The SHiP Experiment at CERN

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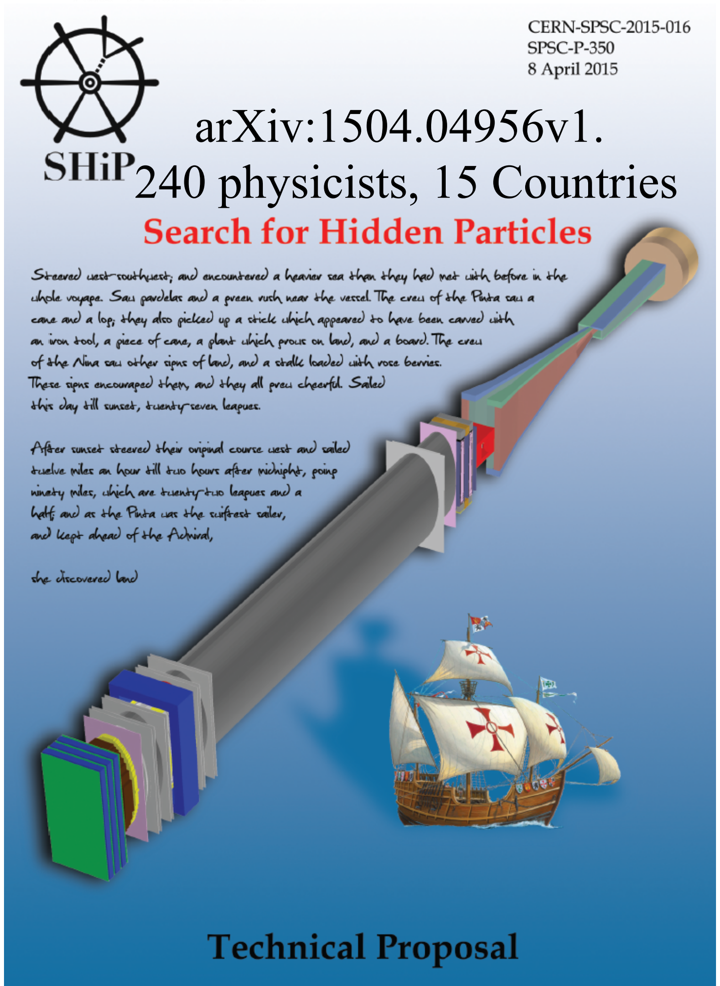
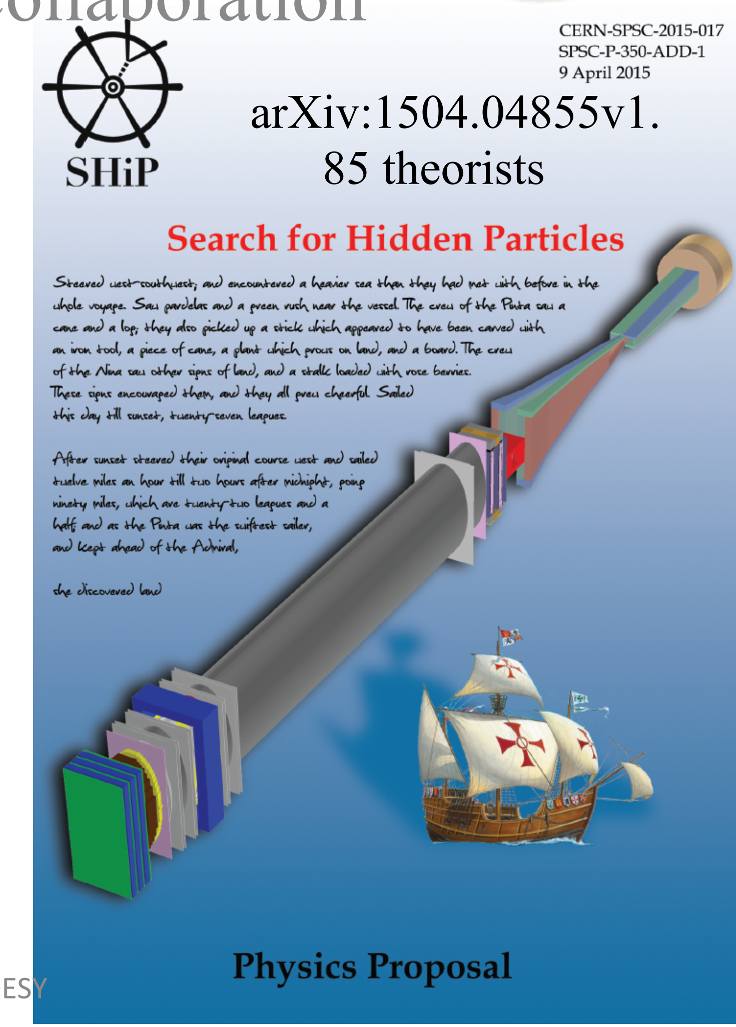
On behalf of the SHiP Collaboration



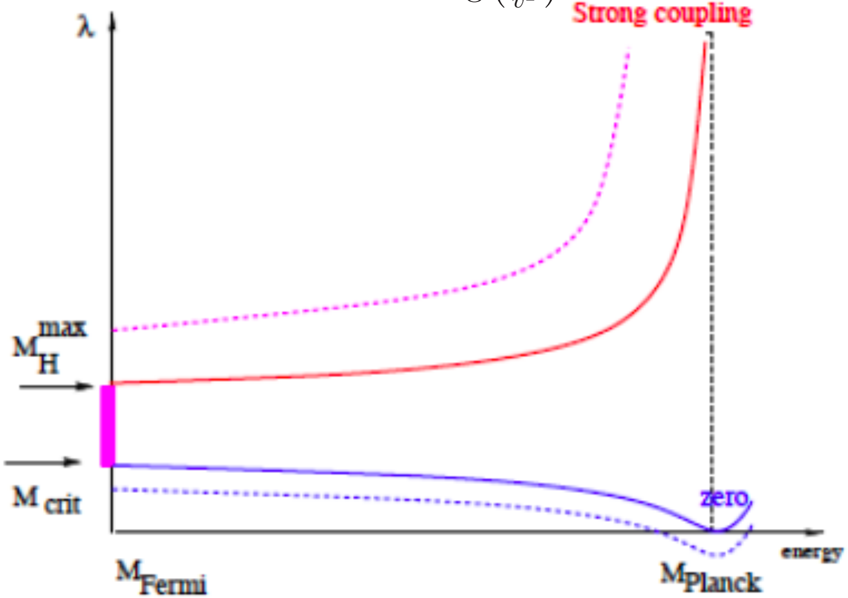


SM may well be a consistent effective theory all the way up to the Plank scale

- ✓ *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

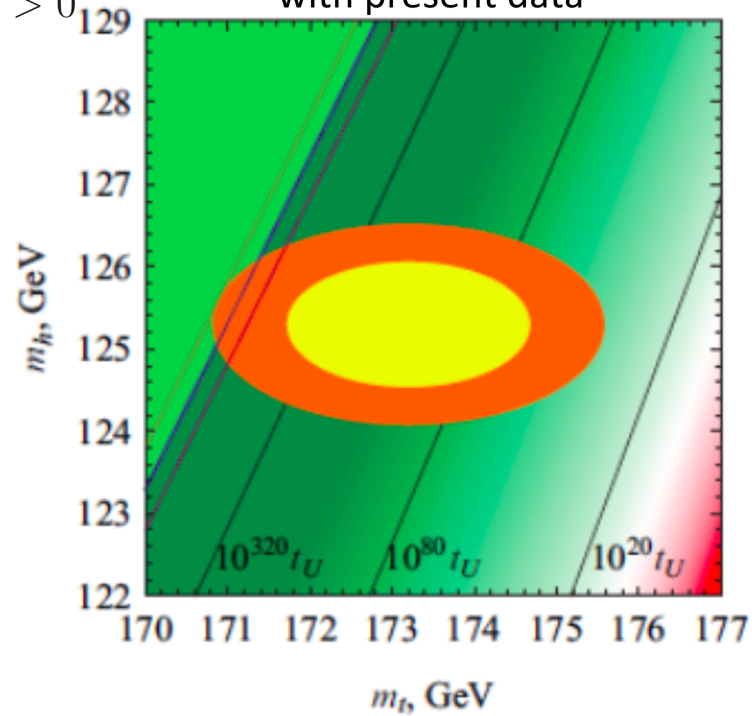
$$\lambda(\Lambda) < \infty \quad \Rightarrow \quad M_H^2 \leq \frac{8\pi^2 v^2}{3\log\left(\frac{\Lambda^2}{v^2}\right)}$$



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

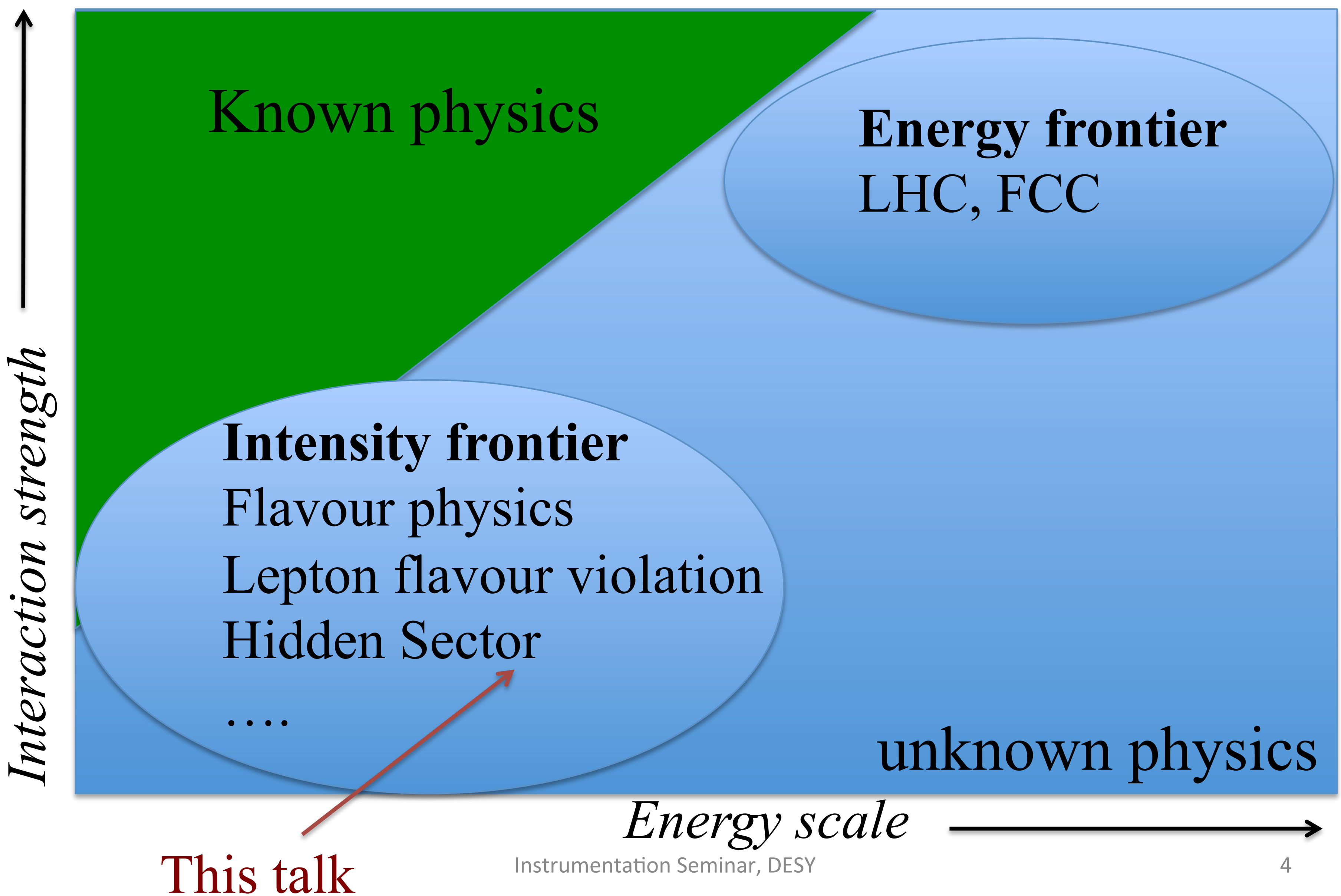
What is the composition of dark matter (~25% of the Universe) ?

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



Search for Hidden Sector (HS)
or very weakly interacting NP

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

Visible Sector ⟷ **Hidden 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	$\pi^0\pi^0$

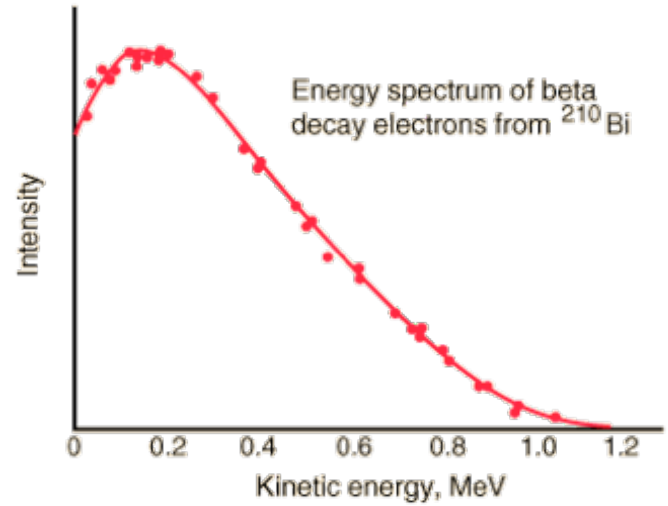
Full reconstruction and PID are essential to minimize model dependence

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!

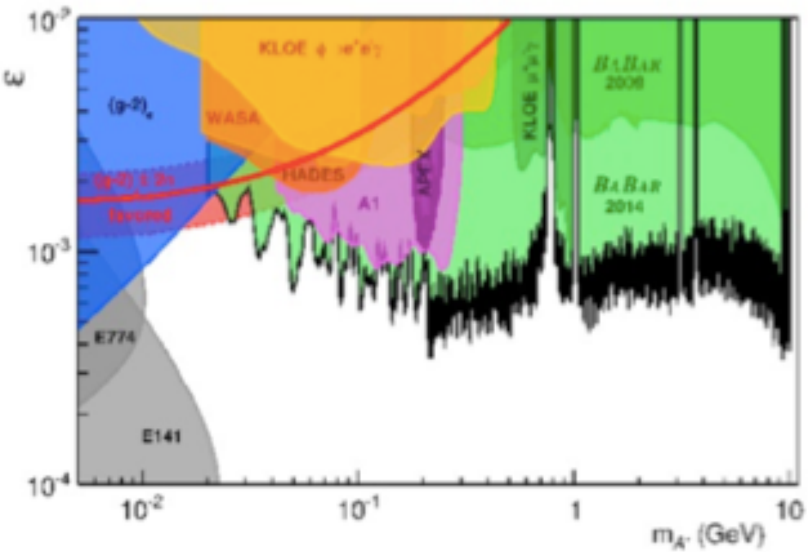
$$n \to p + e^- + \bar{\nu}$$

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

Search for dark photons

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

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



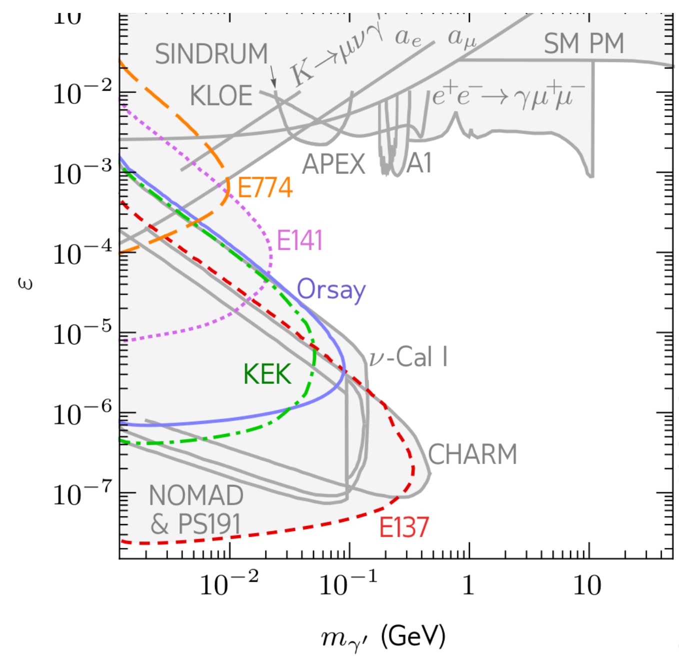
- decay length $c\tau \sim \varepsilon^{-2} m_{\gamma'}^{-1}$
- cosmological constraints (nucleo-synthesis): $\tau < 0.1$ s $\Rightarrow \varepsilon^2 m_{\gamma'} > 10^{-21}$ GeV

γ' production

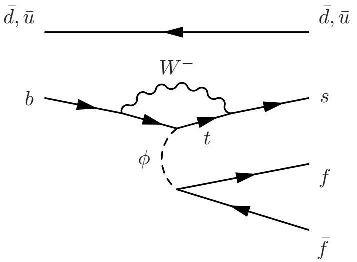
- proton bremsstrahlung:
  - initial-state radiation from the incoming proton, followed by a hard proton-nucleus interaction

- 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

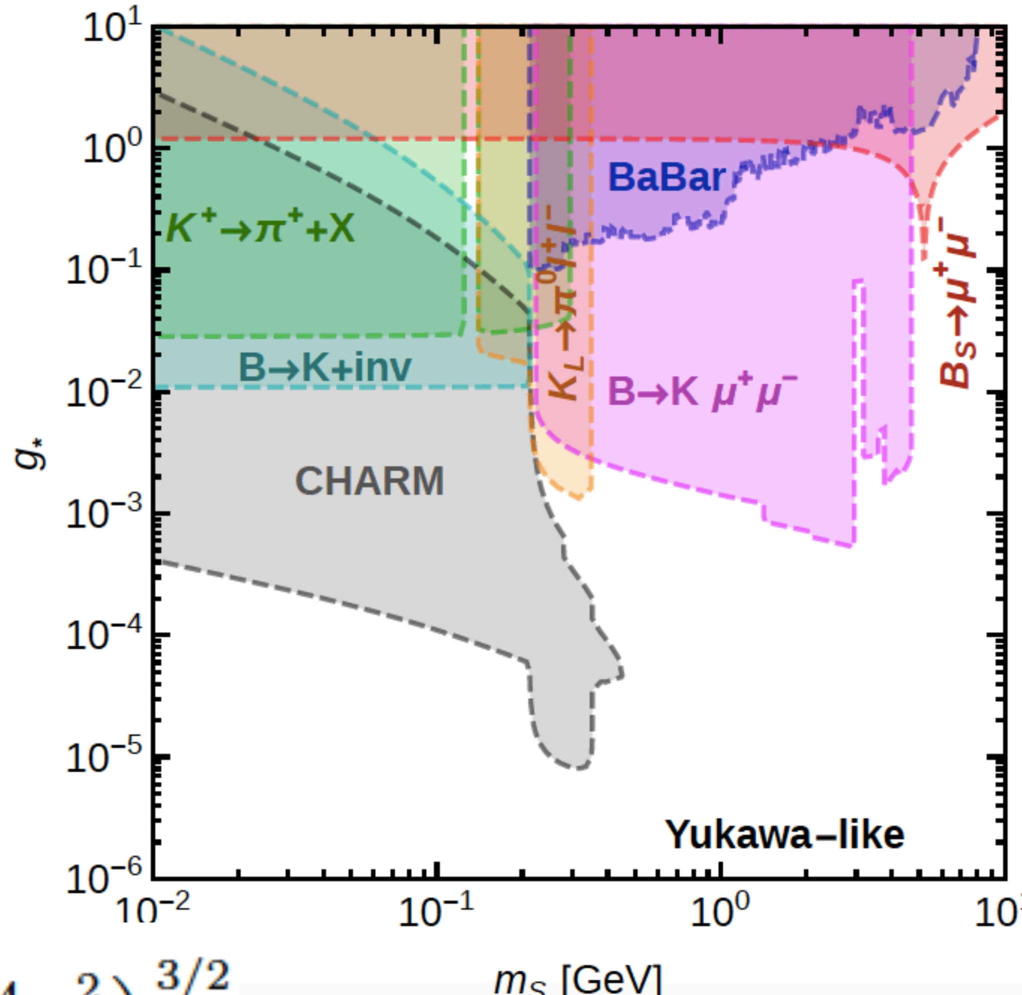


Rare B meson decays mediated by a light scalar ϕ

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

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

B decays favoured compared to D



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

Motivation for Heavy Neutral Leptons

See-saw mechanism for neutrino masses

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

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

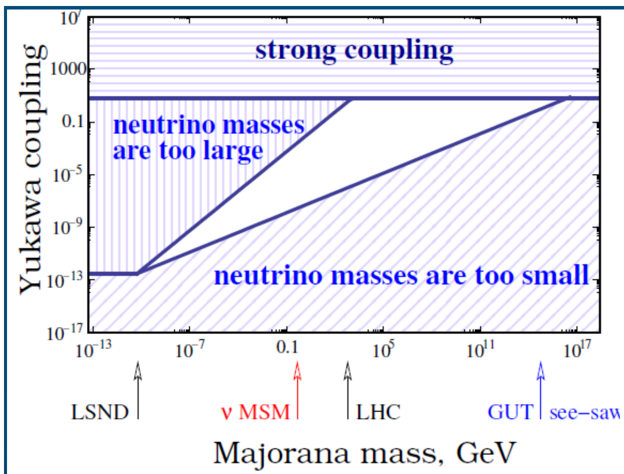
Yukawa term: mixing of N_I with active neutrinos to explain oscillations

Majorana term which carries no gauge charge

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

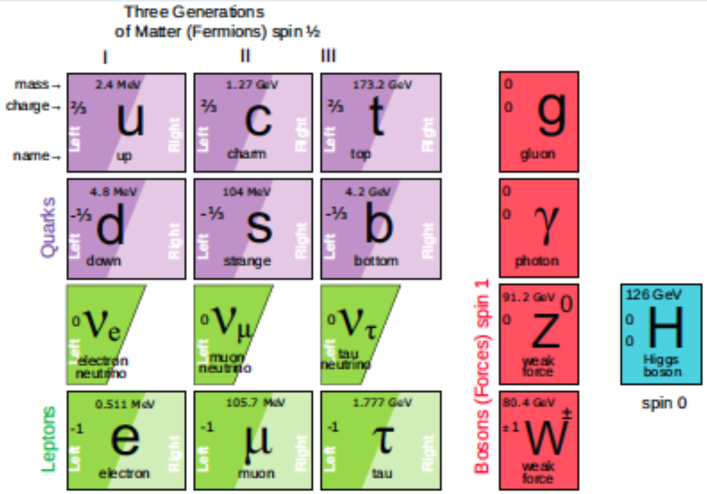
The scale of the active neutrino mass is given by the see-saw formula: $m_\nu \sim \frac{m_D^2}{M}$
where $m_D \sim Y_{I\alpha} v$ *- typical value of the Dirac mass term*

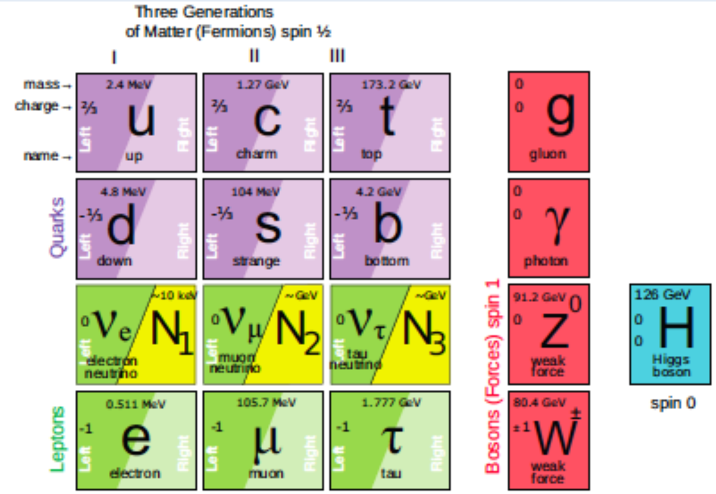
Four "popular" N mass ranges



	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

The νMSM model: leptogenesis and dark matter





N = Heavy Neutral Lepton - HNL

Role of N_1 with mass in keV region: dark matter

Role of $N_2, \; N_3$ with mass in 100 MeV – GeV region: “give” masses to neutrinos and produce baryon asymmetry of the Universe

Role of the Higgs: give masses to quarks, leptons, Z and W and inflate the Universe.

