Probing high-momentum neutrons and protons in asymmetric nuclei

A data-mining project using JLAB CLAS data

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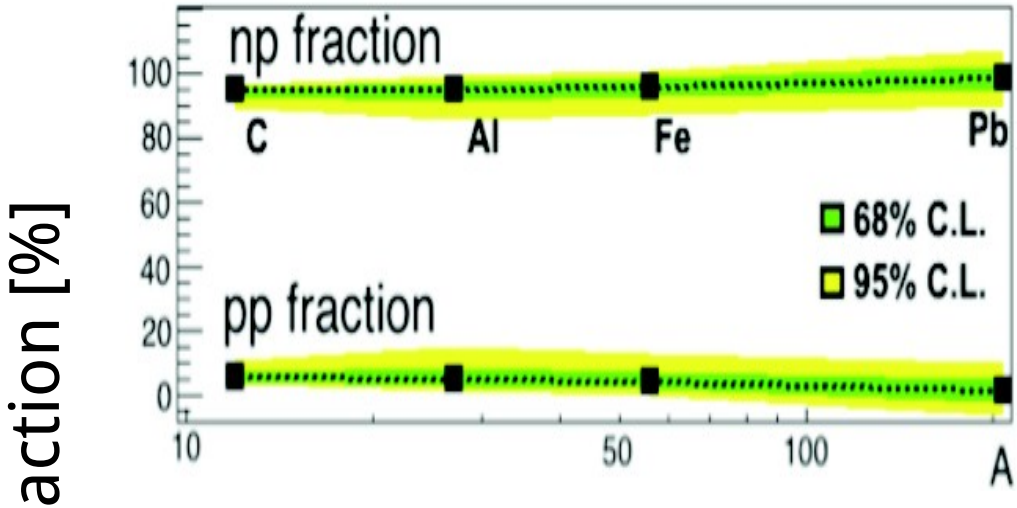
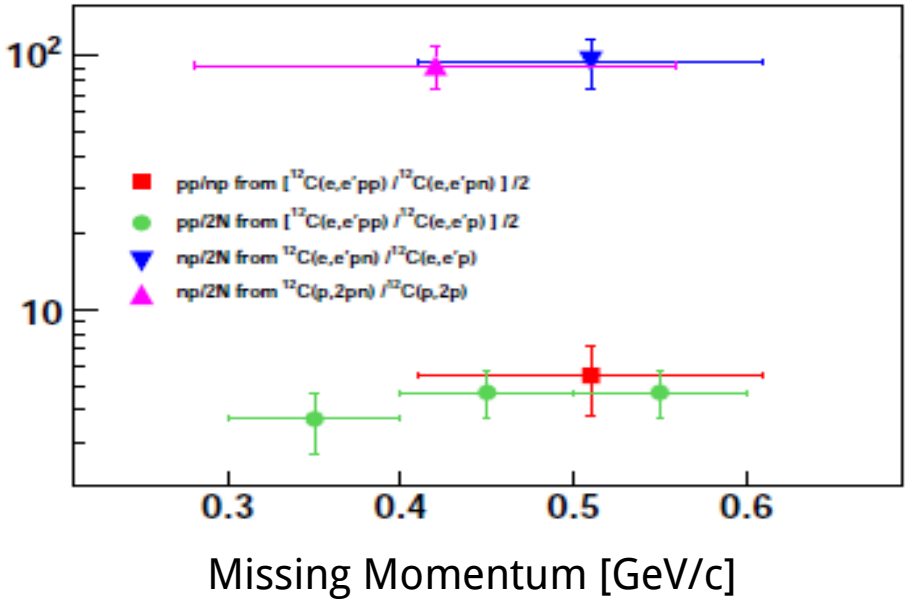
Workshop on high-density nuclear matter, Weizmann Institute

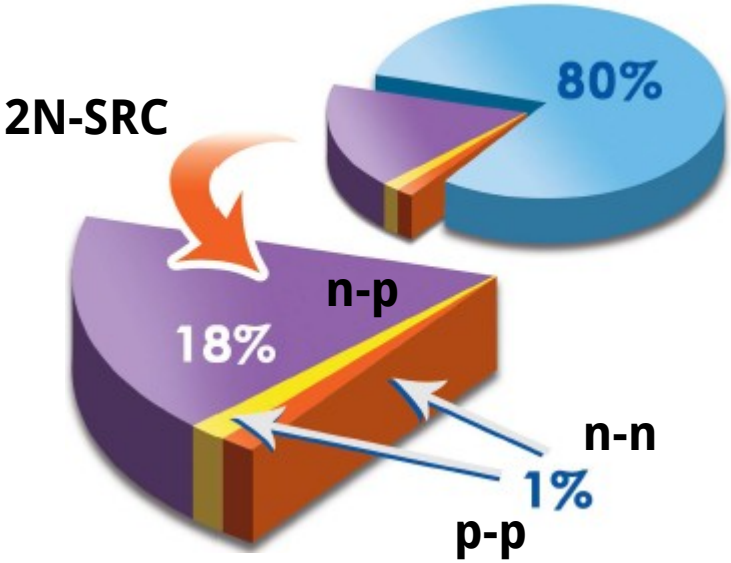
np-dominance in 2N-SRC



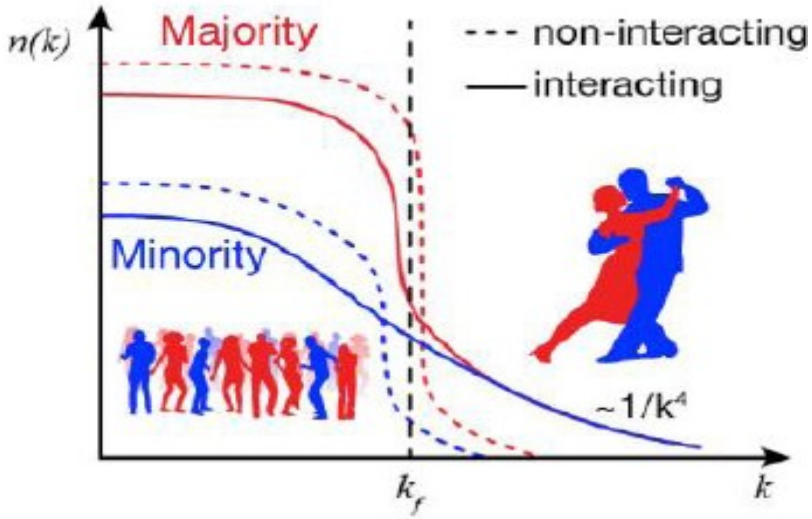
O. Hen et al., Science 346, 614 (2014)



R. Subedi et al., Science 320, 1476 (2008).



np-dominance in asymmetric nuclei



M. Sargsian Phys. Rev. C89(2014)3, 034305

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

N>Z

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

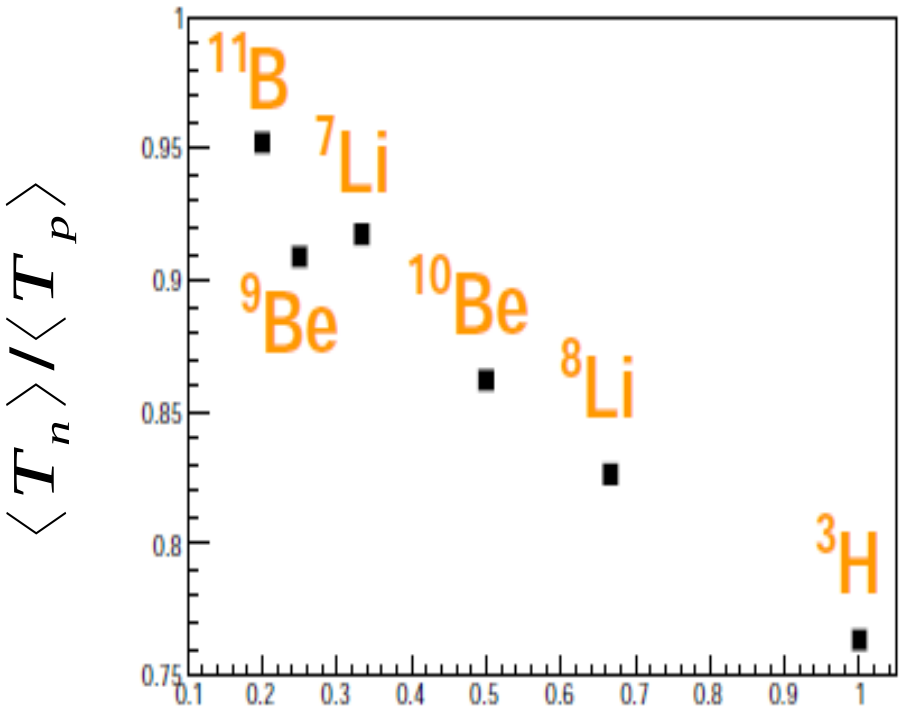
Pauli principle → $\langle T_n \rangle > \langle T_p \rangle$

SRC → $\langle T_p \rangle \overset{?}{>} \langle T_n \rangle$

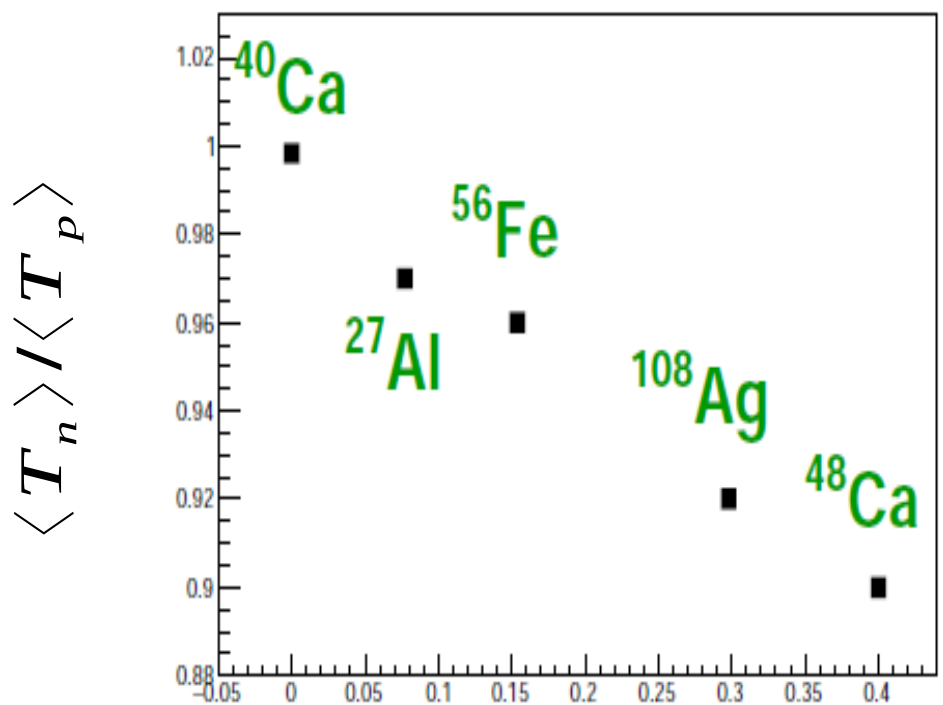
Possible inversion of the momentum sharing

Theoretical predictions for $\langle T_n \rangle / \langle T_p \rangle$ N>Z

Light nuclei (A<12)



Heavy nuclei (A>12)



Neutron Excess [(N-Z)/Z]

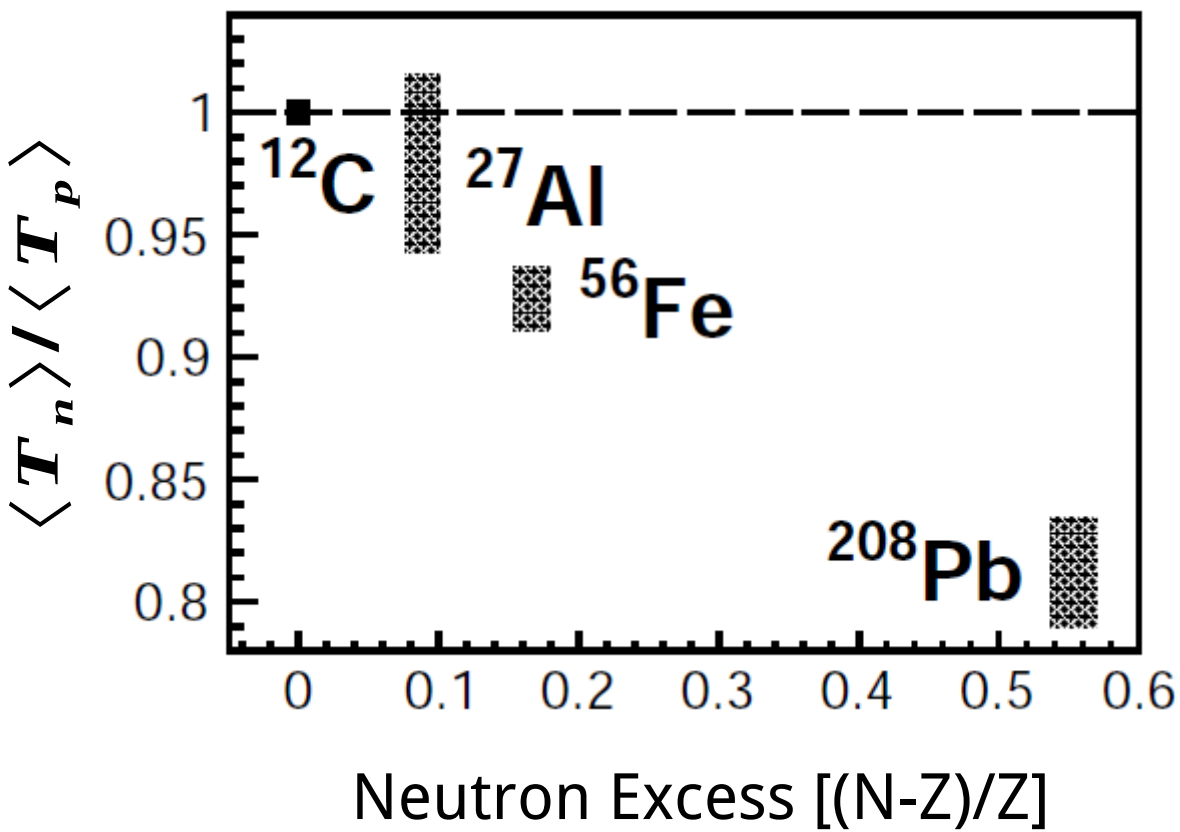
, R. B. Wiringa, R. Sehiavilla. S.C. Pieper, J. Carlson
.Phys. Rev. C89, 024305 (2014)

J. Ryckebusch, M. Vanhalst and W. Cosyn,
arXiv:1405.3814v3 [nucl-th] (2015).

Simple np-dominance model

$$n_p(k) = \begin{cases} \eta \cdot n_p^{M.F.}(k) & k < k_0 \\ \frac{A}{2Z} \cdot a_2(A/d) \cdot n_d(k) & k > k_0 \end{cases}$$

(for neutrons: Z → N)



$n^{M.F.}(k)$:

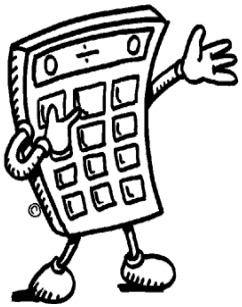
* Wood-Saxon
* Serot- Walecka
* Ciofi & Simula

k_0:

* 300 MeV/c
* k_F

M. Sargsian

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

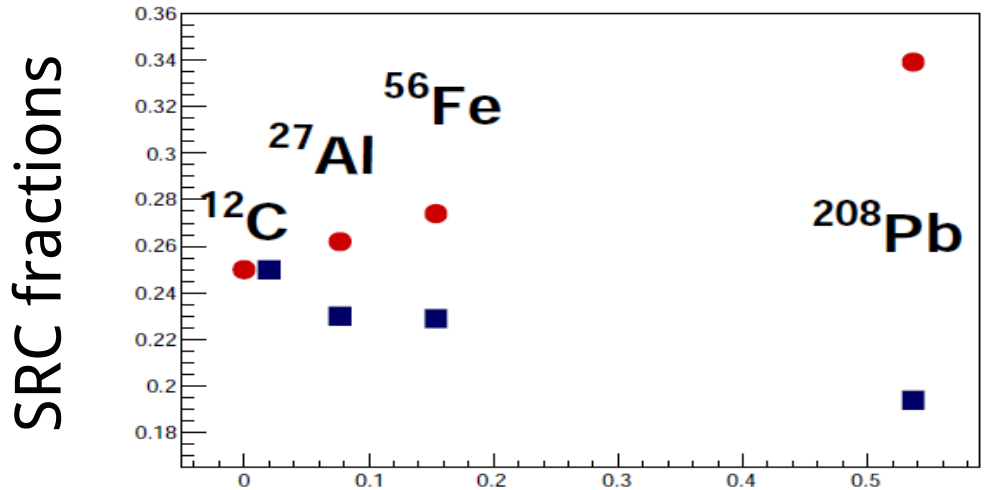


Calculation ⟶ Measurement

Simple estimate based on np-dominance

$$^{208}Pb: \qquad Z=82 \qquad N=126$$

$$R_P=\frac{protons_{k>k_F}}{protons_{k<k_F}}\approx\frac{20}{82-20}=0.32 \qquad R_n=\frac{neutrons_{k>k_F}}{neutrons_{k<k_F}}\approx\frac{20}{126-20}=0.19$$



Neutron Excess [(N-Z)/Z]

The goal:

Extracting $\dfrac{A(e,e'n)_{high}/A(e,e'n)_{low}}{^{12}C(e,e'n)_{high}/^{12}C(e,e'n)_{low}}$ **ratios**

(and same for protons)

The steps:

* **Identify (e,e'n) mean-field events** $(low\ missing\ momentum)$

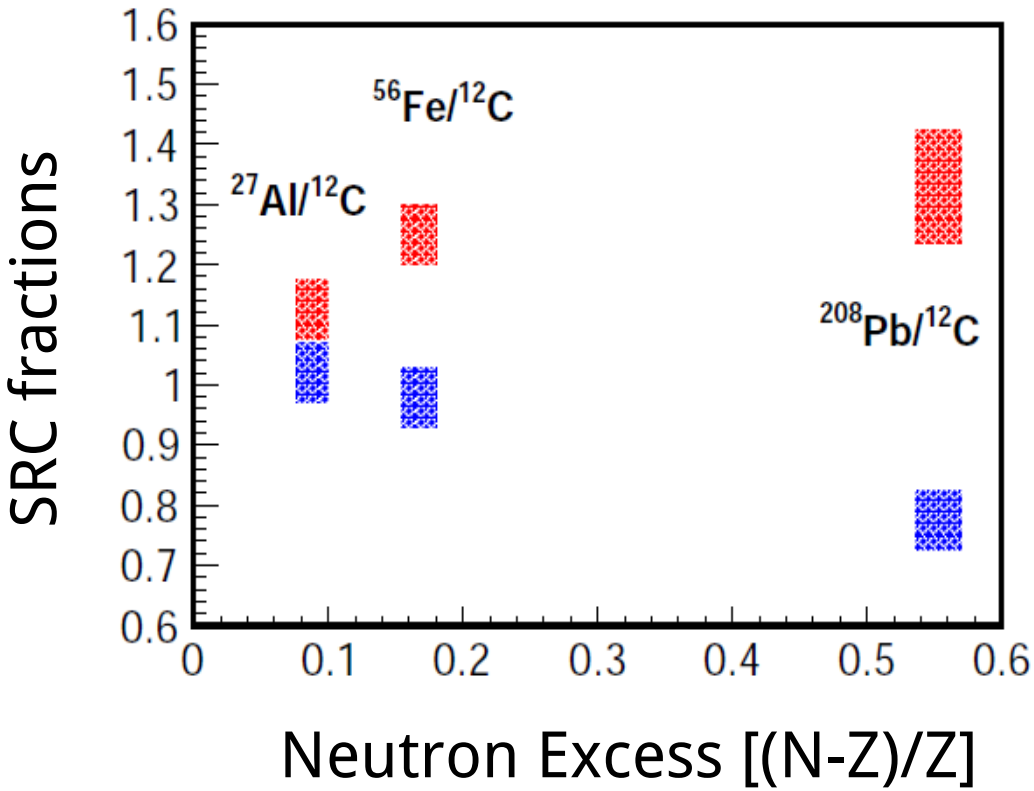
* **Identify (e,e'n) 2N-SRC events** $(high\ missing\ momentum)$

