New Nu's from the DONUT Experiment

Emily Maher
University of Minnesota

DONUT Collaboration

Aichi Univ. of Education
K. Kodama, N. Ushida

Kobe University
S. Aoki, T. Hara

Nagoya University
N. Hashizume, K. Hoshino, H. Iinuma, K. Ito,
M. Kobayashi, M. Miyanishi, M. Komatsu,
M. Nakamura, K. Nakajima, T. Nakano, K. Niwa,
N. Nonaka, K. Okada, T. Yamamori, Takahashi

Univ. of California/Davis
P. Yager

Fermilab
B.Baller, D.Boehnlein, W.Freeman,
B.Lundberg, J.Morfin, R. Rameika

Kansas State Univ.
P. Berghaus, M. Kubanstev, N.W. Reay,
R. Sidwell, N. Stanton, S. Yoshida

Univ. of Minnesota
D. Ciampa, C. Erickson, K. Heller, R. Rusack,
R. Schwienhorst, J. Sielaff, J. Trammell, J. Wilcox
E. Maher

Univ. of Pittsburgh
T. Akdogan, V. Paolone

Univ. of South Carolina
A. Kulik, C. Rosenfeld

Tufts University
T. Kafka, W. Oliver, J. Schneps, T. Patzak

Univ. of Athens
C. Andreopoulos, G. Tzanakos, N. Saoulidou

Gyeongsang University
J.S. Song, I.G. Park, S.H. Chung

Kon-kuk University
J.T. Rhee

Outline

- Motivation/Goals/Status
- Experimental Setup
- Data Analysis
- Results (Nu Tau Events & Charm Events)
- Individual Event Probabilities
- Cross Section Measurement
- Conclusion

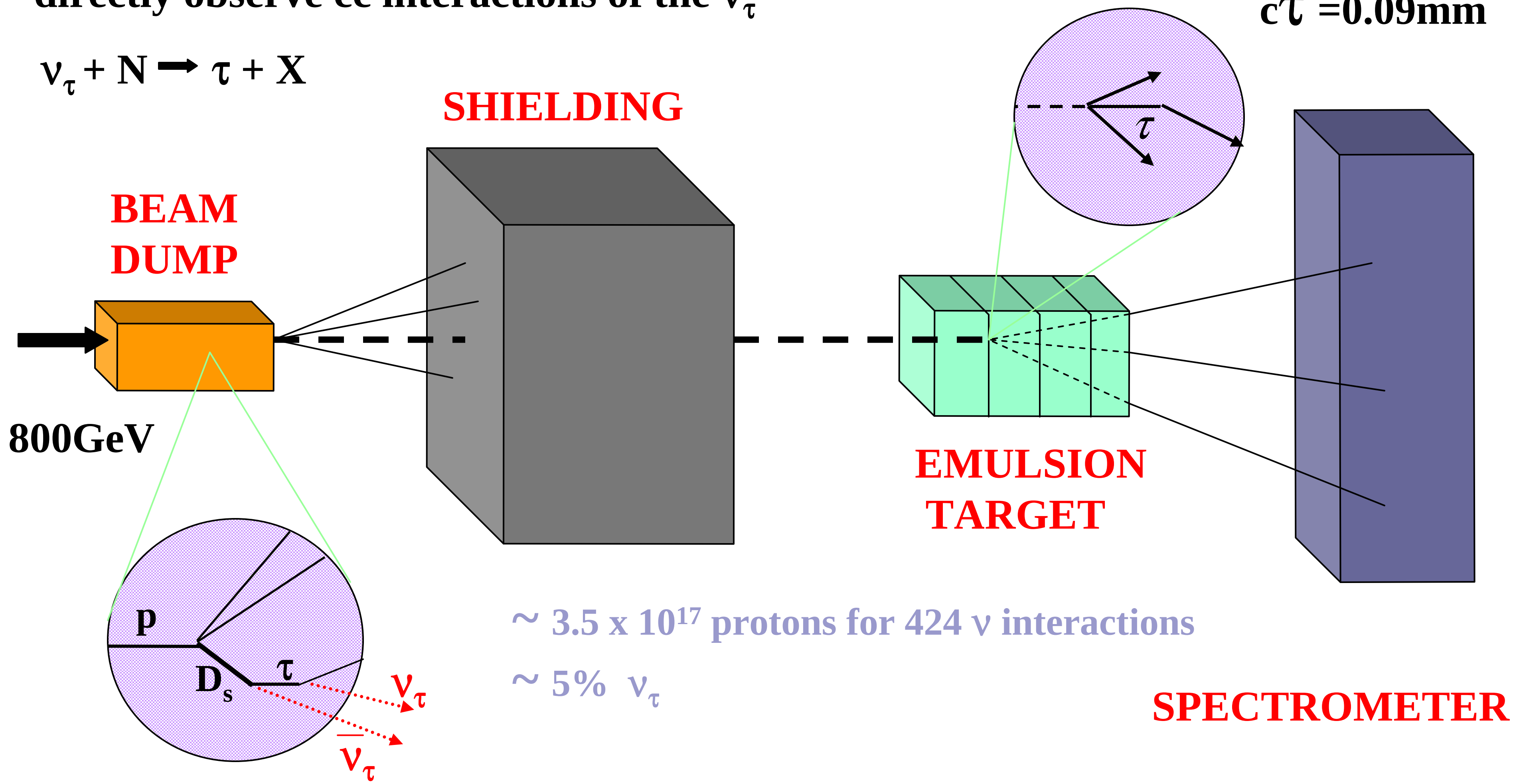
Goals/Motivation/Status

- Goals
  - Directly observe the charged-current interaction of the tau neutrino – Attempted but never sucessfully
  - Answer the question: is the tau neutrino is a standard model particle?
- Motivation
  - Check standard model
  - Neutrino oscillation
- Status
  - Have observed tau neutrino interaction (Phys. Lett. B 504 (2001))
  - Upper limit on tau neutrino magnetic moment (Phys. Lett. B 513 (2001))
  - Paper on technical details of emulsion target (NIM A 493 (2002)
  - Paper on technical details of spectrometer (ref?)
  - Currently working toward cross section measurement for tau neutrino – which will show whether or not the tau neutrino is a standard model particle

Experimental Setup – Block Diagram

directly observe cc interactions of the ν_τ

$\nu_\tau + N \rightarrow \tau + X$



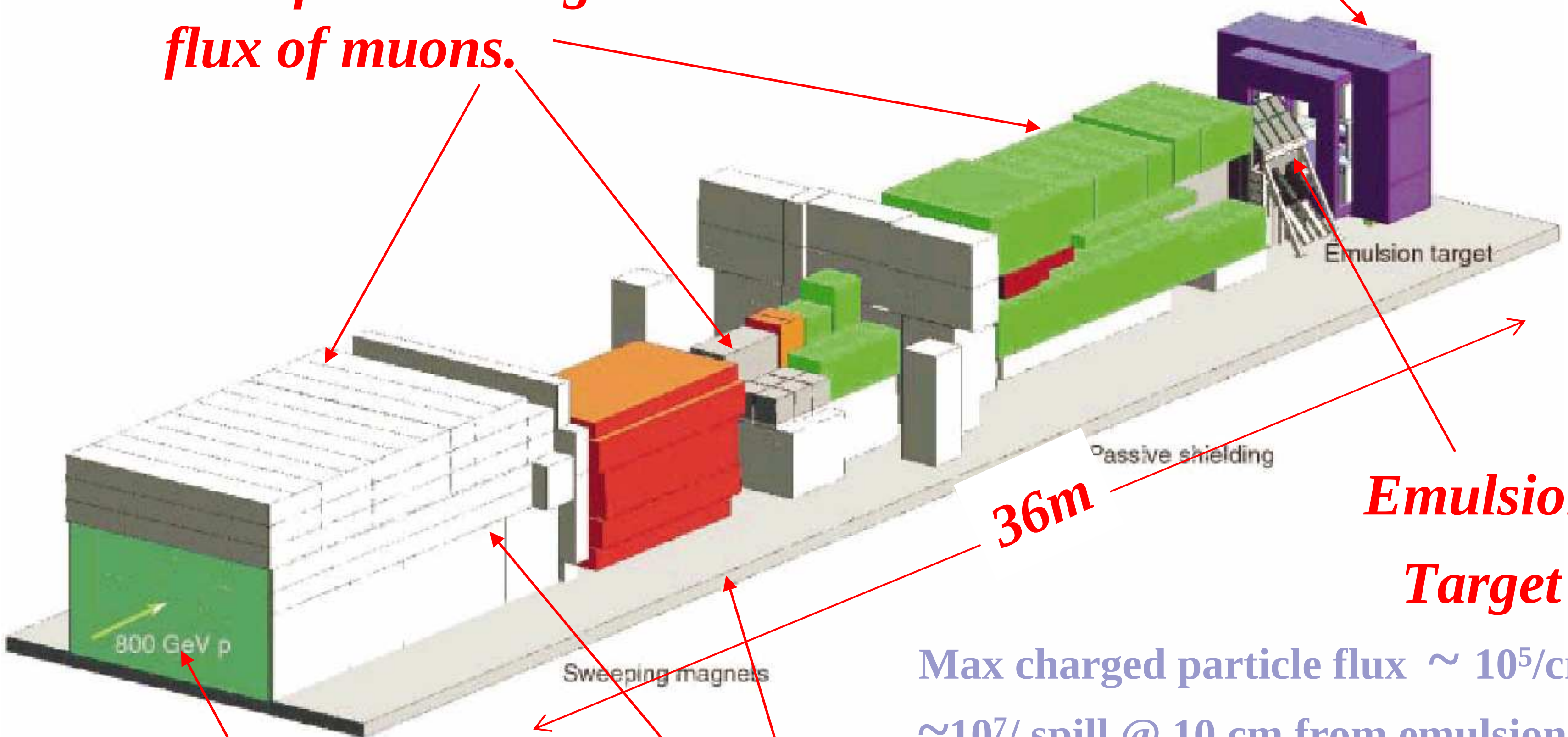
~ 3.5 x 10^{17} protons for 424 ν interactions

~ 5% ν_τ

Shielding- Purify the Neutrino Beam

Shielding to protect emulsion from the high flux of muons.

