# Measurement of charm production and decay by CHORUS

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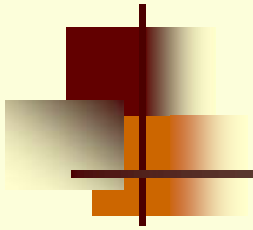
On behalf of CHORUS Collaboration


FrontierScience2005



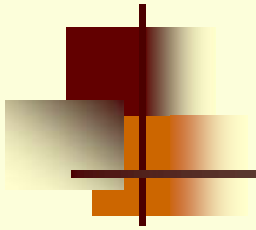
# Outline

## Physics motivation

## The CHORUS experiment

## Results on charm analysis in emulsion

- $D^0$ production in neutrino charged current interaction
- $D^{*+}$ production in neutrino charged current interaction
- Fragmentation properties of charmed particles
- Muonic branching ratio $B_\mu$ of charmed particles
- Anti-neutrino charm production
- Associated charm production
- $\Lambda_c$ and QE charm production



# Physics motivation

The measurement of charmed particles production allows a better understanding of fragmentation processes and nucleon content and a better description of charm production

## Measure strange content of the nucleon

Check strange/antistrange asymmetry

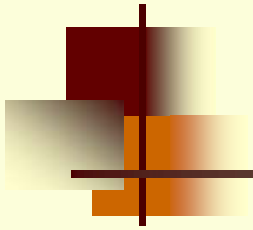
## Measure charmed fraction and charm cross section

## Study fragmentation process and z distribution

## Measure charm mass and $V_{cd}$

## Constrain/study charm production models

- improve Monte Carlo simulation
- prediction on charm expected events in present/future experiments



# Charm available statistics

## Massive high-density detectors

(CDHS, CCFR (NuTeV), CHARMII, NOMAD)

- Cross section measurement depends on knowledge of BR ($C \rightarrow \mu$) ~ 10% and on the uncertainty on it
- Background due to $\pi$, K, $K^0_s$
- not sensitive to low-neutrino energies
- not possible to study separately the different charmed species

## Nuclear emulsions experiments

(E531 - 122 charm events in emulsion, CHORUS)

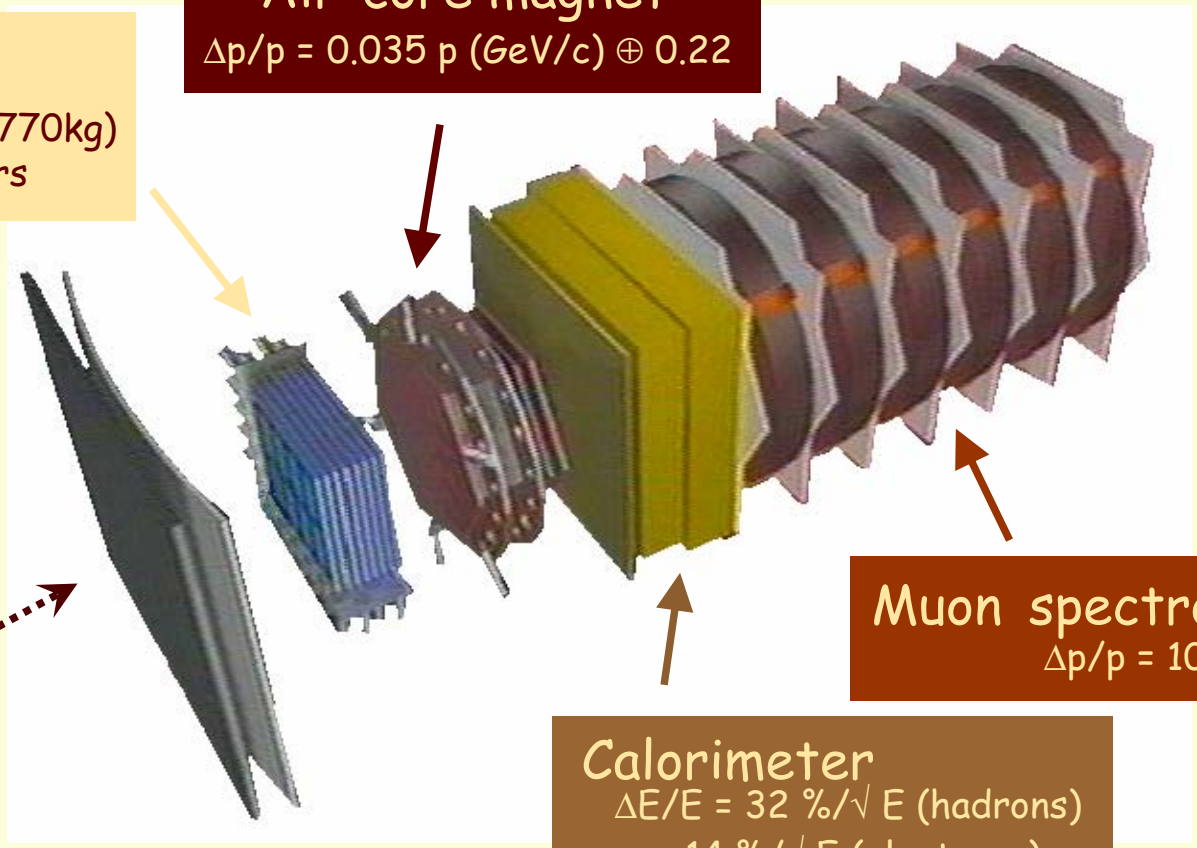
sensitivity to low $E_\nu \Rightarrow m_c$ thr. effect;
reconstruction of the charmed hadron kinematics

