HARP for MiniBooNE

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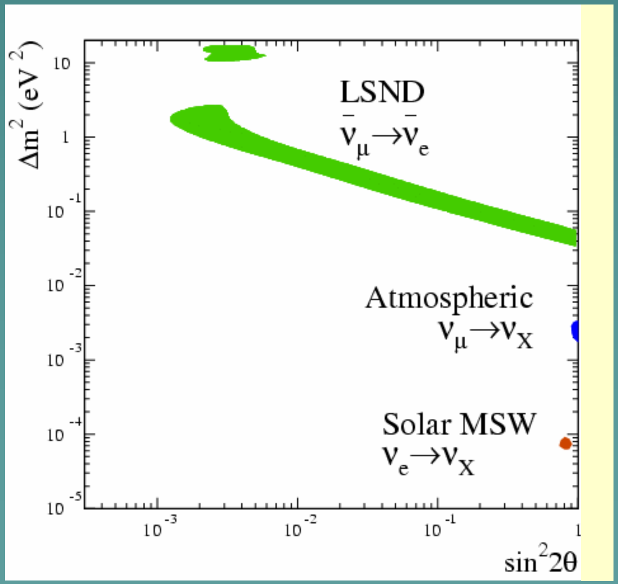
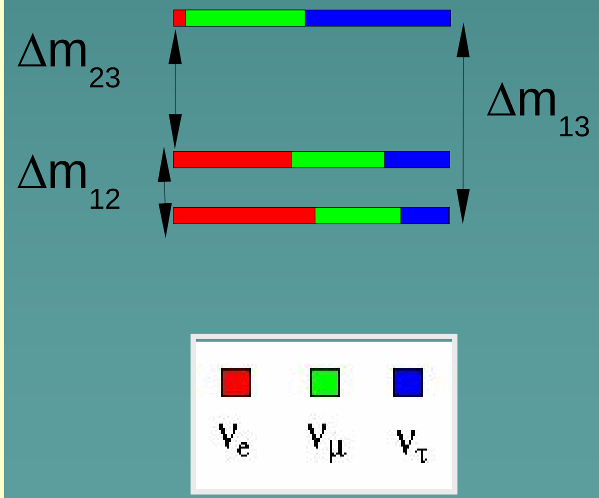
DPF 2004

MiniBooNE Motivation: Interpreting the LSND Signal

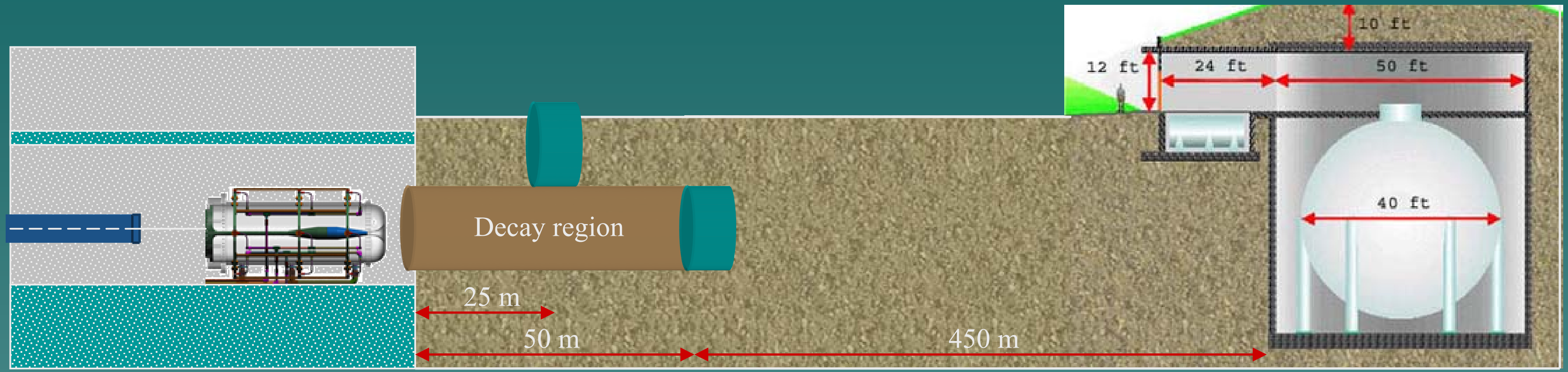
- What to make of 3 independent Δm^2 values?
  - solar exp. (Super-K, K, SNO, KamLAND, …)
    $\Delta m^2 \sim 10^{-5}$ eV^2
  - atmospheric exp. (Super-K, K, …)
    $\Delta m^2 \sim 10^{-3}$ eV^2
  - accelerator exp. (LSND)
    $\Delta m^2 \sim 1$ eV^2

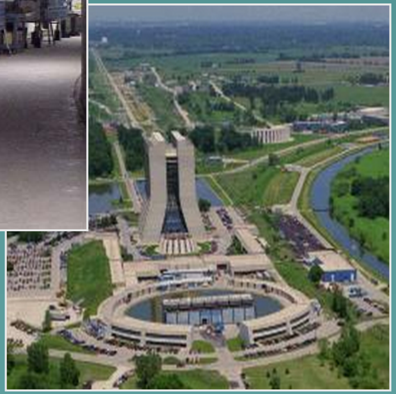
- Atmospheric and solar results are well confirmed.
- Accelerator and reactor based exp. in the atmo. and solar ranges (K2K, MINOS, KamLAND)
- LSND requires confirmation to know how to proceed in the neutrino sector.





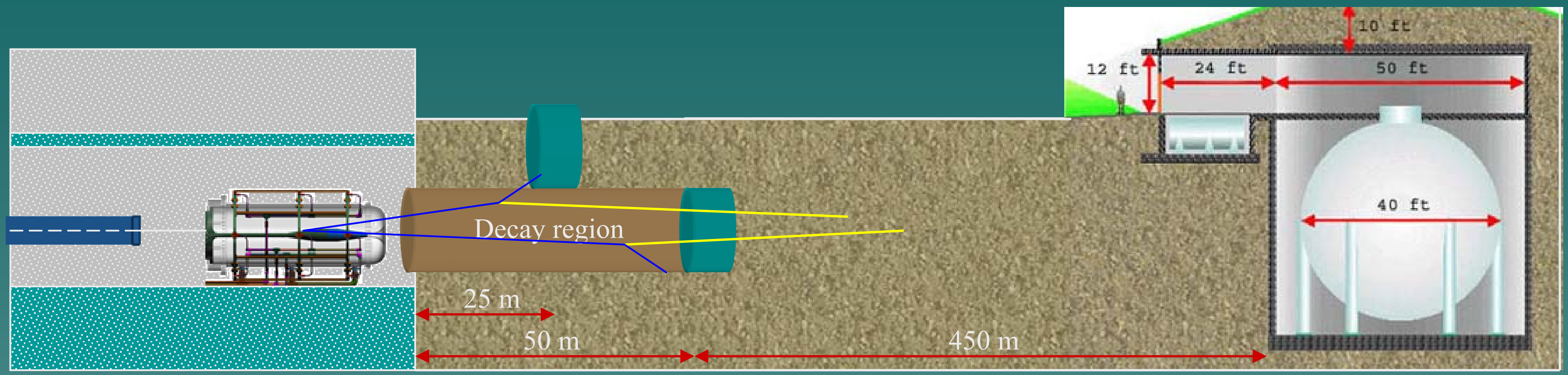
MiniBooNE Overview: Experimental Setup





- MiniBooNE receives 8.9 GeV/c protons from the Fermilab Booster.
- Protons are focused onto a 1.7 interaction length beryllium target producing various secondaries (p's, π's, K's).
- Secondaries are focused via a magnetic focusing horn surrounding the target. The horn receives 170 kA pulses at up to 10 Hz.

MiniBooNE Overview: Experimental Setup



$$\pi^{+} \rightarrow \mu^{+} + \nu_{\mu}$$

$$\quad \hookrightarrow e^{+} + \nu_{e} + \bar{\nu}_{\mu}$$

$$K^{+} \rightarrow \mu^{+} + \nu_{\mu}$$

$$K^{+} \rightarrow \pi^{0} + \mu^{+} + \nu_{\mu}$$

$$K^{+} \rightarrow \pi^{0} + e^{+} + \nu_{e}$$

$$K^{0} \rightarrow \pi^{\pm} + e^{\mu} + \overset{(-)}{\nu}_{e}$$

$$K^{0} \rightarrow \pi^{\pm} + \mu^{\mu} + \overset{(-)}{\nu}_{\mu}$$

- **Secondary mesons (π's, K's) decay in the 50m decay region to produce the MiniBooNE neutrino beam.**
- **A removable 25m absorber can be inserted. A great advantage for studying backgrounds.**
- **The horn is capable of running with the polarity reversed…anti-neutrino mode.**
- **Neutrinos detected ~500 m away in 12m diameter Čerenkov detector.**

MiniBooNE Beam: Neutrino Fluxes

Protons on Be:

$$p + Be \rightarrow \pi^{+}, K^{+}, K_L^{0}$$

Yield a high flux of ν_μ:

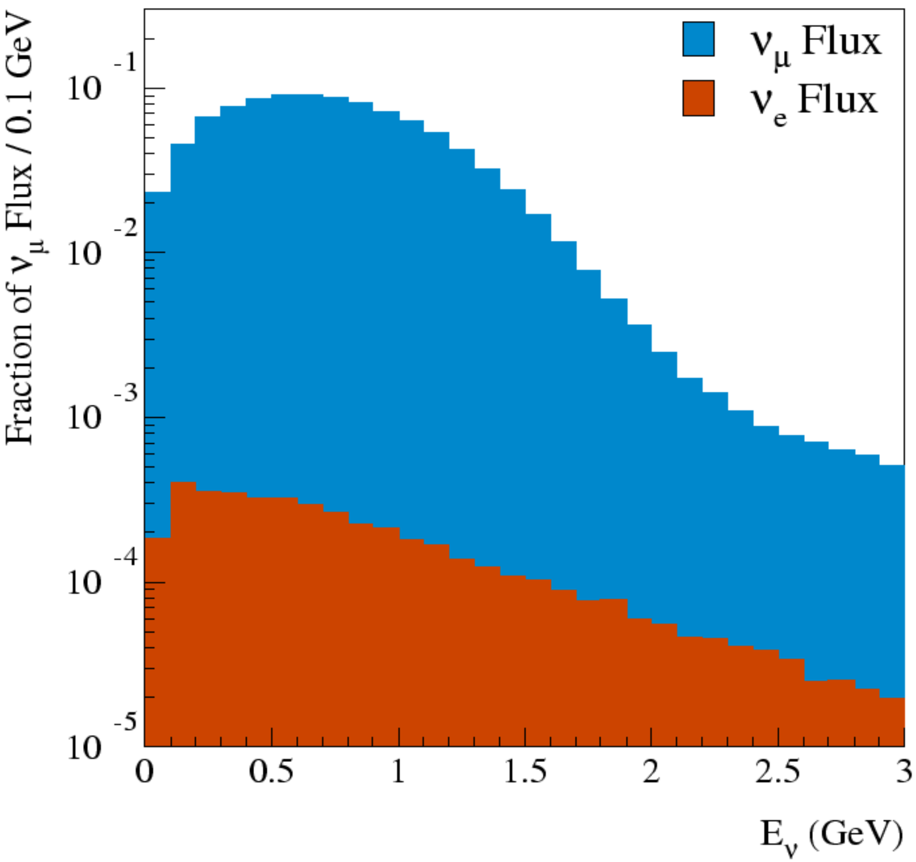
$$\pi^{+} \rightarrow \mu^{+} \nu_\mu$$ (*main ν_μ flux)

$$K^{+} \rightarrow \mu^{+} \nu_\mu, K_L^{0} \rightarrow \pi^{+} \mu^{-} \nu_\mu$$

With a low background of ν_e:

$$\mu^{+} \rightarrow e^{+} \nu_e \bar{\nu}_\mu$$

$$K^{+} \rightarrow \pi^{0} e^{+} \nu_e, K_L^{0} \rightarrow \pi^{-} e^{+} \nu_e$$



Understand fluxes with multiple monitoring systems

MiniBooNE Beam: Understanding ν Fluxes

- E910 @ BNL
  - Ran with protons at *6*, *12.4*, and 17.5 GeV/c
  - Thin Be, Cu, Au targets
  - Component of MB π production model
- **HARP @ CERN**
  - **Measure π & K production from 8.9 GeV/c proton beam**
  - **Knowing the production cross sections from the Be target translates directly into the expected neutrino fluxes at the detector**
- LMC muon spectrometer

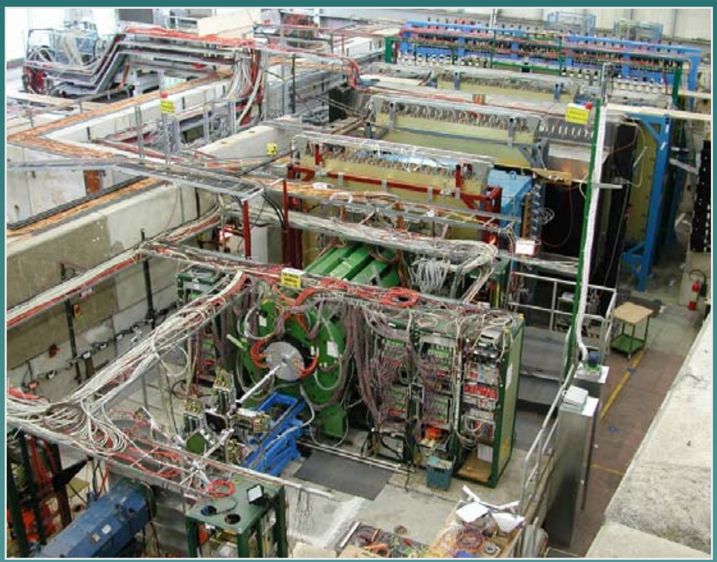
MiniBooNE ν flux: Why HARP ?

- HARP is a Hadron Production Experiment (PS-214) at CERN.
  - **neutrino factory studies**
  - **atmospheric neutrino predictions**
  - **current accelerator based neutrino beams**
  - **input for hadron generators (GEANT4).**
- Range of beam momenta from 1.5 GeV/c to 15 GeV/c.
- Range of target materials and thicknesses: **Be**, C, Al, Cu, Sn, Ta, Pb, H2,O2, N2, D2, K2K.
- Excellent forward coverage – possibility of 4π coverage.
- Overlapping PID detectors (ToF, Ckov, Cal).

At HARP we were able to record ~ 20 million triggers with MiniBooNE replica targets and an incident beam momentum of 8.9 GeV/c.

Hadron Production at HARP

MiniBooNE has cooperated with the **HARP** experiment (PS-214) at CERN to measure hadron production from the **MiniBooNE beryllium target.**

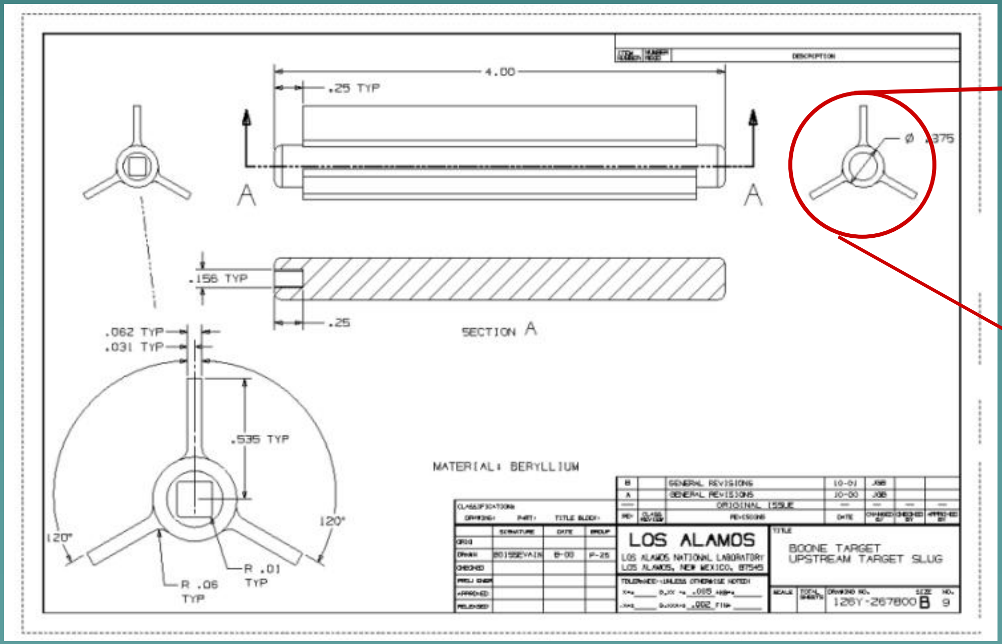


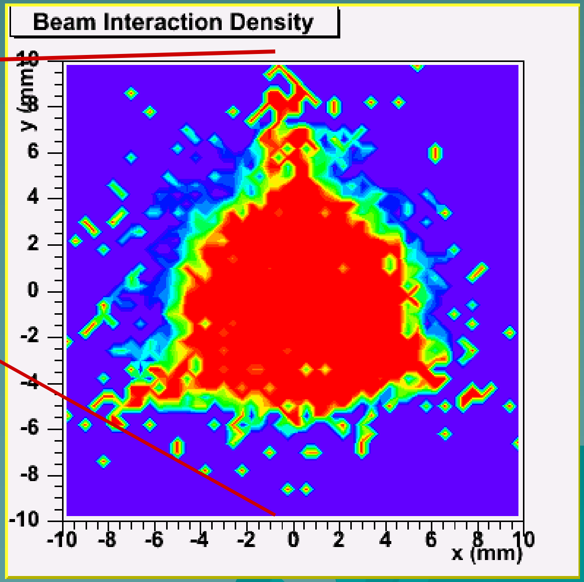
- The first goal is to measure π^+ production cross sections for Be at p_{proton} = 8.9 GeV/c.
- Additional measurements include:
  - π^- production (important for $\bar{\nu}$ running)
  - K production (important for intrinsic ν_e backgrounds)

No target	1.1 M events	Normalization
5% λ Be	7.3 M events	p+Be x-section
50% λ MB replica	5.4 M events	Effects specific to MB target reinteraction absorption scattering
100% λ MB replica	6.4 M events	