* **Extract ratios and their uncertainties**

Simple prediction based on the np-dominance model

$$\frac{A(e,e'n)/^{12}C(e,e'n)_{k>k_0}}{A(e,e'n)/^{12}C(e,e'n)_{k<k_0}}$$

$$\frac{A(e,e'p)/^{12}C(e,e'p)_{k>k_0}}{A(e,e'p)/^{12}C(e,e'p)_{k<k_0}}$$



$$\#A(e,e'N) \propto \begin{cases} \int n^{M.F.}(k)k^2dk & k<k_0 \\ \int n^{SRC}(k)k^2dk & k>k_0 \end{cases}$$

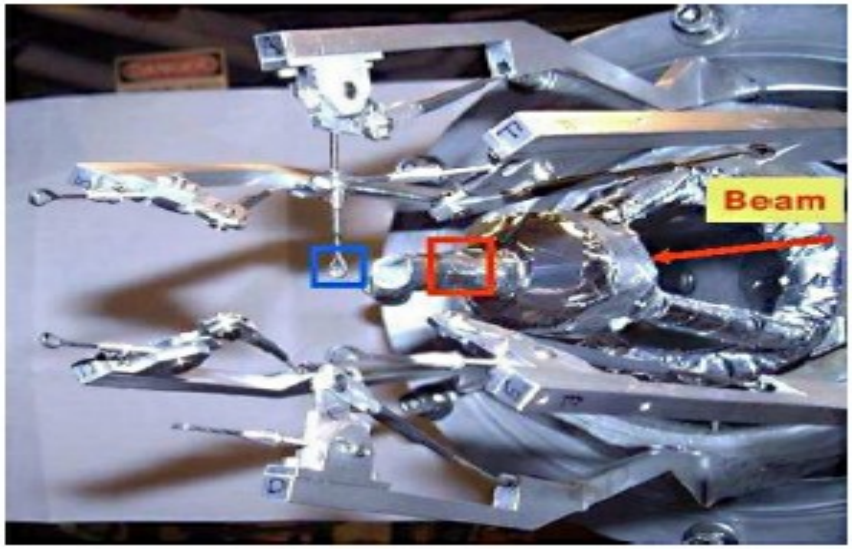
Data Mining

JLAB CLAS EG2 data set

Run at 2004 in Hall-B **5.014 GeV electron beam**

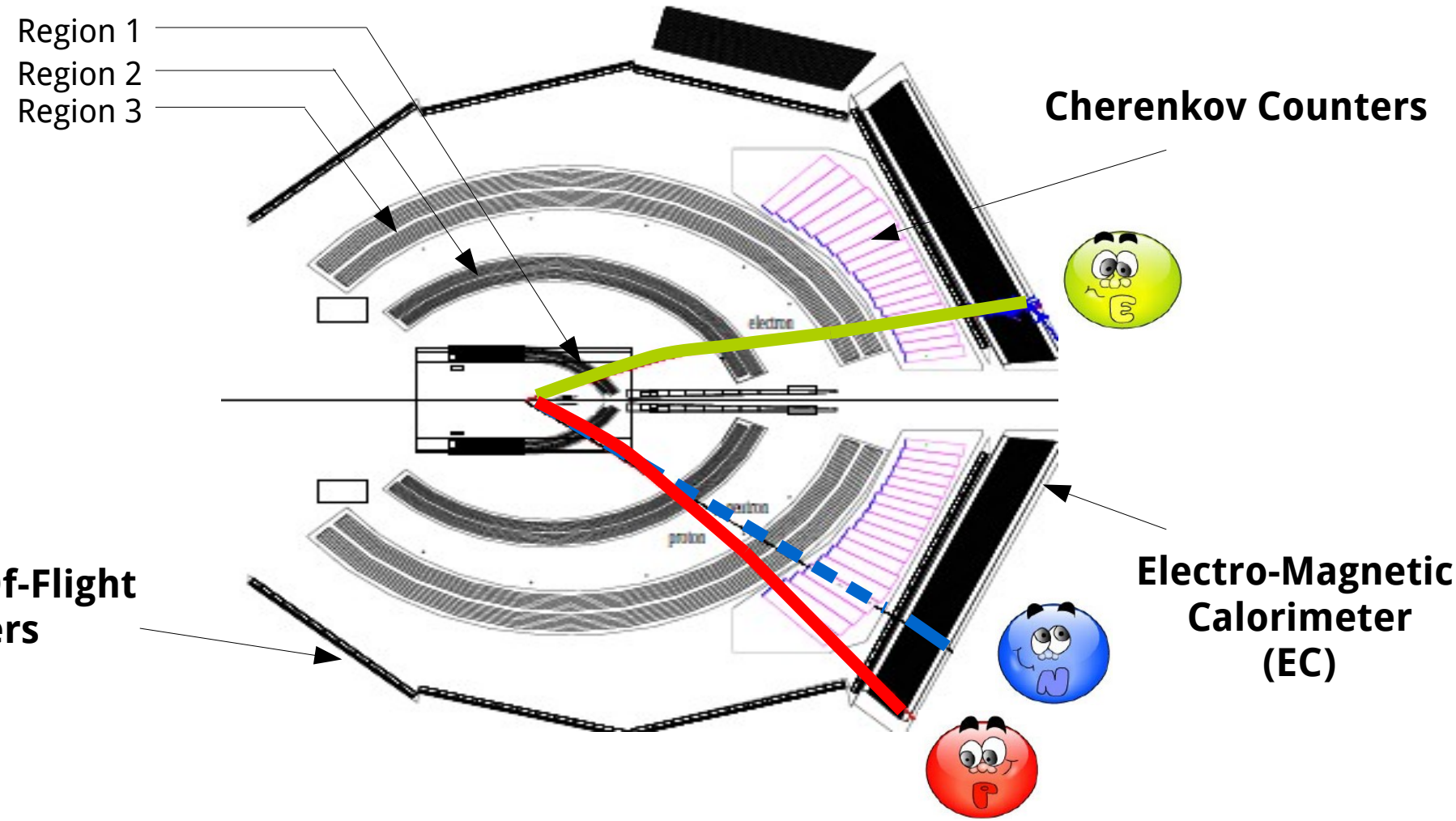
Deuterium + Solid target simultaneously

$$^{12}C/^{27}Al/^{56}Fe/^{208}Pb$$



Particle Identification

Drift Chambers:



CLAS analysis note, L. El Fassi, 2011

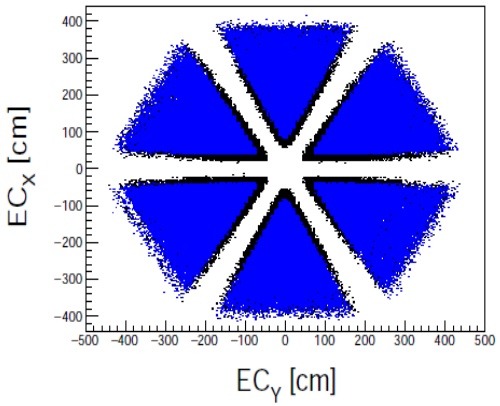
O. Hen et al., Phys. Lett. B 772, 63 (2013) O. Hen et al., Science 346, 614 (2014)

Detecting neutrons in CLAS EC (M. Braverman TAU thesis, 2014)

Detecting neutrons in CLAS EC

* No signals from Drift-Chambers & Time-Of-Flight Counters

* Hit inside the EC fiducial cut

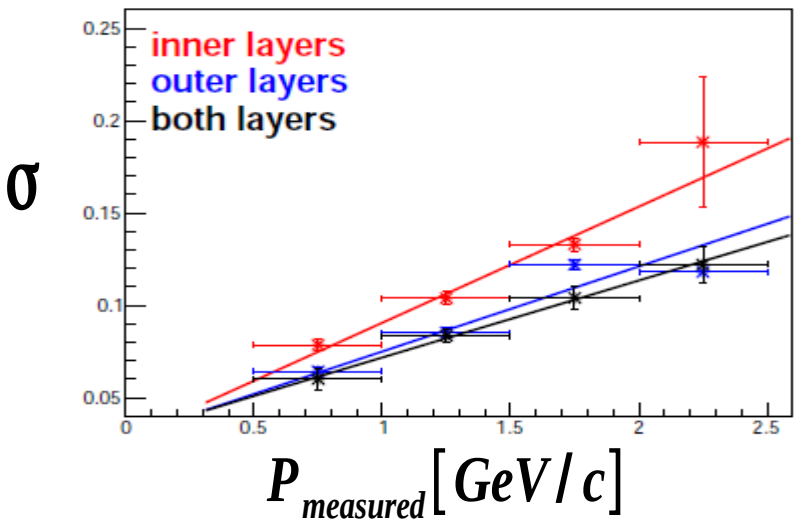


* n/γ separation: β<0.95

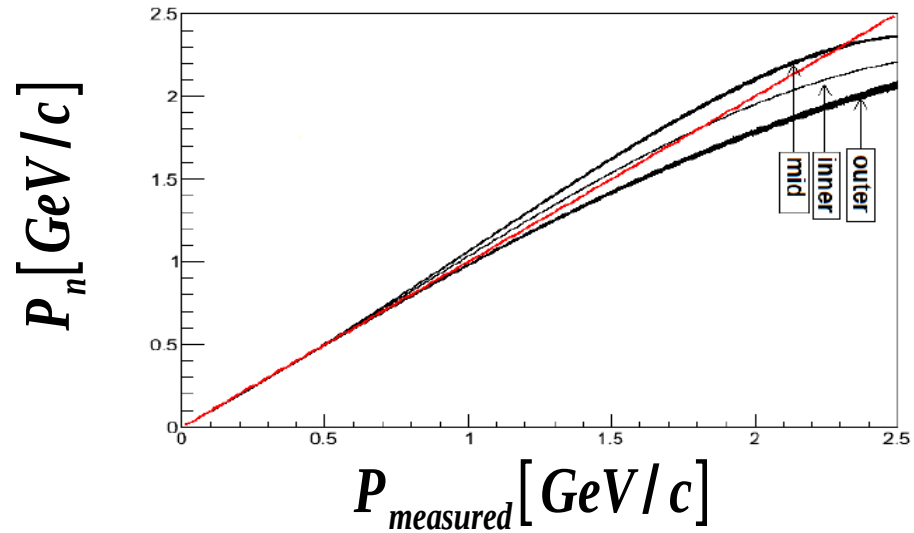
$$\beta = \frac{R}{T \cdot c}$$

Using an exclusive reaction $d(e,e'p\pi^+\pi^-n)$

Momentum resolution

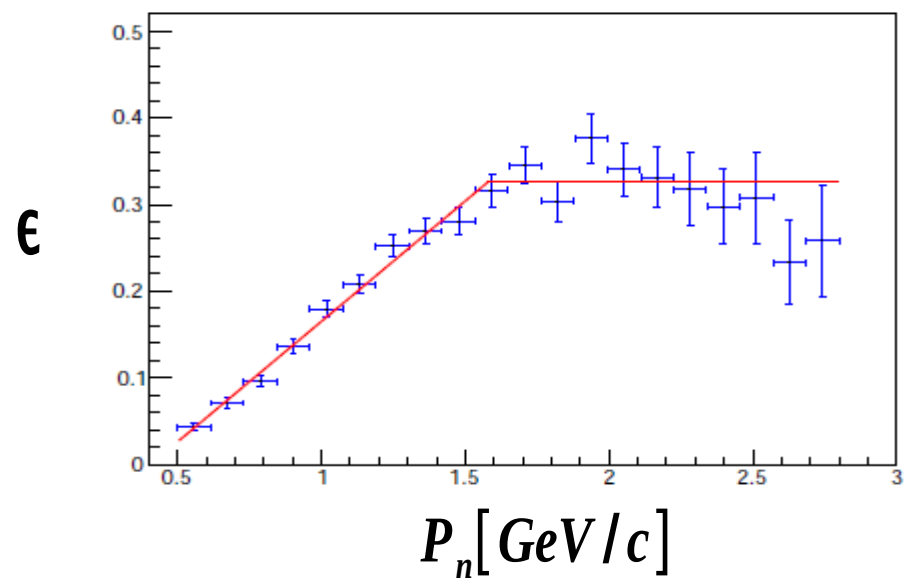


Empirical momentum correction



Detection efficiency

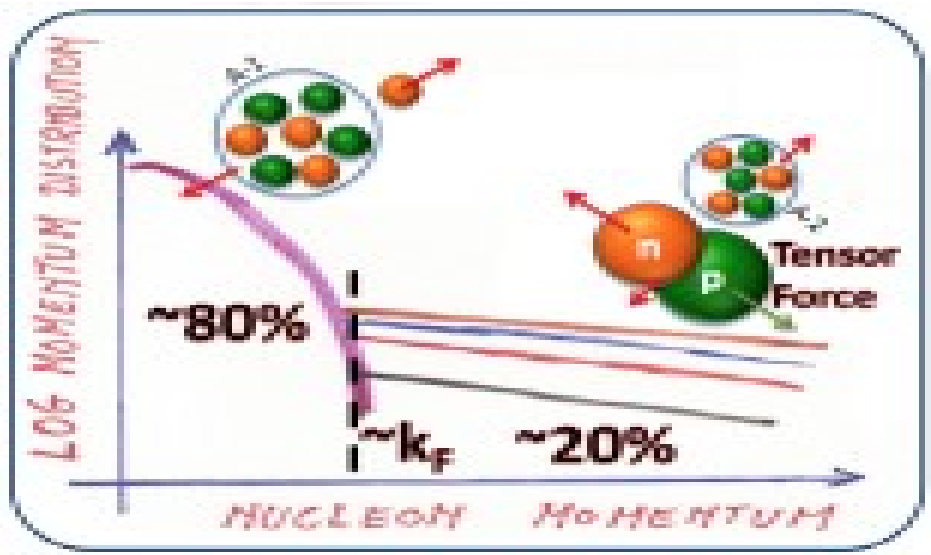
$$\epsilon = \frac{d(e,e'p\pi^+\pi^-)n}{d(e,e'p\pi^+\pi^-n)}$$



Analysis of QE events:

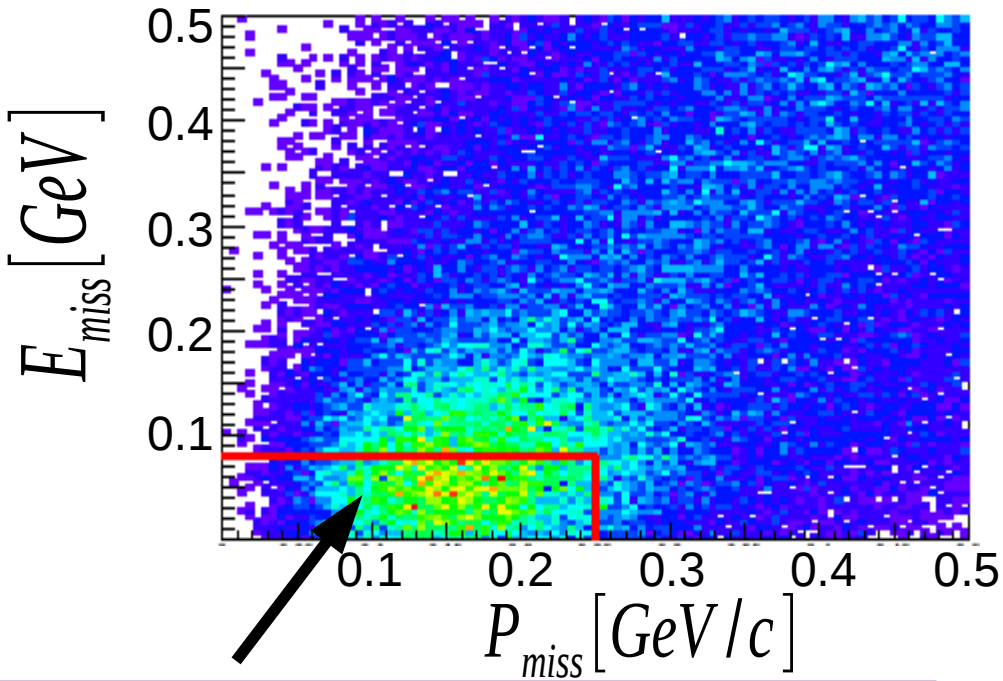
I. Identifying A(e,e'n) and A(e,e'p) mean-field events

II. Identifying A(e,e'n) and A(e,e'p) high-momentum events

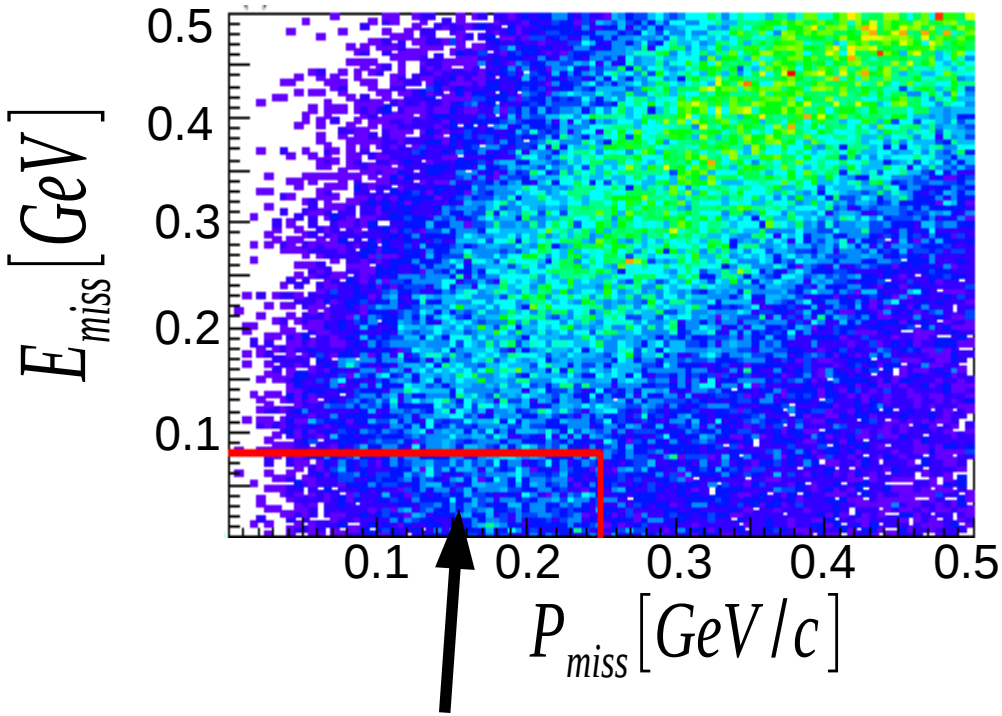


Selecting M.F. QE events

protons



neutrons



QE peak:

P_{miss}<0.25 GeV/c
E_{miss}<0.08 GeV

Problem:

Poor resolution in the EC -

$\Delta P \approx 0.2 GeV/c$

T.G. ONeill et al., Phys. Lett. B 87, 351 (1995).
D. Abbott et al. Phys. Rev. Lett. 80, 5072 (1998).
K. Garrow et al. Phys. Rev. C. 66, 044613 (2002).