# CHORUS experiment

## (CERN Hybrid Oscillation Research ApparatUS)

**Active target**
- nuclear emulsion target (770kg)
- scintillating fiber trackers

**Air-core magnet**
$\Delta p/p = 0.035\ p\ (GeV/c) \oplus 0.22$



**Muon spectrometer**
$\Delta p/p = 10 - 15\%$

**Calorimeter**
$\Delta E/E = 32\ \%/\sqrt{E}$ (hadrons)
$= 14\ \%/\sqrt{E}$ (electrons)

$\nu$

Neutrino beam

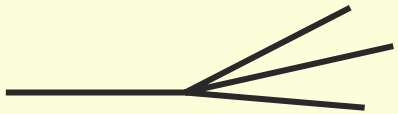
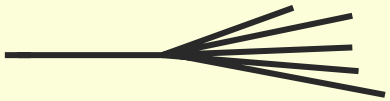
E ~ 27 GeV

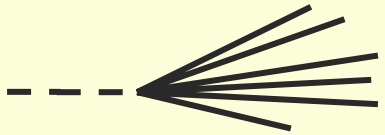
$\nu_\mu : \bar{\nu}_\mu : \nu_e : \bar{\nu}_e$

1.00 : 0.06 : 0.017 : 0.007

# The CHORUS charm data sample

| | |
|---|---|
| Located CC events | 93807 |
| Selected for visual inspection | 2752 |
| Total charm candidates | 2013 |

| | | |
|---|---|---|
| C1 |  | 452 |
| C3 |  | 491 |
| C5 |  | 22 |

| | | |
|---|---|---|
| V2 |  | 819 |
| V4 |  | 226 |
| V6 |  | 3 |

Main background from $\Lambda$, $\pi$, K and $\Sigma$ decays and from "white" interactions

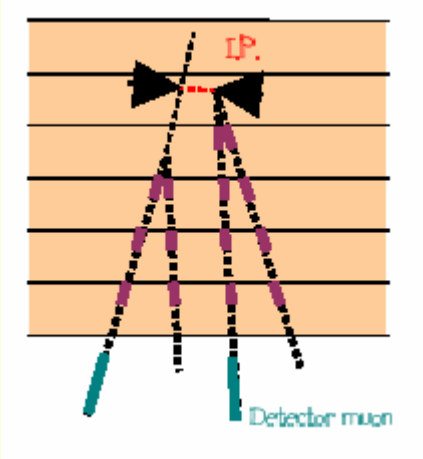
# Measurement of $D^0$ production and of decay branching fractions in $\nu$-N scattering

*Phys. Lett. B. 613 (2005) 105*

## Candidate selection

Primary track matched to el. detector muon

Daughter track matched to el. detector track




## After BG subtraction and efficiency correction:

$$\frac{B(D^0 \rightarrow V4)}{B(D^0 \rightarrow V2)} = 0.207 \pm 0.016 \pm 0.004$$

## The relative rate is:

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

# $D^0$ topological branching fractions

Assuming $B(D^0 \to V4)=0.1339\pm0.0061$ (PDG);

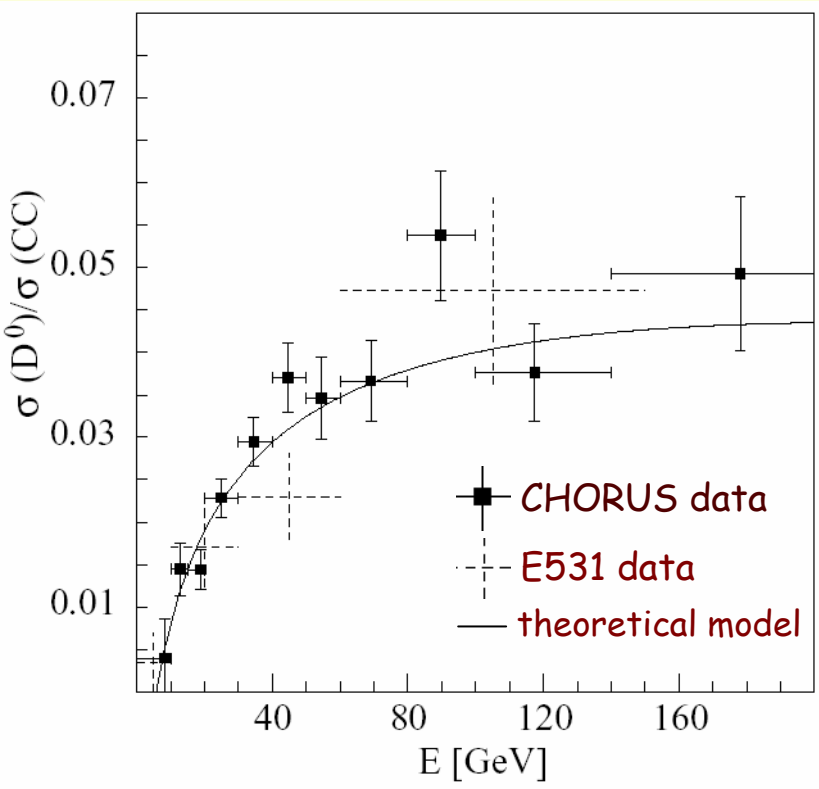
$B(D^0 \to V2) = 0.647 \pm 0.049 \pm 0.031$ $\quad$ $B(D^0 \to V6) = (1.2\,^{+1.3}_{-0.9} \pm 0.2)\times10^{-3}$

$$B(D^0 \to V0) = 0.218 \pm 0.049 \pm 0.036$$

To be compared with:

| | |
|---|---|
| $B(D^0 \to V0) \approx 5\%$ | (PDG) Sum over all exclusive channel for which measurement exist |
| $B(D^0 \to V2) = 0.485 \pm 0.020$ | (PDG) Sum over all exclusive channel for which measurement exist |
| $B(D^0 \to V6) = (0.59 \pm 0.12)\times10^{-3}$ | (FOCUS coll.) sum of all exclusive measured channel |

