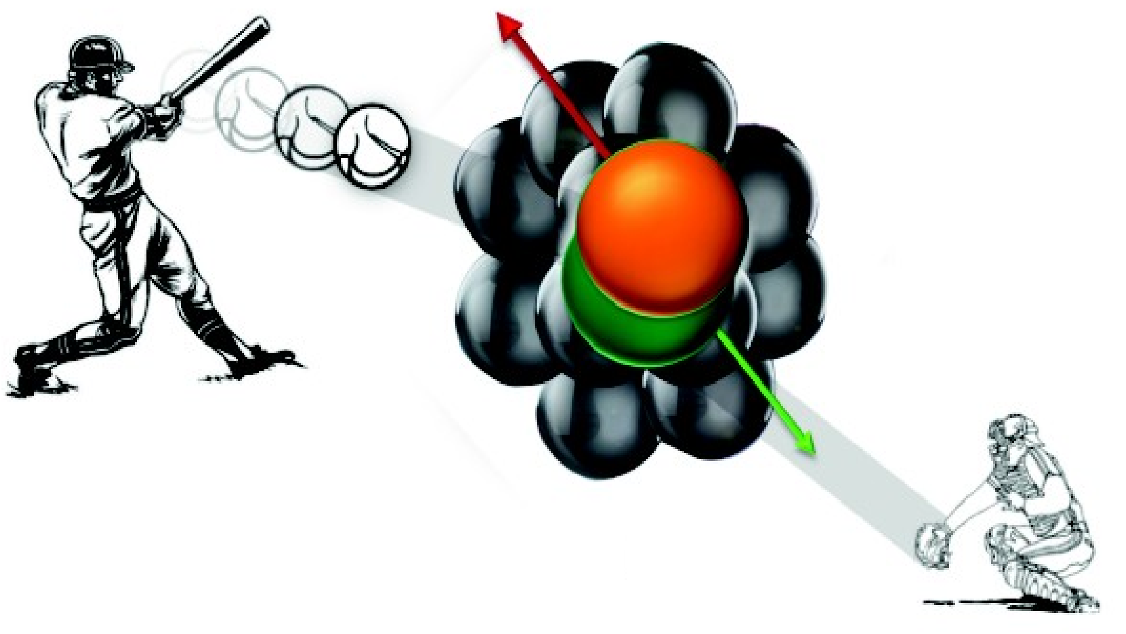
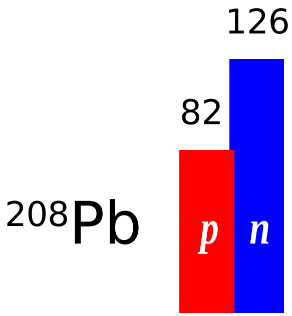
# Short-Range Correlations in neutron-rich nuclei



Meytal Duer
TU Darmstadt

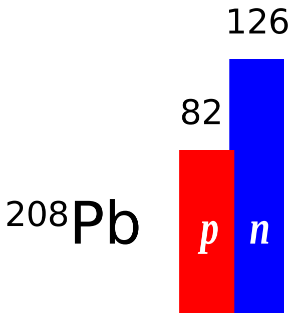
EMMI Physics Day 2019, GSI




# Energy sharing in neutron rich nuclei

Pauli principle

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




# Energy sharing in neutron rich nuclei

Pauli principle

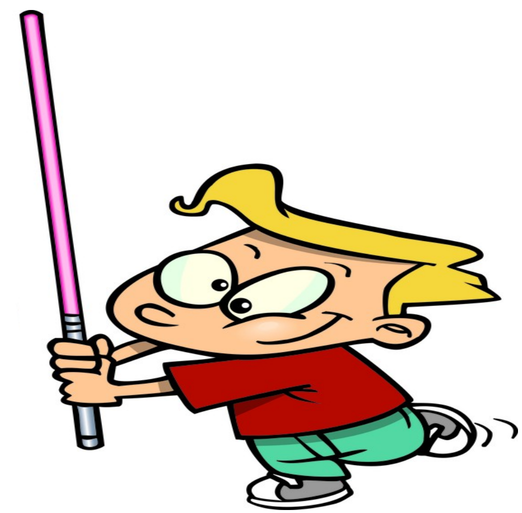
$$\langle E_n^{kin} \rangle > \langle E_p^{kin} \rangle$$

With Short-Range Correlations

?

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

**vs.**



# The Nuclear Hamiltonian

$$H = T + \underbrace{\sum_{i<j=1}^{A} V_{2N}(i,j)}_{\text{2-body}} + \underbrace{\sum_{i<j<k=1}^{A} V_{3N}(i,j,k)}_{\text{3-body}} + \ldots$$

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Mean-Field Approximation: $H = T + \sum_{i=1}^{A} V(i)$

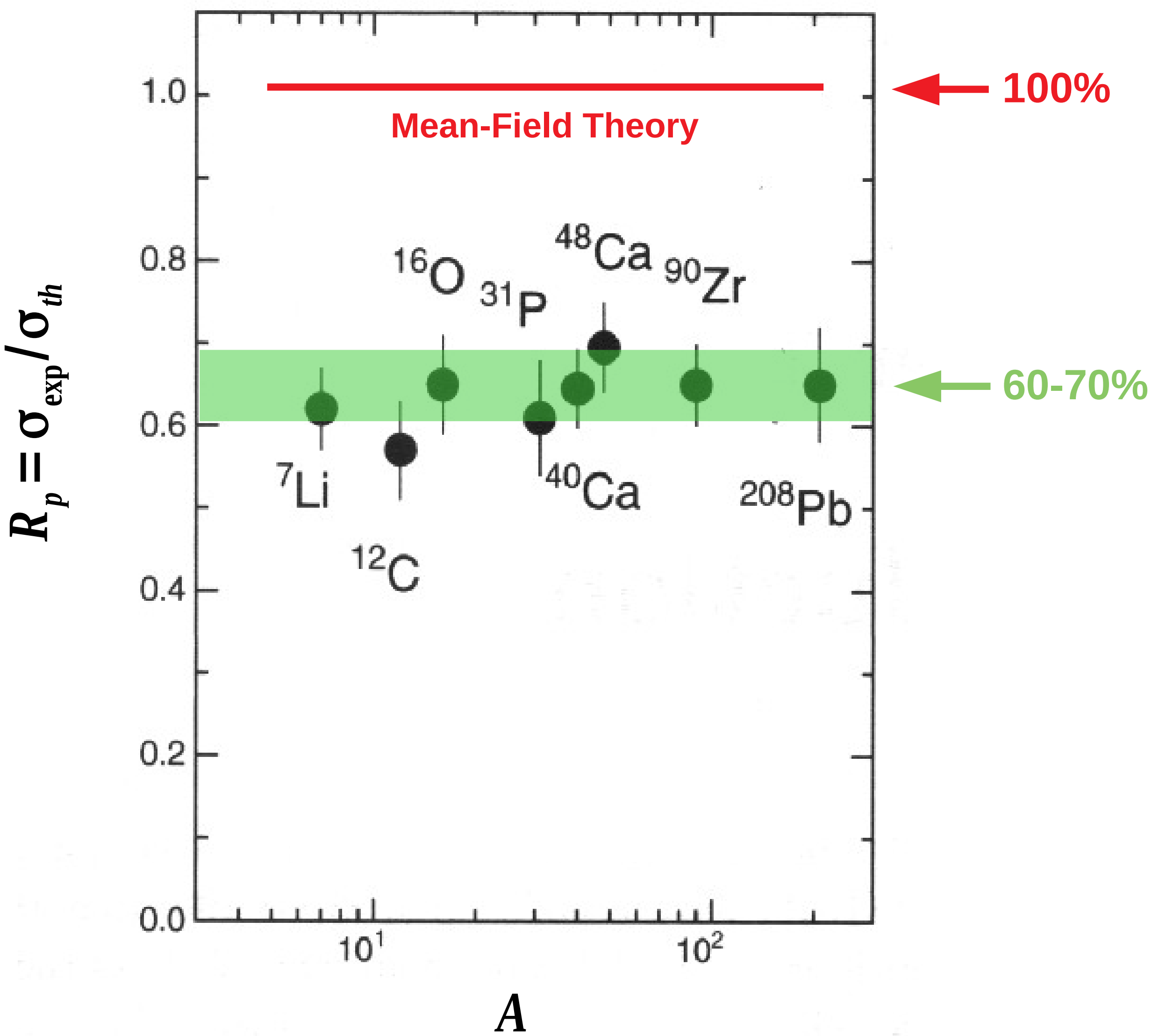
Results in an 'atom like' shell model:

- ✔ Ground state energies
- ✔ Excitation spectrum
- ✔ ...

Wigner, Mayer, and Jenson
(1963 Nobel Prize)

# Single Particle Strength

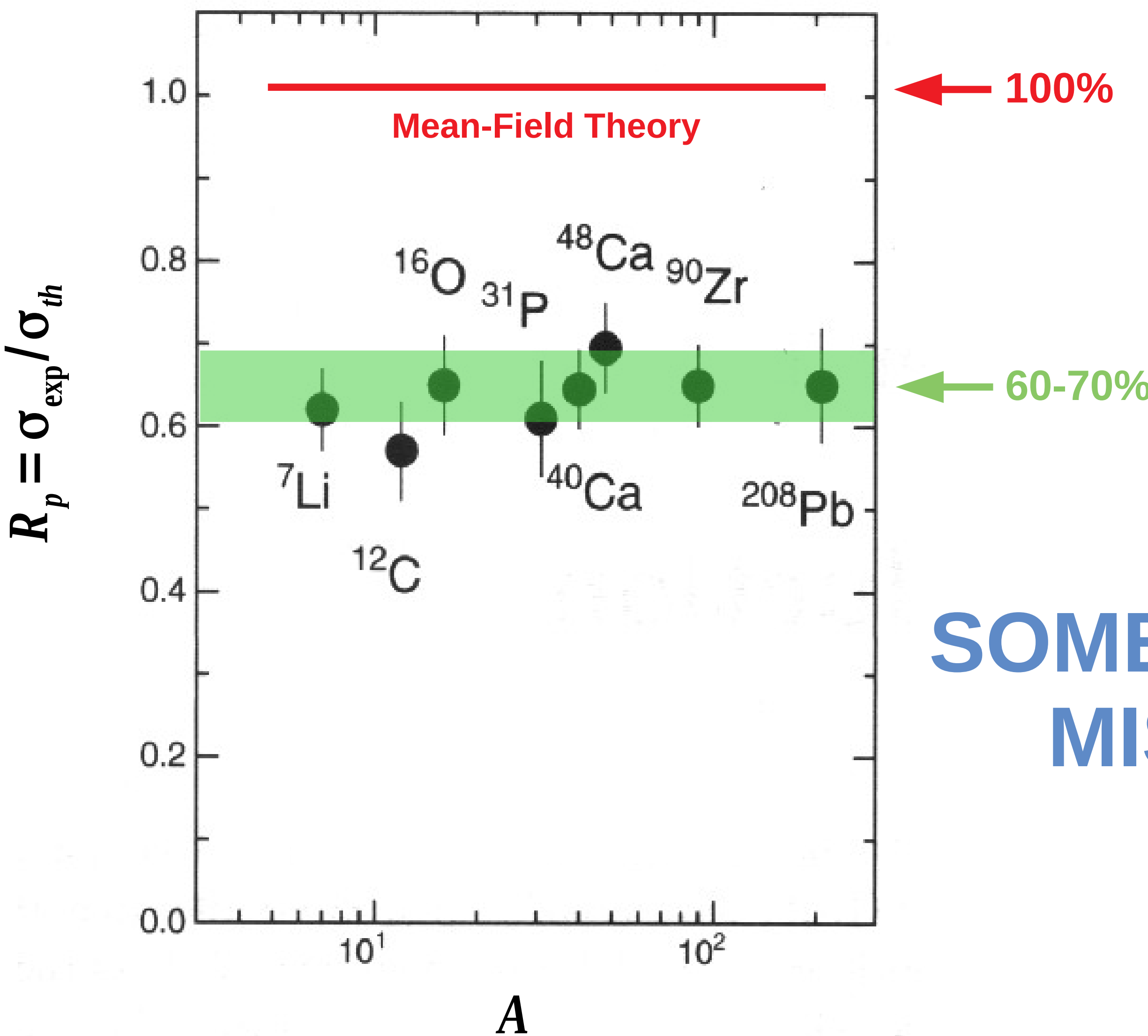
A(e,e'p) reactions




L. Lapikas, Nucl. Phys. A 553 , 297 (1993)

# Single Particle Strength

A(e,e'p) reactions




**SOMETHING IS MISSING !**


L. Lapikas, Nucl. Phys. A 553 , 297 (1993)

# The Nuclear Hamiltonian

$$H = T + \sum_{i<j=1}^{A} V_{2N}(i,j) + \sum_{i<j<k=1}^{A} V_{3N}(i,j,k) + \ldots$$

**2-body** **3-body**

Mean-Field Approximation: $H = T + \sum_{i=1}^{A} V(i)$

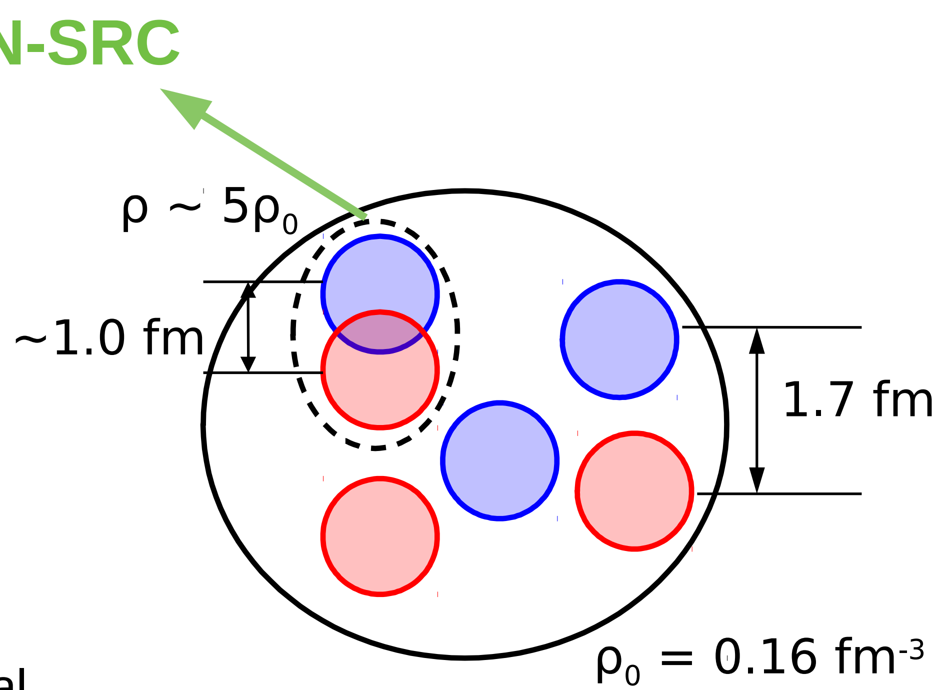
Results in an ‘atom like’ shell model:

- Ground state energies
- Excitation spectrum
- …

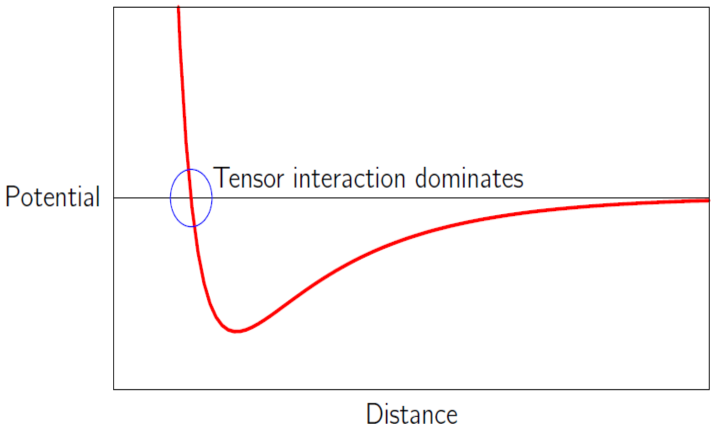
Wigner, Mayer, and Jenson
(1963 Nobel Prize)

**Beyond the Mean-Field: NN Correlations**

# What are Short Range Correlations ?




Scalar part NN potential



# Why Study SRCs ?

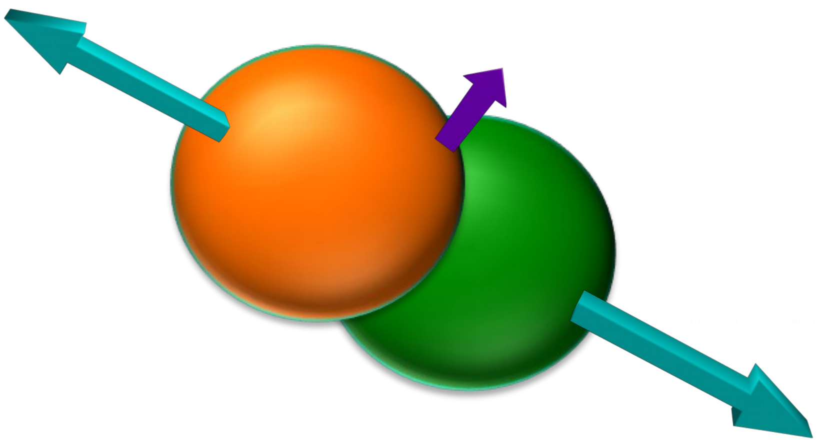
Significant part of the nuclear wave-function (~20%, 60% of the kinetic energy)

NN interaction at short distances

Implications:
Bound nucleon structure
Neutron stars
...

# Study SRCs Experimentally

Coordinate space → Momentum space

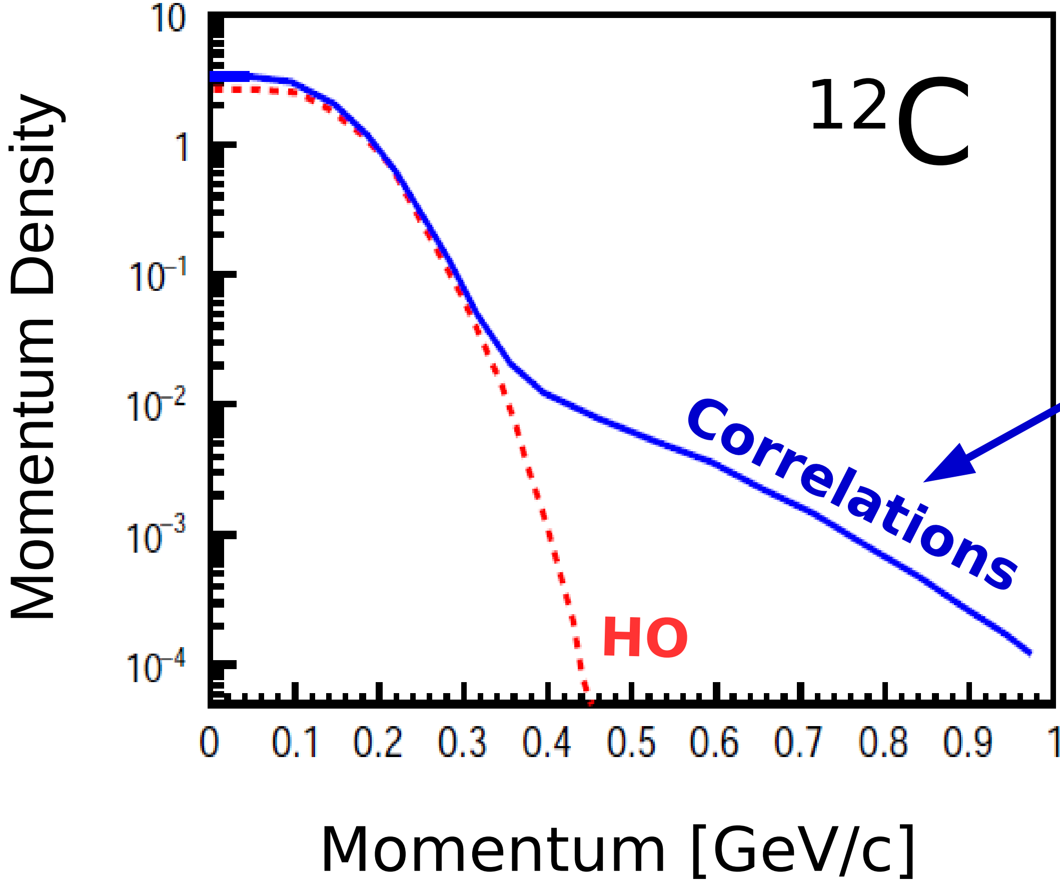


$k_{rel} > k_F$ $k_{CM} < k_F$

$k_F \approx 250$ MeV/c

A pair with:
**large relative momentum**
and **small C.M. momentum**.

