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# Beam asymmetry of the photoproduction of the $\omega$ meson off bound protons in CLAS

Olga Cortés Becerra

CEBAF Large Acceptance Spectrometer

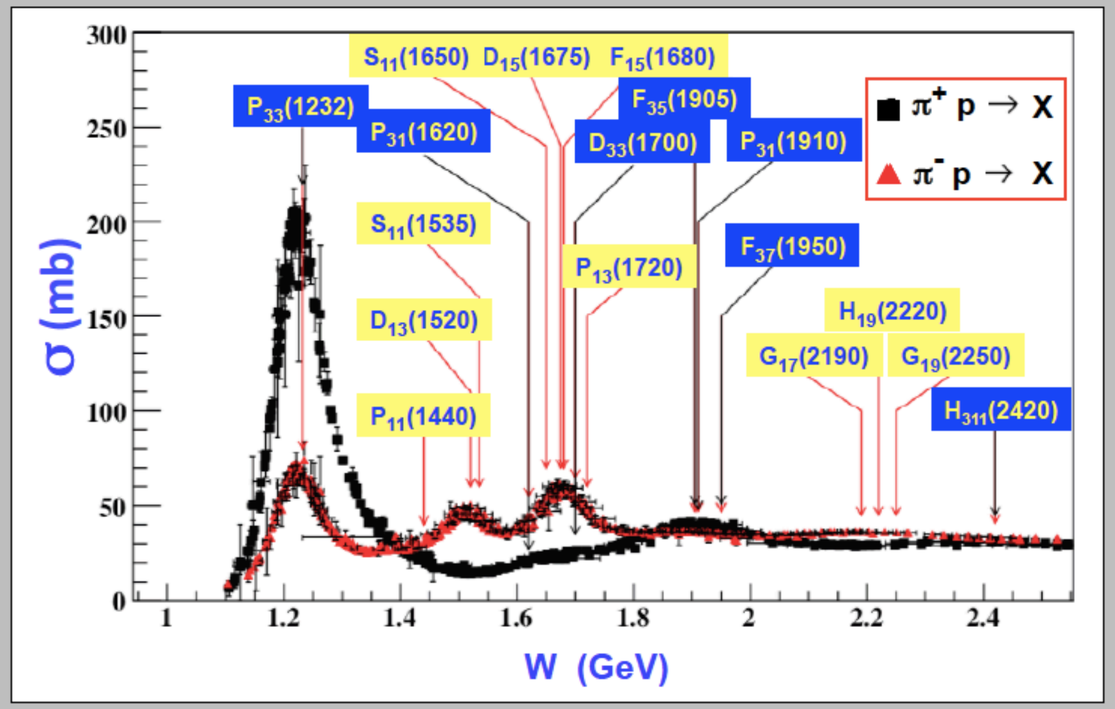
**NSTAR 2022**
**Santa Margherita Ligure**
**October 19 2022**

Jefferson Lab
Thomas Jefferson National Accelerator Facility

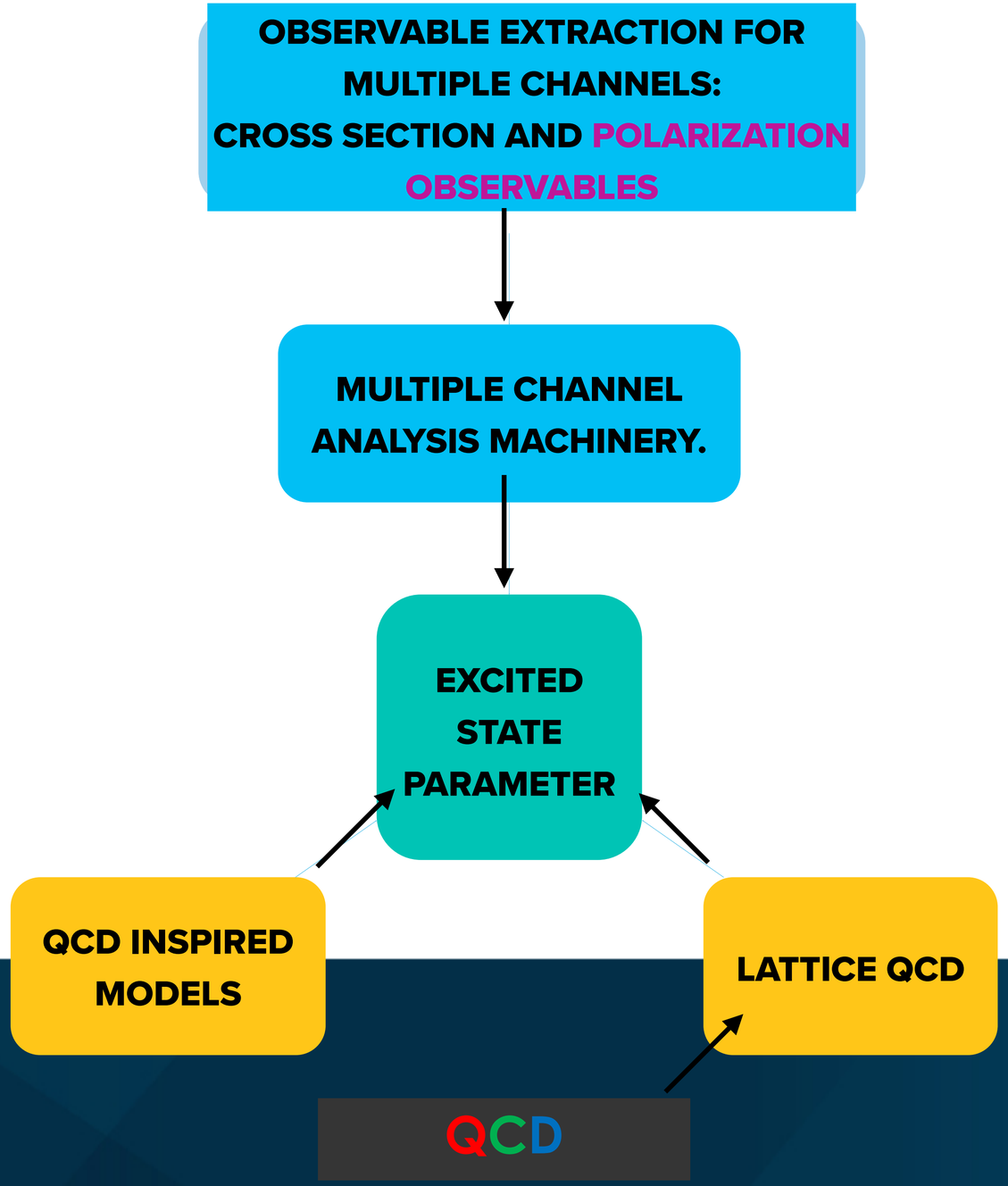
# BARYON SPECTROSCOPY

- Excited states of nucleons manifest in the cross sections as broad distributions: resonances.
  - Strong overlapping.
  - Sophisticated tools are needed to obtain

The baryon spectrum cannot be predicted by perturbation theory




M. Pennington presentation


OBSERVABLE EXTRACTION FOR MULTIPLE CHANNELS: CROSS SECTION AND POLARIZATION OBSERVABLES
MULTIPLE CHANNEL ANALYSIS MACHINERY.
EXCITED STATE PARAMETER
QCD INSPIRED MODELS
LATTICE QCD
QCD


M. Pennington presentation


M. Pennington presentation

# Polarization observables

**UNPOLARIZED CROSS-SECTION**


**POLARIZATION OBSERVABLES.**

| Beam | | Target | | | Recoil | | | Target + Recoil | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | - | - | - | - | $x'$ | $y'$ | $z'$ | $x'$ | $x'$ | $x'$ | $y'$ | $y'$ | $y'$ | $z'$ | $z'$ | $z'$ |
| | - | $x$ | $y$ | $z$ | - | - | - | $x$ | $y$ | $z$ | $x$ | $y$ | $z$ | $x$ | $y$ | $z$ |
| unpolarized | $\sigma_0$ | | $T$ | | | $P$ | | $T_{x'}$ | | $L_{x'}$ | | $\Sigma$ | | $T_{z'}$ | | $L_{z'}$ |
| linearly pol. | $\Sigma$ | $H$ | $P$ | $G$ | $O_{x'}$ | $T$ | $O_{z'}$ | $L_{z'}$ | $C_{z'}$ | $T_{z'}$ | $E$ | $\sigma_0$ | $F$ | $L_{x'}$ | $C_{x'}$ | $T_{x'}$ |
| circularly pol. | | $F$ | | $E$ | $C_{x'}$ | | $C_{z'}$ | | $O_{z'}$ | | $G$ | | $H$ | | $O_{x'}$ | |

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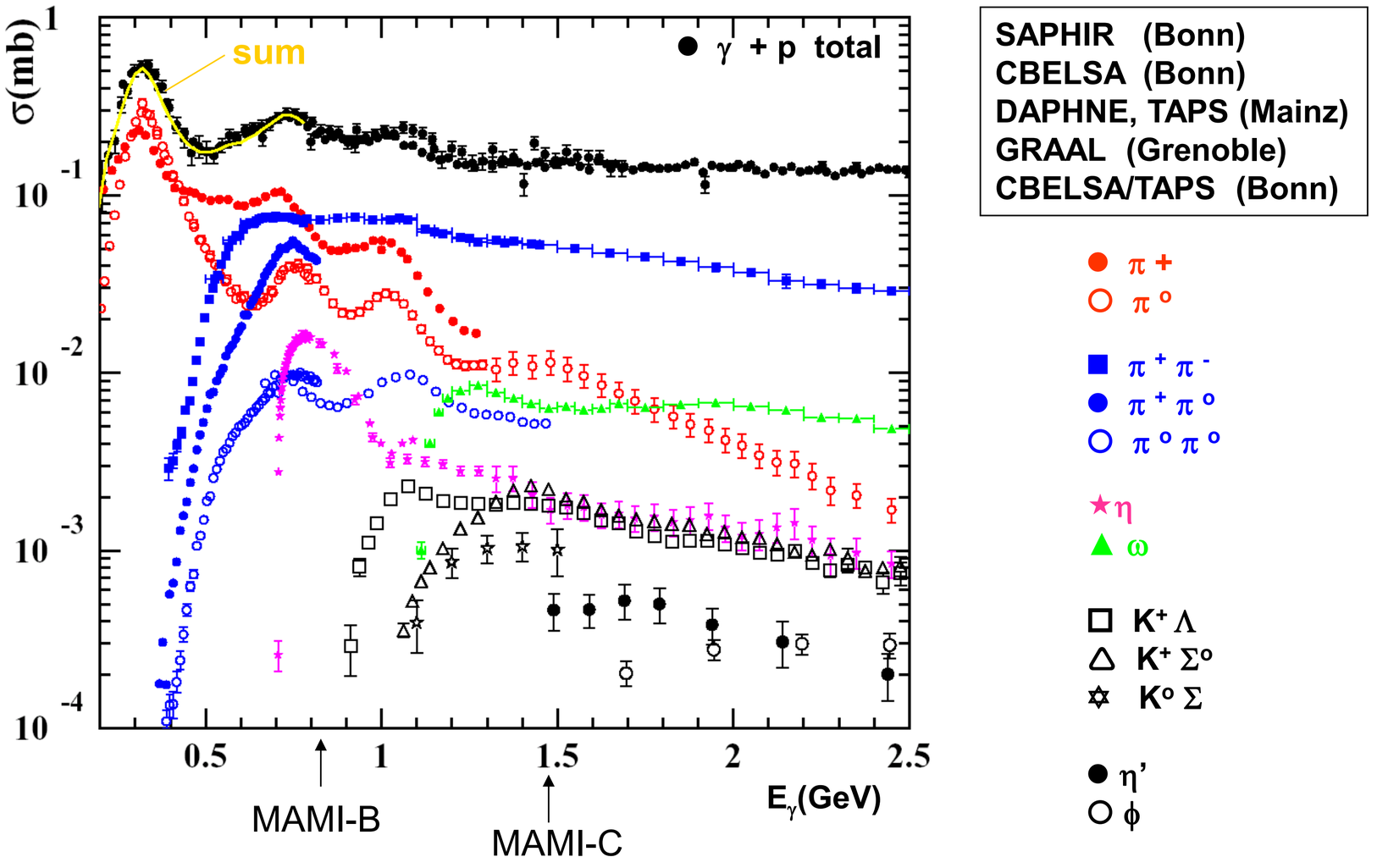
# Why $\omega$?

## Photoproduction from the Proton




Courtesy of S. Schadmand

S. Schadmand

# N*

| Particle | $J^P$ | overall | PWA | $N\gamma$ | $N\pi$ | $\Delta\pi$ | $N\sigma$ | $N\eta$ | $\Lambda K$ | $\Sigma K$ | $N\rho$ | $N\omega$ | $N\eta'$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $N$ | $1/2^+$ | **** | | | | | | | | | | | |
| $N(1440)$ | $1/2^+$ | **** | ○ $\diamond_g$ ★ ▷ | ***- | **** | ***- | *** | - | | | - | | |
| $N(1520)$ | $3/2^-$ | **** | ○ ◇ ★ ▷ | **** | **** | **** | ** | ***- | | | - - - - | | |
| $N(1535)$ | $1/2^-$ | **** | ○ ◇ ★ ▷ | ***- | **** | **- | * | **** | | | - - | | |
| $N(1650)$ | $1/2^-$ | **** | ○ ◇ ★ ▷ | ***- | **** | *** | * | ***- | *- - | - - | - - | | |
| $N(1675)$ | $5/2^-$ | **** | ○ ◇ ★ ▷ | **** | **** | **** | *** | * | * | * | - | | |
| $N(1680)$ | $5/2^+$ | **** | ○ ◇ ★ ▷ | **** | **** | **** | *** | * | * | * | - - - - | | |
| $N(1700)$ | $3/2^-$ | *** | ○ ▷ | ** | *** | **- | * | * | - - | - | - | | |
| $N(1710)$ | $1/2^+$ | ***- | ○ ◇ ▷ | ***- | ***- | *- | | **- | ** | * | * | * | |
| $N(1720)$ | $3/2^+$ | **** | ○ ◇ ★ ▷ | **-- | **** | **- | * | * | **-- | * | *- | * | |
| $N(1860)$ | $5/2^+$ | ** | ▷ | * | ** | | * | * | | | | | |
| $N(1875)$ | $3/2^-$ | *** | ○ ▷ | ** | ** | * | ** | * | * | * | * | * | |
| $N(1880)$ | $1/2^+$ | *** | ○ ▷ | ** | * | ** | * | * | ** | ** | | ** | |
| $N(1895)$ | $1/2^-$ | **** | ○ ▷ | **** | * | * | * | **** | ** | ** | * | * | **** |
| $N(1900)$ | $3/2^+$ | ***- | ○ ◇ ▷ | **** | ** | ** | * | * | ** | ** | - | * | ** |
| $N(1990)$ | $7/2^+$ | ** | ○ ◇ ▷ | **- | ** | | | * | * | * | | | |
| $N(2000)$ | $5/2^+$ | ** | ○ ★ | ** | *- | ** | * | * | - | - | - - | * | |
| $N(2040)$ | $3/2^+$ | * | ▷ | | * | | | | | | | | |
| $N(2060)$ | $5/2^-$ | *** | ○ $\diamond_g$ ▷ | *** | ** | * | * | * | * | * | * | * | |
| $N(2100)$ | $1/2^+$ | ***- | ○ ▷ | ** | ***- | ** | ** | * | * | | * | * | ** |
| $N(2120)$ | $3/2^-$ | *** | ○ ▷ | *** | ** | ** | ** | | ** | * | | * | * |
| $N(2190)$ | $7/2^-$ | **** | ○ ◇ ★ ▷ | ***- | **** | ***- | ** | * | **- | * | * | * | |
| $N(2220)$ | $9/2^+$ | **** | ○ ◇ ★ | ** | **** | | | * | * | * | | | |
| $N(2250)$ | $9/2^-$ | **** | ○ ◇ ★ ▷ | ** | **** | | | * | * | * | | | |
| $N(2300)$ | $1/2^+$ | ** | | | ** | | | | | | | | |
| $N(2570)$ | $5/2^-$ | ** | | | ** | | | | | | | | |
| $N(2600)$ | $11/2^-$ | *** | ★ | | *** | | | | | | | | |
| $N(2700)$ | $13/2^+$ | ** | | | ** | | | | | | | | |

