Tau detection using the Kinematic and Impact Parameter Techniques

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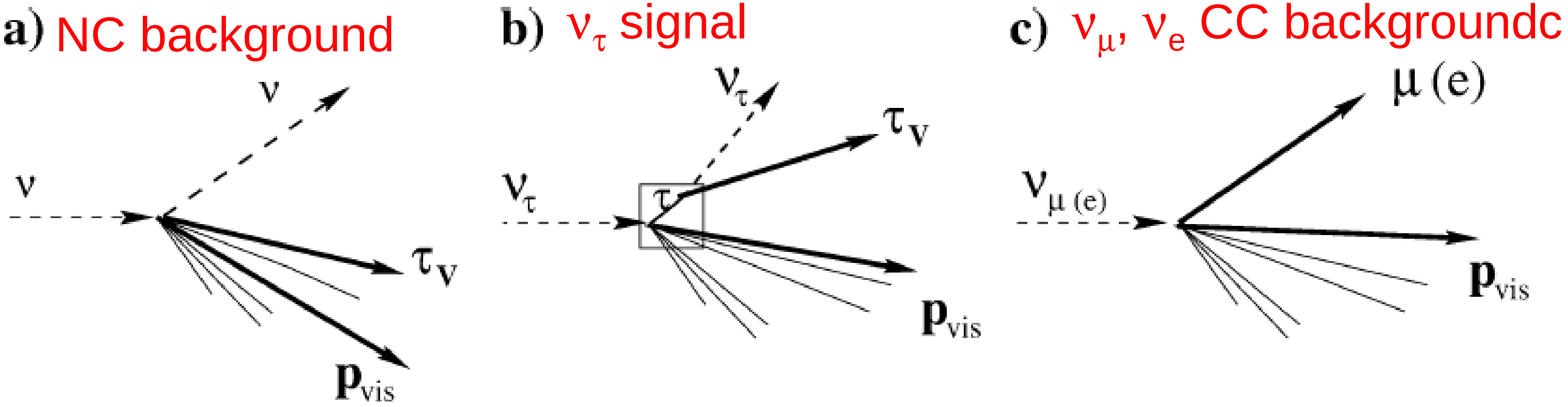
Tau detection techniques

- Currently there are three possible techniques for detecting taus:
  - Observation of decay kink of tau: emulsion technique (already discussed by P. Migliozzi) like in OPERA or CHORUS
  - Kinematic technique: used by NOMAD to identify taus through the kinematic analysis of the tau decay
  - Reconstruction of the impact parameter with a dedicated vertex detector (ie. Silicon detector, prototyped by NOMAD-STAR)
- Pasquale has already covered the emulsion technique
- I will cover the other two techniques and give you some idea of the efficiencies that have been achieved in the past with NOMAD and NOMAD-STAR

Kinematic detection of taus: NOMAD

- NOMAD was a $\nu_\mu \rightarrow \nu_\tau$ neutrino oscillation experiment at the CERN SPS between 1994-1998.
- The main aim was to search for the appearance of ν_τ in a predominantly ν_μ beam: 1.35×10^6 ν_μ CC events for 5×10^{19} pot
- NOMAD used the kinematic technique, where the visible products from the tau decay are measured, and kinematically separated from background by exploiting the fact that taus decay emitting one or two neutrinos (which are not observed)


a) NC background

b) ν_τ signal

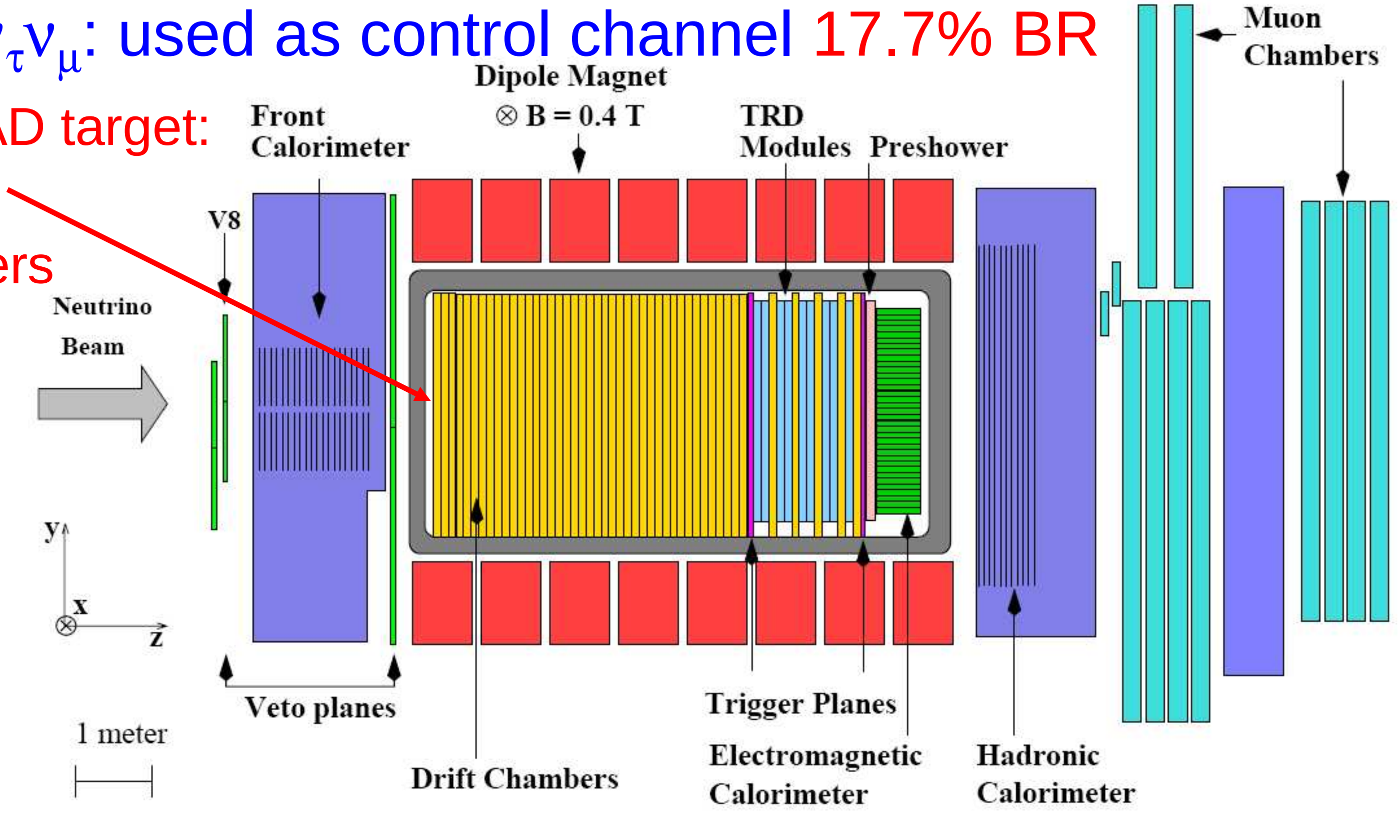
c) ν_μ, ν_e CC backgroundc

NOMAD

- NOMAD was sensitive to 82.4% of the tau decays:
  - $\tau\rightarrow e\nu_\tau\nu_e$: electron decay (main NOMAD channel) 17.7% BR
  - $\tau\rightarrow\pi\nu_\tau$: single pion decay
  - $\tau\rightarrow\pi(n\pi^0)\nu_\tau$: single pion decay with photons

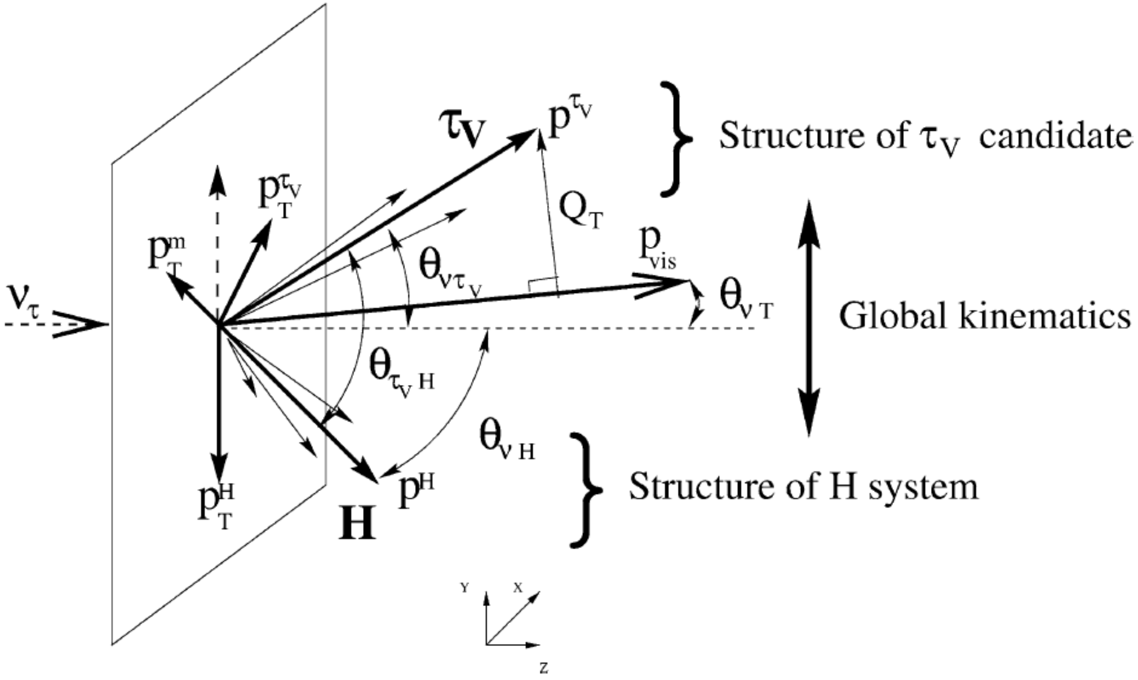
    } 49.5% BR
  - $\tau\rightarrow\pi\pi\pi(n\pi^0)\nu_\tau$: three pion decay with photons 15.2% BR
- $\tau\rightarrow\mu\nu_\tau\nu_\mu$: used as control channel 17.7% BR

