

Search for Hidden Particles

TAU NEUTRINO PHYSICS IN SHiP

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On behalf of the SHiP Collaboration
45 Institutes from 14 Countries

MOTIVATION FOR ν_τ STUDIES

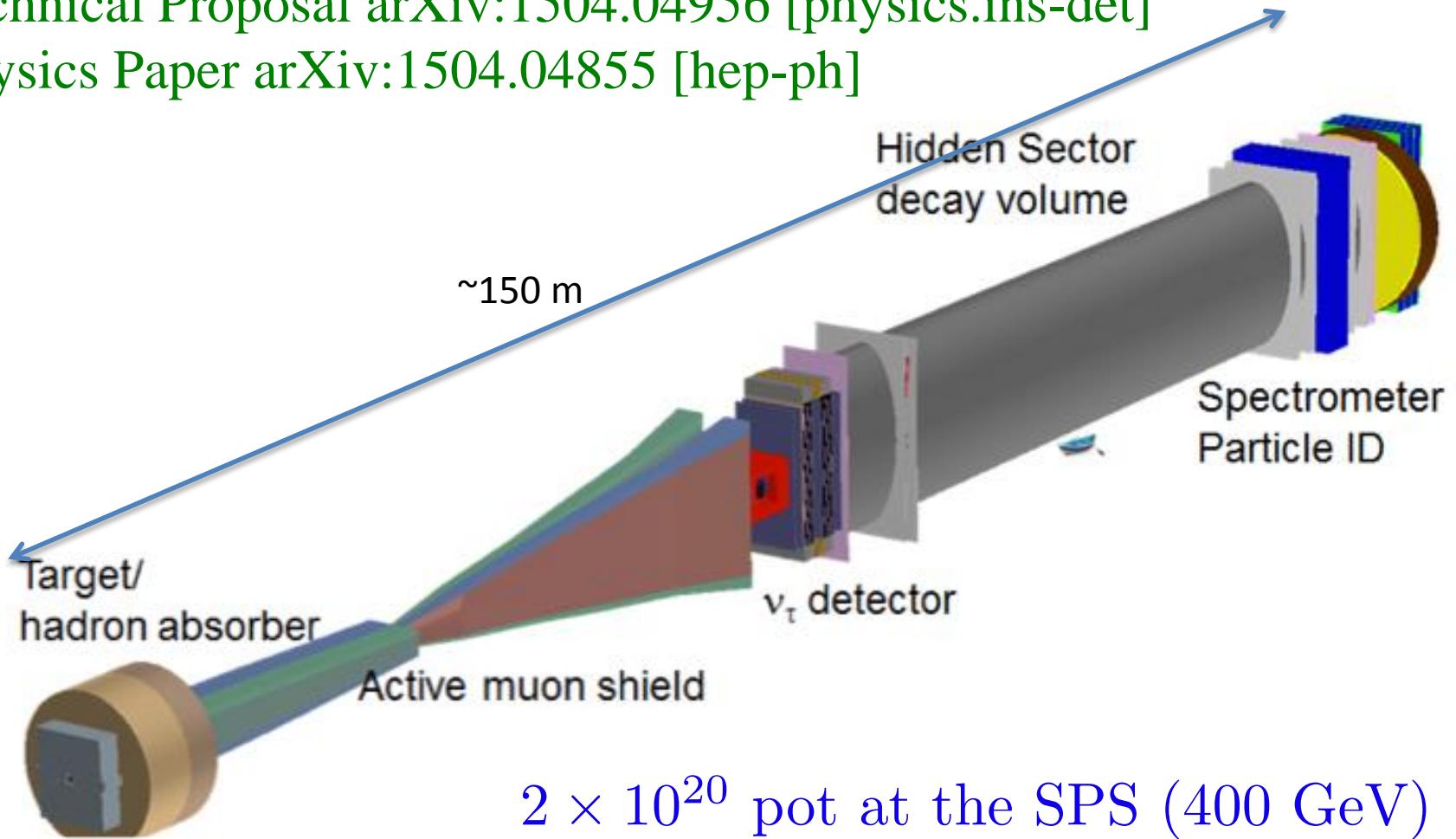
- Less known particle in the Standard Model
- First observation by DONUT at Fermilab in 2001 with 4 detected candidates, *Phys. Lett. B504 (2001) 218-224*
- 9 events (with an estimated background of 1.5) reported in 2008 with looser cuts
$$\sigma^{\text{const}}(\nu_\tau) = (0.39 \pm 0.13 \pm 0.13) \times 10^{-38} \text{ cm}^2 \text{ GeV}^{-1}$$
- 5 ν_τ candidates reported by OPERA for the discovery (5.1σ result) of ν_τ appearance in the CNGS neutrino beam arXiv:1507.01417 [hep-ex]
- Tau anti-neutrino never observed

SHIP AT CERN

SEARCH FOR HIDDEN PARTICLES

Technical Proposal arXiv:1504.04956 [physics.ins-det]

Physics Paper arXiv:1504.04855 [hep-ph]



