Probing 2N-SRC with the A(e,e'n) and A(e,e'p) reactions

A data-mining project using CLAS EG2 data

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NPWG meeting

Layout:

* Motivation

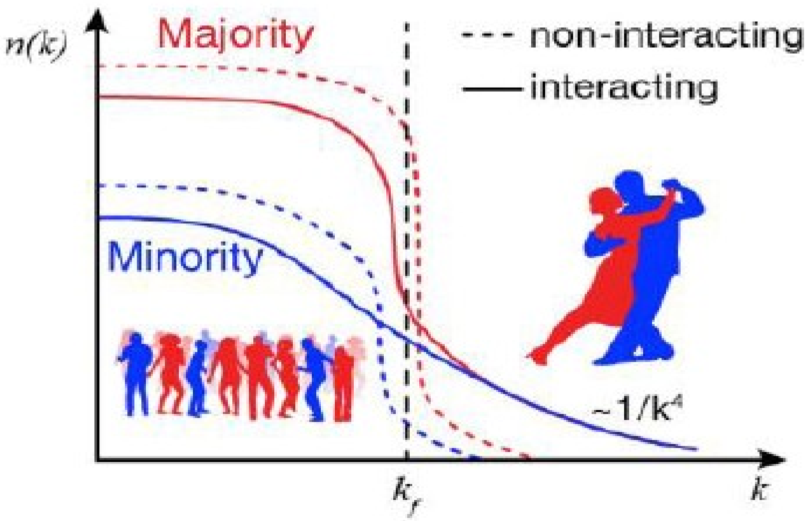
* Analysis of QE events:

    I. A(e,e'p)/A(e,e'n) mean-field ratios

    II. A(e,e'p)/C(e,e'p) && A(e,e'n)/C(e,e'n) high momentum ratios

* Future plans

np-dominance in asymmetric neutron rich nuclei



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

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

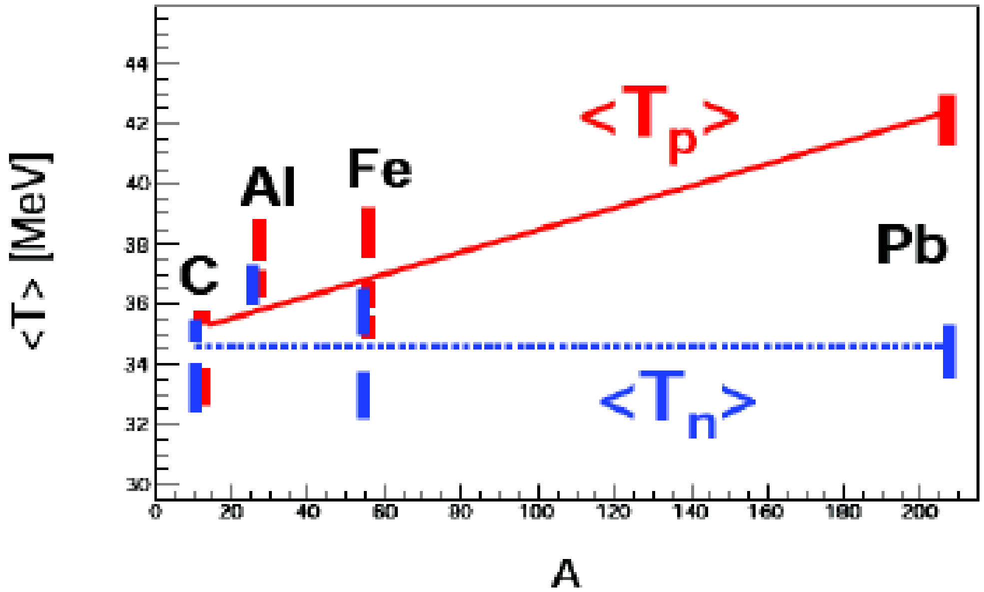
Possible inversion of the momentum sharing

Simple np-dominance model

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

(And the same for neutrons
Z → N)

Prediction:



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

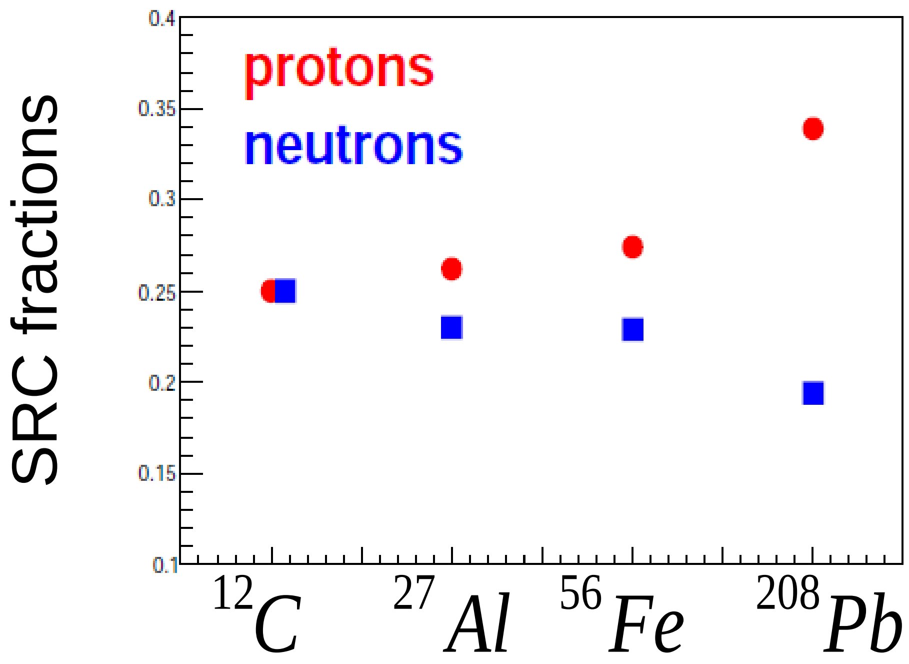
O. Hen et al., Science 346, 614 (2014)

Simple estimate based on np-dominance

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

$$R_p = \frac{protons_{k>k_F}}{protons_{k<k_F}} \approx \frac{20}{82-20} = 0.32$$

$$R_n = \frac{neutrons_{k>k_F}}{neutrons_{k<k_F}} \approx \frac{20}{126-20} = 0.19$$



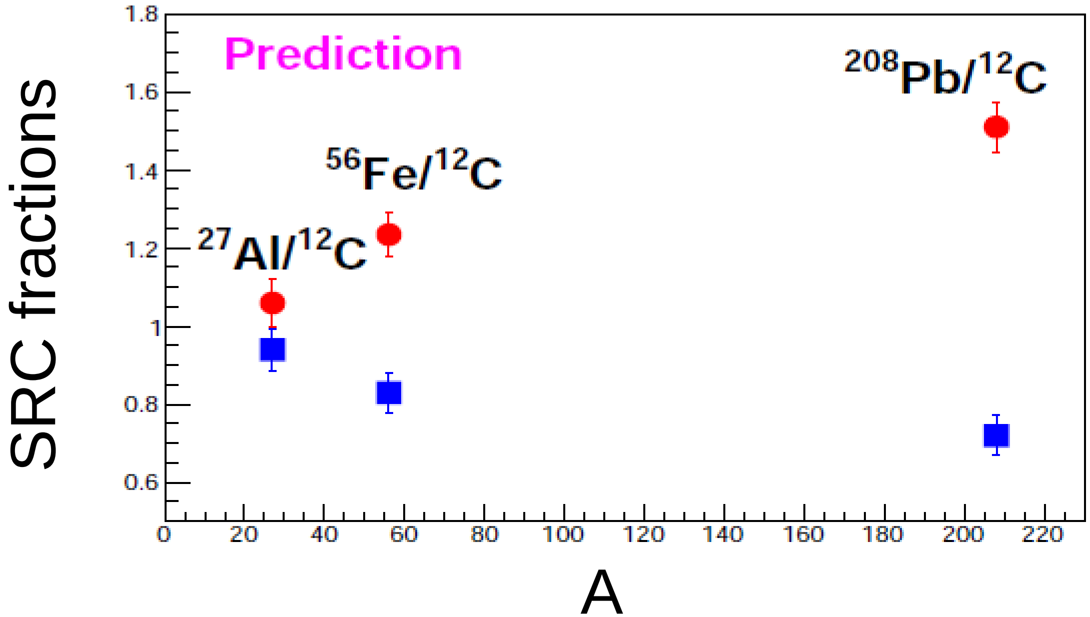
Simple calculation based on the np-dominance model

$$A(e,e'N)_{k<k_F} = \int_0^{k_F} n^{M.F.}(k)k^2dk$$

$$A(e,e'N)_{k>k_F} = \int_{k_F}^{\infty} n^{SRC}(k)k^2dk$$

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

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



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 (low)
* Identify (e,e'n) 2N-SRC events $(high)$
* Extract ratios and their uncertainties

Electrons (Approved CLAS analysis note, L. El Fassi, 2011)

Protons (Approved CLAS analysis note, O. Hen, 2012)

Neutrons - detecting neutrons in CLAS EC.
Calibration was done using the d(e,e'p $\pi^+\pi^-$ n) exclusive reaction(M. Braverman TAU thesis, 2014)

A(e,e'p)/A(e,e'n) mean-field QE ratios

EG2 data: $^{12}C, ^{27}Al, ^{56}Fe, ^{208}Pb$

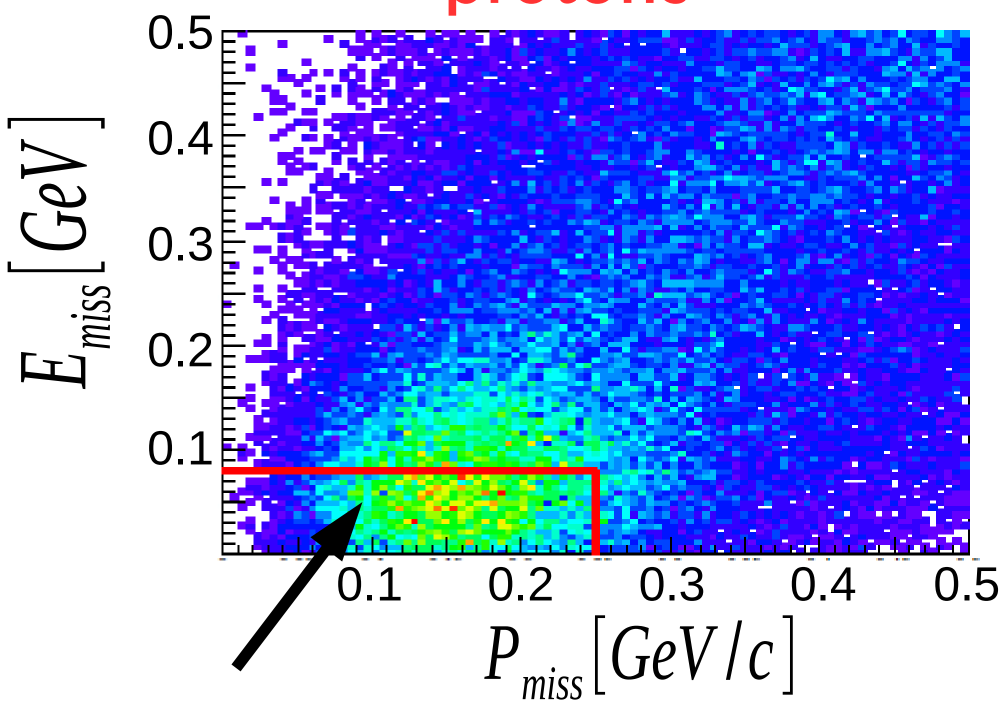
* Identify (e,e'n) & (e,e'p) mean-field QE events

* Extracting the ratios

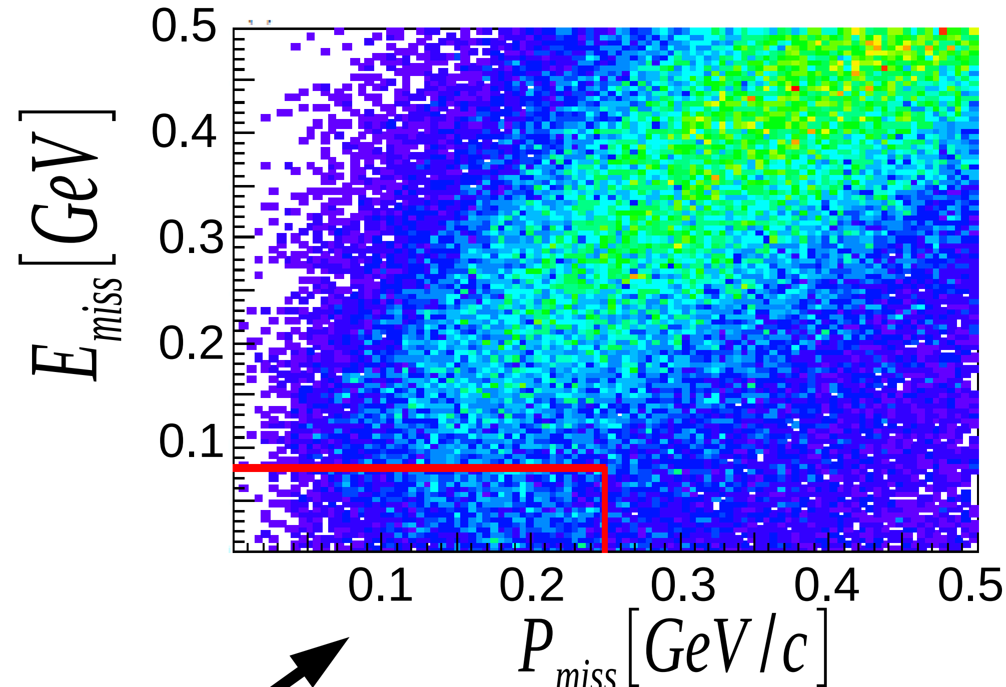
Selecting M.F. QE events

Mean-Field QE events: low initial momentum ($k<k_F$) and separation energy of the knockout nucleon.

protons



neutrons



QE peak [1]-[3]:

$P_{miss}<0.25$ GeV/c

$E_{miss}<0.08$ GeV

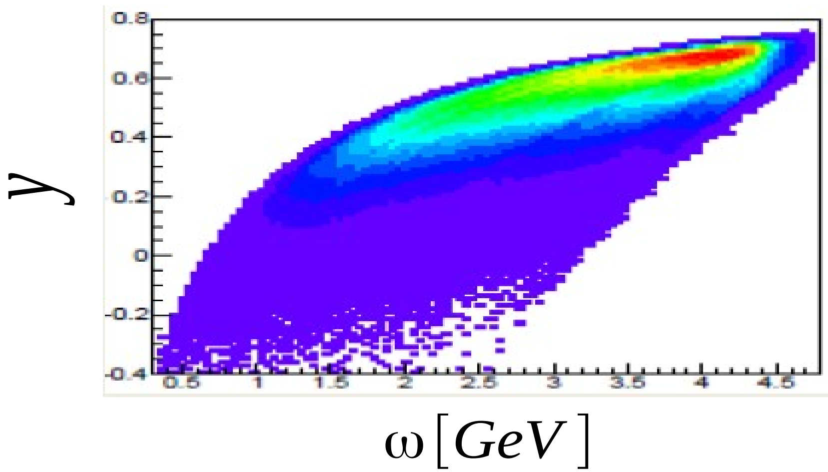
Problem: Poor resolution in the EC $\Delta P \approx 0.2 GeV/c$

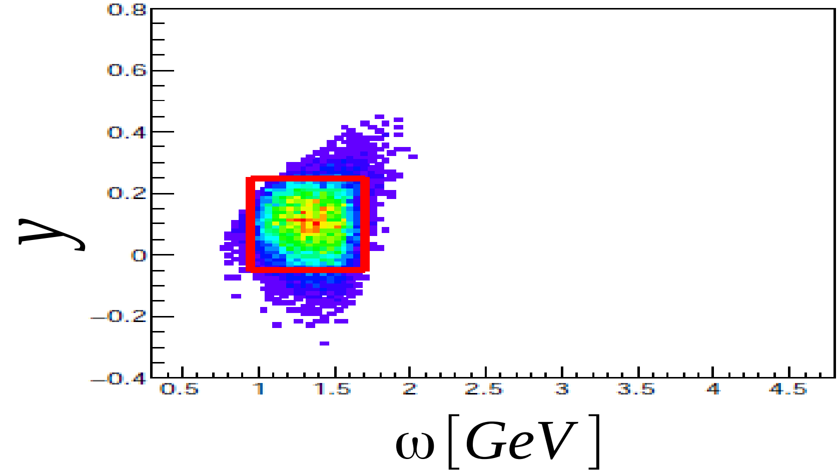
[1] T.G. ONeill et al., Phys. Lett. B 87, 351 (1995).
[2] D. Abbott et al. Phys. Rev. Lett. 80, 5072 (1998).
[3] K. Garrow et al. Phys. Rev. C. 66, 044613 (2002).

