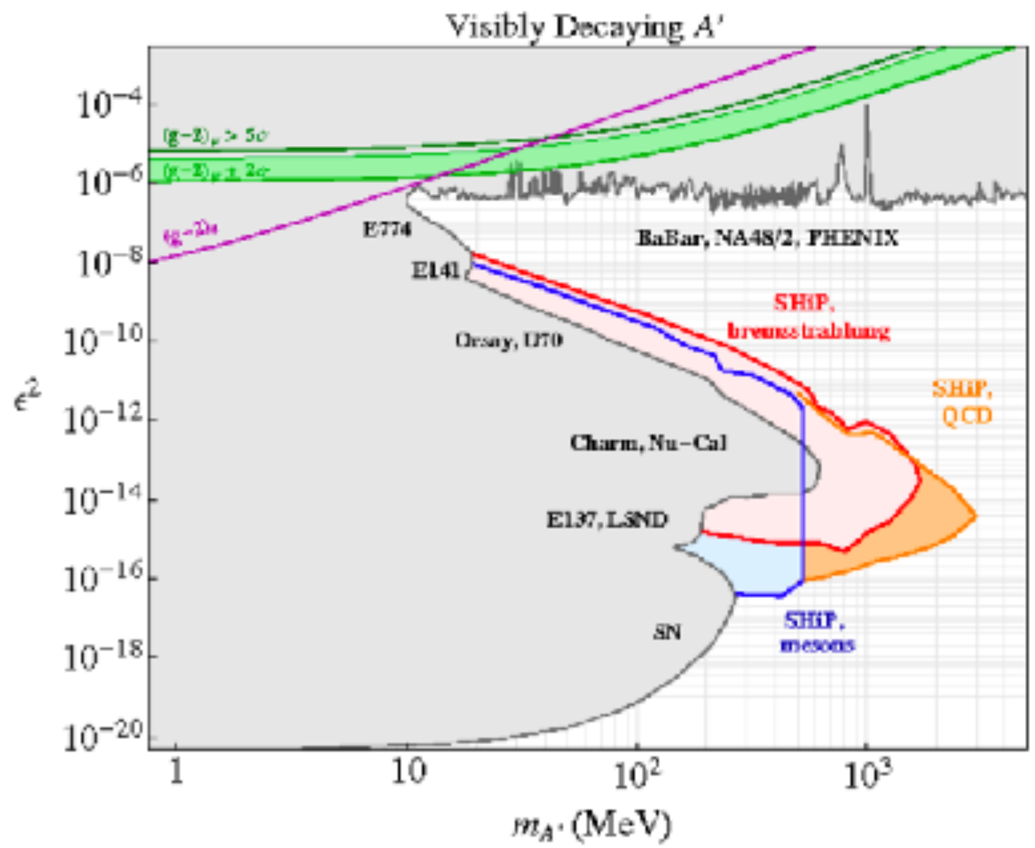
Dark photon coupling to SM particles

arXiv:1509.06765

decay modes

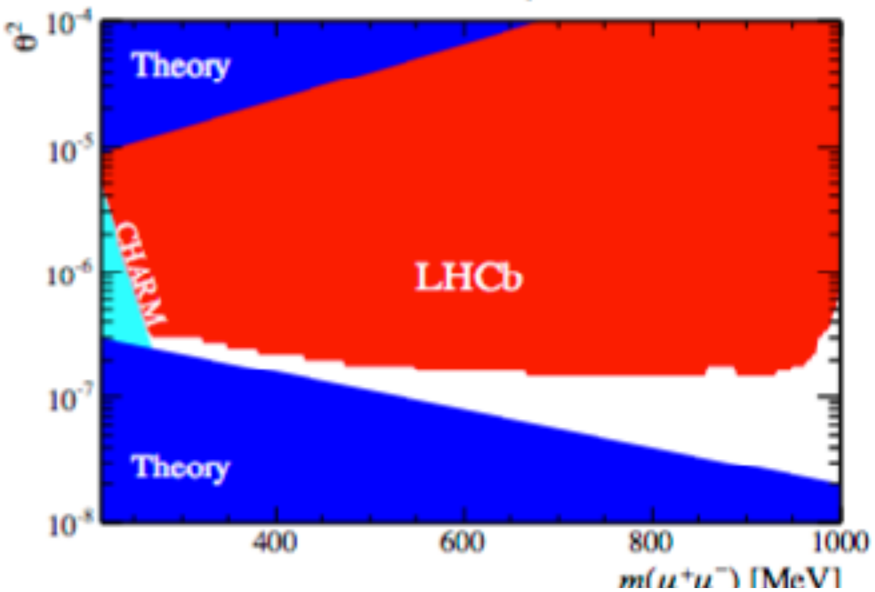




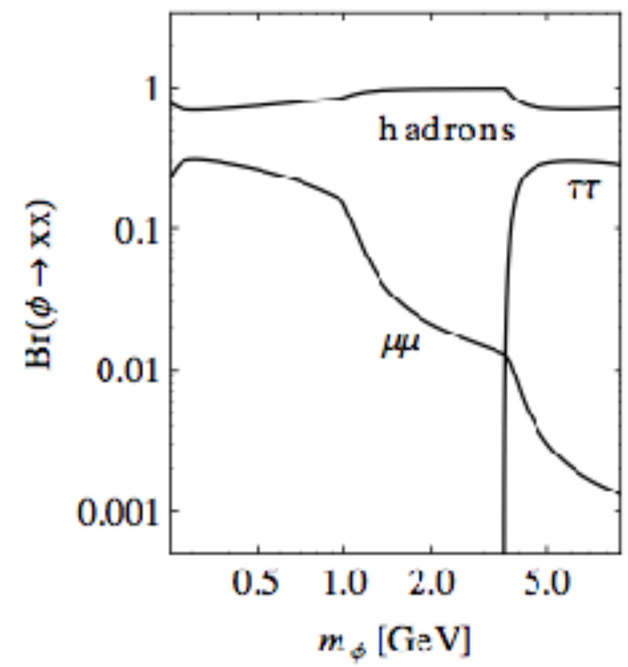


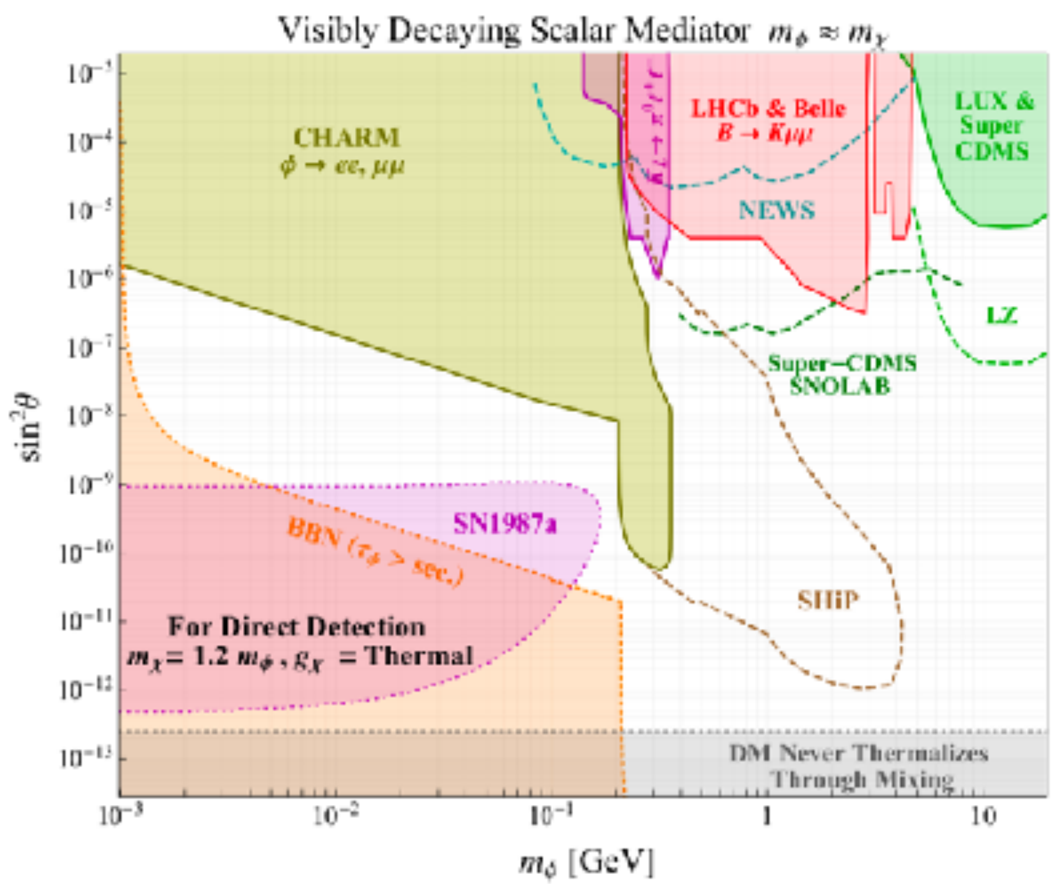
Dark Higgs

[LHCb Collaboration, Phys.Rev.Lett. 115 (2015) 1

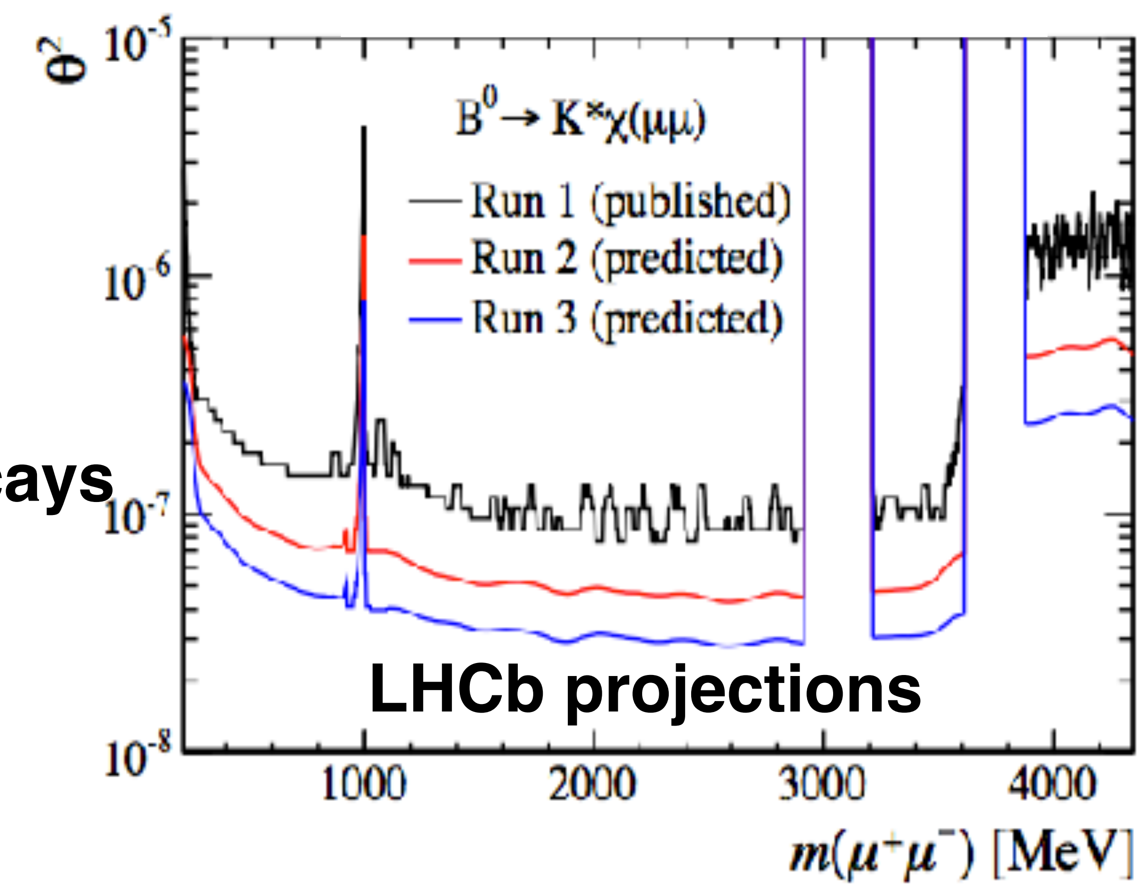


decay modes





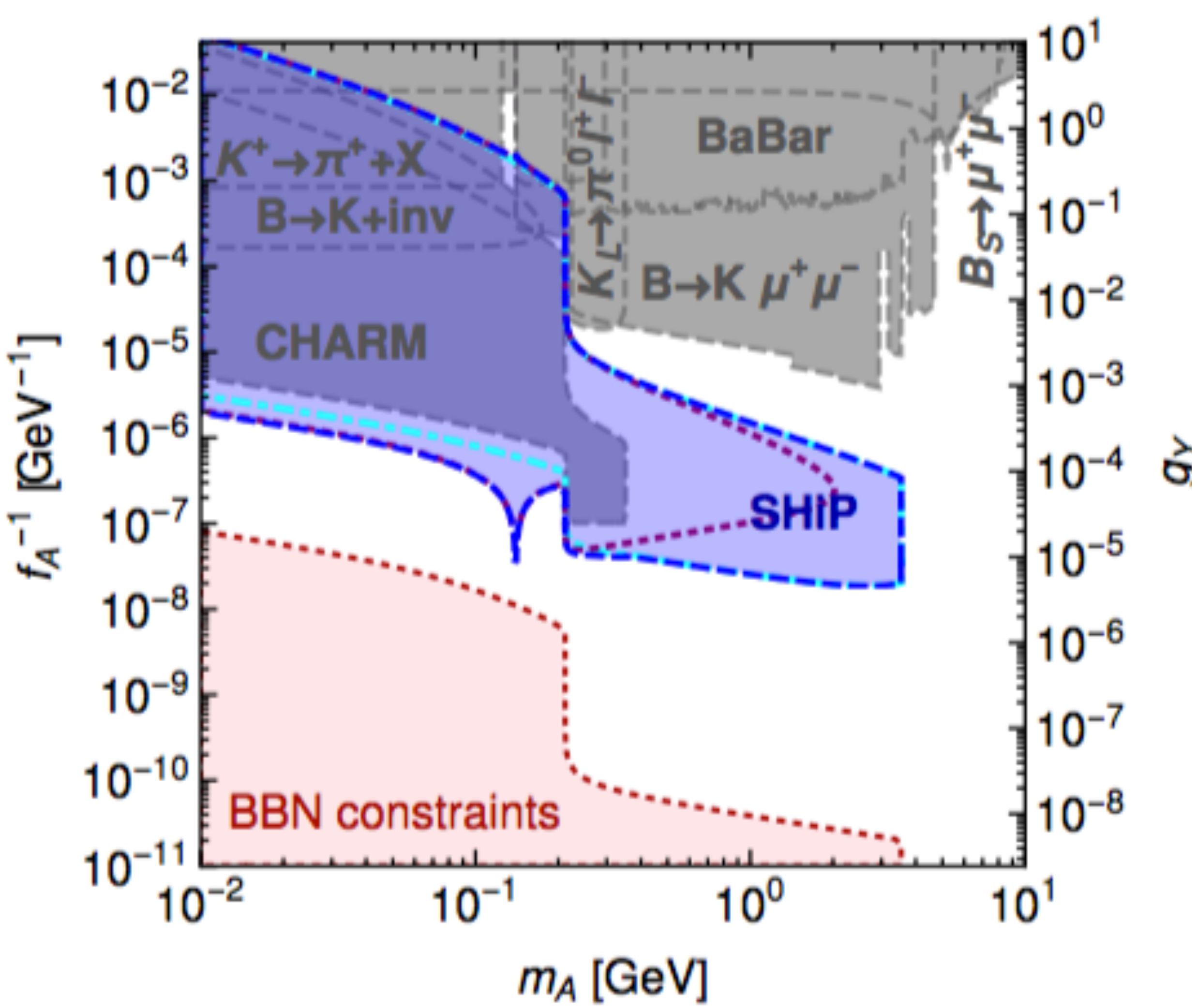
B decays



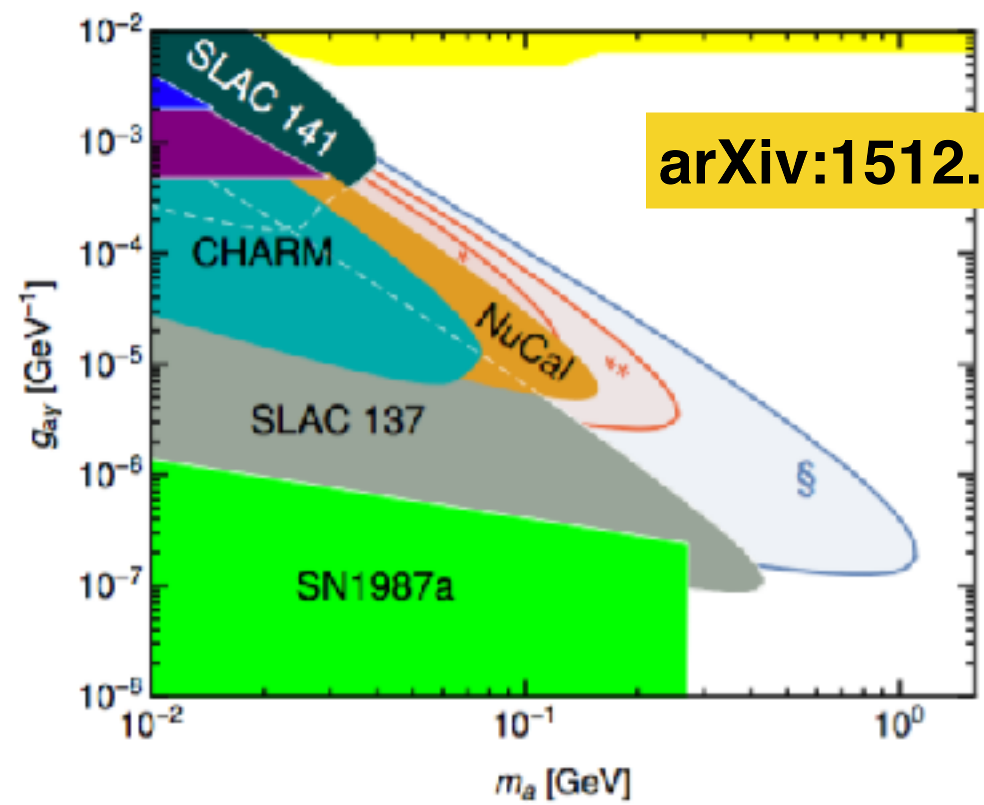
complementary!

Pseudo-scalar portal: ALP or PNGB

coupling to fermions only:
produced in B decays
decay to fermions



coupling to photons only:
decay to photons



arXiv:1512.03069

we are currently studying backgrounds and possible detector improvements for reconstruction of the photon direction

Low mass SUSY (I)

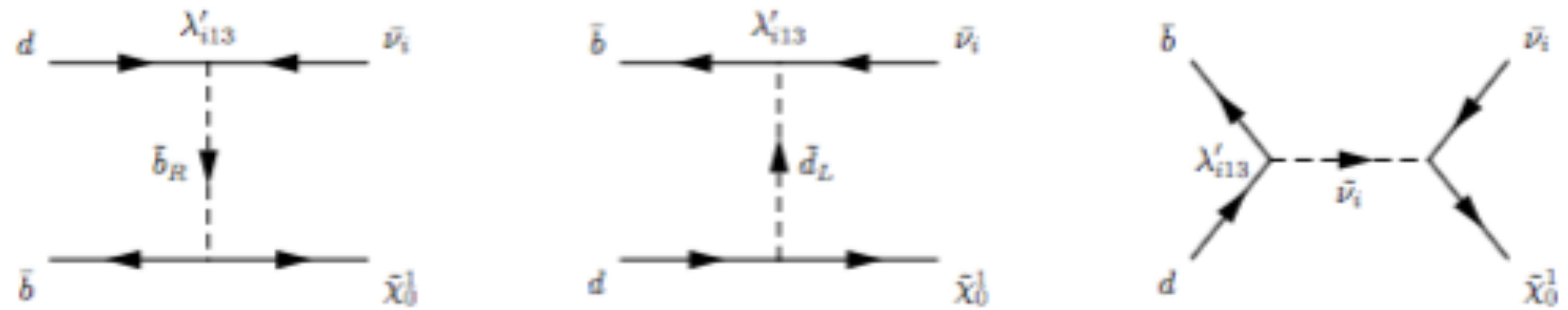
Phys. Rev. D 92, no. 7, 075015 (2015)

Search for SUSY renegades, below the EW scale

Neutralino's in RPV SUSY models

In the constrained MSSM with 5 parameters the lightest neutralino must be heavier than 46GeV but in general even massless neutralino is allowed

production: from decays of D and B mesons



decay: eeν, $\mu\mu$ν, πe, πμ, Ke, Kμ like the HNL

Low mass SUSY (I)

For coupling of order 1 the mass reach for s-fermion masses (assumed the same in this paper) is O(30TeV)

TABLE I. Estimates of SHiP sensitivity to and CHARM bounds on combinations of RPV couplings. In the first three rows we set $M_{\tilde{\chi}_1^0} = 1\,\text{GeV}$ and $M_{\tilde{\chi}_1^0} = 4\,\text{GeV}$ for the last three rows. Indices $j, k = 1, 2$ and $i = 1, 2, 3$ indicate flavor of the final-state leptons.

λ	Expected sensitivity SHiP, $M_{\tilde{f}}^2/\text{TeV}^2$	Upper limit CHARM, $M_{\tilde{f}}^2/\text{TeV}^2$
$\sqrt{\lambda'_{121}\lambda_{ijk}}$	2.4×10^{-3}	2.5×10^{-2}
$\sqrt{\lambda'_{121}\lambda'_{j11}}$	1.2×10^{-3}	–
$\sqrt{\lambda'_{121}\lambda'_{j21}}$	1.4×10^{-3}	–
$\sqrt{\lambda'_{113}\lambda_{ijk}}$	2.4×10^{-3}	2.5×10^{-2}
$\sqrt{\lambda'_{113}\lambda'_{j11}}$	3.9×10^{-3}	–
$\sqrt{\lambda'_{113}\lambda'_{j21}}$	4.0×10^{-3}	–

Low mass SUSY (II)

arXiv:1511.05403

If SUSY is spontaneously broken at not very high energy scale (see models with gauge mediation of SUSY breaking as an example), the particles from SUSY breaking sector may show up at quite low energies.

The Goldstino supermultiplet contains the Goldstino (the Nambu–Goldstone field, fermion) and its superpartners, scalar and pseudoscalar s-goldstinos.

S-goldstino couplings to the SM fields are $\propto 1/F^2$ (scale of SUSY breaking) in the whole model

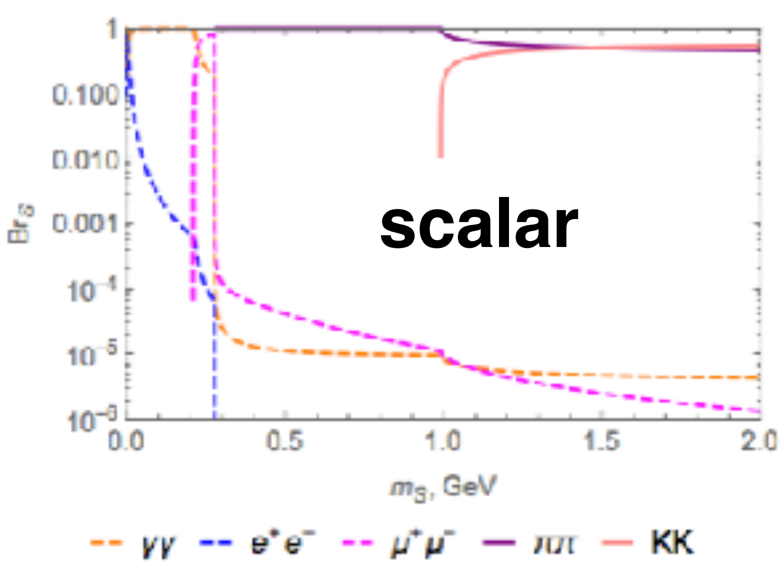
—> their couplings are anticipated to be rather weak.

