Update on eg1dvcs part C analysis: DVCS and pi0-DVMP

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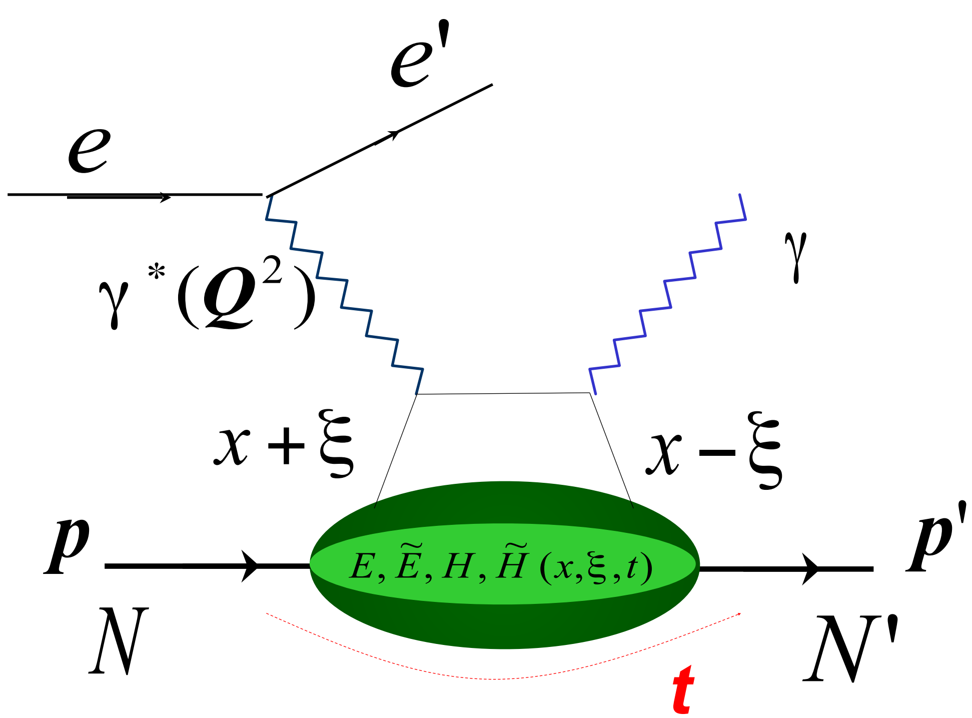
Deeply Virtual Compton Scattering

- GPDs can be interpreted as relating transverse position of partons to longitudinal momentum. Part of 3D imaging of the nucleon.

→ contain information on angular momentum of quarks

- Can be accessed in measurements of cross-sections and asymmetries in, eg: Deeply Virtual Compton Scattering (DVCS).



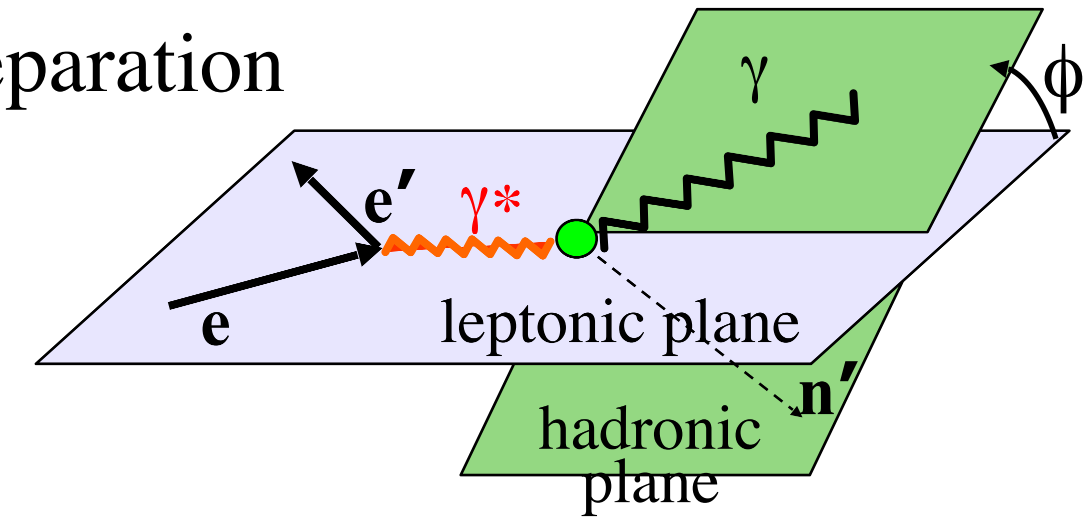
$Q^2 = -(e - e')^2 \qquad t = (p' - p)^2$

$x \pm \xi$ *longitudinal momentum fractions of quarks* $\quad \xi \cong \dfrac{x_B}{2 - x_B}$

- At high exchanged Q^2, access to four GPDs: $E_q, \tilde{E}_q, H_q, \tilde{H}_q\,(x,\xi,t)$

Neutron DVCS

- GPDs from proton and neutron: flavour separation
- Neutron DVCS extremely sensitive to *E*, least-known and least-constrained GPD



$\vec{e^-}$ n *Polarized beam, unpolarized neutron target:*

$$\Delta\sigma_{LU} \sim \sin\phi\ \mathbf{Im}\{F_1 H + \xi(F_1+F_2)\widetilde{H} - kF_2 E\}d\phi \longrightarrow H_n,\ \widetilde{H}_n,\ \mathbf{E_n}$$

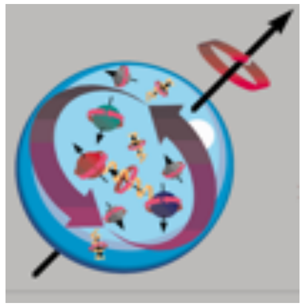
Suppressed because $F_1(t)$ is small

Suppressed because of cancellation between PDF's of u and d quarks

Ji's relation: $$J^q = \frac{1}{2} - J^g = \frac{1}{2}\int_{-1}^{1} x\,dx\,\left\{H^q(x,\xi,0) + E^q(x,\xi,0)\right\}$$

$$J_N = \frac{1}{2} = \frac{1}{2}\Sigma_q + L_q + J_g$$

Important missing link in the nucleon spin puzzle!



Eg1-dvcs experiment

Data taken: Feb – Sept 2009

Beam: polarised electrons

E_e = 4.7 to 6 GeV

polarisation ~ 85%

Longitudinally polarised targets:

NH3 (95 days)

ND3 (33 days)

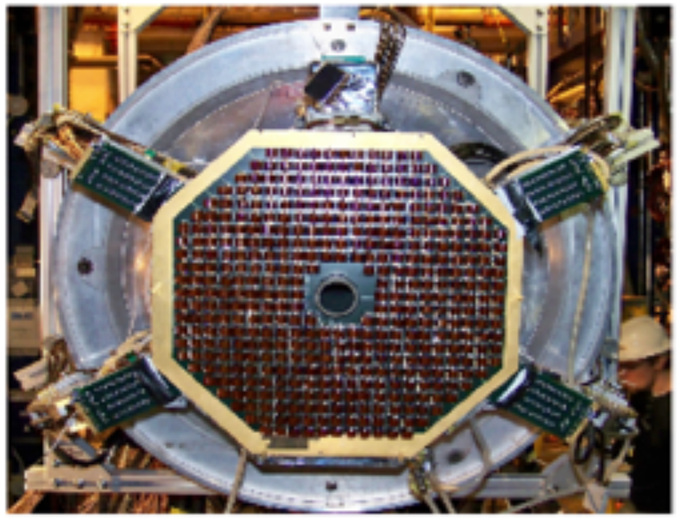
Proton / neutron pol. ~ 80 / 30 %

$$\vec{e} + \vec{d} \rightarrow e' + \gamma + n + (p_s)$$

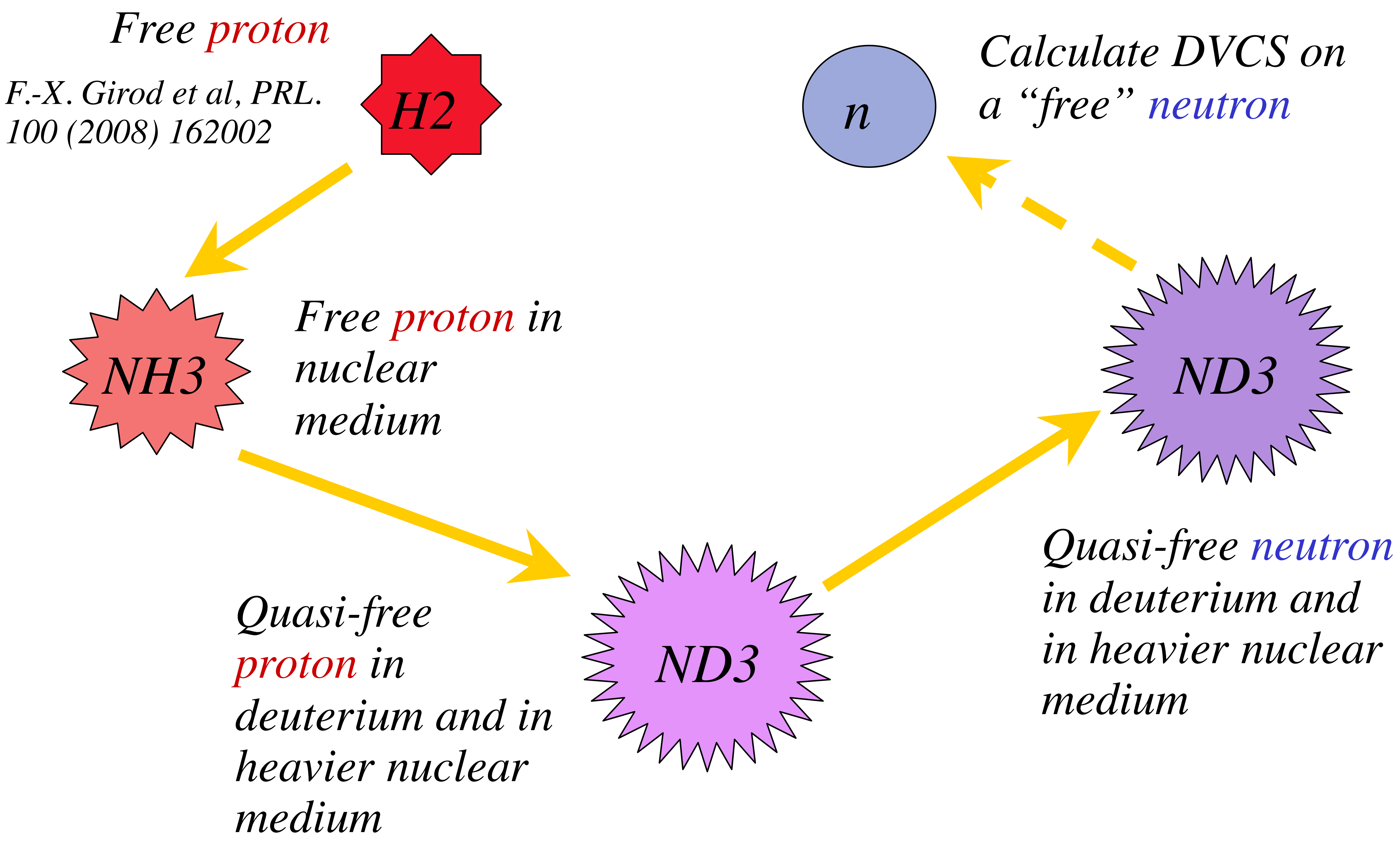
CLAS → Exclusive reconstruction of e', N, and γ. Spectator proton identified via missing mass.

plus

Inner Calorimeter (IC) → high-energy forward photon detection



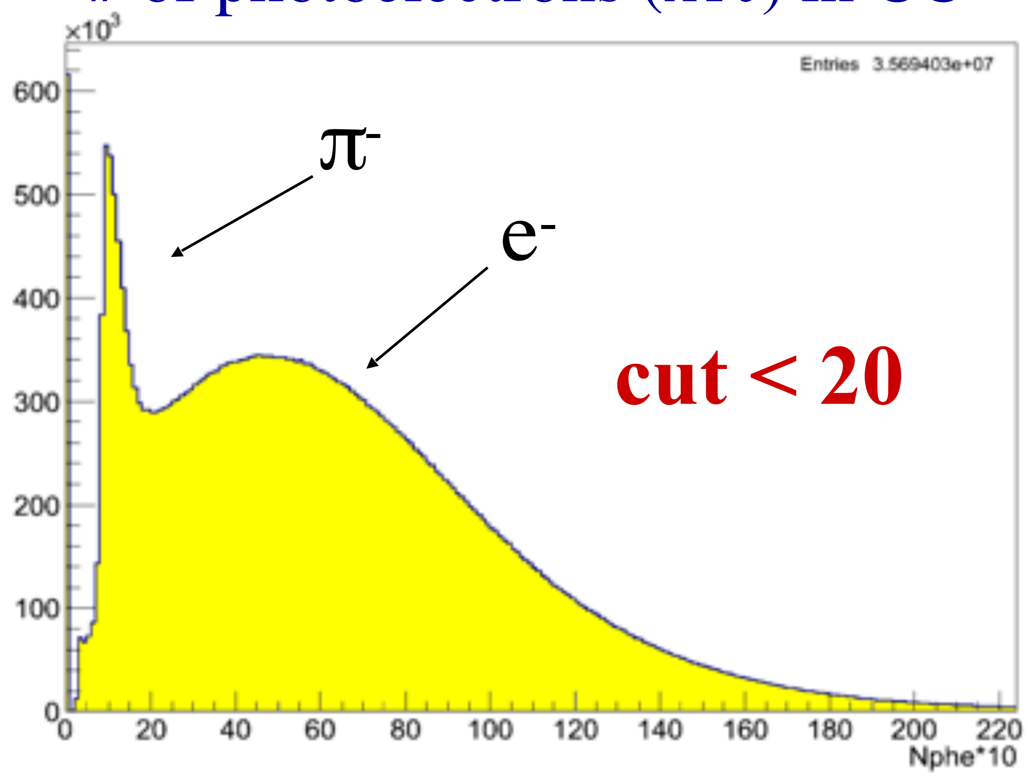
DVCS on different targets



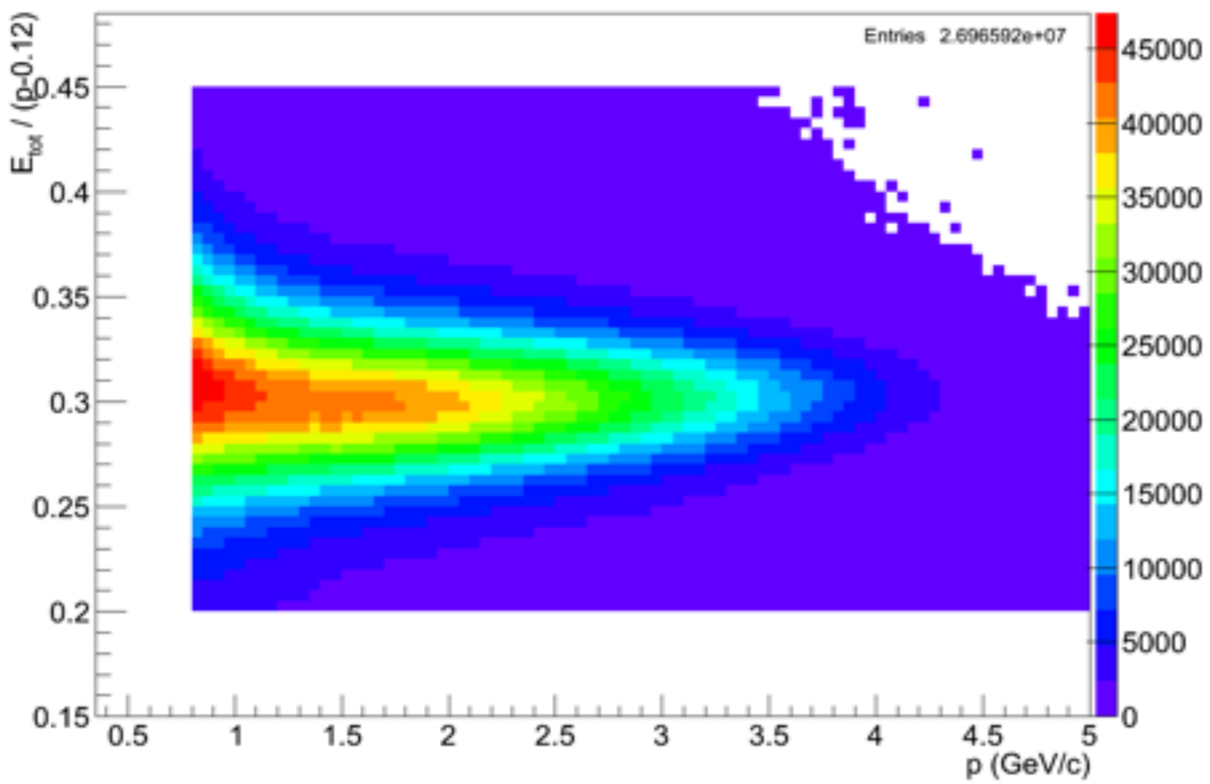
Particle ID – Electrons

- q and p from track-curvature through drift chambers in magnetic field.
- Separation from π^-: on basis of energy deposit in electromagnetic calorimeter (EC) and number of photoelectrons produced in Cerenkov counters (CC).

# of photoelectrons (x10) in CC



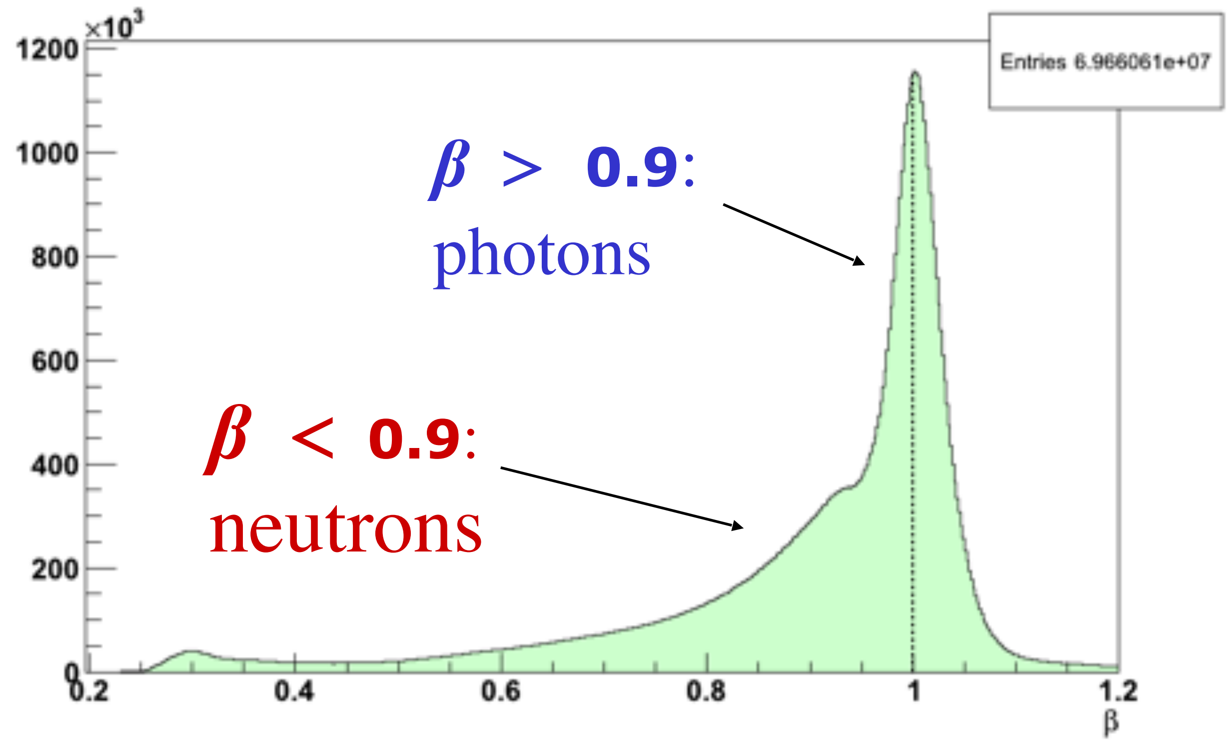
E deposit in EC / *p* vs. *p*



cut p < 0.8 GeV/c **cut E(in) < 60 MeV**

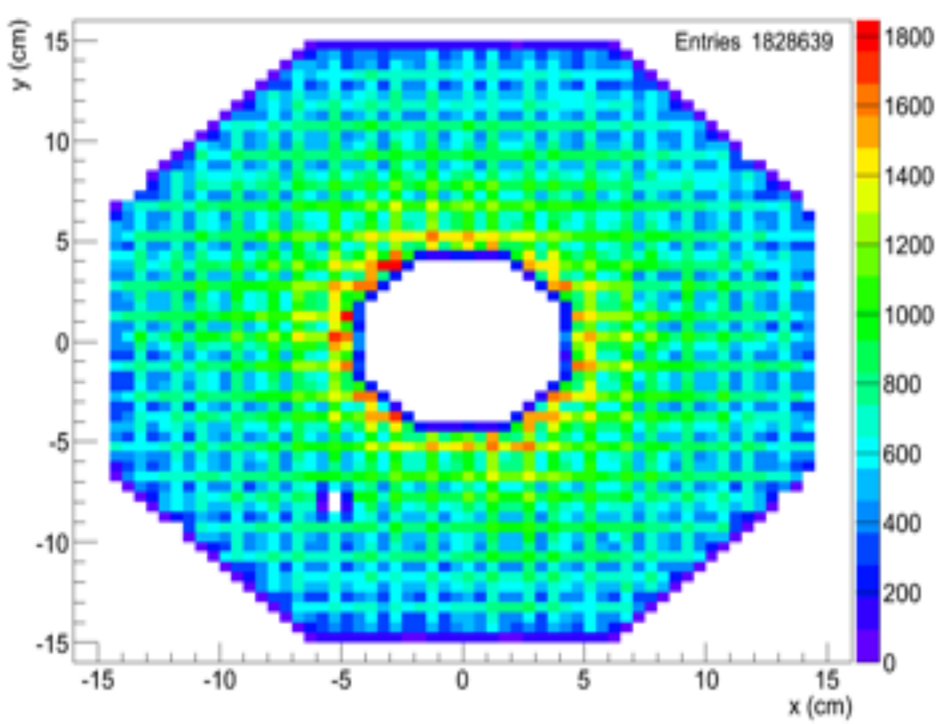
Particle ID – Photons and Neutrons

- β from neutral particles' time of flight to EC



- Forward, low-angle photons in additional Inner Calorimeter

Hits in IC with E deposit > 1 GeV



- **Photons:** E deposited in calorimeters.