Main NOMAD target: 3 tons of drift chambers

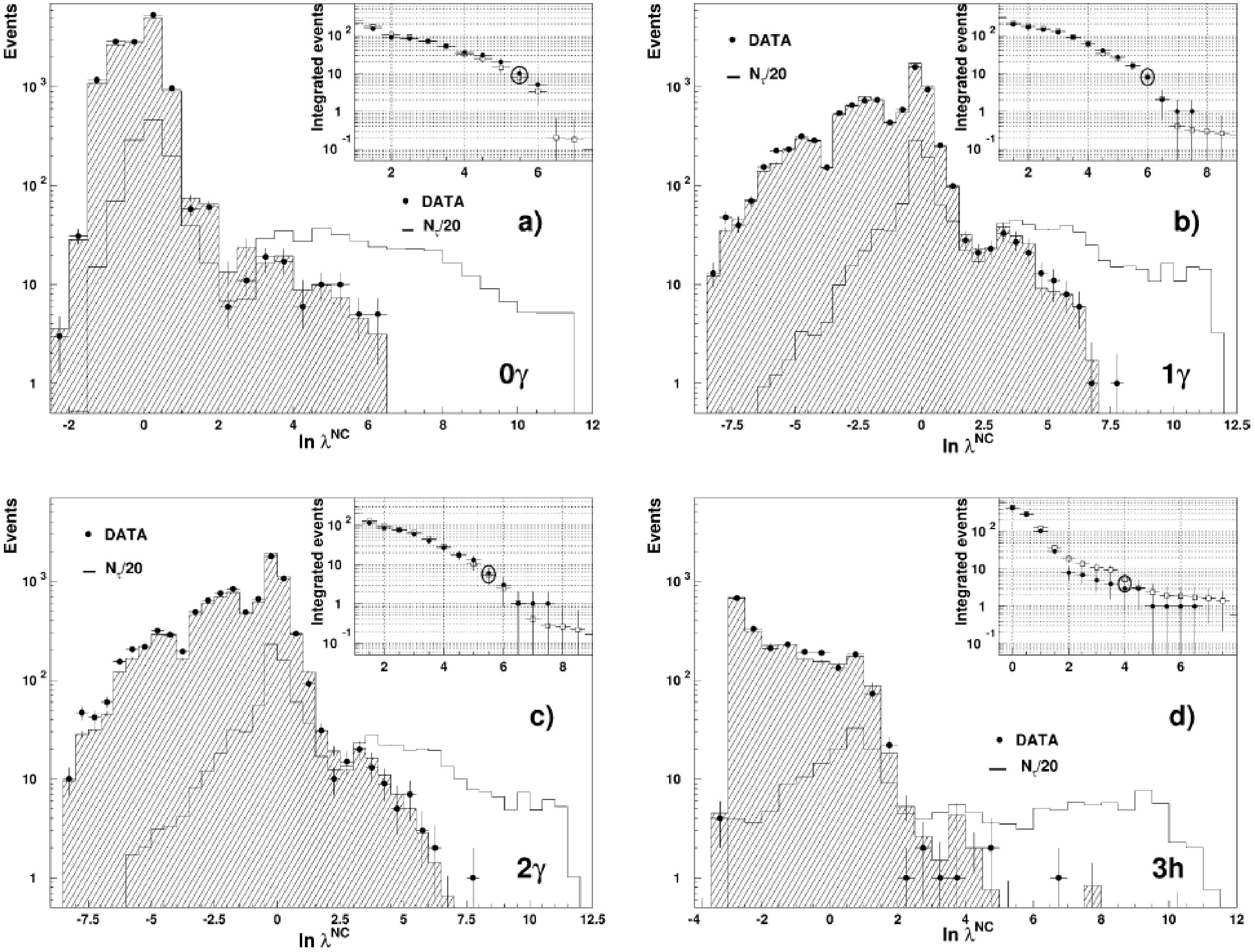


NOMAD

- Original NOMAD analysis relied on separating signal from background by:
  1) Missing transverse momentum of signal vs background
  2) Angle in transverse plane between tau candidate and hadronic jet
- NOMAD analysis became more sophisticated with log like-lihood functions constructed from PDFs for large number of kinematic variables (see Nucl. Phys B 611 (2001) 3-39.)

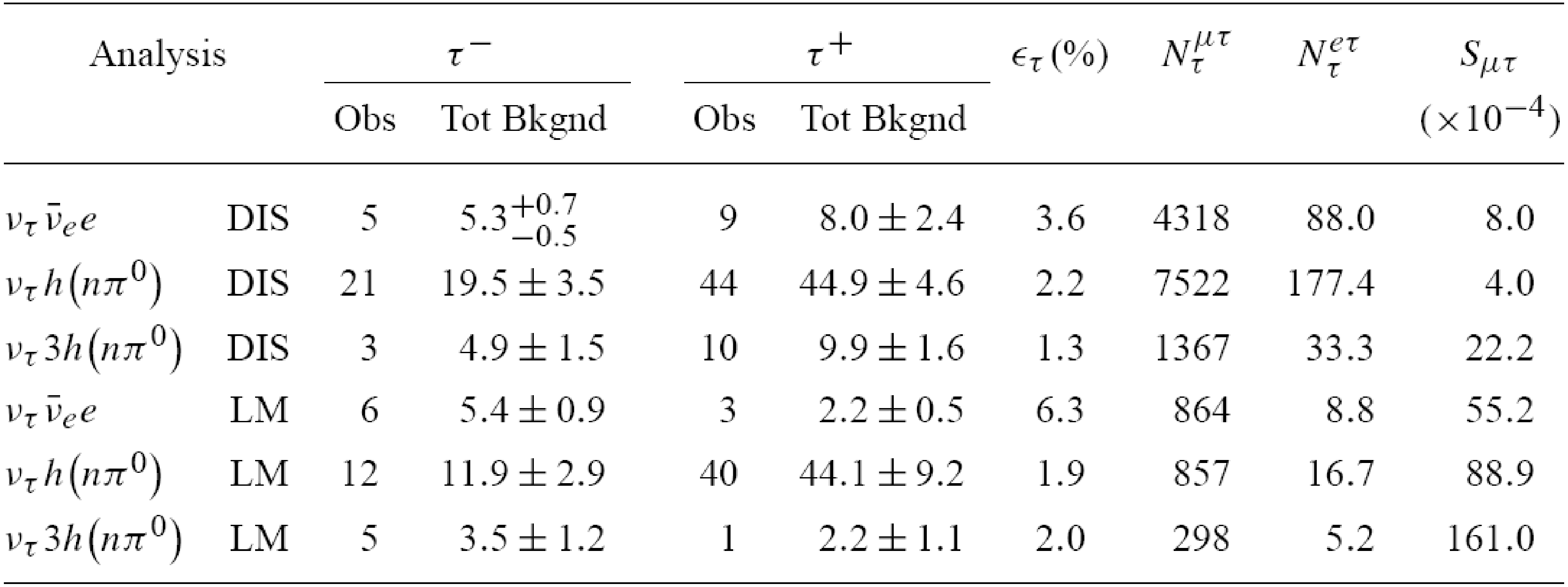


NOMAD hadronic likelihoods



NOMAD

- Final analysis and efficiencies were a result of the combination of the different channels: $N_\tau^{\mu\tau} = N_\mu^{obs} \times \frac{\varepsilon_\tau}{\varepsilon_\mu} \times \frac{\sigma_\tau}{\sigma_\mu} \times BR$



Analysis		τ^- Obs	τ^- Tot Bkgnd	τ^+ Obs	τ^+ Tot Bkgnd	ϵ_τ (%)	$N_\tau^{\mu\tau}$	$N_\tau^{e\tau}$	$S_{\mu\tau}$ ($\times 10^{-4}$)
$\nu_\tau \bar{\nu}_e e$	DIS	5	$5.3^{+0.7}_{-0.5}$	9	8.0 ± 2.4	3.6	4318	88.0	8.0
$\nu_\tau h(n\pi^0)$	DIS	21	19.5 ± 3.5	44	44.9 ± 4.6	2.2	7522	177.4	4.0
$\nu_\tau 3h(n\pi^0)$	DIS	3	4.9 ± 1.5	10	9.9 ± 1.6	1.3	1367	33.3	22.2
$\nu_\tau \bar{\nu}_e e$	LM	6	5.4 ± 0.9	3	2.2 ± 0.5	6.3	864	8.8	55.2
$\nu_\tau h(n\pi^0)$	LM	12	11.9 ± 2.9	40	44.1 ± 9.2	1.9	857	16.7	88.9
$\nu_\tau 3h(n\pi^0)$	LM	5	3.5 ± 1.2	1	2.2 ± 1.1	2.0	298	5.2	161.0

