The Observation and Properties of the Tau-Neutrino: Results From DONuT

George S. Tzanakos
University of Athens, Greece

Outline

Indirect Evidence

The DONUT Experiment

Spectrometer Data Analysis

Emulsion Data Analysis

Backgrounds

τ- signal

ν_τ-N CC cross section

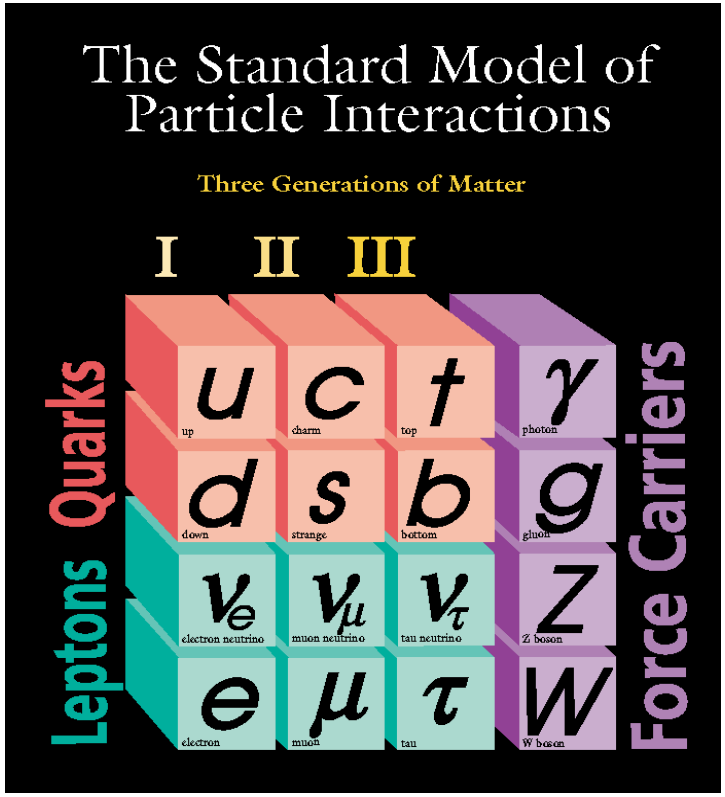
ν_τ Magnetic Moment

ν_τ Mass

S-M properties of the ν_τ from τ-decay

Summary and Conclusions

ELEMENTARY PARTICLES IN THE STANDARD MODEL



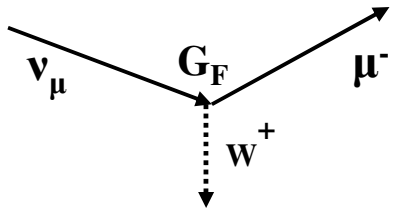
Καθιερωμένο Προτυπο

		T_3
Leptons:	$\begin{pmatrix} \nu_e \\ e \end{pmatrix}$ $\begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}$ $\begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix}$	+1/2 -1/2
Quarks:	$\begin{pmatrix} u \\ d \end{pmatrix}$ $\begin{pmatrix} c \\ s \end{pmatrix}$ $\begin{pmatrix} t \\ b \end{pmatrix}$	+1/2 -1/2

Missing yet: H

(Higgs Boson)

CC Transitions



Search for the Tau-Neutrino

Historical Development

1975- τ - lepton discovered ; 'ν_τ' postulated to exist: $\begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix}$

Late 70's: DELCO, MARK II, : τ - decay studies, Michel Parameter ρ, τ-lifetime, τ-μ Universality.

1980's - MARK II, TASSO, CLEO, ARGUS, LEP: τ - decay studies, 'ν_τ' helicity = -1, spin = ½.

1986 - E531 : Is it possible that 'ν_τ' is in fact ν_e, ν_μ? No, no direct couplings of the τ-lepton to ν_e,or ν_μ.

1991 - LEP demonstrates 3.00 ν 's

2000 – DONUT: Direct Observation: First 4 ν_τ CC events

Indirect Evidence

A. From early studies of τ - lepton decays

- **$\tau - \nu_\tau$ coupling: V-A**
  - (E_e spectrum in $\tau \rightarrow e\, \nu\, \bar{\nu}$)
  - Measurement of the Michel parameter ρ.

  e.g. DELCO Experiment (1979): $\rho = 0.72 \pm 0.15$

  (All evidence from τ-decays consistent with V-A coupling)

- **Strength of coupling from τ-lepton lifetime.**

  If $G_\tau = G_\mu$ (Universality)

  $\rightarrow \tau_\tau \approx (m_\mu/m_\tau)^5 \tau_\mu BR(\tau \rightarrow e) = 2.91 \times 10^{-13}$ s

  First measurement from MARK II : $\tau_\tau = (4.6 \pm 1.9) \times 10^{-13}$ s

Indirect Evidence (Cont)

- **ν_τ helicity: Negative**

  (from $\tau^- \to a_1^- \nu_\tau \to \pi^+\pi^-\pi^-\nu_\tau$), ARGUS, 1990

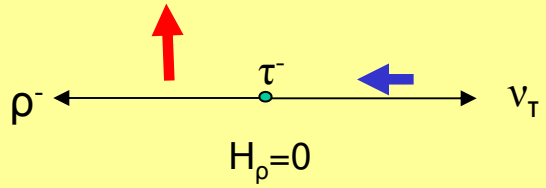
  Measure parity violating asymmetry :

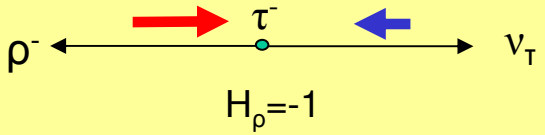
(Asymmetry of orientation of 3-π plane wrt the τ-direction (in the 3-π rest frame) proportional to γ_{AV})

$$\gamma_{AV} = 2g_A g_V/(g_A^2+g_V^2) = 1.14 \pm 0.34^{+0.34}_{-0.17}$$

(SM: $\gamma_{AV} = 1$)

- **ν_τ spin: J = ½, ARGUS, 1992, from $\tau^- \to \rho^-\nu_\tau \to \pi^-\pi^0\nu_\tau$**





(J=3/2 would require the ρ helicity to be in a pure $H_\rho = -1$ state, excluded by the measurements)

Indirect Evidence

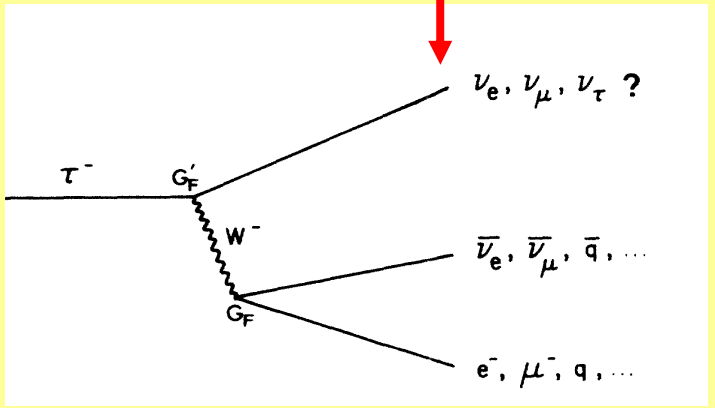
B. From Neutrino Experiments

Q. Can the J=1/2, H = -1, V-A partner of the τ be identified with ν_e, ν_μ ?

A. E531, 1986 measured:

$\Gamma(\tau^- \to l^- \bar{\nu}_l \nu_\mu) < 8.3 \times 10^{-13}$ MeV,

$\Gamma(\tau^- \to l^- \bar{\nu}_l \nu_e) < 3.0 \times 10^{-11}$ MeV



- Experimental average from semileptonic BRs and lifetime:

  $\Gamma(\tau^- \to l^- \bar{\nu}_l \nu_x) \approx (3.5^{+0.5}_{-0.4}) \times 10^{-10}$ MeV

- No direct couplings τ - ν_e, ν_μ : $G_F'/G_F < 0.002$ (0.073) to ν_μ (ν_e)

C. From LEP 1989: Number of light neutrino species

- Z_0 width: $N_\nu = 3.01 \pm 0.15$ (exp) ± 0.05 (theo) (ALEPH)

Postulation of t-quark and nutau

Status in 1990:

TEVATRON

Leptons: $\begin{pmatrix}\nu_e\\ e\end{pmatrix}\begin{pmatrix}\nu_\mu\\ \mu\end{pmatrix}\begin{pmatrix}\nu_\tau\\ \tau\end{pmatrix}$ → DONUT 2000 $\begin{pmatrix}\nu_\tau\\ \tau^-\end{pmatrix}$

Quarks: $\begin{pmatrix}u\\ d\end{pmatrix}\begin{pmatrix}c\\ s\end{pmatrix}\begin{pmatrix}t\\ b\end{pmatrix}$ → CDF, D0, 1995 $\begin{pmatrix}t\\ b\end{pmatrix}$

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

$$\begin{pmatrix}\nu_e\\ e^-\end{pmatrix}\begin{pmatrix}\nu_\mu\\ \mu^-\end{pmatrix}\begin{pmatrix}\nu_\tau\\ \tau^-\end{pmatrix}$$

DONUT Experiment

1994: Proposal to Fermilab (P872)

τ- Lepton Production from $\nu_\tau + N \rightarrow \tau + X$

P872 Collab. (approved June 1994)

Preparation :	**1994-1997**
Data	**1997**
Physics Analysis	**1997- present**
First results announced:	**2000**
Published:	**2001 (4 –events)**

The DONUT Experiment

- Designed to <u>observe directly</u> and study the CC interactions of the ν_τ.
- Used a prompt ν- beam from a proton beam dump.
- Used a hybrid emulsion spectrometer to locate and identify ν_τ – Nucleus CC interactions.
- First 4 events published in Phys. Lett. B 504, 218(2001)

DONUT = Direct Observation of NU Tau

ELSEVIER

12 April 2001

PHYSICS LETTERS B

Physics Letters B 504 (2001) 218–224

www.elsevier.nl/locate/npe

Observation of tau neutrino interactions

DONUT Collaboration

K. Kodama [a], N. Ushida [a], C. Andreopoulos [b], N. Saoulidou [b], G. Tzanakos [b], P. Yager [c], B. Baller [d], D. Boehnlein [d], W. Freeman [d], B. Lundberg [d], J. Morfin [d], R. Rameika [d], J.C. Yun [d], J.S. Song [e], C.S. Yoon [e], S.H. Chung [e], P. Berghaus [f], M. Kubantsev [f], N.W. Reay [f], R. Sidwell [f], N. Stanton [f], S. Yoshida [f], S. Aoki [g], T. Hara [g], J.T. Rhee [h], D. Ciampa [i], C. Erickson [i], M. Graham [i], K. Heller [i], R. Rusack [i], R. Schwienhorst [i], J. Sielaff [i], J. Trammell [i], J. Wilcox [i], K. Hoshino [j], H. Jiko [j], M. Miyanishi [j], M. Komatsu [j], M. Nakamura [j], T. Nakano [j], K. Niwa [j], N. Nonaka [j], K. Okada [j], O. Sato [j], T. Akdogan [k], V. Paolone [k], C. Rosenfeld [l], A. Kulik [k,l], T. Kafka [m], W. Oliver [m], T. Patzak [m], J. Schneps [m]

[a] *Aichi University of Education, Kariya, Japan*
[b] *University of Athens, Athens 15771, Greece*
[c] *University of California/Davis, Davis, CA 95616, USA*
[d] *Fermilab, Batavia, IL 60510, USA*
[e] *Gyeongsang University, Chinju, South Korea*
[f] *Kansas State University, Manhattan, KA 66506, USA*
[g] *Kobe University, Kobe, Japan*
[h] *Kon-kuk University, Seoul, South Korea*
[i] *University of Minnesota, Minnesota, MN 55455, USA*
[j] *Nagoya University, Nagoya 464-8602, Japan*
[k] *University of Pittsburgh, Pittsburgh, PA 15260, USA*
[l] *University of South Carolina, Columbia, SC 29208, USA*
[m] *Tufts University, Medford, MA 02155, USA*

Received 8 January 2001; accepted 16 February 2001
Editor: K. Winter

Abstract

The DONUT experiment has analyzed 203 neutrino interactions recorded in nuclear emulsion targets. A decay search has found evidence of four tau neutrino interactions with an estimated background of 0.34 events. This number is consistent with the Standard Model expectation. © 2001 Published by Elsevier Science B.V.

PACS: 14.60.Lm

DONUT Collaboration

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

***University* of Athens**
C. Andreopoulos, N. Saoulidou. G. Tzanakos

University of California/*Davis*
P. Yager

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

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

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

Kobe University
S. Aoki, T. Hara

Kon-kuk University
J.T. Rhee

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

Nagoya University
T. Furukawa, 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, S. Takahashi, T. Yamamori

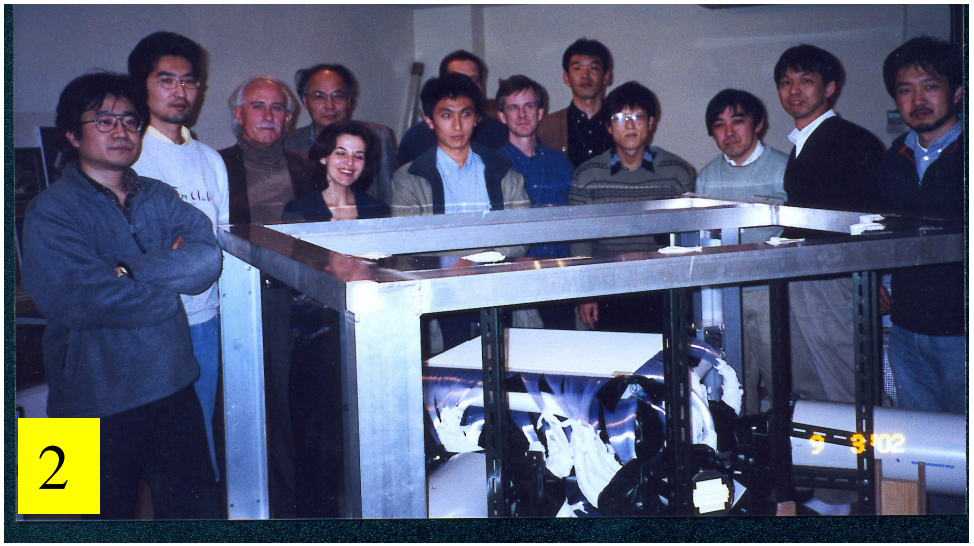
University of Pittsburgh
T. Akdogan, V. Paolone

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

The DONUT Collaboration

1

3

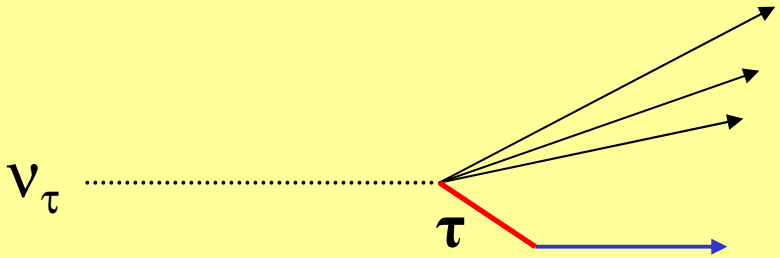

2

1. Fermilab, July 2000
2. Nagoya, March 2002
3. Athens, January 2004

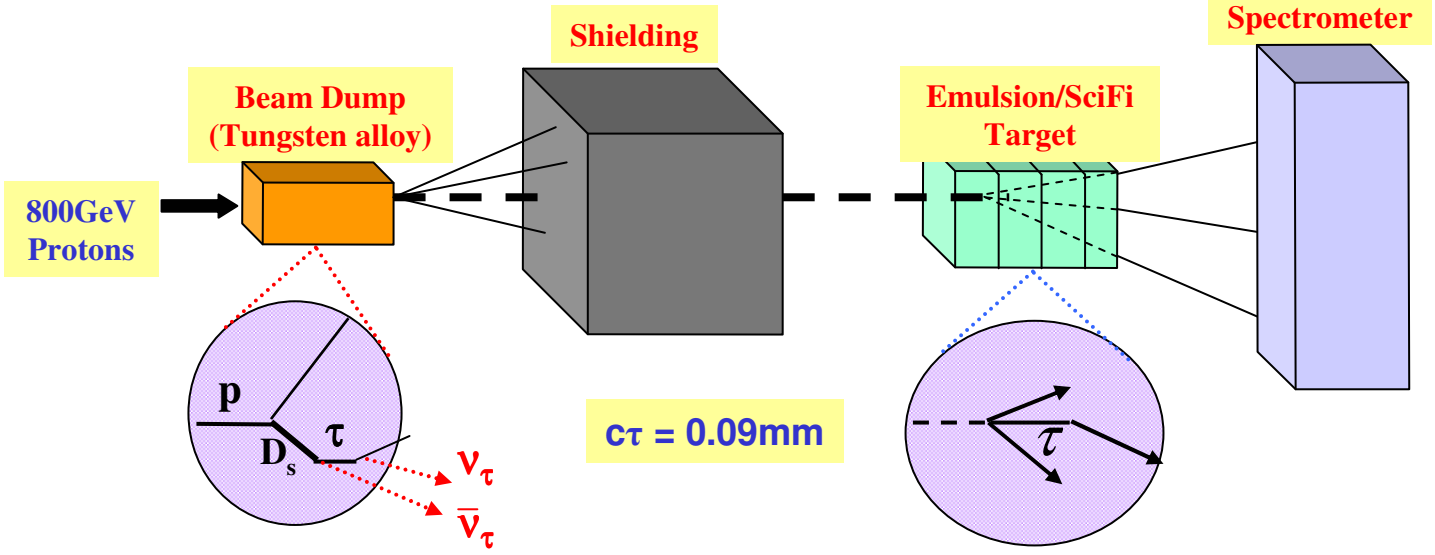
Tau Decay Modes

- Topological BR $\tau \rightarrow$ one charged particle: **86%**
- $\tau \rightarrow e\,\nu\nu$ 18%
- $\tau \rightarrow \mu\,\nu\nu$ 18%
- $\tau \rightarrow \pi\,\nu_\tau$ 11%
- $\tau \rightarrow \rho\,\nu_\tau$ 26%
- $\tau \rightarrow a_1\,\nu_\tau$ 10%
- $c\tau_\tau = 87\ \mu m \Rightarrow 2.3mm$ *mean decay length*

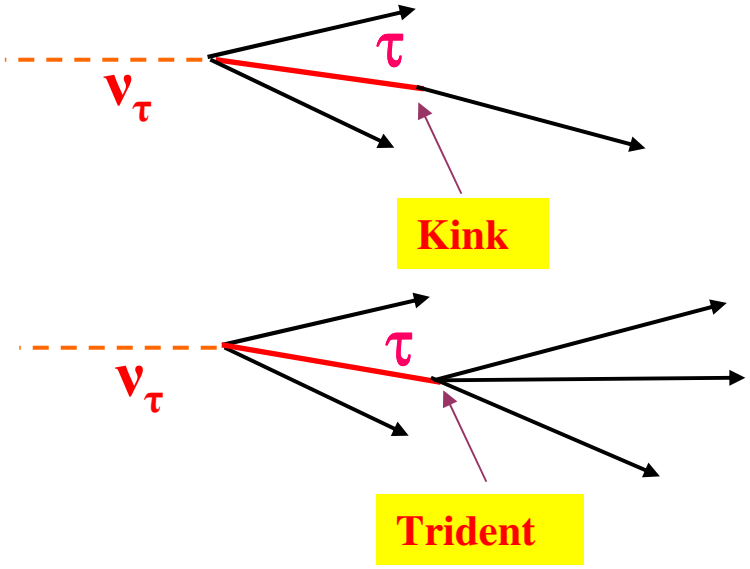
in DONUT



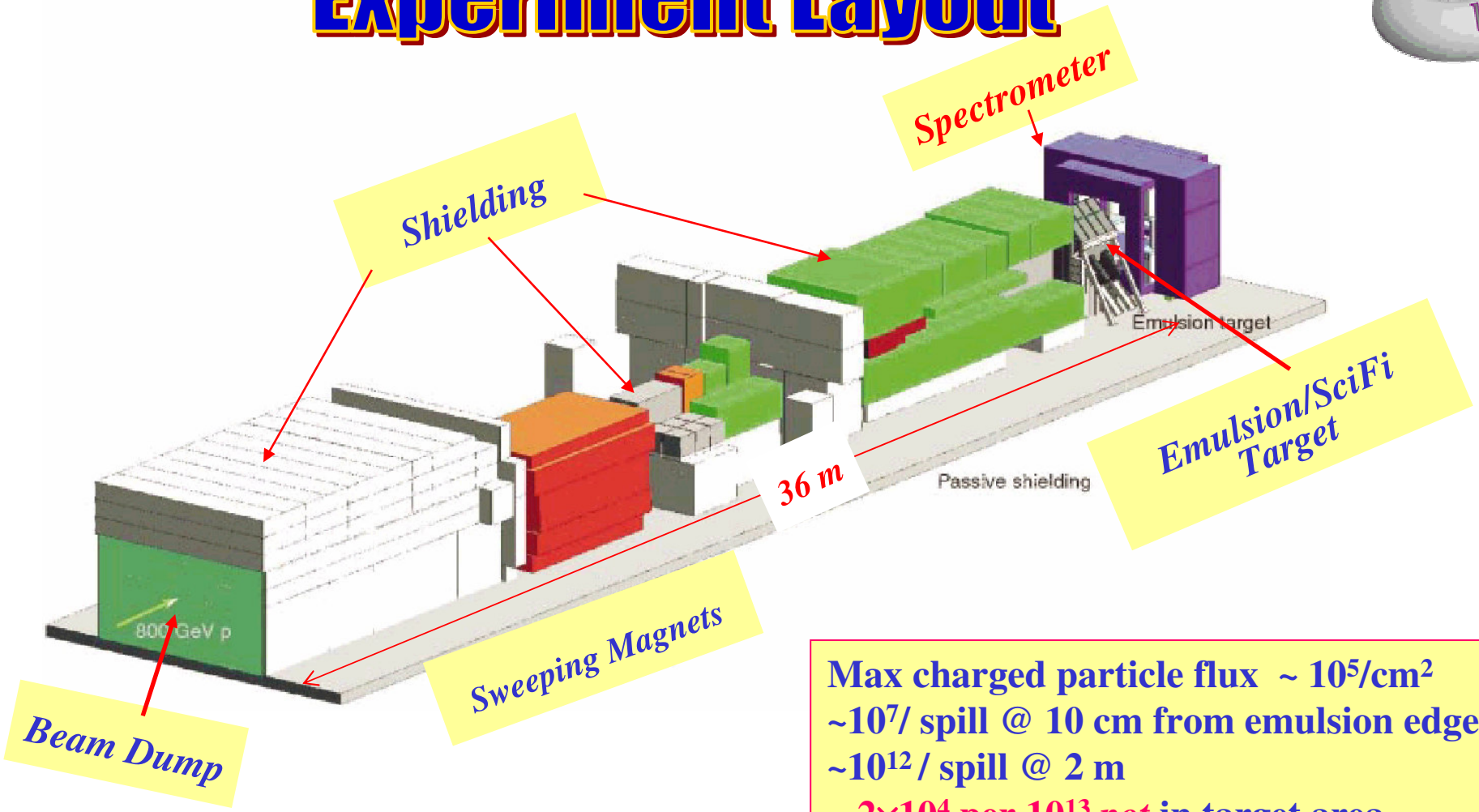
Prompt Neutrino Beam



- 800 GeV protons → Beam Dump → ($D_s \rightarrow \nu_\tau$ + ..)
- Absorb slowly decaying particles (π, K)
- Neutrino beam from D_s (ν_τ) , $D^{\pm}$ (ν_e, ν_μ)
- Magnetic/Passive shield to protect the emulsion
- Emulsion target at 36 m
- Spectrometer: vertex, track ID, P
- Emulsion scanning: Locate vertex, Decay search
- Find ν_τ by topology: Kinks and tridents