IC: cut E < 0.3 GeV

cut low energy IC hits at < 6°

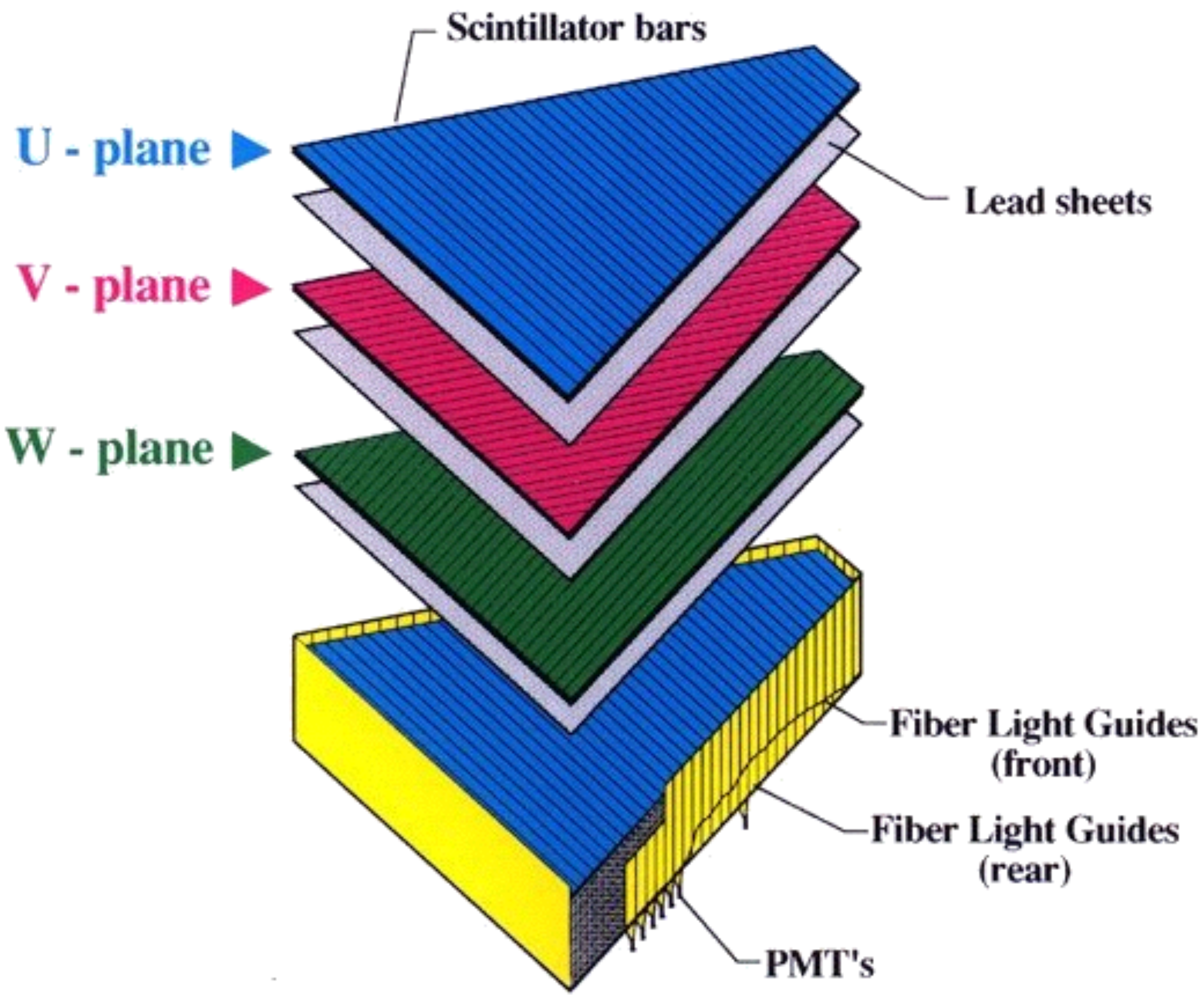
- **Neutrons** — in principle, could reconstruct thus:

$$p_n = \frac{\beta m_n}{\sqrt{1-\beta^2}}$$

$$E_n = \sqrt{m_n^2 + p_n^2}$$

But that's not ideal…

A closer look at the EC

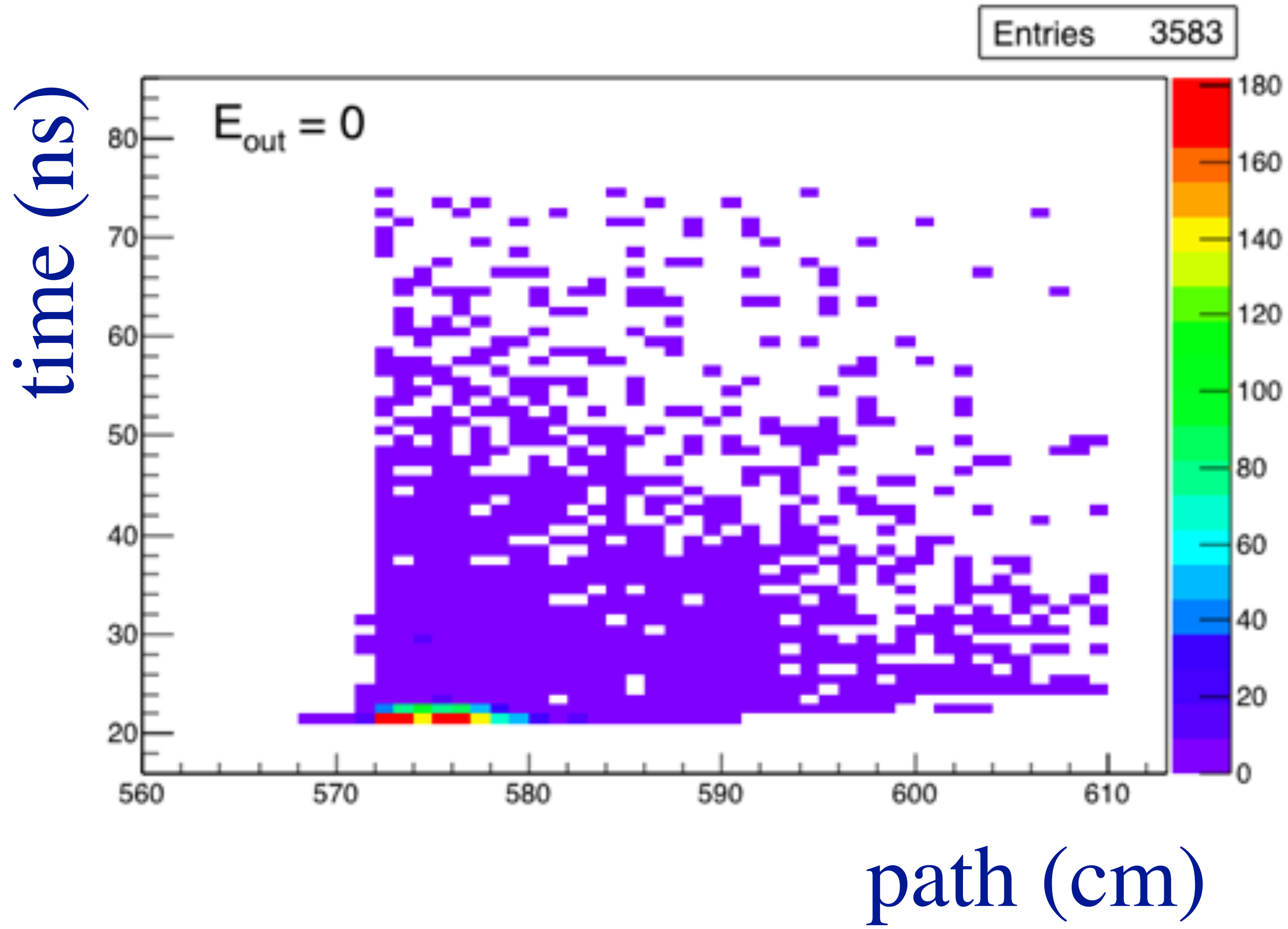


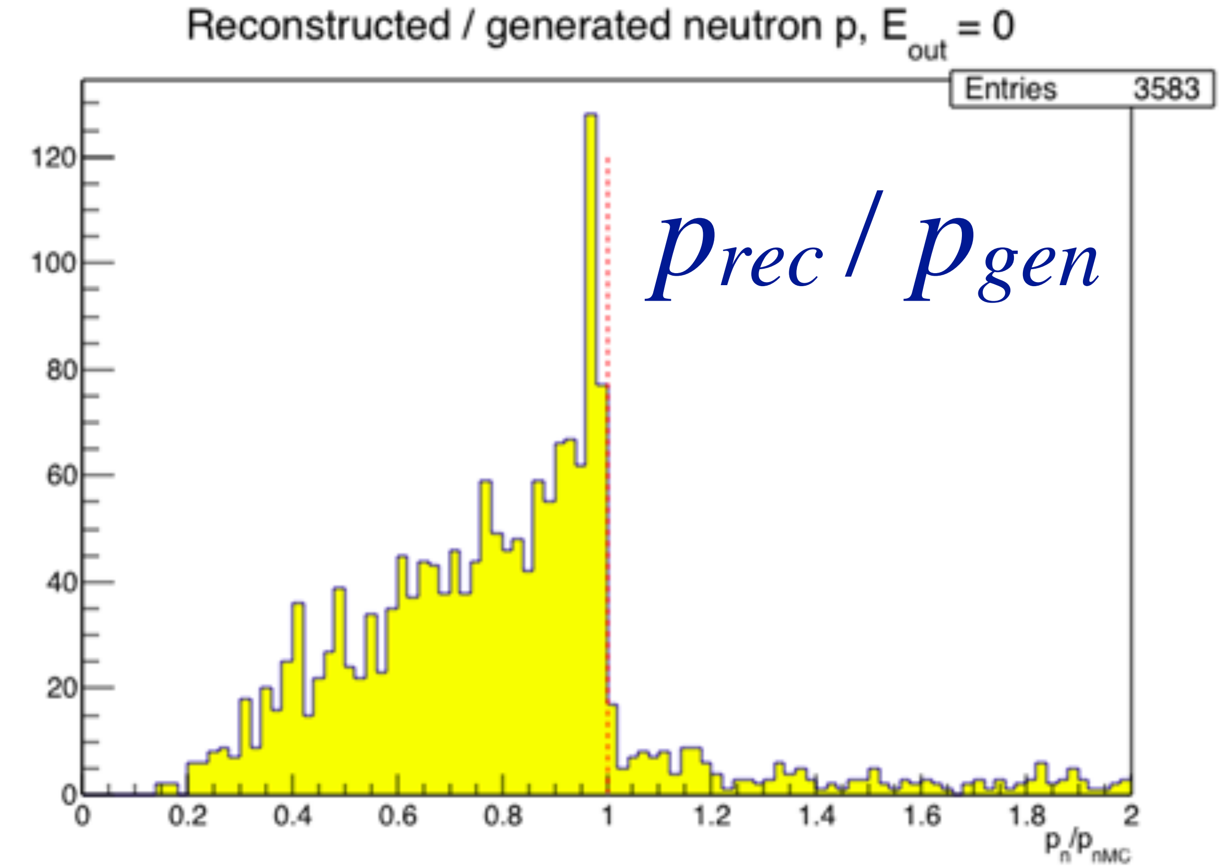
- Divided into two groups of scintillator/lead layers:

Inner and outer.

Inner EC (simulation)

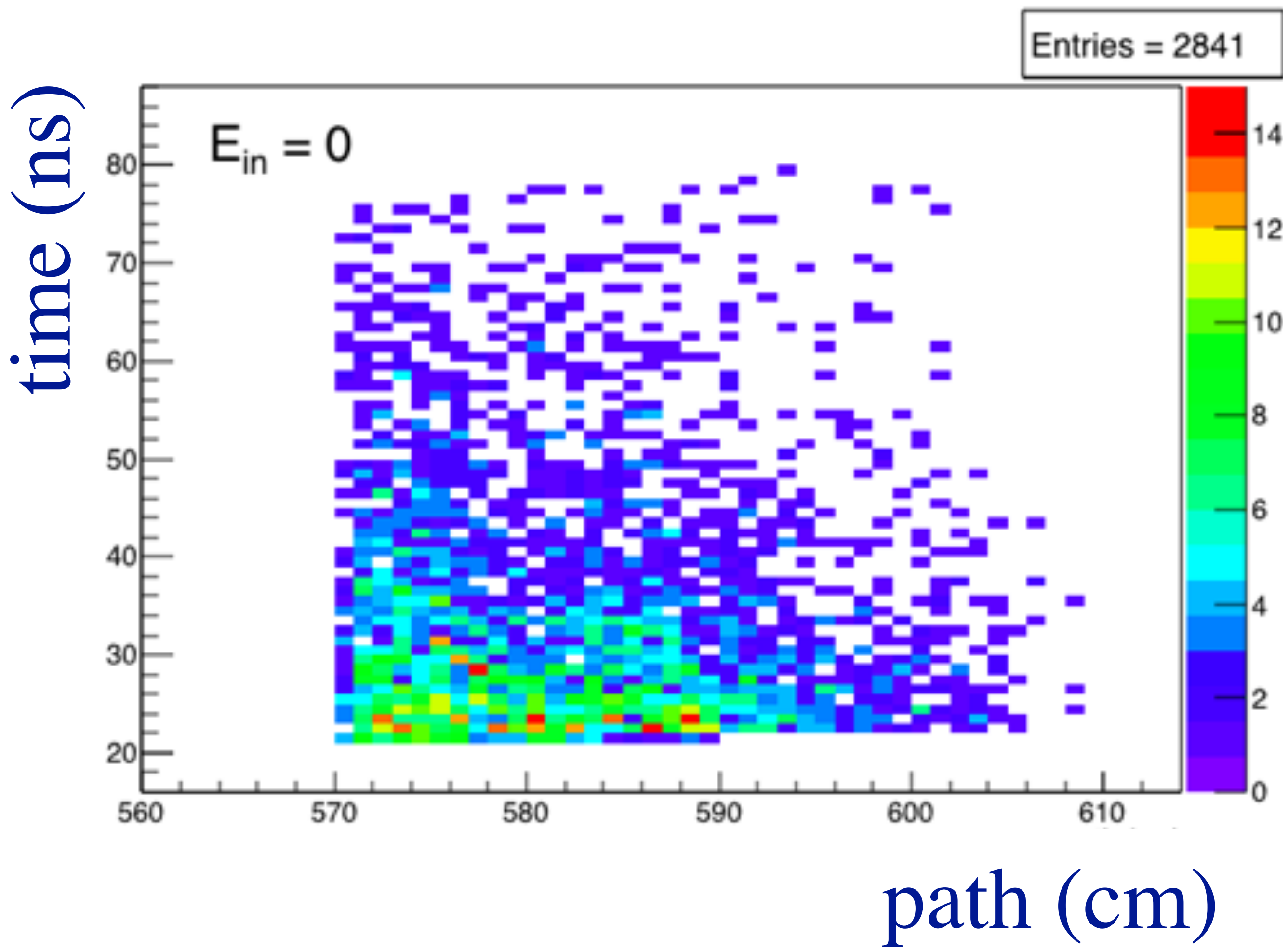
- For ~45% of neutron candidates, there is no energy deposit in outer EC.
- Neutron momentum incorrectly reconstructed:

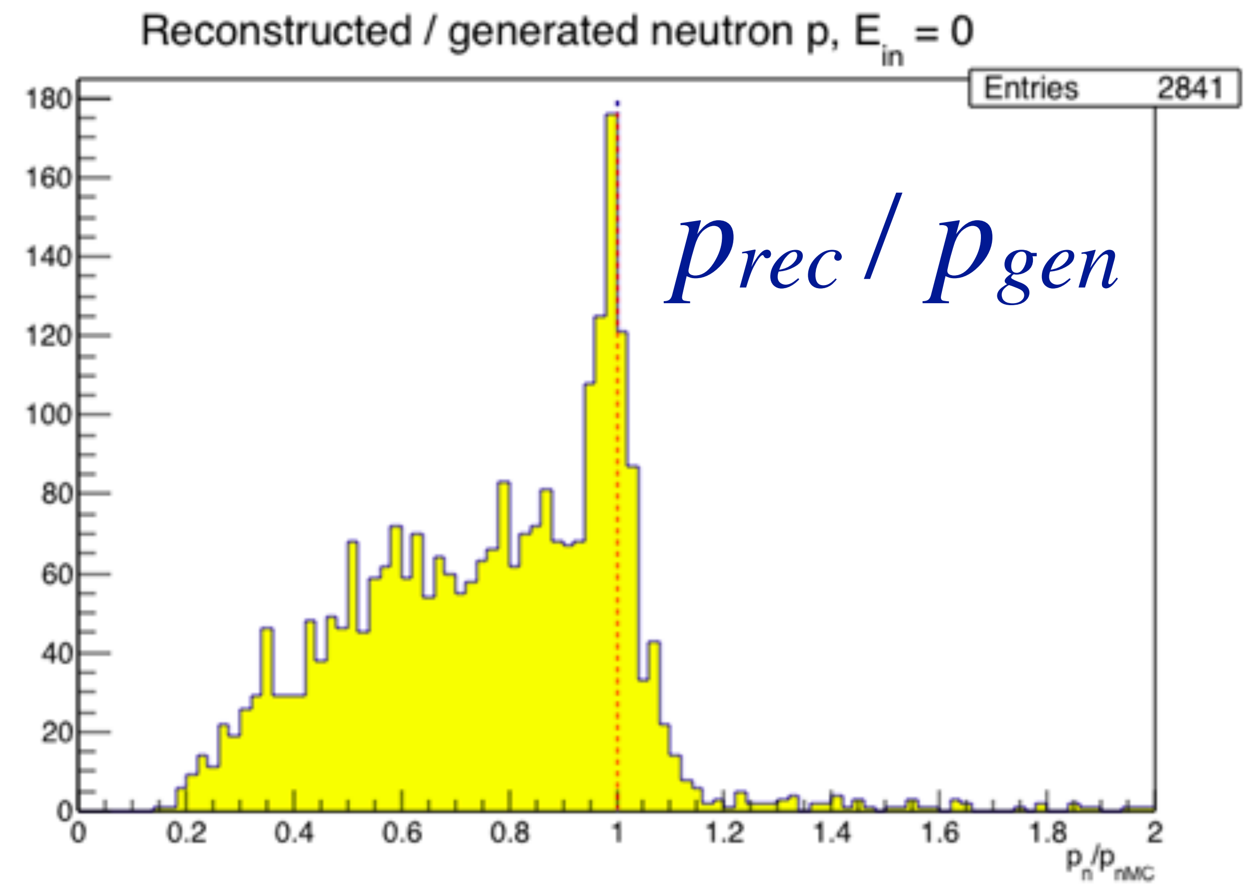




Outer EC (simulation)

- For ~35% of neutron candidates, there is no energy deposit in inner EC.
- Neutron momentum incorrectly reconstructed:



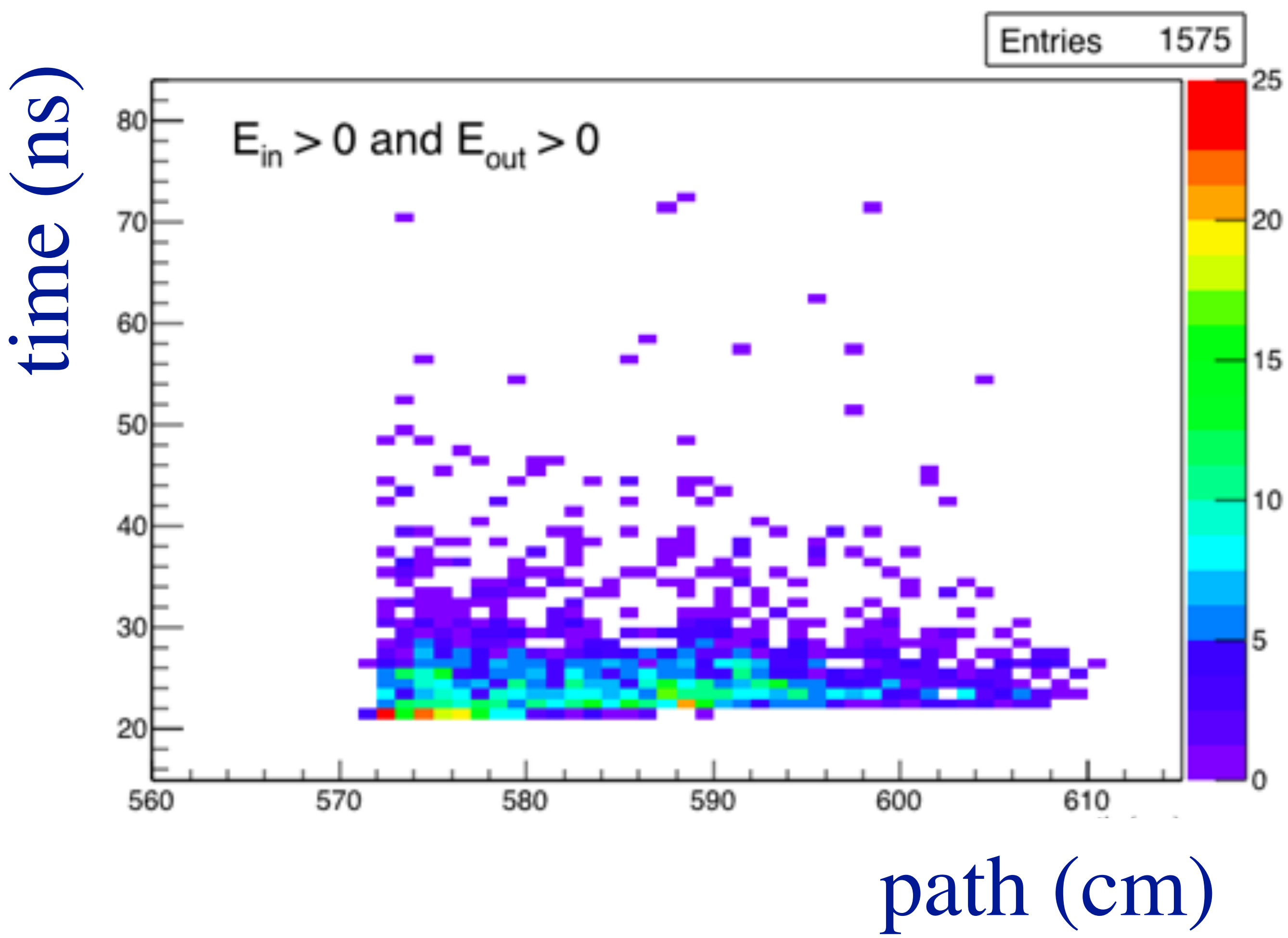


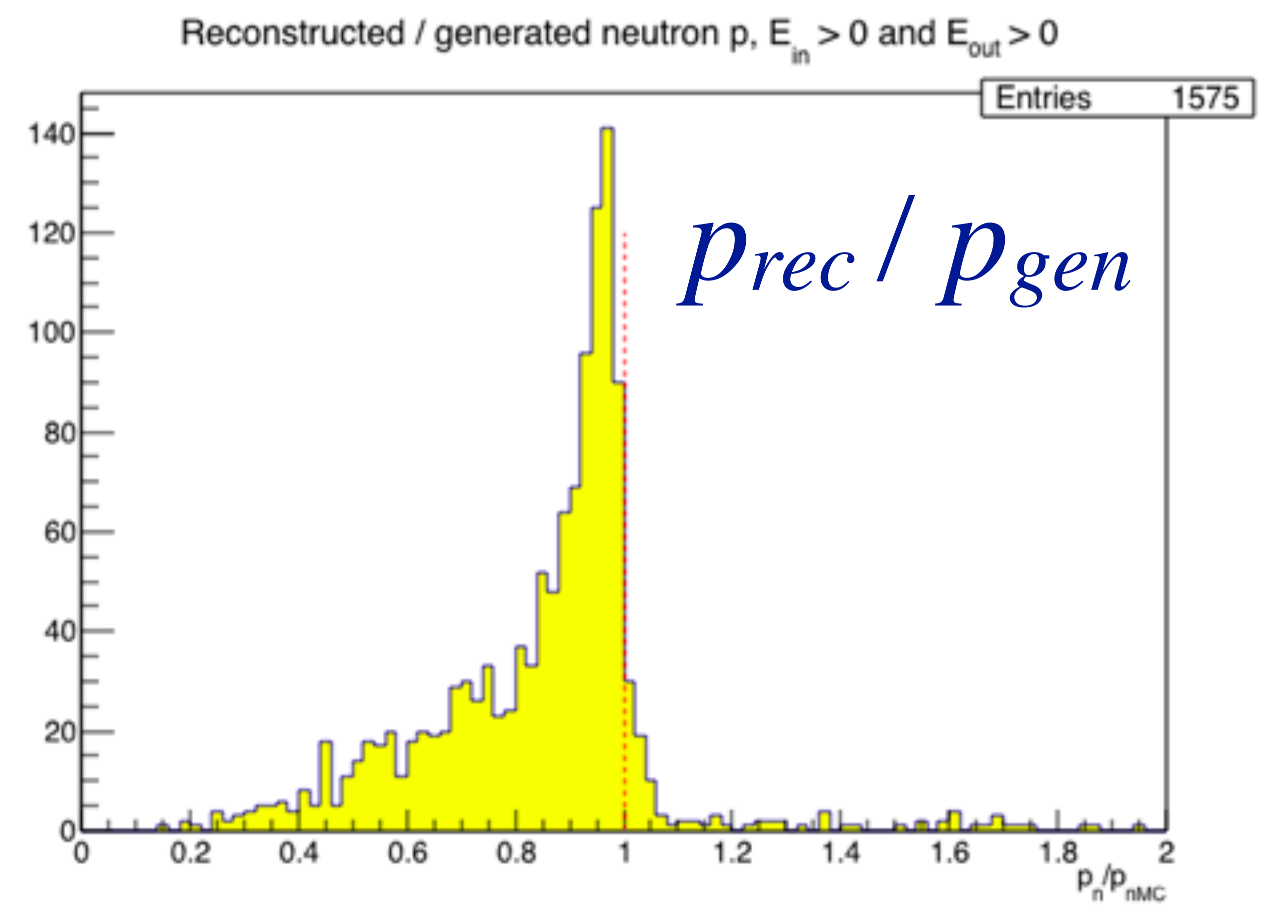
In the case where E(in) = 0, path length needed a -20 cm adjustment (applied for the plots above).

Full EC (simulation)

- For ~20% of neutron candidates, there is an energy deposit in both stacks of the EC.