Solutions

I. Using electron quantities & scattering angle of the nucleon

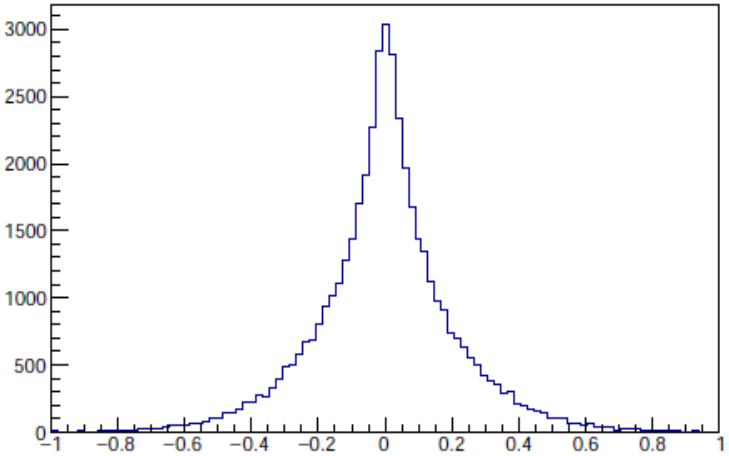
$$-0.05 < y < 0.25 \qquad 0.95 < \omega < 1.7\,GeV \qquad \theta_{pq} < 8^o$$

$$y \equiv [(M_A + \omega)^2 \sqrt{\lambda^2 - M_{A-1}^2 W^2} - |\vec{q}|\lambda]/W^2 \qquad W = \sqrt{(M_A + \omega)^2 - |\vec{q}|^2} \qquad \lambda = (M_{A-1}^2 - M_N^2 + \omega^2)/2$$

II. Using smeared protons to:

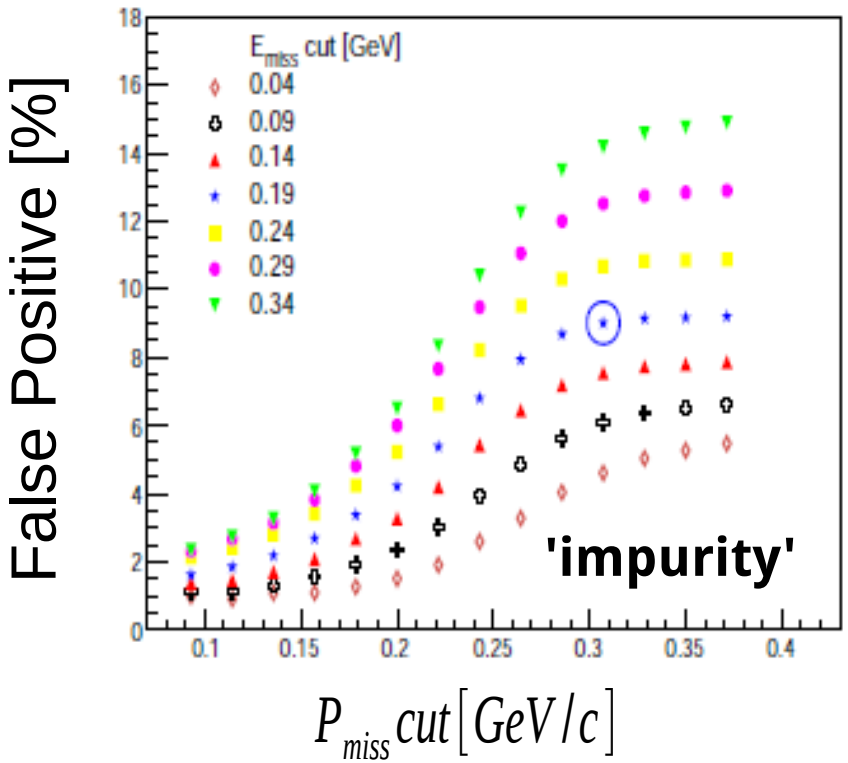
* Define and test the cuts
* Study bin migration

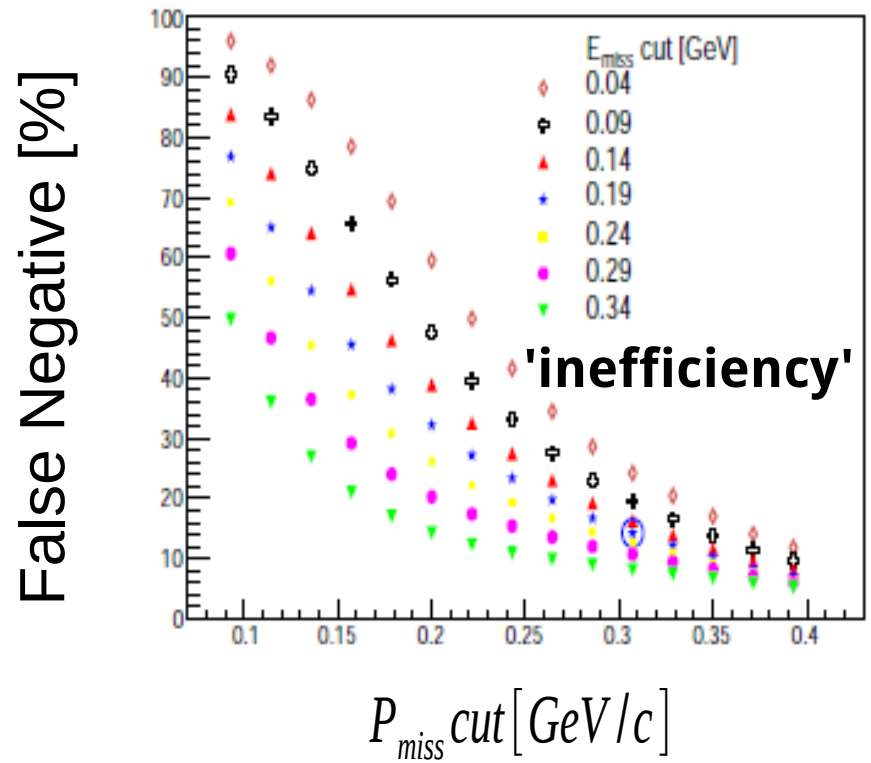
$$P_p \rightarrow P_{smeared} = \sum Gauss(P_p, \sigma)$$



$$P_p - P_{smeared}\,[GeV/c]$$

False Positive & Negative probabilities





The selected cuts for smeared p/n:

$P_{miss} < 0.3\,GeV/c, \quad E_{miss} < 0.19\,GeV$

The cuts for un-smeared p:

$P_{miss} < 0.25\,GeV/c, \quad E_{miss} < 0.08\,GeV$

$False\ Positive \simeq False\ Negative \simeq 10\%$

Selecting high-momentum QE events

(e,e'p): Following CLAS analysis note (O. Hen 2012)

(e,e'n): Same strategy as M.F.:

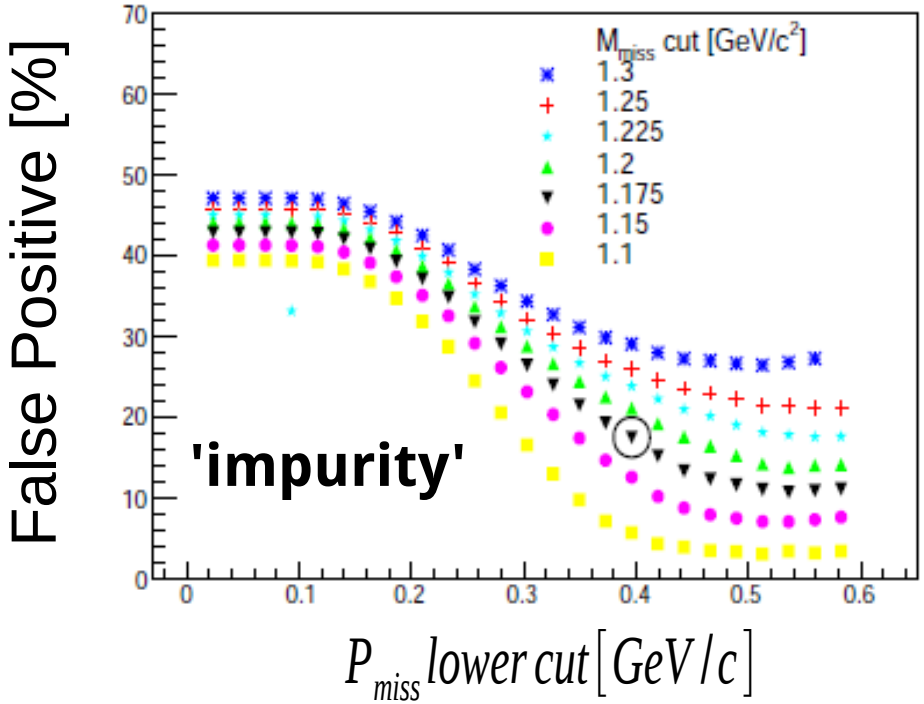
I. **Cut on common quantities:**

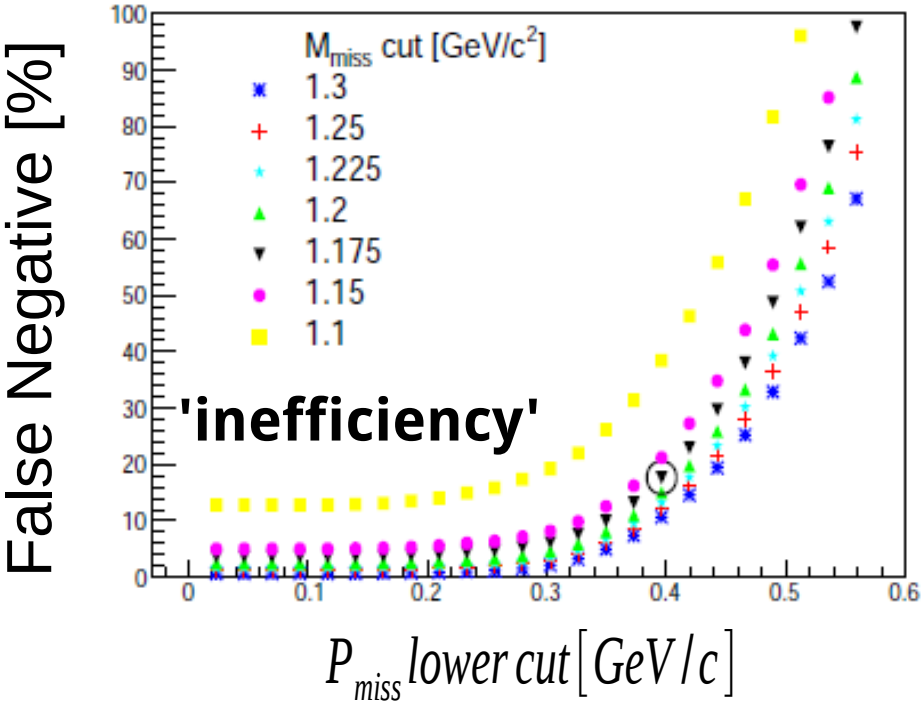
$$x_B > 1.1 \qquad 0.62 \leq \frac{|\vec{P}_N|}{|\vec{q}|} \leq 1.1 \qquad \theta_{Nq} \leq 25^o$$

II. **Using smeared protons:**

To determine cuts on P_{miss} **&** M_{miss}

False Positive & Negative probabilities





The selected cut for smeared p/n: $0.4 < P_{miss} < 1\,GeV/c$, $M_{miss} < 1.175\,GeV/c^2$

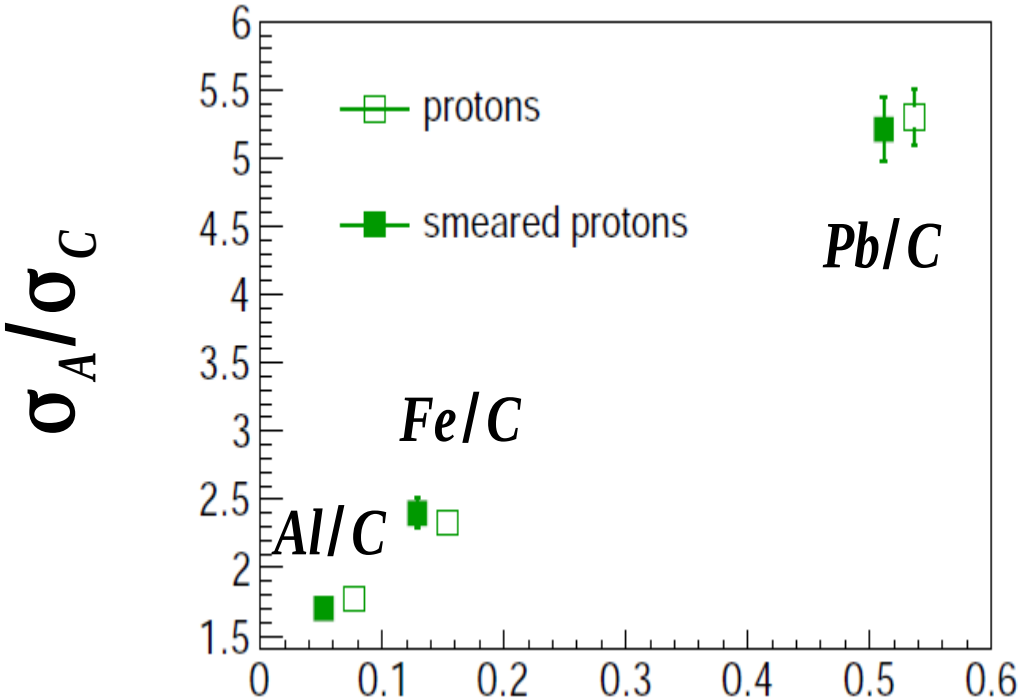
The cut for un-smeared protons: $0.3 < P_{miss} < 1\,GeV/c$, $M_{miss} < 1.1\,GeV/c^2$

$False\ Positive \simeq False\ Negative \simeq 15\ \%$

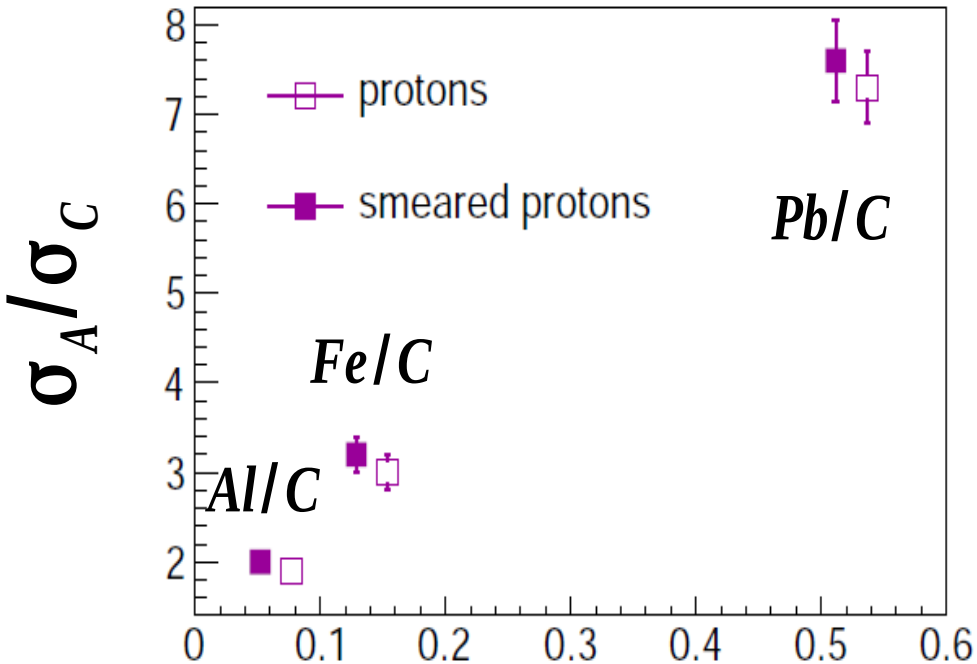
A(e,e'p)/C(e,e'p) ratios

(compare smeared and un-smeared protons)

Mean-Field

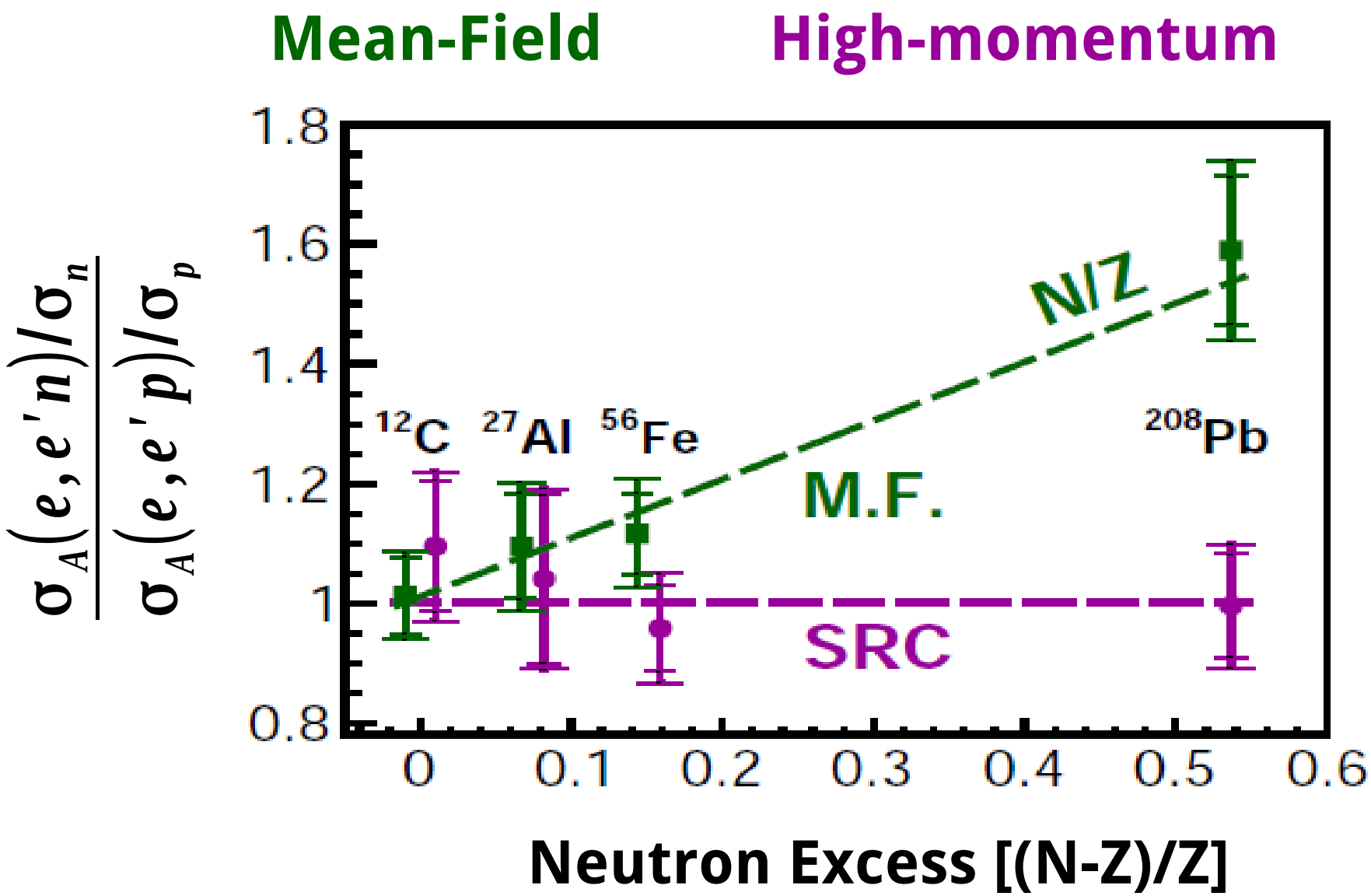


High-momentum



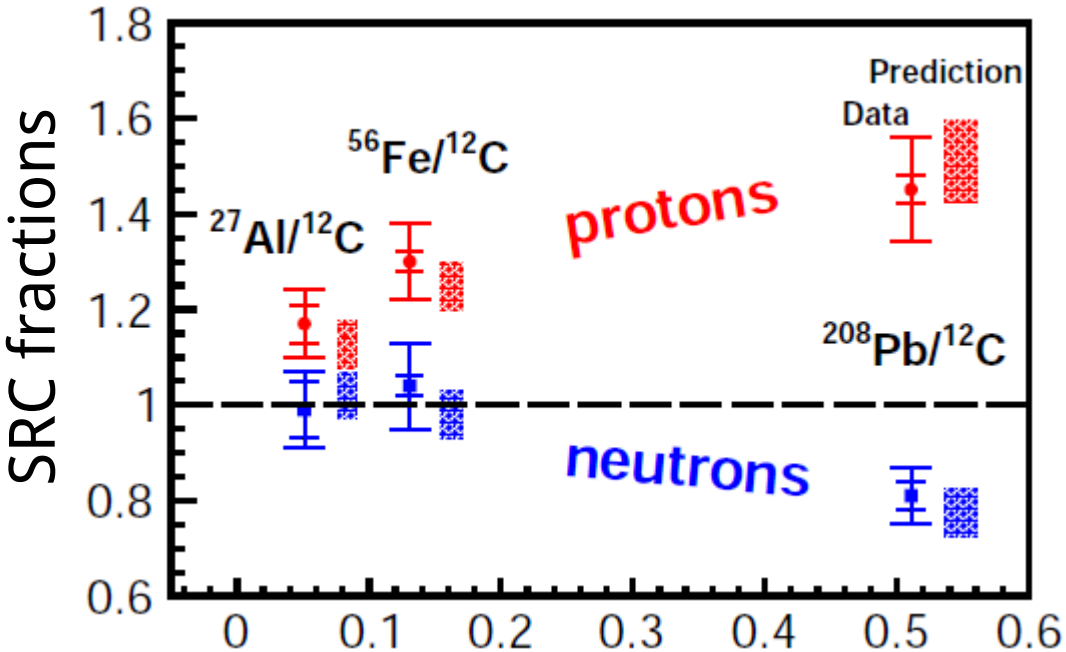
Neutron Excess [(N-Z)/Z]