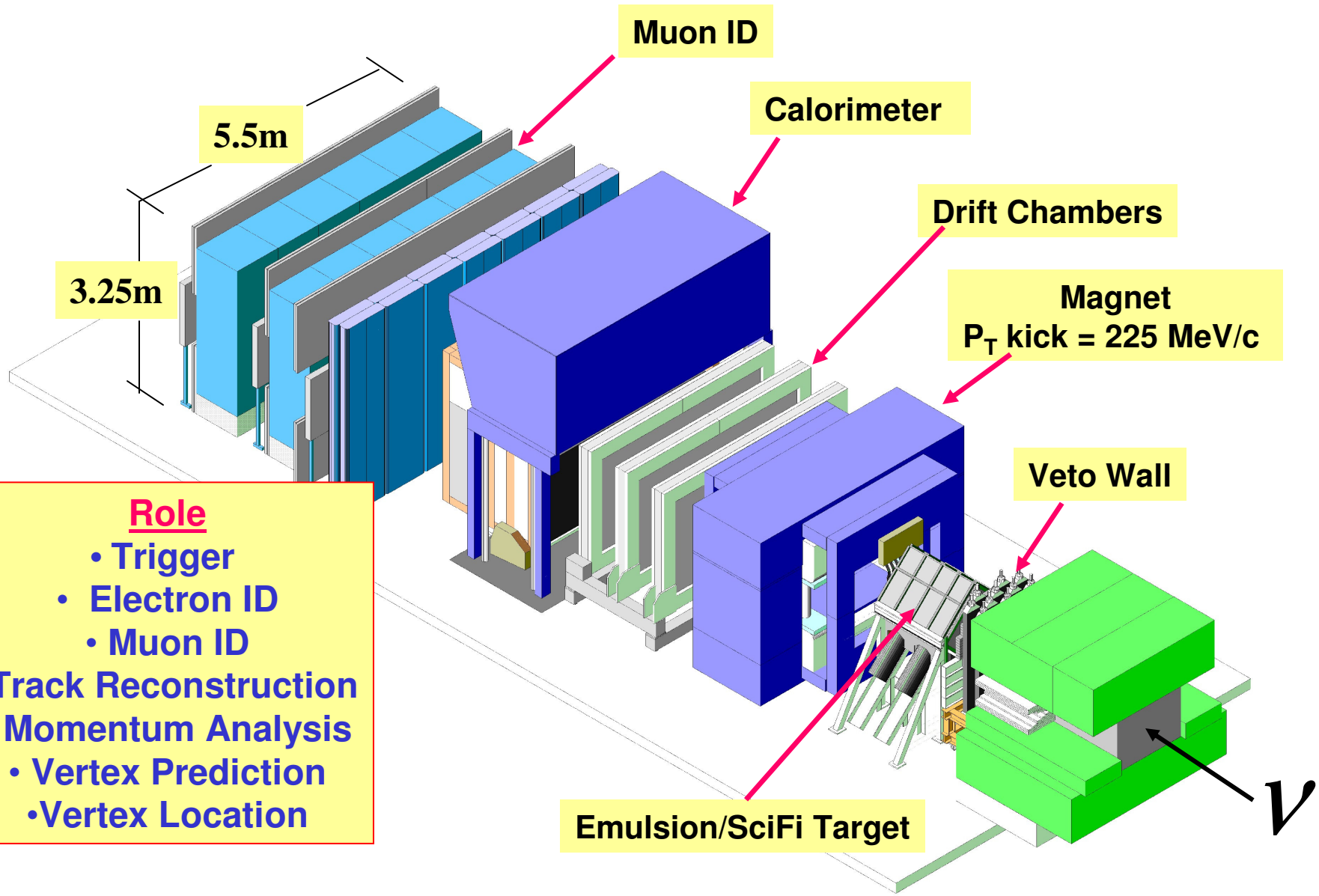
Experiment Layout



Max charged particle flux ~ 10^5/cm^2
~10^7/ spill @ 10 cm from emulsion edge
~10^{12} / spill @ 2 m
~ 2×10^4 per 10^{13} *pot* in target area

- ~ 8 x 10^{12} protons/spill, Spill = 20 sec/min
- Emulsion Target at 36 m from beam dump

Hybrid Emulsion Spectrometer



Role

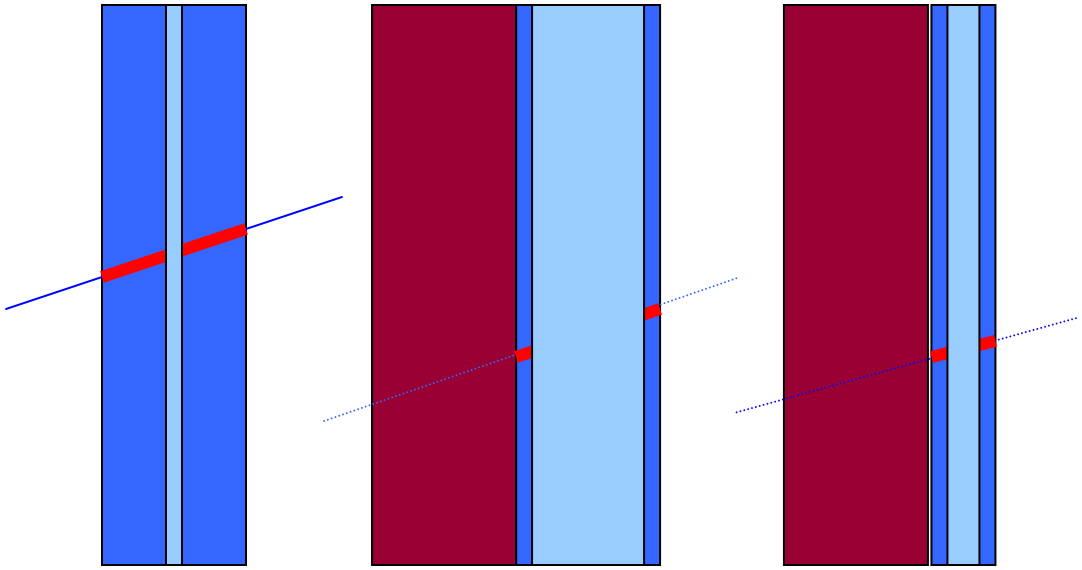
- Trigger
- Electron ID
- Muon ID
- Track Reconstruction
- Momentum Analysis
- Vertex Prediction
- Vertex Location

Emulsion Target Technology

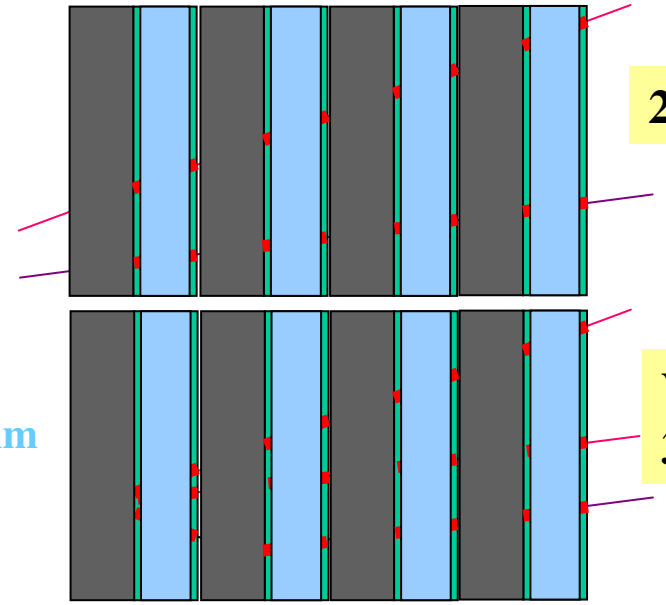
3-D Tracker

Basic Block: Steel / Emulsion / Acrylic / Emulsion

EAE	SEAE	SEAE
BULK	ECC800	ECC200
	1.0 mm	1.0 mm
0.32 mm	0.10 mm	0.10 mm
0.08 mm	0.80 mm	0.20 mm



95% emulsion 5% emulsion

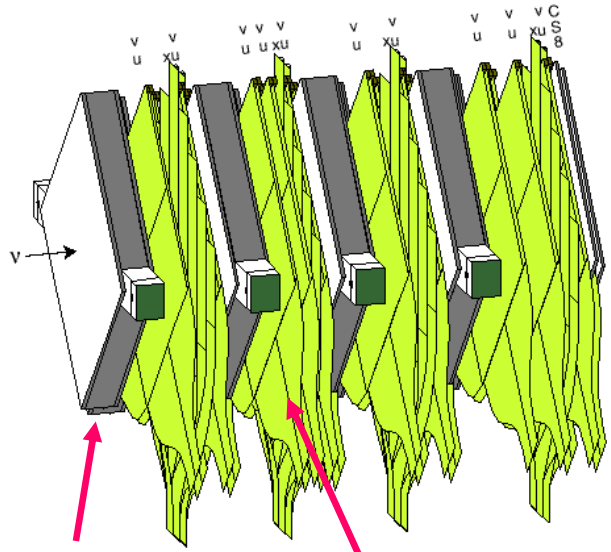


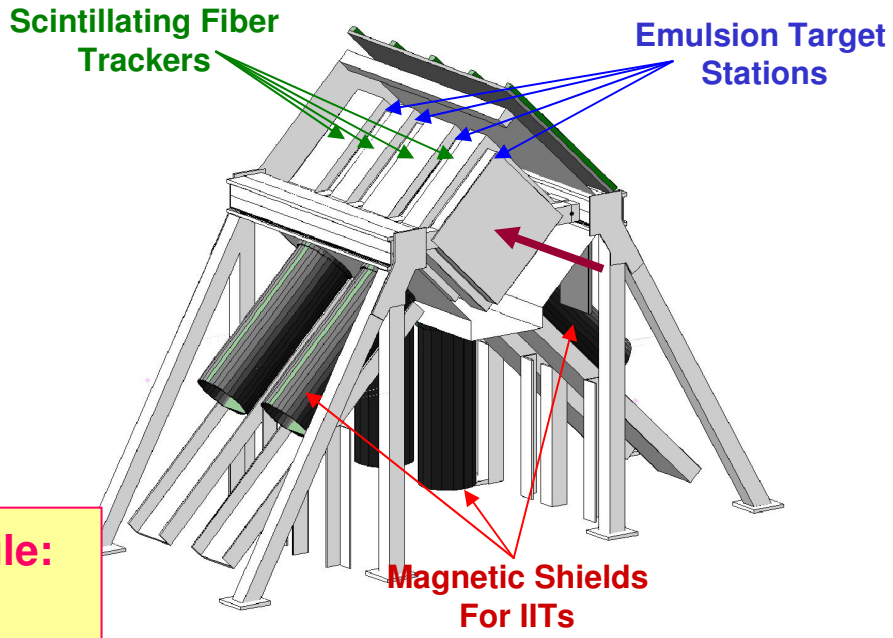
2 tracks

Vertex + 3 tracks

- AgBr suspended in a gel (Fuji ET7C) coated on plastic sheets.
- 29±2 grains per 100 μm for minimum ionizing track
- Spatial Resolution: 0.3 μm
- Vertex Resolution: 0.8 μm
- OPERA: Same idea

DONUT Emulsion/SciFi Target

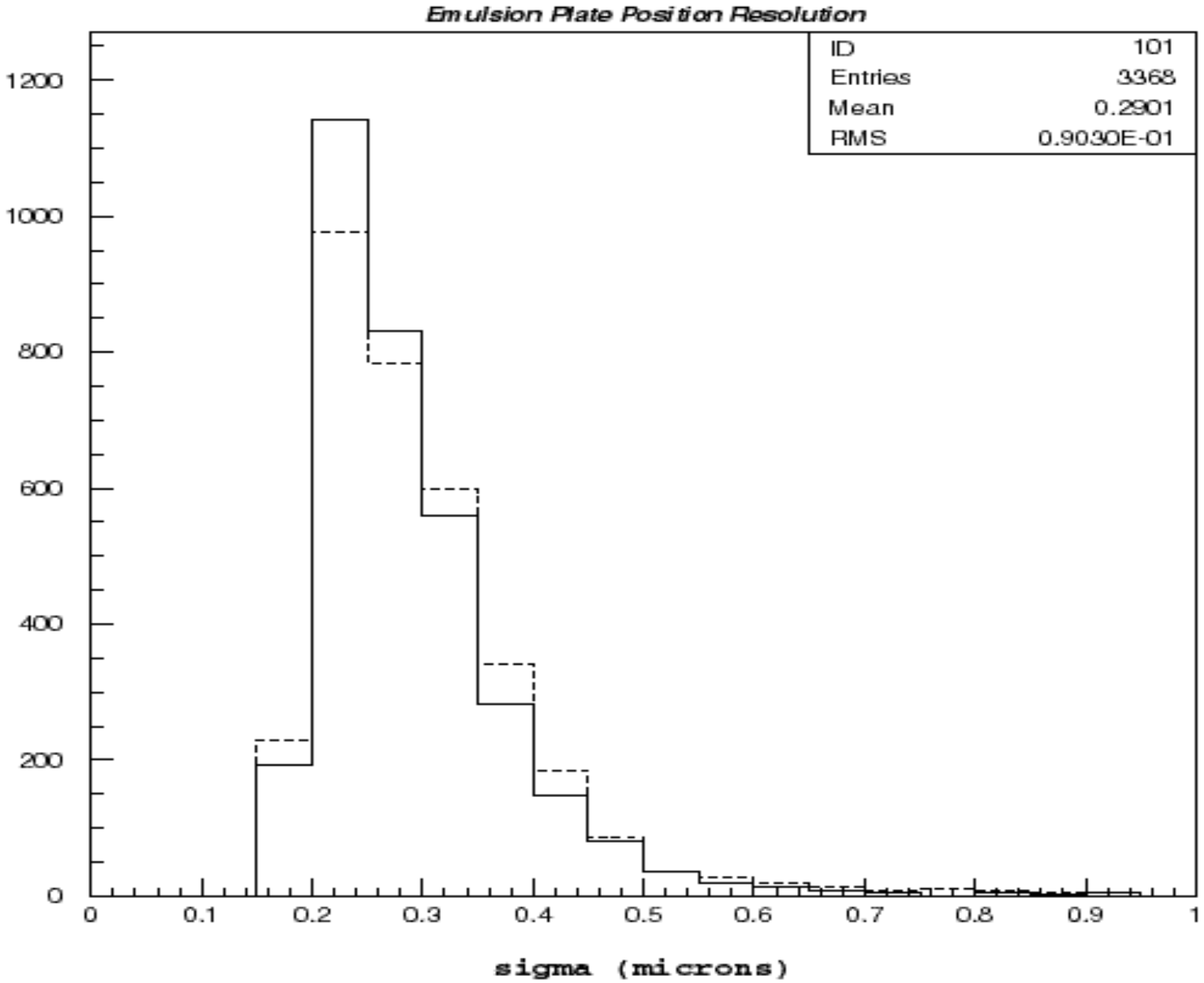




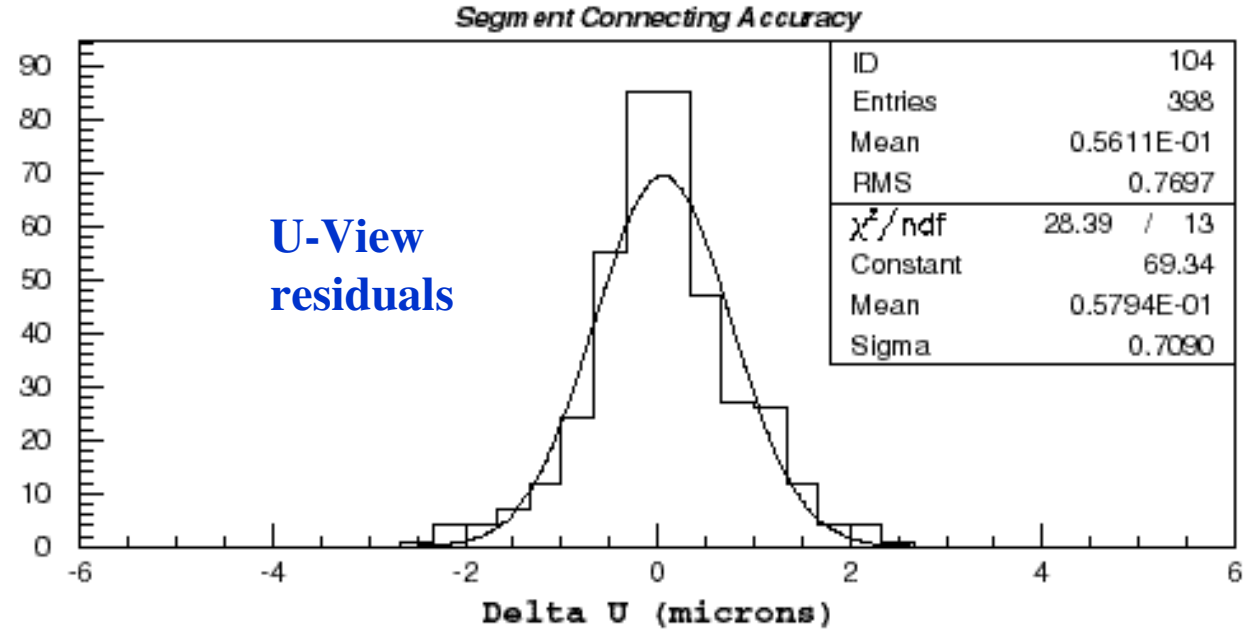
One Module:
2-3 X_0
0.2 - 0.3 λ_{int}

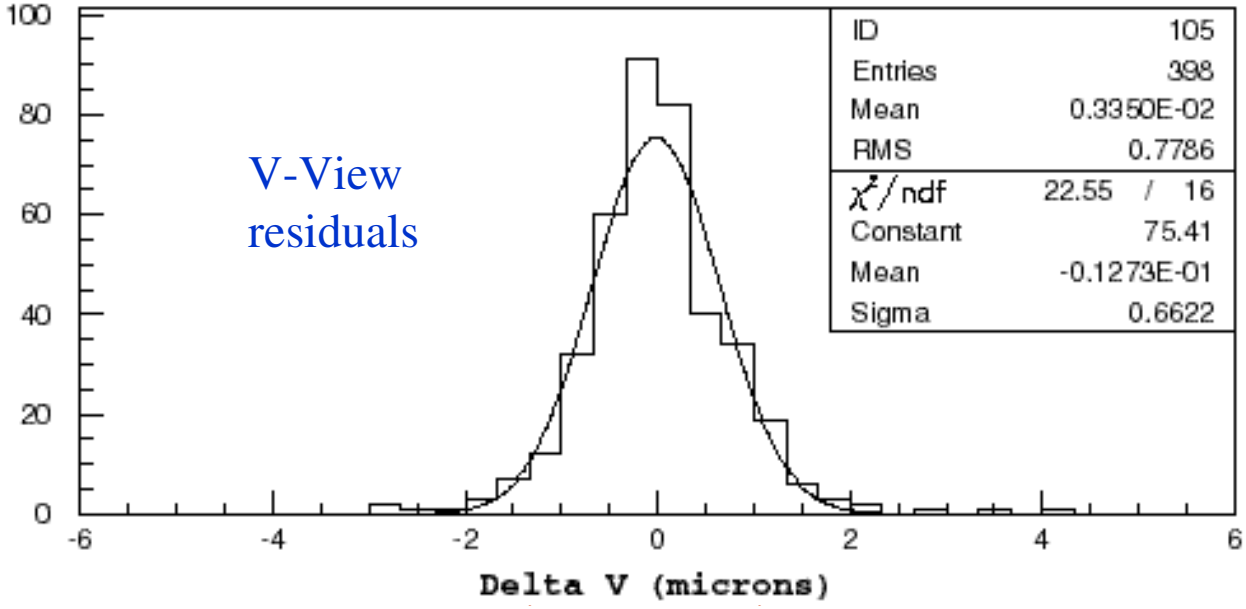
- Fibers → predict vertex
- 4 Emulsion target stations
- Interleaved with sci-fi
- Total 7 modules exposed
- 260 kg total mass of emulsion

Emulsion Tracking



Emulsion Vertexing





Prompt Neutrino Flux/Interactions

- 1. **Primary Source:** $D_s^+ \rightarrow \nu_\tau + \tau^+$
  ↳ $\bar{\nu}_\tau$ + X

$$BR(D_S^\pm \rightarrow \tau^\pm \nu_\tau) = \left(\frac{G_F^2}{8\pi}\tau_{D_S} m_{D_S}\right) \cdot f_{D_S}^2 |V_{cs}|^2 m_\tau^2 \left(1 - \frac{m_\tau^2}{m_{D_S}^2}\right)^2$$

= 6.1±1.0%

- 2. $D^+ \rightarrow \nu\, \tau^+ \rightarrow X\, \nu$ (rate 5% of D_S)
- 3. D_S from secondary interactions in dump (rate 8% of D_S)
- 4. $B \rightarrow \tau\, X$ (rate 1.3% of D_S)

Number of prompt $\nu_e \approx \nu_\mu$, from D decays

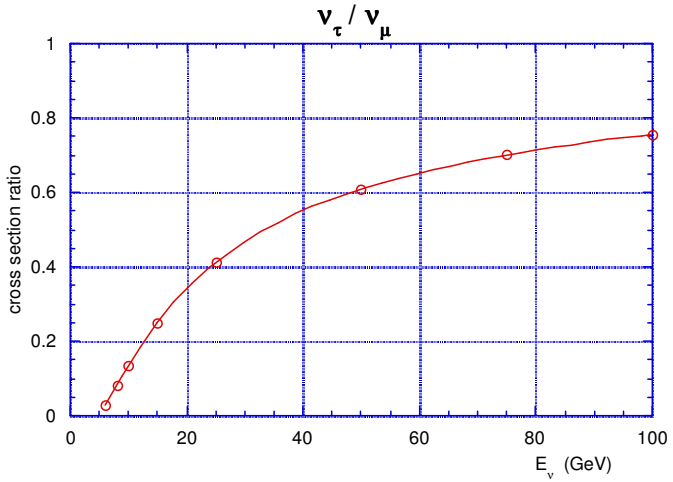
$\nu_e + \nu_\mu$ 2.5×10^{-4} /(*pot* m^2) <E> = 52 GeV
ν_τ 2.1×10^{-5} /(*pot* m^2) <E> = 54 GeV

Total *protons on target* = 3.54×10^{17}

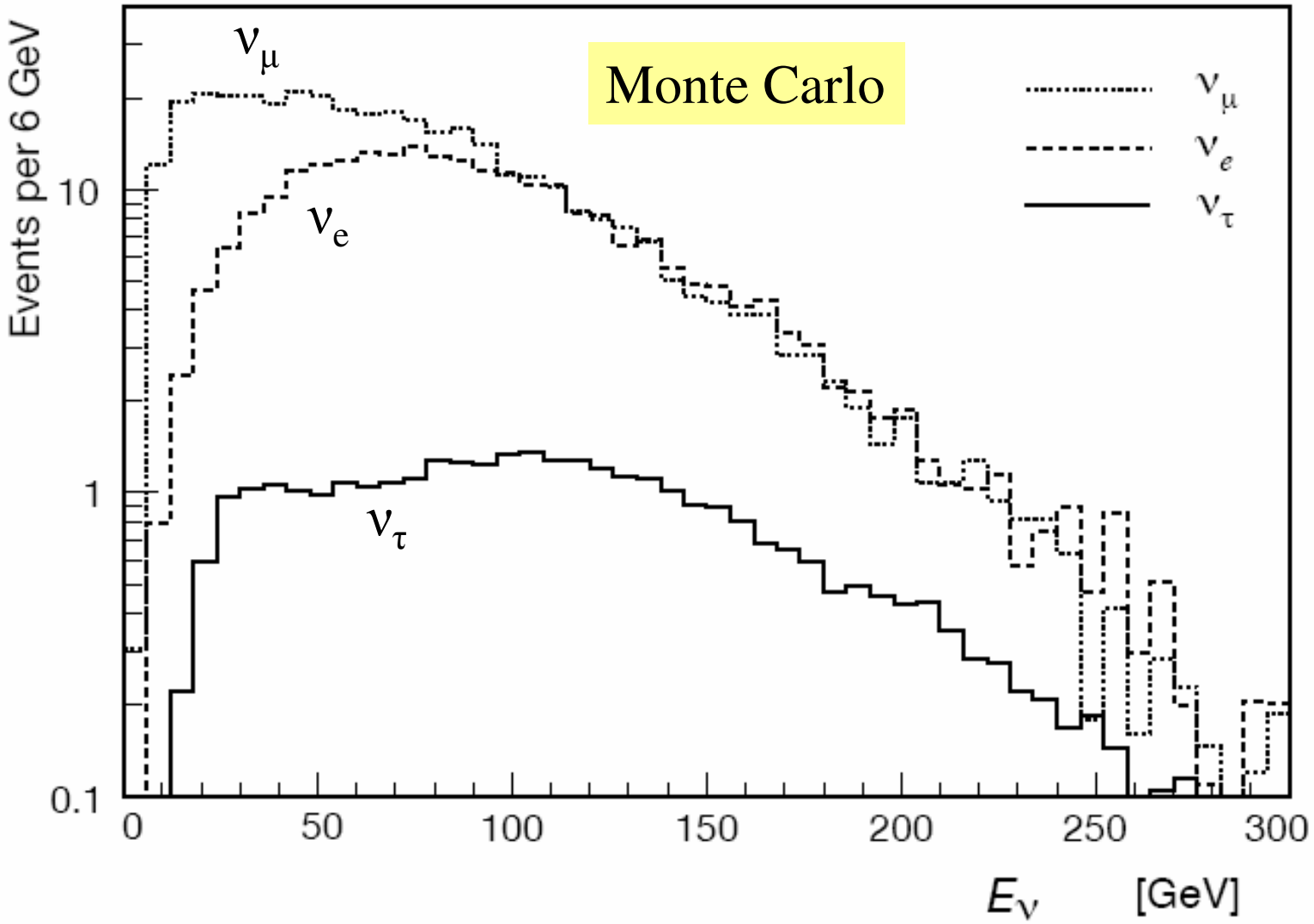
Expected No. of interactions
= 1040±200 (ν_μ, ν_e, ν_τ)