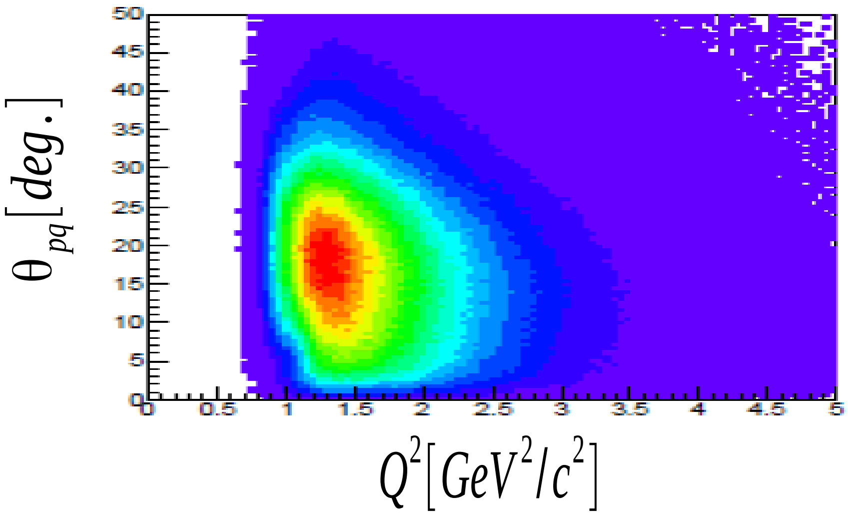
Solution 1: Using cuts common to (e,e'p) and (e,e'n)

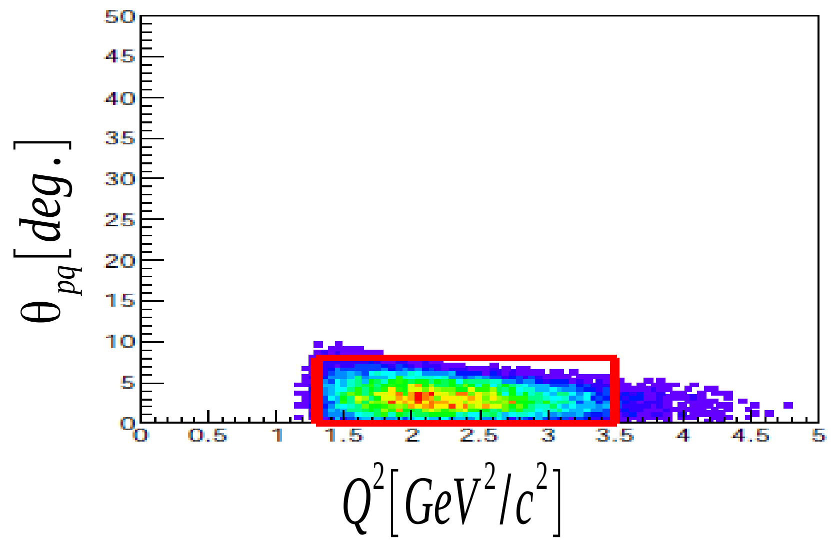
protons

Before the QE cuts	After the QE cuts







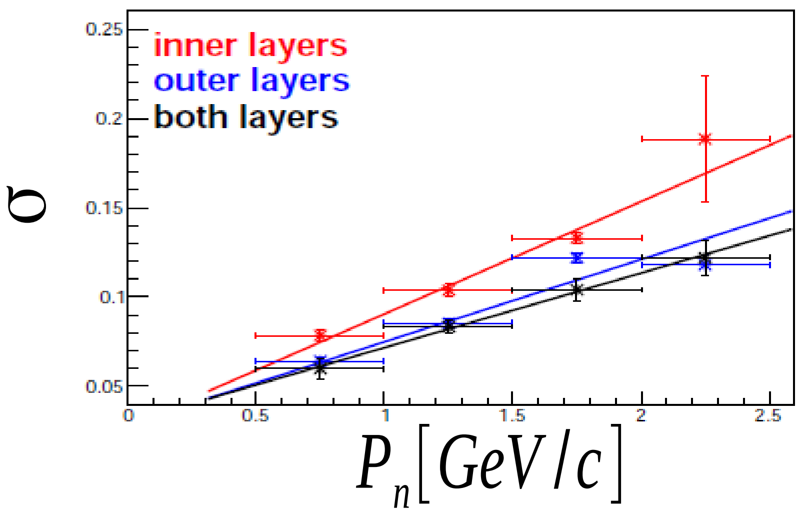


$$y \equiv \left[(M_A + \omega)^2 \sqrt{\Lambda^2 - M_{A-1}^2 W^2} - |\vec{q}|\Lambda \right] / W^2$$

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

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

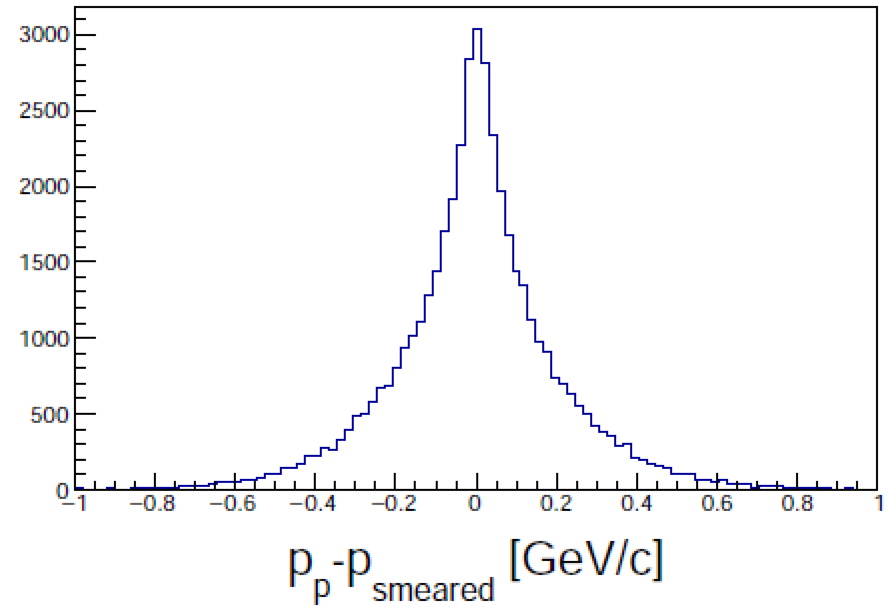
Neutron measured momentum resolution



Neutron interaction probability:

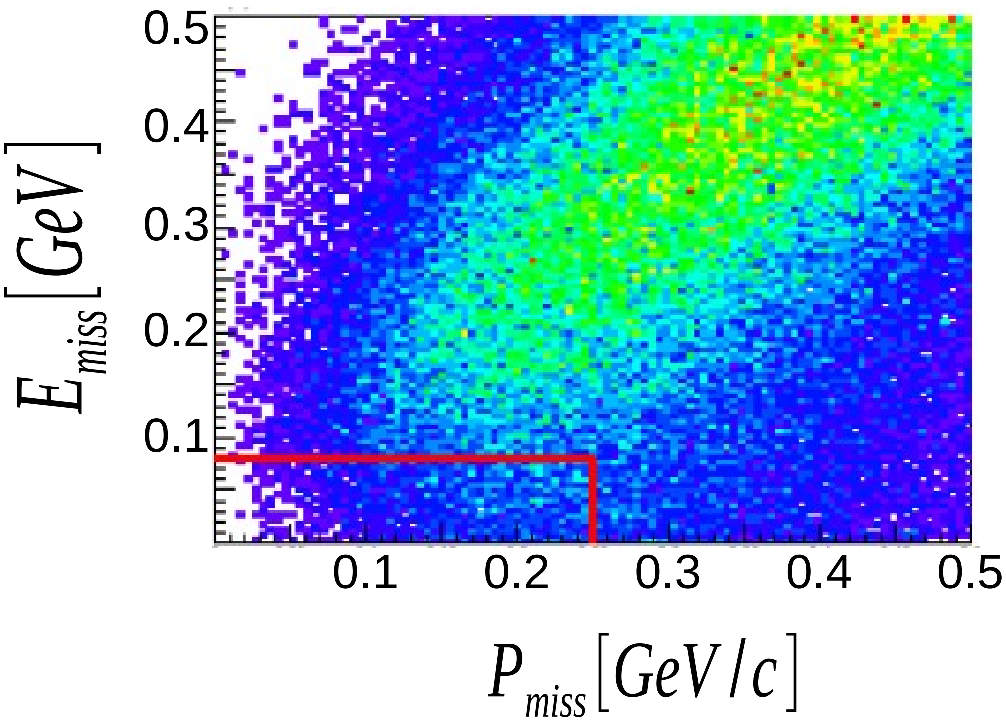
32% - inner layer
47% - outer layer
20% - both layer

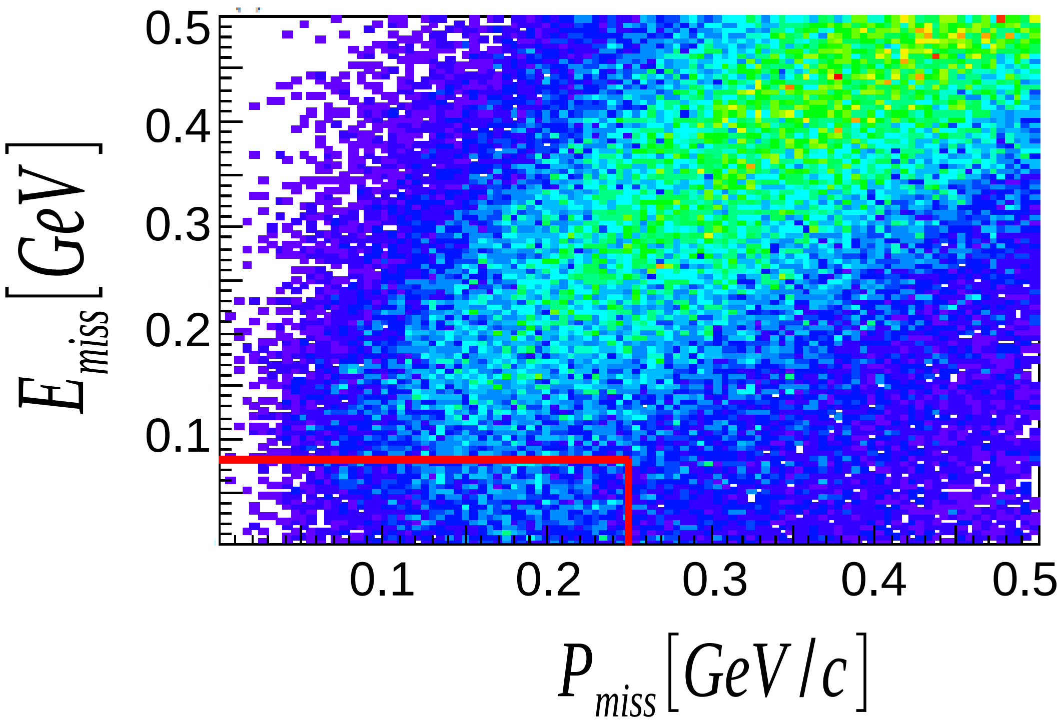
$$P_p \rightarrow P_{smeared} = \sum Gauss(P_p, \sigma)$$



smeared protons

neutrons



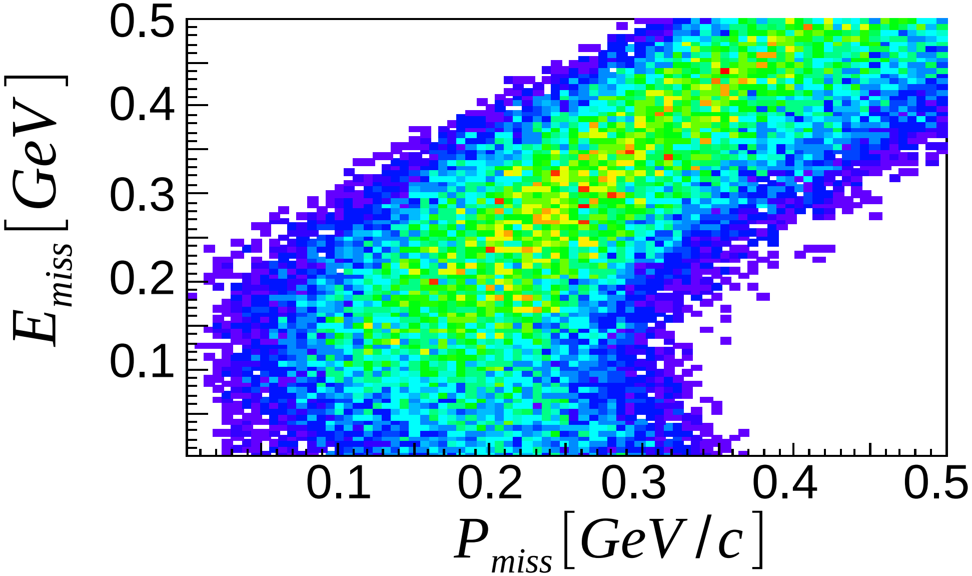


Without applying any cuts

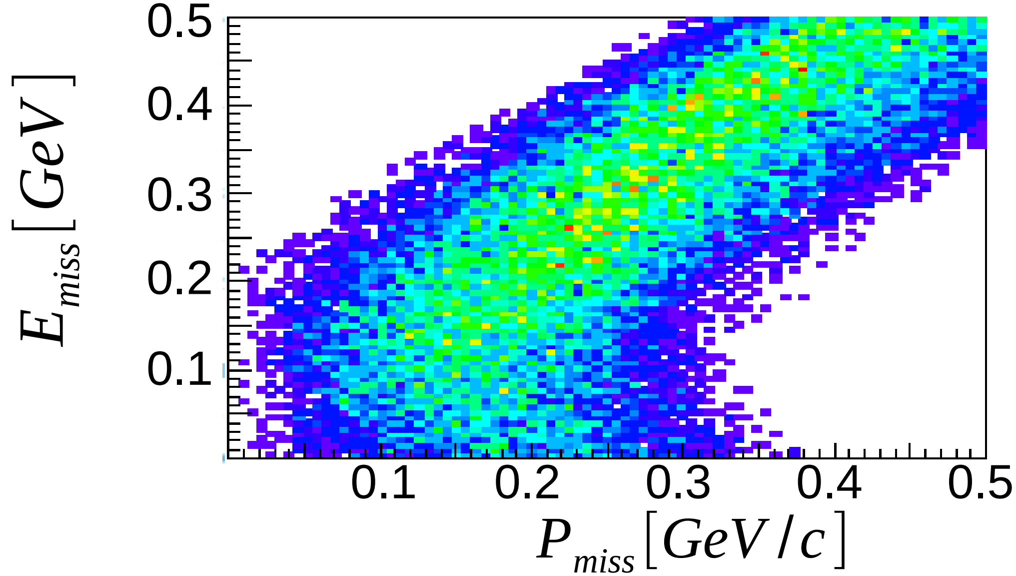
With the selected cuts:

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

smeared protons



neutrons



Problem:
How to determine the P_{miss} and E_{miss} cuts?

