# Charm production with neutrinos

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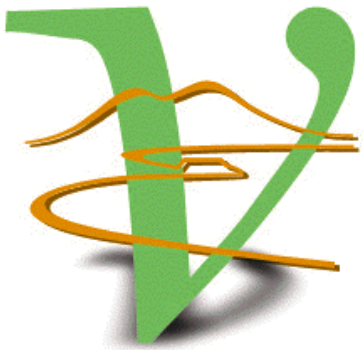
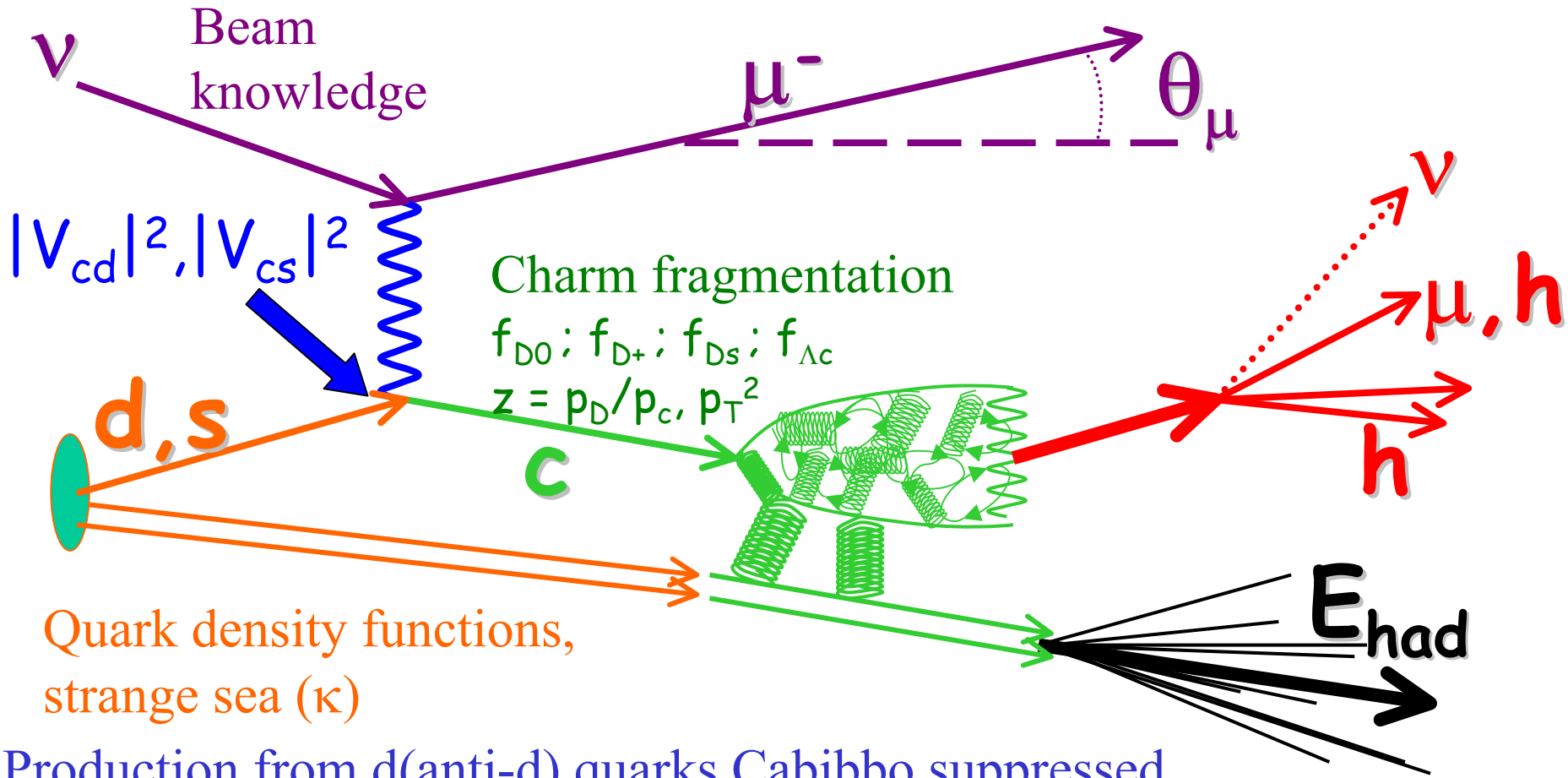


(on behalf of the CHORUS Collaboration)

- Physics motivation
- Results
- Outlook

# ν DIS charm production




Production from d(anti-d) quarks Cabibbo suppressed

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

# Physics motivation

- measure strange content of the nucleon
  - Possible s/anti-s asymmetry → non-p QCD effects
  - crucial role in relating $F_2$ structure function for charged- and neutral-lepton
  - strange sea is important for "stop" searches at hadron colliders: largest background: g+s→W+c

    *R.Demina et al., Phys. ReV. D 62 (2000) 035011*

    *S.J.Brodsky and B.Ma, Phys. Lett. B 381 (1996) 317*
- constrain/study charm production models
  - in NLO pQCD is a challenging theoretical problem
    - » 2 scales, $\Lambda_{QCD}$ and charm mass

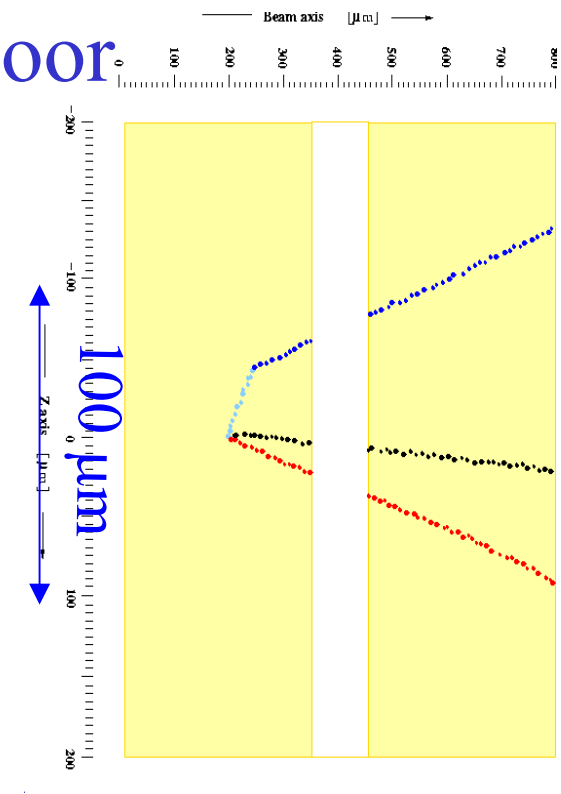
    *(J.Conrad et al. Rev.Mod.Phys. 70 (1998) 1341-1392)*
- measure charm mass and $V_{cd}$

# Experimental techniques

- massive high density detectors (CDHS, CCFR, CHARMII, NuTeV, NOMAD, CHORUS Calo):
  - Pro: large statistics
  - Contra: background from p, K decays; not sensitive to low-neutrino energies ($E_n$<15GeV); not possible to study separately the different charmed types; $B_\mu$ is needed
- bubble chamber filled with heavy liquid (BEBC, Fermilab 15-ft)
- nuclear emulsions (E531, CHORUS)

# Emulsion experiments

- Look "directly" at the decay topology of the charmed hadron with sub-micron resolution
- Contra: the anti-ν statistics is still poor
- Pro:
  - low background; sensitivity to low $E_\nu$
  - $\Rightarrow$ $m_c$ threshold effect
  - hadron species identification
  - reconstruction of charmed hadron kinematics
  - $\Rightarrow$ fragmentation studies