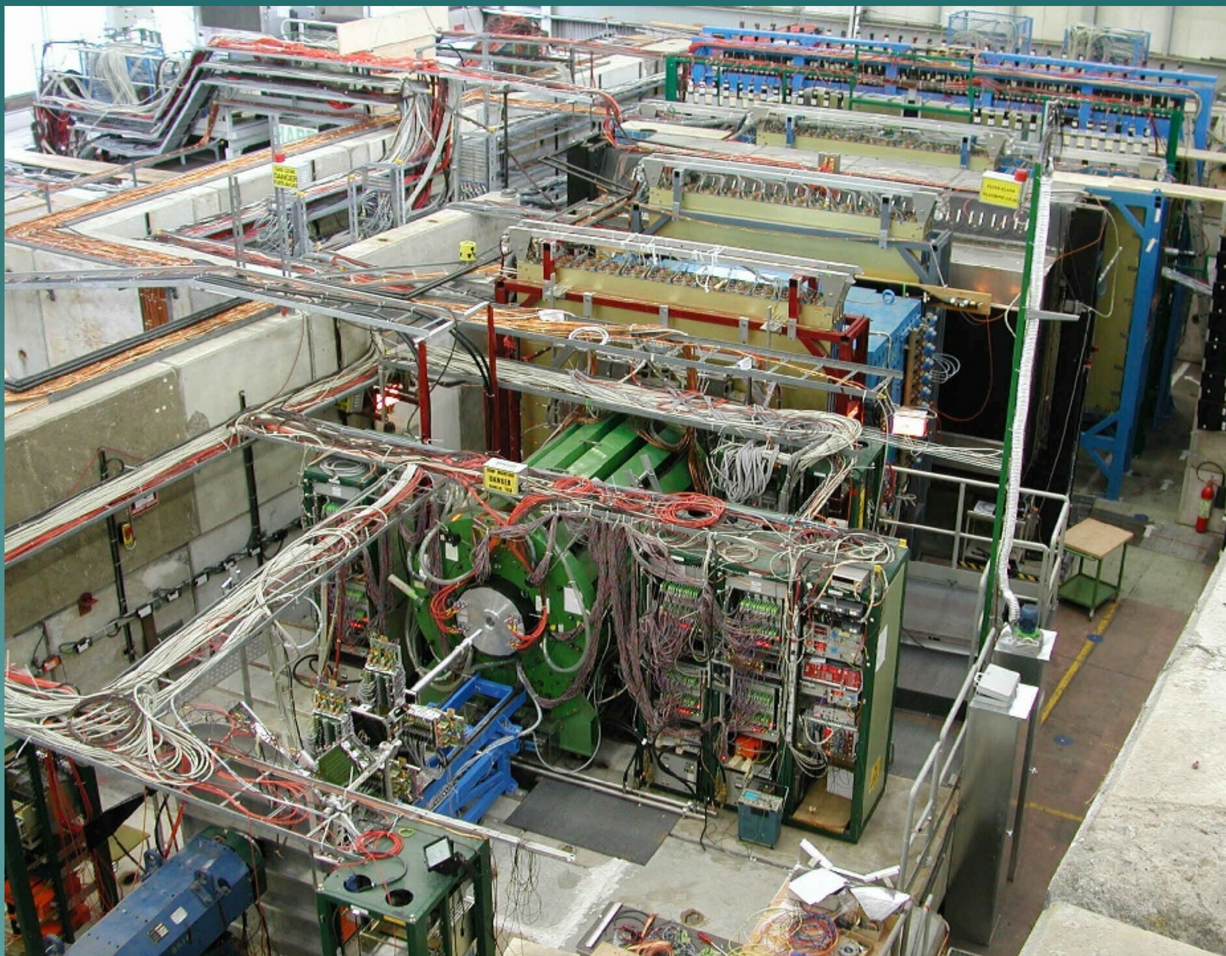
HARP: MB Beryllium Target

- The MB target is ~71 cm long and 1 cm in diameter with cooling fins
  - Comprised of seven ~10 cm slugs
- The MB replica targets used in HARP made up of same ~10 cm slugs
  - 20 cm for 50% λ target
  - 40 cm for 100% λ target
- Ratio of proton position at target face for pion events/all events



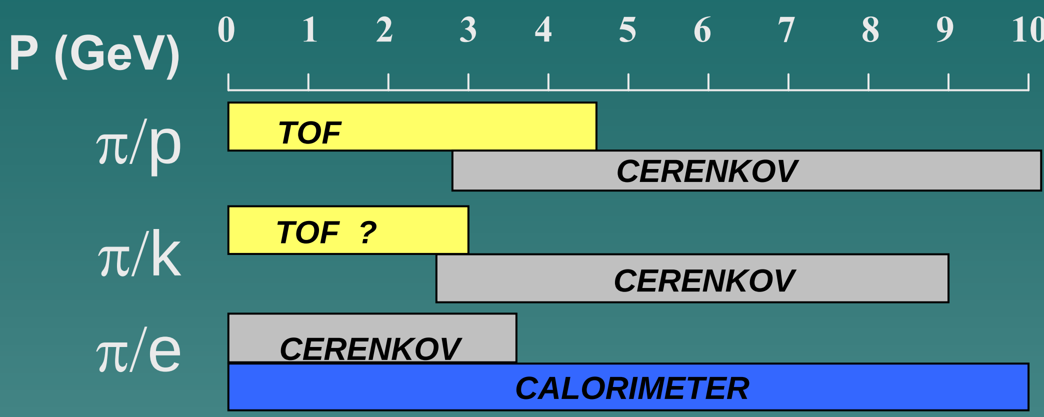


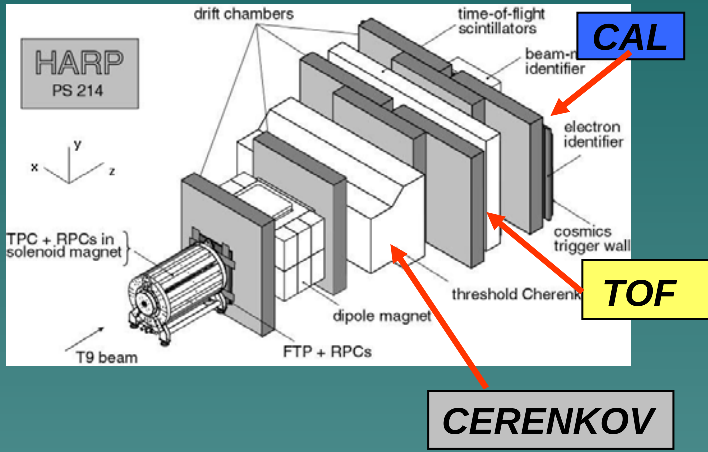
HARP: Detector



- e/h Calorimeter
- ToF Wall
- Drift Chambers
- Čerenkov
- Spectrometer Mag.
- TPC, RPC
- Beam Detectors
  - ToF
  - Čerenkov

HARP Detector: Overlapping PID Detectors





$$P(\pi \mid p, \lambda, \overline{N}_{pe}, E_1, E_2)$$

$p =$ reconstructed momentum

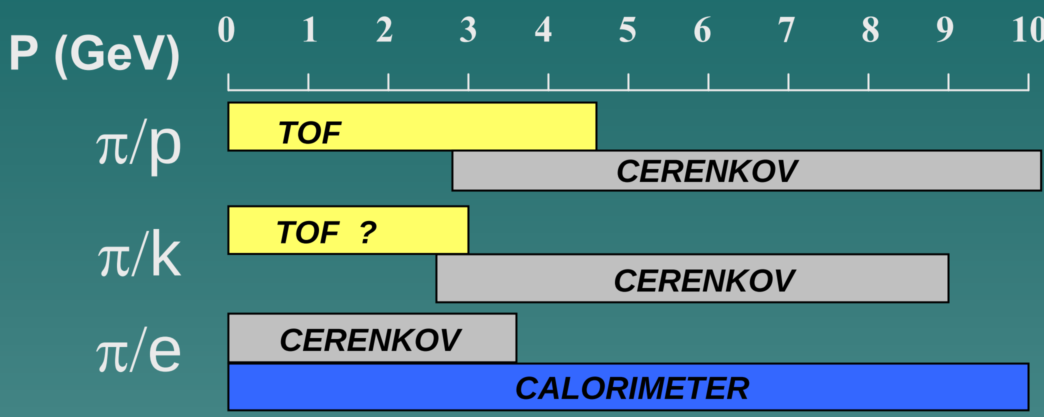
$$\lambda = \left(\frac{tc}{L}\right)^2 - 1$$

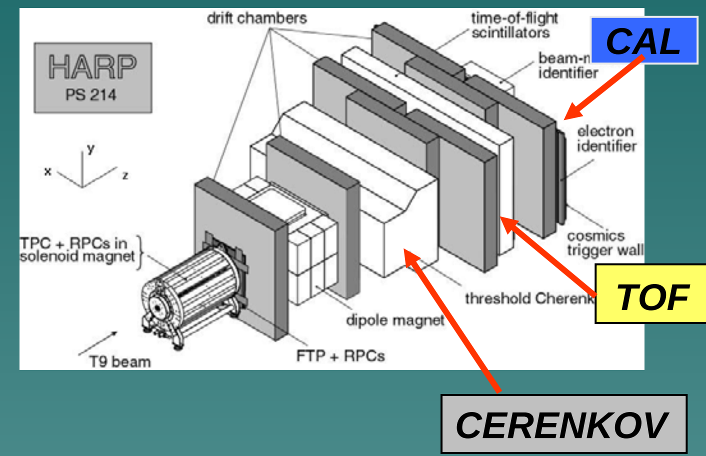
$$\overline{N}_{pe} = N_{pe} * (L_{ckov} / L_{path})$$

