Study of the $A(e,e'n)$ reaction

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Layout

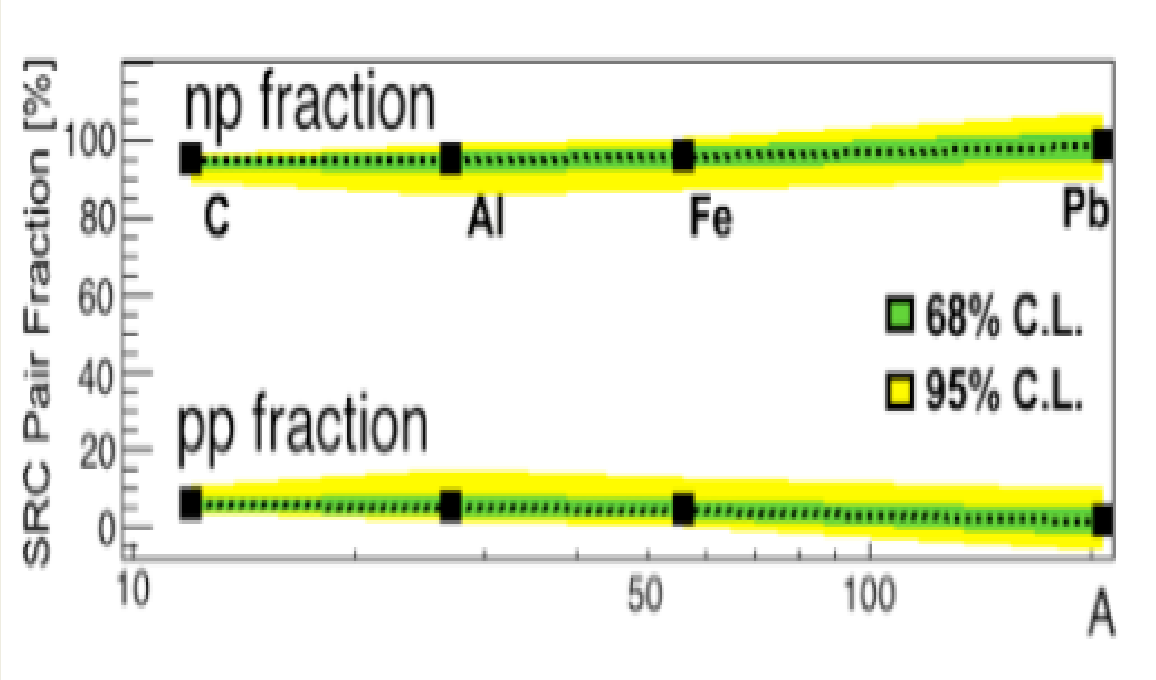
* **Introduction and motivation**

* **Calculating** $\frac{(e,e'p)_A}{(e,e'n)_A}$ **ratio**

* **Missing momentum** $(e, e'p)$ **vs.** $(e, e'n)$

* **Calculating** $\frac{{}^{12}C(e,e'p)_{P_{miss}-high/low}}{{}^{12}C(e,e'n)_{P_{miss}-high/low}}$

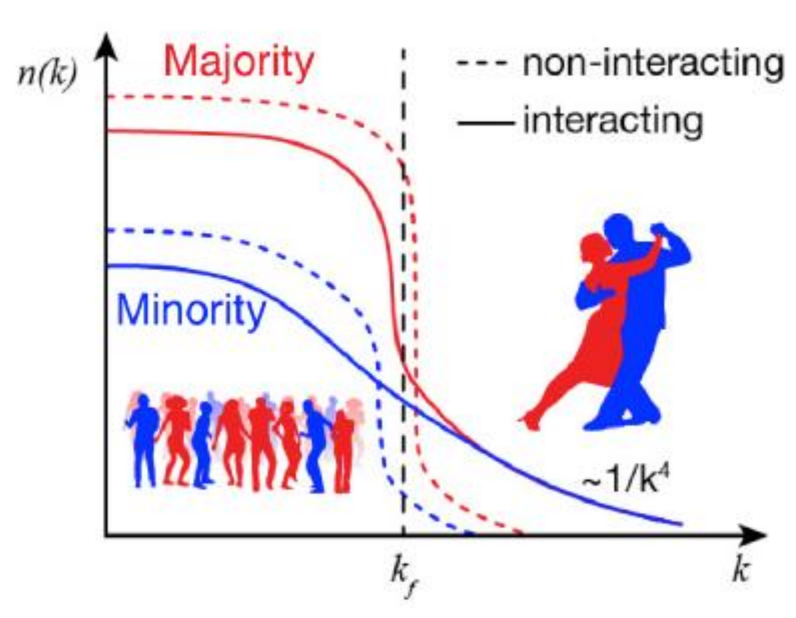
np Dominance



np/pp SRC pairs ratio

O. Hen et al., Science 346, 614 (2014)

np- dominance in asymmetric neutron rich nuclei



Universal nature of SRC:

A proton have greater probability than a neutron to be above the Fermi sea. $(k > K_F)$

Pauli principle ➡ $< K_n > \; > \; < K_p >$

?

SRC ➡ $< K_p > \; > \; < K_n >$

Possible inversion of the momentum sharing.

M. Sargsian Phys. Rev. C89(2014)3, 034305 O. Hen et al., Science 346, 614 (2014).

Protons move faster than neutrons in N>Z nuclei

Light nuclei A<12

Variational Monte-Carlo calculations by the Argonne group.

Nucleus	Asymmetry (N-Z)/A	$<T_p>[MeV]$	$<T_n>[MeV]$	$<T_p>/<T_n>$
^{8}He	0.5	30.13	18.60	1.62
^{6}He	0.33	27.66	19.60	1.41
^{9}Li	0.33	31.39	24.91	1.26
^{3}He	-0.33	14.71	19.35	0.76
^{3}H	0.33	19.61	14.96	1.31
^{8}Li	0.25	28.95	23.98	1.21
^{10}Be	0.20	30.20	25.95	1.16
^{7}Li	0.14	26.88	24.54	1.09
^{9}Be	0.11	29.82	27.09	1.10
^{11}B	0.09	33.40	31.75	1.05

R. B. Wiringa, R. Sehiavilla. S.C. Pieper, J. Carlson, Phys. Rev. C89, 024305 (2014).

Heavy nuclei $(A > 12)$

$$< T_{p(n)} > = \int n_{p(n)}(k) \cdot \frac{k^2}{2m} \cdot d^3k$$

Taking a simple np- dominance model:

$$n_p(k) = \begin{cases} \eta \cdot n_{MF}(k) & k \leq k_0 \\ \dfrac{a_{2(A/d) \cdot n_d(k)}}{2 \cdot Z/A} & k \geq k_0 \end{cases}$$

$$n_n(k) = \begin{cases} \eta \cdot n_{MF}(k) & k \leq k_0 \\ \dfrac{a_{2(A/d) \cdot n_d(k)}}{2 \cdot N/A} & k \geq k_0 \end{cases}$$

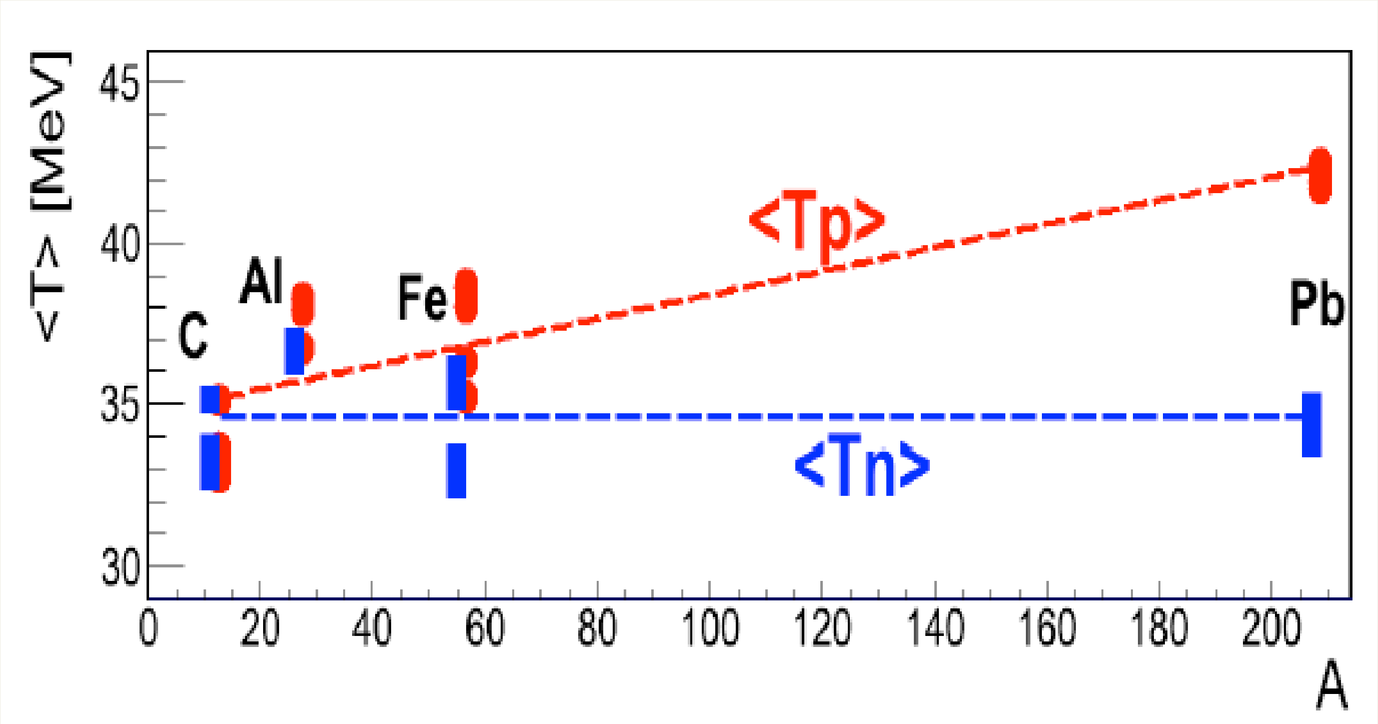
where η is determined by: $4\pi \int n_{p(n)}(k) k^2 dk = 1$

Considered 3 models for $n_{MF}(k)$:

* **Wood Saxon**
* **Serot – Walecka**
* **Ciofi and Simula**

Considered 2 values of k_0:

* **300 MeV/c**
* k_F



O. Hen et al., Science 346, 614 (2014)

How to check this hypothesis experimentally?