# Inclusive charm production cross-section induced by ν

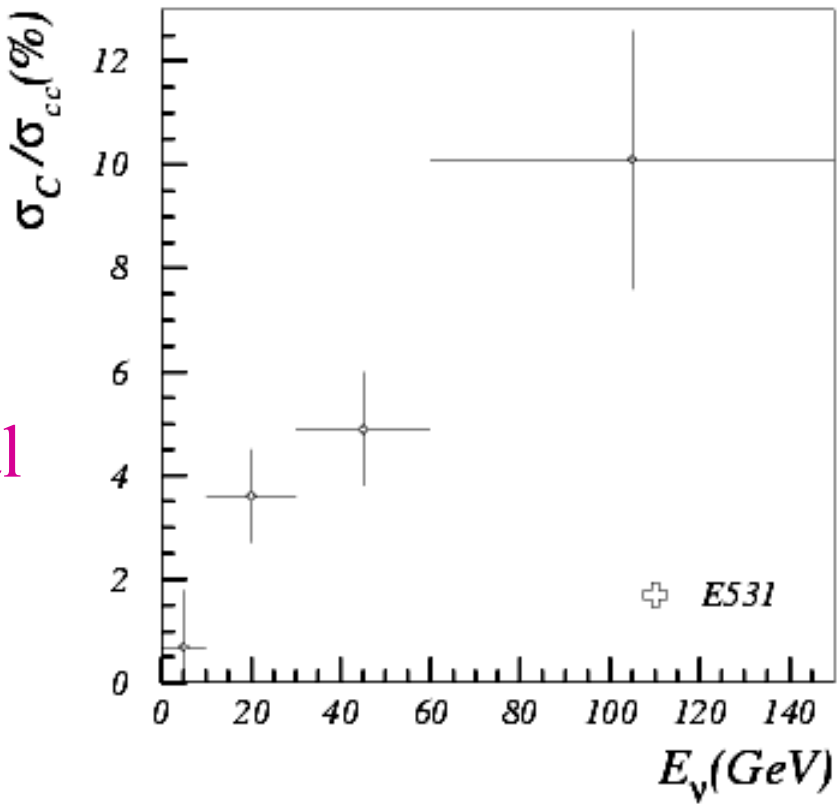
Inclusive charm-production cross-section measurement possible only with nuclear emulsions

So far only E531: 122 events

$$\frac{\sigma(\nu_\mu N \to c\mu^- X)}{\sigma(\nu_\mu N \to \mu^- X)} = 4.9^{+0.7}_{-0.6}\%$$

CHORUS has just got the final Statistics: 2100 charms!

The analysis is in progress!



# CHORUS detector

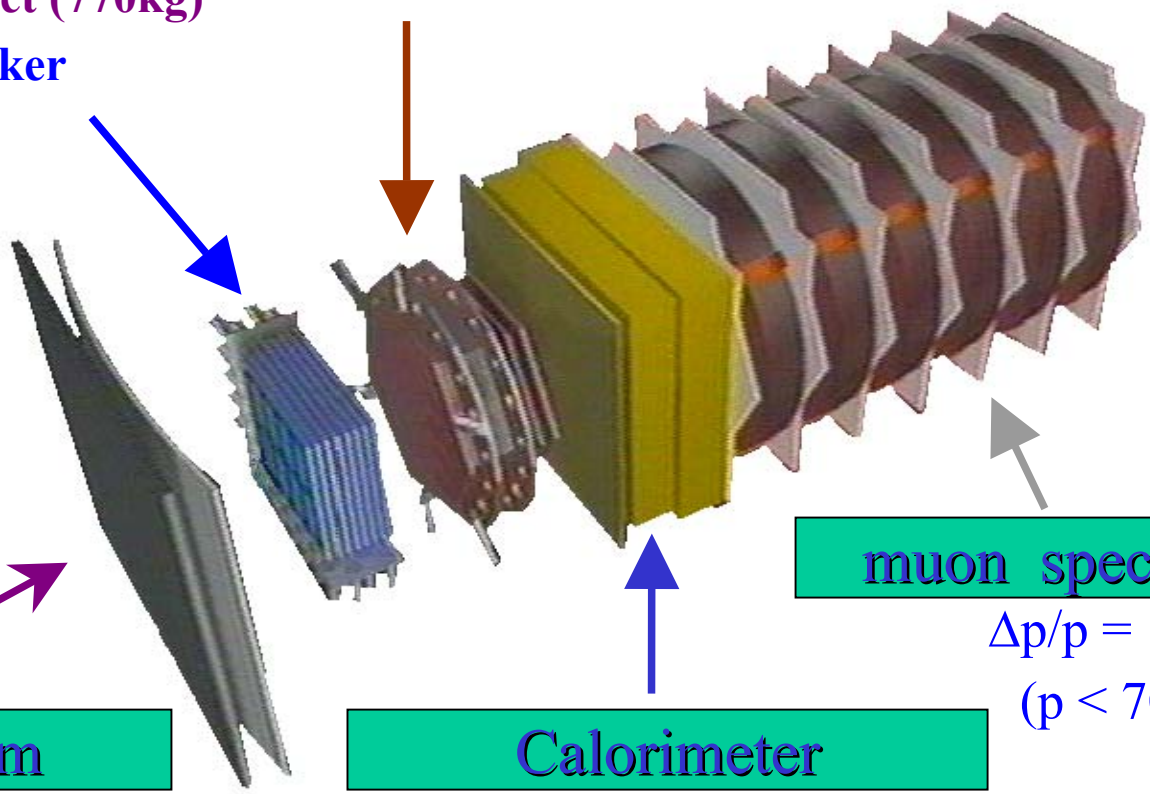
## Active target

-nuclear emulsion target (770kg)

-scintillating fiber tracker

## Air-core magnet

$\Delta p/p = 0.035\ p\ (GeV/c) \oplus 0.22$



## muon spectrometer

$\Delta p/p = 10 \div 15\%$

$(p < 70\ GeV/c)$

## Neutrino beam

$\nu$

$E\nu \sim 27$ GeV

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

**1.00 : 0.05 : 0.017 : 0.007**

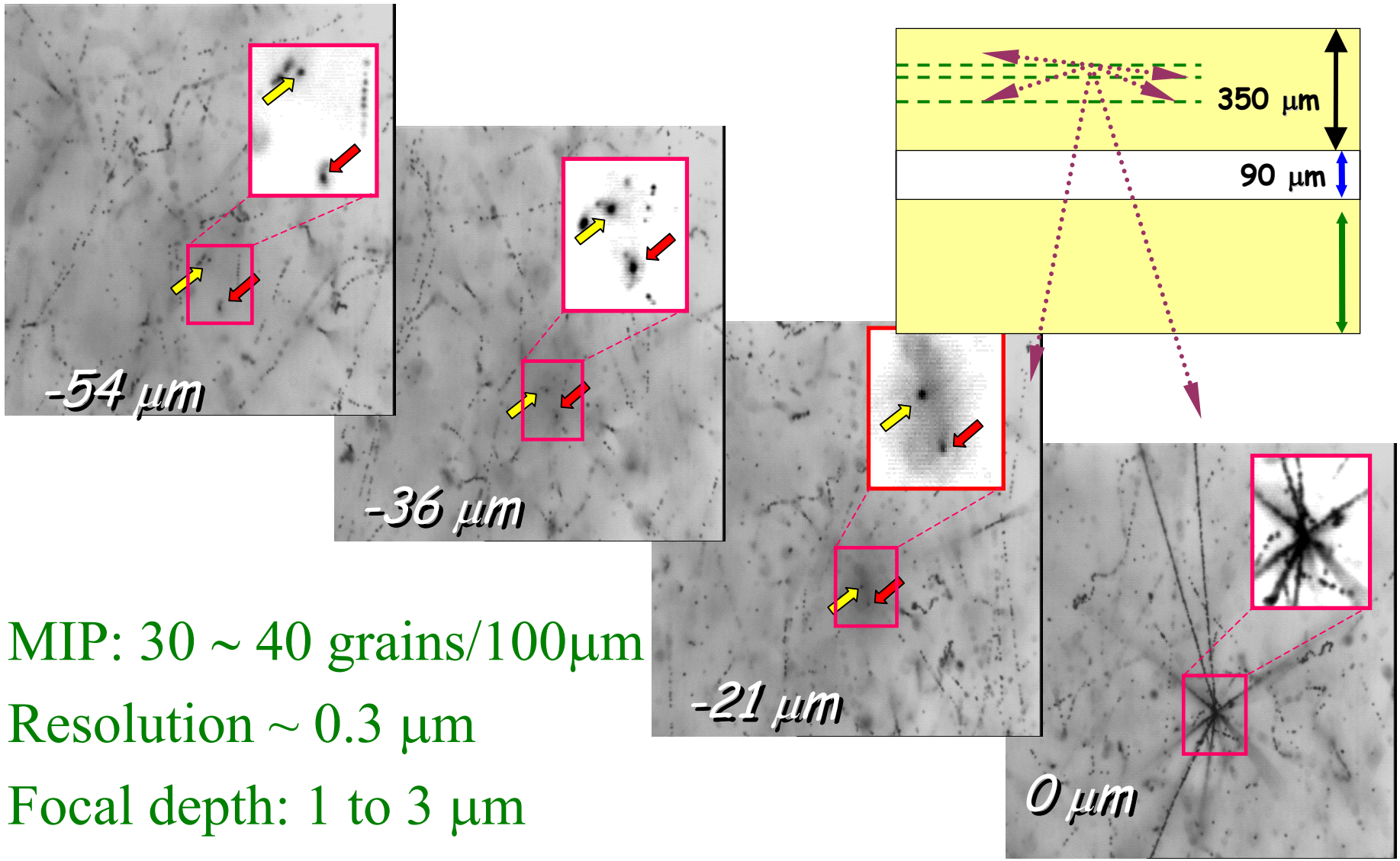
## Calorimeter

$\Delta E/E = 32\ \%/\sqrt{E}$ (hadrons)