# Correlations and High-Momentum tail

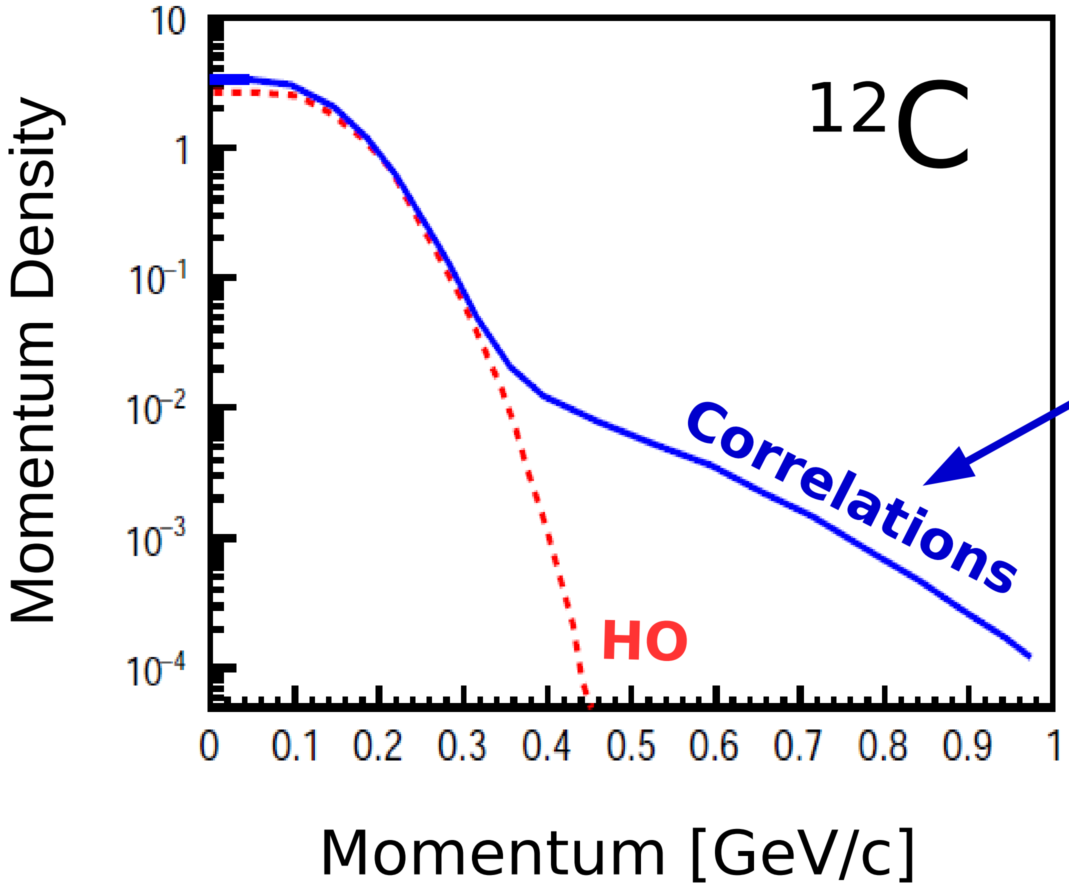



**High-momentum tail:**

**Can be explained by correlations**

Ciofi degli Atti, PRC 53 (1996) 1689

# Correlations and High-Momentum tail



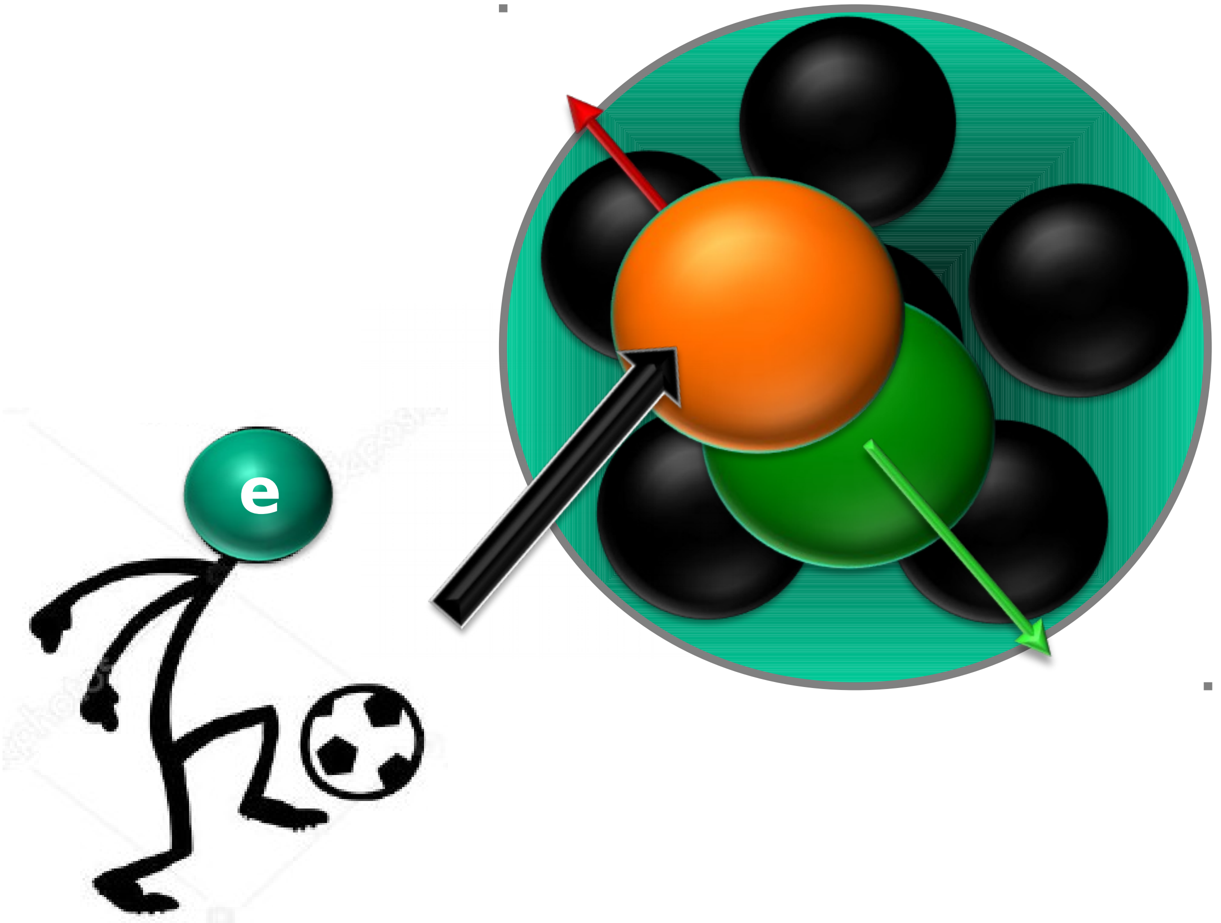

**High-momentum tail:**

**Can be explained by correlations**

**SRC ?**

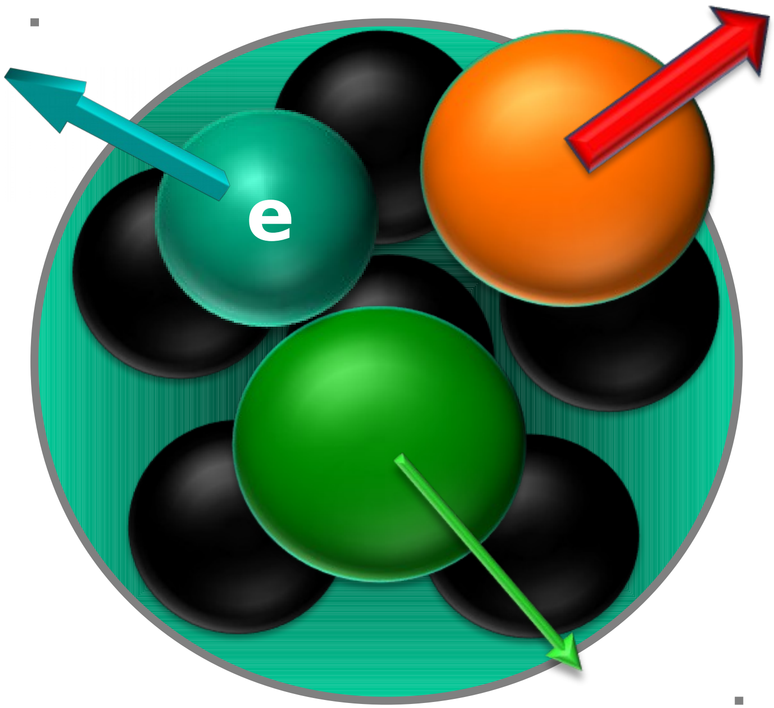
Ciofi degli Atti, PRC 53 (1996) 1689

# Hard Knockout Reaction

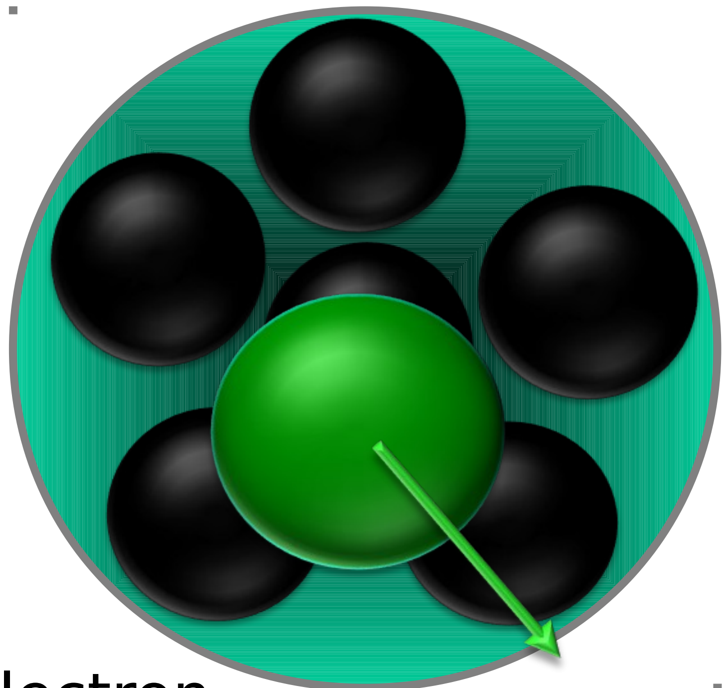



Breakup the pair

# Hard Knockout Reaction



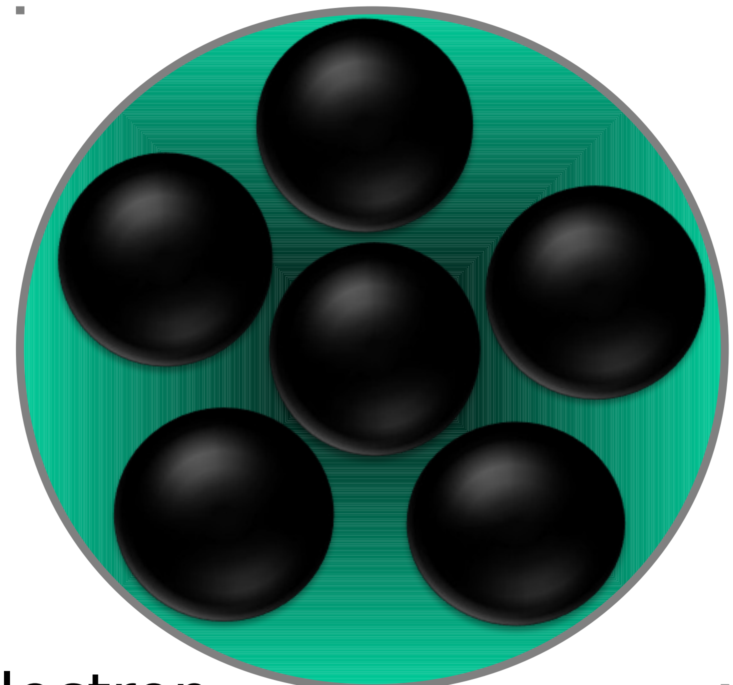
# Hard Knockout Reaction

Detect knockout nucleon

Detect scattered electron

# Hard Knockout Reaction

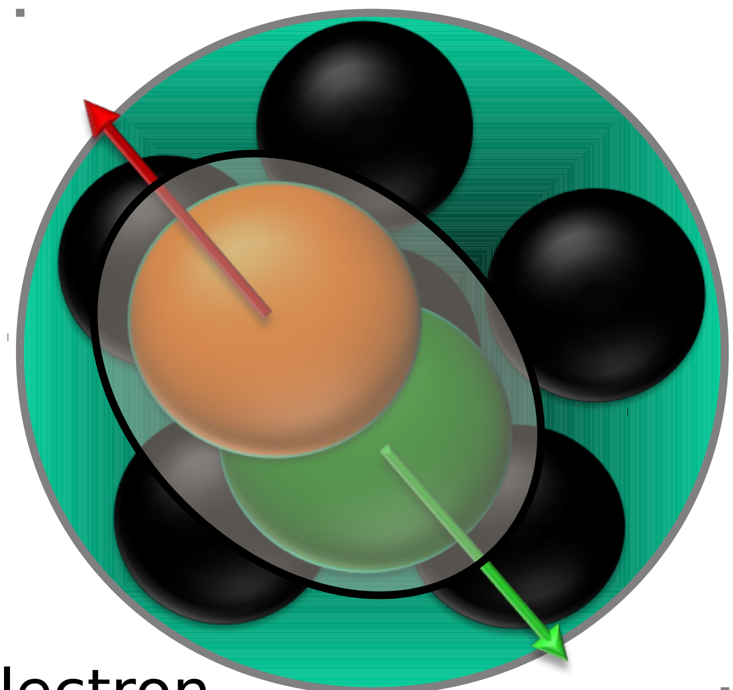
Detect knockout nucleon

Detect scattered electron

Look for its partner

# Hard Knockout Reaction


Reconstruct the 'initial' state

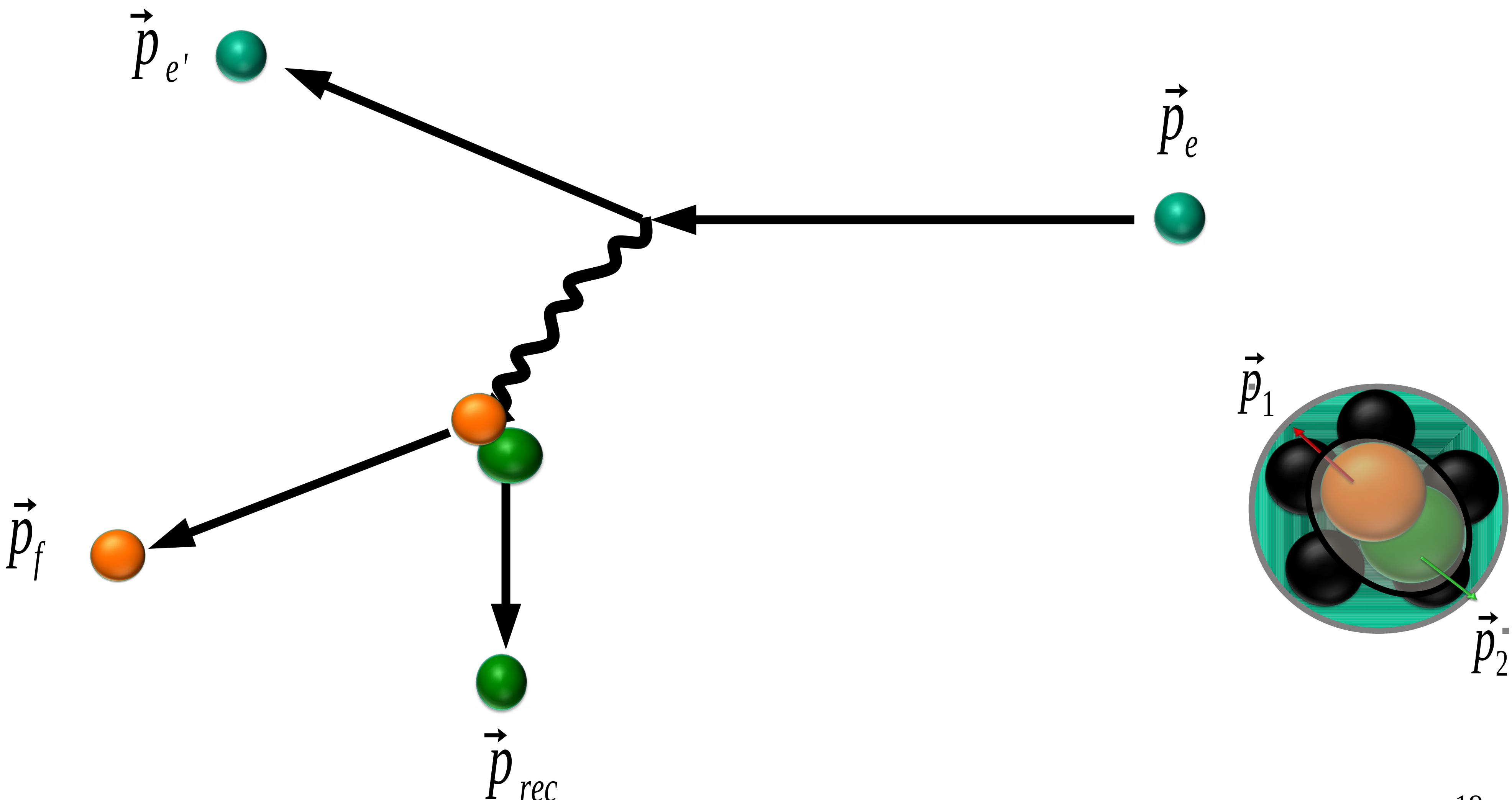


Detect knockout nucleon

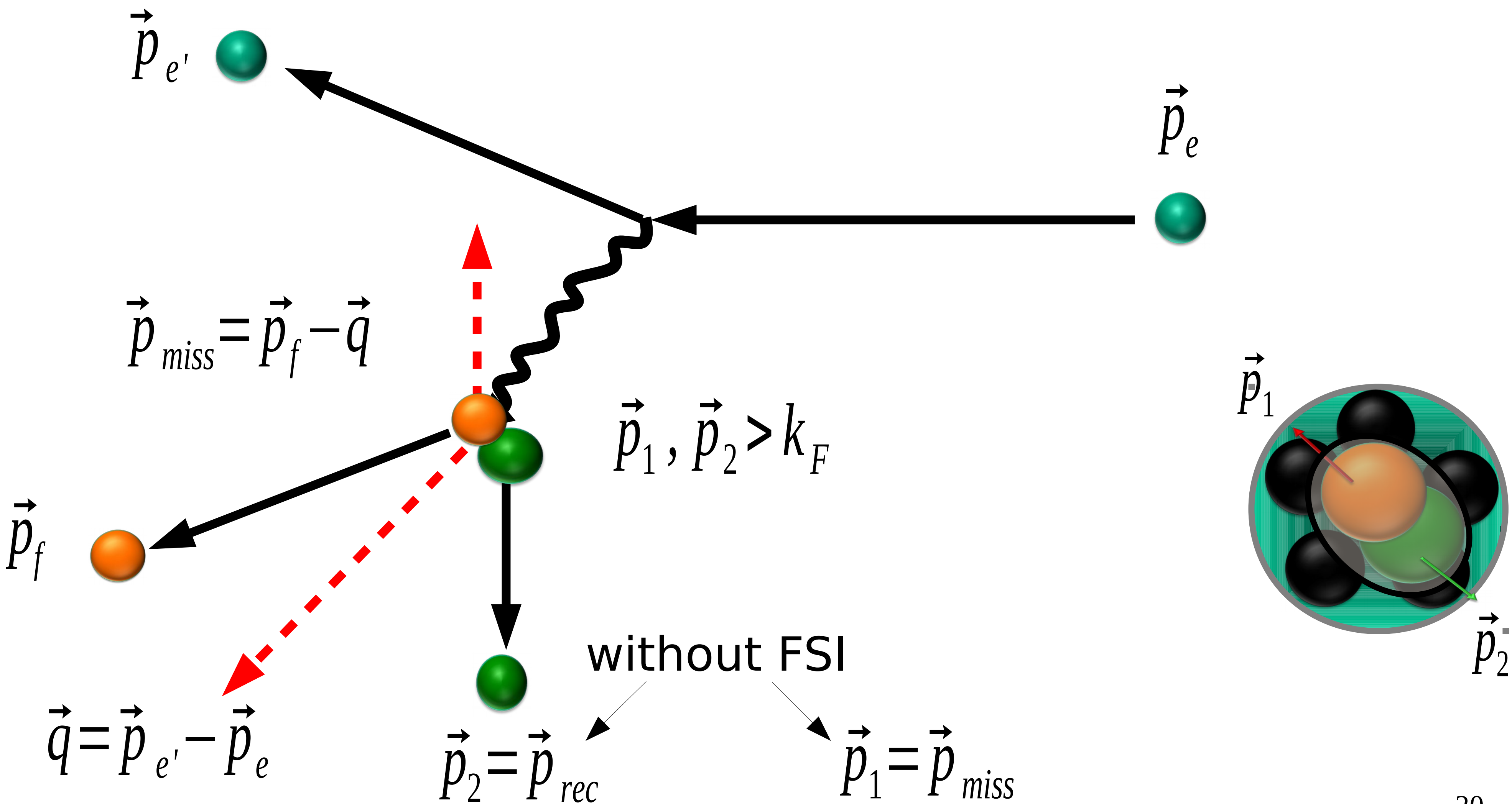
Detect scattered electron

