The SHiP Experiment at CERN

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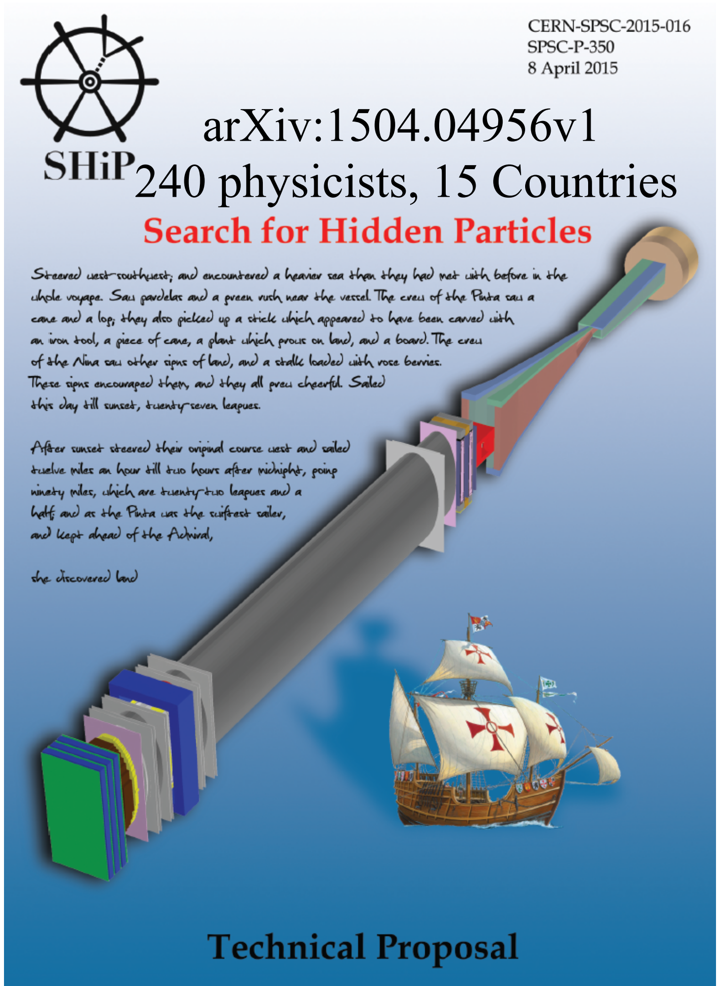
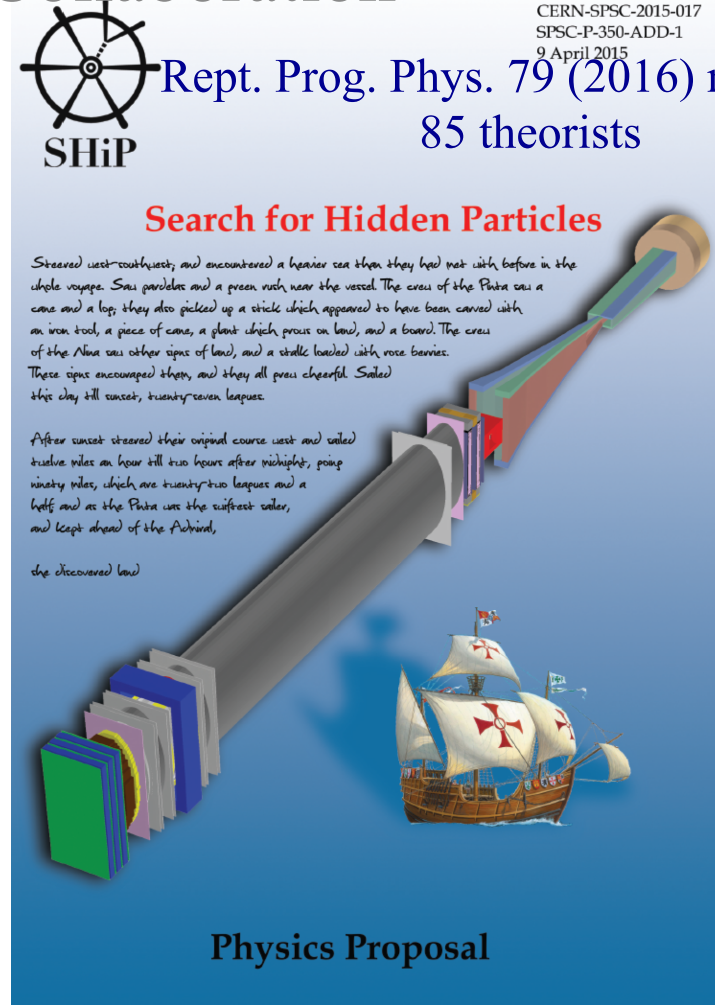
On behalf of the SHiP Collaboration

arXiv:1504.04956v1
240 physicists, 15 Countries



Rept. Prog. Phys. 79 (2016) no. 12
85 theorists

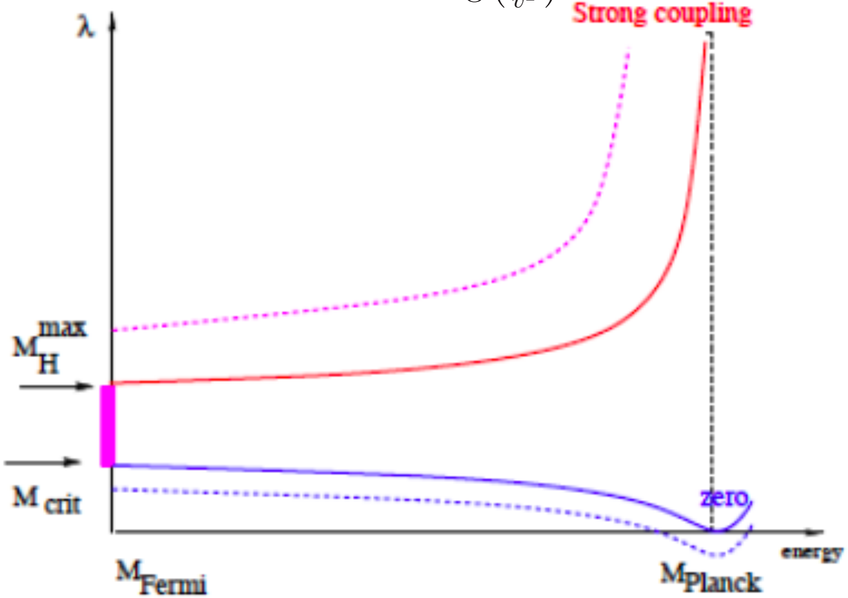


SM may well be a consistent effective theory all the way up to the Plank scale

- ✓ M_H < 175 GeV → SM is a weakly coupled theory up to the Plank energies!
- ✓ M_H > 111 GeV → EW vacuum is stable or metastable with a lifetime greatly exceeding the age of our Universe (Espinosa et al)

S. Heinemeyer, Higgs Physics, arXiv:1405.3781

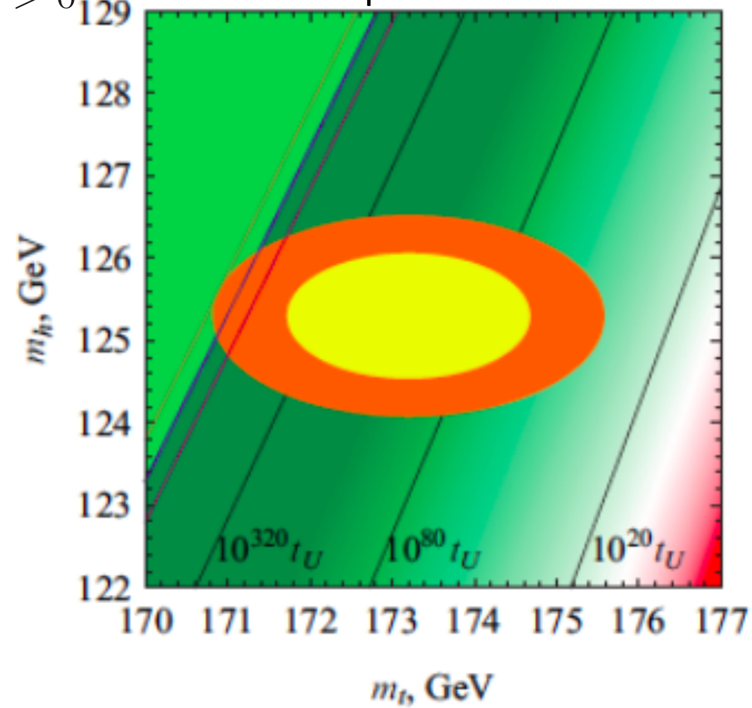
$$\lambda(\Lambda) < \infty \quad \Rightarrow \quad M_H^2 \leq \frac{8\pi^2 v^2}{3\log\left(\frac{\Lambda^2}{v^2}\right)}$$



$1{,}22 \times 10^{19}$ GeV

$\lambda(\Lambda) > 0$

Stable vacuum fully consistent with present data



G. Degrassi et al.,Higgs mass and vacuum stability in the SM at NNLO, JHEP 1208 (2012) 098

- ✓ No sign of New Physics seen

Nevertheless, many open questions in particle physics!

Among the most relevant ones:

Why is the Higgs boson so light (so-called "naturalness" or "hierarchy" problem) ?

What is the origin of the matter-antimatter asymmetry in the Universe ?

Why 3 fermion families ? Why do neutral leptons, charged leptons and quarks behave differently ?

What is the origin of neutrino masses and oscillations ?

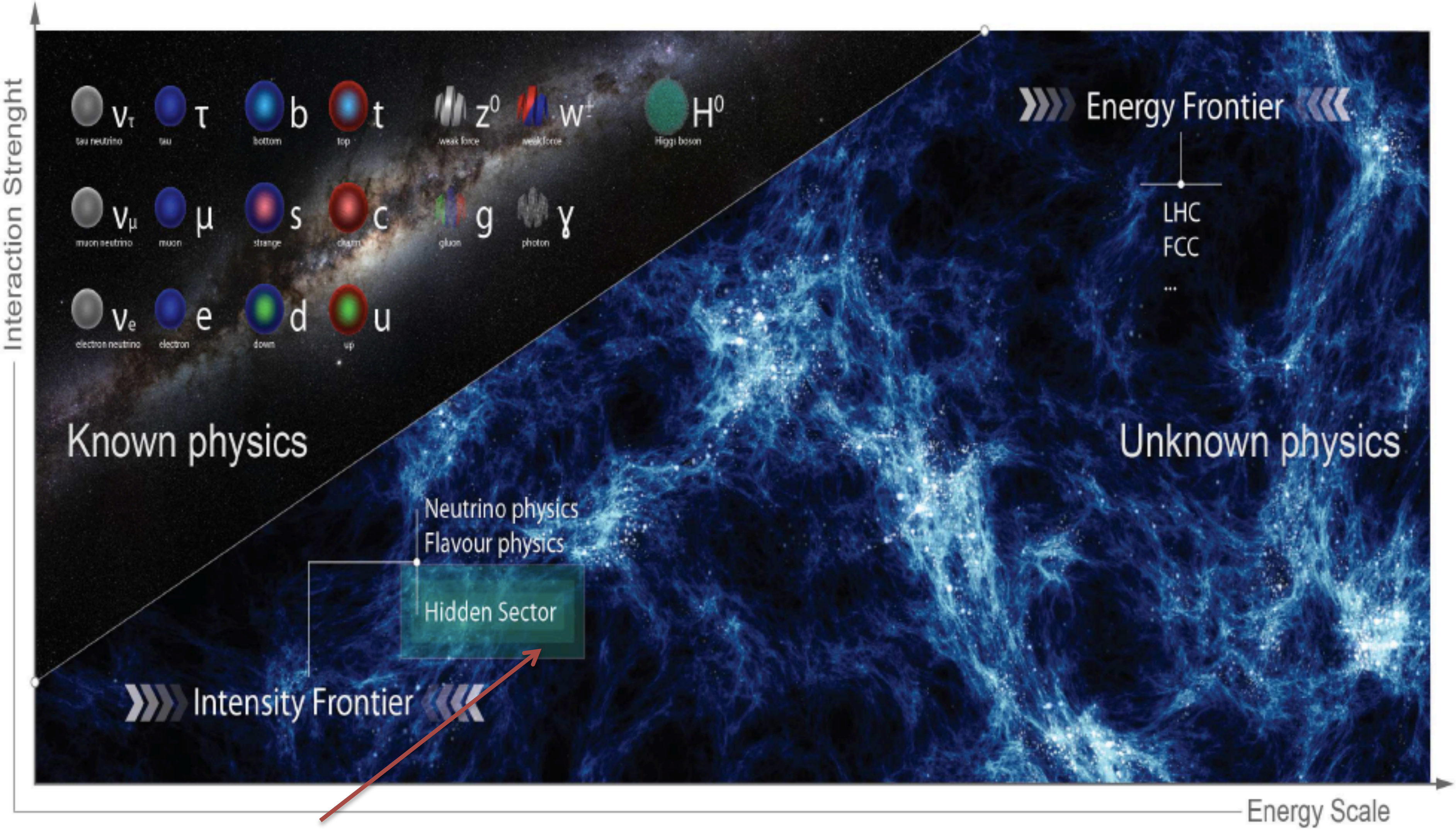
What is the composition of dark matter (~25% of the Universe) ?

However: there is NO direct evidence for new particles (yet…) from the LHC or other facilities

Where is the New Physics ?

i.e. at what E scale(s) will we find the answers to these questions ?

High Intensity Frontier



This talk

Search for Hidden Sector (HS)

or very weakly interacting NP

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

Visible Sector

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

Hidden Sector

Naturally accommodates Dark Matter
(may have very complicated structure)

✓ *HS production and decay rates are strongly suppressed relative to SM*
- *Production branching ratios $O(10^{-10})$*
- *Long-lived objects*
- *Travel unperturbed through ordinary matter*

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

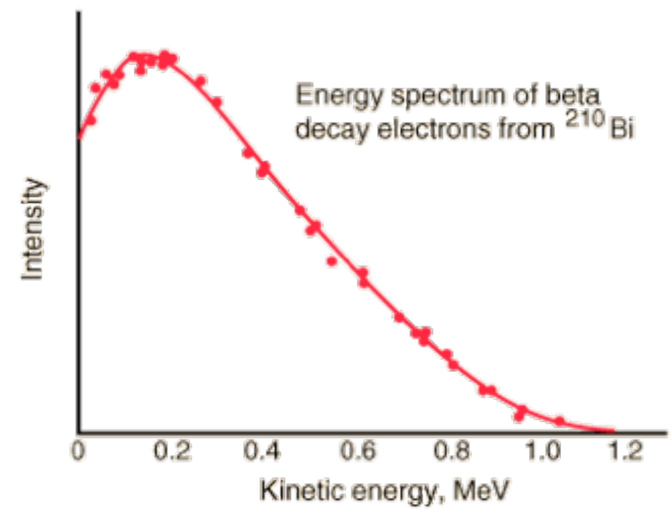
Full reconstruction and PID are essential to minimize model dependence

Experimental challenge is background suppression
→ requires O(0.01) carefully estimated

History lesson - 1930s:

- Back then, the "Standard Model" was photon, electron, nucleons

- Beta decay: $n \to p + e^-$



Continuous spectrum!

- Pauli proposes a radical solution - the neutrino!

$$n \to p + e^- + \bar{\nu}$$

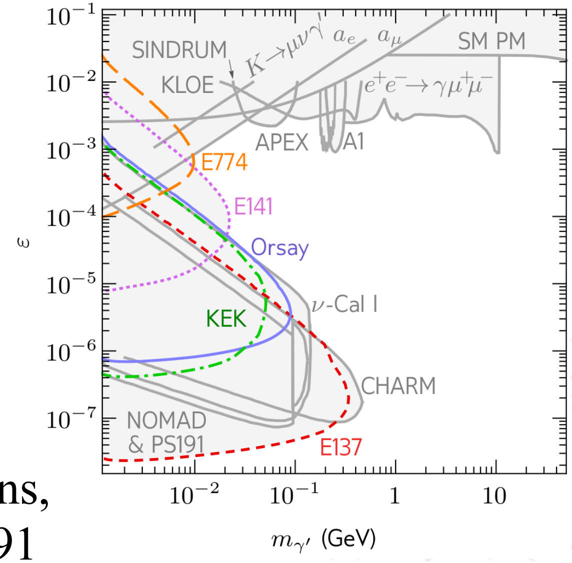
- Great example of a hidden sector!
  - neutrino is electrically neutral (QED gauge singlet)
  - very weakly interacting and light
  - interacts with "Standard Model" through "portal" - $(\bar{p}\gamma^\mu n)(\bar{e}\gamma_\mu \nu)$

Searches for dark photons

- Assuming no lighter hidden particles, γ' decay into SM particles through a virtual photon:

$$\gamma' \to e^+e^-, \quad \mu^+\mu^-, \quad q\bar{q}, \ldots$$

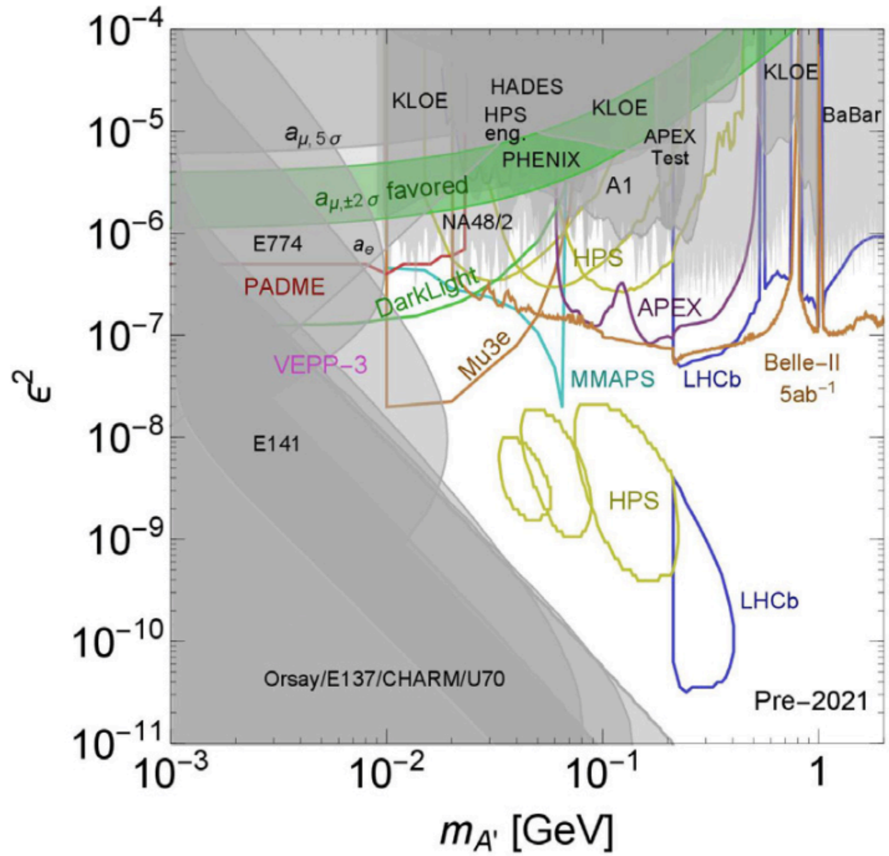
- decay length $c\tau \sim \varepsilon^{-2} m_{\gamma'}^{-1}$
- cosmological constraints (nucleo-synthesis): $\tau < 0.1$ s $\Rightarrow \varepsilon^2 m_{\gamma'} > 10^{-21}$ GeV



US Cosmic Visions, arXiv: 1797.04591

γ' production

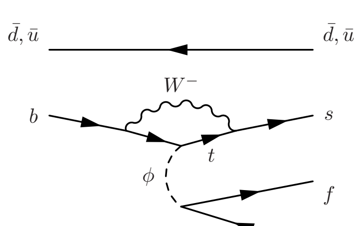
- proton bremsstrahlung:
  - initial-state radiation from the incoming proton, followed by a hard proton-nucleus interaction



- secondary particles decay:

Mass interval (GeV)	Process	$n_{\gamma'}/p.o.t$
$m_{\gamma'} < 0.135$	$\pi^0 \to \gamma\gamma'$	$\varepsilon^2 \times 5.41$
$0.135 < m_{\gamma'} < 0.548$	$\eta \to \gamma\gamma'$	$\varepsilon^2 \times 0.23$
$0.548 < m_{\gamma'} < 0.648$	$\omega \to \pi^0\gamma'$	$\varepsilon^2 \times 0.07$
$0.648 < m_{\gamma'} < 0.958$	$\eta' \to \gamma\gamma'$	$\varepsilon^2 \times 10^{-3}$

Higgs (scalar) portal: production and decay modes

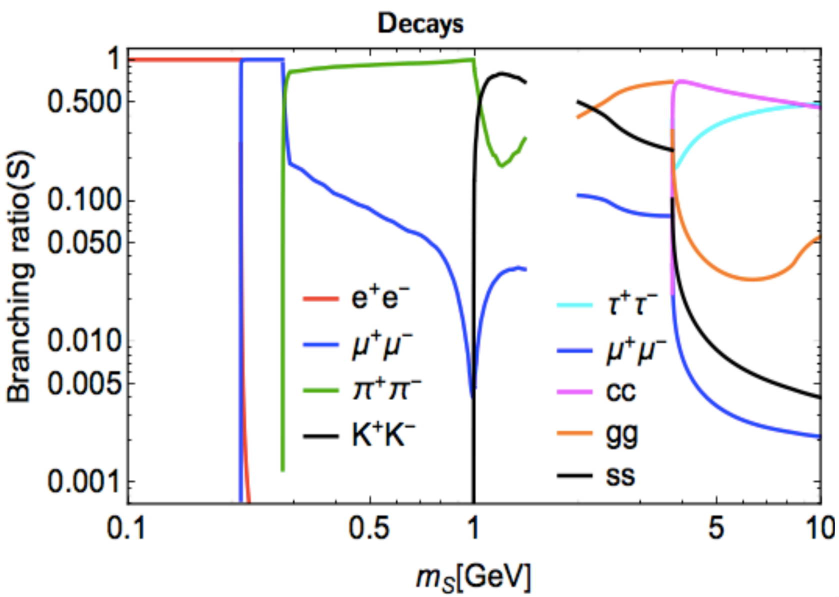


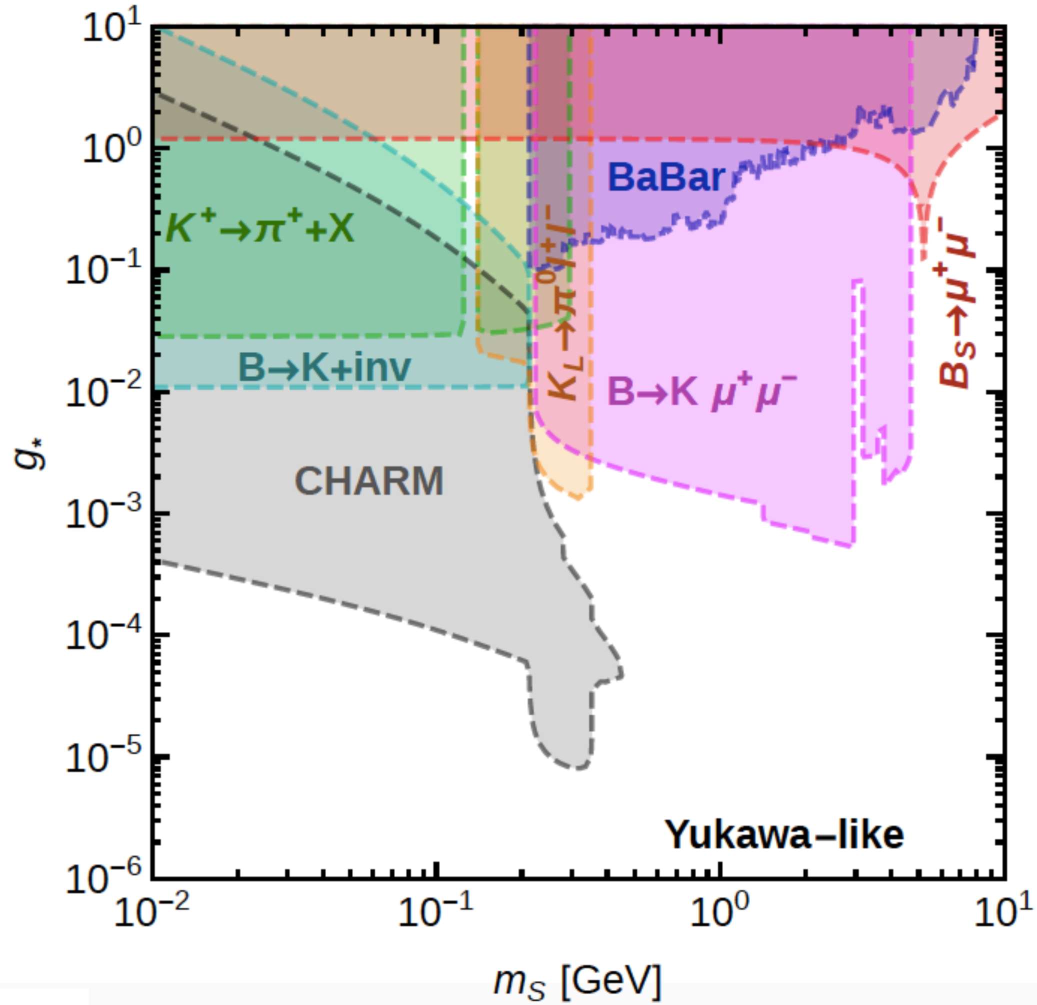
Rare B meson decays mediated by a light scalar ϕ

B decays favoured compared to D

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

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





$$\Gamma(S \to \ell\bar{\ell}) = \frac{g_\star^2 \, m_\ell^2 m_S}{8\pi v^2} \left(1 - \frac{4m_\ell^2}{m_S^2}\right)^{3/2}$$

Motivation for Heavy Neutral Leptons

See-saw mechanism for neutrino masses

Most general renormalisable Lagrangian of SM particles (+3 singlets wrt SM gauge group):

$$L_{singlet} = i\bar{N}_I\partial_\mu\gamma^\mu N_I - Y_{I\alpha}\bar{N}_I^c\tilde{H}L_\alpha - M_I\bar{N}_I^cN_I + h.c.$$

Yukawa term: mixing of N_I with active neutrinos to explain oscillations

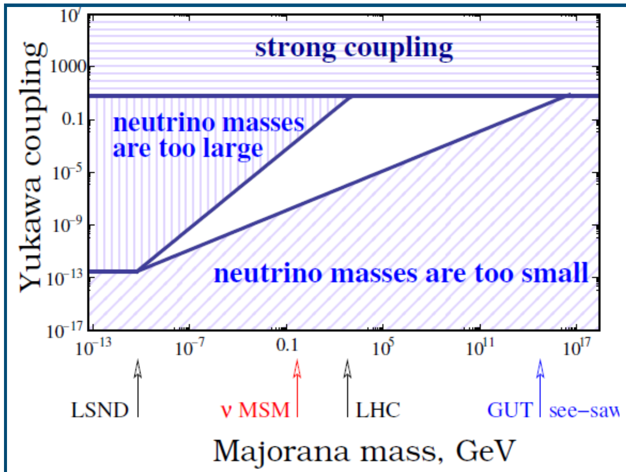
Majorana term which carries no gauge charge

$$v \sim 246 \text{ GeV}$$

The scale of the active neutrino mass is given by the see-saw formula: $m_\nu \sim \frac{m_D^2}{M}$

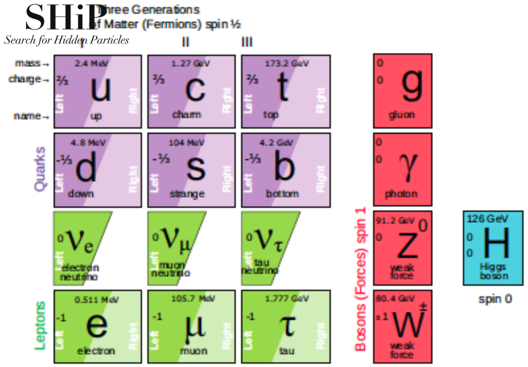
where $m_D \sim Y_{I\alpha}v$ *- typical value of the Dirac mass term*

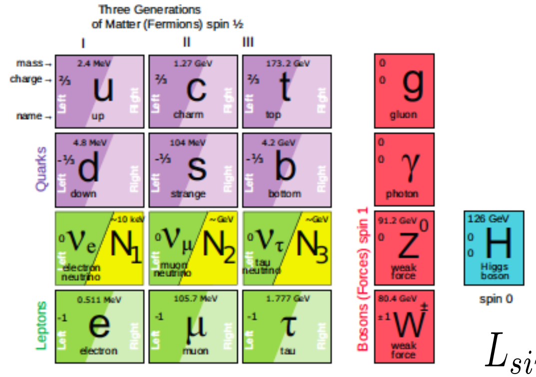
Four "popular" N mass ranges



	N mass	ν masses	eV ν anomalies	BAU	DM	M_H stability	direct search	experiment
GUT see–saw	10^{10-16} GeV	YES	NO	YES	NO	NO	NO	–
EWSB	10^{2-3} GeV	YES	NO	YES	NO	YES	YES	LHC
ν MSM	keV – GeV	YES	NO	YES	YES	YES	YES	a'la CHARM
ν scale	eV	YES	YES	NO	NO	YES	YES	a'la LSND