Spectrometer



Emulsion Target

Max charged particle flux ~ $10^5/cm^2$

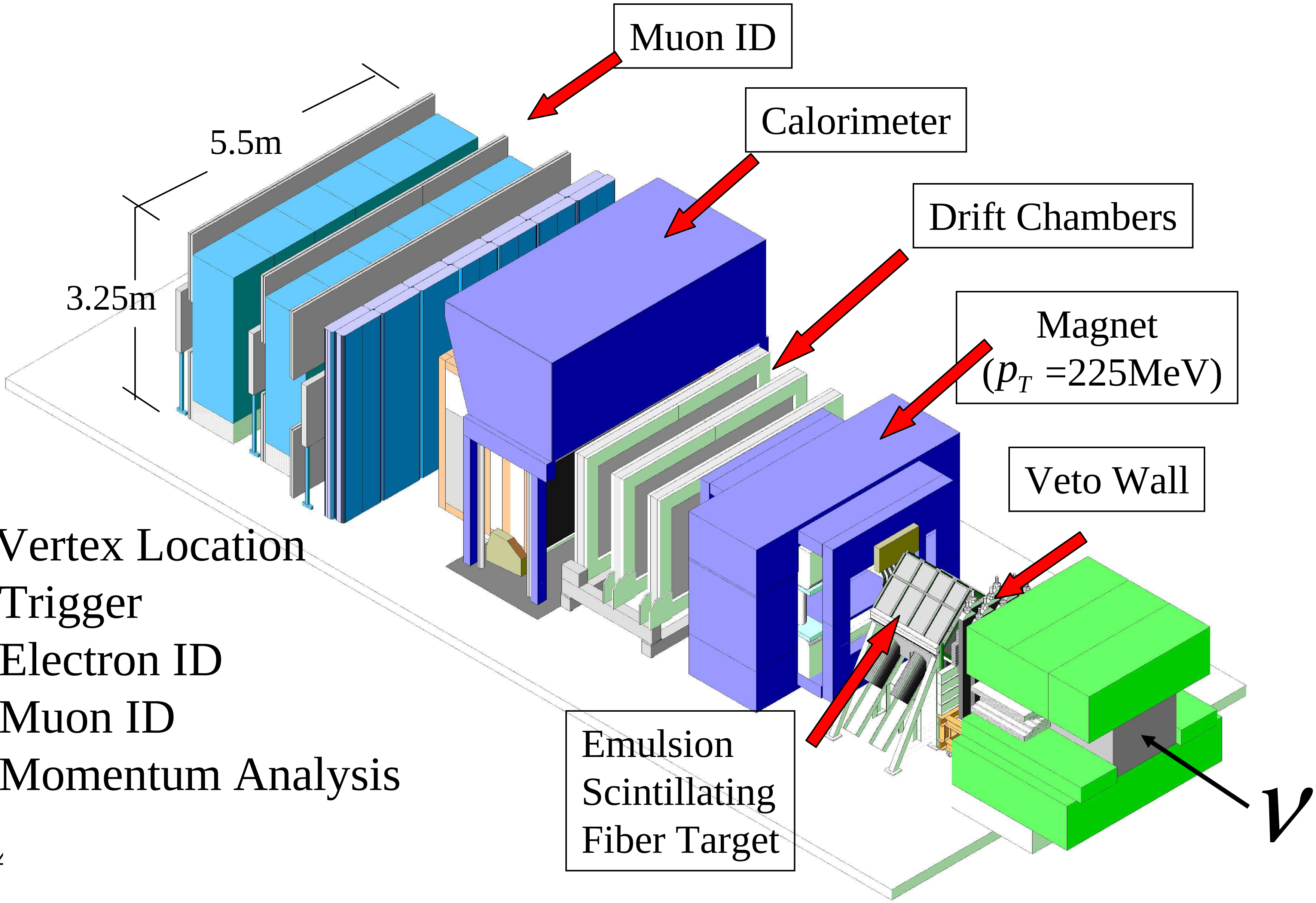
~10^7/ spill @ 10 cm from emulsion edge

~10^{12} / spill @ 2 m

Primary Target

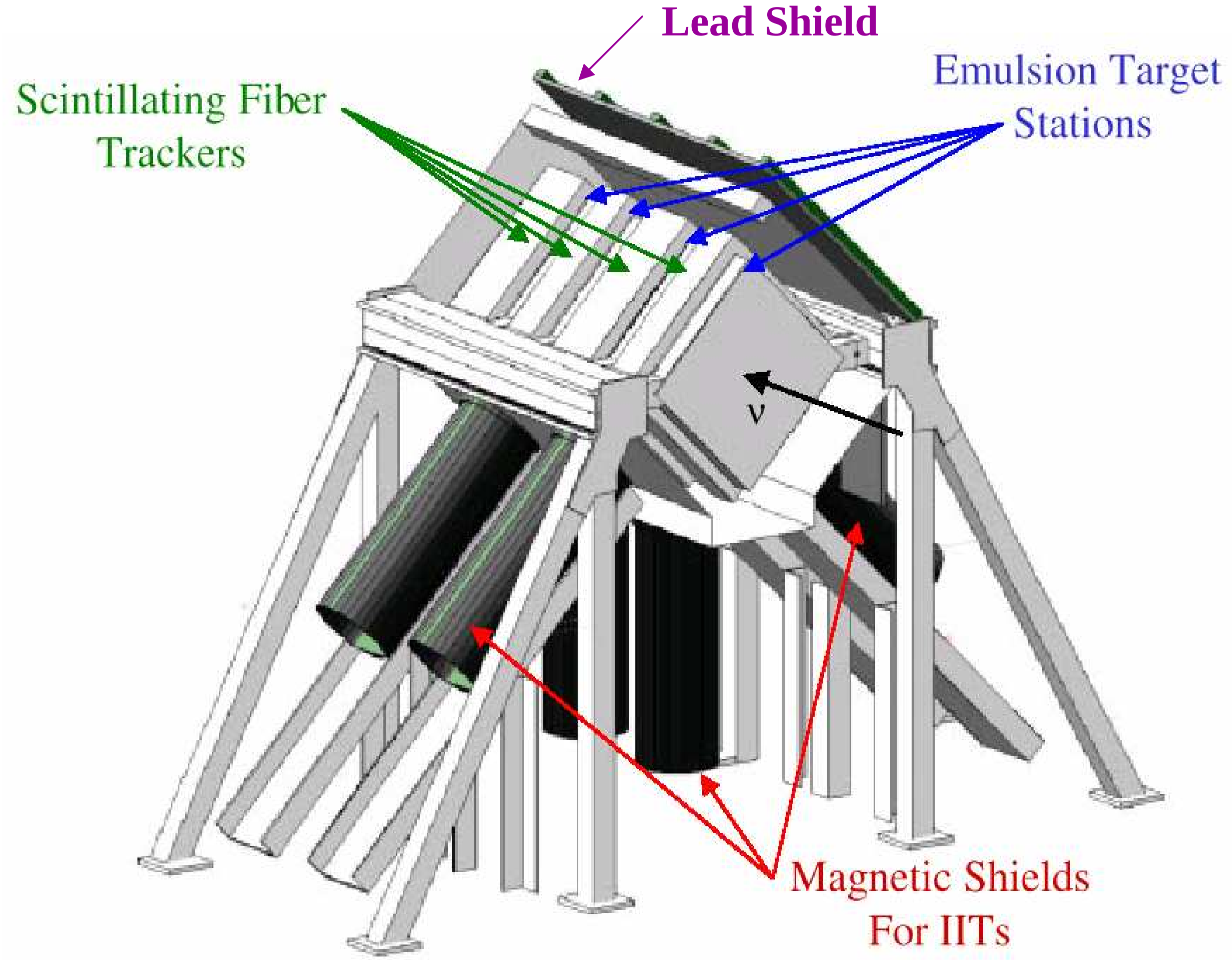
Sweeping Magnets

Spectrometer



- Vertex Location
- Trigger
- Electron ID
- Muon ID
- Momentum Analysis

Emulsion Target Stand



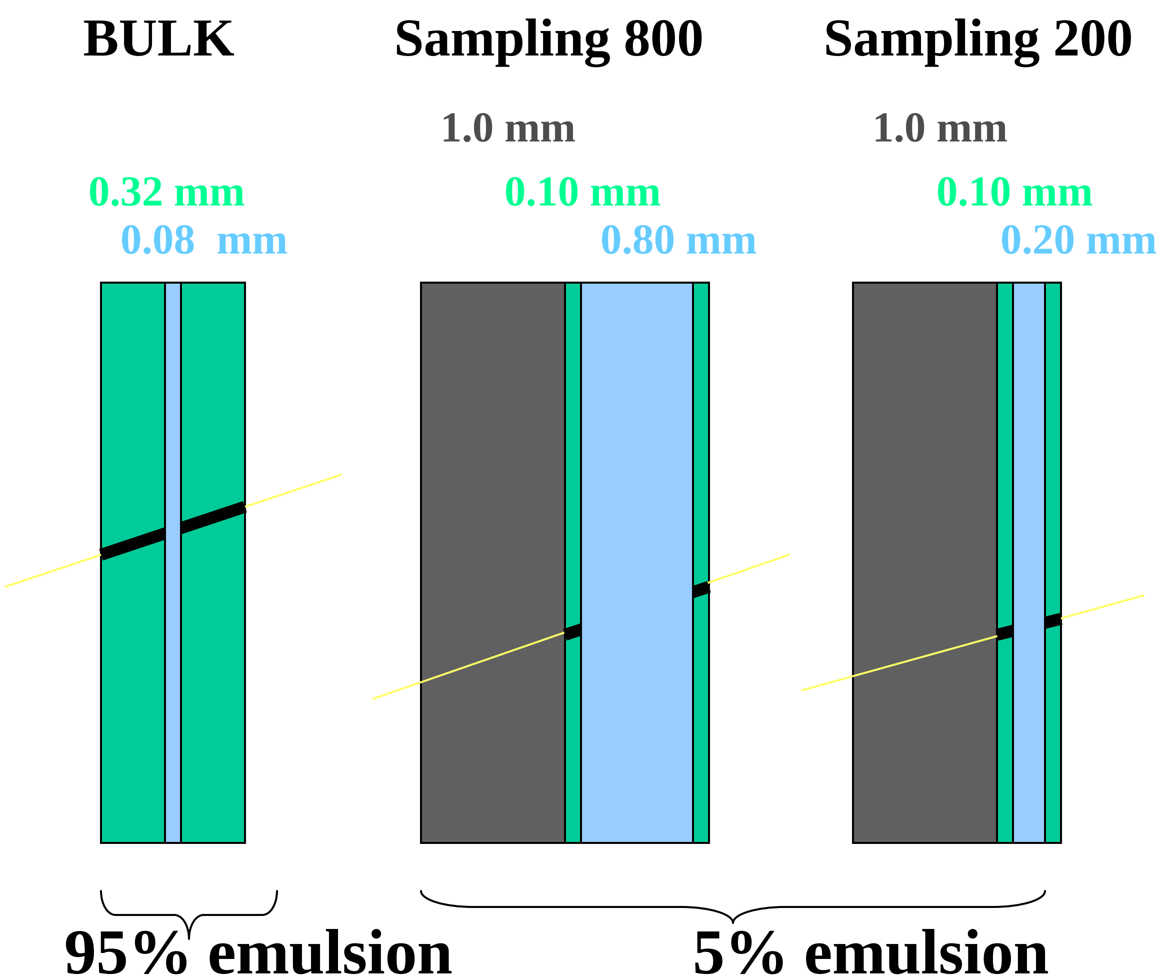
260 kg total mass

500μ Scintillating Fibers

Image Intensifier - CCD Readout.

Emulsion Target Designs

Emulsion modules consist stacks of sheets made of emulsion, acrylic, and steel. Three configurations were used.