- Neutron momentum reconstruction is better but still not perfect:

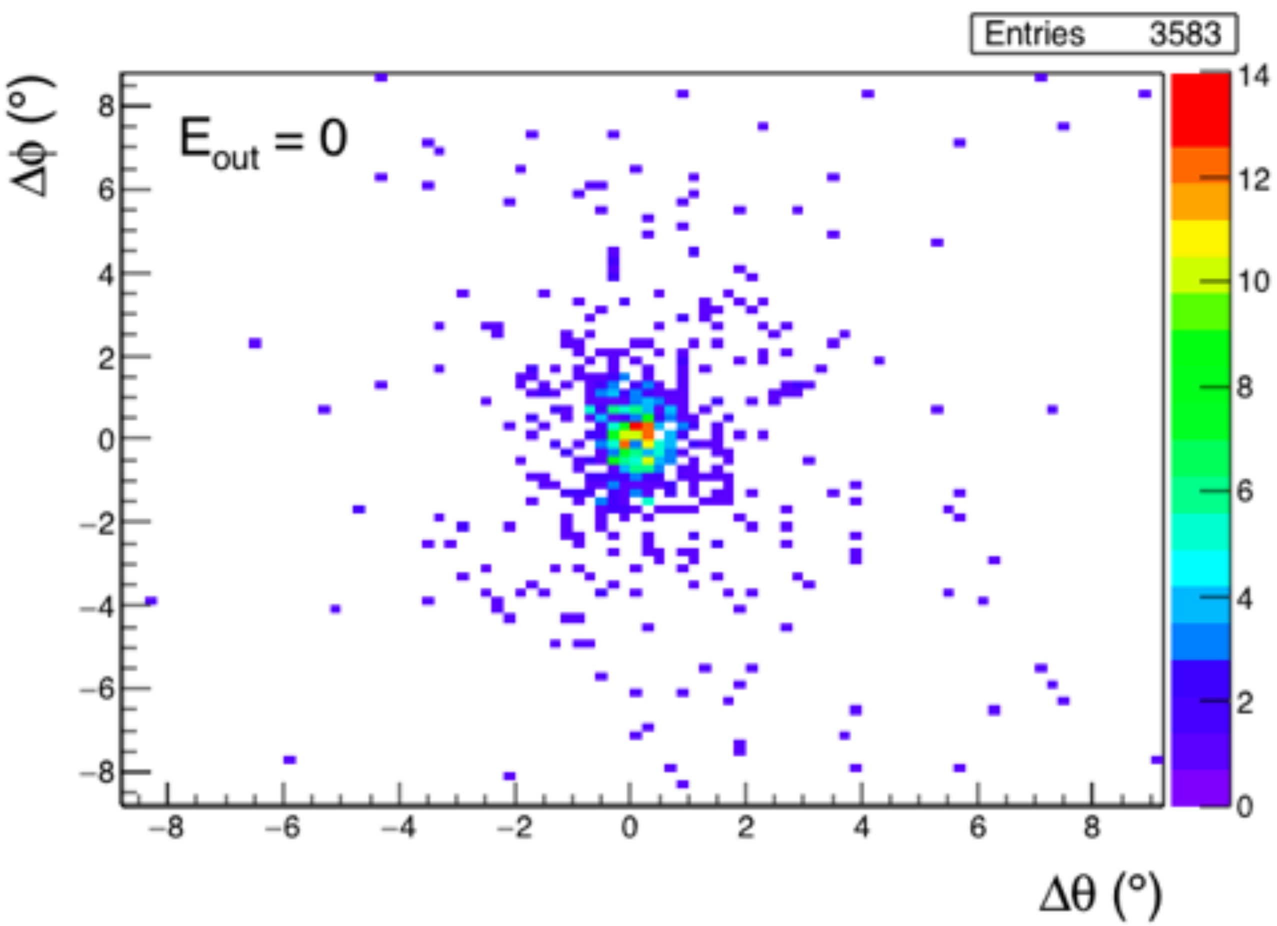


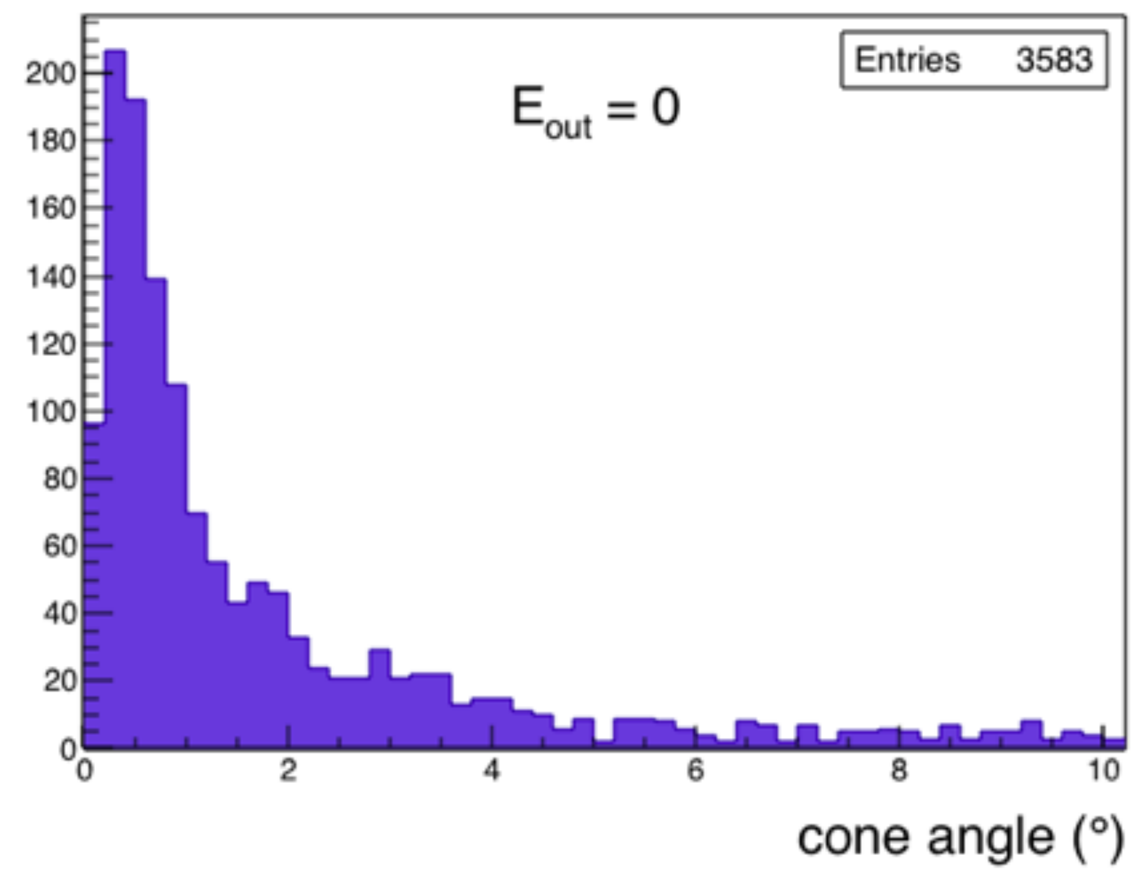


Momentum (and therefore beta) is over-estimated only for a very small fraction of events.

Neutron hit position: inner EC

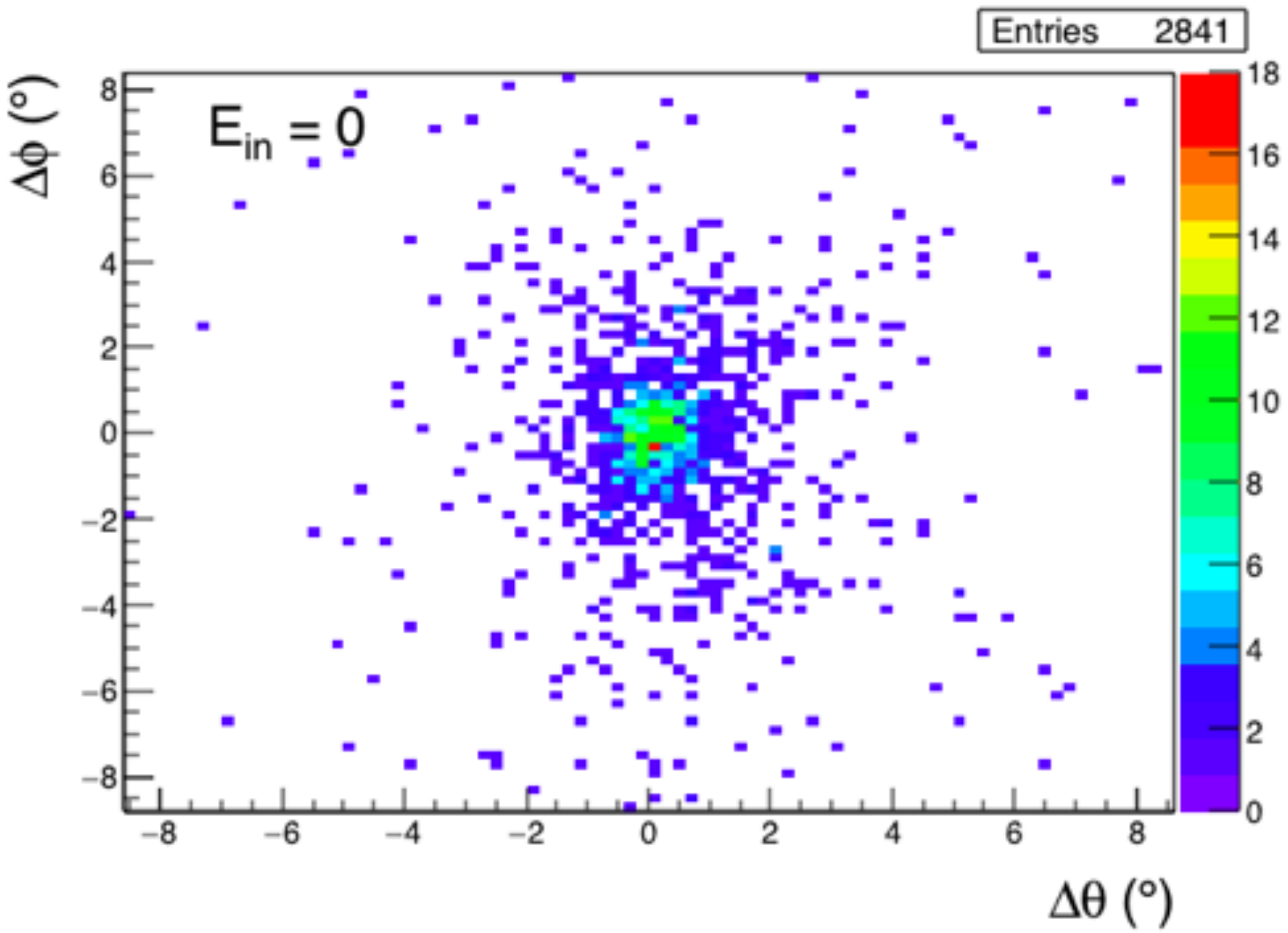
- Compare reconstructed neutron trajectory with generated:

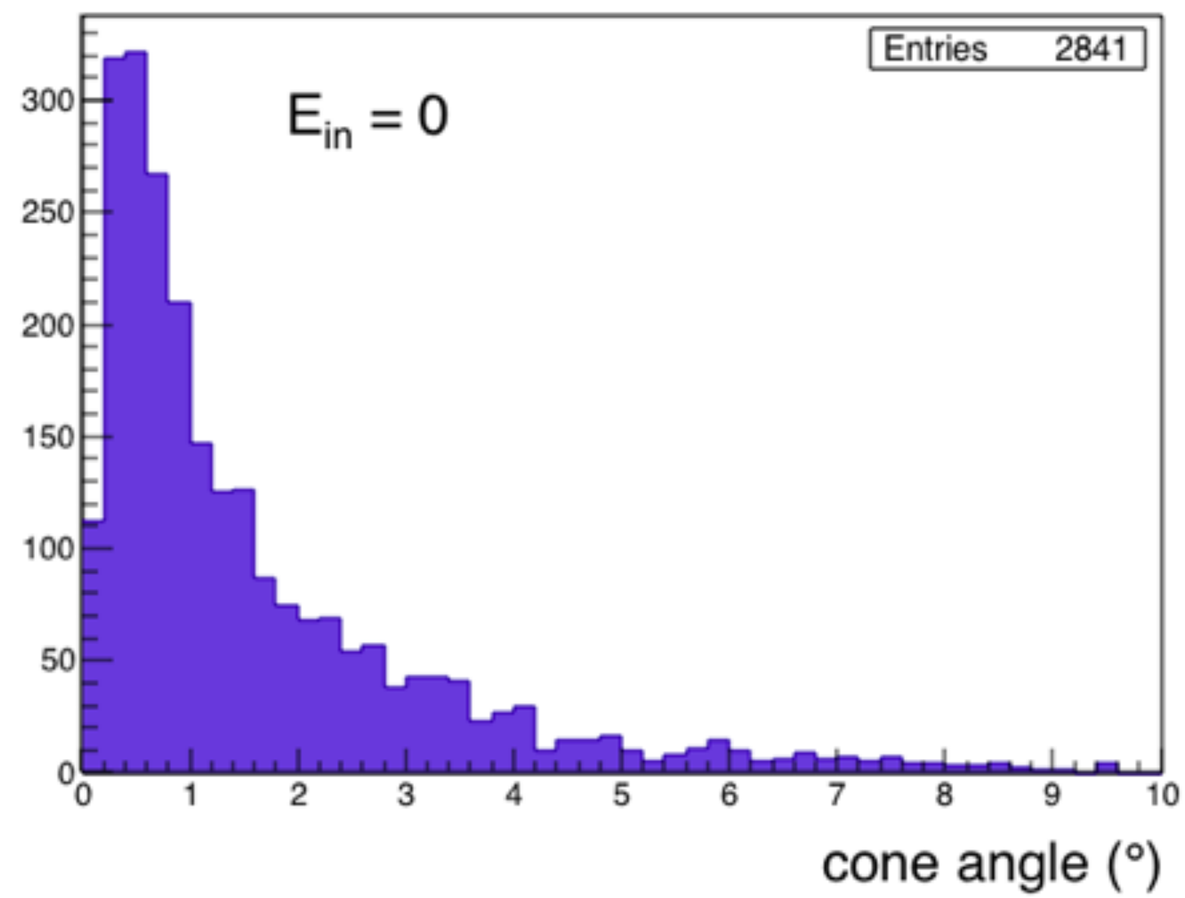




Neutron hit position: outer EC

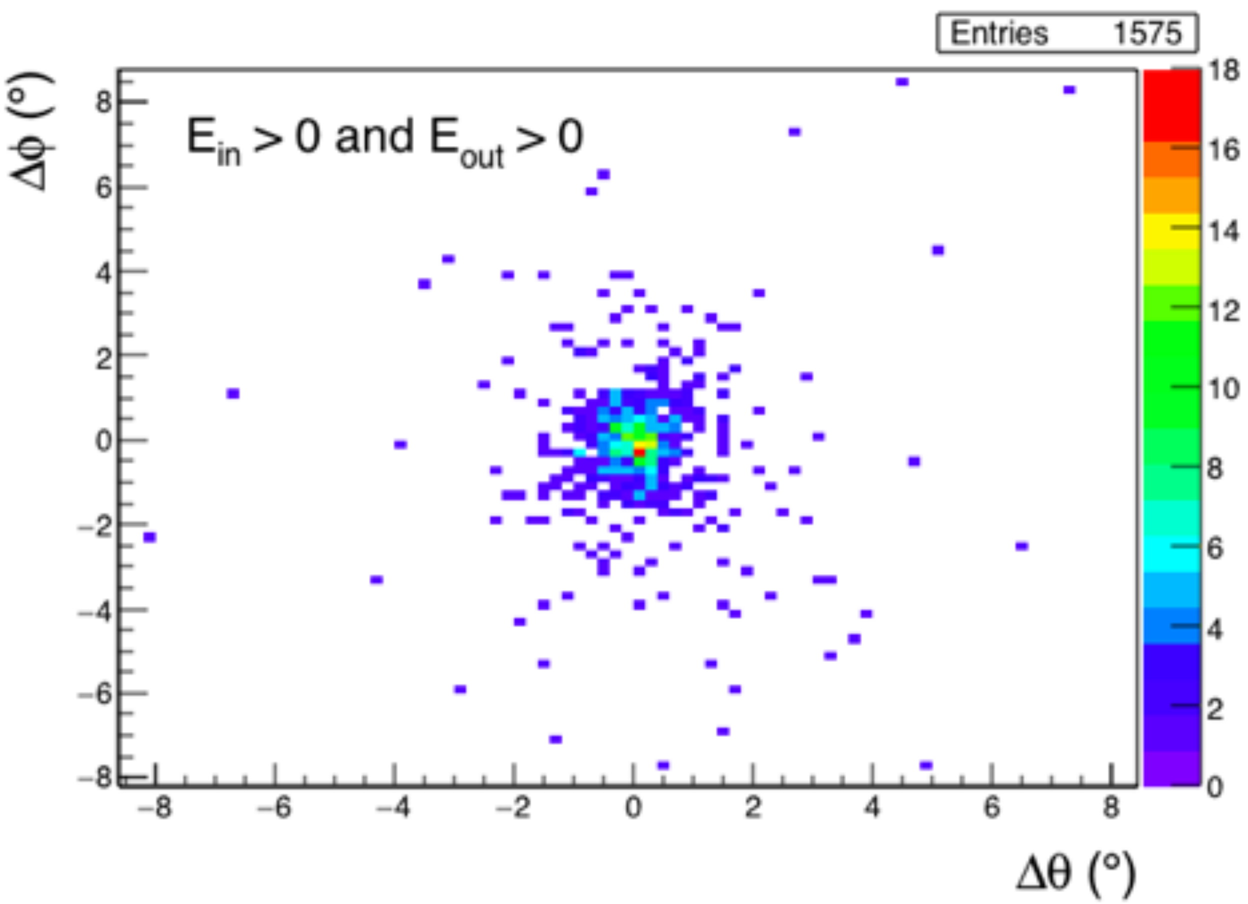
- Compare reconstructed neutron trajectory with generated:

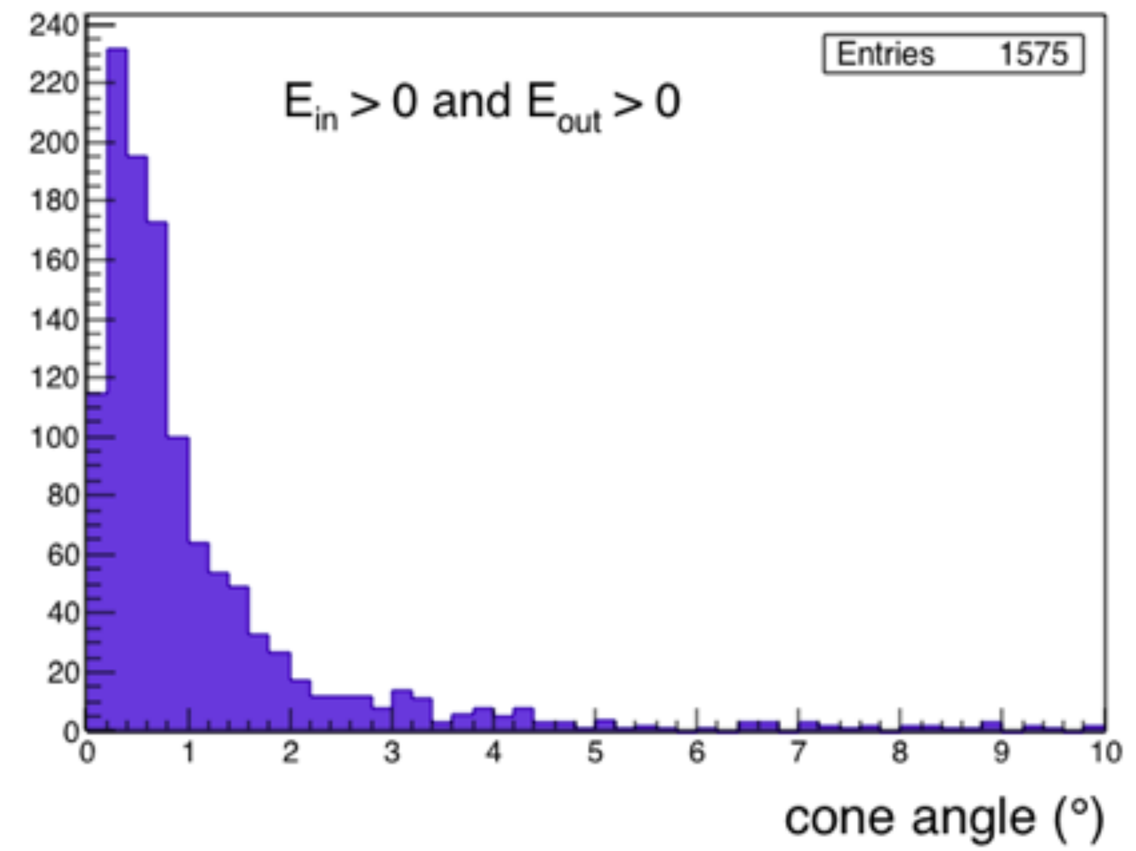




Neutron hit position: full EC

- Compare reconstructed neutron trajectory with generated:

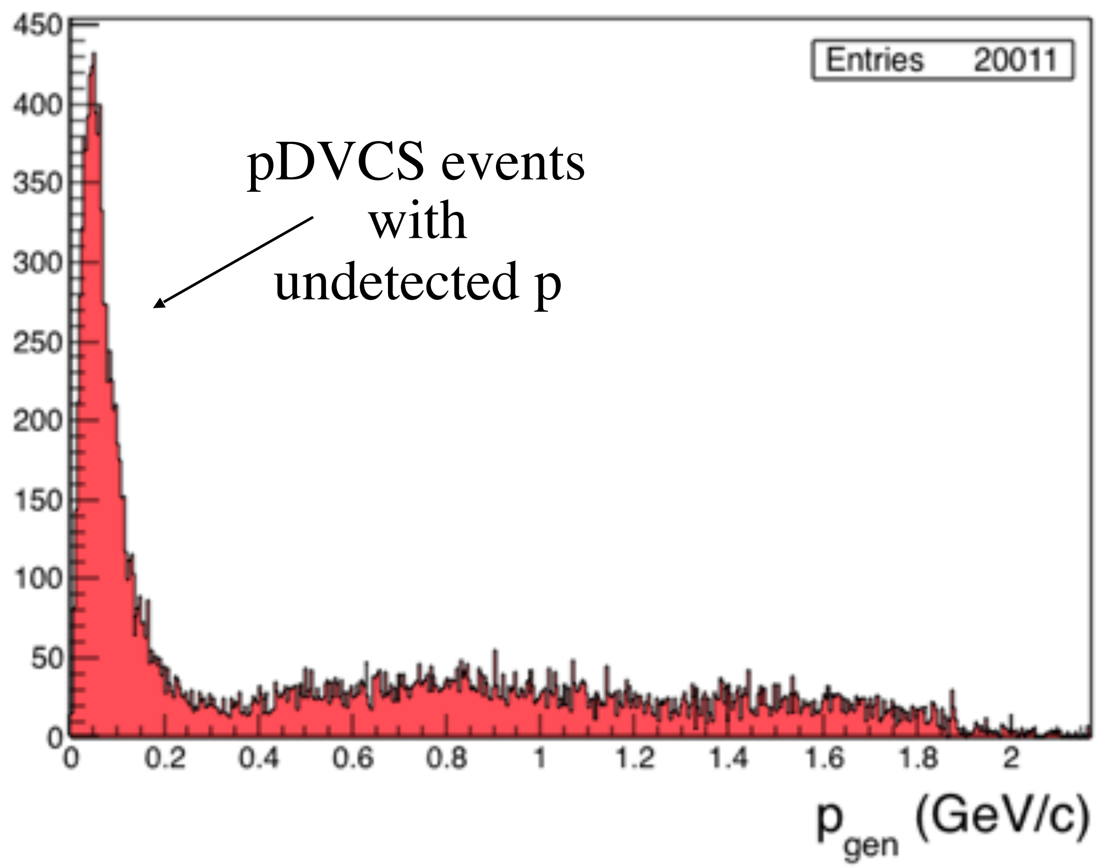




- Direction of the neutron is well reconstructed, wherever in the EC stacks it registers, to ~ 1.5 degrees.

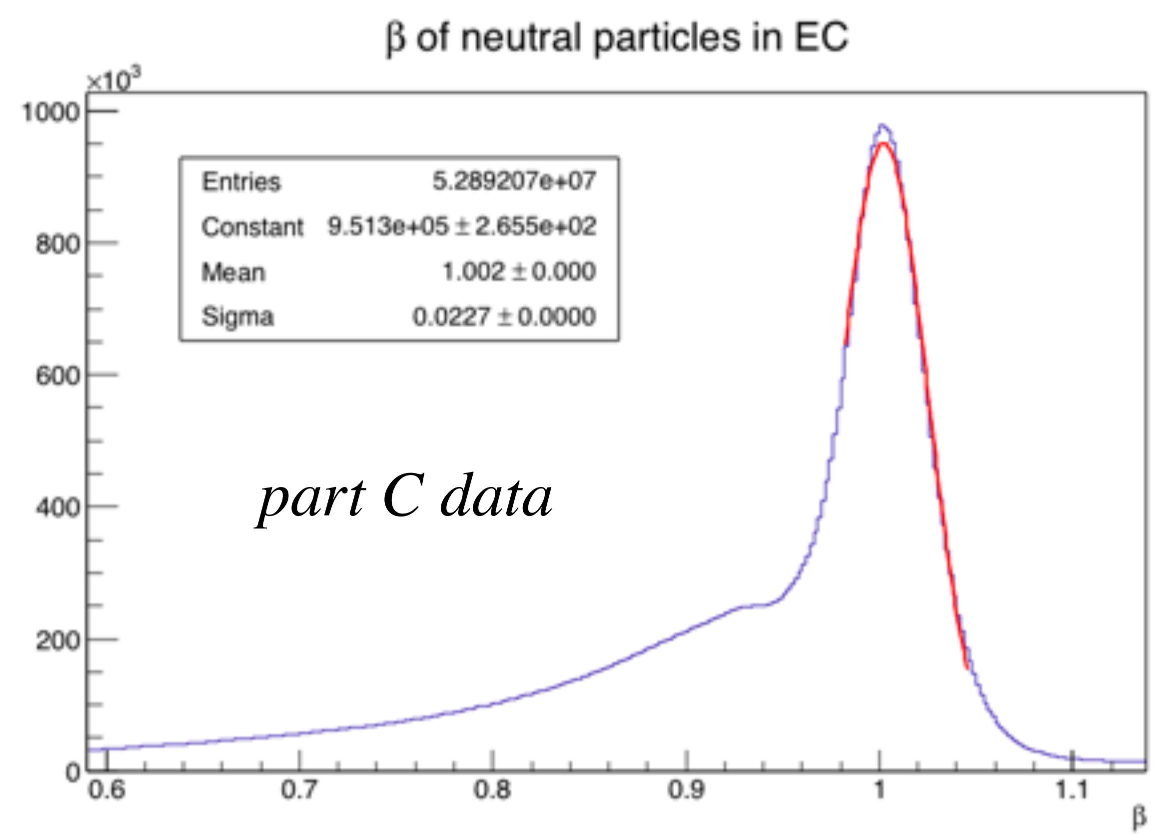
Neutrons: beta cut

- Energy deposit utterly unreliable.
- Beta reconstructs correctly only in a fraction of cases (though it's reliable for photons!).
- Direction of neutron has the highest resolution (on the order of a degree).