$= 14\ \%/\sqrt{E}$ (electrons)

$\Delta\theta_h = 60$ mrad @ 10 GeV

# CHORUS emulsion



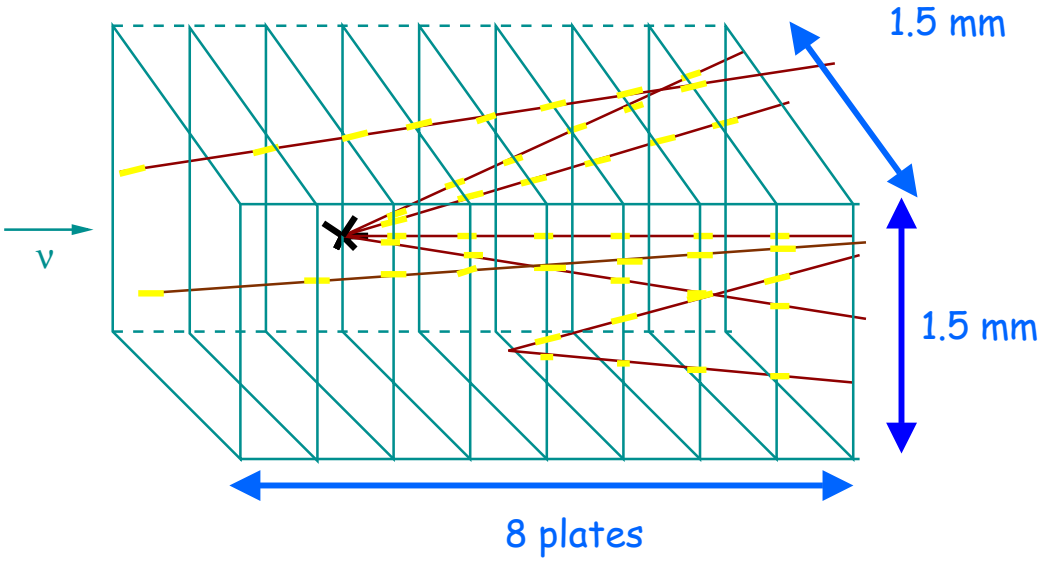

MIP: 30 ~ 40 grains/100μm

Resolution ~ 0.3 μm

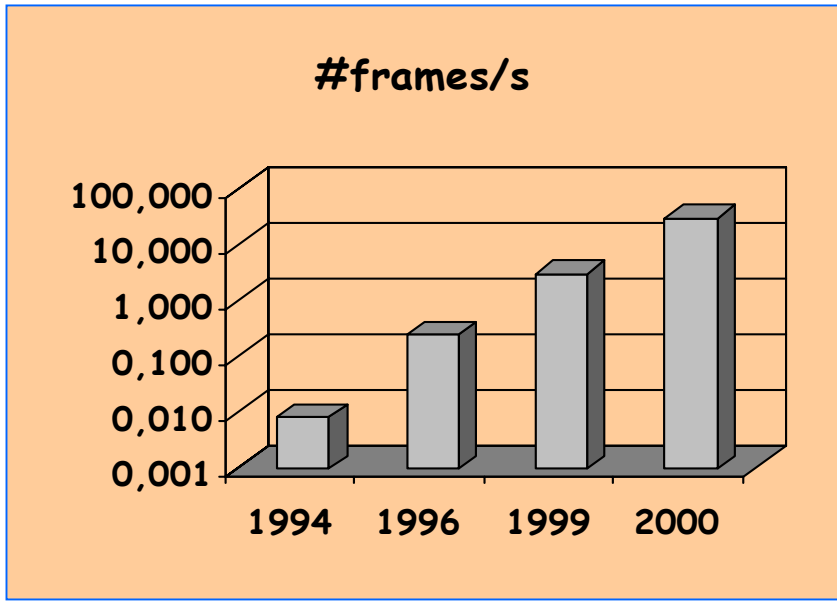
Focal depth: 1 to 3 μm

*S. Aoki et., Nucl. Instr. Meth. A 447 (2000) 361*

# CHORUS Phase II



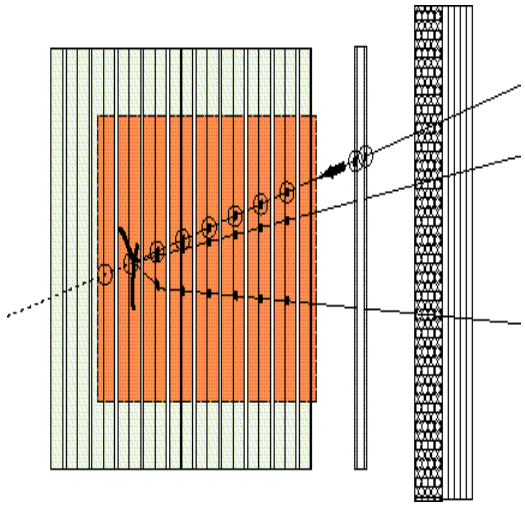

**scanning speed**

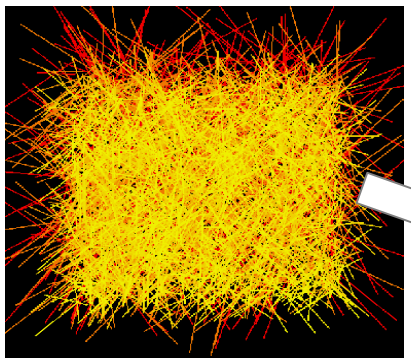



**All tracks ( $\theta$ <400mrad) in the scanning volume (1.5X1.5X6.3mm$^3$) are recorded at 11 min./event**

# Emulsion data acquisition

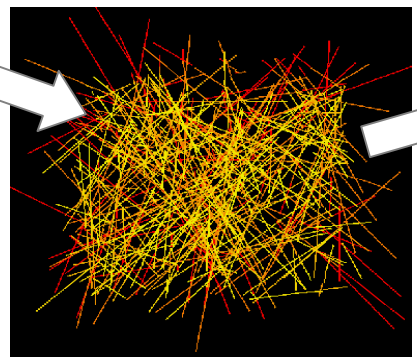
- All track segments ($\theta < 0.4$ rad)
- Fiducial volume: 1.5 x 1.5 $mm^2$ x 8 plates
- Offline analysis of emulsion data

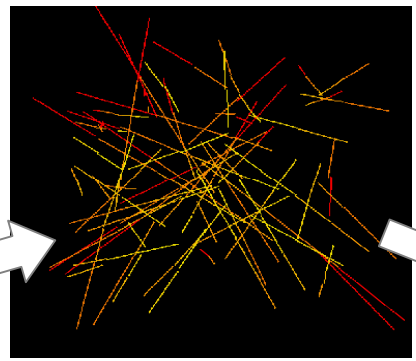




Track segments from 8 plates overlapped

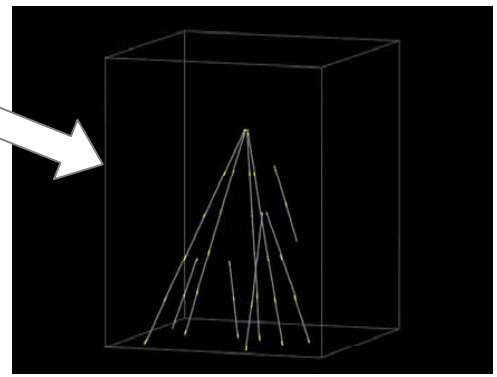
At least 2-segment connected tracks





Eliminate passing-through tracks

Reconstruct full vertex topology



# Selection criteria

- At least one among the charm daughter particles and the muon tracks should be reconstructed by the tracker systems
- Tracks with big impact parameter with respect to vertex point → visual inspection for decay confirmation