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# N*

| Particle | $J^P$ | overall | PWA | $N\gamma$ | $N\pi$ | $\Delta\pi$ | $N\sigma$ | $N\eta$ | $\Lambda K$ | $\Sigma K$ | $N\rho$ | $N\omega$ | $N\eta'$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $N$ | $1/2^+$ | **** | | | | | | | | | | | |
| $N(1440)$ | $1/2^+$ | **** | ○ $\diamond_g$ ★ ▷ | ***- | **** | ***- | *** | - | | | - | | |
| $N(1520)$ | $3/2^-$ | **** | ○ ◇ ★ ▷ | **** | **** | **** | ** | ***- | | | - - - - | | |
| $N(1535)$ | $1/2^-$ | **** | ○ ◇ ★ ▷ | ***- | **** | *** | * | **** | | | - - | | |
| $N(1650)$ | $1/2^-$ | **** | ○ ◇ ★ ▷ | ***- | **** | *** | * | ***- | *- - | - - | - - | | |
| $N(1675)$ | $5/2^-$ | **** | ○ ◇ ★ ▷ | **** | **** | **** | *** | * | * | * | - | | |
| $N(1680)$ | $5/2^+$ | **** | ○ ◇ ★ ▷ | **** | **** | **** | *** | * | * | * | - - - - | | |
| $N(1700)$ | $3/2^-$ | *** | ○ ▷ | ** | *** | ***- | * | * | - - | - | - | | |
| $N(1710)$ | $1/2^+$ | ***- | ○ ◇ ▷ | ***- | ***- | *- | | ***- | ** | * | * | * | |
| $N(1720)$ | $3/2^+$ | **** | ○ ◇ ★ ▷ | ****- | **** | ***- | * | * | ****- | * | *- | * | |
| $N(1860)$ | $5/2^+$ | ** | ▷ | * | ** | | * | * | | | | | |
| $N(1875)$ | $3/2^-$ | *** | ○ ▷ | ** | ** | * | ** | * | * | * | * | * | |
| $N(1880)$ | $1/2^+$ | *** | ○ ▷ | ** | * | ** | * | * | ** | ** | | ** | |
| $N(1895)$ | $1/2^-$ | **** | ○ ▷ | **** | * | * | * | **** | ** | ** | * | * | **** |
| $N(1900)$ | $3/2^+$ | ***- | ○ ◇ ▷ | **** | ** | ** | * | * | ** | ** | - | * | ** |
| $N(1990)$ | $7/2^+$ | ** | ○ ◇ ▷ | *- | ** | | | * | * | * | | | |
| $N(2000)$ | $5/2^+$ | ** | ○ ★ | ** | *- | ** | * | * | - | - | - - | * | |
| $N(2040)$ | $3/2^+$ | * | ▷ | | * | | | | | | | | |
| $N(2060)$ | $5/2^-$ | *** | ○ $\diamond_g$ ▷ | *** | ** | * | * | * | * | * | * | * | |
| $N(2100)$ | $1/2^+$ | ***- | ○ ▷ | ** | *** | ** | ** | * | * | | * | * | ** |
| $N(2120)$ | $3/2^-$ | *** | ○ ▷ | *** | ** | ** | ** | | ** | * | | * | * |
| $N(2190)$ | $7/2^-$ | **** | ○ ◇ ★ ▷ | ***- | **** | ***- | ** | * | ** | * | * | * | |
| $N(2220)$ | $9/2^+$ | **** | ○ ◇ ★ | ** | **** | | | * | * | * | | | |
| $N(2250)$ | $9/2^-$ | **** | ○ ◇ ★ ▷ | ** | **** | | | * | * | * | | | |
| $N(2300)$ | $1/2^+$ | ** | | | ** | | | | | | | | |
| $N(2570)$ | $5/2^-$ | ** | | | ** | | | | | | | | |
| $N(2600)$ | $11/2^-$ | *** | ★ | | *** | | | | | | | | |
| $N(2700)$ | $13/2^+$ | ** | | | ** | | | | | | | | |

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|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $N$ | $1/2^+$ | **** | | | | | | | | | | | |
| $N(1440)$ | $1/2^+$ | **** | ○ $\diamond_g$ ★ ▷ | ***- | **** | ***- | *** | - | | | - | | |
| $N(1520)$ | $3/2^-$ | **** | ○ ◇ ★ ▷ | **** | **** | **** | ** | ***- | | | - - - - | | |
| $N(1535)$ | $1/2^-$ | **** | ○ ◇ ★ ▷ | ***- | **** | *** | * | **** | | | - - | | |
| $N(1650)$ | $1/2^-$ | **** | ○ ◇ ★ ▷ | ***- | **** | *** | * | ***- | *- - | - - | - - | | |
| $N(1675)$ | $5/2^-$ | **** | ○ ◇ ★ ▷ | **** | **** | **** | *** | * | * | * | - | | |
| $N(1680)$ | $5/2^+$ | **** | ○ ◇ ★ ▷ | **** | **** | **** | *** | * | * | * | - - - - | | |
| $N(1700)$ | $3/2^-$ | *** | ○ ▷ | ** | *** | ***- | * | * | - - | - | - | | |
| $N(1710)$ | $1/2^+$ | ***- | ○ ◇ ▷ | ***- | ***- | *- | | ***- | ** | * | * | * | |
| $N(1720)$ | $3/2^+$ | **** | ○ ◇ ★ ▷ | ****- | **** | ***- | * | * | ****- | * | *- | * | |
| $N(1860)$ | $5/2^+$ | ** | ▷ | * | ** | | * | * | | | | | |
| $N(1875)$ | $3/2^-$ | *** | ○ ▷ | ** | ** | * | ** | * | * | * | * | * | |
| $N(1880)$ | $1/2^+$ | *** | ○ ▷ | ** | * | ** | * | * | ** | ** | | ** | |
| $N(1895)$ | $1/2^-$ | **** | ○ ▷ | **** | * | * | * | **** | ** | ** | * | * | **** |
| $N(1900)$ | $3/2^+$ | ****- | ○ ◇ ▷ | **** | ** | ** | * | * | ** | ** | - | * | ** |
| $N(1990)$ | $7/2^+$ | ** | ○ ◇ ▷ | *- | ** | | | * | * | * | | | |
| $N(2000)$ | $5/2^+$ | ** | ○ ★ | ** | *- | ** | * | * | - | - | - - | * | |
| $N(2040)$ | $3/2^+$ | * | ▷ | | * | | | | | | | | |
| $N(2060)$ | $5/2^-$ | *** | ○ $\diamond_g$ ▷ | *** | ** | * | * | * | * | * | * | * | |
| $N(2100)$ | $1/2^+$ | ***- | ○ ▷ | ** | *** | ** | ** | * | * | | * | * | ** |
| $N(2120)$ | $3/2^-$ | *** | ○ ▷ | *** | ** | ** | ** | | ** | * | | * | * |
| $N(2190)$ | $7/2^-$ | **** | ○ ◇ ★ ▷ | ****- | **** | ****- | ** | * | ** | * | * | * | |
| $N(2220)$ | $9/2^+$ | **** | ○ ◇ ★ | ** | **** | | | * | * | * | | | |
| $N(2250)$ | $9/2^-$ | **** | ○ ◇ ★ ▷ | ** | **** | | | * | * | * | | | |
| $N(2300)$ | $1/2^+$ | ** | | | ** | | | | | | | | |
| $N(2570)$ | $5/2^-$ | ** | | | ** | | | | | | | | |
| $N(2600)$ | $11/2^-$ | *** | ★ | | *** | | | | | | | | |
| $N(2700)$ | $13/2^+$ | ** | | | ** | | | | | | | | |

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|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $N$ | $1/2^+$ | **** | | | | | | | | | | | |
| $N(1440)$ | $1/2^+$ | **** | ○ $\diamond_g$ ★ ▷ | ***- | **** | ***- | *** | - | | | - | | |
| $N(1520)$ | $3/2^-$ | **** | ○ ◇ ★ ▷ | **** | **** | **** | ** | ***- | | | - - - - | | |
| $N(1535)$ | $1/2^-$ | **** | ○ ◇ ★ ▷ | ***- | **** | **- | * | **** | | | - - | | |
| $N(1650)$ | $1/2^-$ | **** | ○ ◇ ★ ▷ | ***- | **** | *** | * | ***- | *- - | - - | - - | | |
| $N(1675)$ | $5/2^-$ | **** | ○ ◇ ★ ▷ | **** | **** | **** | *** | * | * | * | - | | |
| $N(1680)$ | $5/2^+$ | **** | ○ ◇ ★ ▷ | **** | **** | **** | *** | * | * | * | - - - - | | |
| $N(1700)$ | $3/2^-$ | *** | ○ ▷ | ** | *** | **- | * | * | - - | - | - | | |
| $N(1710)$ | $1/2^+$ | ***- | ○ ◇ ▷ | ***- | ***- | *- | | ***- | ** | * | * | * | |
| $N(1720)$ | $3/2^+$ | **** | ○ ◇ ★ ▷ | **-- | **** | **-- | * | * | **-- | * | *- | * | |
| $N(1860)$ | $5/2^+$ | ** | ▷ | * | ** | | * | * | | | | | |
| $N(1875)$ | $3/2^-$ | *** | ○ ▷ | ** | ** | * | ** | * | * | * | * | * | |
| $N(1880)$ | $1/2^+$ | *** | ○ ▷ | ** | * | ** | * | * | ** | ** | | ** | |
| $N(1895)$ | $1/2^-$ | **** | ○ ▷ | **** | * | * | * | **** | ** | ** | * | * | **** |
| $N(1900)$ | $3/2^+$ | ***- | ○ ◇ ▷ | **** | ** | ** | * | * | ** | ** | - | * | ** |
| $N(1990)$ | $7/2^+$ | ** | ○ ◇ ▷ | **- | ** | | | * | * | * | | | |
| $N(2000)$ | $5/2^+$ | ** | ○ ★ | ** | *- | ** | * | * | - | - | - - | * | |
| $N(2040)$ | $3/2^+$ | * | ▷ | | * | | | | | | | | |
| $N(2060)$ | $5/2^-$ | *** | ○ $\diamond_g$ ▷ | *** | ** | * | * | * | * | * | * | * | |
| $N(2100)$ | $1/2^+$ | ***- | ○ ▷ | ** | *** | ** | ** | * | * | | * | * | ** |
| $N(2120)$ | $3/2^-$ | *** | ○ ▷ | *** | ** | ** | ** | | ** | * | | * | * |
| $N(2190)$ | $7/2^-$ | **** | ○ ◇ ★ ▷ | ***- | **** | ***- | ** | * | **- | * | * | * | |
| $N(2220)$ | $9/2^+$ | **** | ○ ◇ ★ | ** | **** | | | * | * | * | | | |
| $N(2250)$ | $9/2^-$ | **** | ○ ◇ ★ ▷ | ** | **** | | | * | * | * | | | |
| $N(2300)$ | $1/2^+$ | ** | | | ** | | | | | | | | |
| $N(2570)$ | $5/2^-$ | ** | | | ** | | | | | | | | |
| $N(2600)$ | $11/2^-$ | *** | ★ | | *** | | | | | | | | |
| $N(2700)$ | $13/2^+$ | ** | | | ** | | | | | | | | |

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|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $N$ | $1/2^+$ | **** | | | | | | | | | | | |
| $N(1440)$ | $1/2^+$ | **** | ○ $\diamond_g$ ★ ▷ | ***- | **** | ***- | *** | - | | | - | | |
| $N(1520)$ | $3/2^-$ | **** | ○ ◇ ★ ▷ | **** | **** | **** | ** | ***- | | | - - - - | | |
| $N(1535)$ | $1/2^-$ | **** | ○ ◇ ★ ▷ | ***- | **** | **- | * | **** | | | - - | | |
| $N(1650)$ | $1/2^-$ | **** | ○ ◇ ★ ▷ | ***- | **** | *** | * | ***- | *- - | - - | - - | | |
| $N(1675)$ | $5/2^-$ | **** | ○ ◇ ★ ▷ | **** | **** | **** | *** | * | * | * | - | | |
| $N(1680)$ | $5/2^+$ | **** | ○ ◇ ★ ▷ | **** | **** | **** | *** | * | * | * | - - - - | | |
| $N(1700)$ | $3/2^-$ | *** | ○ ▷ | ** | *** | **- | * | * | - - | - | - | | |
| $N(1710)$ | $1/2^+$ | ***- | ○ ◇ ▷ | ***- | ***- | *- | | ***- | ** | * | * | * | |
| $N(1720)$ | $3/2^+$ | **** | ○ ◇ ★ ▷ | **** | **** | **** | * | * | ****- | * | *- | * | |
| $N(1860)$ | $5/2^+$ | ** | ▷ | * | ** | | * | * | | | | | |
| $N(1875)$ | $3/2^-$ | *** | ○ ▷ | ** | ** | * | ** | * | * | * | * | * | |
| $N(1880)$ | $1/2^+$ | *** | ○ ▷ | ** | * | ** | * | * | ** | ** | | ** | |
| $N(1895)$ | $1/2^-$ | **** | ○ ▷ | **** | * | * | * | **** | ** | ** | * | * | **** |
| $N(1900)$ | $3/2^+$ | ***- | ○ ◇ ▷ | **** | ** | ** | * | * | ** | ** | - | * | ** |
| $N(1990)$ | $7/2^+$ | ** | ○ ◇ ▷ | **- | ** | | | * | * | * | | | |
| $N(2000)$ | $5/2^+$ | ** | ○ ★ | ** | *- | ** | * | * | - | - | - - | * | |
| $N(2040)$ | $3/2^+$ | * | ▷ | | * | | | | | | | | |
| $N(2060)$ | $5/2^-$ | *** | ○ $\diamond_g$ ▷ | *** | ** | * | * | * | * | * | * | * | |
| $N(2100)$ | $1/2^+$ | ***- | ○ ▷ | ** | *** | ** | ** | * | * | | * | * | ** |
| $N(2120)$ | $3/2^-$ | *** | ○ ▷ | *** | ** | ** | ** | | ** | * | | * | * |
| $N(2190)$ | $7/2^-$ | **** | ○ ◇ ★ ▷ | ***- | **** | ***- | ** | * | **- | * | * | * | |
| $N(2220)$ | $9/2^+$ | **** | ○ ◇ ★ | ** | **** | | | * | * | * | | | |
| $N(2250)$ | $9/2^-$ | **** | ○ ◇ ★ ▷ | ** | **** | | | * | * | * | | | |
| $N(2300)$ | $1/2^+$ | ** | | | ** | | | | | | | | |
| $N(2570)$ | $5/2^-$ | ** | | | ** | | | | | | | | |
| $N(2600)$ | $11/2^-$ | *** | ★ | | *** | | | | | | | | |
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# Why studying photoproduction off the bound proton?

