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Physik-Institut

SHiP
Search for Hidden Particles

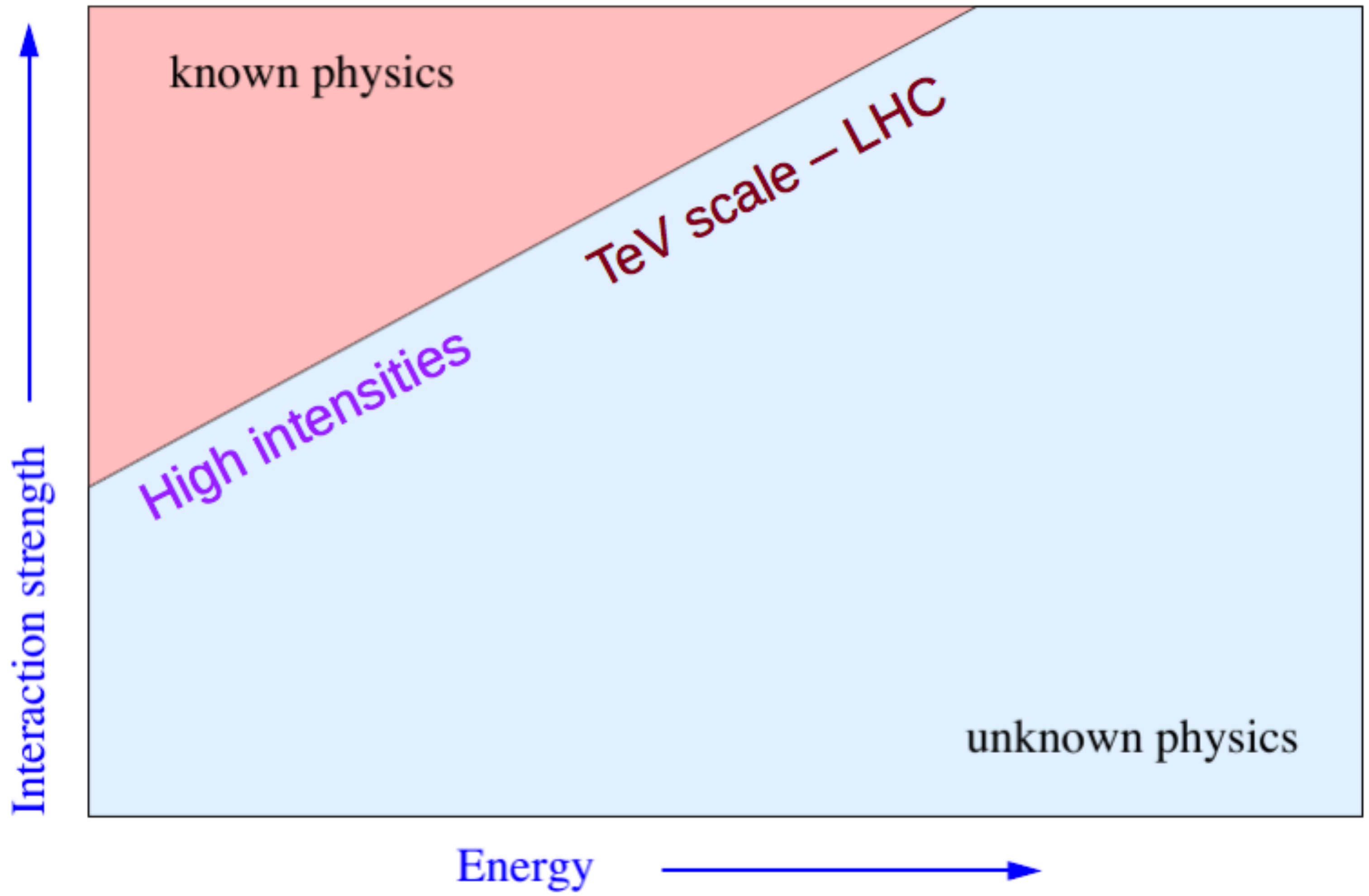
The SHiP Experiment

Nico Serra (Universität Zürich)
On behalf of the SHiP Collaboration

Epiphany Conference 2018

Physics Case

- Naturalness does not seem to be a guiding principle of Nature
- There are some anomalies in flavour physics which (if true) seem again to point out that our theory prejudice was wrong
- We should therefore not forget that we have a 2D problem (Mass VS Coupling)



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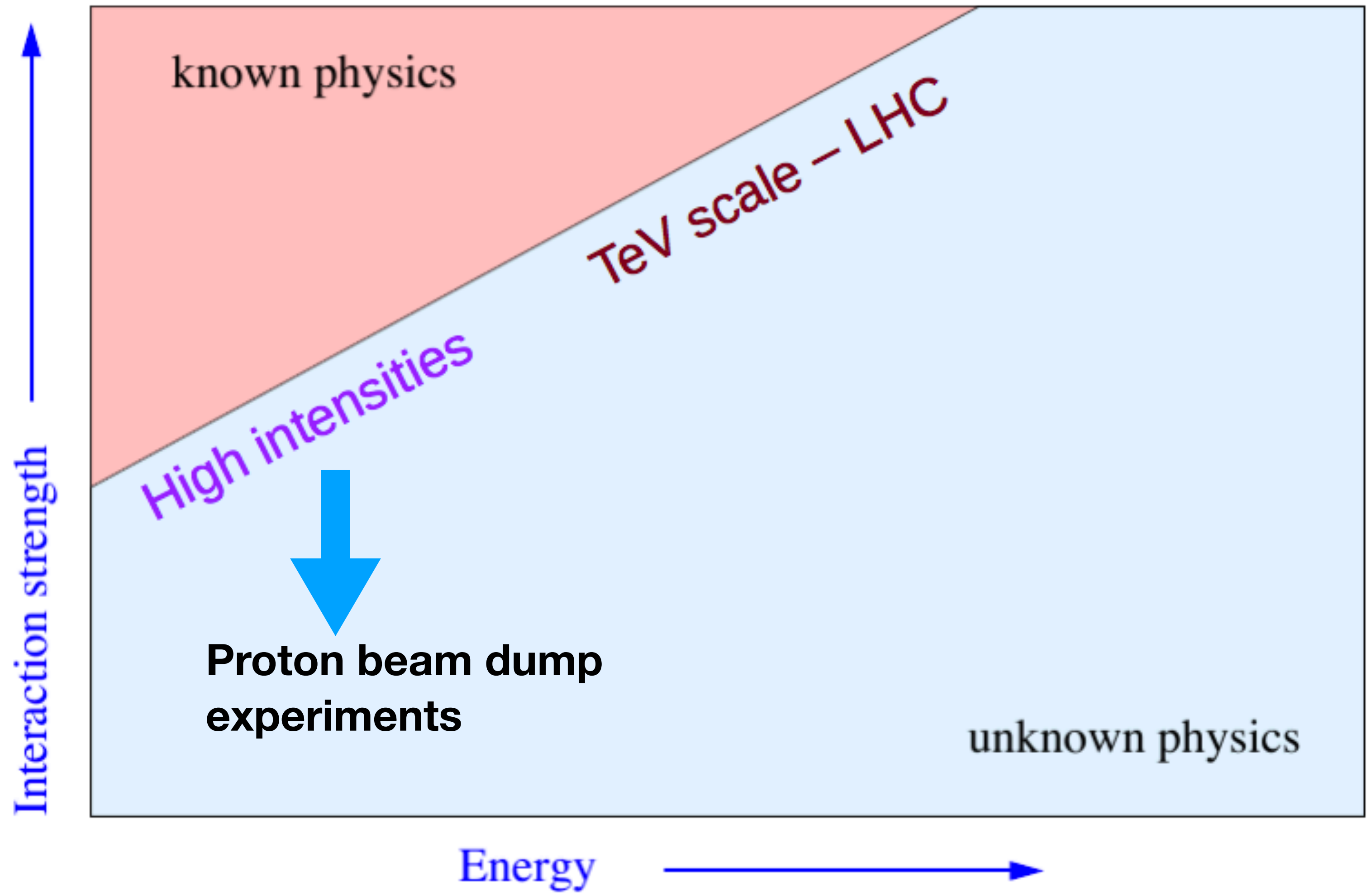


Physics Case

$L = L_{SM} + L_{mediator} + L_{HS}$

Visible Sector

Mediators or portals to the HS:
vector, scalar, axial, neutrino

Hidden Sector
Naturally accommodates Dark Matter (may have rich structure)

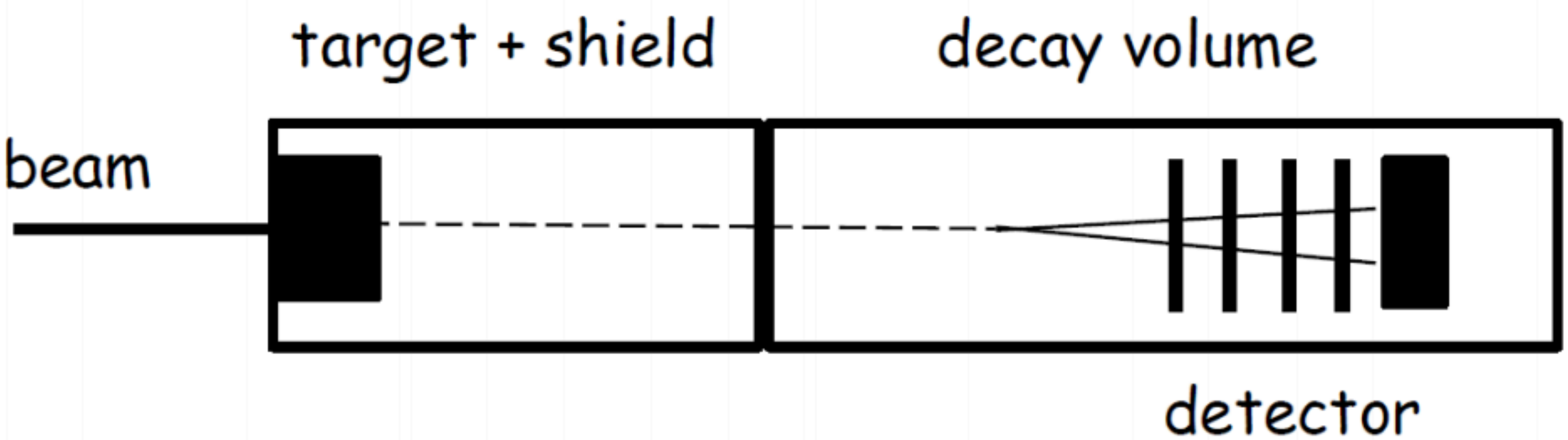
✓ HS production and decay rates are strongly suppressed relative to SM
- Production branching ratios $O(10^{-10})$
- Long-lived objects
- Interact very weakly with matter

Models	*Final states*
HNL, SUSY neutralino	$l^+\pi^-$, l^+K^-, $l^+\rho^-$ $\rho^+\to\pi^+\pi^0$
Vector, scalar, axion portals, SUSY sgoldstino	l^+l^-
HNL, SUSY neutralino, axino	$l^+l^-\nu$
Axion portal, SUSY sgoldstino	$\gamma\gamma$
SUSY sgoldstino	$\pi^0\pi^0$

Full reconstruction and PID are essential to minimize model dependence

Experimental challenge is background suppression

Experimental concept



- High Intensity beam into an heavy target
    - We want particles either coming from heavy meson decays or from pN interactions
    - We want to suppress pion and kaon decays which is source of bkg
- Minimize the flux of SM particles in the detector
- Define a (large) fiducial volume where the background level is approximately zero

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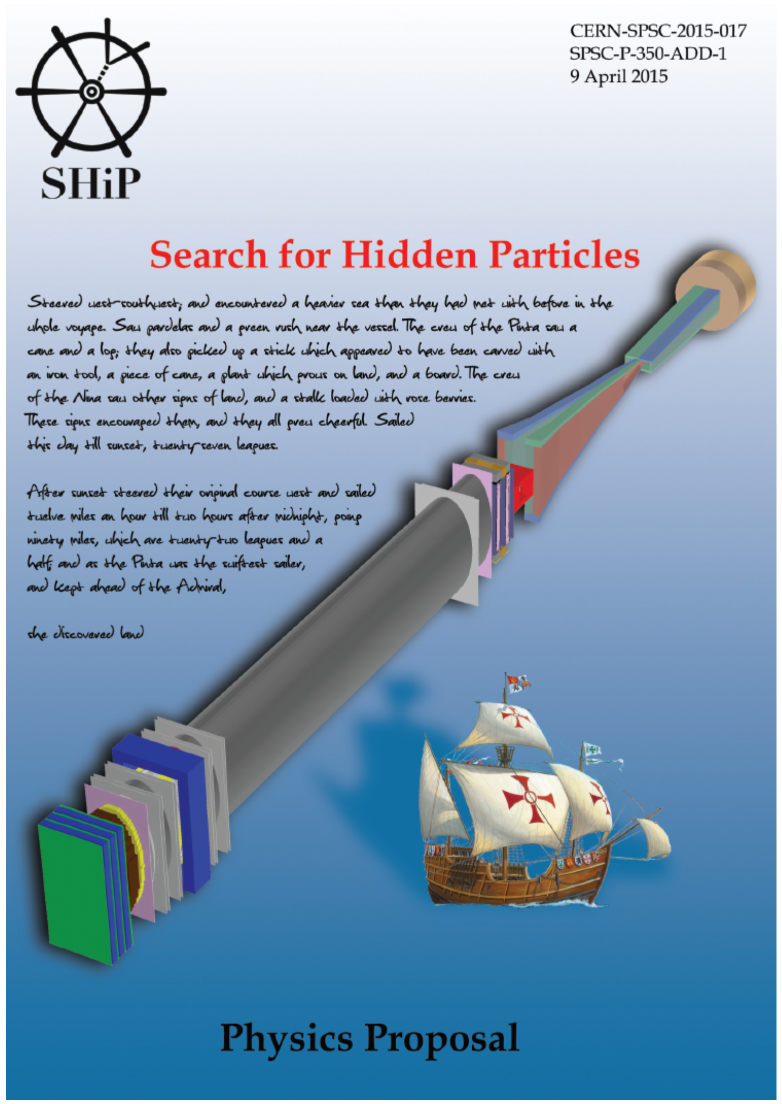

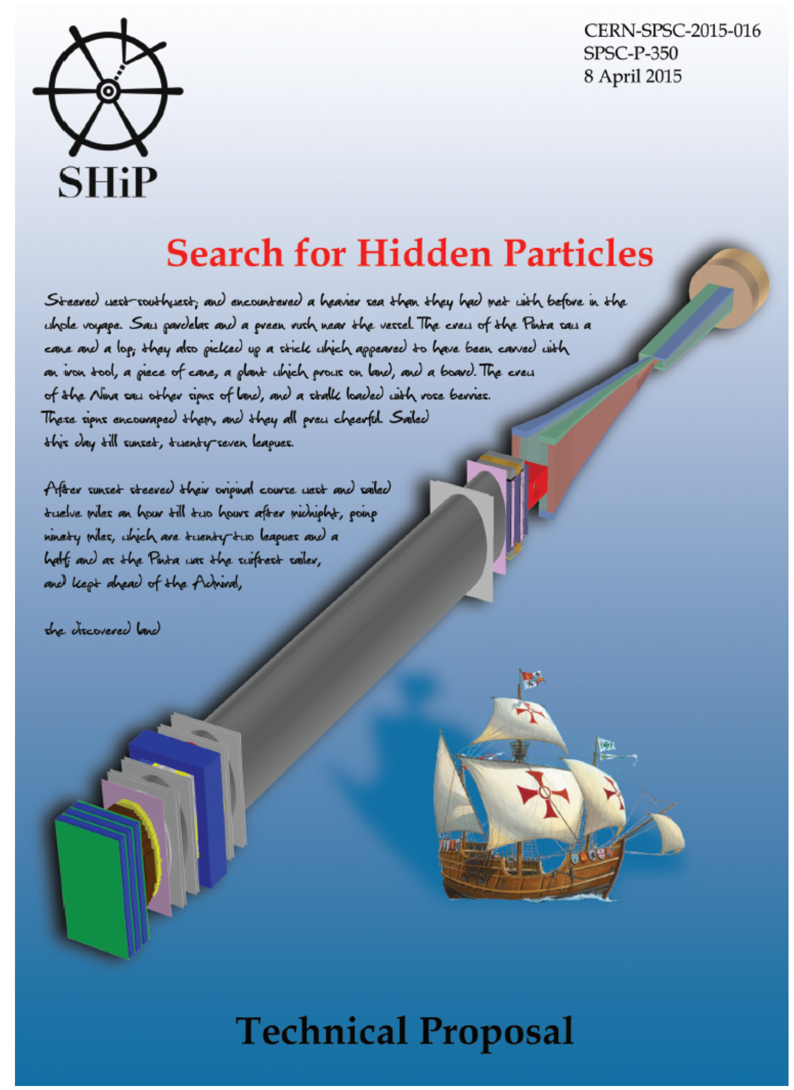

- The technical proposal (250 physicists, 46 institutes, 16 countries) submitted to CERN in Apr 2015 (arXiv:1504.04956)

- Physics Paper (85 physicists, 65 institutes) accepted for publication in Review on Progress in Physics (arxiv:1504.04855)

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SHiP Collaboration

SHiP
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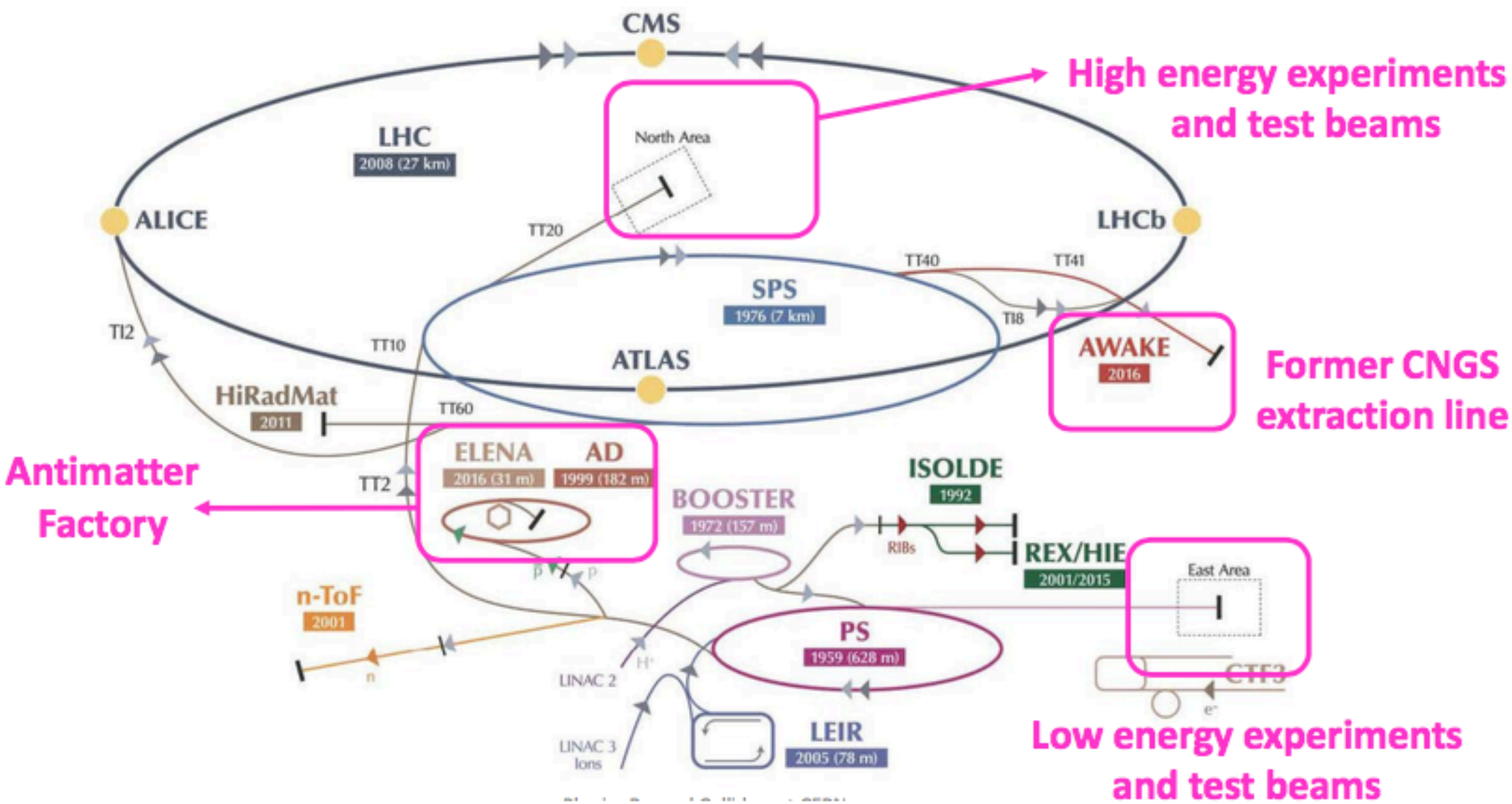
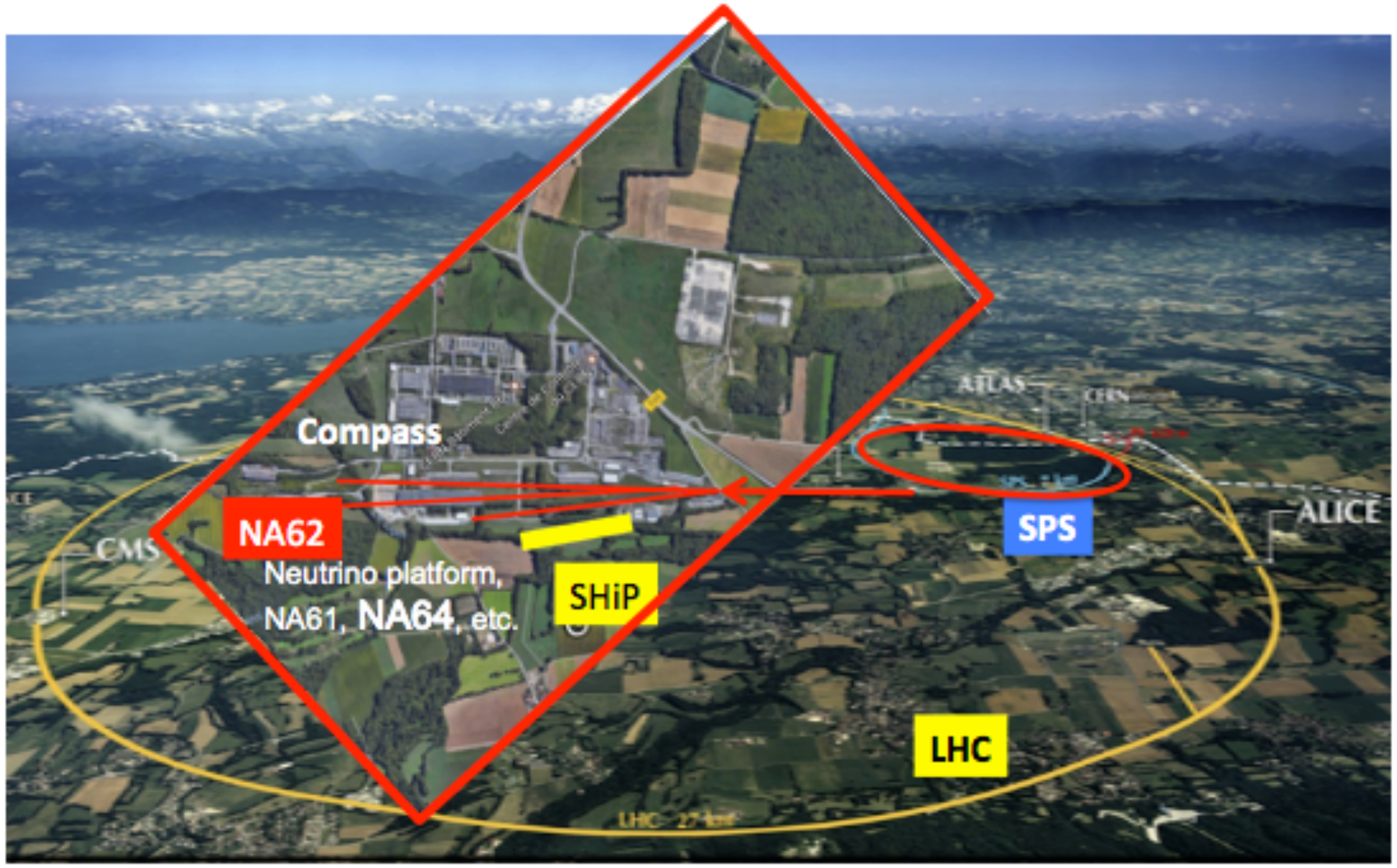
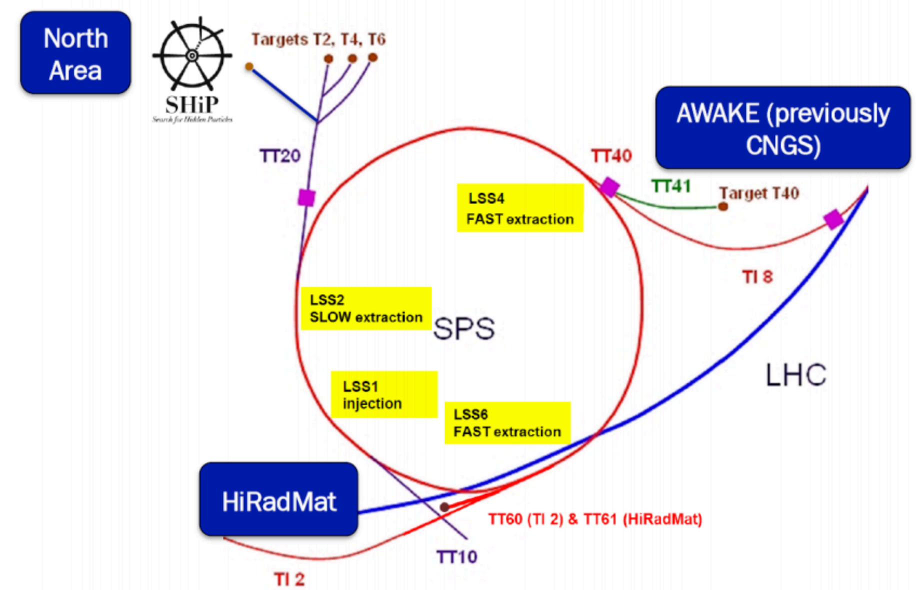
Beam Line



- About 20% of the SPS running for LHC physics
- About 80% availability for fixed target programme

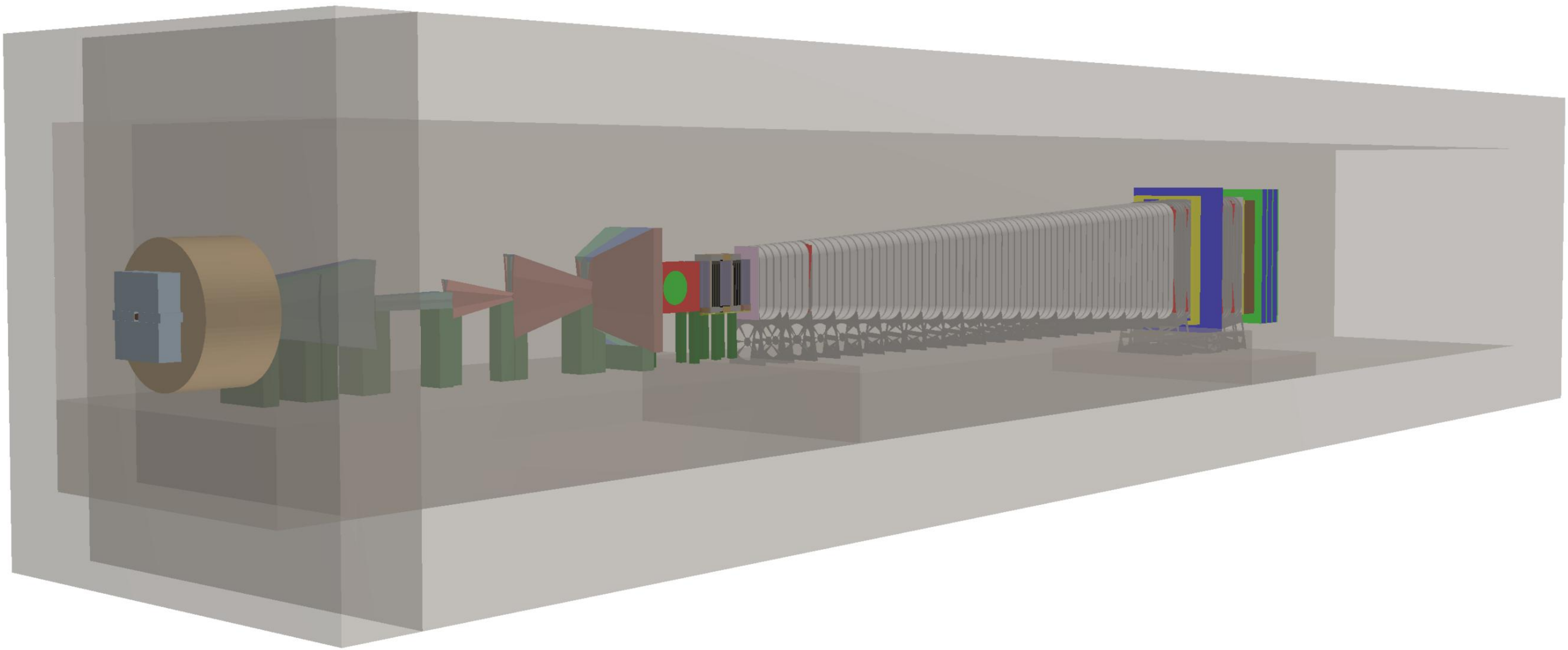
BDF at Prevessin



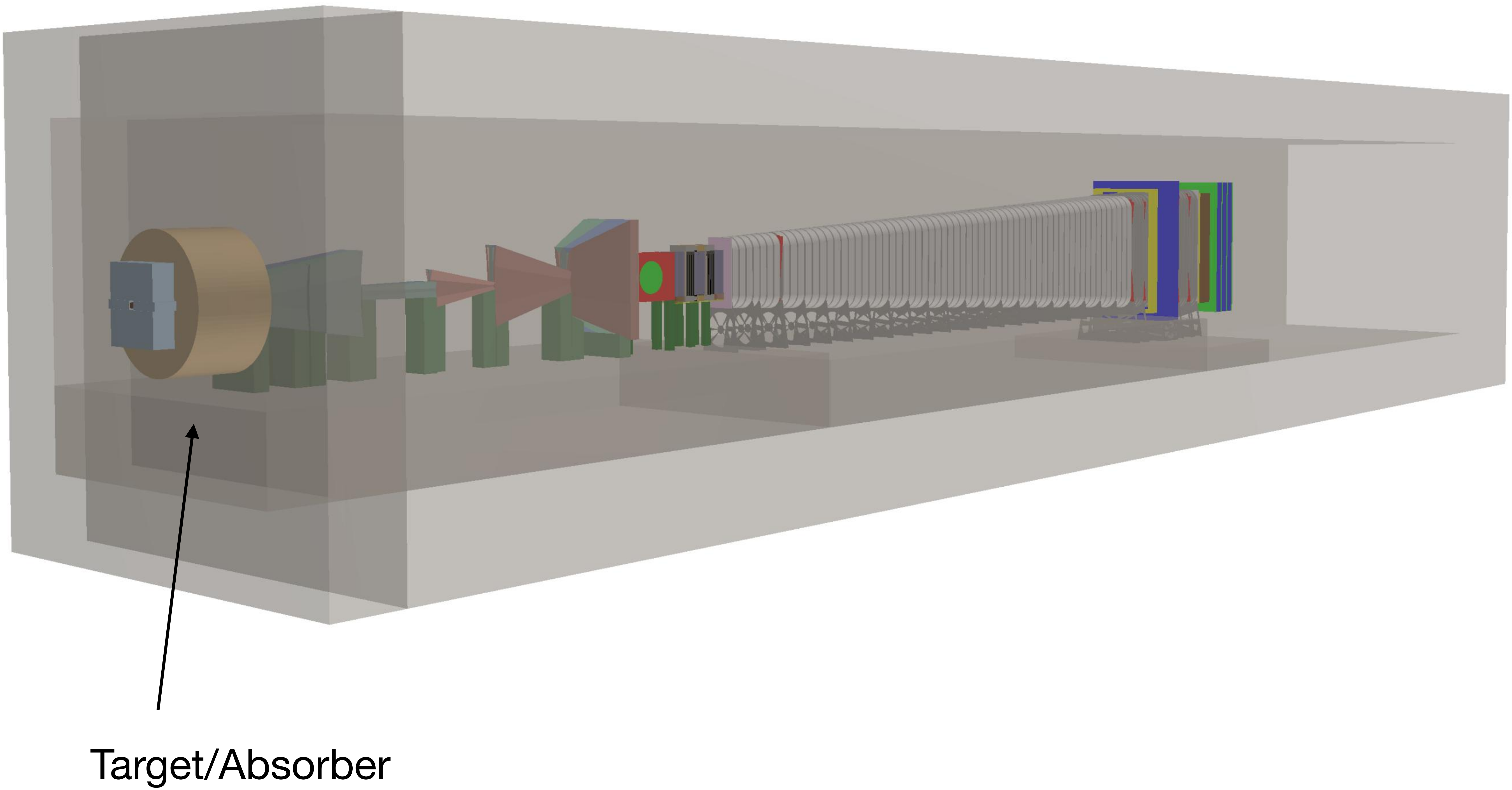


- Very intense proton beam at 400GeV
- Aim to deliver $4x10^{13}$ Protons / spill (at slow extraction)
- Proposed implementation based on minimal modification and compatible with current and planned SPS experiments