# Energy dependence of the cross section ratio and charm mass




Fit parameters for the model curve
(M.Gluk,E.Reya and A.Vogt, Z.Phys.C (1955) 433)

| Variables | Value | Variation |
|---|---|---|
| $m_c$ | $(1.42 \pm 0.08)$ GeV/$c^2$ | fitted |
| $\kappa$ | 0.38 | $\pm 0.10$ |
| $\alpha$ | 1 | $\pm 1$ |
| $\epsilon_p^s$ | $0.083 \pm 0.013 \pm 0.010$ | $\pm 0.02$ |
| $V_{cd}$ | 0.221 | fixed |
| $V_{cs}$ | 0.97437 | fixed |

($\varepsilon^s_p$ as measured in CHORUS, see next slides)

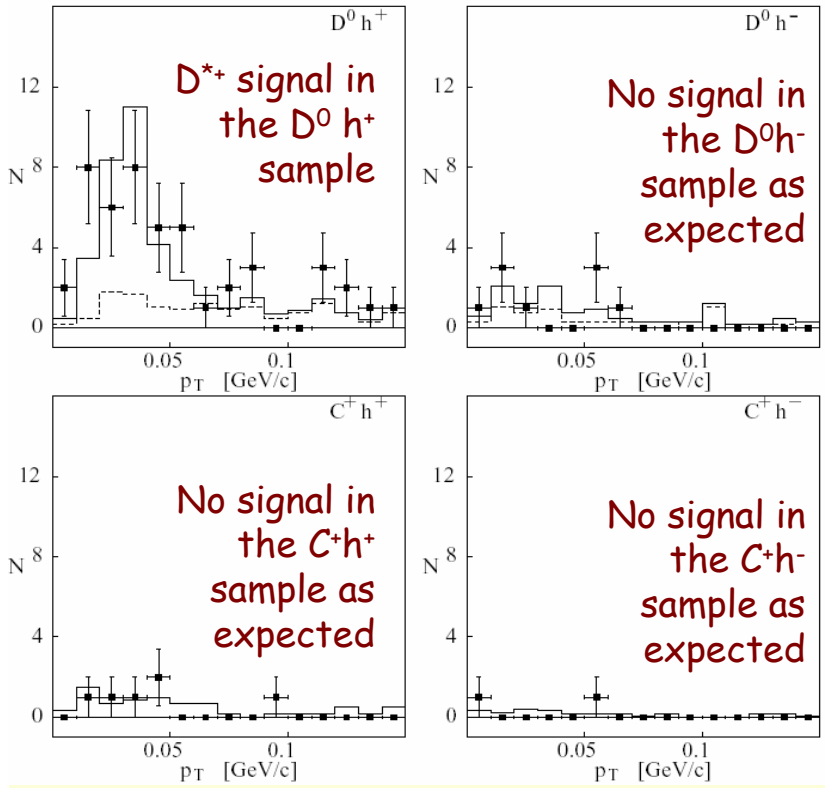
$m_c = (1.42 \pm 0.08(\text{stat}) \pm 0.04(\text{syst}))$ GeV/$c^2$

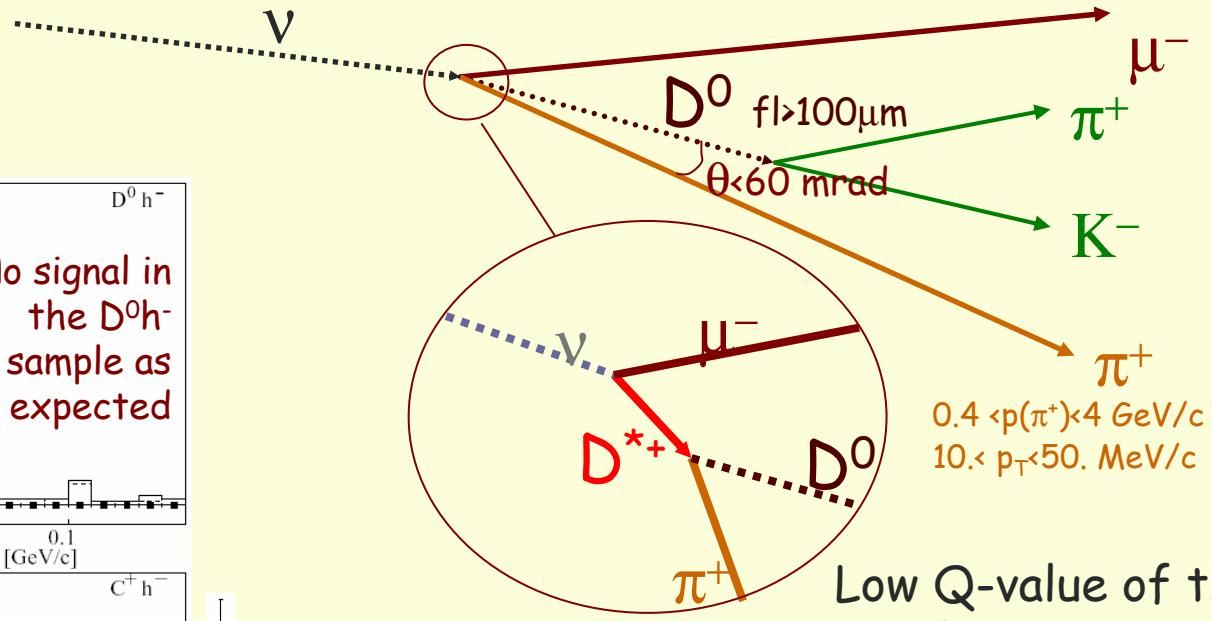
# Measurement of $D^{*+}$ production in CC $\nu$-N scattering