Problem: One body momentum distributions are not observables.

Solution: Define proxy which:

1. Reflects well the difference between proton and neutron momentum distributions.
2. Can be well determined experimentally.

Compare it to calculation.

A direct consequence of np- dominance for asymmetric nuclei:

Protons move faster than neutrons

$< K_p > \; > \; < K_n >$ $\qquad$ $< T_p > \; > \; < T_n >$

^{208}Pb: $\quad N = 128 \quad Z = 82$

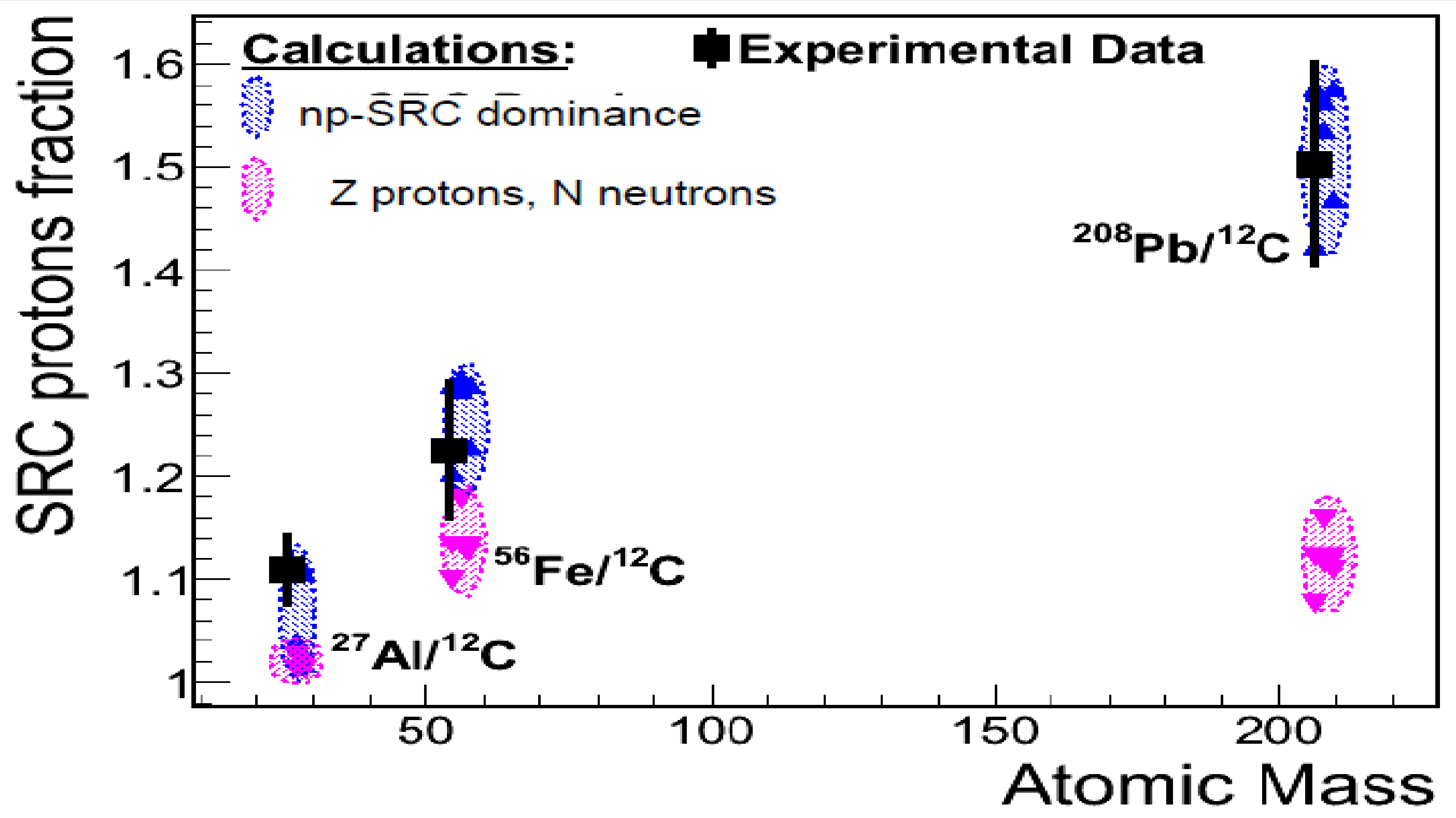
$$R_p = \frac{\#\, protons|_{k>K_F}}{\#\, protons|_{k<K_F}} \approx \frac{16}{82-16} \approx 0.25$$

$$R_n = \frac{\#\, neutrons|_{k>K_F}}{\#\, neutrons|_{k<K_F}} \approx \frac{16}{128-16} \approx 0.15$$

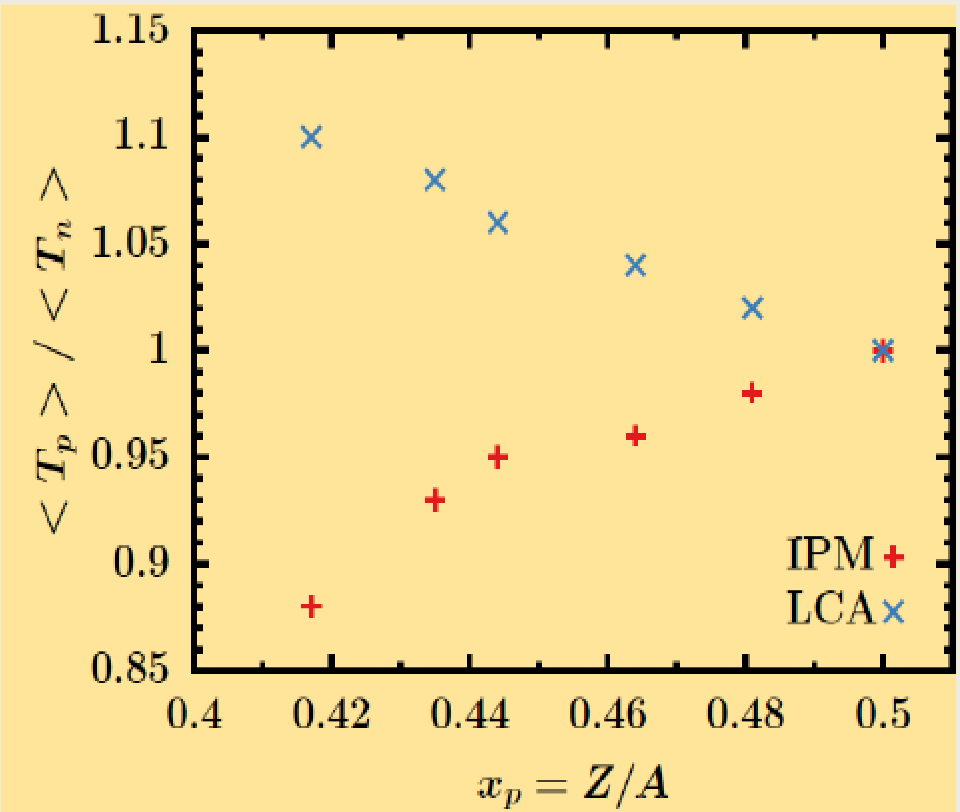
$$\frac{R_p}{R_n} \approx 1.7$$

$$\frac{A(e,e'p)/^{12}C(e,e'p)|high}{A(e,e'p)/^{12}C(e,e'p)|low}$$

$(e, e'p)$ double ratio



Another prediction for $< T_p > / < T_n >$ ratio



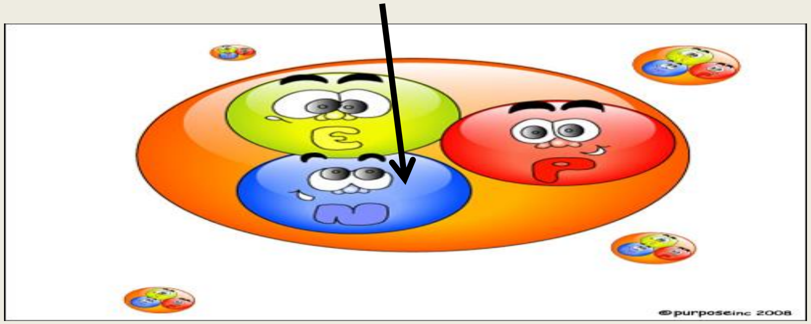
Average kinetic energy per nucleon

	$\langle T_N \rangle$ (MeV)			
	IPM (p)	IPM (n)	LCA (p)	LCA(n)
^{27}Al	16.61	16.92	30.93	30.26
^{40}Ca	16.44	16.42	31.23	31.18
^{48}Ca	15.64	17.84	33.04	30.06
^{56}Fe	16.71	17.45	32.33	31.13
^{108}Ag	16.48	17.81	33.55	31.16

Jan Ryckebusch (Ghent University), ECT Workshop, June 2015.

