

Results from DONUT*:
First Direct Evidence of ν_τ

The primary goal is to directly observe the charged-current interactions of the tau-neutrino

The experiment locates and identifies tau-lepton decays using an emulsion target and spectrometers

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FERMILAB
for the DONUT collaboration

**Direct Observation of Nu Tau*

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Outline

OVERVIEW of EXPERIMENT

NEUTRINO BEAM

The DATA Set

DECAY SEARCH

BACKGROUNDS

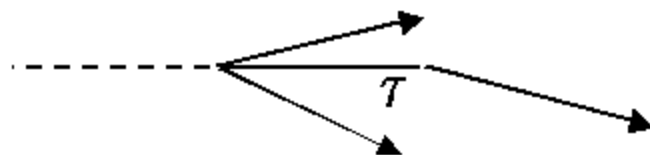
The SIGNAL

CONCLUSION

Essential qua

Overview

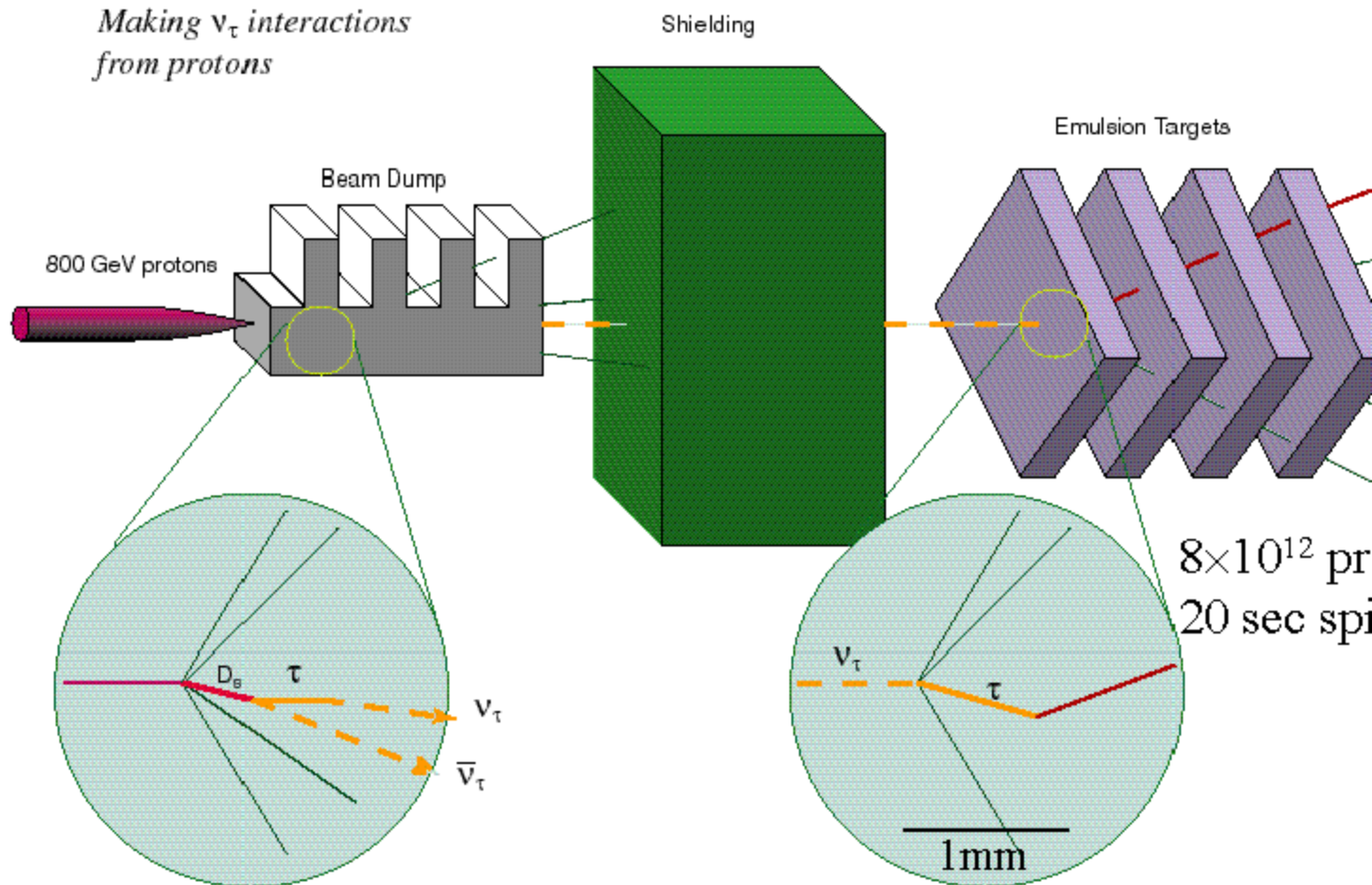
- Use 800 GeV protons \rightarrow beam dump
- Emulsion Target $36m$ from dump
- Magnetic/passive shield protects emulsion
- ν flux < 0.001 of the conventional Fermilab ν beam
- Search for ν_τ interaction by topology: *kin*



Prompt Neutrino Beam

E-872

Making ν_τ interactions from protons



ν Flux / Interactions

Prompt ν beam \Rightarrow number $\nu_e \sim$ number ν_μ

Primary ν_τ source $D_S \rightarrow \nu_\tau \tau \rightarrow \bar{\nu}_\tau X$

$\nu_e + \nu_\mu$	$2.5 \times 10^{-4} / (\text{pot } m^2)$	52 GeV
ν_τ	$2.1 \times 10^{-5} / (\text{pot } m^2)$	54 GeV

Total *protons on target* = 3.6×10^{17}

Calculated number of interactions = 1100 (ν_μ, ν_e, ν_τ)

Data taken from April to September 1997

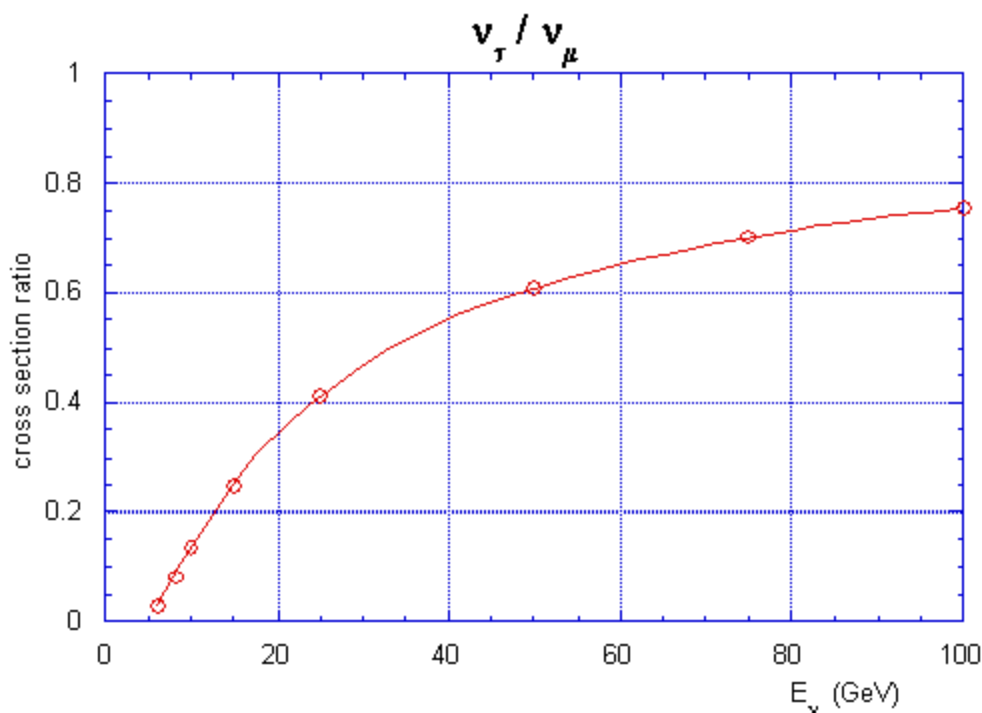
ν_τ Sources

- 1. Primary Source: $D_S^+ \rightarrow \nu \tau^+ \rightarrow X \bar{\nu}$

$$BR(D_S^+ \rightarrow \bar{\nu} \nu_\tau) = \left(\frac{G_F^2}{8\pi} f_{D_S}^2 m_{D_S} \right) \cdot f_{D_S}^2 |V_{cs}|^2 m_\tau^2 \left(1 - \frac{m_\tau^2}{m_{D_S}^2} \right)^2 = 6.1 \pm 1.0\%$$

- 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)

How many ν_τ ?