*Phys. Lett. B. 614 (2005) 155*

Using the decay mode:

$$D^{*+} \rightarrow D^0 \ \pi^+$$




Number of candidates

Background prediction

(1) Expected shape of the candidates normalized to the observed events;

(2-3-4) shape normalized to the total number of $D^0$ and $C^+$ respectively;

Low Q-value of the $D^{*+}$ decay

$\pi^+$ from $D^{*+}$ decay has a relatively low momentum

# Measurement of $D^{*+}$ production in CC $\nu$-N scattering

Assuming $B(D^{*+} \rightarrow D^0 \pi^+)=0.677\pm0.005$ (PDG) the relative rate is:

$$\sigma(D^{*+})/\sigma(D^0)=0.38 \pm 0.09(stat) \pm 0.05(syst)$$

assuming that the $D^{*+}$ and $D^{*0}$ production rate are equal and recalling that $D^{*0}$ always decays into $D^0$ and using the measure of $\sigma(D^0)/\sigma(CC)$ made in CHORUS:

$$\sigma(D^* \rightarrow D^0)/\sigma(D^0)=0.63 \pm 0.17$$

and

$$\sigma(D^{*+})/\sigma(CC)=(1.02 \pm 0.25(stat) \pm 0.15\ (syst))\%$$

To be compared with:

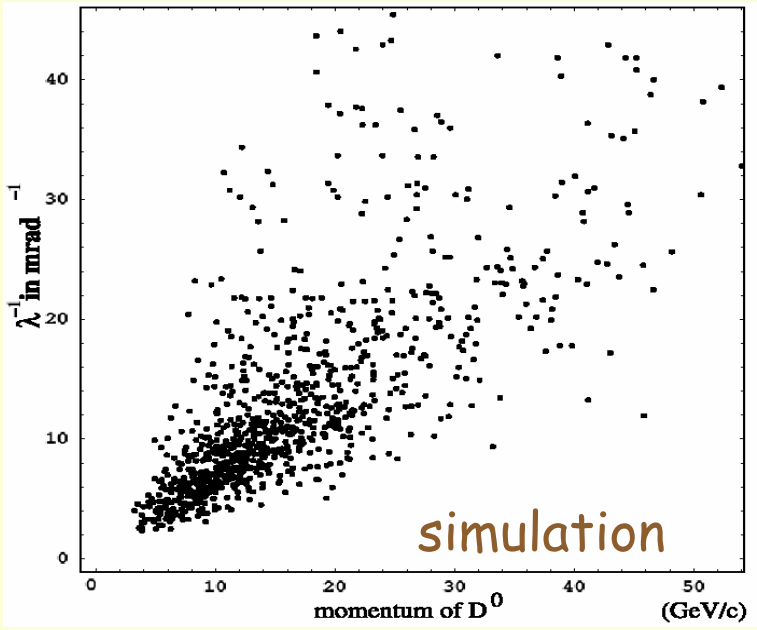
- NOMAD $\sigma(D^{*+})/\sigma(CC)=(0.79 \pm 0.17_{(stat)} \pm 0.10_{(syst)})\%$
- BEBC $\sigma(D^{*+})/\sigma(CC)=(1.22 \pm 0.25)\%$

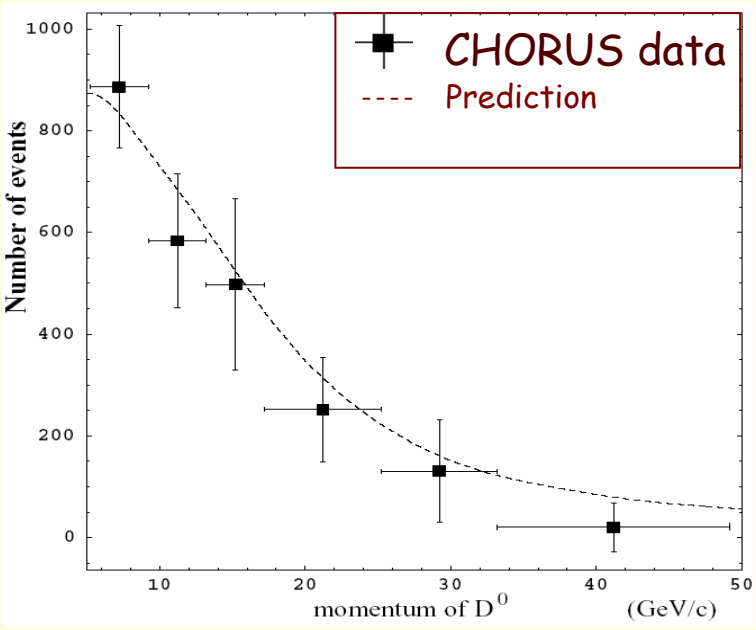
# Measurement of fragmentation properties of charmed particle production in CC neutrino interaction

*Phys. Lett. B 604 (2004) 145*

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

The momentum of $D^0$ can be inferred by the geometrical average of the angle of the decay daughters with respect to the direction of the $D^0$ ($\lambda$)
(as described in *S.Petrera, G.Romano, Nucl.Instrum. And Meth.174 (1980) 61 )*



# Z distribution

<z> = 0.63 ± 0.03(stat) ± 0.01(syst)

Fit to Collins-Spiller distribution:

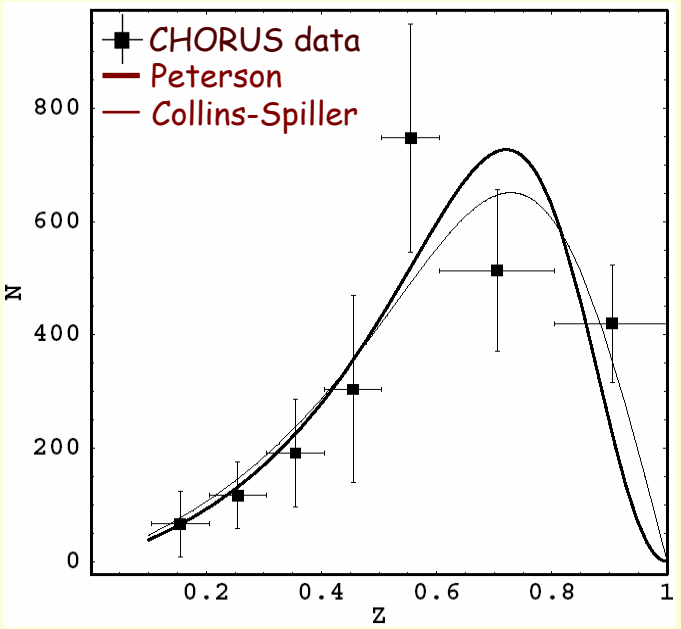
$$D_c^h(z) = \frac{N\left(\frac{\epsilon_{CS}(2-z)}{1-z} + \frac{1-z}{z}\right)(1+z^2)}{\left(1 - \frac{\epsilon_{CS}}{1-z} - \frac{1}{z}\right)^2}$$

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

Fit to Peterson distribution:

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

$\varepsilon_p = 0.108 \pm 0.017 \pm 0.013$




To be compared with:

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

To compare results:

If $z^s$ = $E^D$ / string energy

$\varepsilon^S_p = 0.083 \pm 0.013 \pm 0.010$

If $z^Q$ = P charmed particle / P charm quark

$\varepsilon^Q_p = 0.059 \pm 0.010 \pm 0.008$

# $B_\mu$ muonic branching ratio

*Accepted for publication in Phys. Lett. B*

$$B_\mu = (7.3 \pm 0.8(\text{stat}))\%$$

Considering only events with visible energy above 30 GeV → $B_\mu = (8.3 \pm 1.6_{(\text{stat})})\%$

$B_\mu \times |V_{cd}|^2_{LO} = (0.474 \pm 0.027) \times 10^{-2}$ → $|V_{cd}|_{LO} = (0.236 \pm 0.016)$

(CDHS, CHARM II, CCFR average value)

$B_\mu \times |V_{cd}|^2_{NLO} = (0.534 \pm 0.046) \times 10^{-2}$ (CCFR) → $|V_{cd}|_{NLO} = (0.251 \pm 0.021)$

To be compared with:

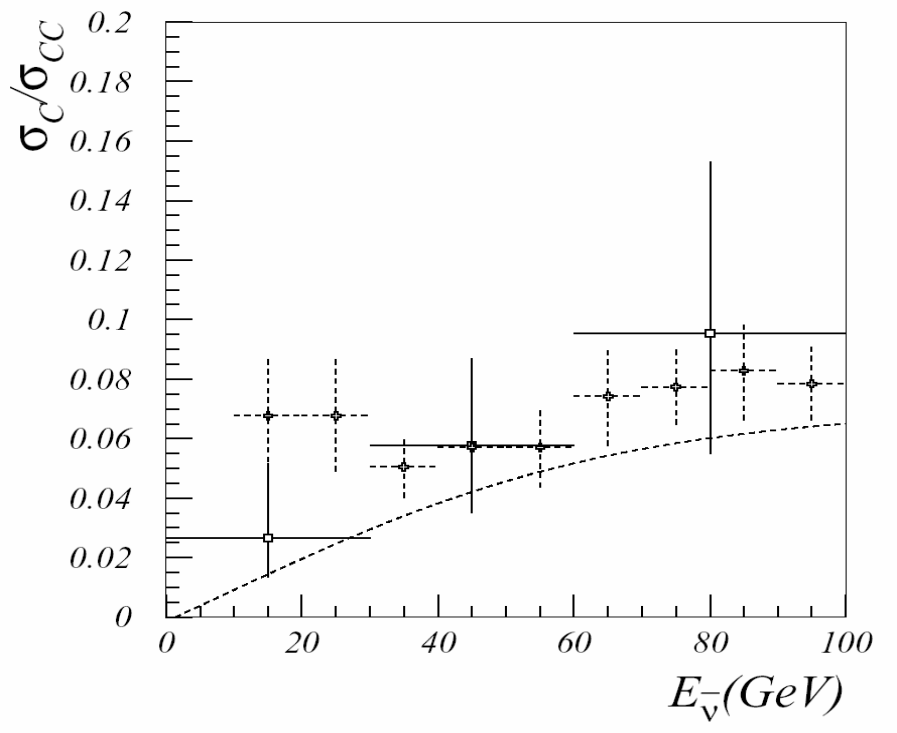
$0.221 < |V_{cd}| < 0.227$ at 90% CL Obtained imposing CKM unitarity and only 3 generations

# Measurement of charm production in antineutrino charged-current interactions

*Phys. Lett. B. 604 (2004) 11-21*

After μ reconstruction cut and charm topology selection

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




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

$E_{\bar{\nu}} \sim 18$ GeV

CHORUS DATA

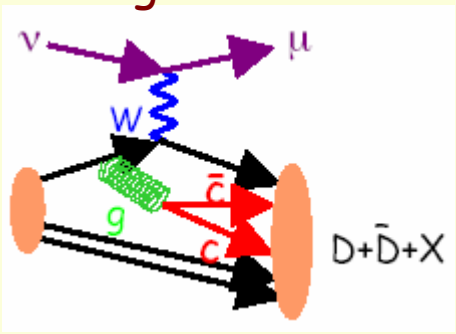
Derived from di-lepton data
(G.de Lellis et al., J.Phys.G28 (2002), 713)