Look for its partner

# Reconstruct the initial state

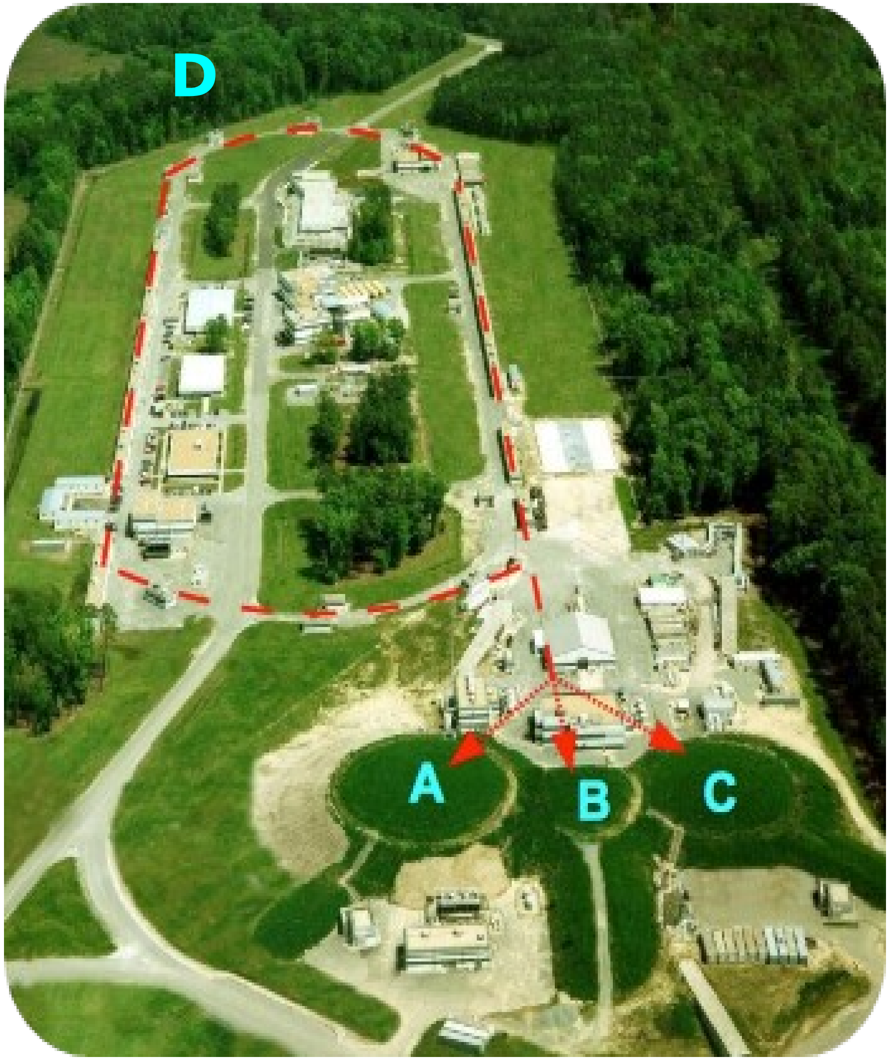


# Reconstruct the initial state

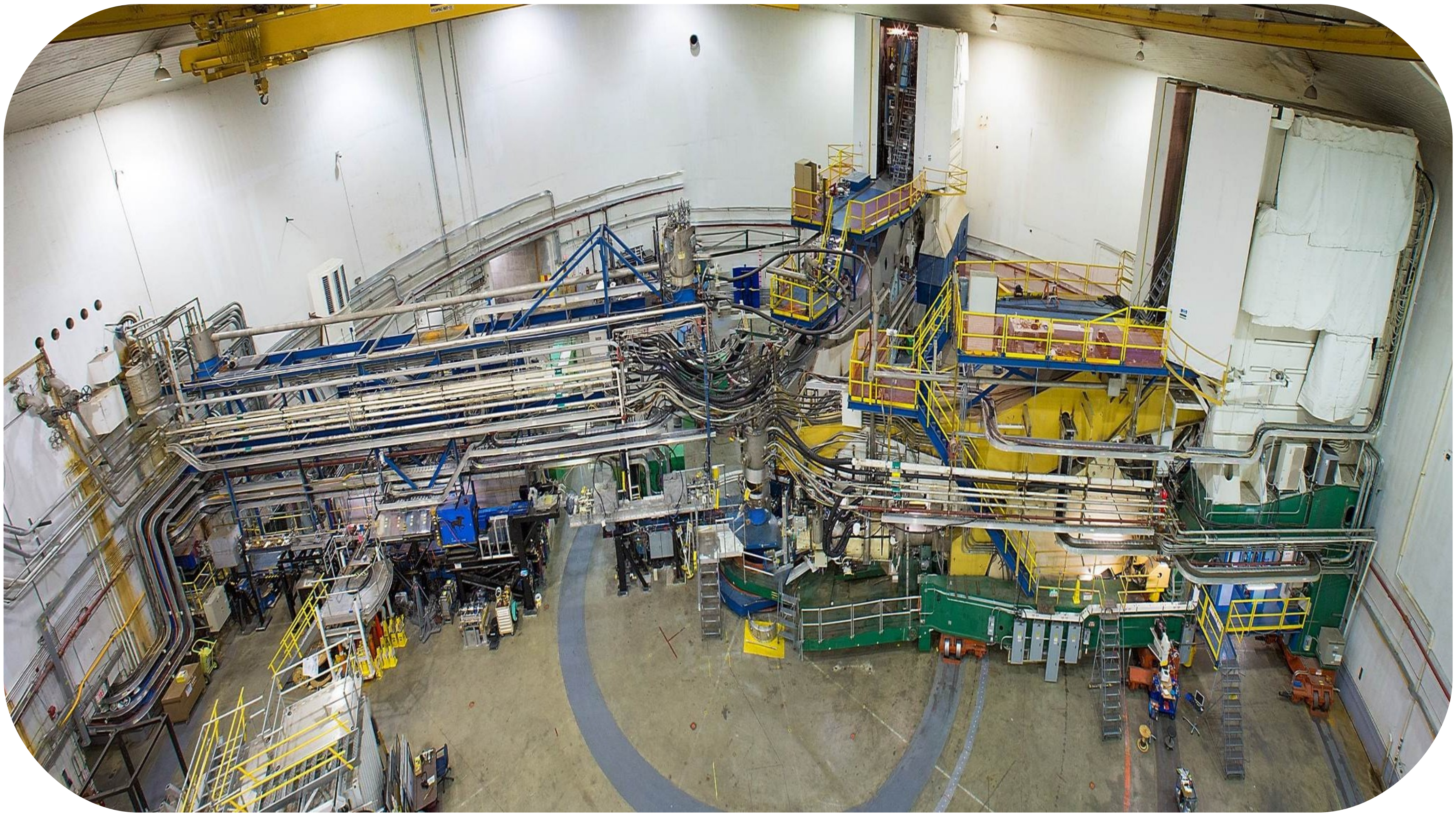


# SRC @ Jefferson Lab

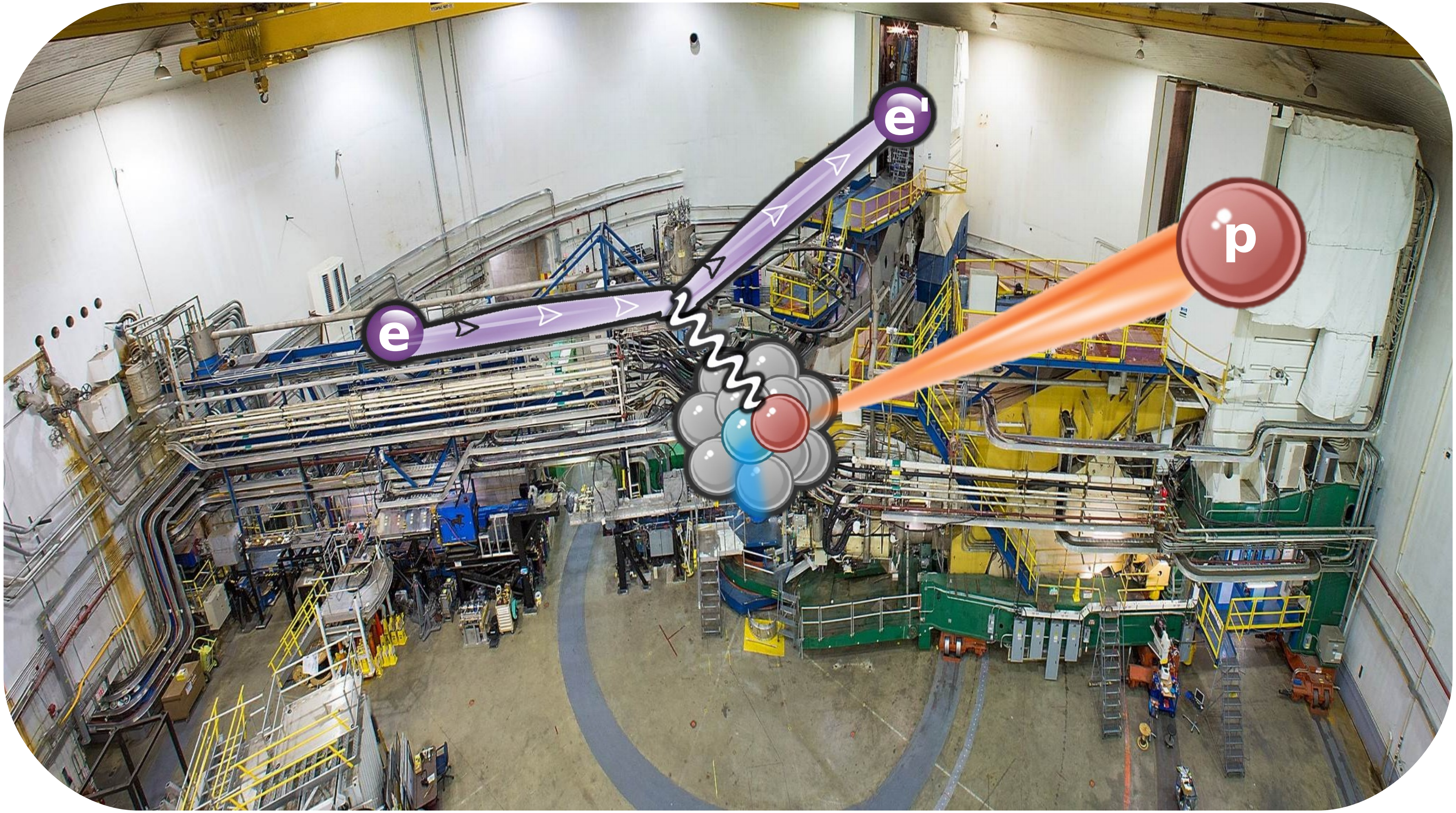
- Virginia, USA
- 12 (6) GeV electron beam
- 4 (3) experimental halls



# Hall-A: High-Resolution Spectrometers



# Hall-A: (e,e'pN)



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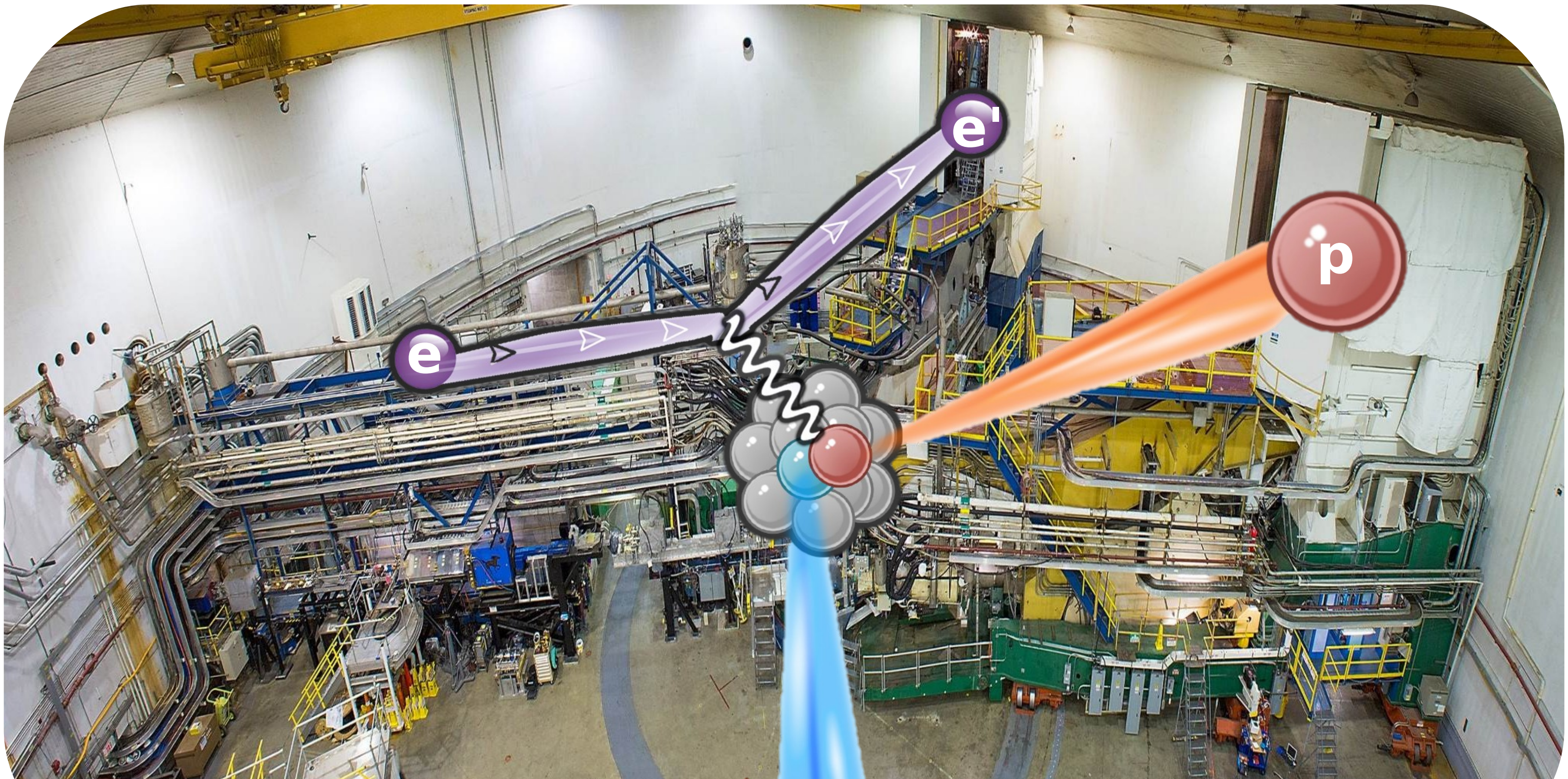
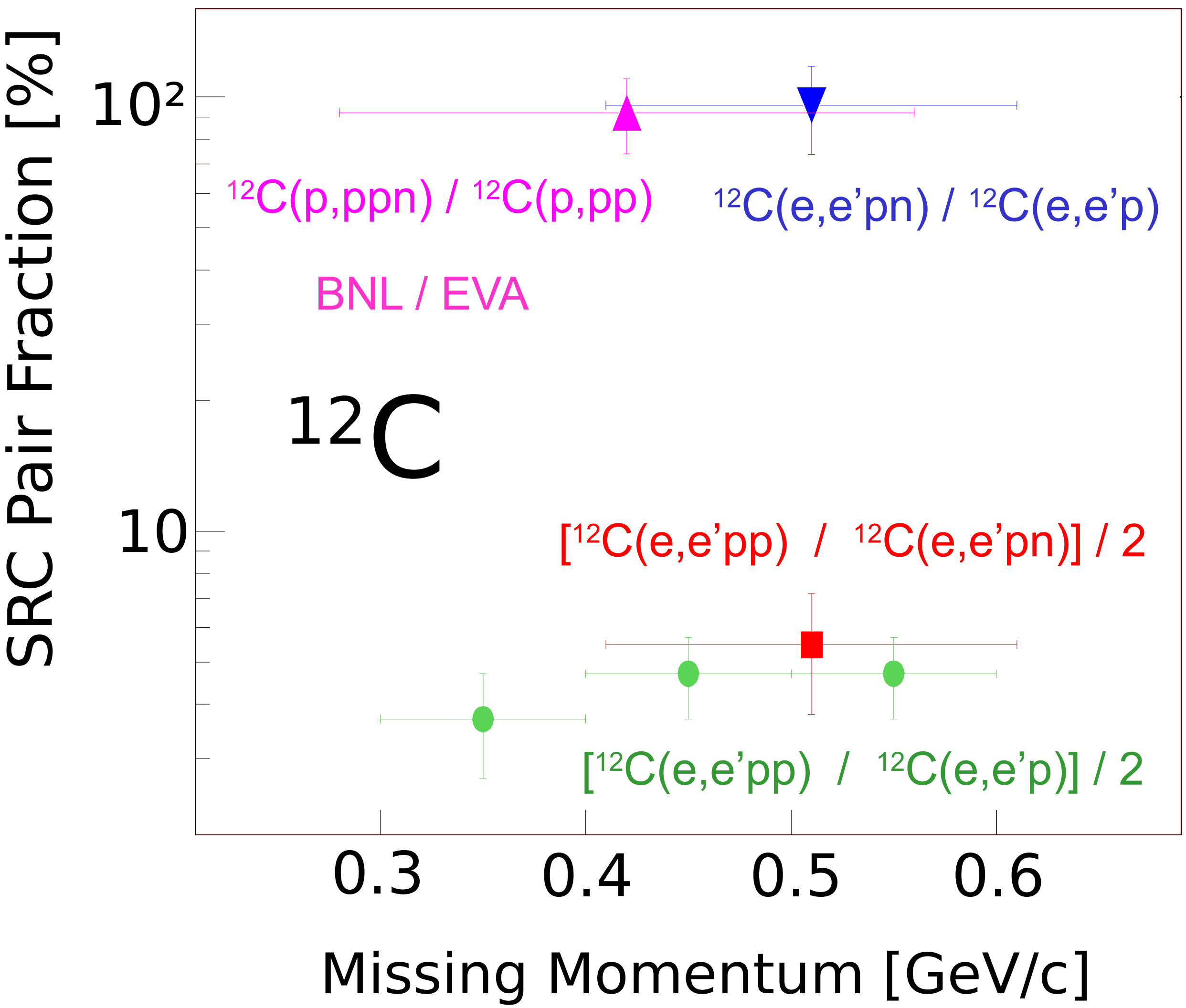



BigBite Spectrometer

Neutron Detector

# High-momentum nucleons go in pairs




Subedi et al., Science 320 (2008)

Piasetzky et al., PRL. 97 162504 (2006)

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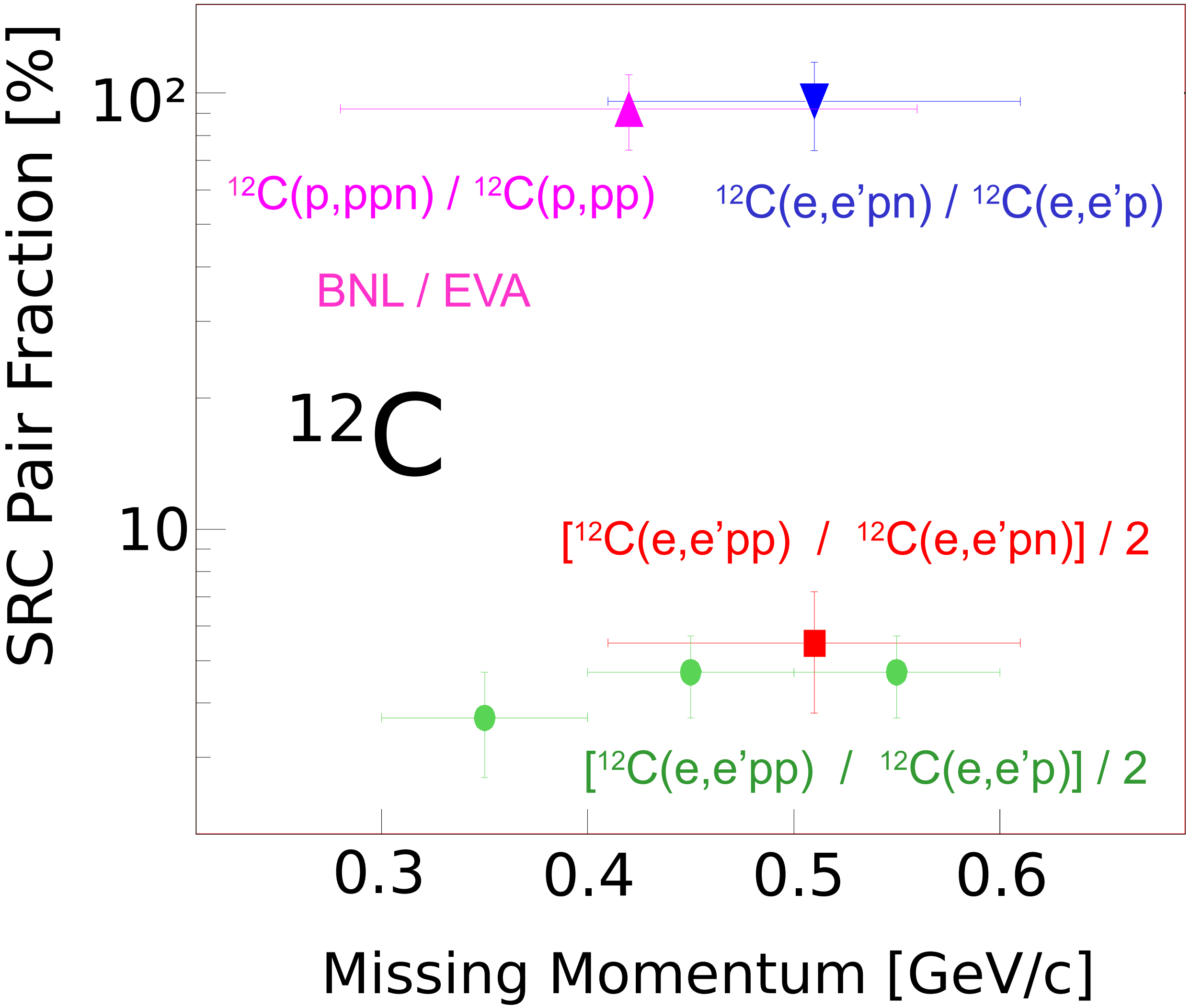


High-momentum tail is dominated by SRC pairs

Subedi et al., Science 320 (2008)

Piasetzky et al., PRL. 97 162504 (2006)

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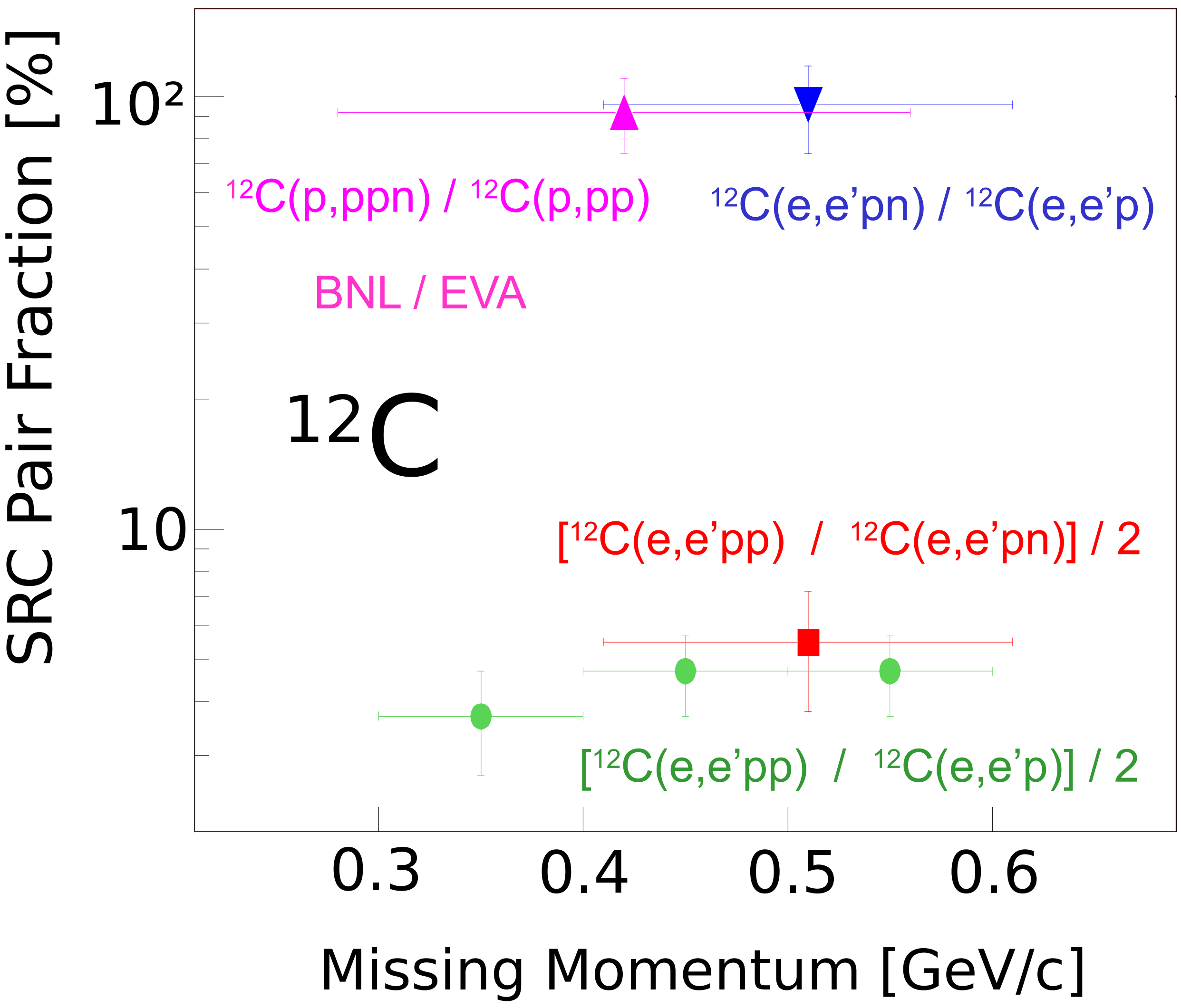