Expected number
 ν_τ interactions:

4.8% of total

Uncertainties:

D_S production $\pm 2\%$

$f_{D_S} \Rightarrow \text{BR}$ $\pm 1\%$

τ Decays

- Topological BR $\tau \rightarrow$ one charged particle

86%

- $\tau \rightarrow e \nu \nu$ 18%

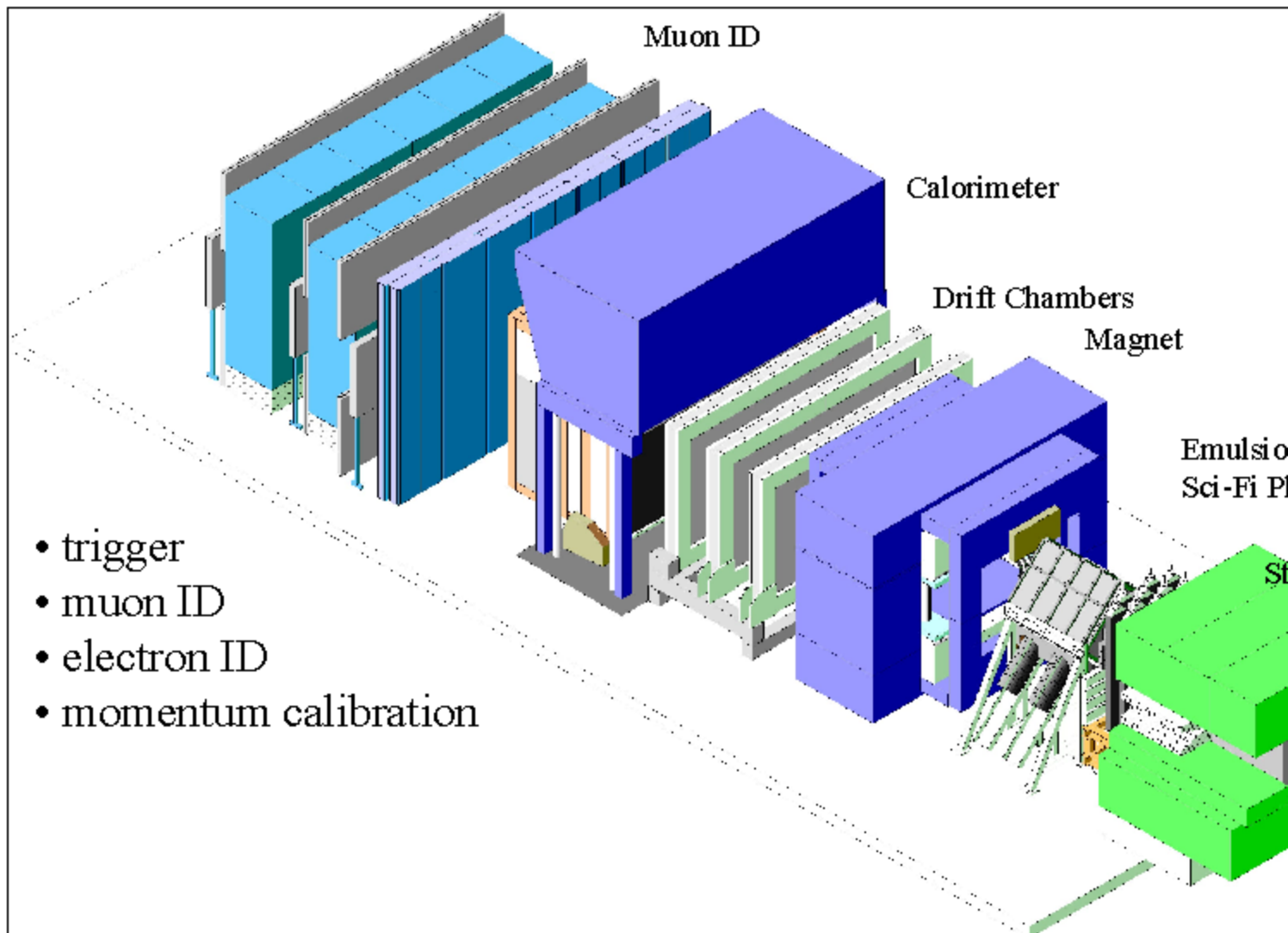
- $\tau \rightarrow \mu \nu \nu$ 18%

- $c\tau_\tau = 87 \mu\text{m} \Rightarrow 2.3\text{mm}$ mean decay length

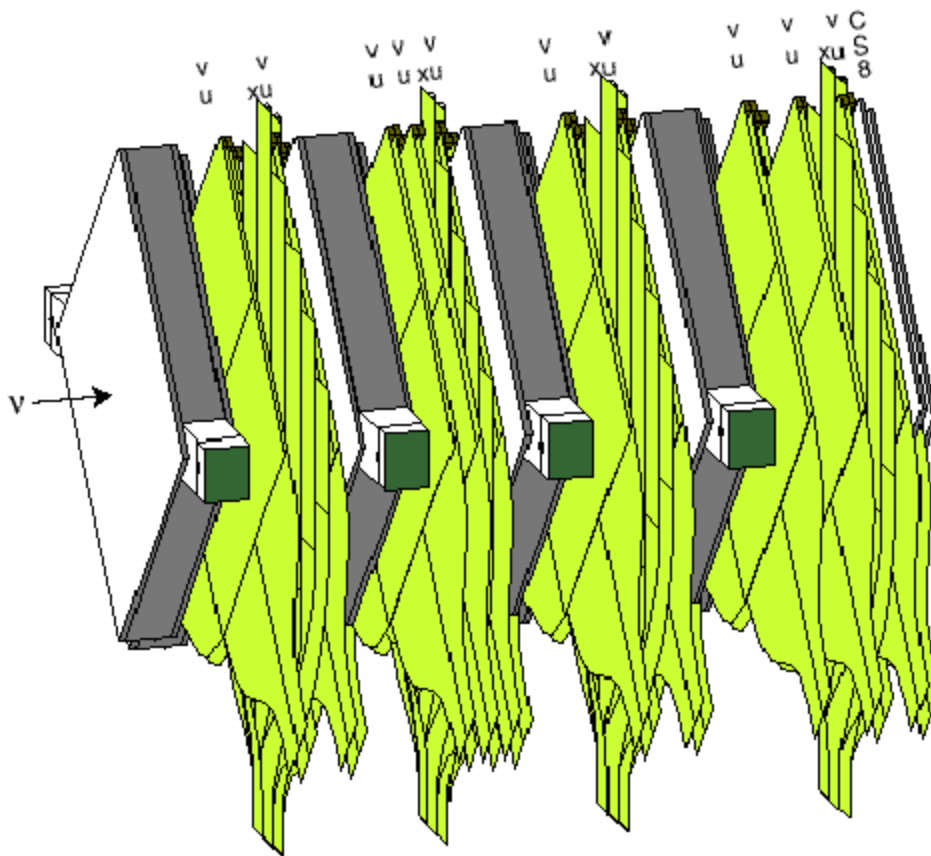
ν_τ

in DONUT

Spectrometer

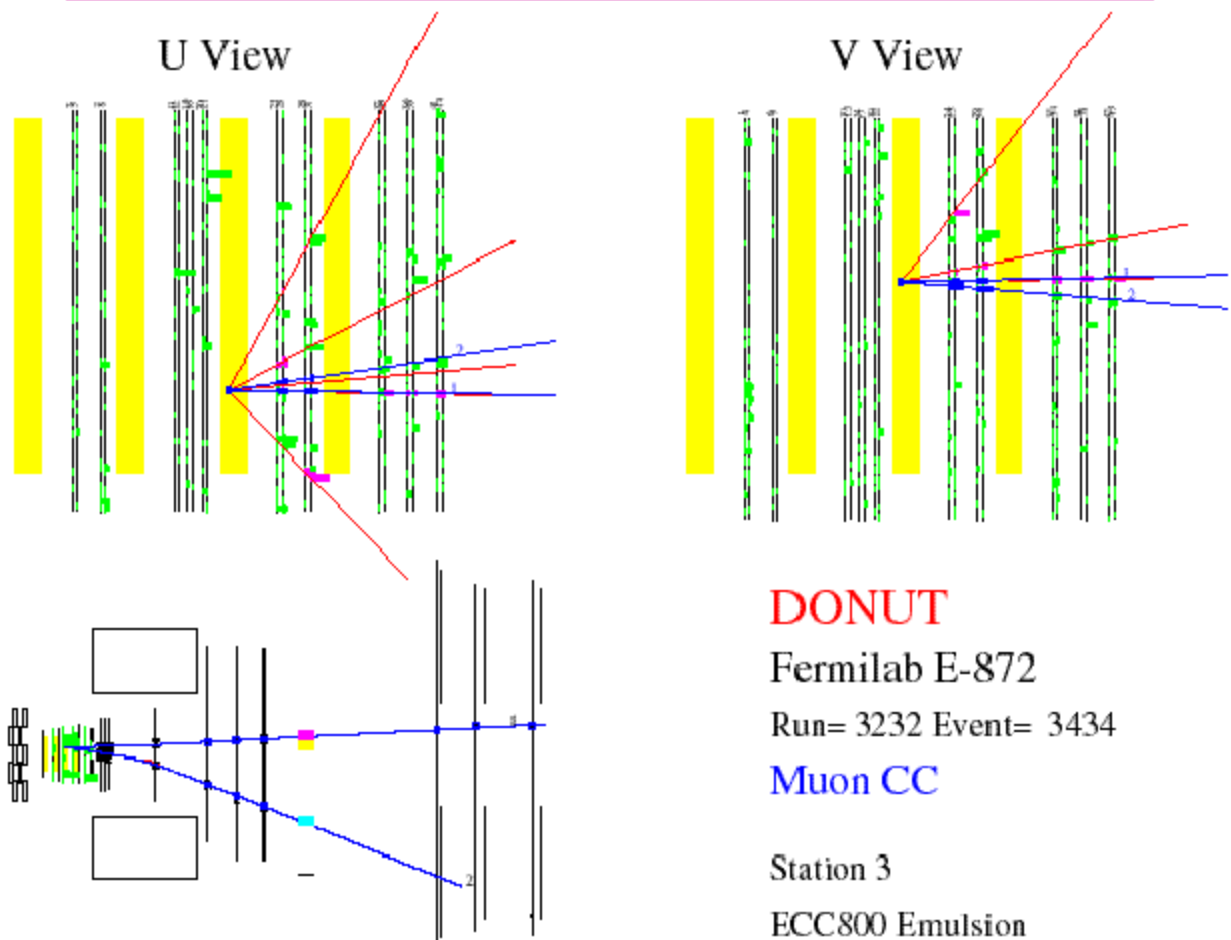


Emulsion Target / Vertex Detector



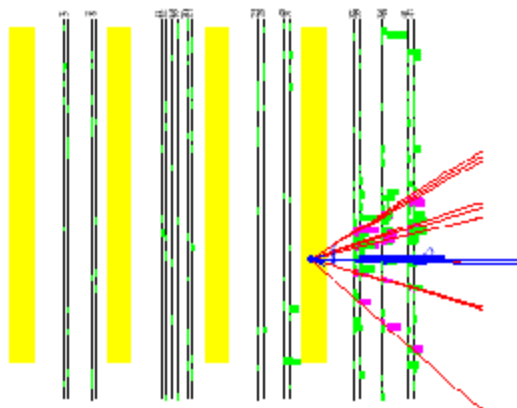
- Four target stations
- 260 kg total mass
- Interleaved with fibers
- Fibers → vtx pointing
- Total 7 modules
- Modules ~2-3 cm
- ~ 0.2 - 0.3 λ_{int}

ν_μ CC interaction

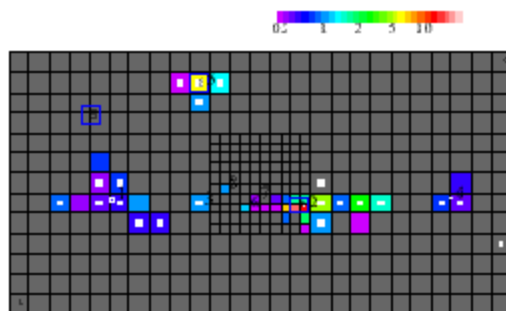