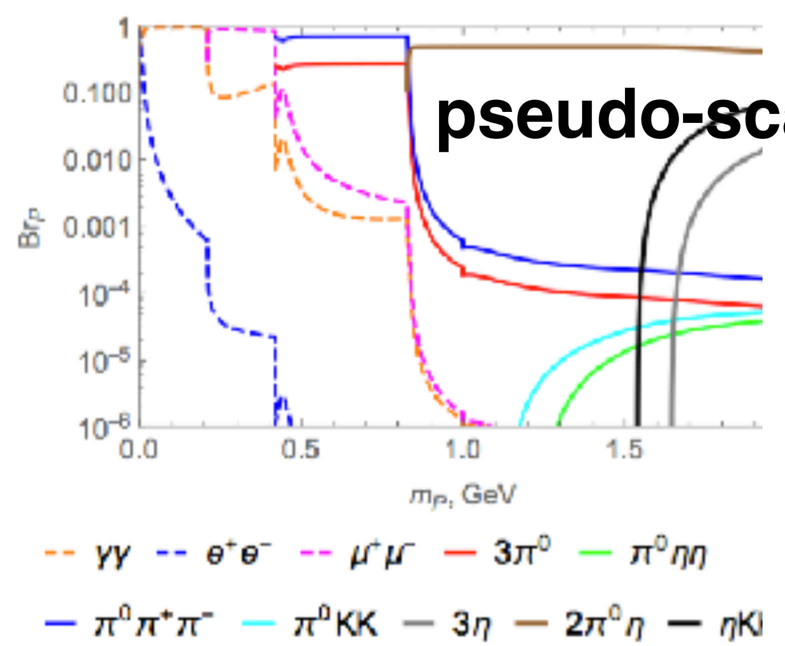
—>test the SUSY breaking scale by hunting for the light s-goldstinos

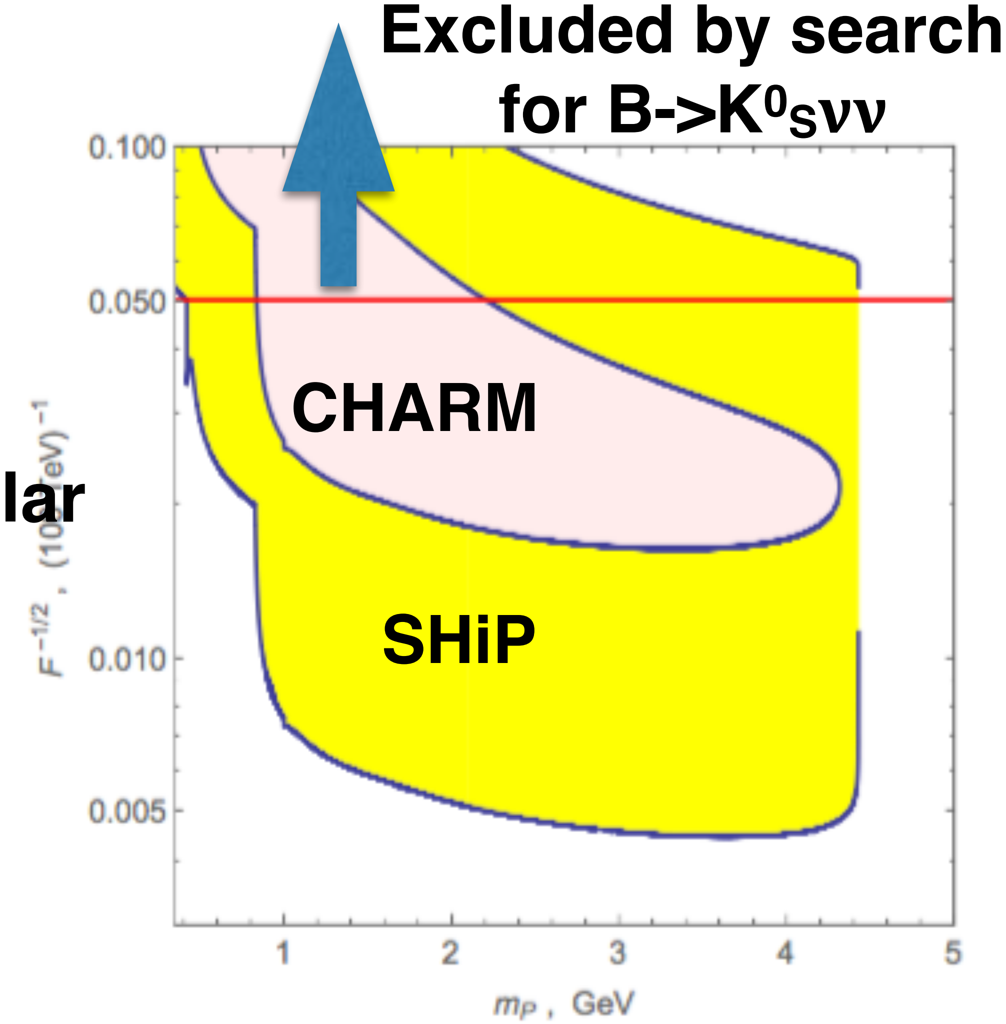
Low mass SUSY (II)

Production: B and D decays

Decay:







SHiP can probe the supersymmetry breaking scale

up to 10^3 TeV for the model without flavor violation and up 10^5 TeV for the model with flavor violating parameters

Backgrounds for the downstream detector:

from TUNED-ON-DATA MonteCarlo we found <0.1 in more than 2e20 pot (*)

(*) except for ALP—>γγ under study

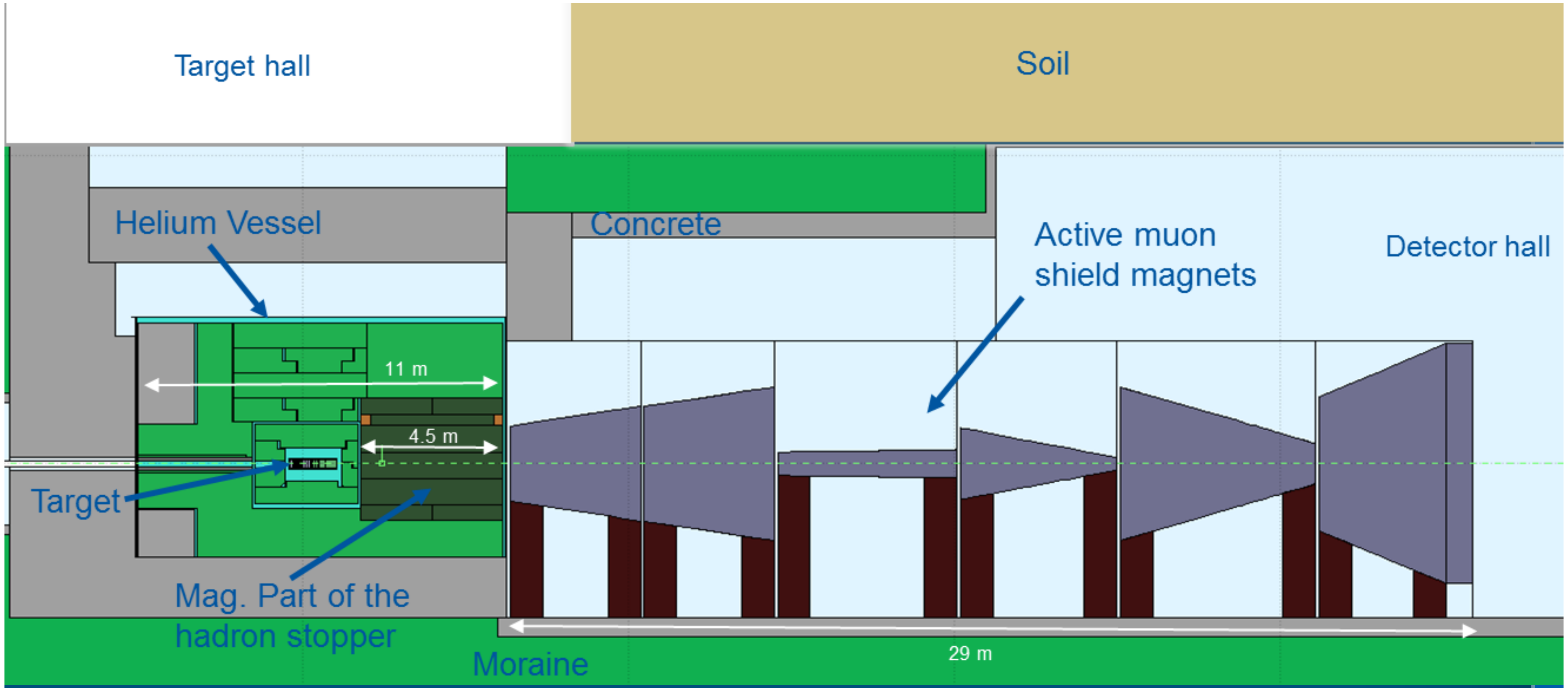
but still investigating

1) from active ν interactions

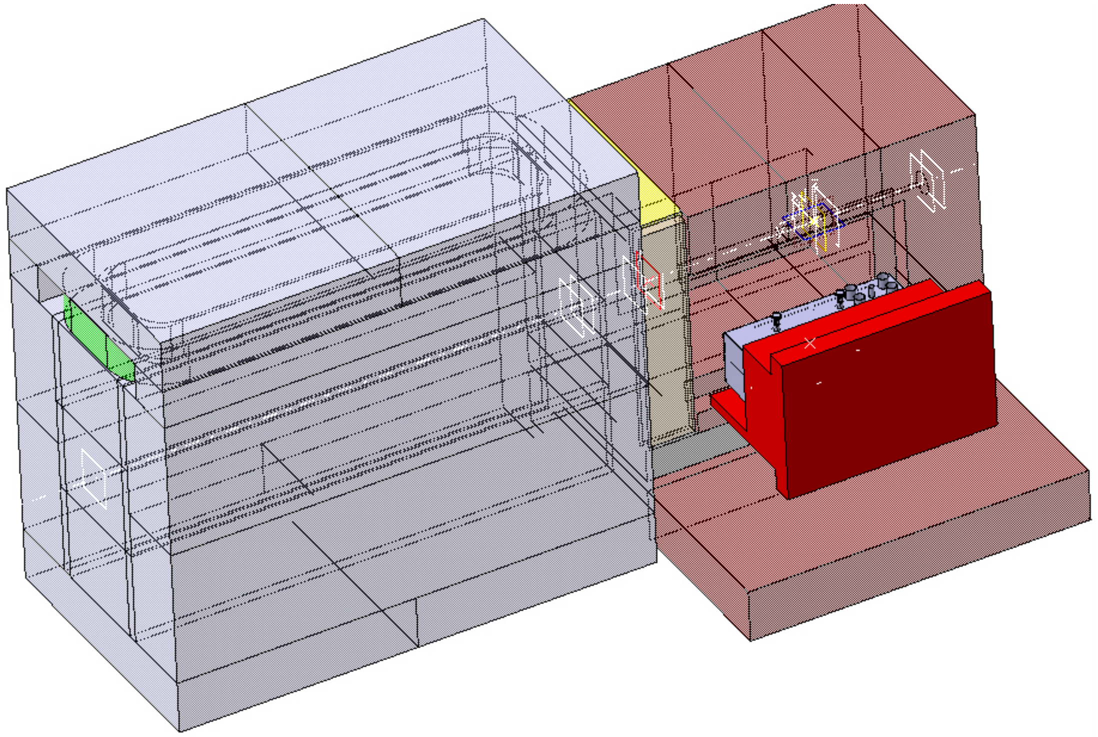
2) from cosmics

3) from μ interactions

4) combinatorial μ background



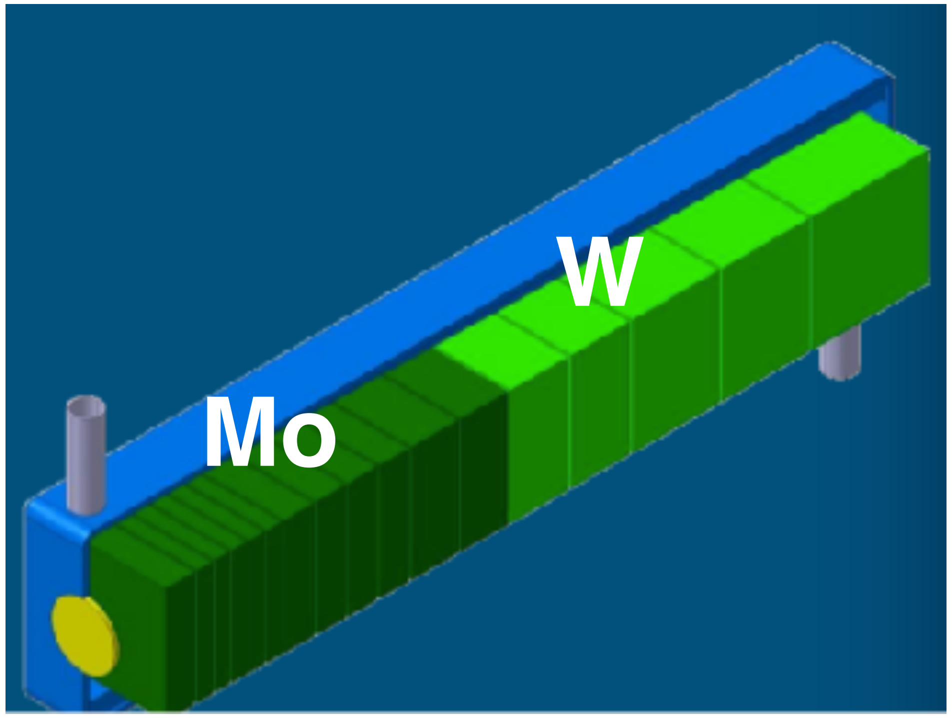
The target complex



Target and muon filter

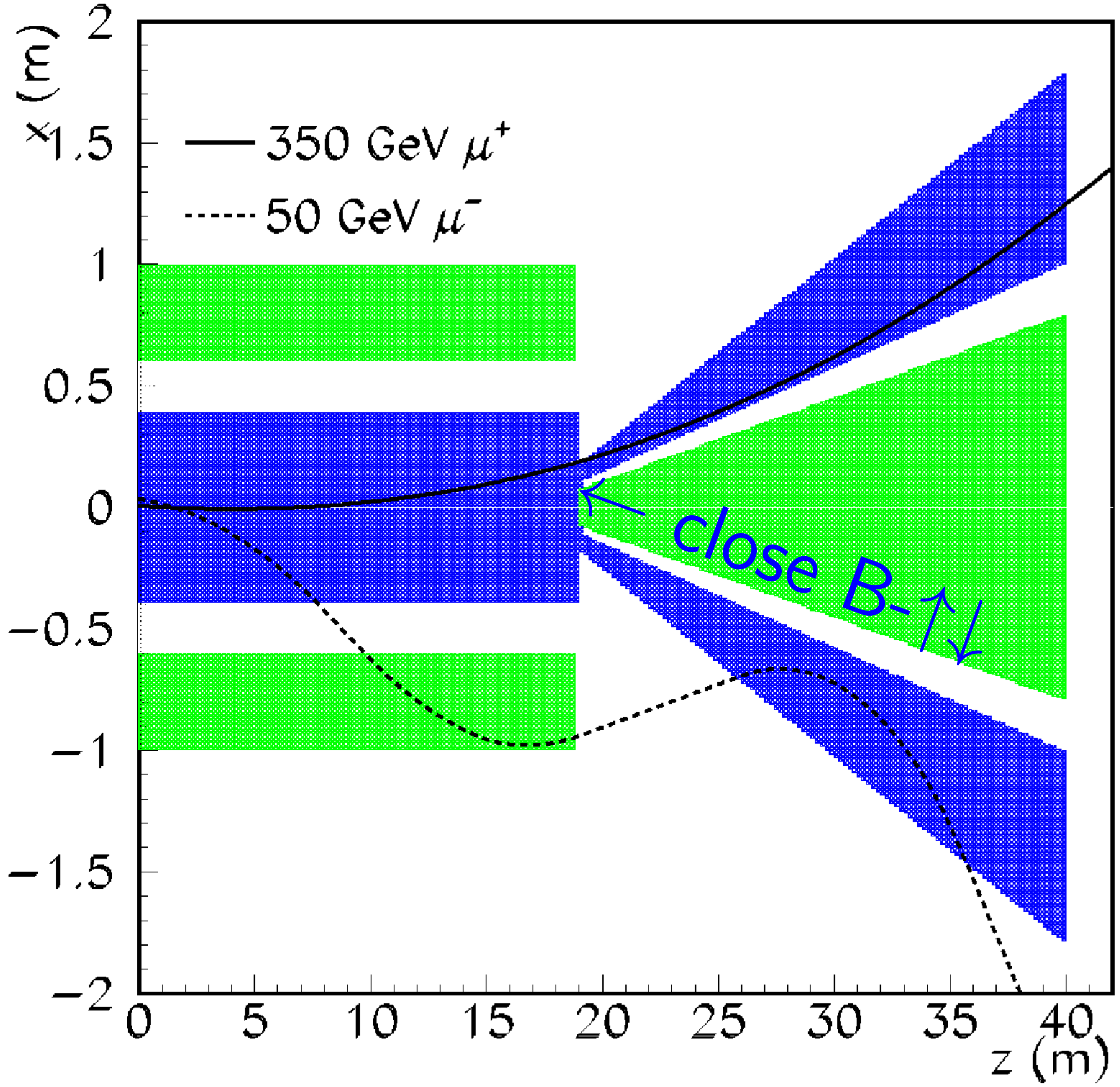
Longitudinally segmented hybrid target: Mo(58cm)/W(58cm)

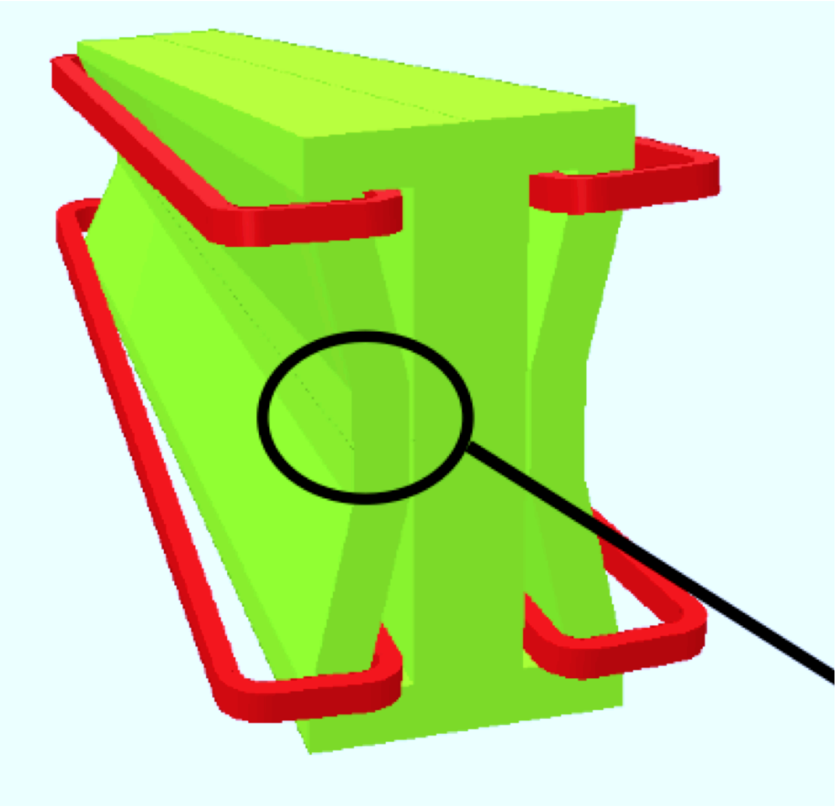
the beam is spread on the target to avoid melting



It is followed by a muon filter.

The issue is not trivial since the muon flux is enormous: 10^{11}/ SPS-spill(5×10^{13} pot)

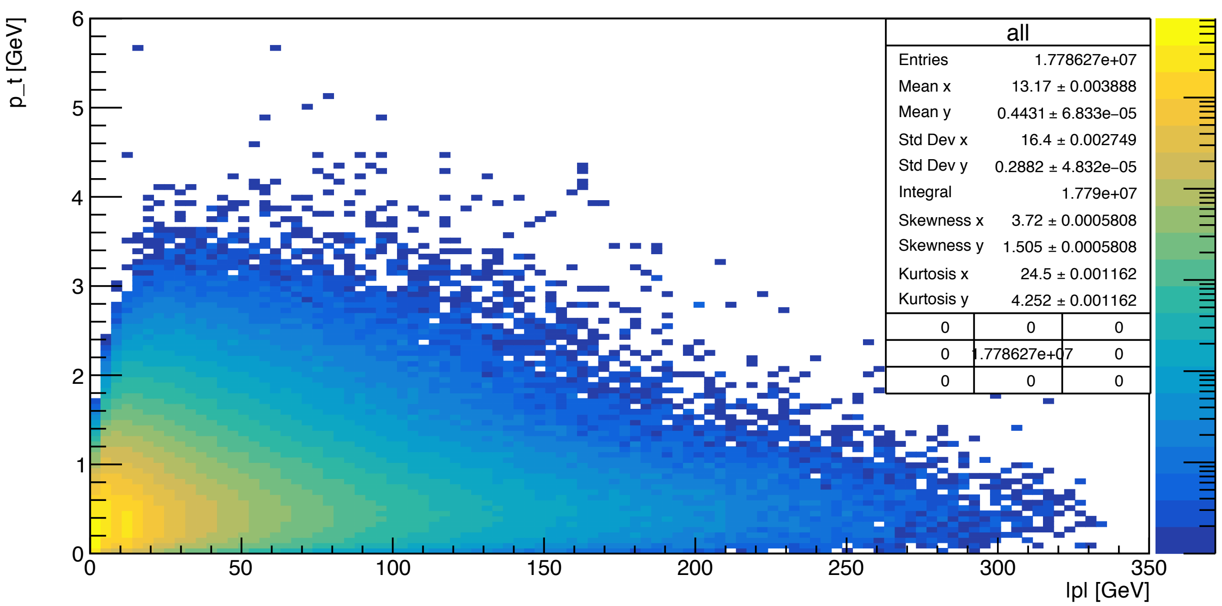


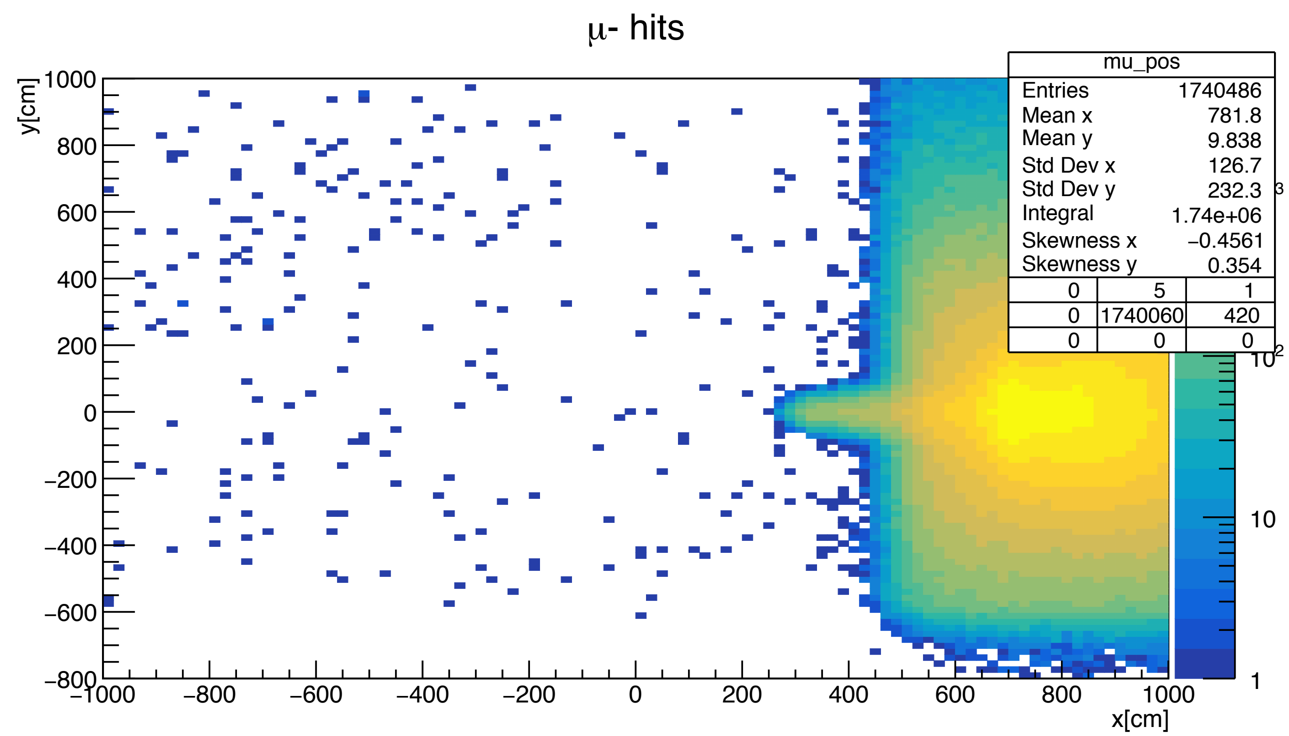


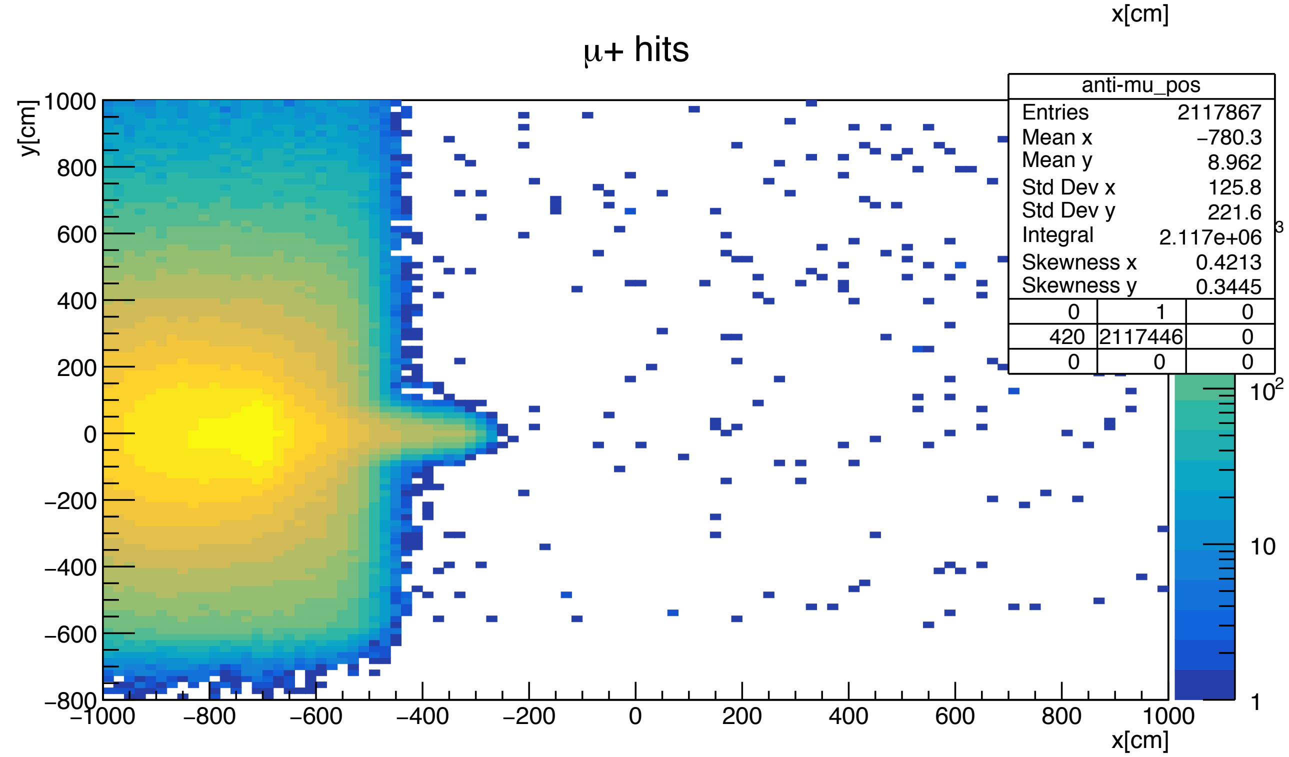
Critical component to optimise to maximise the experimental acceptance