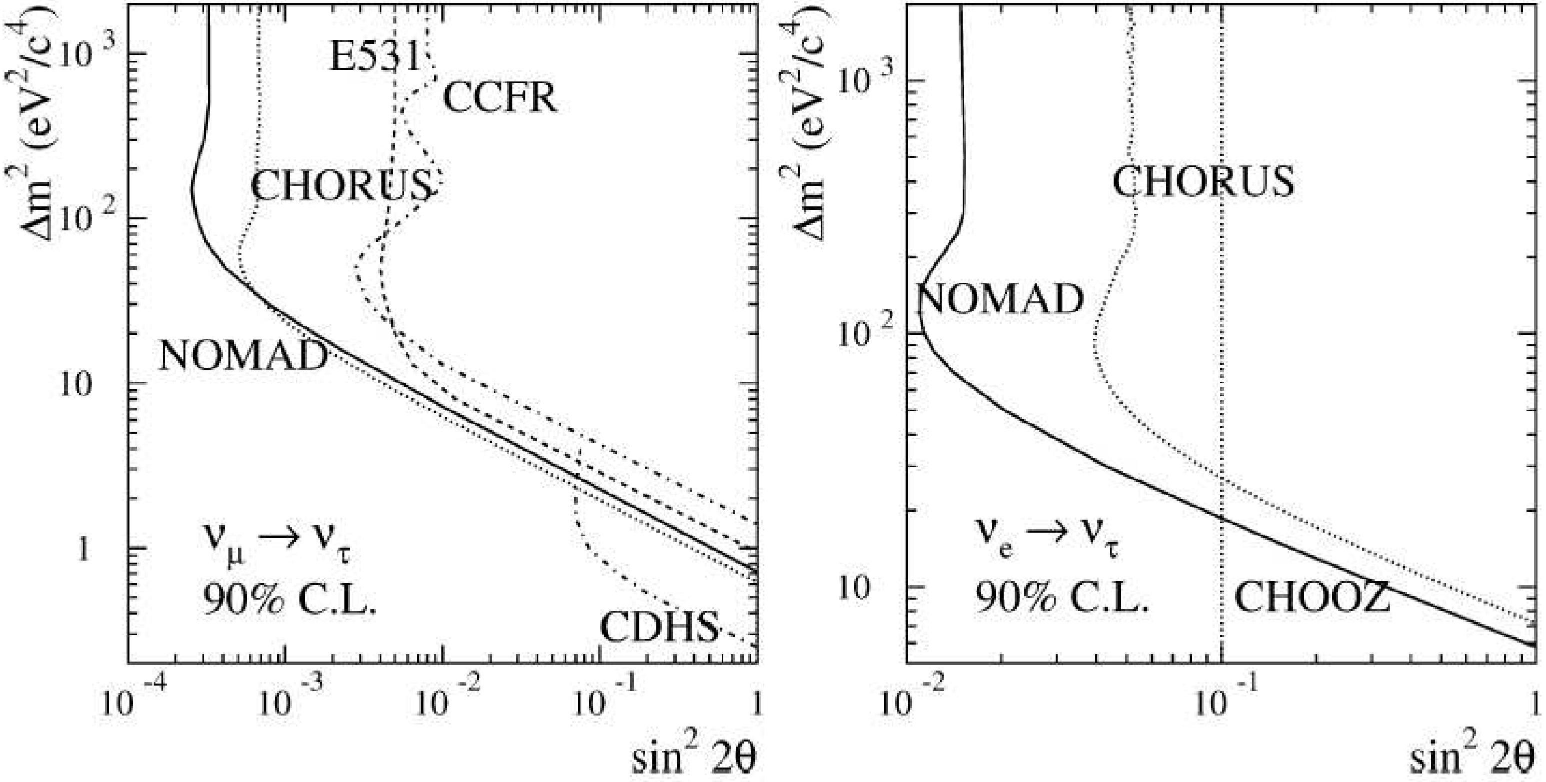
52 50.5 15226 329.4

$$P_{osc}(\nu_\mu \to \nu_\tau) = \frac{N_\tau^{obs}}{N_\tau^{\mu\tau}} < 1.63 \times 10^{-4} \ @90\%CL \qquad P_{osc}(\nu_e \to \nu_\tau) = 0.74 \times 10^{-2} \ @90\%CL$$

NOMAD

- Final oscillation exclusion plots:

$\sin^2 2\theta_{\mu\tau} < 3.3\times10^{-4}\ @\,90\%CL$ $\sin^2 2\theta_{e\tau} = 1.5\times10^{-2}\ @\,90\%CL$ for high Δm^2



- Also set limits of ν_μ and ν_e couplings to the tau:

$P_{\mu\tau} < 4.4\times10^{-4}\ @\,99\%CL$ $P_{e\tau} < 2.0\times10^{-2}\ @\,99\%CL$

What about at Fermilab?

- In principle, a liquid argon detector could also carry out a kinematic tau analysis using NOMAD techniques
- Sampling rate similar to NOMAD (2%X_0), plus dE/dx information, so LAr very good at electron ID
- Could expect similar (maybe better?) efficiencies in LAr:

$$\varepsilon_{eff} = \frac{N_{\tau}^{\mu\tau}}{N_{CC}} = \frac{15226}{1.35\times10^{6}} = 1.1\%$$

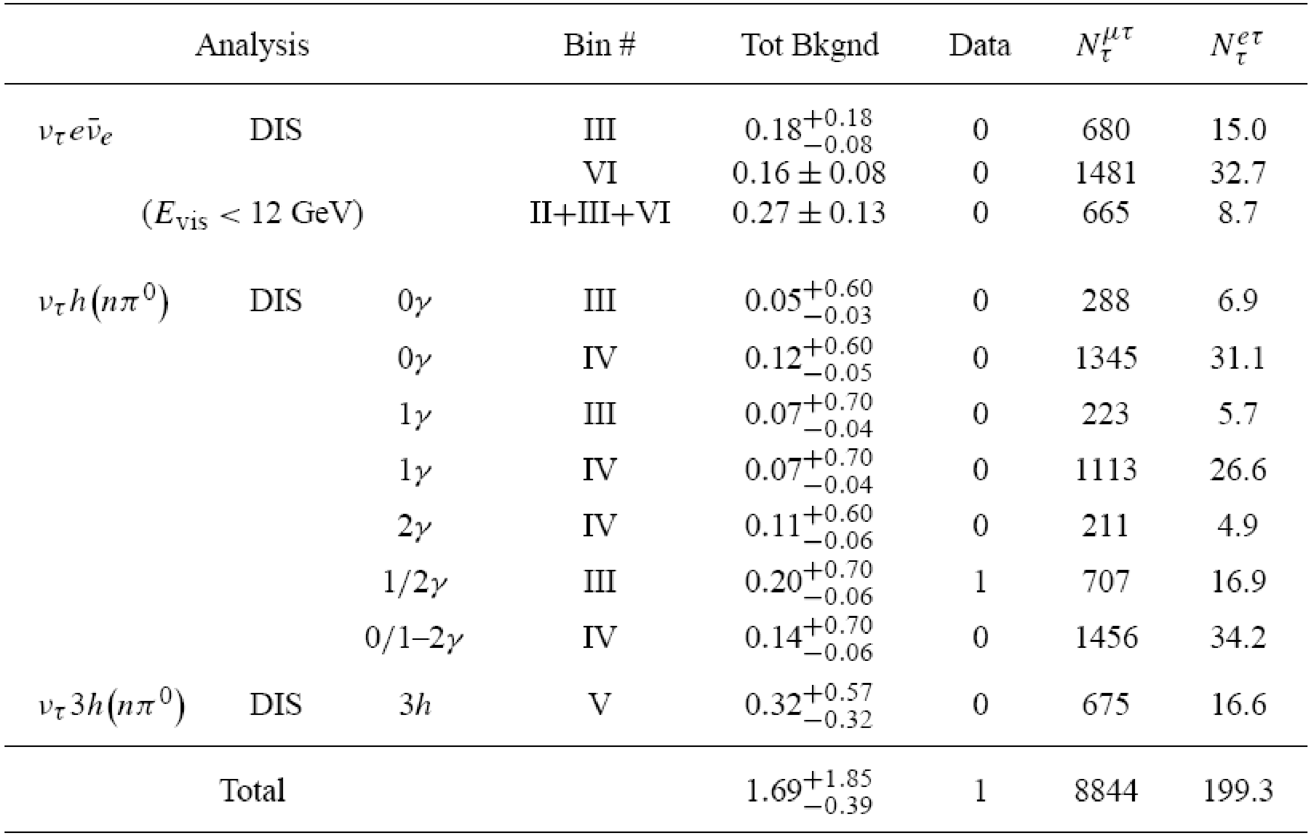
- Assuming same efficiency as NOMAD, to achieve coupling limits ~10^{-6}, would need ~5×10^{8} ν_μ CC events
- We have to consider intrinsic limit of tau production from $D_s \rightarrow \tau\nu_\tau$, calculated by Concha and JJ in 1997:
  - 3.5×10^{-6} at 450 GeV
  - 1.3×10^{-6} at 350 GeV
  - 9.6×10^{-8} at 120 GeV

In 1.44x1.44 m^2

PRD 55, (1997),1297. Also B Van de Vyver: NIMA 385 (1997), 91.

What about at Fermilab?