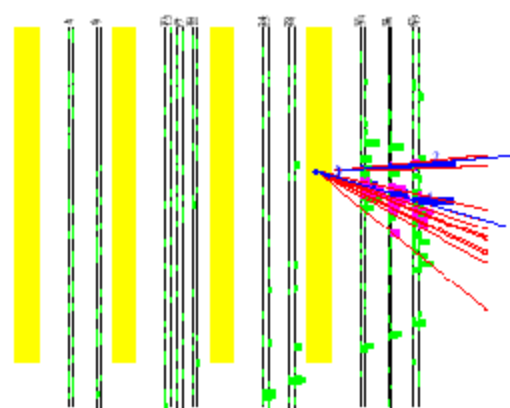


ν_e CC interaction

U View



V View



Cluster ΣE 1.04 GeV

0201004
 0201004
 0201004

DONUT

Fermilab E-872

Run- 3250 Event- 470

Electron CC

Station 4

Bulk Emulsion

ν CC Interactions

75 ν_μ CC interactions
with μ ID'd
47 μ^-
28 μ^+

$$\frac{N(-)}{N(+)} = 1.7$$

expect 1.8

86 ± 11 ν_μ CC interactions

(acceptance corrected)

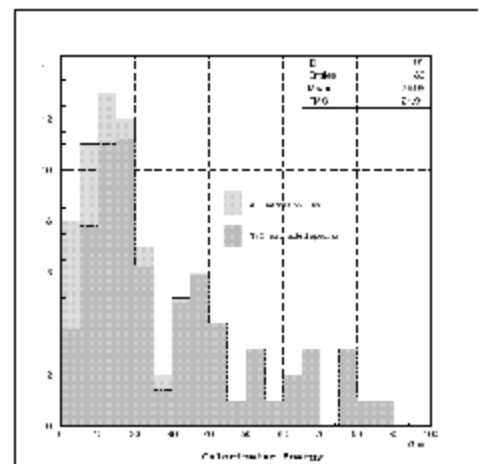
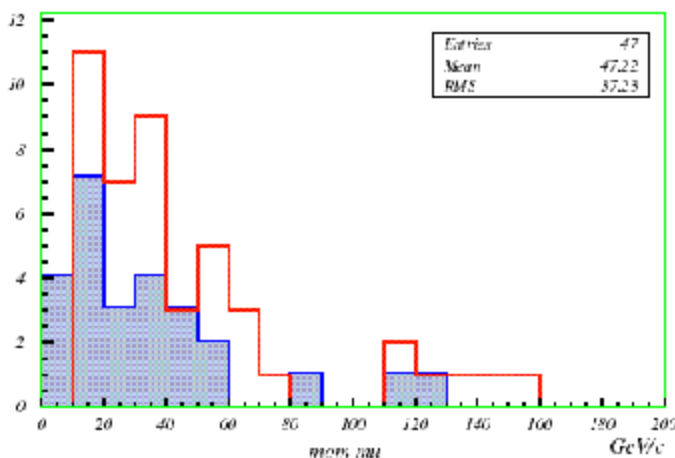
Calorimeter energy spectrum:

79 ± 14 ν_e CC interactions

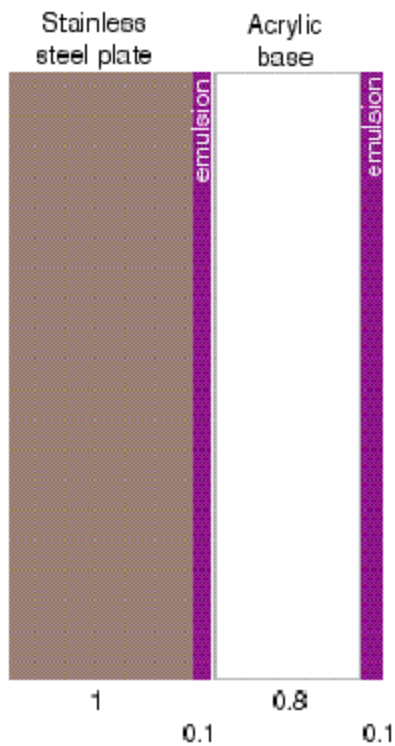
⇒ $\nu_e \sim \nu_\mu$ in no. interactions

⇒ ν_μ non-prompt < 0.3 × prompt

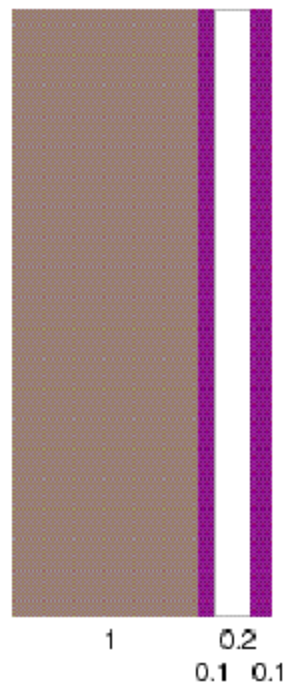
Recall ν_τ rate 4.8% ⇒ 10 ± 3 events



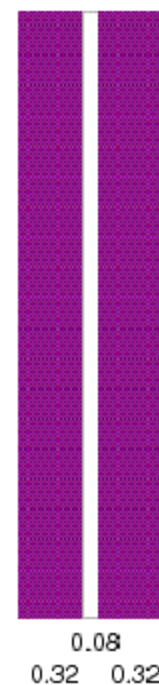
Target Designs



"ECC 800"



