Charm production in neutrino interactions as background source to oscillation signal and as a physics measurement on its own

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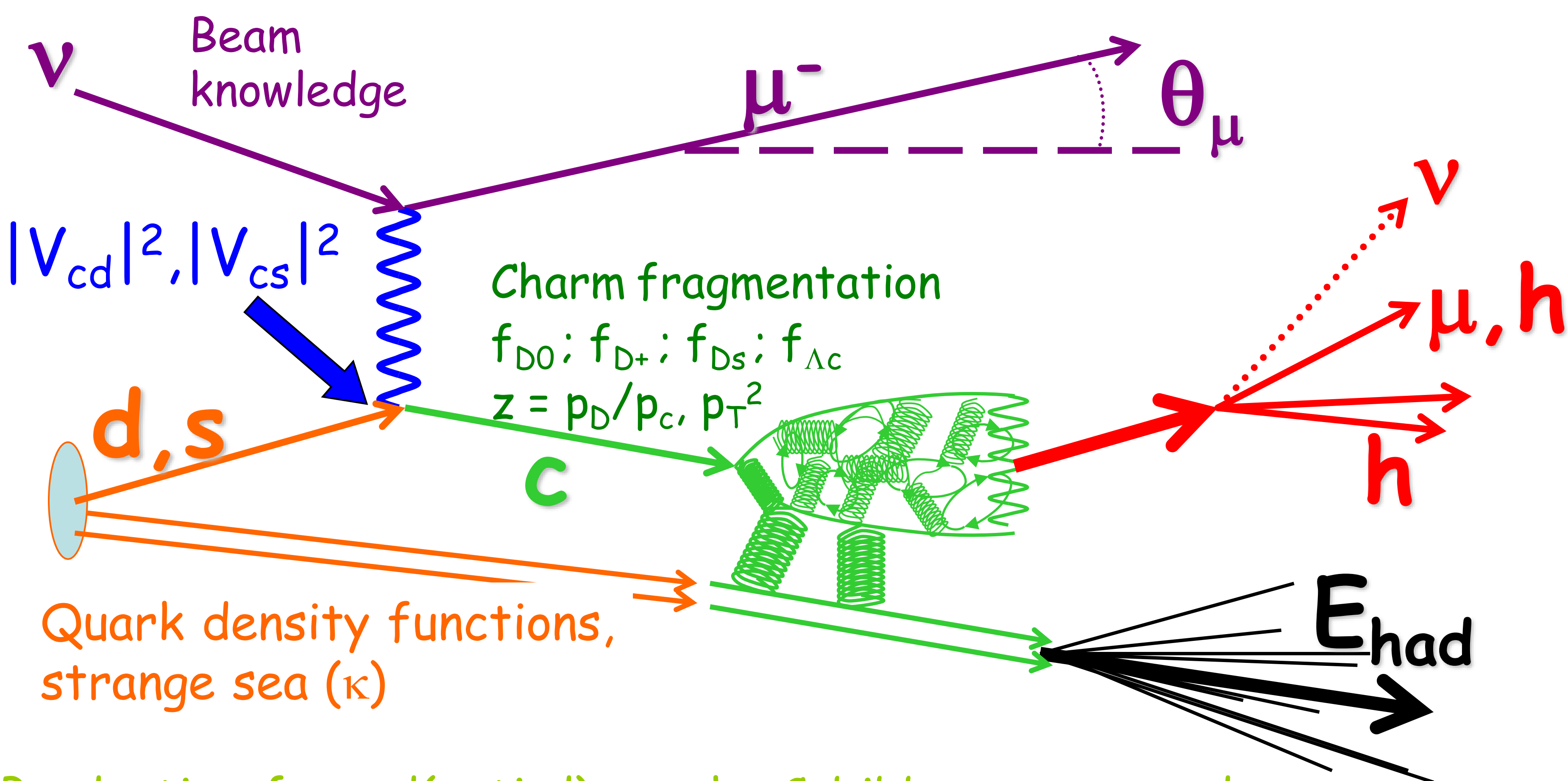
NearDetector WG- CERN 30-31/July/2011

ν DIS charm production



Production from d(anti-d) quarks Cabibbo suppressed

⇒ large s contribution: ≈50% in ν and ≈90% in anti-ν

Dimuon available statistics

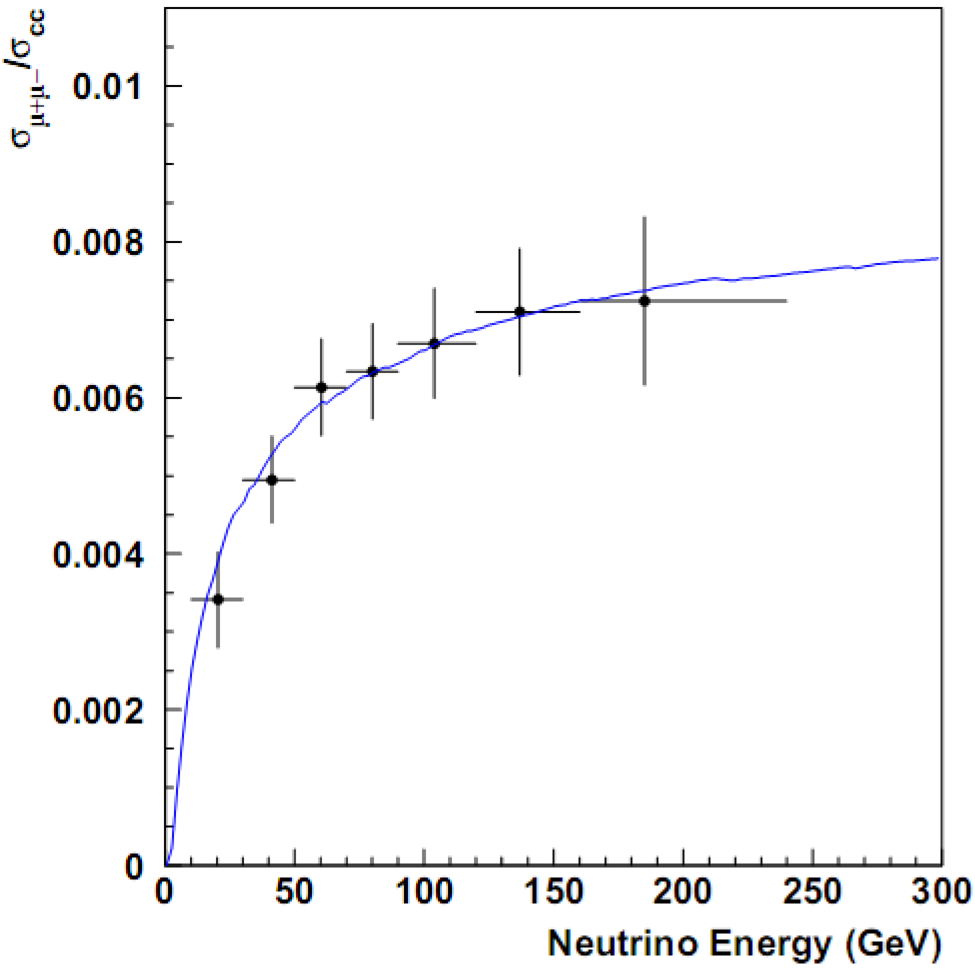
CDHS (CERN WBB)	9922 $\mu^-\mu^+$, 2123 $\mu^+\mu^-$ events	*Zeitschr. Phys. C (1982) 19-31*
CCFR (NuTeV)	5044 $\mu^-\mu^+$, 1062 $\mu^+\mu^-$ events	*Zeitschr. Phys. C (1995) 189-198*
CHARMII (CERN WANF)	4111 $\mu^-\mu^+$, 871 $\mu^+\mu^-$ events	*Eur. Phys. J., C11 (1999) 19-34*
NOMAD (CERN WANF)	2714 $\mu^-\mu^+$, 115 $\mu^+\mu^-$ events	*Phys.Lett.B486:35-48,2000*
CHORUS (CERN WANF)	8910 $\mu^-\mu^+$, 430 $\mu^+\mu^-$ events	*Nucl..Phys.B798:1-16,2008*

