SRC Studies using Triple Coincidence A(e,e'pp) & A(e,e'np) reactions

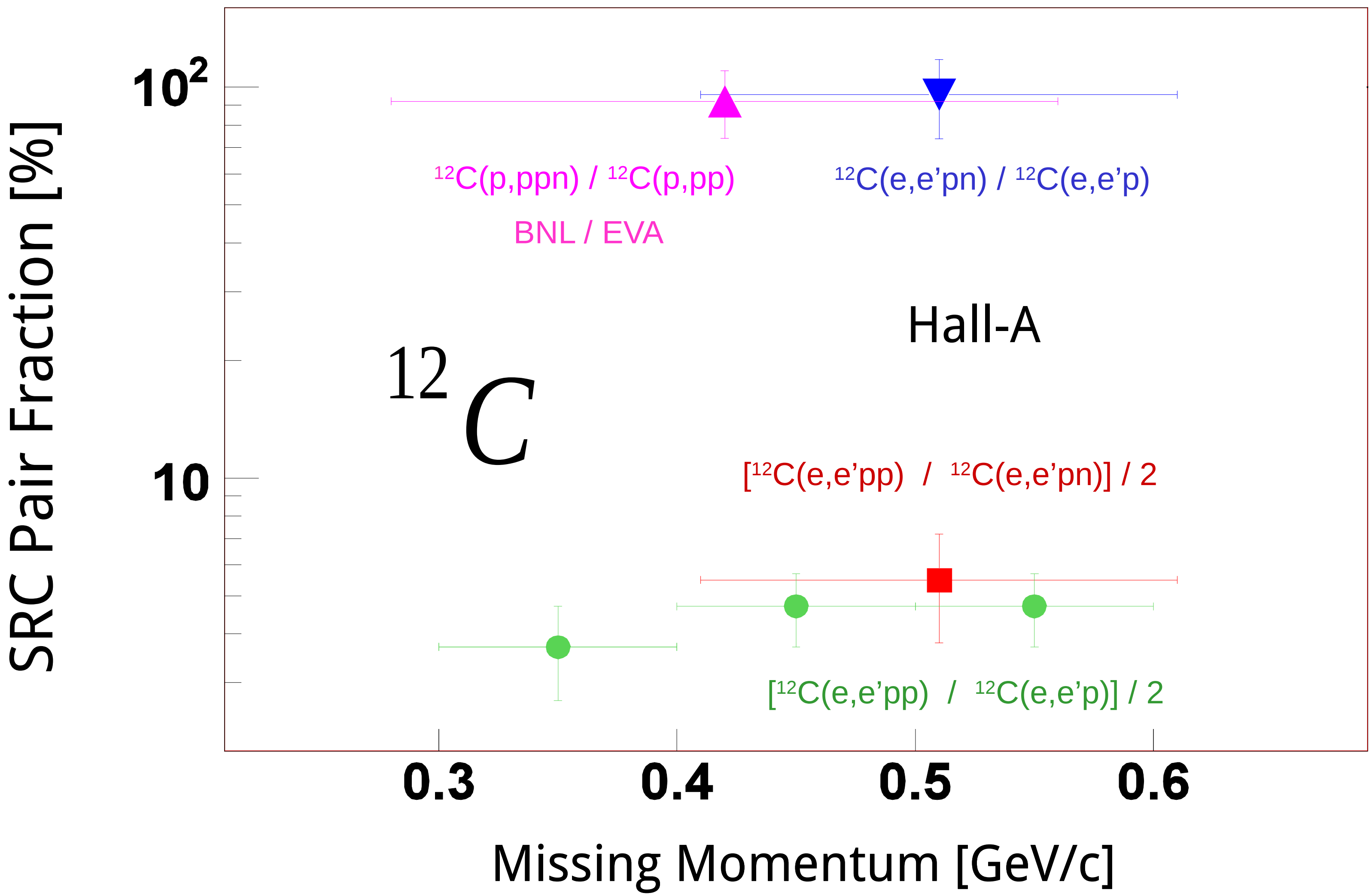
A data-mining project using CLAS EG2 data

Meytal Duer

Tel-Aviv University

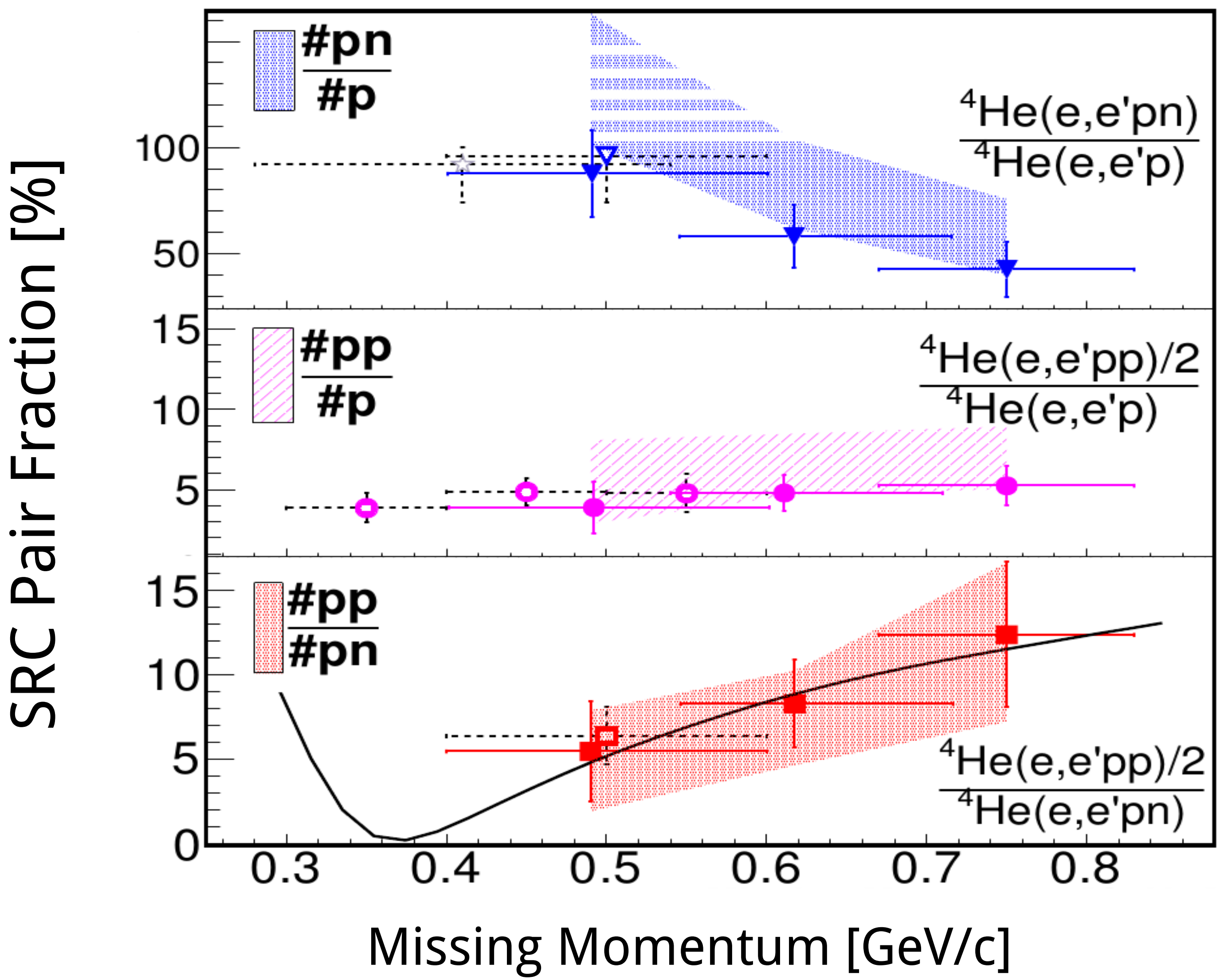
July 12, 2018 NPWG meeting, JLab

np-dominance in 2N-SRC



Subedi et al., Science 320 (2008)   Piasetzky et al., PRL. 97 (2006) 162504

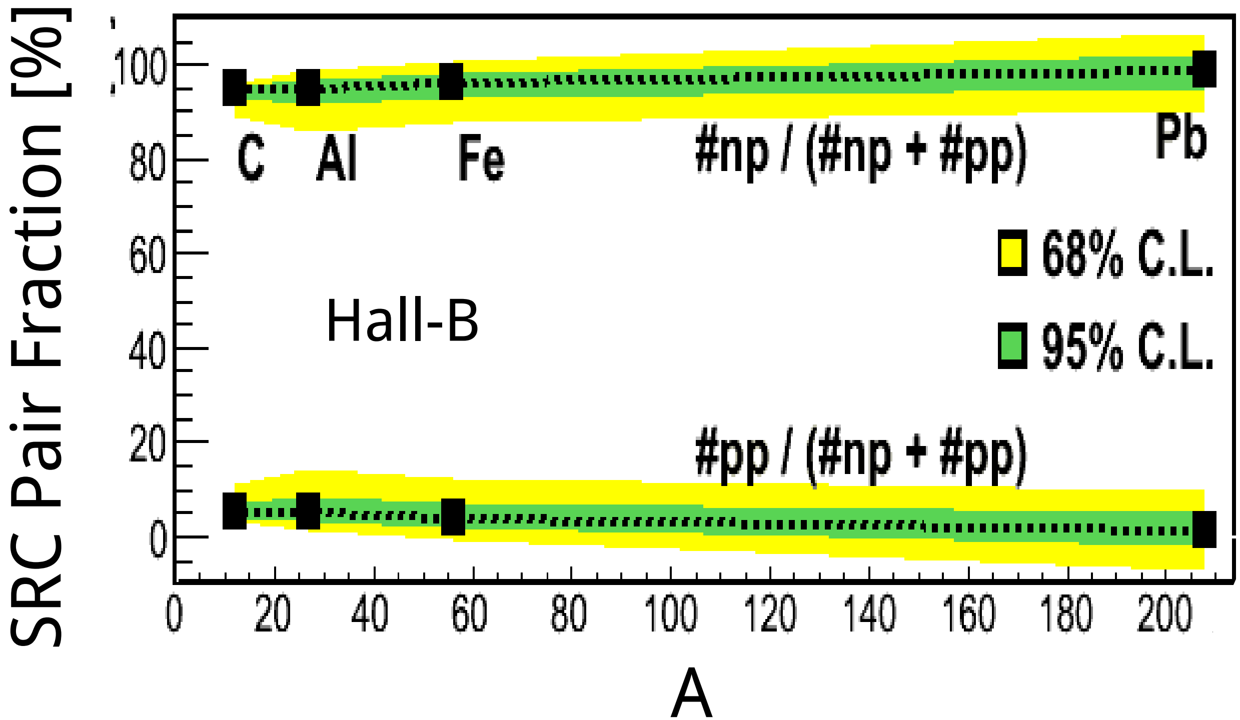
np-dominance in 2N-SRC



Hall-A

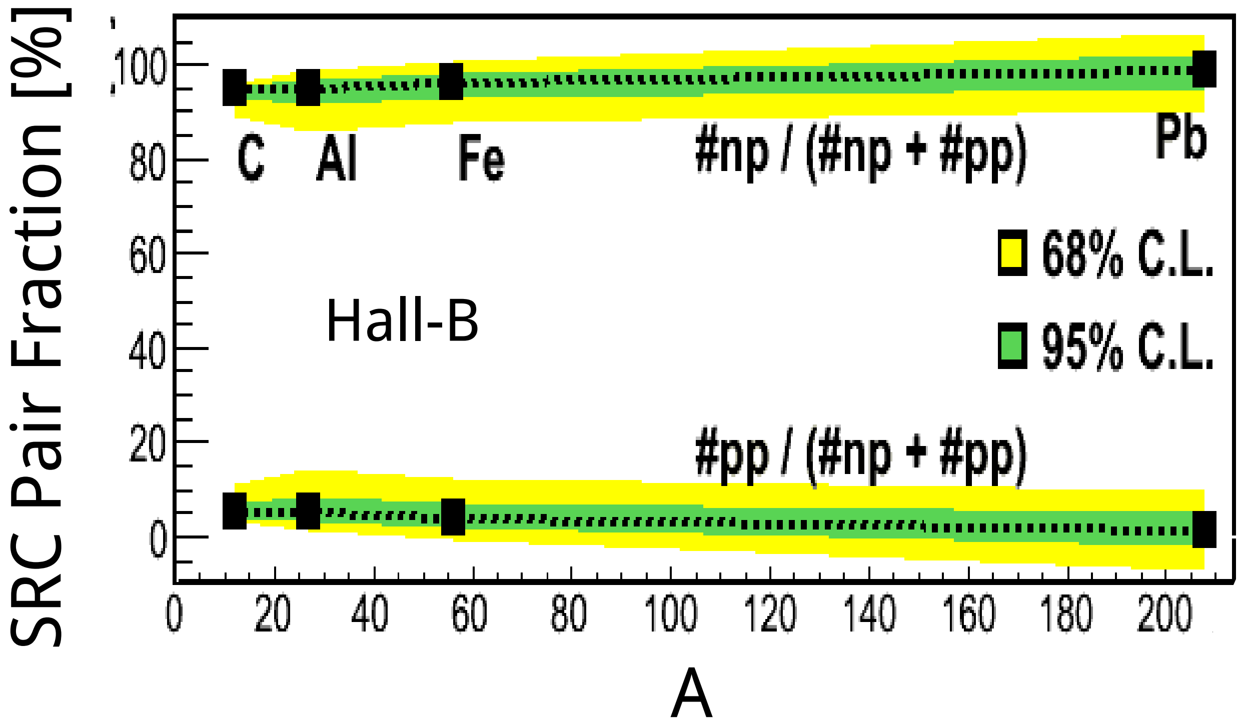
Korover et al. Phys. Rev. Let. 113, 022501 (2014).

np-dominance in 2N-SRC



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

np-dominance in 2N-SRC



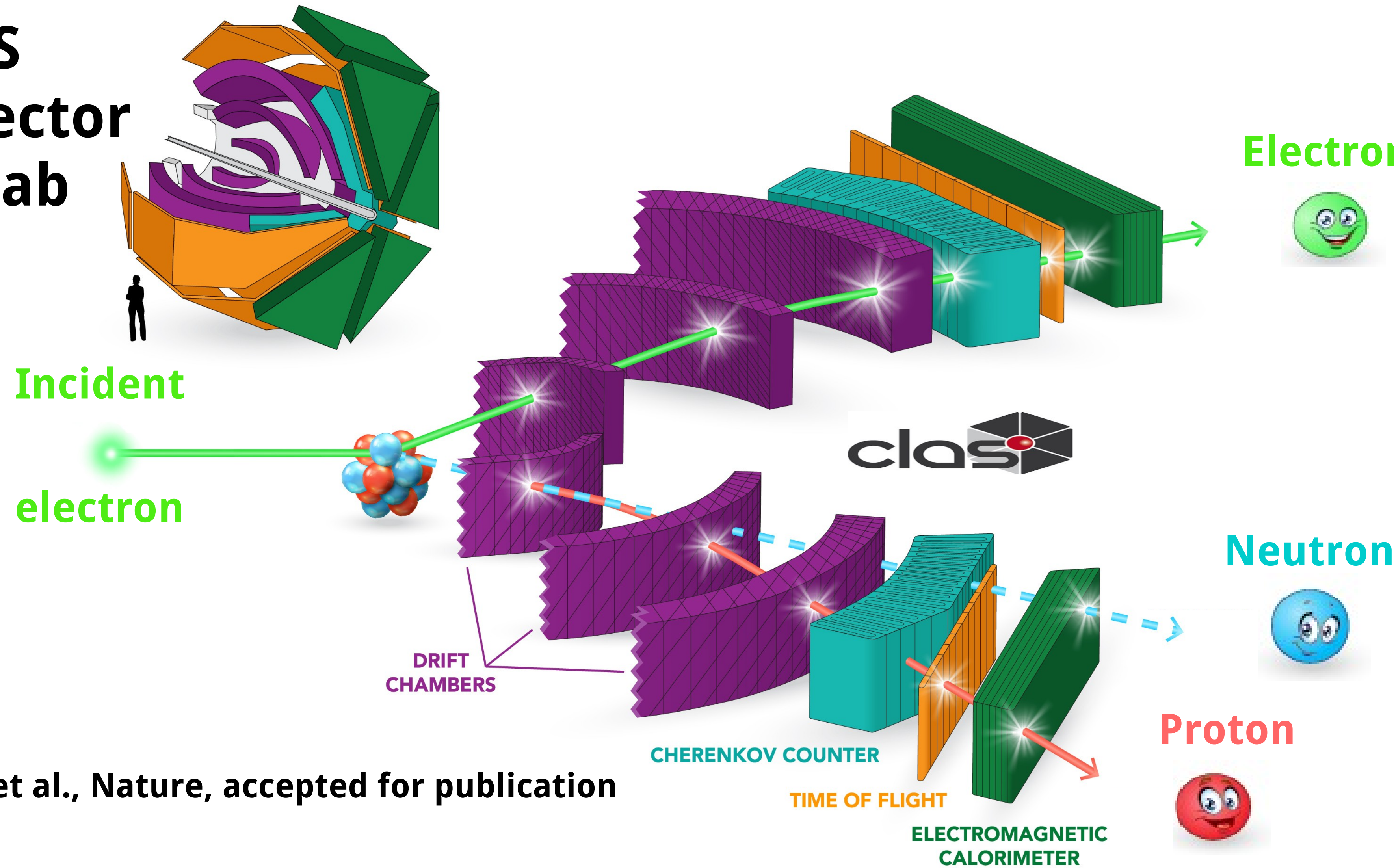
O. Hen et al., Science 346, 614 (2014)

np fractions extracted from (e,e'p) & (e,e'pp) events

No neutrons detection

Experimental Setup

CLAS Detector @ JLab



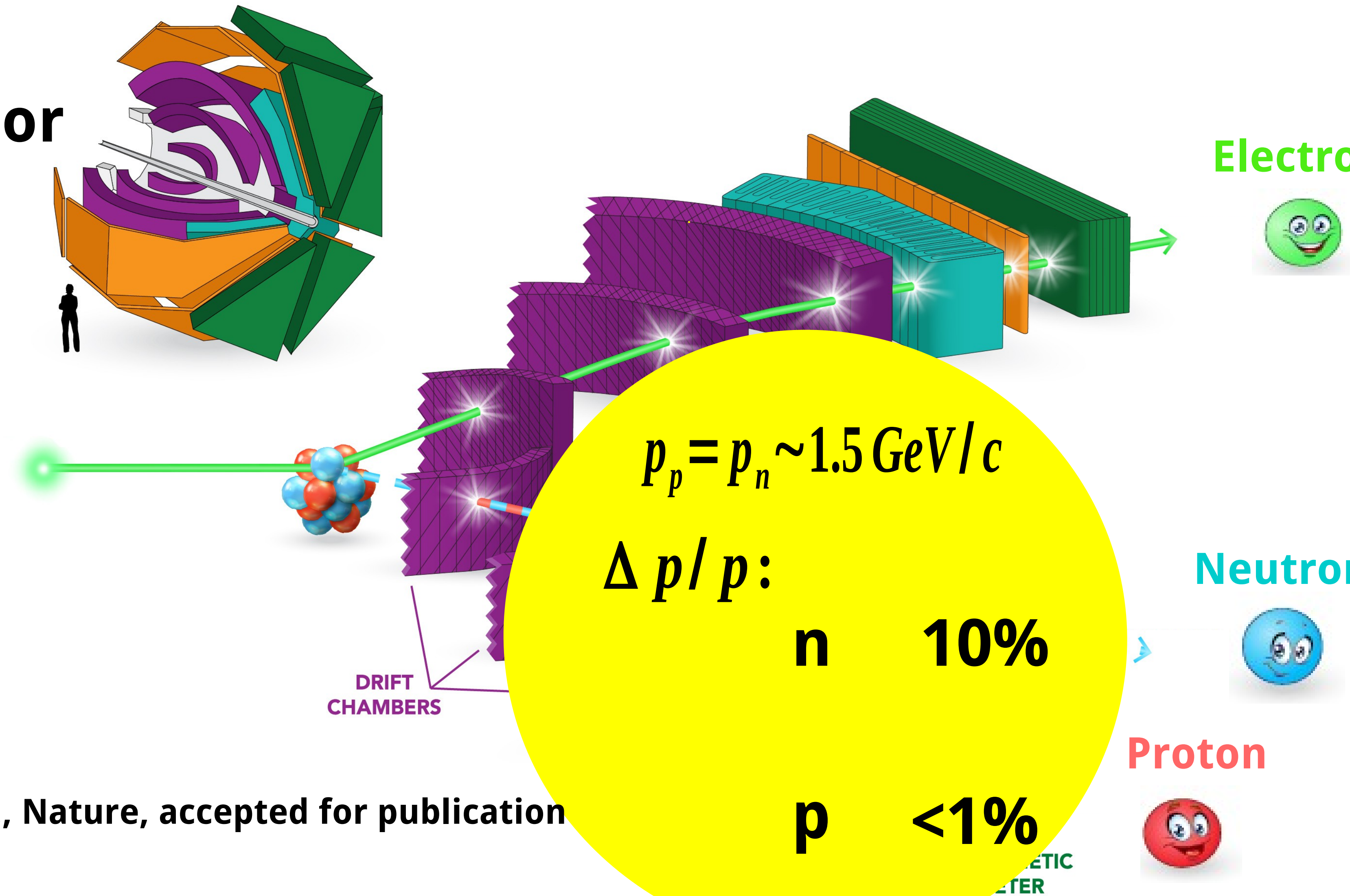
Duer et al., Nature, accepted for publication

El Fassi, Phys. Lett B 712, (2012)   Hen, Science 346, 614 (2014)

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

Experimental Setup

CLAS Detector @ JLab



$$p_p = p_n \sim 1.5\, GeV/c$$

$\Delta p/p$:

n 10%

p <1%

Duer et al., Nature, accepted for publication

El Fassi, Phys. Lett B 712, (2012) Hen, Science 346, 614 (2014)

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

Probing high-momentum protons and neutrons in asymmetric nuclei

Using (e,e'p) & (e,e'n) reactions

The selected cuts:

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

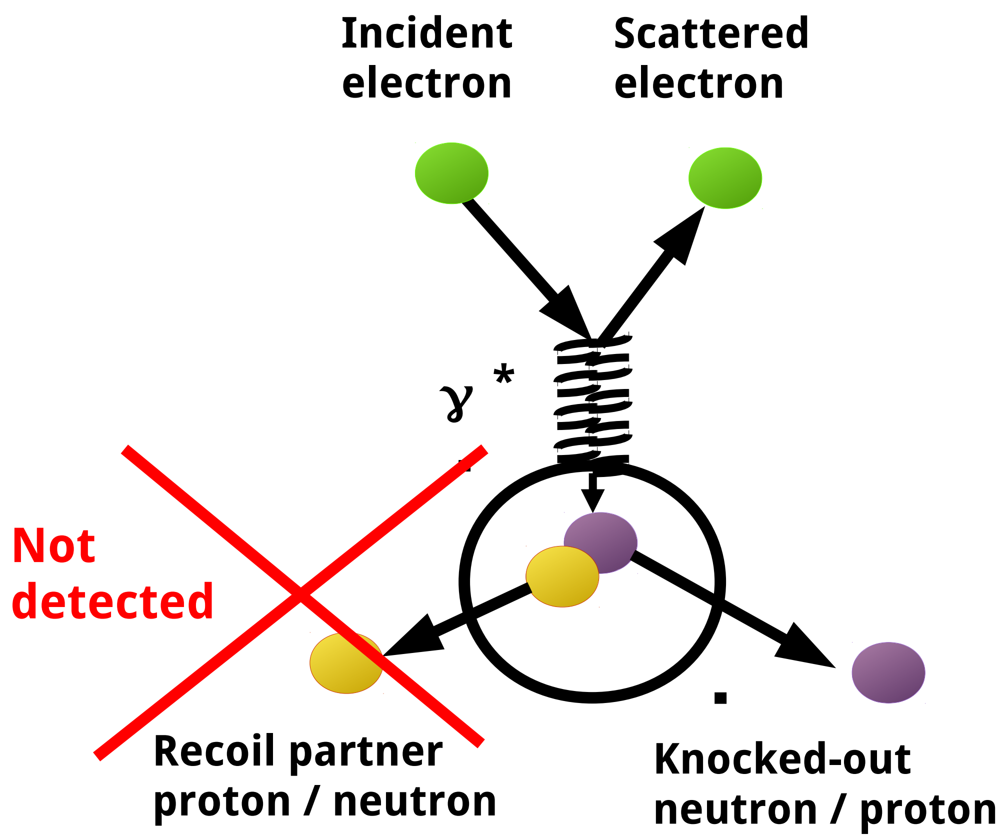
$$0.4 \leq P_{miss} \leq 1\, GeV/c, \qquad M_{miss} \leq 1.175\, GeV/c^2$$

