TAU NEUTRINO PHYSICS IN SHIP

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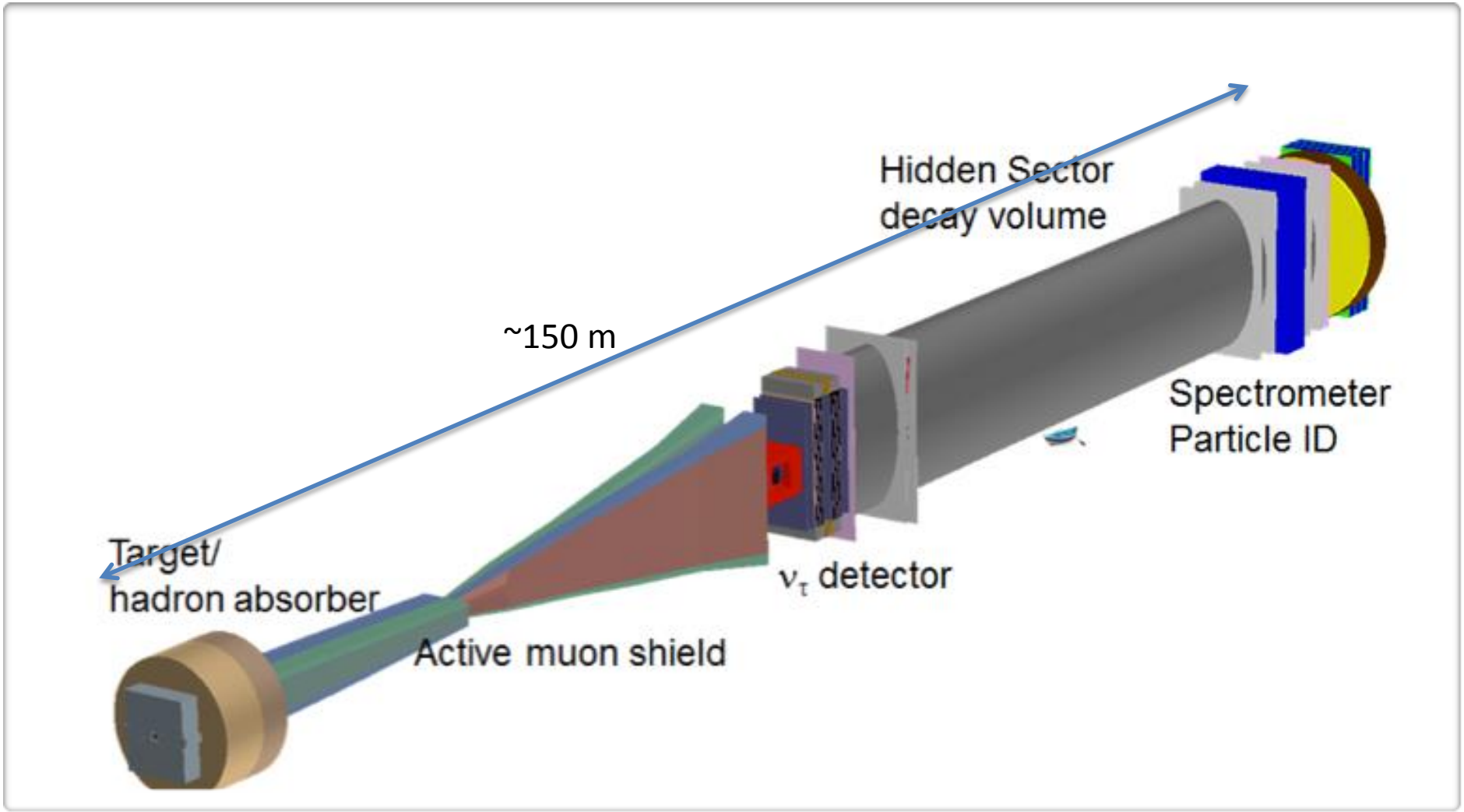
Motivation For ν_τ Studies

- 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) were reported in 2008 with looser cuts

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

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

SHiP At CERN


Hidden Sector
decay volume
~150 m
Spectrometer
Particle ID
Target/
hadron absorber
ν_τ detector
Active muon shield

FACILITY IDEAL TO STUDY ν_τ PHYSICS

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

$\sigma_{c\bar{c}} = 18.1 \pm 1.7$ μbarn

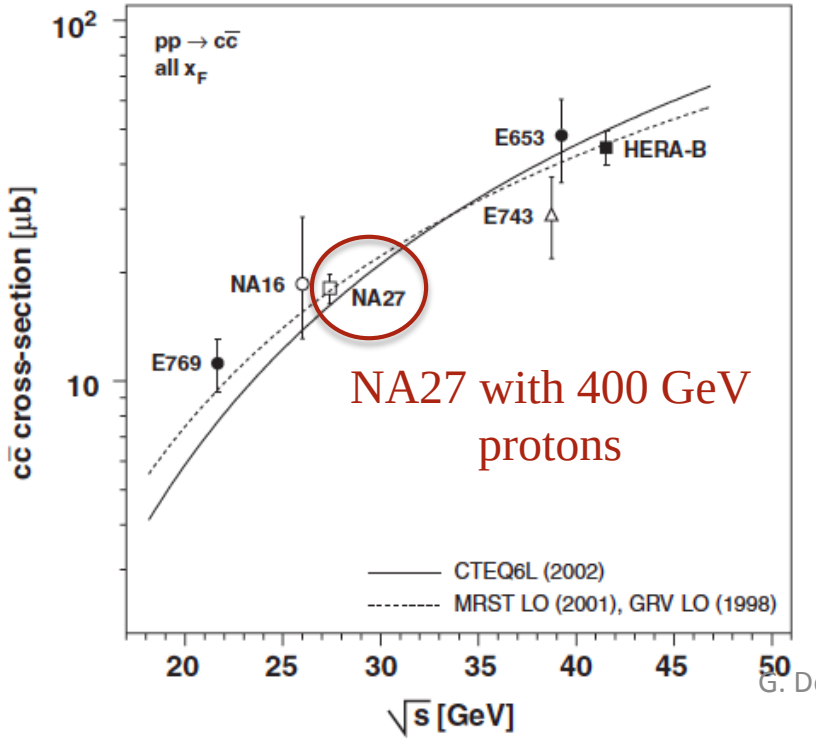
Physics Reports 433 (2006) 127

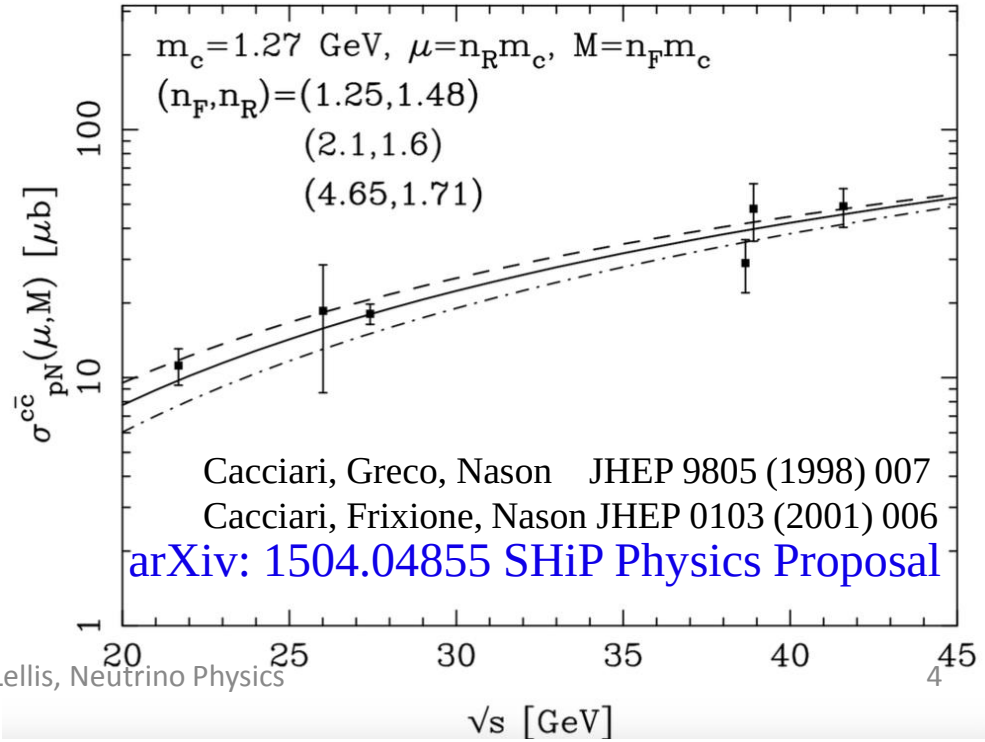
$Br(D_s \to \tau) = (5.54 \pm 0.24)\%$ *PDG 2014*