High statistics, but:

Background due to π, K, K^o_s

Cross section measurement depends on knowledge of
BR ($C \rightarrow \mu$) ~ 10%
and on the uncertainty on it

Dimuon cross-section (CHORUS)

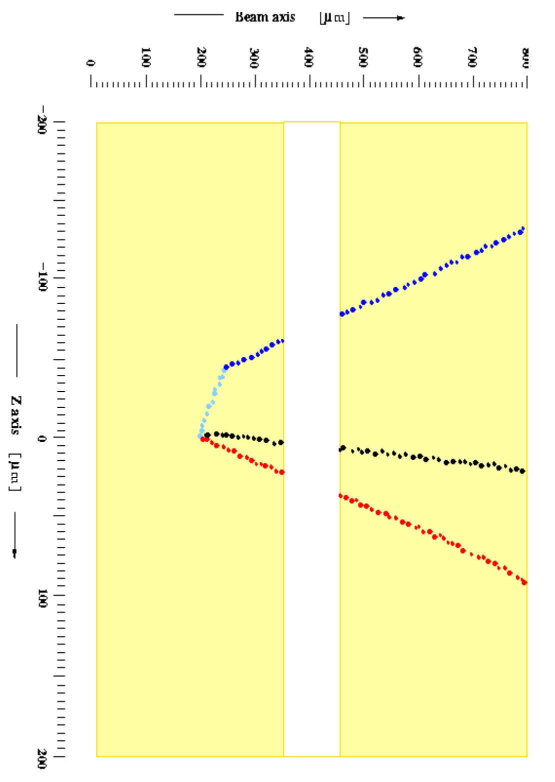


“Micrometric” experiments

These experiments study charm production by looking “directly” at the decay topology of the charmed hadron with micrometric resolution

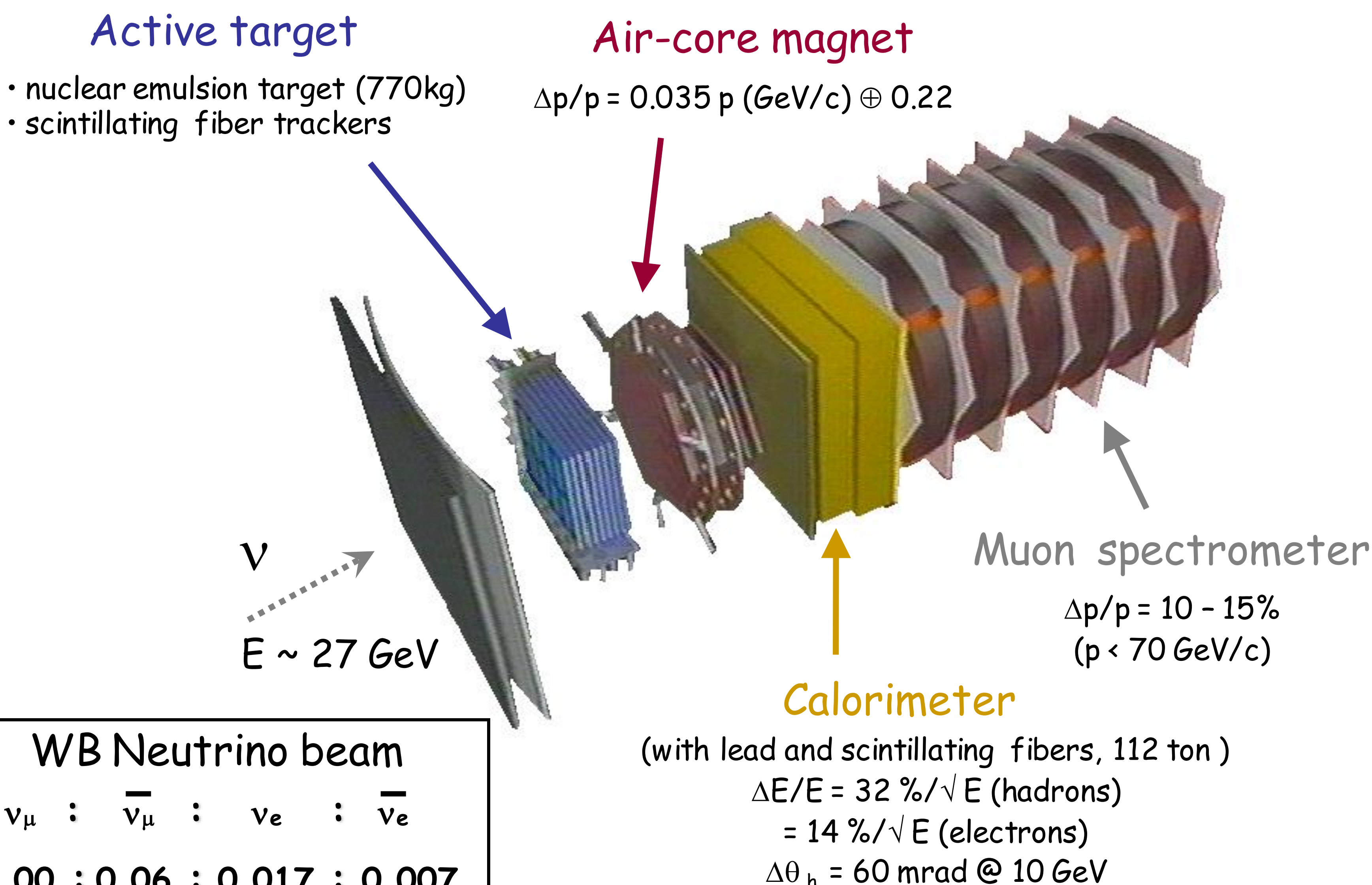
- **Contra:** none, but the difficulty of achieving the expected resolution

- **Pro:** low background; sensitivity to low $E_\nu \Rightarrow m_c$ thr. effect; reconstruction of the charmed hadron kinematics (direction and momentum) $\Rightarrow$ fragmentation studies are possible