FACILITY IDEAL TO STUDY ν_τ PHYSICS

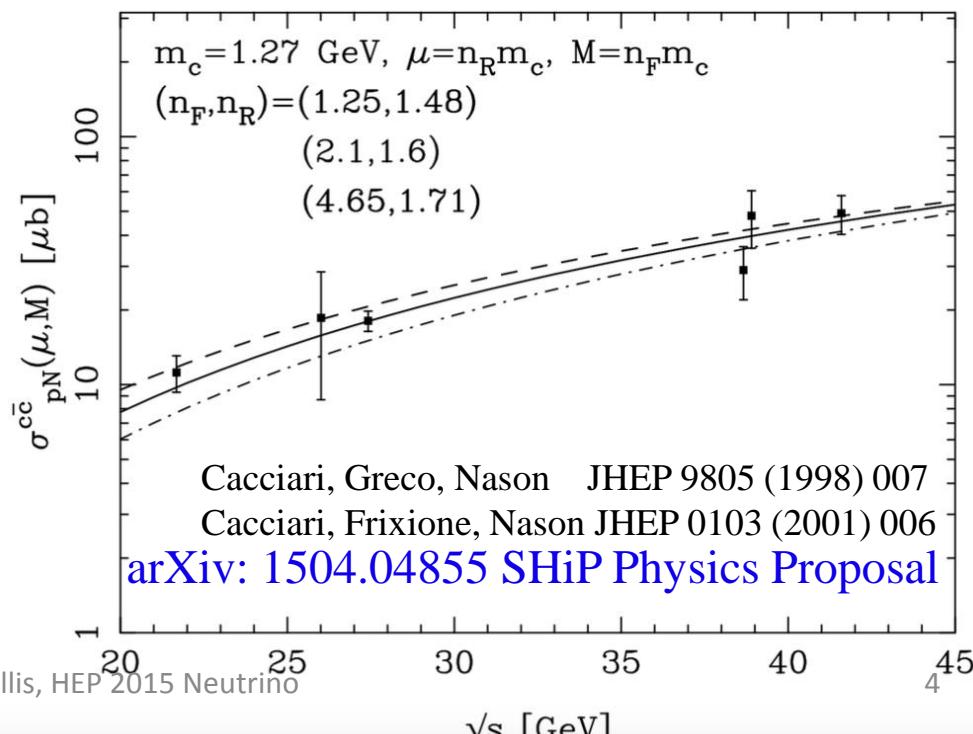
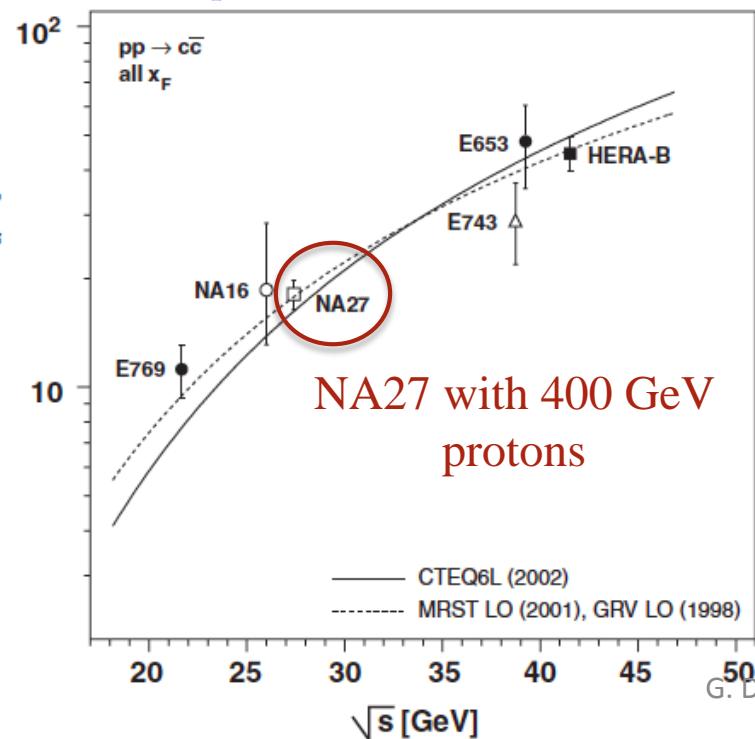
$$N_{\nu_\tau + \bar{\nu}_\tau} = 4N_p \frac{\sigma_{c\bar{c}}}{\sigma_{pN}} f_{D_s} Br(D_s \rightarrow \tau) = 2.85 \times 10^{-5} N_p = 5.7 \times 10^{15}$$

$$\sigma_{c\bar{c}} = 18.1 \pm 1.7 \text{ } \mu\text{barn}$$

Physics Reports 433 (2006) 127

$$\begin{aligned}\sigma_{c\bar{c}} &\propto A \\ \sigma_{pN} &\propto A^{0.71}\end{aligned}$$

$$\begin{aligned}Br(D_s \rightarrow \tau) &= (5.54 \pm 0.24)\% \quad PDG 2014 \\ f_{D_s} &= (7.7 \pm 0.6^{+0.5}_{-0.4})\% \quad JHEP 1309 (2013) 058\end{aligned}$$

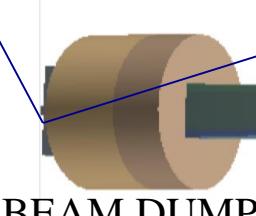
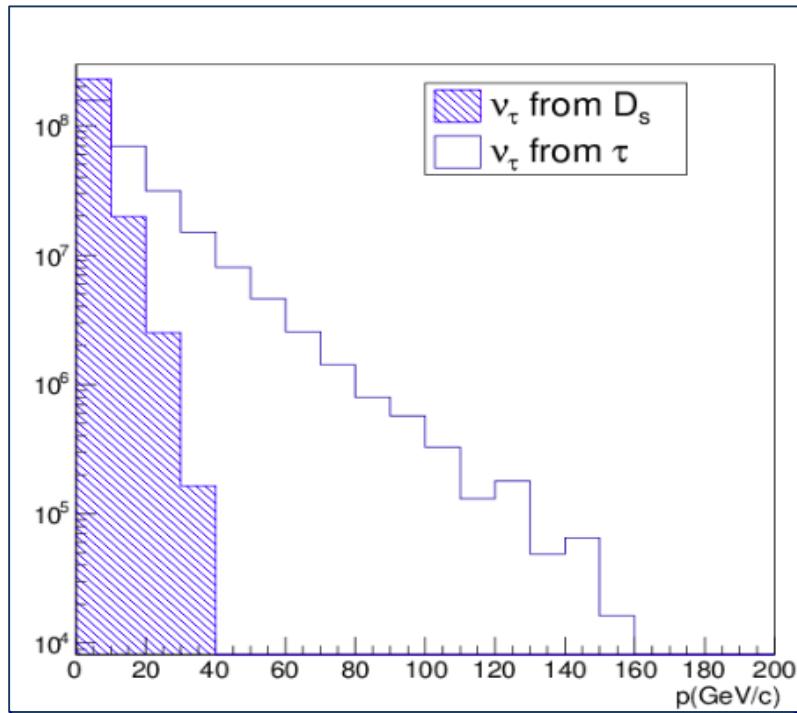


ν_τ FLUXES

*in 5 years run (2×10^{20} pot)