$E_1 =$ deposited in Cal plane 1

$E_2 =$ deposited in Cal plane 2

HARP Detector: Overlapping PID Detectors





Bayes Theorem

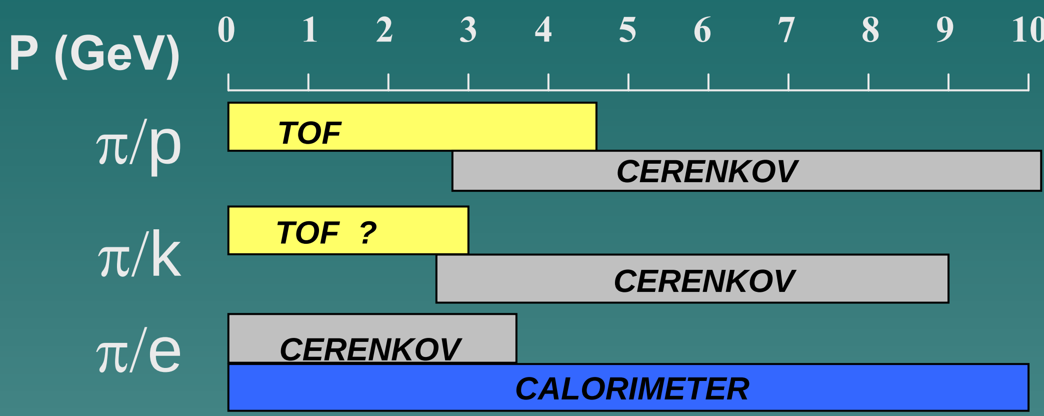
$$P(B_i \mid A) = \frac{P(A \mid B_i) \cdot P(B_i)}{\sum_{\alpha} P(A \mid B_\alpha) \cdot P(B_\alpha)}$$

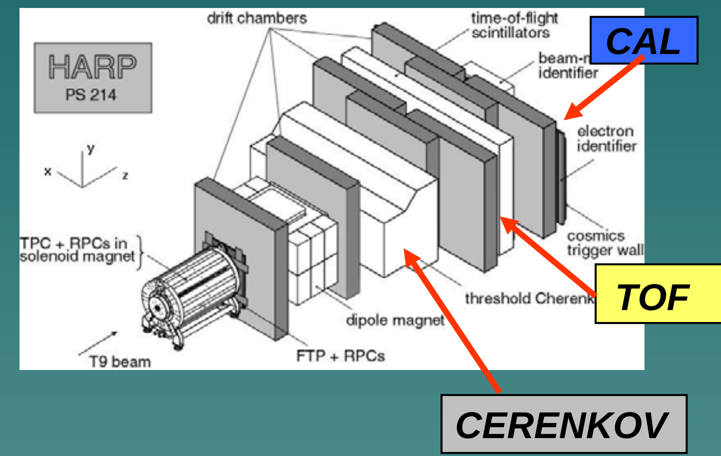
$$P(\pi \mid p, \lambda, \overline{N}_{pe}, E_1, E_2)$$

$$A = \{p, \lambda, \overline{N}_{pe}, E_1, E_2\}$$

$$B_\alpha = \pi, p, e, K, \ldots$$

HARP Detector: Overlapping PID Detectors





tof — cerenkov — calorimeter — momentum distribution

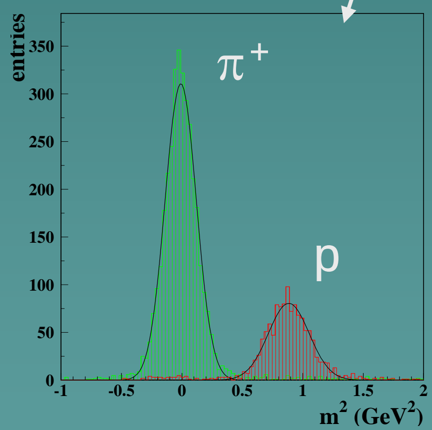
$$P(\pi \mid p,\lambda,\bar{N}_{pe},E_1,E_2)=\frac{P(\lambda \mid \pi,p)\cdot P(\bar{N}_{pe}\mid \pi,p)\cdot P(E_1,E_2\mid \pi,p)\cdot P(\pi \mid p)}{\sum_{\alpha=\pi,p,K,e} P(\lambda \mid \alpha,p)\cdot P(\bar{N}_{pe}\mid \alpha,p)\cdot P(E_1,E_2\mid \alpha,p)\cdot P(\alpha \mid p)}$$

HARP Detector: ID probabilities

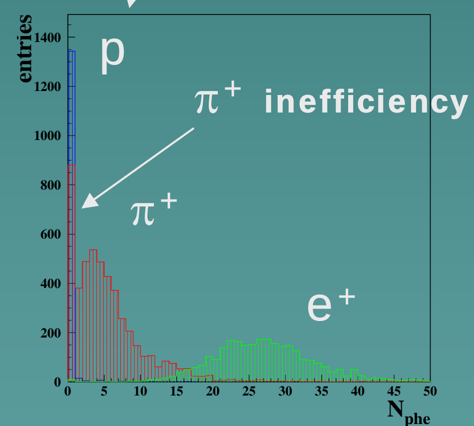
$$P(\lambda \mid \pi, p) \qquad P(\overline{N}_{phe} \mid \pi, p) \qquad P(E_1, E_2 \mid \pi, p)$$

tof ***cerenkov*** ***ecal***

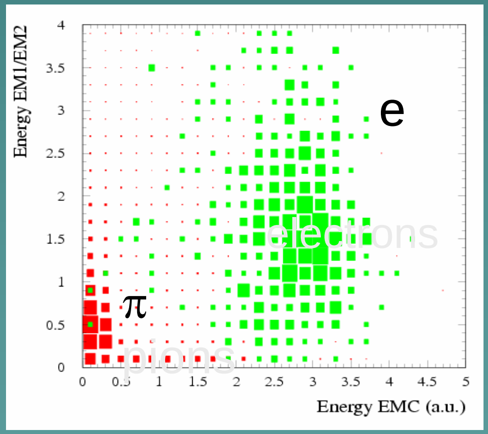
$\lambda = m^2/p^2$



Nphe

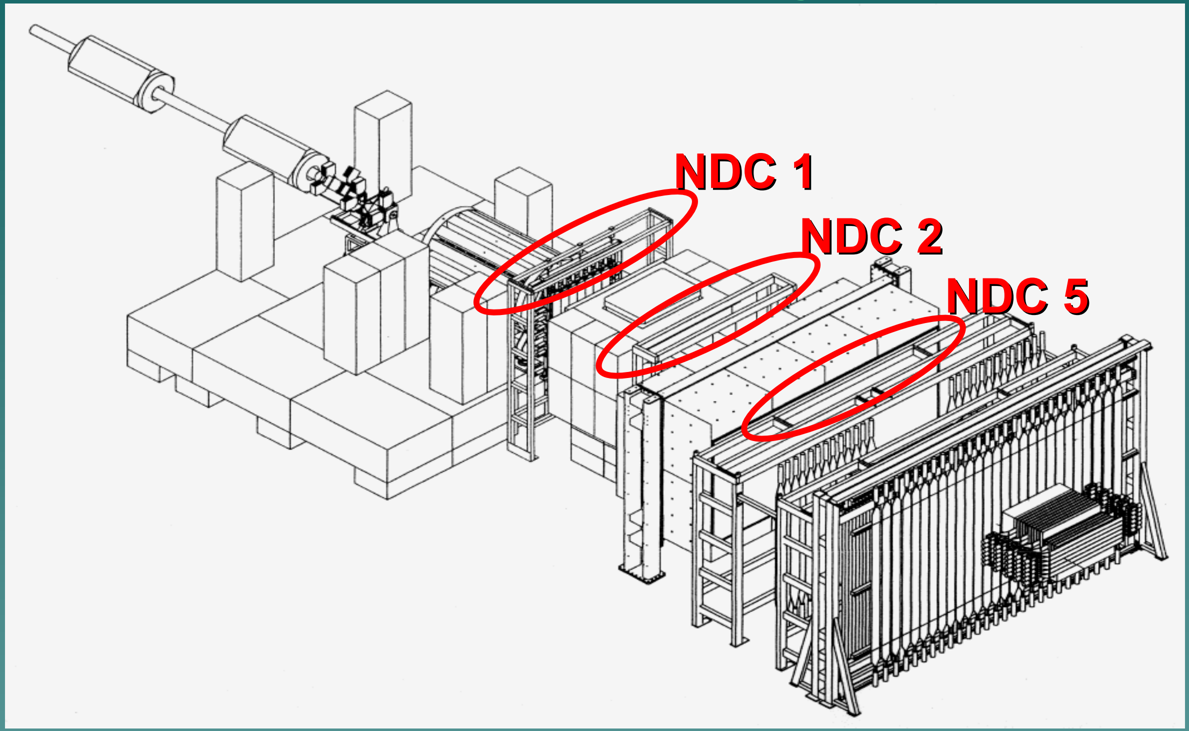


E_1 vs E_2



3 GeV beam particles for $\theta = 0$

HARP: Cross Section Measurement
Forward Analysis



- p_{π} > 1GeV/c
- θ_{π} < 250 mrad
- Main tracking detector: NOMAD drift chambers
- Forward PID detectors

