Charm Identification using Silicon Detectors in a Neutrino Experiment

M. Ellis[1], F.J. Paul Soler[2].
[1] Rutherford Appleton Laboratory.
[2] University of Glasgow and Rutherford Appleton Laboratory.

on behalf of the NOMAD-STAR group
of the NOMAD collaboration.

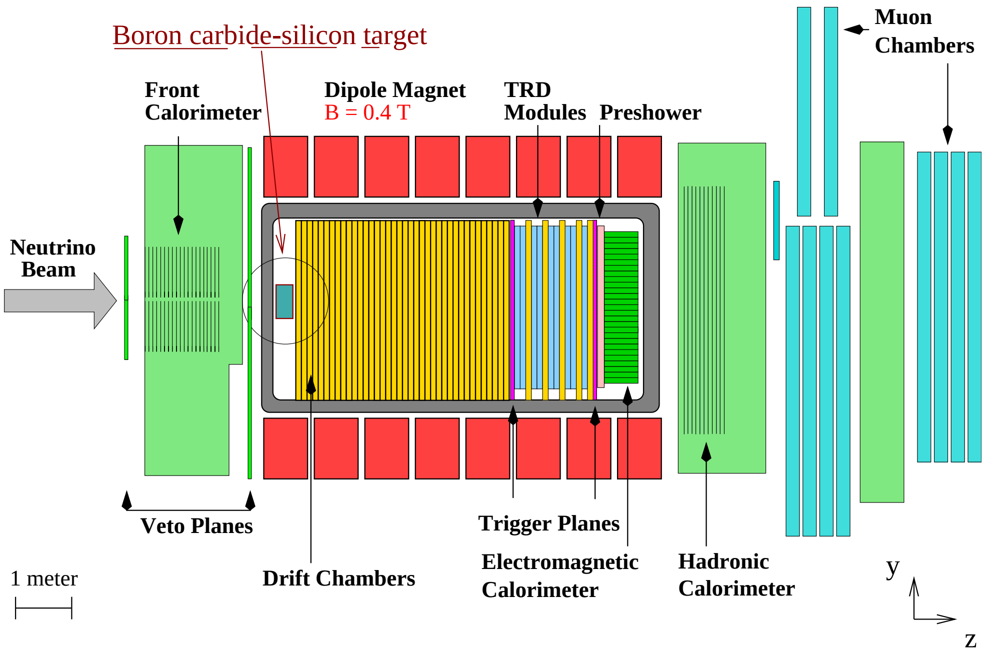
4^{th} NUFACT'02 Workshop,
Neutrino Factories based on Muon Storage Rings.

Imperial College, London.
1–6 July 2002

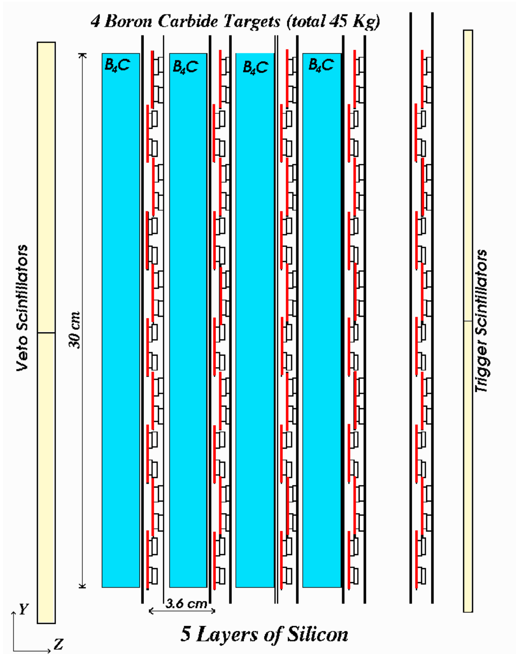
OUTLINE

- Description and motivation for NOMAD-STAR (Silicon TARget in NOMAD)
- Description of NOMAD-STAR silicon ladders
- Performance of NOMAD-STAR
- Reconstruction residuals, vertex resolution and impact parameter
- NOMAD-STAR running conditions and neutrino beam
- Search for short-lived particles
- Charm production results
- Implication charm results for neutrino factory

NOMAD-STAR



Silicon TARget - STAR



1.14 m^2 silicon area

Original Motivation:

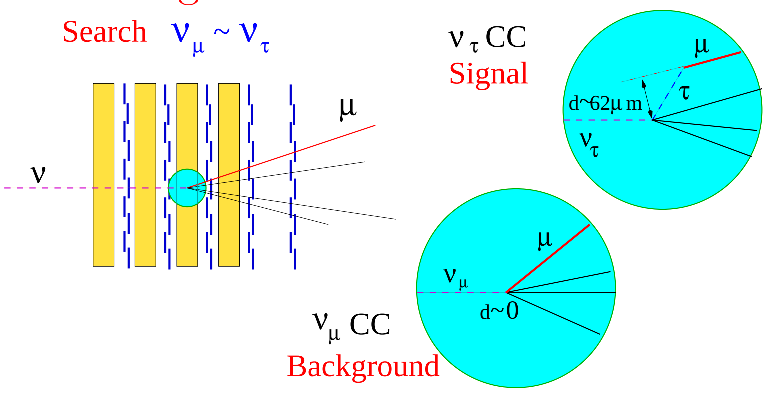
Build prototype silicon detector inside NOMAD to study capabilities

for short-baseline search of $\nu_{\mu,e} \leftrightarrow \nu_\tau$ oscillations.

$$\nu_\tau + N \longrightarrow \quad \tau^- + X$$

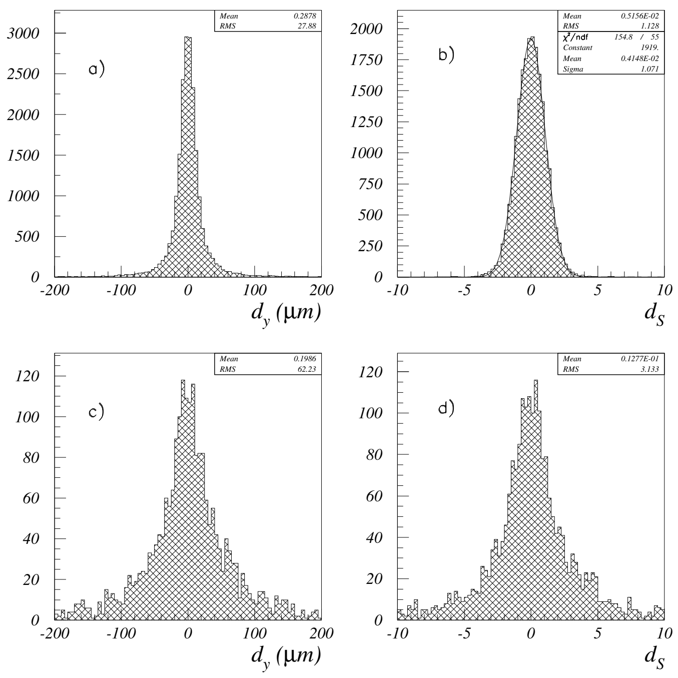
$$\begin{aligned}
\tau^- &\rightarrow \quad \mu^- \overline{\nu}_\mu \nu_\tau \\
\tau^- &\rightarrow \quad e^- \overline{\nu}_e \nu_\tau \\
\tau^- &\rightarrow \quad \pi^- \nu_\tau \\
\tau^- &\rightarrow \quad \rho^- (\pi^- \pi^0) \nu_\tau \\
\tau^- &\rightarrow \quad \pi^+ \pi^- \pi^- + n\pi^0 (n \geq 0) \nu_\tau
\end{aligned}$$