E_{miss} P_{miss} cuts

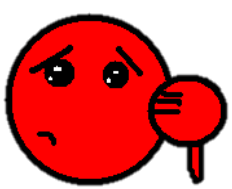
un-smeared protons

'good event':

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

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

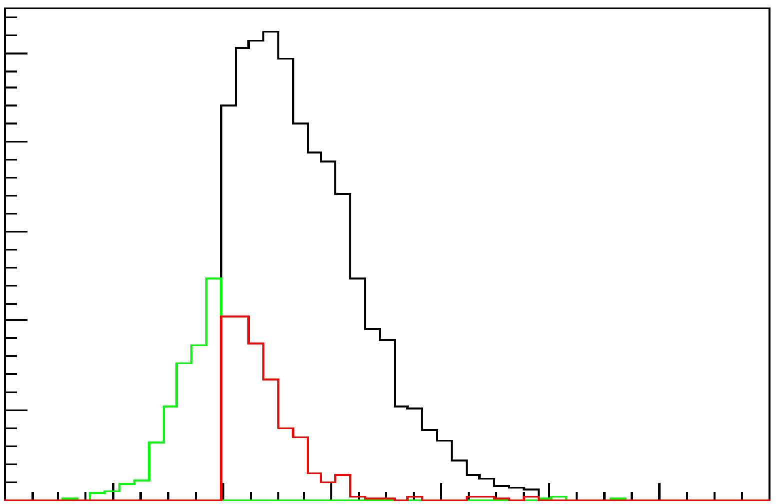
'bad event':



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

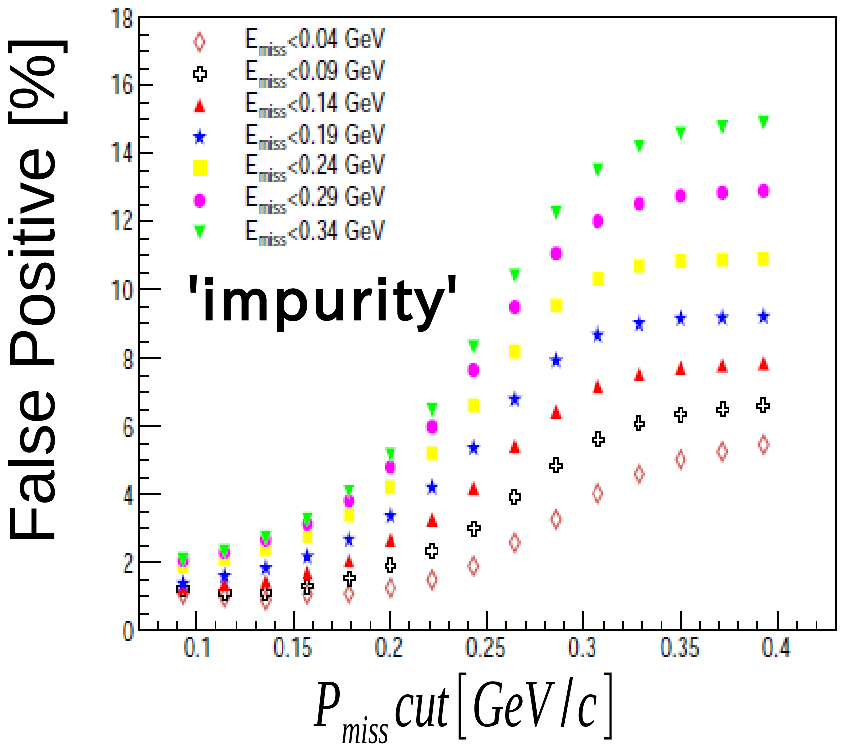
|| $$E_{miss-unsmeared} > 0.08\,GeV$$

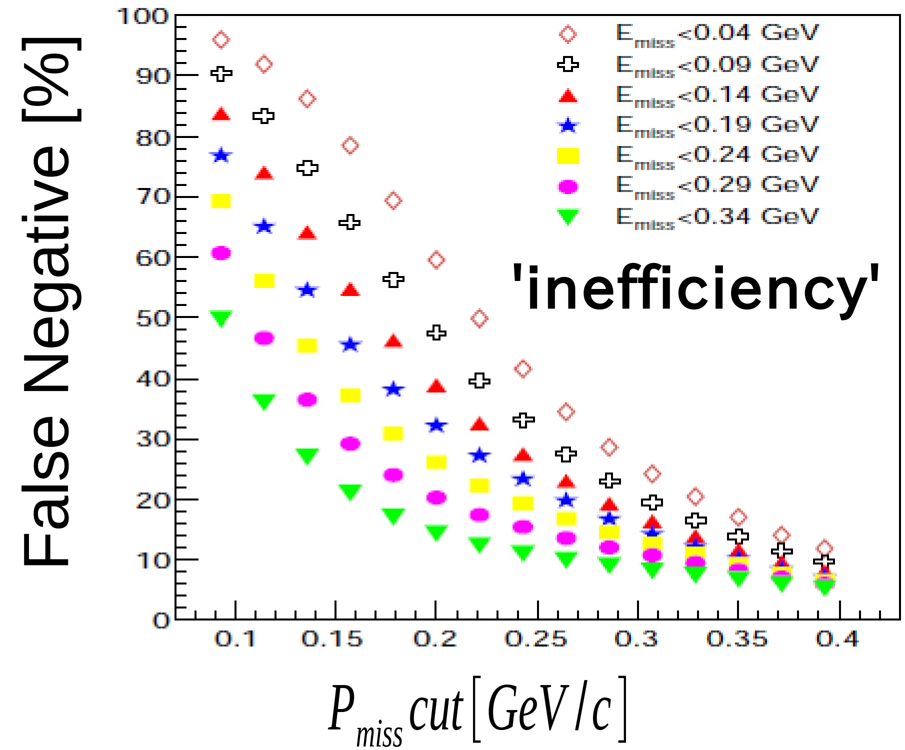
smeared protons (neutrons)



$$P_{miss}\left[GeV/c\right]$$

False Positive & Negative probabilities





The selected cuts for smeared p/n:

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

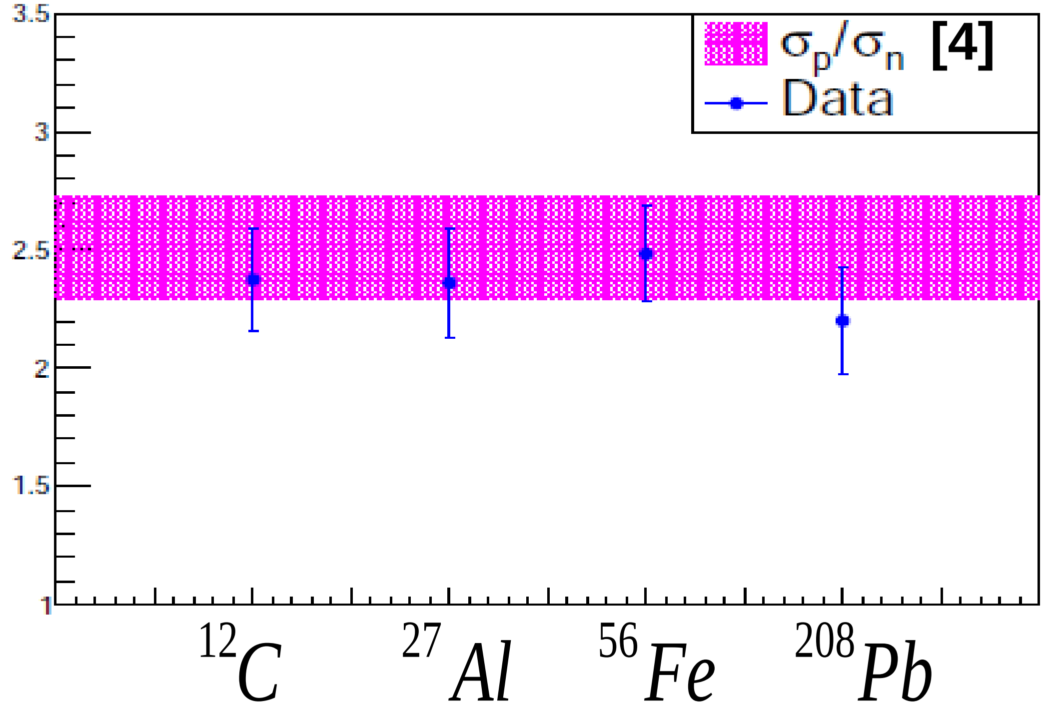
The cuts for un-smeared p:

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

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

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

Analysis of QE events:

☑ I. A(e,e'p)/A(e,e'n) mean-field ratios

☐ II. A(e,e'p)/C(e,e'p) && A(e,e'n)/C(e,e'n) high momentum QE ratios

A(e,e'p)/C(e,e'p) & A(e,e'n)/C(e,e'n) high momentum QE ratios

- [x] A(e,e'p)/C(e,e'p) ratios for un-smeared protons
- [x] A(e,e'p)/C(e,e'p) ratios for smeared protons
- [ ] A(e,e'n)/C(e,e'n) ratios

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

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

1st step:

un-smeared protons

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

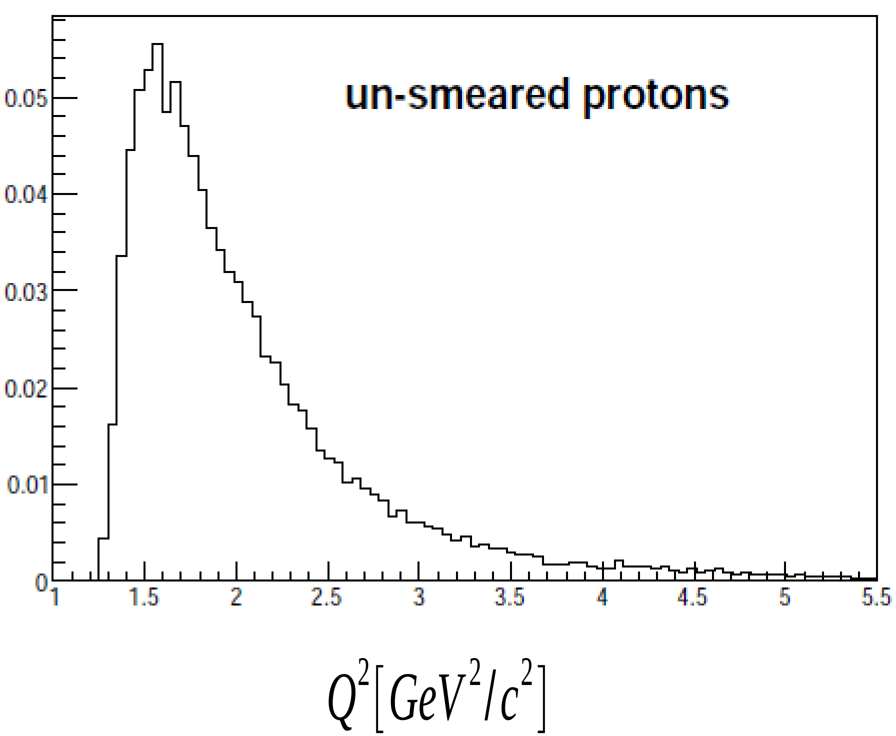
(O. Hen 2012)

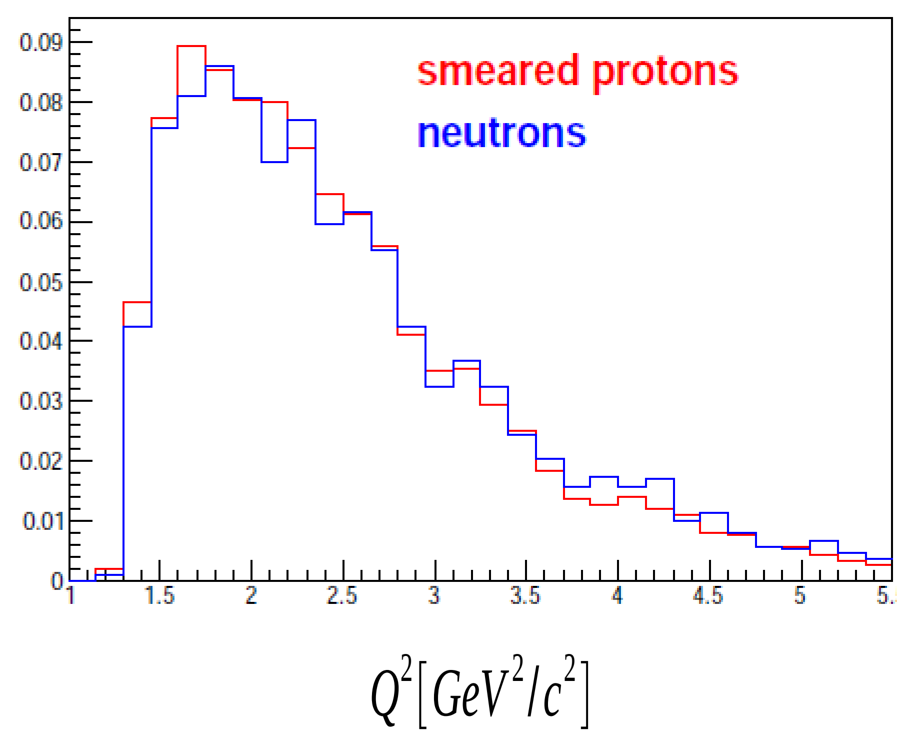
Al/C	Fe/C	Pb/C
1.9±0.08	3.0±0.2	7.2±0.8

2nd step:

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

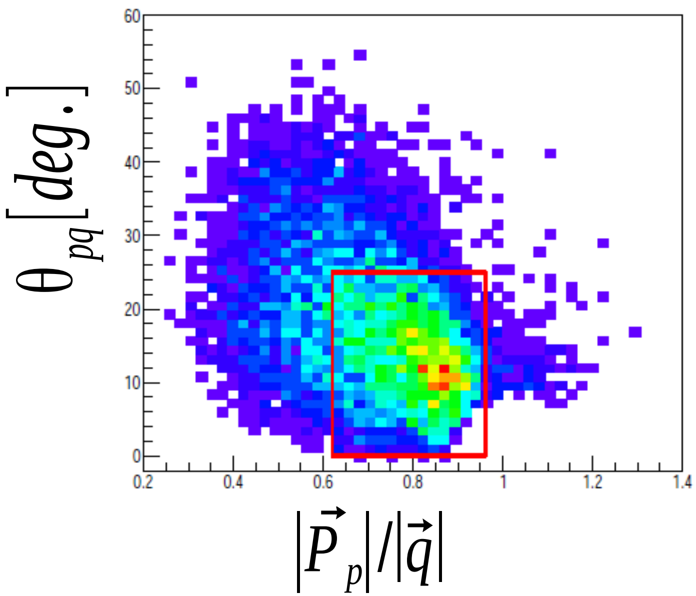
- Low statistics → $x_B > 1.1$
- Poor resolution → smeared protons