What's next?

Neutrons



* **Detecting neutrons in the EC – M. Braverman thesis (2014).**

The goal:

Calculating $\frac{A(e,e'n)/^{12}C(e,e'n)|high}{A(e,e'n)/^{12}C(e,e'n)|low}$ **ratio.**

To do so:

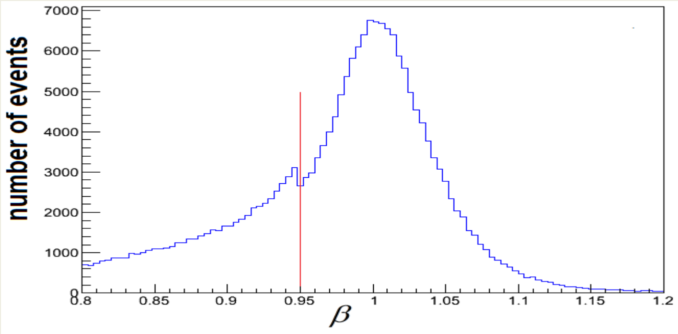
* **Identify $(e, e'n)$ mean field events.**
* **Identify $(e, e'n)$ SRC events.**

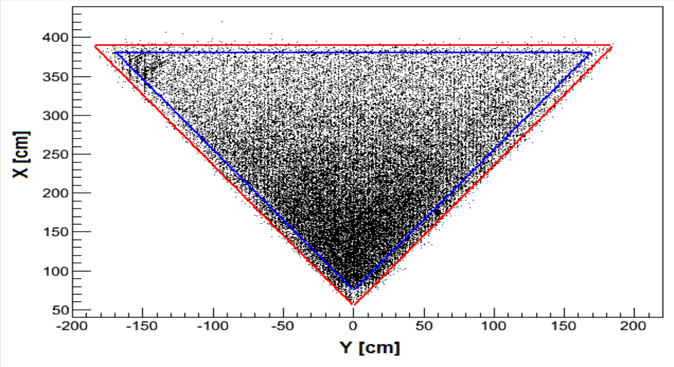
Calculating $\frac{(e,e'p)}{(e,e'n)}$ ratio

* **EG2 data:** ^{2}d , ^{12}C , ^{27}Al , ^{56}Fe , ^{208}Pb
* **Select (e,e'p) QE events**
* **Identify (e,e'n) QE events**
* **Check the event selection**
* **Apply corrections**
* **Calculate $\frac{(e,e'p)}{(e,e'n)}$ ratio**

Select $(e, e'p)$ events

* (e,e'p) events were taken with acceptance similar to nuetrons:
  1. $\beta < 0.95$
  2. EC fiducial cut
  3. $|\vec{p}| < 2.34\ GeV/c$



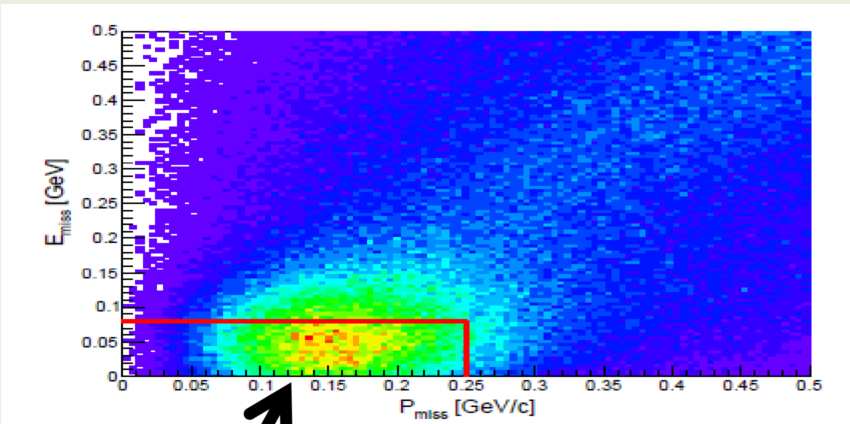


Selecting Quasi-Elastic events

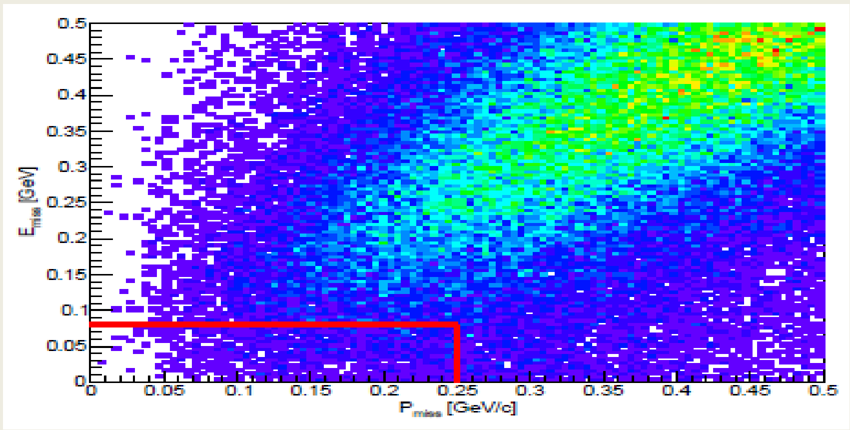
Problem: Low resolution in the EC - $\Delta P \sim 200 \frac{MeV}{c}$.

Solution 1: Using smeared protons.