Expected number of ν_τ interactions: 4.8% of total

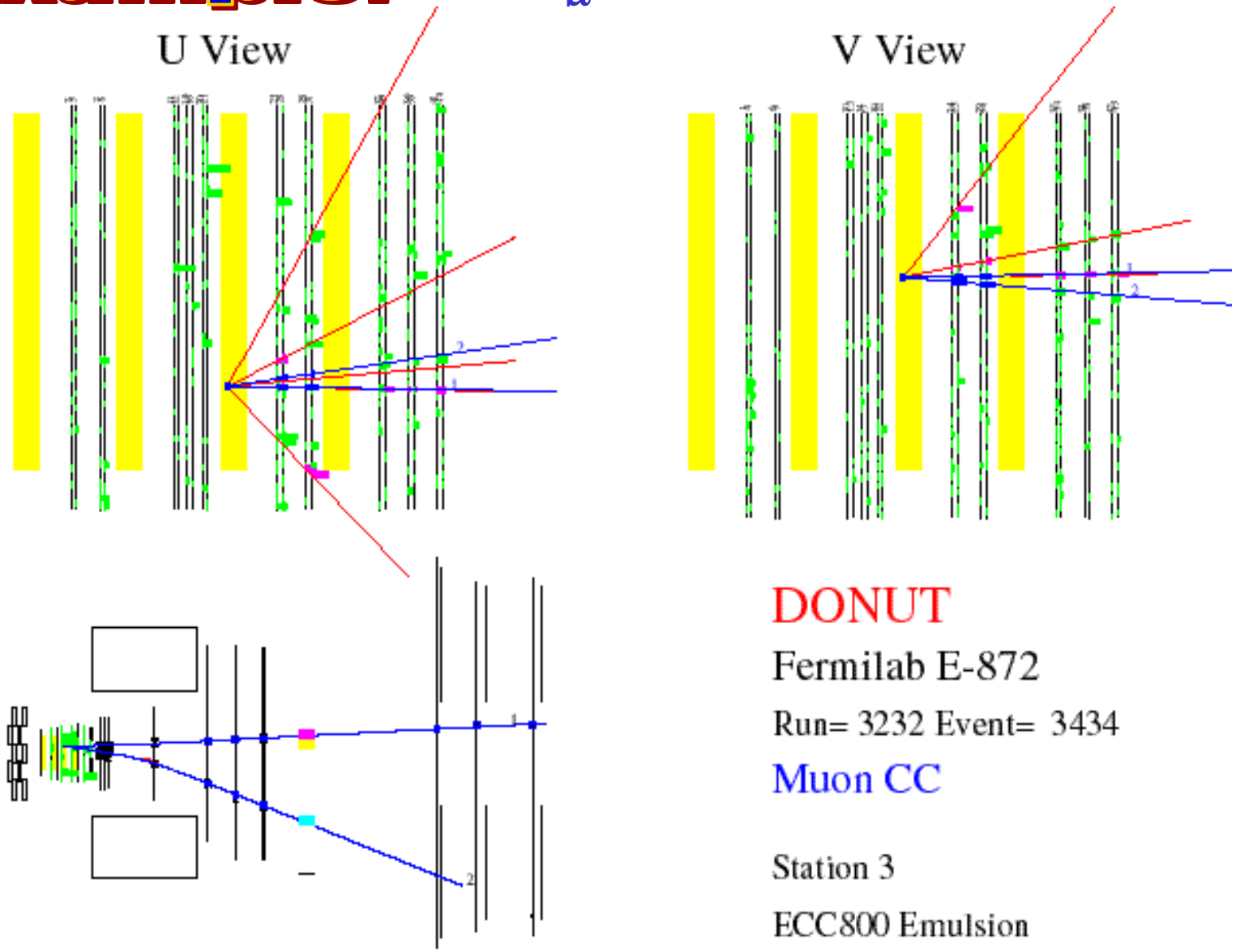
Uncertainties:
D_S production ±20%
$f_{Ds} \Rightarrow$ BR ±15%



Beam Dump Neutrino Energy Spectra



Example: ν_μ CC interaction



DONUT

Fermilab E-872

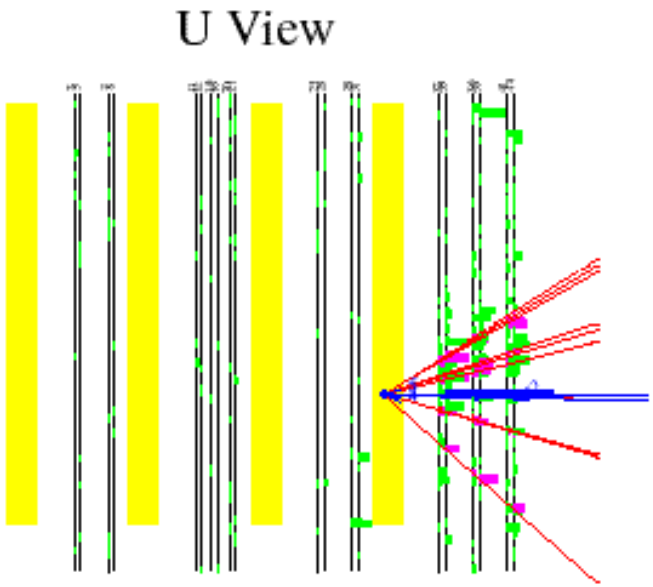
Run= 3232 Event= 3434

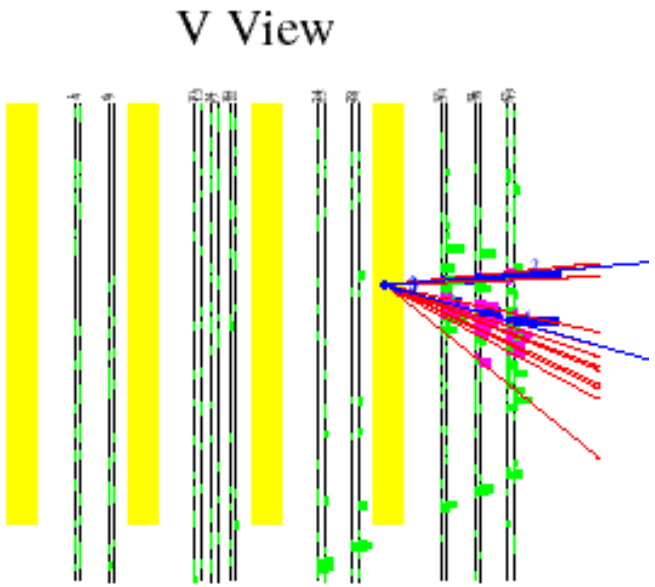
Muon CC

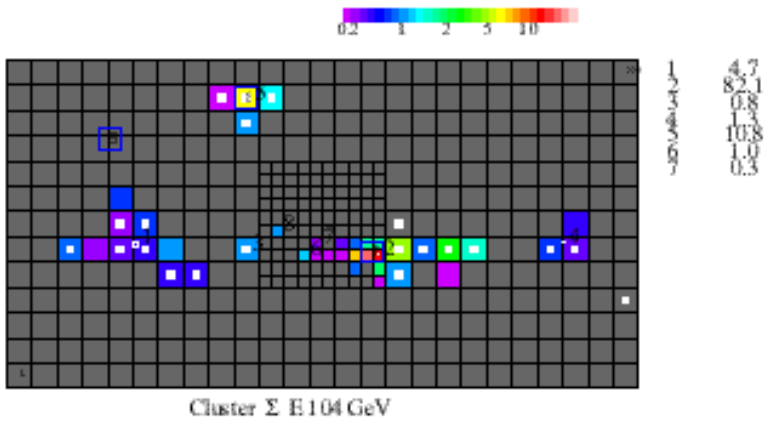
Station 3

ECC800 Emulsion

Example: ν_e CC interaction







DONUT

Fermilab E-872

Run= 3250 Event= 470

Electron CC

Station 4

Bulk Emulsion

EMCAL: Beam View. Tracks disperse in the bend plane

Event Reconstruction in Spectrometer

Track/shower reconstruction, Vertex prediction:

- Info from SciFi, DCs, EMCAL, and Magnet.
- Drift Chambers: $\Delta x \approx \Delta y \approx 320\ \mu m$
- SciFi: $\Delta x \approx \Delta y \approx 170\ \mu m$
- EM Calorimeter: $\sigma_E/E \approx 20\%/\sqrt{E}$
- Magnet: $\int Bdl \approx 0.75\ Tm \rightarrow 225\ MeV/c\ p_T$ kick
- Predict vertex position, spatial resolution:

$\Delta x \approx \Delta y \approx 0.7\ mm, \Delta z \approx 4\ mm$

Flavor Selection

- ν_μ CC interactions by μ - ID (Prompt vs non-prompt)
- ν_e CC Interactions by e -ID
- ν_τ CC Interactions by τ-ID (emulsion scanning)
- CC/NC separation by ANN technique

Data Reduction

6.6×10^6 triggers : **3.54×10^{17} POT**

DONUT Preliminary

$\sim10^3$ **expected vertices from spectrometer**

Software Filter (300)

Physicist scan (20)

Vertex Reconstruction

Fiducial Volume

866 **within fiducial volume**

Total efficiency for retaining an interaction (triggering, filtering, scanning)

ν_e CC	ν_μ CC	ν_τ CC	NC
0.73	0.71	0.72	0.64

Vertex location in Emulsion

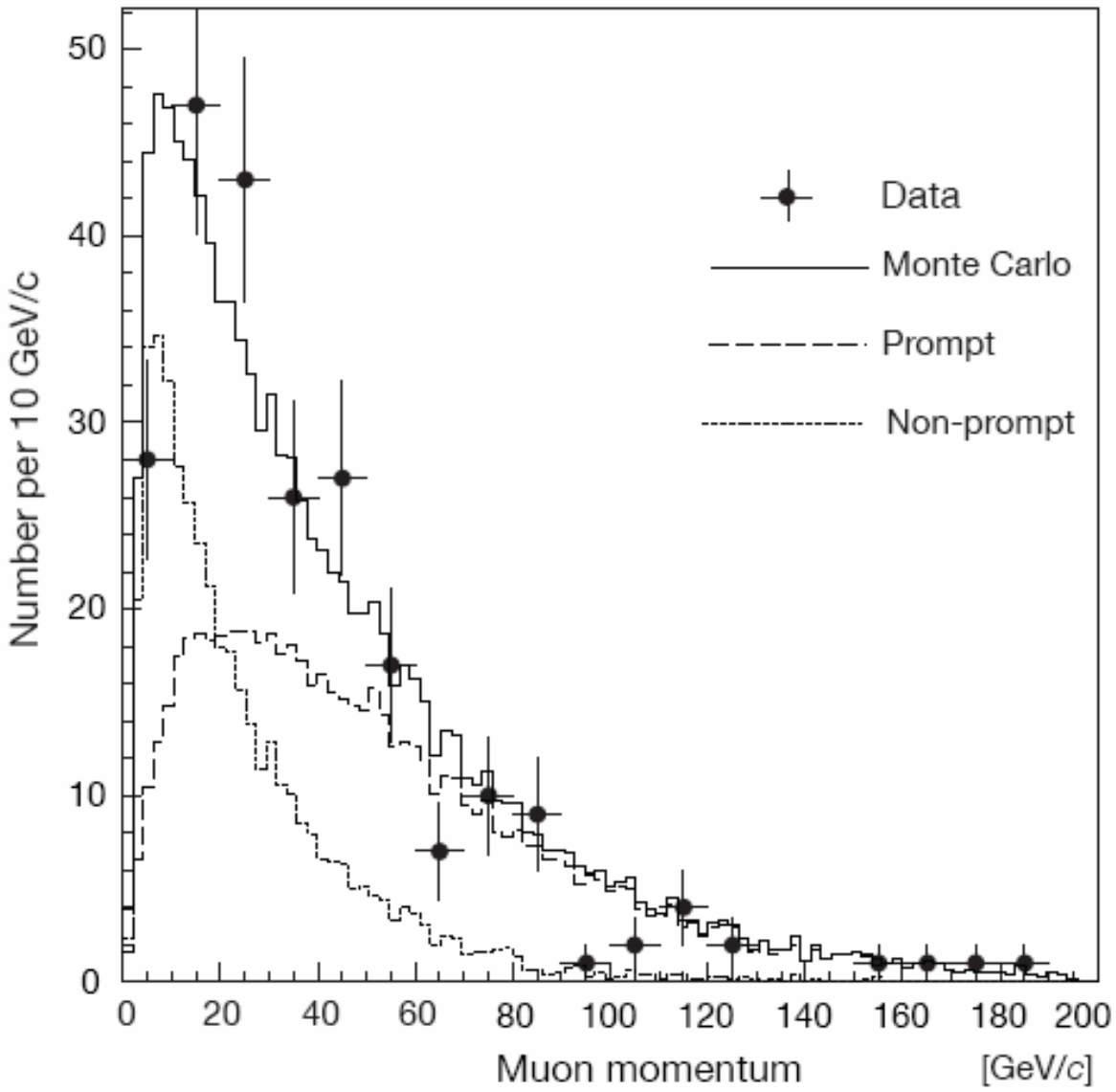
578 **vertex found**

Decay search

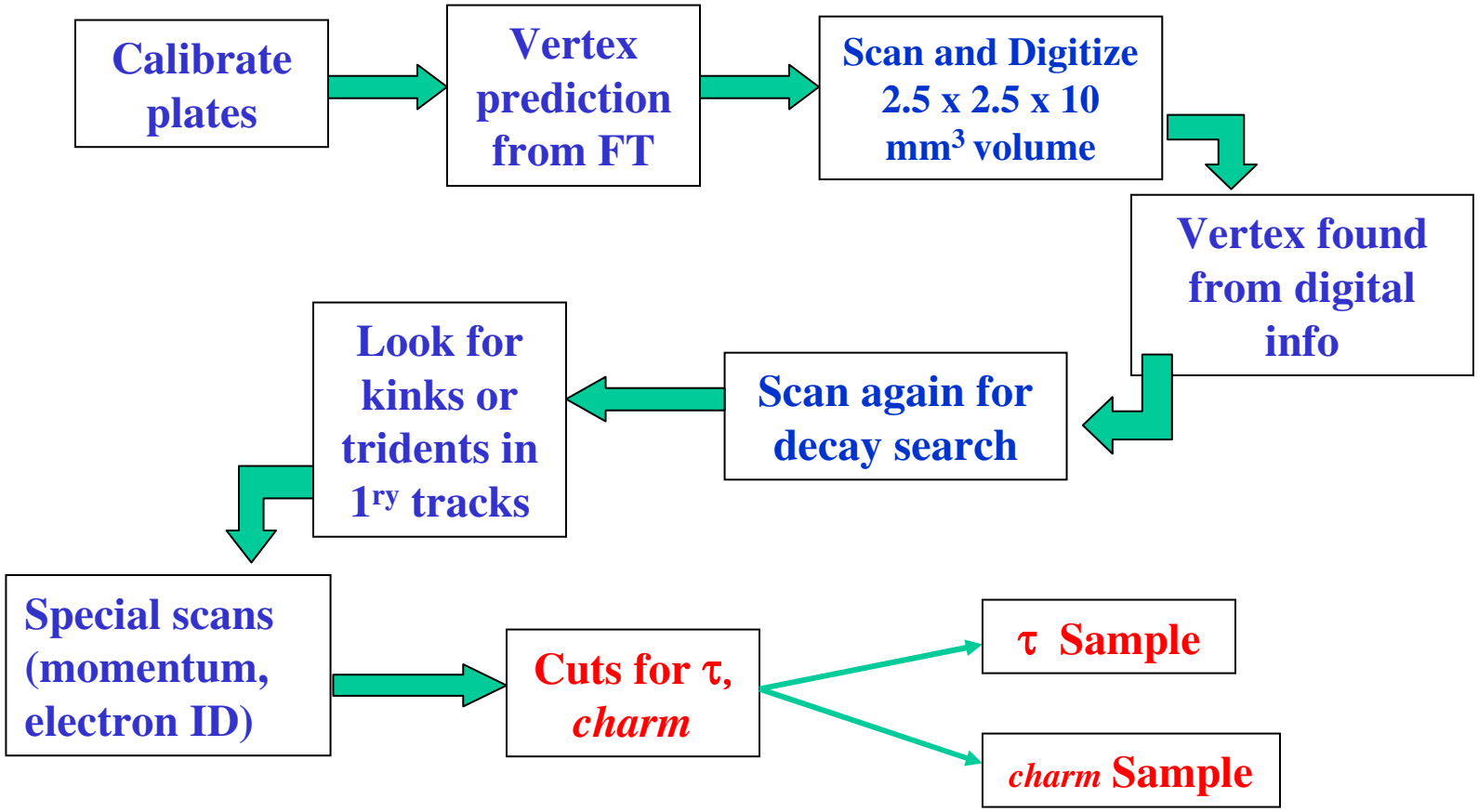
Location efficiency: **67%**

ν_τ candidates

charged charm candidates

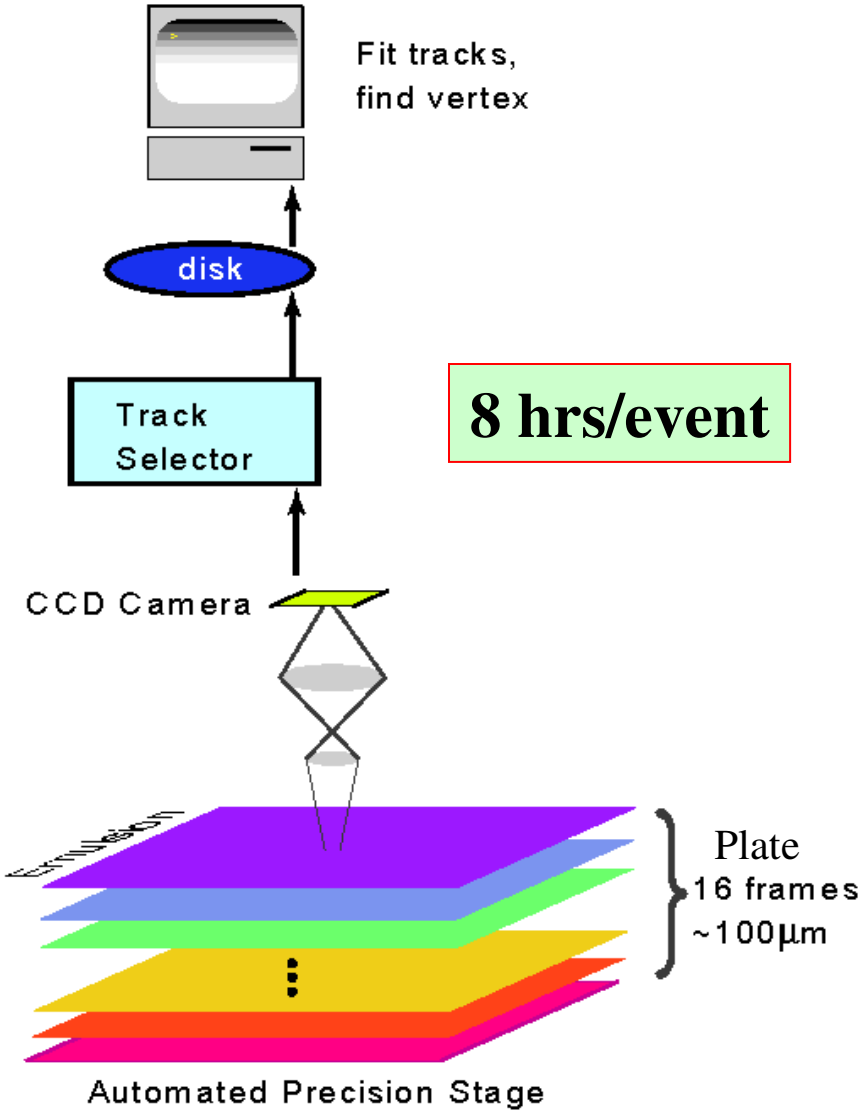

Number per 10 GeV/c
Muon momentum [GeV/c]
Data
Monte Carlo
Prompt
Non-prompt
0
10
20
30
40
50
0
20
40
60
80
100
120
140
160
180
200

Emulsion Scanning/Analysis



Analysis Overview

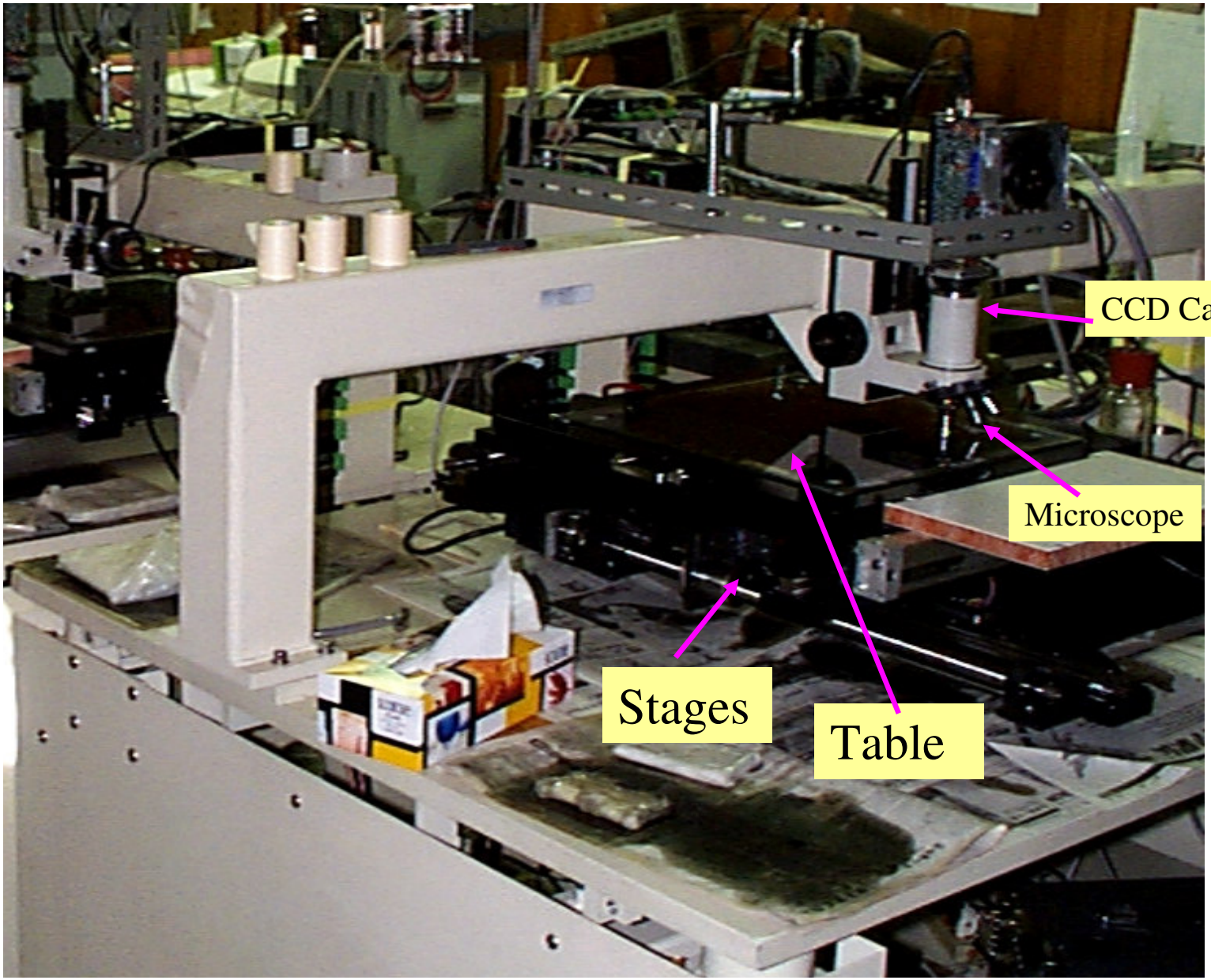
- **Predict interaction point in emulsion from spectrometer tracks** (software + humans)
- **Define a volume in emulsion around predicted interaction point. Digitize all track segments in emulsion volume** (hardware processor at Nagoya University)
- **Search digitized emulsion data for interaction** (software pattern recognition)
- **Use spectrometer to characterize event** (,)
- **Use emulsion data to locate kinks, tridents** (software pattern recognition)