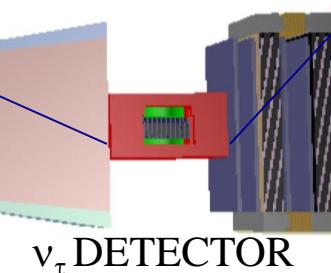
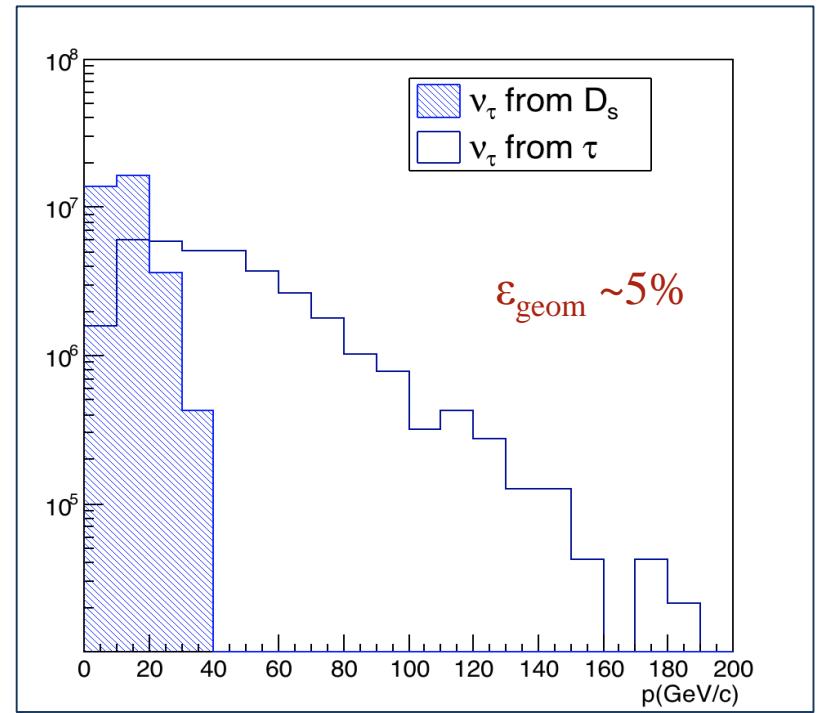
At the beam dump*

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

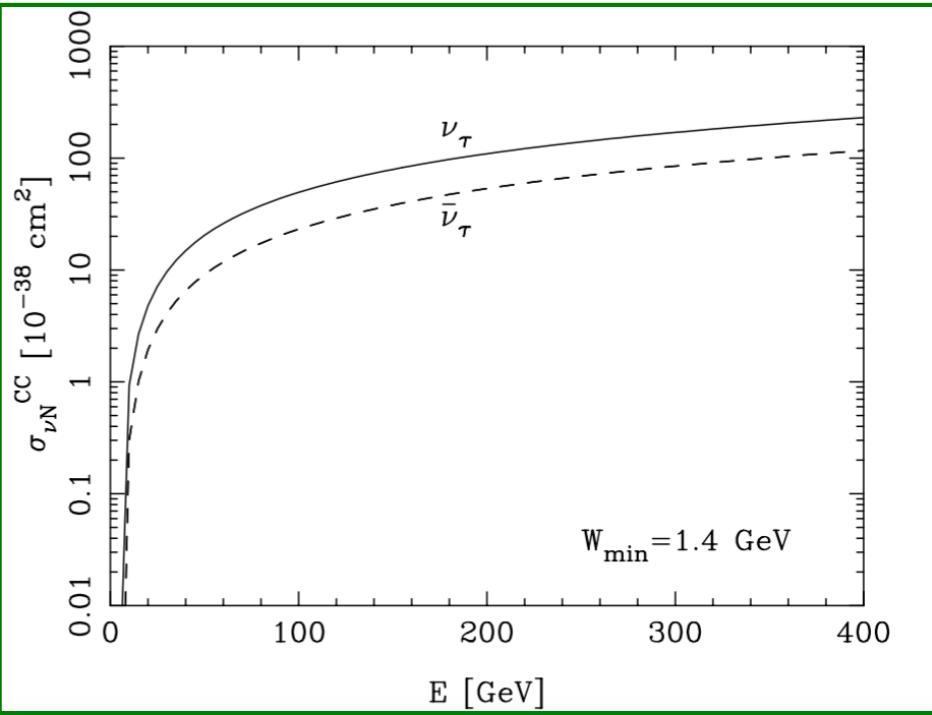


At the neutrino detector*

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



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)

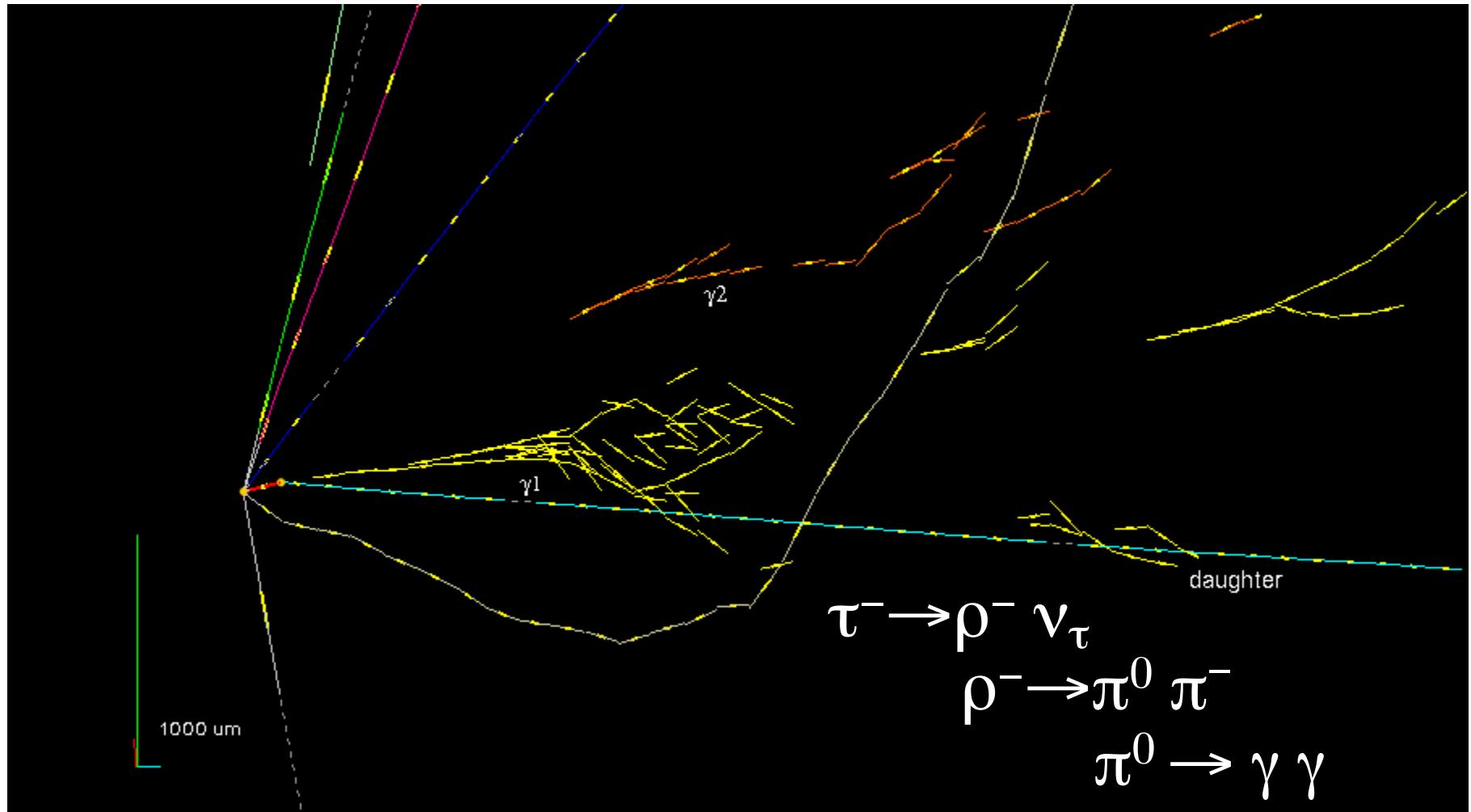
$$N_{\nu_\tau} \approx 6.7 \times 10^3$$