Neutrino masses & BAU *can be solved with Heavy Neutral Leptons (HNL)*





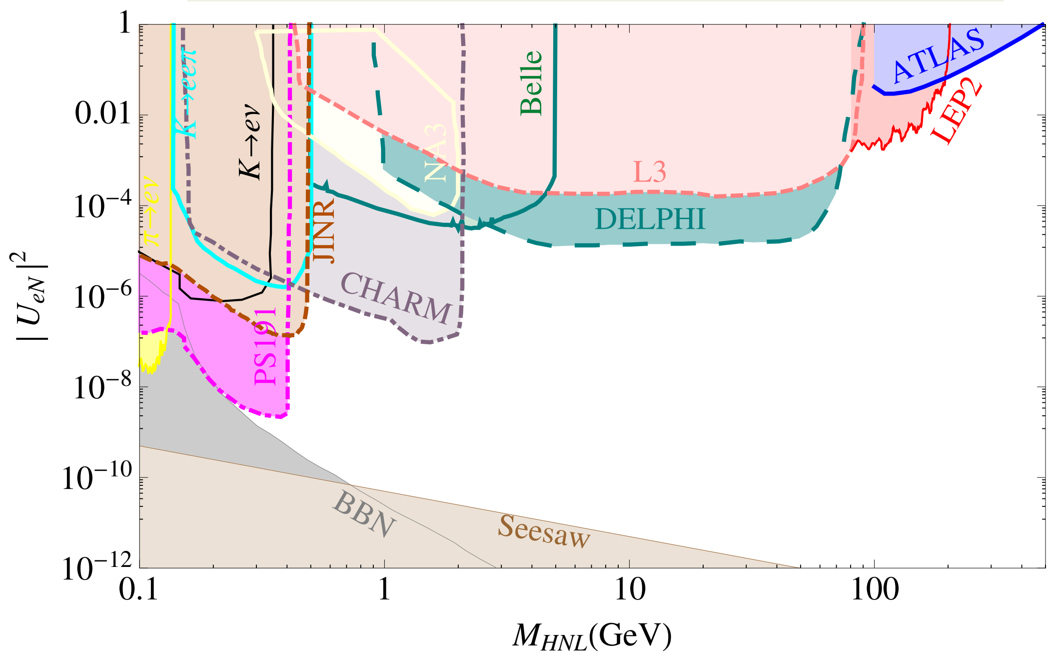
νMSM: T.Asaka, M.Shaposhnikov
PL B620 (2005) 17

N_1 (O(keV) mass) → Dark Matter

$N_{2,3}$ (O(GeV mass) → Neutrino masses and BAU

$$L_{singlet} = i\bar{N}_I \partial_\mu \gamma^\mu N_I - Y_{I\alpha} \bar{N}_I^c \tilde{H} L_\alpha - M_I \bar{N}_I^c N_I + h.c.$$

Existing constraints



Updated SHiP Physics Paper

Previous experiments did not probe cosmologically interesting region for HNL masses above the kaon mass

10

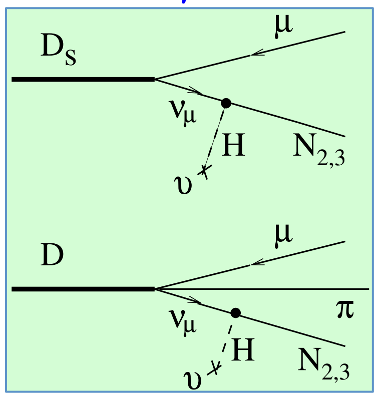
Masses and couplings of HNLs

- ***$M(N_2) \approx M(N_3)$ ~ a few GeV→ CPV can be increased dramatically to explain Baryon Asymmetry of the Universe (BAU)***

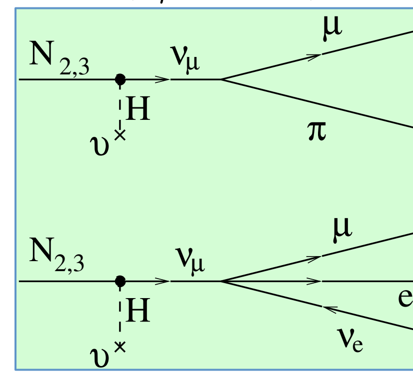
Very weak $N_{2,3}$-to-ν mixing (~ U^2) → $N_{2,3}$ are much longer-lived than SM particles

- Produced in semi-leptonic decays, $\mathrm{K} \to \mu\nu,\ \mathrm{D} \to \mu\pi\nu,\ \mathrm{B} \to \mathrm{D}\mu\nu$
- $\propto \sigma_D \times U^2$
- $U_2^2 = U_{2,\nu_e}^2 + U_{2,\nu_\mu}^2 + U_{2,\nu_\tau}^2$

Example:
$N_{2,3}$ production in charm



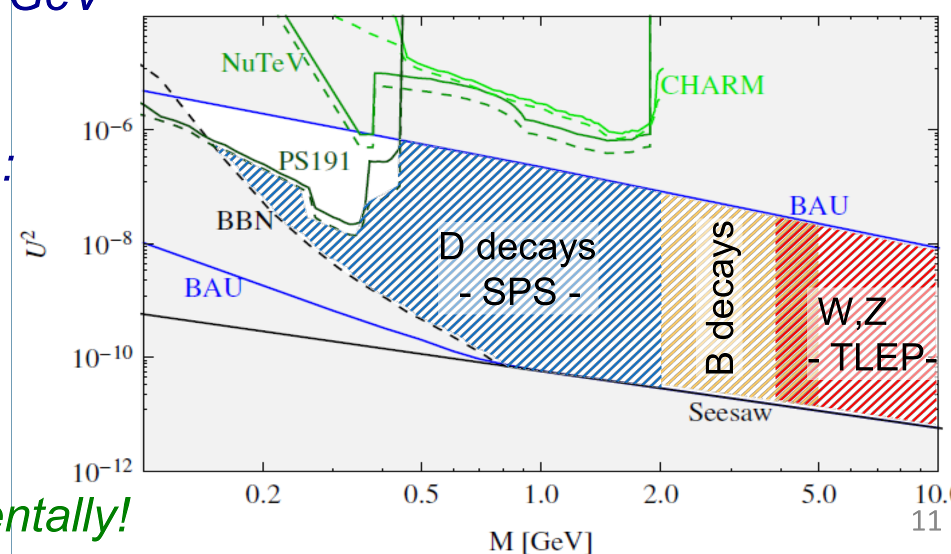
and subsequent decays



- *Typical lifetimes > 10 μs for $M(N_{2,3})$ ~ 1 GeV*
  Decay distance O(km)

- *Typical BRs (depend on flavour mixing):*

$Br(N \to \mu/e\ \pi)$ ~ 0.1 – 50%
$Br(N \to \mu^-/e^-\ \rho^+)$ ~ 0.5 – 20%
$Br(N \to \nu\mu e)$ ~ 1 – 10%

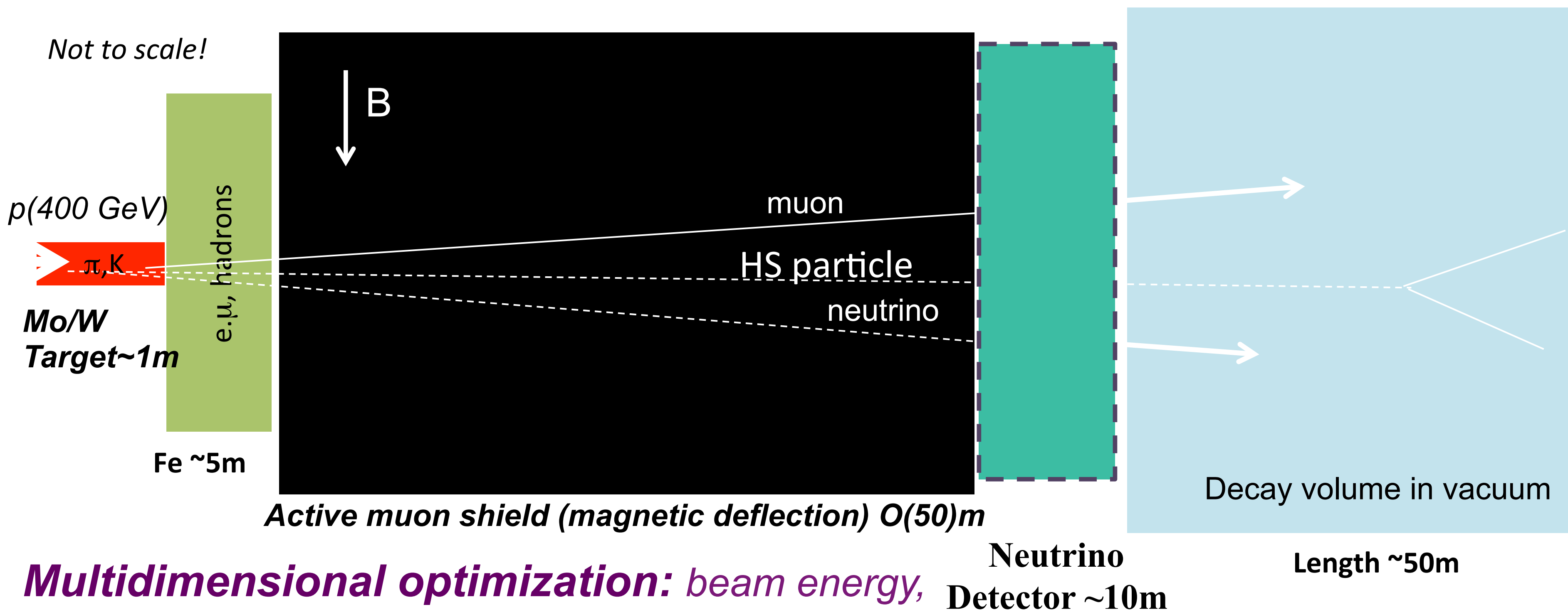


Domain only marginally explored, experimentally!

General experimental requirements

Initial reduction of beam induced backgrounds

- *Heavy target to maximize Heavy Flavour production (large A) and minimize production of neutrinos in $\pi/K \rightarrow \mu\nu$ decays (short λ_{int})*
- *Hadron absorber*
- *Effective muon shield (without shield: muon rate ~$10^{10} \div 10^{11}$ per spill of 4×10^{13} pot)*
- *Slow (and uniform) beam extraction ~1s to reduce occupancy in the detector*



Multidimensional optimization: *beam energy, beam intensity, background conditions and detector acceptance*

ν_τ STUDIES

- Less known particle in the Standard Model
- First observation by DONUT at Fermilab in 2001 with 4 candidates, *Phys. Lett. B504 (2001) 218-224*
- 9 events reported in 2008 with looser cuts
- 5 ν_τ candidates reported by OPERA for the discovery (5.1σ result) of ν_τ appearance in the CNGS neutrino beam PRL 115 (2015) 121802
- 10 ν_τ candidates reported by OPERA (6.1 σ for ν_τ appearance) and first cross-section measurement PRL 120 (2018) 211801
- Tau anti-neutrino never observed

$$N_{\nu_\tau+\bar{\nu}_\tau} = 4N_p \frac{\sigma_{c\bar{c}}}{\sigma_{pN}} f_{D_s} Br(D_s \to \tau) = 2.85 \times 10^{-5} N_p = 5.7 \times 10^{15}$$

Does not account for charm cascade production!

The SHiP experiment at SPS

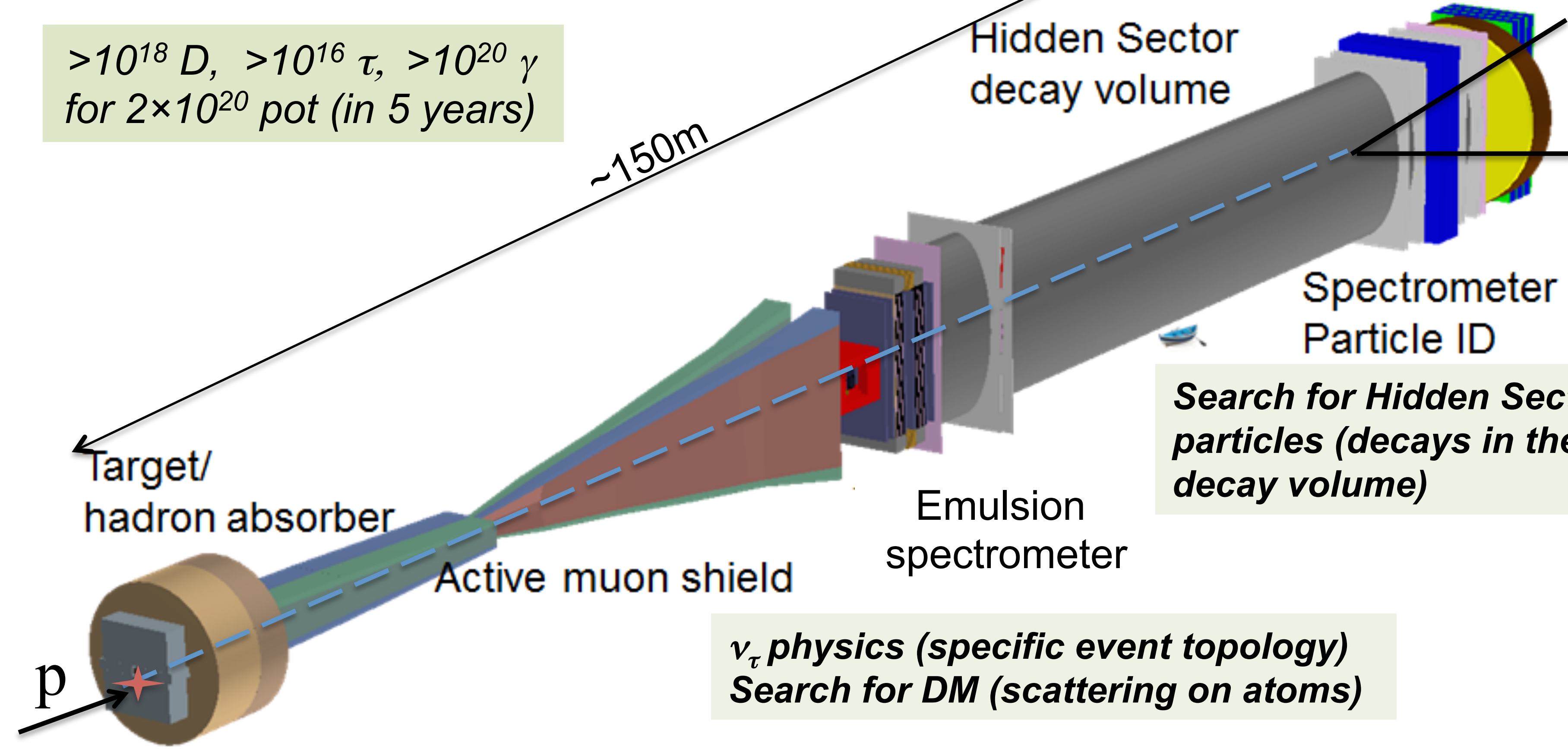
(as implemented in Geant4 for TP)

SHiP Technical Proposal: 1504.04956

"Zero background" experiment

- *Muon shield*
- *Surrounding Veto detectors*

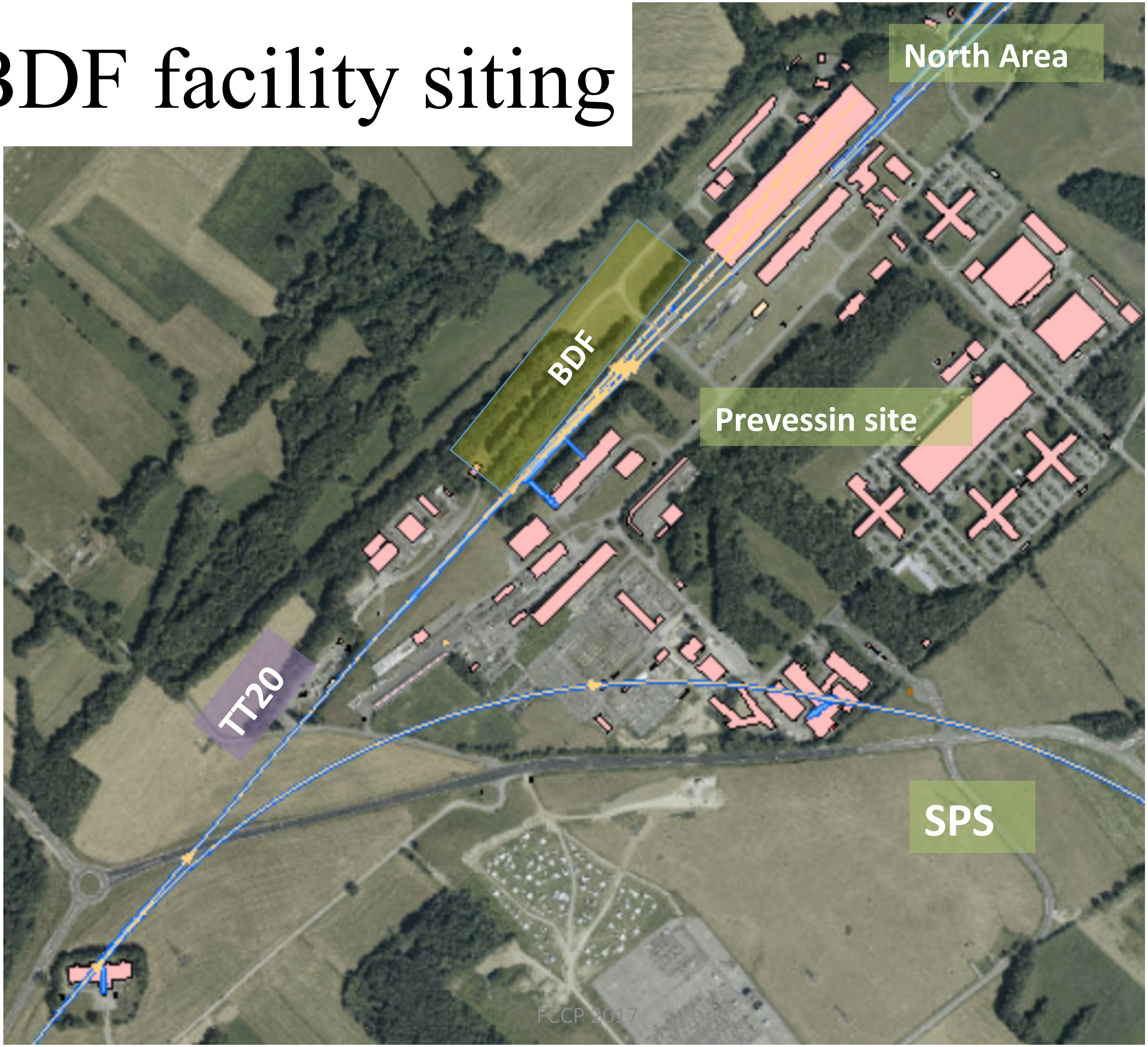
>10^{18} D, >10^{16} τ, >10^{20} γ for 2×10^{20} pot (in 5 years)



Search for Hidden Sector particles (decays in the decay volume)

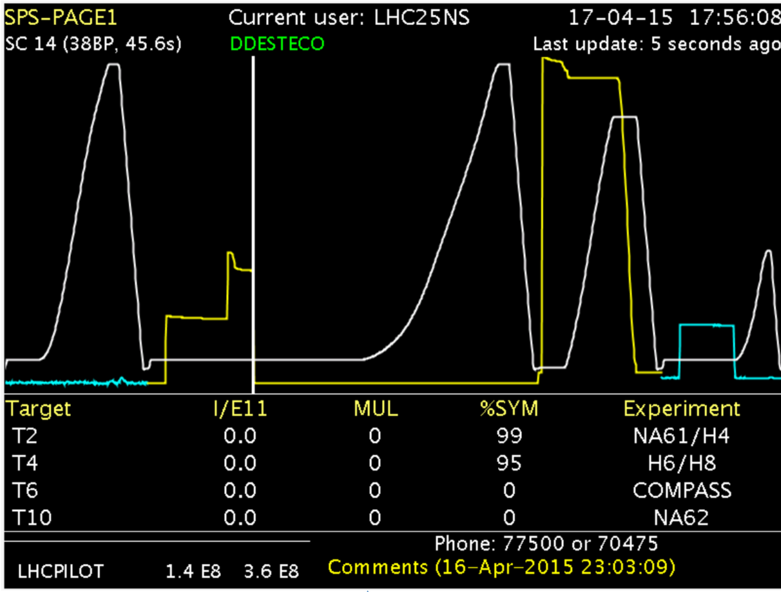
ν_τ physics (specific event topology)
Search for DM (scattering on atoms)

BDF facility siting



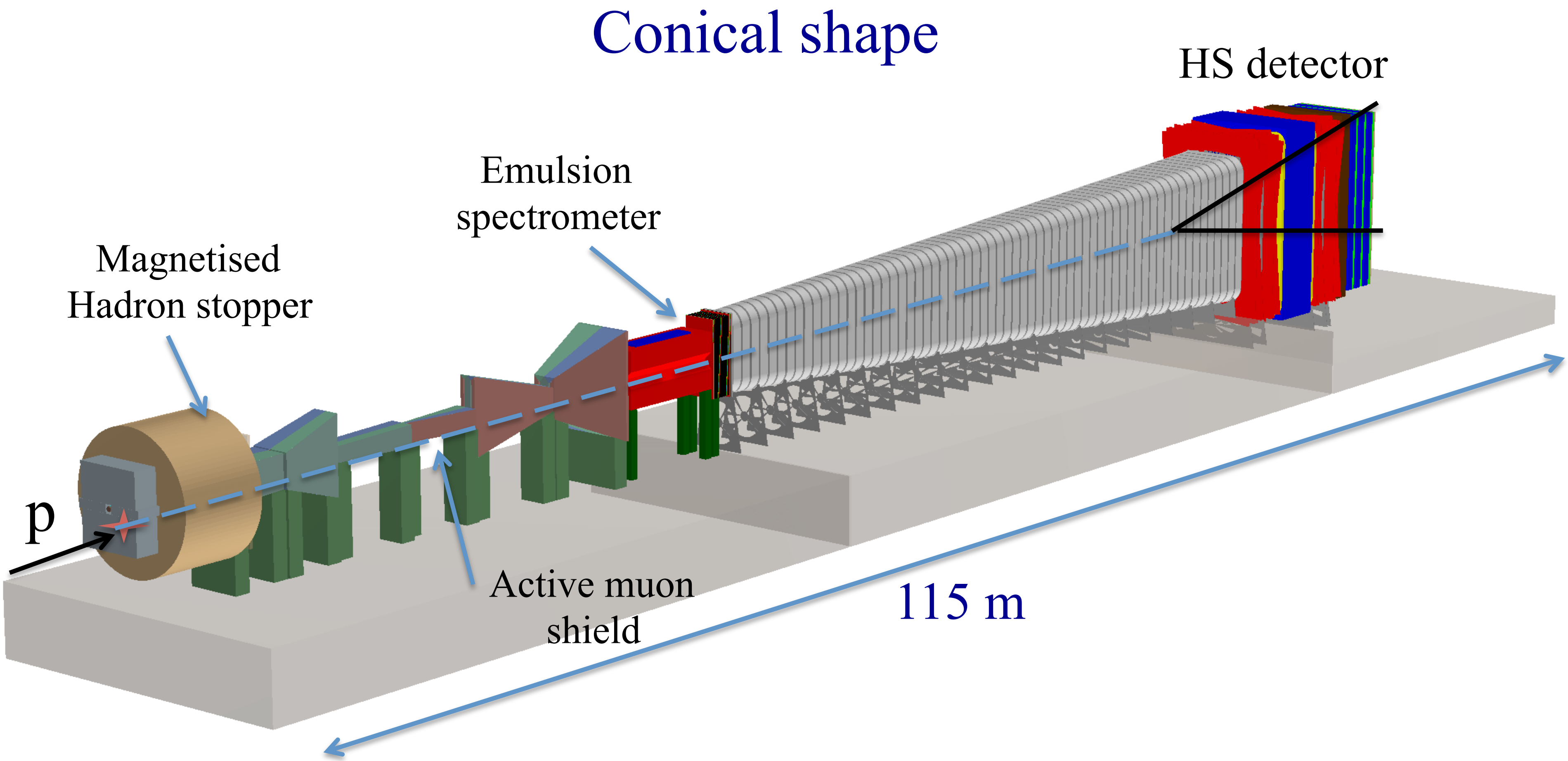
R&D at CERN for extraction and beam lines

- Deployment of the new SHiP cycle
- Extraction loss characterisation and optimisation
  - Reduce p density on septum wires
  - Probe SPS aperture limits during slow extraction
- Development of new TT20 optics
  - Change beam at splitter on cycle-to cycle basis
- Characterisation of spill structure
- R&D and development of laminated splitter and dilution (sweep) magnets



Successful test in April 2015

SHiP optimised design



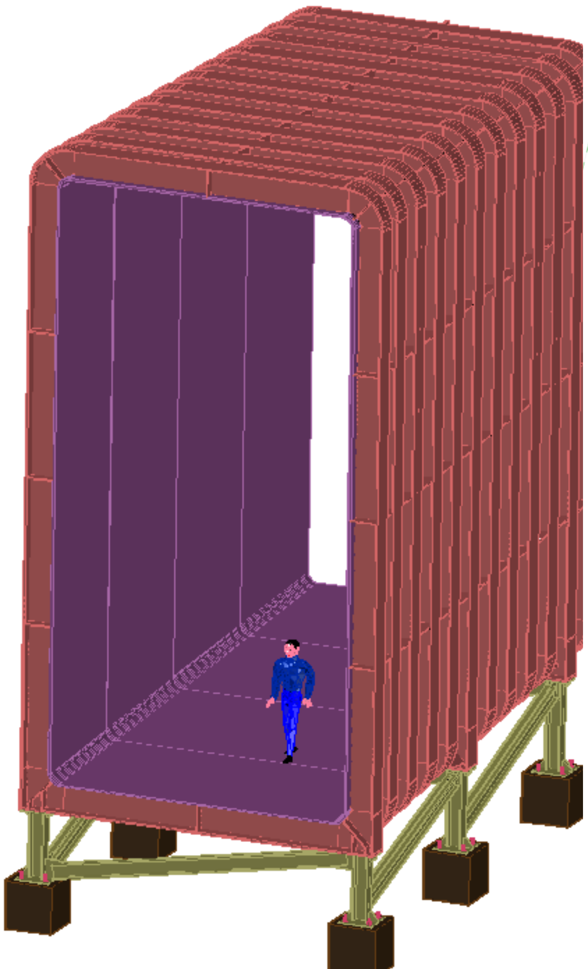
$\sim 2 \times 10^{18}$charmed hadrons

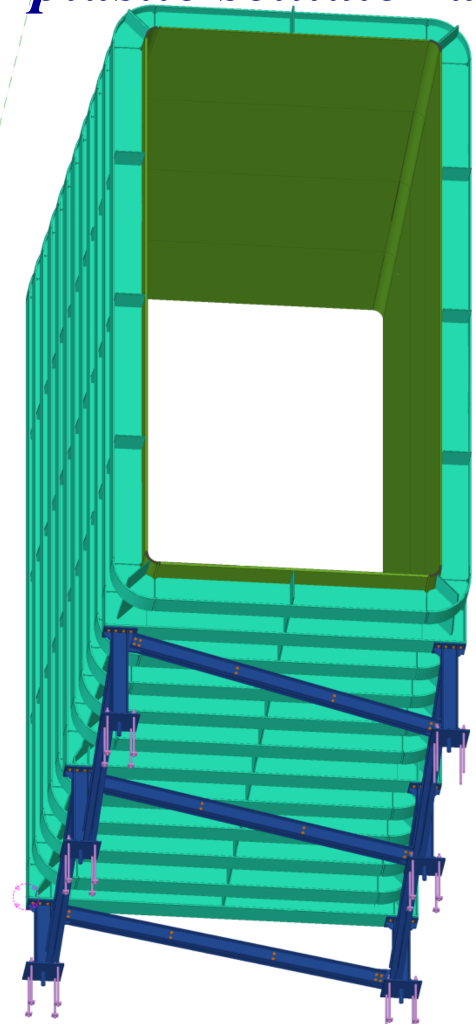
$\sim 1 \times 10^{14}$beauty hadrons

Decay vessel with conical shape

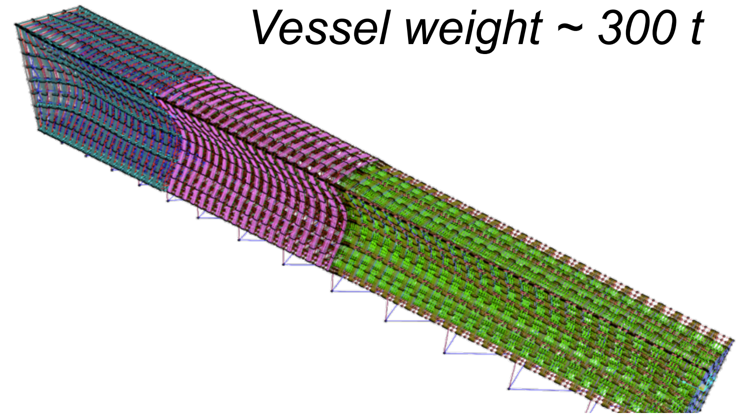
- ✓ ***Estimated need for vacuum: ~ 10^{-3} mbar (<1 ν interaction without any reconstruction cut), will work with ~1mbar***

