Charm production measurements with CHORUS

International Conference on Particle Physics

In Memoriam

Engin Arik and her colleagues

Jaap Panman, CERN

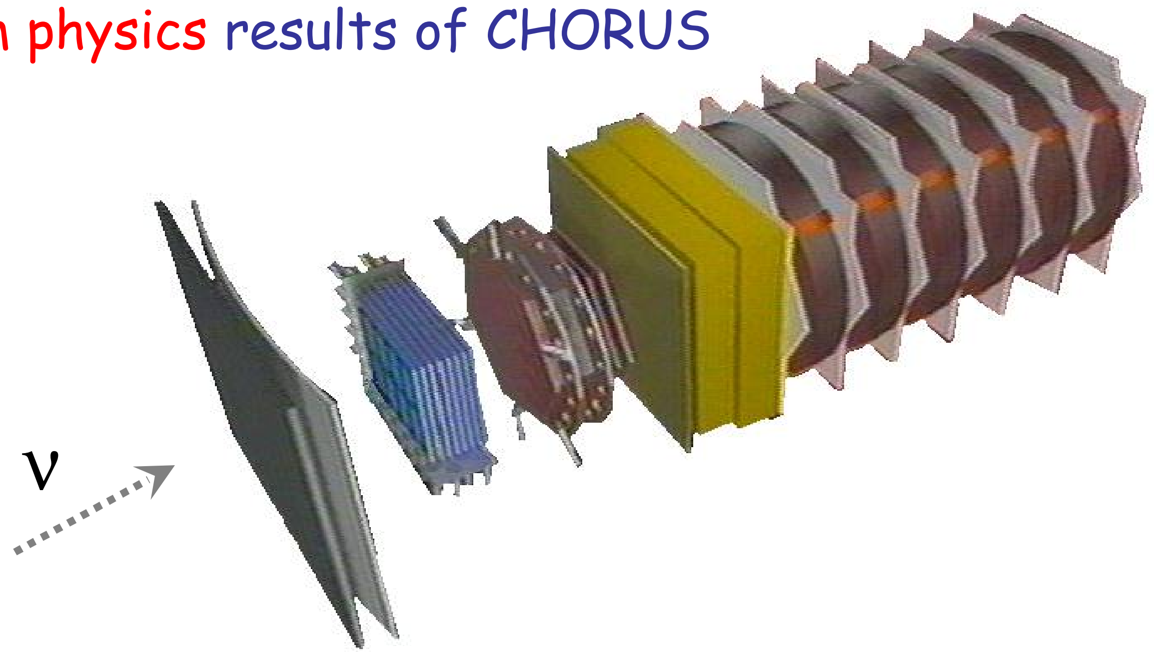
Istanbul 2008

CHORUS experiment

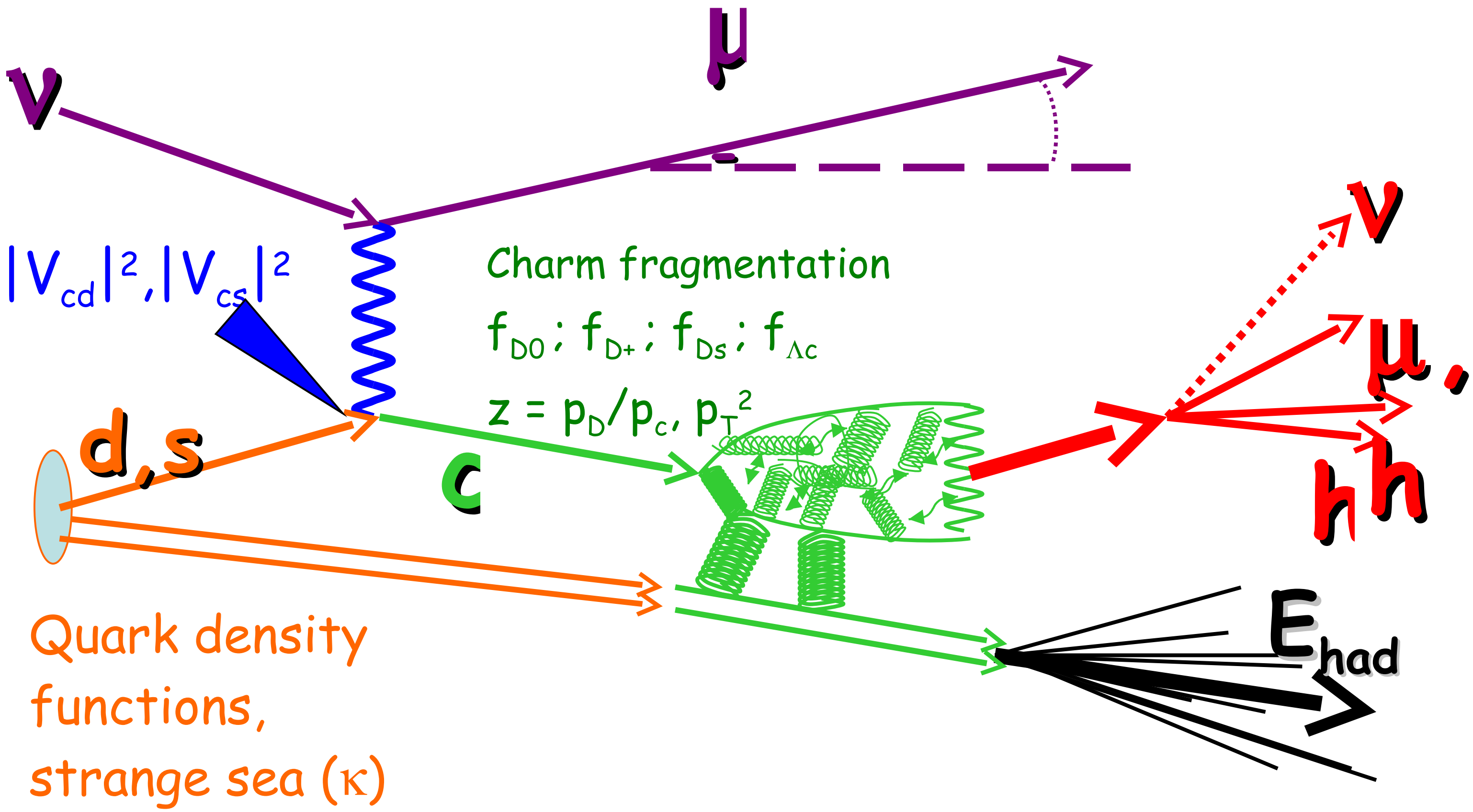
(CERN Hybrid Oscillation Research ApparatUS)

Designed to search for neutrino oscillation by identification of tau decays in an emulsion target (see talk of Prof. Tsenov)

Charm decays have a similar signature
This talk summarizes the
charm physics results of CHORUS



Charm production in deep-inelastic neutrino scattering



Production from down quarks Cabibbo-suppressed

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

Interest in charm production

production in neutrino scattering

Strange content of the nucleon
Charm mass and V_{cd}
Constrain/study charm production models
fragmentation: particle production ratios and distributions

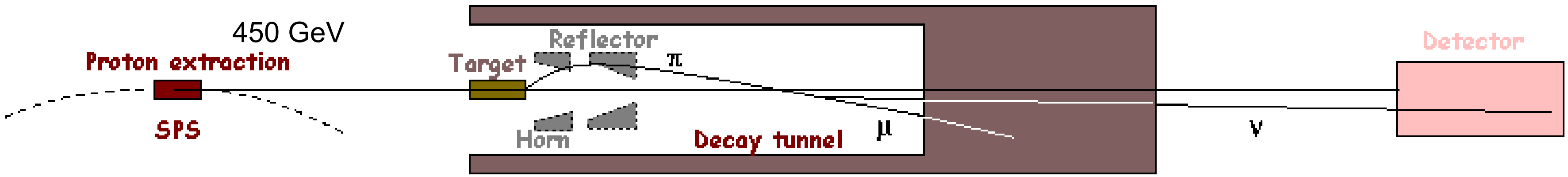
charm decays

Fully inclusive measurements possible

study backgrounds for future high precision oscillation experiments (wrong sign muons, decays)

Neutrino beam

West Area Neutrino Facility at CERN SPS



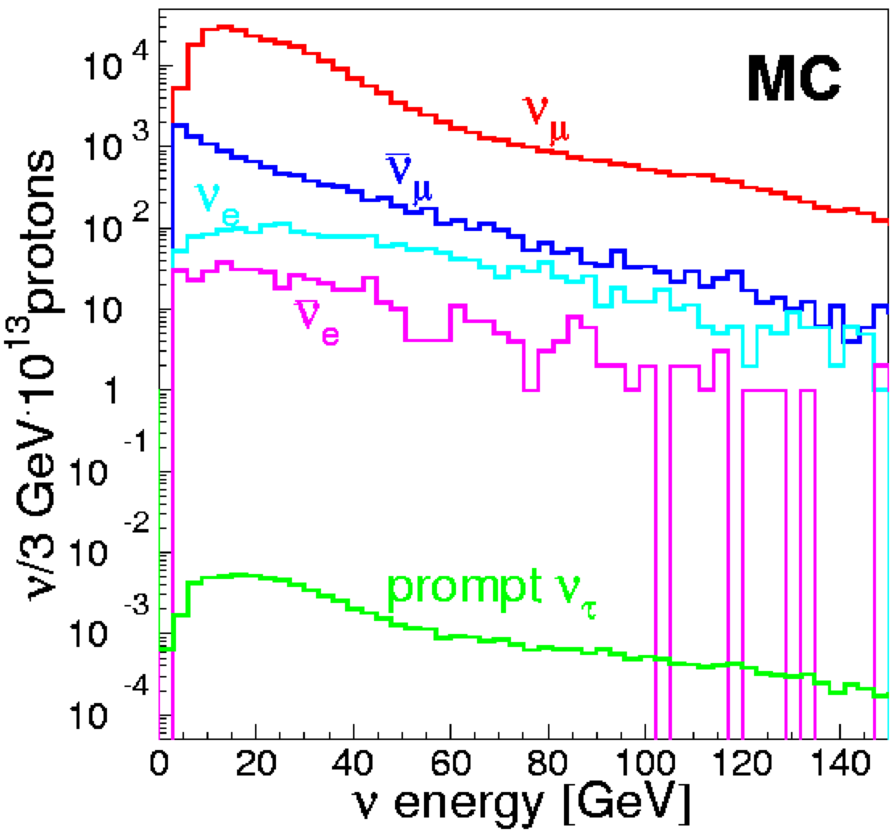
Wide Band Beam

5.06×10^{19} POTs (1994-1997)