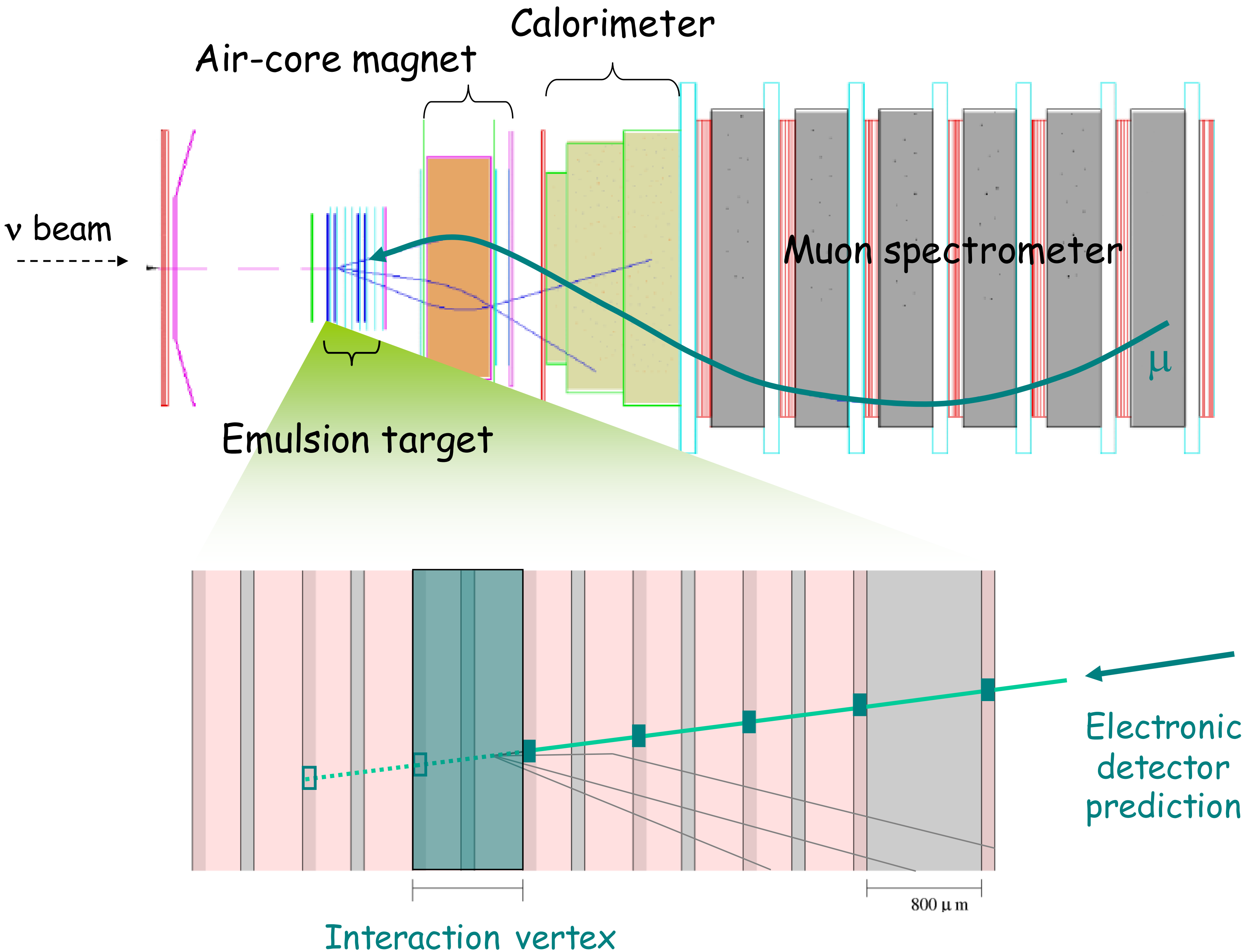
CHORUS experiment

(CERN Hybrid Oscillation Research ApparatUS)



WB Neutrino beam

ν_μ	:	$\bar{\nu}_\mu$	:	ν_e	:	$\bar{\nu}_e$
1.00	:	0.06	:	0.017	:	0.007

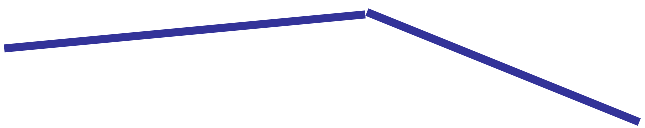

Calorimeter
Air-core magnet
ν beam
Muon spectrometer
μ
Emulsion target
Electronic
detector
prediction
800 μ m
Interaction vertex

The CHORUS charged current data sample and charm subsample

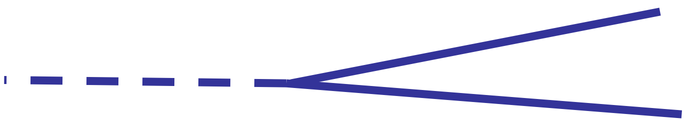
Located CC events 93807

Total confirmed charm candidates 2013

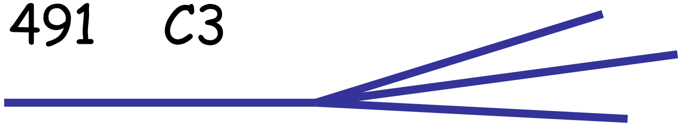
452 C1



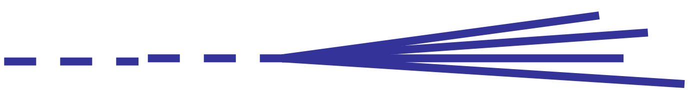
819 V2



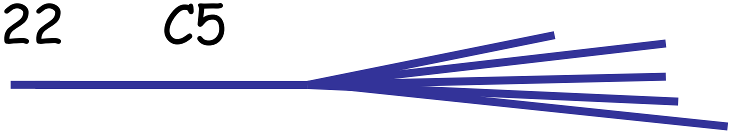
491 C3



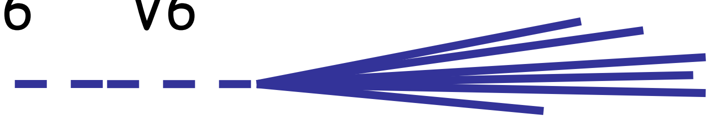
226 V4



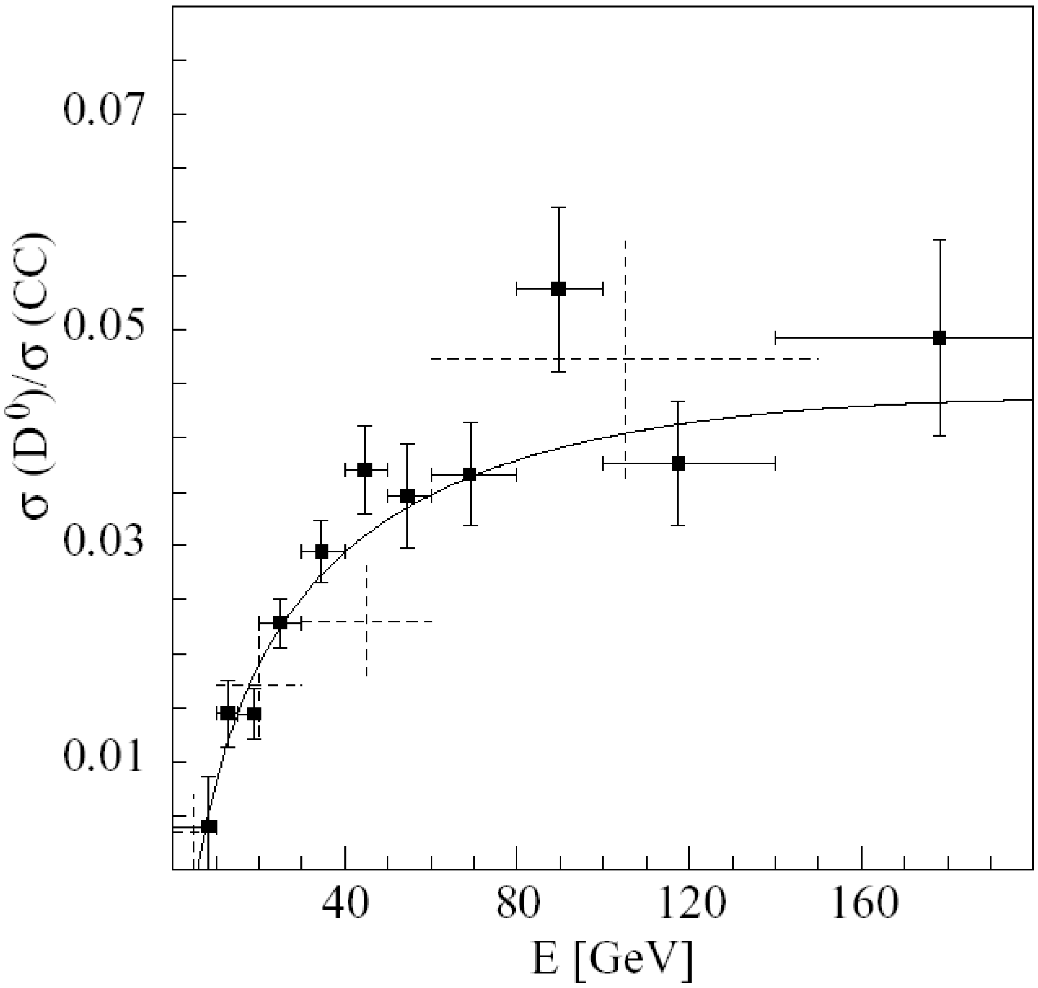
22 C5



6 V6



Measurement of D^0 production



Phys. Lett. B. 613 (2005) 105

Charm mass fit

m_C=1.42±0.08 GeV/c^2

Fit parameters for the model curve

(M.Gluk,E.Reya and A.Vogt, Z.Phys.C (1955) 433)

