# Near-threshold cross-section determination for coherent J/ψ meson photoproduction off deuteron

$$\gamma\, d \rightarrow J/\psi\, d'$$

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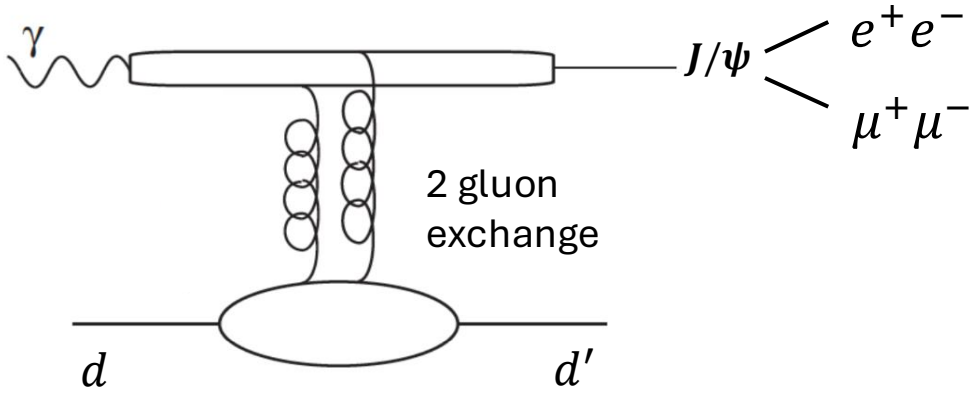
# Introduction

- **Project Goal:** Estimate differential and/or total cross section
- **Technique:** $\gamma d \rightarrow J/\psi d'$ is measured in untagged quasi-real (virtual photon with very small virtuality) photoproduction
- **Means:** Data from Jefferson Lab E12-11-003B
- **Purpose:** Learn about transverse gluon distribution in deuteron (following on the work done for the nucleon)



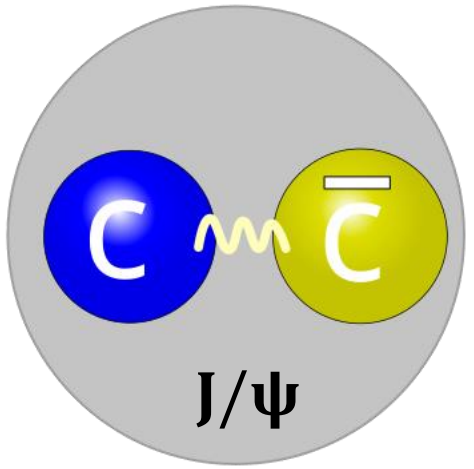

https://www.jlab.org/exp_prog/proposals/18/E12-11-003B.pdf

# The J/ψ Meson

- Bound state of $c$ and $\bar{c}$ pair, called “charmonium”
- Rest mass: $3.0969\ \mathrm{GeV}/c^2$
- Mean lifetime: $7.2 \times 10^{-21}\ s$
- Decay modes we are interested in

$$J/\psi \rightarrow e^+e^- \quad , B.R \sim (5.94 \pm 0.06)\%$$
$$J/\psi \rightarrow \mu^+\mu^- . \quad , B.R \sim (5.93 \pm 0.06)\%$$

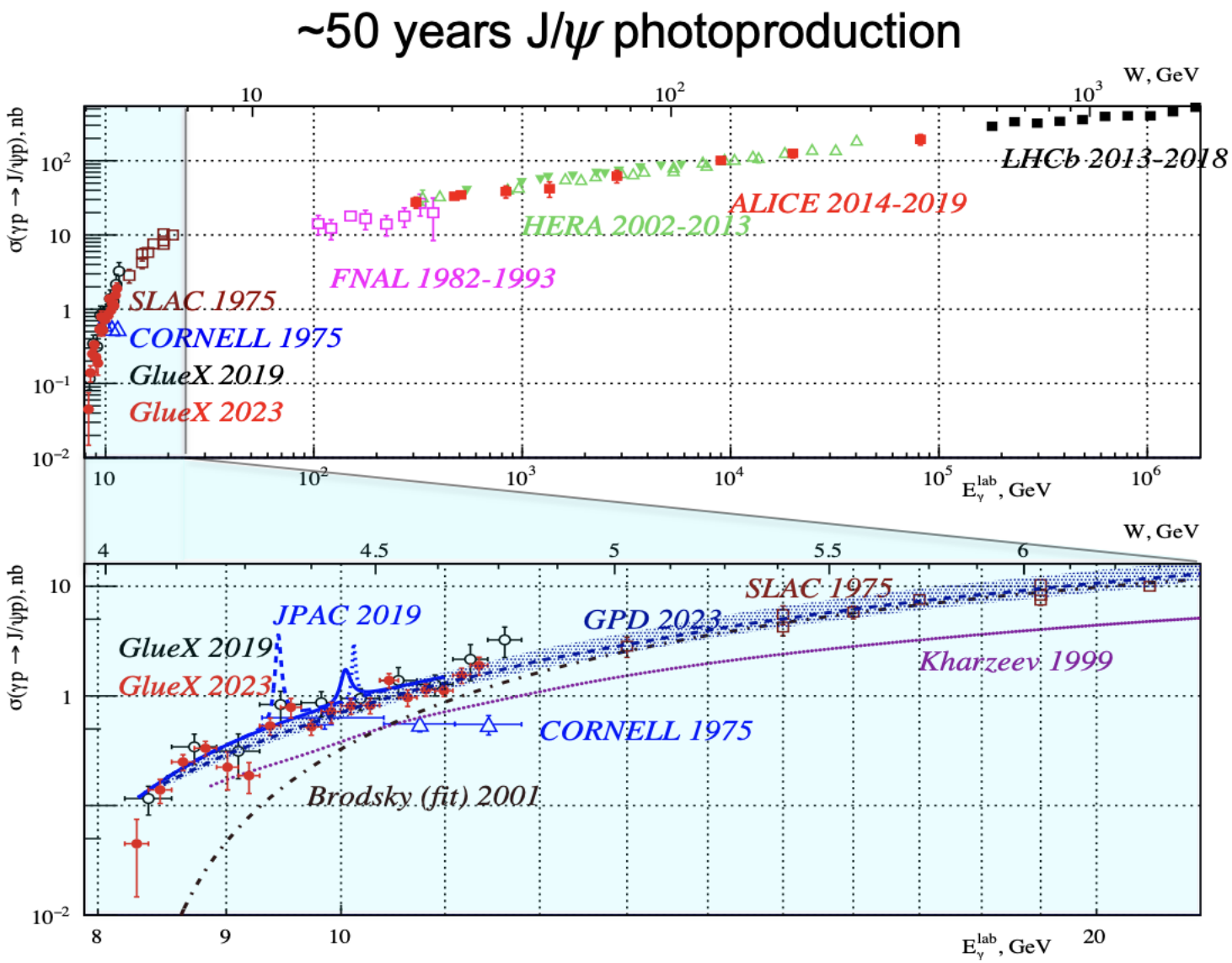
- Experimental Aspects:
  - Clean leptonic decay channels
  - Photo-production is accessible with electron beams
  - Gluonic form factor of target can be extracted from invariant cross section






K. Nakamura et al. (Particle Data Group), JP G 37, 075021 (2010) (URL: http://pdg.lbl.gov)

# J/ψ Photoproduction World Database




Threshold for J/ψ photoproduction ($E_\gamma^{th}$): = 8.20 GeV

Published Data:

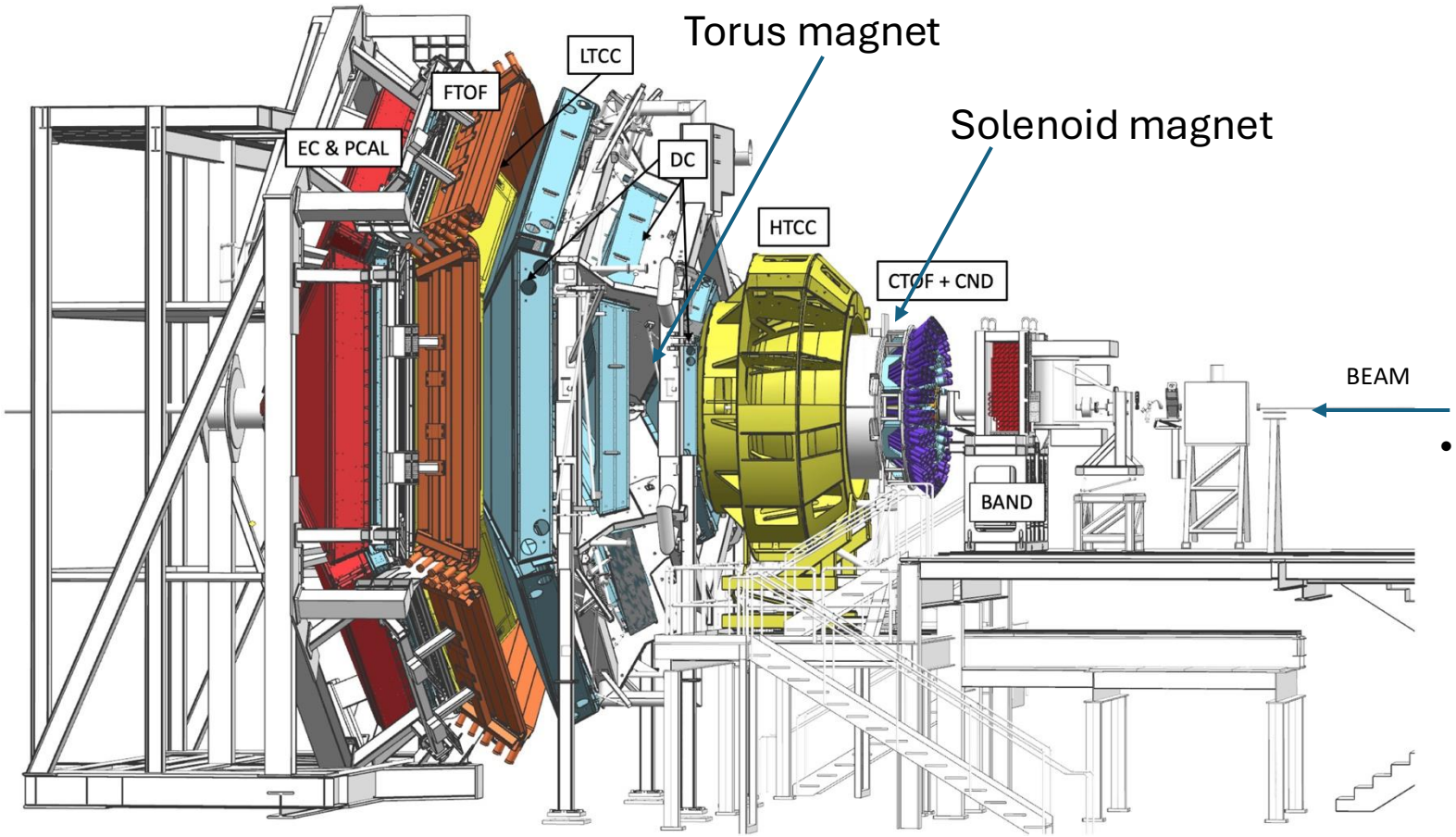
- Cornell ‘75
- SLAC ’75
- CERN NA-14
- FNAL
- LHCb
- ALICE
- HERA
- JLab J/Ψ-007 (Hall C)
- JLab GlueX 2019
- JLab GlueX 2023

In progress:

- JLab CLAS12 (proton, deuteron)

Figure from: L. Pentchev (GlueX Collaboration), *Threshold Charmonium Production at JLab*, BEACH 2024, June 3 – 7 2025, Charleston, SC

# CLAS12 Detector




- Central Detector (CD): Covers $5^{\circ} \leq \theta \leq 35^{\circ}$ includes:
  - Back Angle Neutron Detector (BAND)
  - Silicon Vertex Tracker (hidden)
  - Barrel Micromesh Tracker (hidden)
  - Central Time-of-Flight (CTOF)
  - Central Neutron Detector (CND)
  - Superconducting Solenoid Magnet
- Forward Detector (FD): Covers $5^{\circ} \leq \theta \leq 35^{\circ}$ and $\Delta\theta = 2\pi$ , includes:
  - High Threshold Cherenkov Counter (HTCC)
  - Forward Tagger (FT)
  - Torus magnet
  - Drift Chambers (DC)
  - Hidden Cherenkov counters
  - Time-of-Flight (TOF)
  - Electromagnetic Calorimeter (EC)
  - Pre-shower Calorimeter(PCAL)

https://doi.org/10.1016/j.nima.2020.163419

# The E12-11-003B experiment

- Quasi-Real Photoproduction off Deuterium Target ($\mathrm{LD}_2$)
- Reaction Channels Studied:
  - $ep_{bound} \rightarrow e'J/\psi p$
  - $en_{bound} \rightarrow e'J/\psi n$
  - $ed \rightarrow J/\psi d'$
  - $ed \rightarrow J/\psi pn$
- Experimental Setup:
  - Beam: 10.6 GeV electron beam
  - Target: Liquid deuterium
  - Quasi-real photons: scattered electron not detected, virtual photon with $\mathrm{Q}^2 \approx 0$.
- Detector & Data analysis:
  - Use CLAS12 to detect $e^+, e^-$ ,and recoil deuteron
  - Apply PID cuts to identify clean leptons and hadrons
  - Reconstruct J/ψ invariant mass, study distributions, apply exclusivity cuts
- My Focus is on:
  - Analysis of coherent production: $\gamma^* \mathrm{d} \rightarrow \mathrm{J}/\psi \mathrm{d}'$ (no previous or concurrent experiments and data)
  - Extraction of differential and/or total cross section

Y. Ilieva, B. McKinnon, P. Nadel-Turonski, V. Kubarovsky, S. Stepanyan, Z.W. Zhao, Study of J/psi Photoproduction off Deuteron, JLab E12-11-003B, 2018