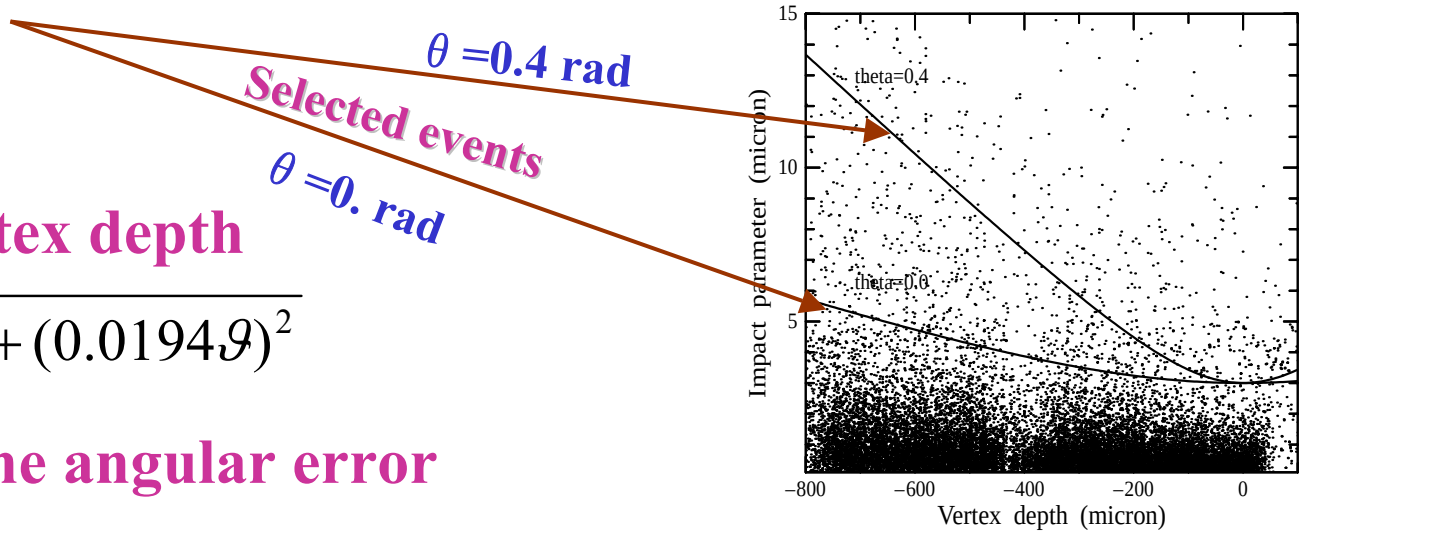
$$IP > \sqrt{3.0^2 + (2\sigma dz)^2}\ \mu m$$

$dz$ = vertex depth

$$\sigma = \sqrt{(0.0305)^2 + (0.0194\vartheta)^2}$$

parameterize the angular error

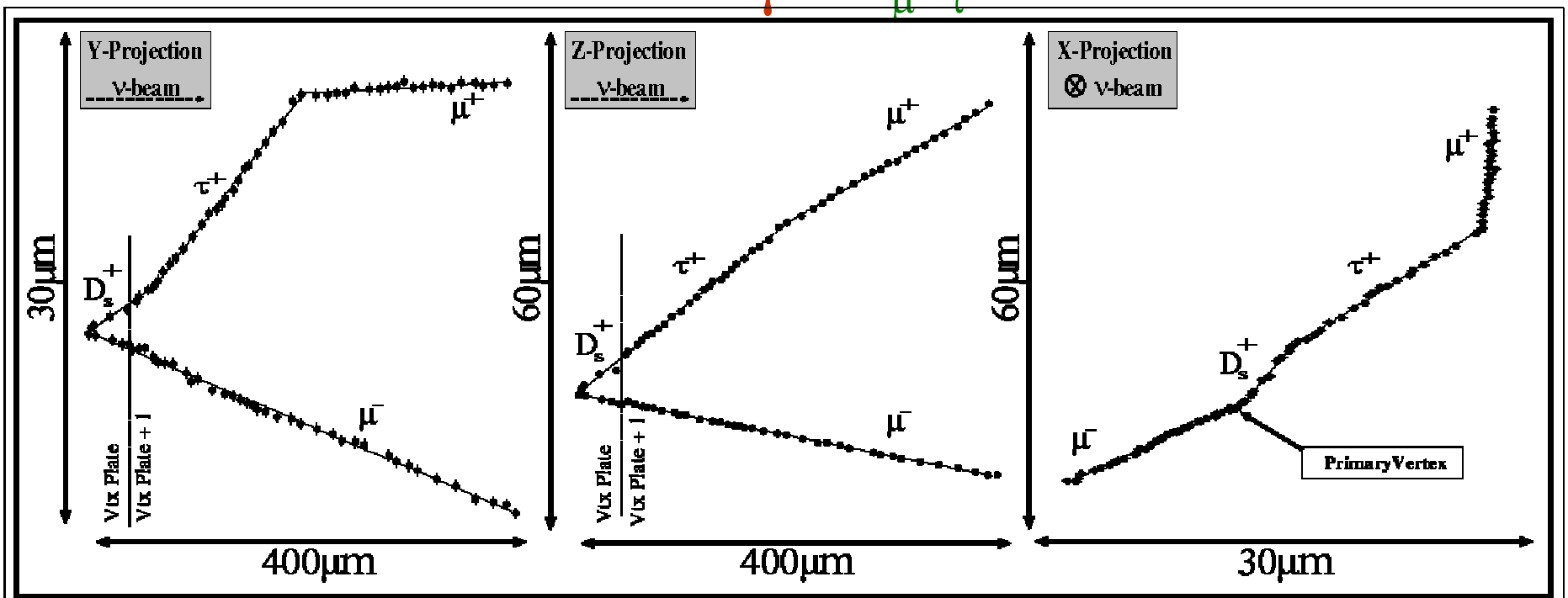
impact parameter vs. vertex depth



# Diffractive $D_s$ production

*Phys. Lett. B 435 (1998) 458, CHORUS Coll.*

$$\nu_\mu N \rightarrow D_s^{*} \mu^- N'$$
$$\hookrightarrow D_s^{+} \gamma$$
$$\hookrightarrow \tau^{+} \nu_\tau$$
$$\hookrightarrow \mu^{+} \nu_\mu \nu_\tau$$



# $D^0$ production rate

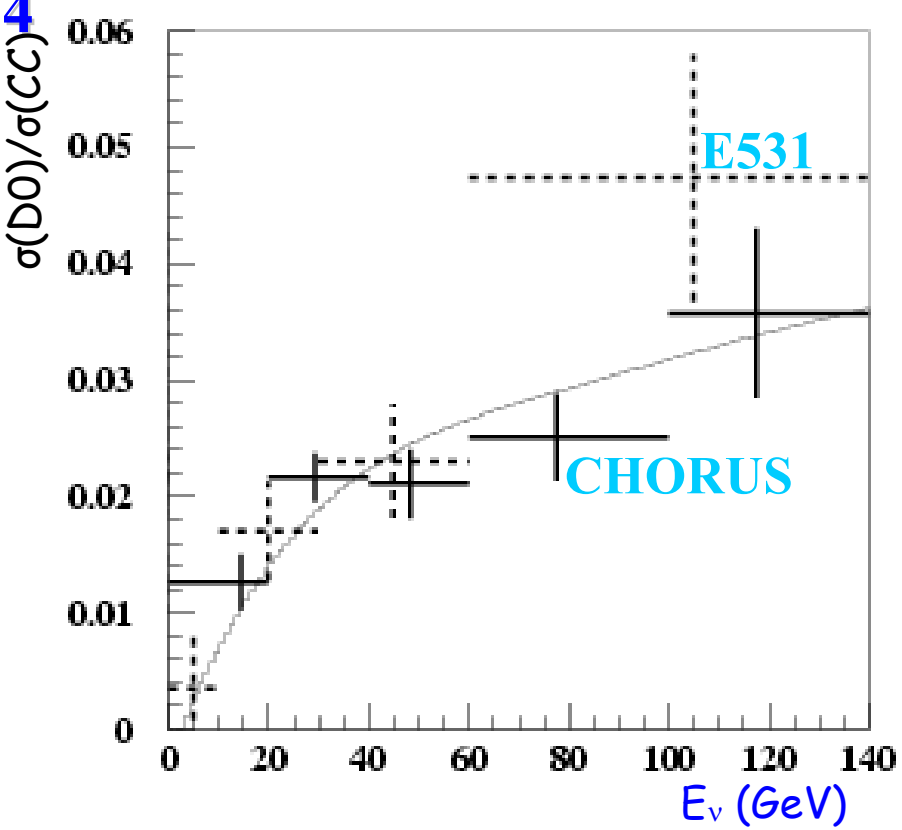
*Phys. Lett. B 527 (2002) 173, CHORUS Coll.*

- **25,693 $\nu_\mu$ CC analyzed (~25% of the full statistics)**
- **851 (3.3%) events selected for visual inspection**
- **Confirmed $D^0$ sample: 226 V2, 57 V4**

**$D^0 \rightarrow V4 / D^0 \rightarrow V2 = 0.231 \pm 0.04$**

$$\frac{\sigma_{D^0}}{\sigma_{CC}} \times BR(D^0 \rightarrow V_2 + V_4) =$$

$$1.99 \pm 0.13(\text{stat}) \pm 0.17(\text{syst})\%$$



# Fully neutral $D^0$ decay mode: preliminary

- No measurement so far, 5% value by comparison with charged modes
- Essential to extract the $D^0$ production cross section
- Essential to get the correct muonic branching fraction and hence the inclusive charm production cross-section from dimuon data

$$f_0 = 1 - f_4\left(1 + \frac{f_2}{f_4} + \frac{f_6}{f_4}\right) = 24.6 \pm 5.6\%$$ (systematic to be evaluated)