- We consider the neutron is on-shell while proton is off-shell.
- The higher the missing momentum is, more Final State Interactions (FSI) events will be present.
- What is the effect of the "off-shellness" of the nucleon in the observables?
- When the medium starts to affect the observables? (particularly important to interpret bound neutron data)

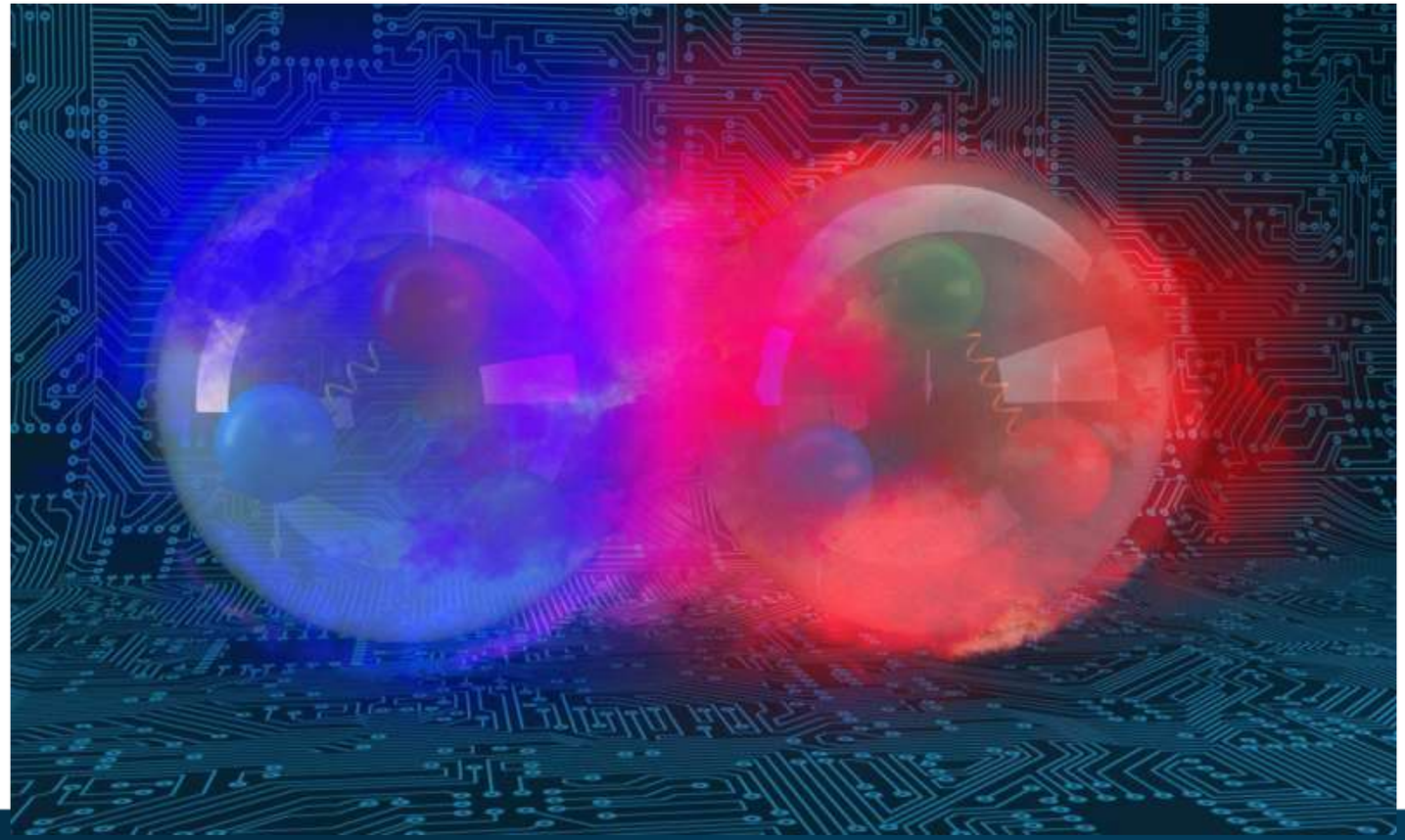

Figure credit: Andrew Sproles, Oak Ridge National laboratory

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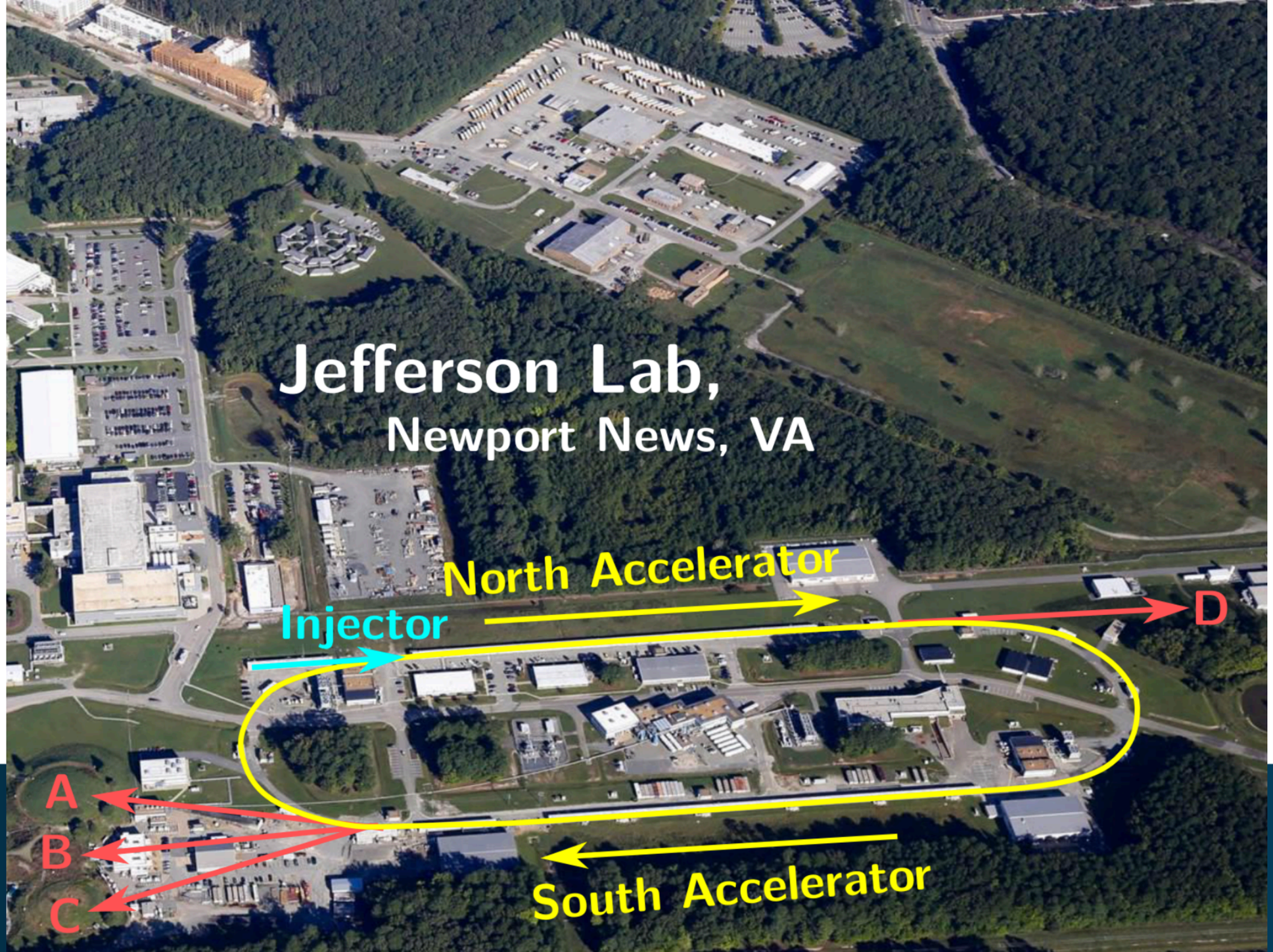
Courtesy A. Schimdt




Courtesy A. Schimdt

# Experimental Layout:
## Quick reminder of g13

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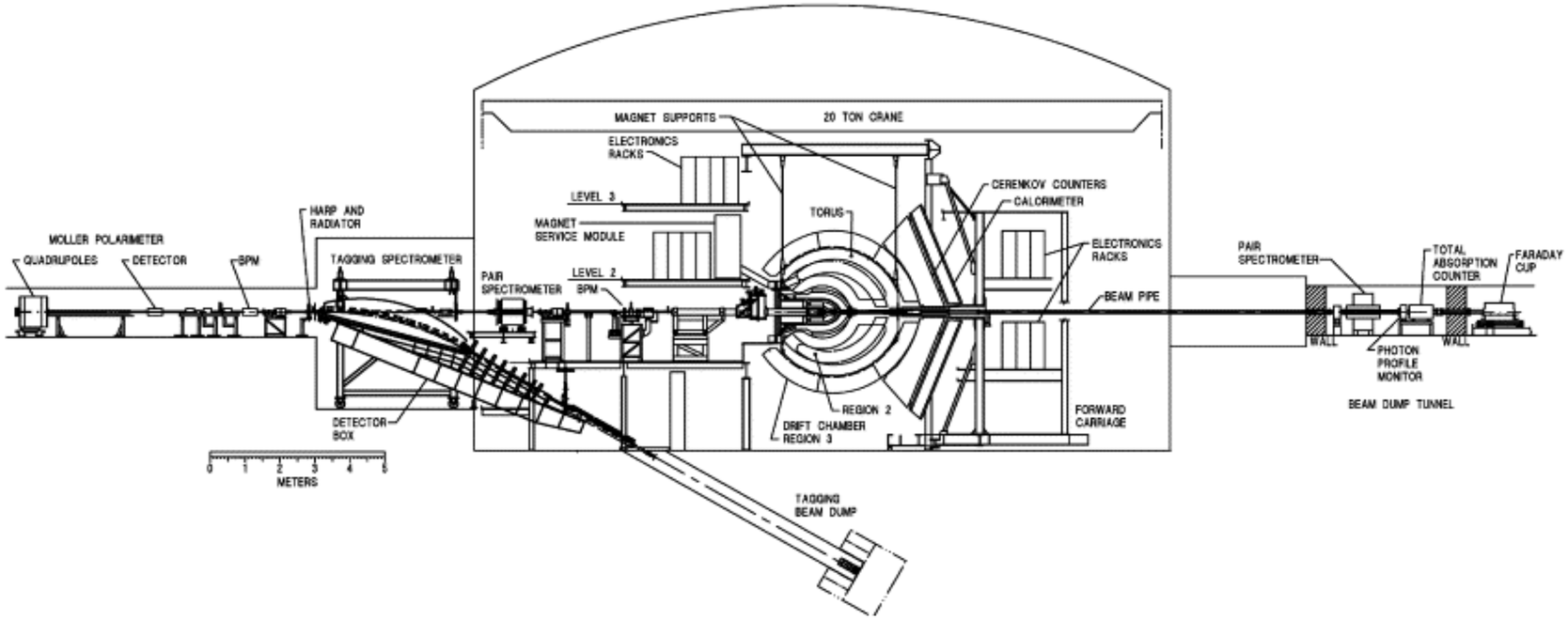

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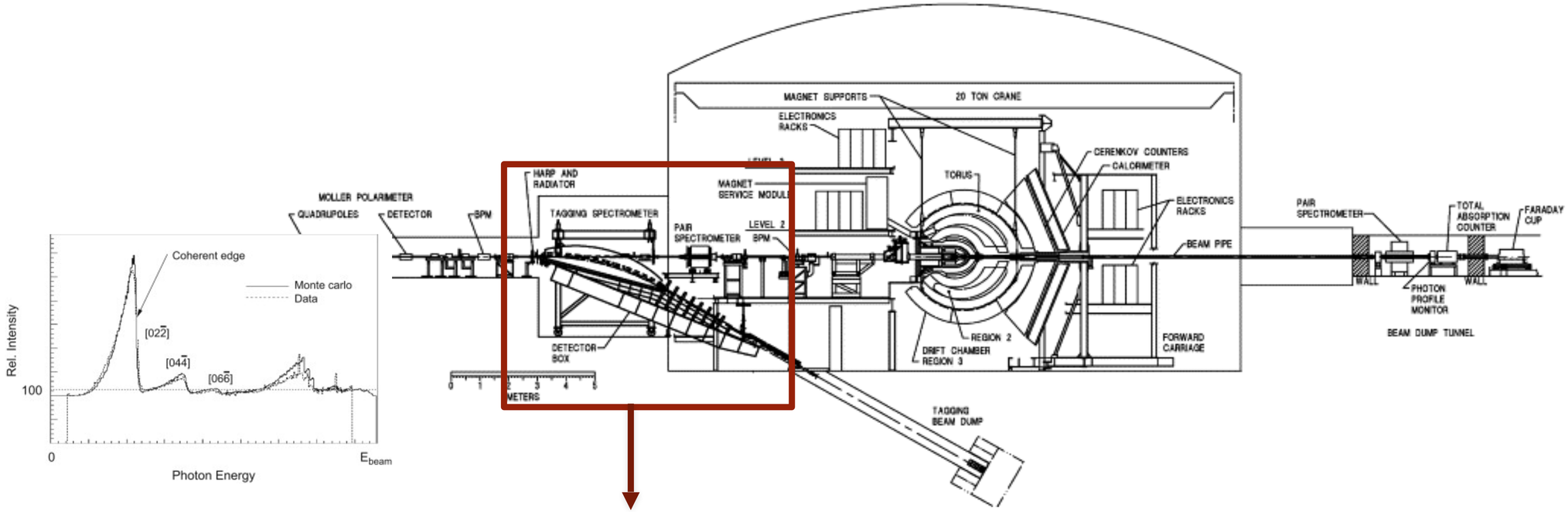
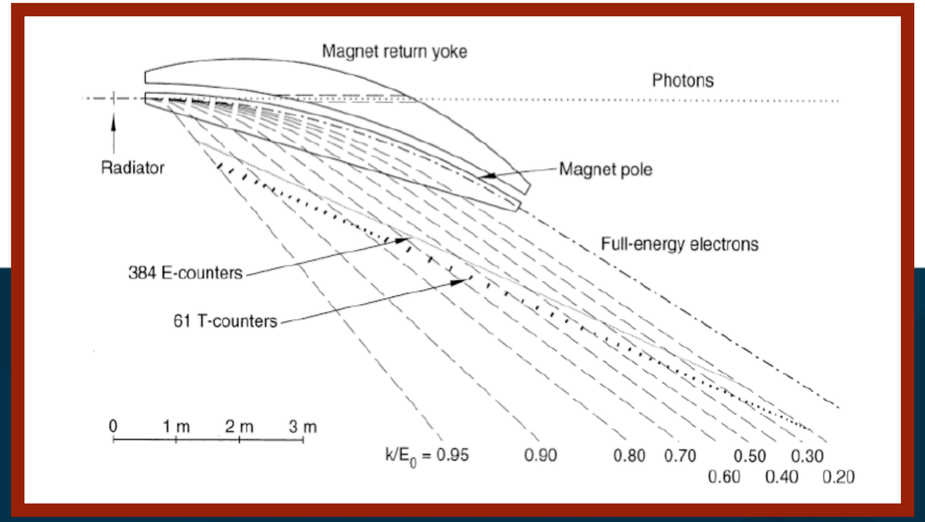
## Quick reminder of g13

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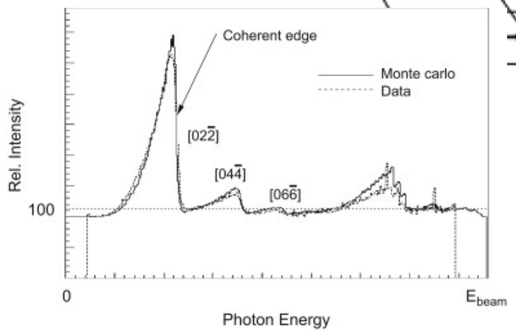
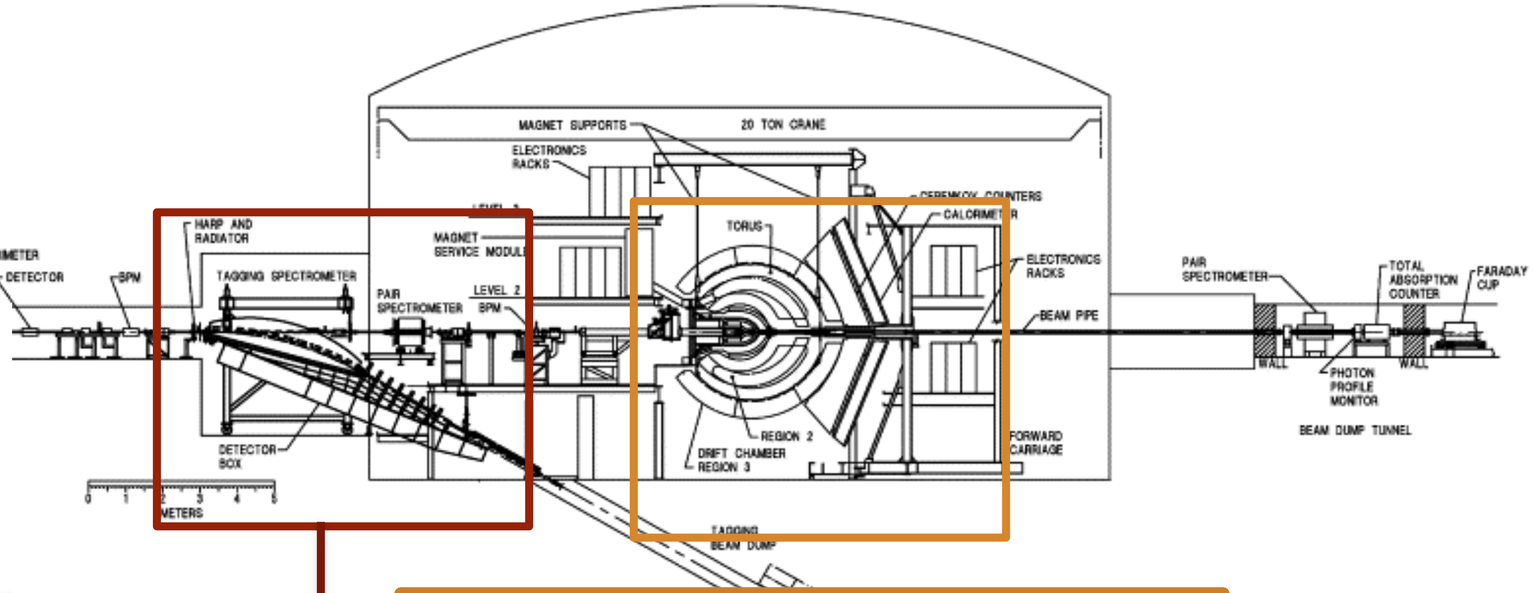
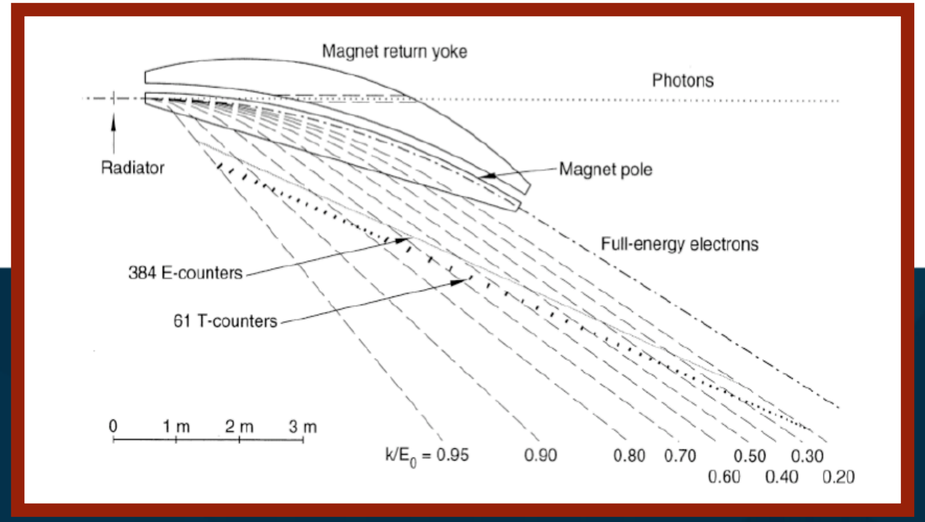
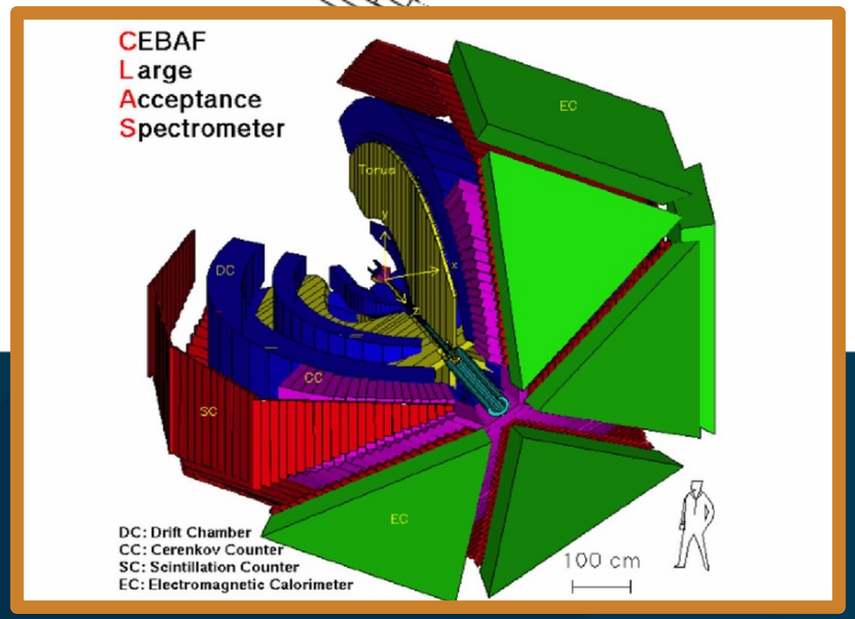
## Quick reminder of g13