- AgBr suspended in a gel (Fuji ET7C) coated on plastic sheets.
- 29±2 grains per 100μm for minimum ionizing track

Resolution

Spatial Resolution: .3μm

Overview of Analysis

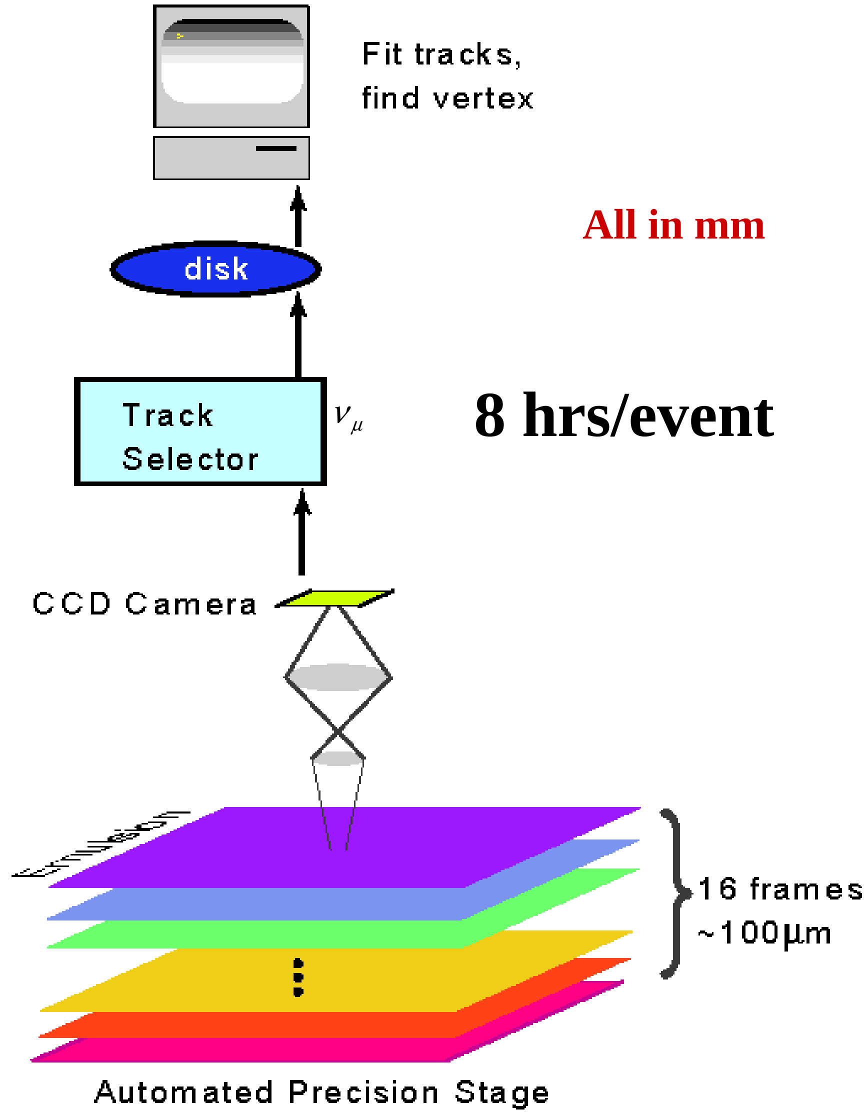
• **Predict interaction point in emulsion from spectrometer tracks** **(software + humans)**

• **Define a volume in emulsion around predicted interaction point. Digitize all track segments in emulsion volume** **(hardware processor at Nagoya University)**

• **Search digitized emulsion data for interaction** **(software pattern recognition)**

•**Use spectrometer to characterize event** (ν_e, ν_μ)

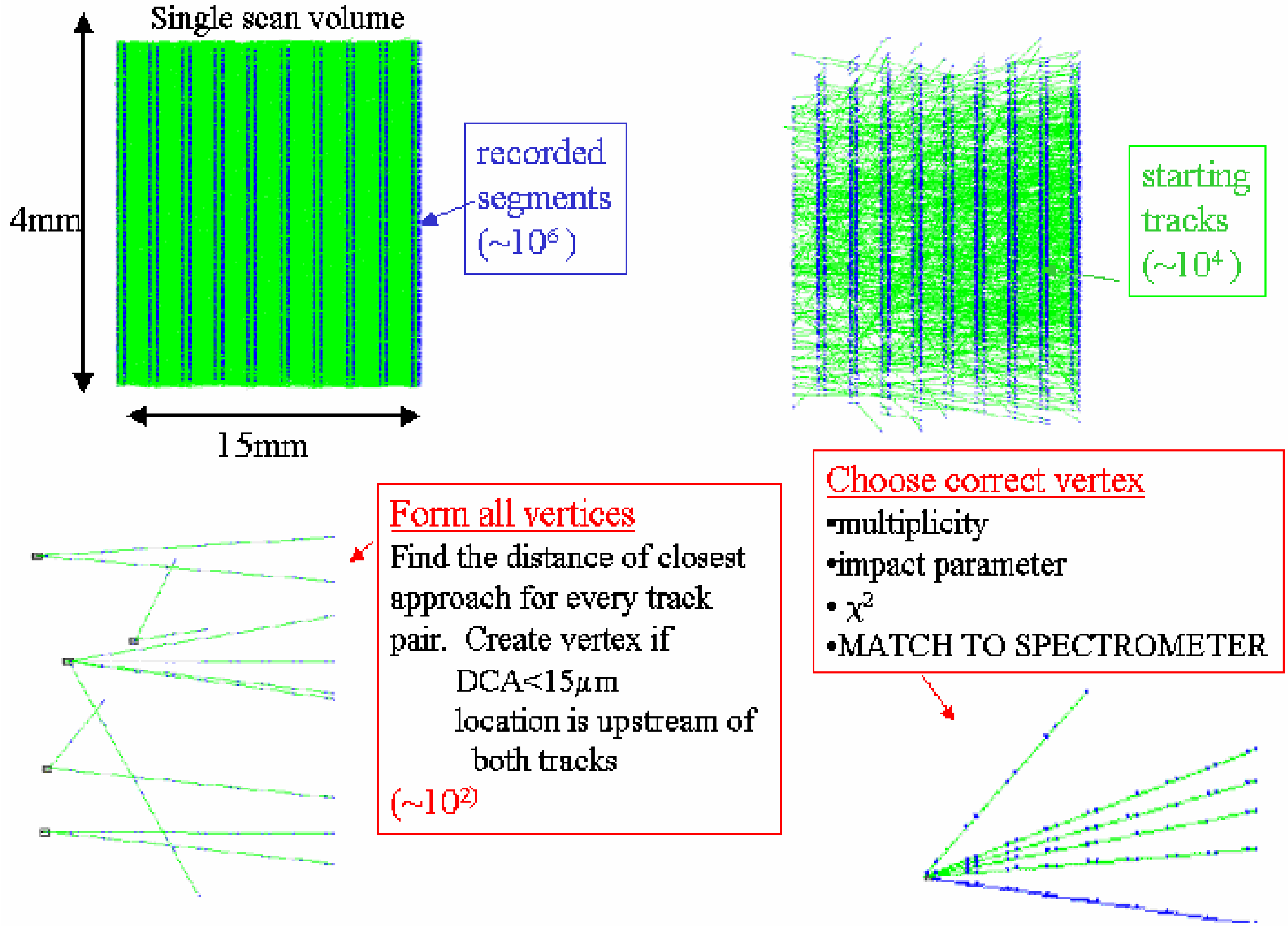
• **Use emulsion data to locate kinks, tridents** **(software pattern recognition)**