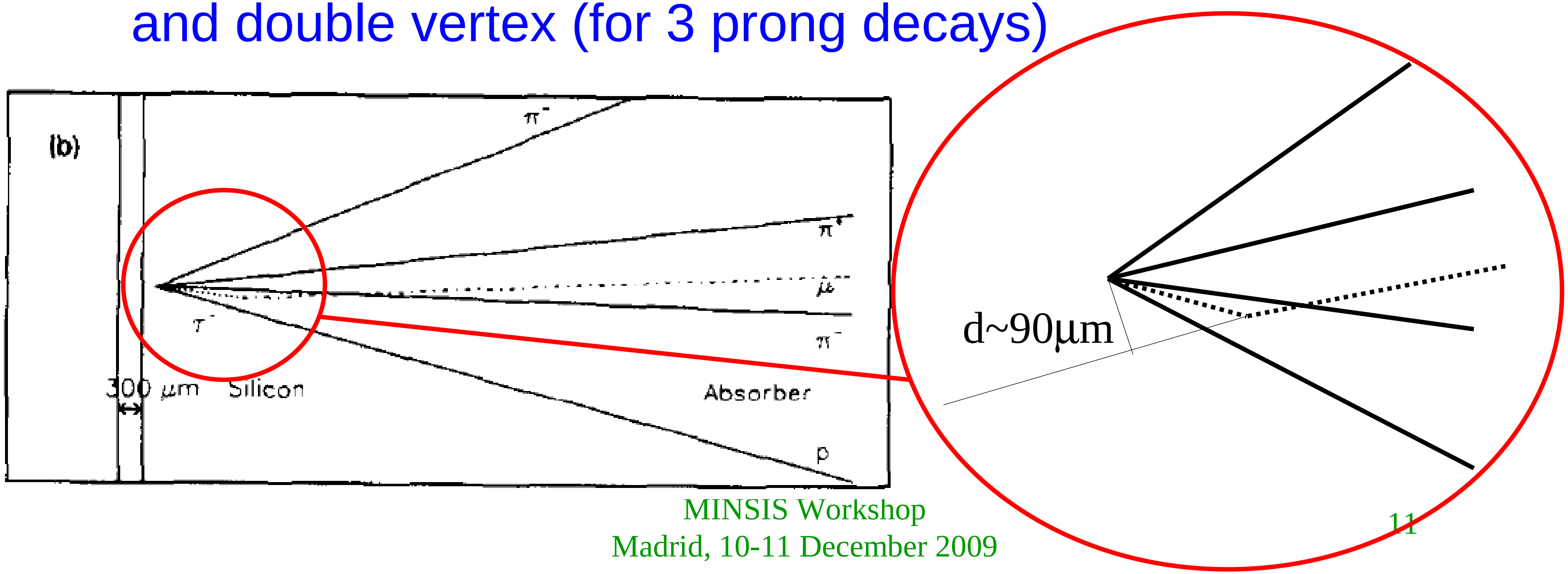
- The main problem is not achieving the rate, but killing the backgrounds using the kinematic technique.
- For example, there were bins in NOMAD which were defined as “low background” bins that could potentially scale better with event rate:



Analysis			Bin #	Tot Bkgnd	Data	$N_\tau^{\mu\tau}$	$N_\tau^{e\tau}$
$\nu_\tau e \bar{\nu}_e$	DIS		III	$0.18^{+0.18}_{-0.08}$	0	680	15.0
			VI	0.16 ± 0.08	0	1481	32.7
	($E_{\text{vis}} < 12$ GeV)		II+III+VI	0.27 ± 0.13	0	665	8.7
$\nu_\tau h(n\pi^0)$	DIS	0γ	III	$0.05^{+0.60}_{-0.03}$	0	288	6.9
		0γ	IV	$0.12^{+0.60}_{-0.05}$	0	1345	31.1
		1γ	III	$0.07^{+0.70}_{-0.04}$	0	223	5.7
		1γ	IV	$0.07^{+0.70}_{-0.04}$	0	1113	26.6
		2γ	IV	$0.11^{+0.60}_{-0.06}$	0	211	4.9
		$1/2\gamma$	III	$0.20^{+0.70}_{-0.06}$	1	707	16.9
		$0/1\text{–}2\gamma$	IV	$0.14^{+0.70}_{-0.06}$	0	1456	34.2
$\nu_\tau 3h(n\pi^0)$	DIS	$3h$	V	$0.32^{+0.57}_{-0.32}$	0	675	16.6
Total				$1.69^{+1.85}_{-0.39}$	1	8844	199.3

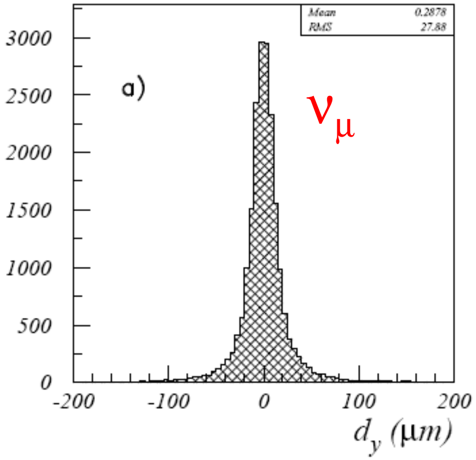
Impact parameter detection of taus

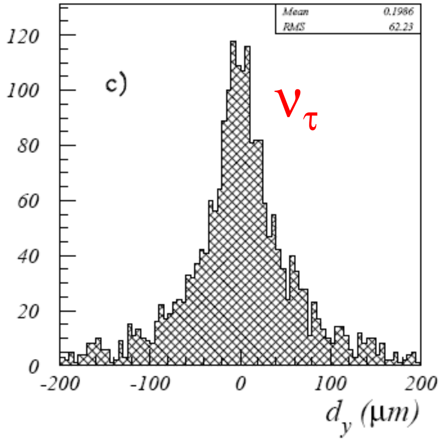
- There is another way of detecting taus in neutrino experiments
- This was invented by Gomez Cadenas et al.
  - NAUSICAA: (Si vertex detector): NIM A 378 (1996), 196-220
  - ESTAR (Emulsion-Silicon Target): NIM A 381 (1996), 223-235
- Identify tau by impact parameter (for one prong decay of τ) and double vertex (for 3 prong decays)

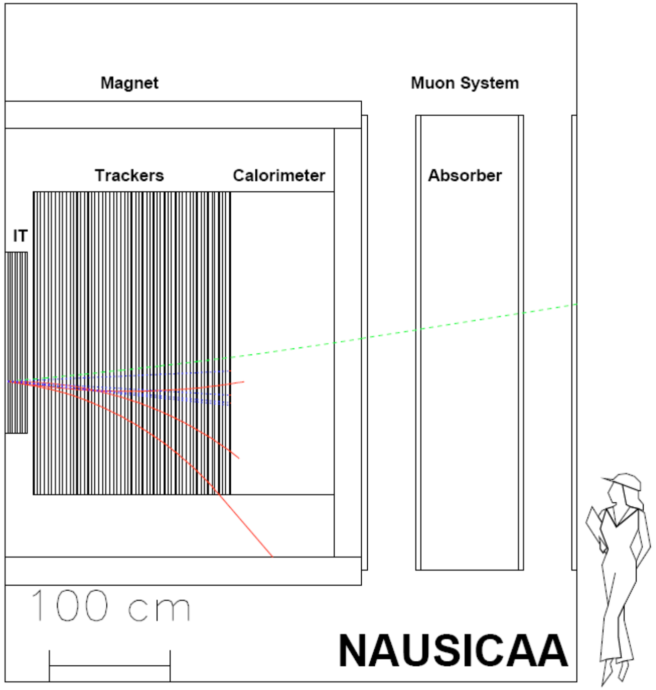


NAUSICAA

- NAUSICAA proposal:
  - Impact parameter resolution ν_μ-CC=28μm
  - Impact parameter resolution ν_τ-CC=62μm







- Efficiencies:
  - $\tau \rightarrow \mu$: ε=10%
  - $\tau \rightarrow \pi(n\pi^0)$: ε=10%
  - $\tau \rightarrow \pi\pi\pi(n\pi^0)$: ε=23%
  - Total eff: ε=0.85x10%+0.15x23%=12%
  - σ_τ/σ_μ=0.29

- Sensitivity at Main Injector with $2\mathrm{x}10^7$ ν_μ CC interactions:

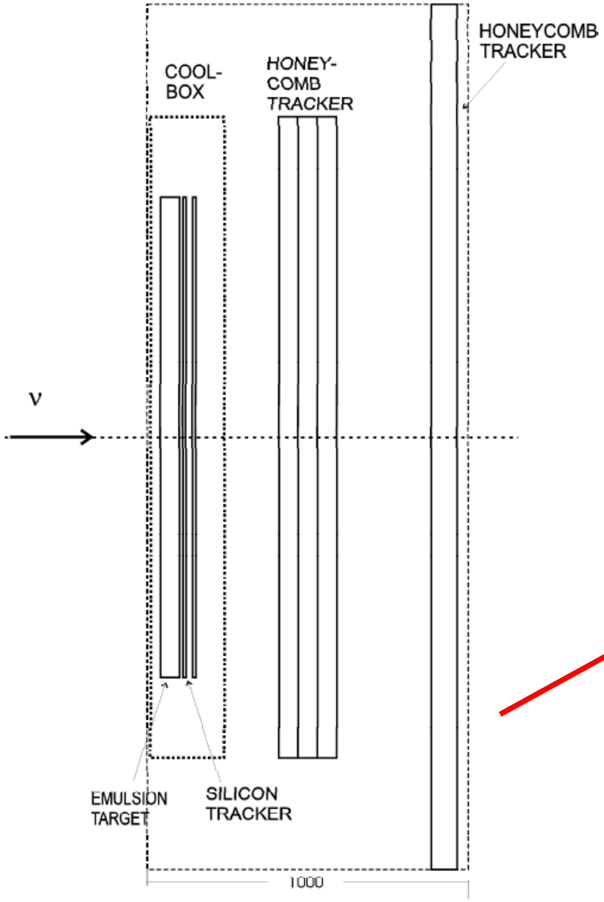
$$P_{osc}(\nu_\mu \rightarrow \nu_\tau) < \frac{2.3}{2\times10^7 \times 0.12 \times 0.29} = 3.2\times10^{-6}$$