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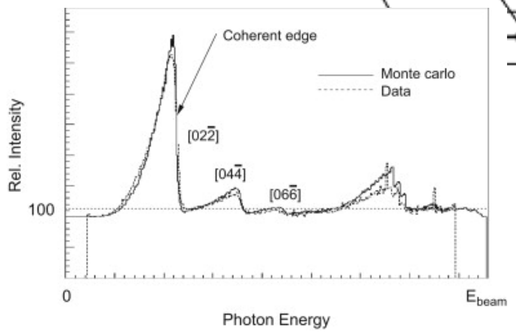
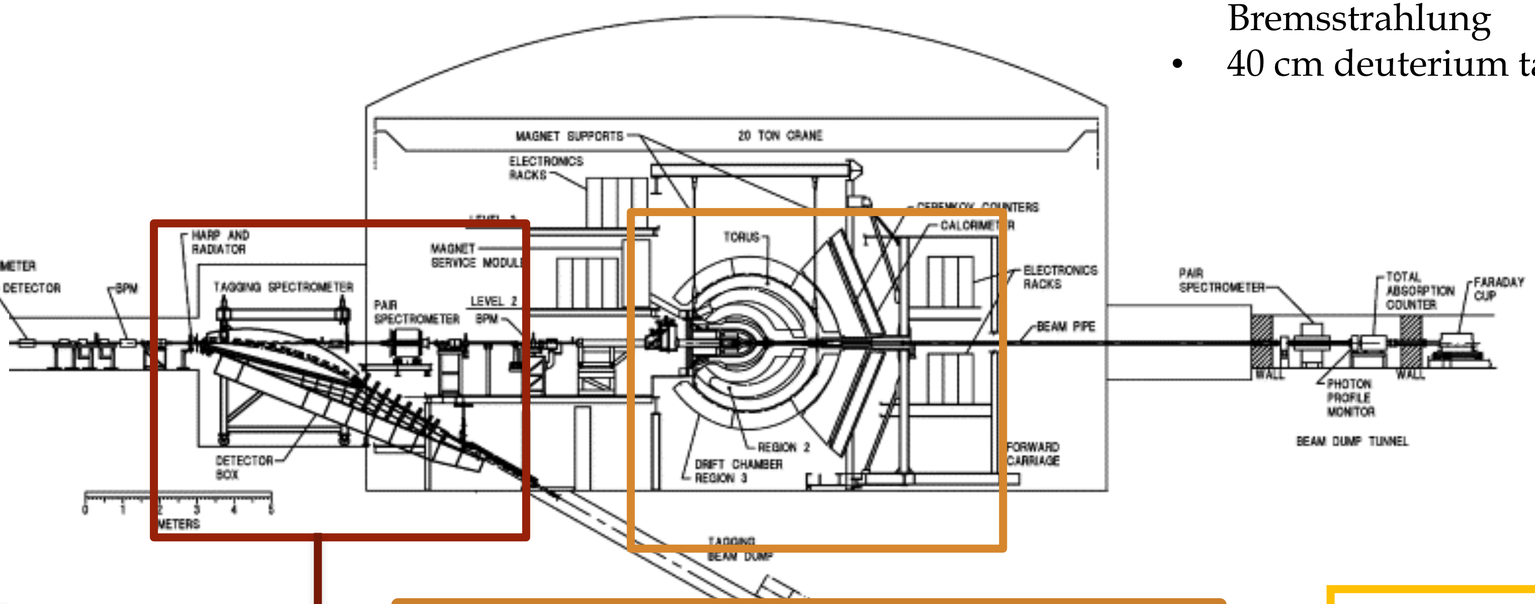
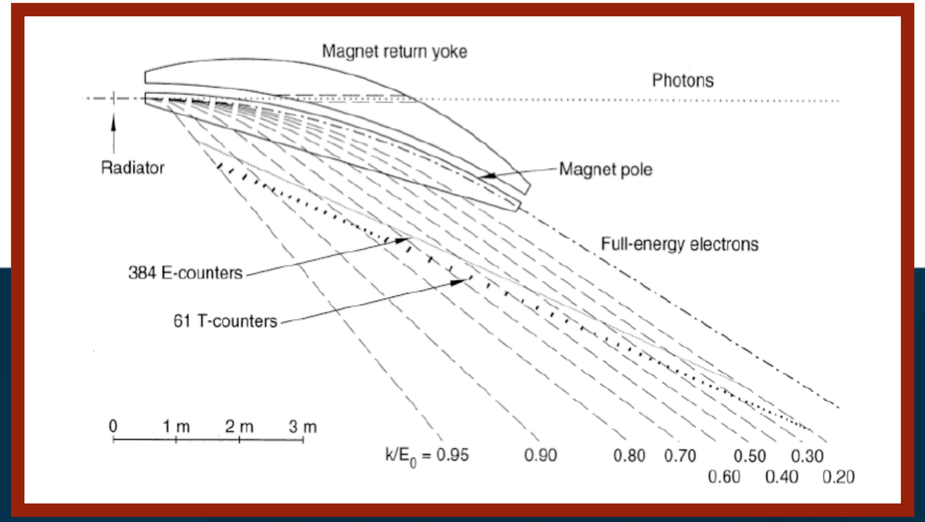
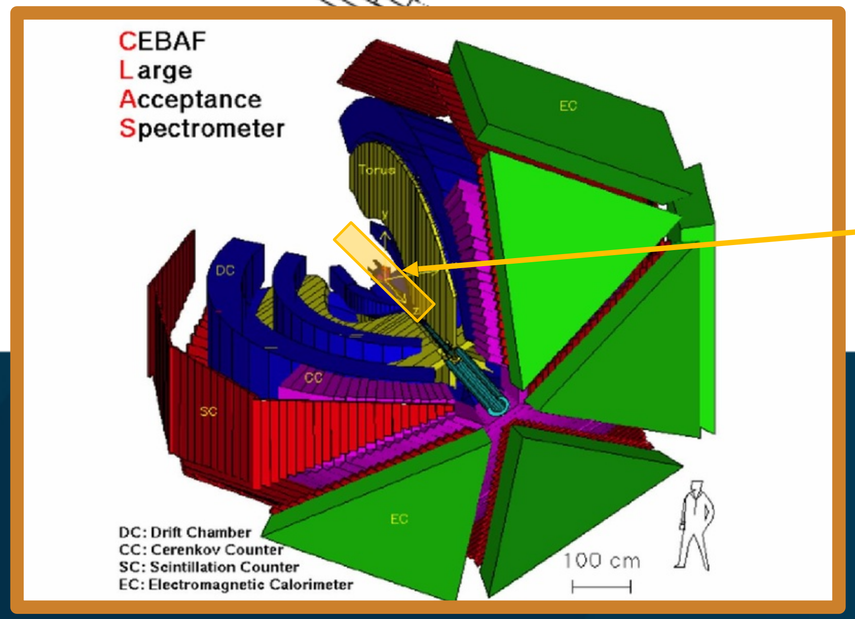
# Experimental Layout:
## Quick reminder of g13

g13b:
- Real photon. $1.1 \leq E_\gamma \leq 2.3$GeV
- Linearly polarized photons: Coherent Bremsstrahlung
- 40 cm deuterium target

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# Data Analysis: Event Reconstruction

# Data Analysis: Event Reconstruction

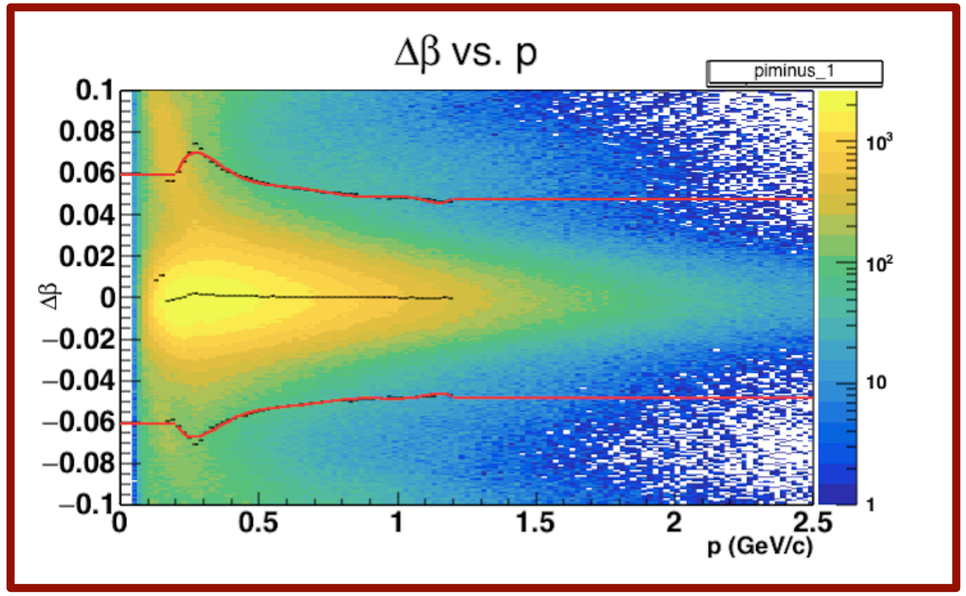
$$\gamma d \to \omega \quad p(n)$$

$$\omega \to \pi^+\pi^- \quad \pi^0$$

$$\pi^0 \to \gamma\gamma$$

# Data Analysis: Event Reconstruction

**Charged particle identification**

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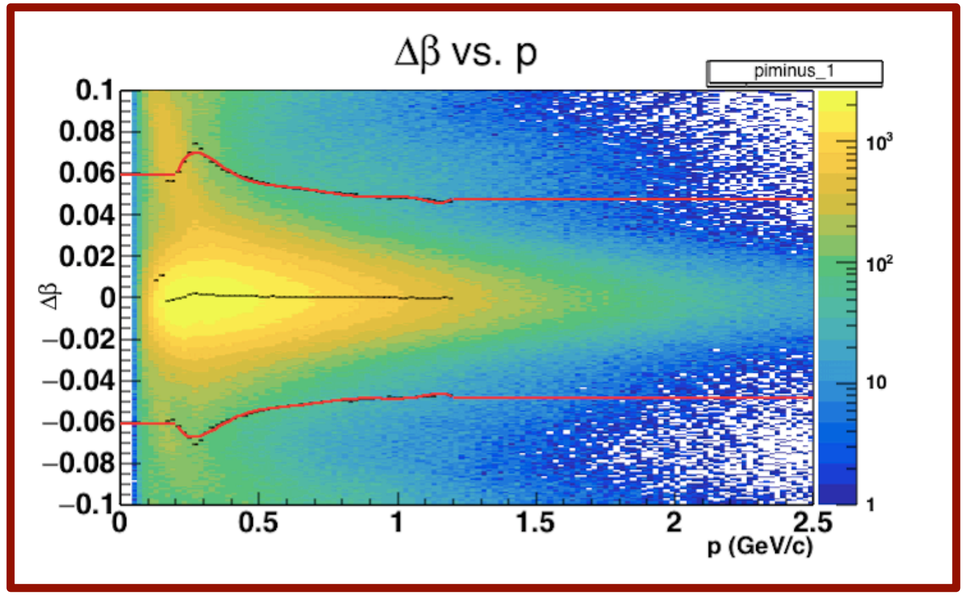
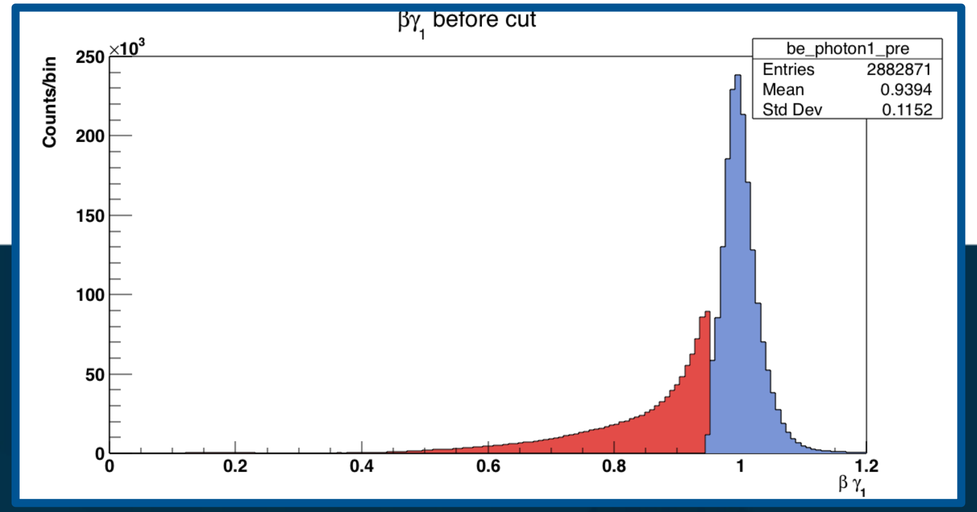