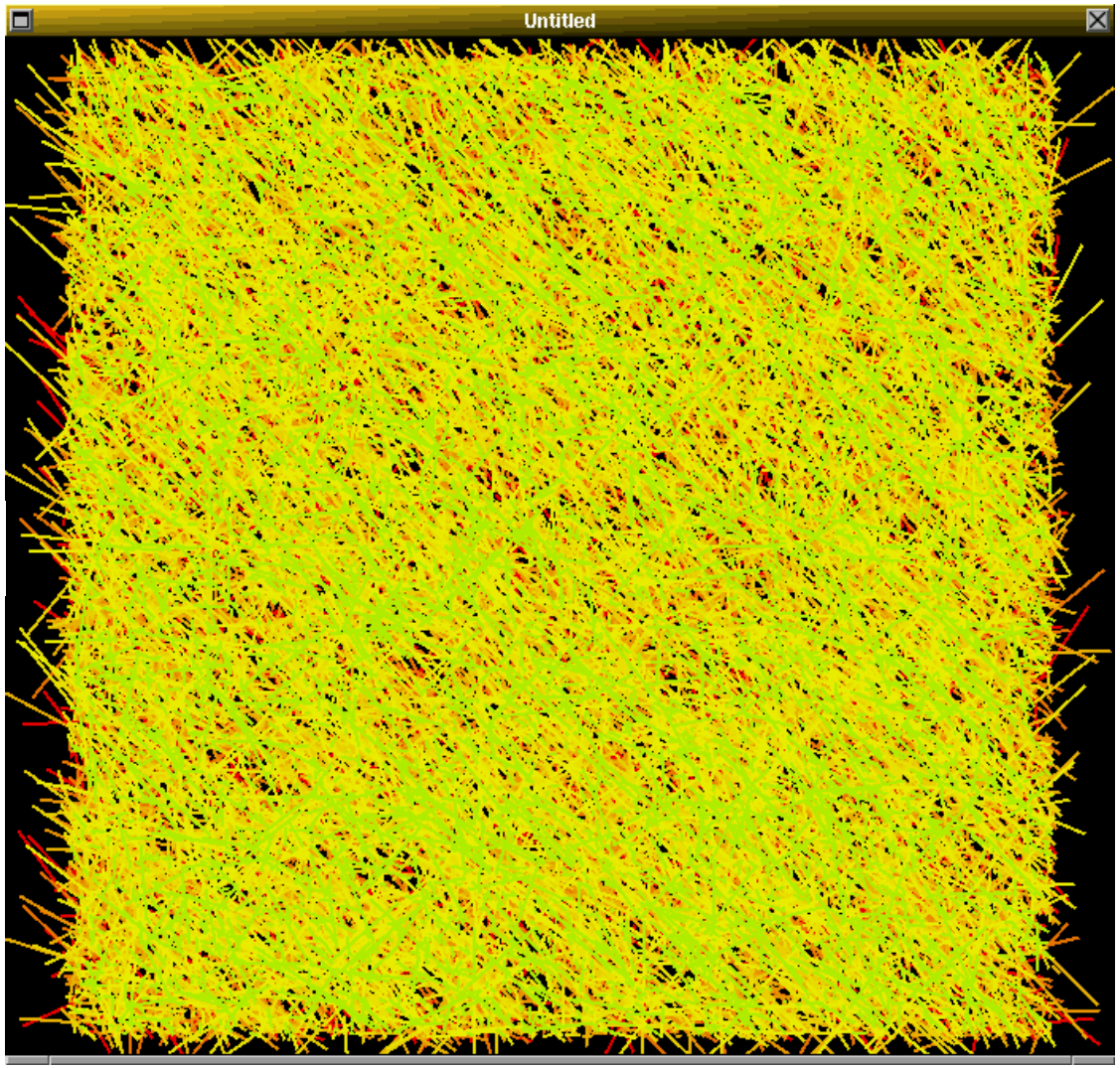
8 hrs/event

Scanning Stations at Nagoya Univ

Scanning Stations at Nagoya Univ



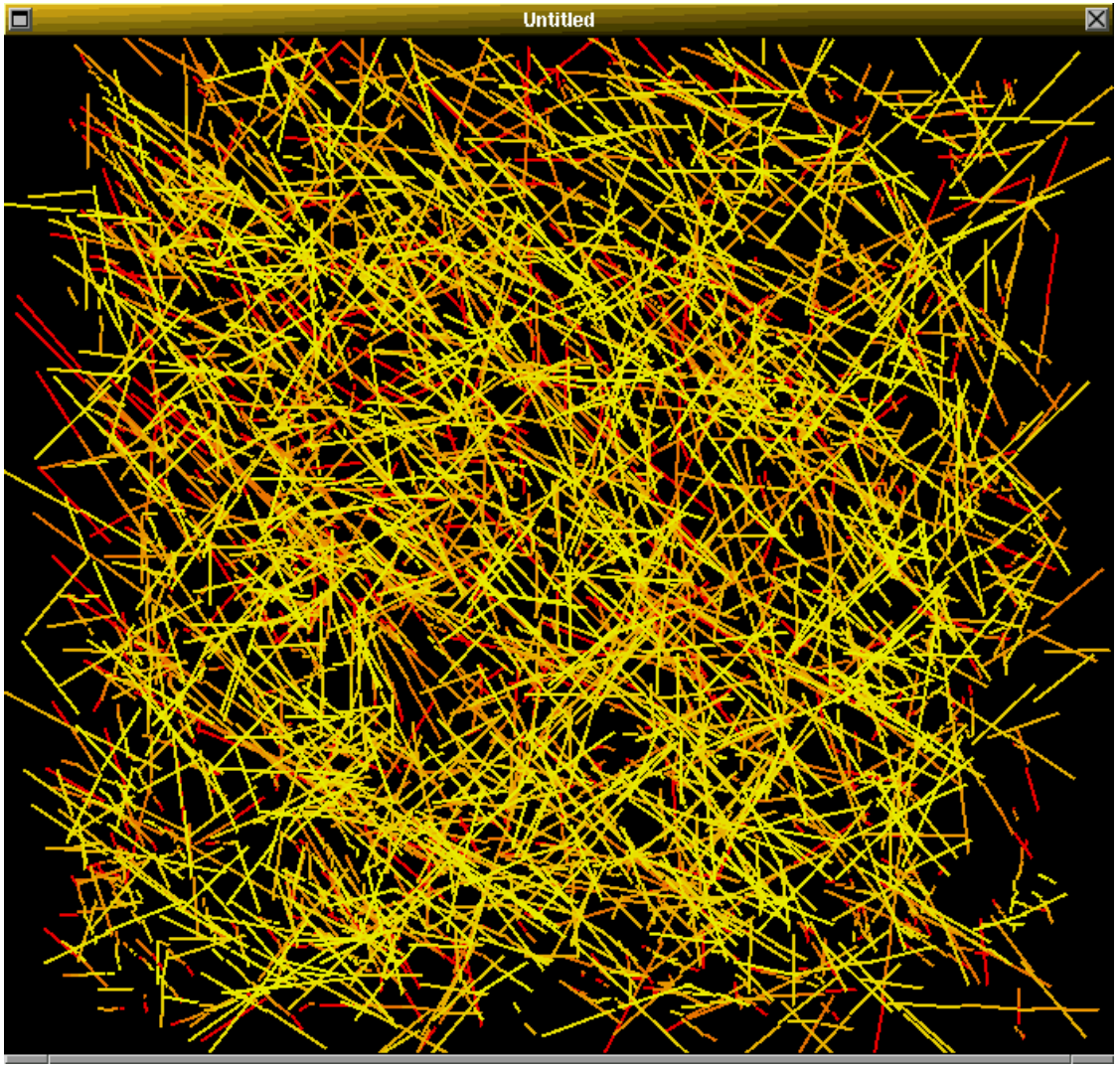
NET-scan in DONUT



Yellow : Upstream
Red : Downstream

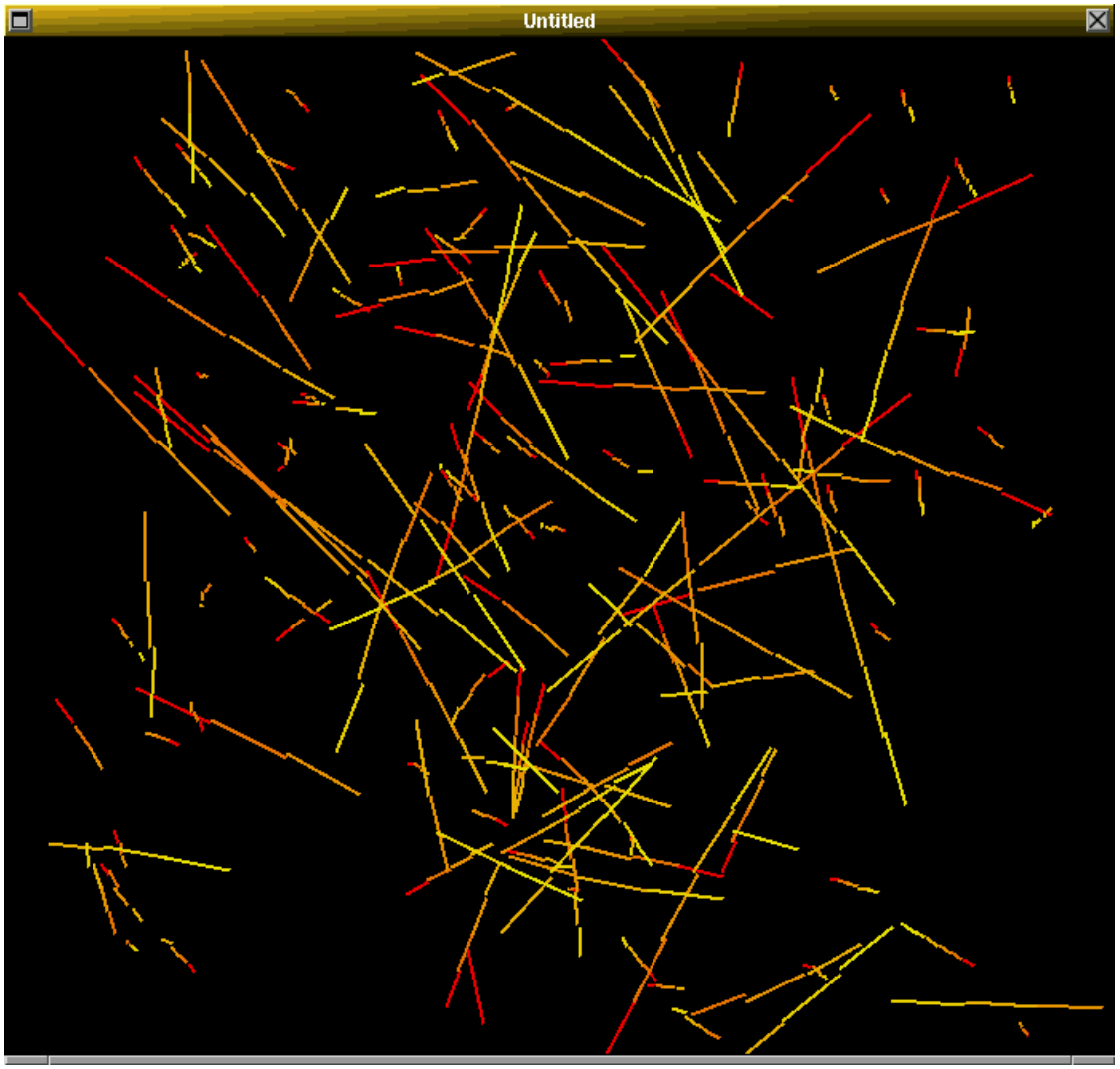
All track segments (~50k seg)

NET-scan in DONUT



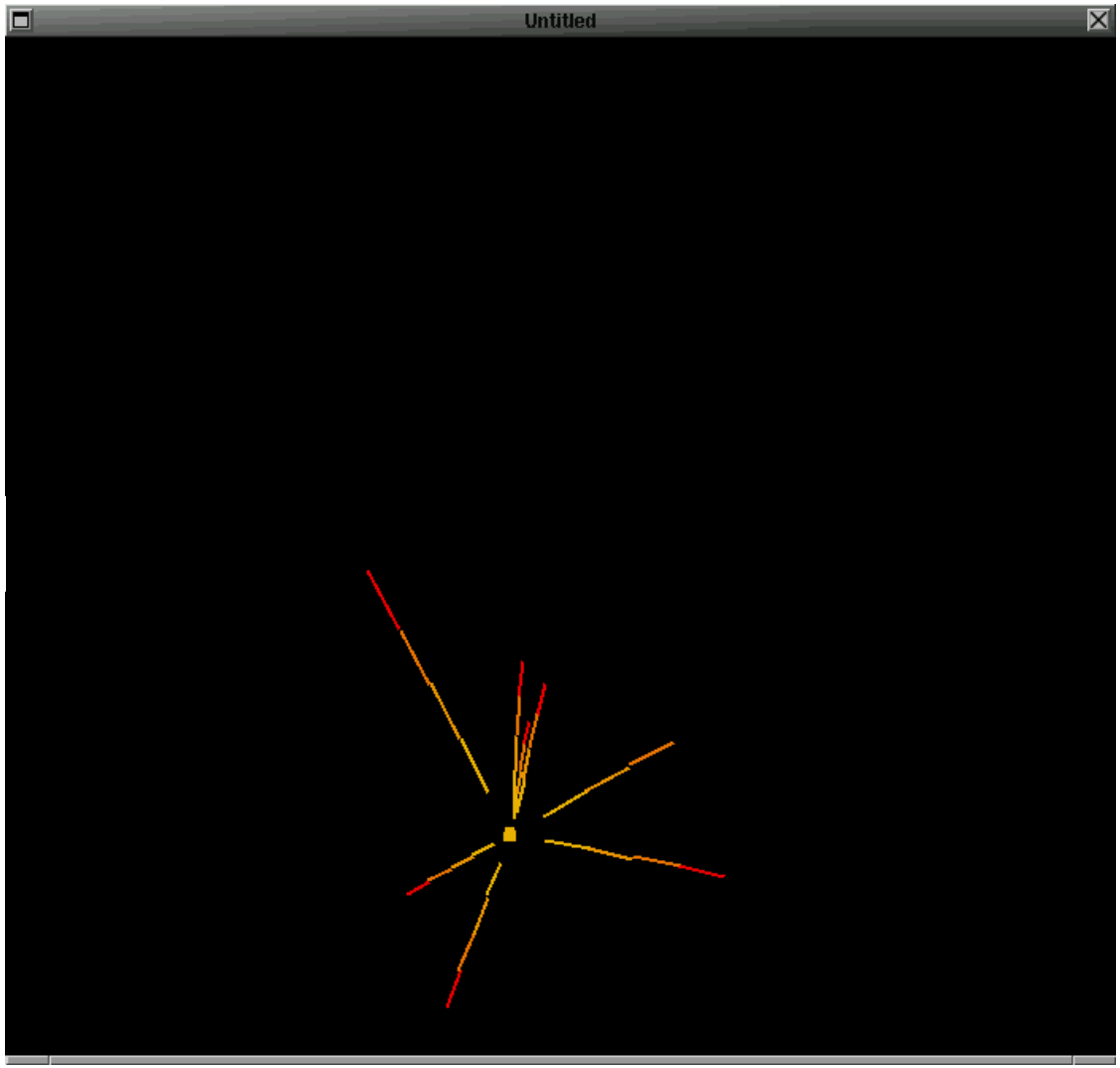
≥2 segments connected (~3k track)

NET-scan in DONUT



Not passing through (~200 track)

NET-scan in DONUT

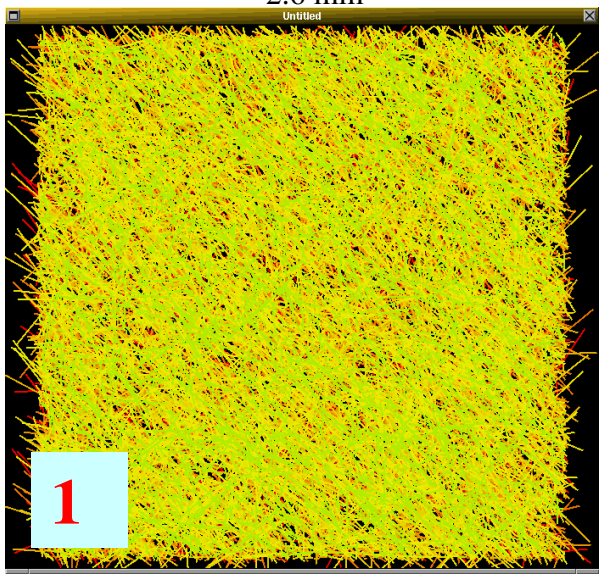


Small impact parameter

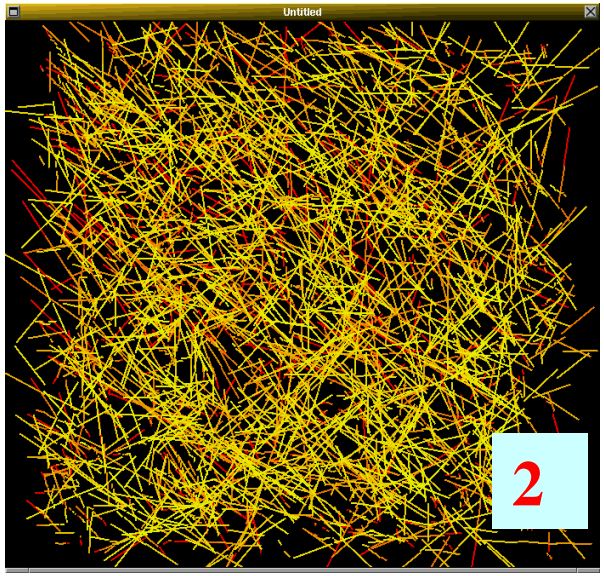
Vertex Location: NET-scan in DONUT

Yellow : Upstream
Red : Downstream

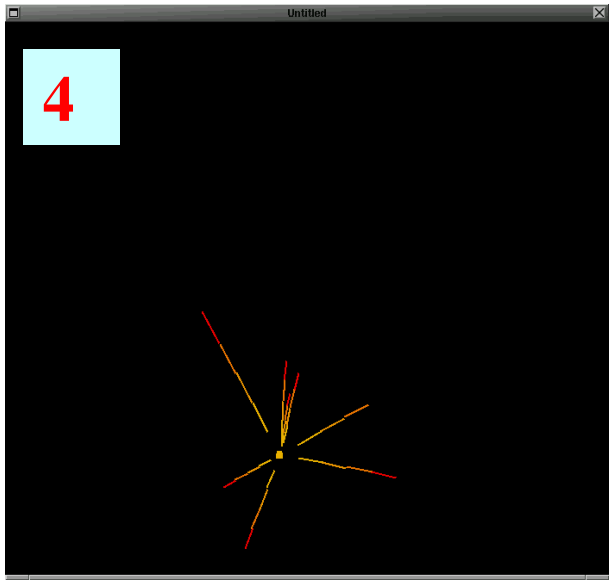
2.6 mm



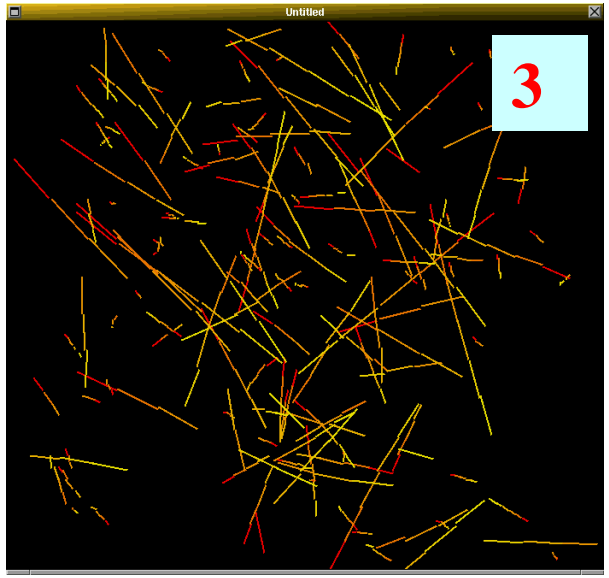
1.
All track segments (~50k seg)



2.
≥2 segments connected (~3k track)



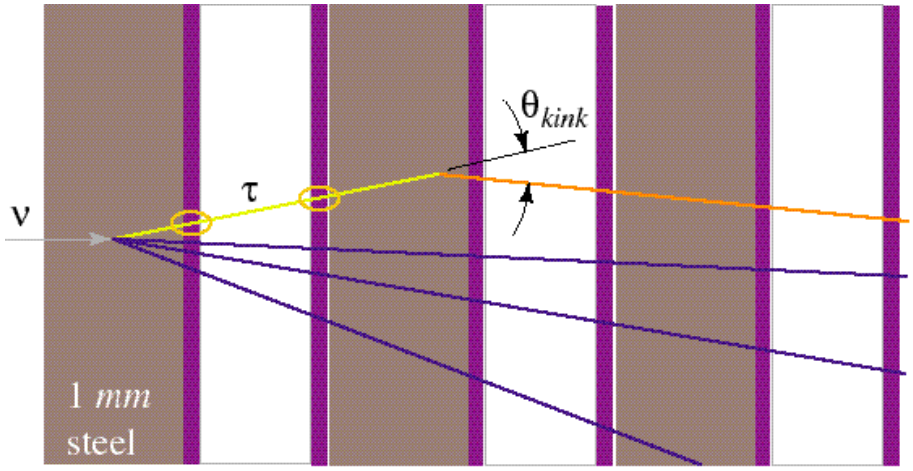
4.
Small impact parameter



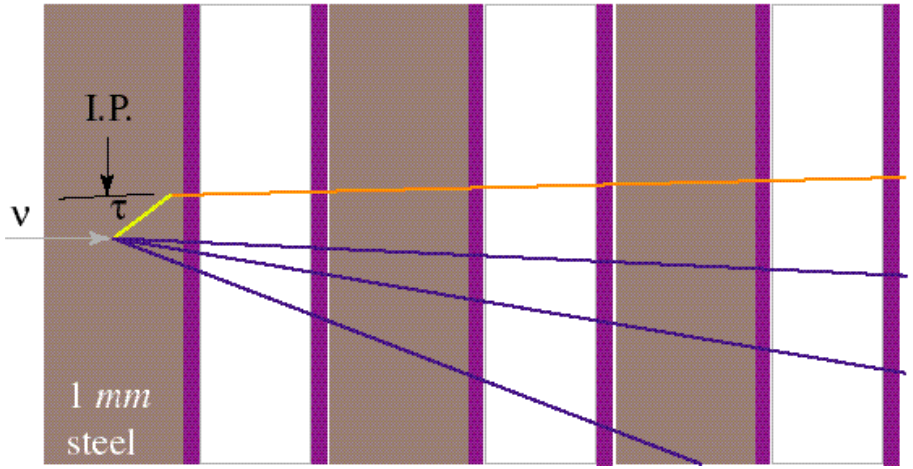
3.
Not passing through (~200 track)

2.6 mm

Decay Search



1. ***Long Decays***
   - parent measured
   - 1-prong (kink)
   - 3-prong (trident)
   - τ ⇒ no 1ry *lepton*
   - ~75% of kinks



2. ***Short Decays***
   - IP wrt 1ry vertex
   - only daughter meas.
   - daughter seen in spect.
   - ~25% of kinks