Impact parameter signature

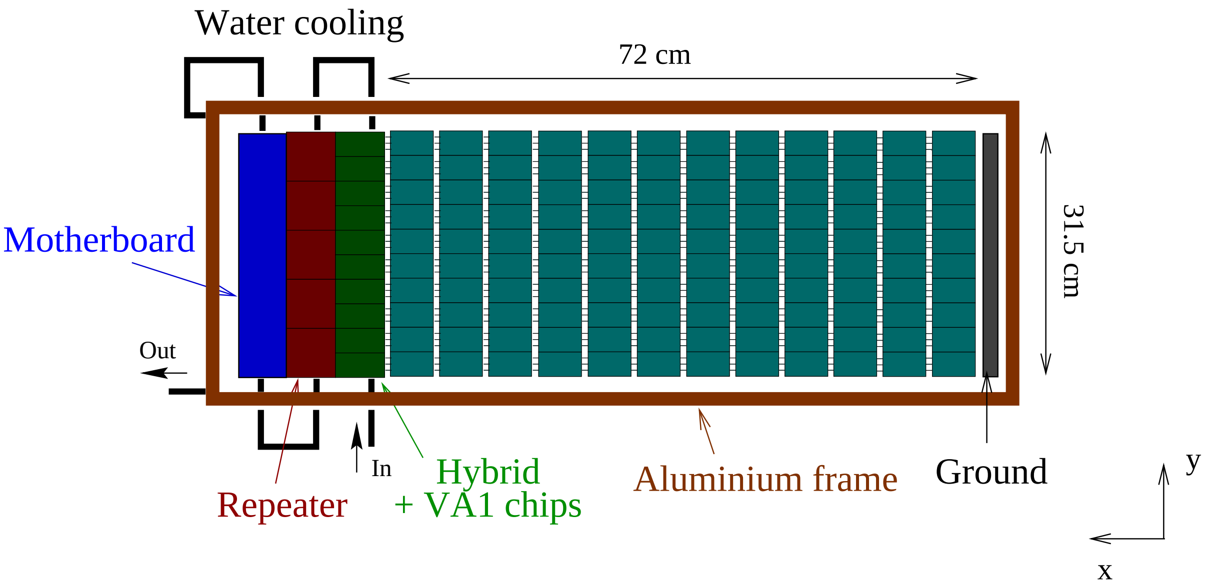


ν_μ-CC

ν_τ-CC

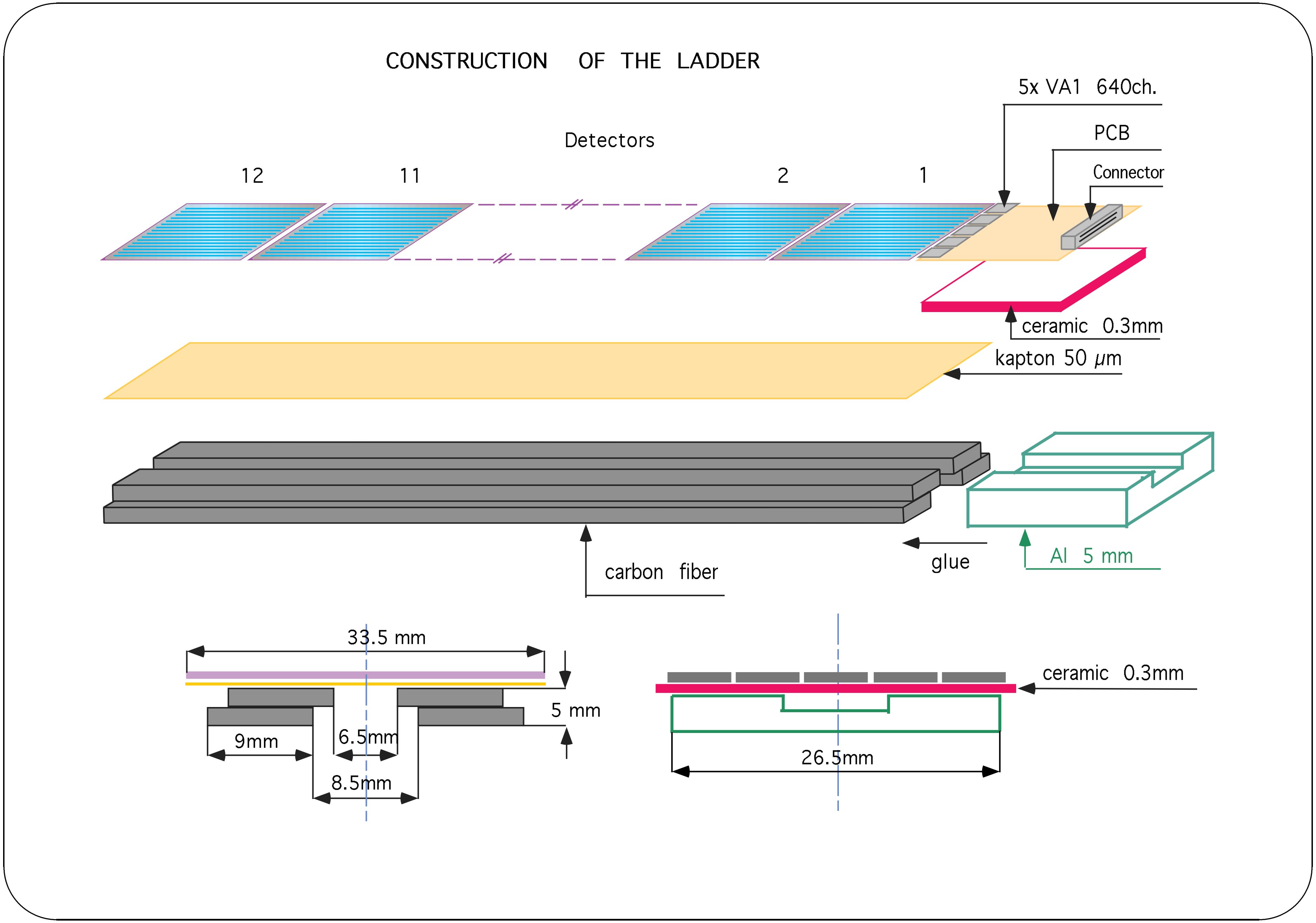


Silicon Layer

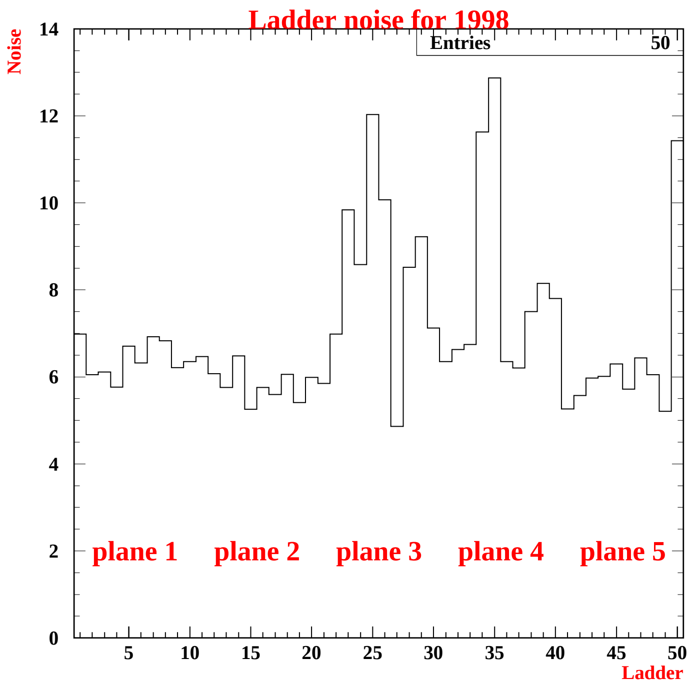


Longest ladders ever built

Hamamatsu detectors: 50 μm (25 μm) readout (floating) pitch

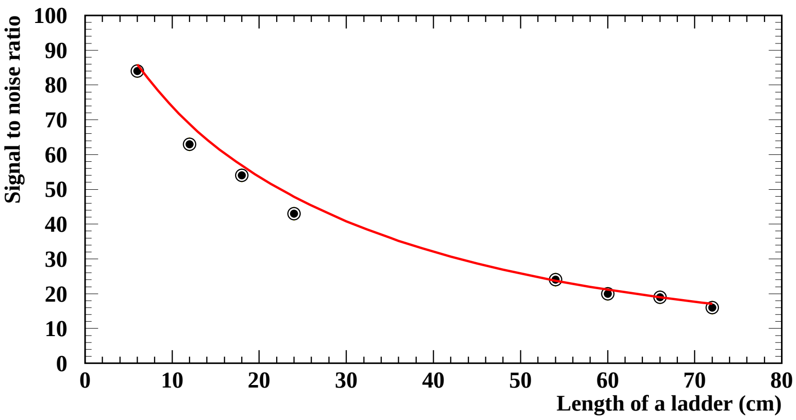

CONSTRUCTION OF THE LADDER
5x VA1 640ch.
PCB
Connector
Detectors
12
11
2
1
ceramic 0.3mm
kapton 50 μm
carbon fiber
glue
Al 5 mm
33.5 mm
5 mm
9mm
6.5mm
8.5mm
ceramic 0.3mm
26.5mm

