Momentum sharing in asymmetric nuclei

A data-mining project using CLAS EG2 data

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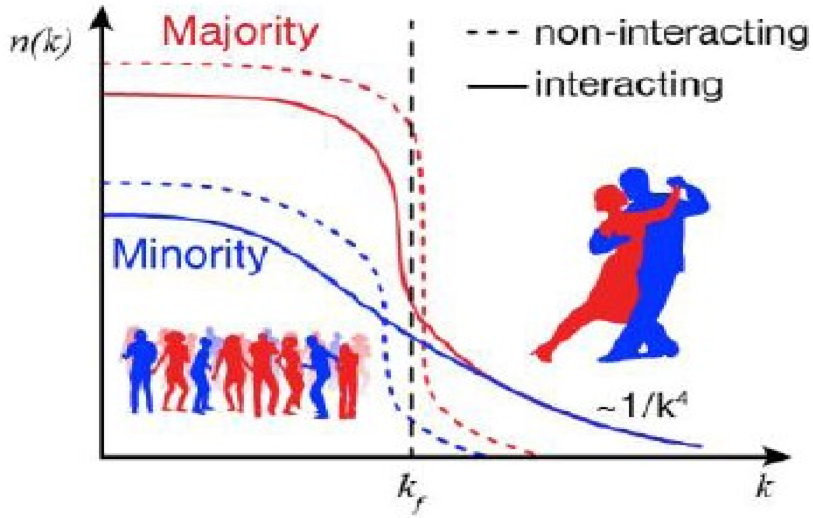
np-dominance in asymmetric nuclei



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

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

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

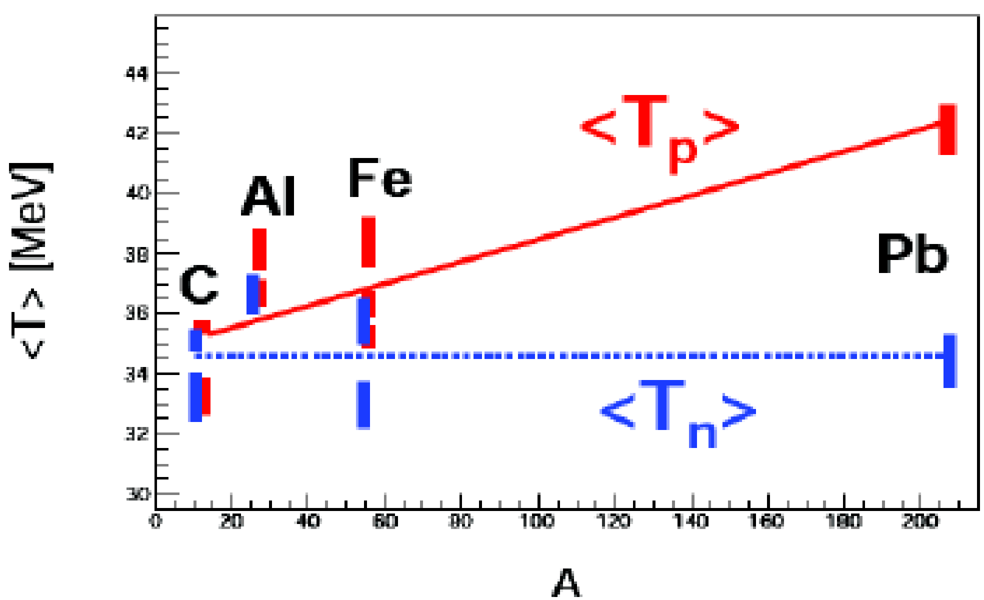
Possible inversion of the momentum sharing

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)

Prediction:



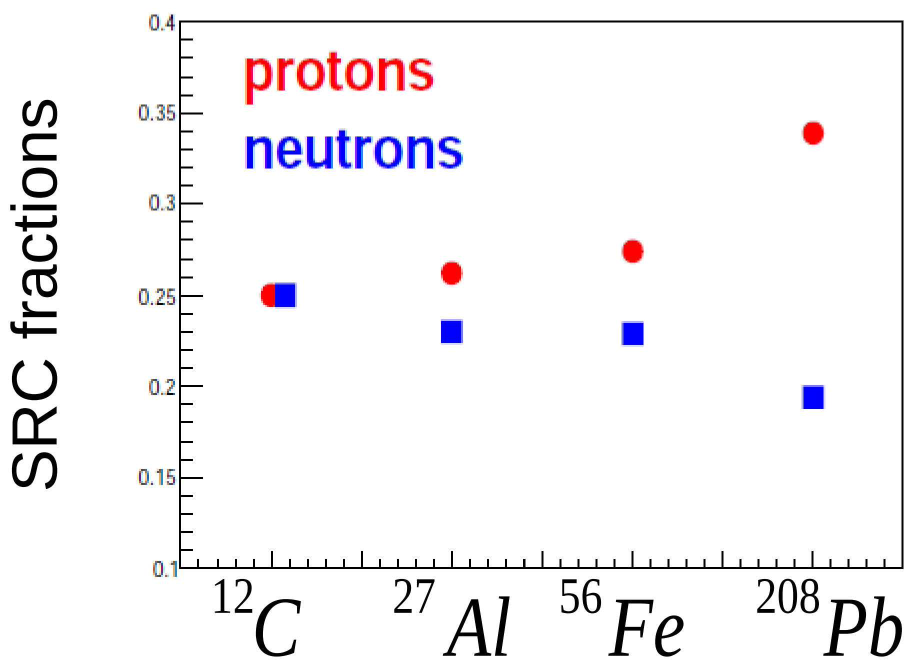
$$\langle T_{p(n)} \rangle = \int n_{p(n)} \cdot \frac{k^2}{2m} \cdot d^3 k$$

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

Simple estimate based on np-dominance

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

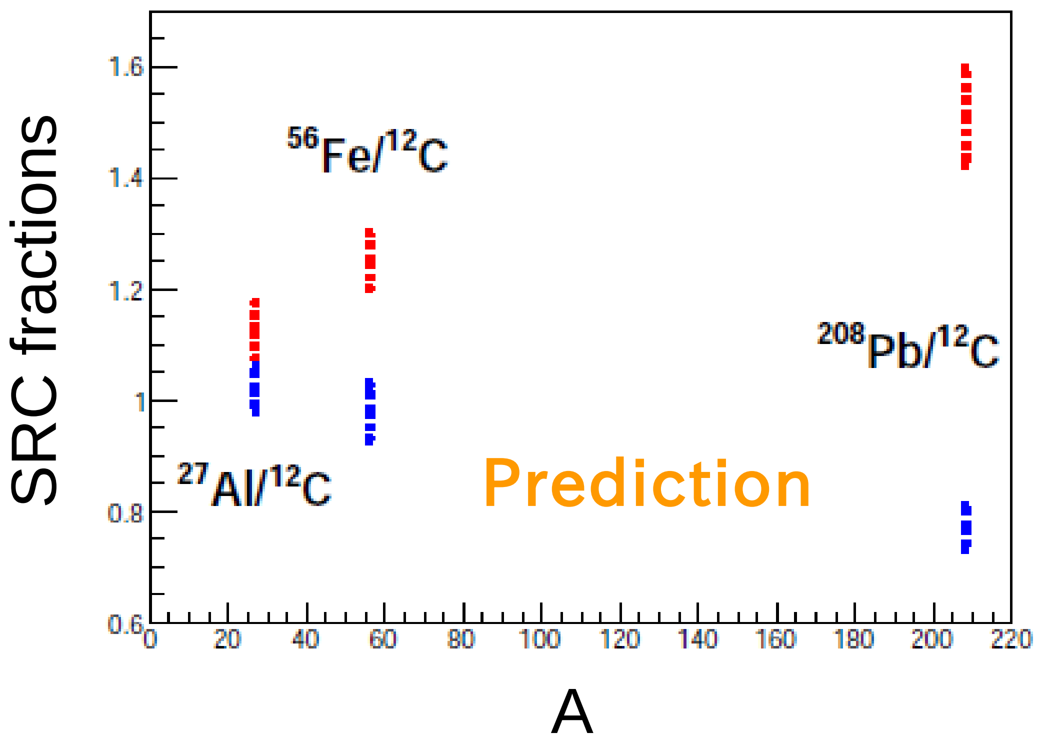
$$R_p = \frac{protons_{k>k_F}}{protons_{k<k_F}} \approx \frac{20}{82-20} = 0.32 \qquad R_n = \frac{neutrons_{k>k_F}}{neutrons_{k<k_F}} \approx \frac{20}{126-20} = 0.19$$



Simple calculation based on the np-dominance model

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

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



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

Motivation

The goal:

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

(and same for protons)

To do so:

* Identify (e,e'n) mean-field events $\left(\textit{low momentum}\right)$
* Identify (e,e'n) 2N-SRC events $\left(\textit{high momentum}\right)$
* Extract ratios and their uncertainties

Electrons [1]

Protons [2],[3]

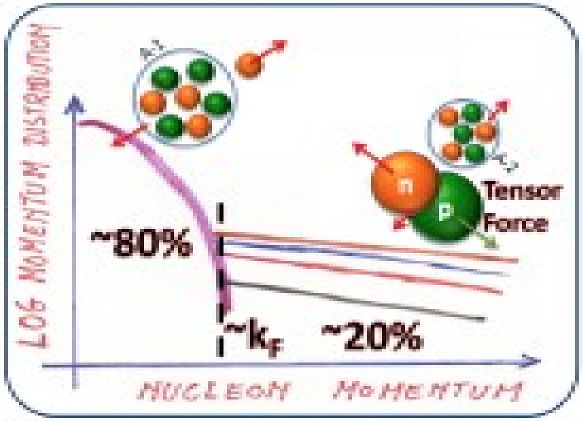
Neutrons - detecting neutrons in CLAS EC
(M. Braverman TAU thesis, 2014)

[1] Approved CLAS analysis note, L. El Fassi, 2011)
[2] O. Hen et al., Phys. Lett. B 772, 63 (2013) [3] O. Hen et al., Science 346, 614 (2014)

Analysis of QE events:

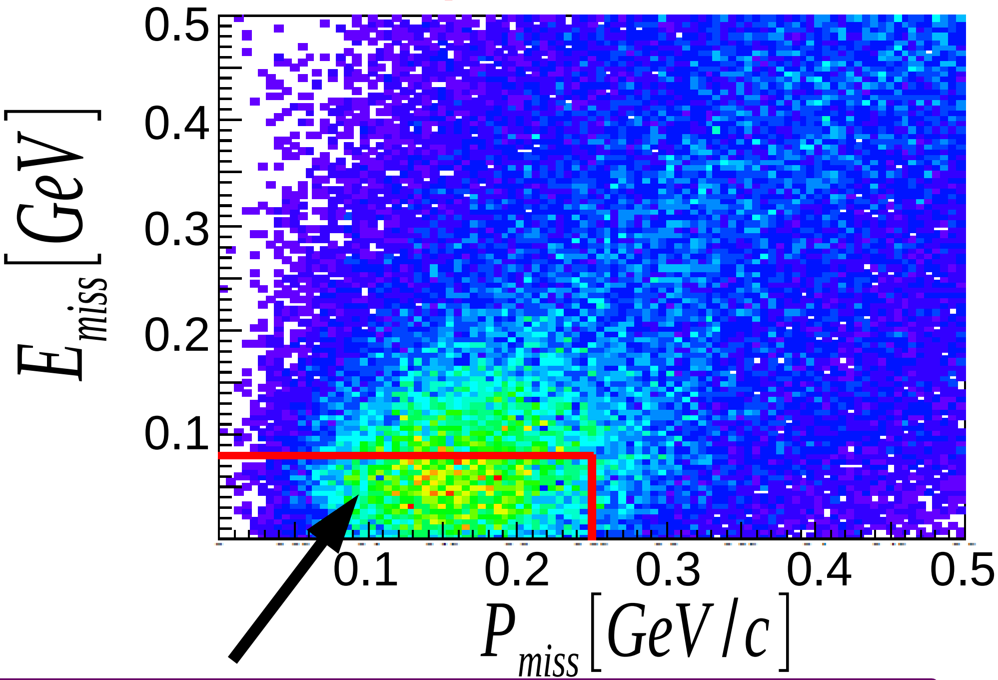
I. Identifying A(e,e'n) and A(e,e'p) mean-field events

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

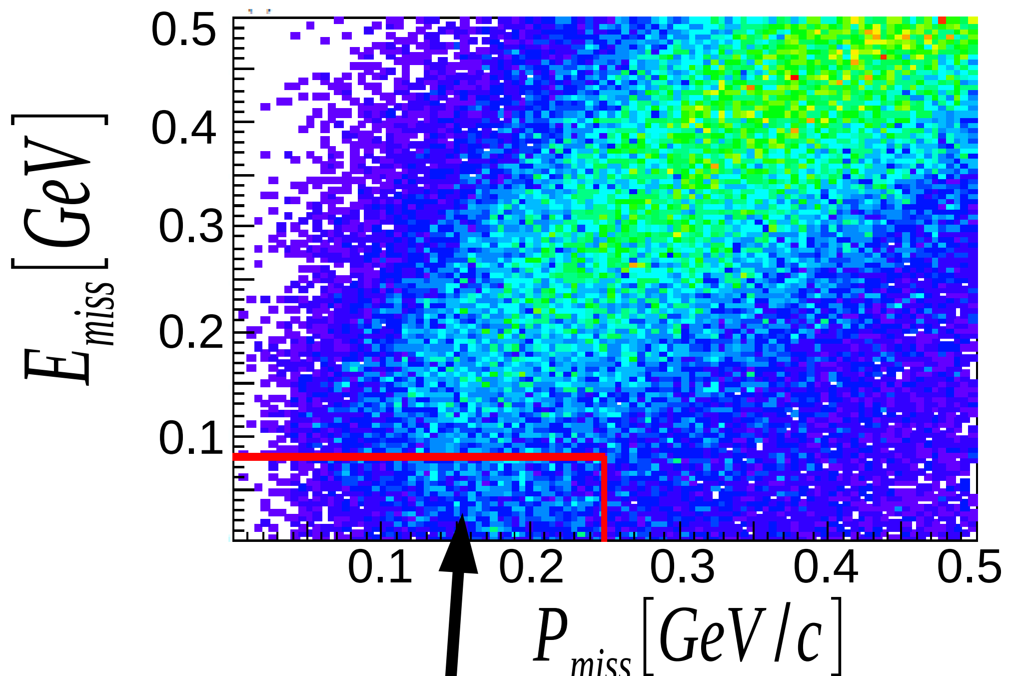


Selecting M.F. QE events

protons



neutrons



QE peak [1]-[3]:

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

Problem:

Poor resolution in the EC -

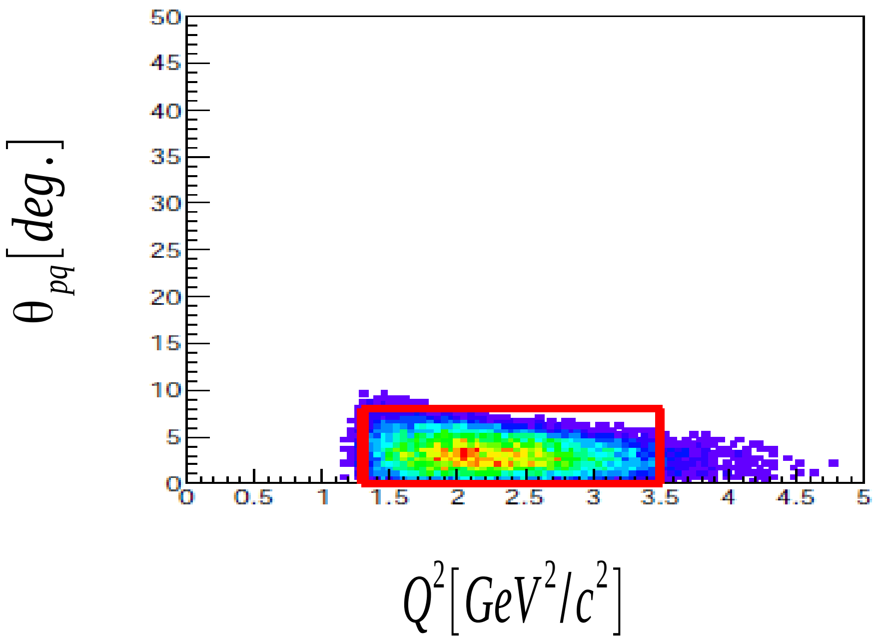
$\Delta P \approx 0.2 GeV/c$

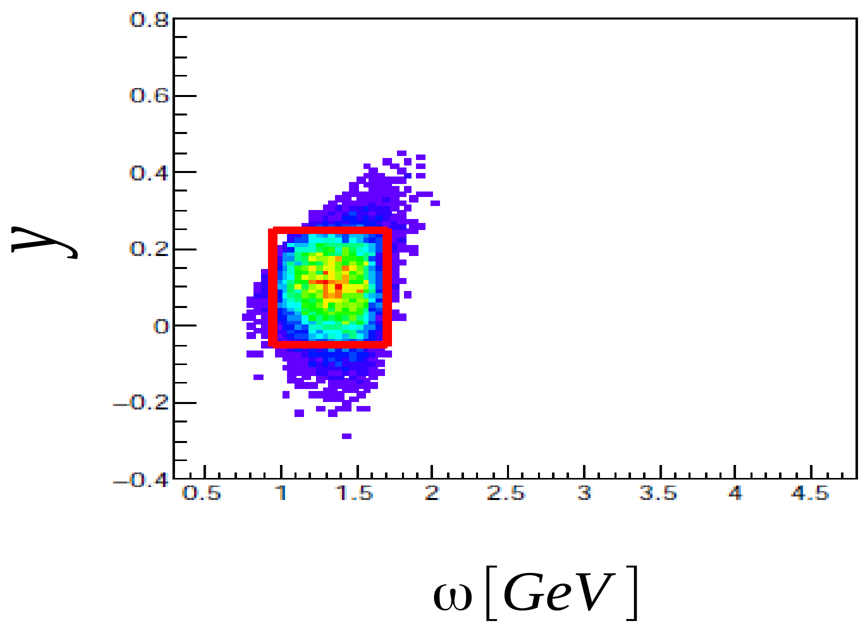
[1] T.G. ONeill et al., Phys. Lett. B 87, 351 (1995).
[2] D. Abbott et al. Phys. Rev. Lett. 80, 5072 (1998).
[3] K. Garrow et al. Phys. Rev. C. 66, 044613 (2002).