Subedi et al., Science 320 (2008)

Piasetzky et al., PRL. 97 162504 (2006)

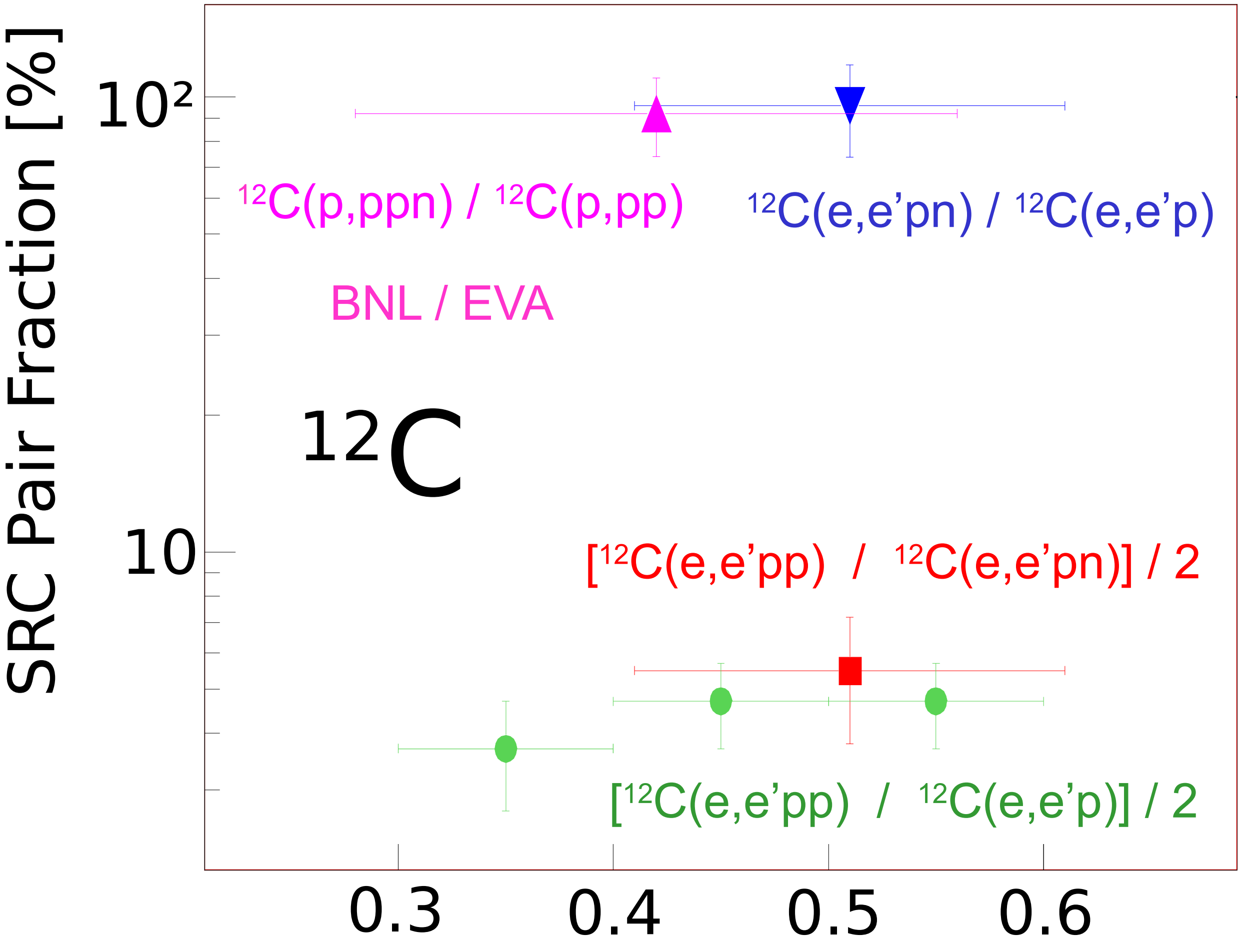
High-momentum tail is dominated by SRC pairs

**np – dominance:**

~90% np pairs

~5% pp (nn) pairs

# High-momentum nucleons go in pairs




High-momentum tail is dominated by SRC pairs

**np – dominance:**

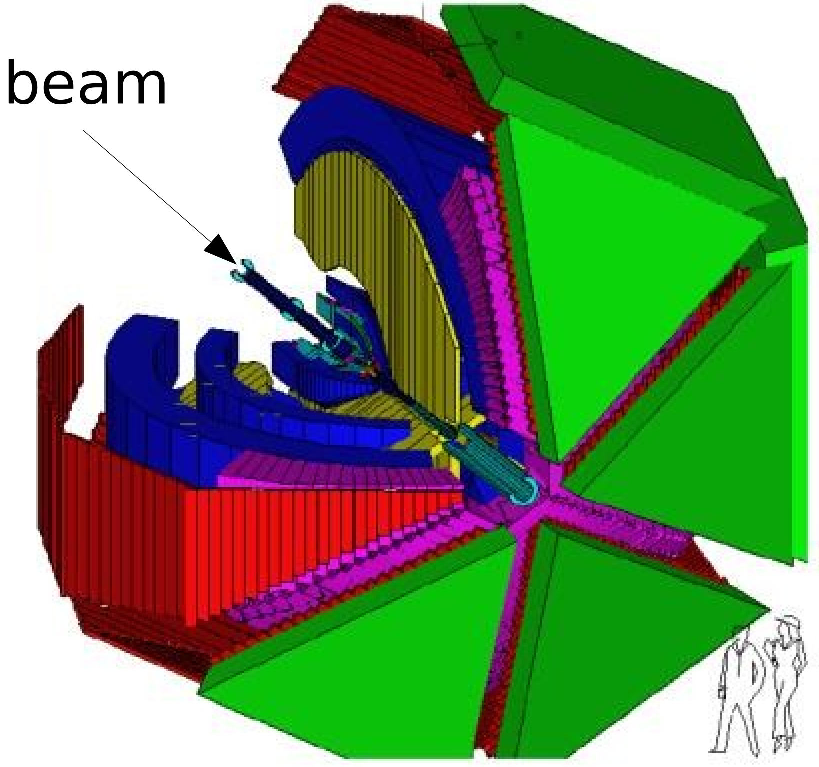
~90% np pairs

~5% pp (nn) pairs

**What about neutron rich nuclei? (N>Z)**

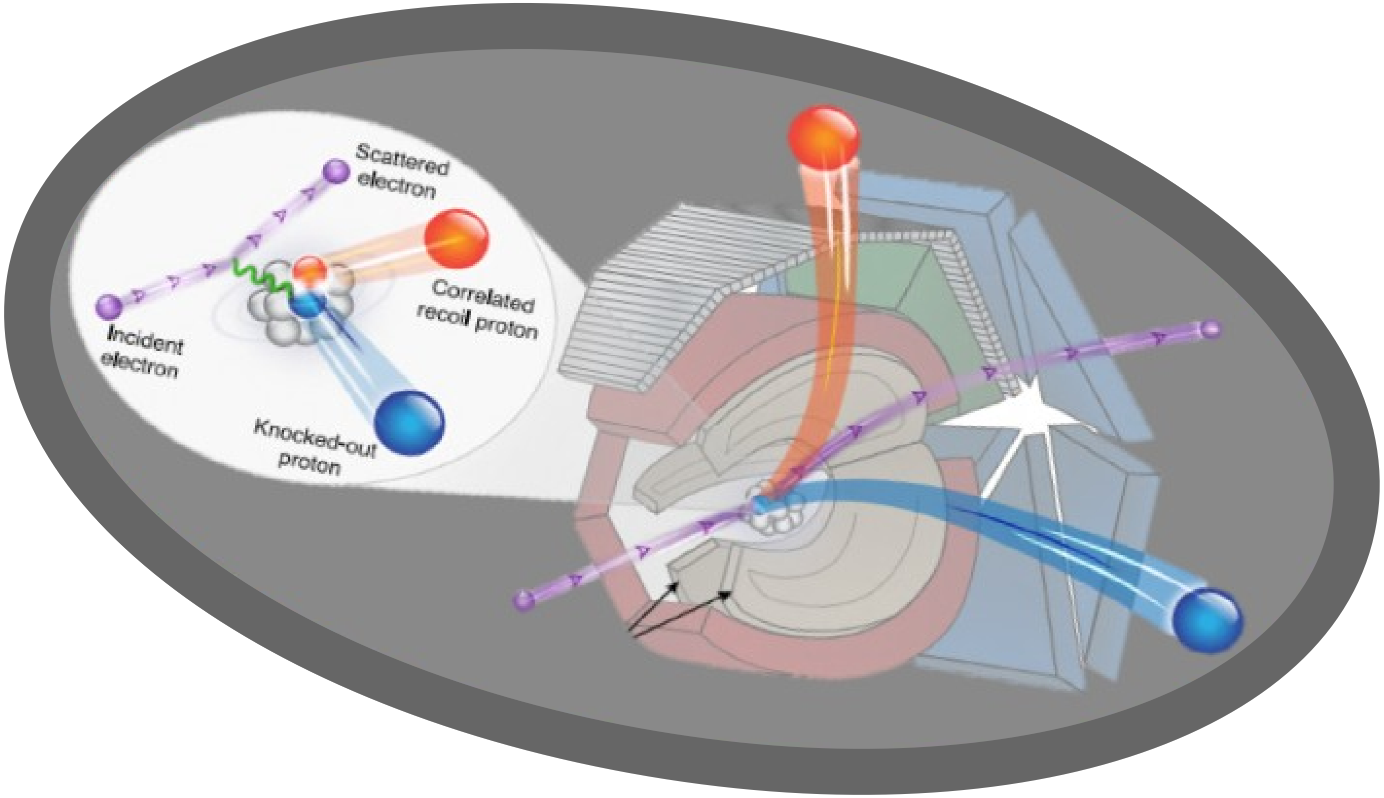
Piasetzky et al., PRL. 97 162504 (2006)

# **C**EBAF **L**arge **A**cceptance **S**pectrometer




- Open (e,e') trigger
- Large-Acceptance
- Low luminosity (~$10^{34}$ $cm^{-2}$ $sec^{-1}$)

# **C**EBAF **L**arge **A**cceptance **S**pectrometer

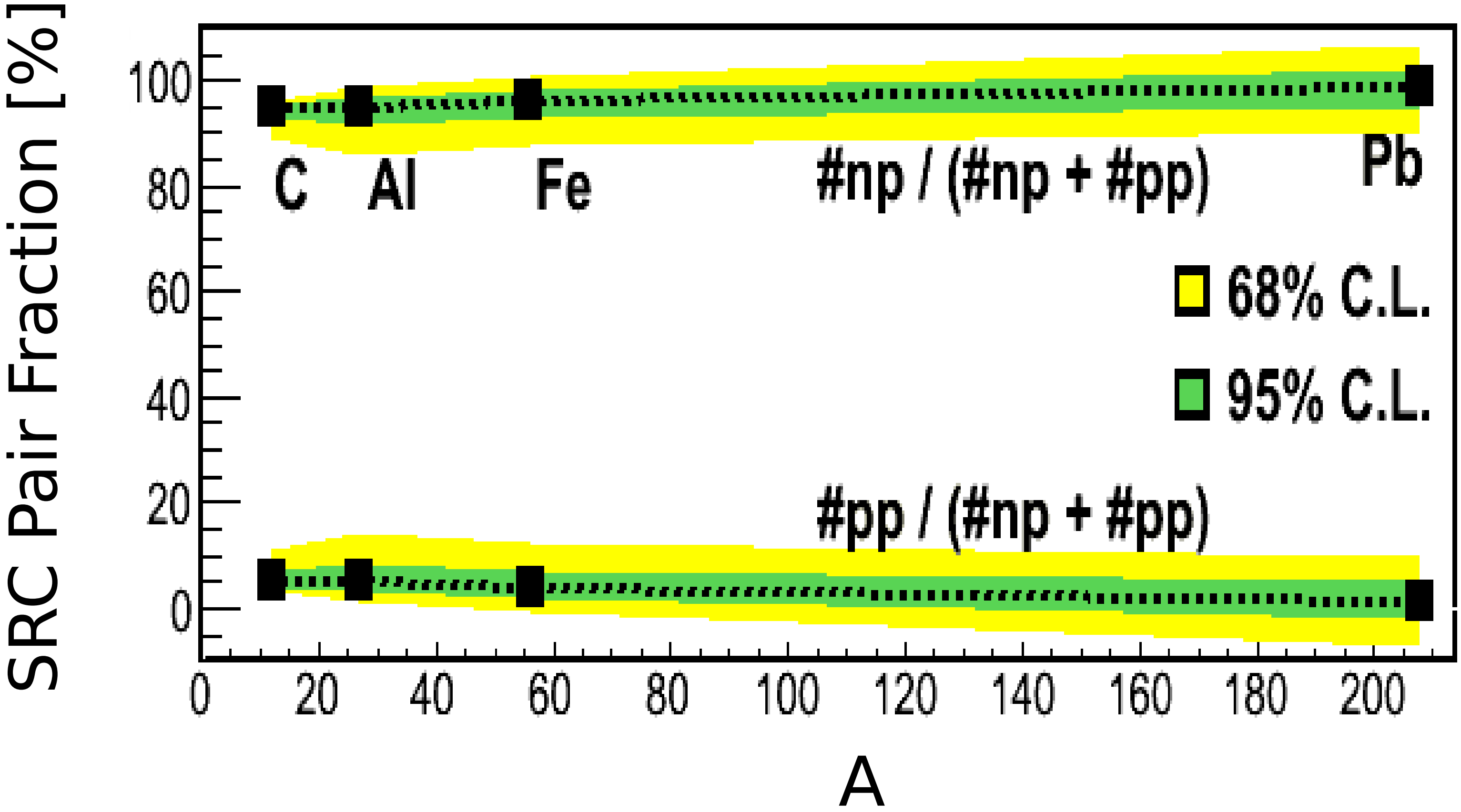



5 GeV electron

C, Al, Fe, Pb targets

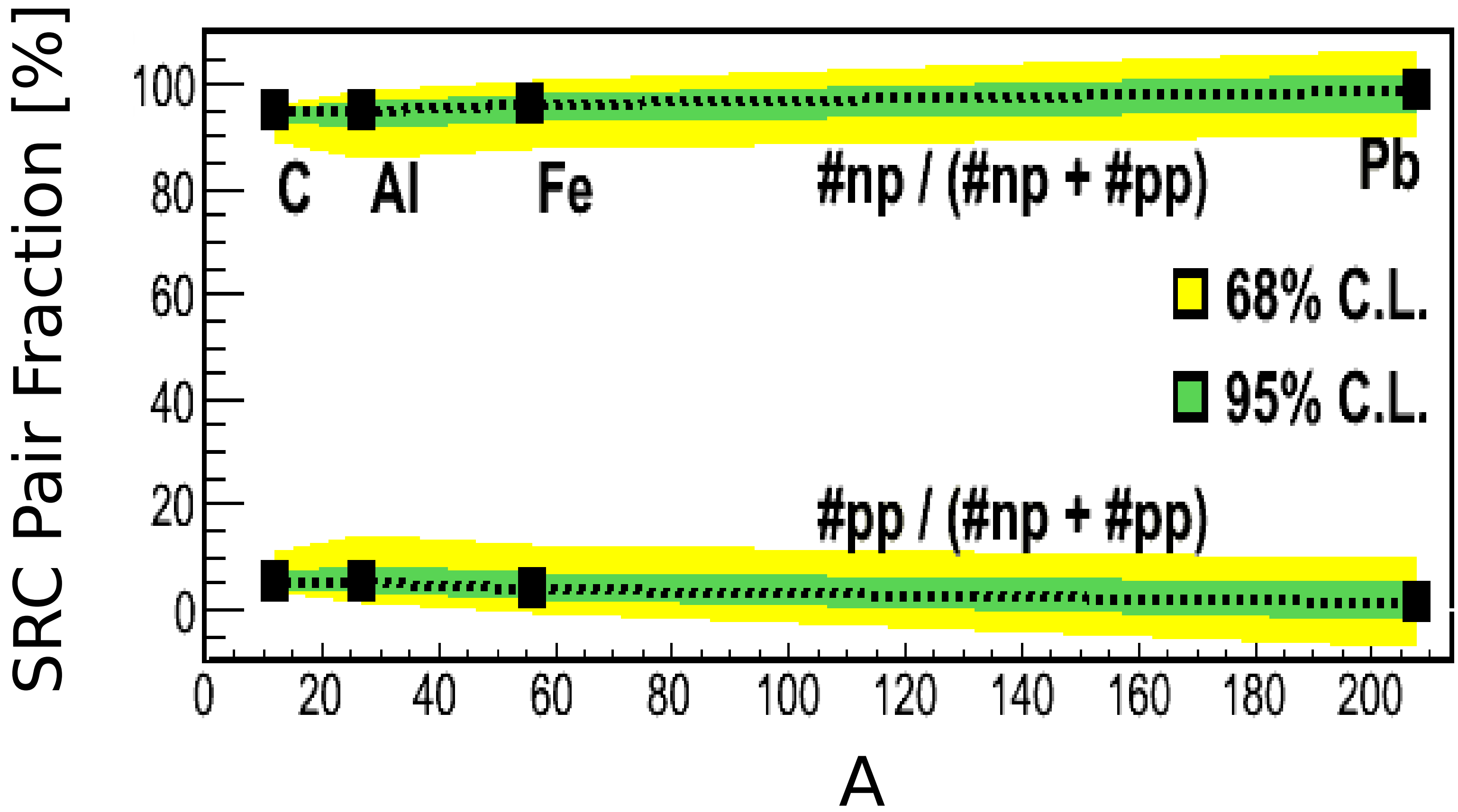
$P_{miss}$ = 300-600 MeV/c

# np – dominance




Hen et al., Science 346 (2014)

