Near-Threshold Measurements of $\gamma + p \rightarrow n + \pi^+$

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understanding the nucleon

A crucial questions in nuclear science is to connect the observed properties of the nucleon with the theoretical framework provided by QCD

- One approach to answer this is through measurements of pion photoproduction at low-energies
- measure absolute cross sections
- angular distributions

understanding the nucleon

pion photoproduction

- fundamental nuclear process
  - involves explicit rearrangement of quarks in the nucleus
    - way to the QDC-based description of nucleon
  - uses EM probe (well understood)
    - simplifies interpretation of results

understanding the nucleon

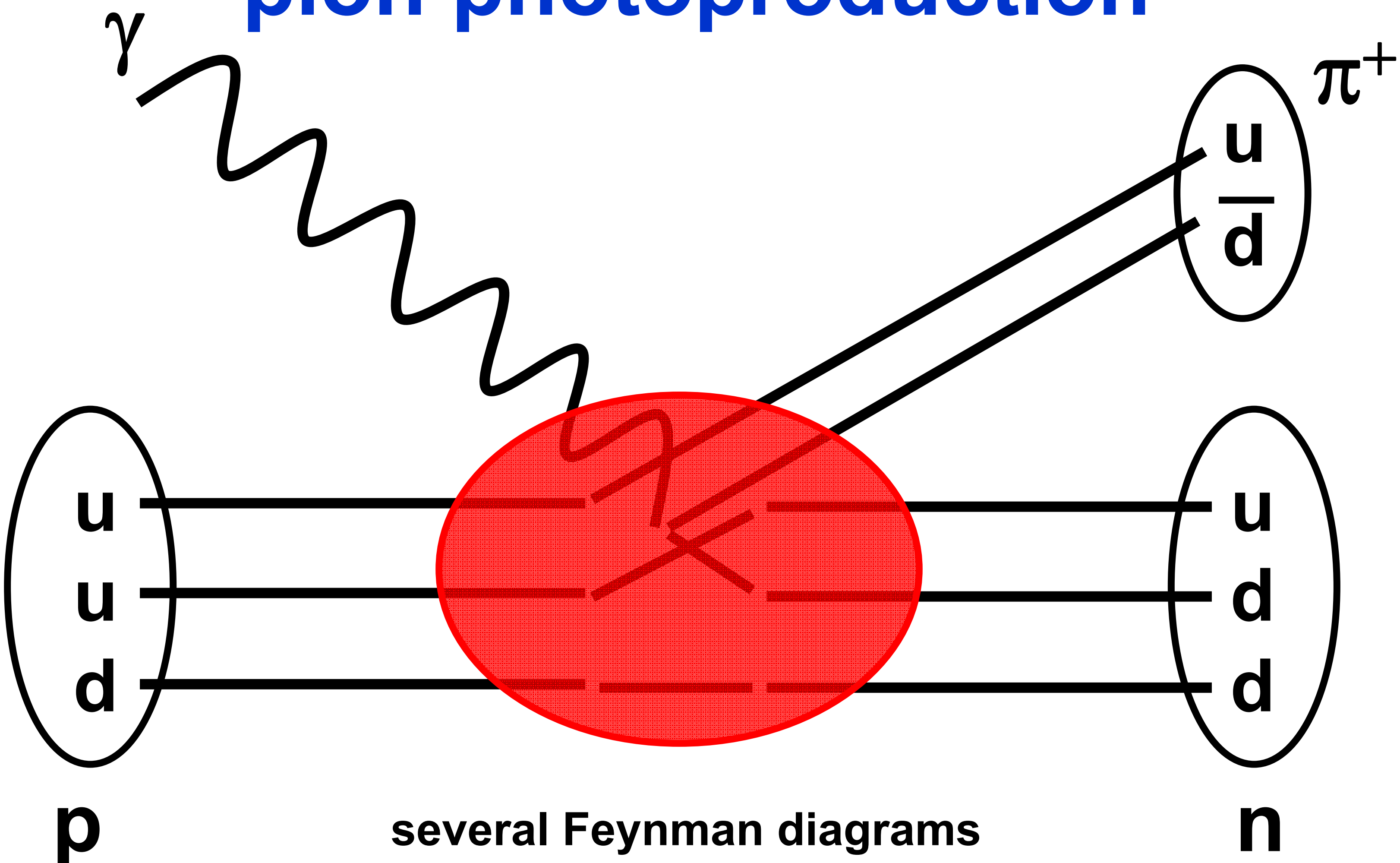
pion photoproduction

- one of the few low-energy phenomena where QCD-based calculations can be made

  - comparison of experimental results with theory provides important test of the various models

  - provide information regarding the underlying dynamics in the nucleon system

pion photoproduction



several Feynman diagrams describing interaction between the γ, p and π

chiral symmetry

- exact …
  - u & d quarks are massless
  - Goldstone boson (pion) have zero mass
- approximate …
  - u& d quarks have finite but small masses (~10 MeV)
  - pion mass (~140 MeV) is small compared with the nucleon mass (~1 GeV)

chiral perturbation theory ChPT

- method to solve QDC in nuclear regime
  - pion & nucleon as appropriate degrees of freedom
  - known symmetries restrict the form of the possible interactions
    - calculations are tractable

- ChPT has been used to predict s- and p-wave contributions to pion photoproduction
  - need to test these against measurements

chiral perturbation theory ChPT

- work on ChPT has produced predictions for the s-wave and p-wave contributions to the pion photoproduction channels
  - $\gamma + p \rightarrow p + \pi^o$
  - $\gamma + n \rightarrow n + \pi^o$
  - $\gamma + p \rightarrow n + \pi^+$
  - $\gamma + n \rightarrow p + \pi^-$
- comparison of experimental measurements with these predictions provides a stringent test of ChPT

E_{0+} amplitude predictions

- lowest order term is the s-wave (E_{0+} amplitude)

- predictions for the E_{0+} amplitude
  - older low-energy theorems (LET)
  - dispersion relations
  - more recently, ChPT calculations

E_{0+} amplitude predictions

- predictions for the s-wave term in the four pion photoproduction channels

channel	ChPT	LET	Disp. Rel.
$\gamma + p \rightarrow p + \pi^o$	-1.16	-2.3	-1.22
$\gamma + n \rightarrow n + \pi^o$	+2.6	-0.5	+1.19
$\gamma + p \rightarrow n + \pi^+$	+28.2	+27.6	+28.0
$\gamma + n \rightarrow p + \pi^-$	-32.7	-31.7	-31.7

pion photoproduction measurements

- experimentally, we measure cross sections and angular distributions
  - these are related to the multipole amplitudes

$$\frac{d\sigma}{d\Omega} = \left(\frac{q}{k}\right)\left[\left|E_{0^+}\right|^2 + \left|\mathrm{p-waves}\right|^2\right]$$

- at threshold, p-wave terms go to zero
  - determine the E_{0+} amplitude directly

ChPT and the s-wave term

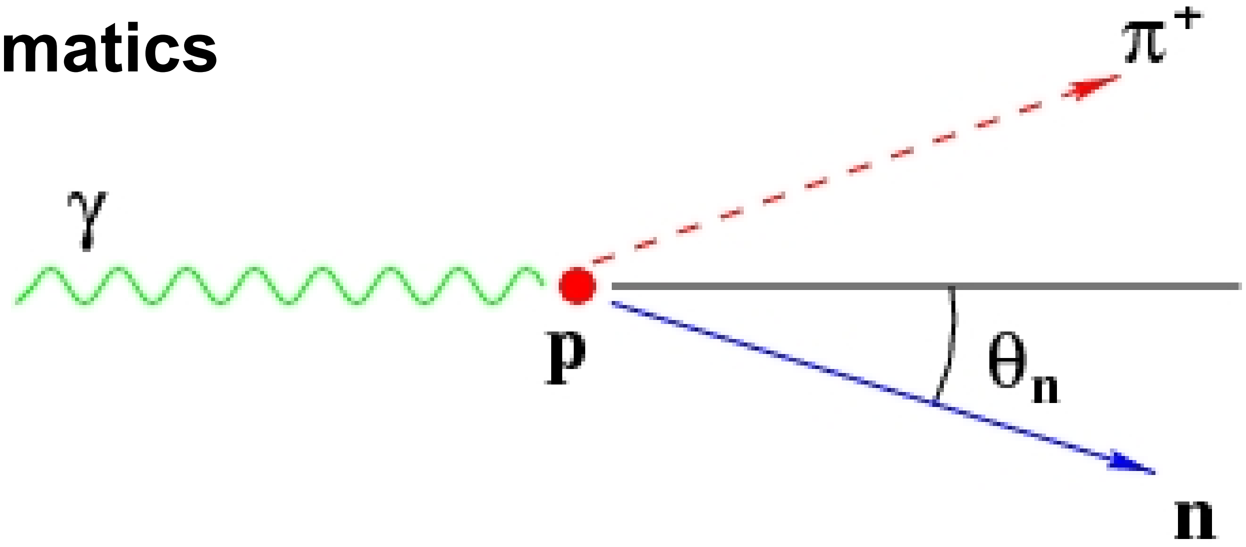
- predictions from ChPT
  - charged channels: similar to older calculations
    - dominated by Kroll-Ruderman term
    - higher-order ChPT terms are small
  - neutral channels: different than older calculations
    - Kroll-Ruderman term vanishes
    - higher-order terms are more important

charged pion channels:

- **Born term dominates**
  - higher-order pion loop contributions are small
    - chiral expansion converges rapidly
    - accurate predictions from ChPT
- **consequently**
  - test the convergence of ChPT calculations
  - provide new constraints on parameters
    - πN scattering length
    - πN coupling constants