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

global lepton-number symmetry broken at the level of O(10^{-4}) leads to the required pattern of sterile neutrino masses consistent with neutrino oscillations data

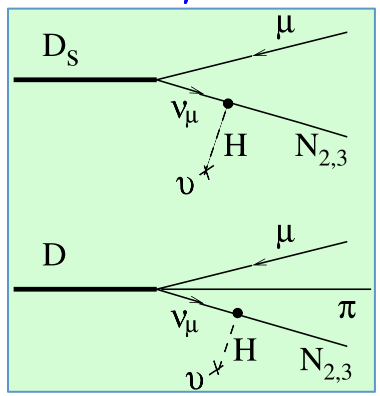
Masses and couplings of HNLs

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

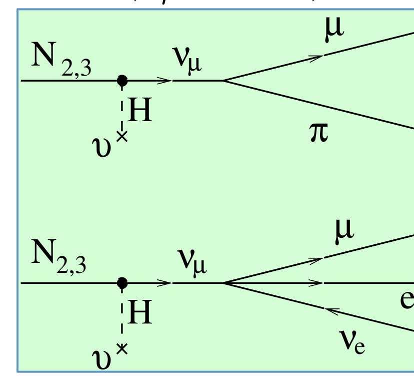
Very weak $N_{2,3}$-to-ν mixing (~ U^2) → $N_{2,3}$ are much longer-lived than SM particles

- 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



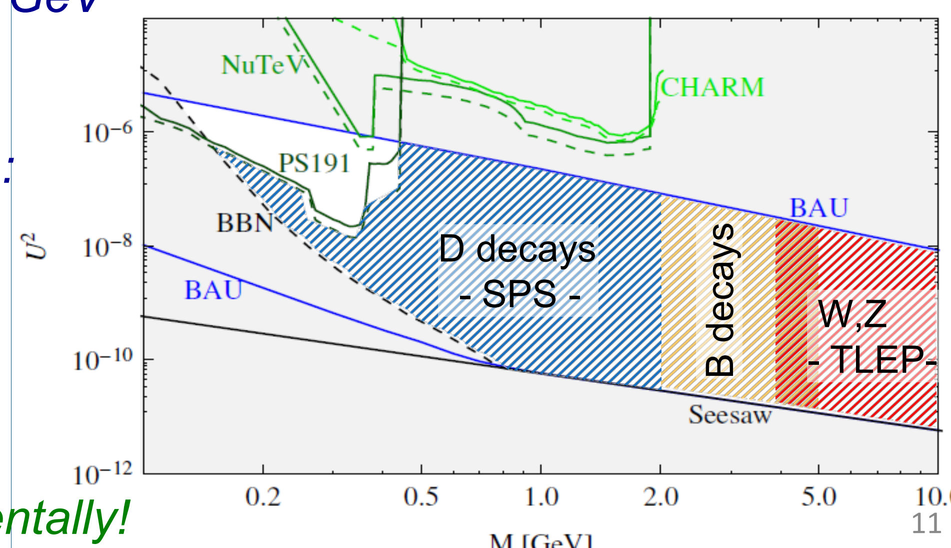
and subsequent decays



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

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

  Br(N → μ/e π)   ~ 0.1 – 50%
  Br(N → μ^-/e$^-$ ρ^+) ~ 0.5 – 20%
  Br(N → $\nu\mu$e)   ~ 1 – 10%



Domain only marginally explored, experimentally!

Common experimental features of Hidden Sector (HS)

- ✓ *Production through hadron decays (π, K, D, B, proton bremsstrahlung, …)*

- ✓ *Decays:*

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

- ✓ *Full reconstruction and PID are essential to minimize model dependence*

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

- ✓ ***Challenge is background suppression → requires O(0.01) carefully estimated***

- ✓ ***Physics with ν_τ produced in D_s decays share many of these features***

ν_τ Studies

- Less known particle in the Standard Model
- First observation by DONUT at Fermilab in 2001 with 4 detected candidates, *Phys. Lett. B504 (2001) 218-224*
- 9 events (with an estimated background of 1.5) reported in 2008 with looser cuts

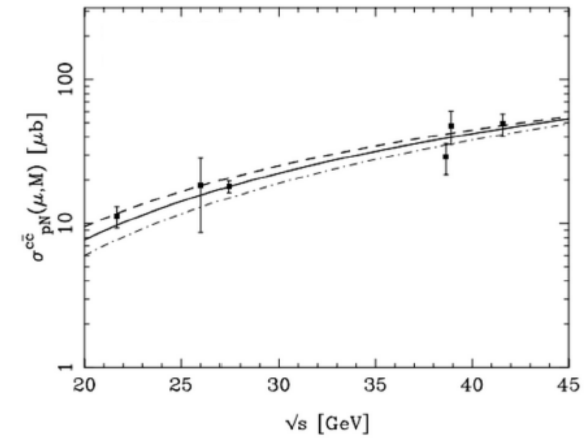
$$\sigma^{const}(\nu_\tau) = (0.39 \pm 0.13 \pm 0.13) \times 10^{-38}\ \text{cm}^2\ \text{GeV}^{-1}$$

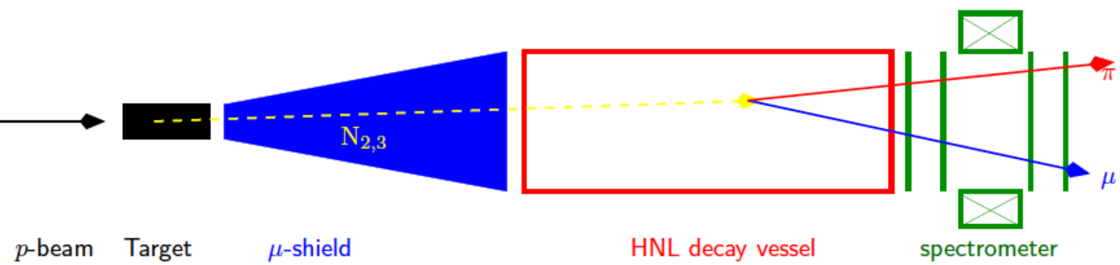
- 5 ν_τ candidates reported by OPERA for the discovery (5.1σ result) of ν_τ appearance in the CNGS neutrino beam PRL 115 (2015) 121802
- Tau anti-neutrino never observed

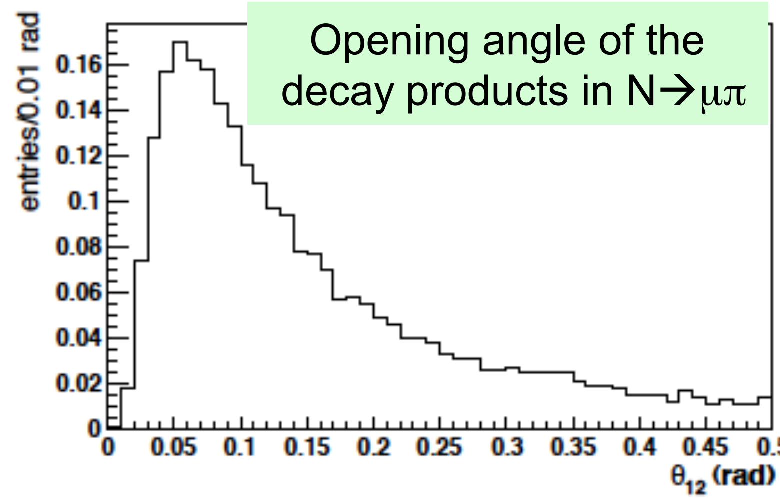
$$N_{\nu_\tau + \bar{\nu}_\tau} = 4 N_p \frac{\sigma_{c\bar{c}}}{\sigma_{pN}} f_{D_s} Br(D_s \to \tau) = 2.85 \times 10^{-5} N_p = 5.7 \times 10^{15}$$

General experimental requirements

- ✓ *Search for HS particles in Heavy Flavour decays*
- ✓ *HS produced in charm and beauty decays have significant P_T*



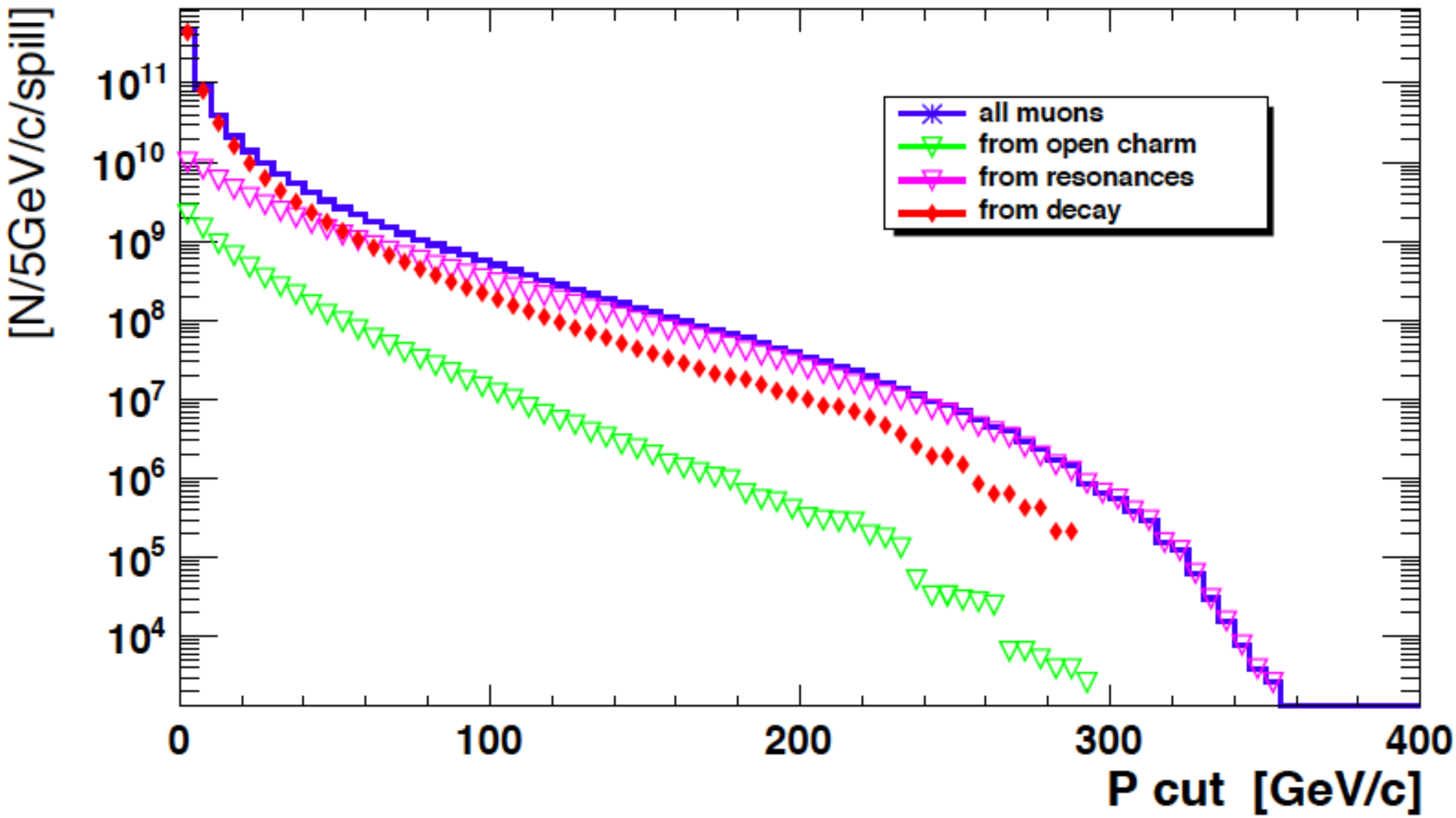




- ✓ *Detector must be placed close to the target to maximize geometrical acceptance*
- ✓ *Effective (and "short") muon shield is essential to reduce muon-induced backgrounds*
- ✓ *With 2 x 10^{20} 400 GeV pot, ~ 3 x 10^{17} charm produced*

Main sources of muons in beam dump

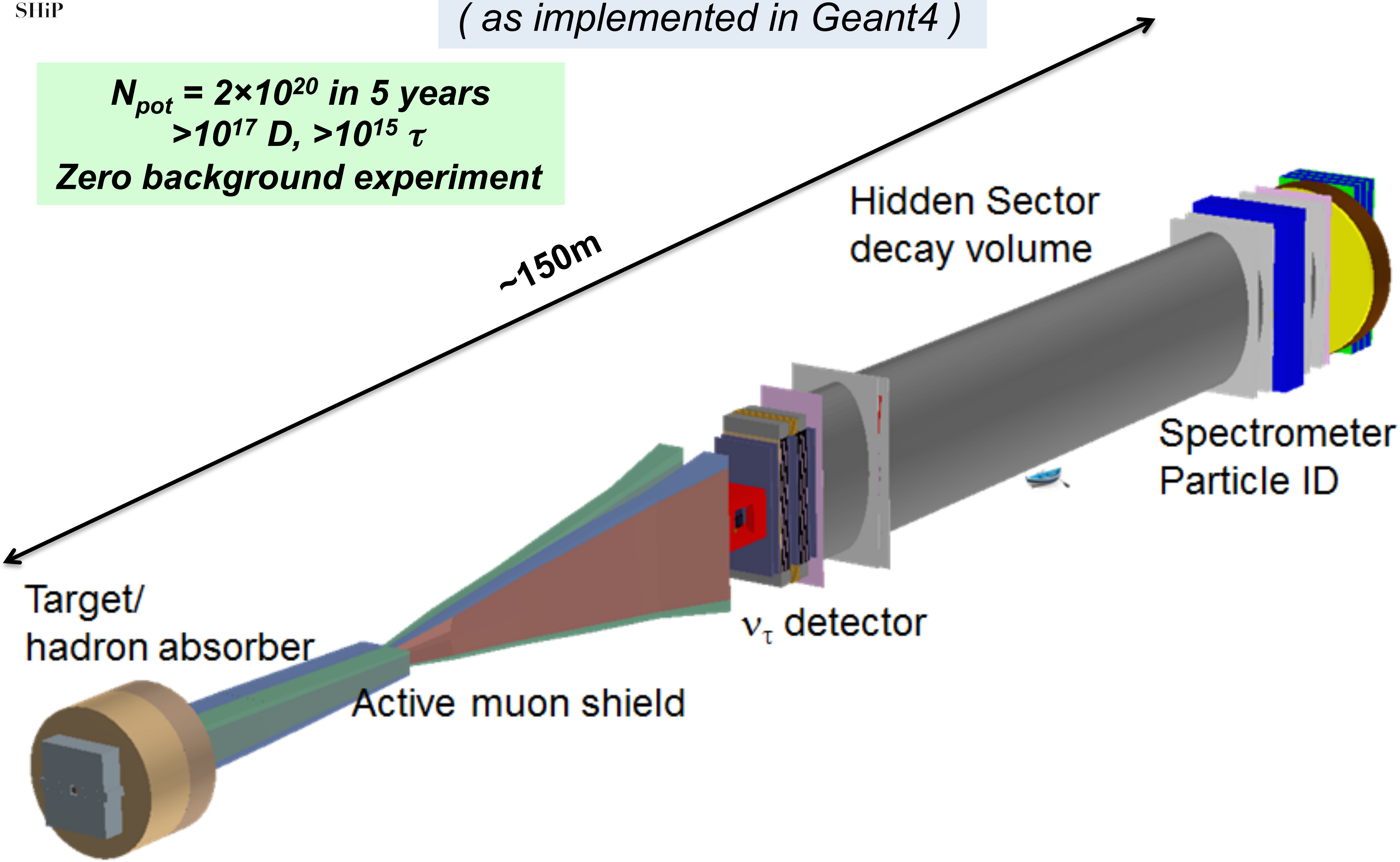
- *Decays of pions populate mainly low momenta*
- *Electromagnetic decays of resonances (η, ρ, etc) populate mainly high momenta*
- *Negligible fraction of muons from charm decays*



The SHiP experiment

(as implemented in Geant4)

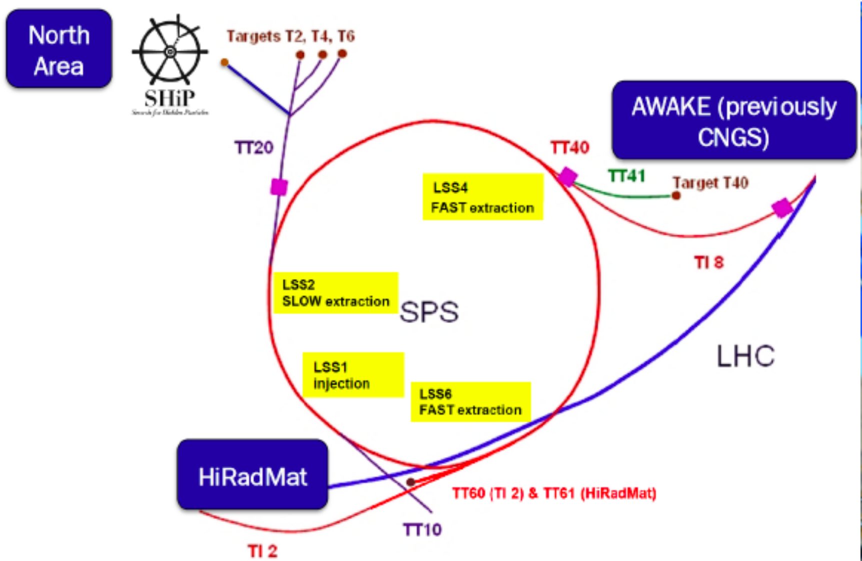
N_{pot} = 2×10^{20} in 5 years
>10^{17} D, >10^{15} τ
Zero background experiment

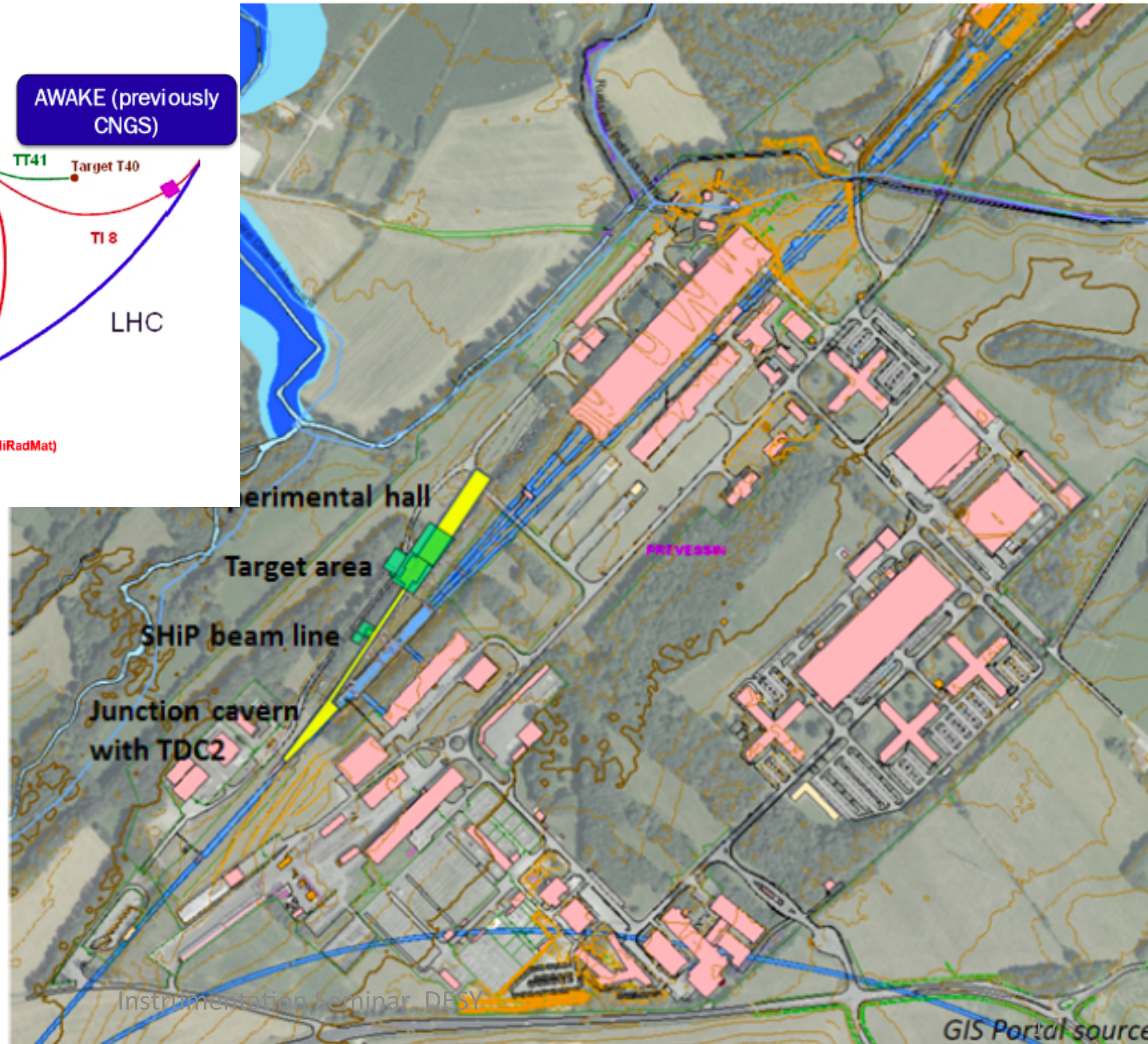


The Fixed-target facility at the SPS: Prevessin North Area site

Proposed implementation based on minimal modification of the SPS complex

High-intensity proton beam: 4 10^{13} ppp, 4 10^{19} pot/yr, 5 years run (as for CNGS)

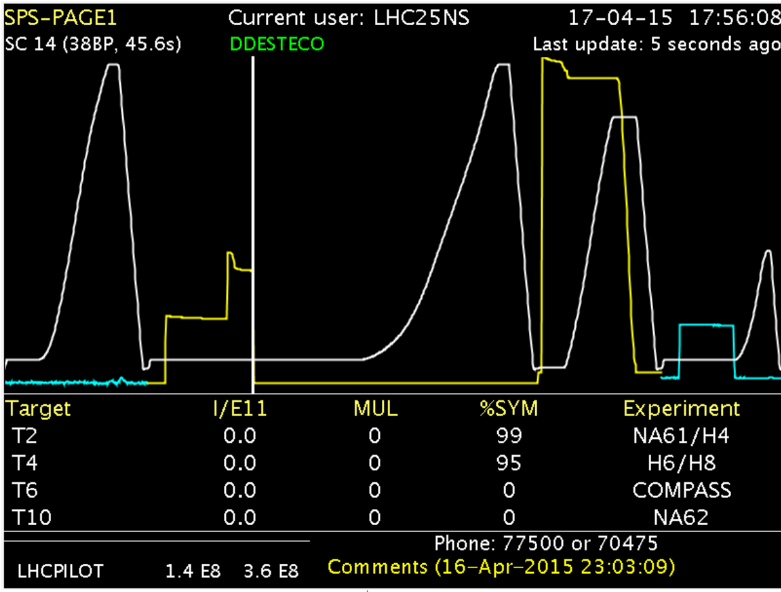




The SHiP facility is located on the North Area, and shares the TT20 transfer line and slow extraction mode with the fixed target programmes