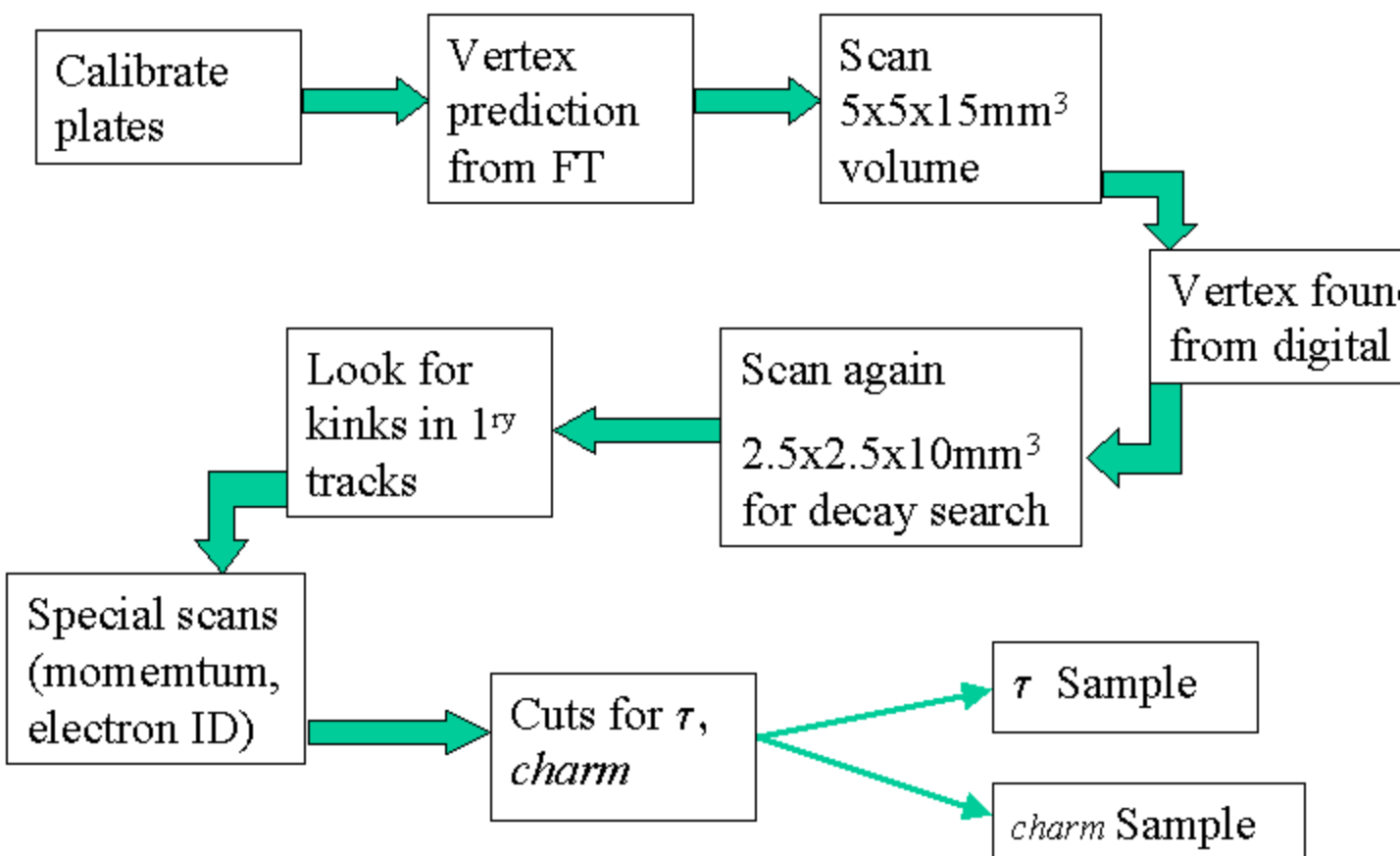
"ECC 200"



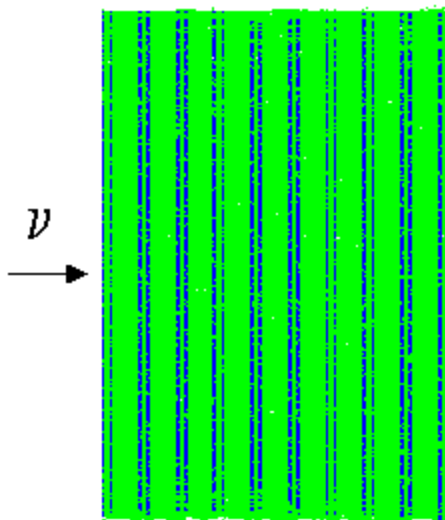
"Bulk"

- 3 target types
- Bulk 95% emulsion
- ECC 5% emulsion
- ECC for OP

Digital Emulsion Analysis

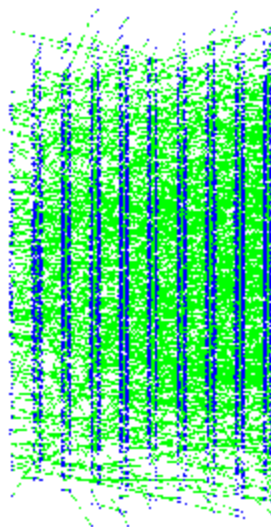


Digital Emulsion Data Analysis

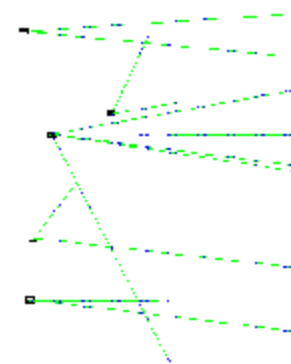


Scan **20 plates** in a
 $2.5 \times 2.5 \times 12 \text{ mm}^3$ volume*
 1.25×10^5 segments
digitized
 9.2×10^4 “tracks”
linked

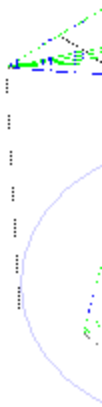
*decay search scan



Remove 6.6×10^3
2-segment and
“penetrating” tracks;
 **4.8×10^3 “starting/
stopping” tracks**
remain



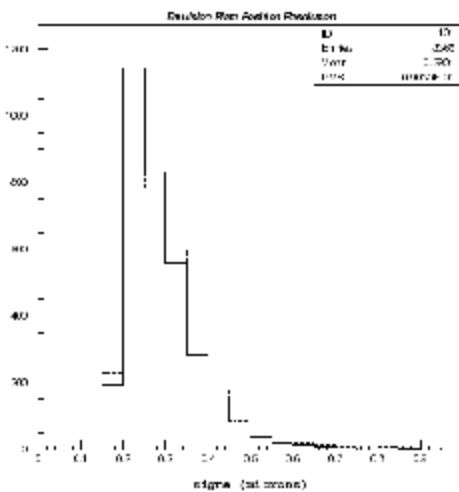
Form vertices by
requiring **Impact
Parameters**
< 10 microns



Select
vertex
emulsi
real tim
“zoom
interes

Emulsion Performance

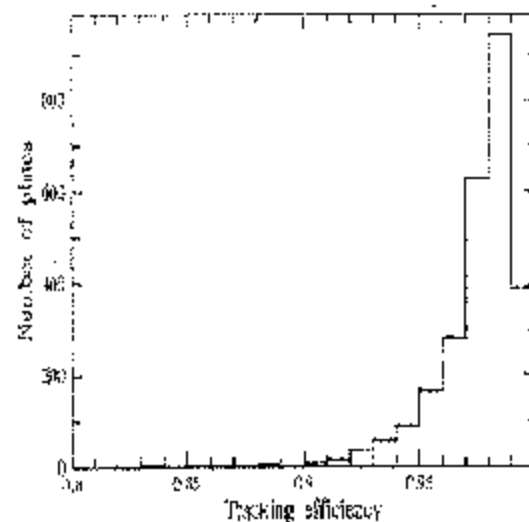
Spatial Resolution



The emulsion track residuals

Average : 0.29 μm

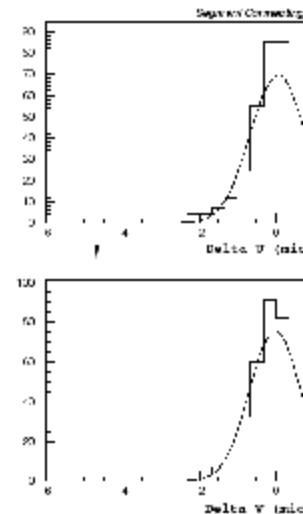
Efficiency



Tracking efficiency for 2632 plates ($\theta < 0.1$ rad);

only 24 plates with connection efficiency $< 90\%$

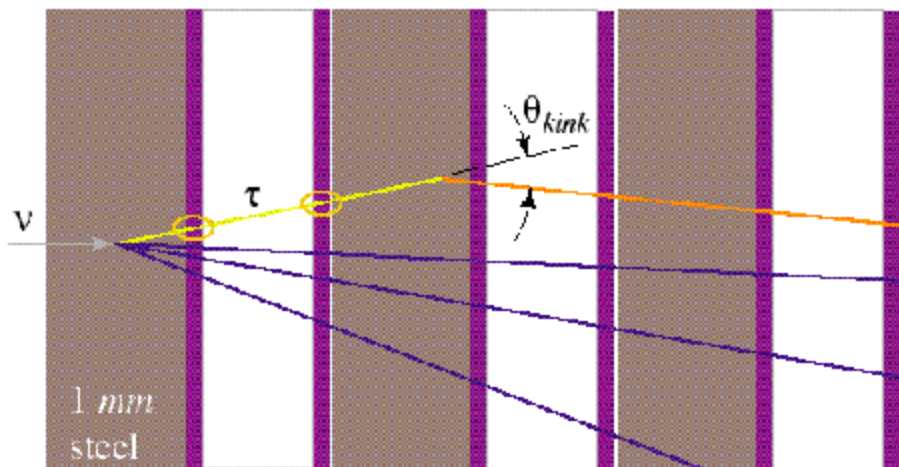
Vertex Pro



Distance of a of emulsion t of emulsion to the primary v with $\theta < 0.1$

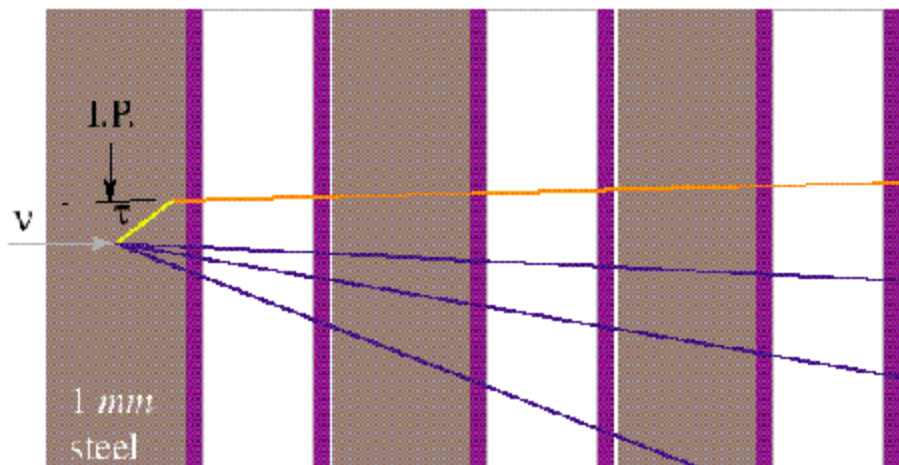
$rms = 0.8 \mu\text{m}$

C1 Decay Search



1. Long Decays

- parent measured
- kink resolved
- $\tau \Rightarrow$ no 1st lep
- $\sim 75\%$



2. Short Decays

- IP wrt 1st vertex
- only daughter
- daughter seen
- $\sim 25\%$

Kink Search:

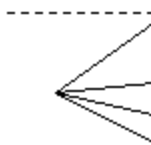
(680 primary tracks in 203 interactions)

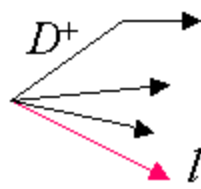
<i>Cut</i>	kinks	% τ remain
none	7642	100
0.01 < kink angle < 0.250	450	7
Parent angle < 0.200 rad	280	9
IP (parent) < 5 μm	142	>9
IP (@ kink) < 5 μm	65	>9
Flight length < 5mm	42	7
C1 (kink)	42	8
“Long” decay		7
Total		7

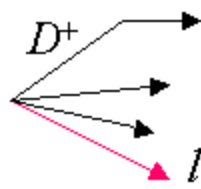
*not cumulative

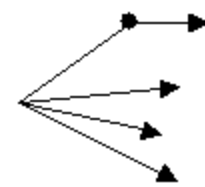
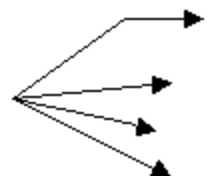
Kinks: Classification

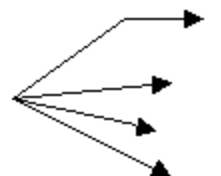
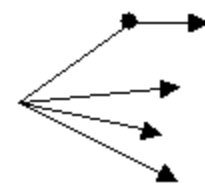
- Randomly associated tracks
 - e.g. Primary track + stale muon track



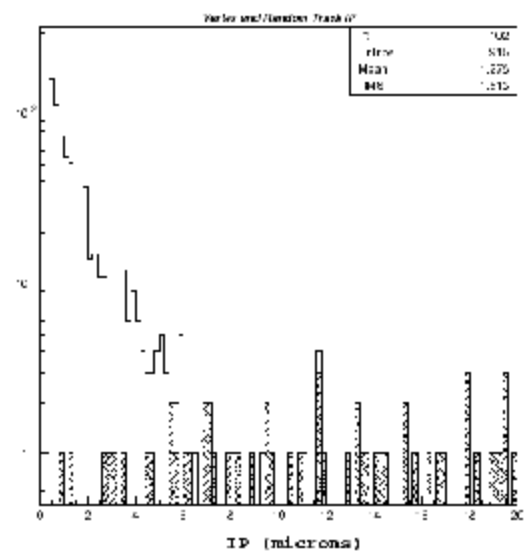
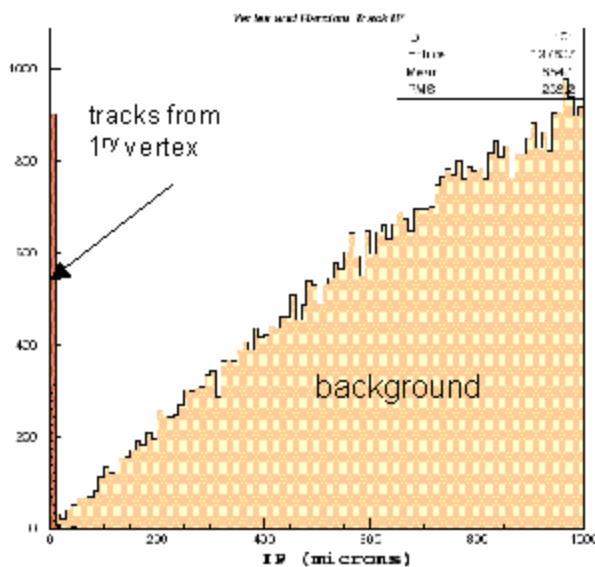
- *Charm* background  *lepton* : not recognized



- Interactions (scattering) 
- Tau signal 

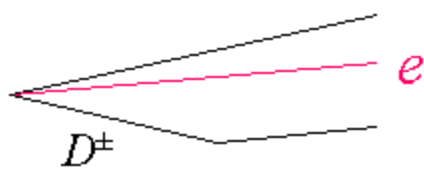


Backgrounds: Random Association



For each event, *all* tracks starting within 1 plate of the vertex are shown
 The shape is characteristic of uncorrelated, uniform distribution:
 $\Rightarrow 80 \text{ tracks/mm}^2/\text{event}$
 Est. random kinks $< 10^{-3}$

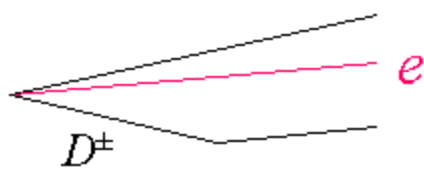
Only 6 tracks within $5\mu\text{m}$



Background : *charm* Production

1. assume $\nu_\mu \sim \nu_e$	168 ± 18	no. CC in
2. <i>charm</i> production	0.081 ± 0.008	13.6 ± 1.3
3. charged charm	0.47 ± 0.05	6.4 ± 0.9
4. “Long” decay & $< 5\text{mm}$	0.66 ± 0.06	4.2 ± 0.7
5. kink detection effic.	0.56 ± 0.06	2.4 ± 0.5
6. <i>charm</i> \rightarrow kink (C1)	0.38 ± 0.02	
$\Pi_{1..6}$	0.9 ± 0.2 events	[1.5 (infla

Expect 2.4 charged *charm* decays : found 2
 \downarrow
Expect 0.9 *charm* kink decays : found 1



Background: *charm* summary

We estimated 0.9 ± 0.2 *charm* events with *kink* :

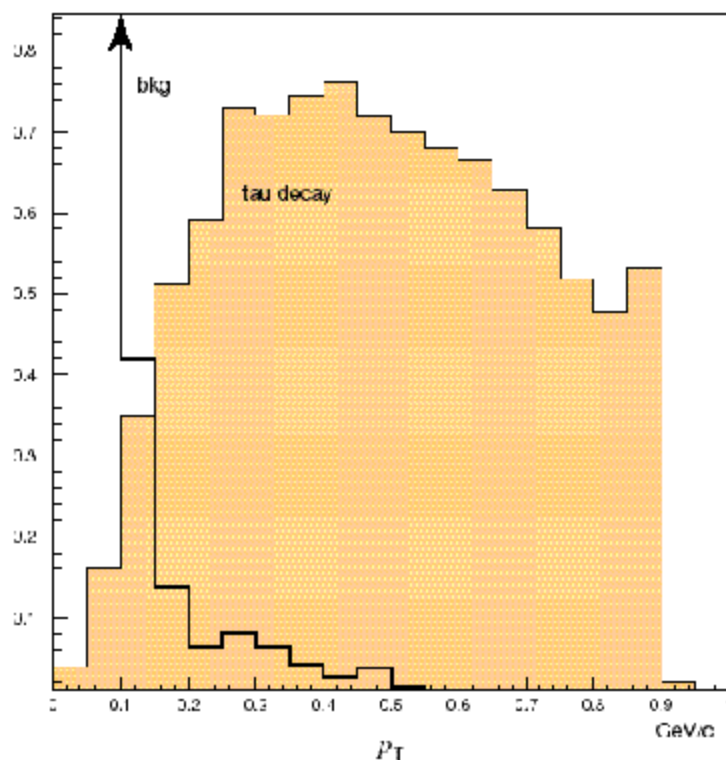
This is a background to τ iff the *lepton* is not identified as

- μ ID prop tubes cover 82% of acceptance \times 96% eff. =
- e ID require $>2X_0$ for emulsion tag or $>3X_0$ FT : 75%