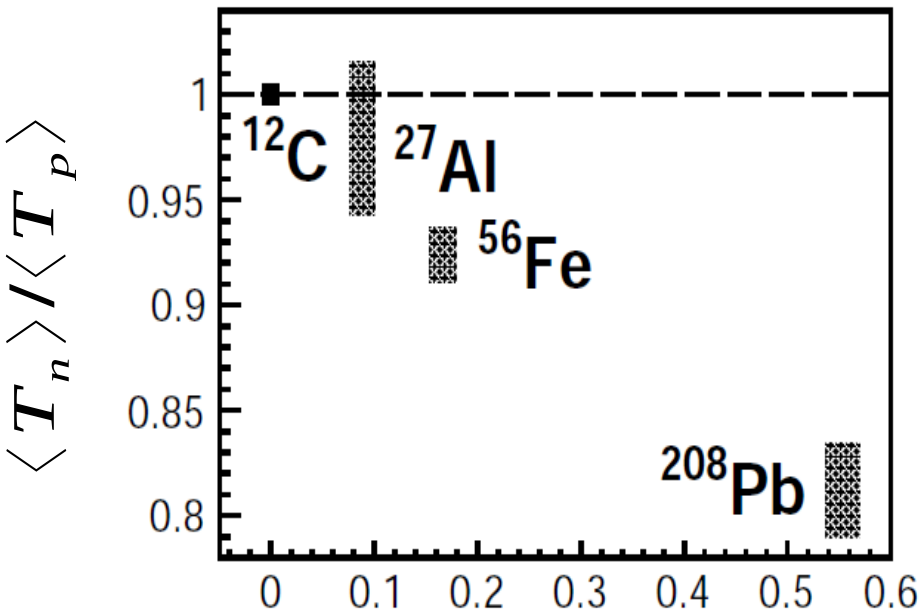
A(e,e'n)/A(e,e'p) ratios



Protons and neutrons super ratios

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





Neutron Excess [(N-Z)/Z]

Protons move faster than neutrons in N>Z nuclei

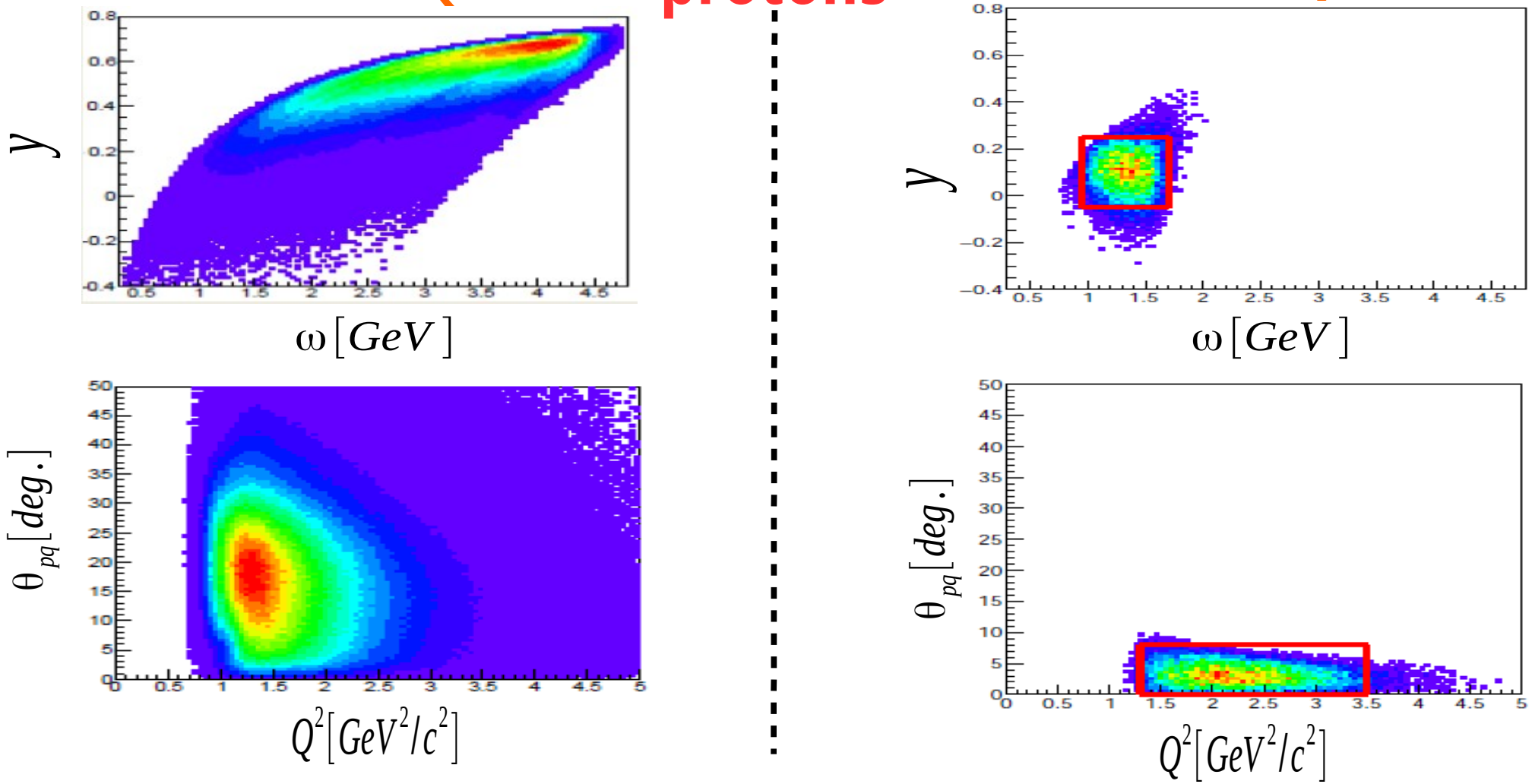
$$\langle T_p \rangle > \langle T_n \rangle$$

Backup Slides

Solution 1: Using cuts common to (e,e'p) and (e,e'n)

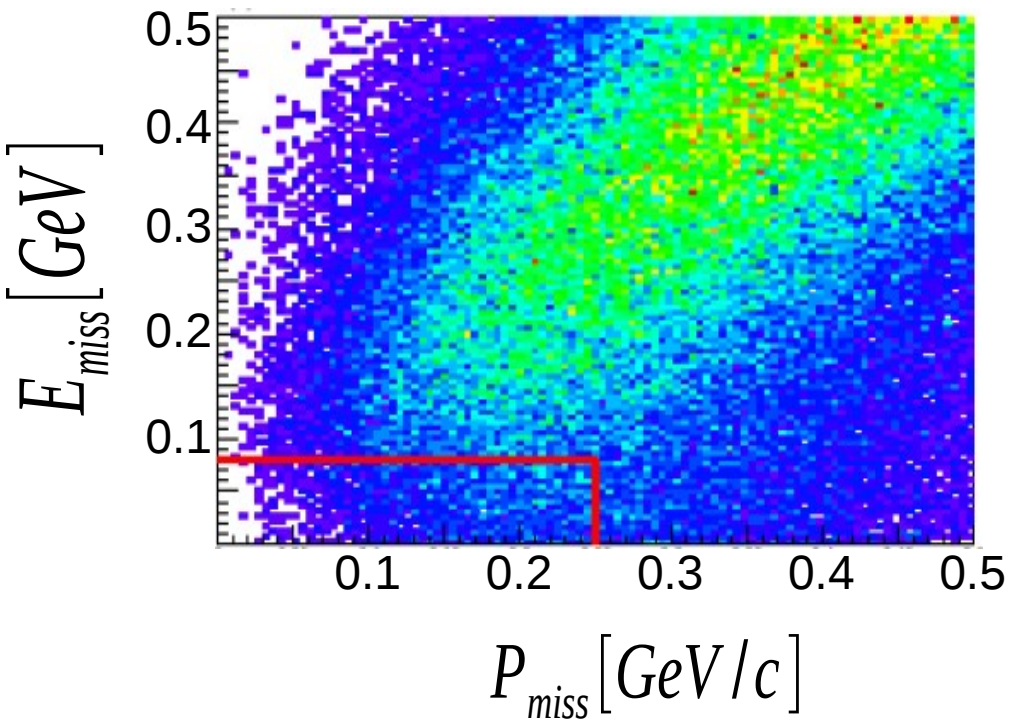
QE cuts: P_{miss}<0.25 GeV/c E_{miss}<0.08 GeV

Before the QE cuts **protons** **After the QE cuts**

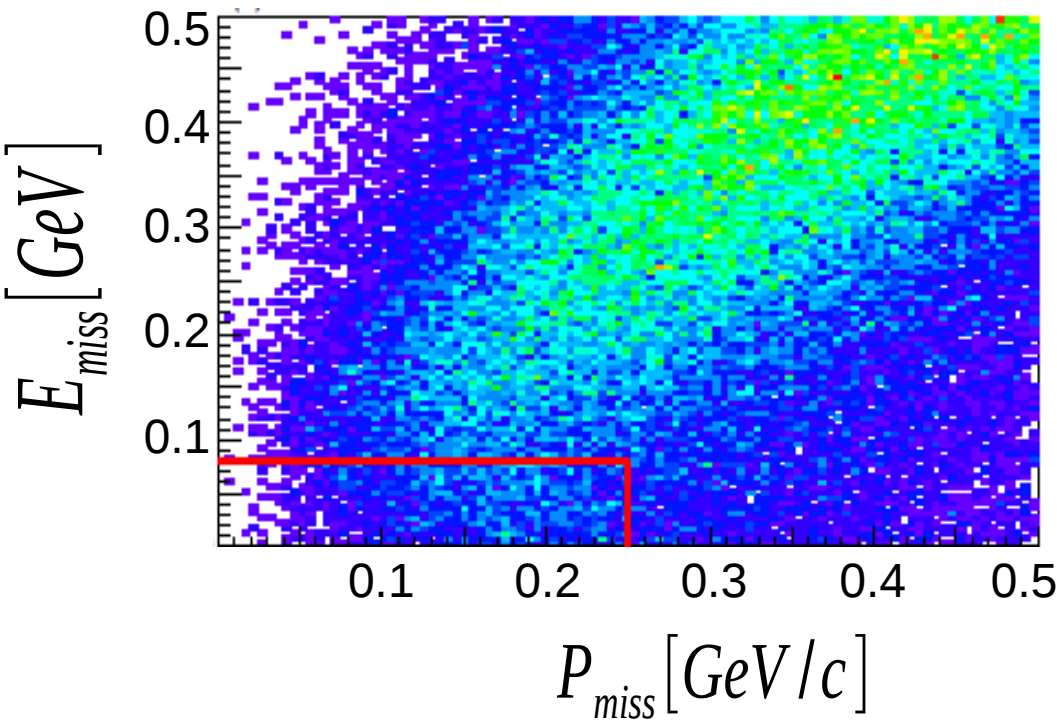


$$y \equiv \left[(M_A + \omega)^2 \sqrt{\Lambda^2 - M_{A-1}^2 W^2} - |\vec{q}|\Lambda \right] / W^2 \qquad W = \sqrt{(M_A + \omega)^2 - |\vec{q}|^2}\ ,\ \Lambda = \left(M_{A-1}^2 - M_N^2 + W^2\right)/2$$

smeared protons



neutrons

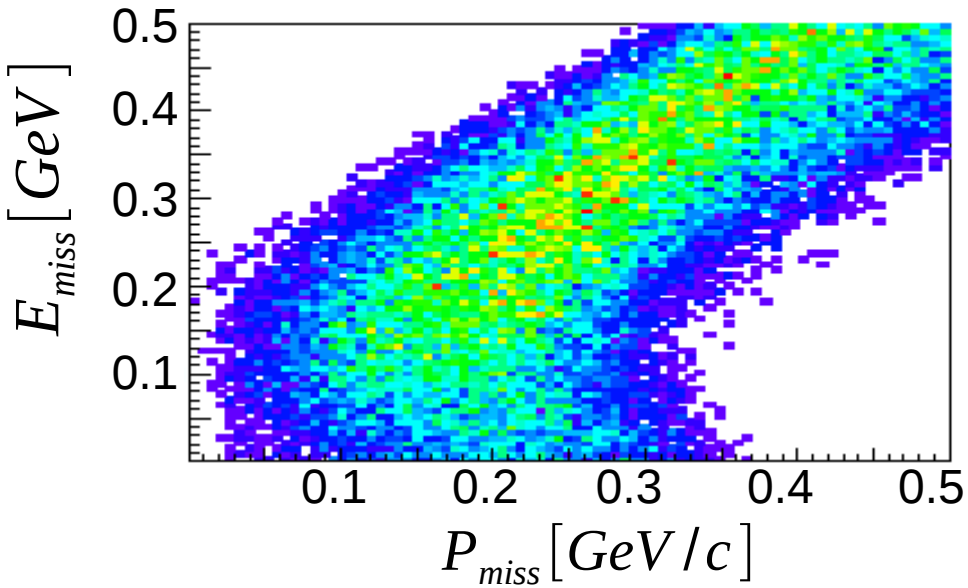


Without applying any cuts

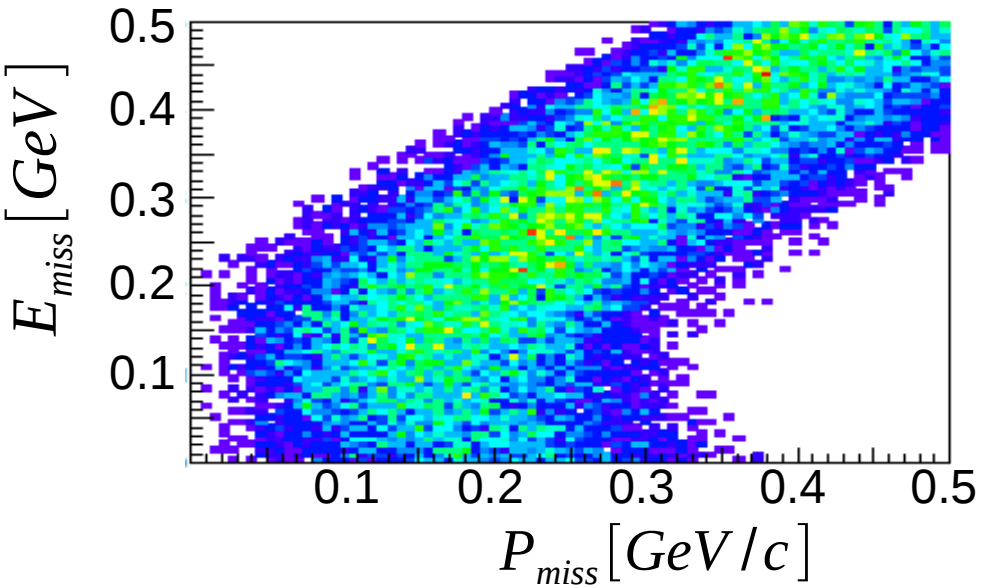
With the common cuts:

$-0.05 < y < 0.25$ $\quad 0.95 < \omega < 1.7\,GeV$ $\quad \theta_{pq} < 8^{o}$ $\quad 1.3 < Q^2 < 3.5\,GeV^2/c^2$

smeared protons



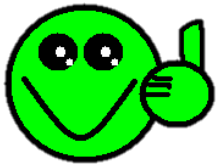
neutrons



E_{miss} P_{miss} cuts

un-smeared protons

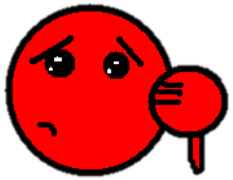
'good event':



$P_{miss-unsmeared} < 0.25\,GeV/c$

&& $E_{miss-unsmeared} < 0.08\,GeV$

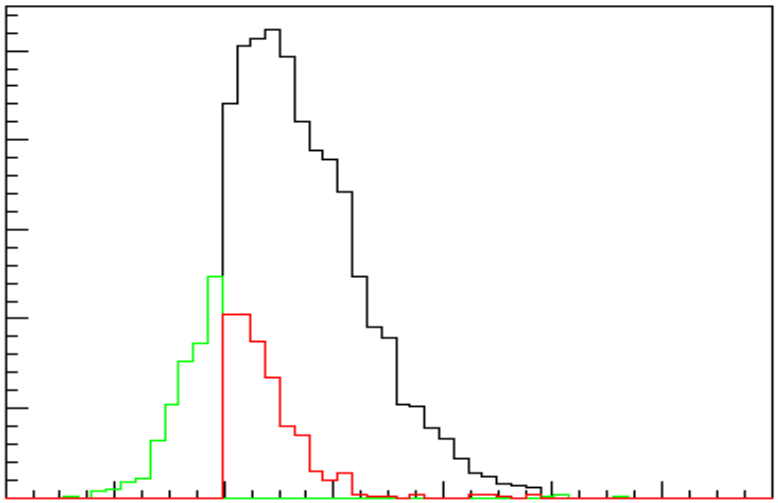
'bad event':



$P_{miss-unsmeared} > 0.25\,GeV/c$

|| $E_{miss-unsmeared} > 0.08\,GeV$

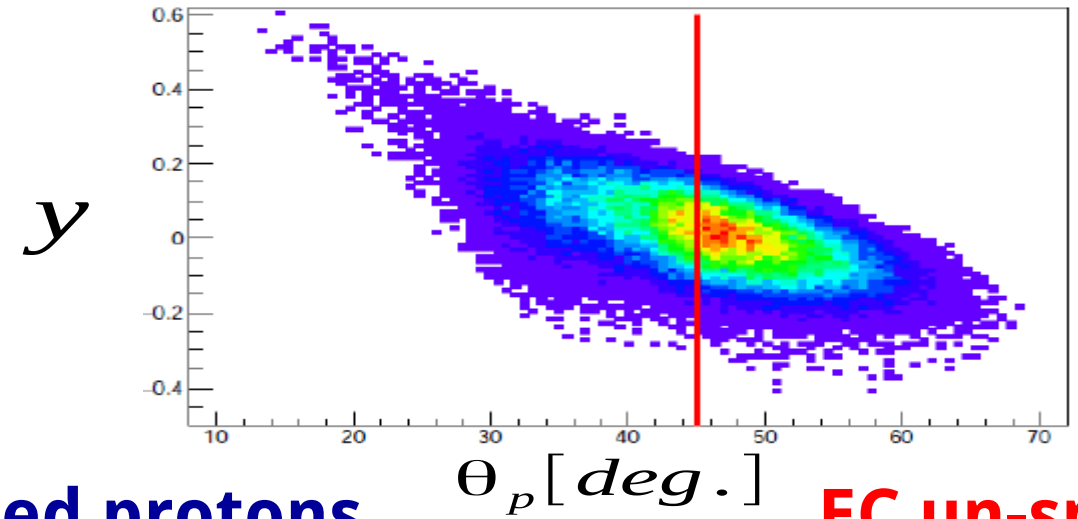
smeared protons (neutrons)



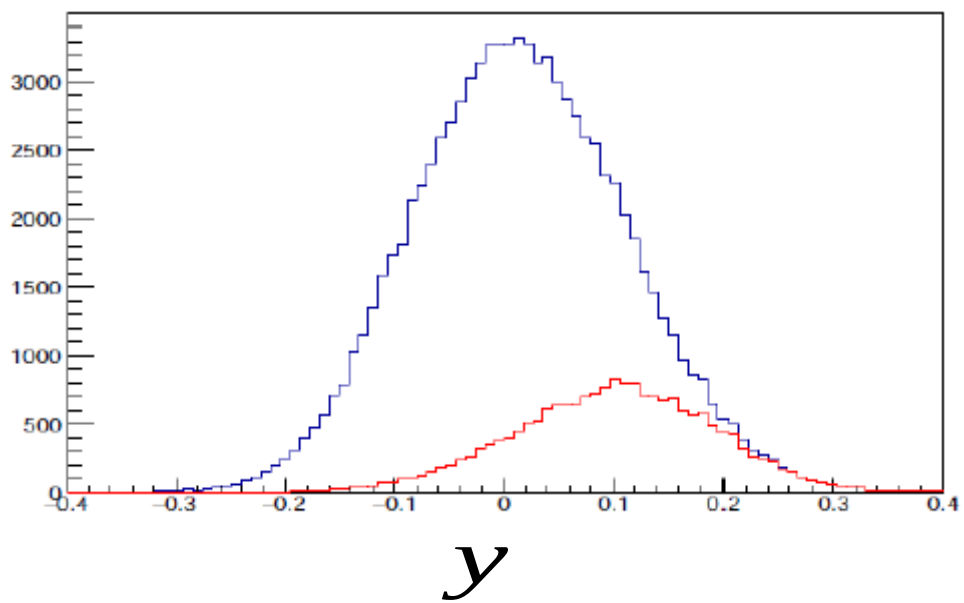
$P_{miss}[GeV/c]$

Comparing un-smeared protons

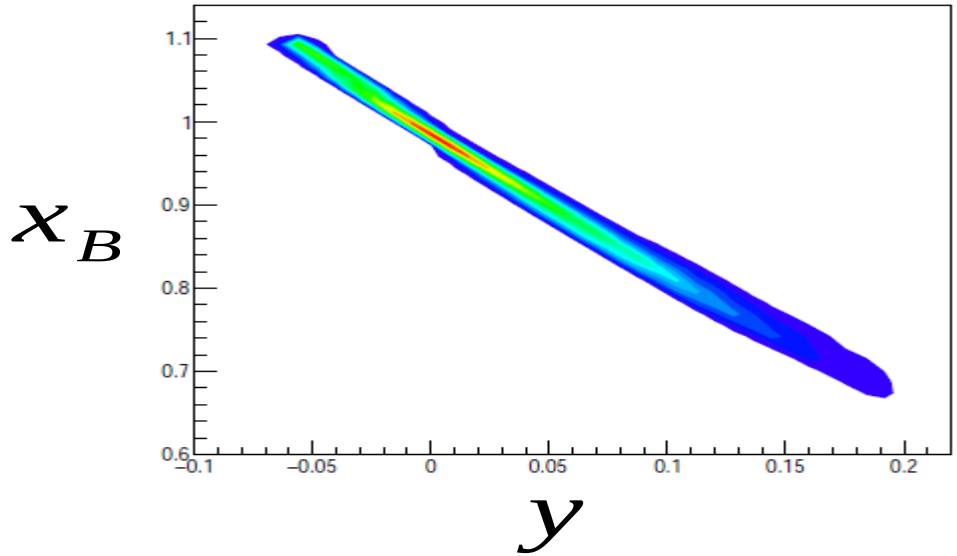
QE cuts: $P_{miss} < 0.25\,GeV/c$ $E_{miss} < 0.08\,GeV$



