Polarization Observables from Two-pion and ρ Meson Photoproduction on Polarized HD Target at JLab

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Outline

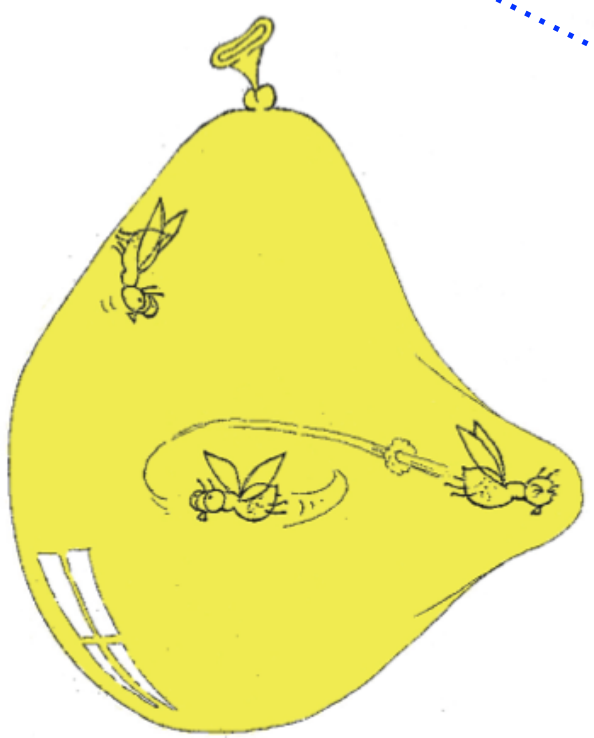
- Physics motivation
- The g14 (HD-ice) experiment
- The reactions $\vec{\gamma}\,\vec{p}(n) \longrightarrow \pi^{+}\pi^{-}p(n)$ and $\vec{\gamma}\,\vec{n}(p) \longrightarrow \pi^{+}\pi^{-}n(p)$
  - The single polarization observable $I^{\odot}$ and the double polarization observable $P_z^{\odot}$
- The reaction $\vec{\gamma}\,\vec{p}(n) \longrightarrow \rho^{0}\,p(n)$
  - First attempt to extract the double polarization observable E

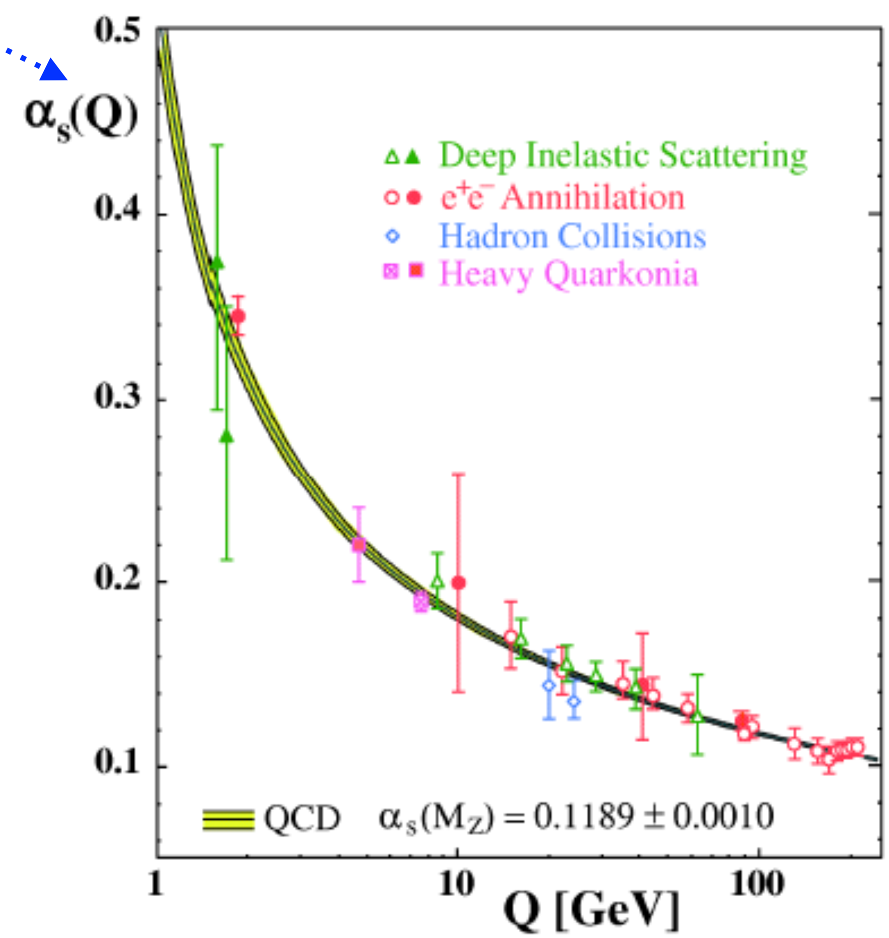
Motivation

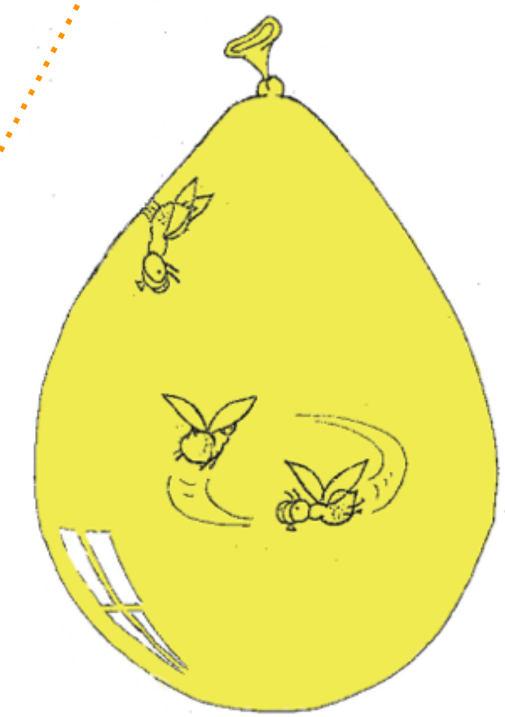
Experimental goal: unravel the nucleon spectrum

confinement

asymptotic freedom







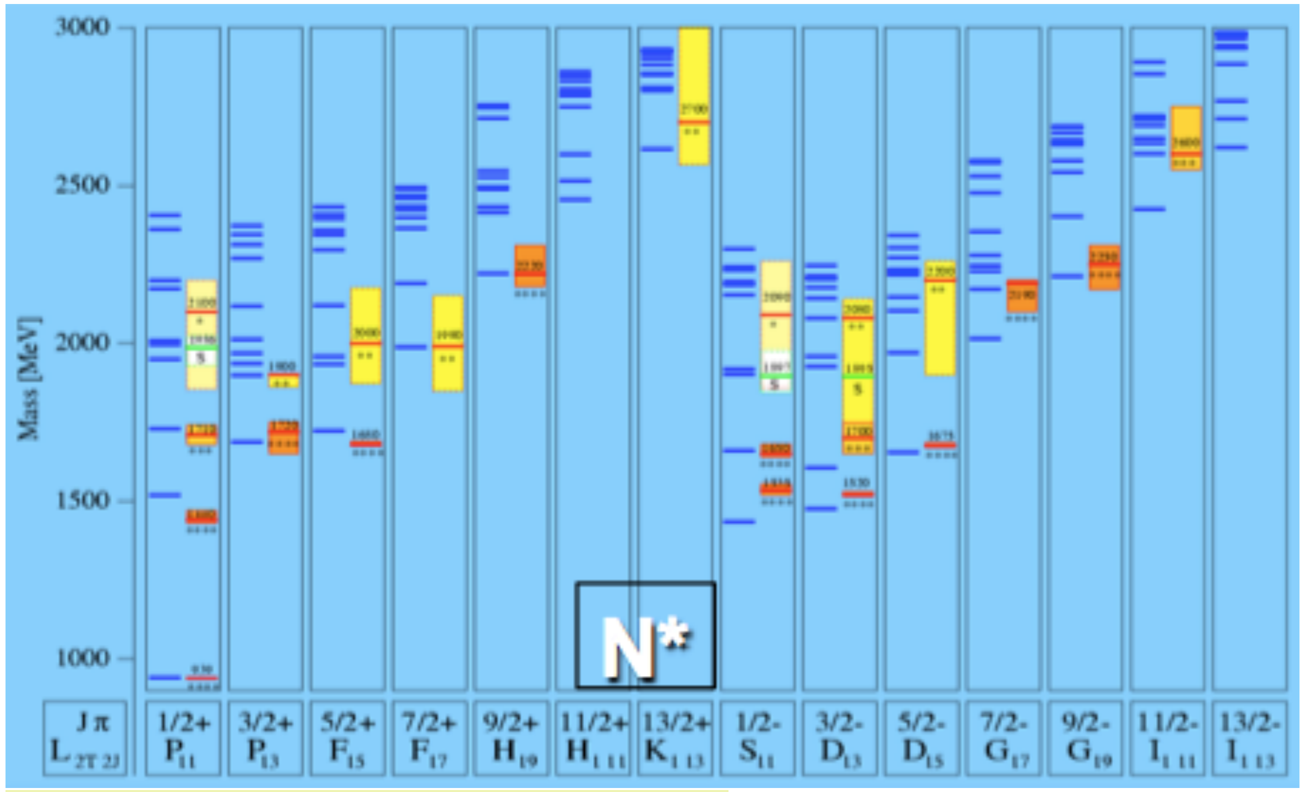
Strong QCD

PQCD

Other approaches are needed:

- LQCD
- Constituent quark Model

Where Have All Resonances Gone?



Thick segments: theoretical prediction
shadowed boxes:experimental results

Discrepancy between predicted and experimentally observed states: "MISSING RESONANCES PROBLEM"

Theoretical models:
other approaches based on different effective degrees of freedom

Experiment:
alternative to strong probes: electroproduction photoproduction

VOLUME 44, NUMBER 13 PHYSICAL REVIEW LETTERS 31 MARCH 1980

Where Have All the Resonances Gone? An Analysis of Baryon Couplings in a Quark Model with Chromodynamics

Roman Koniuk and Nathan Isgur
Department of Physics, University of Toronto, Toronto, Ontario M5S 1A7, Canada
(Received 26 November 1979)

This paper reports on the results of an extensive analysis of baryon couplings in a quark model with chromodynamics. The amplitudes which emerge from the analysis resolve the problem of "missing" baryon resonances by showing that a very large number of states essentially decouple from the partial-wave analyses; those resonances which remain are in remarkable correspondence to the observed states in both their masses and decay amplitudes.

The missing states may be weakly coupled to channels where the pion is in the initial and final states
but they may be observed in other channels

N* summary table

From 2010

Resonance	L_{2I2J}	Status
p	P_{11}	****
n	P_{11}	****
N(1140)	P_{11}	****
N(1520)	D_{13}	****
N(1535)	S_{11}	****
N(1650)	S_{11}	****
N(1675)	D_{15}	****
N(1680)	F_{15}	****
N(1700)	D_{13}	***
N(1710)	P_{11}	***
N(1720)	P_{13}	****
N(1900)	P_{13}	**
N(1990)	F_{17}	**
N(2000)	F_{15}	**
N(2080)	D_{13}	**
N(2090)	S_{11}	*
N(2100)	P_{11}	*
N(2190)	G_{17}	****
N(2200)	D_{15}	**
N(2220)	H_{19}	****
N(2250)	G_{19}	****
N(2600)	$I_{1,11}$	***
N(2700)	$K_{1,13}$	**

...to 2014

Resonance	J^P	Status
p	$1/2^+$	****
n	$1/2^+$	****
N(1140)	$1/2^+$	****
N(1520)	$3/2^-$	****
N(1535)	$1/2^-$	****
N(1650)	$1/2^-$	****
N(1675)	$5/2^-$	****
N(1680)	$5/2^+$	****
N(1685)		*
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)	$5/2^-$	**
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)	$13/2^+$	**

Polarization Observables

$$\gamma + N \to \pi^+ + \pi^- + N$$

Spin states: $\pm 1 \quad \pm\frac{1}{2} \qquad\qquad 0 \qquad\qquad \pm\frac{1}{2}$

$$\frac{d\sigma}{dx_i} = \sigma_0\{(1 + \Lambda_z \cdot \mathbf{P_z}) + \delta_\odot(\mathbf{I}^\odot + \Lambda_z \cdot \mathbf{P}_z^\odot)\}$$

Running conditions:

- circularly polarized photons
- longitudinally polarized target
- not measuring the recoil polarization

Polarization Observables

$$\gamma + N \rightarrow \pi^+ + \pi^- + N$$

Spin states: ± 1 $\quad \pm\frac{1}{2}$ $\quad 0$ $\quad \pm\frac{1}{2}$

$$\frac{d\sigma}{dx_i} = \sigma_0\{(1 + \Lambda_z \cdot \mathbf{P_z}) + \delta_\odot(\mathbf{I}^\odot + \Lambda_z \cdot \mathbf{P}_z^\odot)\}$$

target asymmetry

beam-helicity

beam-target helicity difference

3 possible polarization observables for two-pion photoproduction

$$P_z = \frac{1}{\Lambda_z}\frac{[N(\rightarrow\Rightarrow) + N(\leftarrow\Rightarrow)] - [N(\rightarrow\Leftarrow) + N(\leftarrow\Leftarrow)]}{[N(\rightarrow\Rightarrow) + N(\leftarrow\Rightarrow)] + [N(\rightarrow\Leftarrow) + N(\leftarrow\Leftarrow)]}$$

$$I^\odot = \frac{1}{\delta_\odot}\frac{[N(\rightarrow\Rightarrow) + N(\rightarrow\Leftarrow)] - [N(\leftarrow\Rightarrow) + N(\leftarrow\Leftarrow)]}{[N(\rightarrow\Rightarrow) + N(\rightarrow\Leftarrow)] + [N(\leftarrow\Rightarrow) + N(\leftarrow\Leftarrow)]}$$

$$P_z^\odot = \frac{1}{\Lambda_z\delta_\odot}\frac{[N(\rightarrow\Rightarrow) + N(\leftarrow\Leftarrow)] - [N(\rightarrow\Leftarrow) + N(\leftarrow\Rightarrow)]}{[N(\rightarrow\Rightarrow) + N(\leftarrow\Leftarrow)] + [N(\rightarrow\Leftarrow) + N(\leftarrow\Rightarrow)]}$$

$\rightarrow$ beam orientation

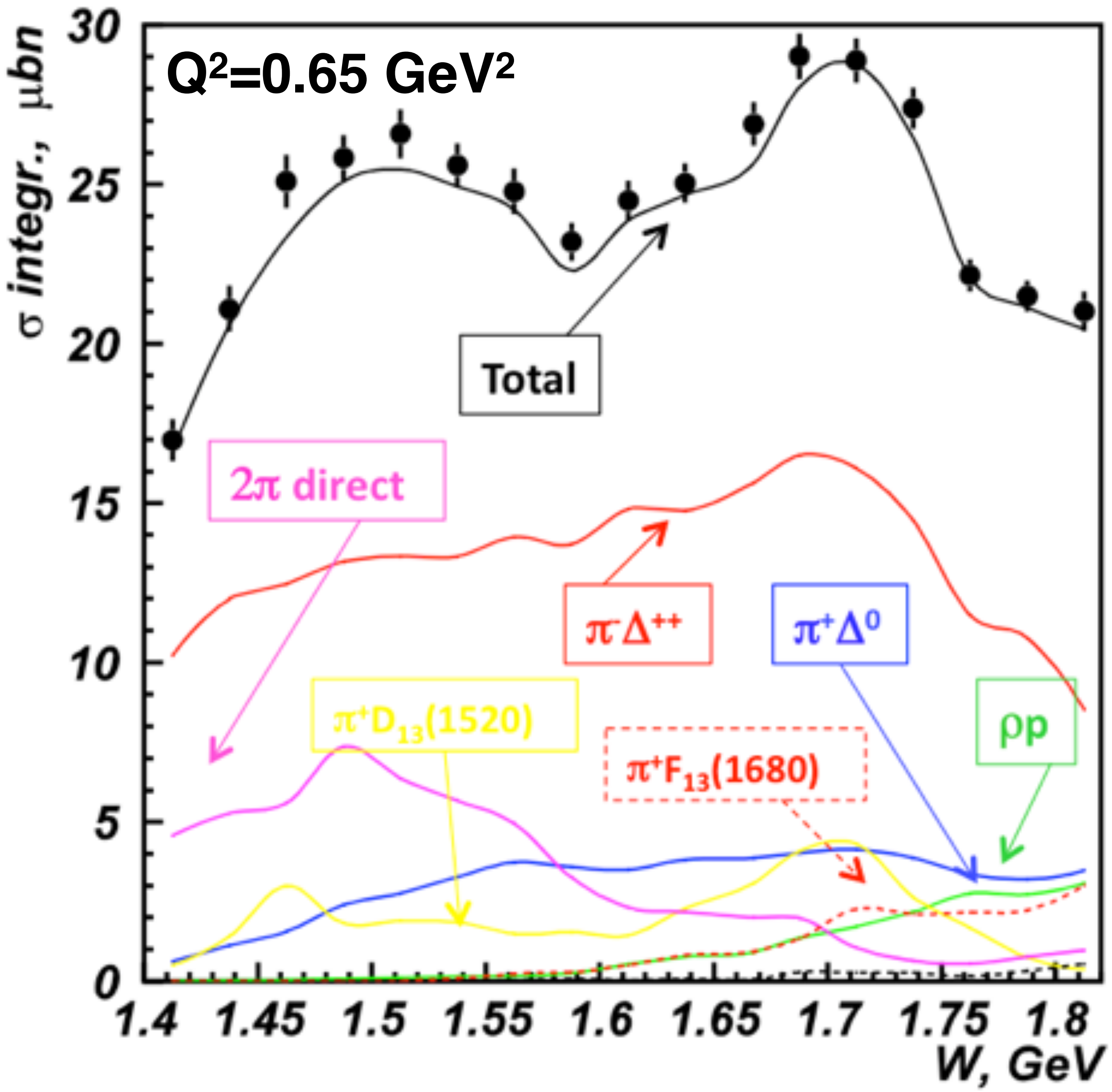
$\Rightarrow$ target orientation

Polarization Observables

$$\gamma^* + N \rightarrow \pi^+ + \pi^- + N$$

it's the final states of several possible reactions

disentangled for electroproduction by V. Mokeev



by V. Mokeev (JLab-Moscow model)

Polarization Observables

$$\gamma + p \rightarrow \rho^0 p \rightarrow \pi^+ \pi^- p$$

1) $\gamma + p \rightarrow \rho^0 p \rightarrow \pi^+ \pi^- p$ ………… rho photoproduction

2) $\gamma + p \rightarrow \pi^- \Delta^{++} \rightarrow \pi^+ \pi^- p$

3) $\gamma + p \rightarrow \pi^+ \Delta^0 \rightarrow \pi^+ \pi^- p$

4) $\gamma + p \rightarrow \pi^+ \pi^- p$

(2–4: unwanted background)

$$\frac{d\sigma}{d\Omega} = \frac{d\sigma_0}{d\Omega}(1 - \Lambda_z \delta_\odot E)$$

E: beam-target helicity difference

Summarizing...

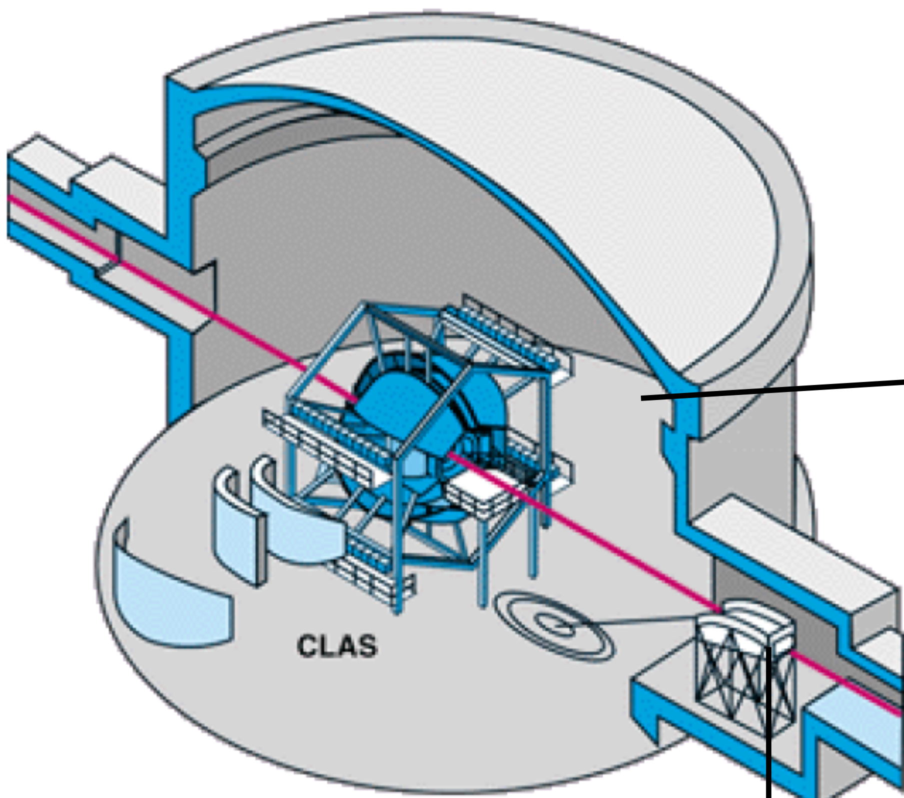
Which are the experimental requirements?

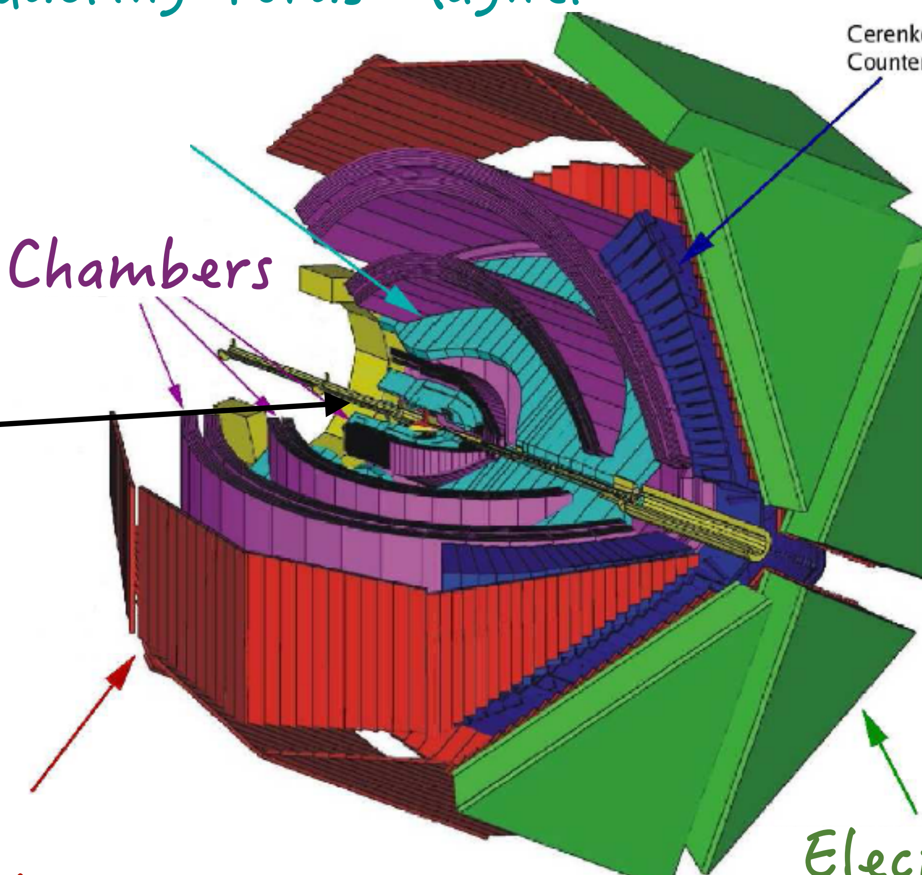
- ✓ polarized beam
- ✓ polarized target
- ✓ proton and neutron target to investigate isospin dependency

→ G14 experiment + CEBAF accelerator

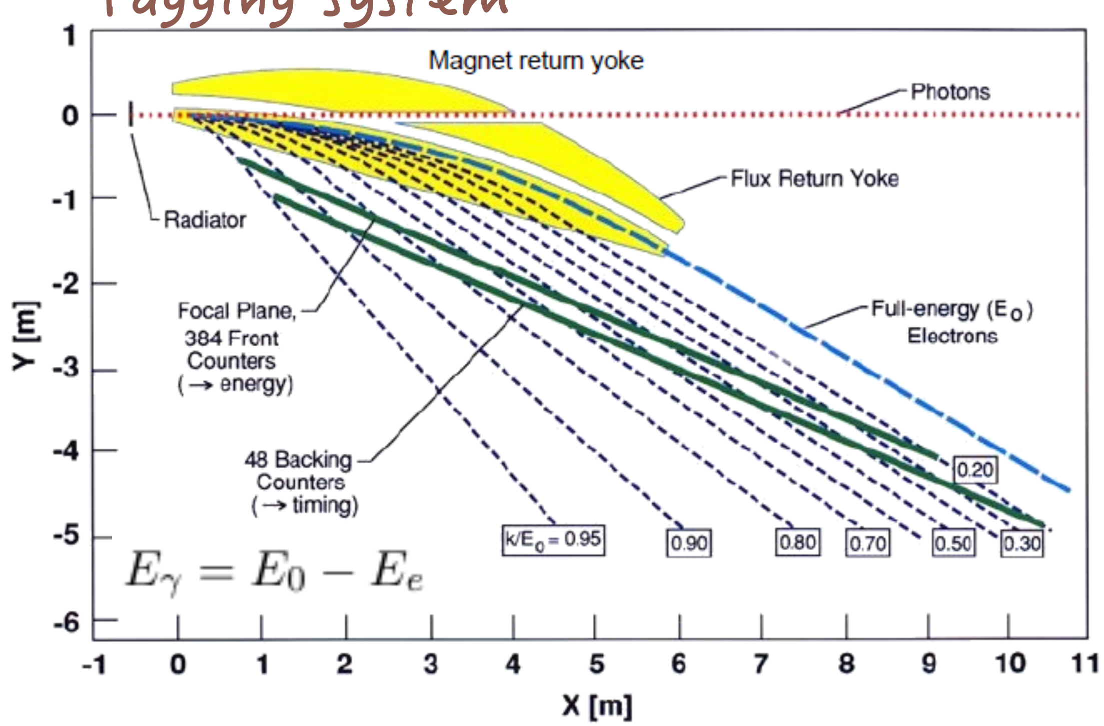
Experimental Setup

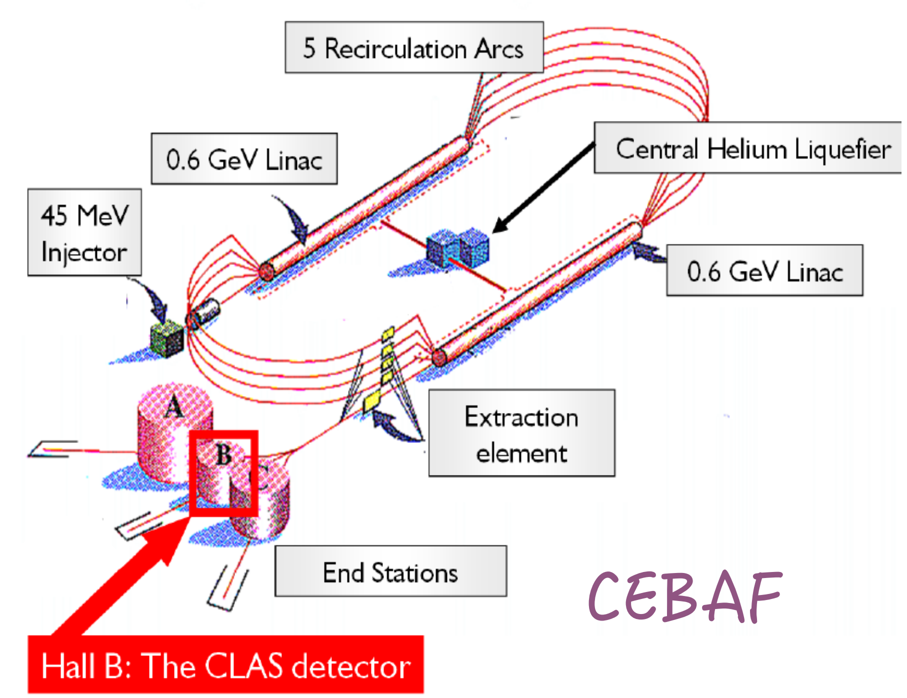
HALL B

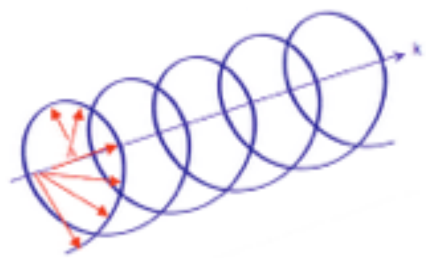




Tagging system







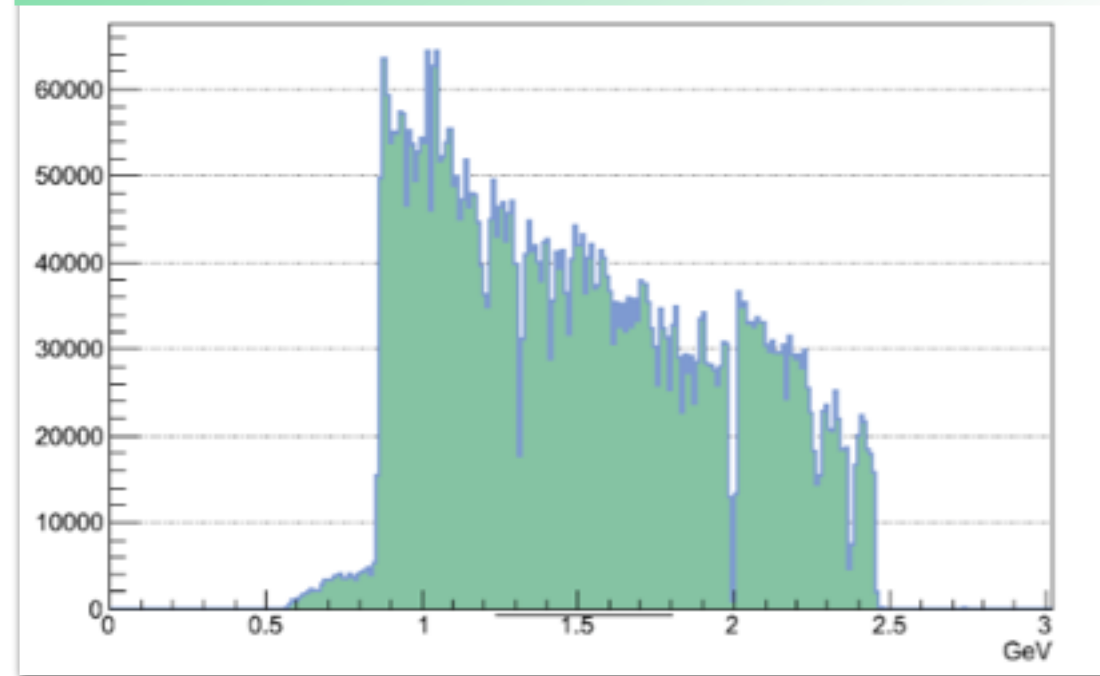
Circularly polarized photons

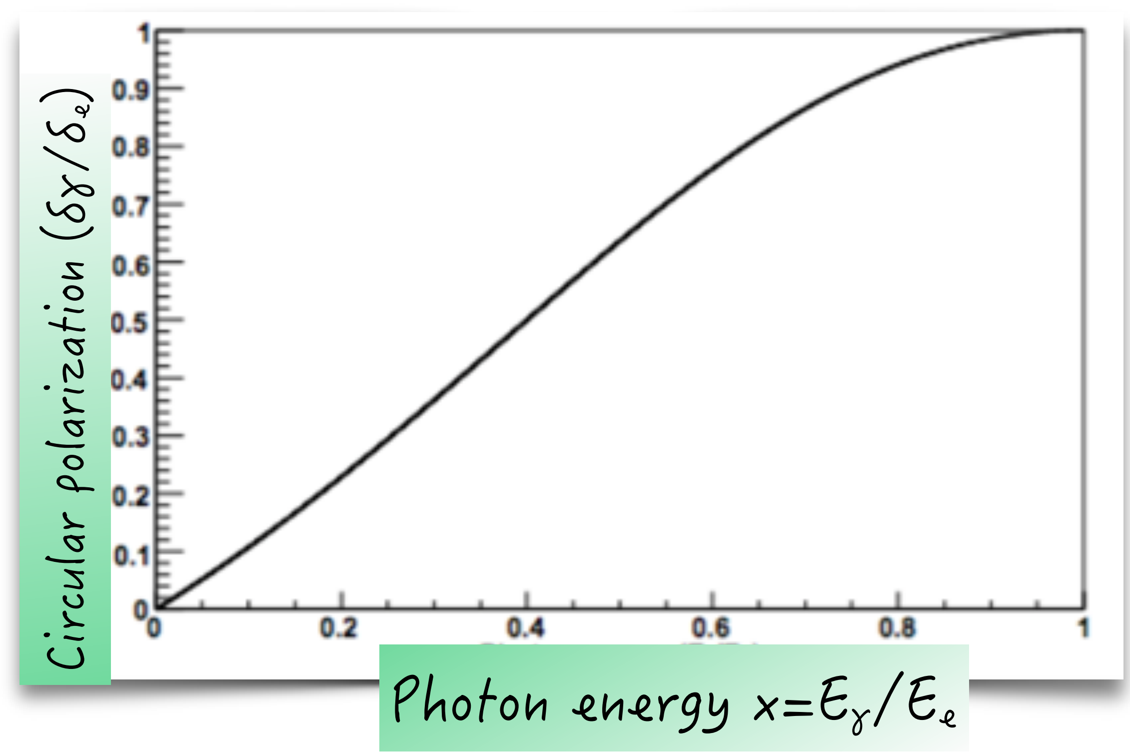
- Produced via Bremsstrahlung of longitudinally polarized electrons from a gold foil radiator ($10^{-4} X_0$).
- CEBAF electron beam polarization >85% (Møller measurement)
- Photons have a degree of circular polarization proportional to the longitudinal polarization of the electron beam.

$$P_{\odot} = P_e \frac{4x - x^2}{4 - 4x + 3x^2}$$

$$x = \frac{E_\gamma}{E_e}$$

Photon Energy Spectrum

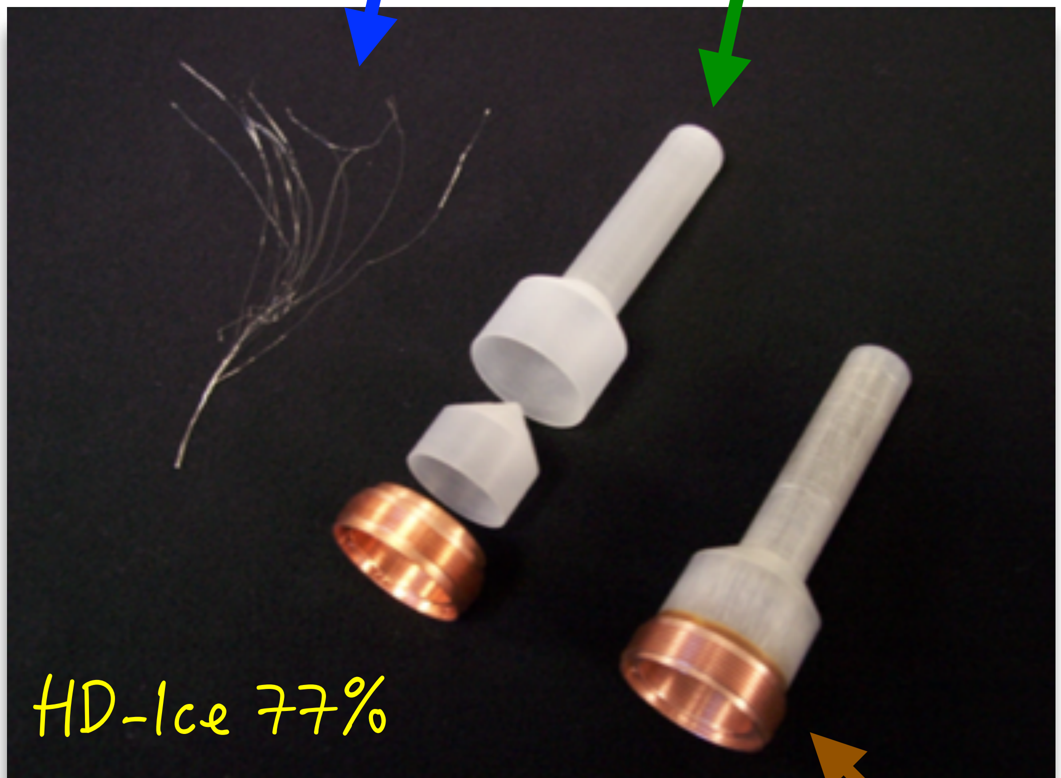




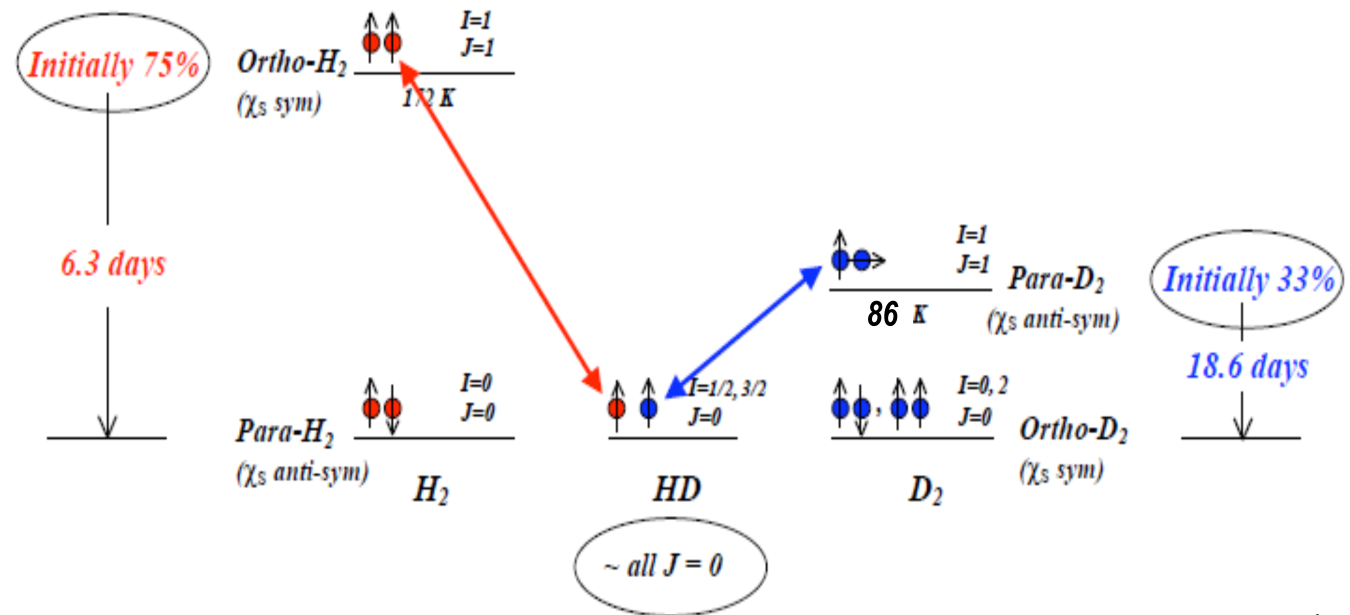
HD frozen-spin target

Al 17%

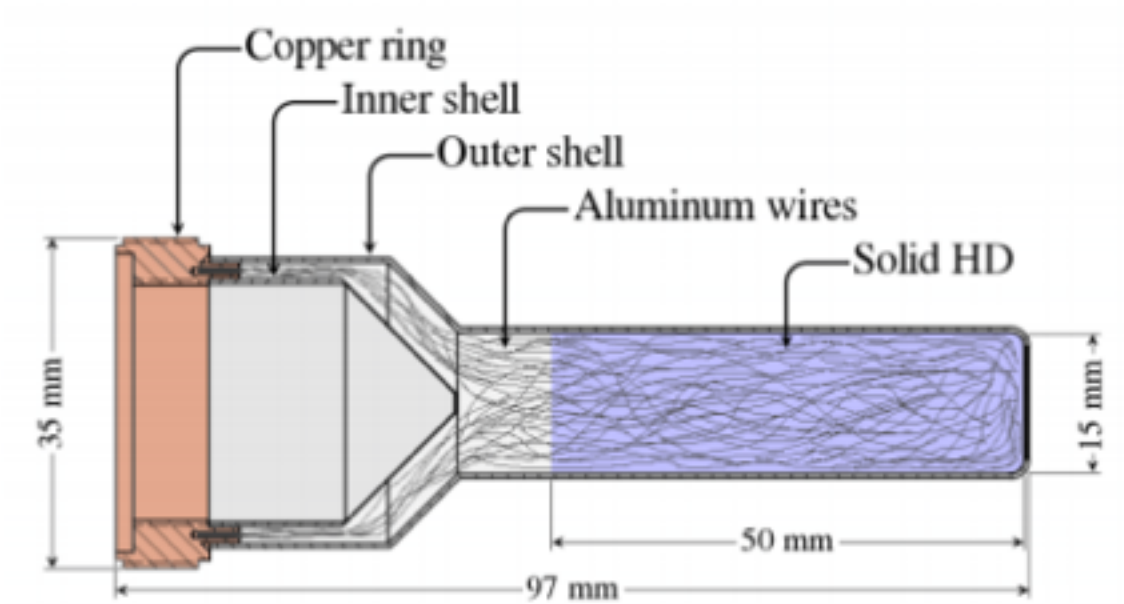
Kel-F 6%



Cu ring with RH/LH threads



by A. Sandorfi

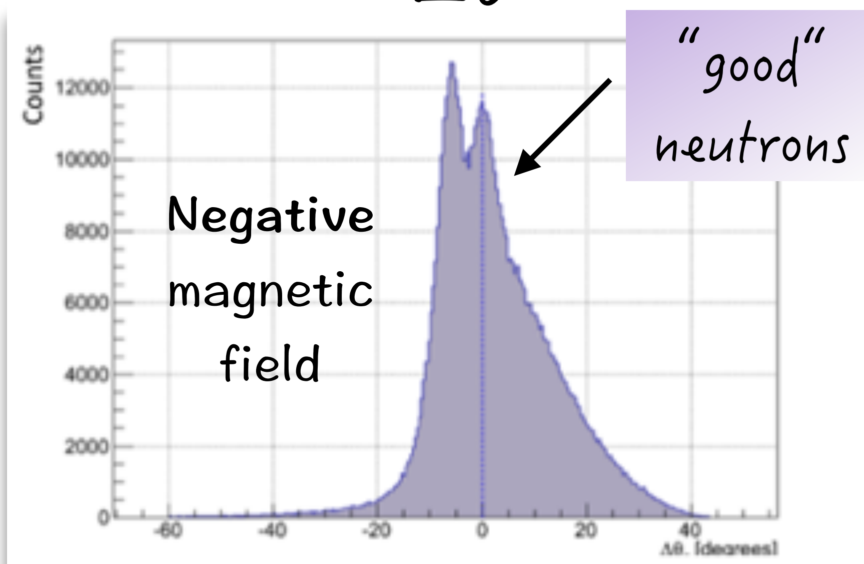


- Kel-F assures low permeation, good thermal, chemical and mechanical resistance, do not add background to NMR measurements
- Al wires allows to conduct out the heat produced during polarization and photonuclear interactions

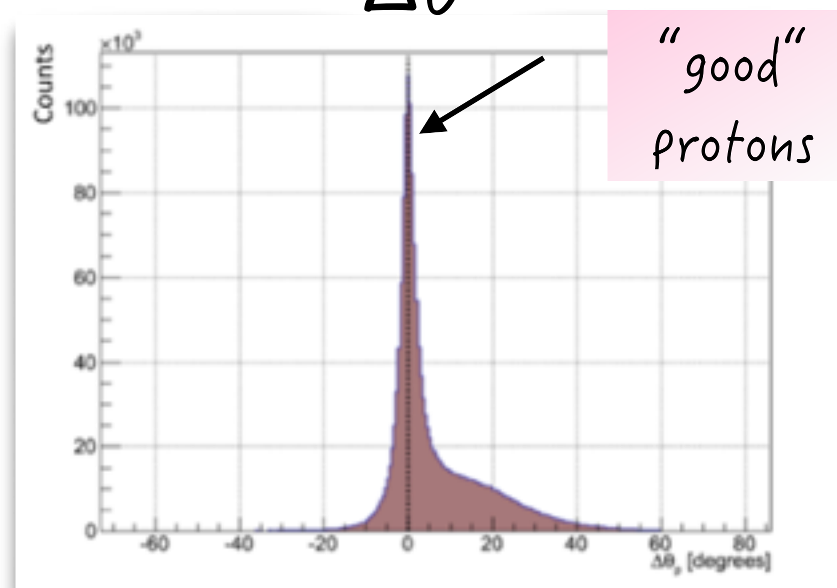
Neutrons (Mis)identification

Considering the reactions $\gamma\, n \rightarrow \pi^+ \pi^- n$ and $\gamma\, n \rightarrow \pi^+ \pi^- (n)$ we found that in many cases the direction of detected neutrons doesn't match the direction of the expected ones.