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

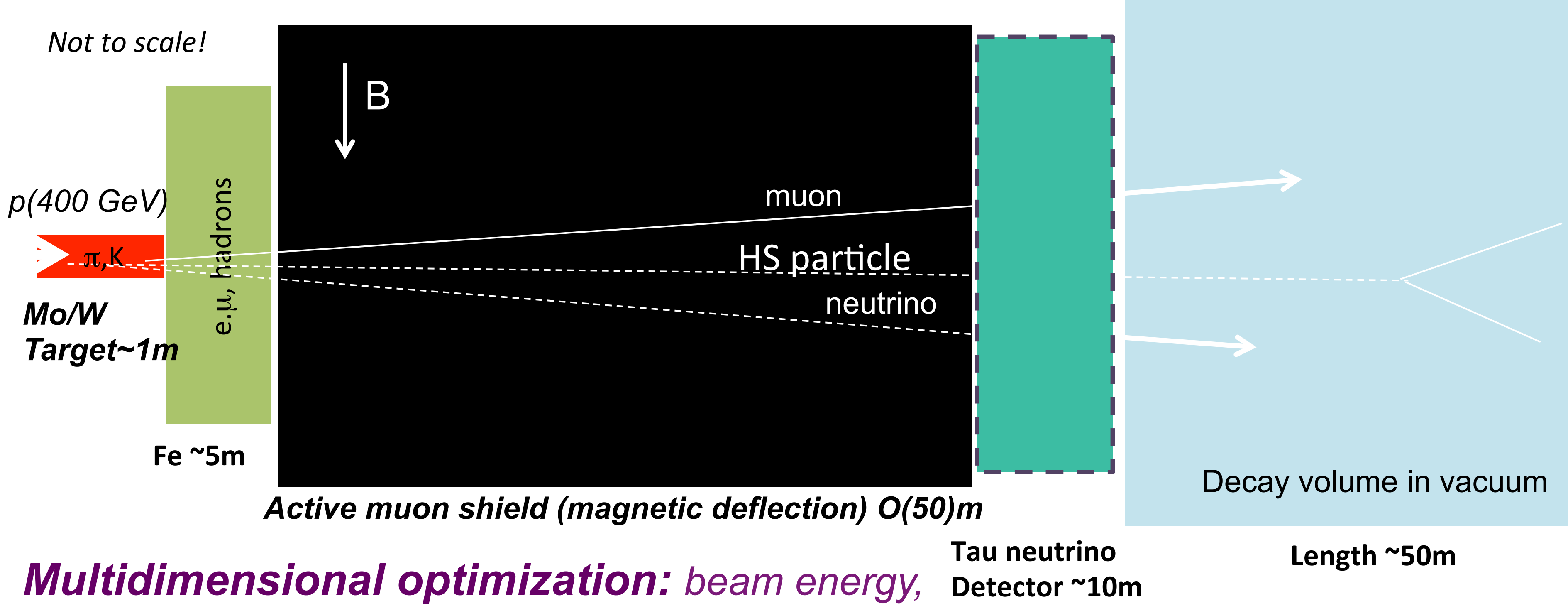


Successful test in April 2015

SHiP beam-line
(incompatible with conventional neutrino facility)

Initial reduction of beam induced backgrounds

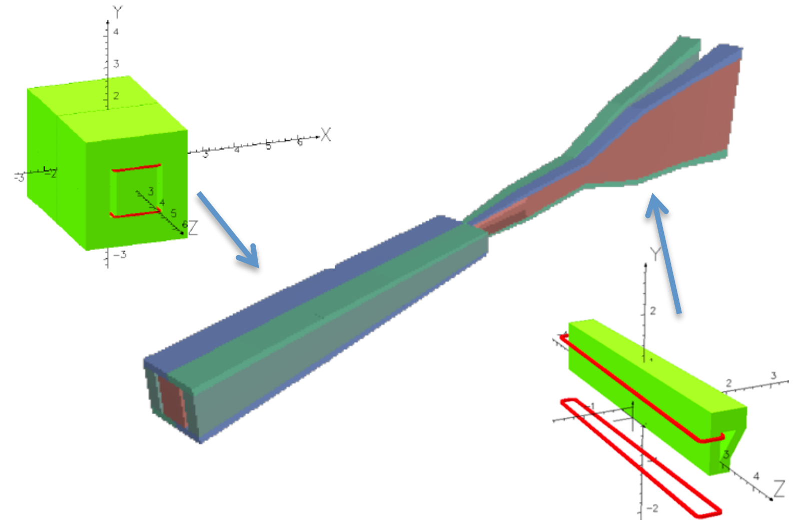
- *Heavy target to maximize Heavy Flavour production (large A) and minimize production of neutrinos in $\pi/K \rightarrow \mu\nu$ decays (short λ_{int})*
- *Hadron absorber*
- *Effective muon shield (without shield: muon rate ~10^{10} per spill of 4×10^{13} pot)*
- *Slow (and uniform) beam extraction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



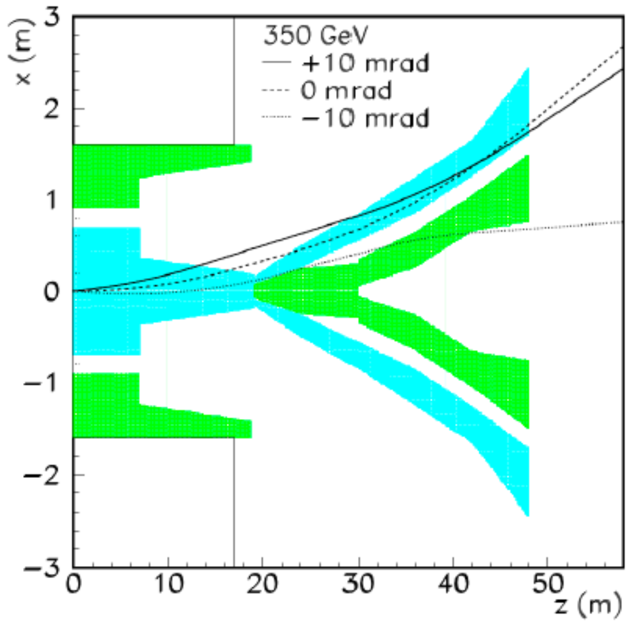
***Multidimensional optimization:** beam energy, beam intensity, background conditions and detector acceptance*

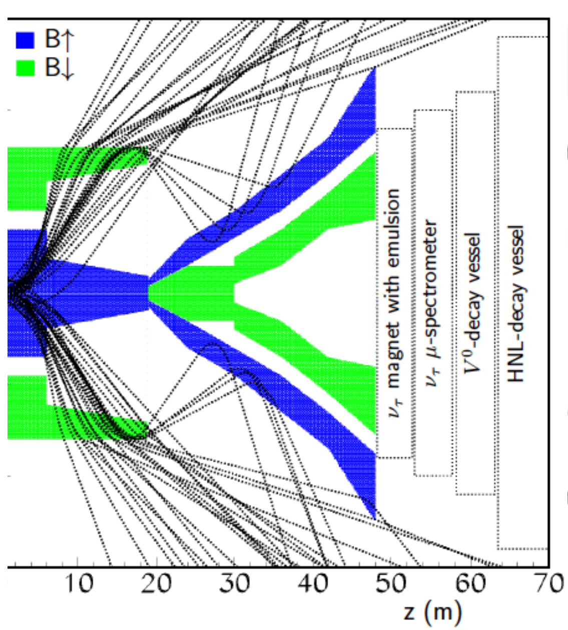
SHiP muon shield

- ✓ *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
- ✓ *< 7k muons / spill (E_μ > 3 GeV), from 10^{10}*
- ✓ *Negligible flux in terms of detector occupancy*

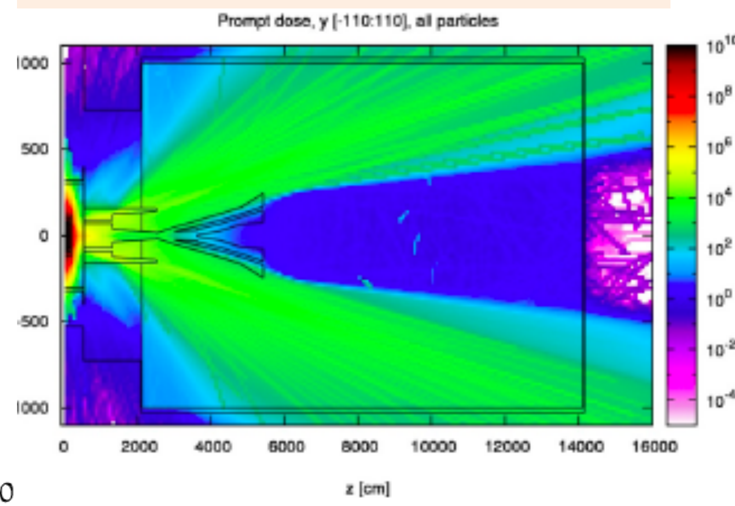


Magnetic sweeper field

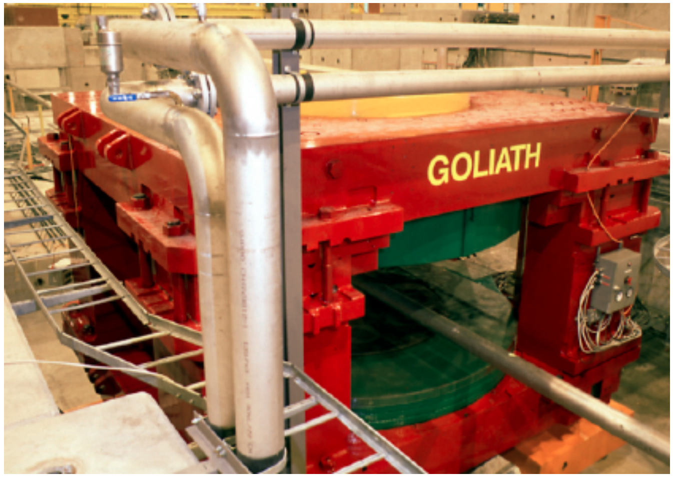




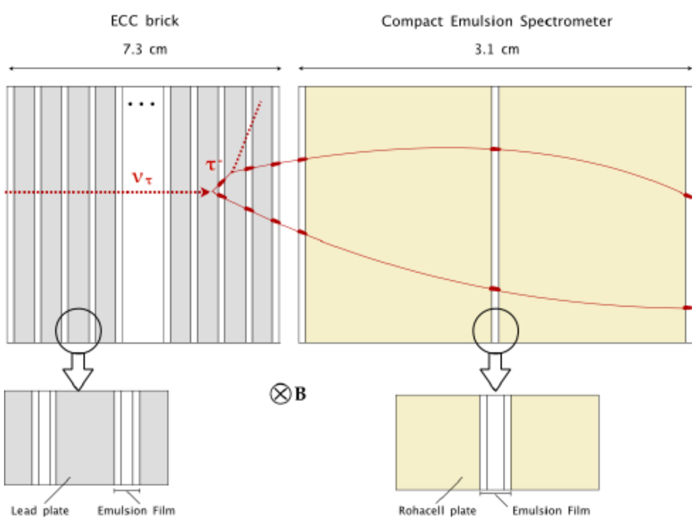
Dose rate (μSv/h) in the SHiP hall

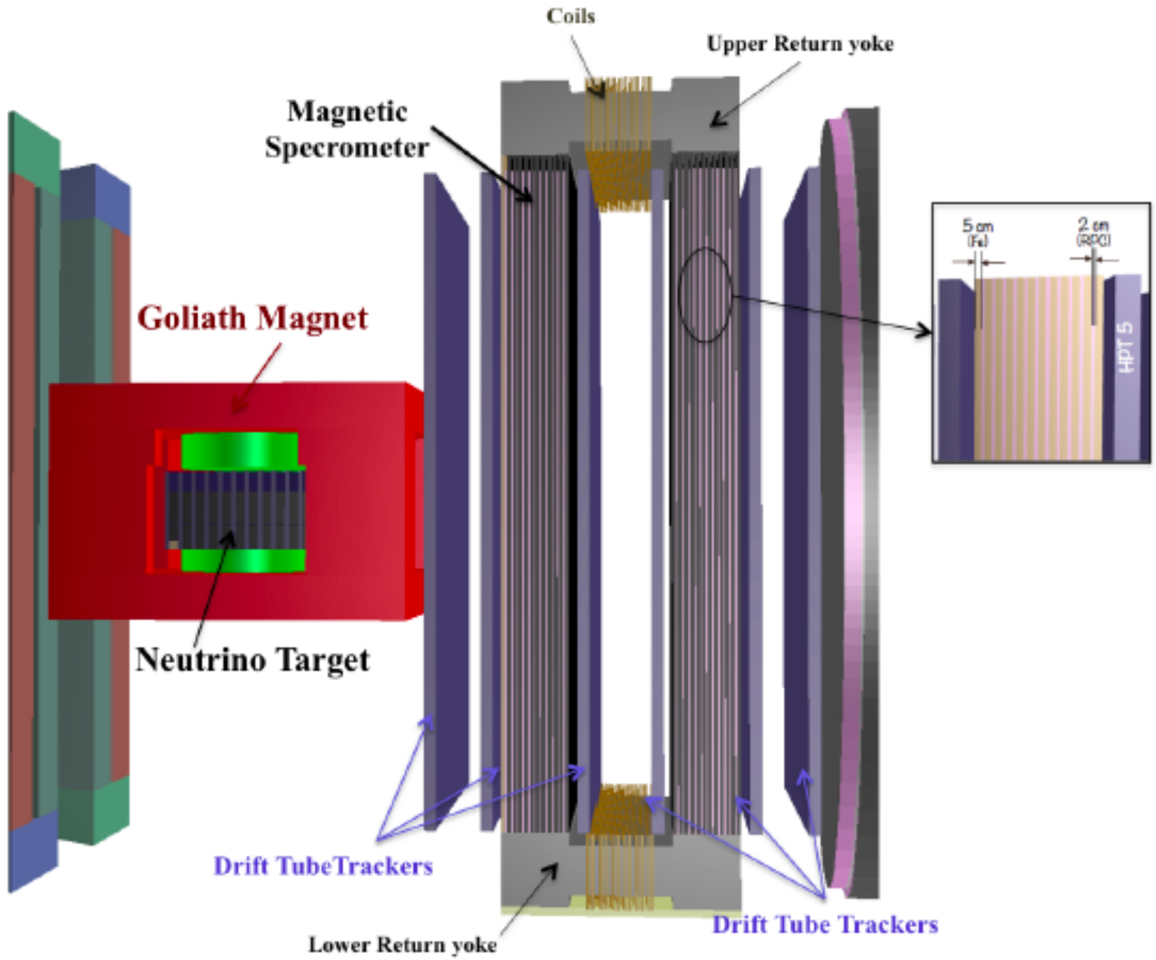


ν_τ detector follows the concept of OPERA

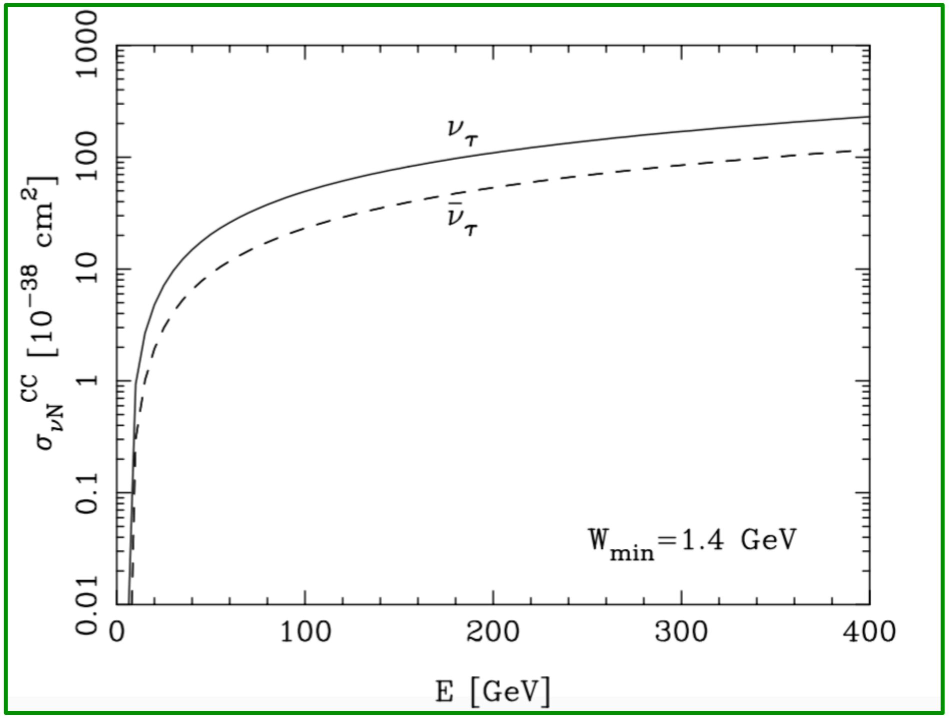


Emulsion Cloud Chamber is the key element of ν_τ detection

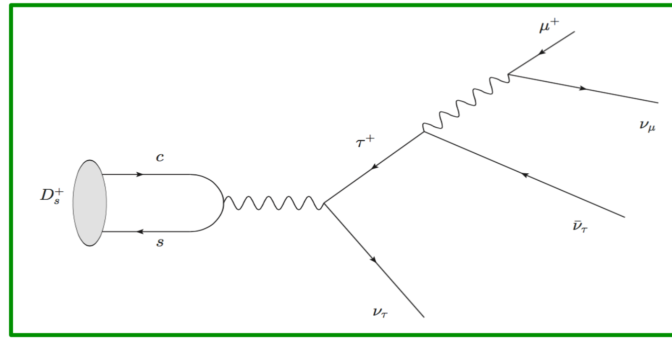




ν_τ Interactions In The Target



M. H. Reno, Phys. Rev. D74 (2006) 033001



Expected number of interactions*

*in 5 years run (2×10^{20} pot)
target mass ~ 9.6 ton (Pb)

$$N_{\nu_\tau} \simeq 6.7 \times 10^3$$

$$N_{\overline{\nu}_\tau} \simeq 3.4 \times 10^3$$

Uncertainty ($\lesssim$10%) from:

- Scale choices
- Pdf
- Target mass correction

20% uncertainty mainly
from scale variations in
c-cbar differential cross-section