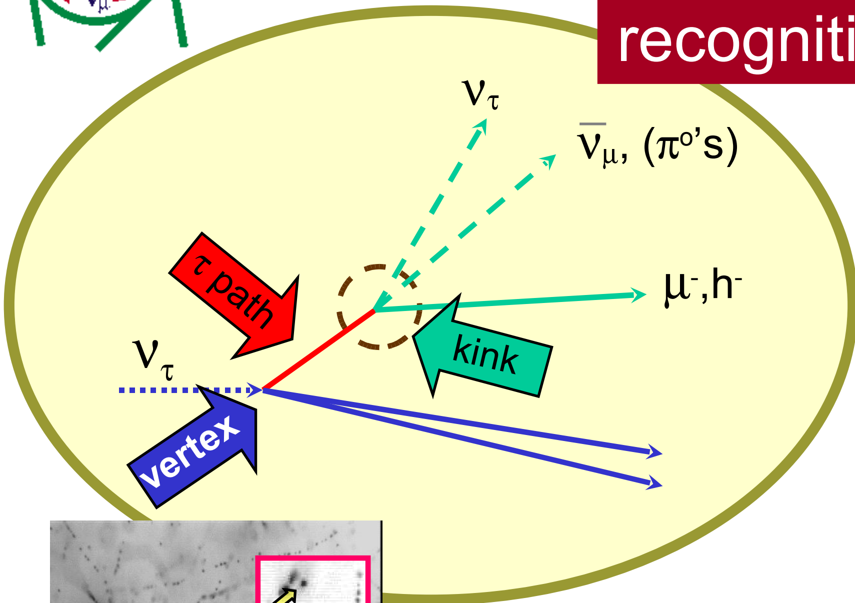
$\langle E\nu_\mu \rangle \sim 27$ GeV

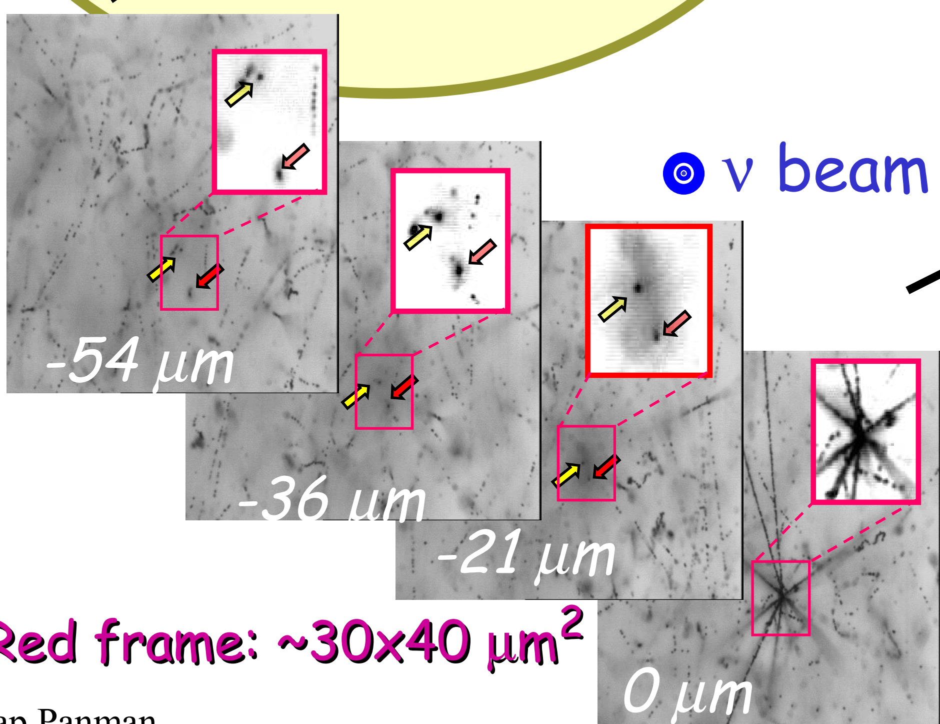
$\langle L \rangle \sim 0.6$ km

Prompt ν_τ : negligible

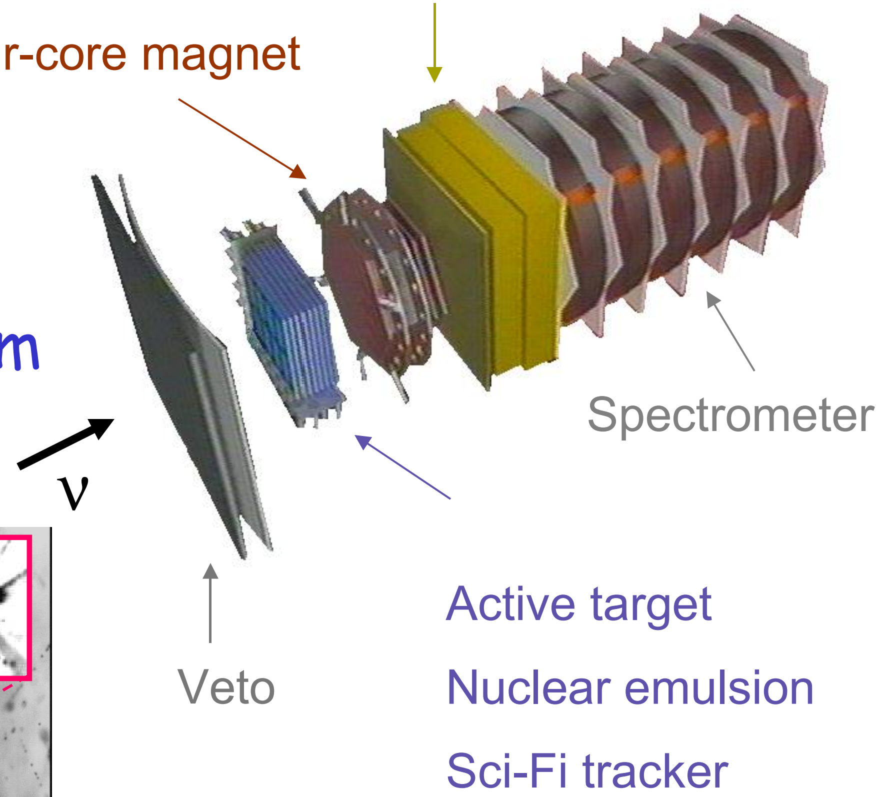


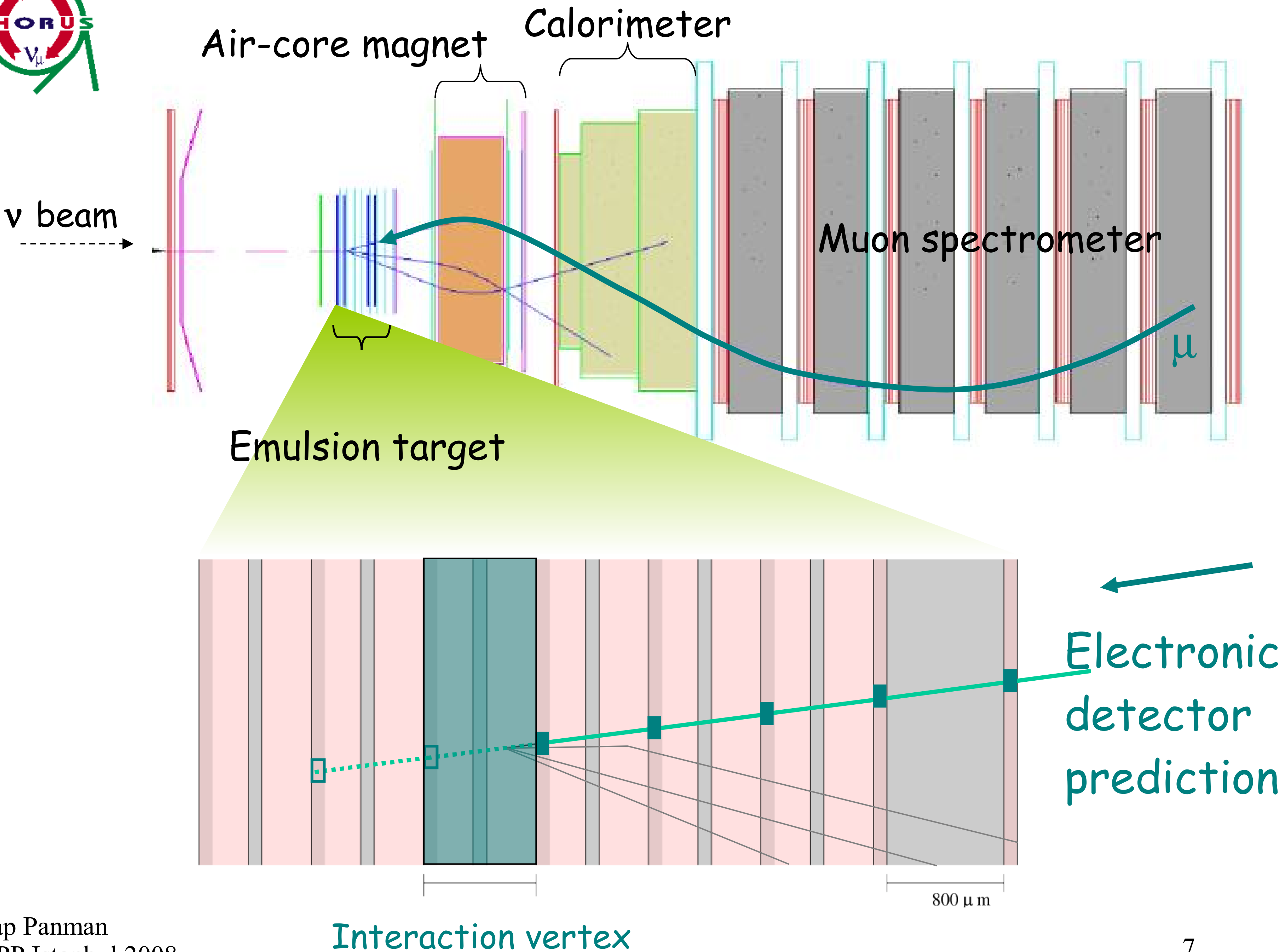
ν_τ and charm detection by decay point recognition





Red frame: ~30x40 μm^2



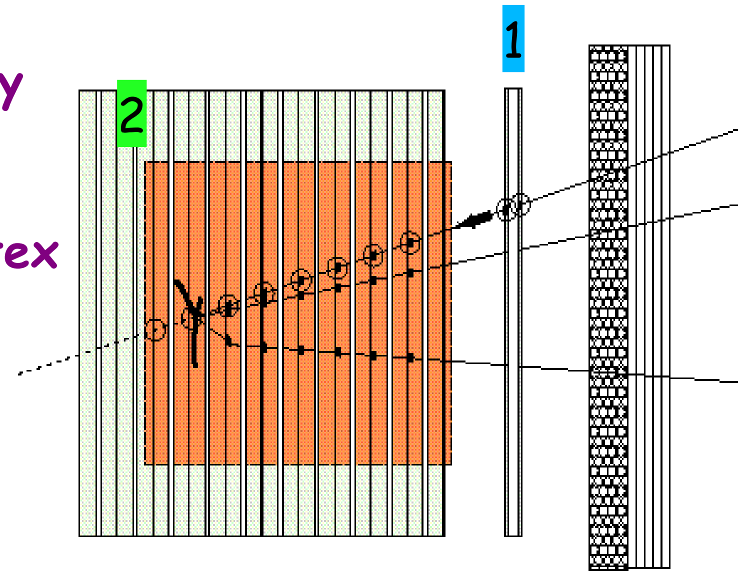

Air-core magnet
Calorimeter
ν beam
Muon spectrometer
μ
Emulsion target
Electronic detector prediction
800 μ m
Interaction vertex

Automatic emulsion data acquisition

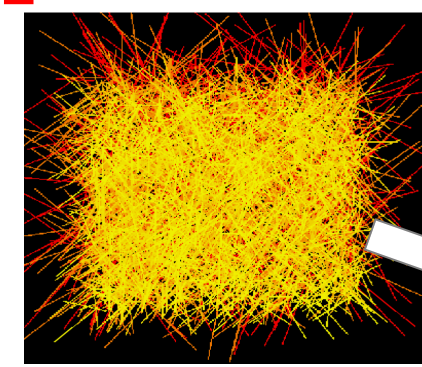
1 **Location of ν interaction vertex guided by electronic detector.**

2 **Full data taking around ν interaction vertex called NetScan**

Volume : 1.5 x 1.5 mm^2 x 6.3 mm
Angular acceptance : 400 mrad
~ 11 minutes / event

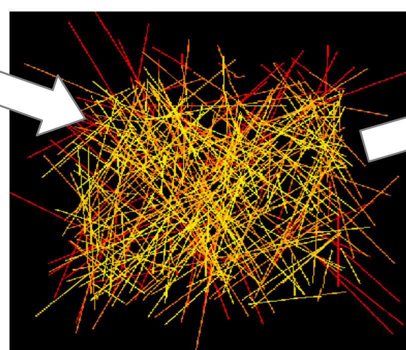


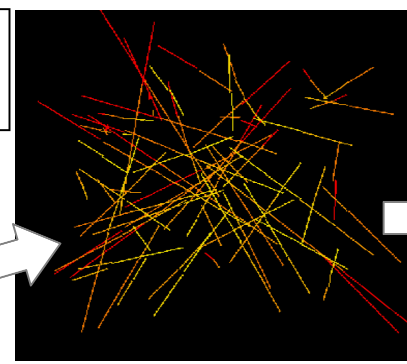
3 **Off-line tracking and vertex reconstruction**



Track segments from 8 plates overlaid

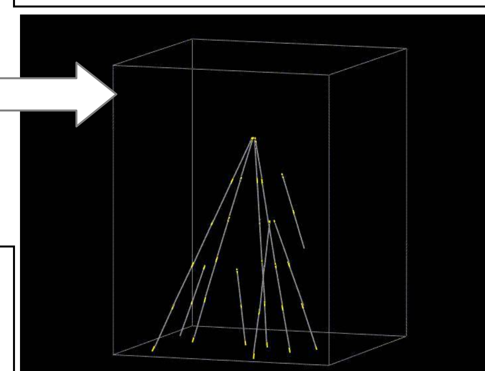
At least 2-segment connected tracks





Eliminate passing through tracks

Reconstruct full vertex topology



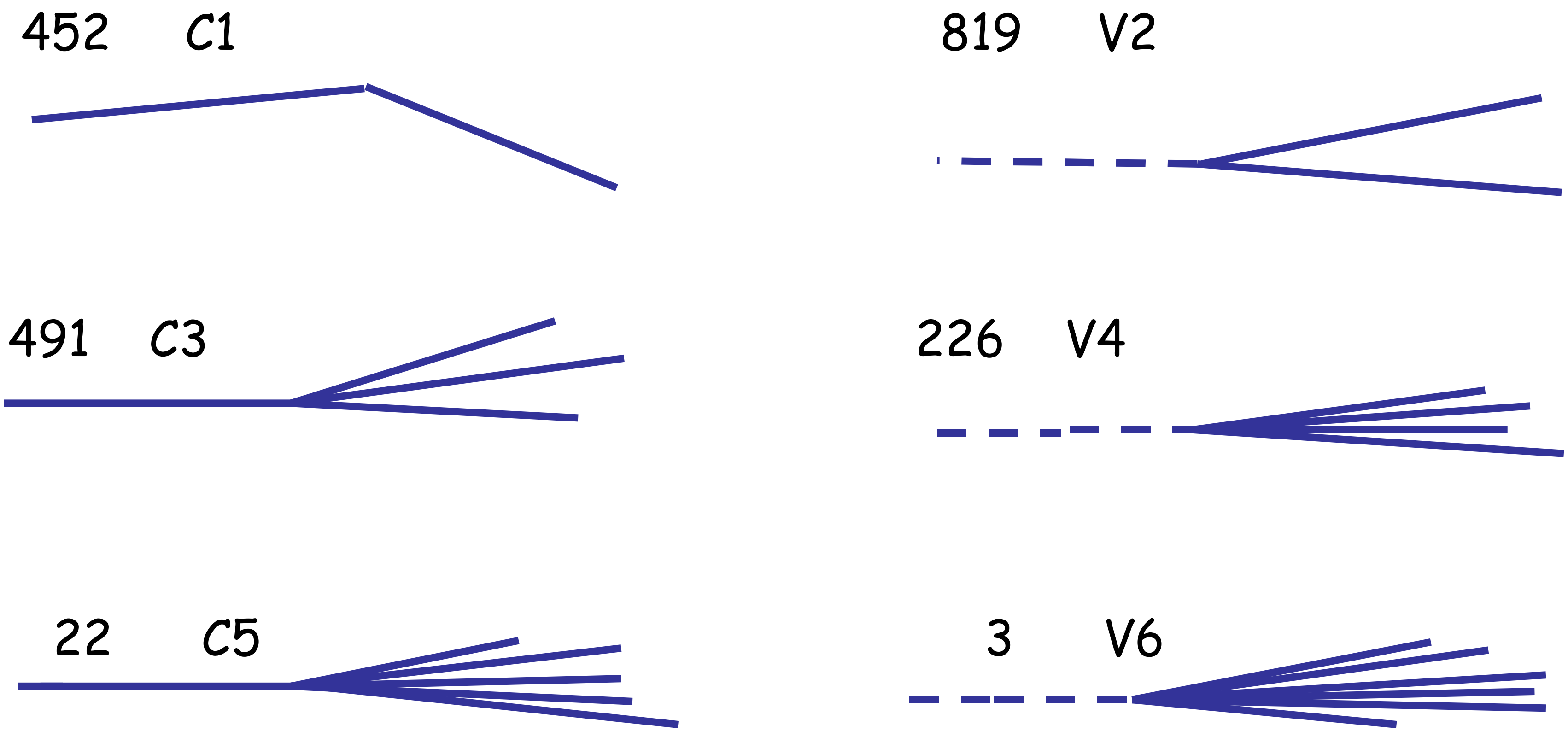
The CHORUS charged current data sample and charm topologies