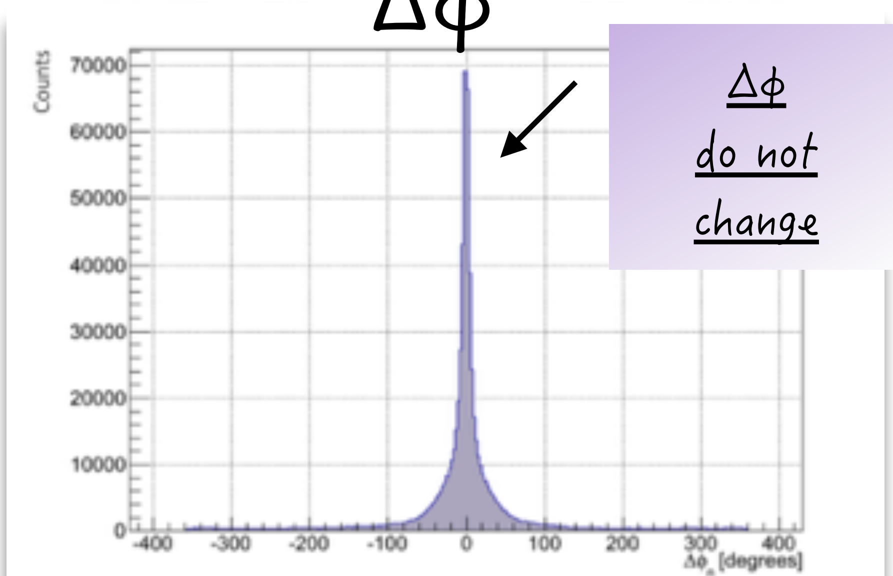
$\Delta\theta^n$



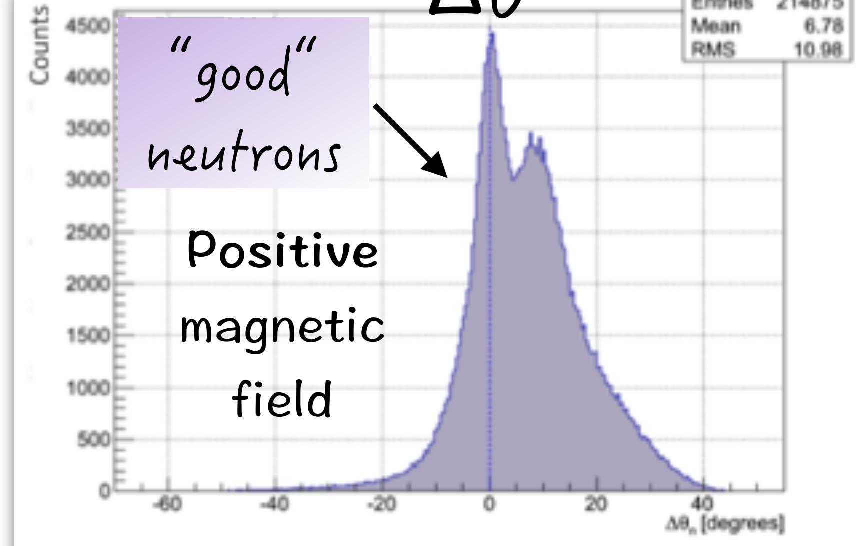
$\Delta\theta^p$



$\Delta\phi^n$

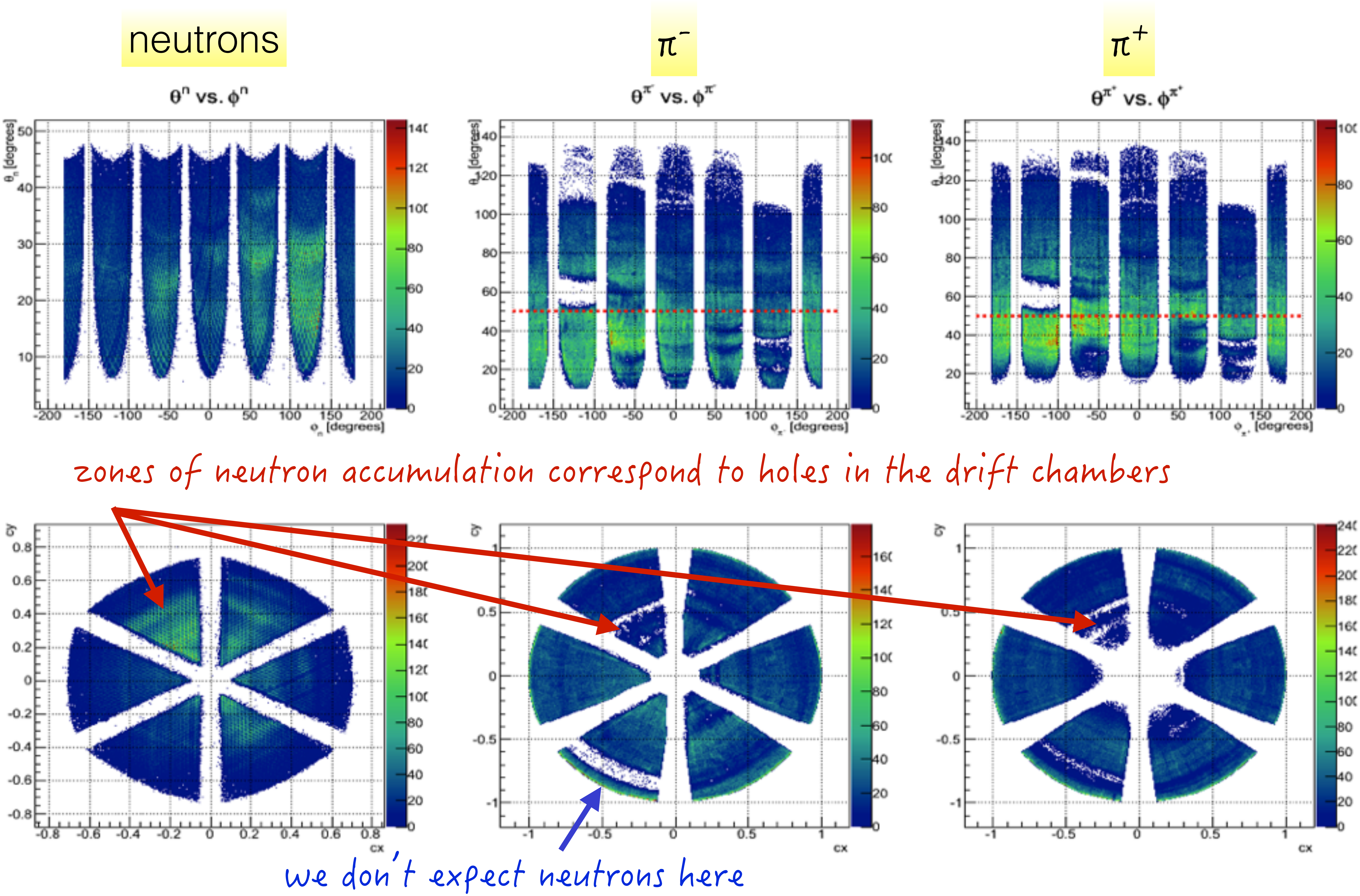


$\Delta\theta^n$



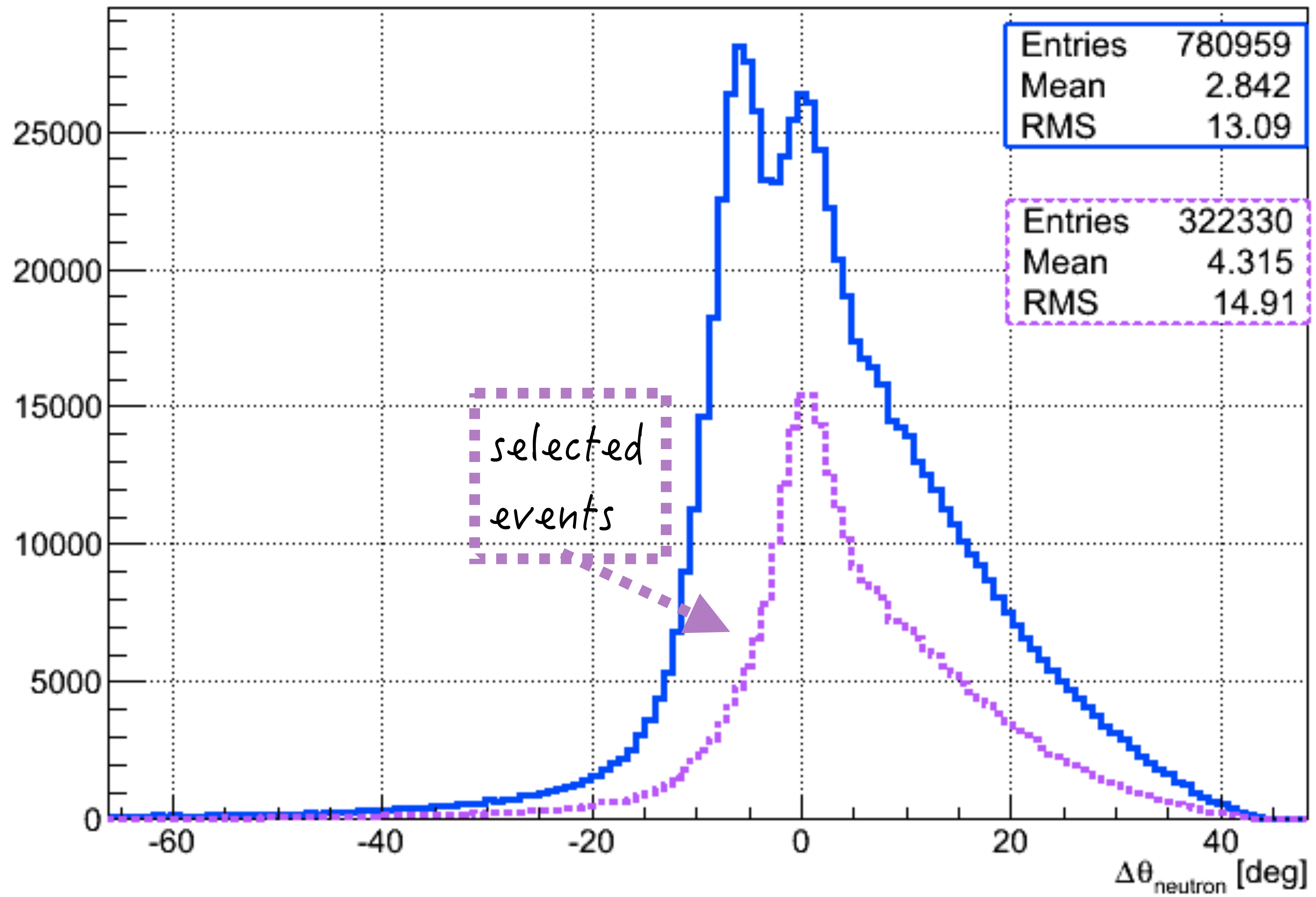
Due to inefficiencies of the Drift Chambers some protons are misidentified as neutrons

Neutrons (Mis)identification: angular distributions

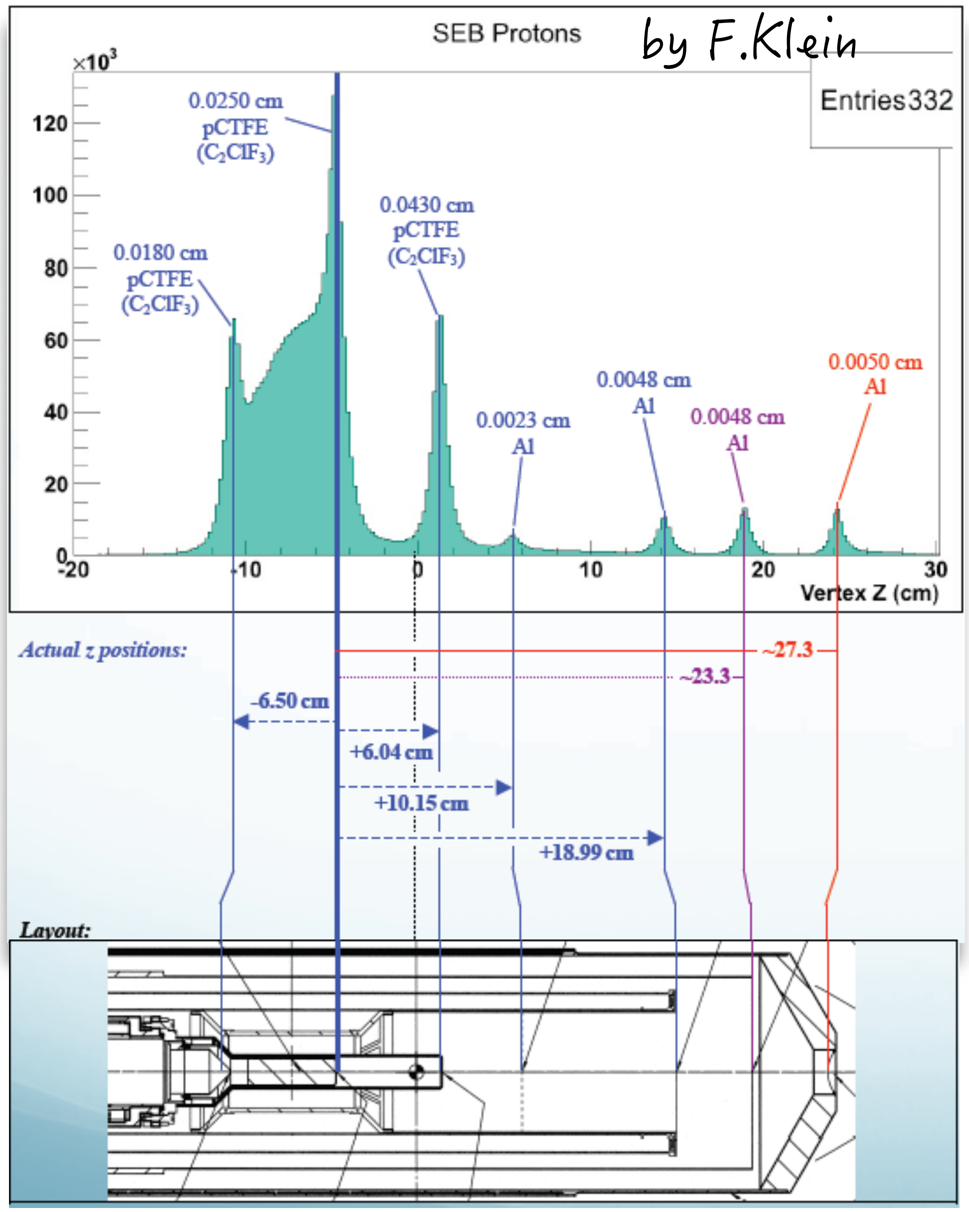


Neutrons (Mis)identification: good event selection

selection criteria: scintillator counter hits used as veto for charged particles in the electromagnetic calorimeter



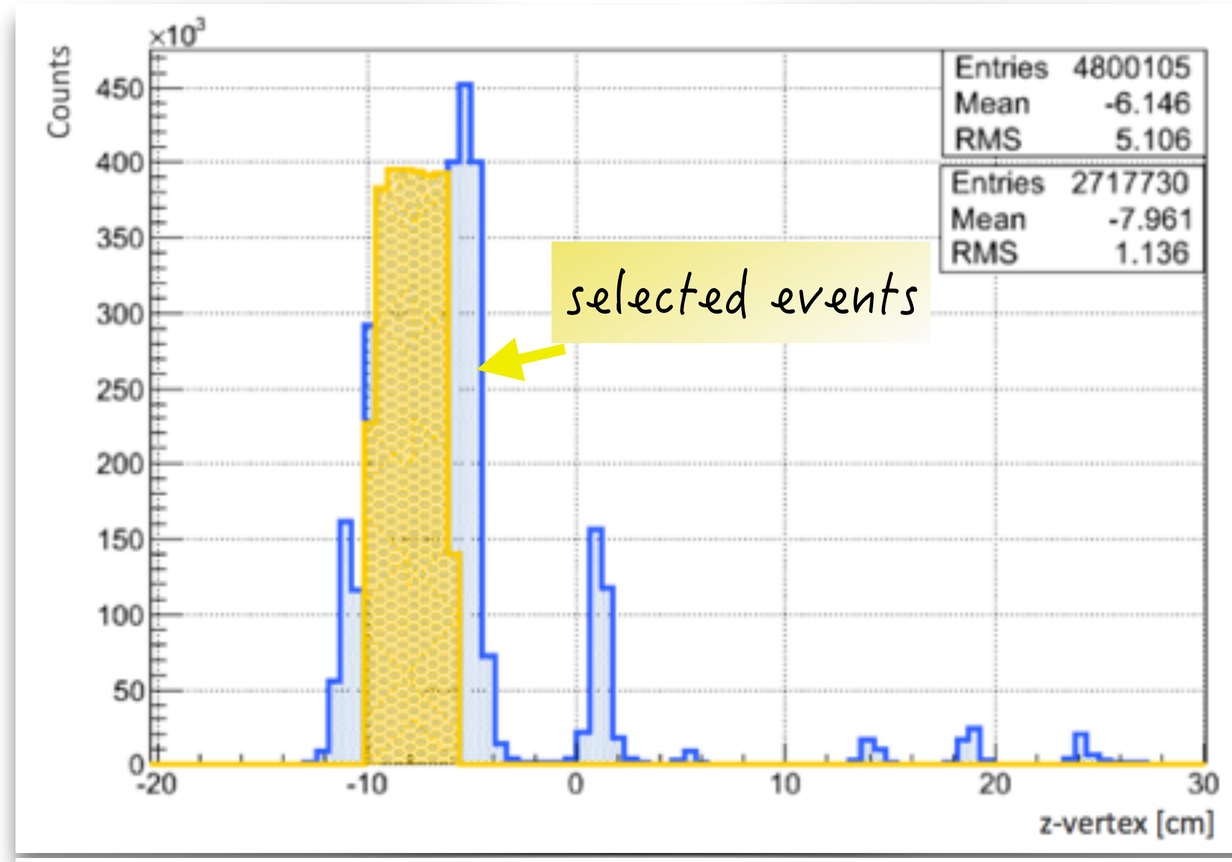
Event selection: z-vertex cut

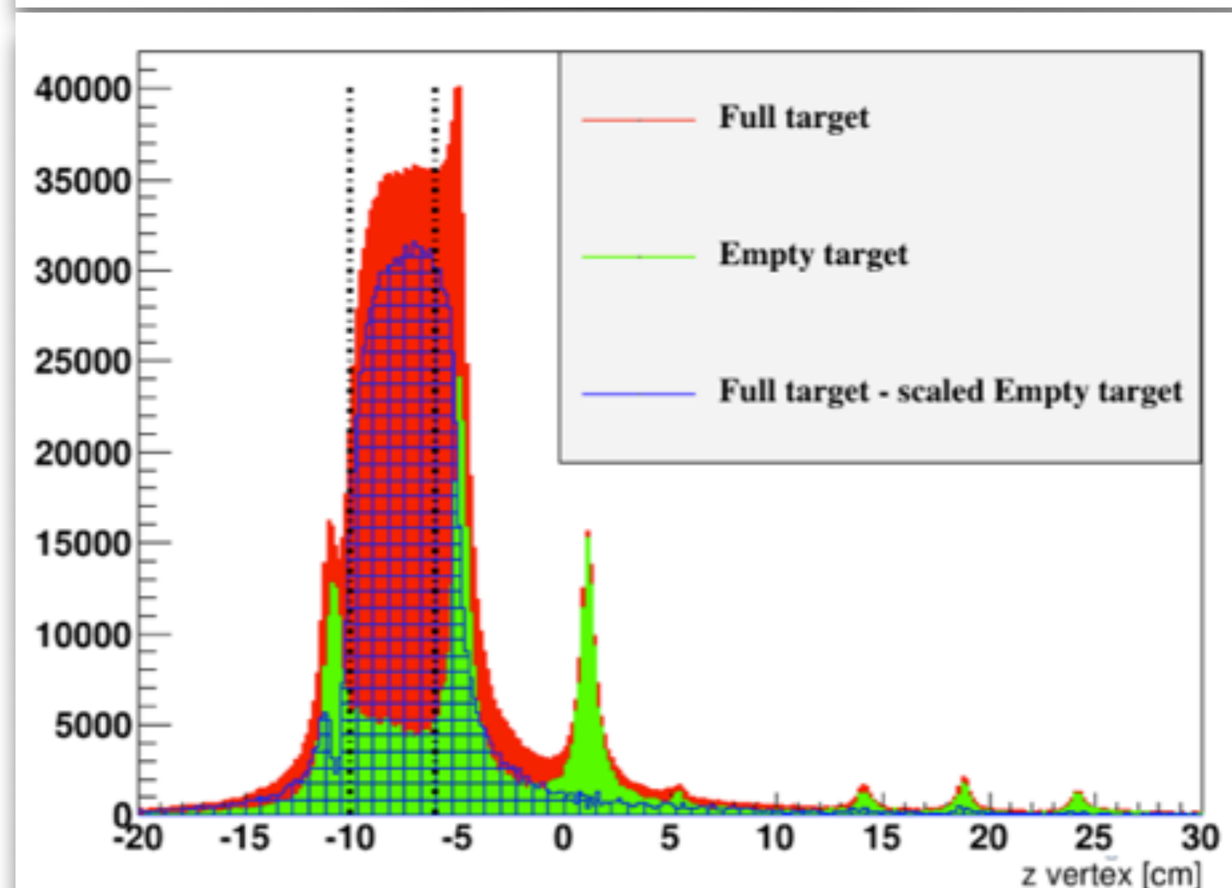


Cut on the computed vertex of charged particles

➡identify event produced in the HD

➡identify background events from Al wires, cell windows and IBC Al foils





Incident photon identification

The *actual photon* is identified as the one whose time is closest to the event vertex time:

$$\Delta T = T_\gamma - T_v$$

studied for each charged particle as a function of their momentum

=

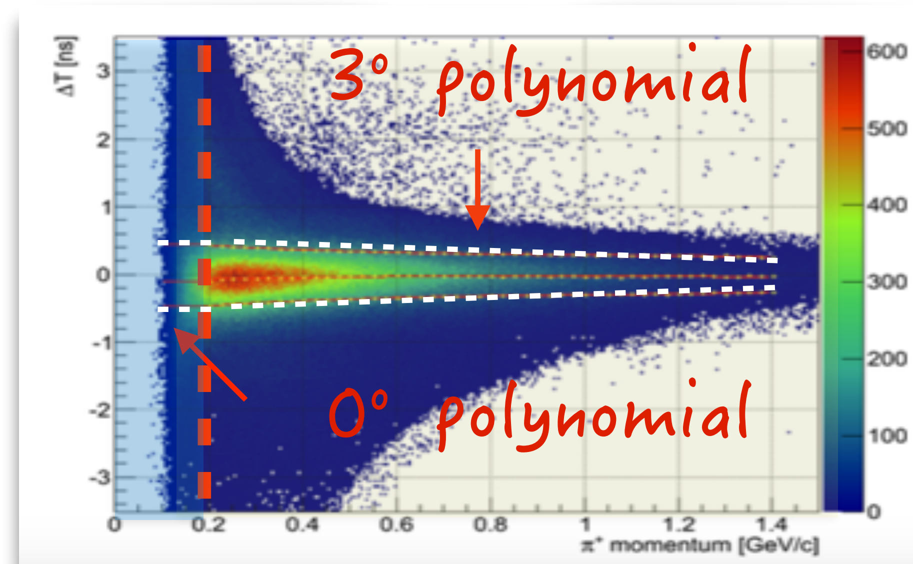
$$T_\gamma = T_{center} + T_{prop}$$

$$T_{prop} = \frac{z^h_{vertex} - z_{target}}{c}$$

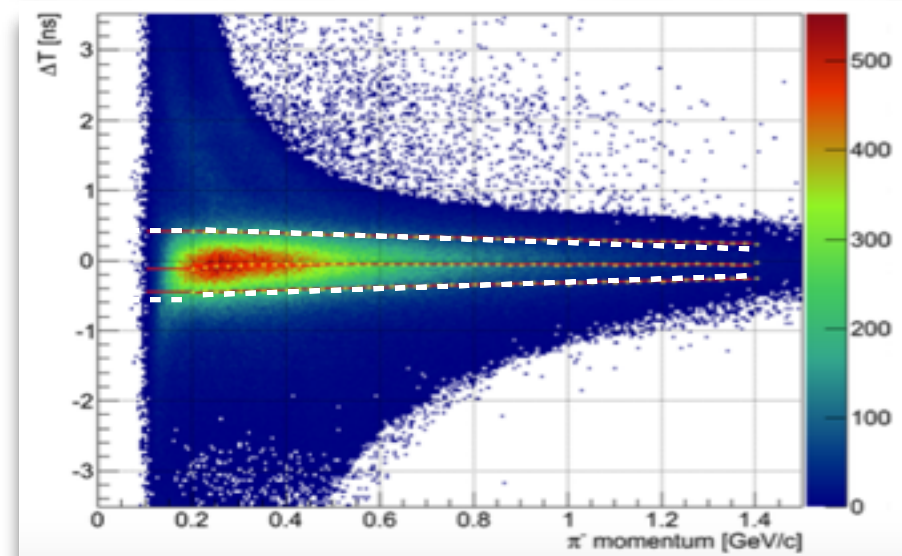
-

$$T_v = T_{ToF} - \frac{L_{ToF}}{\beta c}$$

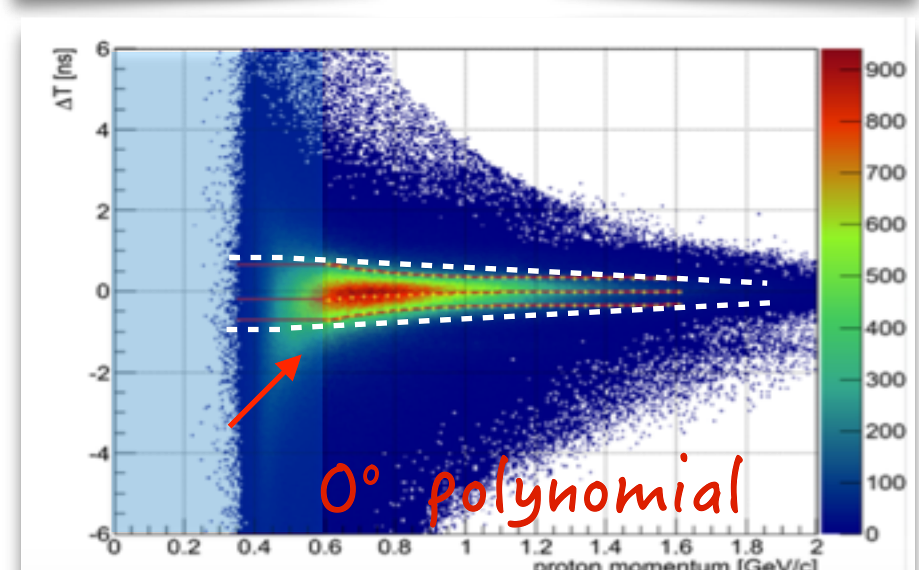
π^+



π^-



p



Charged particles id: Δβ cuts

To improve the identification of the charged particles imposed a cut on the Δβ distributions:

$$\Delta\beta = \beta_{ToF} - \beta_p$$

β_{ToF} measured from the time-of-flight
β_p calculated from momentum

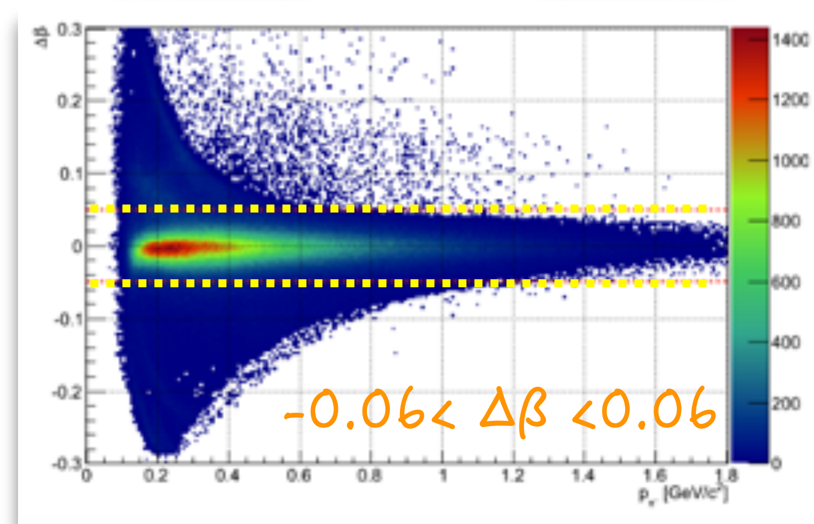
$$\beta_{ToF} = \frac{path_{DC}}{c \cdot T_{tof}}$$

$path_{DC}$ is the pion or proton path from the interaction vertex to the scintillator counters traded by the drift chambers
T_{ToF} is the time measured in the scintillator counters
c is the light speed

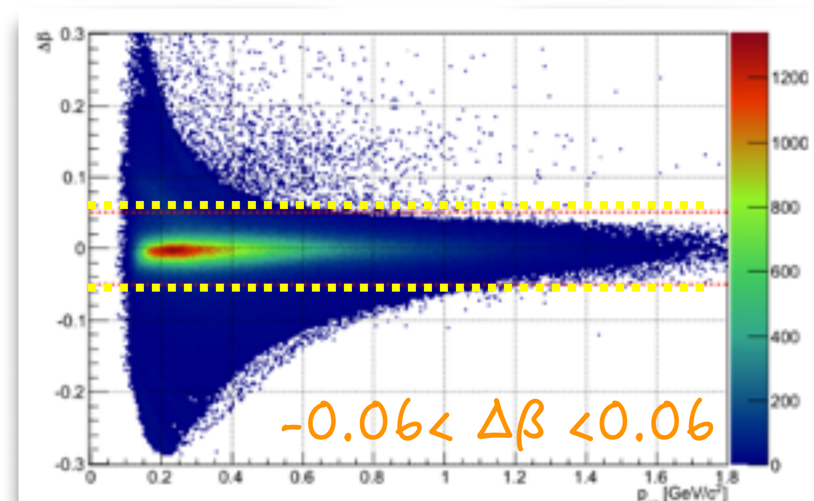
$$\beta_p = \frac{p}{\sqrt{p^2 + m_{PDG}^2}}$$

p is the proton or pions momentum
m_{PDG} is the nominal mass

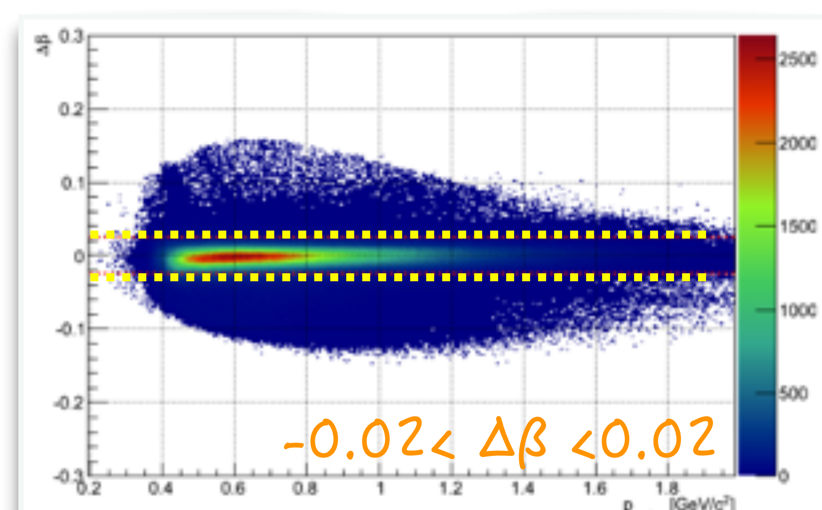
π^+



π^-

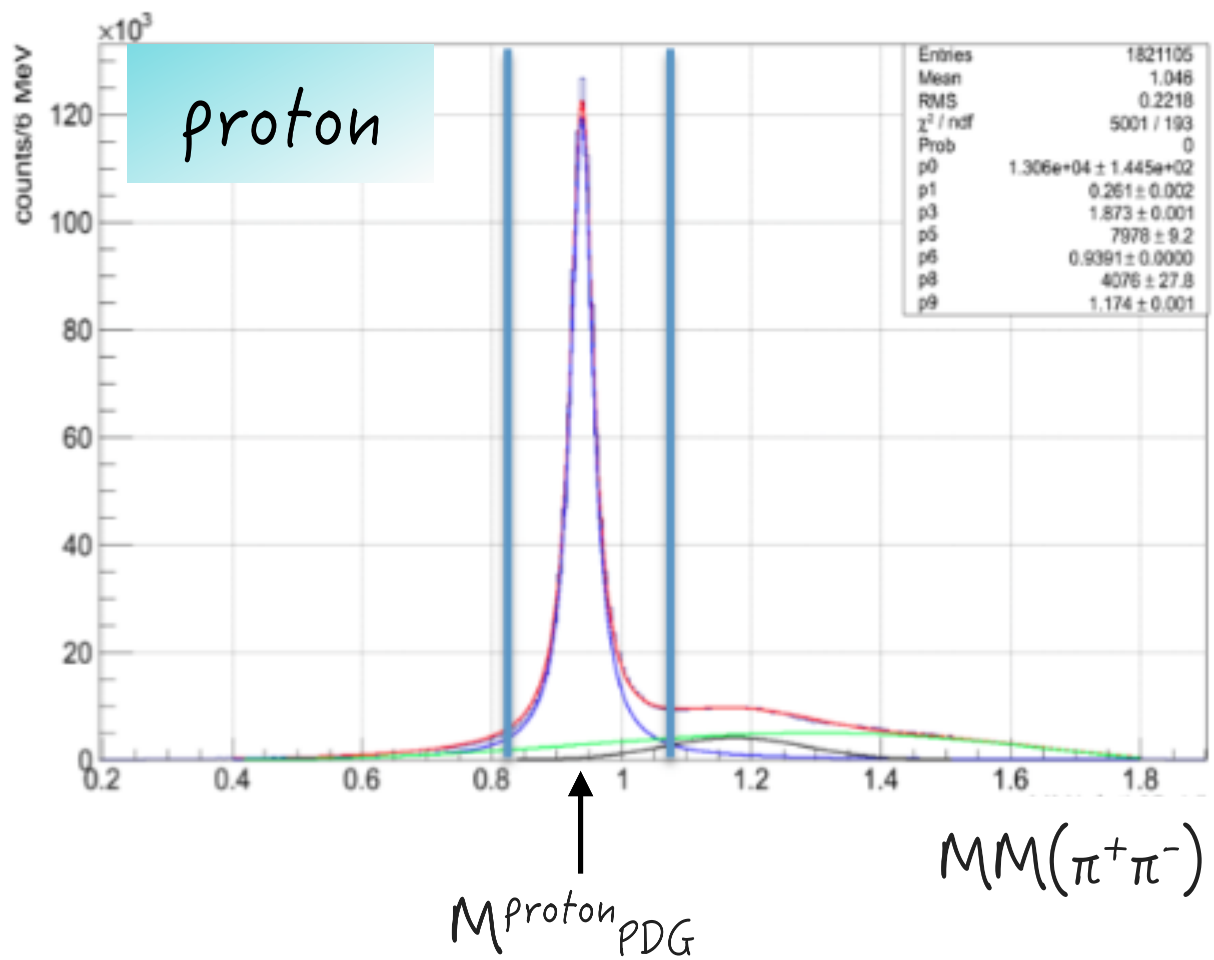


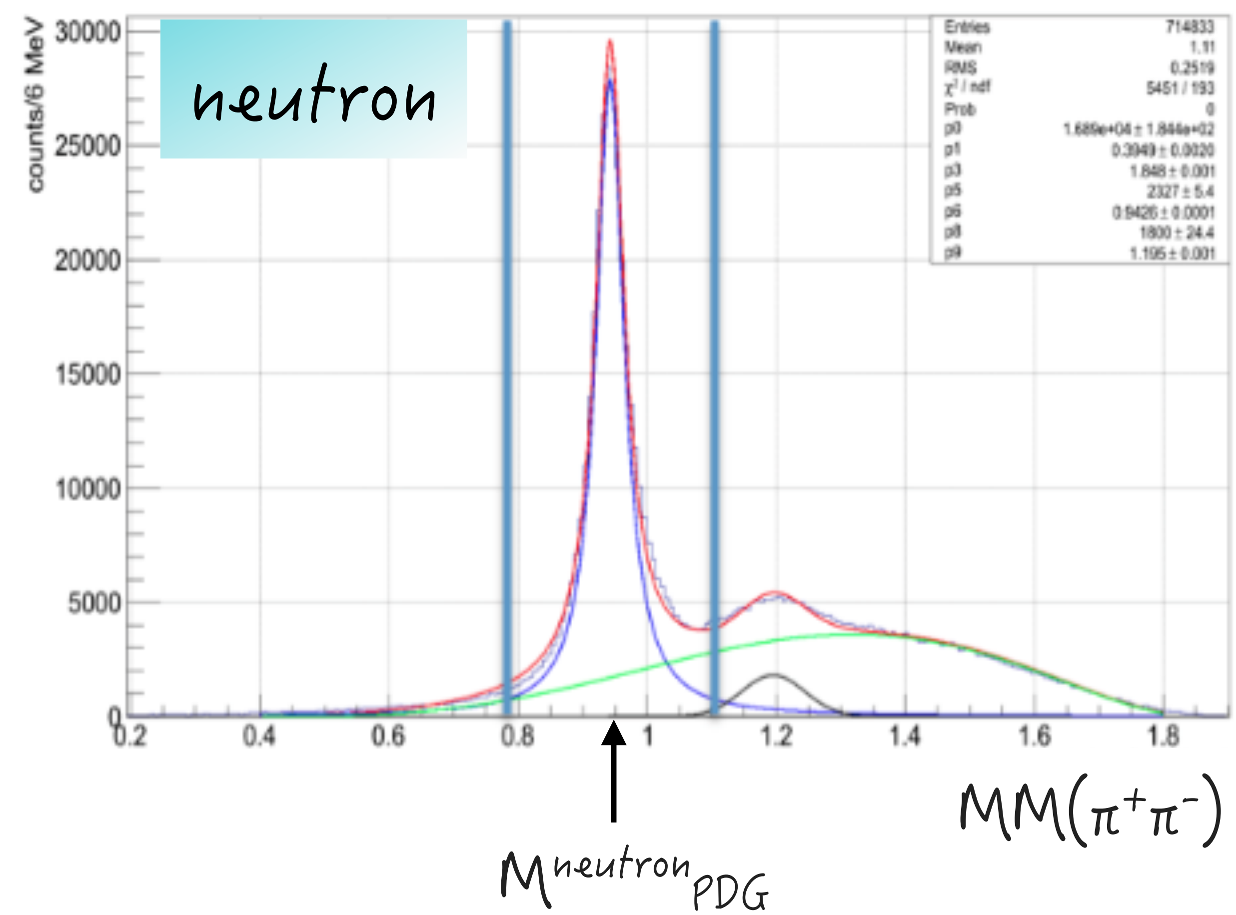
p



Nucleon Missing Mass cuts

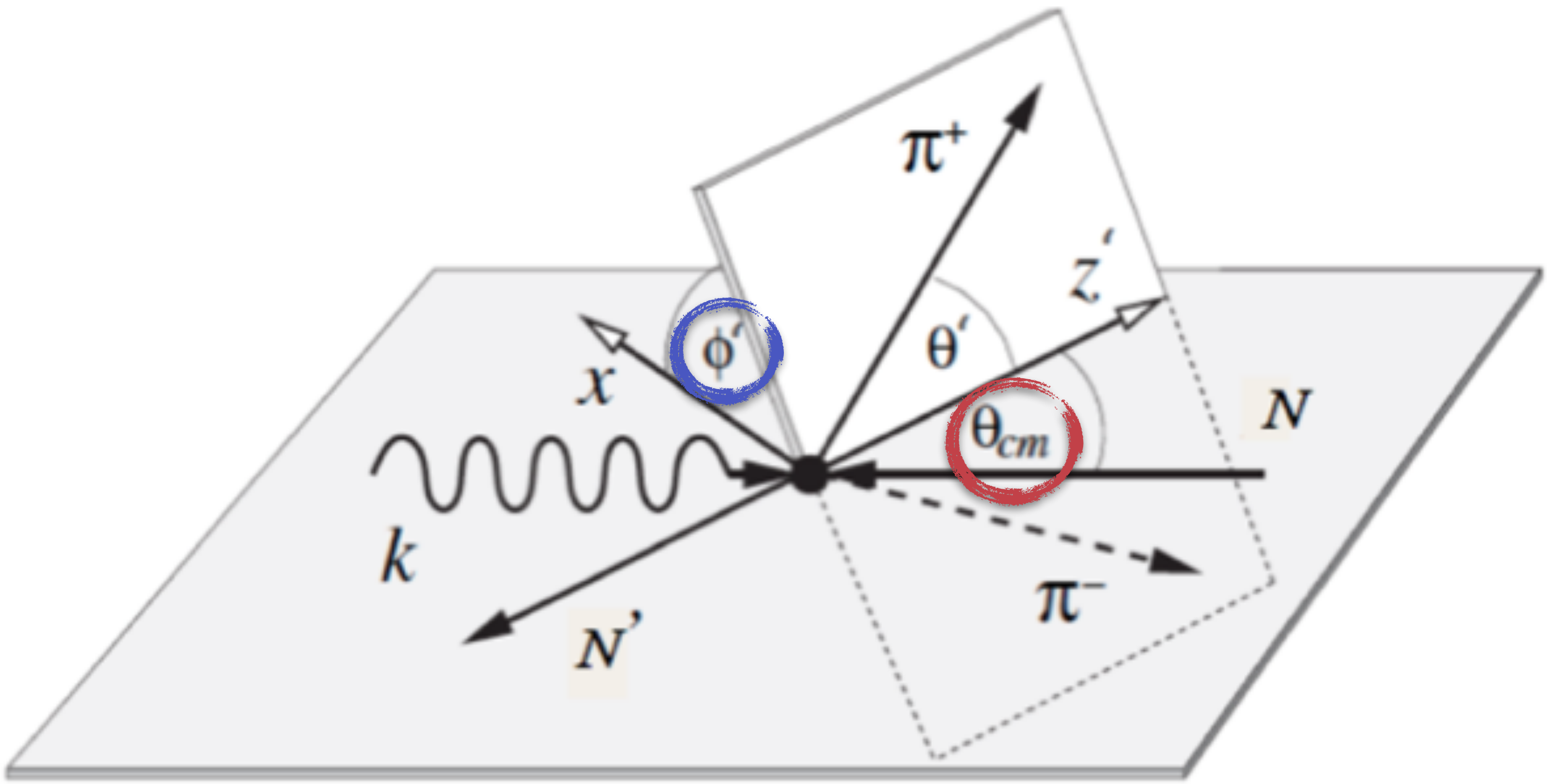
A cut is imposed on the Missing Mass $MM(\pi^+\pi^-)$, to make sure that only the three particles $\pi^+\pi^-p$ and $\pi^+\pi^-n$ were produced in the reaction.





Selected a region of 200 MeV (320 MeV) window around the PDG nucleon mass for the proton (neutron).

Extraction of the Polarization Observables: angles definition



Relevant variables for the extraction of the polarization observables:

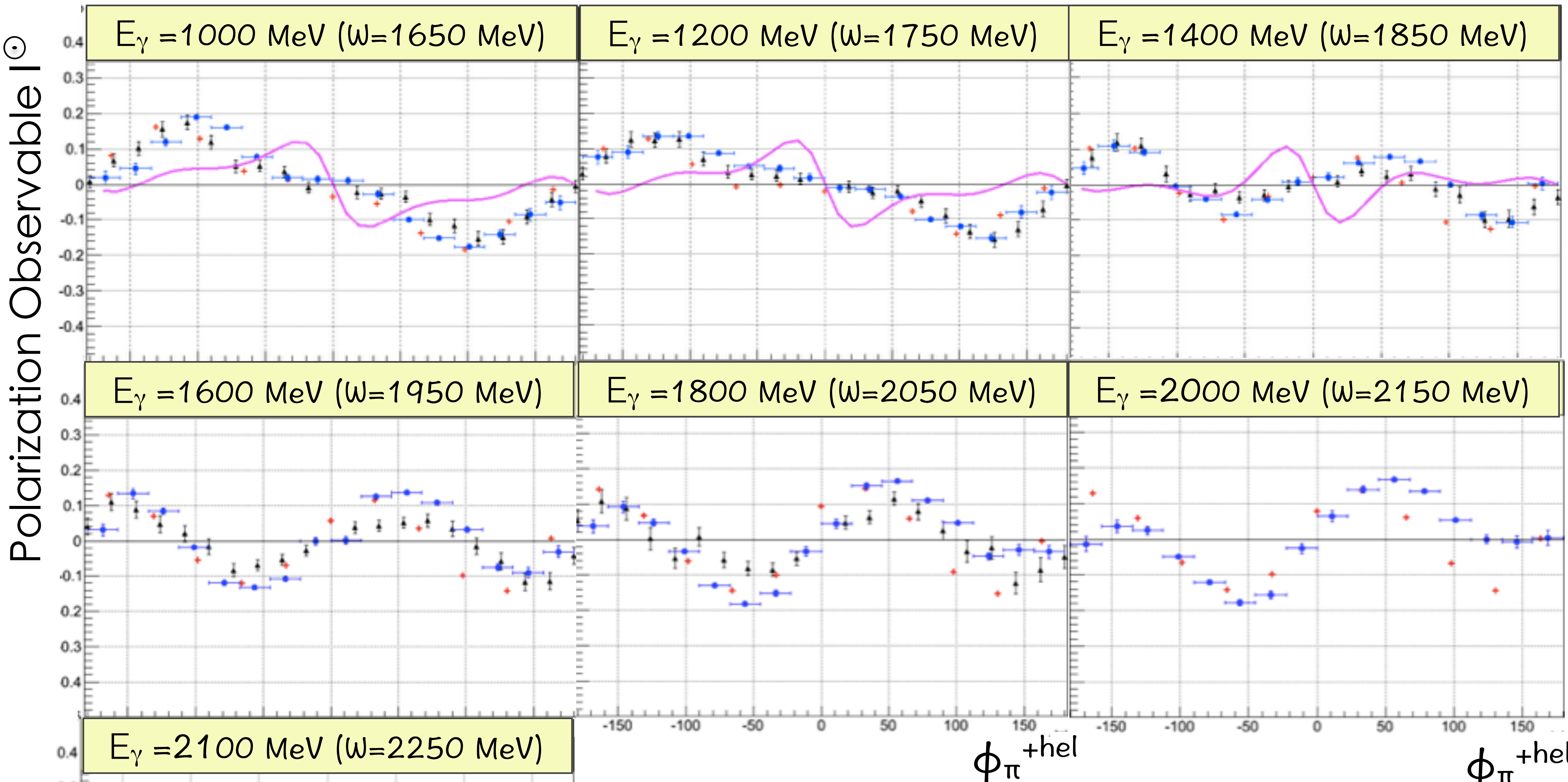
For the two-pion photoproduction:

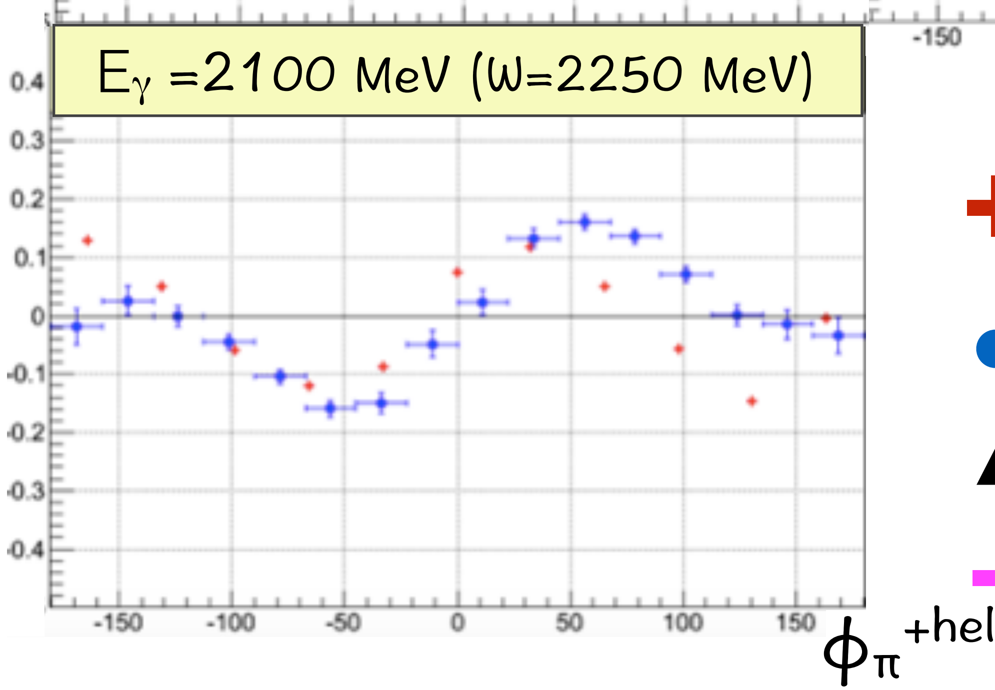
- ϕ_π^{hel} (or ϕ') is the azimuthal angle of the π^+ in the rest frame of the $\pi^+\pi^-$ system.