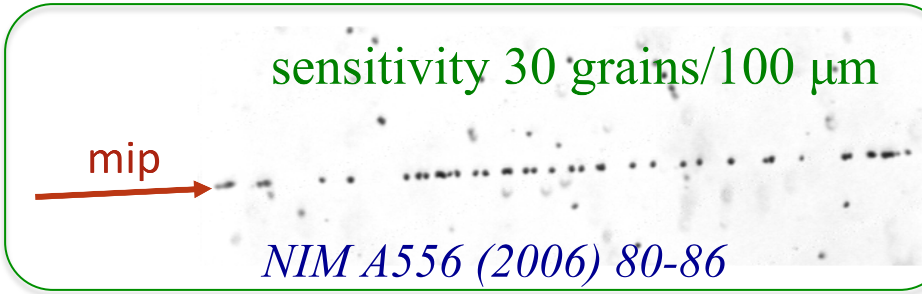
ν_τ DETECTOR

THE UNITARY CELL

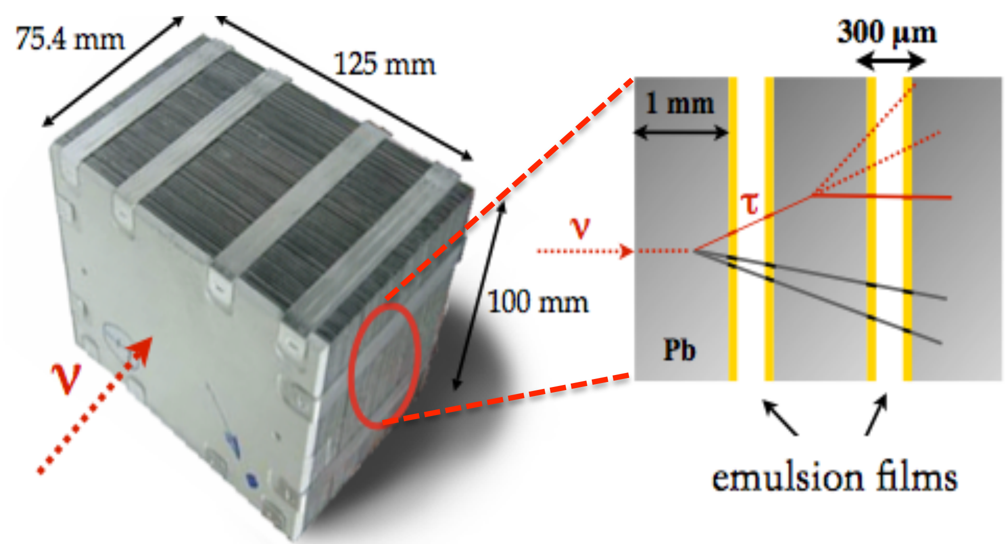
<u>Emulsion Cloud Chamber (ECC)</u>

BRICK

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



10 X_0

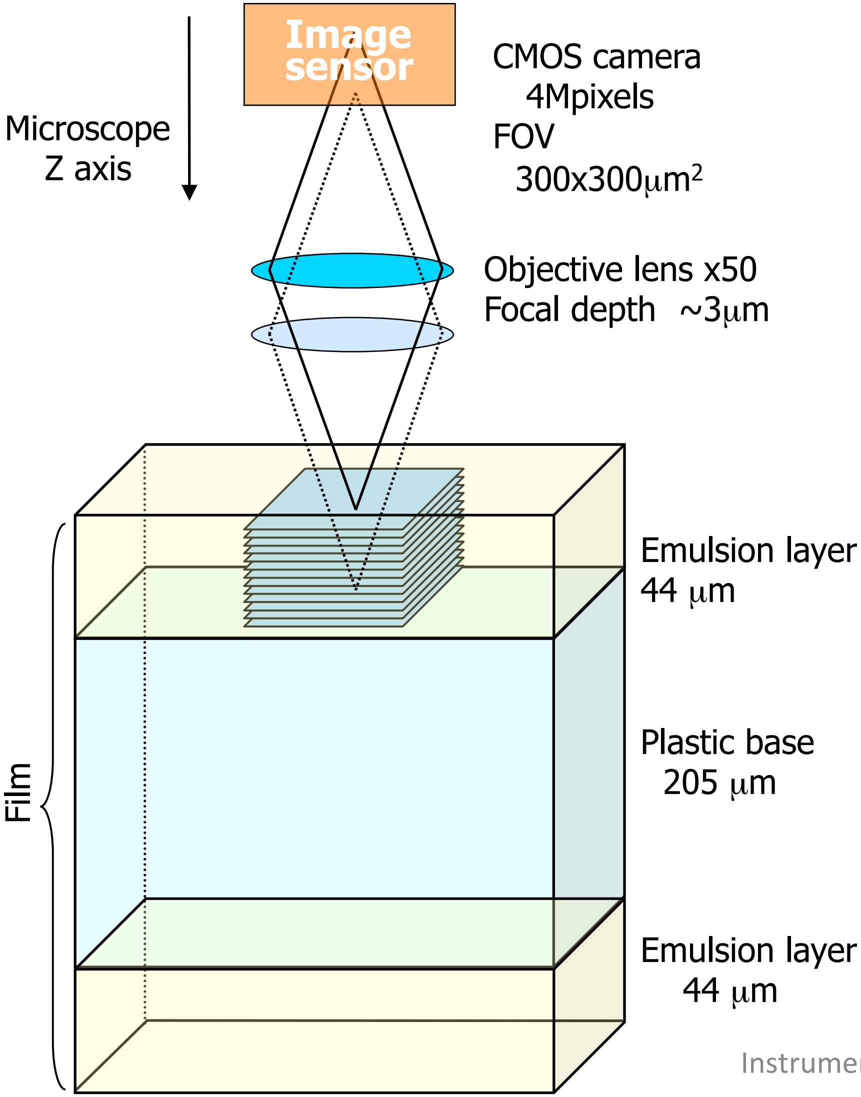


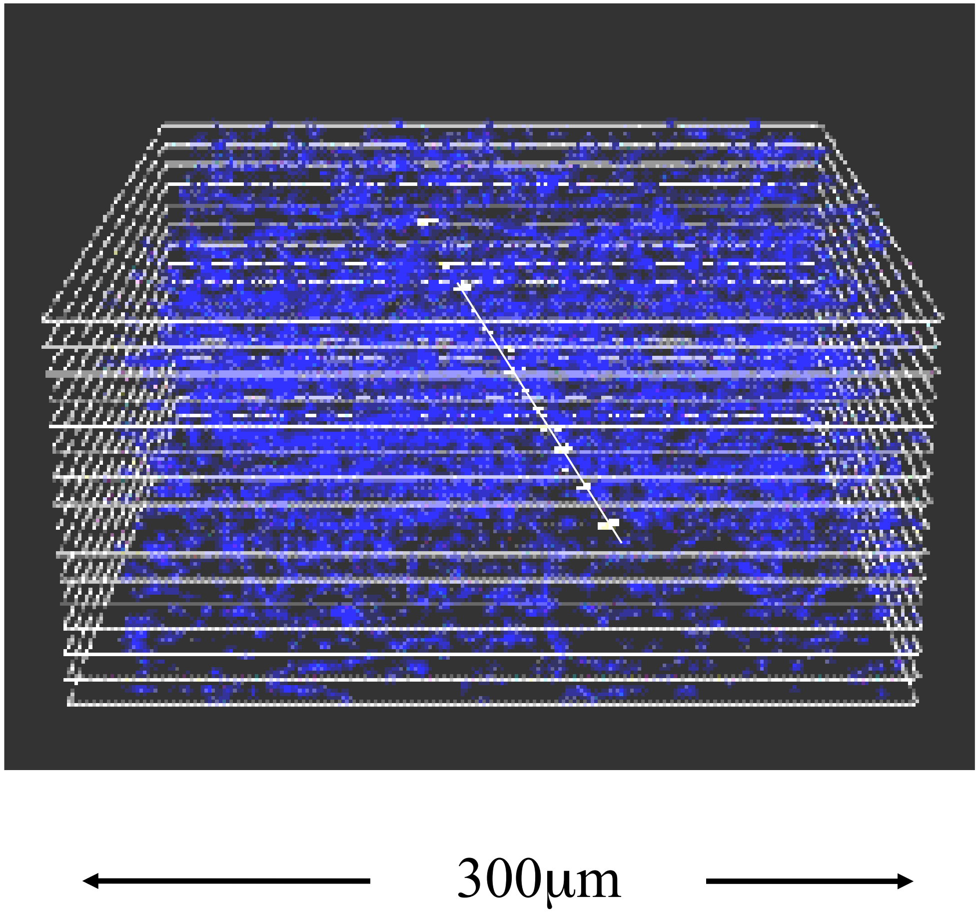
PERFORMANCES

- 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

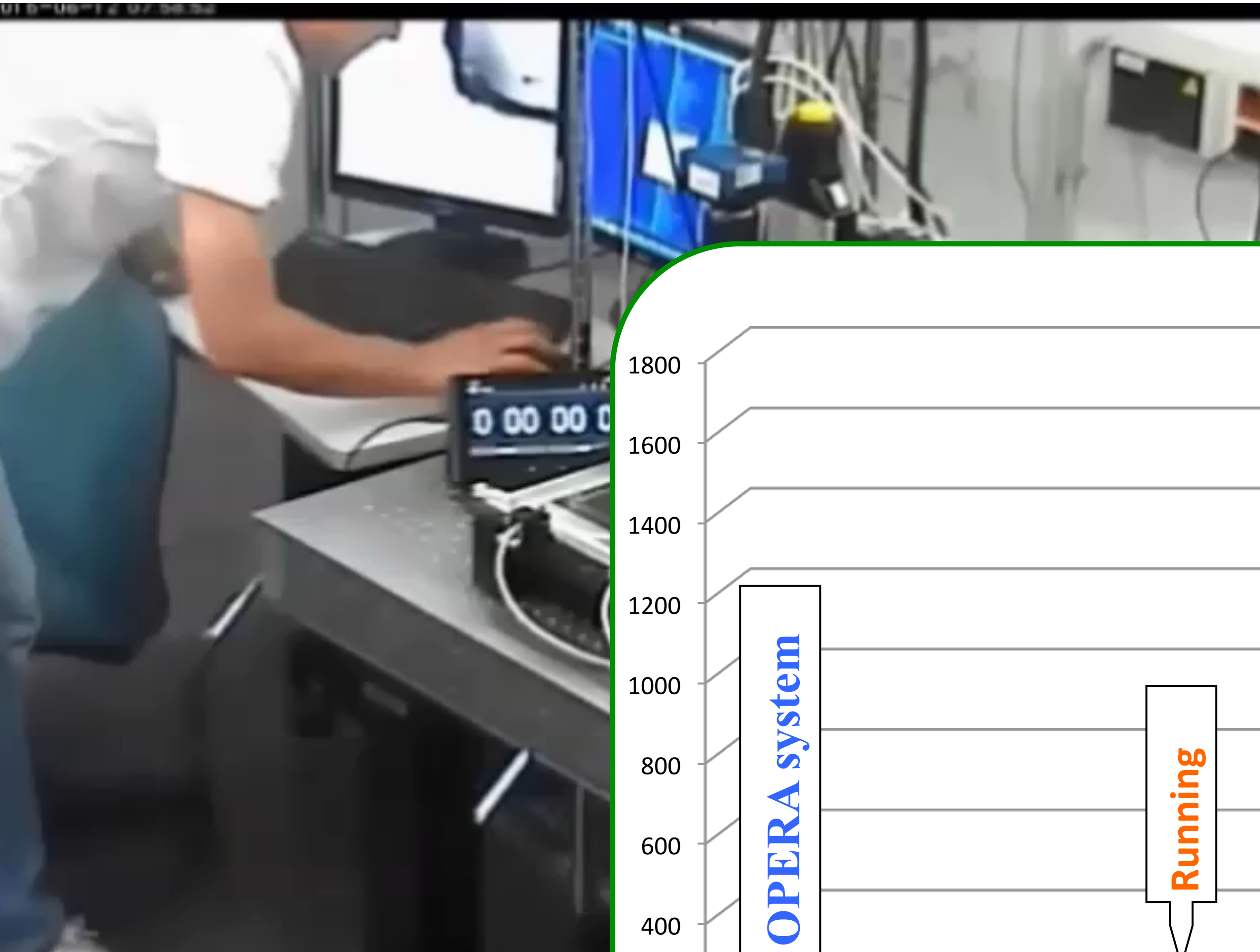
Digitizing Nuclear Emulsion Films

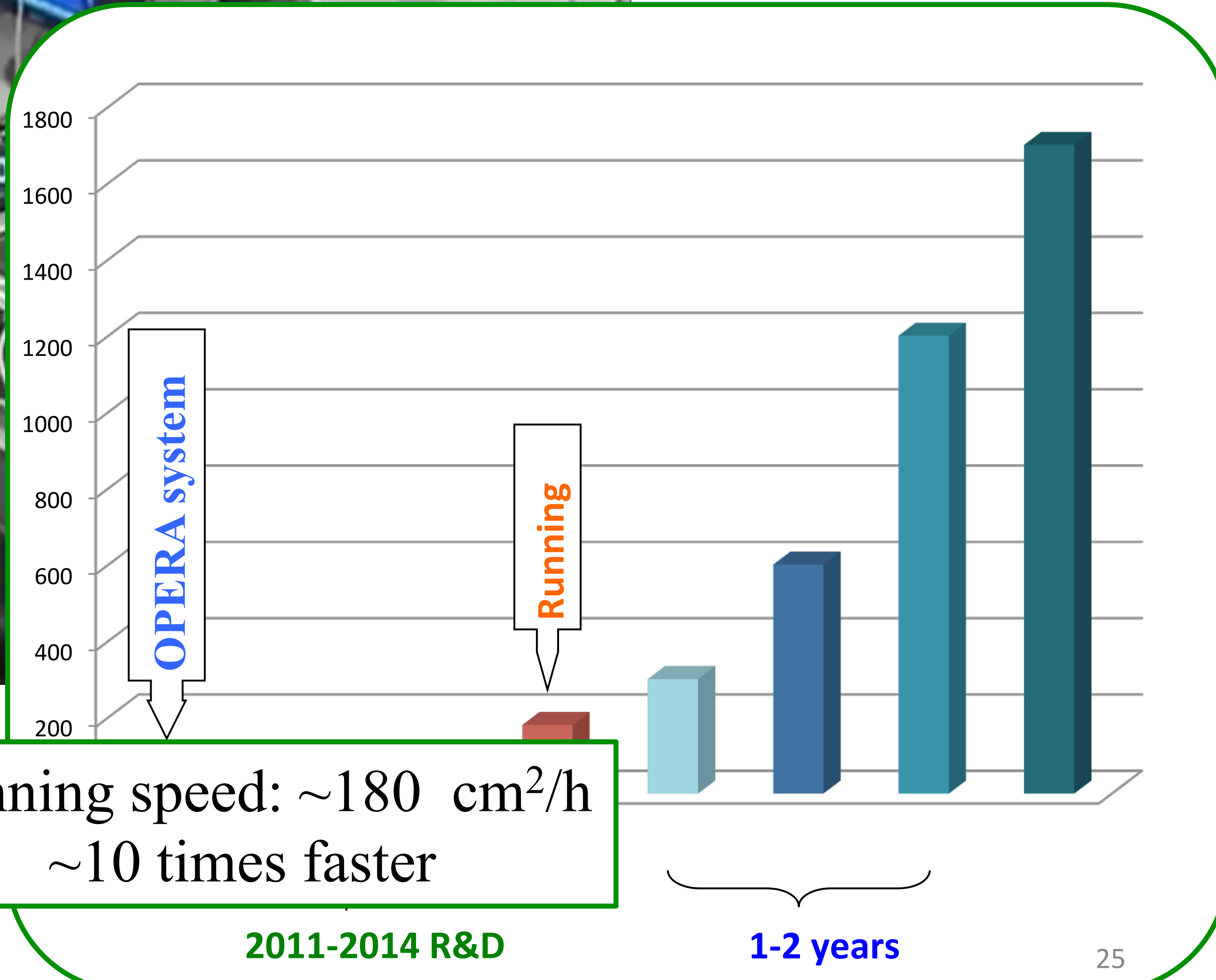




Grain Density ~15 (/45μm)

IMPROVEMENTS IN THE SCANNING SYSTEM



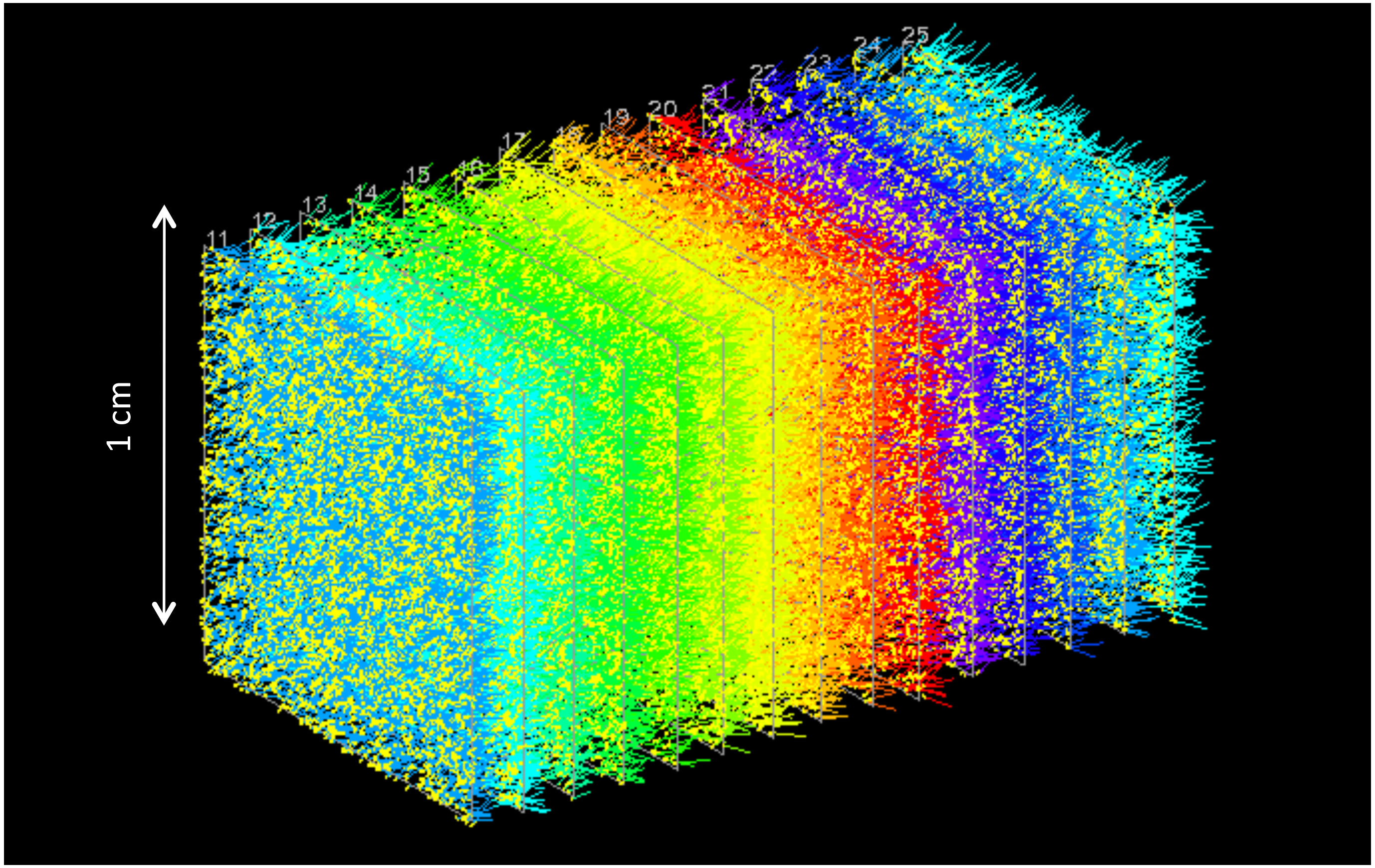


Scanning speed: ~180 cm^2/h
~10 times faster

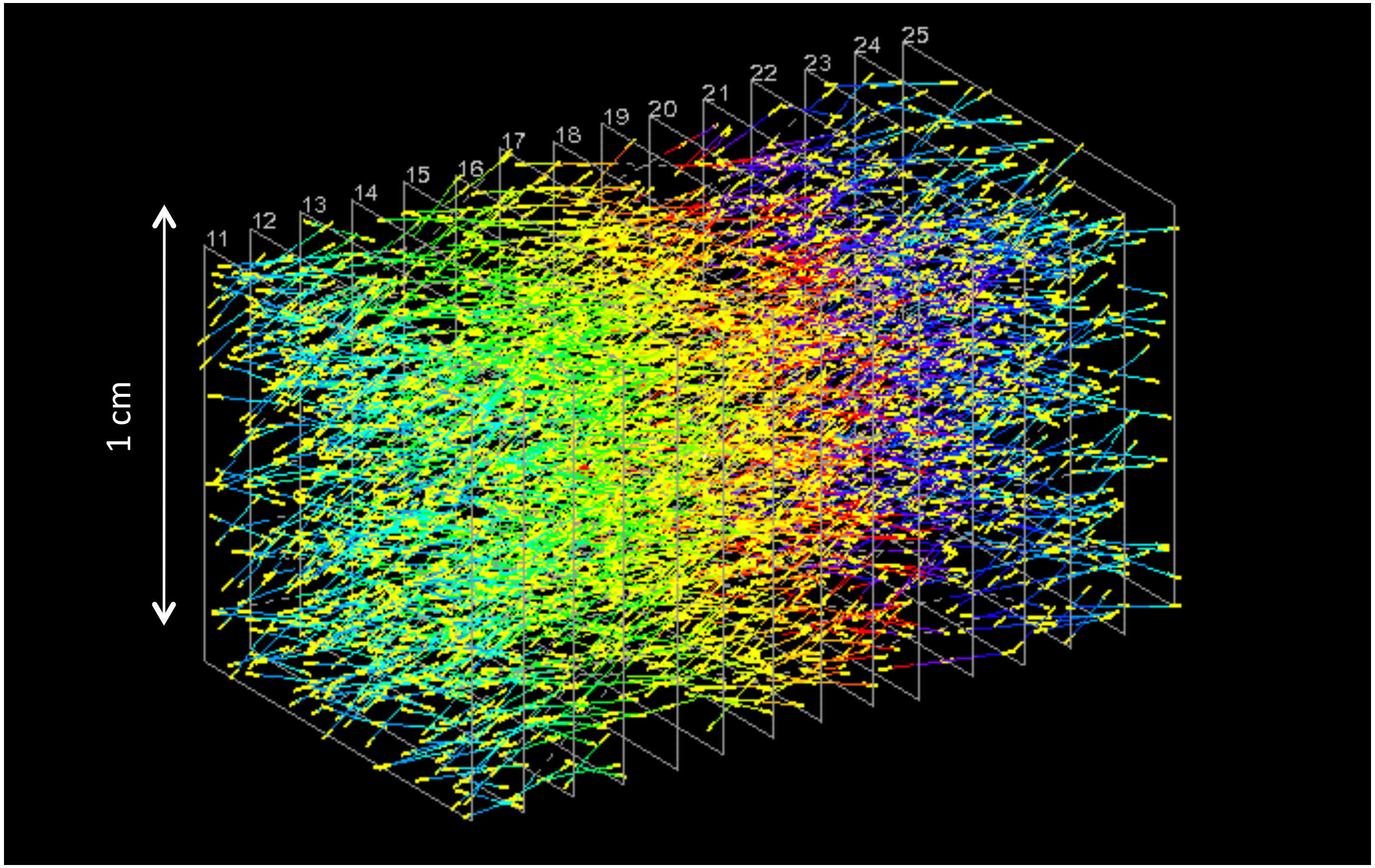
Volume (~2 cm^3) analysed

3D tracks with sub-micrometric accuracy

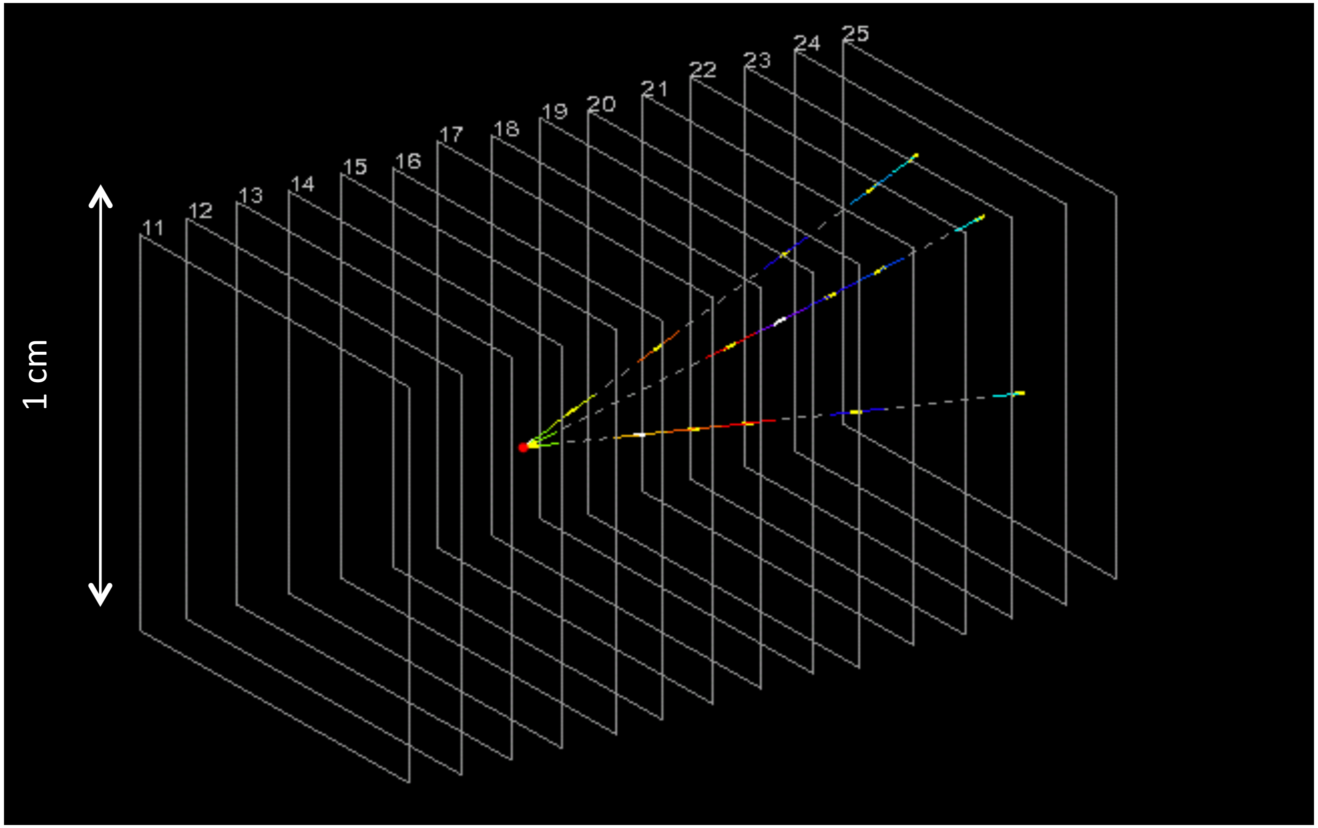
Short Yellow lines → measured tracks
Other colours → extrapolated segments