Solution 1: Using electron quantities & scattering angle of the nucleon

Protons after the QE cuts:

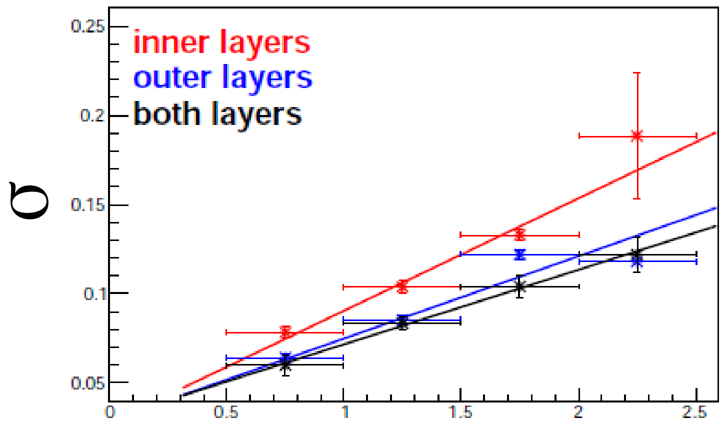
(QE cuts: P_{miss}<0.25 GeV/c E_{miss}<0.08 GeV)





Solution 2: Using smeared protons to define and test the cuts

Neutron measured momentum resolution

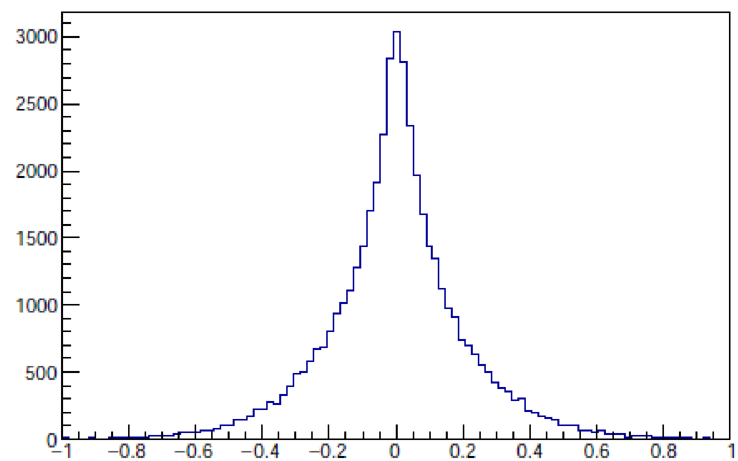


$P_n[GeV/c]$

Neutron interaction probability:

32% - inner layer
47% - outer layer
20% - both layer

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

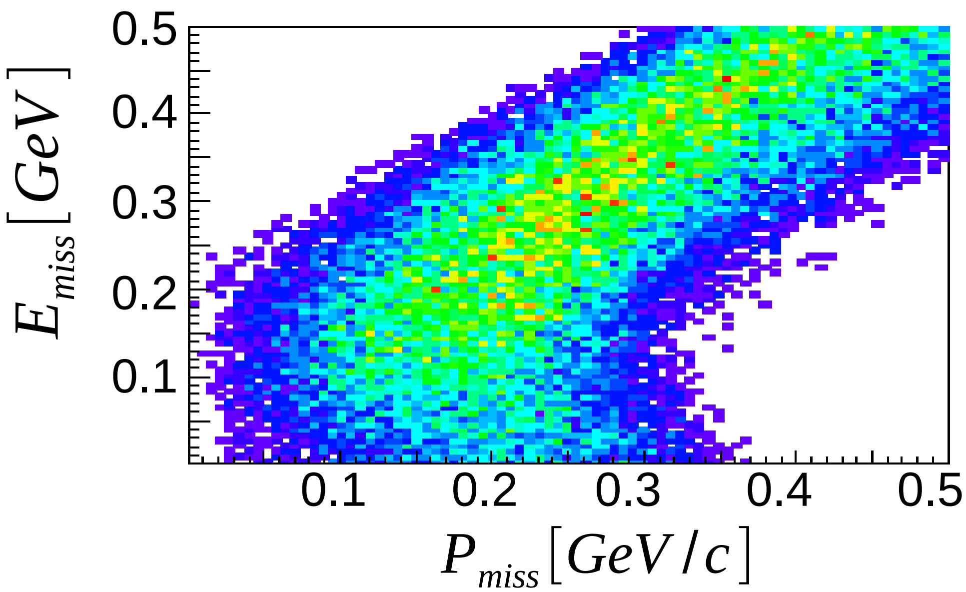


$P_p - P_{smeared}[GeV/c]$

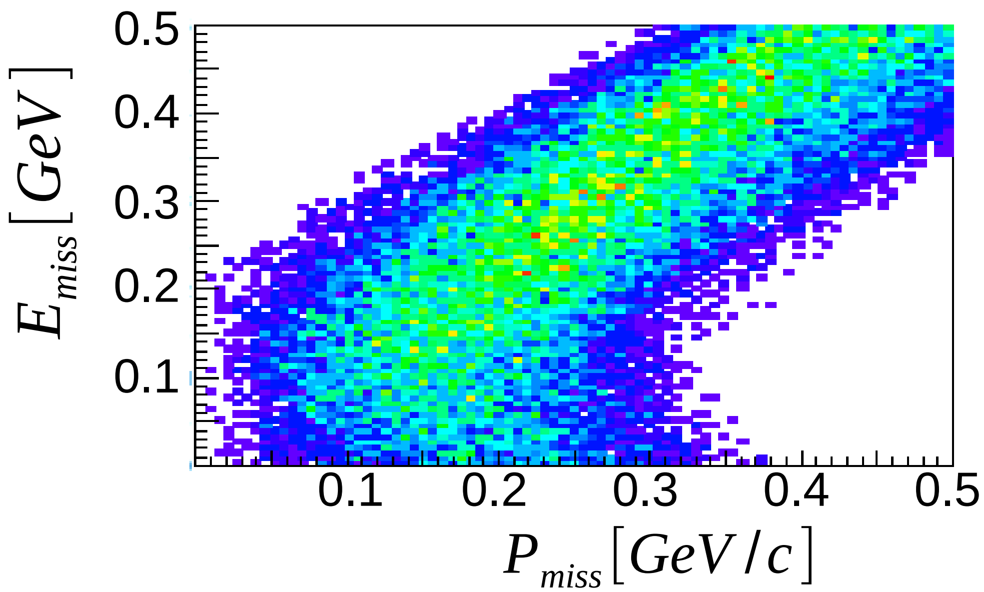
With the common cuts:

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

smeared protons

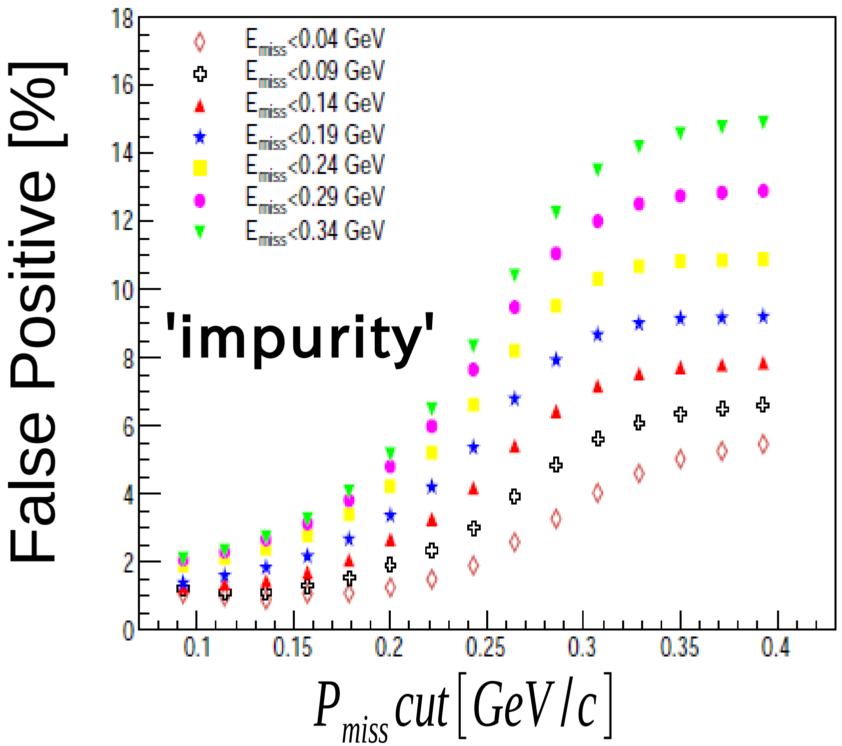


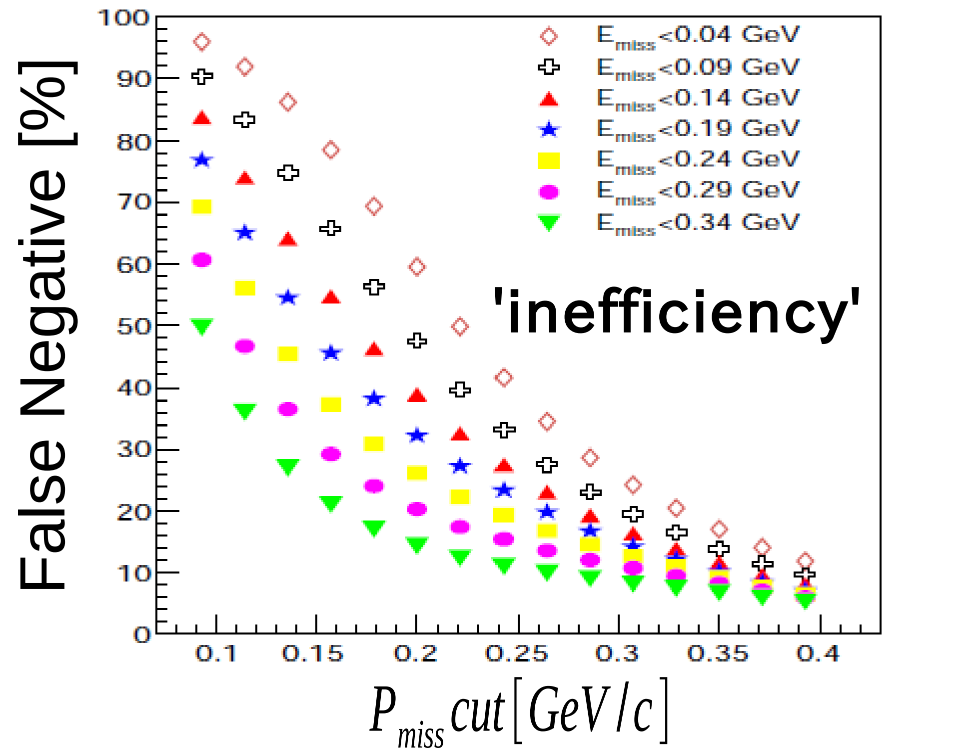
neutrons



How to determine P_{miss} and E_{miss} cuts?

False Positive & Negative probabilities





The selected cuts for smeared p/n:

$P_{miss} < 0.3\, GeV/c, \; E_{miss} < 0.24\, GeV$

The cuts for un-smeared p:

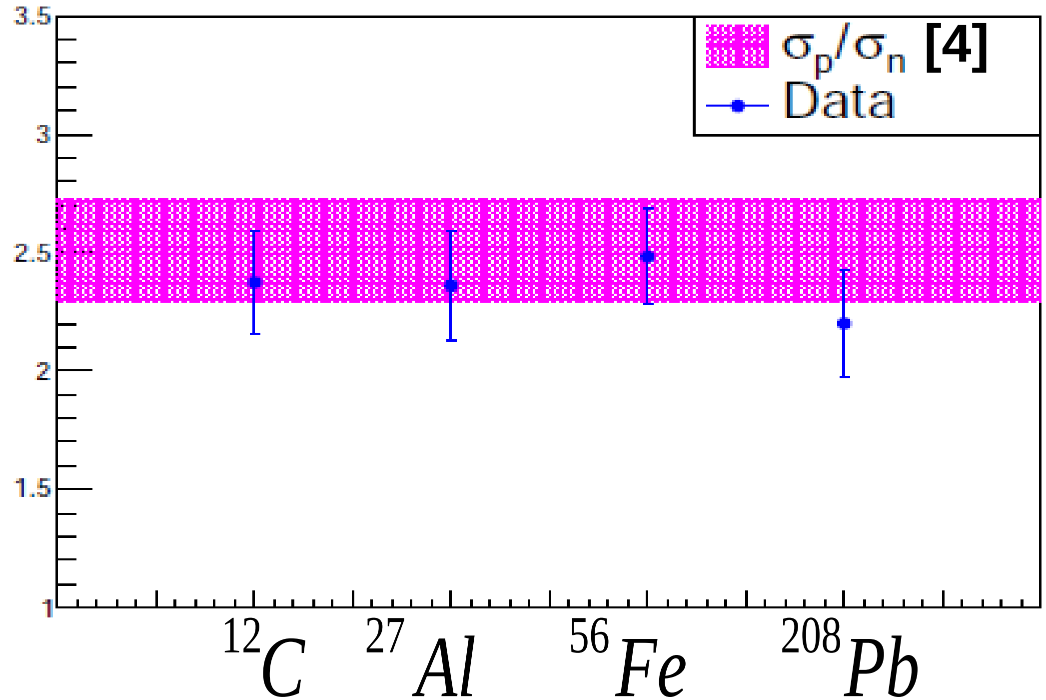
$P_{miss} < 0.25\, GeV/c, \; E_{miss} < 0.08\, GeV$

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

Sanity check:

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

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



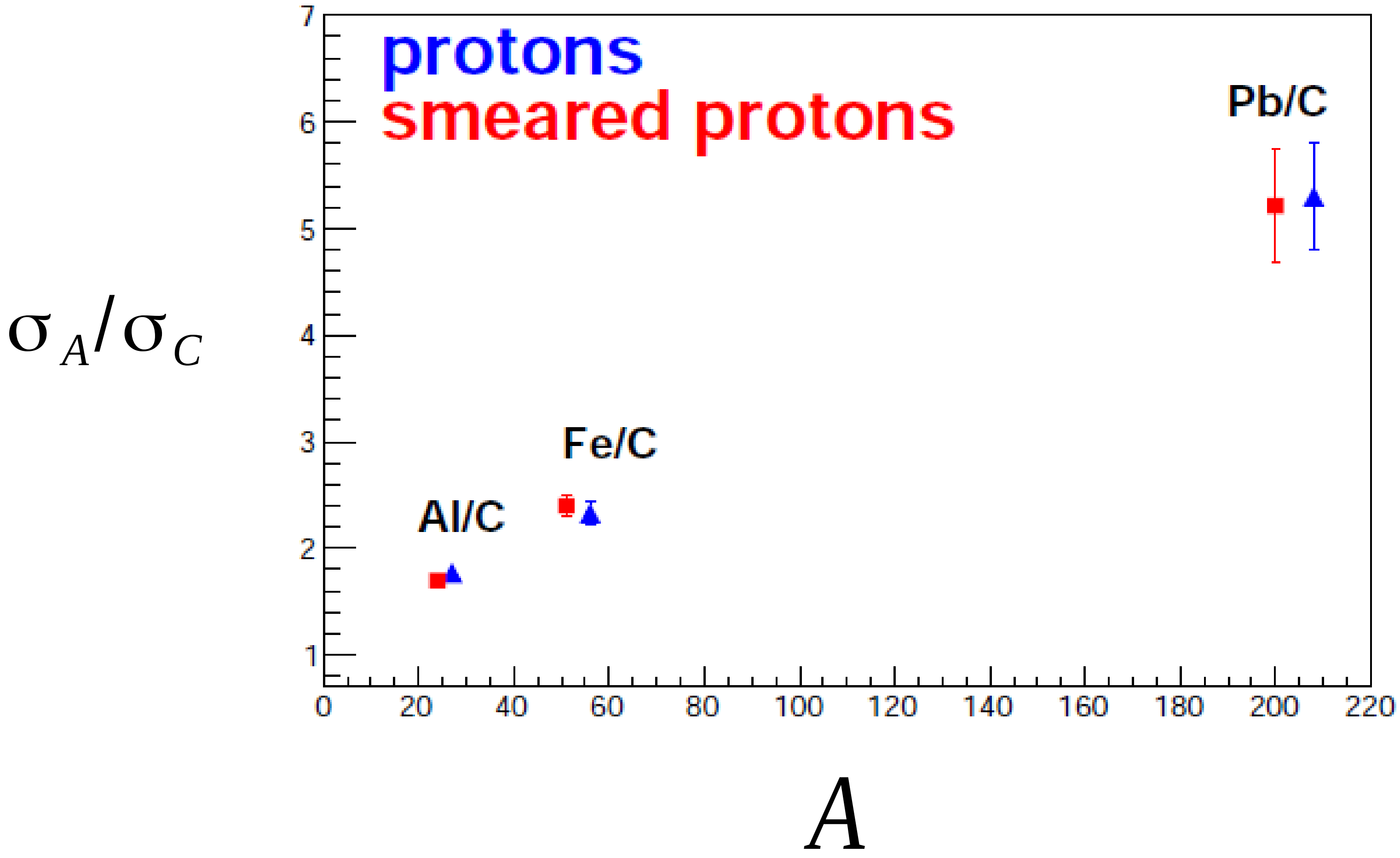
$$\sigma^R_{ep(n)} = \frac{\epsilon}{\tau} G_E^2 + G_M^2$$