For the rho vector meson photoproduction:

- $\theta_{\pi\pi}^{CM}$ is the polar angle of the $\pi^+\pi^-$ pair in the CM system.

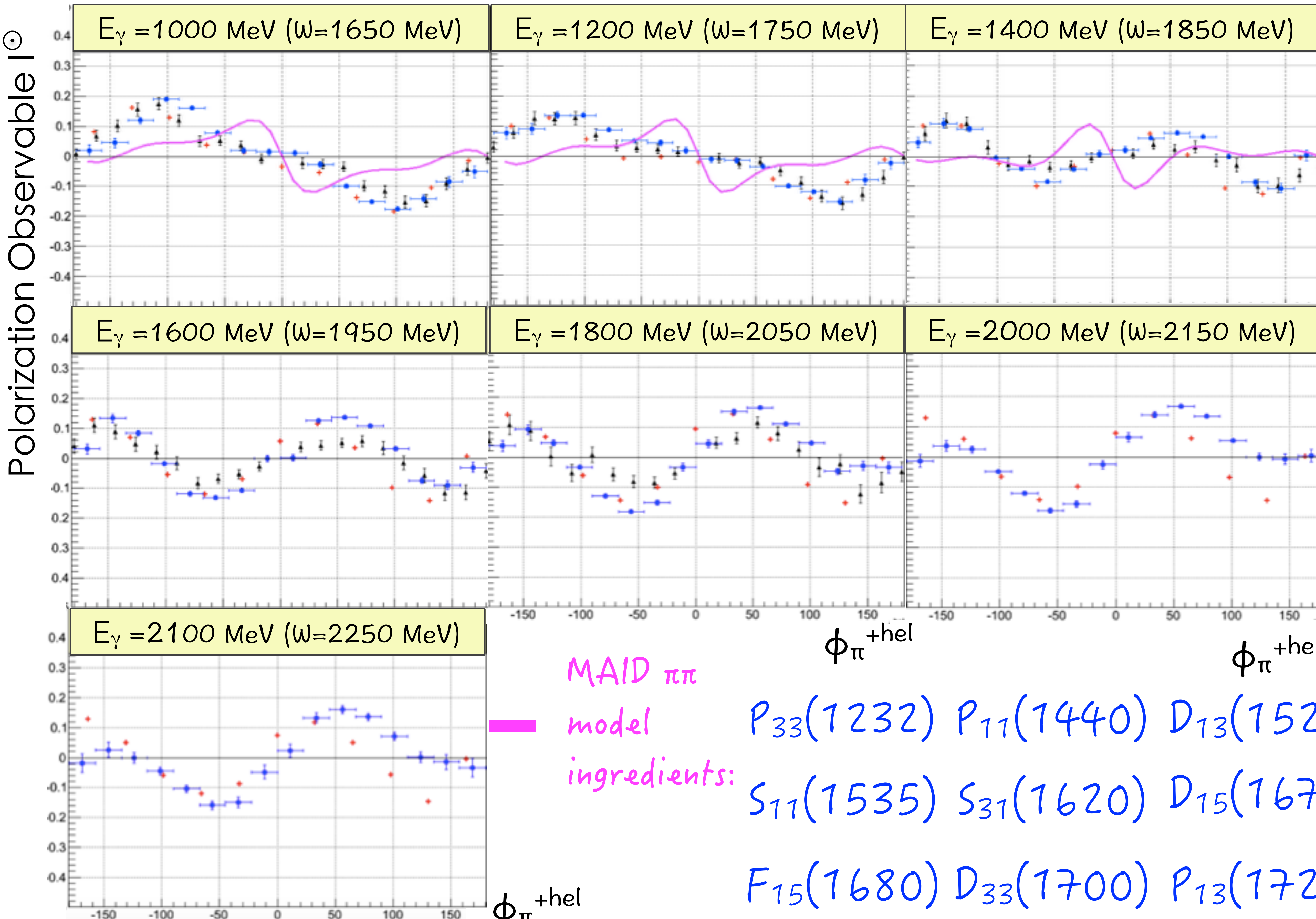
Extraction of $I^{\odot}$ for the reaction $\vec{\gamma}\vec{p}(n) \longrightarrow \pi^+\pi^- p(n)$





✚ g1c data	Unpolarized LHe target	S. Strauch Phys. Rev. Lett. 95 (2005) 162003
● g14 data	HD-ICE target	
▲ g9 data	FROST target	S. Park's CLAS NOTE 2013-012
▬ MAID ππ	model	Fix. and Arenhoevel Eur. Phys. J. A 25 115 (2005)

Extraction of $I^\odot$ for the reaction $\vec{\gamma}\vec{p}(n) \longrightarrow \pi^+\pi^- p(n)$



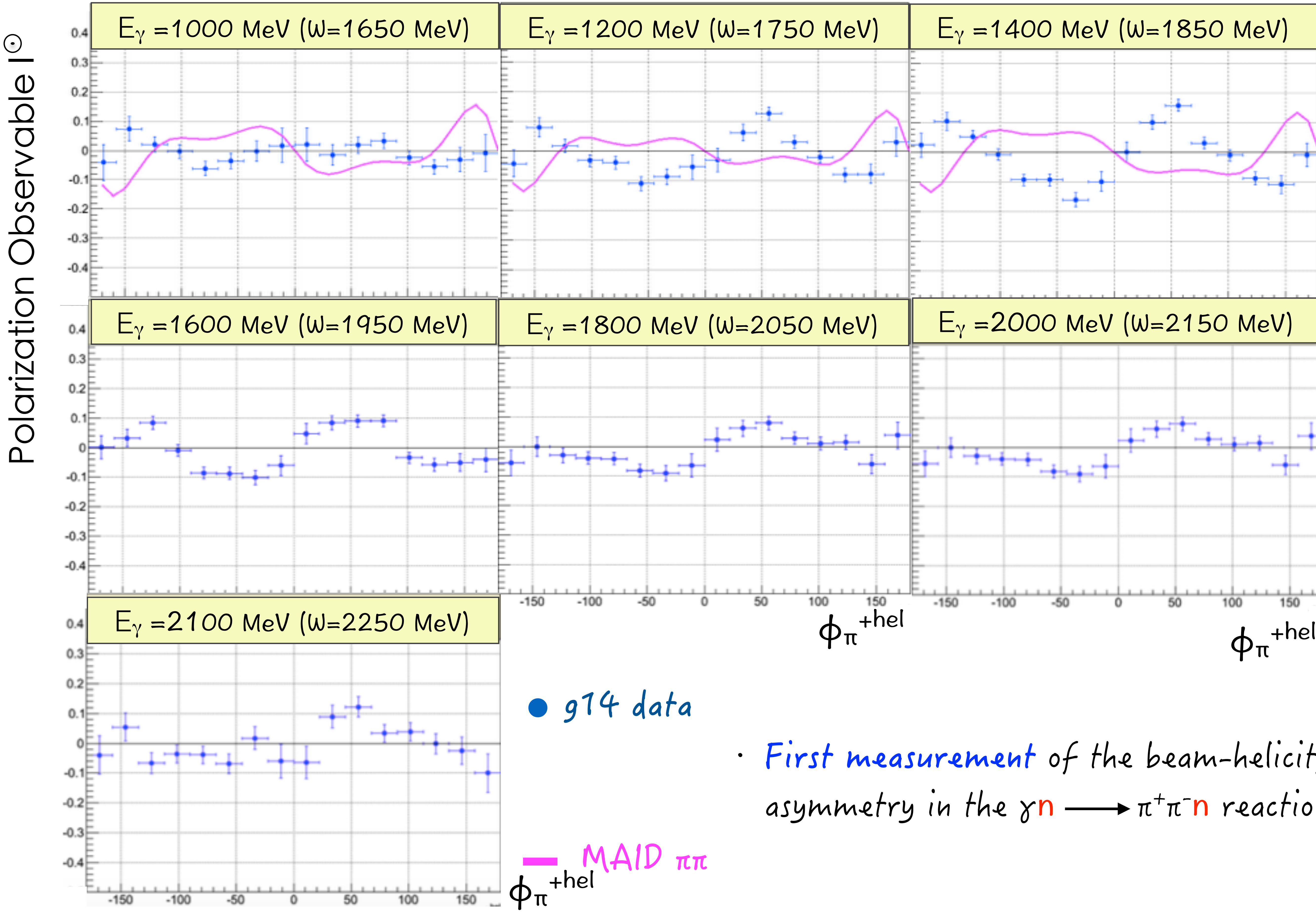
MAID $\pi\pi$ model ingredients:

$P_{33}(1232)$ $P_{11}(1440)$ $D_{13}(1520)$

$S_{11}(1535)$ $S_{31}(1620)$ $D_{15}(1675)$

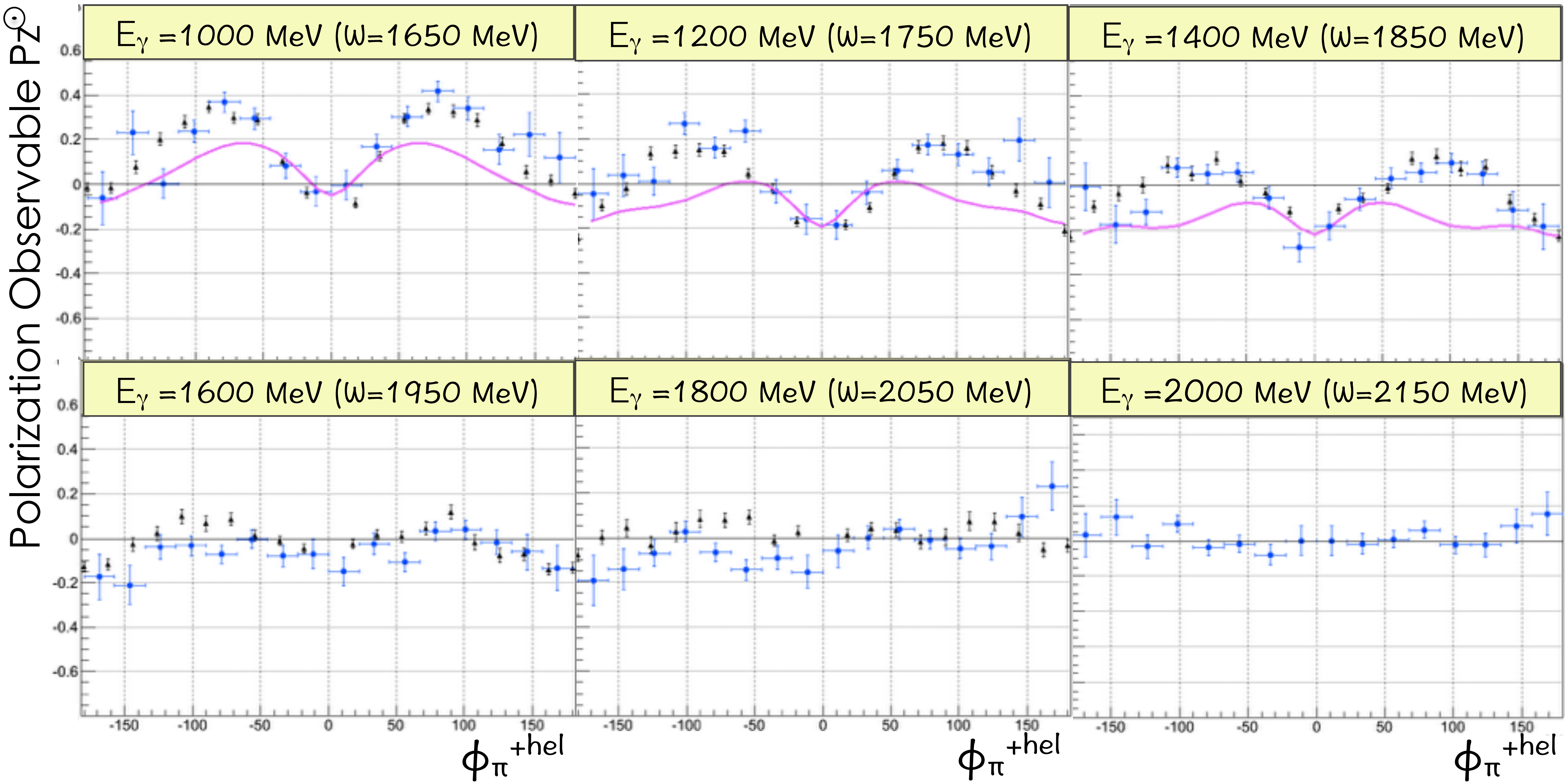
$F_{15}(1680)$ $D_{33}(1700)$ $P_{13}(1720)$

Extraction of $I^{\odot}$ for the reaction $\vec{\gamma}\vec{n}(p) \longrightarrow \pi^+\pi^- n(p)$



- *First measurement* of the beam-helicity asymmetry in the $\gamma n \longrightarrow \pi^+\pi^- n$ reaction

Extraction of $P_z^{\odot}$ for the reaction $\vec{\gamma}\vec{p}(n) \longrightarrow \pi^+\pi^- p(n)$



● g14 data HD-ICE target

▲ g9 data FROST target

— MAID ππ model

Identification of the reaction $\vec{\gamma}\vec{p}(n) \longrightarrow \rho^0 p(n)$

1) SELECTION: $IM(\pi^+ p) > 1.3$ GeV and $IM(\pi^- p) > 1.3$ GeV

Goal ⟶ disentangle the reaction:

$\gamma\, p \longrightarrow \rho^0\, p \longrightarrow \pi^+\pi^- p$

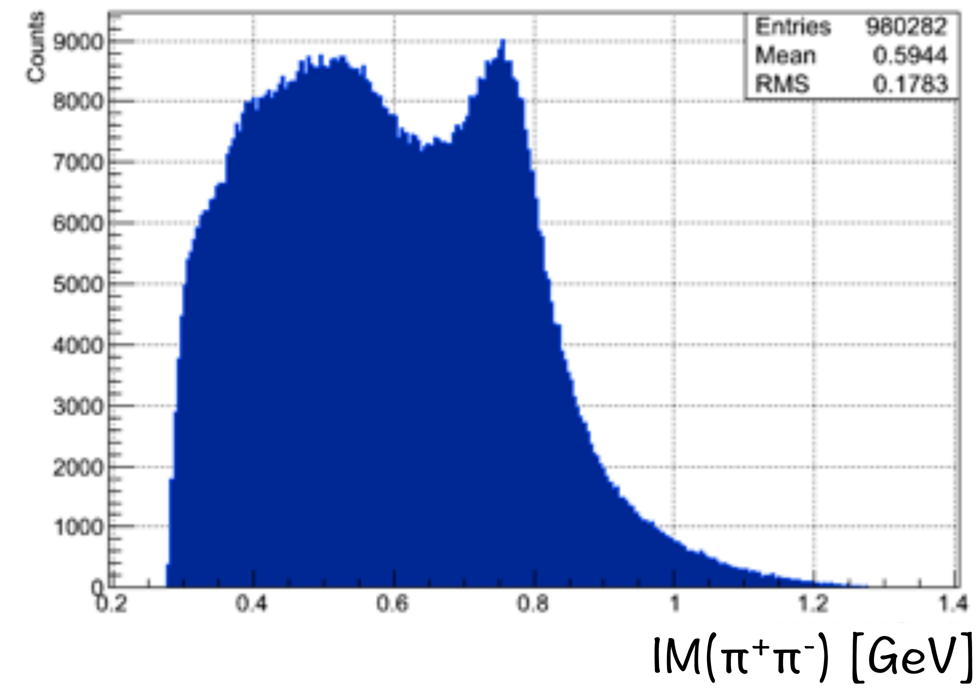
From the three concurrent reactions:

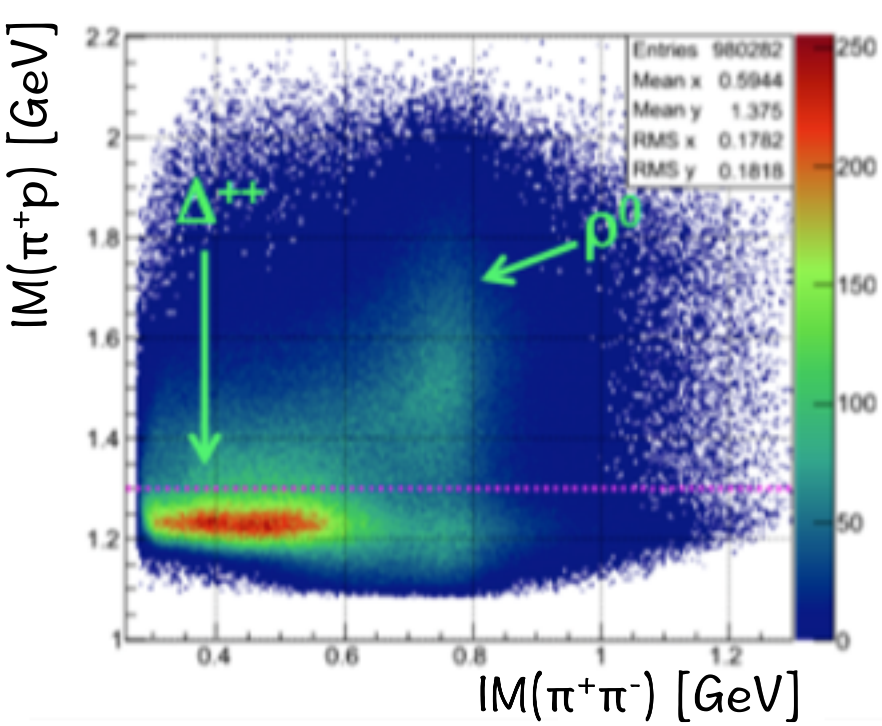
$\gamma\, p \longrightarrow \pi^-\Delta^{++} \longrightarrow \pi^+\pi^- p$

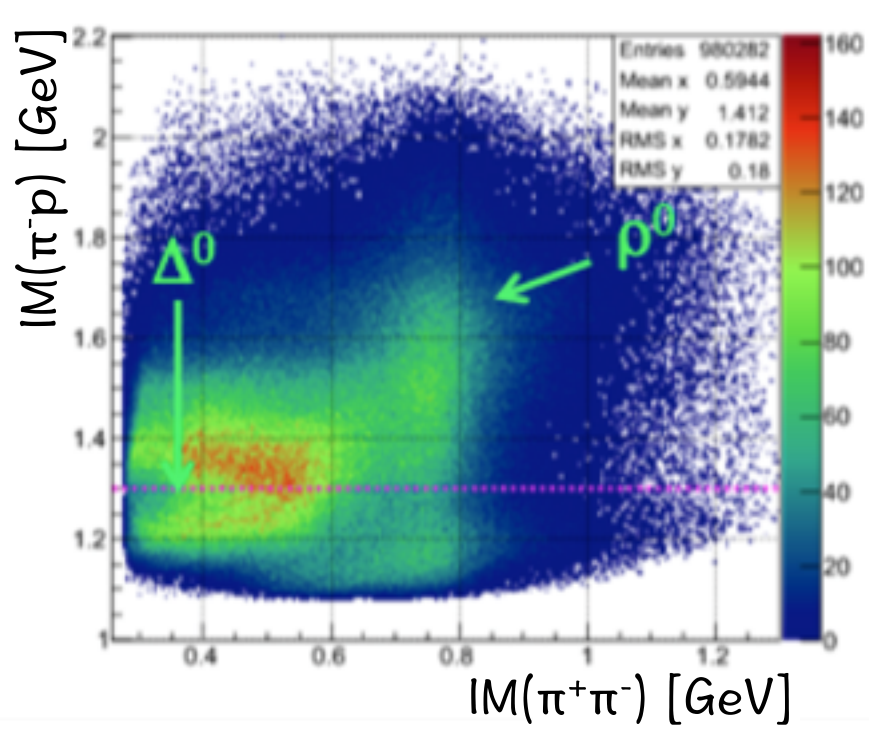
$\gamma\, p \longrightarrow \pi^+\Delta^0 \longrightarrow \pi^+\pi^- p$

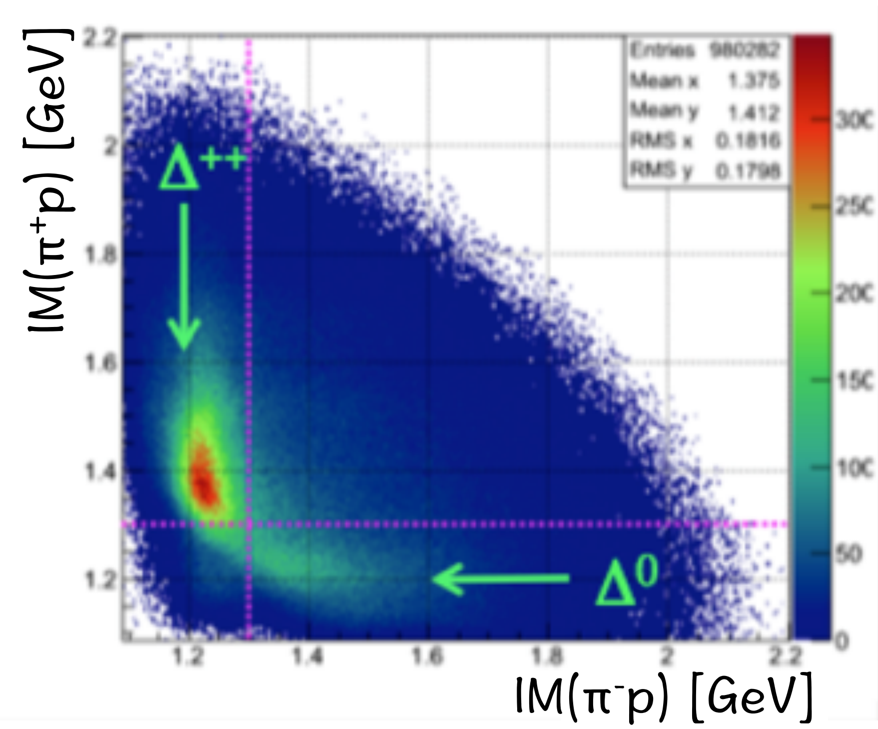
$\gamma\, p \longrightarrow \pi^+\pi^- p$

IM(π⁺π⁻) spectrum

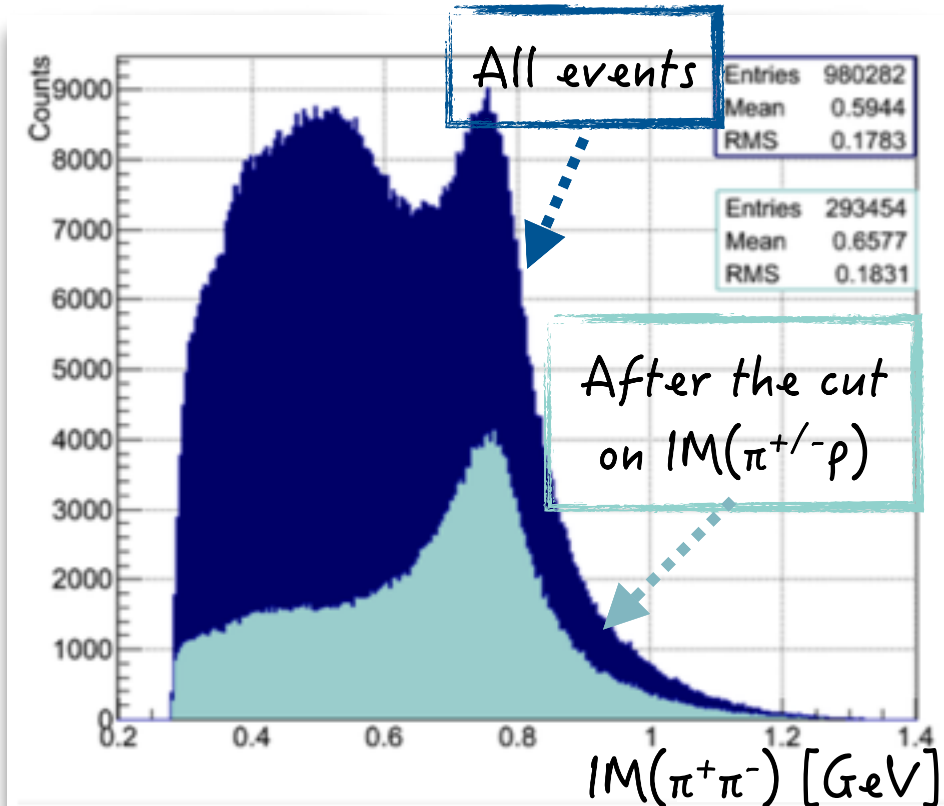








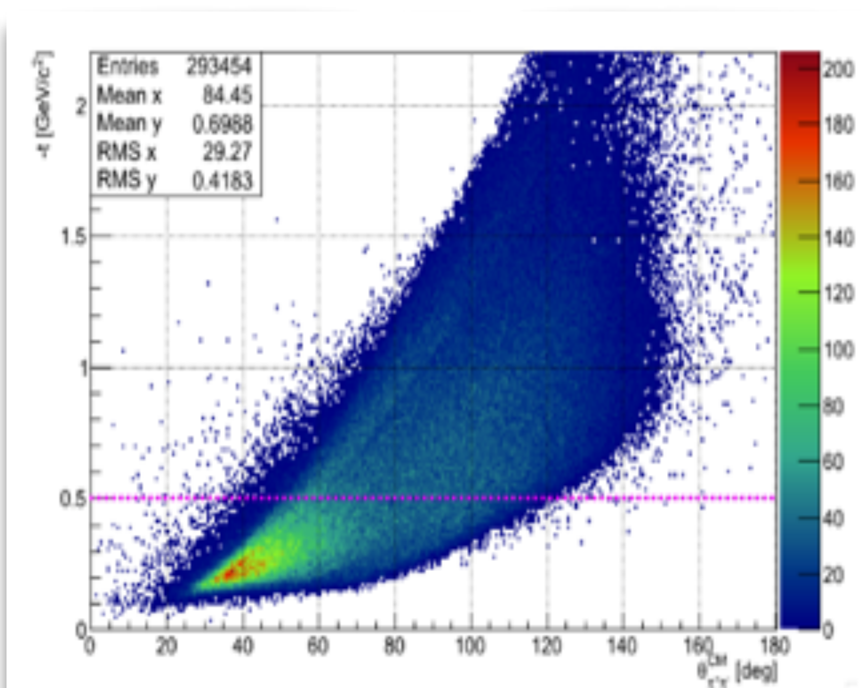
Identification of the reaction $\vec{\gamma}\vec{p}(n) \longrightarrow \rho^0 p(n)$



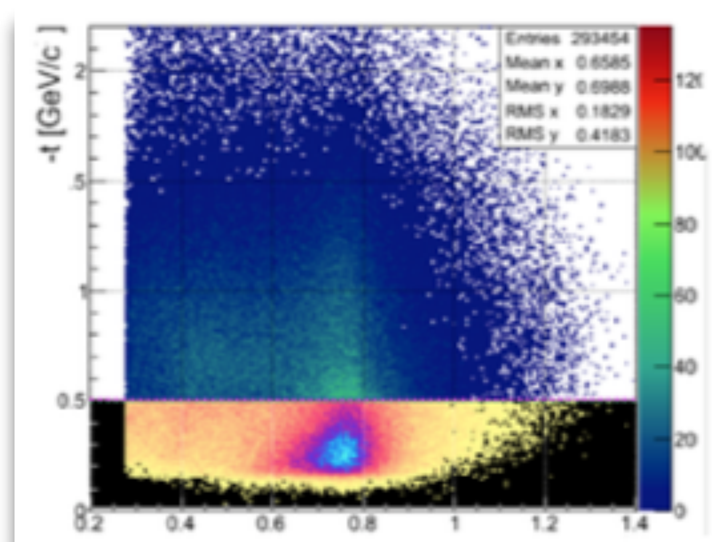
2) SELECTION: cut on -t<0.5 GeV

Diffractive behavior

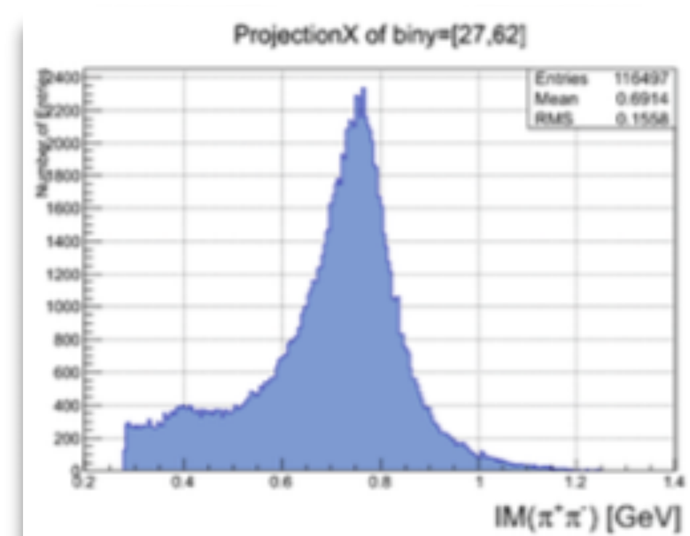
$$t = (\tilde{P}_\gamma - \tilde{P}_\rho)^2 = (\tilde{P}_N - \tilde{P}_{N'})^2 = m_\rho^2 - 2E_\gamma(E_\rho - p_\rho cos\theta_\rho)$$



$-t$ vs. $\theta(\pi^+\pi^-)^{CM}$

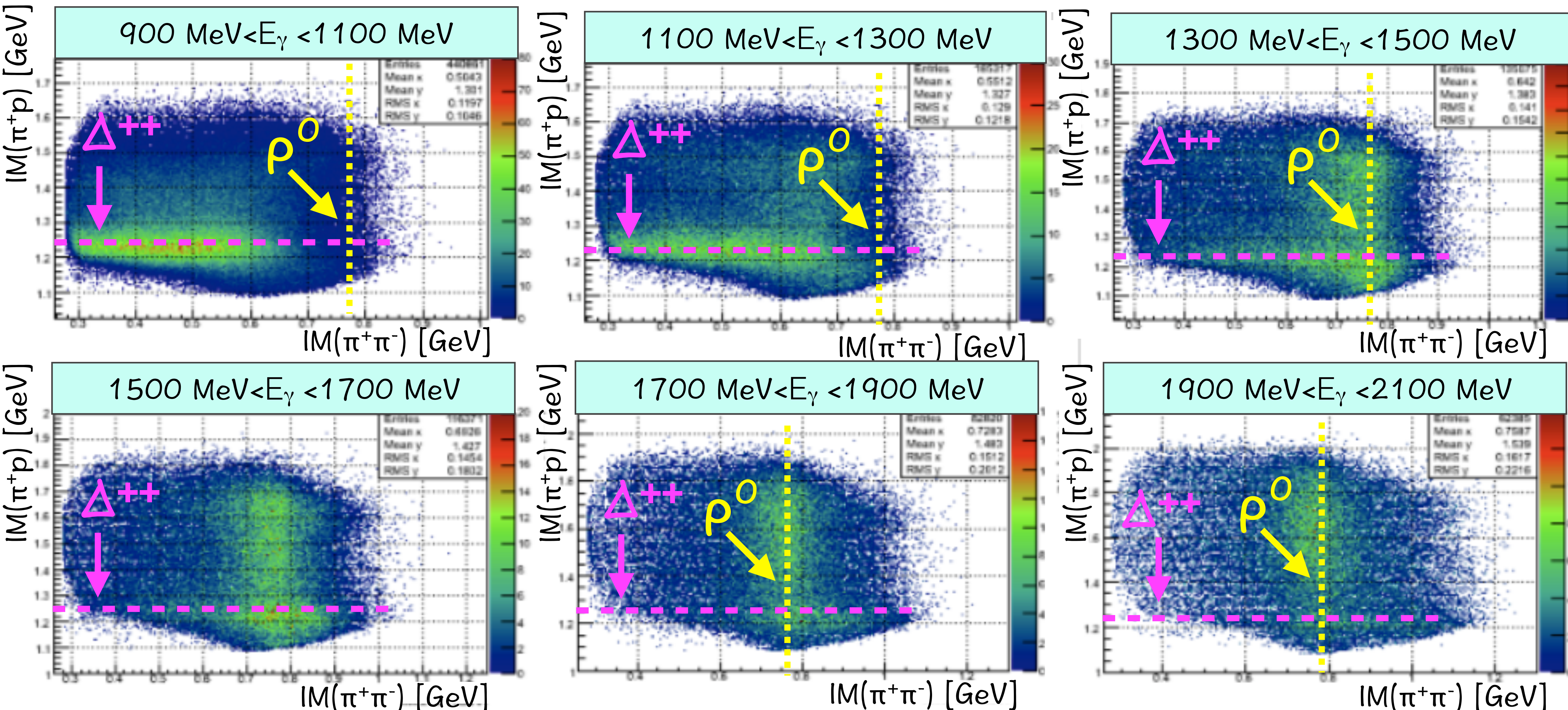


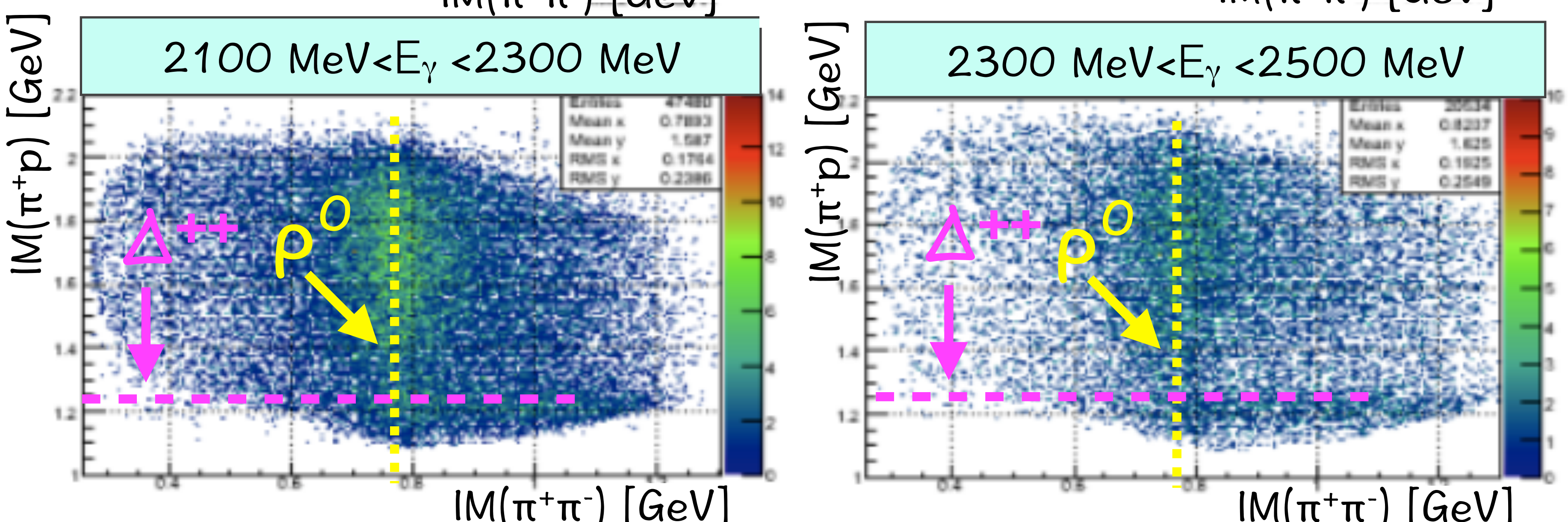
$-t$ vs. IM$(\pi^+\pi^-)$



projections on x

Identification of the reaction $\vec{\gamma}\vec{p}(n) \longrightarrow \rho^0 p(n)$

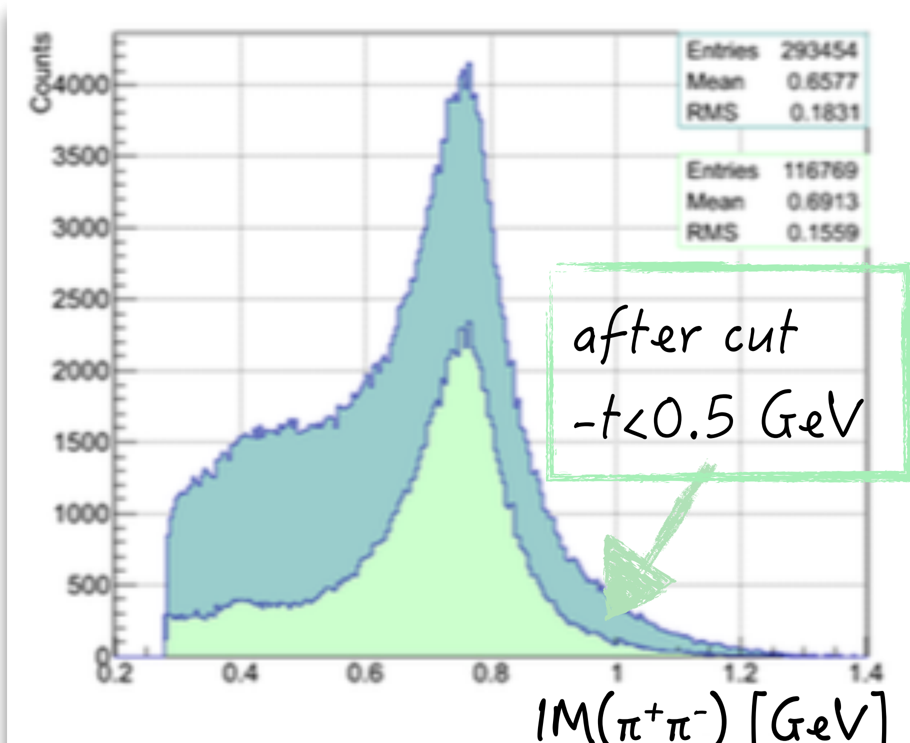




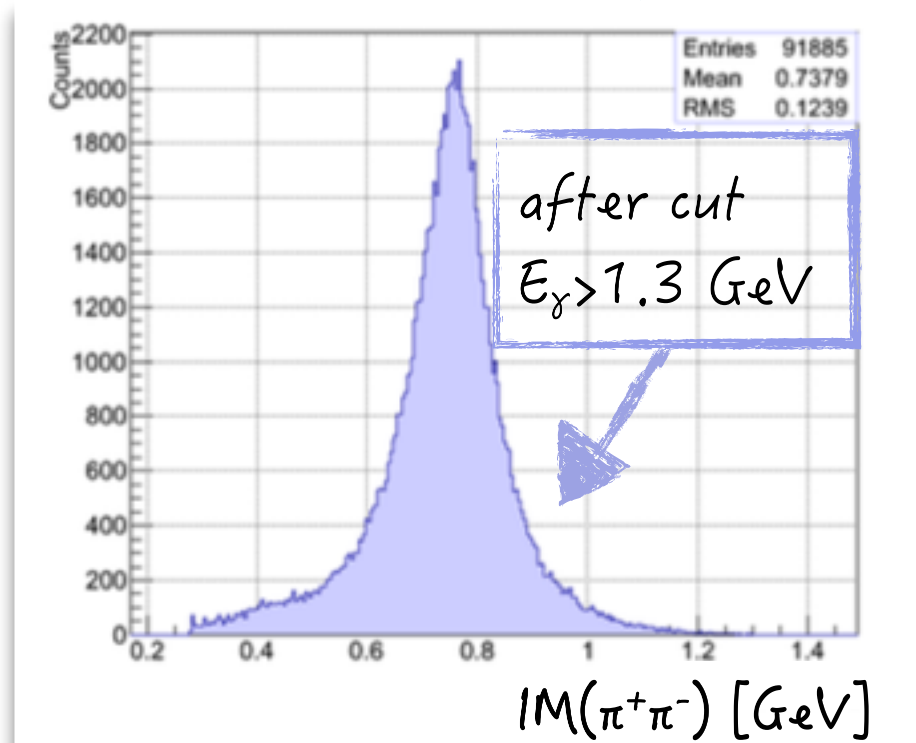
ρ^0 photoproduction is negligible for $E_\gamma < 1.3$ GeV

Identification of the reaction $\vec{\gamma}\vec{p}(n) \longrightarrow \rho^0 p(n)$

3) SELECTION: cut on $E_\gamma > 1.3$ GeV

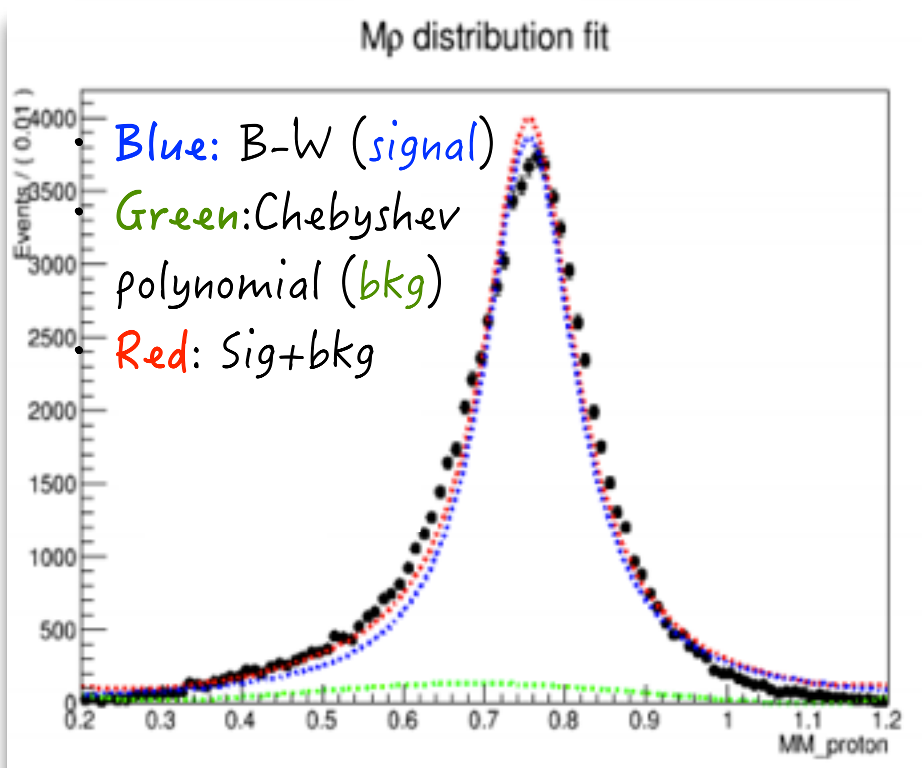


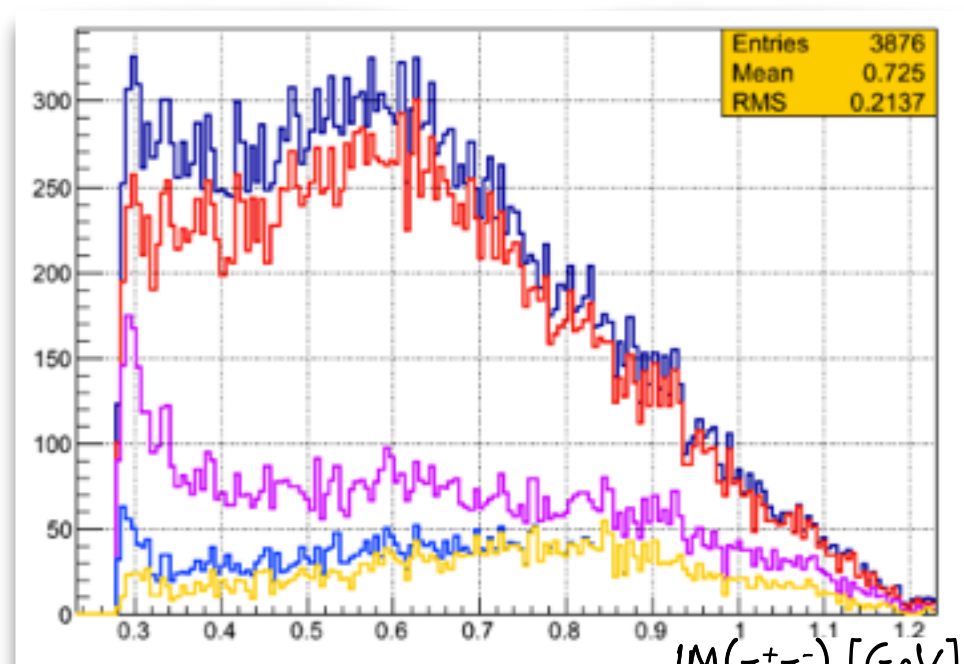
Final $IM(\pi^+\pi^-)$ spectrum



ρ^0 selection cuts

- photon id, particle id
- $0.83 > MM(\pi^+\pi^-) > 1.04$ GeV
- $IM(\pi^+ p)$, $IM(\pi^- p) > 1.3$ GeV
- $-t < -0.5$ GeV
- $E_\gamma > 1.3$ GeV

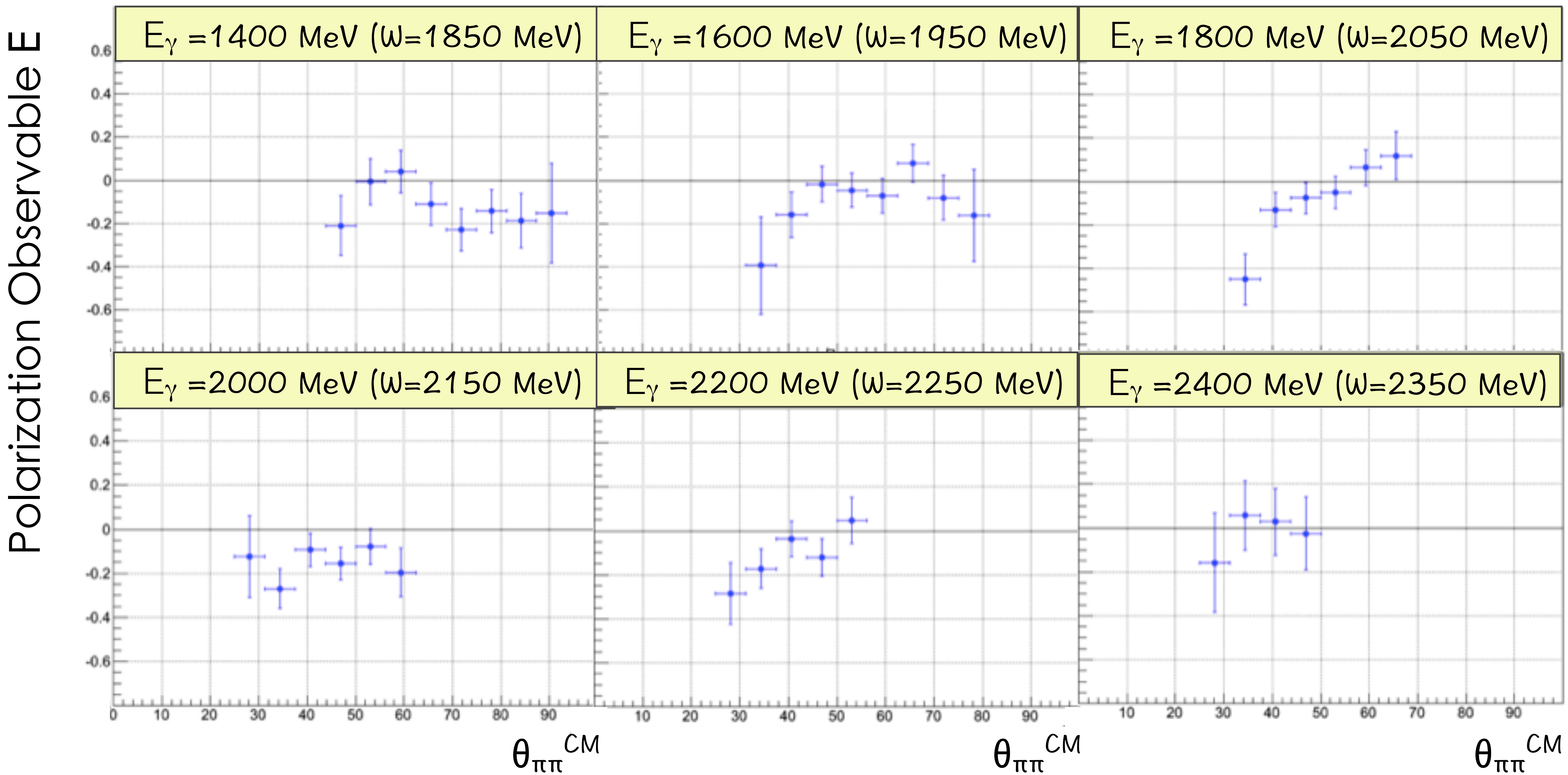




simulated background events

estimated residual background events <10%

Extraction of E for the reaction $\vec{\gamma}\vec{p}(n) \longrightarrow \rho^0 p(n)$



- g14 data   HD-ICE target

- First measurement of the beam-target helicity difference

Very preliminary

Conclusion and Future Perspectives

γ p —> $\pi^+ \pi^-$ p analysis:

- $I^{\odot}$ and $P_z^{\odot}$ have been obtained. Good agreement with previous experiments

γ n —> $\pi^+ \pi^-$ n analysis:

- $I^{\odot}$ has been obtained. *It is a first measurement.*

γ p —> ρ^0 p analysis:

- Tentative approach to select the channel γ p —> ρ^0 p in a limited the phase space.
- The double polarization observable E was obtained. *It is a first measurement.*

Conclusion and Future Perspectives

TO DO :

- Use the full statistic
- Contact with theorists to get curves from other models.
- Accurate study of systematic uncertainties
- Try to extract $P_z^{\odot}$ also in the case of quasi-free neutron
- Try to extract P_z to complete the set of measured observables for two pion photoproduction with circularly polarized photon beam and longitudinally polarized target.