# Data Analysis Plan

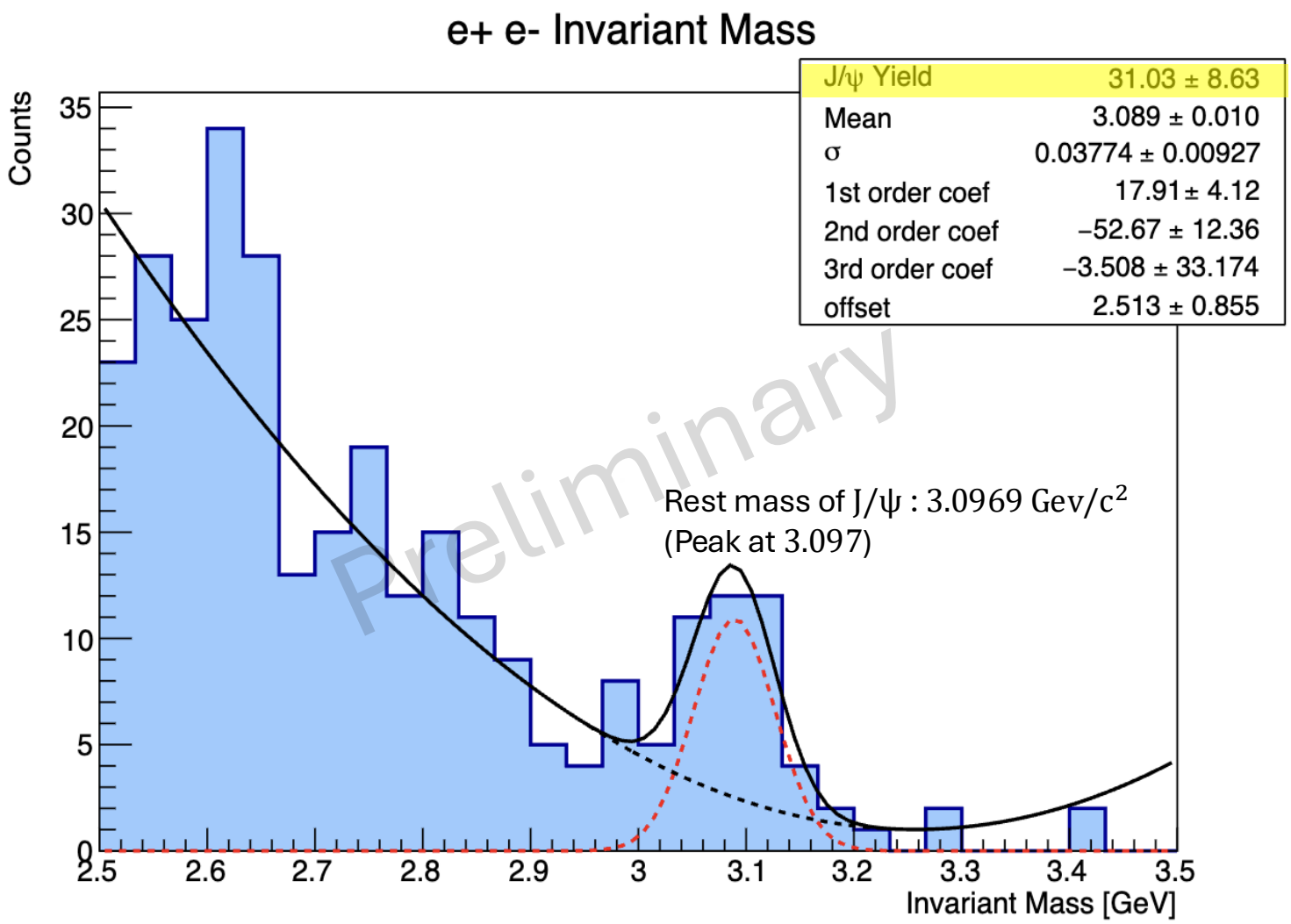
- Yield extraction:
  1. Particle identification
     i. Electron and positron identification
     ii. Deuteron Identification
     iii. J/Psi meson reconstruction
  2. Reaction selection via four-momentum conservation
  3. Background subtraction

- Luminosity determination

- Determination of the CLAS12 acceptance for coherent process

- Binning studies for cross section extraction

# Results From Exploratory Studies




Event Selection (cuts):

- At least one $e^-$, at least one $e^+$, and at least one good $d$
- The leptons are detected in the Forward Detector
- Quasi-real photoproduction: $ed \rightarrow e'd'e^+e^-$ with a forward-going, undetected (missing) $e'$
- $Q^2<5$
- $|\mathrm{MM}^2| < 1$

$$Q^2 = -q^2 = -(\vec{p}_e - \vec{p}_{e'})$$

$$MM^2 = \left(\tilde{P}_e + \tilde{P}_d - \tilde{P}_{e^-} - \tilde{P}_{e^+} - \tilde{P}_{d'}\right)^2 = IM_{e'}$$

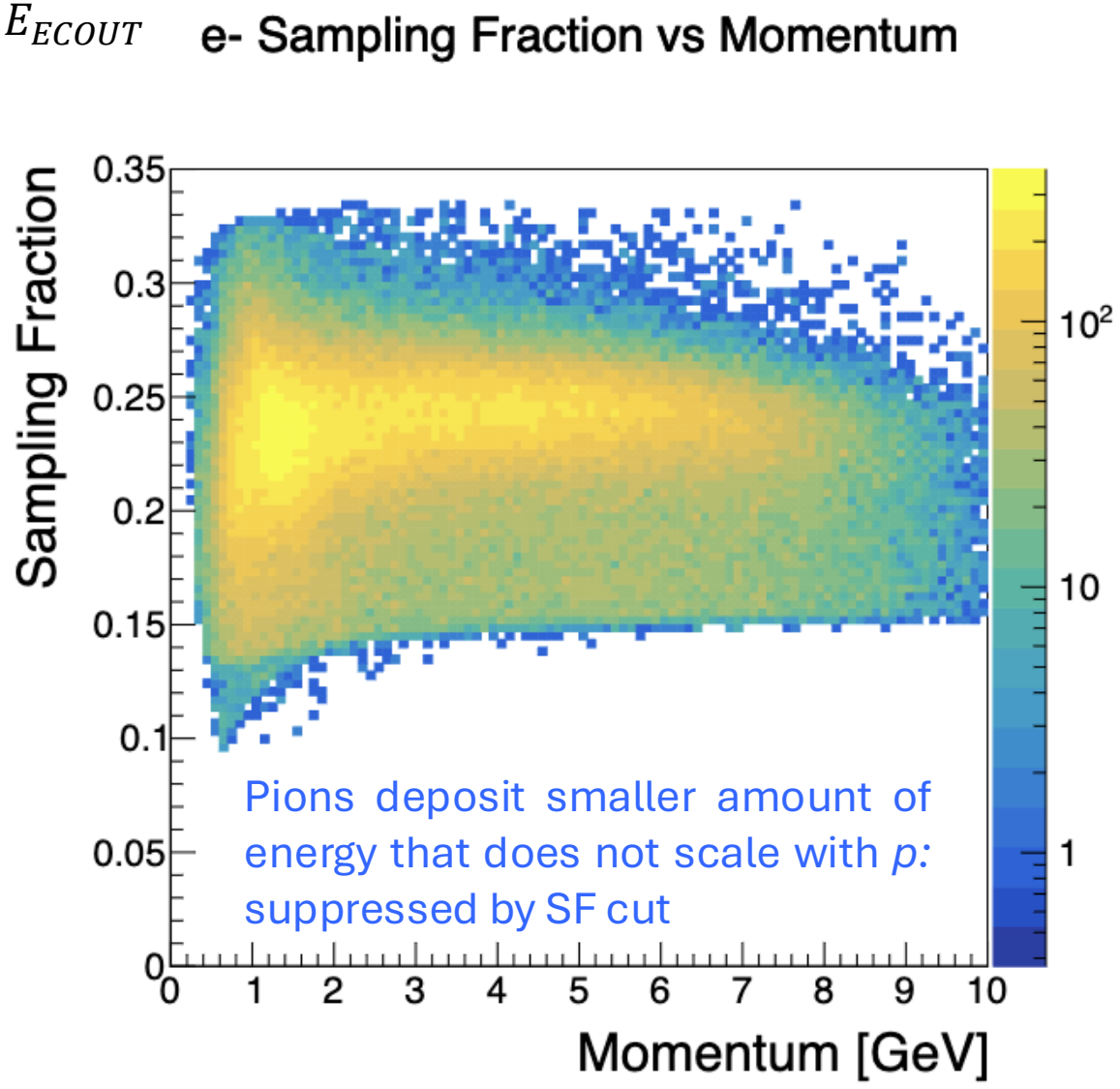
$$IM_{J/\psi} = \sqrt{(\tilde{P}_{e^+} + \tilde{P}_{e^-})^2} = M_{J/\psi} = 3.097\ GeV$$

Richard Tyson, Private Communication, 2024

# Electron and Positron Identification in CLAS12

$$E_{dep,Total} = E_{PCAL} + E_{ECIN} + E_{ECOUT}$$

- Tracking and B-field: Give momentum *p*
- High Threshold Cherenkov Counters (HTCC): Separate electrons with momenta below 4.9 GeV from charged hadrons.
- Electromagnetic Calorimeter (ECAL):
  → Fully contains EM showers from $e^-$, $e^+$
  → $e^-$, $e^+$ deposit significant energy that scales with *p*
  → Sampling fraction :
  $SF = \frac{E_{dep,Total}}{P}$ varies little with *p* for $e^-$, $e^+$; parameterized SF(p) cut applied
- Time-of-Flight (TOF) & Start Counter: Particle ID of charged hadrons