$f_{D_s} = (7.7 \pm 0.6^{+0.5}_{-0.4})\%$ *JHEP 1309 (2013) 058*

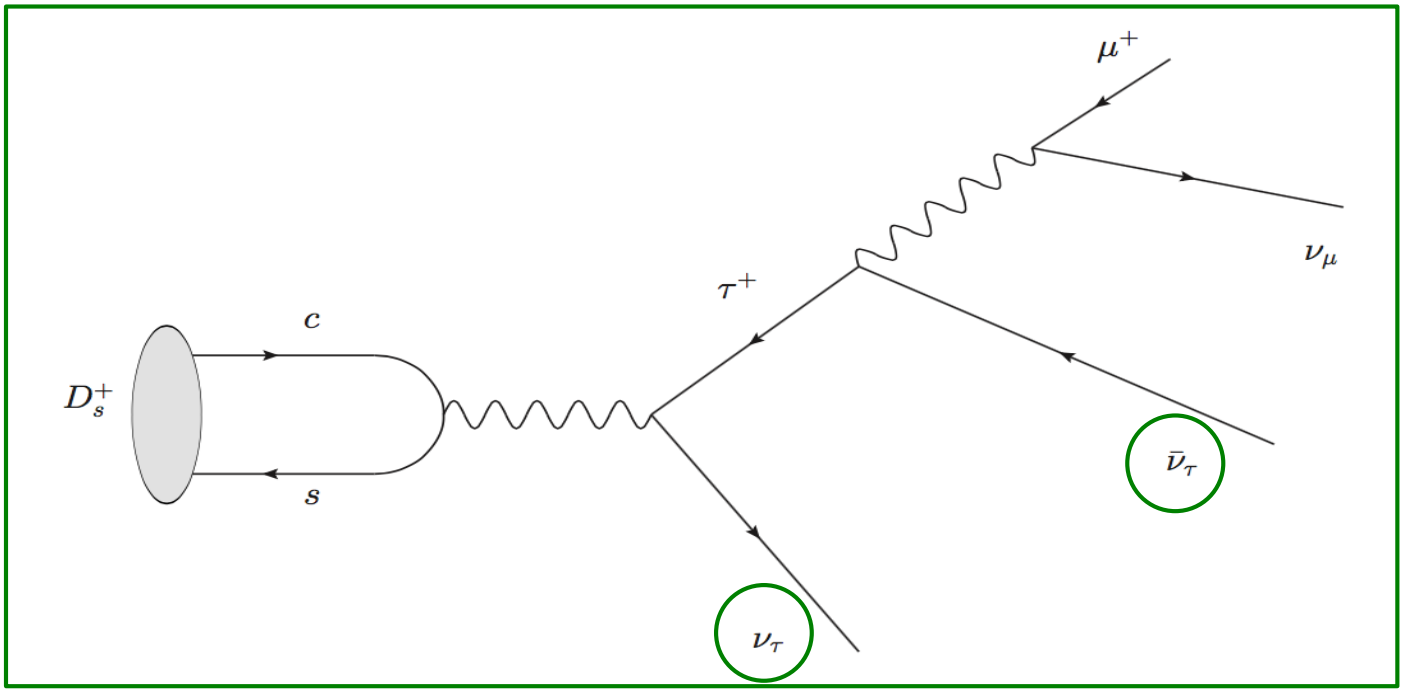
$\sigma_{c\bar{c}} \propto A$

$\sigma_{pN} \propto A^{0.71}$





ν_τ Fluxes



ν_τ FLUXES

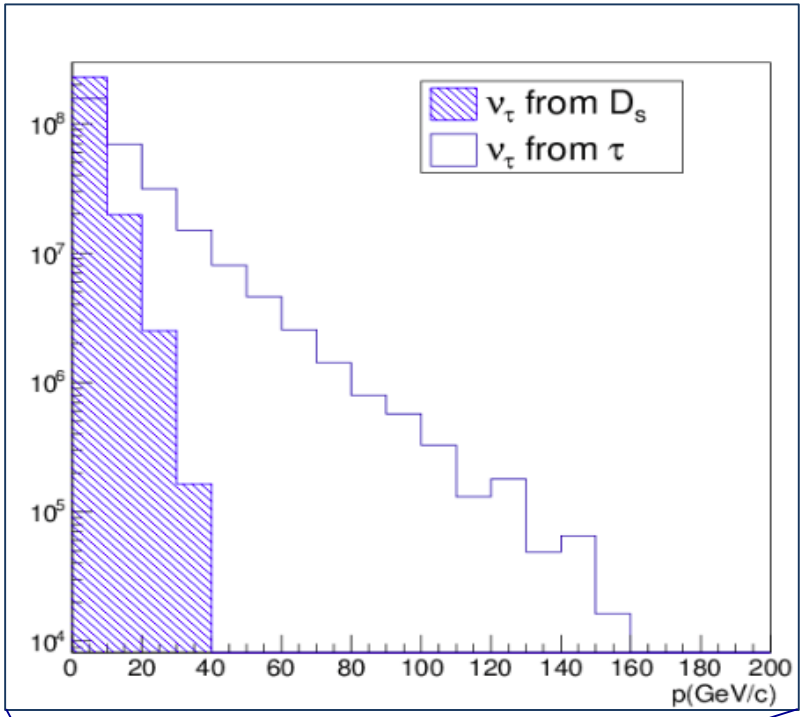
*in 5 years run (2×10^{20} pot)

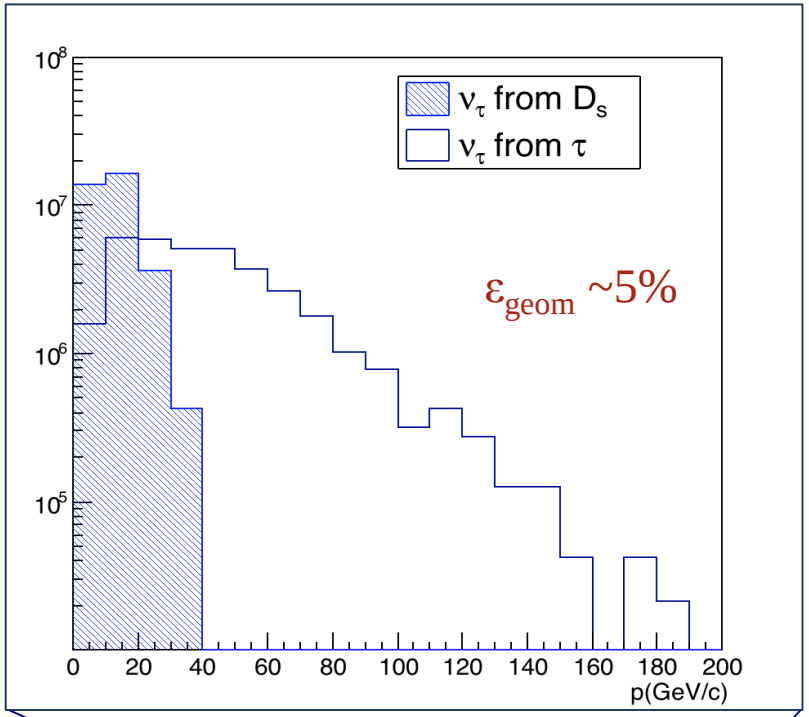
At the beam dump*

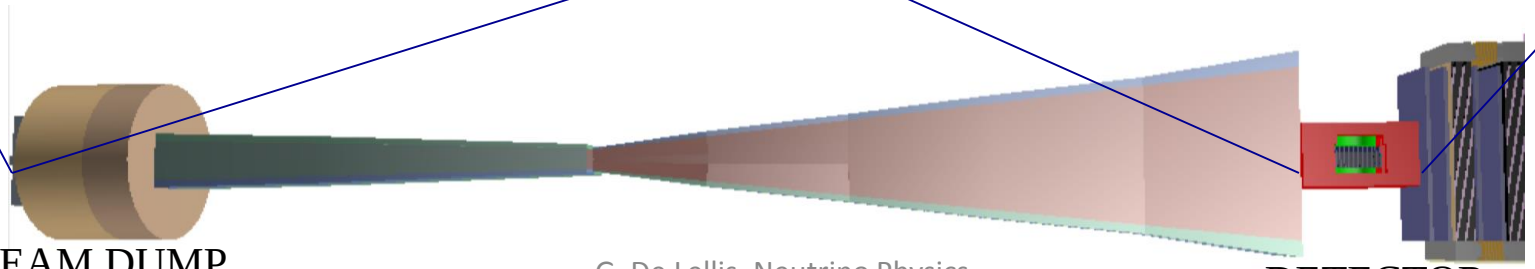
$$N_{\nu_\tau} = N_{\overline{\nu}_\tau} = 2.8 \times 10^{15}$$

At the neutrino detector*

$$N_{\nu_\tau} = N_{\overline{\nu}_\tau} = 1.4 \times 10^{14}$$



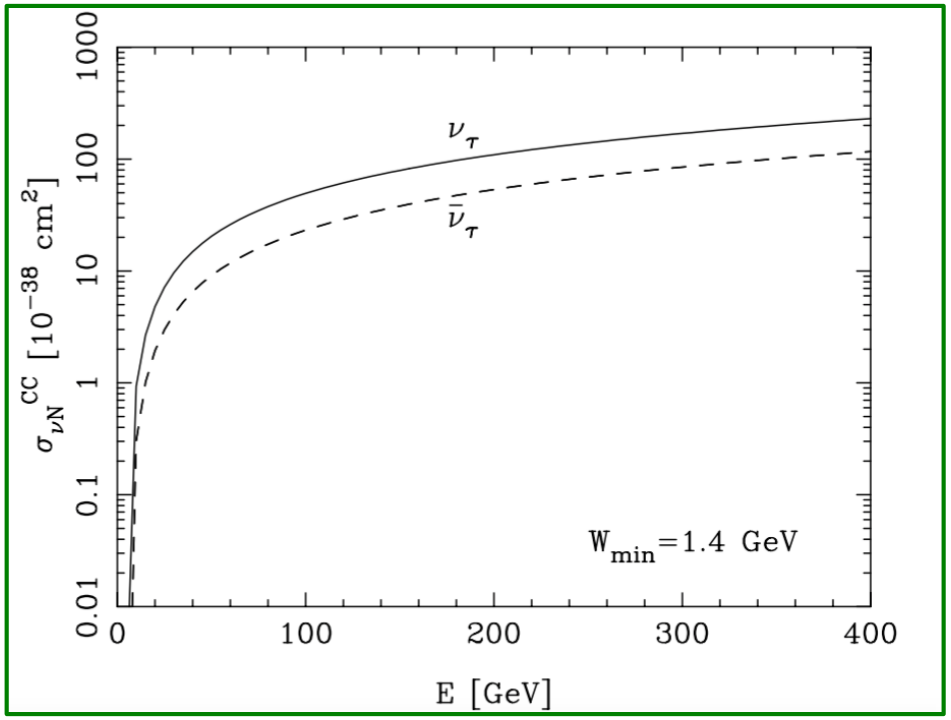




BEAM DUMP

ν_τ DETECTOR

ν_τ Interactions In The Target



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

Uncertainty ($\lesssim$10%) from:

- Scale choices
- Pdf
- Target mass correction

Expected number of interactions*

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

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

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

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

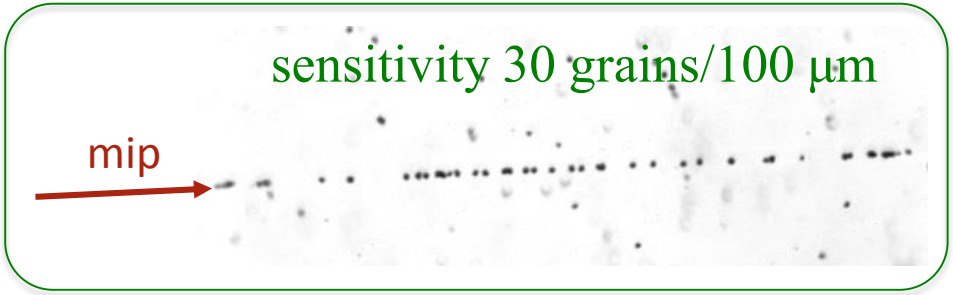
ν_τ DETECTOR

THE UNITARY CELL

Emulsion Cloud Chamber (ECC)