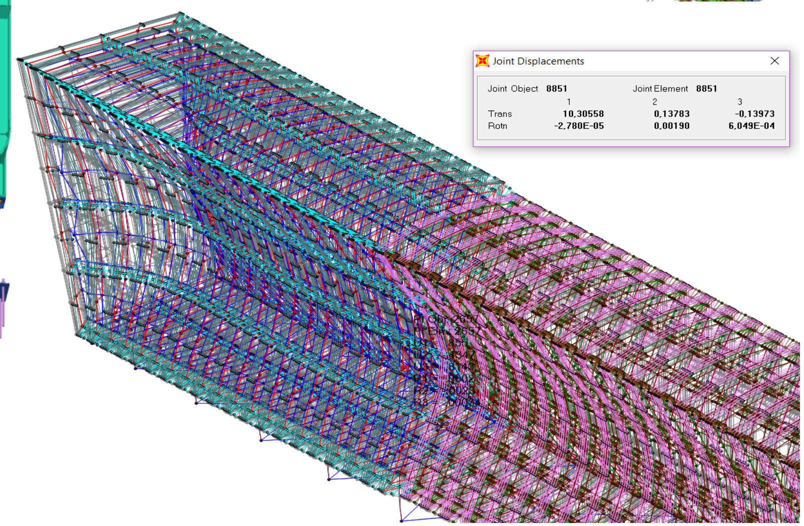
Surrounded by liquid or plastic scillator acting as a veto





Vessel weight ~ 300 t

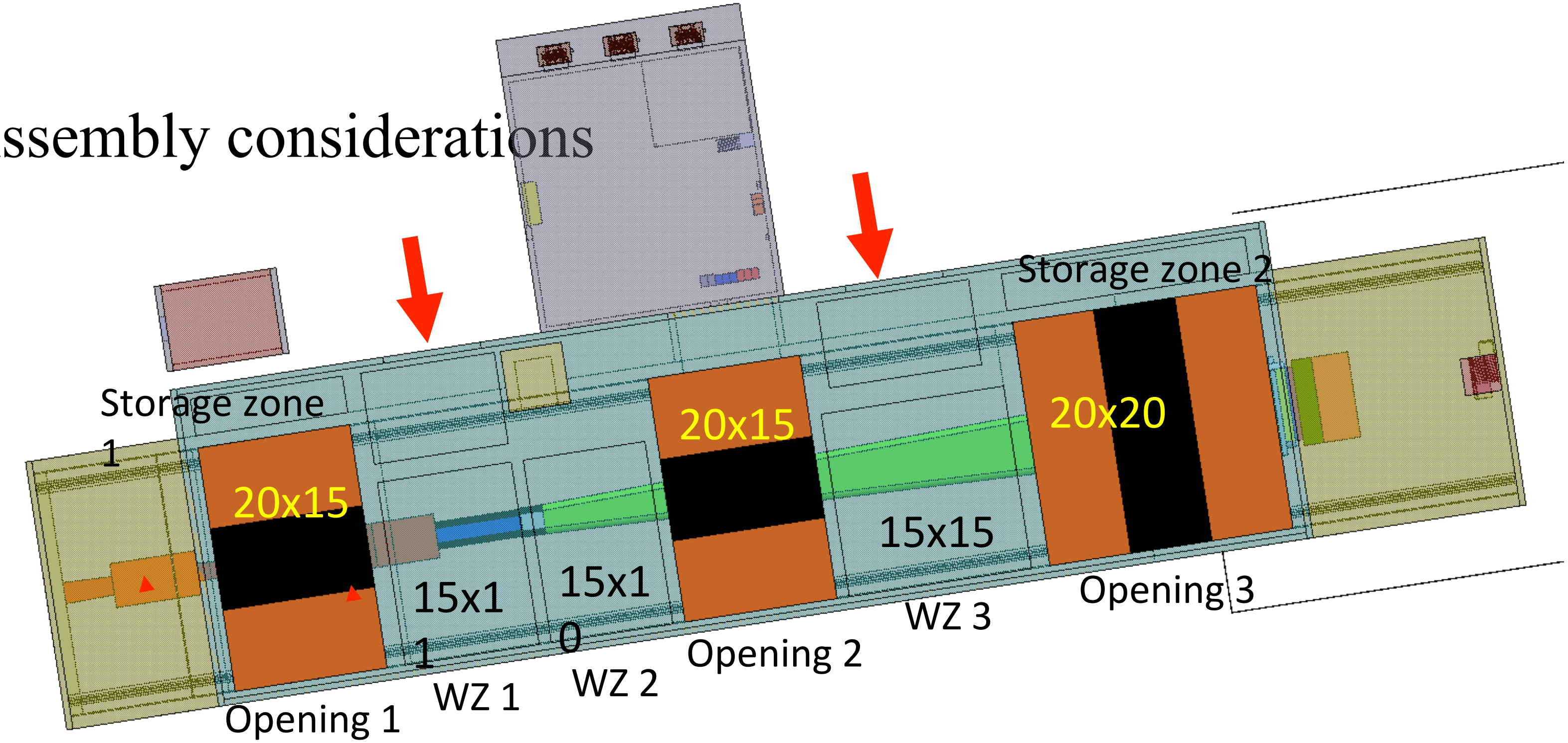


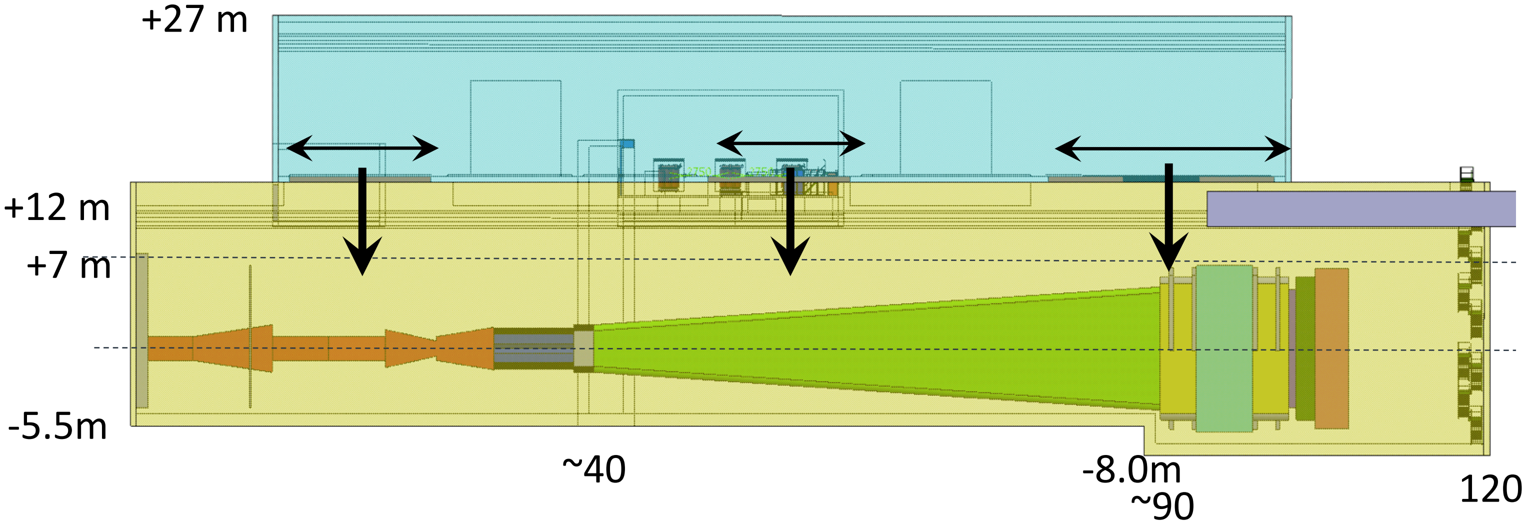


University of Naples and Castaldo

EXPERIMENTAL AREA

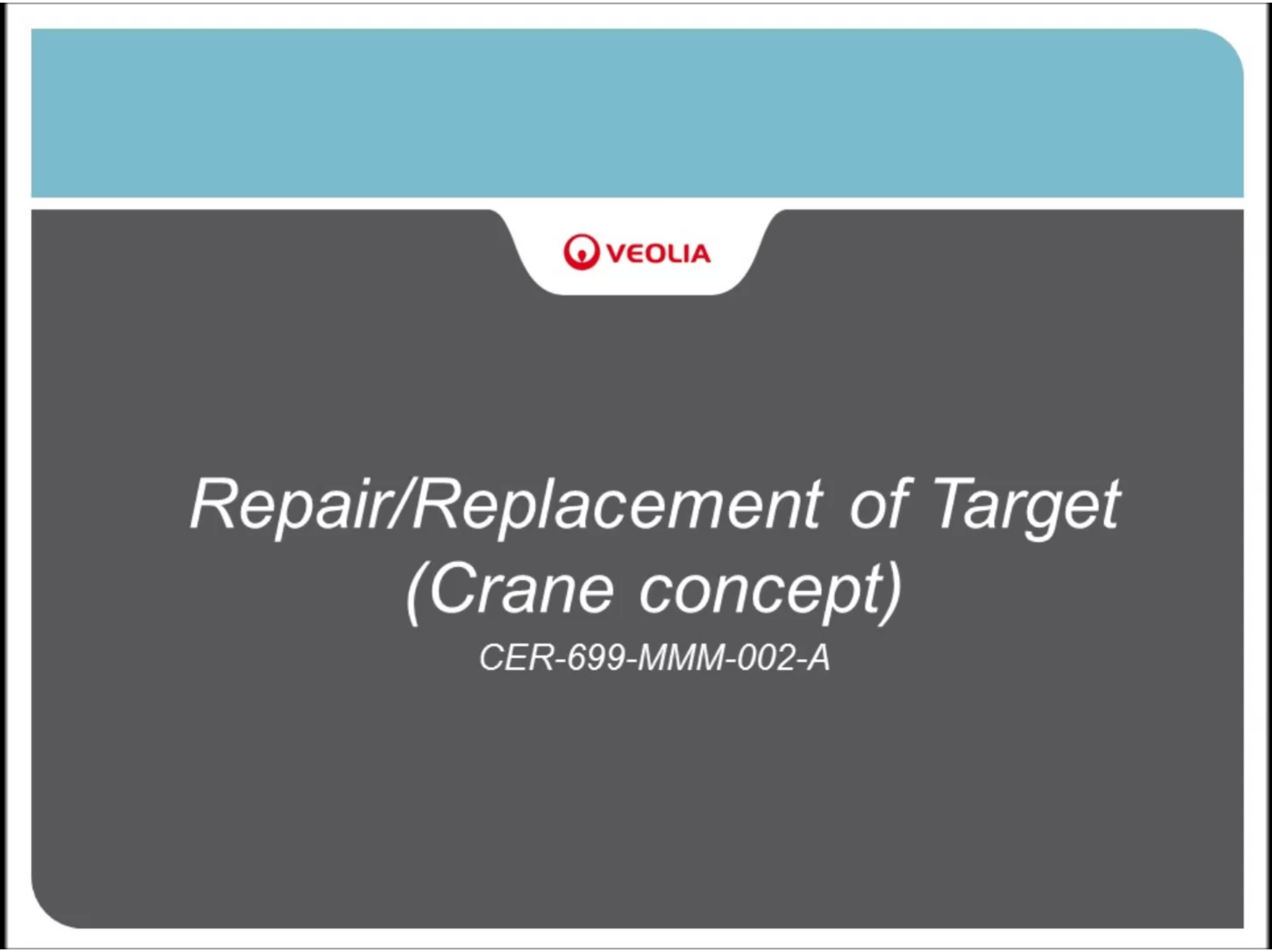
➔ Assembly considerations





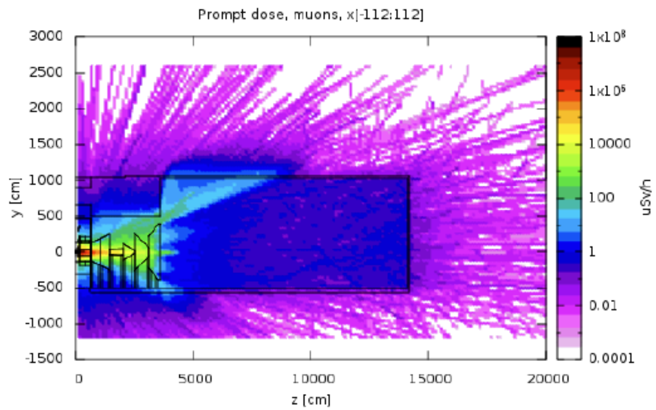
Pablo Santos Diaz

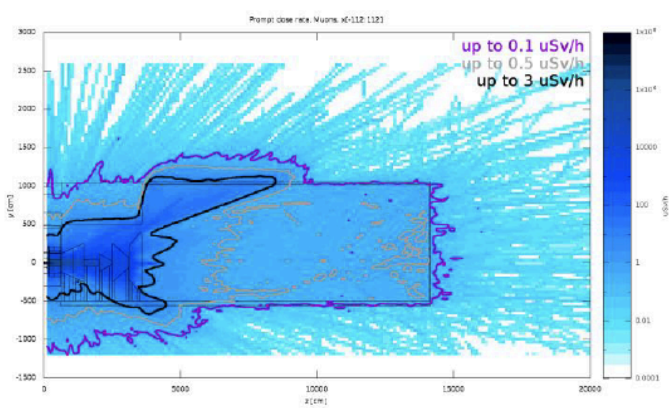
Target Complex studies

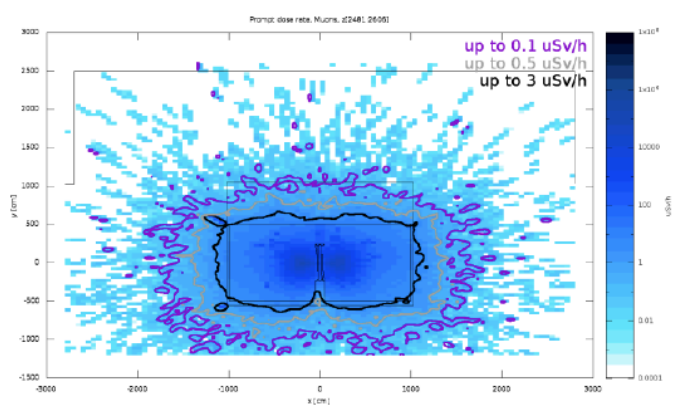


Prompt dose rate SHiP experimental hall

- Using geometry with 150cm long target
- New SHiP magnet and increased roof
- Using $4x10^{13}$ p / 7.2 s



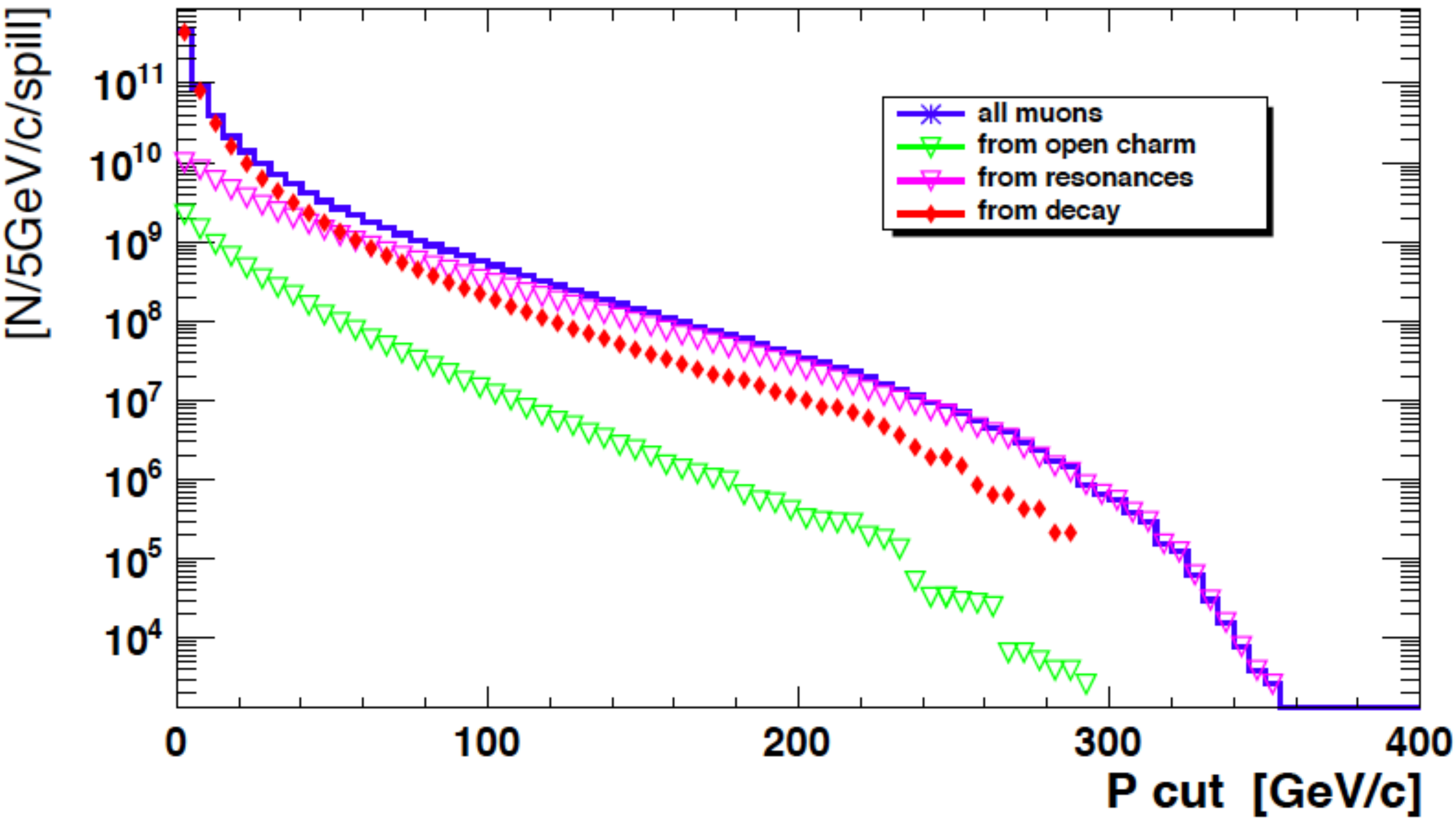




Updating simulations with 1m of concrete roof

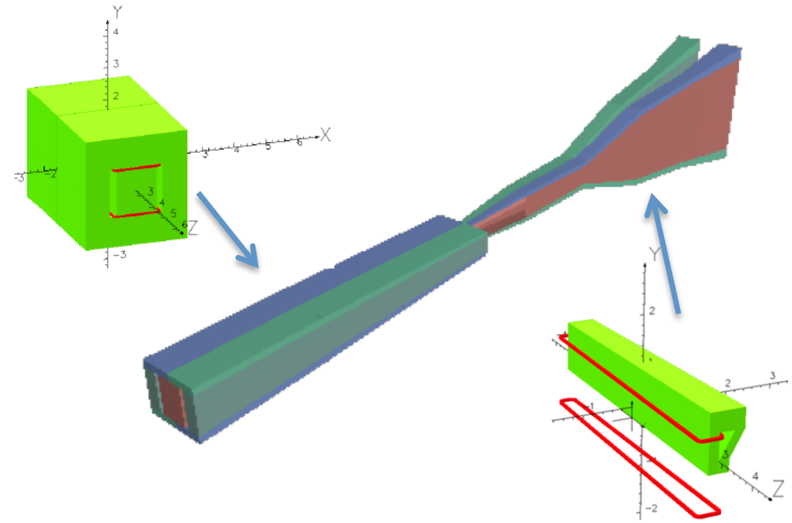
Main sources of muons in beam dump

- *Decays of pions populate mainly low momenta*
- *Electromagnetic decays of resonances (η, ρ, etc) populate mainly high momenta*
- *Negligible fraction of muons from charm decays*

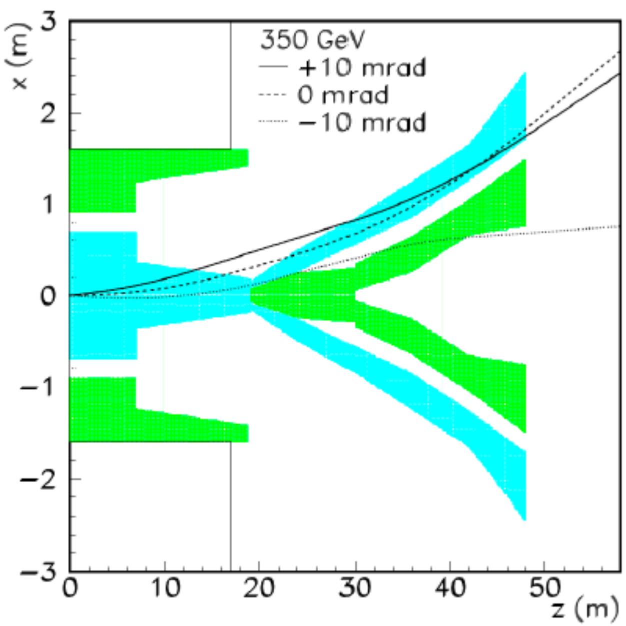


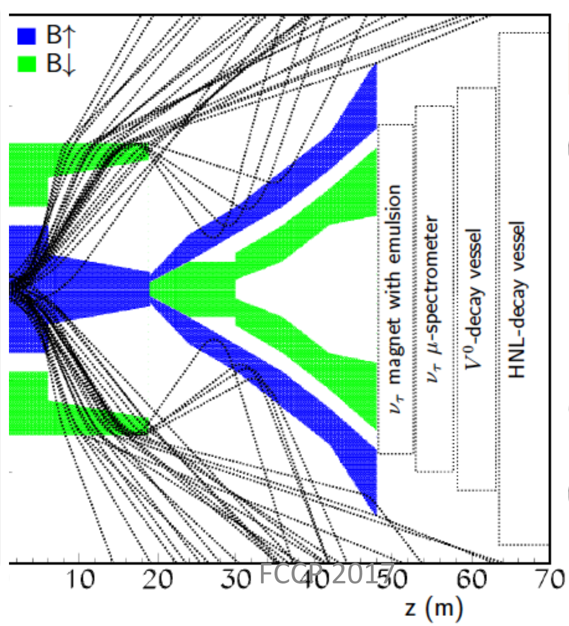
SHiP muon shield, JINST 12 (2017) P05011

- ✓ *Muon flux limit driven by HS background and emulsion-based neutrino detector*
- ✓ *Active muon shield based entirely on magnet sweeper with a total field integral B_y = 86.4 Tm*
  Realistic design of sweeper magnets in progress
  Challenges: flux leakage, constant field profile, modeling magnet shape
- ✓ *~10 KHz rate from ~ 10^{10} Hz*
- ✓ *Negligible flux in terms of detector occupancy*

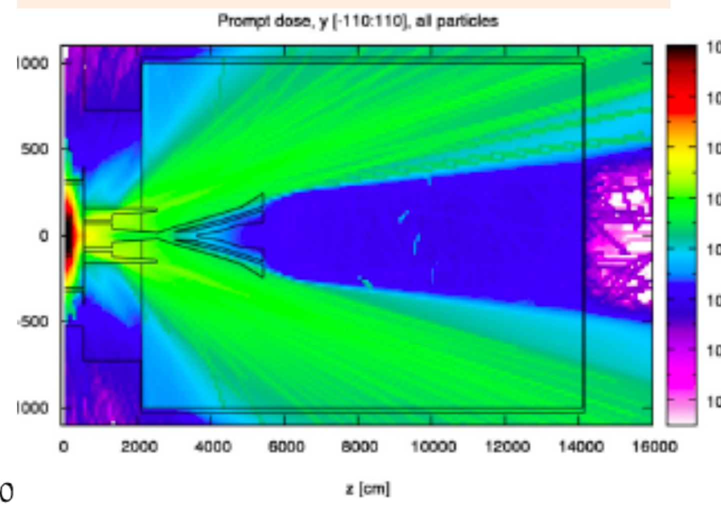


Magnetic sweeper field

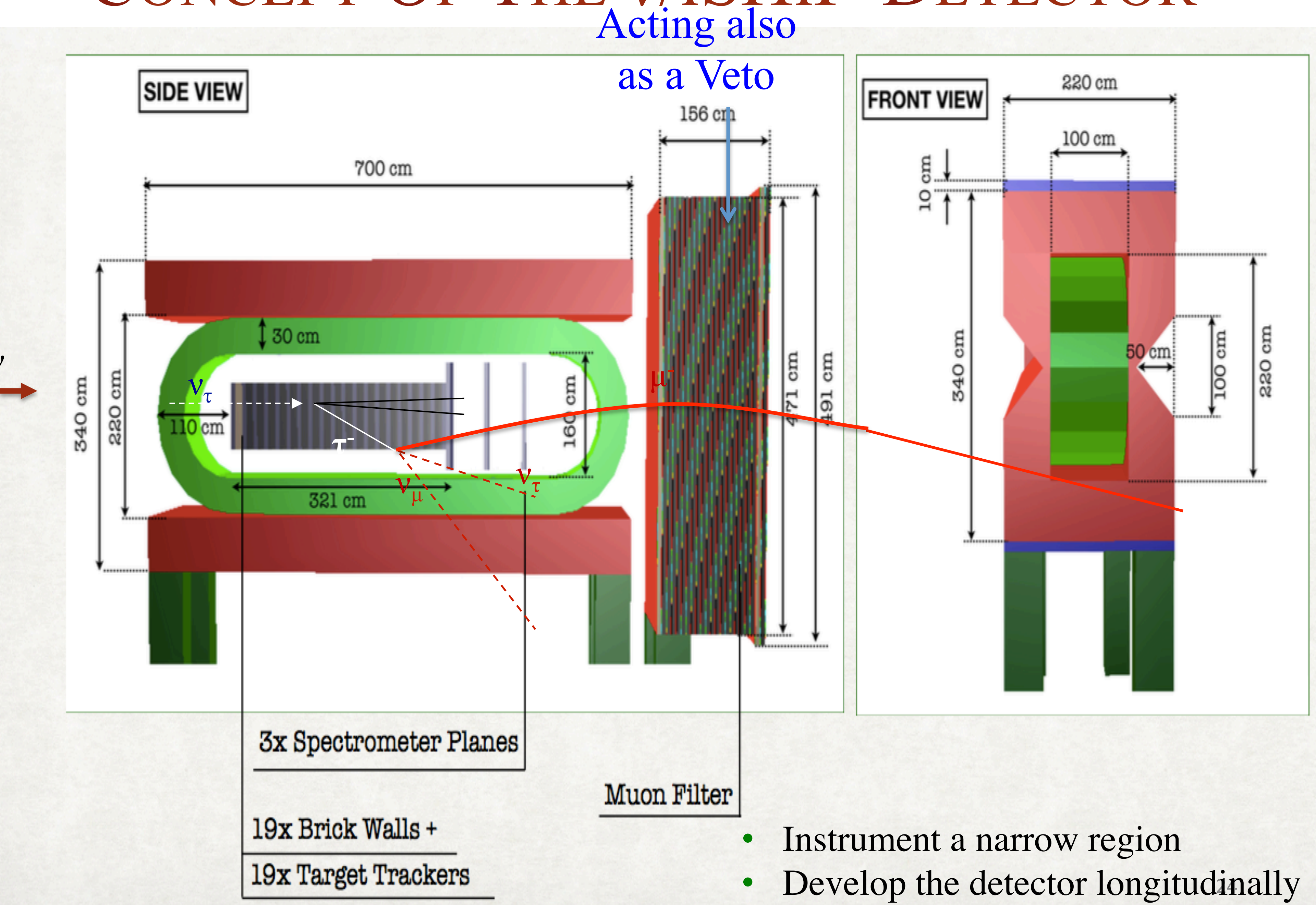




Dose rate (μSv/h) in the SHiP hall

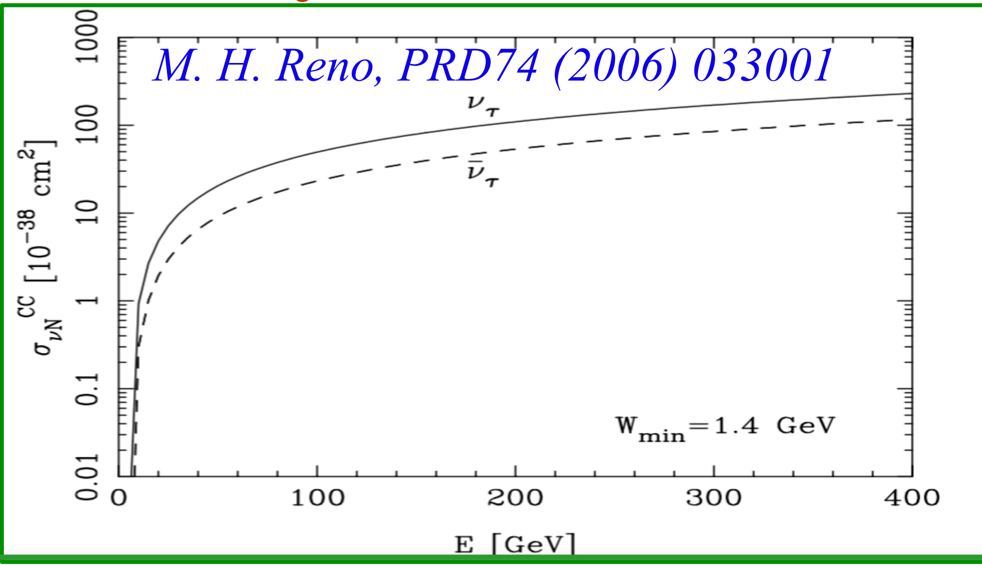


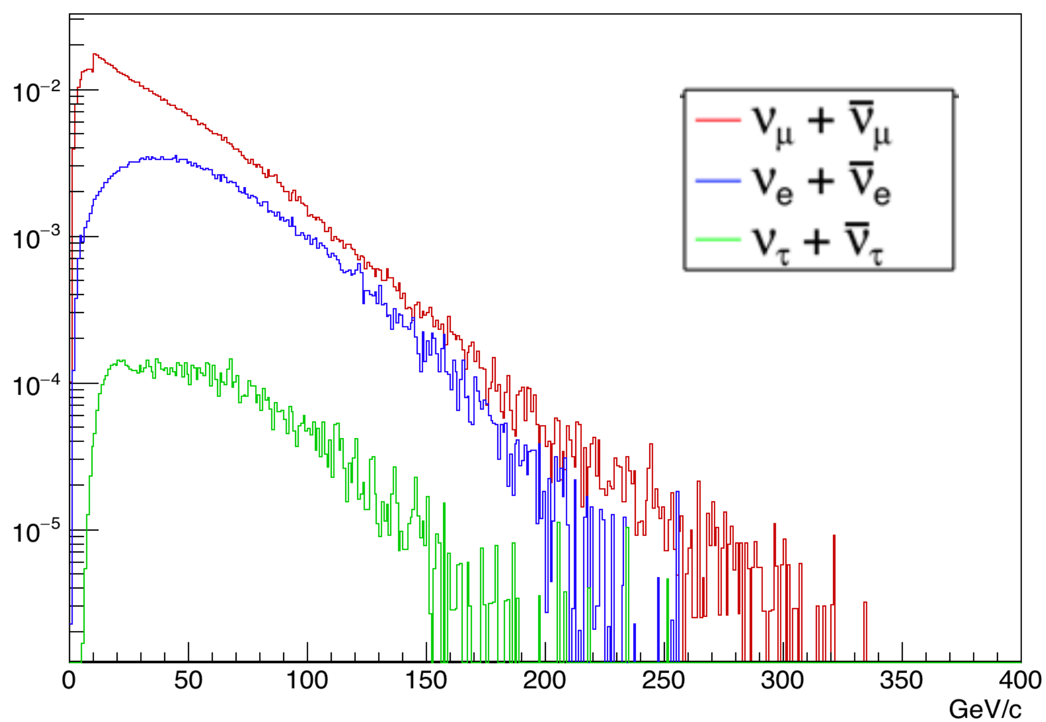
Concept Of The ν/iSHiP Detector



- Instrument a narrow region
- Develop the detector longitudinally

ν_τ Interactions In The Target





Expected number of interactions*

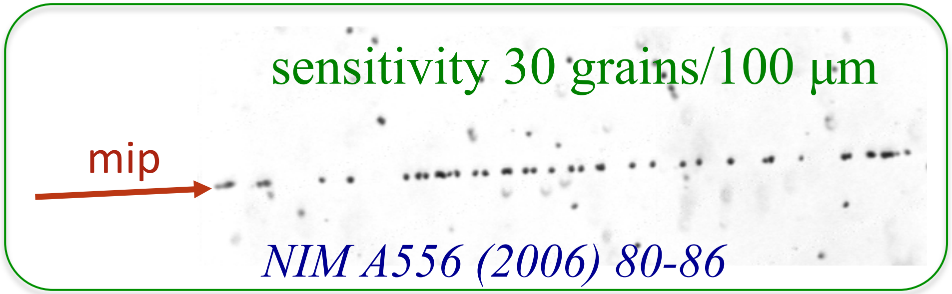
*in 5 years run ($2x10^{20}$ pot)
target mass ~ 7.3 ton (Pb)