Generated MC neutron momentum distribution (*before full neutron selection cuts*)

Max neutron momentum of 2 GeV/c corresponds to max beta of 0.9.

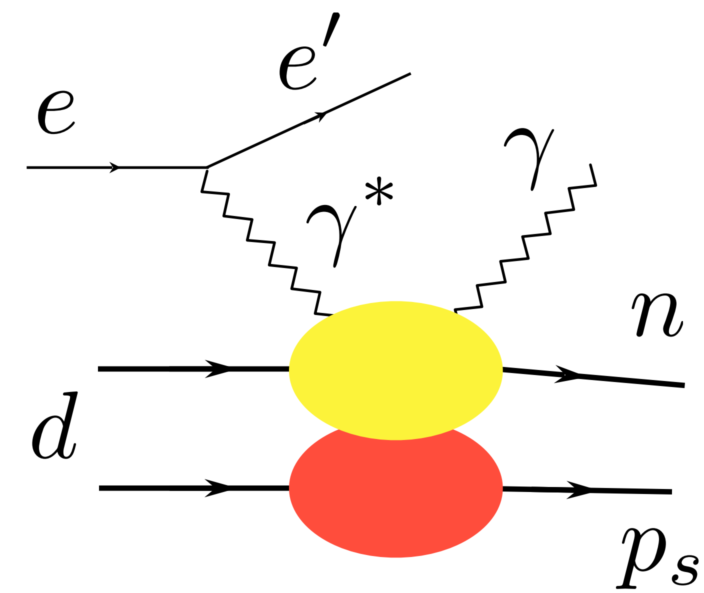


Photon beta peak has sigma ~ 0.023. Cut at 0.9 is well outside of this.

Neutron momentum

- Apply kinematics and conservation laws:

$$\gamma^* + d \to n + \gamma + p_s$$



Energy and momentum conservation:

$$q + d = n + \gamma + p_s$$

where: $d = [m_d, 0, 0, 0]$

$$q = e - e' = [\nu, q_x, q_y, q_z]$$

$$\gamma = [p_\gamma, p_{x\gamma}, p_{y\gamma}, p_{z\gamma}]$$

$$n = [E_n, p_{xn}, p_{yn}, p_{zn}]$$

$$p_s = [E_s, p_{xs}, p_{ys}, p_{zs}]$$

Neutron direction cosines are known:

$$p_{xn} = p_n sin\theta_n cos\phi_n$$

$$p_{yn} = p_n sin\theta_n sin\phi_n$$

$$p_{zn} = p_n cos\theta_n$$

$$E_n = (m_n^2 + p_n^2)^{1/2}$$

Applying Taylor approximation:

$$E_s = (m_s^2 + p_s^2)^{1/2} \approx m_s(1 + \frac{p_s^2}{2m_s^2})$$

Four unknowns (p_{xs}, p_{ys}, p_{zs}, p_n), four equations (for each term in the four-momenta): can be solved!

Neutron momentum

Solving the equations, one can arrive at the expression for the kinetic energy, T_n, of the neutron:

$$T_n = \frac{-(bc - 2a^2 m_n) \pm \sqrt{(bc - 2a^2 m_n)^2 - 4(b^2 - a^2)c^2}}{2(b^2 - a^2)}$$

where the "+" solution gives the correct answer and

$$a = (p_{x\gamma} - q_x) sin\theta_n cos\phi_n + (p_{y\gamma} - q_y) sin\theta_n sin\phi_n + (p_{z\gamma} - q_z) cos\theta_n$$

$$b = p_\gamma - \nu - m_d$$

$$c = (p_\gamma + m_n - m_d - \nu)^2 - (m_s^2 + p_\gamma^2 + q^2 - 2q \cdot p_\gamma)$$

Finally, calculate neutron and spectator momenta:

$$p_n = \sqrt{T_n(T_n + 2m_n)}$$

Adapted from **Manuel Dieterle, Masters Thesis, Basel (2009)**

Neutron DVCS in ND_3 – identifying reaction

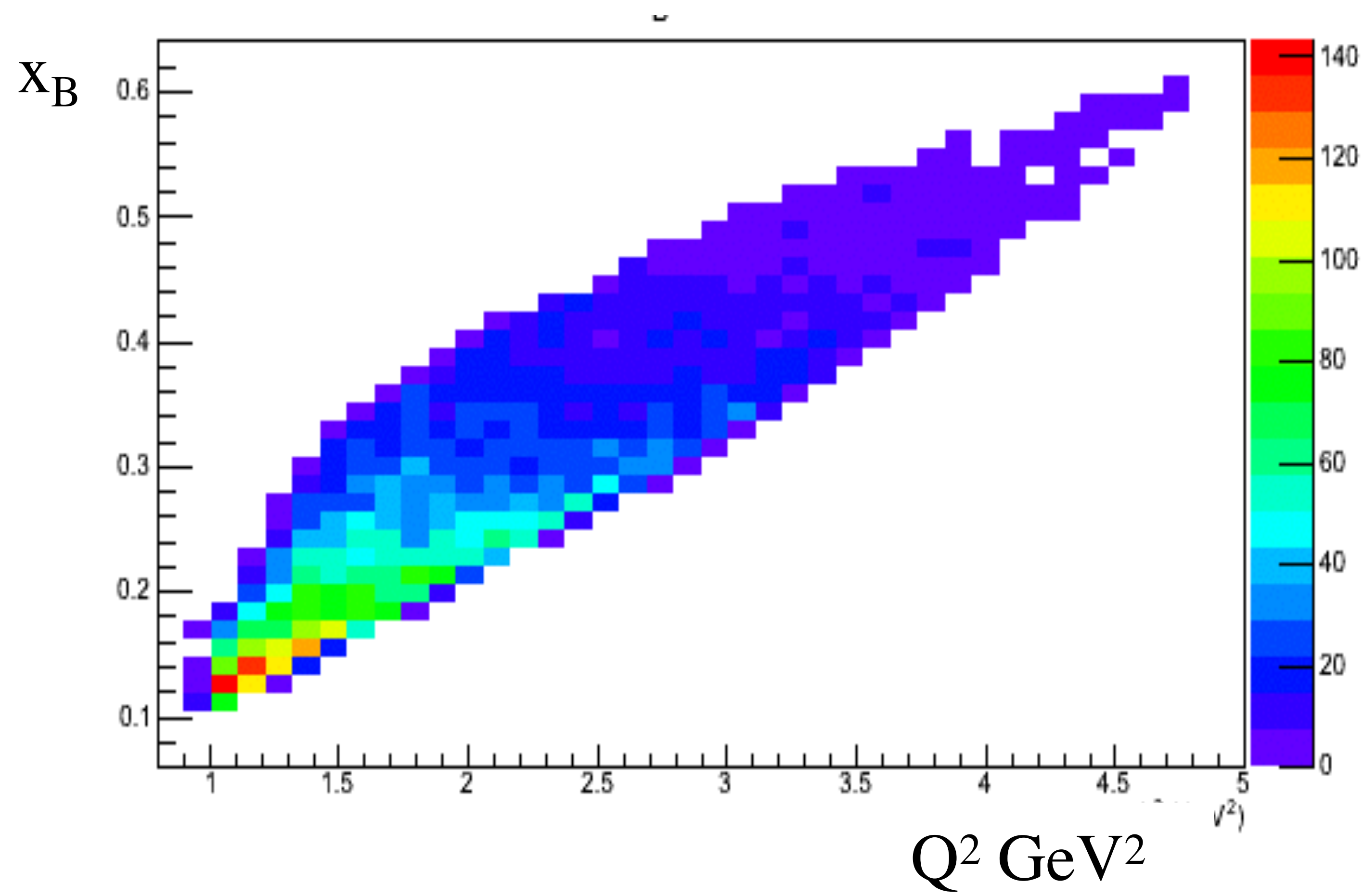
Deep Inelastic Scattering cuts:

- $W > 2$ GeV/c^2 — where W is the missing mass of $(eN \rightarrow e'X)$, isolate resonance region of remaining γN
- $Q^2 > 1$ GeV^2
- $Q^2 > -t$ — Region where factorisation applies

Additional DVCS cuts:

- $E_\gamma > 1$ GeV
- $p_n > 0.4$ GeV/c

Recoiling nucleon should not have a low p



Compare reconstructing neutron momentum from beta and from reaction kinematics.

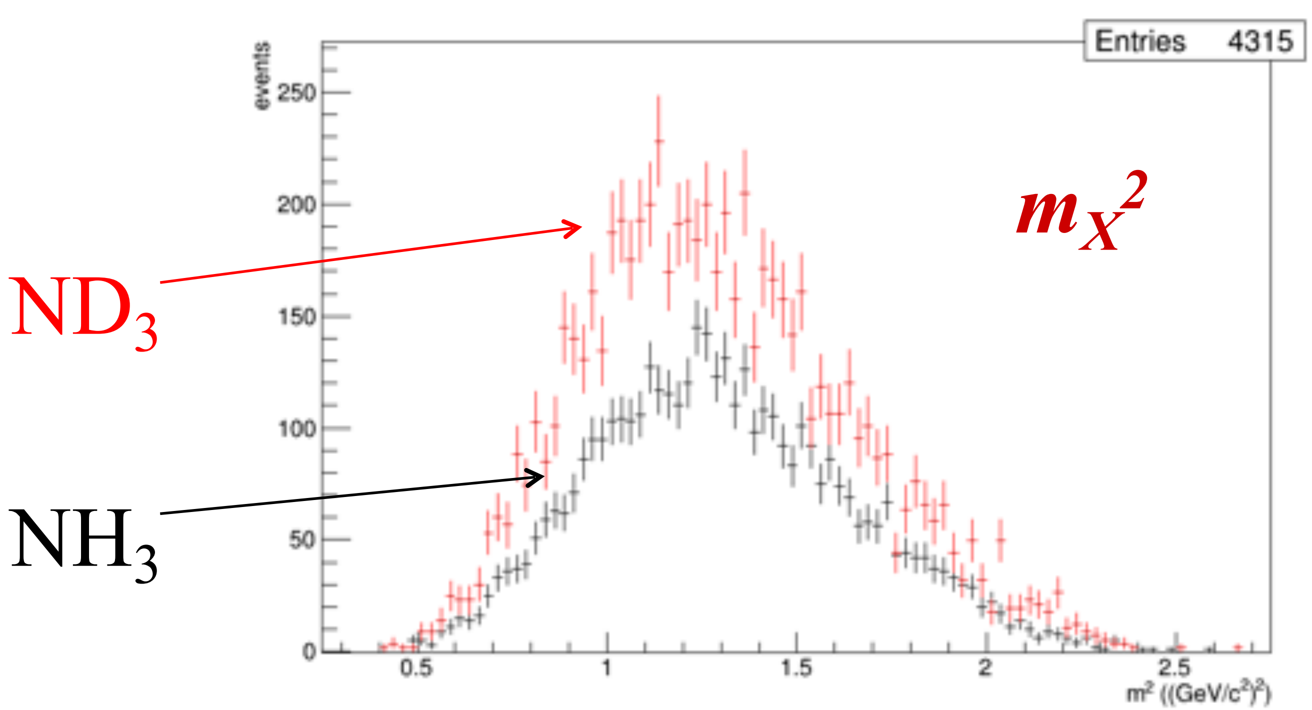
Exclusivity cuts: spectator

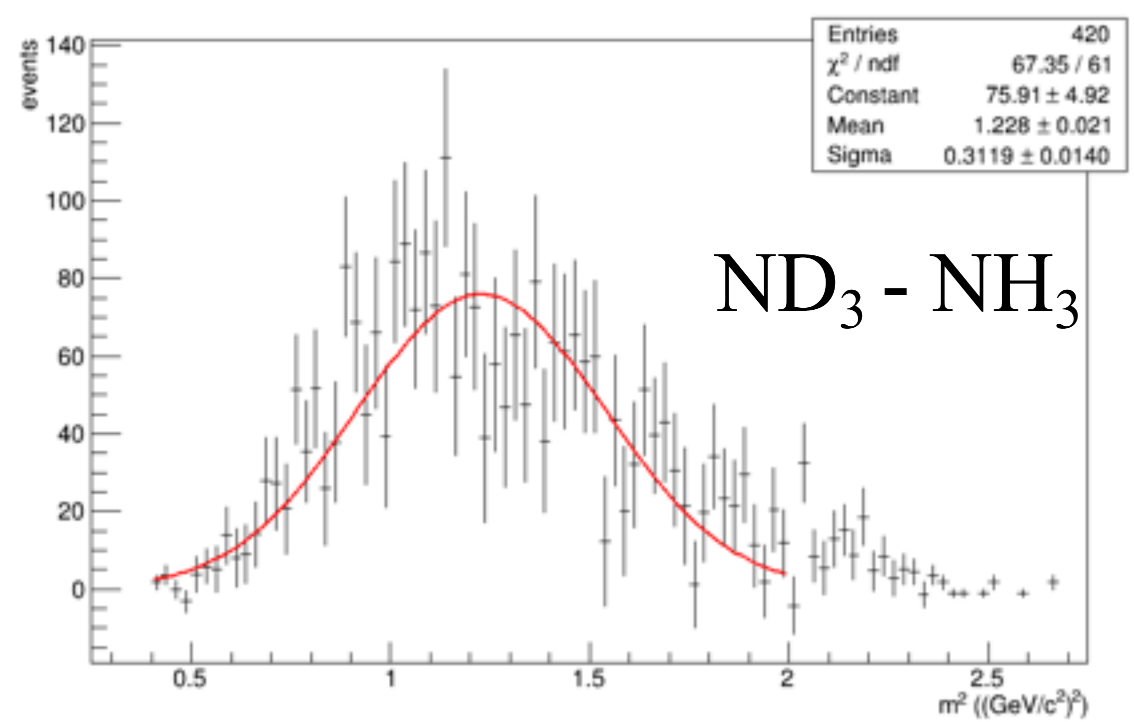
Use NH_3 data to subtract the nuclear background from the ND_3 distributions (normalised by Faraday Cup counts), purely for visibility.

- Missing momentum from $ed \rightarrow e'N'\gamma\ X$ should be low for spectator nucleon in quasi-free reaction: p_X **< 0.2 GeV/c**

If neutron is assigned momentum calculated on the basis of beta:

- Missing mass of spectator from $ed \rightarrow e'N'\gamma\ X$:



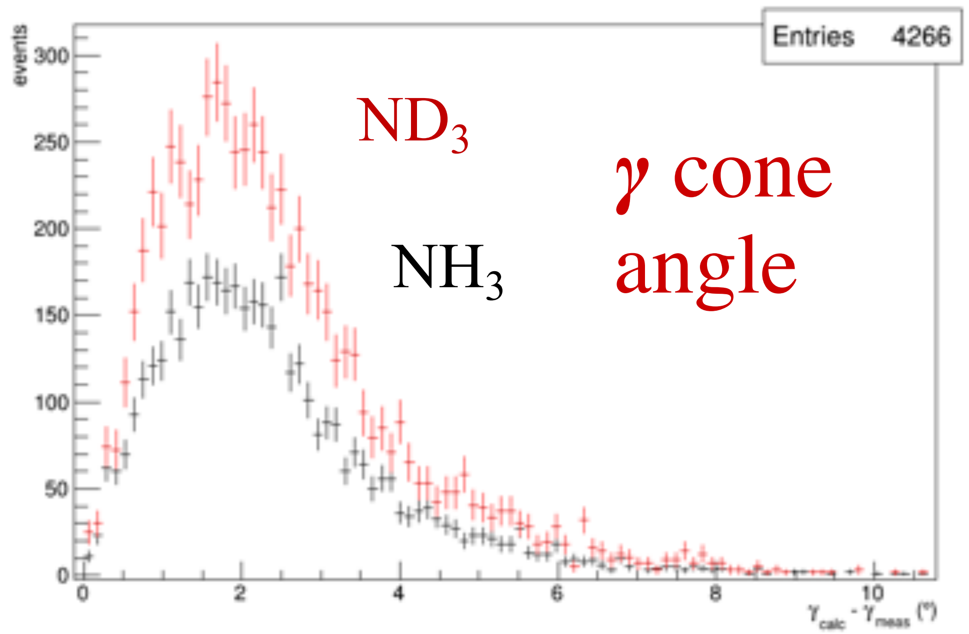


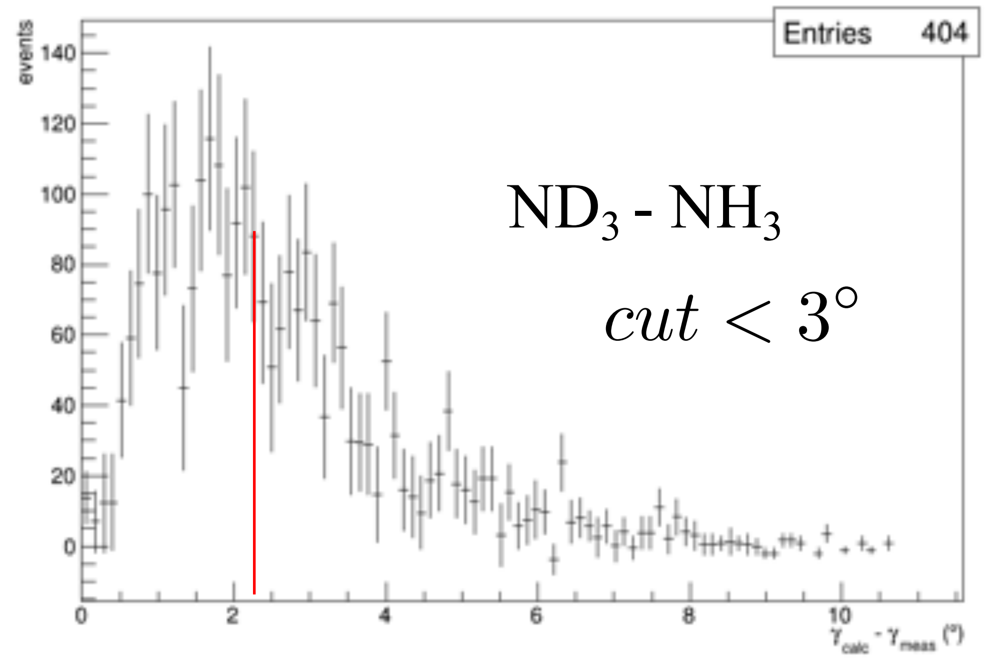
Possible to place a cut: **$0.5 < |m_X^2| < 2$ GeV²/c⁴**

Exclusivity cuts: cone angle

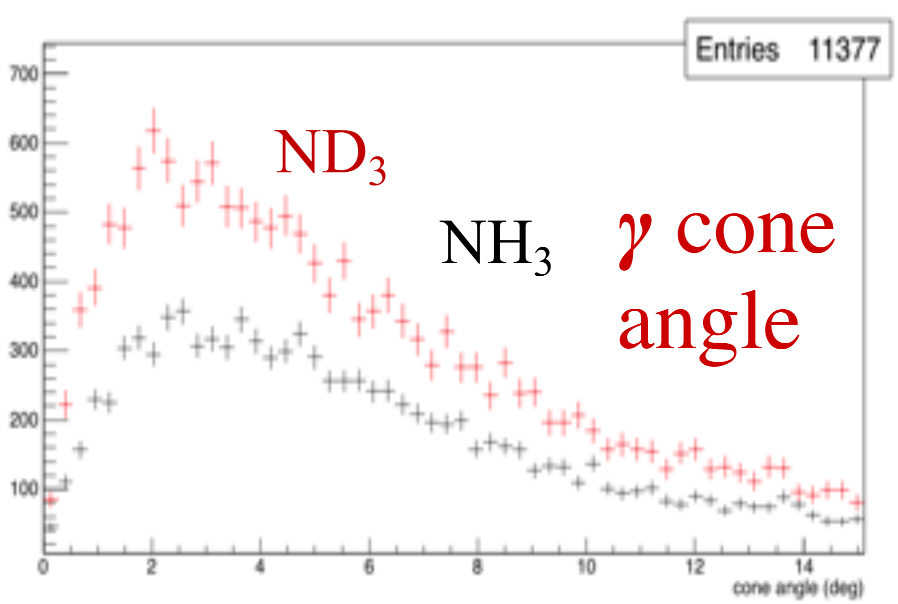
γ cone angle: Difference between calculated and measured γ direction

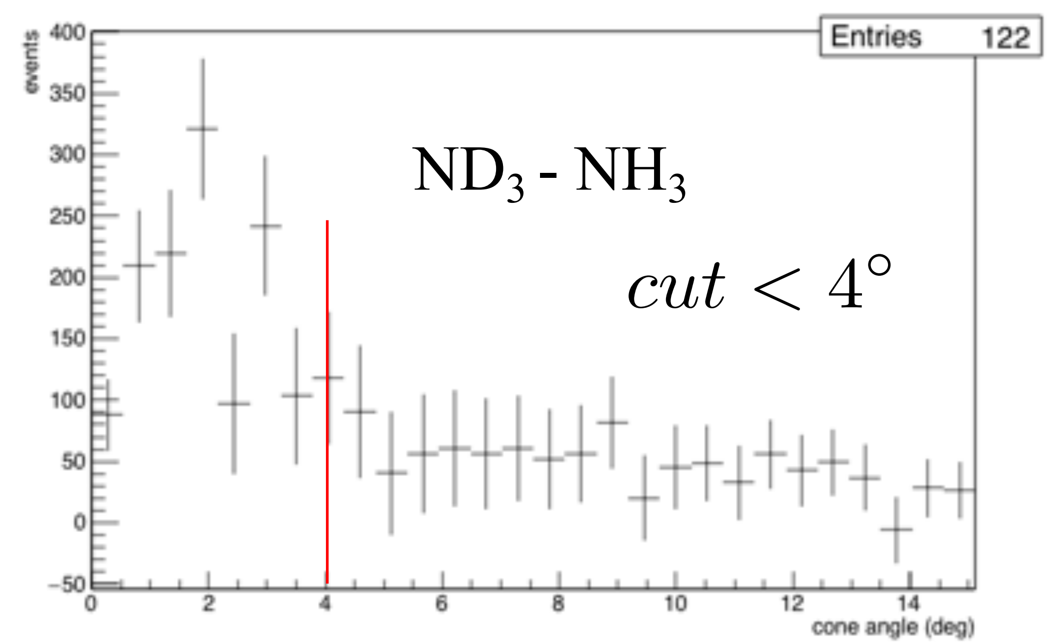
- Neutron momentum calculated from beta:



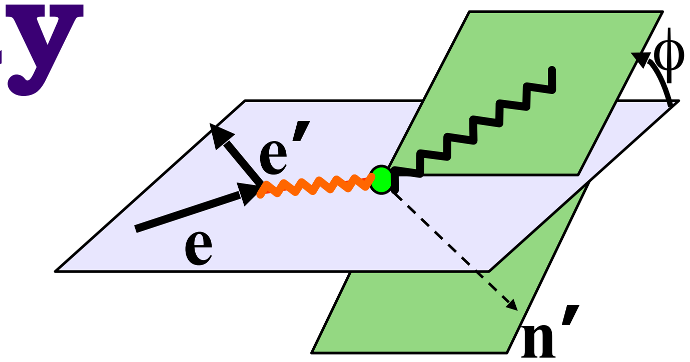


- Neutron momentum calculated from kinematics:



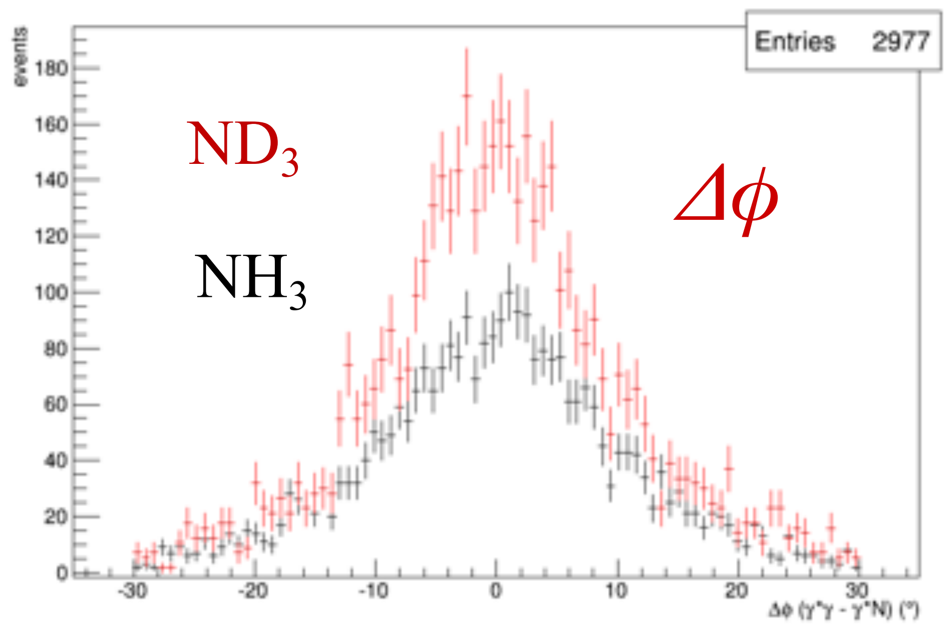


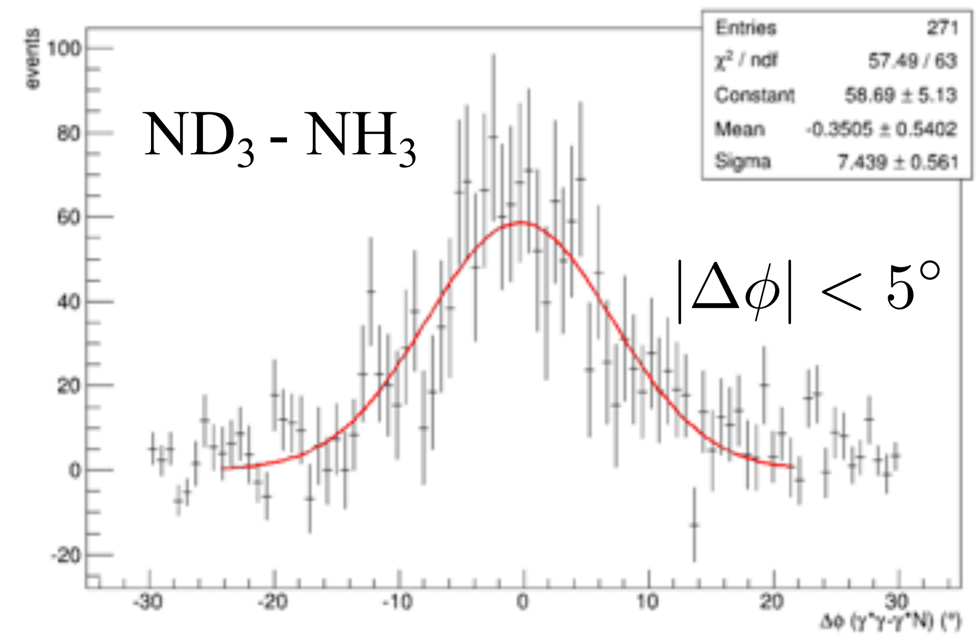
Exclusivity cuts: coplanarity



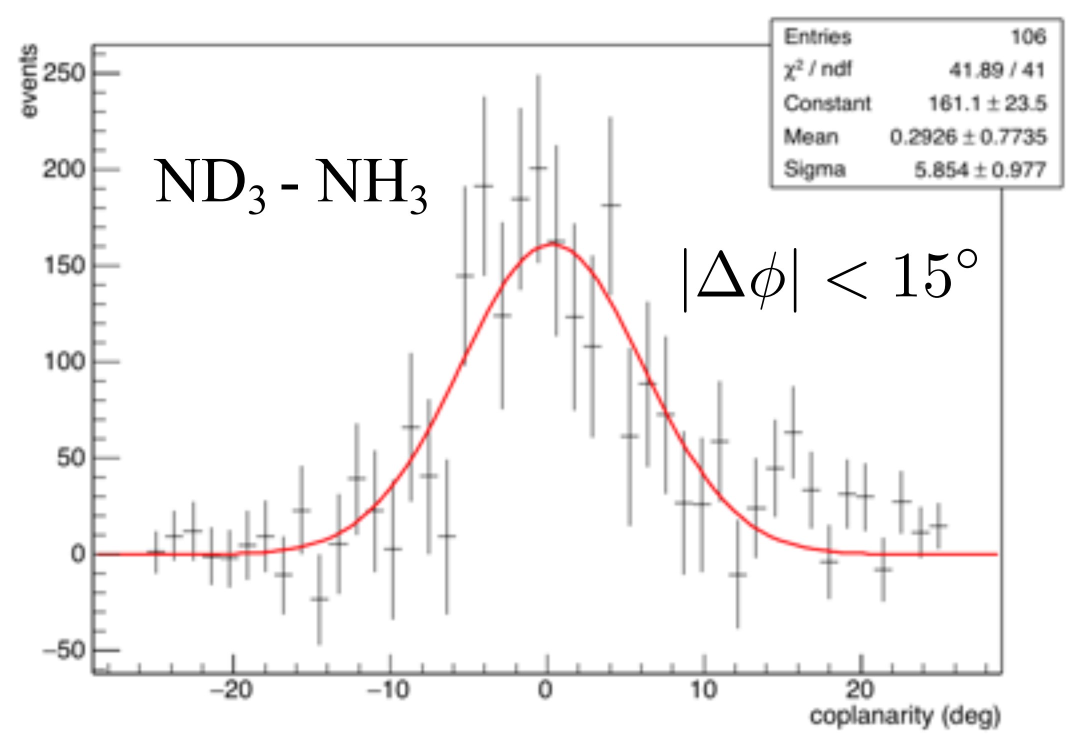
$|\Delta\phi|$ Coplanarity between γ and N

- Neutron momentum calculated from beta:





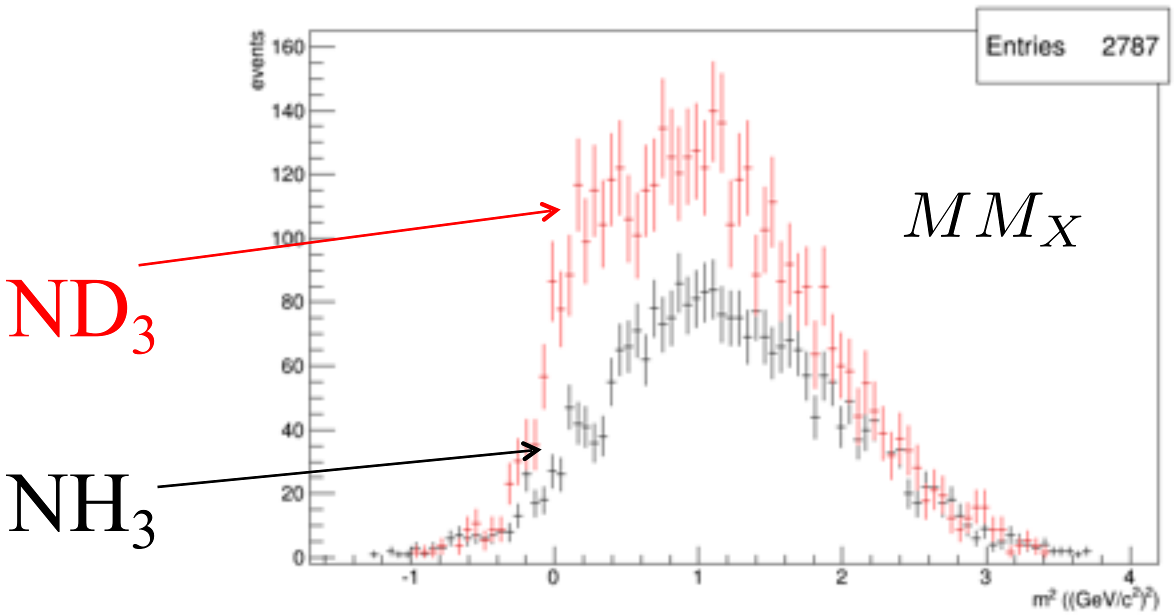
- Neutron momentum calculated from kinematics:



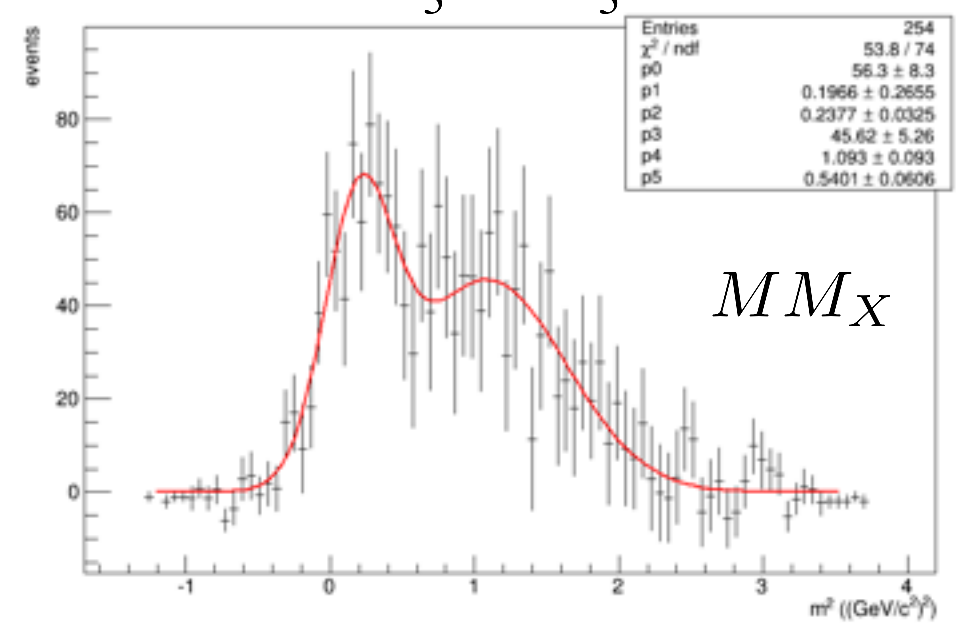
After exclusivity cuts

Missing mass from $eN \rightarrow e'NX$ (should correspond to photon)

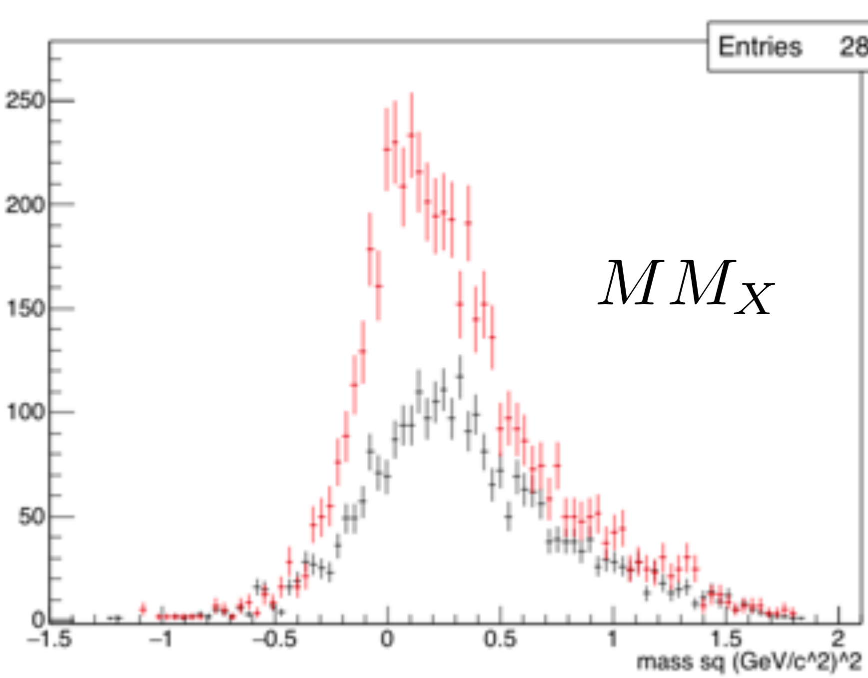
- Neutron momentum calculated from beta:

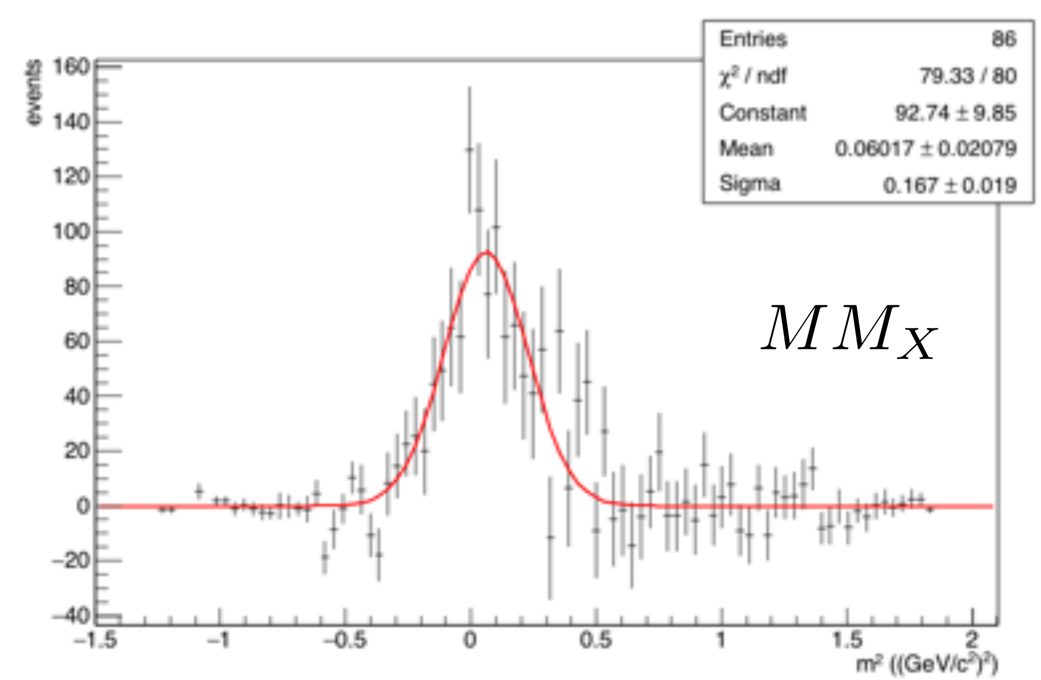


ND_3 - NH_3



- Neutron momentum calculated from kinematics:

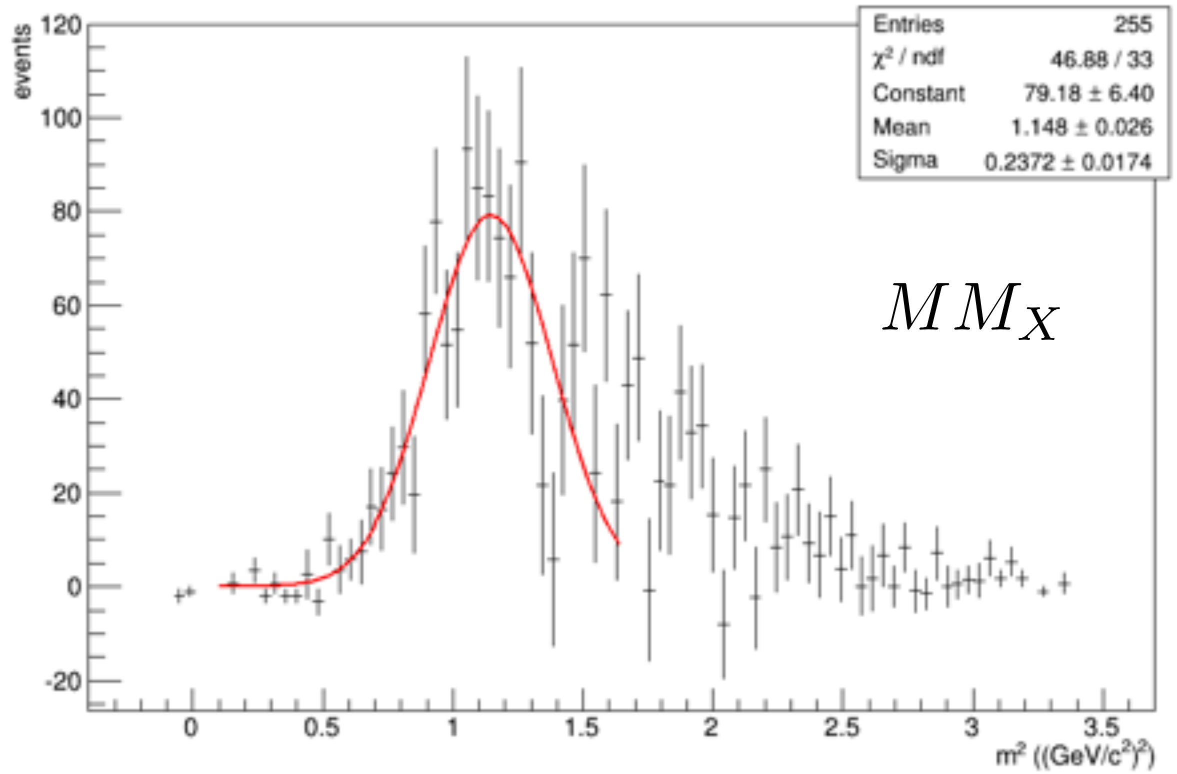




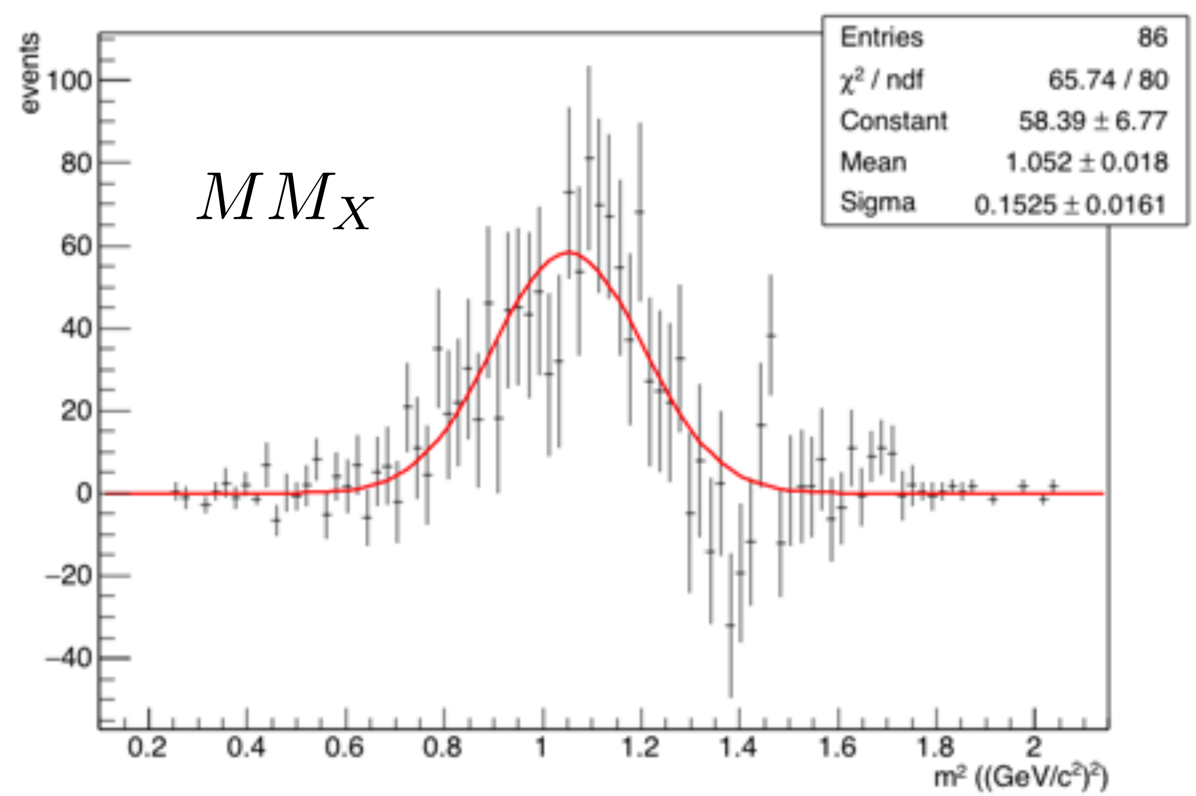
After exclusivity cuts

Missing mass from $eN \rightarrow e'\gamma\ X$ (should correspond to recoil neutron)

- Neutron momentum calculated from beta:



- Neutron momentum calculated from kinematics:

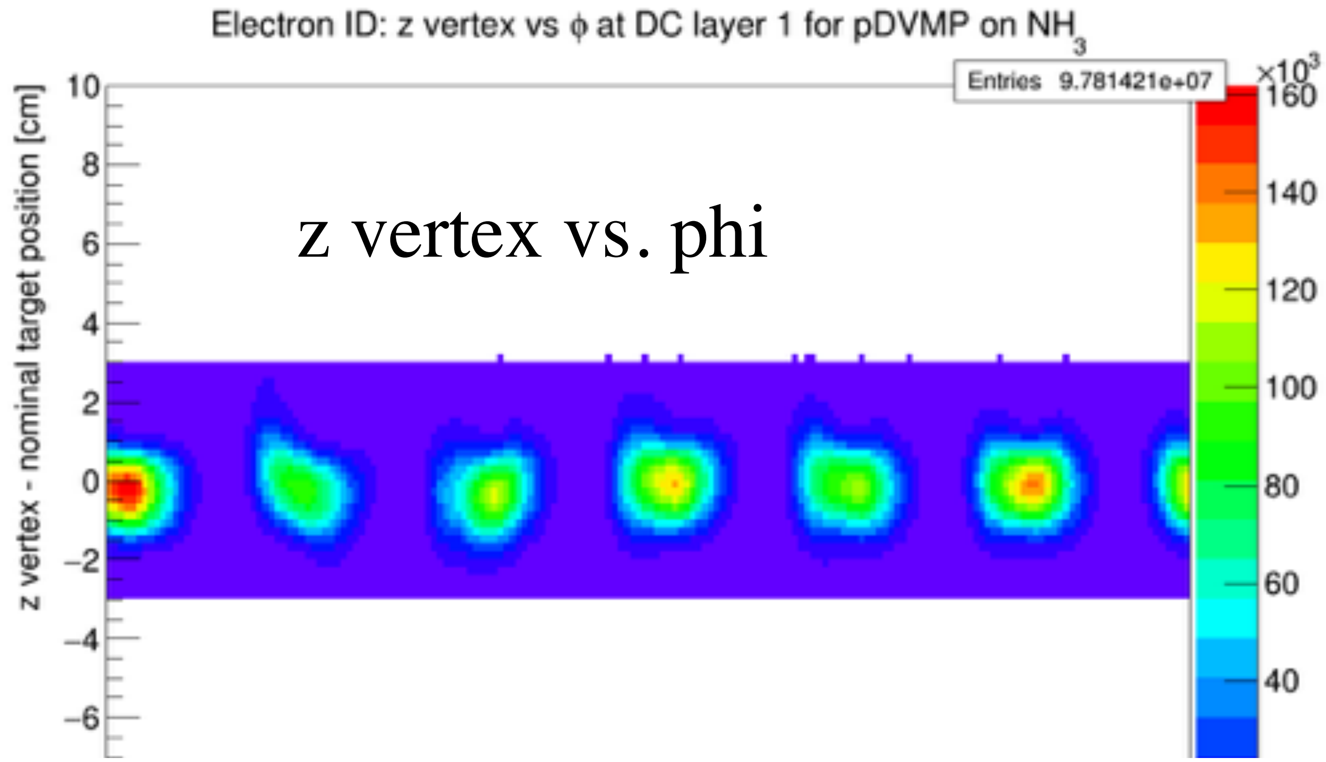


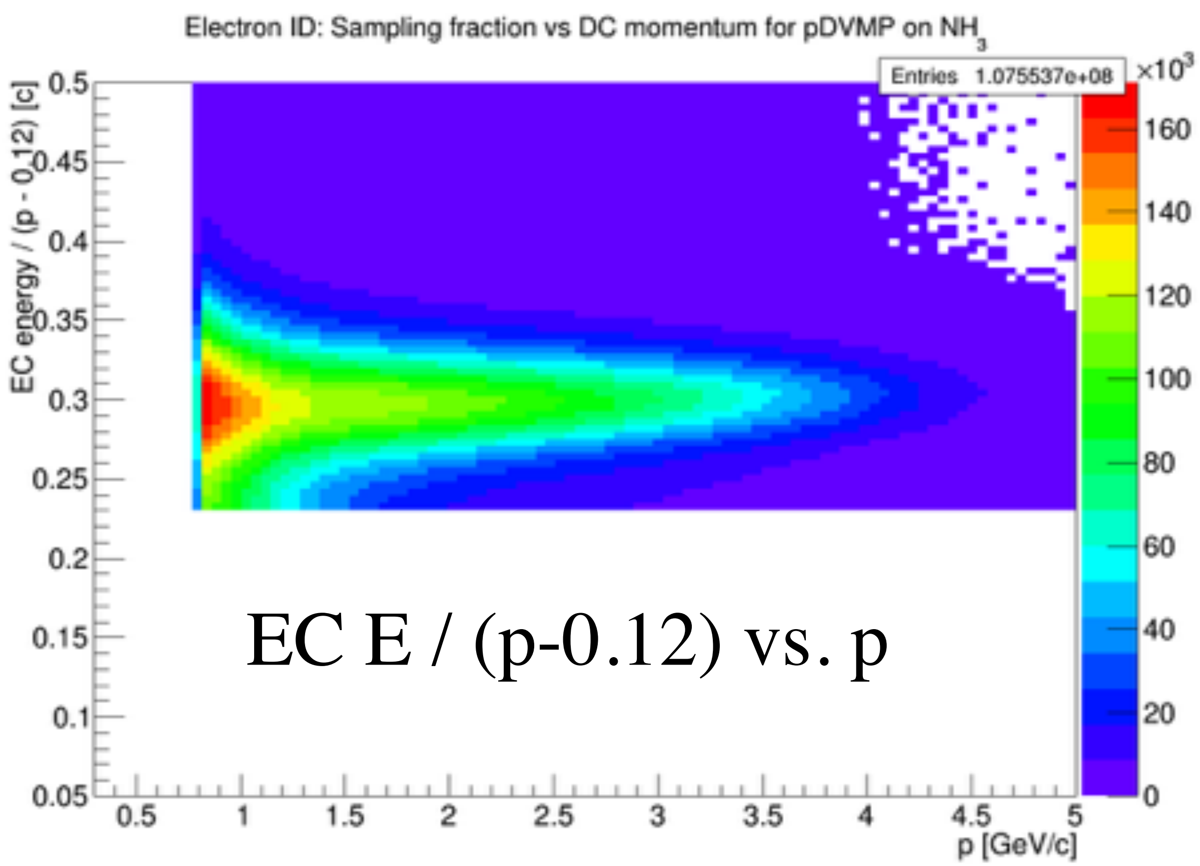
Distributions shown after NH3 subtraction.