All in mm

8 hrs/event

Locating Vertices in Emulsion Data



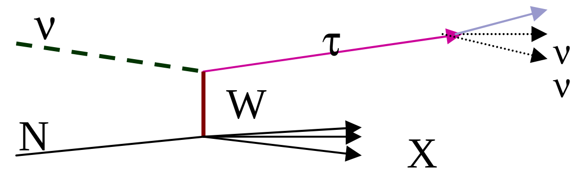
Segment detection efficiency >98%

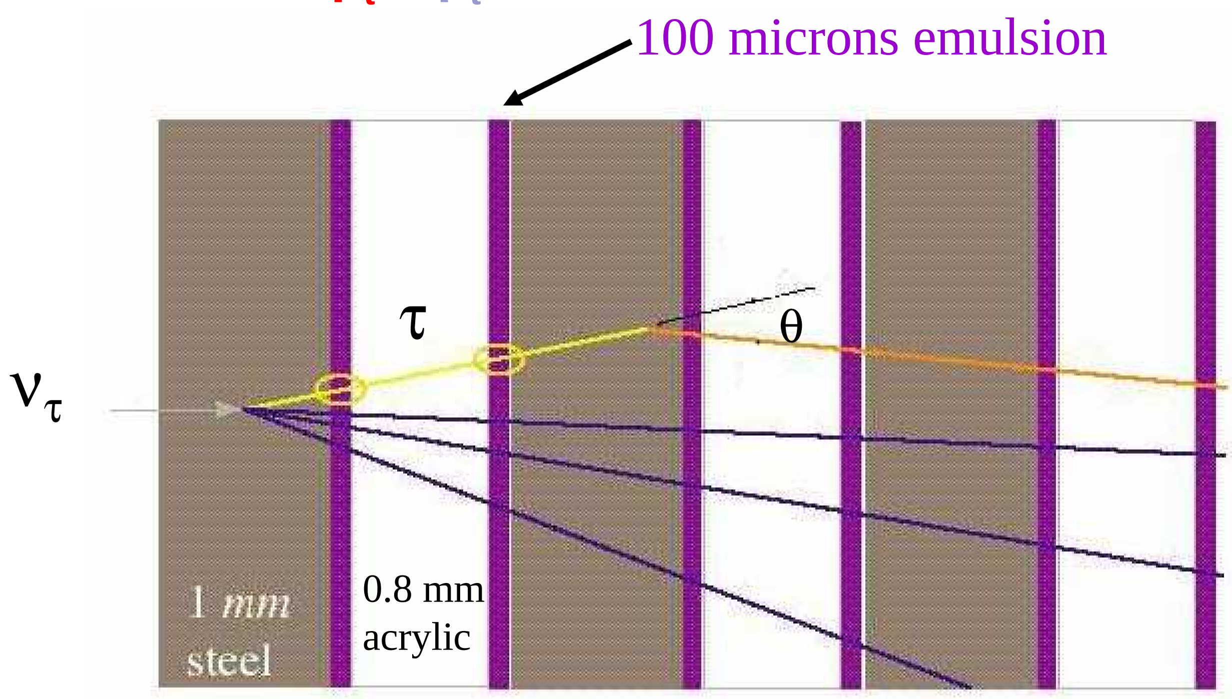
Criteria – Finding ν_τ Interactions

- **No *e*, μ from primary vertex**
- **At least one segment on parent**

  76% of τ's have visible track
- **Decay with one or three charged products**

  85% of decays are single charge
- **Minimum p_t - p_t > 250 MeV/c**





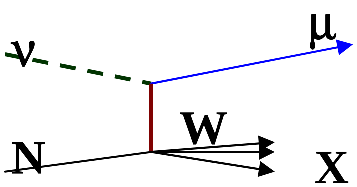
Single Prong

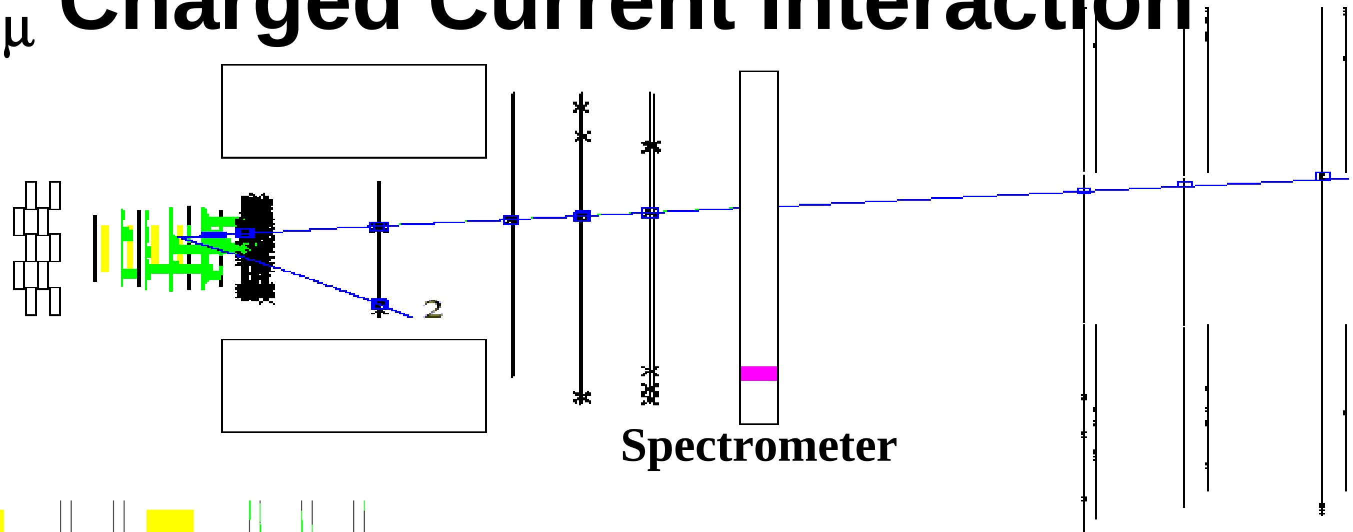
- **Short decay length**

  length < **10 mm** **(mean 2.5 mm)**
- **Small production angle**

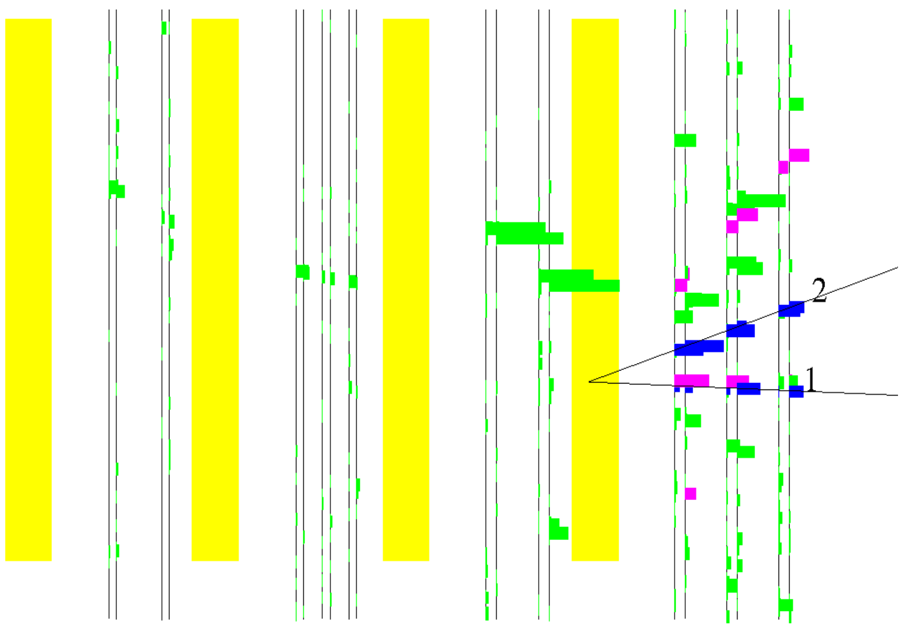
  angle < 200 mr **(mean 40 mr)**

Results ν_μ Charged Current Interaction

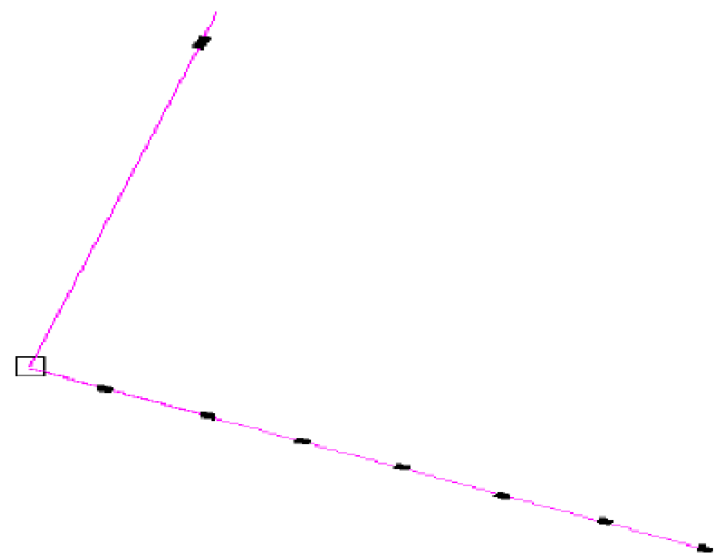




Spectrometer

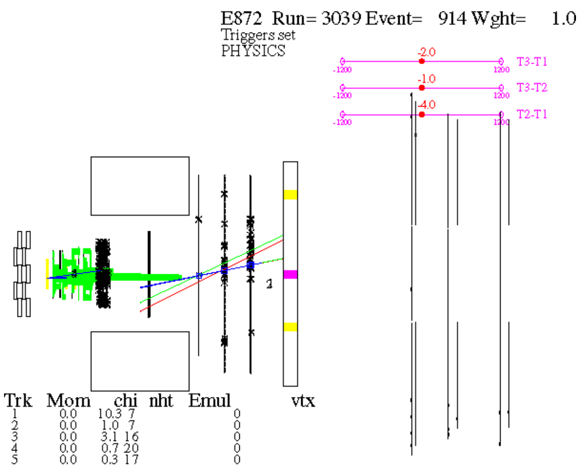


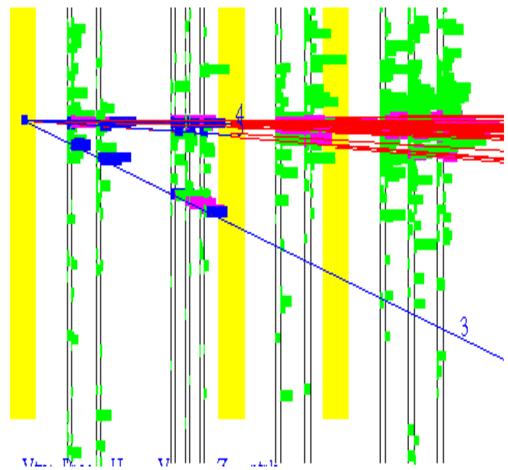
Fiber tracker