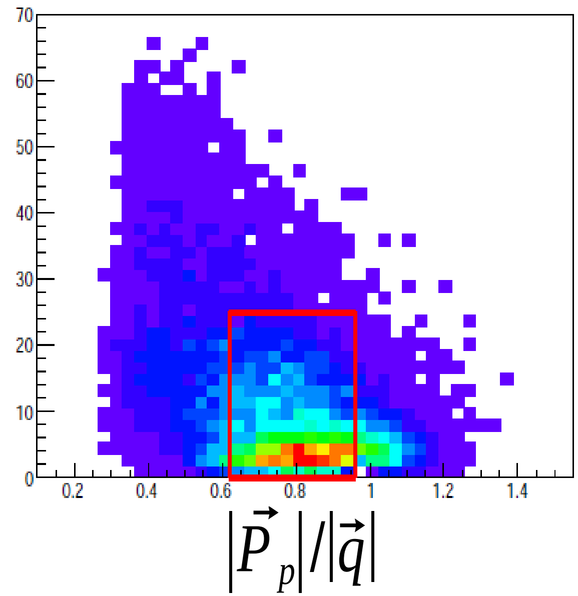


Identifying the Leading Nucleon

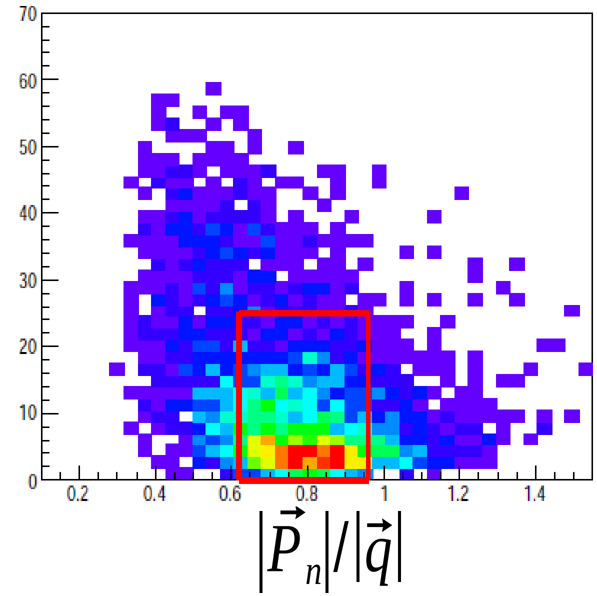
un-smeared protons



smeared protons



neutrons



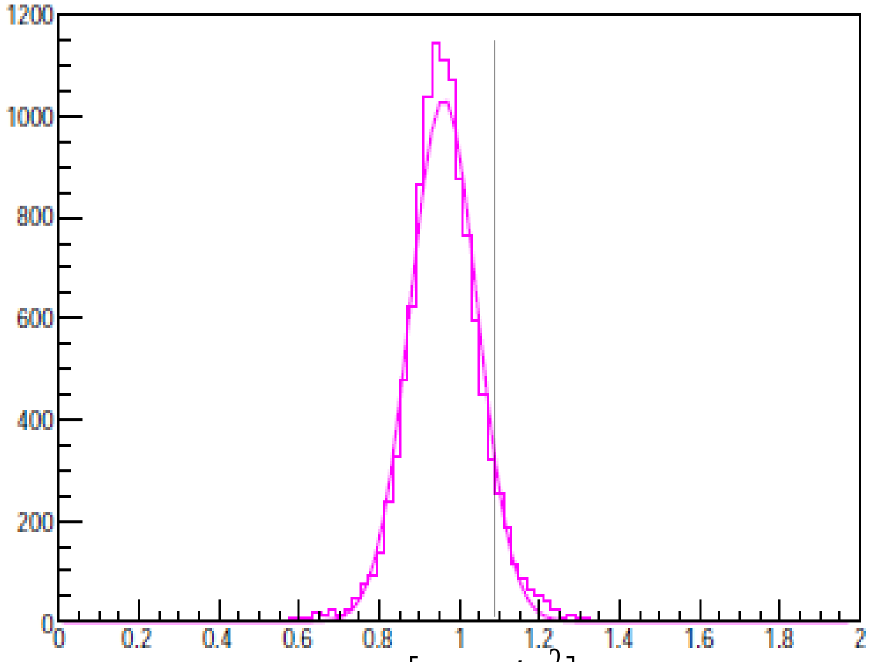
We adopted the cuts (O. Hen 2012):

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

Missing Mass cut

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

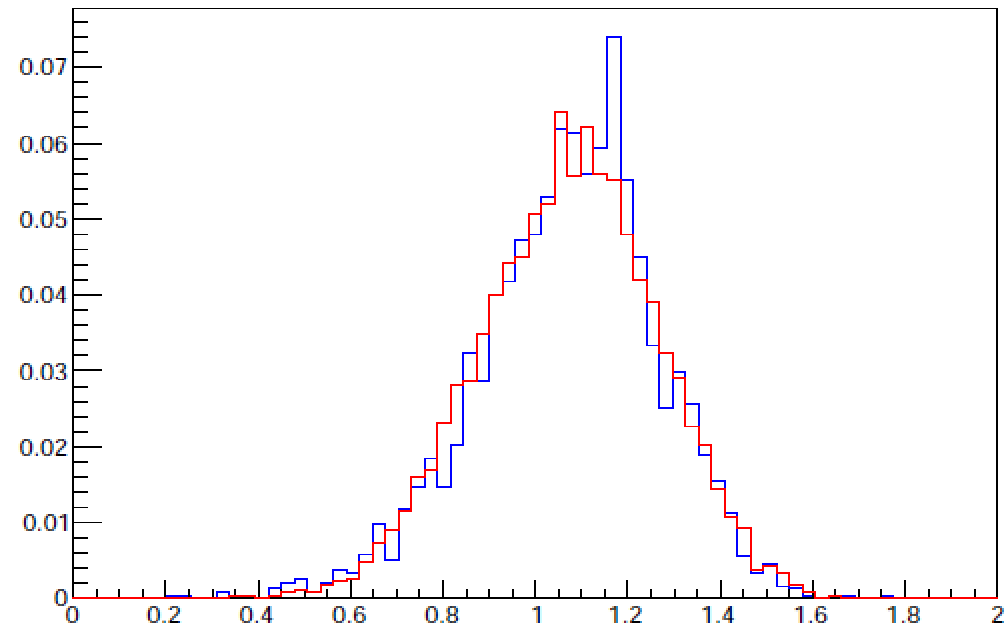
un-smeared protons



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

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

smeared protons neutrons

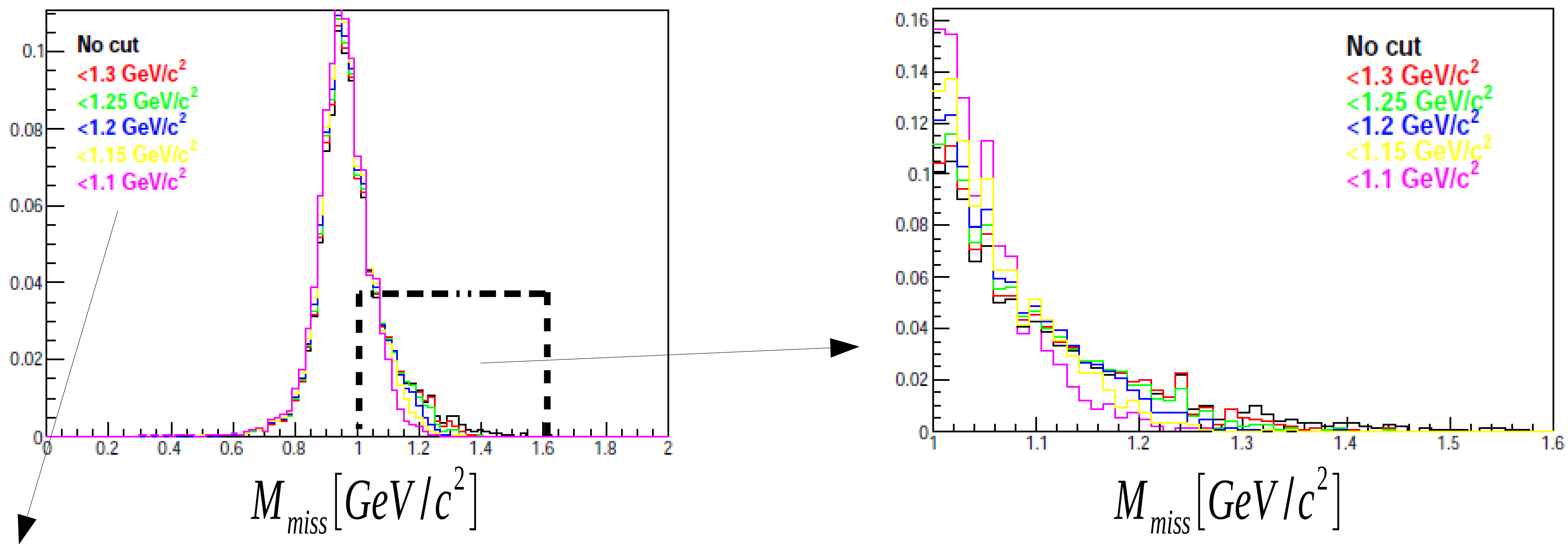


$M_{miss}[GeV/c^2]$

$$M_{miss} < ?$$

Missing Mass cut

un-smeared MM distribution for smeared protons events:



smeared MM cut

The selected cut for smeared p/n:

$$M_{miss} \leq 1.2\, GeV/c^2.$$

Contains ~5% with un-smeared MM>1.1 GeV/c²

The MM cut for un-smeared protons:

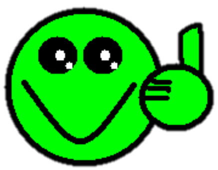
$$M_{miss} \leq 1.1\, GeV/c^2.$$

Missing Momentum cut

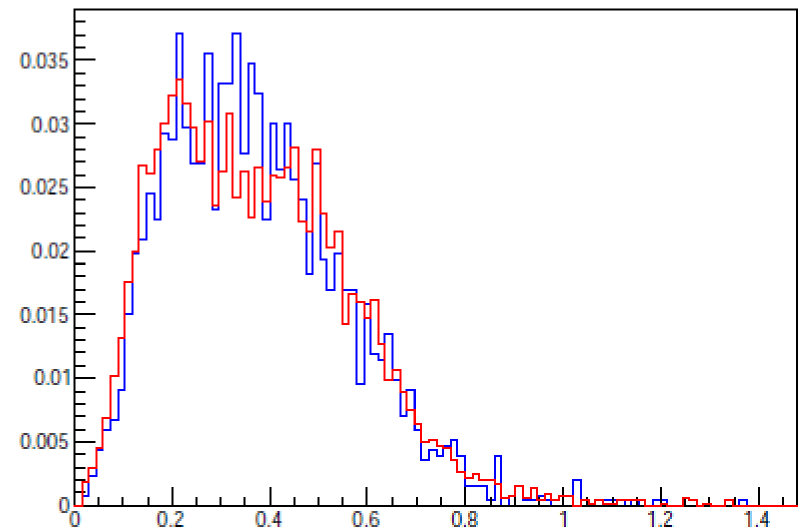
un-smeared protons

smeared protons neutrons

'good event':

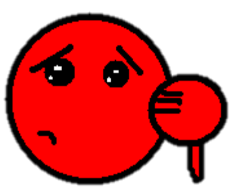


$0.3 < P_{miss-unsmeared} < 1 GeV/c$

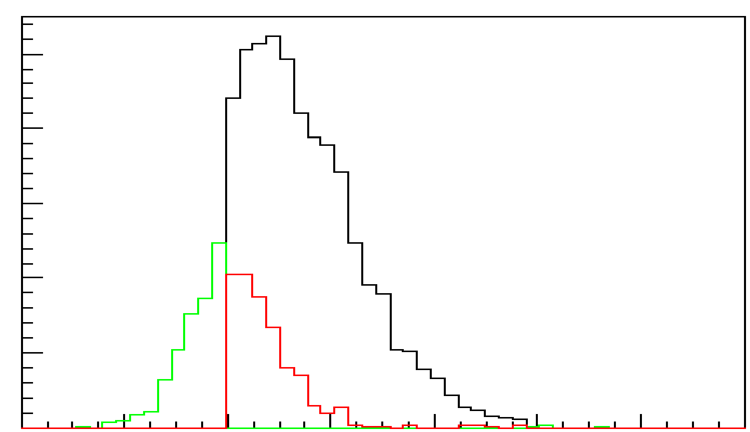


$P_{miss} [GeV/c]$

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

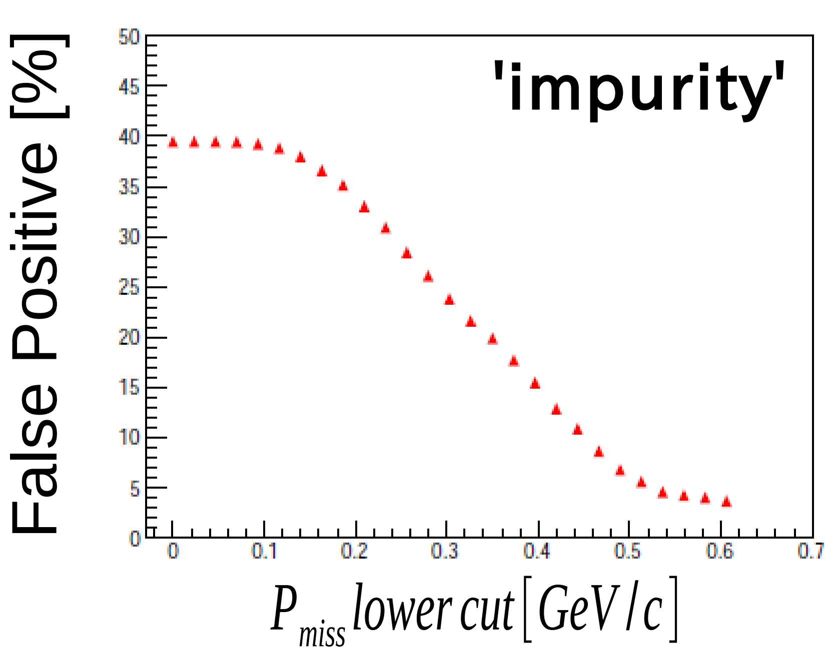


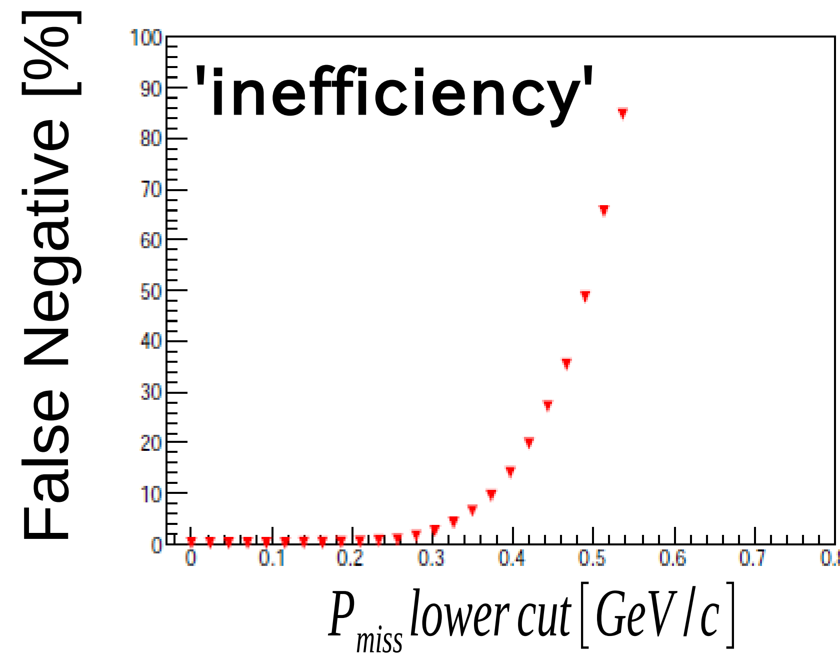
$\| \; P_{miss-unsmeared} > 1 GeV/c$



$P_{miss} [GeV/c]$

False Positive & Negative probabilities





The selected cut for smeared p/n:

$$0.4 < P_{miss} < 1 GeV/c$$

The cut for un-smeared protons:

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

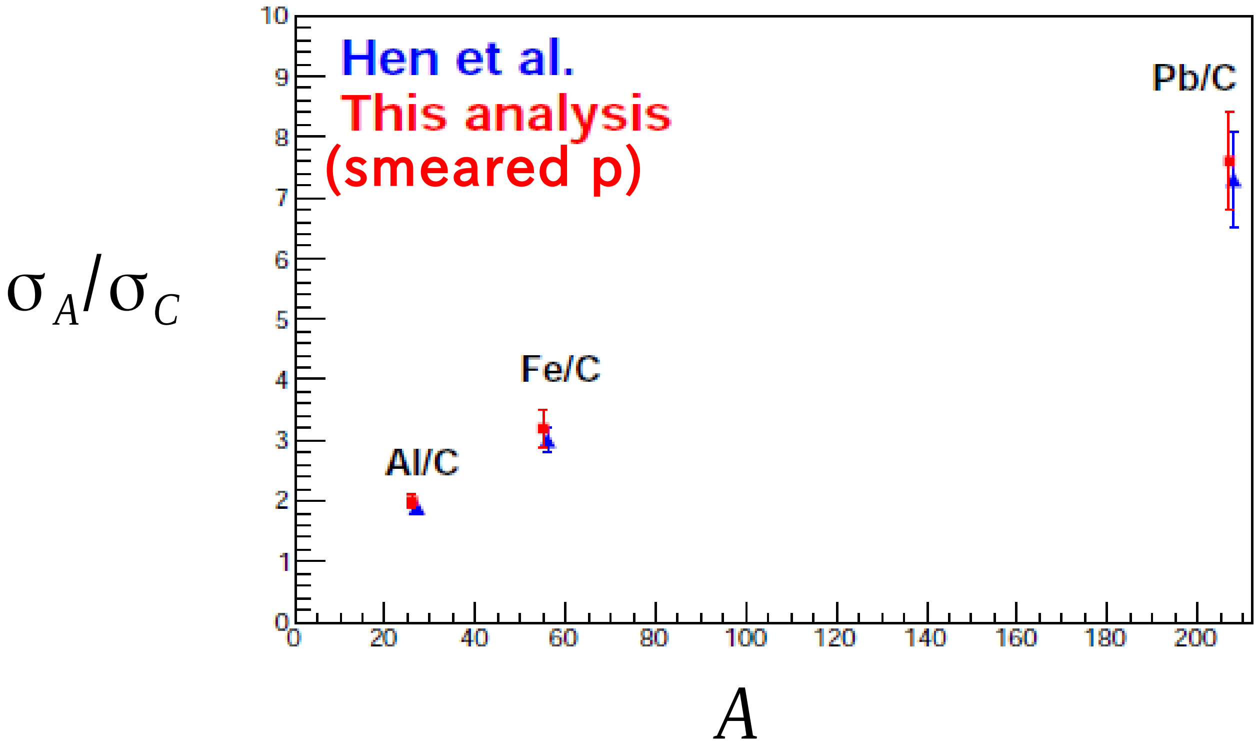
$$False\ Positive \simeq False\ Negative \simeq 15\,\%$$

The selected events:

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

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

Next step: 'Blind analysis'

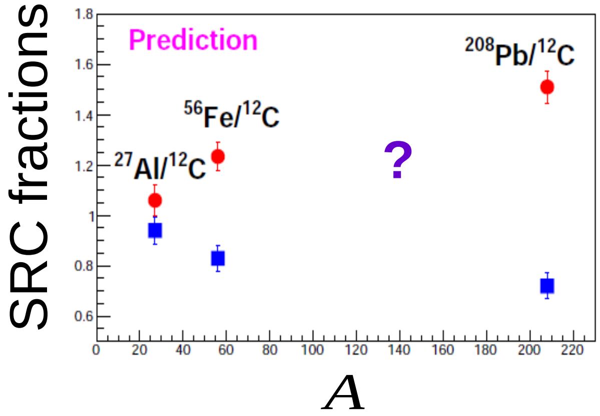
The same ratios for neutrons:

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

And as a sanity check:

$$^{12}C(e,e'p)_{high} \stackrel{?}{=} {^{12}C(e,e'n)_{high}}$$

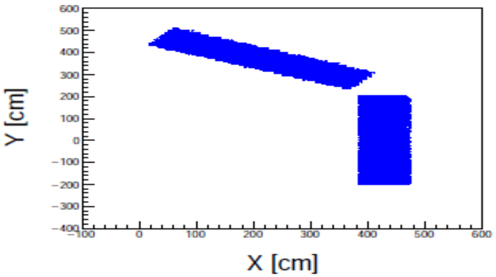
Future Plans



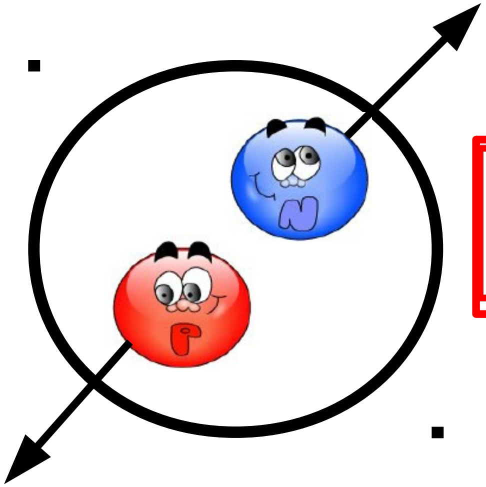
np- dominance

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

Detecting neutrons in CLAS LAC



3N- SRC (e,e'npp)



2N – SRC

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

Backup Slides

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

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

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

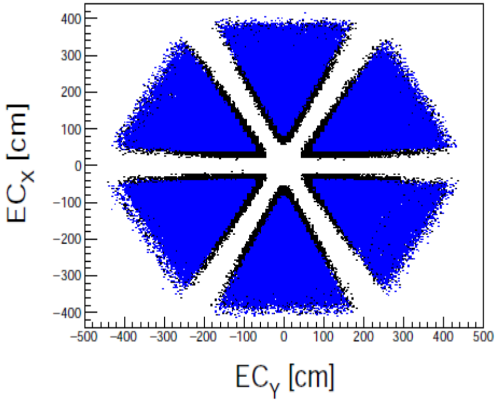
Considered 2 values of K_0:

* 300 MeV/c
* k_F

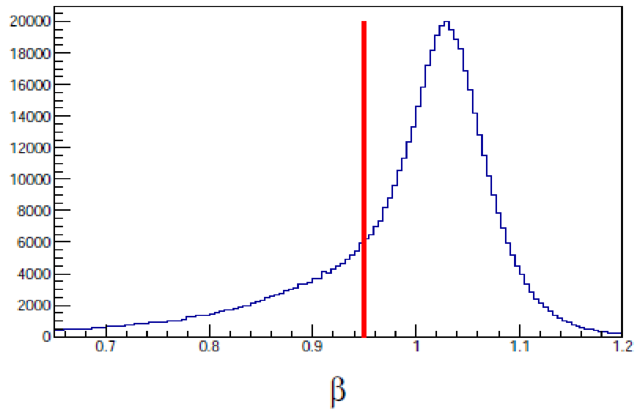
Uncertainty was taken as the difference between the different results.

Detecting neutrons

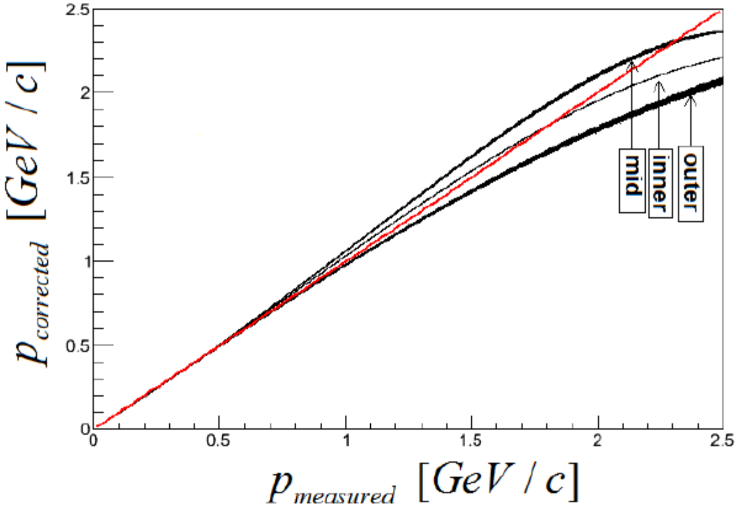
- No DC and SC signals
- EC fiducial cut



- Velocity cut: β<0.95



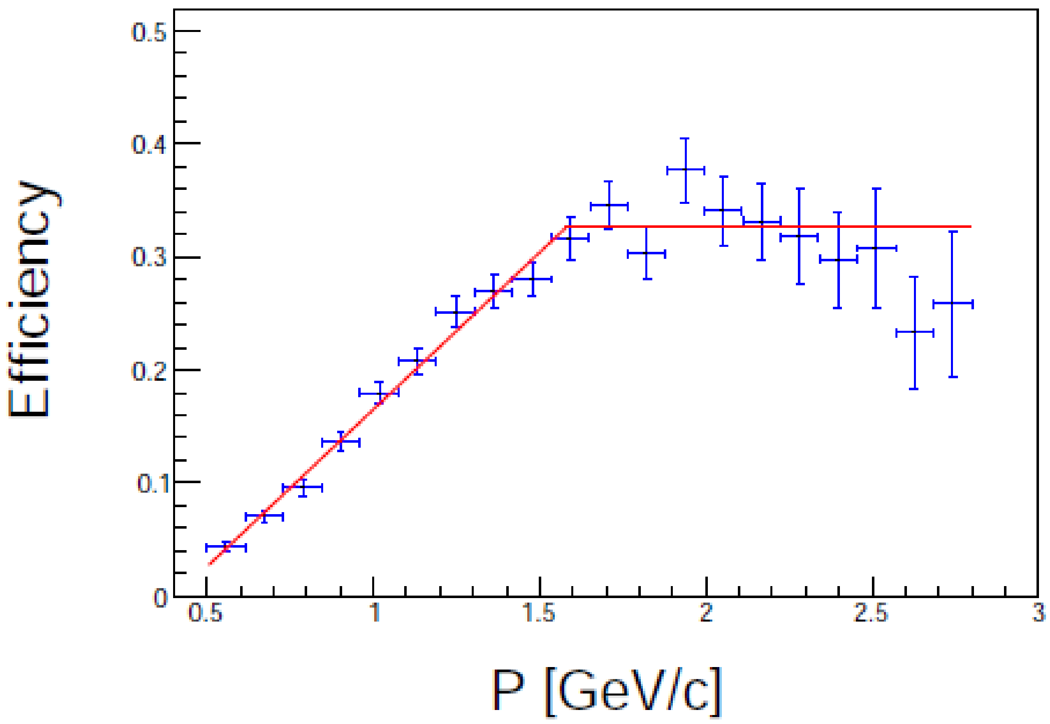
- Momentum cut: p<2.34 GeV/c (β<0.93)