**Neutral particle identification**

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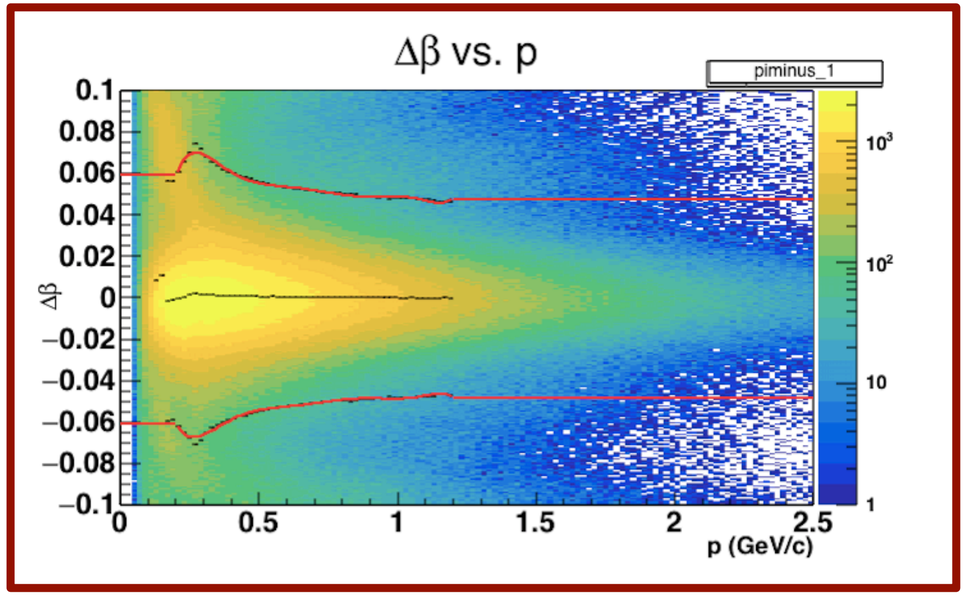
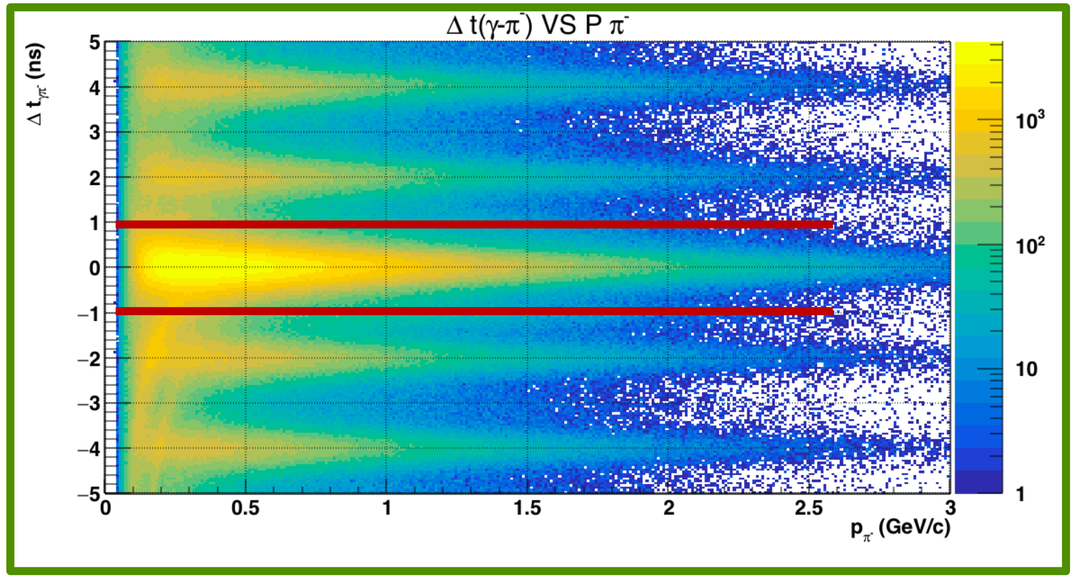



## Incident photon identification

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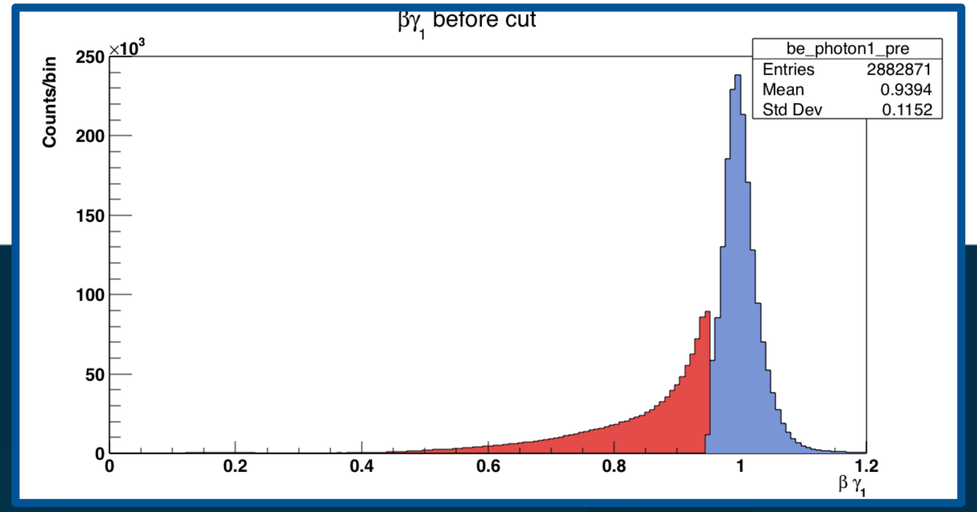


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# Data Analysis: Event Reconstruction

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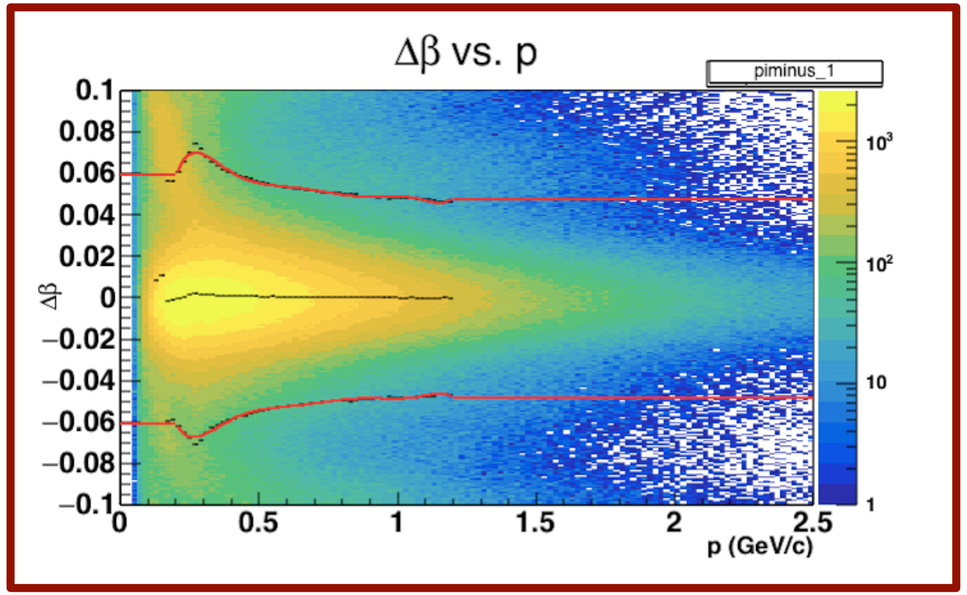


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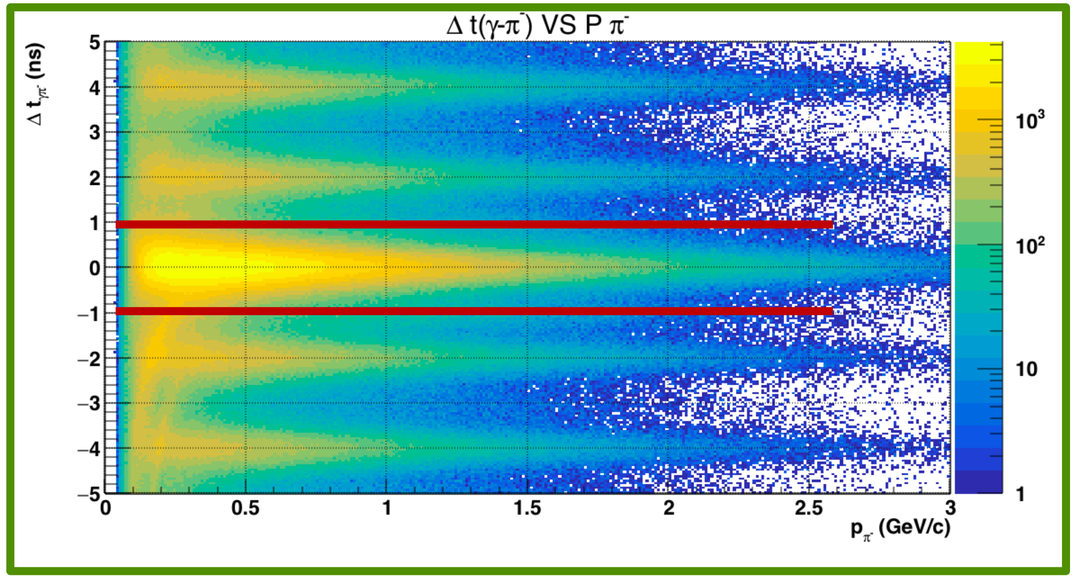


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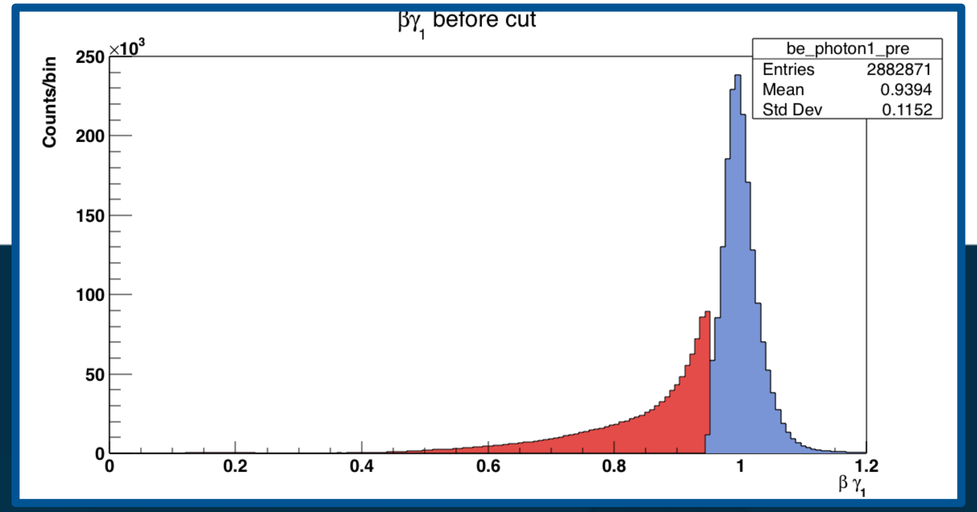
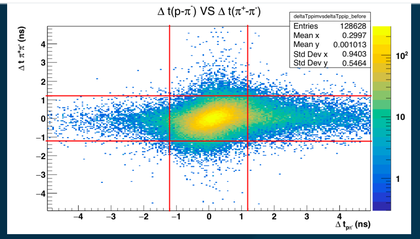
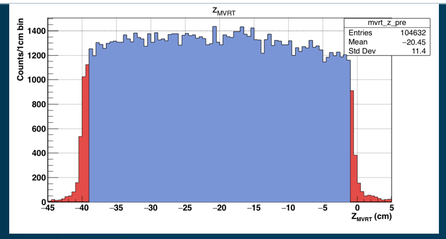



## Other cuts

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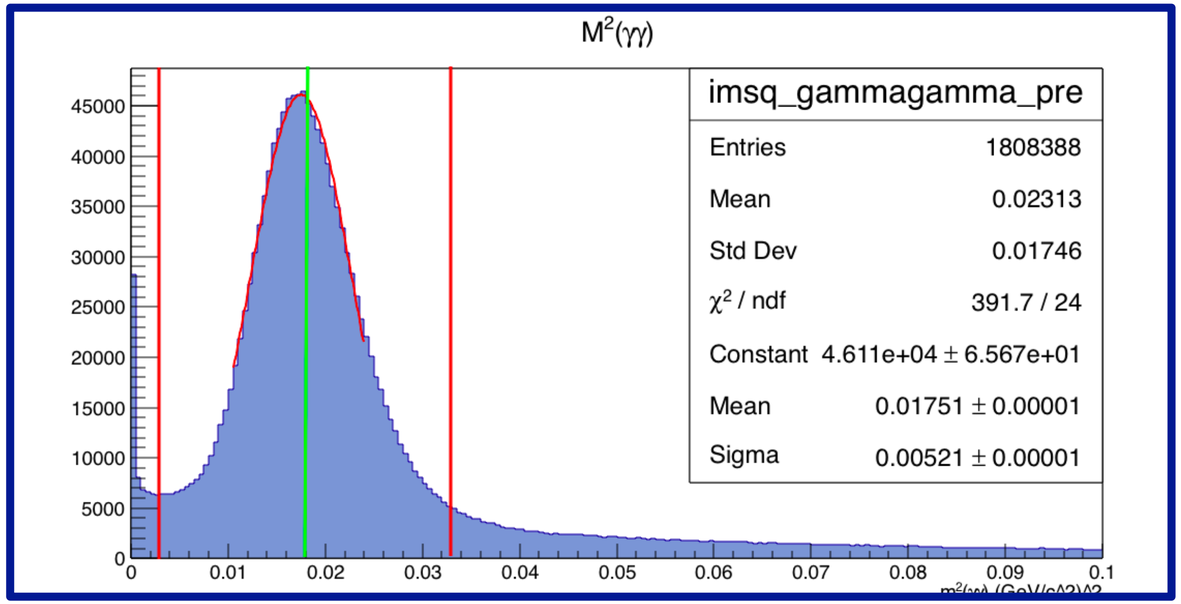

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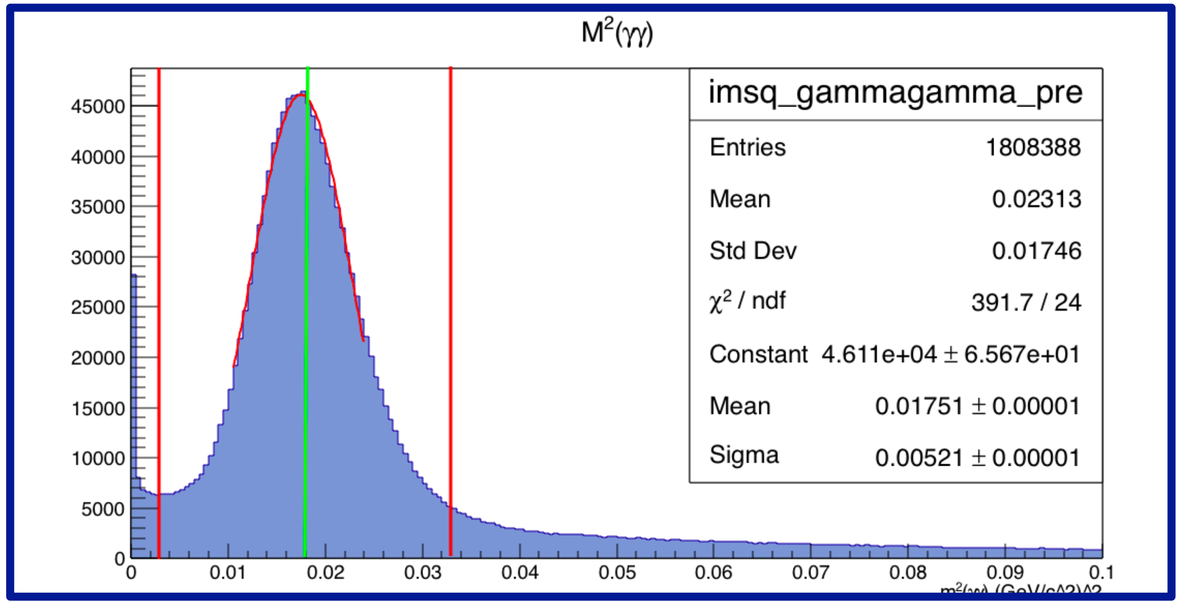