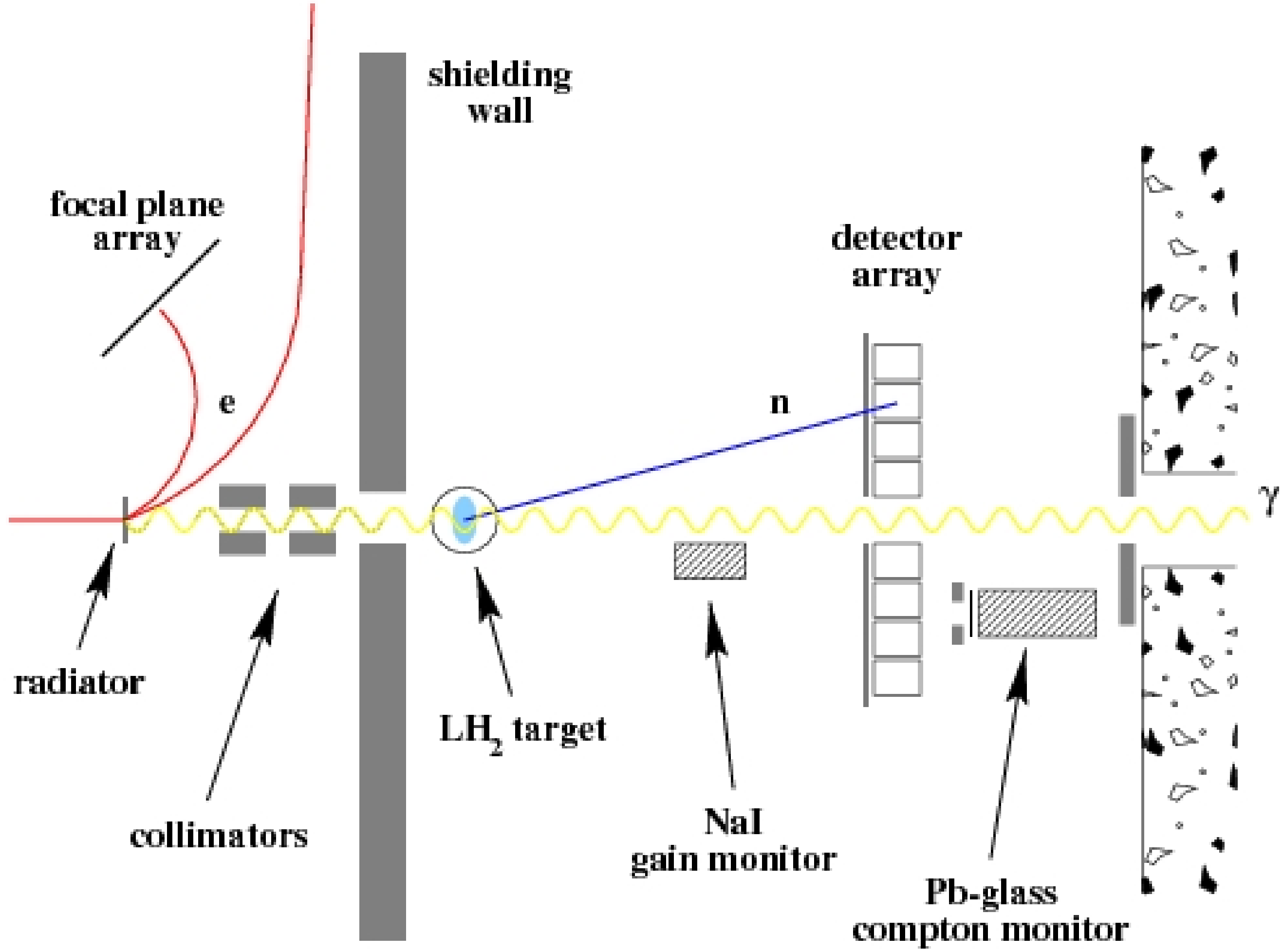
$\gamma + p \rightarrow n + \pi^+$

- kinematics

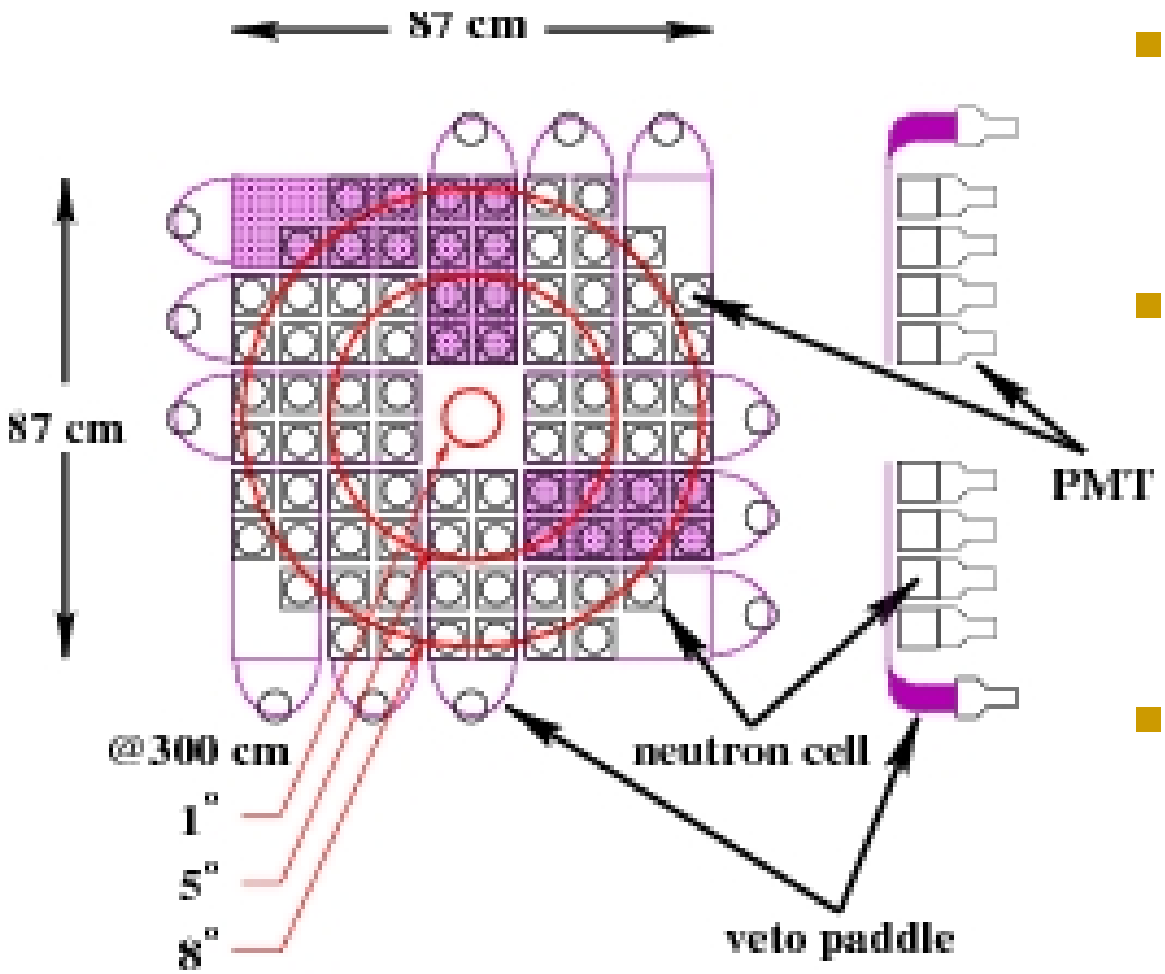


- π has very low energy
- neutron energy large, confined to forward cone
- detect the neutron

$\gamma p \rightarrow n\pi^+$ at SAL



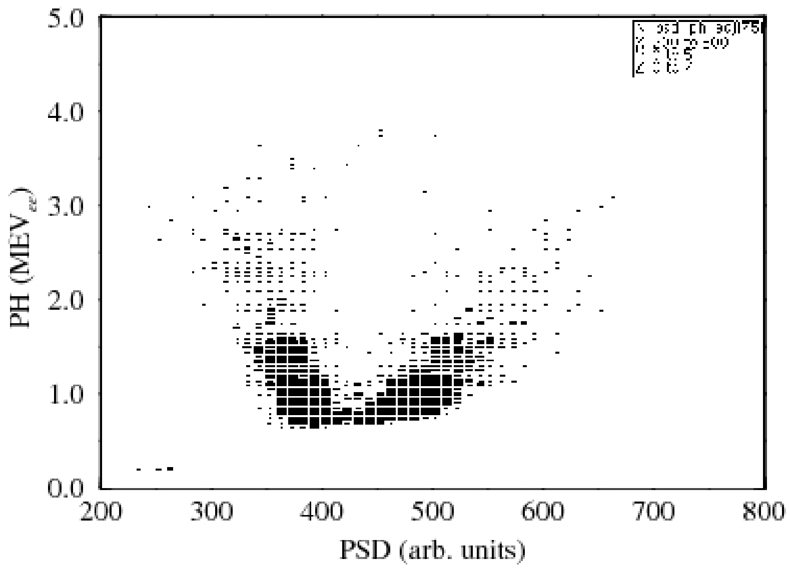
$\gamma p \rightarrow n\pi^+$ at SAL

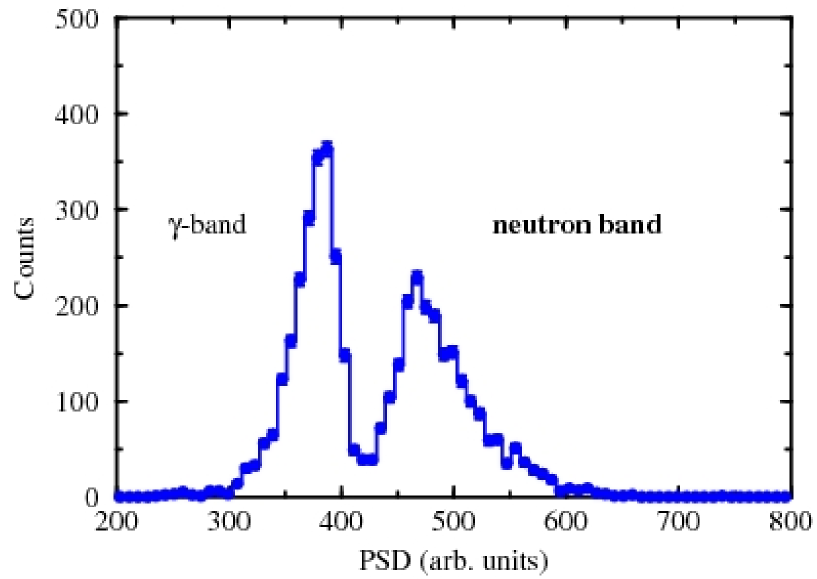


- 84 cells filled with liquid scintillator
- use pulse-shape discrimination to separate neutrons from photons
- thin counter in front to veto charged particles