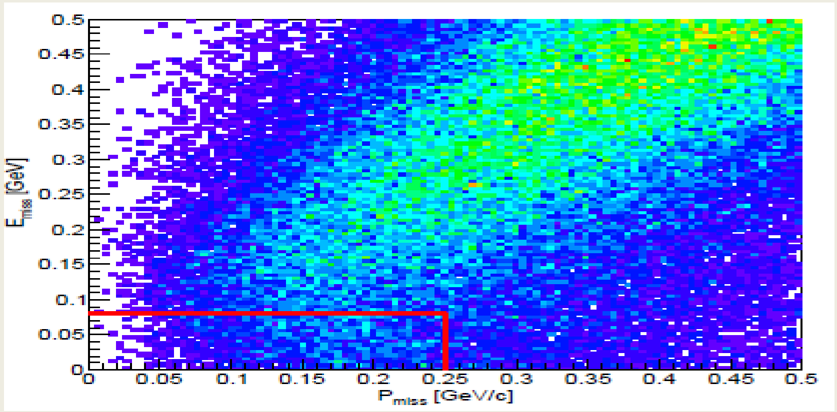
protons



smeared protons



neutrons



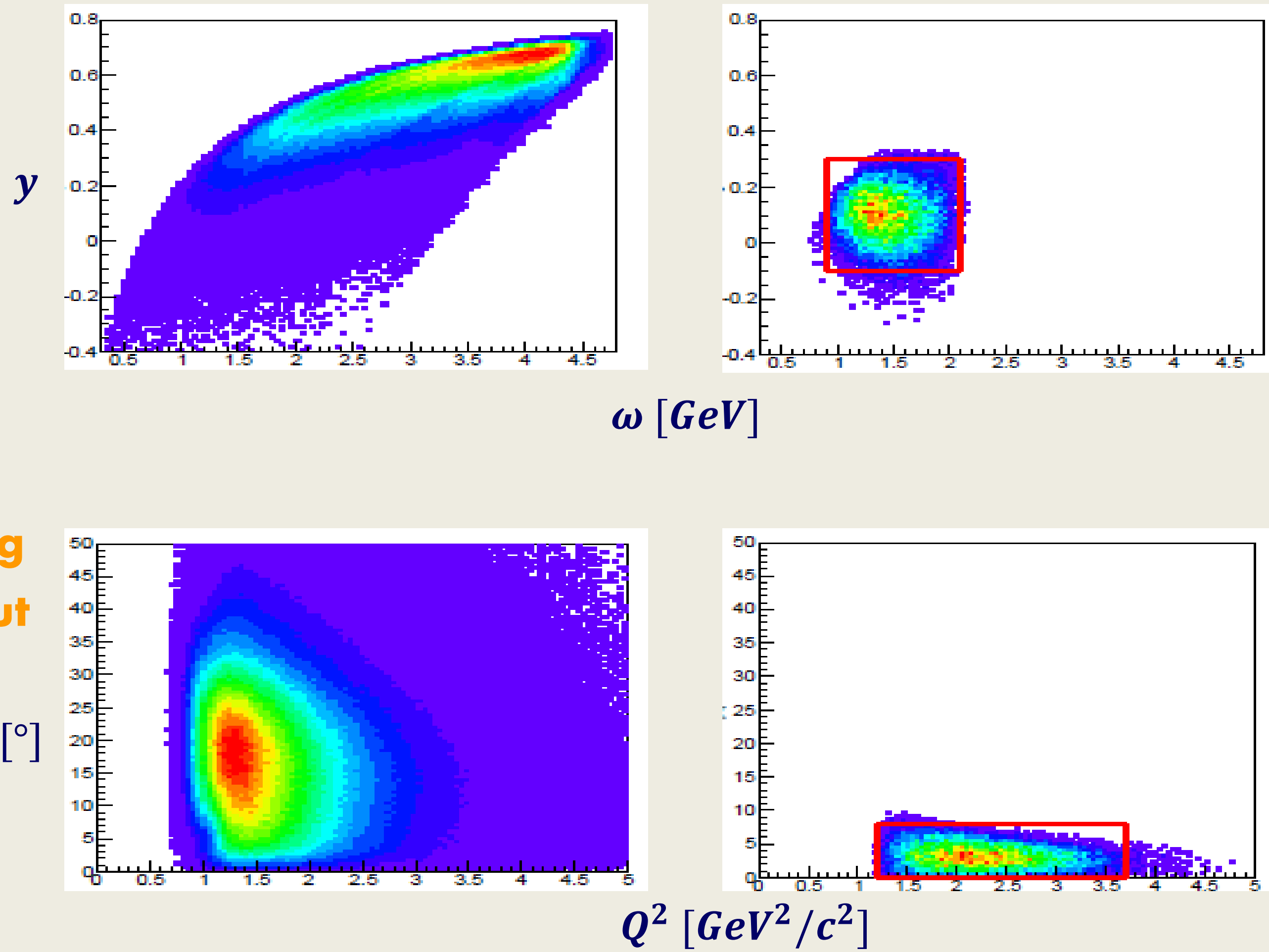
$E_{miss}\ vs.\ P_{miss}$

QE pick:

$P_{miss} < 0.25\ GeV/c$

$E_{miss} < 0.08\ GeV$

Solution 2: Using electron quantities and scattering angle of the nucleon.



before applying the QE cut

after applying the QE cut

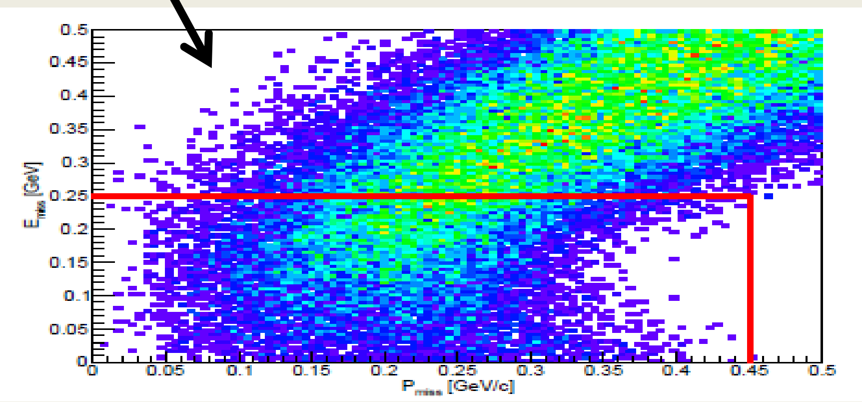
$$y \equiv \left((M_A + \omega)\sqrt{\Lambda^2 - {M^2}_{A-1} W^2} - q\Lambda \right) / W^2$$

$$\Lambda = ({M^2}_{A-1} - {M^2}_N + W^2)/2 \qquad W = \sqrt{(M_A + \omega)^2 - q^2}$$

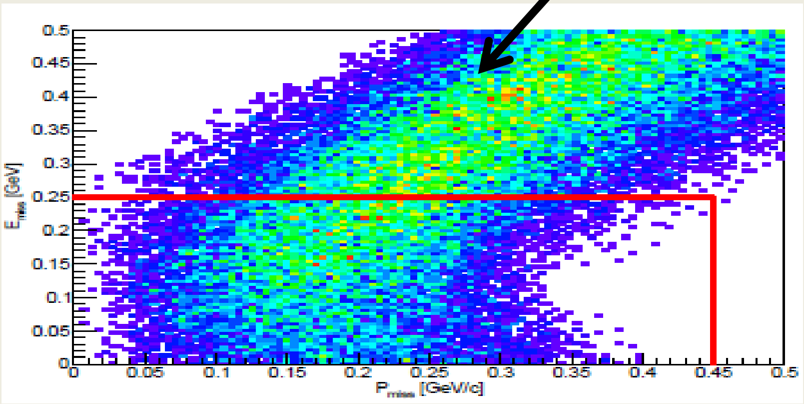
We applied the following cuts:

- $-0.1 < y < 0.3$
- $0.9 < \omega < 2.1\ GeV$
- $\theta_{pq} < 8^{o}$
- $1.2 < Q^2 < 3.7\ GeV^2/c^2$

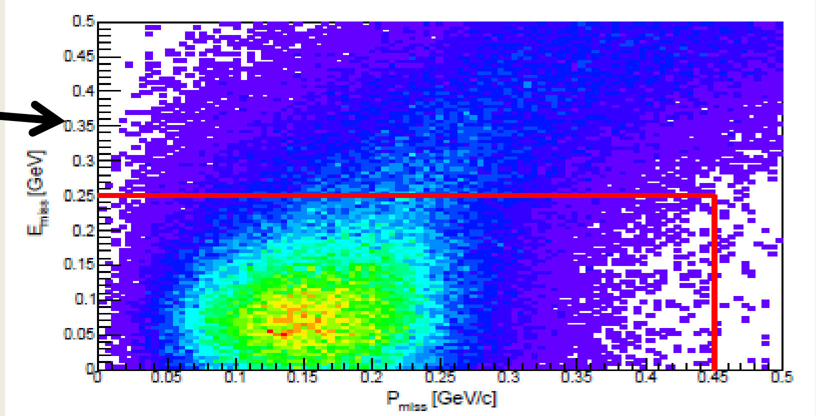
smeared protons



neutrons



un-smeared protons



The selected cuts:

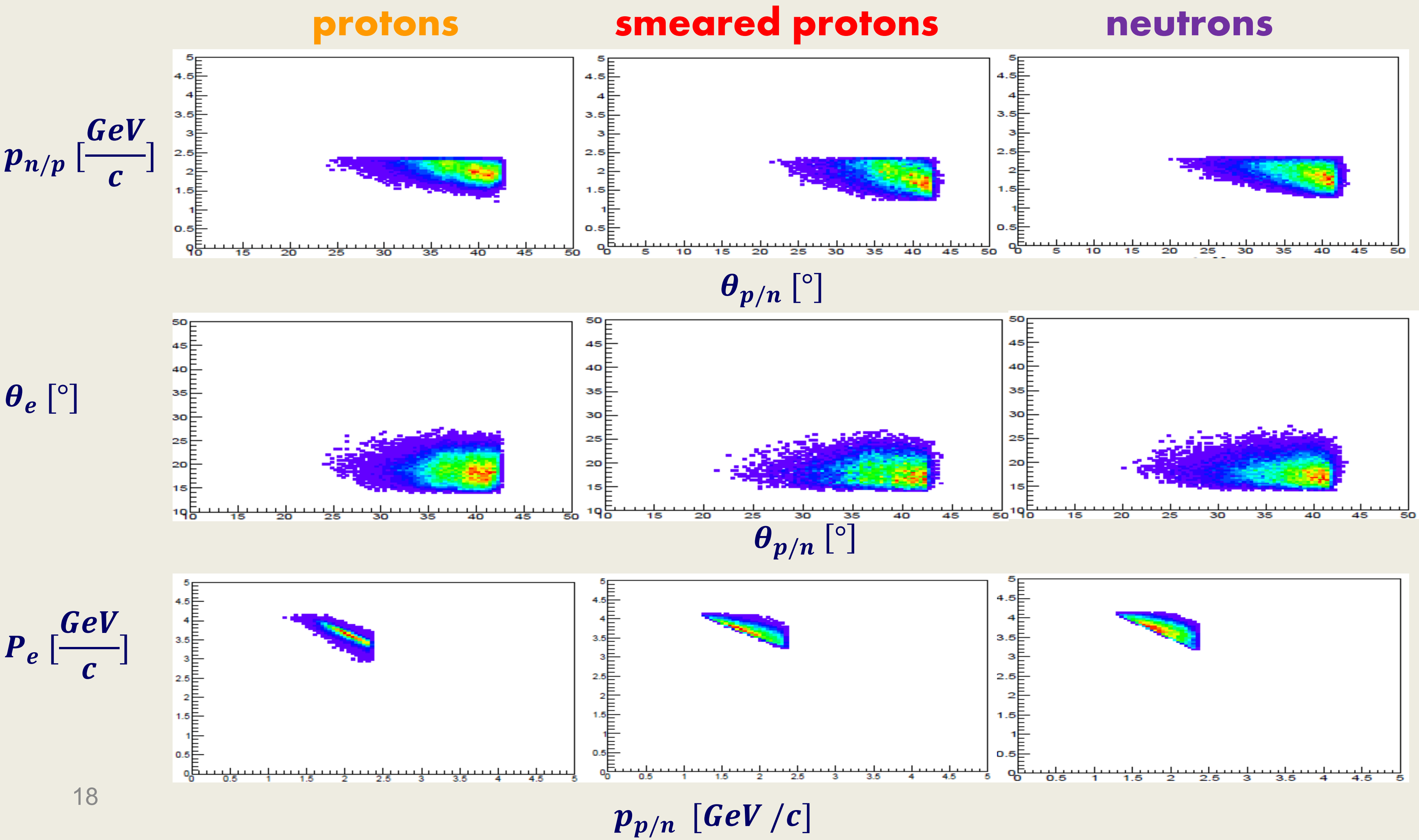
$P_{miss} < 0.45\ GeV/c$

$E_{miss} < 0.25\ GeV$

$E_{miss}\ vs.\ P_{miss}$

Checking Selection - 1

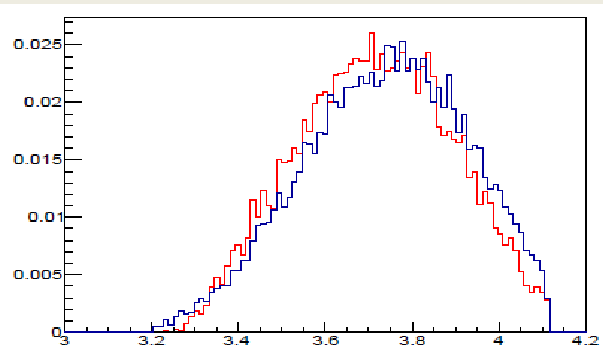
* We looked at pairs of kinematic variables which supposed to be correlated according to 2-body kinematics.



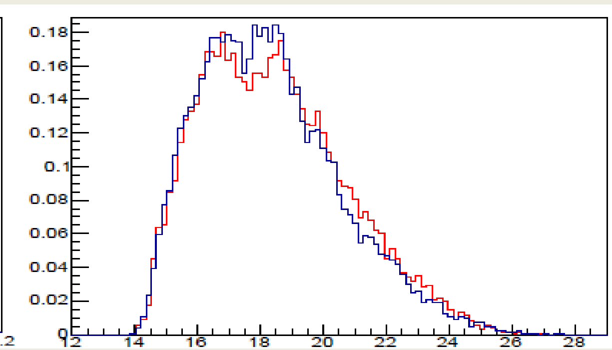
Checking Selection - 2

* We looked at the electron quantities distributions.