Overview of SHiP

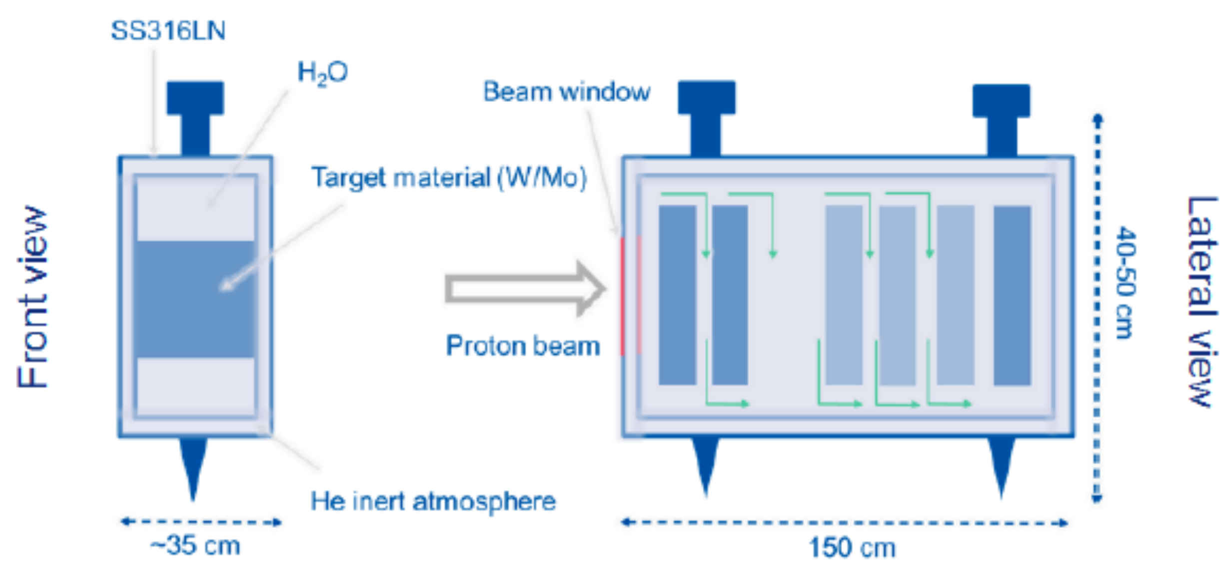


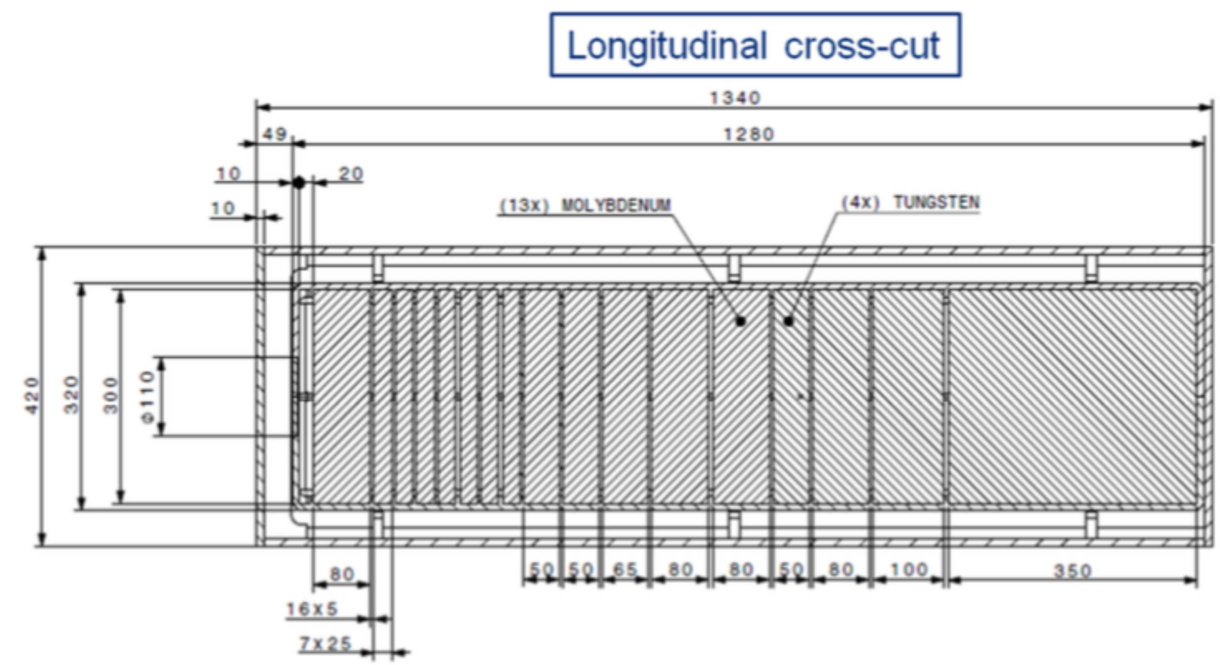
Overview of SHiP

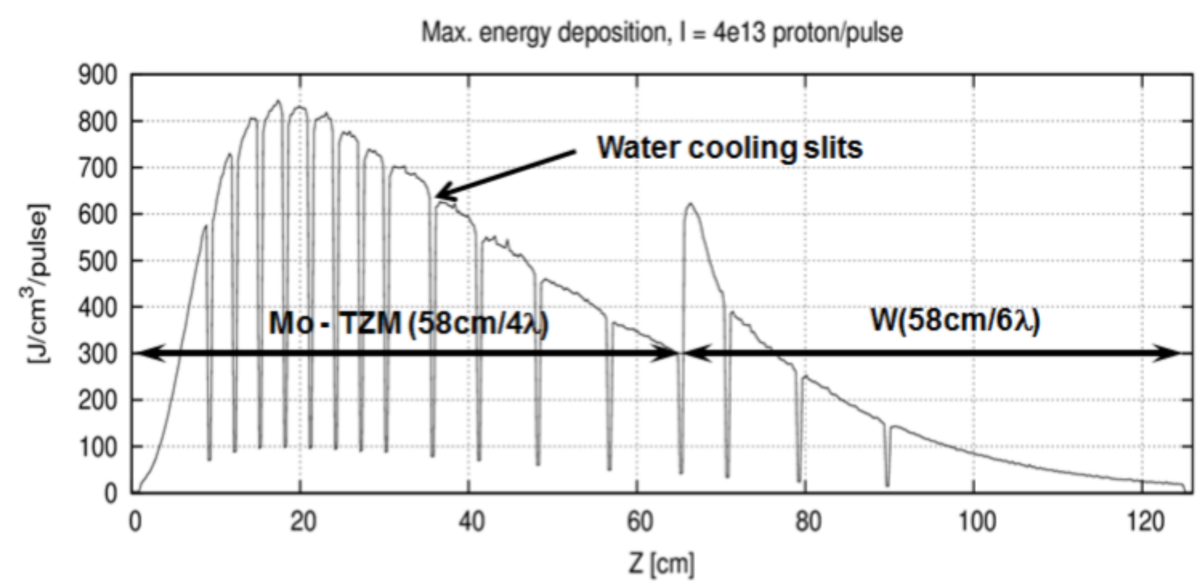


Target

- *Layers of Titanium/Zirconium/Molibdenum for 4λ_{int} in the core of the beam*
- *Followed by Layers of pure W*
- *Each layer is cooled by water*
- *Alternative cooling with He under study*

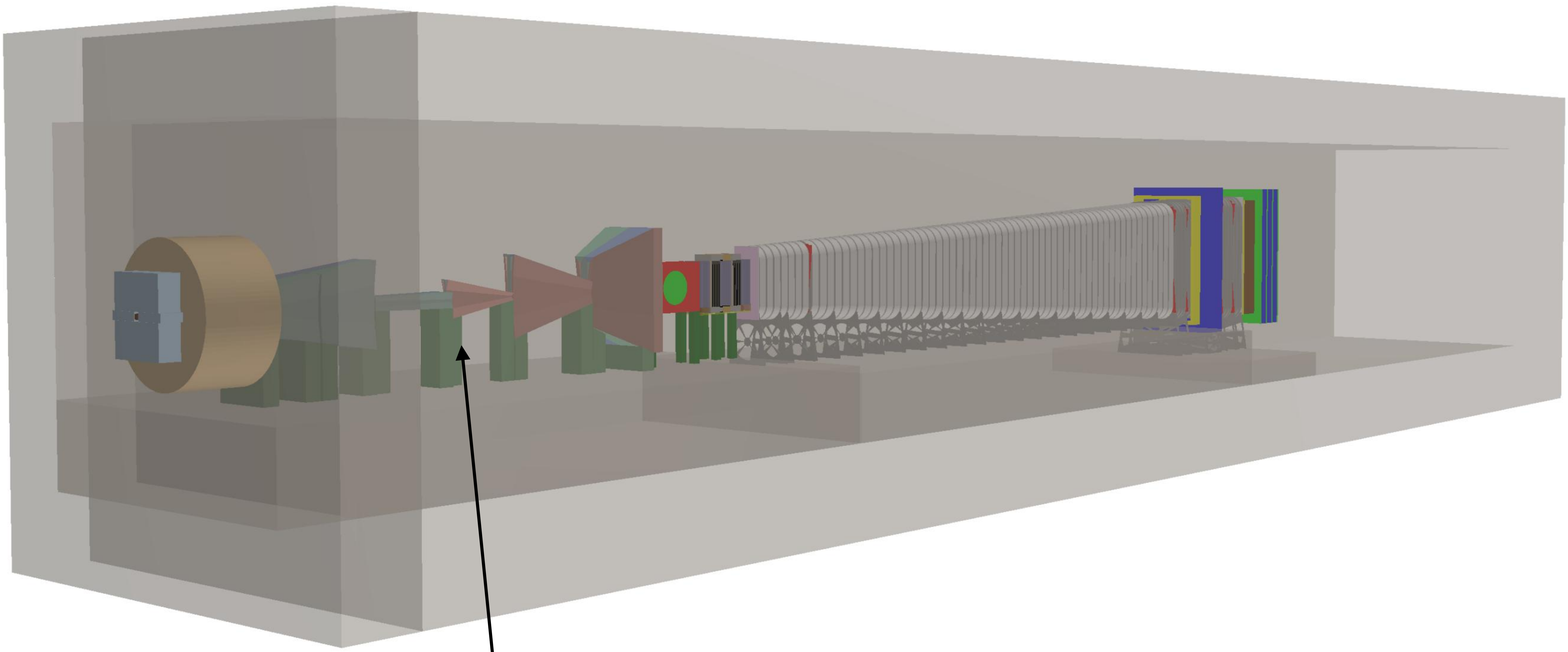






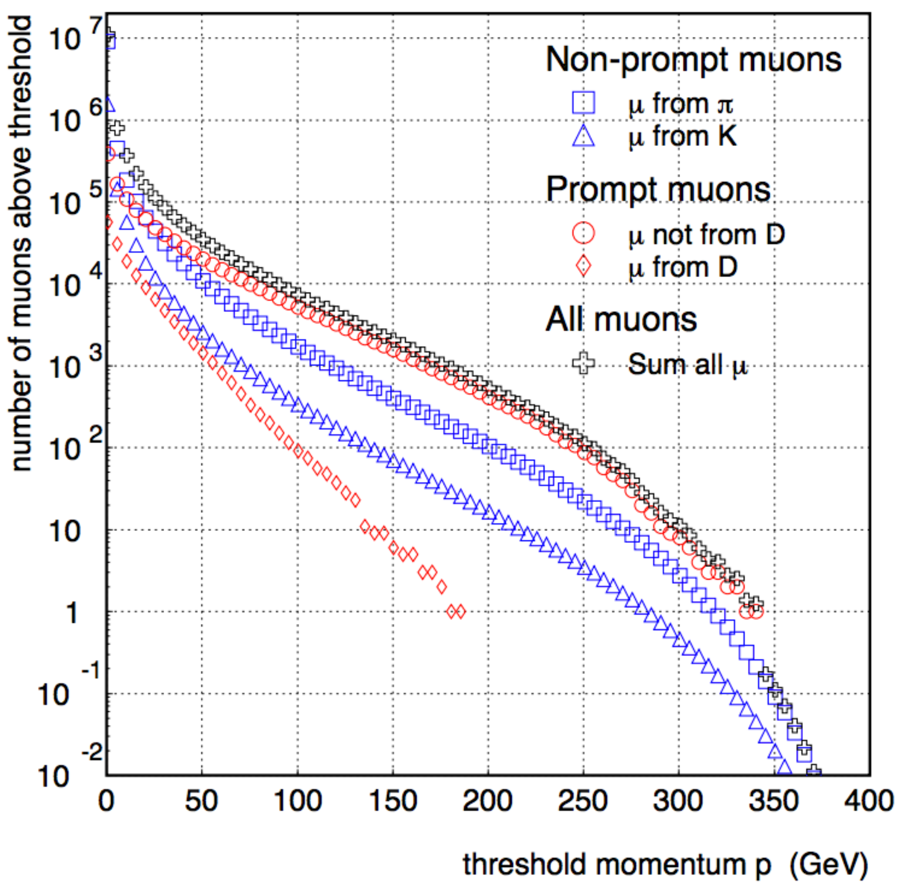
355 kW average,
2.56 MW during 1s spill

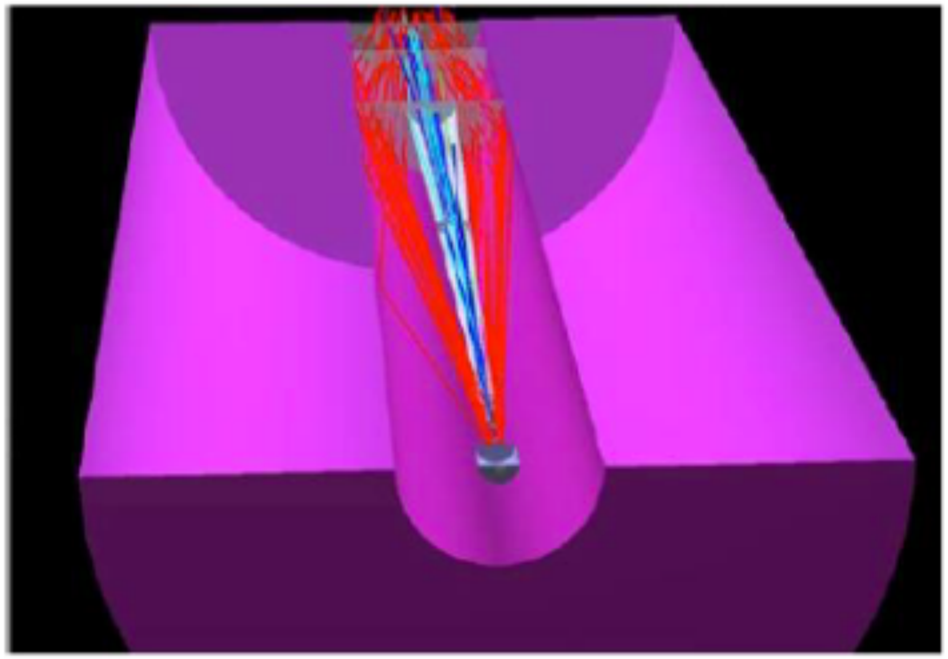
Overview of SHiP



Sweeping magnet

Muon Shield





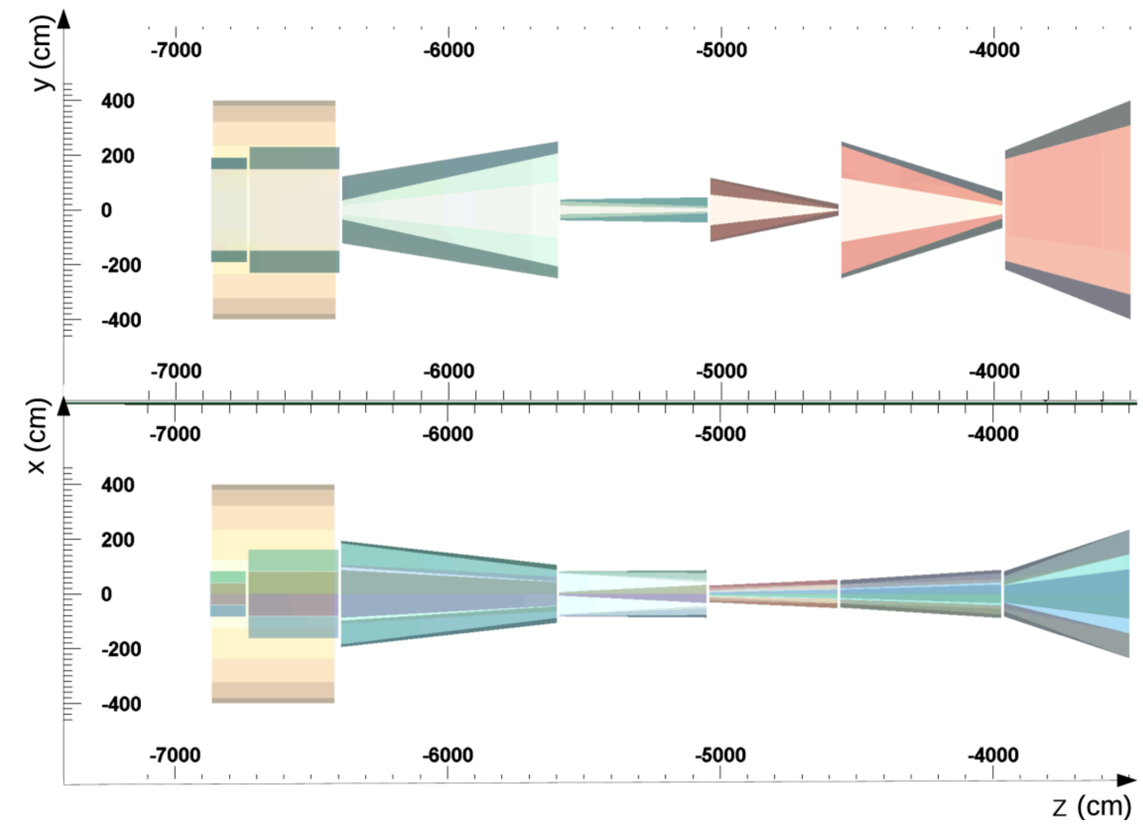
- Distribute the bkg over a long spill: 4×10^{13} PoT/1.3 seconds
- Sweeping magnet
- Decay volume to be far away from the walls

- Heavy target stops hadrons before they decay. After the target and the hadron absorber only muons survive
- Muons come mainly from η, η' and ω

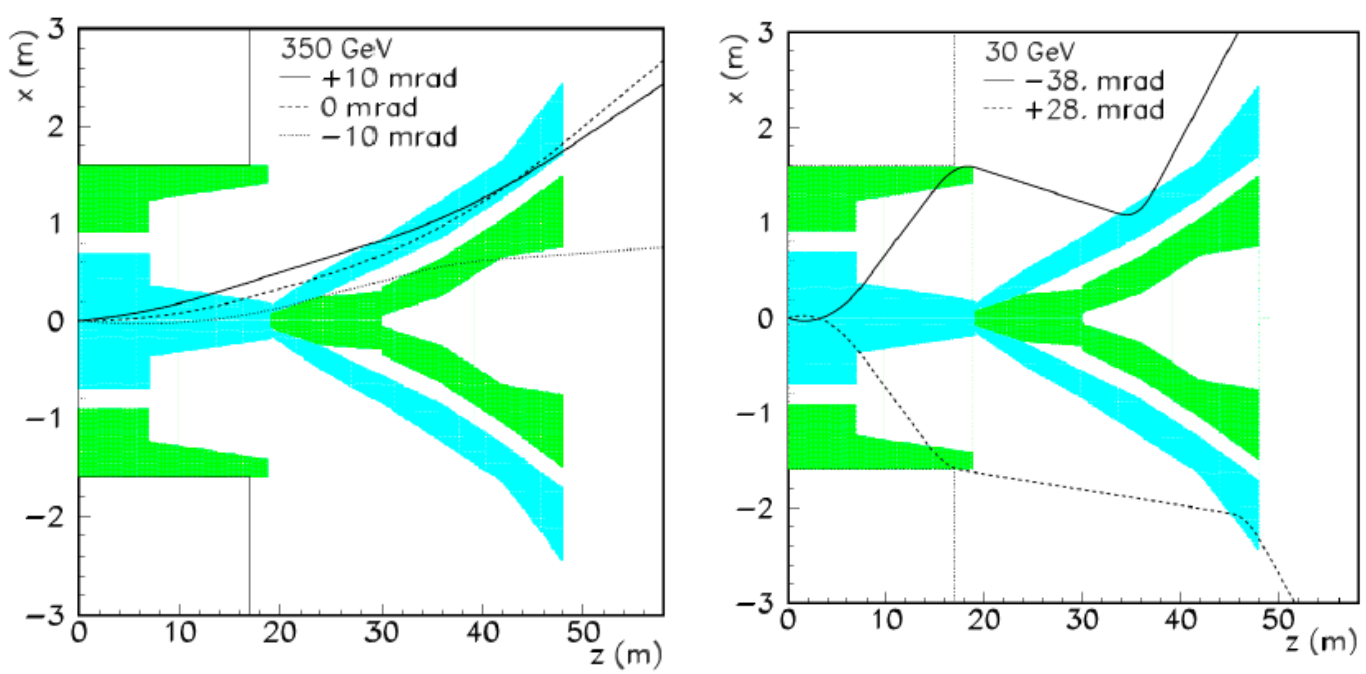
Muon Shield

- Global optimisation of the magnetic field (with Machine Learning) still ongoing

Challenging Aspects:
- Narrow separation between field directions
- Aiming to 1.8T to minimize length (with grain oriented steel sheets)
- Have reliable muon sample to optimise with



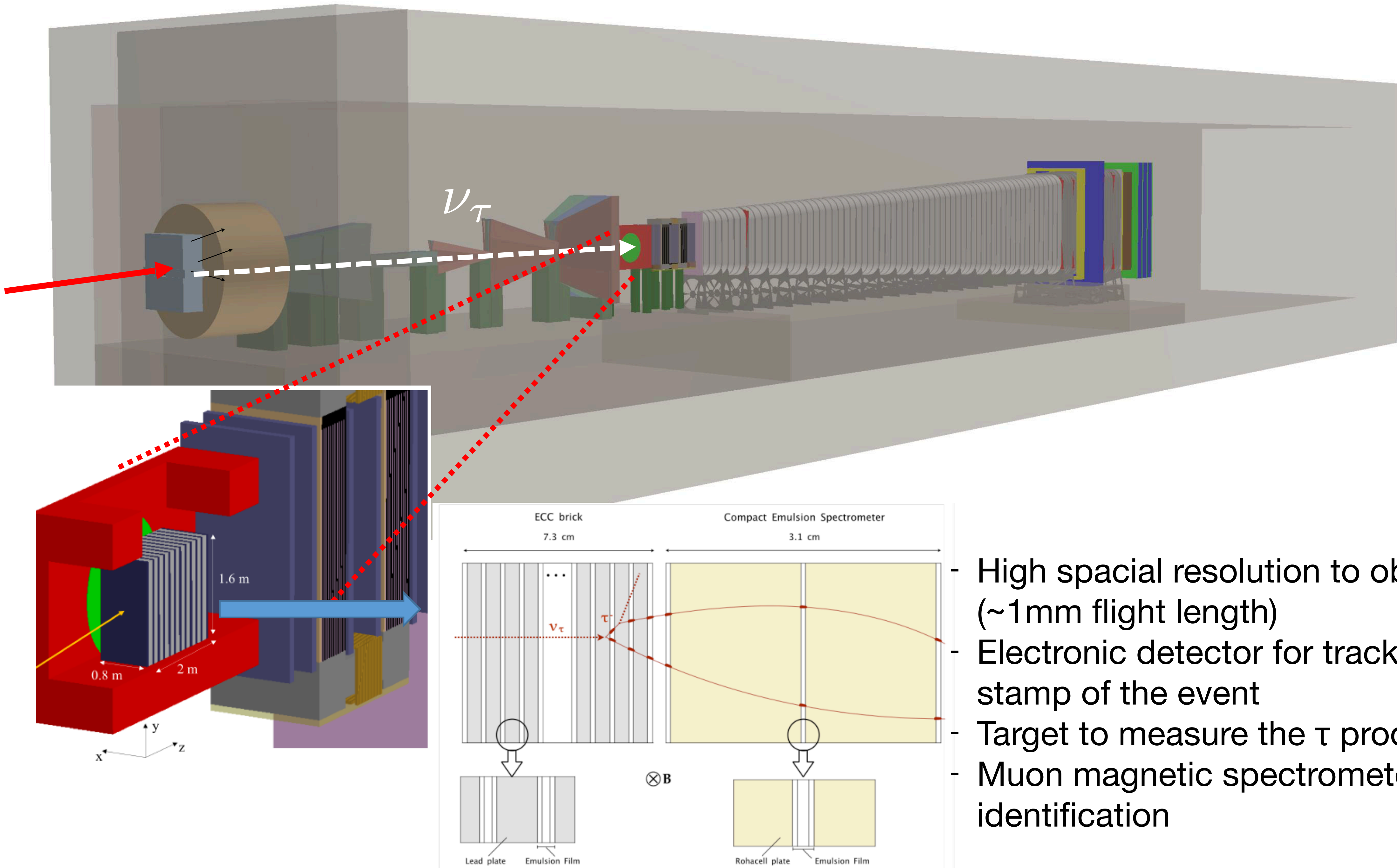
The active muon shield in the SHiP experiment
JINST 12 P05011 2017



Running the simulation with material

- ~3x10^9 muons/spill with magnets off
- With the magnet on 3x10^5 muons/spill
- ~6.5x10^4 muons/spill with p>3GeV