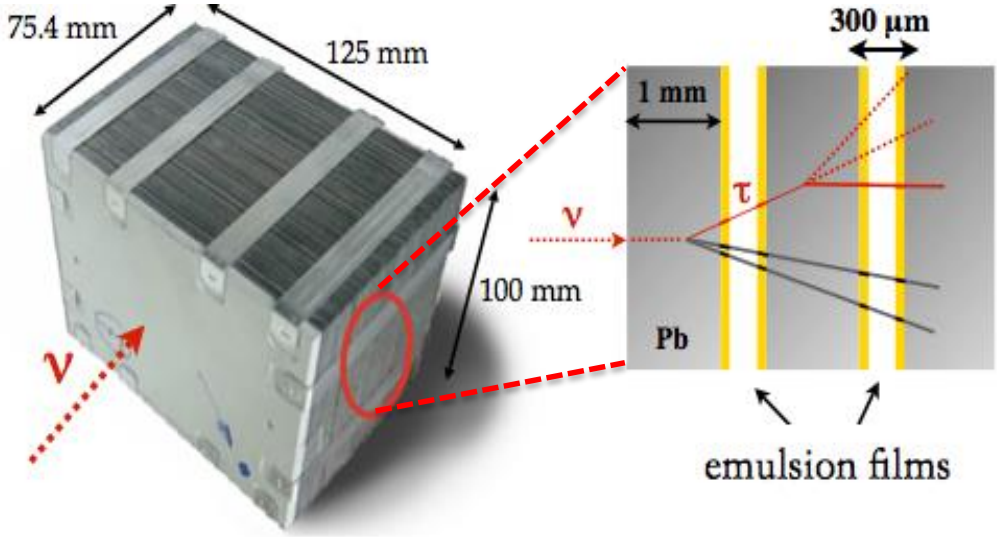
BRICK

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



NIM A556 (2006) 80-86

10 X_0

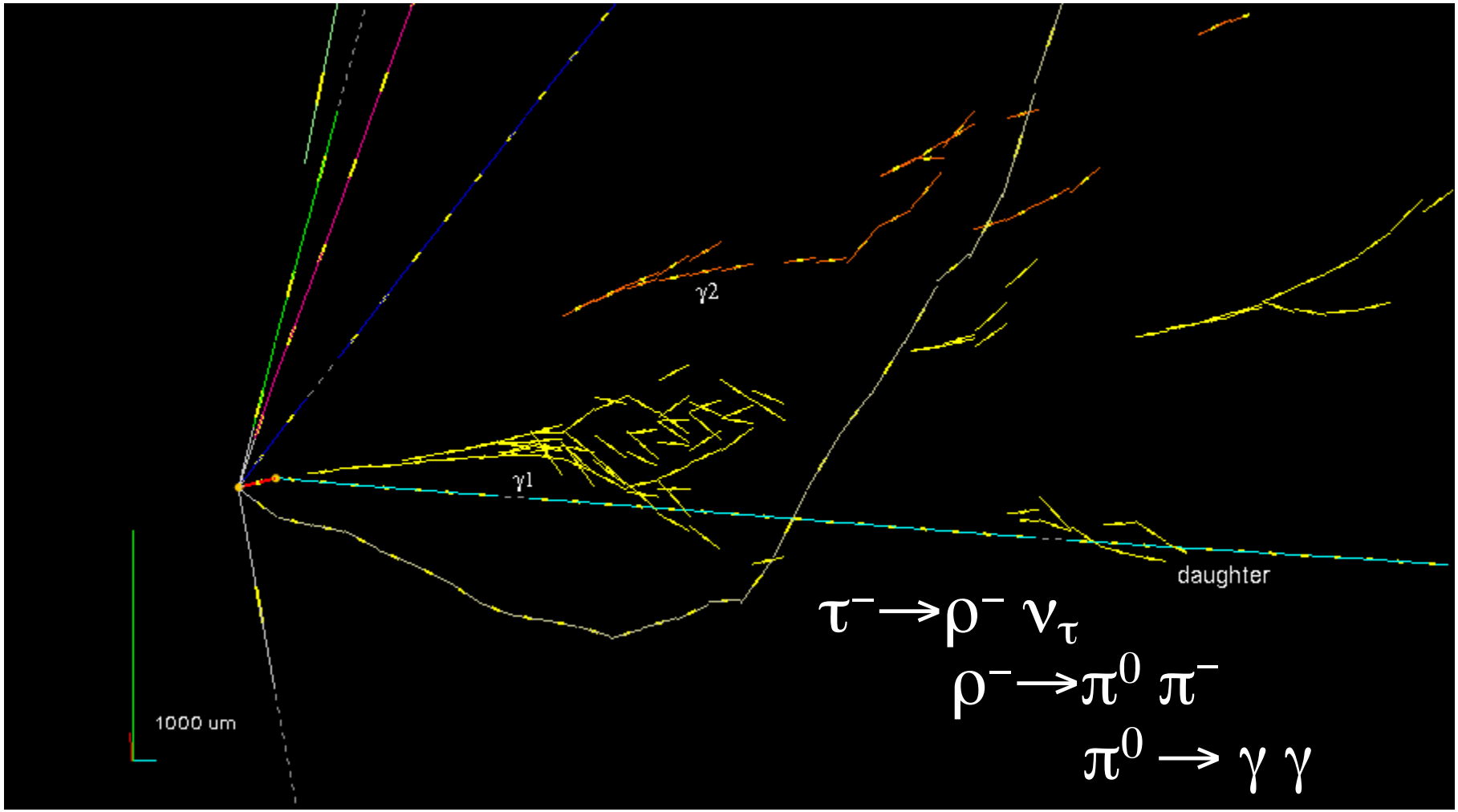


PERFORMANCES

- 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

ν_τ IDENTIFICATION

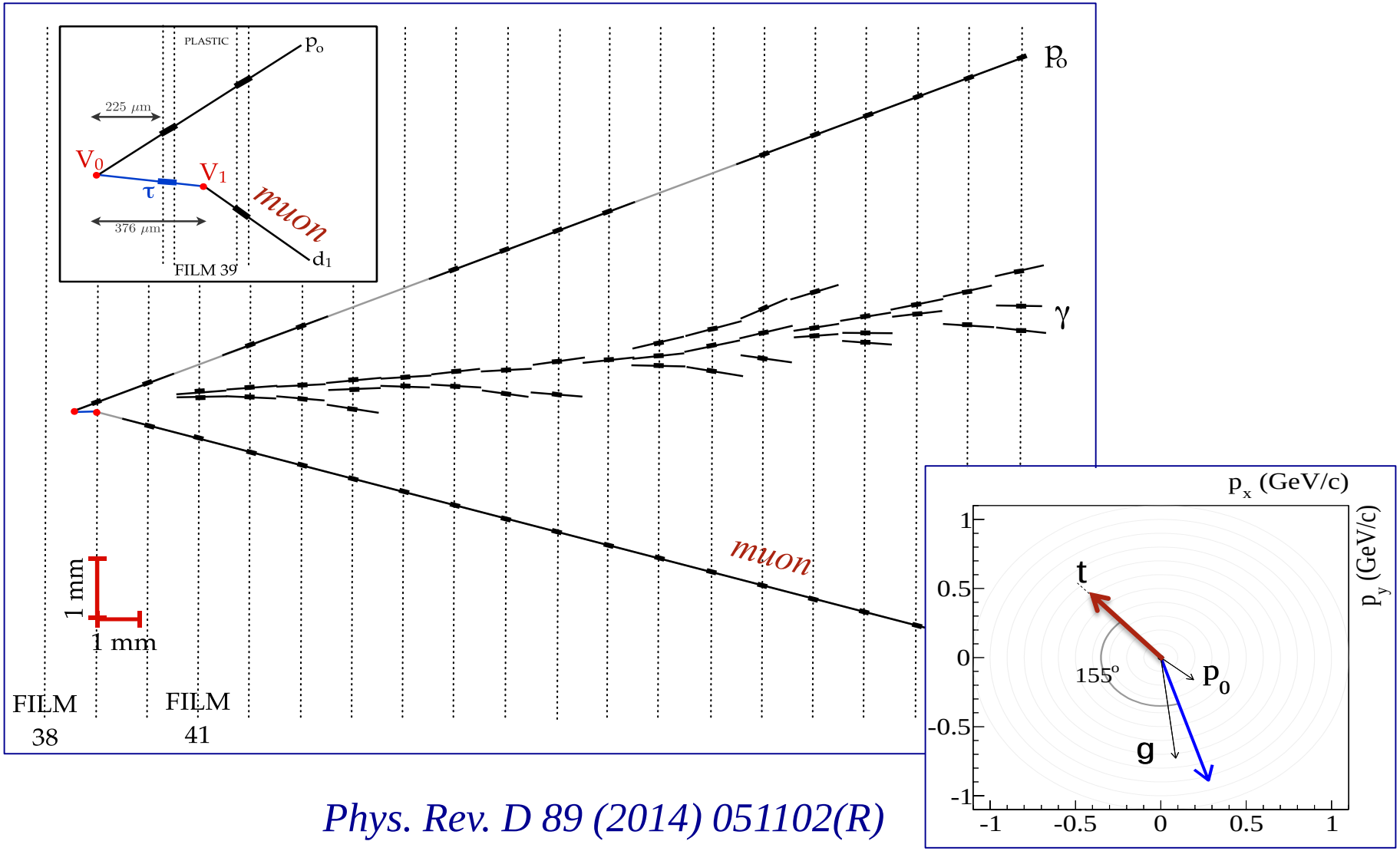
THE FIRST OPERA ν_τ CANDIDATE



Physics Letters B691 (2010) 138

MICROMETRIC RESOLUTION

A ν_τ OPERA CANDIDATE ($\tau \rightarrow \mu$)



Phys. Rev. D 89 (2014) 051102(R)

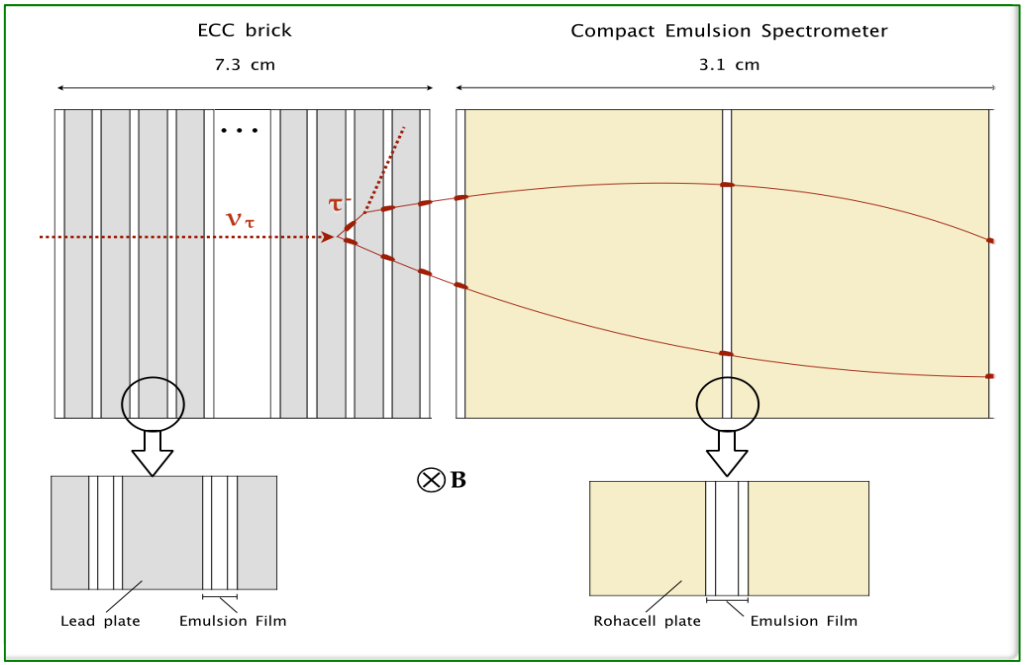
ν_τ/ANTI-ν_τ SEPARATION

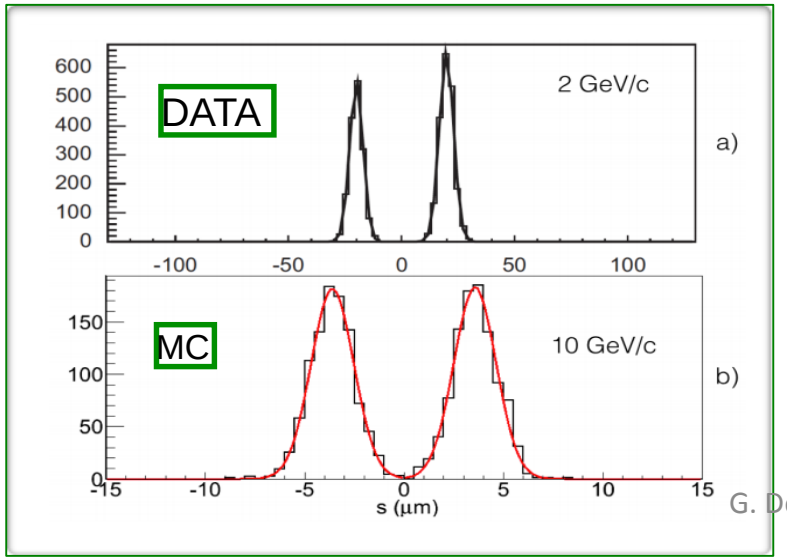
THE COMPACT EMULSION SPECTROMETER

TASK

- Electric charge and momentum measurement of τ lepton decay products
- Key role for the τ→h decay channel