HARP: Cross Section Measurement

$$N_i^{\pi} = \frac{1}{\varepsilon_i^{acc}} \frac{1}{\varepsilon_i^{track}} \left[M_{ij} \cdot \frac{1}{\varepsilon_j^{\pi}} \cdot \eta_j^{\pi} \cdot N_j^{\pi} \right]$$

N_i^{π}: $(p,\theta)_{true}$

ε_i^{acc}: acceptance

ε_i^{track}: tracking efficiency

M_{ij}: migration matrix

ε_j^{π}: pion efficiency

η_j^{π}: pion purity

N_j^{π}: pion yield, $(p,\theta)_{rec}$

HARP: Cross Section Measurement

$$N_i^{\pi} = \frac{1}{\varepsilon_i^{acc}} \frac{1}{\varepsilon_i^{track}} \left[M_{ij} \cdot \frac{1}{\varepsilon_j^{\pi}} \cdot \eta_j^{\pi} \cdot N_j^{\pi} \right]$$

$(p,\theta)_{true}$ — N_i^{π}

acceptance — ε_i^{acc}

tracking efficiency — ε_i^{track}

migration matrix — M_{ij}

pion efficiency — ε_j^{π}

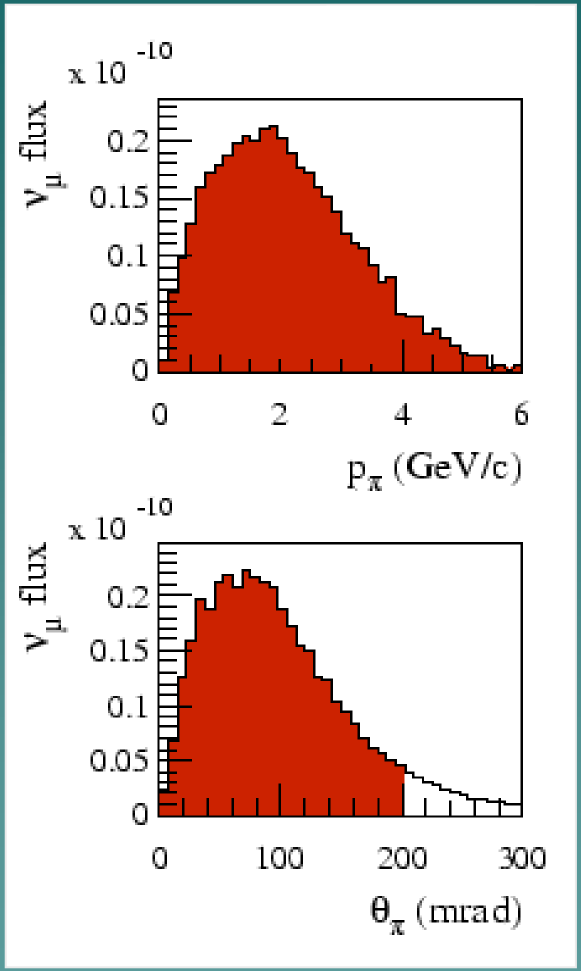
pion purity — η_j^{π}

pion yield — N_j^{π}

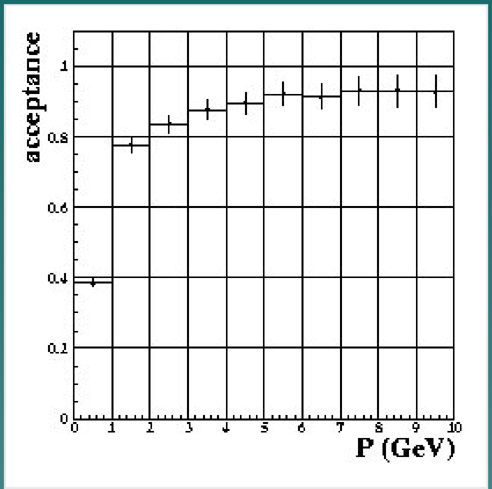
$(p,\theta)_{rec}$ — N_j^{π}

- **Acceptance is determined using the MC (compare to MB requirements)**

MiniBooNE Beam: Relevant Phase Space

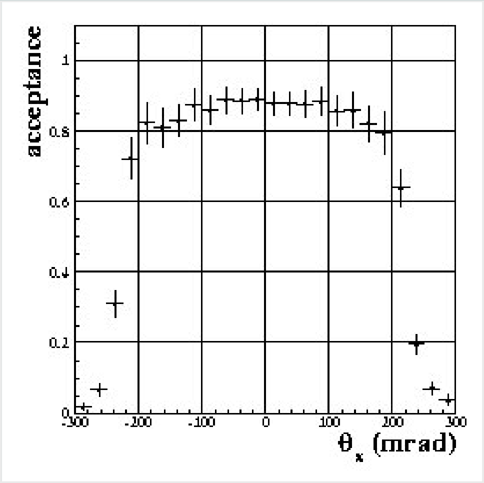


Momentum distribution peaks at ~1.5 GeV/c and trails off at 6 GeV/c.



Acceptance in P for $|\theta_y|$<50 mrad & $|\theta_x|$<200 mrad

Acceptance in θ_x for $|\theta_y|$<50 mrad & P > 1 GeV



Angular distribution of pions is mostly below 200 mrad.

Momentum and Angular distribution of pions decaying to a neutrino that passes through the MB detector.

Acceptance of HARP forward detector

HARP: Cross Section Measurement

$$N_i^{\pi} = \frac{1}{\varepsilon_i^{acc}} \frac{1}{\varepsilon_i^{track}} \left[M_{ij} \cdot \frac{1}{\varepsilon_j^{\pi}} \cdot \eta_j^{\pi} \cdot N_j^{\pi} \right]$$

$(p,\theta)_{true}$ — N_i^{π}

acceptance — ε_i^{acc}

tracking efficiency — ε_i^{track}

migration matrix — M_{ij}

pion efficiency — ε_j^{π}

pion purity — η_j^{π}

pion yield — N_j^{π}

$(p,\theta)_{rec}$ — N_j^{π}

- **Acceptance is determined using the MC (compare to MB requirements)**
- **Tracking Efficiency and Migration (see talk by M. Ellis).**

HARP: Cross Section Measurement

$$N_i^{\pi} = \frac{1}{\varepsilon_i^{acc}} \frac{1}{\varepsilon_i^{track}} \left[M_{ij} \cdot \frac{1}{\varepsilon_j^{\pi}} \cdot \eta_j^{\pi} \cdot N_j^{\pi} \right]$$

$(p,\theta)_{true}$

acceptance

tracking efficiency

migration matrix

pion efficiency

pion purity

pion yield

$(p,\theta)_{rec}$

- **Acceptance is determined using the MC (compare to MB requirements)**
- **Tracking Efficiency and Migration (see talk by M. Ellis).**
- **Raw Particle Yields and Efficiency and Purity of the selection.**

Pion ID: Beam Particles

- Use no target runs to determine correction factor for PID. Beam detector ID is considered "true" ID.

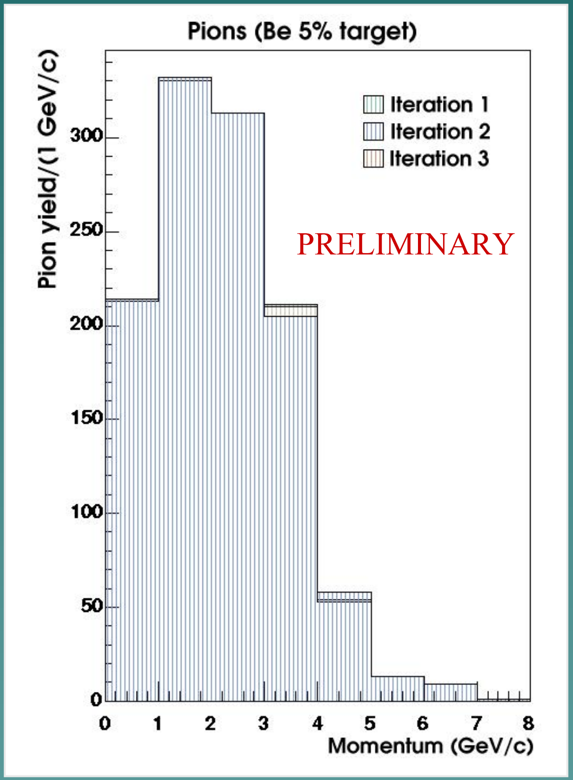
$$\beta_j^{\pi} = \frac{1}{\varepsilon_j^{\pi}} \cdot \eta_j^{\pi}$$

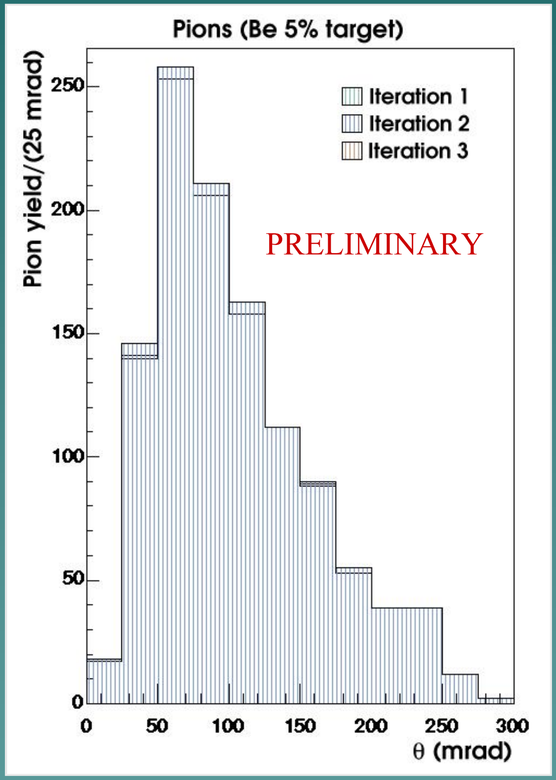
- PID Input (for 1st iteration) is found from crude cuts on detector data. But method is quite insensitive to starting input.