pulse shape discrimination

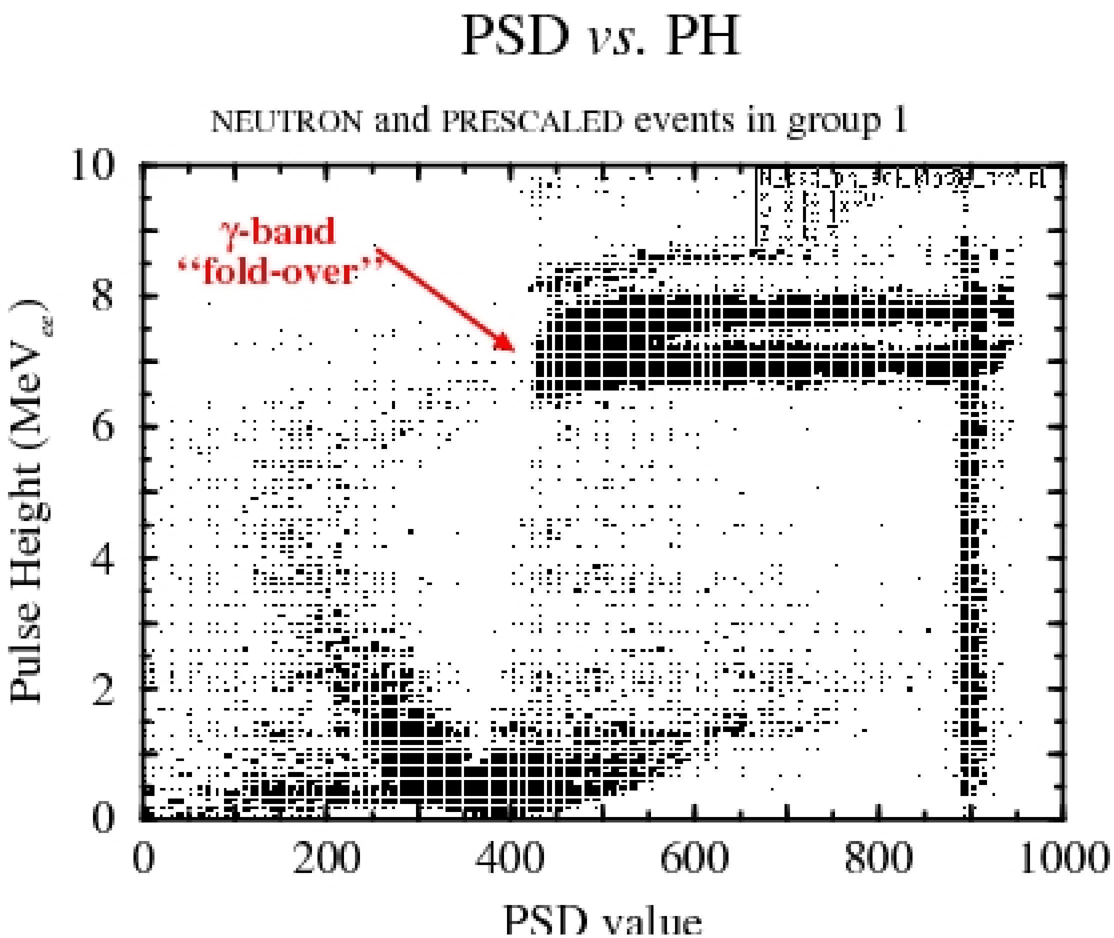
PSD vs pulse height for Am-Be source





projection shows n, γ events separated

pulse shape discrimination

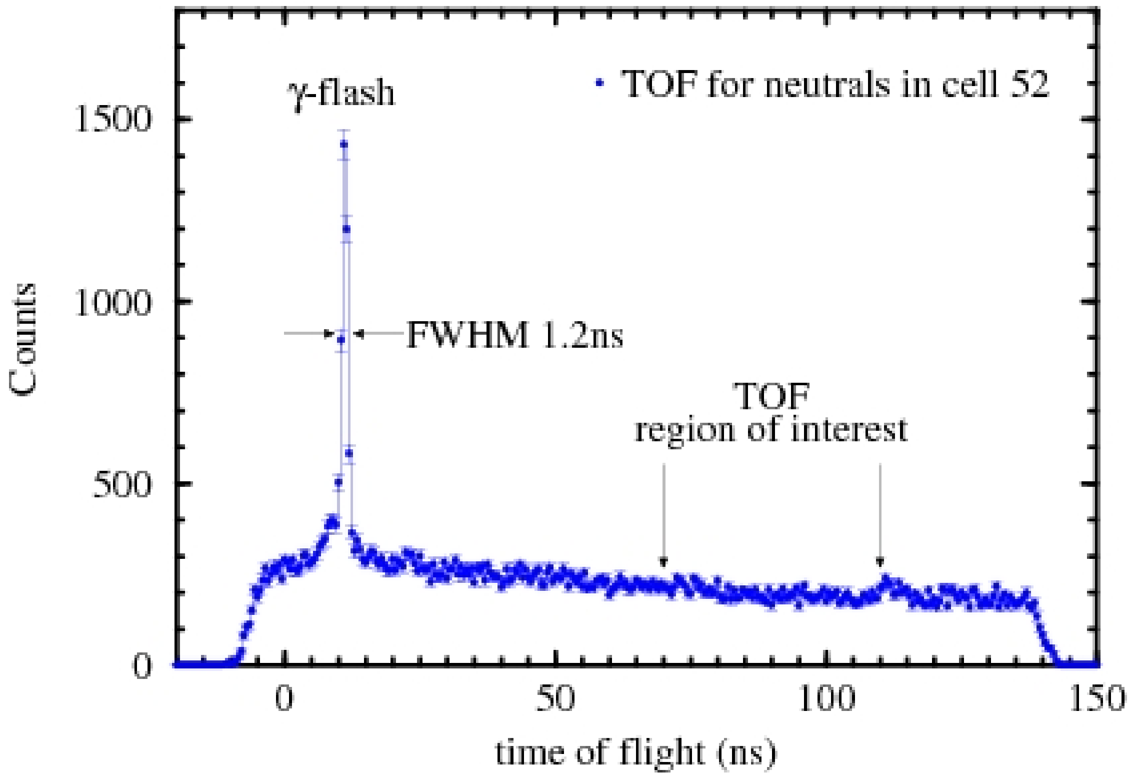


- **high-energy γ pass hardware PSD cut**
- **exclude with analysis cuts**

neutron energy & TOF

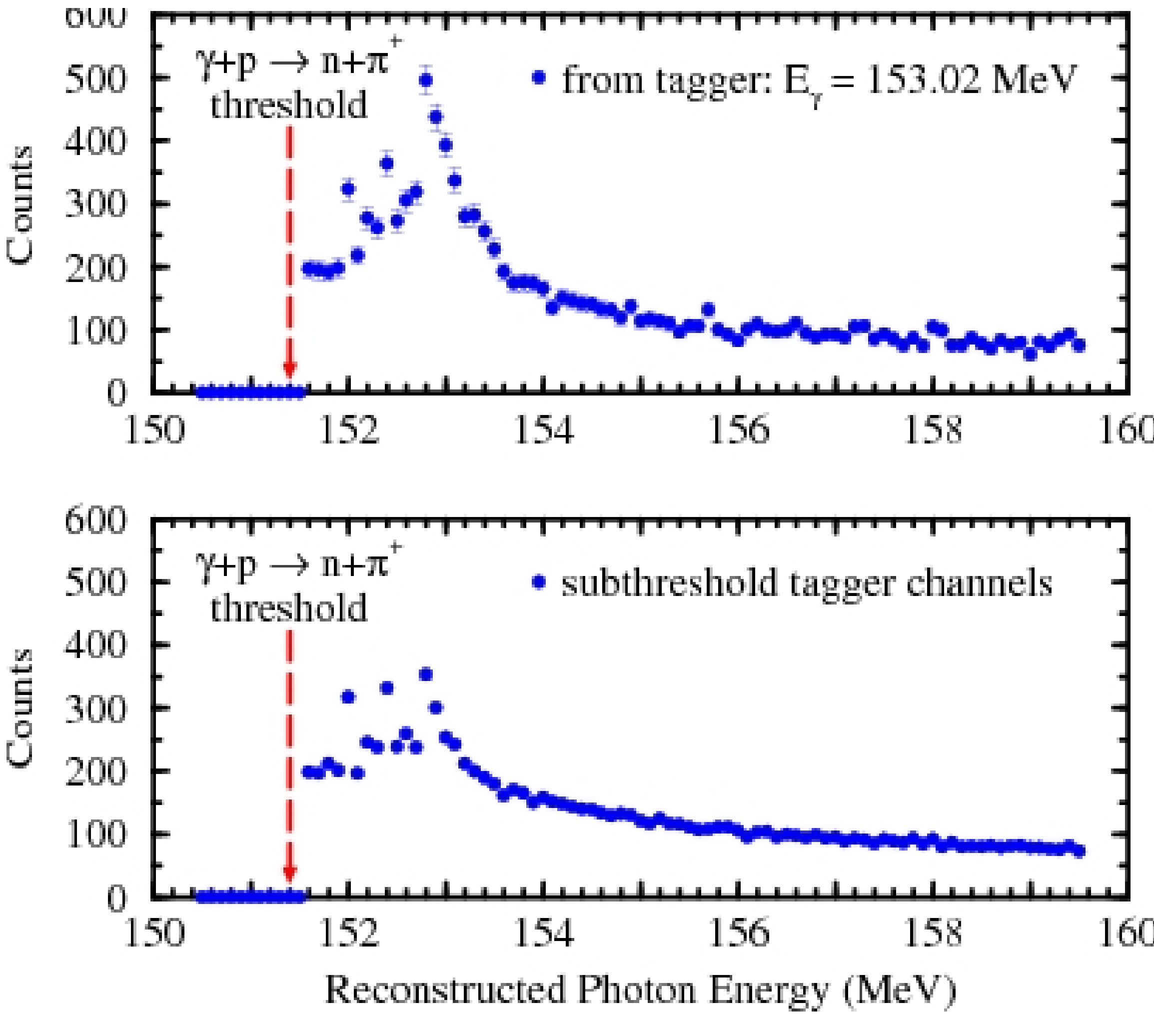
TOF for neutrons from $\gamma + p \rightarrow n + \pi^+$