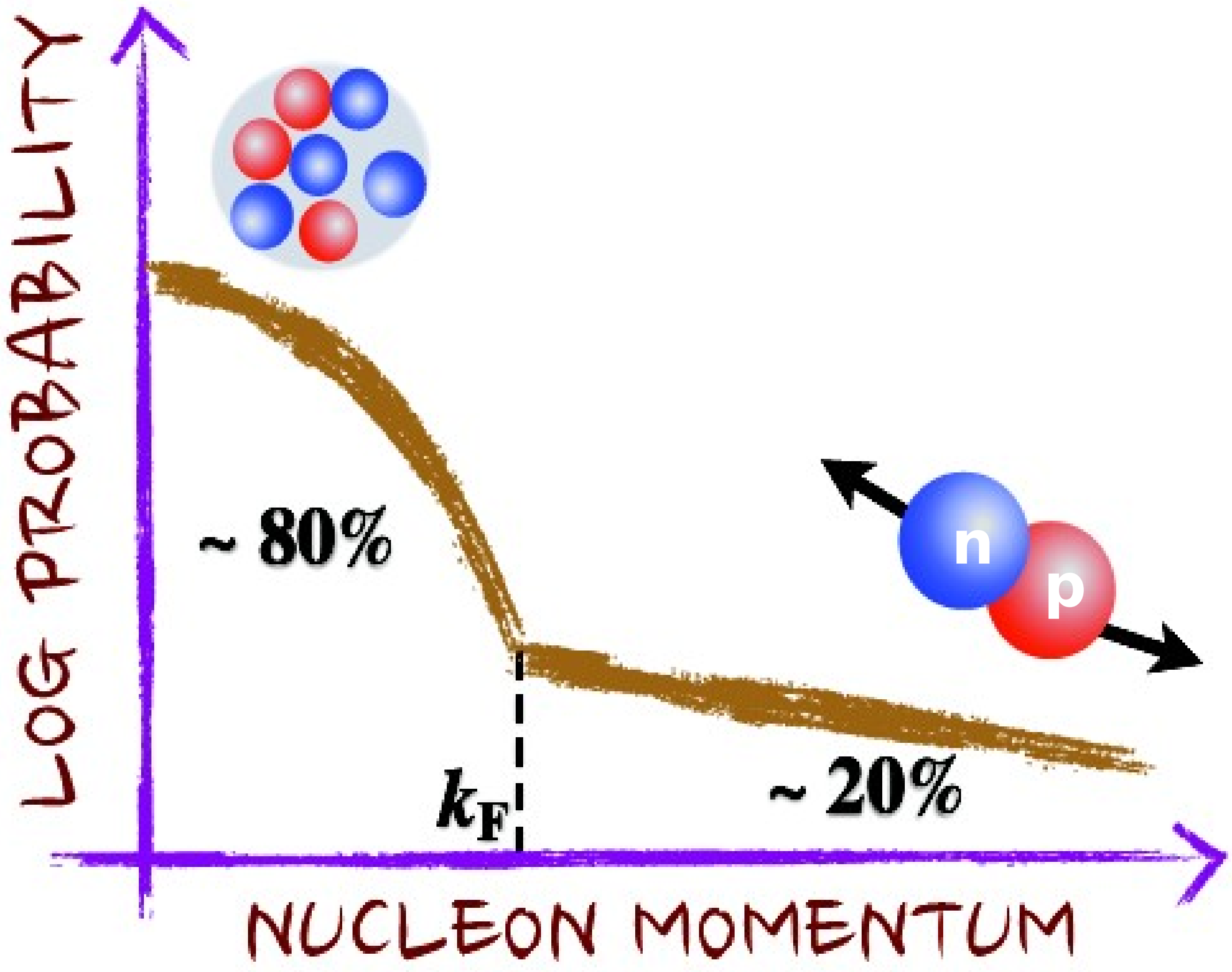
# np – dominance

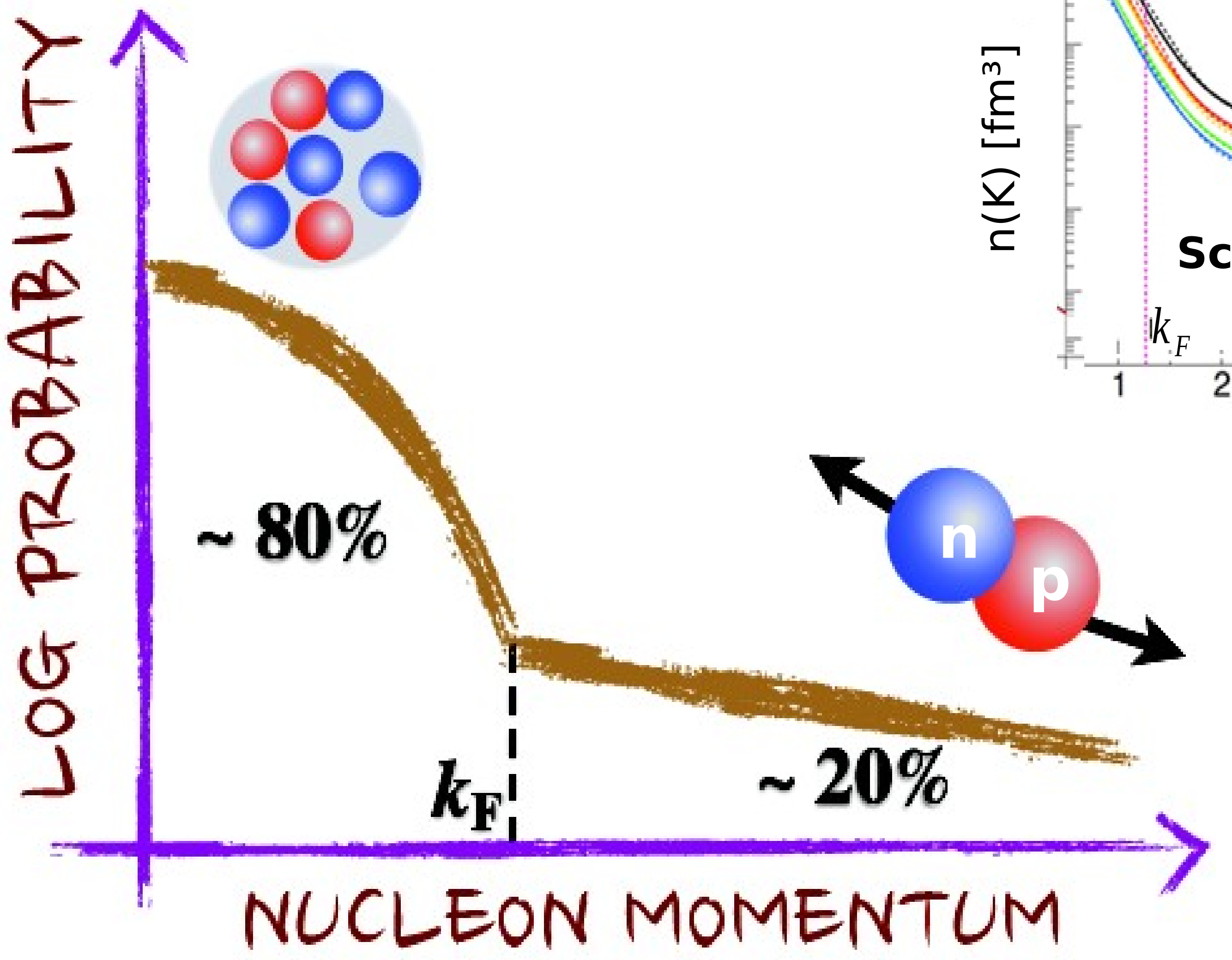



Hen et al., Science 346 (2014)

Inferred from (e,e'p) & (e,e'pp) events

Assuming every (e,e'p) event has a correlated partner


LOG PROBABILITY
~ 80%
$k_F$
~ 20%
n
p
NUCLEON MOMENTUM


LOG PROBABILITY
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~ 80%
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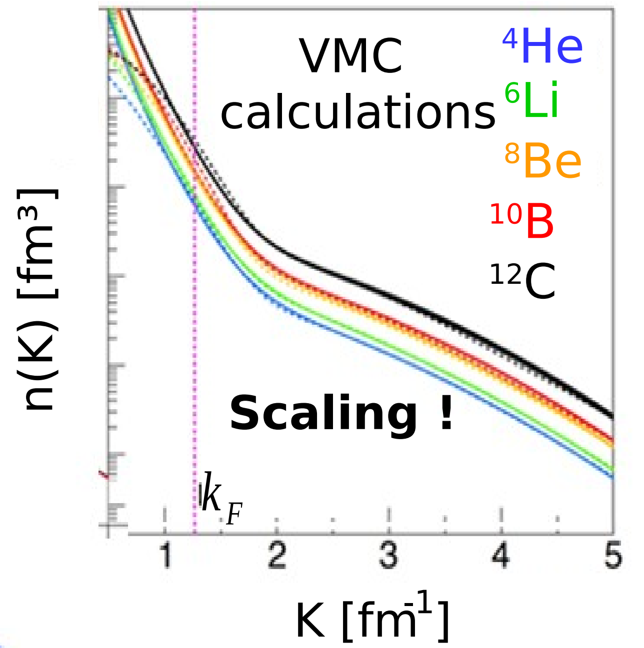
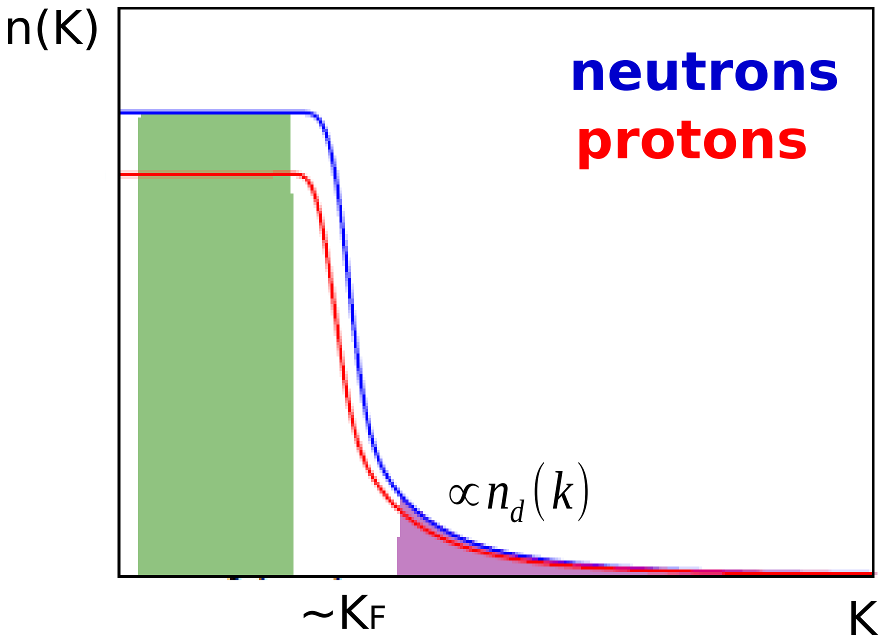
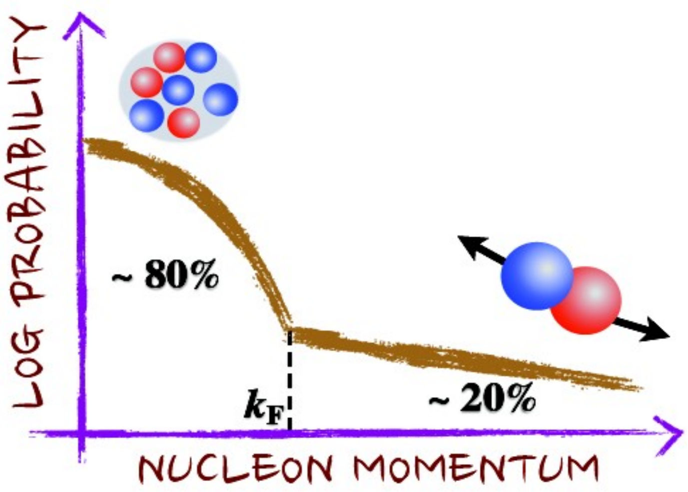
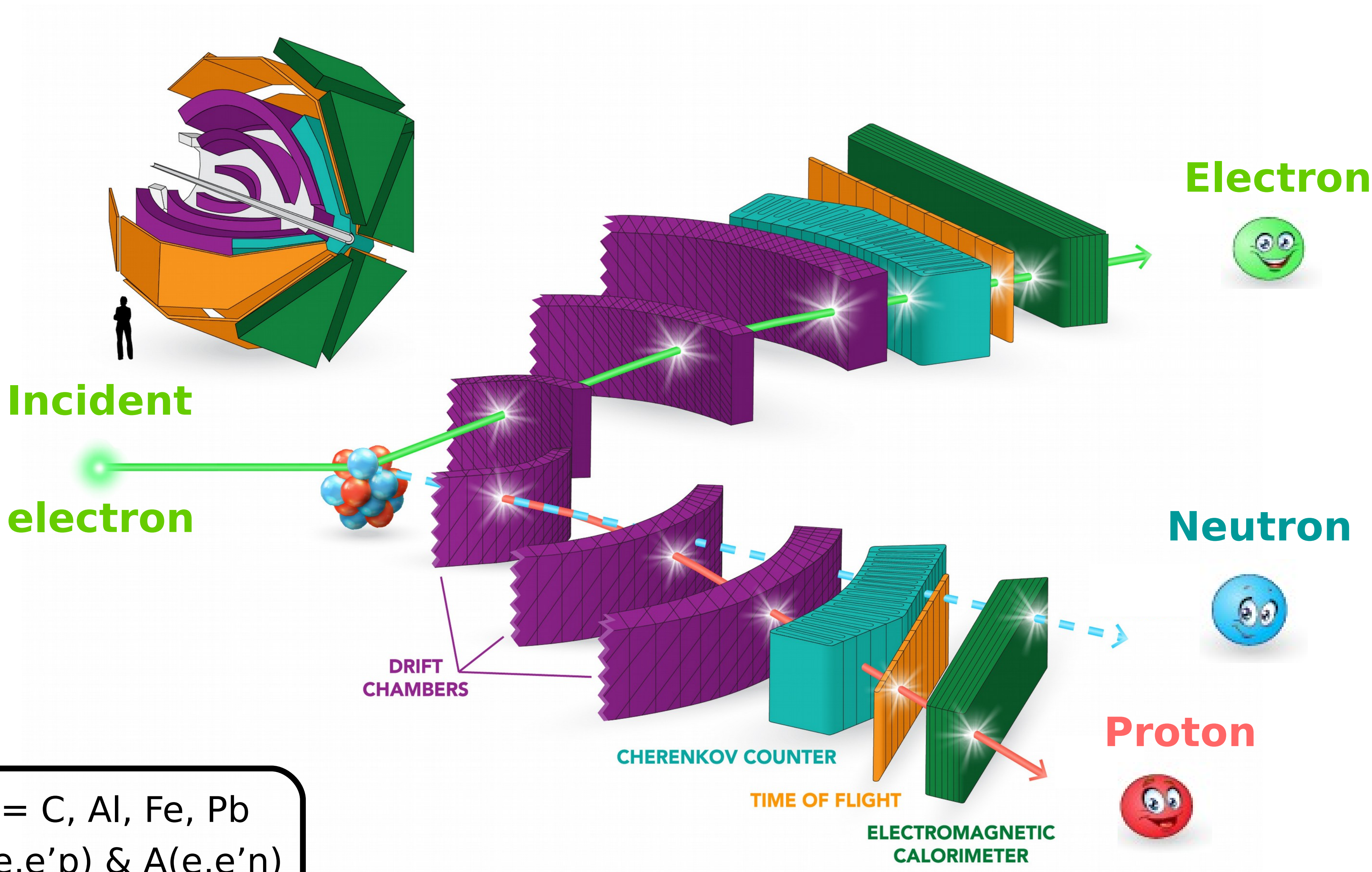

VMC calculations
$^4$He
$^6$Li
$^8$Be
$^{10}$B
$^{12}$C
Scaling !
n(K) [fm$^3$]
K [fm$^{-1}$]
$k_F$
1
2
3
4
5

# Momentum distributions in asymmetric nuclei



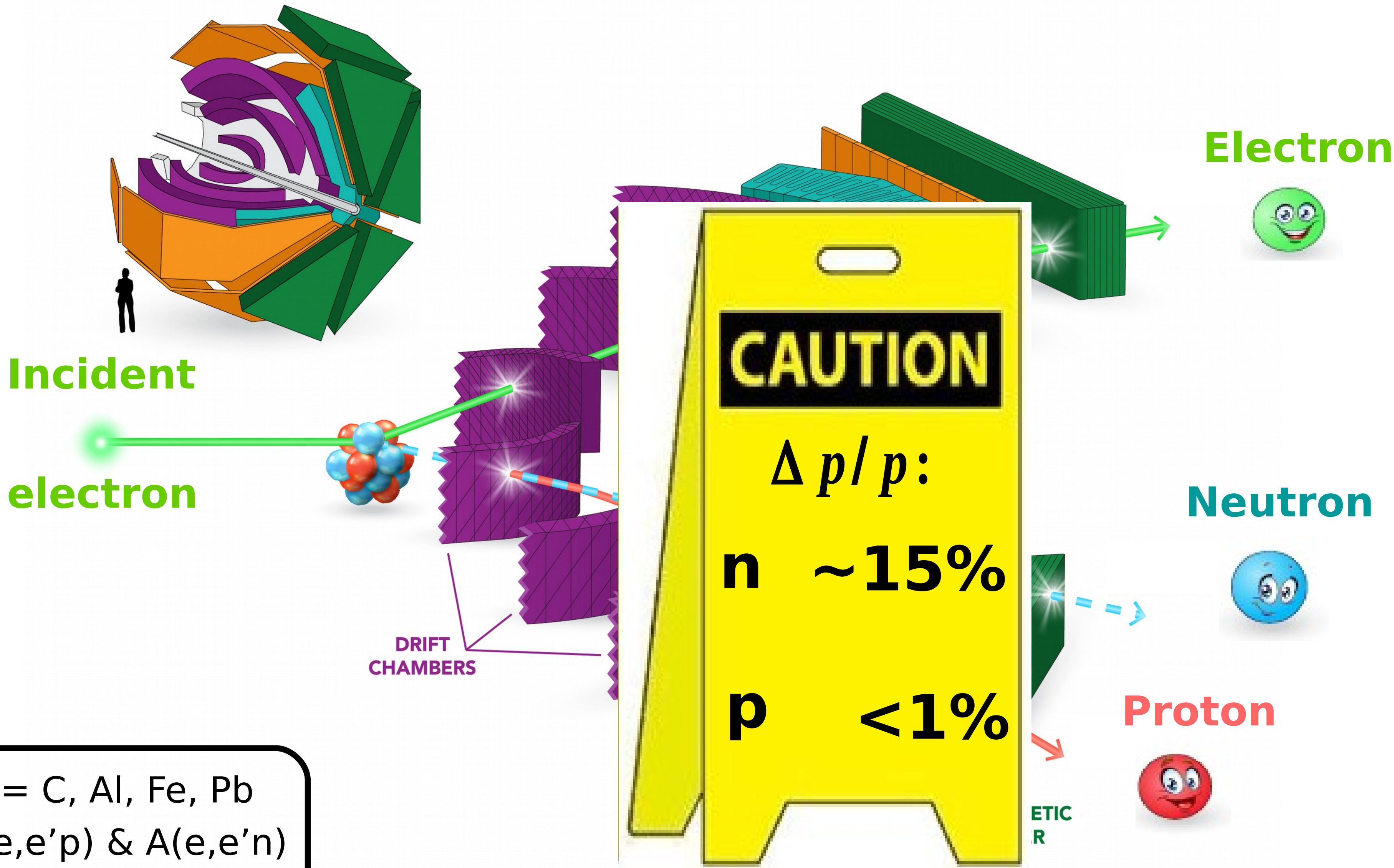



# Proton vs. Neutron Knockout @ clas




A = C, Al, Fe, Pb
A(e,e'p) & A(e,e'n)
double-coincidence

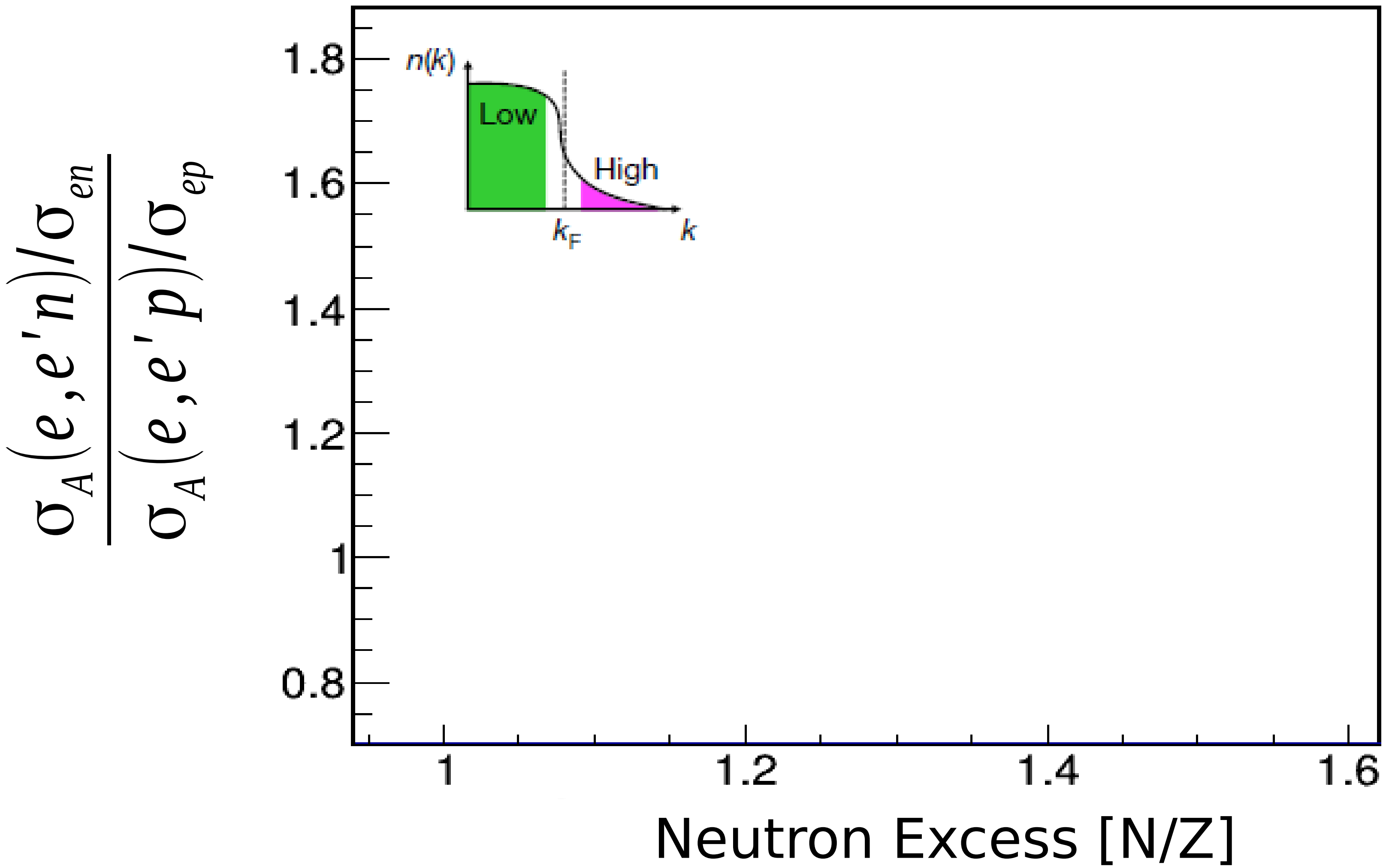
# Proton vs. Neutron Knockout @ clas




A = C, Al, Fe, Pb
A(e,e'p) & A(e,e'n)
double-coincidence

# Results

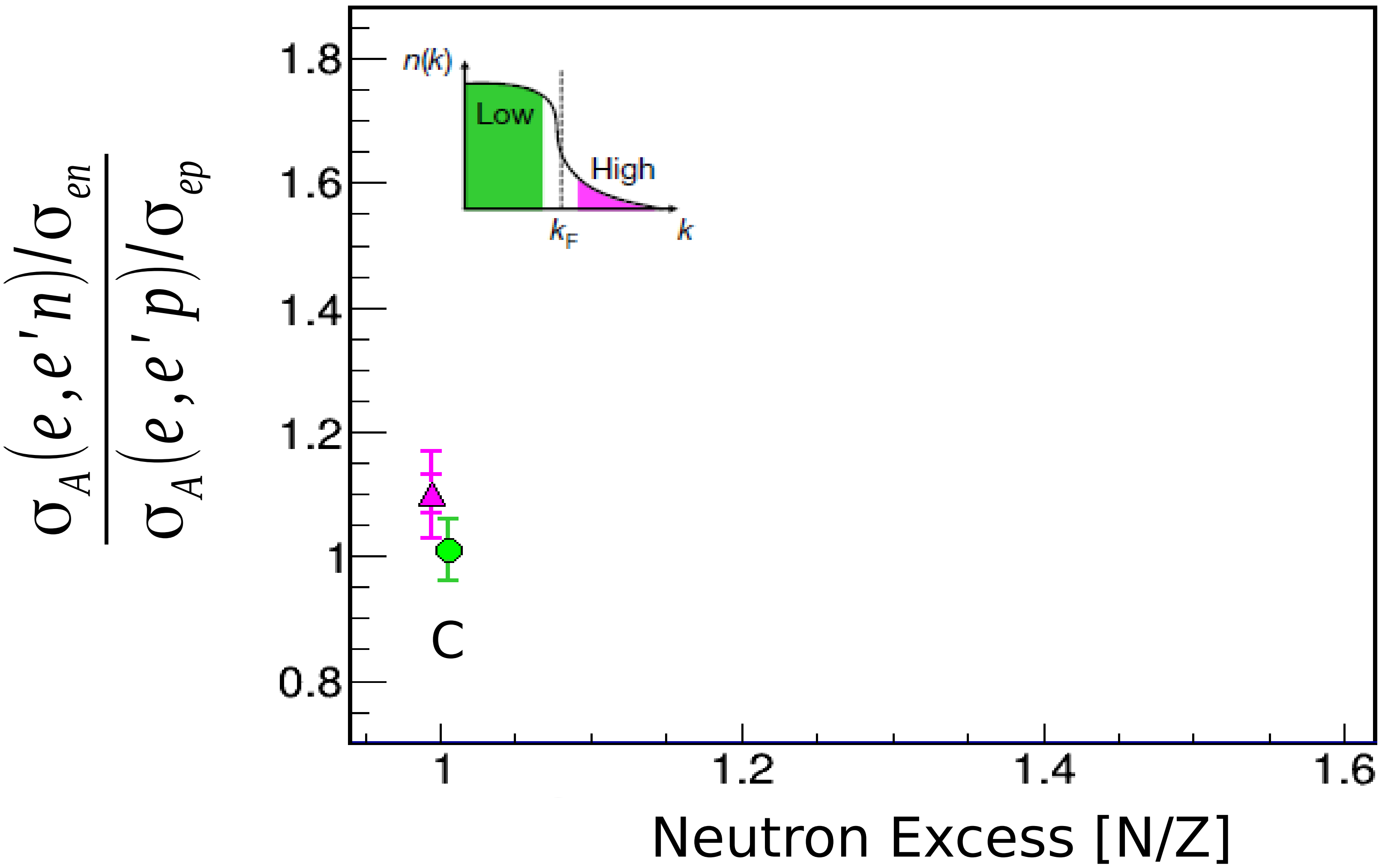
# Proton vs. Neutron Populations






Duer et al. (CLAS Collaboration), Nature, **506**, 617 (2018)