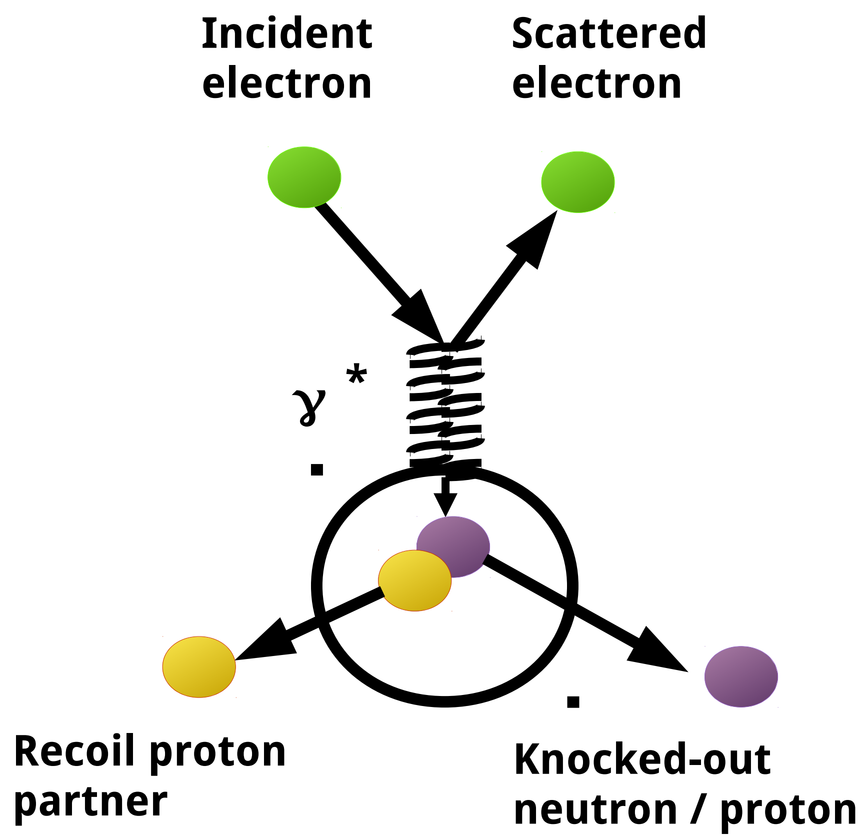
Duer et al., Nature, accepted for publication

(e,e'n) & (e,e'p) → (e,e'np) & (e,e'pp)

Double coincidence

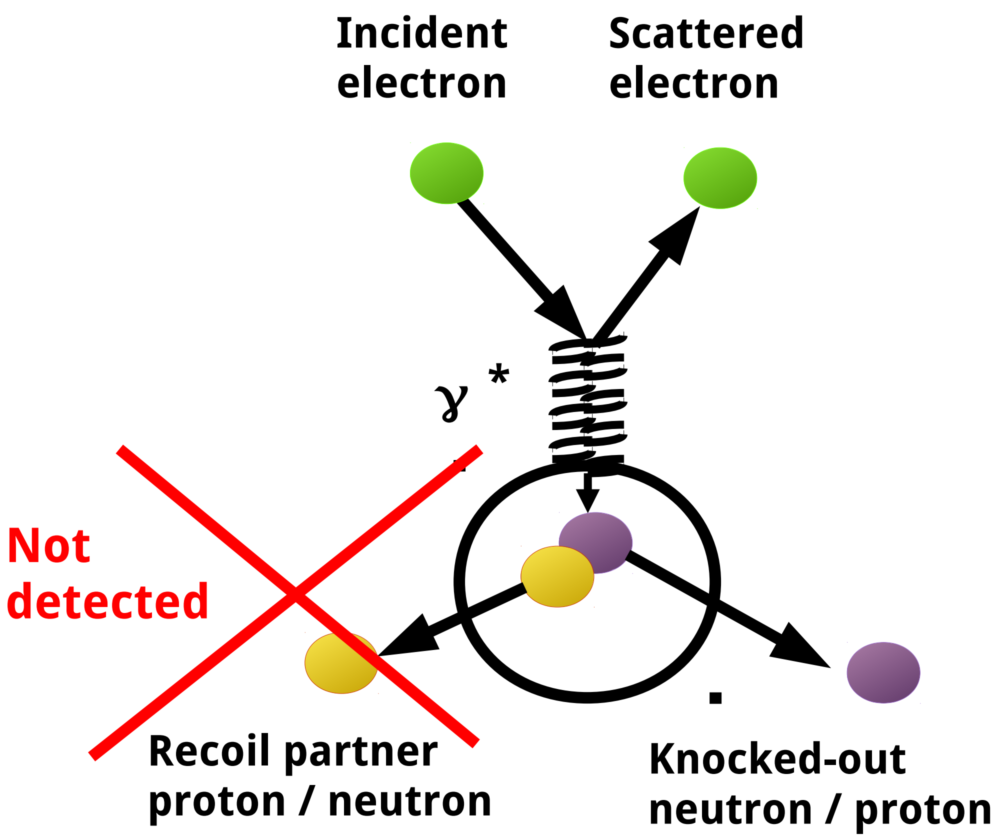
Triple coincidence



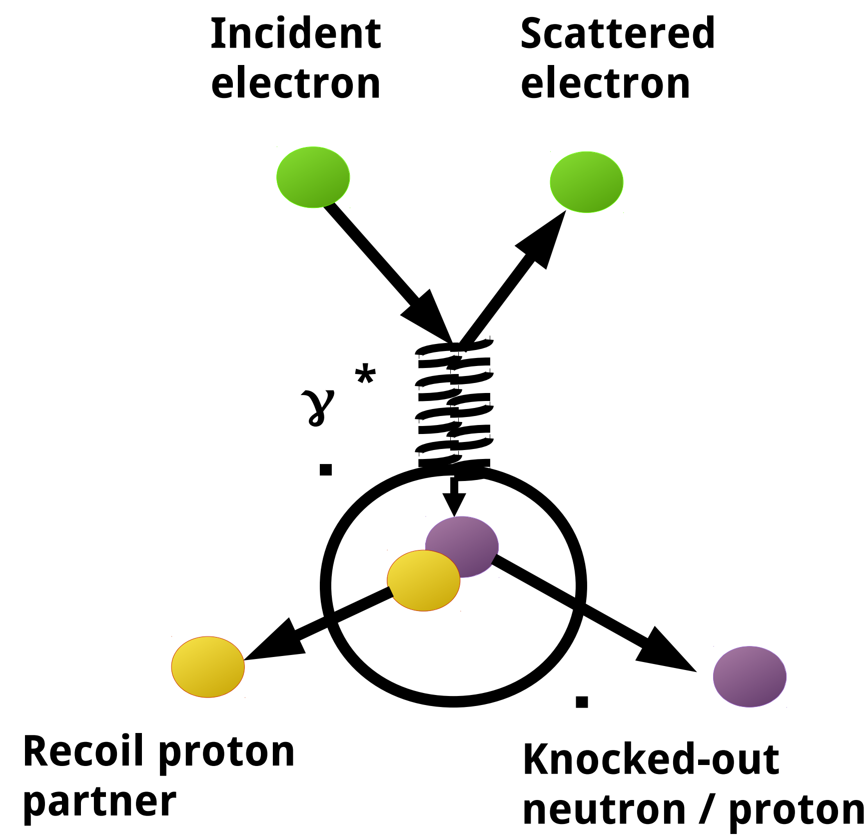


(e,e'n) & (e,e'p) → (e,e'np) & (e,e'pp)

Double coincidence



Triple coincidence



(e,e'np) & (e,e'pp): all cuts used for (e,e'n) & (e,e'p) +

high momentum recoil proton $(|\vec{P}_{recoil}| > 0.35\, GeV/c)$

and energy deposit cut on it

Estimate C(e,e'pp)/C(e,e'np) ratio

$$\frac{\#pp}{\#np} \sim \frac{2 \times 2.5}{18 \times 1/3} \sim 1$$

np-dominance

Estimate C(e,e'pp)/C(e,e'np) ratio

$$\frac{\#pp}{\#np} \sim \frac{2 \times 2.5}{18 \times 1/3} \sim 1$$

np-dominance

n-efficiency

Estimate C(e,e'pp)/C(e,e'np) ratio

Leading p vs. leading n

$$\frac{\#pp}{\#np} \sim \frac{2 \times 2.5}{18 \times 1/3} \sim 1$$

np-dominance

n-efficiency

Estimate C(e,e'pp)/C(e,e'np) ratio

Leading p vs. leading n

p & n cross-sections ratio

$$\frac{\#pp}{\#np} \sim \frac{2 \times 2.5}{18 \times 1/3} \sim 1$$

np-dominance

n-efficiency

Estimate C(e,e'pp)/C(e,e'np) ratio

Leading p vs. leading n

p & n cross-sections ratio

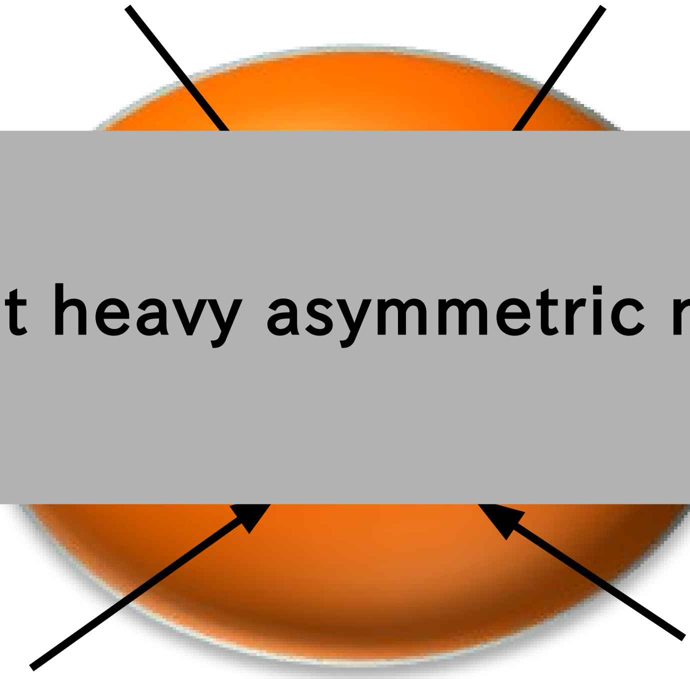
$$\frac{\#pp}{\#np} \sim \frac{2 \times 2.5}{18 \times 1/3} \sim 1$$

np-dominance

n-efficiency

#np=186 #pp=173

Estimate C(e,e'pp)/C(e,e'np) ratio

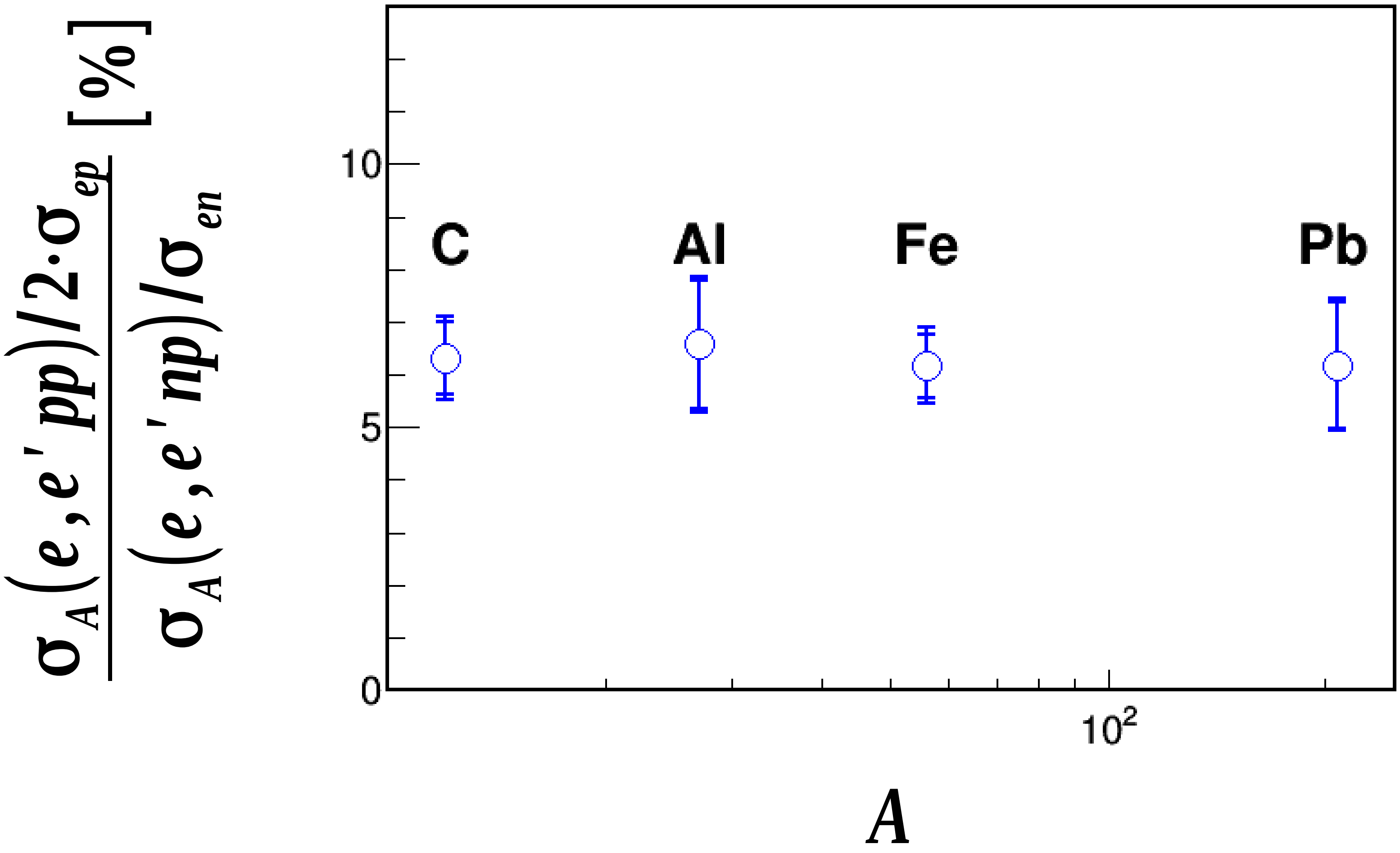


What about heavy asymmetric nuclei?

#np=186 #pp=173

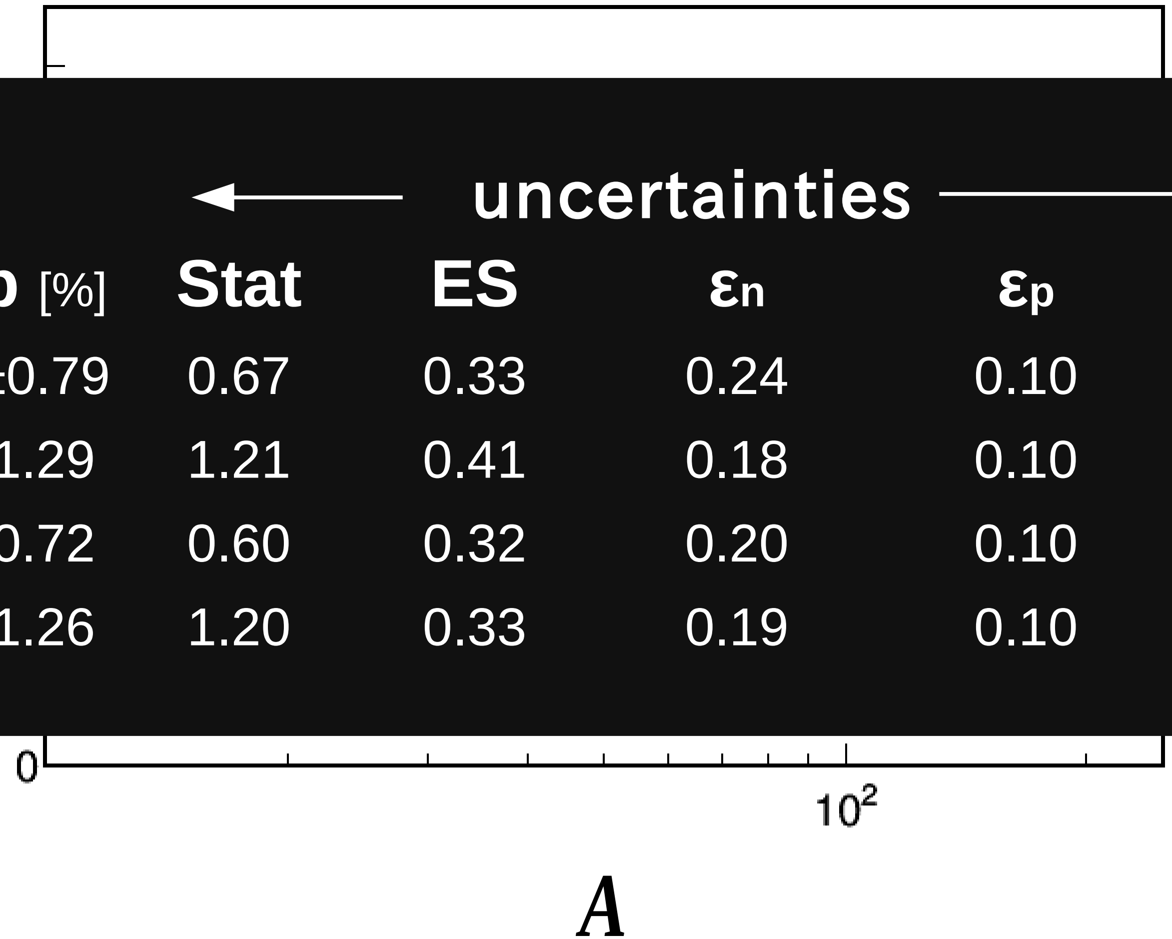
Direct Observation of np-Dominance

A(e,e'pp)/A(e,e'np) ratios



Direct Observation of np-Dominance

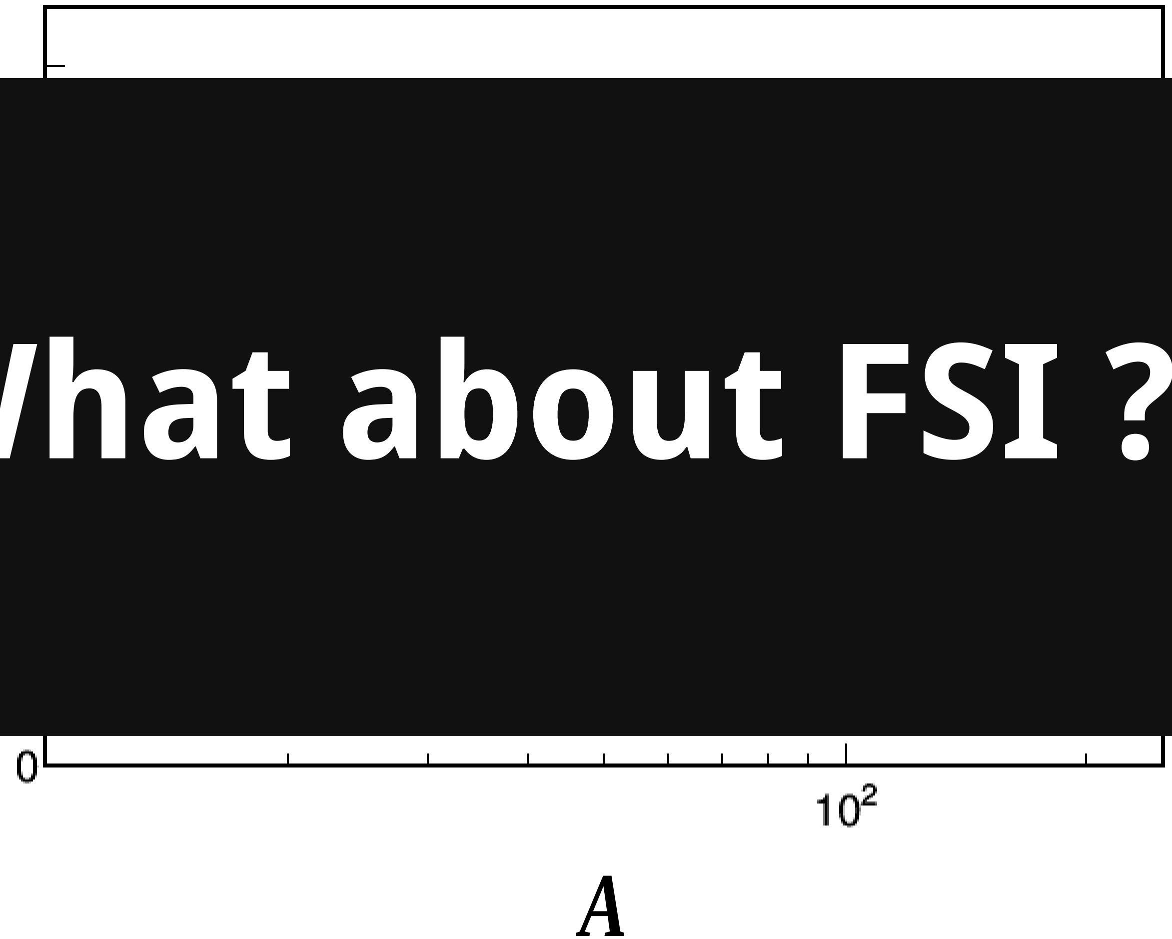
A(e,e'pp)/A(e,e'np) ratios



		← uncertainties →				
Nuclei	**pp/np** [%]	**Stat**	**ES**	**ε_n**	**ε_p**	**T**
C	6.31±0.79	0.67	0.33	0.24	0.10	--
Al	6.57±1.29	1.21	0.41	0.18	0.10	--
Fe	6.17±0.72	0.60	0.32	0.20	0.10	--
Pb	6.19±1.26	1.20	0.33	0.19	0.10	0.06

Direct Observation of np-Dominance

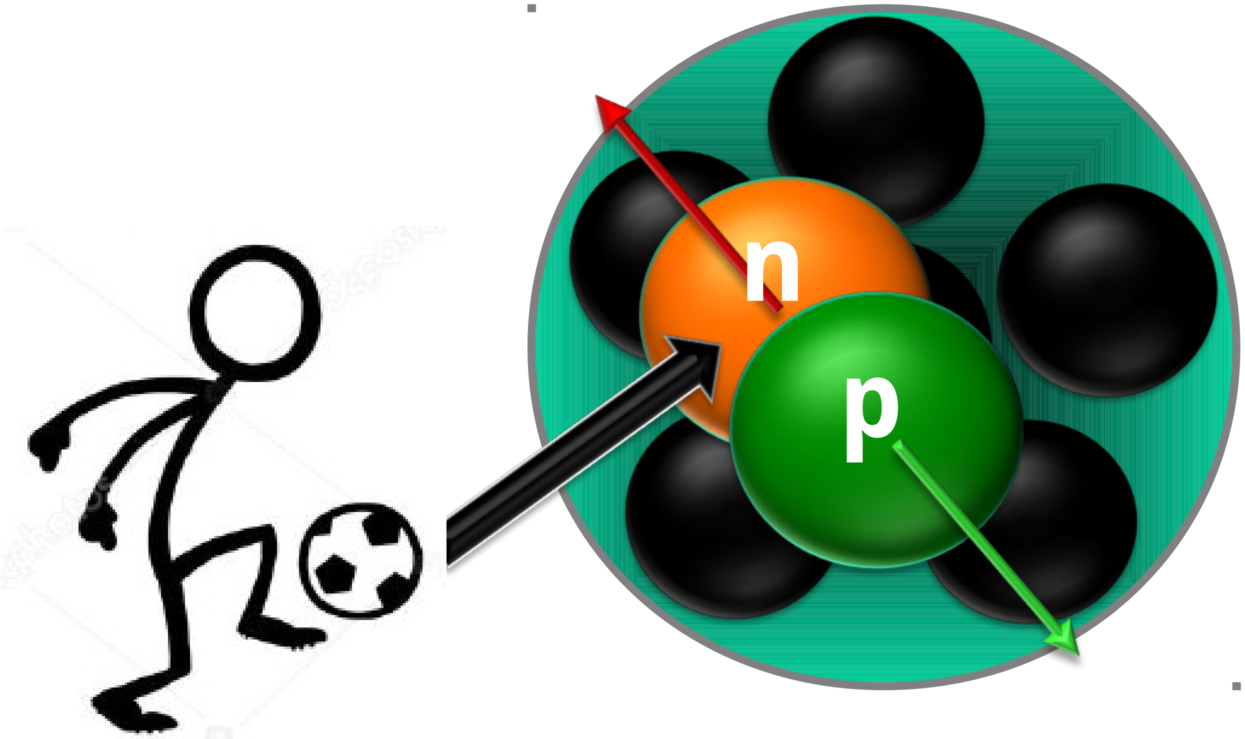
A(e,e'pp)/A(e,e'np) ratios



What about FSI ?