TOSCA

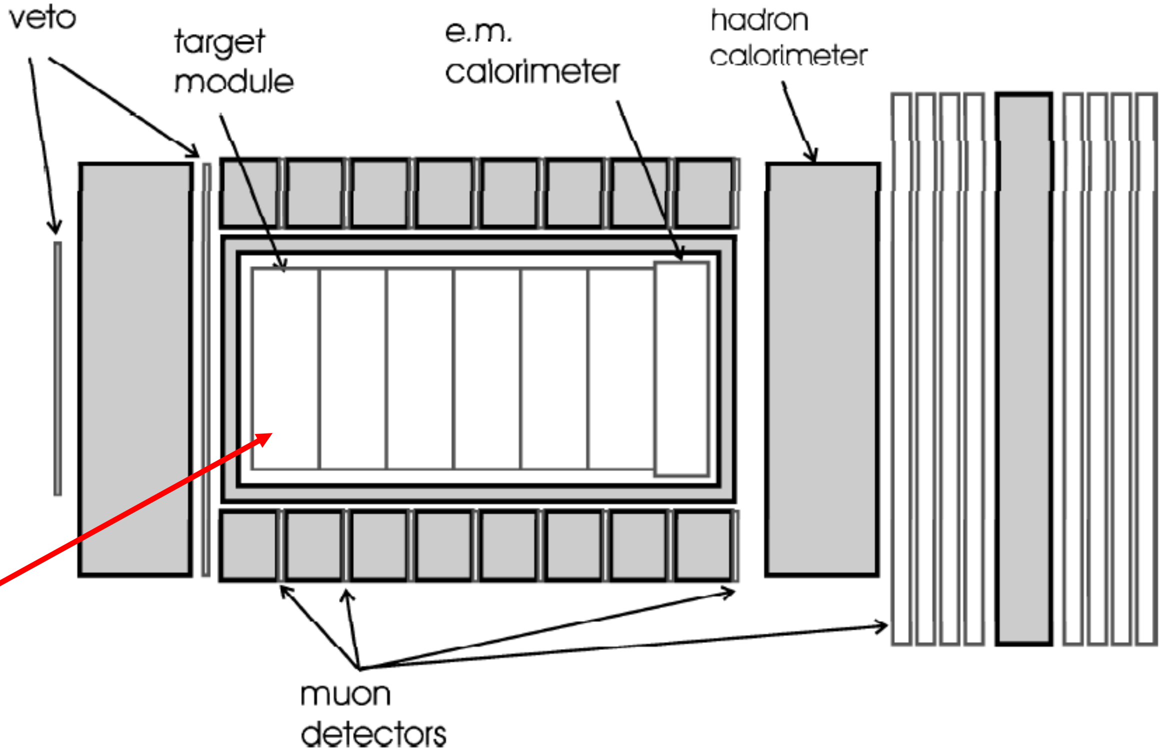
- Historically, the impact parameter idea was dropped because one could have much better sensitivity by combining the power of Emulsion+Si (taus detected in the emulsion but selected using a Si tracker).
- The ESTAR idea was adopted in a Letter of Intent to CERN SPSC (I213) in 1997 called TOSCA:
  - http://tosca.web.cern.ch/TOSCA/Public/LetterOfIntent/
  - Remarkably, the website is still available!
- The idea was to create an Emulsion-Silicon hybrid target with mass 2.4 tons
  - Improved efficiency: $\tau \rightarrow \mu$ 42%, $\tau \rightarrow e$ 10.6%, $\tau \rightarrow h(n\pi^0)$ 27%
  - $\tau \rightarrow 3\pi$ was not considered

TOSCA

- Six modules inside magnetic field
- In each volume Si-emulsion tracker elements



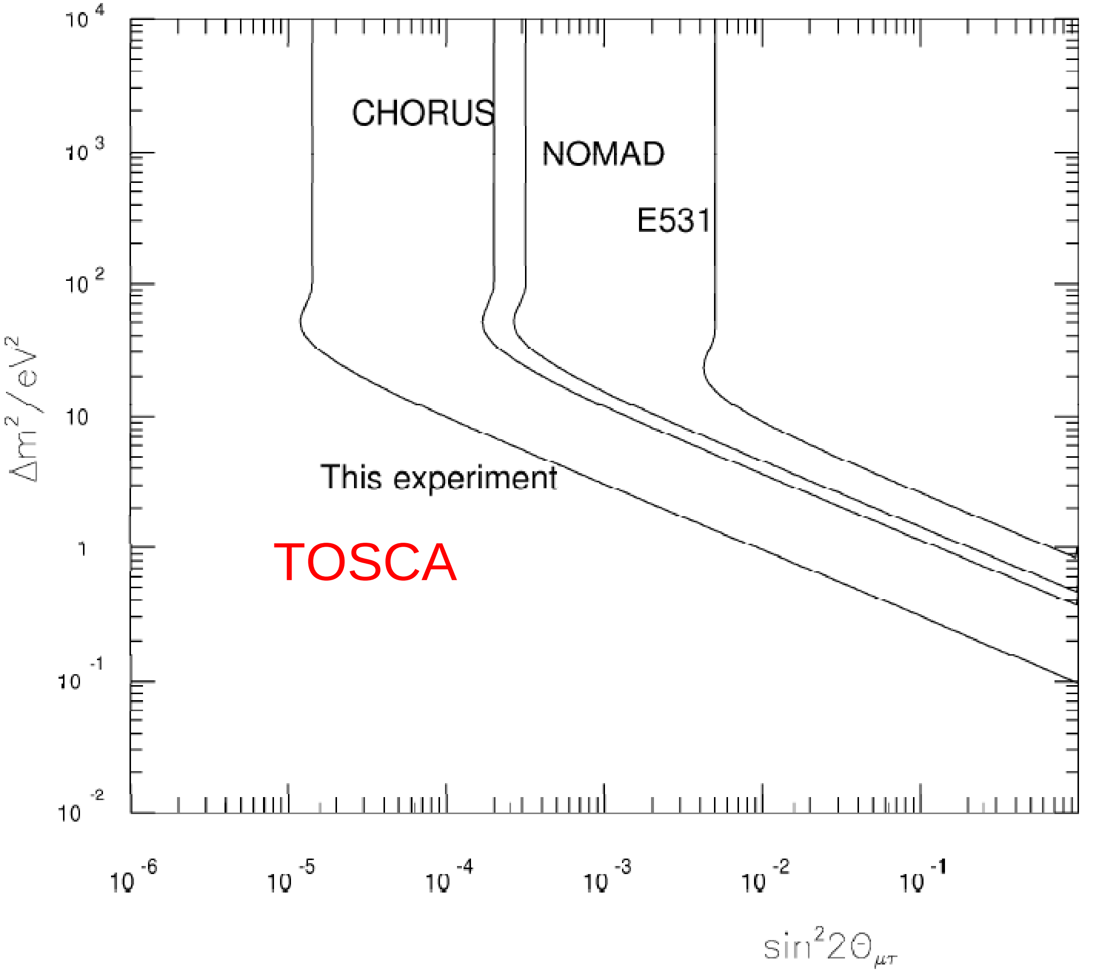
TOSCA LoI



TOSCA

- Final TOSCA predicted sensitivity:

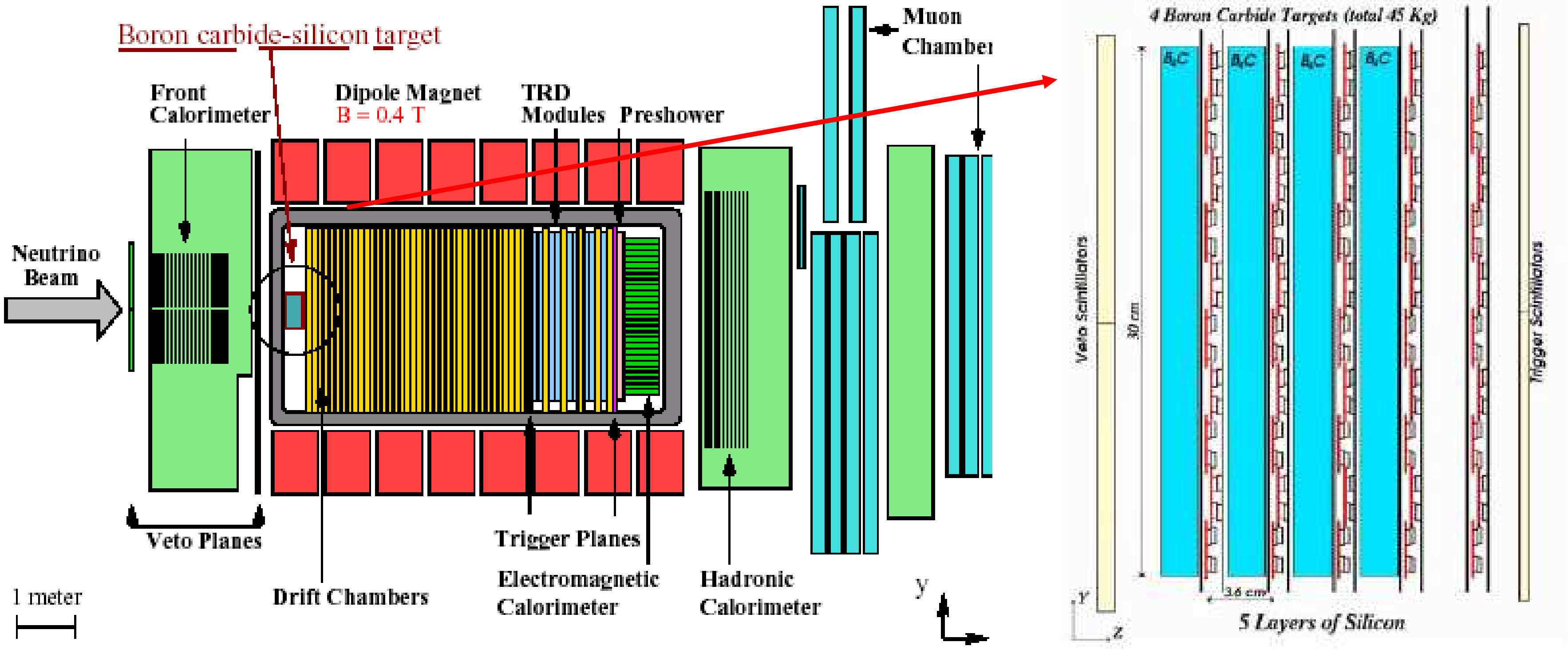
$$P_{osc}(\nu_\mu \rightarrow \nu_\tau) < 0.75 \times 10^{-5} \text{ @ } 90\% CL$$



NOMAD-STAR

- R&D in NOMAD for short baseline ν_τ detector based on silicon: NOMAD-STAR (NIMA 413 (1998), 17; NIMA 419 (1998), 1; NIMA 486 (2002), 639; NIMA 506 (2003), 217.)