Ingredients:

$f_4 = 13.38 \pm 0.58$ from $\Gamma_4 / \Gamma_{tot}$ PDG

$\frac{f_4}{f_2} = 21.6 \pm 1.6\%$

$\frac{f_6}{f_4} = 1.3 \pm 0.7\%$

} CHORUS updated result

new measurement!

$$f_6 = (1.7 \pm 0.9) \times 10^{-3}$$

$$\frac{\sigma_{D^0}}{\sigma_{CC}} = 2.43 \pm 0.18(\text{stat})\%$$

# $\Lambda_c$ production rate

## Statistical approach using flight length distribution

- **Short flight decay: selection A**

**(40 mm < FL <400 mm):**

$\Lambda_c$ enriched sample

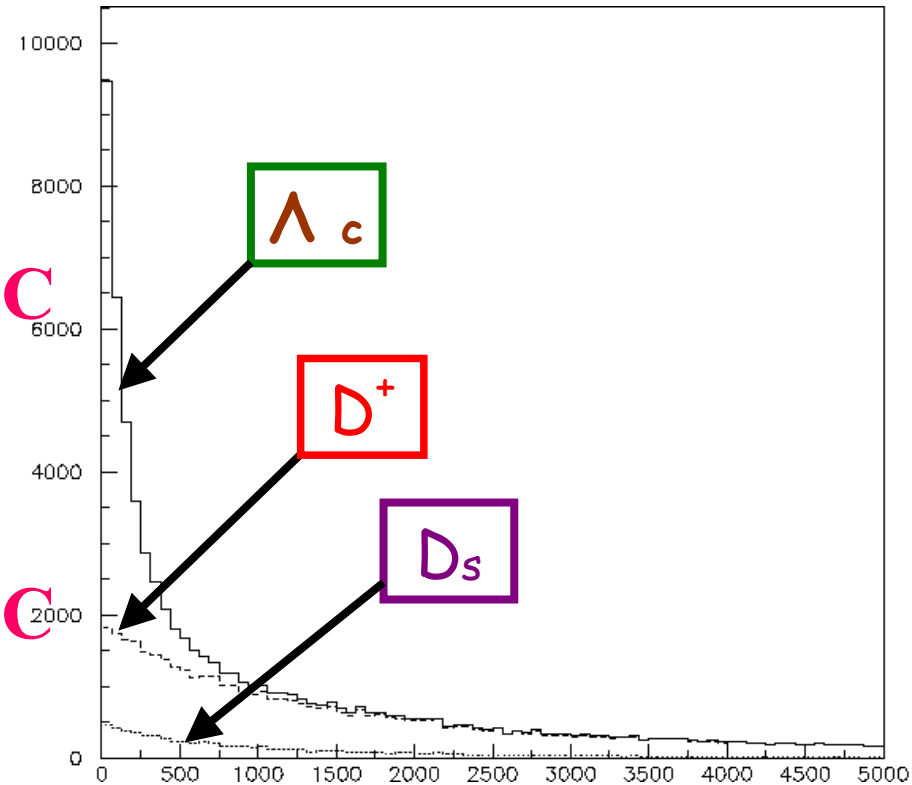
**128 candidates out of 50,414 CC**

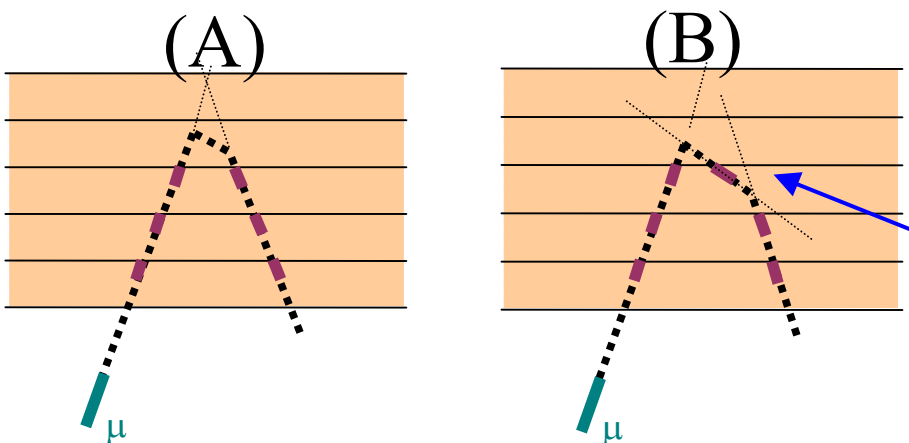
- **Long flight decay: selection B**

**(400 mm < FL < 2400 mm):**

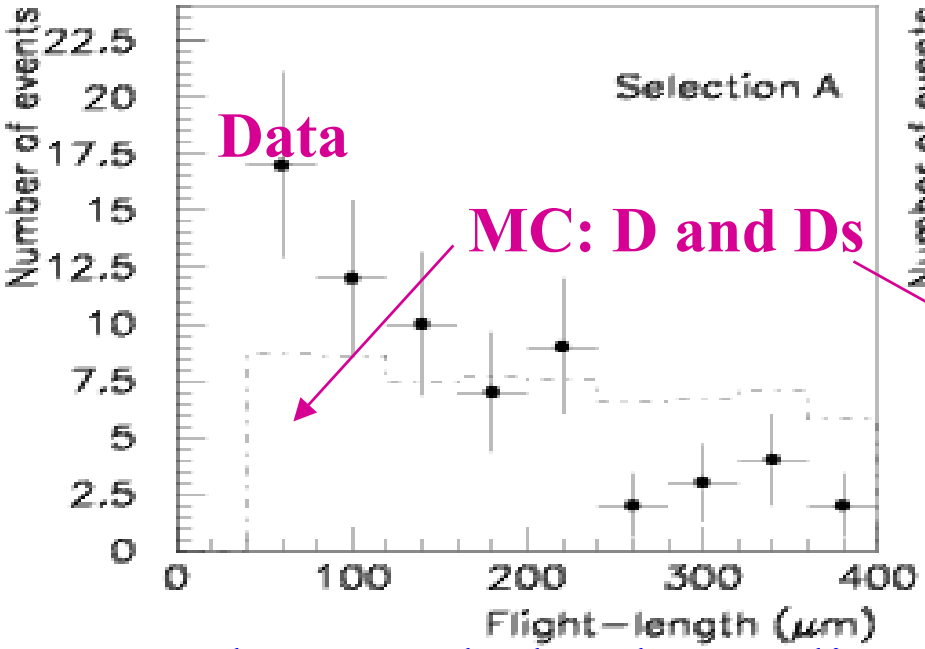
$D^+$, $D_s$ dominated sample

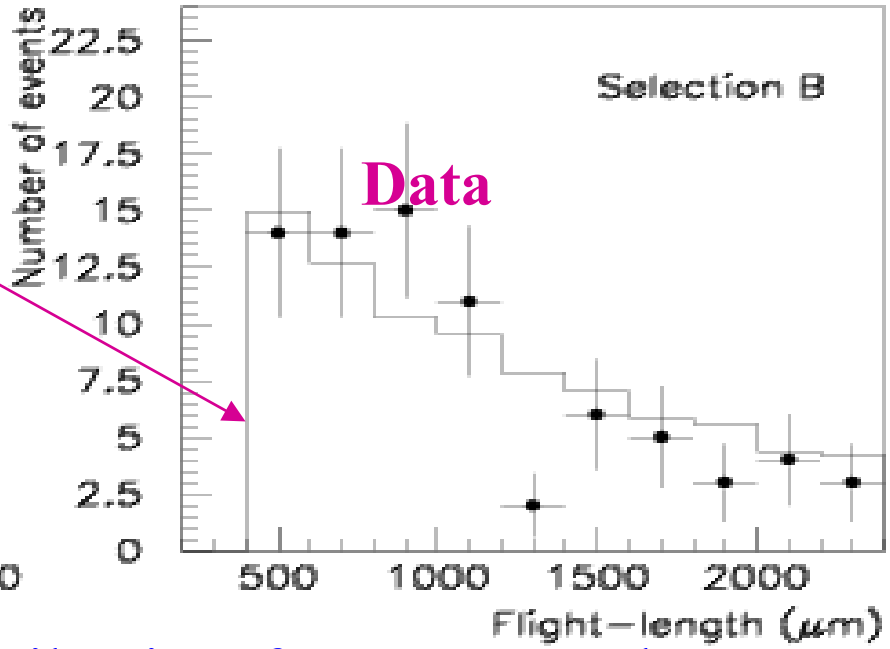
**210 candidates out of 56,761 CC**



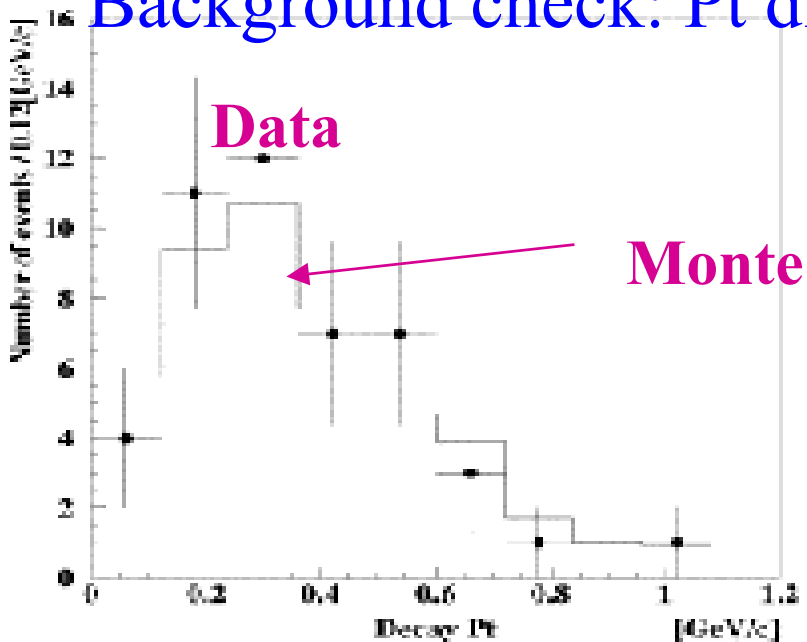



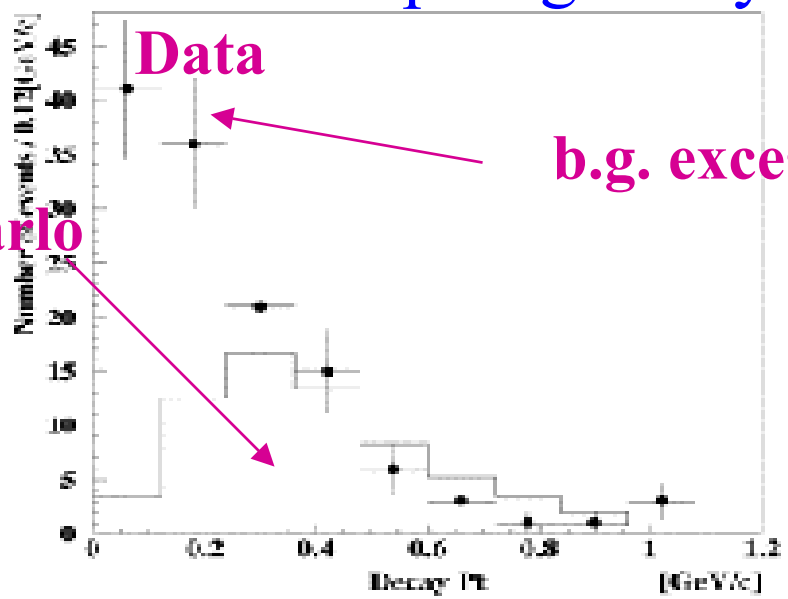
# Evidence for Λc production: 3-prong decays (background free)




# Background check: Pt distribution for 1-prong decays



# $\Lambda_c$ production rate

**Combining short (A) and long (B: only 3-prong) decay searches and correcting for efficiencies and background: 3 equations and 3 unknowns**

- **D+Ds = 1118 ±116(stat)**