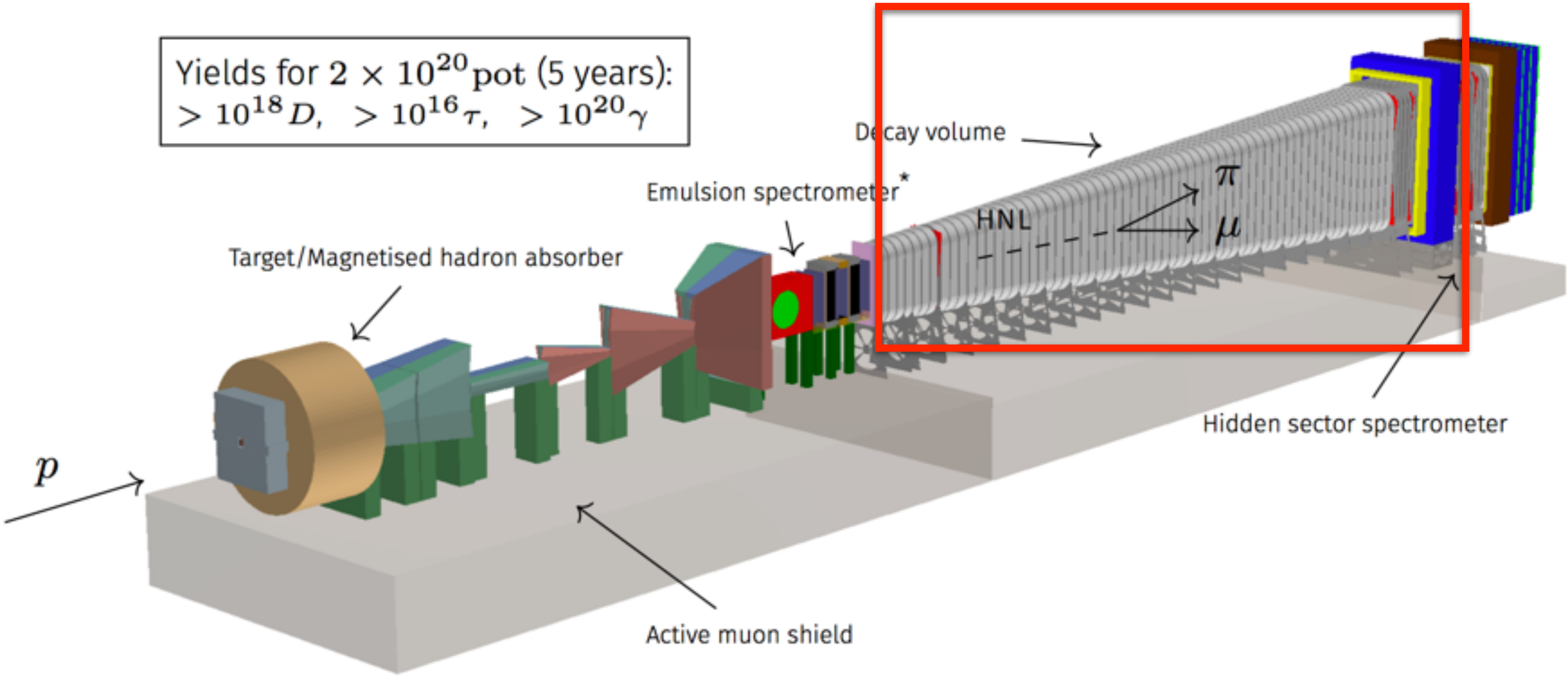
- A measurement of the muon spectrum for the SHiP target at the H4 test-beam at CERN's SPS is planned for spring

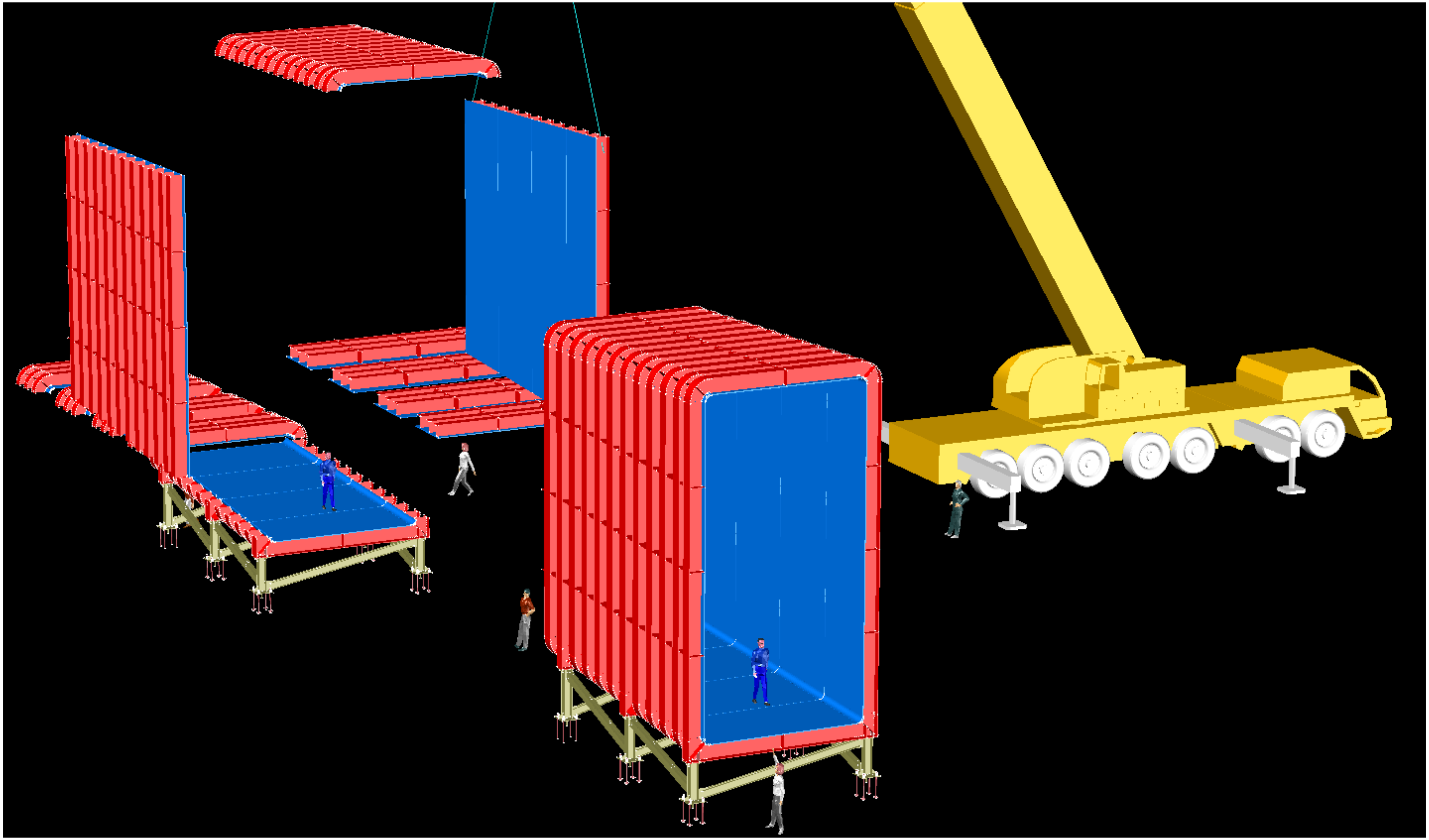
Muon distribution at the tracking stations



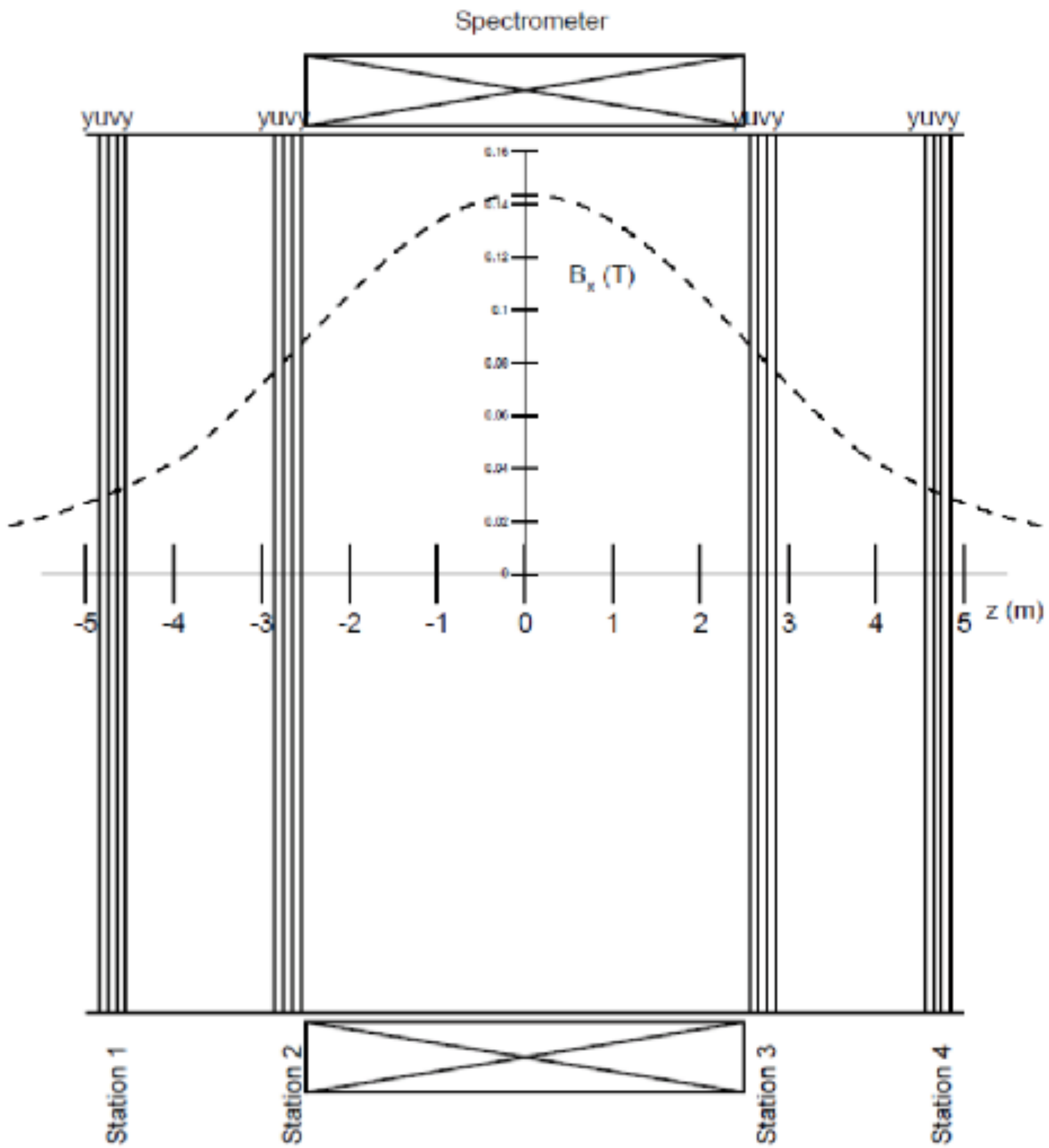


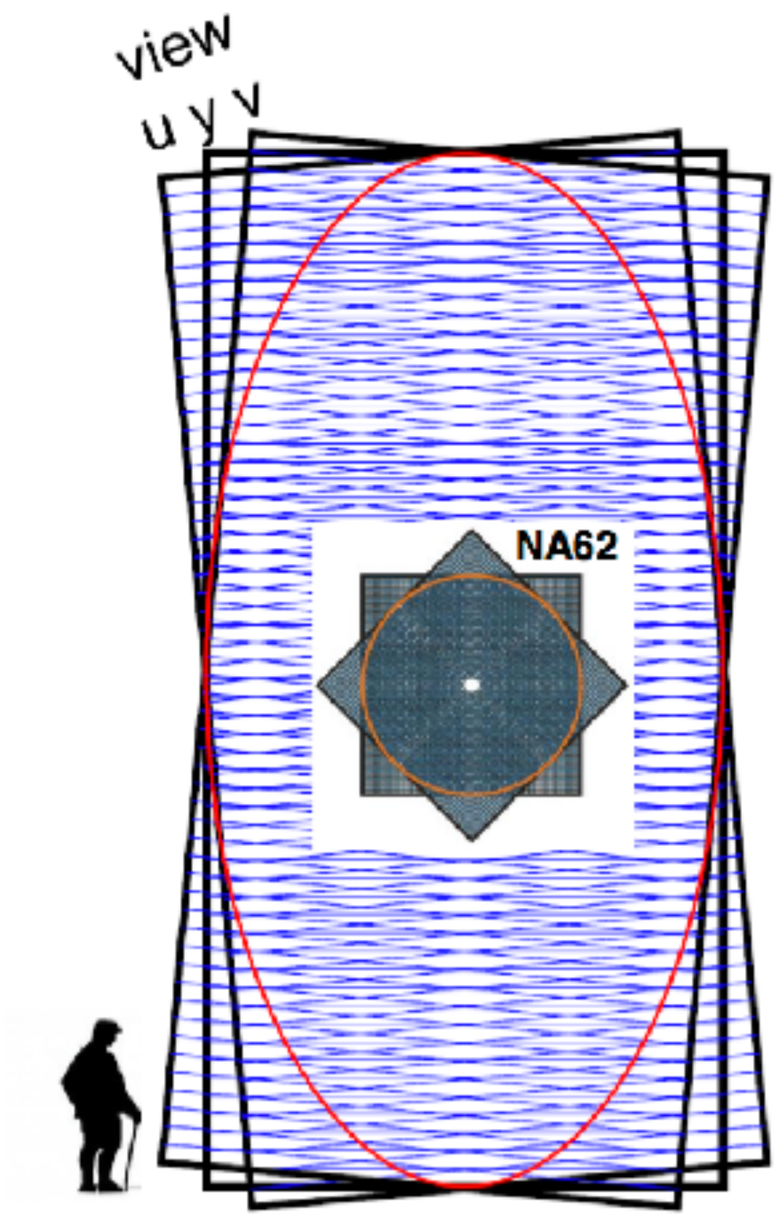



Yields for 2×10^{20}pot (5 years):
$> 10^{18} D, \quad > 10^{16} \tau, \quad > 10^{20} \gamma$
Decay volume
Emulsion spectrometer*
HNL
π
μ
Target/Magnetised hadron absorber
p
Hidden sector spectrometer
Active muon shield

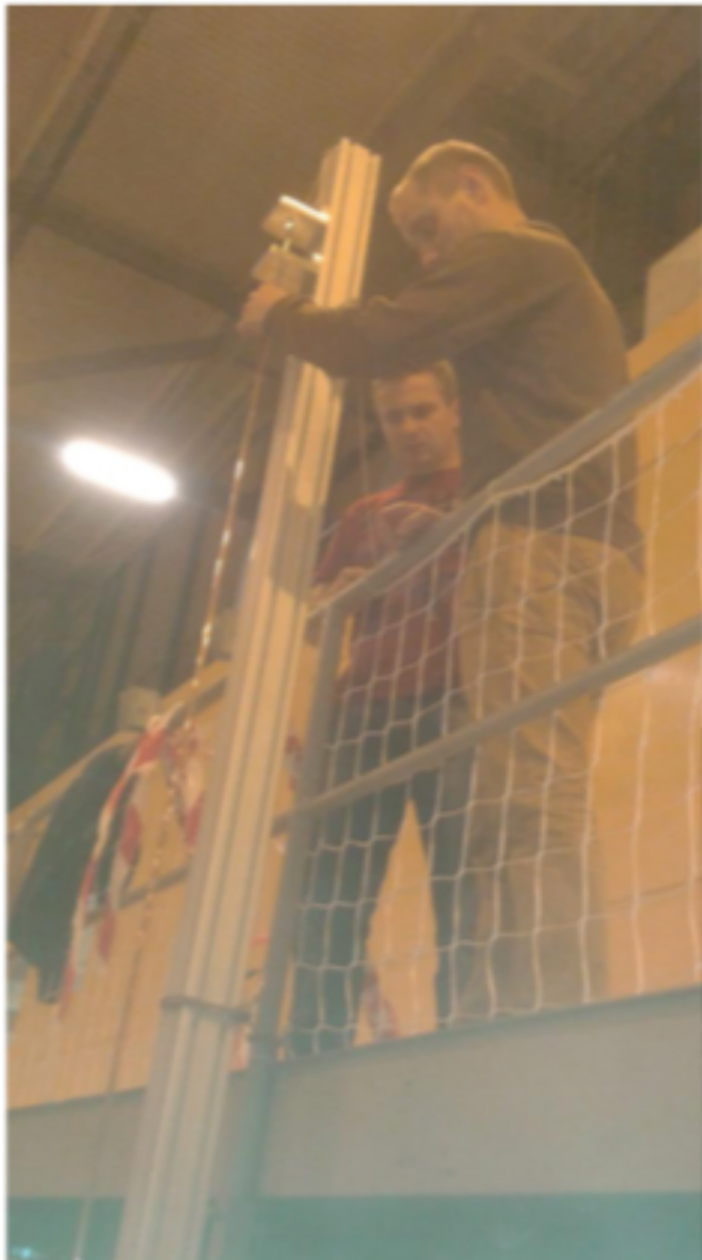


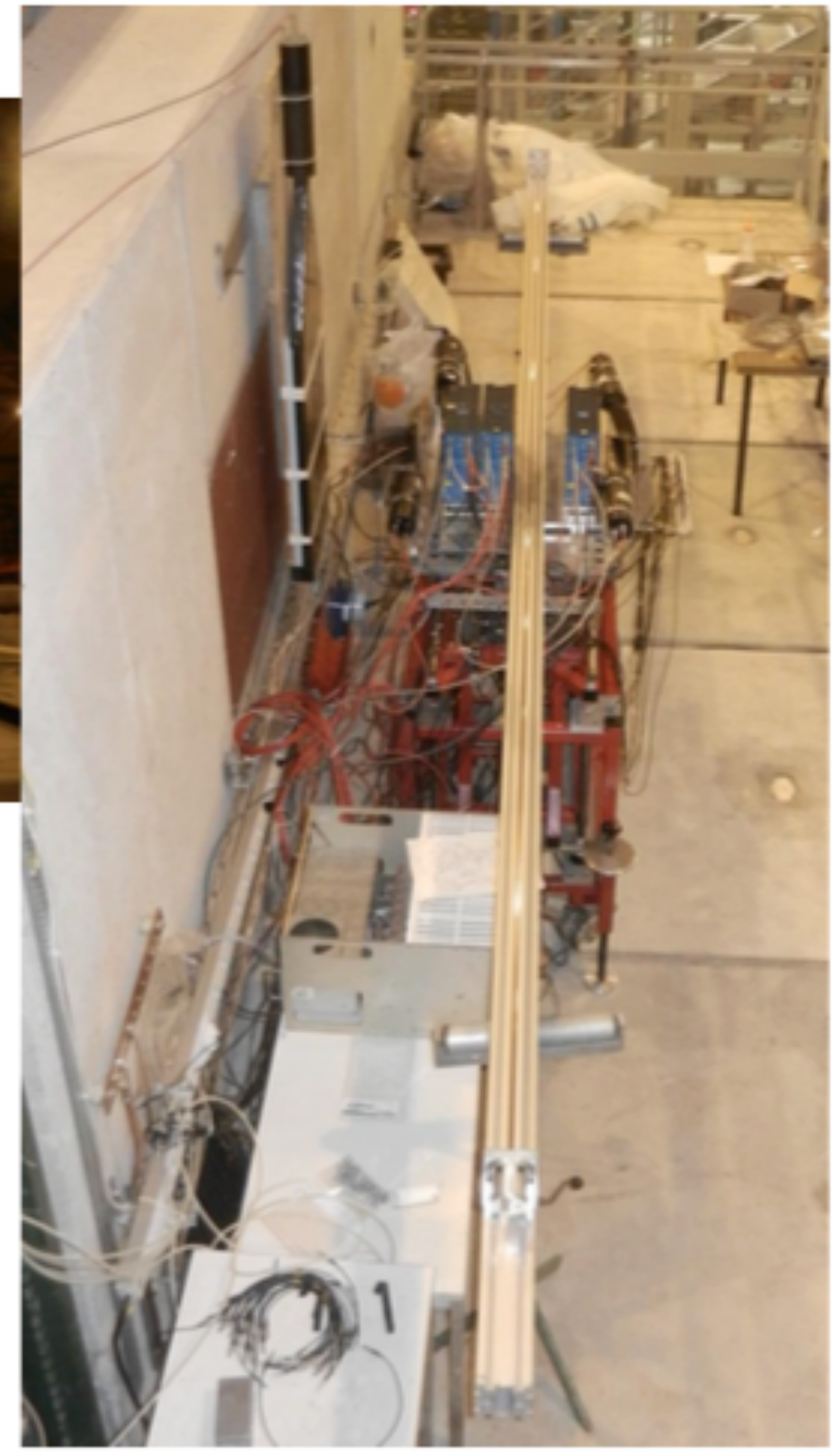
Straw tracker





5m straws!

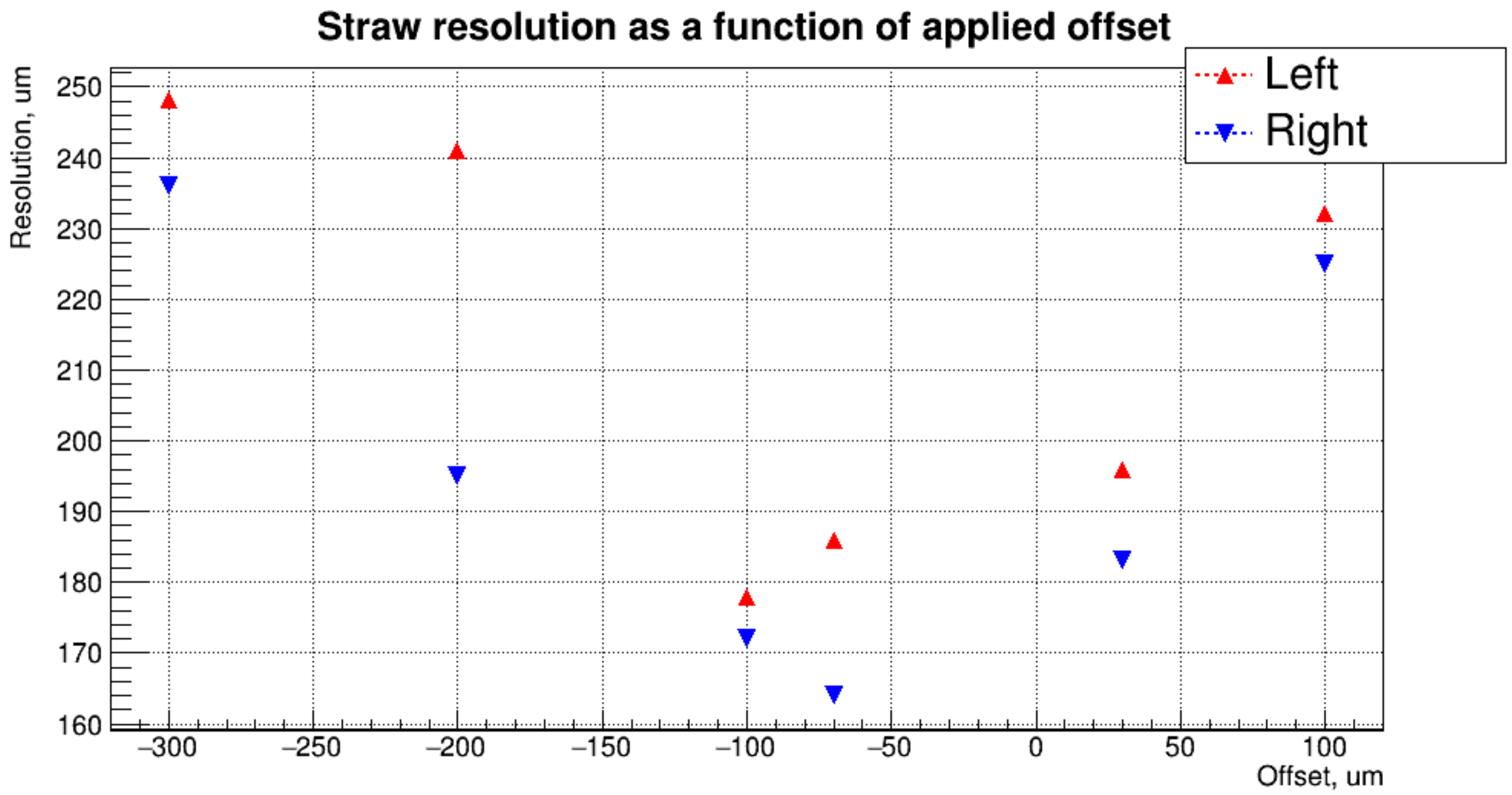




Test beam 2016 results

WORK ONGOING, PRELIMINARY RESULTS

Vladimir Solovev



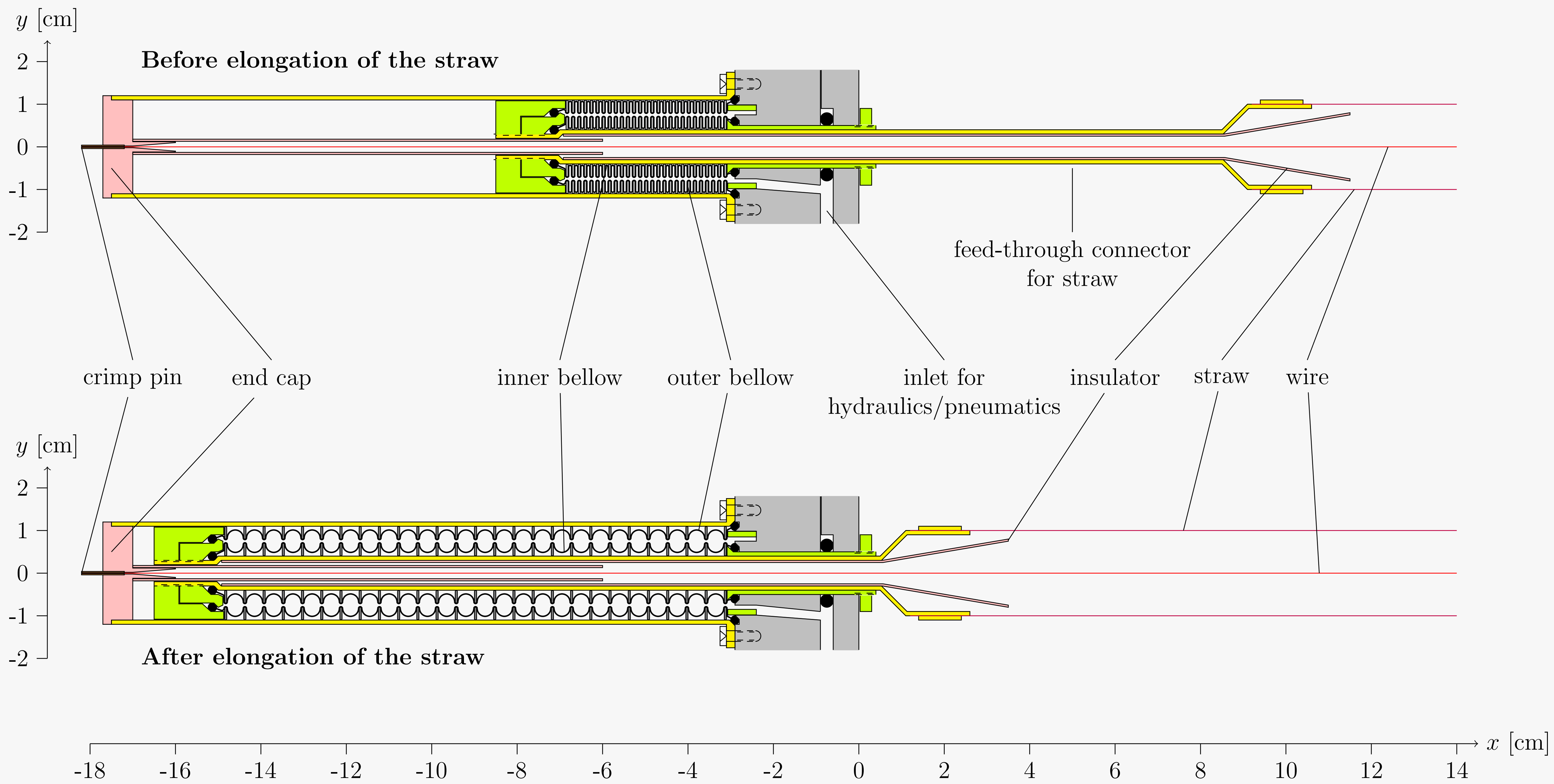
Elongation of Straws

Properties of straws

- $5\,\mathrm{m}$ long with $2\,\mathrm{cm}$ diameter
- Needed longitudinal tension (upscaled from NA62): $5\,\mathrm{kg}$
- ▷ Sagging in center: $2\,\mathrm{mm}$
- ▷ Elongation of a few cm