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

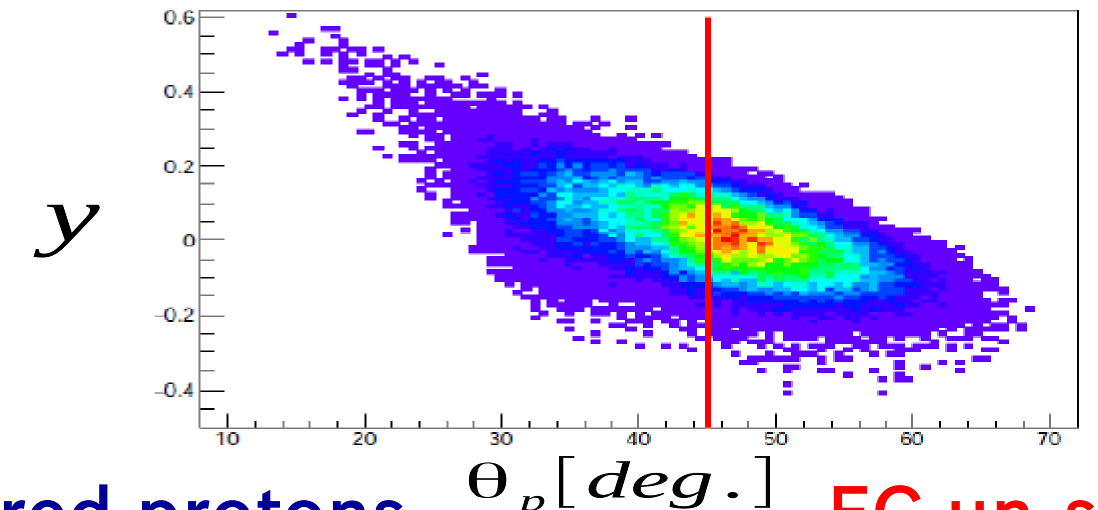
Neutron detection efficiency

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



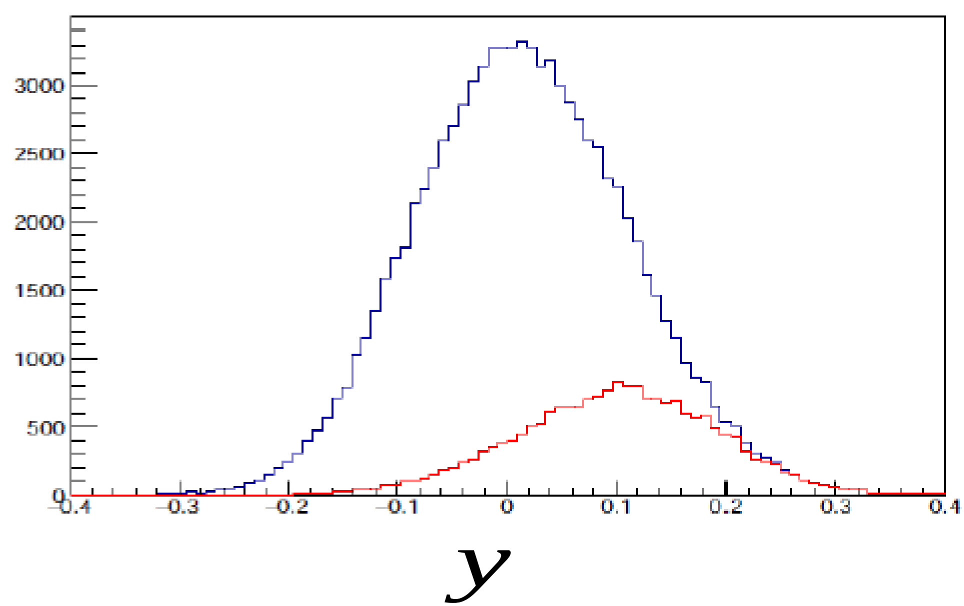
Comparing un-smeared protons

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

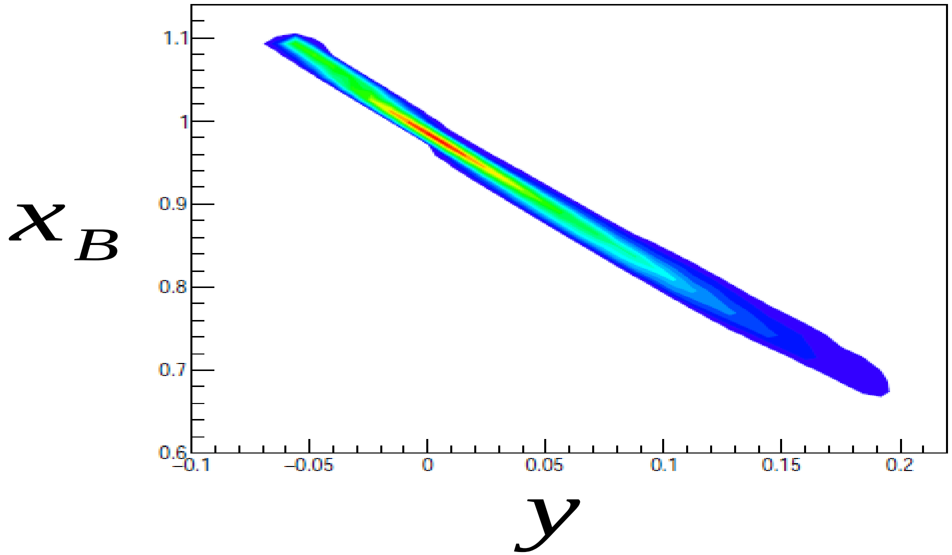


All un-smeared protons

EC un-smeared protons

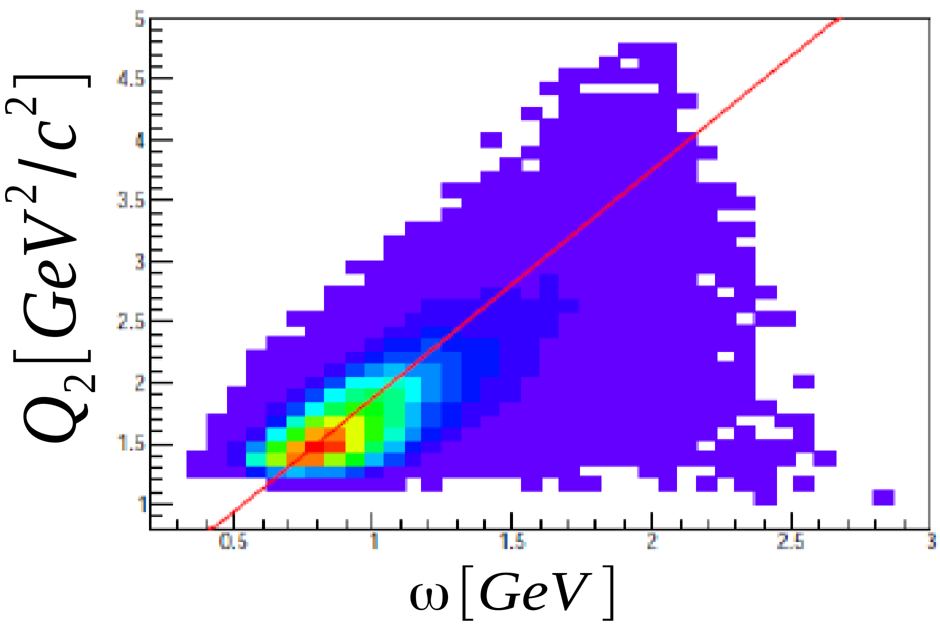


Comparing un-smeared protons

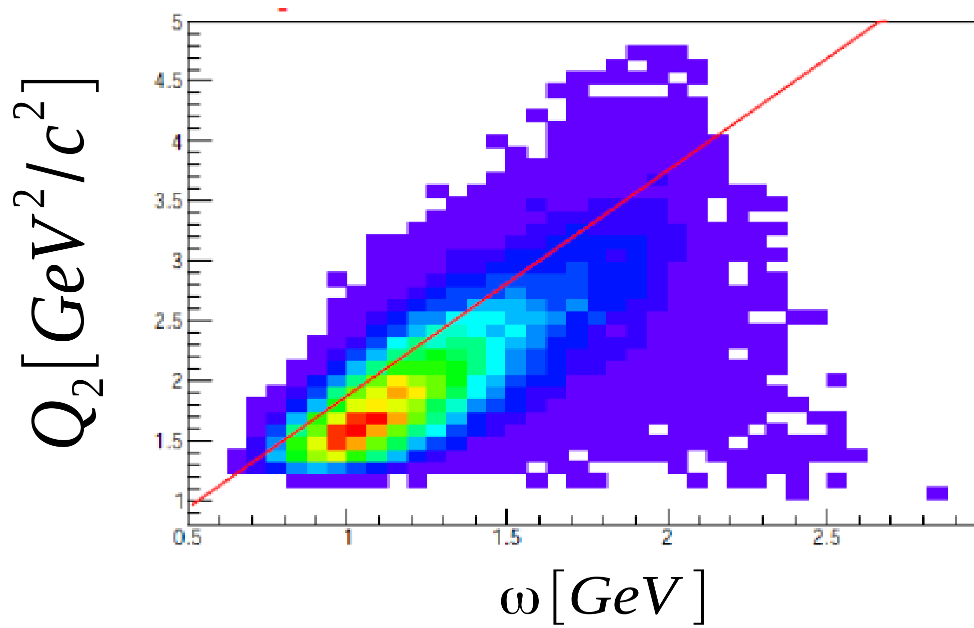


QE events → $x_b \approx 1$

All un-smeared protons



EC un-smeared protons



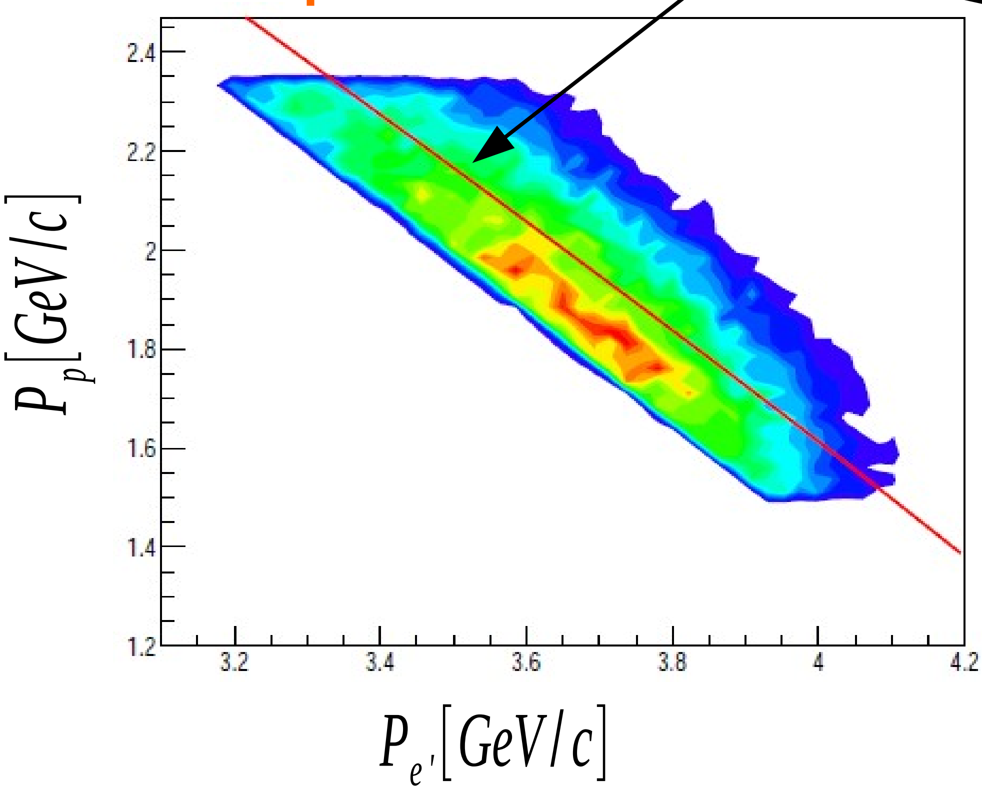
Checking the event selection

Energy momentum conservation:

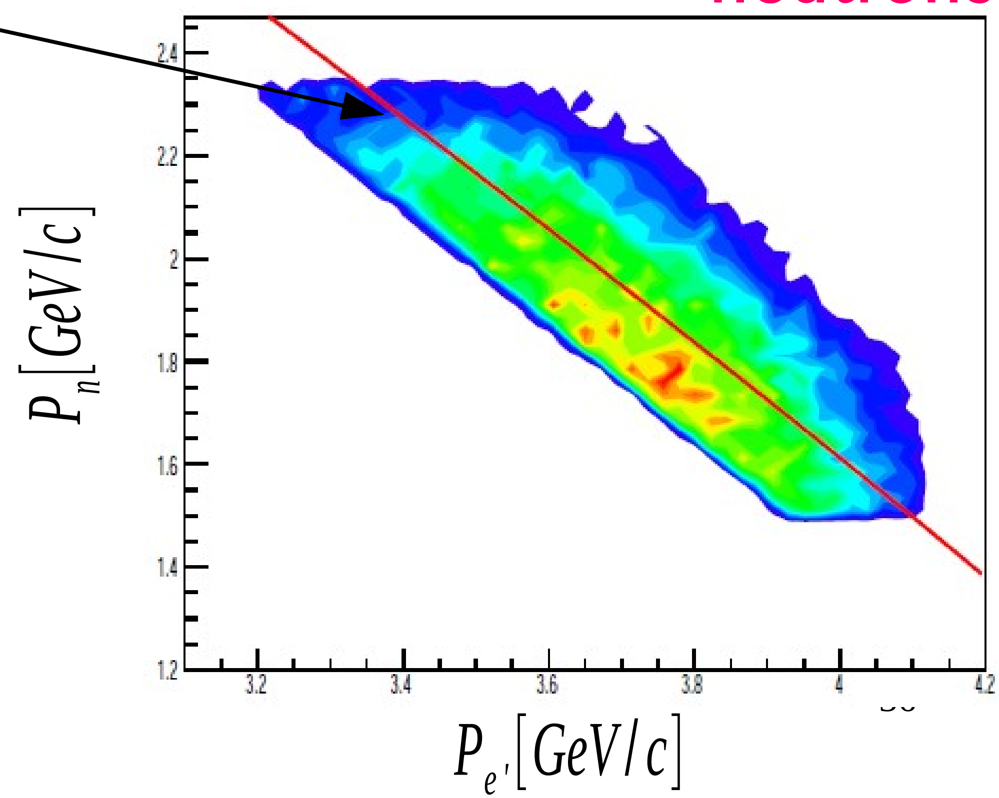
$$\left(E_{beam},\left(0,0,E_{beam}\right)\right)+\left(M_N,\vec{0}\right)=\left(E',\vec{P}_{e'}\right)+\left(E_N,\vec{P}_N\right)$$

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

smeared protons



neutrons

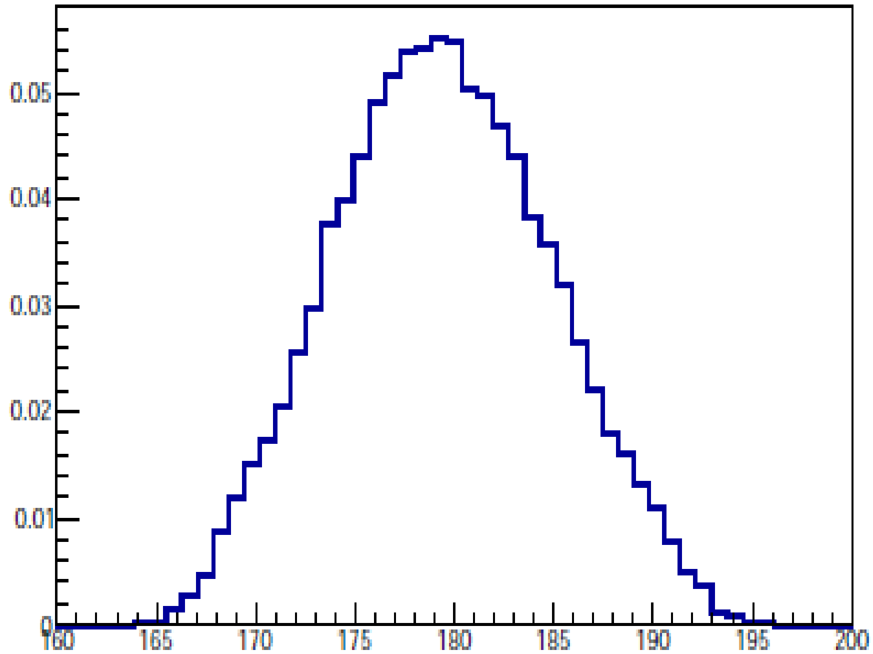


Checking the event selection

From energy momentum conservation:

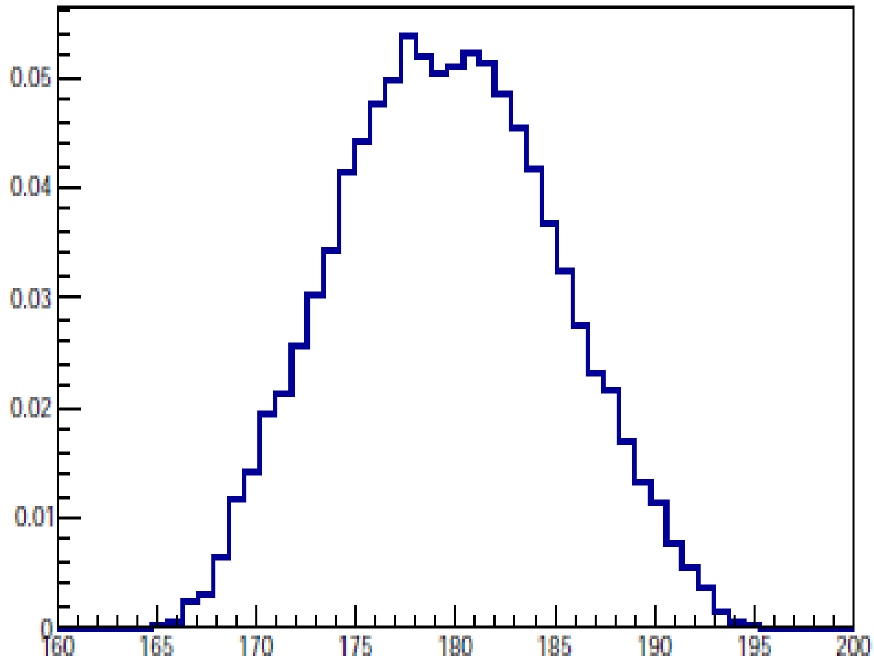
$$|\varphi_N - \varphi_{e'}| = 180^o$$

smeared protons



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

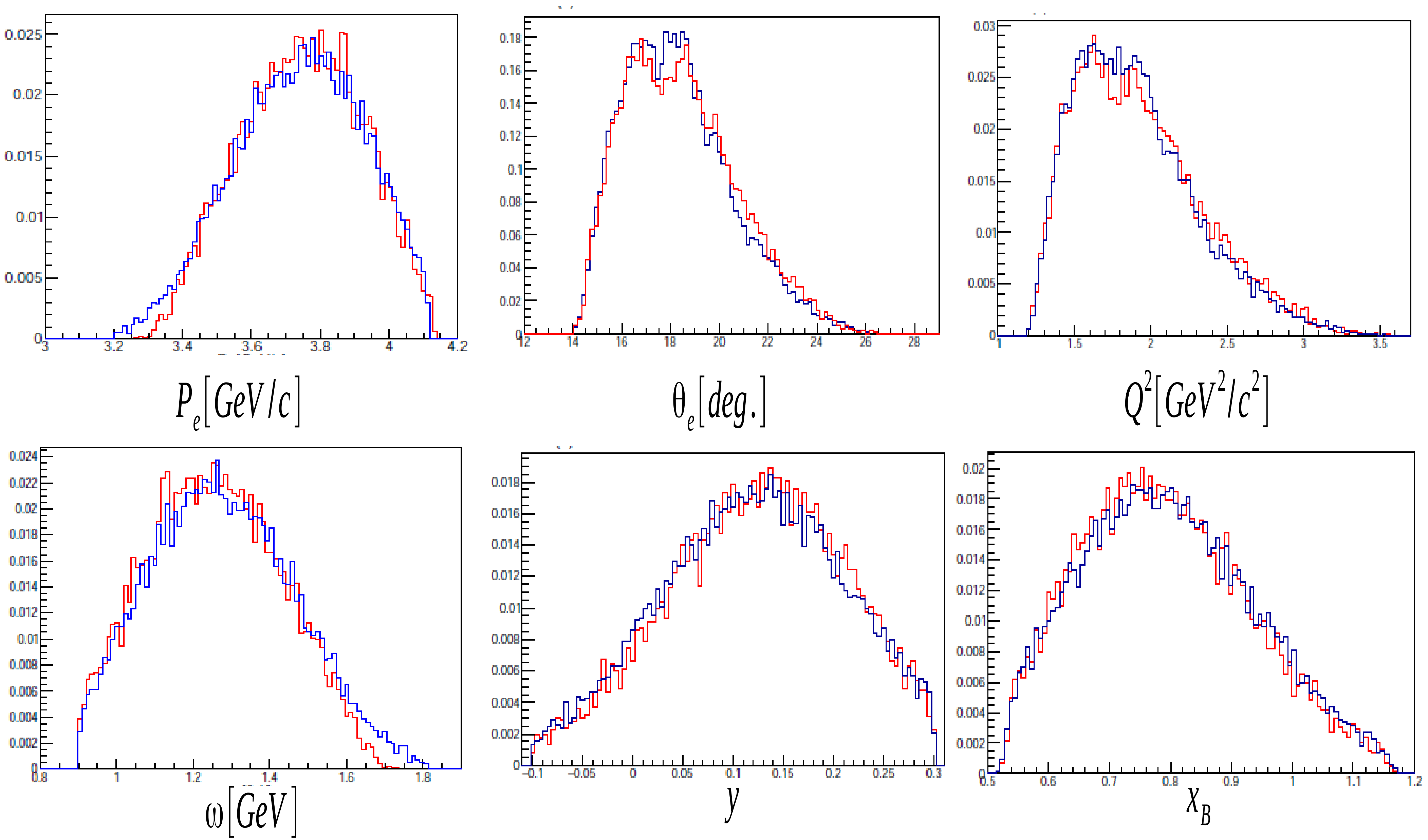
neutrons



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

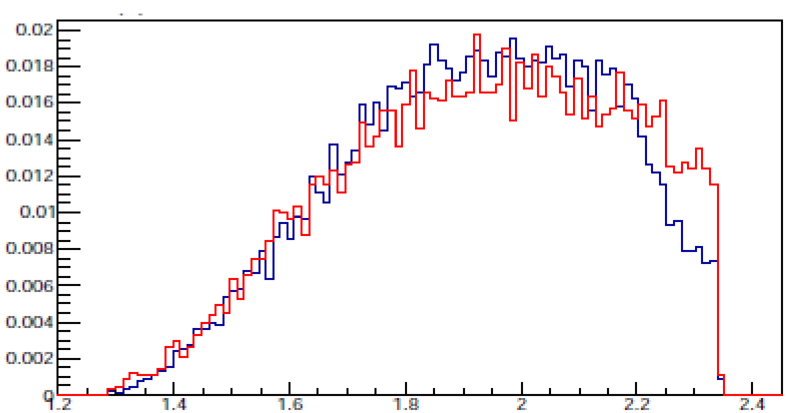
Comparing the smeared protons and neutrons

smeared protons neutrons

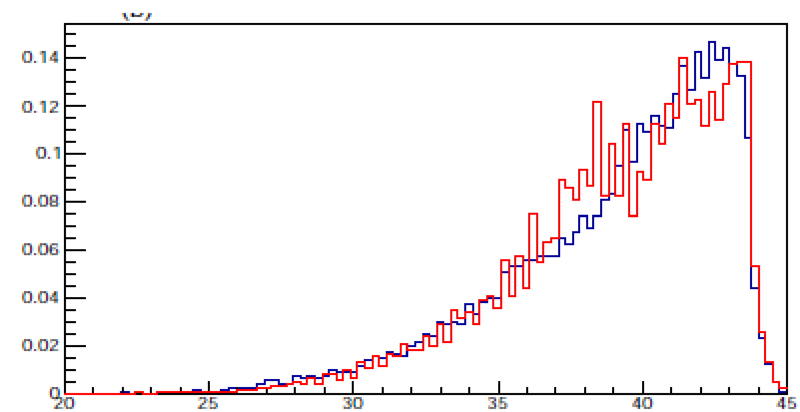


Comparing the smeared protons and neutrons

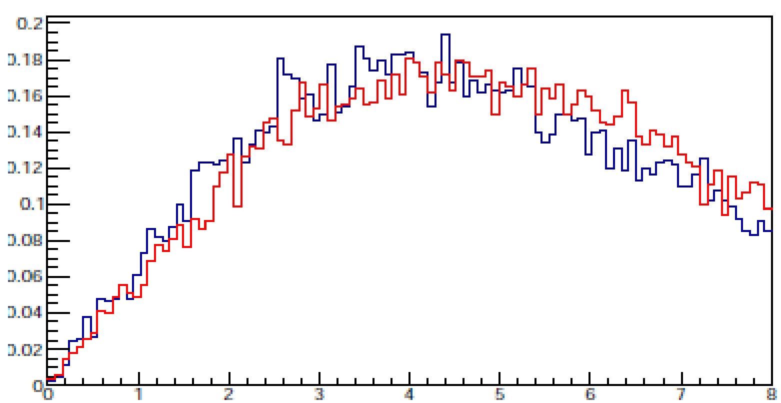
smeared protons | neutrons



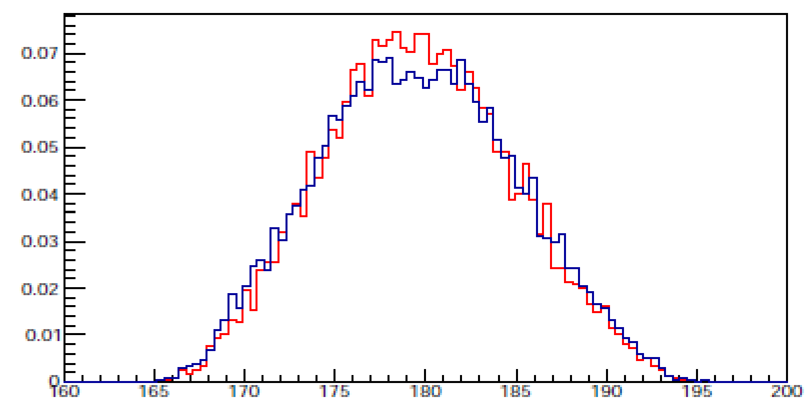
$P_{p/n}[GeV/c]$



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



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



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

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.

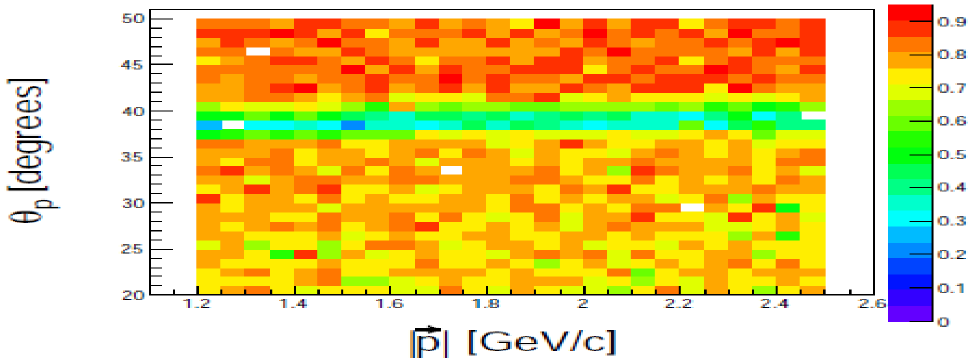
* 100xphi angle uniformly distributed.

* Running through CLAS MC simulation.

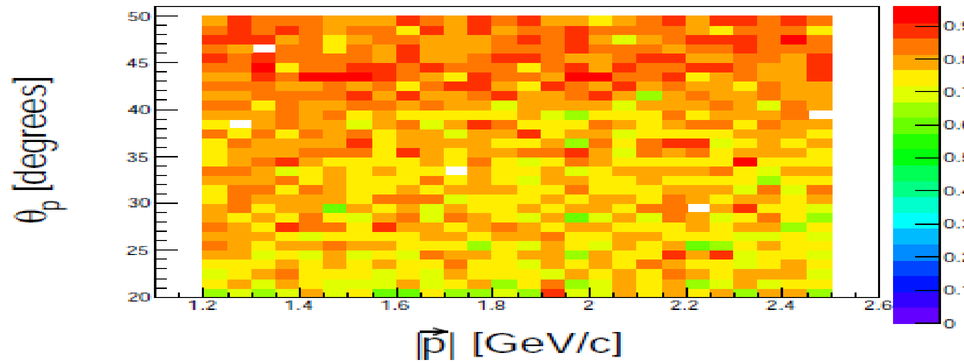
* Dividing event by event by the ratio of reconstructed/generated.

Protons simulation - results

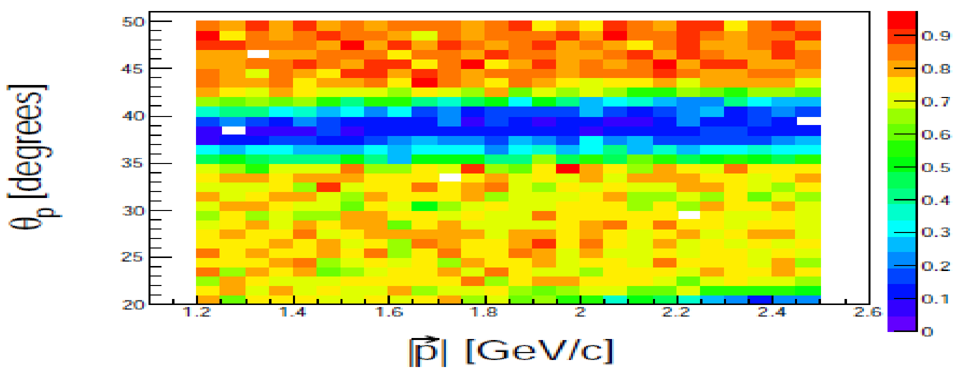
Sector #1



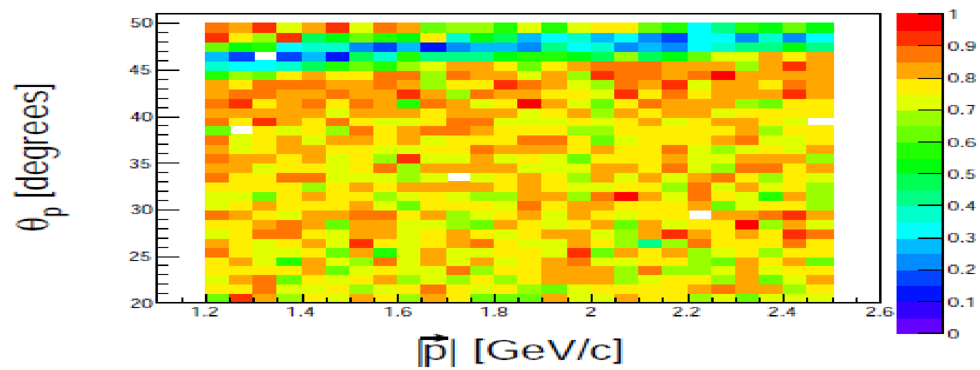
Sector #2



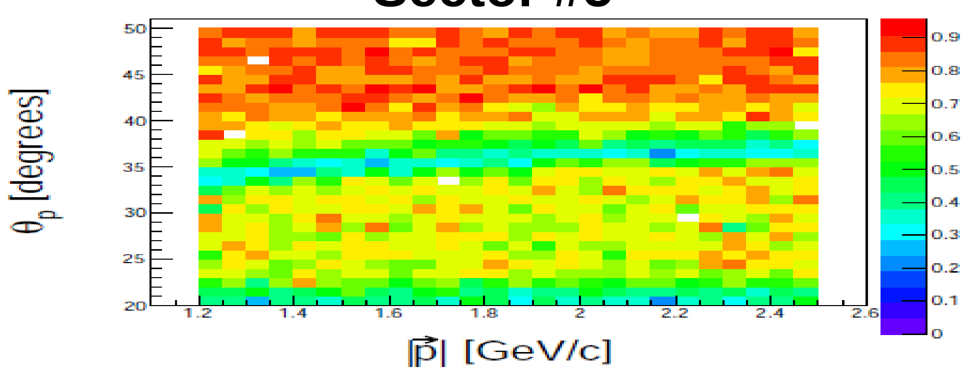
Sector #3



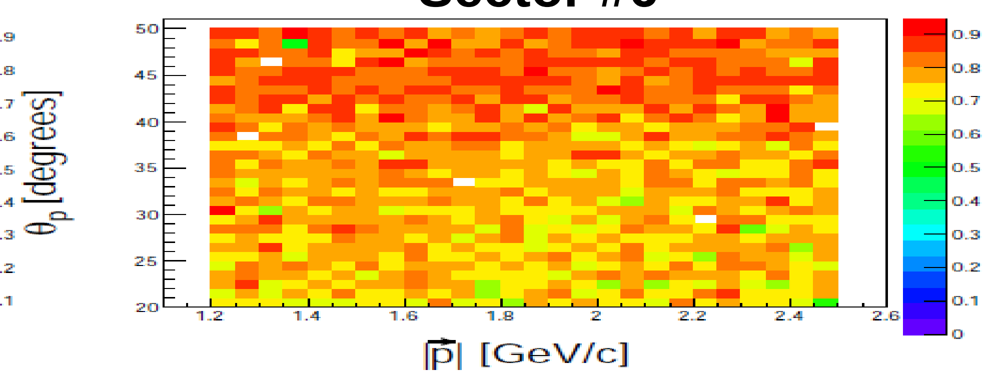
Sector #4



Sector #5



Sector #6



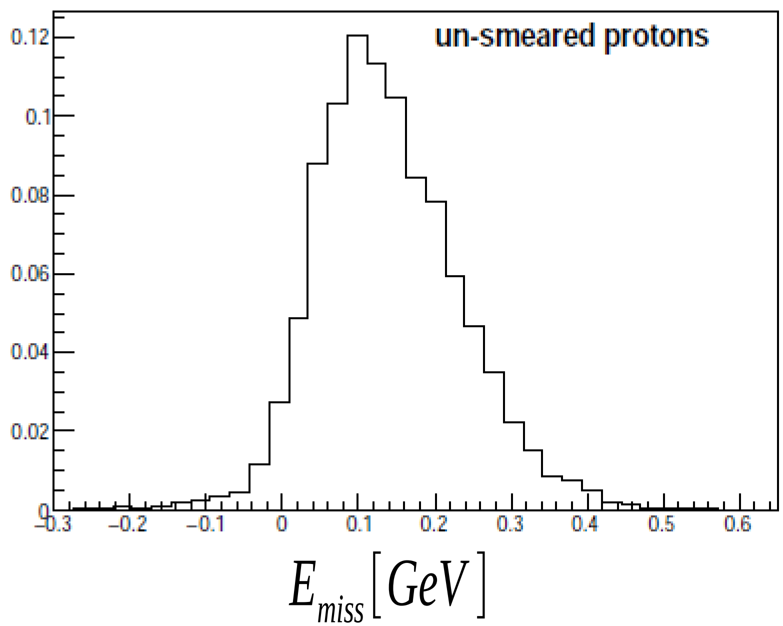
Uncertainties of the event selection

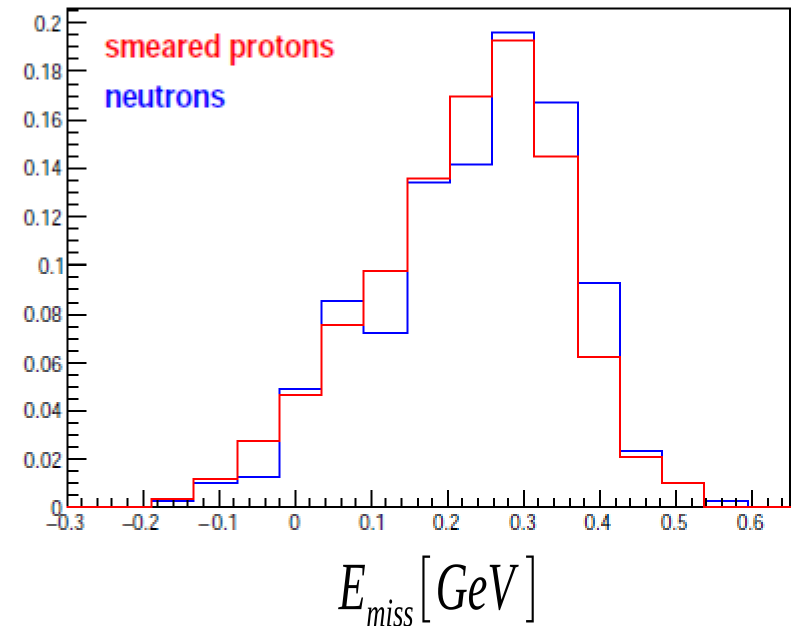
Cut	Cuts sensitivity				
	Range	C	Al	Fe	Pb
-0.05<y<0.25	±0.05	0.84%	0.83%	0.58%	0.81%
0.95<ω<1.7 GeV	±0.05 GeV	2.1%	1.9%	1.9%	1.7%
$\theta_{pq} < 8^o$	$\pm 1^o$	2.0%	1.8%	1.5%	1.4%
$1.3 < Q^2 < 3.5\, GeV^2/c^2$	$\pm 0.2\ GeV^2/c^2$	0.61%	0.39%	0.68%	0.35%
$P_{miss} < 0.3\, GeV/c$	±0.025 GeV/c	0.82%	0.49%	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%