- Need MC to determine efficiency and purity for continuous p, θ
  - Continue to improve particle probability functions for the three detectors using data and MC.
    - Tof, Cerenkov, Calorimeter

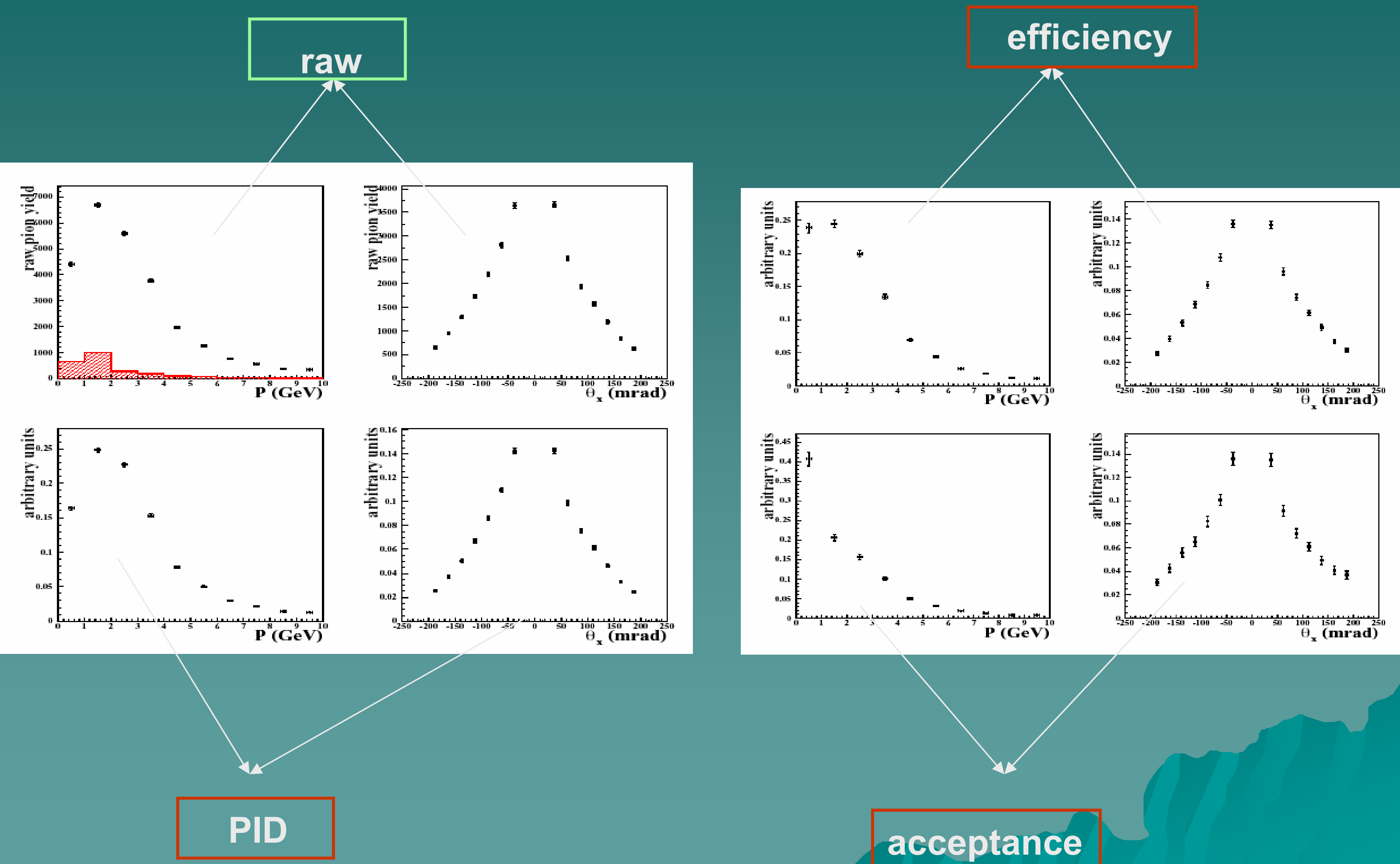
Pion ID: Beryllium 5% Target

- Run iterative PID algorithm on Be 5% target data to extract raw pion yields.
- 90% probability cut
- Additional corrections are needed:
  - PID efficiency and purity determined using no target data (waiting on the MC).
  - Tracking efficiency determined using both data and MC.
  - Acceptance determined from the MC.





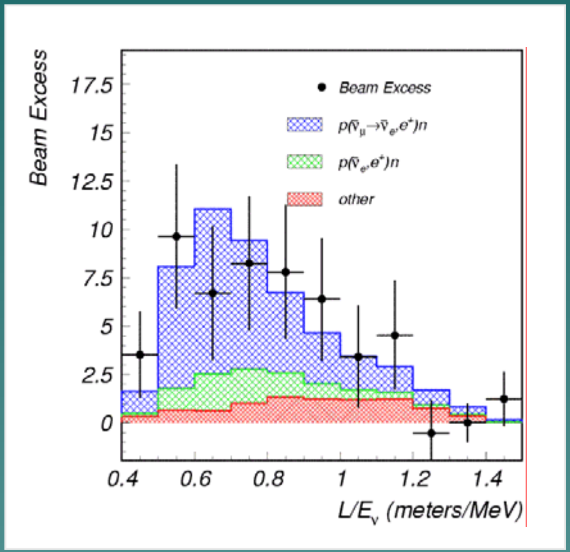
K2K target: Pion yield



HARP for MiniBooNE: Conclusions

- HARP is *very* important for the MiniBooNE experiment.
- We have a large amount of data taken at HARP to measure the π & K production cross sections as well as thick target effects in the MB target.
- Have made good progress toward initial measurement of the π^+ production cross section from the 5% Be target.
- In the near future:
    - Continue to improve particle probability functions for the three detectors using data and MC.
    - Implement tracking, PID, and acceptance corrections to raw particle yields.
    - Move towards normalized pion cross section measurement.
- In the next-to-near future:
    - Study pion absorption and reinteraction effects in the thick target by using data from three different target lengths.
    - How well can we do π/K separation?
    - Finally, generate neutrino fluxes for MiniBooNE using measurements from HARP.

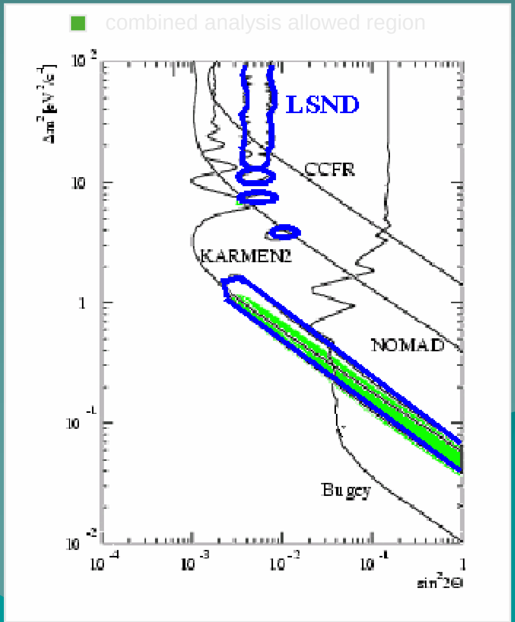
MiniBooNE Motivation: The LSND Result



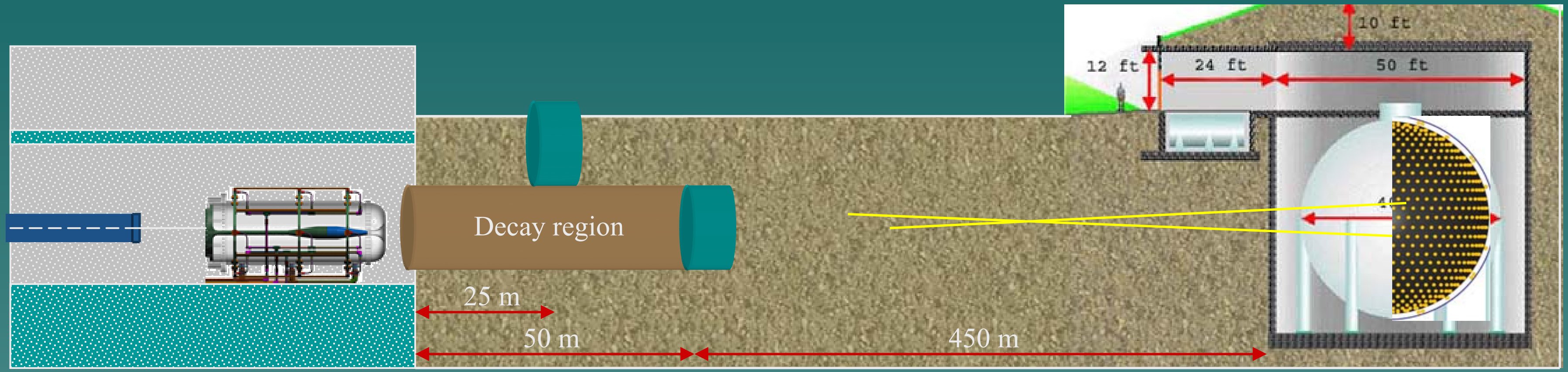
- The Liquid Scintillator Neutrino Detector was the first accelerator based neutrino oscillation experiment to see a signal.
- LSND saw a 3.8σ excess (above expected background) of $\overline{\nu}_e$ in a $\overline{\nu}_\mu$ beam.

$$\text{Prob}(\overline{\nu}_\mu \rightarrow \overline{\nu}_e) = (0.264 \pm 0.067 \pm 0.045)\%$$

- The KARMEN experiment was a similar experiment that saw no signal neutrinos. KARMEN had less statistics and a slightly different experimental L/E.
- A combined analysis of LSND and KARMEN leaves a substantial allowed region.