- **$\Lambda_c$ = 861 ± 198 (stat.) ± 98 (syst.)$^{+140}_{-54}$ (QE)**
- **Br($\Lambda_c \rightarrow$ 3prong) = 24 ± 7 (stat.) ± 4 (syst.)%**

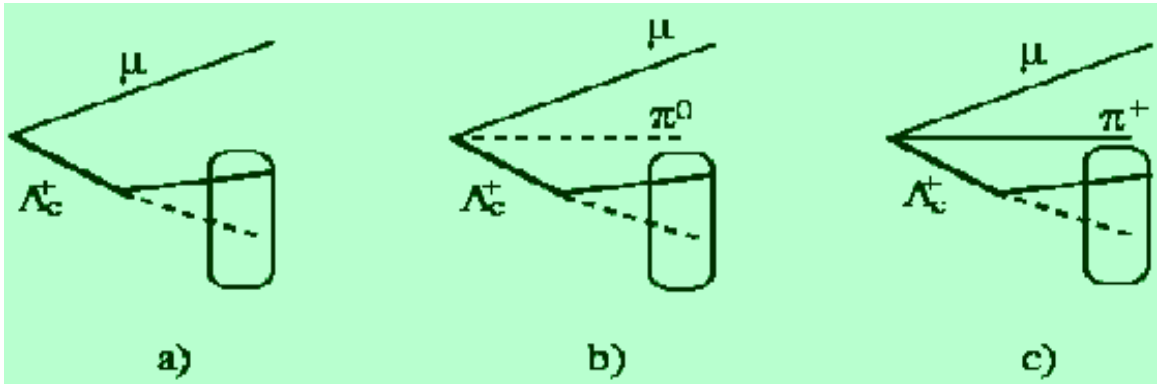
Phys. Lett. B 555 (2003) 156

$$\frac{\sigma_{\Lambda_c}}{\sigma_{CC}} = 1.54 \pm 0.35(\text{stat}) \pm 0.18(\text{syst})\ \%$$

$$\frac{\sigma_{D+D_s}}{\sigma_{CC}} = 2.00 \pm 0.21(\text{stat})\% \qquad \text{by product}$$

$$\frac{\sigma_{charm}}{\sigma_{CC}} = 6.0 \pm 0.4(\text{stat})\% \qquad \text{Preliminary: to be updated with full statistics}$$

# Quasi-elastic charm production




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

Phys.Lett.B 575 (2003) 198 (based on 46105 $\nu_\mu$ CC)

Topological and kinematical selection criteria:

- Require 2 or 3 tracks at primary vertex
- $\Phi \geq 165°$ (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

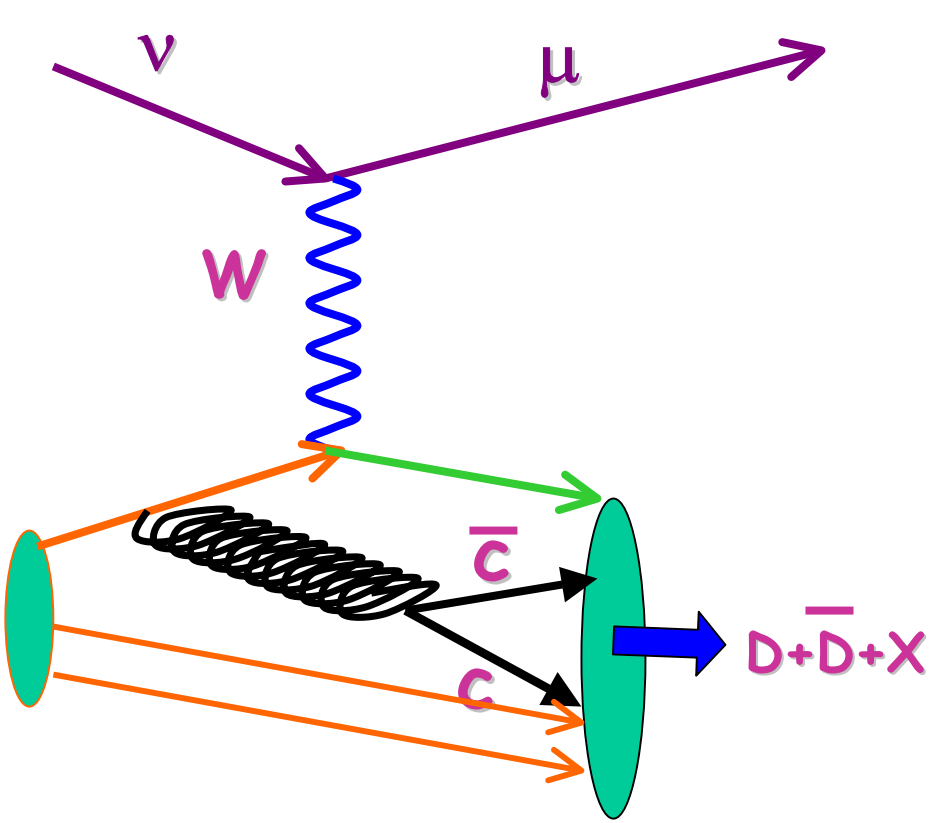
13 events with a background of 1.7 (mainly from DIS Λc)