- 3 OPERA-like emulsion films
- 2 Rohacell spacers (low density material)
- 1 Tesla magnetic field

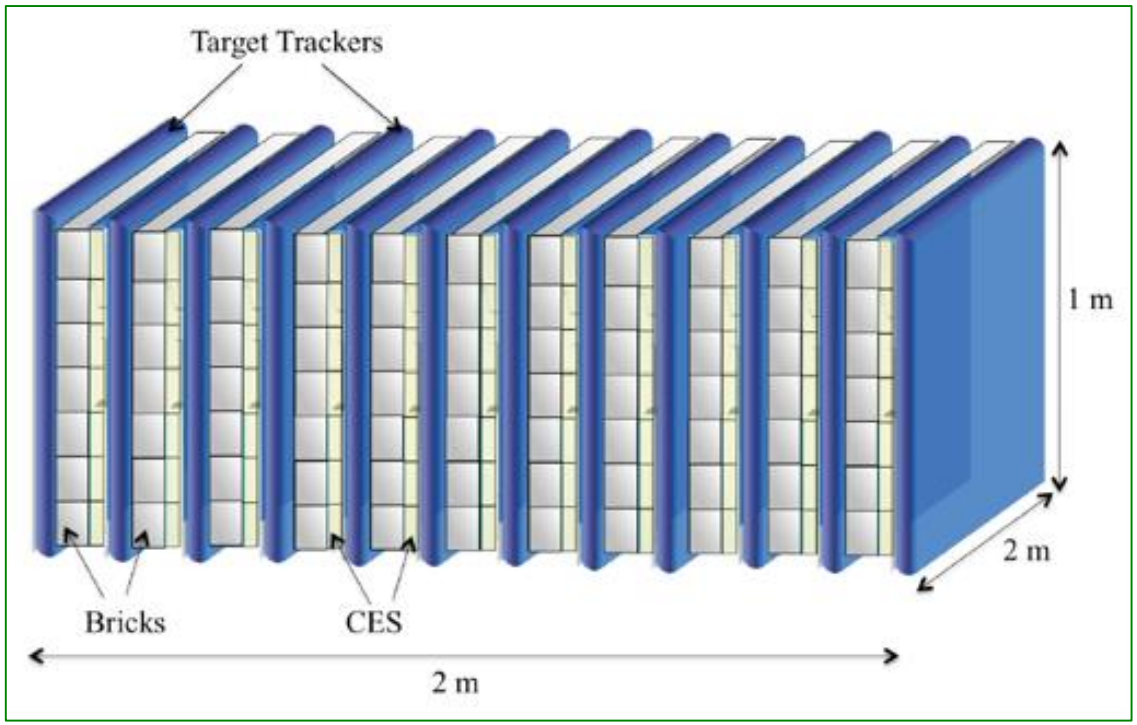




PERFORMANCES

- **Electric charge** determined up to 12 GeV
- **Momentum** estimated from the sagitta
- $\Delta p/p < 20\%$ up to 12 GeV/c

THE NEUTRINO TARGET



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

TARGET TRACKER PLANES

FEATURES

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

REQUIREMENTS

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

POSSIBLE OPTIONS

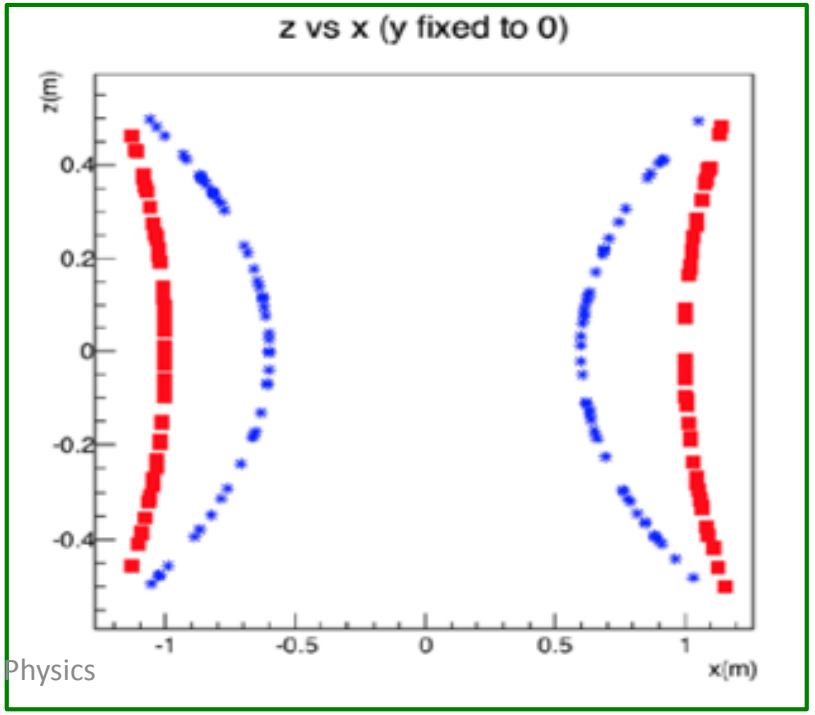
- Scintillating fibre trackers
- Micro-pattern gas detectors (GEM, Micromegas)

THE TARGET MAGNETIZATION

GOLIATH MAGNET
CERN H4 beam line

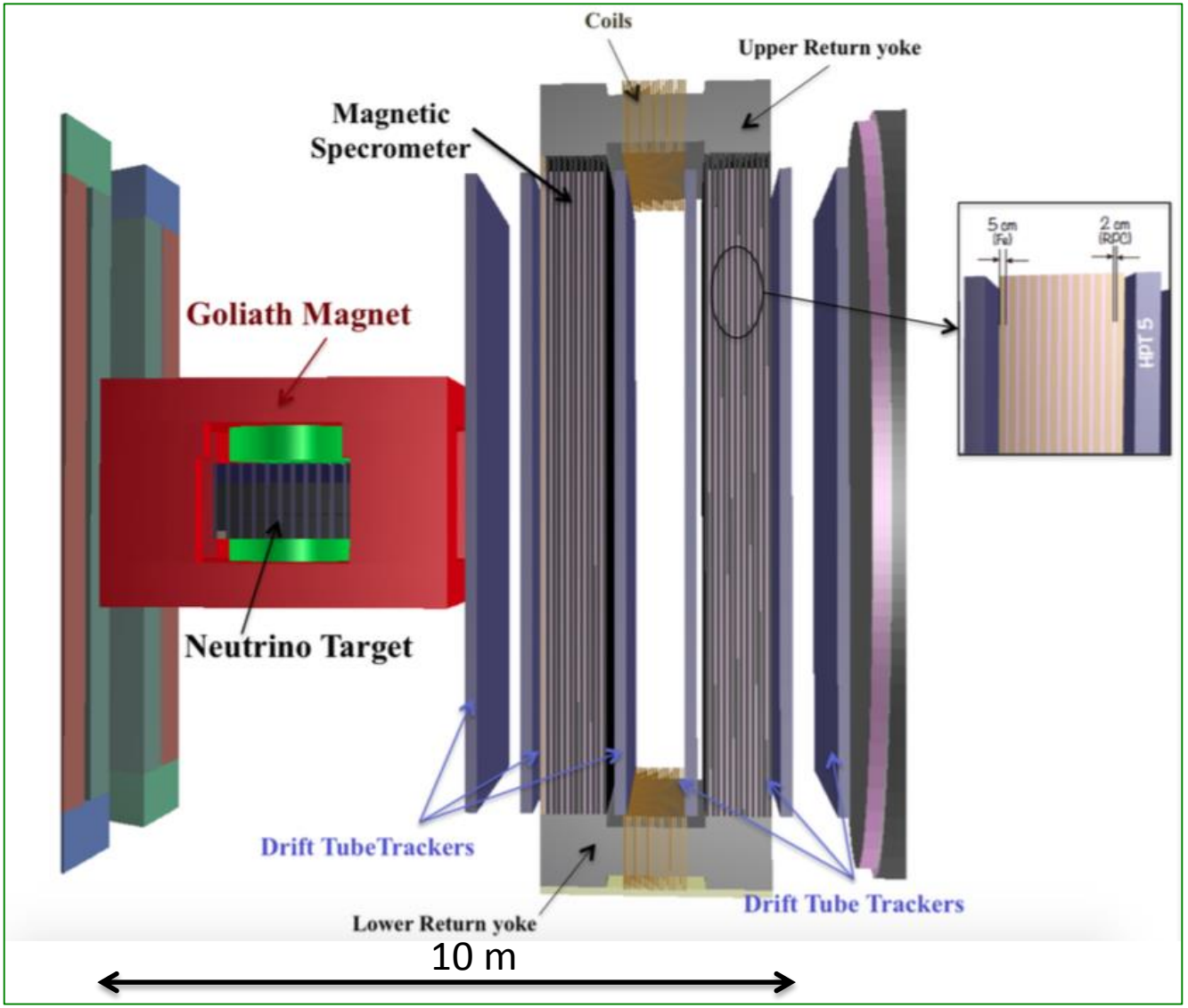
- 1 Tesla vertical magnetic field
- few m^3 volume with constant magnetization