Emulsion Detector

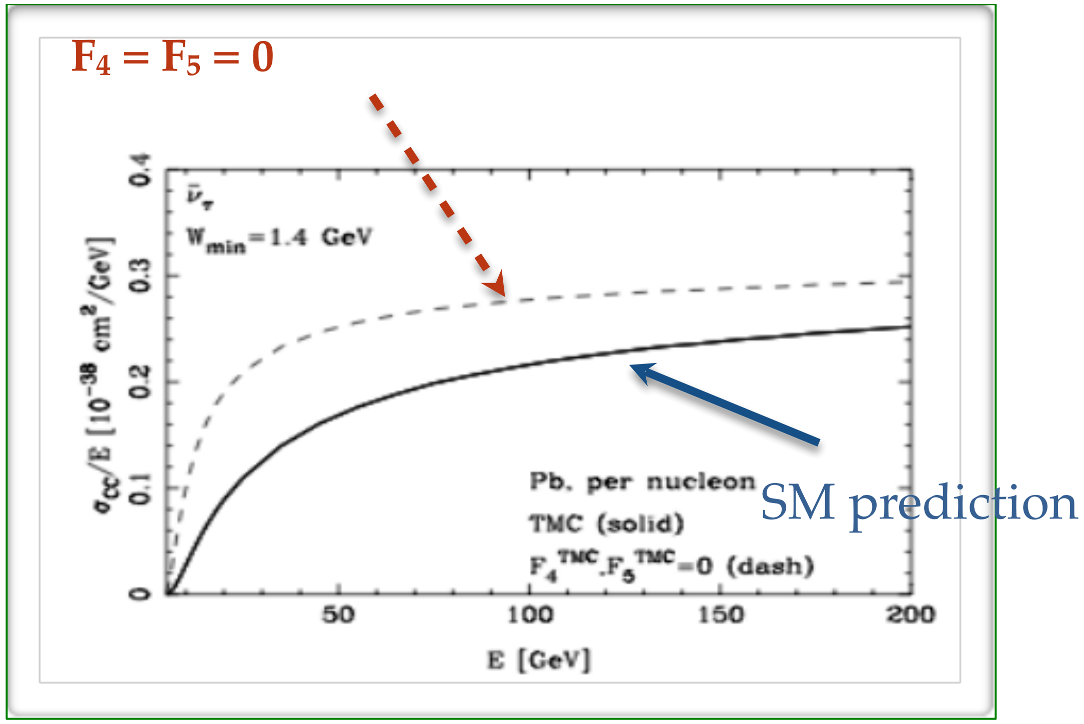


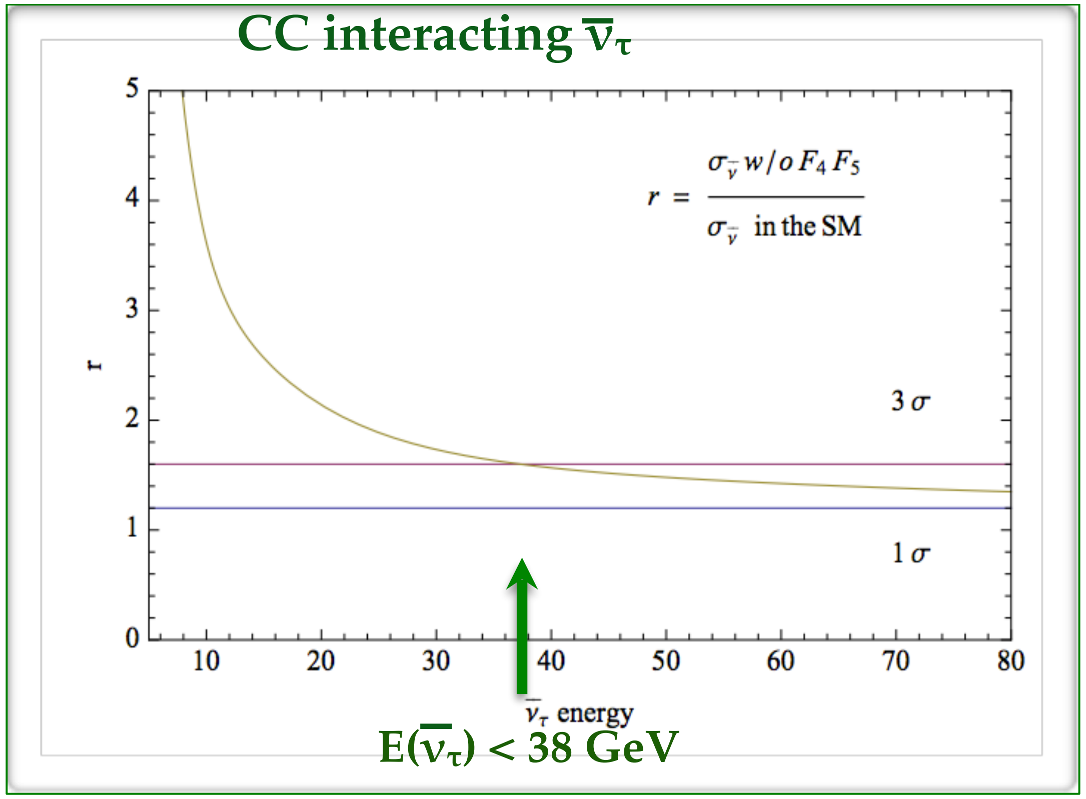
- High spacial resolution to observe the τ decay (~1mm flight length)
- Electronic detector for tracking to give the time stamp of the event
- Target to measure the τ products
- Muon magnetic spectrometer for muon identification

Physics with nu-Tau

First evaluation of F_4 and F_5, not accessible with other neutrinos

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

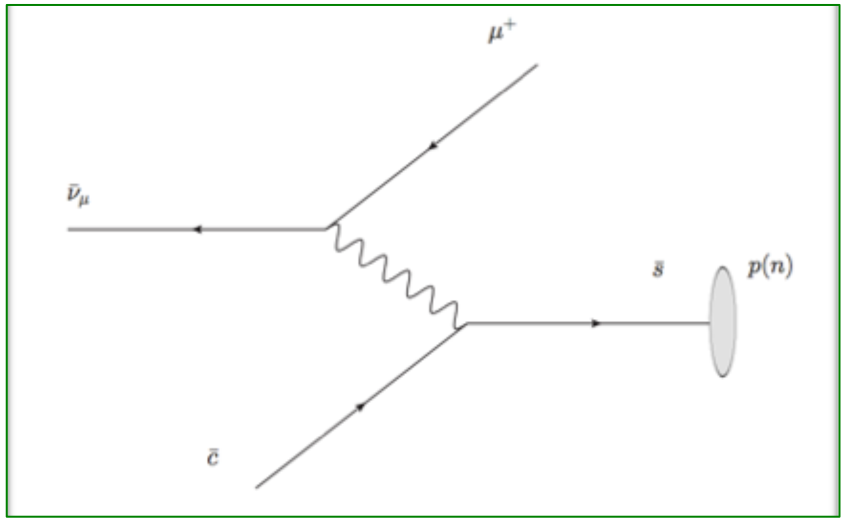


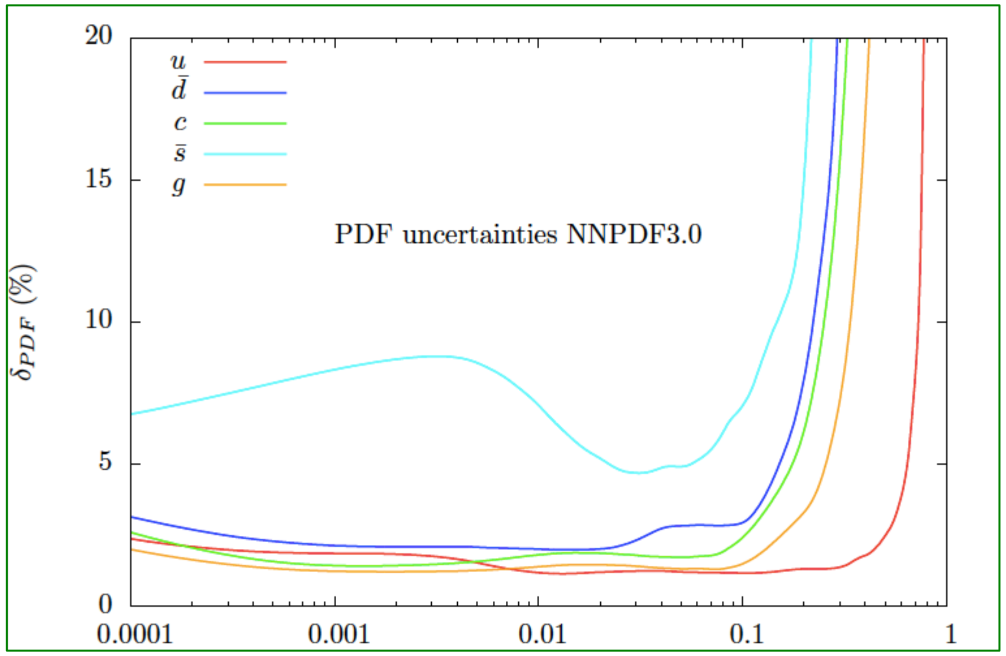


- At LO $F_4 = 0$, $2xF_5 = F_2$
- At NLO $F_4 \sim 1\%$ at 10 GeV

Physics with nu-Tau

- Charmed hadron production in anti-neutrino interactions selects anti-strange quark in the nucleon
- Strangeness important for precision SM tests and for BSM searches
- W boson production at 14 TeV: 80% via $\overline{u}d$ and 20% via $c\overline{s}$

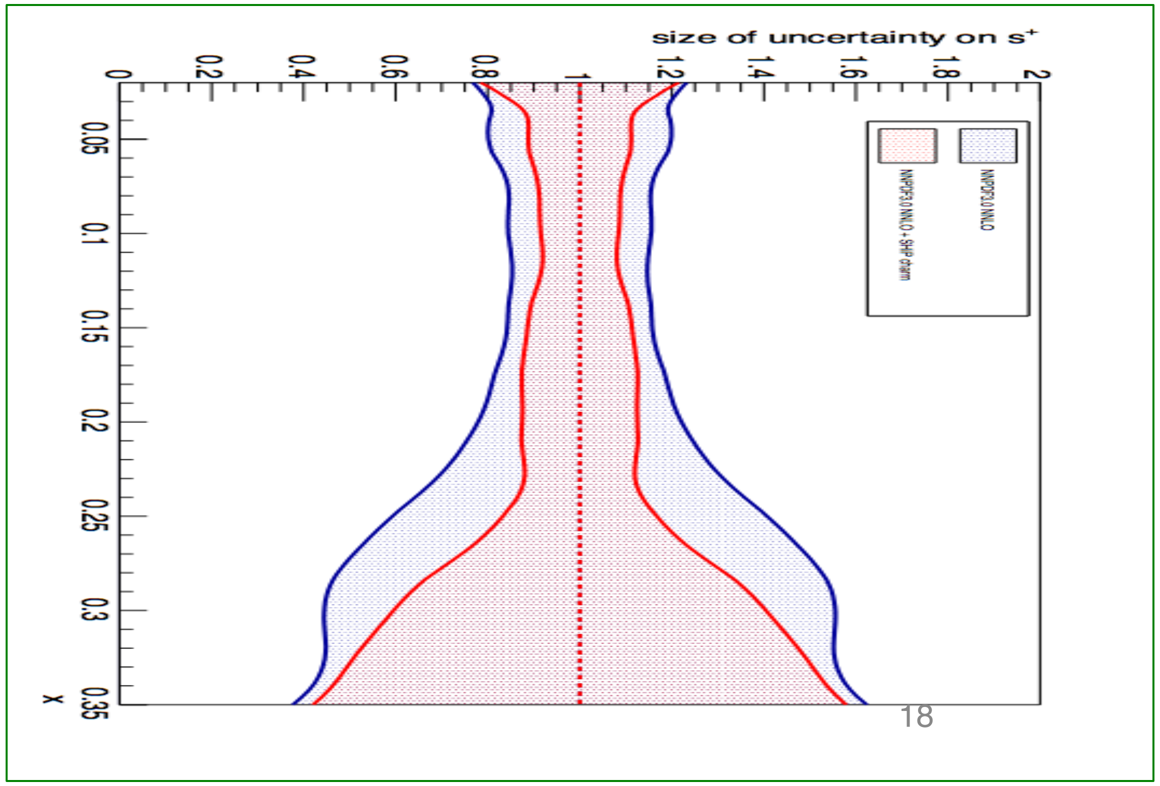




Phys. Rev. D91 (2015) 113005

Fractional uncertainty of the individual parton densities *f(x;m²_W)* of NNPDF3.0

- Significant improvement (factor two) with SHIP data



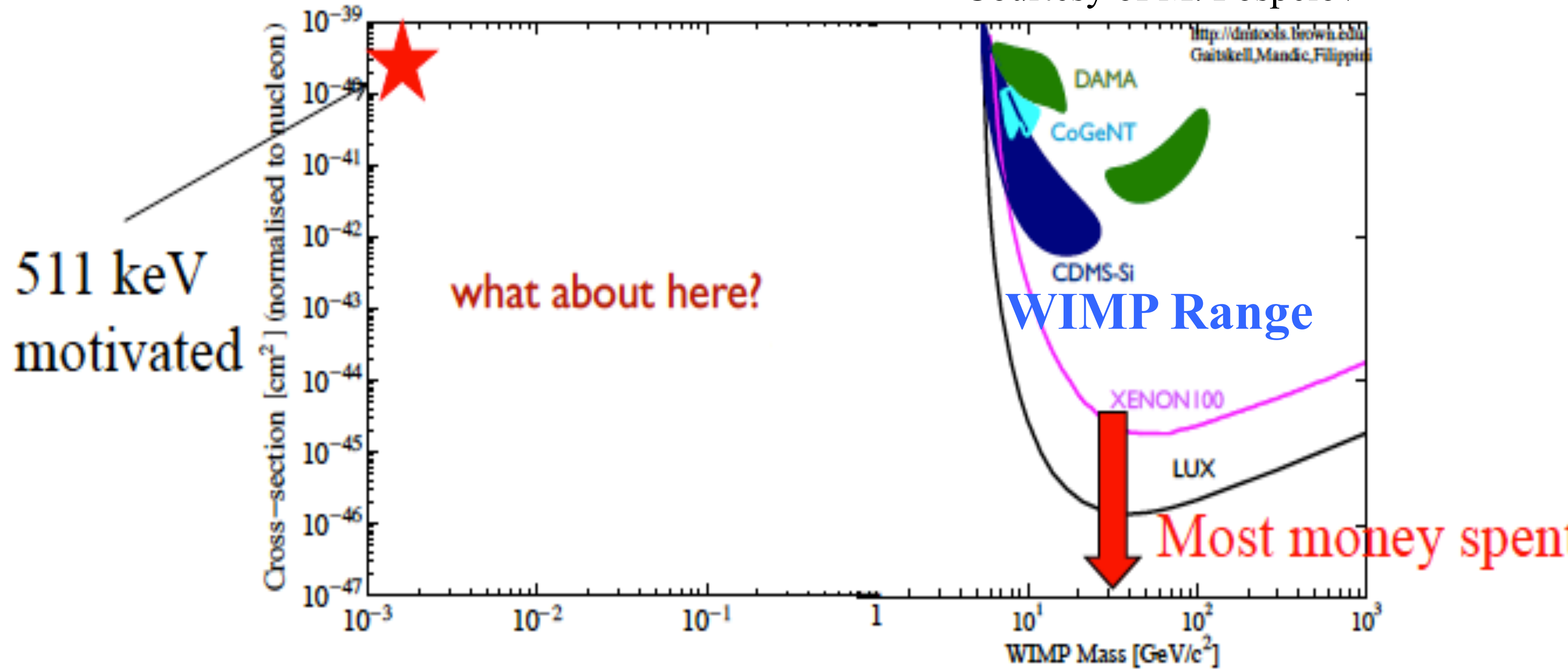
$$s^+ = s(x) + \overline{s}(x)$$

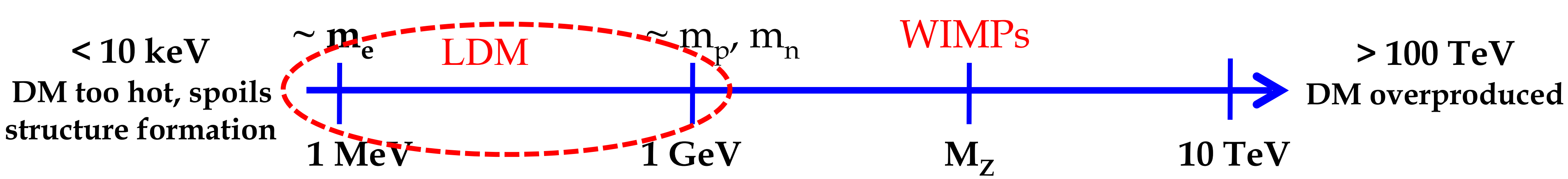
Added to NNPDF3.0 NNLO fit, Nucl. Phys. B849 (2011) 112–143, at $Q^2 = 2$ GeV^2

Light Dark Matter

Mass of Dark Matter particle
$10^{-31} - 10^{20}$ GeV

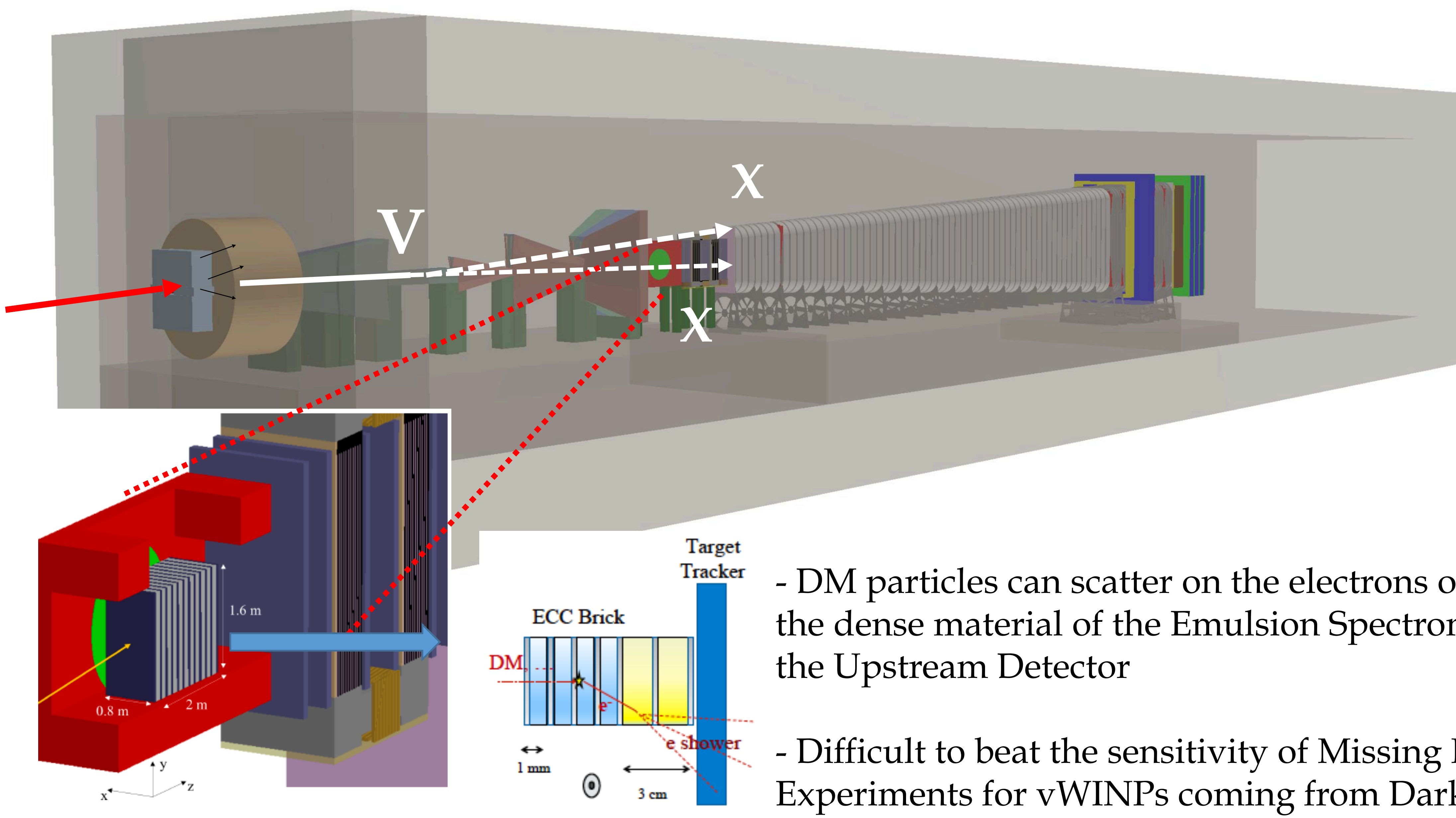
Courtesy of M. Pospelov





Light mediators must be SM singlet, options limited by SM gauge invariance:
1) Vector Portal; 2) Scalar Portal; 3) Neutrino Portal

iSHiP



- DM particles can scatter on the electrons or nuclei of the dense material of the Emulsion Spectrometer in the Upstream Detector

- Difficult to beat the sensitivity of Missing Mass Experiments for vWINPs coming from Dark Photon, but for other models (e.g. scalar, Zprime) SHiP might have a unique sensitivity

iSHiP

χ produced by a dark photon decay

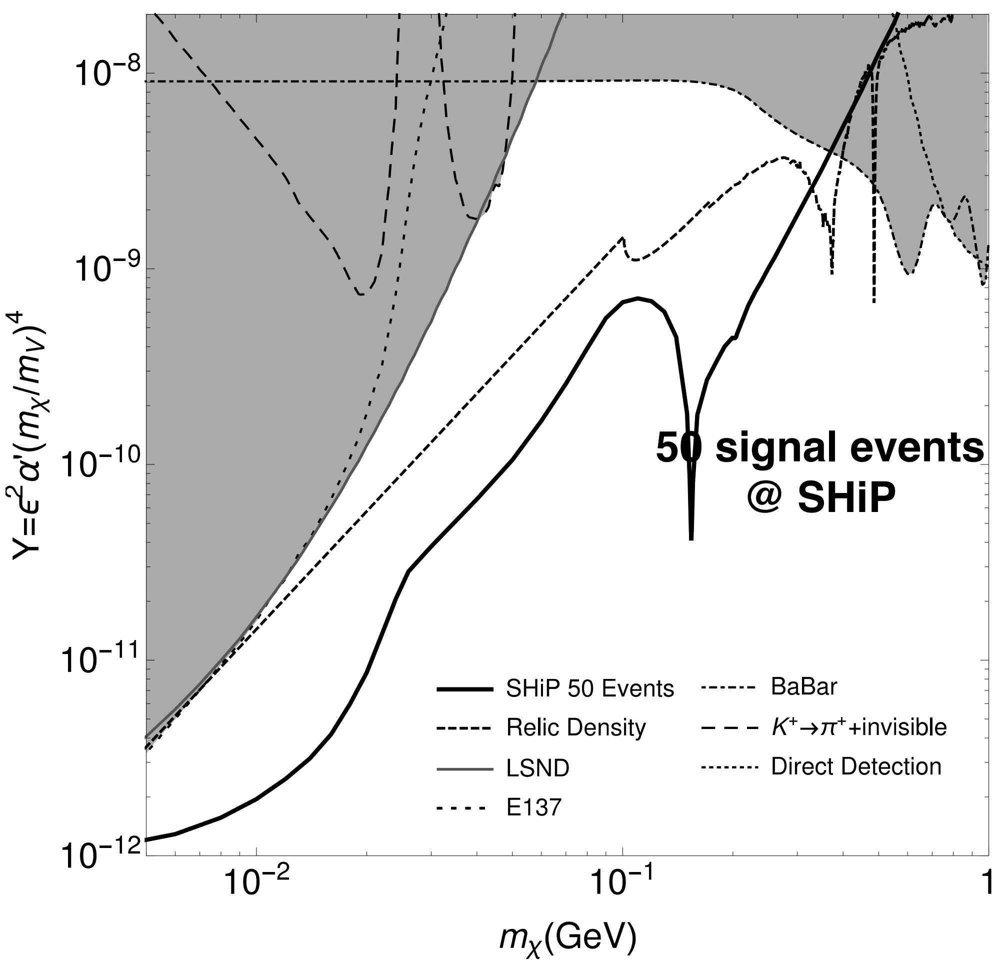
$$\chi e^- \to \chi e^-$$

*>10[20] photons expected in SHiP can be used as **a LDM beam***

Detect LDM via its scattering on atoms of emulsion spectrometer

SHiP would probe even beyond relic density in minimal hidden-photon model

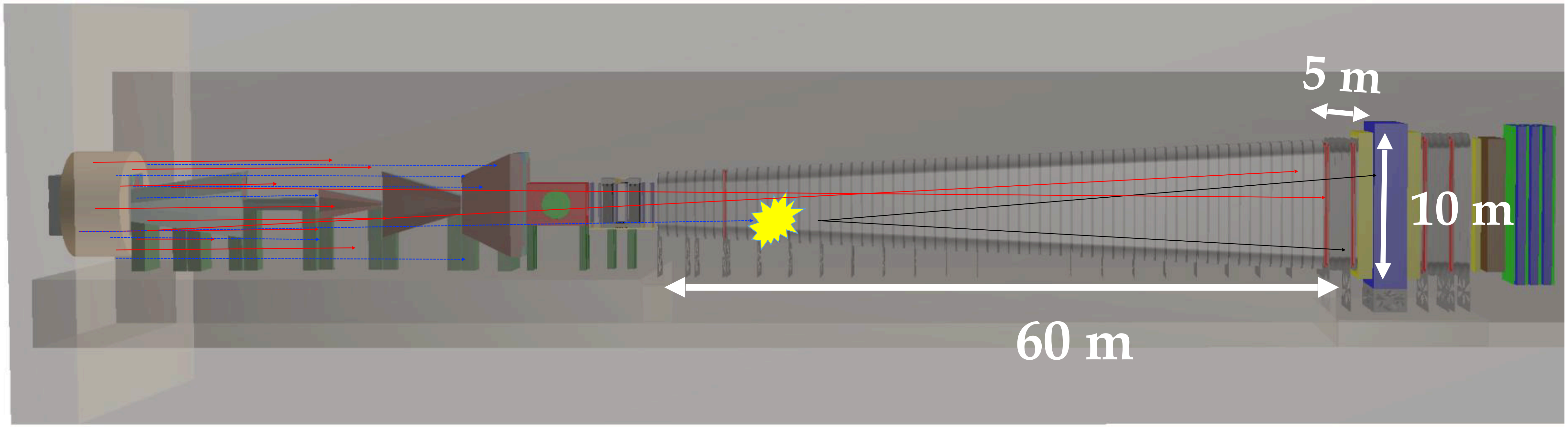
	ν_e	$\bar{\nu}_e$	ν_μ	$\bar{\nu}_\mu$	all
Elastic scattering on e^-	16	2	20	18	56
Quasi - elastic scattering	105	73			178
Resonant scattering	13	27			40
Deep inelastic scattering	3	7			10
Total	137	109	20	18	284



Courtesy of Patrick deNiverville

SHiP Studies ongoing

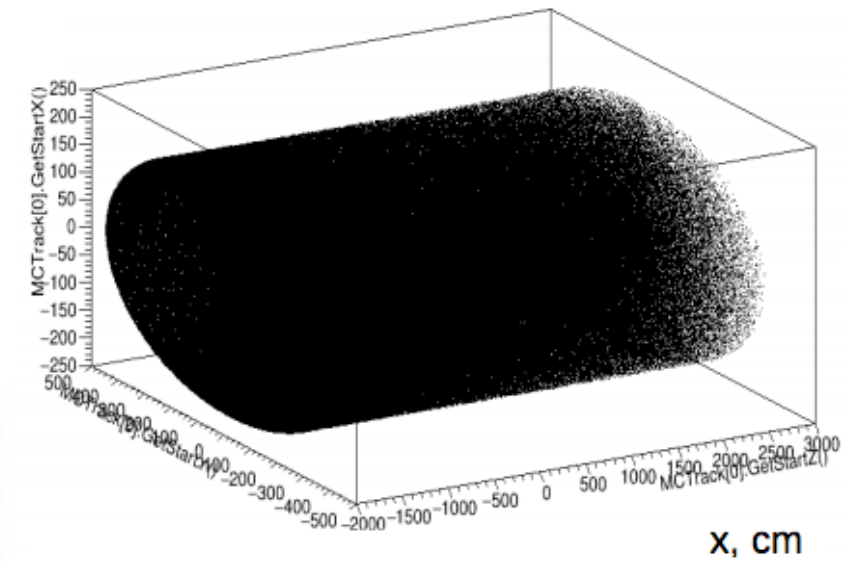
Fiducial Volume

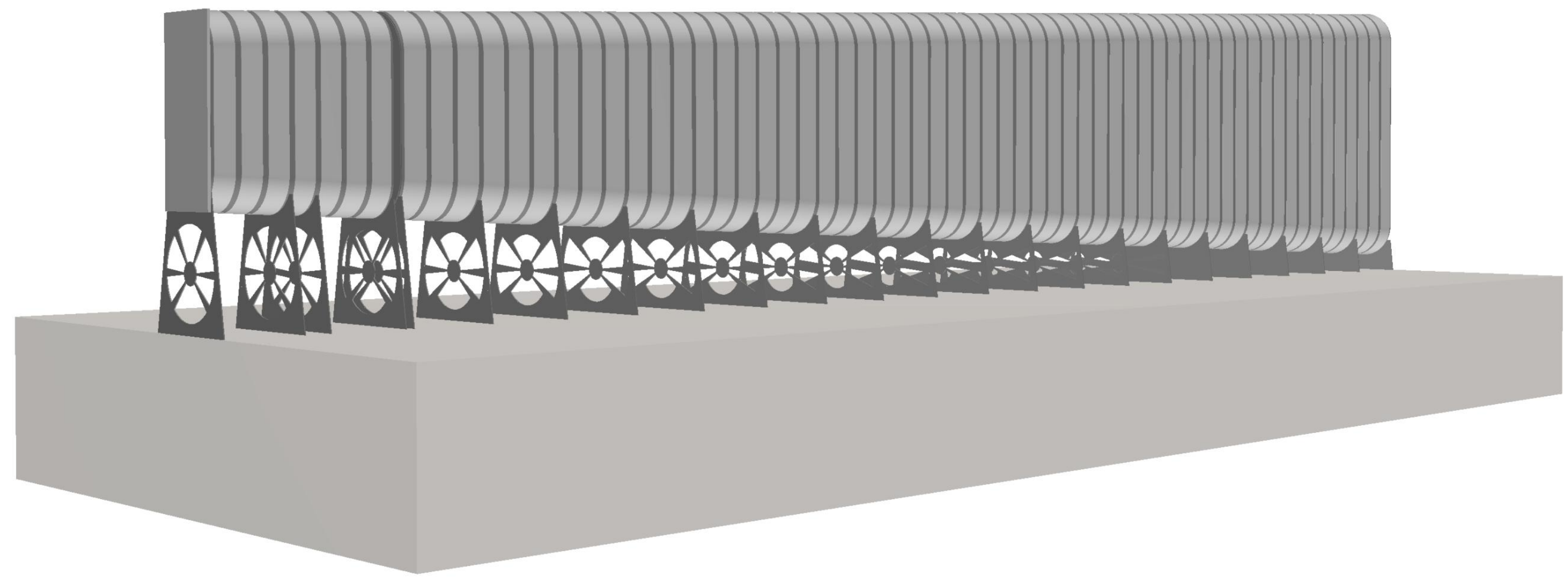


- In order to have a background free experiment we need a fiducial volume with at least 10^{-3} mbar to have negligible bkg from neutrinos interacting in the air

- Veto system around the fiducial volume:
  - Liquid or plastic scintillating in the vacuum vessel walls for vetoing
  - Upstream veto before the entrance window
  - Tracking veto after ~5m of the entrance window