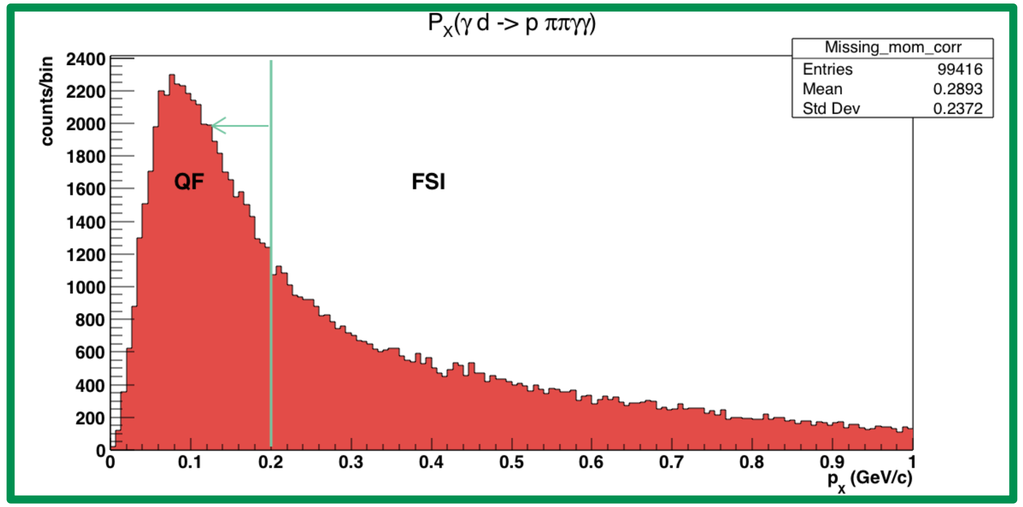

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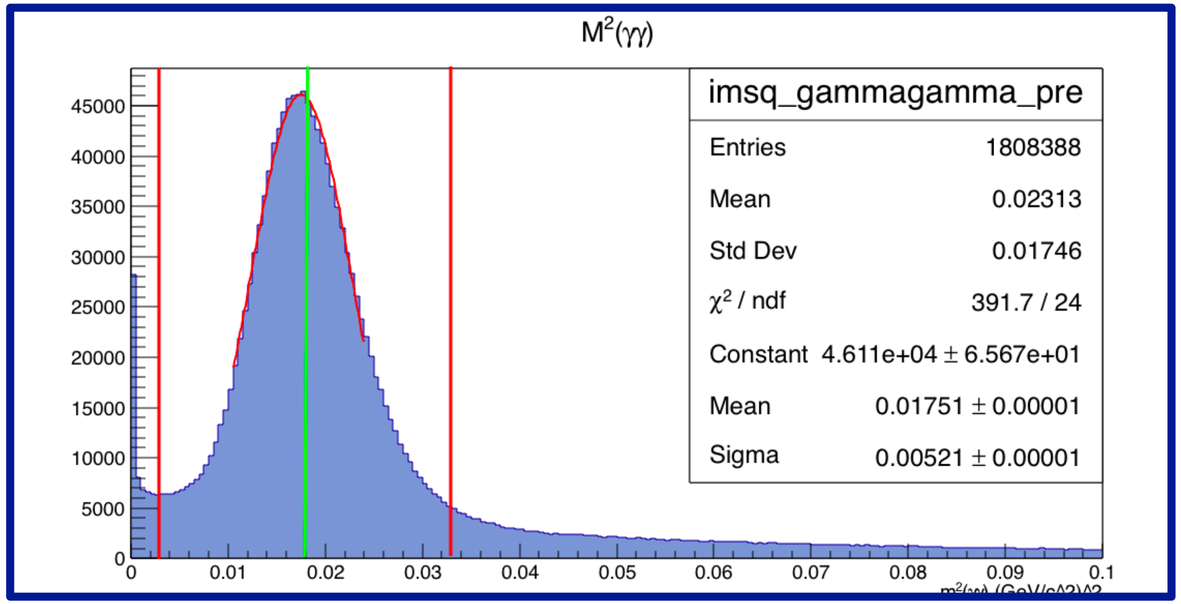


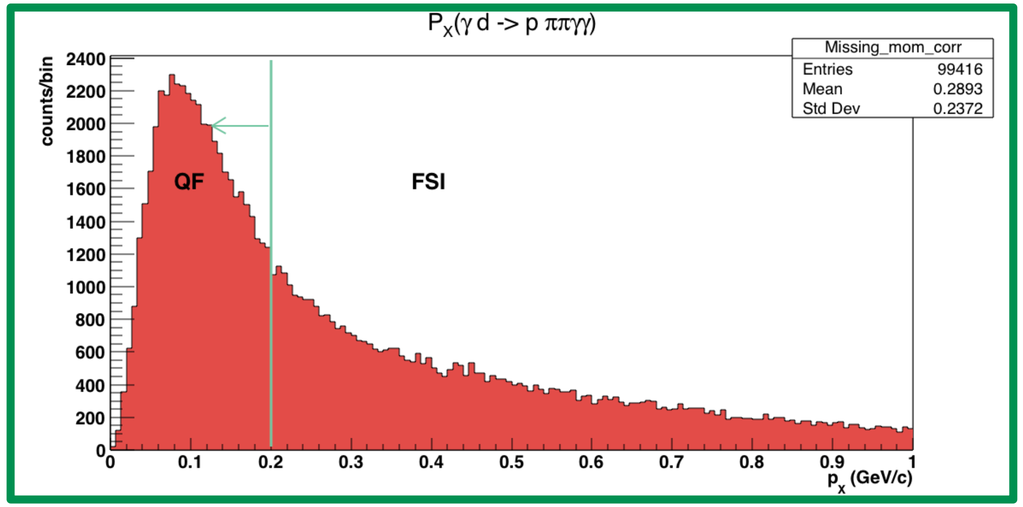


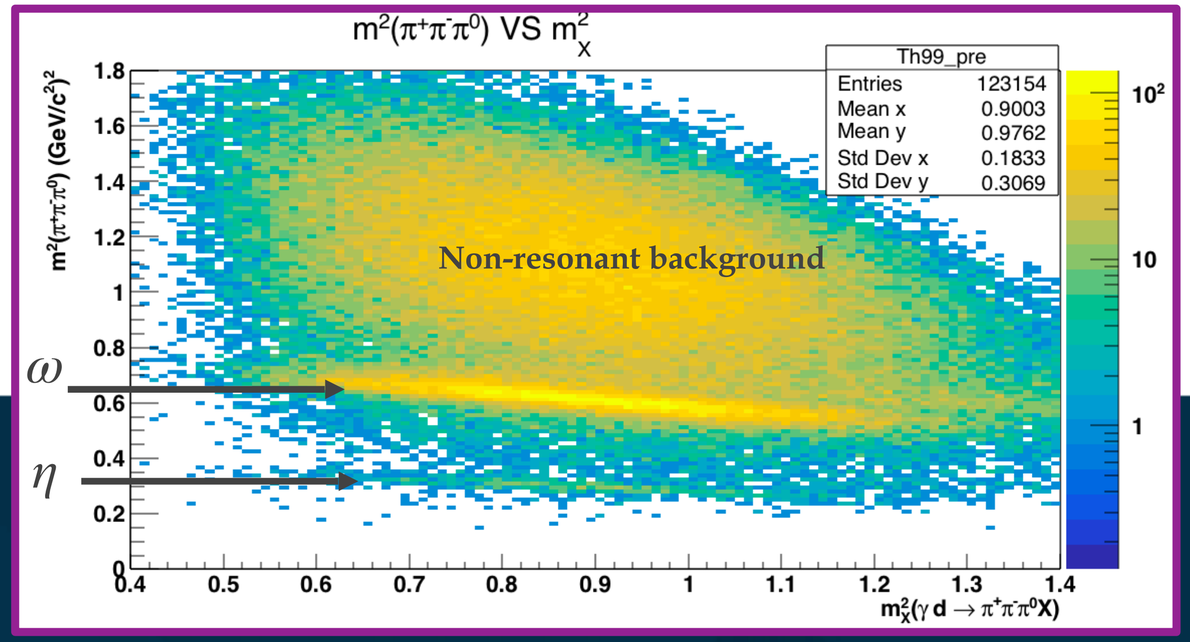

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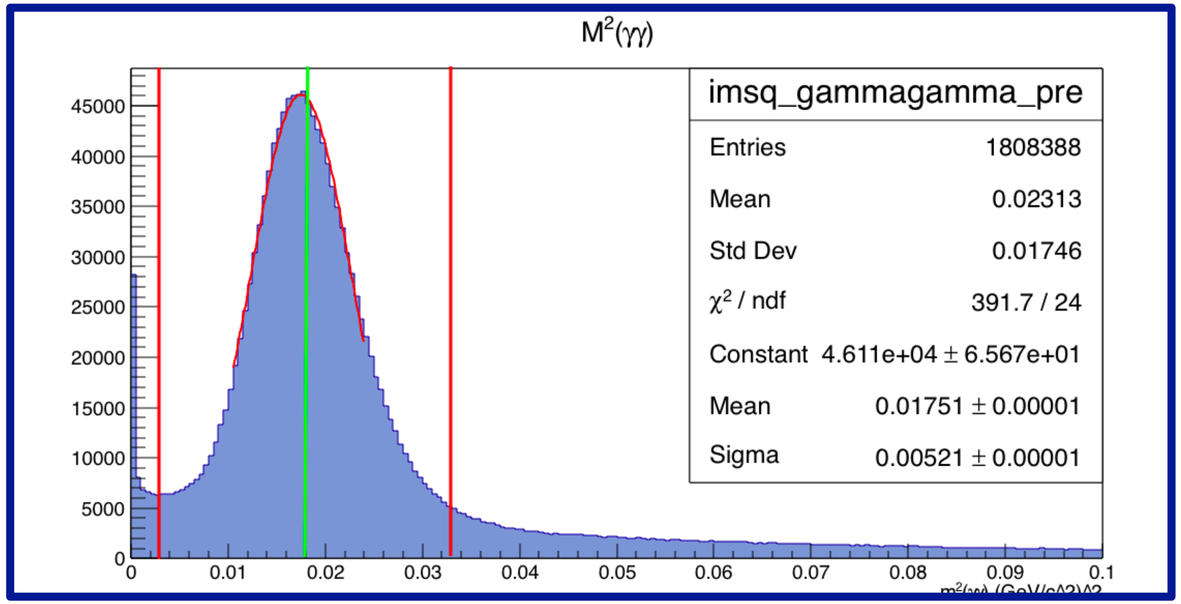
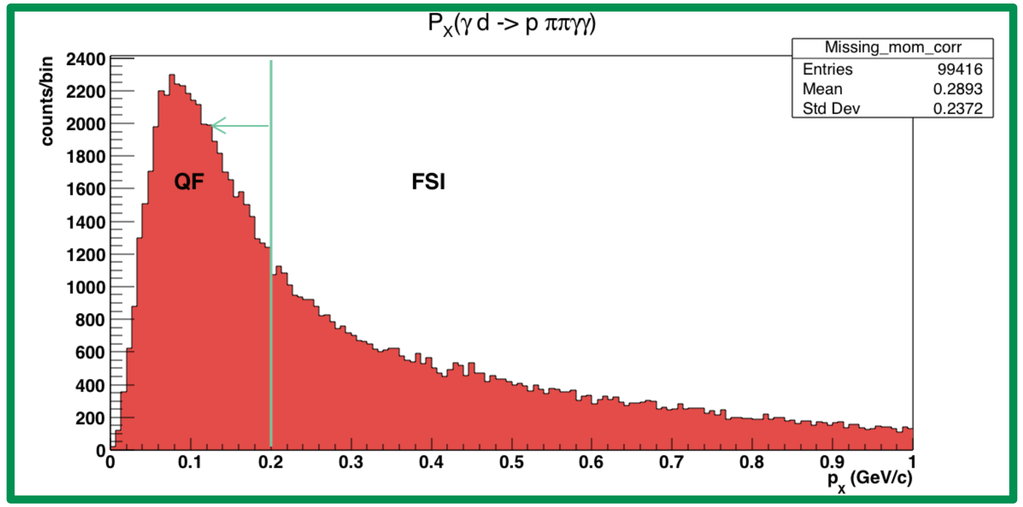
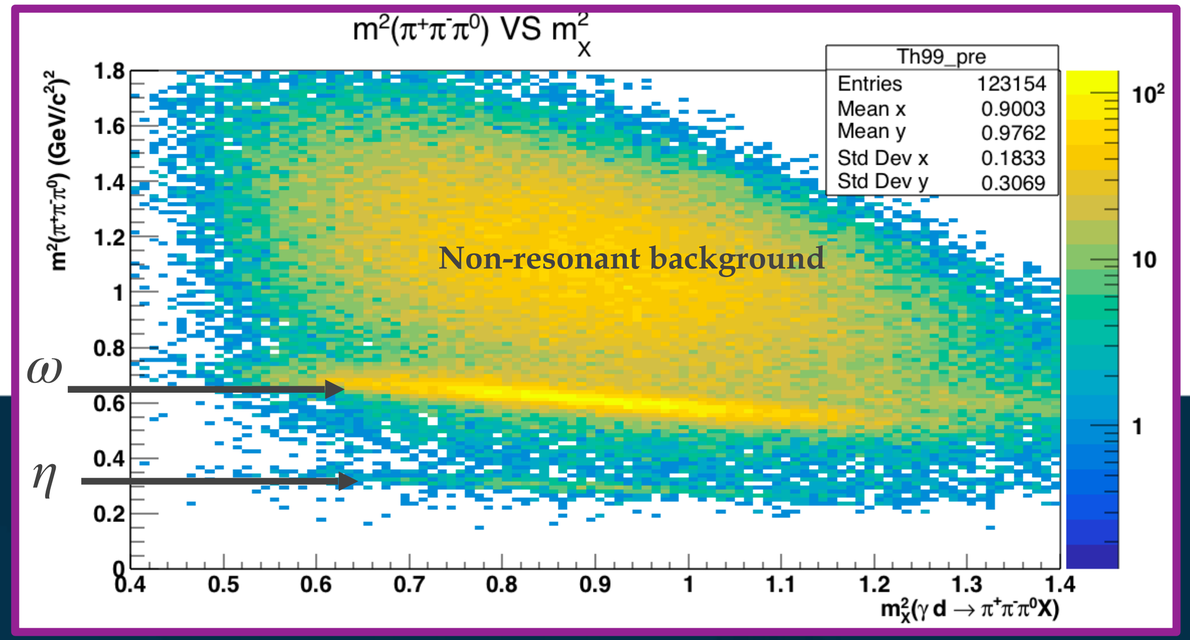
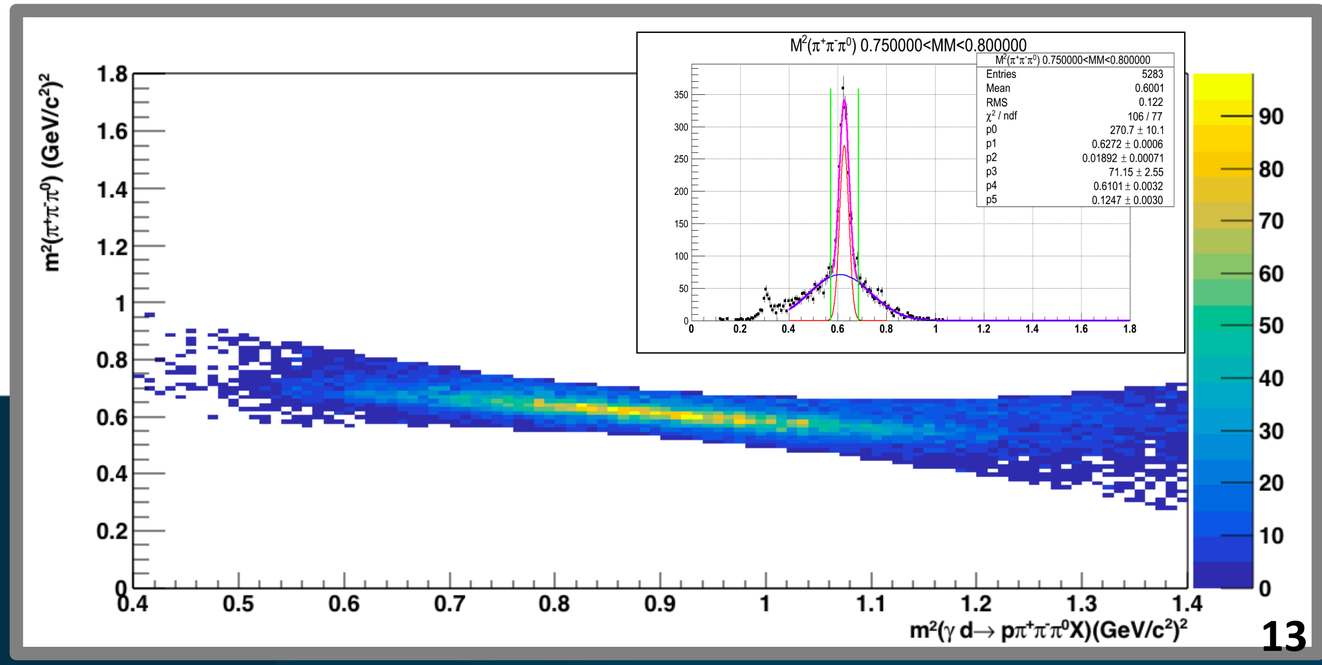
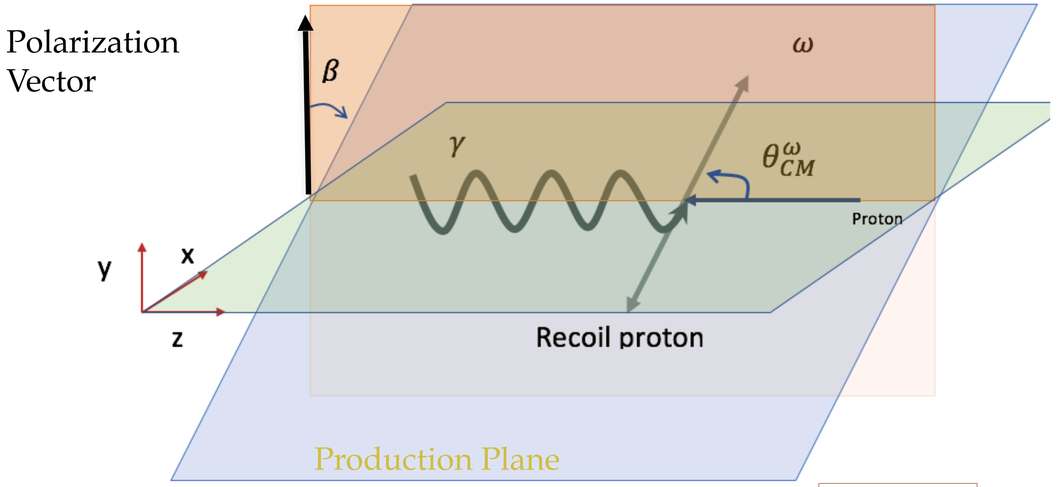