Average Noise



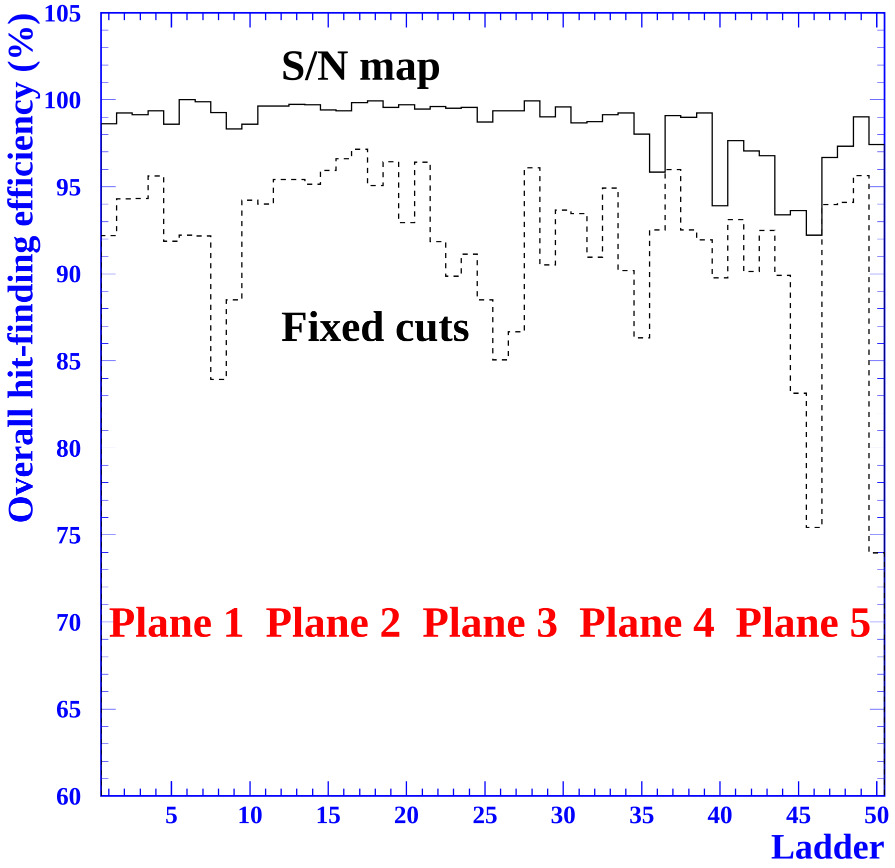
At 72 cm (12 detectors per ladder):

- **Noise ∼ 6 ADC counts (3 μs shaping time)**
- **Signal ∼ 92 ADC counts**
- **S/N = 16:1**

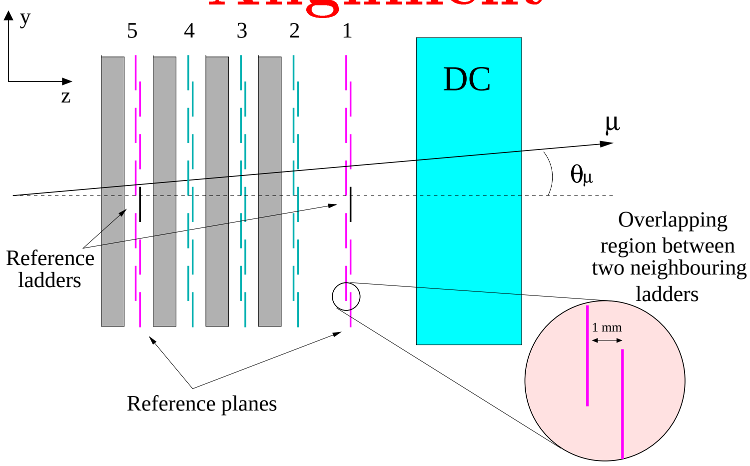


Hit Finding Efficiency

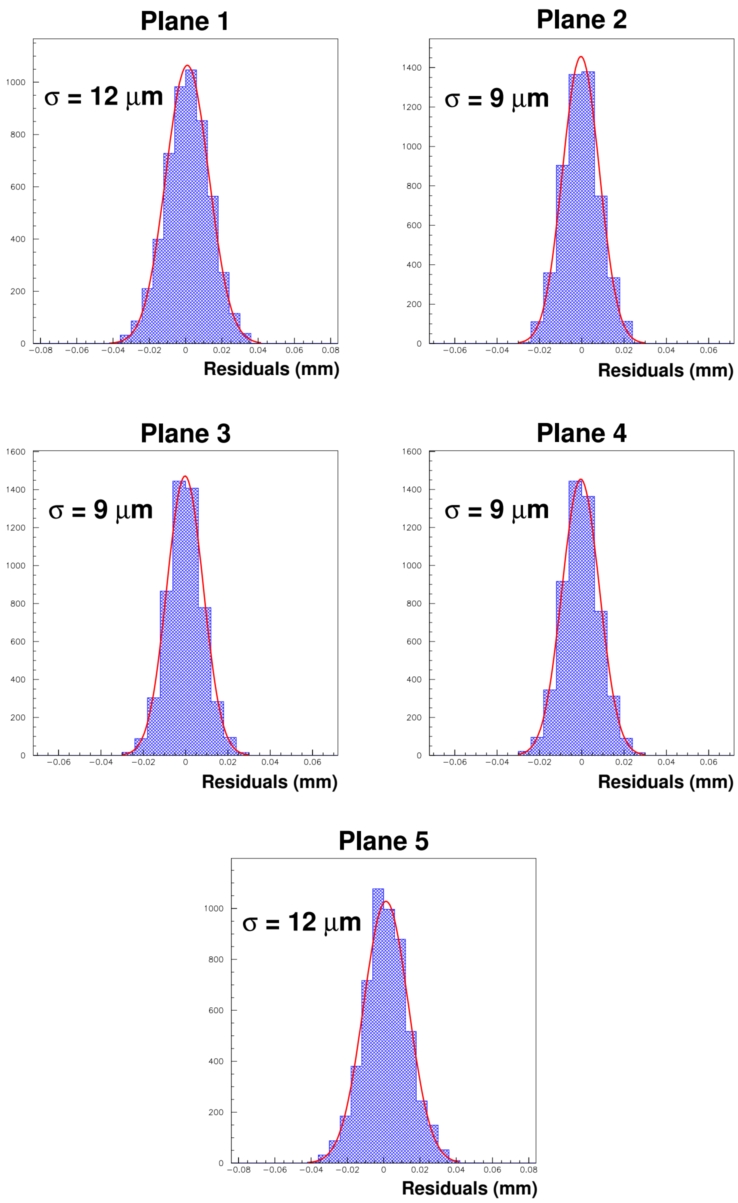
- **Optimisation of S/N seed and cluster cuts makes hit finding efficiency close to 100% for most ladders (all ladders have $\epsilon > 92\%$).**



Alignment



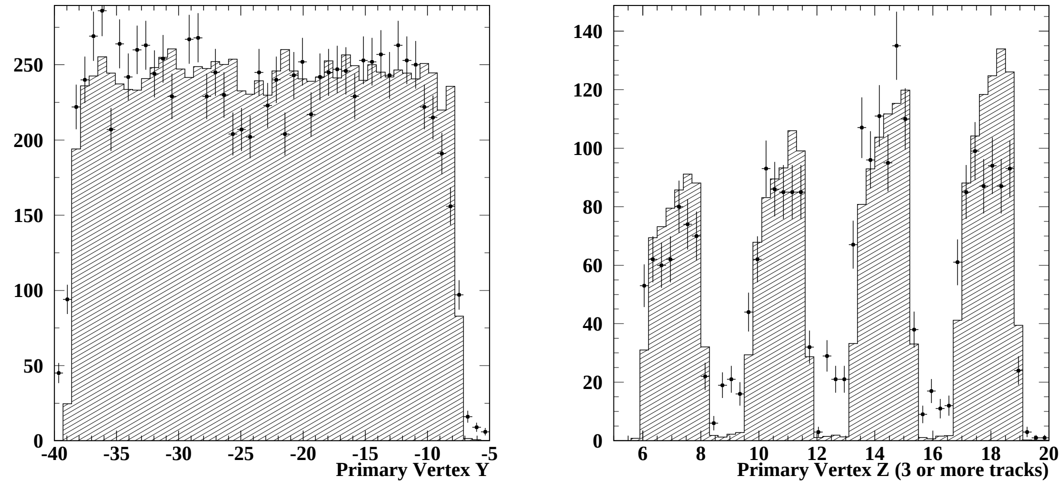
y
z
5
4
3
2
1
DC
μ
θμ
Overlapping region between two neighbouring ladders
Reference ladders
1 mm
Reference planes