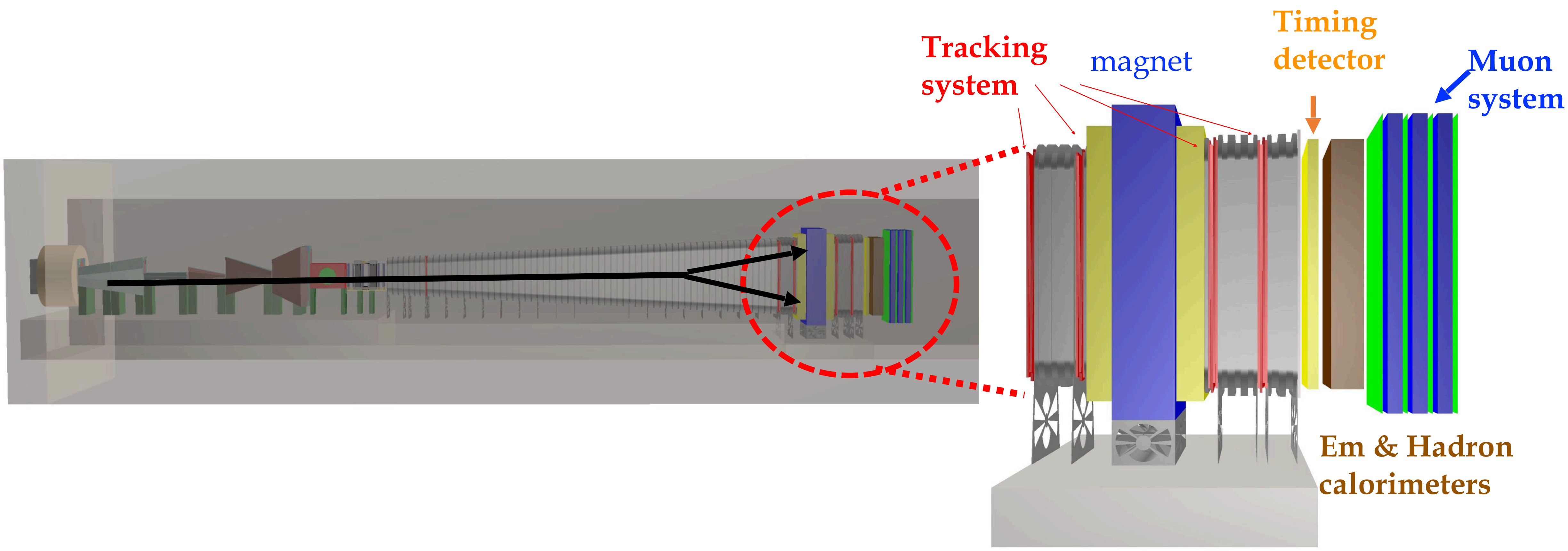
Vacuum Vessel





- The fiducial volume cannot be filled with air at atmospheric pressure, we would expect about 100K neutrino interaction in the experiment
- Of this about 300 would be survive a loose offline selection
- Piramidal frustrum shape to maximise the acceptance

HS Spectrometer



1) Fully reconstructed signal: at least two charged particles (+ π^0 , γ) e.g. N—>$\mu^+\pi^-$ or N—>$\rho^+\mu^-$

2) Partially reconstructed signal (neutirnos in the final state) e.g. N—>$\mu^+\nu\nu$

4) Fully neutral channels e.g. A—> γ γ

Tracking System

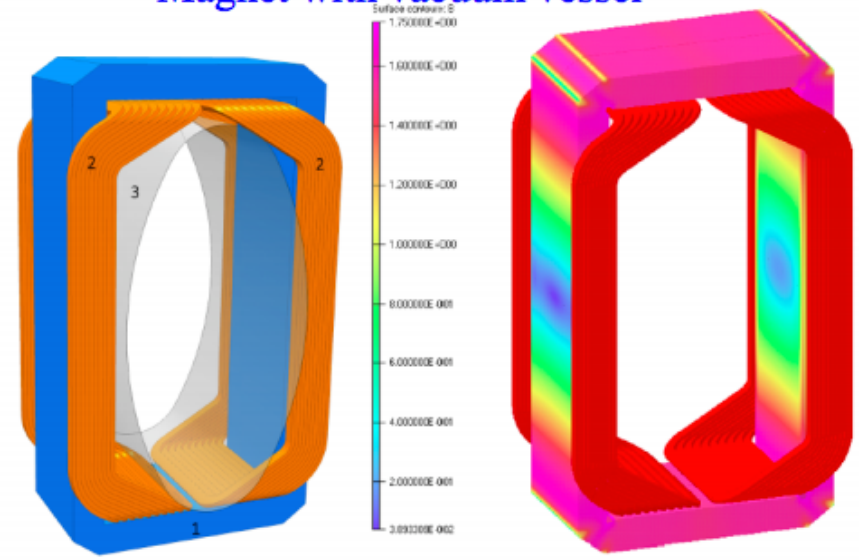
- *material budget per station 0.5% X_0*
  - *position resolution 120 μm per straw, 8 hits per station on average*

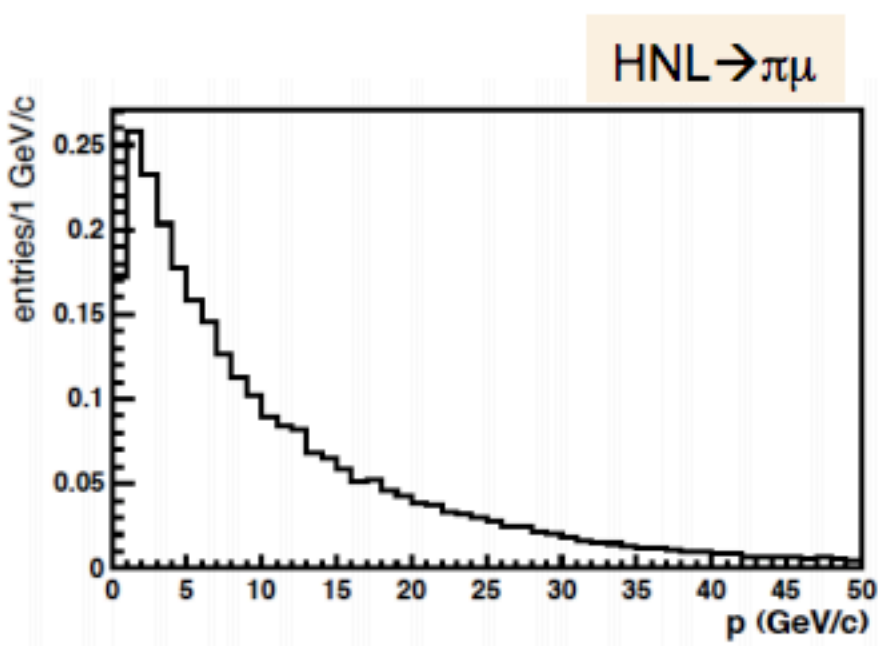
$$\left(\frac{\sigma_p}{p}\right)^2 \approx [0.49\%]^2 + [0.022\%/(\mathrm{GeV}/c)]^2 \cdot p^2$$

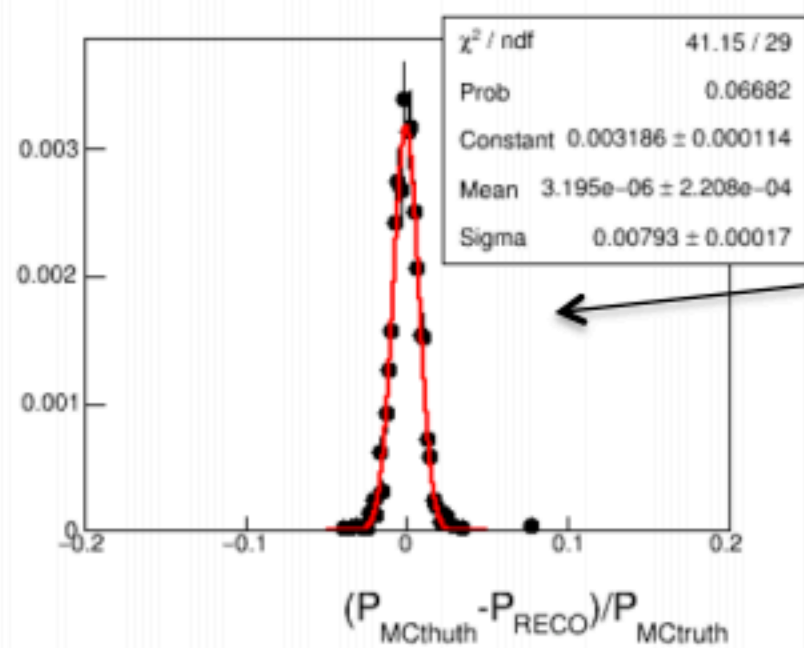
Momentum resolution is dominated by multiple scattering below 22 GeV/c
(For HNL → $\pi\mu$, 75% of both decay products have P < 20 GeV/c)

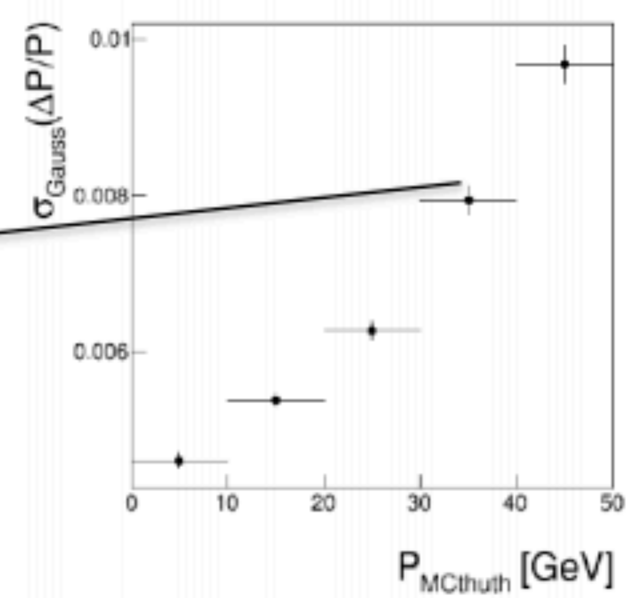
Main difference with Na62:
5m length, vacuum 10^{-2}mbar,

Magnet with vacuum vessel









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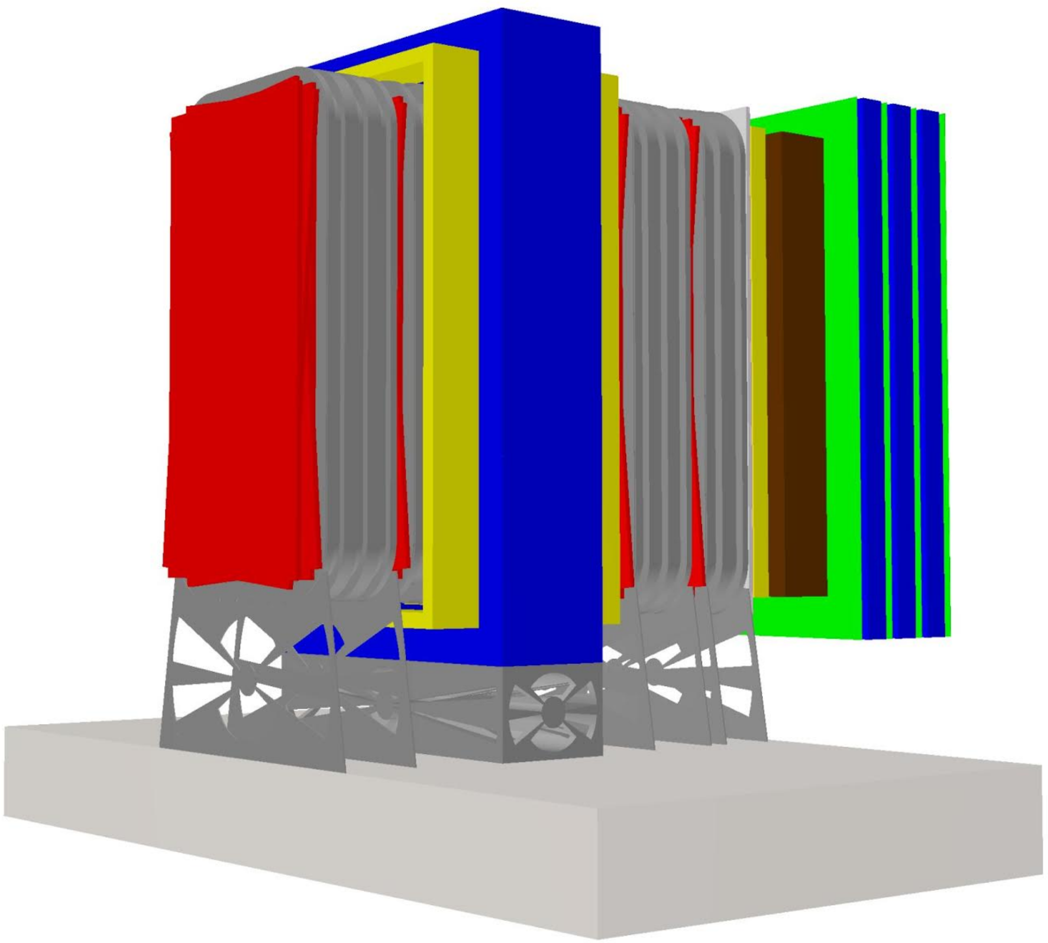
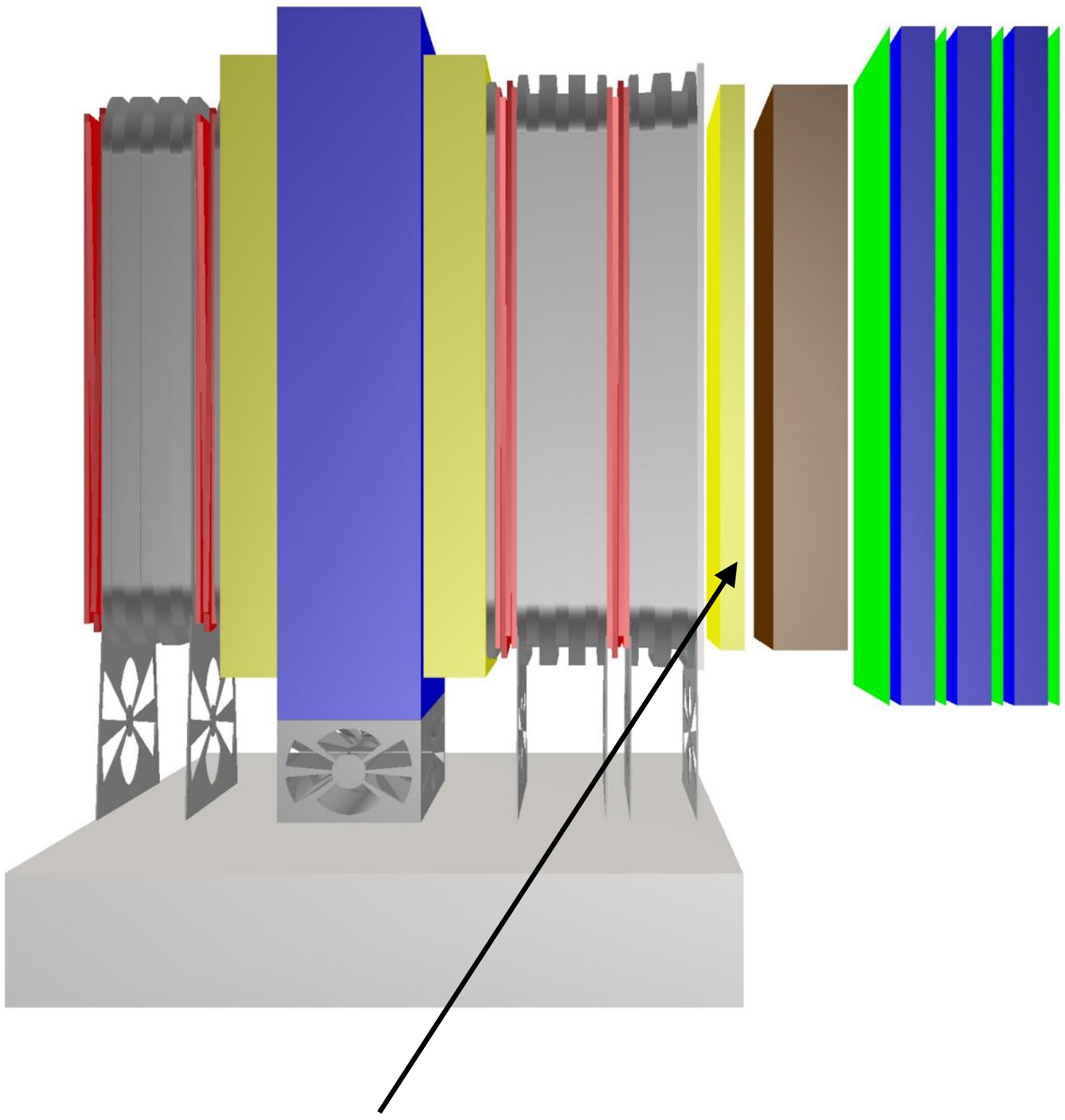




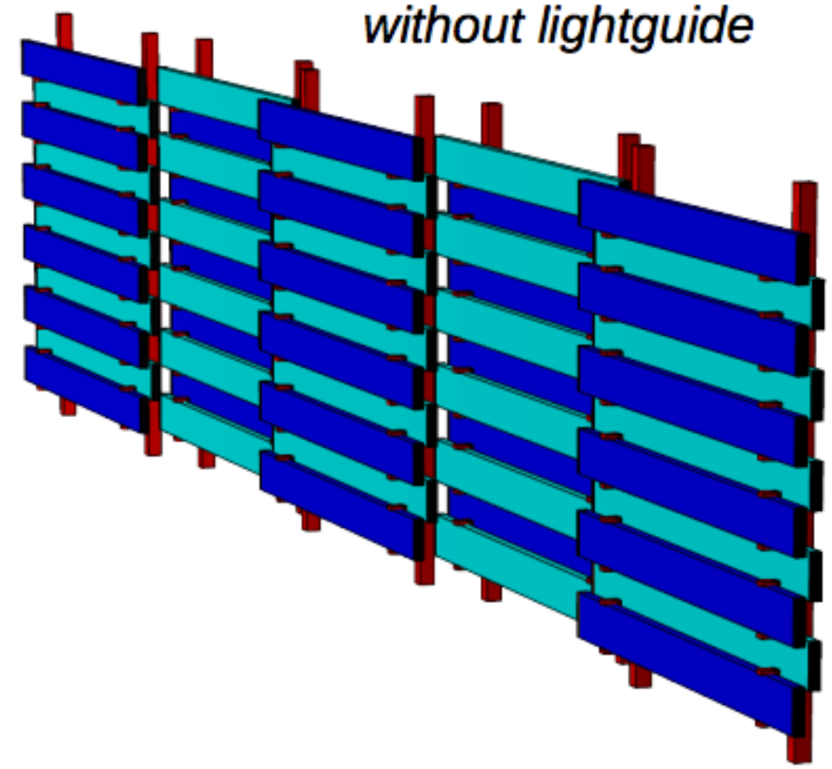
Physics Case

Challenges:
- Large area
- Required time resolution <100ps

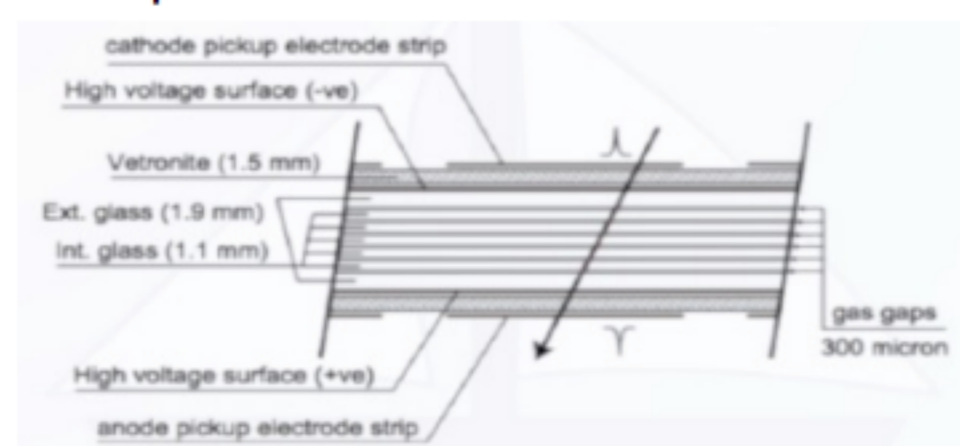
NA61/SHINE, bars with PMTs
UniGe 2006

NA61/SHINE ToF
- 100ps resolution in NA61/ Shine ToF
- Size of scintillator counter 120x10x2.5 cm^3
- Total active area 1.2x7.2 m^2

5-columns setup without lightguide



Multi-gap resistive plate chambers (MRPC)
- ALICE ToF and EEE project
- 61 chambers x 120 cm strips, 3 cm pitch
- 50 ps resolution achievable

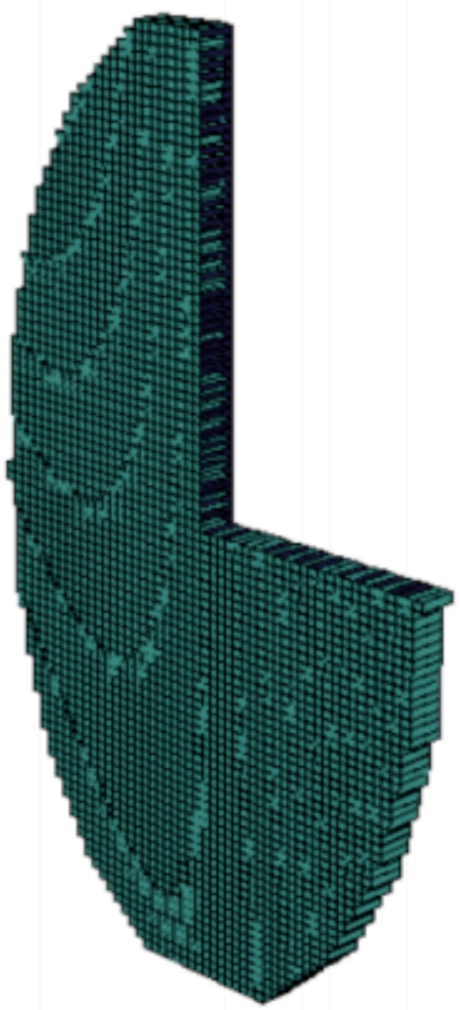


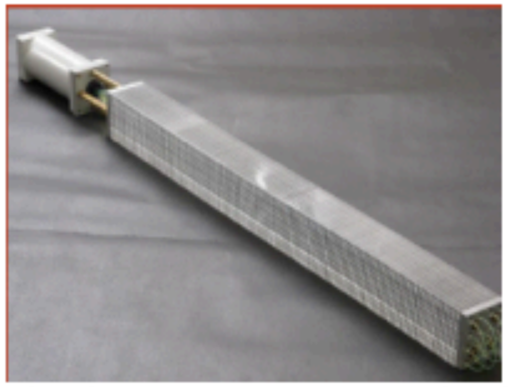
- Plastic scintillating bars read-out by SiPM

Calorimeter

ECAL

- Almost elliptical shape (5 m x 10 m)
- 2876 Shashlik modules
- 2x2 cells/modules, width=6 cm
- 11504 independent readout channels

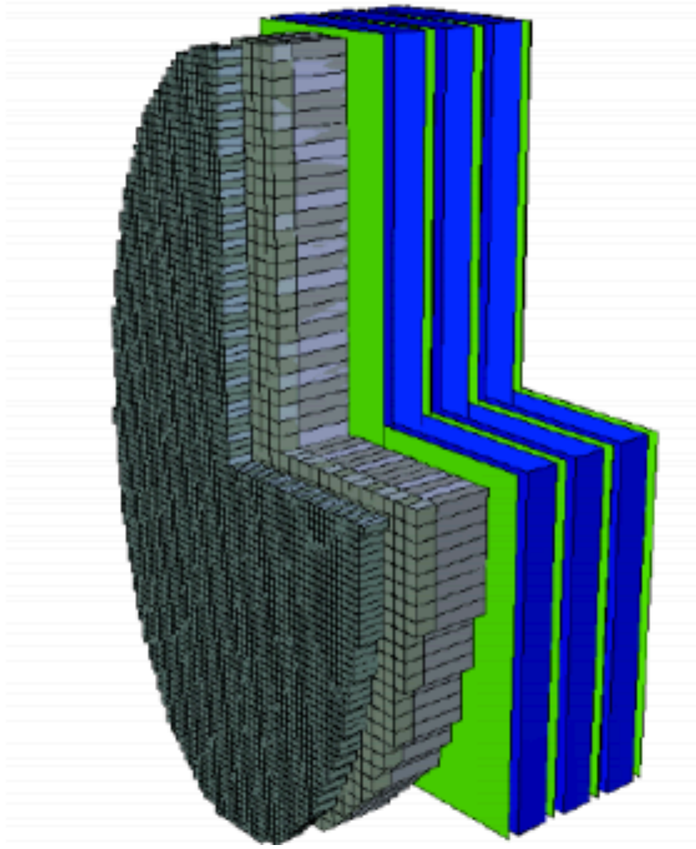




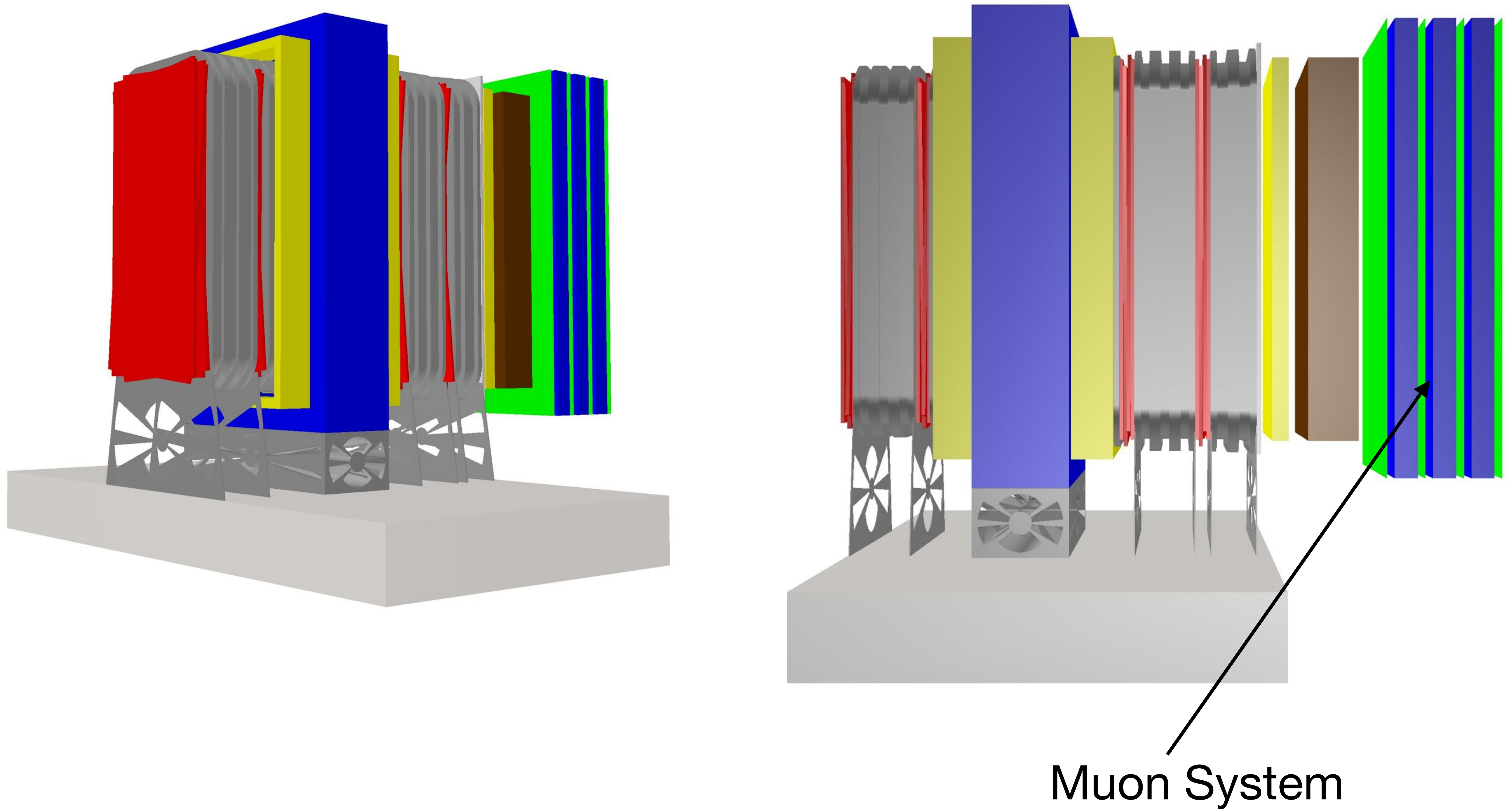
Dimensions	60x60 mm^2
Radiation length	17 mm
Moliere radius	36 mm
Radiation thickness	25 X_0
Scintillator thickness	1.5 mm
Lead thickness	0.8 mm
Energy resolution	1%

HCAL

- Matched with ECAL acceptance
- 2 stations
- 5 m x 10 m
- 1512 modules
- 24x24 cm^2 dimensions
- Stratigraphy: N x (1.5 cm steel+0.5 cm scint)
- 1512 independent readout channels

