Feasibility Study of Λd Elastic Scattering in Data From Photoproduction Off Deuteron

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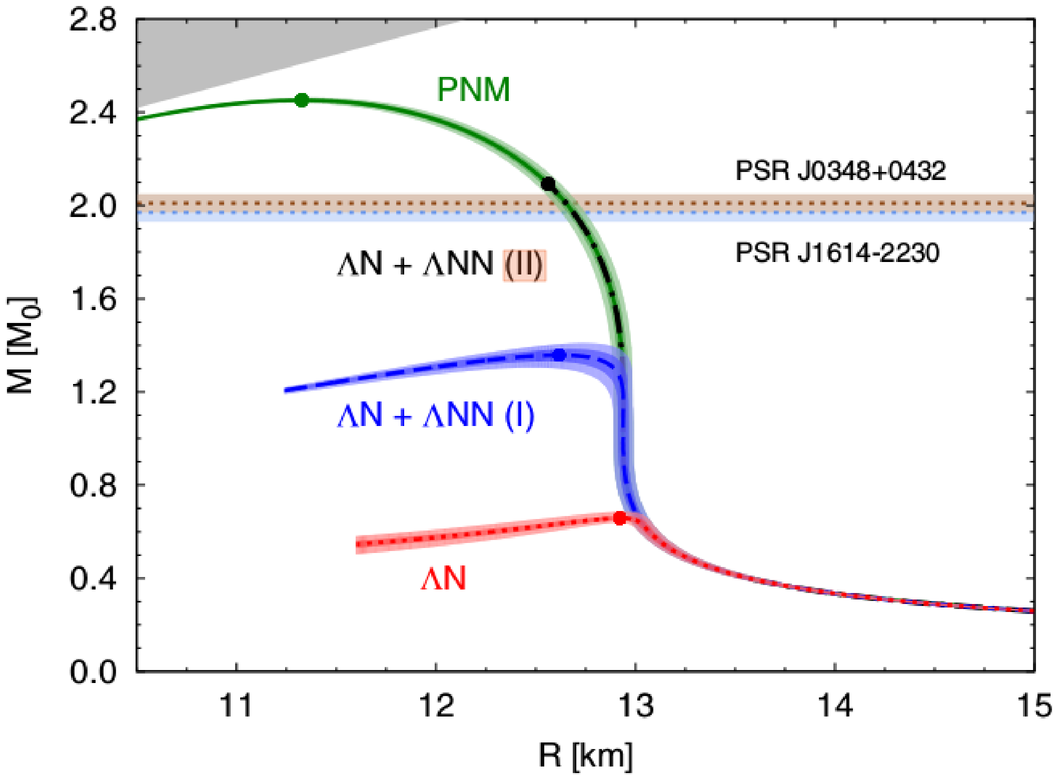
Introduction

- **Goal**: investigate feasibility of extracting Λd elastic signal from photoproduction off deuteron (g13a data)
- **Motivation**: provide novel hyperon-nucleon-nucleon (YNN) scattering data for the study of YN interaction
- **Hyperon Puzzle**: "… the difficulty to reconcile the measured masses of neutron stars (NSs) with the presence of hyperons in their interiors …" (Bombaci, 2016)

Introduction

- NS equations of state not consistent with NS mass measurements of ~2M_{sun}
  - NN, NNN, YN forces included
  - YNN 3-body contribution needs improvement
  - Need more YN interaction constraints to improve YNN 3-body contribution
- Hypernuclear spectroscopy provides YN interaction constraints
  - Nuclear medium effects limit constraint determinations
- YN scattering is cleanest method to constrain constants in potentials
  - No nuclear medium effects → bare YN interaction
  - Existing YN scattering data limited due to short hyperon lifetimes
  - No YNN scattering data exist

NS Mass vs. Radius



[Lonardoni et al., 2015]

Introduction

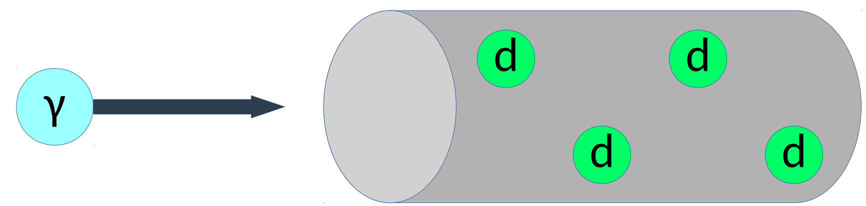
- Want to investigate feasibility of analyzing Λd elastic scattering to supply YNN scattering data

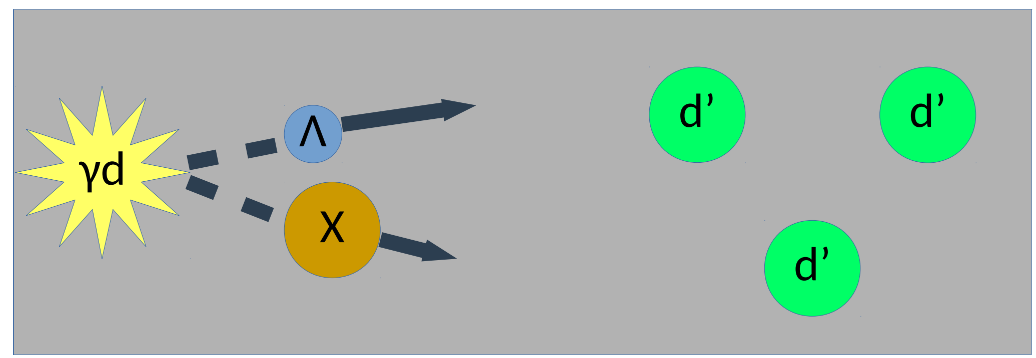
- How do we look for Λd elastic scattering?
  - Produce hyperons (Λ) off target (deuteron), which scatter off other target (deuteron) in same target cell
  - Done in:
    - Λp elastic scattering at JLab (CLAS g11) [Price, 2019 and Rowley, Ongoing PhD]
    - $\Sigma^{\pm}$p elastic scattering at J-PARC [Yoshiyuki Nakada et al., 2019]