Theoretical prediction obtained from leading order calculation with $m_c = 1.31$ GeV/$c^2$

# Associated charm production in CC

- In the past this search was based on the observation of trimuon events $\mu^-(\mu^+\mu^-)$ and same-sign dimuons;
  - Observed rate 60 times larger than expected from theoretical calculations!
    *(K.Hagiwara Nucl.Phys.B 173 (1980) 487*

Charged-current




Gluon bremsstrahlung

## Currently a search is in progress in CHORUS:

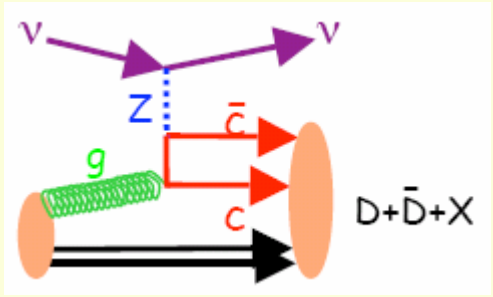
1 event observed and confirmed by kinematical analysis *(Phys. Lett. B. 539 (2002) 188)*

A new analysis with full statistics is in progress (5 events on 95450 CC); The discrepancy between data and prediction should be clarified soon.

We assume that once the charmed quark pair is produced it converts with unit probability into either a charmed particle pair or a boun charmonium state. The relative ratio should be determined

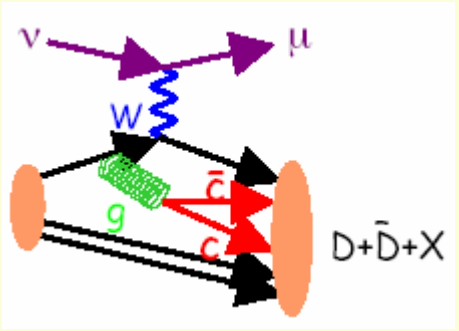
# Associated charm production in NC

Neutral-current




Z-gluon fusion

+




Gluon bremsstrahlung

In the past only one event observed in the E531 emulsion:

Production rate $1.3\ ^{+3.1}_{-1.1} \times 10^{-3}$ normalised to CC

Indirect search performed by NuTeV:

*(A. Alton et al., Phys. Rev. D64 (2001) 539)*

Production rate $(2.6\pm1.6)\times10^{-3}$ normalised to CC at 154 GeV

Currently a search is in progress in CHORUS:

3 candidates on 26568 NC have been found and the cross-section measurement will be finalised by the end of this year

# Measurement of $\Lambda_c$ production

*Phys. Lett. B. 555 (2003) 156*

Short flight lenght sample $\rightarrow$ enriched in $\Lambda_c$

Long flight lenght sample $\rightarrow$ $D^+$ and $D_s^+$ decays should dominate

$$BR(\Lambda_c \rightarrow 3 \text{ prong}) = ( 24 \pm 7 \text{ (stat)} \pm 4 \text{ (syst)} ) \times 10^{-2}$$

$$\sigma(\Lambda_c) / \sigma(CC) \times BR(\Lambda_c \rightarrow 3 \text{ prong}) = ( 0.37 \pm 0.10 \text{ (stat)} \pm 0.02 \text{ (syst)} ) \times 10^{-2}$$

$$\sigma(\Lambda_c) / \sigma(CC) = ( 1.54 \pm 0.35 \text{ (stat)} \pm 0.18 \text{ (syst)} ) \times 10^{-2}$$

# Quasi-elastic charm production

*Phys. Lett. B. 575 (2003) 198*

In the literature only 3 events observed in nuclear emulsions (E531)

## Topological and kinematical selection criteria:

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

13 events with a background of 1.7±0.6 (mainly from DIS $\Lambda_c$)