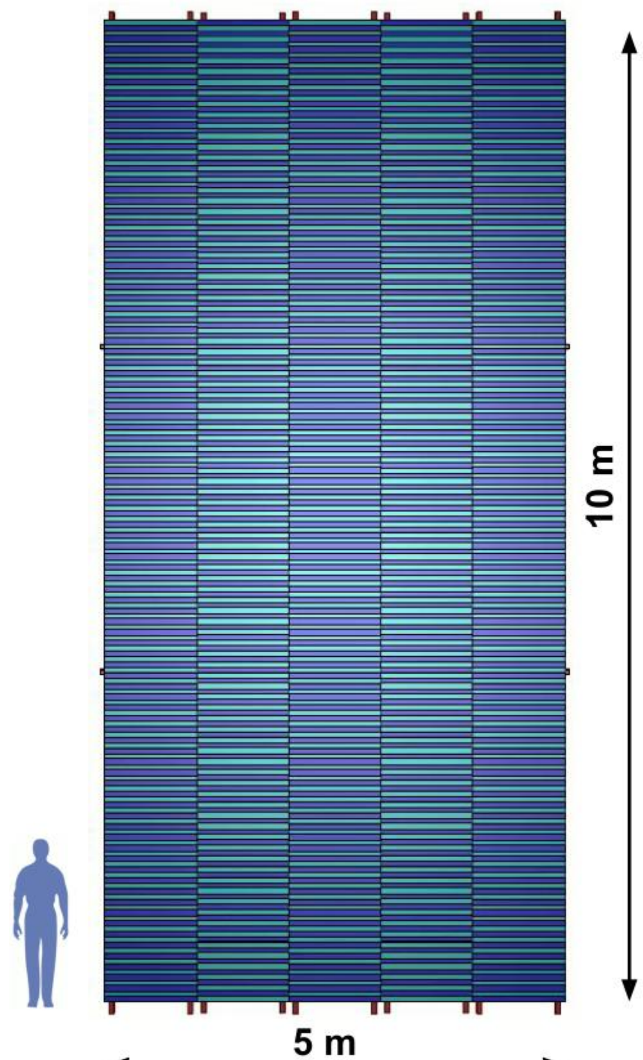
Deal with elongation of straw over time up to $8\,\mathrm{cm}$

- A first idea: Constant straw tension by hydraulics/pneumatics
- 2 cylindrical bellows, one inside the other, separating
  - drift-gas
  - hydraulic-medium
  - vacuum
- Made of rubber, stabilized by metal disc rings or entirely metal
- Keep wire tension independent of straw tension

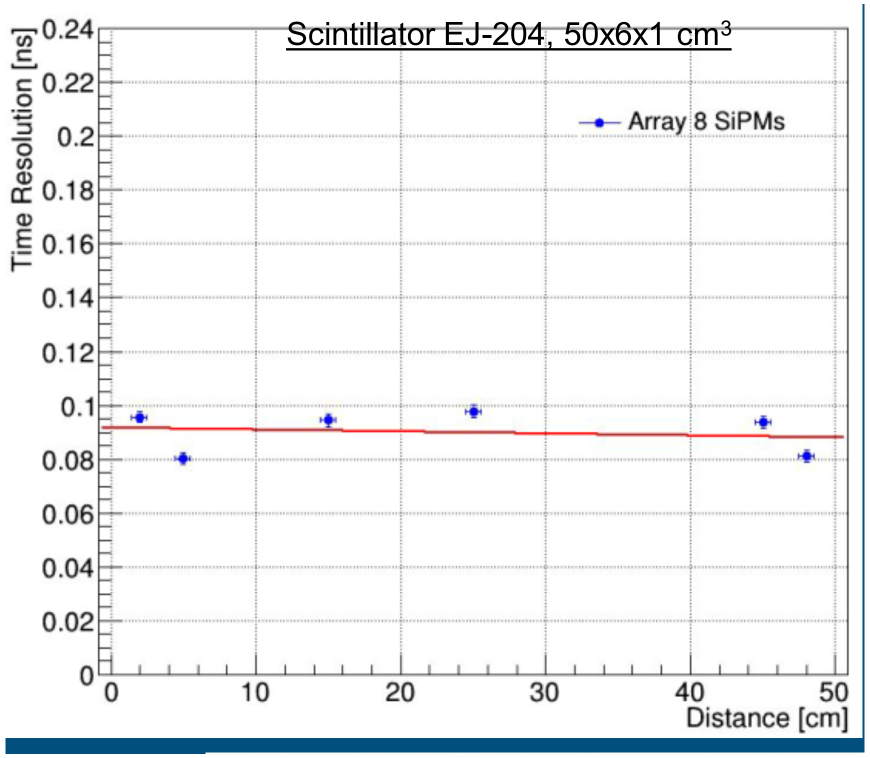


y [cm]
2
1
0
-1
-2
Before elongation of the straw
feed-through connector
for straw
crimp pin
end cap
inner bellow
outer bellow
inlet for
hydraulics/pneumatics
insulator
straw
wire
y [cm]
2
1
0
-1
-2
After elongation of the straw
x [cm]
-18
-16
-14
-12
-10
-8
-6
-4
-2
0
2
4
6
8
10
12
14

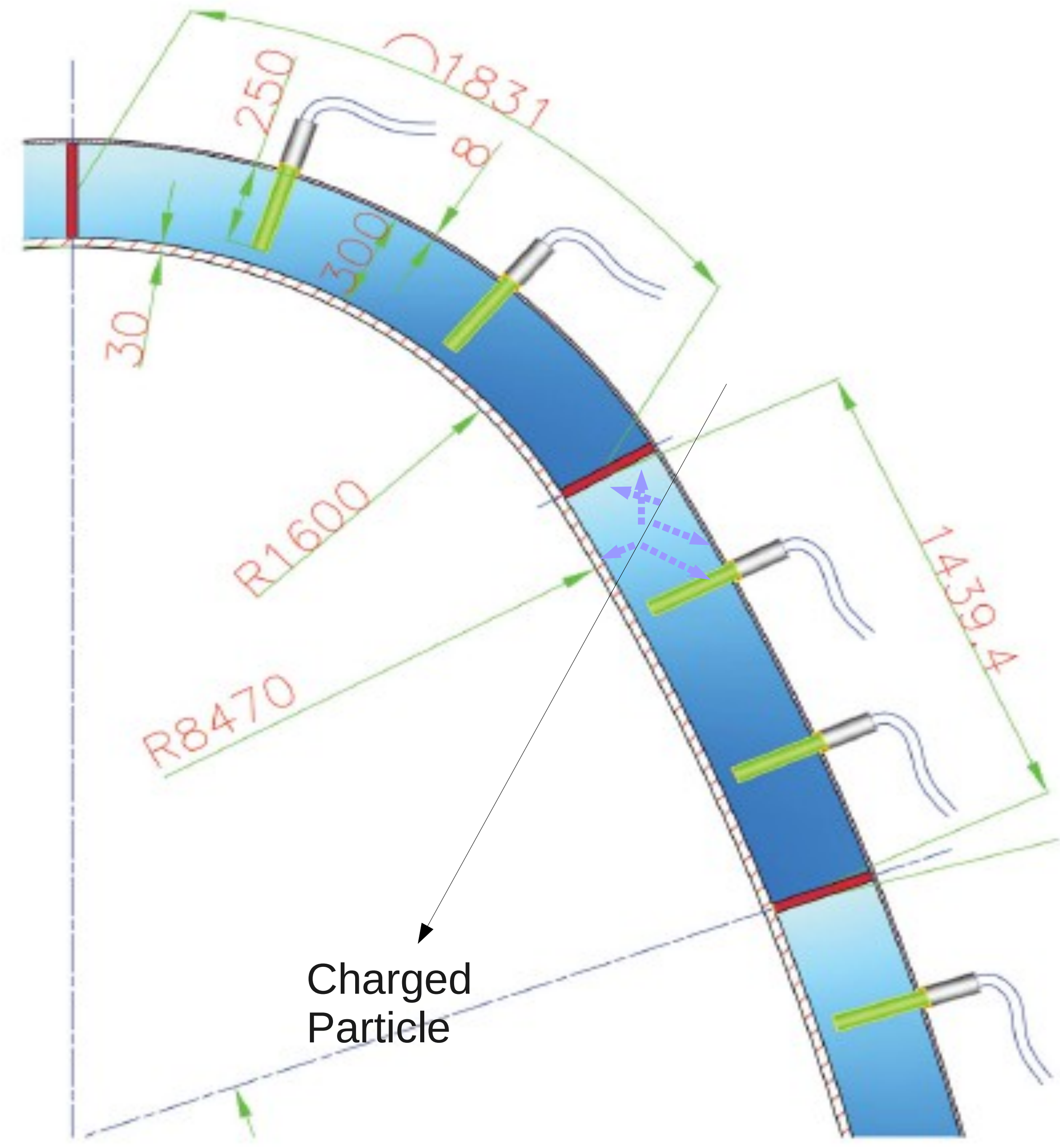
Timing detector

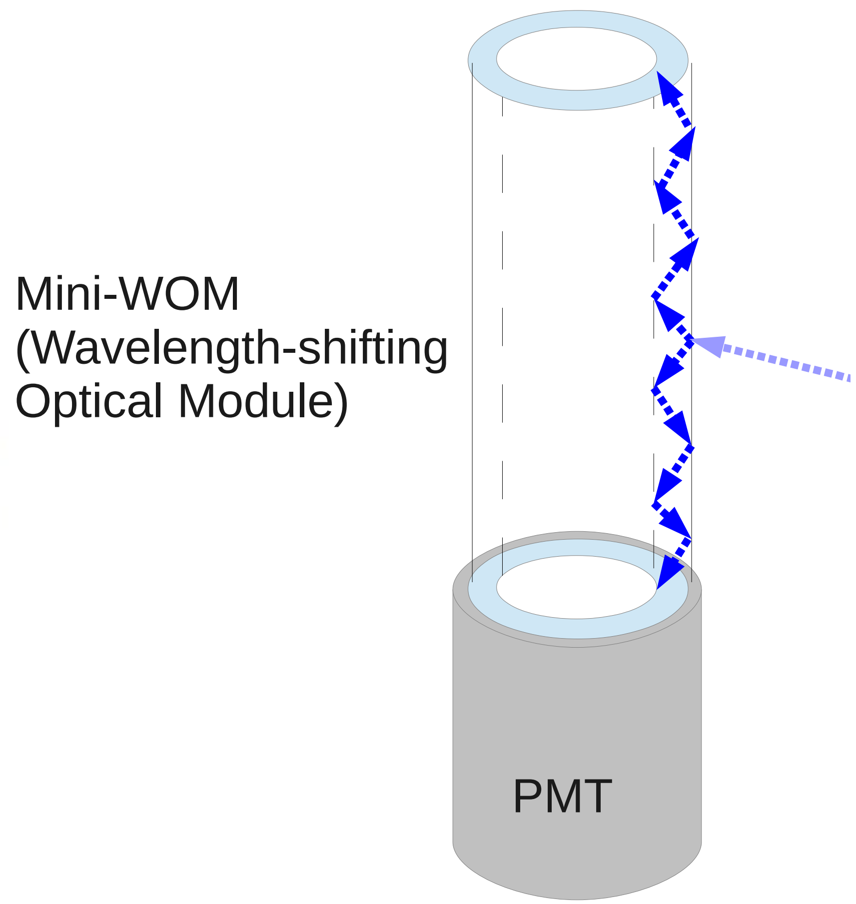


Baseline: 3 x 168 cm

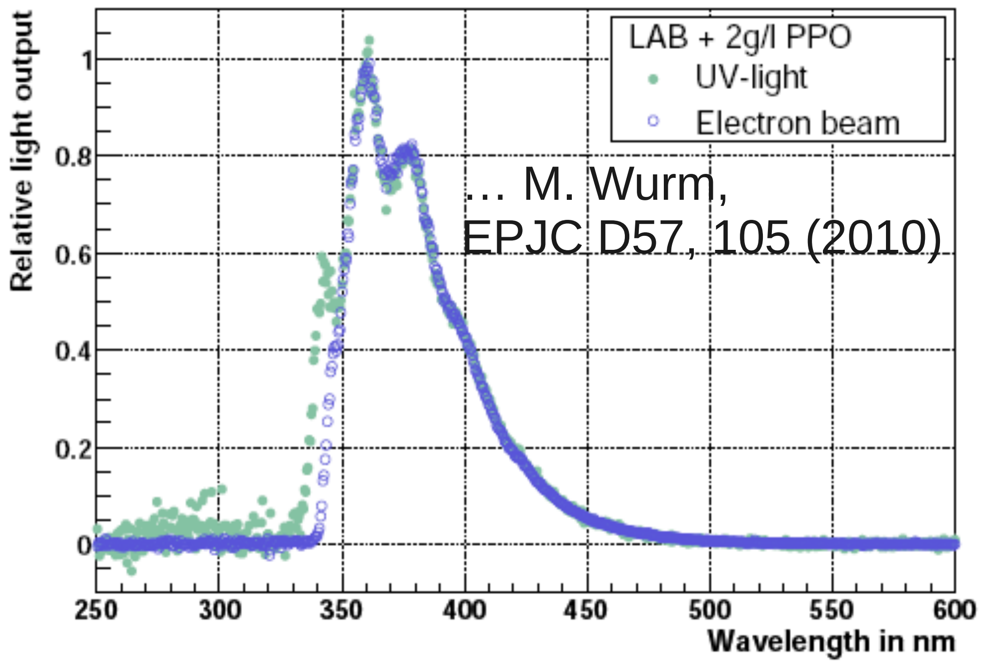


Reminder: WOM-detection principle

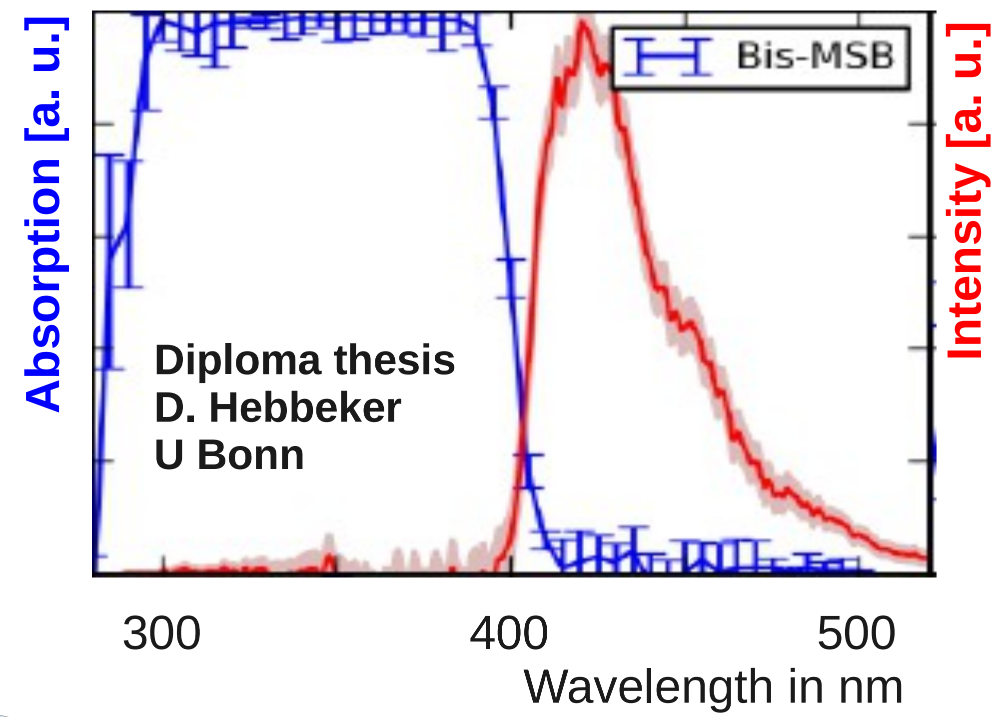


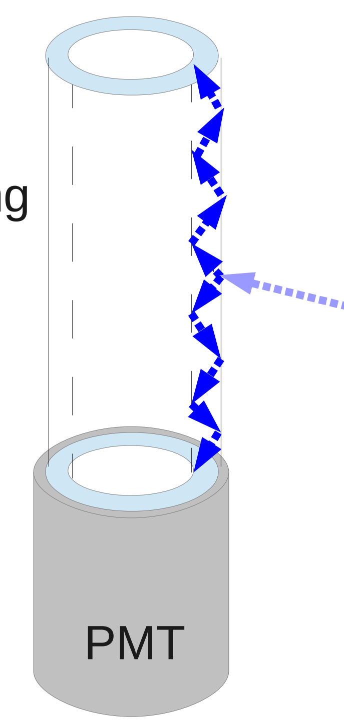


LS: emission spectrum



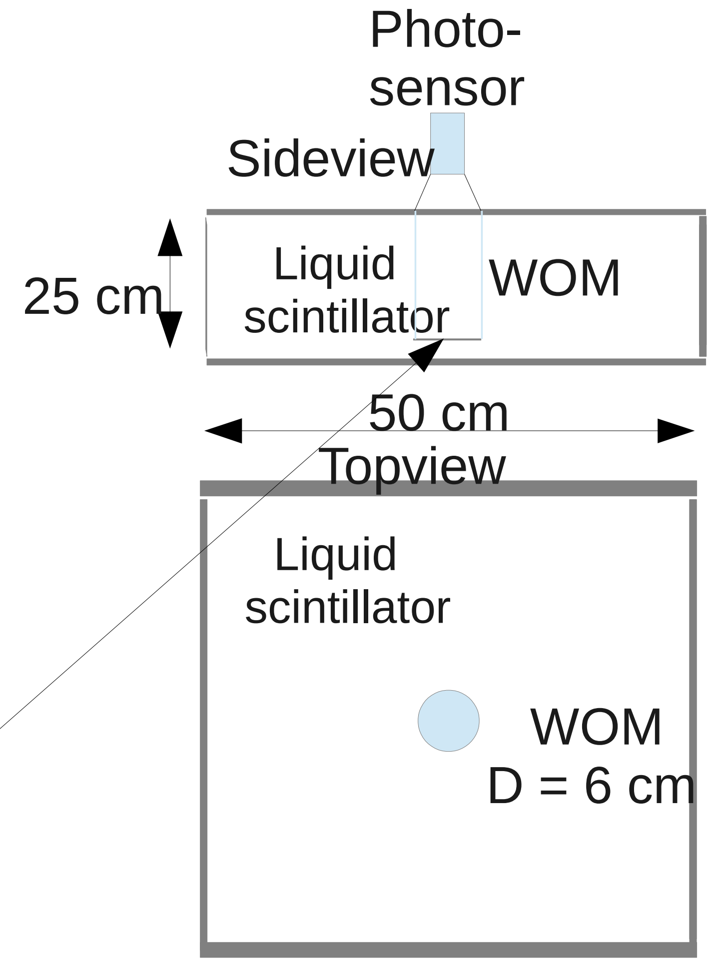
WLS: absorption & re-emission





First LS-filled box with large-area WOM

Place inside



Bachelor thesis: M. Ehlert

Motivations for a good particle identification in SHiP

1) measure the mass of final states from hidden sector particle decays, with and without neutrals

2) distinguishing between models: HNLs, dark scalar, dark vector, SUSY etc.

3) distinguishing final states so to extract the parameters of the νMSM —> together with the measurement of the Dirac phase δ by DUNE/HyperK, information on lepto-genesis (e.g. JHEP 1708 (2017) 018)

As a by-product we will get further suppression of ν induced background

The TP design (1)

requirements considered for ECAL design:

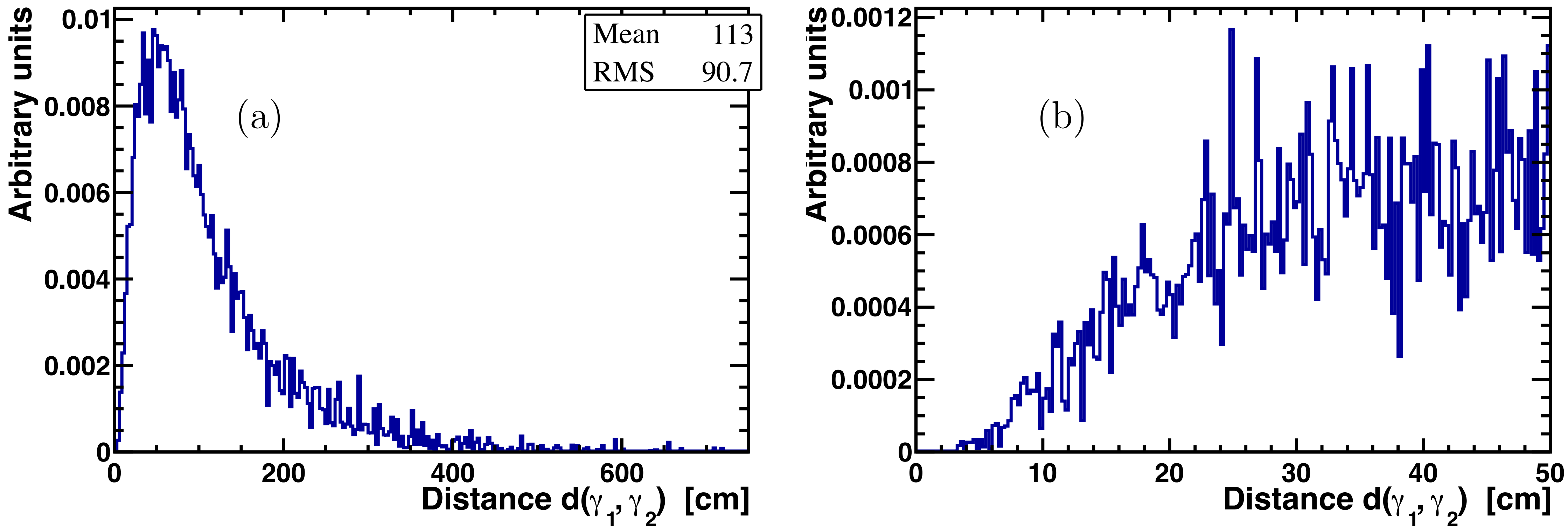
e- and γ reconstruction, energy and position measurement, e-/π separation

- large size

- known technologies

- e-/π separation as good as possible from 1 to 100Gev

- moderate σ(E), granularity to see the two photons from the π^0 from HNL—>ρl



distance of photons in ECAL from π^0's in HNL—>ρ l

need to see separate two photons to distinguish $\pi^0\pi^0$ from ALP—>γγ

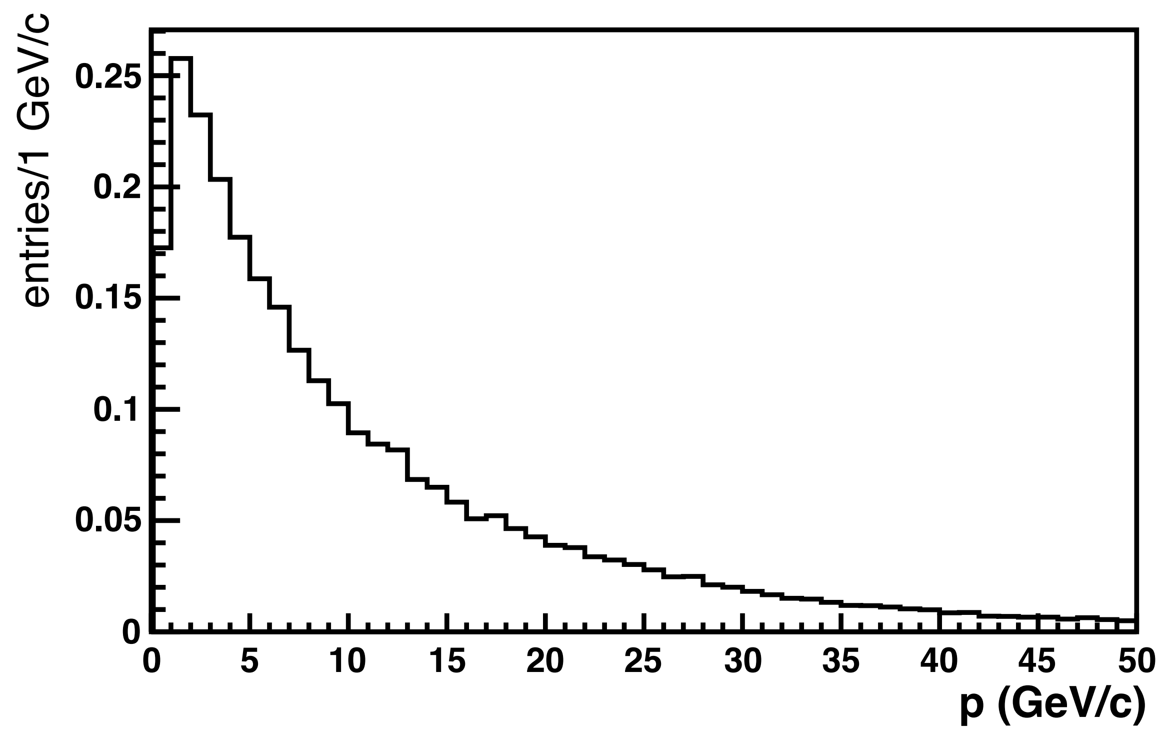
The TP design (2)

requirements considered on HCAL/MUON detector design: μ/π separation (including also ECAL!)