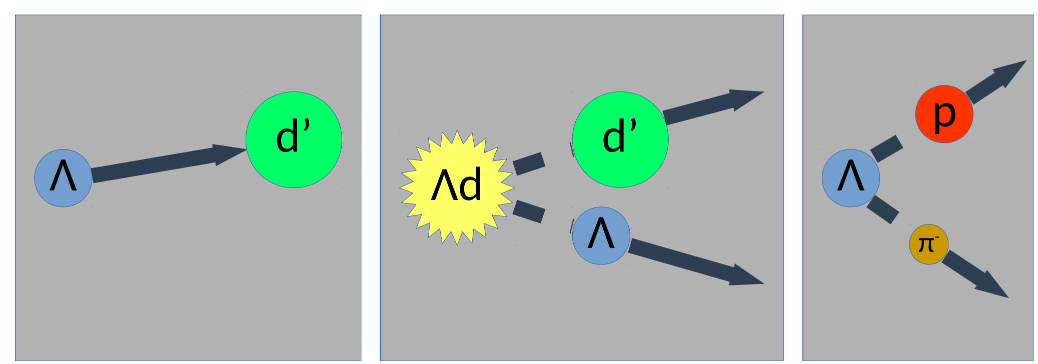
- Method requires two sequential nuclear reactions
  - Need very high luminosity experiment – g13 had very high statistics (50 bn triggers)
  - Need detector with large acceptance – CLAS has large acceptance for charged particles (~2.8π solid angle coverage)
  - Reaction process: $\gamma d \rightarrow X\Lambda$, $\Lambda d' \rightarrow \Lambda d'$, $\Lambda \rightarrow p\pi^-$

Analysis: Concept

- Interested in Λd elastic scattering:
  - γ d→X Λ
  - Λ d’ → Λ d’
  - Λ decays into p π^-
- Final particles detected:
  - d’, p, π^-
  - possibly others (due to X)
- Reconstruct scattered Λ and beam Λ







Analysis: Overview

- Particle Identification (PID, based on time-of-flight technique)
  - Initial PID → reconstructed mass (skimming)
    - Require at least one d,p,π^-; no constraint on other charged/neutral particles
  - Refined PID → particle speed
    - Require exactly one d,p,π^-; no constraint on other charged/neutral particles

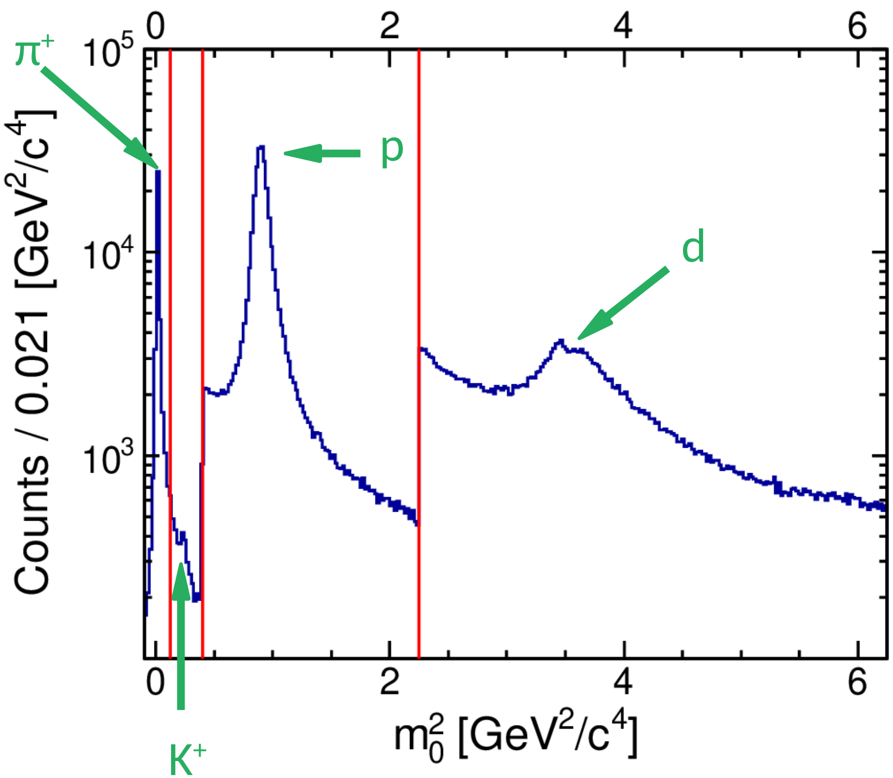
- PID Verification (dE technique)
  - Noisy TOF paddles
  - Accidental Background Reduction: $\gamma d \rightarrow pp\pi^-$

- Reaction Selection: $\Lambda d \rightarrow \Lambda d$
  - Scattered Λ reconstruction
  - "Beam" Λ reconstruction