Film to film connection

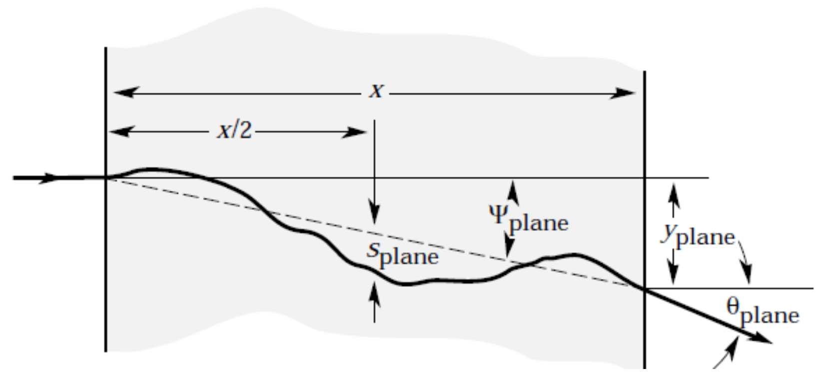


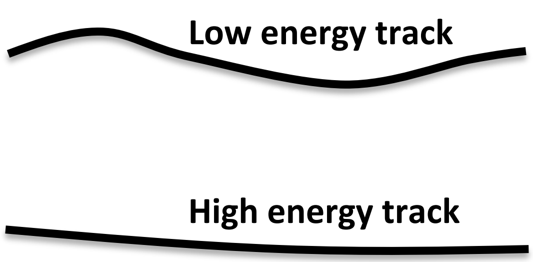
LOCATED NEUTRINO INTERACTION



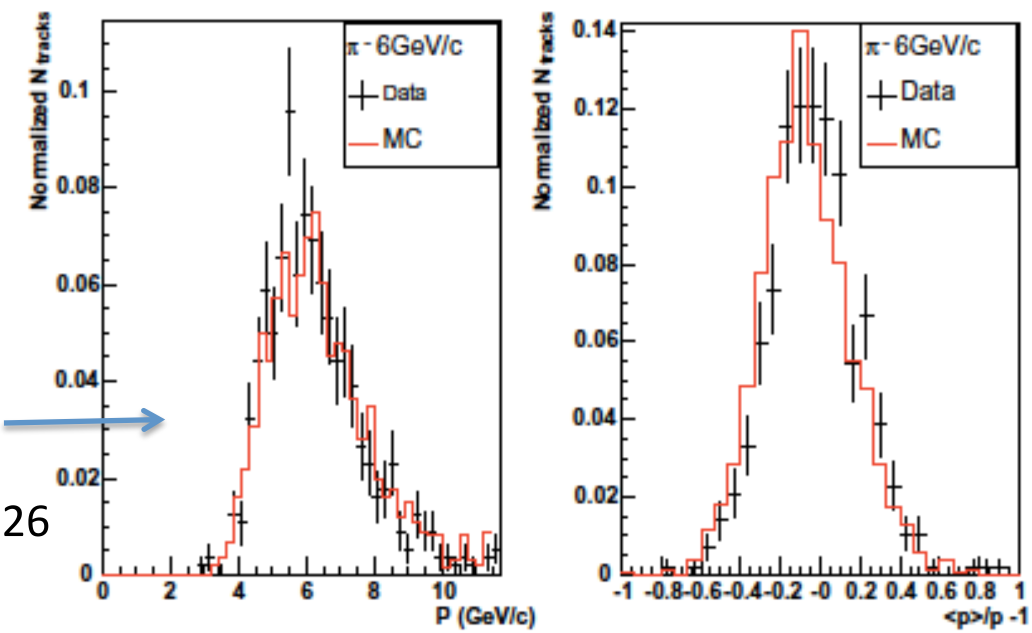
Momentum measurement
by multiple Coulomb scattering

$$\theta^{rms}_{plane} = \frac{14.64\,MeV}{\beta c p}\sqrt{\frac{x}{X_0}}\left(1+0.038\ln\frac{x}{X_0}\right)$$





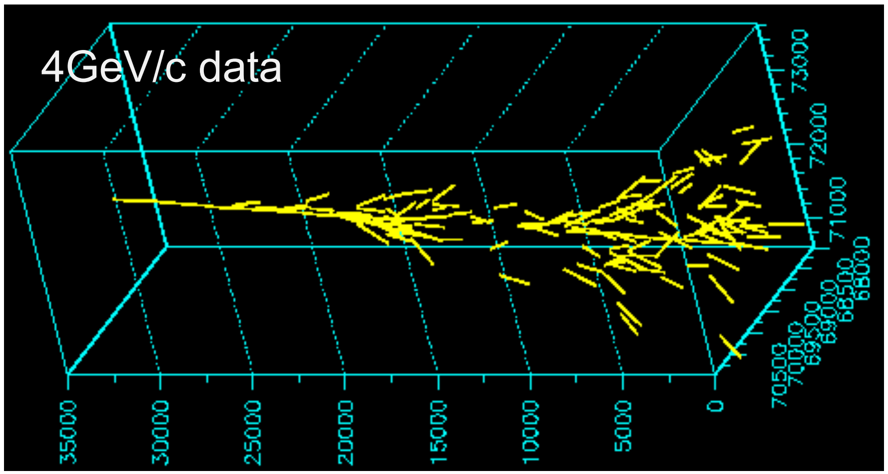
6 GeV π data/MC comparison



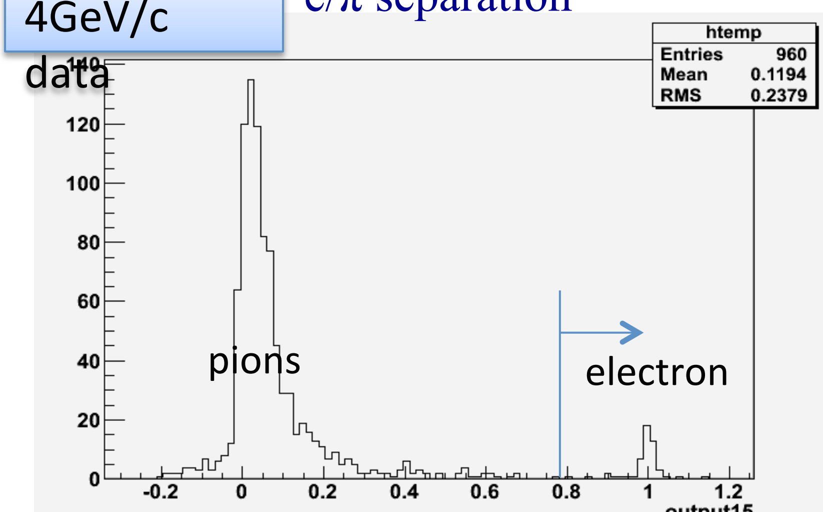
New Journal of Physics 14 (2012) 013026

Electromagnetic shower analysis

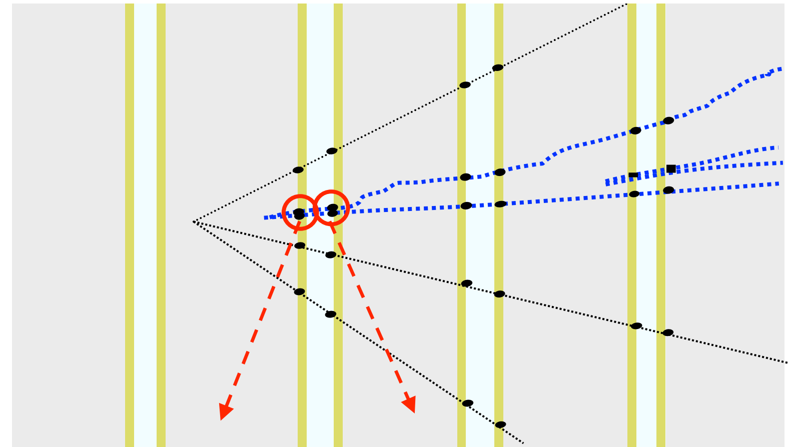
Shower reconstruction

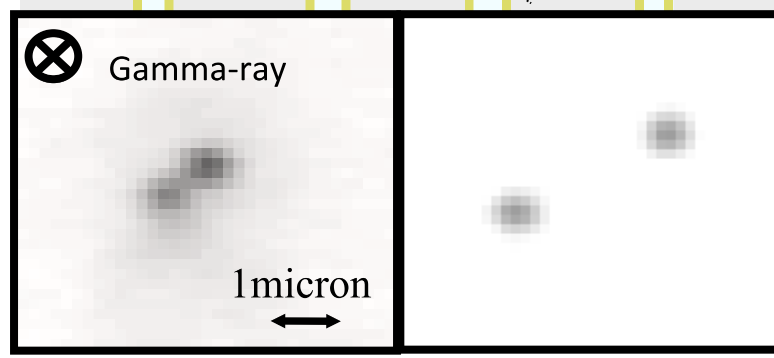


e/π separation

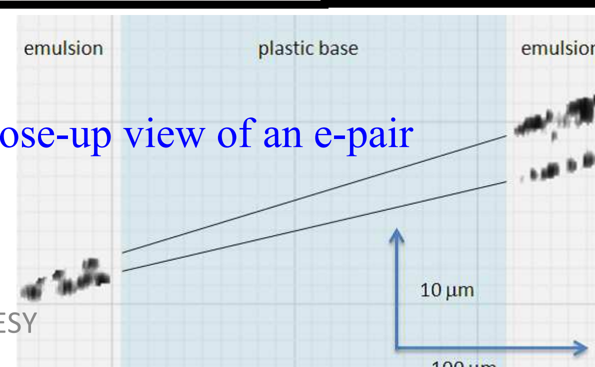


Electron/γ separation by e-pair detection

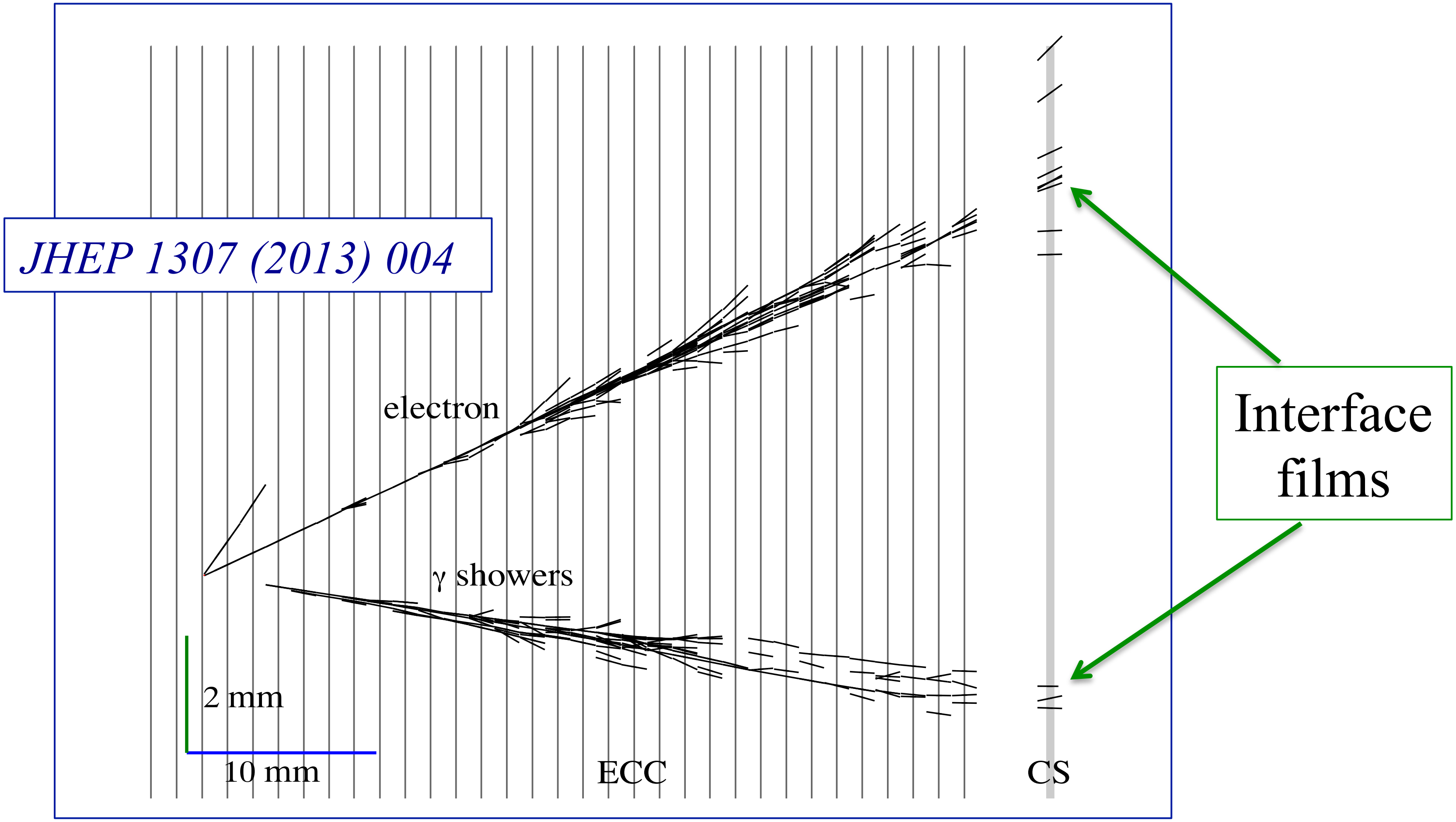




close-up view of an e-pair

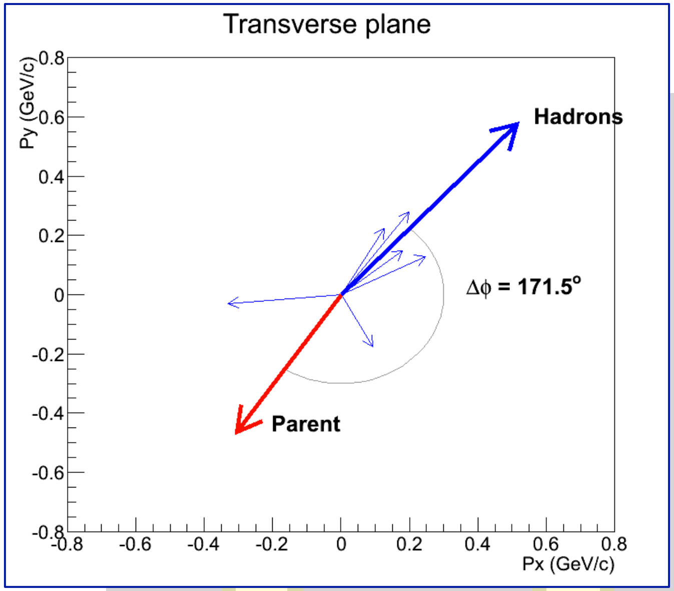


ν_e Interaction Detected in an OPERA Brick

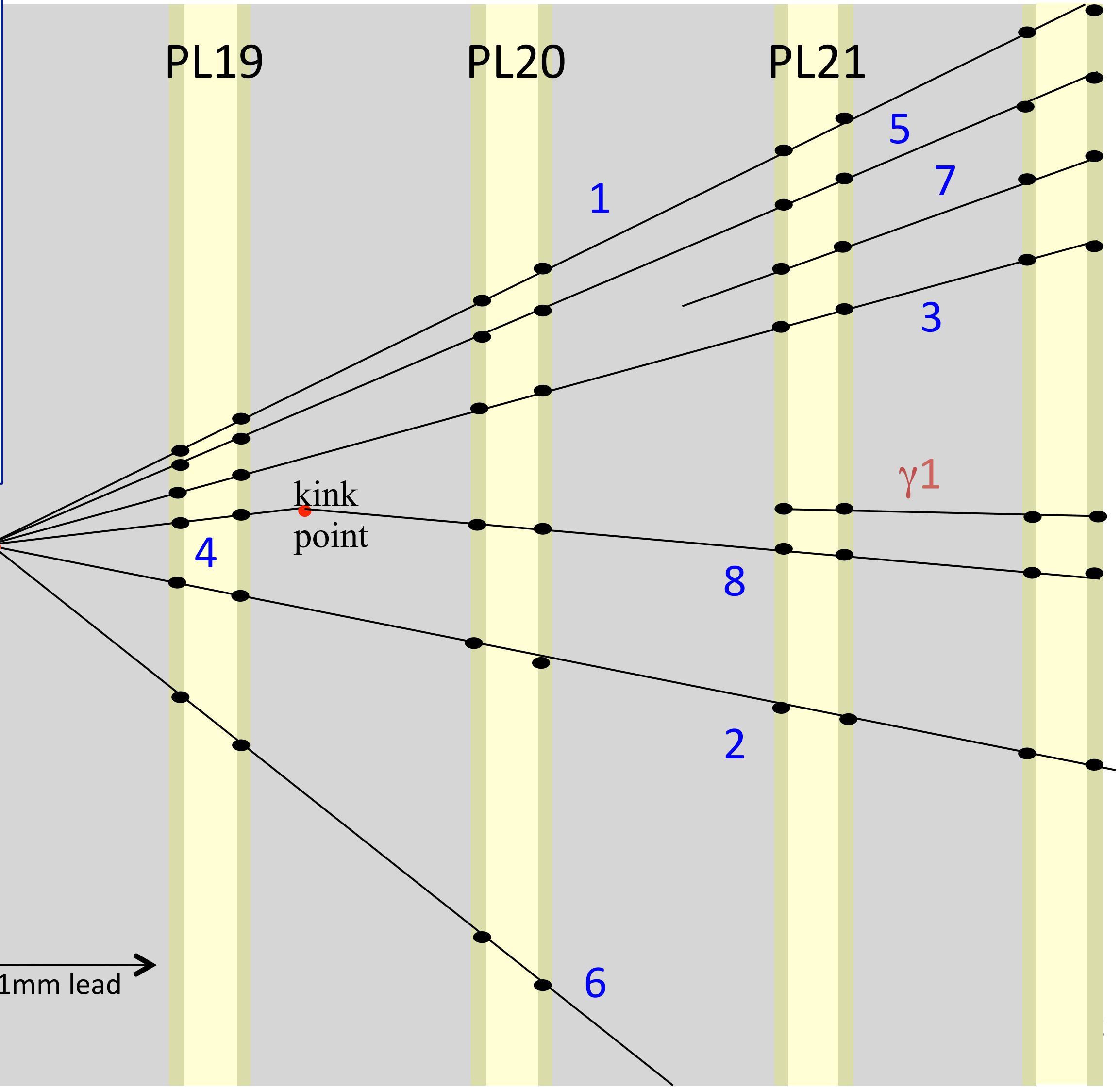


a π^0 is produced at the primary interaction verte and a γ is detected

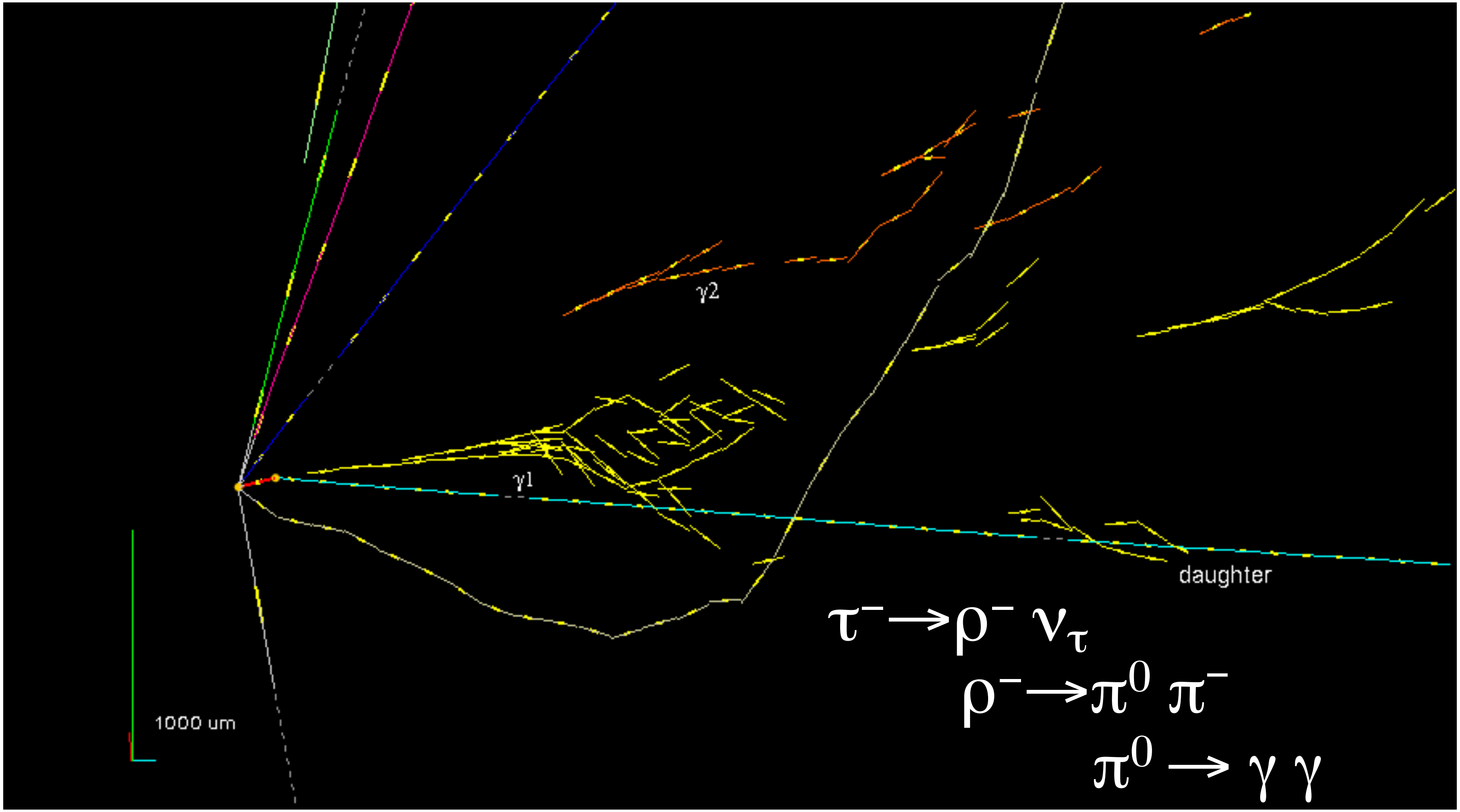
One of the OPERA ν_τ Candidates



Physics Letters B691 (2010) 138



THE FIRST OPERA ν_τ CANDIDATE



Physics Letters B691 (2010) 138

ν_τ/ANTI-ν_τ SEPARATION

THE COMPACT EMULSION SPECTROMETER

Magnetised target → charge and momentum measurement for hadrons

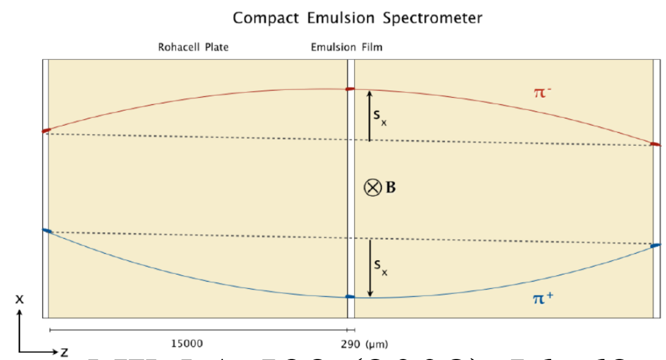
BR(τ → hadrons) ~ 65%

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

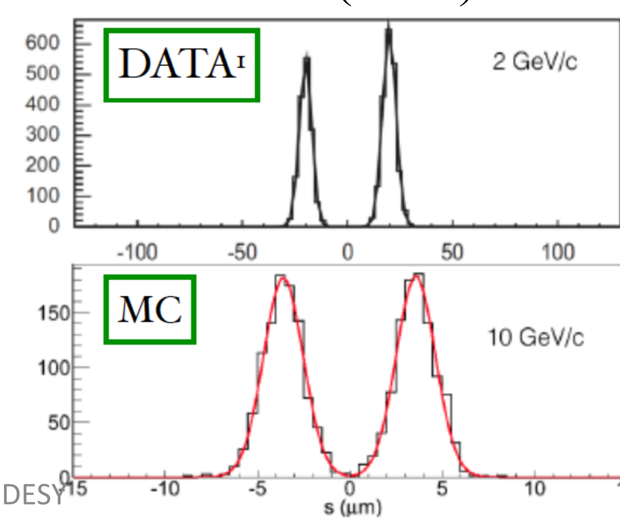
- 1T field
- 3 films interleaved with 2 Rohacell layers (15 mm)
- Thin chamber: 3cm in total
- 90% efficiency for hadronic τ daughters reaching the CES
- Sagitta to discriminate between positive and negative charge