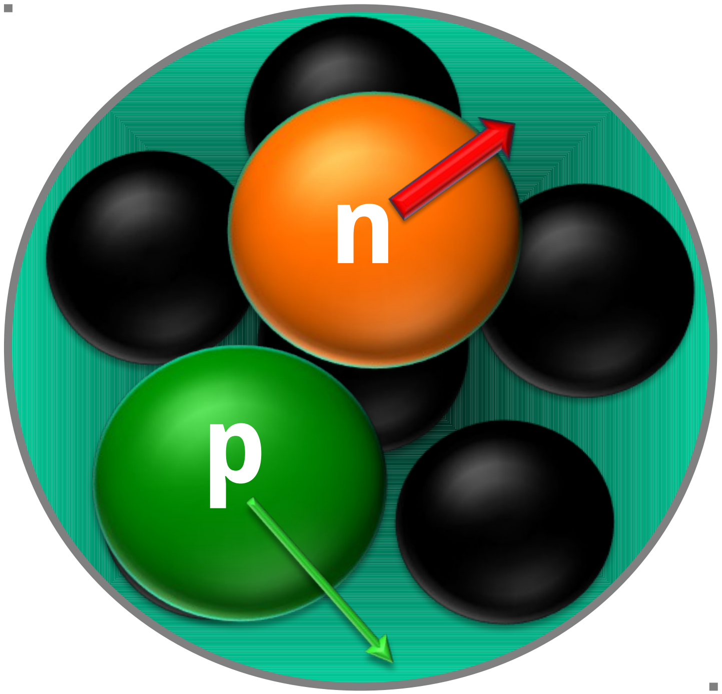
Single Charge Exchange (SCX)

np → pp



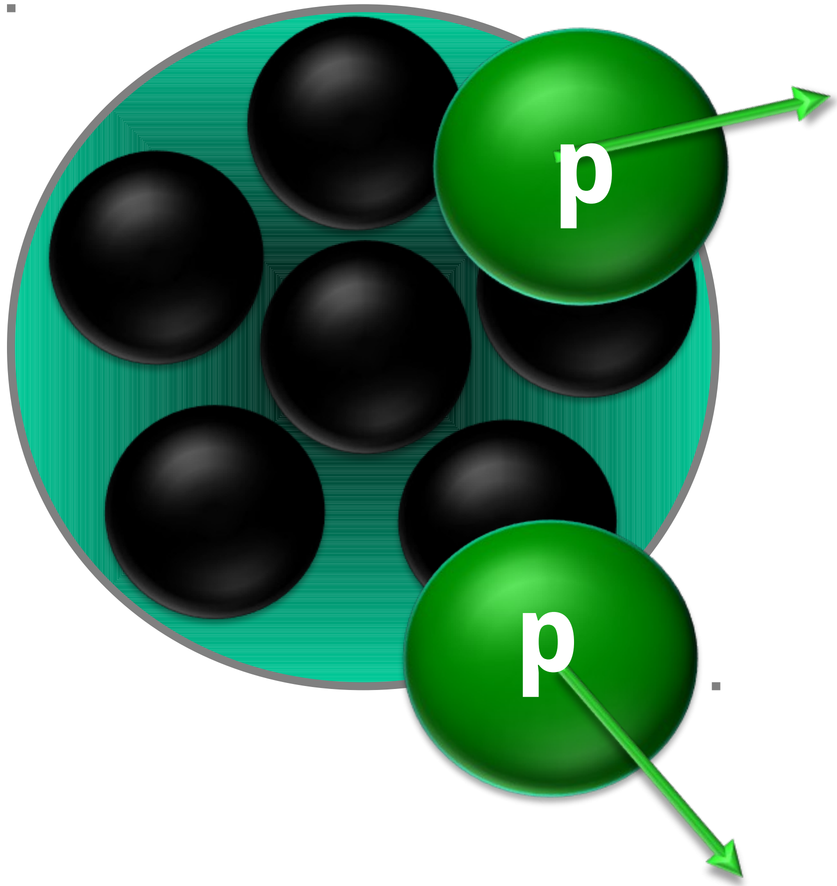
Single Charge Exchange (SCX)

np → pp



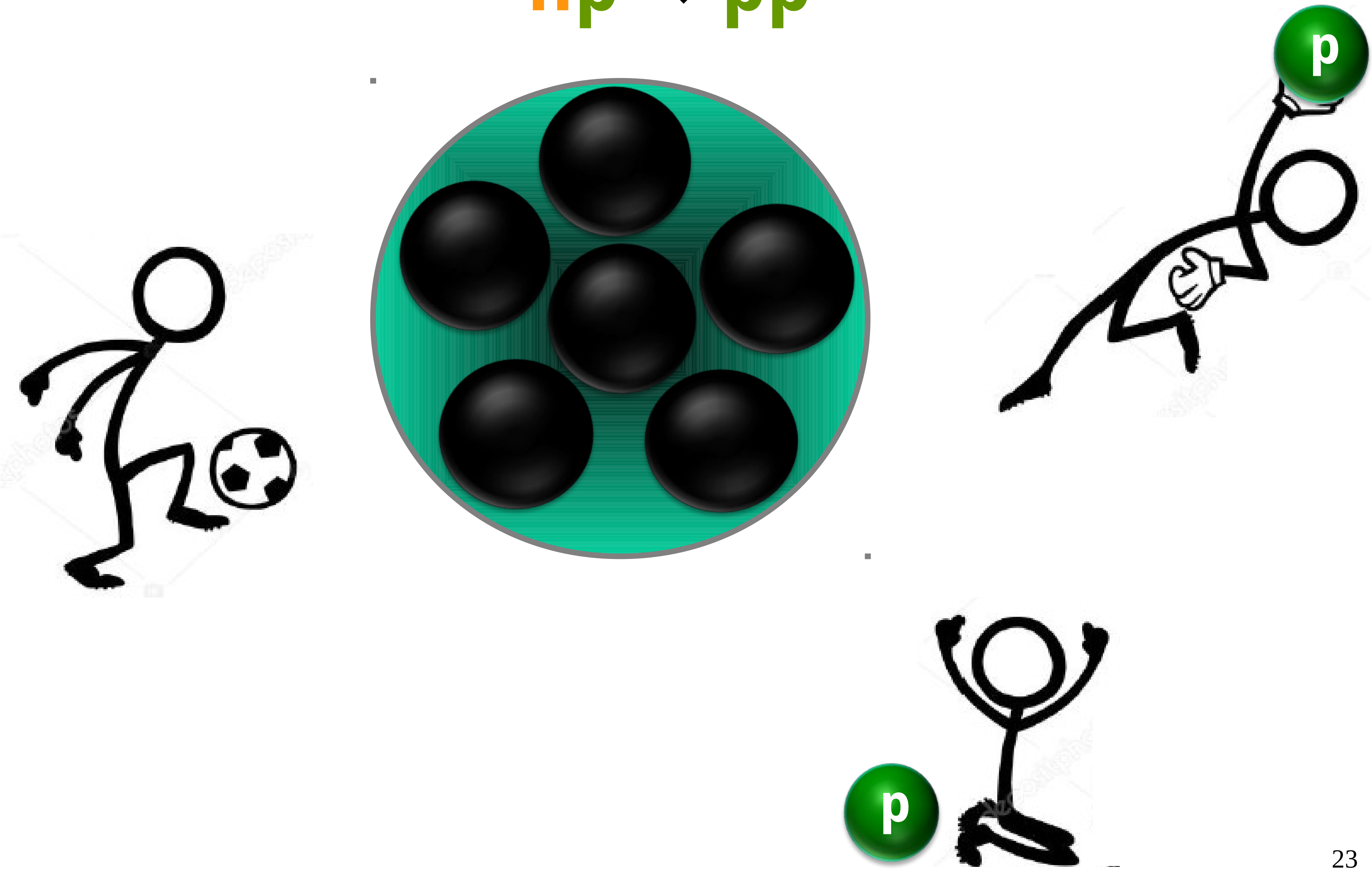
Single Charge Exchange (SCX)

np → pp



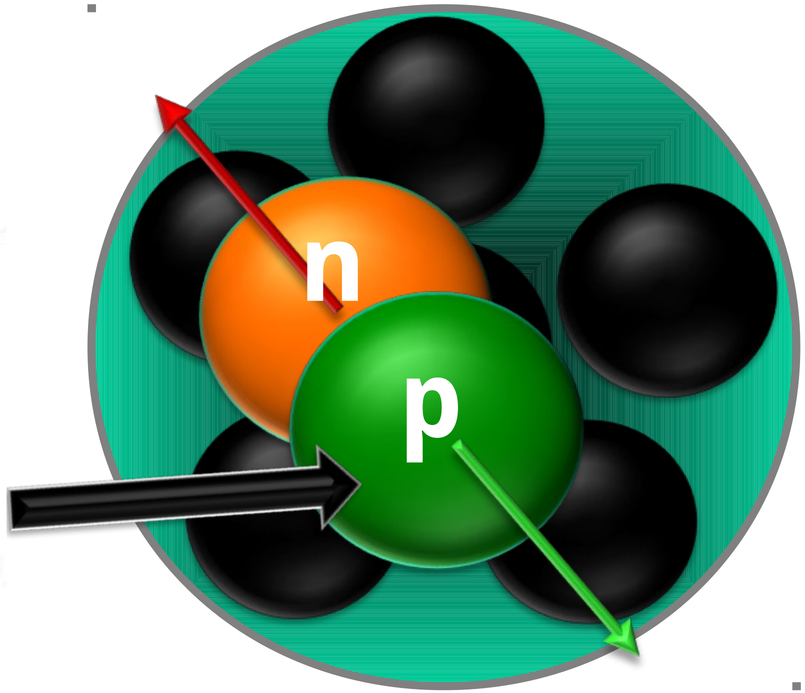
Single Charge Exchange (SCX)

np → pp



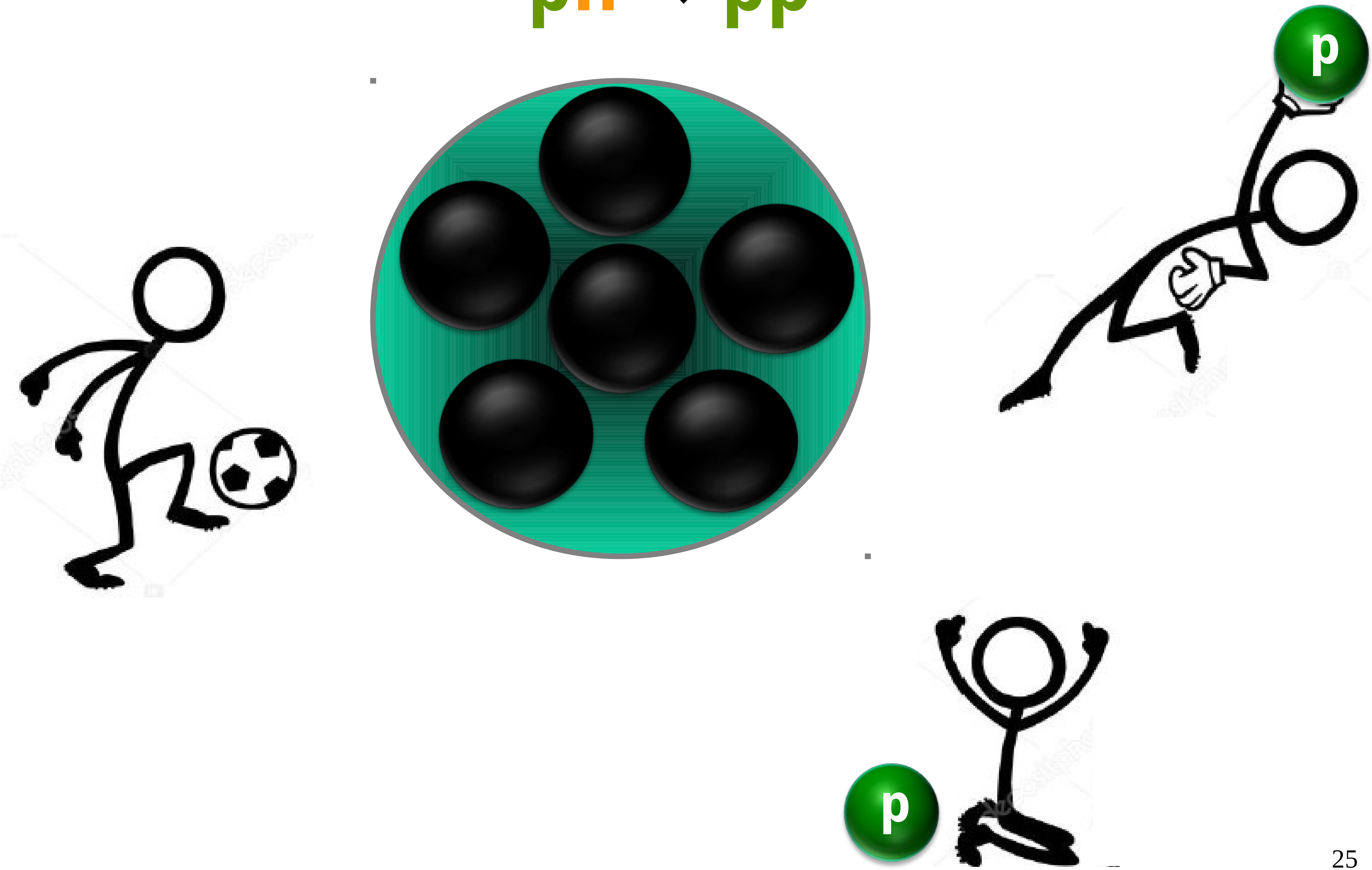
Single Charge Exchange (SCX)

pn → pp



Single Charge Exchange (SCX)

pn → pp



Single Charge Exchange (SCX)

np

$P^{[p]p}$ p p → n p

$P^{n[n]}$ n n → n p

P^{np} n p → n p

pp

$P^{[n]p}$ n p → p p

$P^{p[n]}$ p n → p p

P^{pp} p p → p p

A(e,e'pp) & A(e,e'np)

$$A\left(e,e'pp\right) = \# pp \cdot \underbrace{2 \cdot \sigma_{ep} \cdot P^{pp} \cdot T_{pp}}_{\text{'real' pp}}$$

$$A\left(e,e'np\right) = \# np \cdot \underbrace{\sigma_{en} \cdot P^{np} \cdot T_{np}}_{\text{'real' np}}$$

A(e,e'pp) & A(e,e'np)

$$A(e,e'pp)=\overbrace{\#pp\cdot 2\cdot\sigma_{ep}\cdot P^{pp}\cdot T_{pp}}^{\text{'real' pp}}+\overbrace{\#np\cdot\sigma_{en}\cdot P^{[n]p}\cdot T^{*}+\#pn\cdot\sigma_{ep}\cdot P^{p[n]}\cdot T^{*}}^{\text{SCX}}$$

$$T^{*}=\frac{1}{2}\cdot\left(T_{pp}+T_{np}\right)=T_{pp}=T_{np}$$

$$A(e,e'pp)=\overbrace{\#np\cdot\sigma_{en}\cdot P^{np}\cdot T_{np}}^{\text{'real' np}}$$

A(e,e'pp) & A(e,e'np)

$$A(e,e'pp) = \underbrace{\#pp \cdot 2 \cdot \sigma_{ep} \cdot P^{pp} \cdot T_{pp}}_{\text{'real' pp}} + \underbrace{\#np \cdot \sigma_{en} \cdot P^{[n]p} \cdot T^{*} + \#pn \cdot \sigma_{ep} \cdot P^{p[n]} \cdot T^{*}}_{\text{SCX}}$$

$$T^{*} = \frac{1}{2} \cdot \left(T_{pp} + T_{np}\right) = T_{pp} = T_{np}$$

$$A(e,e'np) = \underbrace{\#np \cdot \sigma_{en} \cdot P^{np} \cdot T_{np}}_{\text{'real' np}} + \underbrace{\#pp \cdot 2 \cdot \sigma_{ep} \cdot P^{[p]p} \cdot T^{*} + \#nn \cdot 2 \cdot \sigma_{en} \cdot P^{n[n]} \cdot T^{*}}_{\text{SCX}}$$

$$\#pp < \#nn < \frac{N(N-1)}{Z(Z-1)} \cdot \#pp$$

(Combinatorial ratio)

Extracting pp/np ratios

$$\sigma_{p/n} = \frac{\sigma_{ep}}{\sigma_{en}}$$

$$\frac{\#pp}{\#np} = \frac{1}{2} \cdot \frac{2 \cdot R \cdot P^{np} - P^{[n]p} - P^{p[n]} / \sigma_{p/n}}{P^{pp} - 2 \cdot \sigma_{p/n} \cdot R \cdot P^{[p]p} - 2 \cdot R \cdot \eta \cdot P^{n[n]}}$$

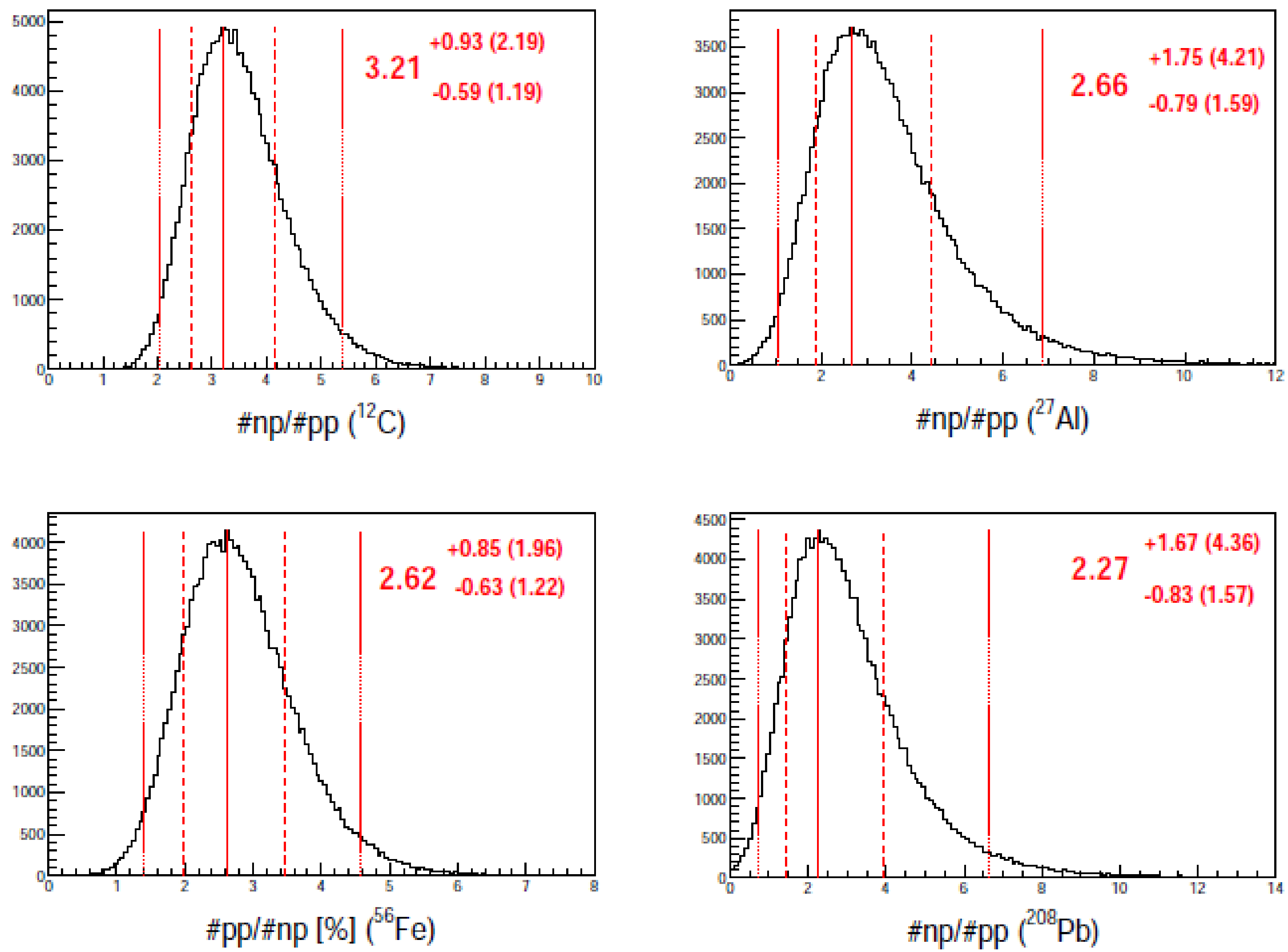
$$R = \frac{A(e,e'pp)/2 \cdot \sigma_{ep}}{A(e,e'np)/\sigma_{en}}$$

$$\eta = \frac{\#nn}{\#pp}$$

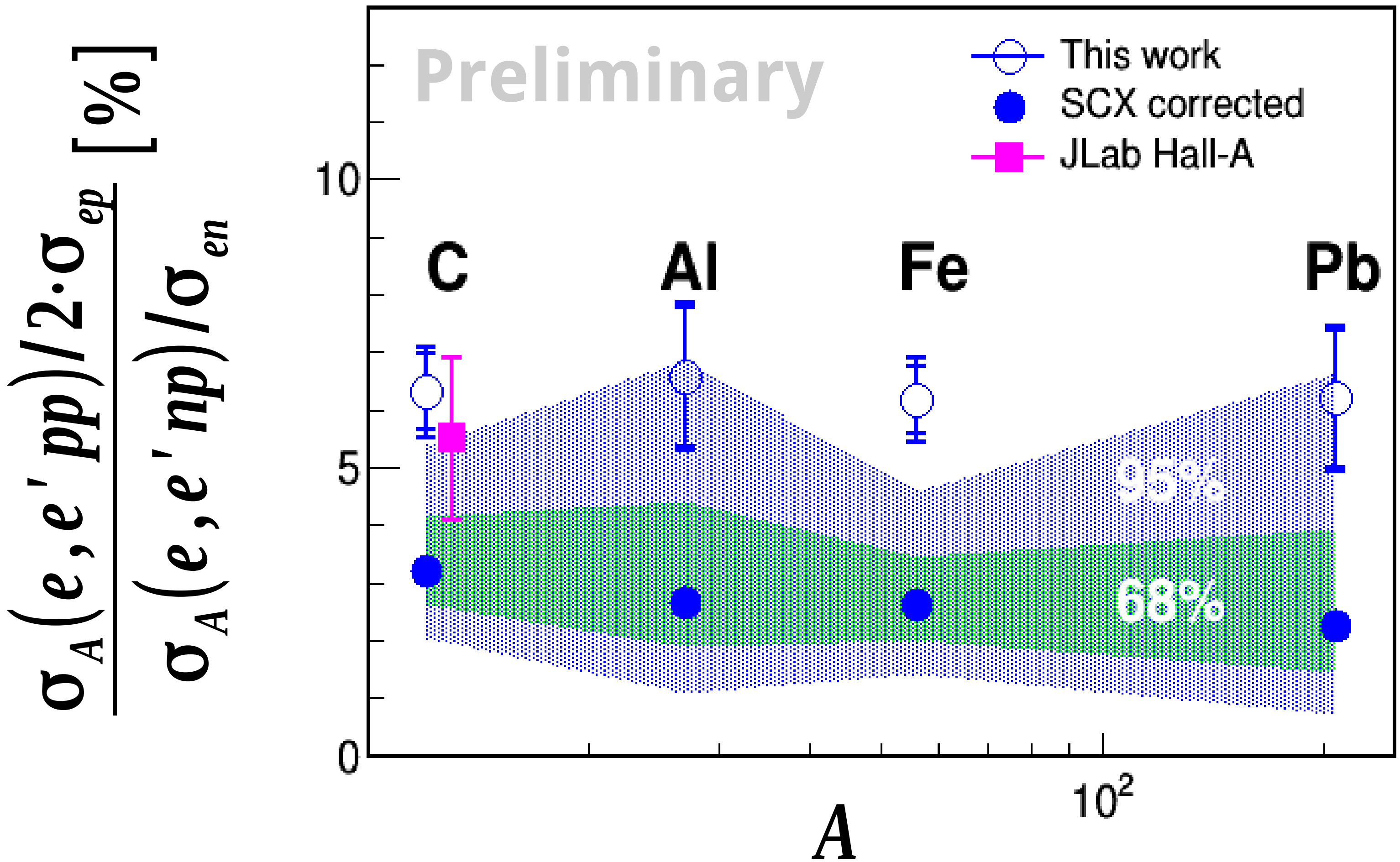
SCX probabilities, Ref. [1], change between ~ 3 – 7 % from C to Pb

[1] C. Colle, W. Cosyn, and J. Ryckebusch, Phys. Rev. C93, 034608 (2016).

Extracting pp/np ratios



Direct Observation of np-Dominance
A(e,e'pp)/A(e,e'np) ratios

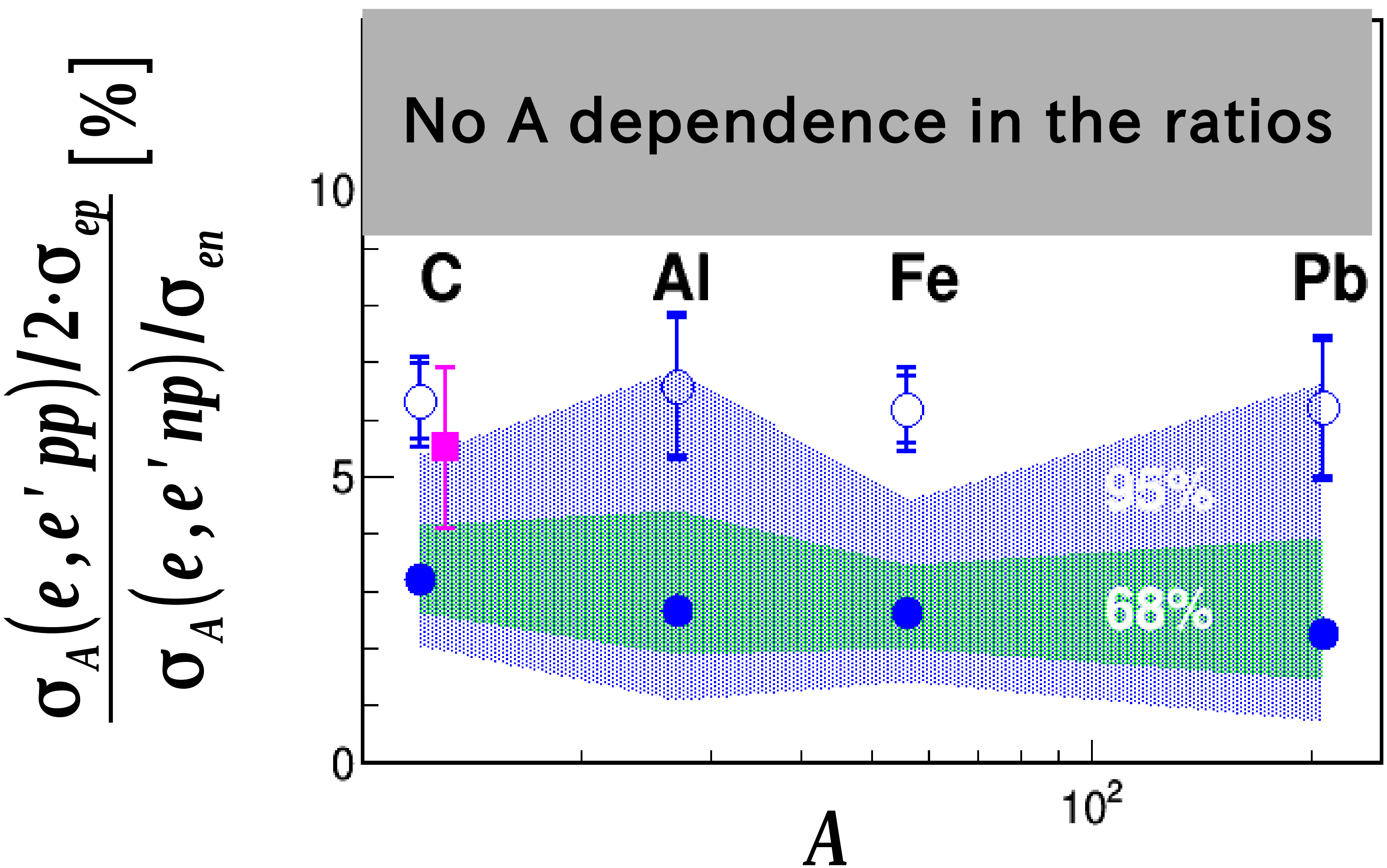


Subedi, Science 320 (2008)

SCX correction: C. Colle, W. Cosyn, Phys. Rev. C 93, 034608 (2016).