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

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

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

(compare smeared and un-smeared protons)



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

Analysis

1st step:

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

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

2nd step:

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

Same strategy:

I. Cut on common quantities:

$x_B > 1.1$

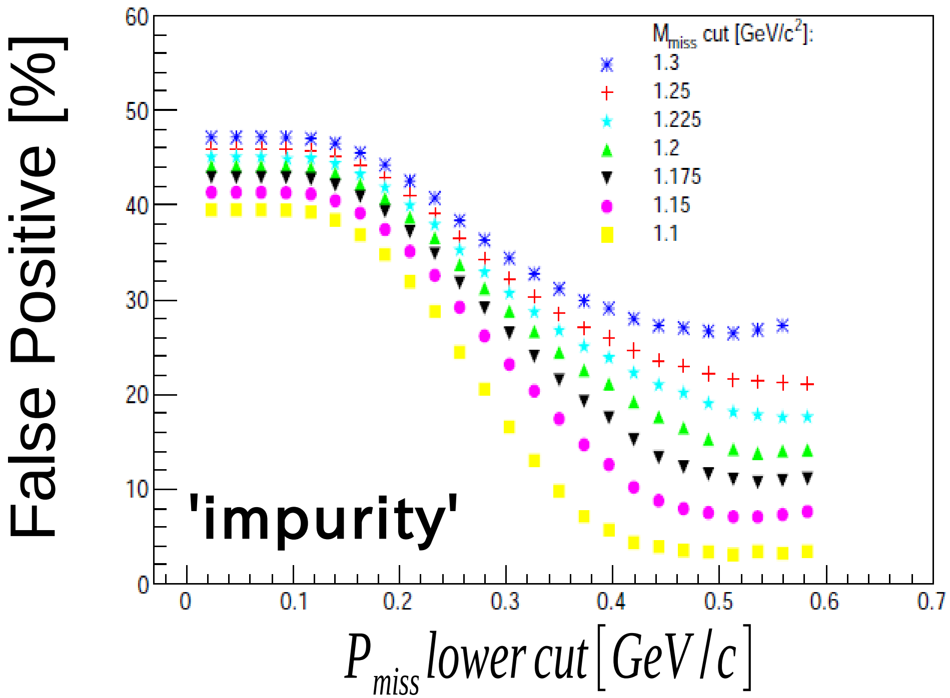
$$0.62 \le \frac{|\vec{P}_N|}{|\vec{q}|} \le 0.96$$

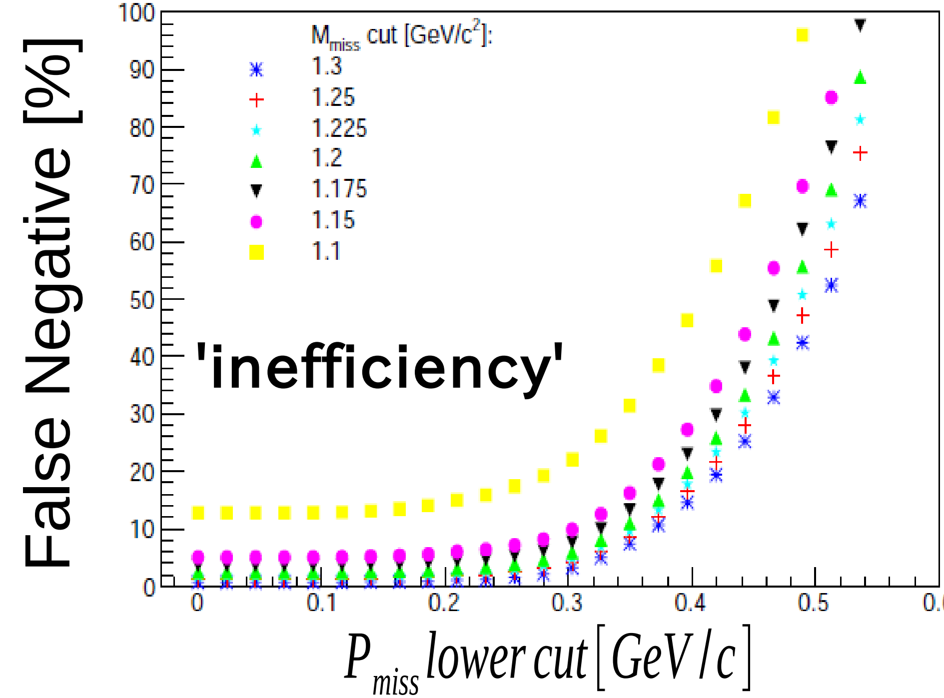
$\theta_{Nq} \le 25^o$

I. Using smeared protons:

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

False Positive & Negative probabilities





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

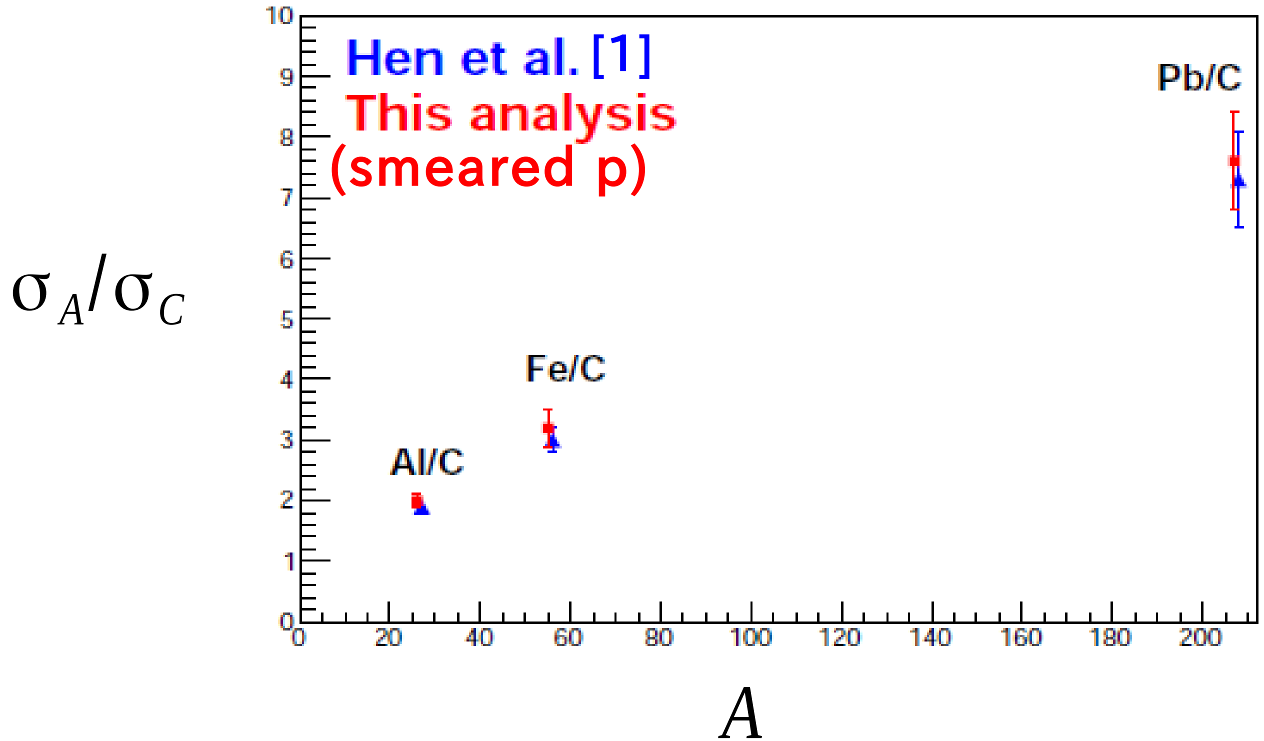
The cut for un-smeared protons: $0.3 < P_{miss} < 1\, GeV/c$, $M_{miss} < 1.1\, GeV/c^2$

$False\ Positive \simeq 15\%$

$False\ Negative \simeq 20\%$

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

(compare smeared and un-smeared protons)



	Al/C	Fe/C	Pb/C
Hen et al. analysis	1.9±0.08	3.0±0.2	7.2±0.8
This analysis (smeared p)	2.0±0.1	3.2±0.3	7.6±0.8

[1] O. Hen et al., Phys. Lett. B 772, 63 (2013)

Sanity check:

$$\frac{^{12}C(e,e'n)_{high}}{^{12}C(e,e'n)_{low}} = 0.101 \pm 0.004 \overset{?}{=} \frac{^{12}C(e,e'p)_{high}}{^{12}C(e,e'p)_{low}} = 0.098 \pm 0.002$$

(Statistical error)

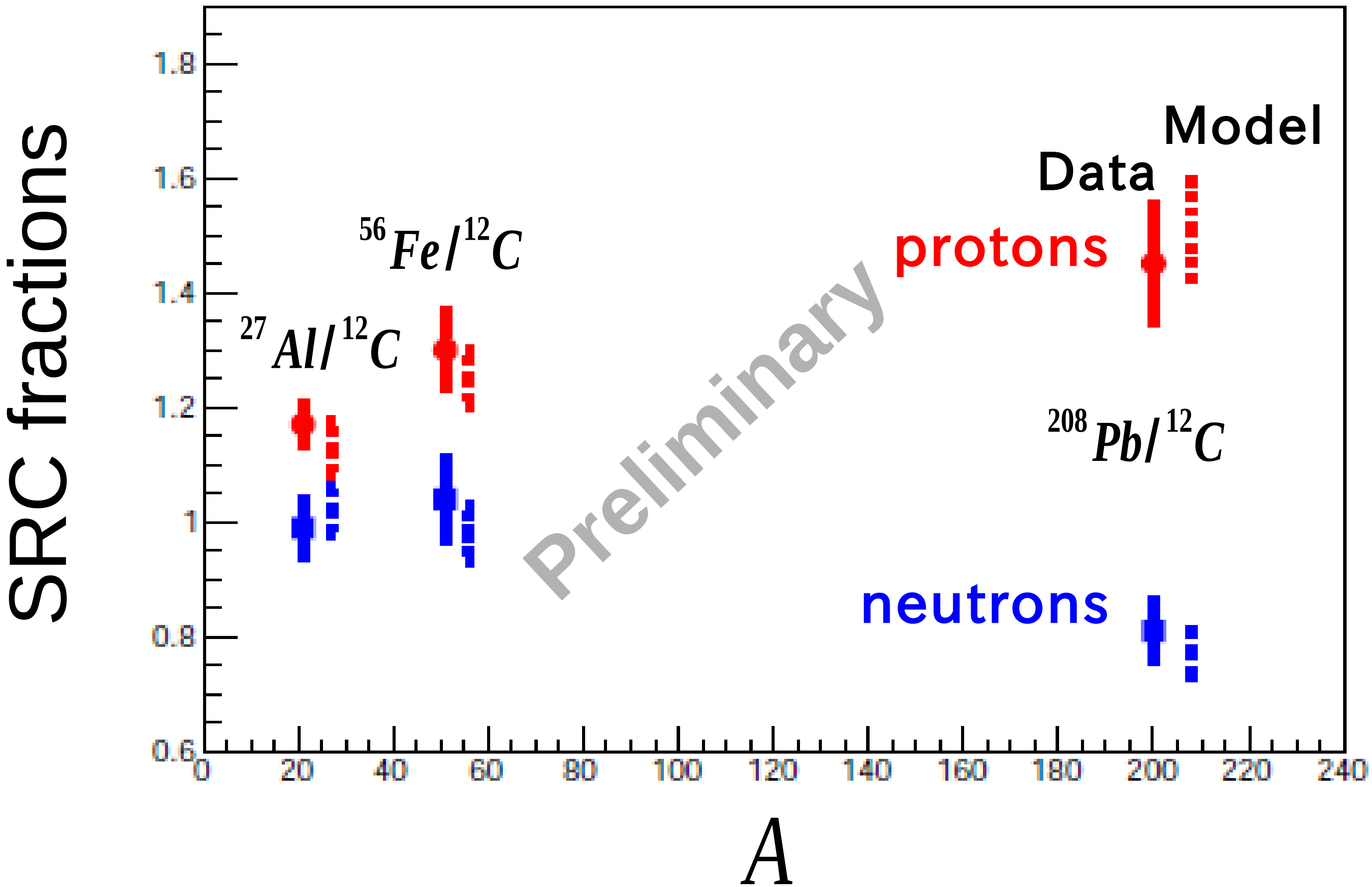
Analysis of QE events:

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

Protons and neutrons super ratios

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



Protons move faster than neutrons in N>Z nuclei

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

Backup Slides

$$A(e,e'N)_{k<k_F} \propto \int_0^{k_0} n^{M.F.}(k)k^2dk \qquad A(e,e'N)_{k>k_F} \propto \int_{k_0}^{\infty} n^{SRC}(k)k^2dk$$

Considered 3 models for $n_{M.F.}$

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

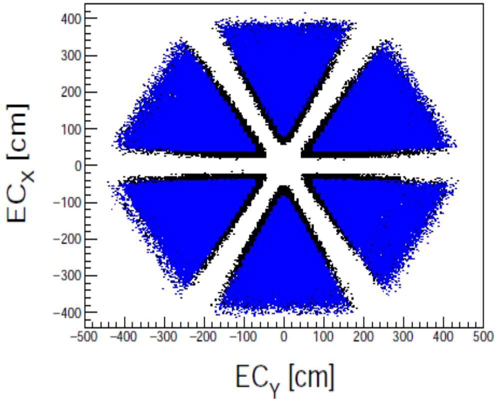
Considered 2 values of K_0:

* 300 MeV/c
* k_F

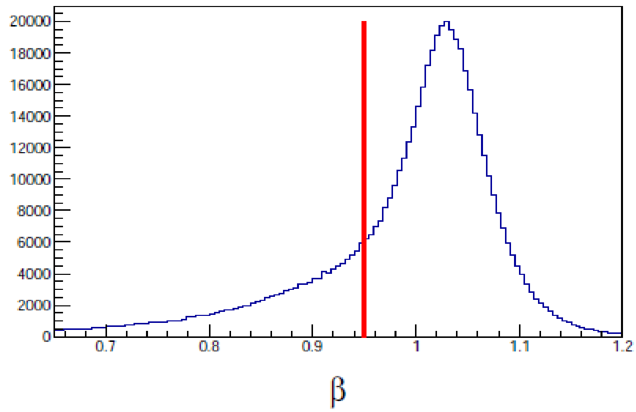
Uncertainty was taken as the difference between the different results.

Detecting neutrons

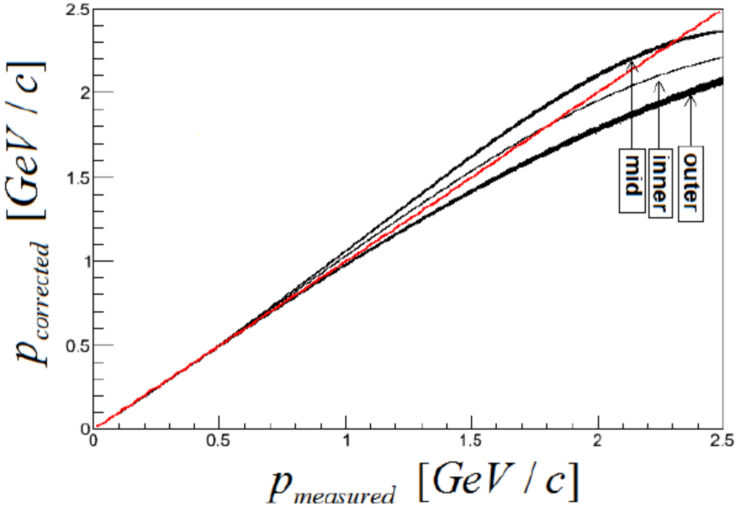
- No DC and SC signals
- EC fiducial cut



- Velocity cut: β<0.95



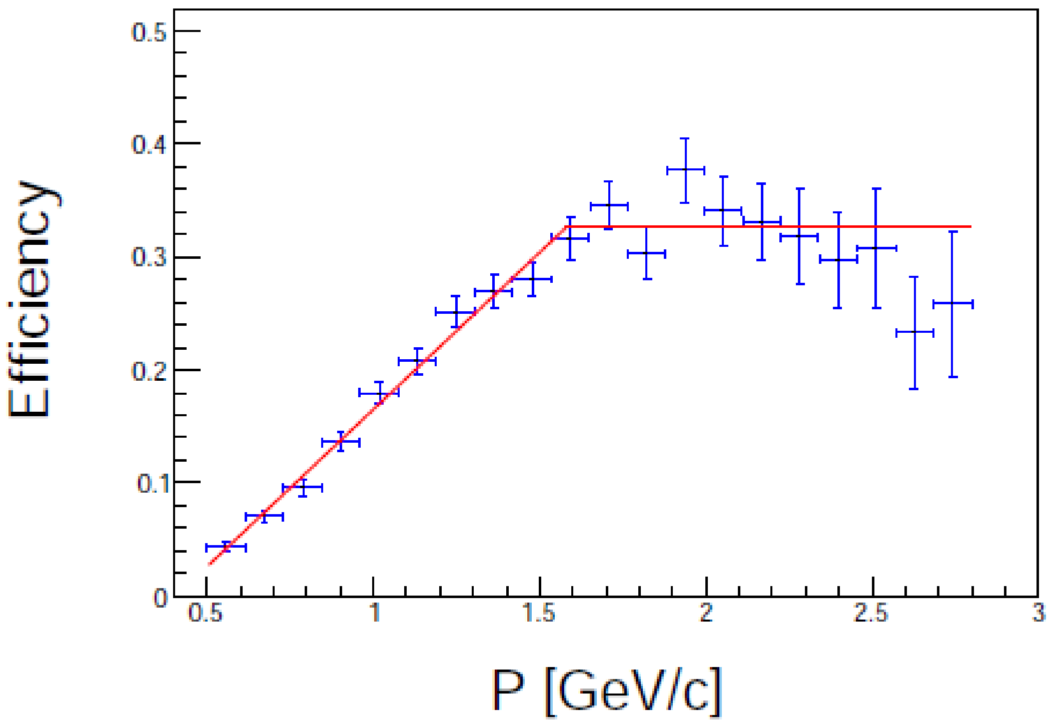
- Momentum cut: p<2.34 GeV/c (β<0.93)