$$N_{\bar{\nu}_\tau} \approx 3.4 \times 10^3$$

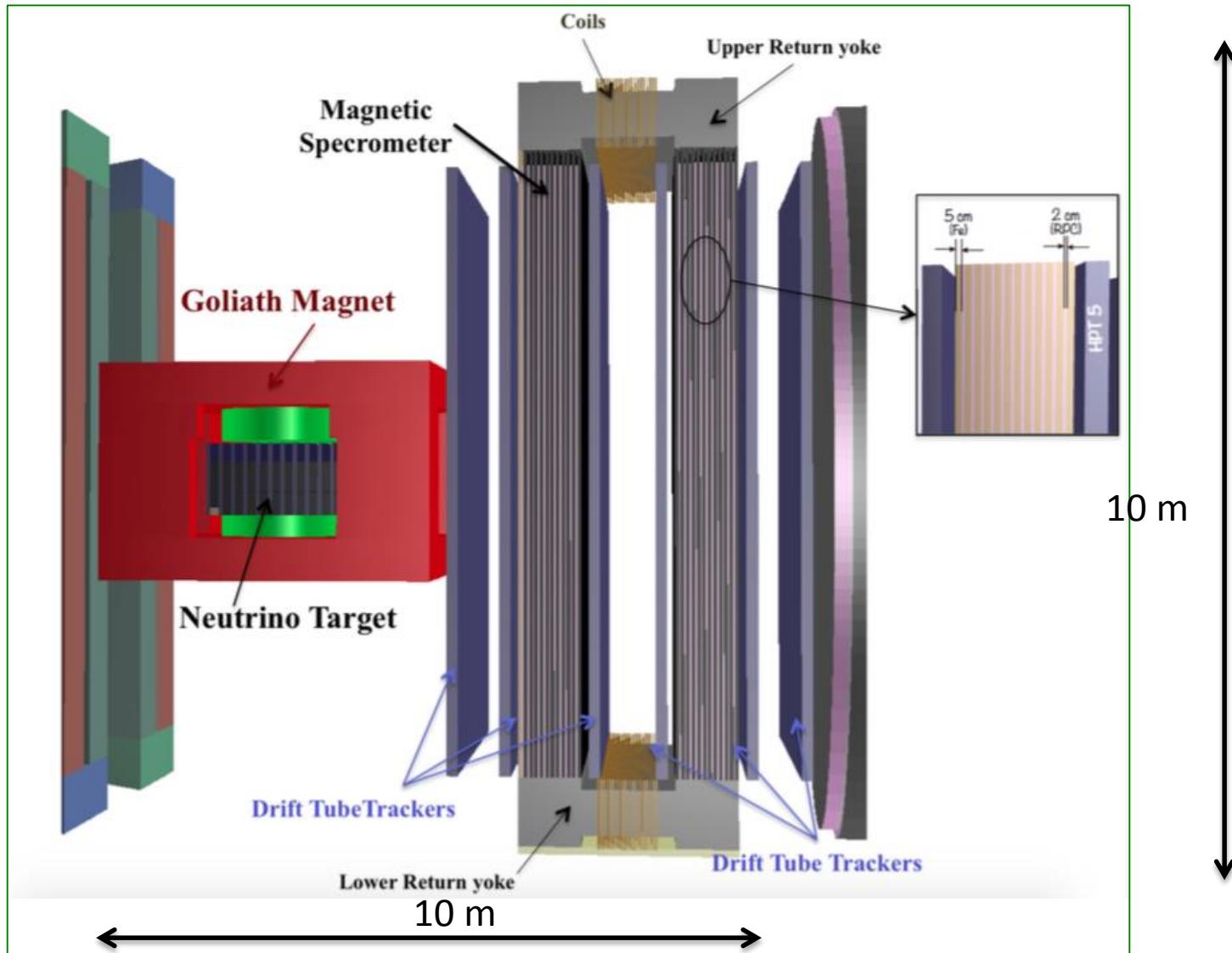
20% uncertainty mainly
from scale variations in
ccbar differential cross-section