measurement at SAL was 70 – 110 ns



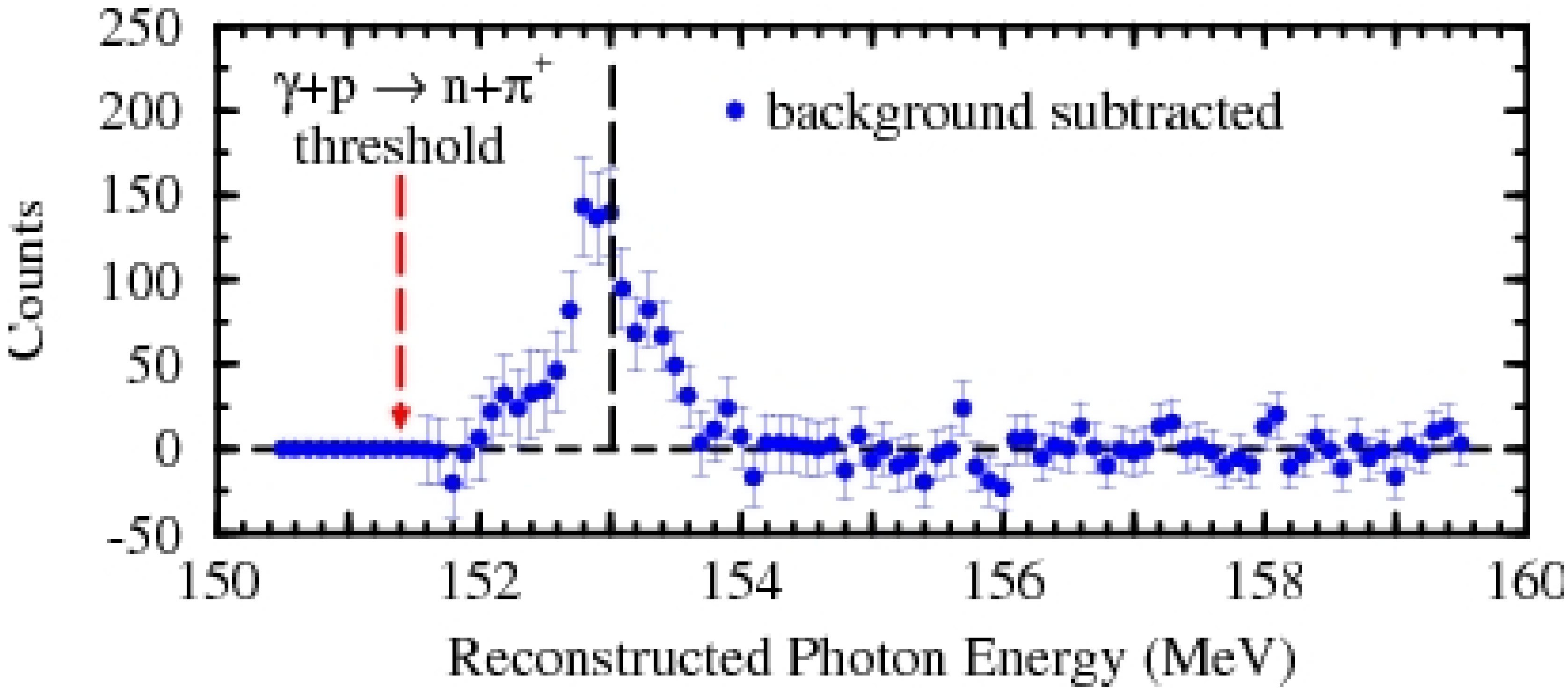
- **good timing resolution (~ 1 ns)**
- **large background**

background subtraction



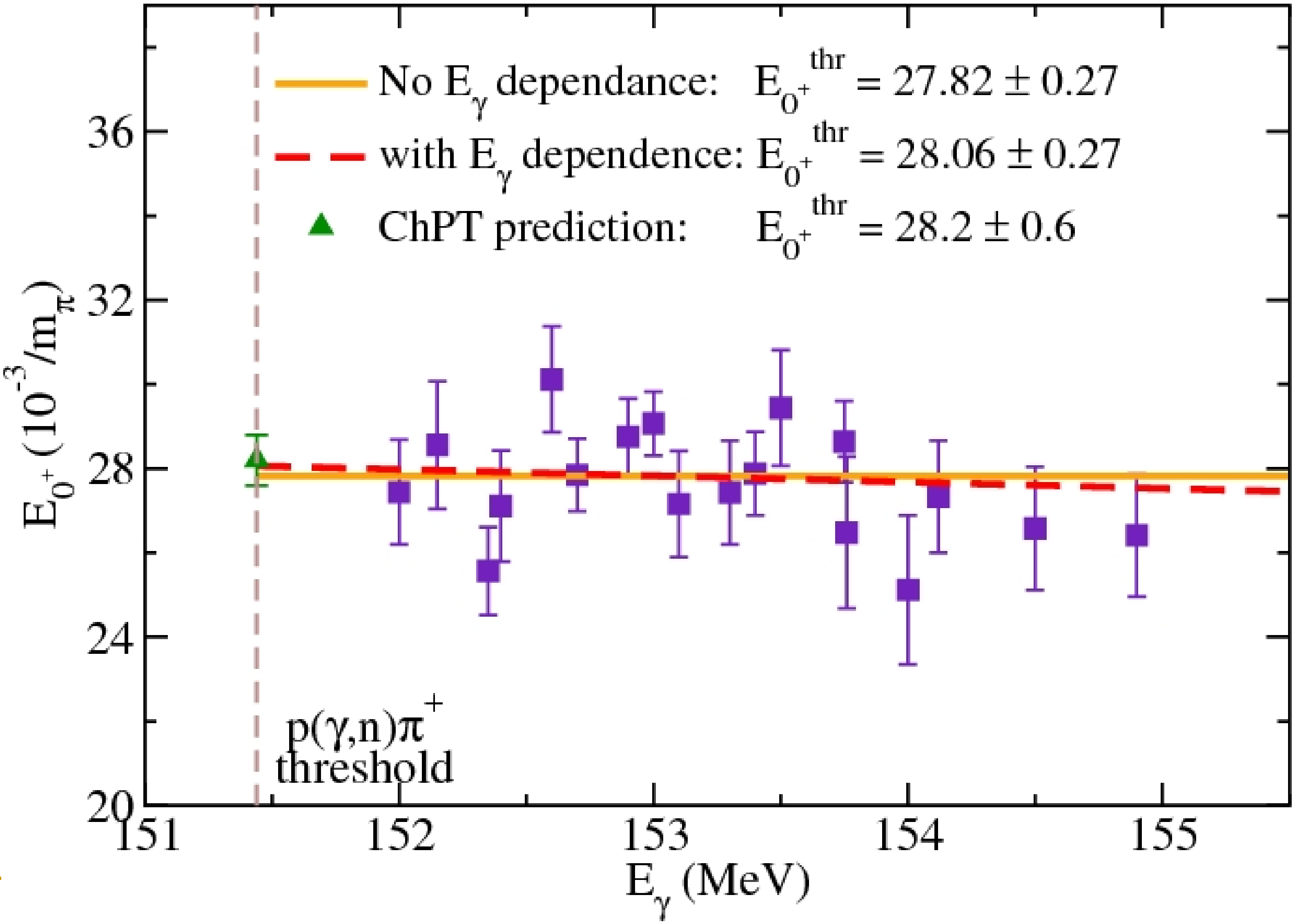
- Use E_n to calculate E_γ
- compare with E_γ from tagger
- "sub-threshold" channels for background subtraction