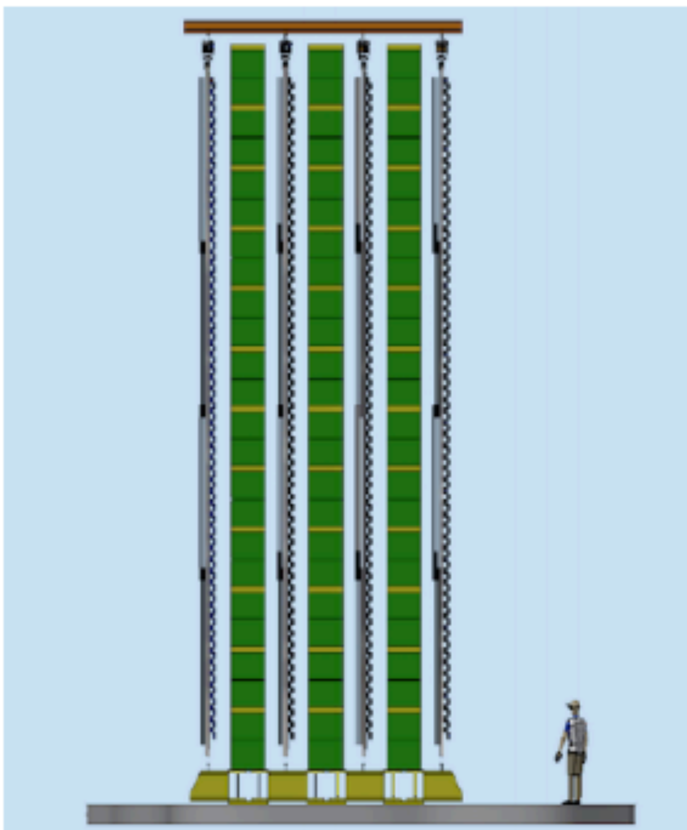


HS Spectrometer



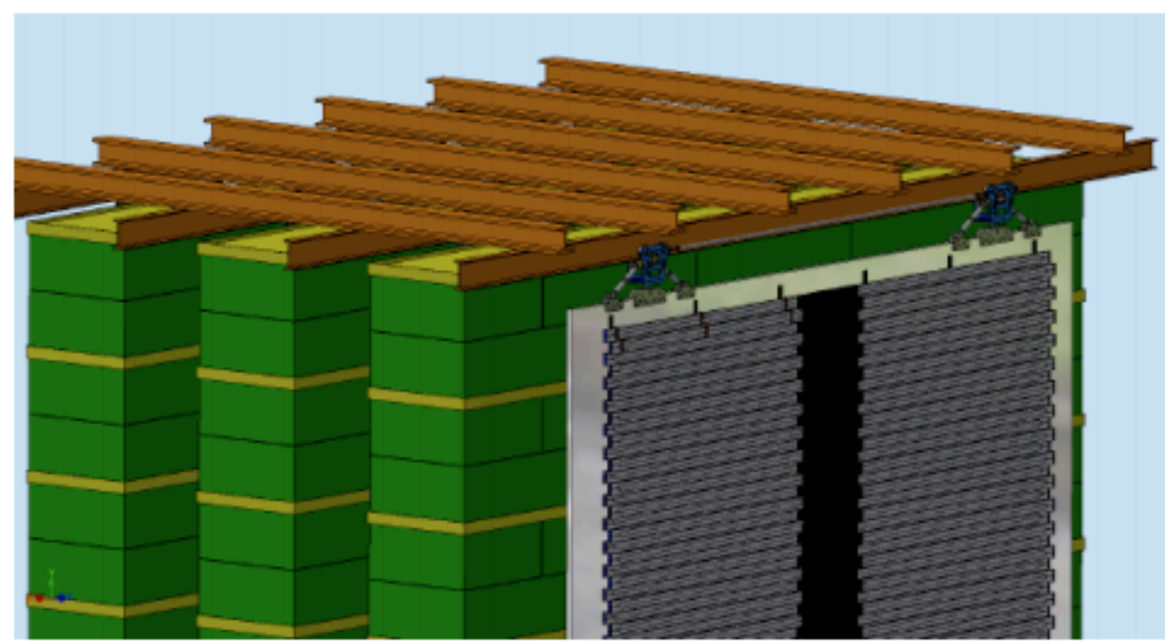
Muon System

Based on scintillating bars, with WLS fibers and SiPM readout

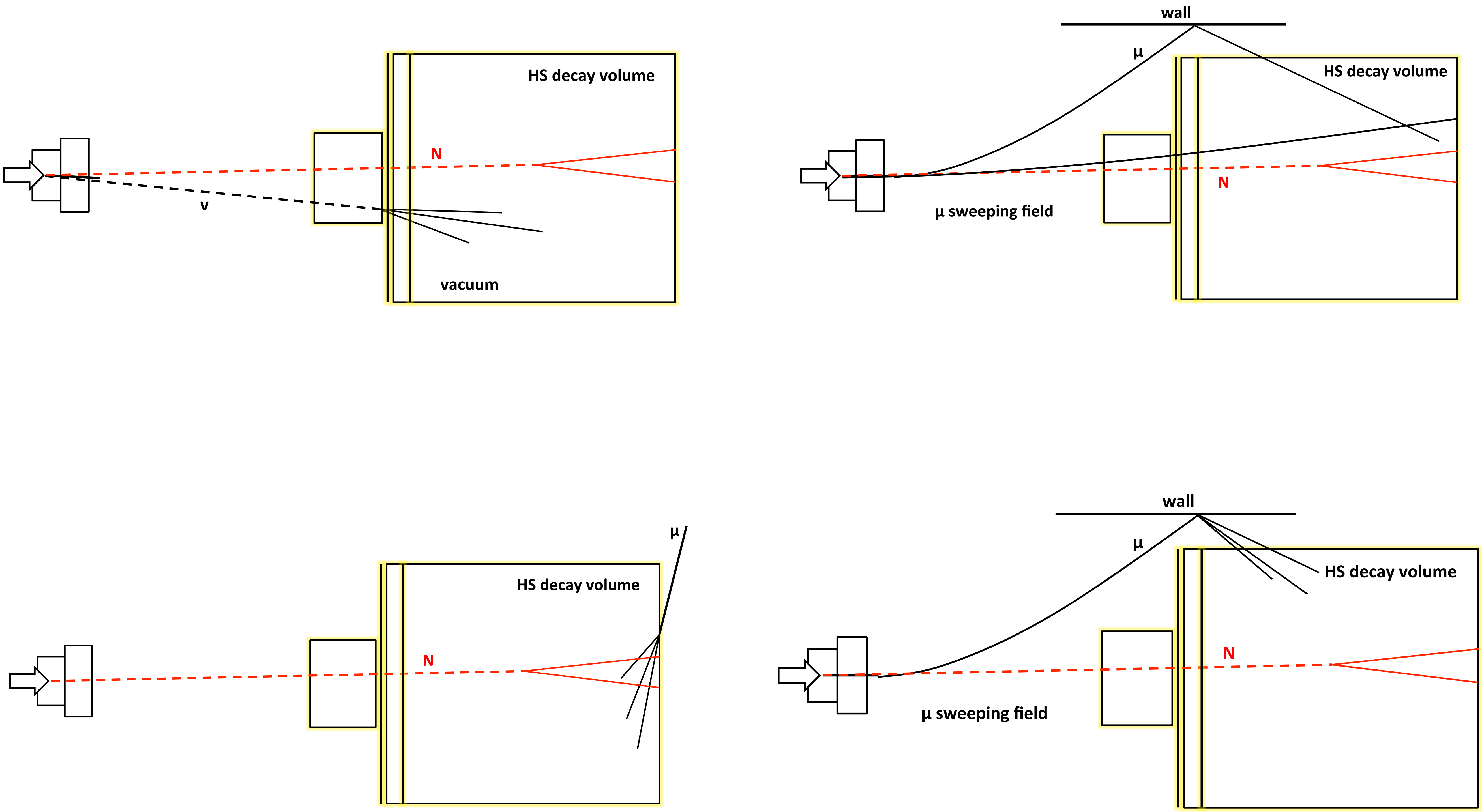


Technical Proposal (preliminary design)
- 4 active stations
- transverse dimensions: 1200x600 cm2
- x,y view
- 3380 bars, 5x300x2 cm3/each
- 7760 FEE channels
- 1000 tons of iron filters

Requirements:
1) High-efficiency identification of muons in the final state
2) Separation between muons and hadrons/ electrons
3) Complement timing detector to reject combinatorial muon background



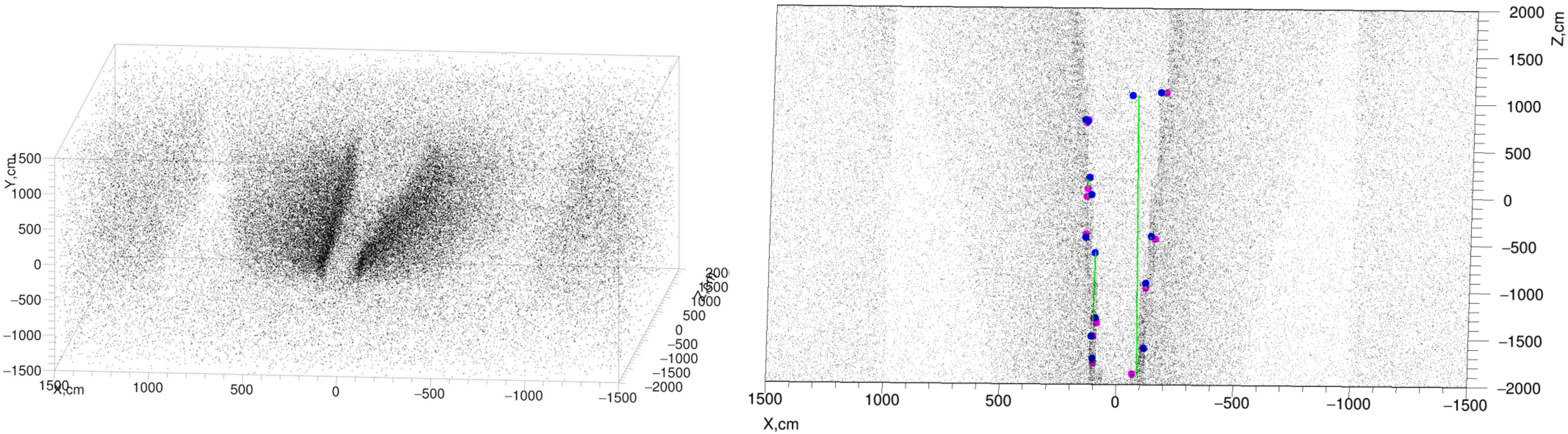
Backgrounds



Background

Using the expected rate of muons (with sweeping magnets) the main background consists of neutrino inelastic:

- Reduced rate of inelastic muons, efficiently killed by vets
- Cosmic muons killed by veto (+ bad pointing)
- Combinatorial muons killed by timing



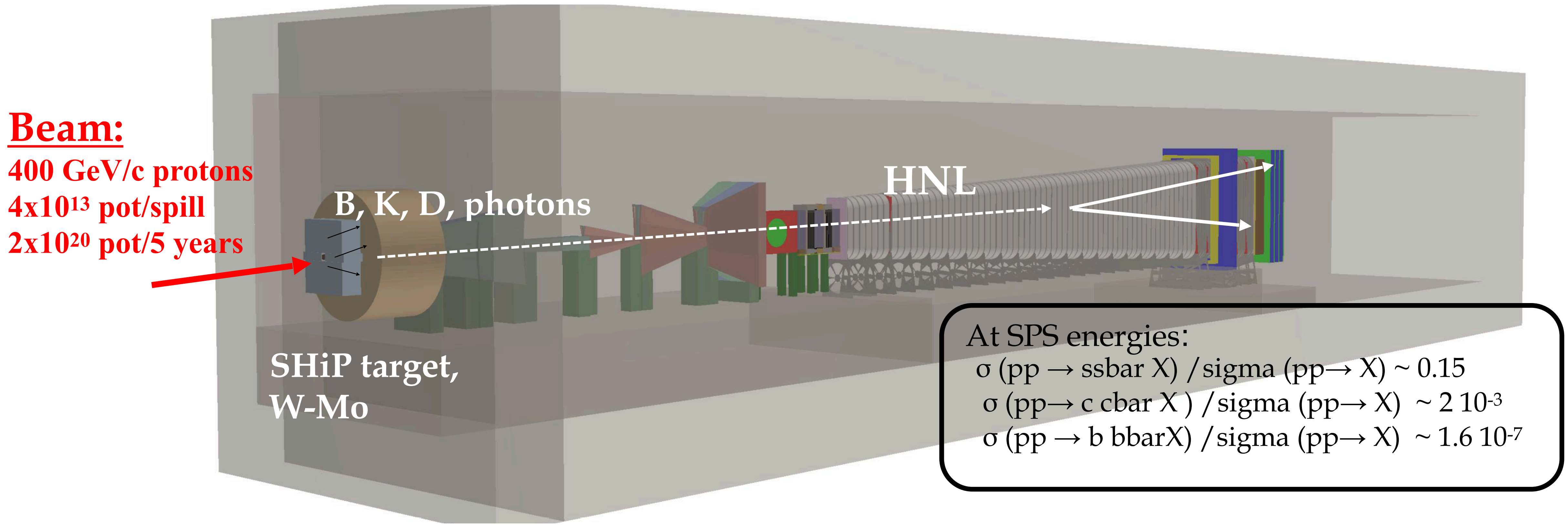
- All studies compatible with zero expected background
- Preparing large simulation to study properties of events with reconstructed vertexes

Physics signals

Signature	Physics	Backgrounds
$\pi^-\mu^+$,$K^-\mu^+$	HNL,NEU	RDM, $K_L^0 \to \pi^-\mu^+\nu_\mu$
$\pi^-\pi^0\mu^+$	HNL($\to \rho^-\mu^+$)	$K_L^0 \to \pi^-\mu^+\nu_\mu(+\pi^0)$, $K_L^0 \to \pi^-\pi^+\pi^0$
π^-e^+,K^-e^+	HNL, NEU	$K_L^0 \to \pi^-e^+\nu_e$
$\pi^-\pi^0e^+$	HNL($\to \rho^-e^+$)	$K_L^0 \to \pi^-e^+\nu_e$, $K_L^0 \to \pi^-\pi^+\pi^0$
$\mu^-e^+ + p^{miss}$	HNL,Higgs Portal (HP)($\to \tau\tau$)	$K_L^0 \to \pi^-\mu^+\nu_\mu$, $K_L^0 \to \pi^-e^+\nu_e$
$\mu^-\mu^+ + p^{miss}$	HNL,HP($\to \tau\tau$)	RDM, $K_L^0 \to \pi^-\mu^+\nu_\mu$
$\mu^-\mu^+$	DP,PNGB,HP	RDM, $K_L^0 \to \pi^-\mu^+\nu_\mu$
$\mu^-\mu^+\gamma$	Chern-Simons	$K_L^0 \to \pi^-\pi^+\pi^0$, $K_L^0 \to \pi^-\mu^+\nu_\mu(+\pi^0)$
$e^-e^+ + p^{miss}$	HNL,HP	$K_L^0 \to \pi^-e^+\nu_e$
e^-e^+	DP,PNGB,HP	$K_L^0 \to \pi^-e^+\nu_e$
$\pi^-\pi^+$	DP,PNGB,HP	$K_L^0 \to \pi^-\mu^+\nu_\mu$, $K_L^0 \to \pi^-e^+\nu_e$, $K_L^0 \to \pi^-\pi^+\pi^0$,$K_L^0 \to \pi^-\pi^+$
$\pi^-\pi^+ + p^{miss}$	DP,PNGB, HP($\to \tau\tau$), HSU,HNL($\to \rho^0\nu$)	$K_L^0 \to \pi^-\mu^+\nu_\mu$, $K_L^0 \to \pi^-e^+\nu_e$, $K_L^0 \to \pi^-\pi^+\pi^0$, $K_L^0 \to \pi^-\pi^+$,$K_S^0 \to \pi^-\pi^+$,$\Lambda \to p\pi$
K^+K^-	DP,PNGB, HP	$K_L^0 \to \pi^-\mu^+\nu_\mu$, $K_L^0 \to \pi^-e^+\nu_e K_L^0 \to \pi^-\pi^+\pi^0$, $K_L^0 \to \pi^-\pi^+$,$K_S^0 \to \pi^-\pi^+$,$\Lambda \to p\pi$
$\pi^+\pi^-\pi^0$	DP,PNGB,HP, HNL($\eta\nu$)	$K_L^0 \to \pi^-\pi^+\pi^0$
$\pi^+\pi^-\pi^0\pi^0$	DP,PNGB,HP	$K_L^0 \to \pi^-\pi^+\pi^0(+\pi^0)$
$\pi^+\pi^-\pi^0\pi^0\pi^0$	PNGB($\to \pi\pi\eta$)	–
$\pi^+\pi^-\gamma\gamma$	PNGB($\to \pi\pi\eta$)	$K_L^0 \to \pi^-\pi^+\pi^0$
$\pi^+\pi^-\pi^+\pi^-$	DP,PNGB,HP	–
$\pi^+\pi^-\mu^+\mu^-$	Hidden Susy (HSU)	–
$\pi^+\pi^-e^+e^-$	Hidden Susy	–
$\mu^+\mu^-\mu^+\mu^-$	Hidden Susy	–
$\mu^+\mu^-e^+e^-$	Hidden Susy	–

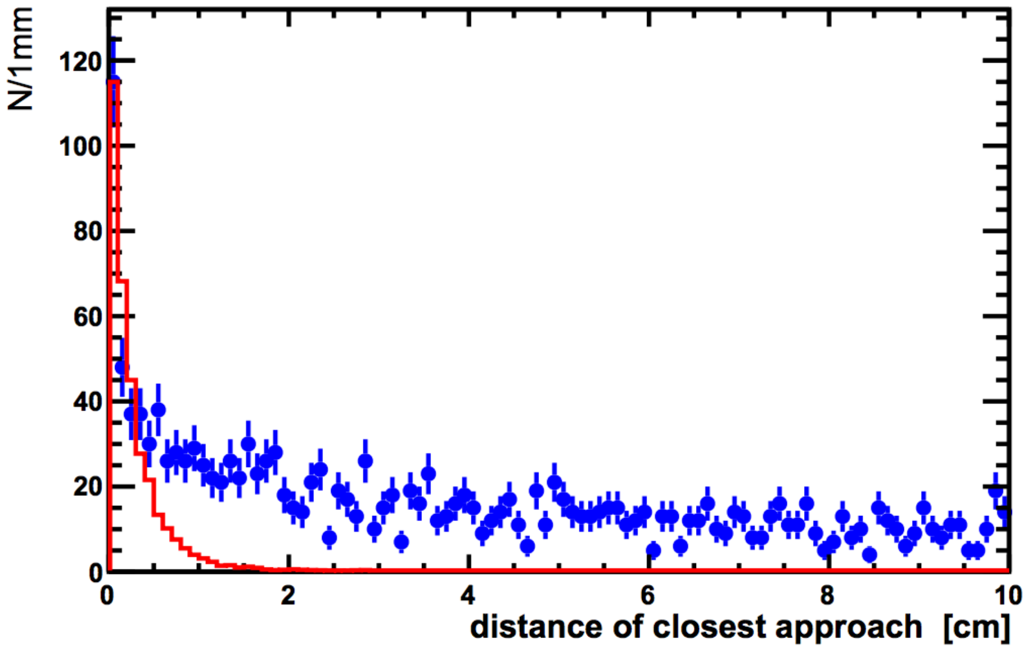
HNL=Heavy Neutral Lepton, NEU=neutralino
DP=Dark Photon, PNGB=Pseudo-Nambu Goldston Boson
Background: RDM=random di-muons from the target

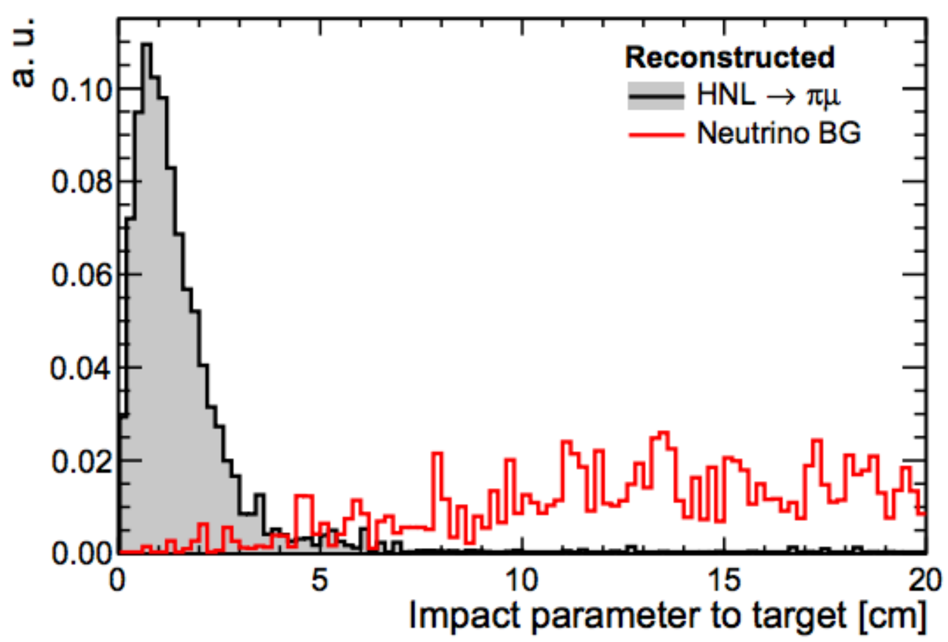
Signal Signature



At SPS energies:

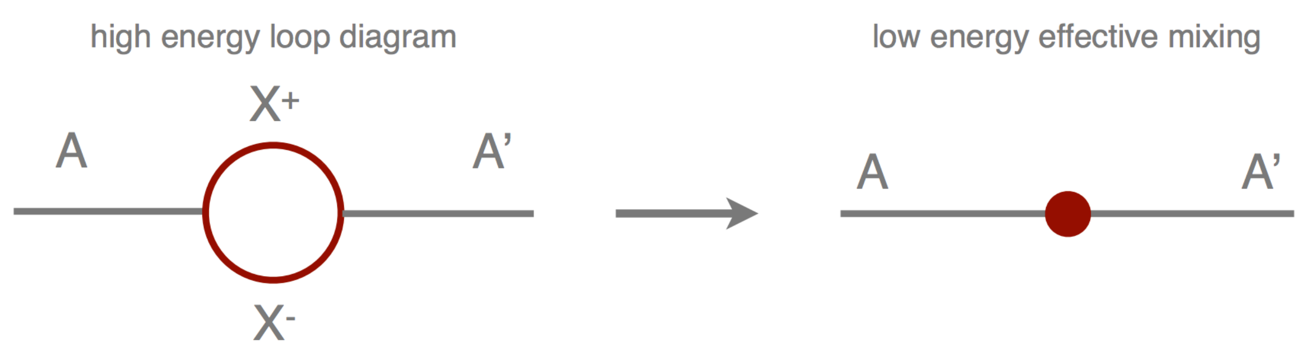
- σ (pp → ssbar X) / sigma (pp→ X) ~ 0.15
- σ (pp→ c cbar X) / sigma (pp→ X) ~ 2 10^{-3}
- σ (pp → b bbarX) / sigma (pp→ X) ~ 1.6 10^{-7}





Dark Photon

- Dark Matter might interact via unknown forces
- Consider an additional U(1)’ symmetry wrt which SM particles are neutral
- If we have some high mass fermions charged under U(1) and U(1)’ we have an effective coupling



QED-like

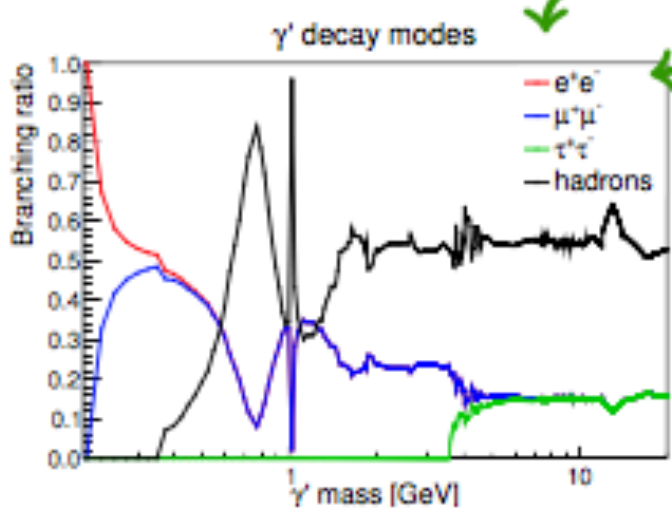
$$\mathcal{L} = \mathcal{L}_{\psi,A} + \mathcal{L}_{\chi,A'} - \frac{\epsilon}{2} F_{\mu\nu}F'^{\mu\nu} + \frac{1}{2}m^2_{A'}(A'_\mu)^2$$

QED fields — $U(1)'$ fields — field strength tensors — mass term

Dark Photon

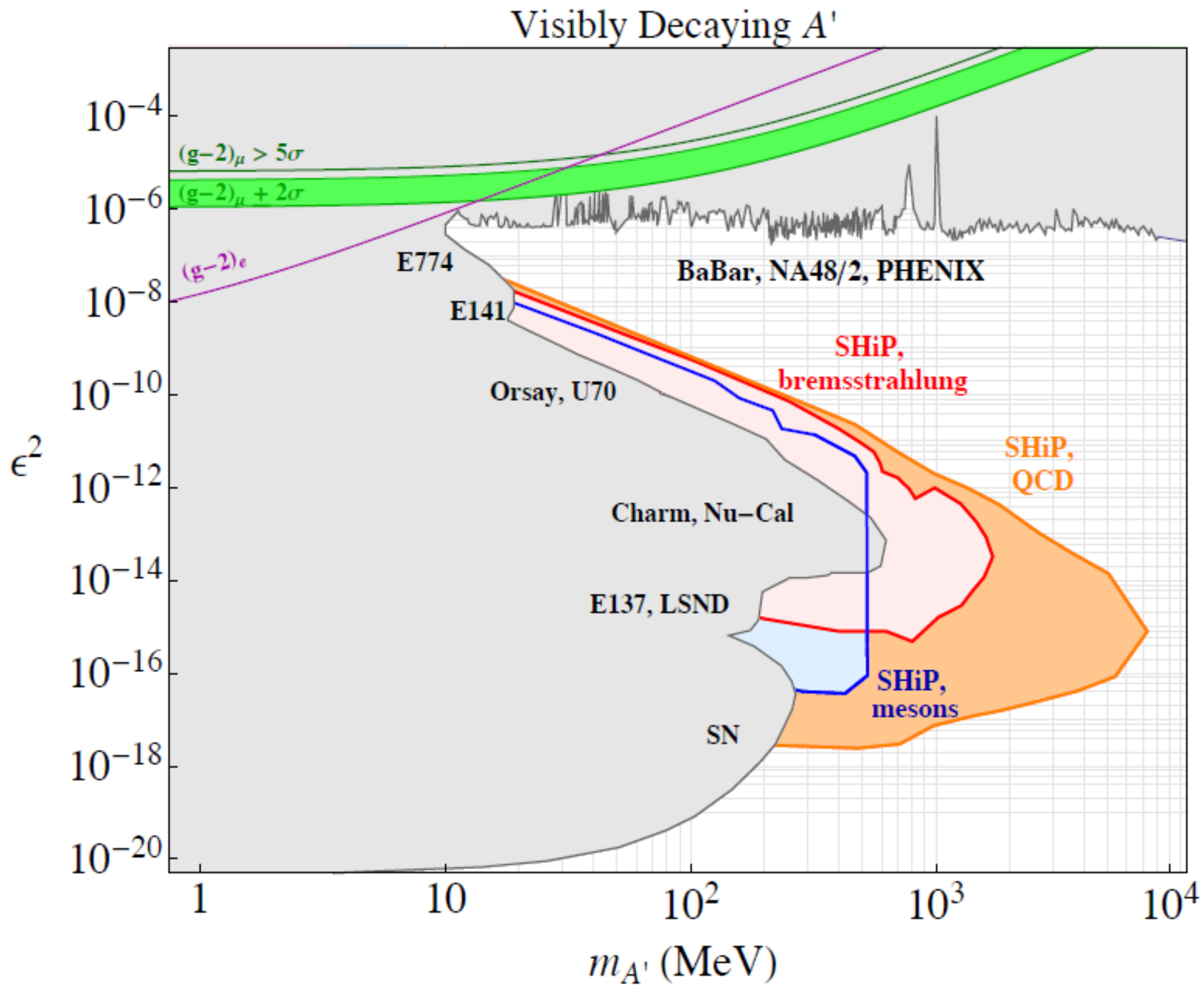
- **Production at SHiP:**
  - meson decays e.g. $\pi^0 \to \gamma V$ ($\sim \epsilon^2$) *arXiv:0906.5614*
  - p bremsstrahlung on target nuclei $pp \to ppV$ *arXiv:1311.3870*
  - large $m_V \Rightarrow$ direct QCD production through underlying $q\bar{q} \to V$, $qg \to V$ (need some more theory work!) *arXiv:1205.3499*

- **Decay:** $$\Gamma_{tot} = \Gamma(\ell^+\ell^-) + \Gamma(\text{hadrons}) + \Gamma(\chi\bar{\chi})$$



$$\frac{\ell\ell}{\chi\chi} \sim \frac{\alpha\epsilon^2}{\alpha_D},$$ α_D = dark fine structure constant

Dark Photon



Visibly Decaying A'
$(g-2)_\mu > 5\sigma$
$(g-2)_\mu \pm 2\sigma$
$(g-2)_e$
E774
E141
Orsay, U70
BaBar, NA48/2, PHENIX
SHiP, bremsstrahlung
SHiP, QCD
Charm, Nu−Cal
E137, LSND
SHiP, mesons
SN
ϵ^2
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^{-12}
10^{-14}
10^{-16}
10^{-18}
10^{-20}
1
10
10^2
10^3
10^4
$m_{A'}$ (MeV)

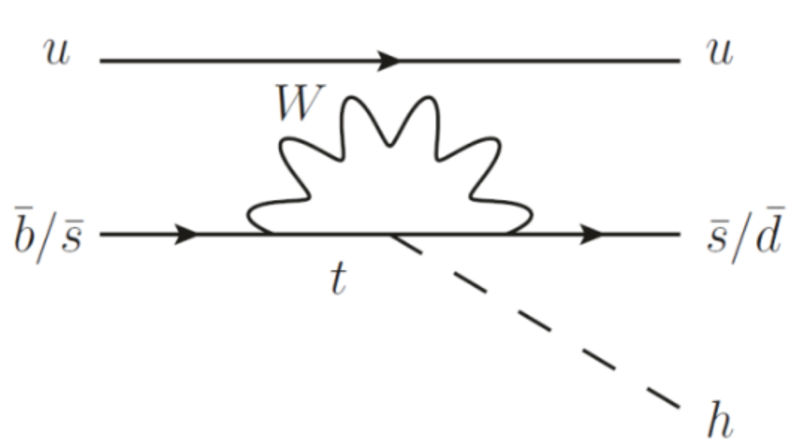
Dark Scalars

At SHiP (according with estimates) we produce around xxx B-mesons, so we can exploit the Higgs portal (search for light Dark Scalars mixing with the Higgs)

$$\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_{HS} + (\alpha_1 S + \alpha S^2) H^\dagger H$$

$$\begin{pmatrix} H \\ h \end{pmatrix} = \begin{pmatrix} \cos\rho & -\sin\rho \\ \sin\rho & \cos\rho \end{pmatrix} \begin{pmatrix} \phi_0' \\ S' \end{pmatrix}$$