Direct Observation of np-Dominance

A(e,e'pp)/A(e,e'np) ratios

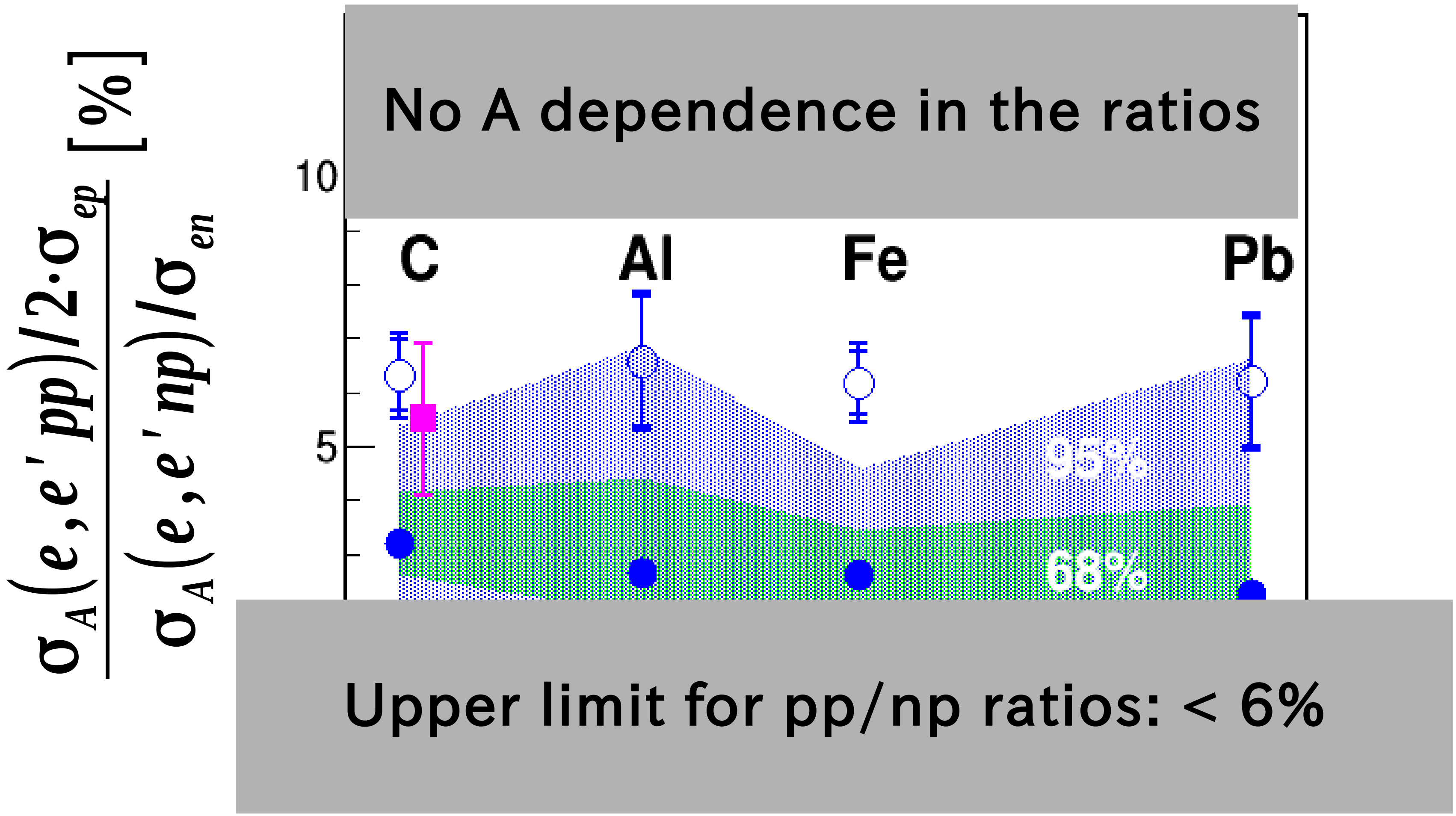


Subedi, Science 320 (2008)

SCX correction: C. Colle, W. Cosyn, Phys. Rev. C 93, 034608 (2016).

Direct Observation of np-Dominance

A(e,e'pp)/A(e,e'np) ratios



Subedi, Science 320 (2008)

SCX correction: C. Colle, W. Cosyn, Phys. Rev. C 93, 034608 (2016).

Analysis Status

Analysis review committee - Done

Paper draft (to be submitted for PRL)

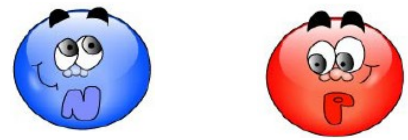
Observation of Proton-Neutron Short-Range Correlation Dominance in Heavy Nuclei via A(e,e'np) and A(e,e'pp) Reactions
or
Direct Observation of Proton-Neutron Short-Range Correlation Dominance in Heavy Nuclei

M. Duer,[1] O. Hen,[2,*] E. Piasetzky,[1] L.B. Weinstein,[3] A. Schmidt,[2] E. O. Cohen,[1] I. Korover,[1] and H. Hakobyan[4]
(The CLAS Collaboration)
[1]*School of Physics and Astronomy, Tel Aviv University, Tel Aviv 69978, Israel*
[2]*Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA*
[3]*Old Dominion University, Norfolk, Virginia 23529*
[4]*Universidad Técnica Federico Santa María, Casilla 110-V Valparaíso, Chile*

We measured the triple coincidence $A(e,e'np)$ and $A(e,e'pp)$ reactions on carbon, aluminum, iron, and lead targets using a 5.01 GeV electron beam and the CEBAF Large Acceptance Spectrometer (CLAS) at the Thomas Jefferson National Accelerator Facility. The measurement was done at $Q^2 > 1.5$ (GeV/c)^2, $x_B > 1$ and missing-momentum > 350 MeV/c, corresponding to the hard breakup of two-nucleon short-range correlated pairs (2N-SRC). The knocked-out neutrons or protons and scattered electrons were detected in coincidence with a proton recoiling almost back to back to the missing momentum, leaving the residual $A-2$ system at low momentum. Using these data we directly verified, for the first time on neutron rich nuclei, that the number of proton-proton SRC pairs is smaller than the number of neutron-proton SRC pairs by about a factor of 20, independent of the neutron excess in the nucleus.

Ad-hoc committee for the paper – Pending

Thank you!



Acknowledgment

Analysis review committee

Data-Mining collaboration

CLAS collaboration

OLD DOMINION UNIVERSITY

Massachusetts Institute of Technology

Jefferson Lab

EX UMBRA IN SOLEM

UNIVERSIDAD TECNICA FEDERICO SANTA MARIA

Backup Slides

Momentum sharing in asymmetric nuclei

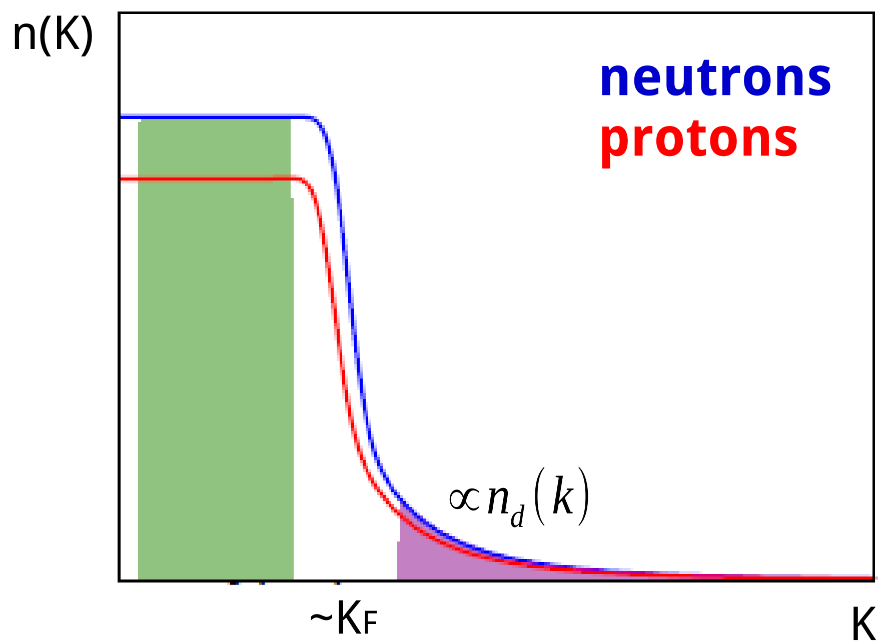
Pauli principle

$$\langle E_n^{kin} \rangle > \langle E_p^{kin} \rangle$$

SRC (np-dominance)

$$\langle E_p^{kin} \rangle \overset{?}{>} \langle E_n^{kin} \rangle$$

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



N>Z

Possible inversion of the momentum sharing

Momentum sharing in asymmetric nuclei

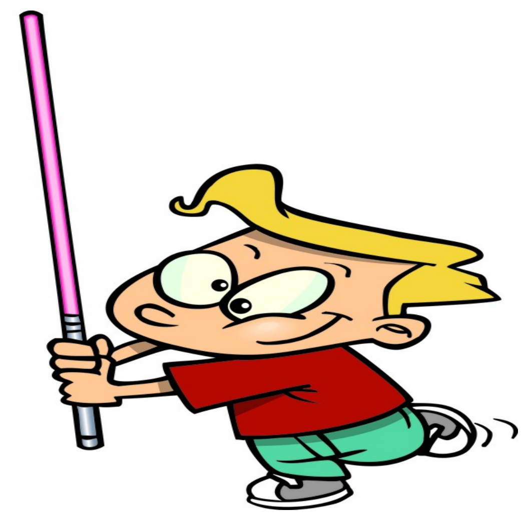
Pauli principle

$$\langle E_n^{kin} \rangle > \langle E_p^{kin} \rangle$$

SRC

$$\langle E_p^{kin} \rangle \overset{?}{>} \langle E_n^{kin} \rangle$$

vs



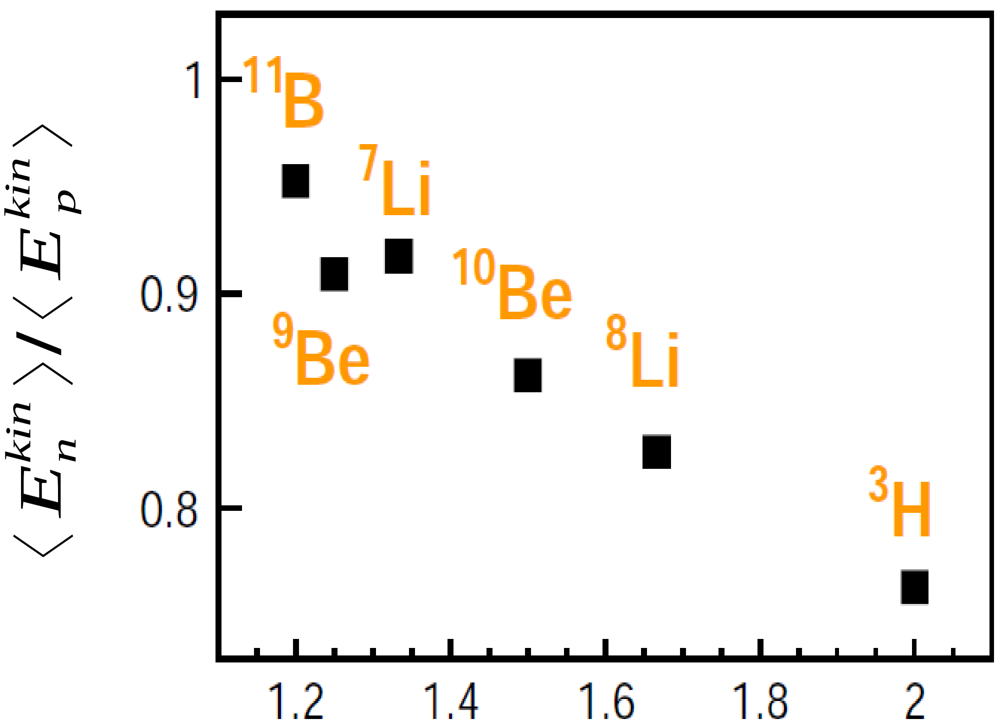
Who wins?

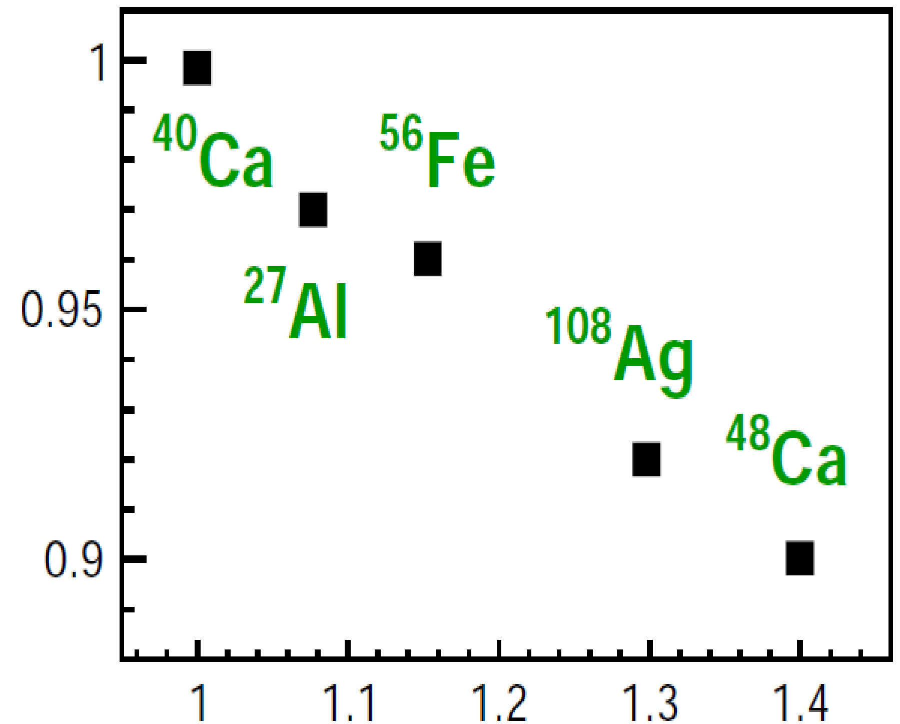
Possible inversion of the momentum sharing

Theoretical predictions (N>Z)

Light nuclei (A<12)

Heavy nuclei (A>12)





Neutron Excess [N/Z]

Z>N:

^{3}He **N/Z =1/2** $\langle E_n^{kin} \rangle / \langle E_p^{kin} \rangle = 1.31$

Wiringa, Phys. Rev. C89, 024305 (2014)

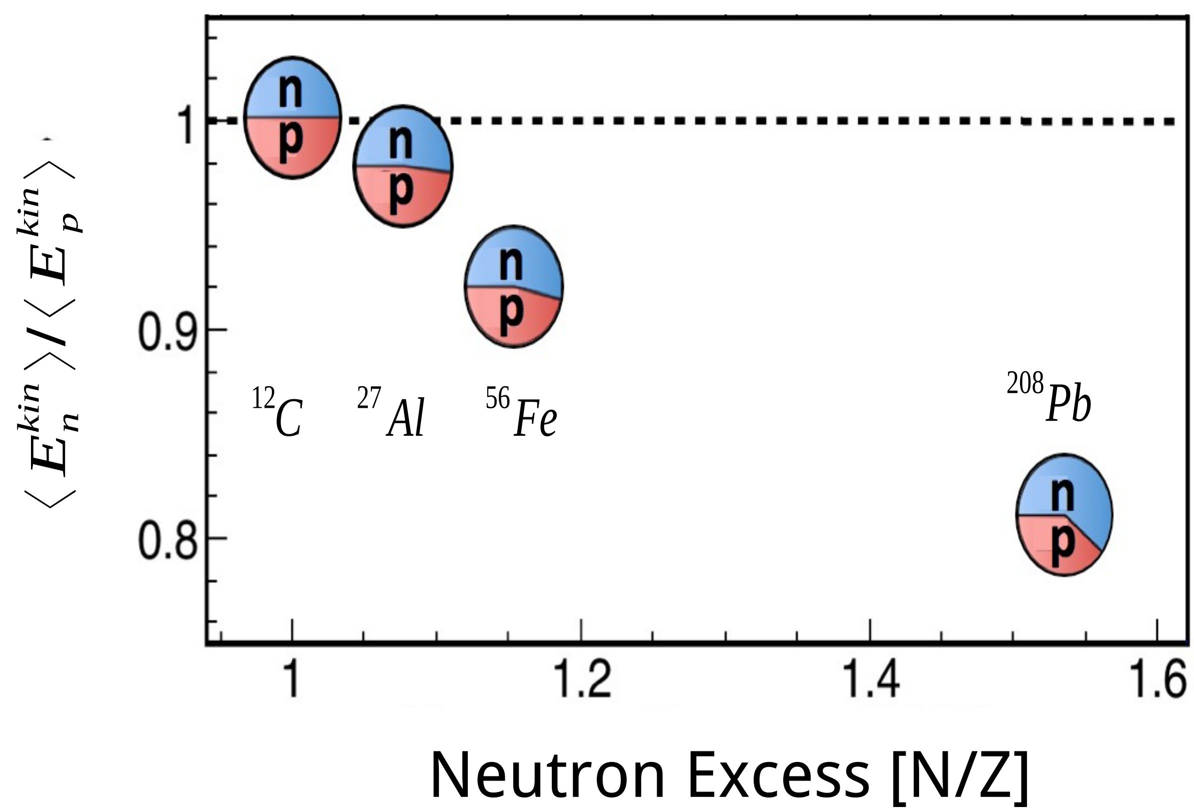
Ryckebusch, J. Phys G42 (2015)

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)

Duer et al., Nature, accepted for publication   Sargsian PRC 89 (2014)   Hen et al., Science 346 (2014)



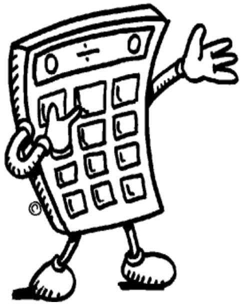
k_0: 300 MeV/c, k_F

$n^{M.F.}(k)$: Wood-Saxon
Serot- Walecka
Ciofi & Simula

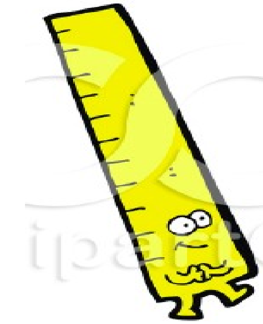
$n_d(k)$: AV18 NN potential

$a_2(A/d)$: Scaling factor

η determined by: $\int n_{p(n)}(k) d^3k = 1$



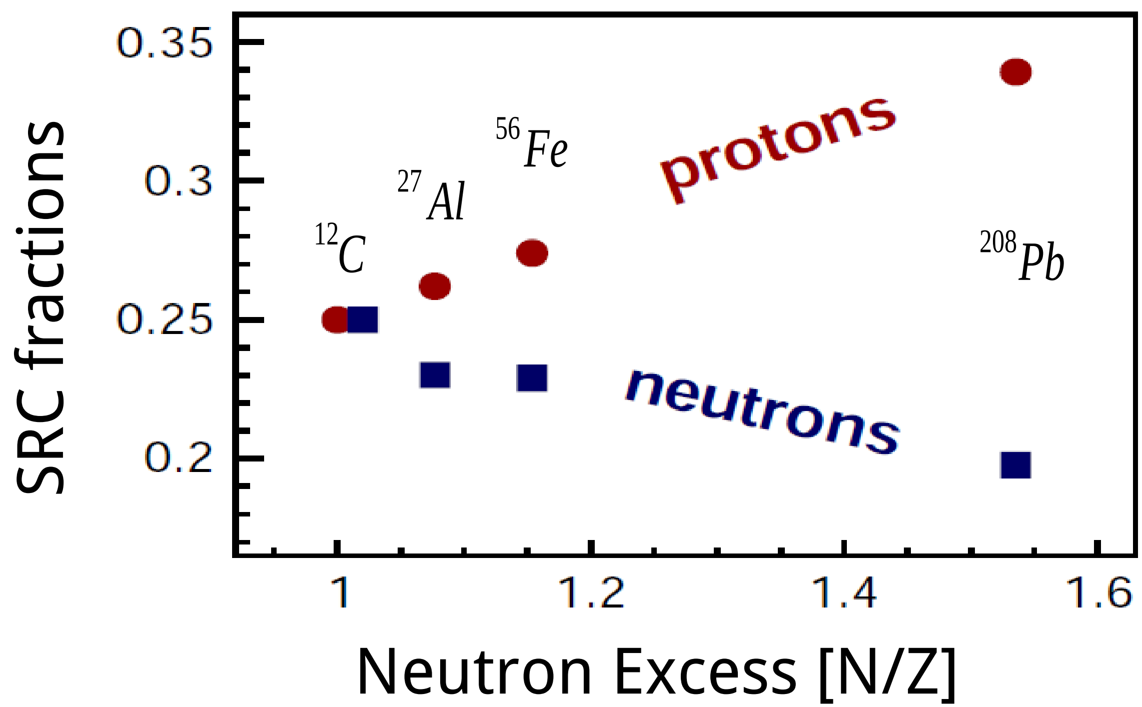
Calculation ⟶ Measurement



Simple estimate based on np-dominance

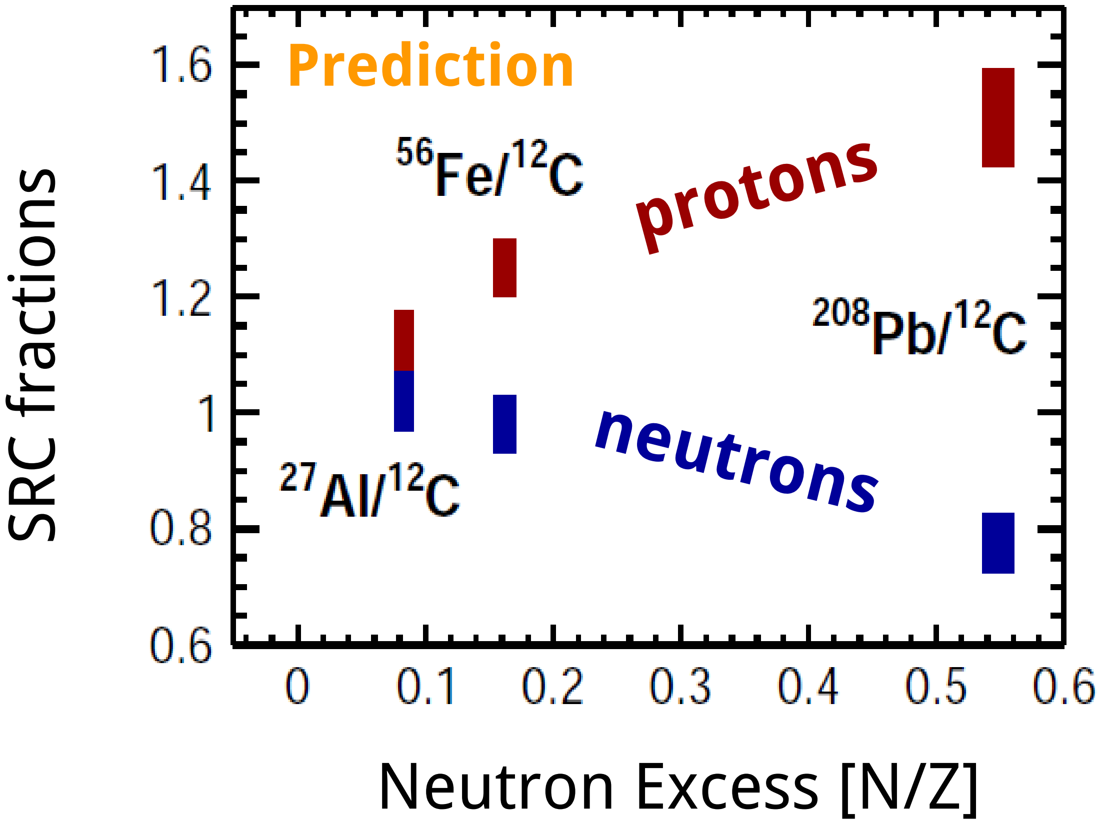
$^{208}Pb: \quad Z = 82 \quad N = 126$ **SRC=20%**

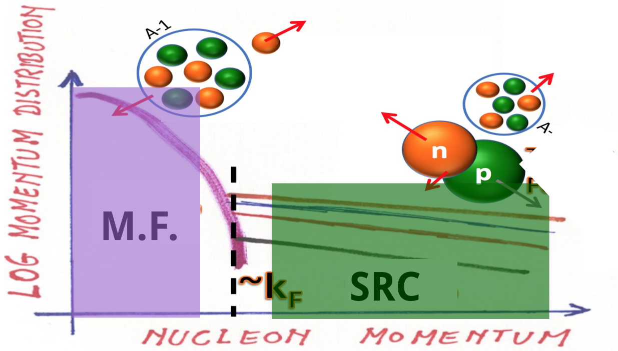
$$R_p = \frac{protons_{k>k_F}}{protons_{k<k_F}} \approx \frac{20}{82-20} = 0.32 \qquad R_n = \frac{neutrons_{k>k_F}}{neutrons_{k<k_F}} \approx \frac{20}{126-20} = 0.19$$