Empirical momentum correction, takes values up to 2.34 GeV/c

Neutron detection efficiency

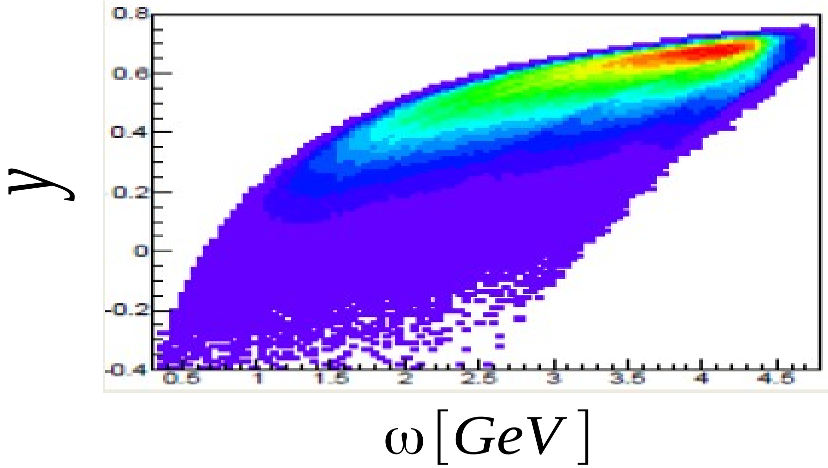
$$\epsilon = \frac{\#d(e, e'p\pi^+\pi^- n)}{\#d(e, e'\pi^+\pi^-)n}$$

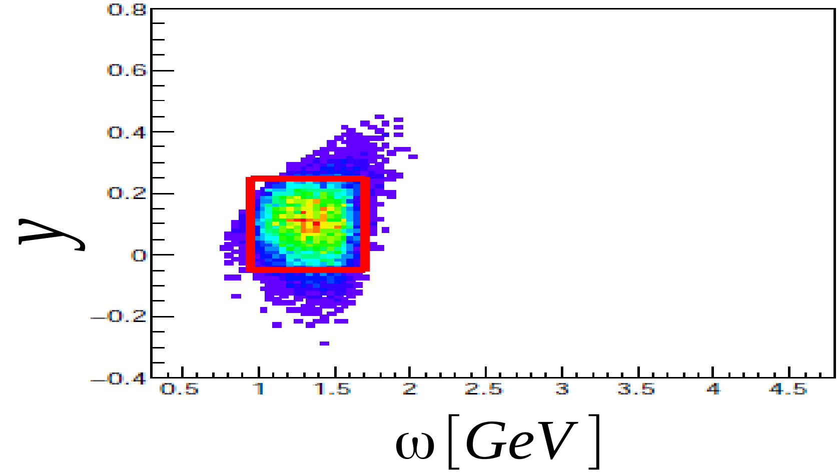


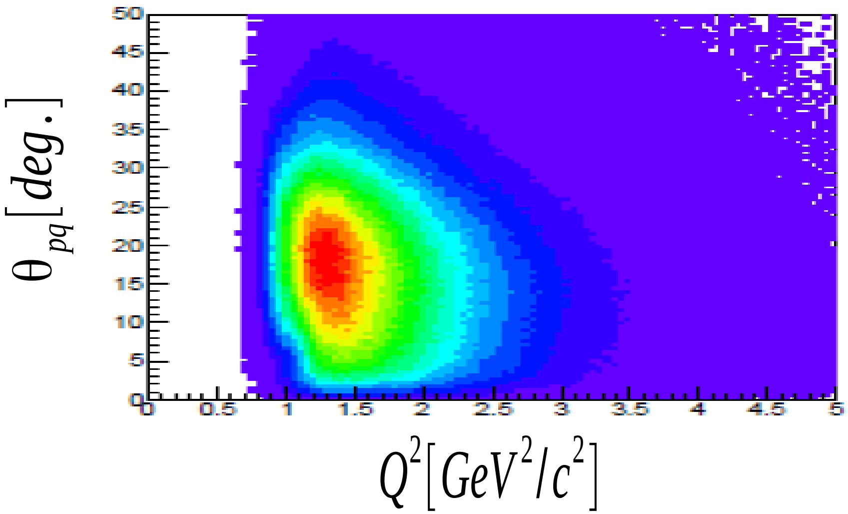
Solution 1: Using cuts common to (e,e'p) and (e,e'n)

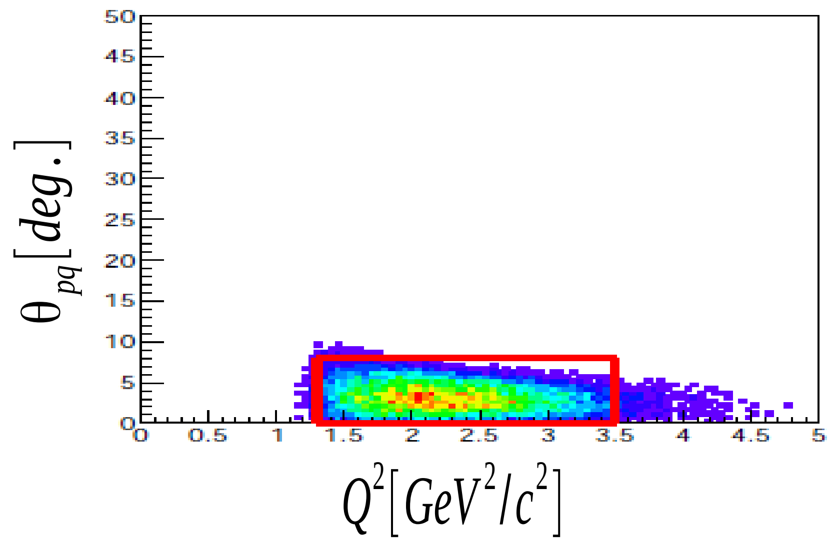
QE cuts: $P_{miss}<0.25$ GeV/c $E_{miss}<0.08$ GeV

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







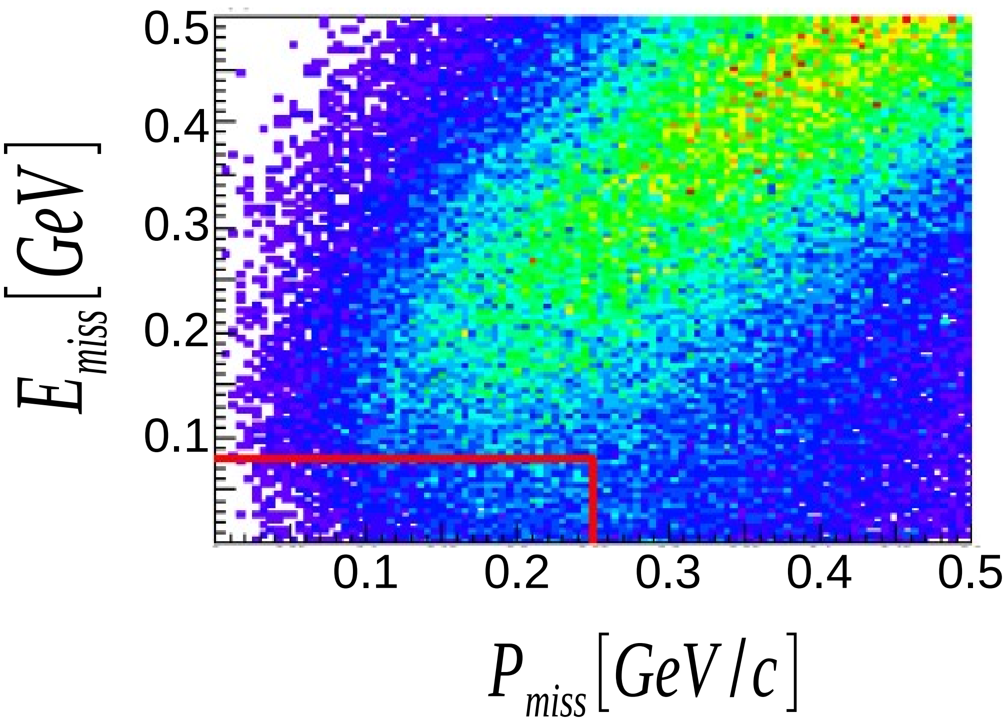


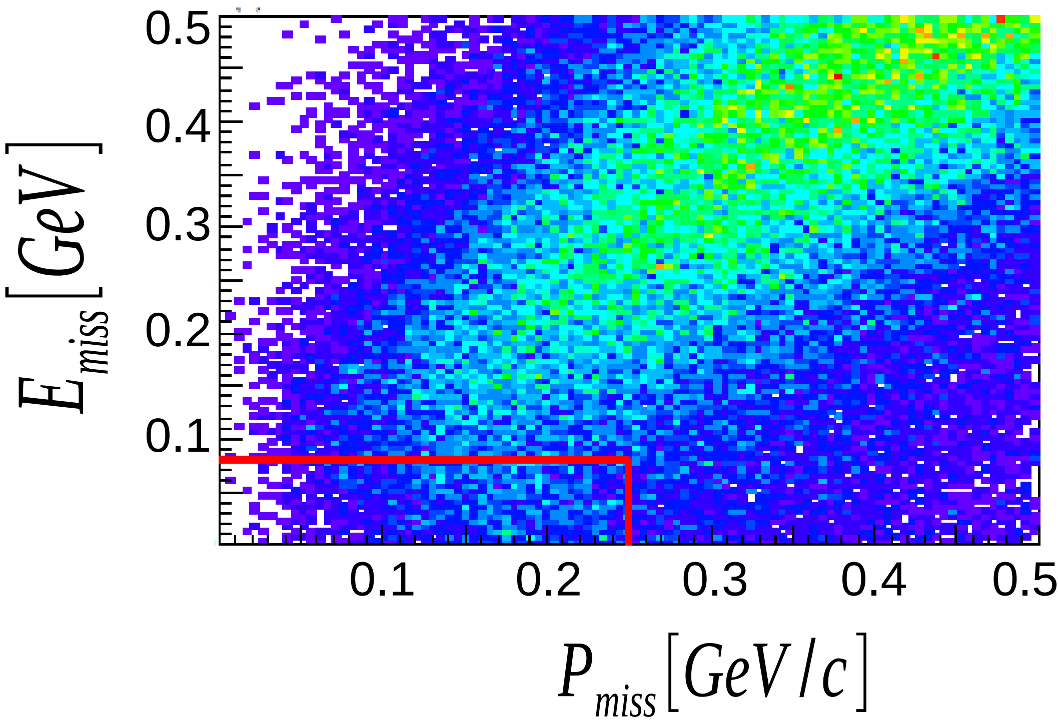
$$y \equiv \left[(M_A+\omega)^2 \sqrt{\Lambda^2 - M_{A-1}^2 W^2} - |\vec{q}|\Lambda \right] / W^2$$

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

smeared protons

neutrons





Without applying any cuts

E_{miss} P_{miss} *cuts*

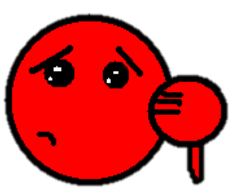
un-smeared protons

'good event':

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

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

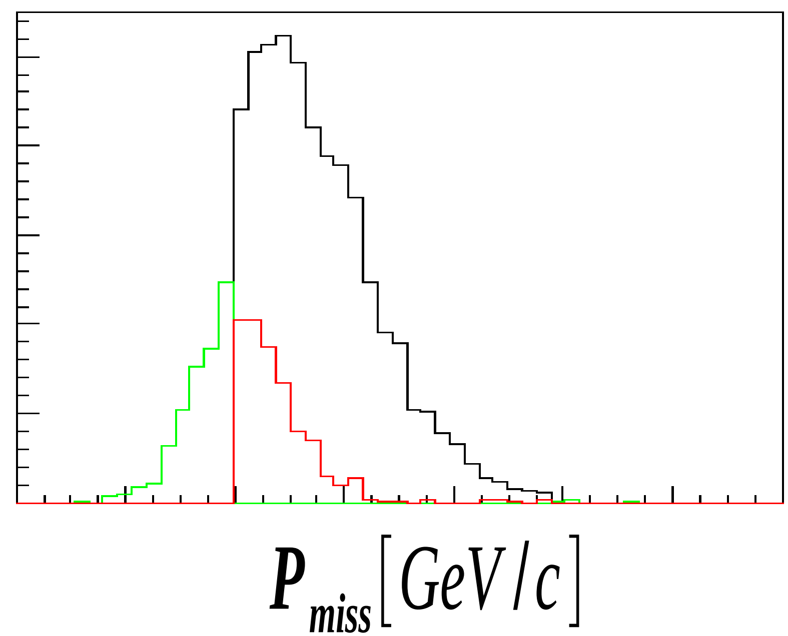
'bad event':



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

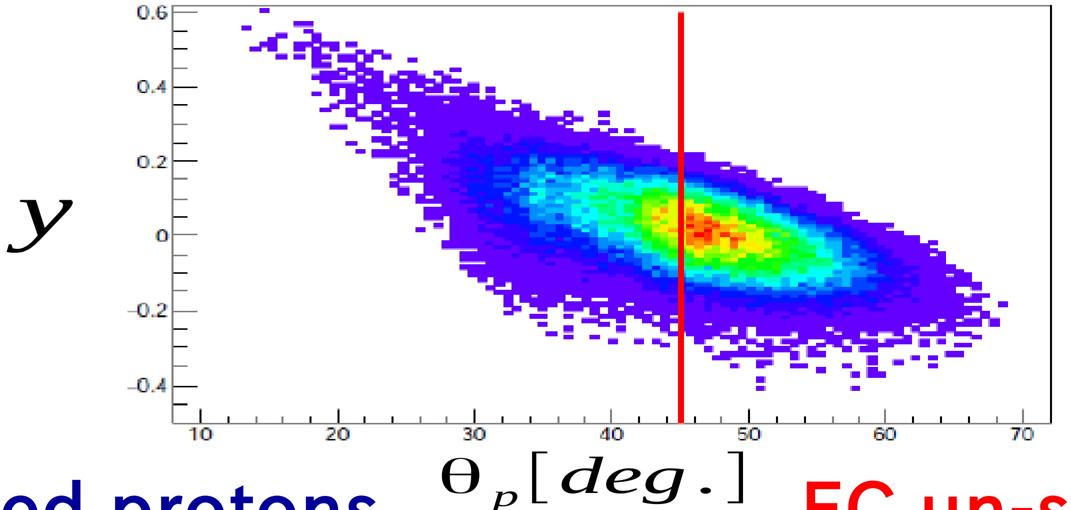
|| $$E_{miss-unsmeared} > 0.08\,GeV$$

smeared protons (neutrons)

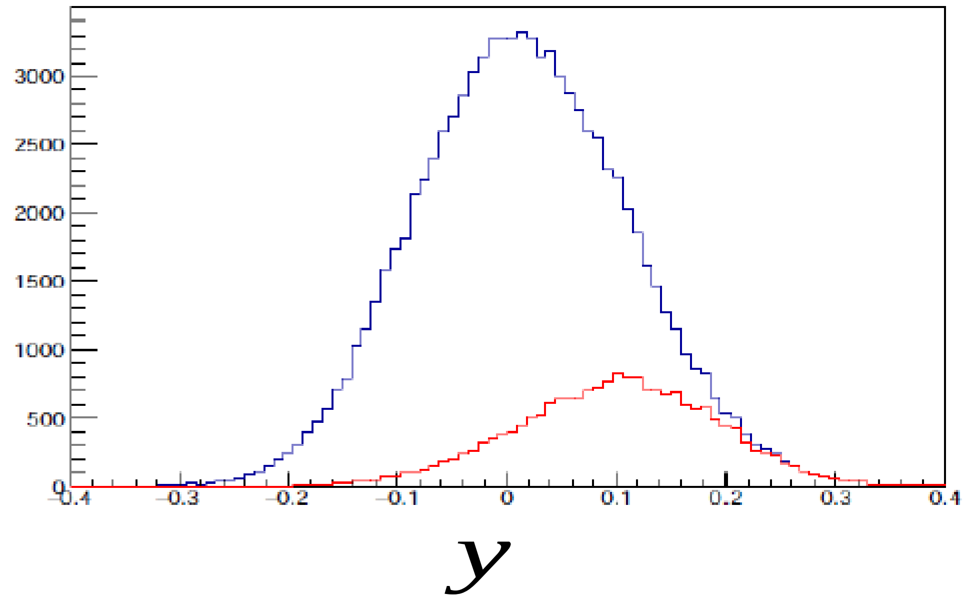


Comparing un-smeared protons

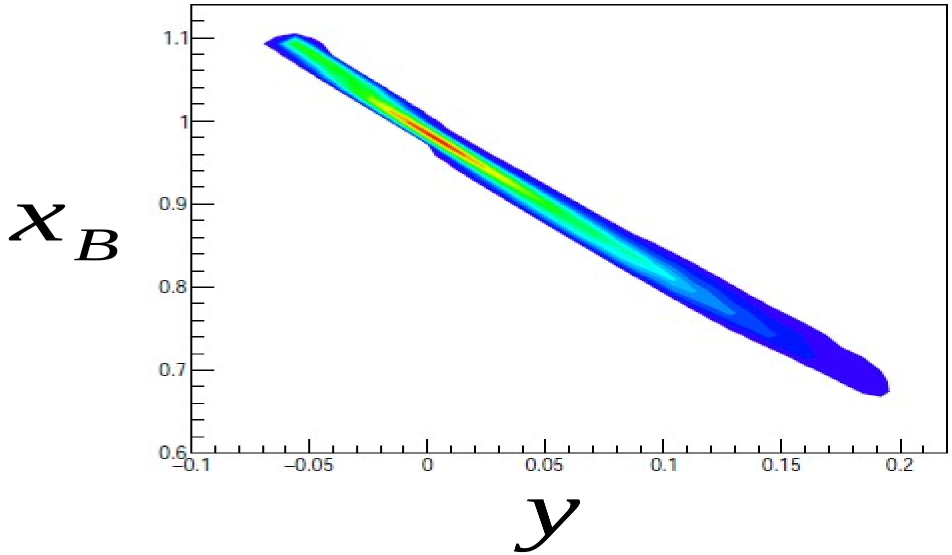
QE cuts: $P_{miss} < 0.25\,GeV/c$ $E_{miss} < 0.08\,GeV$