ν_τ IDENTIFICATION A LA OPERA

THE FIRST OPERA ν_τ CANDIDATE



THE NEUTRINO DETECTOR

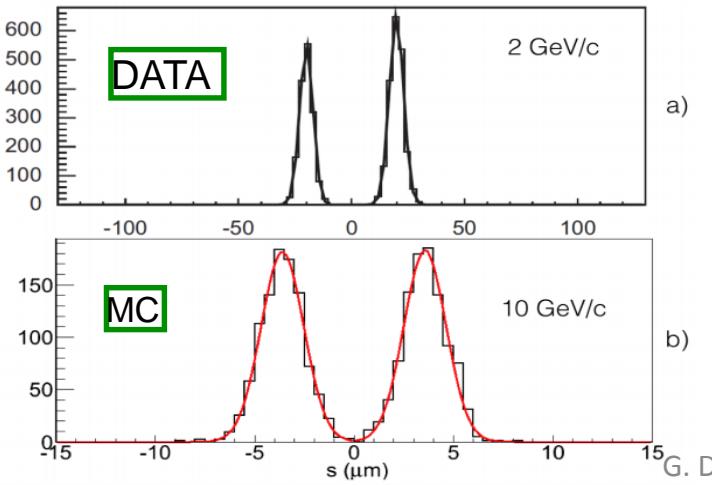
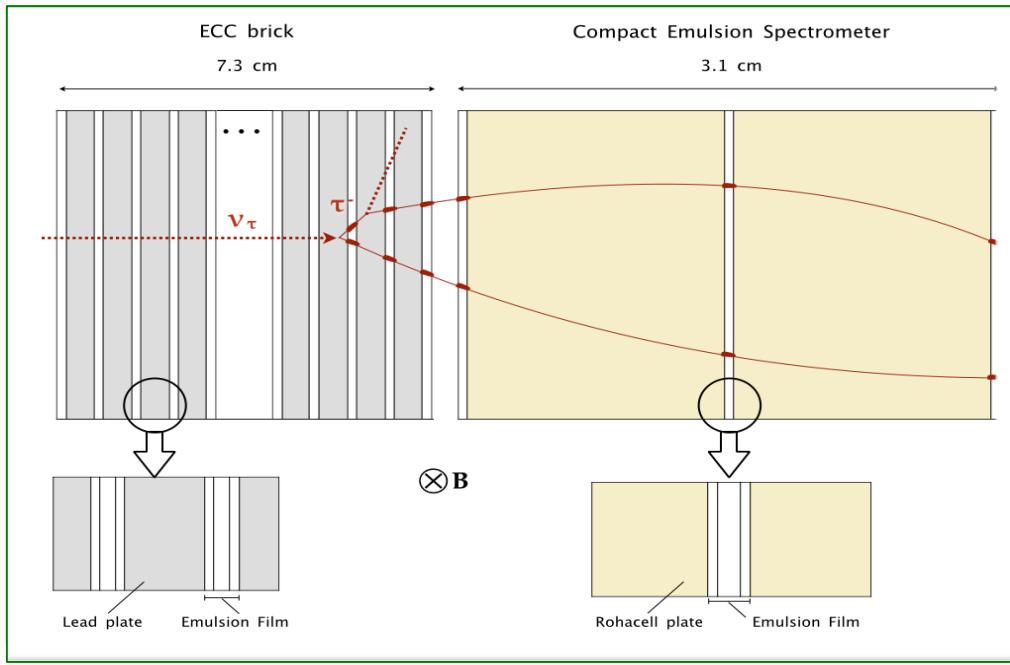


ν_τ /ANTI- ν_τ SEPARATION

THE COMPACT EMULSION SPECTROMETER

TASK

- Electric charge and momentum measurement of τ lepton decay products
 - Key role for the $\tau \rightarrow h$ decay channel
- ↓
- 3 OPERA-like emulsion films
 - 2 Rohacell spacers (low density material)
 - 1 Tesla magnetic field



PERFORMANCES

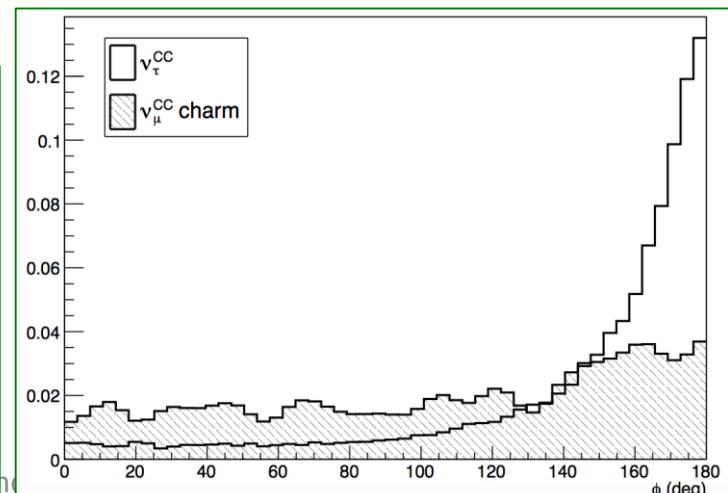
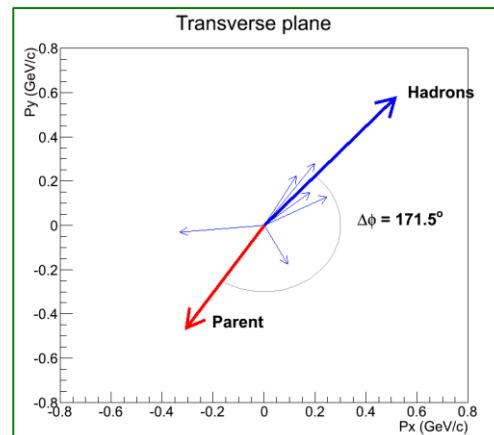
- **Electric charge** determined up to 12 GeV
- **Momentum** estimated from the sagitta
- $\Delta p/p < 20\%$ up to 12 GeV/c

SIGNAL AND BACKGROUND YIELDS

Detection efficiency,
charge measurement,
muon identification included
 $\tau \rightarrow e$ decay channel not included

decay channel	SIGNAL EXPECTATION			BACKGROUND			$R=S/B$ RATIO
	N^{exp}	ν_τ	R	N^{exp}	$\bar{\nu}_\tau$	R	
$\tau \rightarrow \mu$	570	30	19	290	140	2	
$\tau \rightarrow h$	990	80	12	500	380	1.3	
$\tau \rightarrow 3h$	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