Silicon TARget - STAR

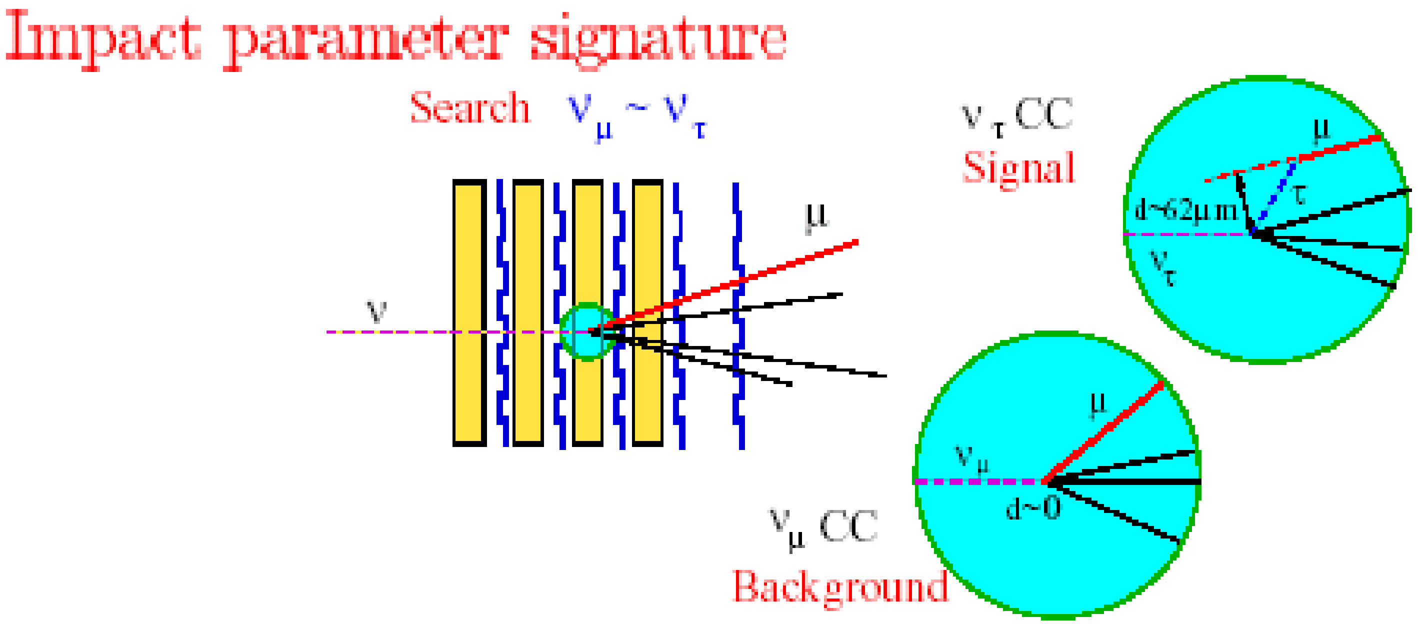


- Total mass: 45 kg of B_4C target (largest density for lowest X_0)

1.14 m^2 silicon area

NOMAD-STAR

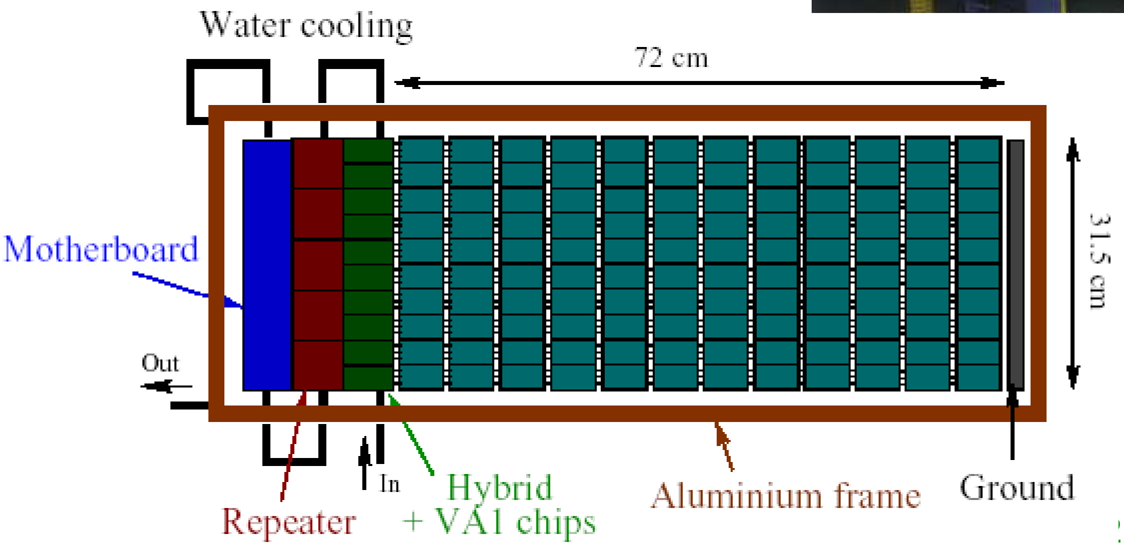
- Aim of NOMAD-STAR: reconstruct short lived particles in a neutrino beam to determine capabilities ν_τ detection: use impact parameter signature of charm decays to mimic ν_τ



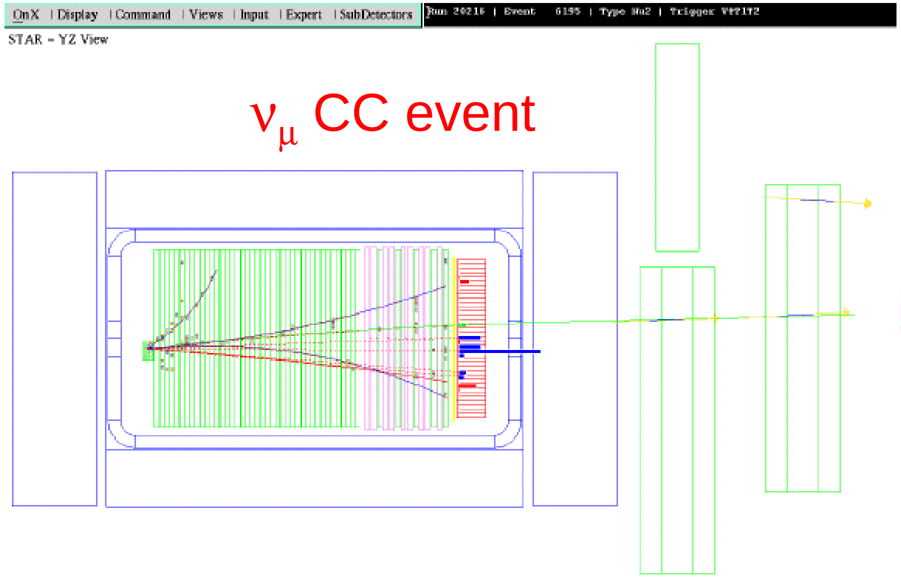
- τ impact parameter ~ 62 μm, normal ν_μ charged current (CC) interactions ~30 μm

NOMAD-STAR

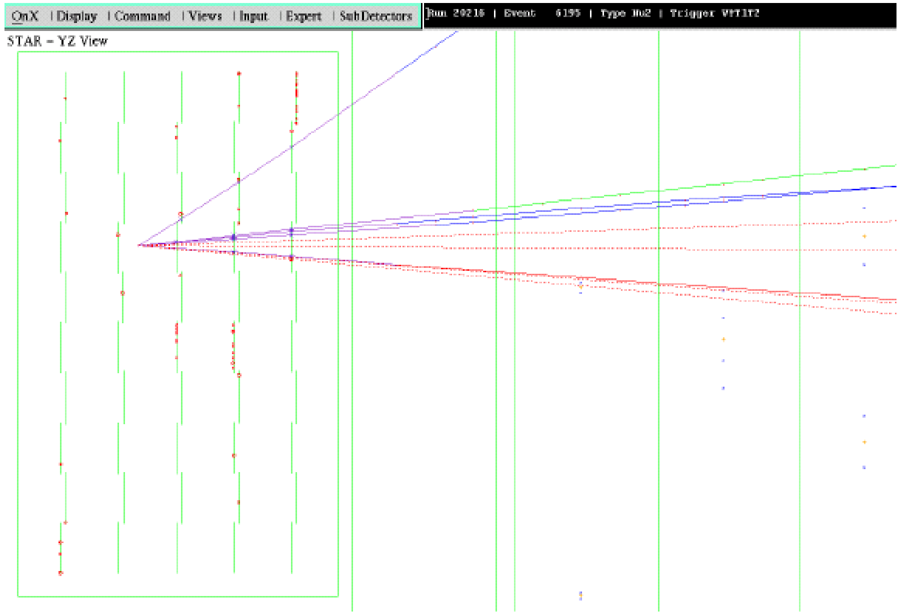
- Longest silicon microstrip detector ladders ever built: 72cm, 12 detectors, S/N=16:1
- Hamamatsu Si Detectors: 300 μm thick, 25 μm pitch, 50 μm readout
- VA1 readout: 3 μs shaping