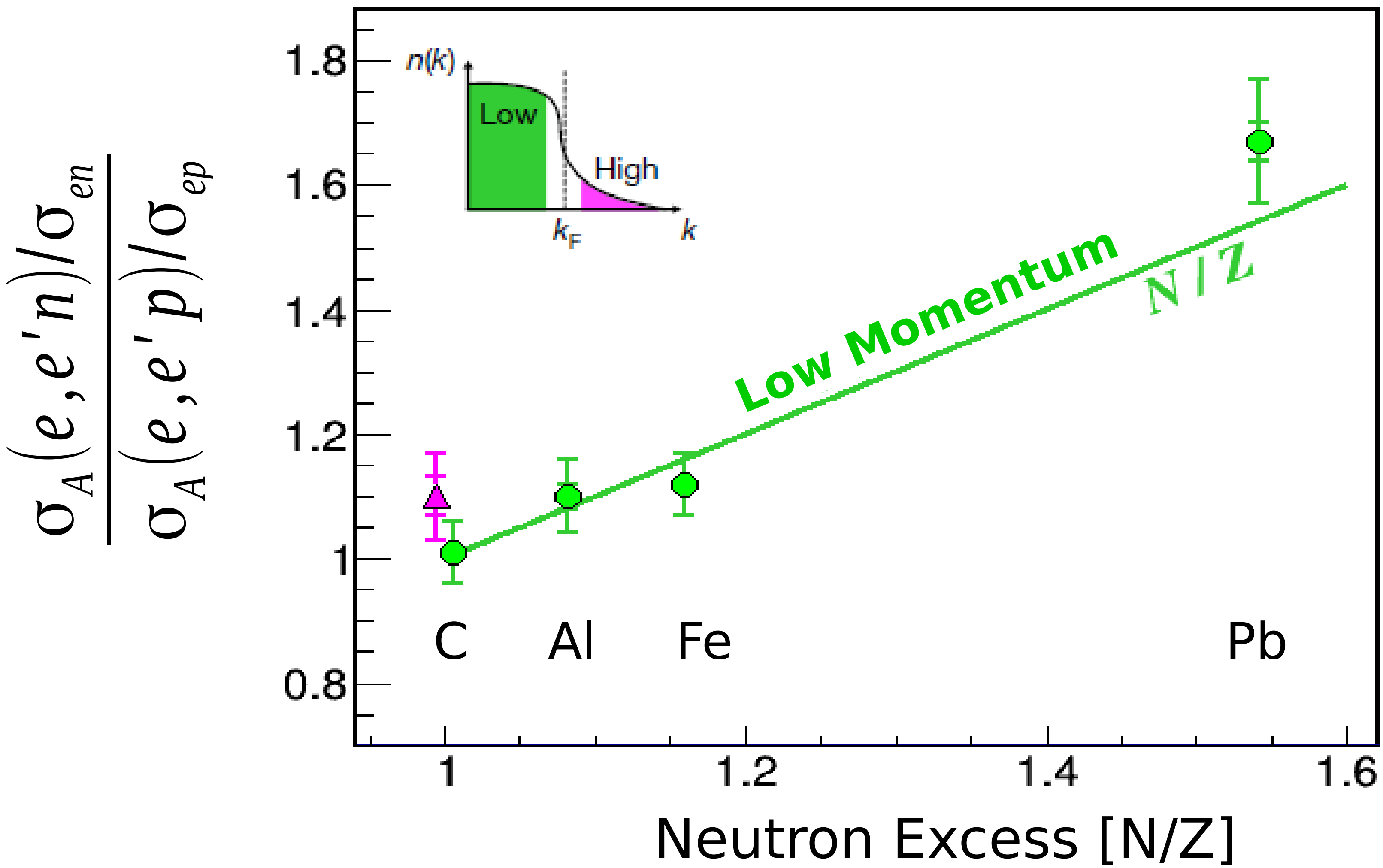
# Proton vs. Neutron Populations





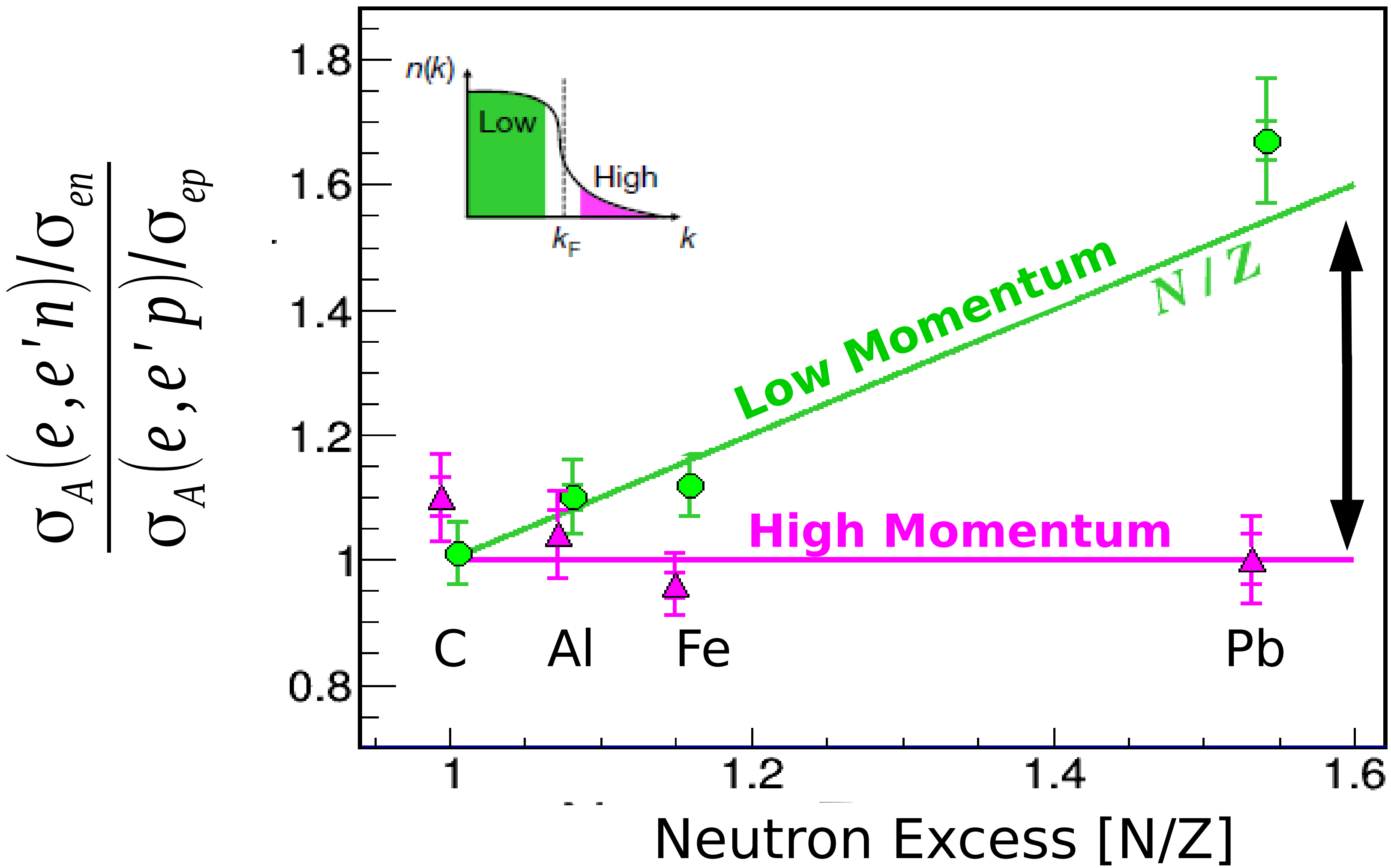

Duer et al. (CLAS Collaboration), Nature, **506**, 617 (2018)

# Low Momentum: n/p ~ N/Z




Duer et al. (CLAS Collaboration), Nature, **506**, 617 (2018)

# High Momentum: #p = #n






Duer et al. (CLAS Collaboration), Nature, **506**, 617 (2018)

# How do the excess neutron pair ?

no correlation

correlation with core protons?

# Correlation Probability

## Simple estimate based on np-dominance

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

$$R_P = \frac{protons_{high}}{protons_{low}} \approx \frac{20}{82-20} = 0.32$$

$$R_n = \frac{neutrons_{high}}{neutrons_{low}} \approx \frac{20}{126-20} = 0.19$$

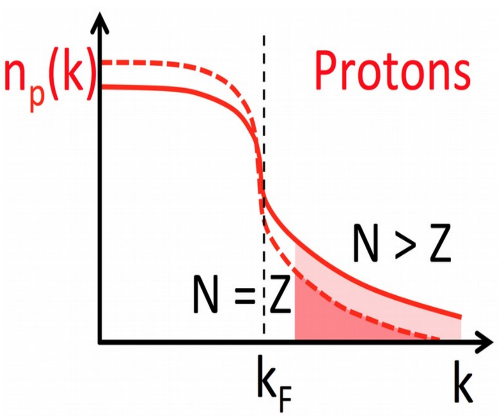
## Experimentally:

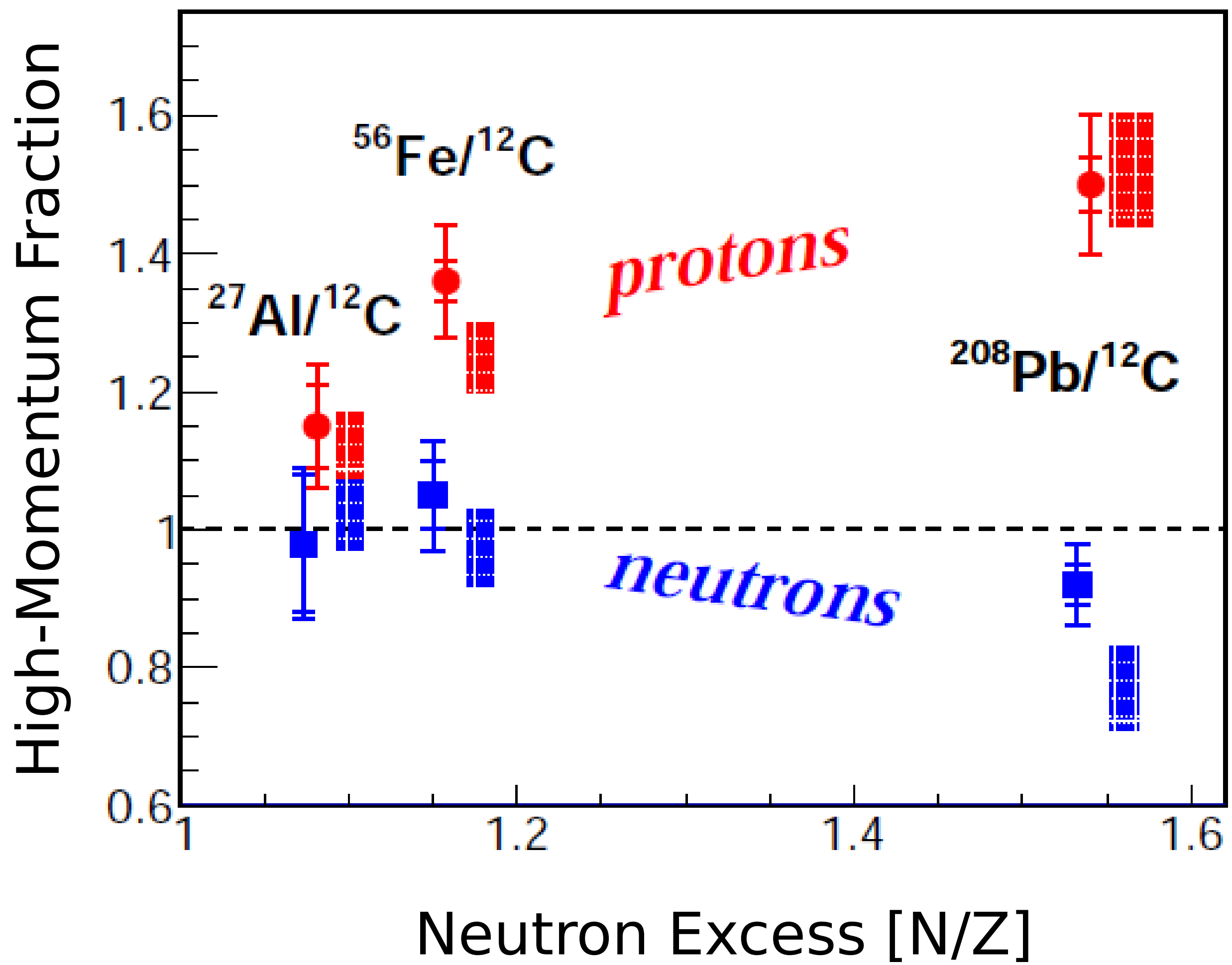
$$\frac{A(e,e'N)_{high}/A(e,e'N)_{low}}{^{12}C(e,e'N)_{high}/^{12}C(e,e'N)_{low}}$$

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

## Correlation Probability:

Neutrons saturate  Protons grow

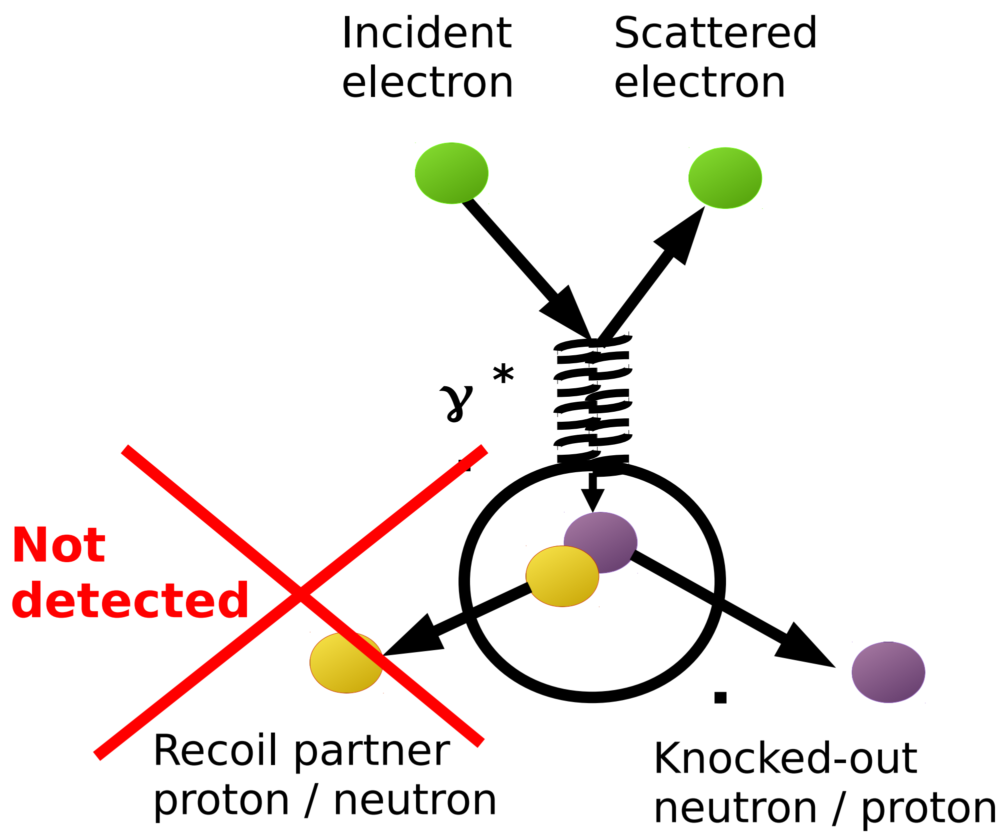


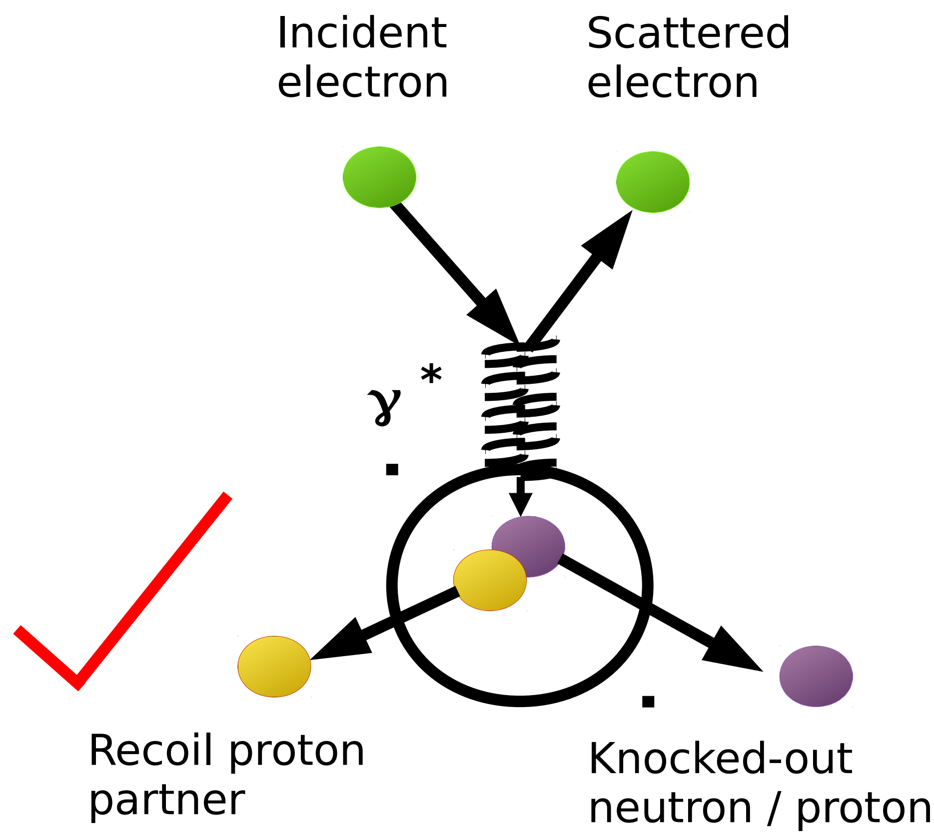

Duer et al. (CLAS Collaboration), Nature, **506**, 617 (2018)