MiniBooNE Overview: Experimental Setup

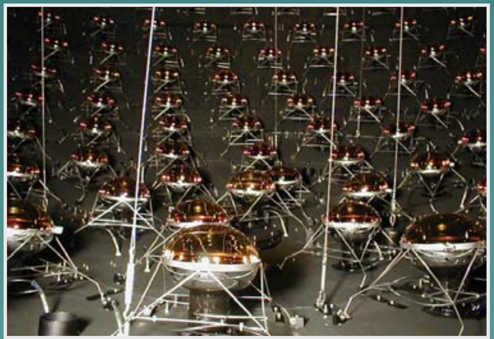


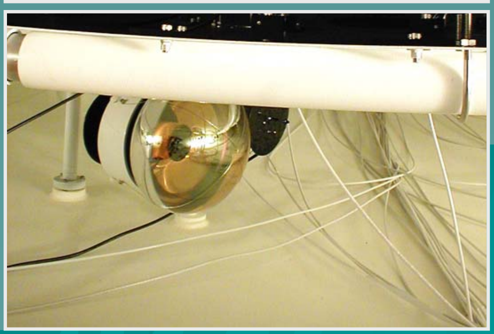
• Neutrinos are detected ~500 m away in a 12 m diameter Čerenkov detector.

• 950,000 liters of mineral oil

• 1280 photomultiplier tubes

• 240 optically isolated veto tubes





Cross Sections from HARP

The first goal is to measure the π^+ production cross sections from the MB target.

Future measurements will include:

- **π^- cross sections (important for anti-neutrino running)**
- **Kaon production cross sections (important for intrinsic ν_e backgrounds)**

$$\sigma_i^{\pi} = \frac{1}{\varepsilon_i^{acc}} \frac{1}{\varepsilon_i^{track}} \sum_{t=1}^{3} \left[M_{ij}^{(t)} \cdot \frac{1}{\varepsilon_j^{\pi(t)}} \cdot \eta_j^{\pi(t)} \cdot N_j^{\pi(t)} \right]$$

acceptance

tracking efficiency

migration matrix

pion efficiency

pion purity

pion yield

$$\varepsilon_i^{track} = \sum_{t=1}^{3} \varepsilon_i^{(t)-track}$$

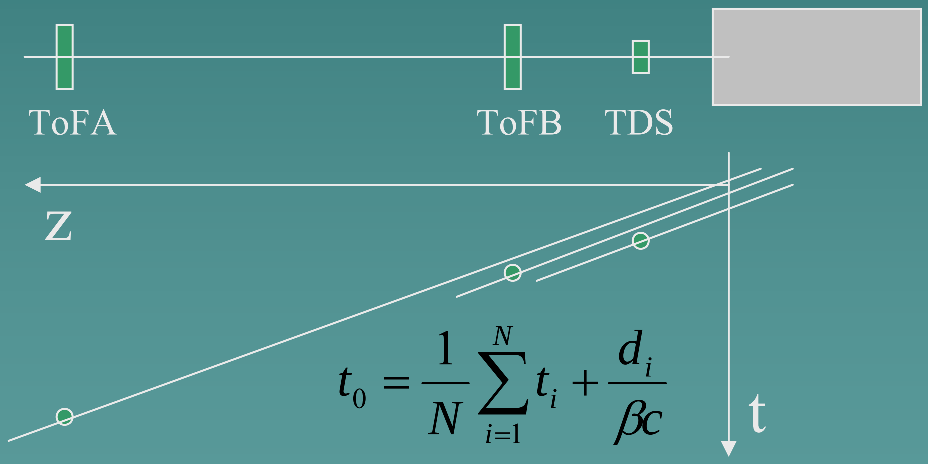
$$\eta_j^{\pi(k)} = \frac{N_j^{\pi(k)} - N_j^{bkg(k)}}{N_j^{\pi(k)}}$$

Time-of-Flight (1)

- **Dependent on TOF wall resolution**
- **Dependent on t_0 resolution**

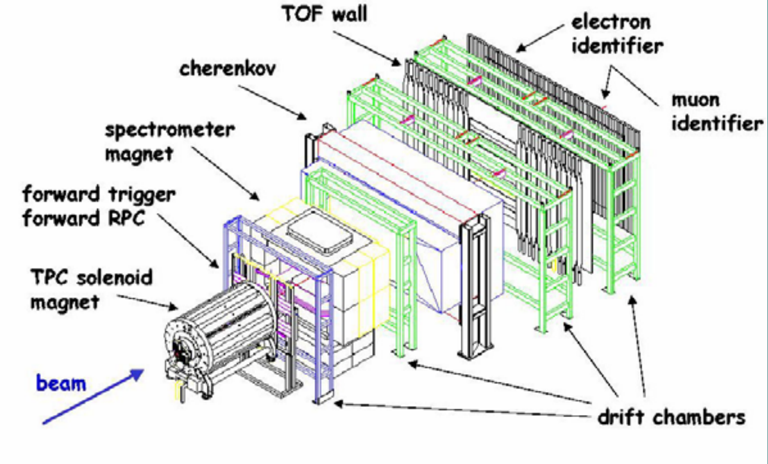
$$t.o.f = t_{wall} - t_0 + t_{offset}$$

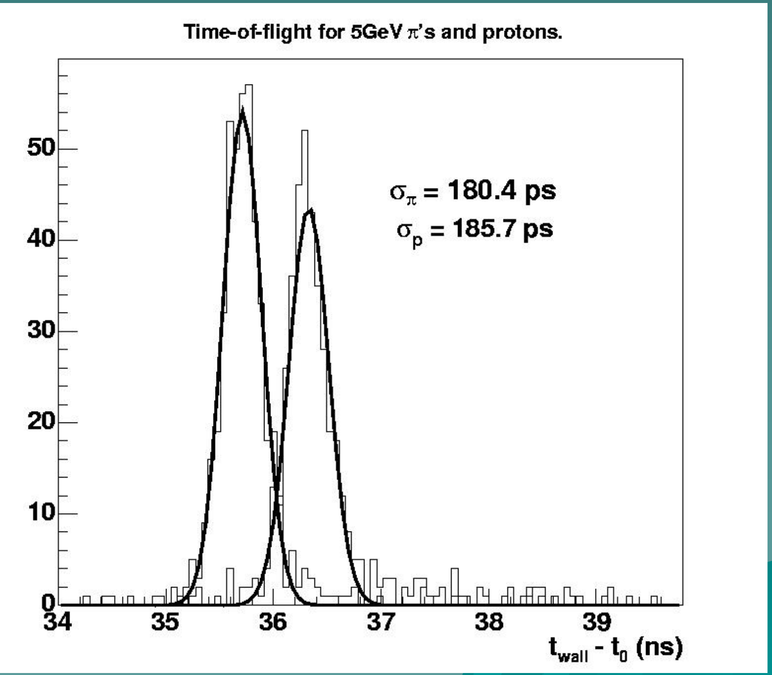
- 3 separate beam timing counters are used to determine t_0.



$$t_0 = \frac{1}{N}\sum_{i=1}^{N} t_i + \frac{d_i}{\beta c}$$

♦ $t0$ ~ 70 ps ♦ $tofw$ ~ 160-170 ps

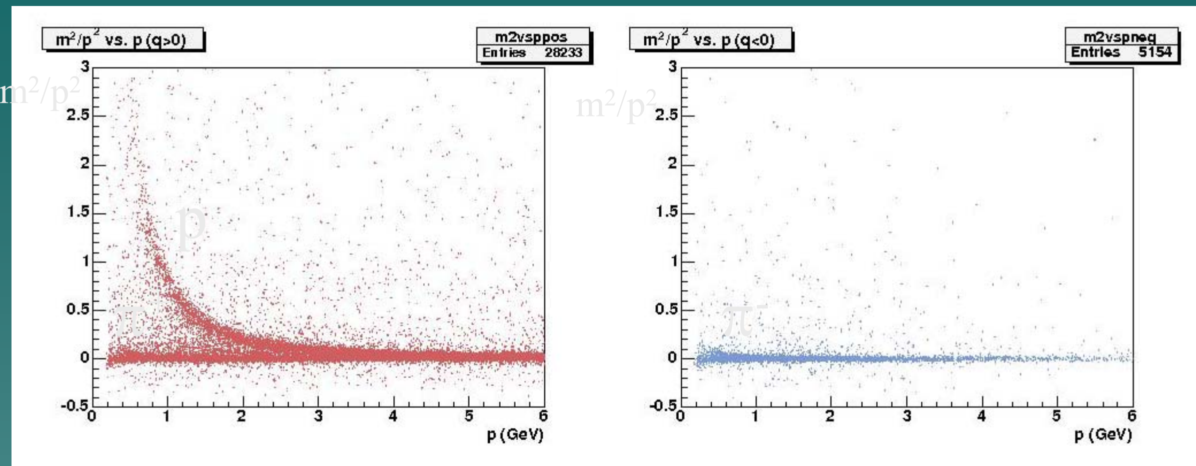




Time-of-Flight (2)