Located CC events 93807

Total confirmed charm candidates 2013

automatic recognition purity ~70%

after “manual scanning” ~97%



CHORUS charm measurements

Neutral D meson production cross-section and decays – unique signature for D^0

D^{*+} production

Charged charmed particles: Λ_c^+, D^+, D_s^+ need to be separated

- Λ_c^+ production, QE charmed baryon production, full separation

Total charm production cross-section

Anti-neutrino data – total production cross-section

Effective branching ratio into muons

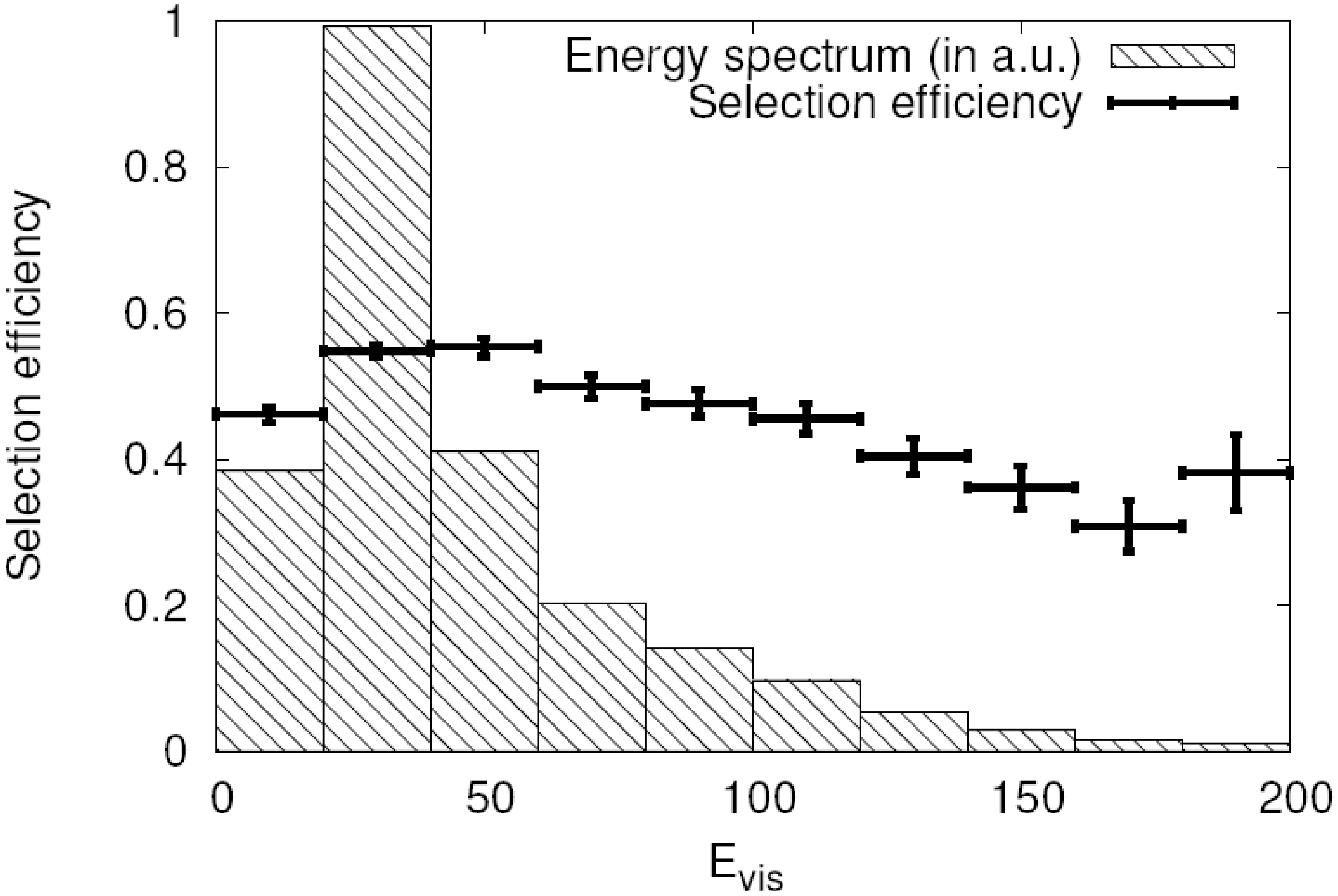
Fragmentation

Interactions in the calorimeter:

- di-muon data
- tri-muon data

Emulsions again: Associated charm production

Efficiency down to low energies



Measurement of D^0 production

Phys. Lett. B 527 (2002) 173, based on ~25% of statistics

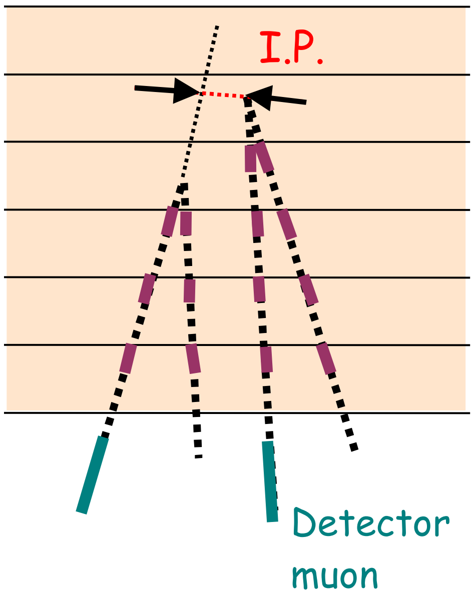
Phys. Lett. B 613 (2005) 105, full statistics

Candidate selection

Primary track matched to detector muon

Daughter track matched to detector track

3 ~ 13 μm < I.P. wrt. 1ry vtx < 400 μm



Confirmed D^0 sample

2 prong (V2)	819 (background: 35)
4 prong (V4)	226 (no background)

Selection efficiencies

V2 : $56.1 \pm 1.8 \times 10^{-2}$

V4 : $75.4 \pm 2.7 \times 10^{-2}$

Background small

V2: 36 from neutral strange particles

V4: no background

Fully neutral D^0 decay modes "V0":

Measured: $$B(D^0 \to V4)/B(D^0 \to V2) = 0.207 \pm 0.016 \pm 0.004$$

From PDG: $$B(D^0 \to V4) = 0.1339 \pm 0.0061 \; [18]$$

Obtained by summing all known 4-prong modes which are complete

This allows us to convert ratios into absolute numbers!

6 prong small: $$B(D^0 \to V6) = (1.2^{+1.3}_{-0.9} \pm 0.2) \times 10^{-3}$$

BR($D^0 \to$ neutrals):

$$B(D^0 \to V0) = 1 - B(D^0 \to V4)[1 + \frac{B(D^0 \to V2)}{B(D^0 \to V4)} + \frac{B(D^0 \to V6)}{B(D^0 \to V4)}]$$

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

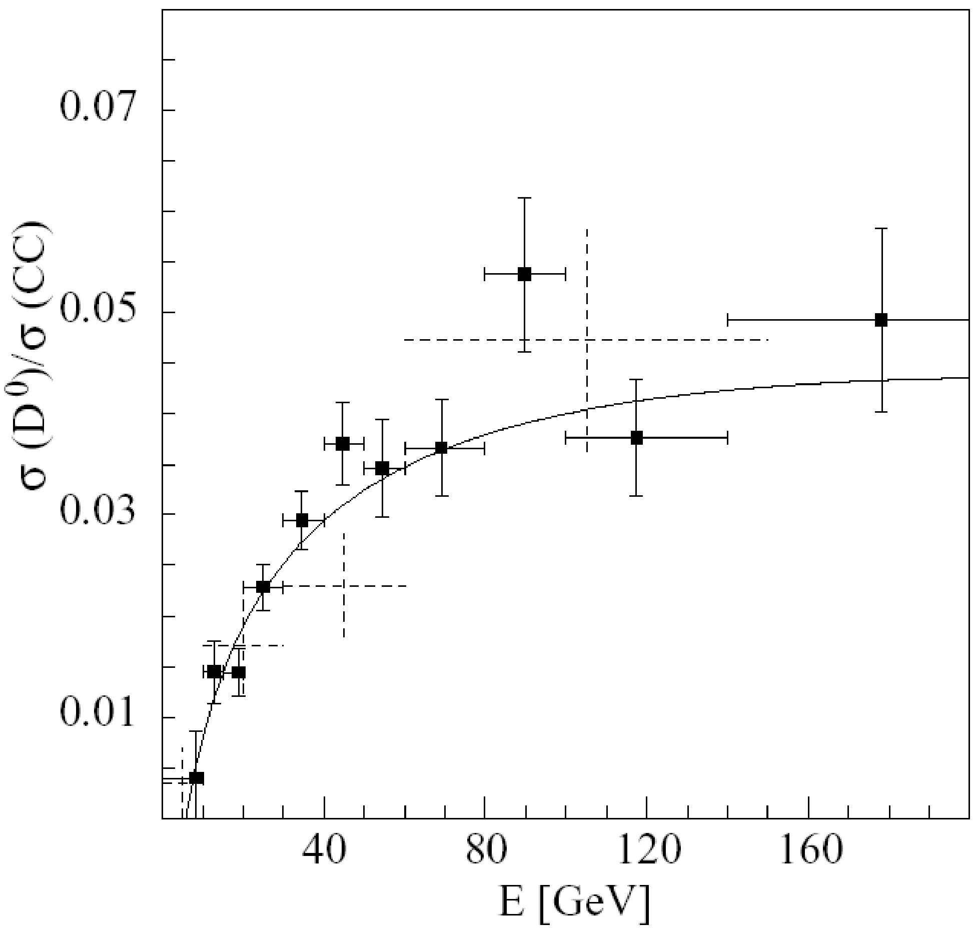
While only 5% is measured in exclusive channels (PDG)

This knowledge allows us to measure total production cross-sections

Total D^0 production cross section:

All D^0's = $N_{V4}/BR4$ $\sigma(D^0)/\sigma(CC) = 0.0269 \pm 0.0018 \pm 0.0013$ 27 GeV average E

For energy dependence use all decay modes, normalized to the V4



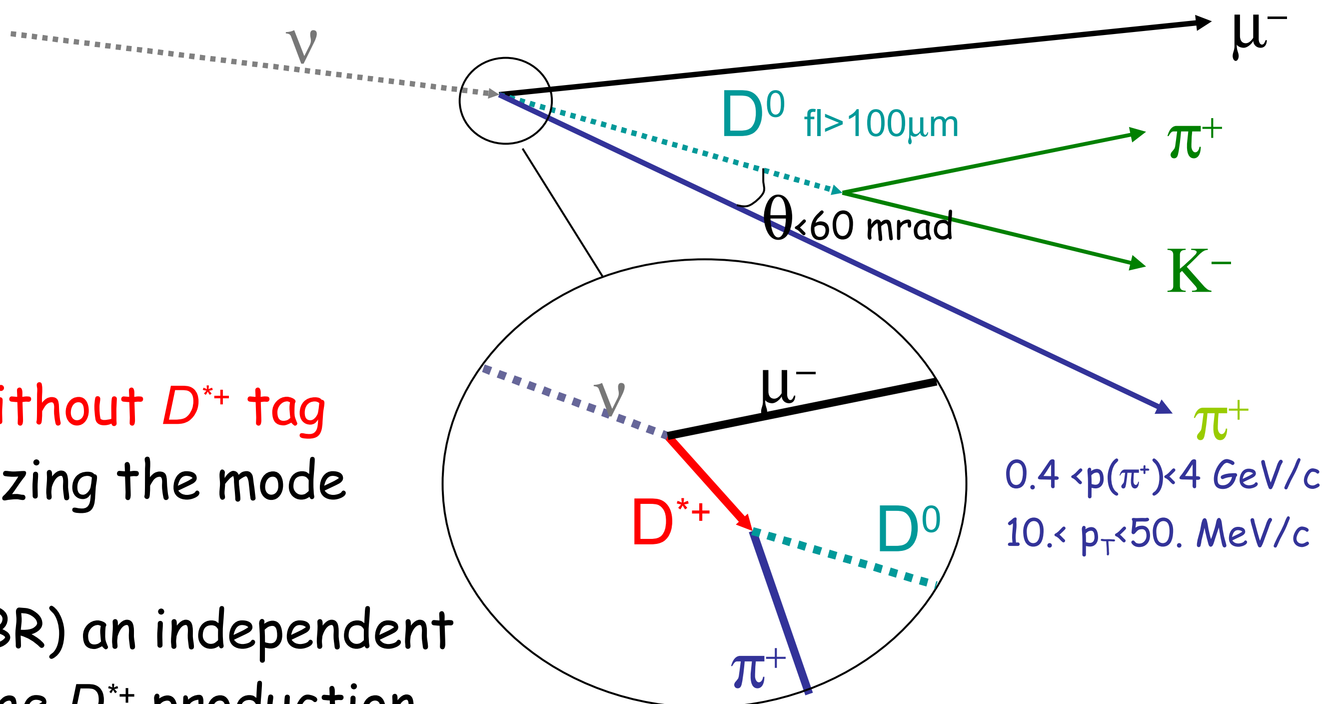
Threshold behaviour is sensitive to effective charm mass:

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 later)

Measurement of D^{*+} production in CC ν-N scattering

Phys. Lett. B 614 (2005) 155



D^0 is recognized without *D^{*+}* tag so that by recognizing the mode

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

(and knowing the BR) an independent measurement of the *D^{*+}* production can be made by looking for a slow pion from the primary vertex with low p_T w.r.t. the *D^0*