# Beam Asymmetry




$$\beta = \phi - \varphi$$

Perpendicular:

$$\varphi = \pi/2$$

Parallel:

$$\varphi = 0$$

$$P_R = \frac{P^{\parallel}}{P^{\perp}}$$

$$\frac{(\frac{dN}{d\phi})^{\perp} - (\frac{dN}{d\phi})^{\parallel}}{(\frac{dN}{d\phi})^{\parallel} + (\frac{dN}{d\phi})^{\perp}} = \frac{1 - F_R + \frac{F_R P_R + 1}{P_R + 1} 2\bar{P}\Sigma \frac{\sin\Delta\phi}{\Delta\phi} \cos(2(\phi - \phi_0))}{1 + F_R + \frac{F_R P_R - 1}{P_R + 1} 2\bar{P}\Sigma \frac{\sin\Delta\phi}{\Delta\phi} \cos(2(\phi - \phi_0))} \quad (1)$$

Background corrected

flux ratio $F_R = \frac{F^{\perp}}{F^{\parallel}}$

$$\bar{P} = \frac{P^{\parallel} + P^{\perp}}{2}$$

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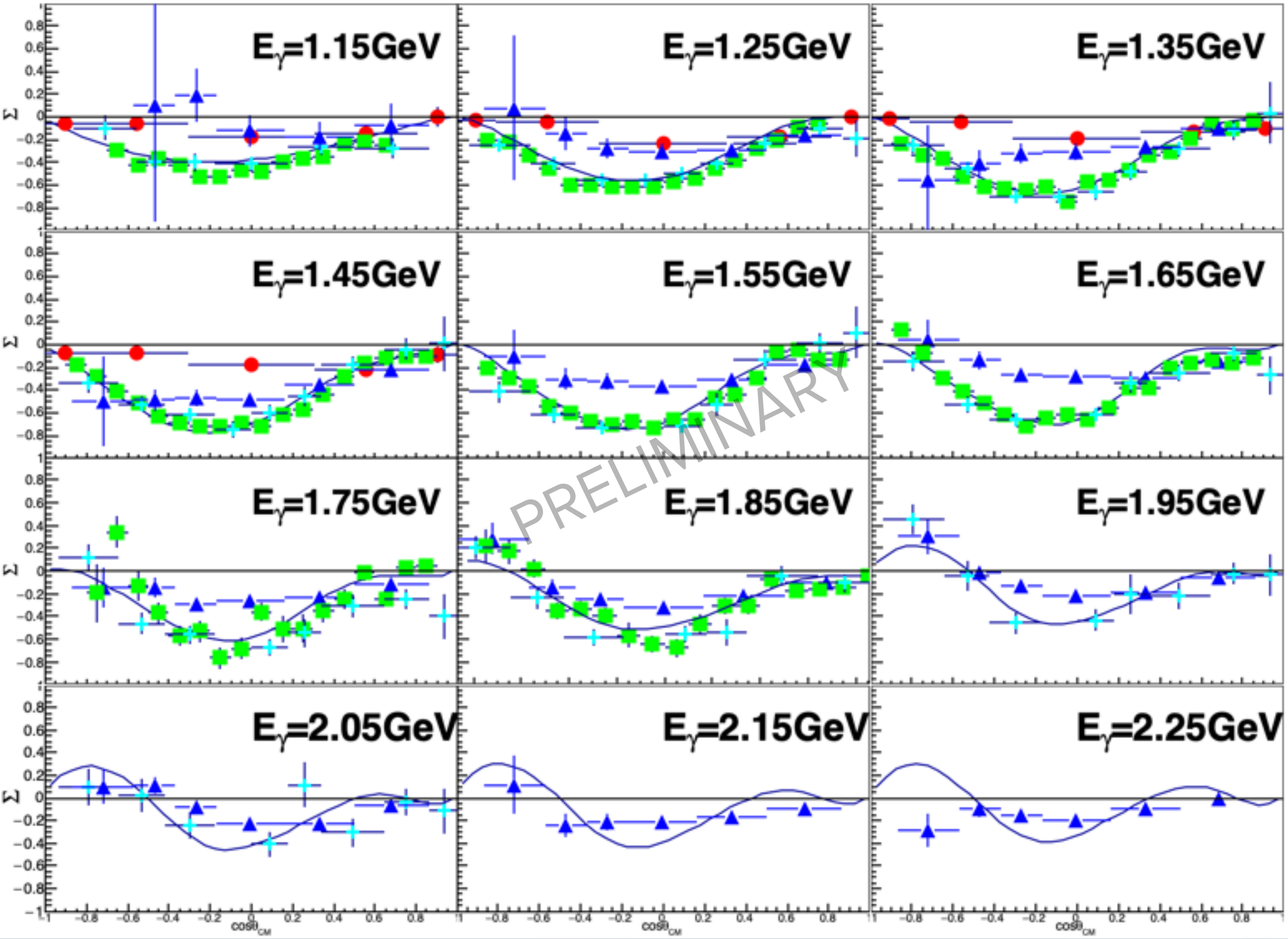


This work
Quasi free GRAAL (2015)
Free proton CLAS (2017)
Free Proton CLAS (2019)
Bonn-Gatchina (2016)

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# Systematic Uncertainties:

| Source of uncertainty | $\lvert\mu_{\Delta\Sigma}\rvert$ |
|---|---|
| $\phi_0$ offset | $10^{-6}$ |
| Photon flux ratio | $\sim 0.001$ |
| Polarization ratio | $< 1\%$ |
| Mean polarization | $5\%$ |
| Neutral particle cut | 0.017 |
| Incident photon identification | 0.001 |
| Out of time cut | 0.000 |
| $z$-vertex cut | 0.009 |
| Missing momentum cut | 0.021 |
| Dilution factor and $3-\sigma$ cut | 0.010 |

Largest source of uncertainty

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# Conclusions

- The $\omega$ channel is relevant in the study of higher mass resonances.
- We calculated the Beam Spin asymmetry for the photoproduced $\omega$ mesons off the bounded proton in the deuteron for $E_\gamma = 1.1 - 2.3$ GeV. (Higher Energies than previous CLAS data)
- Comparison with previous quasi-free data from GRAAL collaboration (V. Vegna et al.) agrees at low energy bins. The amplitude of the asymmetry reported in this work is larger than GRAAL reported results at $E_\gamma = 1.45$ GeV.
- Our results, compared to the free proton events reported from CLAS collaboration (2017 and 2019) are in general smaller in amplitude for middle angle range.
- Very useful discussion born in Santa Margherita. Ho trovato un paio di nuove idee a Portofino! Thank you!

# Thank you!

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# Questions?

This work was supported by the U.S. National Science Foundation NSF PHY-1307340 and NSF-PHY-1615146 and the U.S. Department of Energy Office of Science, Office of Nuclear Physics, under contract contract no. DE-SC0016583

# Backup slides

## Handling Background

- The first approach is to take all the events in the background region and calculate the angular asymmetry $\Sigma$.
- The events selected where those with $M^2(\pi^+\pi^-\pi^0) \geq 3\sigma_i$ (where $i$ denotes the $i$th bin in missing mass squared $M_X^2(\vec{\gamma}p \rightarrow p\pi^+\pi^-\pi^0 X)$ and $\sigma_i$ is the value of $\sigma$ for a gaussian fit around the $\omega$ peak ).
- A 2nd-degree polynomial fit is applied to these points.

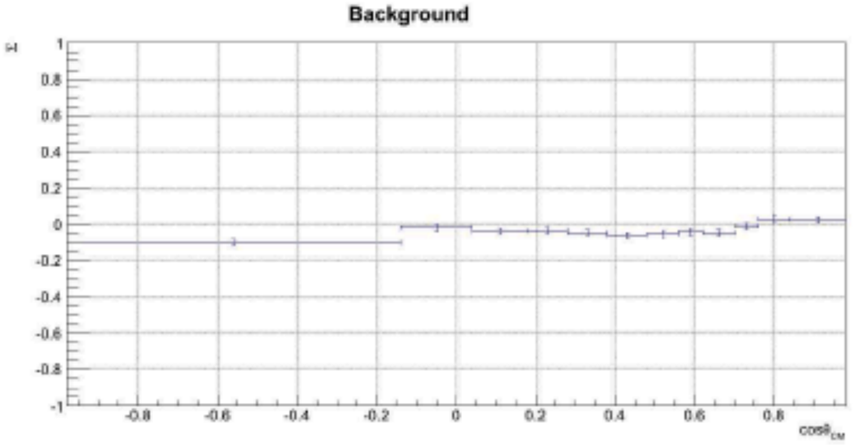



Figure: Example for $E_\gamma = 2.3$ GeV

# Handling Background

- Asymmetry for the background region around zero.
- Dilution factor approach

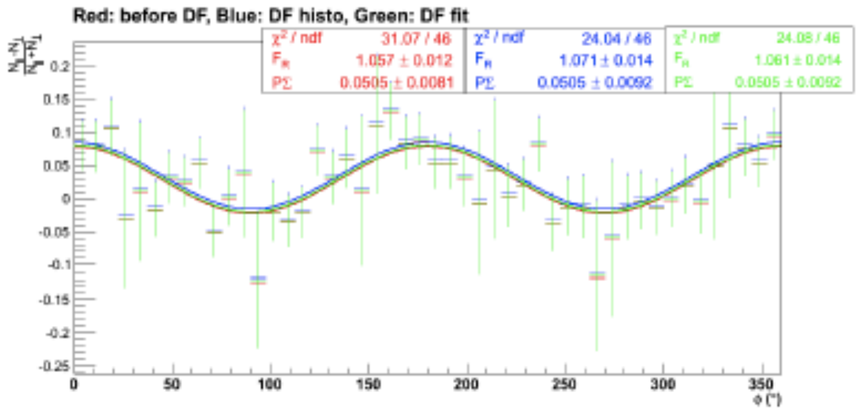
$$F = \frac{\sum_i (A_{tot} - A_{bkg})_i}{\sum_i (A_{bkg})_i}$$

$$\left(\frac{dN}{d\phi}\right)^{\parallel(\perp)}_{signal} = F^{\parallel(\perp)} \left(\frac{dN}{d\phi}\right)^{\parallel(\perp)}_{peak}$$

signal $\rightarrow \mu_i - 3\sigma_i \leq M^2(\pi^+\pi^-\pi^0) \leq \mu_i + 3\sigma_i$

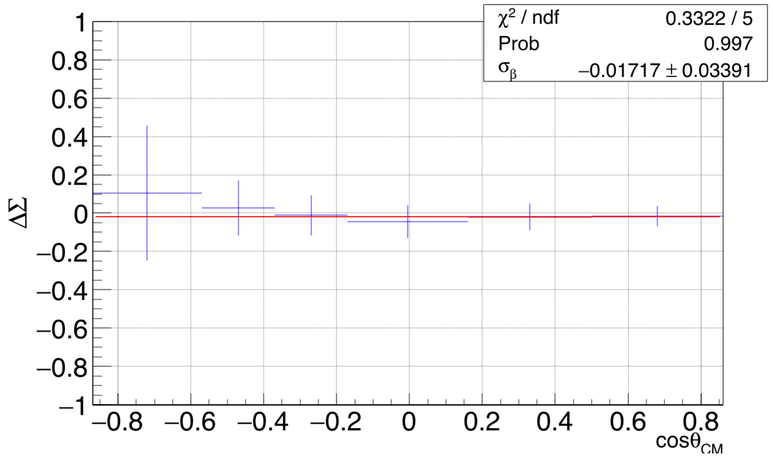
- $A_{peak}$ can be calculated integrating the model or integrating the histogram

| $E_\gamma$ (GeV) | $DF^{\parallel}_{HISTO}$ | $DF^{\parallel}_{FIT}$ | $DF^{\perp}_{HISTO}$ | $DF^{\perp}_{FIT}$ |
|---|---|---|---|---|
| 1.1-1.3 | 0.571 | 0.679 | 0.603 | 0.657 |
| 1.3-1.5 | 0.606 | 0.619 | 0.611 | 0.621 |
| 1.5-1.7 | 0.601 | 0.606 | 0.605 | 0.607 |
| 1.7-1.9 | 0.661 | 0.661 | 0.661 | 0.660 |
| 1.9-2.1 | 0.730 | 0.736 | 0.736 | 0.738 |
| 2.1-2.3 | 0.779 | 0.776 | 0.769 | 0.773 |