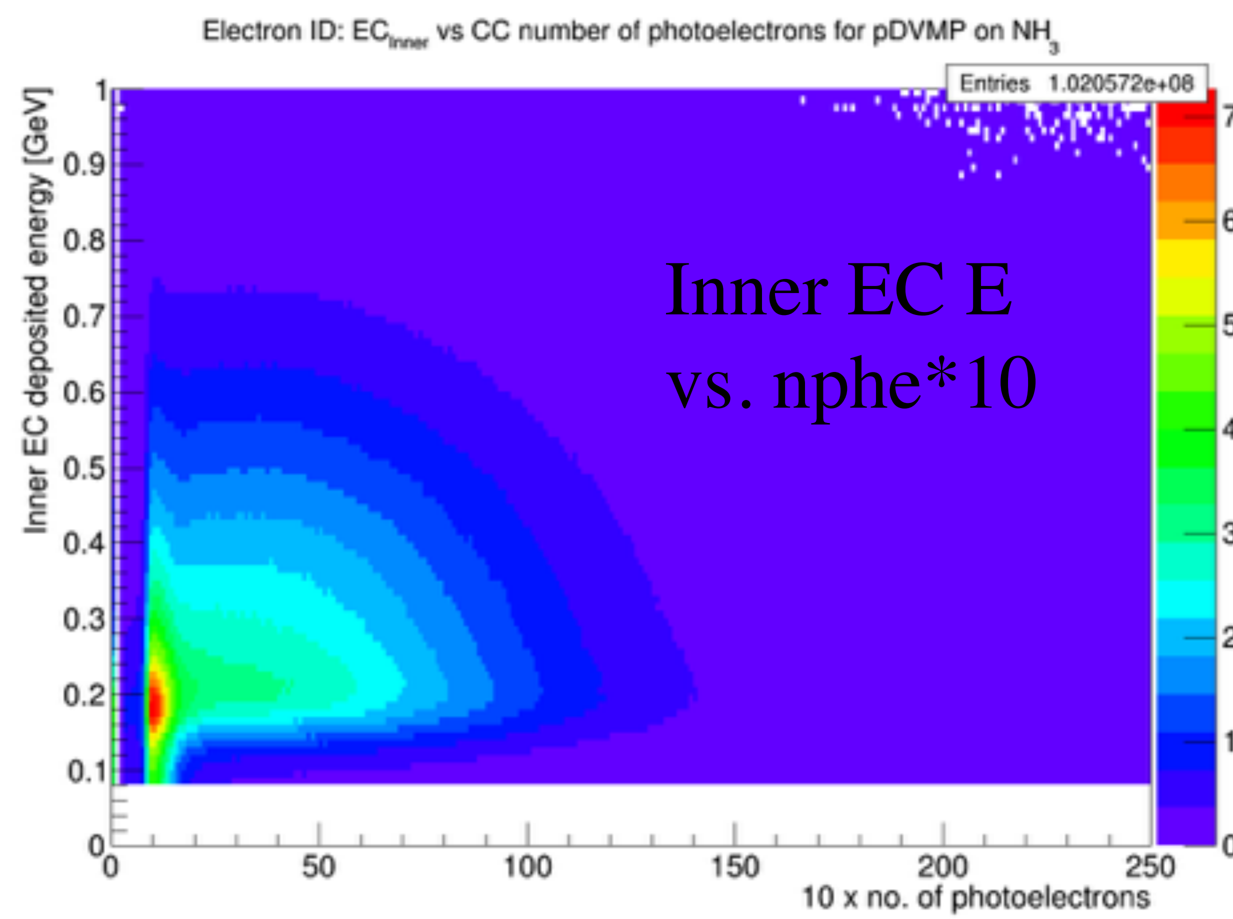
Pi0 electroproduction: Electron ID

Gavin Murdoch, Glasgow University

Standard electron ID cuts:
fiducial cuts, EC E - p cut,
CC cut

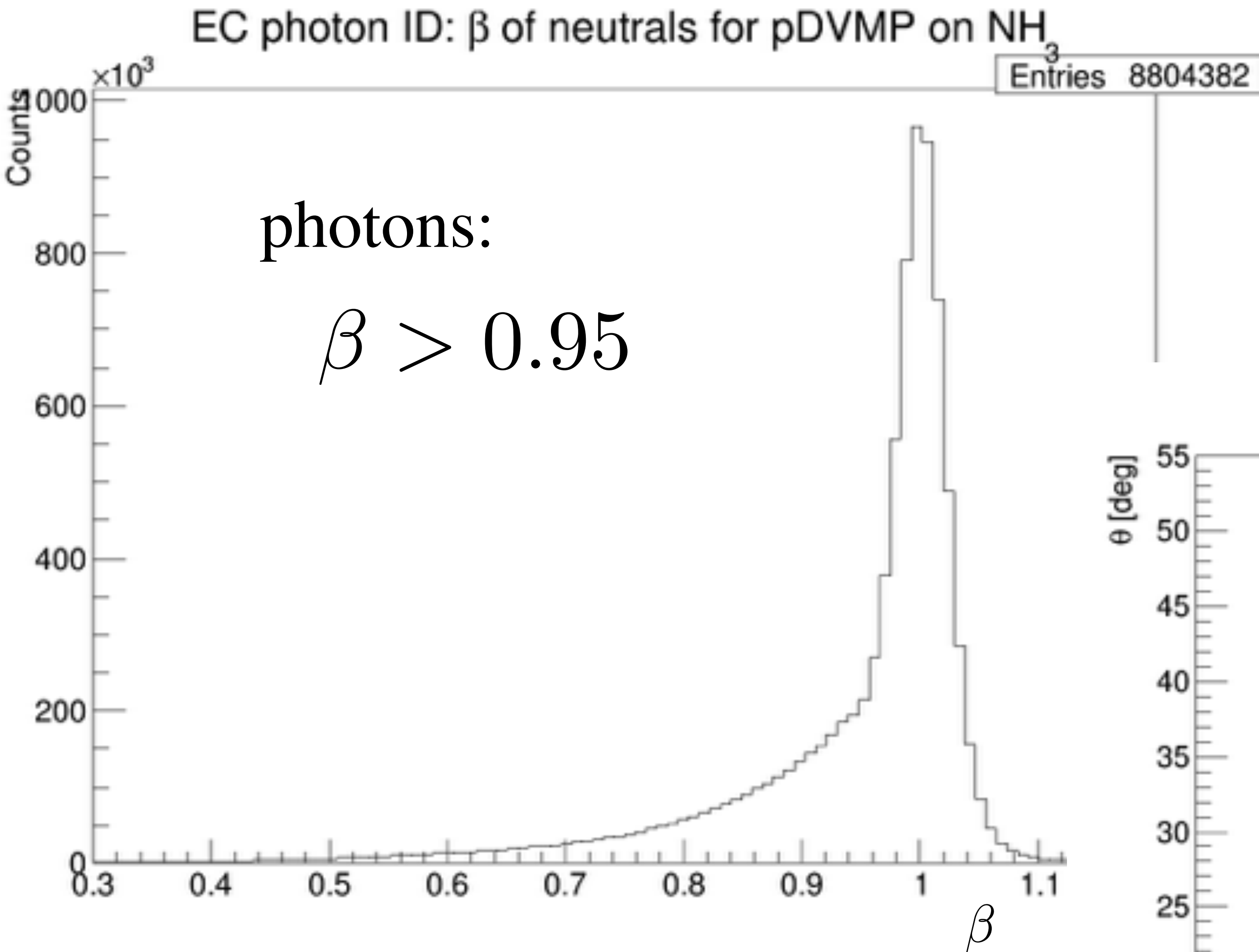


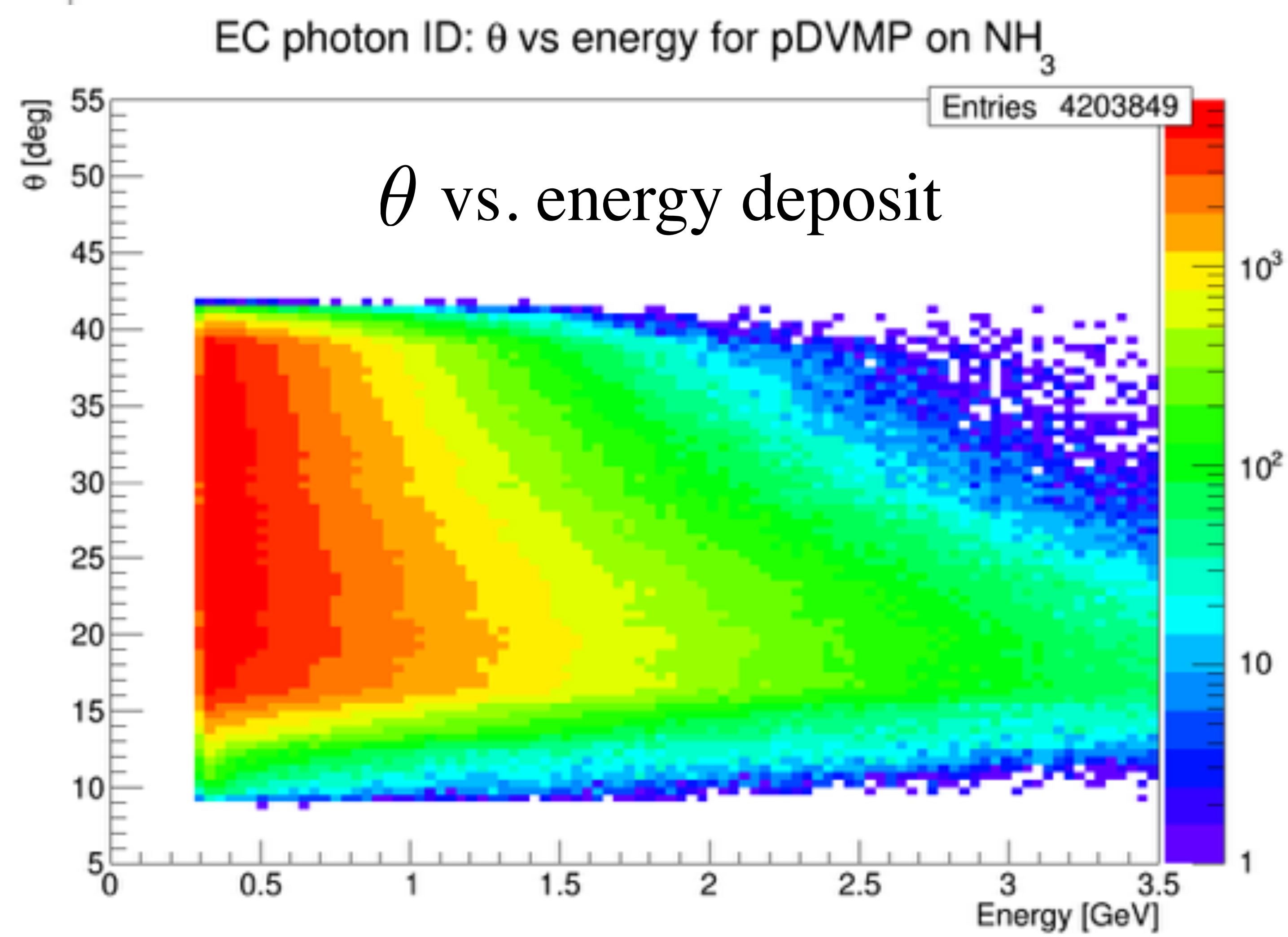




PiO electroproduction: EC photon ID

Gavin Murdoch, Glasgow University





Also fiducial cuts, sampling fraction adjustment.

Pi0 electroproduction: IC photon ID

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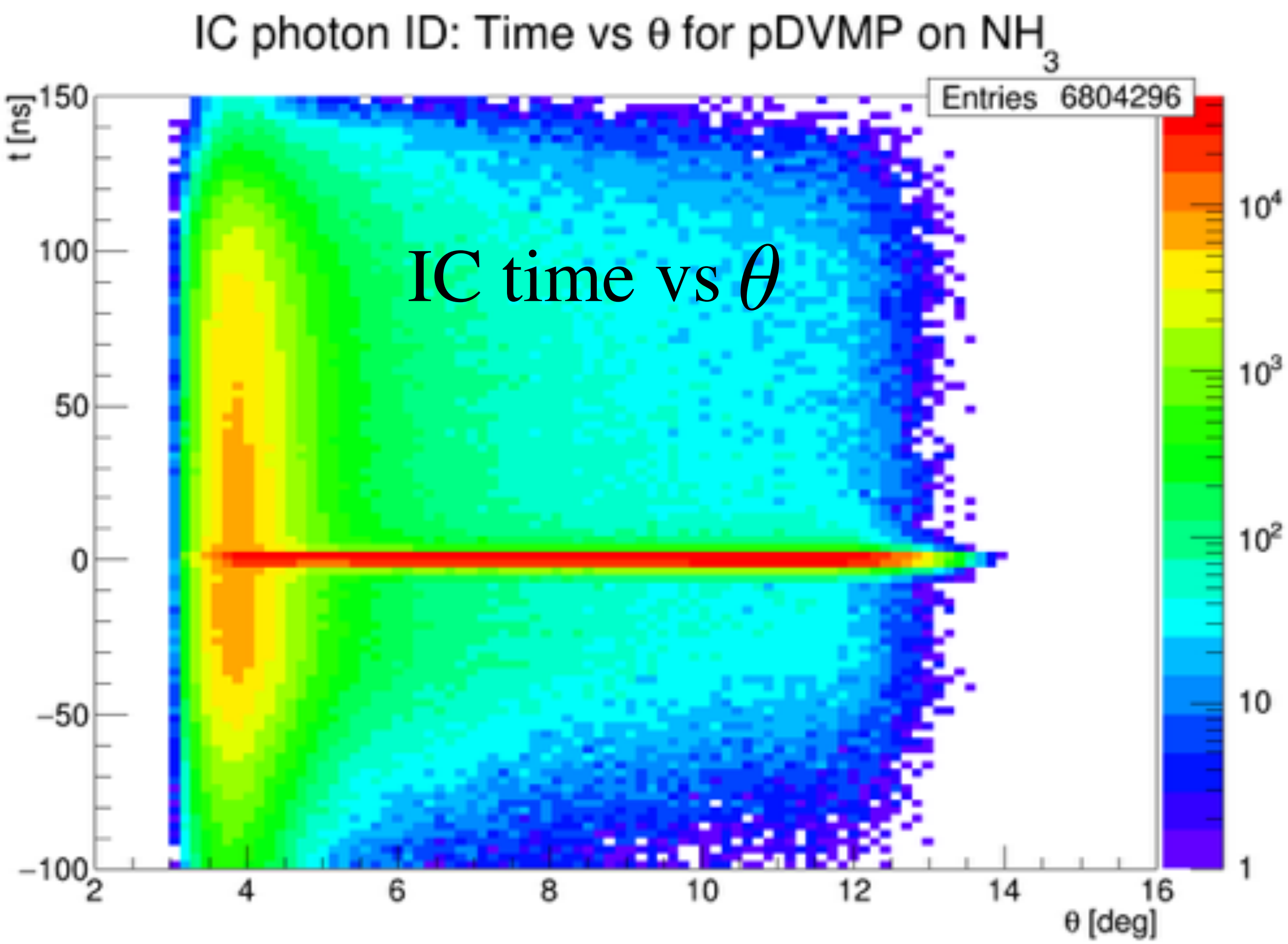
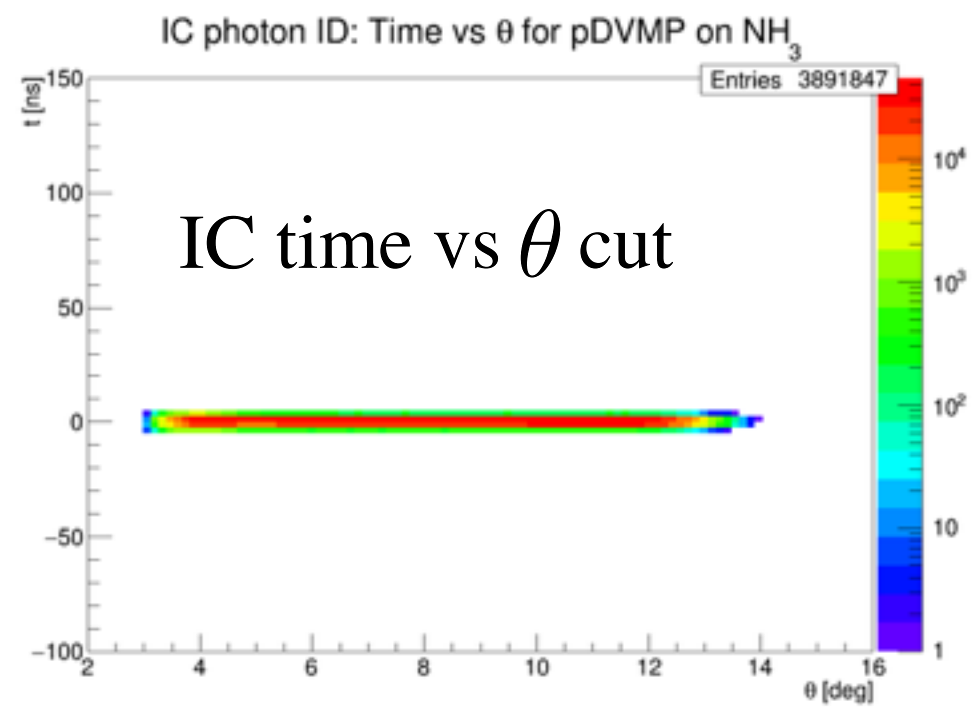
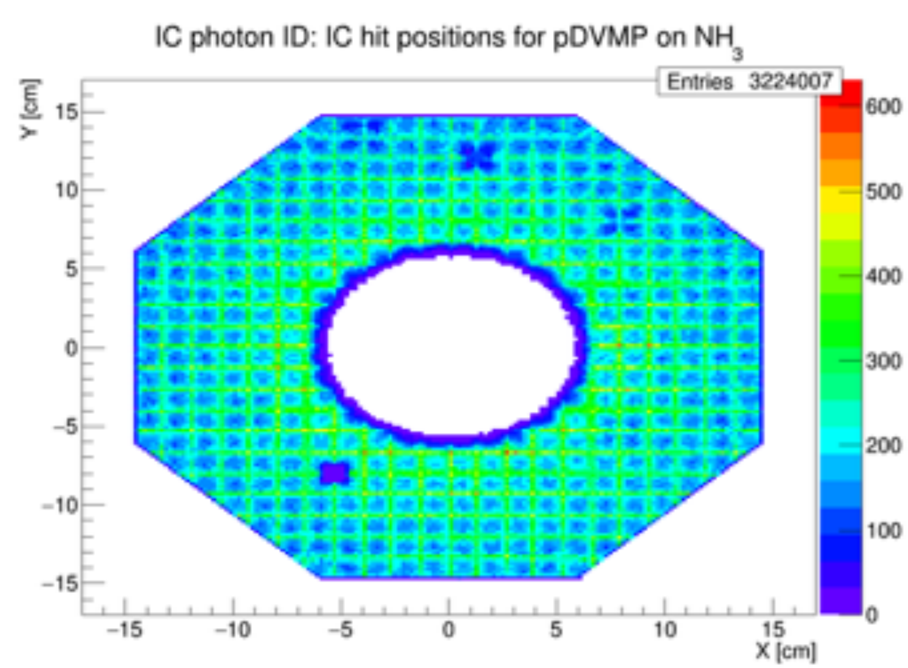




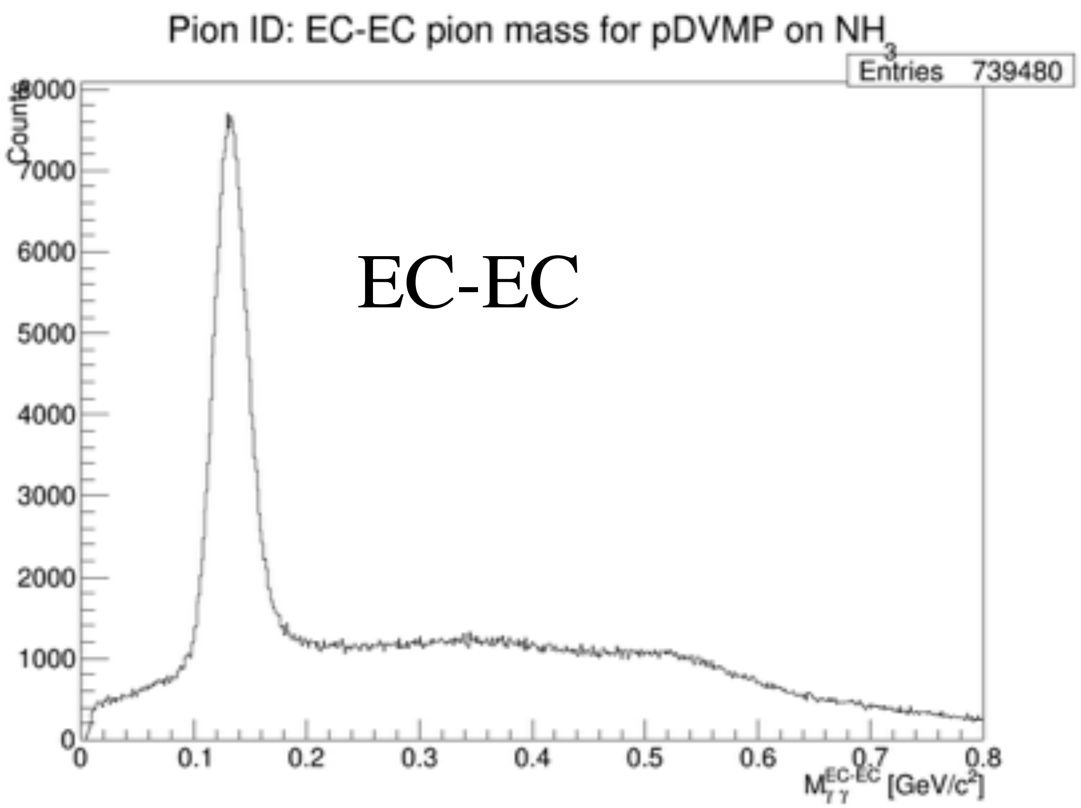


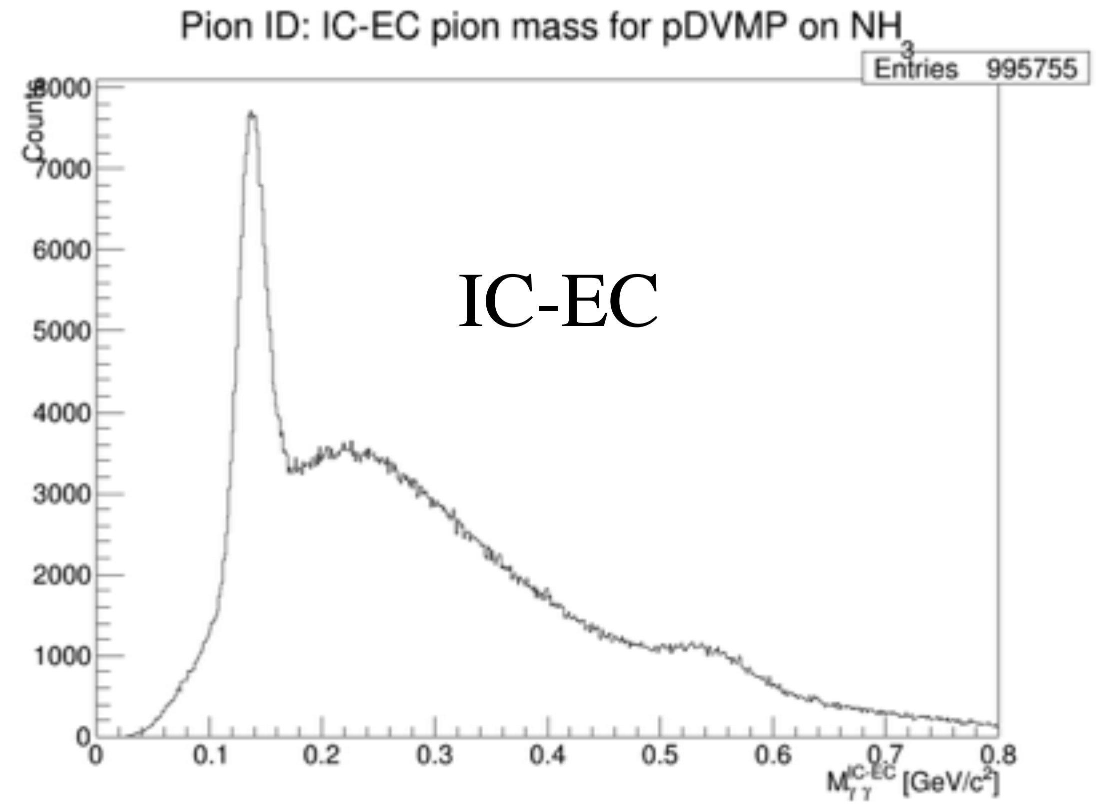
Also hot channel removal
and inner circle cut.