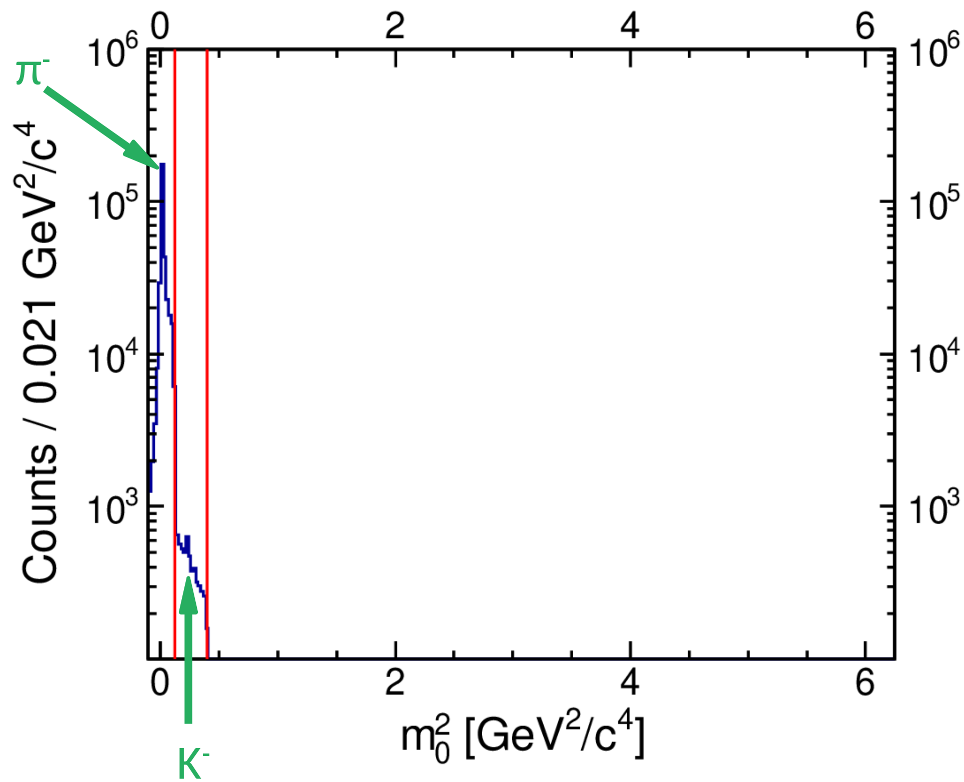
Initial Particle Identification

- $m_0^2 = p^2(1-\beta^2)/\beta^2$; β = Speed = $L/c\Delta t$; p = momentum = qB/r

m_0^2 for positively-charged particles



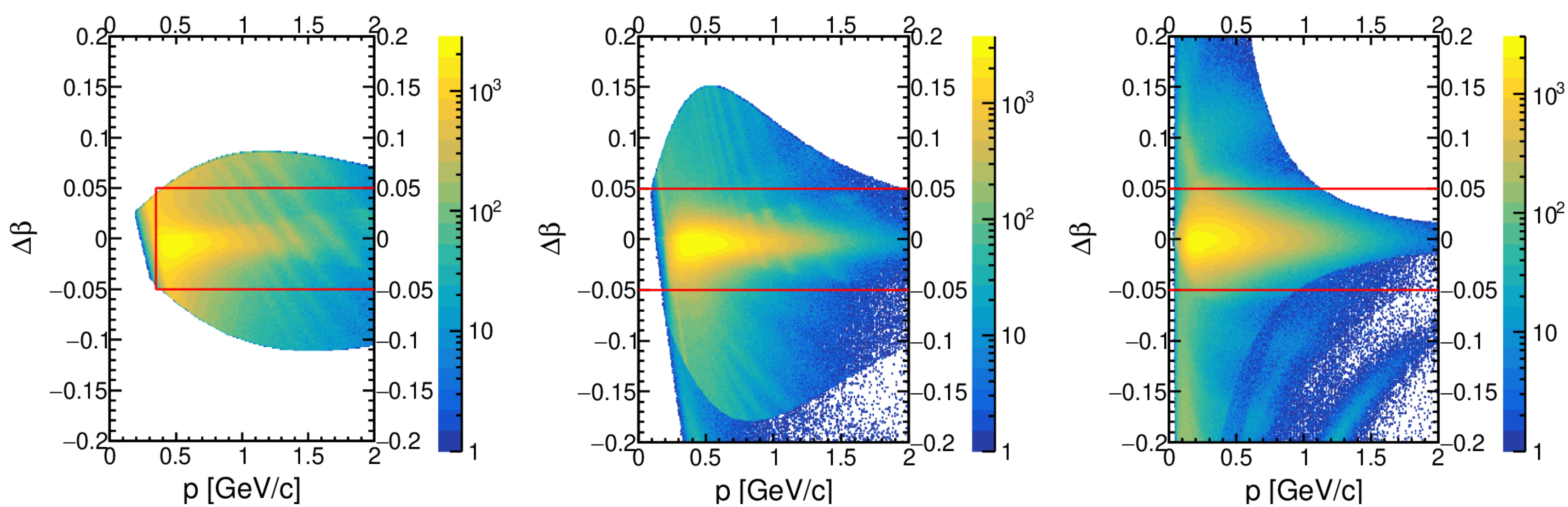
m_0^2 for negatively-charged particles



Refined Particle Identification

- $\beta_{meas} = L/c\Delta t$
- $\beta_{calc} = p/\sqrt{(p^2 + m^2)}$
  - m: mass hypothesis
- $\Delta\beta = \beta_{meas} - \beta_{calc}$
  - m → deuteron, proton, or pion mass

Δβ vs p

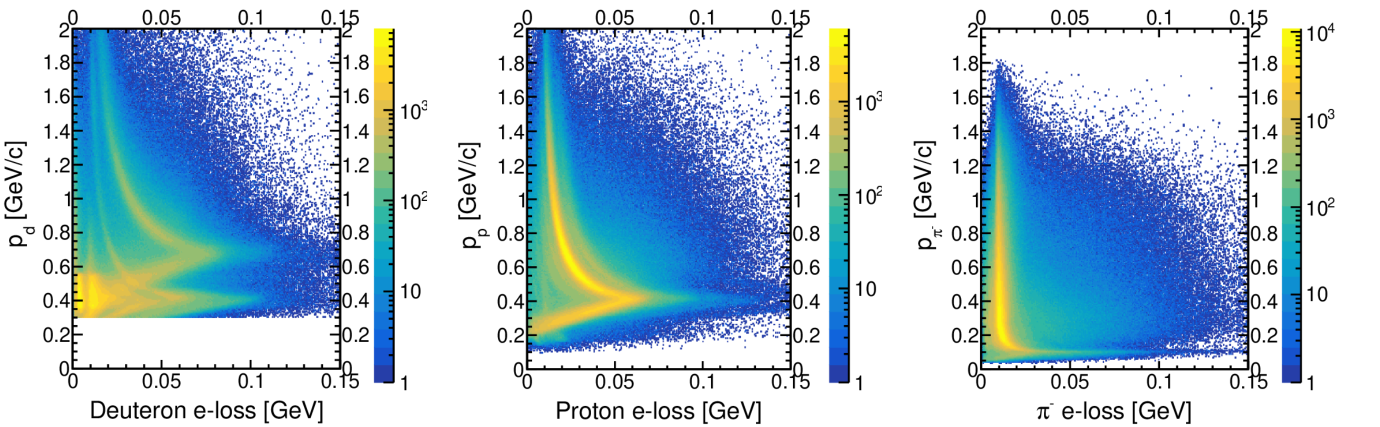


Event distribution of Δβ vs. p for (**left**) deuterons, (**middle**) protons, and (**right**) π^-