Tau/Charm Selection

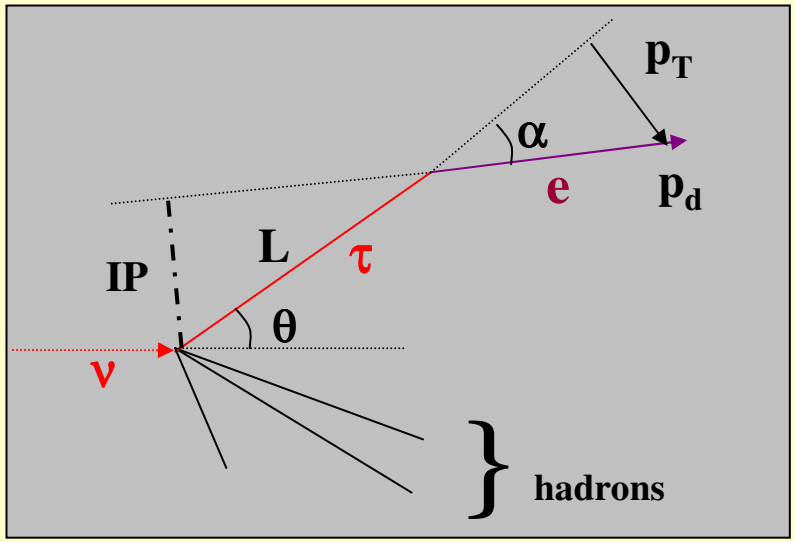
Discriminating Variables

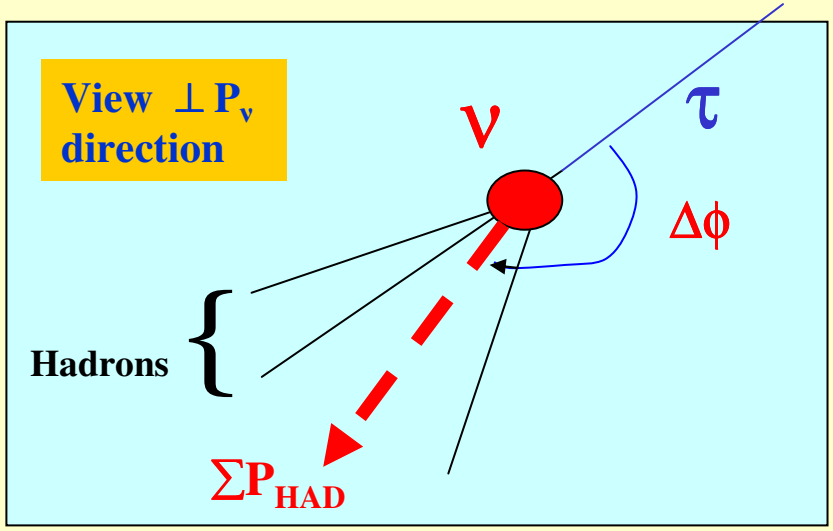
A. **Kinks: 5 Parameters**

- Production angle: θ
- Decay length: L
- Kink angle: α
- Daughter momentum: P_d
- Azimuthal asymmetry: $\Delta\varphi$

B. **Tridents: 4 Parameters**

- Production angle: θ
- Decay length: L
- Azimuthal asymmetry: $\Delta\varphi$
- Sum of IPs: $\Sigma(IP)$





Decay Search Criteria

A. Long Flight Decay Search

1. Parent track L < 10 mm
2. Parent track ≥ 1 seg & daughter track ≥ 3 microtracks
3. IP of parent track wrt primary < 5 μm (if parent ≥ 2 seg)
   IP of parent track wrt primary <(5 +0.01* Dz) μm (if parent = 1 seg)
4. Parent –daughter min distance < 5 μm (if parent ≥ 2 seg)
   Parent –daughter min distance <(5 +0.01* Dz) μm (if parent = 1 seg)
5. $\alpha > 4\sigma_{meas}$ or IP of daughter to primary > $4\sigma_{meas}$

B. Short Flight Decay Search

1. Track ≥ 3 microtracks
2. IP of parent track wrt primary $b_d < 200$ μm
3. IP of parent track wrt primary $bd > 4\ \sigma_{IP}$

Tau/Charm Recognition

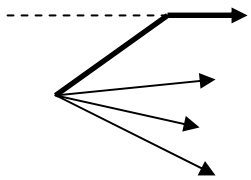
Topology and Kinematical Cuts

Cond #	Parameter	Condition	1-Prong	3-Prong	Comments
1	Parent slope (rad)	<	0.2	0.2	
2	Daughter slope (rad)	<	0.3	0.3	
3	α (rad) (*) (kink angle)	<	0.25	0.25	
4	IP (μm)	<	500	500	IP of daughter wrt primary vtx
5	P_d (GeV/c)	>	1.0	1.0	Daughter momentum
6	P_T (GeV/c)	>	0.25 had (0.1) (e,μ)	0.2	Hadron (lepton) Daughter P_T

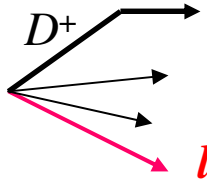
(*) For short decays: Min kink angle

Kink Classification

- Randomly associated tracks
  - e.g. Primary track + stale muon track

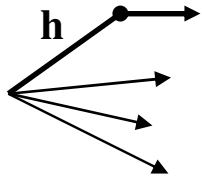


- *Charm* background

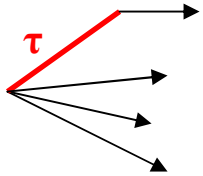


lepton : not recognized

- Interactions (scattering)



- Tau signal



Tau/Charm Selection

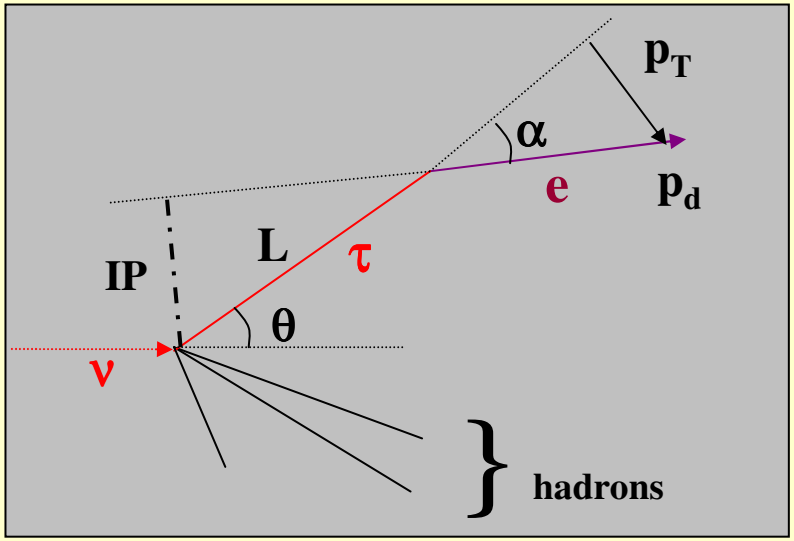
Discriminating Variables

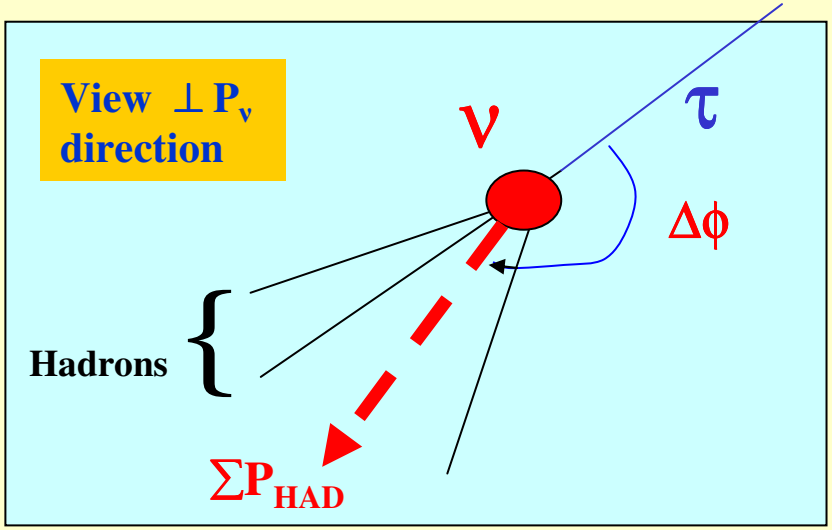
A. Kinks: 5 Parameters

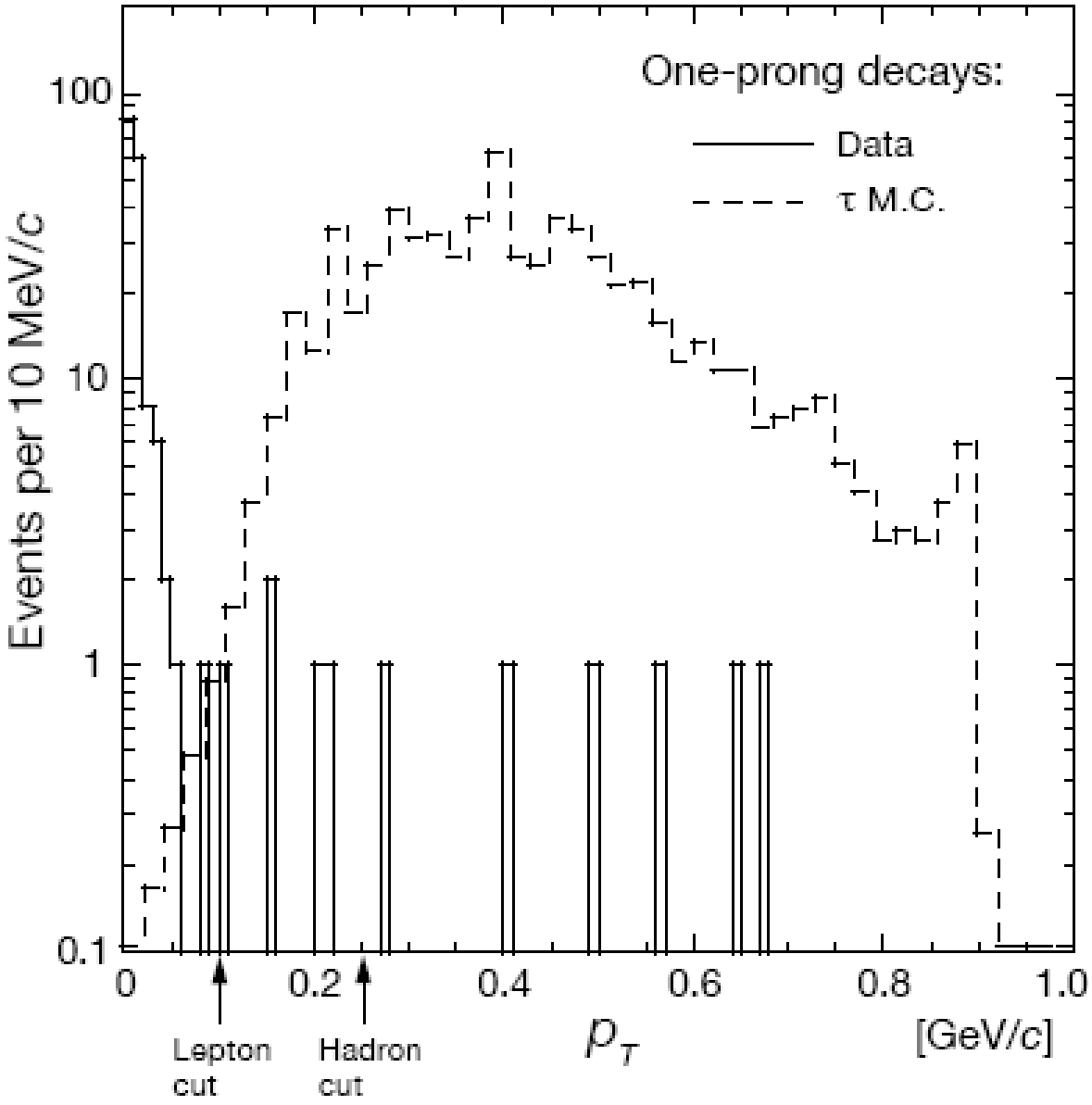
- Production angle: θ
- Decay length: L
- Kink angle: α
- Daughter momentum: P_d
- Azimuthal asymmetry: $\Delta\varphi$

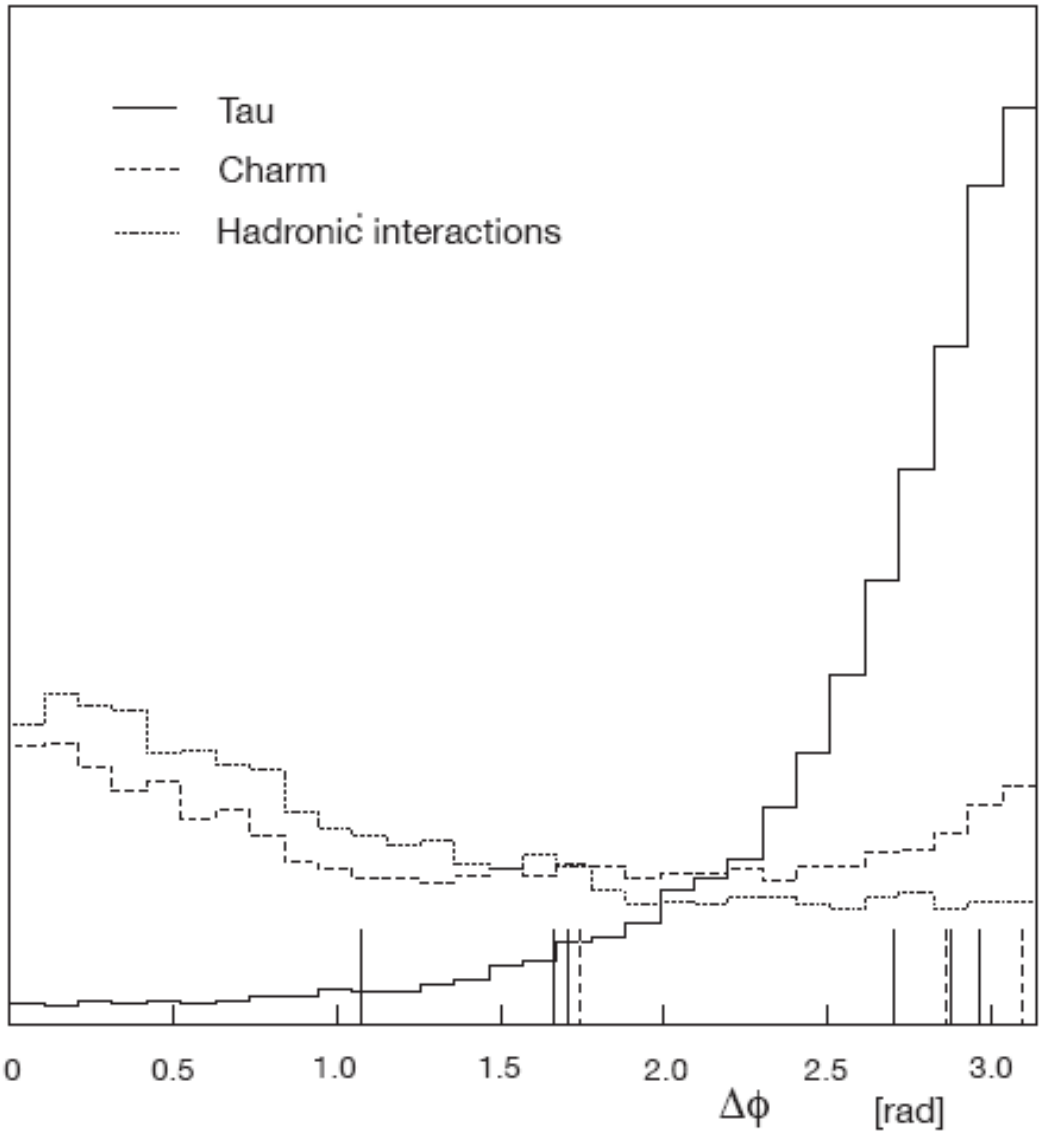
B. Tridents: 4 Parameters

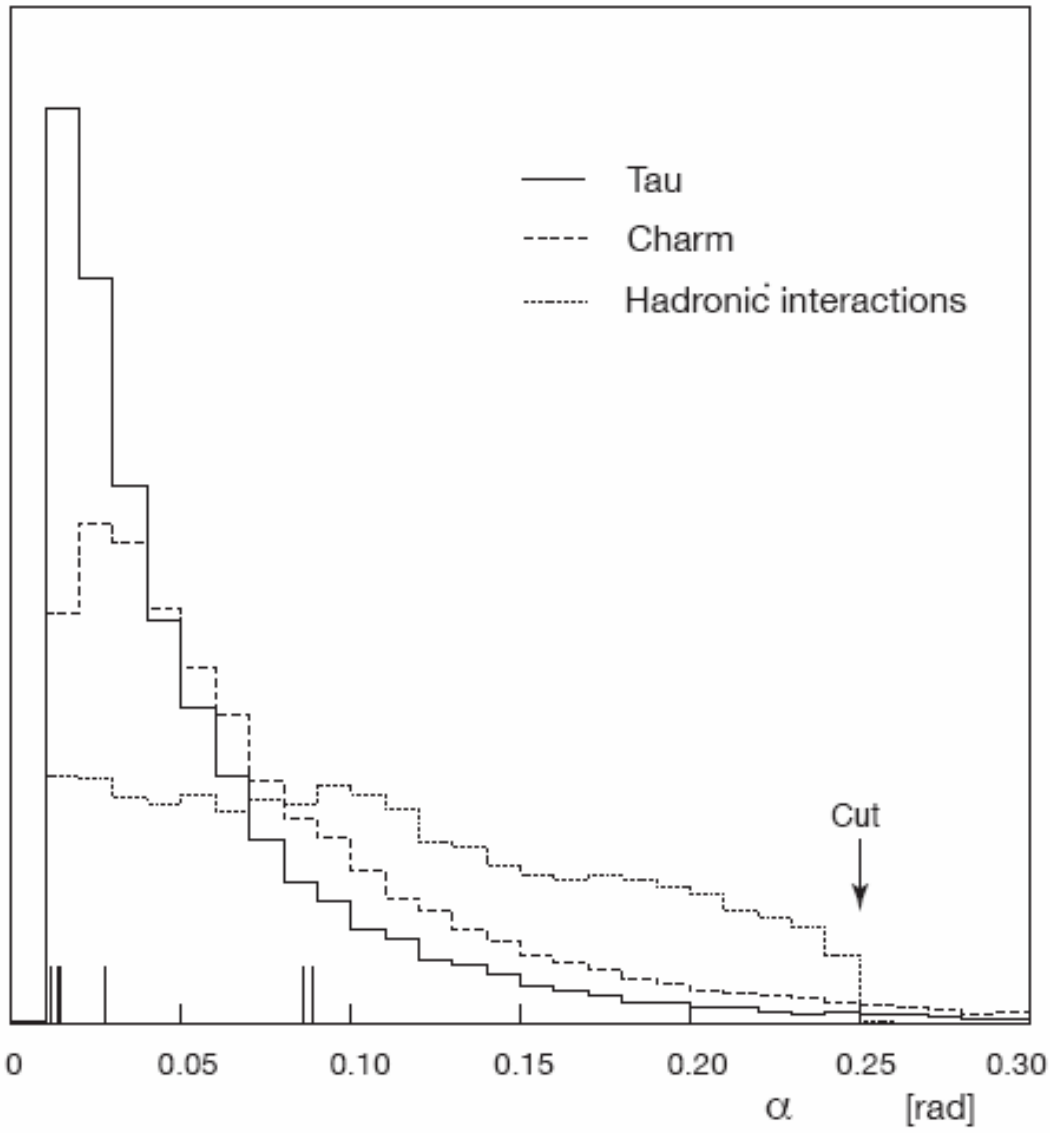
- Production angle: θ
- Decay length: L
- Azimuthal asymmetry: $\Delta\varphi$
- Sum of IPs: $\Sigma(IP)$

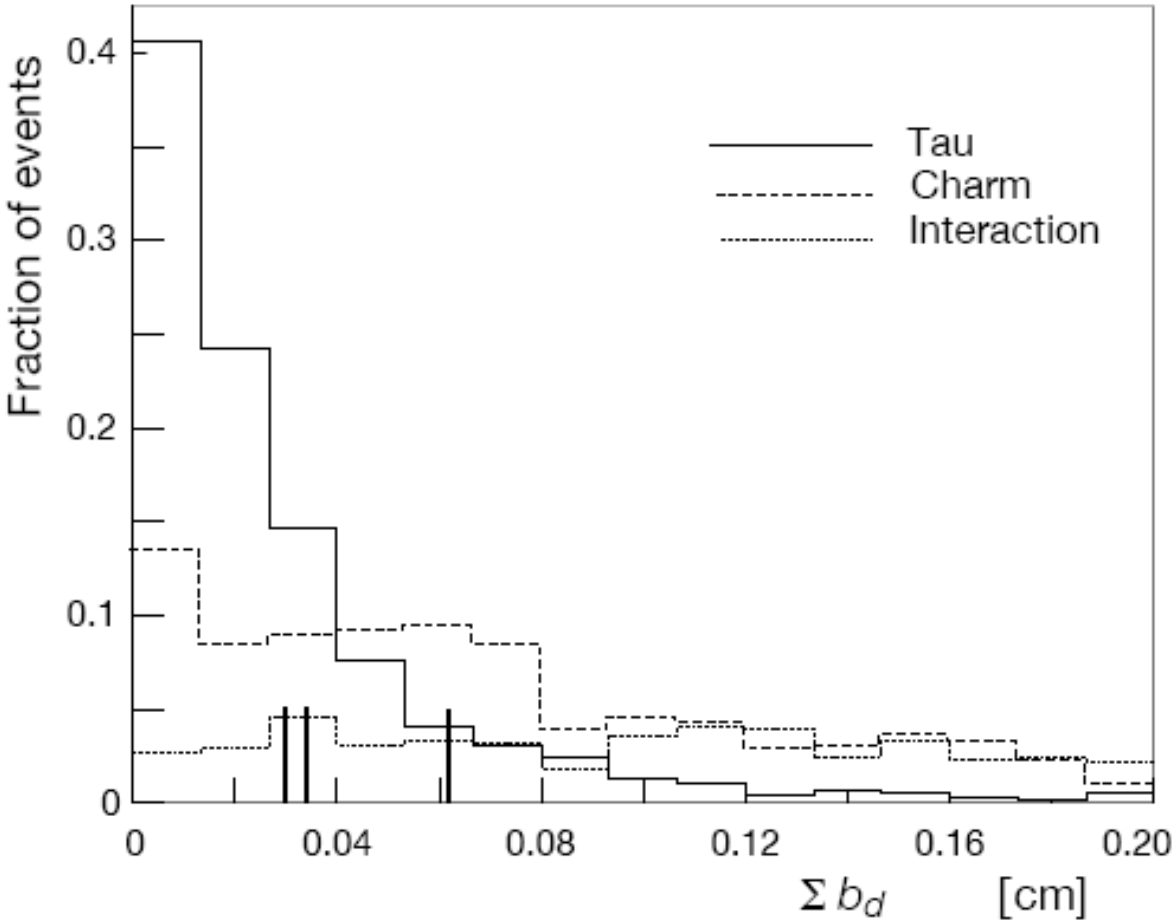


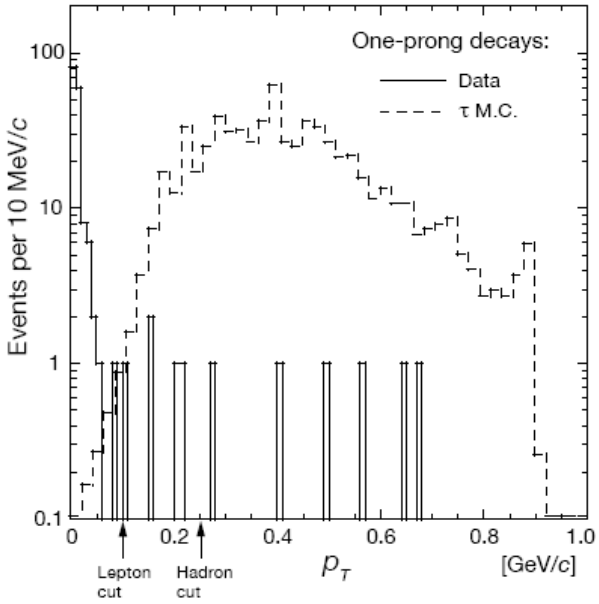


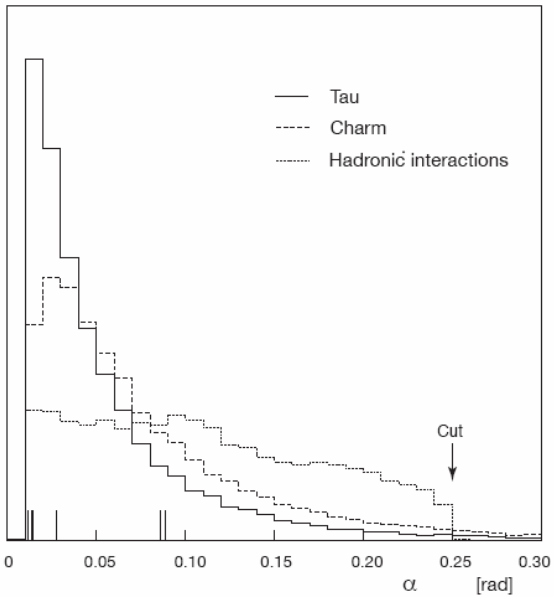

One-prong decays:
Data
τ M.C.
Events per 10 MeV/c
100
10
1
0.1
0
0.2
0.4
0.6
0.8
1.0
p_T
[GeV/c]
Lepton cut
Hadron cut