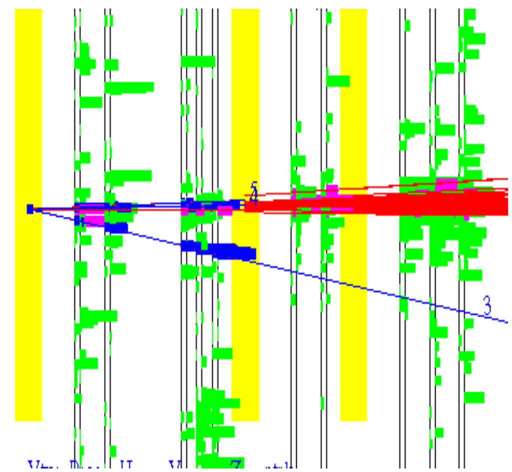


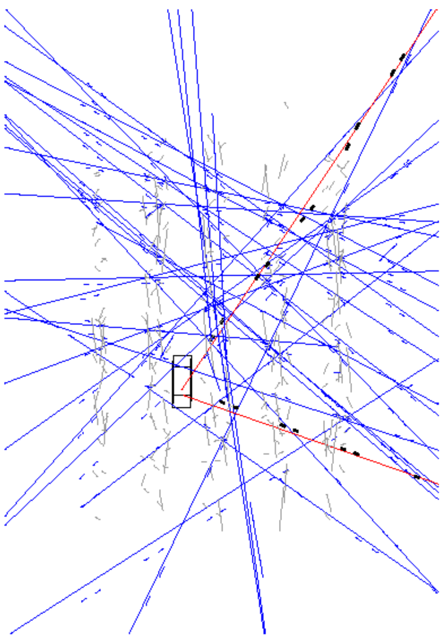
Emulsion

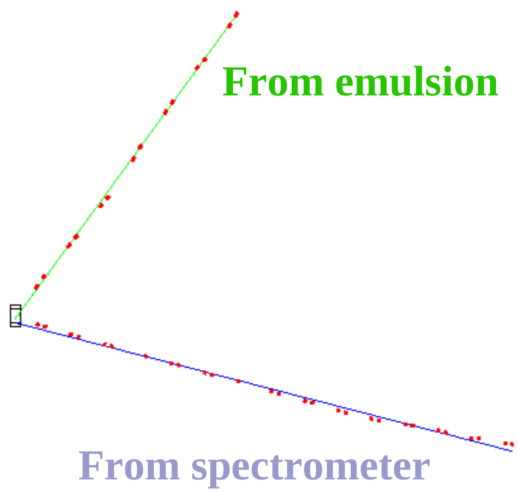
Results ν_e Charged Current Interaction

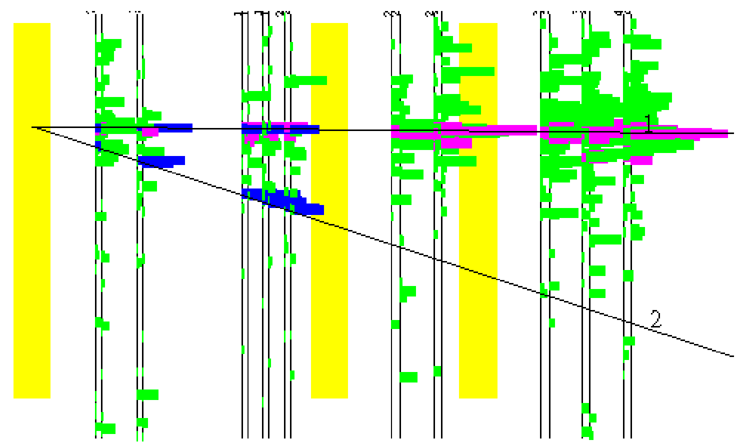












Emulsion tracks to spectrometer

Data Analysis Status – Then and Now

6.6×10^6 triggers

1026 | 898 | predicted vertices from spectrometer

812 | 699 | within fiducial volume

633 | 511 | digitized emulsion data exists

633 | 451 | emulsion vertex location attempted

424 | 264 | vertex found

424 | 203 | systematic decay search

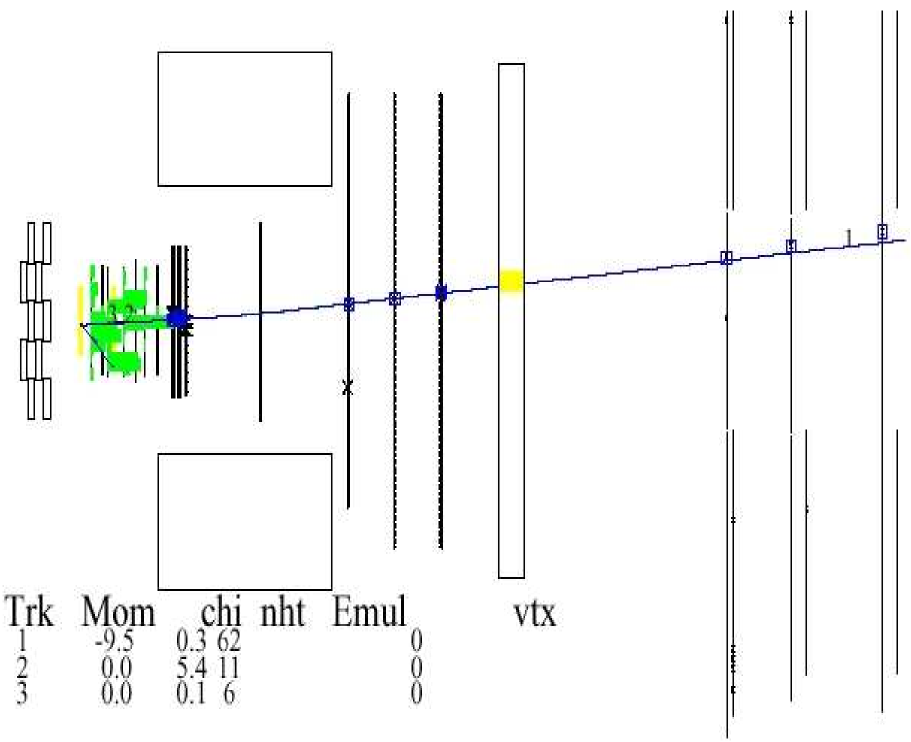
6 | 4 | $\nu\tau$ candidates

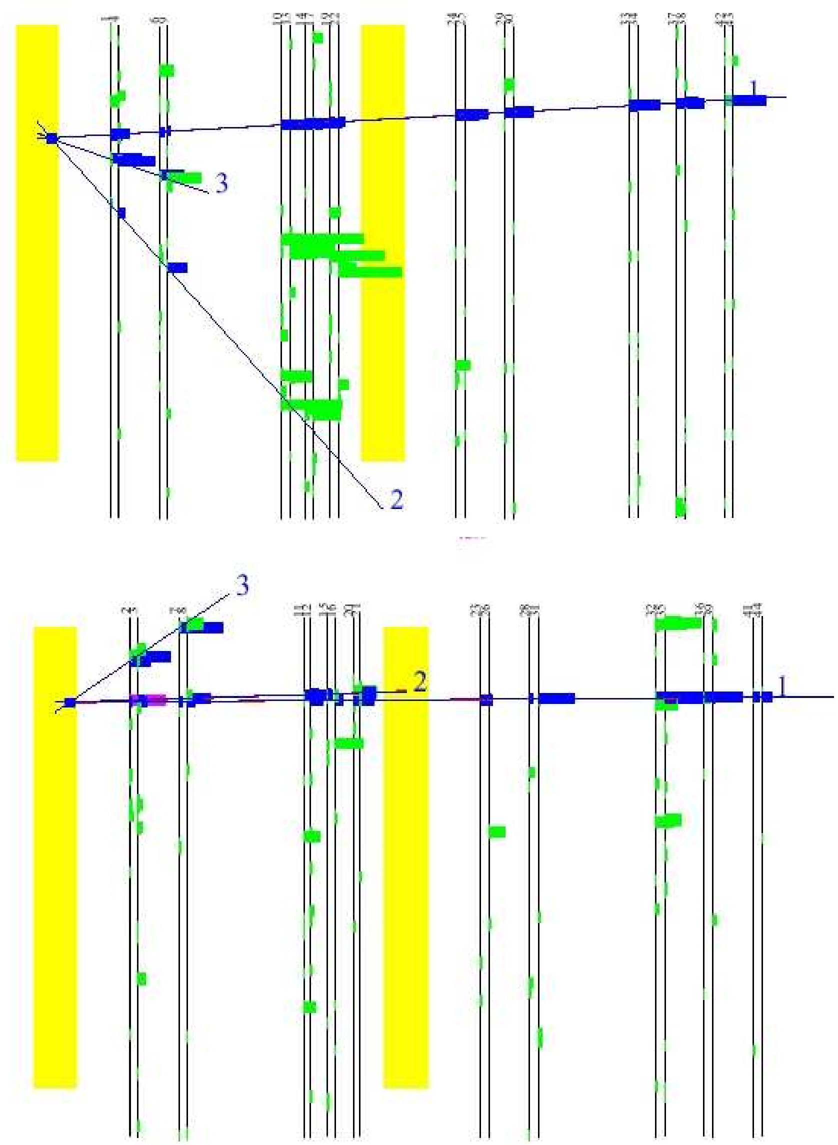
67% | 59%

Location efficiency

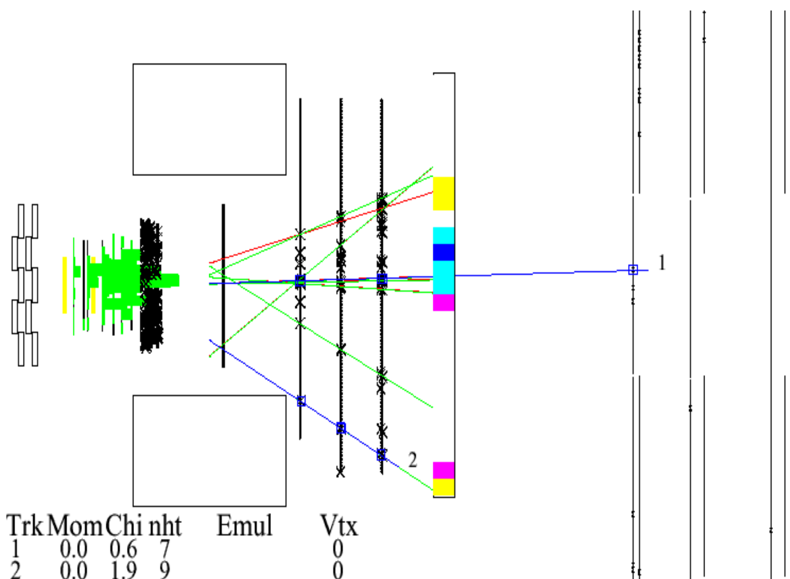
7 charm candidates

Atypical Event – Emulsion Data, Not Located

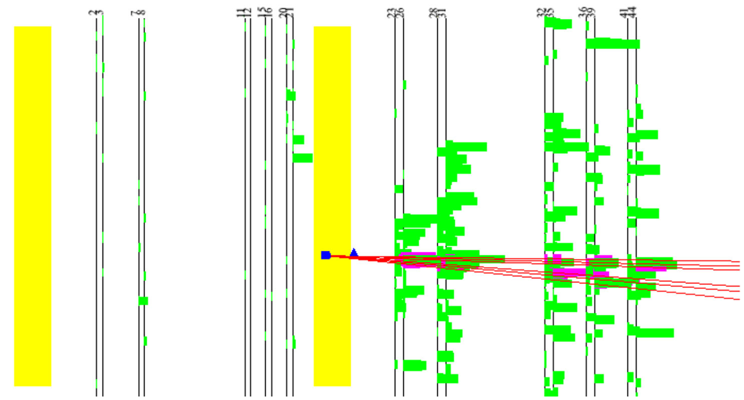




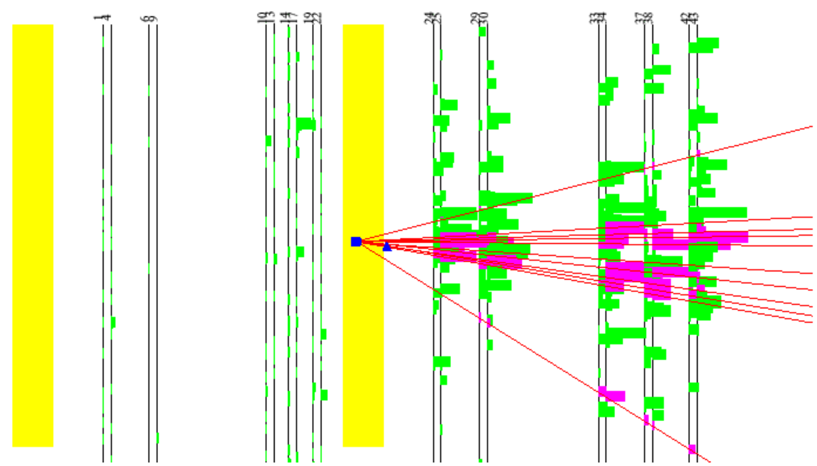
Typical Event – Emulsion Data, Not Located