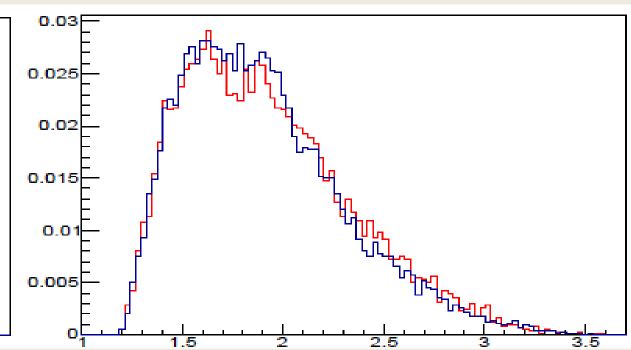
smeared protons neutrons



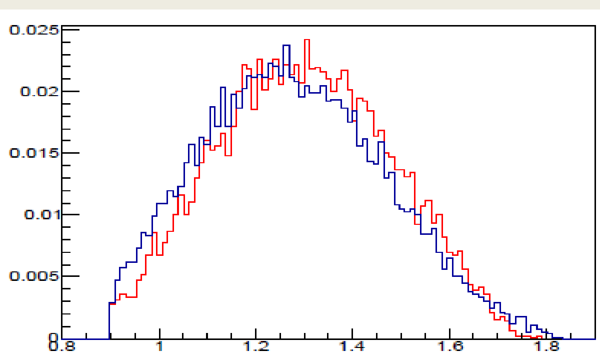
$P_e\left[\frac{GeV}{c}\right]$



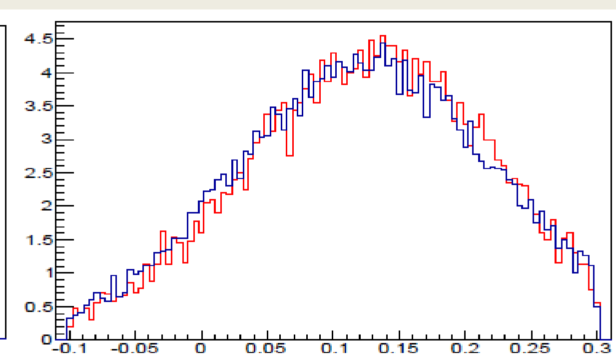
$\theta_e\ [^\circ]$



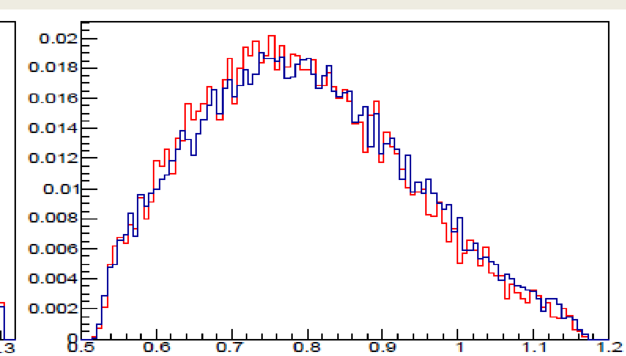
$Q^2\left[\frac{GeV^2}{c^2}\right]$



$\omega\left[\frac{GeV}{c}\right]$



y

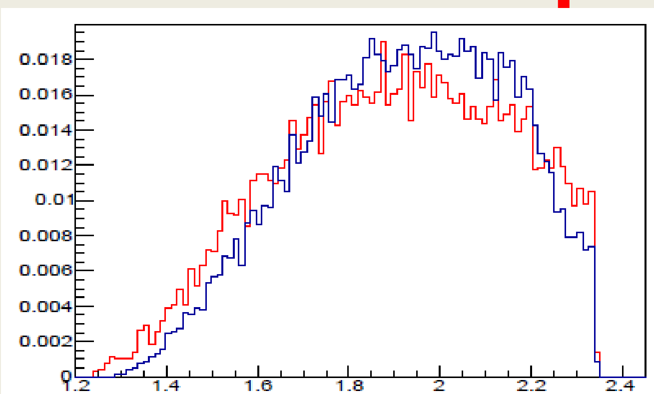


X_B

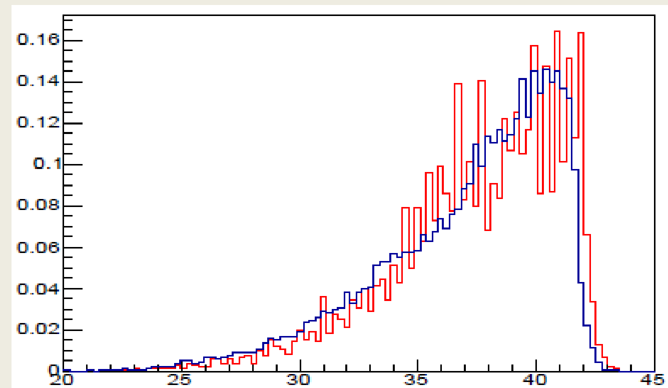
Checking Selection - 3

* **We looked at the smeared proton and neutron quantities.**

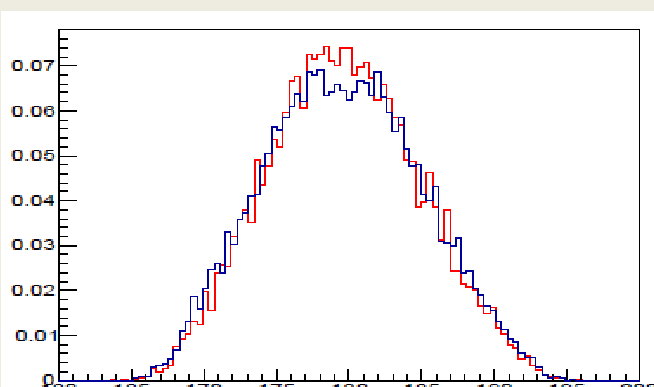
smeared protons **neutrons**



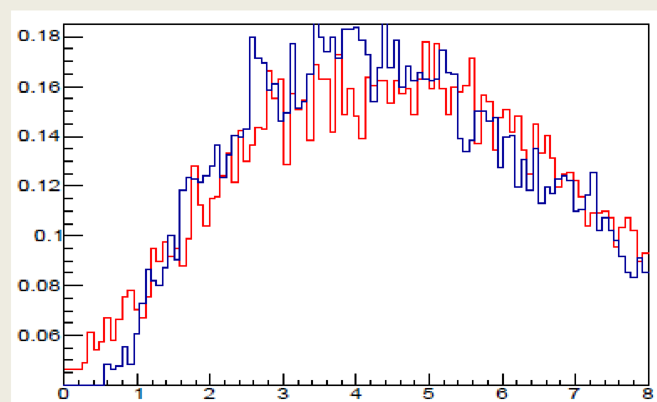
$p_{p/n}\left[\frac{GeV}{c}\right]$



$\theta_{p/n}\,[°]$



$|\varphi_{p/n} - \varphi_e|\,[°]$

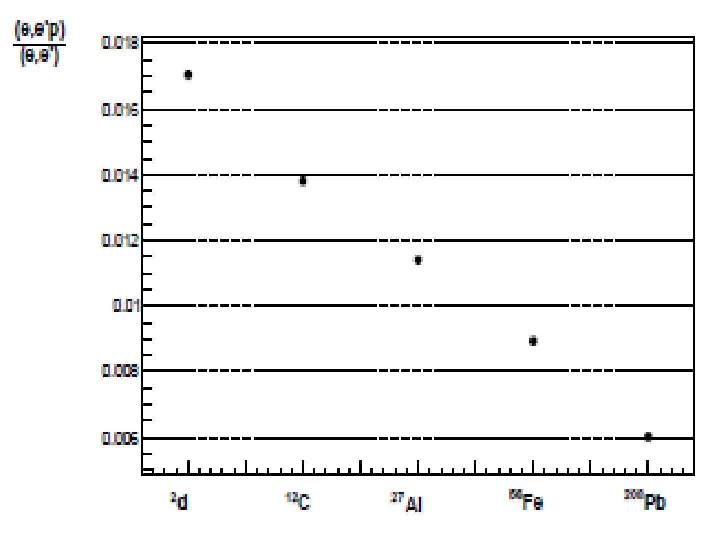


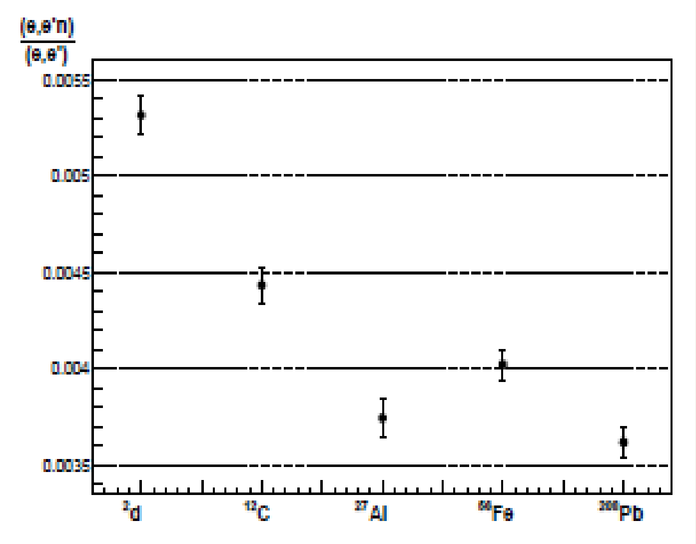
$\theta_{pq\backslash nq}\,[°]$

Checking Selection 4 - Transparency

* **We expect that the amount of (e,e'p) and (e,e'n) relatively to (e,e') will decrease as a function of A.**

un-smeared protons **neutrons**





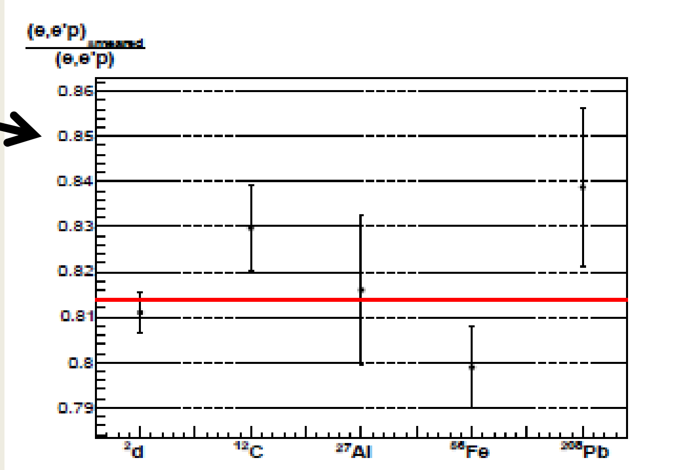
Corrections

Protons:

* **Coulomb correction**
* **Using CLAS Monte-Carlo simulation:**
    1. **Acceptance correction**
    2. **Detection efficiency**

Neutrons:

* **Correction for neutron resolution**
* **Using CLAS Monte-Carlo simulation:**
    1. **Acceptance correction**
    2. **Detection efficiency**
    3. **EC fiducial cut**



$\eta = 0.814 \pm 0.04(0.06) \quad \chi^2/NDF = 1.9$

Acceptance + Detection Efficiency

* **Same good** e
* **10,000** $(e, e'p)$ **events:**

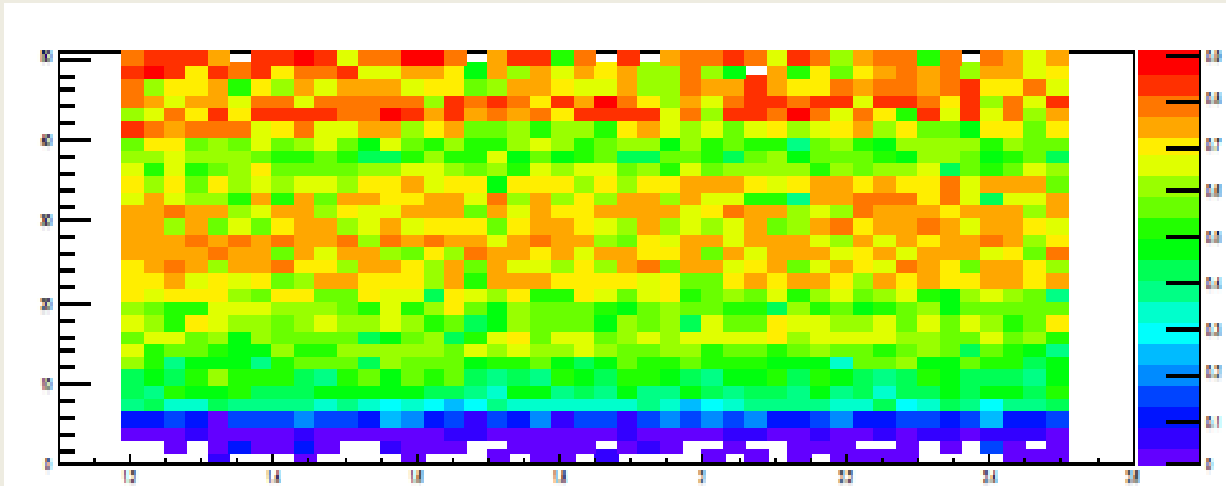
$$p \sim U(1.3, 2.4)$$
$$\theta_p \sim U(10, 50)$$

* **For each of them: 30 times** $\varphi_p \sim U(0, 2\pi)$
* **GSIM Monte-Carlo simulation**
* **GPP**
* **RECSIS**
* **Dividing in discovered/generated by binning in** p **and** θ_p

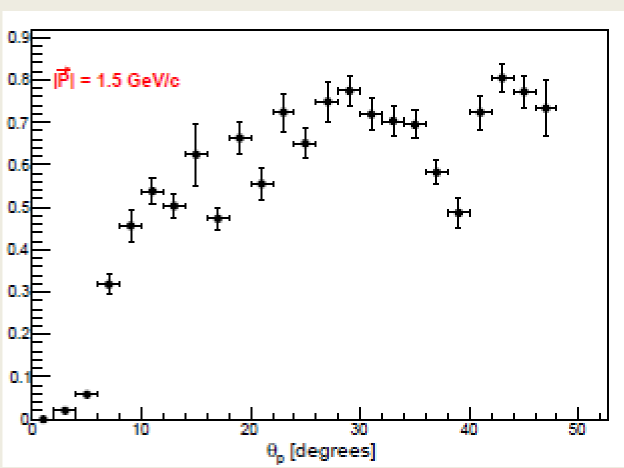
Acceptance + Detection Efficiency

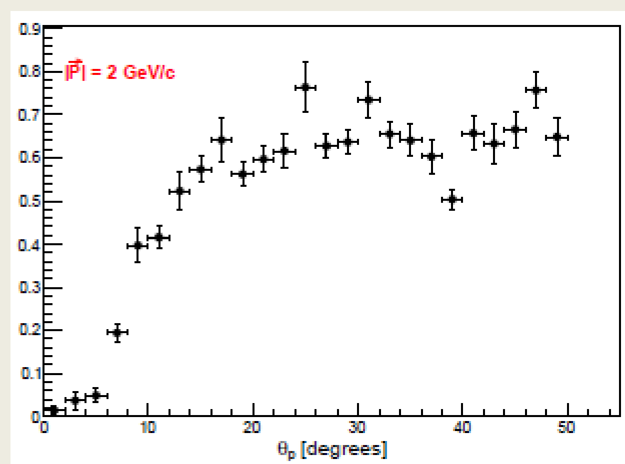
Protons

θ_p [°]