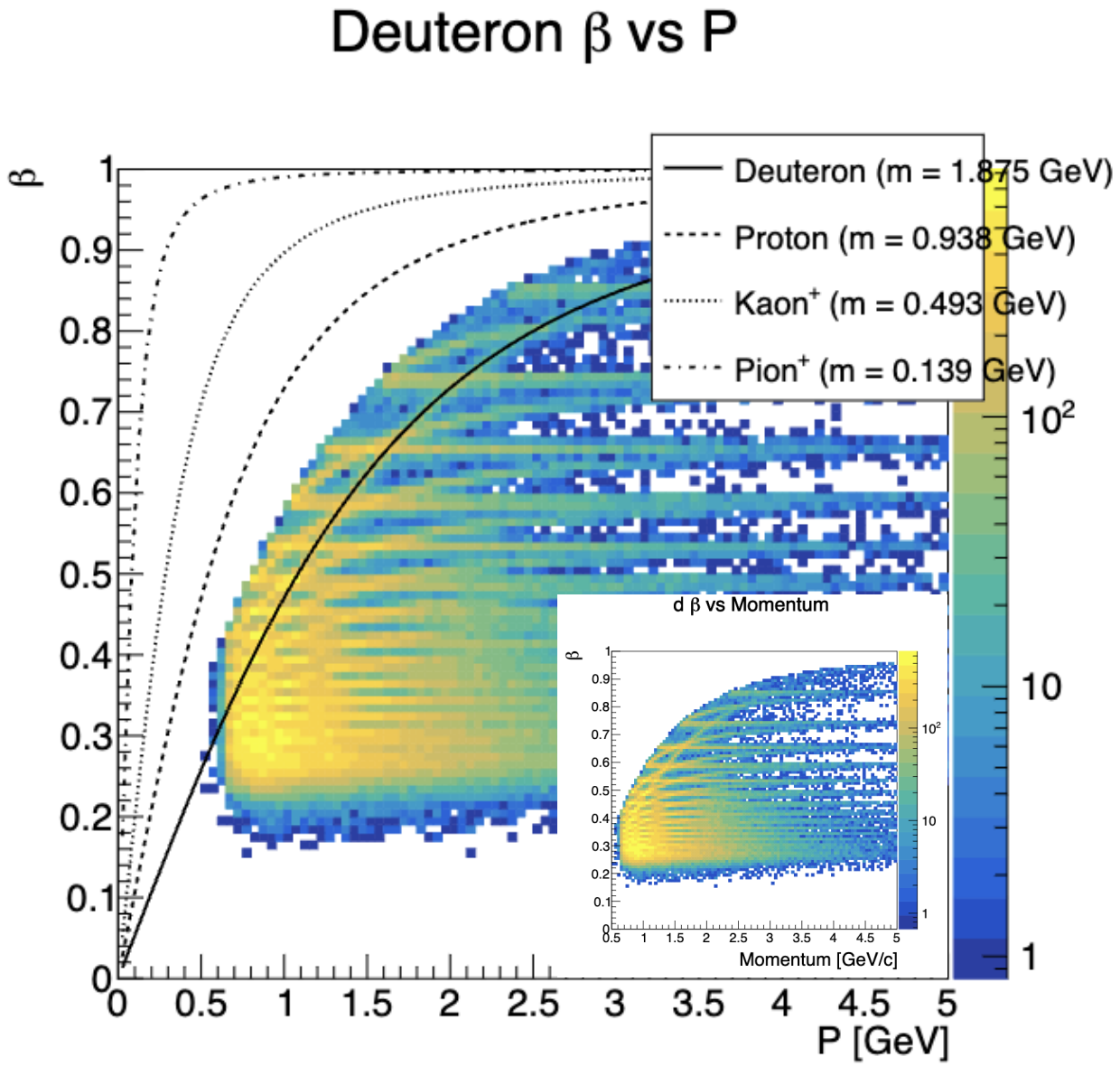


# Deuteron Identification in CLAS12

- Tracking and B-field: Give momentum *p* and path length to TOF detector $L_{TOF}$
- TOF detector: measures flight time $t_{TOF}$
- Particle speed is reconstructed:

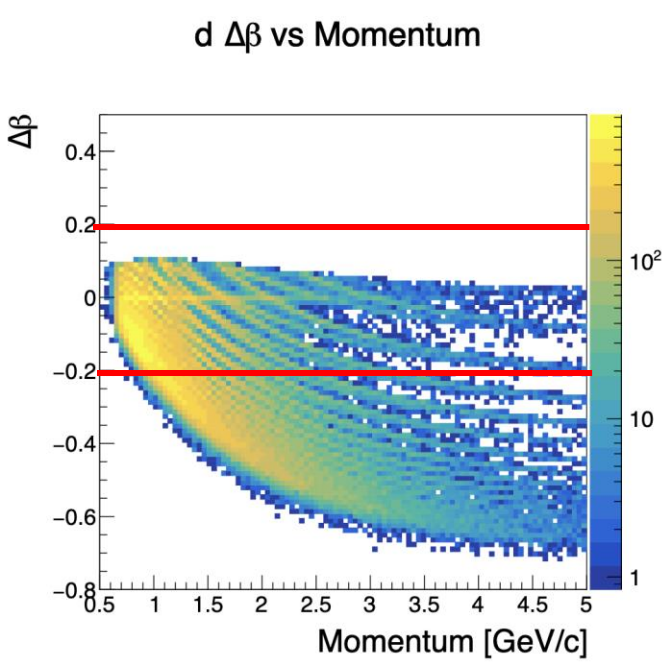
$$\beta_{\text{measured}} \equiv \beta = L_{TOF} / t_{TOF}$$

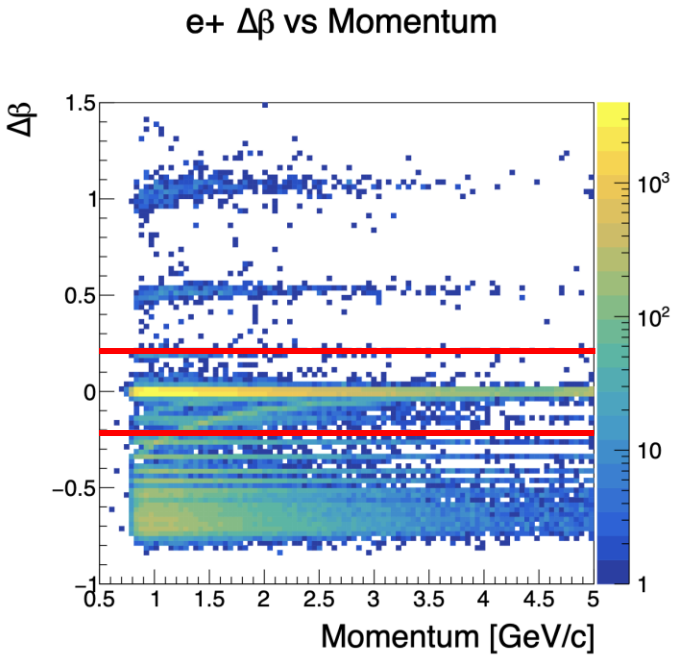
Deuteron events clearly visible; substantial accidental background. Lighter hadrons are removed from sample by pre-selection criteria.