Performances to be achieved

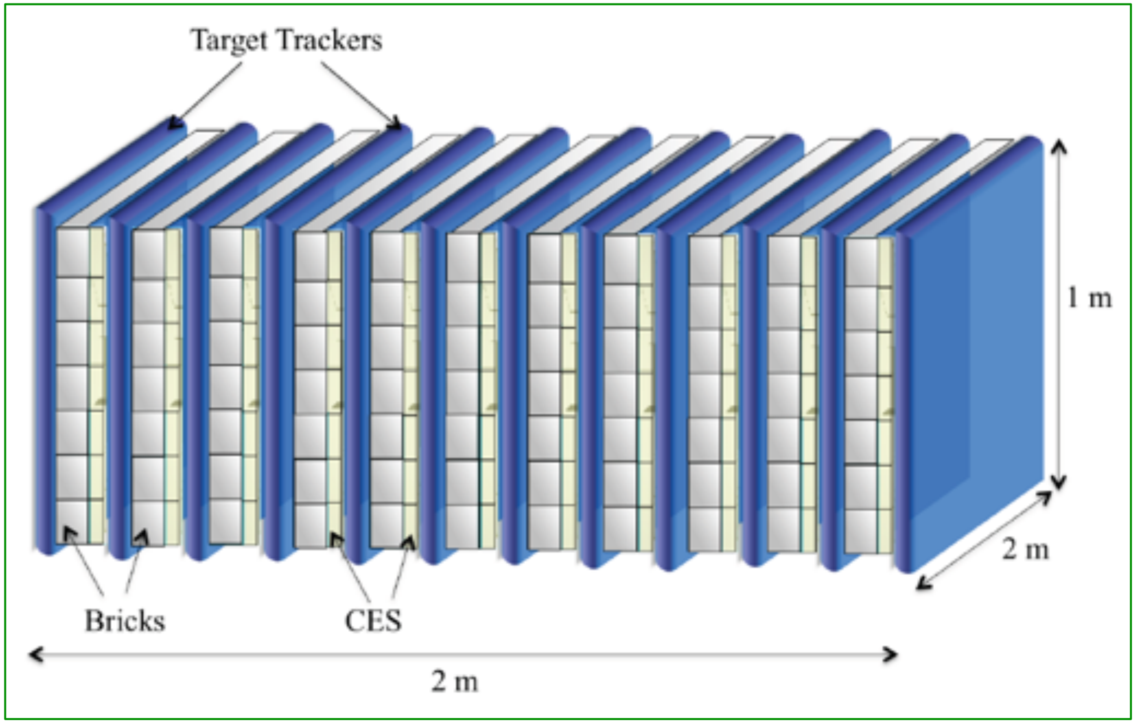
- charge measured up to 10 GeV/c (3 sigma level)
- $\Delta p/p < 20\%$ up to 12 GeV/c

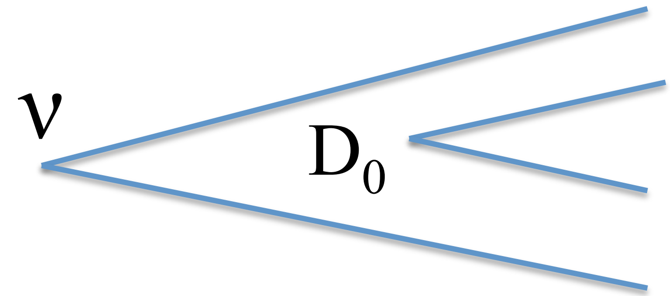


NIM A 592 (2008) 56–62



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

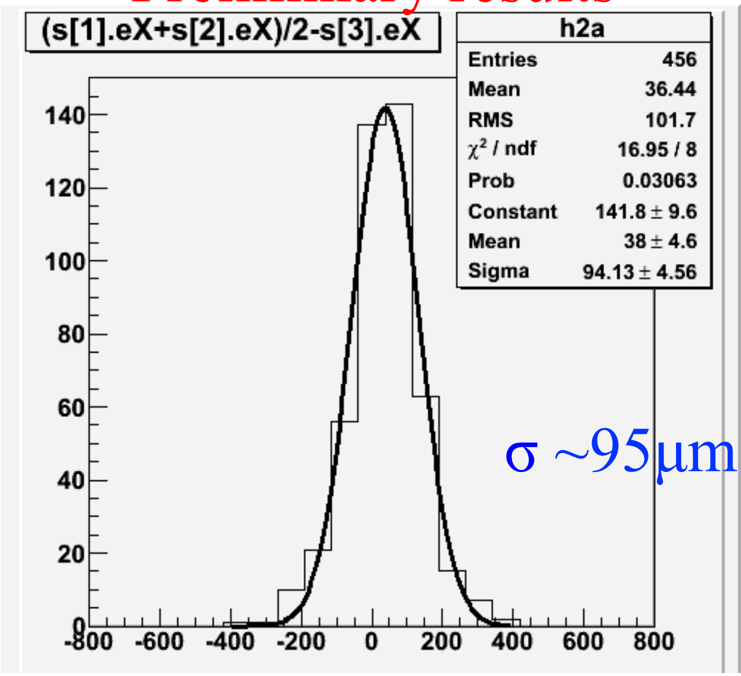
TARGET TRACKER PLANES

POSSIBLE OPTIONS

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

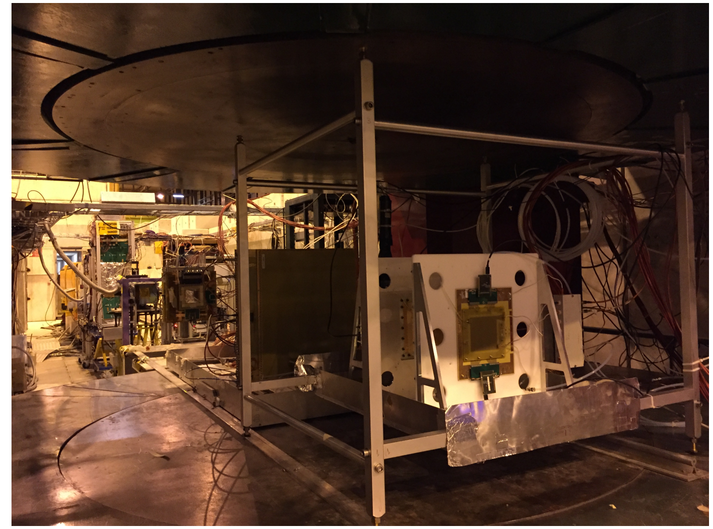
Testing some options

Preliminary results

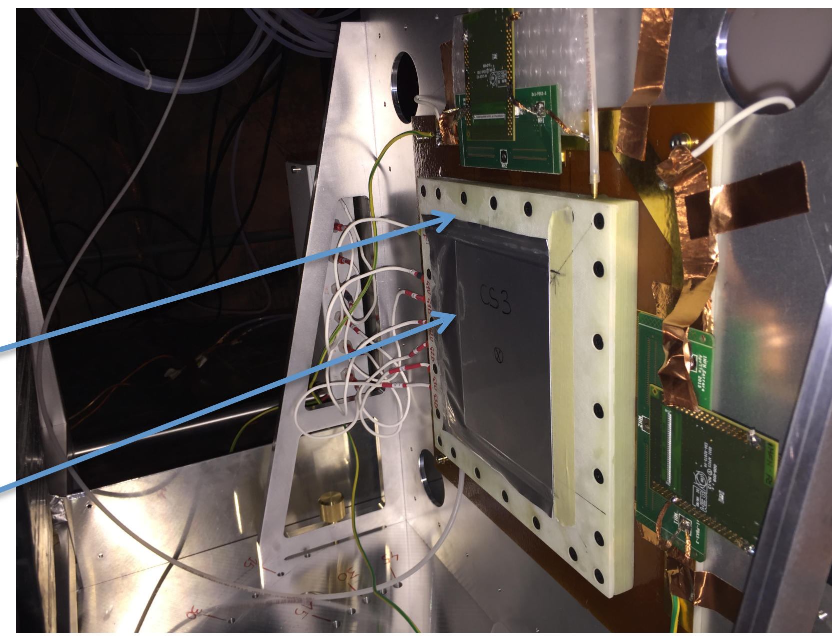


Perpendicular tracks with magnetic field off

Magnetic field and angular effect being studied

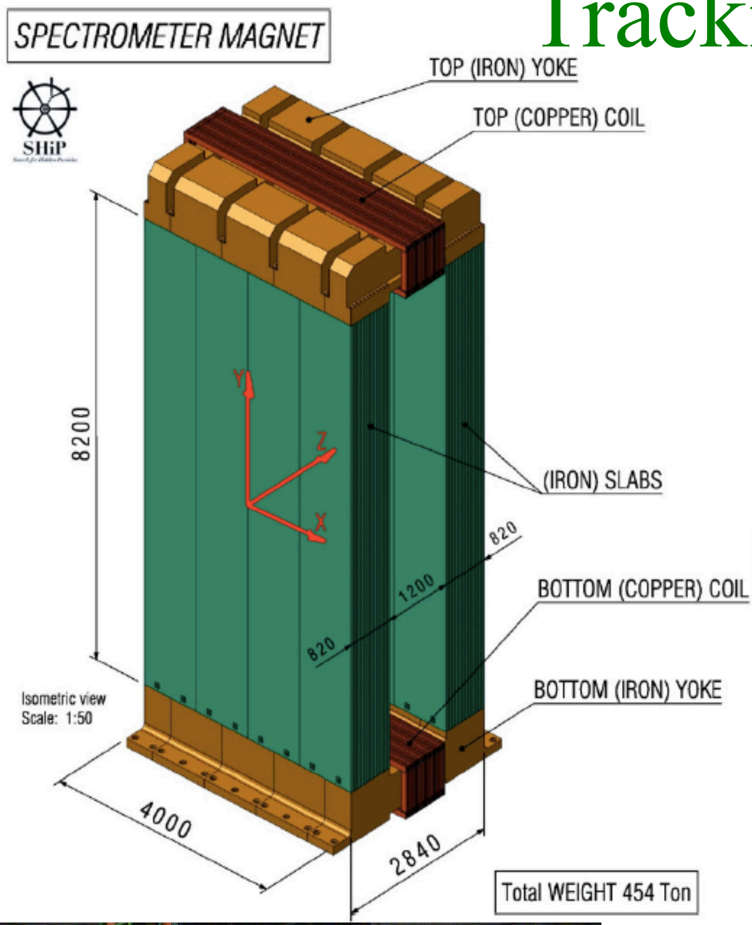


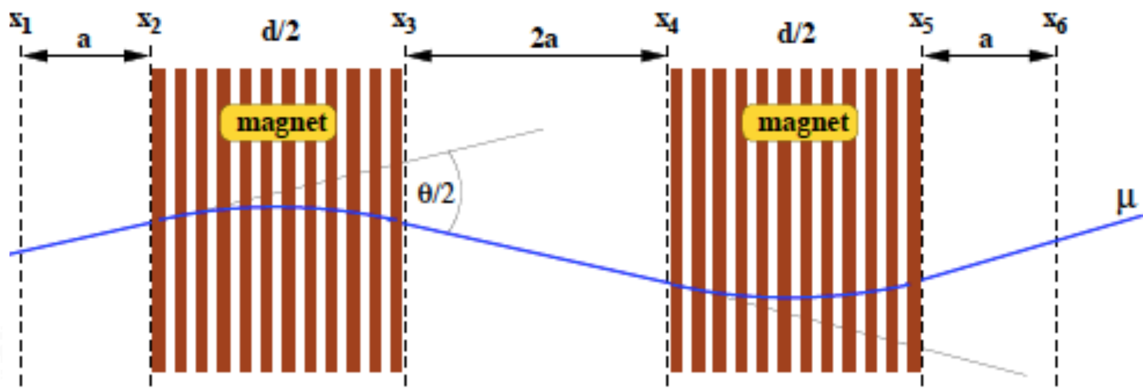
GEM



Emulsion films

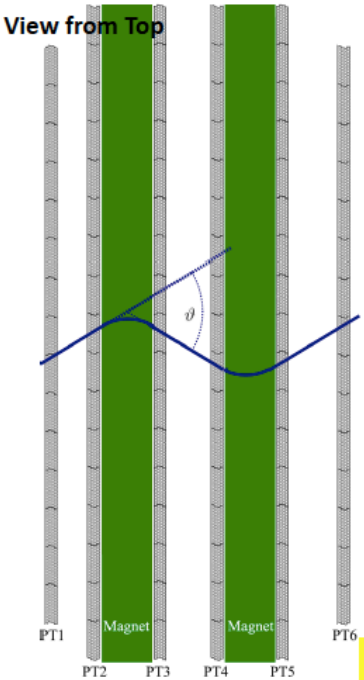
Tracking stations inside the magnet

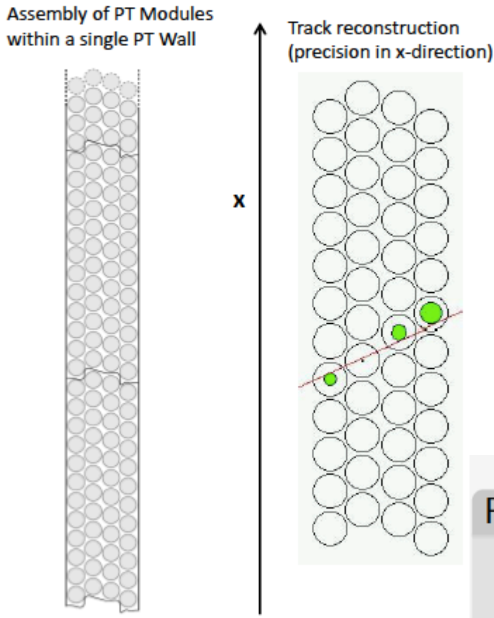




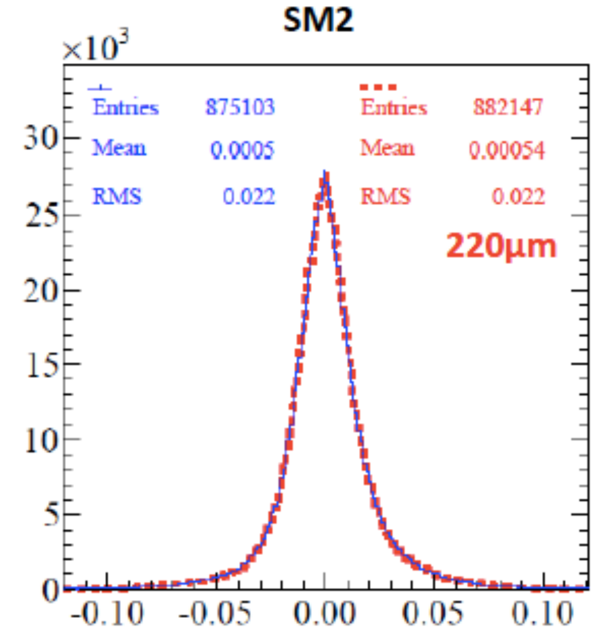
- Requirements:
  - coarse (1 cm) tracking inside the magnetised volume
  - 1ns time resolution
  - Muon rate ~5kHz/m^2 rate
  - Electron rate ~ 1 order higher
- RPC's technology is one option
- Streamer versus avalanche to be studied

Muon momentum measurement and identification



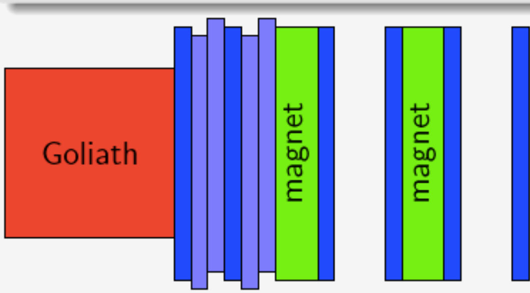


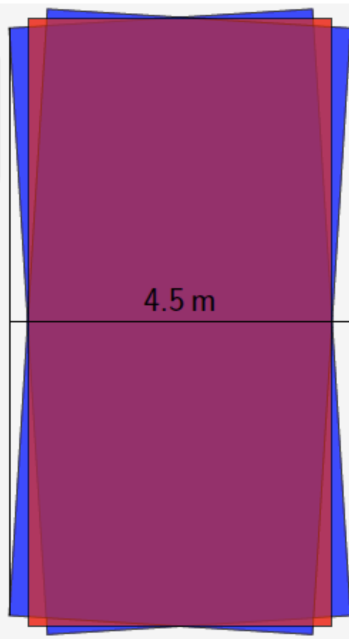
OPERA requirement: Δp/p < 25% for p < 25GeV



Requirements for 3d reconstruction

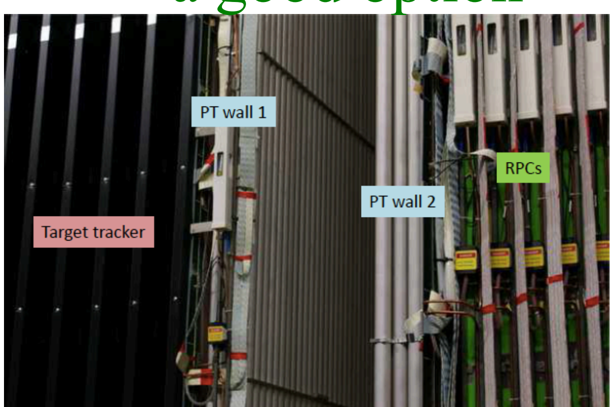
- Stereo angle between planes
- 3 projections to avoid ambiguities





- 2×3 projections
- 2 projections rotated by $\pm 3.6°$
- maximal width: 4.5 m

OPERA drift tubes are a good option



SHiP

Neutrino detector performances

✓ ***Unique capability of detecting all three neutrino flavours***

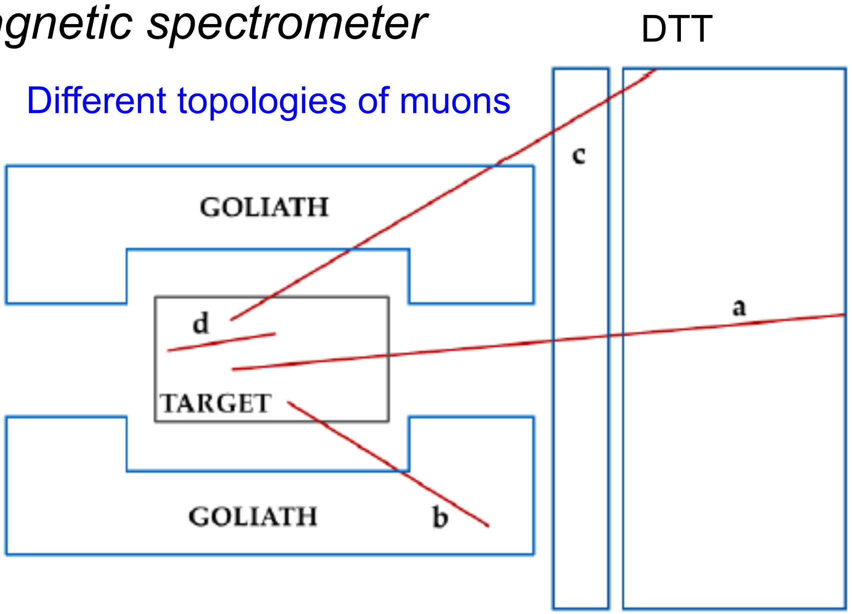
- $\nu_\tau / \bar{\nu}_\tau$ → *ν interaction and τ decay vertices in emulsion target*
- ν_e → *electrons producing em shower in emulsion target*
- ν_μ → *muons identified by TT, DTT and the muon spectrometer of the tau neutrino detector*

	ε_{tot} (%)
$\tau \rightarrow \mu X$	60
$\tau \rightarrow hX$	62
$\tau \rightarrow 3hX$	63
$\tau \rightarrow eX$	56

✓ ***Separation between tau and anti tau-neutrinos by the charge measurement***

- *charge of hadrons is measured by CES*
- *charge of muons is measured by CES and magnetic spectrometer*

	$\tau \rightarrow hX$	$\tau \rightarrow 3hX$	$\tau \rightarrow \mu X$
Correct charge	70%	49%	94%
Wrong charge	0.5%	1.0%	1.5%



Hidden Sector detector concept

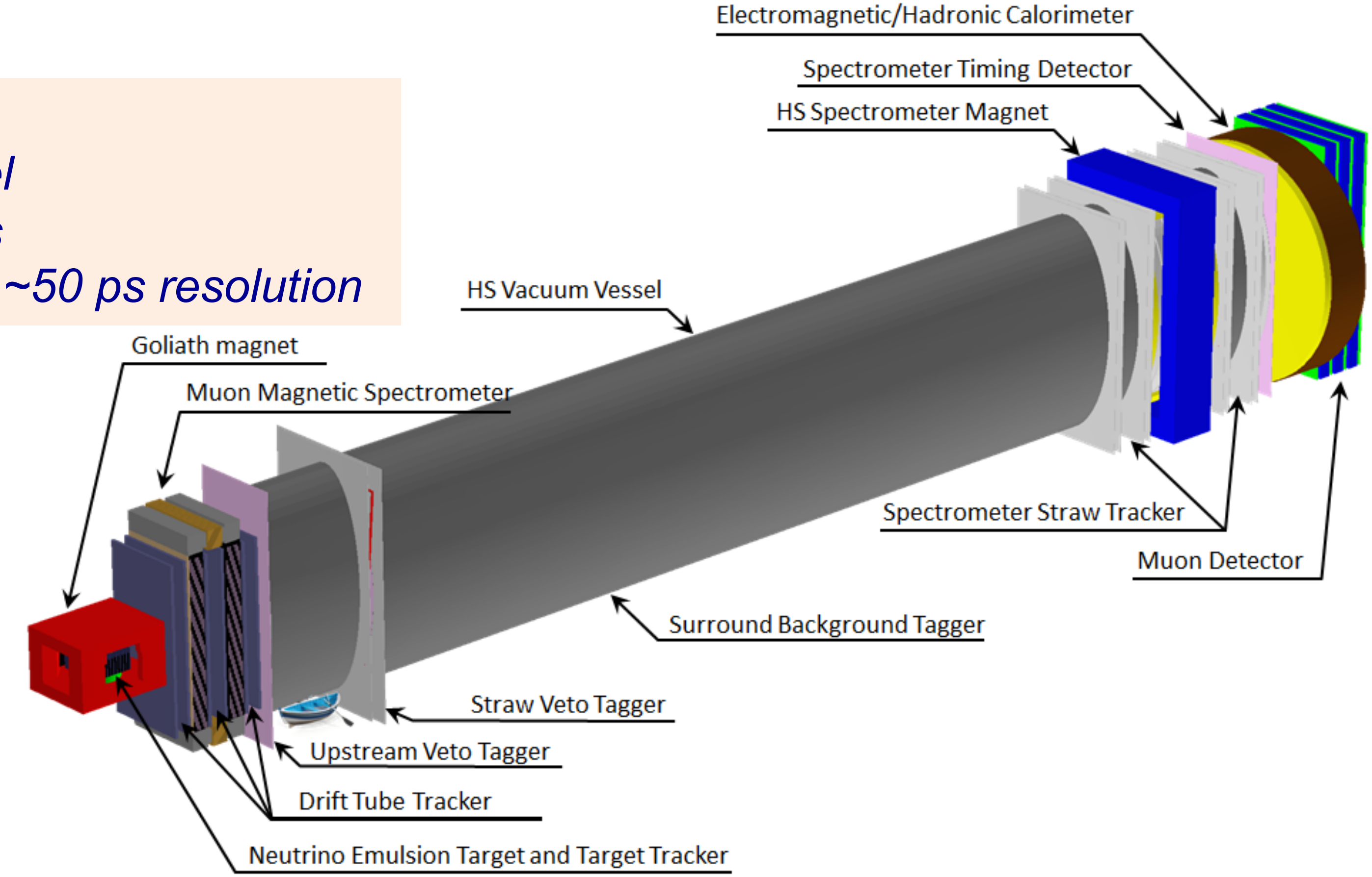
✓ Reconstruction of HS decays in all possible final states