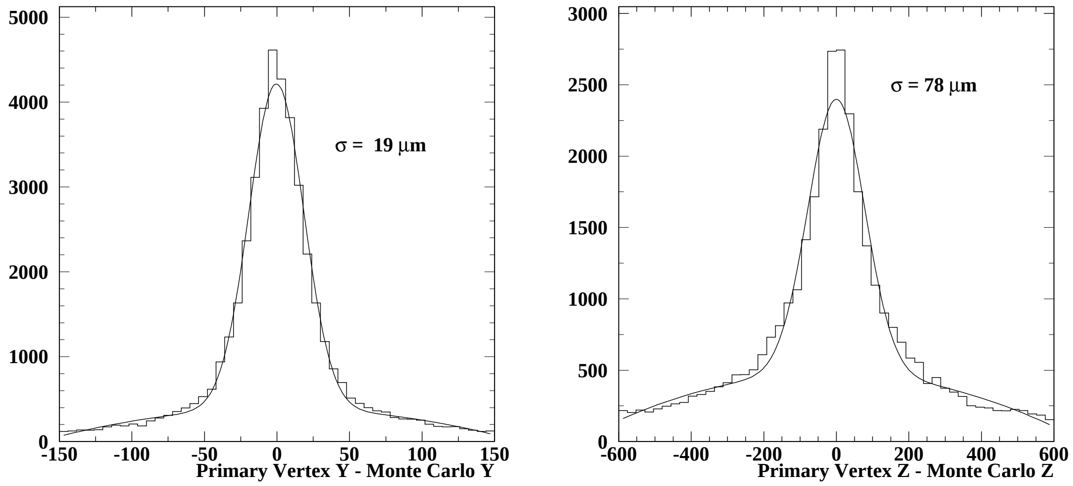
Plane 1
σ = 12 μm
Residuals (mm)
Plane 2
σ = 9 μm
Residuals (mm)
Plane 3
σ = 9 μm
Residuals (mm)
Plane 4
σ = 9 μm
Residuals (mm)
Plane 5
σ = 12 μm
Residuals (mm)

Vertex Distribution

Track and vertex fitting with a full Kalman filter in 2D (y and z). x information from NOMAD drift chambers.

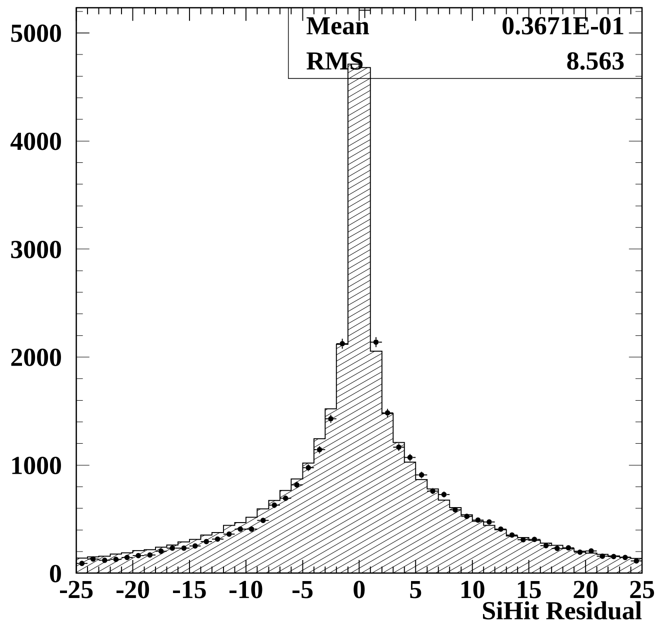


Vertex Resolution



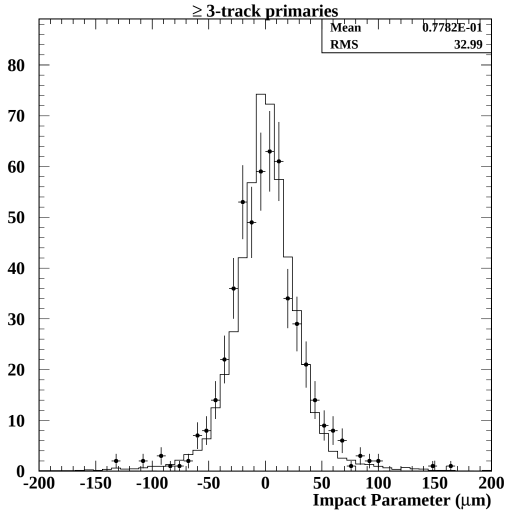
RMS(y) $\sim 19\ \mu$m RMS(z) $\sim 78\ \mu$m