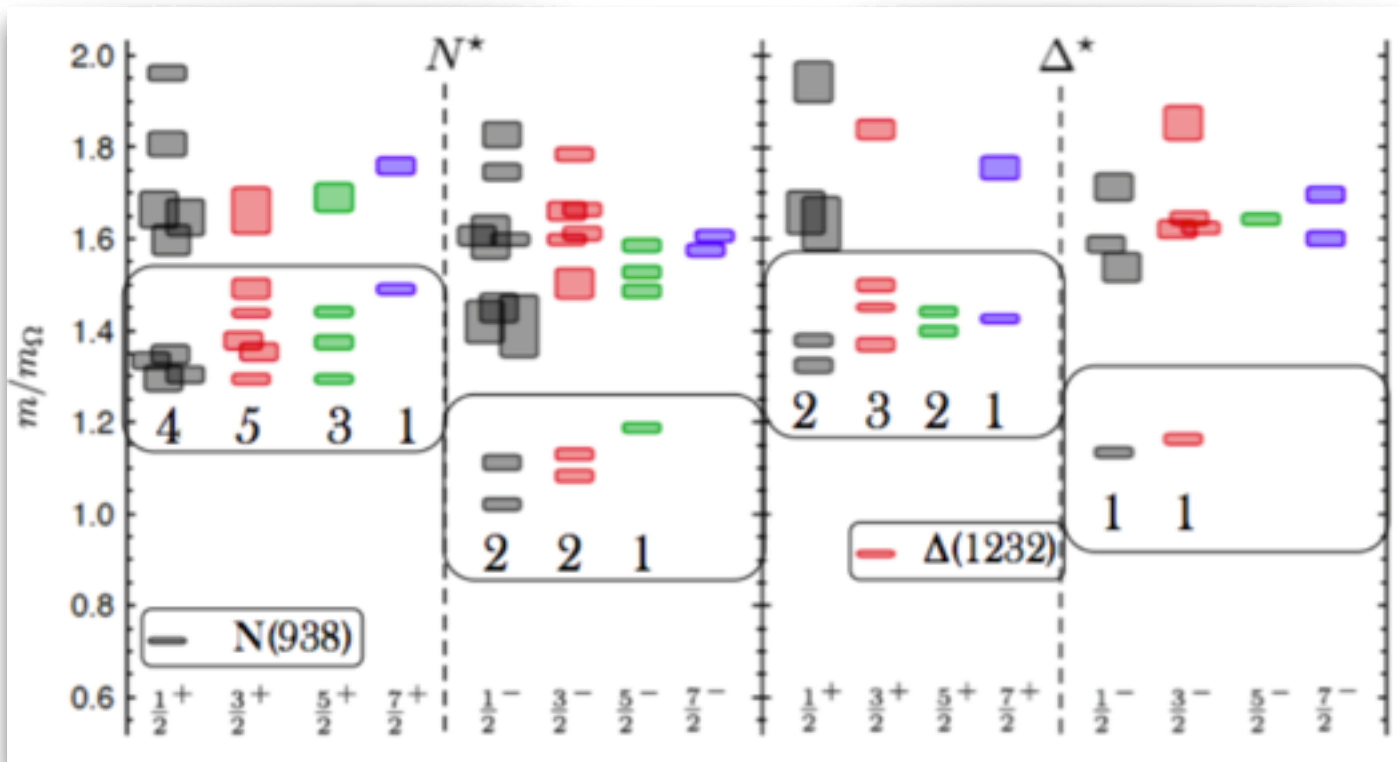
- Don't limit the phase space with the cut on t
- Need to explore different statistical methods (SPlot, QValue, BDT) for background evaluation study.

Thanks for the attention

Backup slides

Where Have All Resonances Gone?

Excited Baryon from LQCD (m_π~400 MeV)



Discrepancy between predicted and experimentally observed states: "MISSING RESONANCES PROBLEM"

Theoretical models:
other approaches based on different effective degrees of freedom

Experiment:
alternative to strong probes: electroproduction photoproduction

VOLUME 44, NUMBER 13 PHYSICAL REVIEW LETTERS 31 MARCH 1980

Where Have All the Resonances Gone? An Analysis of Baryon Couplings in a Quark Model with Chromodynamics

Roman Koniuk and Nathan Isgur
Department of Physics, University of Toronto, Toronto, Ontario M5S 1A7, Canada
(Received 26 November 1979)

This paper reports on the results of an extensive analysis of baryon couplings in a quark model with chromodynamics. The amplitudes which emerge from the analysis resolve the problem of "missing" baryon resonances by showing that a very large number of states essentially decouple from the partial-wave analyses; those resonances which remain are in remarkable correspondence to the observed states in both their masses and decay amplitudes.

The missing states may be weakly coupled to channels where the pion is in the initial and final states but they may be observed in other channels

Evaluation of systematic uncertainties

CONTRIBUTIONS:	Δobs
Circular polarization of photon beam $\delta_{\odot}$	1.5%
Target polarization Λz	10%
Analysis	1.5%
	10,22% Tot

Why measurements on the neutron?

Isospin dependence of the reaction amplitudes in single pseudoscalar meson photoproduction:

γ+p reactions

$$A_{\gamma p\to\binom{\pi^0 p}{K^+\Sigma^0}} = \mp\left[\frac{1}{\sqrt{3}}A^0_{\binom{\pi N}{K\Sigma}} - \frac{1}{3}A^1_{\binom{\pi N}{K\Sigma}}\right]^{(I=1/2)} + \frac{2}{3}A^{(I=3/2)}\binom{\pi N}{K\Sigma}$$

$$A_{\gamma p\to\binom{\pi^+ n}{K^0\Sigma^+}} = \pm\sqrt{2}\left[\frac{1}{\sqrt{3}}A^0_{\binom{\pi N}{K\Sigma}} - \frac{1}{3}A^1_{\binom{\pi N}{K\Sigma}}\right]^{(I=1/2)} + \frac{\sqrt{2}}{3}A^{(I=3/2)}\binom{\pi N}{K\Sigma}$$

$$A_{\gamma p\to\binom{\eta p}{K^+\Lambda}} = +\left[A^0_{\binom{\eta N}{K\Lambda}} - \frac{1}{\sqrt{3}}A^1_{\binom{\eta N}{K\Lambda}}\right]^{(I=1/2)}$$

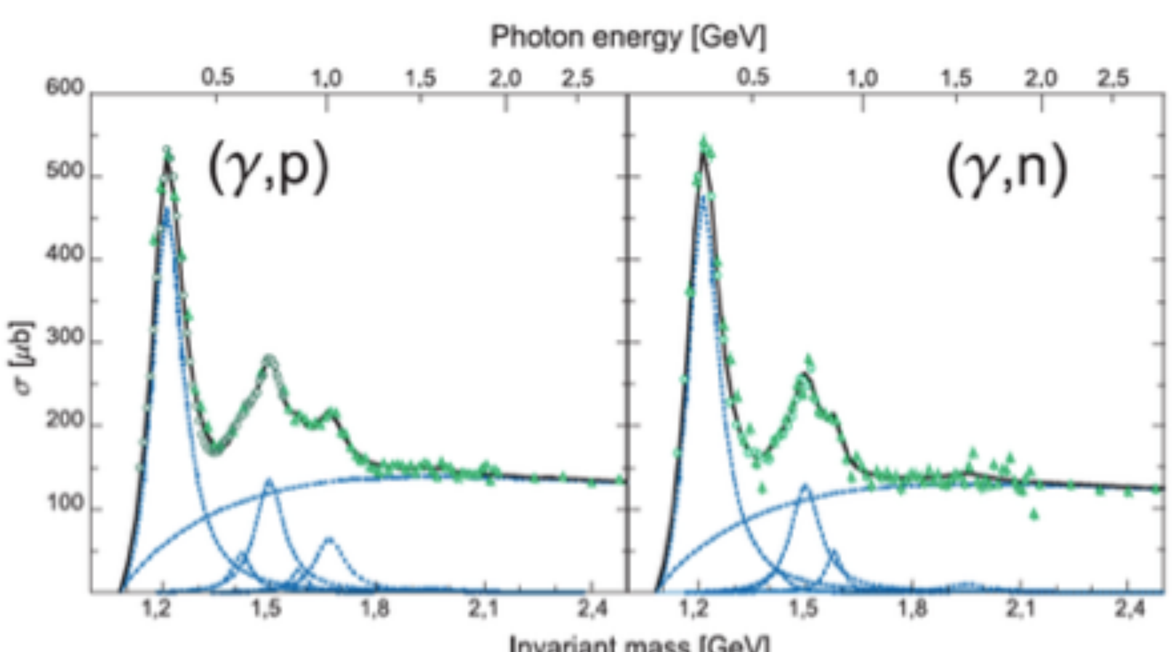
γ+n reactions

$$A_{\gamma n\to\binom{\pi^0 n}{K^0\Sigma^0}} = \pm\left[\frac{1}{\sqrt{3}}A^0_{\binom{\pi N}{K\Sigma}} + \frac{1}{3}A^1_{\binom{\pi N}{K\Sigma}}\right]^{(I=1/2)} + \frac{2}{3}A^{(I=3/2)}\binom{\pi N}{K\Sigma}$$

$$A_{\gamma n\to\binom{\pi^- p}{K^+\Sigma^-}} = \mp\sqrt{2}\left[\frac{1}{\sqrt{3}}A^0_{\binom{\pi N}{K\Sigma}} + \frac{1}{3}A^1_{\binom{\pi N}{K\Sigma}}\right]^{(I=1/2)} + \frac{\sqrt{2}}{3}A^{(I=3/2)}\binom{\pi N}{K\Sigma}$$

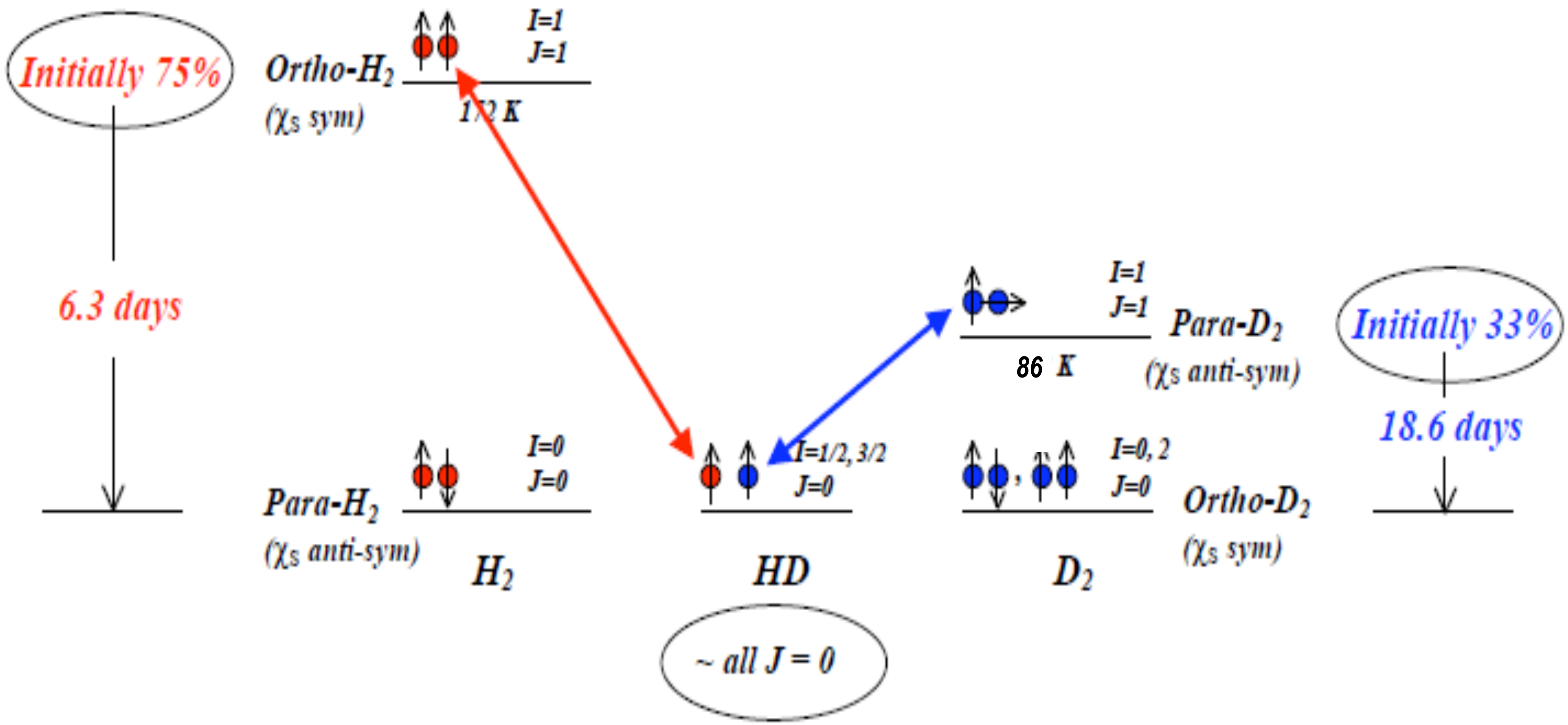
$$A_{\gamma n\to\binom{\eta p}{K^0\Lambda}} = +\left[A^0_{\binom{\eta N}{K\Lambda}} + \frac{1}{\sqrt{3}}A^1_{\binom{\eta N}{K\Lambda}}\right]^{(I=1/2)}$$

A^0, A^1: amplitude components result from coupling the I=1.2 nucleon with iso-scalar and iso-vector components of the photon field to yield a total isospin of 1/2.



The cross section for the reaction γ N ⟶ NX show different structures for proton and neutron. A third resonance region (1600-1700 MeV) is seen on the proton, less pronounced on neutron target.

HD frozen-spin target



ortho-H_2 and para-D_2 are polarizable but are meta-stable and cannot be used to produce polarized targets.

For HD the constraints don't apply and H and D may be independently oriented in the ground state.

HD polarization: "Brute Force and Aging"

HD polarized by using "Brute Force": B=15-17 T , T=10 -15 mk

✗ Brute Force is not compatible with any detector

✗ T_H^1 (longitudinal relaxation time) for pure HD is very long

↓

SOLUTION TO POLARIZE H:

Add ortho-H_2 in solid HD: cross-relaxation between ortho-H_2 and HD spins.

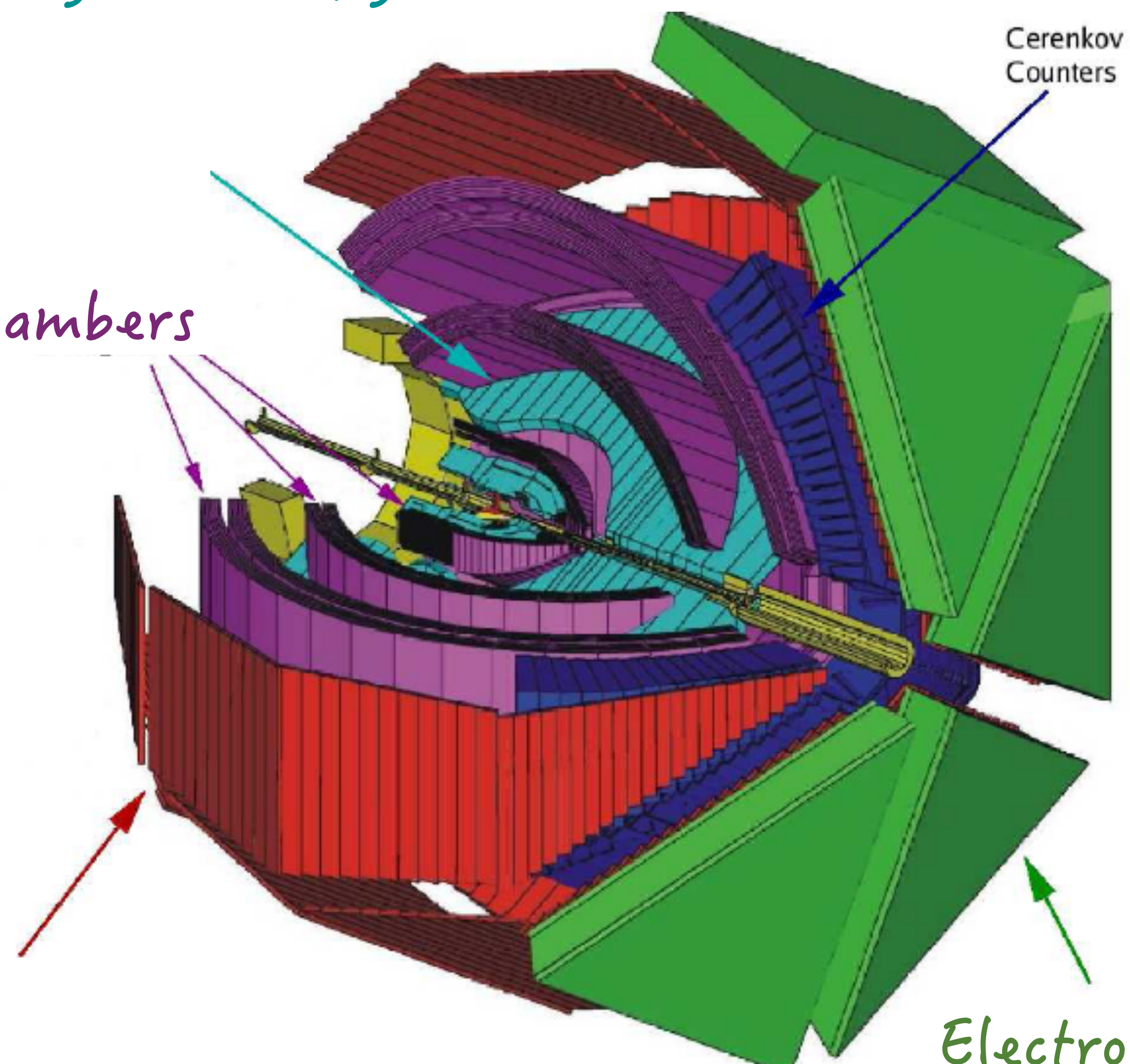
➡ T_H^1 strongly depends on the concentration of ortho-H_2 (minutes for 10^{-3}, months for 10^{-6})

➡ optimal concentration: 10^{-4}

Polarize HD with Brute Force → Aging for 3 months → Frozen-spin target

D is polarized through the adiabatic fast passage

Experimental Setup



charged particles coverage:

θ: 8-142

ϕ: 360 except 6 6 gaps (magnet)

neutral particles coverage:

θ: 8-45

ϕ: 360 except 6 6 gaps (magnet)

Neutron identification

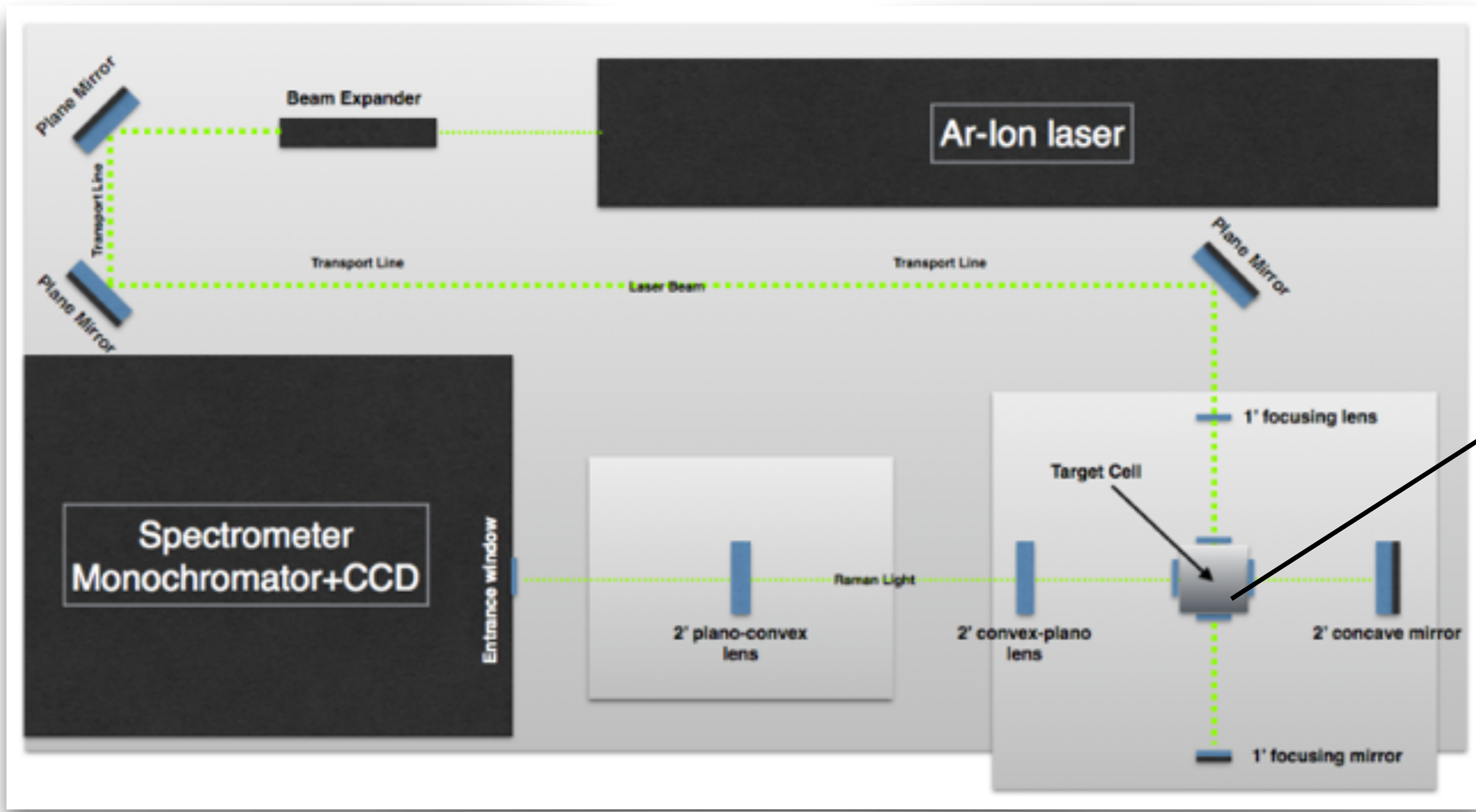
Neutral particles are detected as cluster in the EC not associated with any charged track in the DC.
The directional components (θ,ϕ) of the neutral track and the neutral path length L are found using the vertex (same as charge particles) and cluster position on the EC for that hit

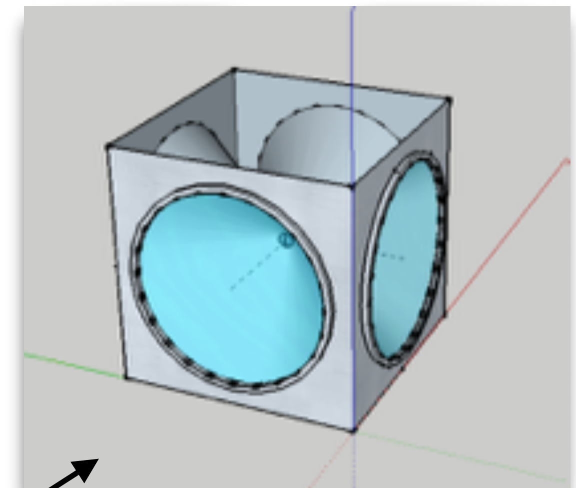
$$\beta = \frac{L_{neutral}}{c(ToF_{EC} - T_v)} = \frac{\sqrt{(x_{EC} - x_v)^2 + (y_{EC} - y_v)^2 + (z_{EC} - z_v)^2}}{c(TOF_{EC} - T_v)}$$

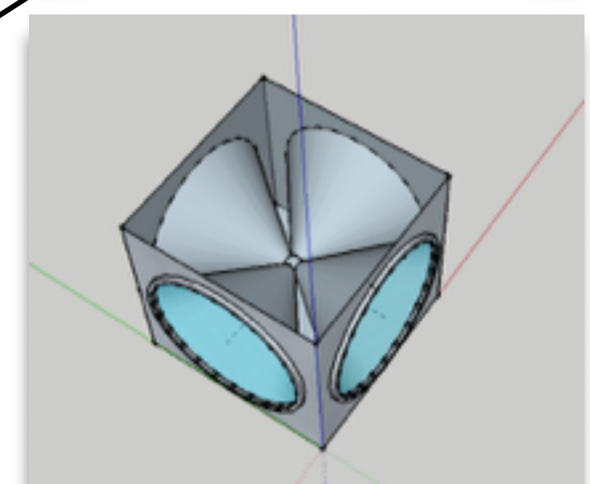
Using the L and time-of-flight we calculate β and hence the momentum is calculated:

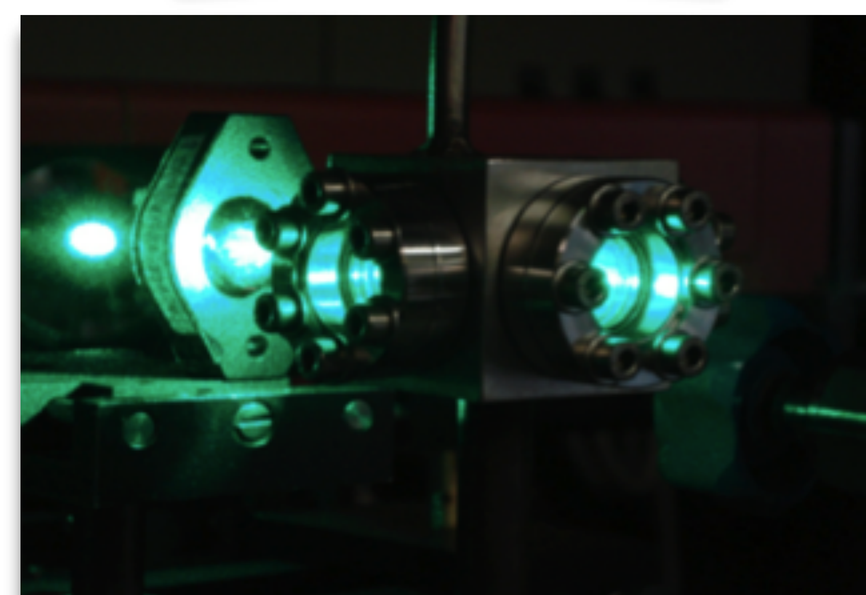
p=Mn/sqrt(1/β^2-1)

Determination of H_2 and D_2 contaminations in HD gas: Raman Spectroscopy









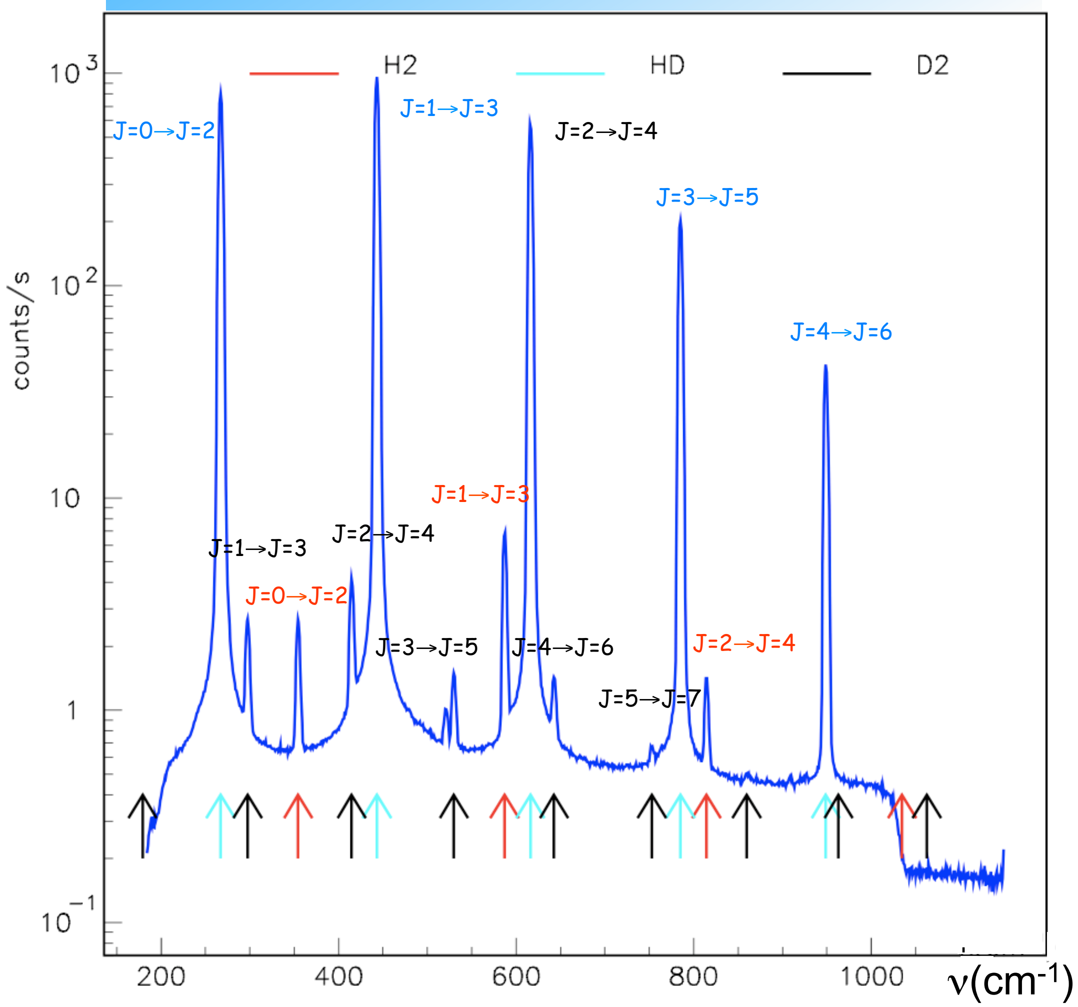
- Laser Ar 15 W
- This setup allow to minimize the amount of laser light entering the spectrometer
- The cell geometry allow to minimize accidental reflections

Raman spectroscopy: results

The data analysis of the measured spectra allow for the determination of H2 and D2 impurities concentrations:

$$I(J,T) = I_0 A(\nu)\nu^3 f(J)\gamma^2 \frac{45\pi^4}{7}\frac{N}{Q(T)} g_s(J)(2J+1)\frac{3(J+1)(J+2)}{2(2J+1)(2J+3)} e^{-\frac{hcb_0 J(J+1)}{KT}}$$

Raman spectrum (log scale)



H_2/HD	JMU-II	JMU-III	USC
RAMAN	**0.00472+-0.00004**	**0.00220+-0.00004**	**0.00387+-0.00004**
Gas Chromatography	0.0049+-0.0002	0.0022+-0.0002	0.0034+-0.0007

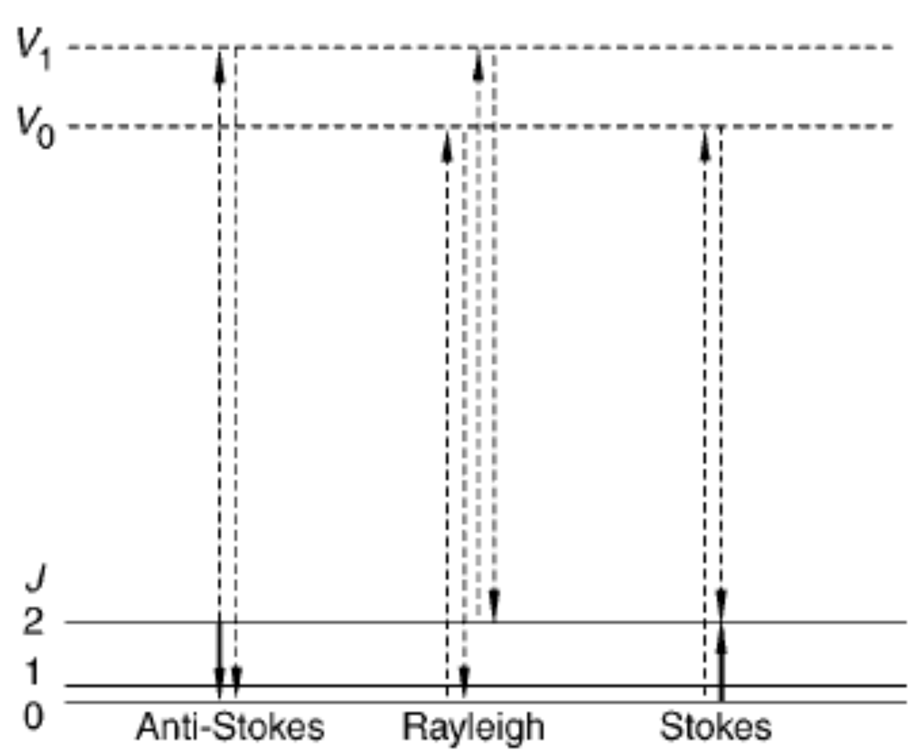
D_2/HD	JMU-II	JMU-III	USC
RAMAN	**0.00416+-0.00008**	**0.0025+-0.0001**	**0.00442+-0.00008**
Gas Chromatography	0.0014+-0.0002	0.0013+-0.0007	0.0033+-0.0032

results for JMU-II and USC used for the two targets used in the g14 experiment

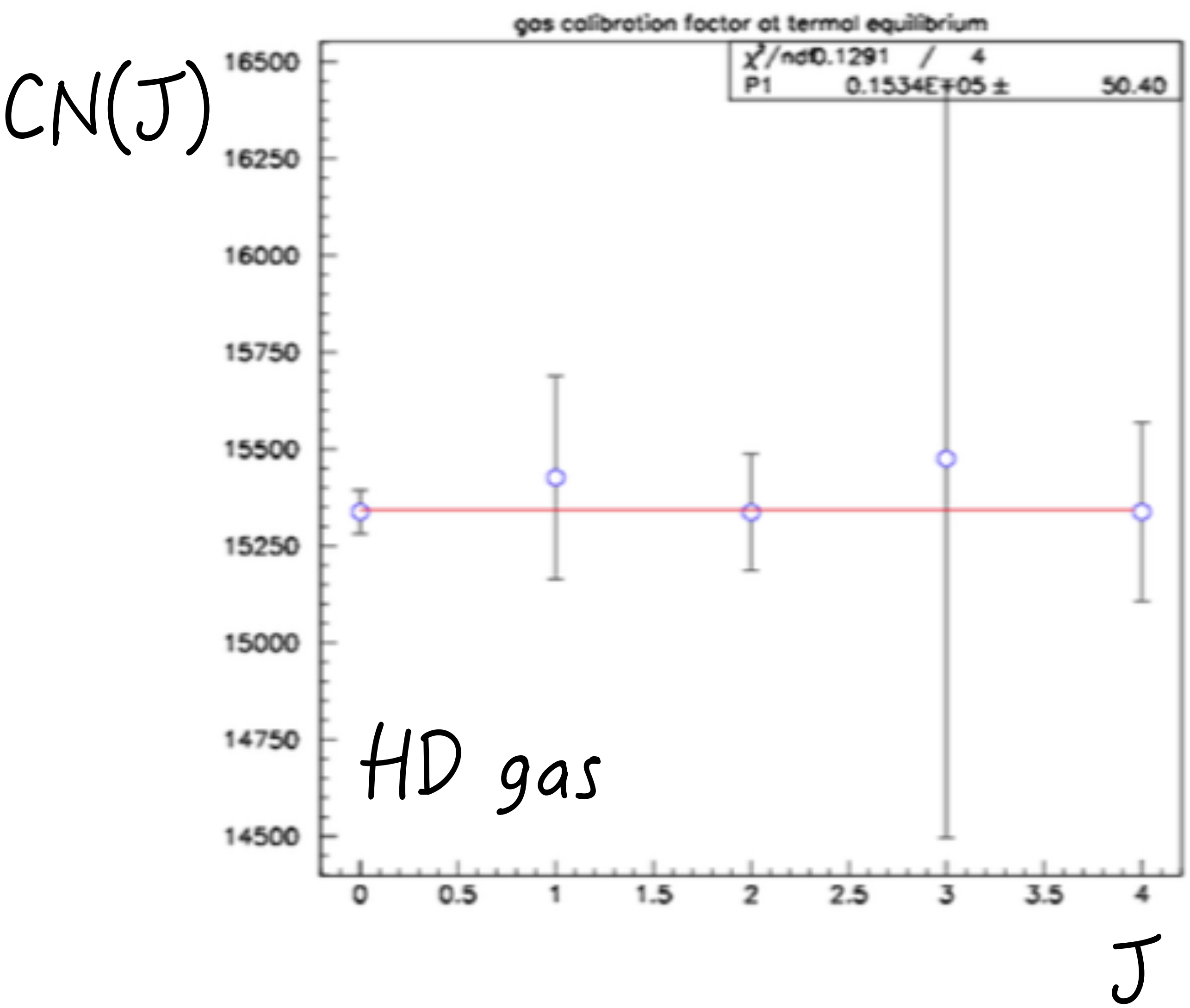
Rotational Raman spectroscopy

When electromagnetic radiation falls on a molecular sample:

A. It may be absorbed if the energy of the radiation corresponds to the separation of 2 energy levels of the molecule
B. Can be scattered
   A. Is scattered with unchanged wavelength (Rayleigh)
   B. It is scattered with increased (decreased) wavelength anti-Stokes (stokes) Raman scattering