P_p $[\frac{GeV}{c}]$

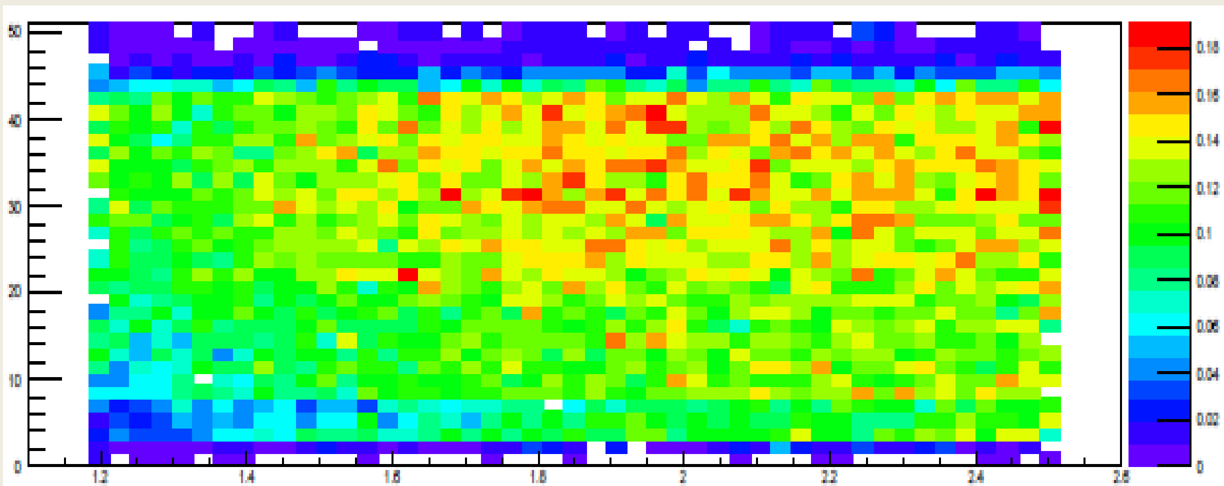




Acceptance + Detection Efficiency + Fiducial Cut

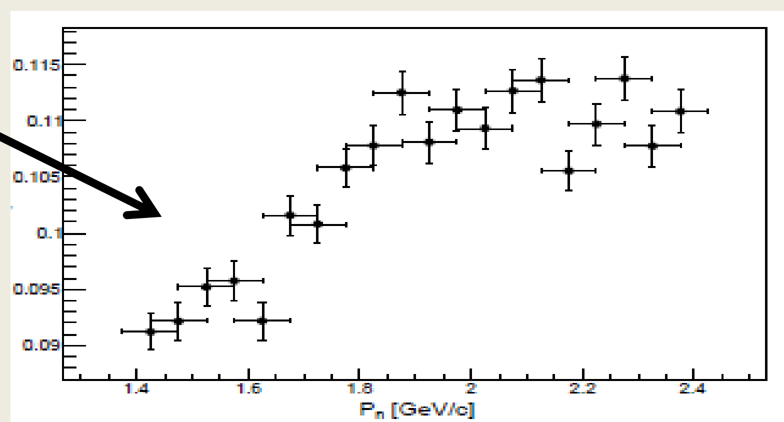
Neutrons

θ_n [°]



P_n [$\frac{GeV}{c}$]

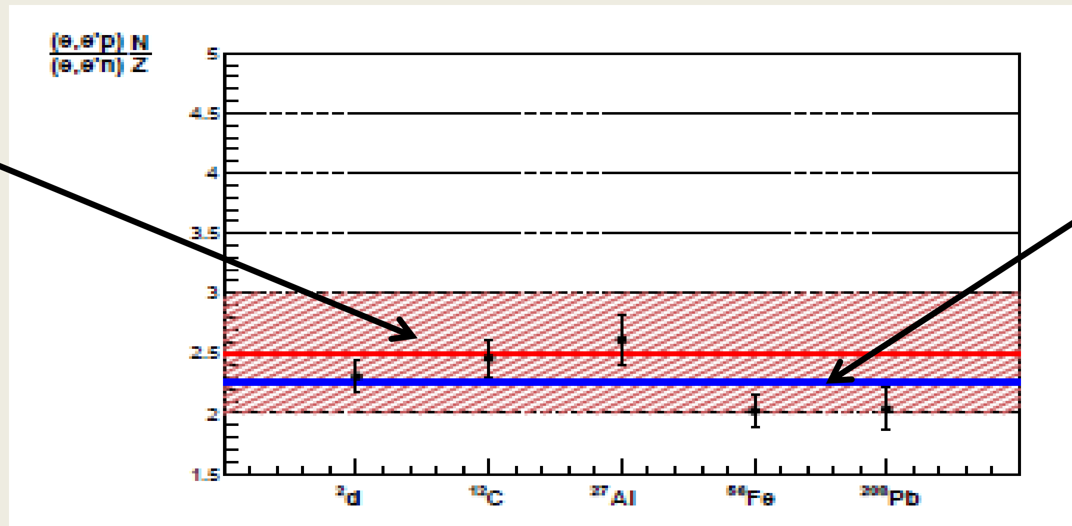
$\theta_n \approx 30^{\circ}$



$E_{beam} = 5.009\ GeV$

$\frac{(e,e'p)}{(e,e'n)} / \frac{Z}{N}$ ratios

2.5 ± 0.5



2.26 ± 0.13

(0.20)

$\frac{\chi^2}{NDF} = 2.3$

Red Lines= $\frac{\sigma_p}{\sigma_n}$ **and its** $\pm 1\sigma$ **limits as taken from [1].**

Blue Line= **our result to a constant fit.**

[1] J. Lachniet, et al. Phys. Rev. Lett. 102, 192001 (2009).

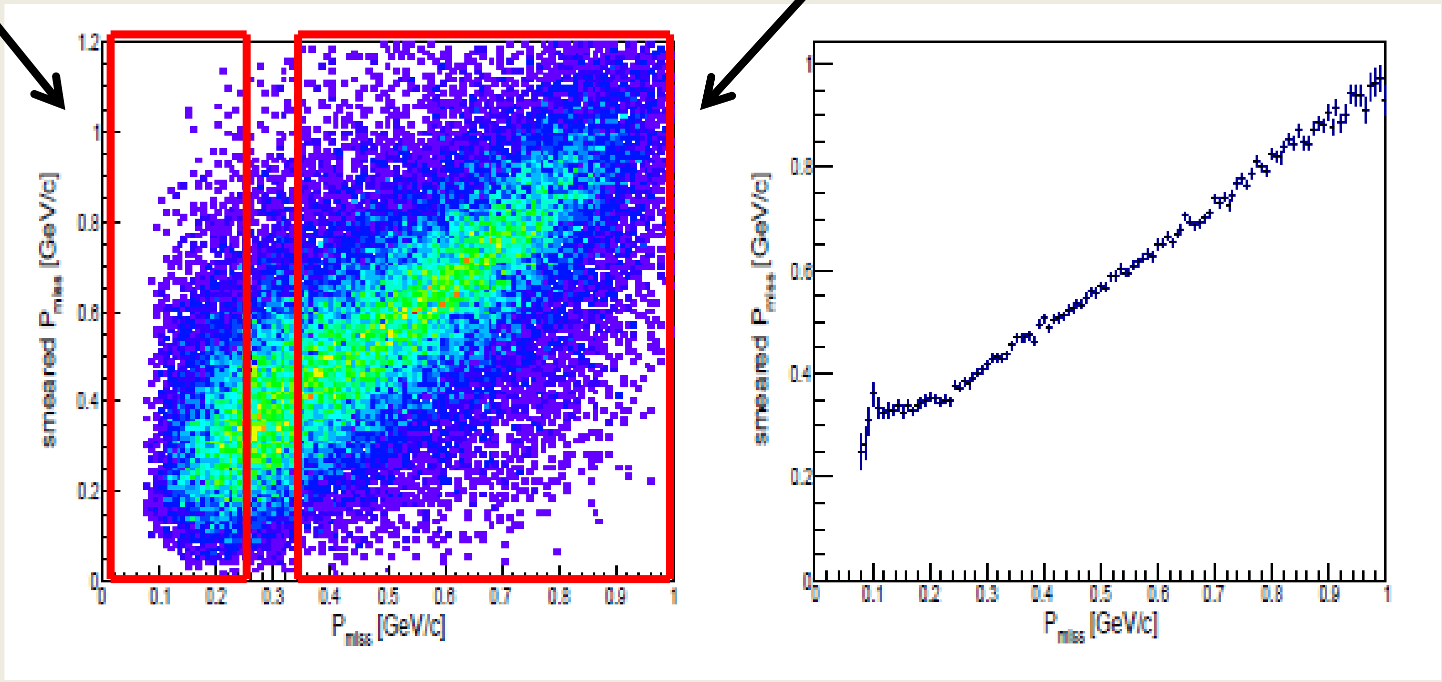
Smeared P_{miss} vs. un-smeared

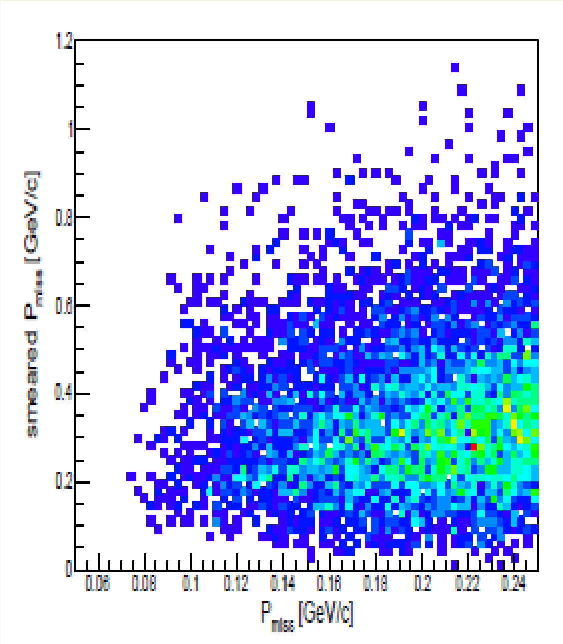
$^{12}C(e,e'p)$ & $^{12}C(e,e'p_{smeared})$