Variables	Value	Variation
m_c	(1.42 ± 0.08) GeV/c^2	fitted
κ	0.38	±0.10
α	1	±1
ϵ_p^s	$0.083 \pm 0.013 \pm 0.010$	±0.02
V_{cd}	0.221	fixed
V_{cs}	0.97437	fixed

(ε^s_p as measured in CHORUS, see next slides)

The relative rate is:

$\sigma(D^0)/\sigma(CC)$=0.0269 ± 0.0018 ± 0.0013

At 27 GeV average neutrino beam

Measurement of D^0 production UPDATE

The D^0 analysis is based on the BR(D^0->4prongs) that has been recently updated in the PDG. With the new value the cross-section becomes

$\sigma(D^0)/\sigma(CC)=0.0252 \pm 0.0017 \pm 0.0012$

It has also an impact on the full neutral branching ratio

BR(D^0-> all neutrals) = $0.17 \pm 0.06 \pm 0.03$

Impact on the muonic braching ratio

$B_\mu = (8.1 \pm 0.9 \pm 0.2)\%$

that is consistent with the value measured with dimuon event analysis

$B_\mu = (9.6 \pm 0.4 \pm 0.8)\%$

From charm quark to charmed hadrons

Z defined as the ratio of the energy of the charmed particle E^D and the energy transfer to the hadronic system ν : $z = E^D / \nu$

$$\frac{d^4\sigma(\nu_\mu N \to \mu^- C X)}{d\xi dy dz dp_T^2} = \frac{d^2\sigma(\nu_\mu N \to \mu^- c X)}{d\xi dy} \times \underline{\underline{\sum_h f_h \times D_c^h(z, p_T^2)}}$$

$$D_c(z) = N \frac{\left(\frac{1-z}{z} + \frac{\varepsilon_c(2-z)}{1-z}\right)}{\left(1 - \frac{1}{z} - \frac{\varepsilon_c}{1-z}\right)^2}(1+z^2)$$

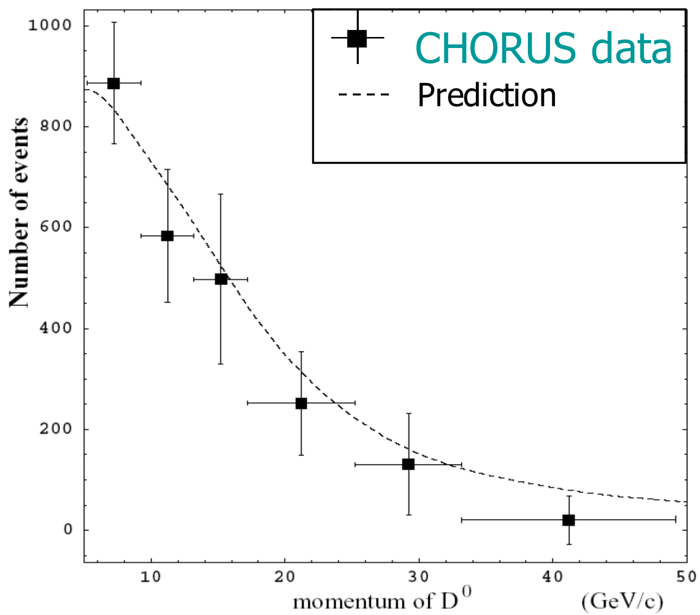
Collins-Spiller
J.Phys. G 11 (1985) 1289

$$D_p(z) = \frac{N}{z\left(1 - \frac{1}{z} - \frac{\varepsilon_p}{(1-z)}\right)^2}$$

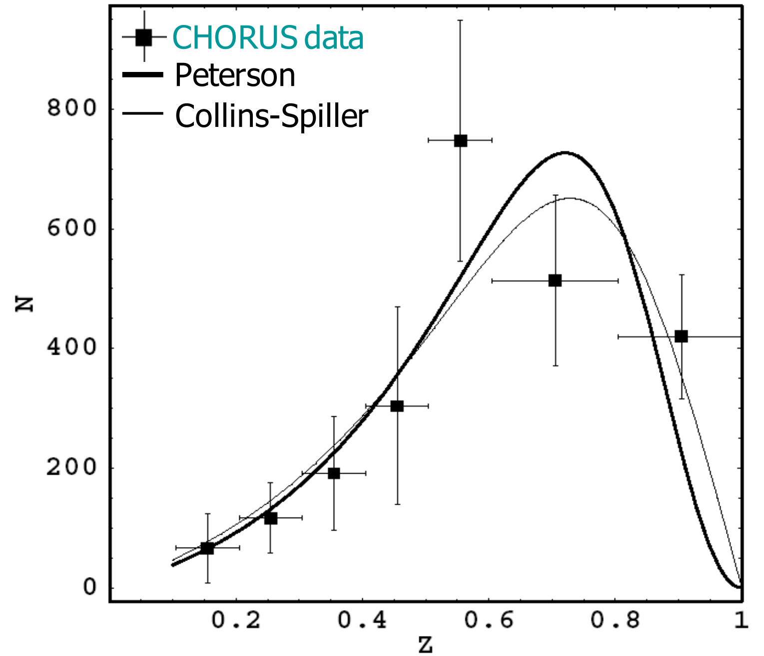
Peterson et al.
Phys.Rev. D 27 (1983) 105

Measurement of fragmentation properties of charmed particle production in CC neutrino interaction

Momentum distribution of D^0's produced inclusively in CHORUS



Z distribution



<z> = 0.63 ± 0.03(stat) ±

Experiment	$\langle z \rangle$	ϵ_P and ϵ_{CS}
CDHS[2]	0.68 ± 0.08	$\epsilon_P^Q = [0.02, 0.14]$
E531[6]	0.59 ± 0.04	$\epsilon_P = 0.076 \pm 0.014$
CCFR[4]	0.56 ± 0.03	$\epsilon_P = 0.22 \pm 0.05$ $\epsilon_{CS} = 0.88 \pm 0.12$
BEBC[5]	$0.59 \pm 0.03 \pm 0.08$	–
CHARM II[3]	0.66 ± 0.03	$\epsilon_P^Q = 0.072 \pm 0.017$
NOMAD[7]	$0.67 \pm 0.02 \pm 0.02$	$\epsilon_P^Q = 0.075 \pm 0.028 \pm 0.036$ $\epsilon_{CS} = 0.13 \pm 0.08 \pm 0.11$
NuTeV[8]	–	$\epsilon_{CS} = 2.07 \pm 0.31$

Fit to Collins-Spiller distribution:

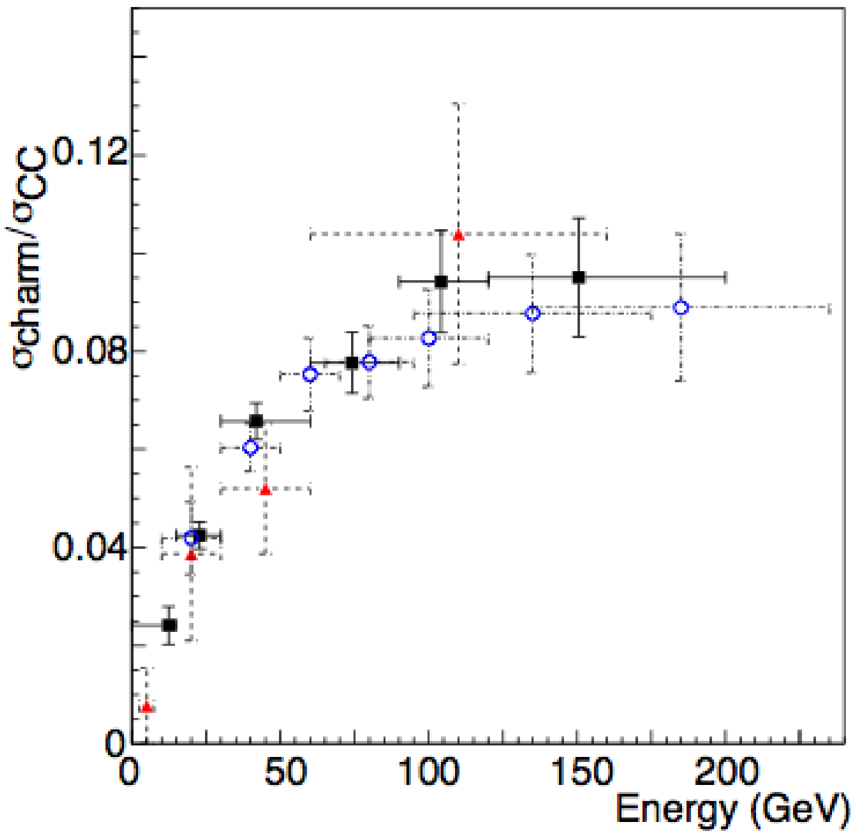
$\varepsilon_{CS} = 0.21^{+0.05}_{-0.04} \pm 0.04$

Fit to Peterson distribution:

$\varepsilon_P = 0.083 \pm 0.013 \pm 0.010$

Measurement of inclusive charm production

Measurement of charm production in neutrino charged-current interactions.
CHORUS Collaboration, CERN-PH-EP-2011-109. Jul 2011. 16 pp.
e-Print: arXiv:1107.0613 [hep-ex]



σ(Charm)/σ(CC)=(5.75$\pm$0.32$\pm$0.30)%

At 27 GeV average neutrino beam

Charmed fractions and inclusive topological branching ratios

$f_{D0} = (43.7 \pm 4.5)\%$

$f_{D+} = (25.3 \pm 4.4)\%$

$f_{\Lambda c+} = (19.2 \pm 4.2)\%$

$f_{Ds+} = (11.8 \pm 4.7)\%$

Likelihood fit to flight length over momentum distribution to obtain the charm production fractions

$$BR(C^+ \to 1\ \text{prong}) = (64 \pm 10)\%$$

$$BR(C^+ \to 3\ \text{prong}) = (35 \pm 6)\%$$

$$BR(C^+ \to 5\ \text{prong}) = (1.4 \pm 0.3)\%$$

$$BR(D^0 \to \text{fully neutrals}) = (17 \pm 6 \pm 3)\%$$

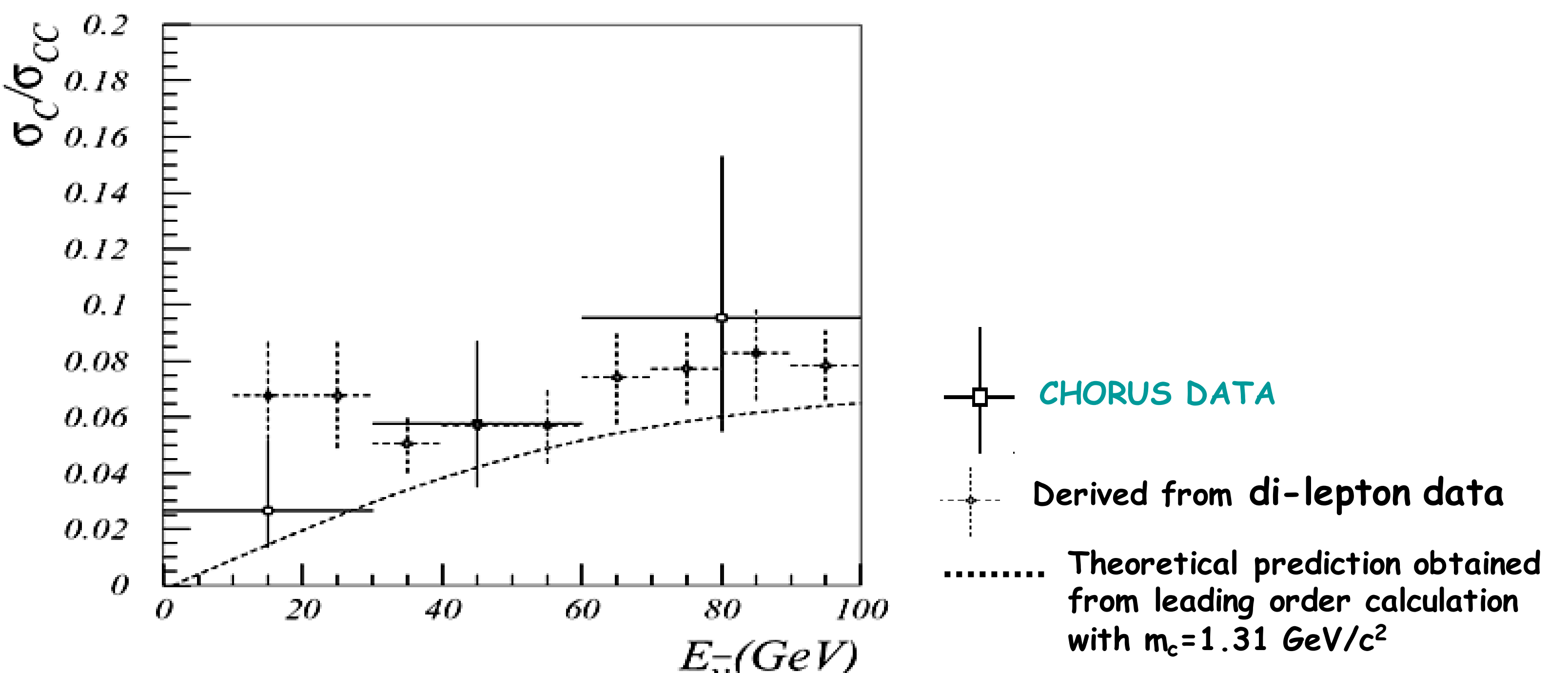
$$BR(D^0 \to 2\ \text{prong}) = (69.1 \pm 3.3)\%$$

$$BR(D^0 \to 4\ \text{prong}) = (14.3 \pm 0.5)\% \quad \text{(PDG)}$$

Measurement of charm production in antineutrino charged-current interactions

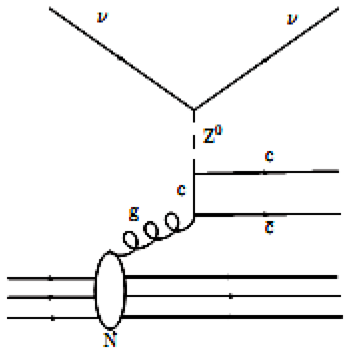
Decay topology	Events	Background
V2	16	1.4 ± 0.2
V4	6	0.13 ± 0.05
C1	4	1.3 ± 0.2
C3	4	0.3 ± 0.1
C5	2	0.02 ± 0.01
TOT	**32**	

$$\frac{\sigma(\bar{\nu} N \rightarrow \mu^+ \bar{c} X)}{\sigma(\bar{\nu} N \rightarrow \mu^+ X)} = 5.0\,^{+1.4}_{-0.9} \pm 0.7\%$$