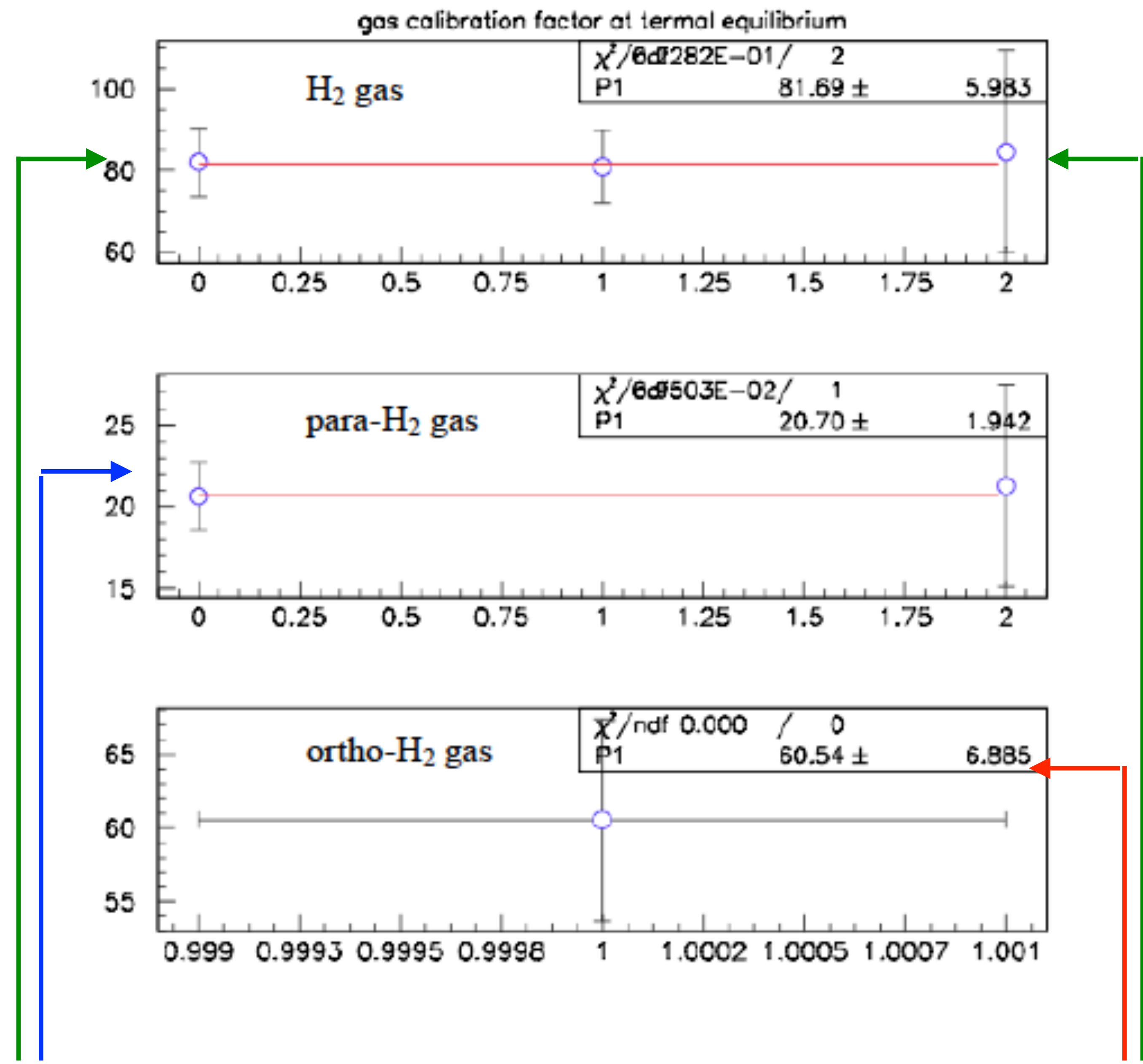


Raman spectroscopy: analysis



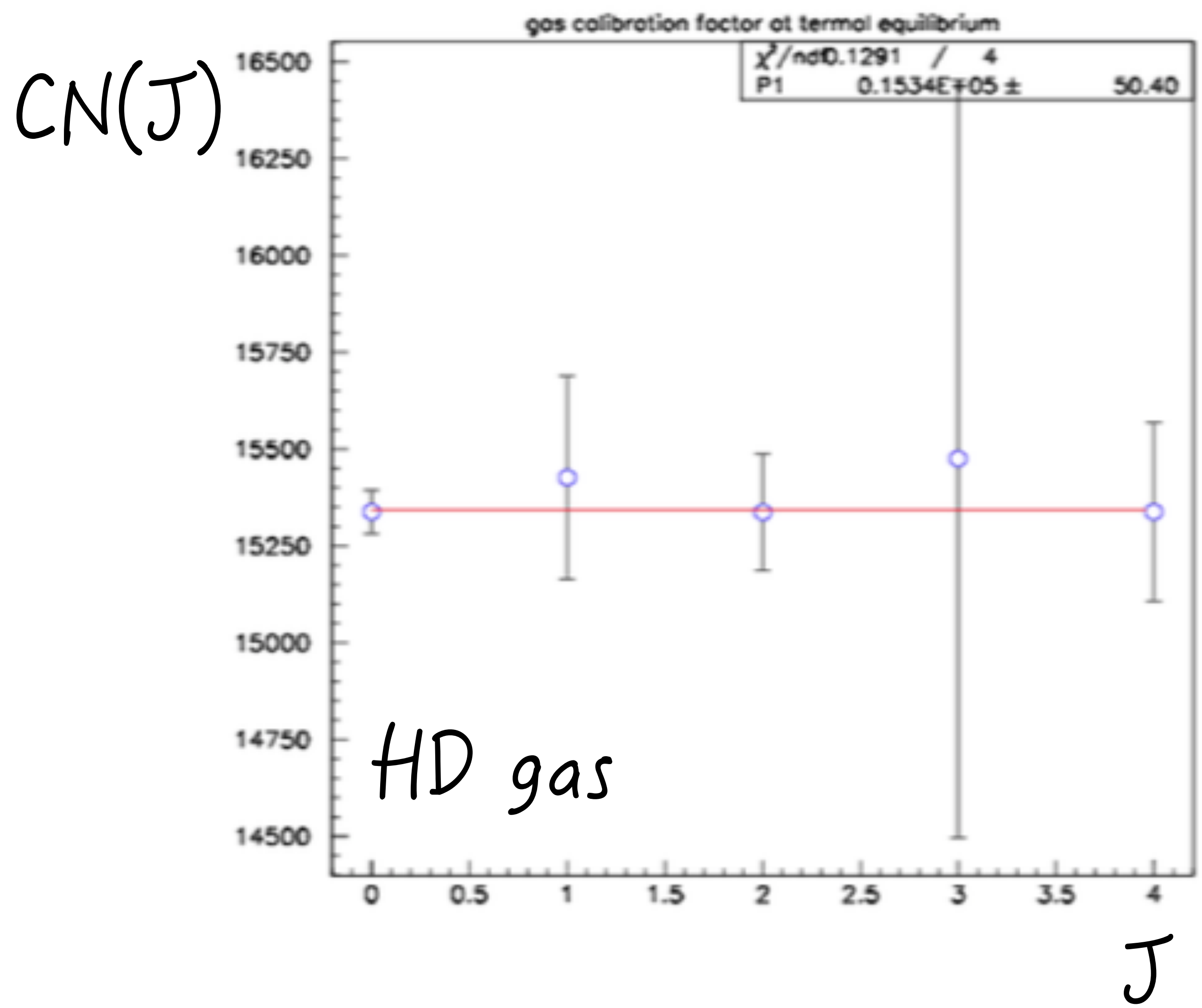
CN should be independent from J

$$CN = \frac{I_{meas}(J)}{h(J)} Q(T) e^{-\frac{(hcb_0 J(J+1))}{KT}}$$

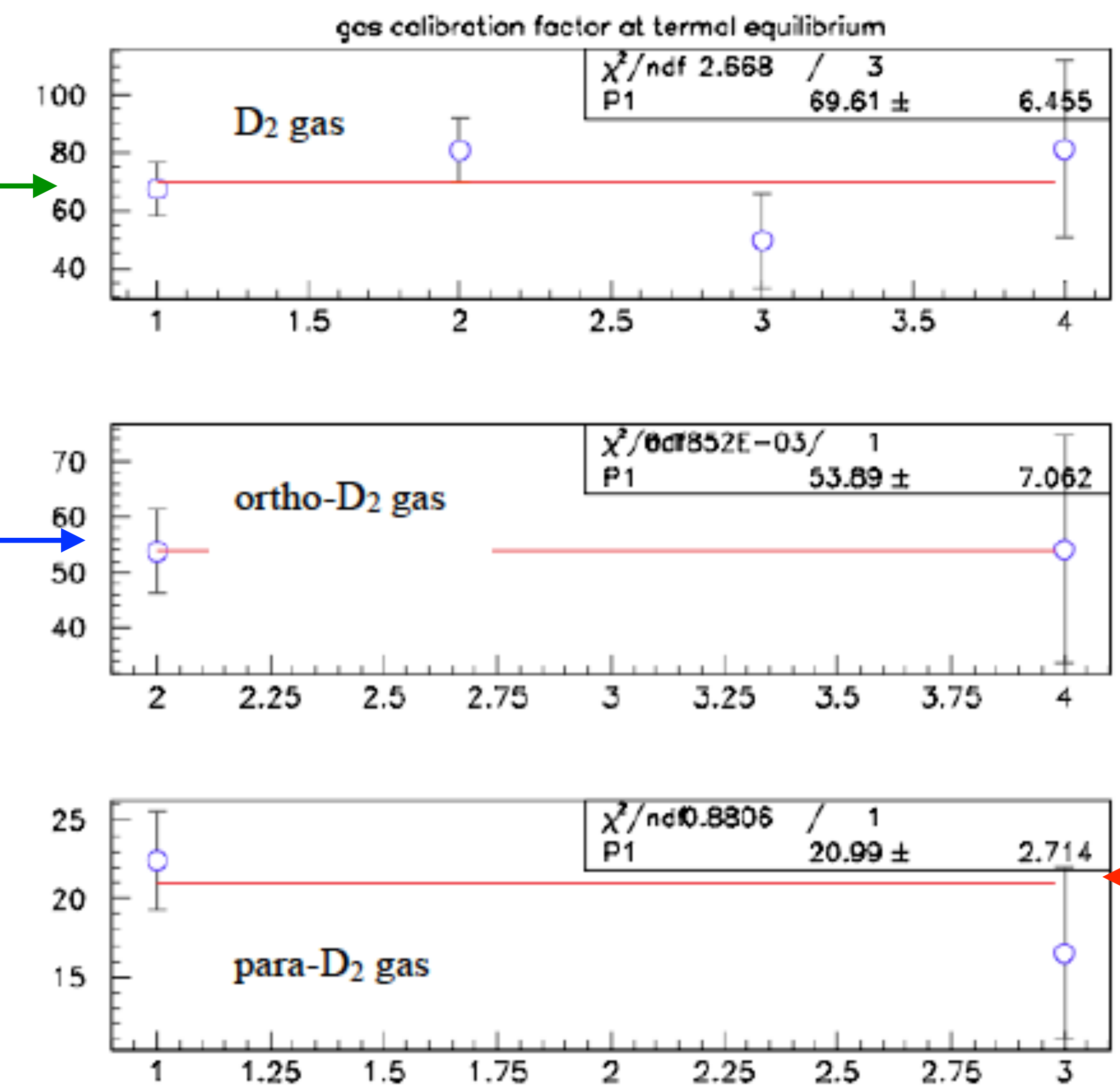


$CN_{para}^{H2} + CN_{orho}^{H2} = CN^{H2}$ $\quad CN_{para}^{H2} / CN^{H2} = 0.25 \quad CN_{ortho}^{H2} / CN^{H2} = 0.75$

Raman spectroscopy: analysis



$$CN = \frac{I_{meas}(J)}{h(J)} Q(T) e^{-\frac{(hcb_0 J(J+1))}{KT}}$$



CN should be independent from J

$CN_{para}^{D2} + CN_{orho}^{D2} = CN^{D2}$ $CN_{ortho}^{D2} / CN^{D2} = 0.666$ $CN_{para}^{D2} / CN^{D2} = 0.3333$

Raman spectroscopy: analysis

In an isotopic equilibrated mixture of H_2-HD-D_2 the intensities ratios is: 100:58:47 (for the most intense lines).

$$I(J,T)=CNf(J,T) \qquad f(J,T)=h(J)/Q(T)\exp-[E_R(J)/KT]$$

$Q(T)$: may be calculated for each peak at a fixed temperature

If $N(H_2)/N(HD)=1$ -> $I(H_2)/I(HD)=100/58=1.7241$

$$I(HD)/I(H_2)=0.58=C_{HD}N_{HD}f_{HD}/C_{H_2}N_{H_2}f_{H_2}=C_{HD}f_{HD}/C_{H_2}f_{H_2}$$

$$C_{HD}/C_{H_2}=I(HD)/I(H_2)f_{H_2}/f_{HD}=0.58f_{HD}/f_{H_2}$$

from which

$$N(H_2)/N(HD)=CN_{H_2}(fit)/CN_{HD}(fit)\times C_{HD}/C_{H_2}= CN_{H_2}(fit)/CN_{HD}(fit)\times 0.58f_{HD}/f_{H_2}$$

similarly for the D_2

Raman spectroscopy: analysis

In an **isotopic equilibrated mixture** of H2-HD-D2 the intensity ratios is: 100:58:47 for the most intense lines

If N(H2)/N(HD)=1 corresponds to I(H2)/I(HD)=100/58=1.7241
the measured ratio I(H2)meas/I(HD) provides N(H2)/N(HD):
1:1.7241=N(H2)/N(HD): I(H2)meas/I(HD)
N(H2)/N(HD)= I(H2)meas/I(HD):1/1.7241=I(H2)meas/I(HD)x0.58

If N(D2)/N(HD)=1 corresponds to I(D2)/I(HD)=47/58=0.810344
the measured ratio I(D2)meas/I(HD) provides N(D2)/N(HD):
1:0.810344=N(D2)/N(DD): I(D2)meas/I(HD)
N(D2)/N(HD)= I(D2)meas/I(HD):1/0.810344=I(D2)meas/I(HD)x1.2340

HD frozen-spin target

Omonuclear molecule H_2 and D_2 must obey to symmetry constraints.

- ψ_{H2mol} must be anti-symmetric under the exchange of identical nuclei
- ψ_{D2mol} must be symmetric under the exchange of spin 1 deuterons

In general:

$\psi_{mol}=\psi_{el}\psi_{vib}\psi_{rot}\psi_{nuc}$

ψ_e and ψ_{vib} symmetric in the ground state

ψ_{rot} symmetry is given by $(-1)^J$
J even -> ψ_{rot} symmetric
J odd -> ψ_{rot} anti-symmetric

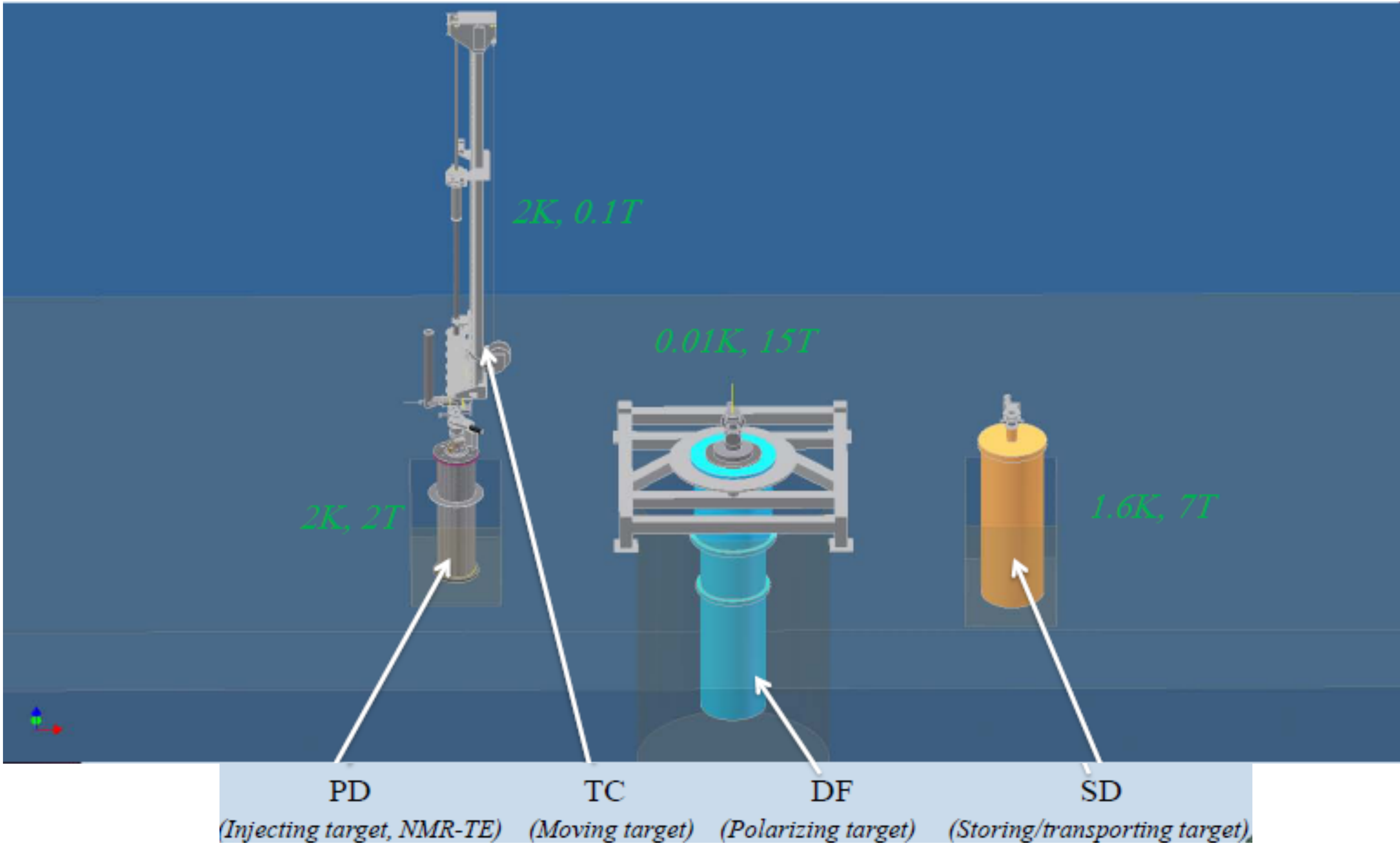
ψ_{Nuc} H_2 ($I_p=1/2$) spins couple to I=0 (antisymm) para-H_2
or I=1 (symm) orto-H_2

ψ_{Nuc} D_2 ($I_d=1$) spins couple to I=0,2 (symm) orto-H_2
or I=1 (antisymm) para-H_2

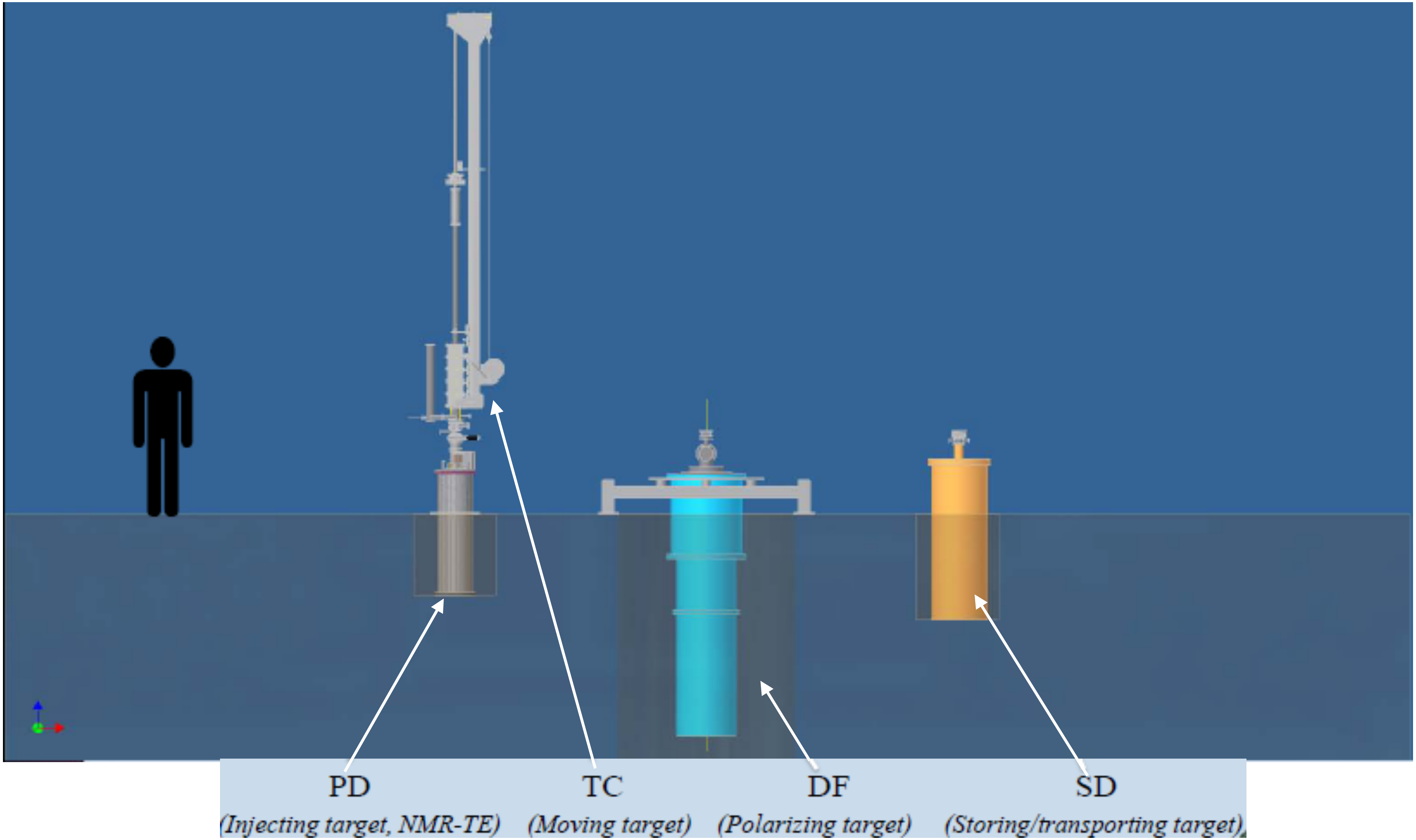
<u>ψ_{H2mol} must be antisymmetric:</u>
I=0 couples to J even para-H_2
I=1 couples to J odd orto-H_2

<u>ψ_{D2mol} must be symmetric:</u>
I=0,2 couples to J even orto-D_2
I=1 couples to J odd para-D_2

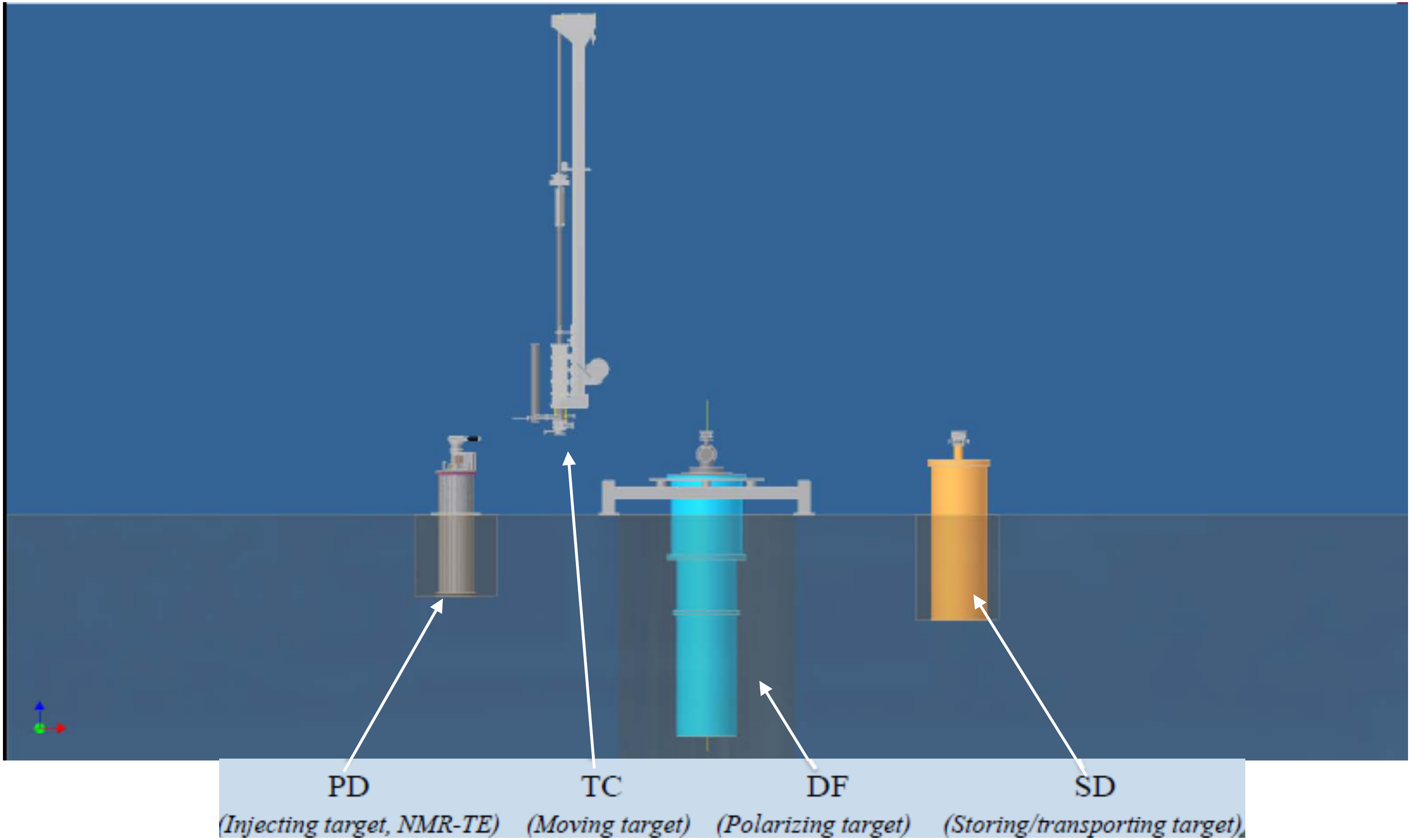
HD frozen-spin target: production cycle



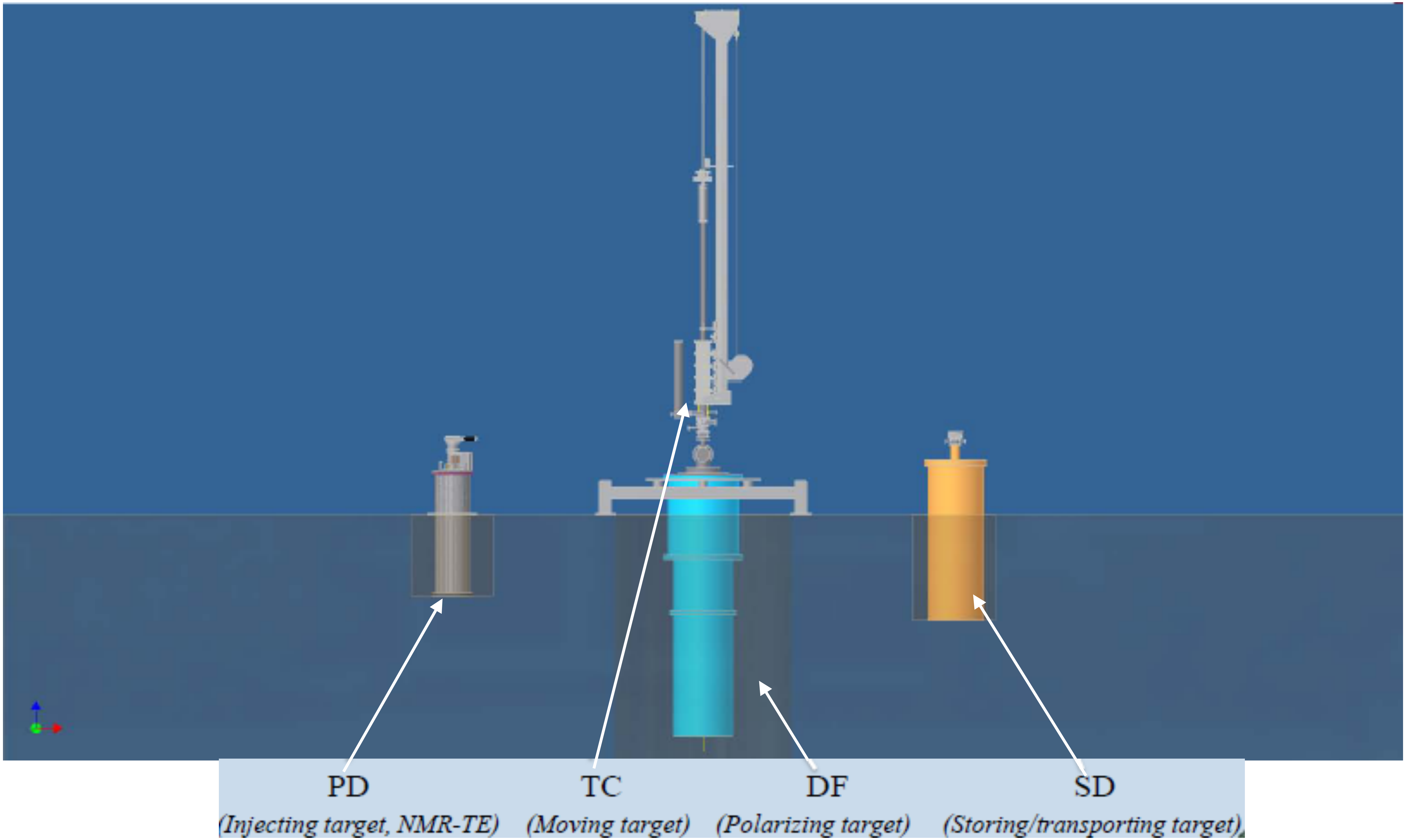
HD frozen-spin target: production cycle



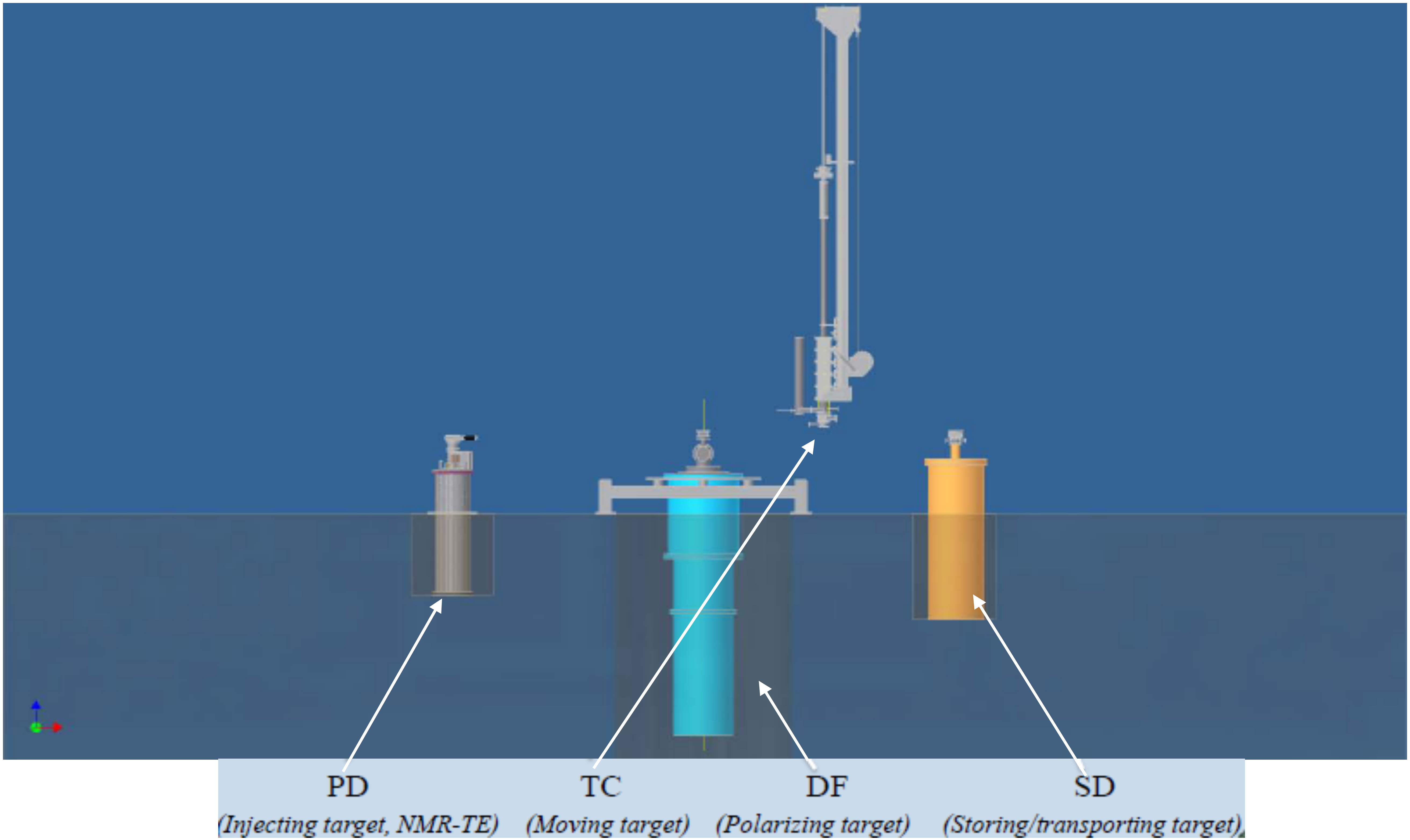
HD frozen-spin target: production cycle



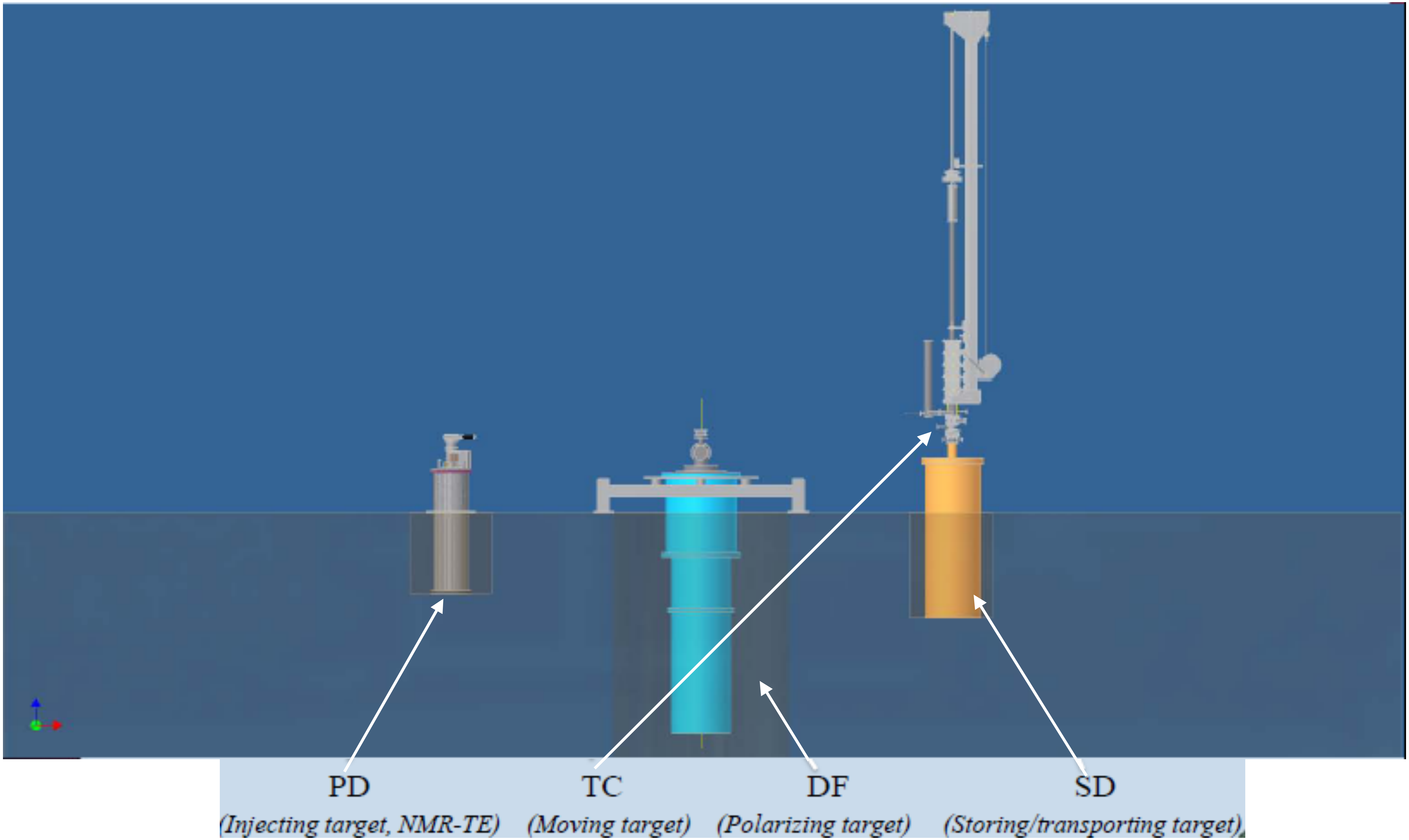
HD frozen-spin target: production cycle



HD frozen-spin target: production cycle



HD frozen-spin target: production cycle



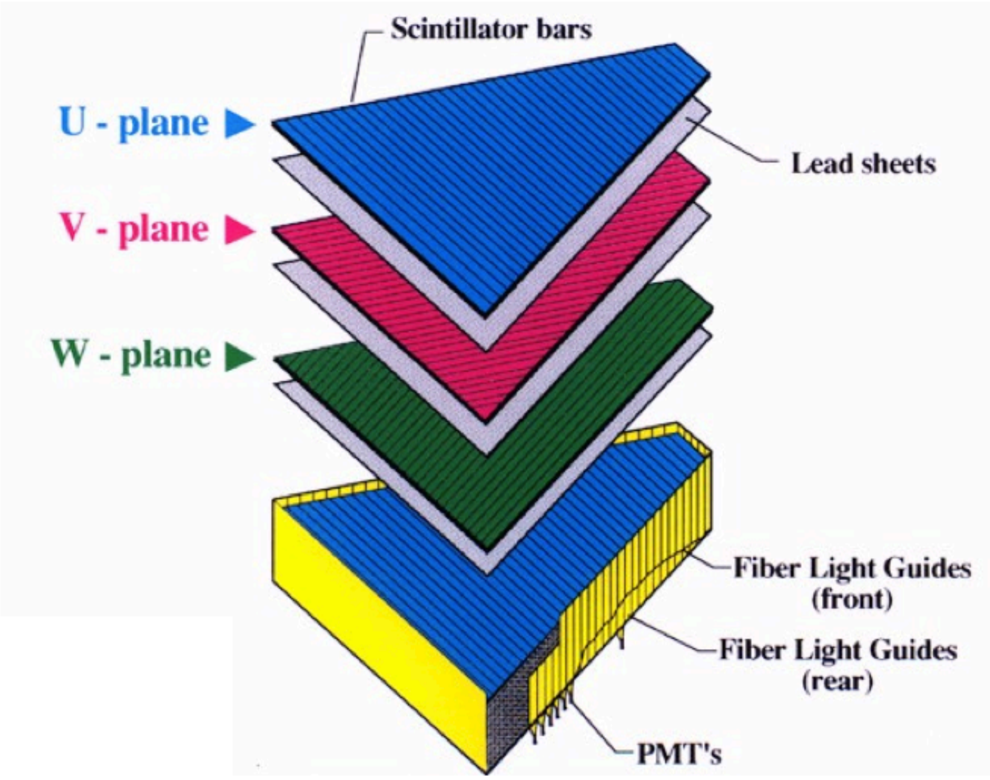
Electromagnetic calorimeter timing calibration

Crucial to perform separation between neutron and photons

The time from the em calorimeter is evaluated using a 5-parameters semi-empirical model:

$$T_{model} = a_0 + a_1 TDC + a_2 \frac{1}{\sqrt{ADC}} + a_3 l^2 + a_4 l^3$$

a_0	includes all constant times
$a_1 TDC_i$	TDC conversion term
$a_2 \frac{1}{\sqrt{ADC_i}}$	time-walk correction term
$a_3 l_i^2 \quad a_4 l i^3$	light attenuation term



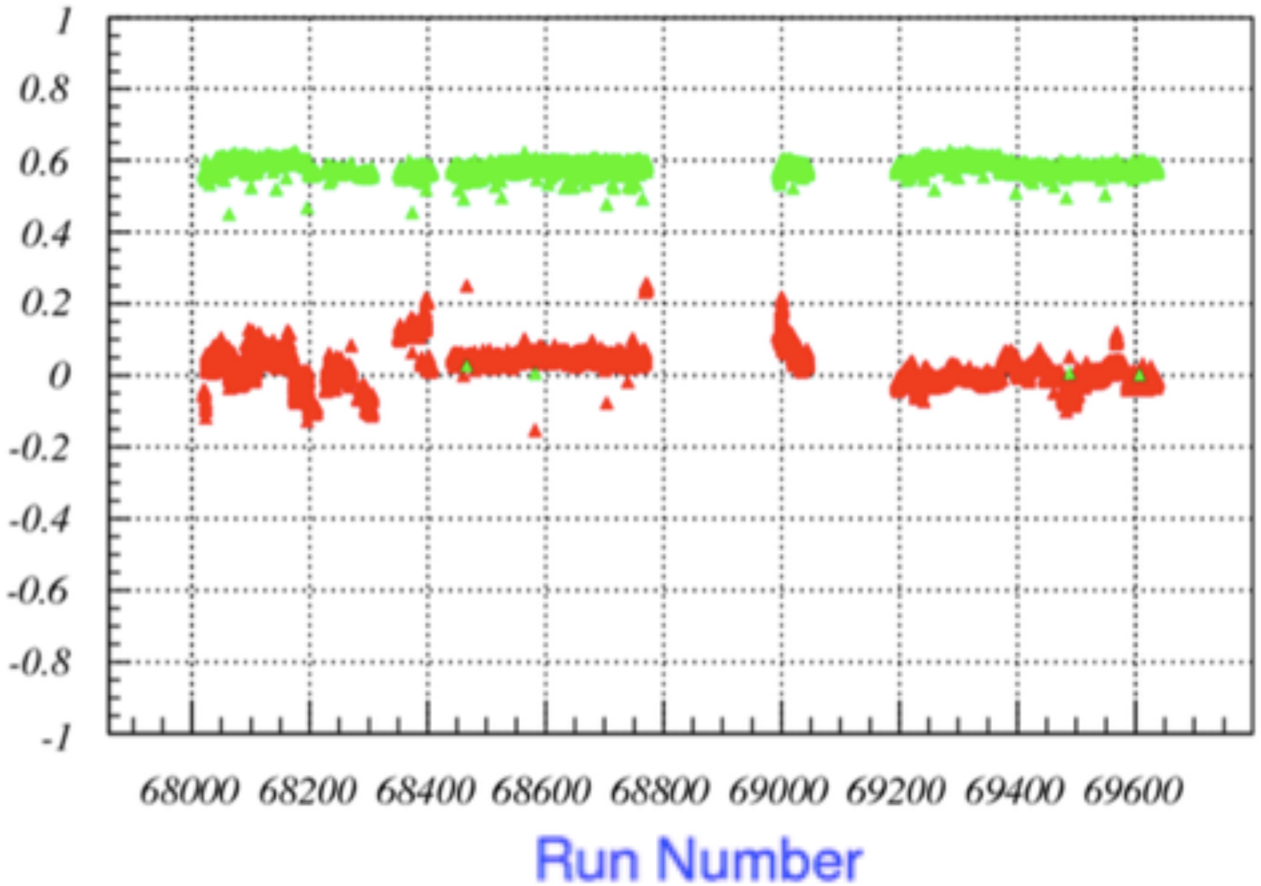
E.M CAL MODULE

To find the best calibration constant: $\chi_j^2 = \sum_{i=1}^{N_j} \frac{|T'_{sc} - T_{model}|^2}{\sigma_{j,i}^2}$

$$T'_{sc} = T_{sc} + \frac{dist_{ec-sc}}{\beta}(n \cdot v)$$

→ actual path from the SC to EC

Electromagnetic calorimeter timing calibration



Mean of difference between the calibrated time measured from the EC and the calibrated time measured from the SC

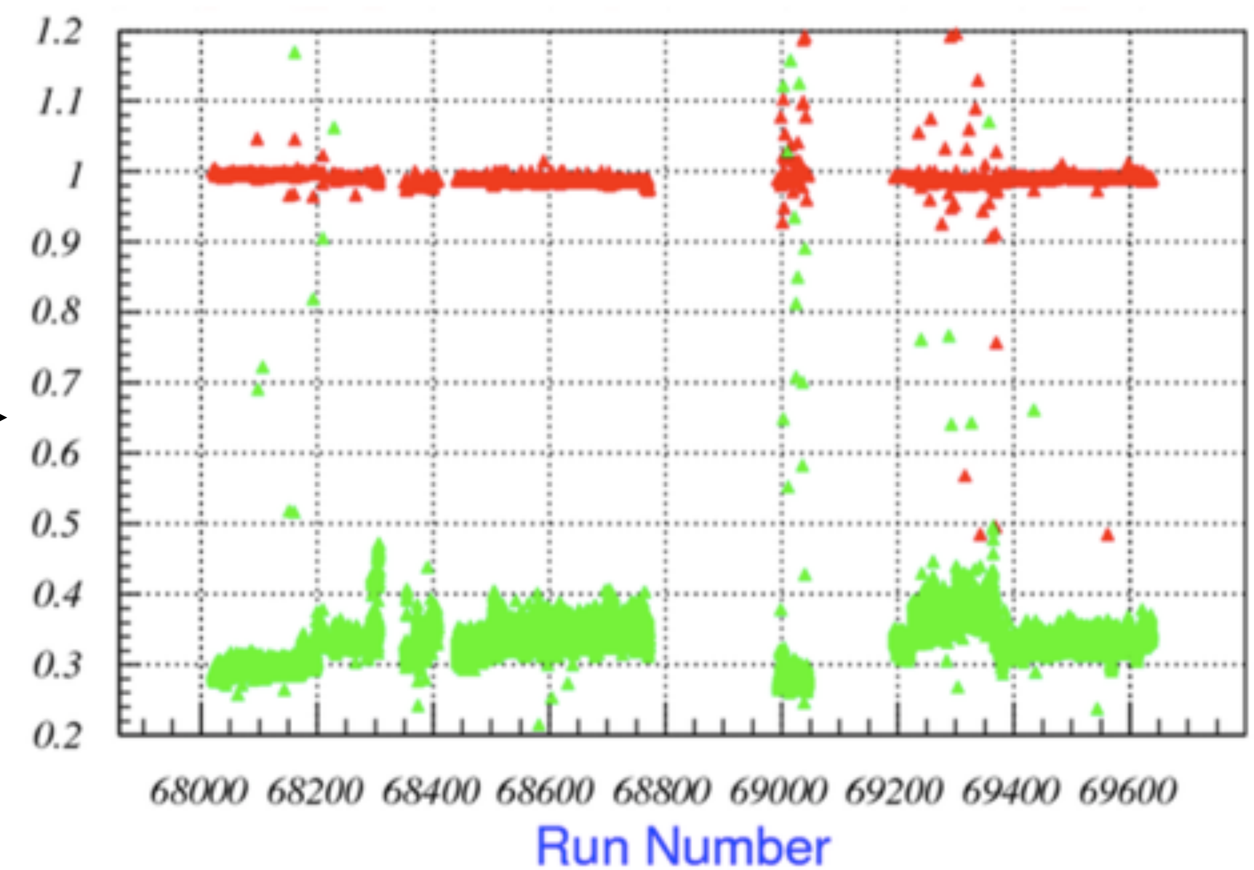
▲ mean

▲ sigma

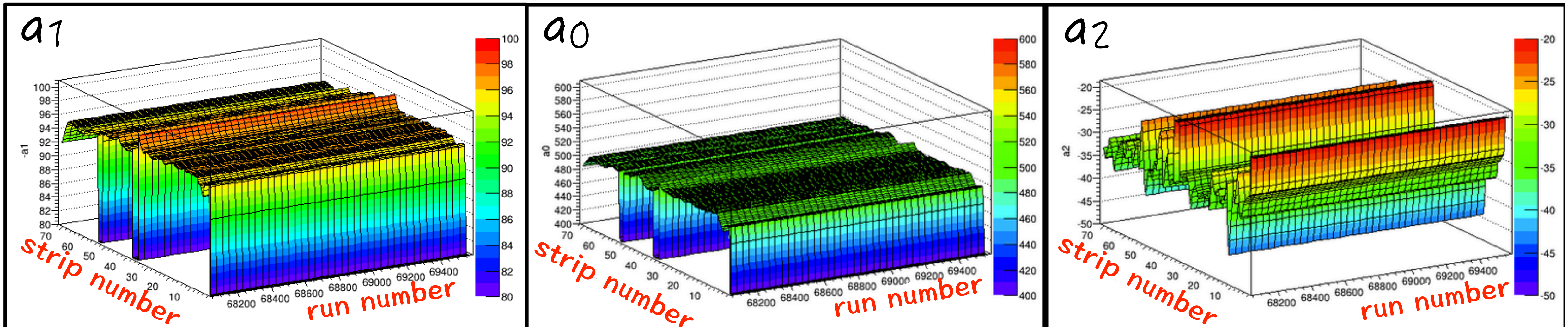
calibrated beta for photons

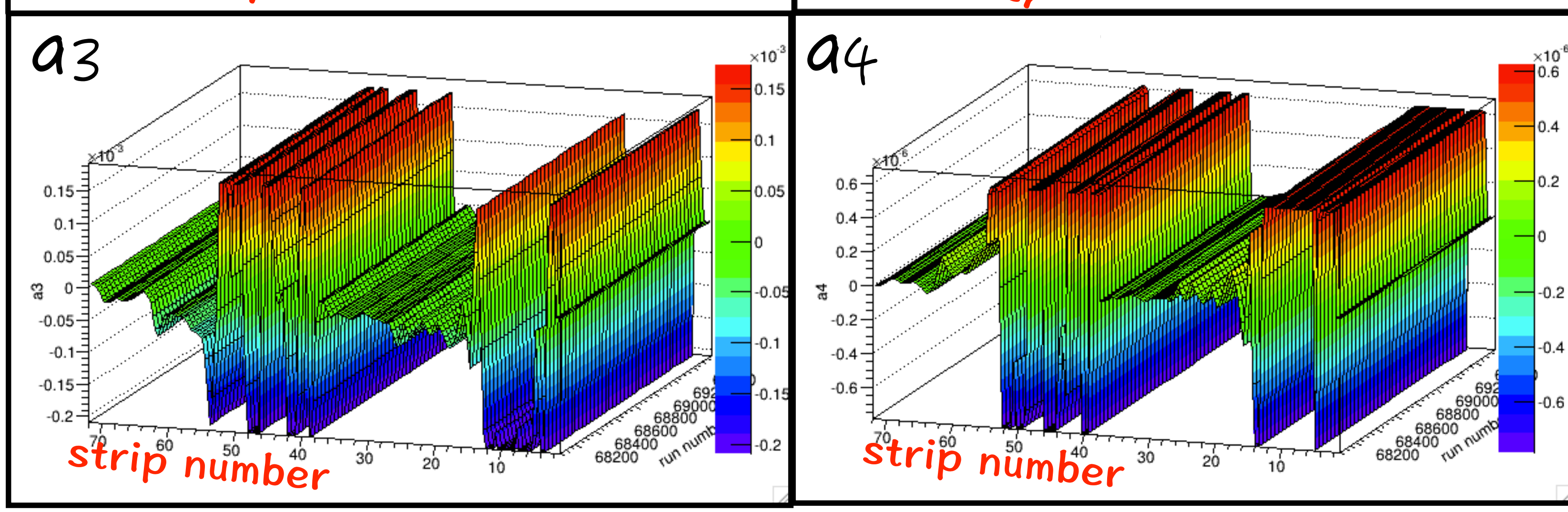
▲ mean

▲ sigma



Electromagnetic calorimeter timing calibration





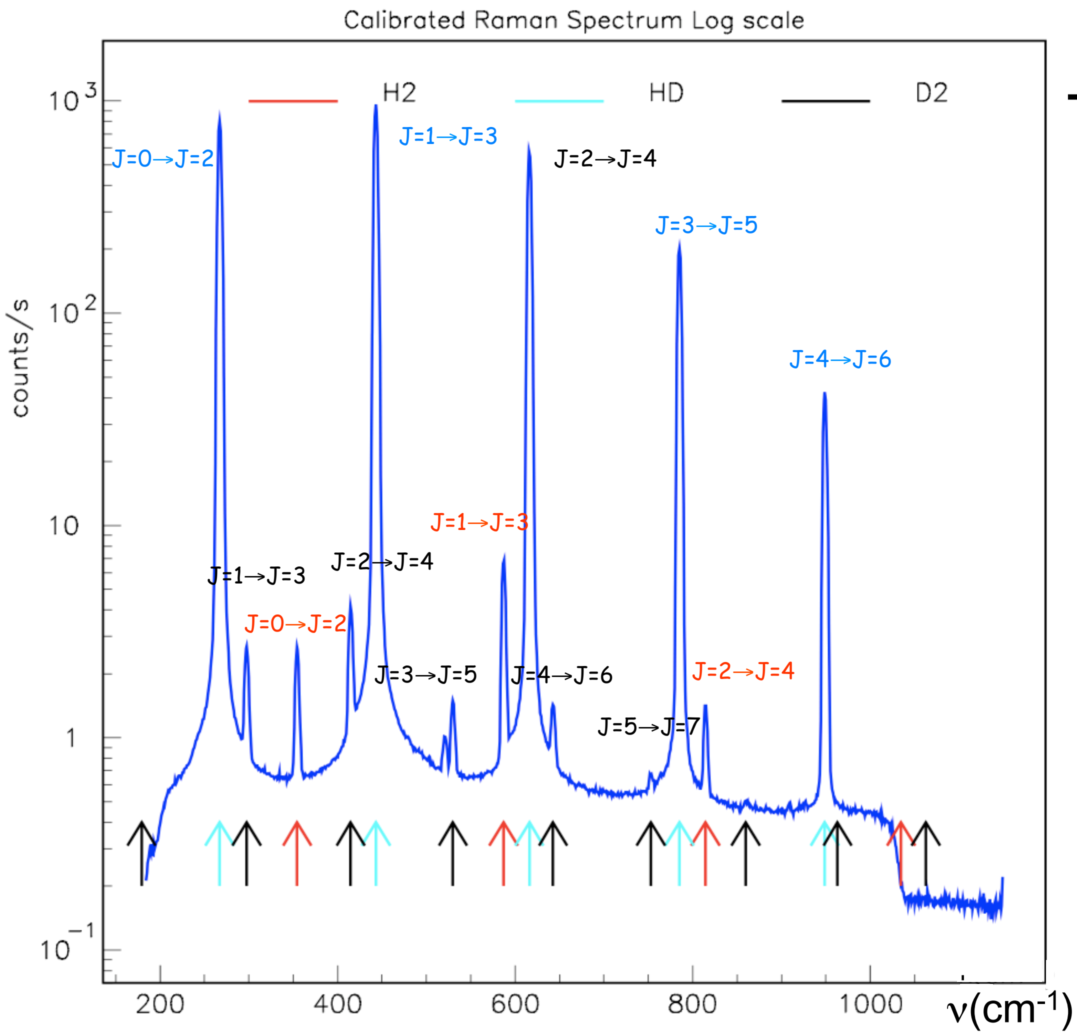
EM calorimeter calibration parameter values as a function of the **run number** (x-axis) and the **strip number** (y-axis)

$$T_{model} = a_0 + a_1 TDC + a_2 \frac{1}{\sqrt{ADC}} + a_3 l^2 + a_4 l^3$$

Good stability of the timing calibration. Only few regions are non-flat.