All un-smeared protons **EC un-smeared protons**

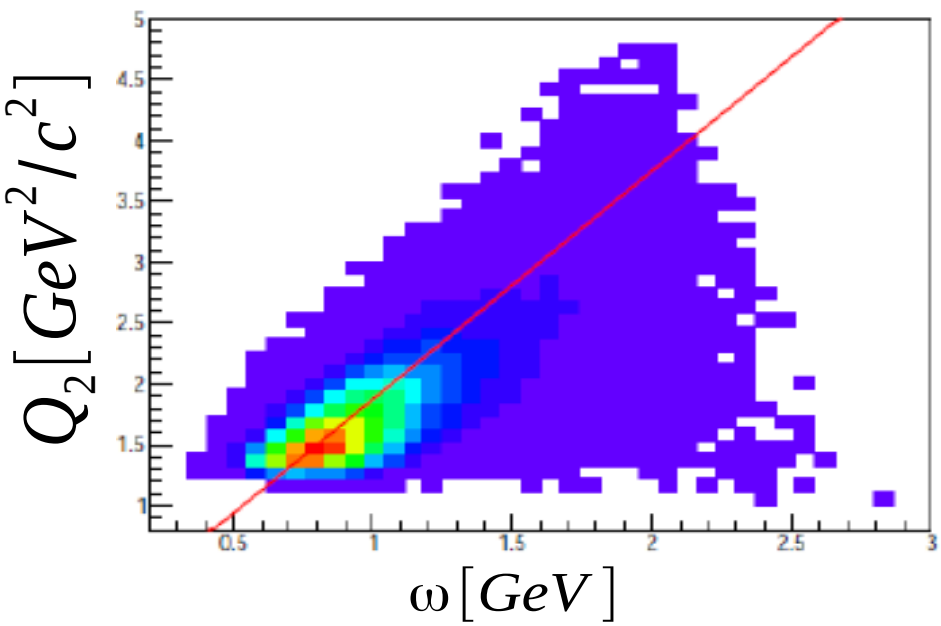


Comparing un-smeared protons

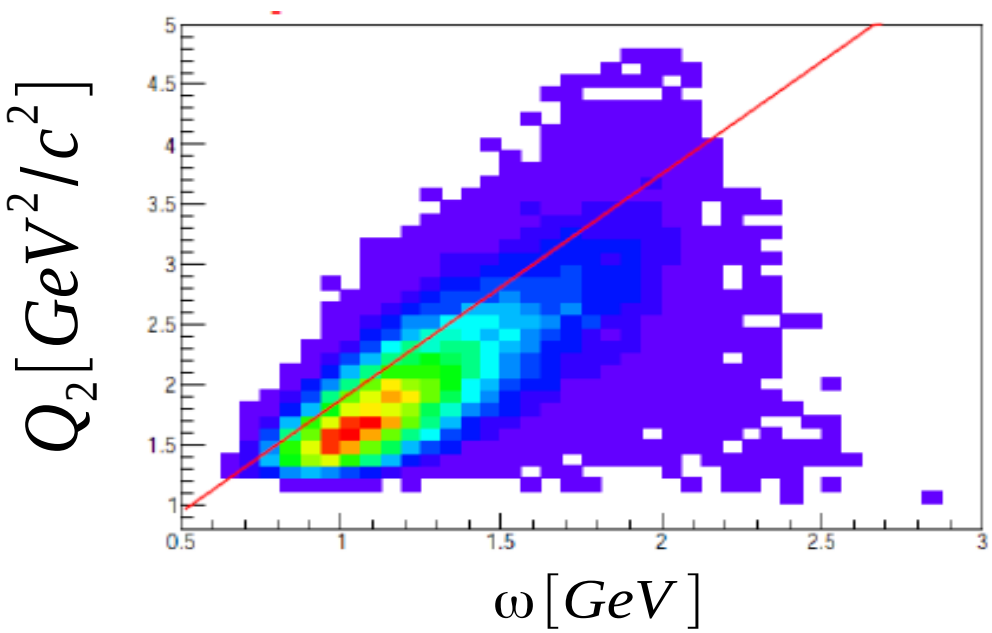


QE events → $x_b \approx 1$

All un-smeared protons



EC un-smeared protons



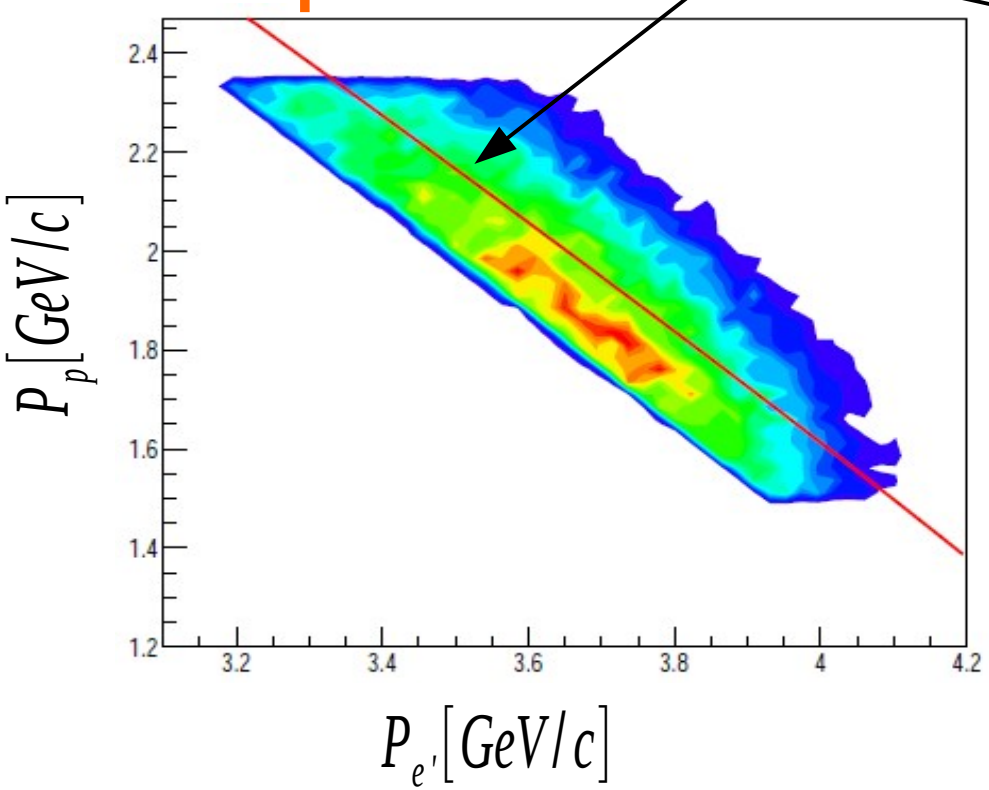
Checking the event selection

Energy momentum conservation:

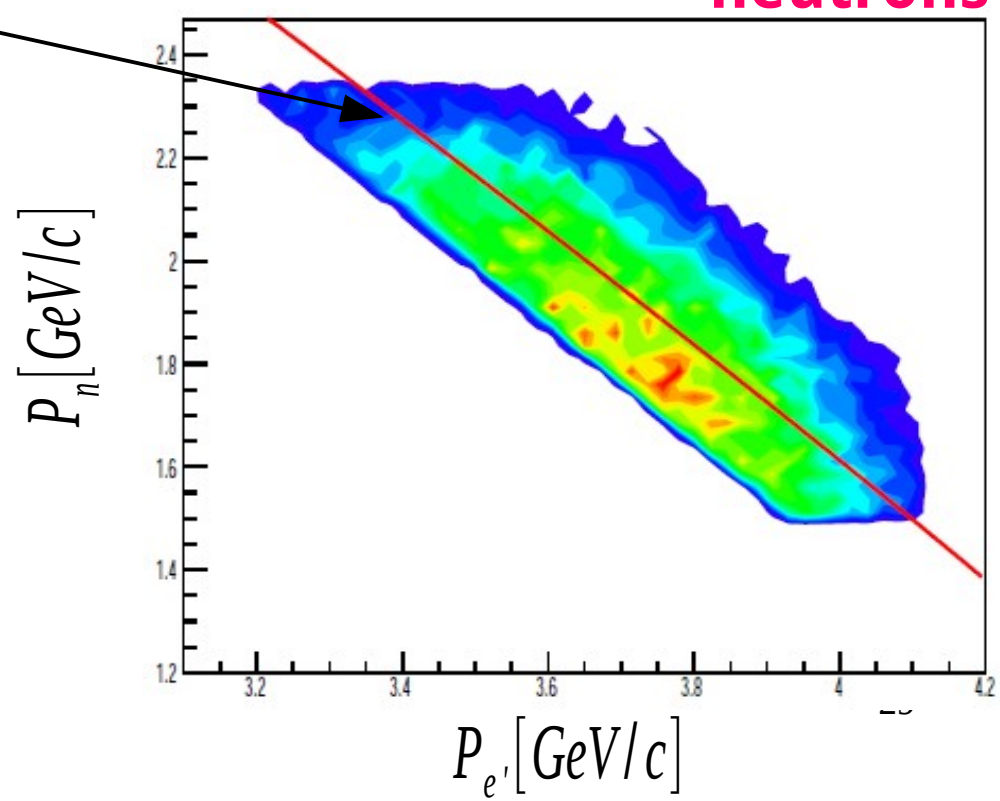
$$\left(E_{beam},\left(0,0,E_{beam}\right)\right)+\left(M_N,\vec{0}\right)=\left(E',\vec{P}_{e'}\right)+\left(E_N,\vec{P}_N\right)$$

$$|\vec{P}_N|=\sqrt{\left(E+M_N-|\vec{P}_{e'}|\right)^2-M_N^2}$$

smeared protons



neutrons

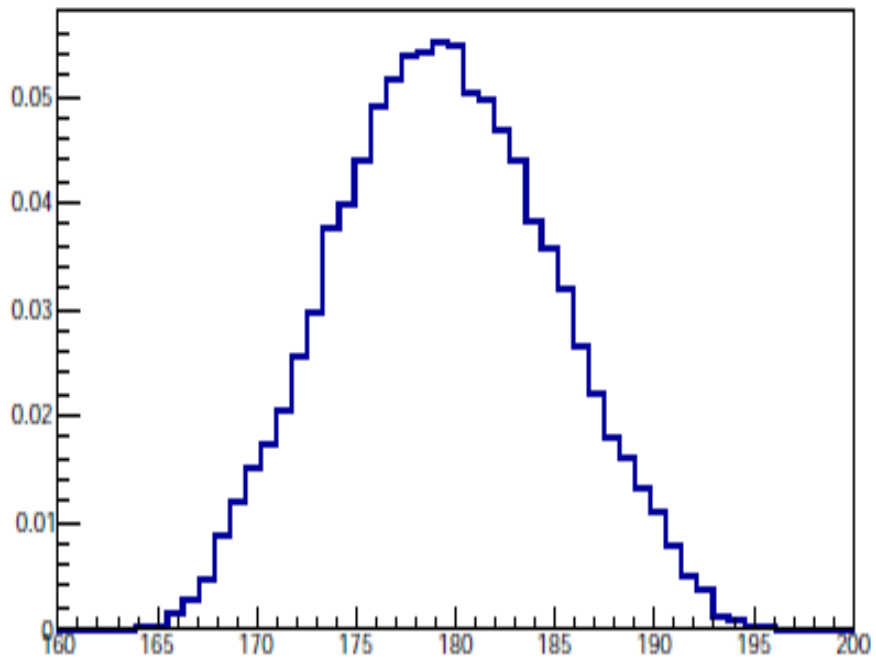


Checking the event selection

From energy momentum conservation:

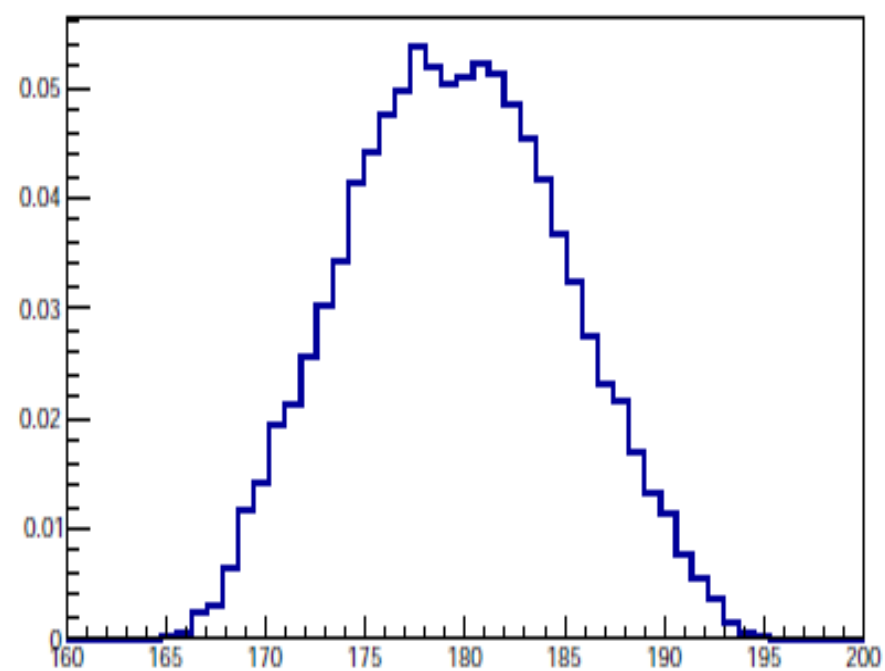
$$|\varphi_N - \varphi_{e'}| = 180^o$$

smeared protons



$$|\varphi_p - \varphi_{e'}| [deg.]$$

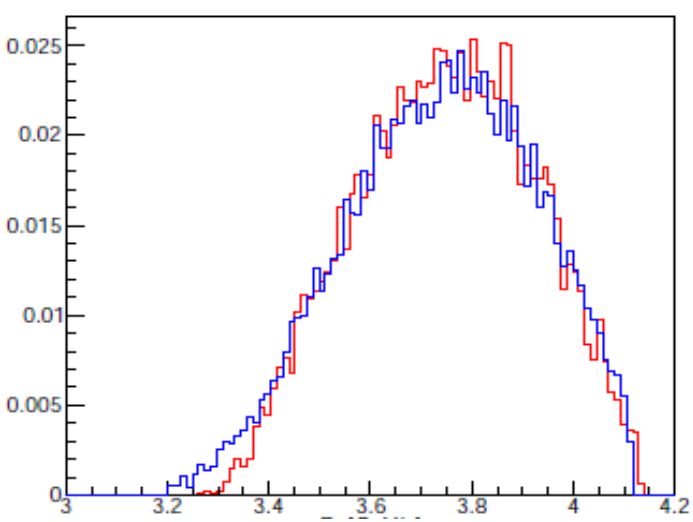
neutrons



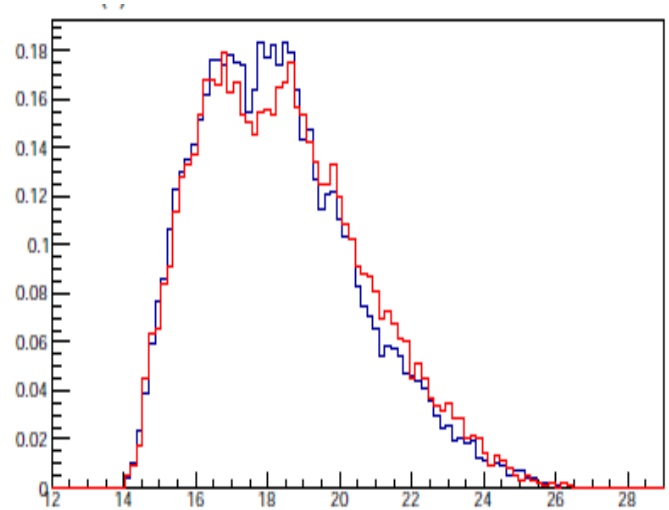
$$|\varphi_n - \varphi_{e'}| [deg.]$$

Comparing the smeared protons and neutrons

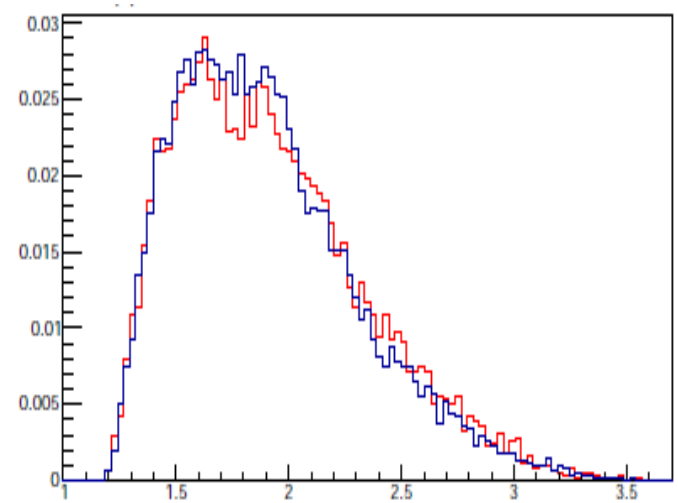
smeared protons **neutrons**



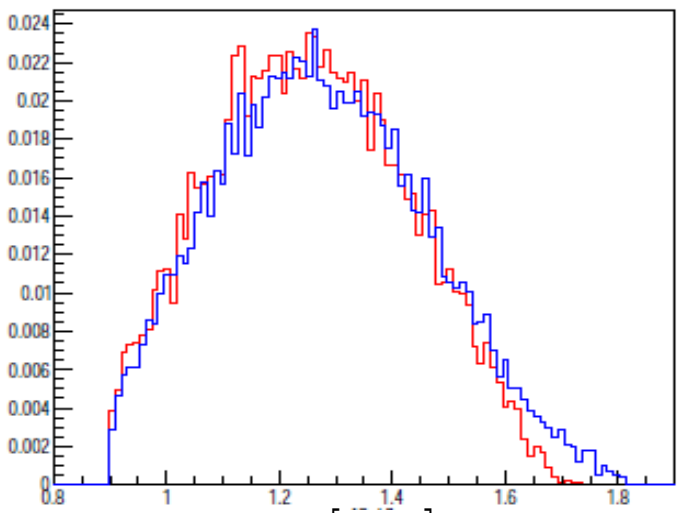
$P_e[GeV/c]$



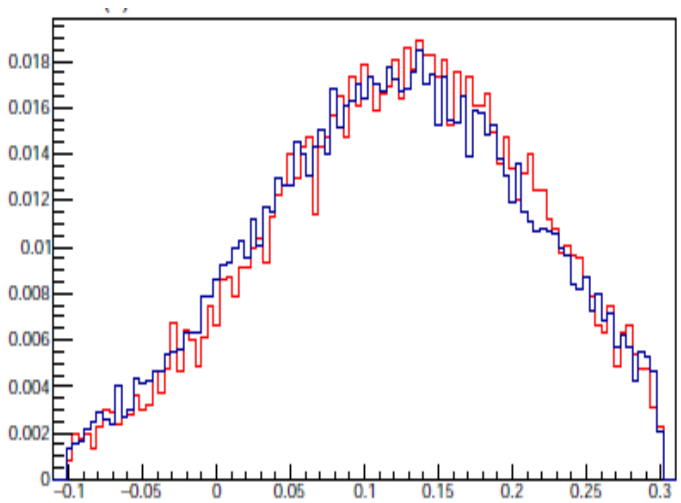
$\theta_e[deg.]$



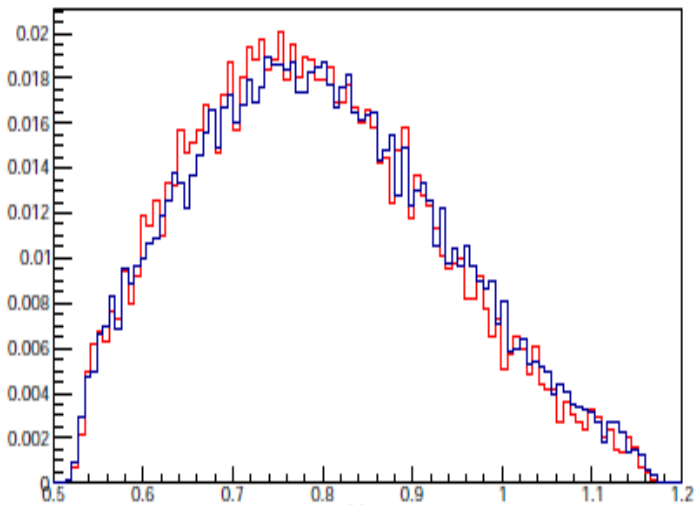
$Q^2[GeV^2/c^2]$



$\omega[GeV]$



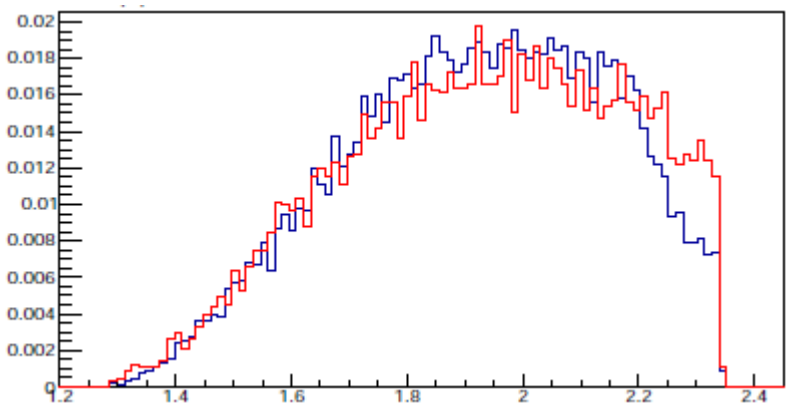
y



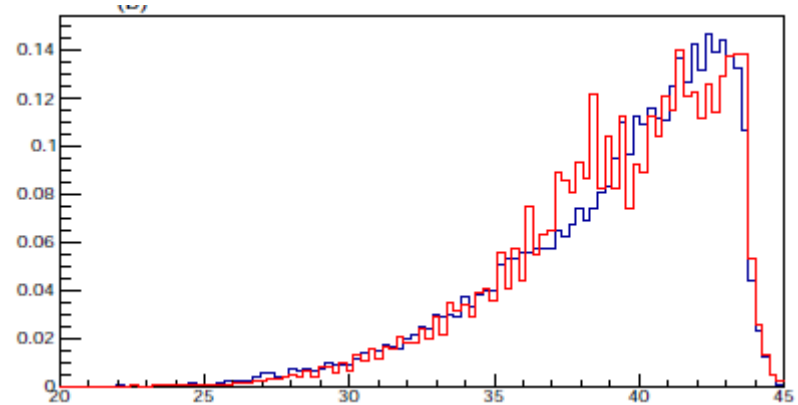
x_B

Comparing the smeared protons and neutrons

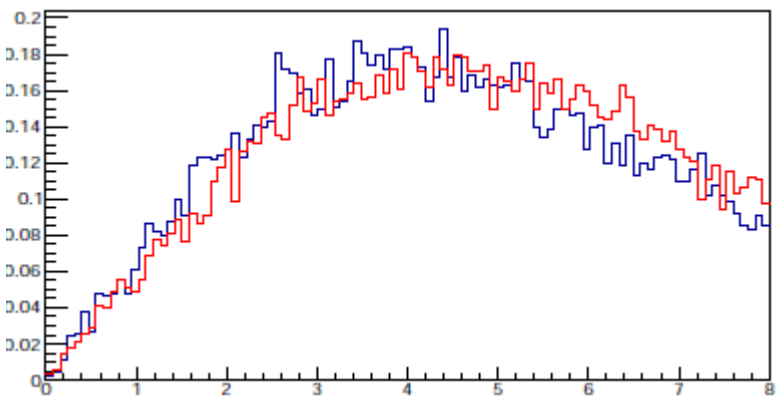
smeared protons **neutrons**



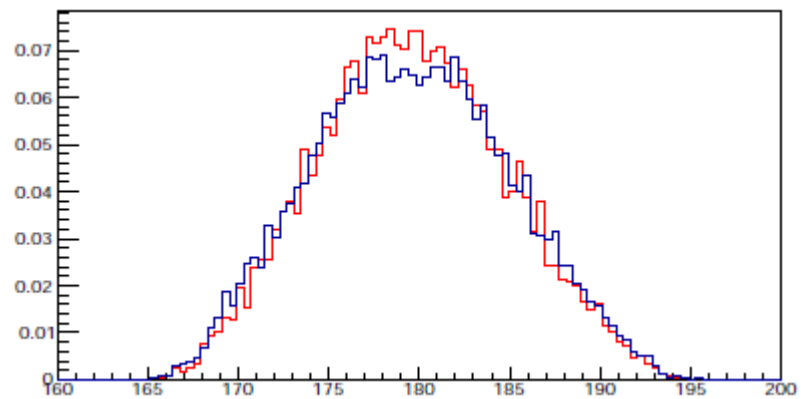
$P_{p/n}[GeV/c]$



$\theta_{p/n}[deg.]$



$\theta_{pq/nq}[deg.]$



$|\varphi_{p/n} - \varphi_e|[deg.]$

Applying corrections

protons

* Coulomb correction
* Detection efficiency
* Acceptance correction

neutrons

* Detection efficiency
* Acceptance correction

Protons simulation

* 10,000 electrons from the data.

* Proton momentum & scattering angle uniformly distributed.

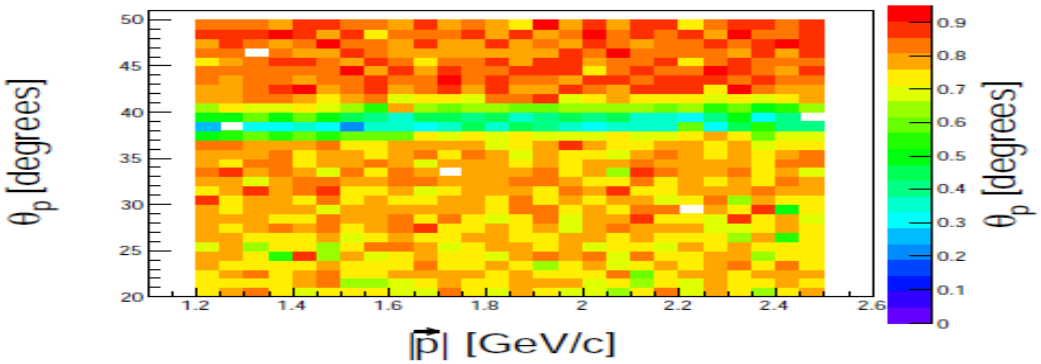
* 100xphi angle uniformly distributed.

* Running through CLAS MC simulation.

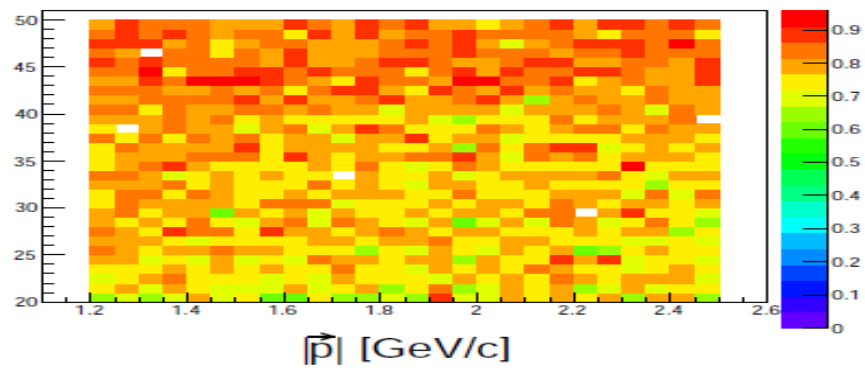
* Dividing event by event by the ratio of reconstructed/generated.

Protons simulation - results

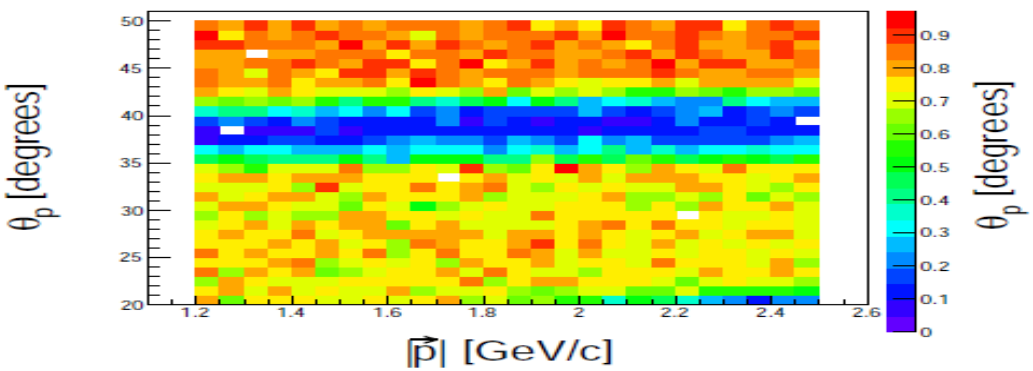
Sector #1



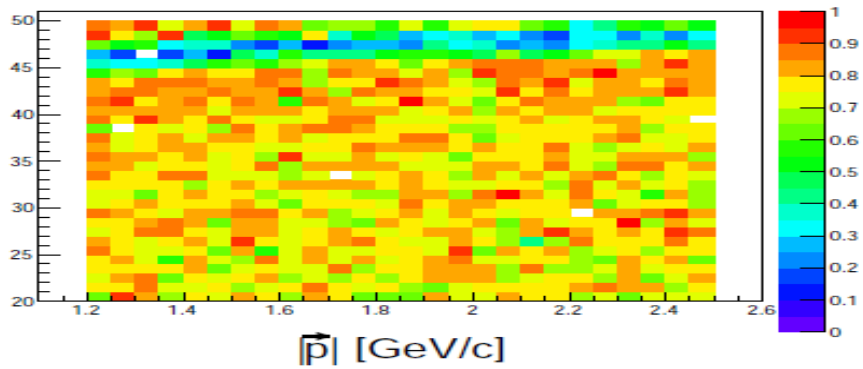
Sector #2



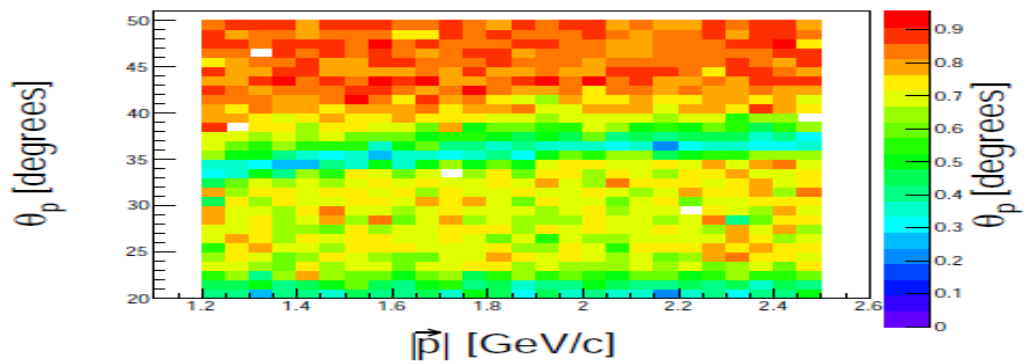
Sector #3



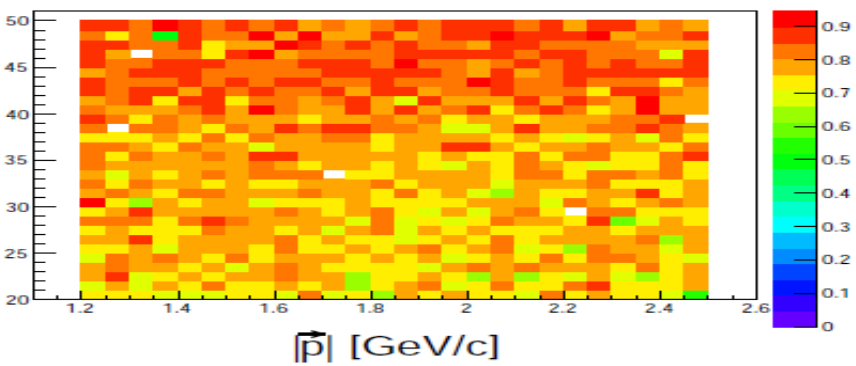
Sector #4



Sector #5

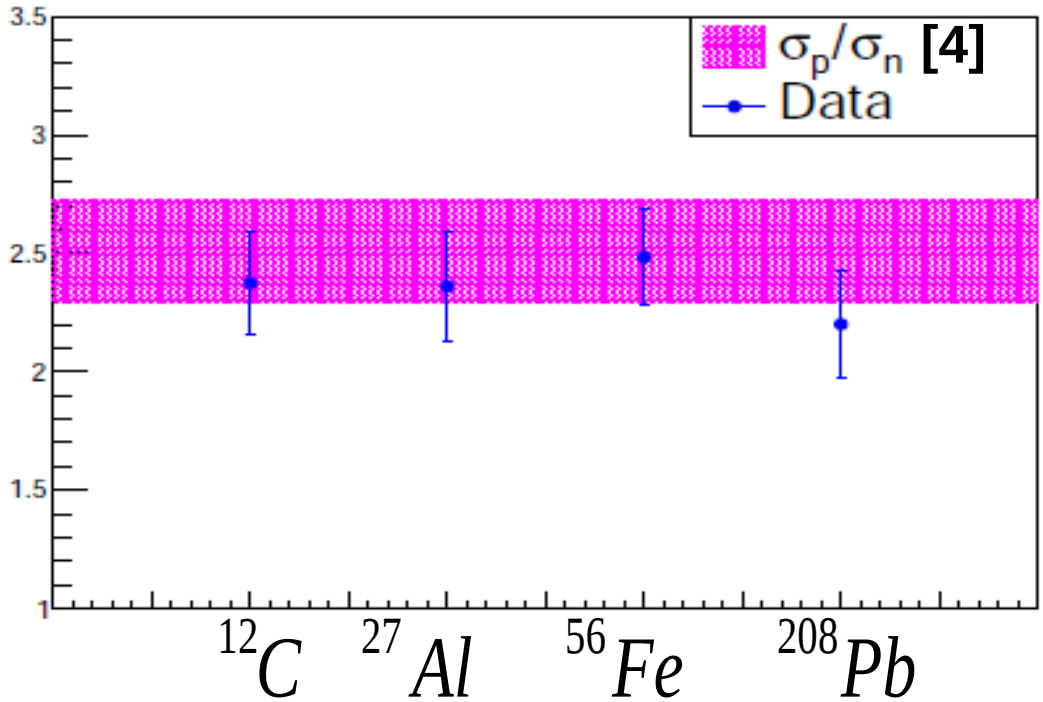


Sector #6



A(e,e'p)/A(e,e'n) M.F. ratios

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



$$\sigma^{R}_{ep(n)} = \frac{\epsilon}{\tau} G_E^2 + G_M^2$$

$$\tau = \frac{Q^2}{4 M_N^2}, \quad \epsilon = \left[1 + 2(1+\tau)\tan^2\left(\frac{\theta_e}{2}\right)\right]^{-1}$$

[4] W. P. Ford, S. Jeschonnek & J. W. Van Orden, arXiv:1411.3306v1 [nucl-th] (2014)

Uncertainties of the event selection

Cut	Cuts sensitivity				
	Range	**C**	**Al**	**Fe**	**Pb**
-0.05<y<0.25	±0.05	0.84%	0.83%	0.58%	0.81%
0.95<ω<1.7 GeV	±0.05 GeV	2.1%	2.0%	1.9%	1.8%
$\Theta_{pq} < 8^o$	±1º	2.0%	1.8%	1.6%	1.4%
$P_{miss} < 0.3\, GeV/c$	±0.025 GeV/c	0.82%	0.49%	0.56%	0.78%
$E_{miss} < 0.19\, GeV$	±0.02 GeV	1.9%	2.2%	2.1%	2.1%
EC fiducial cut: 10 cm	30 cm	0.1%	0.11%	0.10%	0.09%

Contributions to the uncertainty

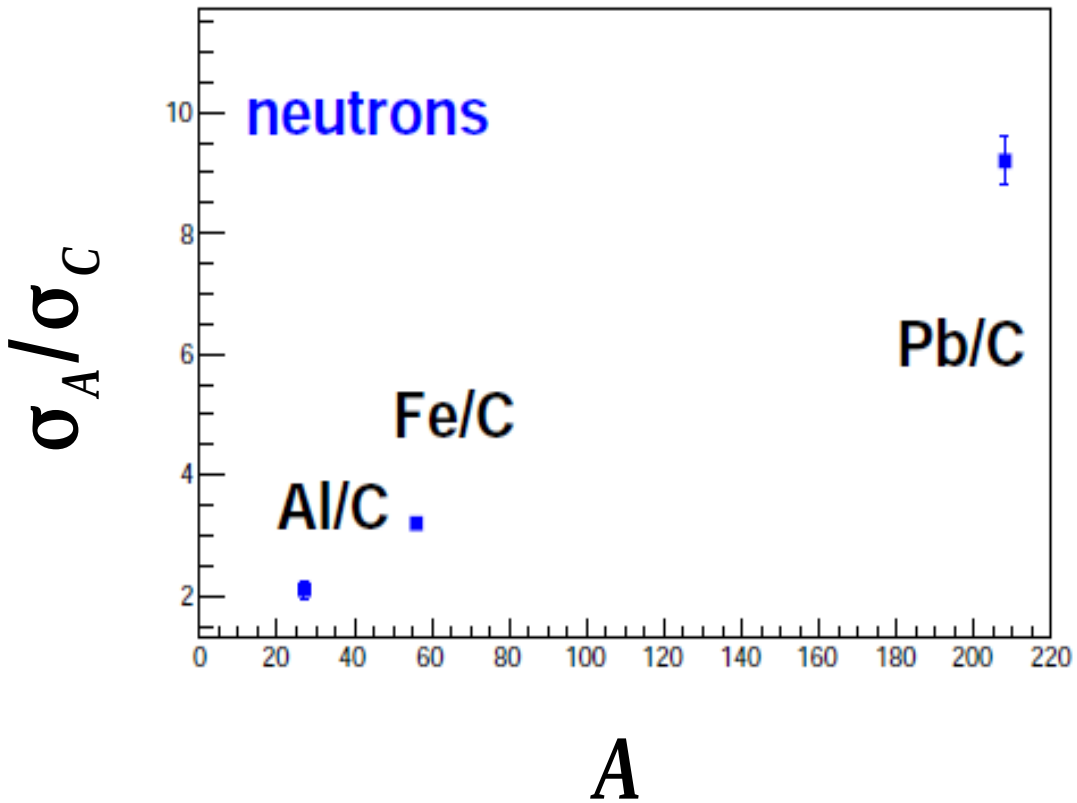
Nuclei	A(e,e'p)/A(e,e'n)	Statistics	Neutron Effic.	Simulation	Event selection
C	2.37±0.17	±0.15	±0.07	±0.031	±0.09
Al	2.36±0.23	±0.19	±0.08	±0.030	±0.09
Fe	2.48±0.20	±0.15	±0.07	±0.032	±0.08
Pb	2.21±0.22	±0.18	±0.09	±0.034	±0.07

Uncertainties of the event selection A(e,e'p)/C(e,e'p) M.F.