- large size
- known technologies
- tag neutral particles such a K^0_L for background rejection (but at the time no practical example)
- μ/π separation for non decaying pions as good as possible from 1 to 100GeV

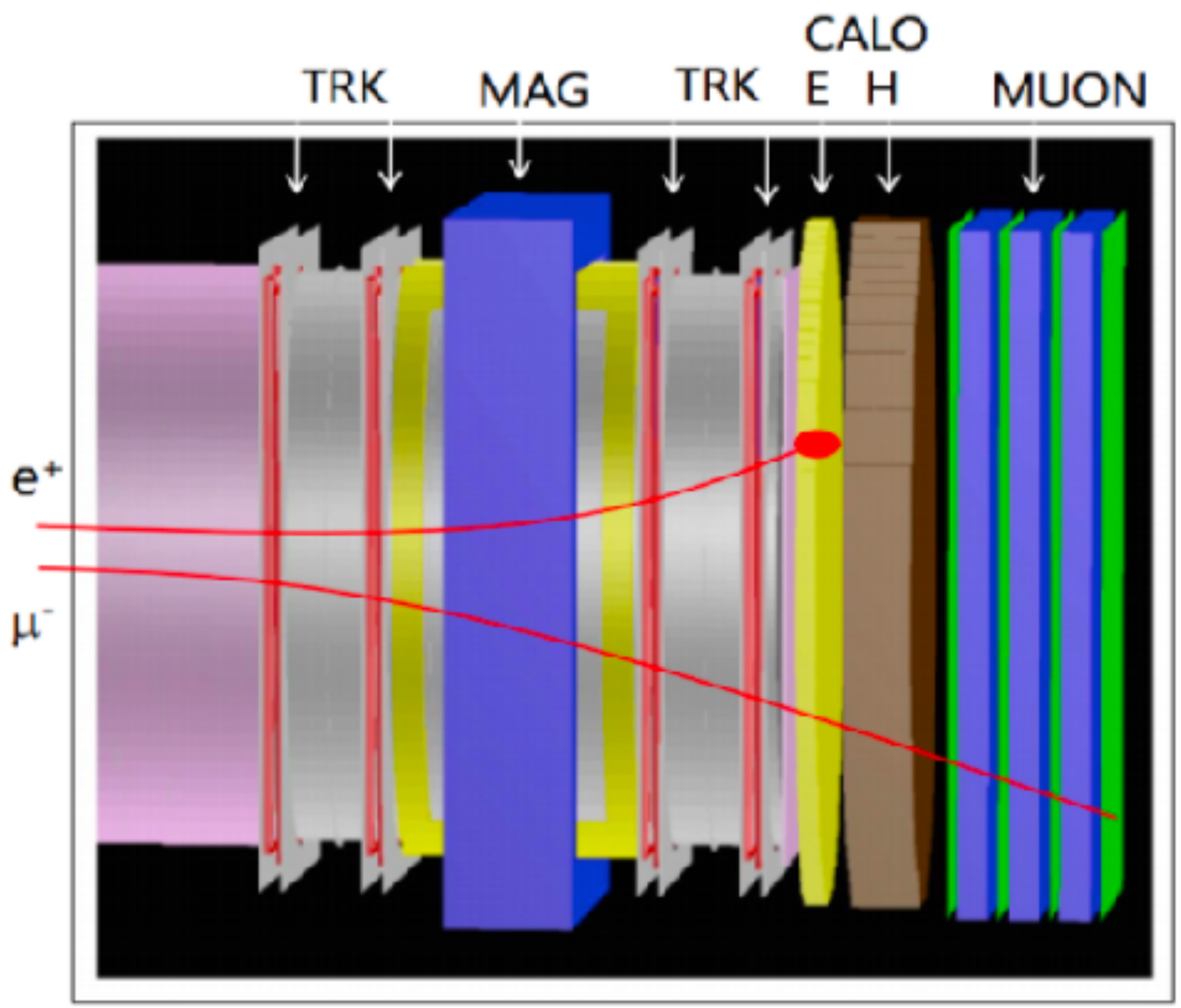
HNL decay product spectrum

(DP harder)

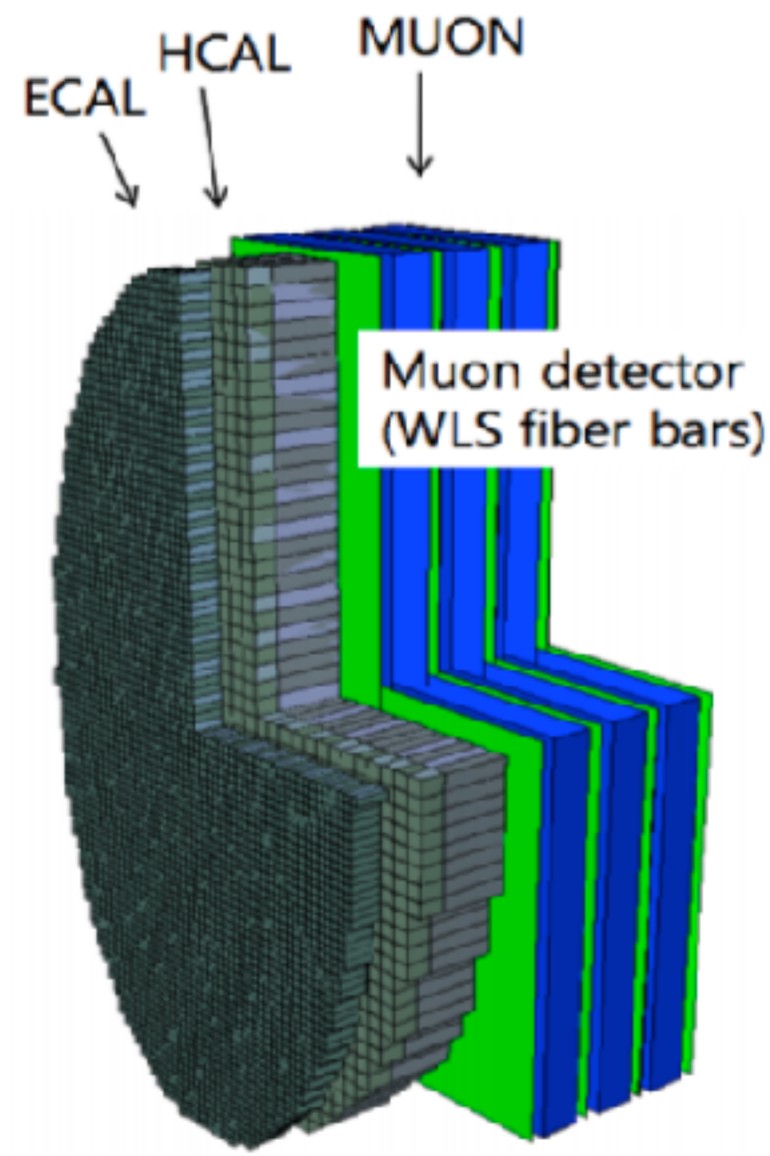


T

Calorimeter and Muon detector

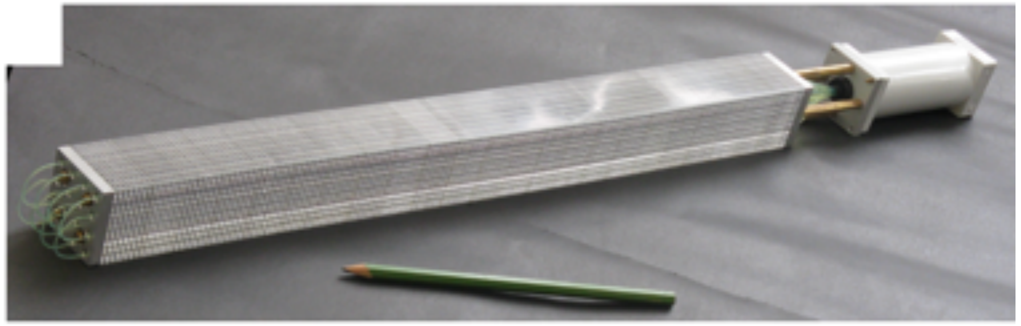


ECAL : e/γ id, π^0 and η reconstruction
(Shashlik technique, LHCb)



HCAL : π/μ separation
(similar technology as ECAL)

Physics: HNL—>ππ⁰l, DP—> πππ⁰, e-/π separation in HNL—>πe



Particle rate —> low

Shashlik (a la LHCb)

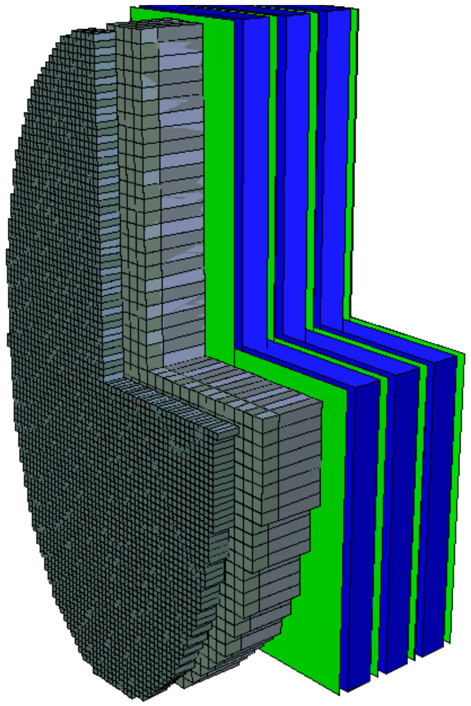
Cells of 6×6 cm^2 cross section

with 140 alternating layers of

1 mm lead and 2 mm scintillator.

Total depth of ~50 cm = 25 X_0

$\sigma(E)/E \approx 5.7\%/\sqrt{E}$

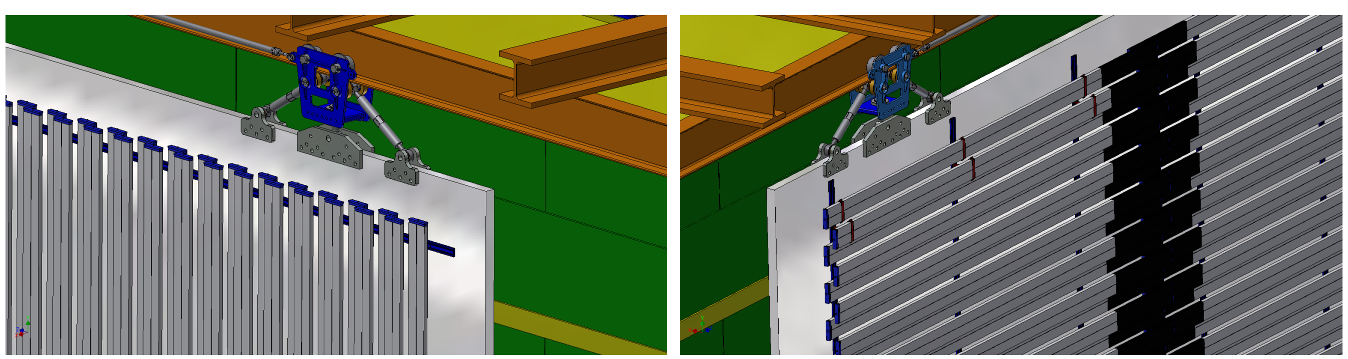


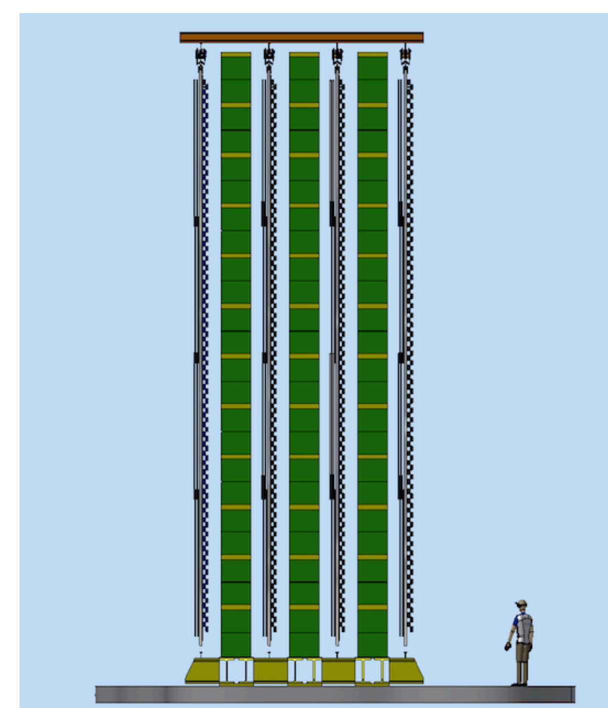
The HCAL and MUON detector in the Technical Proposal

The TP design (2)

Design:

cover μ/π separation above few GeV's <threshold> with "MUON" detector (4 layers of plastic extruded scintillator read out by WLS fibres and SiPMS's and digital readout alternated with 3.4 λ_I iron absorbers) —> a "topological" detector





The TP design (2)

and cover the low momentum region <4GeV with iron Shashlik HCAL with 24x24cm^2 cells with 6.2 λ_I

first thin section (H1) with 18 sampling layers followed by a second section (H2) of 48 layers
(Shashlik was chosen just for conceptual simulation)

Of course the MUON detector threshold depends on what is in front in terms of λ_I

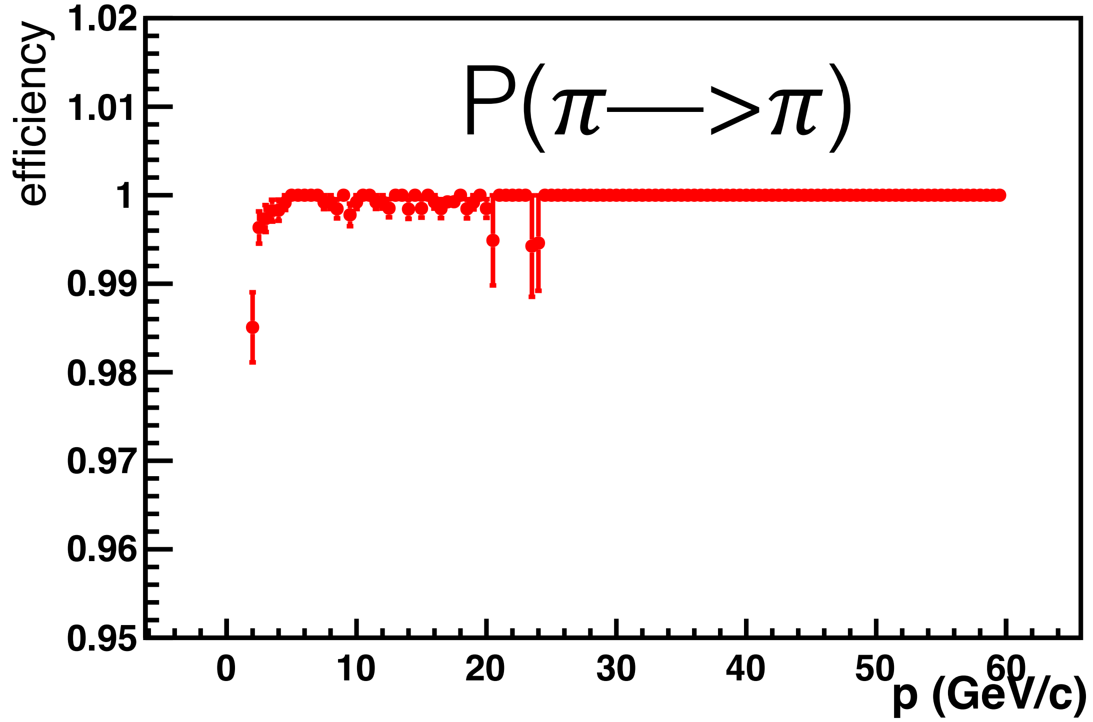
Performance studies already in the TP

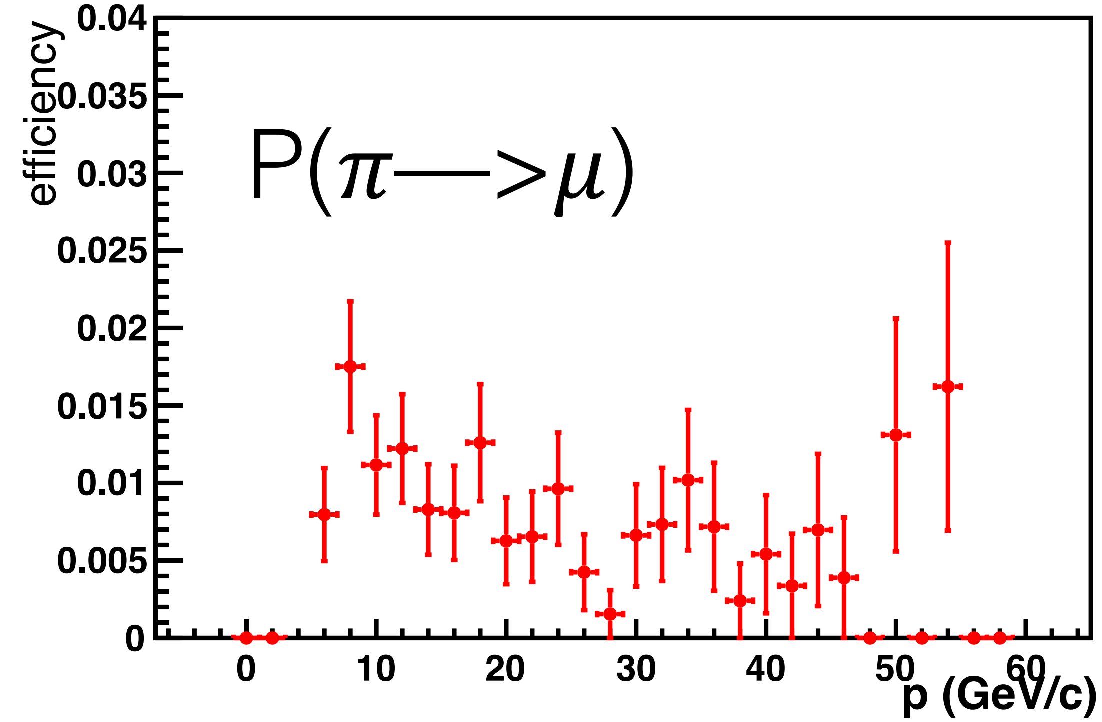
ECAL response studied with FairSHiP MC

HCAL detector optimised stand-alone (not in FairSHiP)

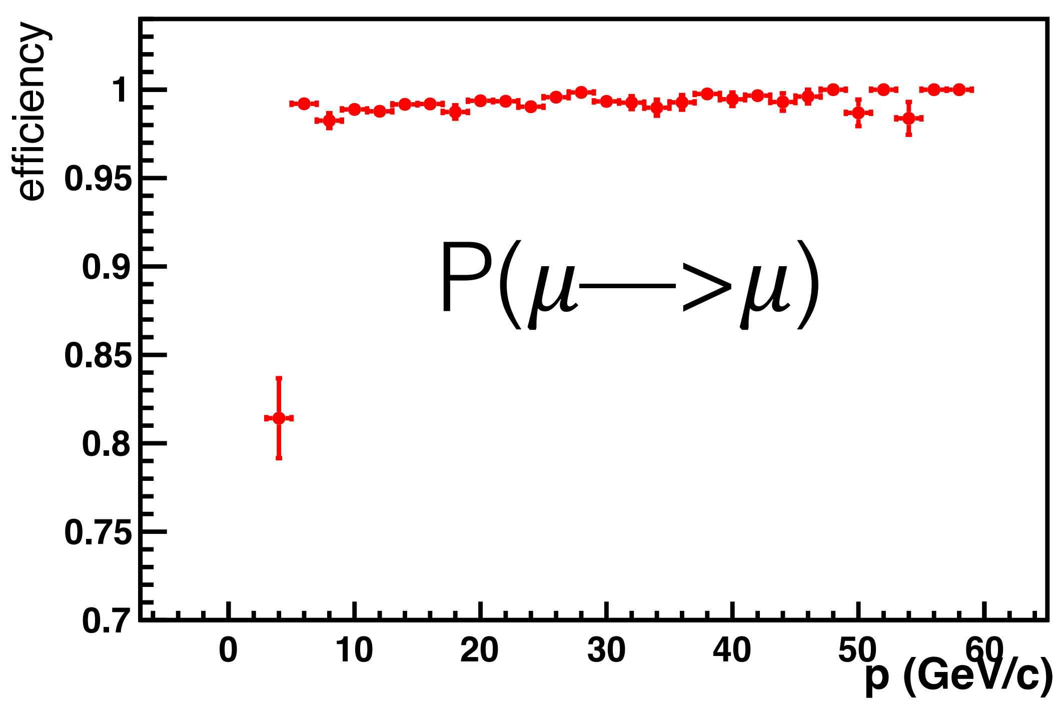
MUON detector NOT optimised but simulated in FairSHiP with HCAL in front ($6.2\lambda_I$)

Beware: hadronic shower response in MC not completely reliable





Performance on non-decaying pions of the MUON detector



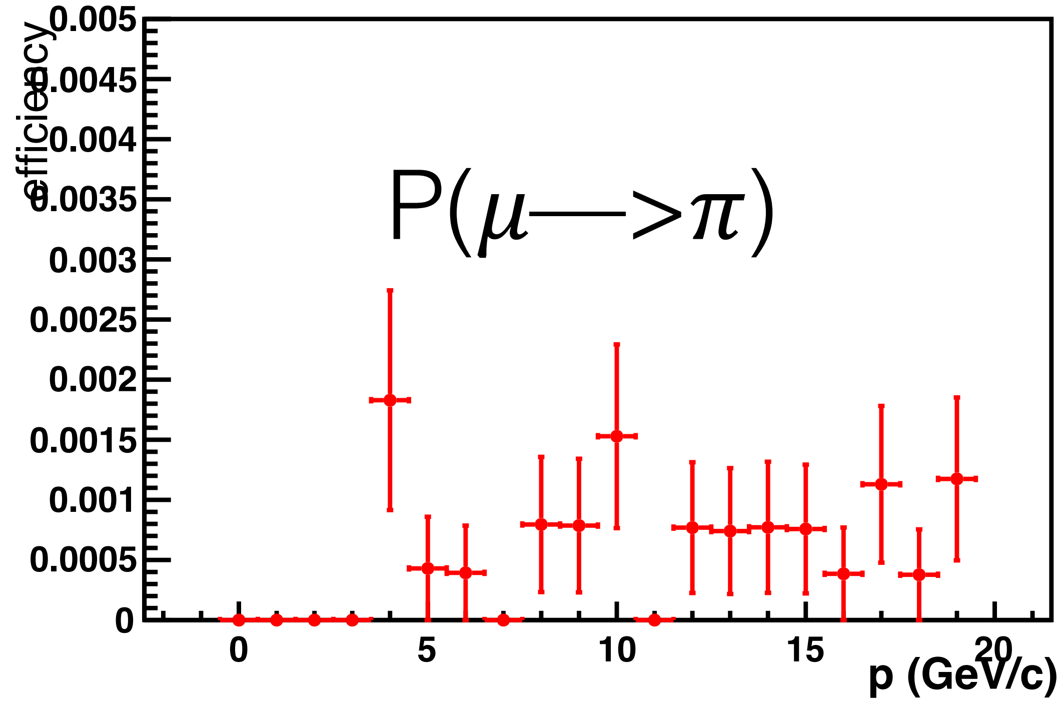


Table 4.8: Pion suppression factors and pion misidentification probabilities at 95% muon identification efficiency, achieved by ECAL $\oplus$ H1$\oplus$H2 in the current geometry.

Track momentum (GeV/c)	1	1.5	2	2.7	3	5	10
π suppression factor	23	32	50	120	160	210	250
π misidentification probability (%)	4.3	3.1	0.20	0.83	0.63	0.48	0.40

HCAL and ECAL combined

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

SHiP

CERN-SHiP-NOTE-2016-CDS number
July 23, 2017

Particle Identification tools and performance in the SHiP Experiment

Behzad Hosseini[1] and Walter Bonivento[1]

[1] INFN Cagliari

Abstract

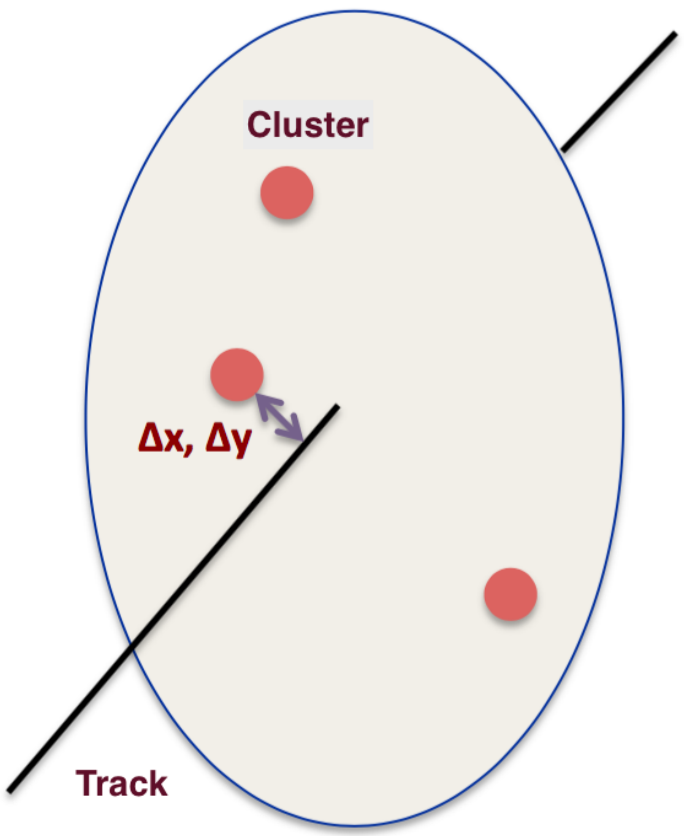
This note describes in detail the implementation and performance of the PID algorithm in the FairSHiP simulation.