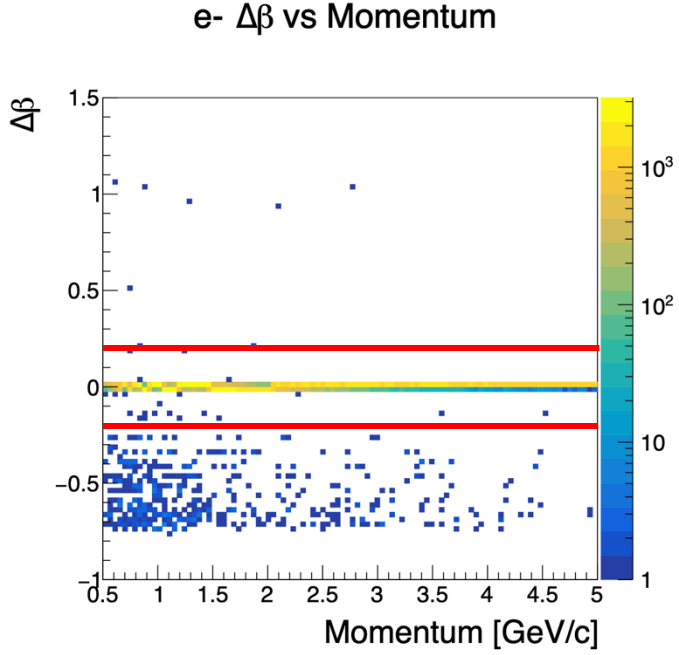


# Background Reduction with TOF

Δβ vs Momentum plots of $d, e^{-}$ and $e^{+}$, using TOF information to reduce background in final state particles




$$\beta_{\text{measured}} \equiv \beta = L_{TOF}/t_{TOF}$$

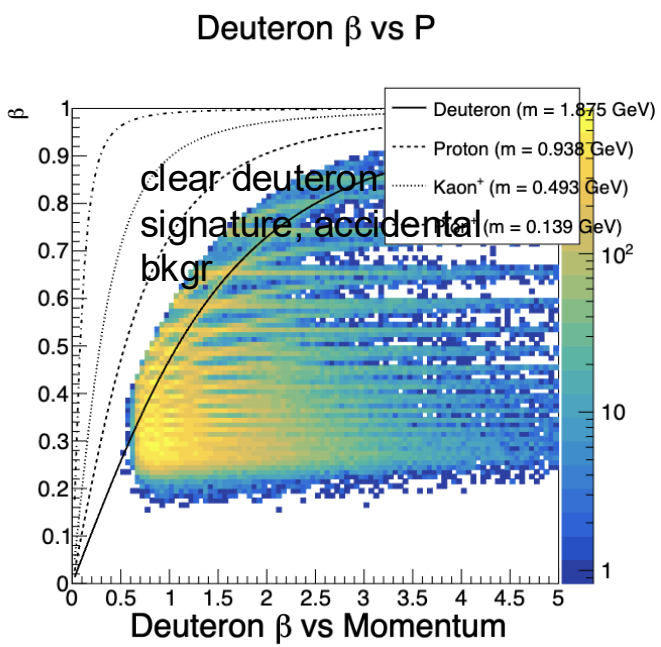
$$\beta_{\text{calculated}} = \frac{p}{\sqrt{p^2 + m^2}}$$

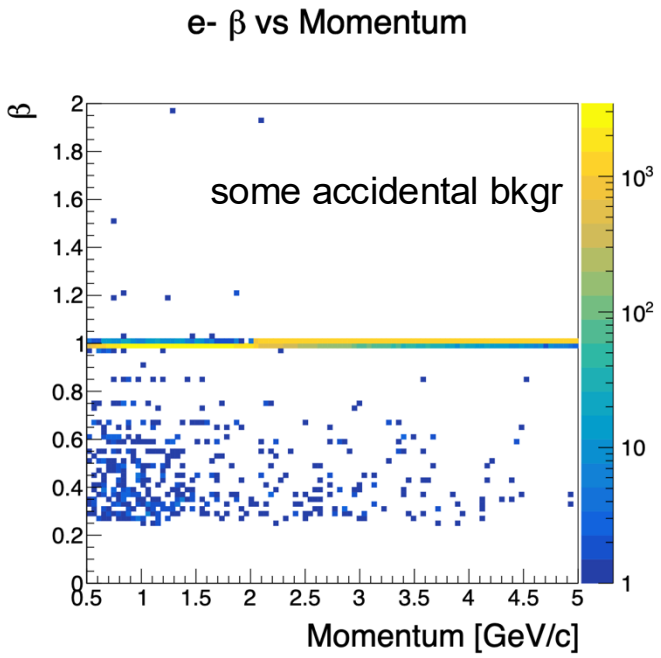
$$\Delta\beta = \beta_{\text{measured}} - \beta_{\text{calculated}}$$

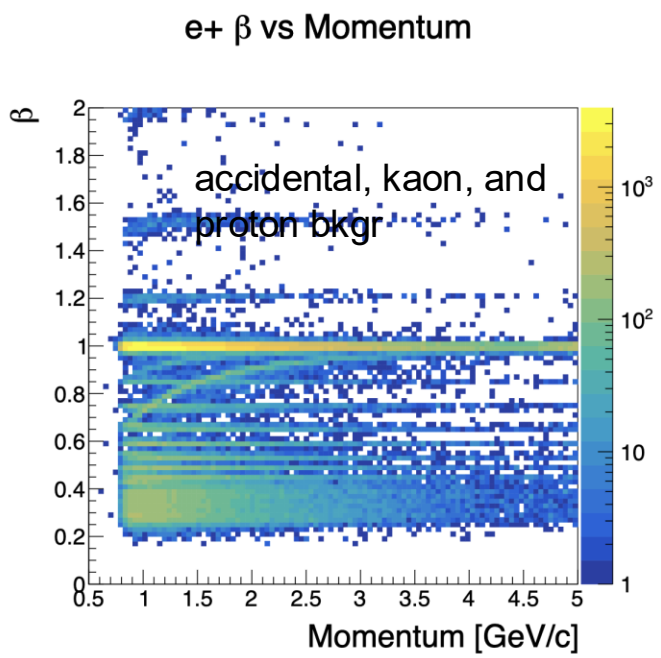
- Initial Δβ cut range selected for lepton pair and $d$ : [-0.2,0.2]
- The Δβ cut further reduces the accidental background and removes lower momentum protons in $e^{+}$ and $e^{-}$ samples
- In next analysis steps the cut will be tightened