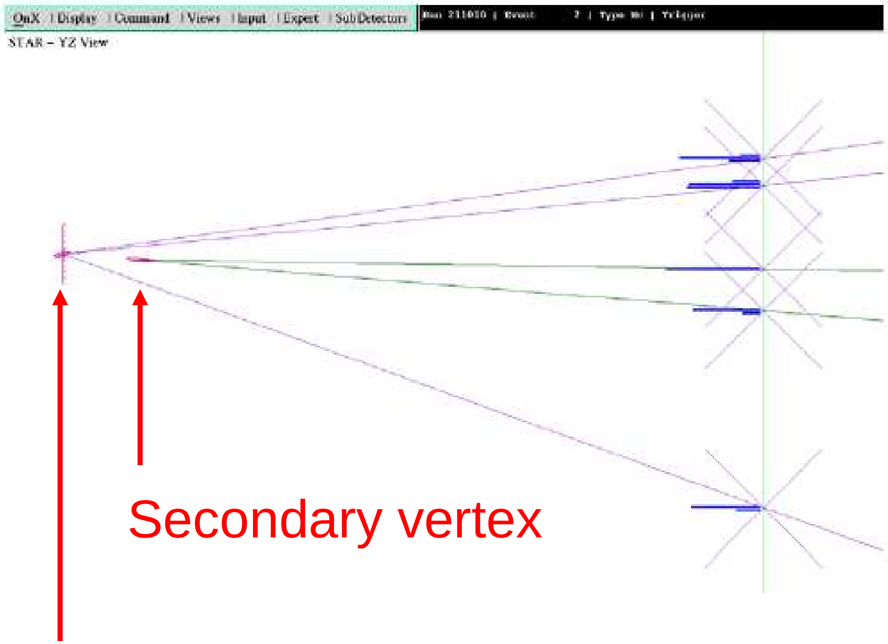
NOMAD-STAR



ν_μ CC event



D^0 Monte Carlo Event

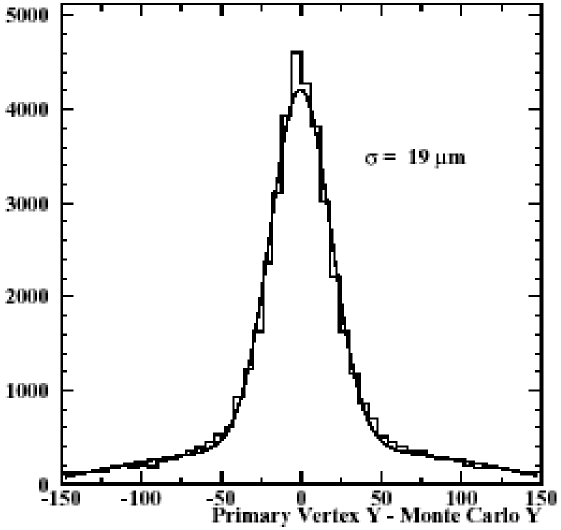


Secondary vertex

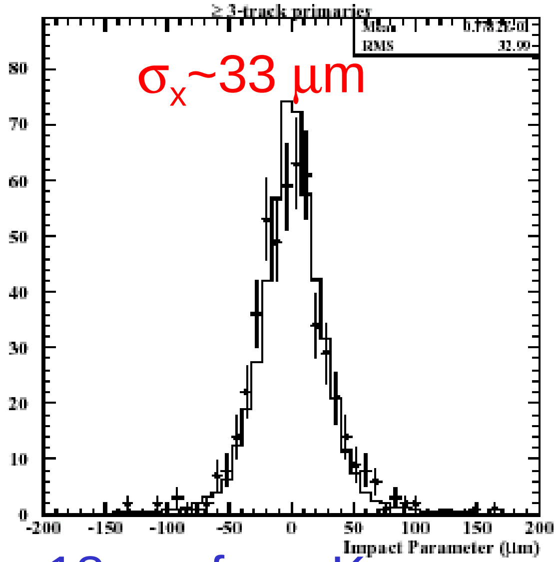
Primary vertex

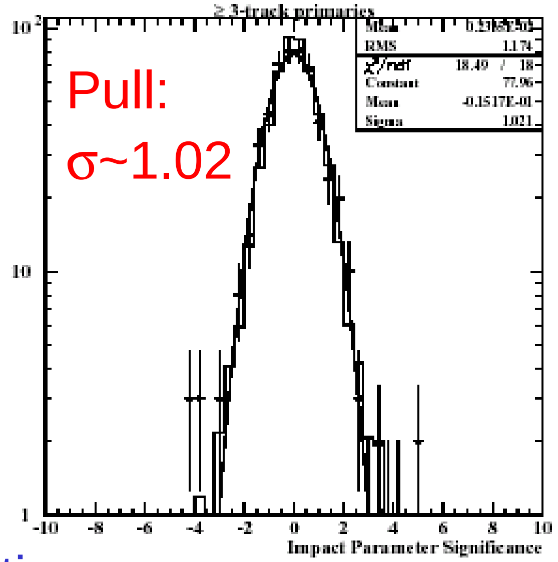
NOMAD-STAR

- Vertex resolution: σ_y = 19 µm



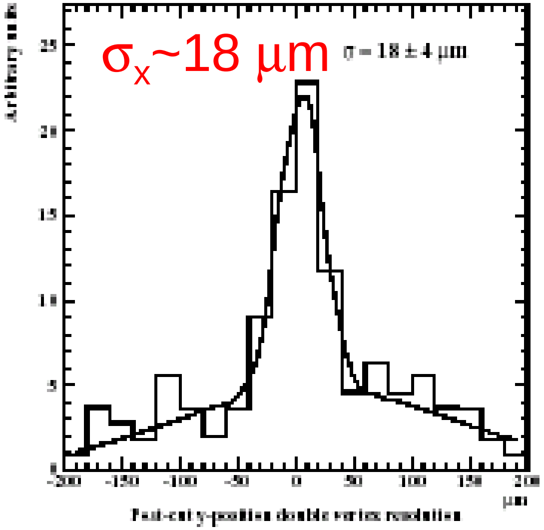
- Impact parameter resolution: 33 µm

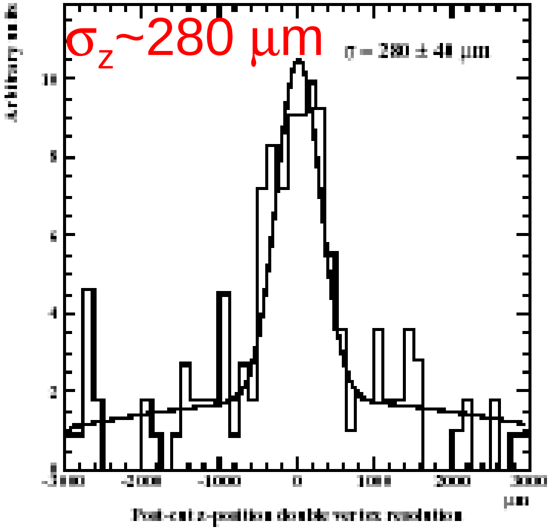

σ_x~33 µm


Pull:

σ~1.02

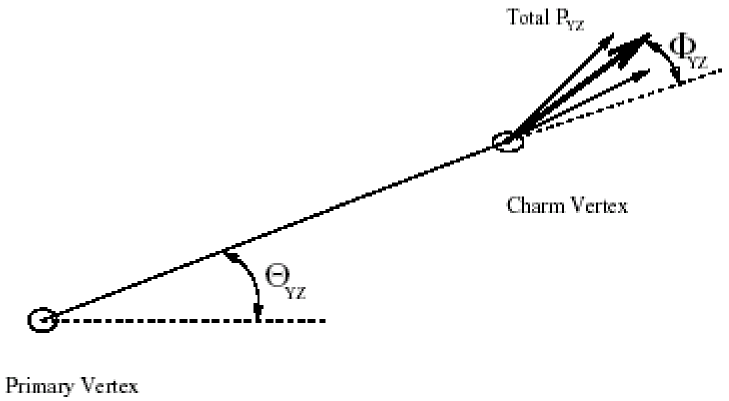
- Double vertex resolution: 18 µm from K_s reconstruction


σ_x~18 µm

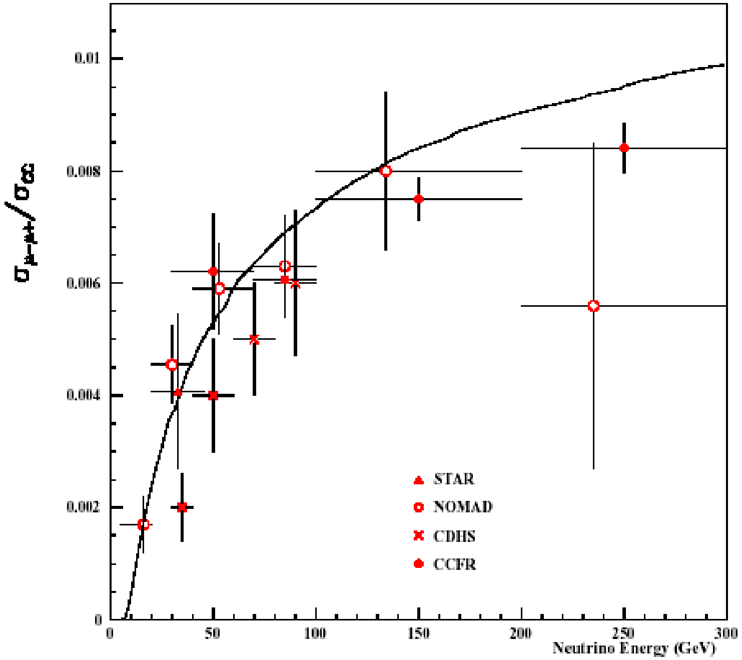

σ_z~280 µm

NOMAD-STAR

- Charm event reconstruction:
  - Implementation of Kalman filter
  - Constrained fit method: extract charm signatures for each charm mass
- Used NOMAD-STAR to search for charm events: marginal statistical accuracy, but was a good proof of principle