background subtraction

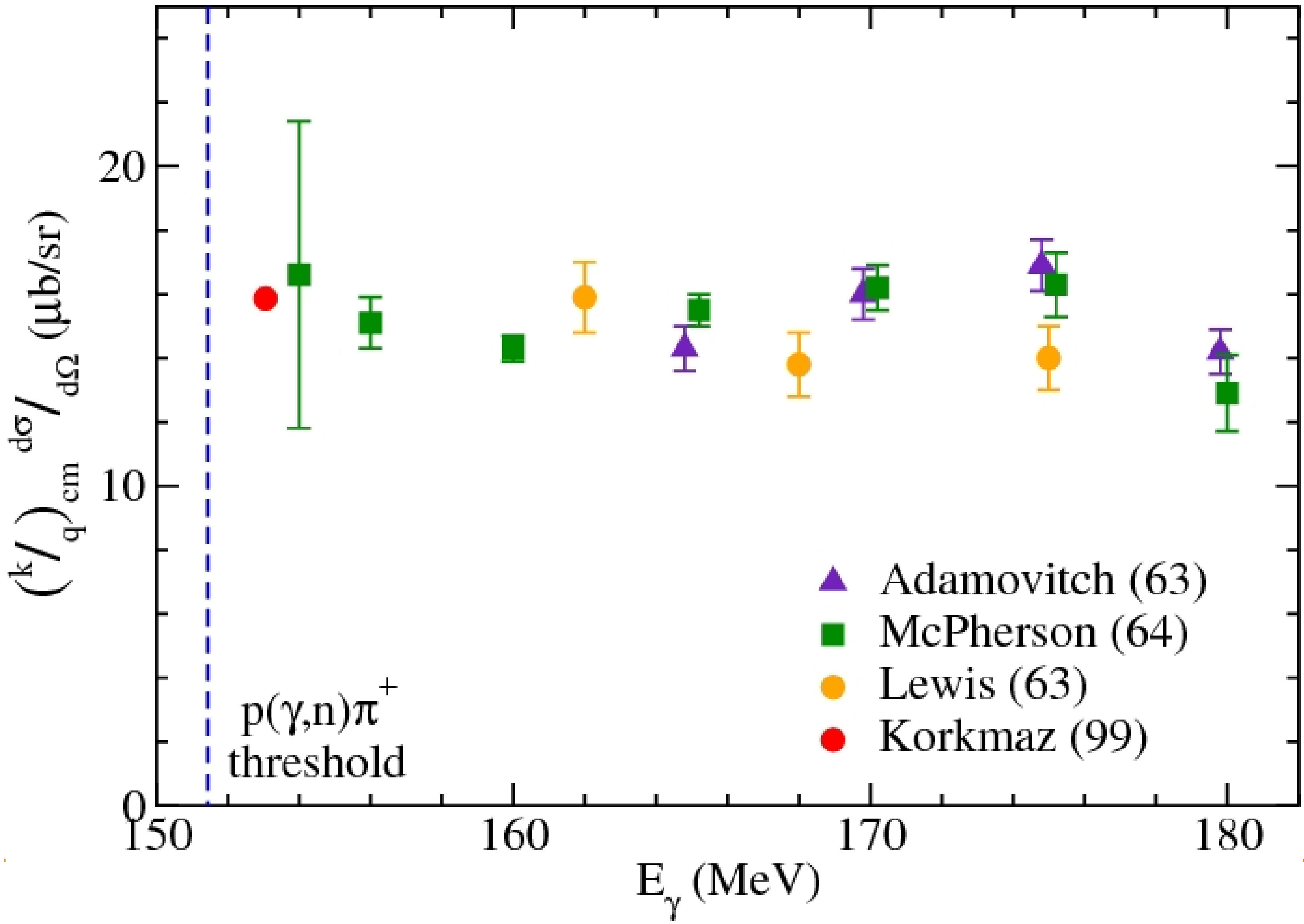


- **after subtraction**
  - **reconstructed energy agree with tagger value**
  - **events away from peak – flat and consistent with zero**

Final Results



Final Results



ChPT and the s-wave term

- the ChPT predictions for the E_{0+} amplitude are in good agreement with the experimental measurements.

- for $\gamma + p \rightarrow p + \pi^{o}$ (from Mainz & SAL)
- for $\gamma + p \rightarrow n + \pi^{+}$ (from SAL measurement)

beyond the s-wave ….

- above threshold, the p-wave contributions quickly begin to dominate

- measurements of the differential cross sections provides information about the p-wave contributions

beyond the s-wave ….

- explicitly including the p-wave terms, the differential cross section can be expressed as:

$$\frac{d\sigma}{d\Omega} = \left(\frac{q}{k}\right)\left[A(E_\pi) + B(E_\pi)\cos(\theta) + C(E_\pi)\cos^2(\theta)\right]$$

- the parameters A, B and C are related to the E_{0+}, E_{1+}, M_{1+}, and M_{1-} multipoles

beyond the s-wave ….

- fitting the three energy-dependent parameters $A(E_\pi)$, $B(E_\pi)$ and $C(E_\pi)$ to the differential cross sections
  - gives 3 bi-linear combinations of the 4 low-energy multipoles E_{0+}, E_{1+}, M_{1+}, and M_{1-}

- to reliably determine A, B and C requires high-quality measurements which cover a large energy and angle range

neutral channel: $\gamma + p \rightarrow p + \pi^o$

- **experiment** (Mainz and SAL)
  - nearly 1200 data points for $E_\gamma < 200$ MeV
    - cover large energy and angular range
    - good agreement between different experiments

- **theory**
  - s- and p-wave multipoles to NLO; $O(p^4)$

good agreement between theory and experiment for the s- and p-waves

charged channels: $\gamma + p \rightarrow n + \pi^{+}$ $\gamma + n \rightarrow p + \pi^{-}$

- **experiment**
  - one recent measurement on each channel
    - < 50 data points on each
    - sparse energy and angular coverage

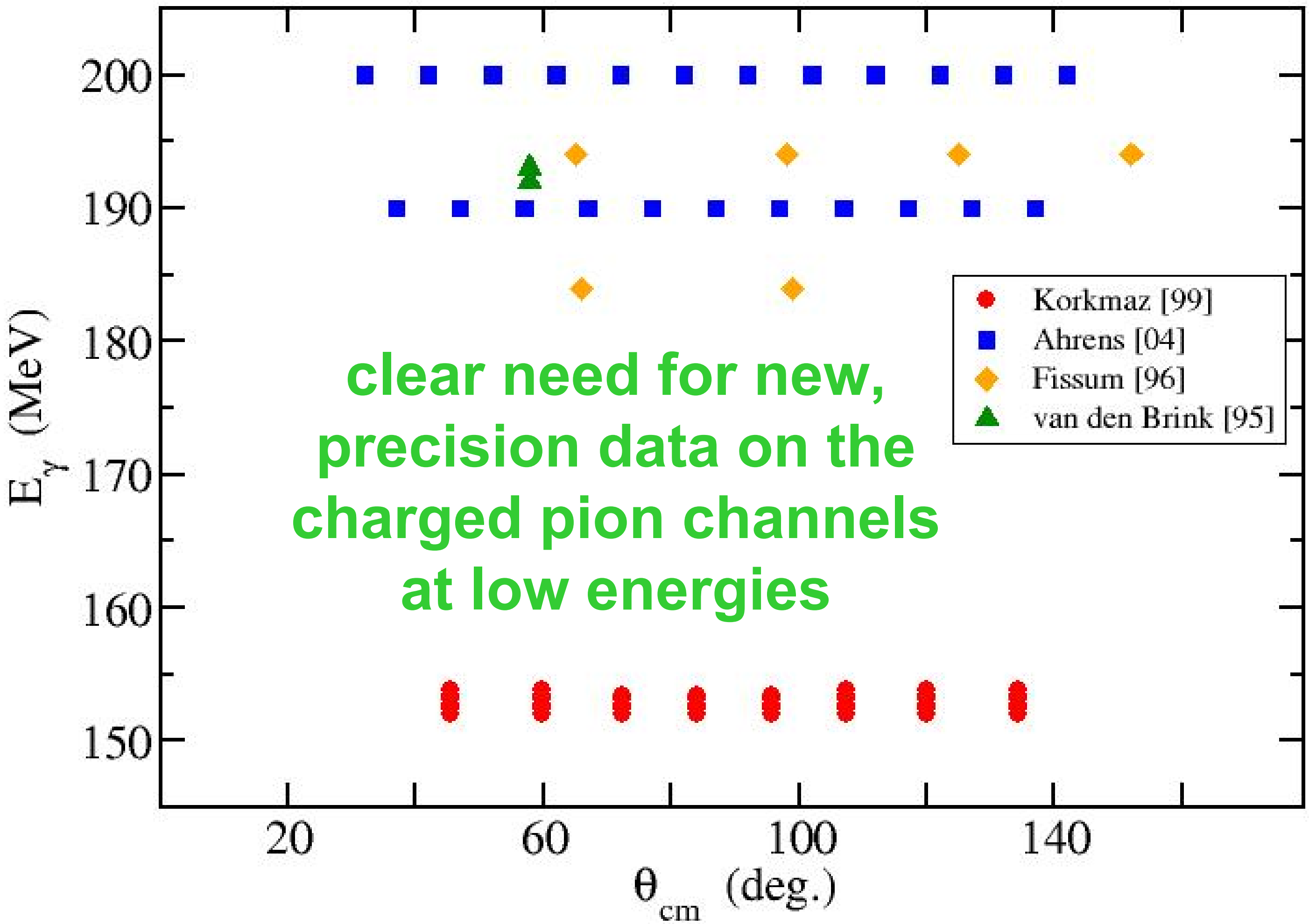
- **theory**
  - ChPT calculations are more difficult
  - only done to leading order; $O(p^3)$

beyond the s-wave ….

- precise measurements of p-wave contributions to $\gamma + p \rightarrow n + \pi^+$ will test these higher-order terms in ChPT

- suitable data sets do not exist for charged pion photoproduction
  - existing data is very close to threshold or at E_γ > 180 MeV

existing data for $\gamma + p \rightarrow n + \pi^+$



Pion program @ MAX-lab

MAX-lab PAC approved 2 experiments

- NP-014
  - (γ,π^+) differential cross sections up to 200 MeV
  - detect outgoing π^+ in scintillator counters
- NP-017
  - (γ,π^-) absolute cross sections near threshold
  - detect 140 MeV γ from π^- capture in LD_2 target

beyond the s-wave ….

- ChPT calculations for $\gamma + p \rightarrow n + \pi^+$ are different than for $\gamma + p \rightarrow p + \pi^o$
  - different structure functions are involved
  - one-loop contributions differ
  - role of counter-terms different

- **it is important to determine the p-wave contributions to $\gamma + p \rightarrow n + \pi^+$**

- **complements work on the neutral channel**

(γ,π^+) program @ MAX-lab

- **MAX-lab program**
  - solid targets (CH_2, C, CD_2)
  - plastic scintillator telescopes at various angles

- straight-forward measurements
  - simple target and detectors
  - well understood pion ID and efficiencies
  - standard analysis methods