All un-smeared protons EC un-smeared protons

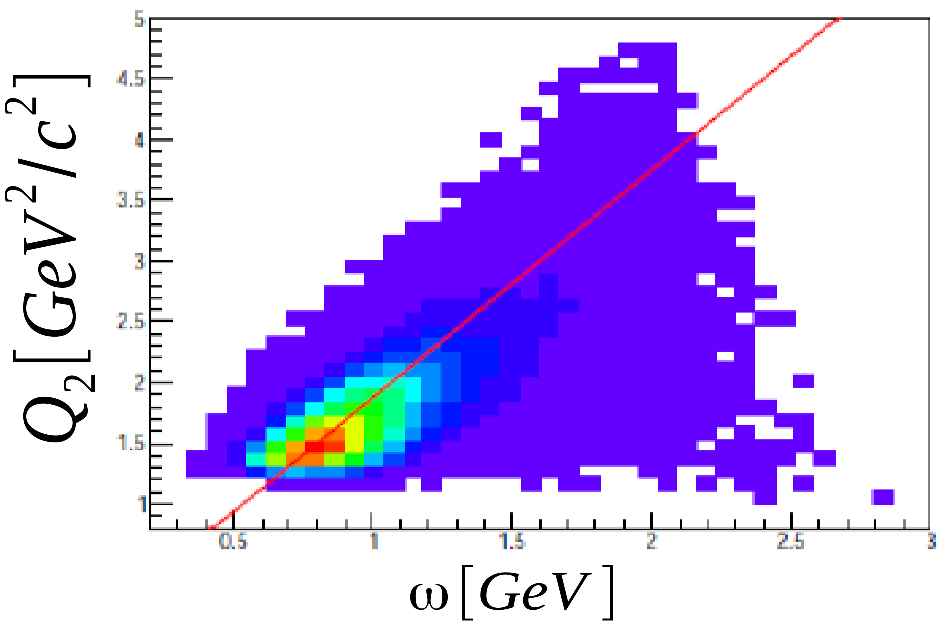


Comparing un-smeared protons

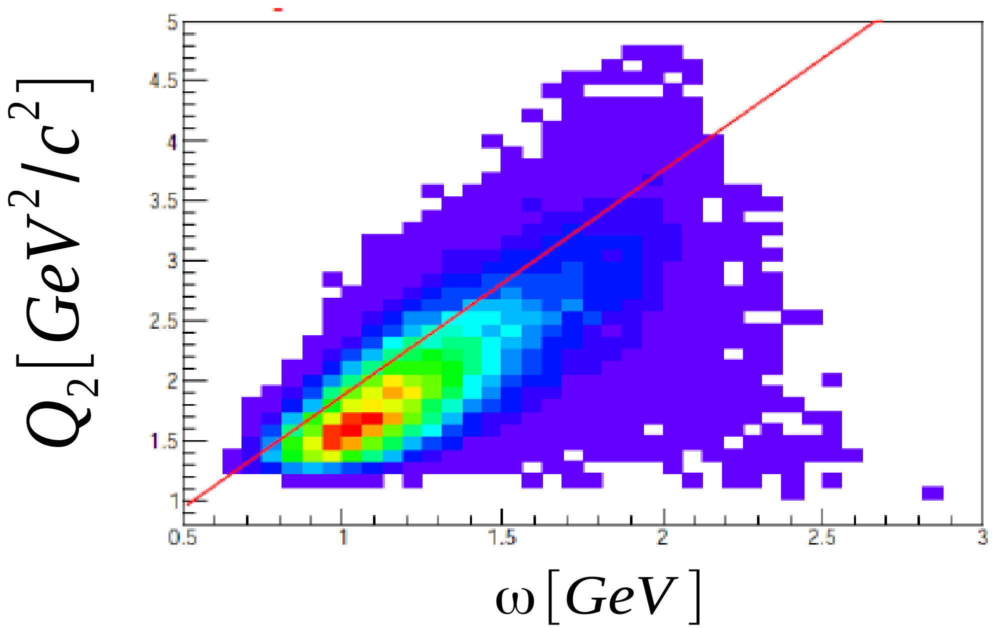


QE events → $x_b \approx 1$

All un-smeared protons



EC un-smeared protons



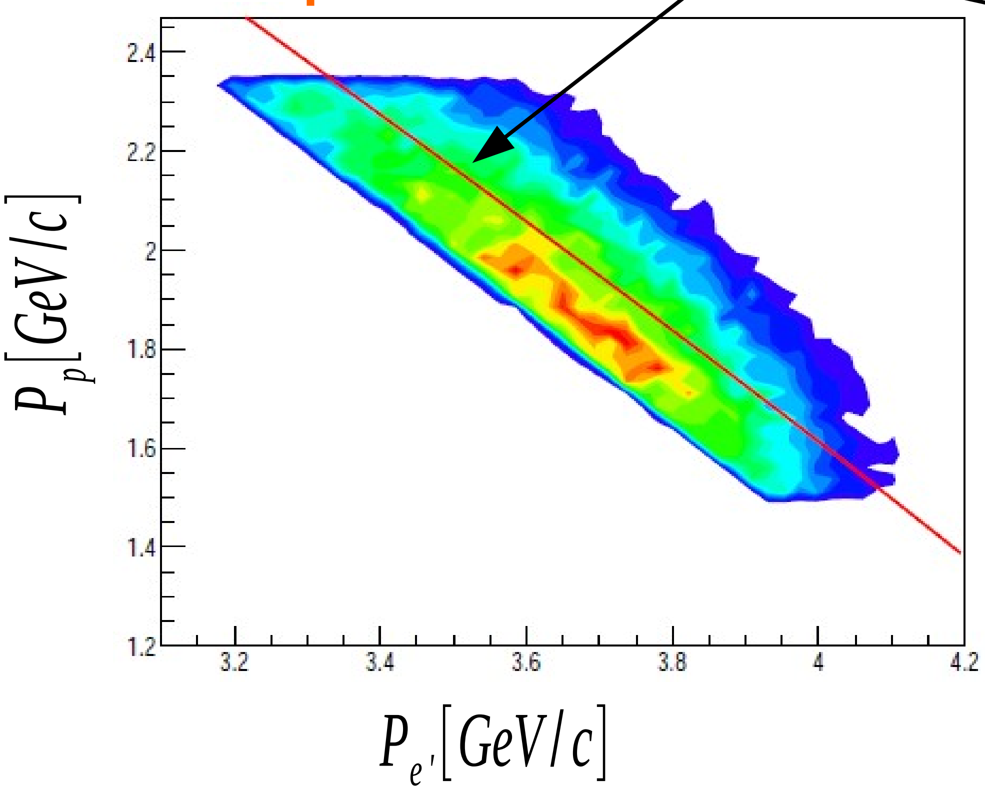
Checking the event selection

Energy momentum conservation:

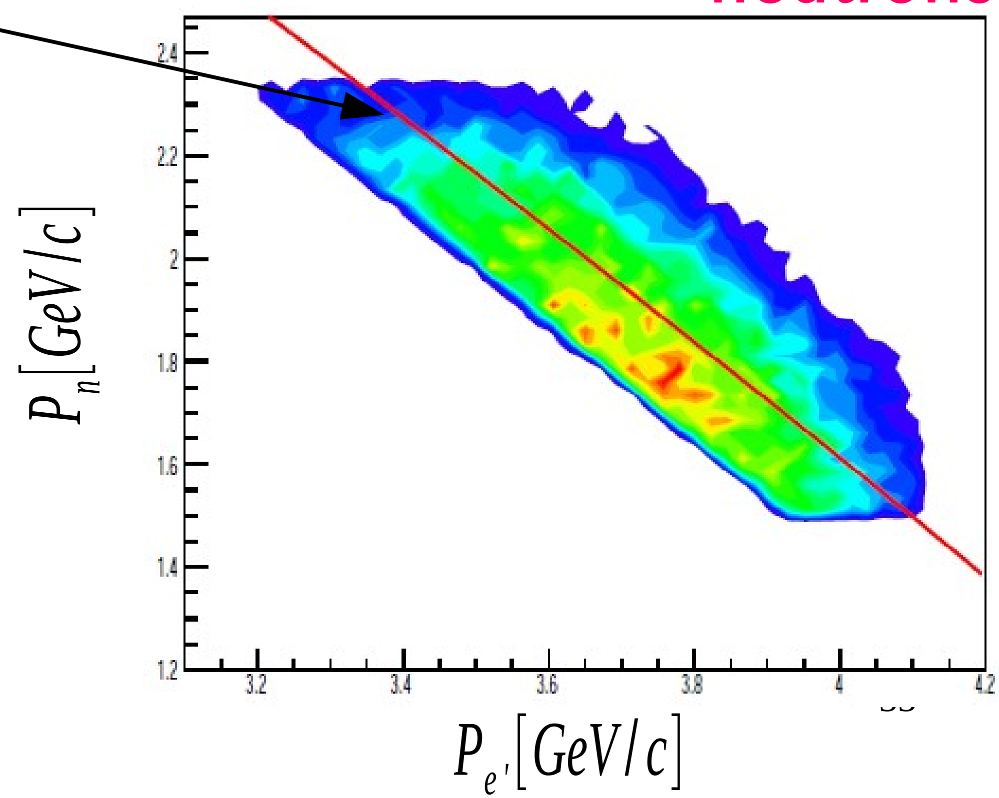
$$\left(E_{beam},\left(0,0,E_{beam}\right)\right)+\left(M_N,\vec{0}\right)=\left(E',\vec{P}_{e'}\right)+\left(E_N,\vec{P}_N\right)$$

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

smeared protons



neutrons

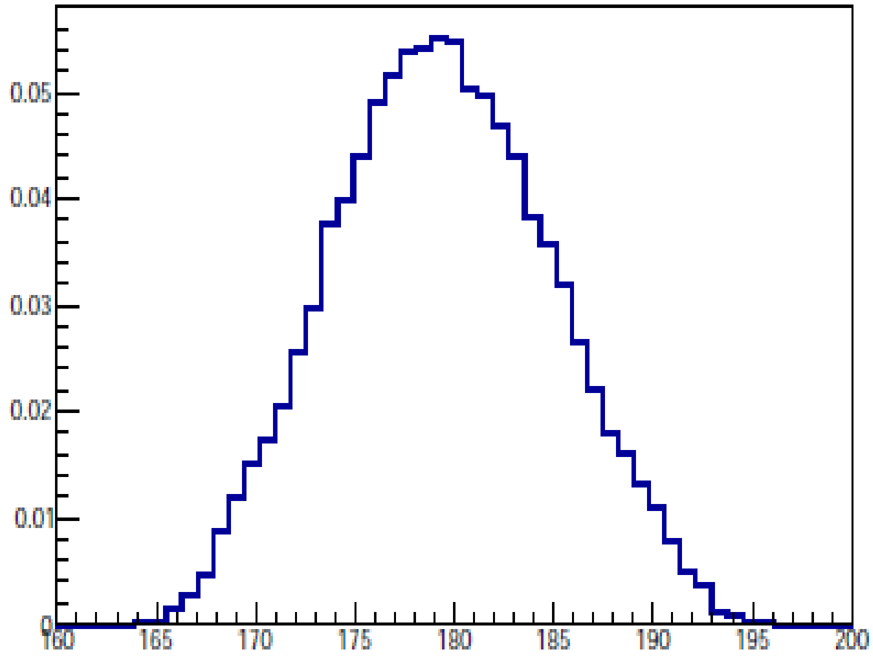


Checking the event selection

From energy momentum conservation:

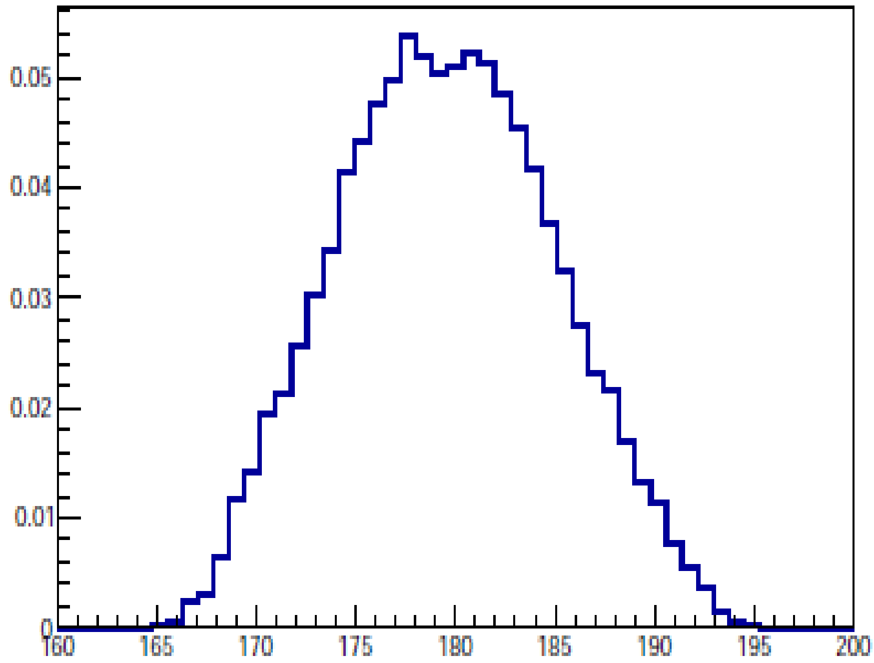
$$|\varphi_N - \varphi_{e'}| = 180^o$$

smeared protons



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

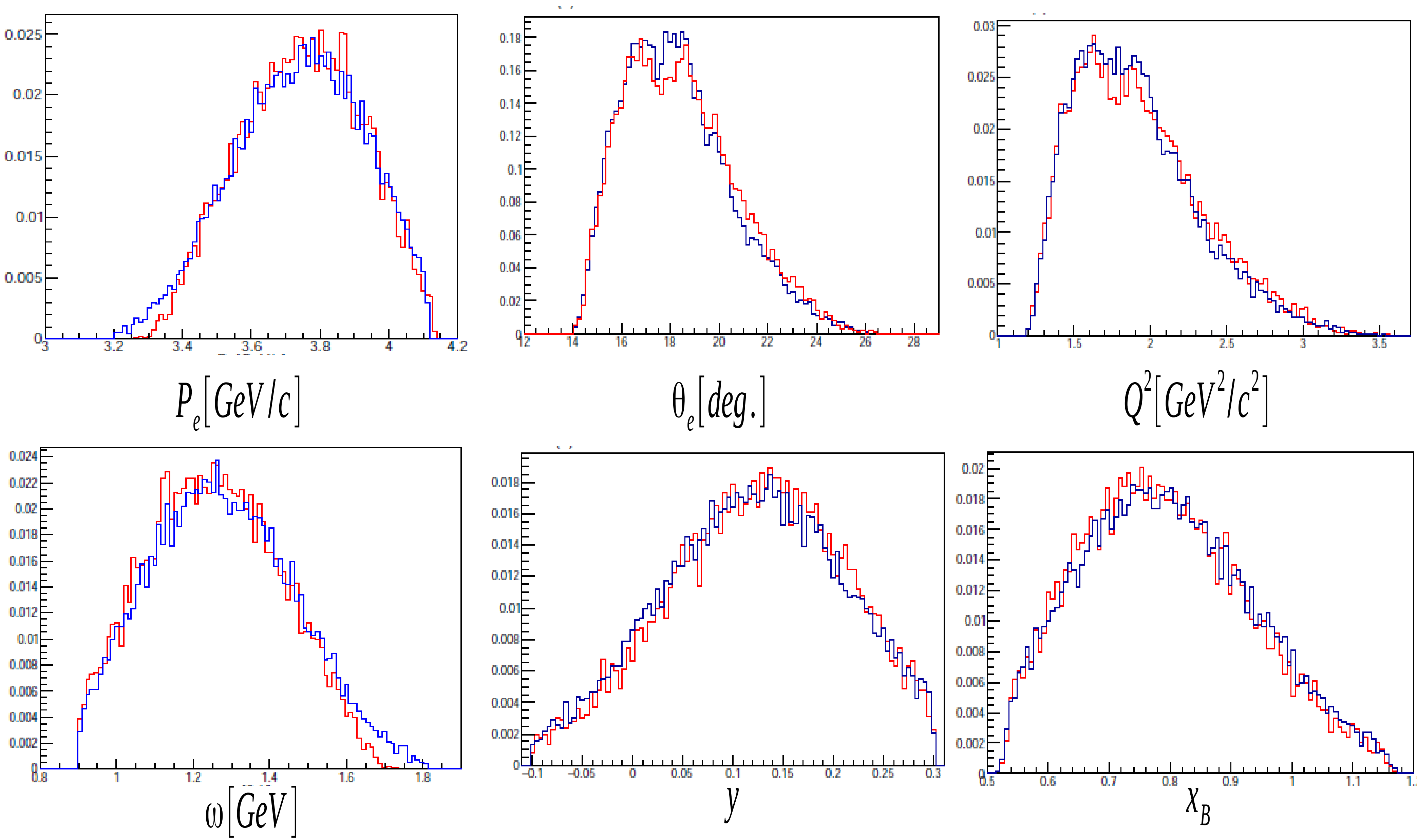
neutrons



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

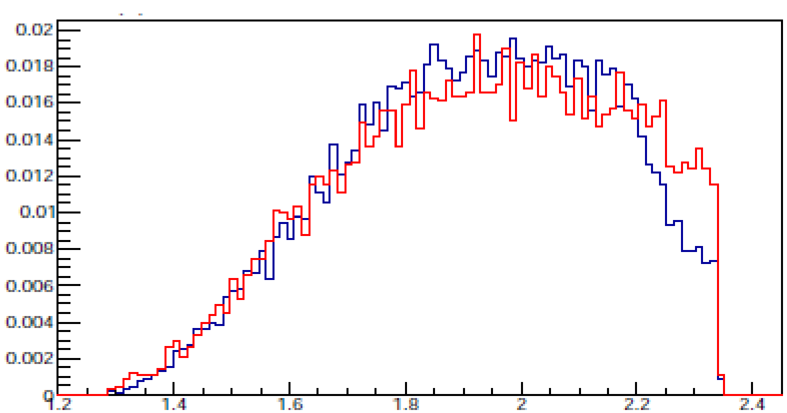
Comparing the smeared protons and neutrons