Cut	Cuts sensitivity			
	Range	Al/C	Fe/C	Pb/C
-0.05<y<0.25	±0.05	1.6%	1.3%	1.2%
0.95<ω<1.7 GeV	±0.05 GeV	1.4%	0.8%	2.0%
$\Theta_{pq} < 8^o$	±1º	1.9%	1.9%	1.6%
$P_{miss} < 0.3\, GeV/c$	±0.025 GeV/c	2.0%	2.0%	1.8%
$E_{miss} < 0.19\, GeV$	±0.02 GeV	1.8%	1.8%	1.9%

Nuclei	A(e,e'p)/C(e,e'p)	Statistics	FP & FN	Event selection
Al/C	1.71±0.08	±0.05	±0.02	±0.06
Fe/C	2.4±0.11	±0.03	±0.02	±0.1
Pb/C	5.2±0.23	±0.1	±0.05	±0.2

A(e,e'n)/C(e,e'n) M.F. ratios

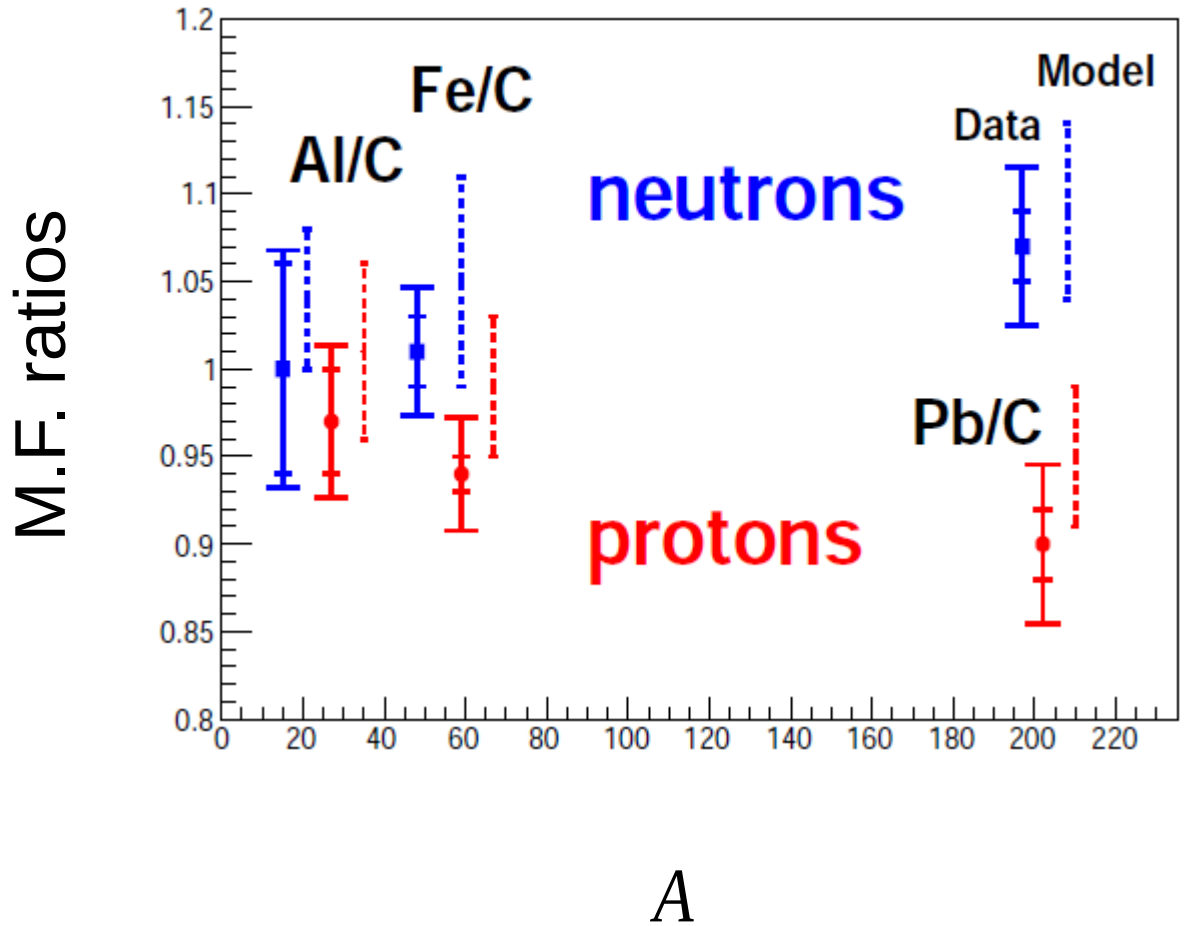


Nuclei	A(e,e'p)/A(e,e'n)	Statistics	FP & FN	Event selection
Al/C	2.1±0.14	±0.12	±0.02	±0.06
Fe/C	3.2±0.12	±0.07	±0.02	±0.1
Pb/C	9.2±0.4	±0.17	±0.06	±0.06

Uncertainties of the event selection A(e,e'n)/C(e,e'n) M.F.

Cut	Cuts sensitivity			
	Range	Al/C	Fe/C	Pb/C
-0.05<y<0.25	±0.05	0.8%	1.3%	1.2%
0.95<ω<1.7 GeV	±0.05 GeV	1.4%	1.2%	1.7%
$\Theta_{pq} < 8^o$	±1º	1.5%	1.6%	1.0%
$P_{miss} < 0.3\, GeV/c$	±0.025 GeV/c	1.2%	1.3%	1.5%
$E_{miss} < 0.19\, GeV$	±0.02 GeV	0.8%	0.9%	1.4%

Protons and neutrons M.F ratios



np-dominance model:

protons

neutrons

Data:

protons

neutrons

Corrected for transparency and normalized by Z (N).

1st step:

Following approved CLAS analysis note (O. Hen 2012) to identify high momentum (e,e'p) events

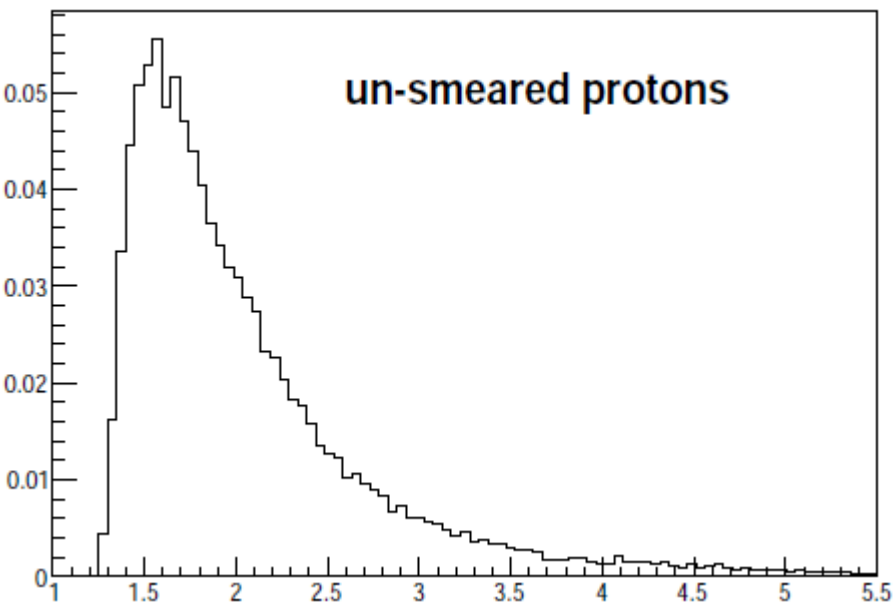
* $x_B > 1.2$
* $0.62 \leq |\vec{P}_{lead}| / |\vec{q}| \leq 0.96$
* $\theta_{pq} \leq 25^o$
* $0.3 \leq P_{miss} \leq 1 GeV/c$
* $M_{miss} \leq 1.1 GeV/c^2$

2nd step:

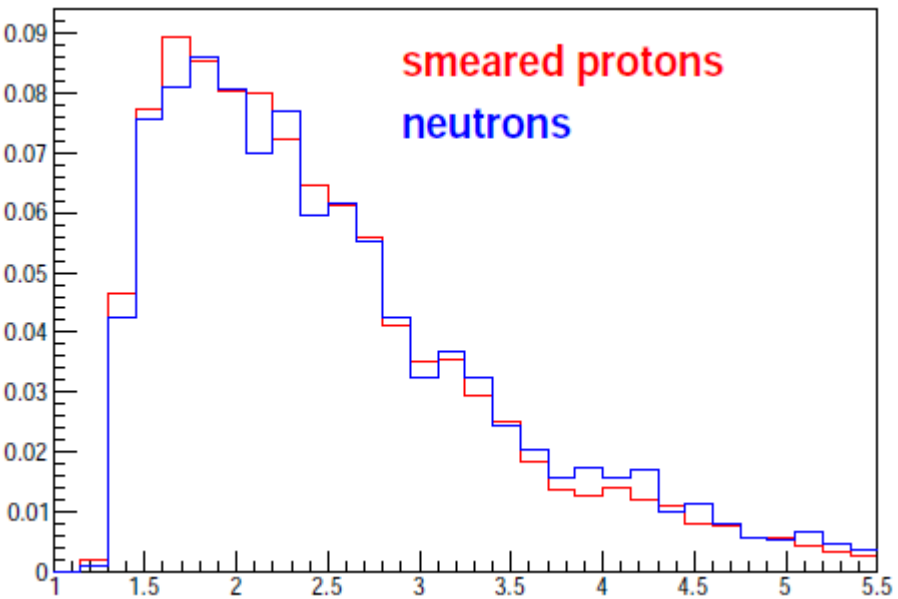
Modifying the cuts to select high momentum (e,e'n) events

* Low statistics → $x_B > 1.1$

* Poor resolution → smeared protons



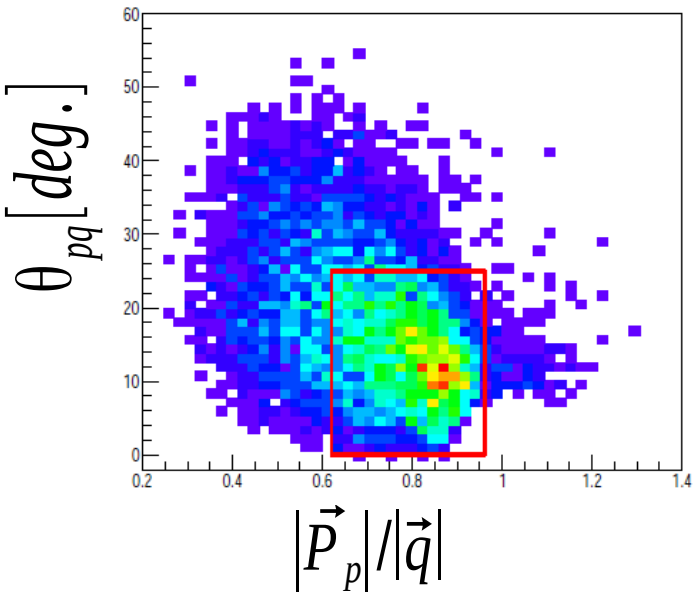
$Q^2[GeV^2/c^2]$

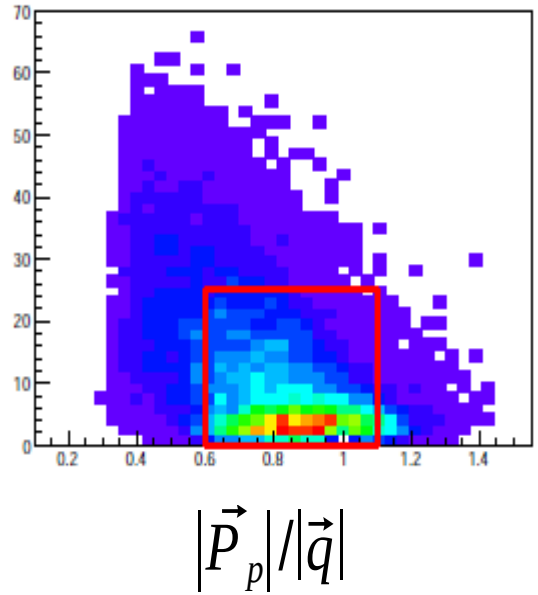


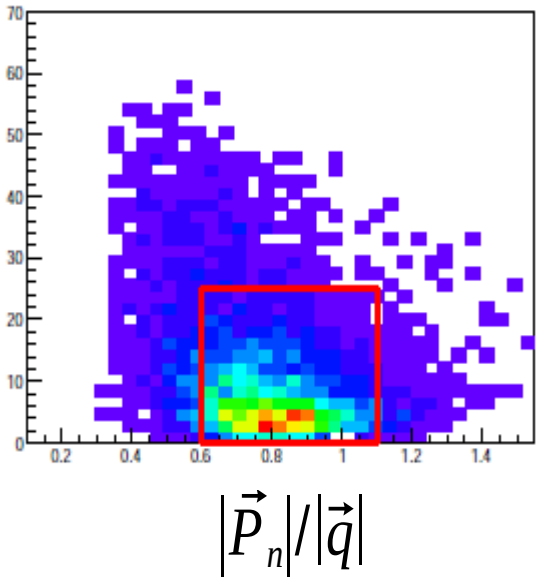
$Q^2[GeV^2/c^2]$

Identifying the Leading Nucleon

un-smeared protons | smeared protons | neutrons







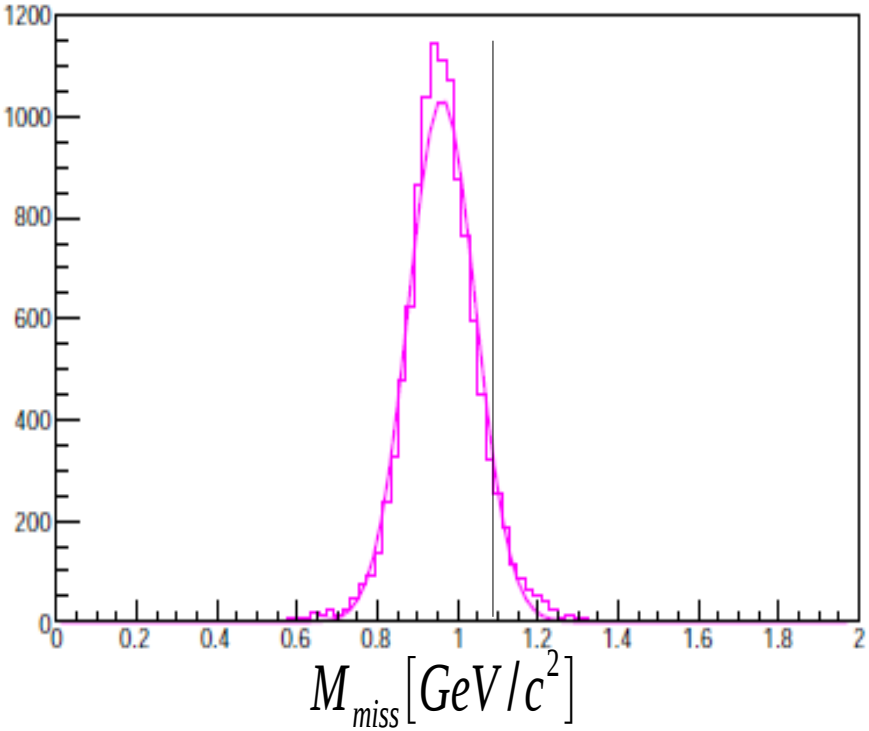
$$\theta_{pq} \leq 25^o$$
$$0.62 \leq \frac{|\vec{P}_N|}{|\vec{q}|} \leq 0.96$$

$$\theta_{pq} \leq 25^o$$
$$0.62 \leq \frac{|\vec{P}_N|}{|\vec{q}|} \leq 0.96$$

Missing Mass cut

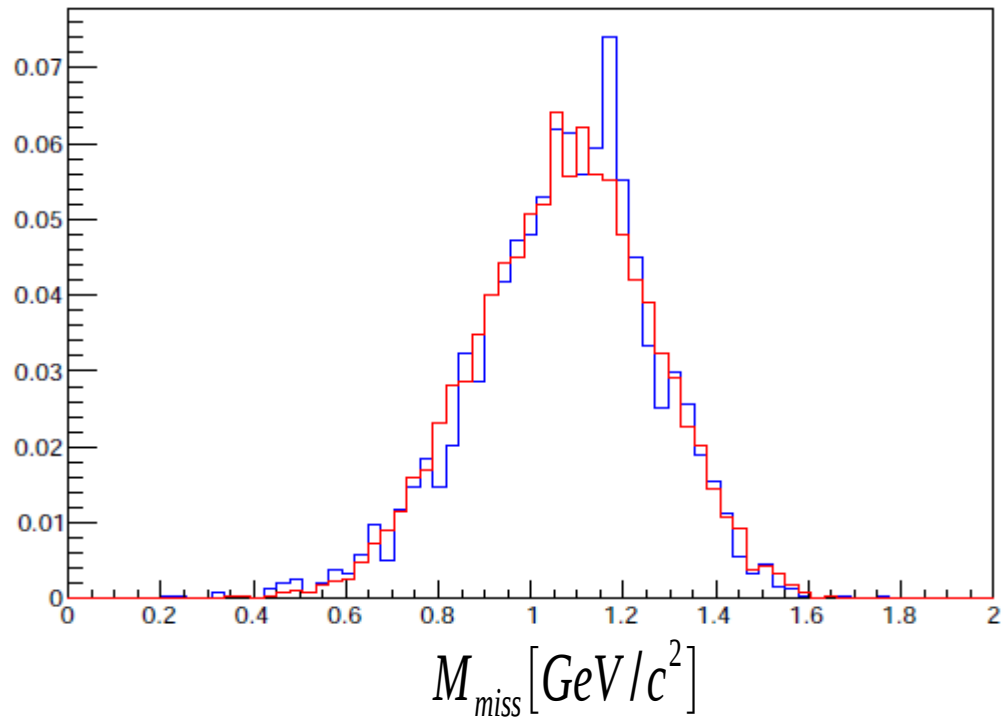
$$M_{miss}^2 = \left(\bar{q} + 2m_N - \overline{P_{lead}}\right)^2$$

un-smeared protons



$$M_{miss} \leq mean + m_\pi = 1.1 GeV/c^2$$

smeared protons neutrons

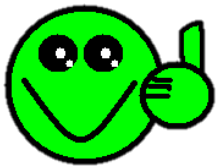


$$M_{miss} < ?$$

Missing Momentum & Missing Mass cuts

un-smeared protons

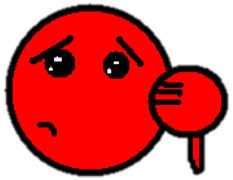
'good event':



$0.3 < P_{miss-unsmeared} < 1 GeV/c$

&& $M_{miss-unsmeared} < 1.1 GeV/c^2$

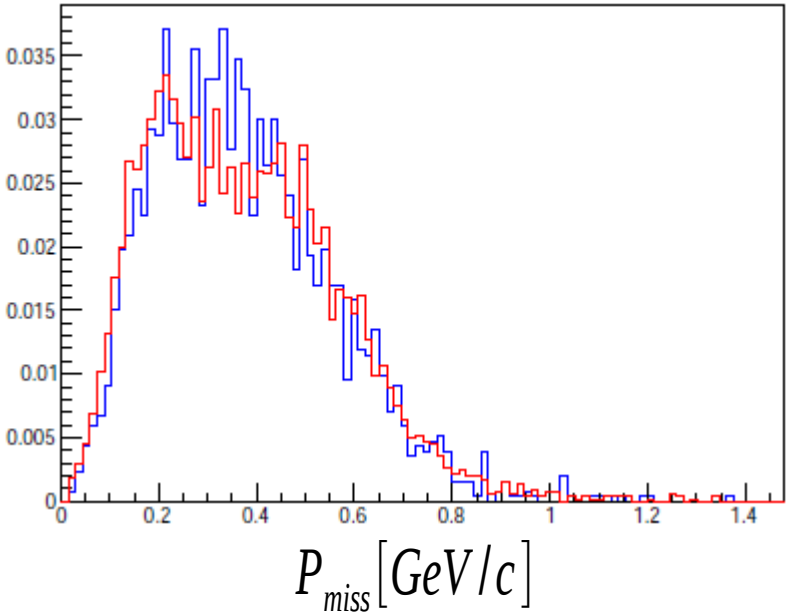
'bad event': $P_{miss-unsmeared} < 0.3$



|| $P_{miss-unsmeared} > 1 GeV/c$

|| $M_{miss-unsmeared} > 1.1 GeV/c^2$

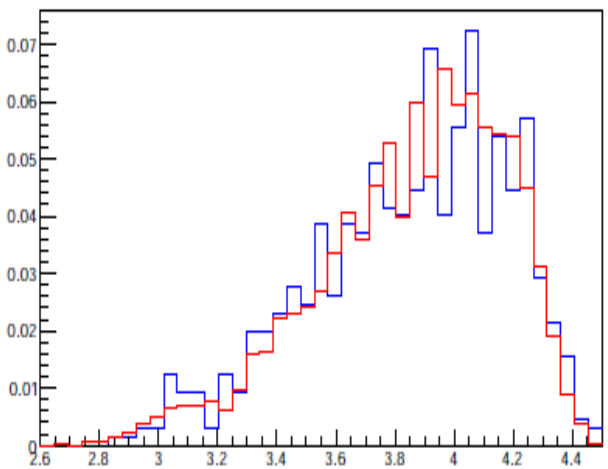
smeared protons neutrons



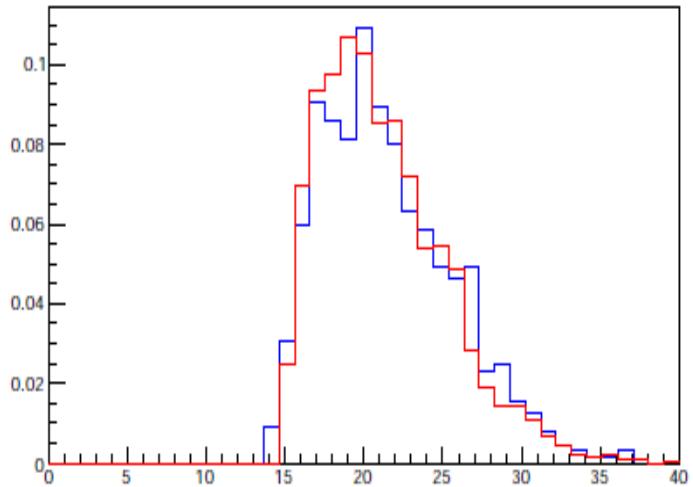
The selected events:

This analysis (smeared protons & neutrons)	Proton analysis (O. Hen et al.)
$x_B > 1.1$	$x_B > 1.2$
$0.62 < p/q < 1.1$	$0.62 < p/q < 0.96$
$\theta_{pq} < 25^o$	$\theta_{pq} < 25^o$
$M_{miss} < 1.2\,GeV/c^2$	$M_{miss} < 1.1\,GeV/c^2$
$0.4 < P_{miss} < 1\,GeV/c$	$0.3 < P_{miss} < 1\,GeV/c$

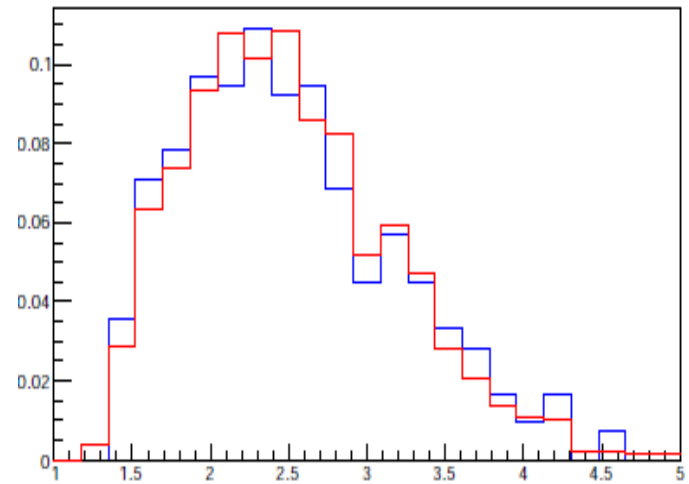
Comparing smeared protons & neutrons distributions:



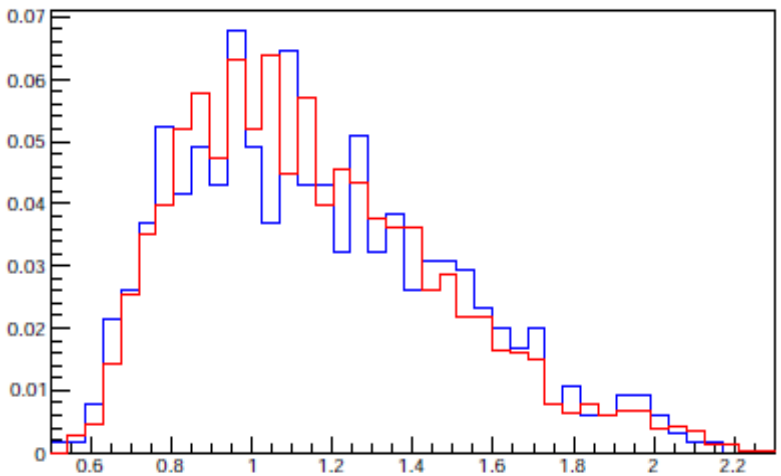
$P_e[GeV/c]$



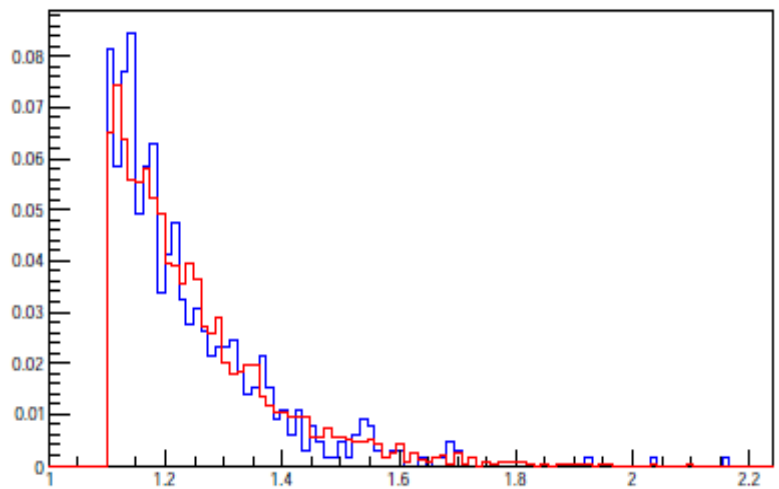
$\theta_e[deg.]$



$Q^2[GeV^2/c^2]$

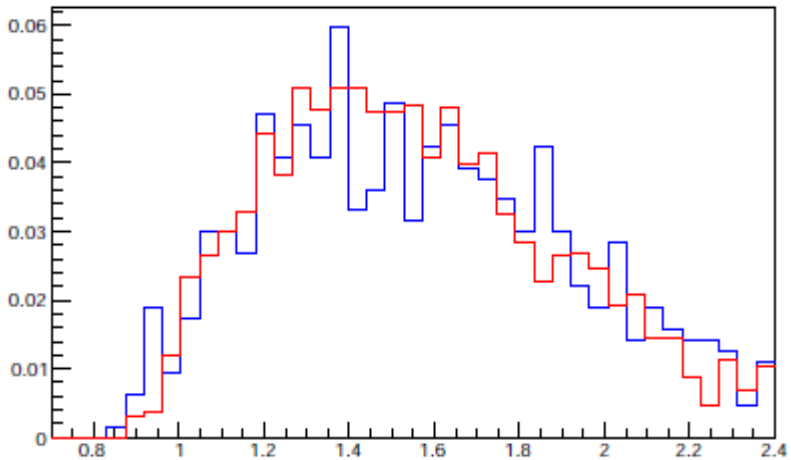


$\omega[GeV]$

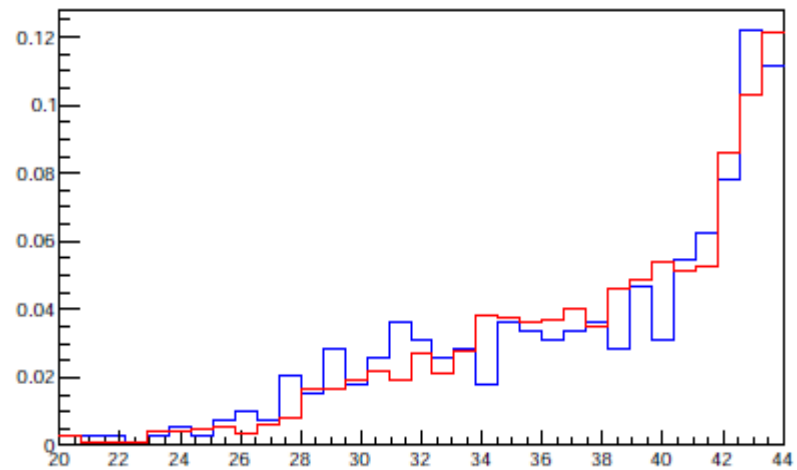


x_B

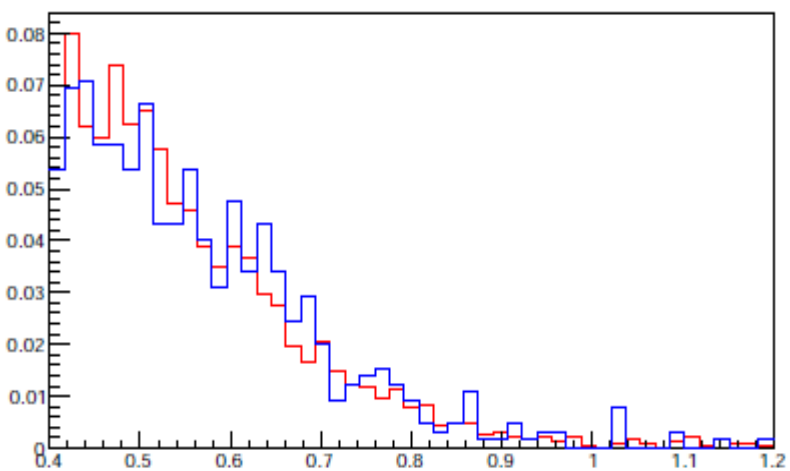
Comparing smeared protons & neutrons distributions:



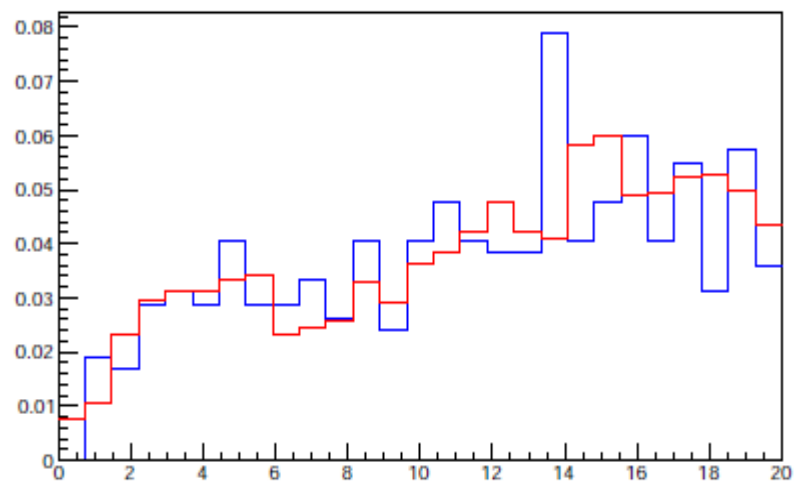
$P_{p/n}[GeV/c]$



$\theta_{p/n}[deg.]$

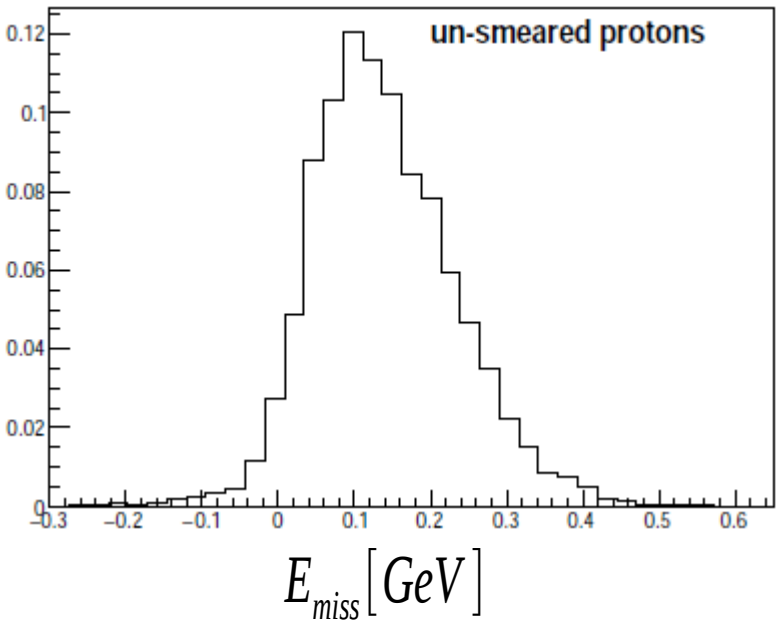


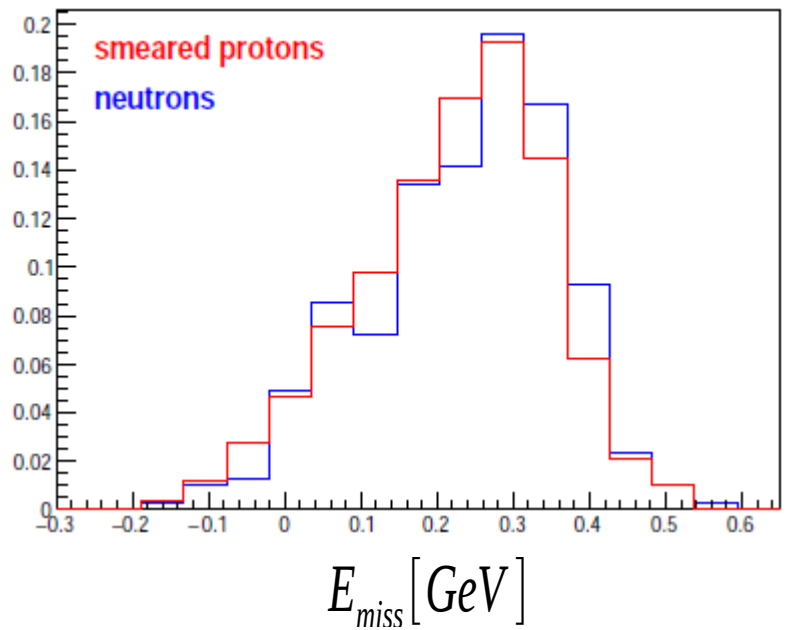
$P_{miss}[GeV/c]$

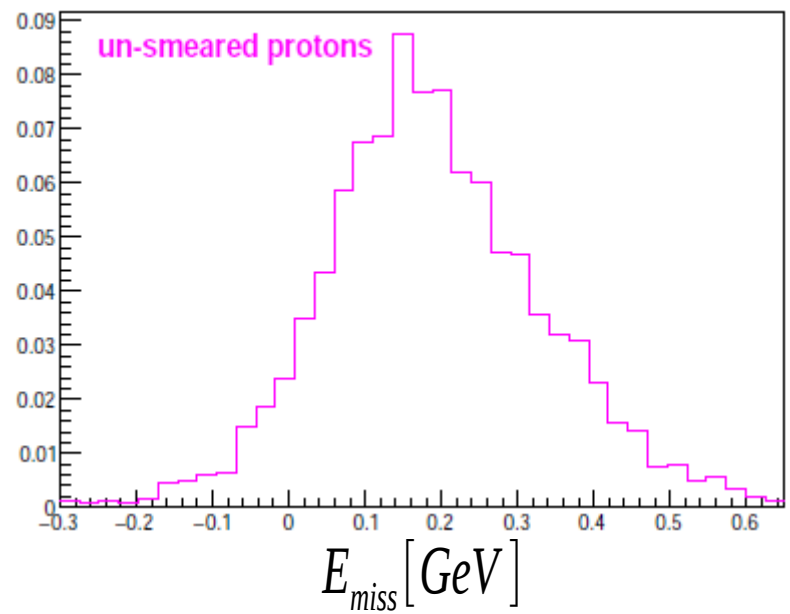


$\theta_{pq/nq}[deg.]$

Missing energy distribution







A(e,e'p)/C(e,e'p) ratios

(for smeared protons)

Corrections:

1. Normalization: target density & beam charge (FC)

	C	Al	Fe	Pb
Beam charge	3581.8	2719.4	5632.3	5079.6
Thickness [g/cm²]	0.3	0.156	0.315	0.159

2. Radiative correction

3. False positive & negative probabilities

	C	Al	Fe	Pb
False positive [%]	15.1	14.5	15.0	14.2
False negative [%]	14.9	14.7	14.8	14.6

Contributions for the uncertainty

1. Statistical error

2. Cut sensitivity

Cut	Sensitivity range	Al/C	Fe/C	Pb/C
x>1.1	±0.05	0.83%	1.5%	2.0%
0.62<p/q<1.1	±0.05	2.0%	2.5%	2.4%
$\theta_{pq} < 25^{o}$	±5°			
$M_{miss} < 1.175 GeV/c^2$	±0.05 GeV/c²	1.7%	1.8%	1.2%
$0.4 < P_{miss} < 1 GeV/c$	±0.025 GeV/c	2.2%	1.1%	2.6%

3. Radiative correction (negligible)

4. False positive and negative probabilities

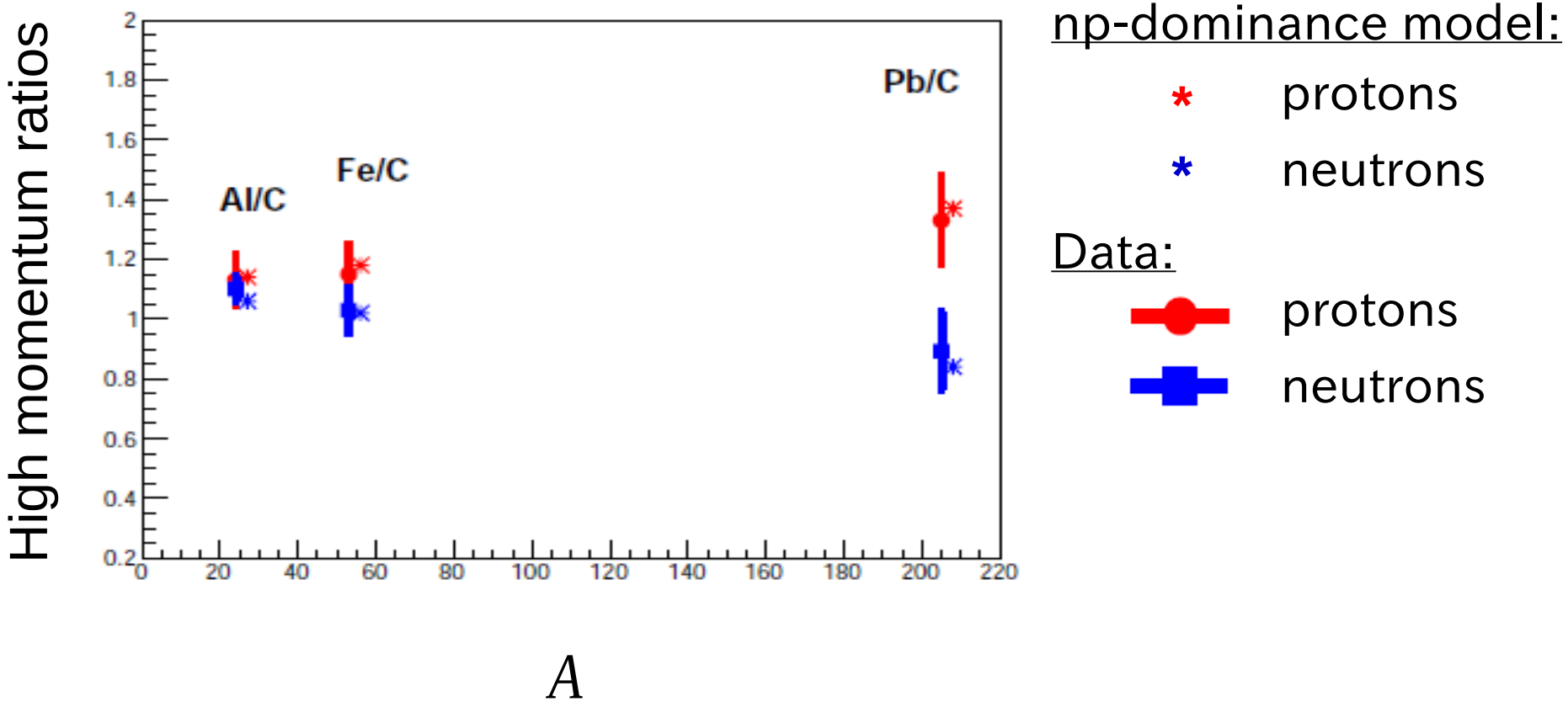
Al/C	Fe/C	Pb/C
0.3%	0.9%	1.0%

5. Target density and beam charge (negligible)

Contributions for the uncertainty

	Al/C	**Fe/C**	**Pb/C**
σ_A/σ_C	2.0±0.1	3.2±0.3	7.6±0.8
Event selection	±0.13 (92%)	±0.25 (80%)	±0.75 (93%)
False positive & negative	±0.02 (14%)	±0.03 (10%)	±0.08 (10%)
Statistics	±0.08 (57%)	±0.06 (20%)	±0.15 (19%)

Protons and neutrons high momentum ratios



Corrected for transparency and normalized by Z (N)