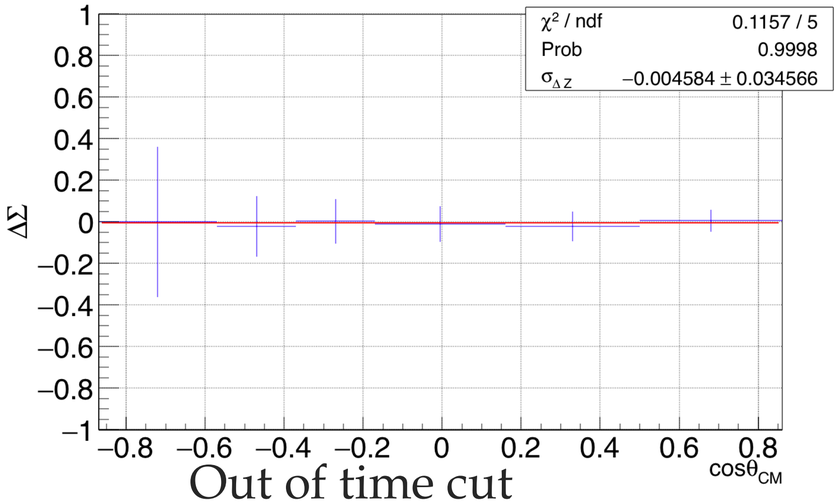


# Systematic Uncertainties: related with event selection

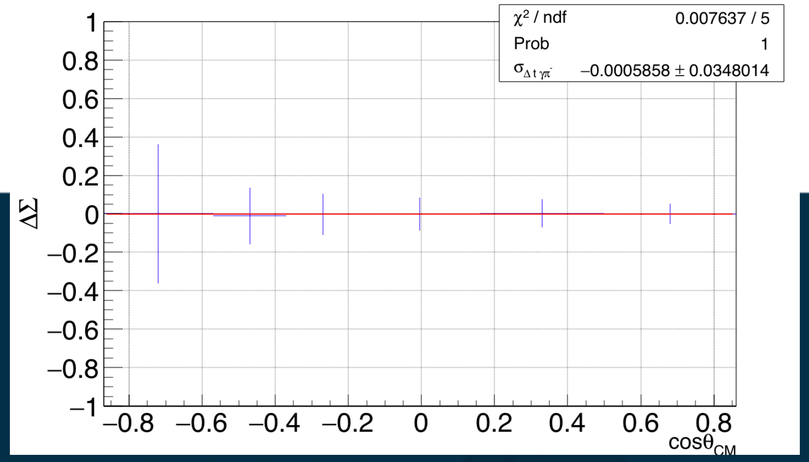
Neutral particle identification



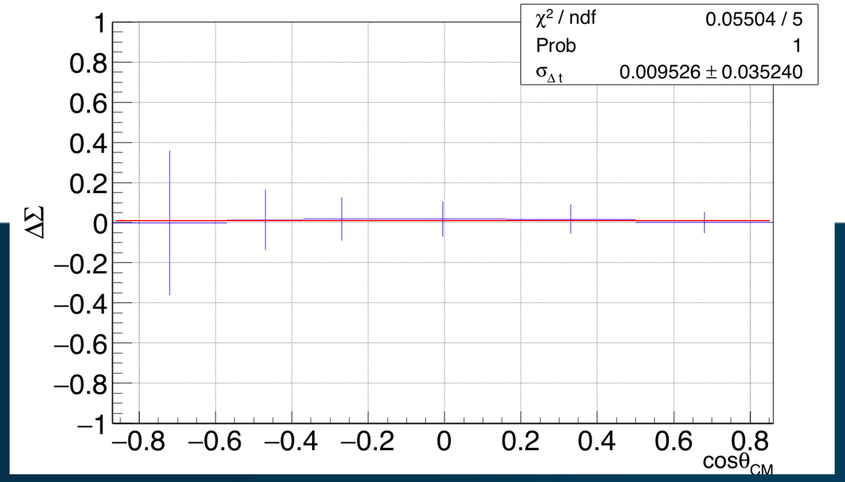

z-vertex




Photon identification cut




Out of time cut

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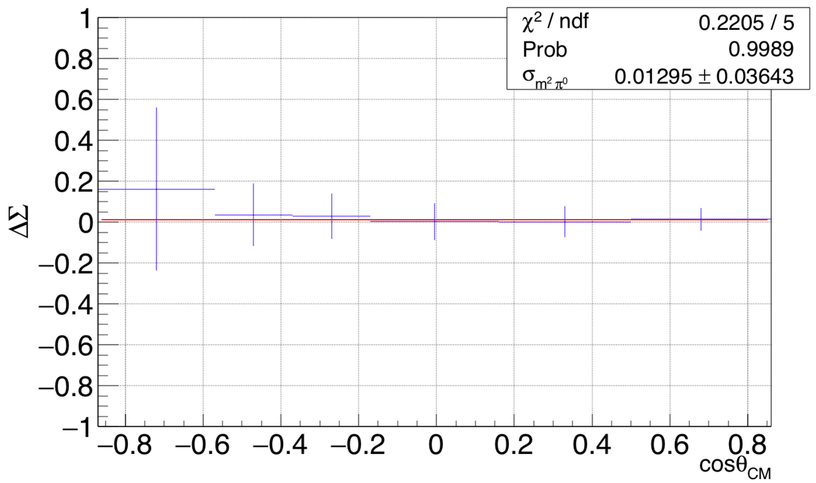
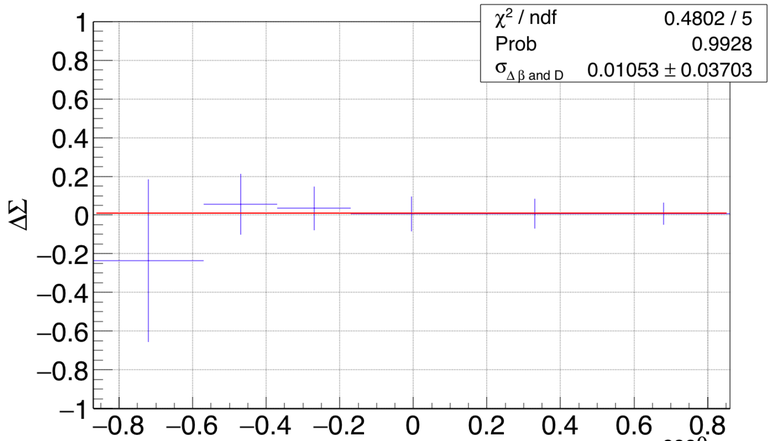
# Systematic Uncertainties: related with event selection

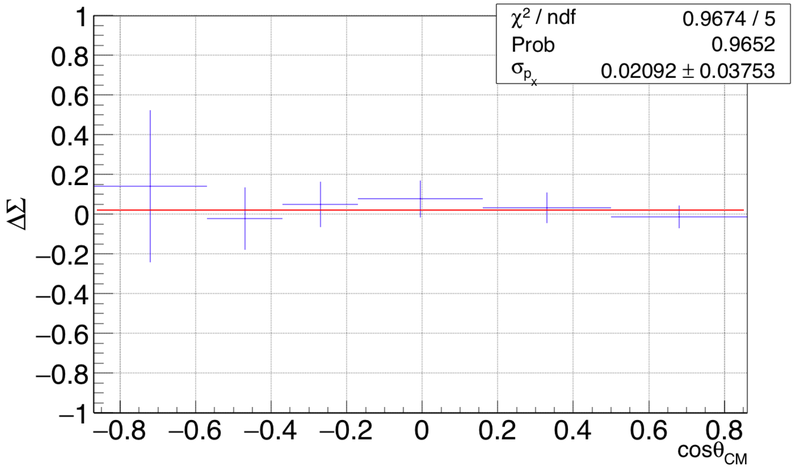
$\pi^0$ reconstruction

3$\sigma$ cut - dilution factor




p missing cut



$$\frac{(\frac{dN}{d\phi})^{\perp} - (\frac{dN}{d\phi})^{\parallel}}{(\frac{dN}{d\phi})^{\parallel} + (\frac{dN}{d\phi})^{\perp}} = \frac{1 - F_R + \frac{F_R P_R + 1}{P_R + 1} 2\bar{P}\Sigma \frac{\sin\Delta\phi}{\Delta\phi} \cos(2(\phi - \phi_0))}{1 + F_R + \frac{F_R P_R - 1}{P_R + 1} 2\bar{P}\Sigma \frac{\sin\Delta\phi}{\Delta\phi} \cos(2(\phi - \phi_0))} \quad (1)$$

with the flux ratio $F_R = \frac{F^{\perp}}{F^{\parallel}}$, polarization ratio $P_R = \frac{P^{\parallel}}{P^{\perp}}$, average of the polarization $\bar{P} = \frac{P^{\parallel} + P^{\perp}}{2}$, $\frac{\sin\Delta\phi}{\Delta\phi}$ correction for the bin width $\Delta\phi$ and $\phi_0$ is the offset of the photon polarization vector [1]. We fix all but one variable in the fit, $\Sigma$.

- $P_R$ and $\bar{P}$ are found using the polarization tables.
- Calculate $F_R$ based on a fit over the (1) integrated over all the $\cos\theta$ bins.

| $E_\gamma(GeV)$ | $P_R$ | $\bar{P}$ |
|---|---|---|
| 1.1-1.3 | 0.88 | 0.754 |
| 1.3-1.5 | 1.01 | 0.782 |
| 1.5-1.7 | 0.96 | 0.750 |
| 1.7-1.9 | 0.94 | 0.676 |
| 1.9-2.1 | 0.99 | 0.730 |
| 2.1-2.3 | 1.02 | 0.695 |

[1] Ref. N. Zachariou PhysRevC.91.055202 (2015)

$$\frac{(\frac{dN}{d\phi})^{\perp} - (\frac{dN}{d\phi})^{\parallel}}{(\frac{dN}{d\phi})^{\parallel} + (\frac{dN}{d\phi})^{\perp}} = \frac{1 - F_R + \frac{F_R P_R + 1}{P_R + 1} 2\bar{P}\Sigma \frac{\sin\Delta\phi}{\Delta\phi} \cos(2(\phi - \phi_0))}{1 + F_R + \frac{F_R P_R - 1}{P_R + 1} 2\bar{P}\Sigma \frac{\sin\Delta\phi}{\Delta\phi} \cos(2(\phi - \phi_0))} \quad (1)$$

with the flux ratio $F_R = \frac{F^{\perp}}{F^{\parallel}}$, polarization ratio $P_R = \frac{P^{\parallel}}{P^{\perp}}$, average of the polarization $\bar{P} = \frac{P^{\parallel} + P^{\perp}}{2}$, $\frac{\sin\Delta\phi}{\Delta\phi}$ correction for the bin width $\Delta\phi$ and $\phi_0$ is the offset of the photon polarization vector [1]. We fix all but one variable in the fit, $\Sigma$.

- $P_R$ and $\bar{P}$ are found using the polarization tables.
- Calculate $F_R$ based on a fit over the (1) integrated over all the $\cos\theta$ bins.

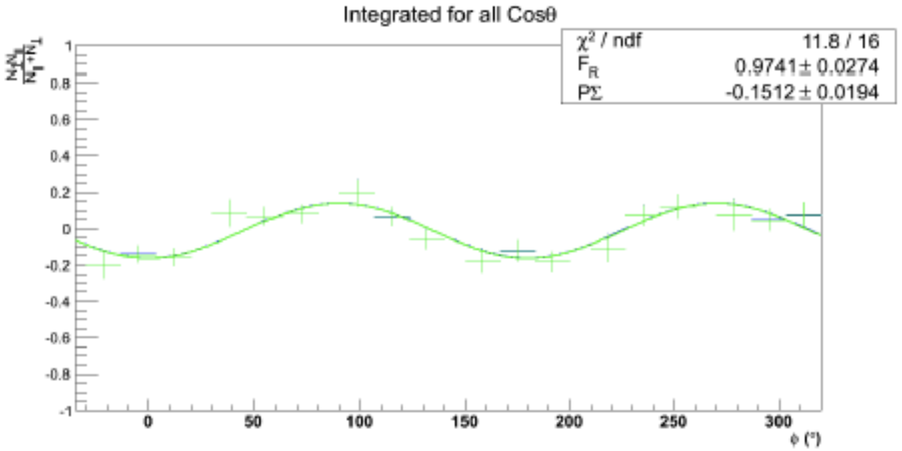



Figure: Example of fit for $1.7 < E_\gamma < 1.8$GeV

[1] Ref. N. Zachariou PhysRevC.91.055202 (2015)

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$$\frac{(\frac{dN}{d\phi})^{\perp} - (\frac{dN}{d\phi})^{\parallel}}{(\frac{dN}{d\phi})^{\parallel} + (\frac{dN}{d\phi})^{\perp}} = \frac{1 - F_R + \frac{F_R P_R + 1}{P_R + 1} 2\bar{P}\Sigma \frac{\sin\Delta\phi}{\Delta\phi} \cos(2(\phi - \phi_0))}{1 + F_R + \frac{F_R P_R - 1}{P_R + 1} 2\bar{P}\Sigma \frac{\sin\Delta\phi}{\Delta\phi} \cos(2(\phi - \phi_0))} \quad (1)$$

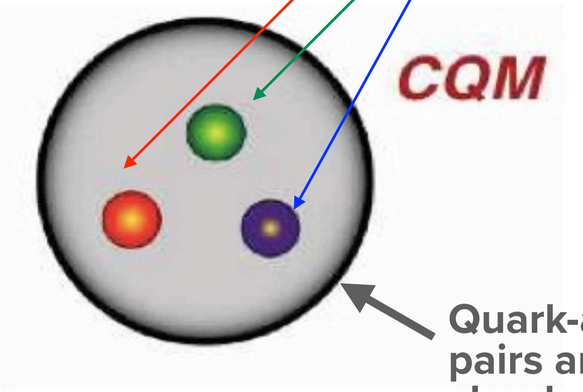
with the flux ratio $F_R = \frac{F^{\perp}}{F^{\parallel}}$, polarization ratio $P_R = \frac{P^{\parallel}}{P^{\perp}}$, average of the polarization $\bar{P} = \frac{P^{\parallel} + P^{\perp}}{2}$, $\frac{\sin\Delta\phi}{\Delta\phi}$ correction for the bin width $\Delta\phi$ and $\phi_0$ is the offset of the photon polarization vector [1]. We fix all but one variable in the fit, $\Sigma$.

- $P_R$ and $\bar{P}$ are found using the polarization tables.
- Calculate $F_R$ based on a fit over the (1) integrated over all the $\cos\theta$ bins.
- $\phi_0 = 0$ as suggested by large statistics channel study

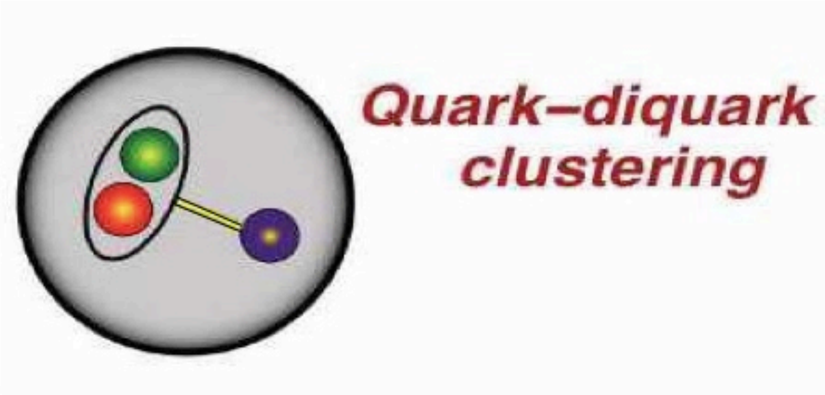
[1] Ref. N. Zachariou PhysRevC.91.055202 (2015)

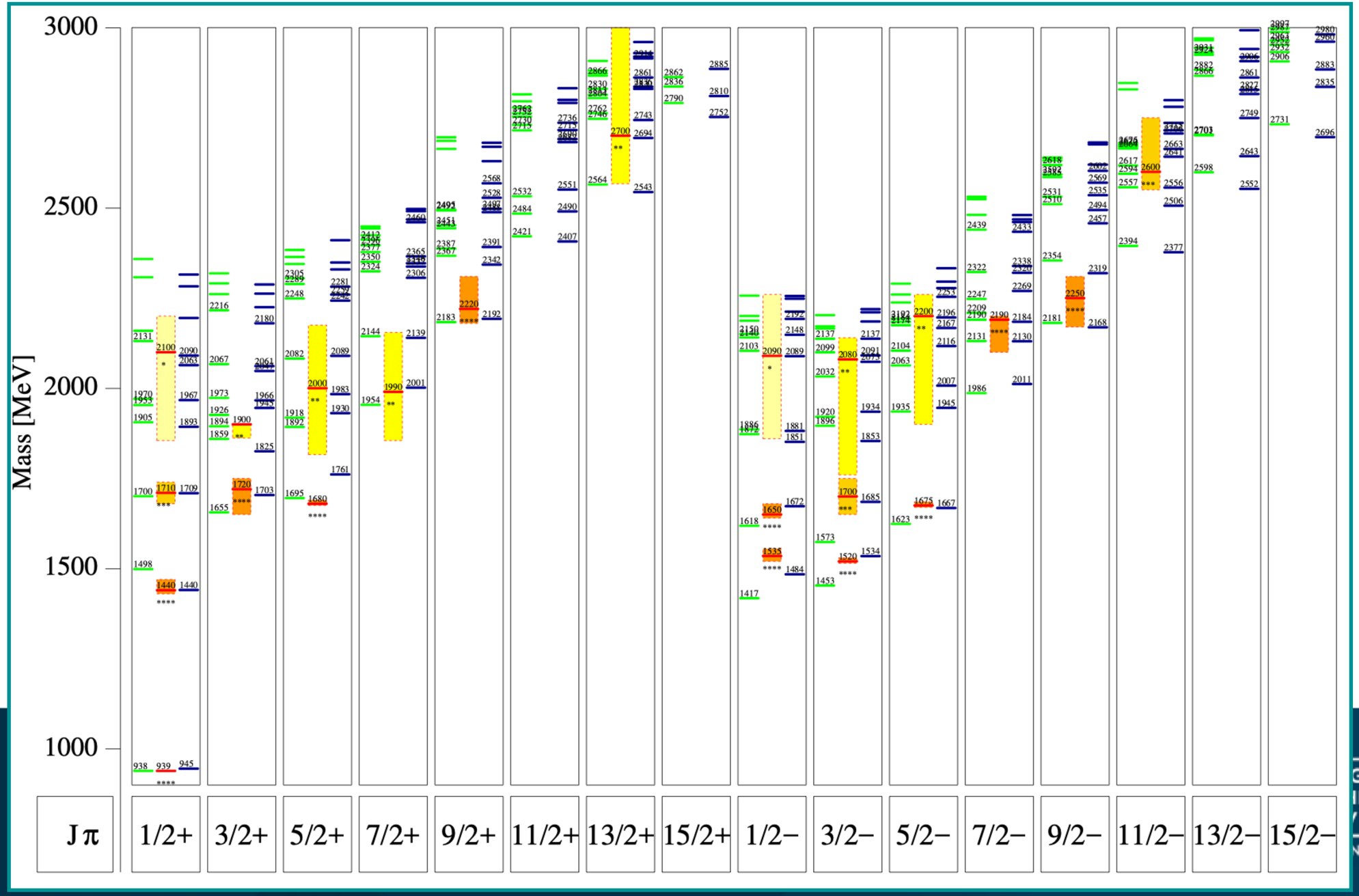
Hadron modeled as a ground state of
"constituent quarks"

**Fundamental quarks from the QCD Lagrangian**




**Quark-antiquark pairs and gluons cloud**



Mass [MeV]
3000
2500
2000
1500
1000
Jπ
1/2+
3/2+
5/2+
7/2+
9/2+
11/2+
13/2+
15/2+
1/2−
3/2−
5/2−
7/2−
9/2−
11/2−
13/2−
15/2−