The goal:

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

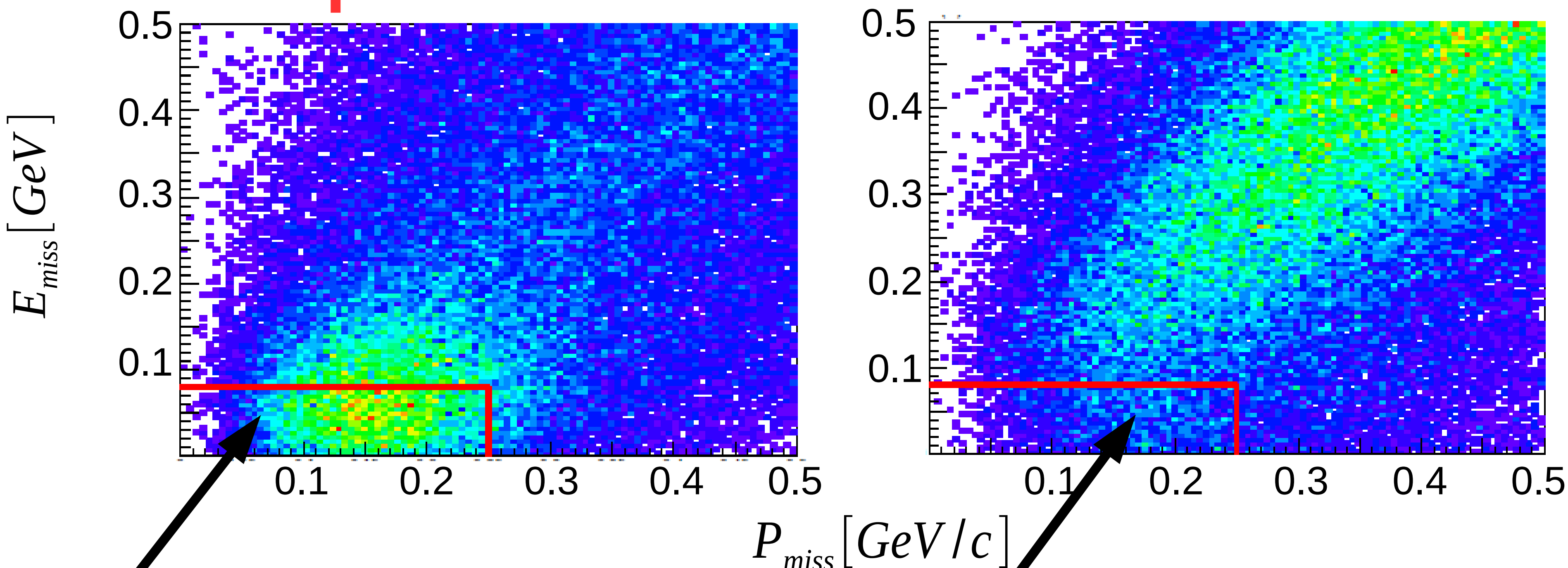




Selecting M.F. QE events

$$\vec{p}_{miss} = \vec{p}_N - \vec{q} \qquad E_{miss} = \omega - T_N - T_B$$

protons **neutrons**



QE peak:

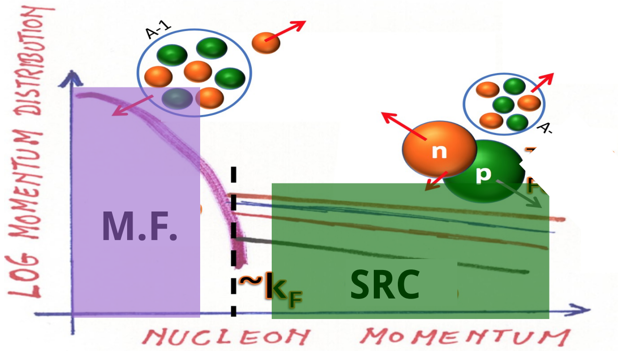
$P_{miss}<0.25$ GeV/c
$E_{miss}<0.08$ GeV

Problem:

Poor resolution in the EC -

$$\Delta P \approx 0.1 GeV/c$$

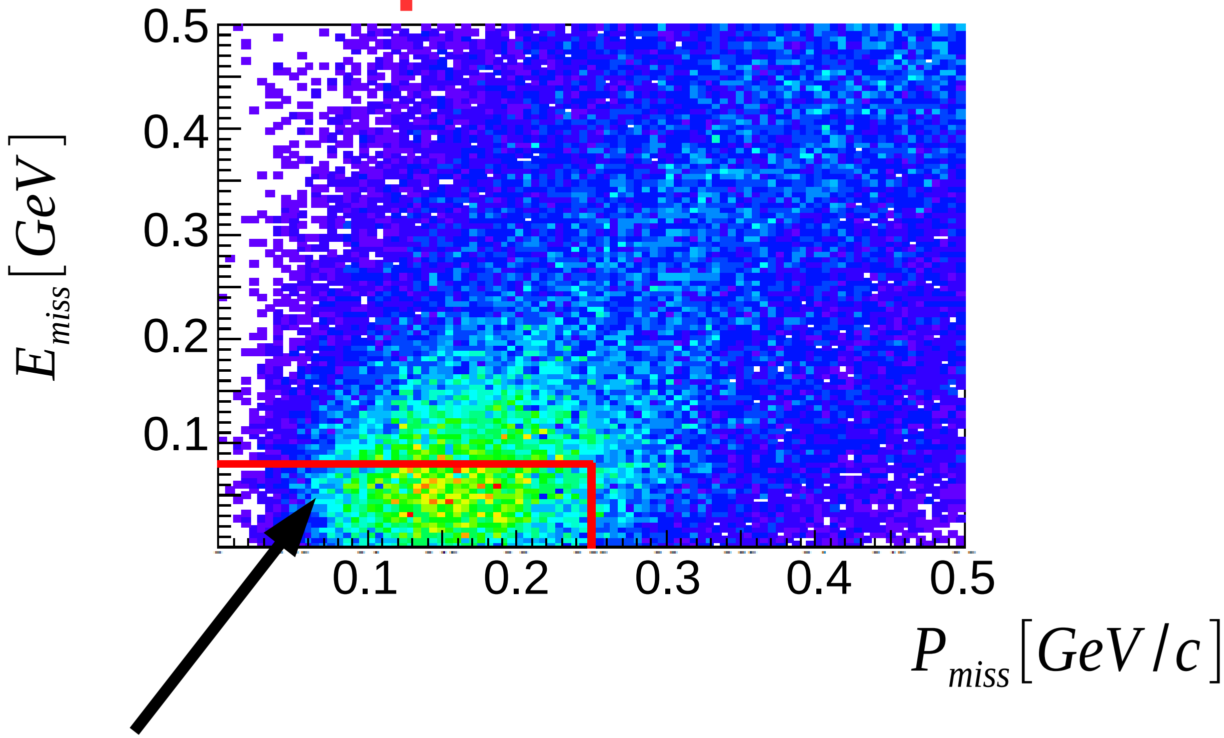
Oneill et al., Phys. Lett. B 87 (1995), Abbott et al. Phys. Rev. Lett. 80 (1998), Garrow et al. Phys. Rev. C. 66 (2002)



Selecting M.F. QE events

$$\vec{p}_{miss} = \vec{p}_N - \vec{q} \qquad E_{miss} = \omega - T_N - T_B$$

protons



QE peak:

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

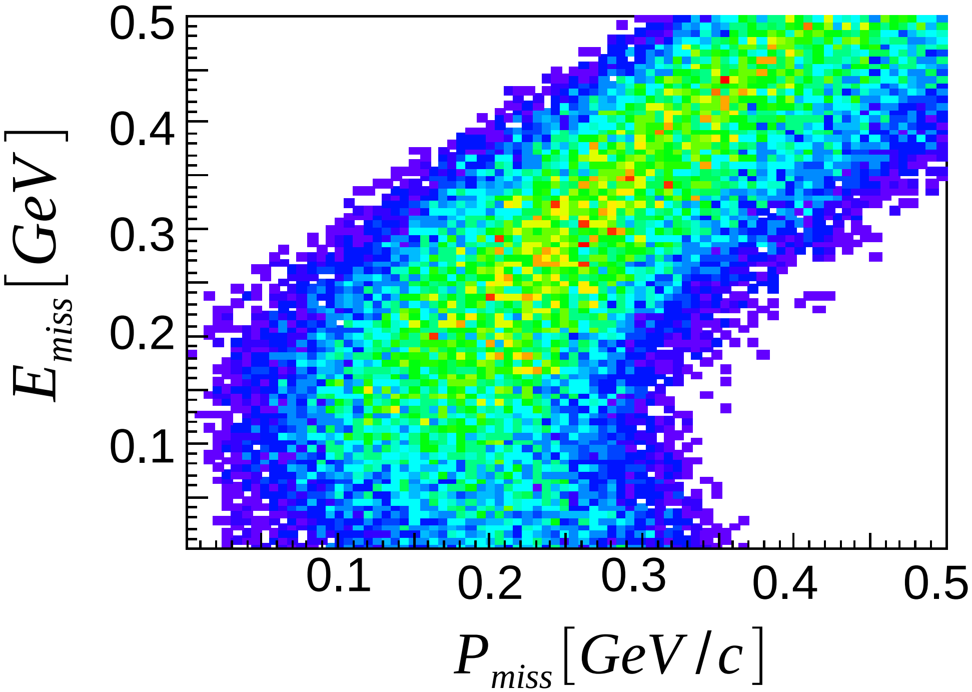
Oneill et al., Phys. Lett. B 87 (1995), Abbott et al. Phys. Rev. Lett. 80 (1998), Garrow et al. Phys. Rev. C. 66 (2002)

Solution

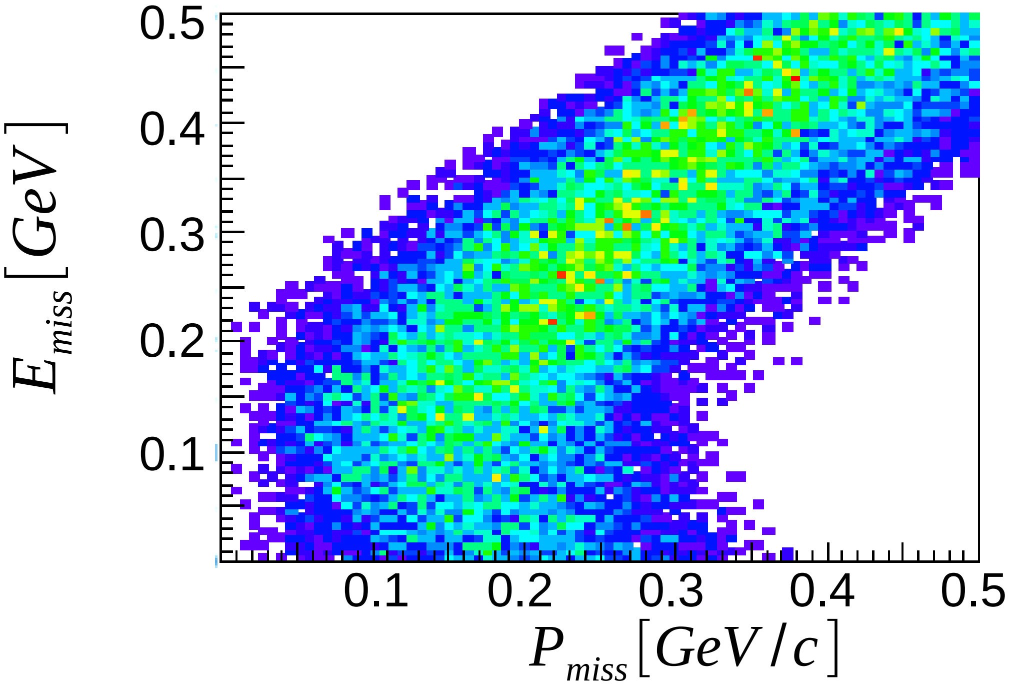
Using smeared protons to:

* Define and test the cuts
* Study bin migration

smeared protons

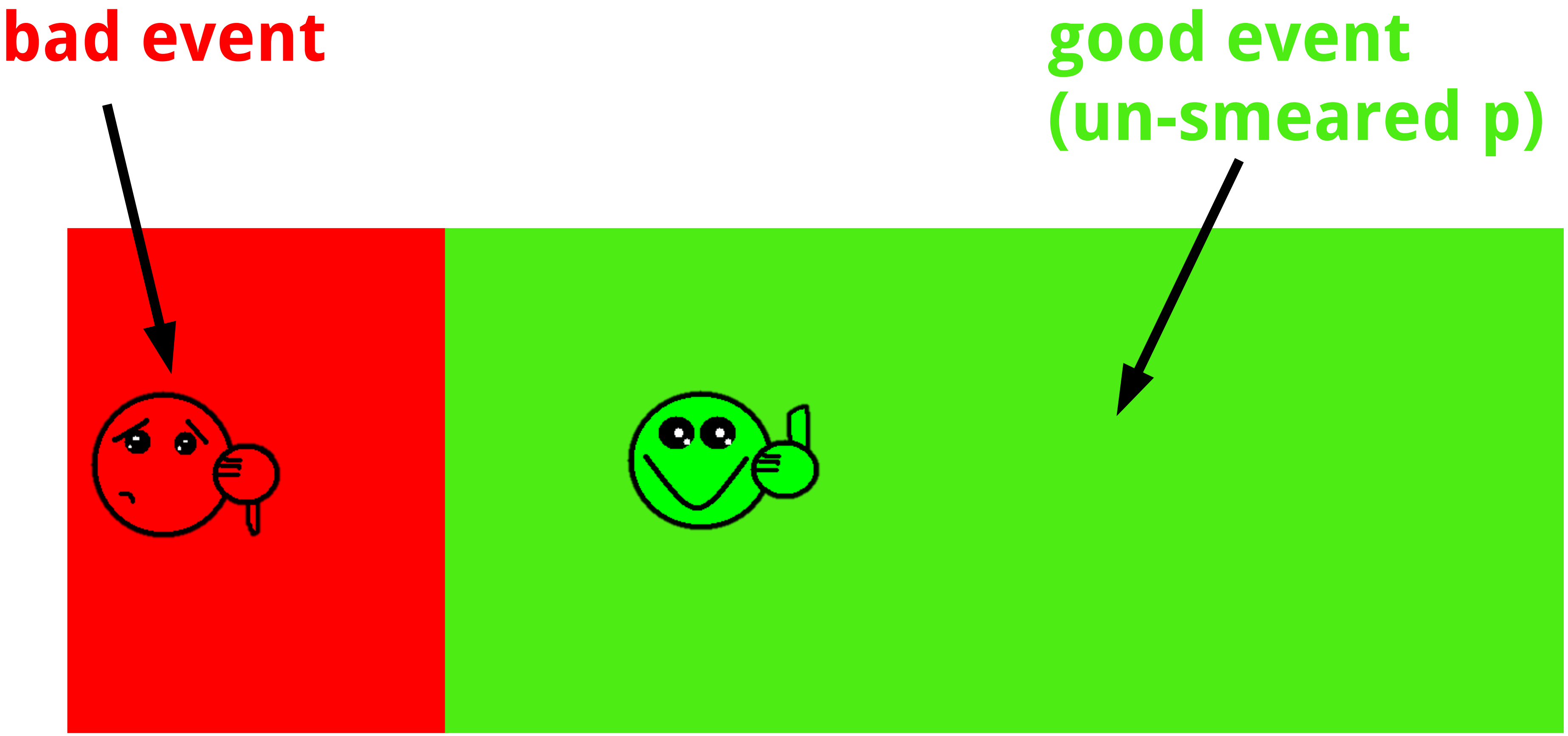


neutrons

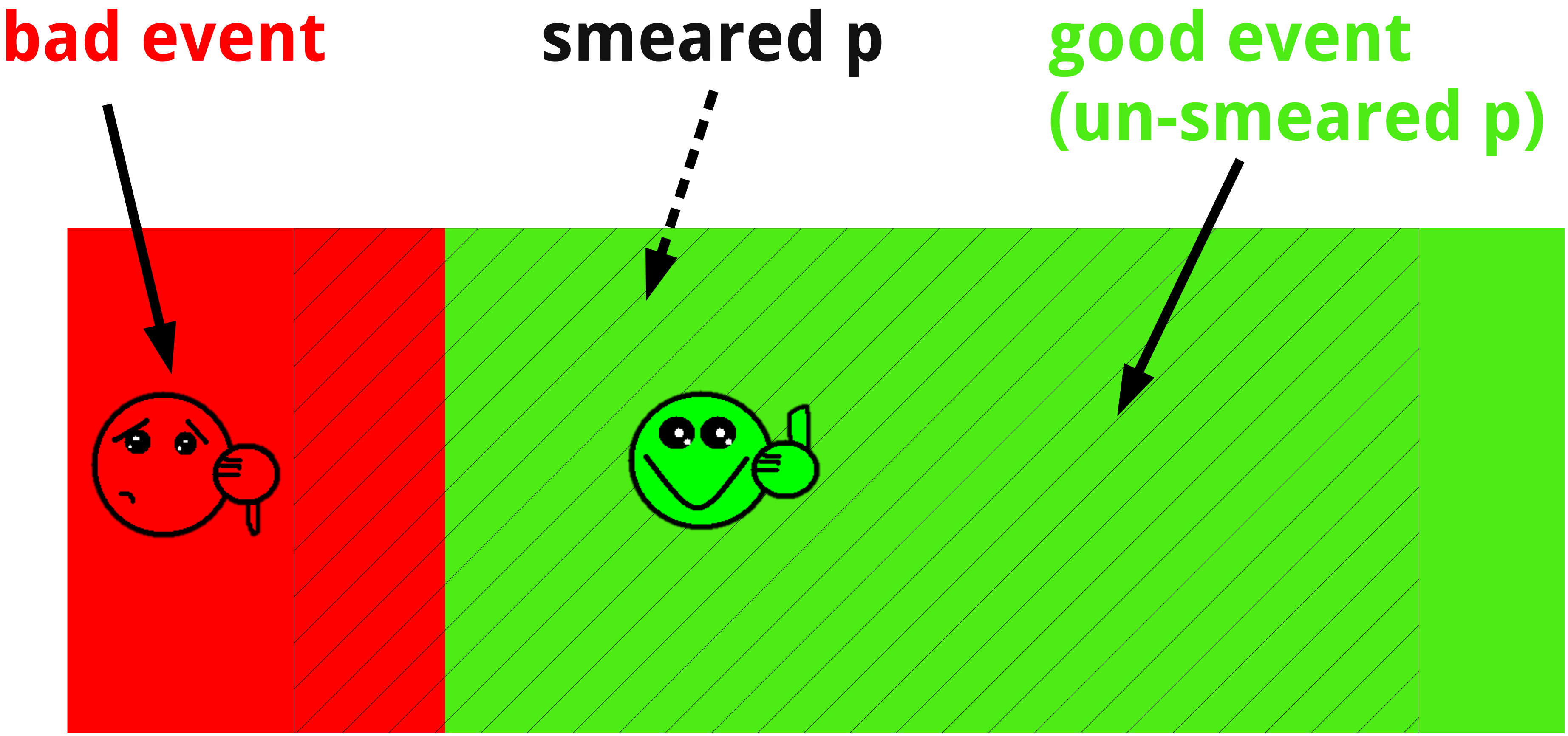


With cuts: $-0.05 < y < 0.25$ $0.95 < \omega < 1.7\,GeV$ $\theta_{pq} < 8^o$

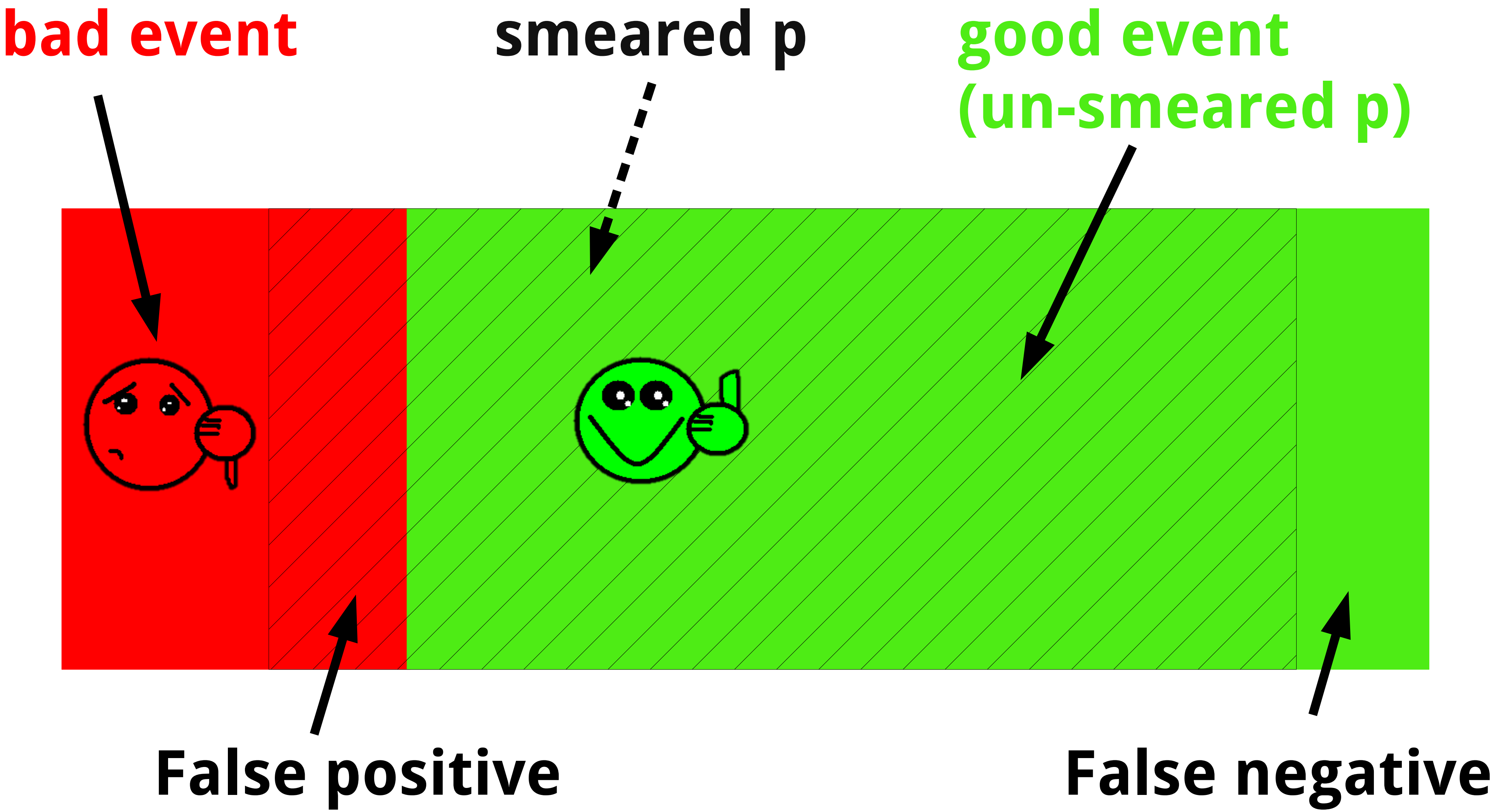
False Positive & Negative probabilities



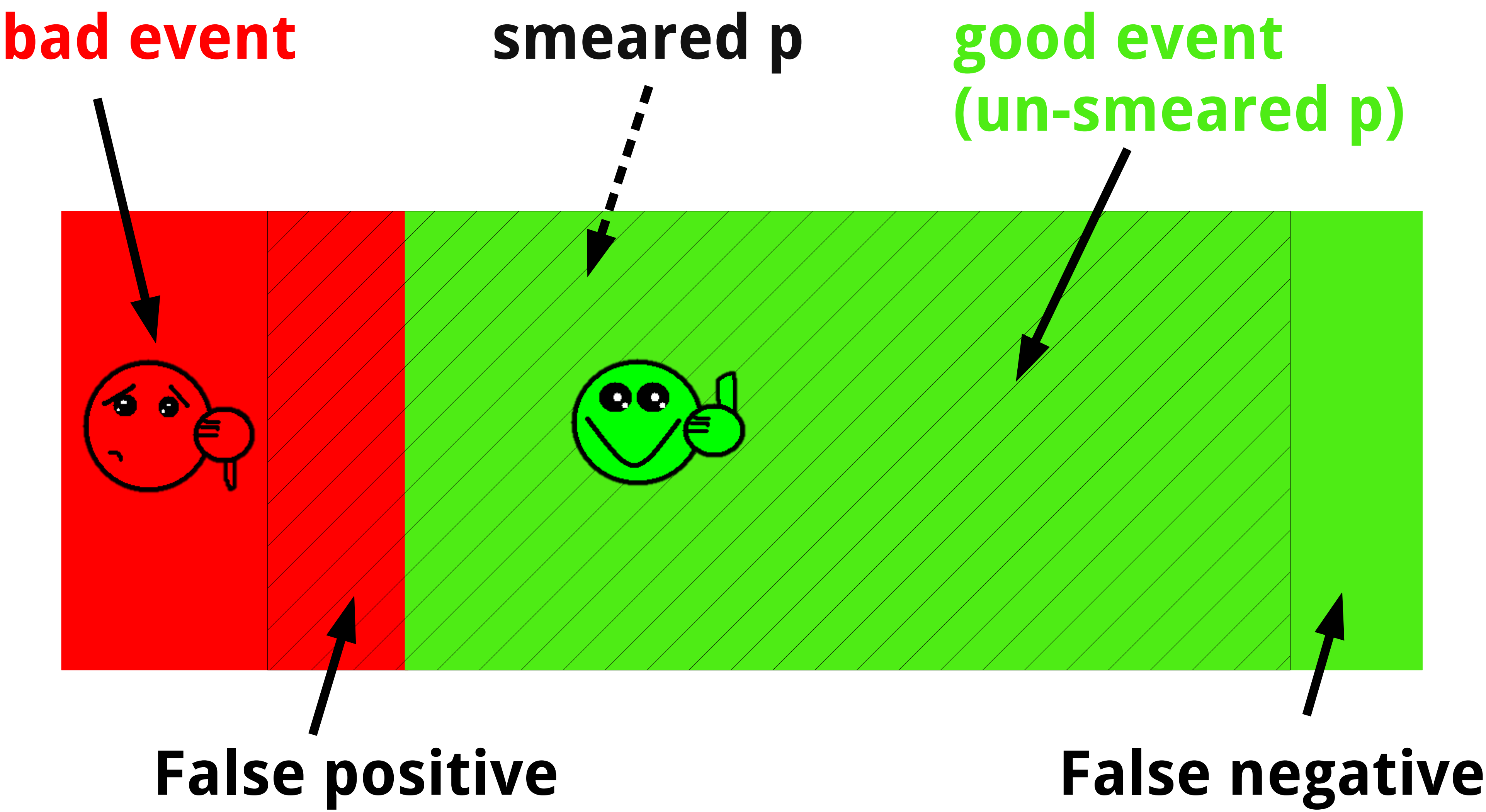
False Positive & Negative probabilities



False Positive & Negative probabilities

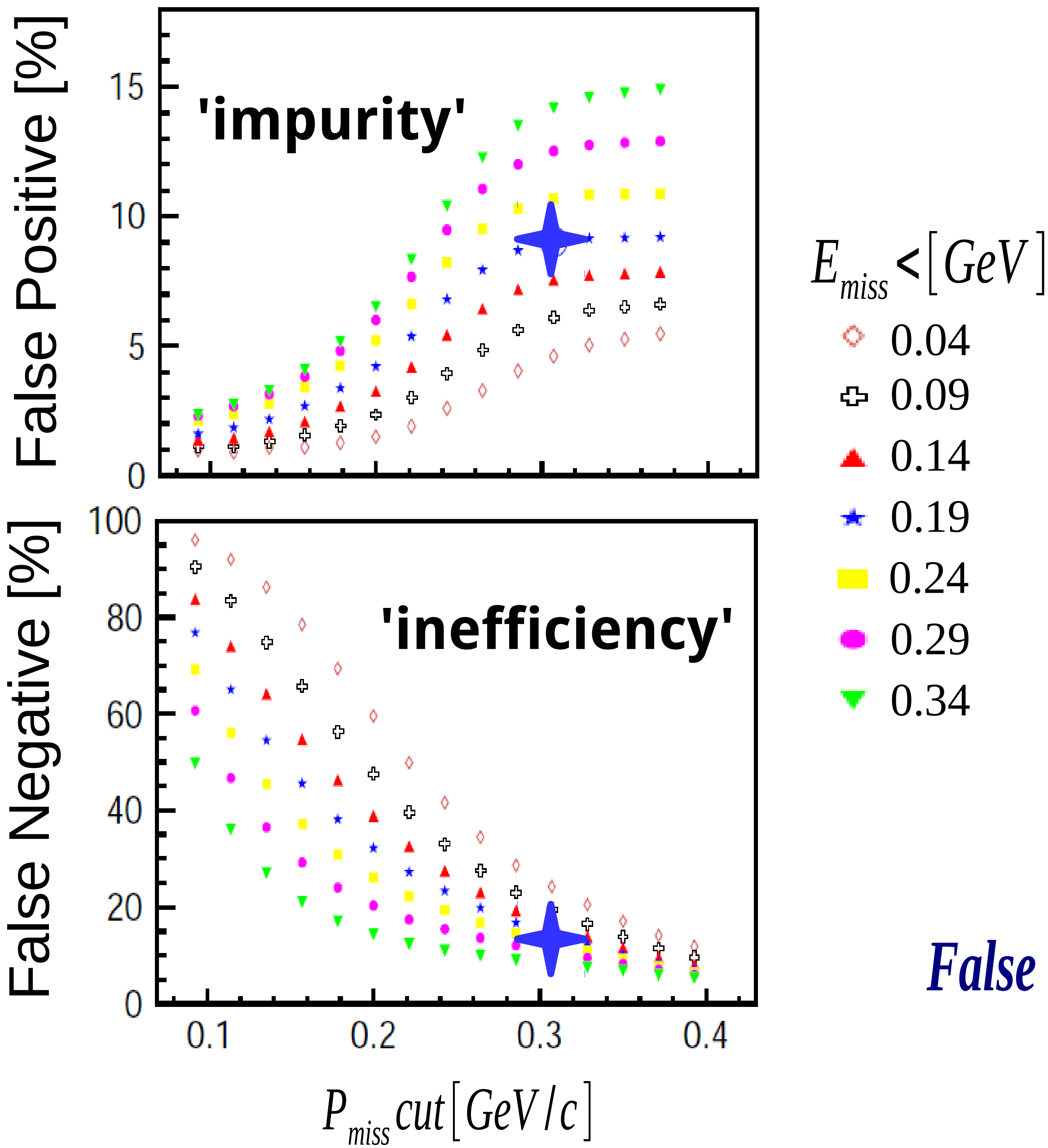


False Positive & Negative probabilities



Goal: Find cuts that minimize
false positive & negative

False Positive & Negative probabilities



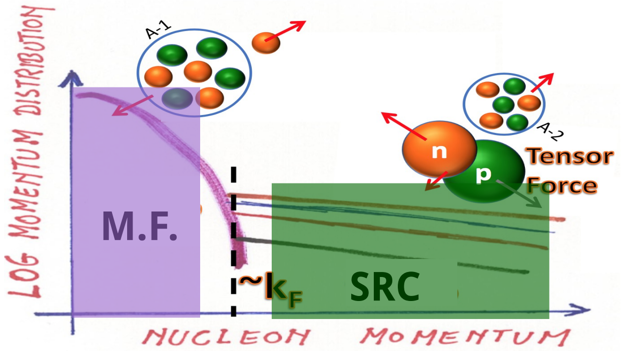
smeared p/n cuts:

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

un-smeared p cuts:

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

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



High-momentum QE events

(Same procedure as M.F.)

The selected cuts:

$$x_B > 1.1$$

$$0.62 < \vec{p}/\vec{q} < 1.1$$

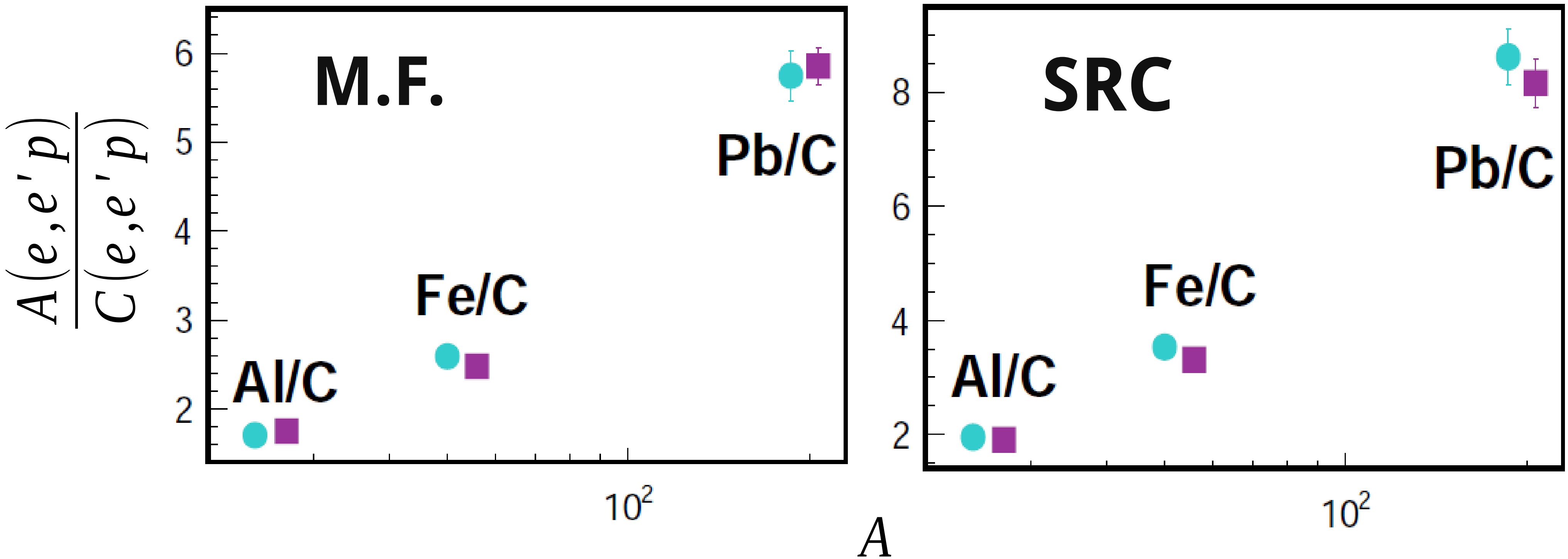
$$\theta_{pq} < 25^o$$

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

$$M_{miss} < 1.175\,GeV/c^2$$

Compare smeared & un-smeared protons

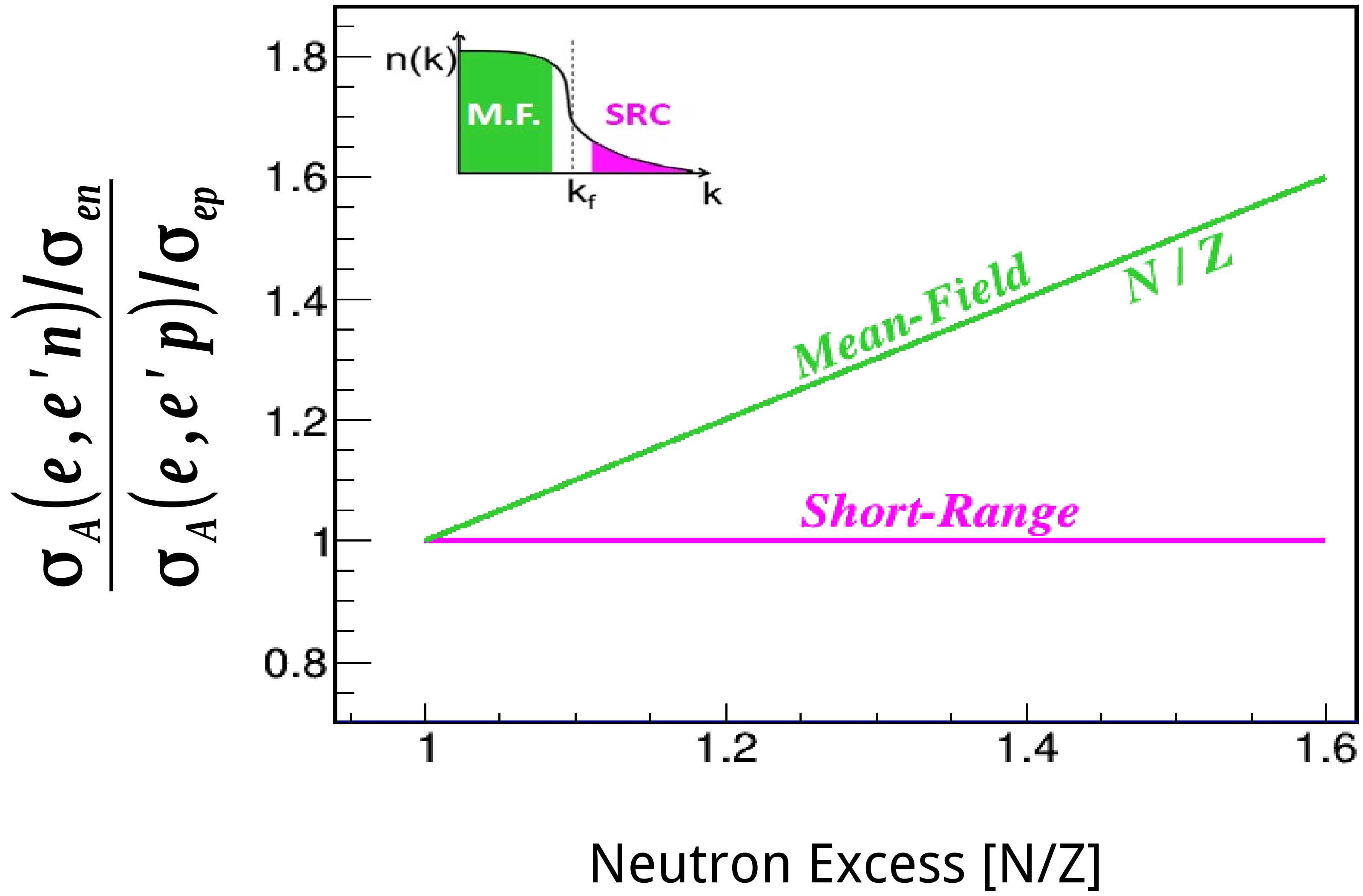
smeared protons   un-smeared protons



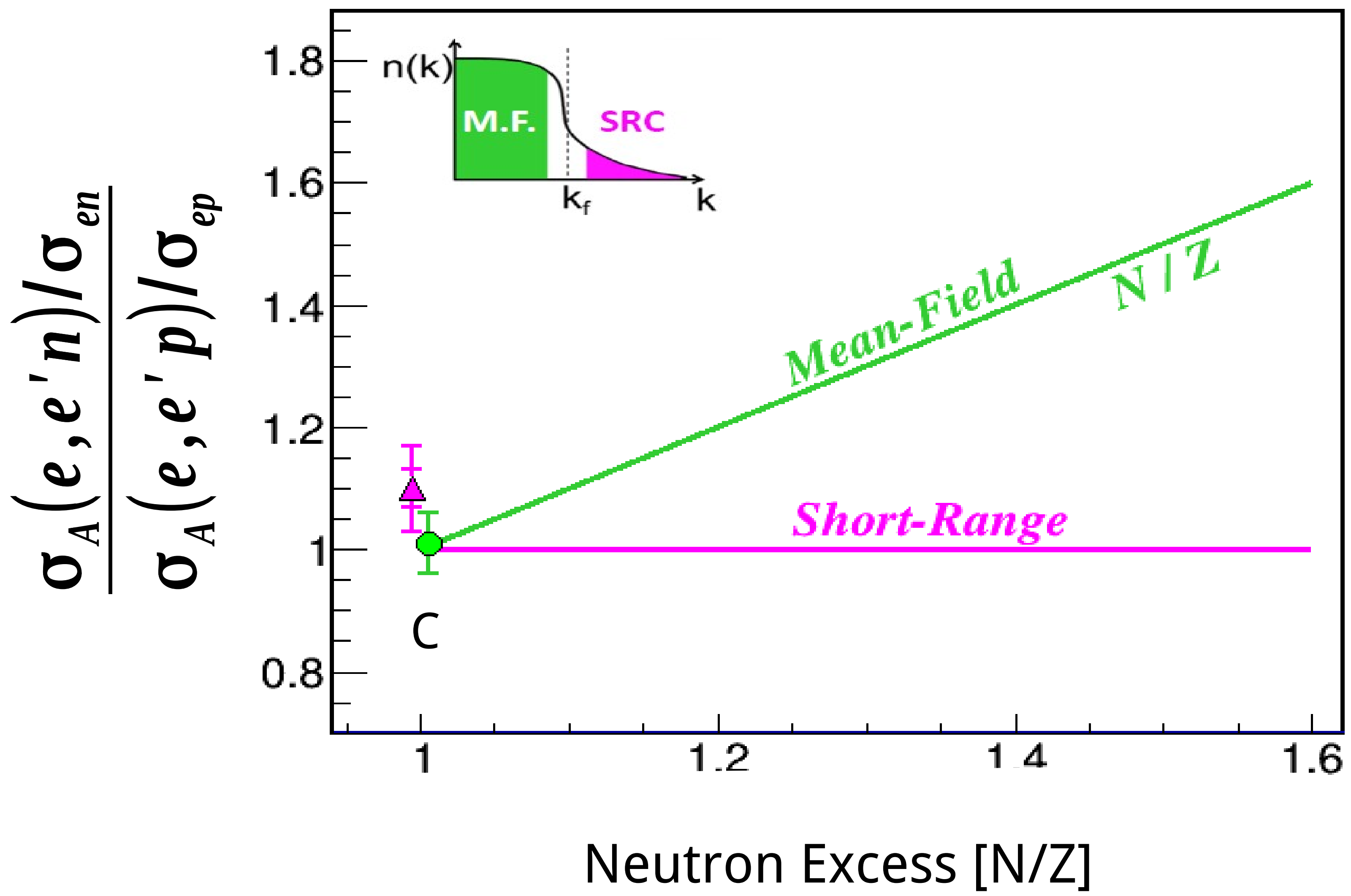
Next step:

Blind analysis for neutrons

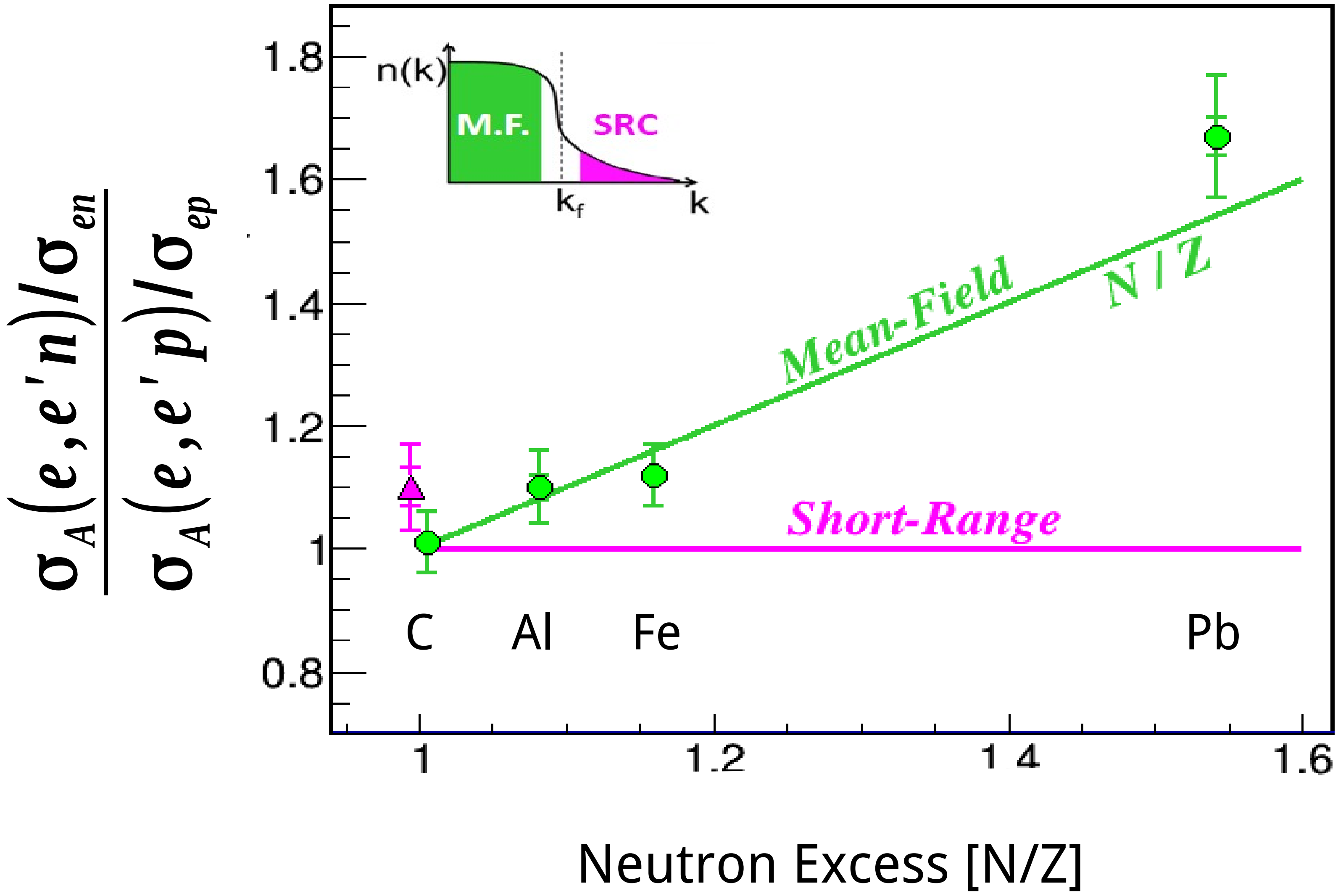
A(e,e'n)/A(e,e'p) ratios



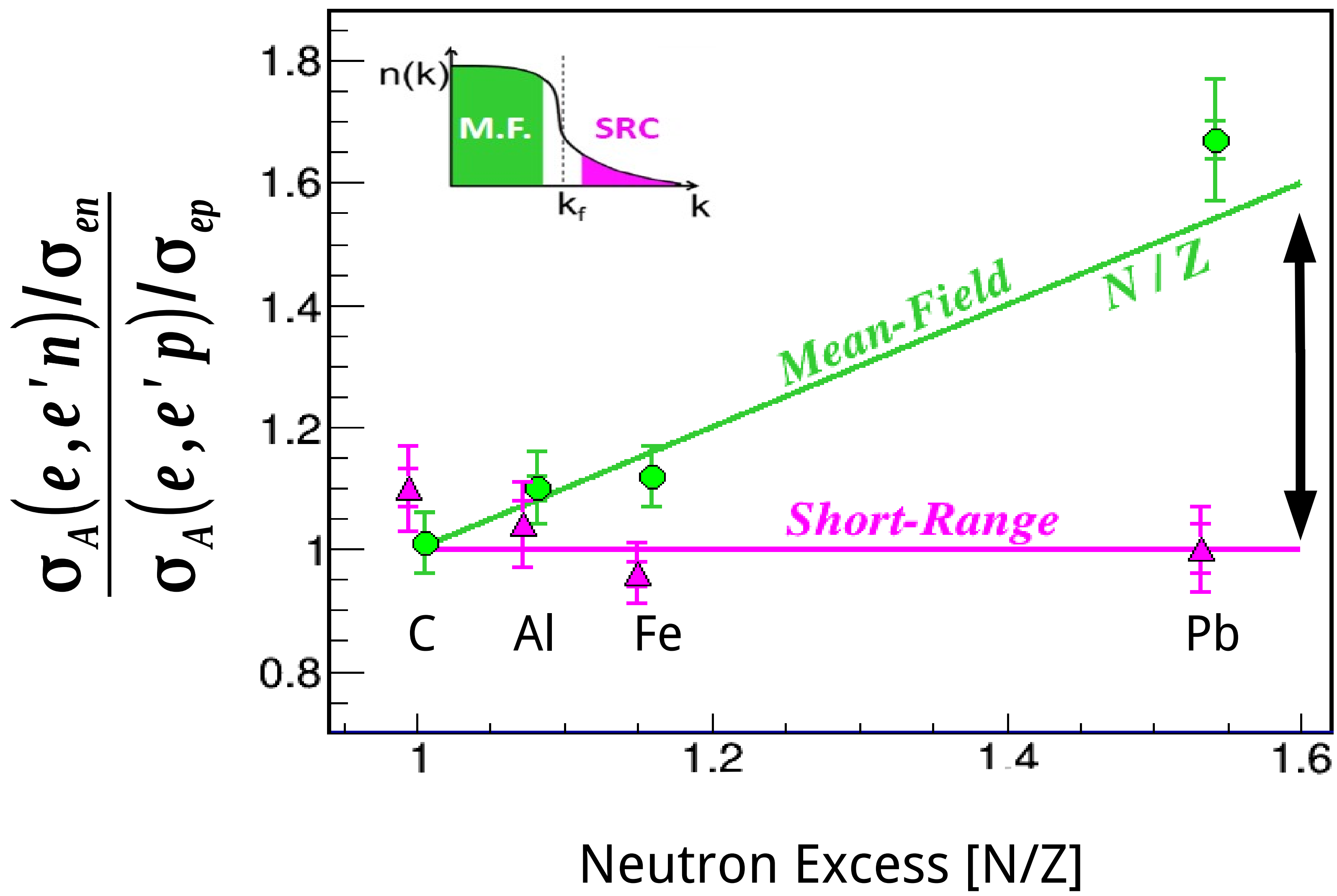
A(e,e'n)/A(e,e'p) ratios

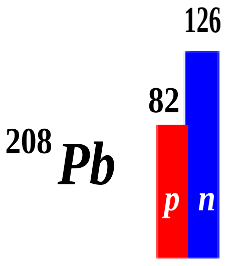


A(e,e'n)/A(e,e'p) ratios



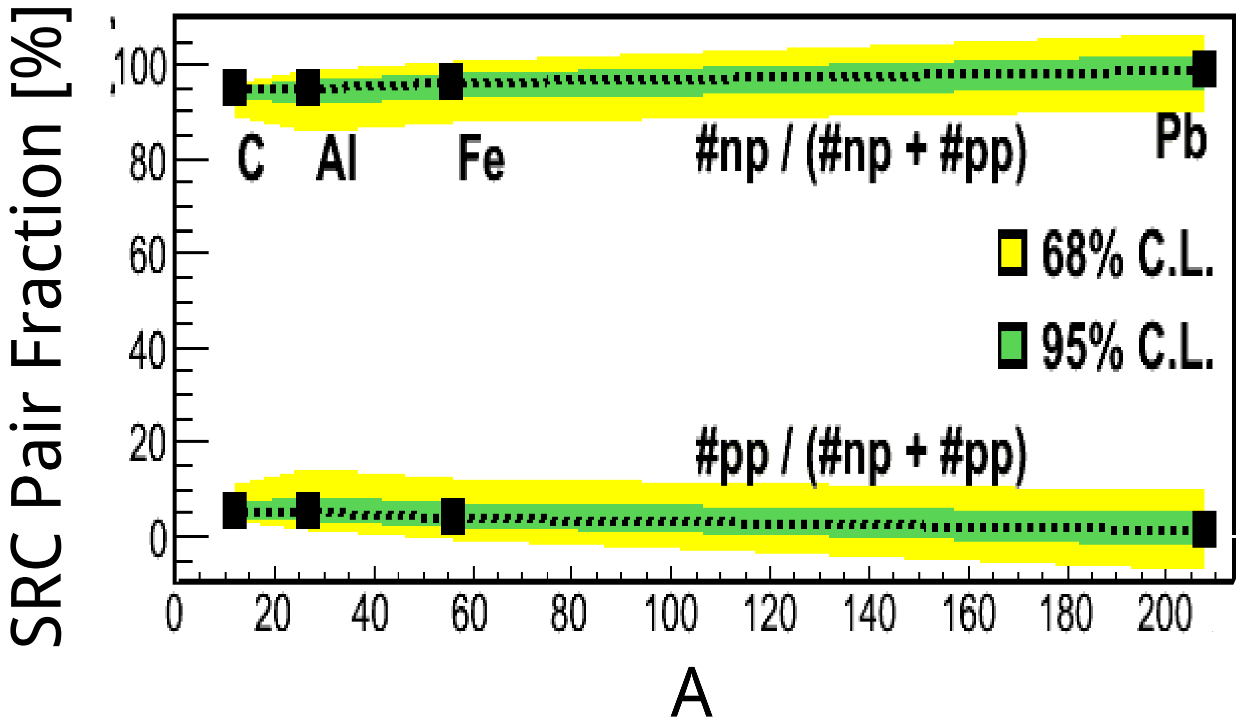
A(e,e'n)/A(e,e'p) ratios





Duer et al., Nature, accepted for publication

np-dominance in 2N-SRC



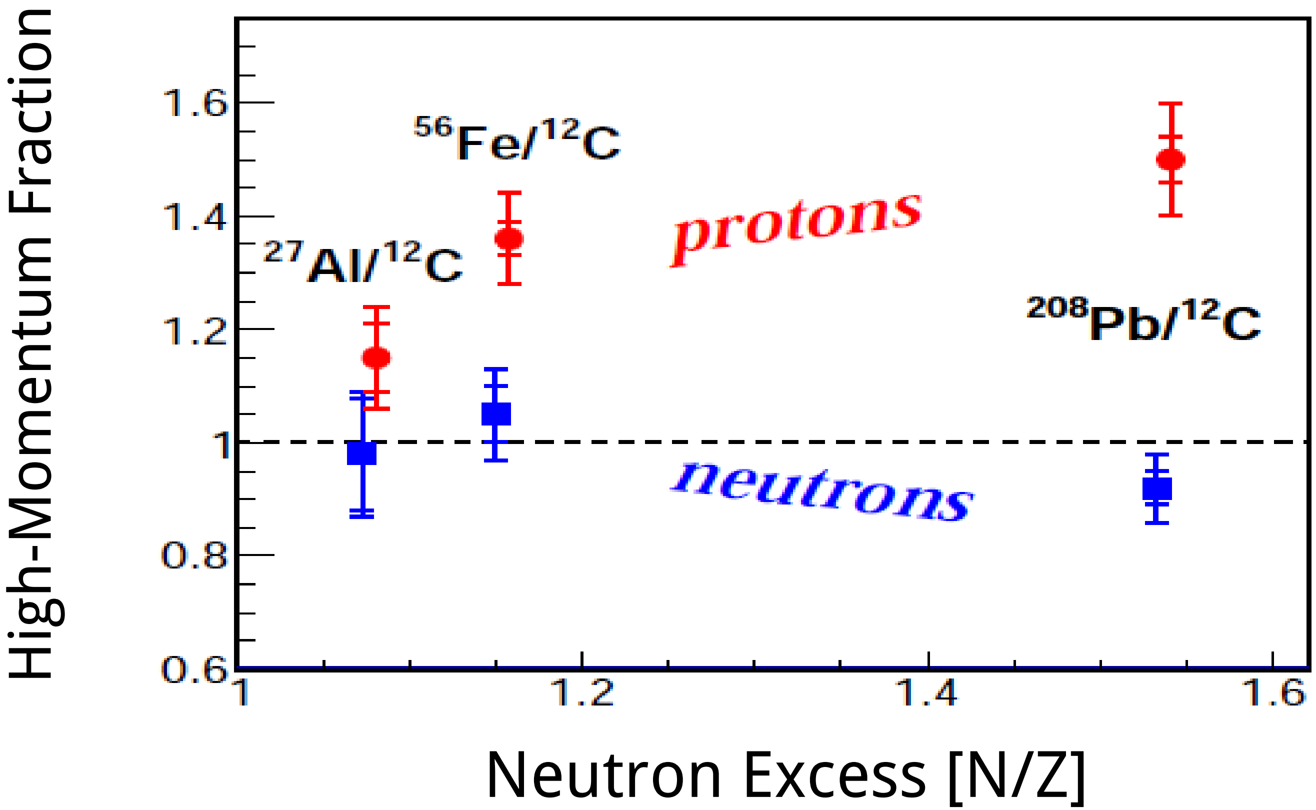
O. Hen et al., Science 346, 614 (2014)

np fractions extracted from (e,e'p) & (e,e'pp) events

No neutrons detection

Protons and neutrons super ratios

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



More Neutrons => More Correlated Protons

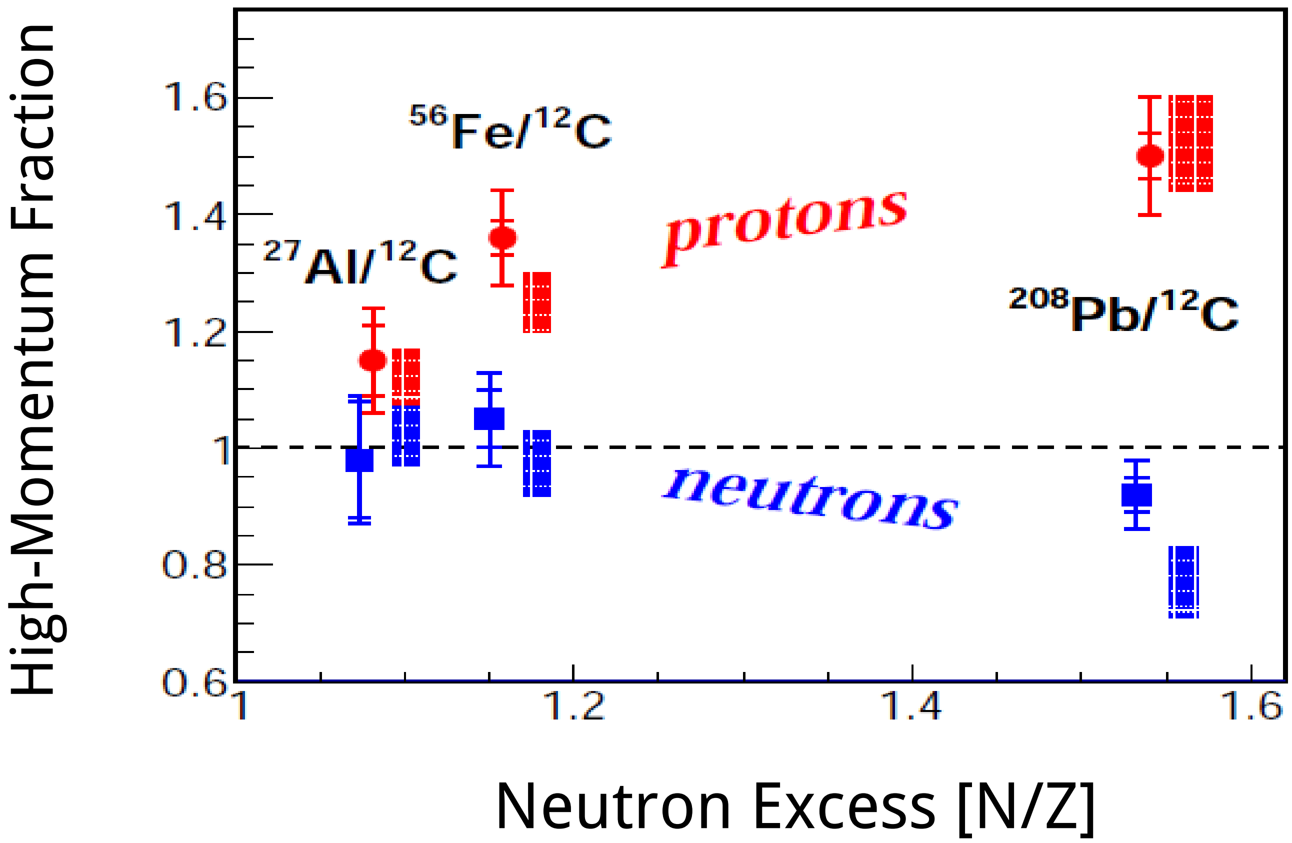
Duer et al., Nature, accepted for publication

“Building” nuclei from C to Pb

Adding more neutrons increases the fraction of high momentum (correlated) protons.

Protons and neutrons super ratios

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

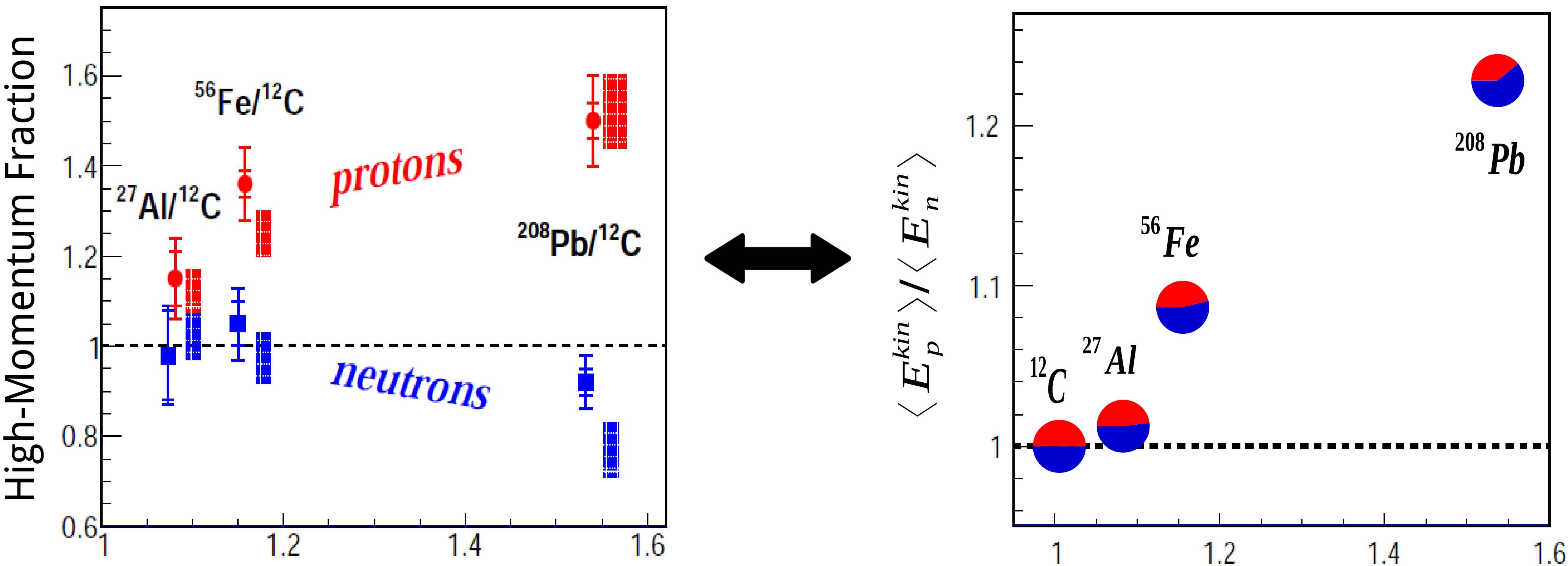


Our simple model works

Duer et al., Nature, accepted for publication

Kinetic Energy Sharing

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



Neutron Excess [N/Z]

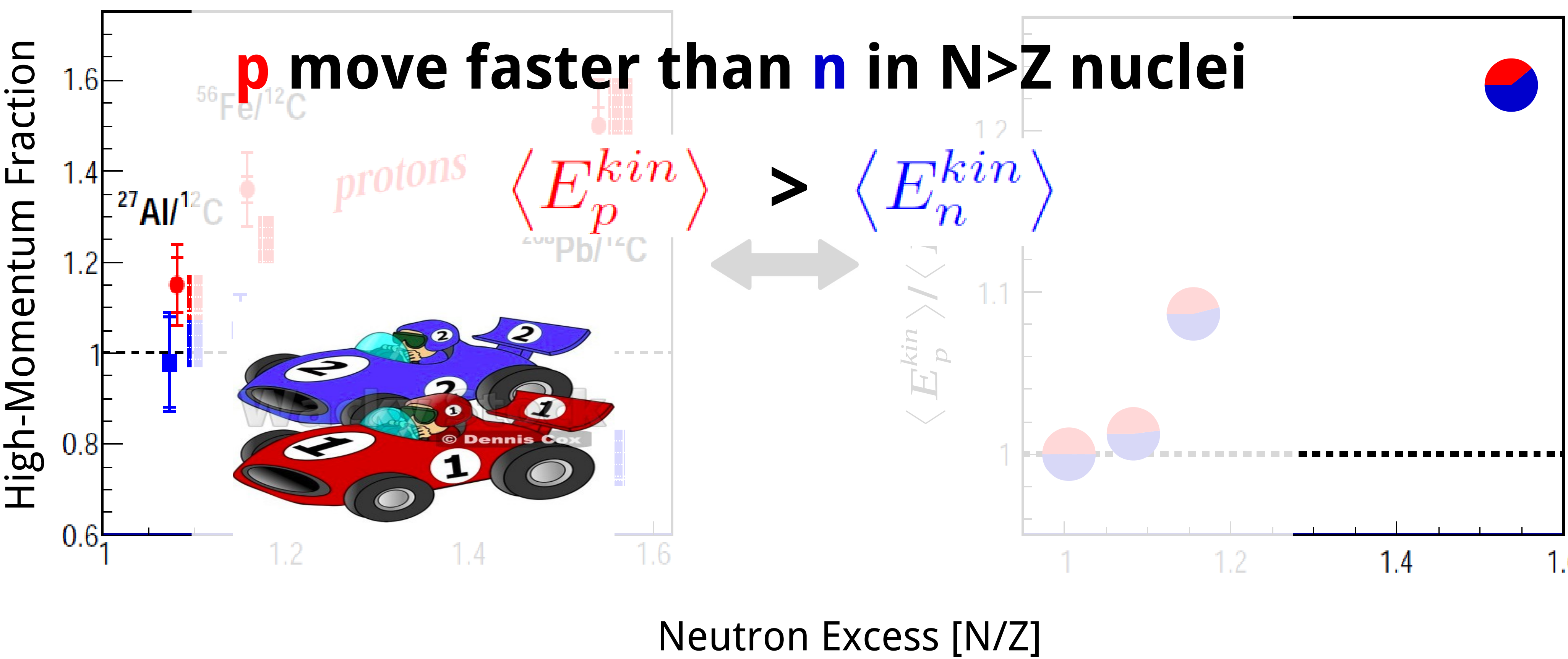
Duer et al., Nature, accepted for publication

Kinetic Energy Sharing

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

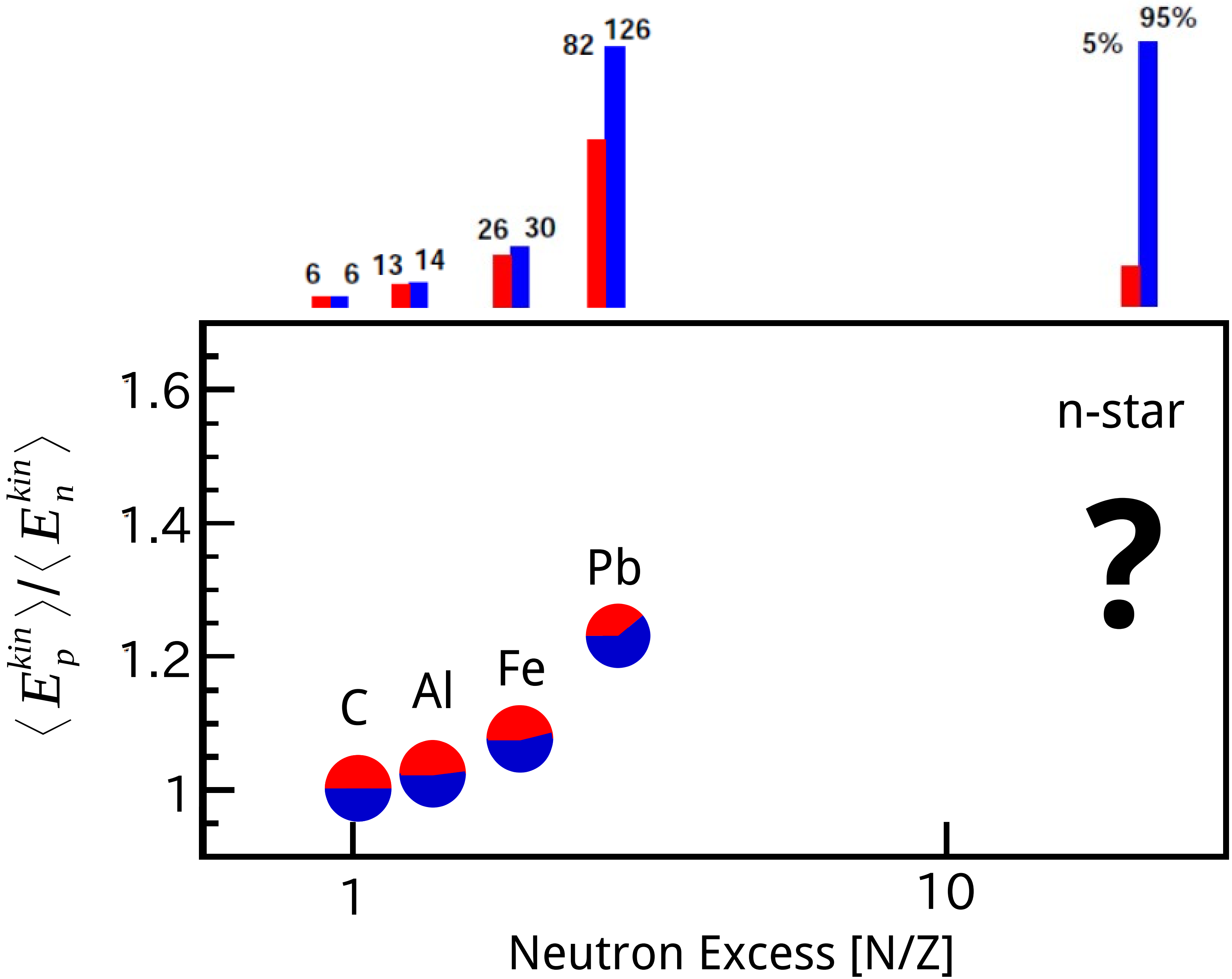
p move faster than n in N>Z nuclei

$$\langle E_p^{kin} \rangle > \langle E_n^{kin} \rangle$$



Duer et al., Nature, accepted for publication

What happens in N>>Z?



Detecting neutrons in CLAS

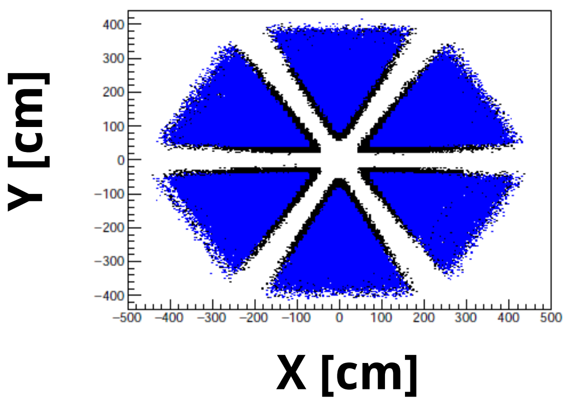
$$8^o \leq \theta \leq 45^o$$

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

* Hit inside the EC fiducial cut

↓

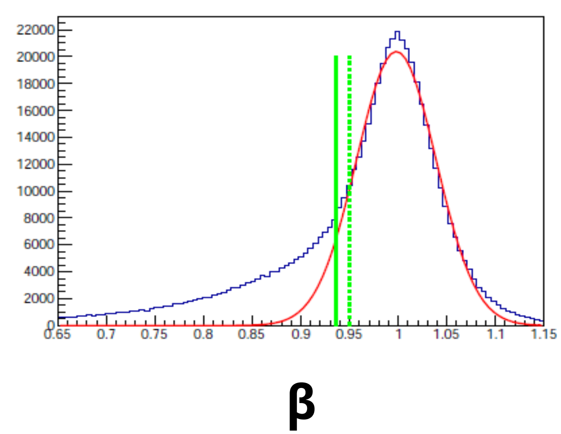
Neutral particle



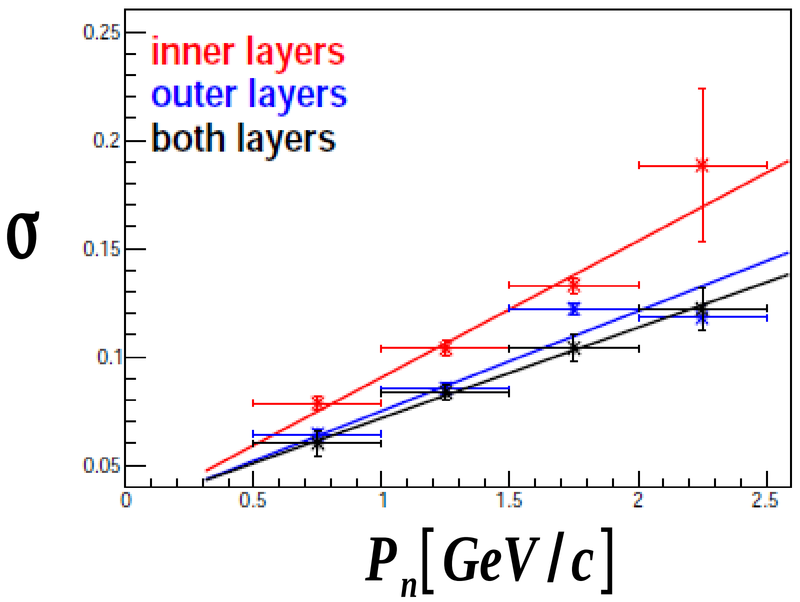
* n/γ separation: β<0.95 (β<0.936)

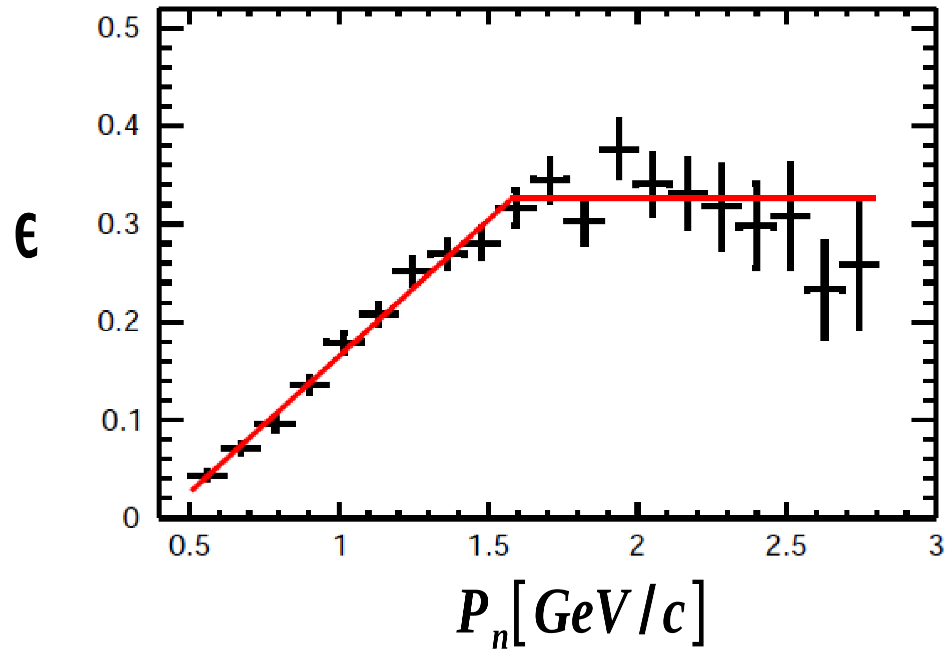
↓

Neutron



Neutron resolution & detection efficiency





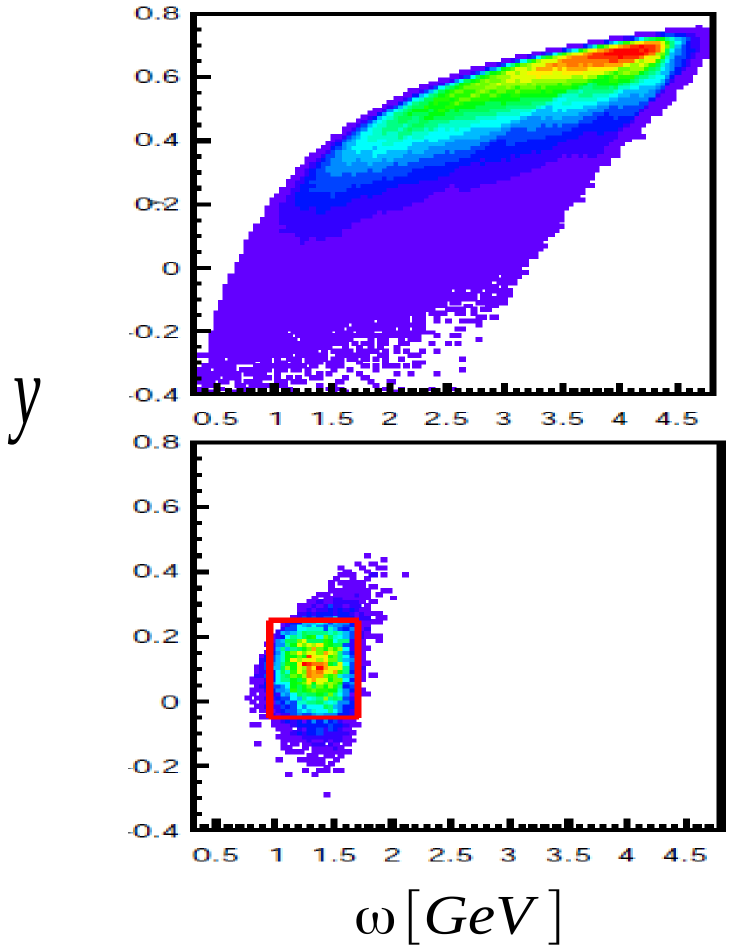
$$\epsilon = \frac{d(e,e'p\pi^+\pi^-n)}{d(e,e'p\pi^+\pi^-)n}$$