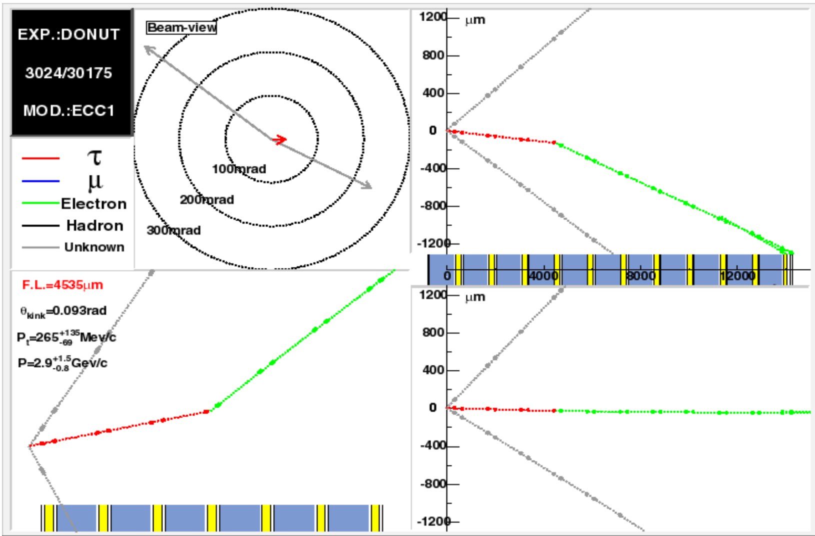
U View

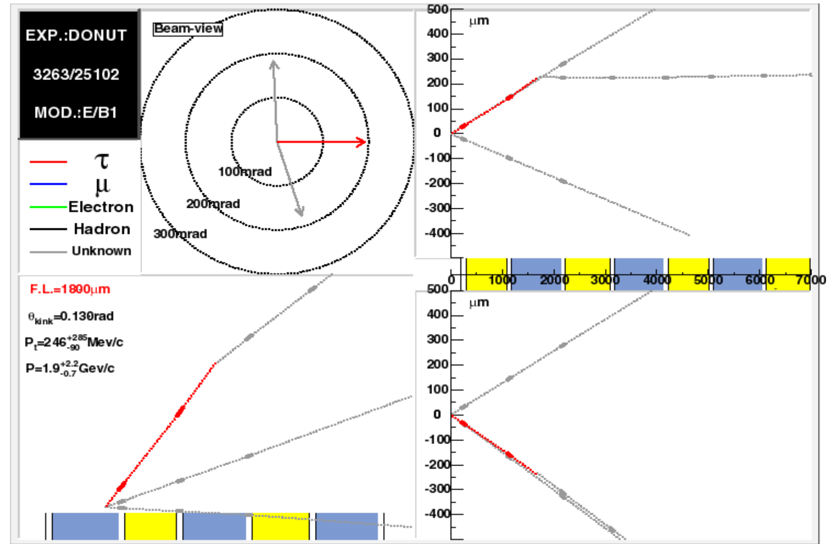


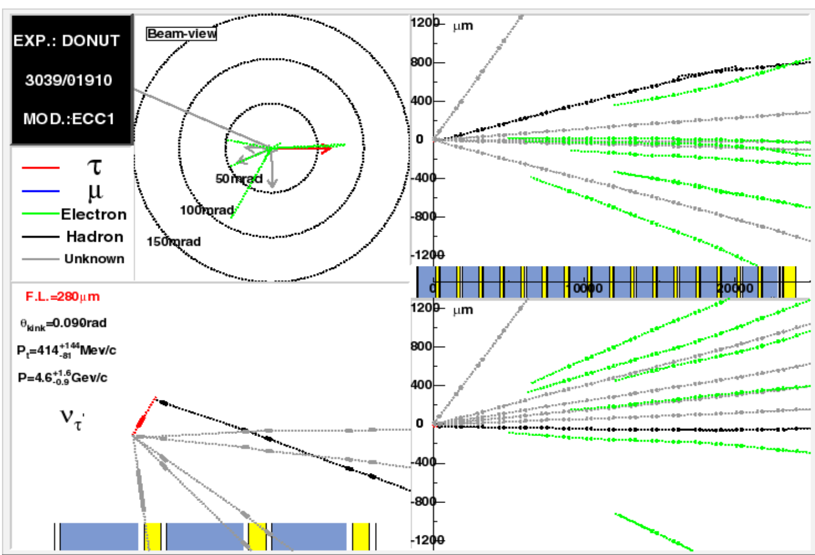
V View

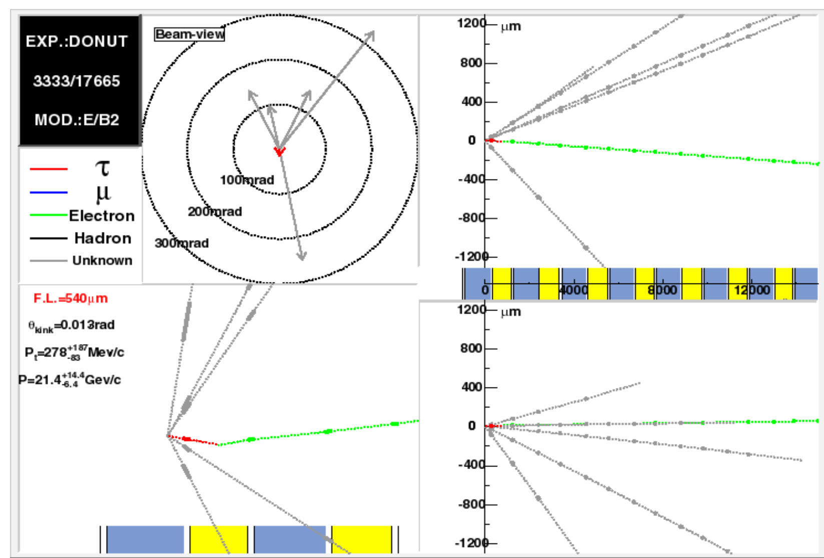


Phase 1 ν_τ Candidates

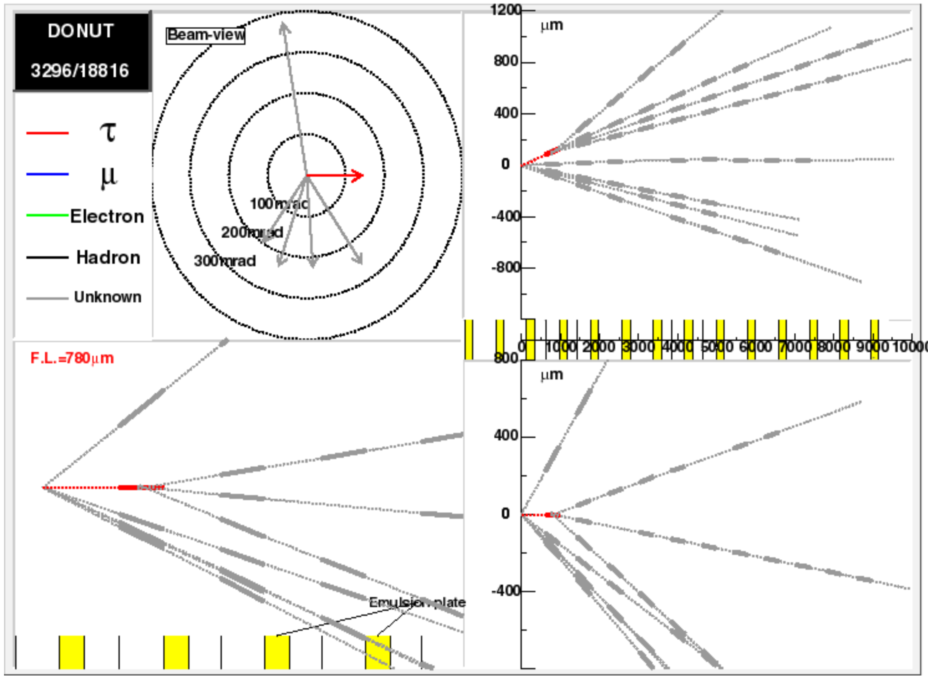


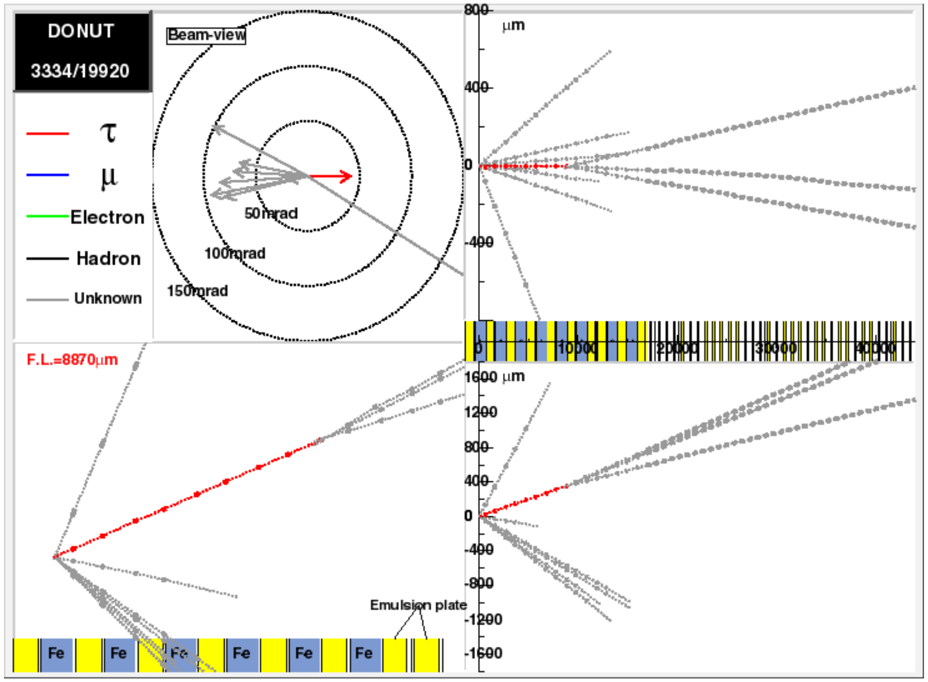






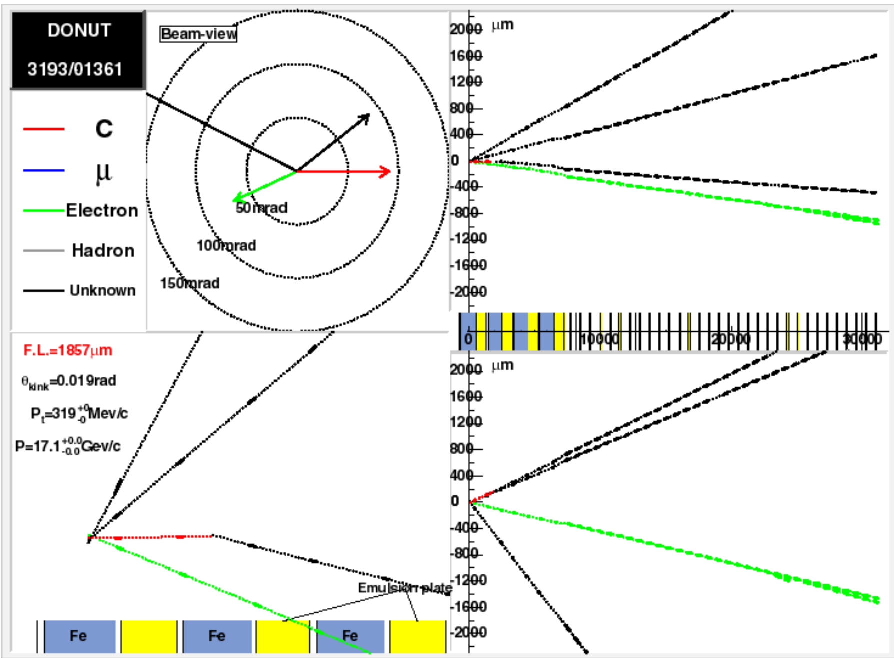
Phase 2 ν_τ Candidates

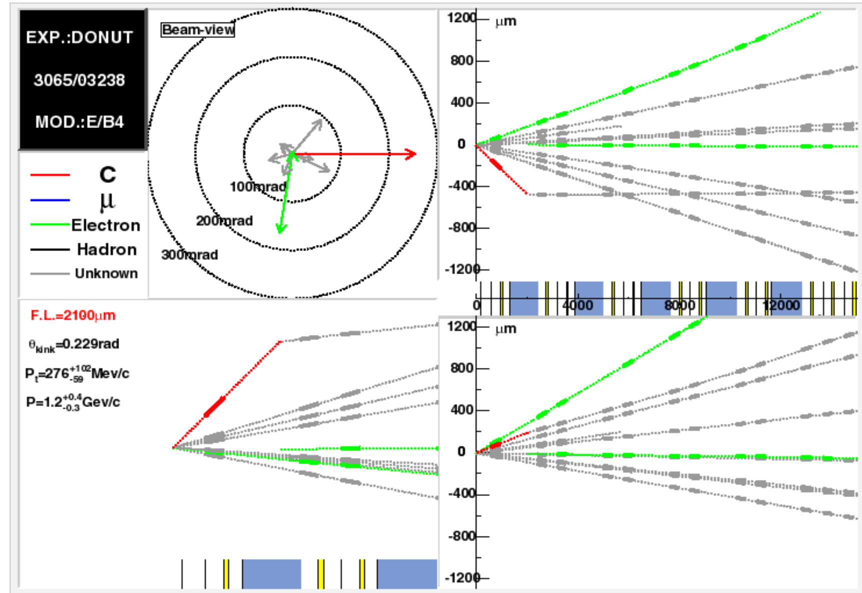


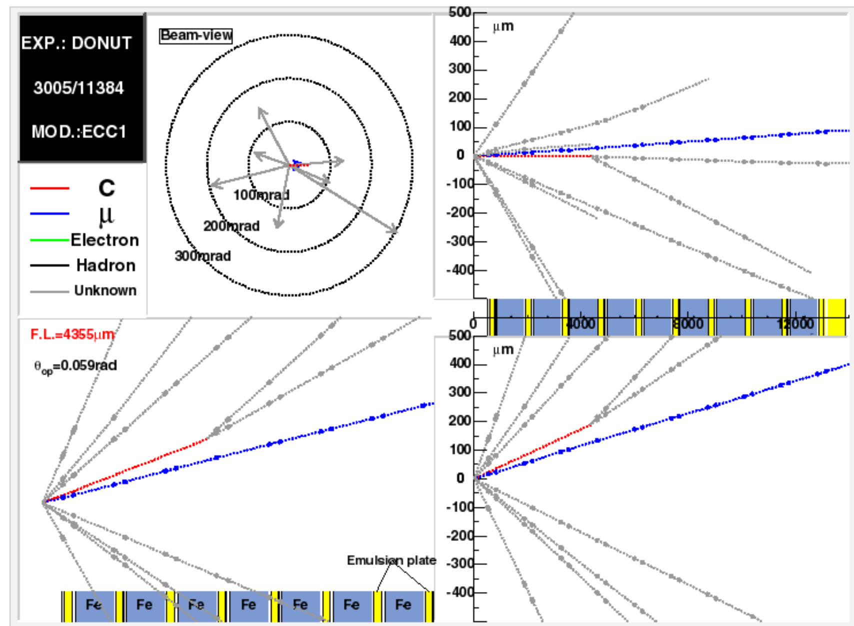


Results

Charm Candidates







Individual Event Probabilities
How Many Events Do We Expect?