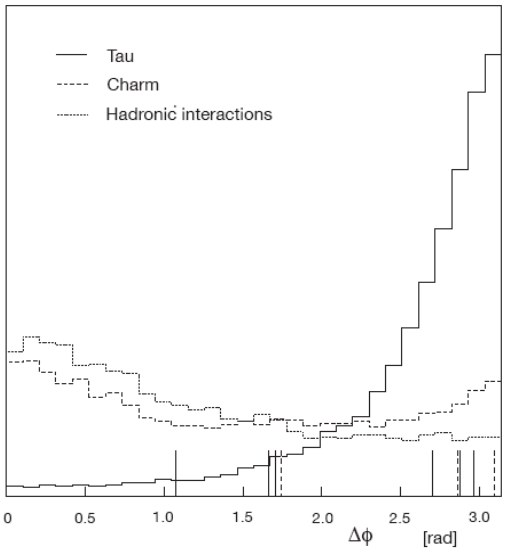

Tau
Charm
Hadronic interactions
0
0.5
1.0
1.5
2.0
2.5
3.0
Δφ
[rad]

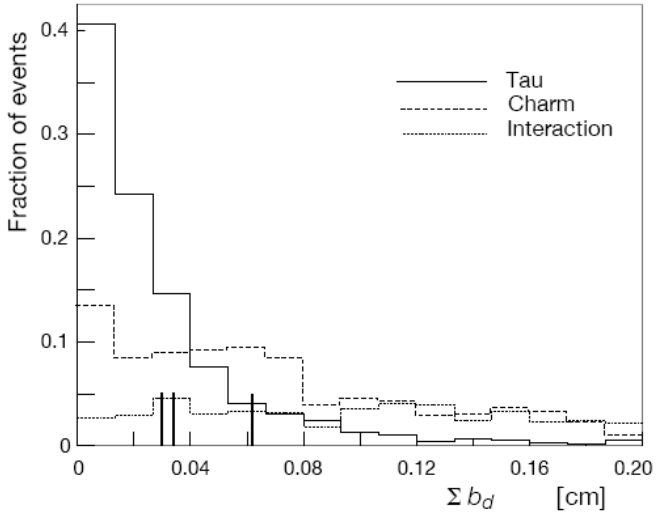

Tau
Charm
Hadronic interactions
Cut
0
0.05
0.10
0.15
0.20
0.25
0.30
α [rad]


Fraction of events
0.4
0.3
0.2
0.1
0
0
0.04
0.08
0.12
0.16
0.20
Σ b_d [cm]
Tau
Charm
Interaction


One-prong decays:
Data
τ M.C.
Events per 10 MeV/c
100
10
1
0.1
0
0.2
0.4
0.6
0.8
1.0
Lepton cut
Hadron cut
p_T
[GeV/c]


Tau
Charm
Hadronic interactions
Cut
0
0.05
0.10
0.15
0.20
0.25
0.30
α
[rad]


Tau
Charm
Hadronic interactions
0
0.5
1.0
1.5
2.0
2.5
3.0
Δφ
[rad]


Fraction of events
0.4
0.3
0.2
0.1
0
Tau
Charm
Interaction
0
0.04
0.08
0.12
0.16
0.20
Σ b_d
[cm]

ν - tau Selection

For each candidate produce individual probability of being Tau, Charm, or hadron interaction. Use Bayes's Theorem:

$$P(\{x_k\}|i) = \frac{\mathcal{W}_i \mathcal{P}(\{x_k\}|i)}{\sum_j \mathcal{W}_j \mathcal{P}(\{x_k\}|j)}$$

$P(\{x_k\}|i)$ = Probability of selecting event of type "i"

$\mathcal{W}_i$ = prior probability for event type "i"

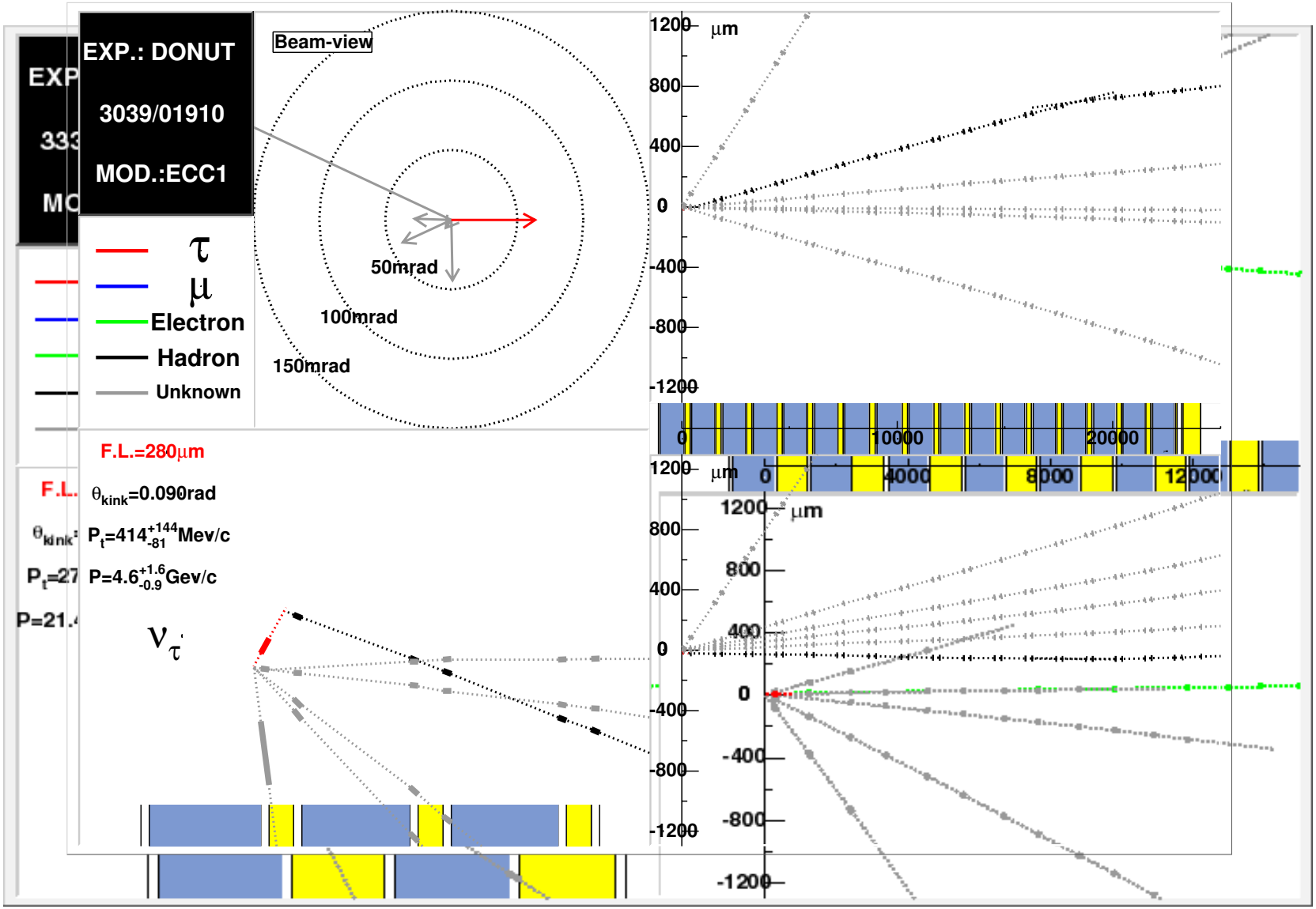
$\{x_k\}$ = set of parameters

$\mathcal{P}(\{x_k\}|i)$ = PDF of event "i" evaluated at $\{x_k\}$

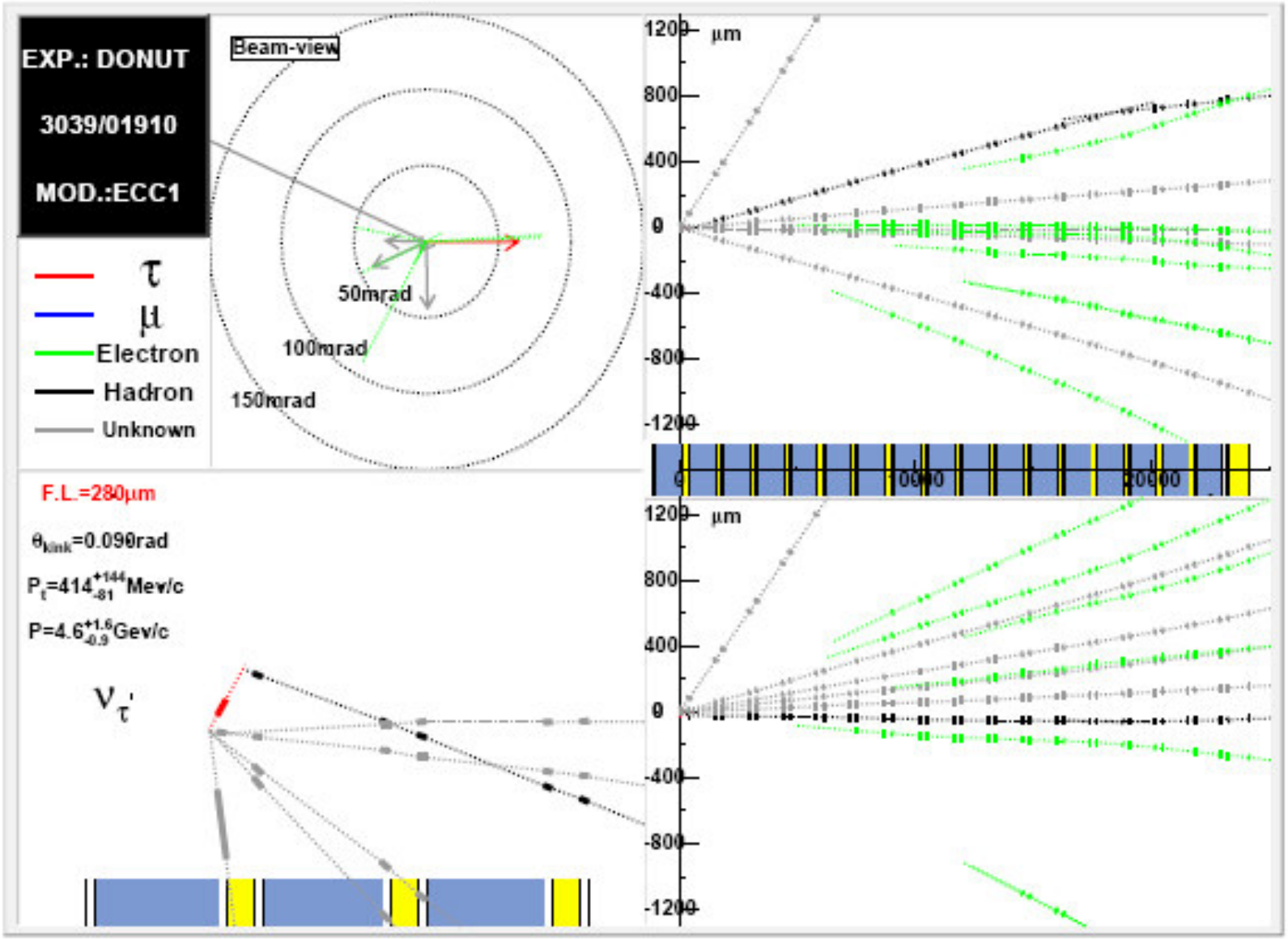
$\{x_k\}$ = $(\theta, L, \alpha, P_d, \Delta\varphi)$ for kinks

$\{x_k\}$ = $(\theta, L, \Delta\varphi, \Sigma IP)$ for tridents

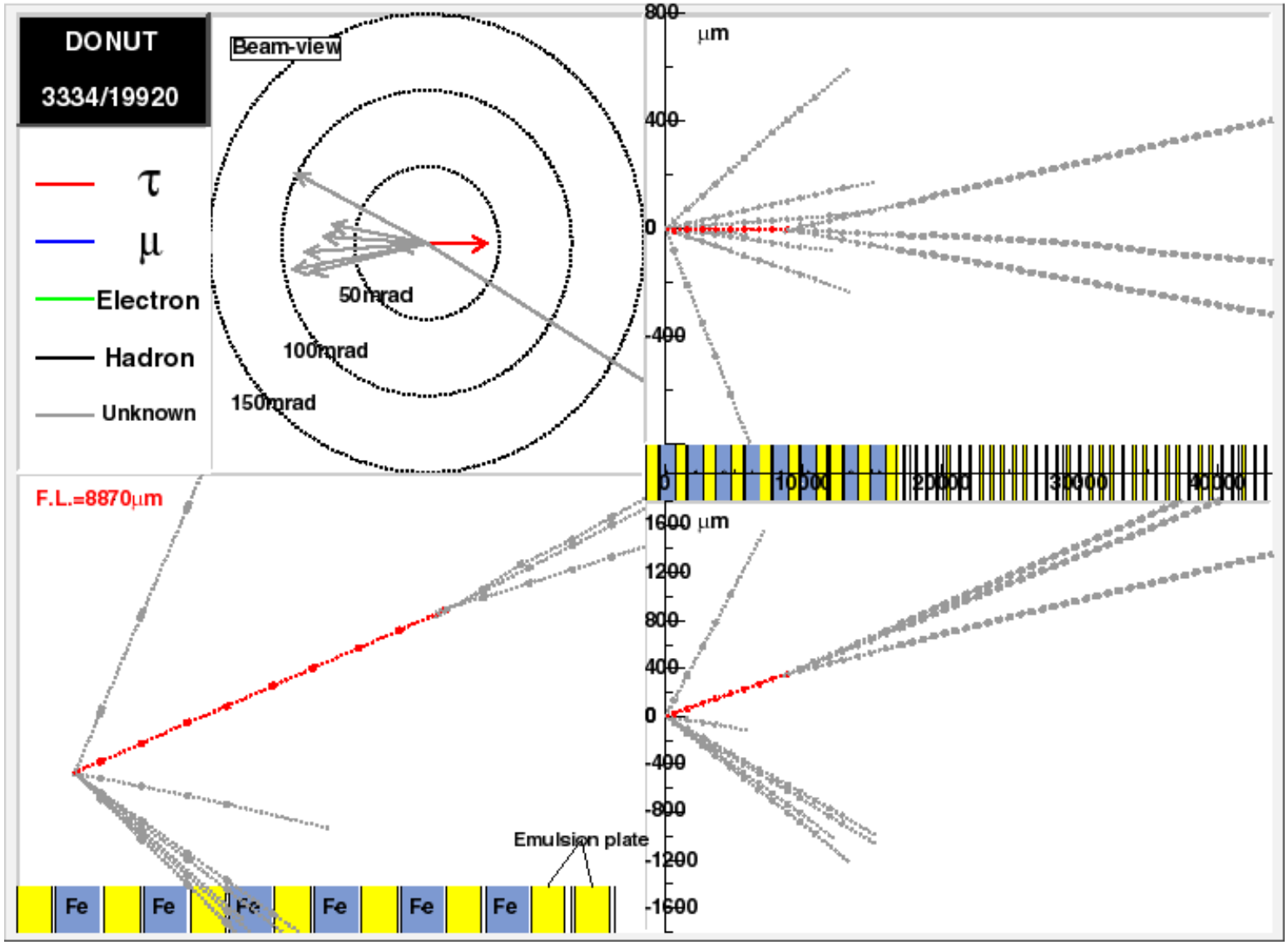
Example 1: Kink: ν_τ CC interaction



Example 2: Kink: ν_τ CC interaction

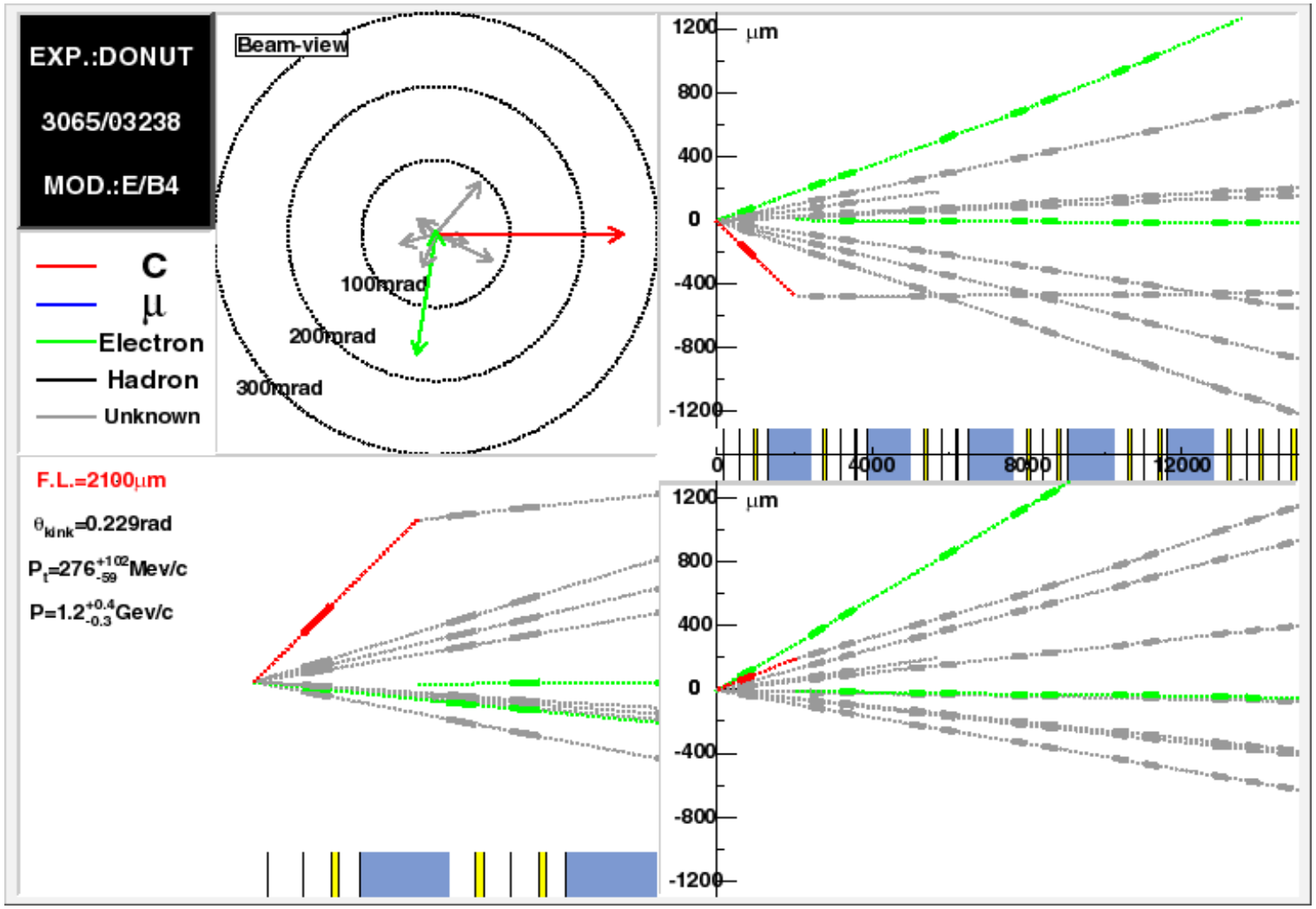


Example 3: Trident: ν_τ CC interaction



Charm Example:

Charm event: e + c



Data Reduction

DONUT Preliminary

6.6×10^6 triggers : 3.54×10^{17} POT

10^3 expected

866 within fiducial volume

578 vertex found

9 ν_τ candidates

Location efficiency: 67%

7 charged charm candidates

ν - ταυ Event List

Kinks

Run	Event	FL (mm)	θ_{kink} (rad)	IP (μm)	Daugt	P (GeV/c)	P_T (GeV/c)	P(τ)	P(c)	P(int)
3024	30175	4.47	0.093	416	e	5.2	0.48	0.53	0.47	0.0
3039	01910	0.28	0.089	24	h	4.6	0.41	0.96	0.04	0.0
3140	22143	4.83	0.012	60	μ^+	22.2	0.20	0.97	0.03	0.0
3333	17665	0.66	0.011	8	e	59	0.69	0.98	0.02	0.0
3024	18706	1.71	0.014	23	e	50	0.70	1.00	0.00	0.0
3139	22722	0.44	0.027	12	h	15.8	0.35	0.50	0.29	0.21

ν - ταυ Event List

Tridents

Run	Event	FL (mm)	θ_d (rad)	IP (μm)	P (GeV/c)	P_T (GeV/c)	P(τ)	P(c)	P(int)
3296	18816	0.80	0.054	38	5.0	0.27	0.71	0.29	0.0
			0.190	148	1.3	0.25			
			0.130	112	1.9	0.25			
3334	19920	8.88	0.017	147	11.6	0.20	1.0	0.0	0.0
			0.011	98	15.7	0.17			
			0.011	94	3.2	0.04			
3250	01713	0.83	0.133	110	1.3	0.17	0.87	0.12	0.01
			0.192	161	2.4	0.46			
			0.442	355	0.5	0.21			

$\nu_\tau N$ Cross Section Estimation

Use the known DIS linear energy dependence of the cross section to extract absolute $\nu_\tau N$ cross section:

- $\sigma_\nu / E = \text{slope} = \sigma^{\text{const}} K(E)$, $K = 1$, for ν_e, ν_μ

  $(0.667 \pm 0.0014) \times 10^{-38}$ cm^2/GeV/Nucleon, for ν_μ

  $(0.334 \pm 0.0080) \times 10^{-38}$ cm^2/GeV/Nucleon, for $\bar{\nu}_\mu$

- Equal numbers of prompt ν, $\bar{\nu}$'s
- Can use $\langle \sigma_\nu / E \rangle = (0.505 \pm 0.016) \times 10^{-38}$ cm^2/GeV/Nucleon

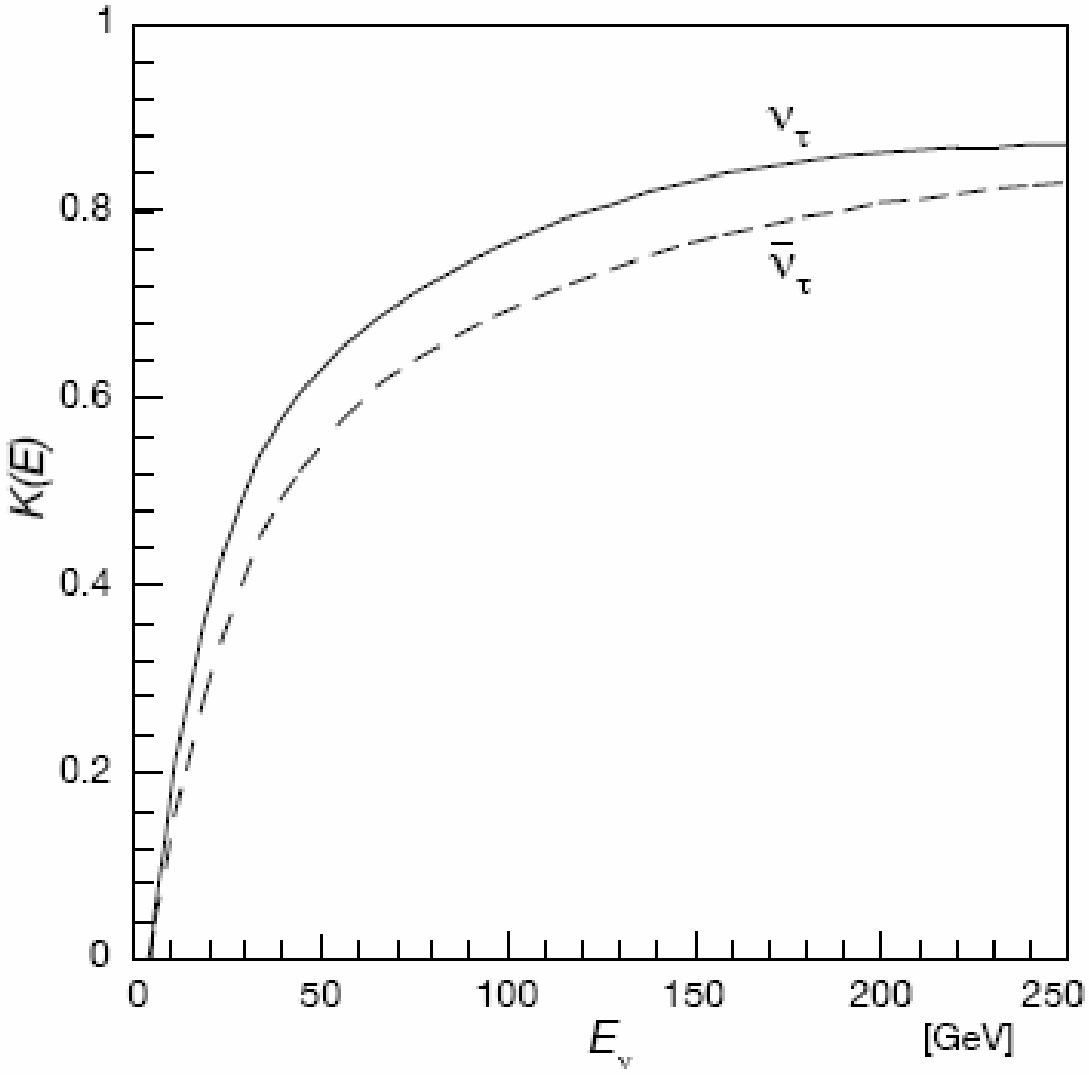
$\nu_\tau N$ Cross Section Estimation

$$N_{\rm int} = \frac{N_\nu^{\rm tgt}}{\rm pot} \cdot {\rm pot} \cdot \varepsilon \cdot \frac{\sigma^{\rm const}}{Area} \cdot \frac{M_{\rm tgt}}{m_{\rm nucleon}} \cdot \frac{f}{N_\nu^{\rm MC}} \sum EKTt = \sigma^{\rm const} \varepsilon C f \left\langle \sum EKTt \right\rangle$$

$$\sigma_{\nu_i} = \sigma_{\nu_i}^{\rm const} \, E \, K\left(E\right), \qquad i = e, \mu, \tau$$

$$\sigma_\tau^{\rm const} = \frac{N_\tau^{\rm exp}}{\varepsilon_{\rm TOT} \cdot C_\tau \cdot \left(f \left\langle \sum EKTt \right\rangle\right)_\tau}$$

$$\varepsilon_{\rm TOT} = \varepsilon_{\rm FS} \cdot \varepsilon_{\rm trig} \cdot \varepsilon_{\rm loc} \cdot \varepsilon_\tau \cdot \qquad \approx 0.20 \pm 0.02$$