Identification of not working strip channels

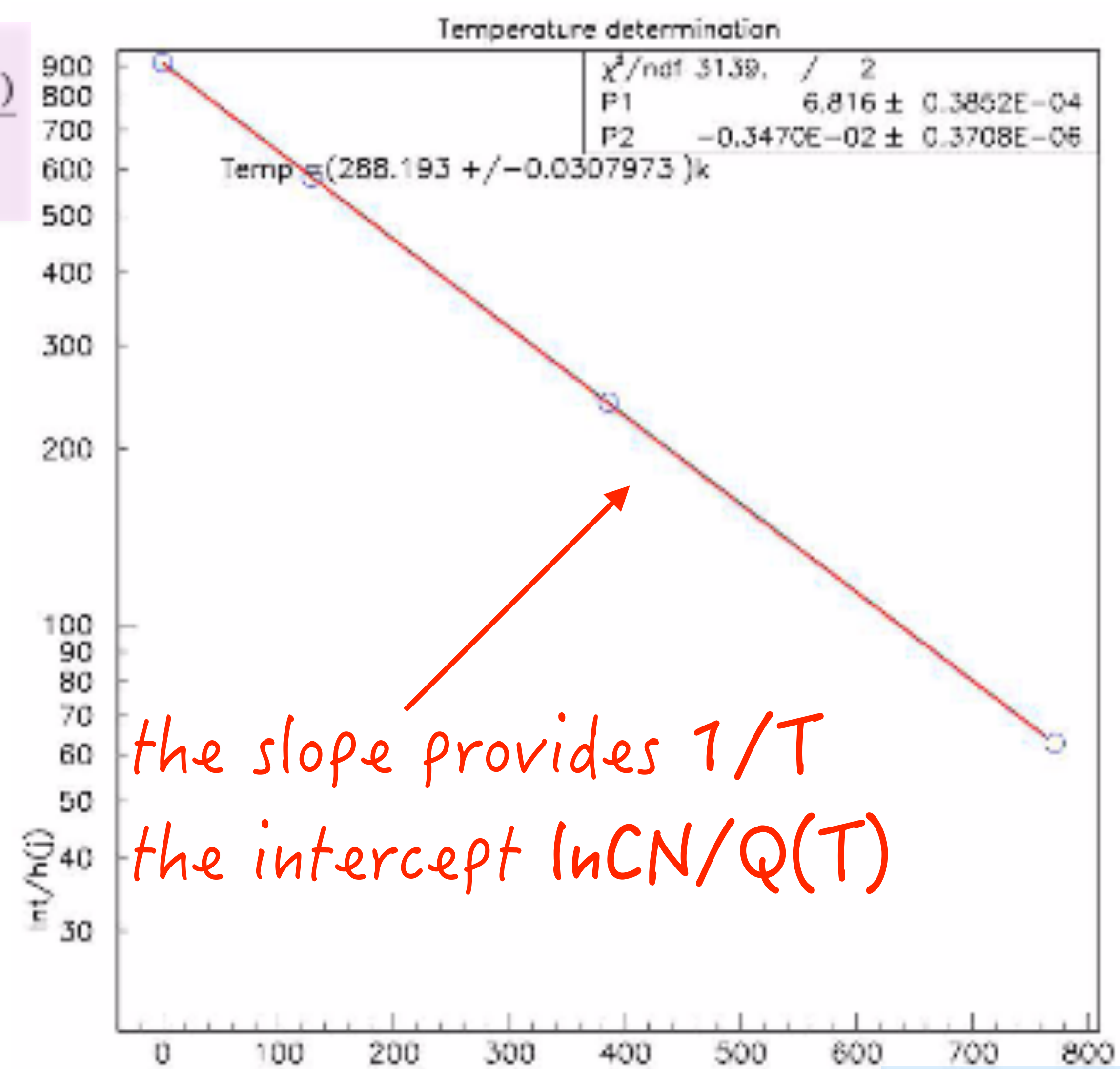
Raman spectroscopy: analysis



$$I(J,T) = C\frac{N}{Q(T)}h(J)\exp\left(-\frac{hcb_0 J(J+1)}{KT}\right)$$

$$\ln\frac{I_{meas}(J)}{h(J)} = \ln\frac{CN(J)}{Q(T)} - \frac{hcb_0 J(J+1)}{K}\frac{1}{T}$$

$$\ln\frac{I_{meas}(J)}{h(J)}$$



the slope provides 1/T

the intercept lnCN/Q(T)

$$\frac{hcb_0 J(J+1)}{K}$$

ΔJ=+-2 Raman selection rules

Extraction of $I^{\odot}$ and $P_z^{\odot}$: experimental method

g14 Running condition:

We need to combine two periods from two different target →

$\delta_{\odot}^{g2} = 83.4\%$ $\delta_{\odot}^{s5} = 88.8\%$

$\Lambda(H)_z^{g2} = 27.6\%$ $\Lambda(D)_z^{g2} = 26.9\%$

$\Lambda(H)_z^{s5} = -0.8\%$ $\Lambda(D)_z^{s5} = -6.0\%$

$\frac{Lg2}{Ls5} = 0.36$ luminosity ratio

$$I^{\odot} = \frac{1}{\delta_{\odot}^{g2}} \frac{[N(\rightarrow\Rightarrow)^{g2} - N(\leftarrow\Rightarrow)^{g2}]}{[N(\rightarrow\Rightarrow)^{g2} + N(\leftarrow\Rightarrow)^{g2}] + \frac{L^{g2}}{L^{s5}} \frac{\Lambda_z^{g2}}{\Lambda_z^{s5}} [N(\rightarrow\Leftarrow)^{s5} + N(\leftarrow\Leftarrow)^{s5}]} +$$

$$+ \frac{1}{\delta_{\odot}^{s5}} \frac{L^{g2}}{L^{s5}} \frac{\Lambda_z^{g2}}{\Lambda_z^{s5}} \frac{[N(\rightarrow\Leftarrow)^{s5} - N(\leftarrow\Leftarrow)^{s5}]}{[N(\rightarrow\Rightarrow)^{g2} + N(\leftarrow\Rightarrow)^{g2}] + \frac{L^{g2}}{L^{s5}} \frac{\Lambda_z^{g2}}{\Lambda_z^{s5}} N[(\rightarrow\Leftarrow)^{s5} + N(\leftarrow\Leftarrow)^{s5}]}$$

Extraction of I and Pz: experimental method

Similarly to before:

$$N_{\sigma(\rightarrow\Rightarrow)} = L(\rightarrow\Rightarrow)(1 + \overline{\Lambda}_z(\Rightarrow)\mathbf{P_z} + \overline{\delta}_{\odot}(\rightarrow)(\mathbf{I}^{\odot} + \overline{\Lambda}_z(\Rightarrow)\mathbf{P_z}^{\odot})$$

$$N_{\sigma(\leftarrow\Rightarrow)} = L(\leftarrow\Rightarrow)(1 + \overline{\Lambda}_z(\Rightarrow)\mathbf{P_z} - \overline{\delta}_{\odot}(\leftarrow)(\mathbf{I}^{\odot} + \overline{\Lambda}_z(\Rightarrow)\mathbf{P_z}^{\odot})$$

$$N_{\sigma(\rightarrow\Leftarrow)} = L(\rightarrow\Leftarrow)(1 - \overline{\Lambda}_z(\Leftarrow)\mathbf{P_z} + \overline{\delta}_{\odot}(\rightarrow)(\mathbf{I}^{\odot} - \overline{\Lambda}_z(\Leftarrow)\mathbf{P_z}^{\odot})$$

$$N_{\sigma(\leftarrow\Leftarrow)} = L(\leftarrow\Leftarrow)(1 - \overline{\Lambda}_z(\Leftarrow)\mathbf{P_z} - \overline{\delta}_{\odot}(\leftarrow)(\mathbf{I}^{\odot} - \overline{\Lambda}_z(\Leftarrow)\mathbf{P_z}^{\odot})$$

$$P_z^{\odot} = \frac{1}{\delta_{\odot}^{g2}\Lambda_z^{s5}} \frac{[N(\rightarrow\Rightarrow)^{g2} - N(\leftarrow\Rightarrow)^{g2}]}{[N(\rightarrow\Rightarrow)^{g2} + N(\leftarrow\Rightarrow)^{g2}] + \frac{L^{g2}}{L^{s5}}\frac{\Lambda_z^{g2}}{\Lambda_z^{s5}}[N(\rightarrow\Leftarrow)^{s5} + N(\leftarrow\Leftarrow)^{s5}]} +$$

$$+\frac{1}{\delta_{\odot}^{s5}}\frac{L^{g2}}{L^{s5}}\frac{1}{\Lambda_z^{s5}} \frac{[N(\rightarrow\Leftarrow)^{s5} - N(\leftarrow\Leftarrow)^{s5}]}{[N(\rightarrow\Leftarrow)^{g2} + N(\leftarrow\Leftarrow)^{g2}] + \frac{L^{g2}}{L^{s5}}\frac{\Lambda_z^{g2}}{\Lambda_z^{s5}}N[(\rightarrow\Leftarrow)^{s5} + N(\leftarrow\Leftarrow)^{s5}]}$$

Extraction of $I^{\odot}$ and $P_z^{\odot}$: experimental method

$$\frac{d\sigma}{dx_i} = \sigma_0\{(1+\Lambda_z \cdot \mathbf{P_z}) + \delta_{\odot}(\mathbf{I}^{\odot} + \Lambda_z \cdot \mathbf{P}_z^{\odot})\} \qquad (1)$$

differential cross section
$\delta_{\odot}$ degree of circular polarization
Λ_z degree of target polarization

$$\frac{d\sigma}{dx_i} = \frac{N_{events}}{\epsilon \cdot F \cdot \rho \cdot \Delta x_i} = \frac{N_{events}}{\epsilon L \Delta x_i} \qquad (2)$$

ε detection efficiency
F number of incoming photons
ρ target area density
L=Fρ integrated luminosity
Δx_i kinematic bin

confronting (1) and (2):

$$N_{events} = \sigma_0(\cdot L \cdot \Delta x_i)(1+\bar{\Lambda}_z \cdot \mathbf{P_z}) + \bar{\delta}_{\odot}(\mathbf{I}^{\odot} + \bar{\Lambda}_z \cdot \mathbf{P_z}^{\odot})$$

N_{ev} # of events measured

For different combination of beam →(←) and target polarization ⇒(⇐) alignment:

$$N_{\sigma(\rightarrow\Rightarrow)} = L(\rightarrow\Rightarrow)(1+\bar{\Lambda}_z(\Rightarrow)\mathbf{P_z} + \bar{\delta}_{\odot}(\rightarrow)(\mathbf{I}^{\odot} + \bar{\Lambda}_z(\Rightarrow)\mathbf{P_z}^{\odot})$$

$$N_{\sigma(\leftarrow\Rightarrow)} = L(\leftarrow\Rightarrow)(1+\bar{\Lambda}_z(\Rightarrow)\mathbf{P_z} - \bar{\delta}_{\odot}(\leftarrow)(\mathbf{I}^{\odot} + \bar{\Lambda}_z(\Rightarrow)\mathbf{P_z}^{\odot})$$

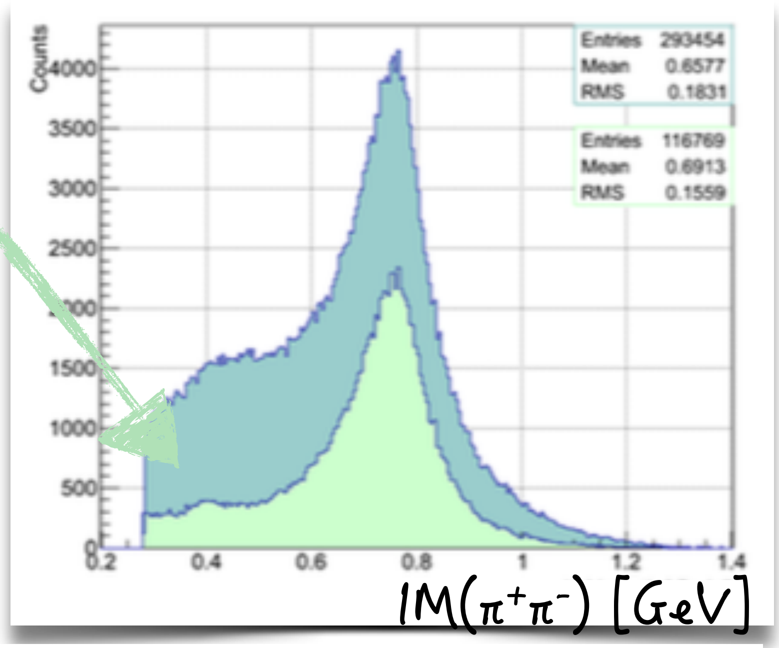
$$N_{\sigma(\rightarrow\Leftarrow)} = L(\rightarrow\Leftarrow)(1-\bar{\Lambda}_z(\Leftarrow)\mathbf{P_z} + \bar{\delta}_{\odot}(\rightarrow)(\mathbf{I}^{\odot} - \bar{\Lambda}_z(\Leftarrow)\mathbf{P_z}^{\odot})$$

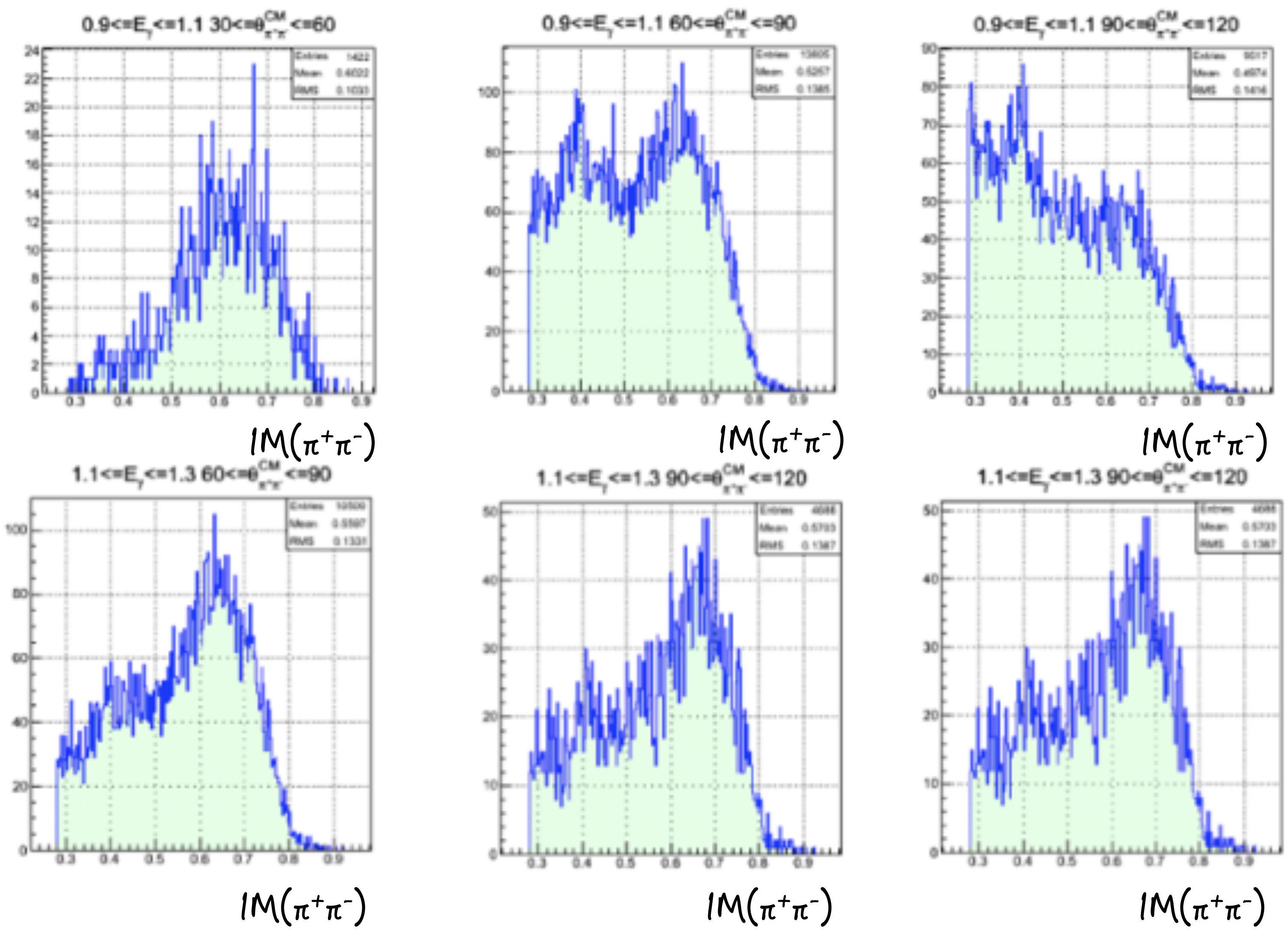
$$N_{\sigma(\leftarrow\Leftarrow)} = L(\leftarrow\Leftarrow)(1-\bar{\Lambda}_z(\Leftarrow)\mathbf{P_z} - \bar{\delta}_{\odot}(\leftarrow)(\mathbf{I}^{\odot} - \bar{\Lambda}_z(\Leftarrow)\mathbf{P_z}^{\odot})$$

in a single dataset the target polarization direction did not change!!!

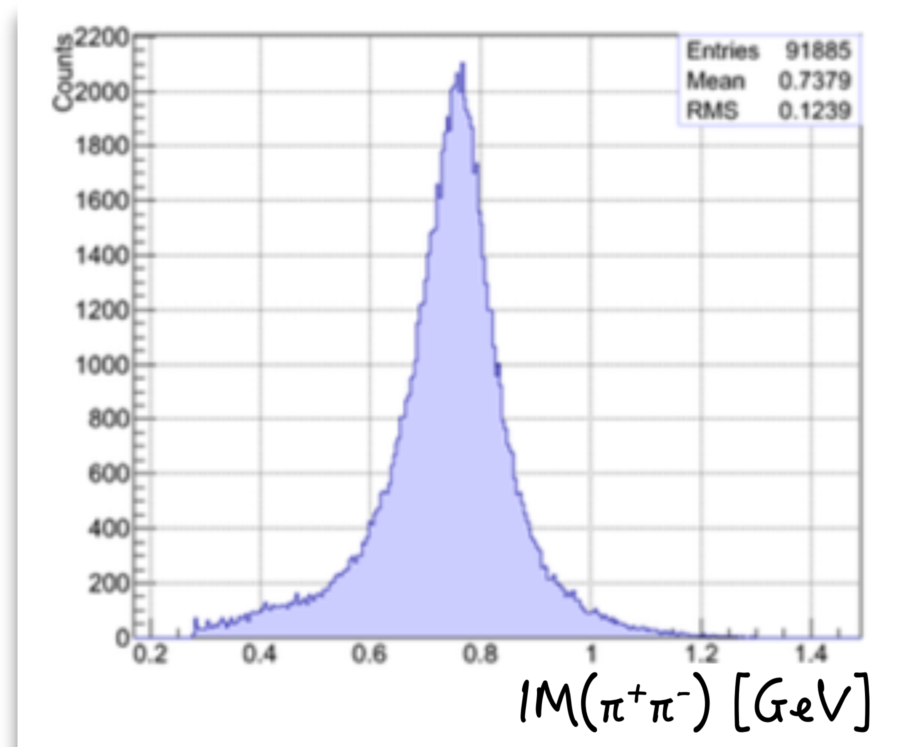
Identification of the reaction $\gamma p \longrightarrow \rho^0 p$: cut on E_γ

In order to remove this bump we require E_γ>1.3 GeV. For E_γ<1.3 GeV the reaction is dominated by the background

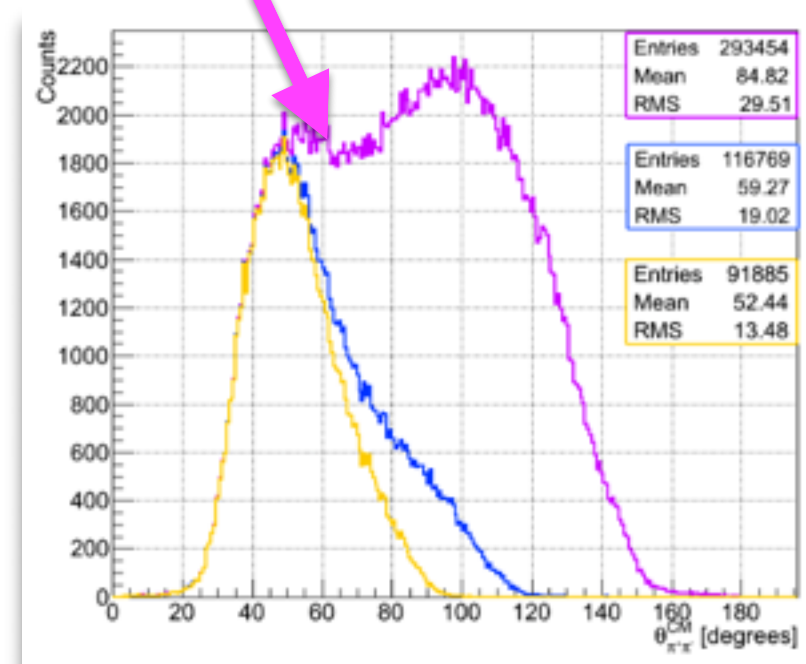




Final IM($\pi^+\pi^-$) spectrum

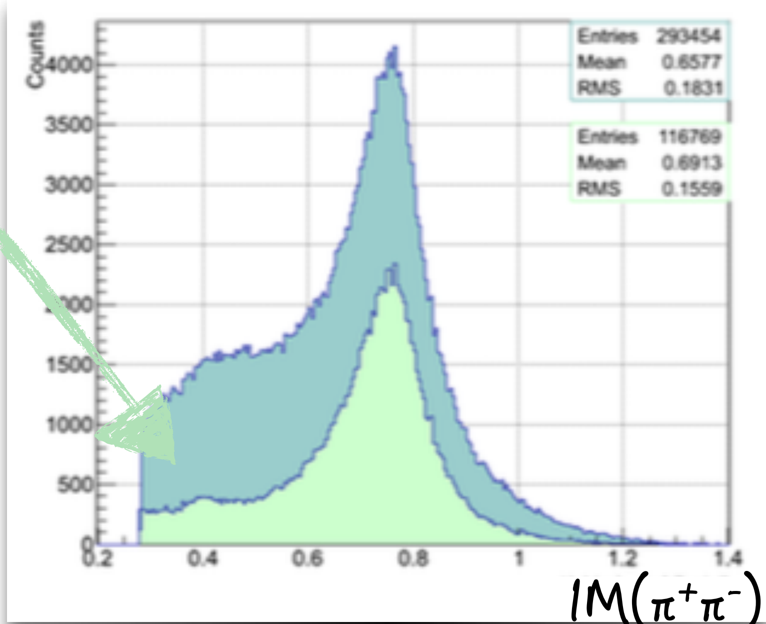


After cut on IM(π^+p), IM(π^-p) > 1.3 GeV

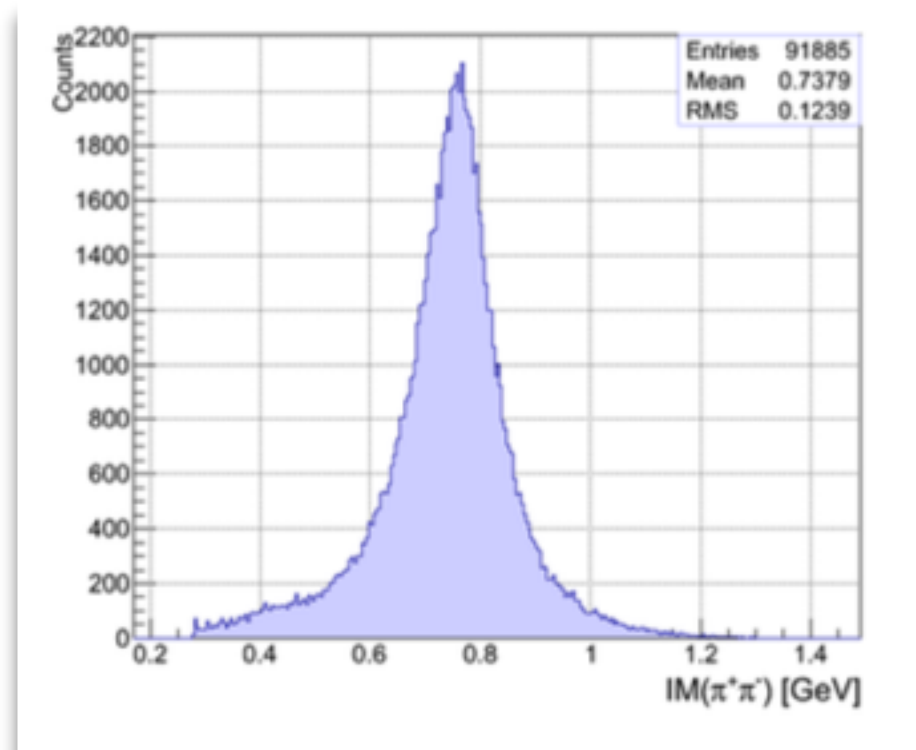


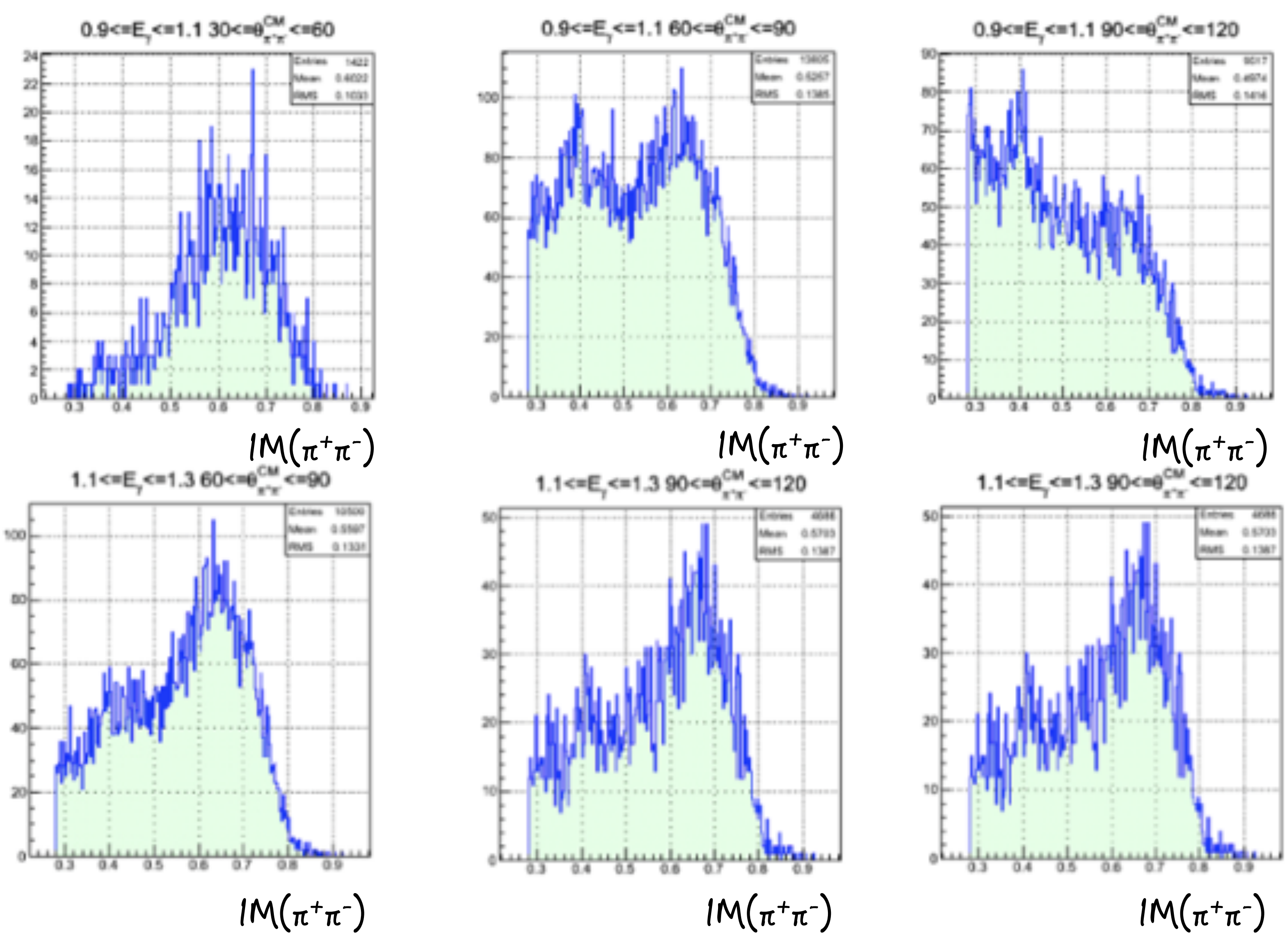
Identification of the reaction $\gamma p \longrightarrow \rho^0 p$: cut on E_γ

In order to remove this bump we require $E_\gamma > 1.3$ GeV. For $E_\gamma < 1.3$ GeV the reaction is dominated by the background

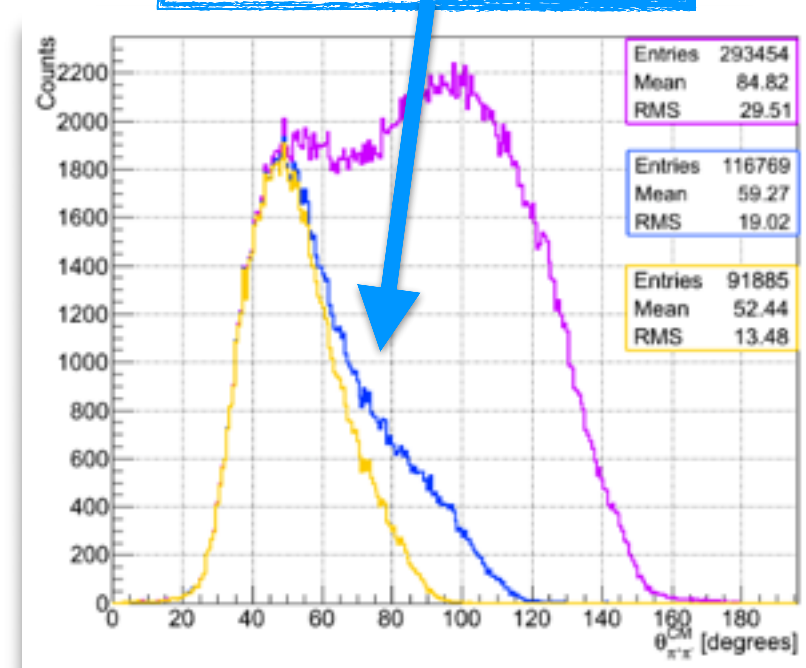


Final $IM(\pi^+\pi^-)$ spectrum



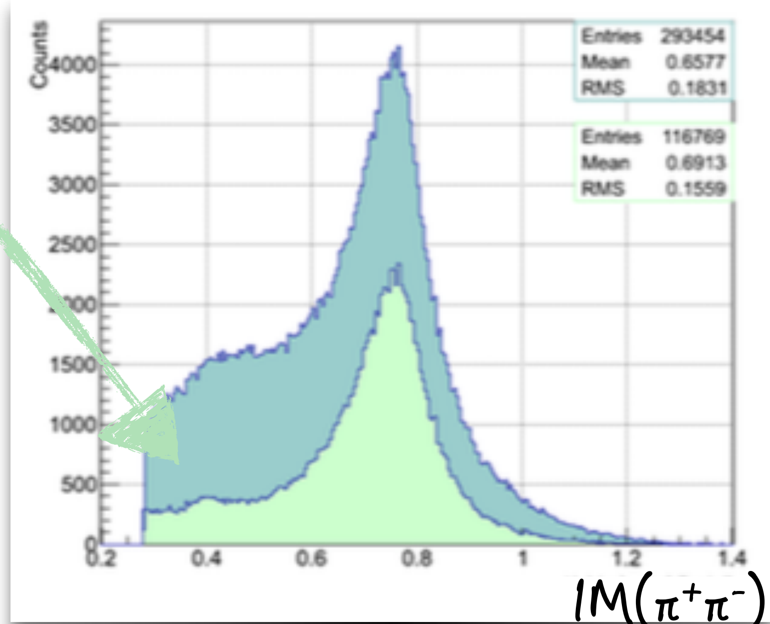


After cut on $-t < 0.5$ GeV

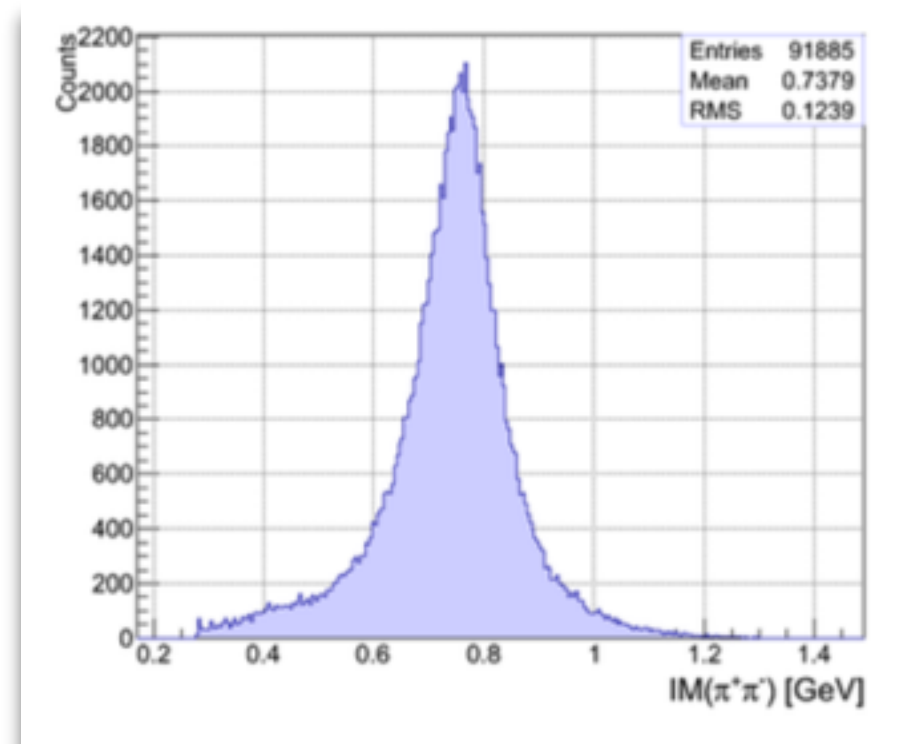


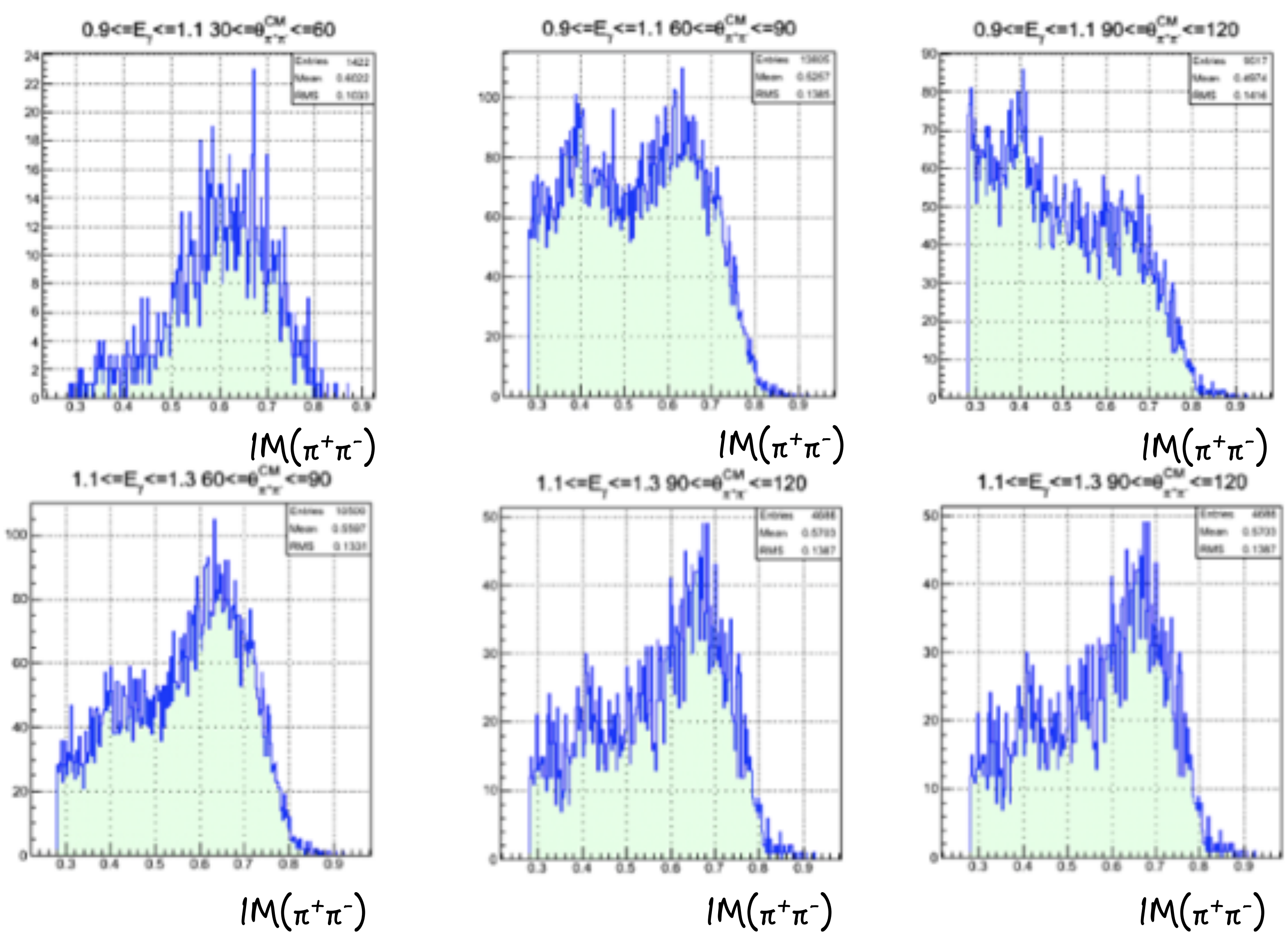
Identification of the reaction $\gamma p \longrightarrow \rho^0 p$: cut on E_γ

In order to remove this bump we require $E_\gamma > 1.3$ GeV. For $E_\gamma < 1.3$ GeV the reaction is dominated by the background