Pi0 electroproduction: pi0 ID

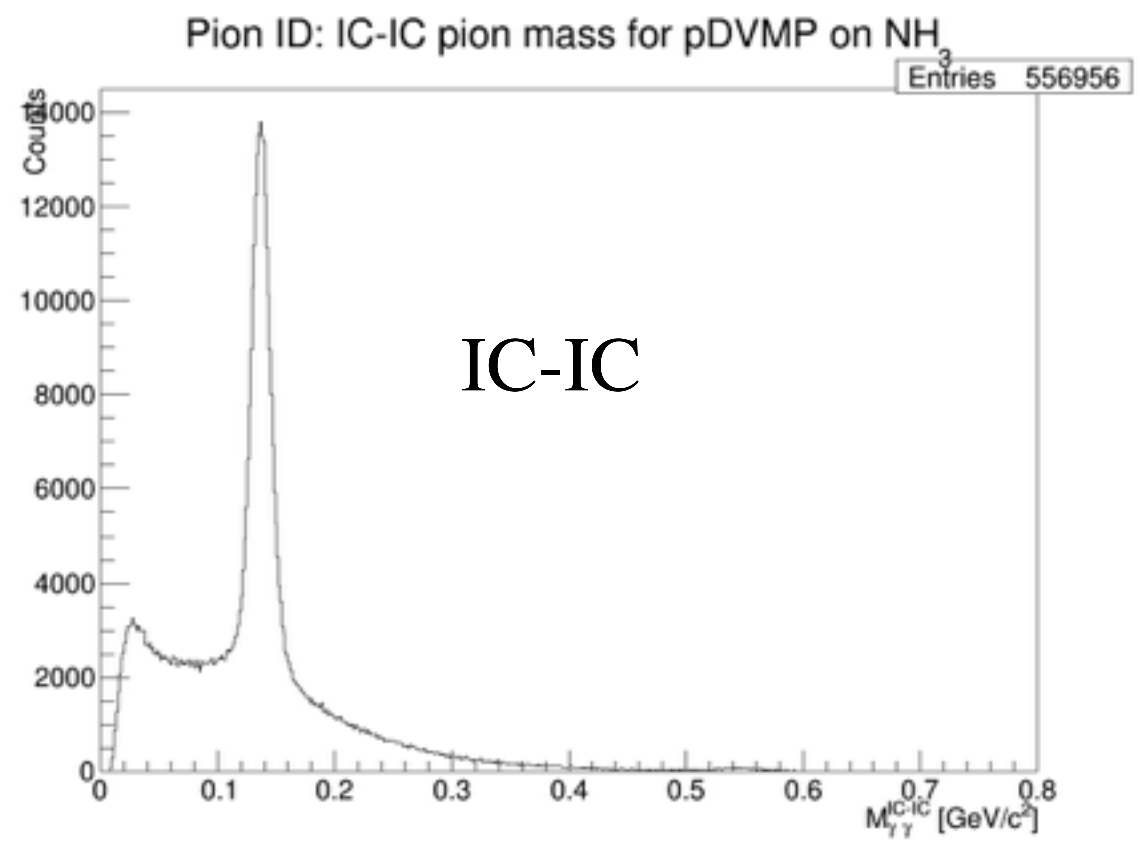
Gavin Murdoch, Glasgow University

Reconstruct rest mass of combined pairs of photons:





Cut around pi0 peak.



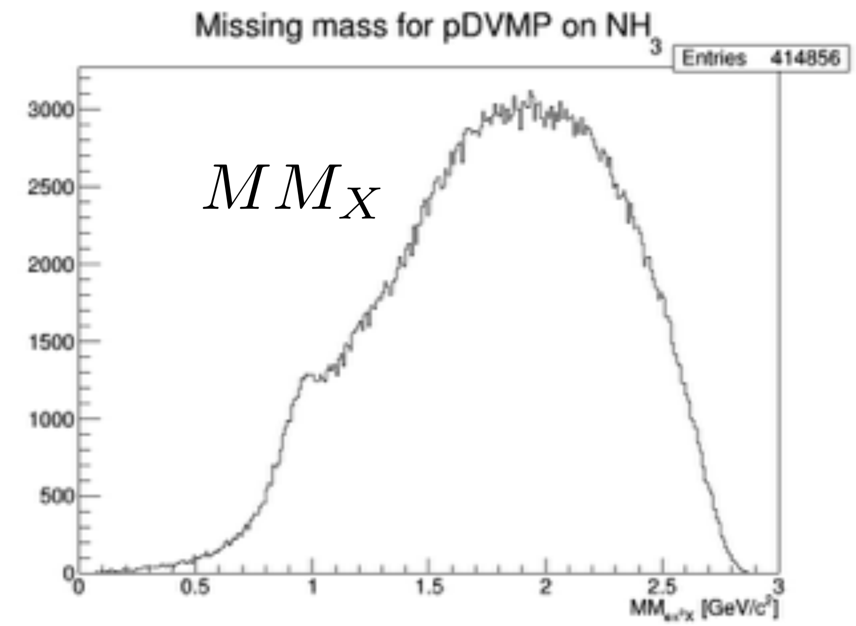
Recoil reconstruction: p-pi0 on NH3

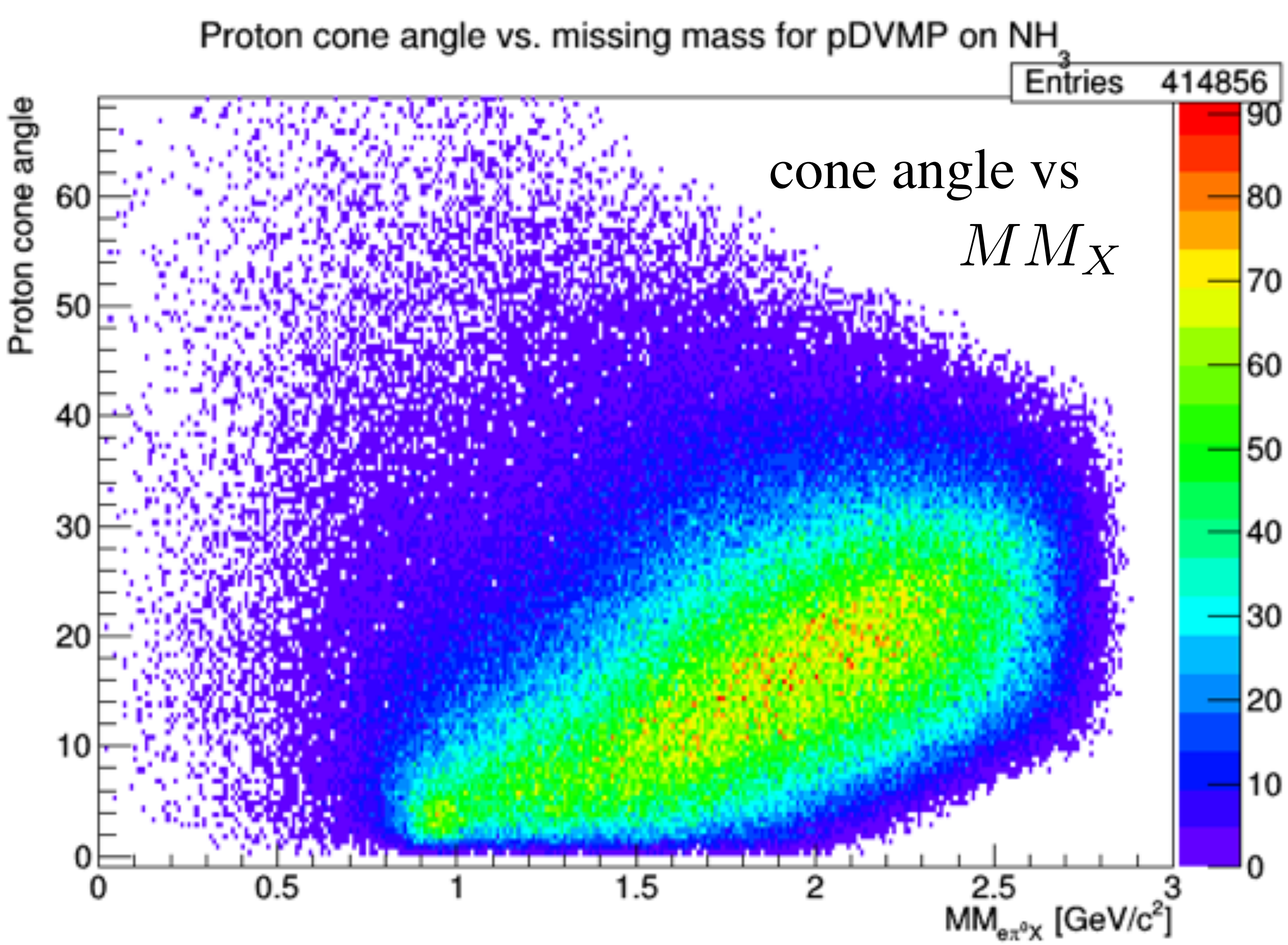
Gavin Murdoch, Glasgow University

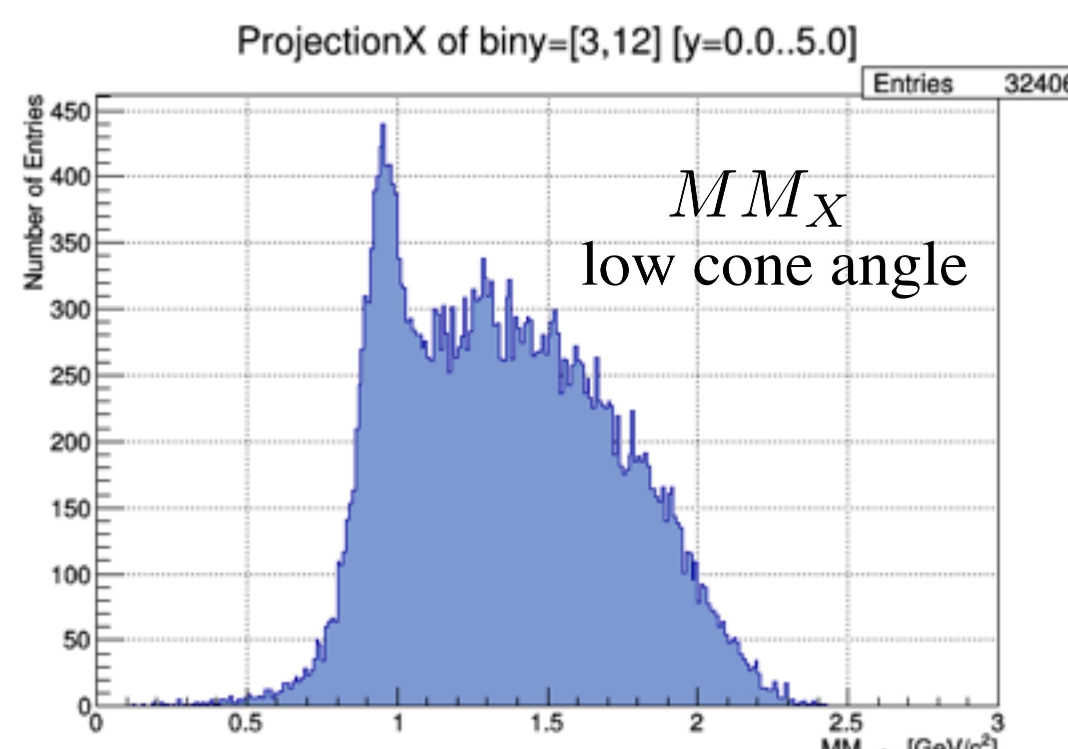
Try reconstructing neutrons from missing mass and neutron candidate direction, determine cut on basis of p-pi0. Start with pi0 electro-production on proton (part B data):

$$e + p \rightarrow e' + \pi^0 + X$$

Cone angle: between calculated and measured nucleon direction.







Recoil reconstruction: p-pi0 on ND3

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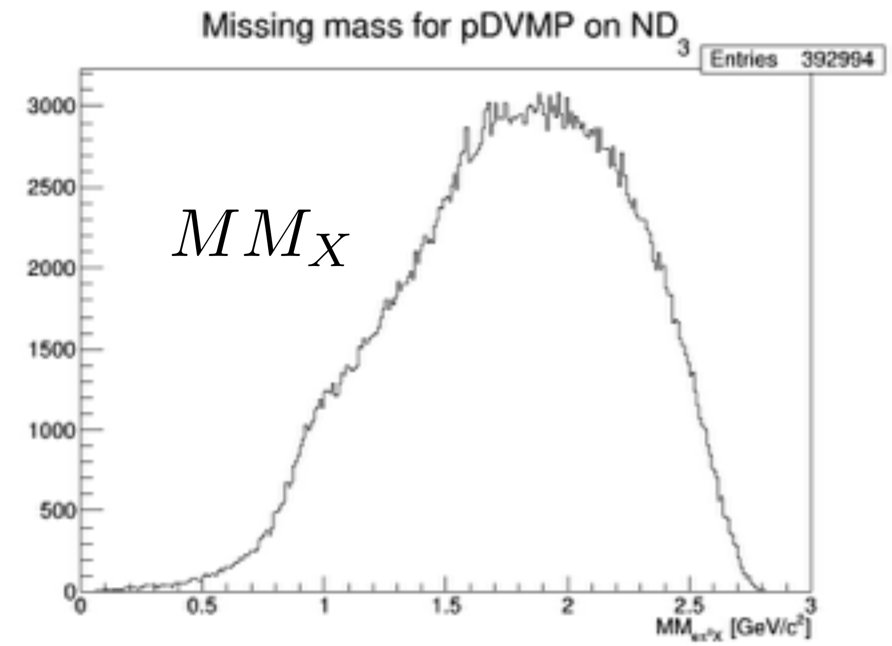
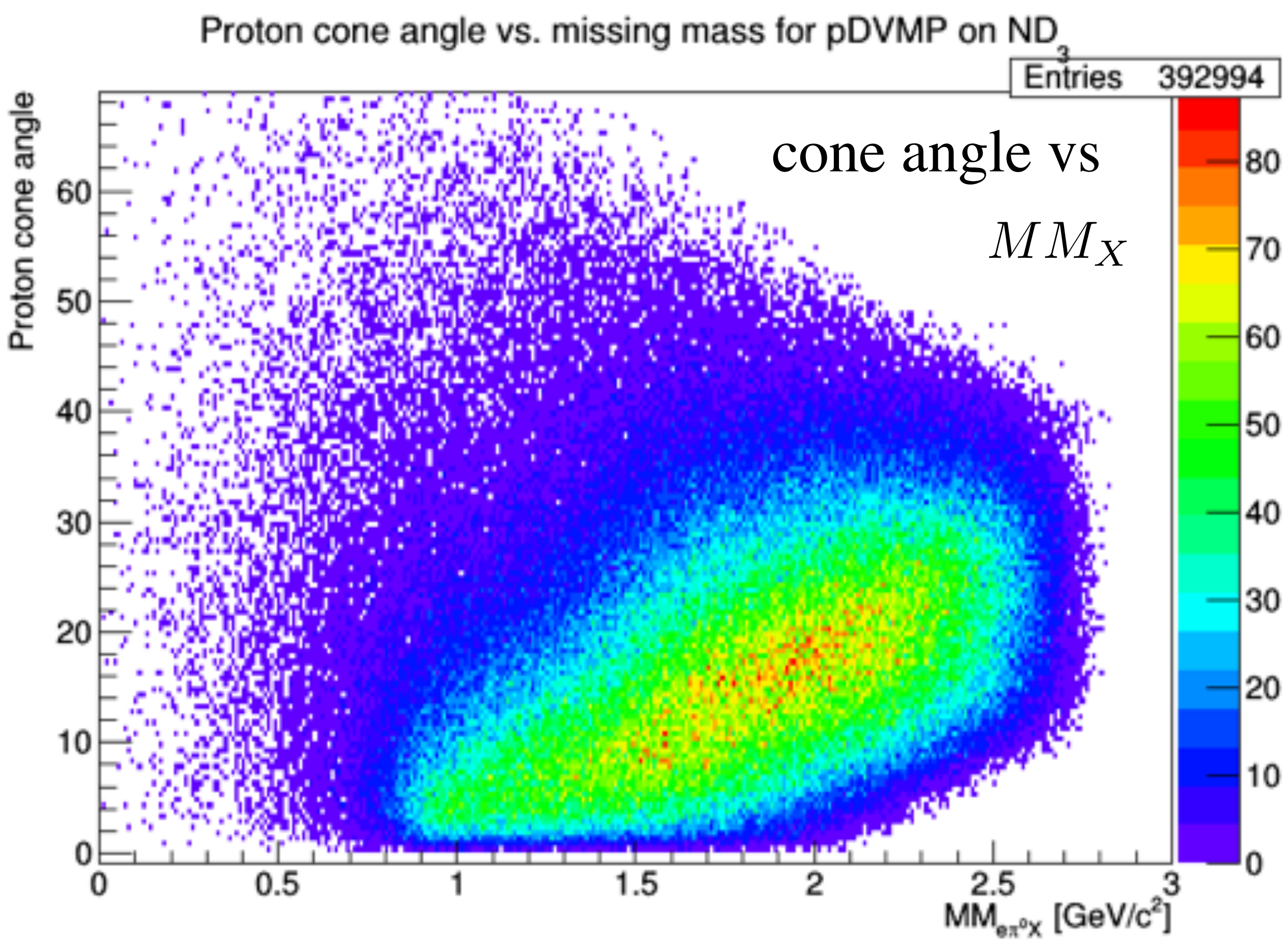
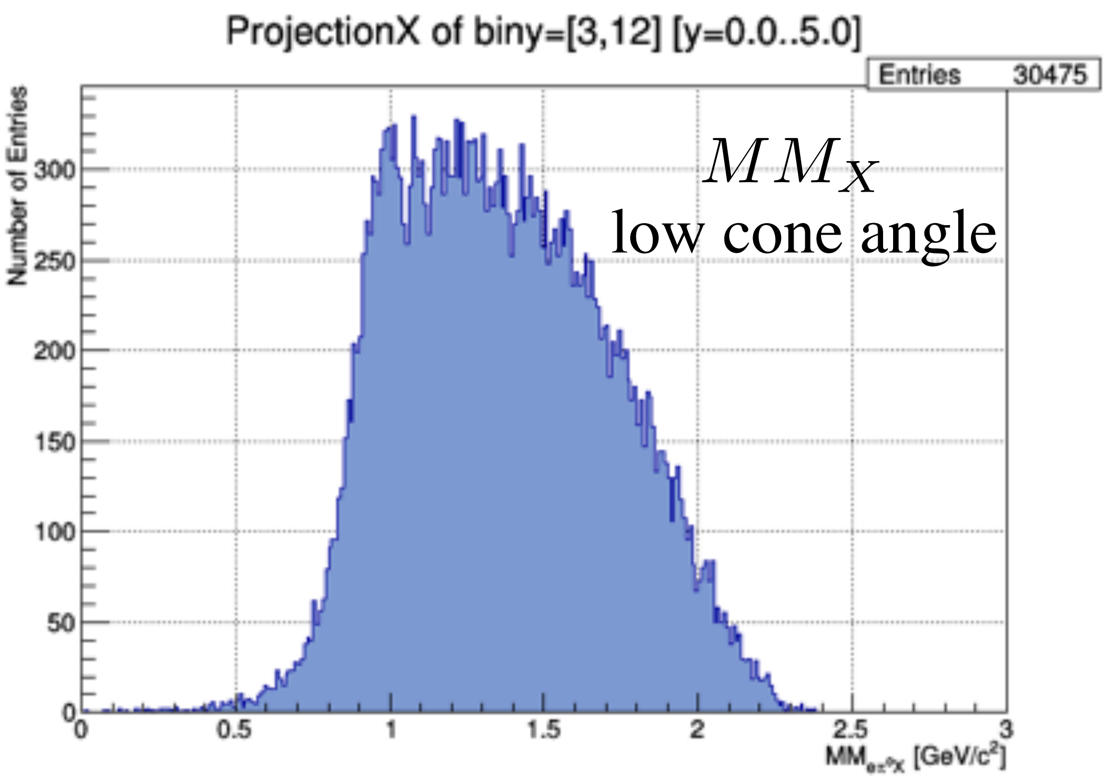
Next, check pi0 electro-production on proton from part C: Fermi smearing.

$$e + p \to e' + \pi^0 + X$$



Cone angle (between calculated and measured nucleon direction) vs MM(X):