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 with ~50 ps resolution*

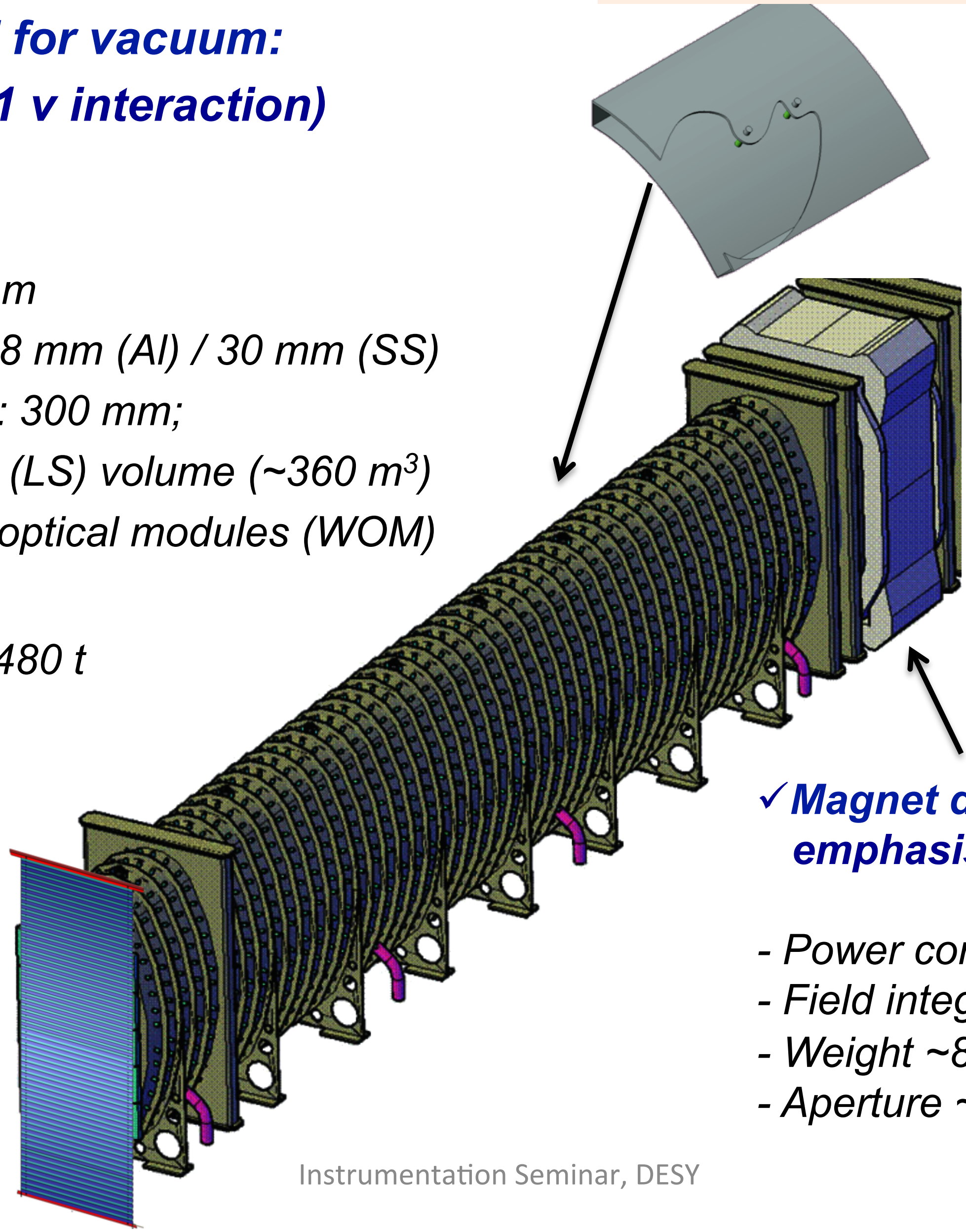


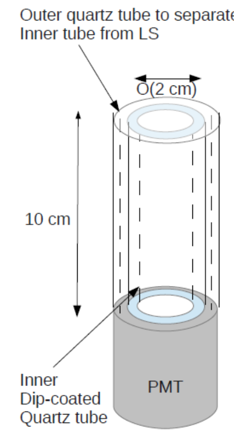
HS decay volume and spectrometer magnet

- ✓ ***Estimated need for vacuum:***
  ~ 10^{-3} mbar (<1 ν interaction)

- ✓ ***Vacuum vessel***
  - *10 m x 5 m x 60 m*
  - *Walls thickness: 8 mm (Al) / 30 mm (SS)*
  - *Walls separation: 300 mm;*
  - *Liquid scintillator (LS) volume (~360 m^3) readout by WLS optical modules (WOM) and PMTs*
  - *Vessel weight ~ 480 t*

LS cell with WOMs

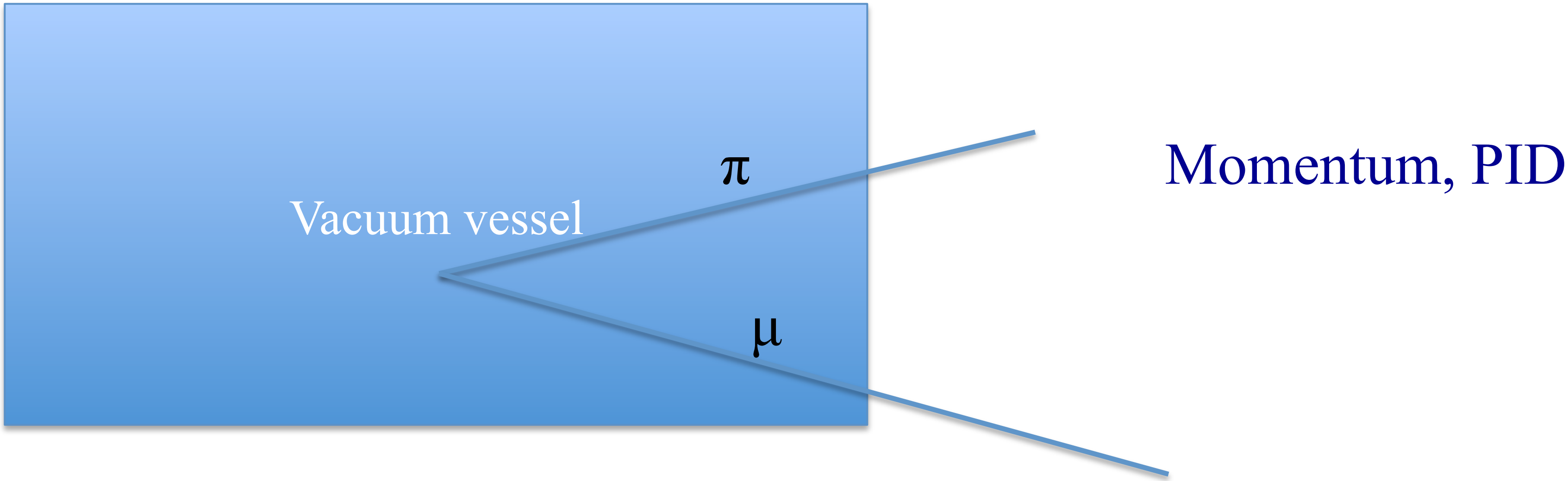




✓ ***Magnet designed with an emphasis on low power***

- *Power consumption < 1 MW*
- *Field integral: 0.65Tm over 5m*
- *Weight ~800 t*
- *Aperture ~50 m^2*

Signal features



- Main background: neutrino interactions
- Reduce this background by:
  - IP cut
  - Invariant mass
- Important to
  - Measure precisely the momentum
  - Identification the particle
- Reduce combinatorial background by precise timing

Momentum resolution of the HS (straw tubes) tracker

SHiP

- material budget per station 0.5% X_0

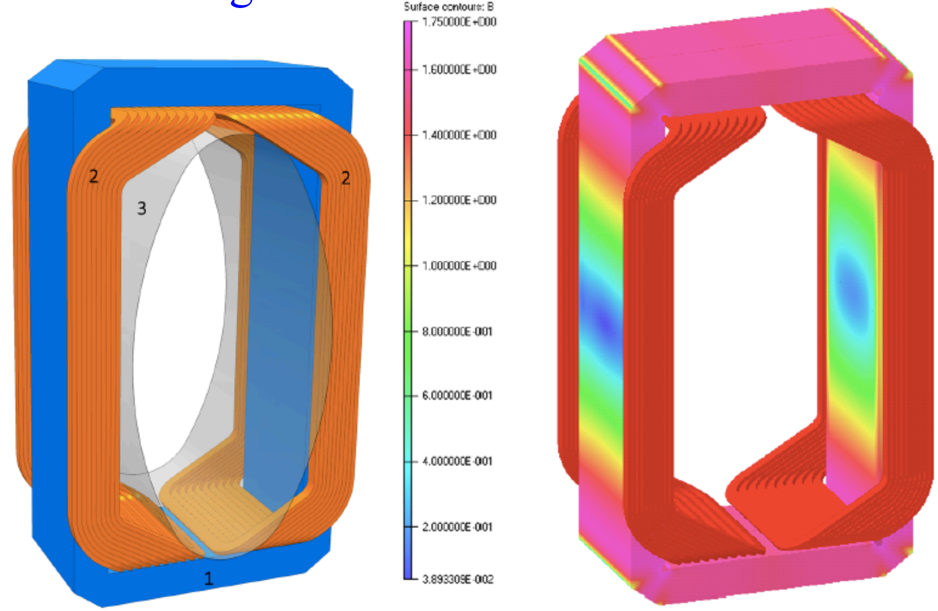
- position resolution 120 μm per straw, 8 hits per station on average

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

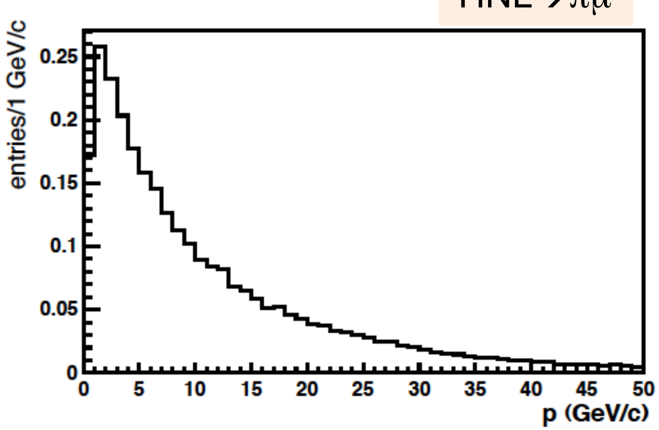
Momentum resolution is dominated by multiple scattering below 22 GeV/c

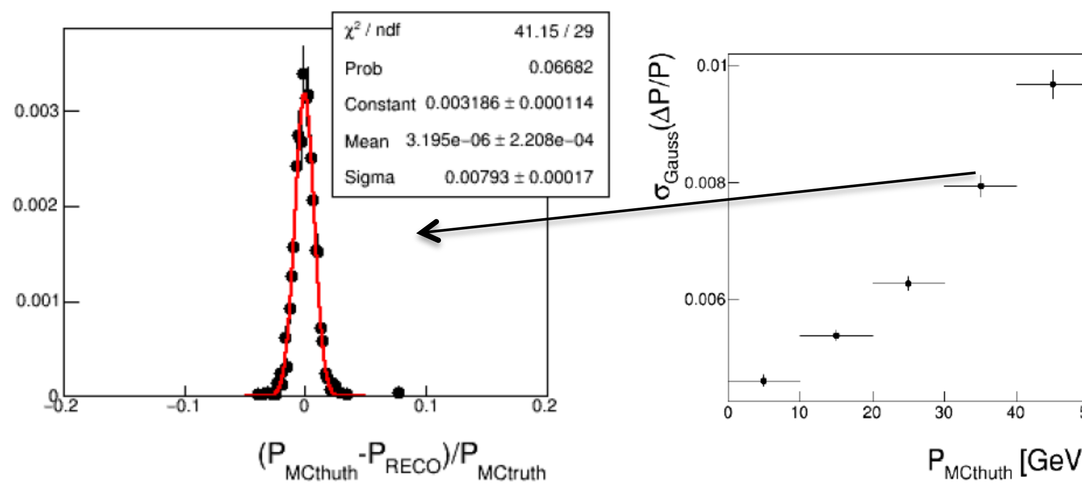
(For HNL → $\pi\mu$, 75% of both decay products have P < 20 GeV/c)

Magnet with vacuum vessel



HNL→$\pi\mu$





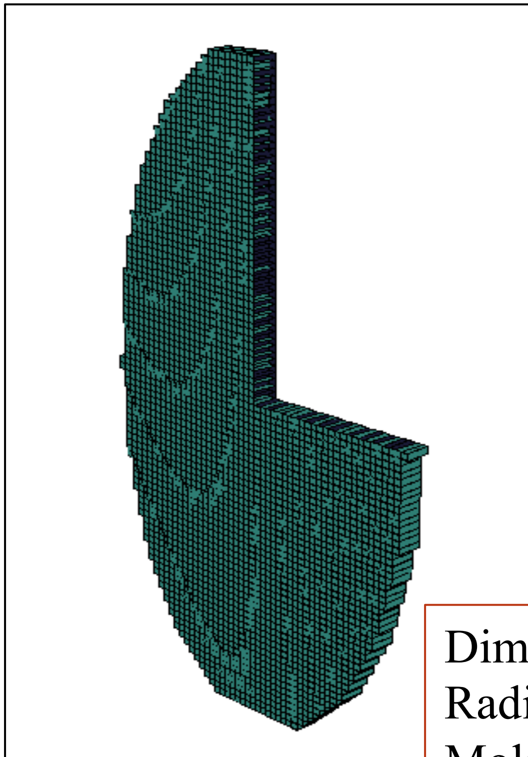
Vertex resolution *(also driven by multiple scattering and ΔP/P):*

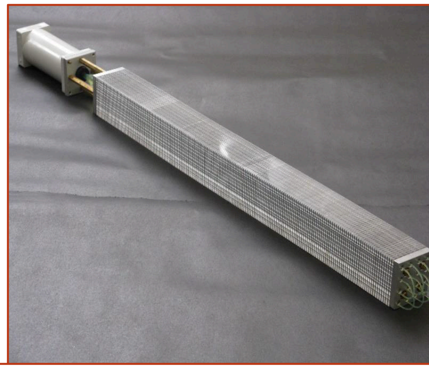
σ_{xy} ~ O(mm), σ_z ~ O(cm)

Calorimeters

ECAL

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

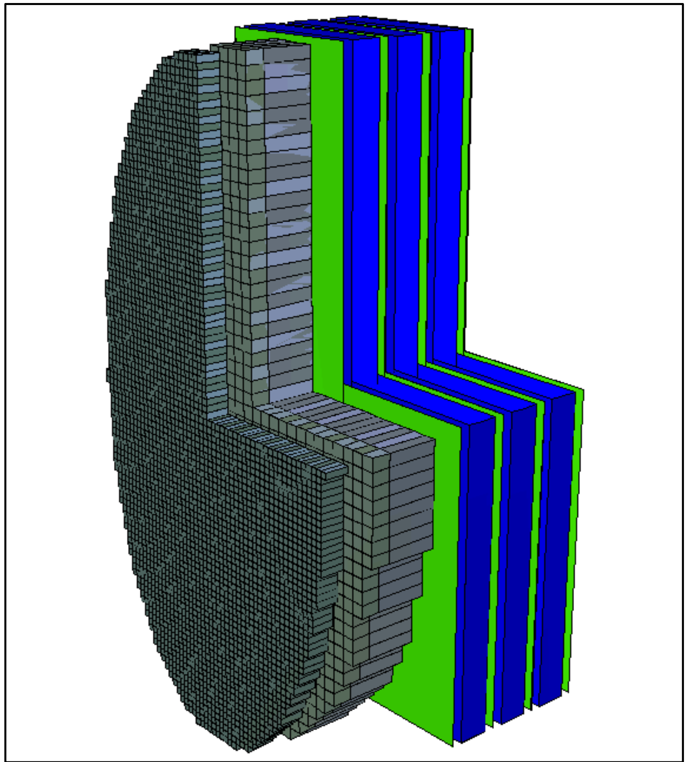




Dimensions	60x60 mm^2
Radiation length	17 mm
Moliere radius	36 mm
Radiation thickness	25 X_0
Scintillator thickness	1.5 mm
Lead thickness	0.8 mm
Energy resolution	1%

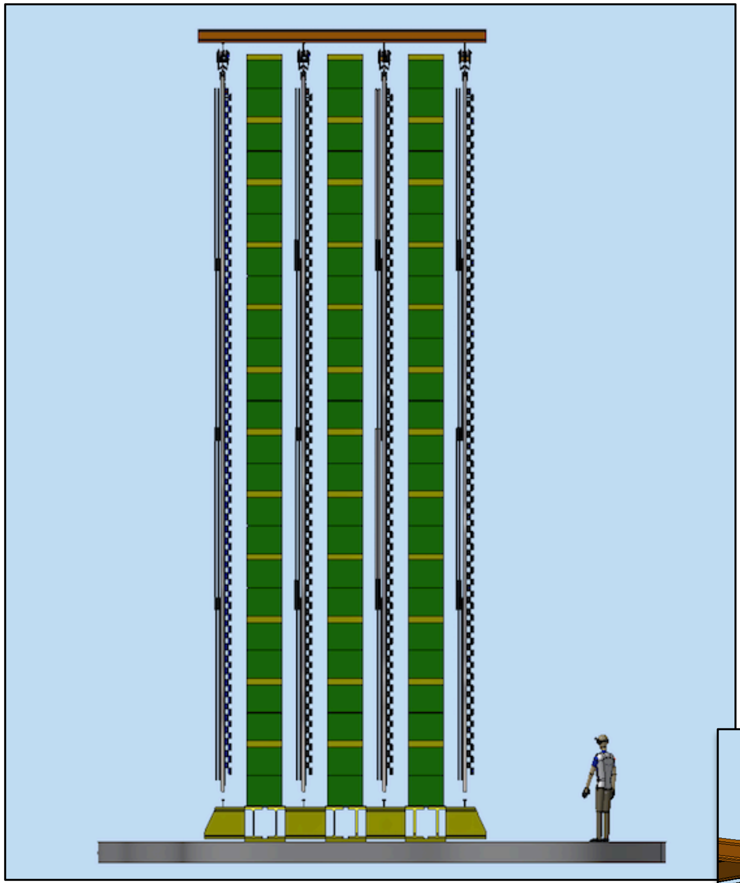
HCAL

- 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



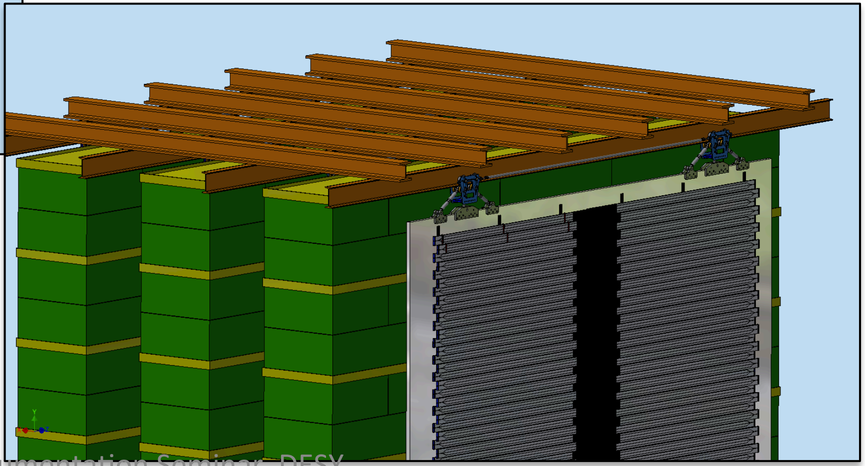
Muon System

Based on scintillating bars, with WLS fibers and SiPM readout



Requirements:

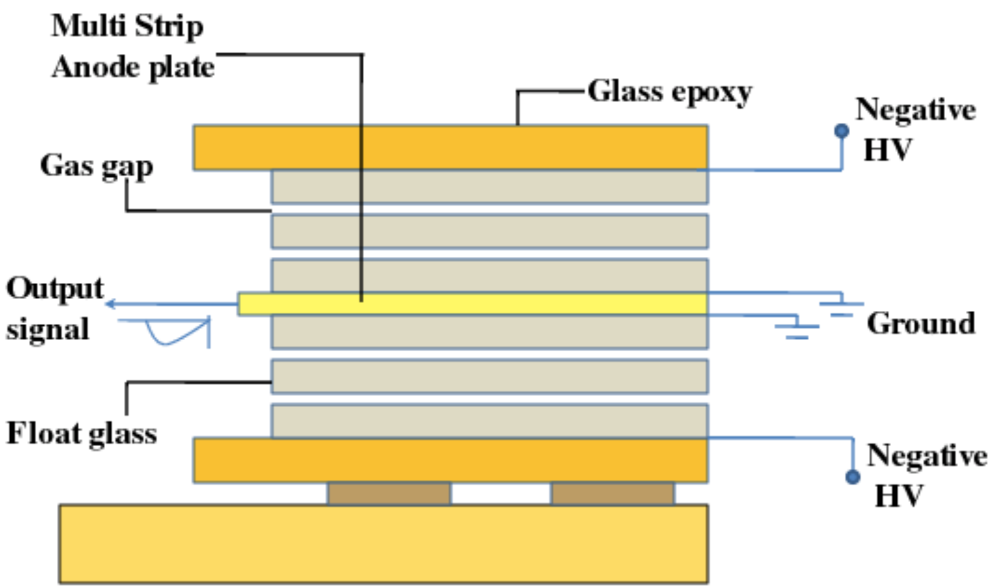
- High-efficiency identification of muons in the final state
- Separation between muons and hadrons/electrons
- Complement timing detector to reject combinatorial muon background



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

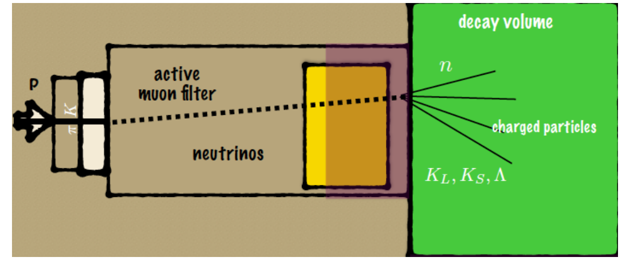
Timing detector (< 100ps)

Multi-gap RPC is one option



σ_{xy} ~ 1cm

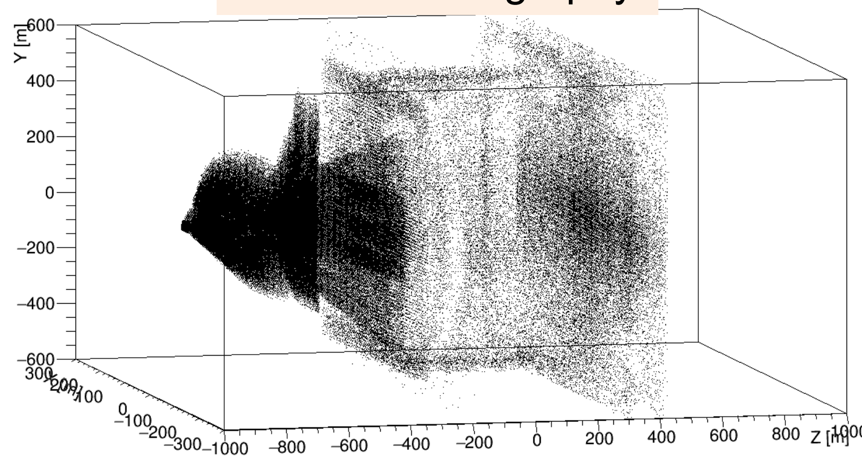
HS Backgrounds (1)



Main sources of background

✓ ***Neutrino DIS interactions with material in the vicinity of the HS decay volume***
(interactions of ν with air in the decay volume are negligible at 10^{-3} mbar)