- $-0.1 < y < 0.3$
- $\theta_{pq} < 8^o$
- $0.9 < \omega < 2.1\ GeV$
- $1.2 < Q^2 < 3.7\ GeV^2/c^2$
- $\beta < 0.95$
- **EC fiducial cut**
- $|\vec{p}| < 2.34\ GeV/c$

low

high



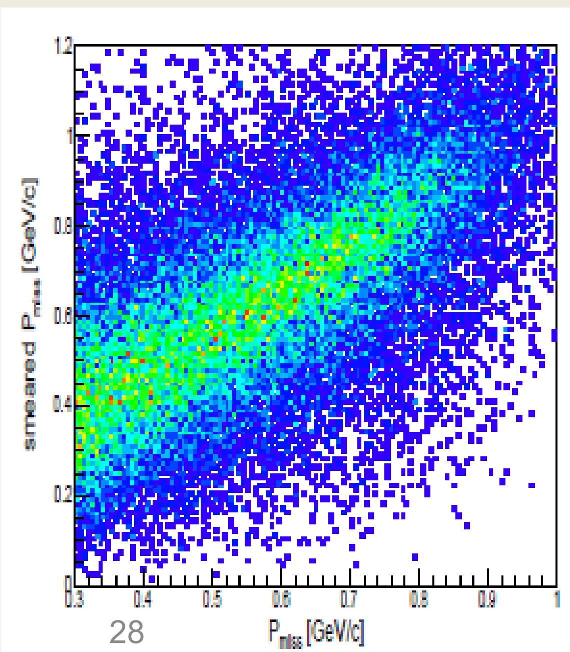


Low (lost events)

$$0 < P_{miss} < 0.25\ GeV/c$$

$$\eta_{low} = \left.\frac{\#(e,e'p)_{smeared}}{\#(e,e'p)}\right|_{P_{miss}<0.25} = 0.63 \pm 0.01$$

Statistical error



High (gain events)

$$0.35 < P_{miss} < 1\ GeV/c$$

$$\eta_{high} = \left.\frac{\#(e,e'p)_{smeared}}{\#(e,e'p)}\right|_{0.35<P_{miss}<1} = 1.17 \pm 0.02$$

Back to neutrons

With $\mathbf{E_{miss} < 0.25\ GeV}$**:** $\frac{\sigma_p}{\sigma_n} = 2.26 \pm 0.2$

$$\frac{\left.\frac{^{12}C(e,e'n)}{^{12}C(e,e'p)}\right|_{P_{miss}<0.25}}{\eta_{low}\cdot\frac{\sigma_p}{\sigma_n}} = 1.05 \pm 0.13(0.10)$$

Statistical error

$$\frac{\left.\frac{^{12}C(e,e'n)}{^{12}C(e,e'p)}\right|_{0.35<P_{miss}<1}}{\eta_{high}\cdot\frac{\sigma_p}{\sigma_n}} = 1.02 \pm 0.17(0.14)$$

Acceptance , detection efficiency , statistical , $\eta_{low,high}$, $\frac{\sigma_p}{\sigma_n}$, neutron resolution, fiducial cut (neutrons)

Before looking at the A-dependence:

* $R_p = \frac{{}^{12}C(e,e'p)_{0.35<p_{miss}<1}}{{}^{12}C(e,e'p)_{p_{miss}<0.25}}$

* $R_n = \frac{{}^{12}C(e,e'n)_{0.35<p_{miss}<1}}{{}^{12}C(e,e'n)_{p_{miss}<0.25}}$

?
$R_p \approx R_n$

* **Review all the uncertainties of the ratios presented**

* **Prepare a review for the CLAS analysis committee**

Future Plans

np- dominance

$$\frac{A(e,e'n)/{}^{12}C(e,e'n)|high}{A(e,e'n)/{}^{12}C(e,e'n)|low}$$

2N – SRC

$(e,e'np_{back})$

3N- SRC

$(e,e'npp)$

Backup slides

(e, e') selection

In order to select (e, e') events we applied the following cuts:

- $-0.1 < y < 0.3$
- $0.9 < \omega < 2.1\ GeV$
- $1.2 < Q^2 < 3.7\ GeV^2/c^2$

$(e, e'n)$ selection

In order to select $(e, e'n)$ events we applied the following cuts and corrections:

* $-0.1 < y < 0.3$
* $0.9 < \omega < 2.1\ GeV$
* $1.2 < Q^2 < 3.7\ GeV^2/c^2$
* $\theta_{pq} < 8^o$
* $\beta < 0.95$
* **EC fiducial cut**
* $|\vec{p}| < 2.34\ GeV/c$
* $P_{miss} < 0.45 \frac{GeV}{c}$
* $E_{miss} < 0.25\ GeV$
* **Acceptance correction + detection efficiency + EC fiducial cut**
* **Effectiveness of the EC**

$(e, e'p)$ selection

In order to select $(e, e'p)$ events we applied the following cuts and corrections:

* $-0.1 < y < 0.3$
* $0.9 < \omega < 2.1\ GeV$
* $1.2 < Q^2 < 3.7\ GeV^2/c^2$
* $\theta_{pq} < 8^o$
* $\beta < 0.95$
* $|\vec{p}| < 2.34\ GeV/c$
* $\mathrm{P_{miss}} < 0.45 \frac{\mathrm{GeV}}{\mathrm{c}}$
* $E_{miss} < 0.25\ GeV$
* **Acceptance correction + detection efficiency**
* **Coulomb correction**

$\frac{(e,e'p_{smeared})}{(e,e'p)}$ selection

In order to select $(e,e'p)$ smeared and un-smeared events we applied the following cuts and corrections:

- $-0.1 < y < 0.3$
- $0.9 < \omega < 2.1\ GeV$
- $1.2 < Q^2 < 3.7\ GeV^2/c^2$
- $\theta_{pq} < 8^o$
- $\beta < 0.95$
- **EC fiducial cut**
- $|\vec{p}| < 2.34\ GeV/c$
- $\mathrm{P_{miss}} < 0.45 \frac{\mathrm{GeV}}{\mathrm{c}}$
- $E_{miss} < 0.25\ GeV$
- **Coulomb correction**

$\left.\frac{(e,e'p_{smeared})}{(e,e'p)}\right|_{p_{miss-low/high}}$ selection

In order to select $(e, e'p)$ smeared and un-smeared events we applied the following cuts and corrections:

* $-0.1 < y < 0.3$
* $0.9 < \omega < 2.1\ GeV$
* $1.2 < Q^2 < 3.7\ GeV^2/c^2$
* $\theta_{pq} < 8^o$
* $\beta < 0.95$
* **EC fiducial cut**
* $|\vec{p}| < 2.34\ GeV/c$
* $P_{miss} < 0.25 \frac{GeV}{c}$ or $0.35 < P_{miss} < 1\ GeV/c$
* **Coulomb correction**

$(e, e'n)$ selection

In order to select $(e, e'n)$ events we applied the following cuts and corrections:

- $-0.1 < y < 0.3$
- $0.9 < \omega < 2.1\ GeV$
- $1.2 < Q^2 < 3.7\ GeV^2/c^2$
- $\theta_{pq} < 8^o$
- $\beta < 0.95$
- **EC fiducial cut**
- $|\vec{p}| < 2.34\ GeV/c$
- $E_{miss} < 0.25\ GeV$
- $P_{miss} < 0.25 \frac{GeV}{c}$ or $0.35 < P_{miss} < 1\ GeV/c$
- **Acceptance correction + detection efficiency + EC fiducial cut**
- **Divided by** $\eta_{low} = 0.63 \pm 0.01$ or $\eta_{high} = 1.17 \pm 0.02$

$(e, e'p)$ selection

In order to select $(e, e'p)$ events we applied the following cuts and corrections:

- $-0.1 < y < 0.3$
- $0.9 < \omega < 2.1\ GeV$
- $1.2 < Q^2 < 3.7\ GeV^2/c^2$
- $\theta_{pq} < 8^o$
- $\beta < 0.95$
- $|\vec{p}| < 2.34\ GeV/c$
- $E_{miss} < 0.25\ GeV$
- $P_{miss} < 0.25 \frac{GeV}{c}$ or $0.35 < P_{miss} < 1\ GeV/c$
- **Acceptance correction + detection efficiency**
- **Coulomb correction**