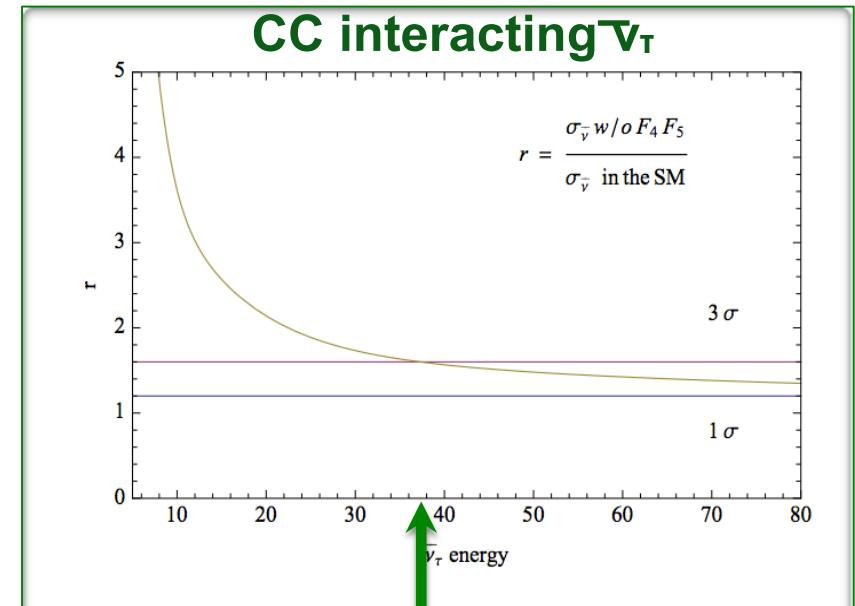
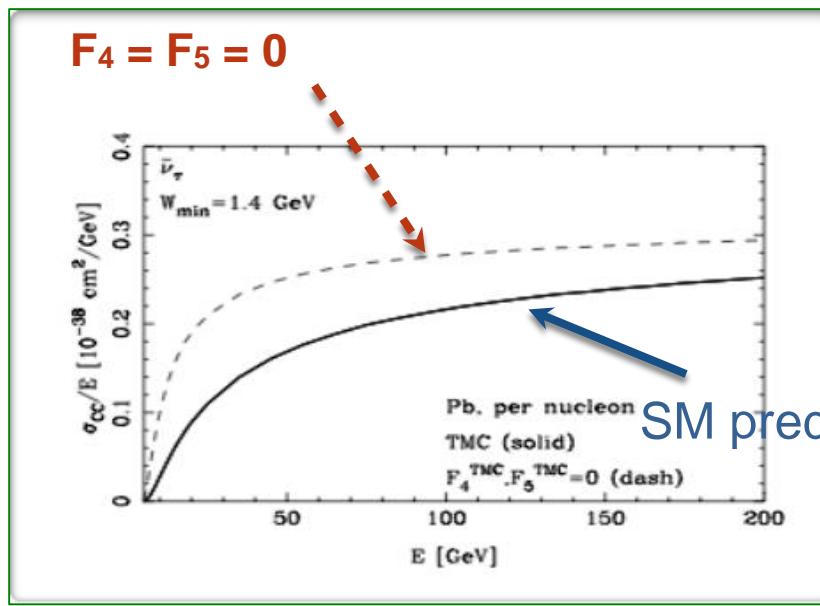


The analysis can be improved by exploiting a likelihood approach

F_4 AND F_5 STRUCTURE FUNCTIONS

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

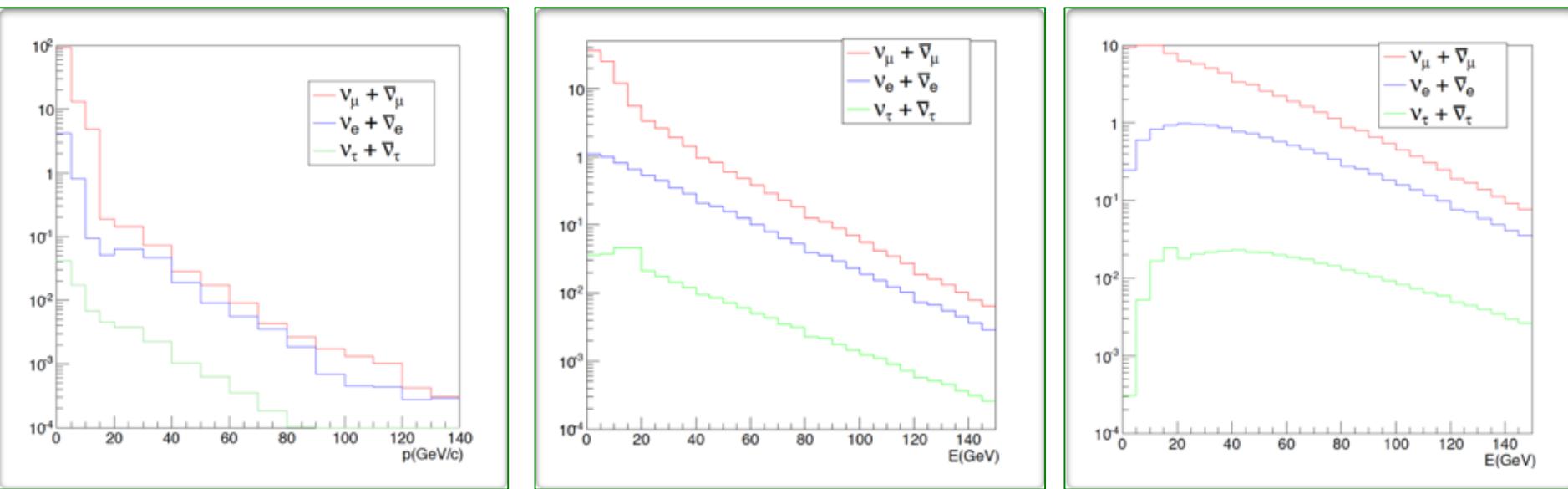
$$\begin{aligned} \frac{d^2\sigma^{\nu(\bar{\nu})}}{dxdy} = & \frac{G_F^2 M E_\nu}{\pi(1+Q^2/M_W^2)^2} \left((y^2x + \frac{m_\tau^2 y}{2E_\nu M}) F_1 + \left[(1 - \frac{m_\tau^2}{4E_\nu^2}) - (1 + \frac{Mx}{2E_\nu}) \right] F_2 \right. \\ & \pm \left. \left[xy(1 - \frac{y}{2}) - \frac{m_\tau^2 y}{4E_\nu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



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

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 \Rightarrow high neutrino fluxes from their decays, including remnant pion and kaon decays



	$\langle E \rangle$ (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}

	$\langle E \rangle$ (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}

	$\langle E \rangle$ (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

CHARM PHYSICS @SHIP

- Neutrino induced charm production
Physics Reports 399 (2004) 277
- Advantage of the emulsion technology:
 topological, very loose kinematical cuts