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

➡ QE production is about 15% of $\Lambda_c$ production

# Conclusion

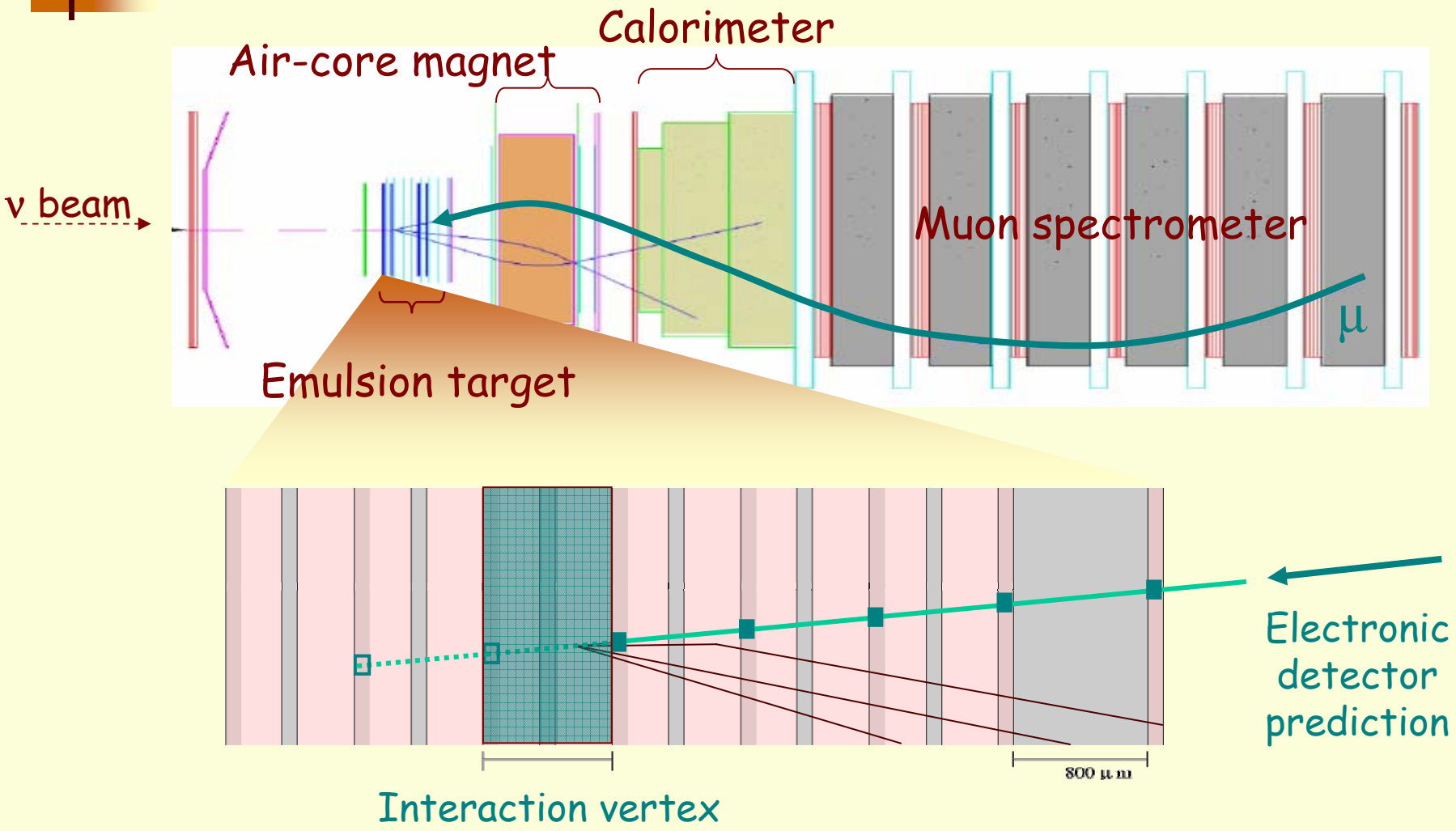
Interesting charm physics results from CHORUS thanks to:

- High beam flux;
- Nuclear emulsion target (0.8t);
- Kinematical reconstruction

## Analyses in progress

- Charmed fractions
- Total charm production cross-section
- x distribution charm (anti-charm) events
- measurement of fragmentation properties with charged charmed hadrons
- $D^0$-$\bar{D}^0$ mixing
- Particle multiplicities in $\nu$-N interactions