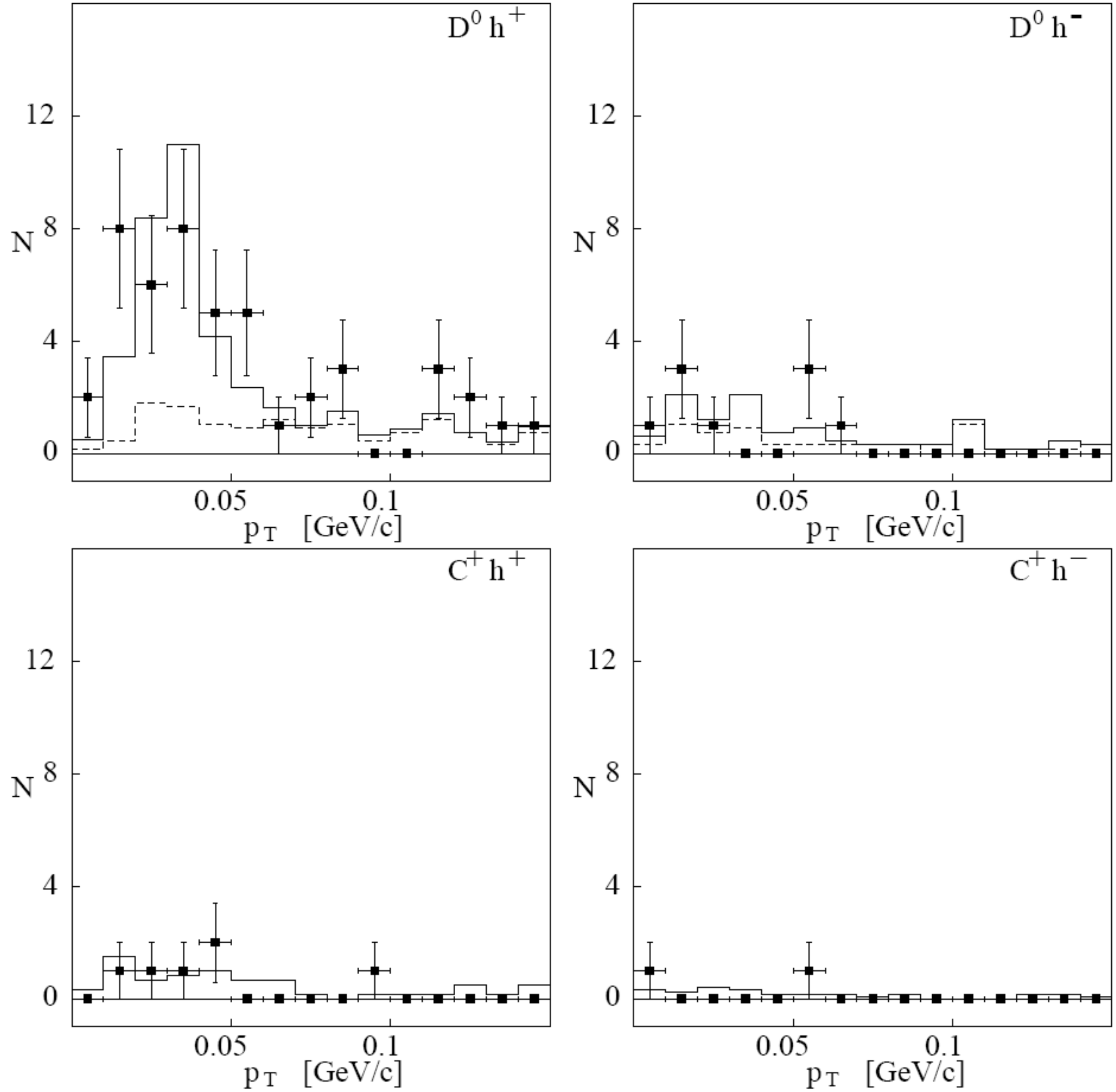
D^{*+} production

p_T w.r.t. the D^0 of slow pion from the primary vertex

$D^{*+} \rightarrow D^0\, \pi^+$ signal only expected for positive pions "near" neutral charm decays

nothing seen for negative pions
(no D^{*-} in neutrino interactions)
Also not near charged charm

27 events in signal region with 5 events background



D^{*+} production results

Assuming $B(D^{*+} \to D^0 \pi^+)=0.677 \pm 0.005$ *(PDG)* the relative rate is:

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

By using the measurement of $\sigma(D^0)/\sigma(CC)$ made in CHORUS:

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

(Assuming production of D^{*+} and D^{*0} equal)
Fraction of all D^0 produced through D^*

$\sigma(D^*\text{->}D^0)/\sigma(D^0)=0.63 \pm 0.17$

Fraction consistent with naive ¾ expectation for V/(P+V)

fragmentation

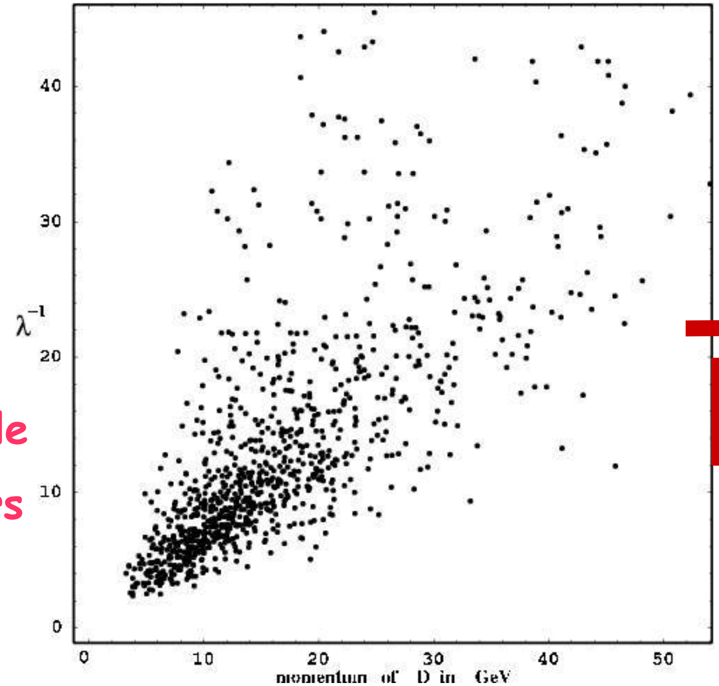
Phys. Lett. B 604 (2004) 145

A pure sample of D^0 events is obtained using neutral particle decays. Thus using the neutrals, avoid complications of different particle types. D^0 produced by DIS processes.

Need to measure momenta of the D! (low efficiency)

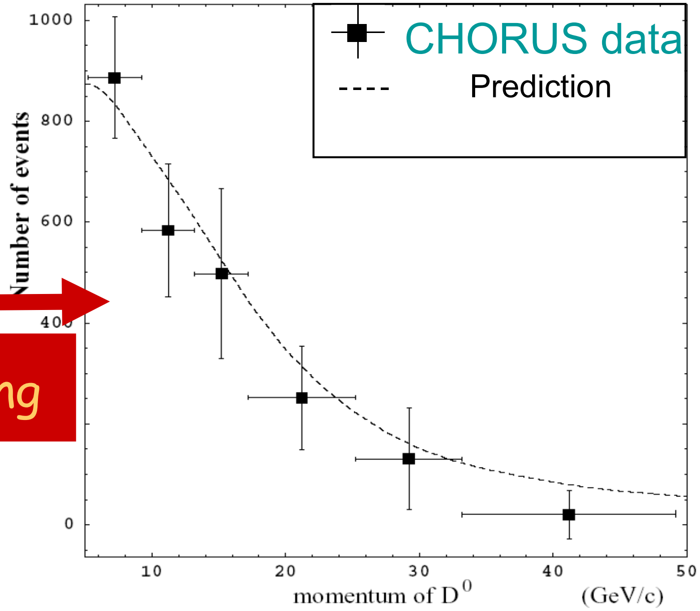
Use decay angle measurements (precise and always available)

Inverse of geometrical mean of opening angle of daughters



D Momentum

Unfolding



Factorization of production and fragmentation

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

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

Fit to Collins-Spiller distribution:

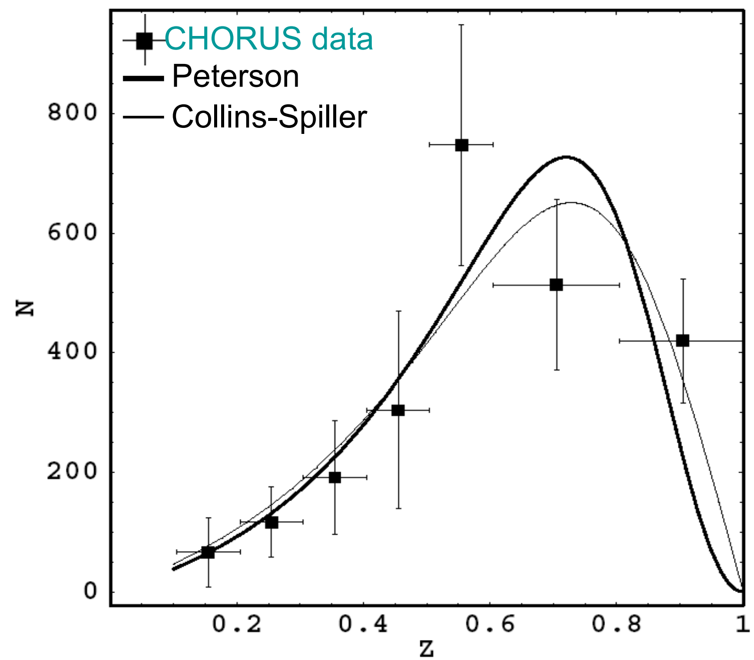
$\varepsilon_{cs} = 0.21^{+0.05}_{-0.04} \pm 0.04$

Fit to Peterson distribution:

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

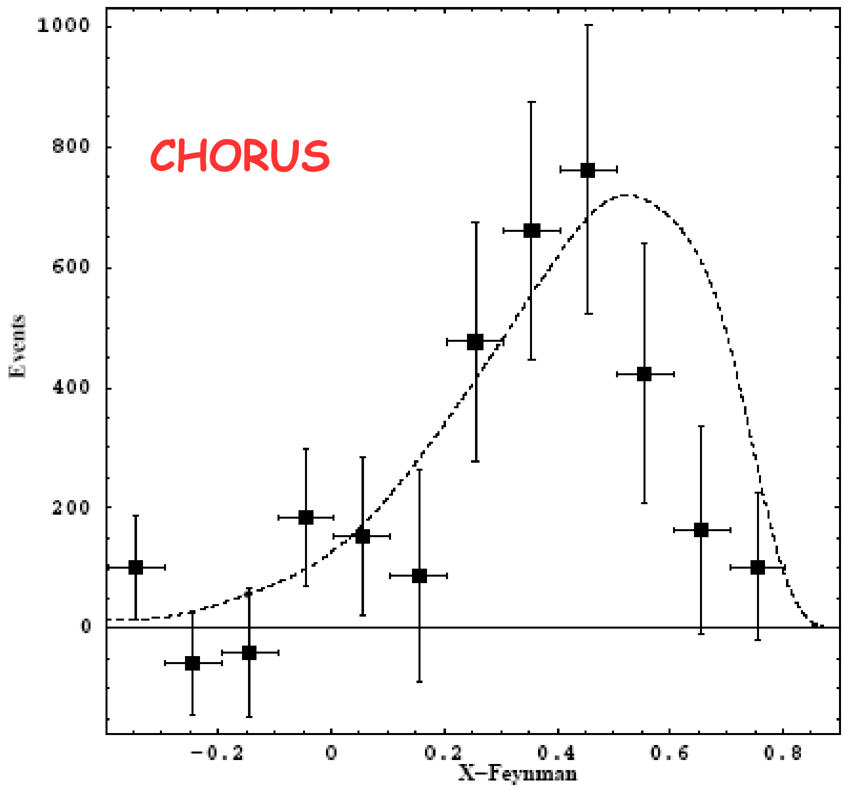
$$D_c(z) = N\left(\frac{1-z}{z} + \frac{\epsilon_c(2-z)}{1-z}\right)(1+z^2)\left(1 - \frac{1}{z} - \frac{\epsilon_c}{1-z}\right)^{-2}$$

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

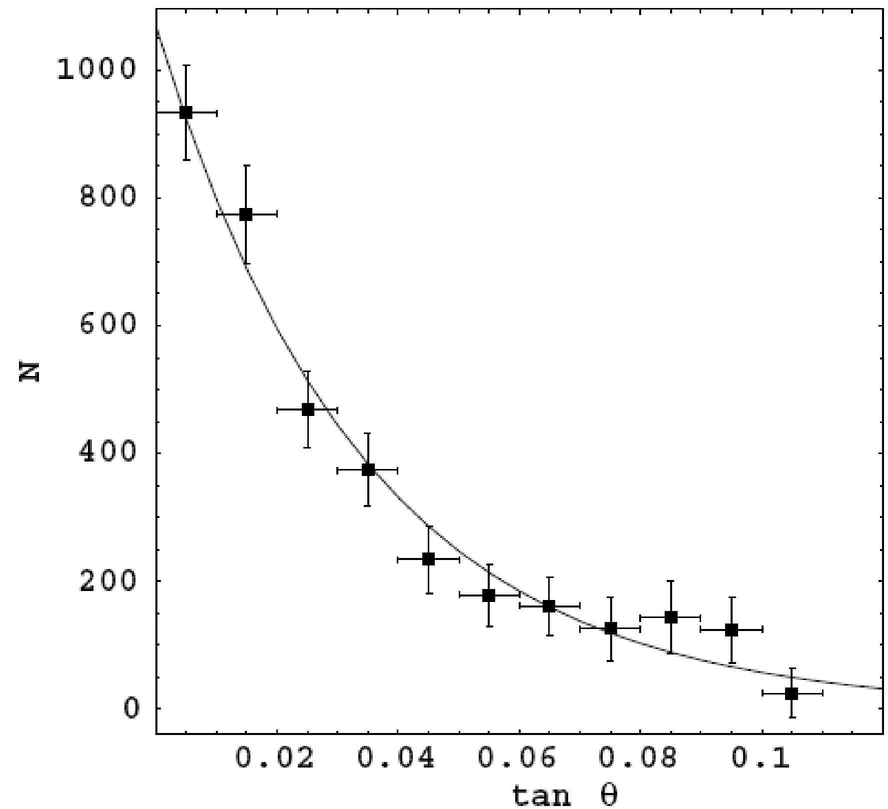


Feynman x and PT distribution

Most charmed particles are produced in the forward region



PT not so precise: use angle theta "out of the lepton plane" as transverse variable:



Measurement of Λ_c production

Phys. Lett. B 555 (2003) 156

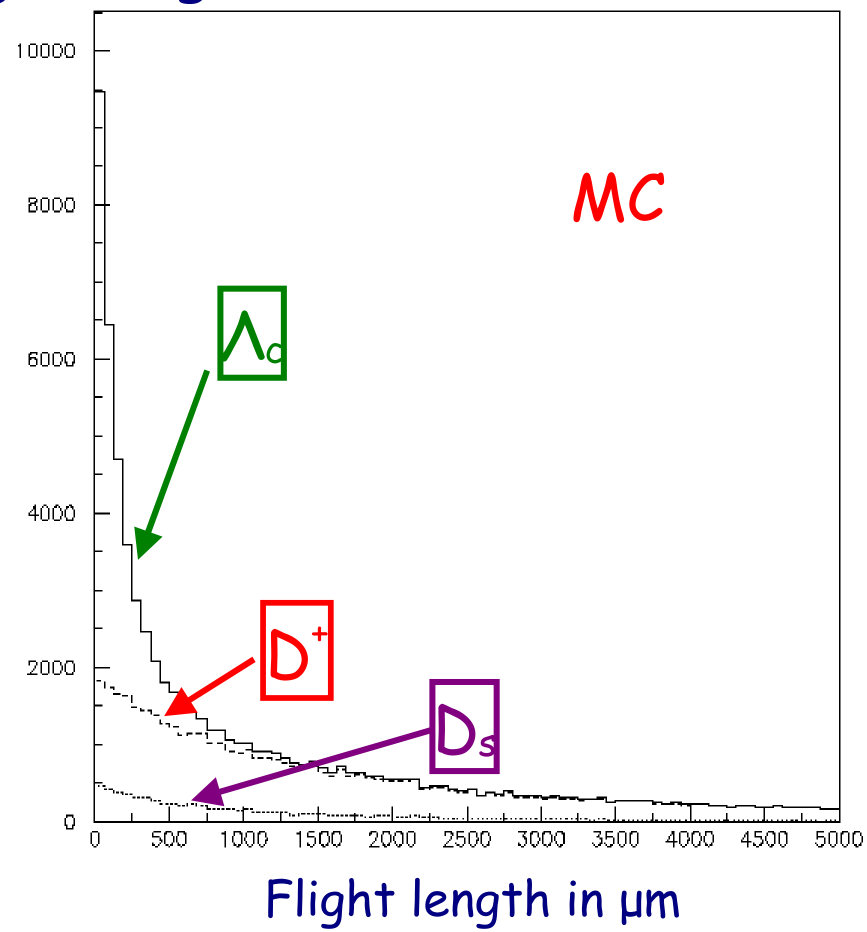
Strategy

A statistical approach using flight length distribution

Two different sets of criteria have been adopted:

Short flight decay : Λ_c enriched sample

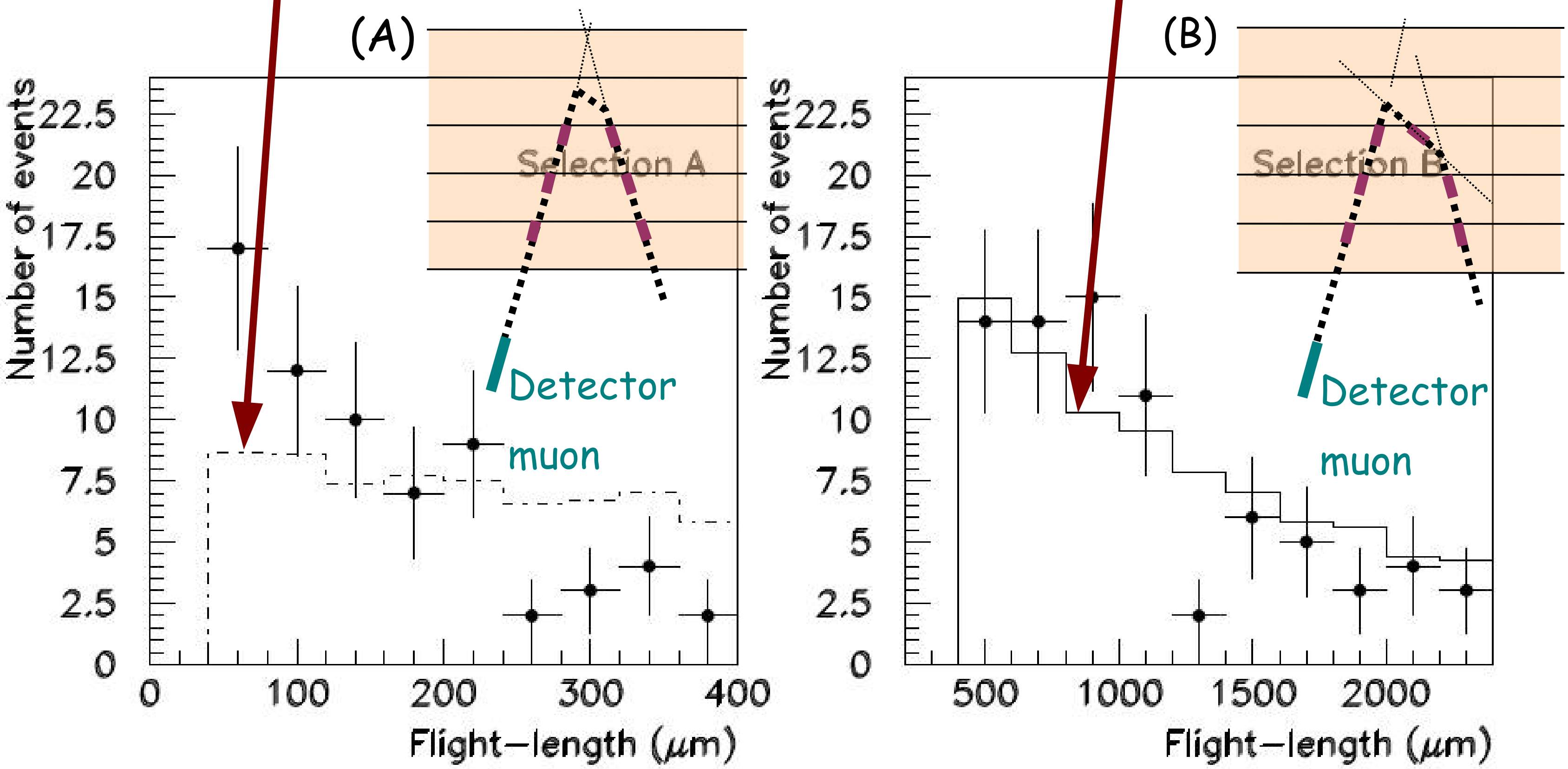
Long flight decay : D^+, D_s dominant



Λ_c production

D-mesons alone cannot explain distribution at small flight length

for >400 mm D alone is OK

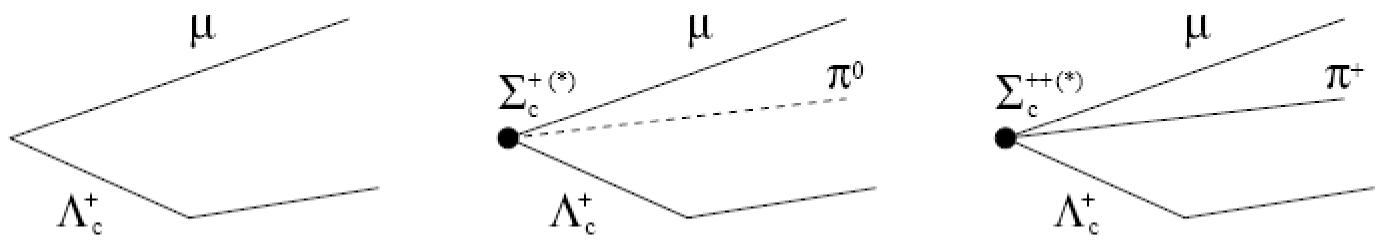


σ (Λc) /σ(CC)= (1.54 ± 0.35(stat) ± 0.18 (syst)) %

Quasi-elastic production

Phys. Lett. B 575 (2003) 198

Quasi-elastic charmed baryon production topologies



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:

2 or 3 tracks at primary vertex

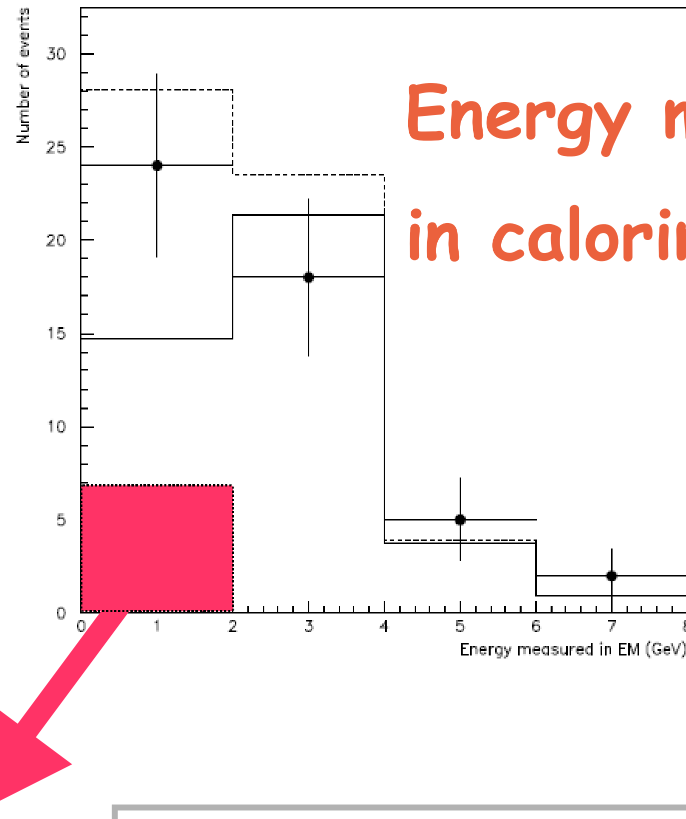
Flight length < 200 μm (enriches Λc sample)

Calorimeter energy < 10 GeV and electromagnetic energy < 2 GeV

$\Phi \geq 165°$ (angle between muon and charm in the transverse plane)

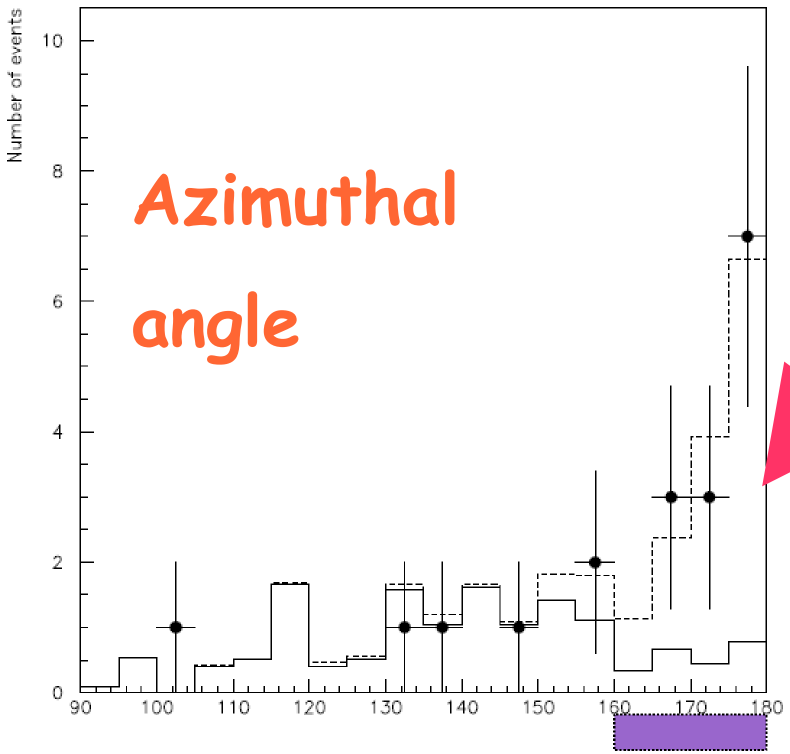
Kinematical selection of QE candidates

Events in first energy bin



Energy measured in calorimeter

Azimuthal angle



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

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

15% of Λc produced in QE processes

Total charm production cross-section

Need now to measure charged AND neutral charmed particles

More difficult for charged charm than neutral charm because:

efficiencies for different charmed hadrons are different

important to know the production fractions first

efficiencies also depend on decay topology:

	Λ_c^+	D^+	D_s^+
$C^+ \rightarrow 1p$ (%)	17.1 ± 1.3	21.7 ± 0.9	23.9 ± 1.2
$C^+ \rightarrow 3p$ (%)	40.8 ± 1.6	49.0 ± 1.2	57.7 ± 1.4
$C^+ \rightarrow 5p$ (%)	44.2 ± 5.2	52.7 ± 6.5	57.3 ± 3.4
$\epsilon_{3p}/\epsilon_{1p}$	2.3 ± 0.2	2.3 ± 0.1	2.4 ± 0.1

Separate types by life-time – needed to distinguish D^+ from D_s^+

use decay-angle as momentum estimator

(Λc analysis used flight length alone)

Charmed fractions and inclusive topological branching ratios

$f_{D0} = (45.7 \pm 3.1)\%$ ***from*** D^0 ***analysis***

$f_{D+} = (24.5 \pm 3.8)\%$

$f_{Ds+} = (11.3 \pm 4.7)\%$

$f_{\Lambda c+} = (18.5 \pm 3.6)\%$

Likelihood fit to life-time distribution to obtain the charm production fractions