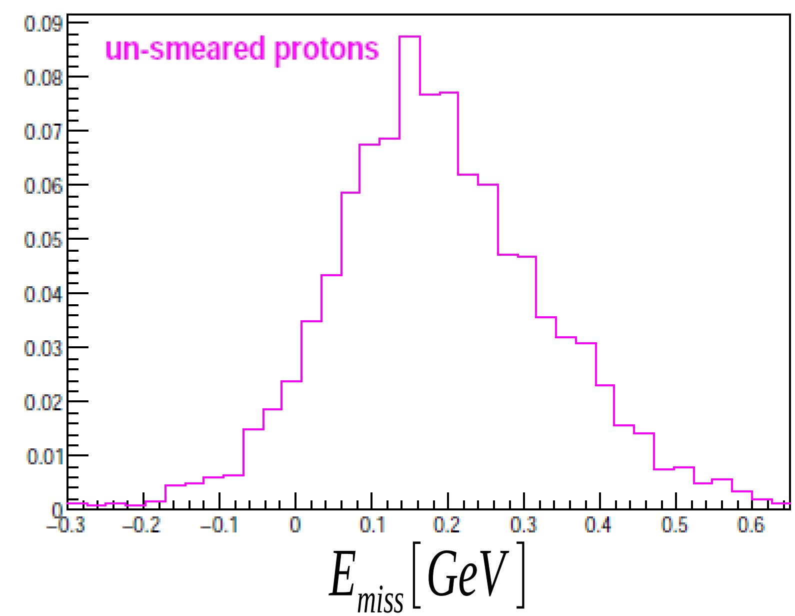
Contributions to the uncertainty

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%)

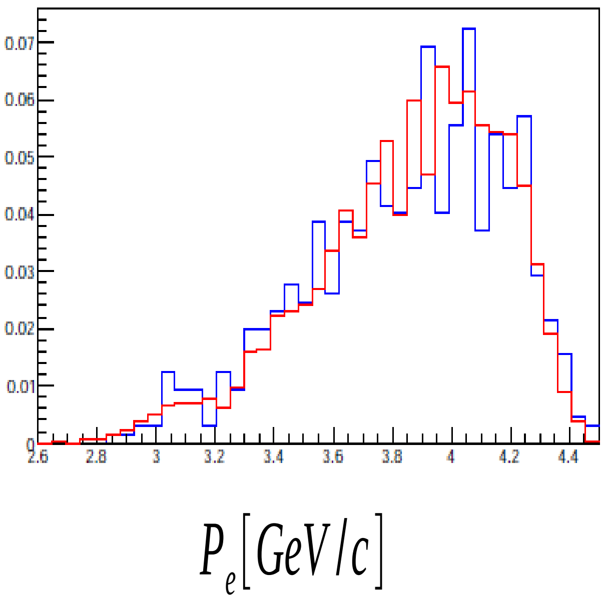
Missing energy distribution

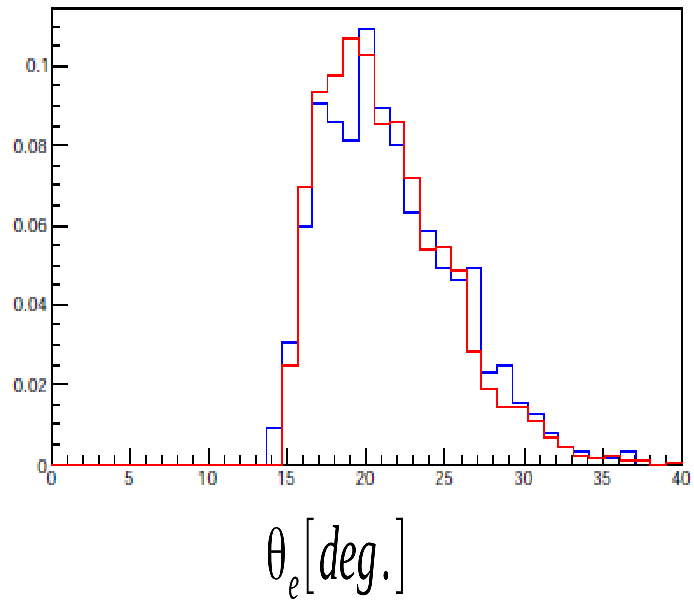


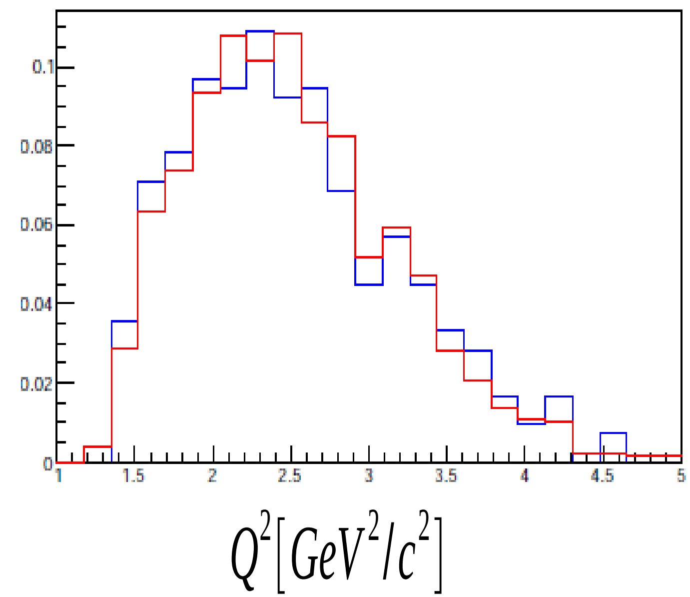


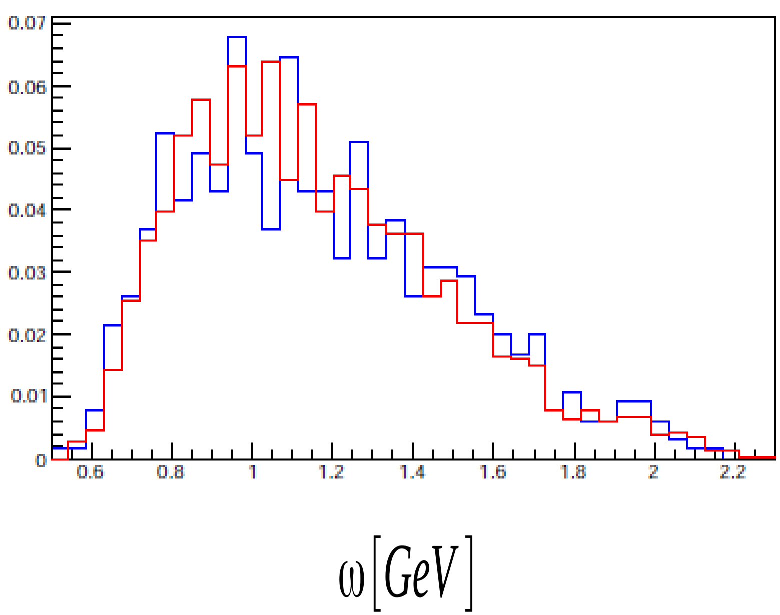


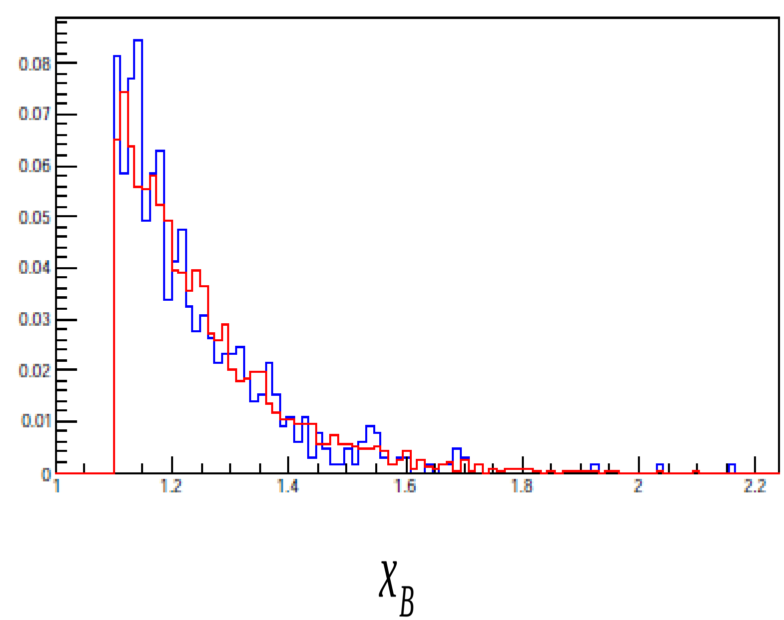
Comparing smeared protons & neutrons distributions:



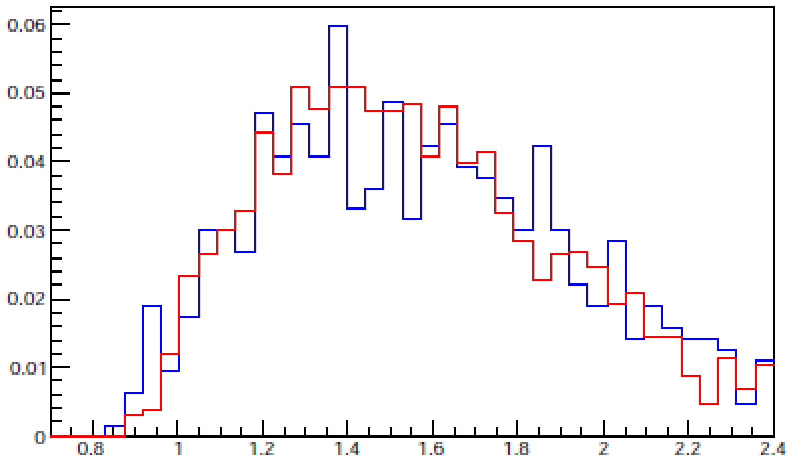




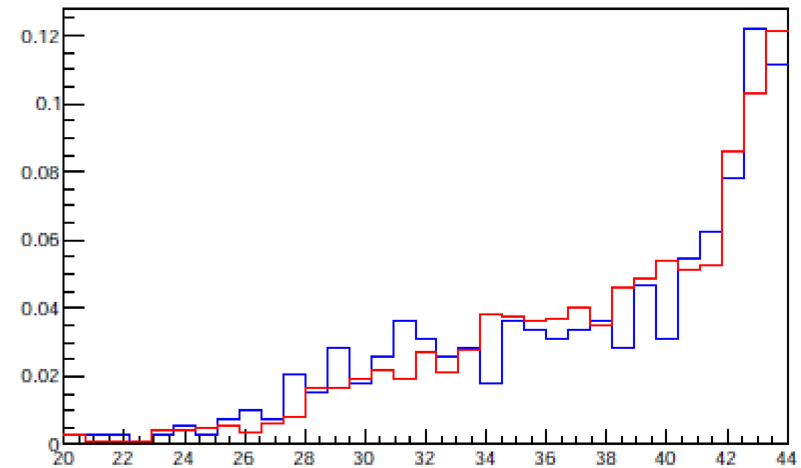




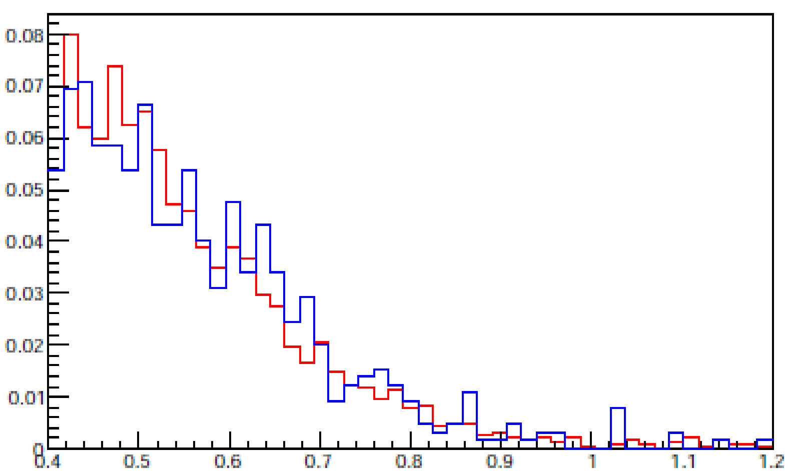
Comparing smeared protons & neutrons distributions:



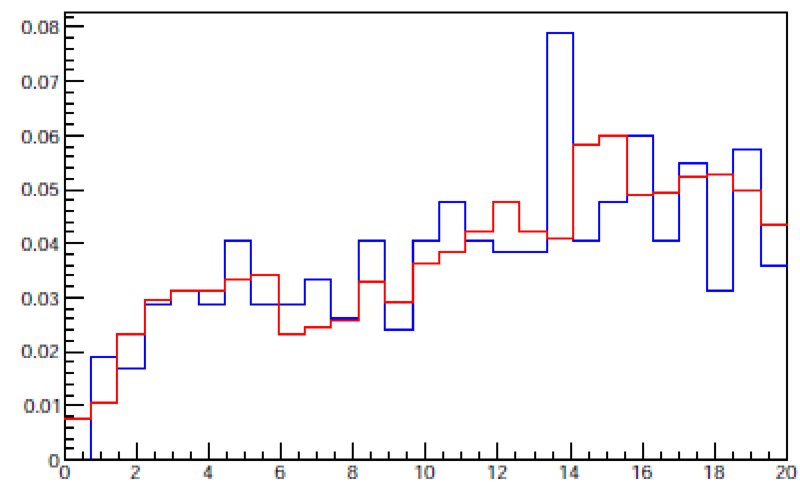
$P_{p/n}[GeV/c]$



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



$P_{miss}[GeV/c]$



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

(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/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%)