smeared protons neutrons

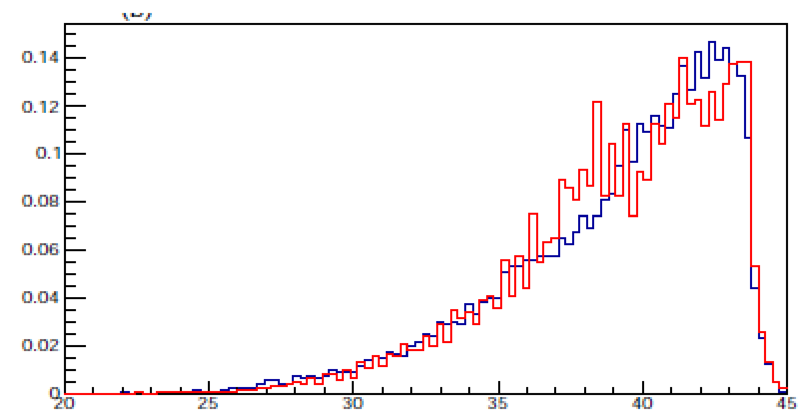


Comparing the smeared protons and neutrons

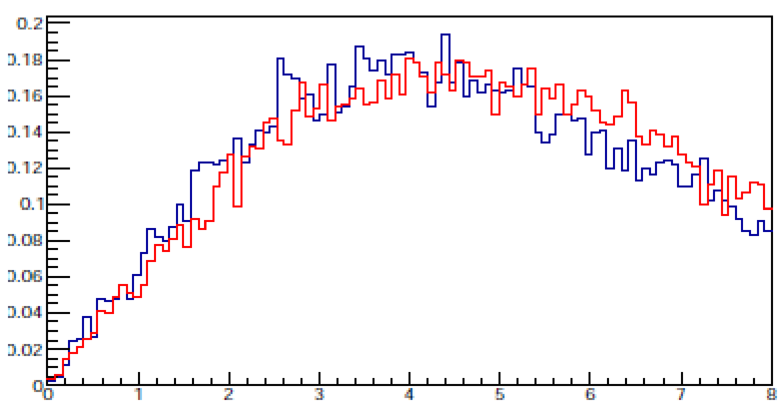
smeared protons **neutrons**



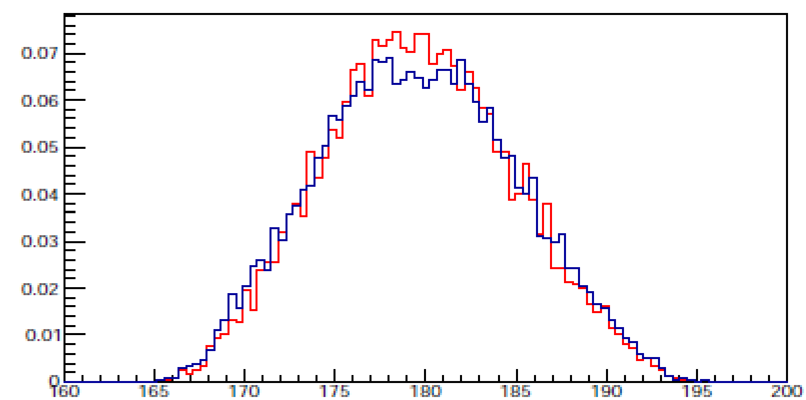
$P_{p/n}[GeV/c]$



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



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



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

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.

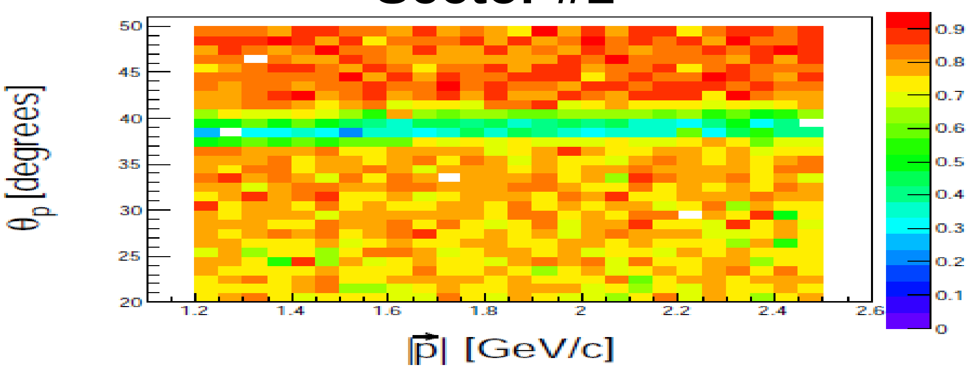
* 100xphi angle uniformly distributed.

* Running through CLAS MC simulation.

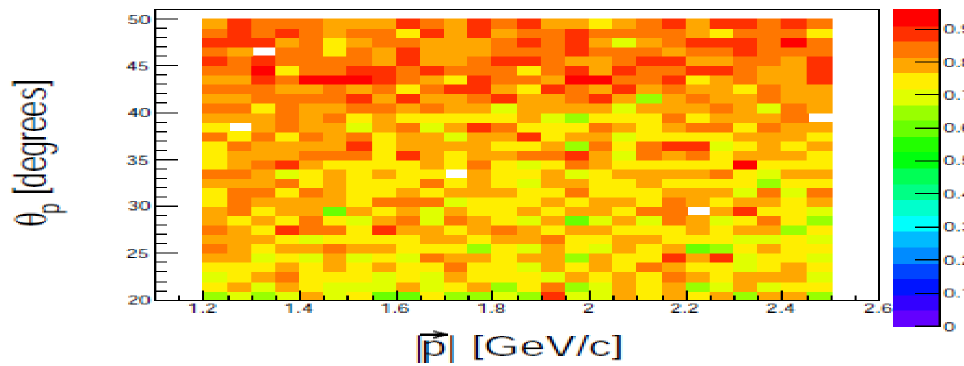
* Dividing event by event by the ratio of reconstructed/generated.

Protons simulation - results

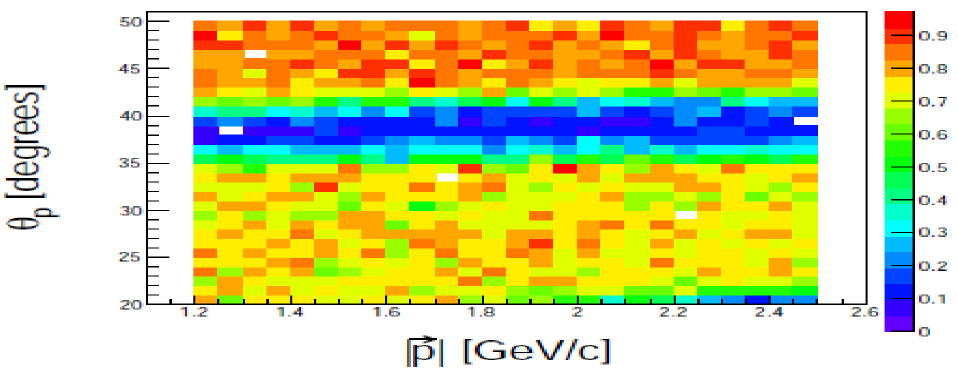
Sector #1



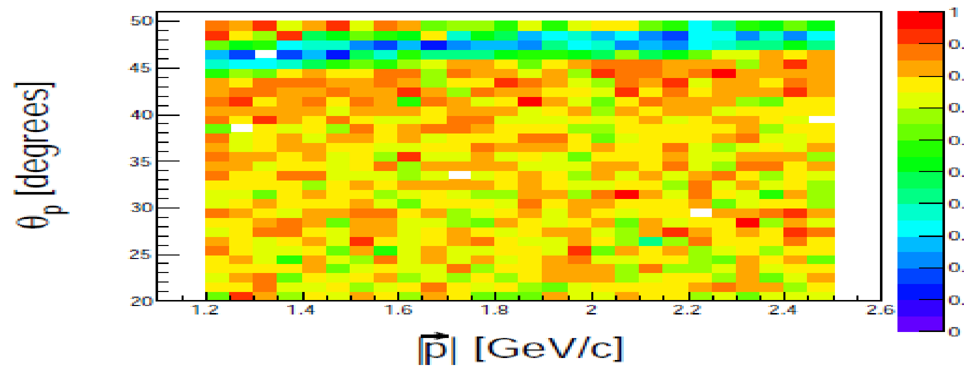
Sector #2



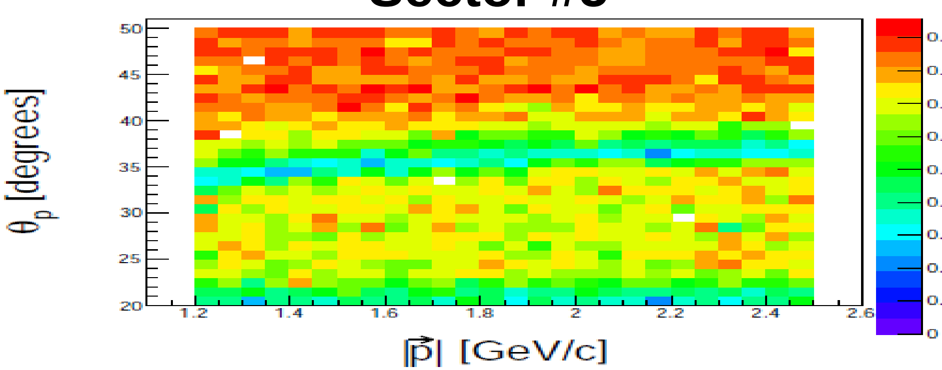
Sector #3



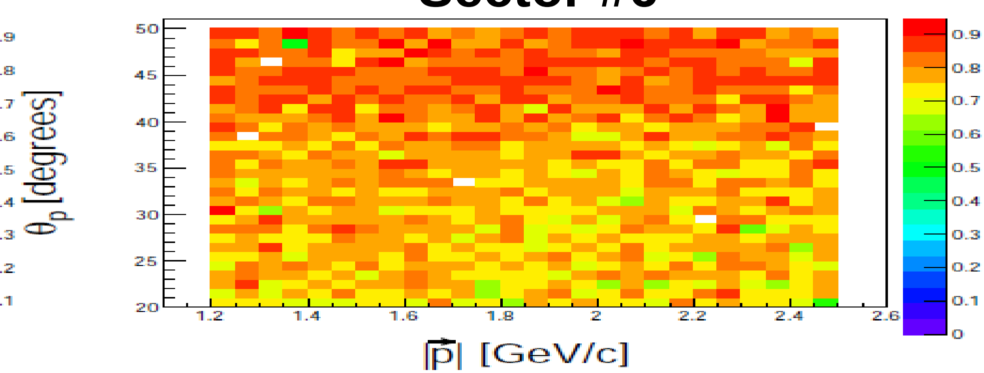
Sector #4



Sector #5



Sector #6



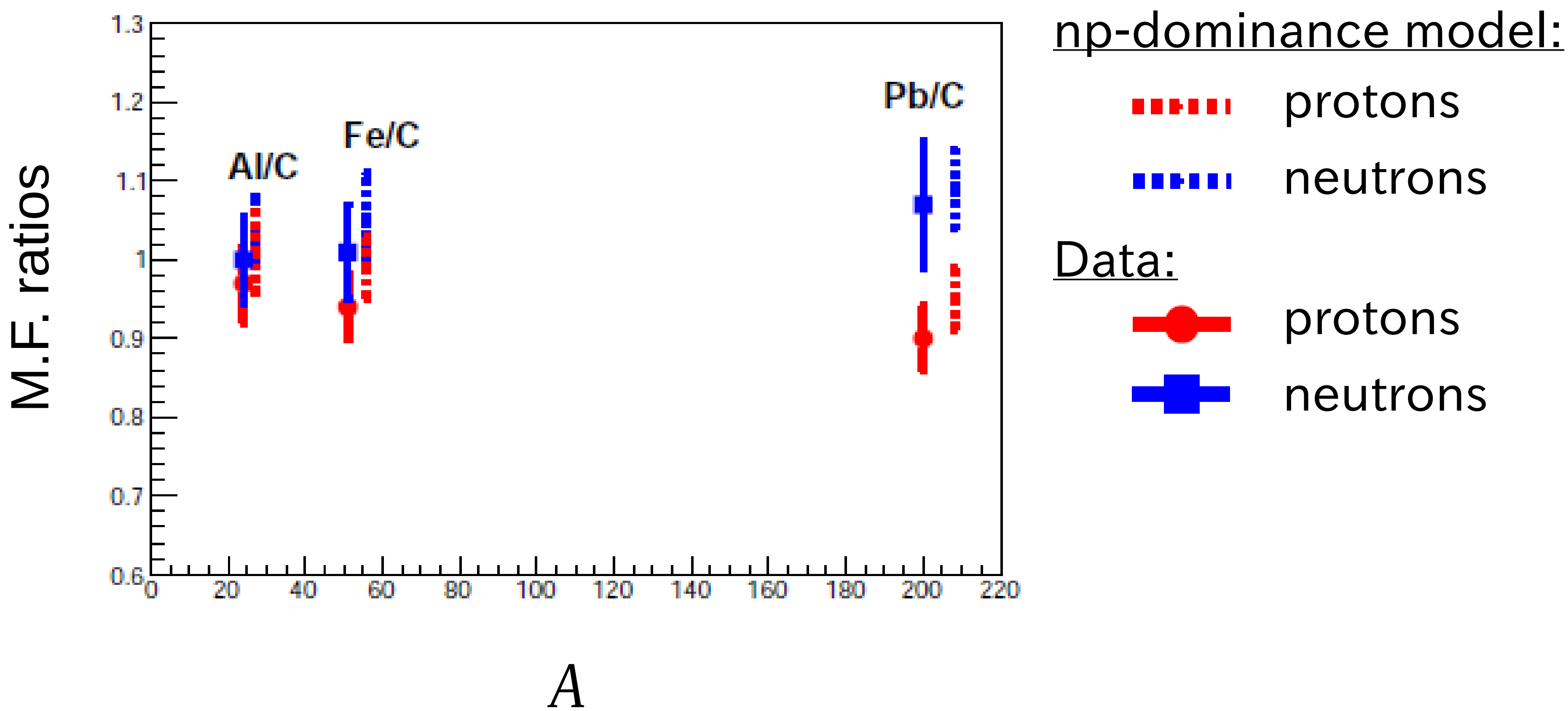
Uncertainties of the event selection

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%	1.9%	1.9%	1.7%
$\theta_{pq} < 8^o$	±1º	2.0%	1.8%	1.5%	1.4%
$1.3 < Q^2 < 3.5\, GeV^2/c^2$	±0.2 GeV²/c²	0.61%	0.39%	0.68%	0.35%
$P_{miss} < 0.3\, GeV/c$	±0.025 GeV/c	0.82%	0.49%	0.56%	0.38%
$E_{miss} < 0.24\, GeV$	±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

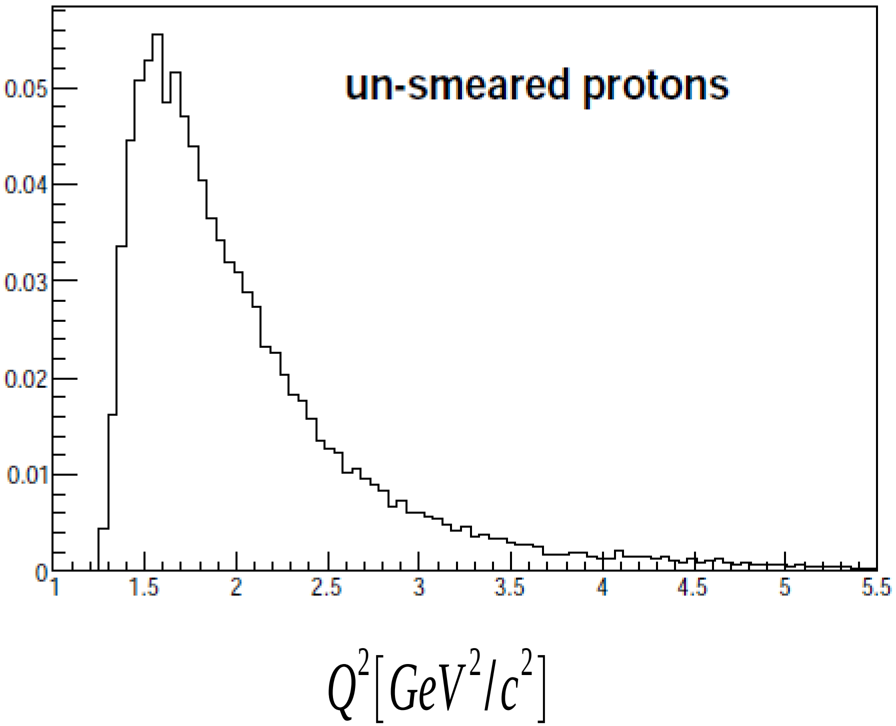
Nuclei	A(e,e'p)/A(e,e'n)	Statistics	Neutron Effic.	Simulation	Event selection
C	2.37±0.23	±0.15 (59%)	±0.07 (27%)	±0.031 (11%)	±0.19 (74%)
Al	2.36±0.26	±0.19 (73%)	±0.08 (29%)	±0.030 (11%)	±0.17 (62%)
Fe	2.48±0.24	±0.15 (62%)	±0.07 (29%)	±0.032 (12%)	±0.18 (75%)
Pb	2.21±0.24	±0.18 (75%)	±0.09 (37%)	±0.034 (12%)	±0.13 (54%)

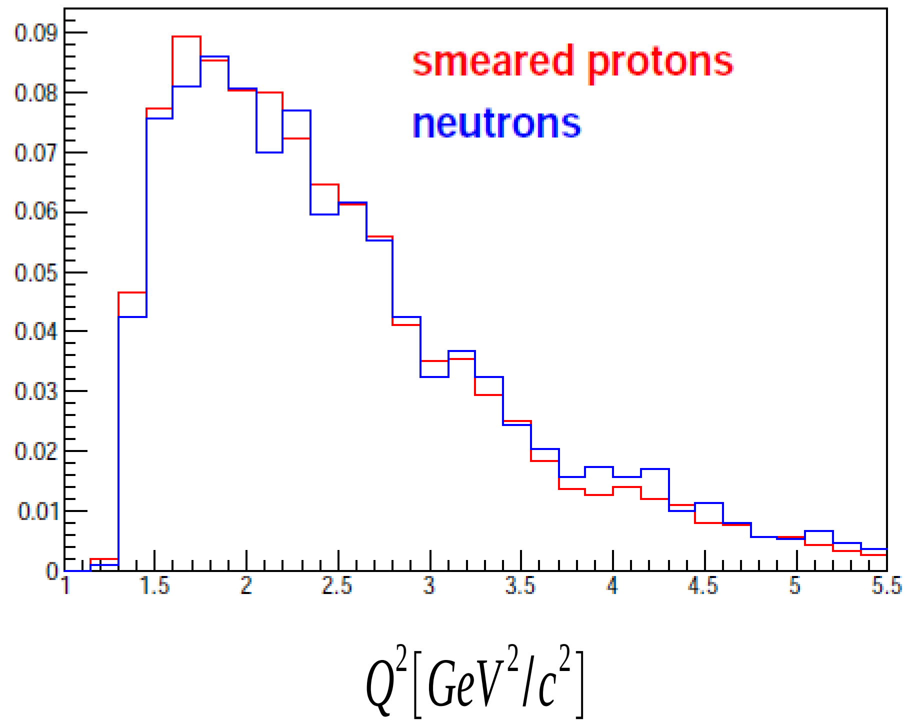
Protons and neutrons M.F ratios



Corrected for transparency and normalized by Z (N).