Theory references:



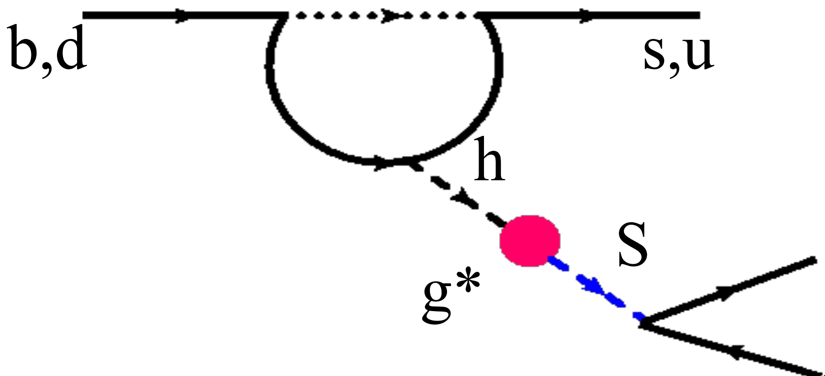
$$\Gamma(K \to \pi\phi) \sim (m_t^2 |V_{ts}^* V_{td}|)^2 \propto m_t^4 \lambda^5$$

$$\Gamma(D \to \pi\phi) \sim (m_b^2 |V_{cb}^* V_{ub}|)^2 \propto m_b^4 \lambda^5$$

$$\Gamma(B \to K\phi) \sim (m_t^2 |V_{ts}^* V_{tb}|)^2 \propto m_t^4 \lambda^2$$

➜ Decay: $S \to \gamma\gamma, ee, \mu\mu, \pi\pi, KK$

Dark Scalars

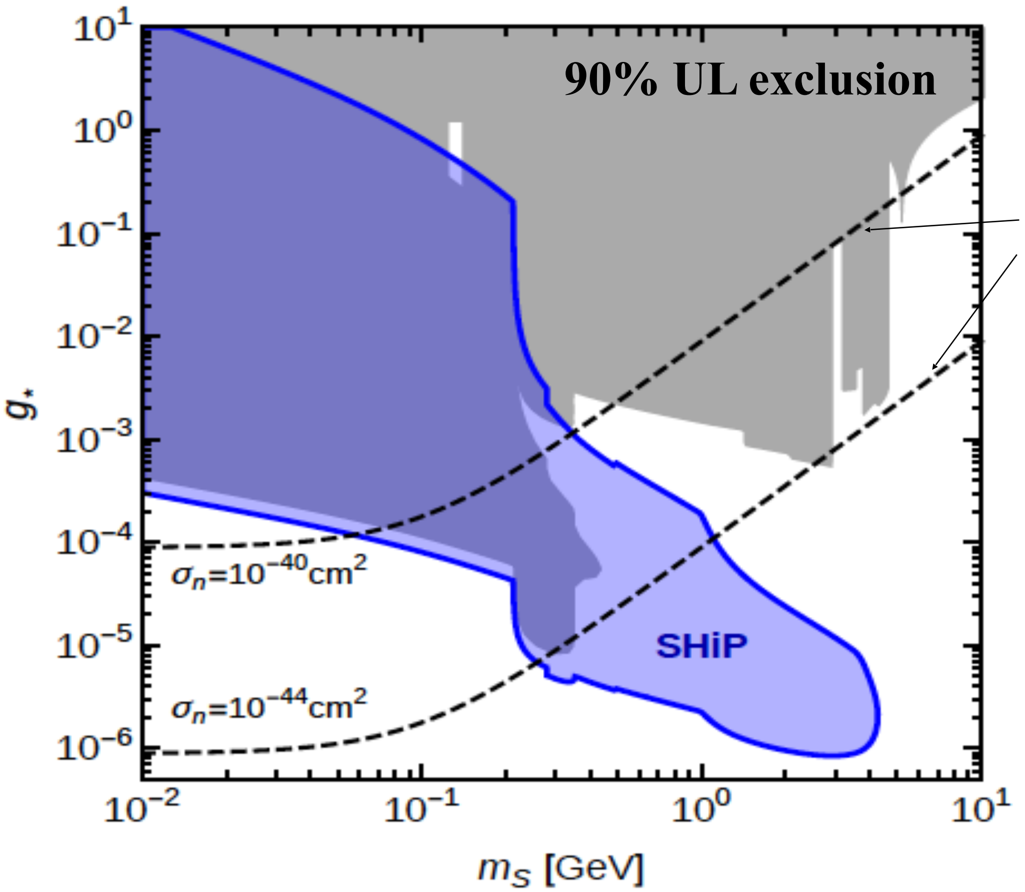


$\rightarrow \Gamma(K \to \pi\phi) \sim (m_t^2 |V_{ts}^* V_{td}|)^2 \propto m_t^4 \lambda^5$

$\Gamma(D \to \pi\phi) \sim (m_b^2 |V_{cb}^* V_{ub}|)^2 \propto m_b^4 \lambda^5$

$\rightarrow \Gamma(B \to K\phi) \sim (m_t^2 |V_{ts}^* V_{tb}|)^2 \propto m_t^4 \lambda^2$

e^+e^-, $\pi^+\pi^-$, K^+K^-, $\mu^+\mu^-$, …
detected in the downstream spectrometer



The SHiP Physics case,
Rept.Prog.Phys. 79 (2016) no.12, 124201

Contours of constant DM nucleon cross section, where we assumed that S acts as the mediator between DM and nucleons:

⟶ current limits from LUX experiment assuming $m_\chi \sim$ 5-10 GeV and k = 0.1

$$\sigma_n \simeq 10^{-40}\text{cm}^2 \left(\frac{\kappa}{0.1}\right)^2 \left(\frac{g_\star}{0.01}\right)^2 \left(\frac{\text{GeV}}{m_S}\right)^4$$

ALPS

Pseudo-scalar can arise from spontaneously broken U(1) symmetry:

- An example is the axion, introduce to solve the strong CP problem (m~10^{-5} eV)
- Axion-Like particles (ALPs) ca arise from other broken symmetries

ALPs can couple to: gauge bosons, fermions or gluons

Gauge Boson

$$\mathcal{L} \supset \frac{1}{4} g_{a\gamma\gamma} \phi F^{\mu\nu} F_{\mu\nu}$$

$$g_{a\gamma\gamma} \sim \frac{\alpha}{4\pi f_a}$$

Fermions

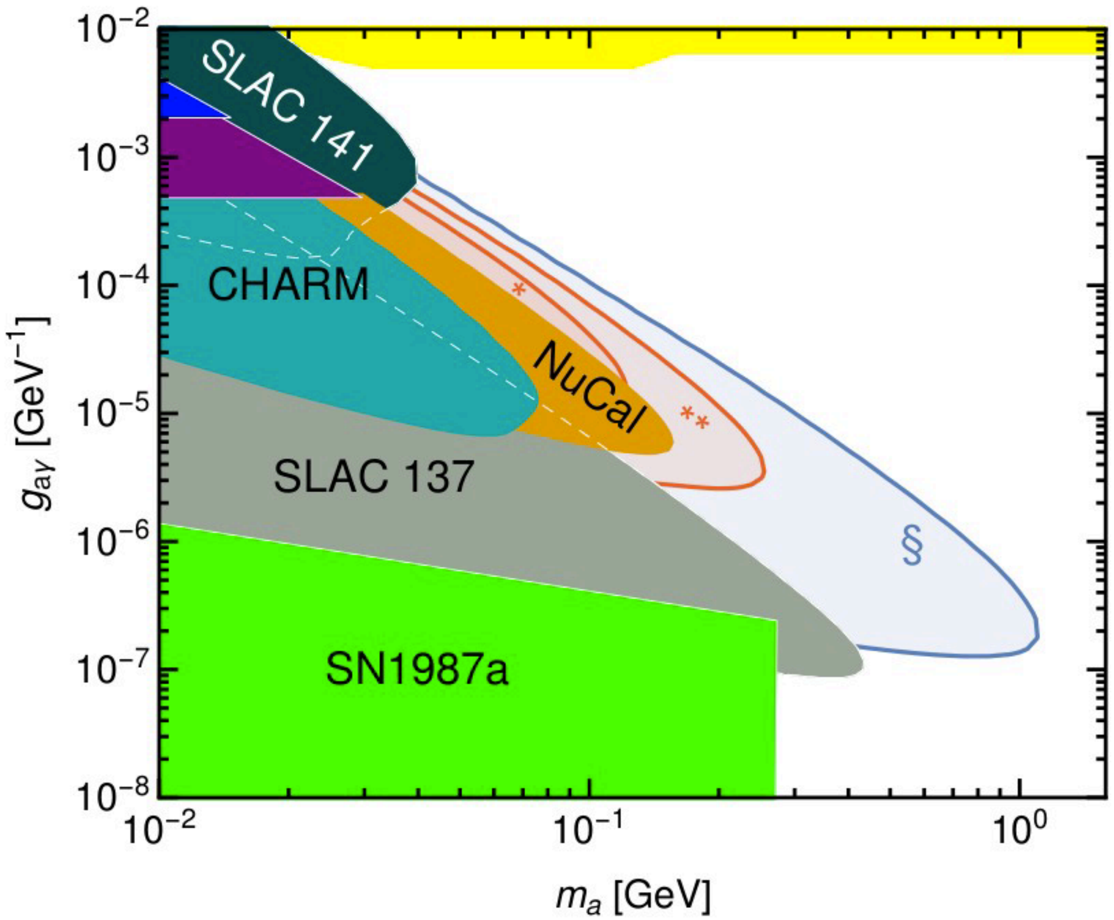
$$\mathcal{L} \supset \frac{\partial_\mu \phi}{f_a} \bar{\psi} \gamma^\mu \gamma^5 \psi$$

Coupling proportional to $1/f_a$ (scale of the spontaneous broken symmetry)

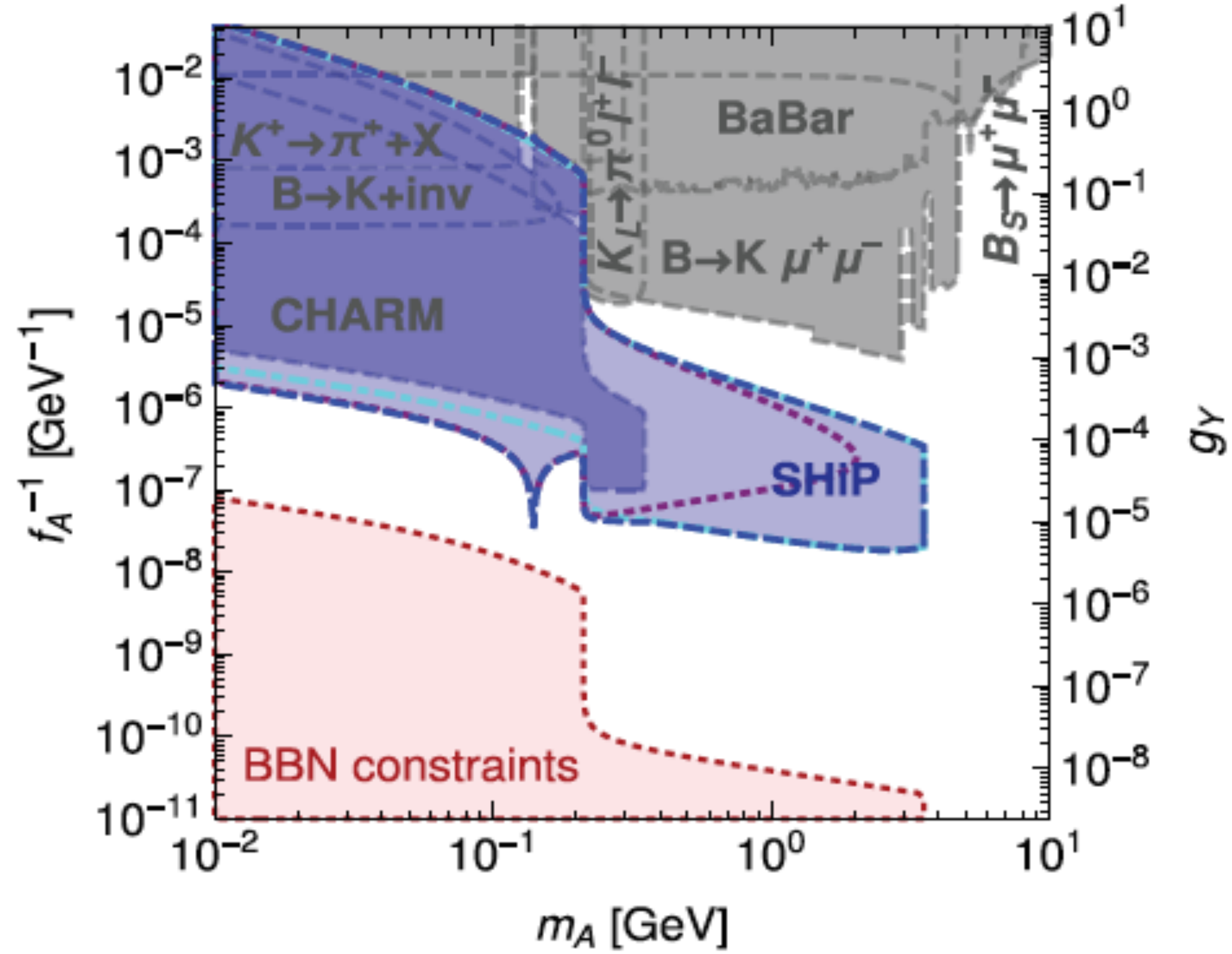
Two signature in SHiP: $A' \longrightarrow \gamma\gamma$ and $A' \longrightarrow \mu^+\mu^-$

ALPS

A′⟶ γ γ

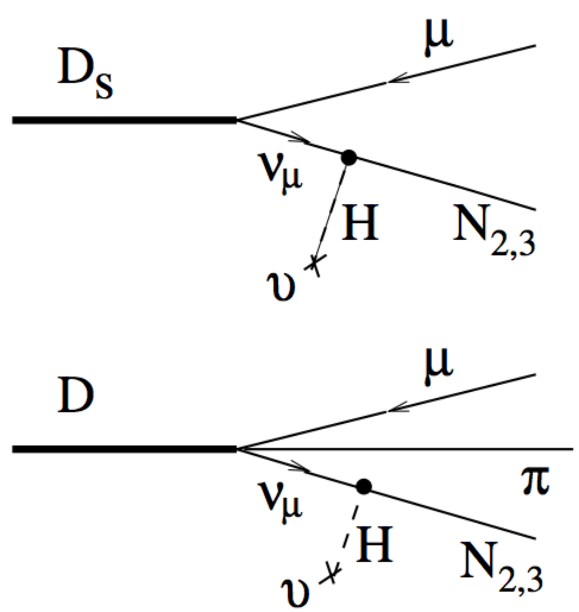

SLAC 141
CHARM
NuCal
SLAC 137
SN1987a
§
$g_{a\gamma}$ [GeV^{-1}]
m_a [GeV]

A′⟶ μ+μ-

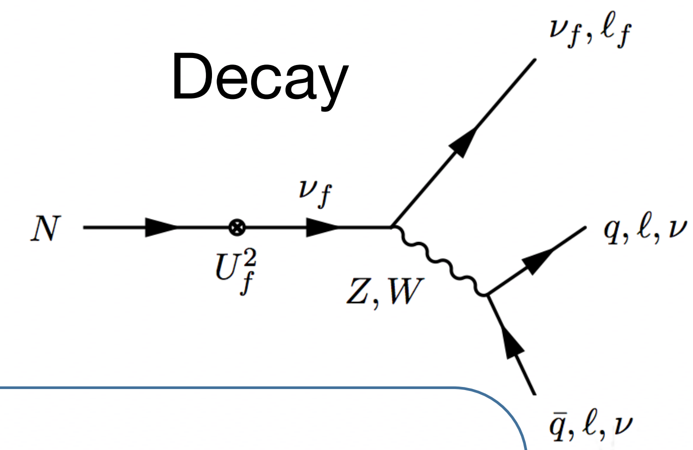

BaBar
$K^+ \to \pi^+ + X$
B→K+inv
$K_L \to \pi^0 l^+ l^-$
B→K $\mu^+\mu^-$
$B_S \to \mu^+\mu^-$
CHARM
SHiP
BBN constraints
f_A^{-1} [GeV^{-1}]
g_Y
m_A [GeV]

HNLs

Production



Decay



$N \rightarrow H^0\nu$, with $H^0 = \pi^0, \rho^0, \eta, \eta'$
$N \rightarrow H^{\pm}\ell^{\mp}$, with $H = \pi, \rho$
$N \rightarrow 3\nu$
$N \rightarrow \ell_i^{\pm}\ell_j^{\mp}\nu_j$
$N \rightarrow \nu_i\ell_j^{\pm}\ell_j^{\mp}$

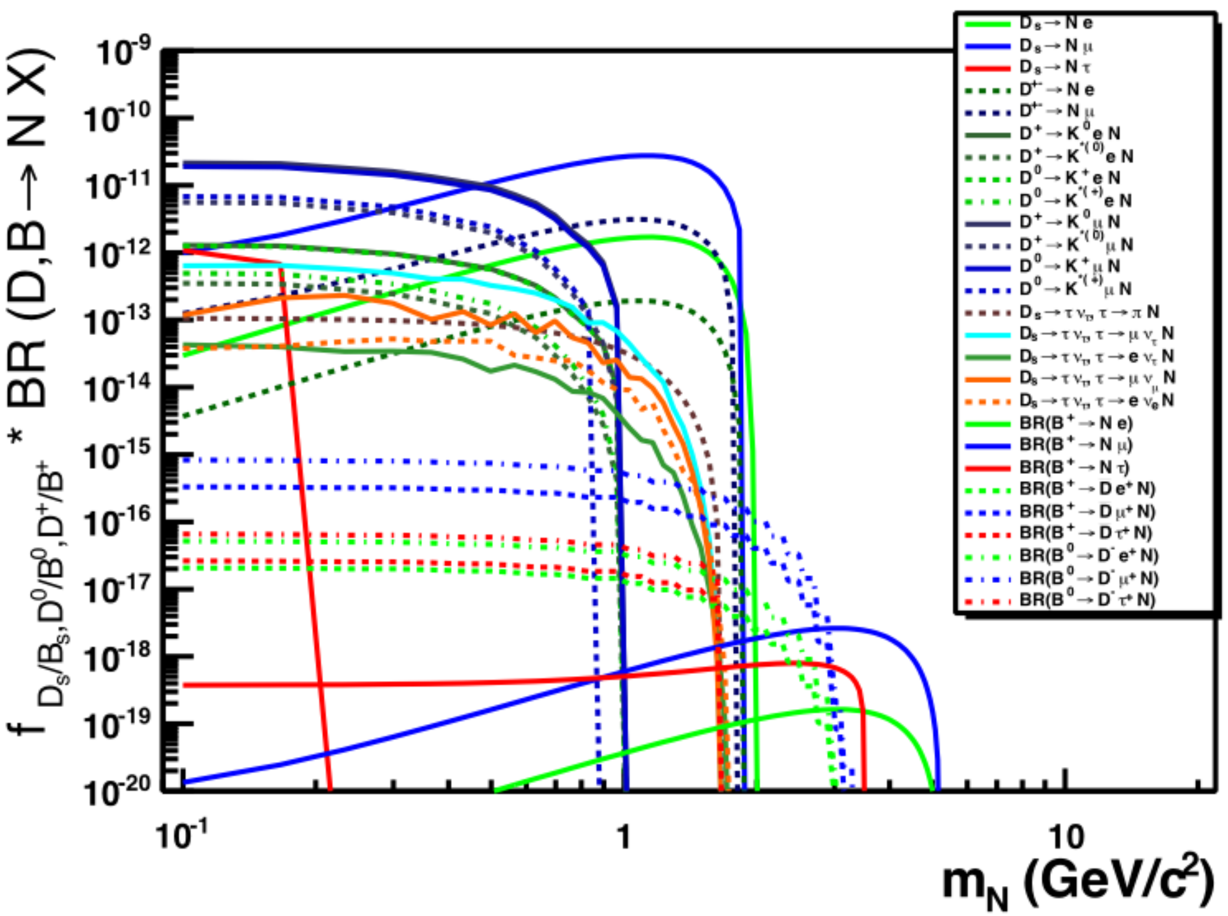
- Production and decays are both suppressed by U^2 , so the sensitivity is proportional to U^4

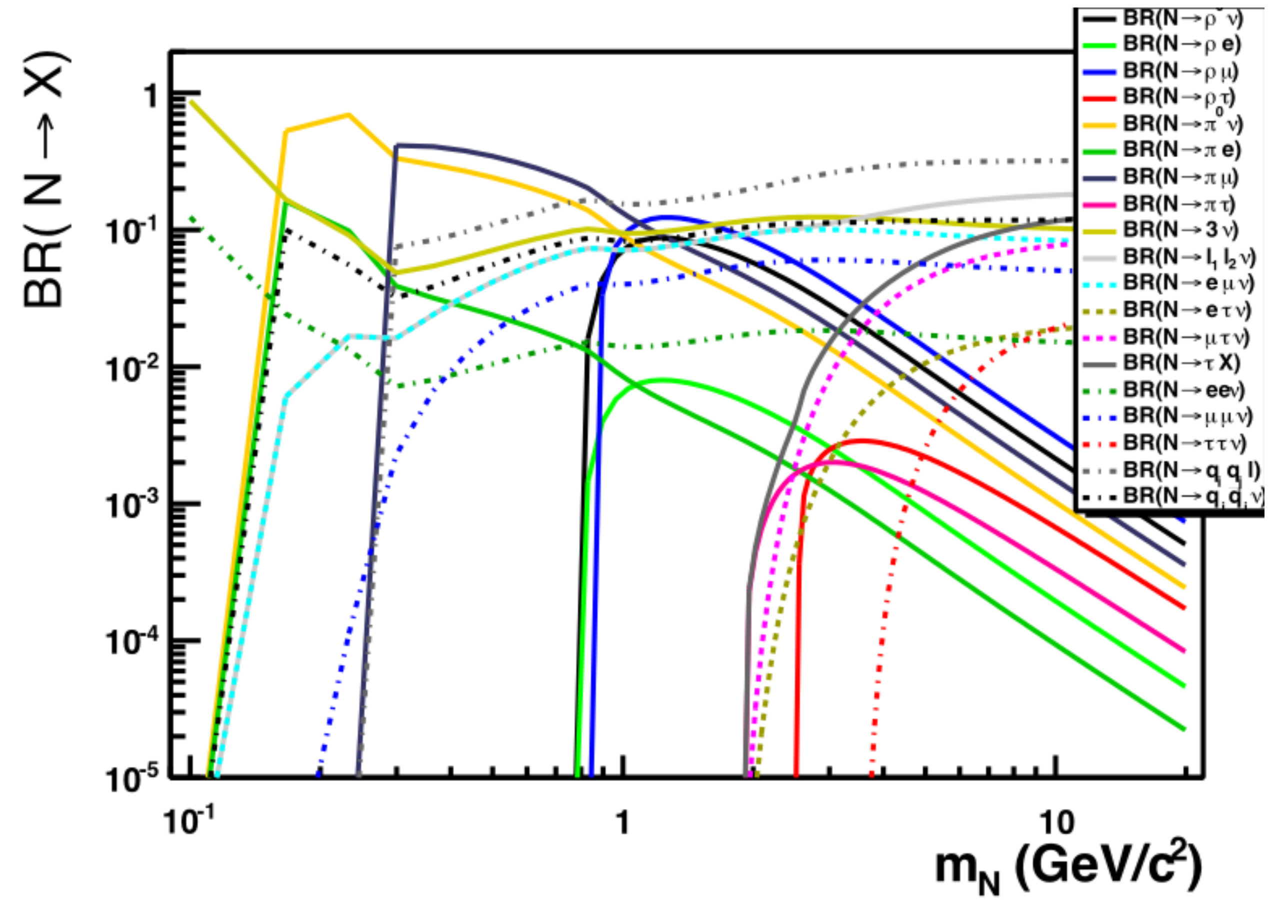
- If the mass is small enough they can be produced in semileptonic meson decays (pions, kaons, D-mesons, B-mesons), at higher masses they will be produced by W and Z