Neutrino tomography

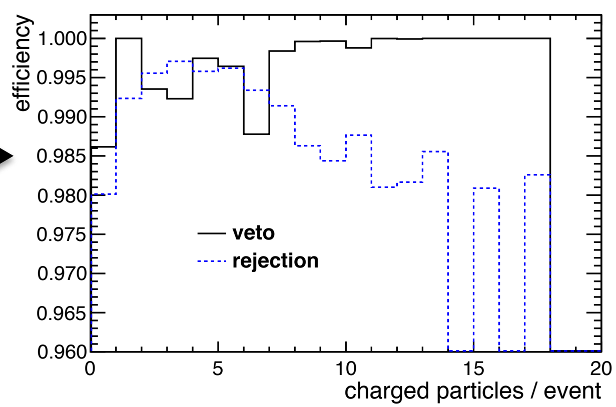


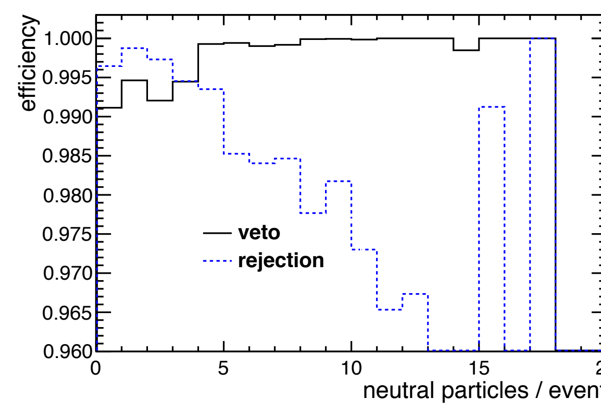
Origin of neutrino interactions

- *Walls of the decay volume (>80%)*
- *Tau neutrino detector*
- *HS tracking system*

Combination of veto and selection cuts reduces the ν-induced background to zero

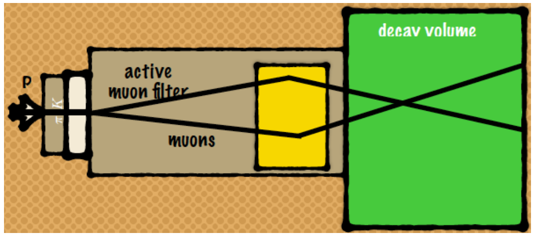
Veto efficiency increases with event multiplicity →





HS Backgrounds (2)

✓ ***Muon combinatorial background***



Simulation predicts O(10^{12}) muon pairs in the decay volume in 5 years of data taking

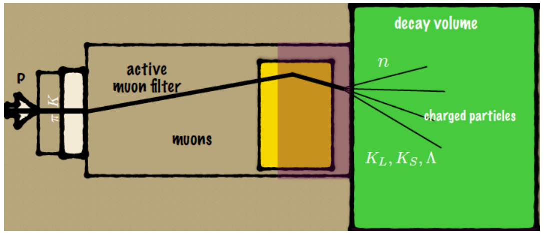
Suppressed by:

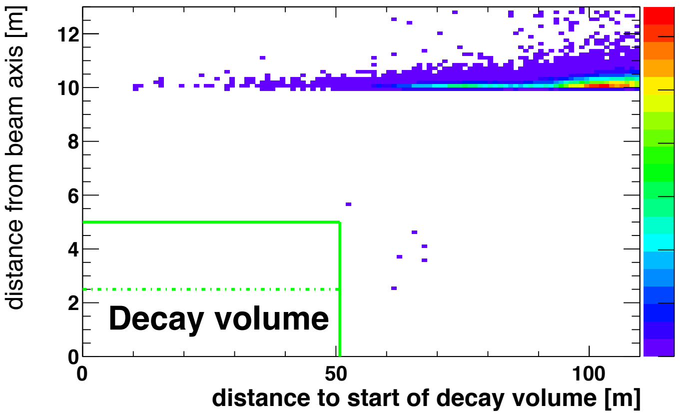
- *Basic kinematic and topological cuts ~10^4*
- *Timing veto detectors ~10^7*
- *Upstream veto and surrounding veto taggers ~10^4*

✓ ***Muon DIS interactions***

- *V^0s produced in the walls of the cavern*
- *DIS close to the entry of the decay volume*

→ smaller than neutrino induced background





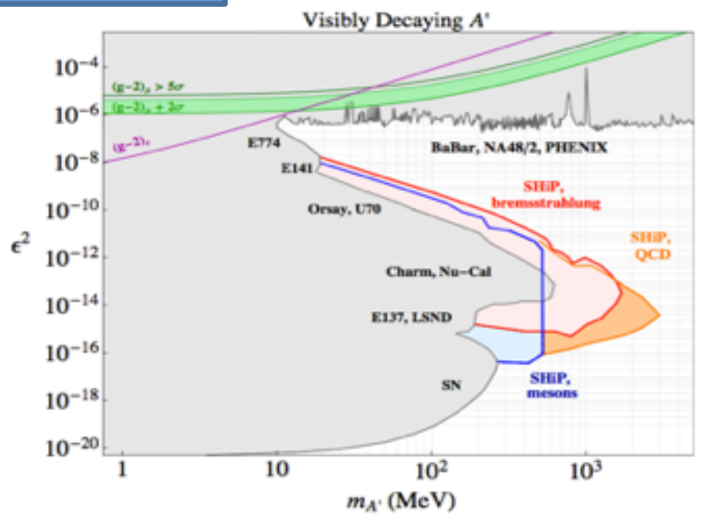
✓ ***Cosmics***

Background summary: no evidence for any irreducible background

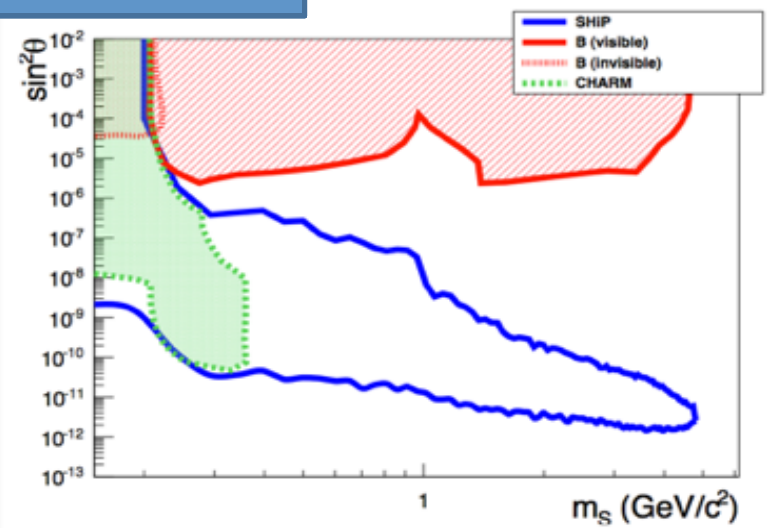
SHiP sensitivity to Hidden Sector

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

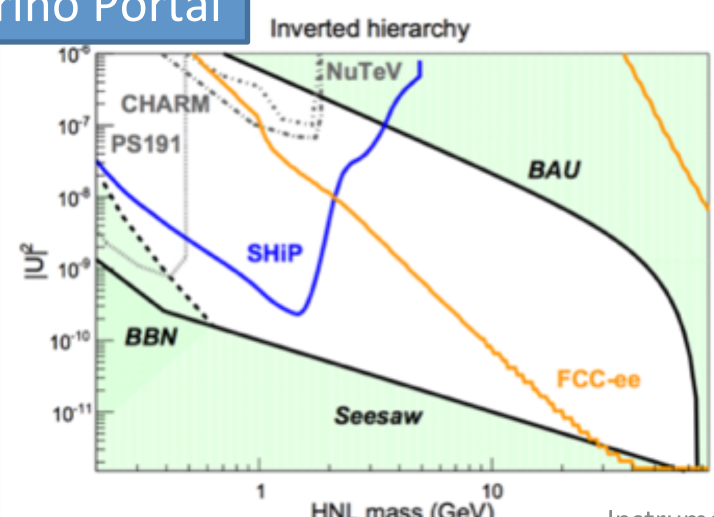
Vector Portal



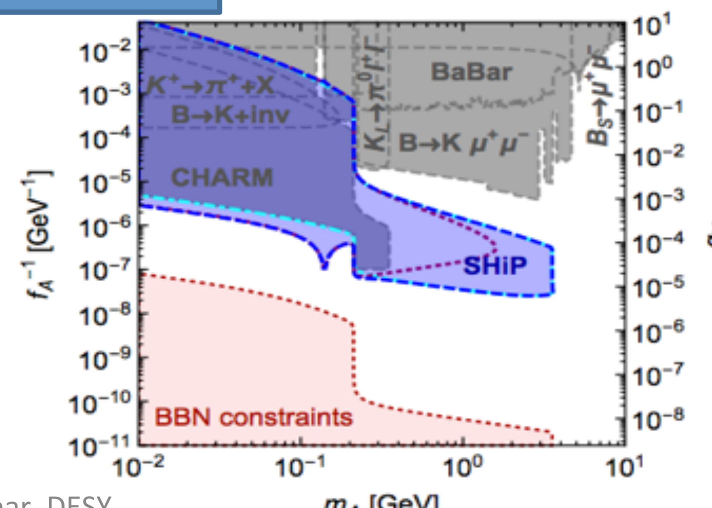
Scalar Portal



Neutrino Portal



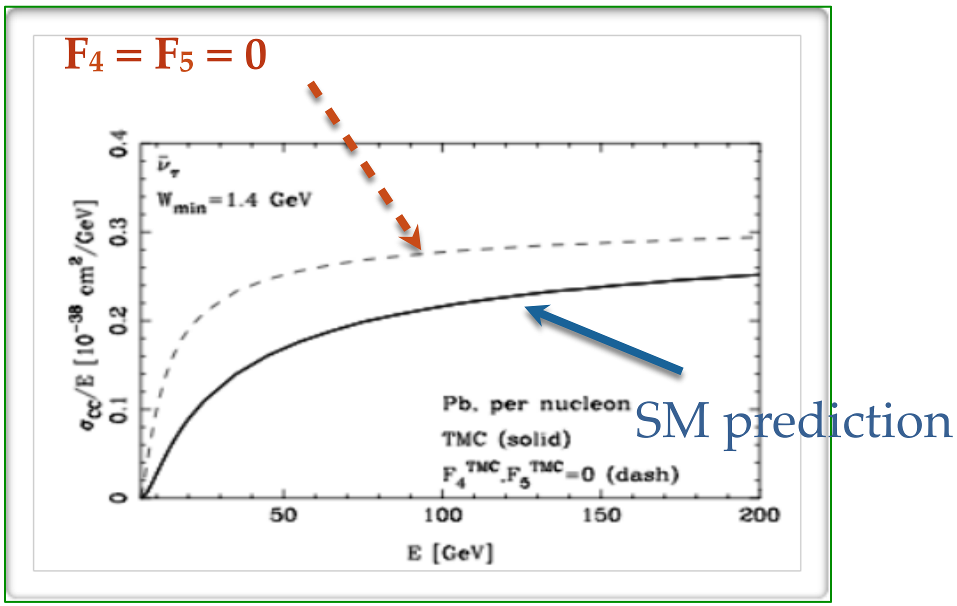
Axion Portal

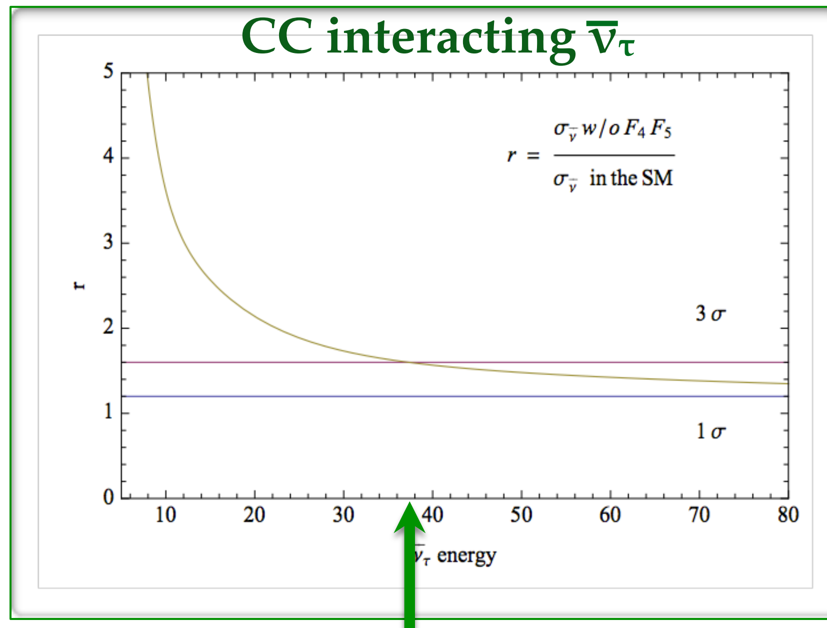


F_4 and F_5 Structure Functions

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

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



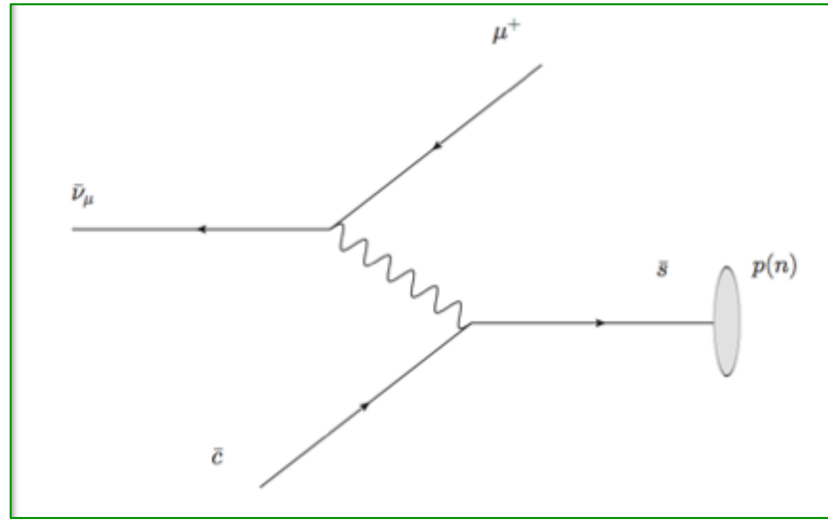


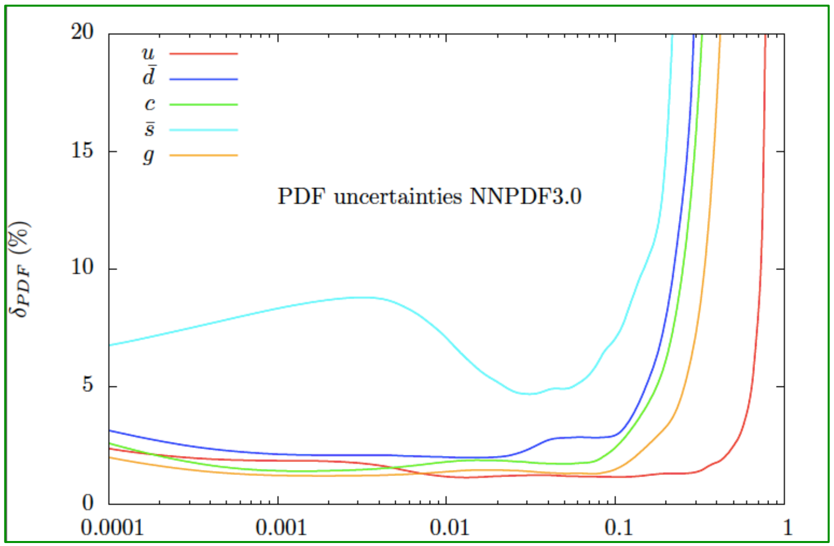
$E(\bar{\nu}_\tau) < 38$ GeV

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

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 $c\bar{s}$

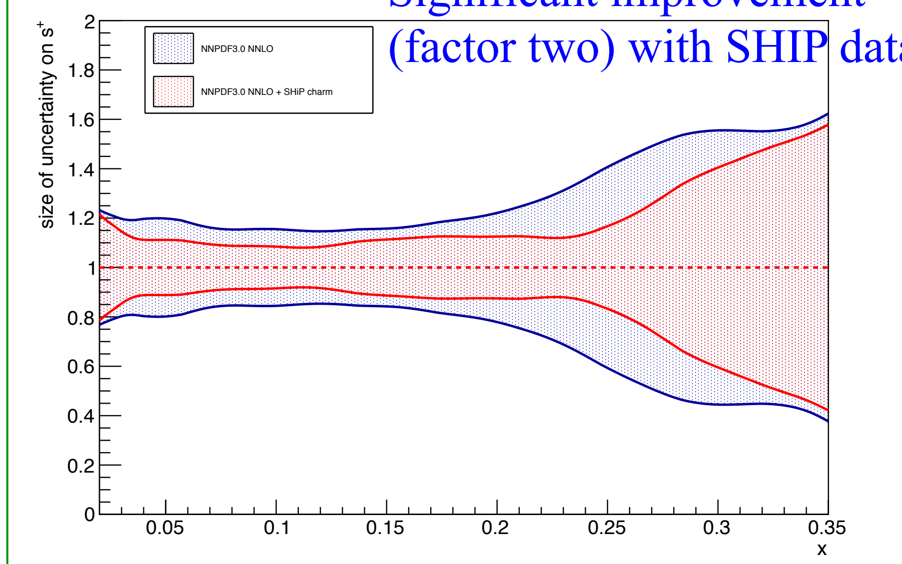




Phys. Rev. D91 (2015) 113005

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

χ produced by a dark photon decay

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

P. deNiverville, D. McKeen, and A. Ritz, Phys.Rev. D86 (2012) 035022

$\alpha' =$ dark photon coupling with χ

SIGNAL SELECTION

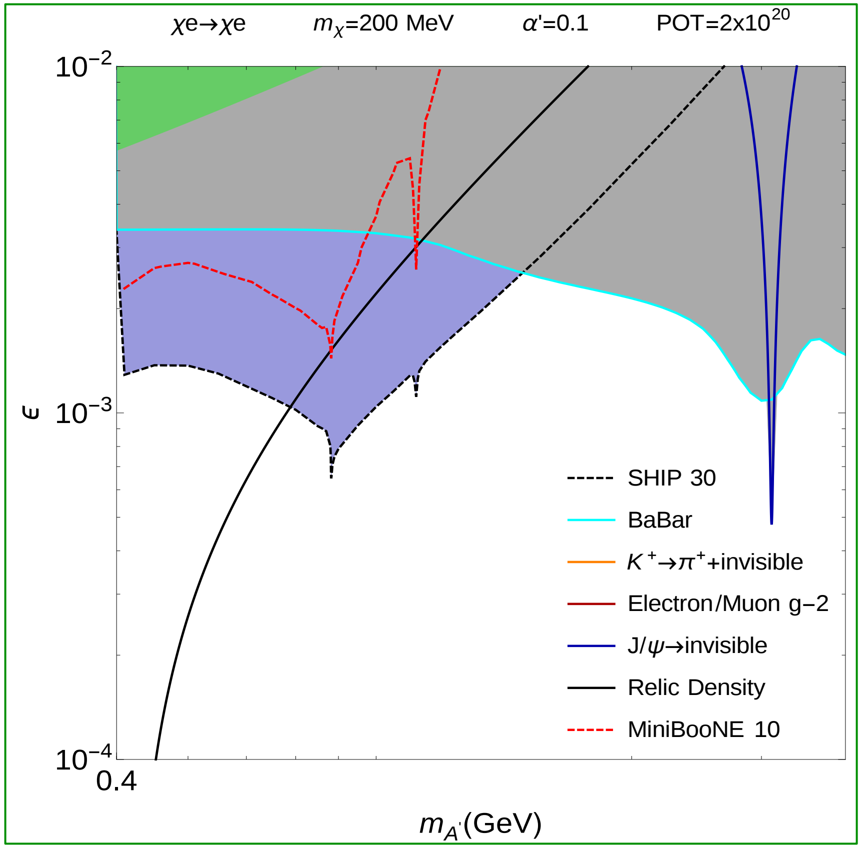
$$\begin{cases} 0.01 < \theta < 0.02 \\ E < 20 \text{ GeV} \end{cases}$$

BACKGROUND PROCESSES

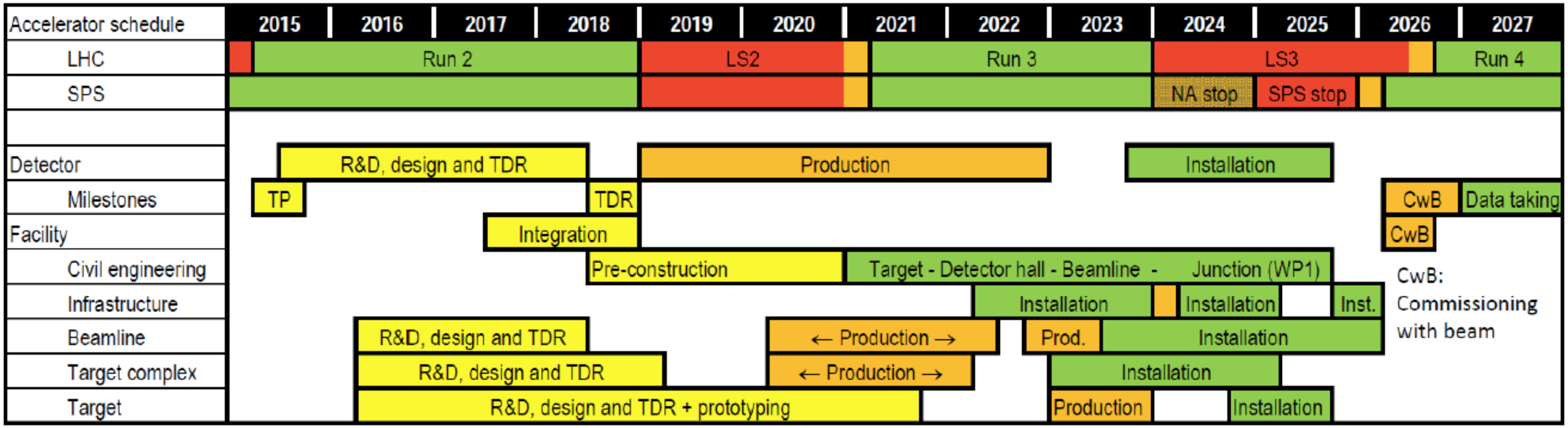
	ν_e	$\bar{\nu}_e$	ν_μ	$\bar{\nu}_\mu$	all
Elastic scattering on e^-	16	2	20	18	56
Quasi - elastic scattering	105	73			178
Resonant scattering	13	27			40
Deep inelastic scattering	3	7			10
Total	137	109	20	18	284

$\epsilon =$ dark photon coupling with e.m. current

$m_A =$ dark photon mass



Project schedule



~10 years from TP to data taking

- ✓ *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)*
- ✓ *All TDRs by the end of 2018*
- ✓ *Four years for detector construction, plus two years for installation*
- ✓ *Updated schedule with new accelerator schedule (Run 2 up to end 2018, 2 years LS2) relaxes current schedule*
  - ➔ ***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*
- ✓ *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 recommendations delivered in January 2016*
- ✓ *SHiP could therefore constitute a key part of the CERN Fixed Target programme in the HL-LHC era. SPSC* ***recommends*** *that the SHiP proponents proceed with the preparation of a Comprehensive Design Report (CDR), and that this preparation be made in close contact with the planned Fixed Target working group.*
- ✓ *SHiP is an experiment recognised at CERN (grey book) since May 2016*
- ✓ *Optimisation of the design going on: many technological choices still waiting for your contribution!*