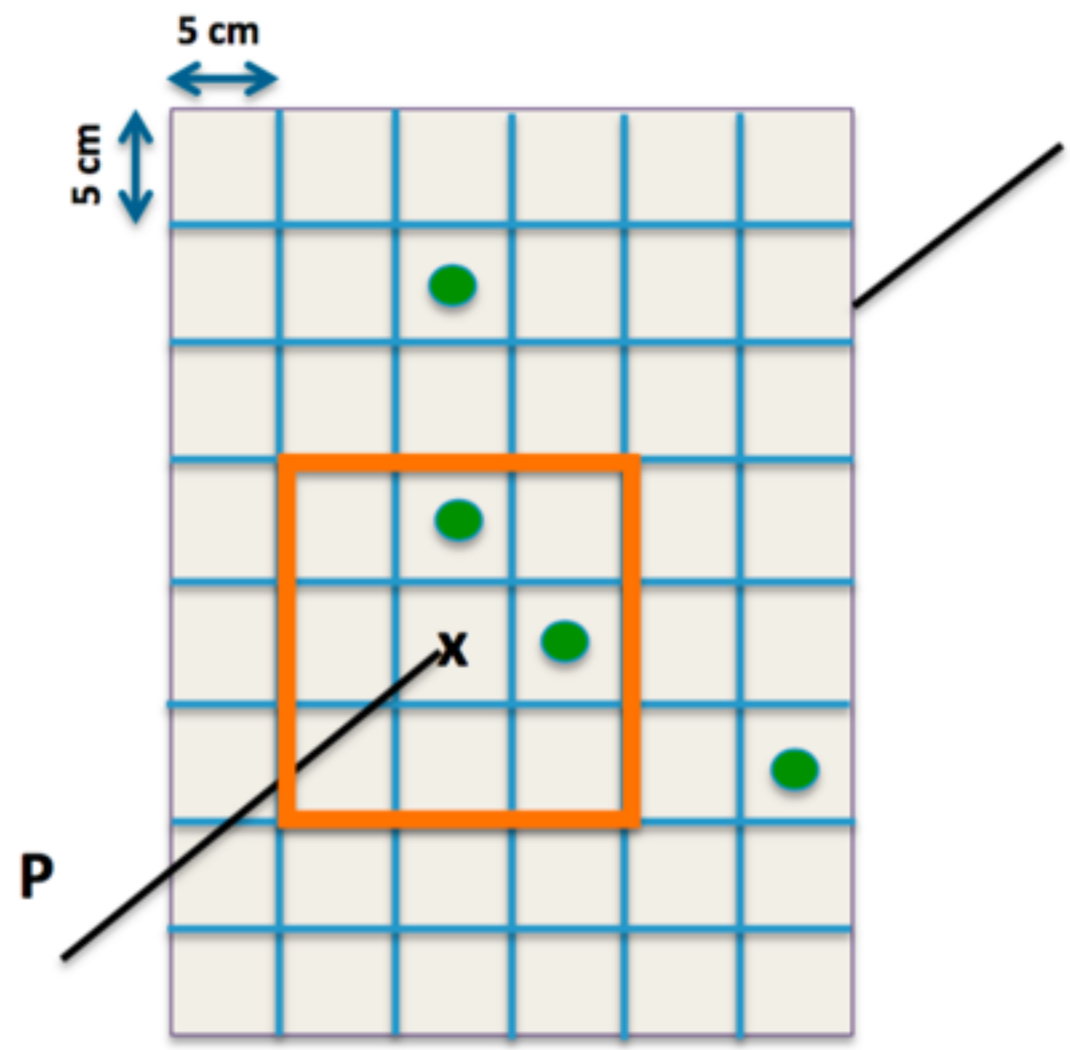
Post-TP performance studies with FairSHiP

PID software implemented in FairSHiP

- A new 30000 events are generated with the last updated FairShip using pythia8.
  - μμ, ee, ππ, μπ, πe, μμυ, eeυ, μeυ
- Following cuts aplied:
  - 1 HNL candidate
  - Vertex and tracks are in the fiducial volume
  - N.d.f > 25
  - DOCA < 1 cm
  - X^2 / n.d.f < 5
  - $P_{Daughters}$ > 1 GeV
  - IP cut: 2boddy (<10), 3boddy (>10 & <250)
  - No particle out of the acceptance of the PID detectors

24/11/2016 9th SHiP Collaboration Meeting - Behzad





ECAL/HCAL cuts (position extrapolated at shower max)

Δx,Δy and E/p (for e- should be around 1)

MUON detector cuts: Δx,Δy ,#hits, penetration

All cuts momentum dependent

for p<5 Gev check HCAL penetration and consistency with mip

PID with signal channels: HNL, Dark Photon

REC → GEN ↓	μ-μ	e-e	π-π	μ-π	π-e	μ-e
μ-μ 2 body	324/328 **98.78%**			4/328 **1.22%**		
e-e 2 body		280/281 **99.64%**			1/281 **0.36%**	
π-π 2 body			278/294 **94.56%**	4/294 **1.36%**	12/294 **4.08%**	
μ-π 2 body	4/273 **1.47%**		1/273 **0.36%**	266/273 **97.44%**		2/273 **0.73%**
π-e 2 body		1/296 **0.33%**	2/296 **0.67%**		287/296 **97%**	6/296 **2%**

REC → GEN ↓	μ-μ	e-e	μ-e	μ-π	π-e
μ-μ 3 body	283/287 **98.61%**			4/287 **1.39%**	
e-e 3 body		269/275 **98.91%**			3/275 **1.09%**
μ-e 3 body		3/279 **1.08%**	275/279 **98.56%**		1/279 **0.36%**

1GeV

REC → GEN ↓	μ-μ	e-e	π-π	μ-π	π-e	μ-e
μ-μ 2 body	287/291 **98.63%**			4/291 **1.37%**		
e-e 2 body		266/267 **99.63%**			1/267 **0.37%**	
π-π 2 body		3/297 **1%**	268/297 **90.24%**	5/297 **1.68%**	20/297 **6.73%**	1/297 **0.34%**
μ-π 2 body	23/296 **7.77%**		2/296 **0.68%**	259/296 **87.5%**	1/296 **0.34%**	11/296 **3.72%**
π-e 2 body		12/236 **5.08%**			221/236 **93.64%**	3/236 **1.27%**

REC → GEN ↓	μ-μ	e-e	μ-e	μ-π	π-e
μ-μ 3 body	312/317 **98.42%**			5/317 **1.58%**	
e-e 3 body		230/231 **99.57%**			1/231 **0.43%**
μ-e 3 body		12/240 **5%**	223/240 **92.92%**		5/240 **2.08%**

400MeV

REC → GEN ↓	μ-μ	e-e	π-π	μ-π	π-e	μ-e
μ-μ 2 body	324/328 98.78%			4/328 1.22%		
e-e 2 body		280/281 99.64%			1/281 0.36%	
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e-e 3 body		230/231 99.57%			1/231 0.43%
μ-e 3 body		12/240 5%	223/240 92.92%		5/240 2.08%

pion decays in flight

REC → / GEN ↓	μ-μ	e-e	π-π	μ-π	π-e	μ-e
μ-μ 2 body	324/328 98.78%			4/328 1.22%		
e-e 2 body		280/281 99.64%			1/281 0.36%	
π-π 2 body			278/294 94.56%	4/294 1.36%	12/294 4.08%	
μ-π 2 body	4/273 1.47%		1/273 0.36%	266/273 97.44%		2/273 0.73%
π-e 2 body		1/296 0.33%	2/296 0.67%		287/296 97%	6/296 2%

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e-e 3 body		230/231 99.57%			1/231 0.43%
μ-e 3 body		12/240 5%	223/240 92.92%		5/240 2.08%

charge exchange reaction (can occur at any depth) et al. (in MC they are seen as true e-)

the other mis-id's depend are due to overlapping tracks in CALO's

ν-induced background

Doca<1 & 10 < IP < 250

VETO on =SBT+upstream veto+muon detector of neutrino detector

'otal events from Iaroslava: 249
Ve remain with 128 events.

Accepted Invariant mass: **InvMass<10GeV**

To scale to 2e^{20} pot divide by 8.3 for Air and 66.4 for He

Most of the **μπ** events have rejected due to the IP>10

10 < IP < 250 cm
(as for N→μμυ)

	μ-μ IP>10	e-e IP>10	μ-e IP>10	μ-π IP>10	π-π IP>10
Rec	3	1	11	105	8

N_{air} = 1.8
N_{helium} = 0.22

if vacuum =10^{-3} bar, background=0.016 events even without PID; NB: these are the neutrinos only

Why evolving compared to TP?

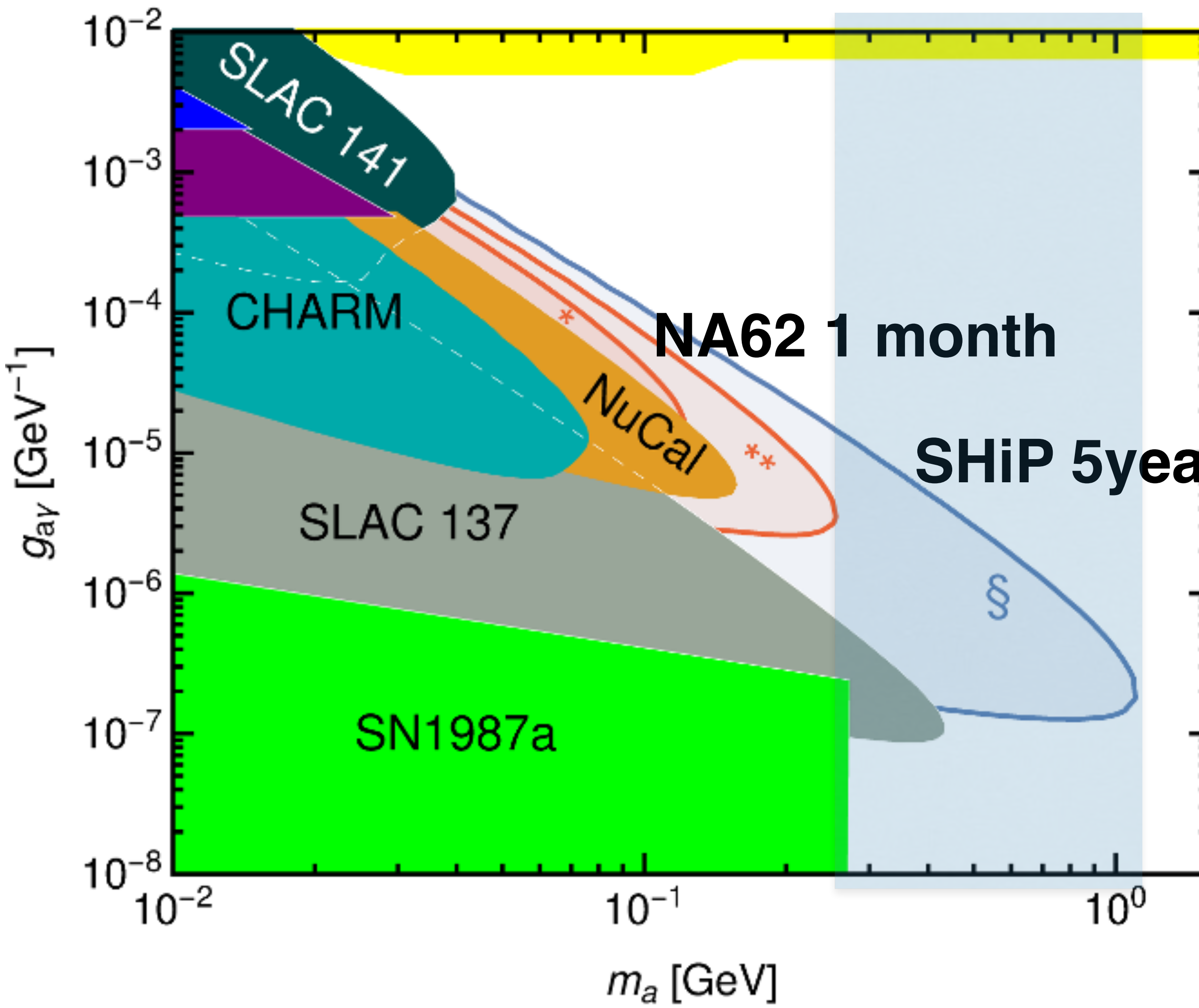
1) reduce possibly cost of Shashlik
2) add the measurement of shower direction for neutral final states (need few mrad resolution for ALP—>γγ) and possibly suppress background
3) improve e/π separation

of course it is a 5x10 m^2 guy (or lady)…

Search for

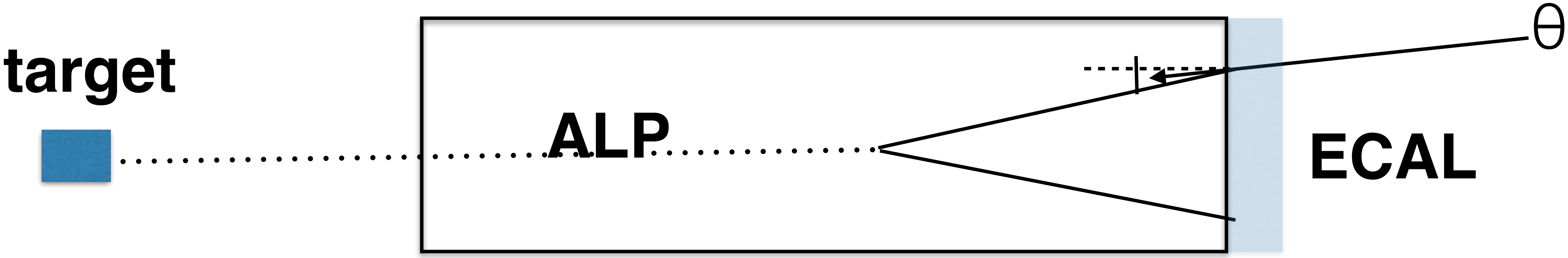
ALP—>γγ

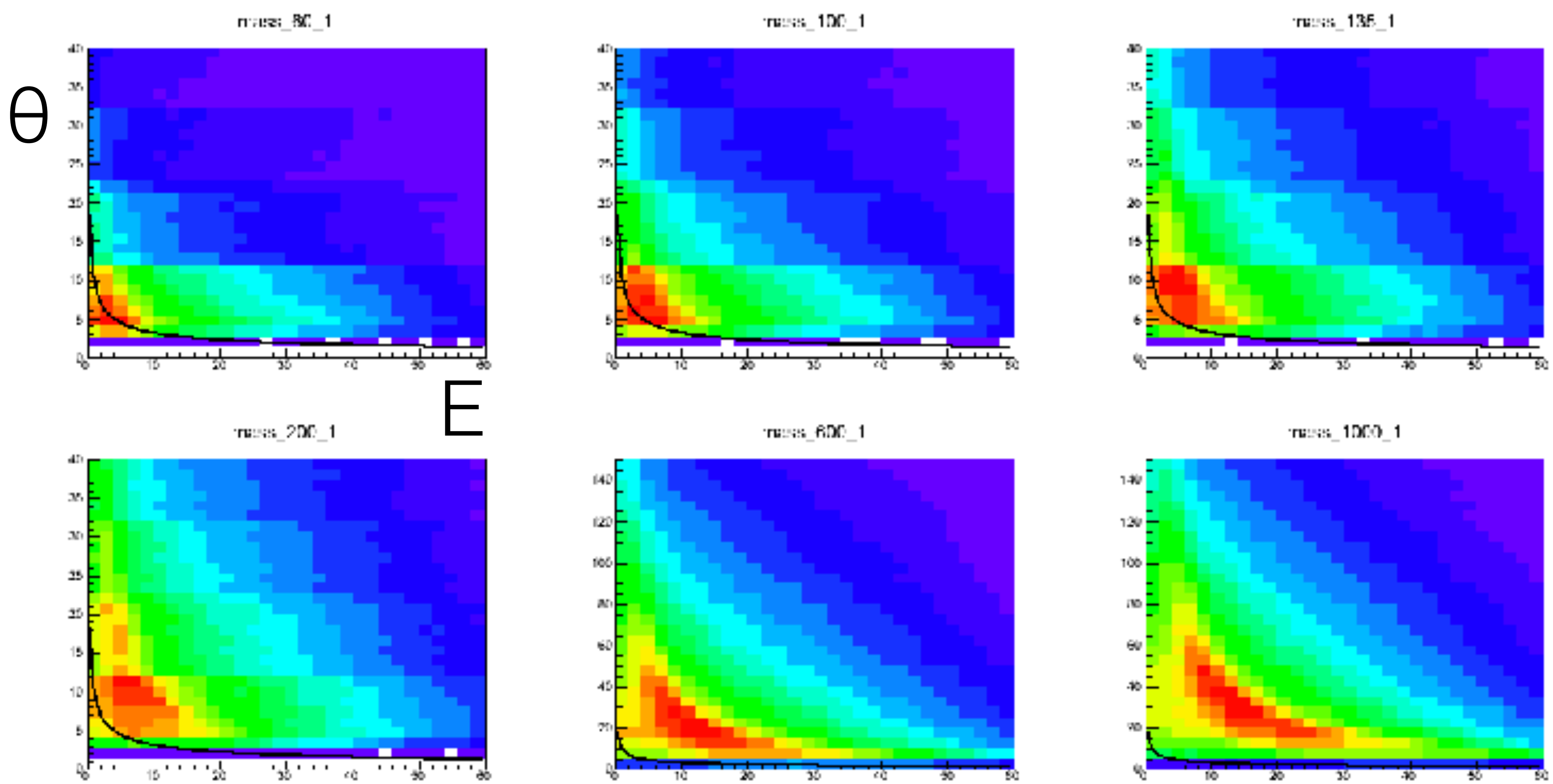
JHEP 1602 (2016) 018



300MeV-1GeV

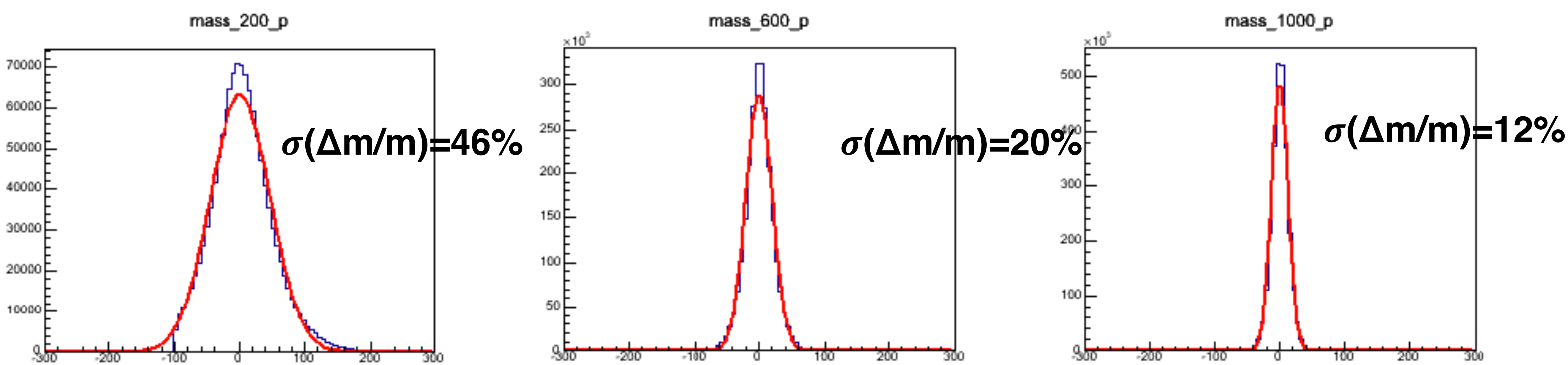
ANGLES





$\sigma(\theta)=10\,\text{mrad}/\sqrt{E}$ ->black curve

Why to care about mass reconstruction? imagine we find 10 two-photon only events. Wouldn't you like to see an accumulation of a mass peak to claim we have a discovery (and not some background)?



the mass region which is only for us (not for NA62)

The measurement of the shower direction

This is not a completely new subject:

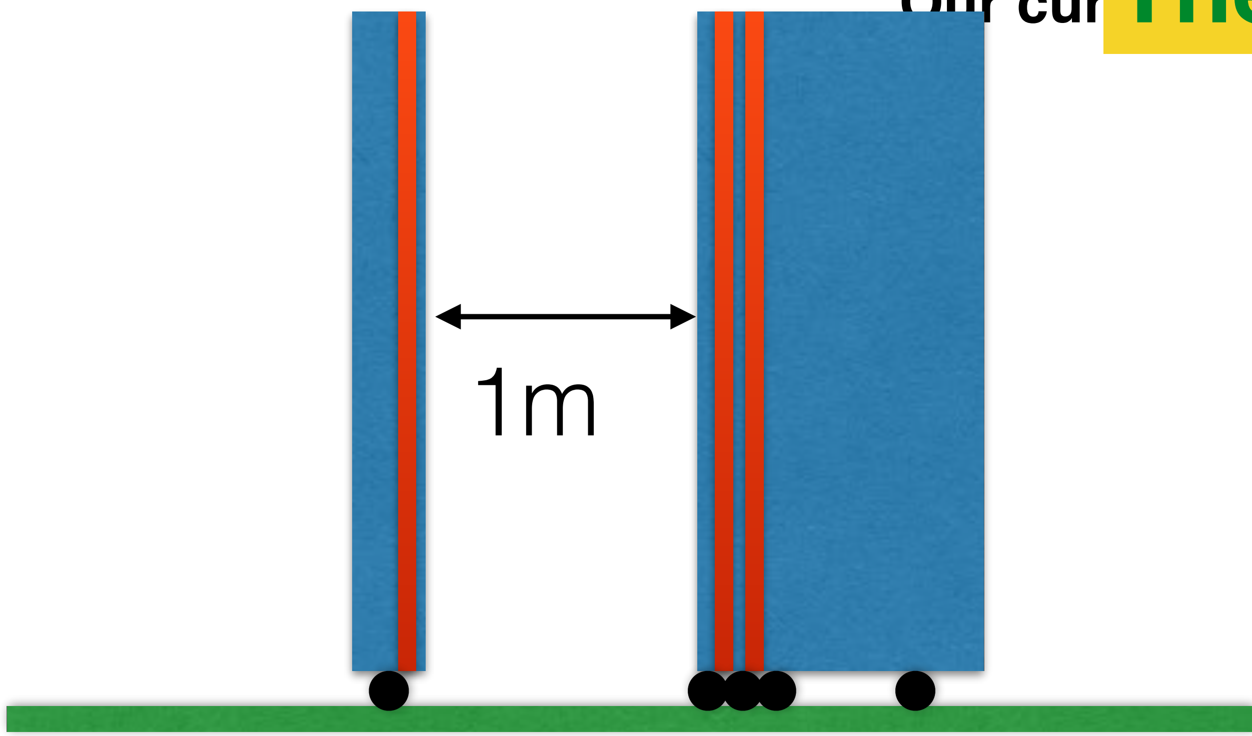
- e.g. ATLAS, though in one direction only (η)

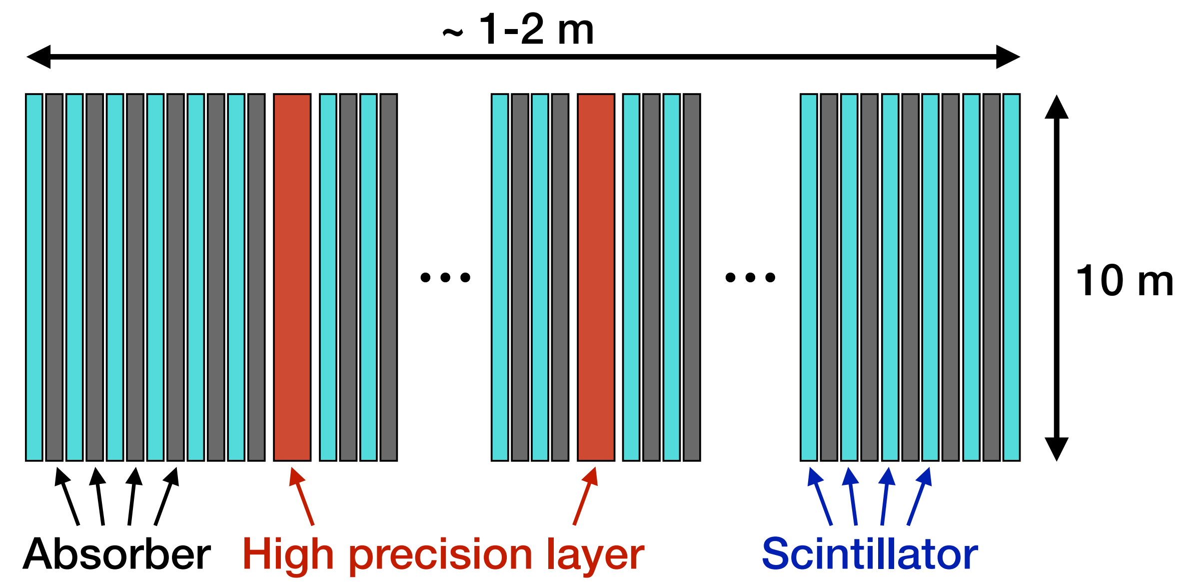
- γ-ray experiments (e.g. FERMI) in space can measure it with high precision but very low efficiency (here we need full efficiency)

In SHiP we can take advantage of the fixed target configuration that leaves some room in the longitudinal direction —> increase the lever arm

I show here some new ideas supported by GEANT simulation but work is not finished!