HNLs

Normal hierarchy of active neutrino masses

$U^2_e:U^2_\mu:U^2_\tau = 1:16:3.8$



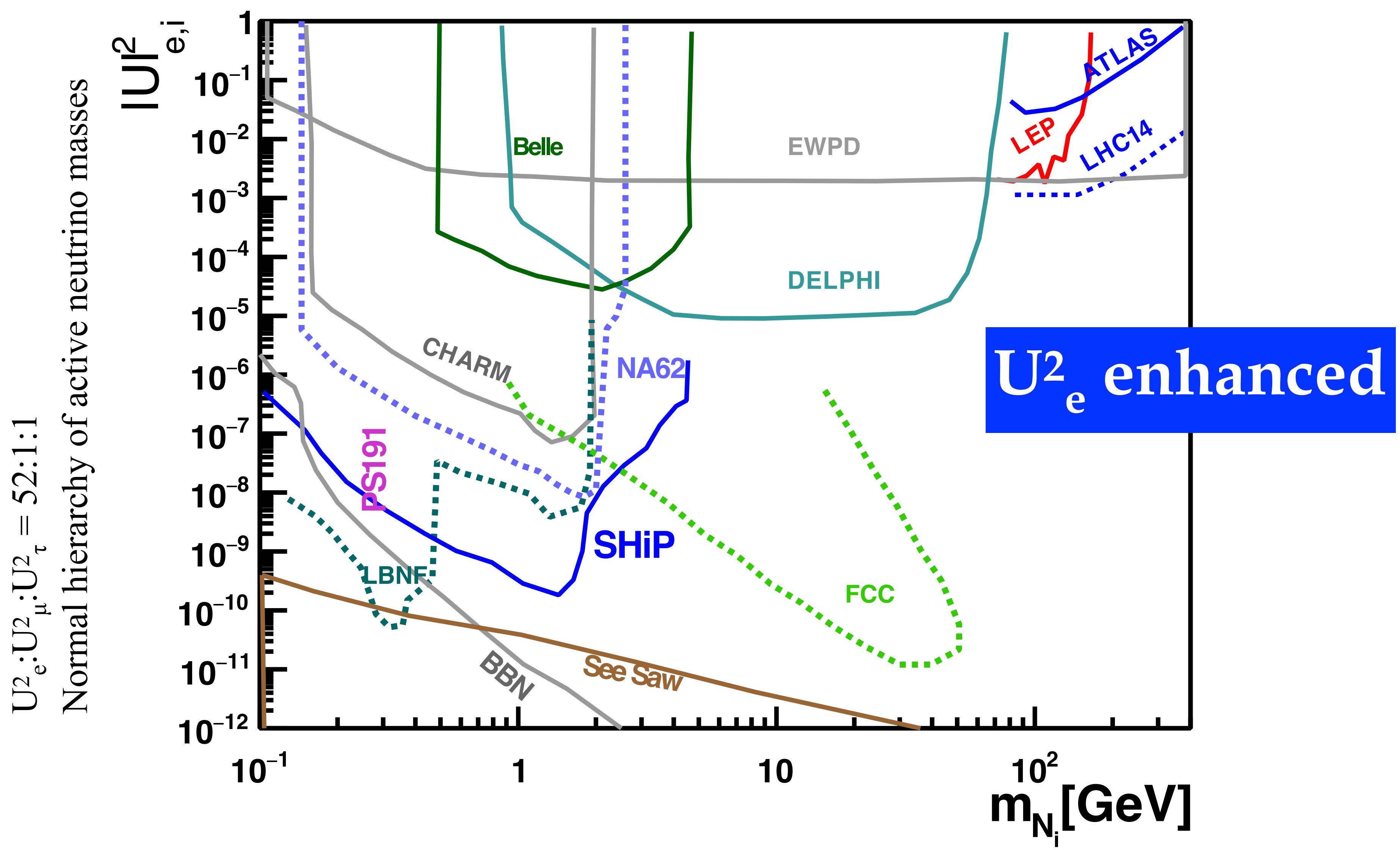


Green-ish: U^2_e dominated

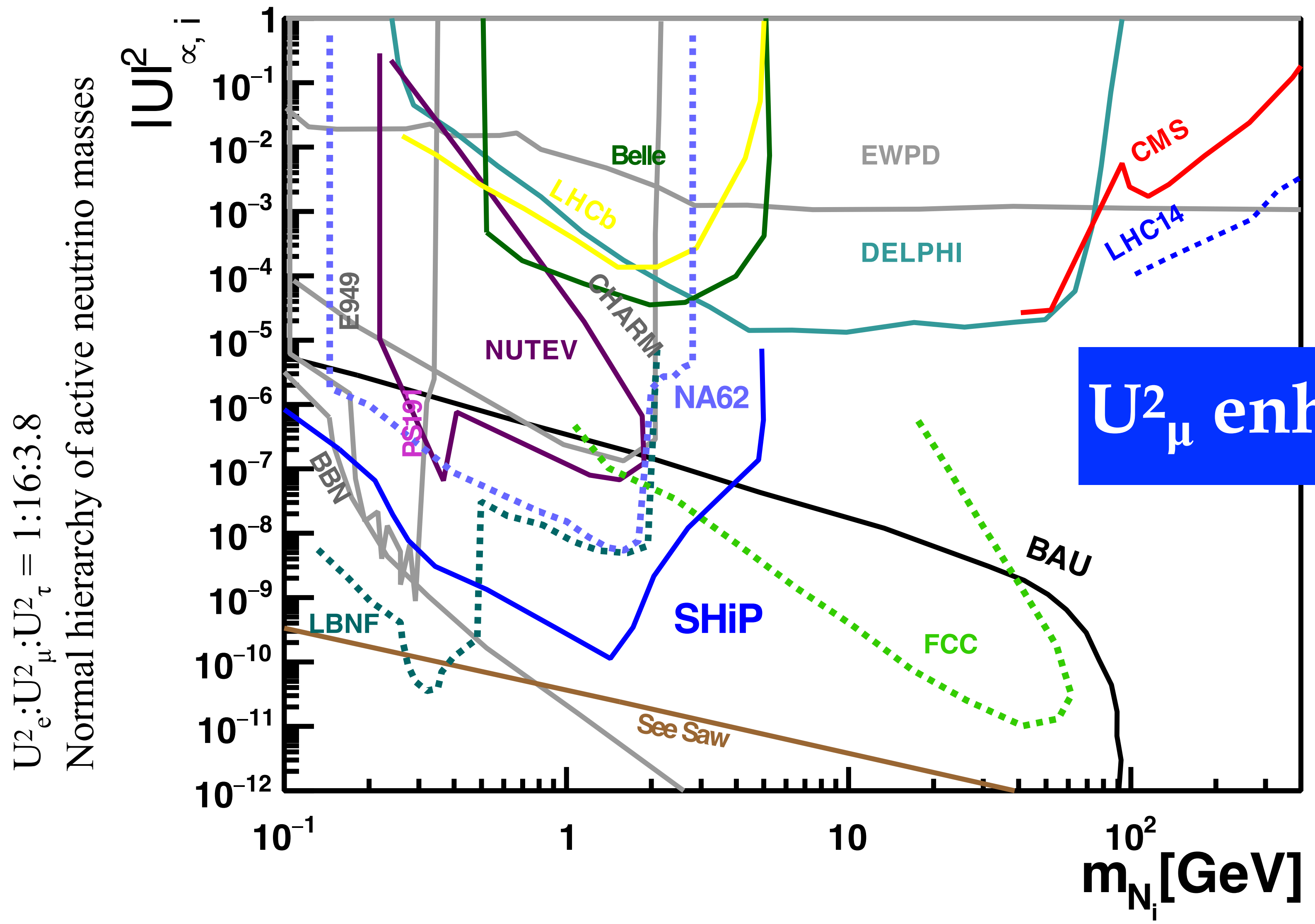
Blue-ish: U^2_μ dominated

Red-ish : U^2_τ dominated

HNLs

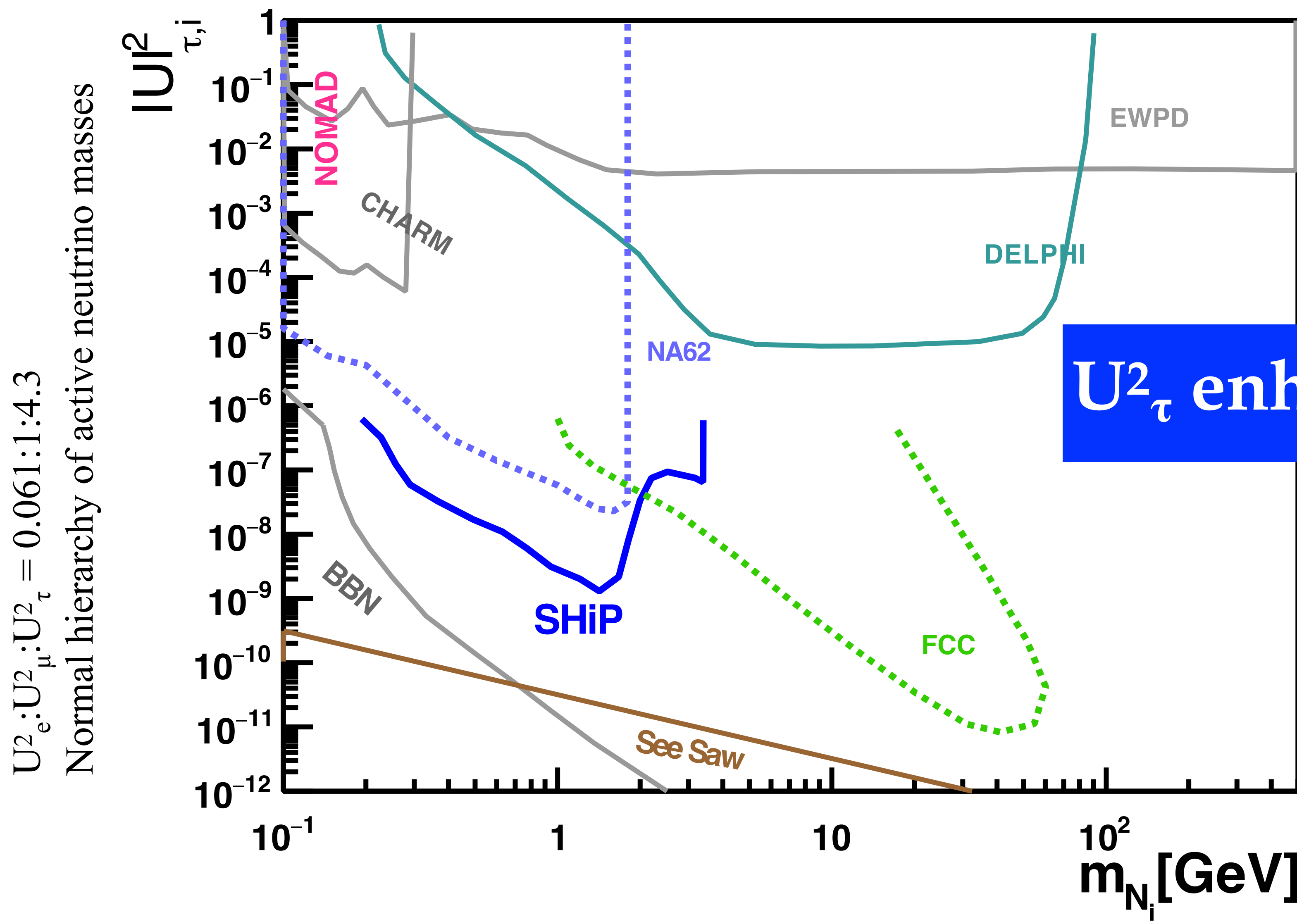

$U^2_e:U^2_\mu:U^2_\tau = 52:1:1$
Normal hierarchy of active neutrino masses
$|U|^2_{e,i}$
m_{N_i}[GeV]
Belle
EWPD
DELPHI
CHARM
NA62
PS191
SHiP
LBNF
FCC
BBN
See Saw
LEP
ATLAS
LHC14
U^2_e enhanced

HNLs



U^2_μ enhanced

HNLs



U^2_τ enhanced

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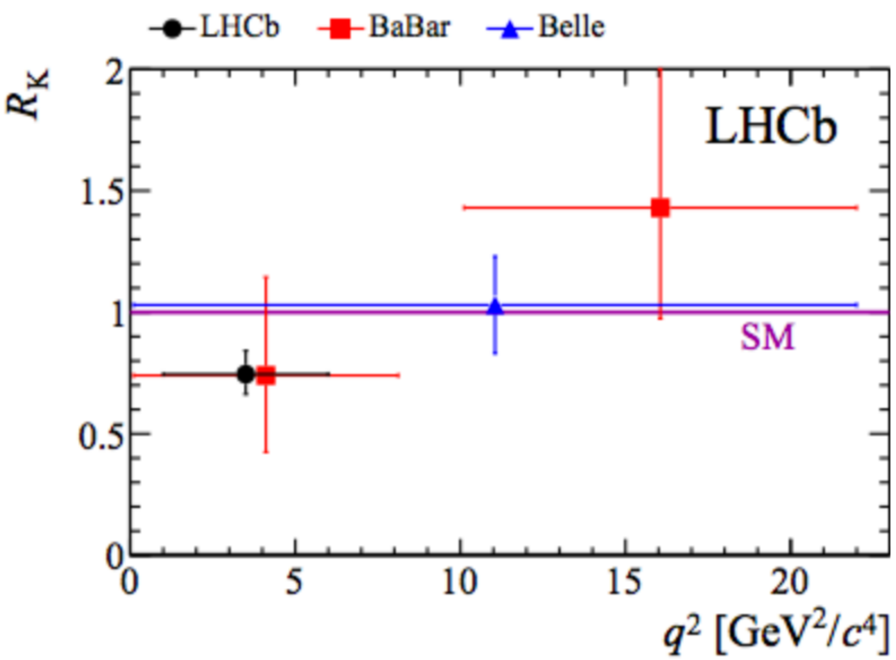
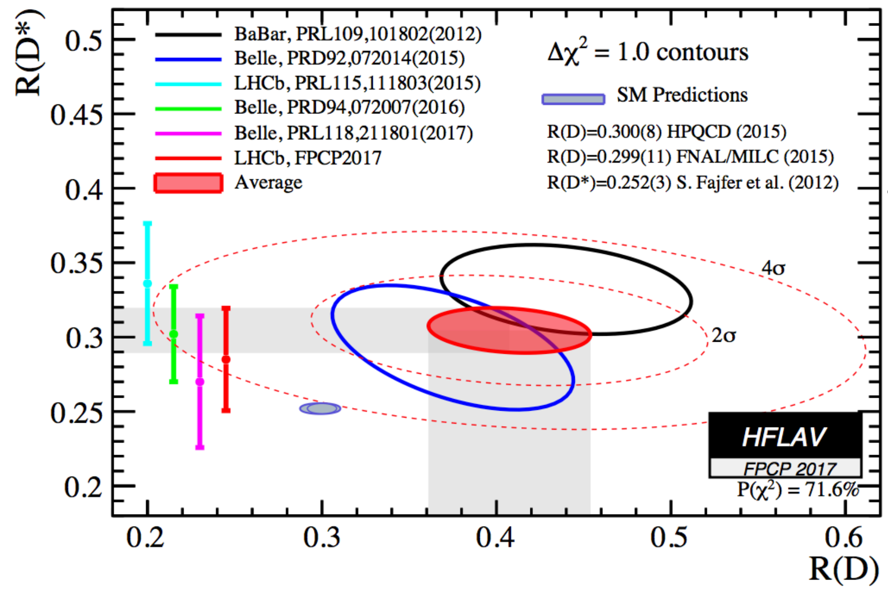
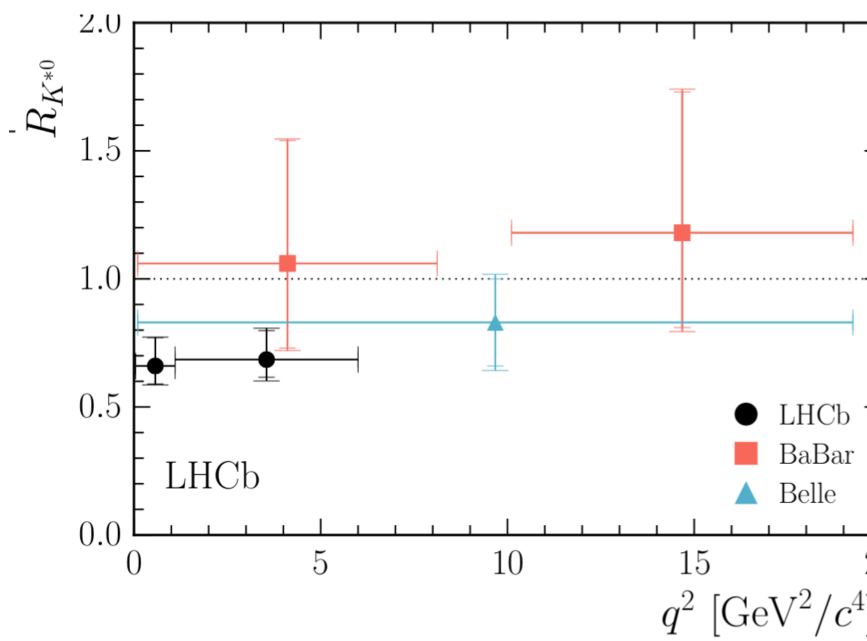
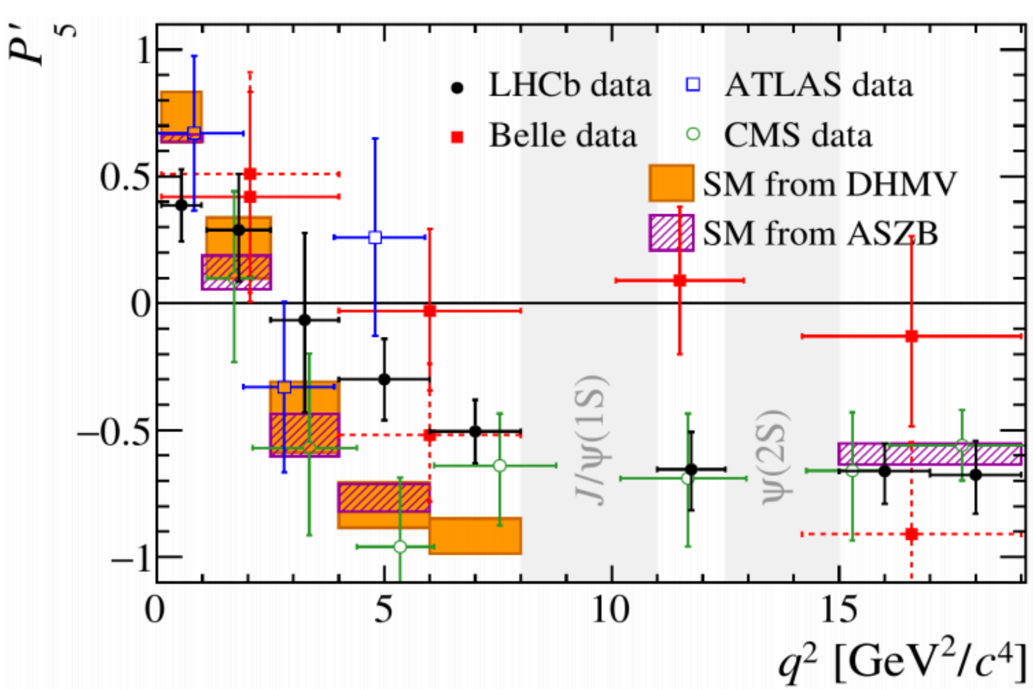
Tau3Mu

SHiP
Search for Hidden Particles



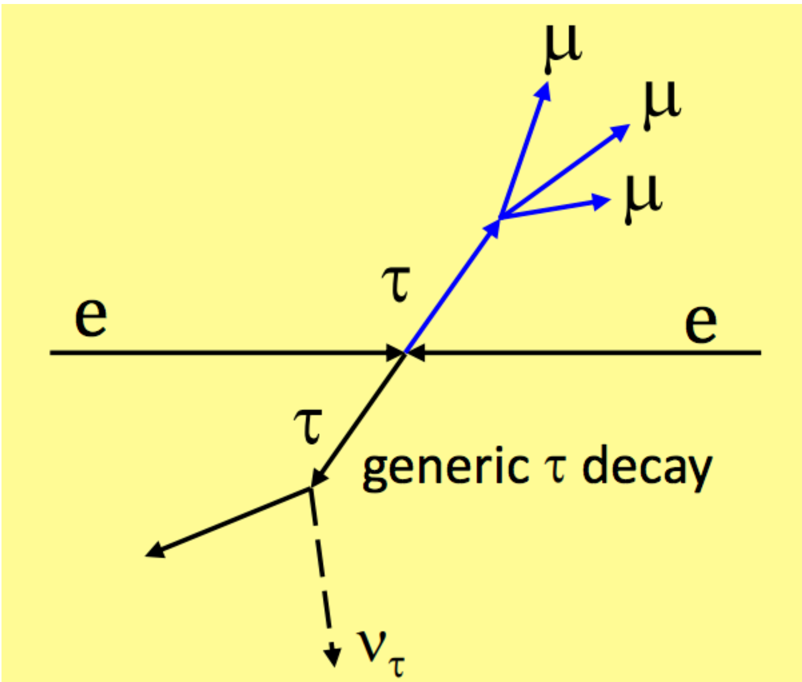


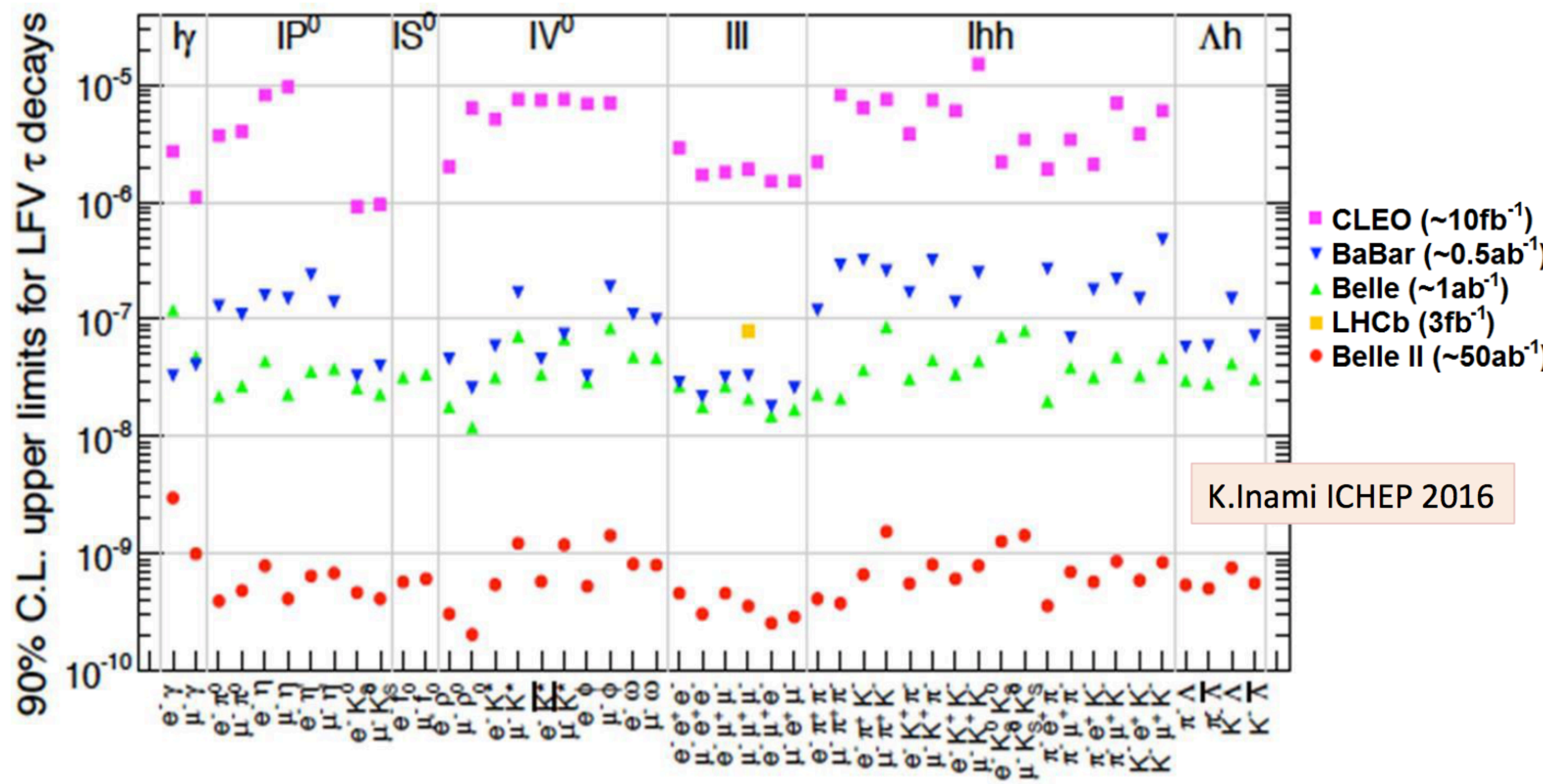




- A number of deviations from SM expectations in B-meson decays with significant around 3sigmas
- Much too early to conclude anything, but if confirmed point towards particular scenarios of NP
- In any case show how little constraint is LFU (not in gauge boson decays)
- In general all these models predict LFV and in particular tau—>3μ decays

Tau3Mu

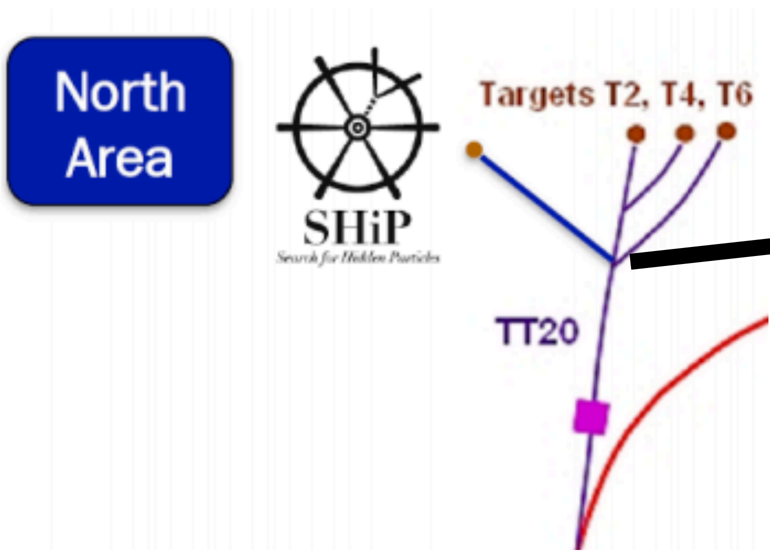


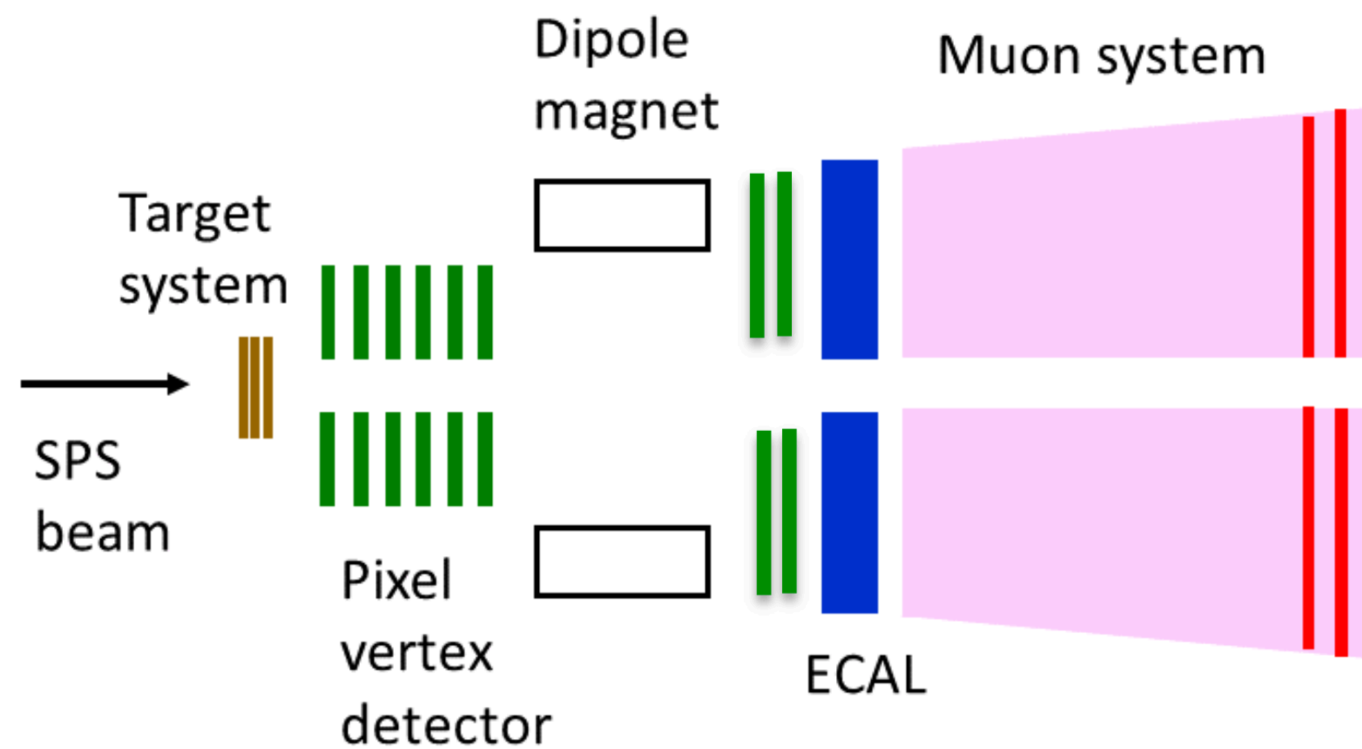


- *BELLE reached O(10^{-8}) sensitivity using ~10^9 ττ events*
- *BELLE II plans to collect ~5×10^{10} ττ events*
- *Expected sensitivity for UL (τ→3μ) varies from 10^{-9}(BELLE II TDR) to few×10^{-10}*

Can a dedicated experiment at the BDF do better than this?

τSHiP

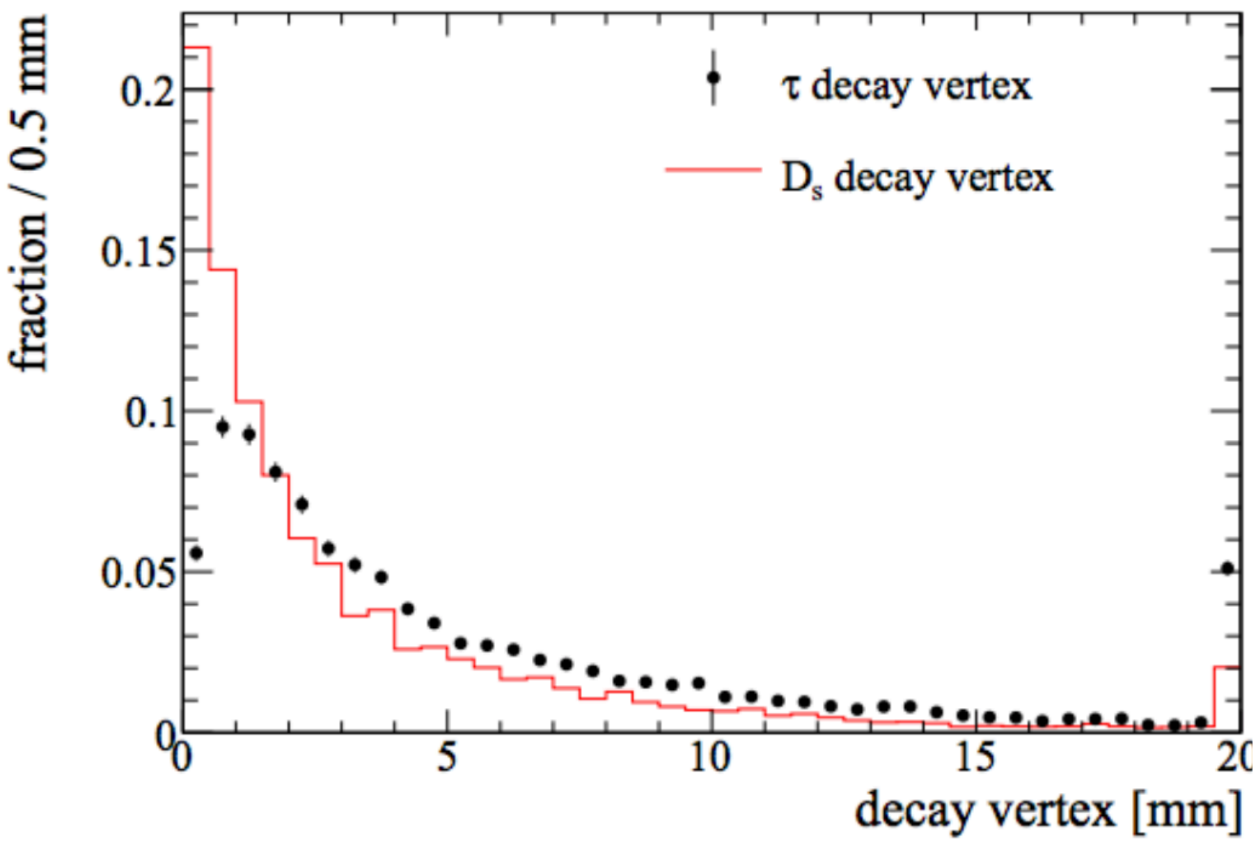


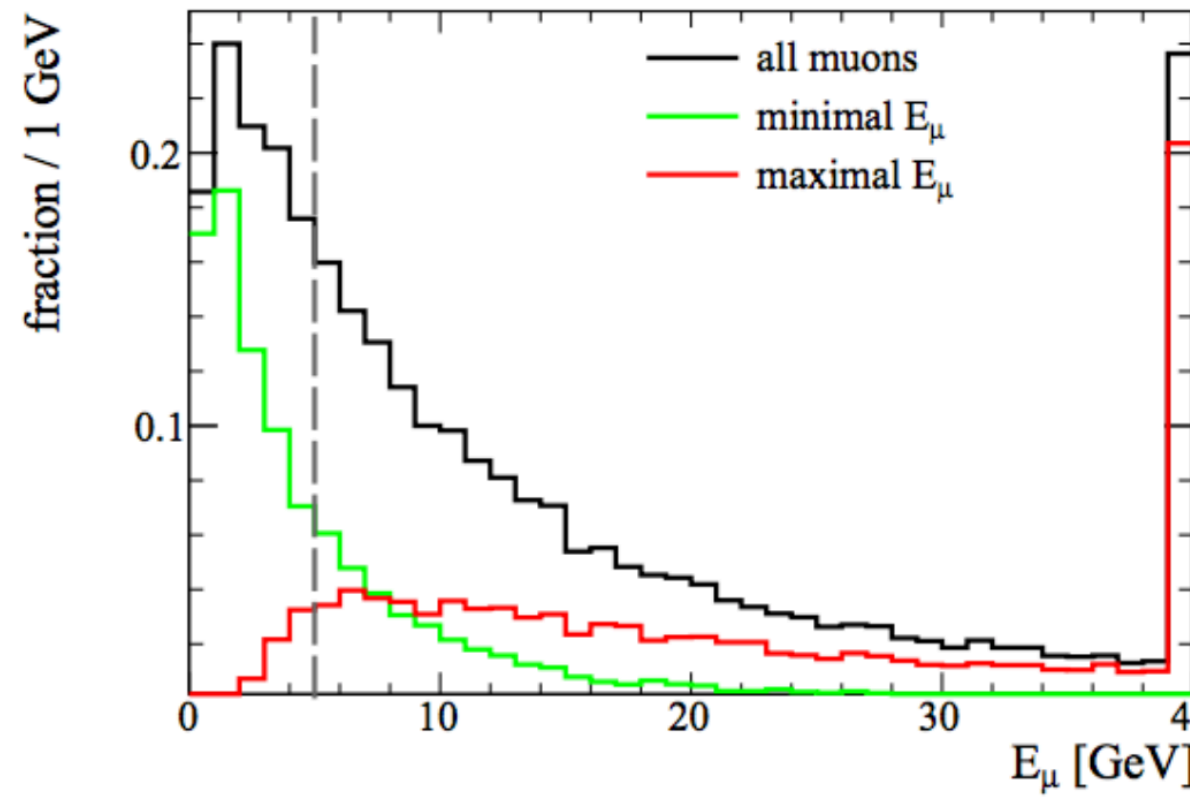


- *Thin (~1mm thick) W target(s), i.e. 1% of SHiP beam*
- *~ 5×10^{13} τ leptons produced in 5 years*
- *Backgrounds include*
  - Combinatorial bckg., mainly from muons produced in em decays of η, ρ, ω, ...