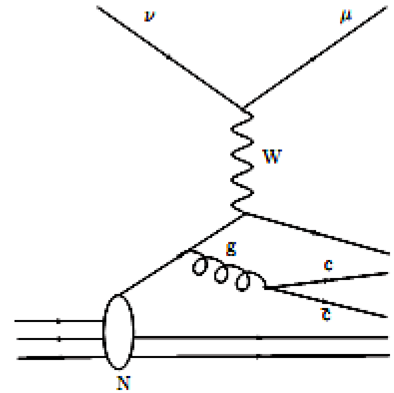


Associated charm production

boson gluon fusion



gluon bremsstrahlung

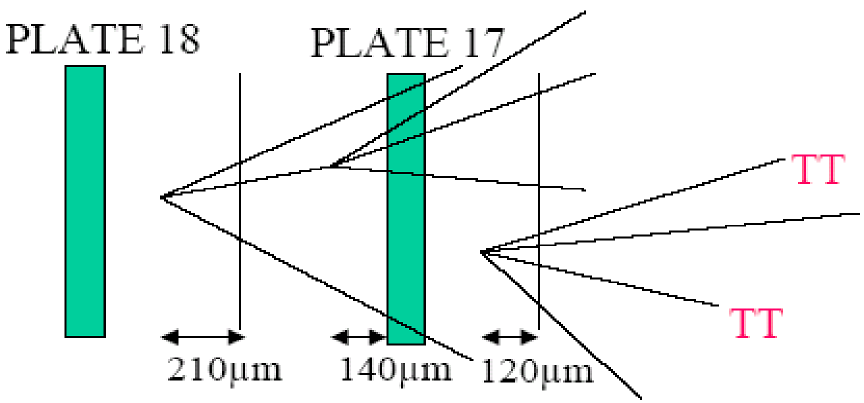


3 observed events in NC sample

topologies

- C1+V2
- V2+V2
- C3+V4

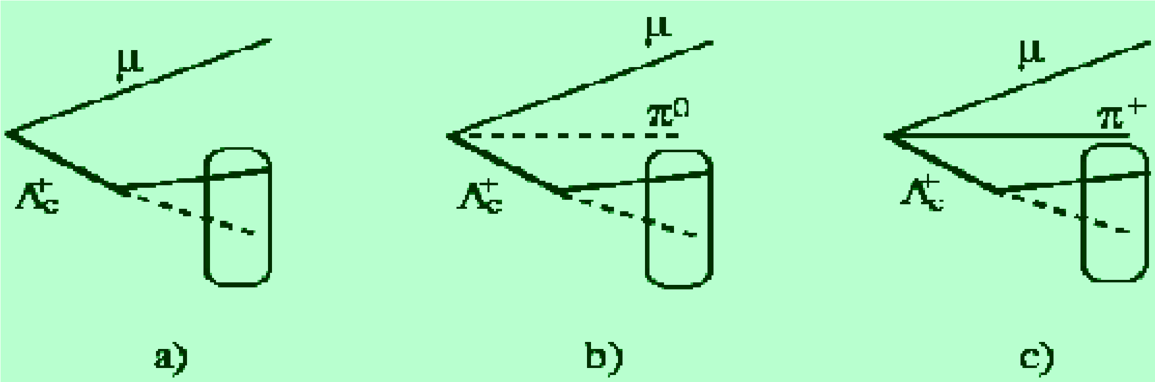
Background= 0.18 ± 0.06



$$\sigma(c\tilde{c}\nu)/\sigma(NC)=(3.6^{+2.9}_{-2.4})\times 10^{-3}$$

Quasi-elastic charm production

Phys.Lett.B 575 (2003) 198   based on 46105 ν_μ CC



a) $\nu_\mu n \to \mu^- \Lambda_c^+$ **b)** $\nu_\mu n \to \mu^- \Sigma_c^+ (\Sigma_c^{*+})$ **c)** $\nu_\mu p \to \mu^- \Sigma_c^{++} (\Sigma_c^{*++})$

Topological and kinematical selection criteria:

- Require 2 or 3 tracks at primary vertex
- $\Phi \geq 165^\circ$ (angle between muon and charm in the transverse plane)
- Flight length < 200 μm (enriched Λc sample)
- Calorimeter energy < 10 GeV and electromagnetic energy < 2 GeV

13 events with a background of 1.7±0.6 (mainly from DIS Λc)

$$\frac{\sigma_{QEcharm}}{\sigma_{CC}} = 0.23^{+0.12}_{-0.06}(\text{stat})^{+0.02}_{-0.03}(\text{syst})\%$$

QE production is about 15% of Λc production

Why we should measure more accurately QE charm production?

Λ_c^+ BRANCHING FRACTIONS

Revised 2002 by P.R. Burchat (Stanford University).

Most Λ_c^+ branching fractions are measured relative to the decay mode $\Lambda_c^+ \to pK^-\pi^+$. However, there are no completely model-independent measurements of the absolute branching fraction for $\Lambda_c^+ \to pK^-\pi^+$. Here we describe the measurements that have been used to extract $B(\Lambda_c^+ \to pK^-\pi^+)$, the model-dependence of the results, and the method we have used to average the results.

Error about 30%!

…However, it is also stressed that this number is rather arbitrary. Indeed Ref. [2] advocates method B suggesting that one should reanalyze the Bbar decay channels. As a result, if this interpretation is correct, then:

(i). heavy baryon tables would change;

(ii). measured charm counting in b-decay would decrease;

(iii). Bbar → baryon decay models should be reanalyzed.

A model independent measurement is possible by exploiting QE charm production

A Direct evaluation of the Lambda+(c) absolute branching ratios: A New approach.
P. Migliozzi, G. D'Ambrosio, G. Miele and P. Santorelli
Published in Phys.Lett. B462 (1999) 217-224

Table 5
Accuracy achievable (ΔBR), assuming a 100% error on $\mathscr{R}$, as a function of the collected charged-current statistics