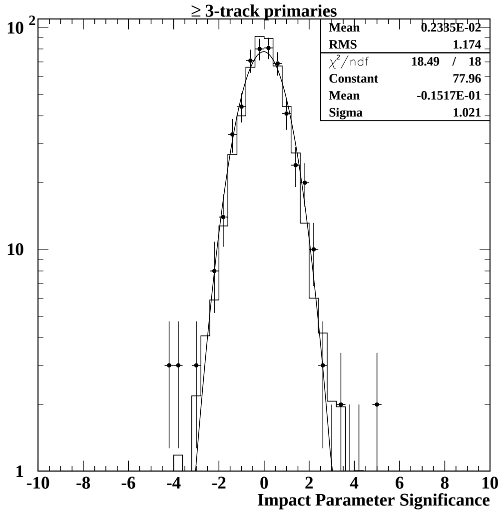
Hit Residuals



Residuals $\sim 8.6\mu m$

Impact Parameter Resolution

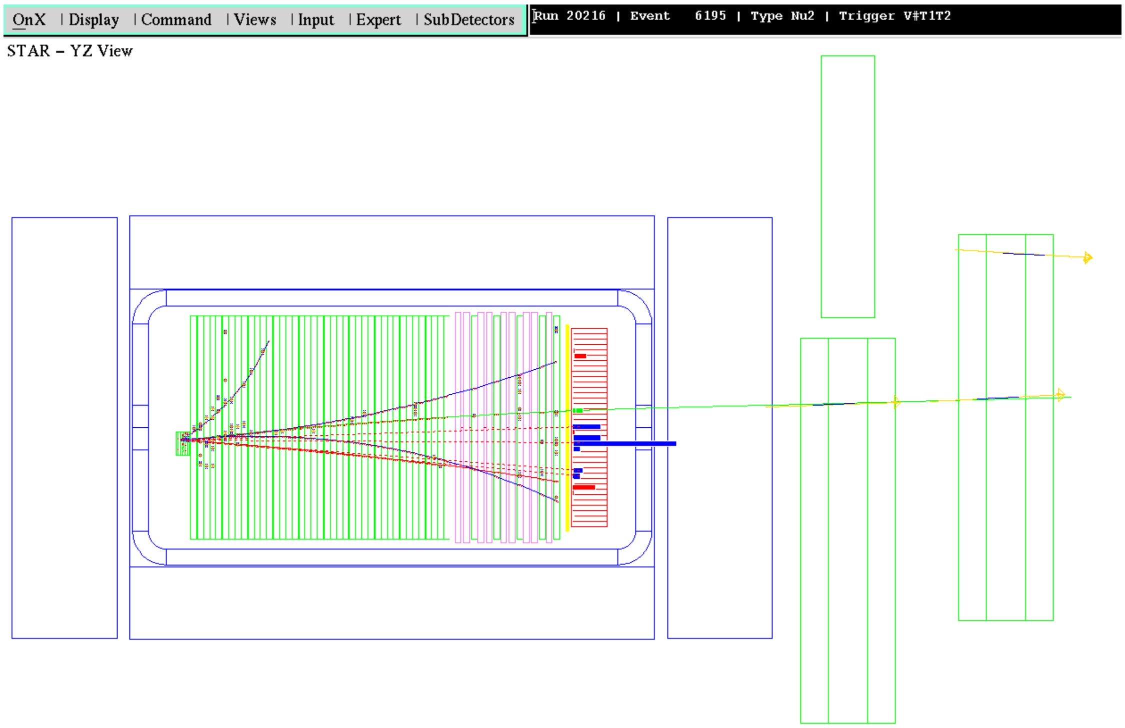


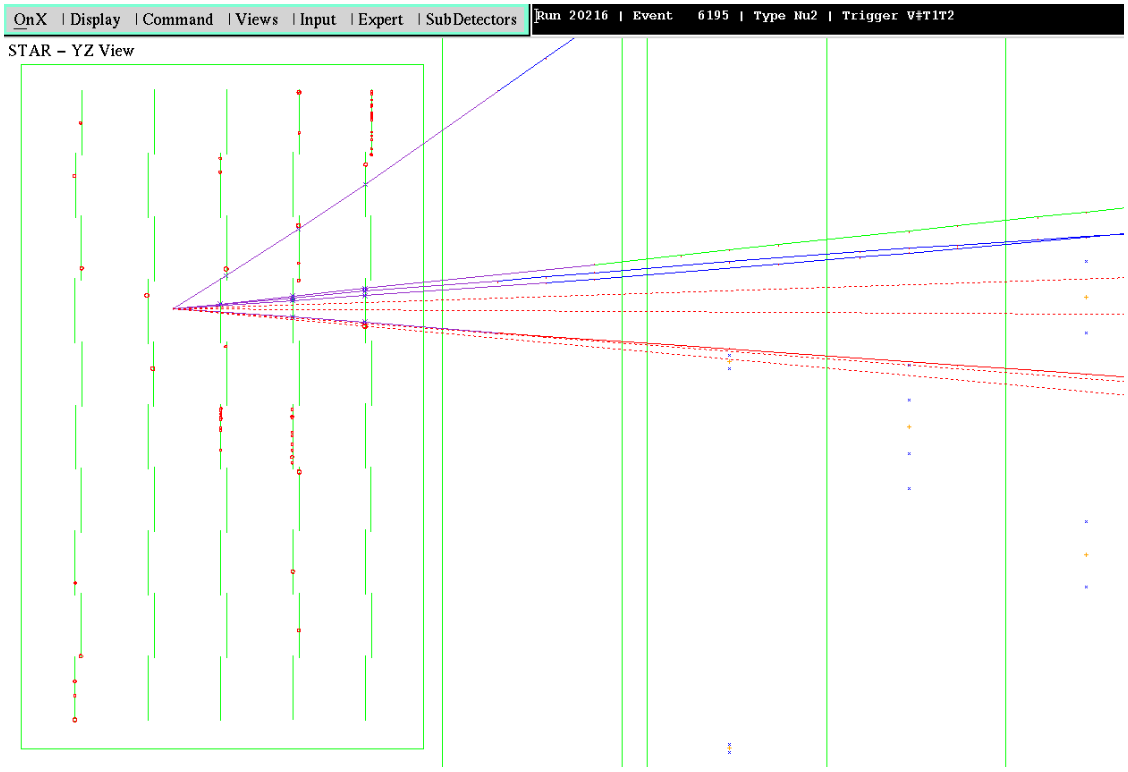


Measured Impact Parameter for ν_μ-CC $\sim 33\mu m$

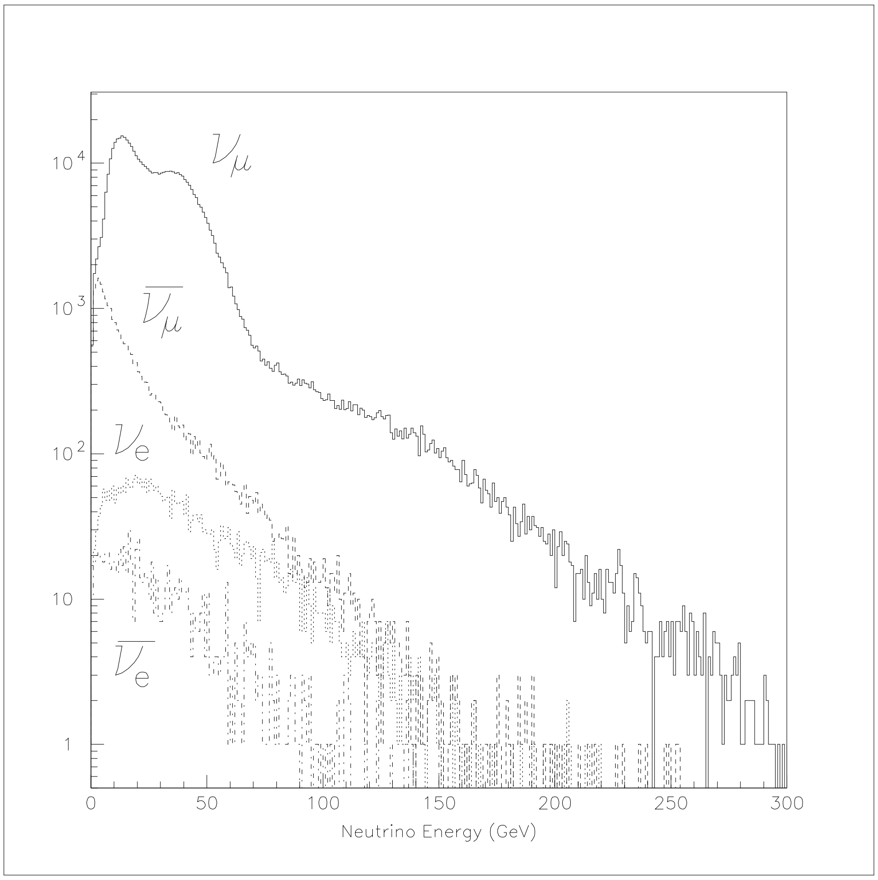
Estimated Impact Parameter for ν_τ-CC $\sim 62\mu m$