PID Verification

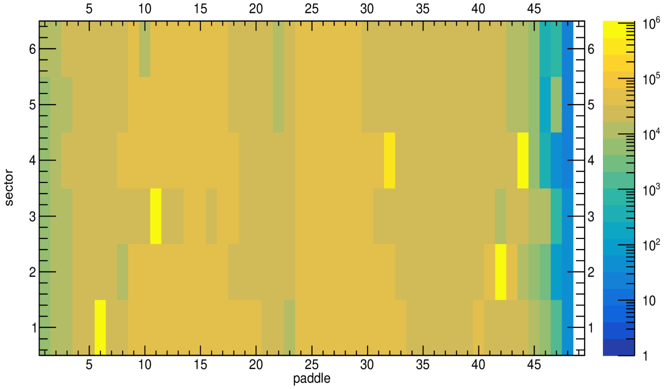
- e-loss: charged-particle energy deposition in TOF scintillators
- Deuteron sample: unphysical signature → problems with deuteron e-loss determinations → noisy TOF paddles for deuteron tracks

Particle momentum vs. energy deposition



Event distribution of momentum vs. e-loss for (**left**) deuteron tracks, (**middle**) proton tracks, and (**right**) pion tracks.

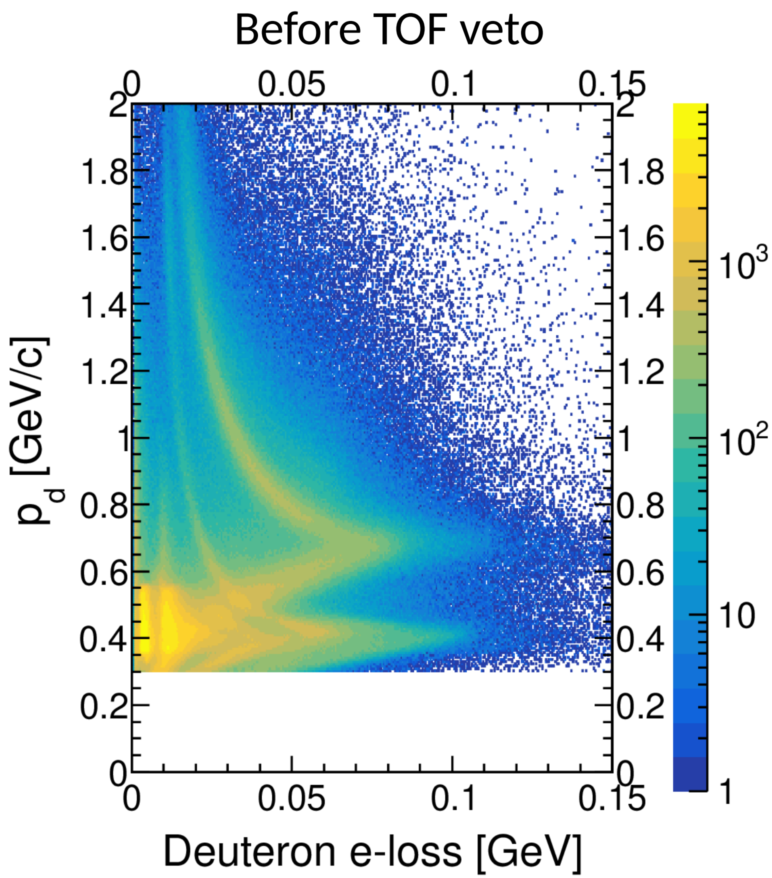
Deuteron sector vs. paddle

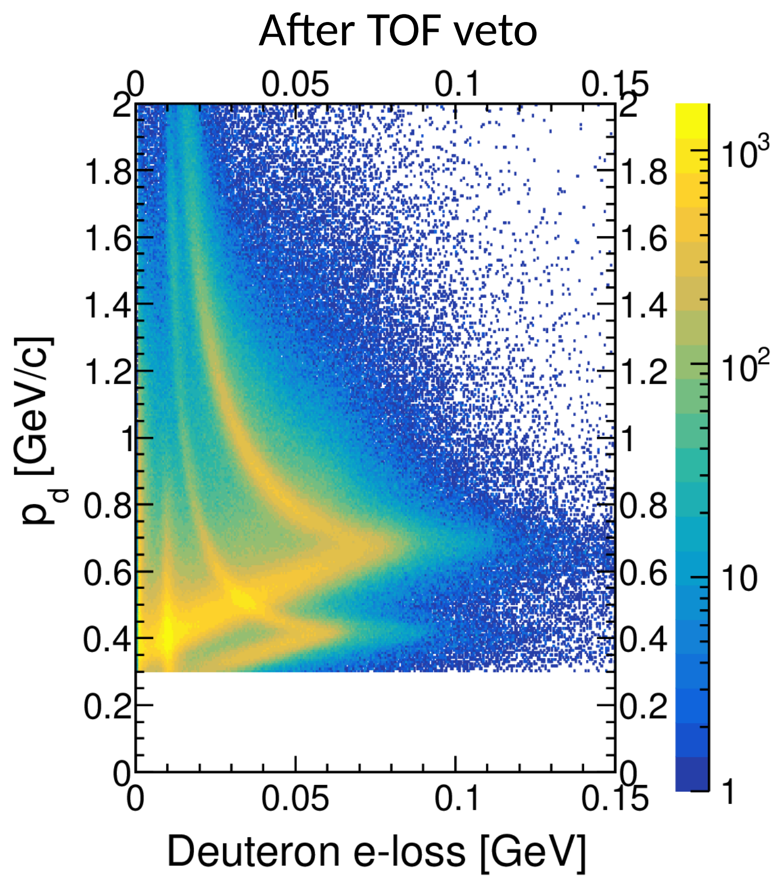


Event distribution over TOF sector and paddle number of deuteron tracks.