Magnetic field behavior in the target region

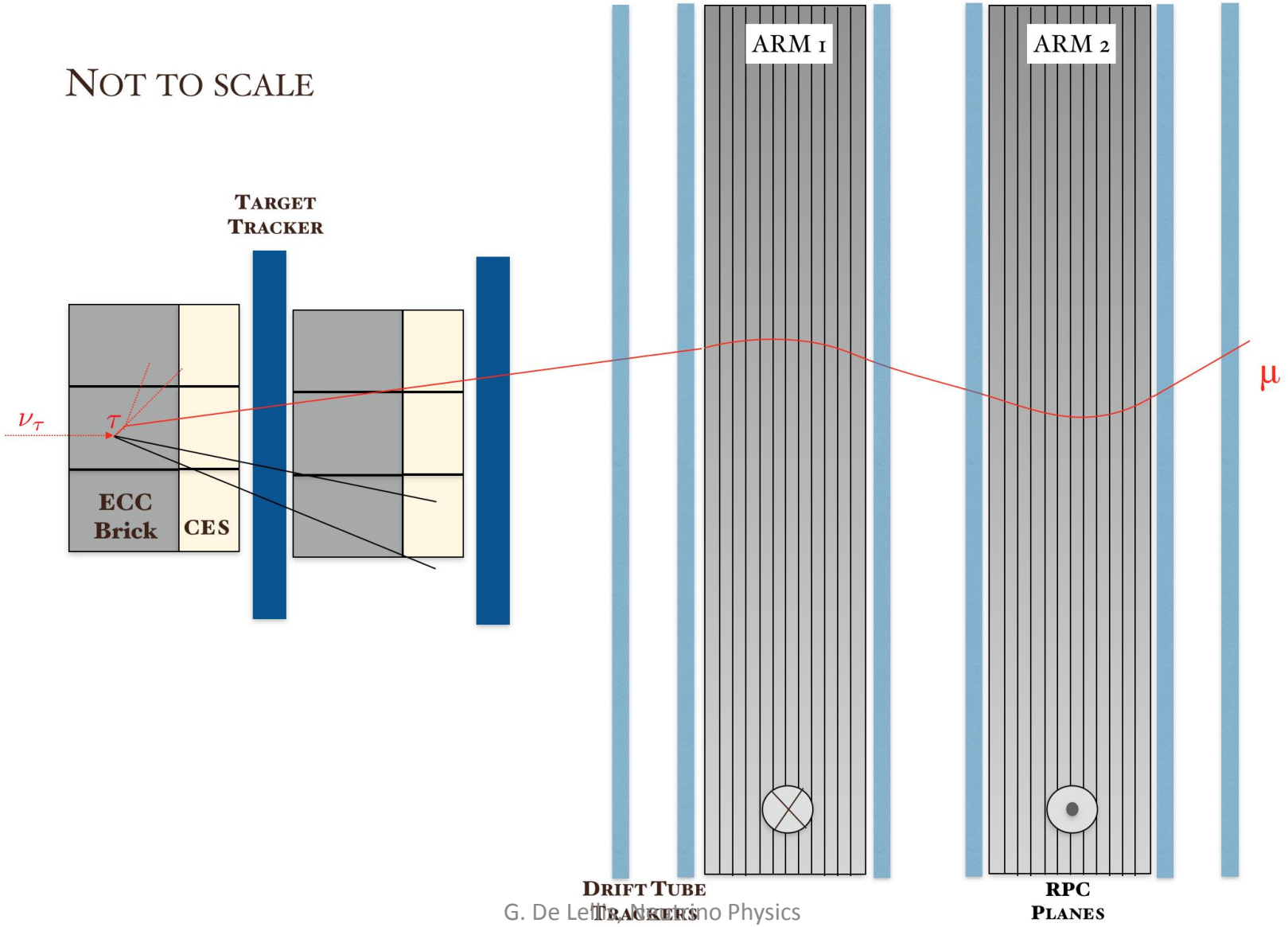


Within the blu curves B ≈ 1.5 T
Within the red curves B >=1 T

The Neutrino Detector



An Interaction In The Neutrino Detector



PERFORMANCES OF THE DETECTOR

$$\epsilon_{tot} = \epsilon_{geom} \times \epsilon_{loc} \times \epsilon_{ds}$$

Charge measurement performed with

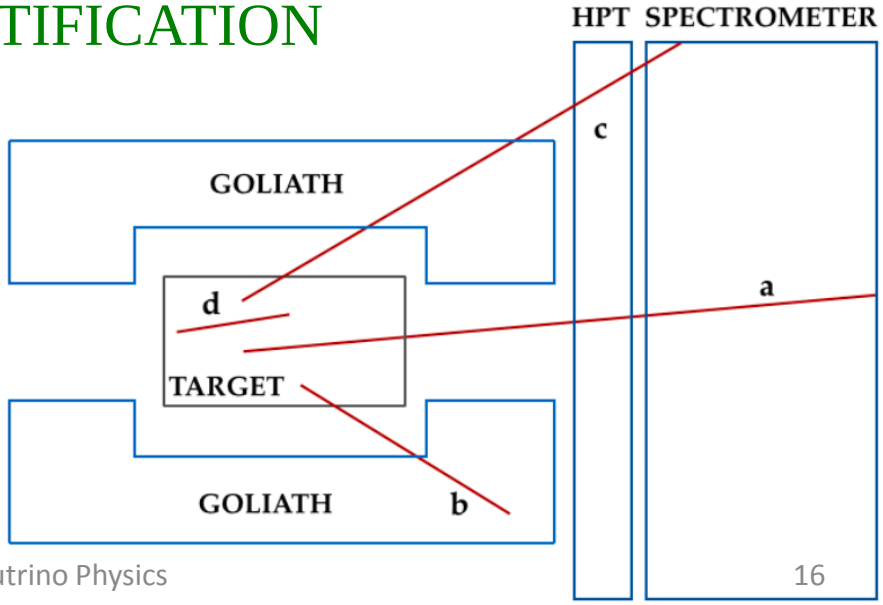
- Compact Emulsion Spectrometer (hadrons and muons)
- magnetic spectrometer (muons only)

	τ→μ	τ→h	τ→3h	τ→e
ε_{tot} (%)	60	62	63	56
ε_{charge} (%)	94	70	49	/
η_{mis}(%)	1.5	0.5	1.0	/

MUON IDENTIFICATION

- Muons come from τ→μ decays and ν_μ CC interactions
- μ identification at primary vertex crucial for charm background rejection

$$\epsilon_\mu \sim 90\%$$



SIGNAL AND BACKGROUND YIELDS

SIGNAL EXPECTATION

BACKGROUND

R=S/B RATIO

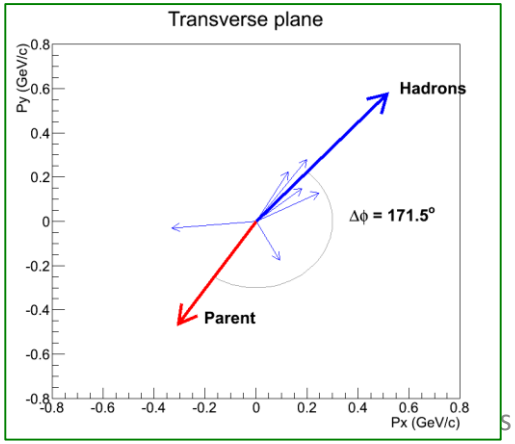
Decay search finding efficiency, charge measurement, muon identification included

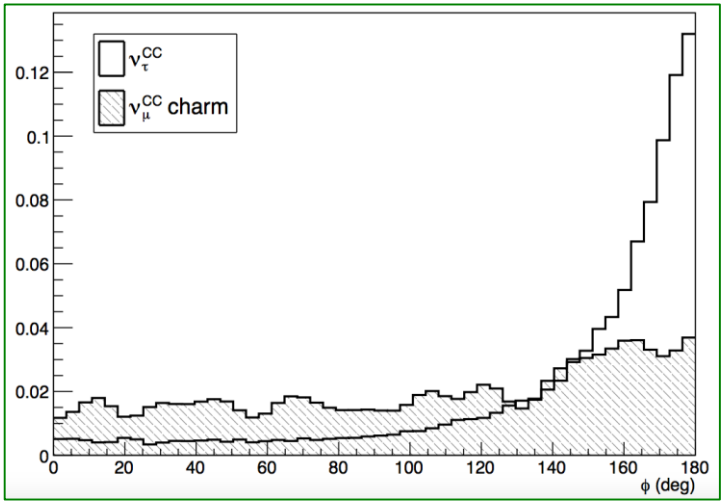
τ→e decay channel not exploited

decay channel	ν_τ			$\bar{\nu}_\tau$		
	N^{exp}	N^{bg}	R	N^{exp}	N^{bg}	R
$\tau \to \mu$	570	30	19	290	140	2
$\tau \to h$	990	80	12	500	380	1.3
$\tau \to 3h$	210	30	7	110	140	0.8
total	1770	140	13	900	660	1.4

Main background source: charm production in ν_μ^{CC} (anti-ν_μ^{CC}) and ν_e^{CC} (anti-ν_e^{CC}) interactions, when the primary lepton is not identified

The analysis can be improved by exploiting the likelihood approach



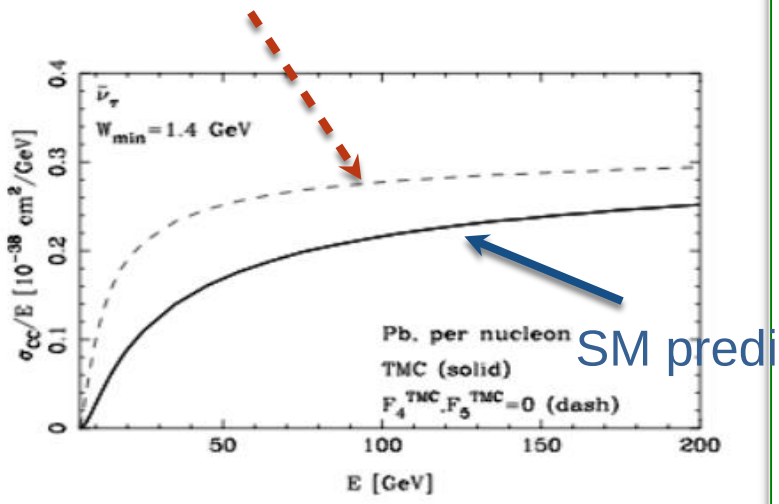


F_4 AND F_5 STRUCTURE FUNCTIONS

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

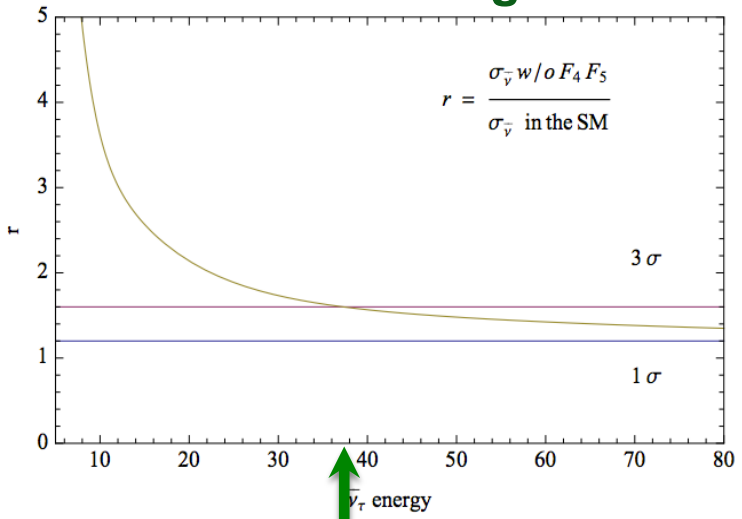
$$\frac{d^2\sigma^{\nu(\bar{\nu})}}{dxdy} = \frac{G_F^2 M E_\nu}{\pi(1+Q^2/M_W^2)^2}\left((y^2x + \frac{m_\tau^2 y}{2E_\nu M})F_1 + \left[(1-\frac{m_\tau^2}{4E_\nu^2}) - (1+\frac{Mx}{2E_\nu})\right]F_2 \right.$$
$$\left. \pm \left[xy(1-\frac{y}{2}) - \frac{m_\tau^2 y}{4E_\nu M}\right]F_3 + \frac{m_\tau^2(m_\tau^2+Q^2)}{4E_\nu^2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

$F_4 = F_5 = 0$



SM prediction

CC interacting $\bar{\nu}_\tau$



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

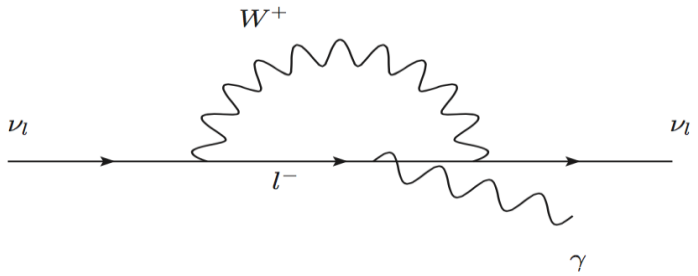
- At LO $F_4 = 0$, $2xF_5 = F_2$
- At NLO $F_4 \sim 1\%$ at 10 GeV

TAU NEUTRINO MAGNETIC MOMENT

A massive neutrino may interact e.m.