(γ,π^+) program @ MAX-lab

- xSAL group: ΔE + monolithic E counters
  - counters at 50° and 90°

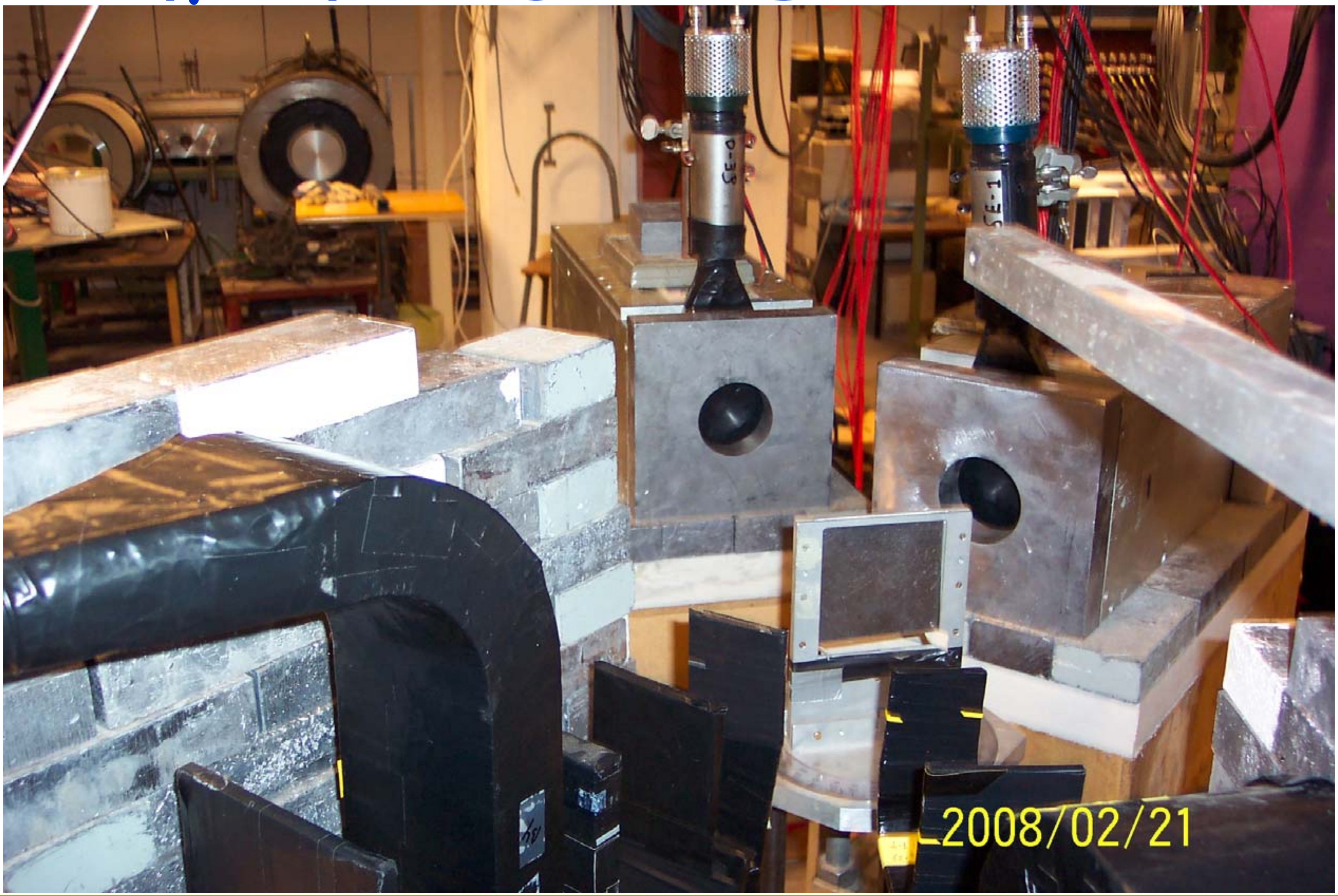
- RANGE group multiple ΔE-E layers
  - counters at 90° and 130°

- two independent groups
  - different detector systems and analyses
  - gives cross-check on results

(γ,π^+) with the xSAL counters

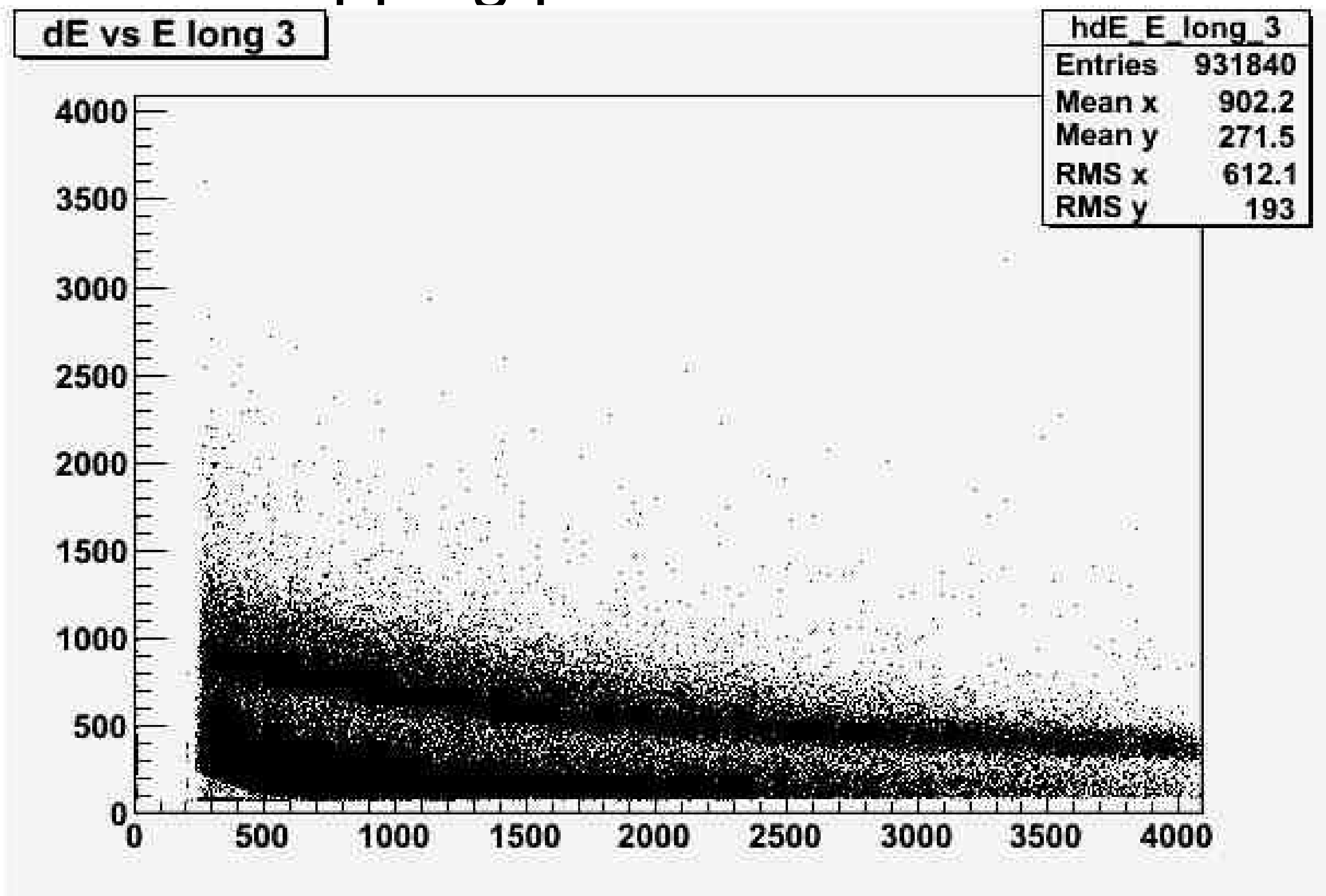
- <u>trigger</u>
  - ΔE-E coincidence
  - Σ-threshold (ΔE+E)
    (to eliminate background electron events)
- <u>data acquisition</u>
  - long- and short-gate ADC
    - look for $\pi\rightarrow\mu$ decay in long-gate ADC
  - TDC started by “delayed” E-signal
    - look at time distribution for $\pi\rightarrow\mu$ candidate events