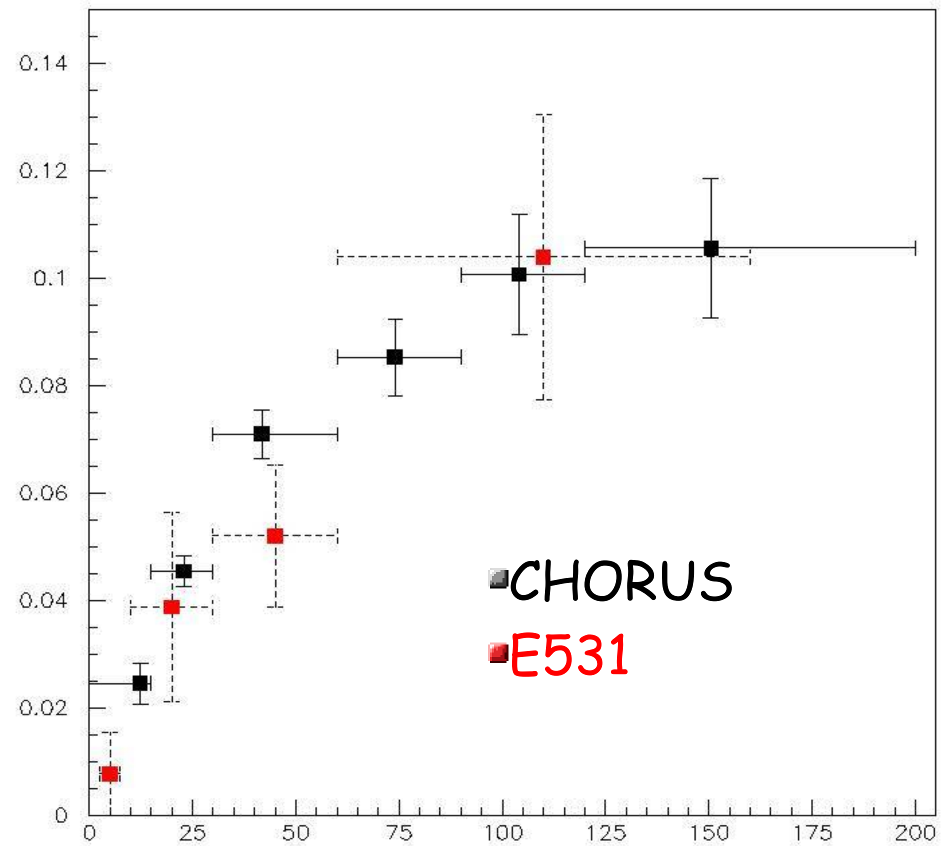
$BR(C^+ \to 1 \text{ prong}) = (64.7 \pm 6.4)\%$

$BR(C^+ \to 3 \text{ prong}) = (34.3 \pm 3.5)\%$

$BR(C^+ \to 5 \text{ prong}) = (1.0 \pm 0.2)\ \%$

Preliminary numbers!

Inclusive charm production
Energy dependence (neutrinos)



Preliminary

$\sigma(\text{Charm})/\sigma(CC)=(5.9\pm0.4)\%$

At 27 GeV average neutrino beam

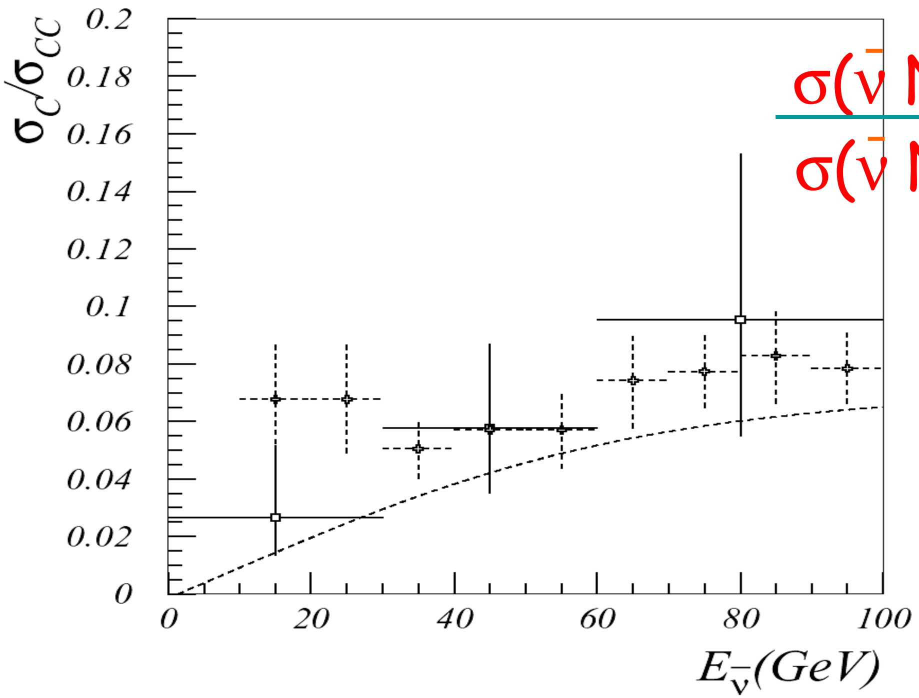
Charm production in anti-neutrino interactions

Phys. Lett. B 604 (2004) 11

Similar analysis for anti-neutrino interactions

Statistics much lower – used anti-neutrino contamination in the beam (tagging by positive muon)

32 charm events in total



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

CHORUS DATA

Derived from di-lepton data

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

Muonic branching ratio of charmed particles

Phys. Lett. B 549 (2002) 48, based on ~25% of statistics

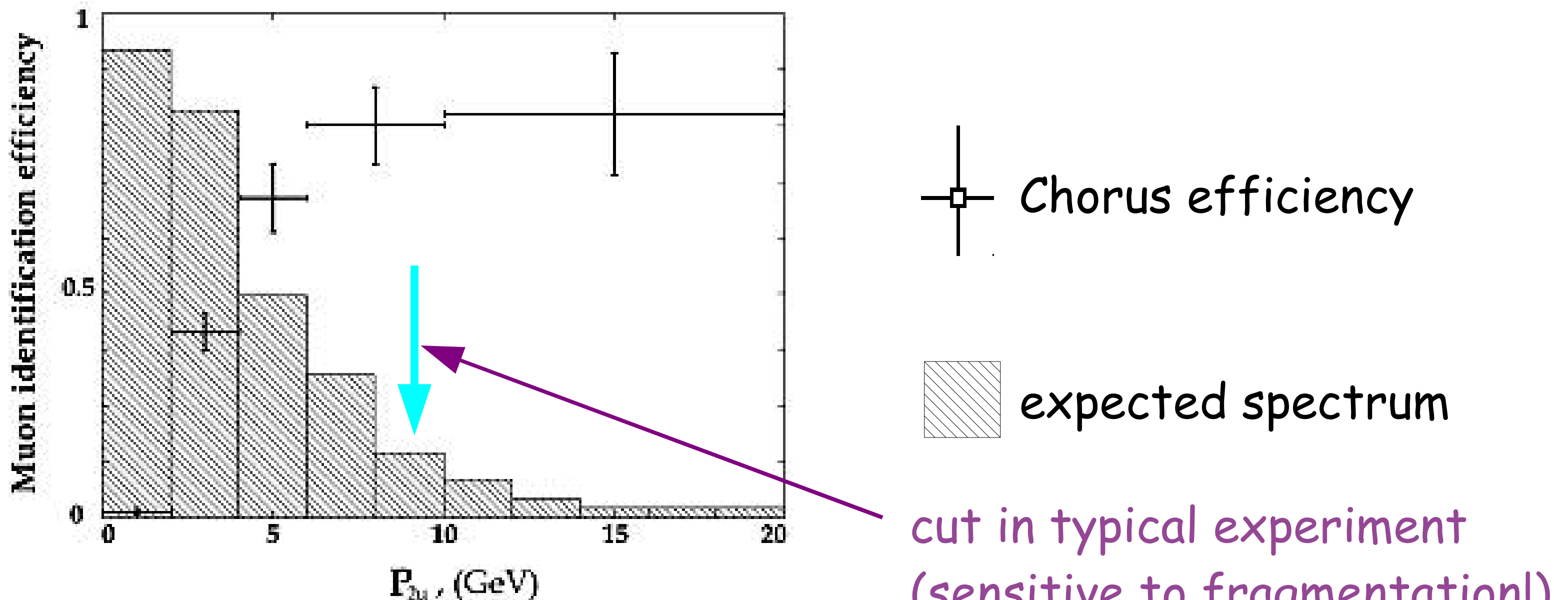
Phys. Lett. B 626 (2005) 24, full statistics

Measurements of charm production in neutrino interactions with electronic detectors use di-muon events to tag charm

CHORUS can identify charm independently of the muon and then look if any of the daughter particles is a muon

Direct measurement of muonic branching ratio B_μ

Difficulty is soft muon spectrum



Results for B_μ

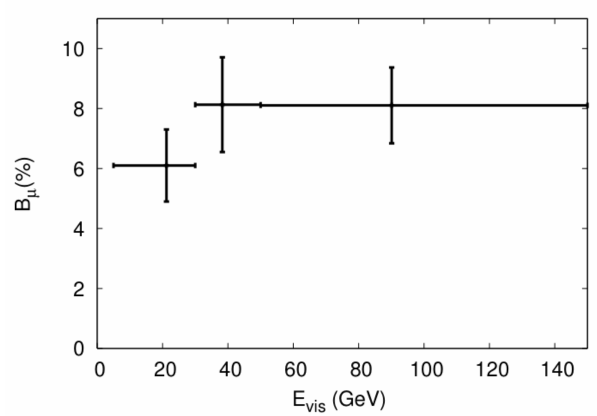
Sample of recognized muons in charm decays by topology

Number of prongs	Selected	Background	$\varepsilon_\mu^{\mathrm{id}}$,%	$\overline{B_\mu}$ (%)
C1	20	0.8	36.0 ± 3.4	$10.8 \pm 2.4 \pm 0.5$
V2	34	9.8	34.5 ± 1.9	$8.3 \pm 1.4 \pm 0.4$
C3	17	8.4	26.4 ± 2.6	$6.1 \pm 1.6 \pm 0.6$
C1+C3	37	9.2	31.7 ± 3.1	$8.6 \pm 1.4 \pm 0.4$
V2+V4	36	9.8	30.1 ± 1.5	$8.1 \pm 1.5 \pm 0.3$
Inclusive	73	19.0	30.4 ± 2.1	$7.3 \pm 0.7 \pm 0.2$

B_μ (All Charm)= $(7.3\pm0.8_{(stat)})\%$

For the D^0 the B_μ can be readily obtained (take into account V0):

B_μ (D^0)= $(6.5\pm1.2_{(stat)})\%$



Energy dependence

Di-muons in the calorimeter

Nucl. Phys. B 798 (2008) 1

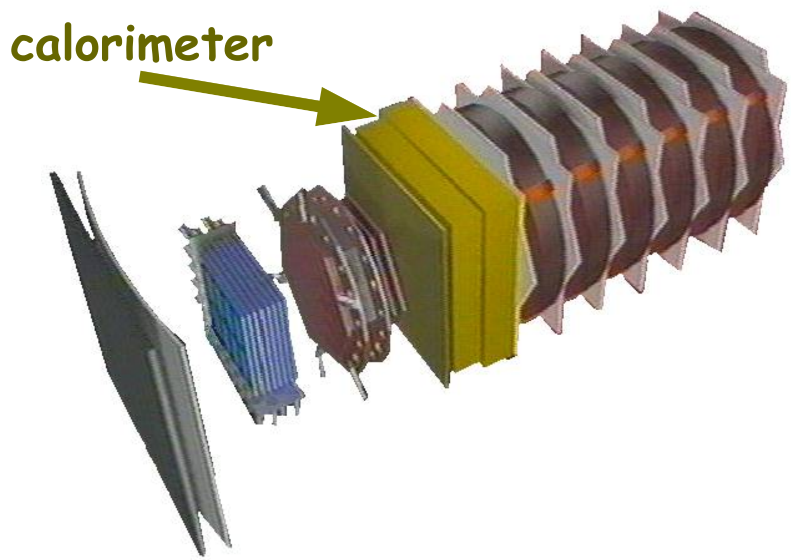
CHORUS triggered also on **interactions in the calorimeter**

For charm physics the di-muon and tri-muon analysis are relevant

Trigger on >=2 tracks in the calorimeter or spectrometer

Analysis requires two muons with momentum and charge measured in the spectrometer

Higher statistics than in the emulsion, but background due to π, K, K^o_s decays



Di-muon 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*

Measured:

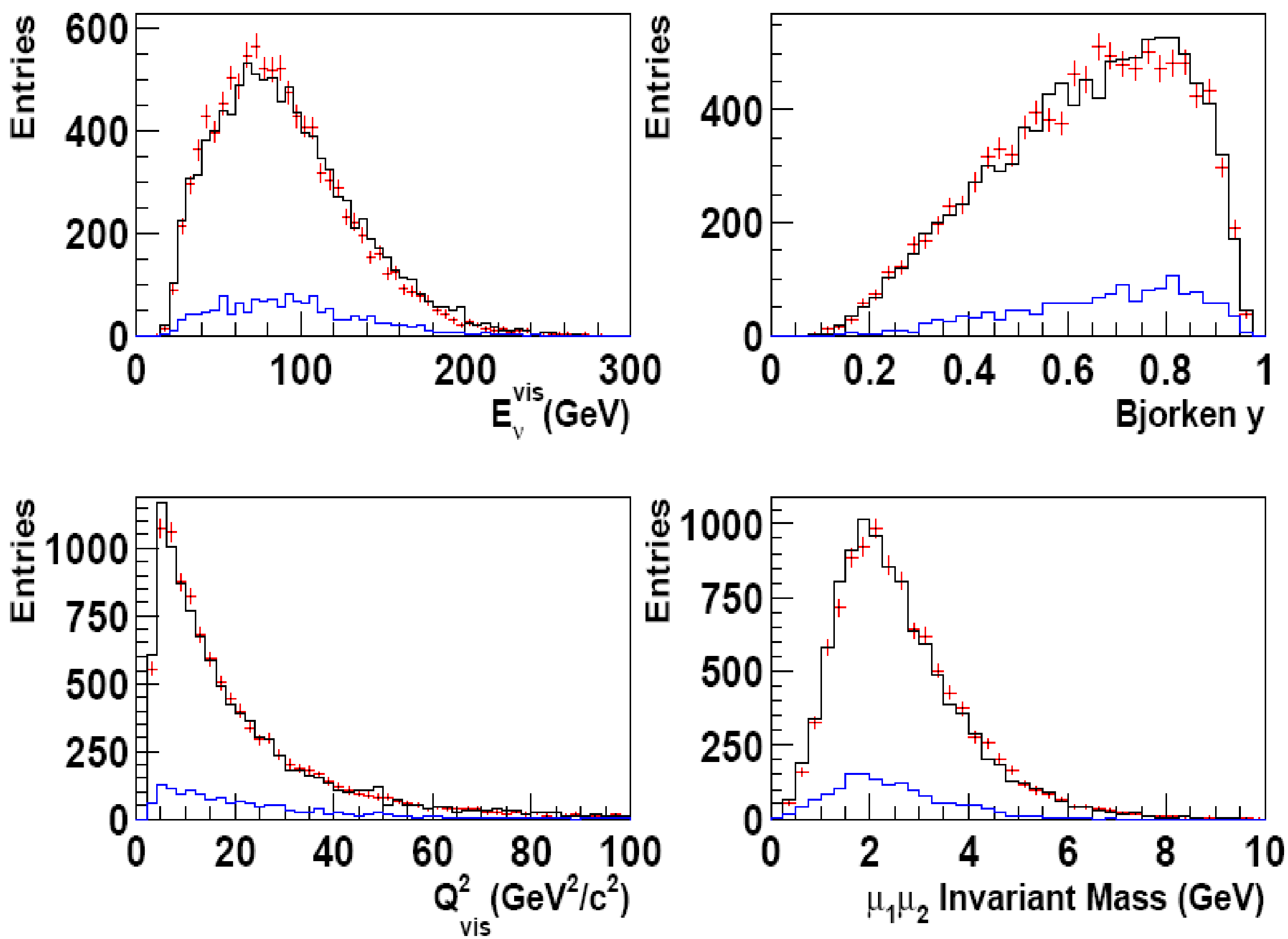
momentum, angle and charge of muons
energy of hadronic shower