# Deuteron Identification in CLAS12

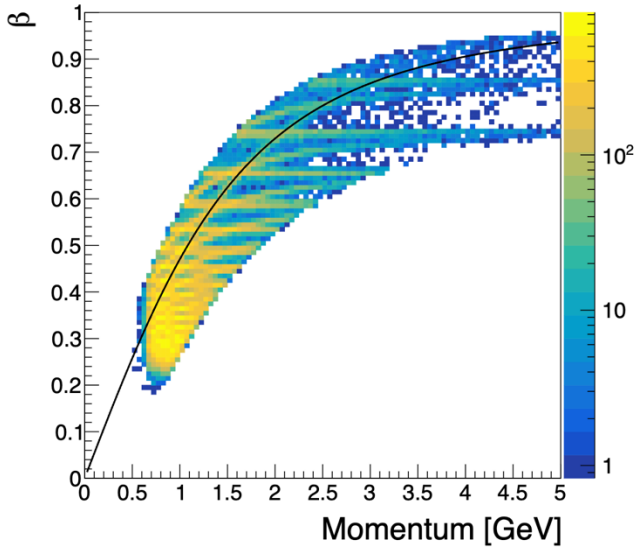
Before applying Δβ cut

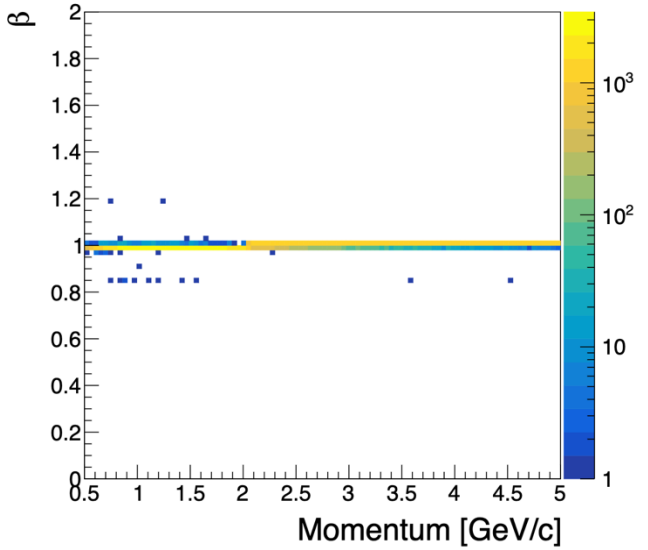


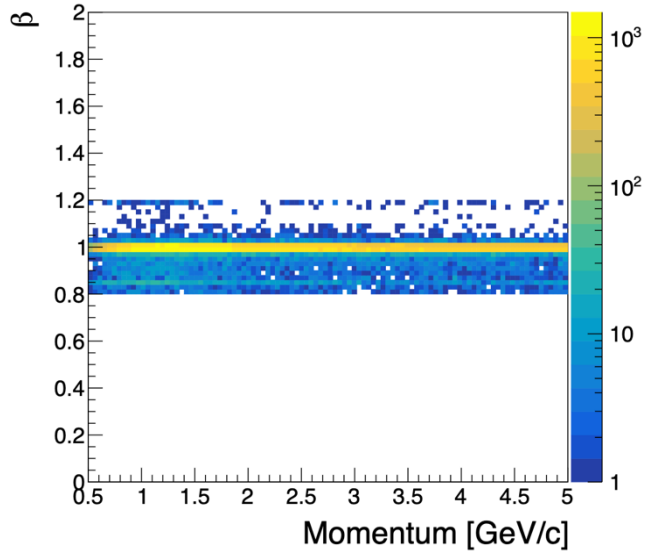



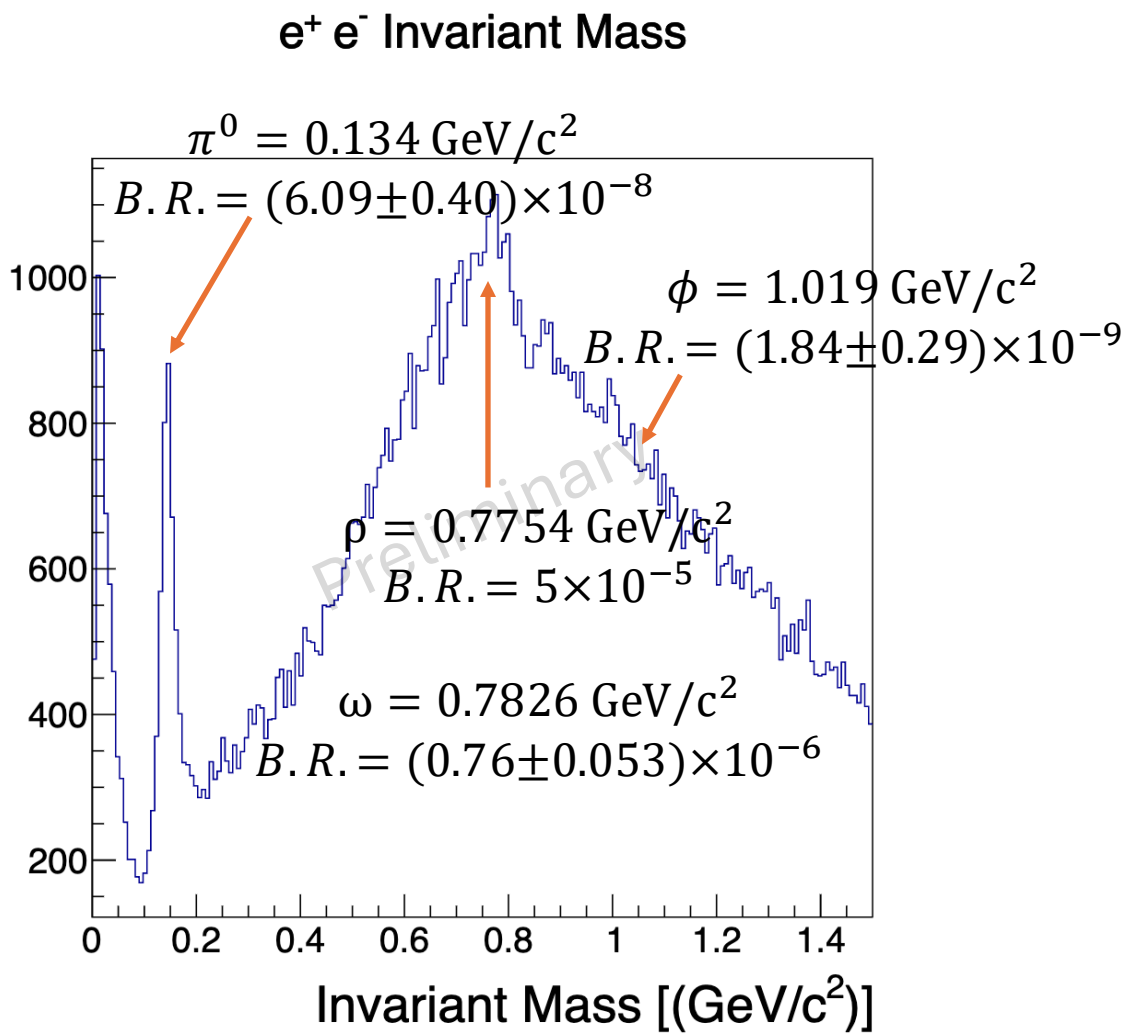

After applying Δβ cut

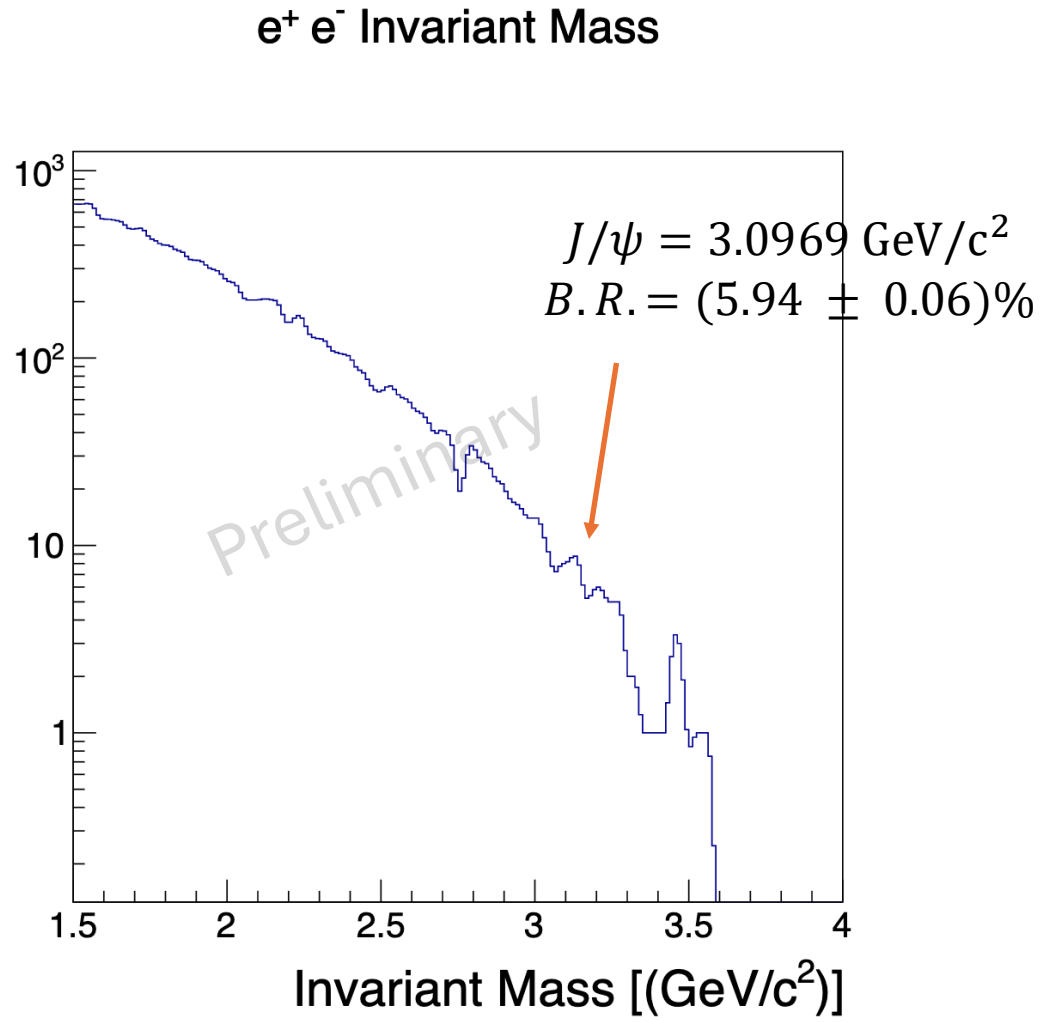


# J/ψ Identification




- A fraction of data sample shown (allows fast processing)
- High statistics and clear signature of $\pi^0$ mesons – will use the $\pi^0$ sample to refine the PID of electrons, positrons, and deuterons, and for systematic studies