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

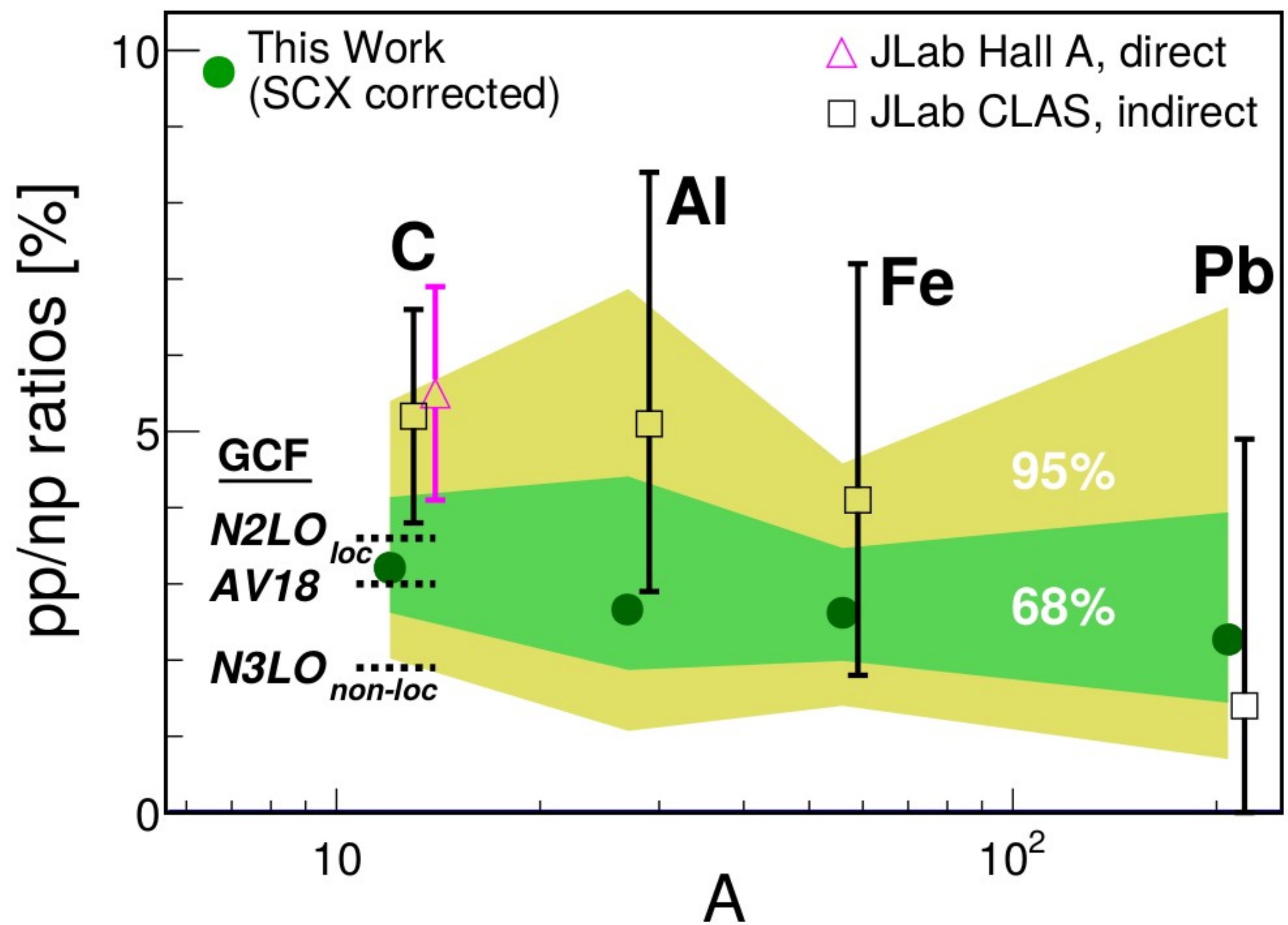
## Double coincidence




## Triple coincidence



# Direct Observation of np-dominance




Duer et al. (CLAS Collaboration), PRL 122 (2019)

SCX correction: Colle et al., PRC 93, 034608 (2016)

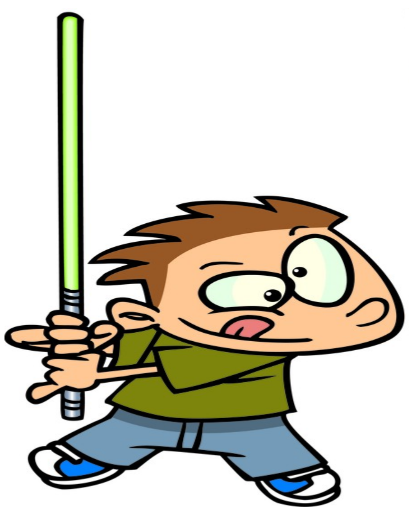
# Kinetic Energy sharing in neutron rich nuclei

Pauli principle

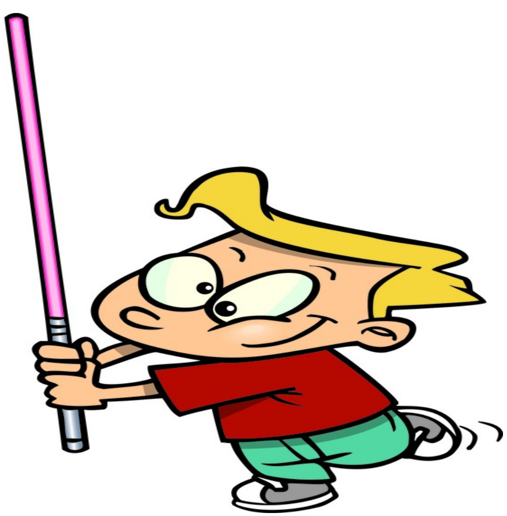
$$\langle E_n^{kin} \rangle > \langle E_p^{kin} \rangle$$

With SRC

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



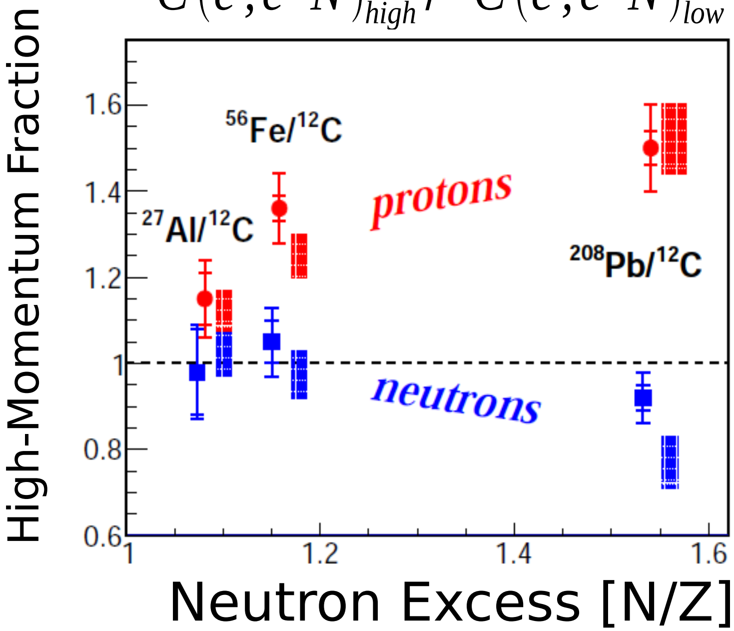
**vs.**



# **Who wins?**

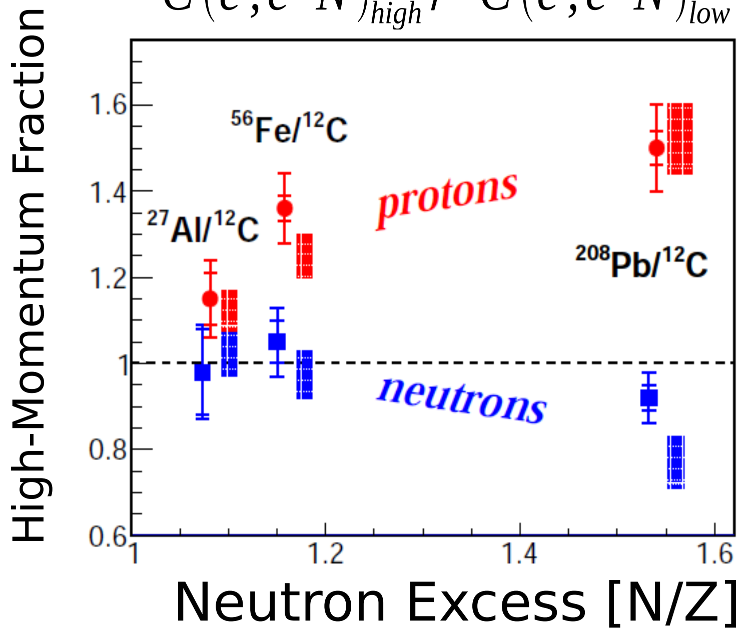
# Kinetic Energy sharing in neutron rich nuclei

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



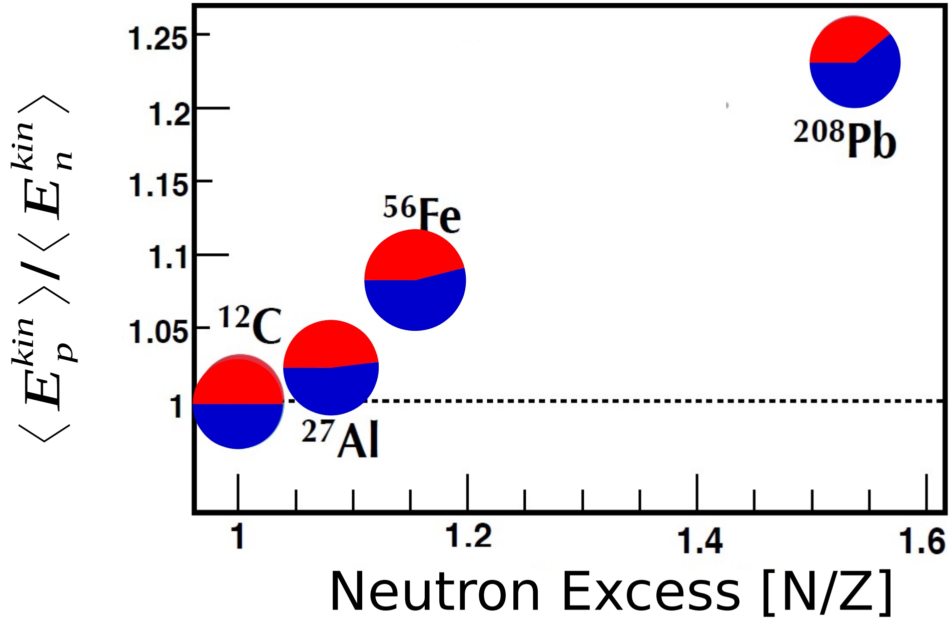
# Kinetic Energy sharing in neutron rich nuclei

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




⇒

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



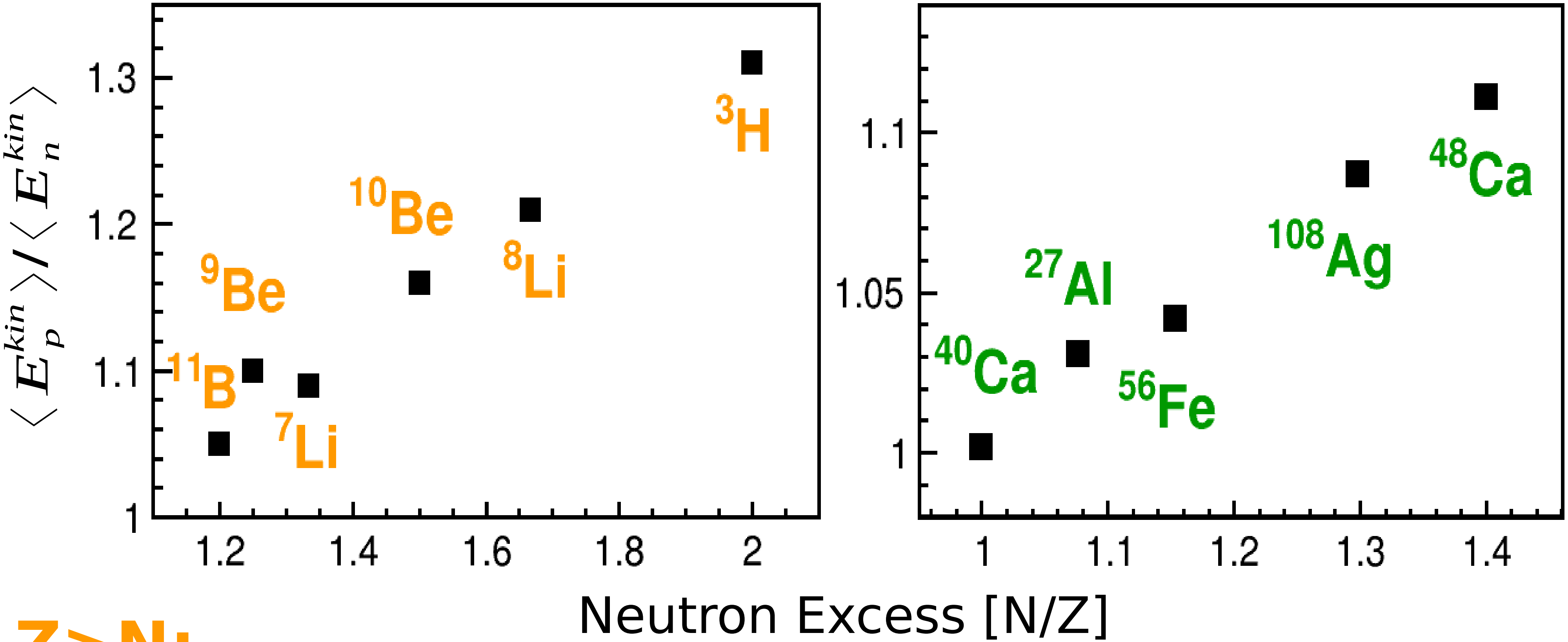

$n_{p(n)}$: Simple np-dominance model

**Protons move faster than neutrons in N>Z nuclei**

$$\langle E^{kin}_p\rangle > \langle E^{kin}_n\rangle$$

# Theoretical predictions (N>Z)

**Light nuclei (A<12)** **Heavy nuclei (A>12)**




**Z>N:**

$^3He$ **N/Z =1/2** $\langle E_p^{kin} \rangle / \langle E_n^{kin} \rangle = 0.76$

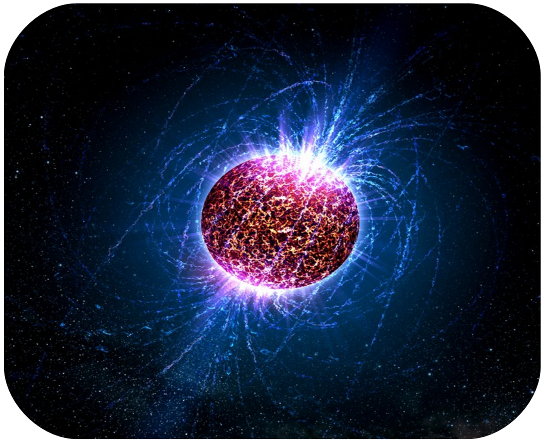


Wiringa et al., Phys. Rev. C89, 024305 (2014)

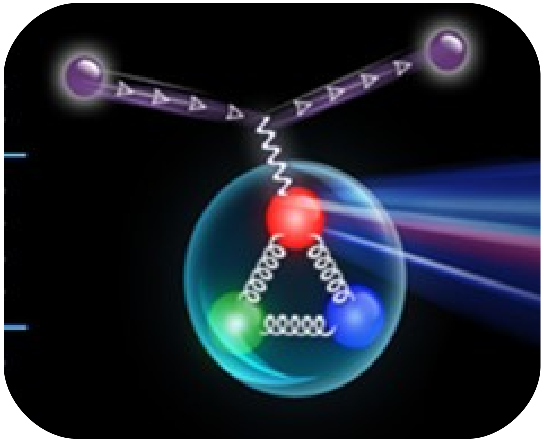
Ryckebusch et al., J. Phys G42 (2015)

# Implications

**Neutron Stars**



**Bound Nucleon Structure (the EMC Effect)**



**And more...**

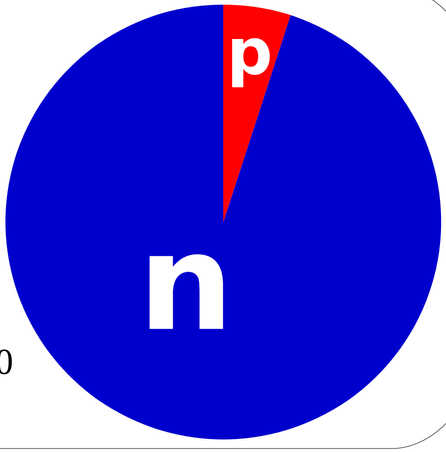
# Nuclear density Asymmetry

neutron star

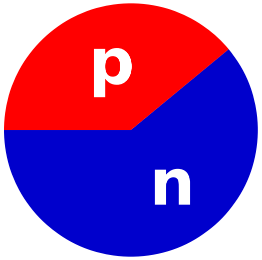
$$A \approx 10^{57}$$

$$\frac{N}{Z} \approx \frac{95\,\%}{5\,\%} \approx 20$$

$$\rho = (2-5)\rho_0$$




n-rich nuclei




$$A \lesssim 200$$

$$N/Z \lesssim 1.5$$

$$\rho_0 = 0.16\, fm^{-3}$$

# Nuclear density Asymmetry

**SRCs**

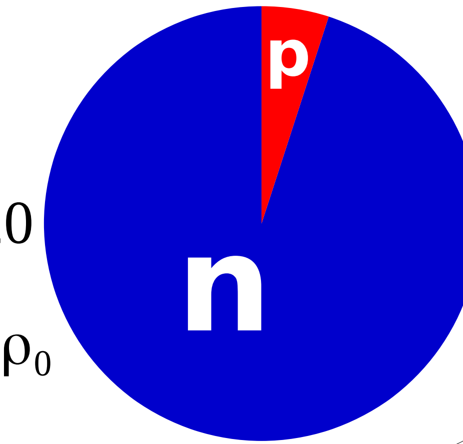
A few times average nuclear density

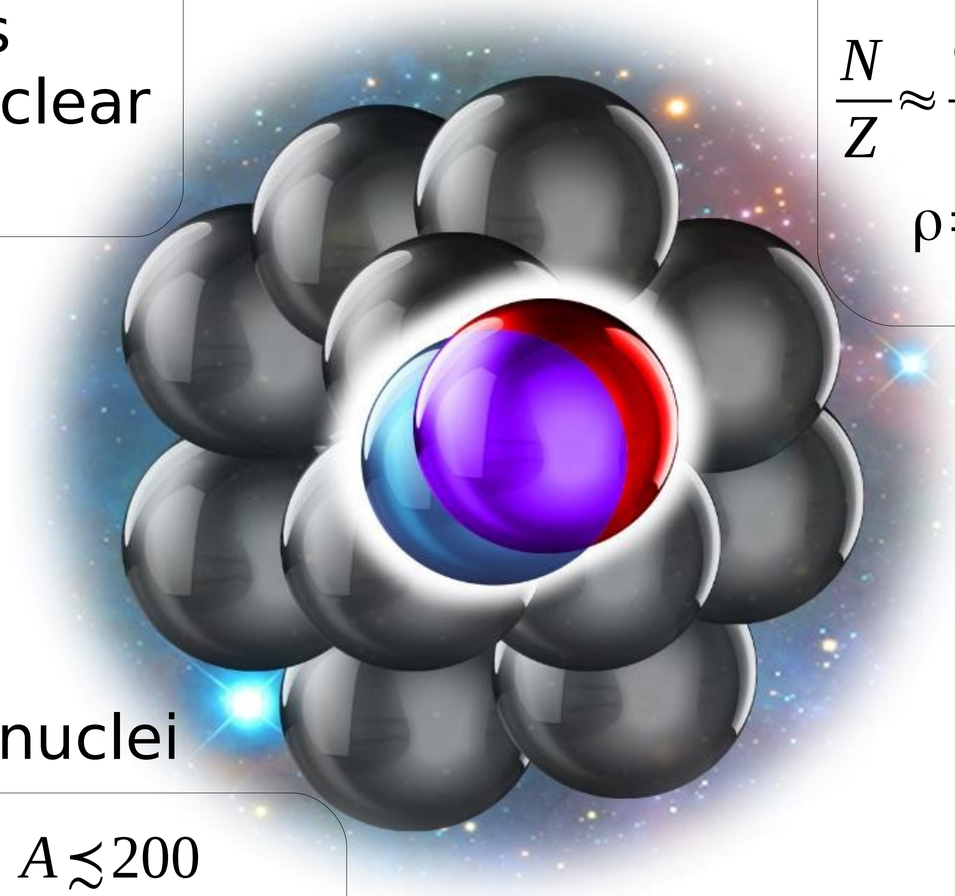
**neutron star**

$A \approx 10^{57}$

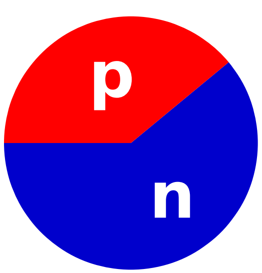
$\frac{N}{Z} \approx \frac{95\%}{5\%} \approx 20$