Recoil reconstruction: n-pi0 on ND3

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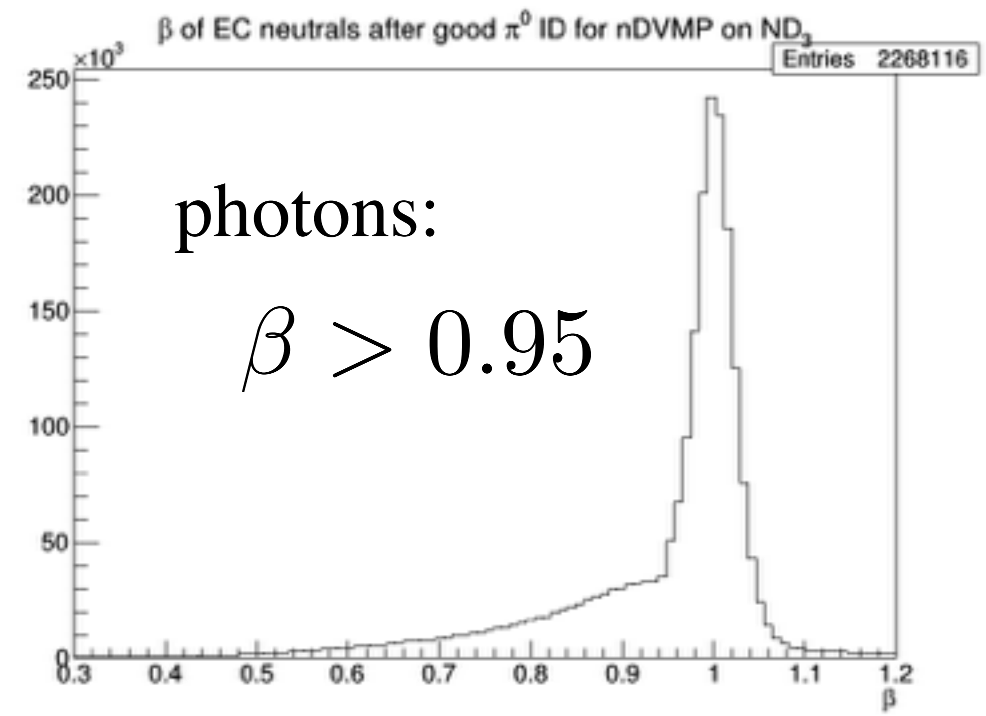
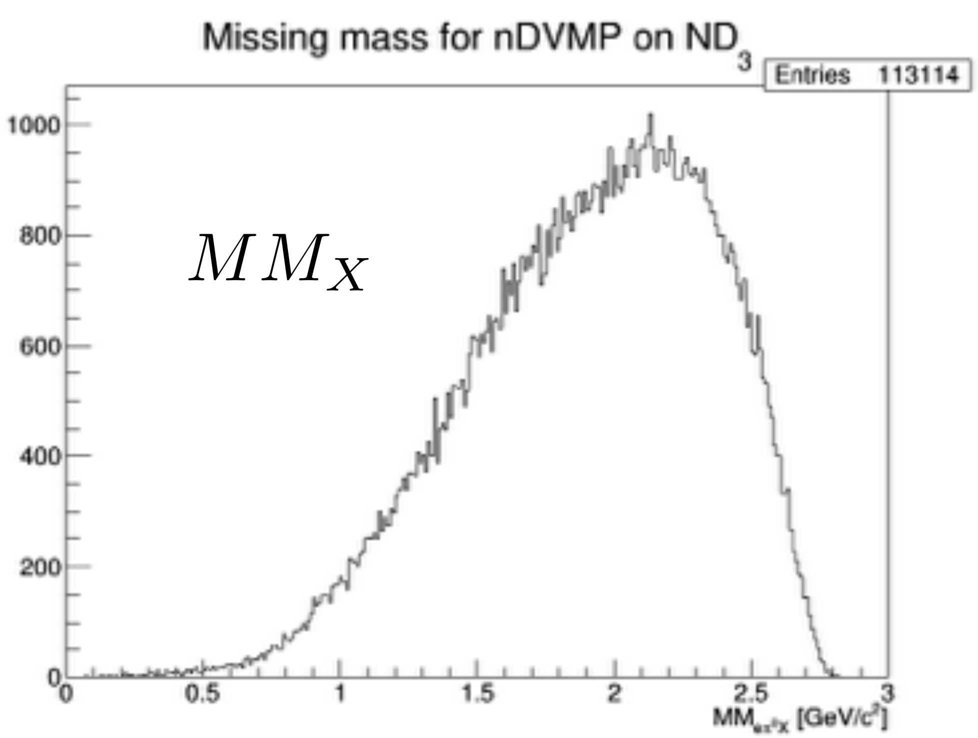
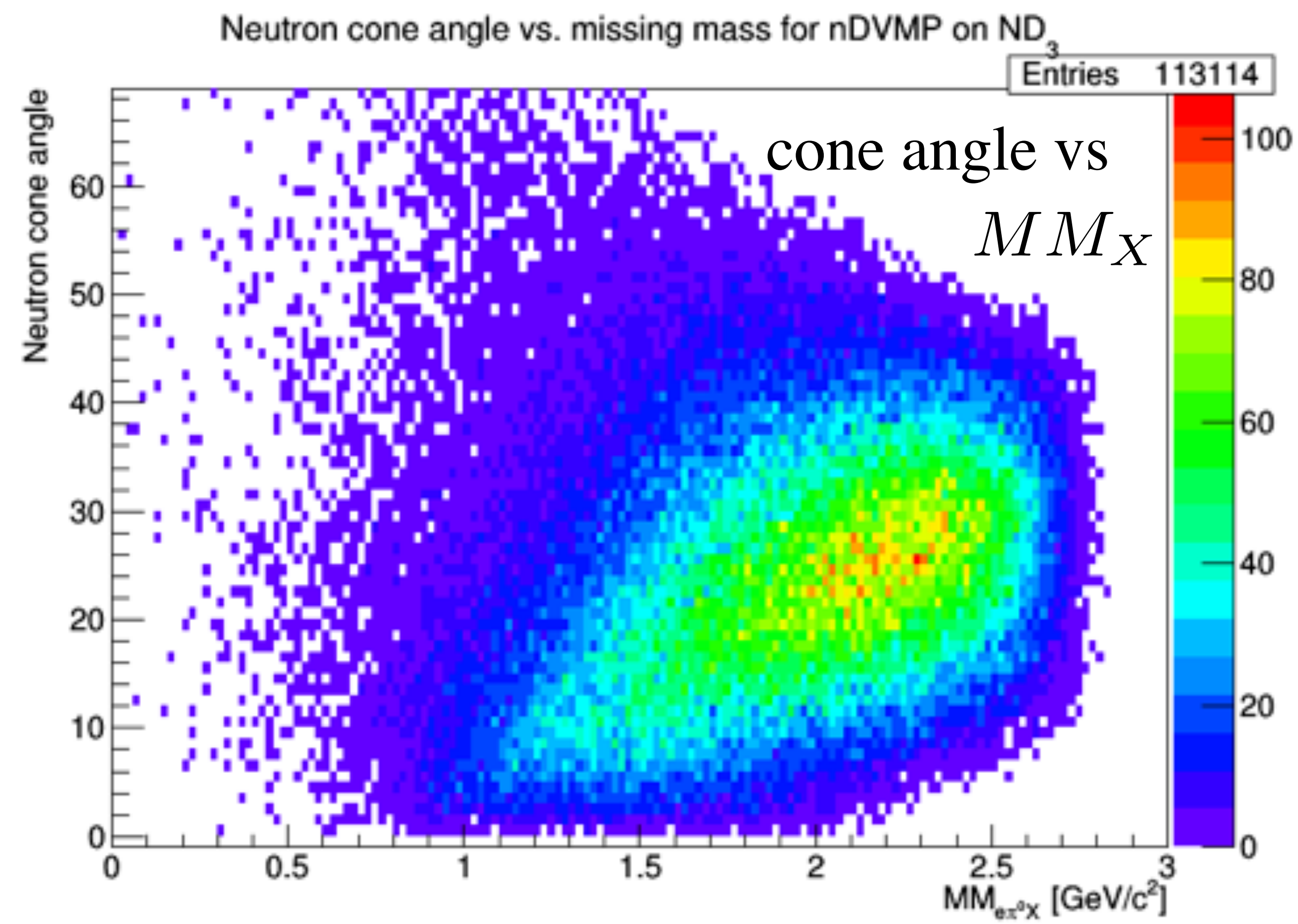
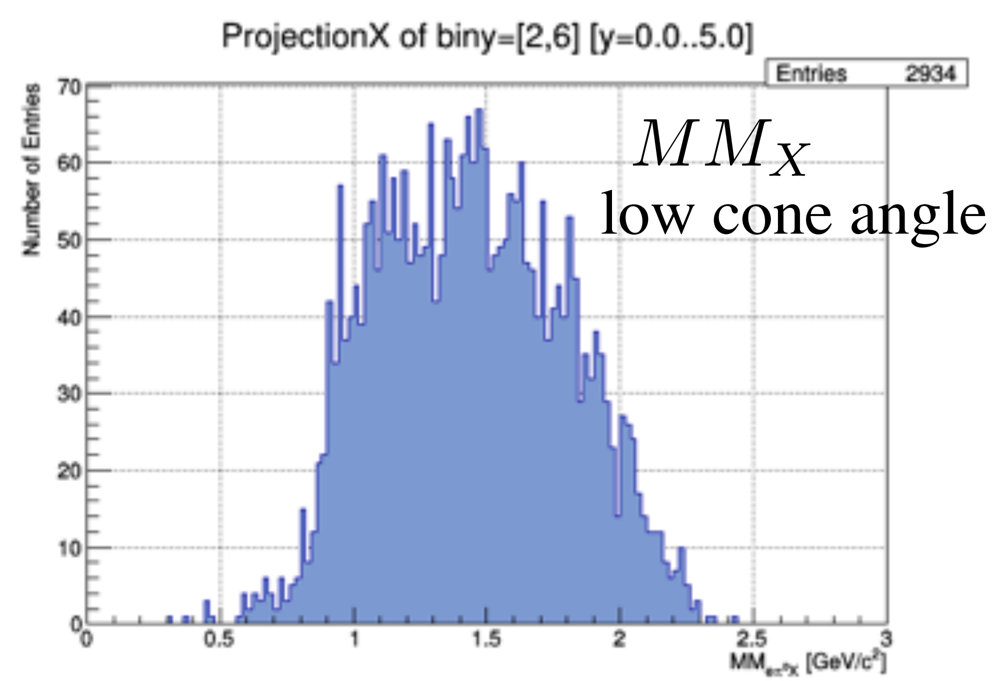


$$e + n \rightarrow e' + \pi^0 + X$$







Neutron efficiency low, no discernible peak.

In summary

- Originally, reconstructed neutron fully from EC beta: very low stats, low resolution, large backgrounds, unclear where to place exclusivity cuts.

- Attempt to identify exclusive events via recoil hadron direction matching and missing mass, test in the case of pi0-production: Fermi-smearing masks peak, huge background and low stats.

- Calculate neutron and spectator momenta on basis of neutron direction: cleaner distributions, still very low stats.

- Next: systematic study of exclusivity cuts. Might not be possible to extract a pi0 measurement.

- *Possible other channels, e.g.:* $e + n \rightarrow e' + \pi^- + p$

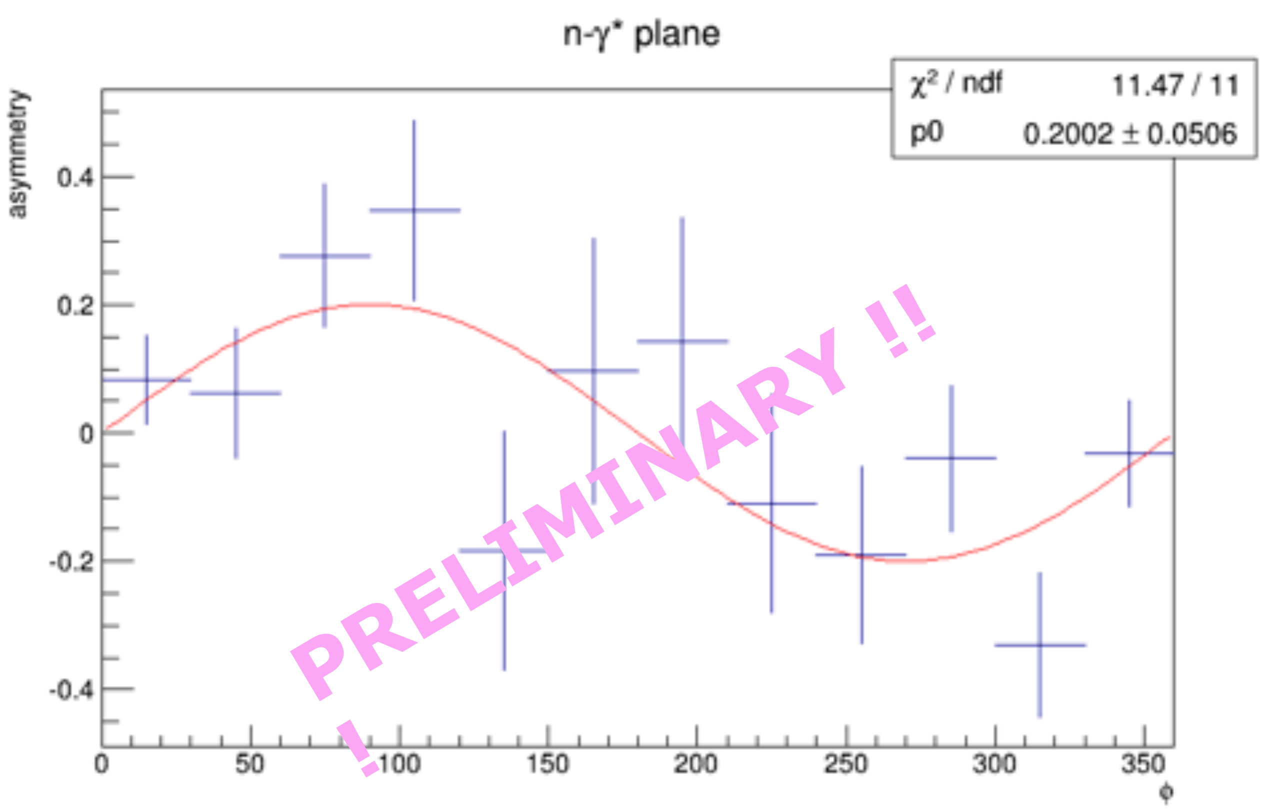
THANK YOU!

Backup

A_{LU} in neutron DVCS on ND_3

- Beam-spin asymmetry (A_{LU}):

One previous measurement from Hall A @ JLab, $A_{LU} \sim 0$. Big statistical and systematic uncertainties, slightly different kinematic region.
(M. Mazouz et al, PRL 99 (2007) 242501)



Fit: $A_{LU} = p_0 \sin\varphi$

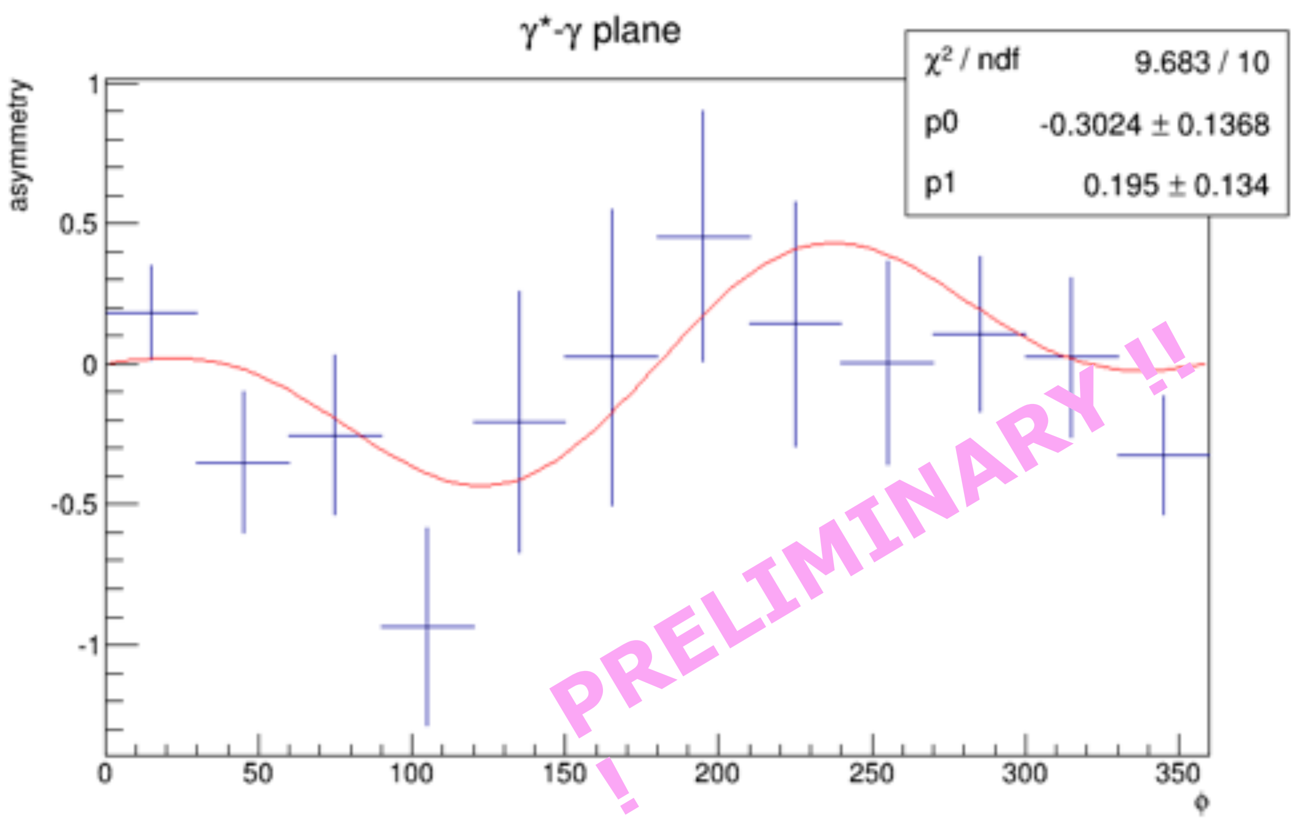
$$\frac{N^+ - N^-}{P(N^+ + N^-)} \approx 0.20 \pm 0.05$$

Uncorrected for π^0 contamination, which has an asymmetry of its own!

A_{UL} in neutron DVCS on ND_3

First measurement.

v Target-spin asymmetry (A_{UL}):



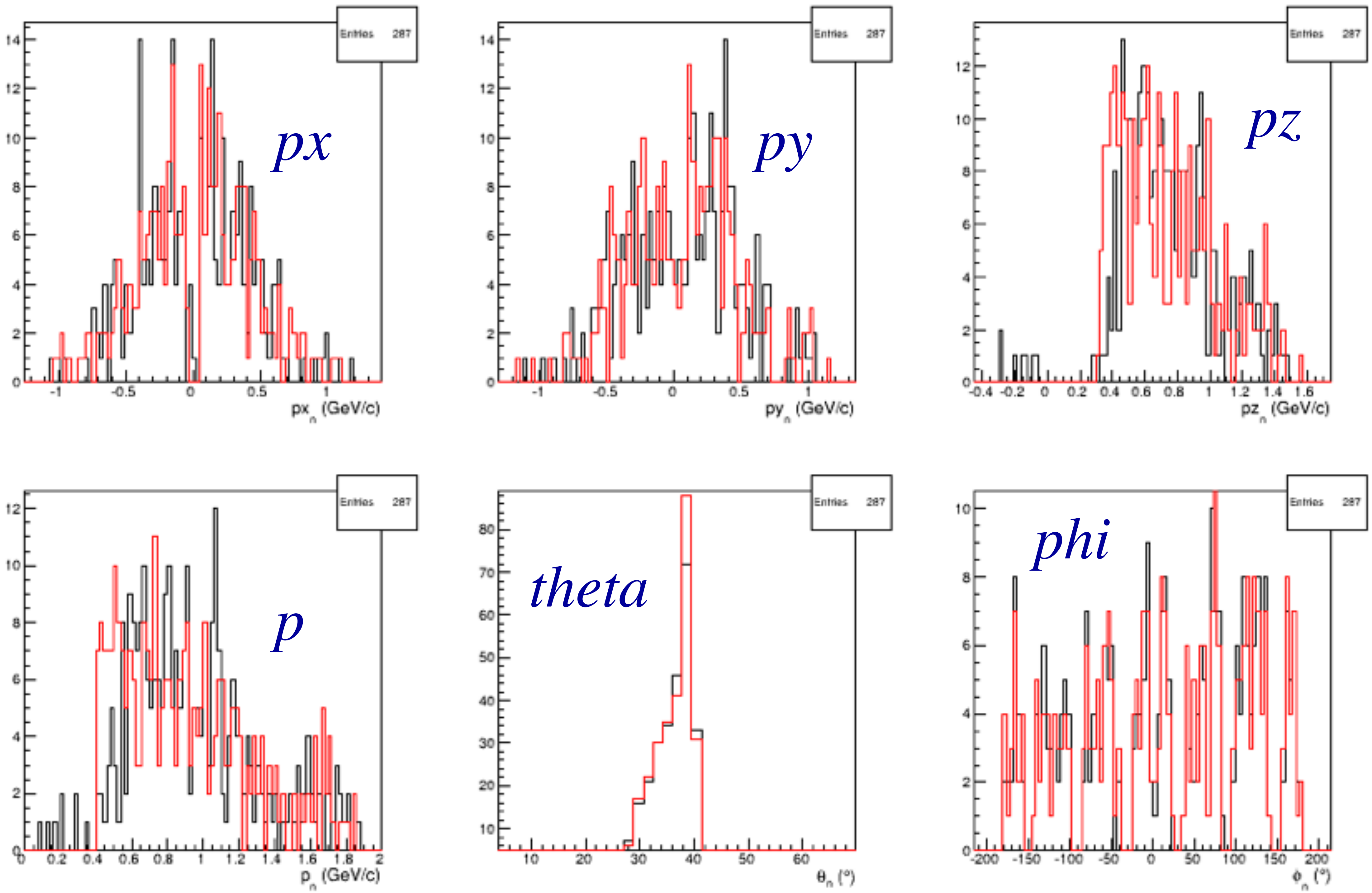
Fit: $$A_{UL} = \frac{p_0 \sin\varphi}{1 + p_1 \cos\varphi}$$

$$p_0 \approx -0.30 \pm 0.14$$

$$p_1 \approx 0.195 \pm 0.134$$

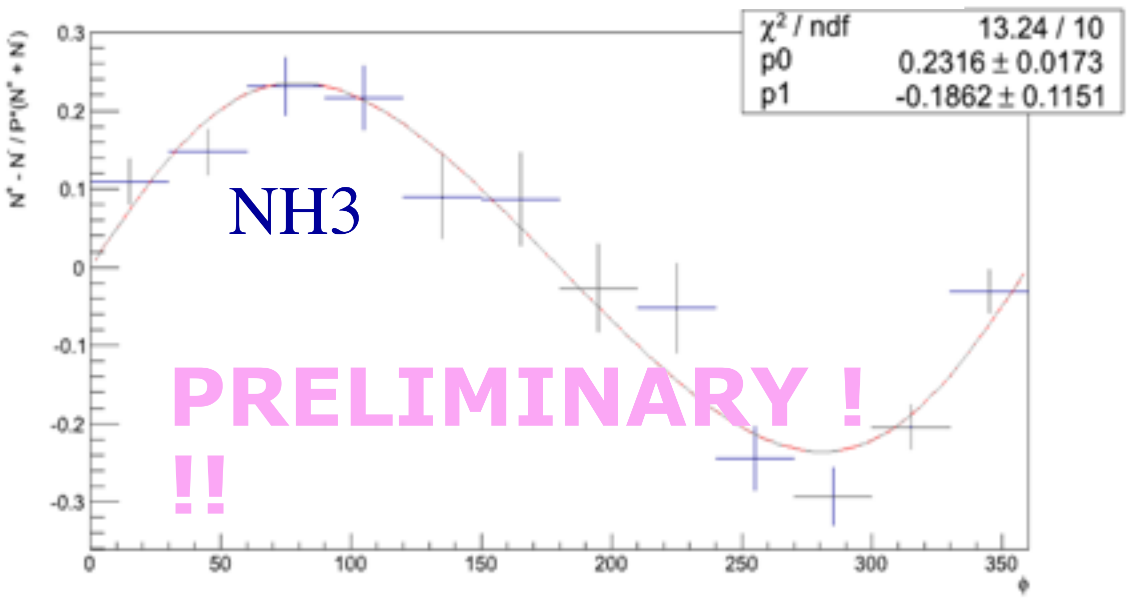
Uncorrected by the dilution factor due to the nuclear background!

Simulation: neutrons.

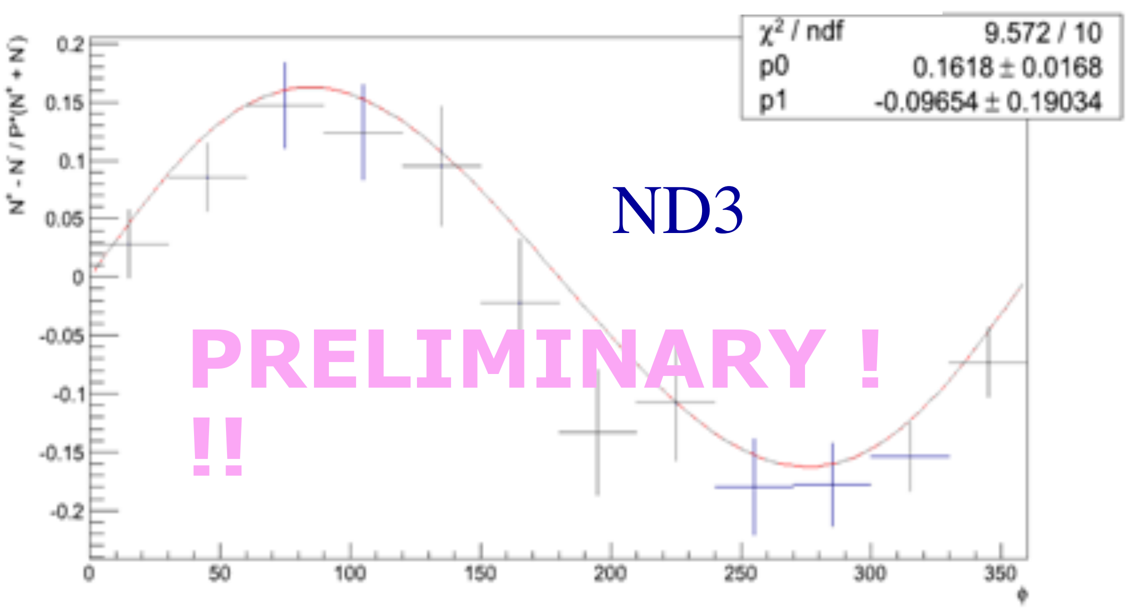


Distributions after exclusivity cuts. *generated, reconstructed*

A_{LU} – check on proton DVCS in NH_3 and ND_3



Fit: $A = \dfrac{p_0 \sin\varphi}{1 + p_1 \cos\varphi}$



Previously measured result on H_2 is in range 0.2 -0.3.

F.-X. Girod et al, PRL. 100 (2008) 162002

$$\frac{N^+ - N^-}{P(N^+ + N^-)} \approx 0.23 \pm 0.02$$

Uncorrected for π^0 contamination

$\longrightarrow$ *actual A_{LU} larger!*

Deuterium target – smearing due to Fermi motion requires wider data cuts. $\dfrac{N^+ - N^-}{P(N^+ + N^-)} \approx 0.16 \pm 0.02$

π^0 contamination more significant

$\longrightarrow$ *measured A_{LU} lower than on NH3*