\therefore Total *charm* background : $0.23 \times 0.9 = 0.21 \pm 0.04$ events

τ Background : *Interactions*

“NC interactions” + hadron scatter = τ background

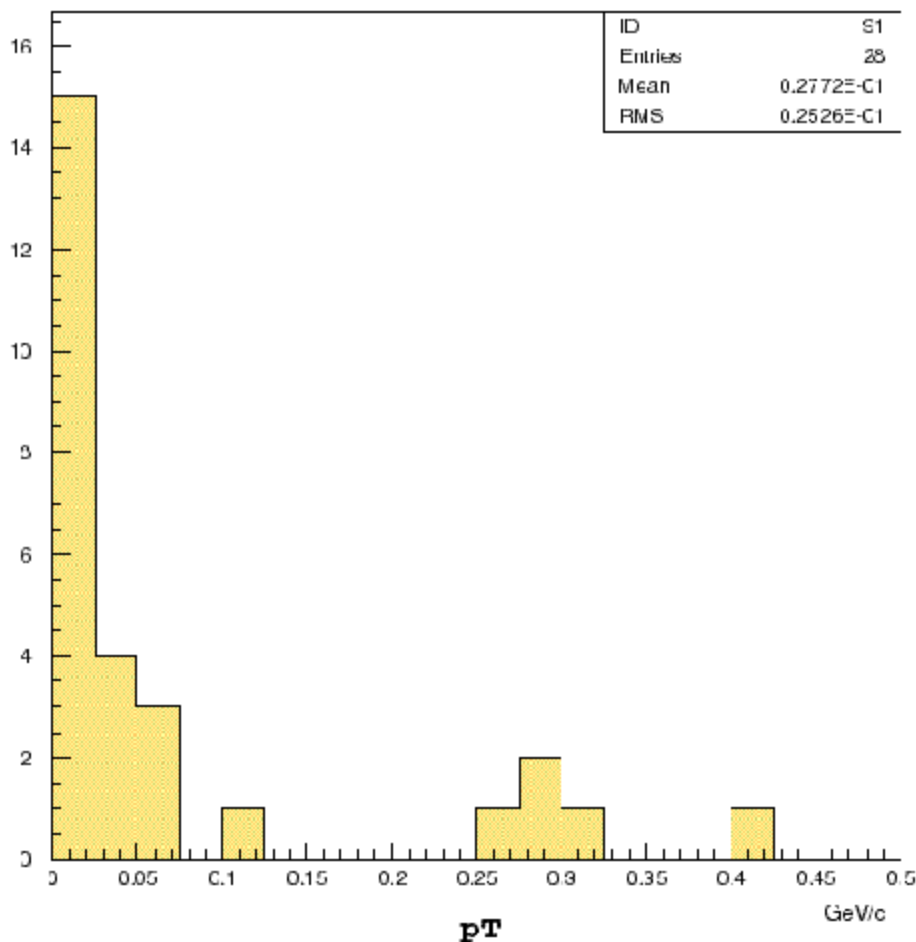


- Rapidly decreasing with
- Depends on total path l
- *Short* decays is separate

Estimated background us
GEANT calculation :

0.20 ± 0.06 even
for $p_T > 250$ MeV/c

Background: Interactions Distribution of Kinks

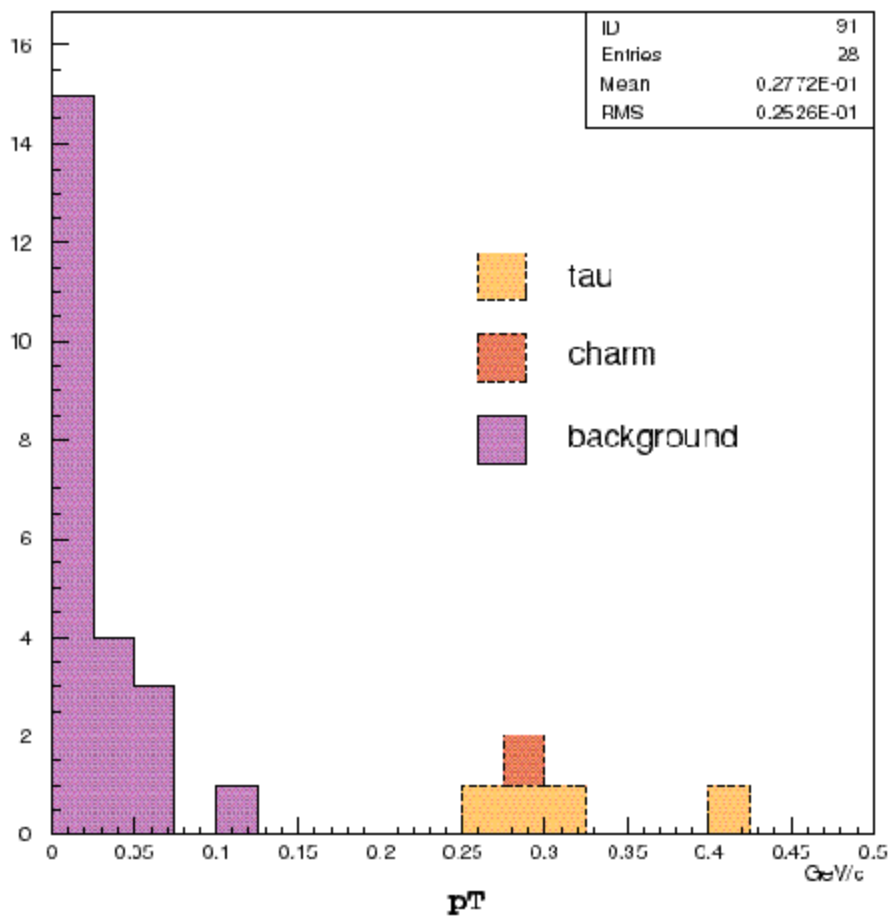


Kinks for which p_T computed using sc

It does not include from kink list

Recall: only tracks “NC-like” events a of τ background (τ

Background+Signal: Interactions Distribution of Kinks



Same plot as previous
but *color enhanced*

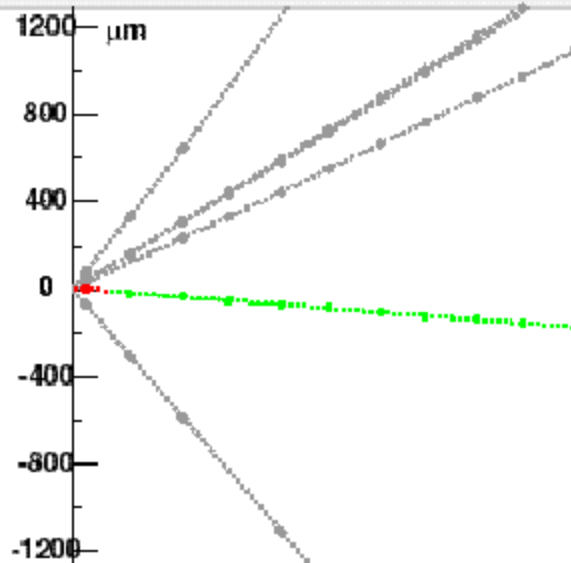
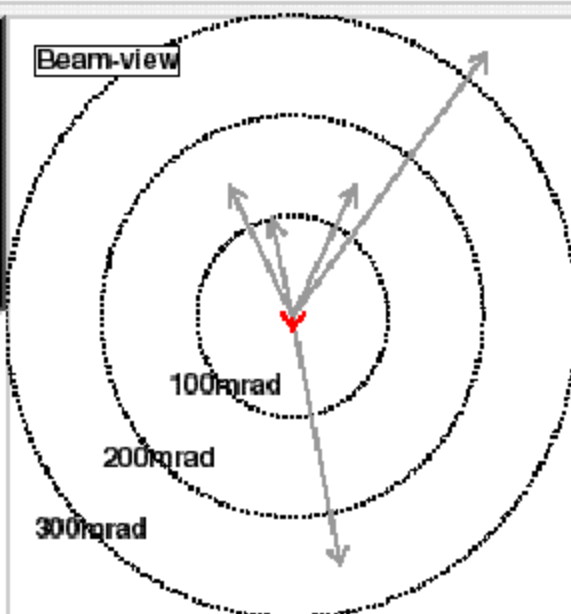
EXP.:DONUT

3333/17665

MOD.:E/B2

- τ
- μ
- Electron
- Hadron
- Unknown

Beam-view

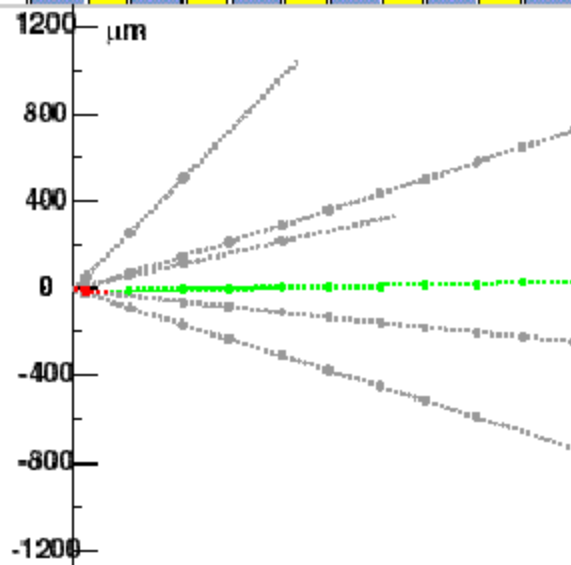
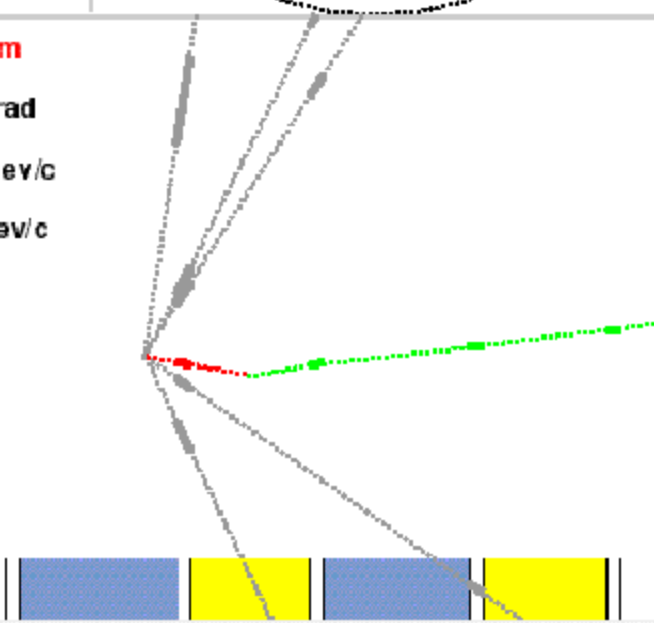