(γ,π^+) program @ MAX-lab



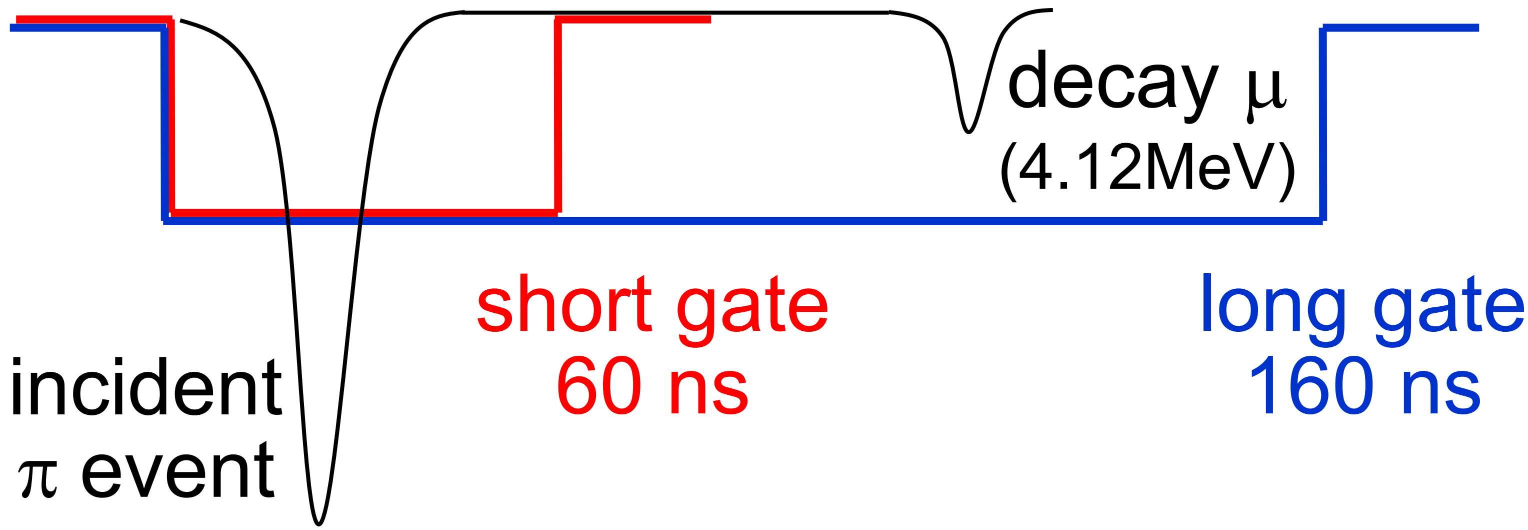
π identification

- ΔE vs E stopping power



π identification

- $\pi \rightarrow \mu$ decay



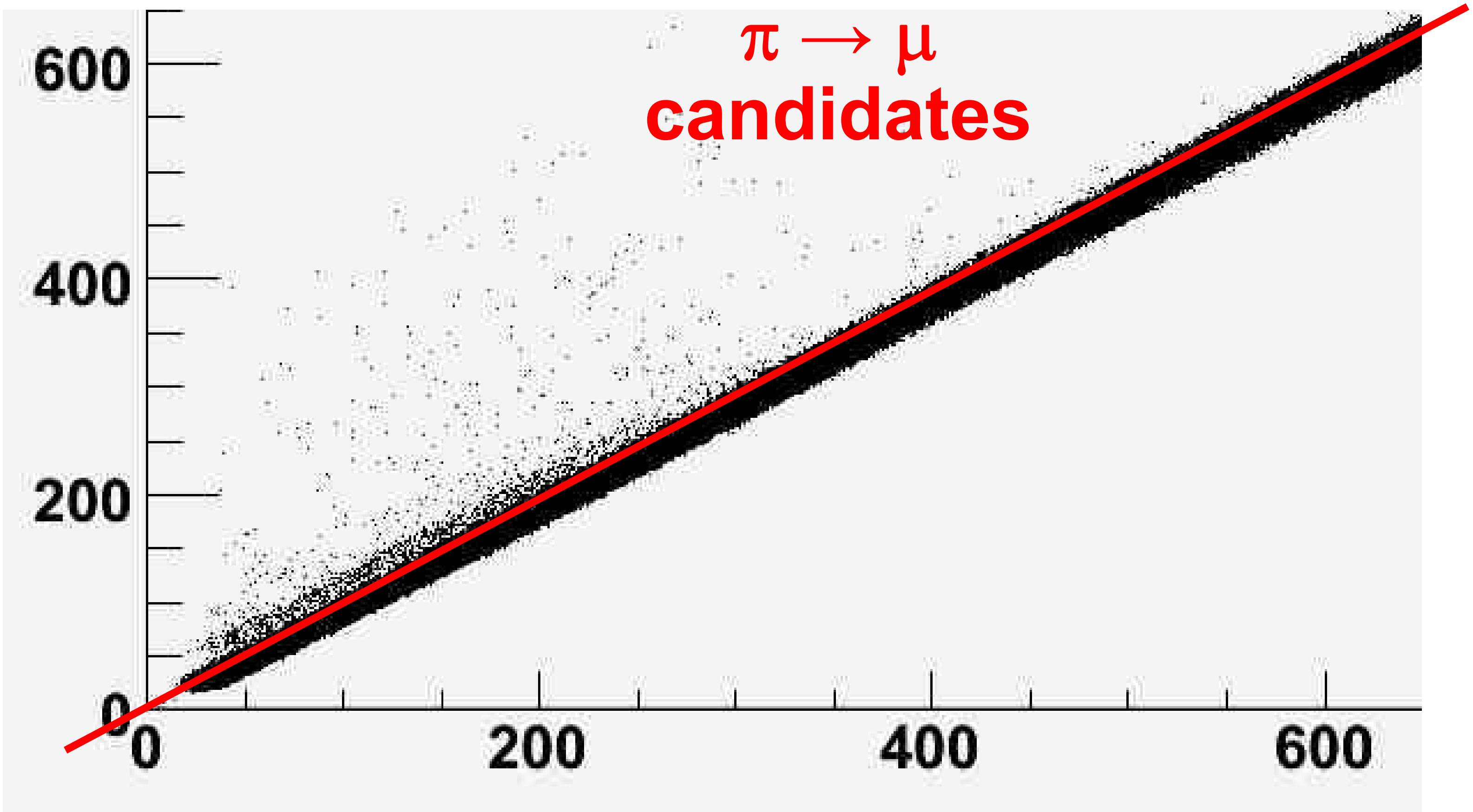
non- π events -- same energy in long/short gates