The SplitCal



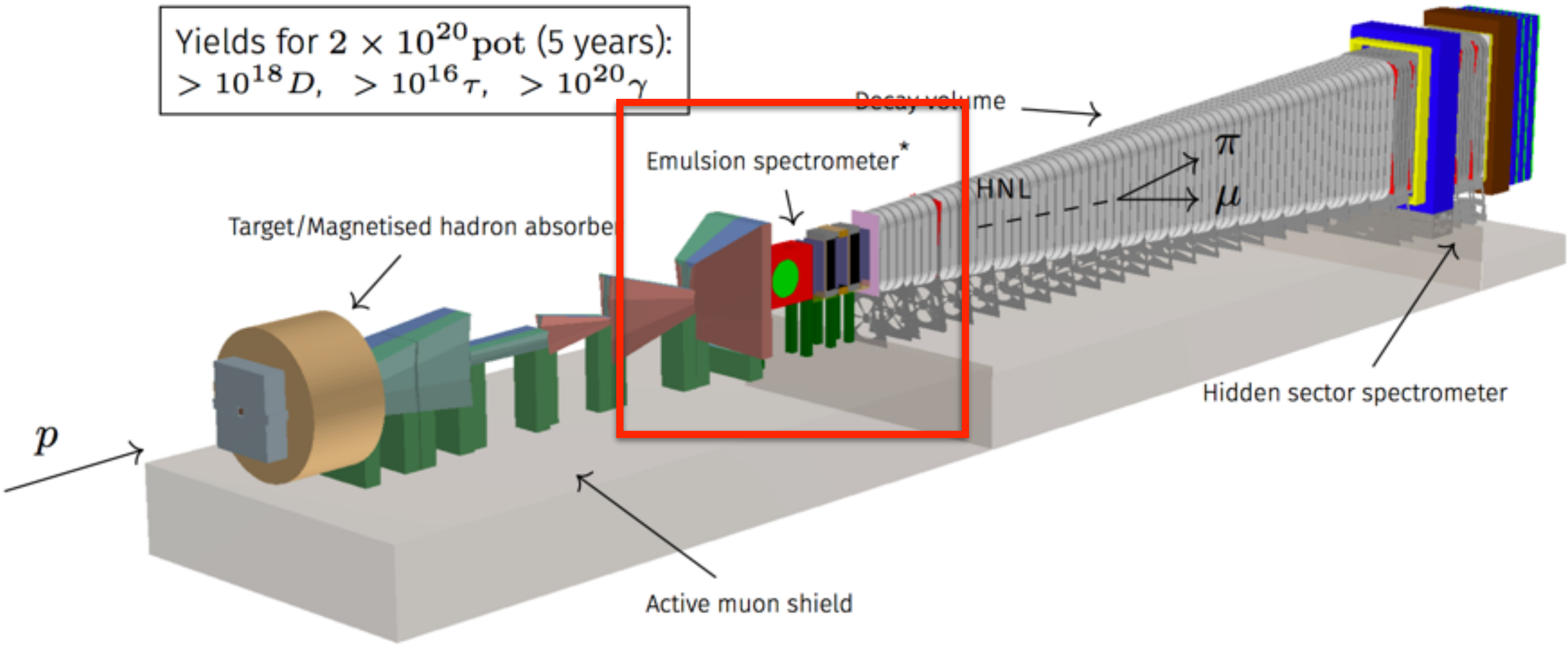


150µm pads

Implemented in GEANT-based simulation with some simplifying assumptions

in blue a sampling ECAL with X-Y plastic scintillator bars readout via WLS fibres from the sides, coarse granularity

in red the high precision layers at $3X_0$, $5X_0$ and $6.5\ X_0$ (µ-pattern gas detectors with pad readout with digital readout) that could also be staged



Yields for 2×10^{20} pot (5 years):
$> 10^{18} D, \quad > 10^{16} \tau, \quad > 10^{20} \gamma$
Decay volume
Emulsion spectrometer*
HNL
π
μ
Target/Magnetised hadron absorbe
p
Hidden sector spectrometer
Active muon shield

Physics with the upstream detector

Structure functions in the Standard Model

ν_τ DIS

Nucl. Phys. B84, 467 (1975)

$$W_{\mu\nu} = \overline{\sum_{\text{spin } N}} \sum_F \langle N|J_\mu^{\circledast}|F\rangle\langle F|J_\nu|N\rangle\,\delta(q+p-p_F)$$
$$= -\delta_{\mu\nu}W_1 - \frac{1}{M^2}p_\mu p_\nu W_2 - \frac{1}{2M^2}\epsilon_{\mu\nu\alpha\beta}p_\alpha q_\beta W_3 - \frac{1}{M^2}q_\mu q_\nu W_4$$
$$- \frac{1}{2M^2}(p_\mu q_\nu + p_\nu q_\mu)W_5\,,$$

decomposition of the hadronic tensor with them reversal invariant structure functions $W_i(q^2,\nu)$
(p is 4momentum of nucleon)

Assuming Bjorken scaling

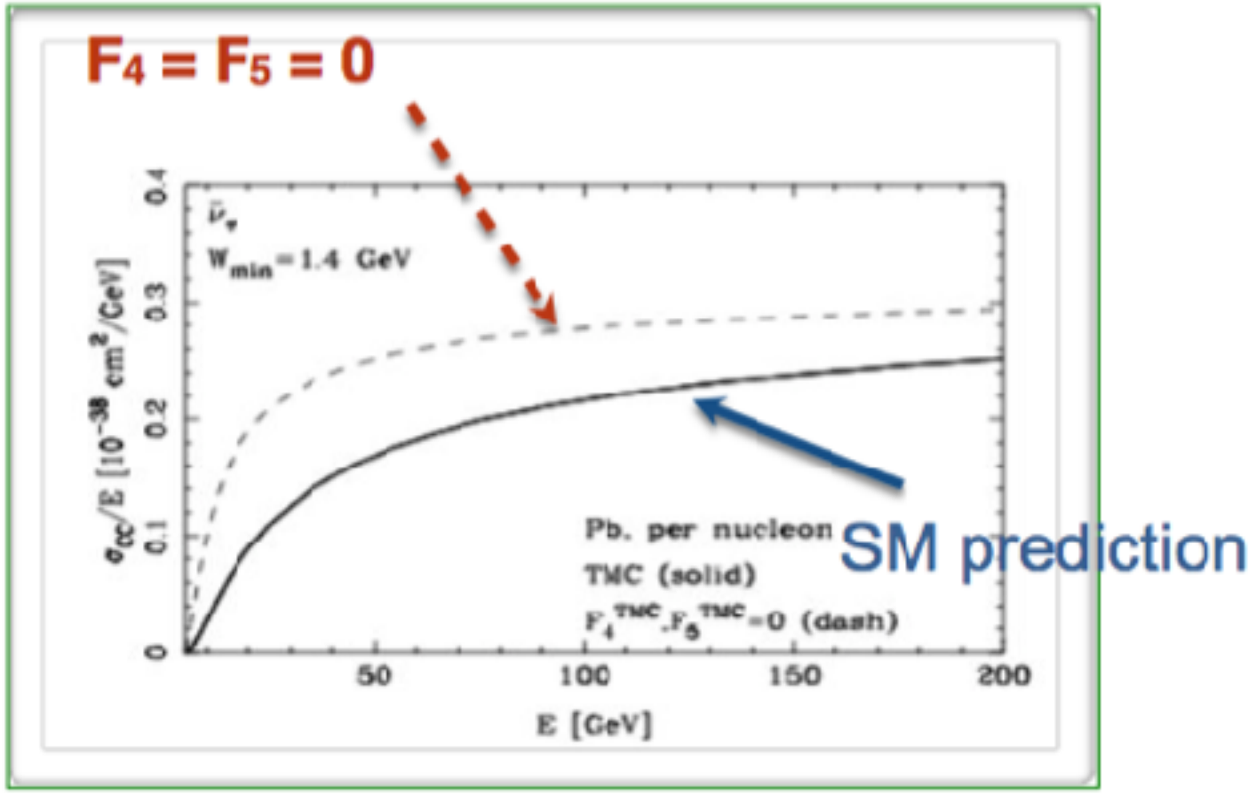
$$\lim_{\mathrm{Bj}} MW_1 = F_1(x)\,, \qquad \lim_{\mathrm{Bj}} \nu W_k = M F_k(x)\,,$$

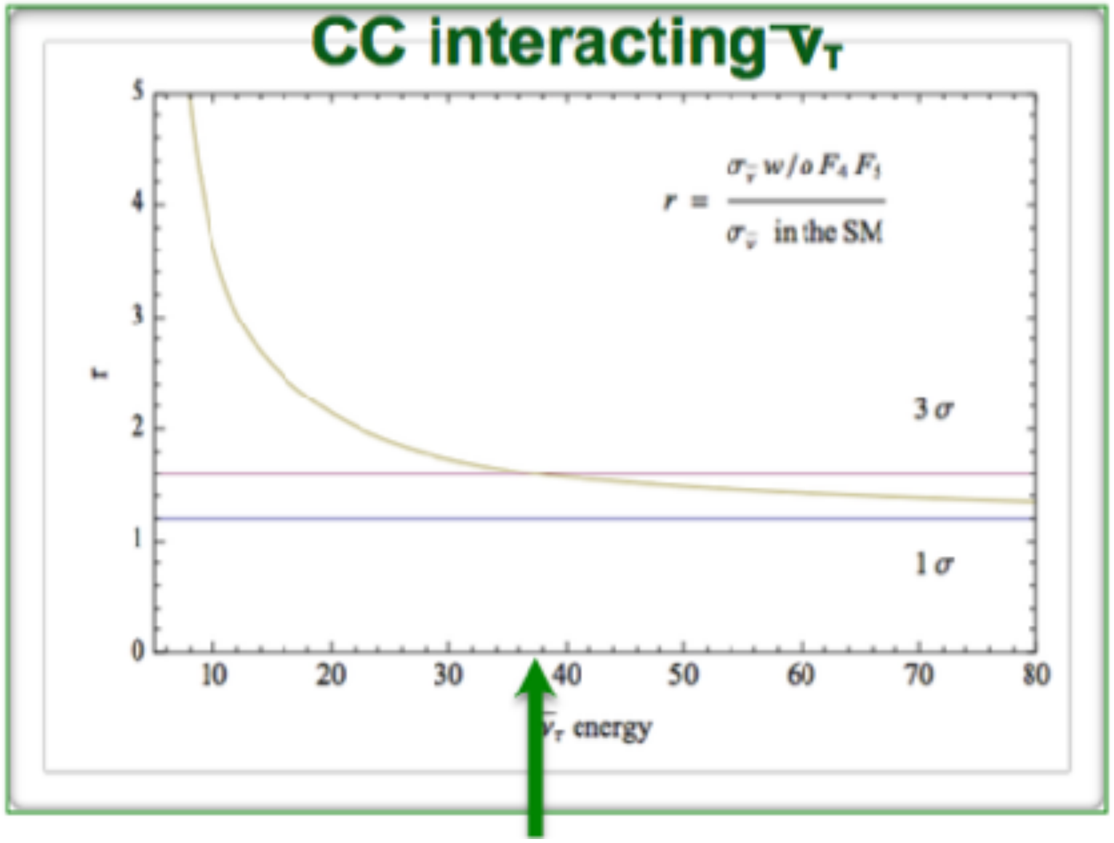
$$\frac{d^2\sigma^{\nu,\bar\nu}}{dx\,dy} = \frac{G^2ME}{\pi}\left\{\left(xy + \frac{m^2}{2ME}\right)y\,F_1 + \left[(1-y) - \left(\frac{M}{2E}xy + \frac{m^2}{4E^2}\right)\right]F_2\right.$$
$$\left.\mp\left[xy(1-\tfrac{1}{2}y) - \frac{m^2}{4ME}y\right]F_3 + \frac{m^2}{M^2}\left[\left(\frac{M}{2E}xy + \frac{m^2}{4E^2}\right)F_4 - \frac{M}{2E}F_5\right]\right\}$$

Assuming $2xF_1 = F_2$ (Callan-Gross), and $-xF_3=F_2$, verified experimentally, it follows that $F_4 = 0$ and $2xF_5=F_2$ (Albrecht-Jarlskog). LO QCD (parton model) confirms these relations.

F_4 and F_5 cannot be measured in ν_μ and ν_e scattering since they are suppressed by mass terms

ν_τ DIS



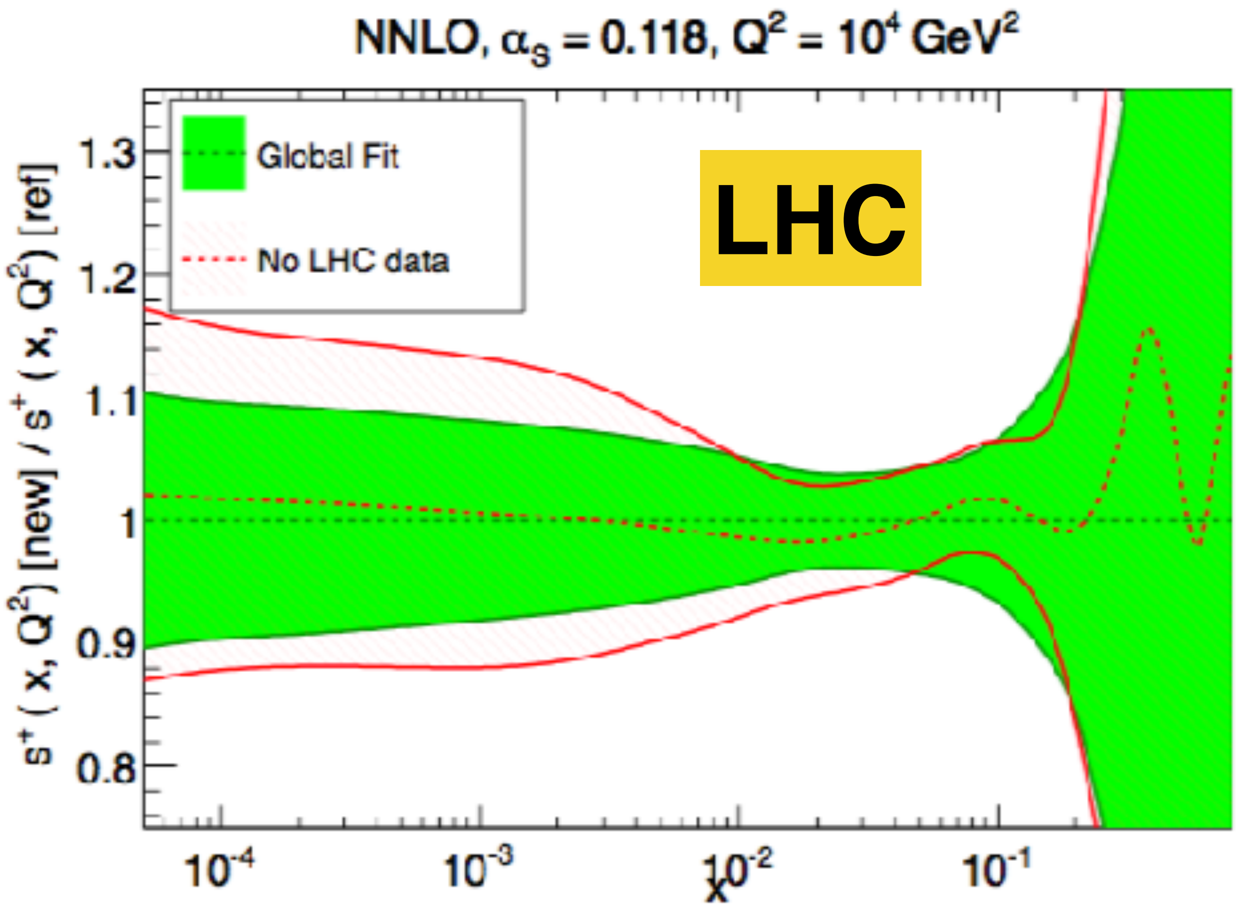


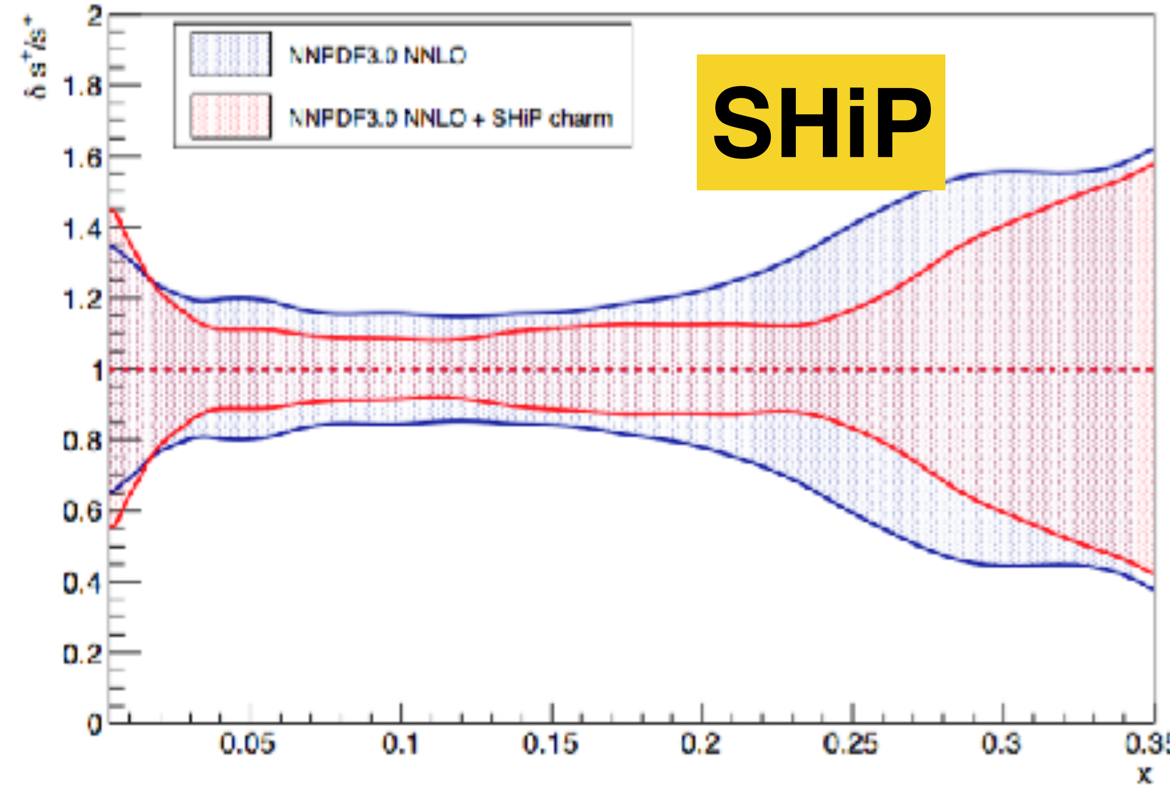
With SHiP we can test for the first time the full neutrino DIS formula providing one of last remaining fundamental tests of the SM.

NB: $\sigma(\nu_\tau)<\sigma(\nu_\mu)$ in the SM, and half the difference comes from reduced phase space and half from F_5

…and not to forget that the anti-ν_τ was not observed so far…

s-quark structure function





LHC and SHiP will probe the strangeness distribution in different ranges of x.

With $Q^2 \sim M_W^2$ measurements of W and W+c production at the LHC constraint on strangeness at $x < 10^{-2}$

SHiP is sensitive above this range

Searches for NP

Lepton universality tests

Phys.Rev. D92 (2015) 7, 073016

No wonder that the third generation is the most interesting in this respect, less tested, higher mass ecc.(e.g. 2HDM)

Also some hints of LUV from LHCb, B Factories ecc.

In the presence of NP, the effective Hamiltonian for the scattering process $\nu_\tau + N \rightarrow \tau + X$

$$\mathcal{H}_{eff} = \frac{4G_F V_{ud}}{\sqrt{2}}\Big[(1+V_L)\,[\bar{u}\gamma_\mu P_L d]\,[\bar{l}\gamma^\mu P_L \nu_l] + V_R\,[\bar{u}\gamma^\mu P_R d]\,[\bar{l}\gamma_\mu P_L \nu_l]$$

$$+S_L\,[\bar{u}P_L d]\,[\bar{l}P_L\nu_l] + S_R\,[\bar{u}P_R d]\,[\bar{l}P_L\nu_l] + T_L\,[\bar{u}\sigma^{\mu\nu}P_L d]\,[\bar{l}\sigma_{\mu\nu}P_L\nu_l]\Big]$$

In which G_F is the Fermi coupling constant
$Vq\bar{q}$ is Cabibbo-Kobayashi-Maskawa (CKM) matrix element
$P_{L,R} = (1 \mp \gamma_5)/2$, $\sigma_{\mu\nu} = i[\gamma_\mu, \gamma_\nu]/2$

DIS cross section written including possible BSM couplings between light quarks and third generation leptons and compared to SM

We studied so the effect on total cross sections; differential yet to be done

Effect of NP on cross section: scalar-tensor model

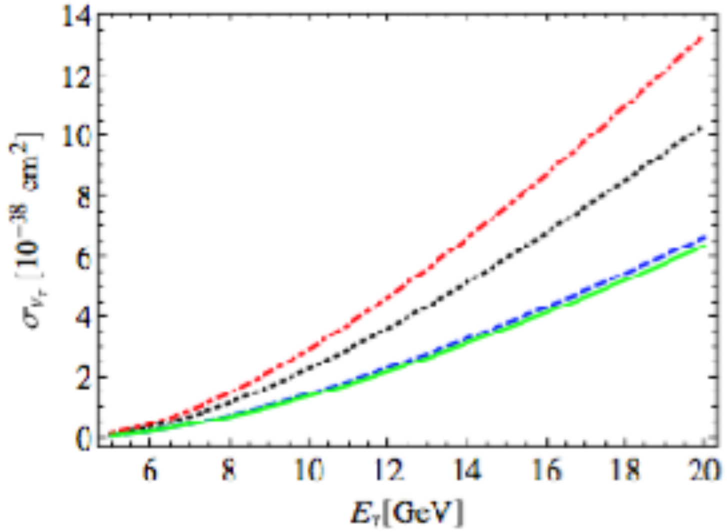


FIG. 10 (color online). $S \pm T$ model: The total cross section of $\nu_\tau + N \to \tau + X$ in the scalar-tensor model. The green solid line corresponds to the standard model prediction $S_R = S_L = T_L = 0$. The blue dashed, black dotted and red dot dashed lines correspond to $(S_R, S_L, T_L) = (-0.19, 0.68, 0.072)$, $(1.98, 0.42, -0.13)$, $(-1.87, -1.31, 0.18)$.

parameters allowed by τ hadronic branching ratio values

$A_S = S_R + S_L$ $B_S = S_R - S_L$

$$\frac{d\sigma_{\rm LQS}}{dxdy} = \frac{G_F^2 M E_\nu}{4\pi}(A_S^2 + B_S^2) y \left(xy + \frac{m_\ell^2}{2ME_\nu} \right) F_1,$$

$$\frac{d\sigma_{\rm LQT}}{dxdy} = \frac{8 G_F^2 M E_\nu}{\pi} T_L^2 \left(y \left(xy + \frac{m_\ell^2}{2ME_\nu} \right) F_1 + 2\left(1 - y - \frac{Mxy}{4E_\nu} - \frac{m_\ell^2}{8E_\nu^2} \right) F_2 - \frac{m_\ell^2}{ME_\nu} F_5 \right)$$

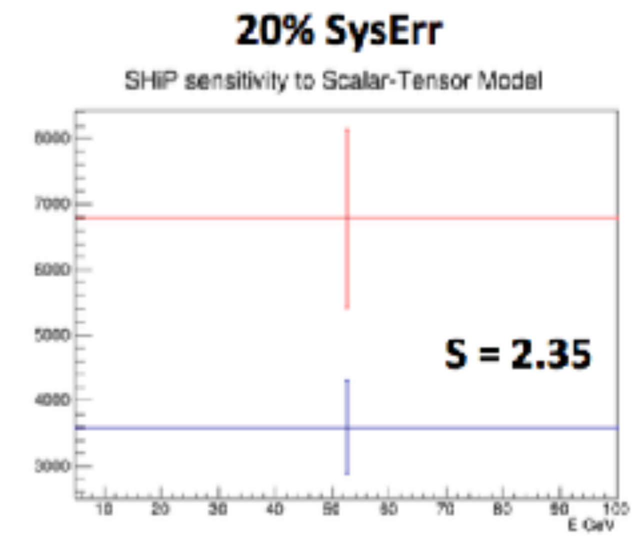
Preliminary results

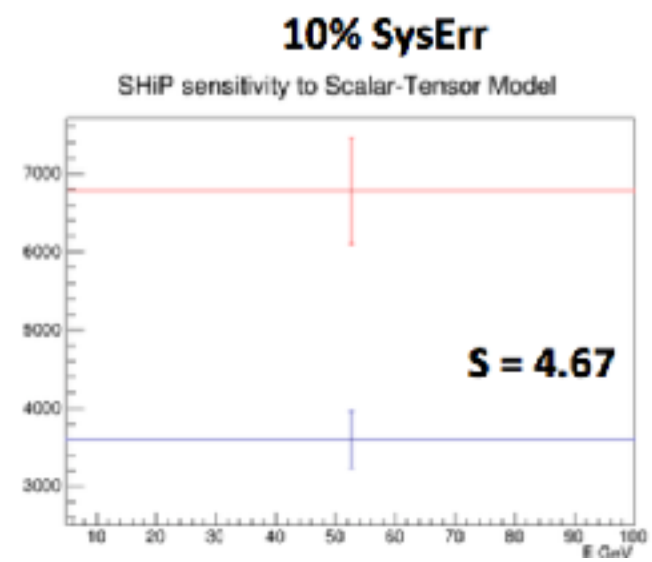
blue=SM

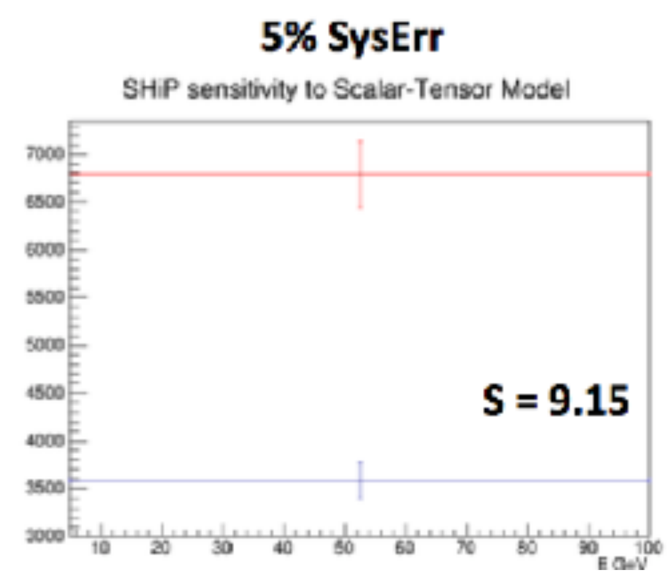
red=scalar and tensor model (e.g a scalar Leptoquark);

results depend on the level of total error: normalization important!