PID Verification

- Veto of TOF paddle noise in deuteron tracks removes unphysical signature





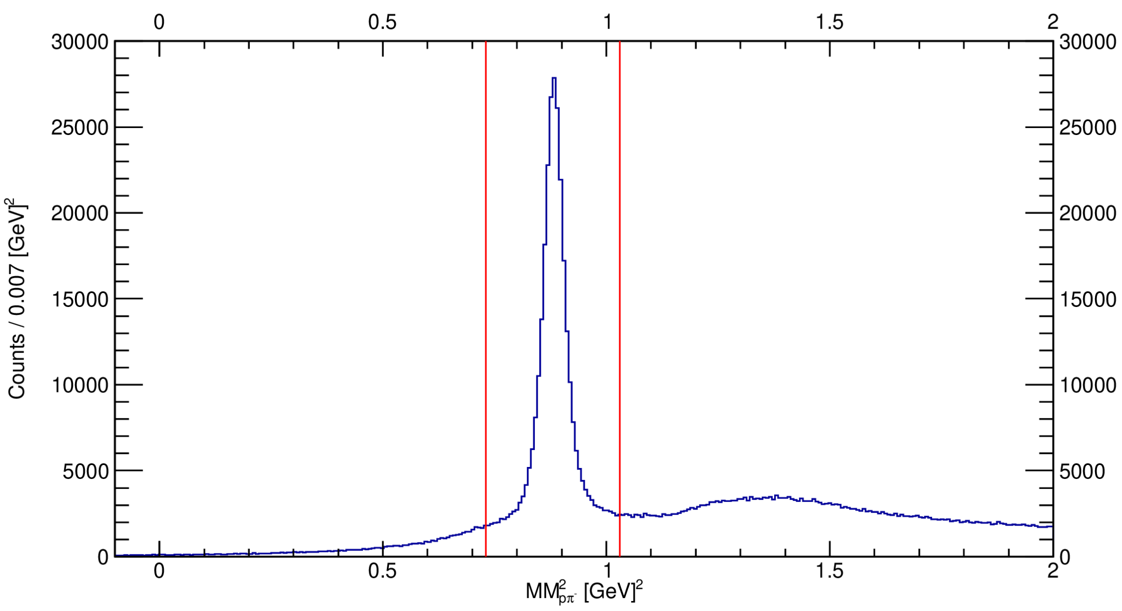
PID Verification

- What about the protons in the deuteron track?
  - Proton signature: accidental protons from $\gamma d \rightarrow pp\pi^-$

- What about the pions in the deuteron track?
  - Not reduced in this study
  - Not dominant after Λd elastic scattering event selection

Accidental Background Reduction

- $MM^2_{p\pi} = [P_\gamma + (m_d,\mathbf{0}) - P_p - P_{\pi-}]^2$, using true proton track
- Veto events with $MM^2_{p\pi}$ within $m_p^{\ 2} \pm 0.15$ GeV^2/c^4