INTERACTING CC-DIS		
	<E>(GeV)	Yield
ν_e	59	1.1×10^6
ν_μ	42	2.7×10^6
ν_τ	52	3.2×10^4
ν_e-bar	46	2.6×10^5
ν_μ-bar	36	6.0×10^5
ν_τ-bar	70	2.1×10^4

Large enhancement in a thick target
due to hadron cascade effect

ν_τ DETECTOR

THE UNITARY CELL

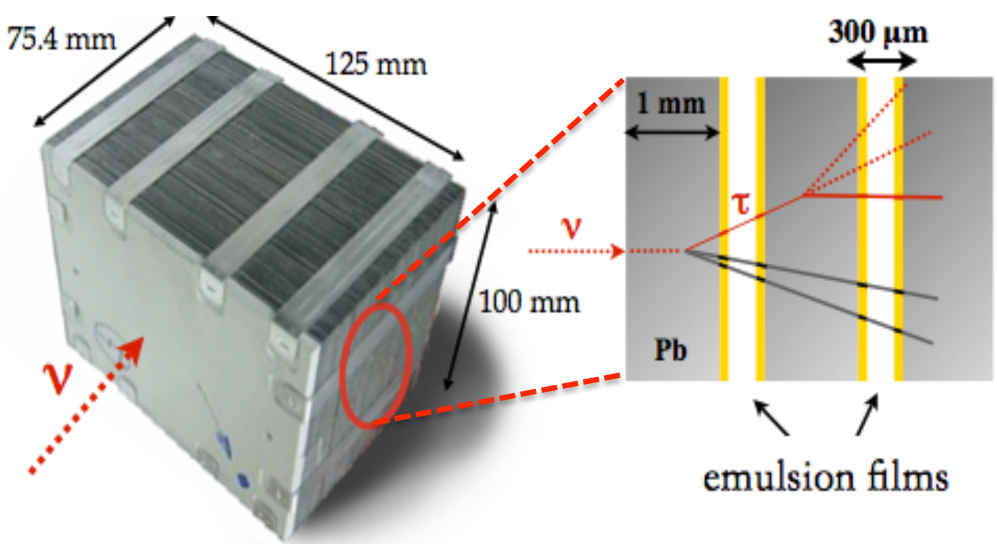


Emulsion Cloud Chamber (ECC)

BRICK

- passive material → lead
  (massive target)
- tracking device → nuclear emulsions
  (high resolution)

10 X_0

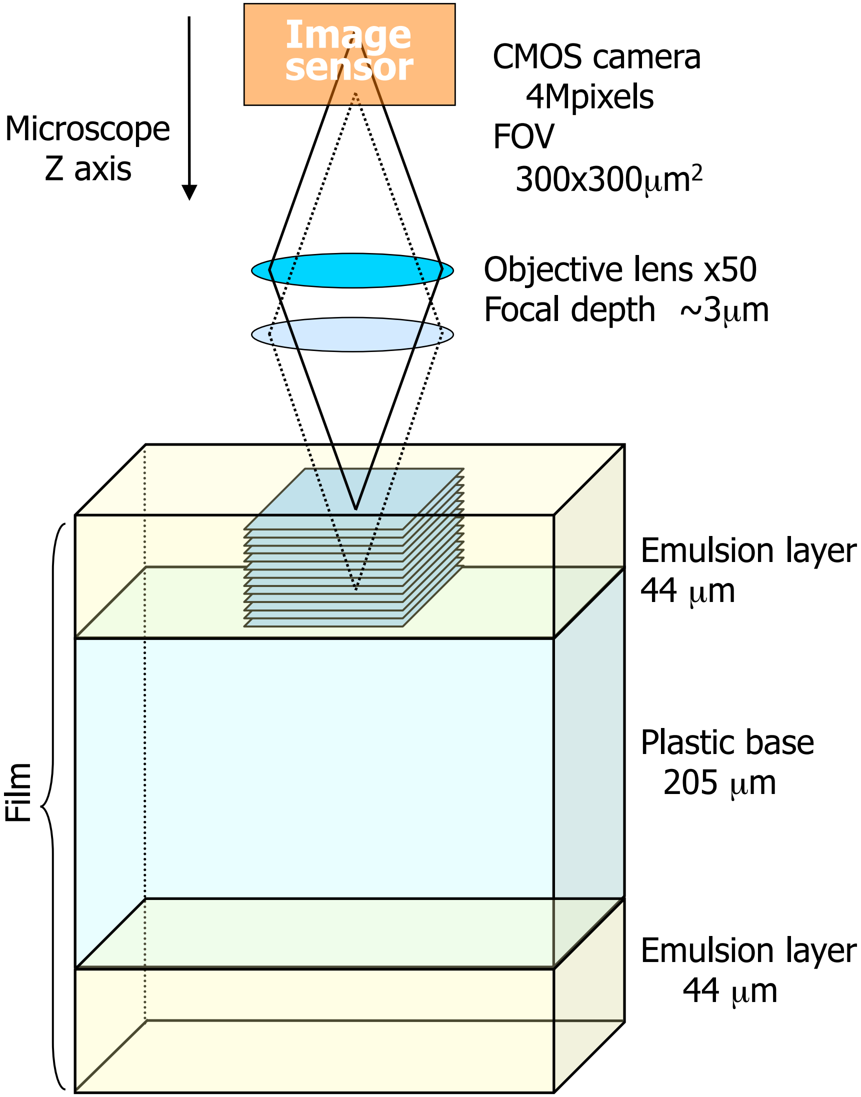


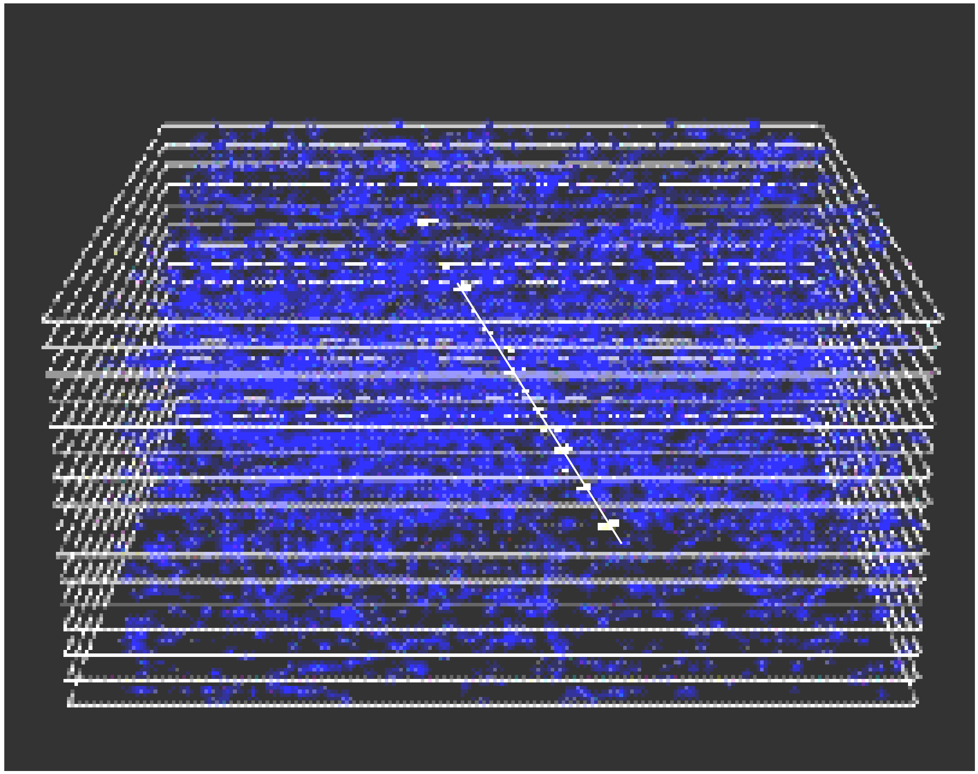
PERFORMANCES

- Primary and secondary vertex definition with μm resolution
- Momentum measurement by Multiple Coulomb Scattering
  - largely exploited in the OPERA experiment
- Electron identification: shower ID through calorimetric technique

OPERA: 1 event in 1 brick
SHIP: ~230 events/brick

Digitizing Nuclear Emulsion Films

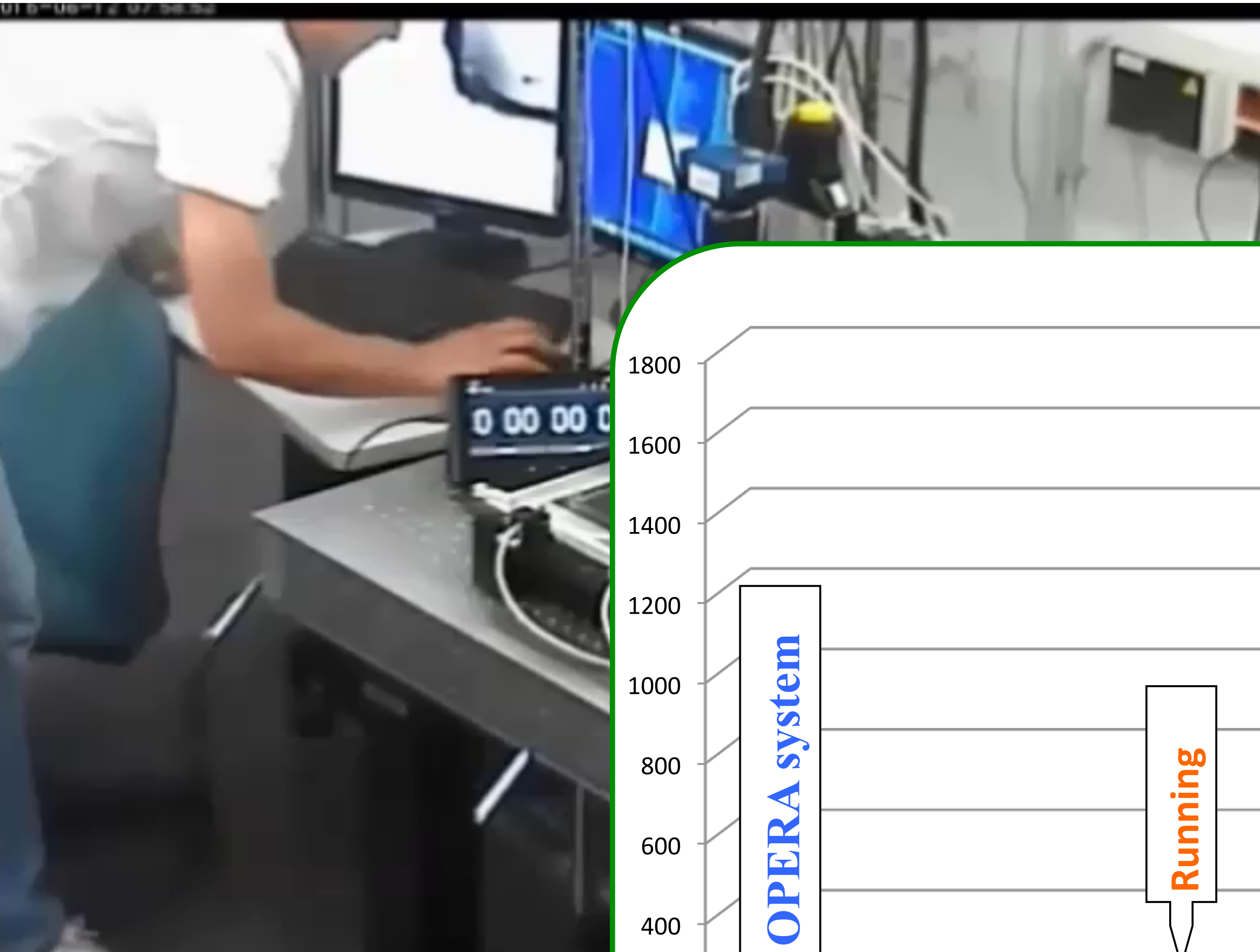


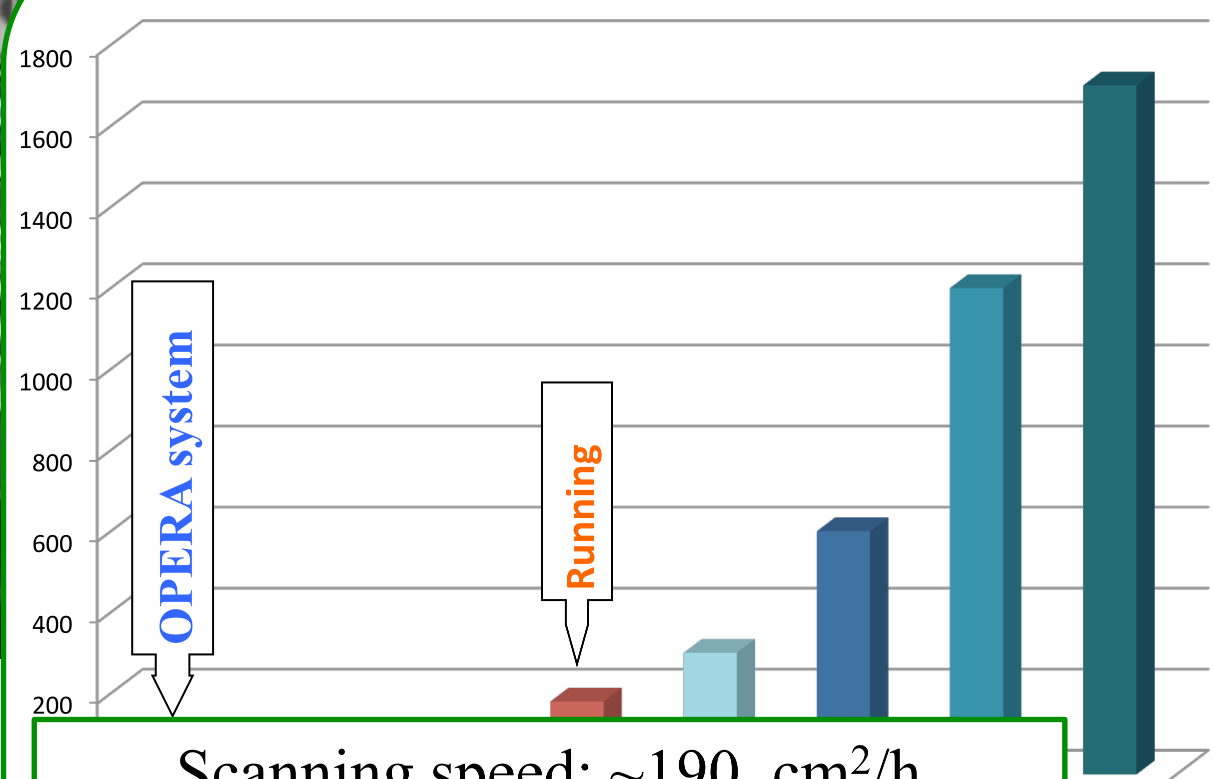


300μm

Grain Density ~15 (/45μm)

Important Technological Developments





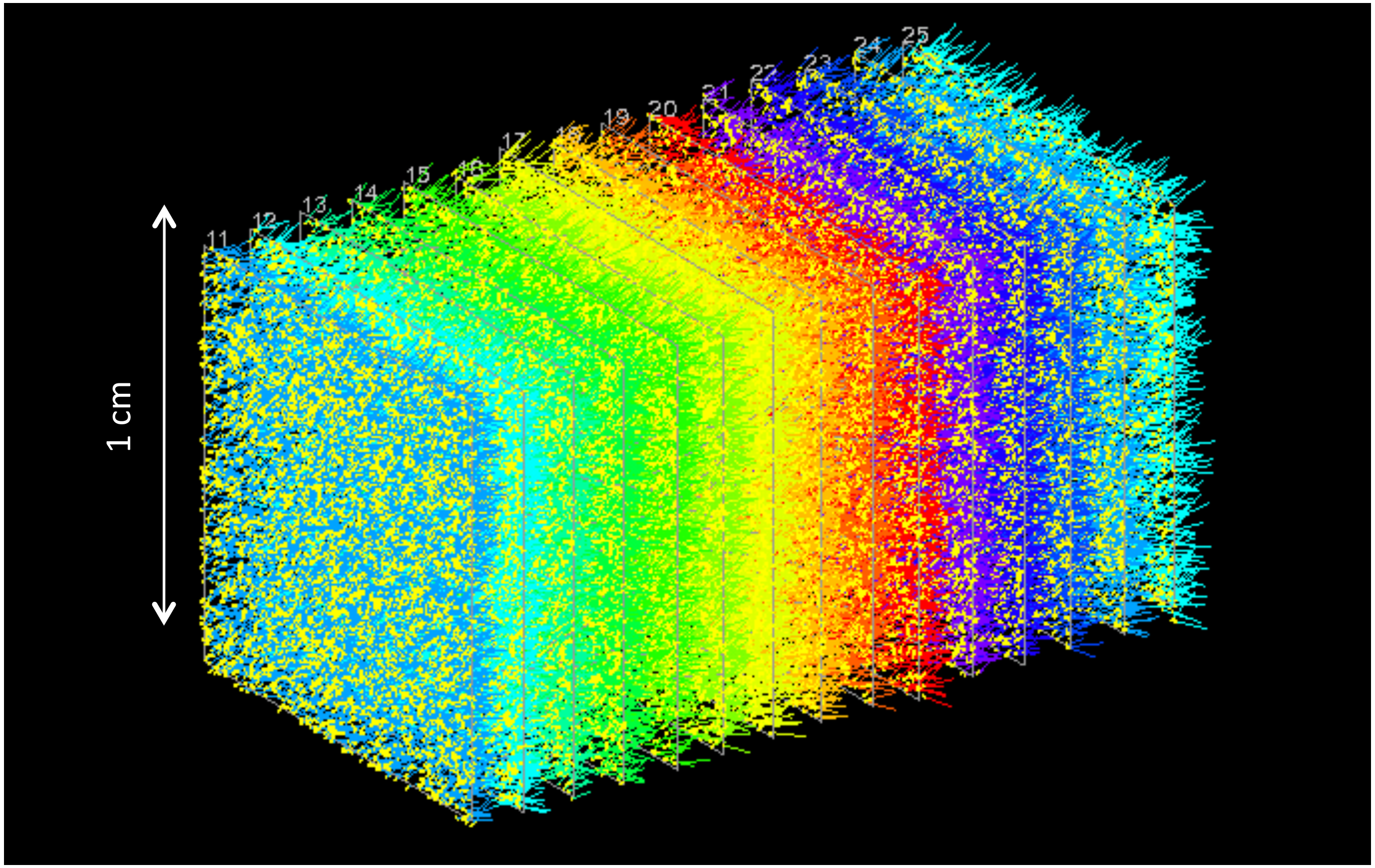
Scanning speed: ~190 cm^2/h
~10 times faster
with a much wider angular acceptance

JINST 8 (2013) P01023
JINST 10 (2015) P11006
JINST 11 (2016) P06002
Scientific Reports 7 (2017) 7310

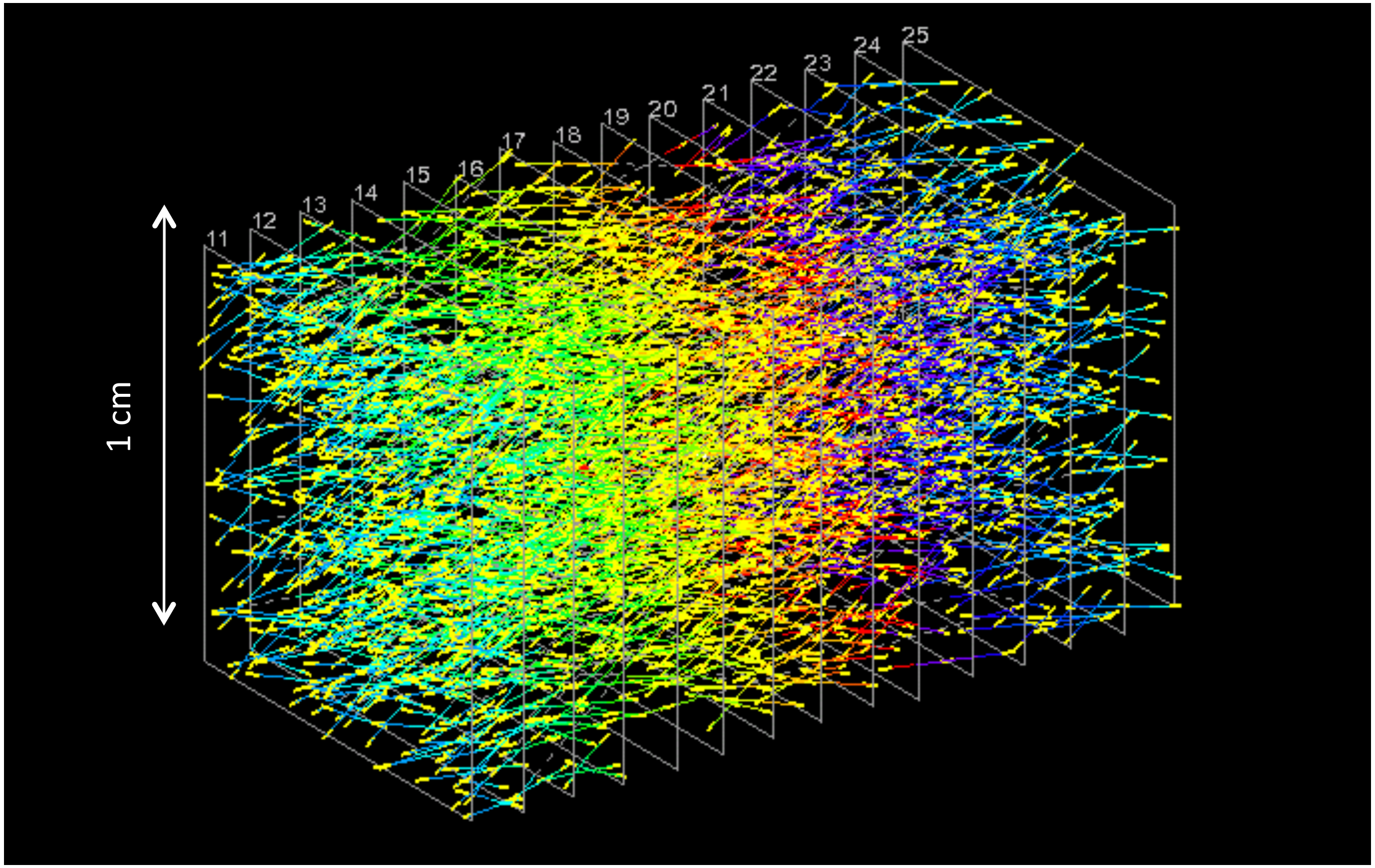
Volume (~2 cm^3) analysed

3D tracks with sub-micrometric accuracy

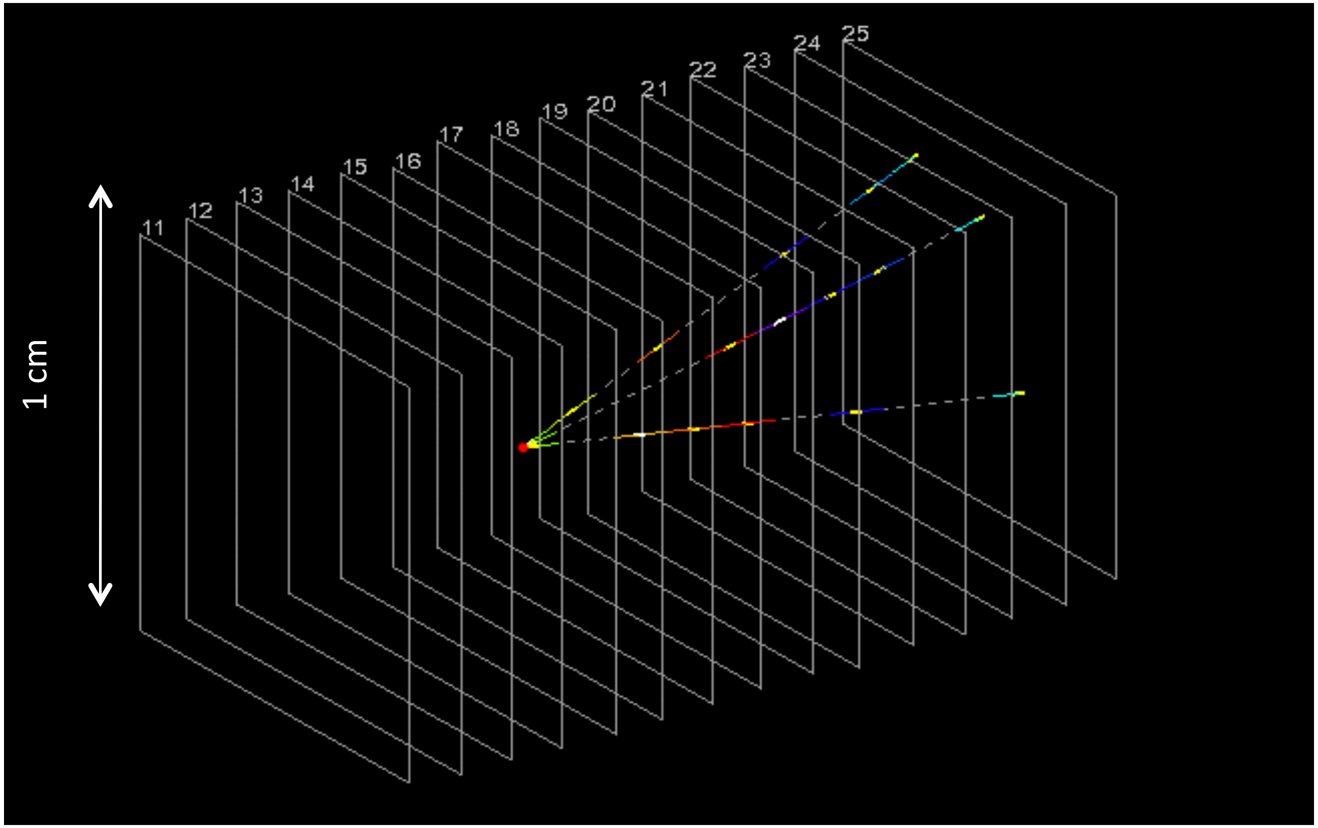
Short Yellow lines → measured tracks
Other colours → extrapolated segments