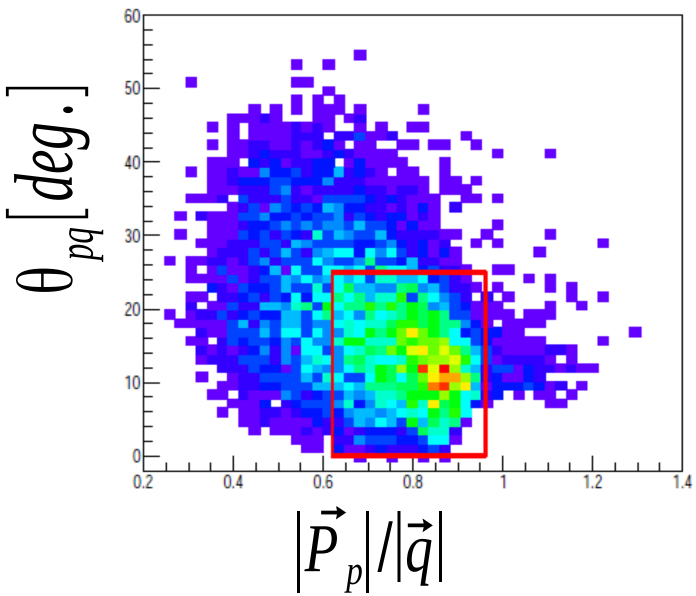
* Low statistics → $x_B > 1.1$
* Poor resolution → smeared protons



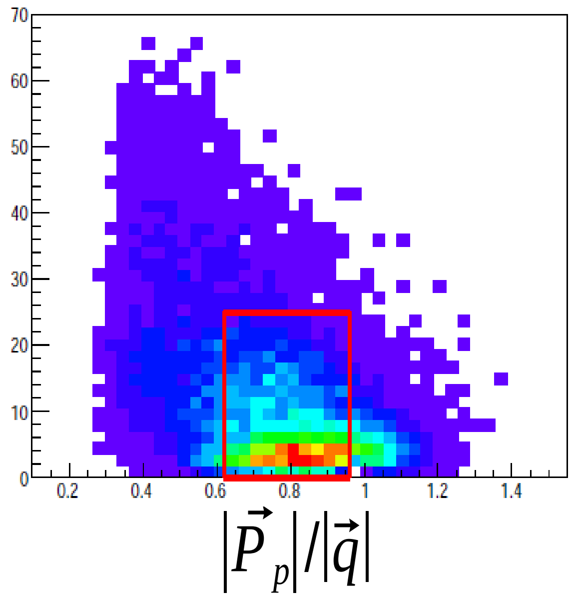


Identifying the Leading Nucleon

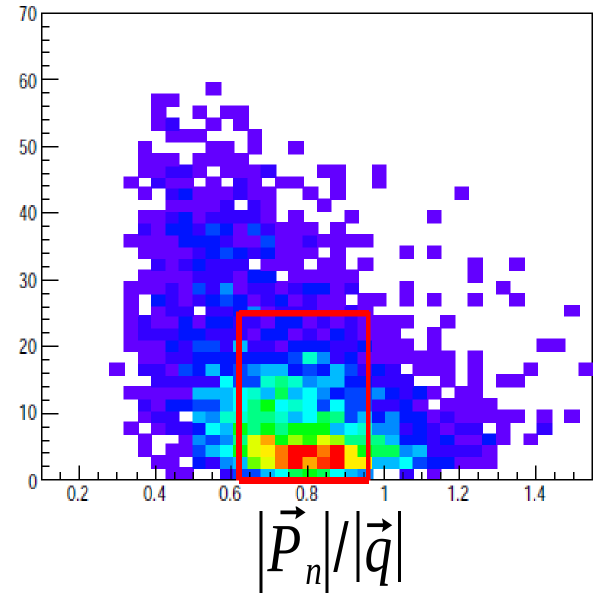
un-smeared protons



smeared protons



neutrons



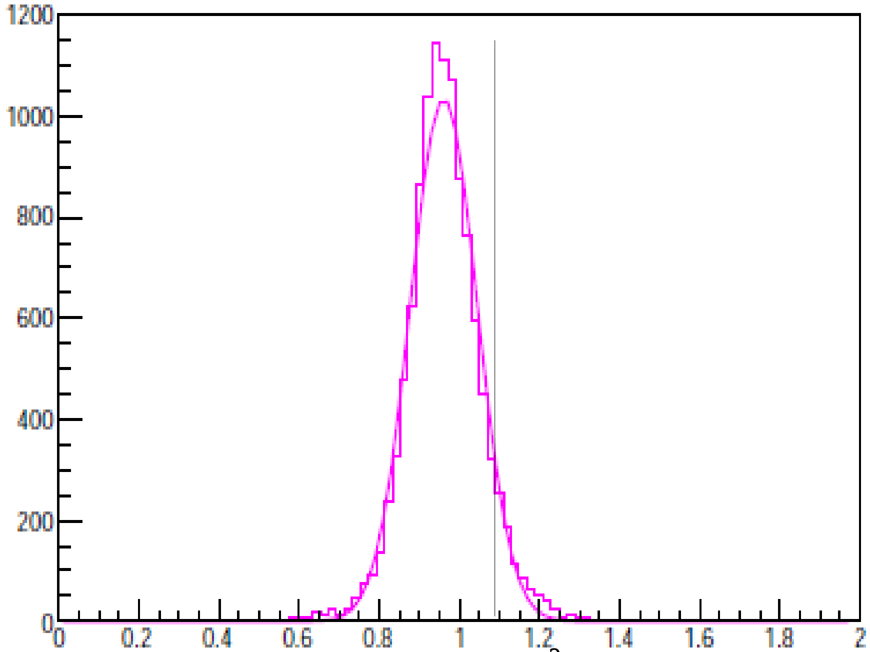
We adopted the cuts (O. Hen 2012):

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

Missing Mass cut

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

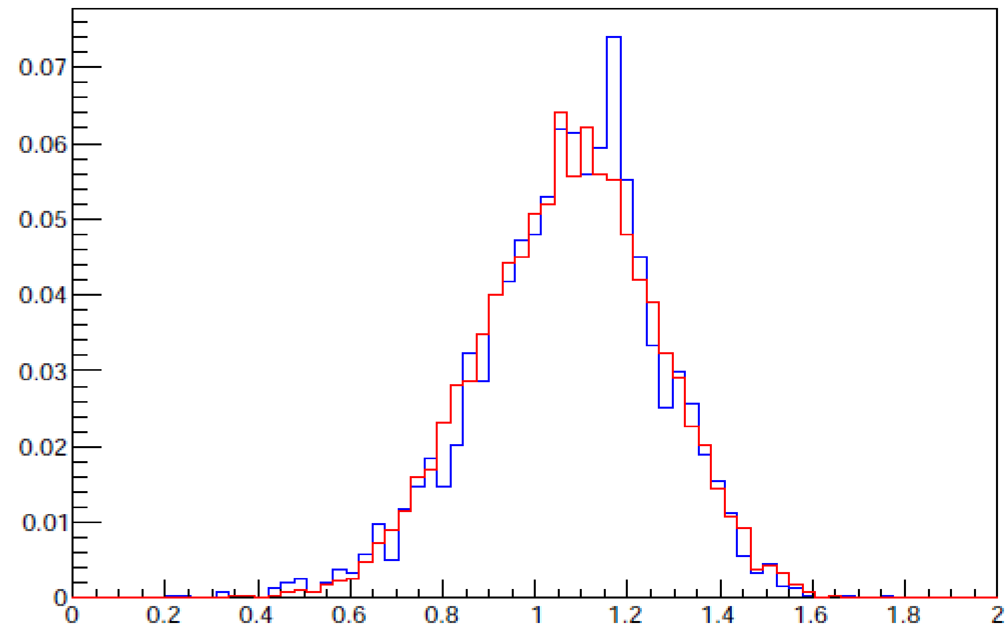
un-smeared protons



$M_{miss}[GeV/c^2]$

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

smeared protons neutrons



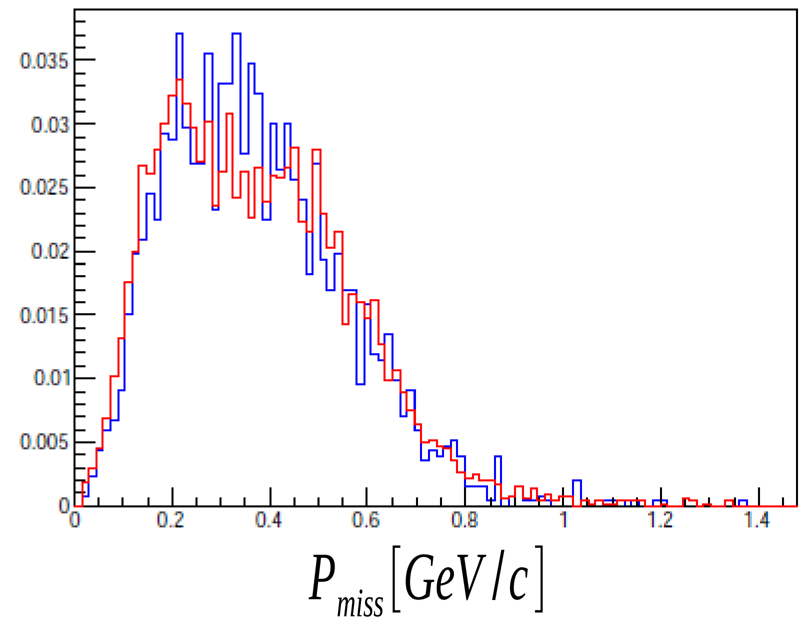
$M_{miss}[GeV/c^2]$

$$M_{miss} < ?$$

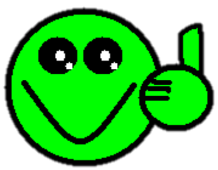
Missing Momentum & Missing Mass cuts

un-smeared protons

smeared protons neutrons



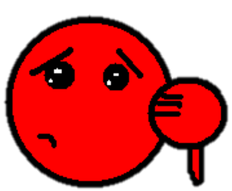
'good event':



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

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

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



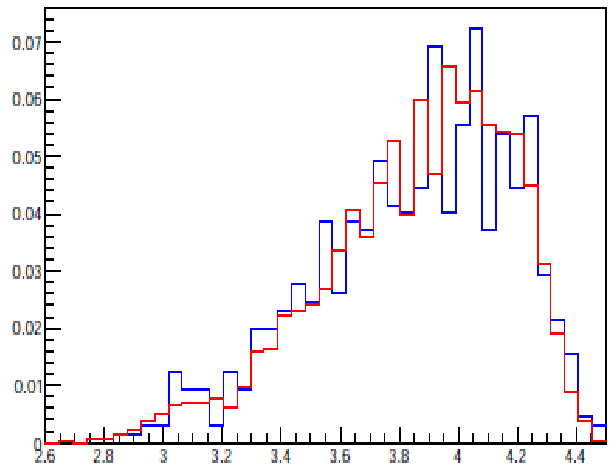
|| $P_{miss-unsmeared} > 1 GeV/c$

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

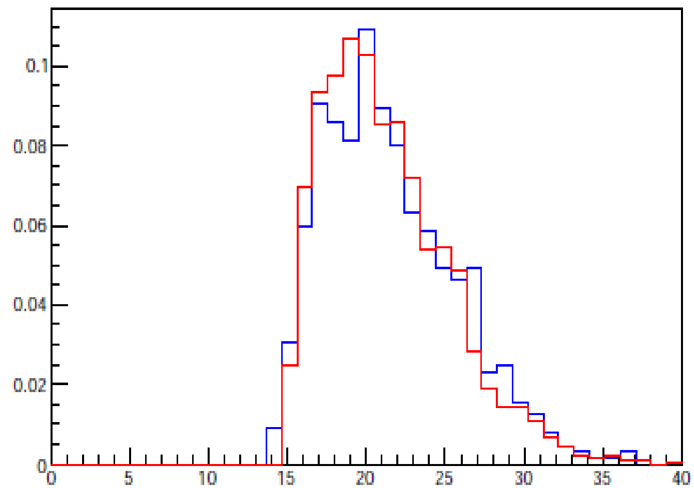
The selected events:

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

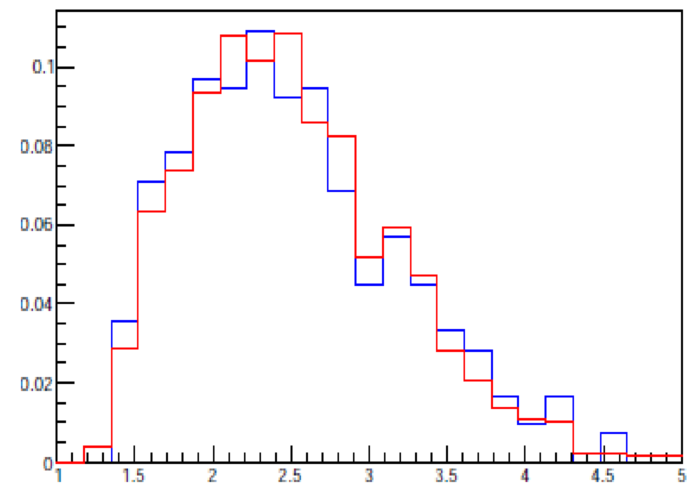
Comparing smeared protons & neutrons distributions:



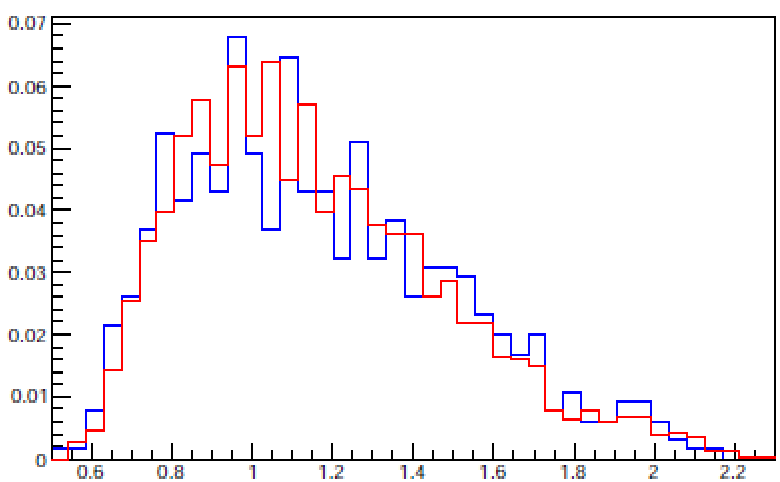
$P_e[GeV/c]$



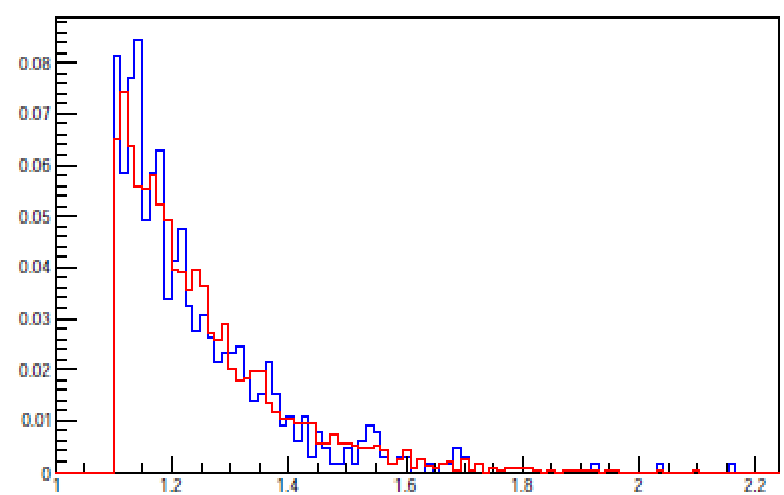
$\theta_e[deg.]$



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

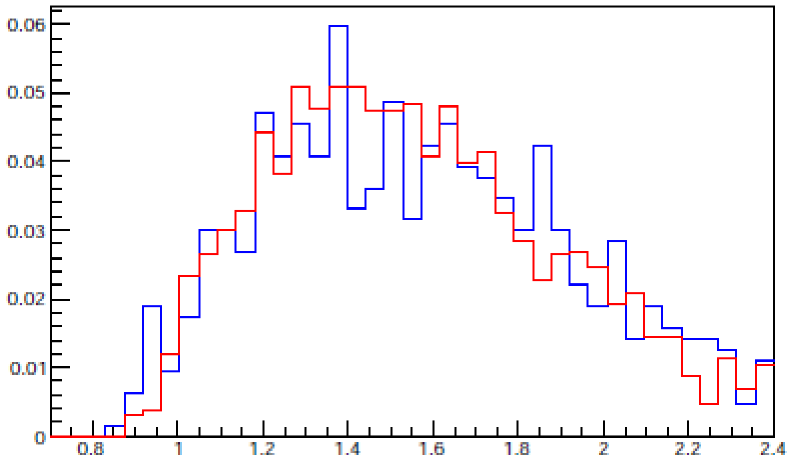


$\omega[GeV]$

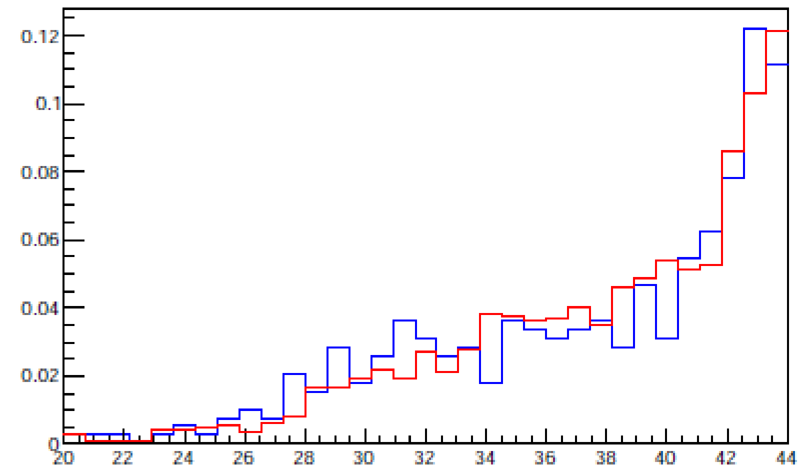


x_B

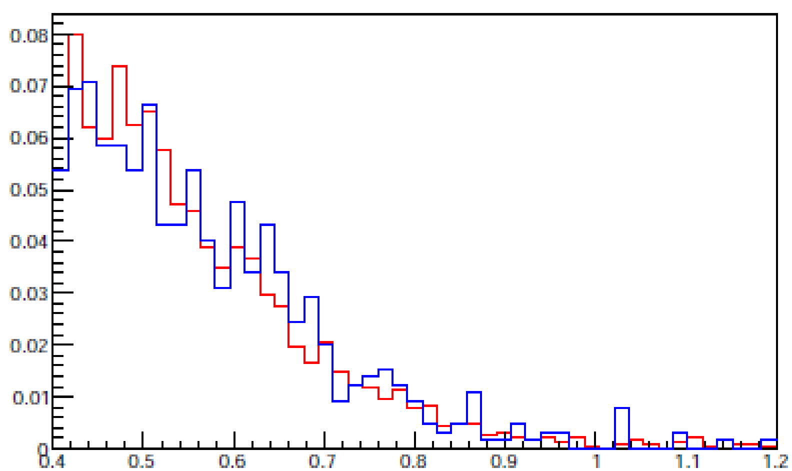
Comparing smeared protons & neutrons distributions:



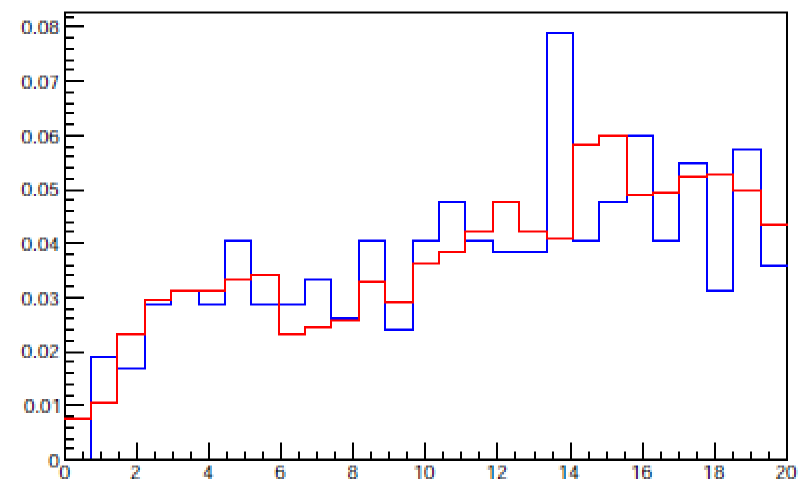
$P_{p/n}[GeV/c]$



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

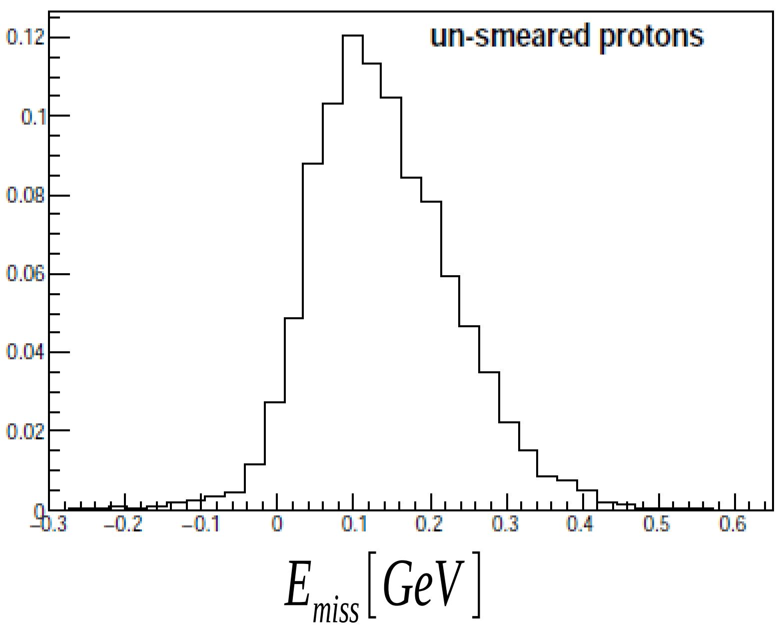


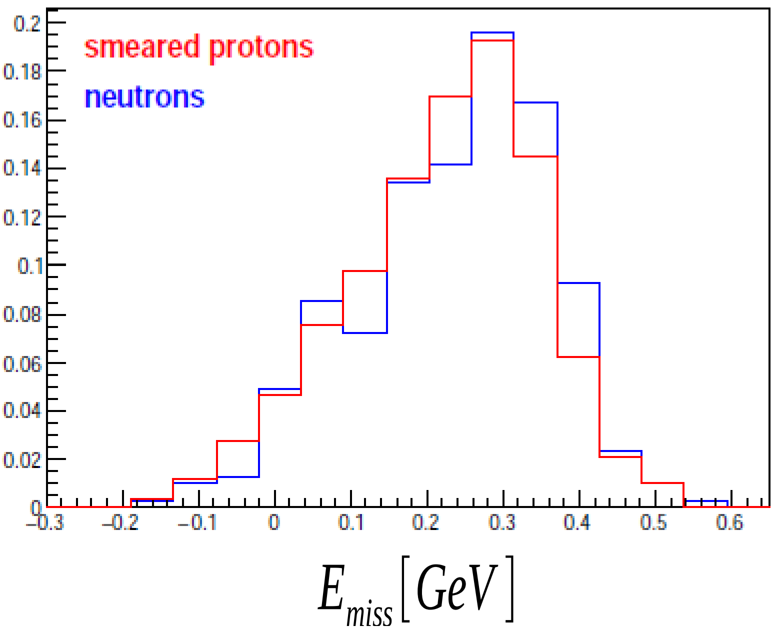
$P_{miss}[GeV/c]$

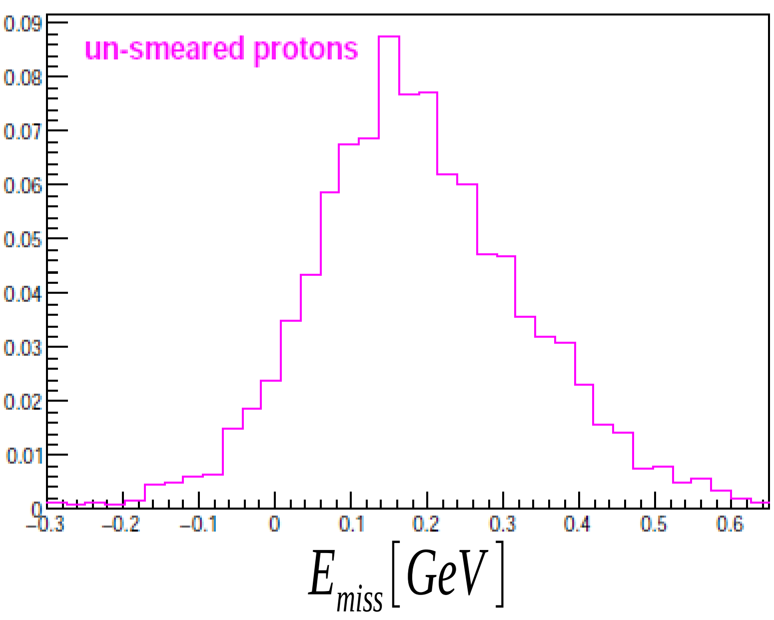


$\theta_{pq/nq}[deg.]$

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

Radiative Correction

Done using Misak code (CLAS NOTE 90-007) for inclusive (e,e') processes

Input file:

```
INCIDENT    ELECTRON     5.014   0.000   0.000   0.000   0.000   3.000
TARGET      PB         208.000  82.000   0.260  25.000   0.025   0.010
RAD_EFFECT YES           0.14   0.020   0.010   0.010   0.050   0.010

SWELLING    V2           0.000   0.200   0.000   0.000   0.000   0.000
EMC         NES          0.000   0.000   0.000   0.000   0.000   0.000

ELEC_SPECT               0.000   0.000   0.000   0.000   0.000   0.000
Ee` -RANGE NES           2.710   3.430   0.015   0.000   0.000   0.000
THe -RANGE               0.000   0.000   0.000  22.500   0.000   0.000
Q0  -RANGE NES           0.830   0.840   0.010   0.000   0.000   0.000
W   -RANGE NO            0.900   0.910   0.025   0.000   0.000   0.000
X   -RANGE YES           1.10    1.78   0.025   0.000   0.000   0.000

INTEGRATION              0.000   0.001   0.001   0.001   0.000 200.000
```

Output file:

$\theta_e[deg.]$	$E'[GeV]$	σ	σ_R	σ_R/σ	x_B
13.5000000	4.42063046	4.43465996	3.27398014	0.738270819	1.10000038
13.5000000	4.43228626	4.22524166	3.08815813	0.730883181	1.12499964
13.5000000	4.44349337	3.98750830	2.88599110	0.723758042	1.14999974
13.5000000	4.45427656	3.72525787	2.67181277	0.717215538	1.17499924
13.5000000	4.46466017	3.43619990	2.44445562	0.711383402	1.19999981
13.5000000	4.47466516	3.12433052	2.20719647	0.706454217	1.22499967
13.5000000	4.48431253	2.80245376	1.96815252	0.702296138	1.25000024
13.5000000	4.49362087	2.47654080	1.73224092	0.699459851	1.27500081
13.5000000	4.50260735	2.16126084	1.50825989	0.697861135	1.30000043
13.5000000	4.51128817	1.86491084	1.30000114	0.697084904	1.32499838
13.5000000	4.51968002	1.59822047	1.11500192	0.697652161	1.34999883
13.5000000	4.52779675	1.36697018	0.955449700	0.698954284	1.37500083
13.5000000	4.53565025	1.17481065	0.823031425	0.700565159	1.39999974
13.5000000	4.54325438	1.02072394	0.716113329	0.701573968	1.42499936
13.5000000	4.55062103	0.903844237	0.633903861	0.701341927	1.45000100
13.5000000	4.55775976	0.818772256	0.572003424	0.698611140	1.47499907
13.5000000	4.56468248	0.759974122	0.527037442	0.693493903	1.49999964
13.5000000	4.57139826	0.721946955	0.496739984	0.688056052	1.52500010
13.5000000	4.57791615	0.687721431	0.469726115	0.683017969	1.55000007
13.5000000	4.58424473	0.595497608	0.406235248	0.682177782	1.57499981
13.5000000	4.59039259	0.522537053	0.355940789	0.681178093	1.60000086
13.5000000	4.59636641	0.463264525	0.314598382	0.679090142	1.62499917
13.5000000	4.60217428	0.413414866	0.279868931	0.676968694	1.64999843
13.5000000	4.60782337	0.370711714	0.249916166	0.674152315	1.67500007
13.5000000	4.61331940	0.333176047	0.223424718	0.670590580	1.70000076
13.5000000	4.61866808	0.299870700	0.200065240	0.667171657	1.72499883
13.5000000	4.62387705	0.269912452	0.178801313	0.662441909	1.75000262

For each target 34 files: $13.5 < \theta_e < 30 [deg.]$

Final correction:

Nuclei	C	Al	Fe	Pb
Correction factor	0.776	0.785	0.729	0.724

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<0.96	±0.05	2.0%	2.5%	2.4%
$\theta_{pq} < 25^o$	±5°			
$M_{miss} < 1.2 GeV/c^2$	±0.05 GeV/c^2	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

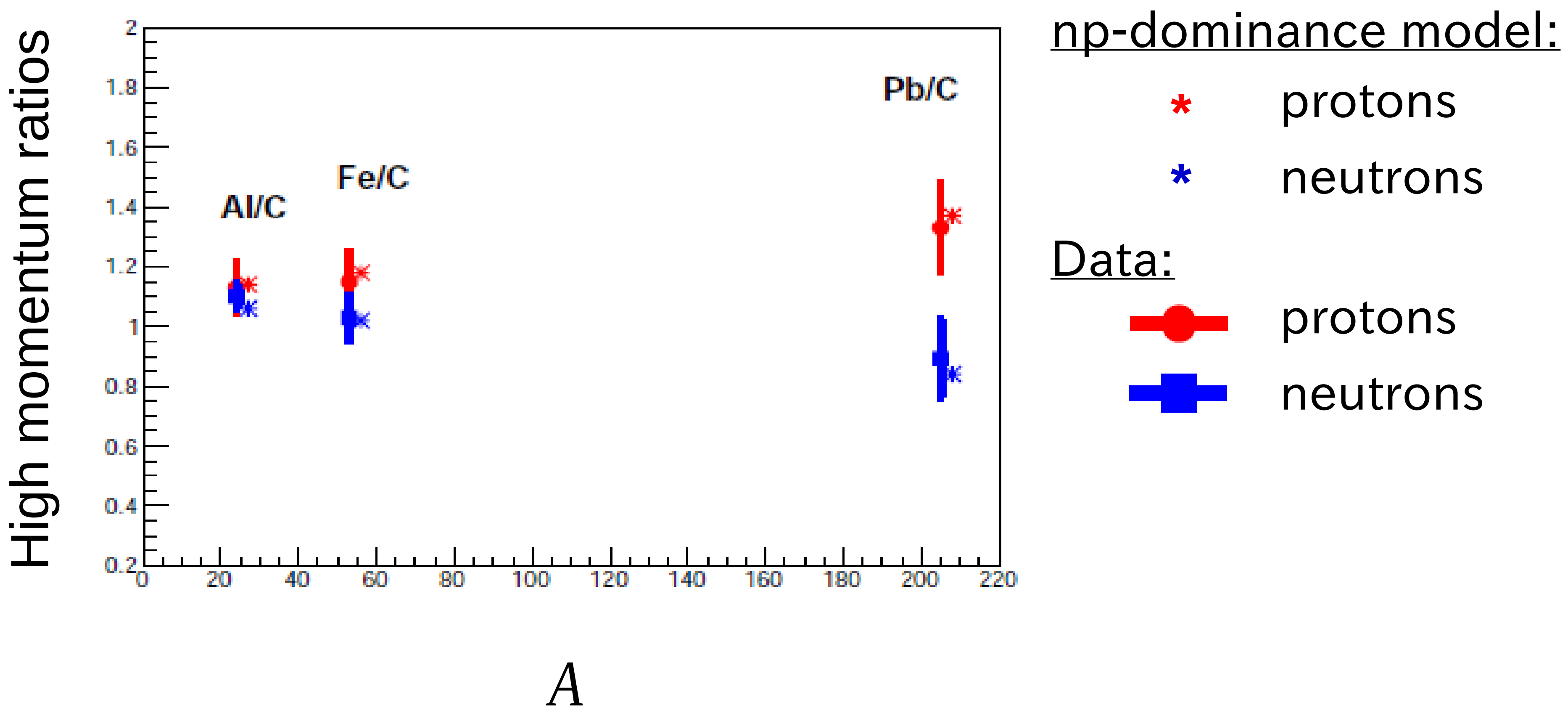
Al/C	Fe/C	Pb/C
0.3%	0.9%	1.0%

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)