  - Bckg. from various semileptonic D decays, e.g. $D^+ \to \eta\mu^+\nu$, $\eta \to \mu^+\mu^-$

τSHiP





- *About 90% of τ-decay vertex in the air*
- *Timing and vertex resolution allow to reject combinatorial background*
- *About 50% τ-decay in acceptance*
- *τ-SHiP* has the potential to extend the sensitivity region $BR(\tau \to \mu^+\mu^+\mu^-) < 10^{-10}$

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Conclusions

SHiP
Search for Hidden Particles

- The SHiP experiment at the BDF facility allows to search a broad variety of signals for very weakly interacting long lived particles and more

- Emulsion spectrometer can be used to search indirectly for HS particles via the vWIMP scattering (iSHiP) or to do ν_τ physics (*vSHiP*)

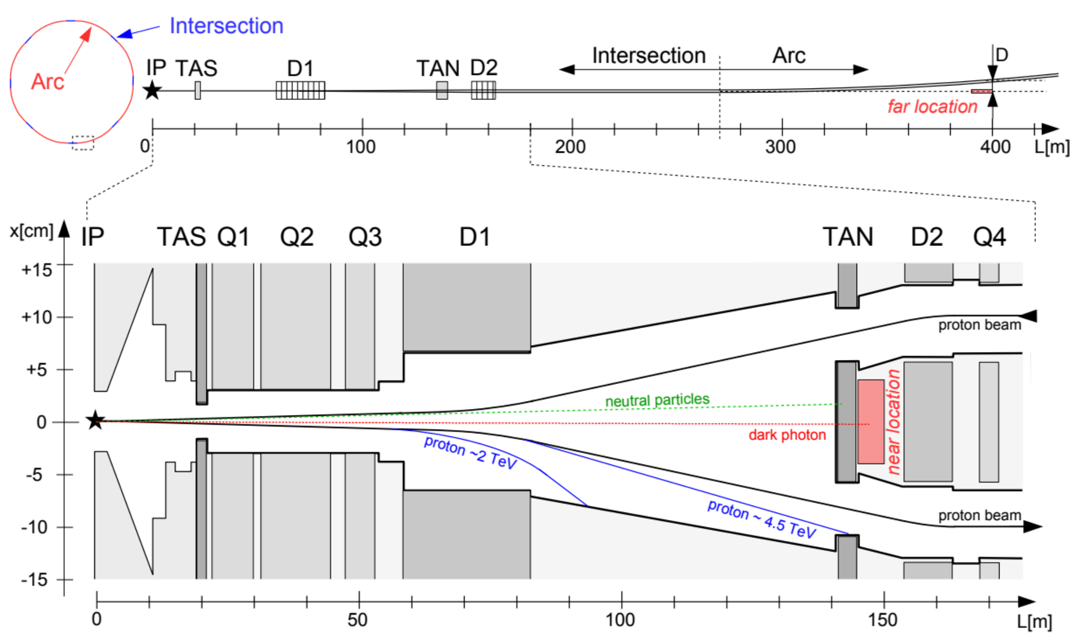
- HS particle can be searched for in an inclusive way in the fiducial volume (dSHiP)

- The BDF can be used to search for LFV decays e.g. $\tau \rightarrow \mu^+\mu^+\mu^-$ and more (τSHiP)

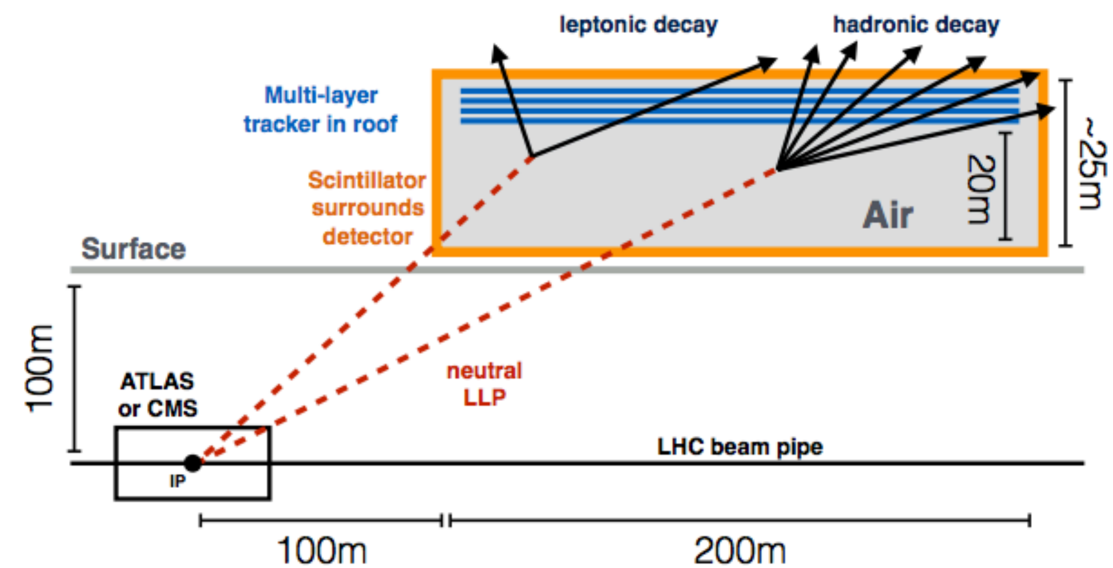
Backup

Competitors

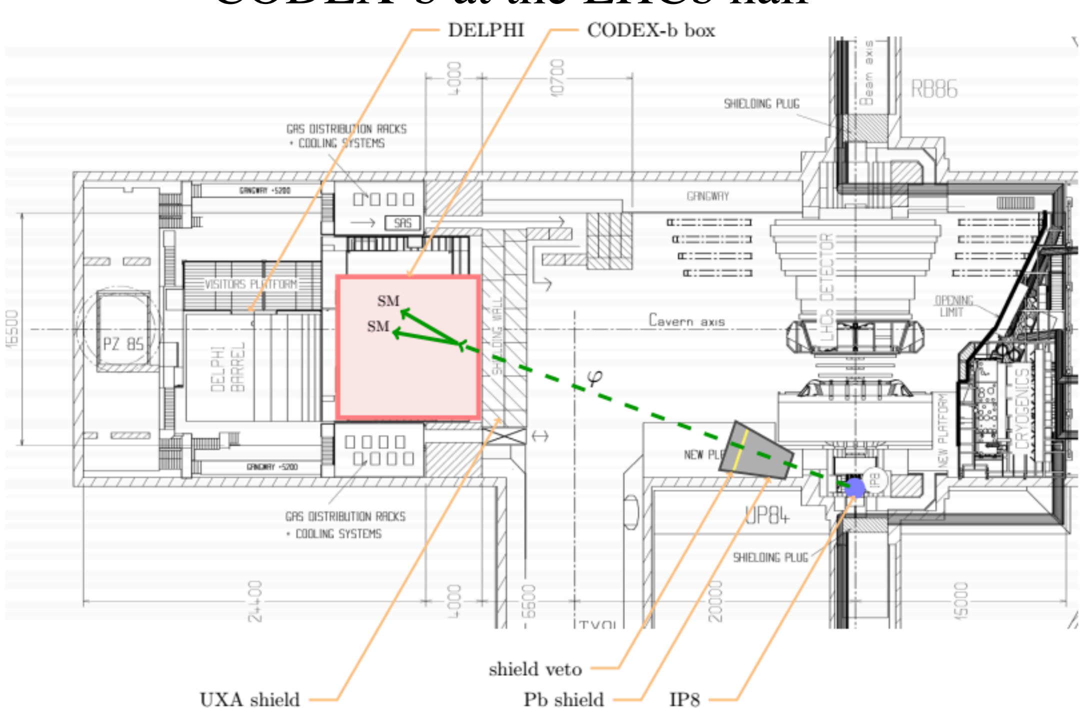
FASER at a few hundred meter downstream of ATLAS or CMS to search for forwardproduced light vWIMPs



MATHUSLA intends to operate at surface, ~100 m above ATLAS or CMS

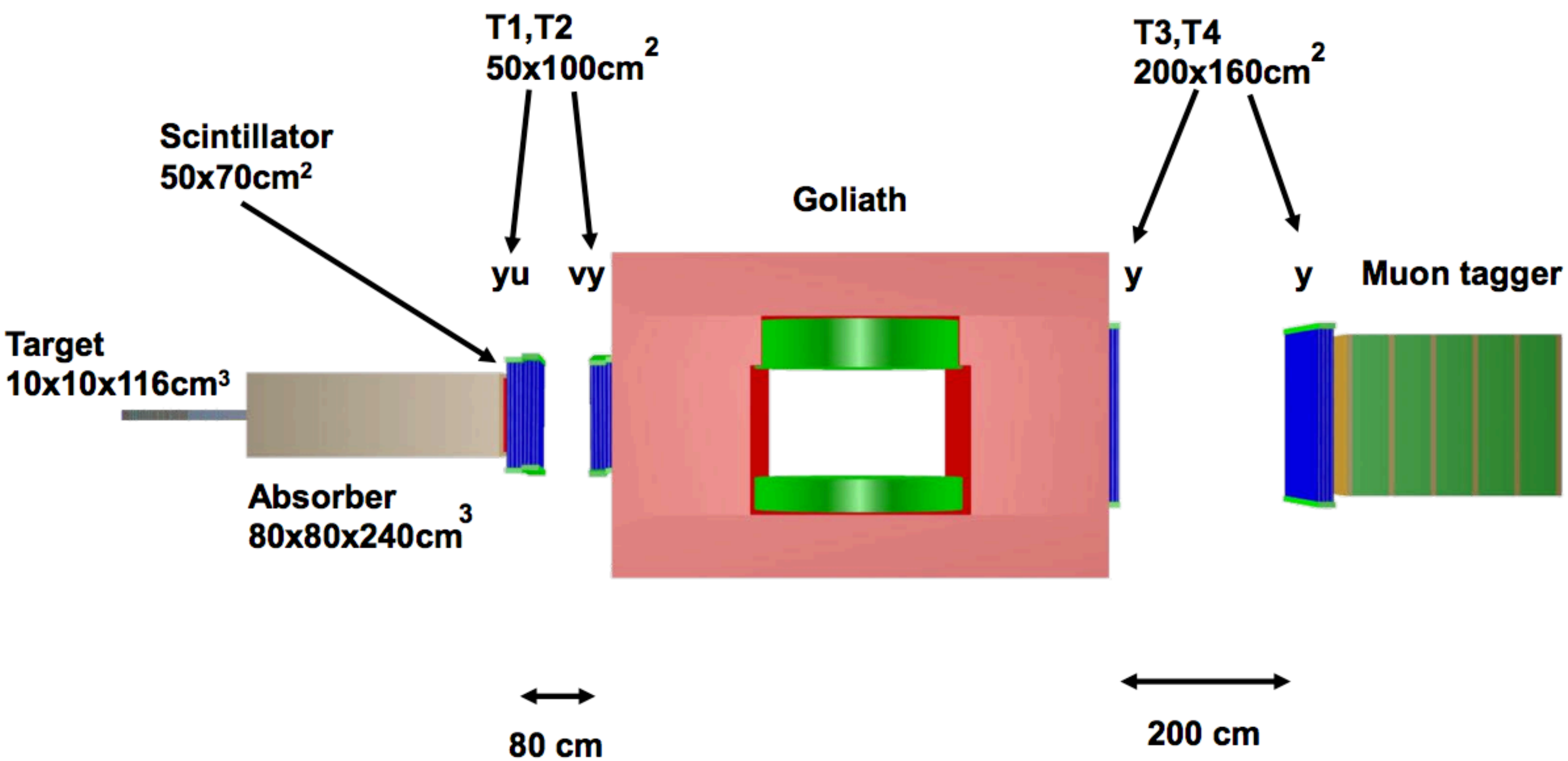


CODEX-b at the LHCb hall



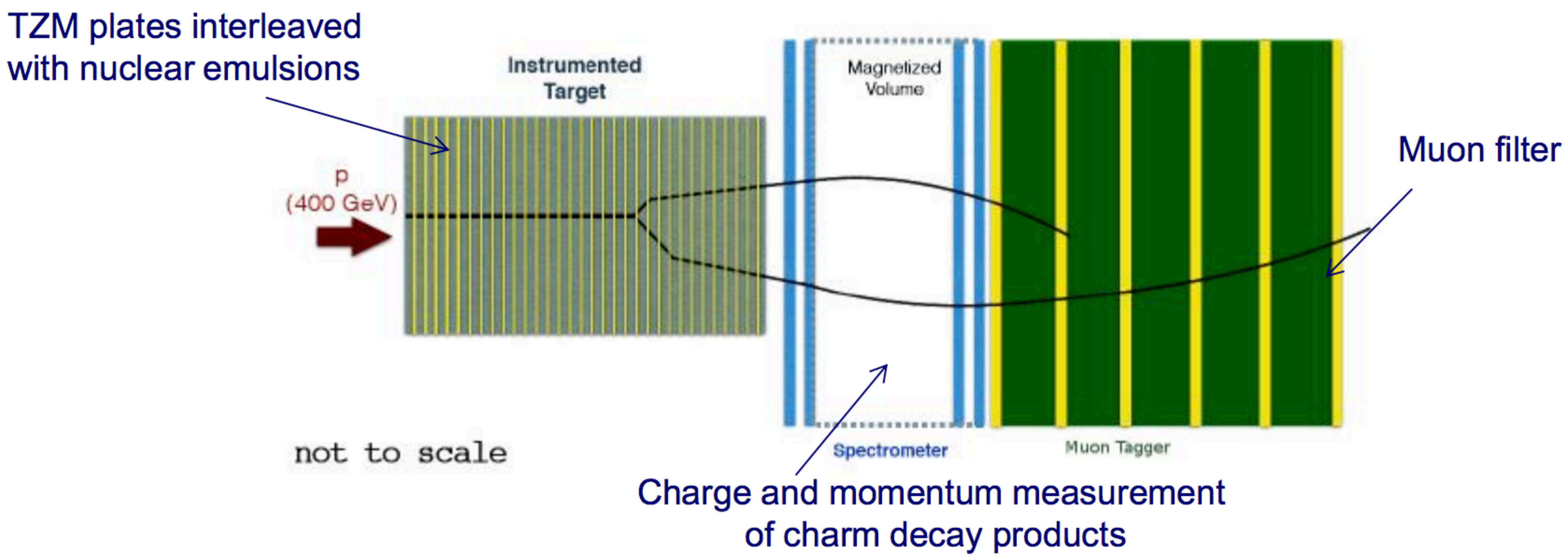
- Proliferation of proposals searching for hidden sector, especially at LHC
- Competitive with SHiP for some channels (assuming we are all with zero bks), especially from HS from B-meson decays, while we are normally much better for charm
- This shows an increasingly interest in the Hidden Sector Physics
- Advantage of a BDF facility is that more flexible to expand the physics case (e.g. tau—>3mu)

Muon Flux



- Measurement of the muon flux in 2018 to validate the simulation in dangerous corner of the phase
- Replica of the SHiP target followed by a muon spectrometer, we expect about 10^{11} PoT

Charm Cascade

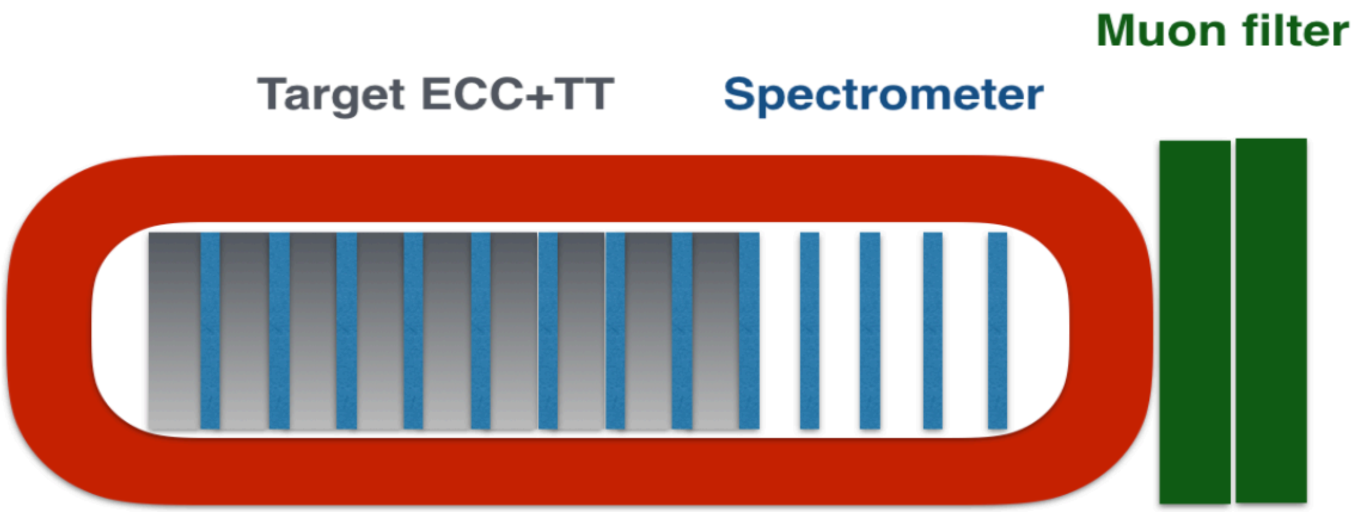


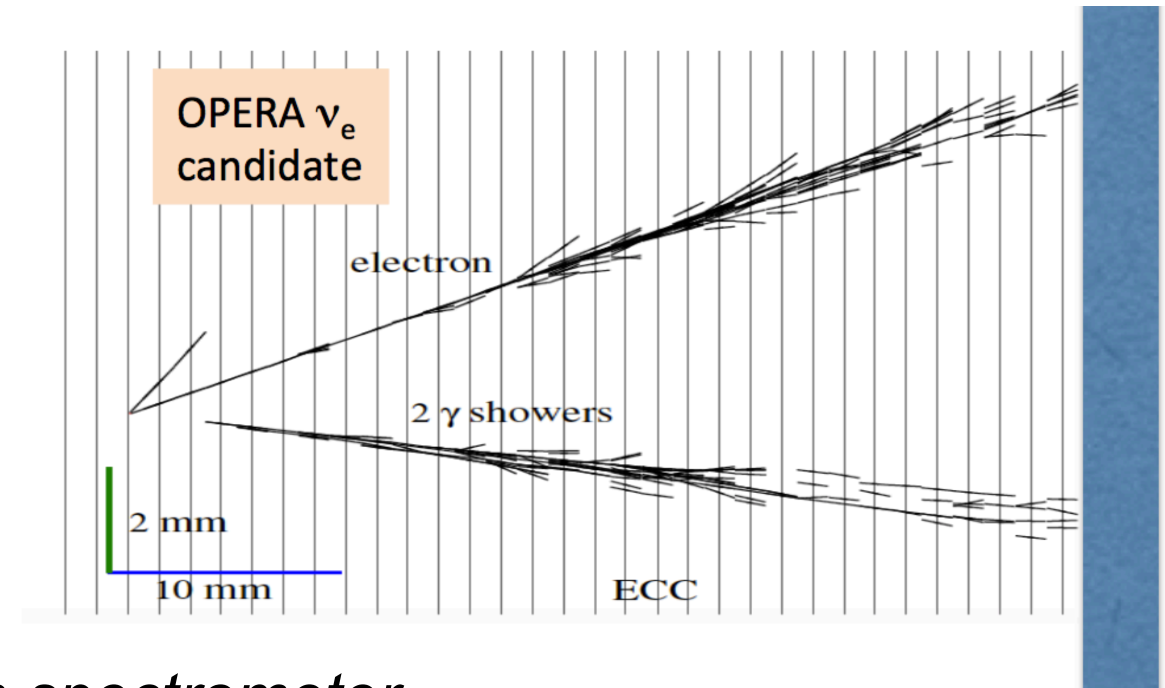
- Due to the thickness of the target, cascade charm production has to be taken into account
- Both the signal and the background depend on charm cascade production

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

Overview of SHiP

Physics with nu-Tau





Single long magnet hosting the emulsion and muon spectrometer

Muon identification using a filter outside the magnet

Possible improvements:

Analog readout of TT to provide calorimetric information

Optimize the distance between consecutive TT planes (currently ~$10X_0$)

Use a combination of TT and ECC to measure electromagnetic and hadronic showers in the event

Muon Shield

The active muon shield in the SHiP experiment
JINST 12 P05011 2017

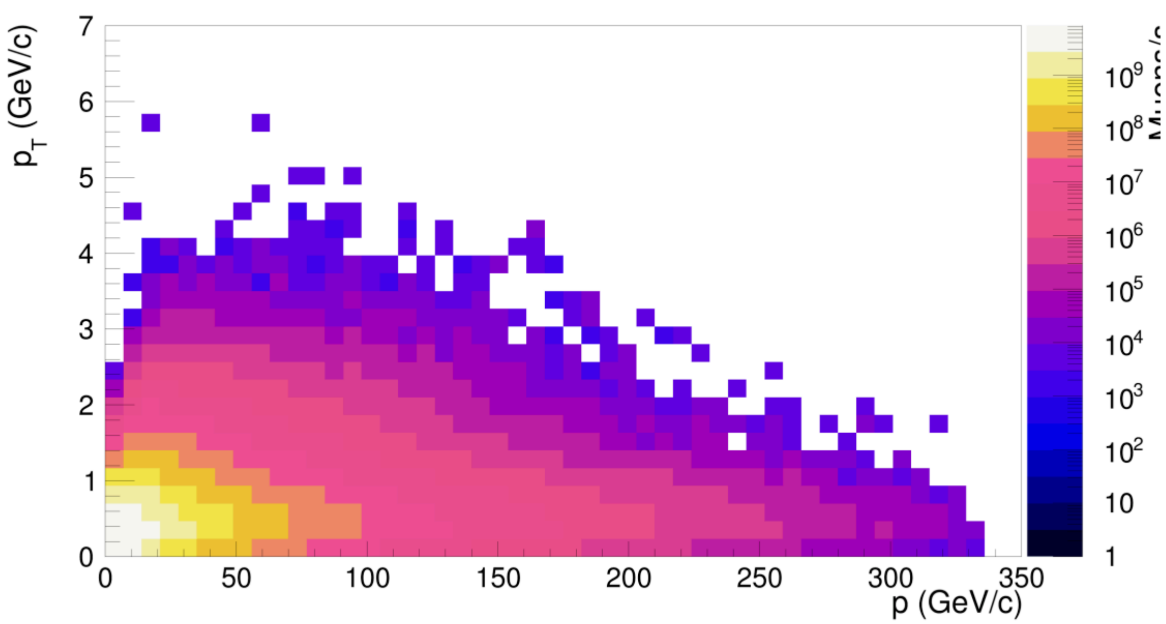


Figure 1. Transverse momentum versus momentum distribution of muons, as generated by Pythia [5, 7].

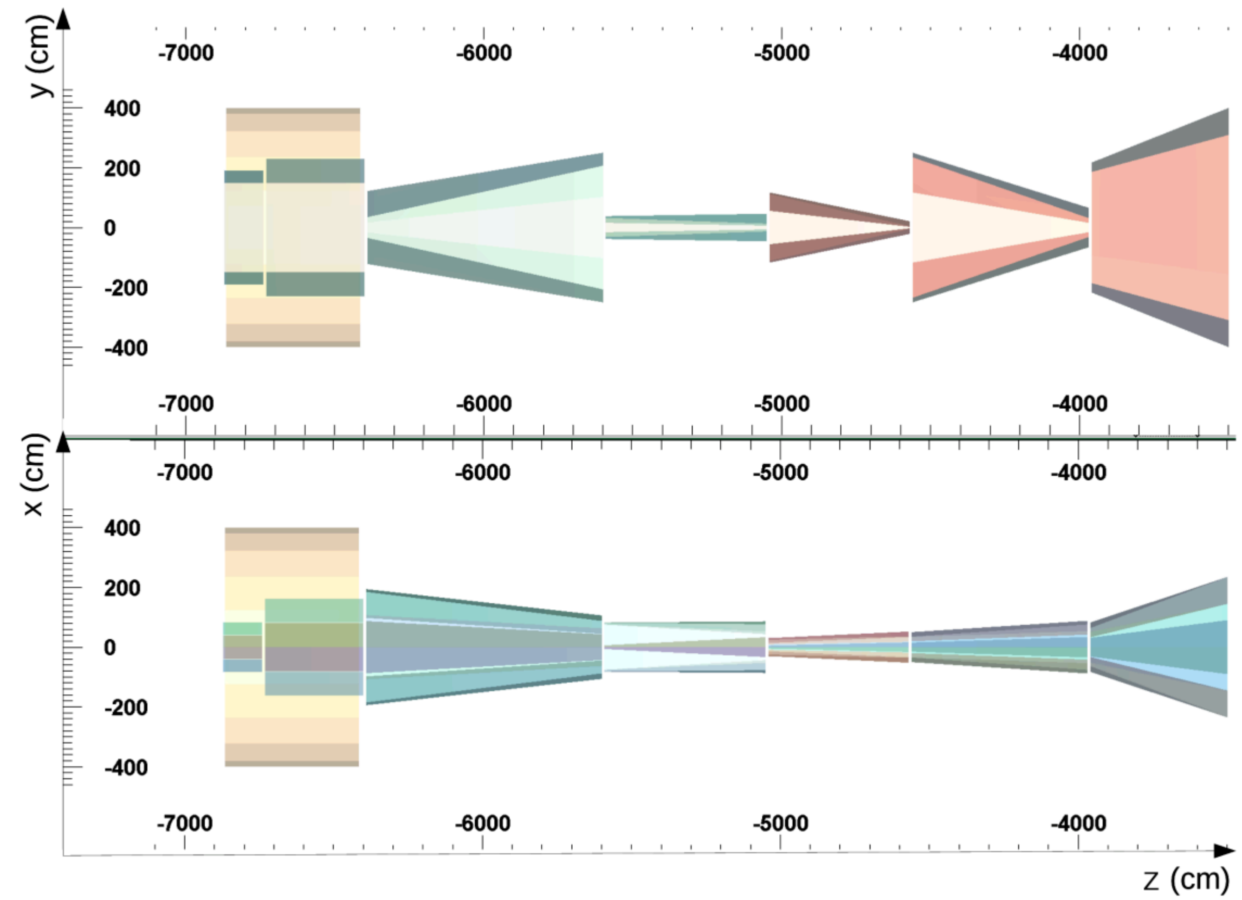


Figure 4. Geometric view of the optimized muon shield, showing at the top, the *z*-*y* plane view, and at the bottom, the *z*-*x* plane view. SHiP defines the origin of the coordinate system to be in the center of the decay vessel. Color shading is used to enhance the contrast between different magnetic field orientations.

Running the simulation with material

- ~3x10^9 muons/spill with magnets off
- With the magnet on 3x10^5 muons/spill
- ~6.5x10^4 muons/spill with p>3GeV

Opimization of the muon shield includes muon rate, weight (1.850 Tons) and length (34 meters)

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Physics with nu-Tau

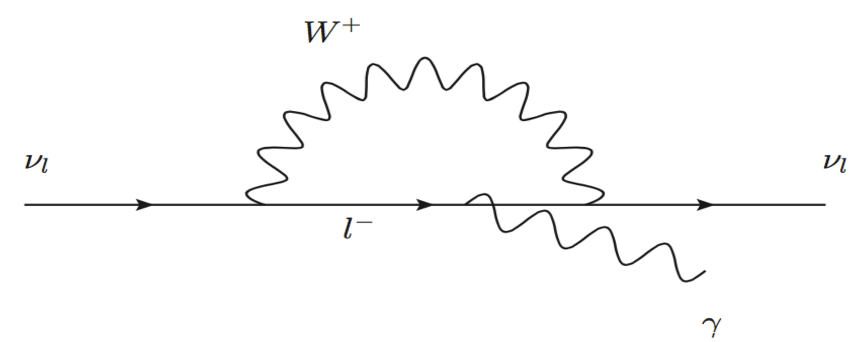
SHiP
Search for Hidden Particles

A massive neutrino may interact e.m.
→ magnetic moment proportional to its mass

$$\mu_\nu = \frac{3\, e\, G_F\, m_\nu}{8\,\pi^2\,\sqrt{2}} \simeq (3.2 \times 10^{-19}) \left(\frac{m_\nu}{1\,\mathrm{eV}}\right) \mu_B$$

Current limits

$$\begin{cases} (\nu_e) & \mu_\nu < 2.9 \cdot 10^{-11} \mu_B \\ (\nu_\mu) & \mu_\nu < 6.9 \cdot 10^{-10} \mu_B \end{cases}$$



$$\left.\frac{\sigma_{(\nu e, \bar{\nu} e)}}{dT}\right|_{\mu_\nu} = \frac{\pi \alpha_{em}^2 \mu_\nu^2}{m_e^2} \left(\frac{1}{T} - \frac{1}{E_\nu}\right)$$

No interference as it involves a spin flip of the neutrino

IN SHiP

$$n_{evt} = \frac{\mu_\nu^2}{\mu_B^2} \int \Phi_{\nu_\tau} \sigma^\mu N_{nucl} dE = 4.3 \times 10^{15} \frac{\mu_\nu^2}{\mu_B^2}$$

$\theta_{\nu-e}^2 < 2m_e/E_e$

SIGNAL SELECTION

$$\begin{cases} \theta_{\nu-e} < 30\, mrad \\ \mathrm{E}_e > 1\ \mathrm{GeV} \end{cases}$$

BACKGROUND PROCESSES

$\nu_x(\bar{\nu}_x) + e^- \to \nu_x(\bar{\nu}_x) + e^-$	NC	750 (NC + CC)
$\nu_e + e^- \to e^- + \nu_e$	CC	
$\nu_e + n \to e^- + p$	QE	11700 (QE + QE)
$\bar{\nu}_e + p \to n + e^+$	QE	
$\nu_e(\bar{\nu}_e) + N \to e^-(e^+) + X$	DIS	1700

Assuming 5% systematics from DIS measurements

SHiP can explore a region down to

$$\mu_\nu = 1.3 \times 10^{-7} \mu_B$$