Film to film connection



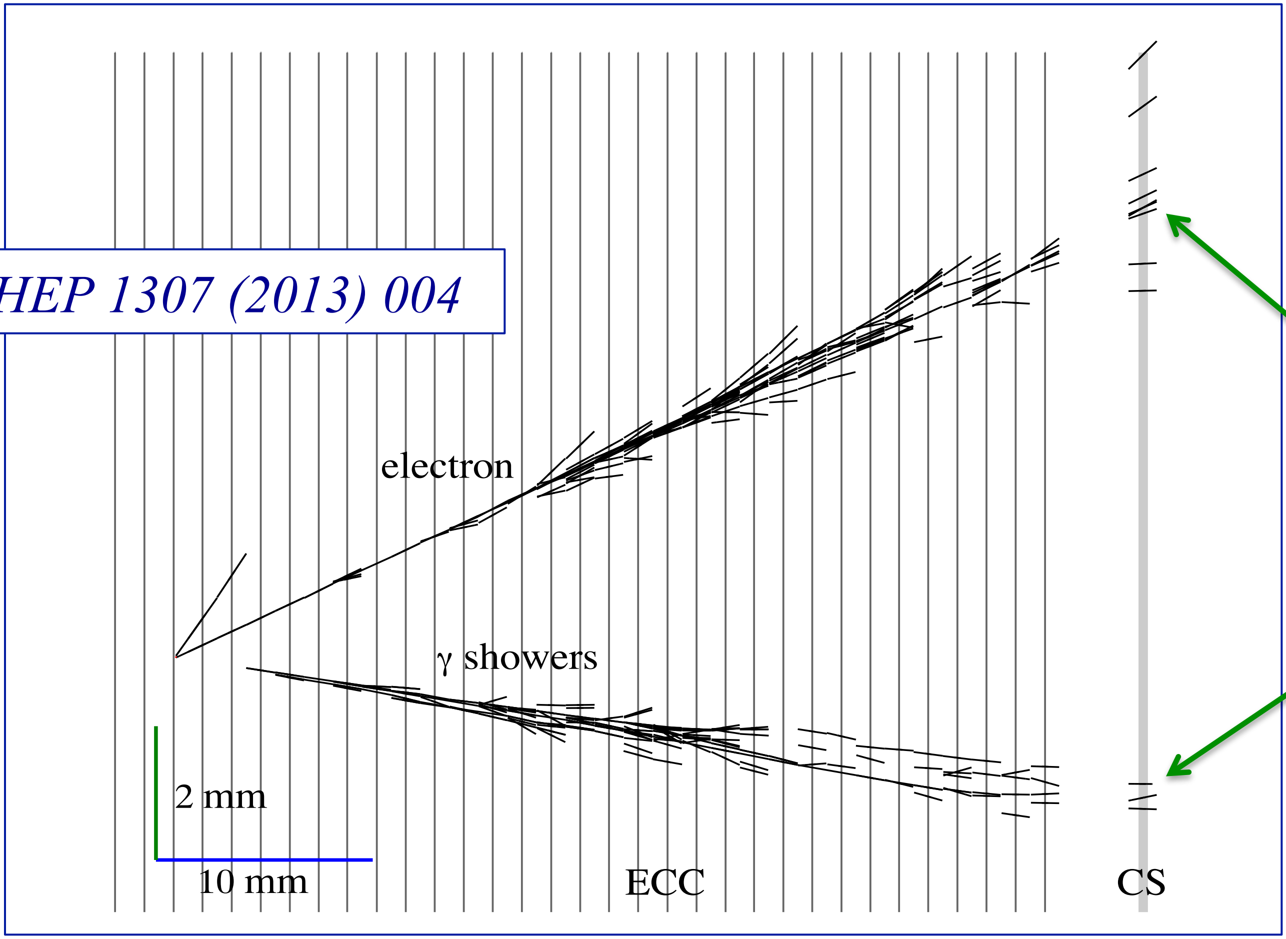
LOCATED NEUTRINO INTERACTION



ν_e Interaction Detected in an OPERA Brick

UNIQUE IN ITS CAPABILITY OF IDENTIFYING ALL THREE NEUTRINOS

JHEP 1307 (2013) 004

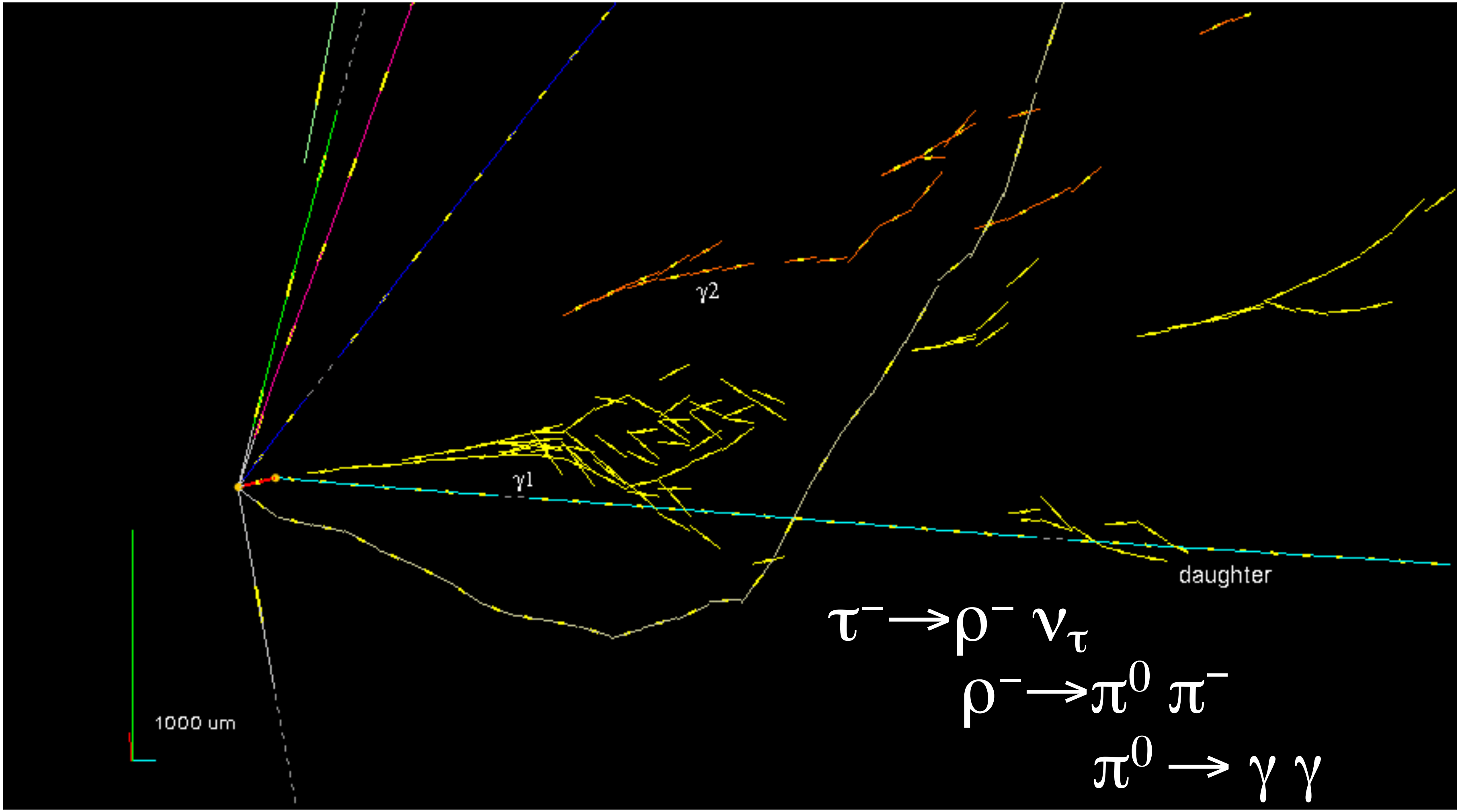


Interface films

a π^0 is produced at the primary interaction vertex and a γ is detected

The First OPERA ν_τ Candidate

Discovery of tau neutrino appearance in a muon neutrino beam
PRL 115 (2015) 121802, PRL 120 (2018) 211801.



Physics Letters B691 (2010) 138

ν_τ/ANTI-ν_τ SEPARATION

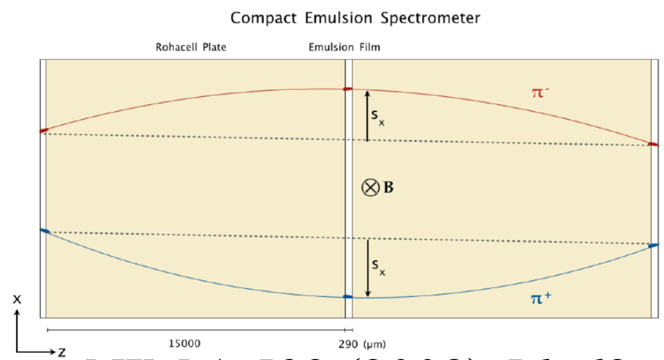
THE COMPACT EMULSION SPECTROMETER

Magnetised target → charge and momentum measurement for hadrons

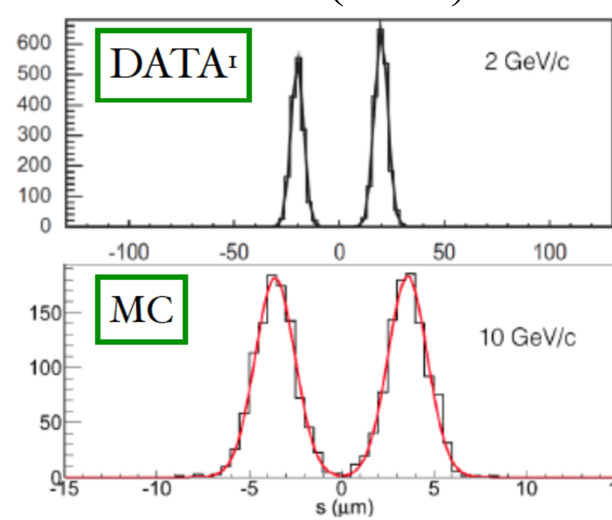
BR(τ → hadrons) ~ 65%

Use Compact Emulsion Spectrometer (CES) → R&D going on

- 1T field
- 3 films interleaved with 2 Rohacell layers (15 mm)
- Thin chamber: 3cm in total
- 90% efficiency for hadronic τ daughters reaching the CES
- Sagitta to discriminate between positive and negative charge



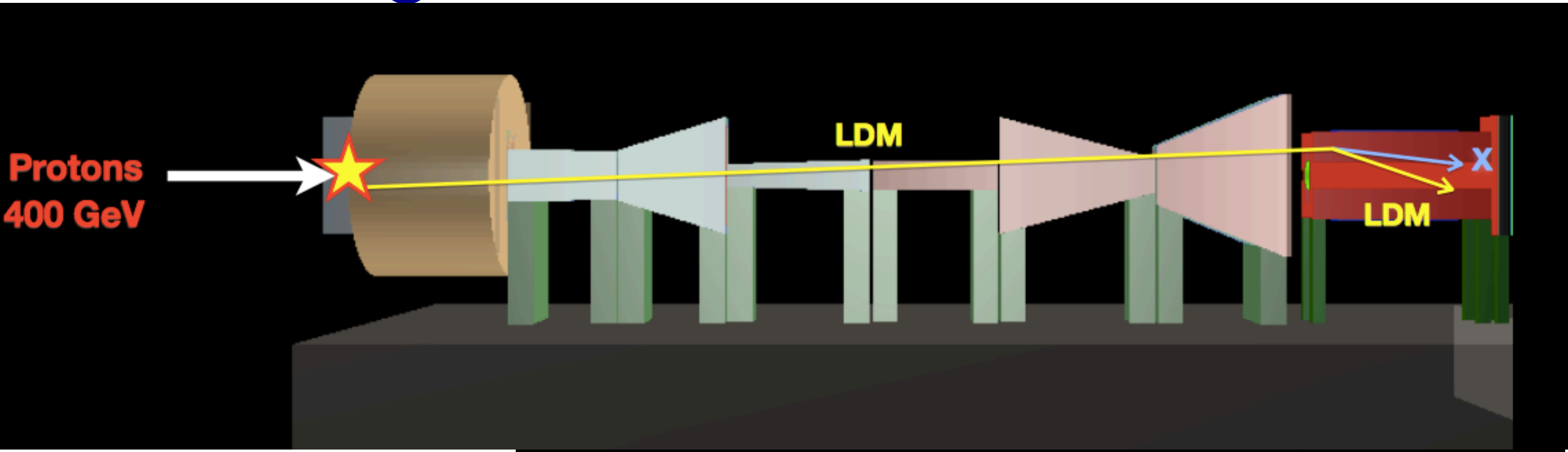
NIM A 592 (2008) 56–62



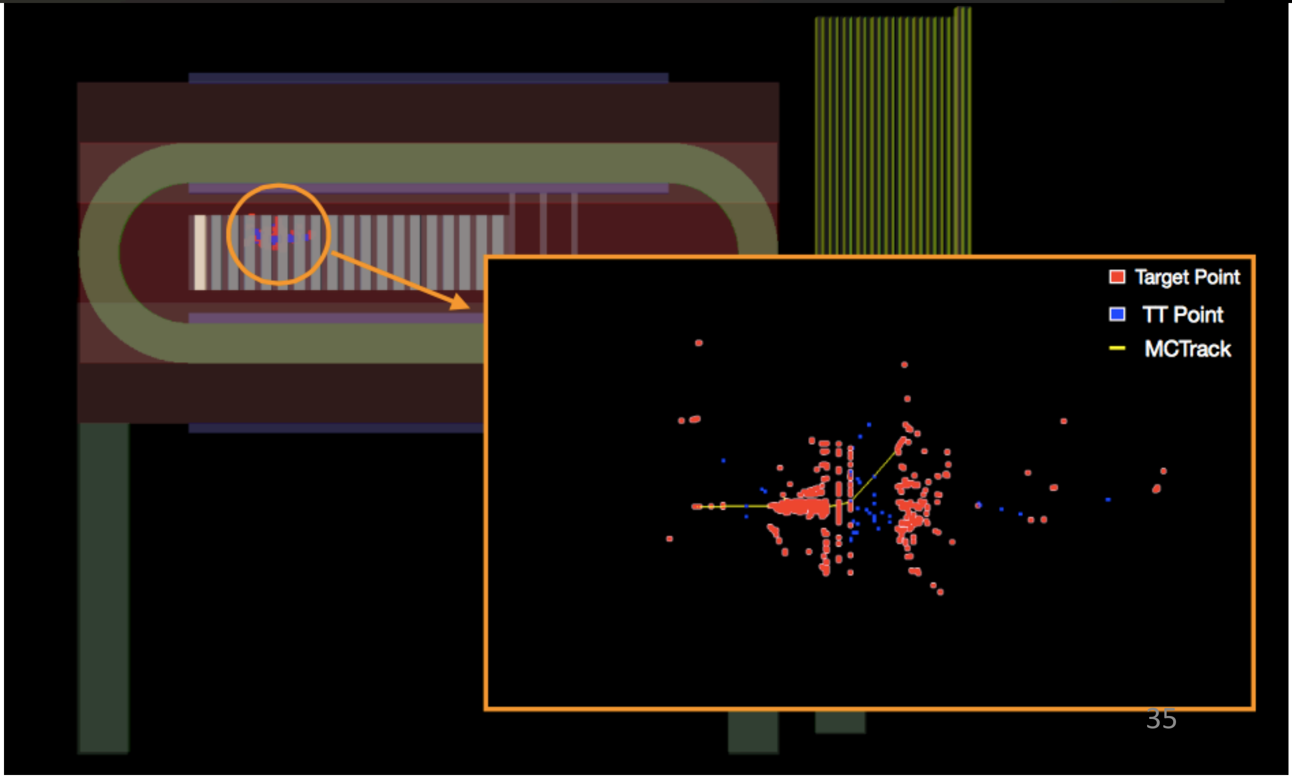
Performances to be achieved

- charge measured up to 10 GeV/c (3 sigma level)
- $\Delta p/p < 20\%$ up to 12 GeV/c

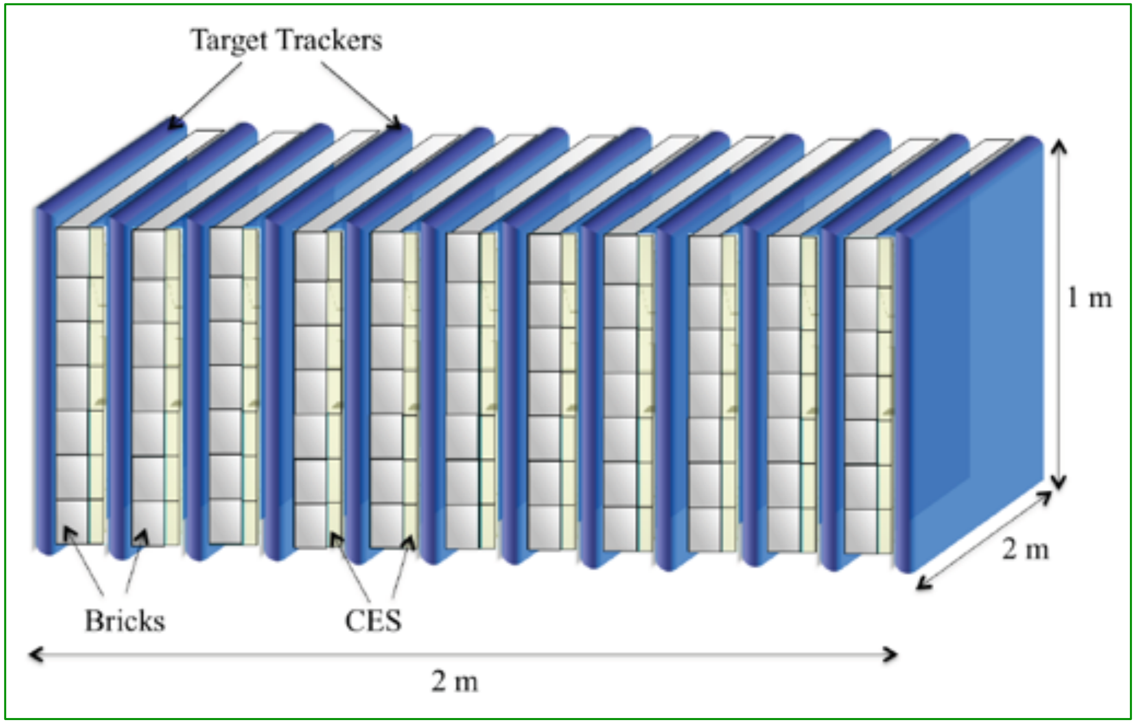
Light dark matter detection

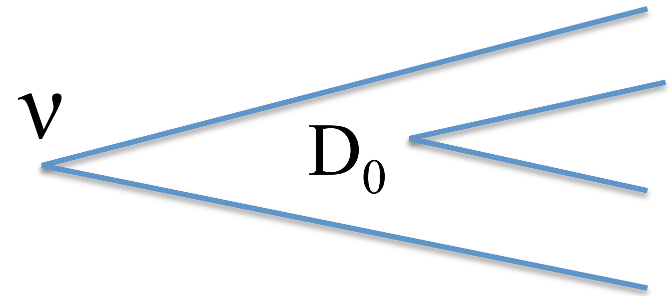


$$\chi e^- \to \chi e^-$$



THE TARGET TRACKER





- 12 target tracker (TT) planes interleaving the 11 brick walls
- first TT plane used as veto
- Transverse size ~ 2x1 m^2

FEATURES

- Provide time stamp
- Link muon track information from the target to the magnetic spectrometer

REQUIREMENTS

- Operate in 1T field
- X-Y position resolution < 100 μm
- high efficiency (>99%) for angles up to 1 rad

TARGET TRACKER PLANES

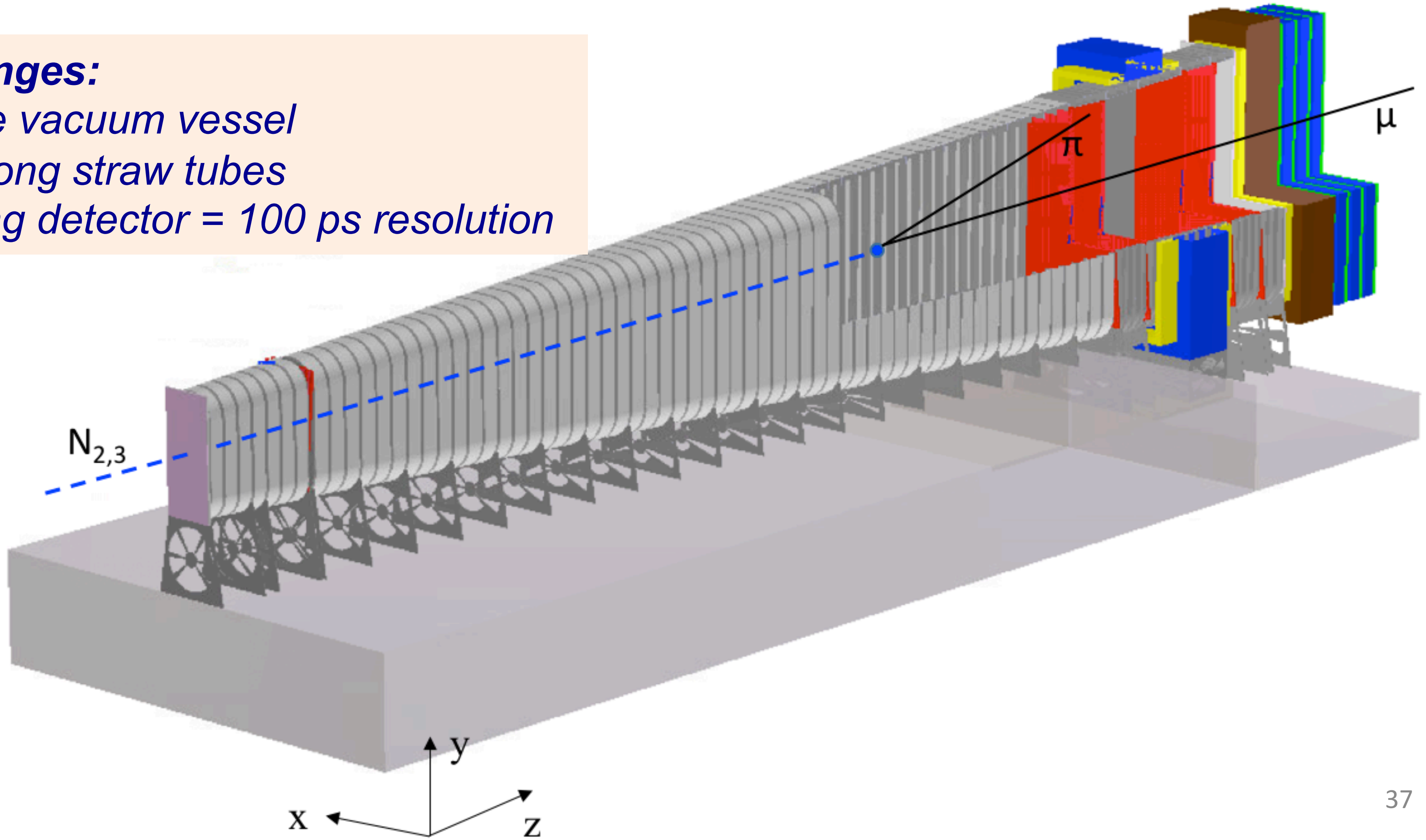
POSSIBLE OPTIONS

- Scintillating fibre trackers
- Micro-pattern gas detectors (GEM, Micromegas)

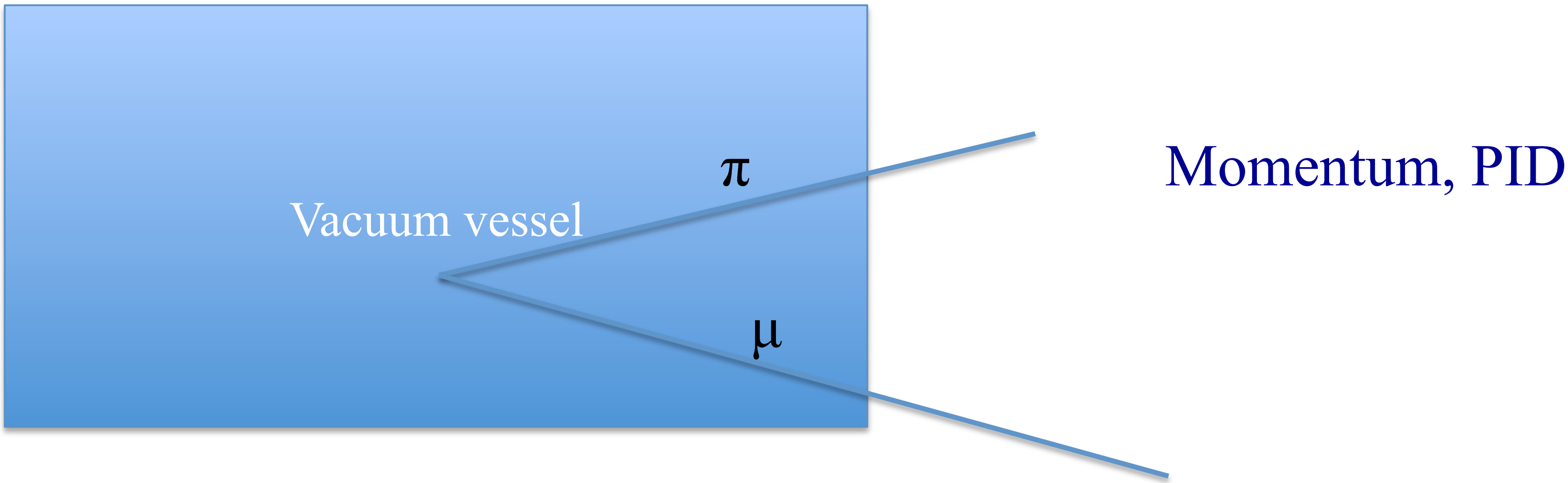
Hidden sector detector concept

✓ *Reconstruction of HS decays in all possible final states*
Long decay volume protected by various Veto Taggers, Magnetic Spectrometer followed by the Timing Detector, and Calorimeters and Muon systems.
All heavy infrastructure is at distance to reduce neutrino / muon interactions in proximity of the detector

Challenges:
- *Large vacuum vessel*
- *5 m long straw tubes*
- *Timing detector = 100 ps resolution*



Signal features

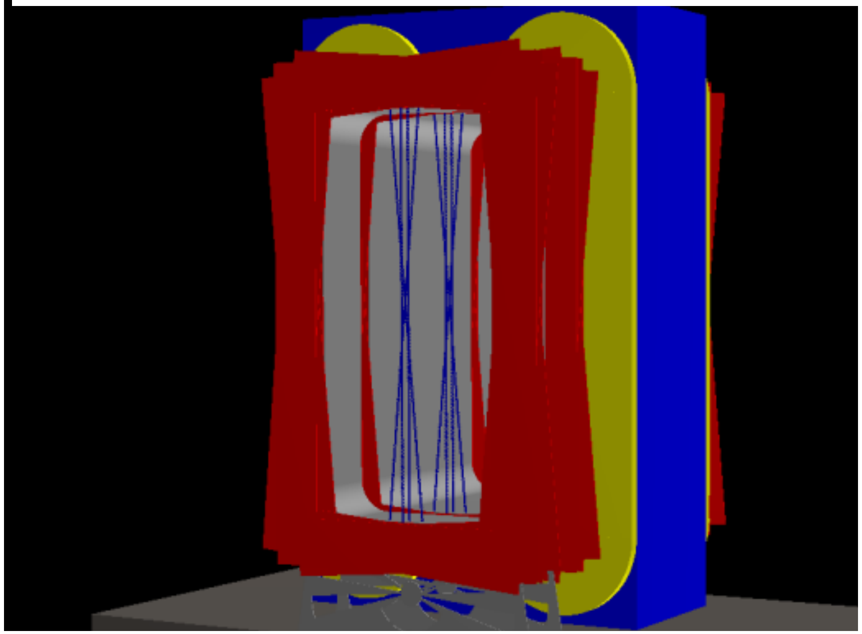


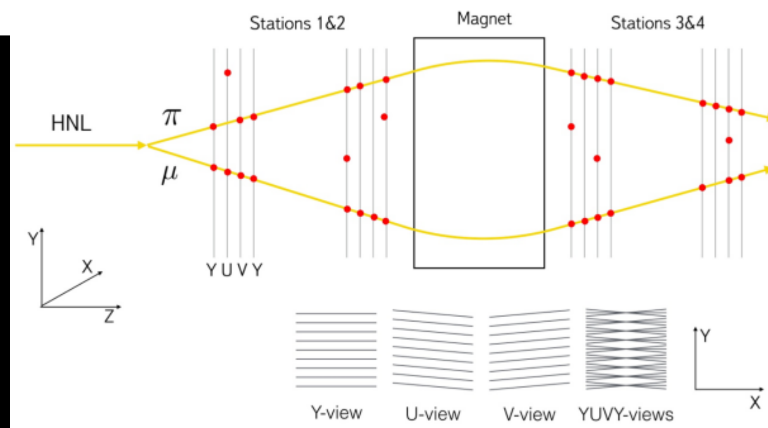
- Background is reduced by:
    - IP cut
    - Invariant mass
- Important to
    - Measure precisely the momentum
    - Identify particles
- Reduce combinatorial background by precise timing