# Vertex location procedure



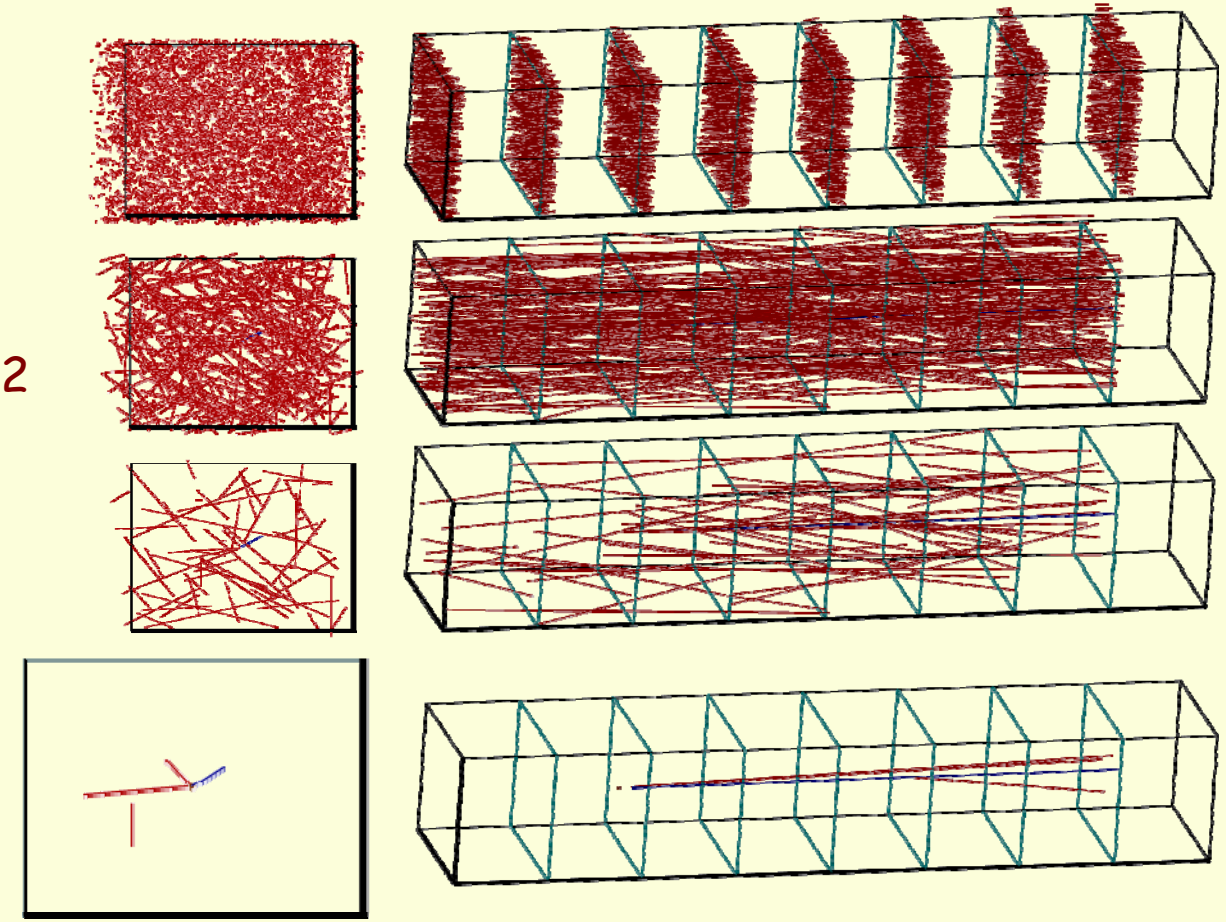
# Nuclear emulsion analysis

All track segments in fiducial volume

After a low momentum tracks rejection and number of segments ≥ 2

After rejection of passing-through tracks

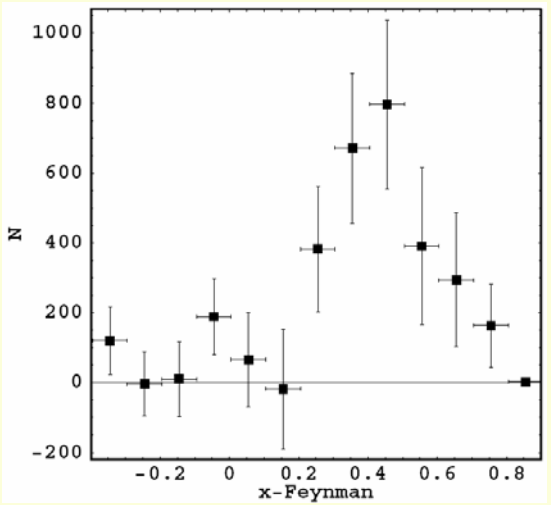
Tracks confirmed by electronic detectors



# Fragmentation properties

$$X_F = 2\,\gamma\,\frac{p_L^{\,D} - \beta\,E^D}{W}$$

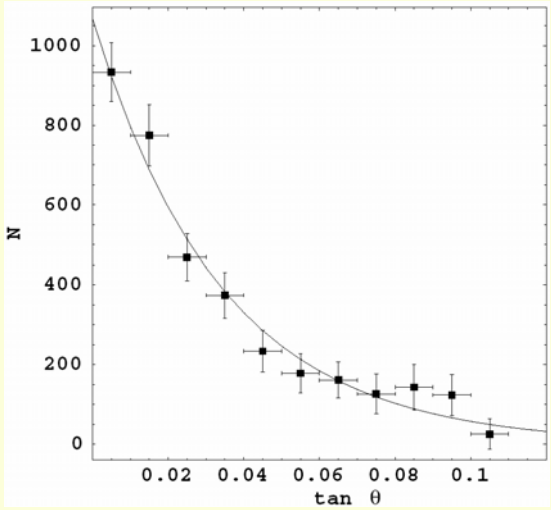
$p_L^{\,D}$ longitudinal momentum of $D^0$
$E^D$ energy of $D^0$
$W$ invariant mass




From the distribution we mesure $\langle X_F \rangle$:

$\langle X_F \rangle = 0.38 \pm 0.04(\text{stat}) \pm 0.03(\text{syst})$

To be compared with NOMAD: $\langle X_F \rangle = 0.47 \pm 0.05$




From the distribution production angle out of the lepton plane we mesure:

$\langle \tan\theta^{out} \rangle = 0.030 \pm 0.002$

forward-backward asymmetry:

$\langle A \rangle = 0.79 \pm 0.14_{(\text{stat})} \pm 0.05_{(\text{syst})}$

To be compared with E531: $\langle A \rangle = 0.620 \pm 0.092$

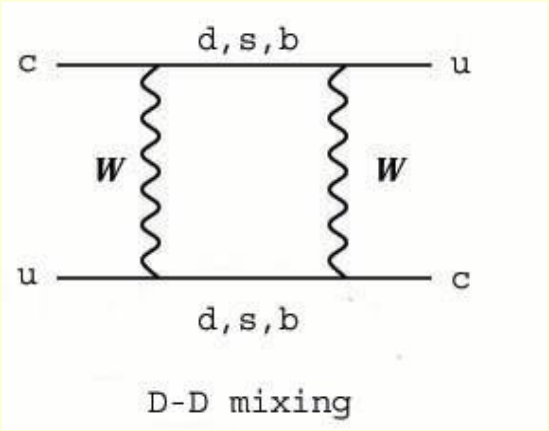
# Charm transitions serve as excellent probes of New Physics

## $D^0$-$\bar{D}^0$ mixing

Processes strongly suppressed in the Standard Model

only at one loop in the Standard Model:

possible new physics particles in the loop



D-D mixing

interaction couples dynamics of $D^0$ and $\bar{D}^0$

$$|D(t)\rangle = \begin{pmatrix} a(t) \\ b(t) \end{pmatrix} = a(t)\left|D^0\right\rangle + b(t)\left|\overline{D^0}\right\rangle$$

Time-dependence: coupled Schrödinger equations

$$i\frac{\partial}{\partial t}|D(t)\rangle = \left(M - \frac{i}{2}\Gamma\right)|D(t)\rangle = \begin{bmatrix} A & p^2 \\ q^2 & A \end{bmatrix}|D(t)\rangle$$

Diagonalize: mass eigenstates ≠ flavor eigenstates

$$\left|D_{1,2}\right\rangle = p\left|D^0\right\rangle \pm q\left|\overline{D^0}\right\rangle$$

Ref. Alexey A. Petrov – talk @BEACH 2004, IIT, Chicago