We expect 14.6 tau neutrino charged current interactions.

Of those ~85% will be single prong and ~15% will be tridents events.

We expect 12.4 single prong events and 2.2 trident events.

Of the 12.4 single prong events, the probability of passing the selection cuts is 0.52.

So we expect to observe 6.4 single prong events. We observe 4 events.

Of the 2.2 trident events, the probability of passing the selection cuts is 0.90.

So we expect to observe 2 trident events. We observe 2 events.

Individual Event Probabilities
How Many Background Events Do We Expect?

For the 424 neutrino interactions we can calculated the expected number of background events.

$N_{bkg\_single} = 0.8$ and $N_{bkg\_trident} = 2.0$ (1 interaction in Fe, 1 charm).

1. A signal of 4 single prong events with an expected background of 0.8 events

   A signal of 2 trident events with an expected background of 2.0 events

   The Poisson probability of all signal events being background

	Single Prong Events	Trident Events
$f(N:\mu) = \dfrac{\mu^N \cdot e^{-\mu}}{N!}$	$f(4:0.8) = \dfrac{\mu^N \cdot e^{-\mu}}{N!} = 0.008$	$f(2:2) = \dfrac{\mu^N \cdot e^{-\mu}}{N!} = 0.27$

2. The above method is based on applying cuts to the data set. If we could use a different analysis which uses the events' topology, the analysis would contain more information, so it would be more accurate. This analysis will give a relative probability of each candidate being a tau neutrino event, which can be used to calculate a probability that all of the events are background. Since each event is a independent, the probability that all events are background is calculated using the following equation:

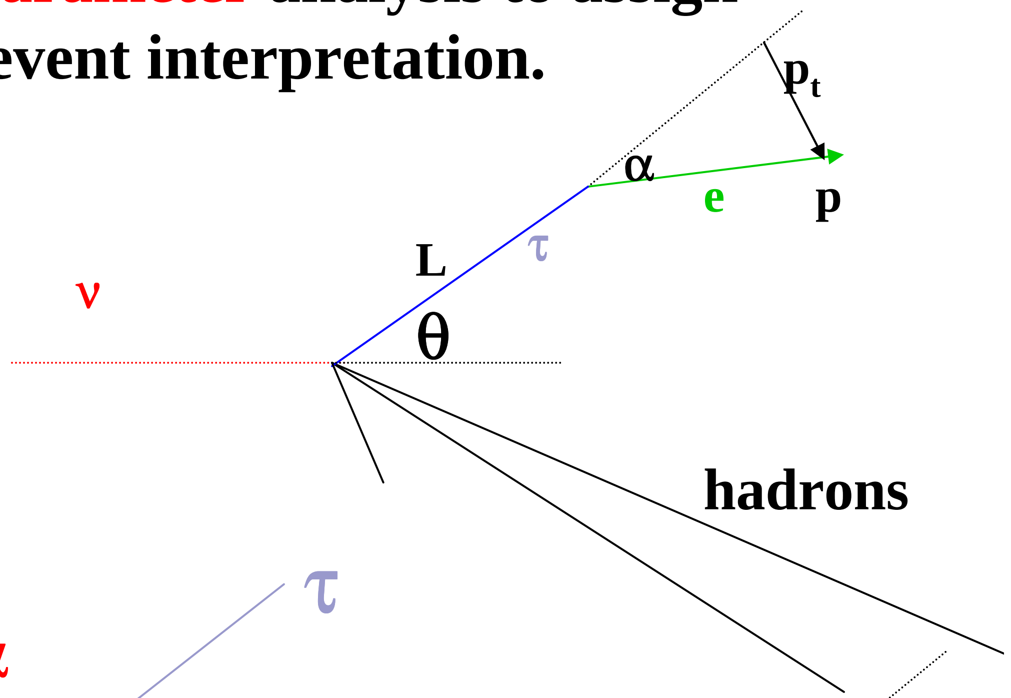
$$P_{all\_bkg} = \prod_i (1 - P(i \mid \nu_\tau))$$

Individual Event Probabilities - Observables

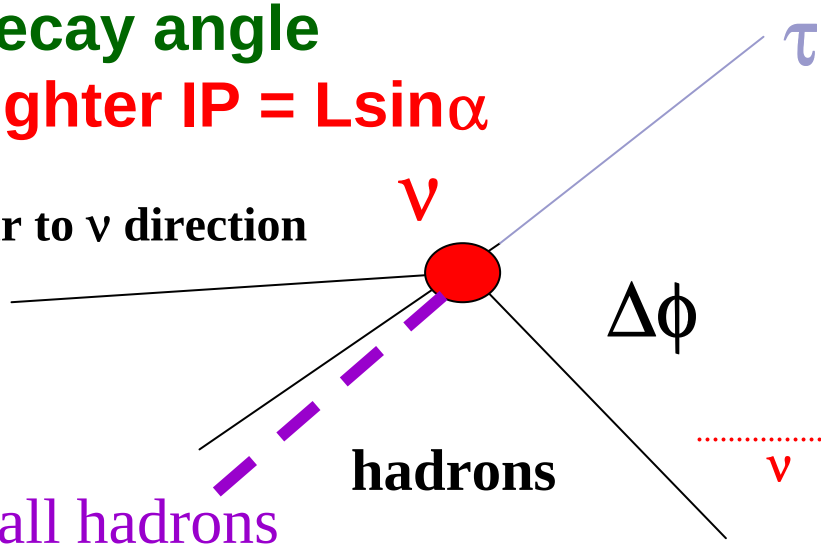
Use 4-parameter or 5-parameter analysis to assign probabilities to event interpretation.

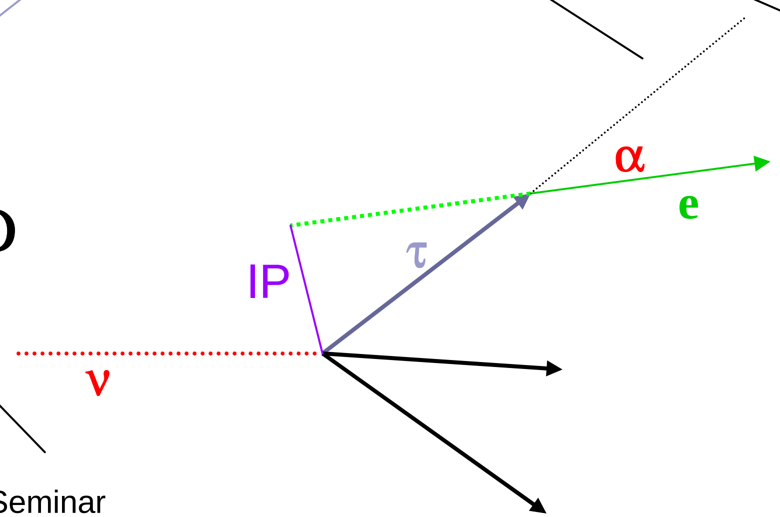
Parameters

- Track production angle θ
- Event angular symmetry Δϕ
- Track decay length L
- Daughter momentum
- Daughter decay angle
- Sum of daughter IP = Lsinα



View perpendicular to ν direction





Vector sum of all hadrons

Individual Event Probabilities

$$P(x\,|\,\text{event}_i) = \frac{A_i \cdot PDF_i(x)}{\sum_j A_j \cdot PDF_j(x)}$$

P = The probability of a set of observables, *x*, being a result of event$_i$, where $i \in \{\nu_\tau \text{cc, charm, hadronic interaction}\}$.

Two inputs for each event type:

1. A_i <u>prior probability</u>:

   Knowledge of the likelihood of each event *i*

   Relative Normalization (aka N_{signal}, $N_{charm\ bkg}$, $N_{int.\ bkg}$),

2. $PDF_i(x)$: <u>probability density function</u>

   Probability of finding event in (x, $x+\Delta x$)

   where *x* is a 4- (for trident events) or 5- (for single prong events) tuple of parameters specific to the individual event

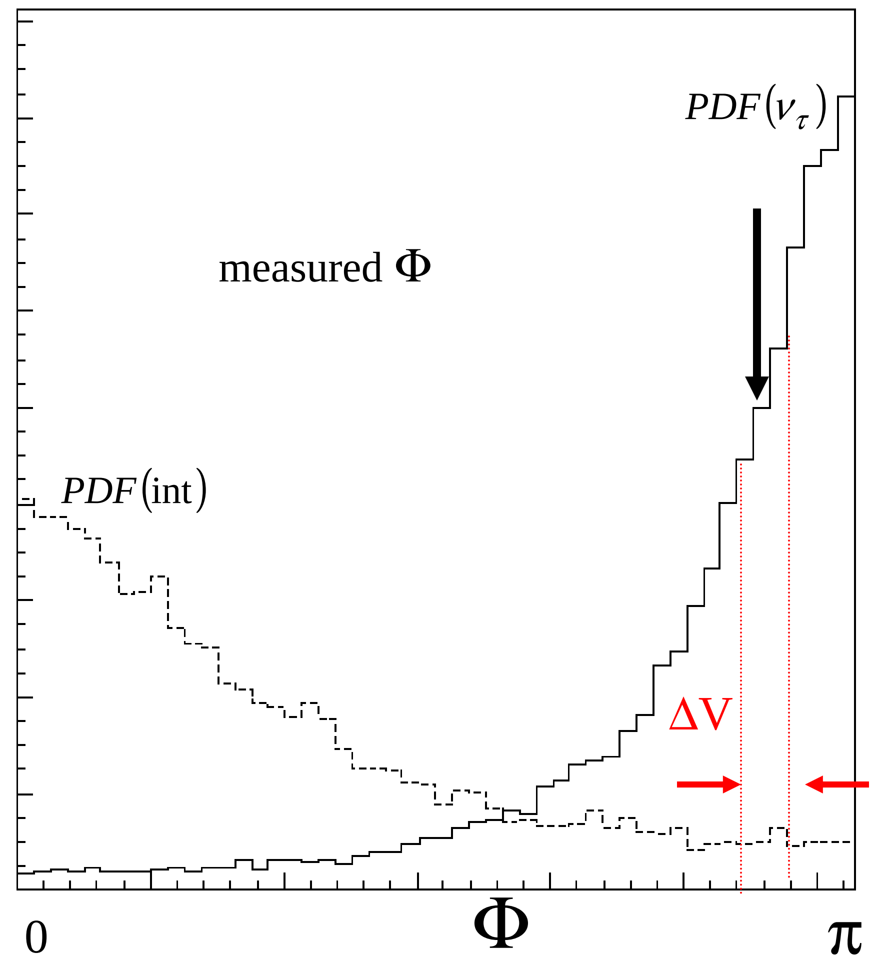
Individual Event Probability 1-D example: ν_τ vs hadron interaction