Kinematics

Results are obtained using a global fit to the distributions

Good description of the kinematics is essential

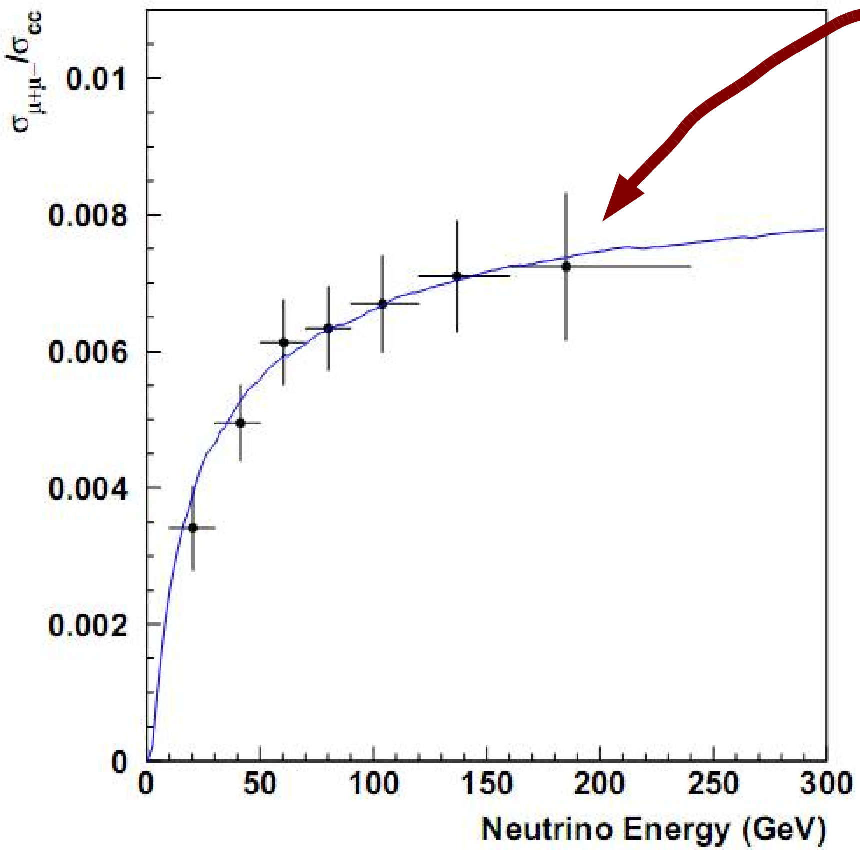
+ Data
- Fit
- Background



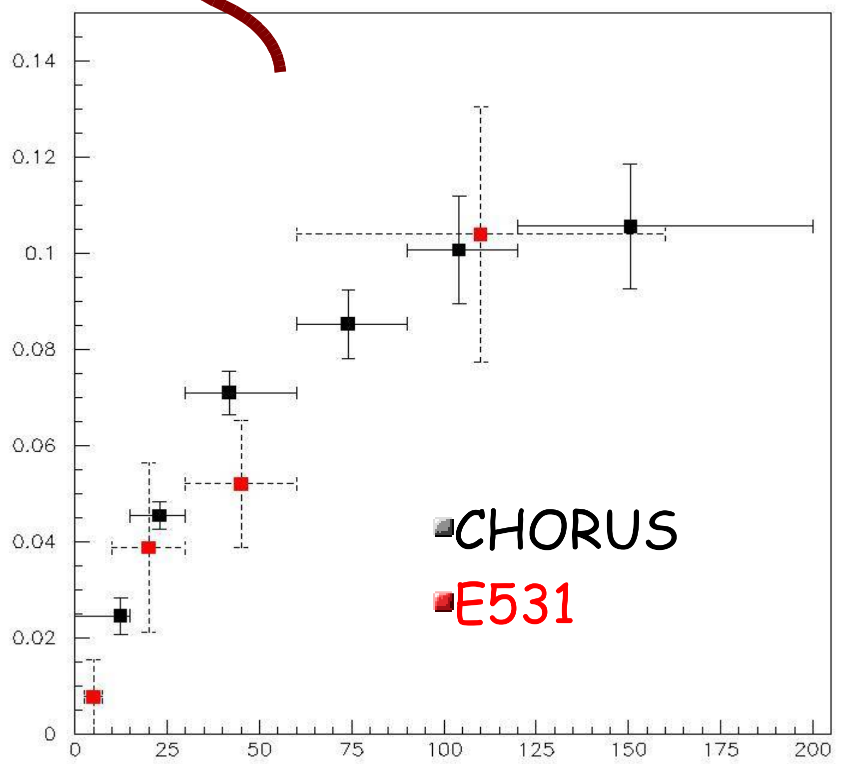
Di-muon cross-section

Consistent with
B_μ (All Charm)= (7.3±0.8(stat))%

Di-muon data



Emulsion data



Result of analysis

Di-muon data

- m_c = 1.26 ± 0.16 (stat) ± 0.09 (syst)
- κ = 0.33 ± 0.05 (stat) ± 0.05 (syst)
- ε_P = 0.065 ± 0.005 (stat) ± 0.009 (syst)
- B_μ = 0.096 ± 0.004(stat) ± 0.008 (syst)

Emulsion data

m_c $(1.42 \pm 0.08)\ \mathrm{GeV}/c^2$

using same α and κ $1.30 \pm 0.08\ \mathrm{GeV}/c^2$

$\epsilon_P = 0.108 \pm 0.017 \pm 0.013.$

using same definition $0.059 \pm 0.010 \pm 0.008$

$\overline{B_\mu} = [7.3 \pm 0.8\ (\mathrm{stat}) \pm 0.2\ (\mathrm{syst})] \times 10^{-2}$

using E > 30 GeV $B_\mu = 0.085 \pm 0.010$

Other di-muon data

Experiment	m_c	k	B_μ
CDHS	–	$0.47 \pm 0.08 \pm 0.05$	0.084 ± 0.014
NOMAD	$1.3 \pm 0.3 \pm 0.3$	$0.48 \pm 0.08 \pm 0.15$	$0.095 \pm 0.007 \pm 0.013$
CHARM II	$1.8 \pm 0.3 \pm 0.3$	$0.39 \pm 0.07 \pm 0.07$	$0.091 \pm 0.007 \pm 0.007$
CCFR	$1.3 \pm 0.2 \pm 0.1$	$0.44 \pm 0.07 \pm 0.05$	$0.109 \pm 0.008 \pm 0.006$
NUTEV	$1.33 \pm 0.19 \pm 0.10$	$0.32 \pm 0.06 \pm 0.04$	$0.1140 \pm 0.0108 \pm 0.0115$

Trimuon events in ν_μ CC interactions

Phys. Lett. B 596 (2004) 44

if di-muons -> single charm are then tri-muons double-charm?

CDHS and HPWF (1978): ~100 $\mu^- \mu^- \mu^+$ events

- origin largely unknown

CHORUS:

~6x10^6 2μ calorimeter triggers

observed: 42 $\mu^- \mu^- \mu^+$, 3 $\mu^- \mu^+ \mu^+$ (Pμ > 5 GeV/c)

Detailed Monte-Carlo (LEPTO/JETSET/GEANT)

4x10^6 events with full detector simulation

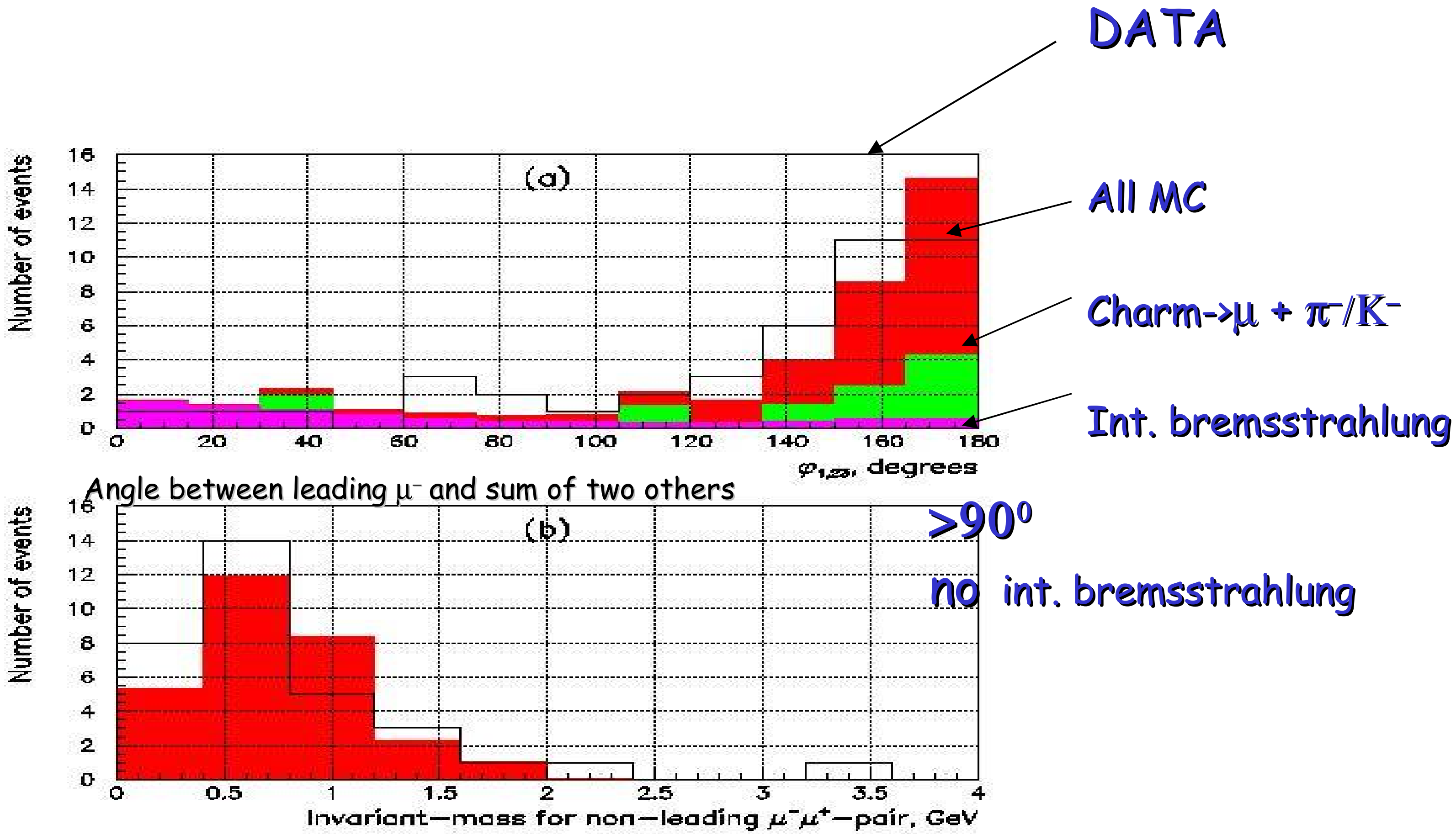
present knowledge of production rates and

μ-decays of η, ρ, ω, η', ϕ

data-MC validation using 2μ events (known origin)

data-MC comparison for 3μ event sample

Expected sources



Details

main 3μ sources MC $\mu^-\mu^-\mu^+$ predictions

Meson	*Decay*	*BR* $\times 10^5$	$(N_{3\mu}/N_{CC}) \times 10^6$	N_{meson}
$\eta(548)$	$\mu^+\mu^-\gamma$	31±4	61±20	11.2±4.5
$\rho(770)$	$\mu^+\mu^-$	4.60±0.28	9.0±1.0	2.8±0.7
$\omega(782)$	$\mu^+\mu^-$	9.0±3.1	11.7±4.9	3.8±1.7
$\omega(782)$	$\pi^0\mu^+\mu^-$	9.6±2.3	12.5±4.3	3.0±1.0
$\eta'(958)$	$\mu^+\mu^-\gamma$	10.4±2.6	4.5±1.2	1.5±0.5
$\phi(1020)$	$\mu^+\mu^-$	28.7±2.0	1.64±0.18	0.8±0.2
All mesons	-	-	-	23.1±5.0

Charm->μ + π^-/K^- decay 8.3±2.8

Internal bremsstrahlung (theoretical) 8.6±4.5

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Conclusions – MC predictions on 3μ rate are in agreement with measurements

Observed in experiment: 42 $\mu^-\mu^-\mu^+$

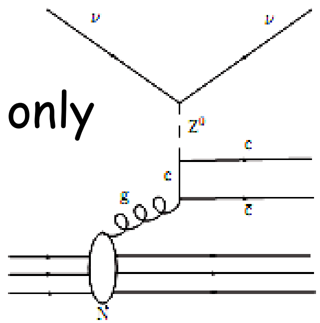
No sign of associated charm production --> need emulsion!