→ magnetic moment proportional to its mass

$$\mu_\nu = \frac{3\,e\,G_F\,m_\nu}{8\,\pi^2\,\sqrt{2}} \simeq (3.2\times10^{-19})\left(\frac{m_\nu}{1\,\mathrm{eV}}\right)\mu_B$$



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

No interference as it involves a spin flip of the neutrino

Current limits

(ν_e) $\quad \mu_\nu < 2.9\cdot10^{-11}\mu_B$

(ν_μ) $\quad \mu_\nu < 6.9\cdot10^{-10}\mu_B$

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

IN SHiP

SIGNAL SELECTION

$\theta_{\nu-e} < 30\,mrad$

$E_e > 1$ GeV

$$n_{evt} = \frac{\mu_\nu^2}{\mu_B^2}\int \Phi_{\nu_\tau}\sigma^\mu N_{nucl}dE = 4.3\times10^{15}\,\frac{\mu_\nu^2}{\mu_B^2}$$

BACKGROUND PROCESSES

$\nu_x + e^-$	$\rightarrow$	$\nu_x + e^-$	NC	390
$\nu_e(\bar{\nu}_e) + e^-$	$\rightarrow$	$e^- + \nu_e(\bar{\nu}_e)$	CC	
$\nu_e + n$	$\rightarrow$	$e^- + p$	QE	2440
$\bar{\nu}_e + p$	$\rightarrow$	$e^+ + n$	QE	
$\nu_e(\bar{\nu}_e) + N$	$\rightarrow$	$e^-(e^+) + X$	DIS	730

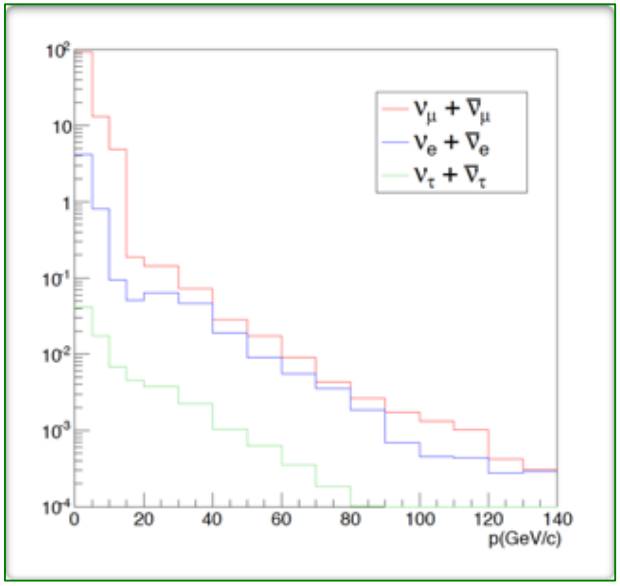
Assuming 5% systematics from DIS measurements

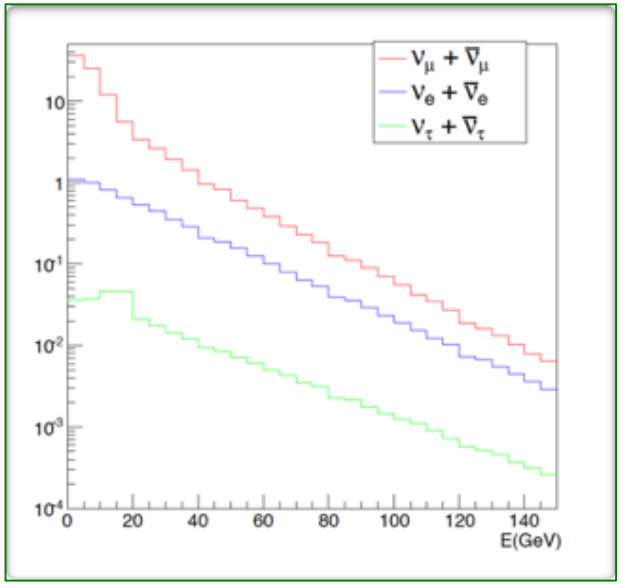
SHiP can explore a region down to

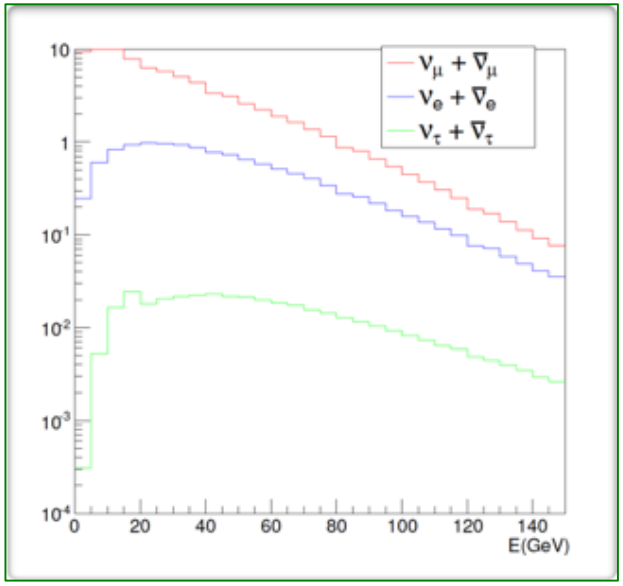
$$\mu_\nu = 1.5\times10^{-7}\mu_B$$

NOT ONLY TAU NEUTRINOS

- SHiP setup ideally suited to study neutrino and anti-neutrino physics for all three active flavours
- High charmed hadrons production rates ⇒ high neutrino fluxes from their decays, including remnant pion and kaon decays







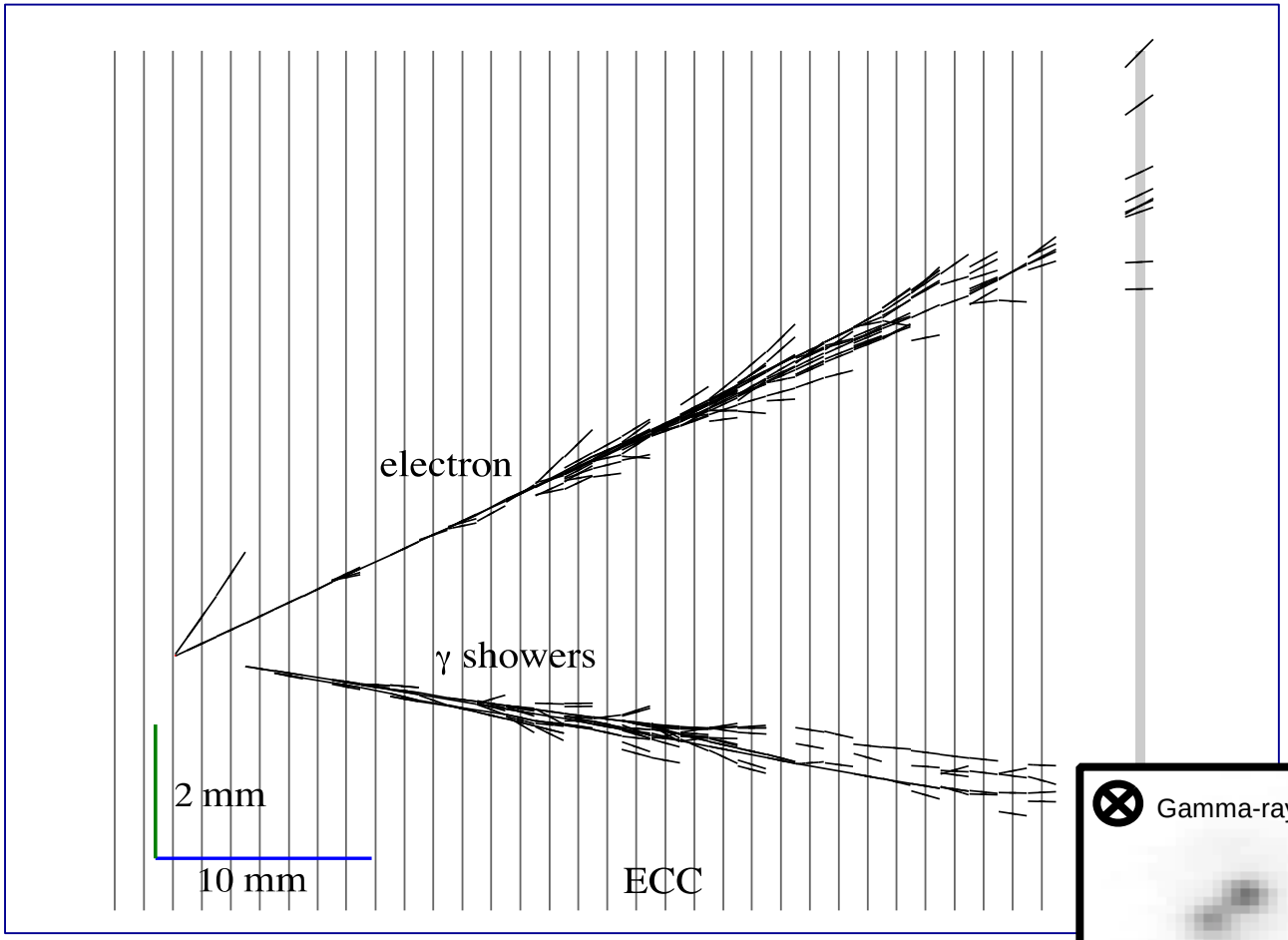
	<E> (GeV)	Beam dump
N_{ν_μ}	1.4	4.4×10^{18}
N_{ν_e}	3	2.1×10^{17}
N_{ν_τ}	9	2.8×10^{15}
$N_{\bar{\nu}_\mu}$	1.5	2.8×10^{18}
$N_{\bar{\nu}_e}$	4	1.6×10^{17}
$N_{\bar{\nu}_\tau}$	8	2.8×10^{15}

	<E> (GeV)	Neutrino target
N_{ν_μ}	8	5.2×10^{16}
N_{ν_e}	28	3.6×10^{15}
N_{ν_τ}	28	1.4×10^{14}
$N_{\bar{\nu}_\mu}$	8	4.0×10^{16}
$N_{\bar{\nu}_e}$	27	2.7×10^{15}
$N_{\bar{\nu}_\tau}$	26	1.4×10^{14}