1
0.8
0.6
0.4
0.2
0
K(E)
ν_τ
$\bar{\nu}_\tau$
0
50
100
150
200
250
E_ν
[GeV]

$\nu_\tau N$ Cross Section Estimation

Quantity	Value
$\sigma(\mathrm{pN} \to \mathrm{D}^{\pm}\mathrm{X})$	$21 \pm 2\ \mu\mathrm{b}$
$\sigma(\mathrm{pN} \to \mathrm{D}^{0}\mathrm{X})$	$41.3 \pm 2.6\ \mu\mathrm{b}$
$\sigma(\mathrm{pN} \to \mathrm{D}_s\mathrm{X})$	$7.9 \pm 1.2\ \mu\mathrm{b}$
$\sigma(\mathrm{pN} \to \Lambda_c\mathrm{X})$	$8 \pm 5\ \mu\mathrm{b}$
$\sigma_{tot}(\mathrm{pW})$	1650 mb
α	0.99 ± 0.03
n	6.1 ± 0.1
b	$0.80 \pm 0.10\ (\mathrm{GeV}/c)^{-2}$

Type	C_ℓ $\times 10^{40}\ \mathrm{cm}^{-2}$	$f\ \langle \sum EKTt \rangle_\ell$ GeV
ν_e	1.64 ± 0.38	$4.62^{+1.41}_{-0.94}$
ν_μ	1.55 ± 0.36	$4.33^{+1.32}_{-0.88}$
ν_τ	0.289 ± 0.085	$3.30^{+0.69}_{-0.52}$

	ν_e CC	ν_μ CC prompt	ν_μ CC non-prompt	ν_τ CC	NC_{eff}
MC fraction	0.190	0.208	0.163	0.018	0.421
MC fraction $\times$ 578	110	120	94	10	244
Data	120	225		9	224
Difference	10 ± 11	11 ± 15		-1 ± 3	-20 ± 15

$\nu_\tau N$ Cross Section Estimation

$f\left\langle \sum EKTt \right\rangle$ From MC vs b and n

$$\frac{d^2\sigma}{dx_F dp_T^2} = A\, e^{-bp_T^2}\,(1-|x_F|)^n$$

b same for all charm species

n sensitive to quark content, left as parameter

$$f\left\langle \sum EKTt \right\rangle = 51.6\; n^{-1.52}$$

Agrees with MC to within 10% for 4 < n < 10

$$\sigma_{\text{const}}\left(\nu_\tau\right) = 9\left(0.335\; n^{1.52}\right) \times 10^{-40}\text{cm}^2\text{GeV}^{-1}$$

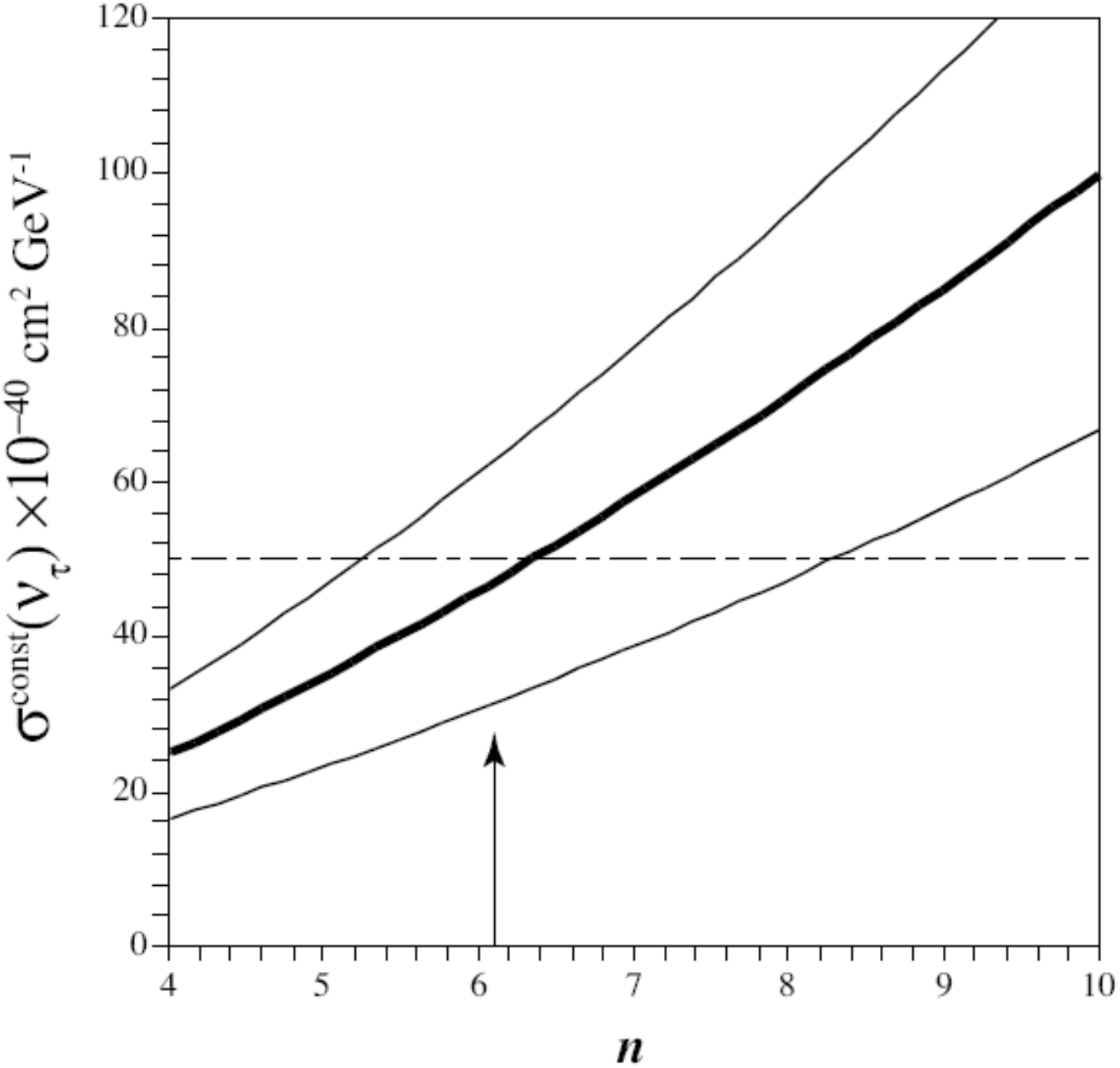
Relative errors: Stat = 33%, Syst = 33%

Cross section estimate: Use Pythia-derived n = 6.1

$$\sigma_{\text{const}}\left(\nu_\tau\right) = 0.47 \pm 0.16 \pm 0.16 \times 10^{-38}\text{cm}^{\;2}\text{GeV}^{-1}$$

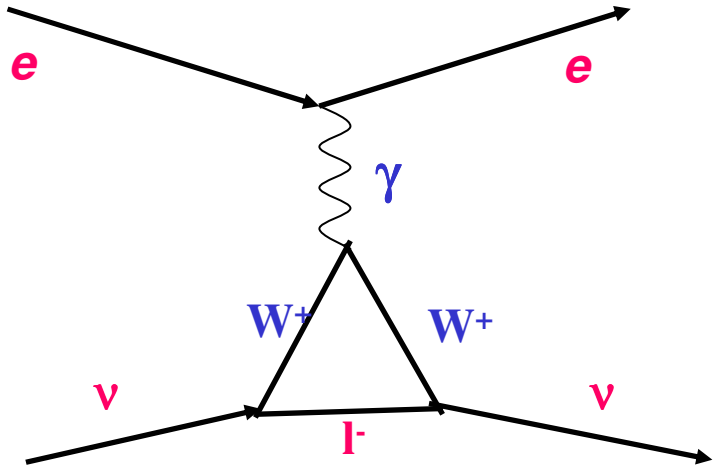
SM: 0.50×10^{-38} cm^{-2}GeV^{-1} Assuming lepton Universality

ν_τ


120
100
80
60
40
20
0
4
5
6
7
8
9
10
$\sigma^{const}(\nu_\tau) \times 10^{-40}$ cm^2 GeV^{-1}
n

ν - tau Magnetic Moment

Interaction of ν with e^- via a dipole moment has a distinct signature
- single, forward e^-
- dominates EW process for $T_e/E_\nu < 0.2$



$$\frac{d\sigma^{\mu}}{dy} \propto \left(\frac{\mu_\nu}{\mu_B}\right)^2 \left(\frac{E_\nu}{T} - 1\right)$$

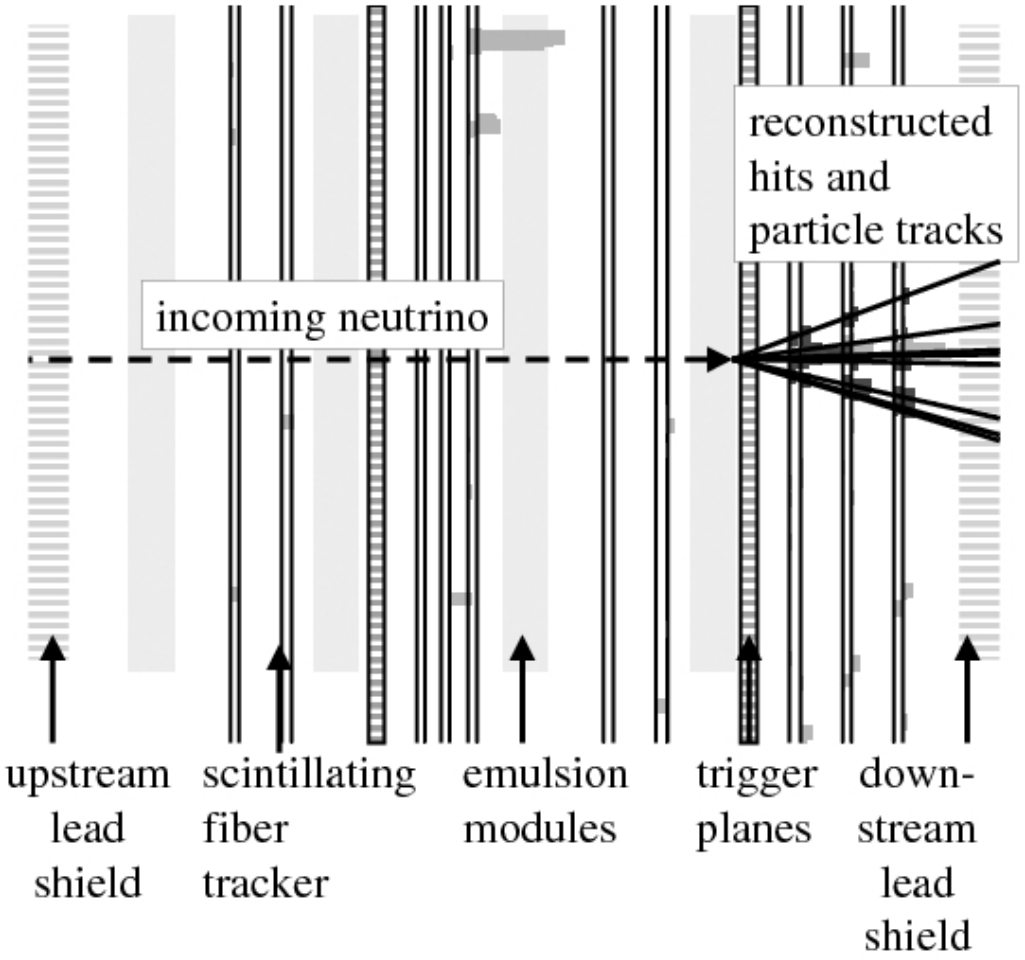
1 event observed after cuts
2.3 Bgnd events expected

$\mu_\nu < 3.9 \times 10^{-7}\ \mu_B$ **90% CL**

Published in Phys. Lett. B 513, 23 (2001)

ν - tau Magnetic Moment

One candidate event: $\nu_\tau e \rightarrow \nu_\tau e$



NuTau Properties from DONUT

- The DONUT Experiment has directly detected the tau-neutrino as a neutral particle responsible for the reaction:

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

- 9 CC ν_τ-Nucleus interactions have been observed corresponding to 3.54×10^{17} Protons on the beam dump.
- Charm production consistent with expectations
- Preliminary DIS slope σ_ν /E consistent with SM.
- Magnetic moment limit: $\mu_\nu < 3.9 \times 10^{-7}\ \mu_B$ @ 90% CL

ν - tau Mass

- **Most stringent experimental limit: ALEPH, 1998**

  From $\tau^- \rightarrow 2\pi^- \pi^+ \nu_\tau$ @ $\tau^- \rightarrow 3\pi^- 2\pi^+(\pi^0)\nu_\tau$

  (From the fit of the distribution of E_h vs m_h)

  $$m_{\nu\tau} < 18.2 \text{ MeV/c}^2 \text{ at 95\% CL}$$

  Effective mass squared:

  $$m^2_{\nu\tau} = \sum_i |U_{\tau i}|^2 m^2_i \rightarrow m^2_{\nu\tau} \leq \text{Max}_i \{m^2_i\}$$

- **Cosmological: From combined cosmological data (WMAP, CBI, ACBAR, 2dFGRS, and Lyman α data) and some cosmological assumptions:**

  Constraint: $\sum_i m_i \leq$ (0.17 – 2.0) eV

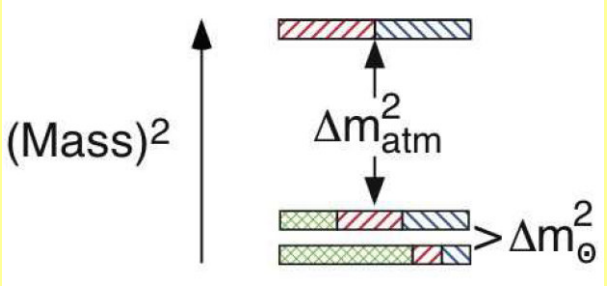
  (Seljak et al., astro-ph/0604335

  J. Lesgourgues and S. Pastor , Phys. Rep. 429, 307(2006)

- **Combine with Oscillation Data:**

$\Delta m^2_{12} = 8 \times 10^{-5}\ eV^2$

$|\Delta m^2_{13}| = 2.5 \times 10^{-3}\ eV^2$



$m_1 \sim m_2 < 0.05$ eV, $m_3 < 0.07$ eV, Normal Hierarchy

$m_1 \sim m_2 < 0.062$ eV, $m_3 < 0.045$ eV, Inverted Hierarchy

(Seljak et al., astro-ph/0604335)

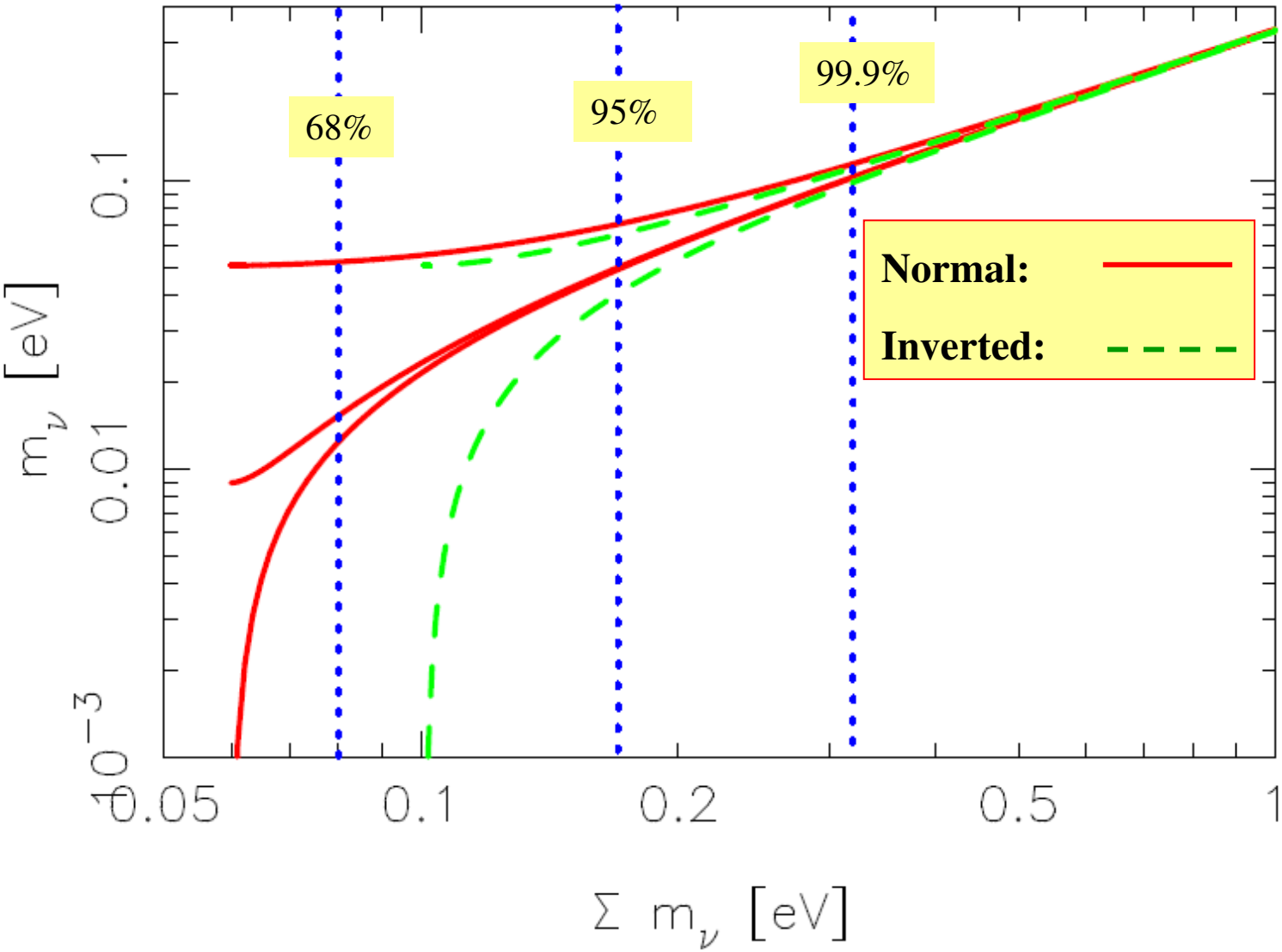
Same information to get limits on Heaviest ν_i

$0.04 <$ Mass [Heaviest ν_i] $<$ (0.07 – 0.7) eV

(B. Kayser, arXiv:0804.1947v1 [hep-ph] 9 Apr 2008)

m_i versus $\sum_i m_i$

(Seljak et al., astro-ph/0604335)



Present S-M Properties

V-A coupling: τ- decay

• τ – ν_τ coupling: V-A : τ-lepton decay parameters: LEP (ALEPH, DELPHI, L3, OPAL), ARGUS, SLD, MAC, CLEO. Most precise ALEPH.

Michel Parameters

Parameter	SM	ALEPH	PDG Fit	PDG Average
ρ (e or μ)	3/4	0.742±0.014 ± 0.006	0.745±0.008	0.749±0.008
ξ (e or μ)	1	0.986±0.068 ± 0.031	0.985±0.030	0.981±0.031
η (e or μ)	0	0.012±0.026± 0.004	0.013±0.020	0.015±0.021
(δξ) (e or μ)	3/4	0.776±0.045± 0.024	0.746±0.021	0.744±0.022

Present S-M Properties

Universality

Strength of coupling from τ-lepton lifetime. If $G_\tau = G_\mu$ (Universality)

$$\rightarrow \quad \tau_\tau \approx (m_\mu/m_\tau)^5 \tau_\mu BR(\tau \rightarrow e) = 2.91 \times 10^{-13}\ s$$

Most precise data from DELPHI, ALEPH, L3, OPAL, CLEO

$$\tau_\tau = (2.909 \pm 0.014 \pm 0.010) \times 10^{-13}\ s \quad \text{(DELPHI)}$$

$$\tau_\tau = (2.906 \pm 0.010) \times 10^{-13}\ s \quad \text{(PDG Average))}$$

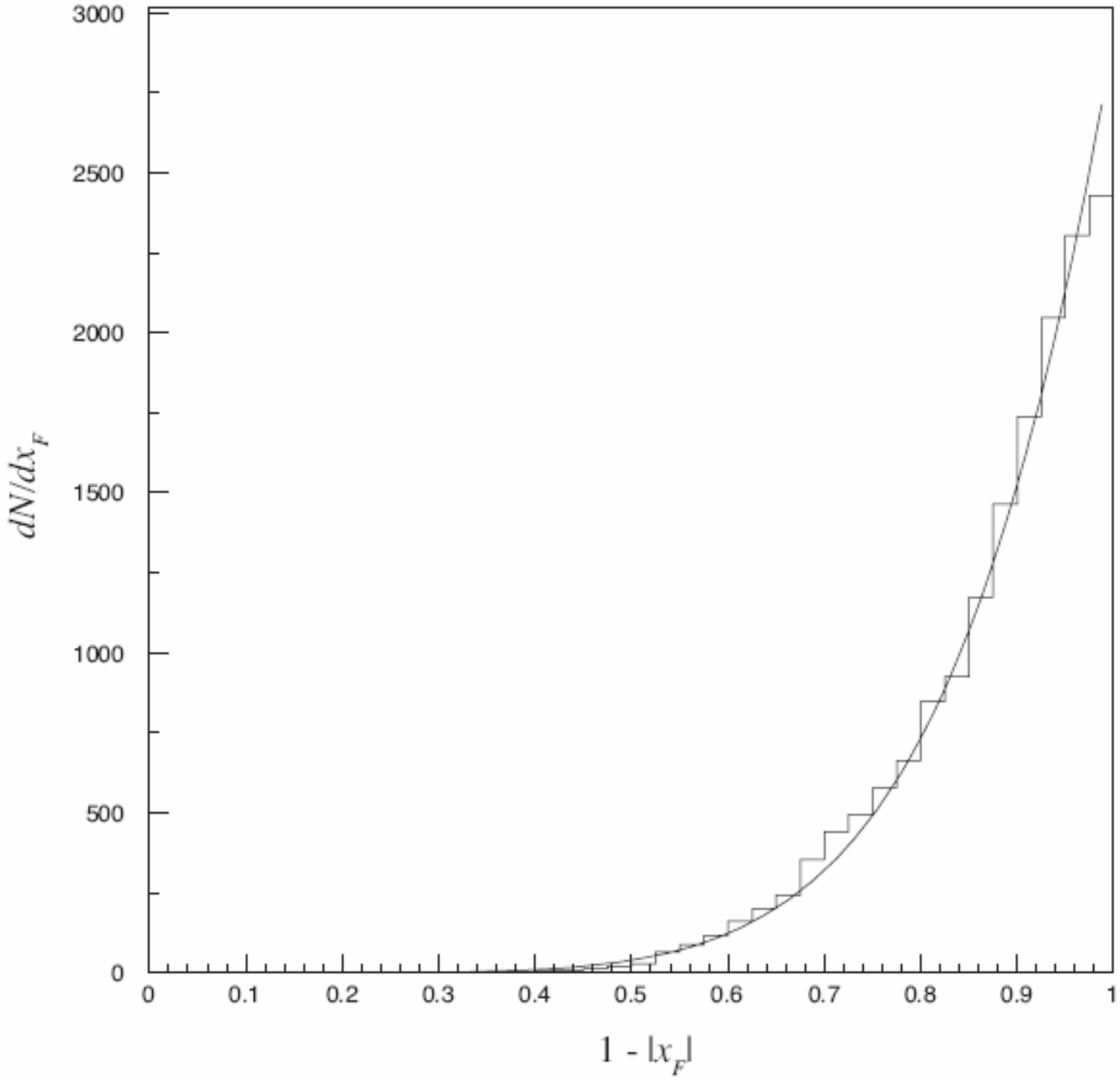
Number of Neutrinos from tle LEP Experiments