π events -- +4.12 MeV in long gate

plot of long vs. short will show offset for π events

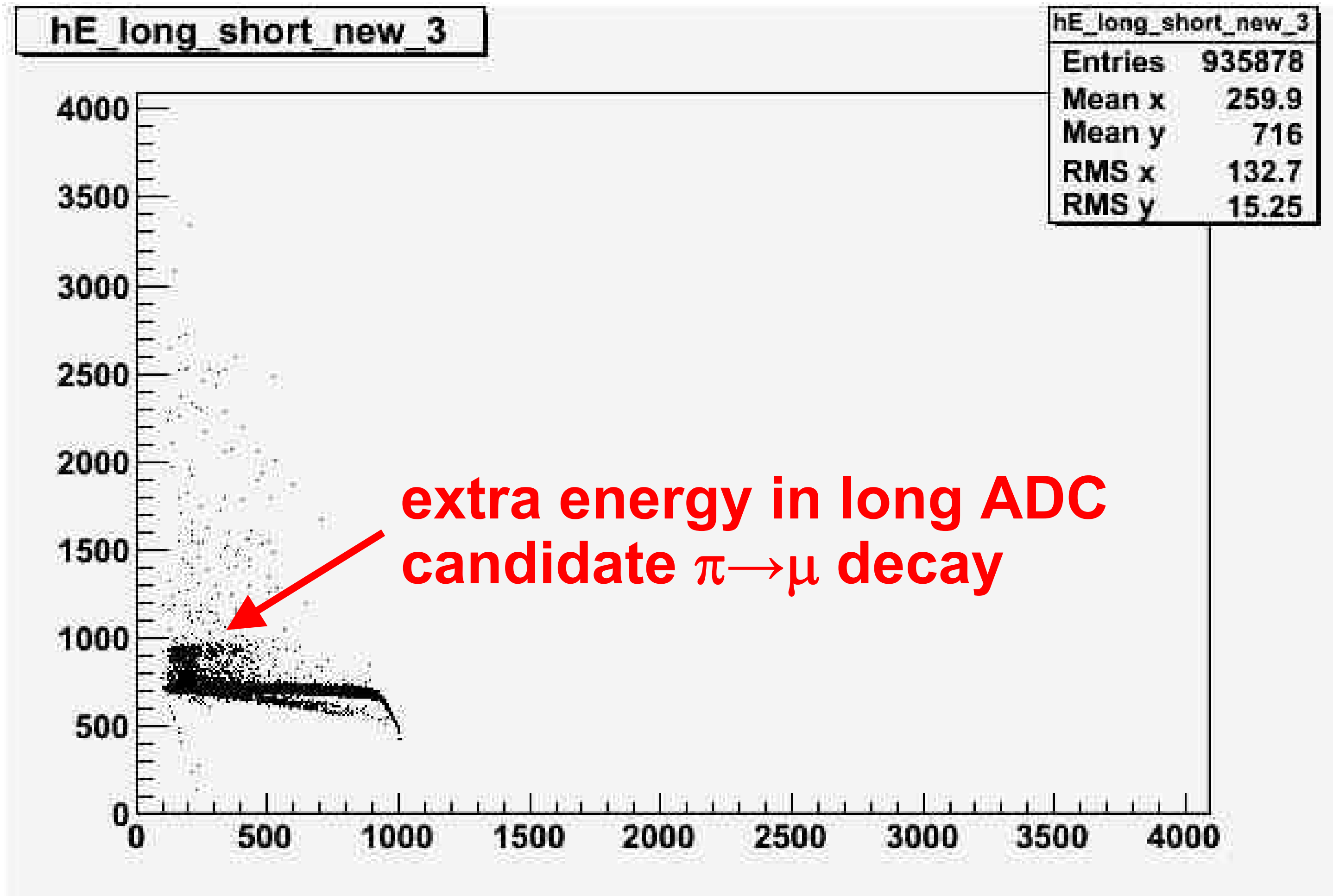
π identification

- $\pi \rightarrow \mu$ decays now seen



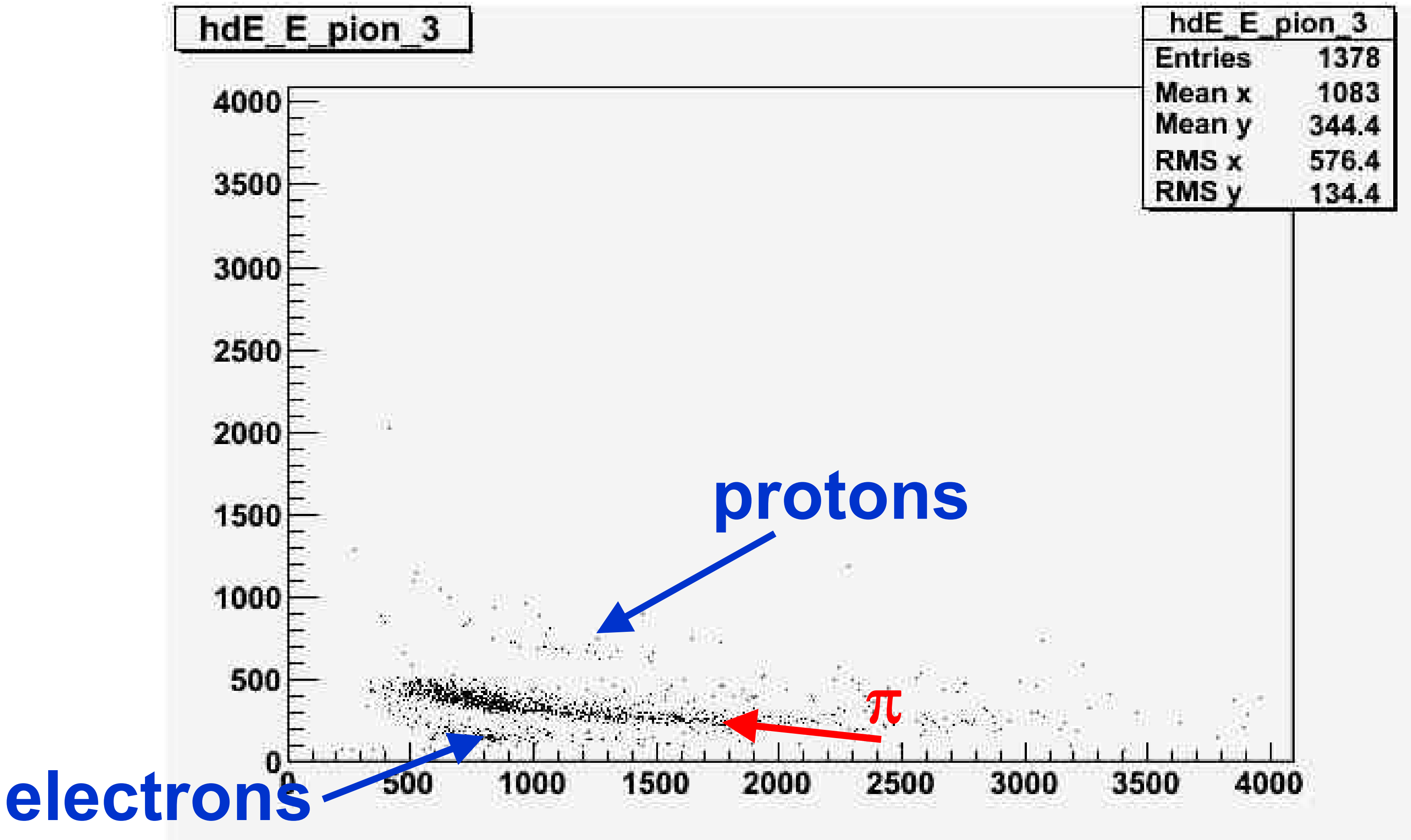
π identification

- look for the π→μ decay



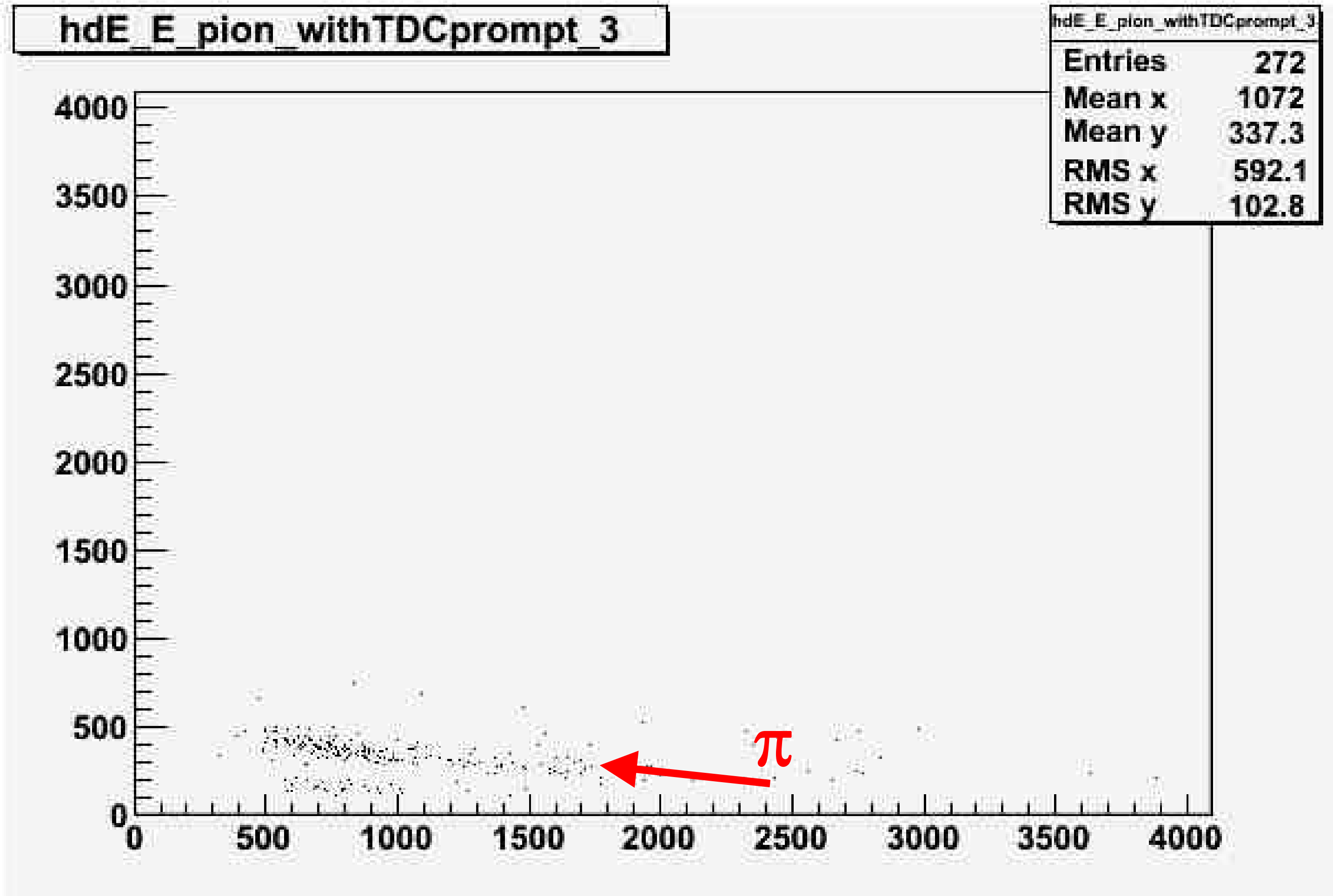
π identification

- select π→μ candidates



π identification

- ΔE vs E with tagger prompt cut



analysis – the next step

- pion identification looks good
  - need to optimize the particle ID cut
  - iterate using ΔE vs. E and long vs. short
  - need to determine fraction of pions lost by this particle ID cut
  - difficult to determine π detection efficiency with the long/short ADC method

analysis – the next step

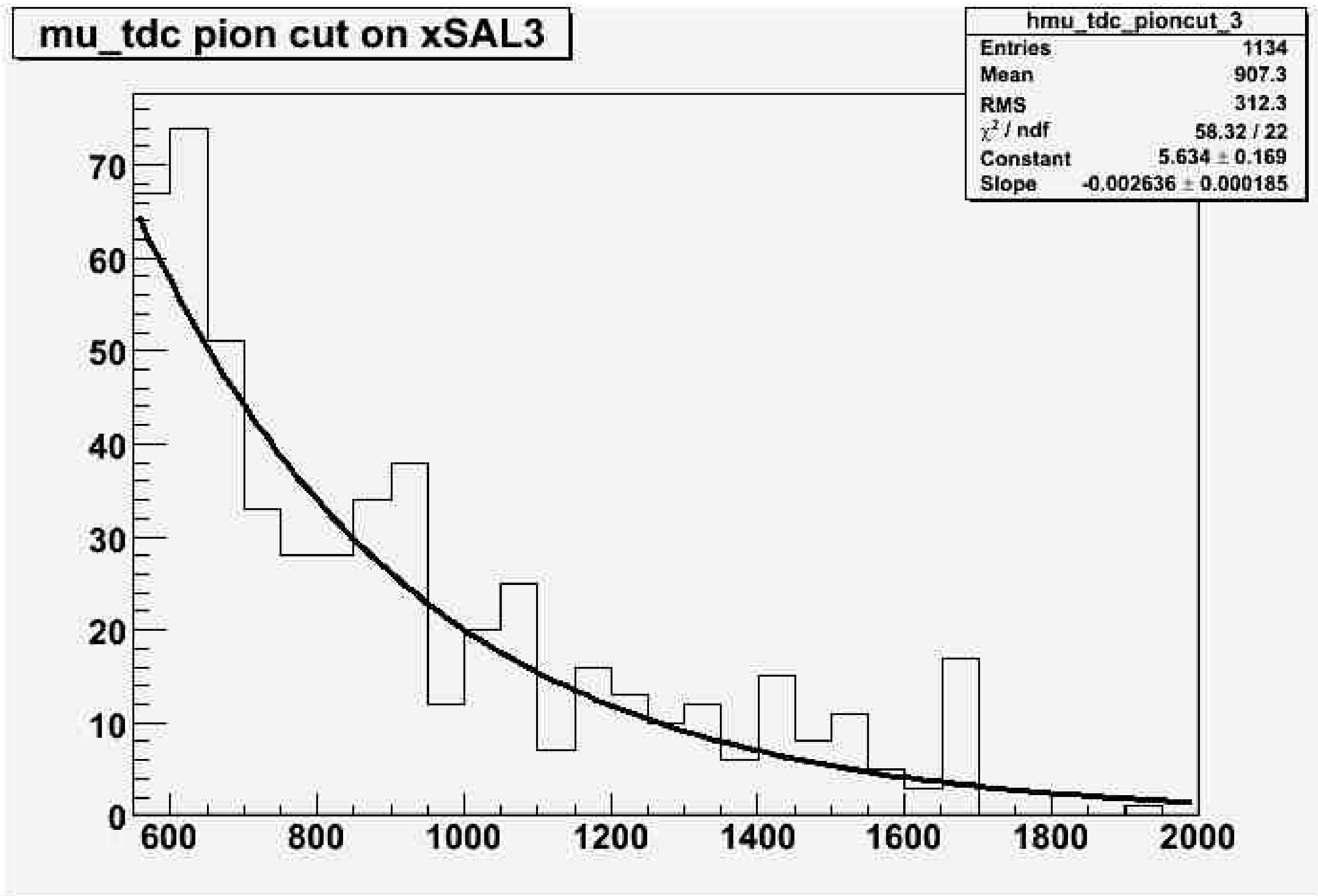
- pion detection efficiency

- use muon TDC
  - started by "pion" event in E counter
  - stopped by "muon" event in E counter
  - should see 25 ns lifetime of $\pi \to \mu$ decay

  - determine efficiency from time range used for event analysis

π identification

- muon TDC – shows 26 ns pion decay constant



(γ,π^+) program @ MAX-lab

- development work in 2006, 2008
  - new counters
  - checked pion identification methods
  - understand tagging efficiency, etc

- 4-weeks production run – underway
  - seeing pion events
  - running with CH_2, C (background subtraction)
  - $\gamma + p \rightarrow n + \pi^+$ angular distributions later this year

(γ,π^+) program @ MAX-lab

anticipated energy/angular coverage