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

QE production is about 15% of Λc production

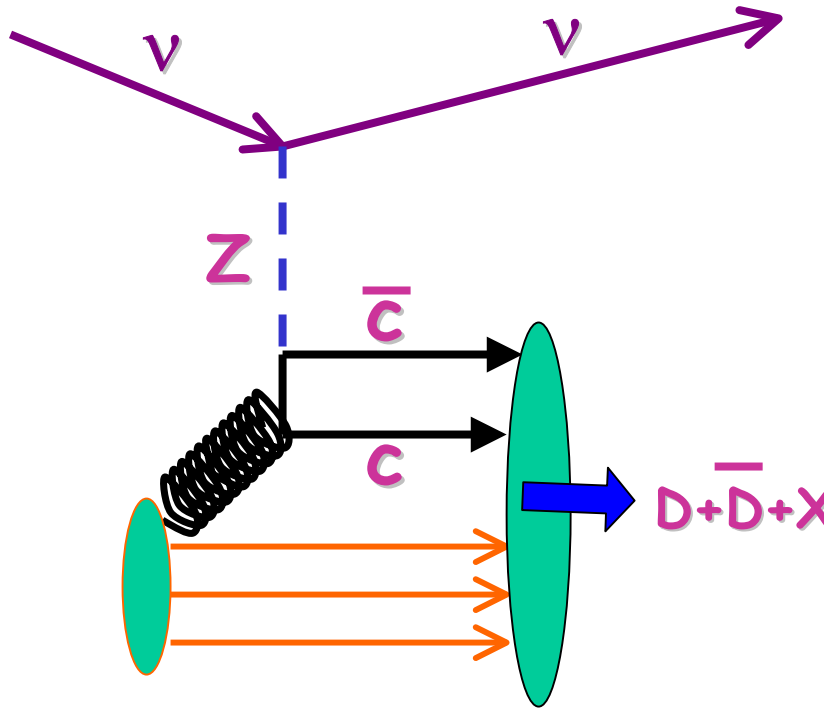
# Associated charm production

## CC




Gluon Bremsstrahlung

## NC




Z-Gluon Fusion

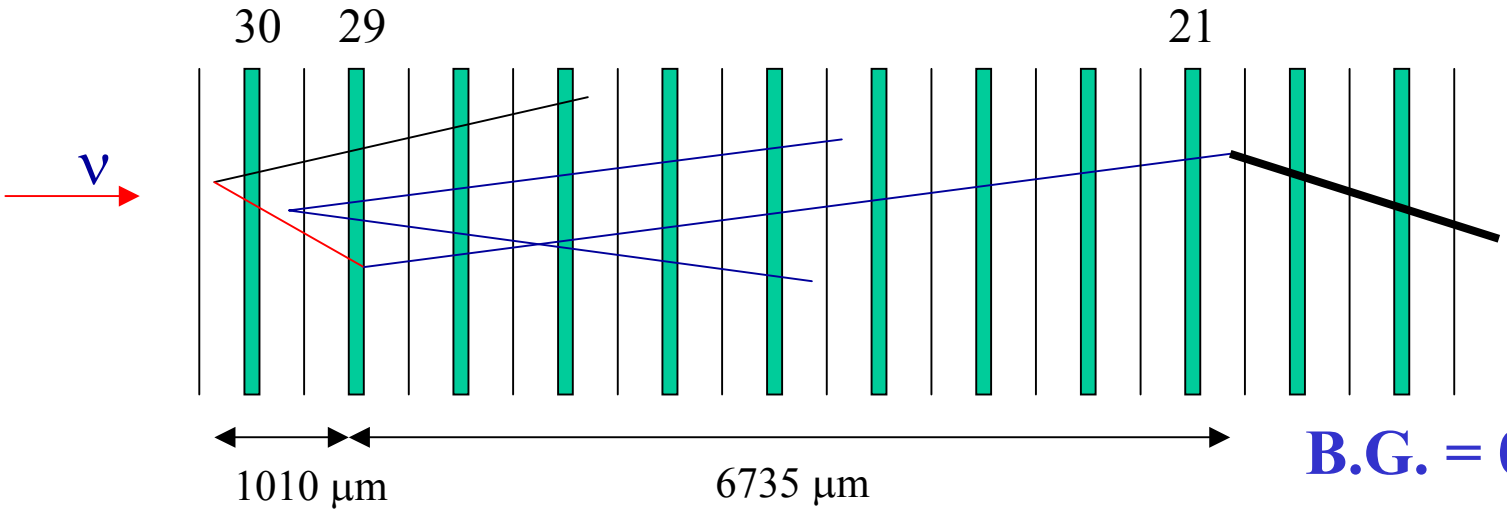
# Associated charm production in CC

- In the past this search was based on the observation of tri-muon events $\mu^-(\mu^+\mu^-)$ and same-sign di-muons:
  - Large background from $\pi$ and K decays
  - Observed rate 60 times larger than expected from theoretical calculations! *(K.Hagiwara Nucl.Phys.B 173 (1980) 487)*
- Currently a search is in progress in CHORUS
  - 1 event observed and confirmed by kinematical analysis

    (Phys. Lett B 539 (2002) 188, CHORUS coll.)
  - A new analysis with a larger statistics is in progress. The discrepancy between data and theoretical predictions will be clarified soon.