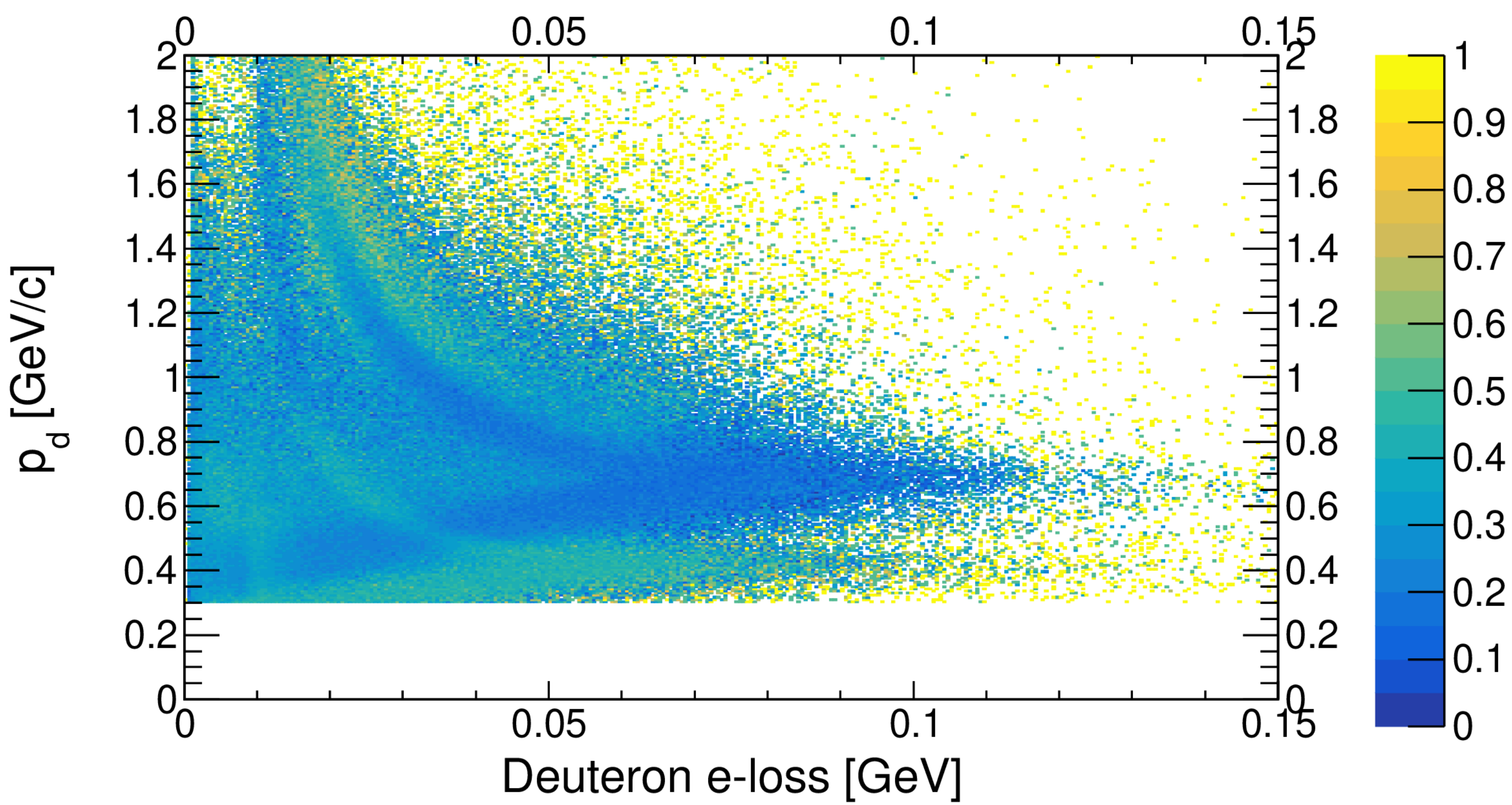


Event distribution of $MM^2_{p\pi}$ with red lines showing the cuts used in the analysis.

Accidental Background Reduction

- ~ 900,000 events removed
- Proton signature remains, but is not dominant after Λd elastic scattering event selection

Fraction of Events removed by $MM^2_{p\pi}$ cuts



Reaction Selection

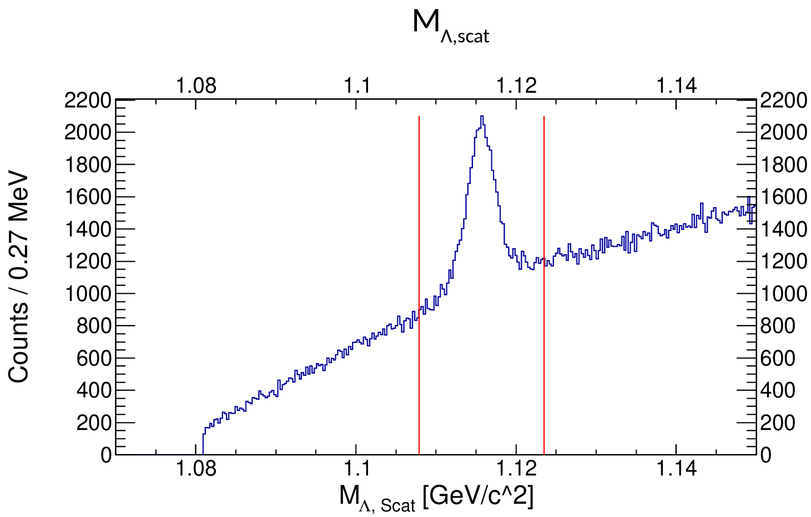
- How do we know $dp\pi^-$ measured final state came from Λd elastic?

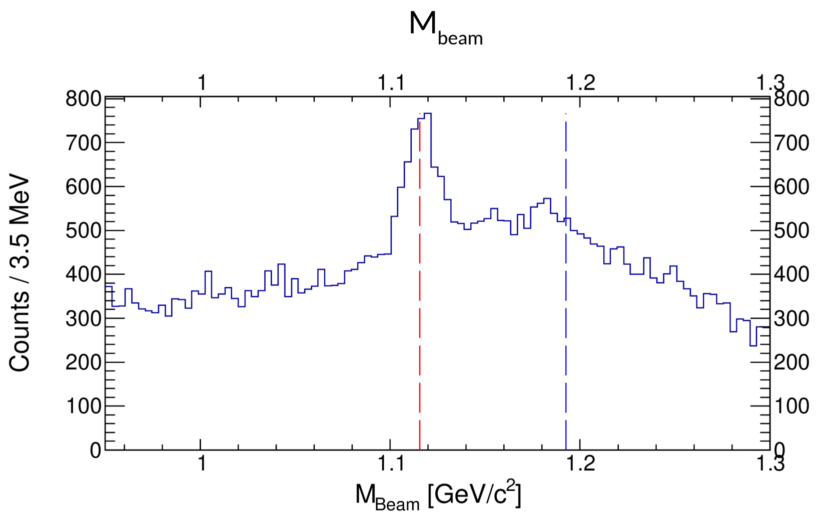
  Definitions:

  – $P_{\Lambda\text{-scat}} = P_p + P_\pi$
  – $P_{d'} = (m_d, \mathbf{0}) \rightarrow$ secondary deuteron
  – $P_{beam} + P_{d'} = P_{\Lambda\text{-scat}} + P_{d\text{-meas}} \rightarrow P_{beam}$ can be determined

- Knowing $P_{\Lambda\text{-scat}}$ and P_{beam}, we determine Λd elastic events:

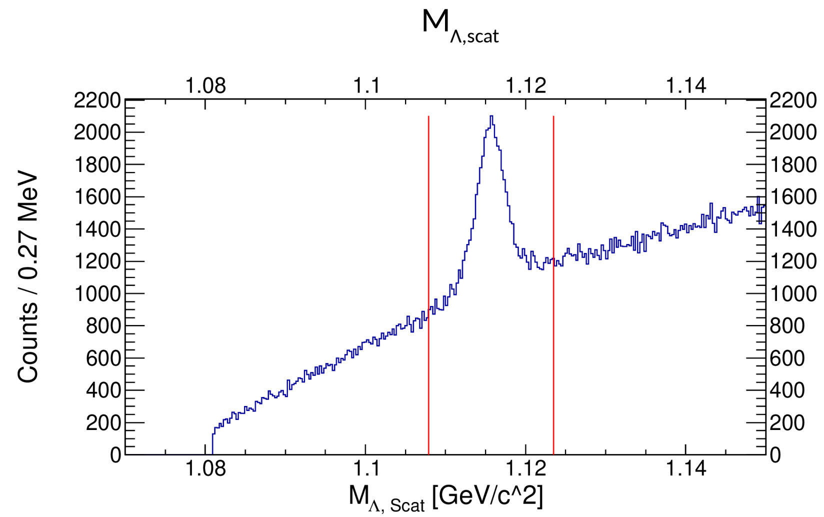
  – $m_\Lambda = 1.1157$ [GeV/c^2]
  – Look for enhancement at $M_{beam} = \sqrt{(P_{beam})^2} \approx m_\Lambda$
  – Look for enhancement at $M_{\Lambda,scat} = \sqrt{(P_{\Lambda\text{-scat}})^2} \approx m_\Lambda$
  – If both true, we have Λd elastic event