F.L.=540 μ m

$\theta_{\text{kink}}=0.013\text{rad}$

$P_{\tau}=276_{-83}^{+187}\text{ MeV/c}$

$P_{\mu}=21.4_{8.4}^{+14.4}\text{ GeV/c}$



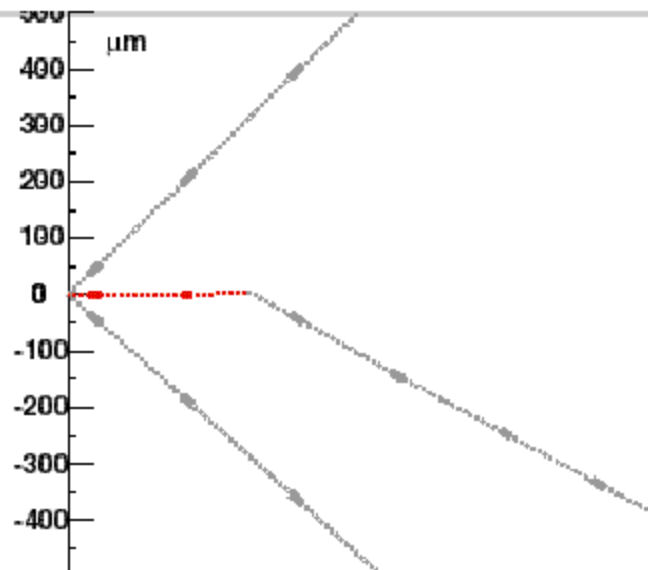
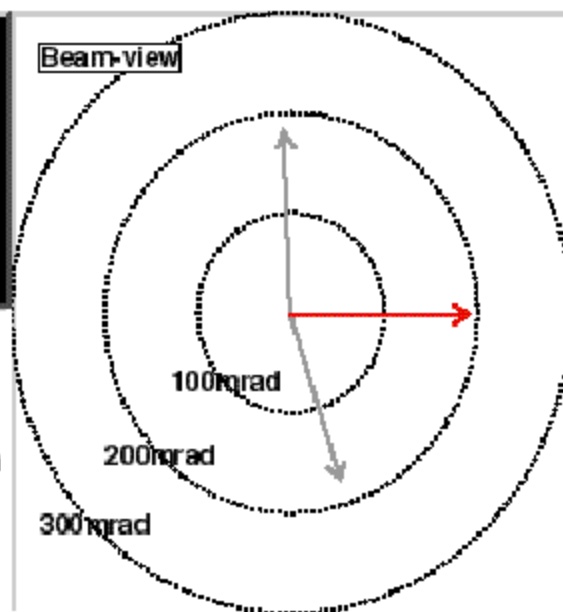
EXP.:DONUT

3263/25102

MOD.:E/B1

- τ
- μ
- Electron
- Hadron
- Unknown

Beam-view

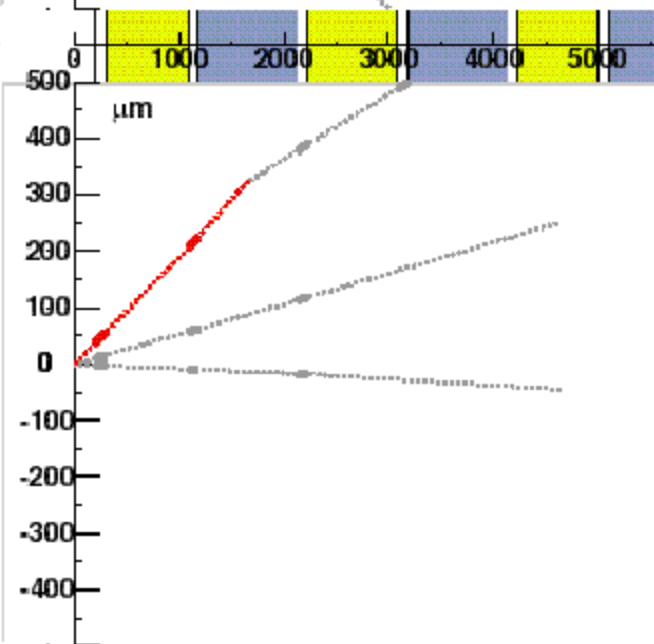
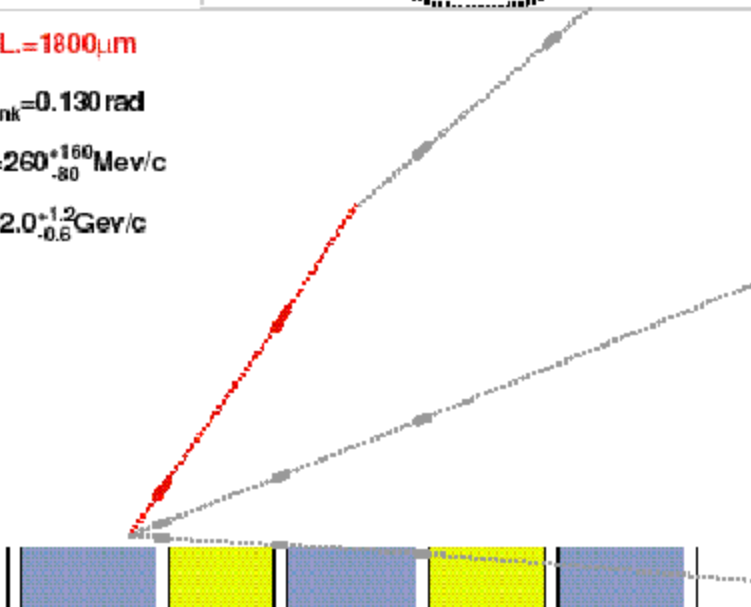


F.L.=1800 μ m

$\theta_{\text{link}}=0.130$ rad

$P_{\tau}=260^{+160}_{-80}$ Mev/c

$P=2.0^{+1.2}_{-0.6}$ Gev/c



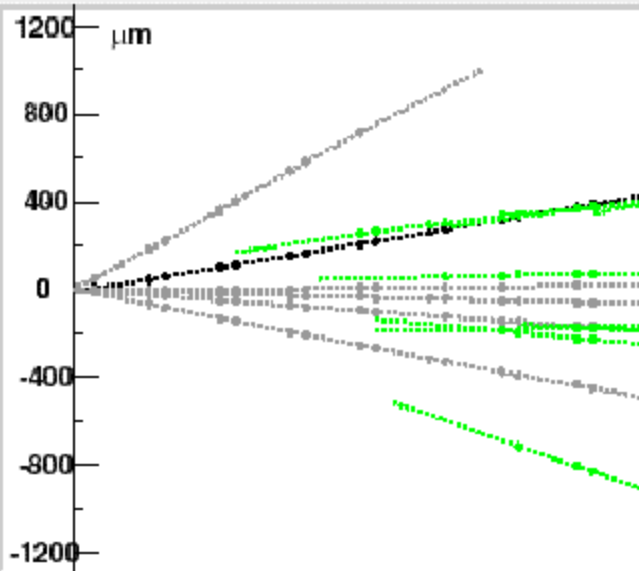
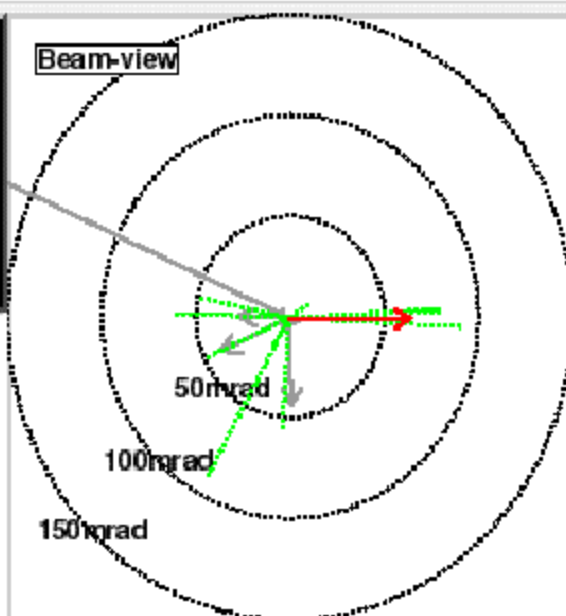
EXP.: DONUT