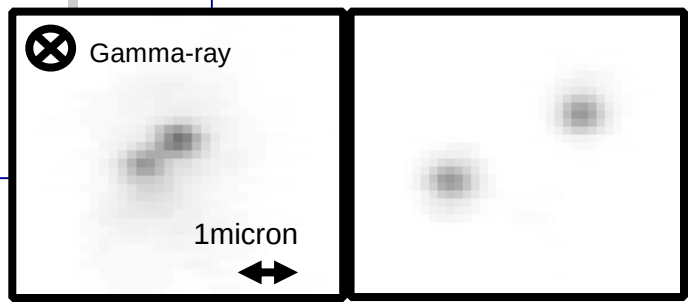
	<E> (GeV)	CC DIS interactions
N_{ν_μ}	29	1.7×10^{6}
N_{ν_e}	46	2.5×10^{5}
N_{ν_τ}	59	6.7×10^{3}
$N_{\bar{\nu}_\mu}$	28	6.7×10^{5}
$N_{\bar{\nu}_e}$	46	9.0×10^{4}
$N_{\bar{\nu}_\tau}$	58	3.4×10^{3}

ELECTRON NEUTRINOS

Excellent π^0/γ separation thanks to the micrometric accuracy



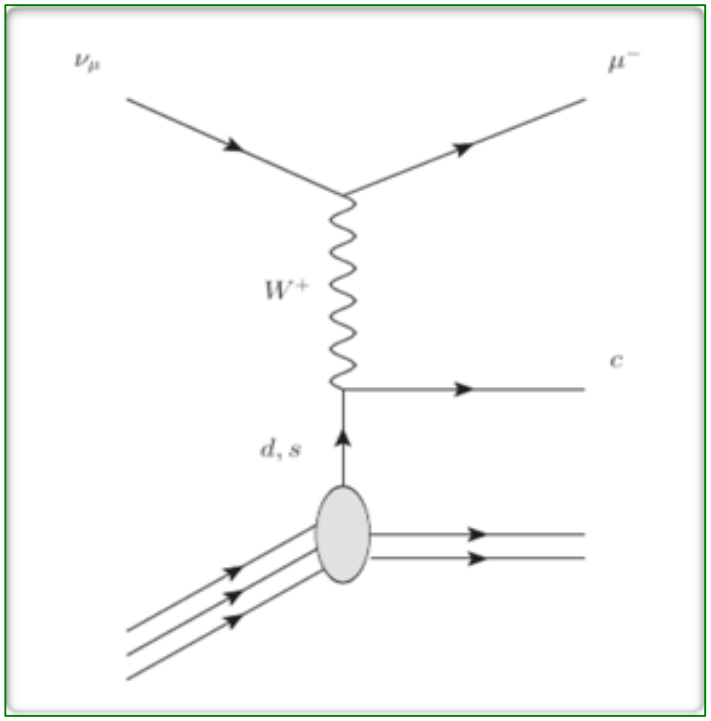
JHEP 1307 (2013) 004



A close-up of an electron pair

Neutrino-Induced Charm Production @SHiP

- Large charm production in ν_μ^{CC} and ν_e^{CC} interactions
- Process sensitive to strange quark content of the nucleon



- Charm production with electronic detectors tagged by di-muon events (high energy cut to reduce background)
- Nuclear emulsion technique: charmed hadron identification through the observation of its decay *Physics Reports 399 (2004) 277*
- Loose kinematical cuts ➞ good sensitivity to the slow-rescaling threshold behaviour and to the charm quark mass

CHARM PHYSICS @SHiP

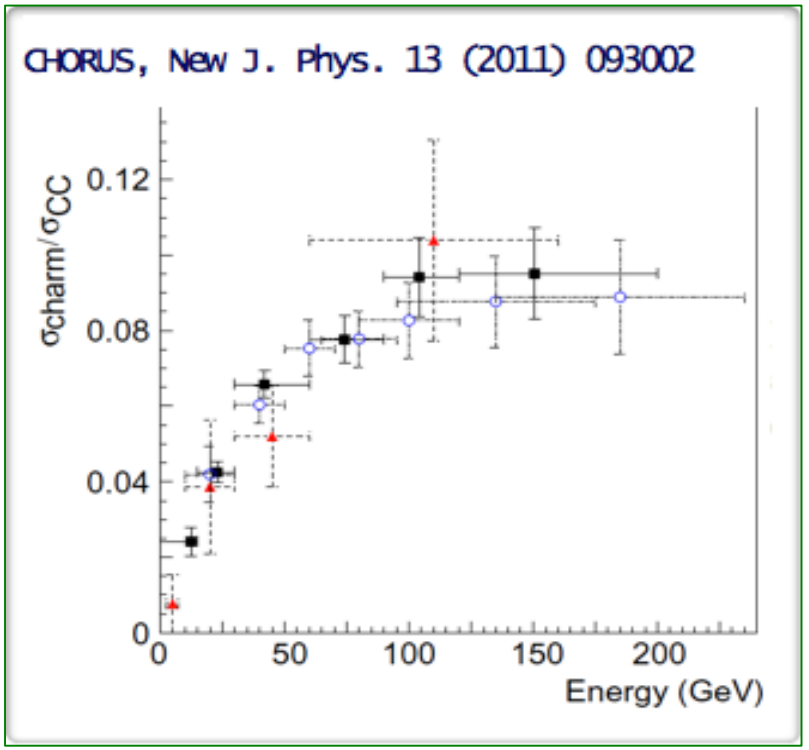
- Fraction of neutrino-induced charm events
- Convolution of CHORUS data with SHiP spectrum

ν_μ CC

$$f(charm) = \frac{\int \Phi_{\nu_\mu} \sigma^{CC}_{\nu_\mu} \left(\frac{\sigma_{charm}}{\sigma^{CC}_{\nu_\mu}} \right) dE}{\int \Phi_{\nu_\mu} \sigma^{CC}_{\nu_\mu} dE} \approx 4\%$$

ν_e CC

$$f(charm) = \frac{\int \Phi_{\nu_e} \sigma^{CC}_{\nu_e} \left(\frac{\sigma_{charm}}{\sigma^{CC}_{\nu_e}} \right) dE}{\int \Phi_{\nu_e} \sigma^{CC}_{\nu_e} dE} \approx 6\%$$



Expected charm exceeds the statistics available in previous experiments by more than one order of magnitude

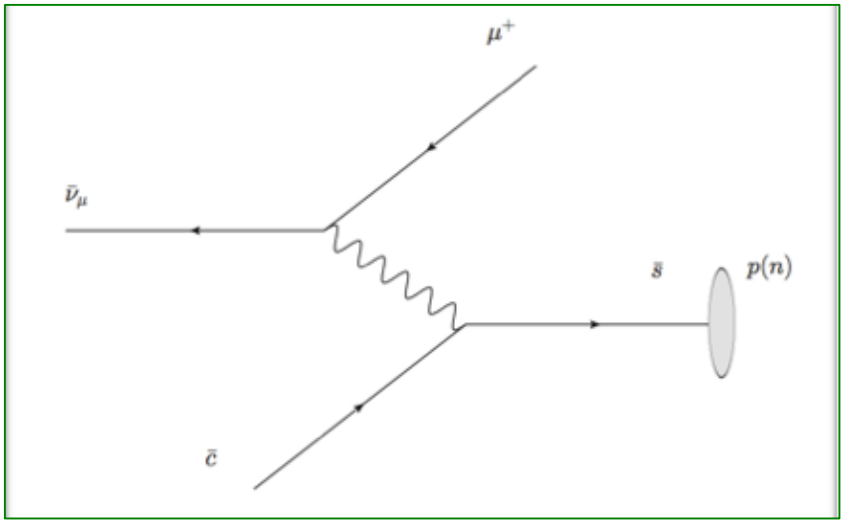
	Expected events
ν_μ	$6.8 \cdot 10^4$
ν_e	$1.5 \cdot 10^4$
$\bar{\nu}_\mu$	$2.7 \cdot 10^4$
$\bar{\nu}_e$	$5.4 \cdot 10^3$
total	$1.1 \cdot 10^5$

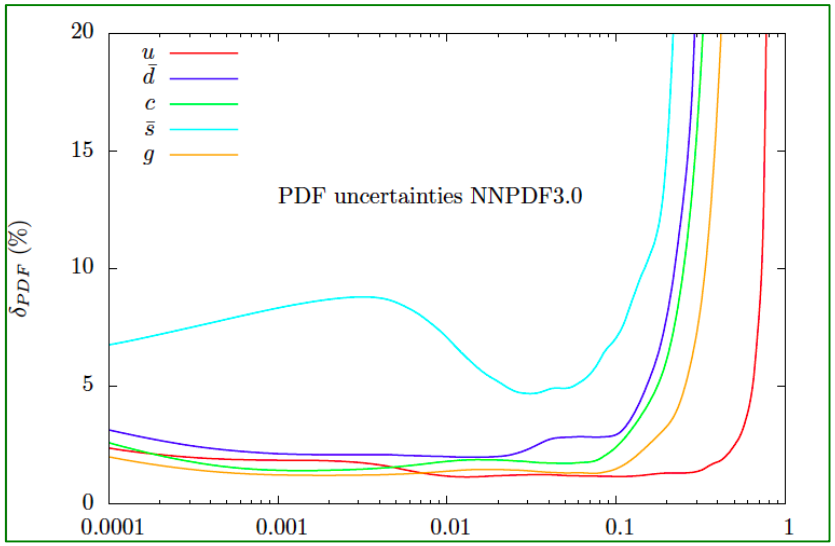
In NuTeV ~5100 ν_μ
~ 1460 anti-ν_μ
In CHORUS ~2000 ν_μ
32 anti-ν_μ

No charm candidate from ν_e and ν_τ interactions ever reported!