1. Assume the only possibilities are ν_τ or hadron interaction.
2. Use only one parameter Φ to evaluate event.

3333_17665 has Φ = 2.8 rad

$$P(\nu_\tau|\Phi) \equiv \frac{A_\nu \cdot PDF(\Phi|\nu_\tau)}{A_\nu \cdot PDF(\Phi|\nu_\tau) + A_{\text{int}} \cdot PDF(\Phi|\nu_\tau)}$$

Expect 0.22 interaction evts.	A_{int}	=	0.22
Expect 6.4 ν_τ events	$A_{\nu\tau}$	=	6.4
PDF(int. | Φ = 2.8)		=	0.23
PDF(ν_τ | Φ = 2.8)		=	0.81



$$P(\nu_\tau|\Phi = 2.8) = \frac{(6.4)\cdot(.81)}{(6.4)\cdot(.81)+(.22)\cdot(.23)} = 0.99$$

Tau Candidate Individual Event Probabilities

Single Prong Event Parameters

- Track production angle
- Event angular symmetry
- Track decay length
- Daughter decay angle
- Daughter momentum

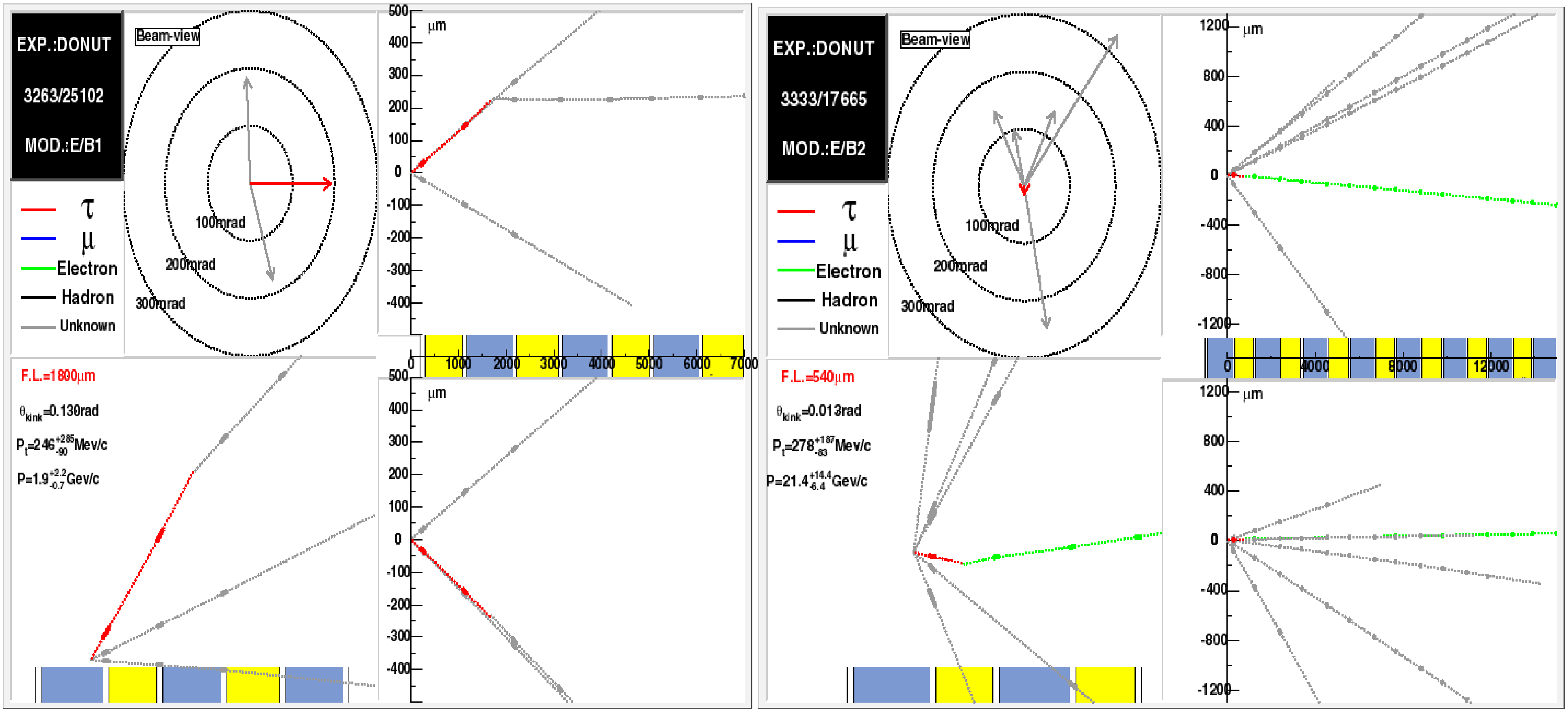
Trident Event Parameters

- Track production angle
- Event angular symmetry
- Track decay length
- Sum of daughter IP's

	Single Prong				Tridents	
	3024_30175	3039_01910	3263_25102	3333_17665	3334_19920	3296_18816
ν_τ cc	.70	.98	.16	.99	.99	.85
ν + charm	.30	.02	.14	.01	.01	.15
ν + hadron scatter	0	0	.70	0	0	0

Probability all events are background = 7.6 x 10^-8

3263_25102 (Scatter) & 3333_17665 (Tau)



Charm Candidate Individual Event Prob.

Single Prong Event Parameters

- **Track production angle**
- **Event angular symmetry**
- **Track decay length**
- **Daughter decay angle**
- **Daughter momentum**

Trident Event Parameters

- **Track production angle**
- **Event angular symmetry**
- **Track decay length**
- **Sum of daughter IP's**

7 Charm Candidates:
3 Single Prong
1 Trident
3 Neutral Vees

	Single Prong			Trident
	2986_00355	3065_03238	3193_01361	3245_22786
ν_τ cc	0	0	0	0
ν + charm	.99	.94	.98	1.0
ν + hadron scatter	.01	.06	.02	0

Cross Section Measurement

- Check to see if the number of tau neutrino charged current interactions DONUT observed agrees with theory – check lepton universality
- Cross section can be calculated in different ways
  - Absolute cross section - first principles
  - Relative cross section – normalize against number of muon neutrino and electron neutrinos
- For second approach, the following quantities are necessary:
  - Must define specific cuts to create data set (neutrino and tau neutrino data sets)
  - Must know efficiencies (trigger, selection, location, identification)
  - Must know the number of electron and muon neutrino charged current interactions
    - Electrons – multiple scattering, electron ID
    - Muons – Muon ID

Conclusion

- Sampling emulsion tracker + spectrometer works even better than expected
  - Still learning to use all of its power
    - Near 100% reconstruction efficiency possible (68% now – from 59%)
      - (<50% was previously "excellent" ie CHORUS)
    - Particle id, Momentum measurement, Single event probabilities
- Increasing event sample continues
  - From 203 to 424
- Better understanding of efficiencies and more tau and charm events
  - Improved understanding of backgrounds and systematics
  - Cross section measurements
- Technology for future detectors to study short lived particles.

Individual Event Probabilities
How Many Events Do We Expect?

For the 433 neutrino interactions we calculate how many tau neutrino charged current events we expect to observe using:

$$N_{\nu\tau} = N_{\text{data}} \frac{\text{Rate}_{\nu\tau} \cdot \varepsilon_{\nu\tau}^{\text{total}}}{\sum_i \text{Rate}_i \cdot \varepsilon_i^{\text{total}}}$$

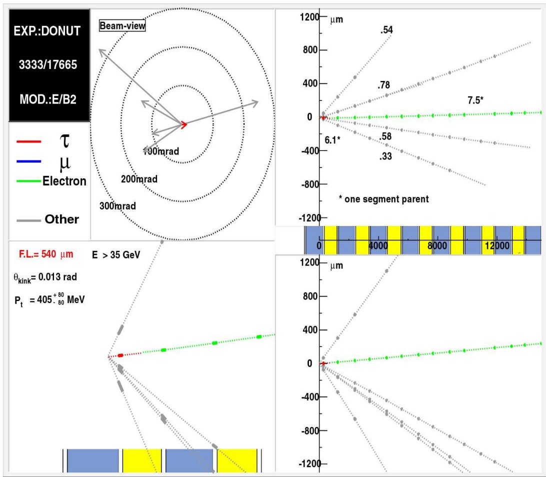
where Rate i is the calculated rate of a type i event, and ε_i is the total efficiency of a type i event, where $i \in \{\nu_\mu \text{ prompt cc}, \nu_e \text{ cc}, \nu_\mu \text{ nonprompt cc}, \nu \text{ nc}, \nu_\tau \text{cc}\}$.

	Rate (per kg proton)	$\varepsilon^{\text{total}}$	Expected Number
ν_μ prompt cc	$2.3 \pm 0.5 \times 10^{-18}$	0.59	92
ν_e cc	$2.7 \pm 0.6 \times 10^{-18}$	0.57	104
ν_μ non prompt cc	$4.4 \pm 0.7 \times 10^{-18}$	0.34	108
ν nc	$3.0 \pm 0.8 \times 10^{-18}$	0.51	96
ν_τ cc	$0.37 \pm 0.13 \times 10^{-18}$	0.57	14.6

Individual Event Probabilities
Prior Probability Calculation

To calculate the prior probability, must know

1. Expected number of neutrino interactions in detector
2. Probability of the process resulting in a kinked track (trident)
3. Trigger, selection, and location efficiencies
4. Probability that the event passes the tau selection criteria



Example: Calculating the prior probability of event 3333_17665 (single prong decay to electron)

	Tau	D	Ds	Λ_c	Charm
Num.exp. interactions:	14.6	5.2	1.9	2.16	
BR to single prong:	0.85	0.46	0.37	0.65	
Selection probability:	0.52	0.13	0.14	0.09	
Prior Probability:	6.4	0.3	0.1	0.1	0.54

Individual Event Probabilities

Probability Density Function Calculation

Calculating multi-dimensional probability density for a candidate event

1. Each event has measured values of parameters $\rightarrow (\Phi,\Theta_p,L)$ or $(\Phi,\Theta_p,L,\Theta_k,P)$
2. Define a (small) interval in parameter space around measured values: Δv
3. Simulate hypothesis event type:

   count number of events which pass all tau selection cuts (N_{total})

   count number of events which are within the interval Δv ($N_{\Delta v}$)

Tridents

$\Phi \pm \Delta\Phi$

$\Theta_p \pm \Delta\Theta_p$

$L \pm \Delta L$

Δv

Single Prong

$\Phi \pm \Delta\Phi$

$\Theta_p \pm \Delta\Theta_p$

$L \pm \Delta L$

$\Theta_k \pm \Delta\Theta_k$

$P \pm \Delta P$

Δv

probability density for event $\equiv \dfrac{N_{\Delta v}}{N_{total} \cdot \Delta v}$