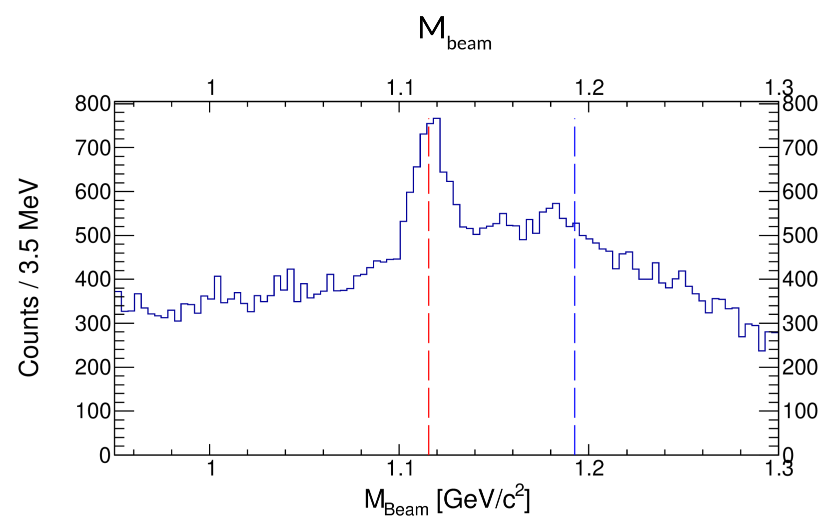




Results

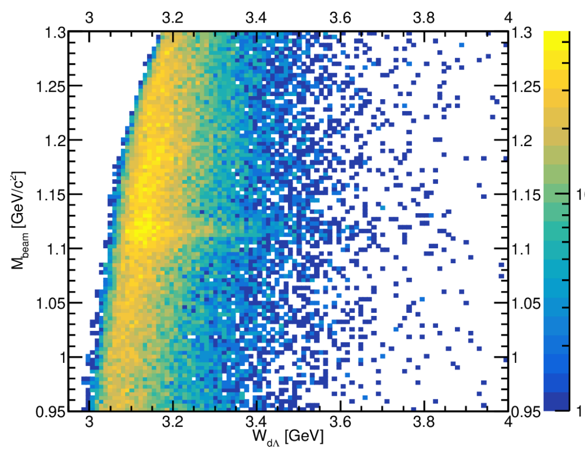
- Analysis performed on g13a subset of g13 data
  - ~ 2000 Λd elastic scattering events in g13a
  - ~ 4000 expected in all of g13
- Possible enhancement around Σ^0 mass in M_{beam}
  - m_Σ = 1.1926 GeV/c^2
  - May allow for $\Sigma^0 d \rightarrow \Lambda d$ reaction measurements

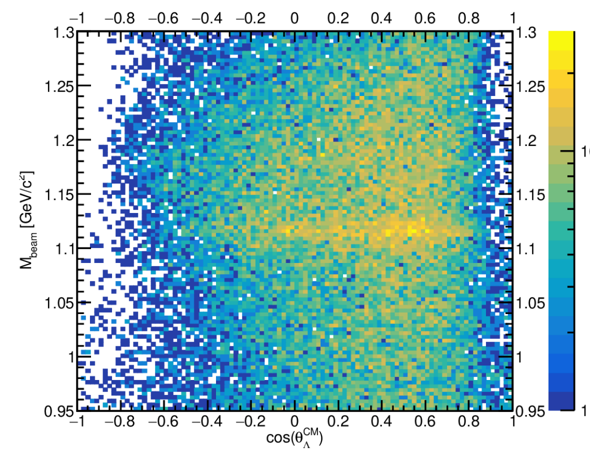




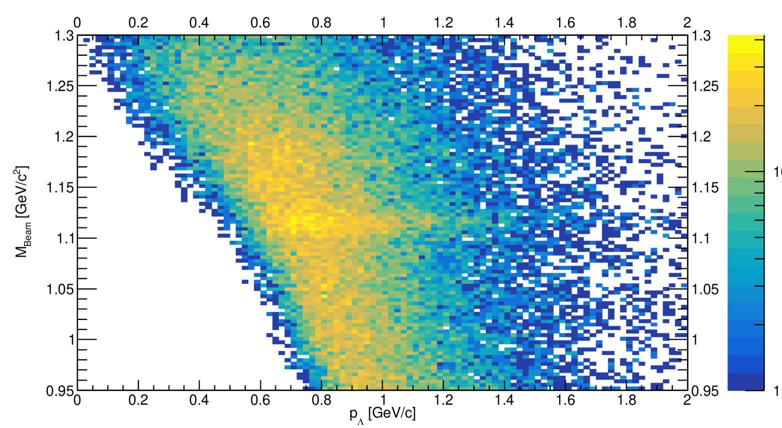
Results

- Can expect cross-sections determined in the regions:
  - p_Λ above 0.7 GeV/c
  - $\cos(\theta_\Lambda^{CM})$ between −0.6 and 0.9
  - $W_{d\Lambda}$ between 3 GeV^2 and 3.8 GeV^2





- $W_{d\Lambda} = \sqrt{s_{d\Lambda}}$
- $s_{d\Lambda} = (P_d + P_\Lambda)^2 = m_d^2 + m_\Lambda^2 + 2(E_d E_\Lambda - \mathbf{p}_d \bullet \mathbf{p}_\Lambda)$