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

Solution I

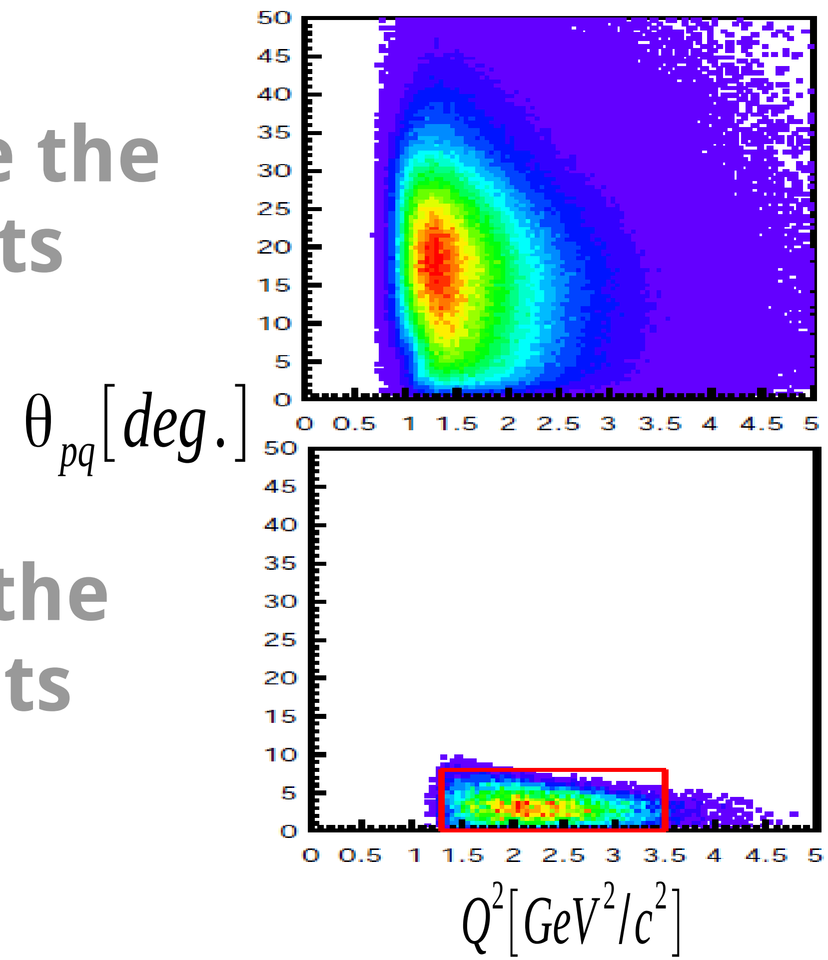
Using electron & nucleon angular cuts

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



Before the QE cuts

After the QE cuts



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

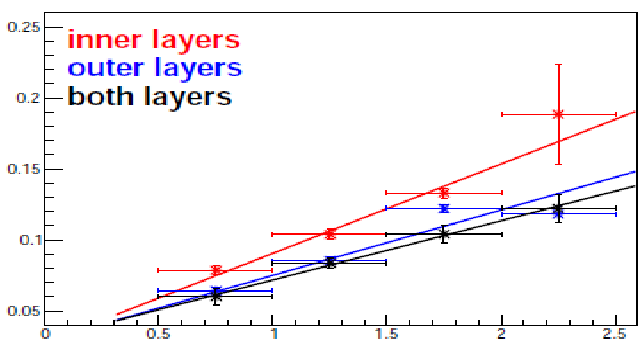
$y\equiv[(M_A+\omega)^2\sqrt{\lambda^2-M_{A-1}^2W^2}-|\vec{q}|\lambda]/W^2$ $\quad W=\sqrt{(M_A+\omega)^2-|\vec{q}|^2}$ $\quad \lambda=(M_{A-1}^2-M_N^2+\omega^2)/2$

Solution II

Using smeared protons to:

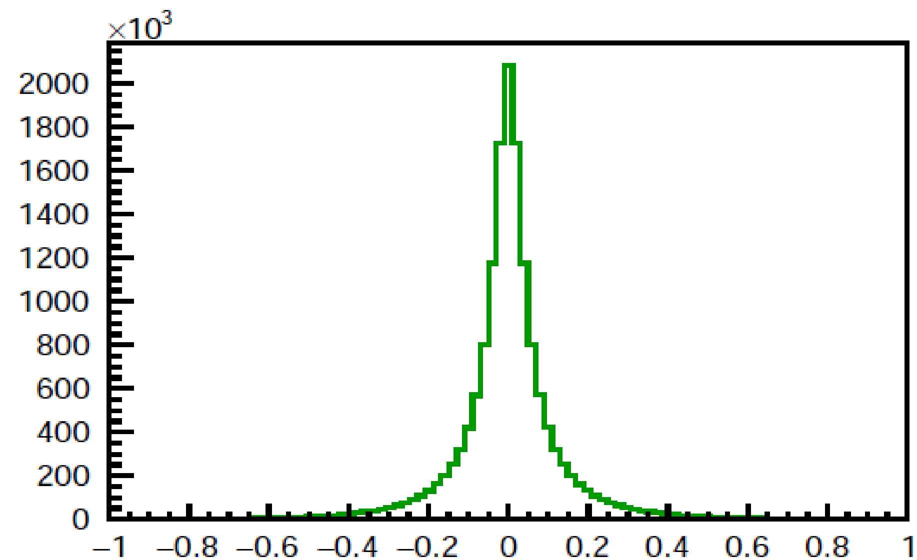
* Define and test the cuts
* Study bin migration

σ



$P_n[GeV/c]$

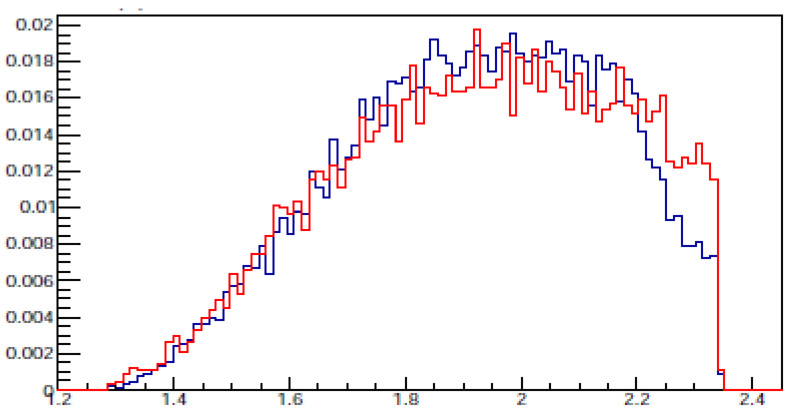
$$P_p \rightarrow P_{smeared} = \sum Gauss(P_p, \sigma)$$



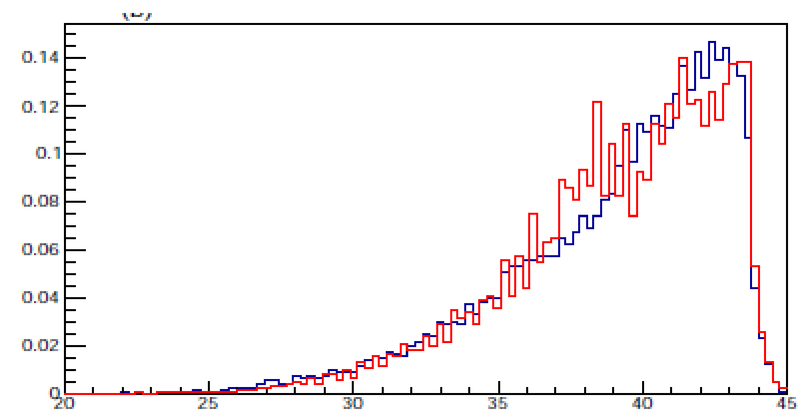
$P_p - P_{smeared}[GeV/c]$

Comparing the smeared protons and neutrons

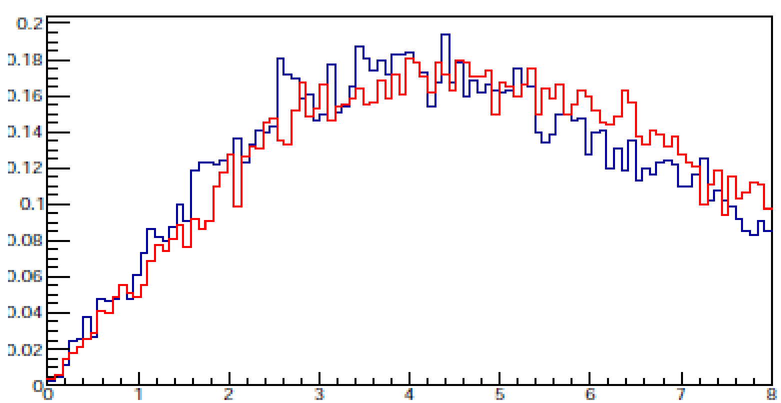
smeared protons **neutrons**



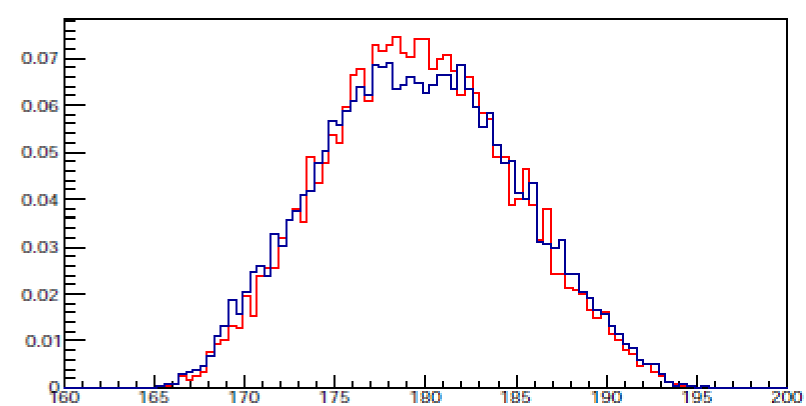
$P_{p/n}[GeV/c]$



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



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



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

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.

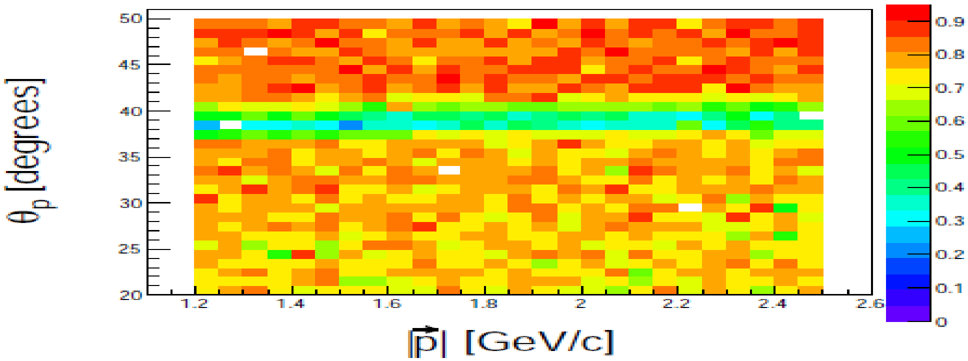
* 100xphi angle uniformly distributed.

* Running through CLAS MC simulation.

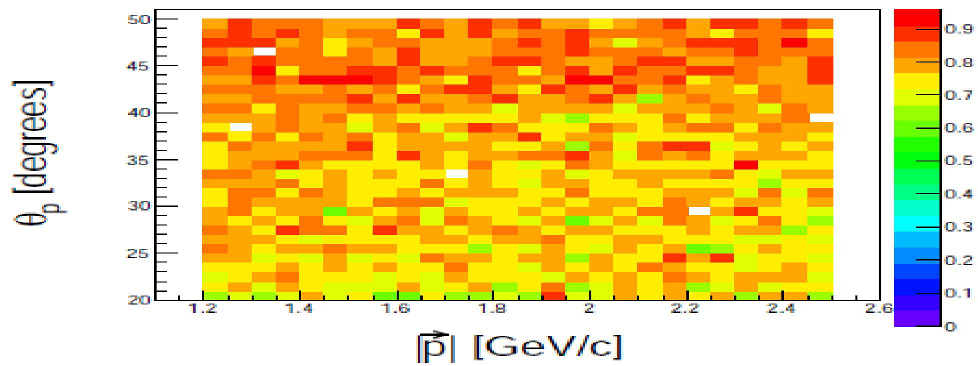
* Dividing event by event by the ratio of reconstructed/generated.

Protons simulation - results

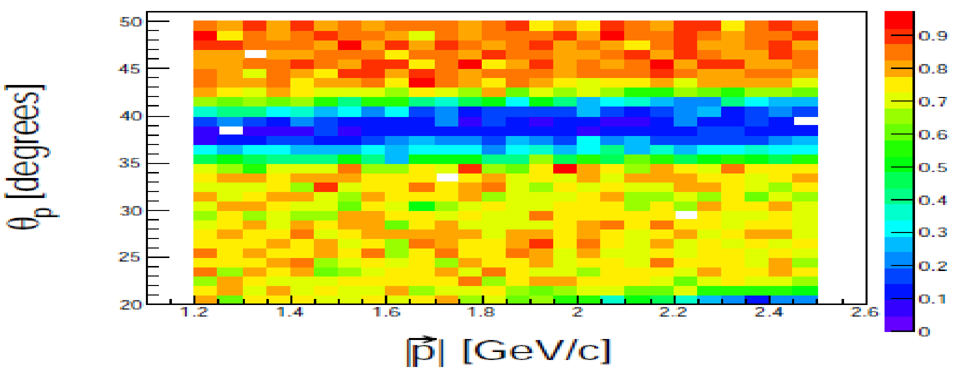
Sector #1



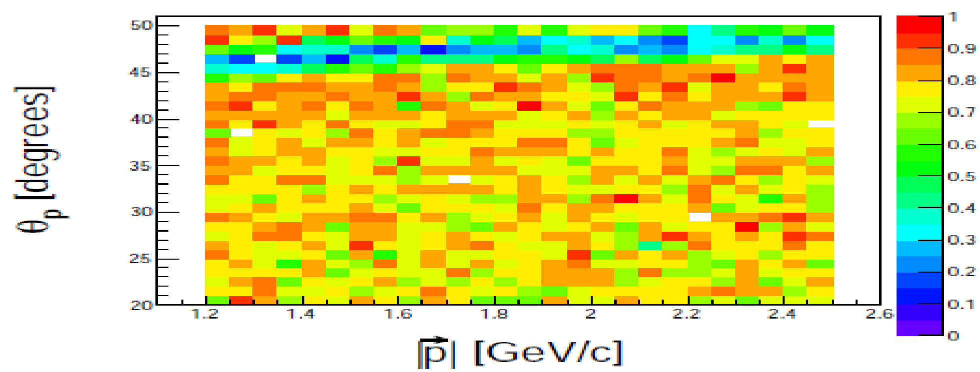
Sector #2



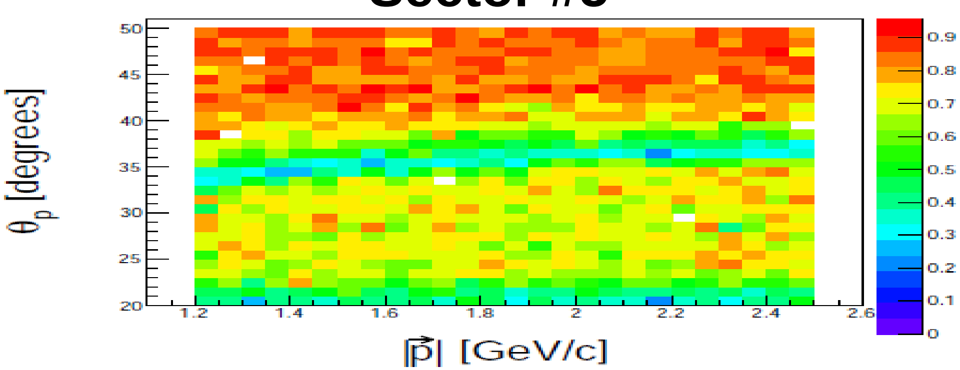
Sector #3



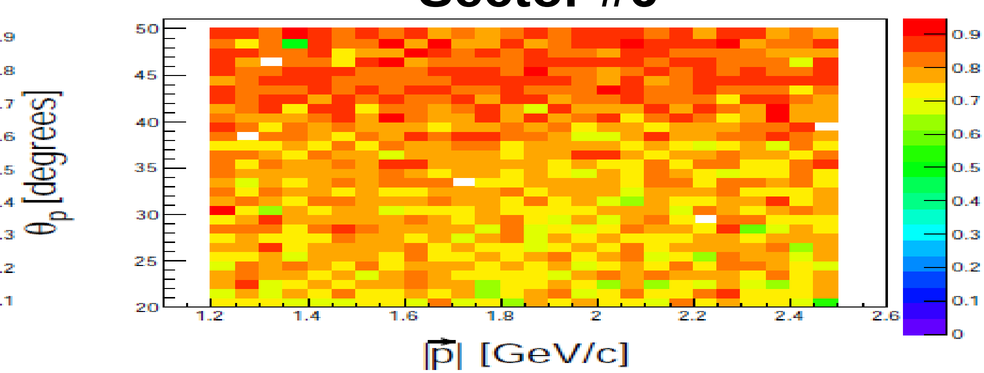
Sector #4



Sector #5

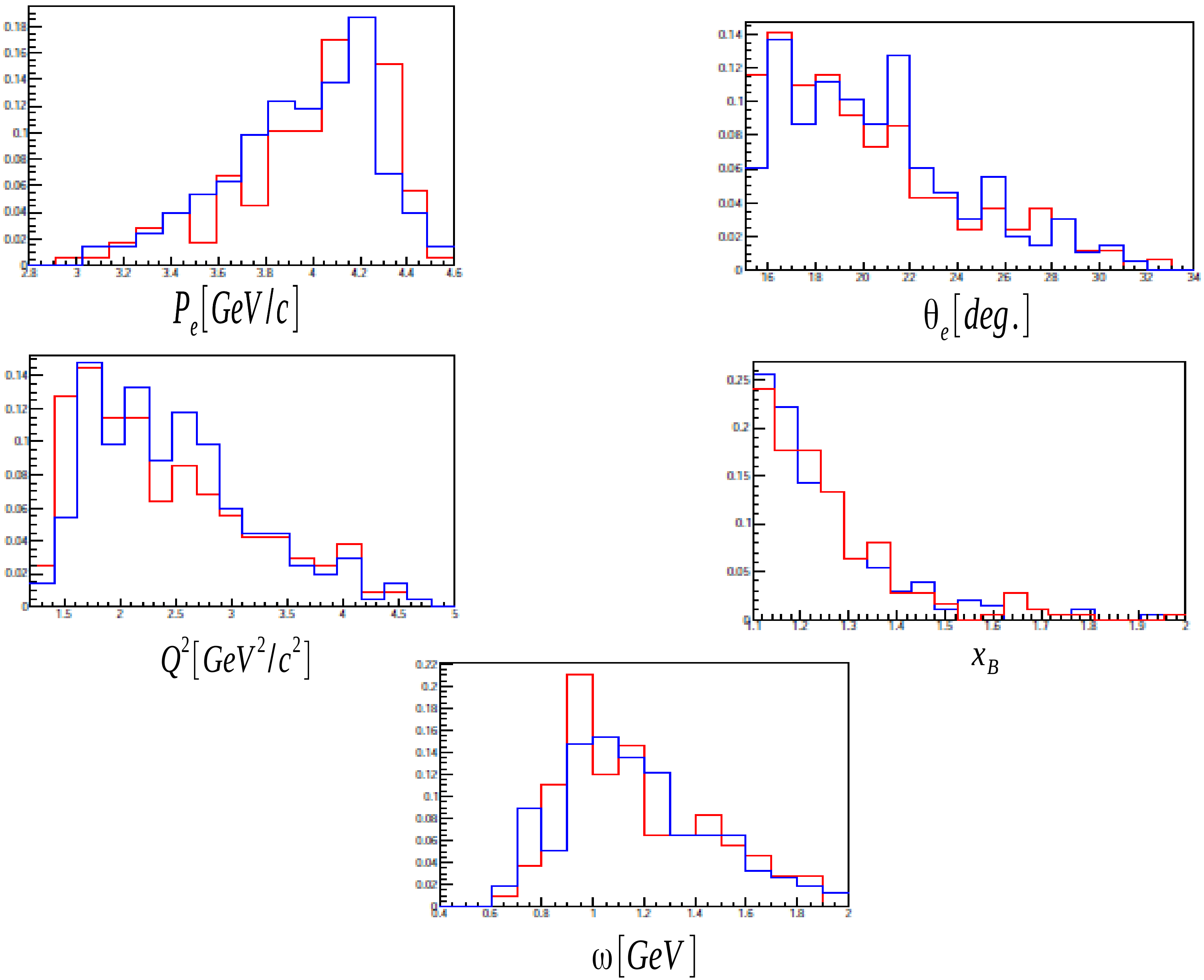


Sector #6



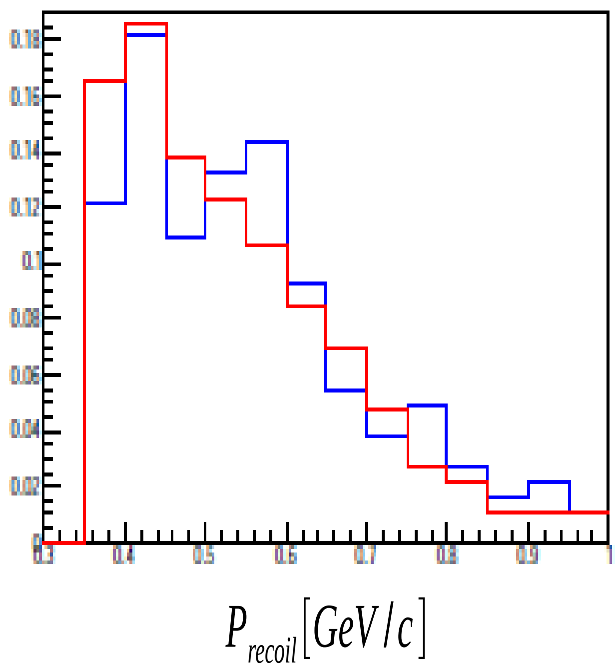
Electron kinematics

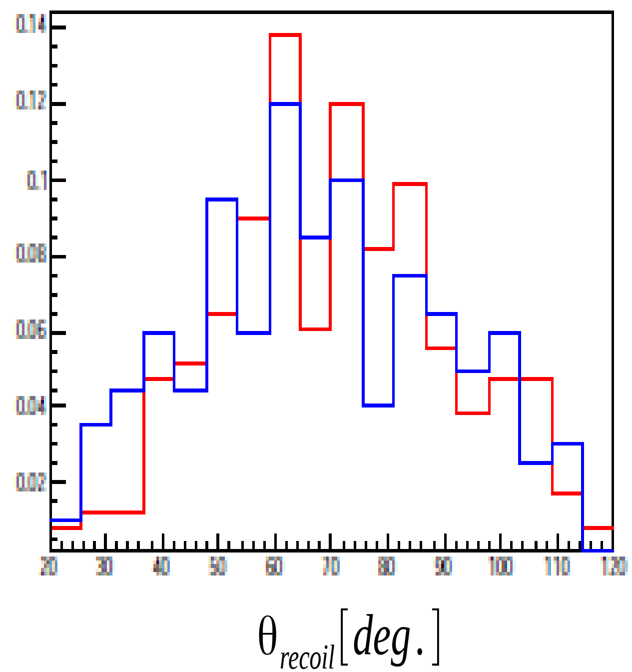
smeared protons **neutrons**



Recoil proton kinematics

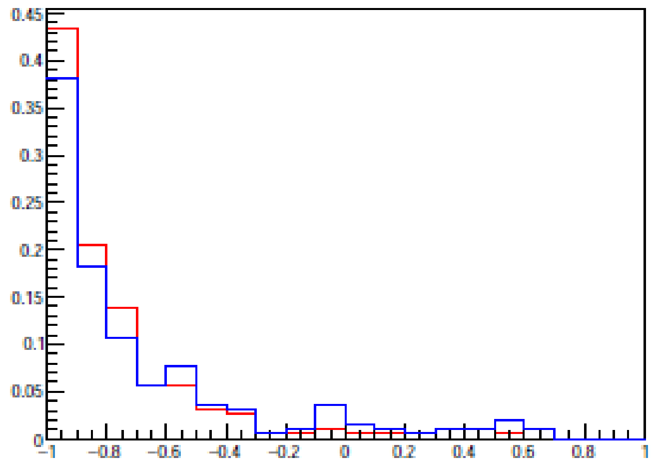
smeared protons neutrons





Opening angle distribution

smeared protons neutrons



$$\cos\left(\theta_{\vec{P}_{miss},\vec{P}_{recoil}}\right)$$