Associated charm production

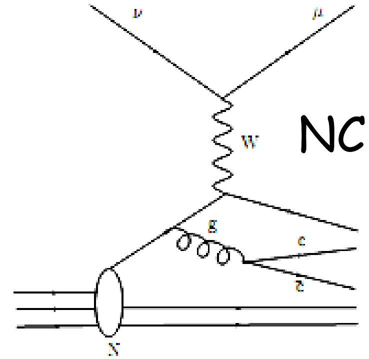
Eur. Phys. J. C 52, (2007) 543

boson gluon fusion

NC only



gluon bremsstrahlung



NC and CC

Using NetScan technique to reconstruct vertices and inspect events with 2 secondary vertices "manually"

Compared to the usual charm analysis: additional criteria to reduce background:

- "V2" require **a-coplanarity** to reject strange particle decays and "minimum mass" for V2
- "C1" require **decay PT** to reject "white kinks"

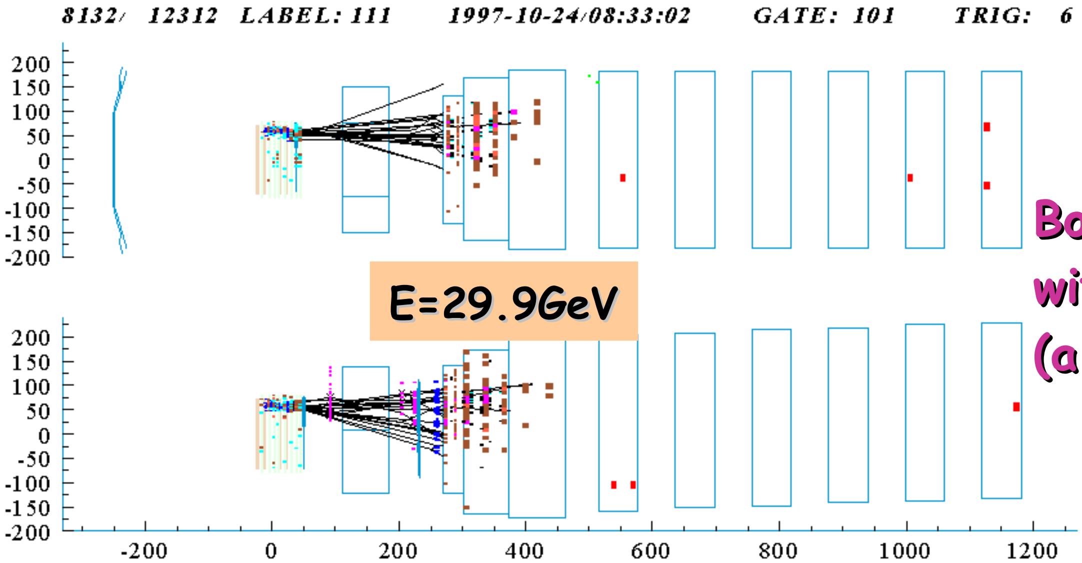
Background estimates:

NC: 0.03 events from non 2c and 0.15 events from CC associated charm

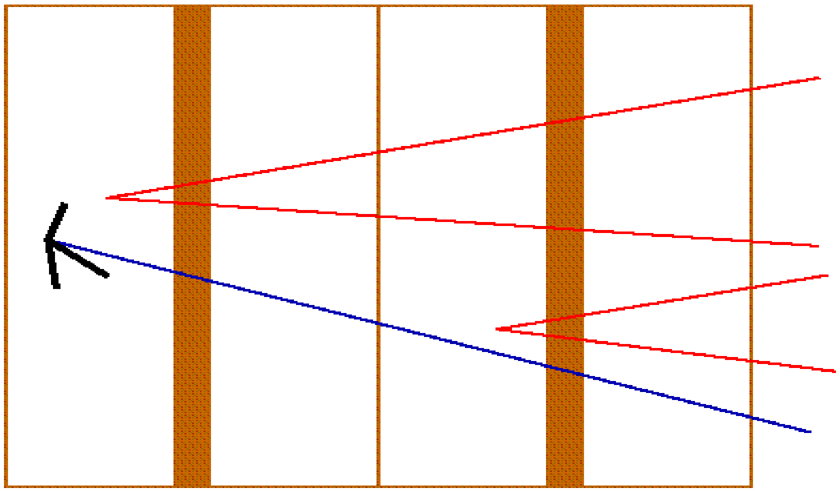
CC: 0.18 events from non 2c

topology with 2 neutral decays almost without background

example of NC event



Both neutral decays inconsistent with two-body decay (a-coplanarity)



TT #5, P_{d1} > 1.39 GeV/C @ 90CL.

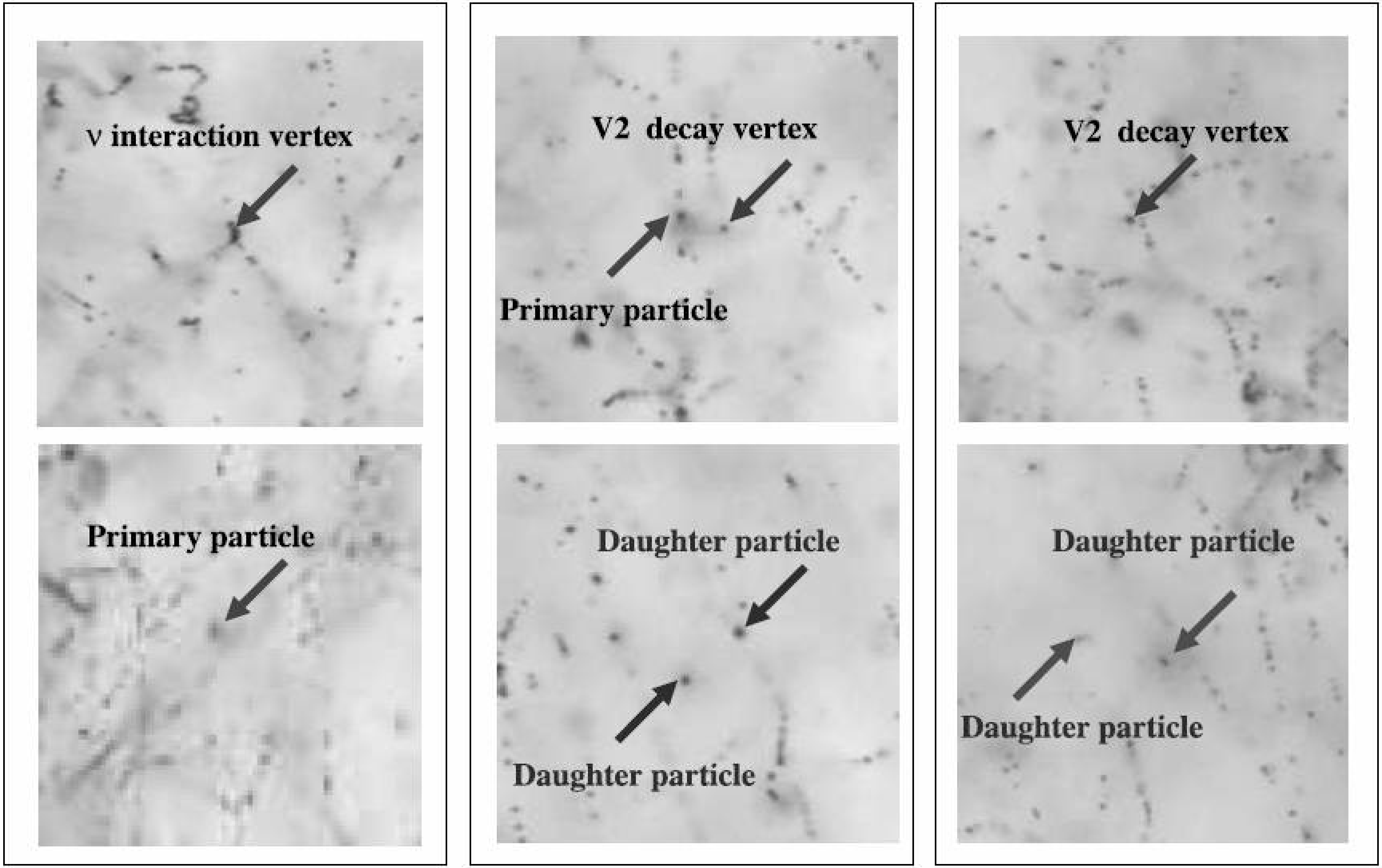
TT #8, P_{d2}>4.66 GeV/C @ 90 CL.

P_{d3}>3.33 GeV/c @ 90 CL.

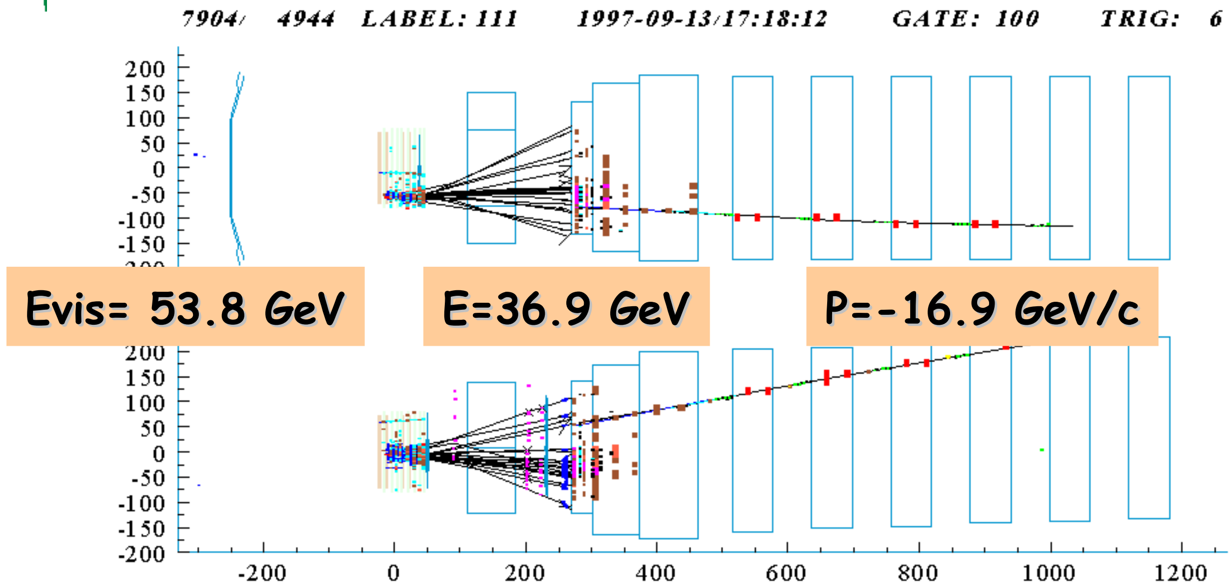
TT #3 P_{d4}>2.72 GeV/c @ 90 CL.

TT #6 P_p>0.66 GeV/C @ 90 CL.

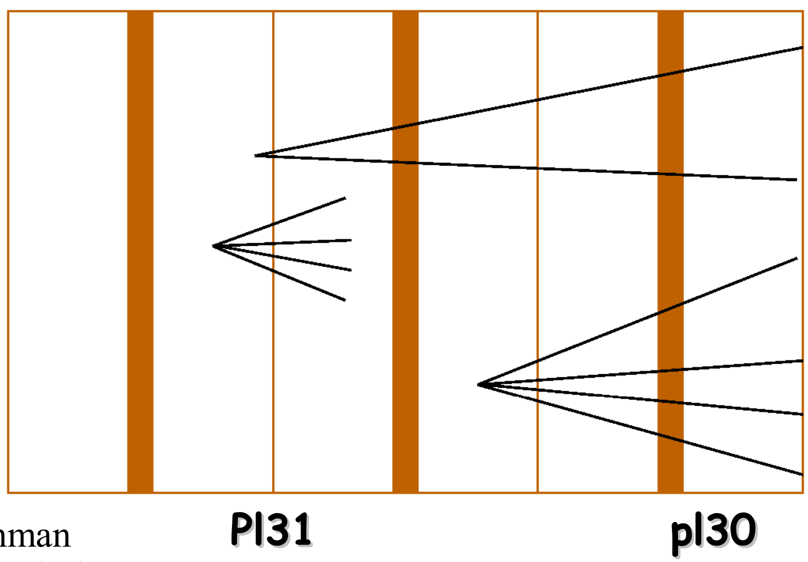
Emulsion view of the same NC event



example of CC event



Both neutral decays inconsistent with two-body decay
(a-coplanarity)



P_{d1}>4.70 GeV/c @ 90 CL.(TT #2)

P_{d2}>0.67 GeV/c @ 90 CL.

P_{d2}>1.92 GeV/c @90 CL.(TT #5)

P_{d3}>2.32 GeV/c @90 CL.(TT #7)

Results

candidates

3 NC: V2+V2 background: 0.18 event (mainly from CC 2c)

C1+V2

C3+V4

1 CC: V2+V4 background: 0.18 event (mainly with Cx)

NC $$\frac{\sigma(c\bar{c}\nu)}{\sigma_{\mathrm{NC}}^{\mathrm{DIS}}} = (3.62^{+2.95}_{-2.42}(\mathrm{stat}) \pm 0.54(\mathrm{syst})) \times 10^{-3}$$

CC $$\frac{\sigma(c\bar{c}\mu^{-})}{\sigma_{\mathrm{CC}}} < 9.69 \times 10^{-4}$$ if interpreted as upper limit

$$1.95^{+3.22}_{-1.44}(\mathrm{stat}) \pm 0.29(\mathrm{syst}) \times 10^{-4}$$ interpreted as signal

SUMMARY

Although designed for neutrino oscillation search

CHORUS has been able to make many charm production and decay measurements