Channel	$N_\mu = 10^6$	$N_\mu = 10^5$	$N_\mu = 10^4$
$\Lambda_c^+ \to p\bar{K}^0$	$(\pm 0.2 \pm 0.05)\%$	$(\pm 0.6 \pm 0.05)\%$	$(\pm 1.8 \pm 0.05)\%$
$\Lambda_c^+ \to pK^- \pi^+$	$(\pm 0.3 \pm 0.09)\%$	$(\pm 0.9 \pm 0.09)\%$	$(\pm 2.8 \pm 0.09)\%$
$\Lambda_c^+ \to p\bar{K}^0\eta$	$(\pm 0.1 \pm 0.02)\%$	$(\pm 0.5 \pm 0.02)\%$	$(\pm 1.7 \pm 0.02)\%$
$\Lambda_c^+ \to p\bar{K}^0\pi^+ \pi^-$	$(\pm 0.2 \pm 0.04)\%$	$(\pm 0.6 \pm 0.04)\%$	$(\pm 1.0 \pm 0.04)\%$
$\Lambda_c^+ \to pK^- \pi^+ \pi^0$	$(\pm 0.3 \pm 0.08)\%$	$(\pm 0.9 \pm 0.08)\%$	$(\pm 2.8 \pm 0.08)\%$
$\Lambda_c^+ \to \Lambda\pi^+ \pi^0$	$(\pm 0.2 \pm 0.06)\%$	$(\pm 0.8 \pm 0.06)\%$	$(\pm 2.3 \pm 0.06)\%$
$\Lambda_c^+ \to \Lambda\pi^+ \pi^+ \pi^-$	$(\pm 0.2 \pm 0.06)\%$	$(\pm 0.7 \pm 0.06)\%$	$(\pm 2.3 \pm 0.06)\%$
$\Lambda_c^+ \to \Lambda\pi^+ \eta$	$(\pm 0.2 \pm 0.03)\%$	$(\pm 0.5 \pm 0.03)\%$	$(\pm 1.7 \pm 0.03)\%$
$\Lambda_c^+ \to \Sigma^+ \pi^0$	$(\pm 0.1 \pm 0.02)\%$	$(\pm 0.4 \pm 0.02)\%$	$(\pm 1.0 \pm 0.02)\%$
$\Lambda_c^+ \to \Sigma^+ \pi^+ \pi^-$	$(\pm 0.2 \pm 0.06)\%$	$(\pm 0.7 \pm 0.06)\%$	$(\pm 2.3 \pm 0.06)\%$
$\Lambda_c^+ \to \Sigma^- \pi^+ \pi^+$	$(\pm 0.2 \pm 0.03)\%$	$(\pm 0.5 \pm 0.03)\%$	$(\pm 1.7 \pm 0.03)\%$
$\Lambda_c^+ \to \Sigma^0\pi^+ \pi^0$	$(\pm 0.2 \pm 0.03)\%$	$(\pm 0.5 \pm 0.03)\%$	$(\pm 1.7 \pm 0.03)\%$
$\Lambda_c^+ \to \Sigma^0\pi^+ \pi^+ \pi^-$	$(\pm 0.1 \pm 0.02)\%$	$(\pm 0.4 \pm 0.02)\%$	$(\pm 1.0 \pm 0.02)\%$
$\Lambda_c^+ \to \Sigma^+ \pi^+ \pi^- \pi^0$	$(\pm 0.2 \pm 0.05)\%$	$(\pm 0.7 \pm 0.05)\%$	$(\pm 2.2 \pm 0.05)\%$
$\Lambda_c^+ \to \Lambda\mu^+ \nu_\mu$	$(\pm 0.2 \pm 0.04)\%$	$(\pm 0.6 \pm 0.04)\%$	$(\pm 1.8 \pm 0.04)\%$
$\Lambda_c^+ \to \Lambda e^+ \nu_e$	$(\pm 0.2 \pm 0.04)\%$	$(\pm 0.6 \pm 0.04)\%$	$(\pm 1.8 \pm 0.04)\%$

A Near Detector at a NuFact could perform this measurement

Diffractive D_s production

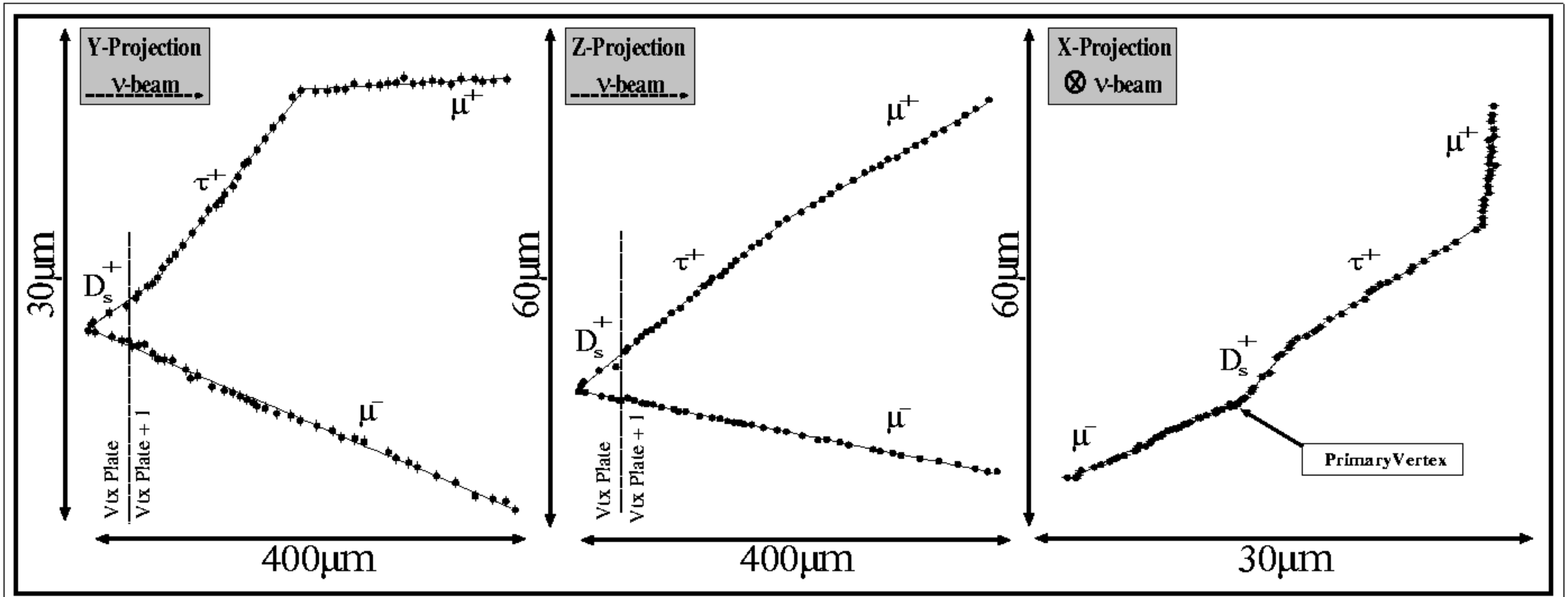
P. Annis et al. (CHORUS) Phys. Lett. B 435 (1998) 458-464

$\nu_\mu N \rightarrow D_s^* \mu^- N'$

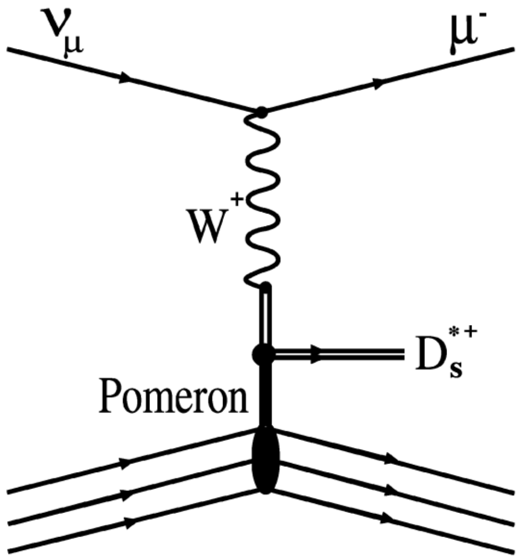
$\hookrightarrow D_s^+ \gamma$

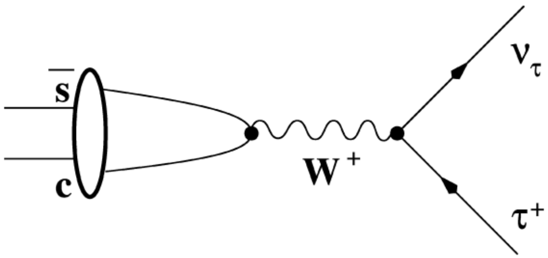
$\hookrightarrow \tau^+ \nu_\tau$

$\hookrightarrow \mu^+ \nu_\mu \nu_\tau$



Diffractive D_s production @NuFact





$$BR\left(D_s \to l^- \bar{\nu}_l\right) = \frac{G_F^2}{8\pi} \times |V_{Qq}|^2 \times f_{D_s}^2 \times \tau_{D_s} M_{D_s} \times m_l^2 \times \left(1 - \frac{m_l^2}{M_{D_s}^2}\right)^2,$$