ν_μ Charged Current (CC) Event





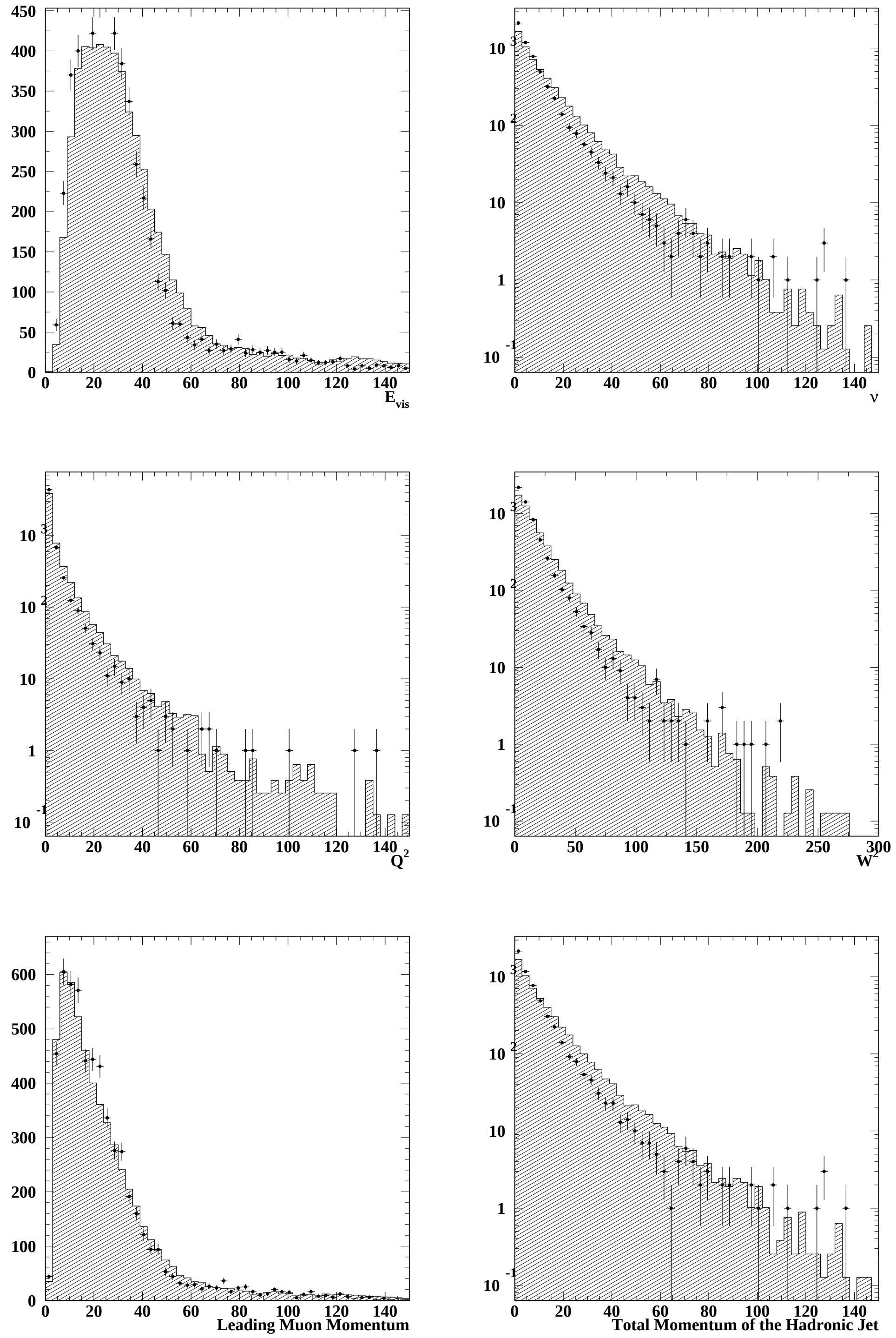
Neutrino Beam



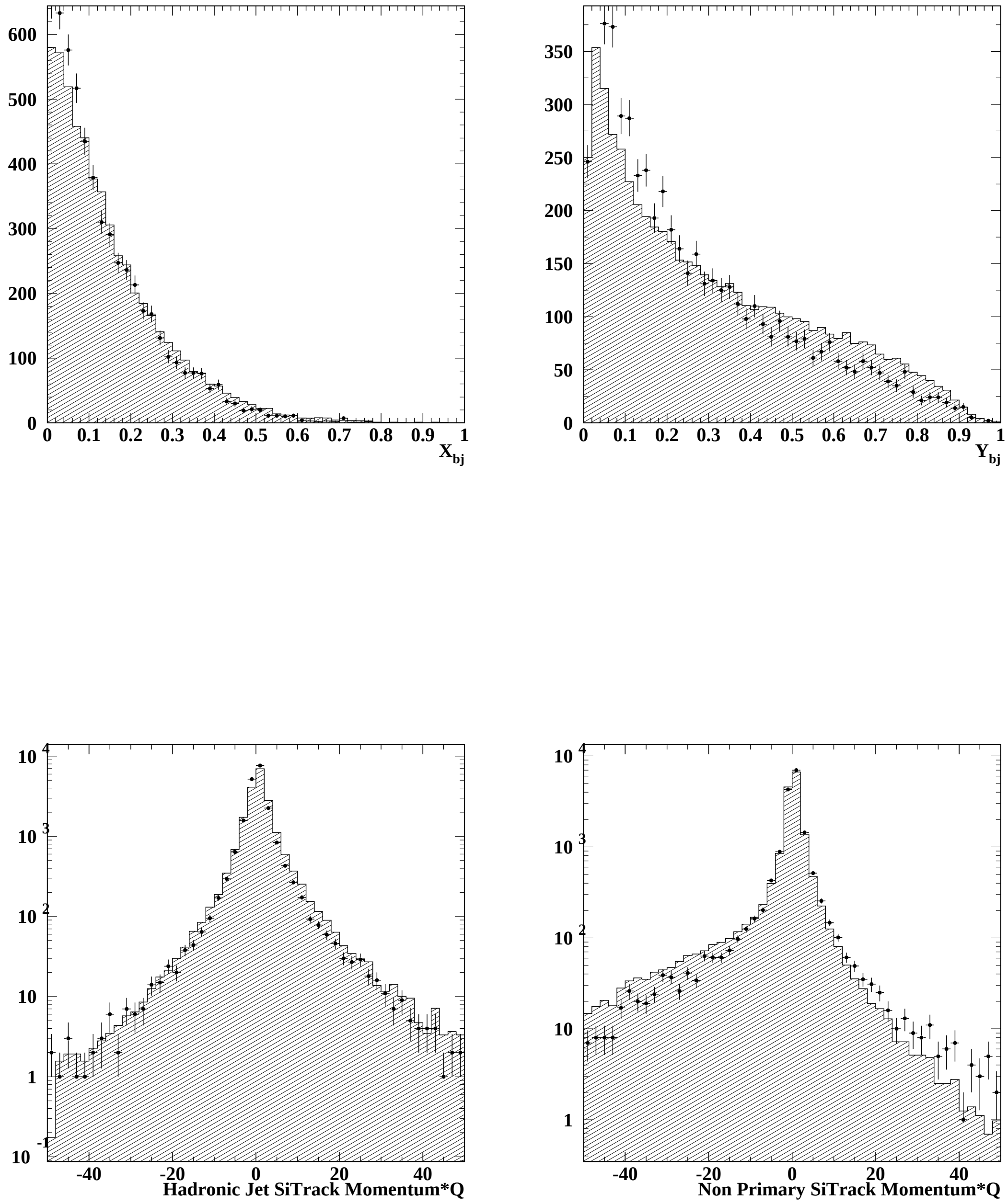
Neutrino beam predictions for NOMAD-STAR

Neutrino	Average Energy (GeV)	Concentration (%)
ν_μ	30.60	94.12
$\overline{\nu_\mu}$	19.83	5.02
ν_e	42.18	0.69
$\overline{\nu_e}$	31.11	0.17

Kinematic Variables (I)

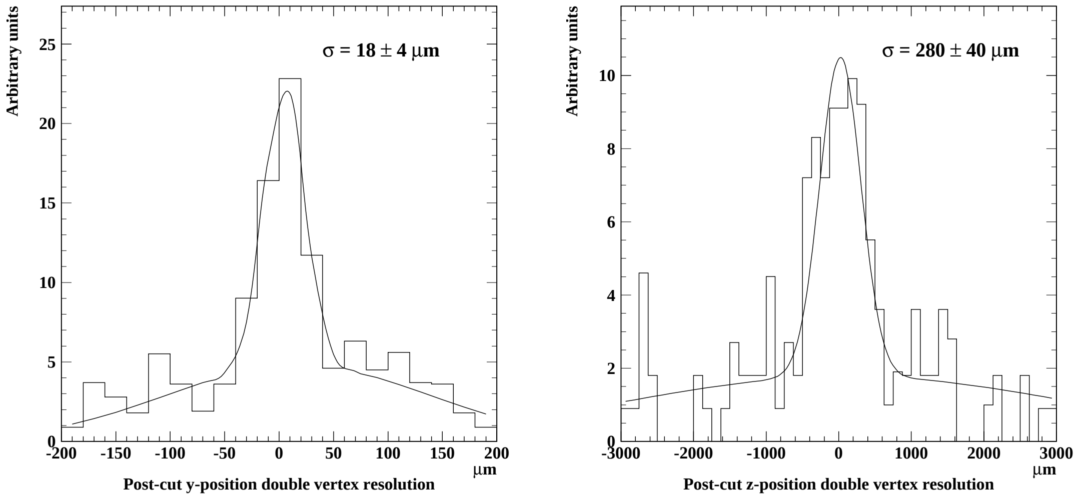


Kinematic Variables (II)



Short Lived Particles

- Use short lived particle reconstruction to mimic τ decay and to measure double vertex resolution.
- Use of K_s reconstruction for double vertex resolution:



- Search in NOMAD-STAR of charm mesons (D^0, D^+, D_s^+).
- Previous experiments used nuclear emulsion (E531, CHORUS)
- First search of charm using silicon detectors in a neutrino beam: proof of principle

DATA

- NOMAD-STAR data set (1998 run): 98,858 events recorded
- Total number of ν_μ charged current (CC) interactions with a vertex in NOMAD-STAR fiducial volume: 11,528.
- Reconstruction efficiency for an event with a reconstructed impact parameter (minimum three tracks): 1545 events (13.4%)