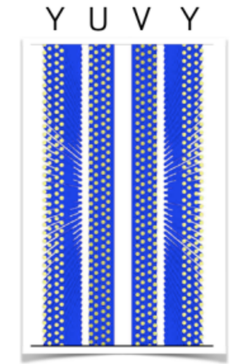
Momentum measurement

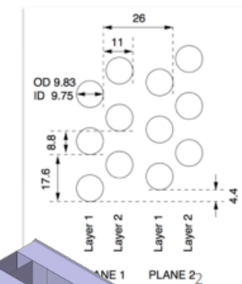
- *material budget per station 0.5% X_0*
- *position resolution 120 μm per straw, 8 hits per station on average*

Straw Tracker

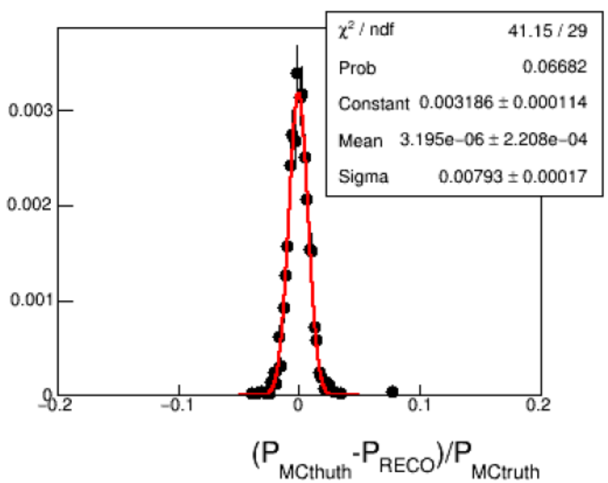


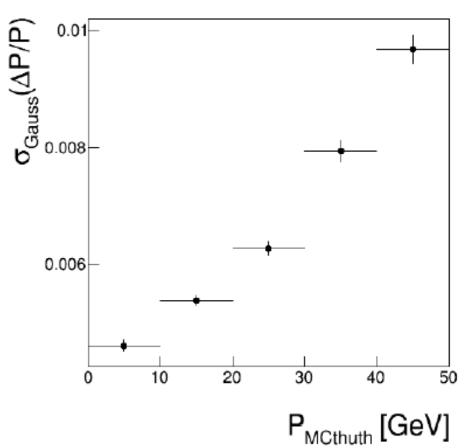


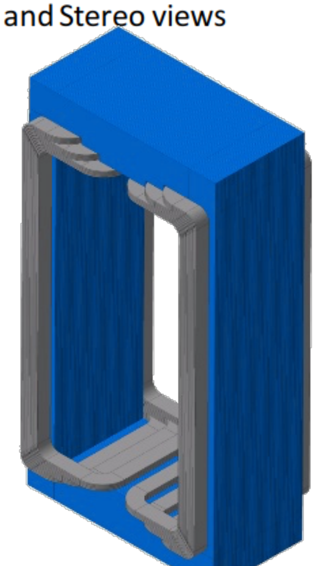


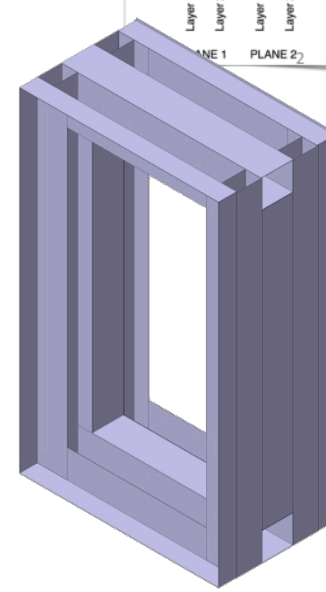


- 2 stations before and after the magnet
- 4 views in each station: 2 Y-views and 2 Stereo-views
- 4 straw tube layers in each view
- $\pm 5^o$ between Y and Stereo views





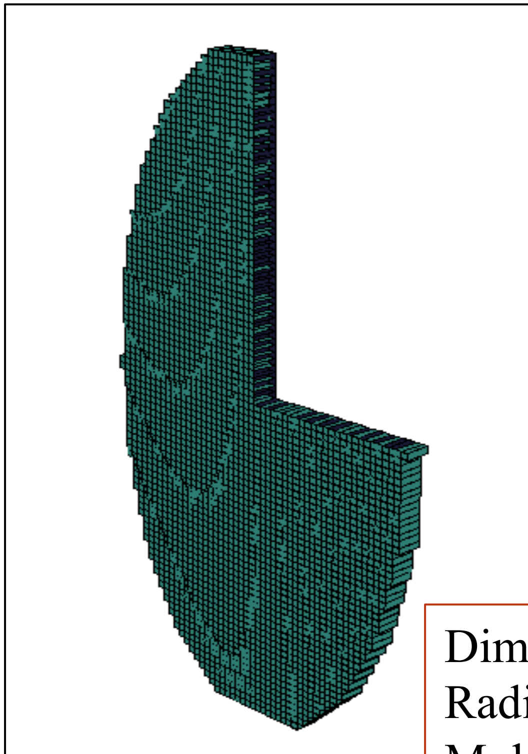


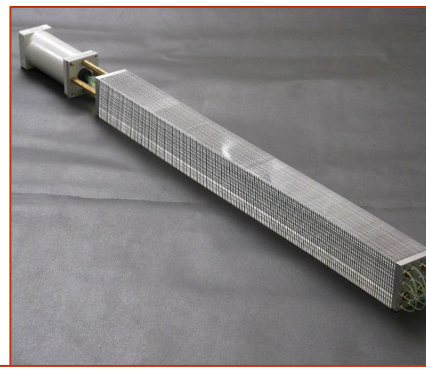


Calorimeters

ECAL

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

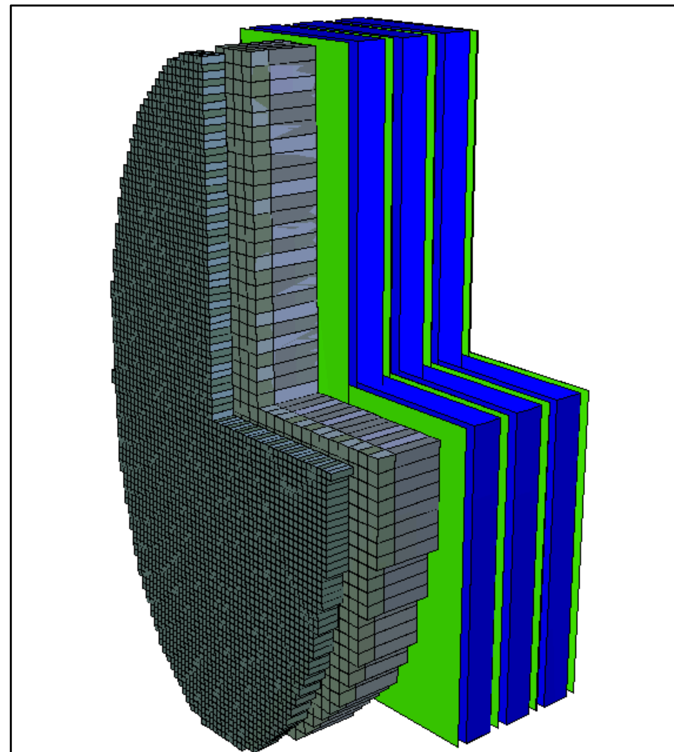




Dimensions	60x60 mm^2
Radiation length	17 mm
Moliere radius	36 mm
Radiation thickness	25 X_0
Scintillator thickness	1.5 mm
Lead thickness	0.8 mm
Energy resolution	1%

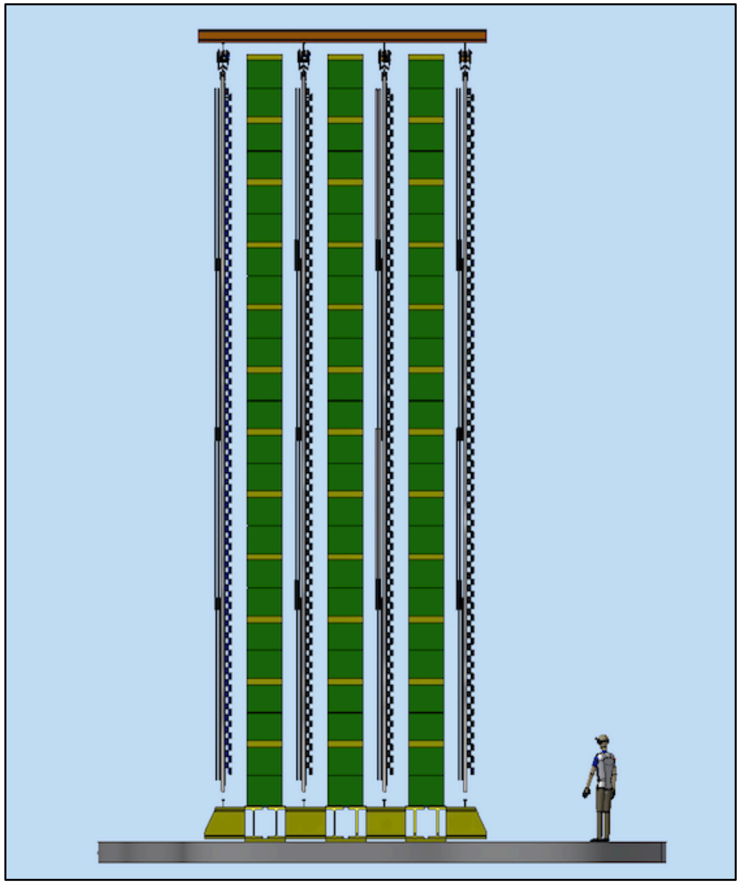
HCAL

- 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



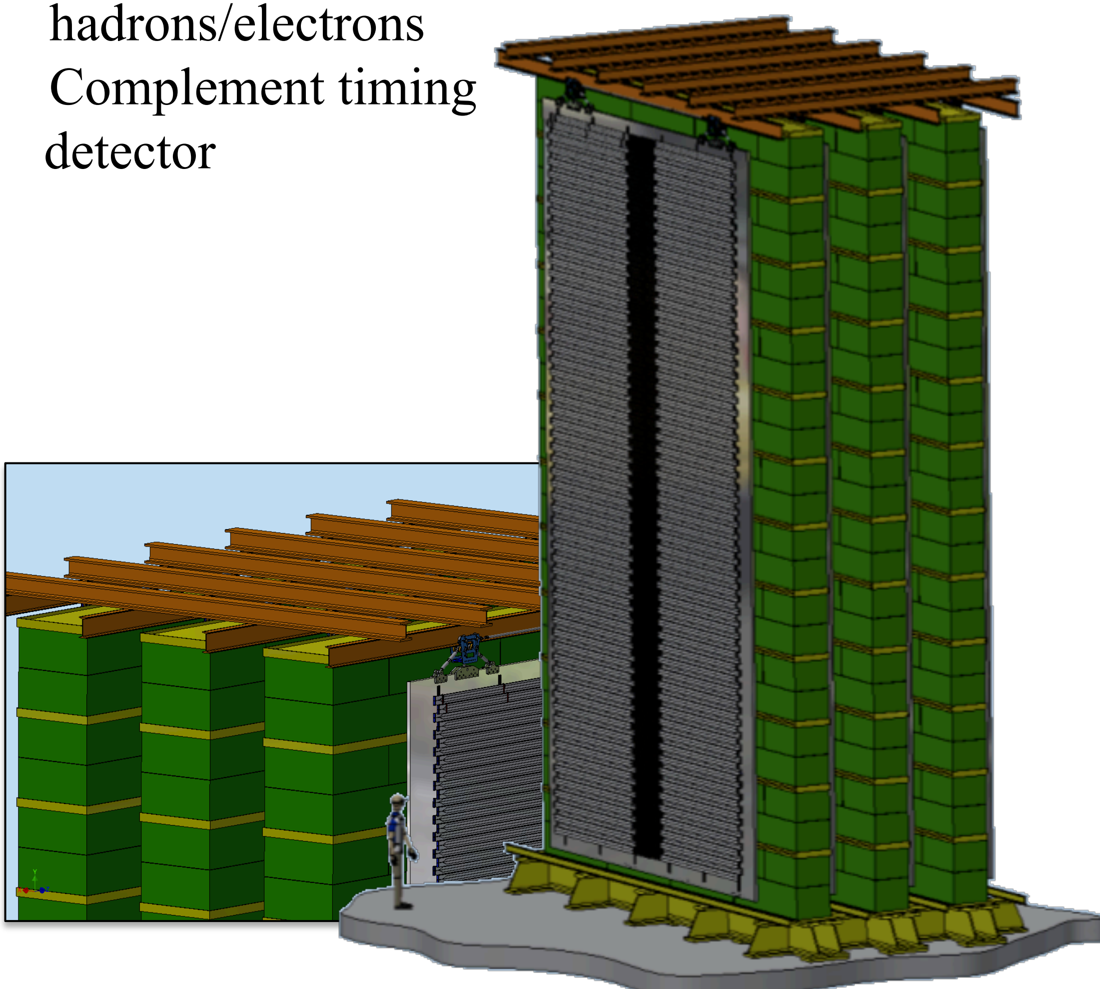
Muon System

Based on scintillating bars, with WLS fibers and SiPM readout



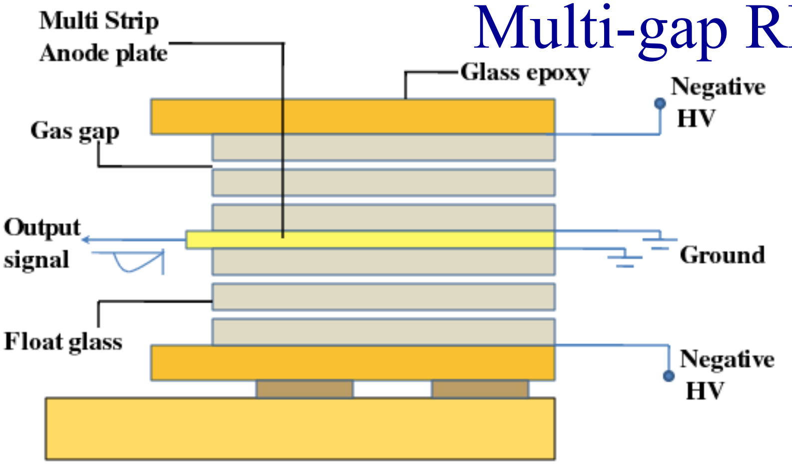
Technical Proposal (preliminary design)
- 4 active stations
- transverse dimensions: 1200x600 cm^2
- x,y view
- 3380 bars, 5x300x2 cm^3/each
- 7760 FEE channels
- 1000 tons of iron filters

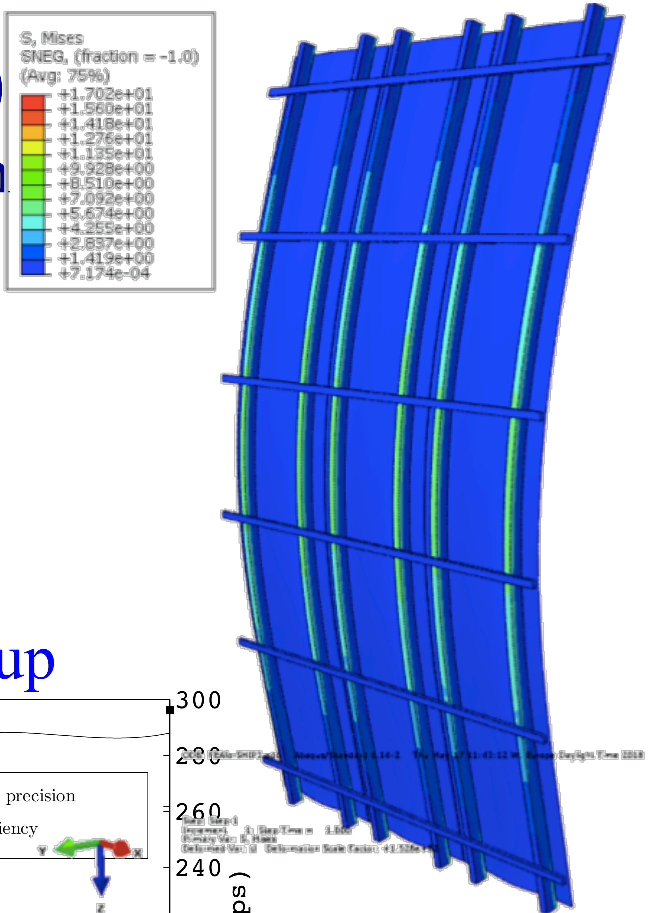
Requirements:
- High-efficiency identification of muons in the final state
- Separation between muons and hadrons/electrons
- Complement timing detector



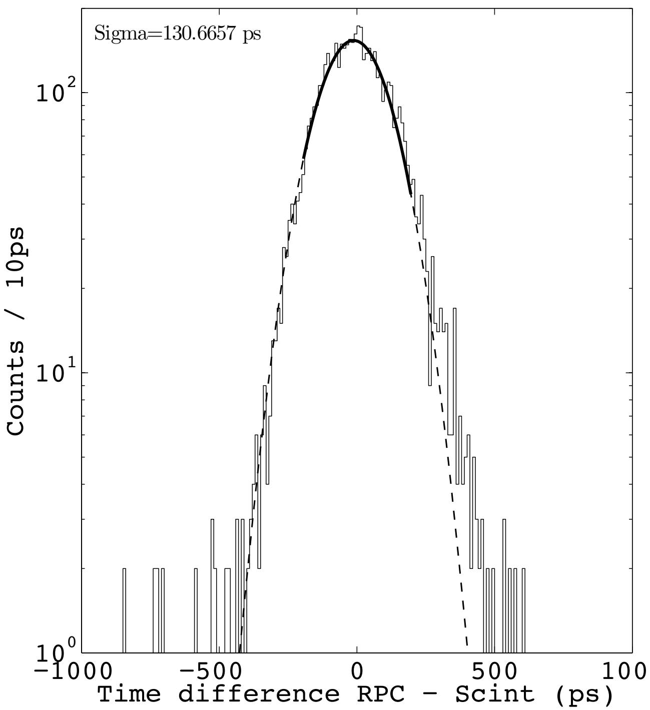
Timing detector (~100ps)

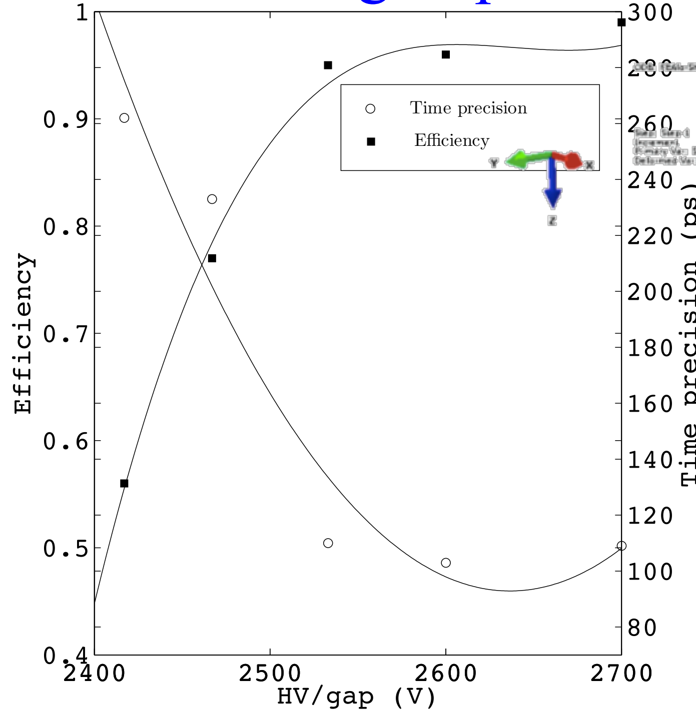
Multi-gap RPC is one option



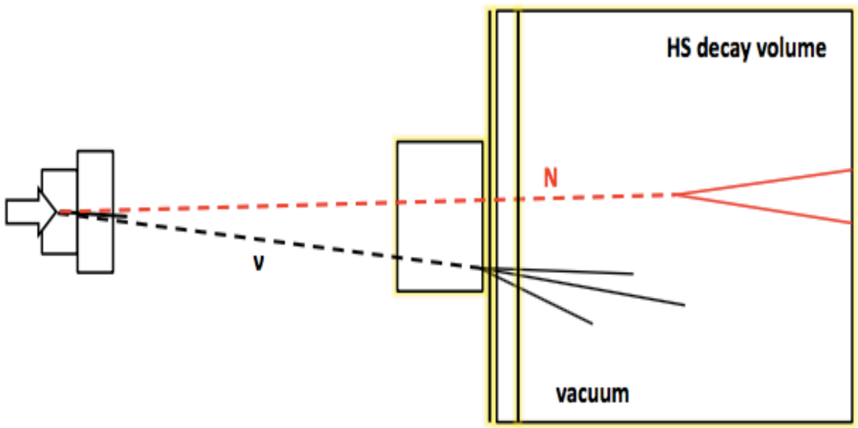


Measurements by the Coimbra group

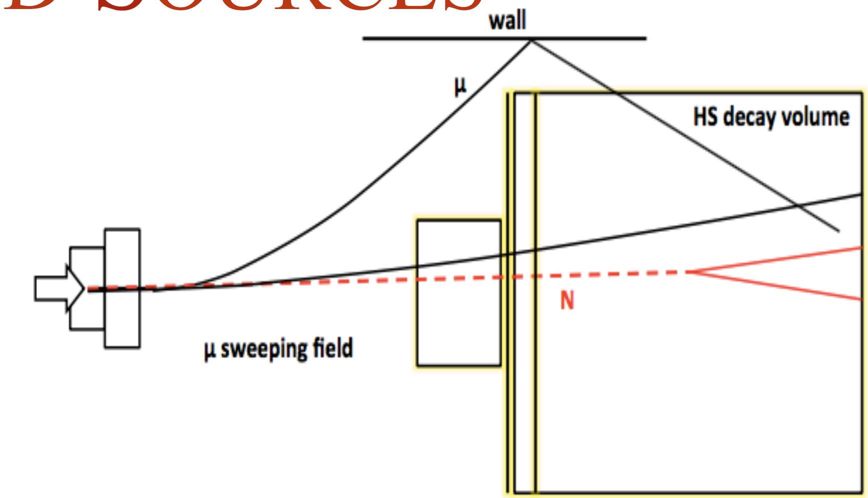




Background Sources

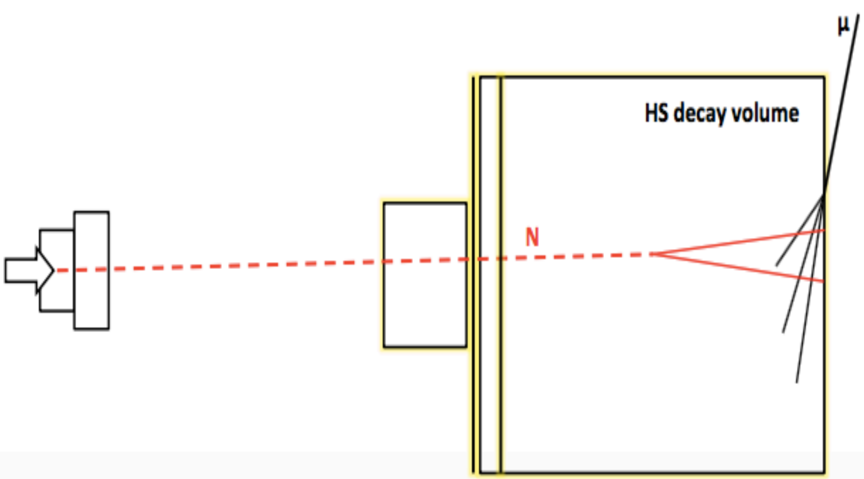


Neutrino interactions

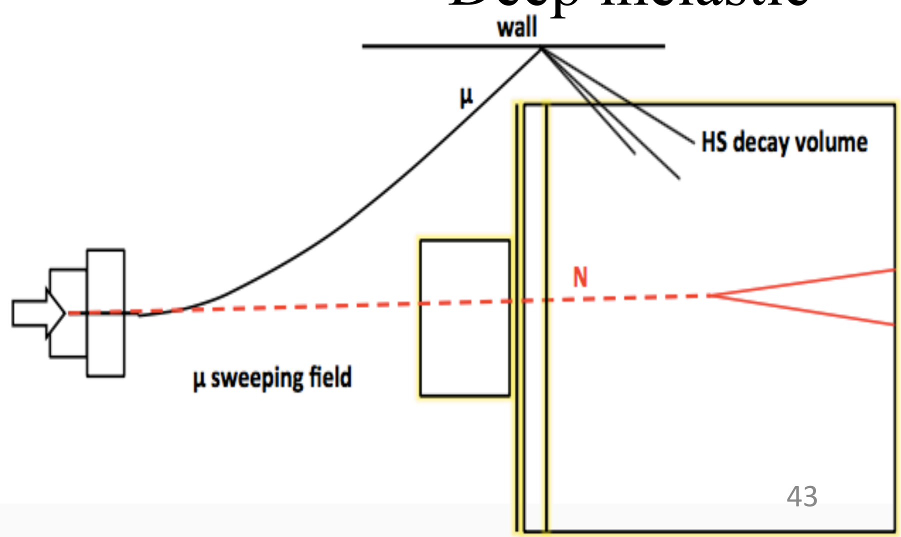


Muon combinatorial

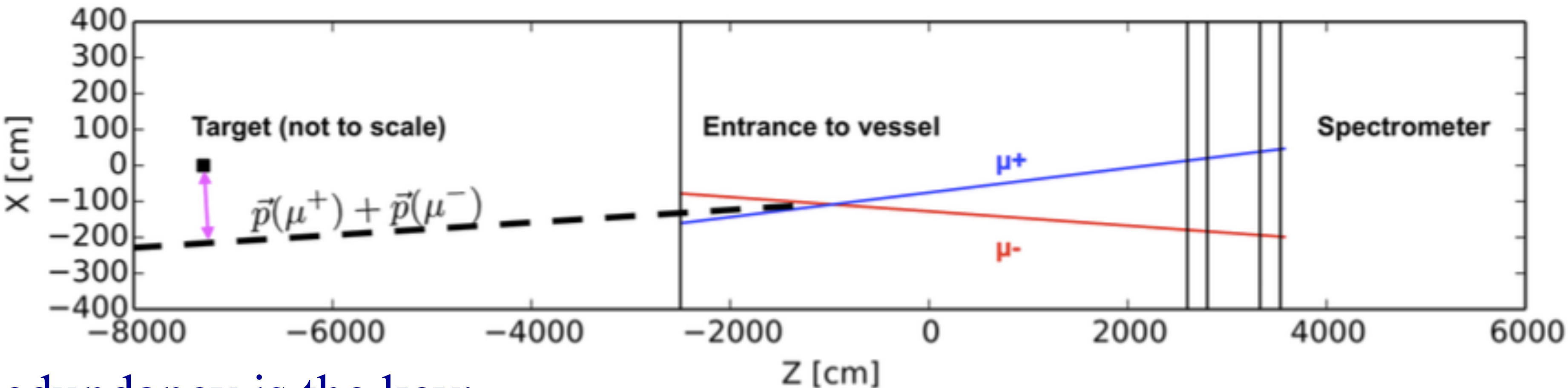
Cosmic-ray muon



Deep inelastic



BACKGROUND STUDIES



Redundancy is the key:

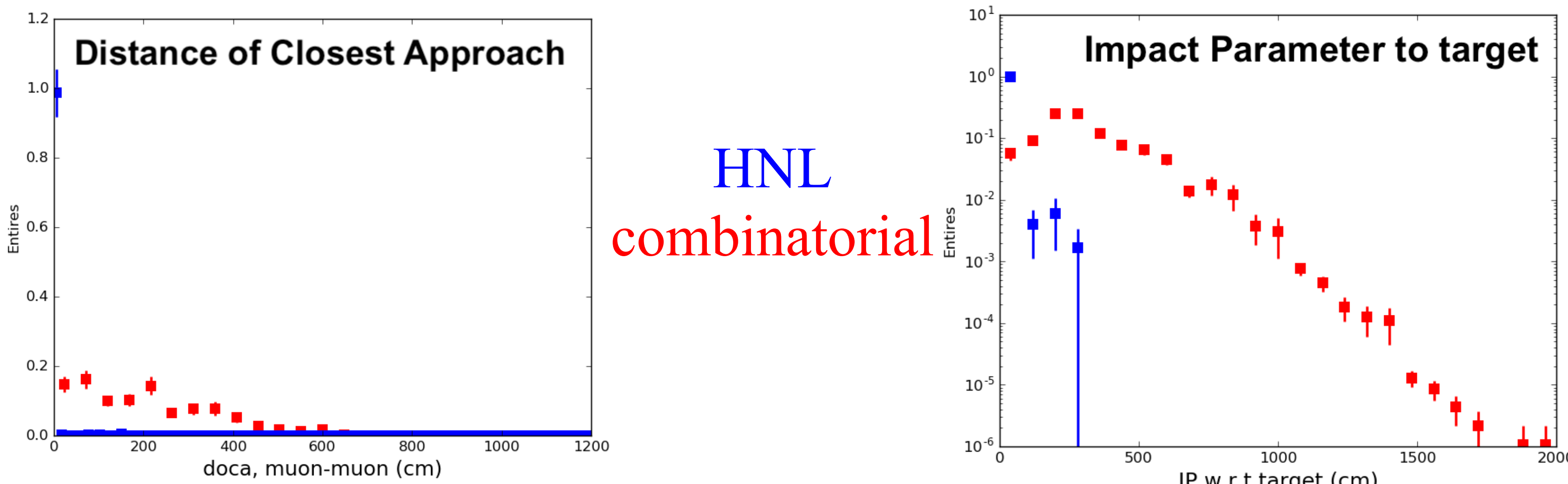
1. Combining momentum and vertex information to reject candidates not originating from collision points
2. Combine veto sub-systems where background typically leave several hits → very effective veto
   1. Surrounding the vessel
   2. Veto at the the vessel entrance
3. Timing information between candidate tracks (σ =100ps)