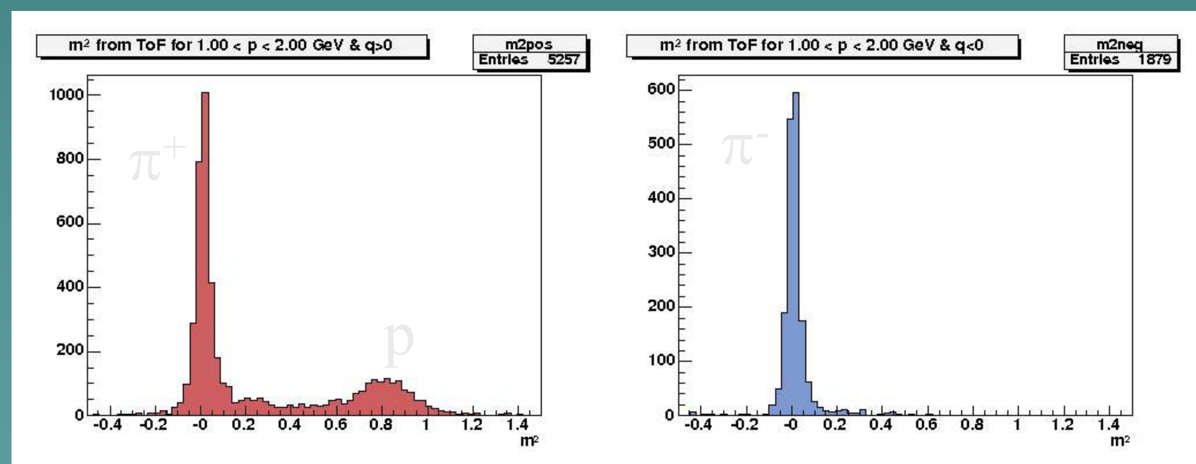
$$\lambda \equiv \frac{1}{\beta^2} - 1 = \left(\frac{t \cdot c}{L}\right)^2 - 1$$

- additionally dependent on path length resolution of drift chambers



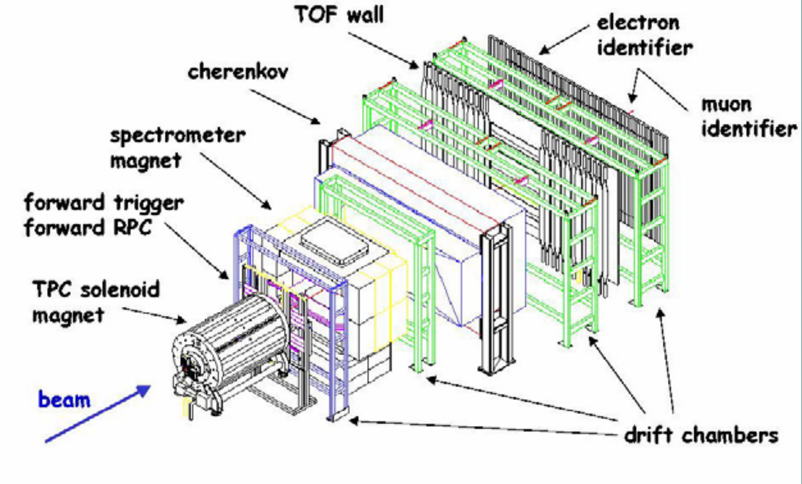
$$m^2 = \frac{p^2}{c^2}\lambda$$

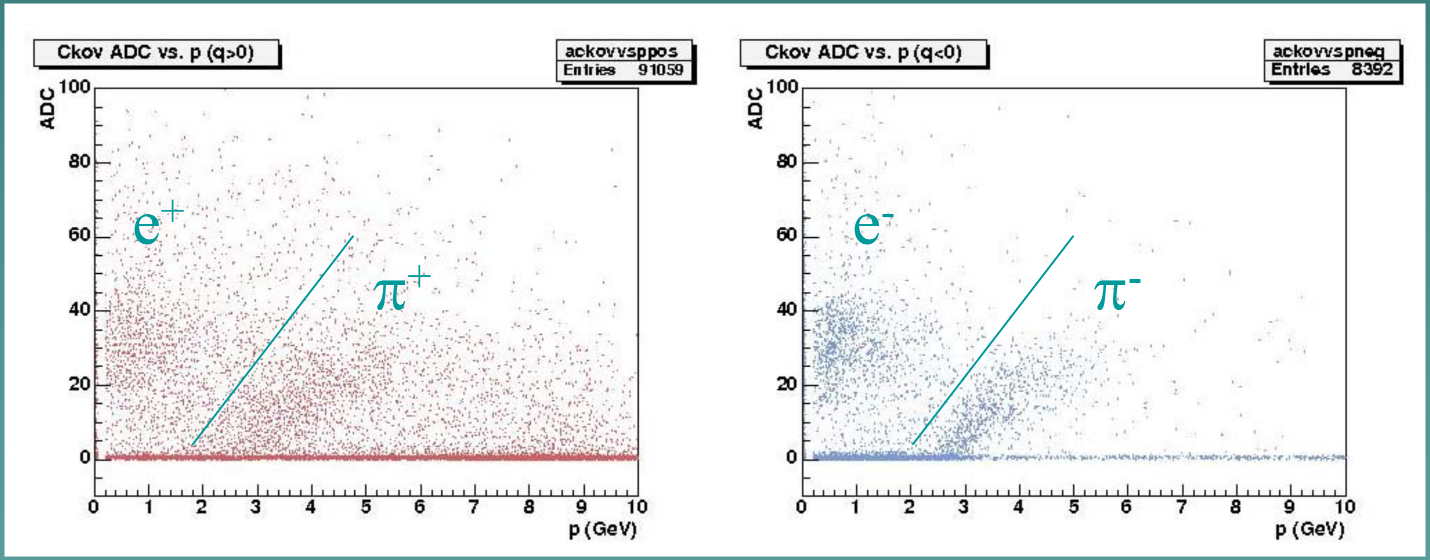
- additionally dependent on momentum resolution of drift chambers



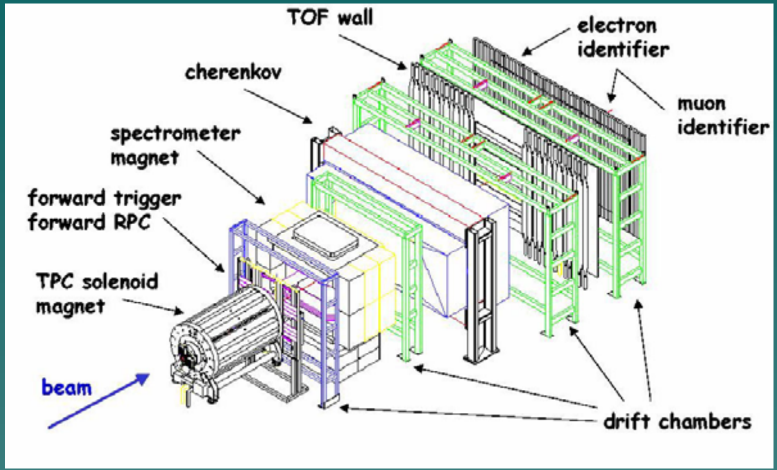
Čerenkov

- Identifies electrons below ~ 2.5 GeV
- π threshold ~ 2.6 GeV
- K threshold ~ 9.3 GeV
- p threshold ~ 17.6 GeV

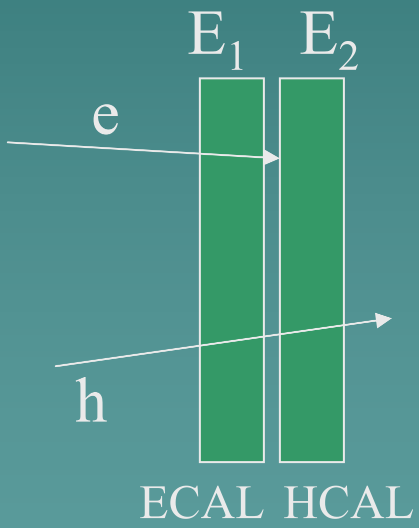




electron/hadron Calorimeter



- Two parallel modules - ECAL, HCAL
- Vertical scintillator planes



- electrons lose most of their energy in ECAL.
- $E_1/E \sim 1$ & $E/p \sim 1$.
- hadrons lose very little of their energy.
- $E_1/E < 1$ & $E/p << 1$