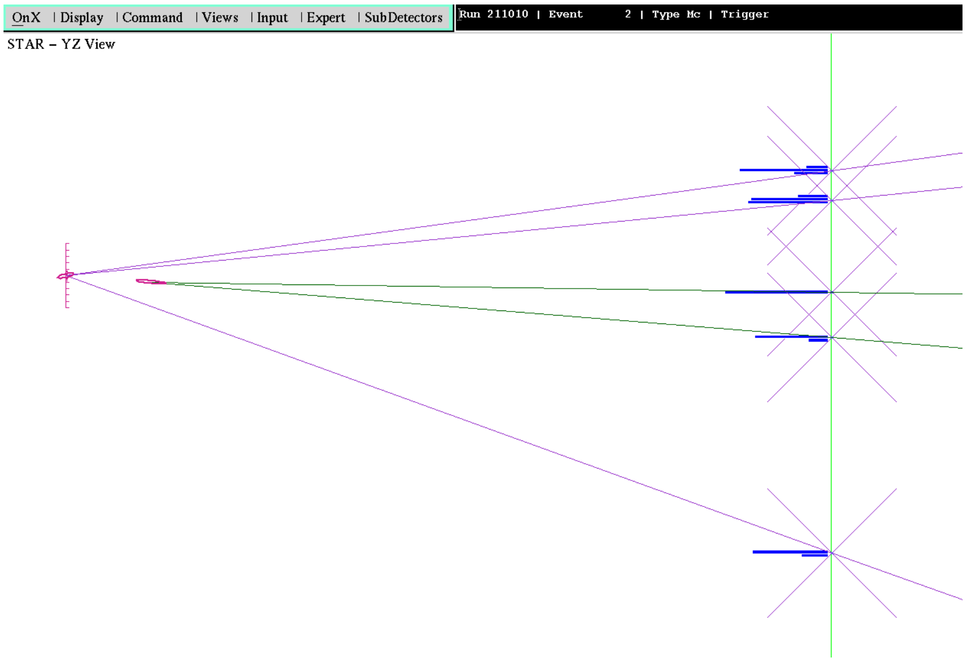
	Number of Events	Rate
All Events	11528	100.0%
Events with a Vertex	10846	94.0%
Vertex and a μ^-	5099	44.2%
Vertex and a μ^+	591	5.1%
Vertex and a $\mu^\pm$	5690	49.3%
Impact Parameter (μ^-)	1393	12.1%
Impact Parameter (μ^+)	152	1.3%
Impact Parameter ($\mu^\pm$)	1545	13.4%

Monte Carlo

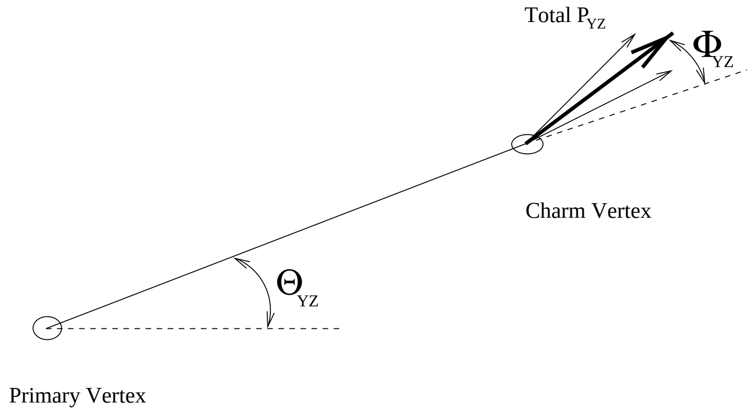
- NOMAD-STAR ν_μ CC Monte Carlo: 62,880 events
- NOMAD-STAR ν_μ NC Monte Carlo: 15,011 events
- NOMAD-STAR $\overline{\nu_\mu}$ CC Monte Carlo: 20,388 events
- Reconstruction efficiency for events with a reconstructed impact parameter $\sim$ 30% for CC and 0.2% for NC

	ν_μ CC	ν_μ NC	$\overline{\nu_\mu}$ CC
All Events	62880 (100.0%)	15011 (100.0%)	20388 (100.0%)
Events Vertex	57602 (91.6%)	11741 (78.2%)	16982 (83.3%)
Vertex and $\mu^\pm$	44678 (71.1%)	77 (0.5%)	15605 (76.5%)
Impact Parameter	19114 (30.4%)	33 (0.2%)	5867 (28.8%)

D^0 Monte Carlo Event



Constrained Fit



- Constrained kinematic fit to impose D^0, D^+ and D_s^+ decays:
  - $D^0 \to K^-\pi^+\pi^0\pi^0$, $K^-\pi^+\pi^0$, $\pi^-\pi^+K_S^0\pi^0\pi^0$, $\pi^-\pi^+K_S^0\pi^0$, $\pi^-\pi^+K_S^0$, $K^-\pi^+$, $\pi^-\pi^+\pi^0$, $K^-\pi^+\pi^+\pi^-$, $K^-\pi^+\pi^+\pi^-\pi^0$, $\pi^-\pi^+\pi^+\pi^-\pi^0$ ($\sim$ 60.7%).
  - $D^+ \to K^-\pi^+\pi^+$, $K^-\pi^+\pi^+\pi^0$, $K^-K^+\pi^+\pi^0$, $\pi^-\pi^+\pi^+K_S^0$, $K^-\pi^+\pi^+\pi^0\pi^0$, $\pi^-\pi^+\pi^+\pi^0$, $\pi^-\pi^+\pi^+\pi^0K_S^0$ ($\sim$ 23.9%).
  - $D_s^+ \to K^+K^-\pi^+\pi^0$, $K^+K^-\pi^+$, $K^-\pi^+\pi^+K_S^0$, $K^+\pi^+\pi^-$, $\pi^-\pi^+\pi^+$ ($\sim$ 17.6%).

- Perform χ^2 minimisation of variables p_{x_i}, p_{x_i}, p_{x_i} (for each particle) and angle Θ_{yz} between production and decay:

$$\chi^2 = \sum_{j=1}^{J}\sum_{i=1}^{I}(x_i - x_i^0)(G_x)_{ij}(x_j - x_j^0) + \sum_{k=1}^{K} 2\alpha_k^T f_k(x,y)$$

with $f_k(x,y) = 0$:

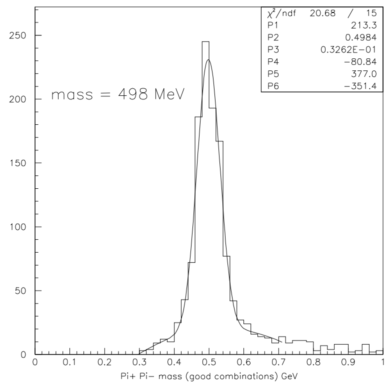
$$f_1 = P - \sum_{i=1}^{n}\sqrt{p_{x_i}^2 + p_{y_i}^2 + p_{z_i}^2},$$

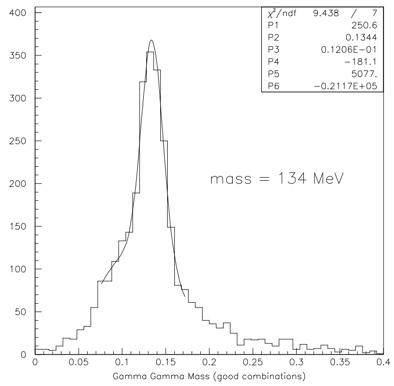
$$f_2 = \sqrt{P^2 + M^2} - \sum_{i=1}^{n}\sqrt{p_{x_i}^2 + p_{y_i}^2 + p_{z_i}^2 + m_i^2},$$

$$f_3 = \cos^{-1}\left(\frac{\tan\Theta_{yz}\sum_{i=1}^{n} p_{y_i} + \sum_{i=1}^{n} p_{z_i}}{\sqrt{\sum_{i=1}^{n} p_{y_i}^2 p_{z_i}^2\left[1+\tan\left({\Theta_{yz}}^2\right)\right]}}\right).$$

Charm search

- π^0 and K_s^0 identification: V^0 reconstruction





- Selection cuts

Cut	Number of combinations	Efficiency
$\chi^2 < 20$	7567	100.0%
$\sigma_{mass} < 160$ MeV	6645	87.8%
$\Delta_{mass} < 150$ MeV	6370	84.2%
$\Delta_Z < 4000\ \mu$m	5376	71.0%
$\sigma_Z < 400\ \mu$m	5265	69.6%
$\frac{c\tau_{rec}}{c\tau_{PDG}} < 6$	5057	66.8%
$2 < P_D < 40$ GeV	5056	66.8%
$P_{max} > 0.5$	1910	25.2%
$P_D^* < 200$ MeV	1573	20.8%
$\Theta_{YZ} < 10°$	1528	20.2%
$\Phi_{YZ} < 10°$	1484	19.6%
$Q_{sum} = \{0, 1, 2\}$	1083	14.3%

Charm results

- Monte Carlo signal

Meson	Simulated	Imp. Param.	Reconst.	Efficiency
D^0	4574	1586	161	3.51 ± 0.27 %
D^+	2441	845	86	3.52 ± 0.37 %
D_s^+	110	38	14	12.7 ± 3.2 %
Other charm	386	133		
Total charm	7511	2602		