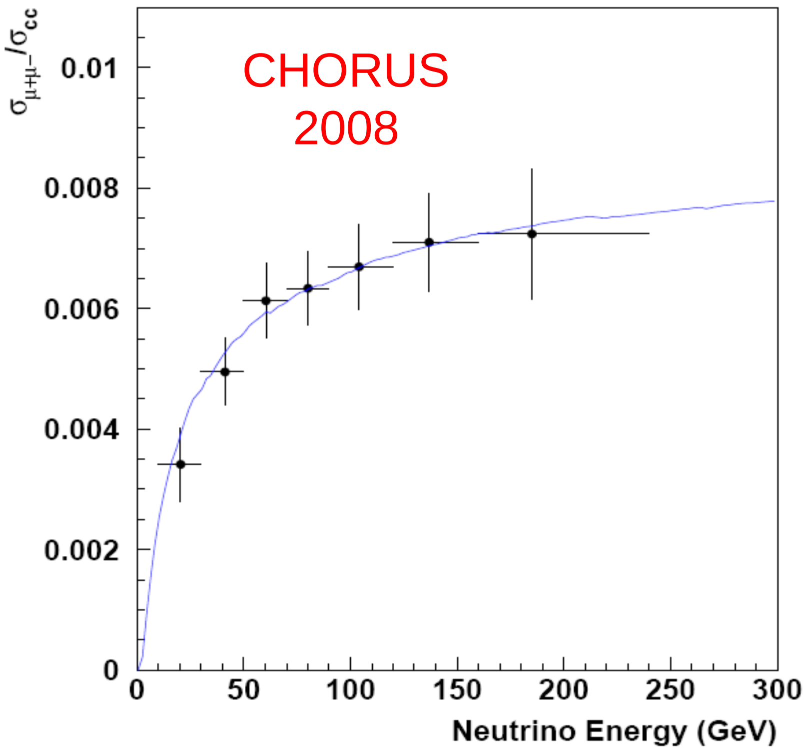


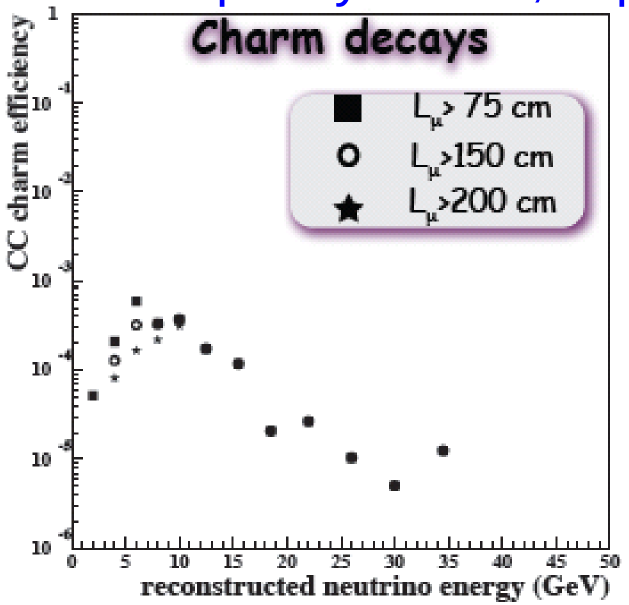
Meson	Num events	Back-ground	Production Rate	Efficiency
D^0	24	13.3	13.3±1.0%	3.5%
D^+	10	3.8	3.8±0.5%	3.5%
D_s^+	11	5.2	5.2±0.6%	12.7%
Total	45	22.3	7.2±2.4%	



Charm measurement at Near Detector

- Amongst other things, we need to measure charm cross-section to validate size of charm background in wrong-sign muon signature
- Charm cross-section and branching fractions poorly known, especially close to threshold

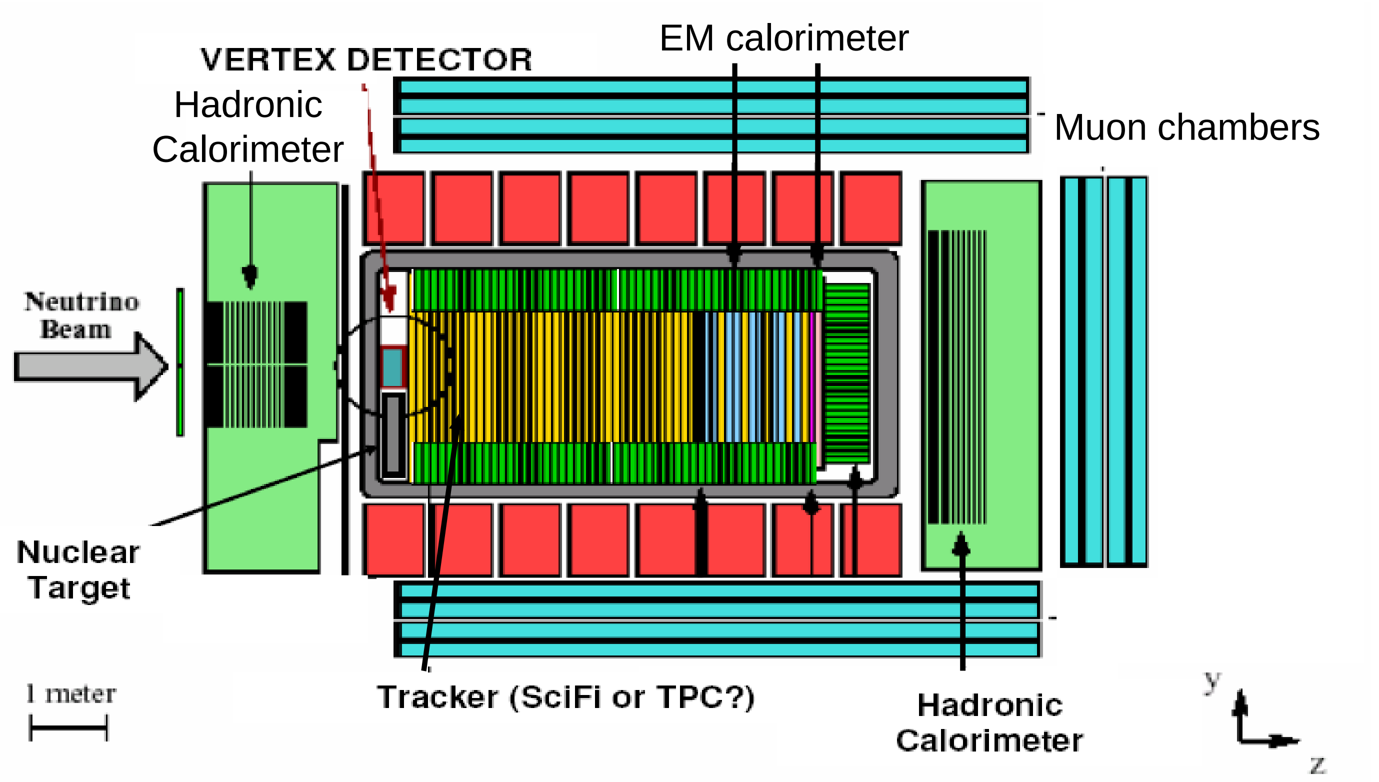




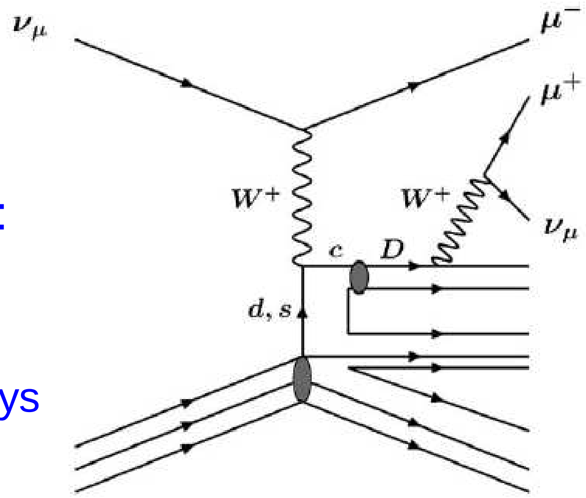
- Semiconductor vertex detector only viable option in high intensity environment (~10^9 ν_μ CC events/year)
- Emulsion would perish

Neutrino Factory Near Detector

- Need to have some vertex detector (like NOMAD-STAR) in front of a magnetised tracking detector with muon ID
- It could look like NOMAD with Silicon vertex detector target, but would need to be made more hermetic to make sure events do not escape sides.



Neutrino Factory Near Detector for taus?



- Rates: approx 10^9 ν_μ CC events/year in 1 ton detector
- Assume 12% eff from NAUSICAA
- Tau looks like charm so charm background a problem
- Inclusive charm production at 27 GeV (from CHORUS): 6.4±1.0%
  - From 10-30 GeV: ~4%→4×10^7 charm events!!
  - Charm produced in CC reaction with d or s quark so always have lepton
  - Associated charm in NC interaction (see charm review De Lellis et al. Phys Rep 399 (2004), 227-320)
  - For anti-ν_e background could create D^- which looks like signal, but need to identify e^+ to reject background!!!
- So, very important to have light detector (ie Scintillating Fibre tracker?) behind vertex detector to identify positron (B-field as well) with high efficiency: assume ~80% (still have 8×10^6 background for 1.2×10^8 signal)
- Then need to use kinematic methods a la NOMAD to reduce background:

$$P_{\mu\tau} < \frac{2.48}{1.2\times10^8\times1.1\%} = 1.9\times10^{-6}$$

Very tough!

Some personal thoughts

- Probably best possibility and sensitivity for MINSIS detector is OPERA-like experiment – can probably achieve ~10^{-6} level.
- However, it would also be a good opportunity for a Liquid Argon detector to do tau search a la NOMAD (maybe not as sensitive but could be complementary, like in the NOMAD/CHORUS approach 15 years ago)
- A TOSCA like detector could also be done for MINSIS – however adding Silicon complicates things and do not gain any more since scanning technology has advanced so much that can potentially scan all emulsion obviating the need for the Si detector
- A Silicon Target only (a la NAUSICAA) has less efficiency but does not rely on emulsion (faster analysis?). Can achieve: ~3×10^{-6}
- At a neutrino factory near detector one can measure charm and taus - I don't think can use emulsion or LAr since rate too high
- If use Vertex Detector+Spectrometer then can detect taus but there is insidious antineutrino charm background. I think we can reduce this with combination of impact parameter+kinematics but sensitivity ~2×10^{-6}

Very preliminary, need to do full simulations to understand better!