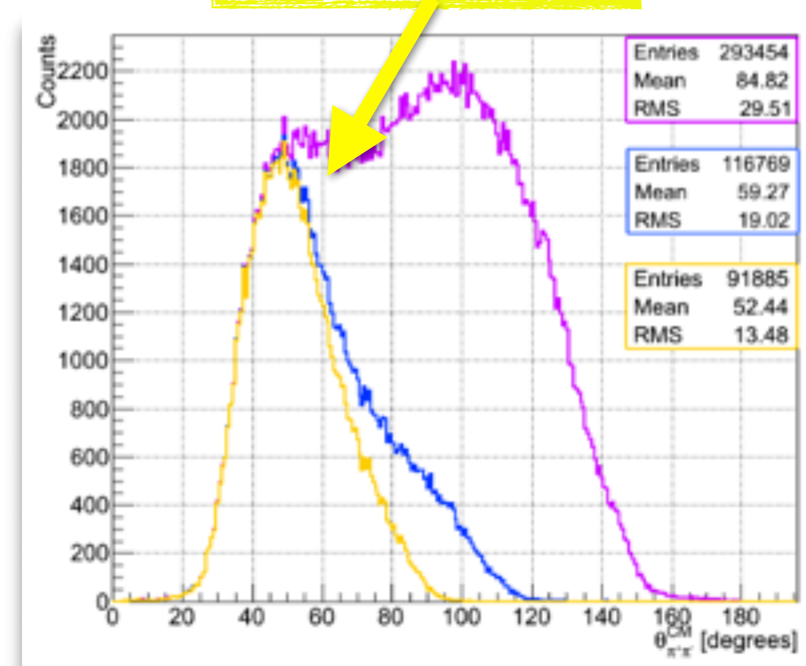


Final IM(π+π-) spectrum





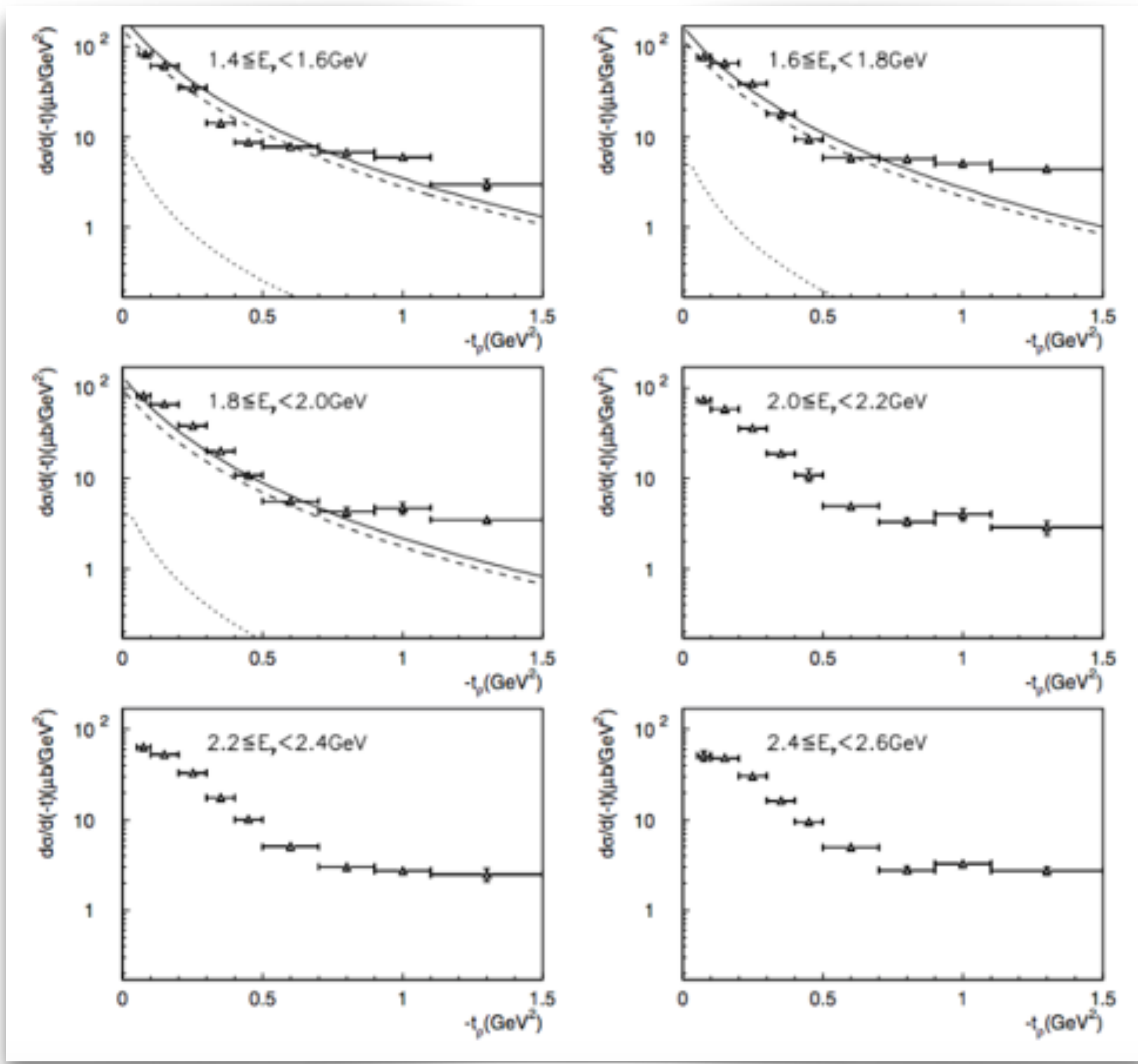
After $E_\gamma > 1.3$ GeV



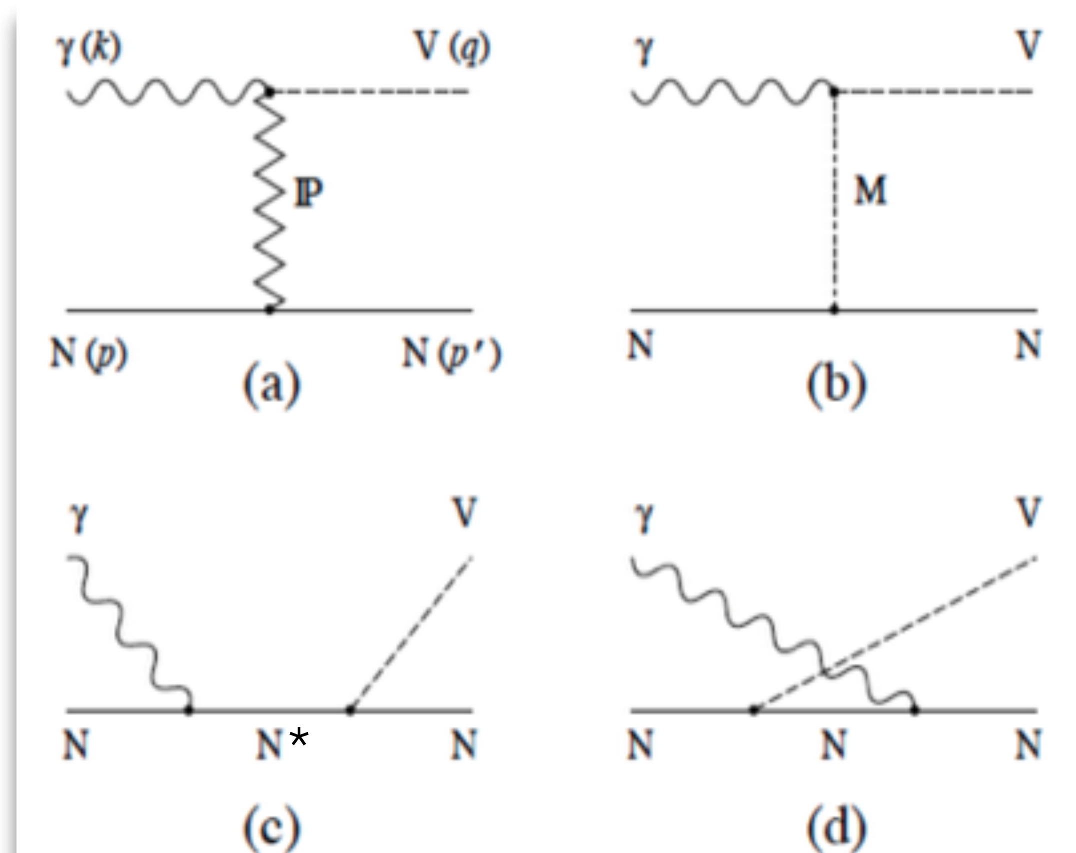
The reaction γ p —> ρ⁰ p

<u>Diffractive behavior</u>:
The differential cross section shows an exponential fall-off with the squared recoil momentum:
the process has more probability to happen at small t or, equivalently, at small $\theta_{\pi\pi}^{CM}$.

$$t = (\tilde{P}_\gamma - \tilde{P}_\rho)^2 = (\tilde{P}_N - \tilde{P}_{N'})^2 = m_\rho^2 - 2E_\gamma(E_\rho - p_\rho cos\theta_\rho)$$

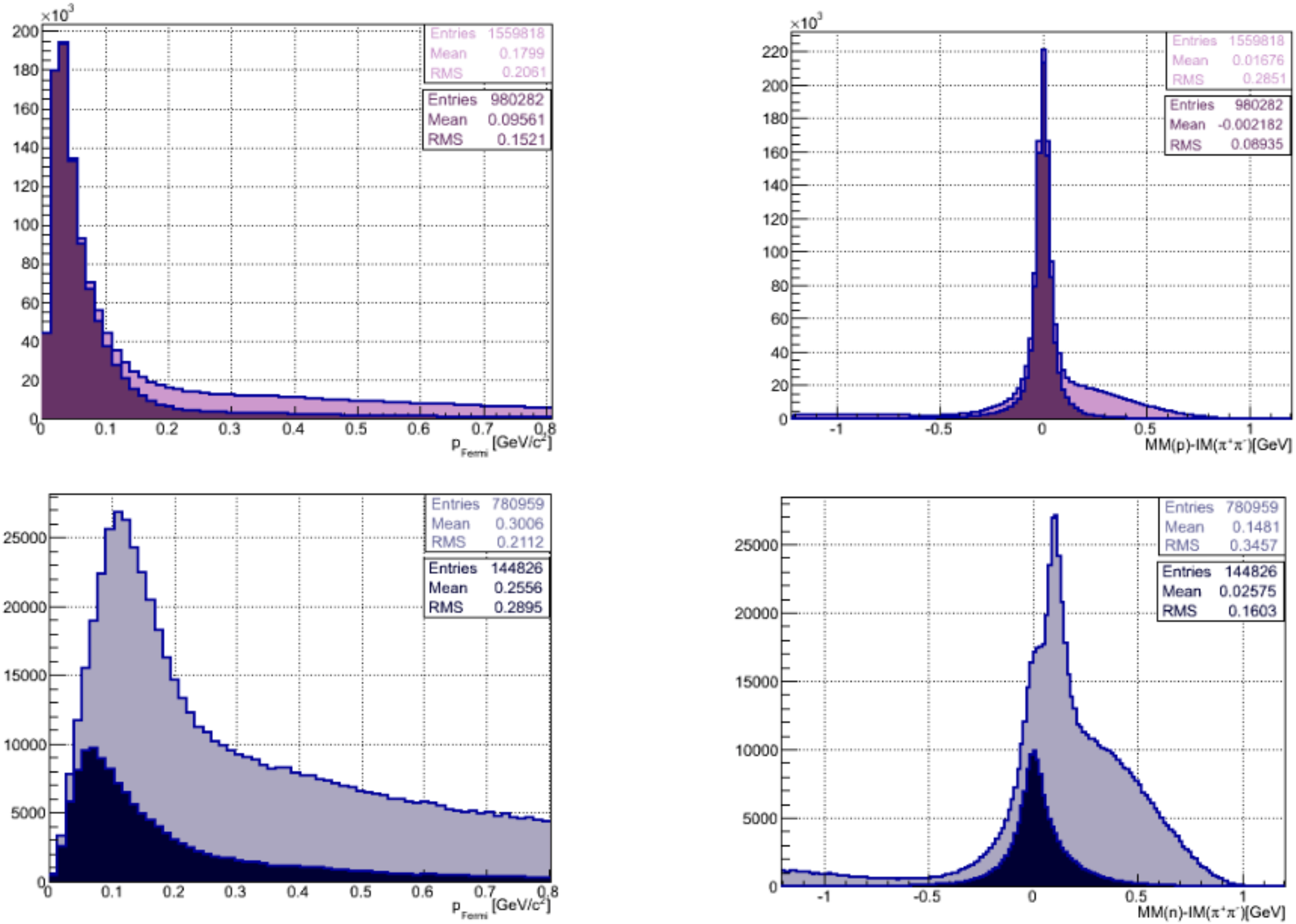


[Eur. Phys. J A 23 2 (2005)]



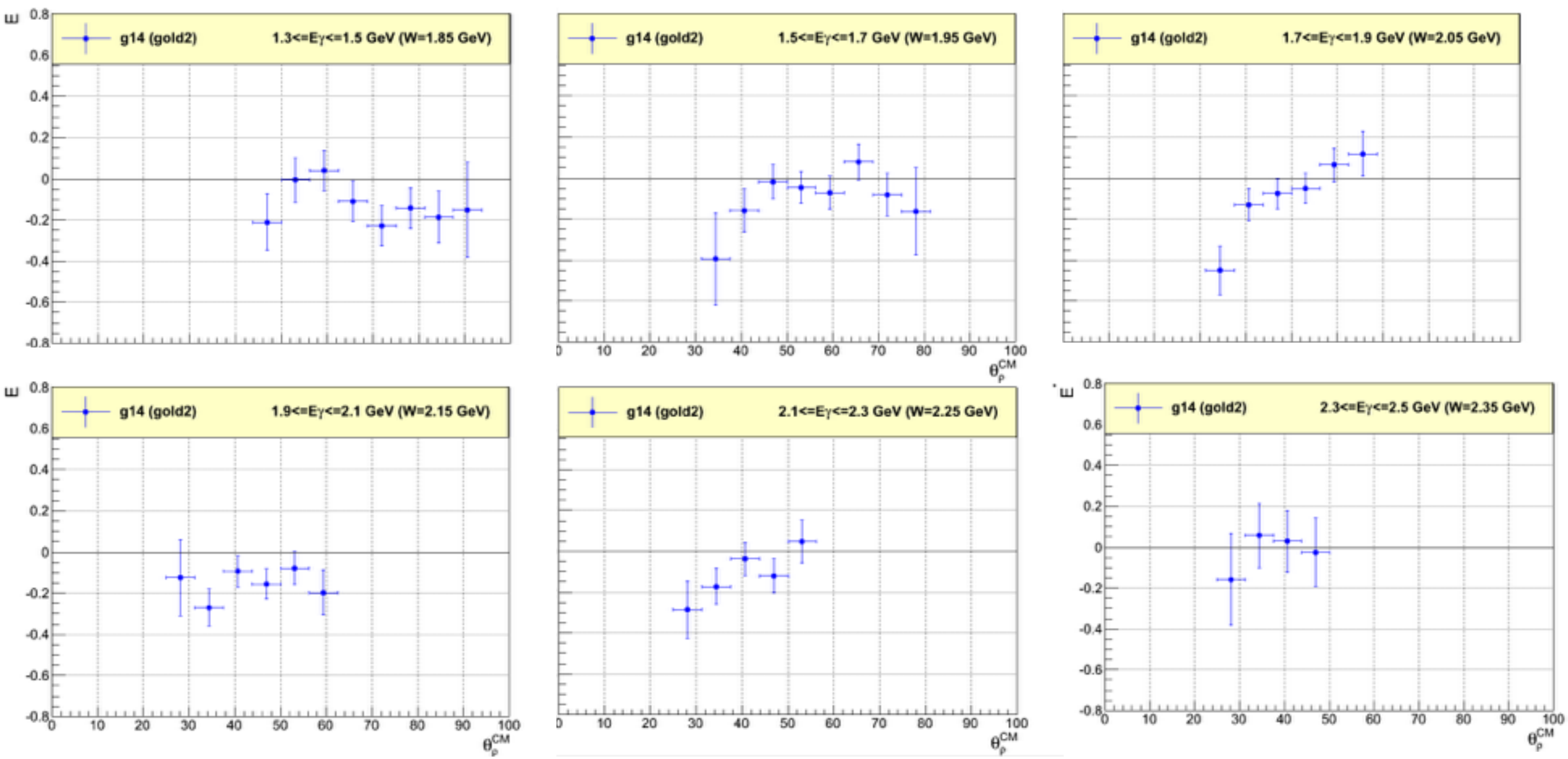
<u>Diagramatic rapresentation of the rho photoproduction mechanism:</u>

a) exchange of a Pomeron
b) exchange of a pseudoscalar meson
c) and d) contribution of baron resonances

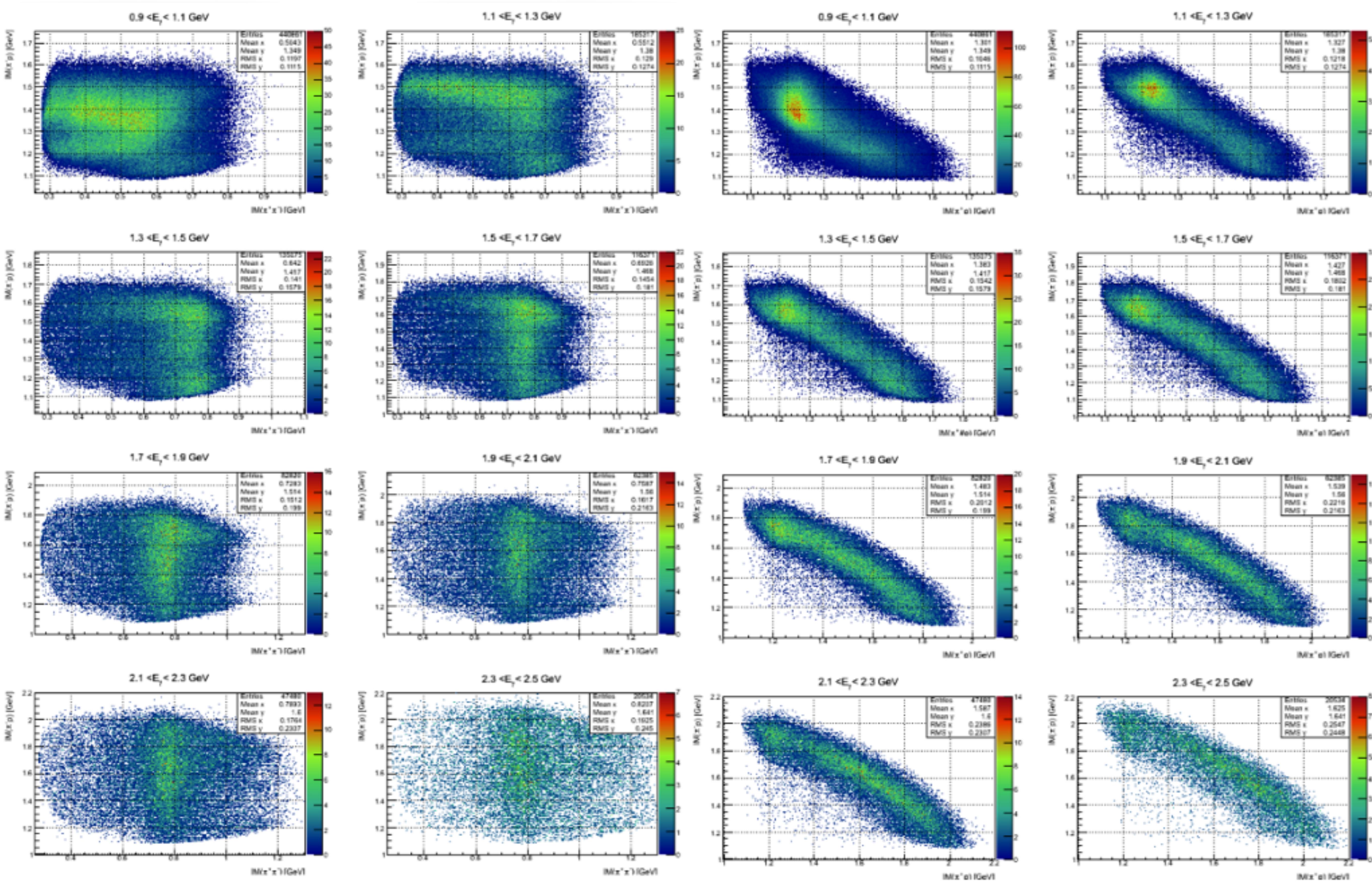

×10^3
Entries 1559818
Mean 0.1799
RMS 0.2061
Entries 980282
Mean 0.09561
RMS 0.1521
p_Fermi [GeV/c^2]
×10^3
Entries 1559818
Mean 0.01676
RMS 0.2851
Entries 980282
Mean -0.002182
RMS 0.08935
MM(p)-IM(π+π-)[GeV]
Entries 780959
Mean 0.3006
RMS 0.2112
Entries 144826
Mean 0.2556
RMS 0.2895
p_Fermi [GeV/c^2]
Entries 780959
Mean 0.1481
RMS 0.3457
Entries 144826
Mean 0.02575
RMS 0.1603
MM(n)-IM(π+π-)[GeV]

$$\frac{d\sigma}{d\Omega} = \frac{d\sigma_0}{d\Omega}(1 - \delta_l \Sigma) cos2\phi + P_z^T \delta_l sin2\phi - P_z^T \delta_\odot E$$

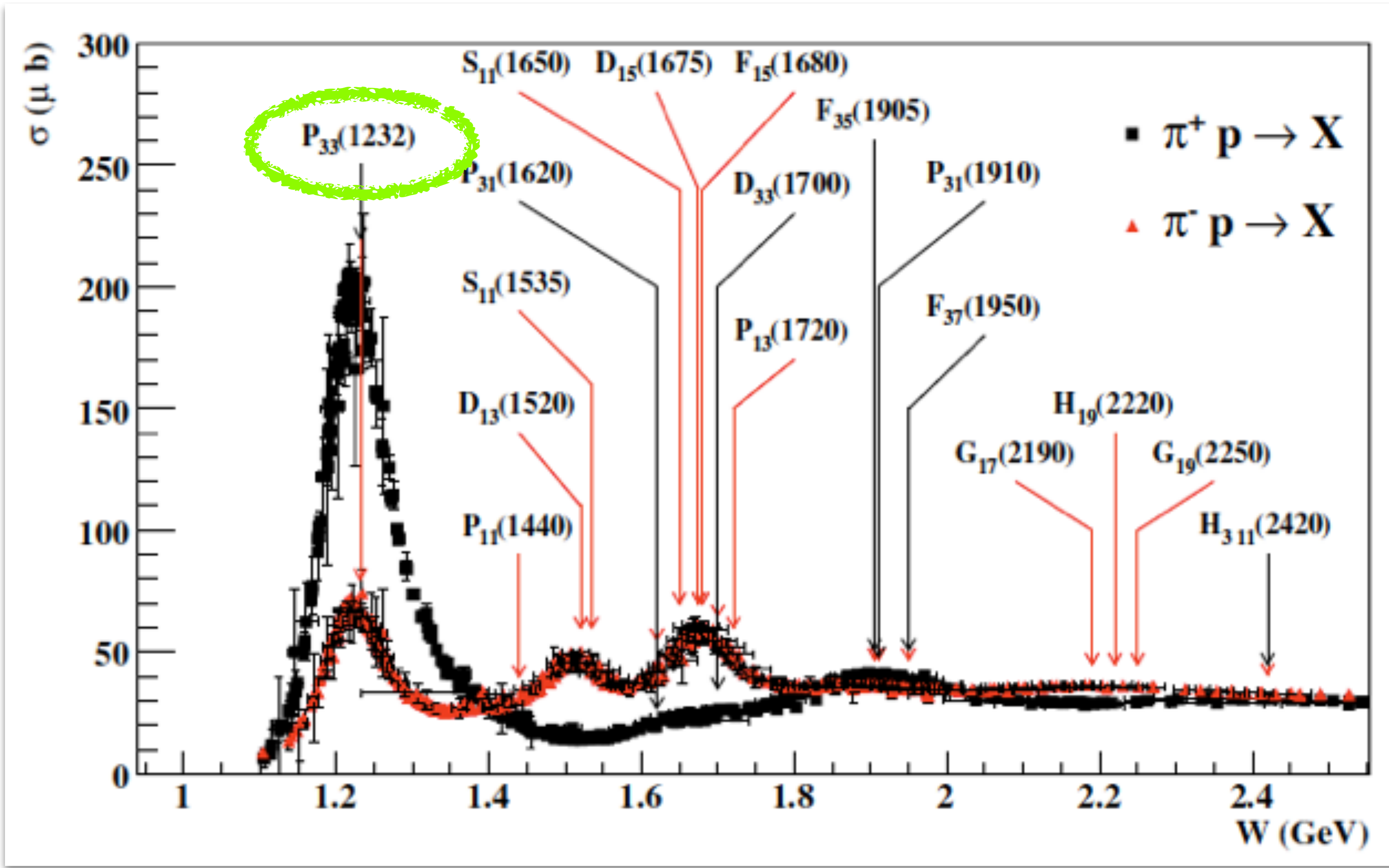
$$E = \frac{1}{\delta_\odot \Lambda_z} \frac{[N(\rightarrow\Rightarrow) - N(\leftarrow\Rightarrow)]}{[N(\rightarrow\Rightarrow) + N(\leftarrow\Rightarrow)]}$$



Identification of the reaction $\gamma p \longrightarrow \rho^0 p$



What should we look at?



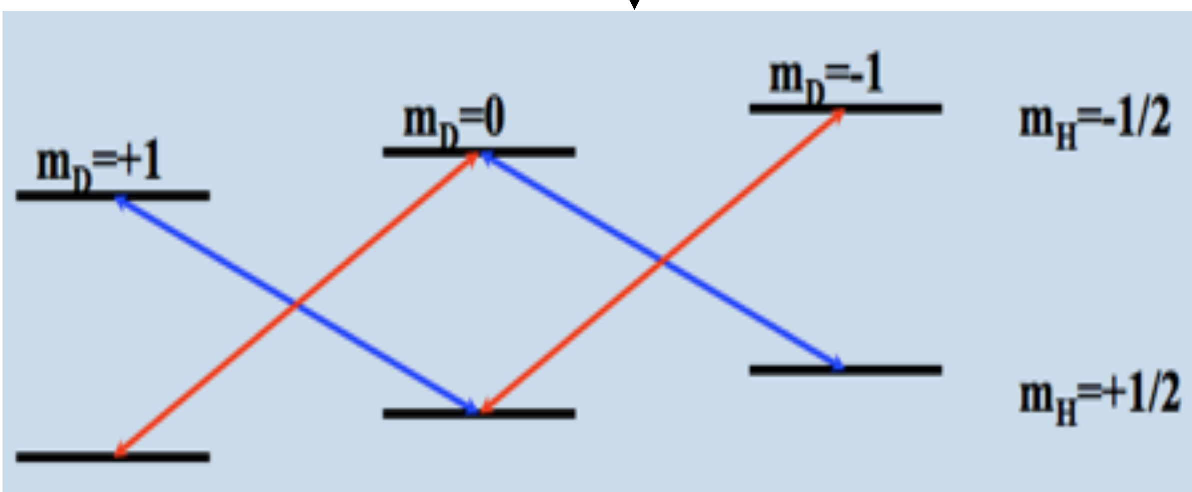
- Resonances with **** rating
- $\tau \sim 10^{-23}$s $\Gamma \sim 100$ MeV
  - ➡ SEVERE OVERLAP OF THE STATES
  - ➡ Only the $P_{33}(1232)$ (Δ) can be clearly isolated
  - ➡ we cannot use simply use the energy for identification

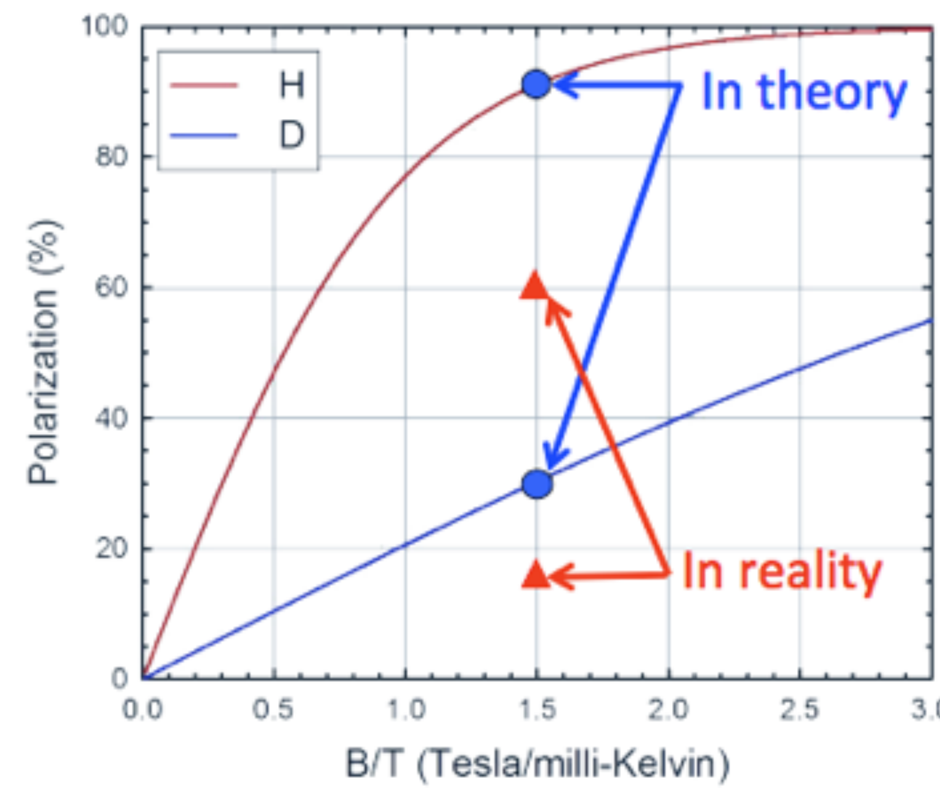
What should we look at?

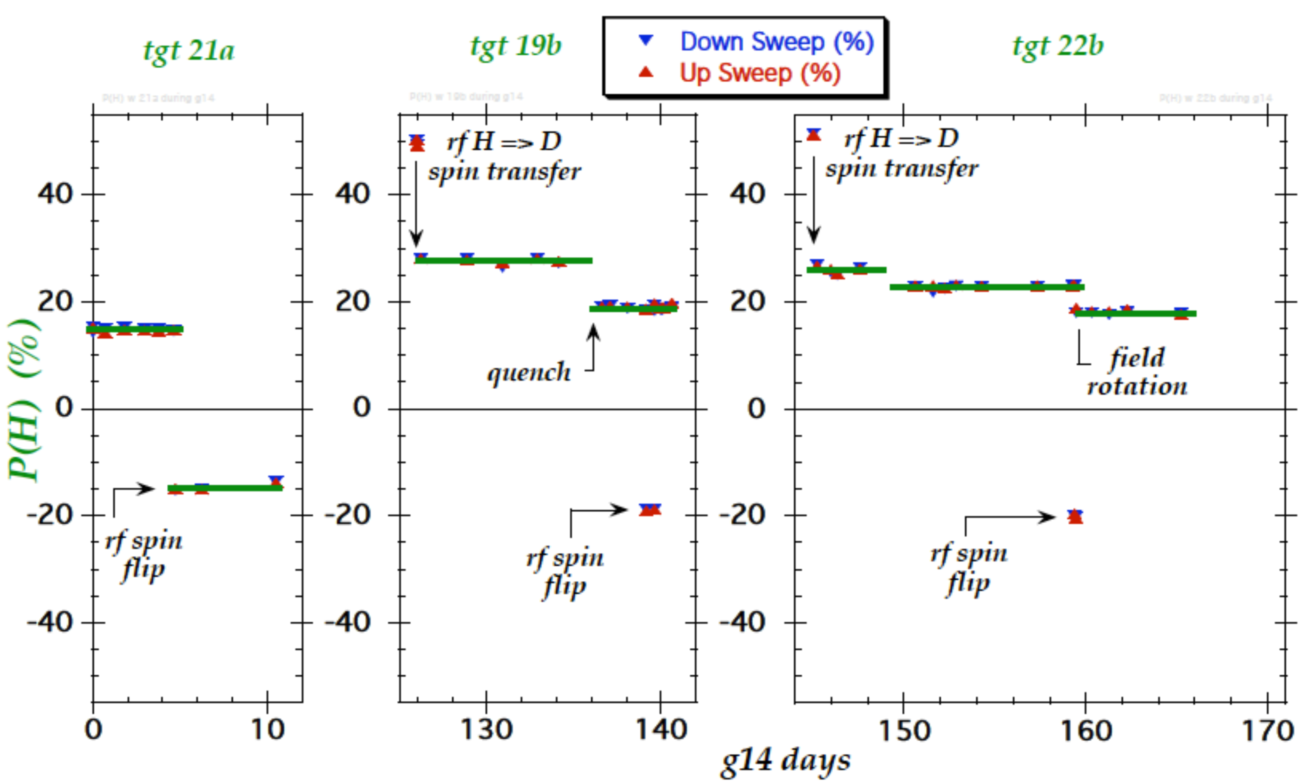
Polarization Observables

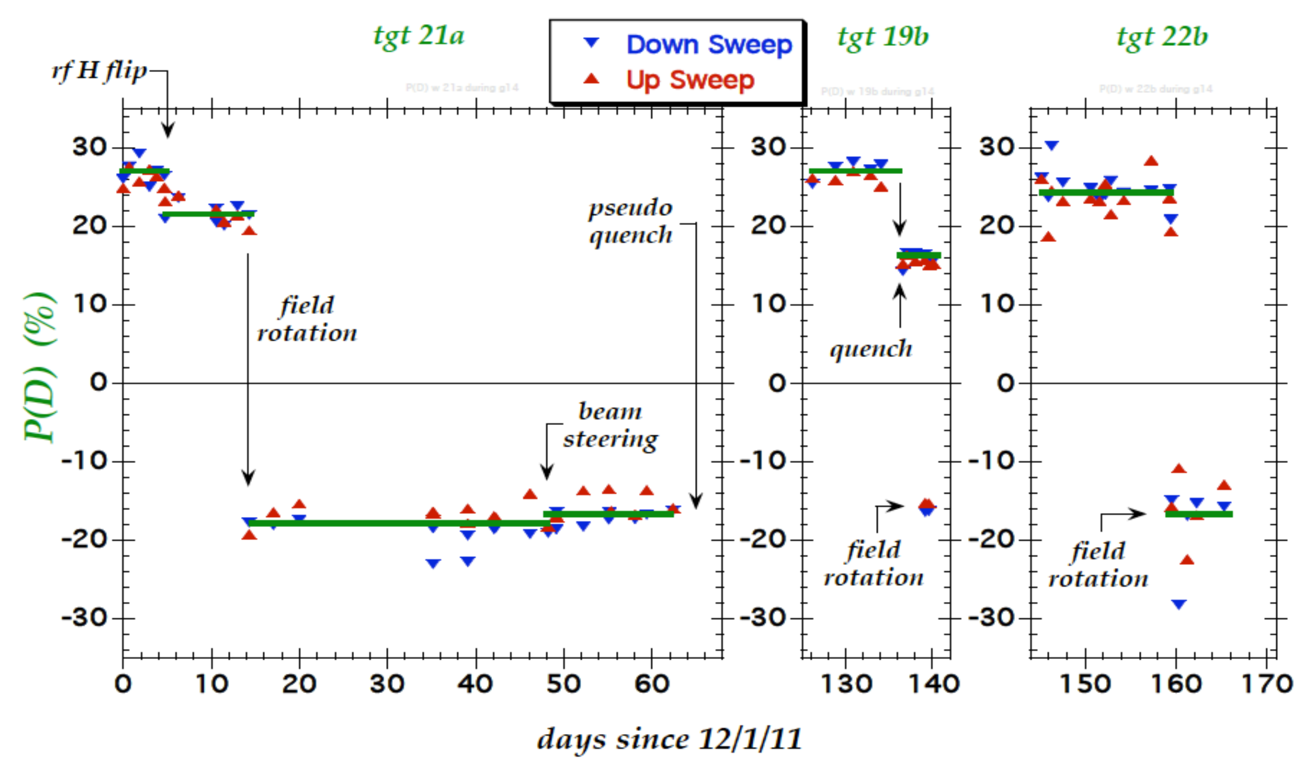
HD frozen-spin target

D is polarized through "adiabatic fast passage"





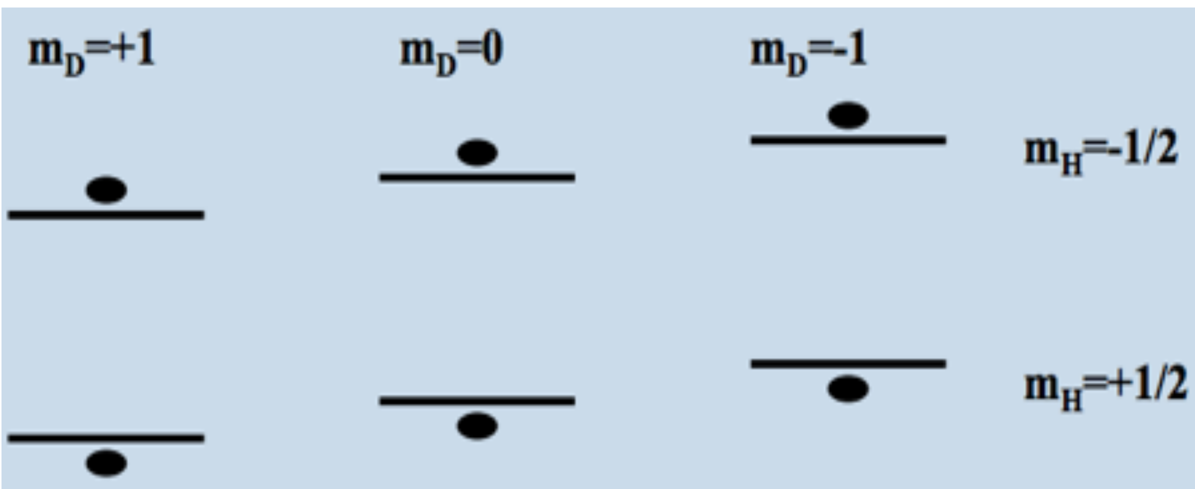


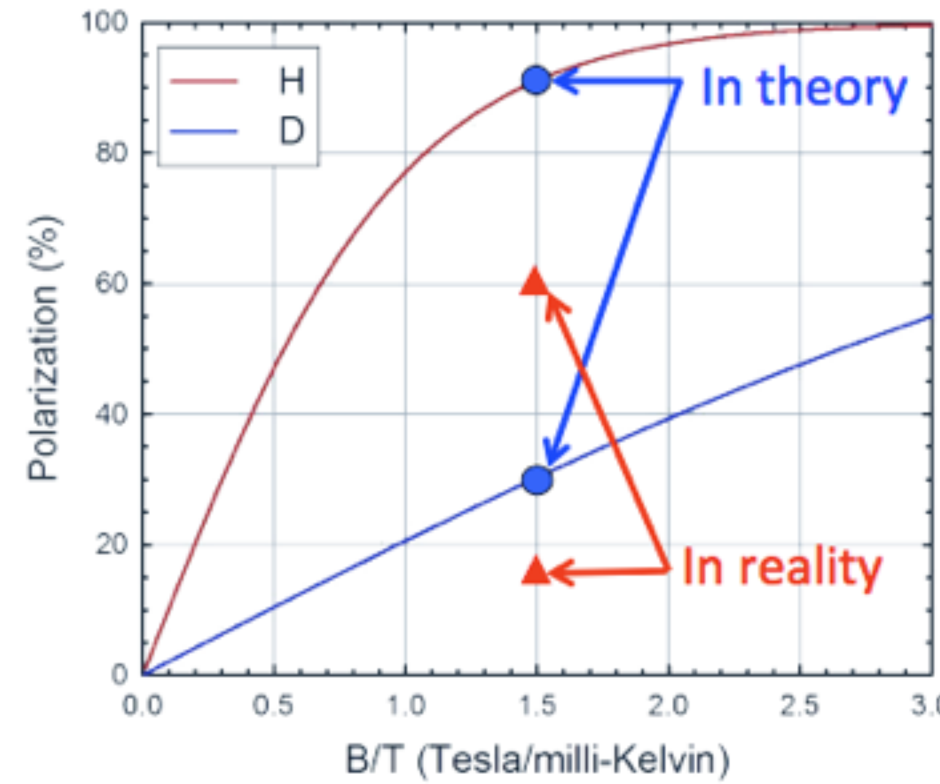


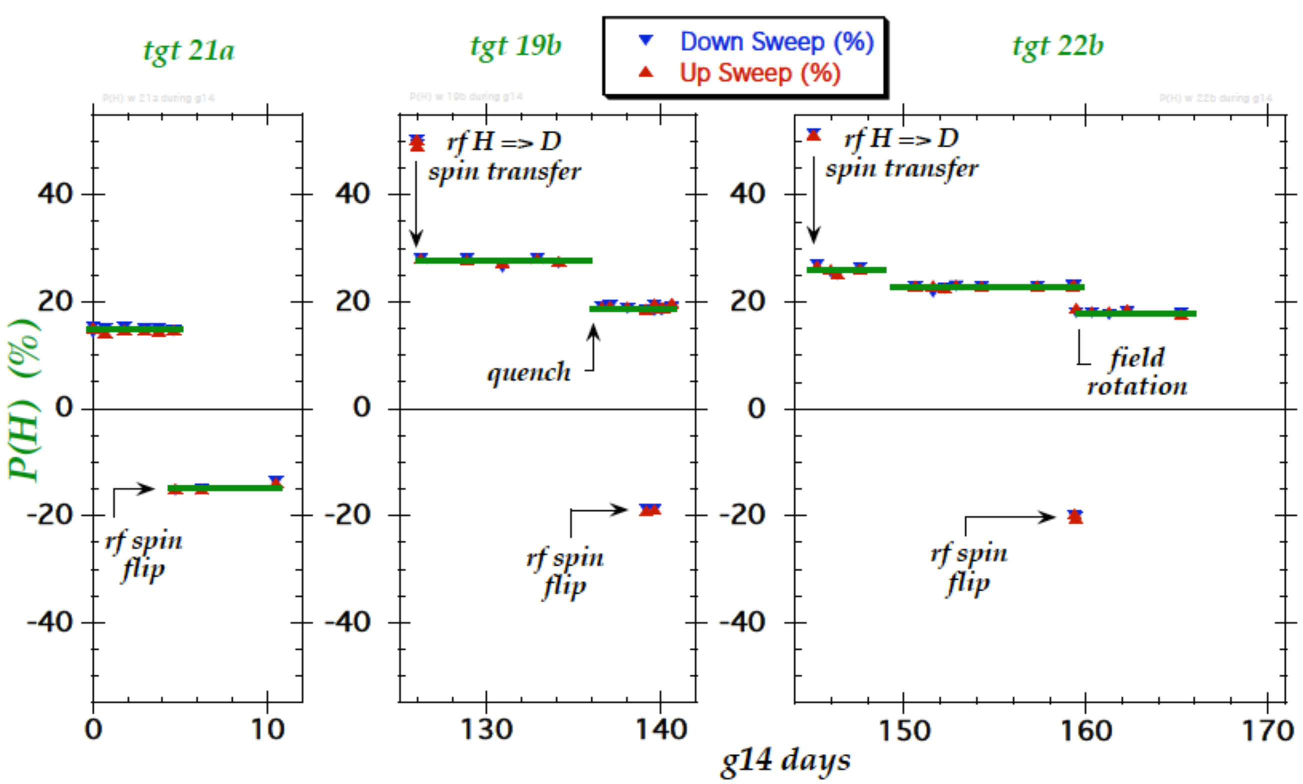
HD frozen-spin target

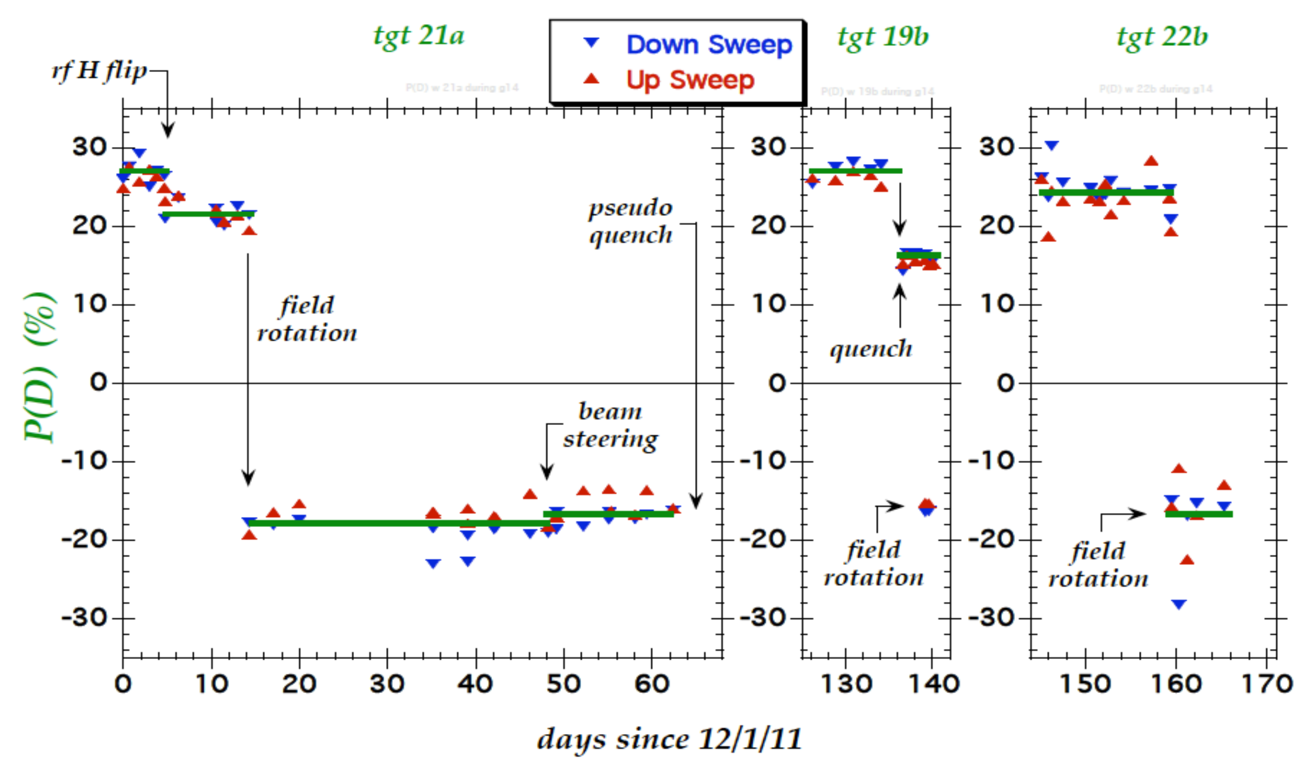
All 6 states are equally populated:

$P_H = 0$ $P_D = 0$





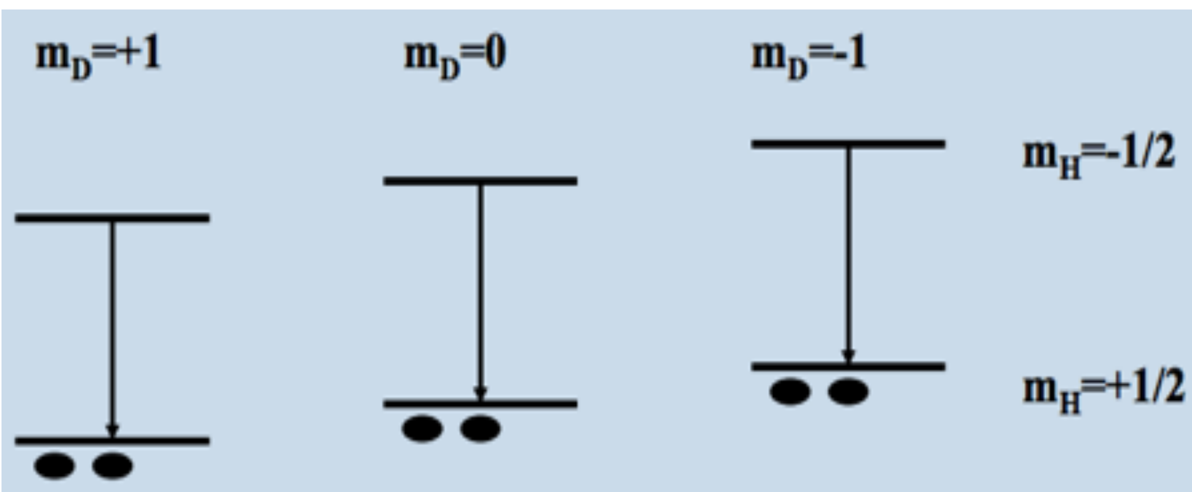


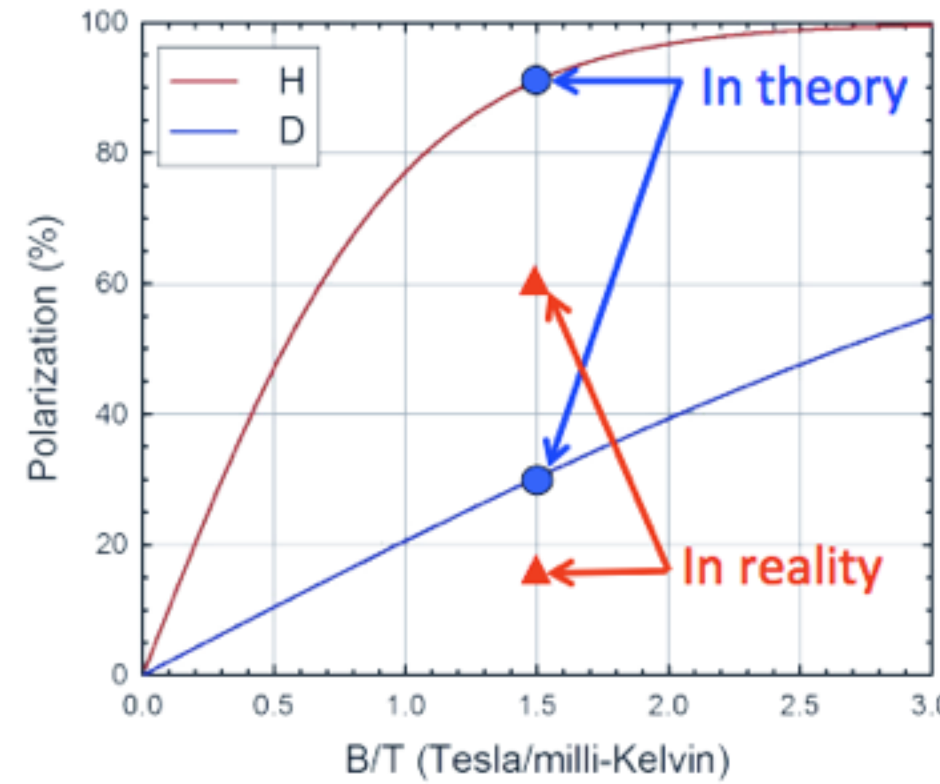


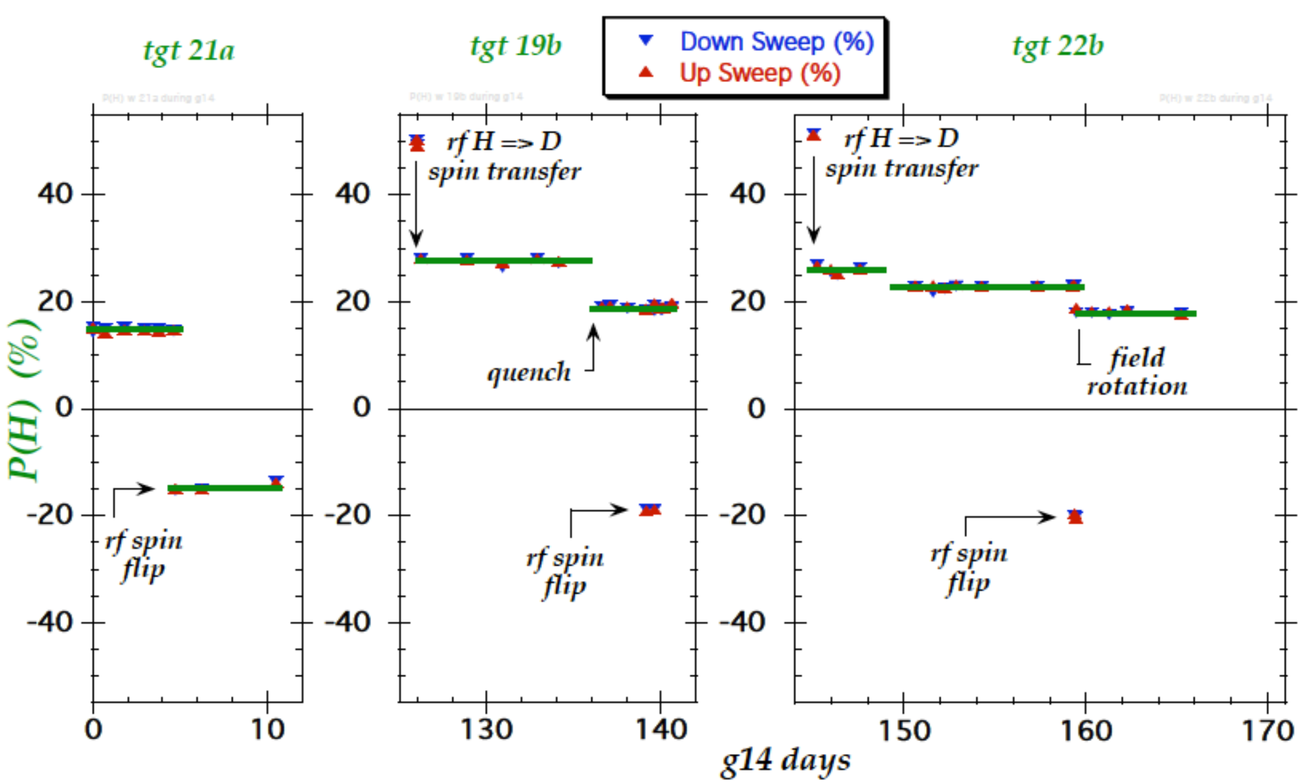
HD frozen-spin target

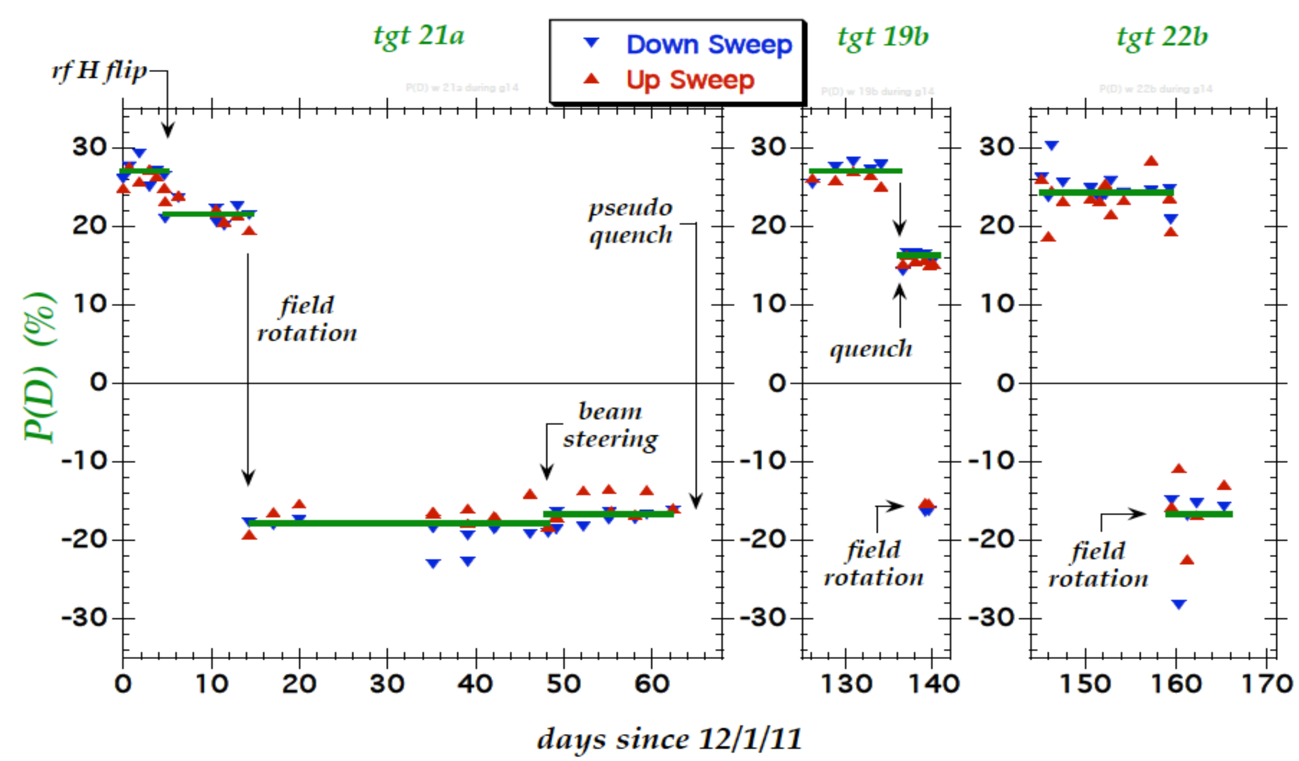
Polarize H with the Brute Force:

$P_H=1$ $P_D=0$





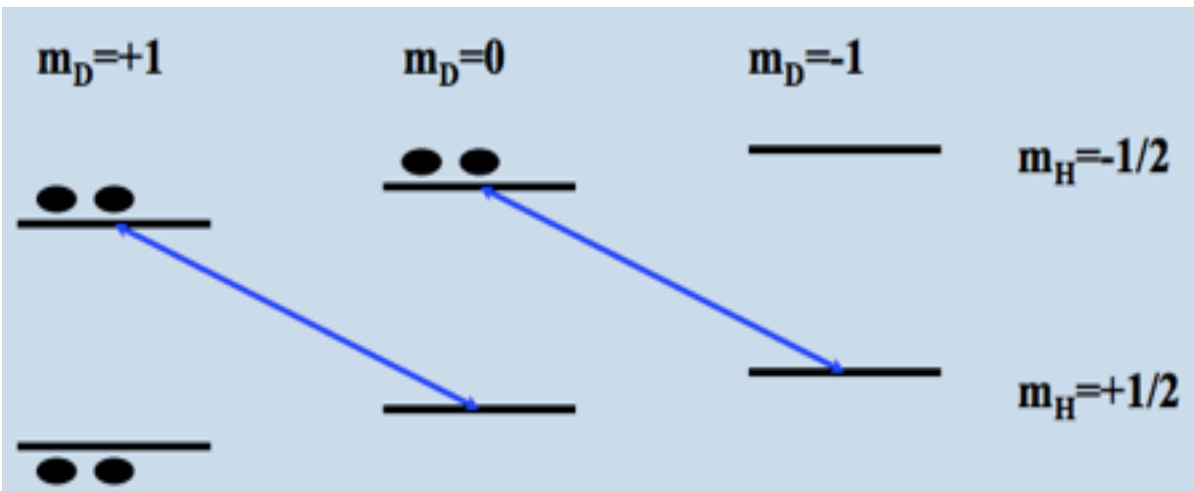


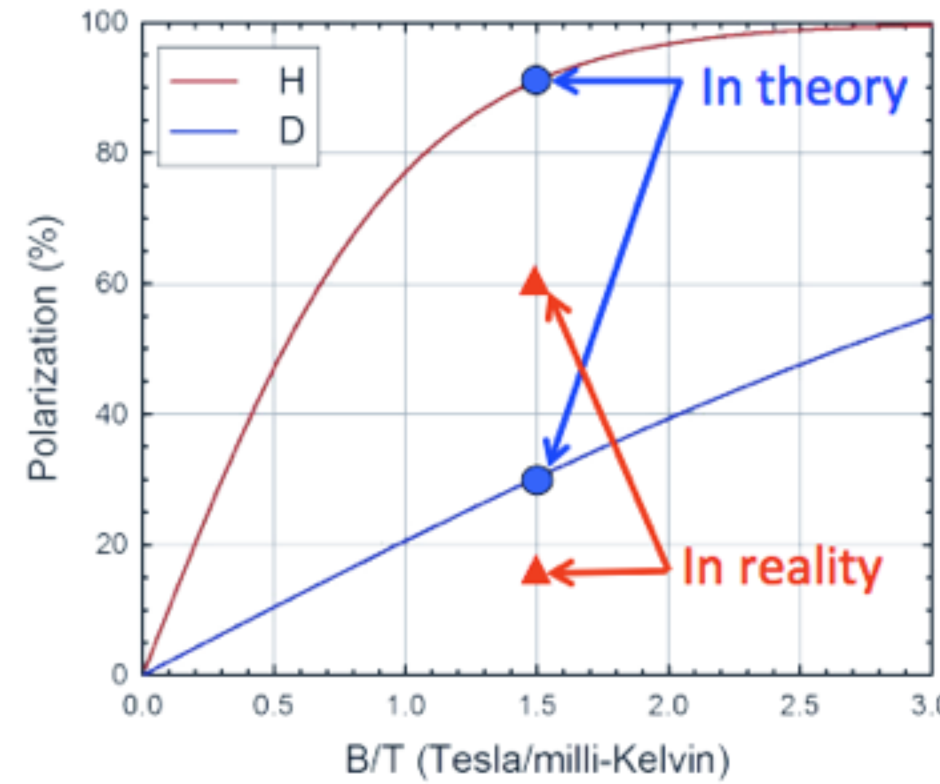


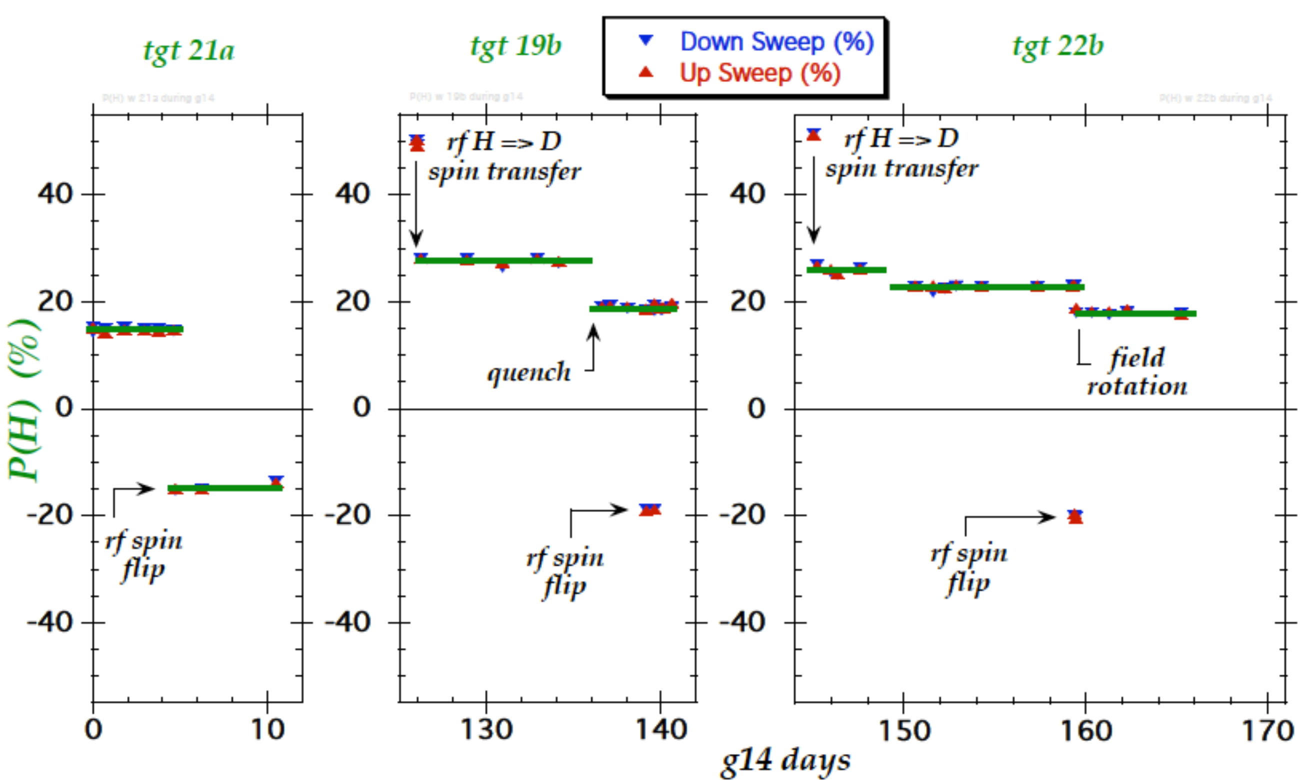
HD frozen-spin target

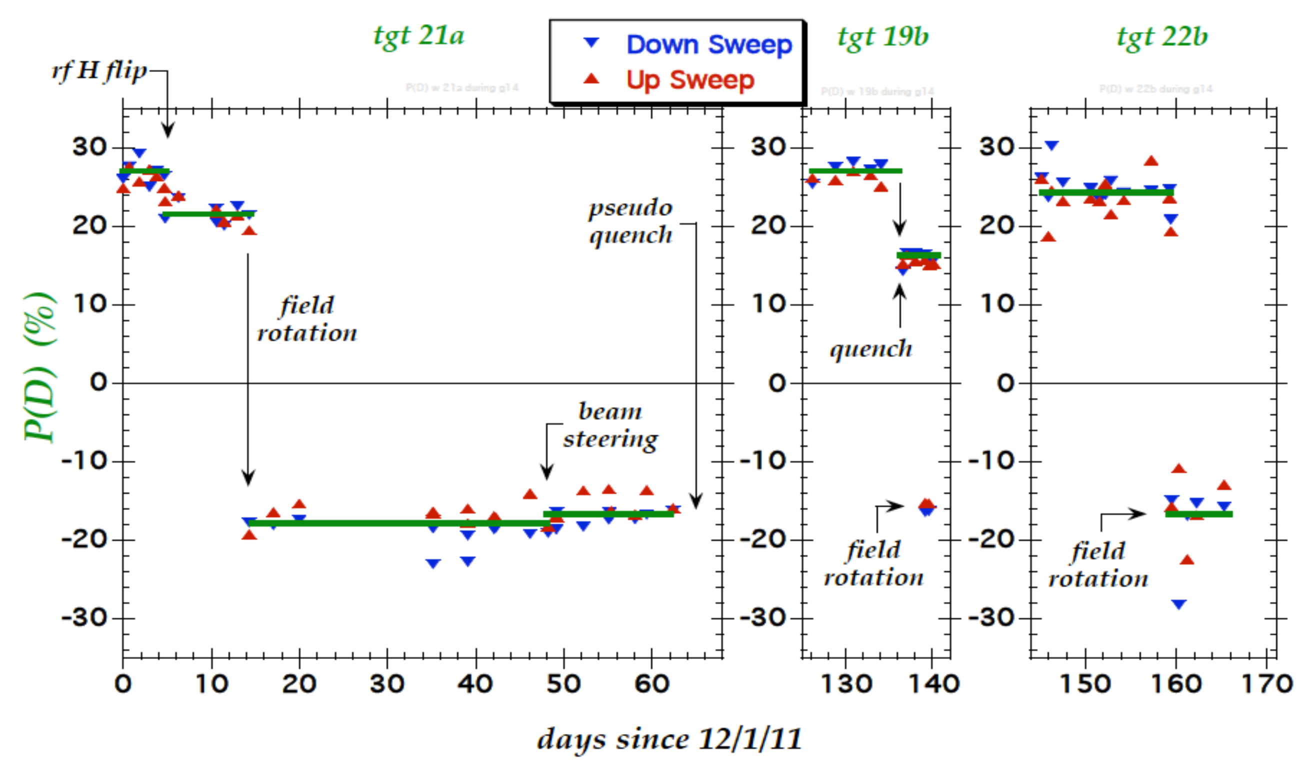
Induce RF transition to polarize D:

$P_H=-1/3$ $P_D=+2/3$





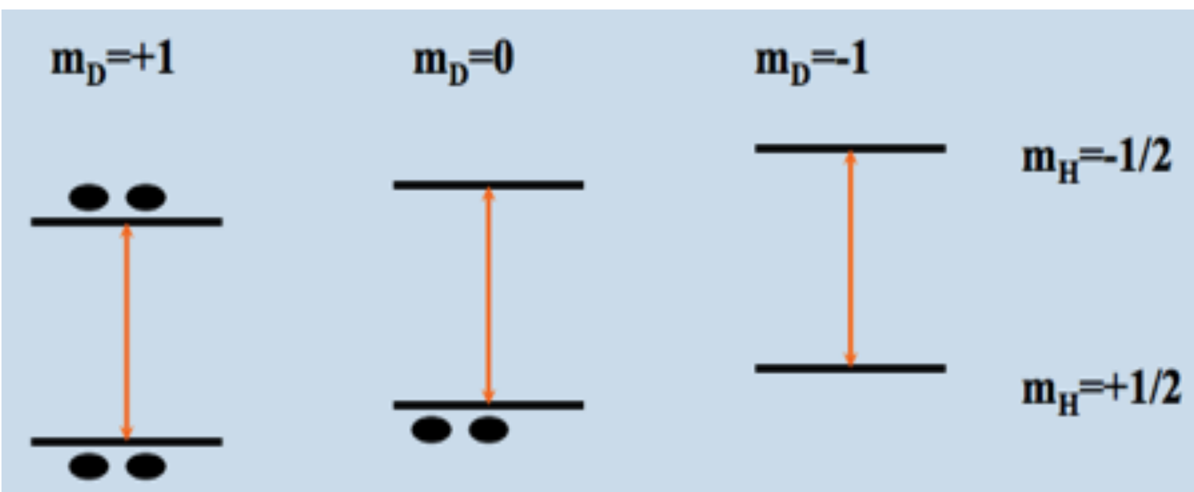


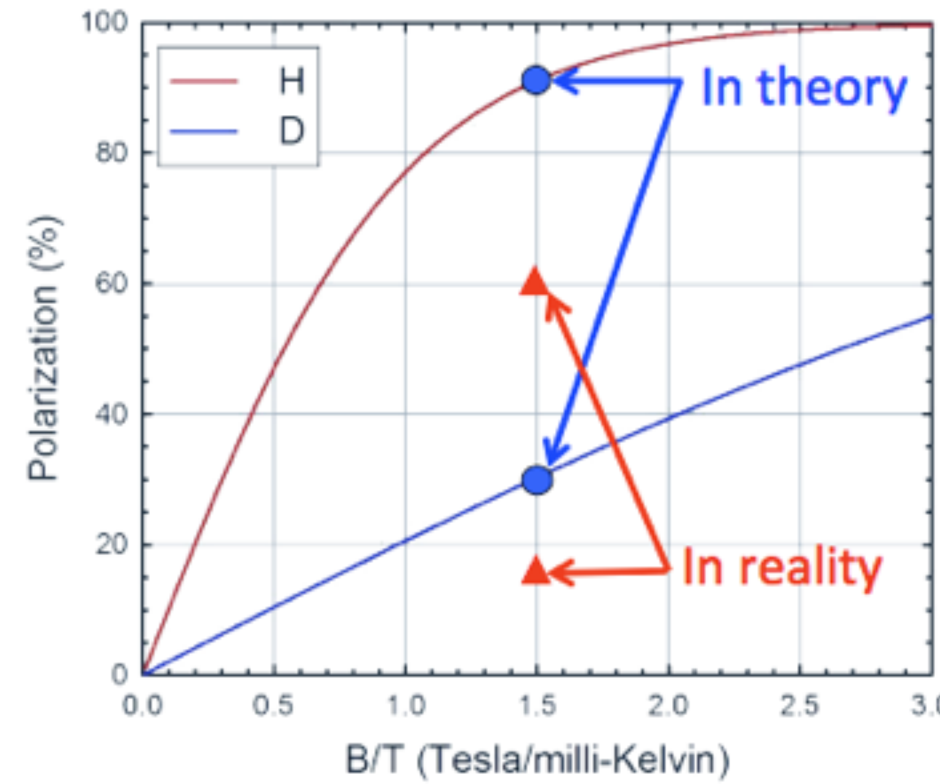


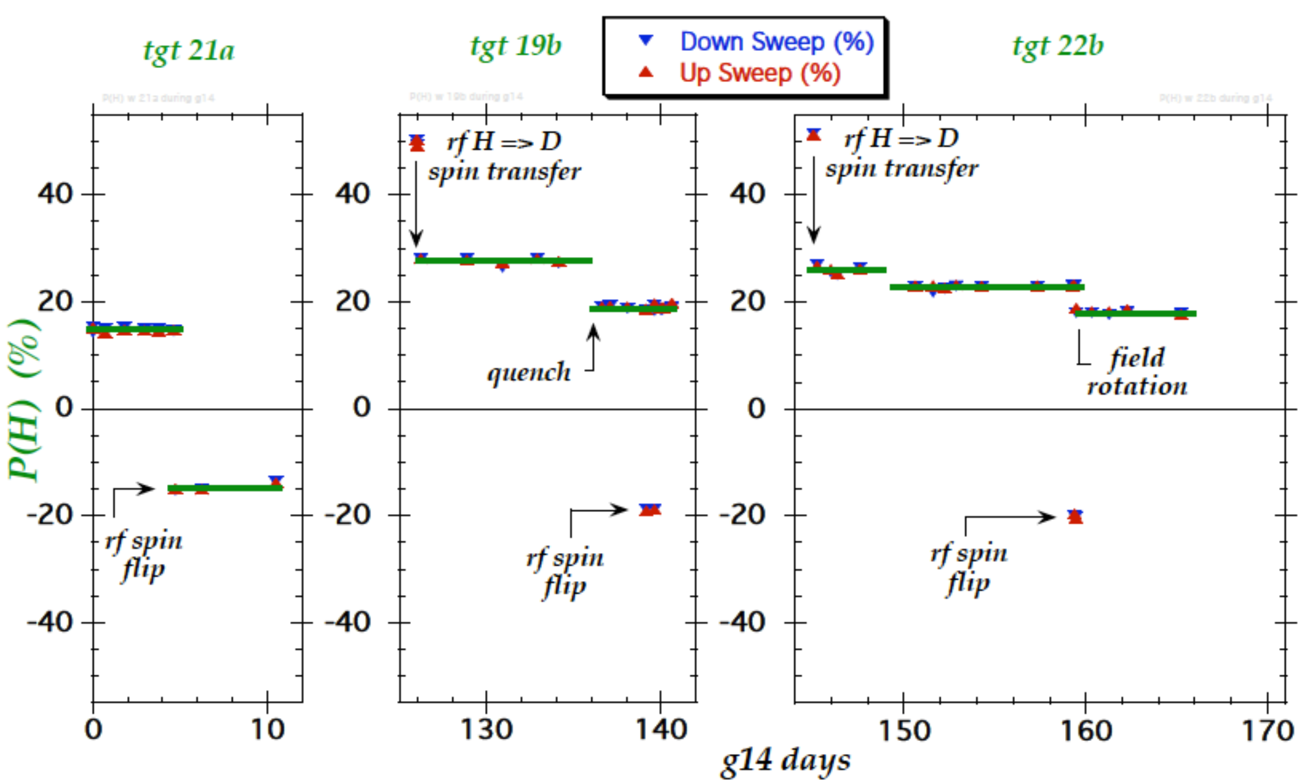
HD frozen-spin target

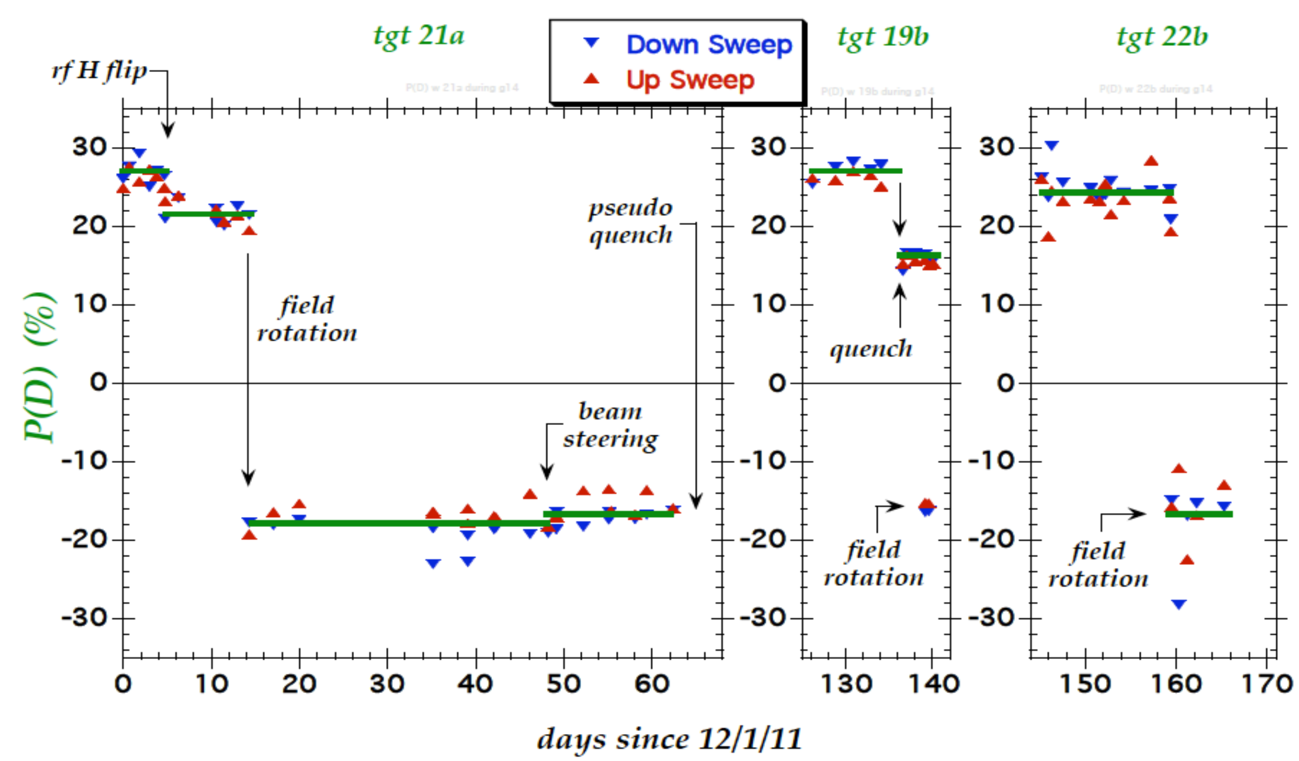
Induce RF transition to reverse P_H:

$P_H = +1/3$ $P_D = +2/3$









What we measure with CLAS

proton target

$\gamma p \longrightarrow \pi^0 p, \pi^+ n$

$\gamma p \longrightarrow \eta p$

$\gamma p \longrightarrow \eta' p$

$\gamma p \longrightarrow KY\ (K^+\Lambda,\ K^+\Sigma^0,\ K^0\Sigma^+)$

$\gamma p \longrightarrow \pi^+\pi^- p$ ----- Dominates photoproduction cross section for W>1.6 GeV

$\gamma p \longrightarrow \omega p, \rho p, \phi p$

bound neutron target

$\gamma n \longrightarrow \pi^- p$

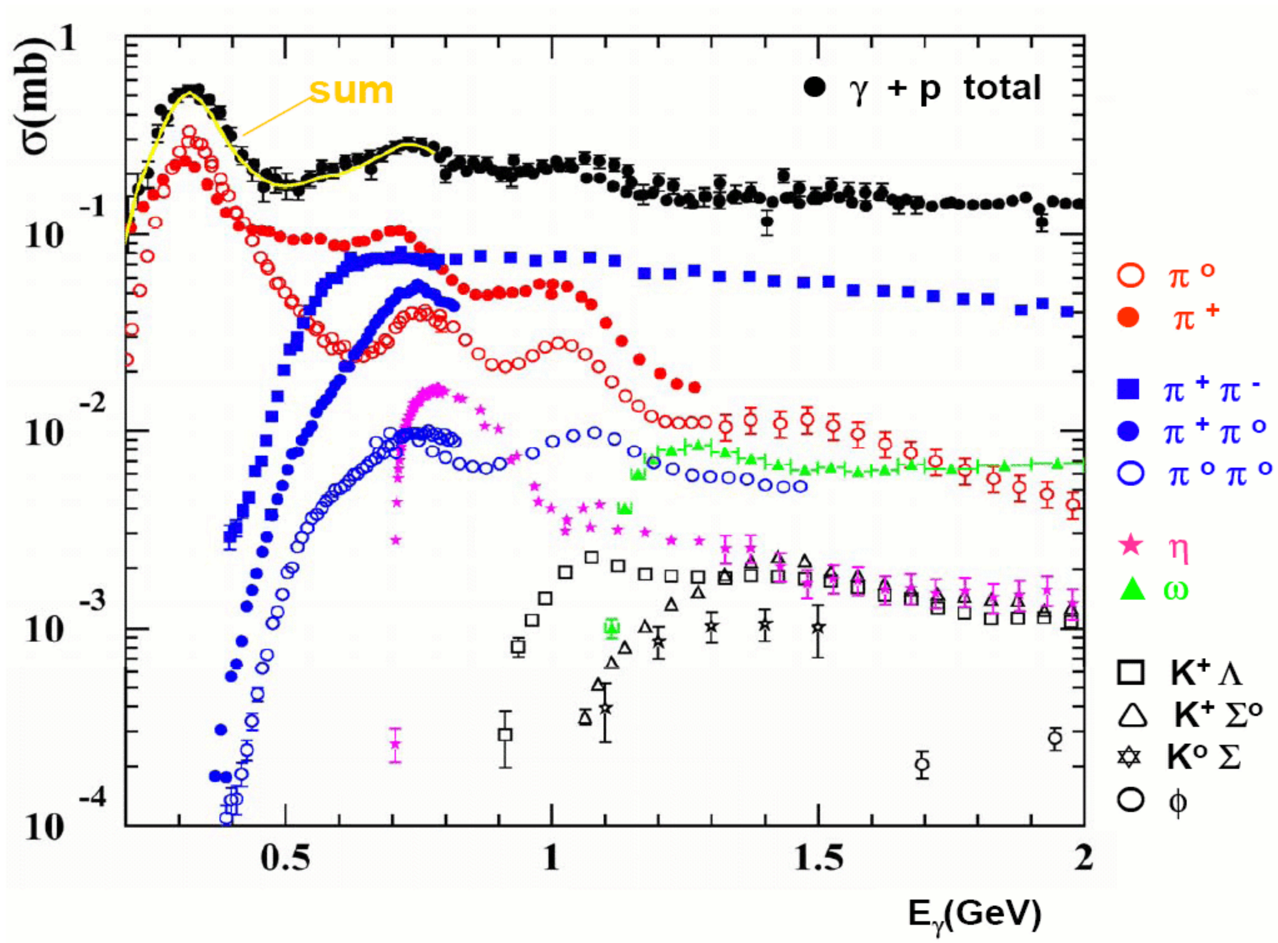
$\gamma n \longrightarrow \eta p$

$\gamma n \longrightarrow \eta' p$

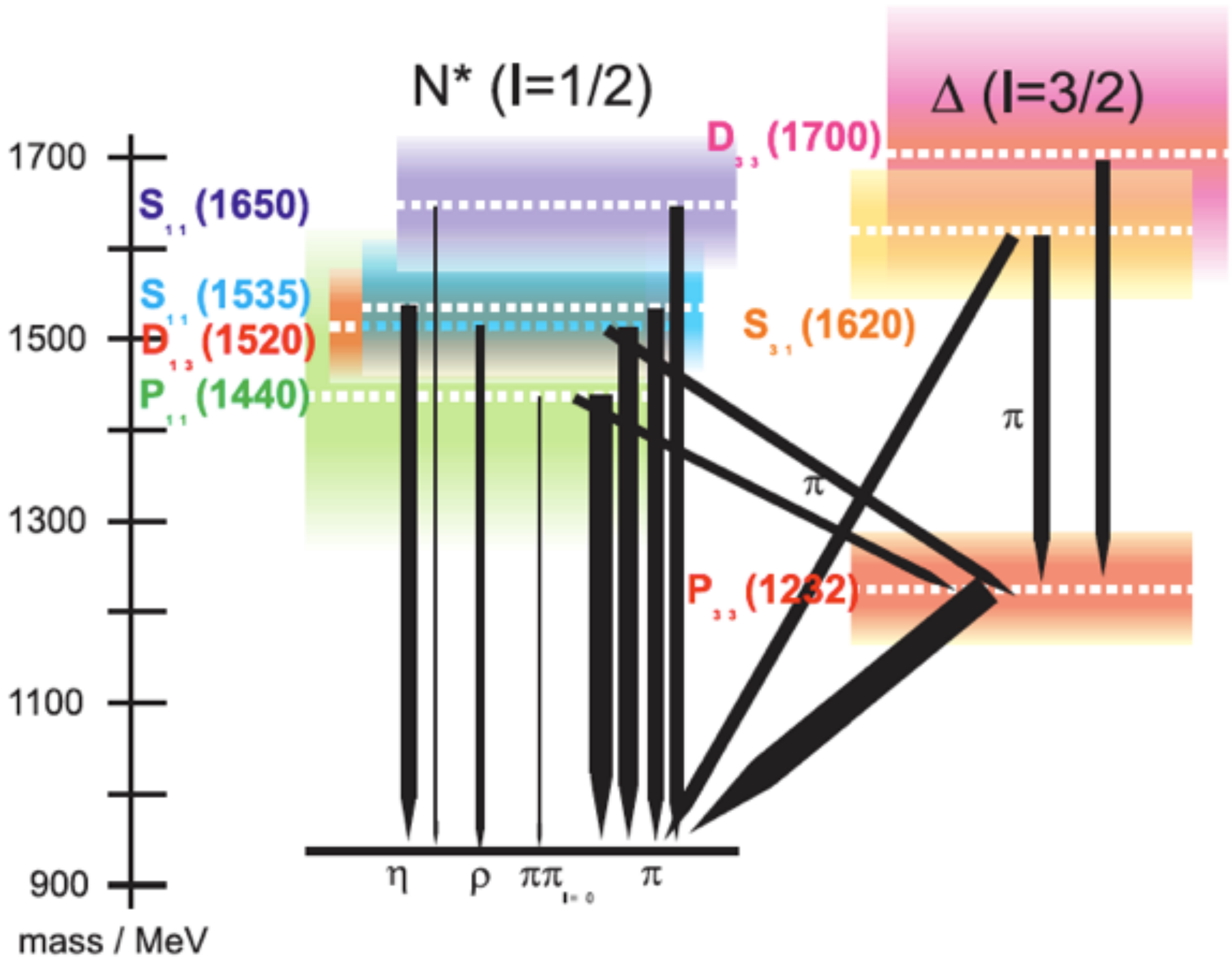
$\gamma n \longrightarrow K^0\Lambda,\ K^+\Sigma^-$

$\gamma n \longrightarrow \pi^+\pi^- n$

$\gamma n \longrightarrow \omega p, \rho p, \phi p$



What should we look at?



- lowest lying resonances
- $\tau \sim 10^{-23}$ s $\Gamma \sim 100$ MeV

➡ SEVERE OVERLAP OF THE STATES

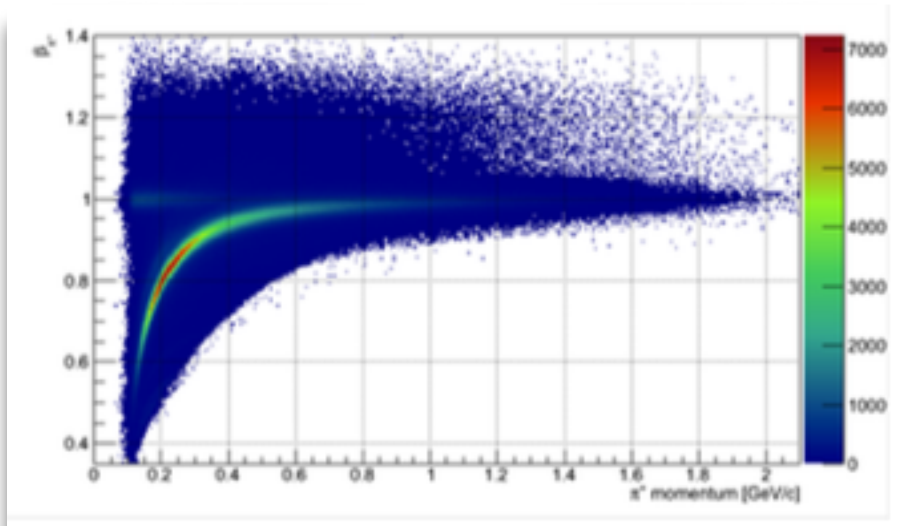
➡ Only the $P_{33}(1232)$ (Δ) can be isolated

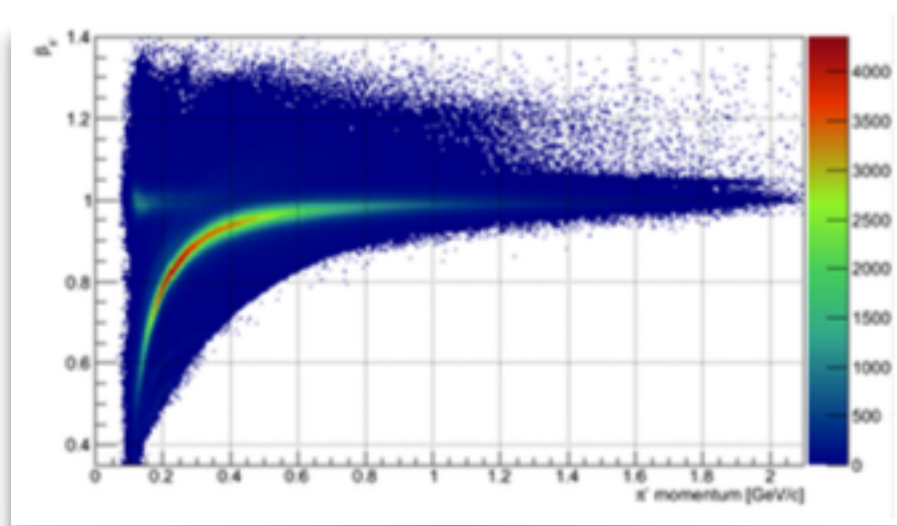
How can we disentangle them?

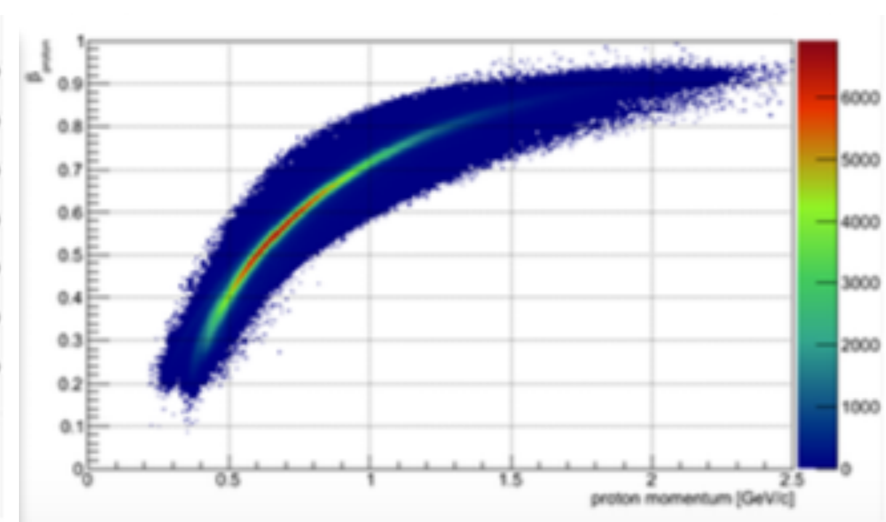
Polarization Observables

Final $\pi^+\pi^-p$ distributions

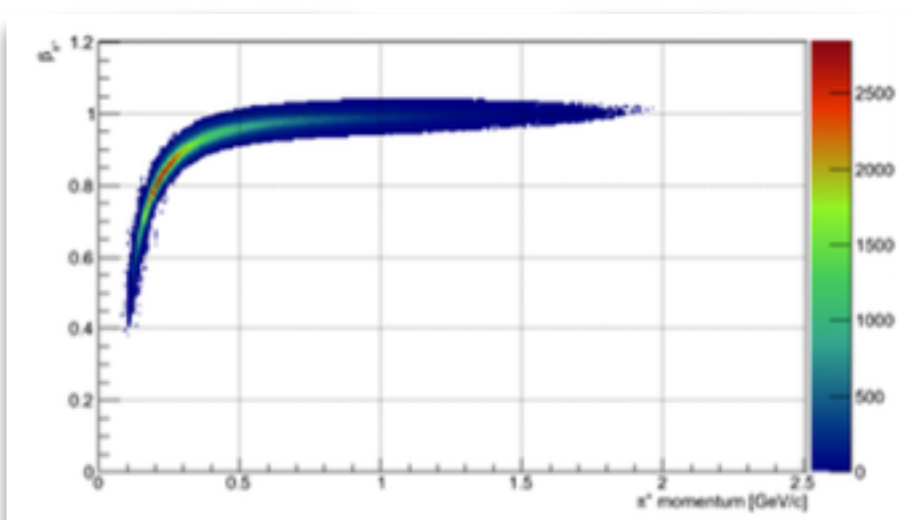
β vs. p before the selection cuts

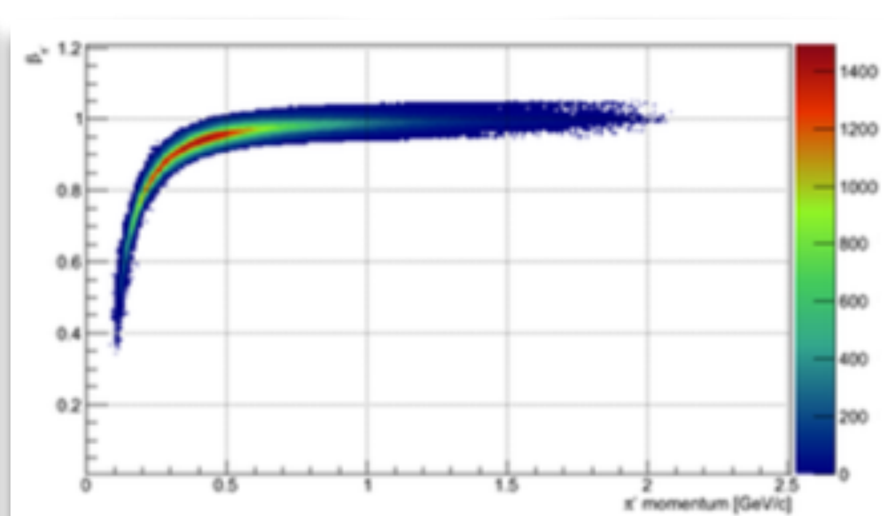


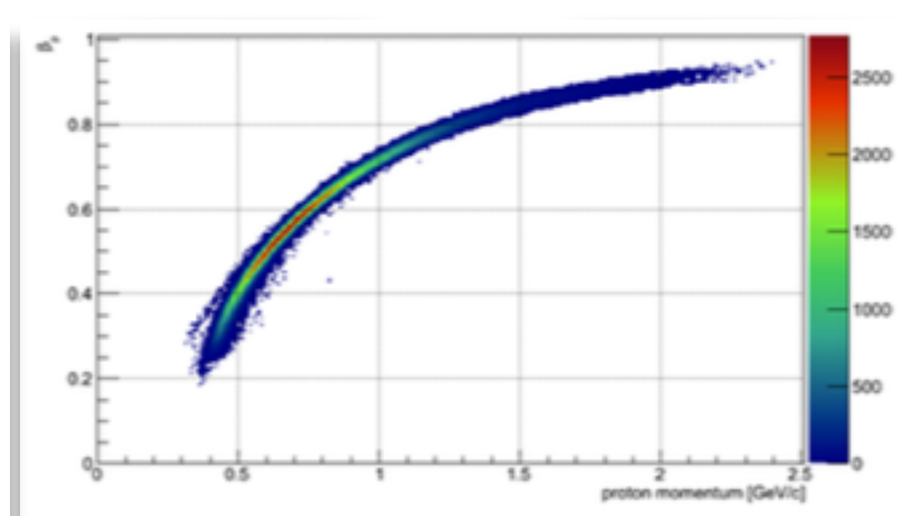




π^+ π^- p







β vs. p after the selection cuts

Identification of the reaction $\gamma p(n) \longrightarrow \rho^0 p(n)$