Summary and Outlook

- **Goal**: investigate feasibility of analyzing Λd elastic scattering from photoproduction off deuteron
- **Conclusion**: analyzing Λd elastic scattering from photoproduction off deuteron is feasible. Can expect approx. 4000 events in g13.
- Total and differential cross sections for Λd elastic scattering can be determined:
  - For Λ beam momentum above 0.7 GeV/c
  - For $W_{d\Lambda}$ between 3 GeV and 3.8 GeV
  - For $\cos(\theta_{\Lambda}^{CM})$ between −0.6 and 0.9
- Determination of total cross section for $\Lambda d \rightarrow \Sigma^0 d$ might be possible; expect limited statistics

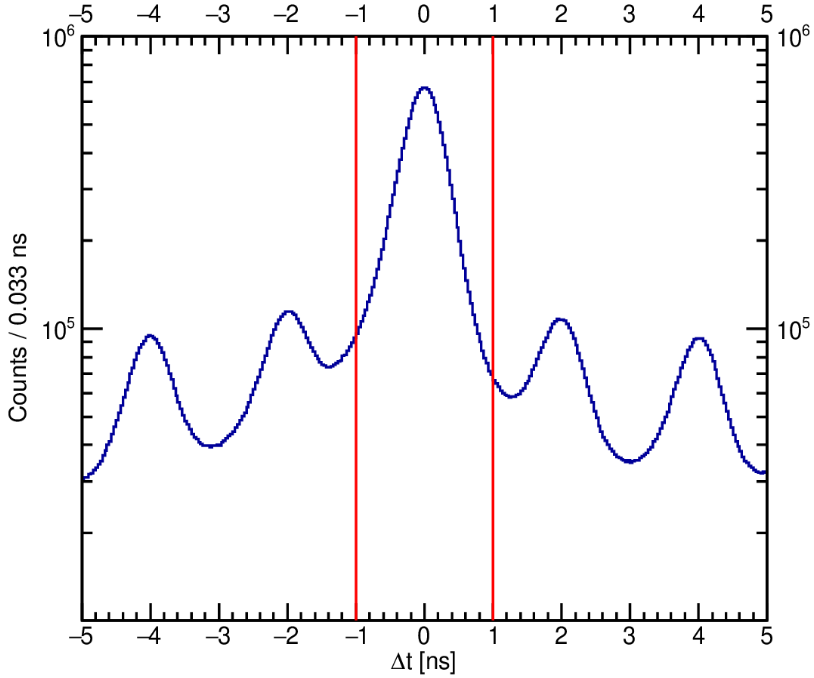
Accidental Background Reduction

- Reaction $\gamma d \rightarrow pp\pi^-$ is very dominant γd reaction
- Need photon beam information
- “Good” photons: photons in coincidence with fastest particle in event ($\Delta t = t_{v,\gamma} - t_{v,fast}$ within ±1 ns)
  - $t_{v,\gamma}$ = Photon vertex time = $t_{center\text{-}of\text{-}CLAS} + (z + 20\text{ cm})/c$
    - $t_{center\text{-}of\text{-}CLAS}$ is time of photon at center of the CLAS
    - z is z-component of vertex position common to all tracks in event
  - $t_{v,fast}$ = Fastest-particle vertex time = $t_{fast} - L_{fast}/c\beta_{fast}$
    - t_{fast} is the time when that fastest particle reaches TOF detector
    - L_{fast} is the associated path length of fastest particle from vertex to TOF detector
    - β_{fast} is the speed of fastest particle

Accidental Background Reduction

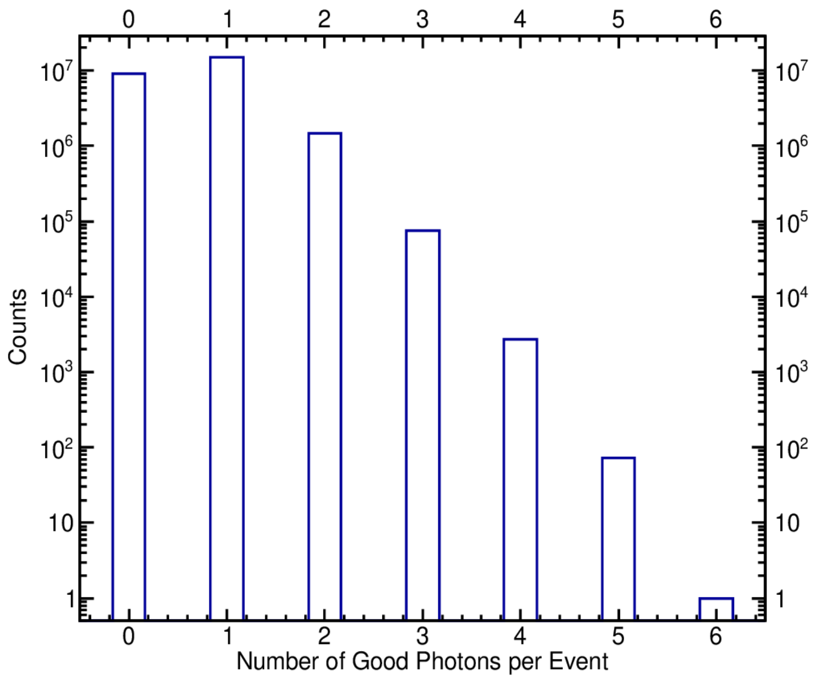
- “Good” photon event is event with $|\Delta t| < 1$ ns
- Require 1 good photon per event

Photon Coincidence, Δt



Distribution of photon coincidence times. Red lines depict the cuts defining “good” photons.

Number of good photons



Distribution of number of good photons per event.

Extra Slides

- CLAS is optimized to detect multiple-charged-particle final states
- Large acceptance of ~2.8π
  - Polar angle coverage between 8° and 140°
  - 360° azimuthal coverage, except in magnet coil shadow

- Photon tagger → photon beam; tags photons in beam
- Torus magnet → azimuthal magnetic field
- Start-counter → start times to trigger
- TOF detectors → charged-particle energy deposition and time-of-flight
- Drift chambers (DC) → charged particle trajectories