# First observation in CC

## Phys. Lett B 539 (2002) 188, CHORUS Coll.




$N_s = 2$
$N_h = 6$

**B.G. = 0.04±0.01**

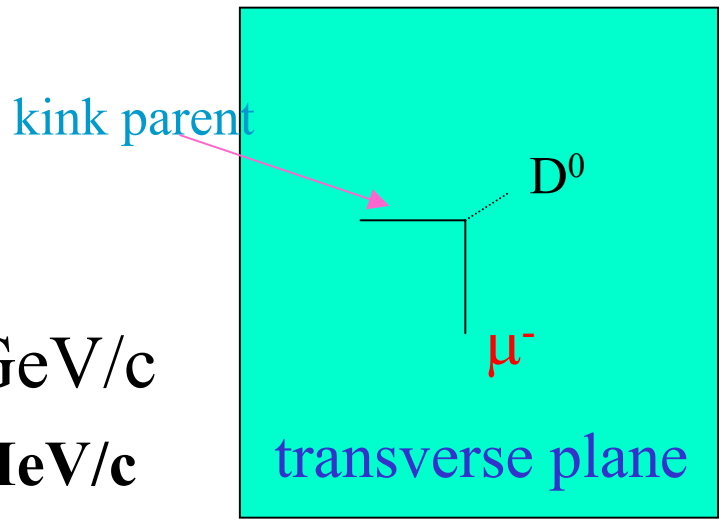
$D^0$ f.l. = 340 μm

1st vertex

$\theta_{kink}$ = 420 mrad
f.l. = 1010 μm

2ry vertex

$\theta_2$ = 310 mrad
f.l. = 7560 μm




$p\beta = 500^{+180}_{-110}$ MeV/c

dE/dx → proton

P = 0.78 GeV/c

$P_\perp$ > **330 MeV/c**

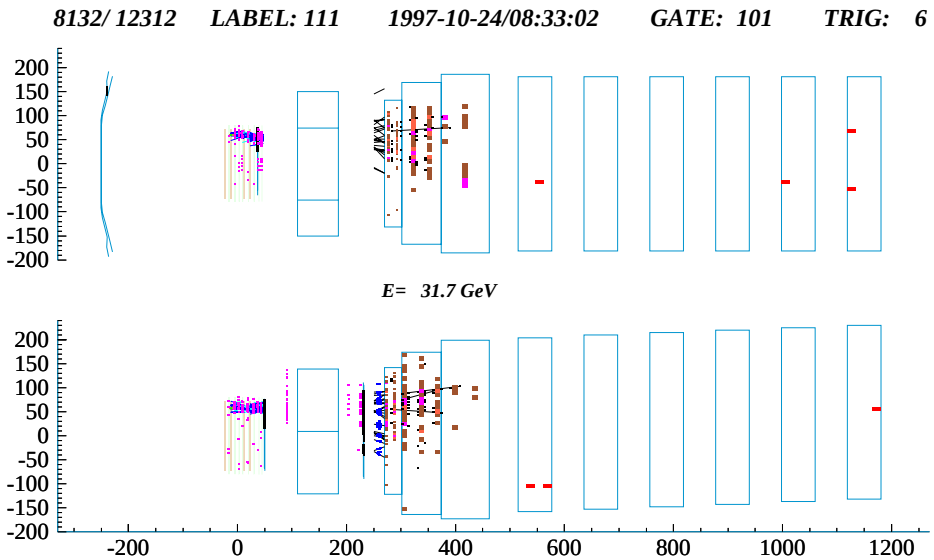
# Associated charm production in NC

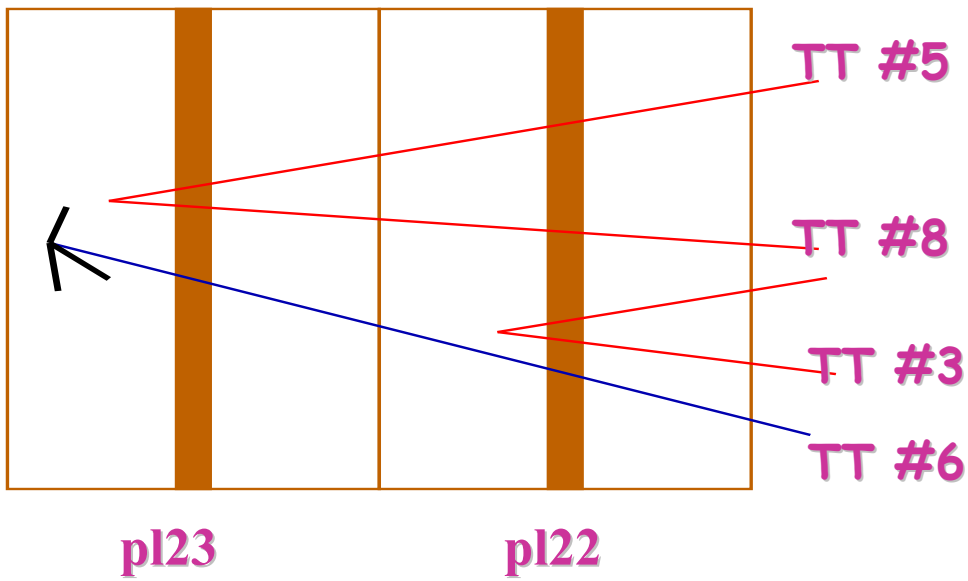
- Neutral-current interactions (g-brem. + Z-g fusion)
  - In the past only one event observed in the E531 emulsion
    - Production rate $1.3^{+3.1}_{-1.1} \times 10^{-3}$ normalised to CC
  - Indirect search performed by NuTeV

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

    - Production rate $(2.6 \pm 1.6) \times 10^{-3}$ normalised to CC at 154 GeV
    - $m_c = (1.40^{+0.83}_{-0.36} \pm 0.26)$ GeV, in agreement with other measurements
  - Currently a search for this process is in progress in CHORUS
    - Several candidates have been found and the cross-section measurement will be finalised by the end of this year.

# Event 81332312




## V2&V2 in 0mu

1ry@pl23

Ns=1, Nh=3

V2(1) @pl 23

Δθ =96.3 mrad

fl= 62.8μm

V2(2) @pl 22

fl= 976.6μm

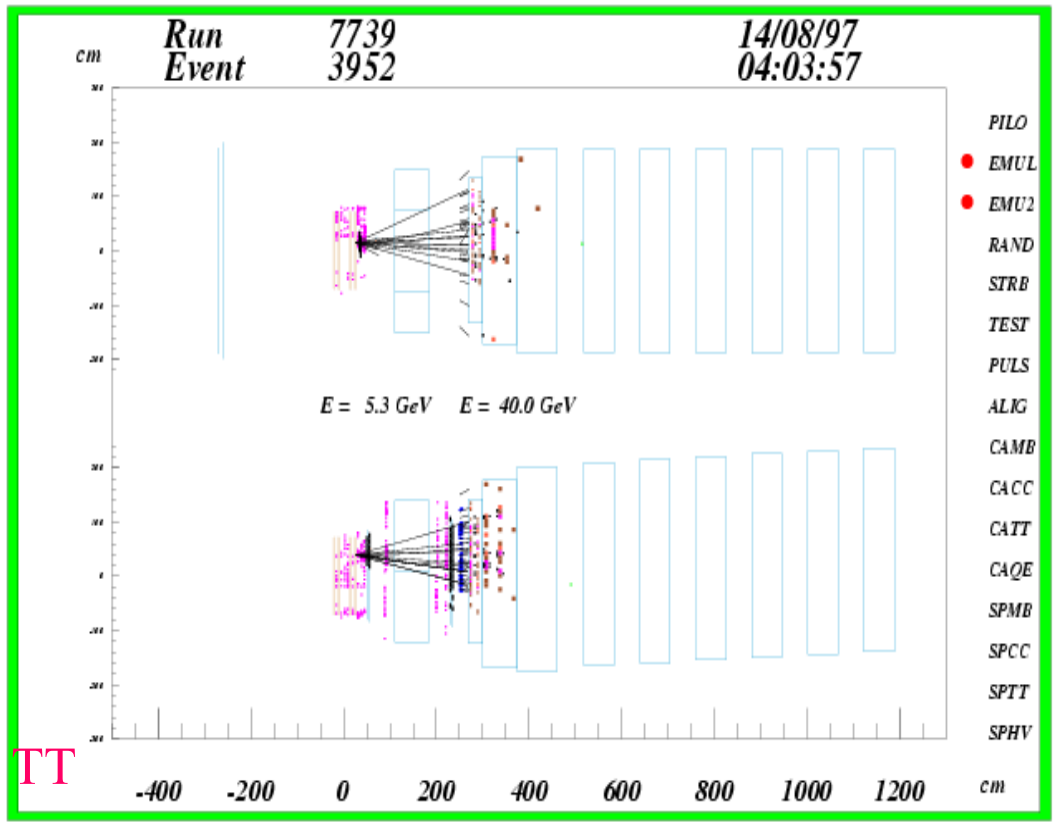
Δθ =203.4 mrad

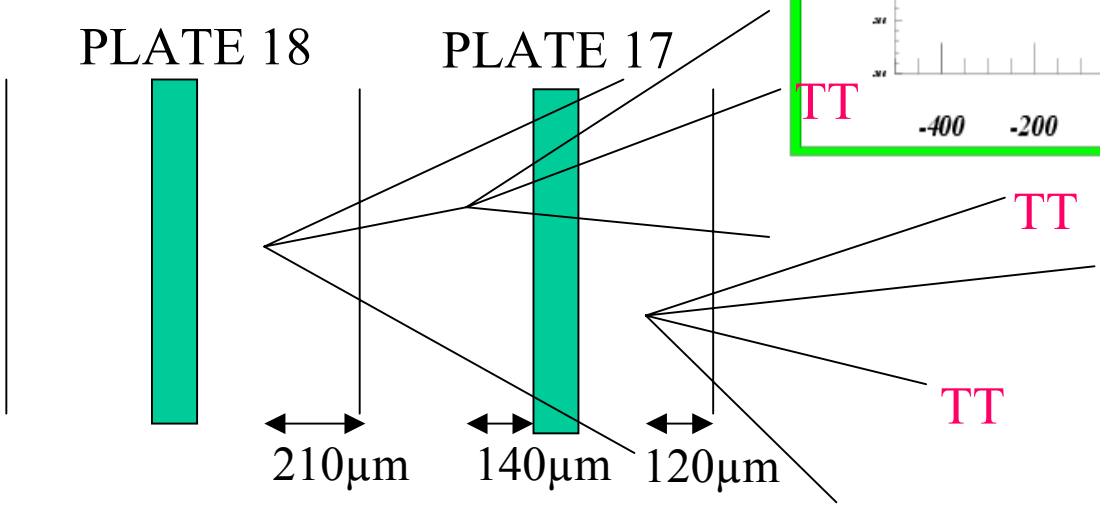
# Event 77393952

Ns = 6
Nh = 1 (gray)

4Vee @ pl 17
FL = 884 μm

C3 @ pl 17
FL = 426 μm



# Conclusions and Outlooks

- **200K events in CHORUS for Charm analysis**
- **From a sub-sample of data CHORUS has measured:**
  - Diffractive $D_s^*$ production (Phys. Lett. B 435 (1998) 458)
  - $\sigma(D^0)/\sigma(CC)$ (Phys. Lett B 527 (2002) 173)
  - CC associated charm production (Phys.Lett. B 539 (2002) 188)
  - $B_\mu$ (Phys. Lett B 548 (2002) 48): first direct measurement
  - $\sigma(\Lambda_c)/\sigma(CC)$ (Phys.Lett.B 555 (2003)156)
  - QE $\Lambda_c$ production (Phys.Lett.B 575 (2003) 198)
- **Analyses in progress:**
  - Associated charm production in CC and NC
  - D* production
  - $D^0$ decay→ all neutrals
  - Charm topological branching ratio
  - Anti-neutrino charm production