As a result

- Zero background experiment
- Well defined control regions to measure background

μ COMBINATORIAL

- Active muon shield reduces the muon rate reaching the spectrometer from 10^{11} Hz down to 10^{4} Hz



- Loose set of selection cuts to remove the background , while being efficient on the signal
  - Momentum, IP, DOCA
  - Veto systems
  - Timing information

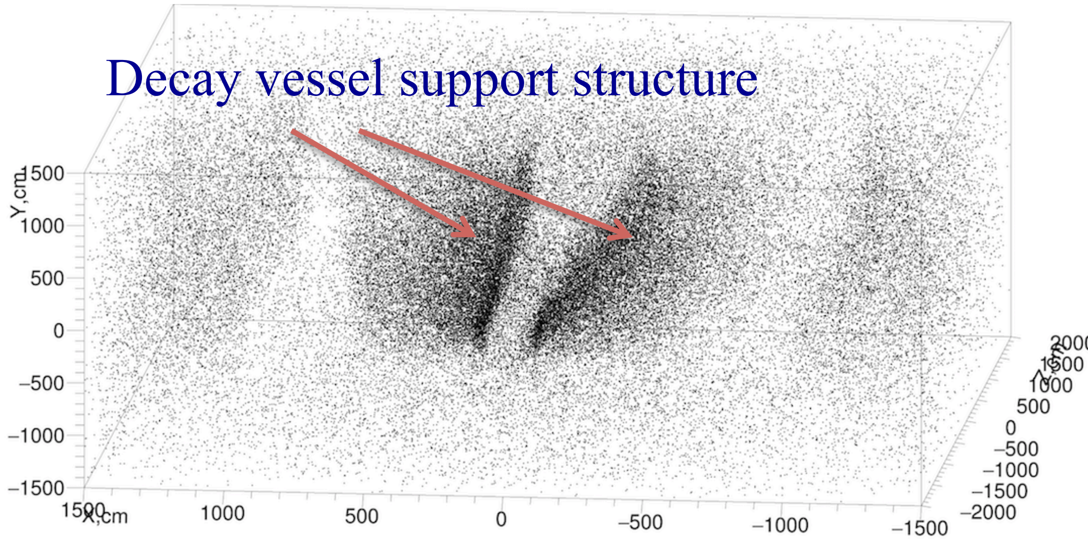
  As a result

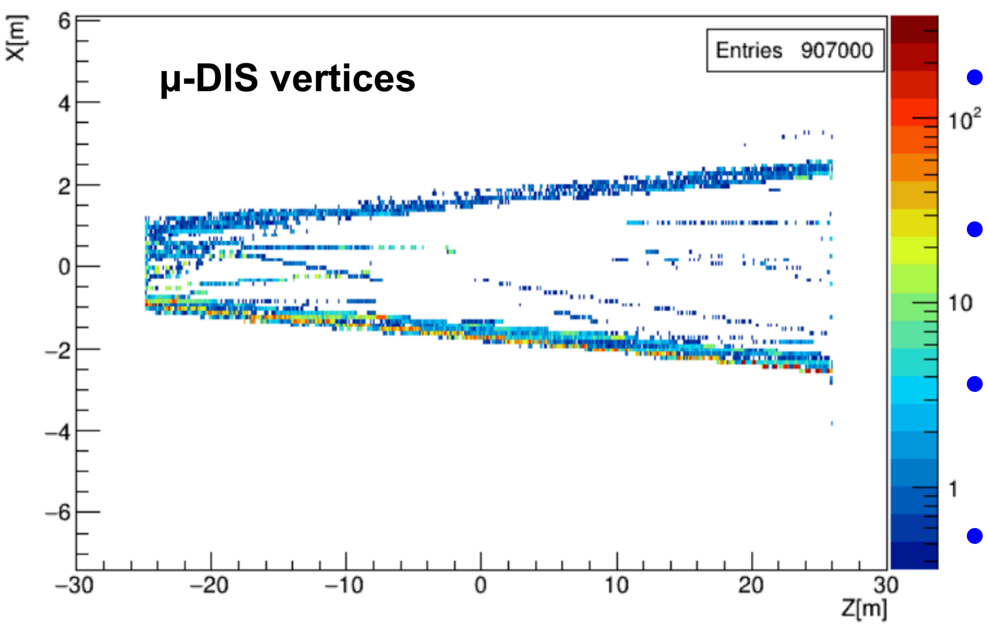
  - 10^{-4} combinatorial muons in the SHiP lifetime

NEUTRINO AND μ-DIS INTERACTIONS

All neutrino interactions along the SHiP lifetime

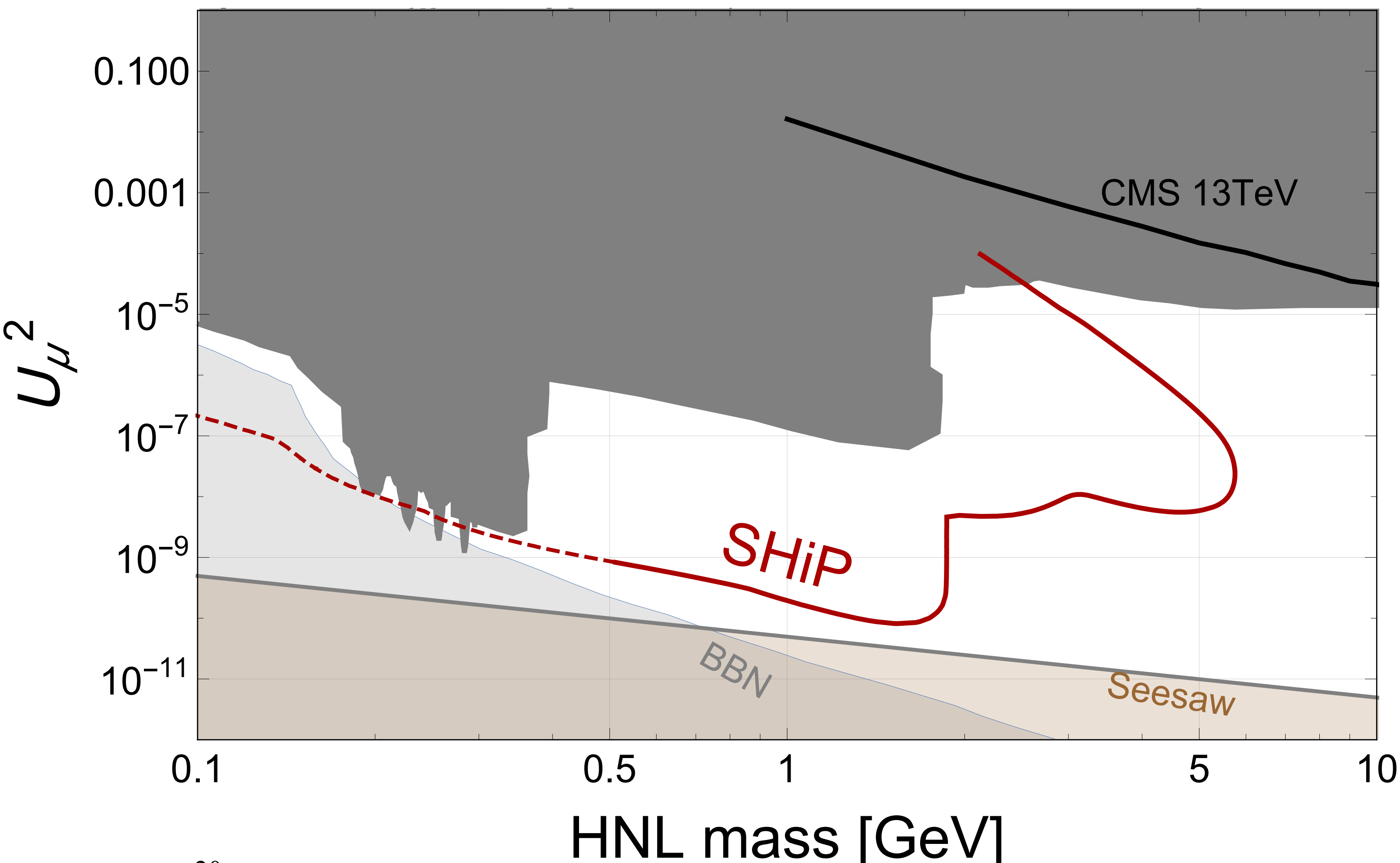
- Neutrinos induced V^0s in the decay vessel structure
- Particle id, vertex position and veto systems
- → 0 background events





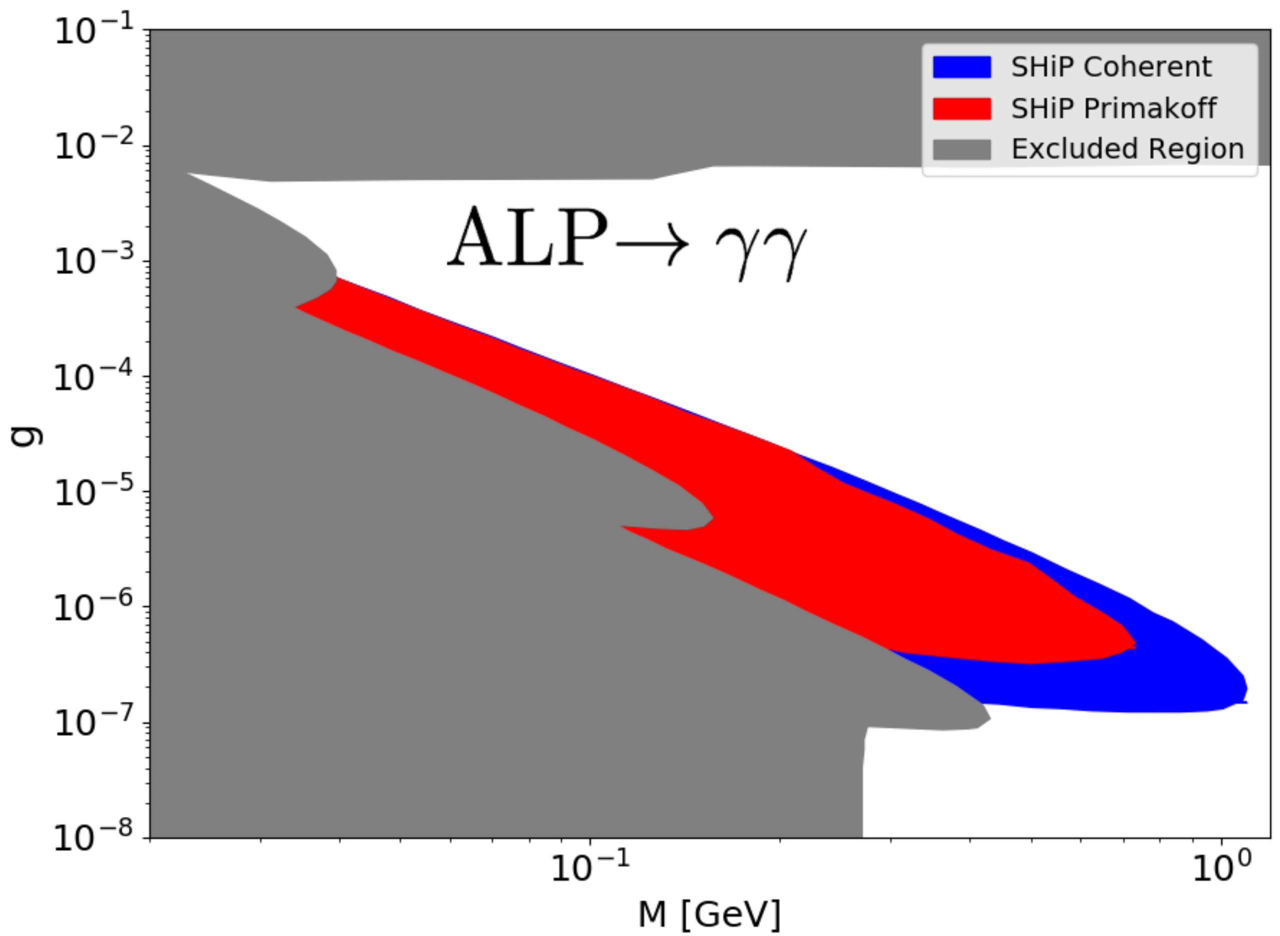
- Difficult source are μ-DIS with the decay vessel producing V^0s
- Produced a sample corresponding to 1/40 of lifetime
- Veto detector and loose selection on momentum, IP, DOCA
- → < 10^{-3} DIS events in SHiP lifetime

SHiP Sensitivity to Heavy Neutral Leptons



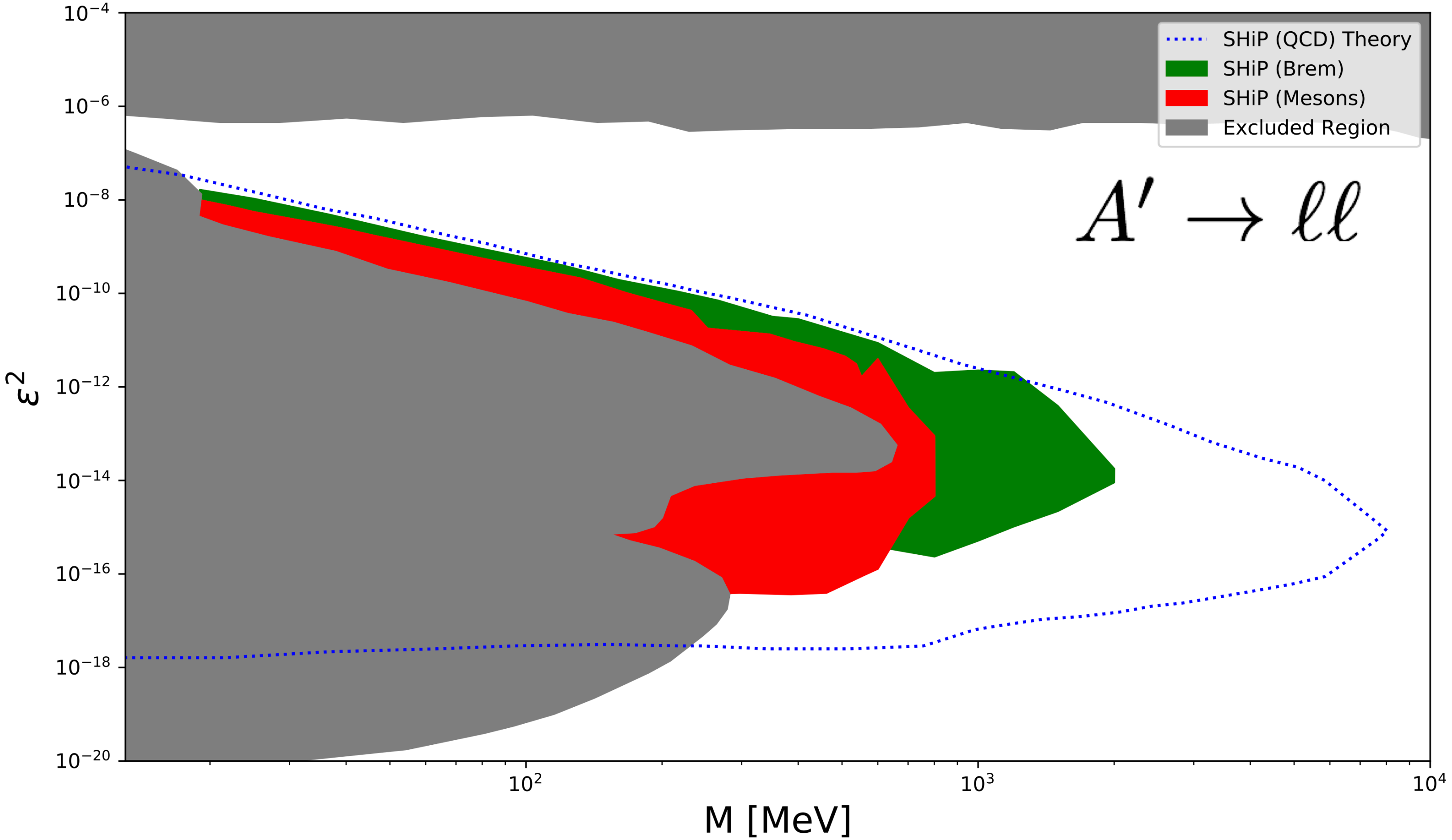
Based on $2x10^{20}$ pot
@400 GeV in 5 years

SHiP Sensitivity to Axion-Like Particles



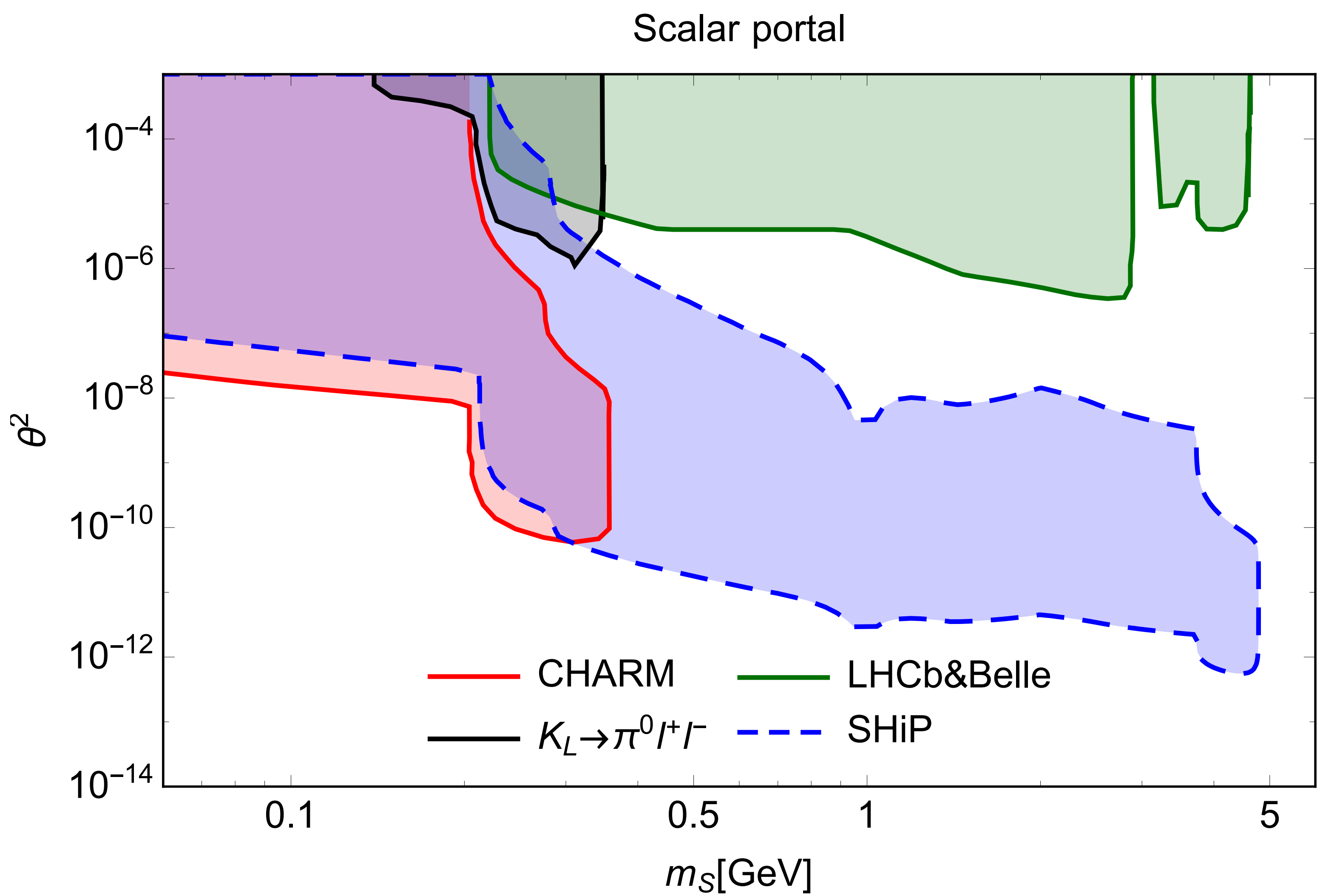
Based on $2x10^{20}$ pot
@400 GeV in 5 years

SHiP Sensitivity to Dark Photons



Based on $2x10^{20}$ pot
@400 GeV in 5 years

SHiP Sensitivity to Dark Scalars

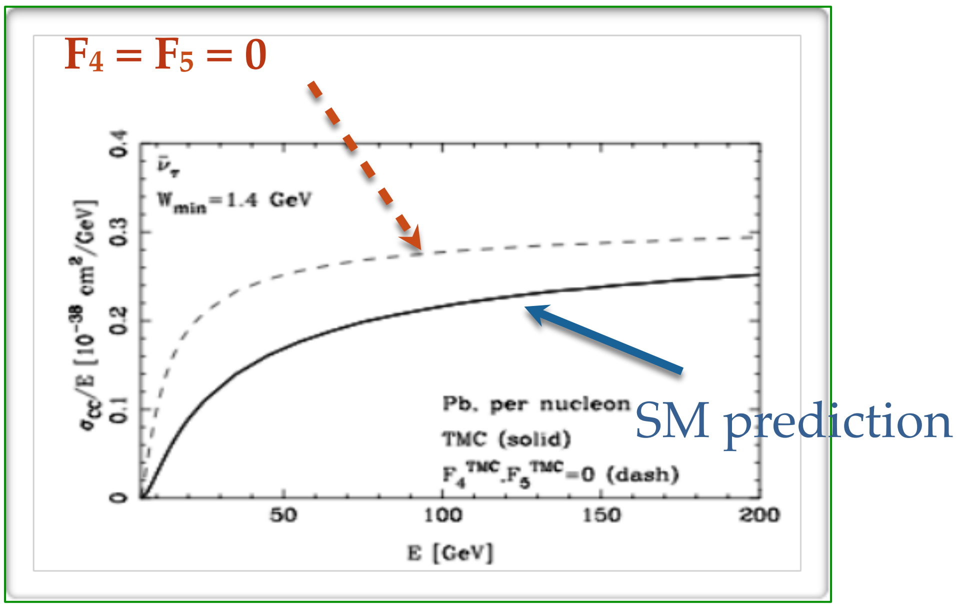


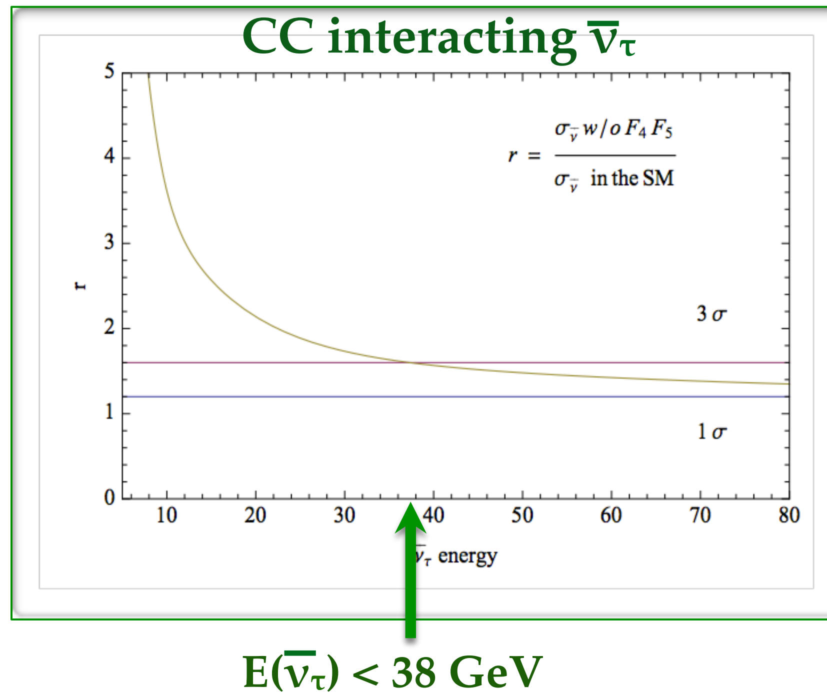
Based on 2×10^{20} pot
@400 GeV in 5 years

F_4 and F_5 Structure Functions

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

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



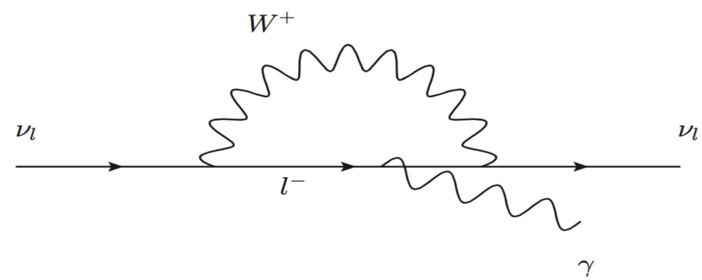


- At LO $F_4 = 0$, $2xF_5 = F_2$
- At NLO $F_4 \sim 1\%$ at 10 GeV

Tau Neutrino Magnetic Moment

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

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

No interference as it involves a spin flip of the neutrino

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

IN SHiP

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

SIGNAL SELECTION

- $\theta_{\nu-e} < 30\, mrad$
- $E_e > 1$ GeV

BACKGROUND PROCESSES

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

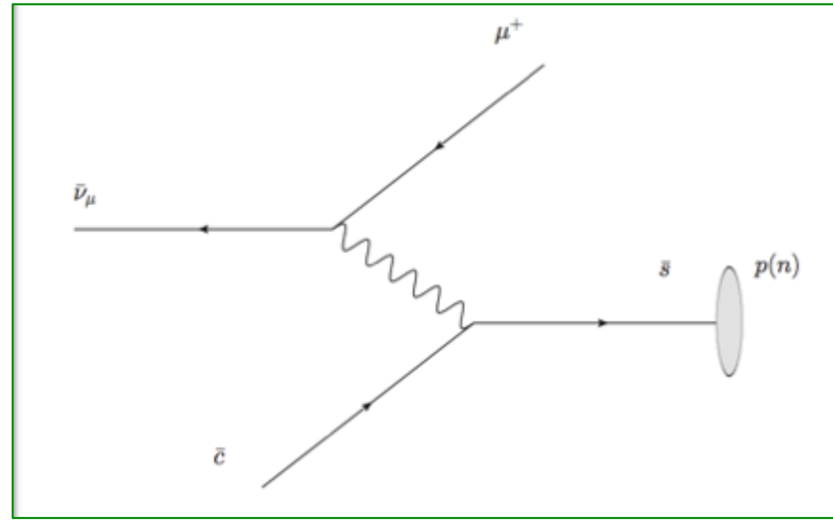
Assuming 5% systematics from DIS measurements

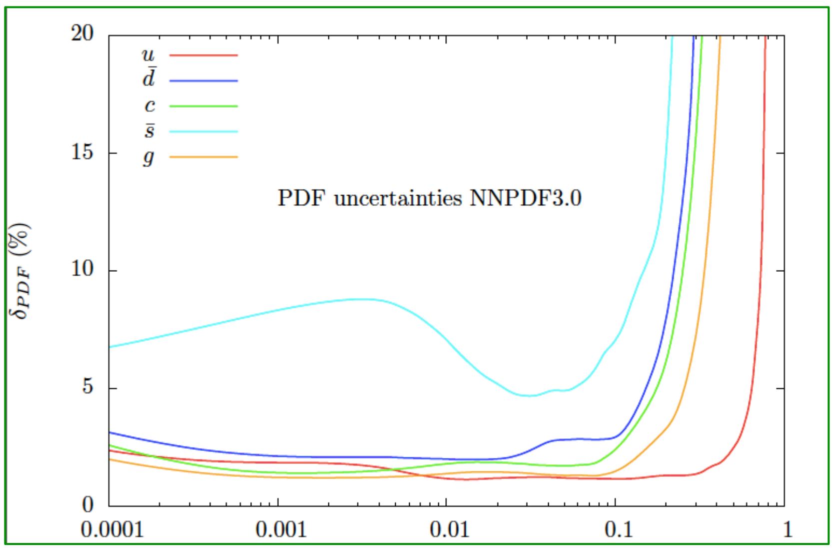
SHiP can explore a region down to

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

STRANGE QUARK NUCLEON CONTENT

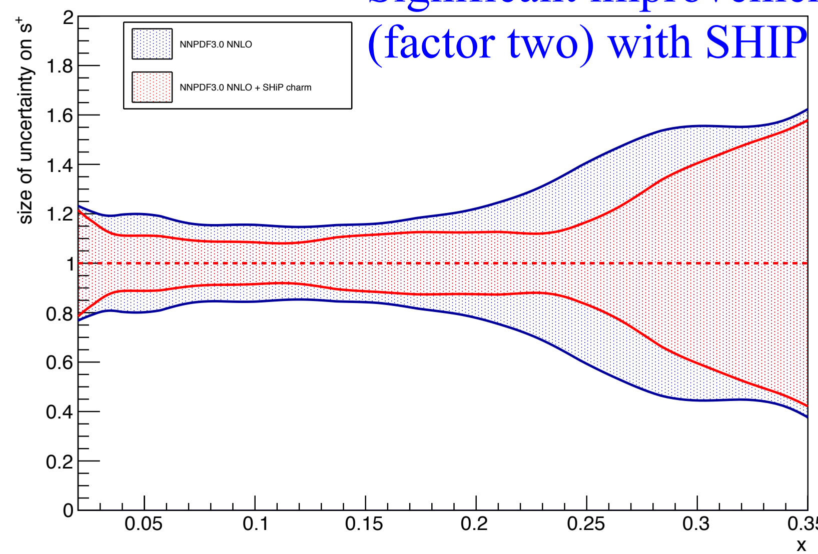
- Charmed hadron production in anti-neutrino interactions selects anti-strange quark in the nucleon
- Strangeness important for precision SM tests and for BSM searches
- W boson production at 14 TeV: 80% via $u\bar{d}$ and 20% via $c\bar{s}$