# Summary

- Started investigation of $J/\psi$ production via the reaction $\gamma d \rightarrow J/\psi\, d'$ focusing on $J/\psi \rightarrow e^+e^-$ decay channel.
- Data taken with CLAS12 at Jefferson Lab in E12-11-003B experiment.
- All final-state particles, $e^+, e^-$ and $d'$ detected.
- Ongoing work:
    - Refine and finalize PID cuts
    - Study and apply further background reduction methods using $\pi^0$ events

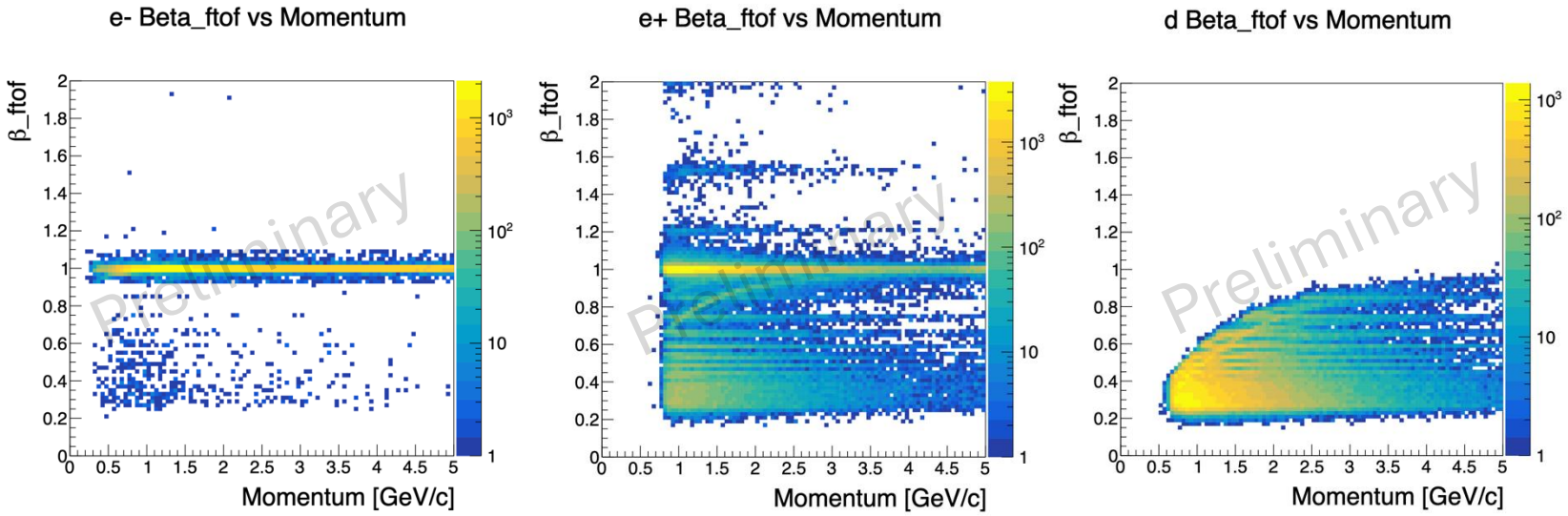
# References


- Tyson, Richard  (2023) J/ψ near-threshold photoproduction off the proton and neutron with CLAS12. PhD thesis, University of Glasgow.
- CLAS12ForwardTagger(FT)Technical Design Report, December7,2012, VersionV2.0
- K. Nakamura et al. (Particle Data Group), JP G 37, 075021 (2010) (URL: http://pdg.lbl.gov)
- The CLAS12 Spectrometer at Jefferson Laboratory, Volume 959, 2020