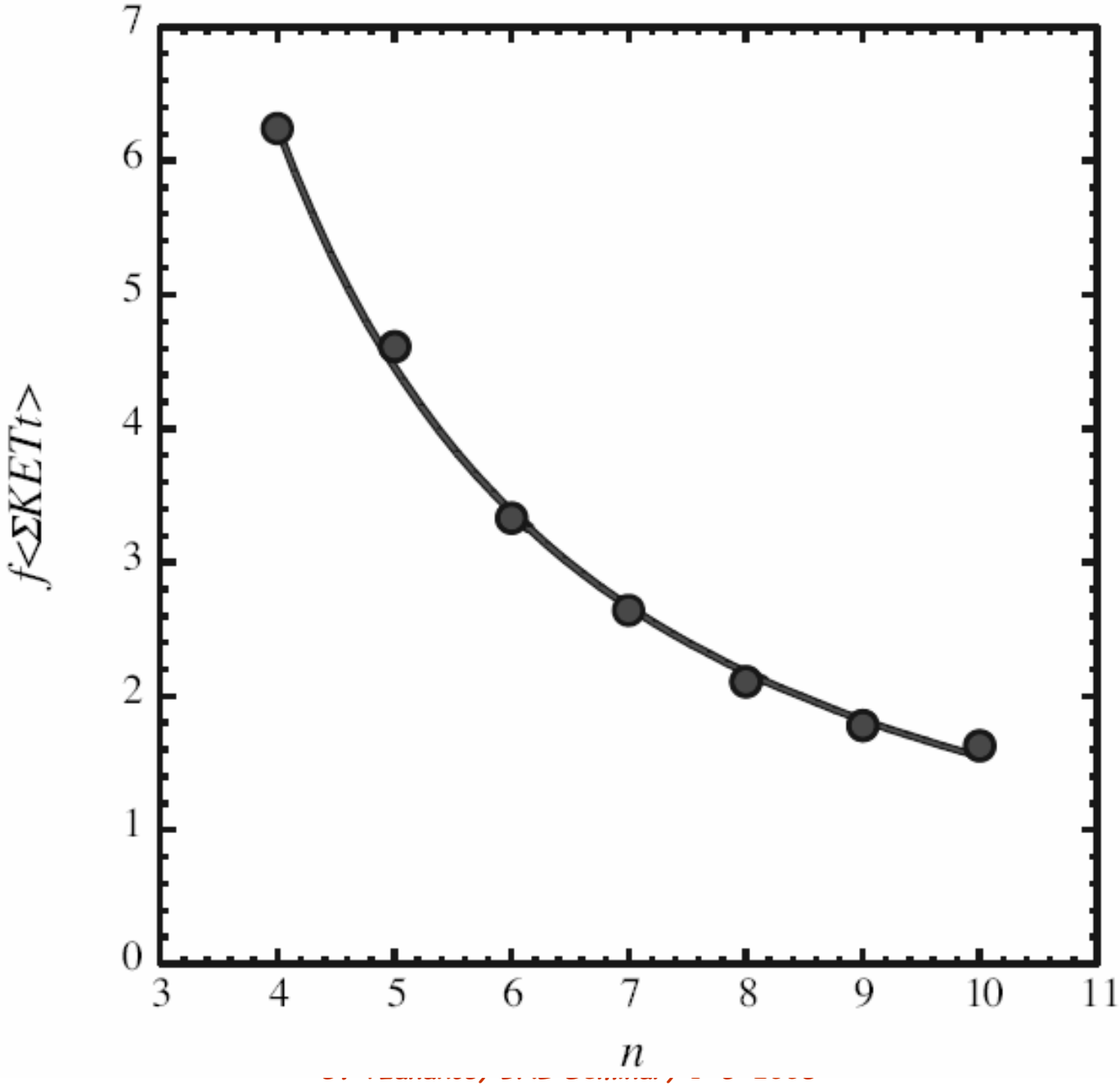
$$N_\nu = 2.9840 \pm 0.0082$$

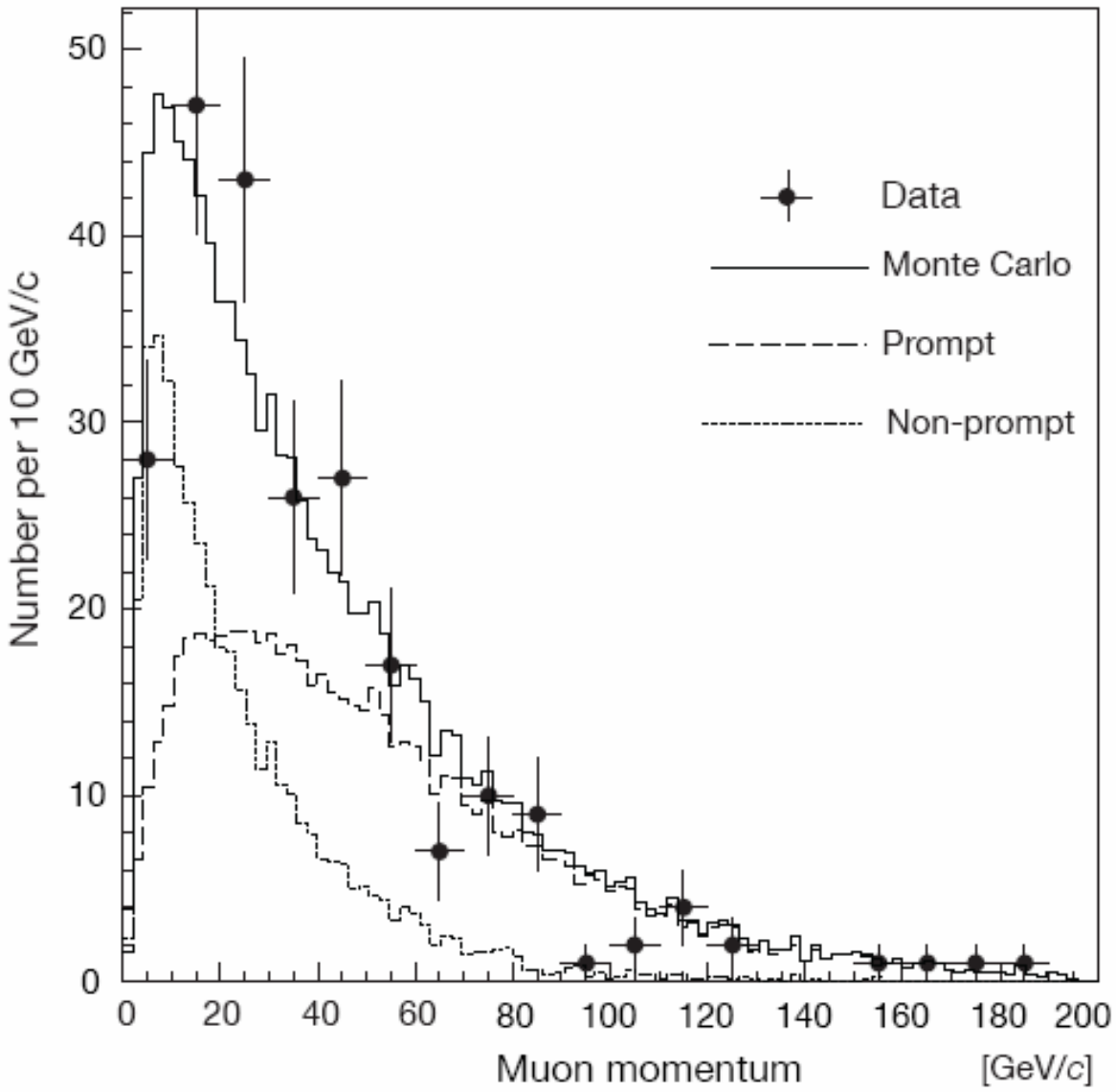
Summary and Conclusions

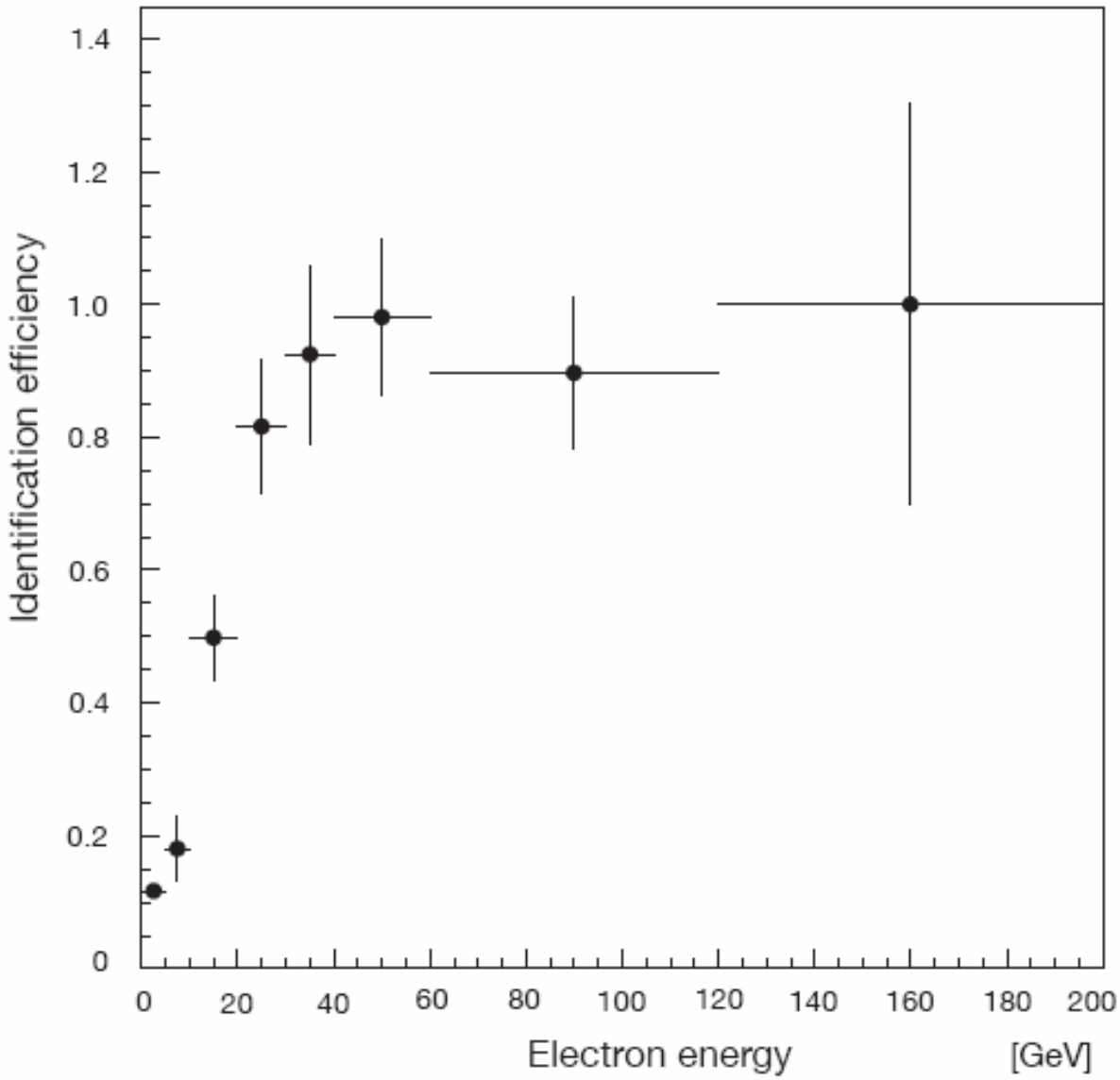
- DONuT has *directly observed the tau-neutrino as a particle* via its CC interactions with nuclei.
- *9 (CC) tau events* have been identified in DONuT. Number consistent with expectations from the S-M. (Also consistent with charm production from prompt ν_μ, ν_e).
- First measurement of ν_τN DIS consistent with S-M.
- We have precise τ – decay studies from collider experiments (Michel parameters, life time) and $N_\nu = 3$ from LEP which are in excellent agreement with the S-M.
- **Conclusion:** Above properties justify assigning this neutral particle of J=1/2, H = -1, as the weak isospin ½ partner of the τ-lepton .

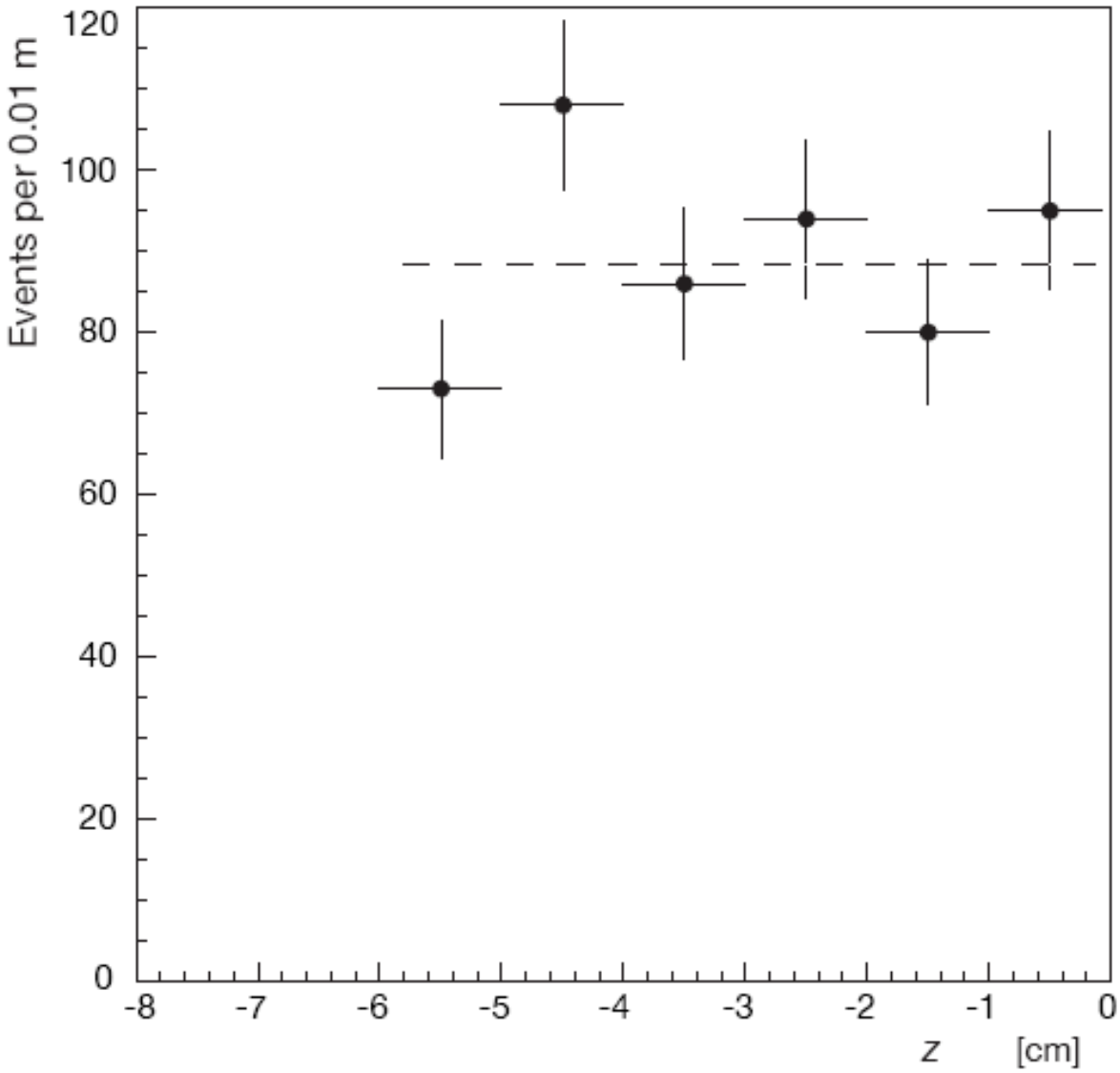
Backup slides

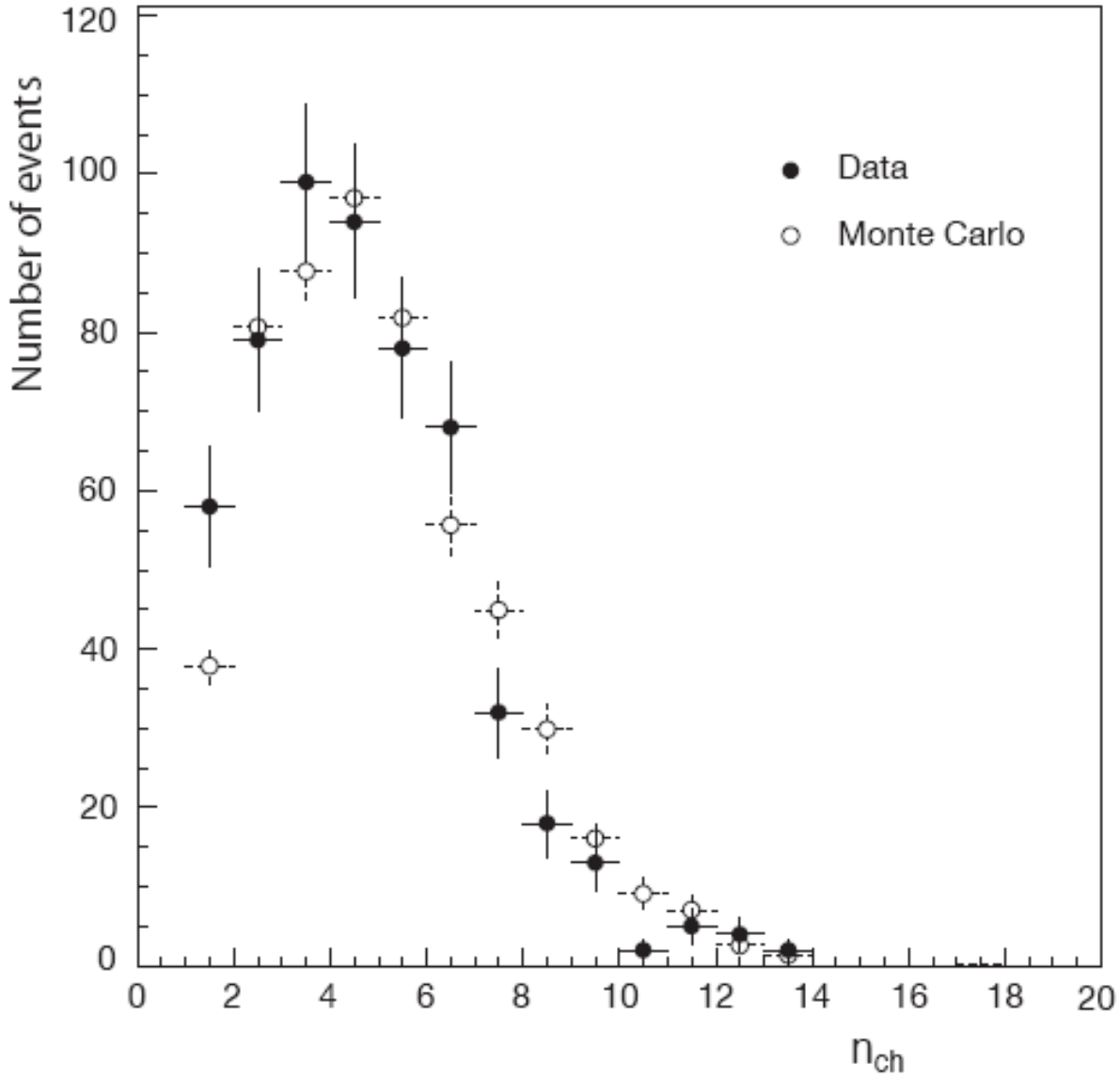

3000
2500
2000
1500
1000
500
0
dN/dx_F
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
$1 - |x_F|$

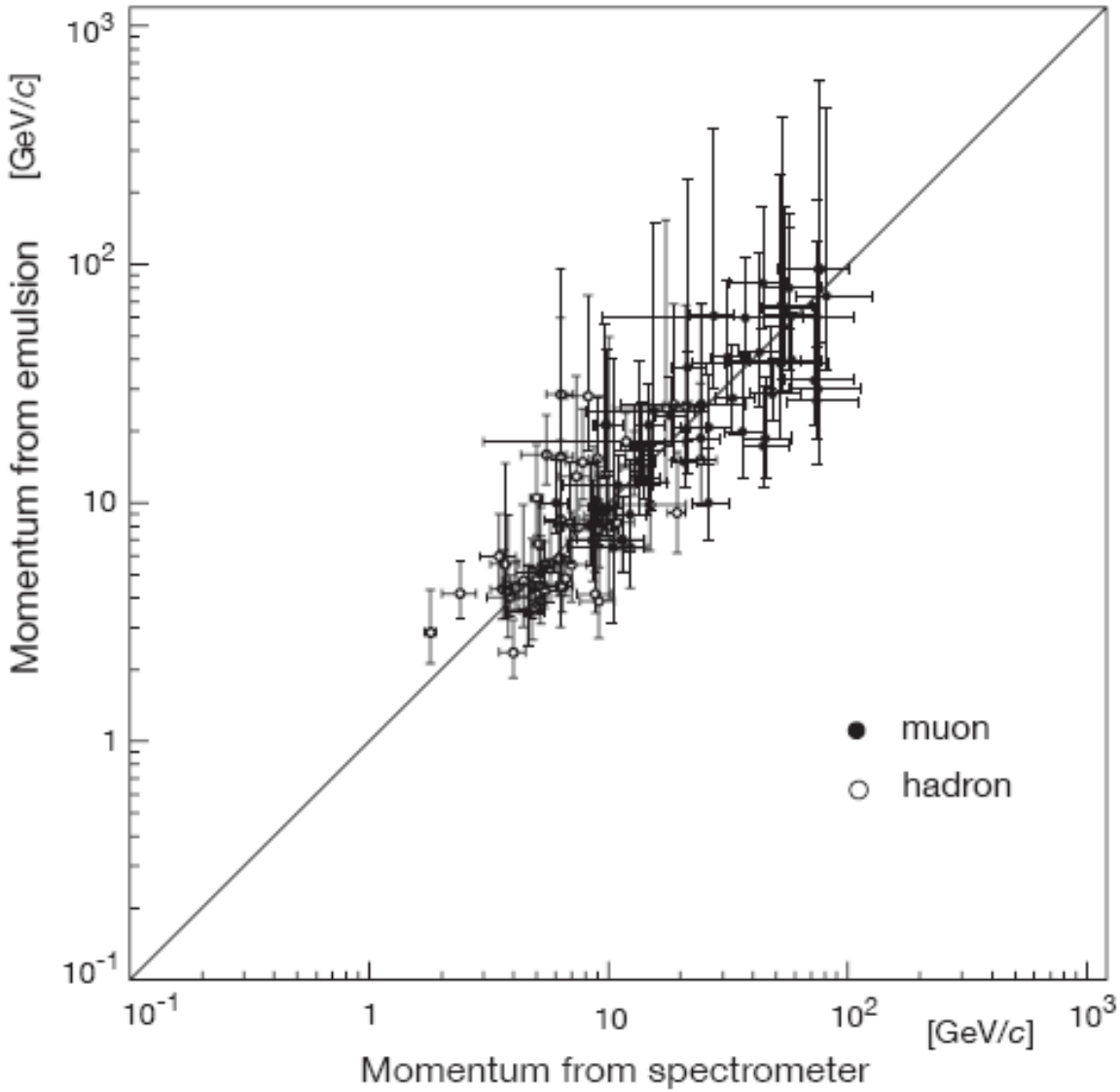

7
6
5
4
3
2
1
0
3
4
5
6
7
8
9
10
11
n
f<ΣKETt>
ν_τ


Number per 10 GeV/c
Muon momentum
[GeV/c]
Data
Monte Carlo
Prompt
Non-prompt
0
10
20
30
40
50
0
20
40
60
80
100
120
140
160
180
200


Identification efficiency
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0
0
20
40
60
80
100
120
140
160
180
200
Electron energy
[GeV]


Events per 0.01 m
120
100
80
60
40
20
0
-8
-7
-6
-5
-4
-3
-2
-1
0
z [cm]


Number of events
120
100
80
60
40
20
0
0
2
4
6
8
10
12
14
16
18
20
n_{ch}
Data
Monte Carlo


Momentum from emulsion [GeV/c]
10^3
10^2
10
1
10^{-1}
muon
hadron
10^{-1}
1
10
10^2
[GeV/c]
10^3
Momentum from spectrometer