Phys. Rev. D91 (2015) 113005

Fractional uncertainty of the individual parton densities $f(x;m^2_W)$ of NNPDF3.0



- Significant improvement (factor two) with SHIP data

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

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

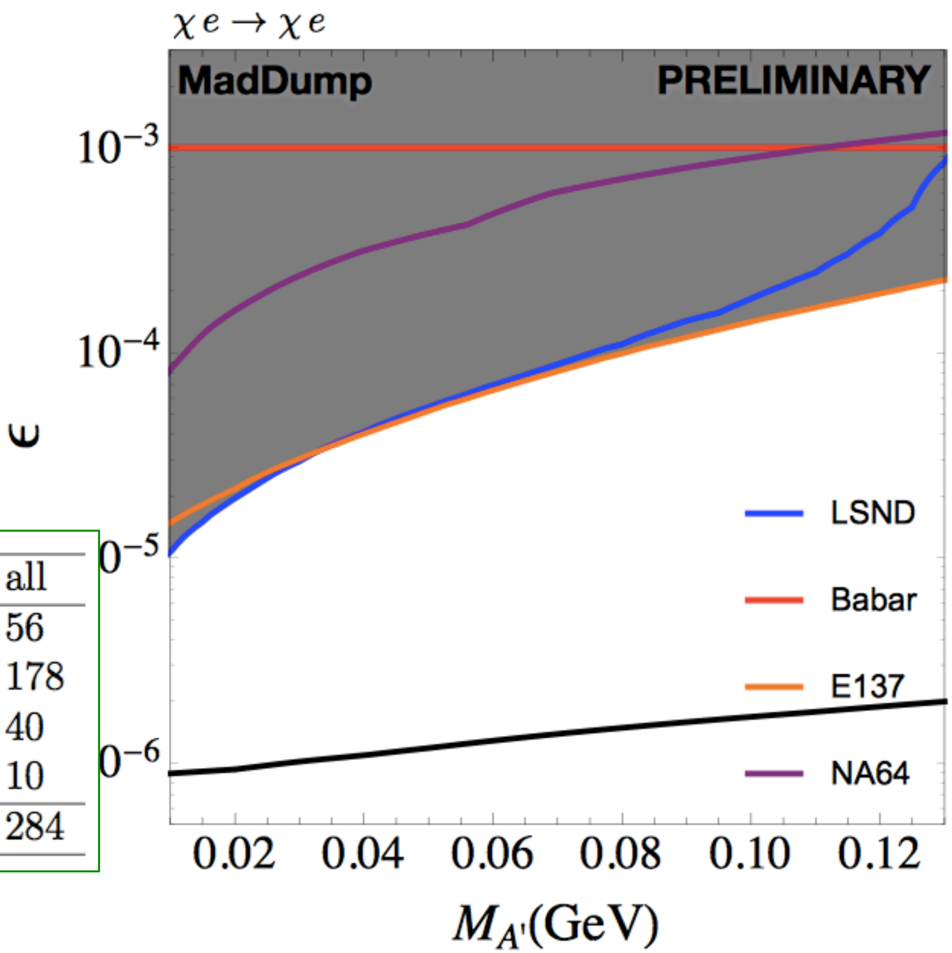
DARK MATTER SEARCH WITH THE NEUTRINO DETECTOR

SIGNAL SELECTION

$$\begin{cases} 0.01 < \theta < 0.02 \\ E < 20\ \text{GeV} \end{cases}$$

BACKGROUND PROCESSES

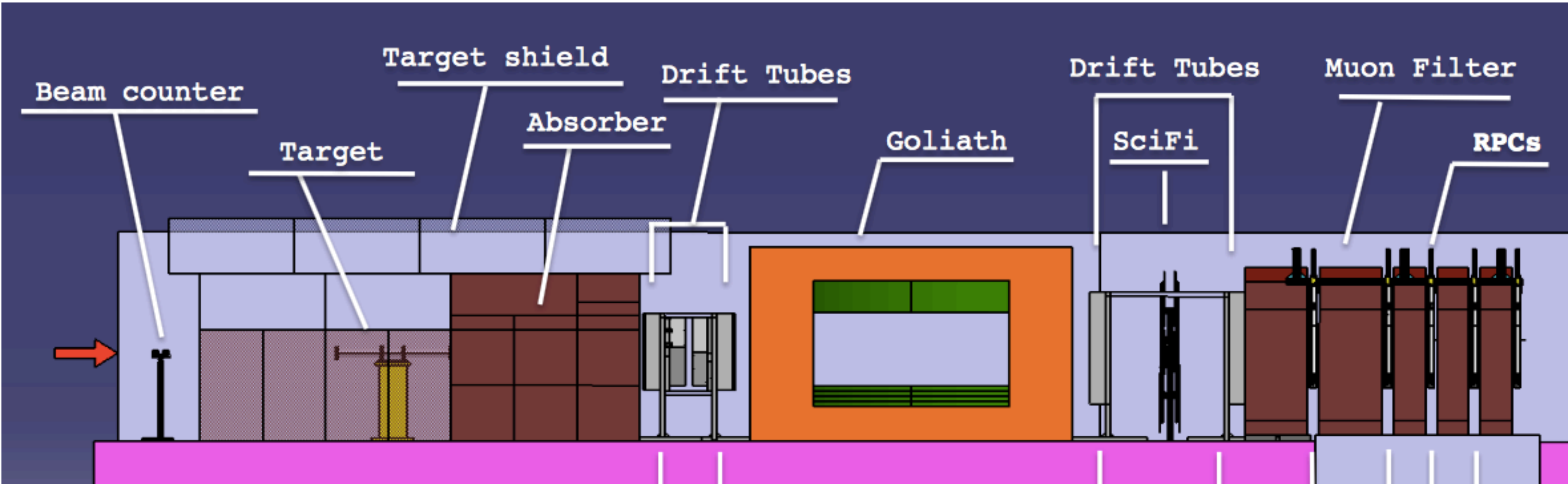
	ν_e	$\bar{\nu}_e$	ν_μ	$\bar{\nu}_\mu$	all
Elastic scattering on e^-	16	2	20	18	56
Quasi - elastic scattering	105	73			178
Resonant scattering	13	27			40
Deep inelastic scattering	3	7			10
Total	137	109	20	18	284



ϵ = dark photon coupling with e.m. current

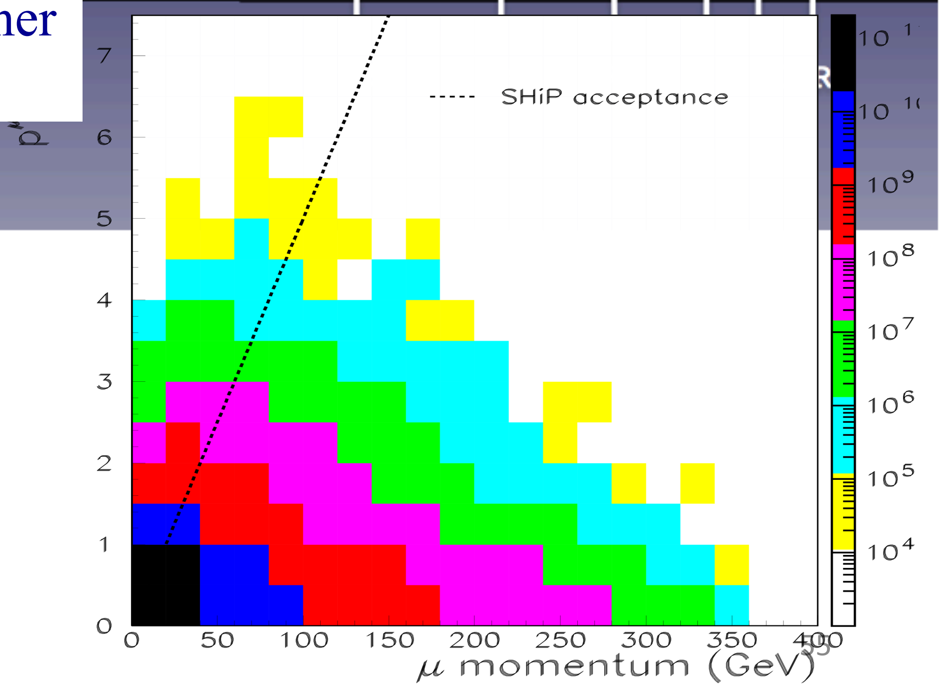
m_A = dark photon mass

Muon Flux Measurement, SPSC-EoI-016



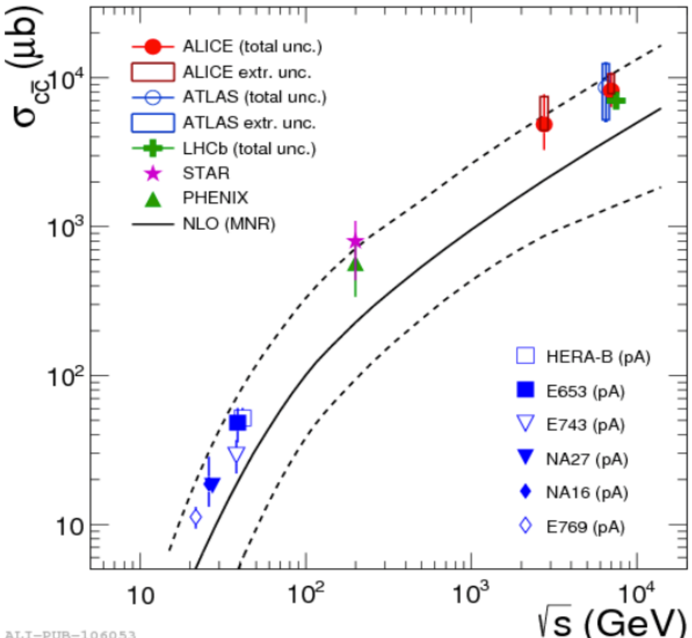
10^{11} pot → 100 events in the dangerous corner
Validate simulation

Replica of the SHiP target, TZM and W



Motivation for charm measurement

- Charm production in **proton interactions** and in **hadron cascades** in the SHiP target important for HNL normalization and ν_τ cross-section measurements



- Collection of charm hadroproduction cross-section with NLO predictions

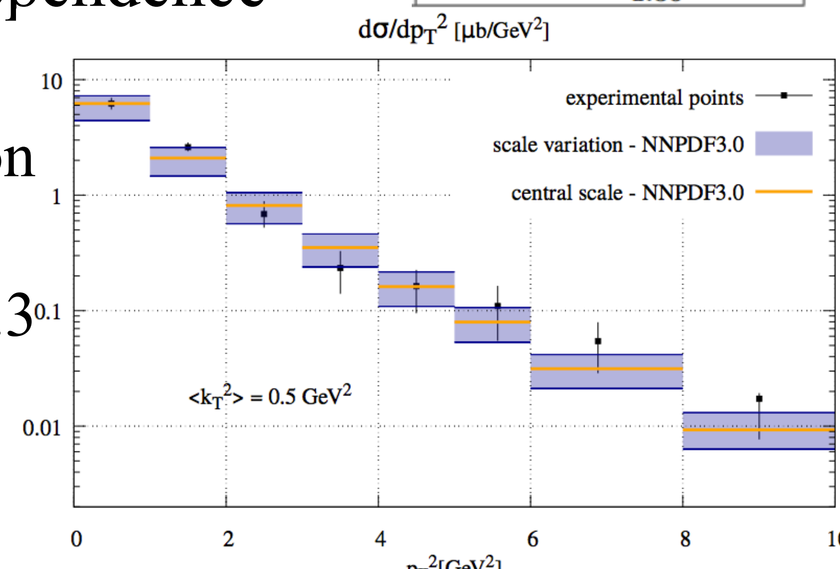
	exp NA27
$\sigma[\mu b]$	18.1 ± 1.7

th NLO $(m_c = 1.3)$
$24.3^{+80.1}_{-12.4}$

th NLO $(m_c = 1.5)$
$10.1^{+22.6}_{-4.8}$

th NLO $(m_c = 1.8)$
$3.12^{+4.86}_{-1.36}$

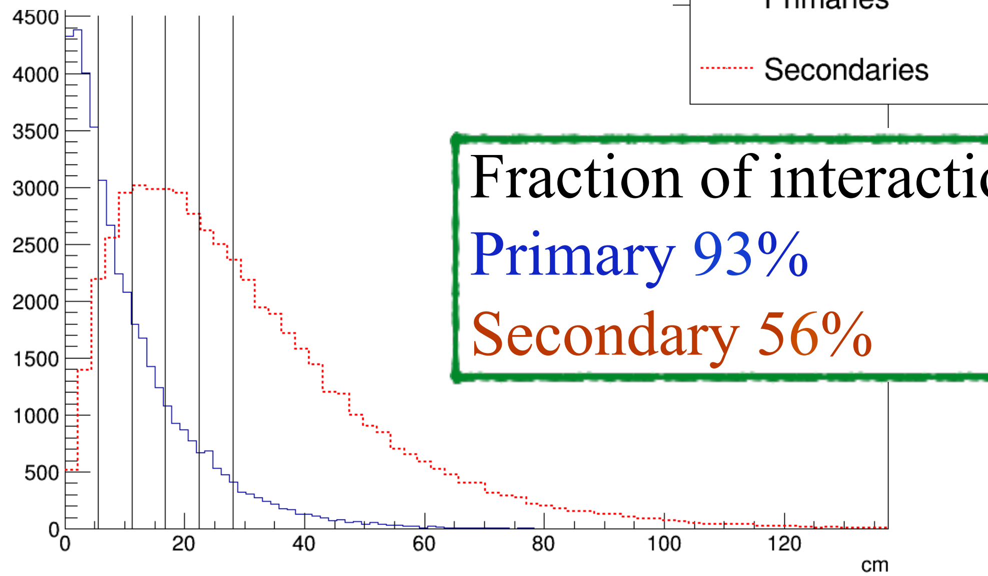
- Main source of uncertainty given by scale dependence



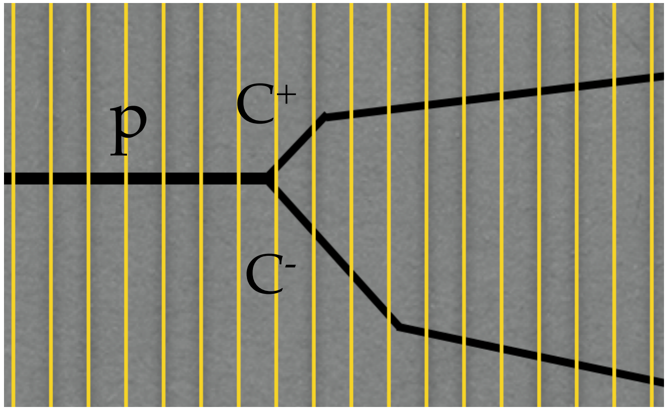
- Missing information: charm production in **hadron cascades**
- Charm yield from cascade expected 2.3 times larger than prompt contribution
- Angular and energy spectra available only for 500 GeV pions in E791

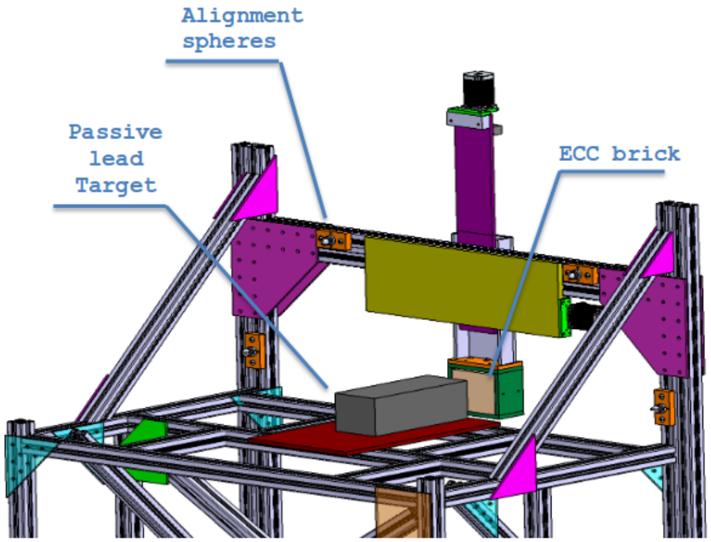
Target instrumentation

Distribution of charmed pairs

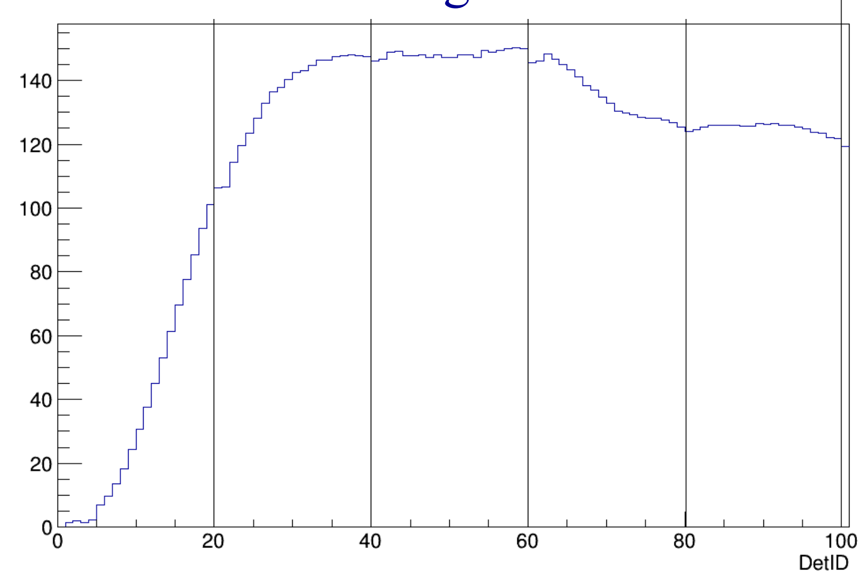


Fraction of interactions
Primary 93%
Secondary 56%

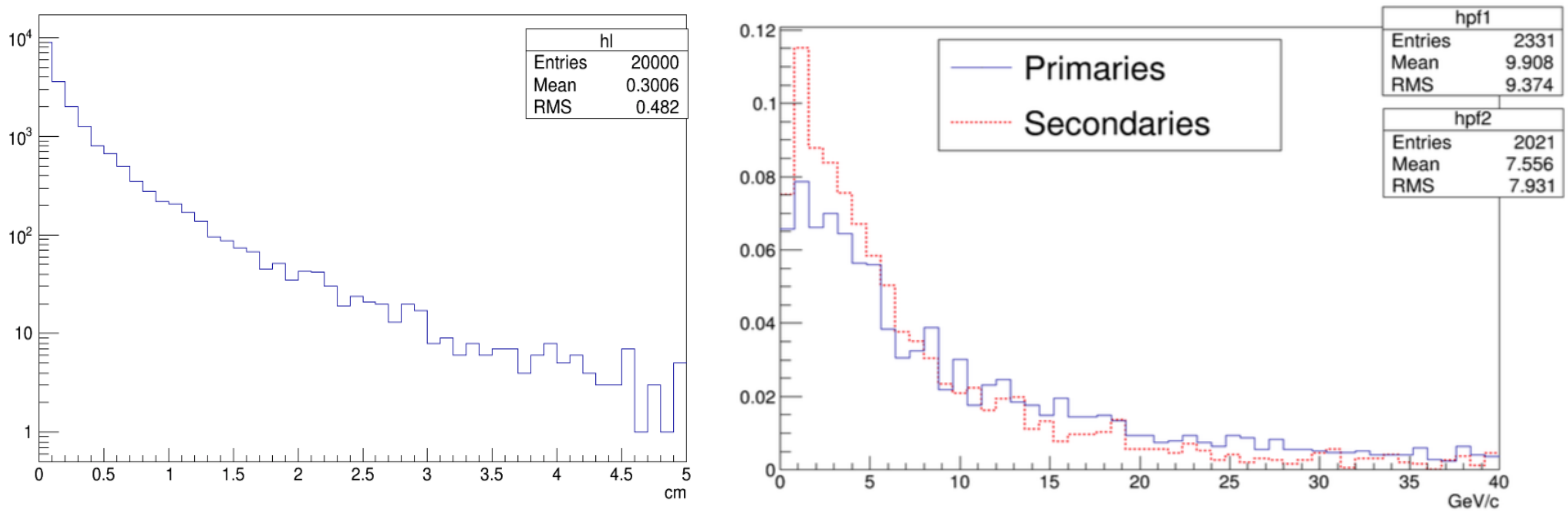




Number of particles/proton in 5 target units

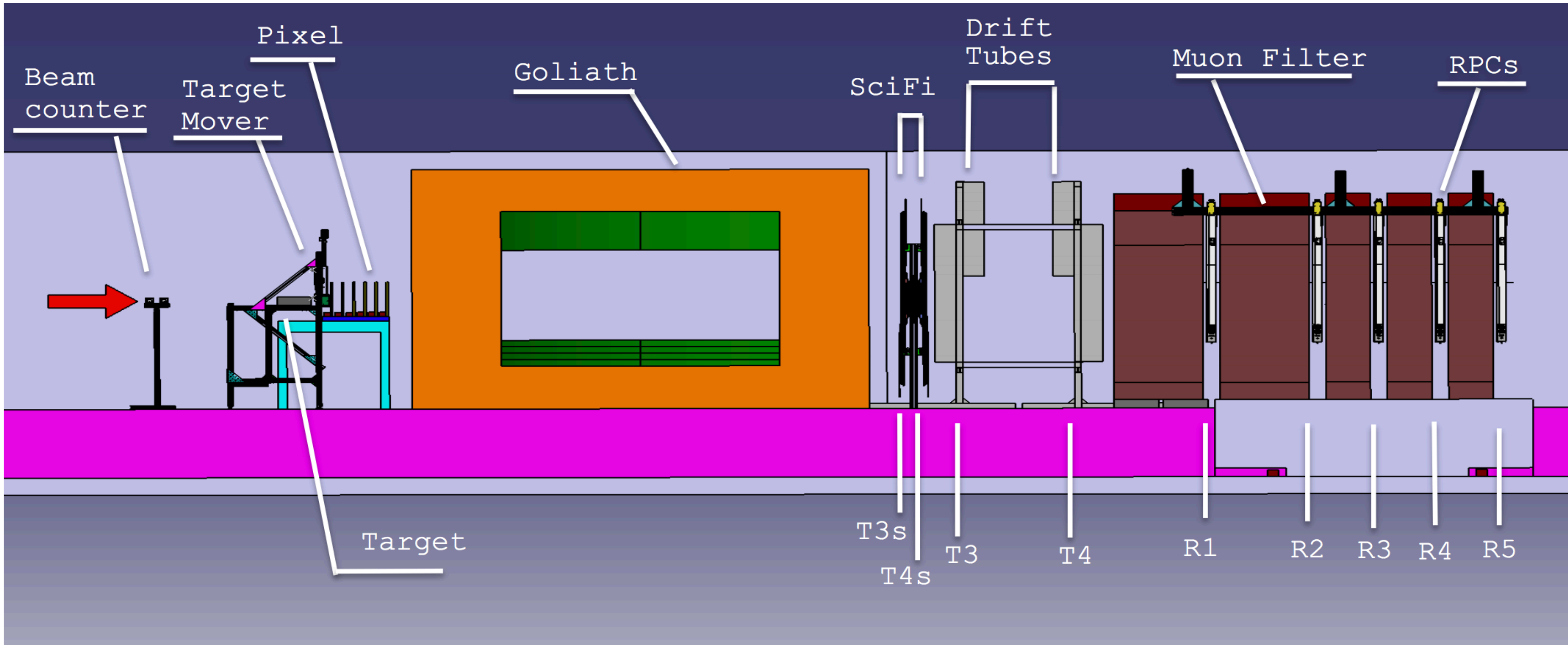


Charm Detection In The Target



Config	Density=10^3 tr/mm^2			Density=3×10^3 tr/mm^2		
	Nruns	Npot ($\times10^6$ pot)	Npair	Nruns	Npot ($\times10^6$ pot)	Npair
1	11	8.3	640	4	9.0	700
2	17	2.5	170	5	2.3	140
3	21	2.3	170	7	2.2	160
4	35	2.9	170	12	2.9	170
5	35	3.5	140	12	3.6	150
Total	119	19	1290	40	20	1320

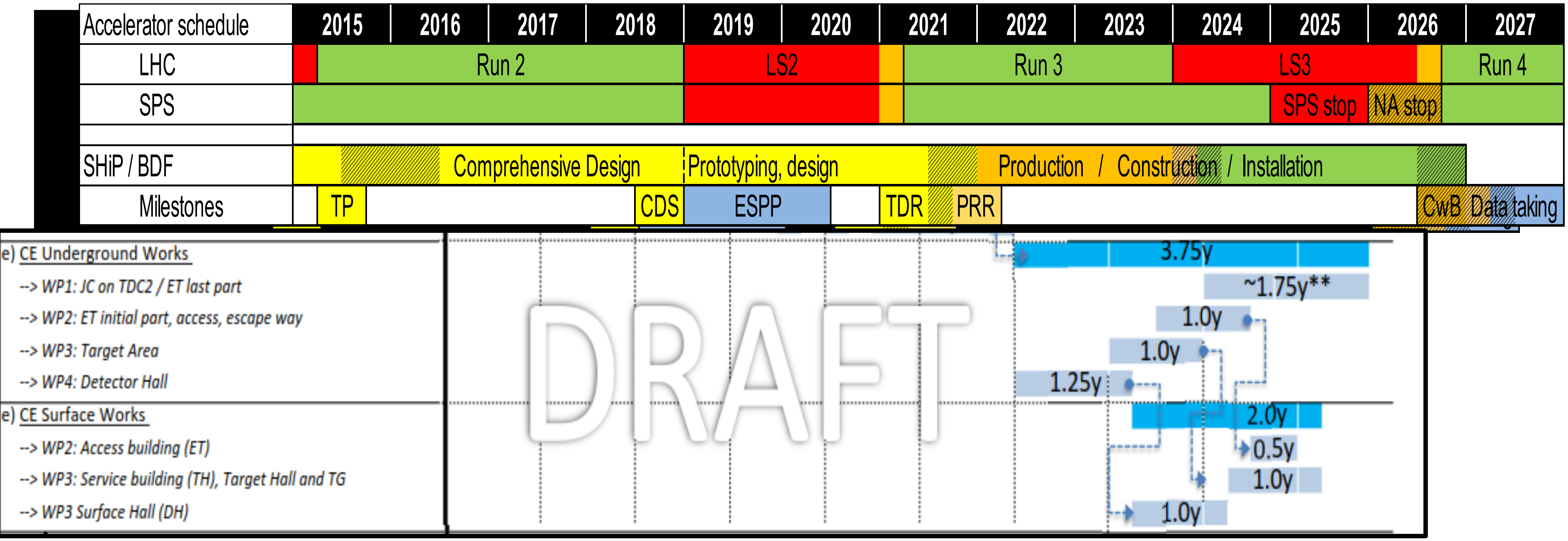
CHARM CROSS-SECTION MEASUREMENT, SPSC-EOI-017



- **Lead target**, 12×10 cm^2 Pb blocks (few cm) interleaved with emulsion to identify charm topology
- **Spectrometer** to measure momentum and charge of the charm daughters
- **Muon tagger** to identify muons

- Instrument ~1.6 λ to study charm production including the cascade effect
- July 2108: ~150 fully reconstructed charm-pais
- Data taking after LS2: > 1000 fully reconstructed charmed pairs

Project schedule



- ✓ *Schedule optimized to avoid interference with operation of North Area*
  - ➔ *Preparation of facility in four clear and separate work packages (target complex, detector hall, beam line and junction cavern)*
- ✓ *Input to the European Strategy panel by 2018*
- ✓ *Comprehensive Design Study by 2019*
- ✓ *Four years for detector construction, plus two years for installation*
  - ➔ ***Data taking 2026***

Summary

SHIP to complement searches for New Physics at CERN in the largely unexplored domain of new, very weakly interacting particles with masses O(10) GeV

- ✓ *Unique opportunity for ν_τ physics and light dark matter searches*
- ✓ *Sensitivity improves past experiments by O(10000) for Hidden Sector and by O(~1000) for ν_τ physics*
- ✓ *The SHiP proposal submitted in April 2015 to the SPS Committee at CERN with positive recommendations delivered in January 2016*
- ✓ *SHiP is an experiment recognised at CERN (grey book) since May 2016*
- ✓ *SHiP is preparing input for European Strategy by December 2018*
- ✓ *Comprehensive Design Study by 2019 to the SPSC*
- ✓ *Optimisation of the design going on: many technological choices and analyses still waiting for your contribution!*