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 $c\bar{s}$





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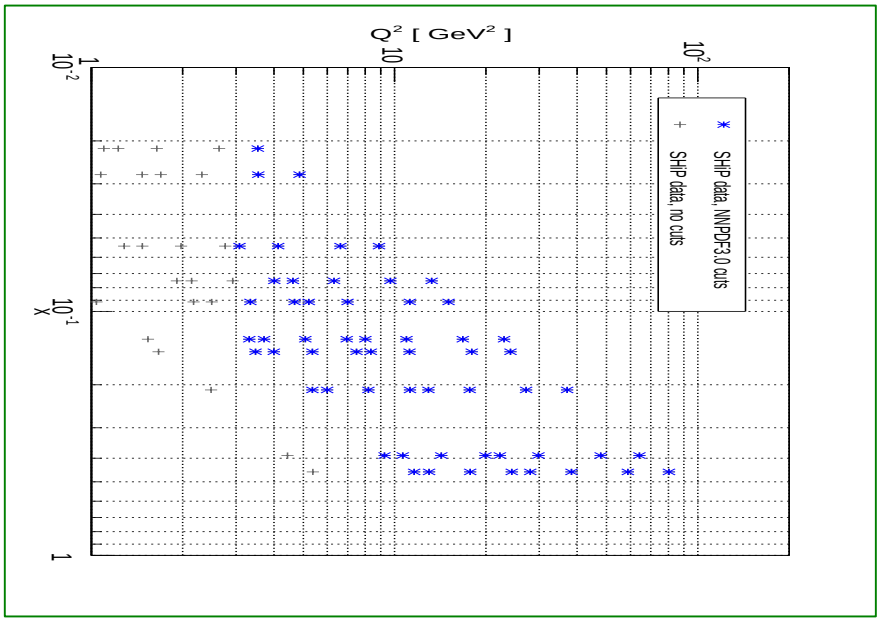
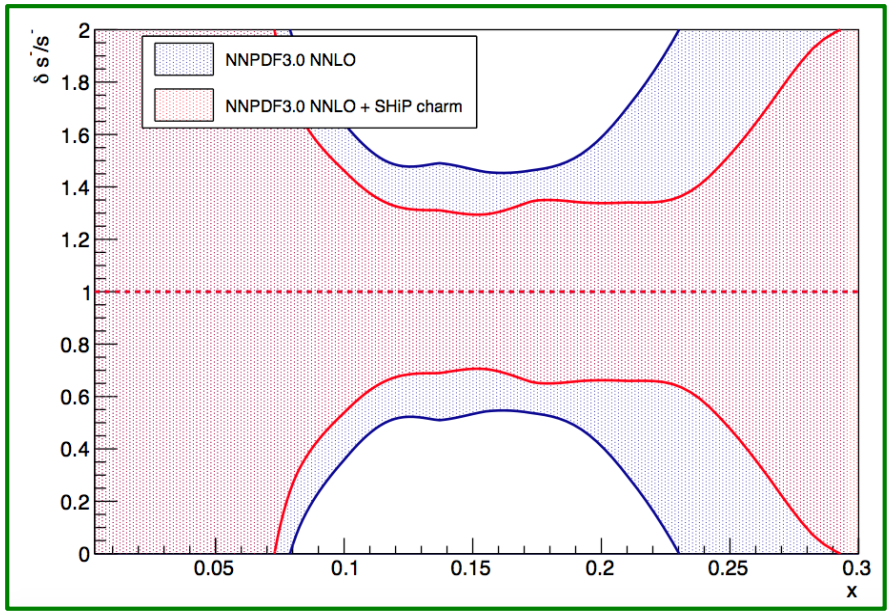
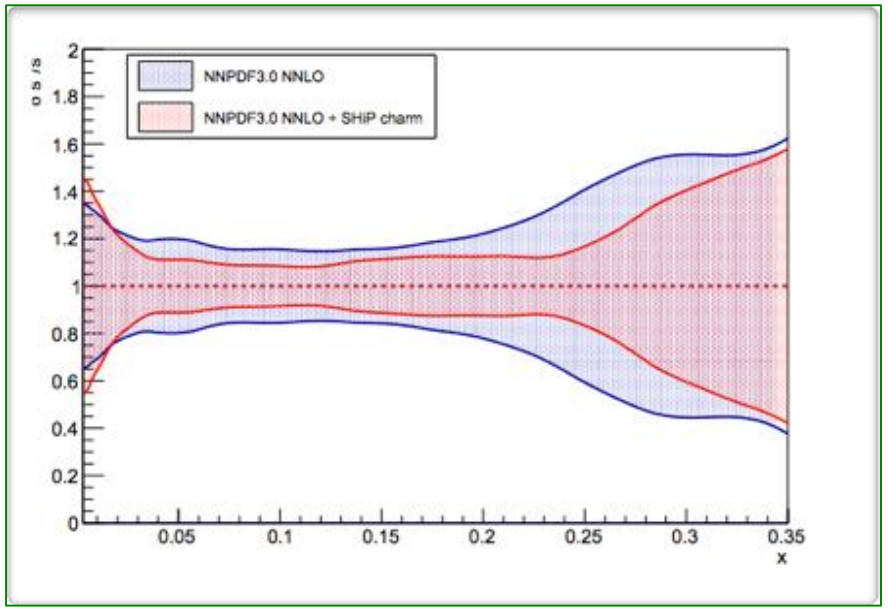
Fractional uncertainty of the individual parton densities $f(x;m^2_W)$ of NNPDF3.0



STRANGE QUARK NUCLEON CONTENT

- Improvement achieved on s^+/s^- versus x
- Significant improvement (factor two) with SHIP data





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

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

Nucl.Phys. B849 (2011) 112–143, at $Q^2 = 2$ GeV^2

EXOTIC PARTICLES: CHARMED PENTAQUARK

- Multi-quark states seen by several experiments
- Search for multi-quark states in neutrino interactions
- Unlike processes as e^+e^- scattering, θ^0_c production in anti-neutrino interactions is favoured by the presence of three valence quarks
- c-bar quarks in anti-neutrinos

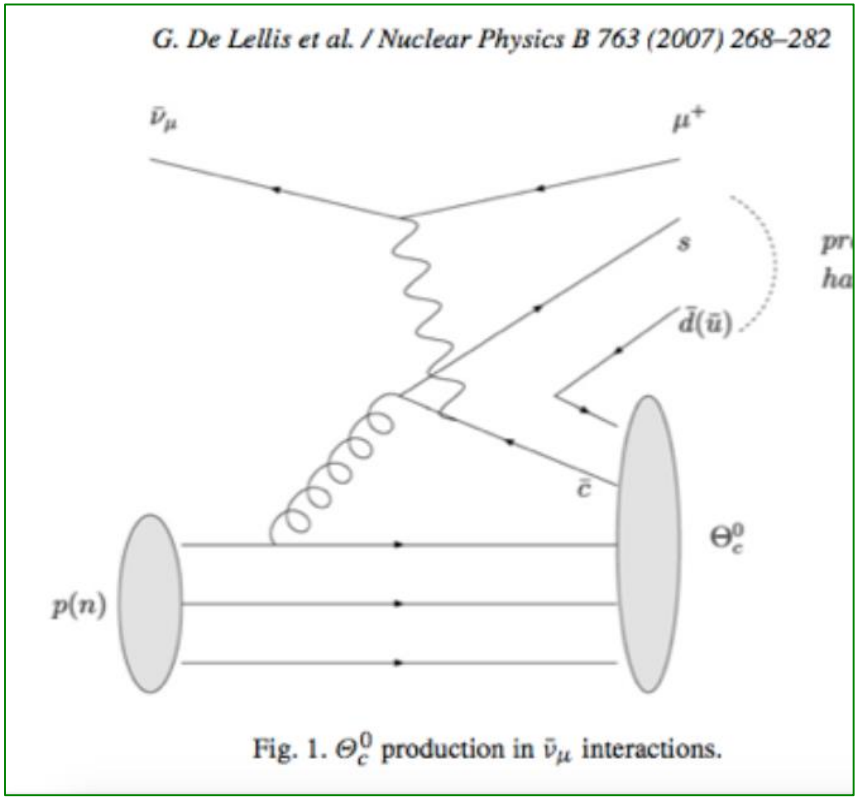


Fig. 1. Θ^0_c production in $\bar{\nu}_\mu$ interactions.

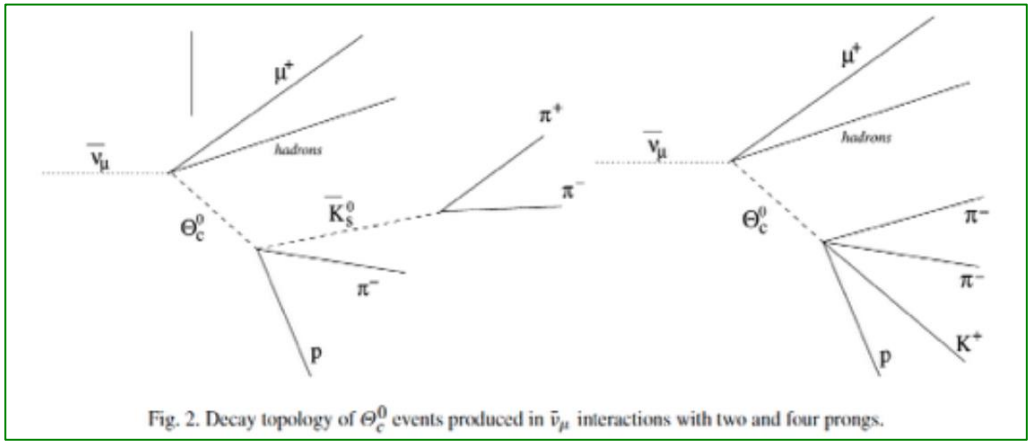


Fig. 2. Decay topology of Θ^0_c events produced in $\bar{\nu}_\mu$ interactions with two and four prongs.

Currently limited by the anti-neutrino statistics in CHORUS

$$\sigma_{\Theta^0_c}/\sigma_{\bar{\nu}} < 0.039 \text{ at } 90\% \text{ C.L.}$$

Charm from anti-ν_μ

CHORUS 32 SHiP 27000

DARK MATTER SEARCH

χ produced by a dark photon decay

$$\chi e^- \rightarrow \chi e^-$$

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

α' = dark photon coupling with χ

SIGNAL SELECTION

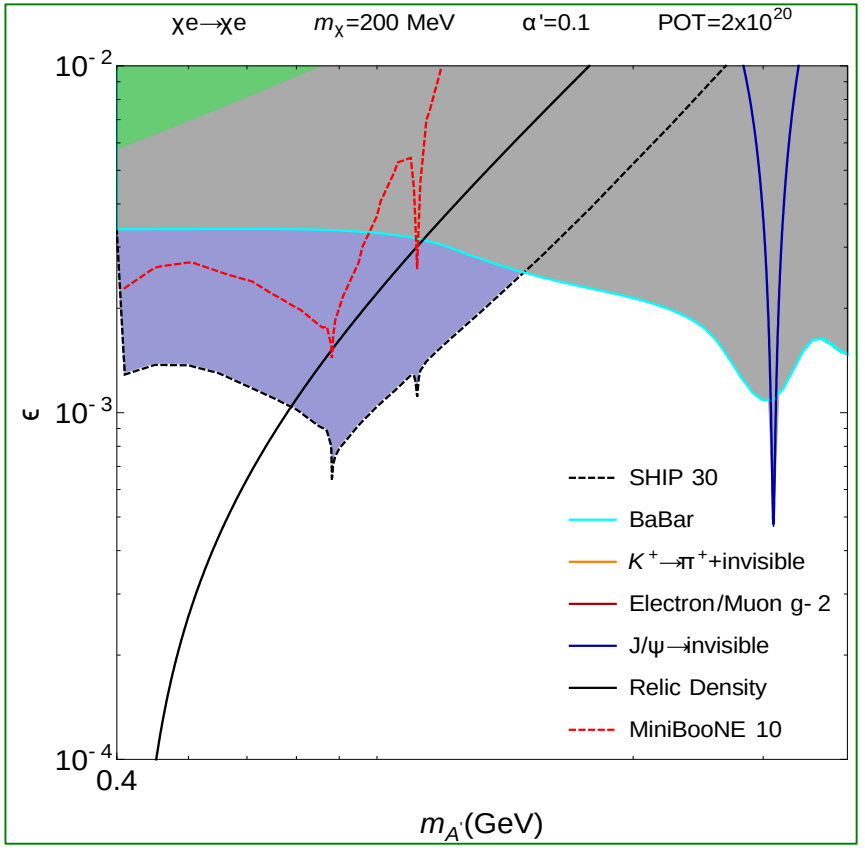
$$\begin{cases} 0.01 < \theta < 0.02 \\ E < 20 \text{ GeV} \end{cases}$$

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

ϵ = dark photon coupling with e.m. current

m_A = dark photon mass



CONCLUSIONS

- Unique tau neutrino and anti-neutrino physics
- Rich neutrino physics program
- Strange quark content
- Dark matter search