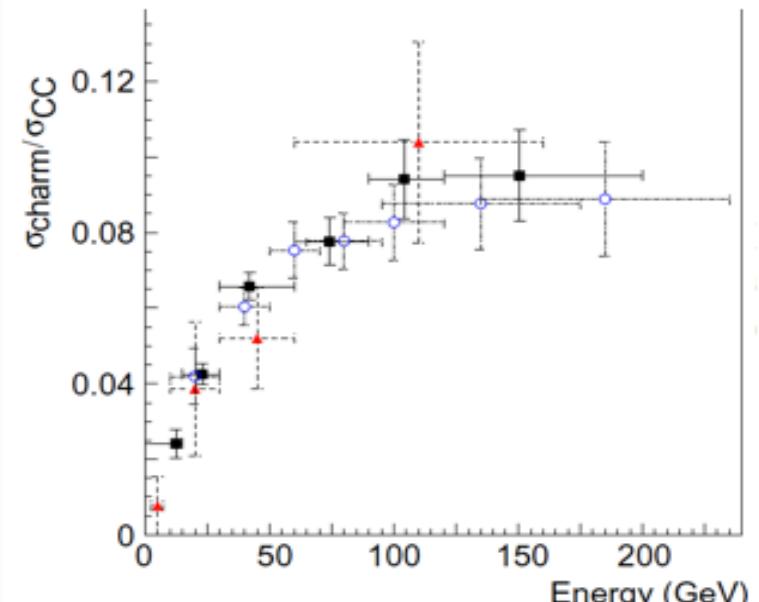
$$\nu_\mu^{CC} \\ f(charm) = \frac{\int \Phi_{\nu_\mu} \sigma_{\nu_\mu}^{CC} \left(\frac{\sigma_{charm}}{\sigma_{\nu_\mu}^{CC}} \right) dE}{\int \Phi_{\nu_\mu} \sigma_{\nu_\mu}^{CC} dE} \approx 4\%$$

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

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	$1.1 \cdot 10^5$

CHORUS, New J. Phys. 13 (2011) 093002



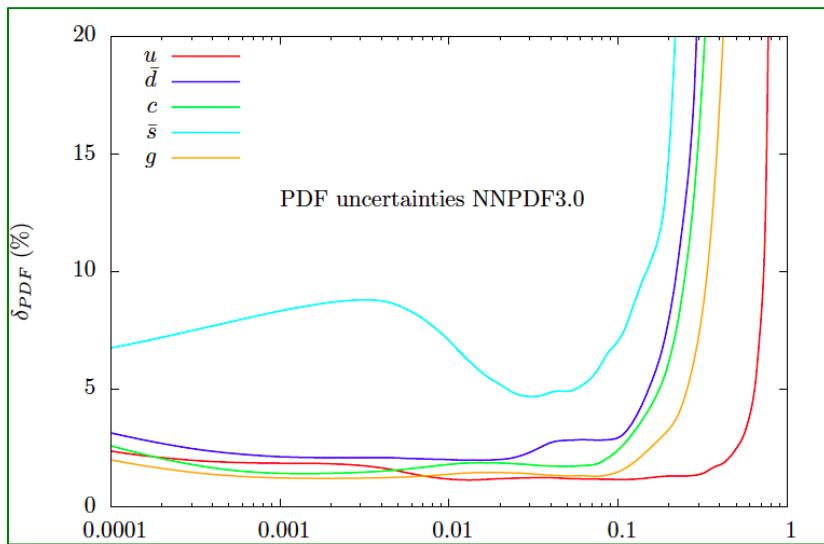
In NuTeV ~5100 ν_μ
 ~1460 anti- ν_μ

In CHORUS ~2000 ν_μ
 32 anti- ν_μ

No charm candidate from ν_e and ν_τ interactions ever reported!

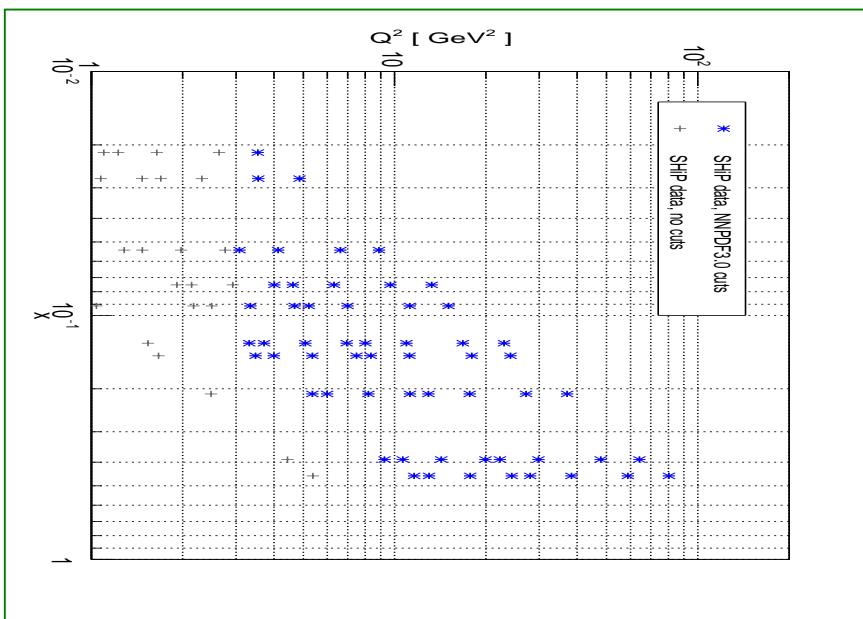
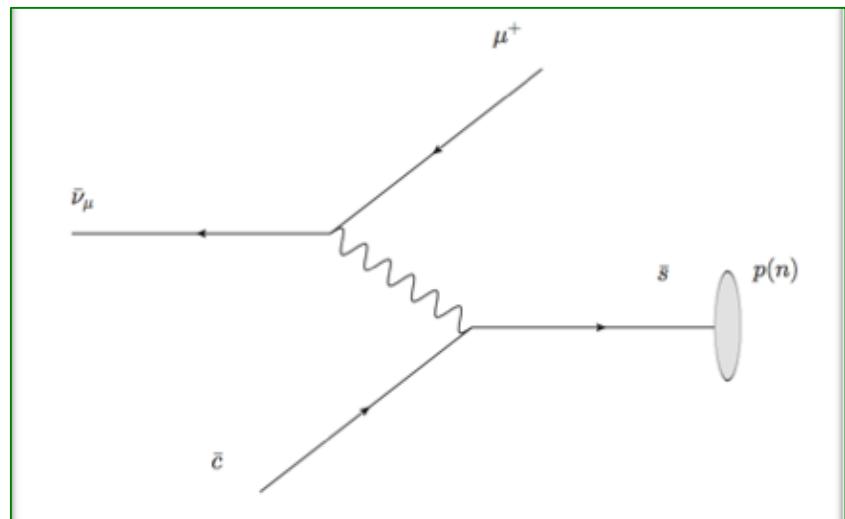
STRANGE QUARK NUCLEON CONTENT