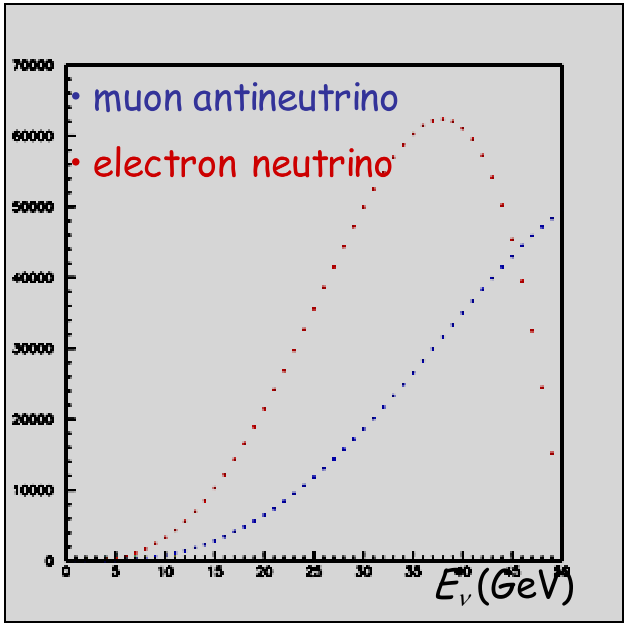
Experiment	Channel	f_{D_s} (MeV)
WA75 [12]	$D_s \to \mu$	232±45±52
CLEO I [13]	$D_s \to \mu$	344±37±52±42
CLEO II [14]	$D_s \to \mu$	280±19±28±34
E653 [15]	$D_s \to \mu$	194±35±20±14
BEATRICE [16]	$D_s \to \mu$	323±44±12±34
BES [17]	$D_s \to l$	$430^{+150}_{-130}\pm40$
L3 [18]	$D_s \to \tau$	309±58±33±38

30% error

Once the absolute value of f_{Ds} is measured with an accuracy of 10% or better, one would feel more confident about the predictions of the decay constants in the B system, f_B and f_{Bs}, which are crucial quantities for a quantitative understanding of $B^0_{(s)}$bar–$B^0_{(s)}$ oscillations and the extraction of V_{td} (V_{ts}) from them.

Absolute determination of D(s) branching ratios and f(D(s)) extraction at a neutrino factory.
G. De Lellis, P. Migliozzi, P. Zucchelli.
Published in Phys.Lett. B507 (2001) 7-13

Charm cross-section at Neutrino Factory energies



$$\frac{N_{CHARM}}{N_{CC}} = \frac{\int \Phi_{\nu_l}(E)\sigma^{CC}(E)\frac{\sigma(Charm)}{\sigma^{CC}}(E)dE}{\int \Phi_{\nu_l}(E)\sigma^{CC}(E)dE}$$

Calculation inputs:

- Neutrino Factory Flux from 50 GeV muon decay with polarization $P_\mu=0$
- Oscillation probability
- Charm cross section as function of energy from CHORUS
- world average neutrino CC cross-section

Charm cross-section at Neutrino Factory energies

neutrino charm production

$\sigma(\nu_e N \to e^- \text{ Charm } X)/\sigma(CC) = (5.85 \pm 0.36)\%$

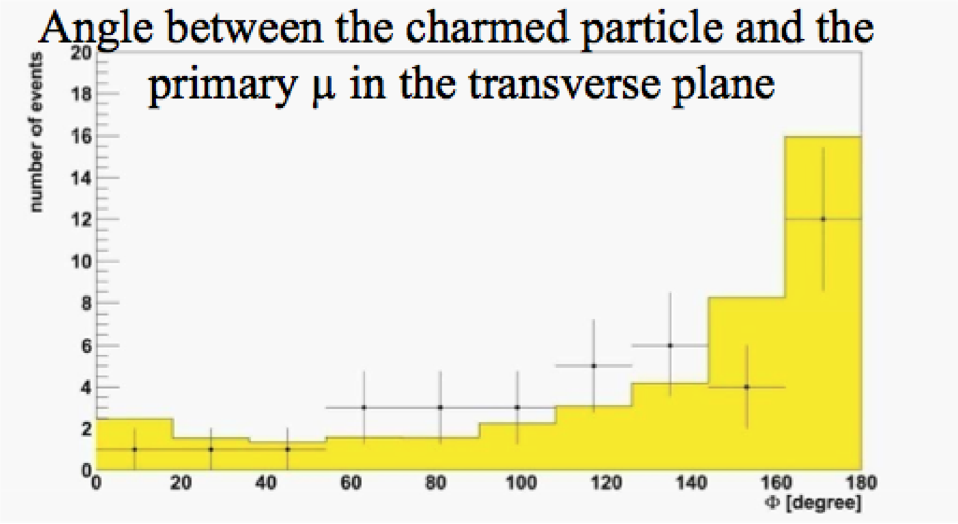
$\sigma(\nu_e N \to e^- C^+ X)/\sigma(CC) = (3.12 \pm 0.20)\%$

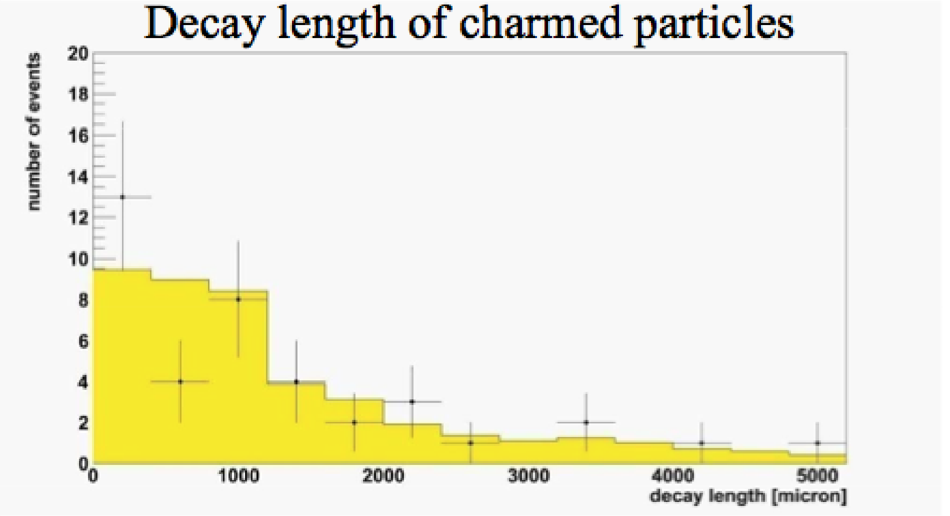
Anti-neutrino charm production

$\sigma(\bar{\nu}_\mu N \to \mu^+ \overline{\text{Charm}} X)/\sigma(CC) = (4.89 \pm 1.72)\%$

The importance of measuring charms (OPERA case)

Topology	Observed events	Expected events		
		Charm	Background	Total
Charged 1-prong	13	15.9	1.9	17.8
Neutral 2-prong	18	15.7	0.8	16.5
Charged 3-prong	5	5.5	0.3	5.8
Neutral 4-prong	3	2.0	<0.1	2.1
Total	39	39.1±7.5	3.0±0.9	42.2±8.3





Conclusions

- More than 2000 charm events collected by CHORUS experiments out of 93807 CC events
- Charm (charged and neutrals) inclusive cross-section, Semi-leptonic branching ratio, D* production, Fragmentation parameters, associated charm production measured
- First direct measurement of charm induced by anti-neutrino (32 events)
- CHORUS measurements can be used for charm background prediction in the future golden and silver channel investigations
- We have now solid reference numbers to evaluate the background and the efficiency of experiments operating at future neutrino facilities
- Mandatory experiments looking "directly" at the decay topology of the charmed hadron with micrometric resolution