3039/01910

MOD.:ECC1

- τ
- μ
- Electron
- Hadron
- Unknown

Beam-view

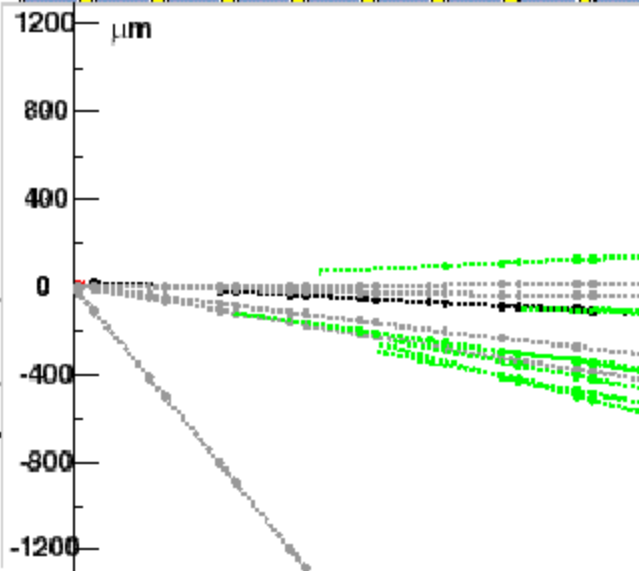
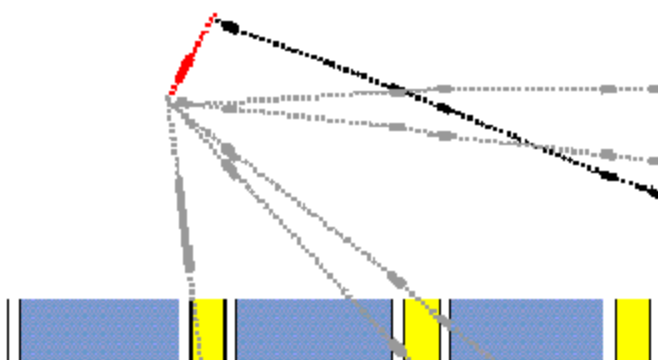


F.L.=280 μm

$\theta_{\text{link}}=0.090\text{rad}$

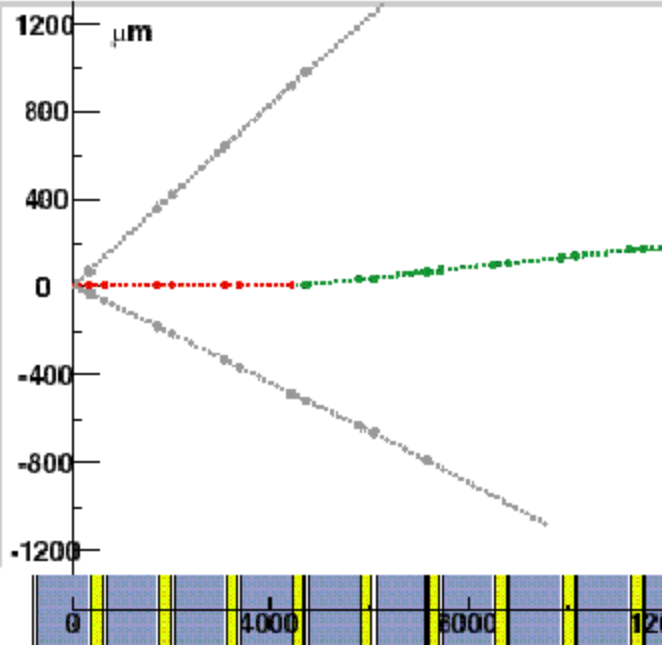
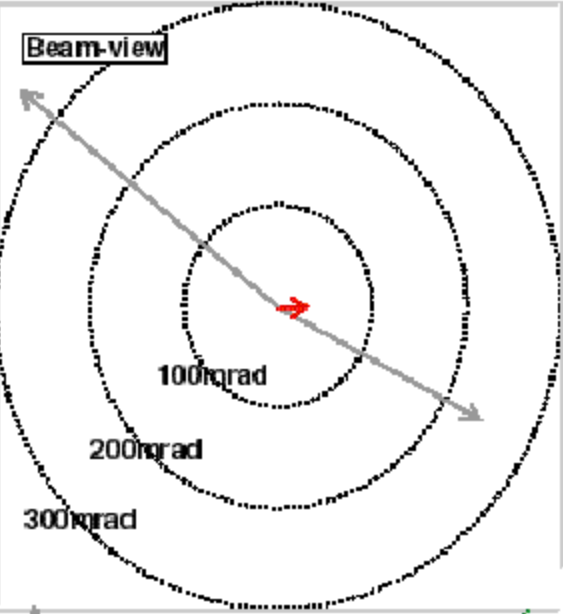
$P_{\tau}=414^{+144}_{-81}\text{MeV}/c$

$P=4.6^{+1.6}_{-0.9}\text{GeV}/c$

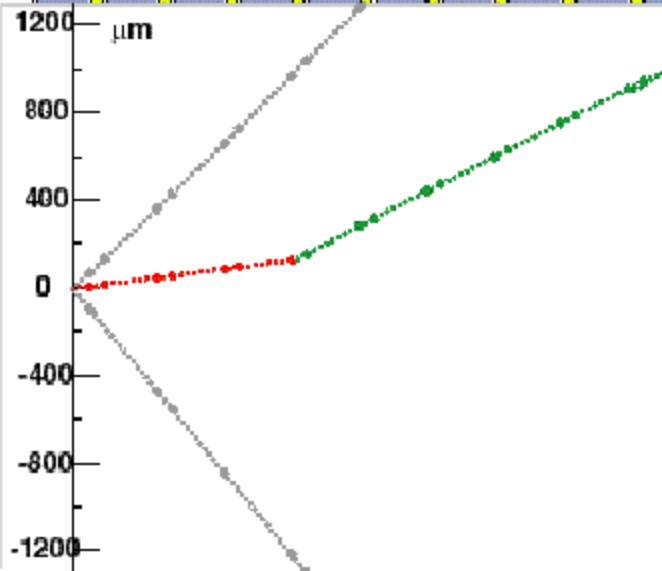
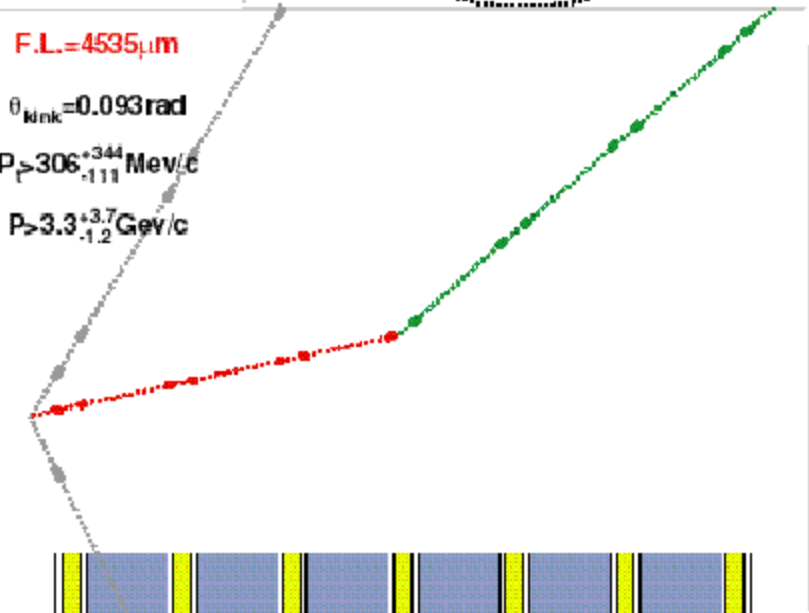


EXP.: DONUT
 3024/30175
 MOD.: ECC1

- τ
- μ
- Electron
- Hadron
- Unknown



F.L.=4535 μ m
 $\theta_{\text{kink}}=0.093\text{rad}$
 $P_{\tau} > 306^{+344}_{-111} \text{ MeV}/c$
 $P_{\mu} > 3.3^{+3.7}_{-1.2} \text{ GeV}/c$



Summary: τ candidates

from 203 set

- 4 events from *Long* decay search;

$$\text{expect } (203)(0.048)(0.86)(0.76)(0.65) = 4.1 \pm 1.4$$

τ frac C1 decay *Long* *kink eff*

Background Analysis:

Charm : 0.21 ± 0.04 events

Hadronic interactions : 0.20 ± 0.06 events

Sum Background: 0.41 ± 0.15 events

Fluctuation bkg \rightarrow signal : Poisson prob. 8×10^{-4}

In Conclusion

- “Long” Decay Search kink list only 65 events (after)
- Randomly assoc. kinks $<10^{-3}$ for entire 203 event s
- *charm* background for τ calculated at 0.21 ± 0.04 ev
- Interaction background calc. at 0.20 ± 0.06 events (μ)
 - Kink data supports MC calc.
- Signal events far from kink background in p_T

⇒ We conclude that these events are the evidence for observing the process:

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