# Cross checking $\beta$ using path length and FTOF hit time data

63 files
spring 2019

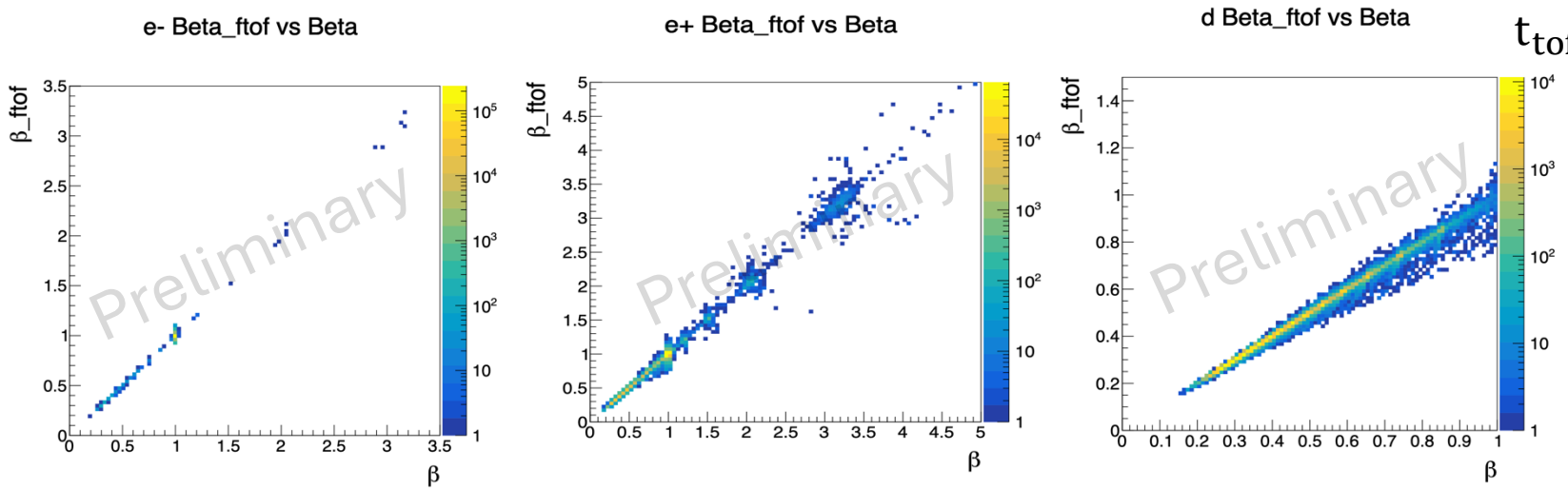
No cuts applied



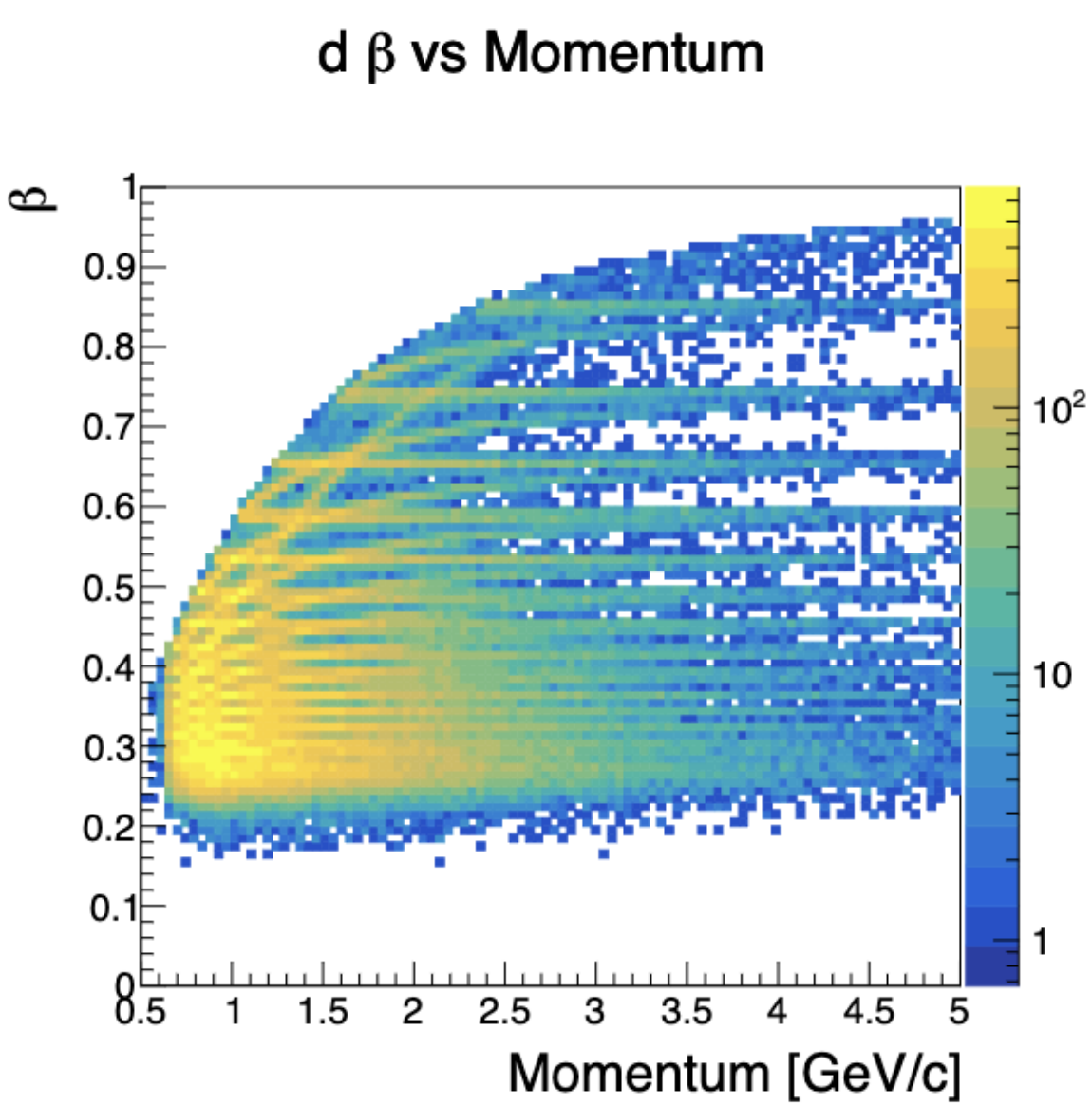

$$\beta_{measured} \equiv \beta = \frac{v}{c} = \frac{L}{t_{tof\_correct} \cdot c}$$

$$t_{tof\_correct} = t_{TOF} - t_{st}\ (\text{FTOF1B})$$

No cuts applied




The Event Builder β and $\beta_{TOF}$ are different. To understand how Event Builder β is determined. Study further.


d β vs Momentum
β
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Momentum [GeV/c]
10²
10
1

# Events in the jpsi train:(.../train/jpsi)

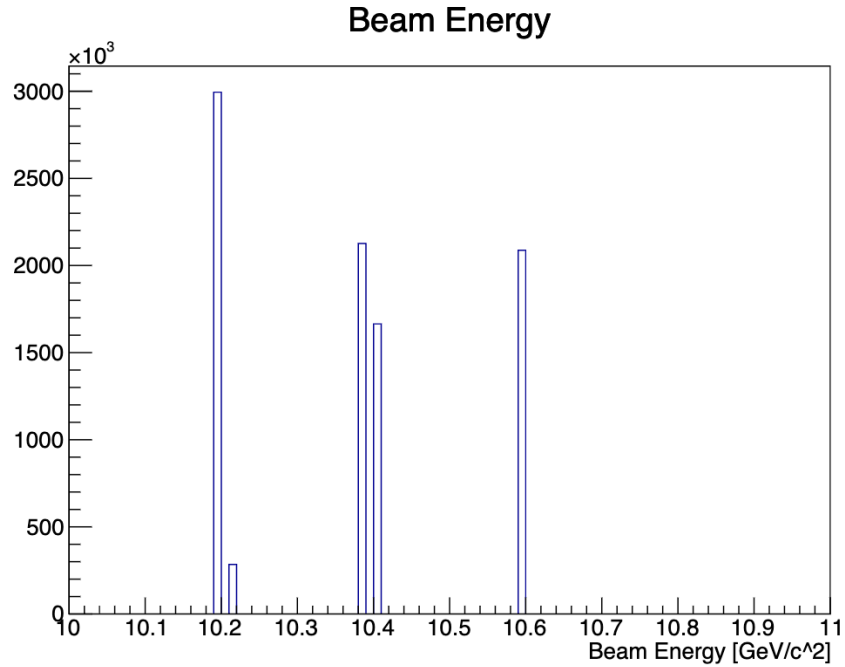
- $e^+e^-$ pair + at least one other positive charged particle:
  - At least 1 electron, 1 positron
  - And more than 1 total positive charged particle
- Two or more same-sign electrons/positrons + additional positive particles:
  - ≥ 2 electrons and ≥ 1 positive charged particle OR
  - ≥ 2 positrons and > 2 positive charged particles
- $\mu^+\mu^-$ pair in the Forward Detector + at least one other positive particle (FD):
  - At least 1 $muon^-$, 1 $muon^+$
  - And > 1 positive particle in the Forward Detector
- Two or more same-sign muons + additional positive particles (FD):
  - ≥ 2 $muon^-$ and ≥ 1 positive (FD) OR
  - ≥ 2 $muon^+$ and > 2 positive (FD)
- High-momentum $e^+e^-$ pair:
  - At least 1 high-momentum electron and 1 high-momentum positron
- Two or more high-momentum same-sign electrons or positrons:
  - ≥ 2 high-momentum electrons OR
  - ≥ 2 high-momentum positrons
- High-momentum $\mu^+\mu^-$ pair:
  - At least 1 high-momentum $muon^-$ and 1 high-momentum $muon^+$
- Forward Tagger electron + Forward Detector proton + high-momentum $e^+$ or $e^-$:
  - At least 1 electron in FT
  - And 1 proton in FD
  - Plus either a high-momentum electron or positron

# Data Sample

CLAS12 Run Group B Data

- Runs: Spring2019 (249), Fall2019 (181), and  Spring2020 (122) -> Total 552 runs
- Fall2019/torus+1/pass2/v1/dst/train/jpsi/
- spring2019/torus-1/pass2/v0/dst/train/jpsi/
- spring2020/torus-1/pass2/v1/dst/train/jpsi/

| Run Period | Beam Energy (GeV) |
|---|---|
| Spring 2019 | 10.6 |
| Spring 2019 | 10.6 |
| Spring 2019 | 10.2 |
| Fall 2019 | 10.41 |
| Spring 2020 | 10.39 |



- $Q^2 = -q^2 = -(k - k')^2 \rightarrow |\vec{q}|^2 = 2E_{beam}|\overrightarrow{p_{miss}}|(1 - cos\theta_{miss})$
- Transferred momentum=$\vec{q} = \overrightarrow{p_1} - \overrightarrow{p_2}$
- $|\vec{q}|^2 = |\overrightarrow{p_1} - \overrightarrow{p_2}|^2 = |\overrightarrow{p_1}|^2 + |\overrightarrow{p_2}|^2 - 2\,|\overrightarrow{p_1}|\,|\overrightarrow{p_2}|cos\theta$
- In high energy limit, we assume, $|\overrightarrow{p_1}| = |\overrightarrow{p_2}| = p$
- $|\vec{q}|^2 = p^2 + p^2 - 2p^2cos\theta = 2p^2 - 2p^2cos\theta = 2p^2(1 - cos\theta) = 2|\overrightarrow{p_1}|\,|\overrightarrow{p_2}|(1 - cos\theta)$

- $|\overrightarrow{p_1}| = E_{beam}$ : incoming beam electron energy (assuming it's a massless or relativistic electron).
- $|\overrightarrow{p_2}|$ = $|\overrightarrow{p_{miss}}|$ : magnitude of the missing momentum vector
- $\theta_{miss}$ : polar angle (θ) of the missing momentum vector (w.r.t. beam axis),