$$S = \frac{Num_{NP} - Num_{SM}}{NP_{Err}}$$

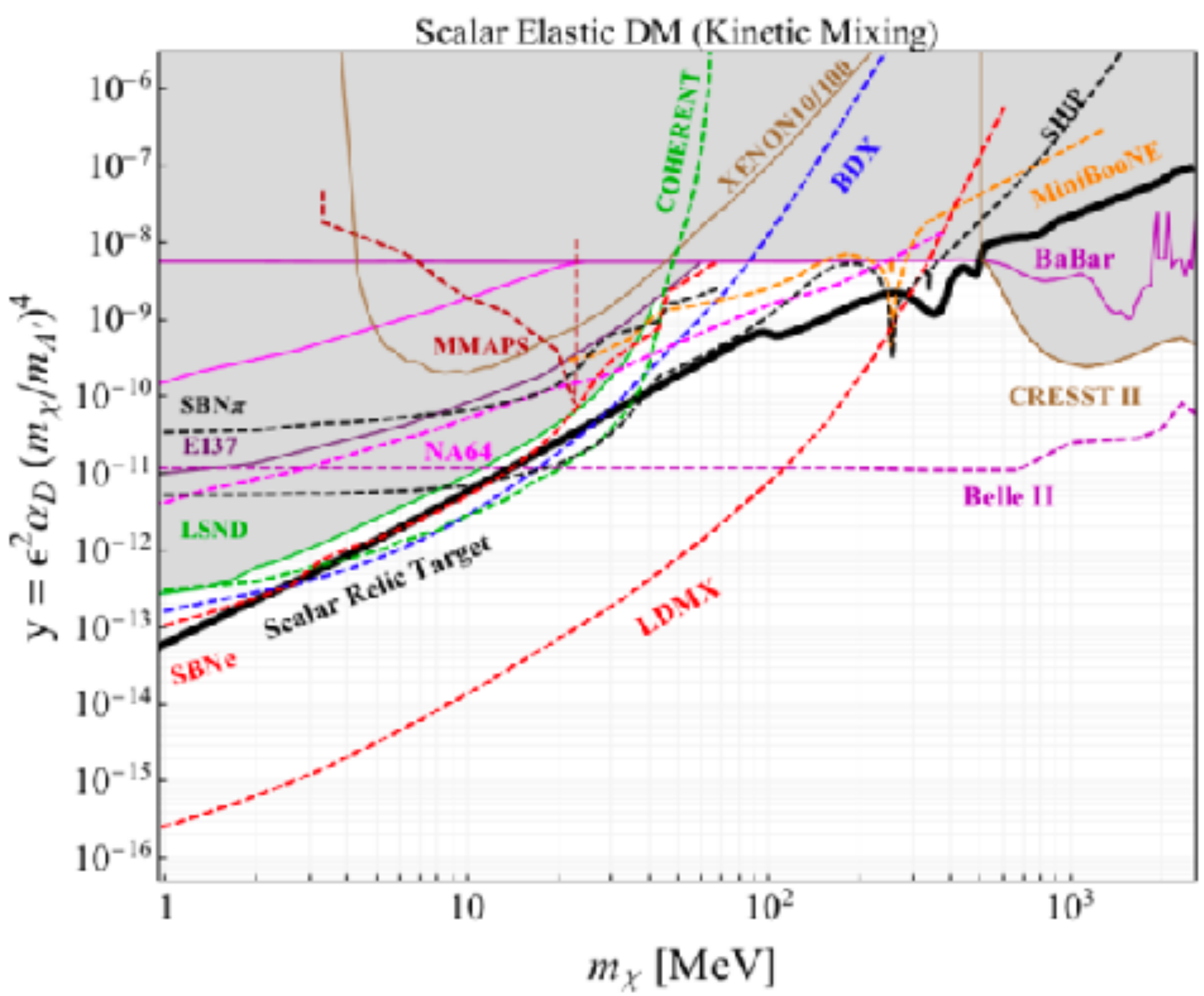






χ scattering

Dark photon decaying to dark matter

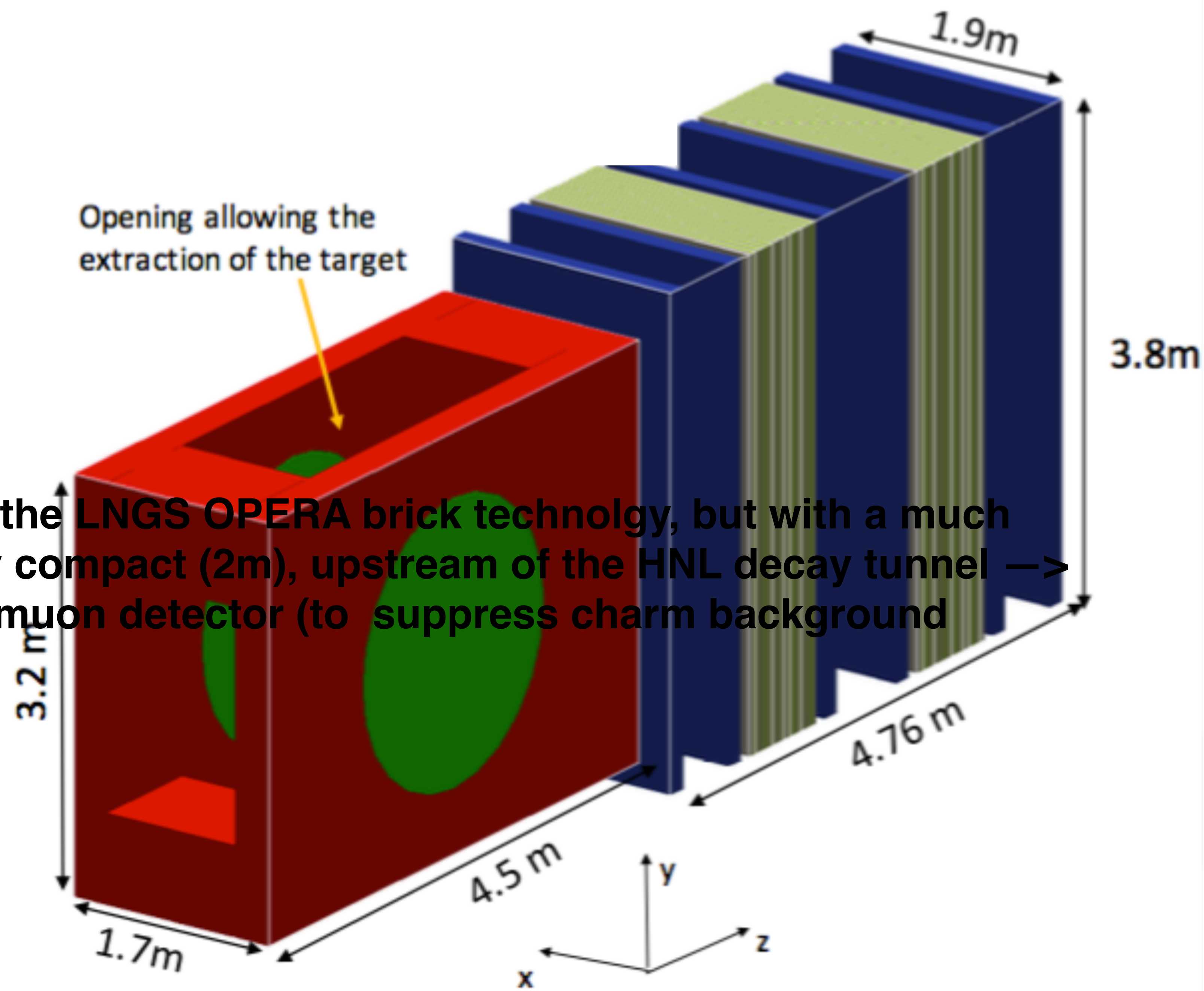


US Cosmic Visions: New Ideas in Dark Matter 2017 : Community Report arXiv:1707.04591v1 [hep-ph]

Detect neutral current interaction on atomic e-

—>not a background-free search (but calculable)

Light ν's detector

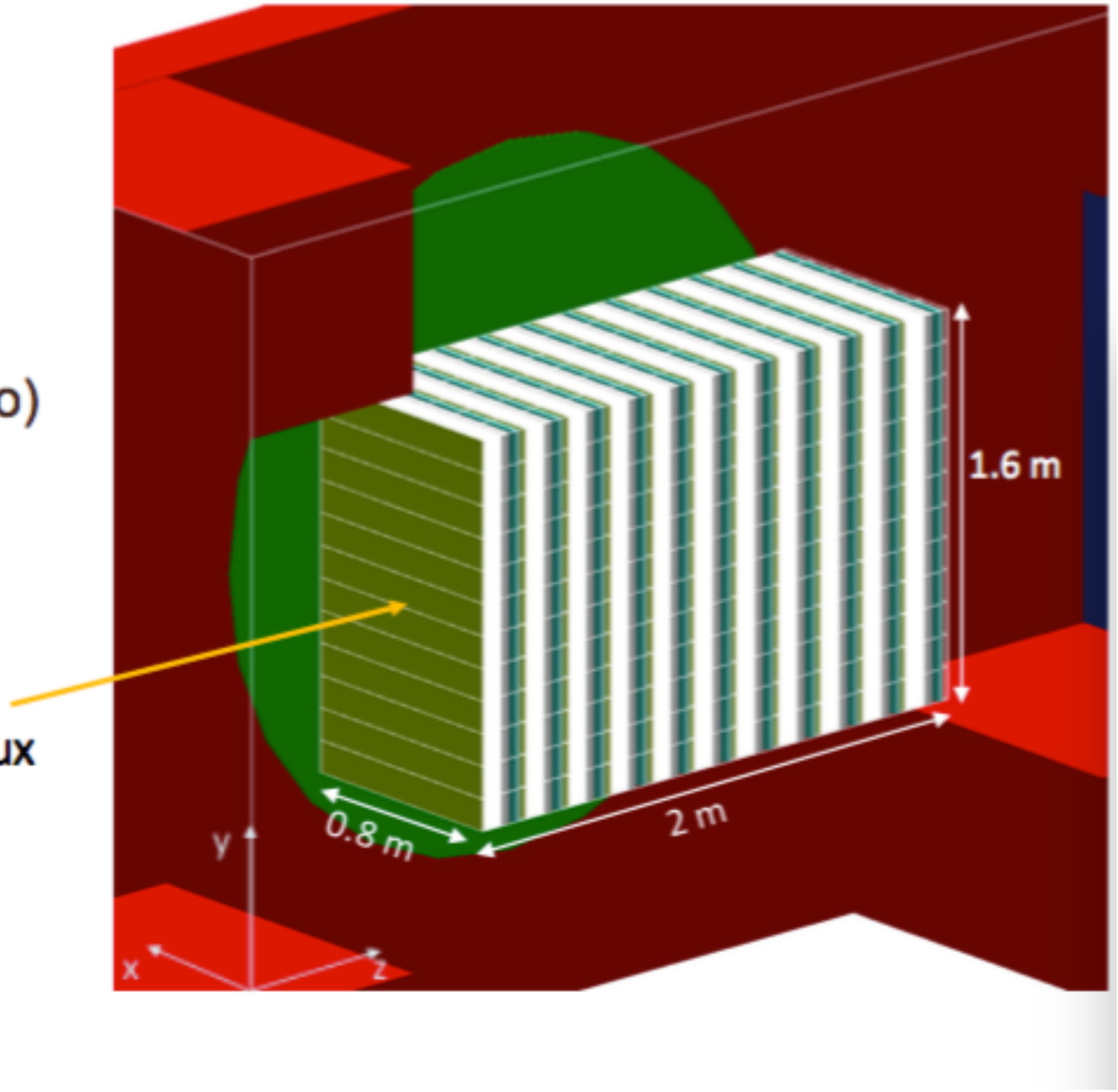


Emulsion based detector with the LNGS OPERA brick technolgy, but with a much smaller mass (750 bricks) very compact (2m), upstream of the HNL decay tunnel —> with B field and followed by a muon detector (to suppress charm background

Neutrino target

- 6 columns (along x direction)
- 12 rows (along y direction)
- 11 walls (along z direction)
- 12 layers of Target Trackers (upstream layer acting as veto)

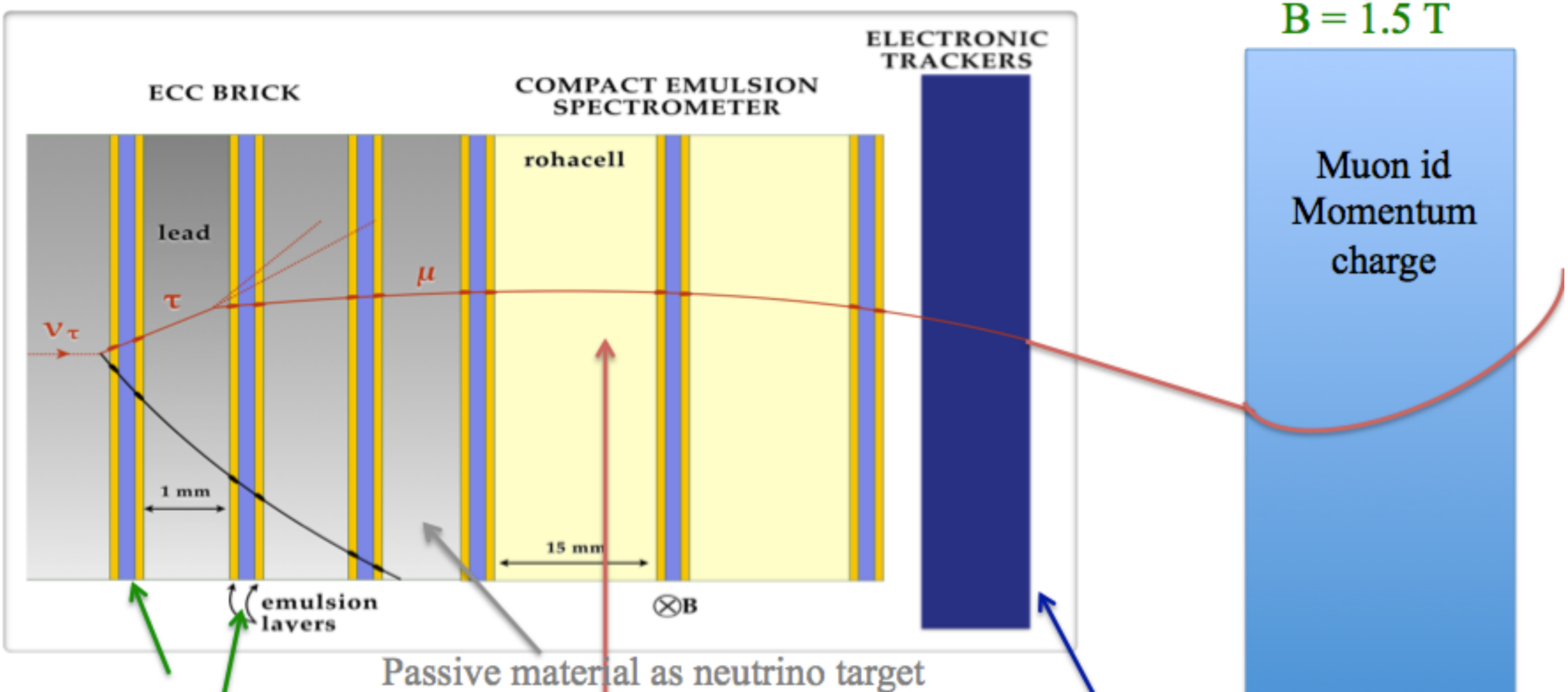
Total dimensions: 0.8x1.6x2 m^3



Neutrino target

Hybrid detector principle

Muon spectrometer
$B = 1.5$ T



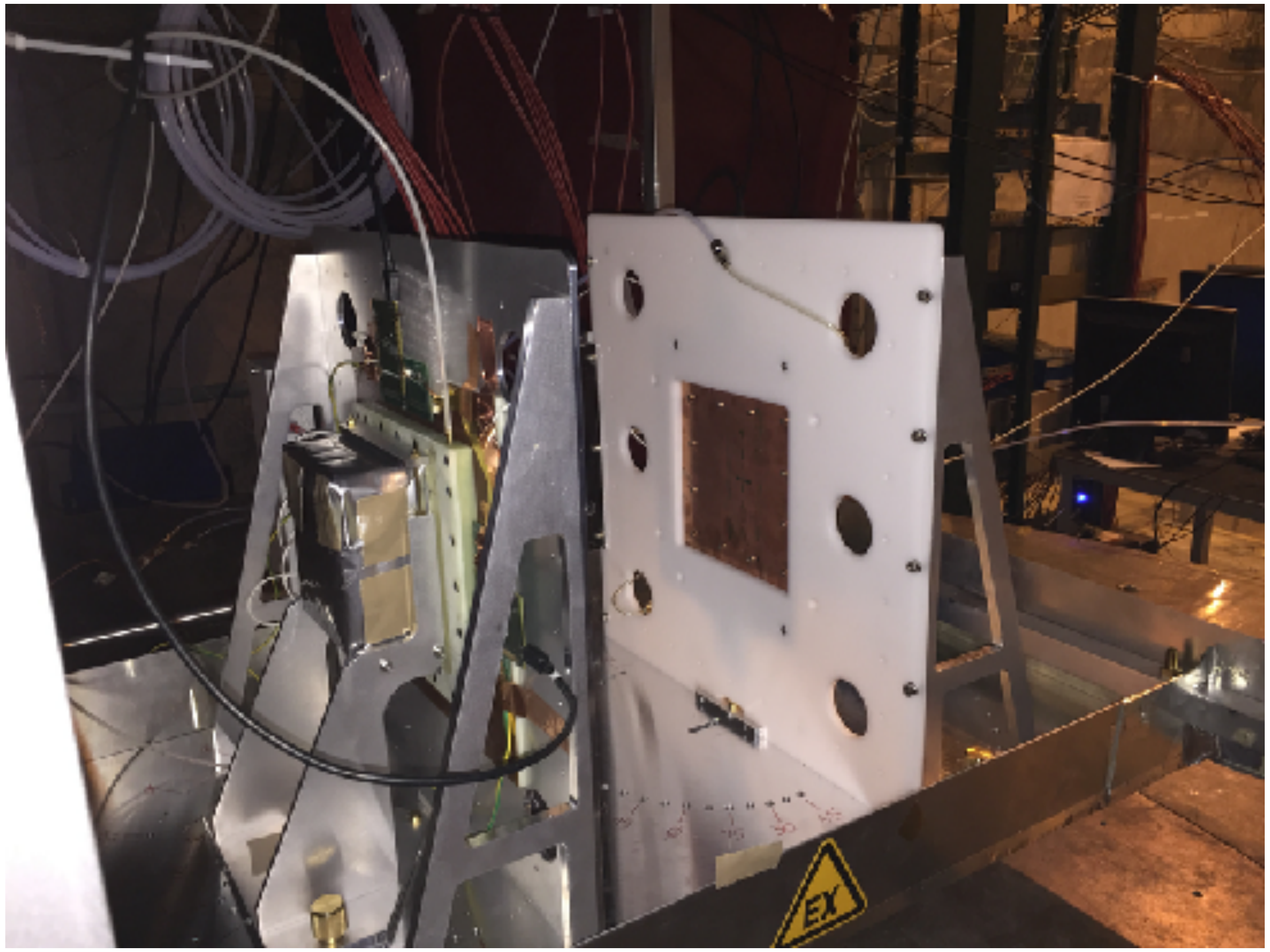
Passive material as neutrino target

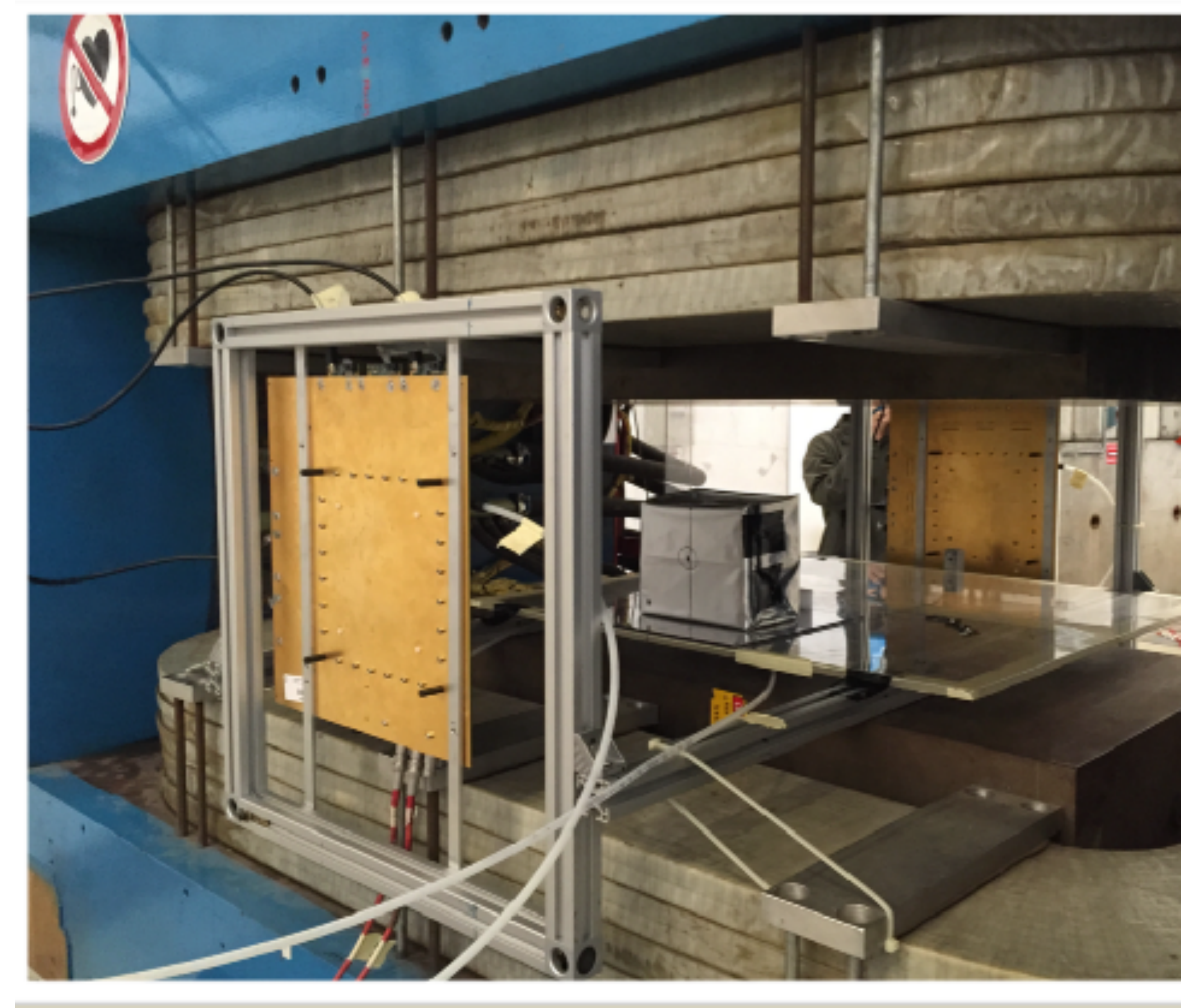
Nuclear emulsions as μm accuracy trackers: τ production and decay vertices

Electronic trackers to provide the "time stamp" and match emulsion tracks

measure the charge of τ daughters

Neutrino target

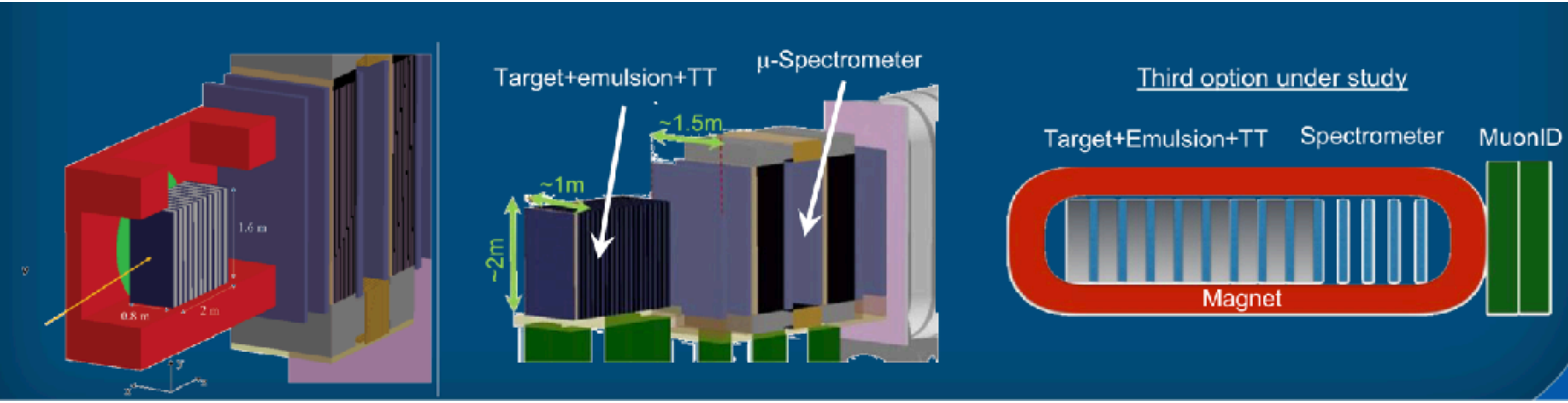




also tested together with GEMs and μWells and with MicroMegas

AIDA 2020

Test beam funded by AIDA 2020



WITH MAGNET

- Dimensions: 0.8 x 2 x 1.6 m^3
- Number of ECC bricks: 924
- Total mass: ~7 tons
- Horizontal magnetic field

WITHOUT MAGNET

- Dimensions: 1.12 x 2.68 x 2.04 m^3
- Number of ECC bricks: 3600
- Total mass: ~28 tons (x4)
- No magnetic field

WITH MAGNET

Pros

1. Hadronic (BR 65%) and muonic (BR 17%) tau decay channel used for ν_τ/anti-ν_τ separation
2. Momentum measurement for hadrons performed with MCS algorithms in the brick and with sagitta method in CES.

Contra

1. Lower sensitivity in LDM searches.
2. Target volume limited by the magnetised region.
3. Multiple scattering of particles in magnet iron.

WITHOUT MAGNET

Pros

1. Increase in the LDM sensitivity
2. Increase neutrino statistics
3. CES not needed anymore: simplification of the target, further increase in target mass
4. Avoid multiple scattering in magnet iron

Contra

1. Without CES no possibility to measure hadron charge.
2. Only muonic channel (BR 17%) used to discriminate ν_τ/anti-ν_τ.
3. Momentum measurement for hadrons rely only on MCS in the brick.

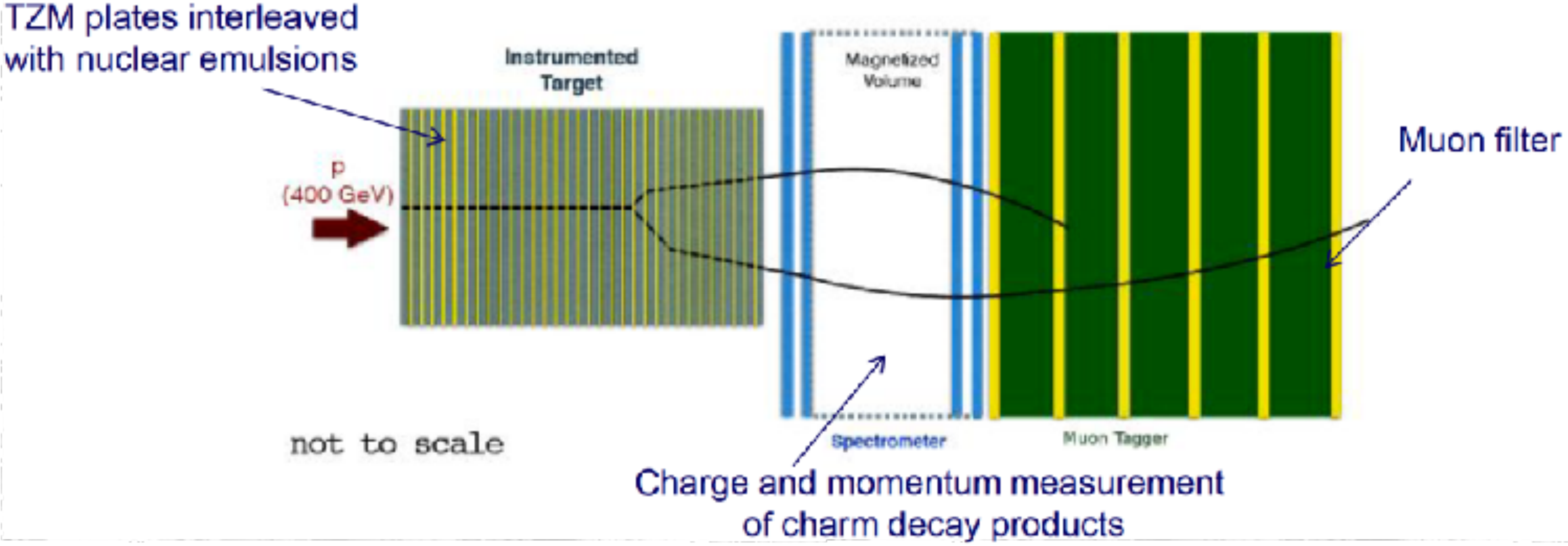
Coming next!

Measurement of charm production in SHiP target

Both the expected flux of hidden particles and the expected number of ν_τ interactions strongly depend on the number of charmed hadrons produced in the SHiP p target.

Due to the thickness of the SHiP p target (12 λ_{int}),the contribution of charm cascade production is expected to increase the charm rate by a factor of 2.

Dedicated measurement of $d^2\sigma/(dE\, d\Omega)$ using 400 GeV protons on a SHiP-like target at H4



Take home message!

We have shown here that an intensity/acceptance increase compared to past hadronic beam dump experiments gives access to a very rich physics program

Many models (and theories…SUSY…), that provide a deep connection with cosmology, can be tested in an unexplored range of parameters

SHiP will also allow to complete the experimental tests of the SM description of deep inelastic ν scattering with the reconstruction of the ν_τ interactions

The protons are there…