- Monte Carlo background

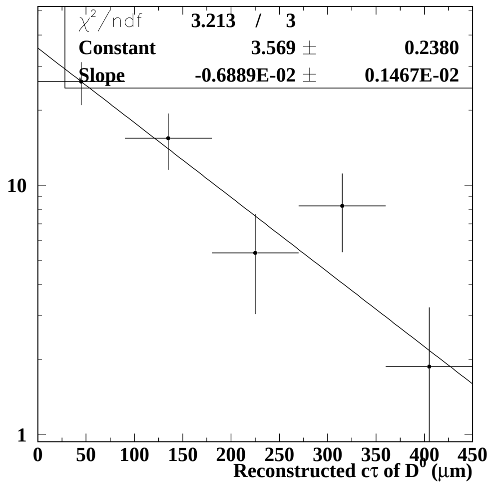
Meson	Reconstructed	Background
D^0	183	0.957 ± 0.070 %
D^+	52	0.272 ± 0.038 %
D_s^+	71	0.371 ± 0.044 %

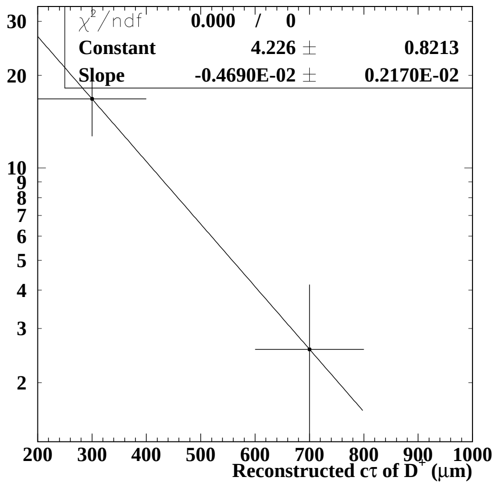
- Data

Meson	Reconstructed	Background	Production Rate
D^0	24	13.33 ± 0.98	4.2 ± 2.0 %
D^+	10	3.79 ± 0.53	2.4 ± 1.3 %
D_s^+	11	5.17 ± 0.61	0.64 ± 0.36 %
Total Charm	45	22.3 ± 1.3	7.2 ± 2.4 %

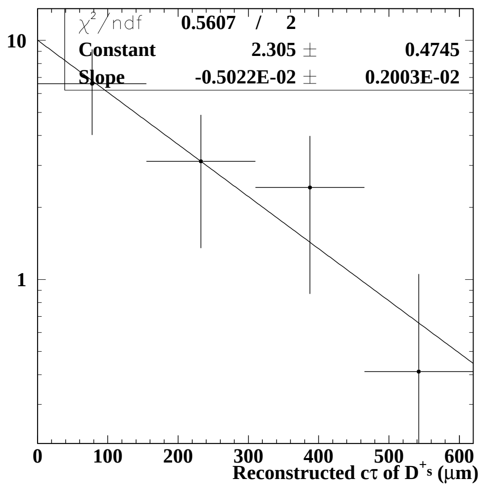
Meson Lifetime ($c\tau$) Cross-checks

- Reconstructed D^0: 145^{+39}_{-25} μm (World ave: 123.7 μm)
- Reconstructed D^+: 213^{+183}_{-67} μm (World ave: 315 μm)





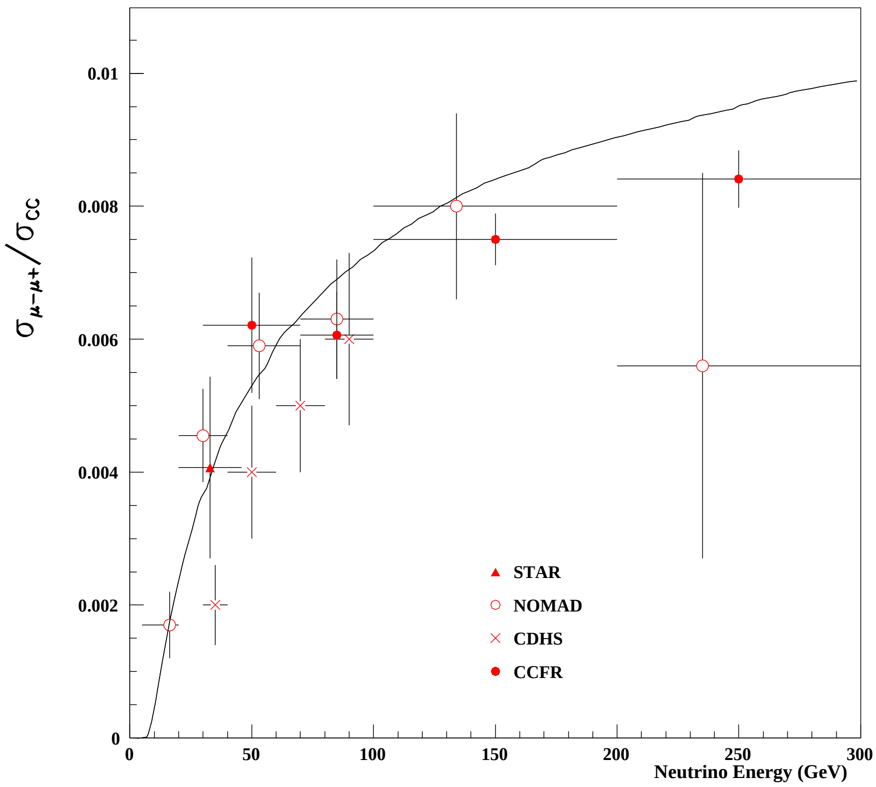
- Reconstructed D_s^+: 199^{+132}_{-56} μm (World ave: 148.6 μm)



Other Experiments

	NOMAD-STAR	E531	CHORUS
Mean energy	33 GeV	22 GeV	27 GeV
D^0	$(4.2 \pm 2.0)\%$	$(2.2 \pm 0.4)\%$	$(1.99 \pm 0.13 \pm 0.17)\%$
D^+	$(2.4 \pm 1.3)\%$	$(1.6 \pm 0.4)\%$	
D_s^+	$(0.64 \pm 0.36)\%$	$(0.25^{+0.20}_{-0.11})\%$	
Total charm	$(7.2 \pm 2.4)\%$	$(4.9^{+0.7}_{-0.6})\%$	

Estimated opposite sign dimuon rate from NOMAD-STAR



Implications for Neutrino Factory

- Low charm efficiency due to:
  - Small size of STAR (72 cm $\times$ 36 cm $\times$ 15 cm)
  - Only 5 layers with one projection (2D tracker)
- Efficiency of 3.5% for D^0, D^+ and 12.7% for D_s^+ would be lower limit for larger 3D trackers.
- At a near detector of a neutrino factory (10^{20} μ/year) one could record $\sim$ 200 million ν_μ CC interactions (depending on the target mass)
- For NOMAD-STAR efficiency that would be $\sim 3 \times 10^5$ D^0, $\sim 2 \times 10^5$ D^+ and 1.6×10^5 D_s^+, but this could be improved
- Measurement of charm production cross-section as a function of energy can be used to determine charm mass
- V_{cd} can be measured by comparing the rates of production of charm and anti-charm by neutrinos and anti-neutrinos.
- D^0 - $\overline{D^0}$ mixing can be tested at a neutrino factory by tagging the meson by the sign of the lepton at the primary vertex and searching for its decay.
- More studies need to be performed on more realistic neutrino factory near detector concepts for charm physics.

CONCLUSIONS

First silicon system for ν experiment.

- Large silicon surface (1.1 m^2)
- Good quality Foxfet detectors 50 μm readout pitch
- Longest ladders ever constructed (12 detectors, 72 cm)
- Low noise electronics

NOMAD-STAR performance as expected.

- S/N for 12 detectors (72 cm) is $\sim$ 16:1
- Reconstruction efficiency $> 92\%$
- Very good spatial resolution $\sim$ 8.6 μm
- Vertex resoution $\sim$ 19 μm
- Impact parameter resolution $\sim$ 33 μm

NOMAD-STAR took data 1997-1998.

- Approximately 11,500 ν_μ CC events.
- A total of 45 charm mesons (D^0, D^+, D_s^+) were selected with a background of 22.
- Selection efficiencies of 3.5% for D^0, 3.5% for D^+ and 12.7% for D_s^+ were found
- Total charm rate of $(7.2 \pm 2.4)\%$ at 33 GeV average energy

Neutrino factory implications.

- A 3D tracker can improve reconstruction and selection efficiency.
- Even with a NOMAD-STAR performance: $\sim 0.6 \times 10^6$ charm events/year at a neutrino factory
- This sample of charm events can be used for a measurement of the charm mass, V_{cd} and $D^0 - \overline{D^0}$ mixing.