- 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 $c\bar{s}$



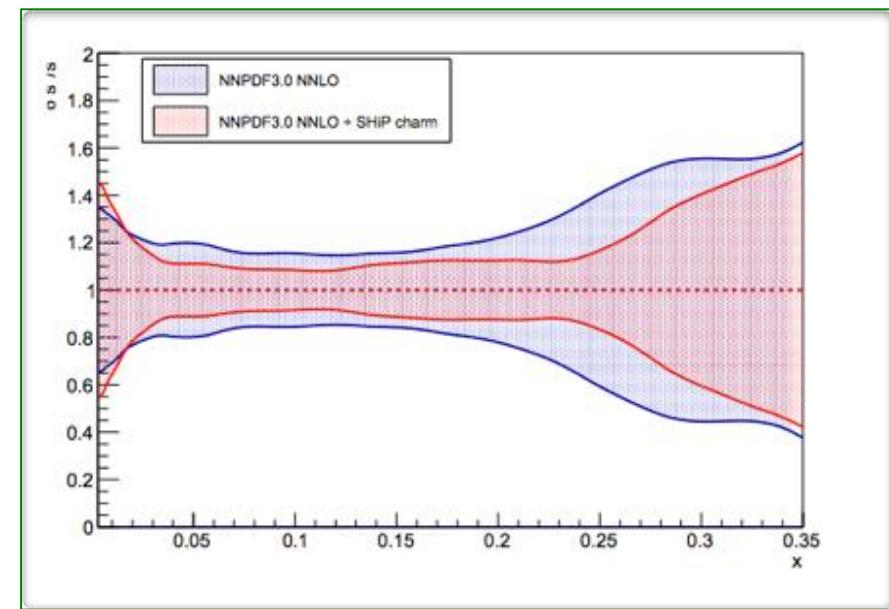
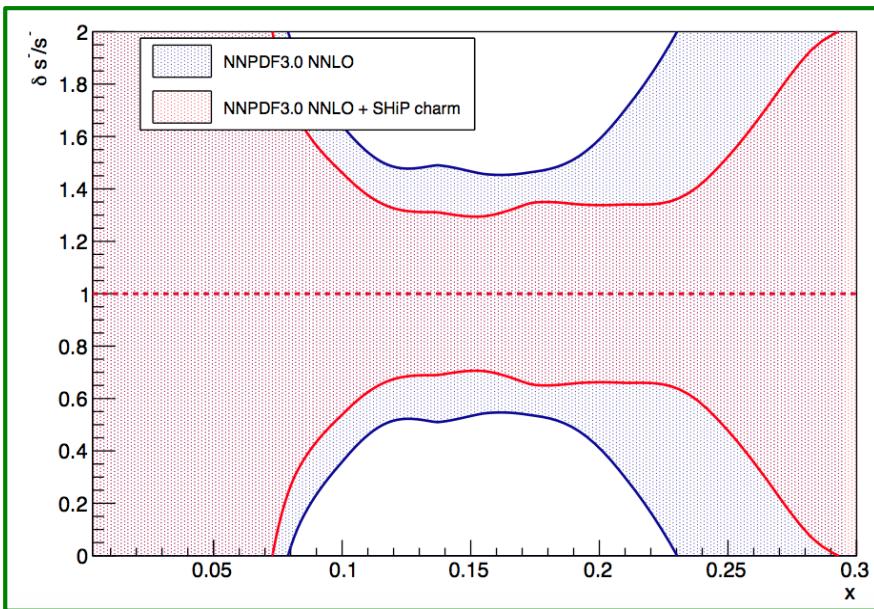
Phys. Rev. D91 (2015) 113005

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



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

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

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

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*

SIGNAL SELECTION

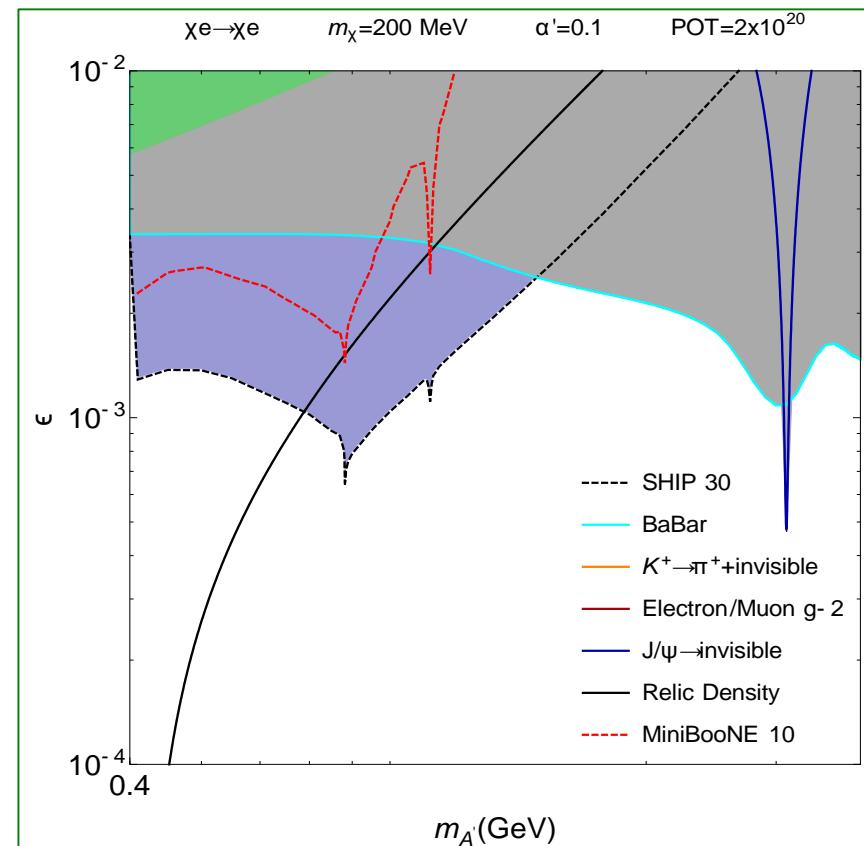
$$\begin{cases} 0.01 < \theta < 0.02 \\ E < 20 \text{ GeV} \end{cases}$$

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

α' = dark photon coupling with χ



CONCLUSIONS

- SHiP experiment proposed at CERN
- Unique tau neutrino and anti-neutrino physics
- Rich neutrino physics program
- Strange quark content
- Dark matter search
- Other topics: charmed pentaquark search, tau neutrino magnetic moment