$\rho = (2-5)\rho_0$



**n-rich nuclei**




$A \lesssim 200$

$N/Z \lesssim 1.5$

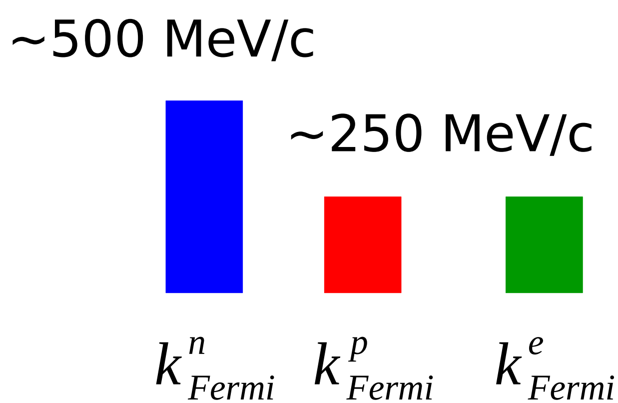
$\rho_0 = 0.16\, fm^{-3}$

# Implication for Neutron Stars

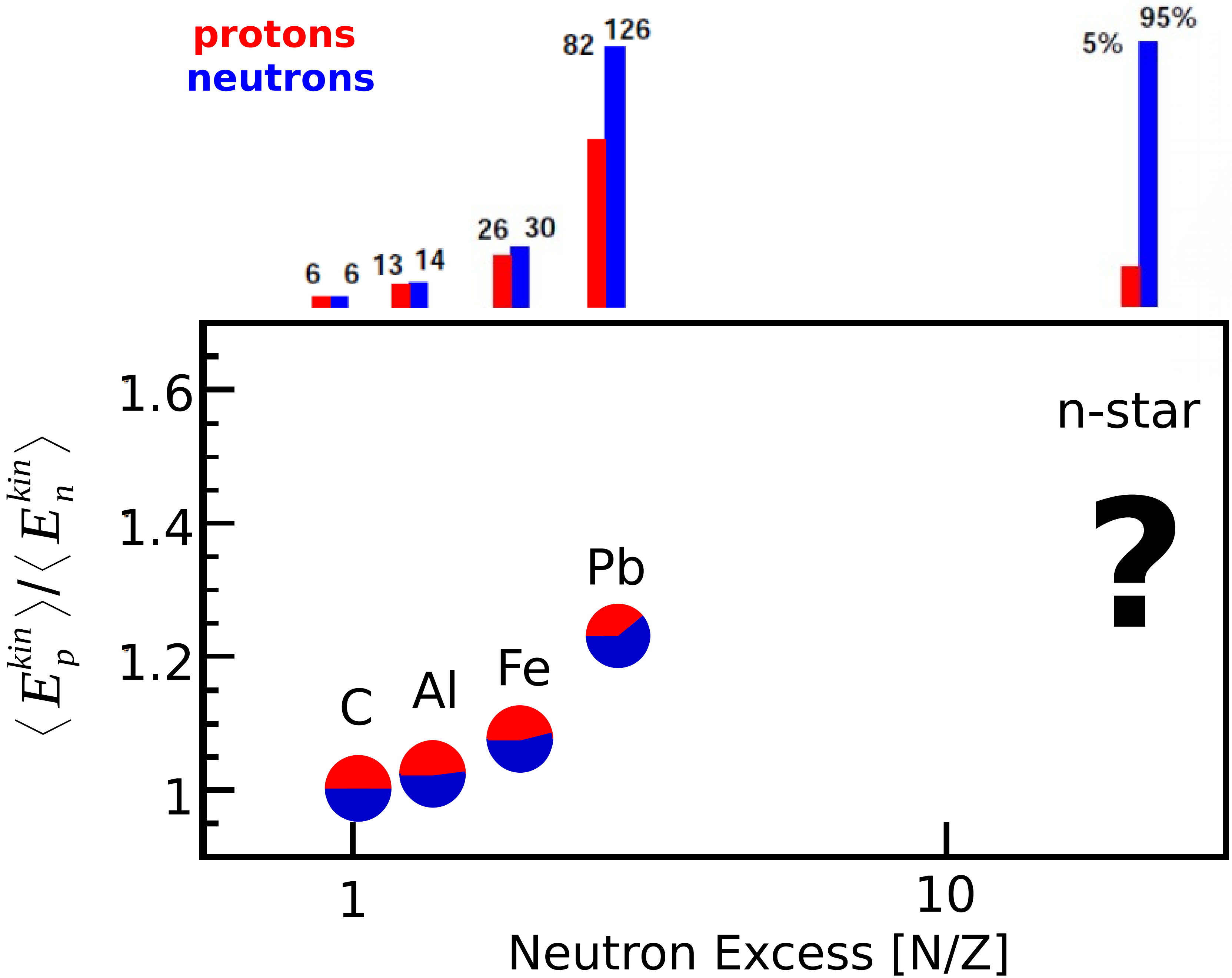
Most accepted models assume:

**~95% neutrons**, **~5% protons**, and **~5% electrons**.

Neglecting np-SRC interaction, one can assume 3 separate Fermi gases:

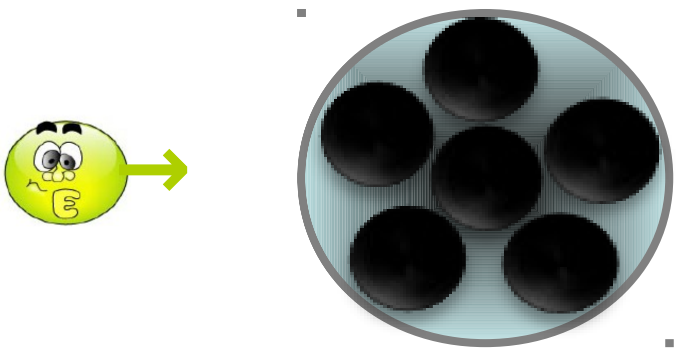


# Implication for Neutron Stars

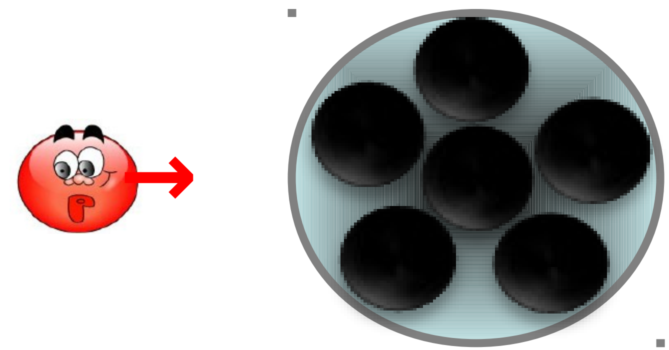


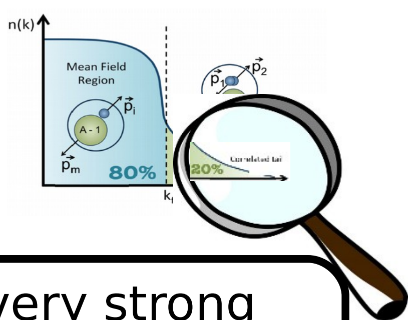

# Present & Future directions

## Lepton scattering



## Hadron scattering



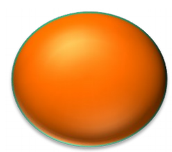



QE pp scattering have a very strong preference for reacting with forward going high-momentum nuclear protons

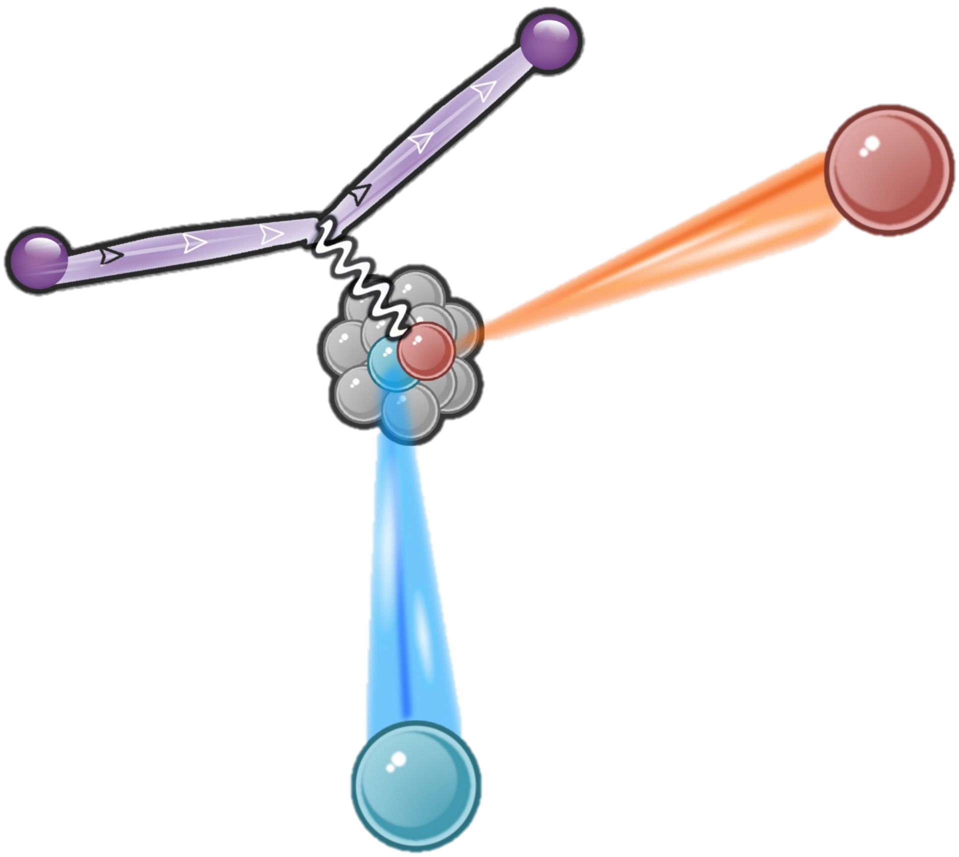
# Inverse kinematics

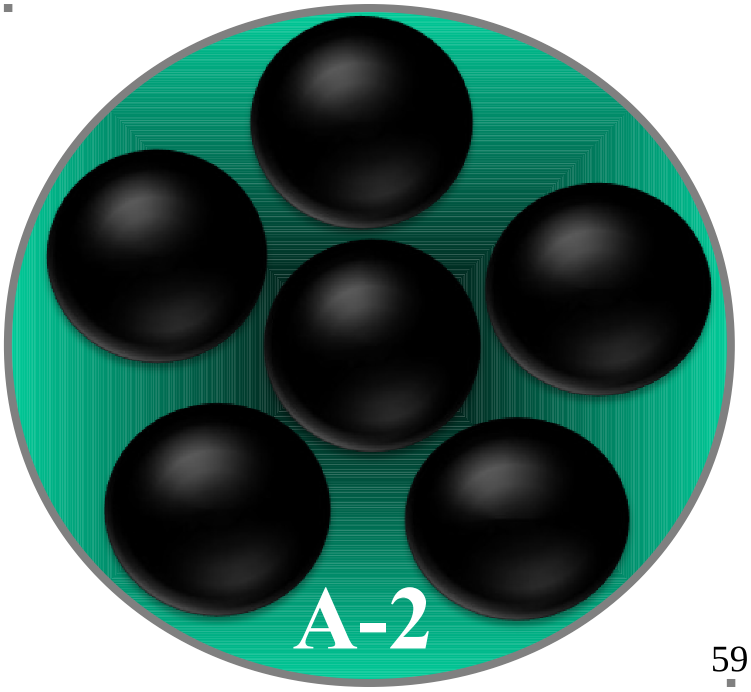
incident
nucleus

target
proton



# Inverse kinematics

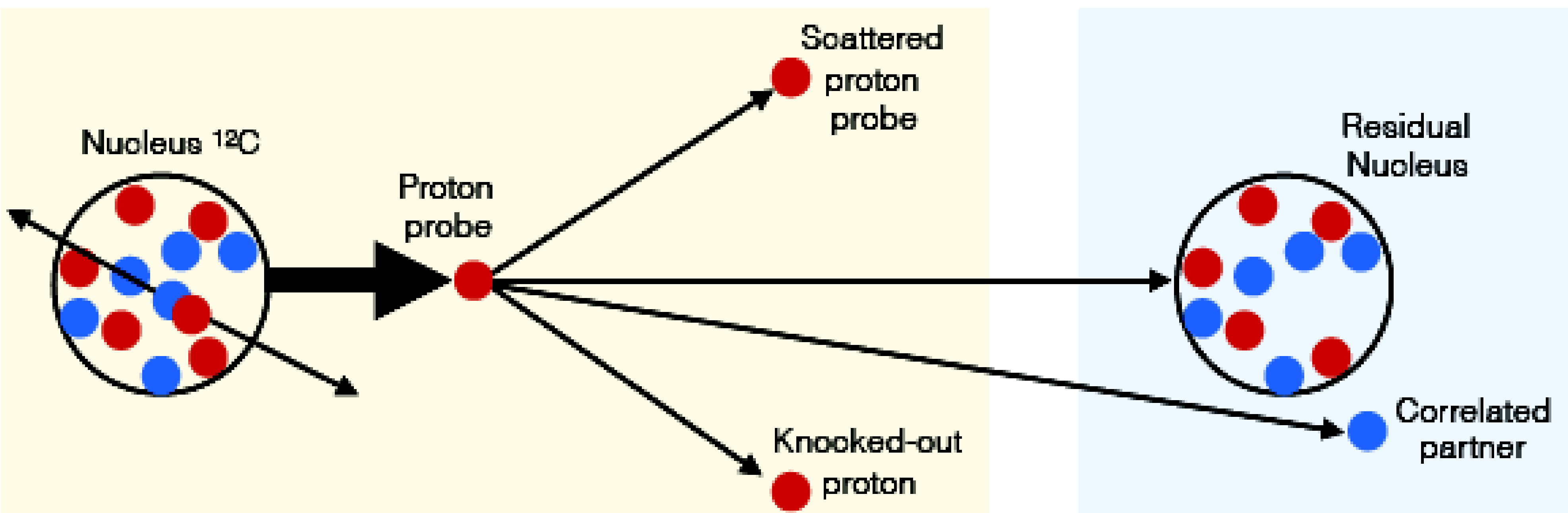




# Inverse kinematics @ JINR

$^{12}C$ beam at 4 GeV/c/u on $LH_2$ target.

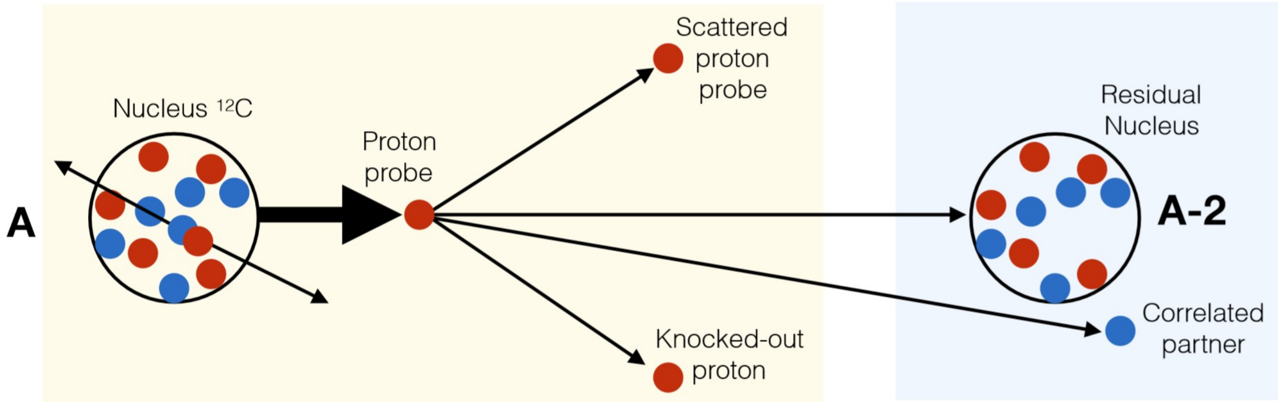
Measure incoming beam and all reaction fragments.

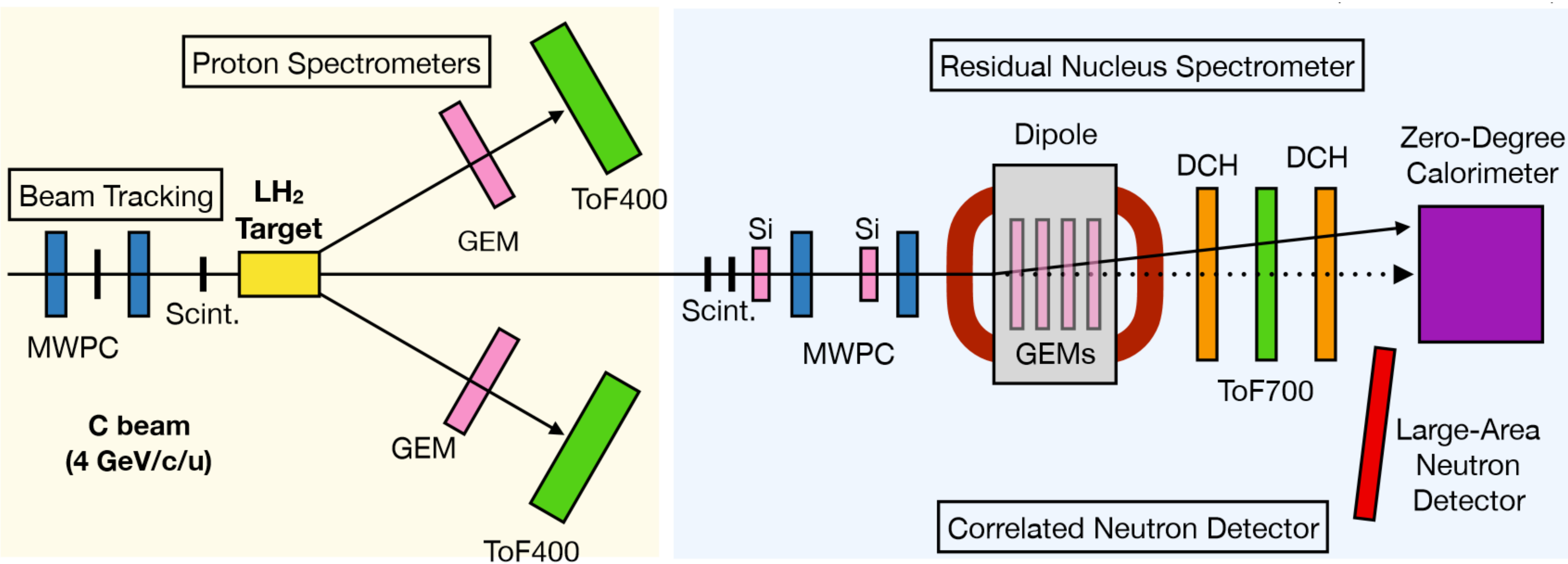





*Courtesy of M. Parsyuk*

# Experimental Setup



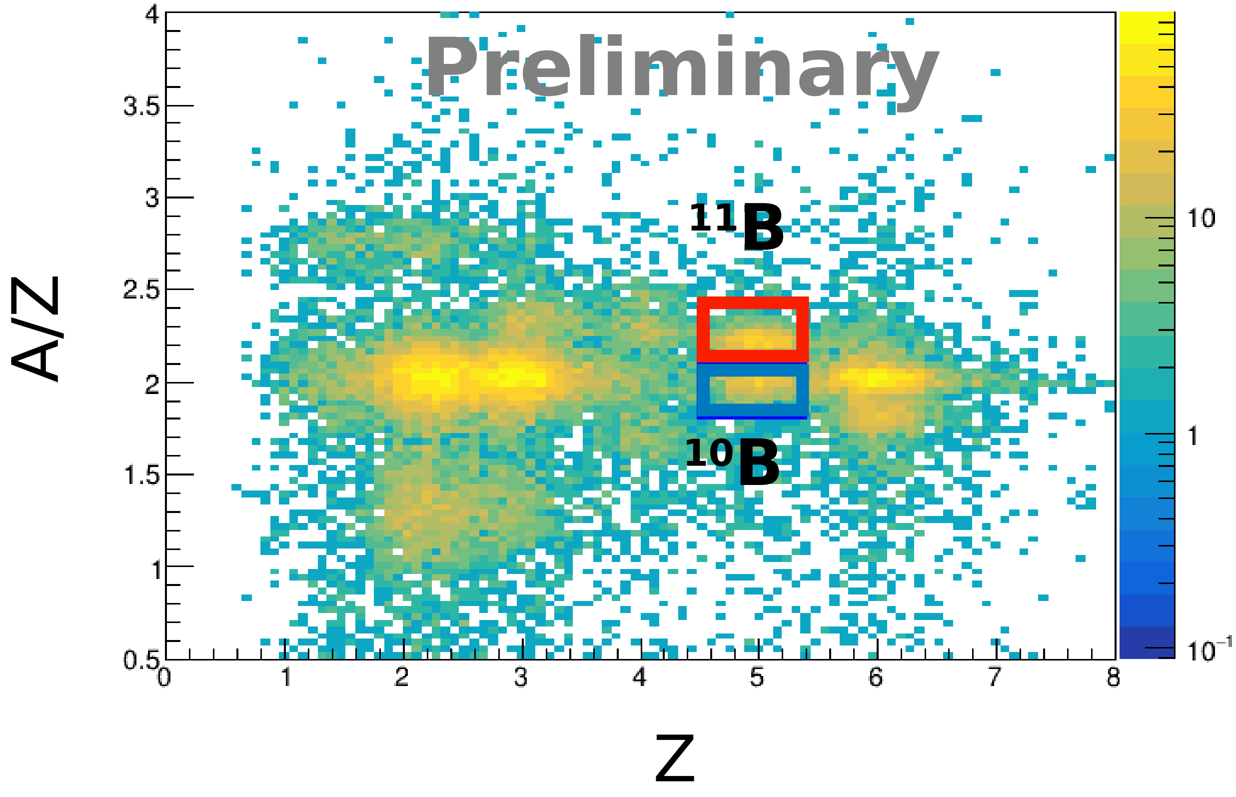



*Courtesy of M. Parsyuk*

# $1^{st}$ run @ March 2018

## Fragment identification

$^{12}C(p,2pn)^{10}B$, $^{12}C(p,2px)X$ , $^{12}C(p,2p)^{11}B$

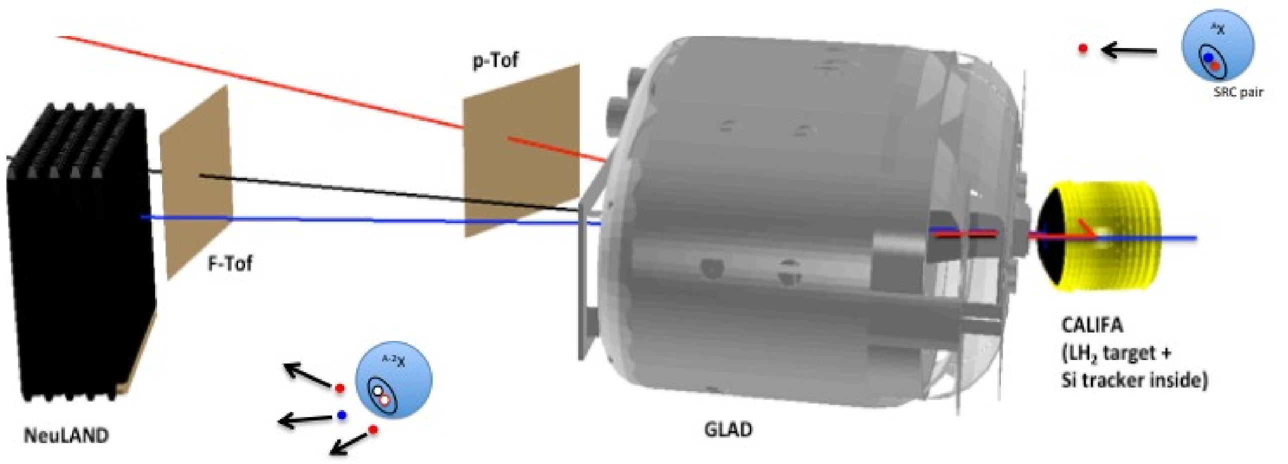



*Courtesy of M. Parsyuk*

# SRC @ R3B

E=1GeV/u beams from GSI accelerator on $LH_2$ target.

Isotopic chains




Proposed for next GSI PAC:
$^{12}C$, d+p, $^{16}C$+p



*Courtesy of A. Corsi*

# Thank you !

Data-Mining collaboration

CLAS collaboration

Old Dominion University

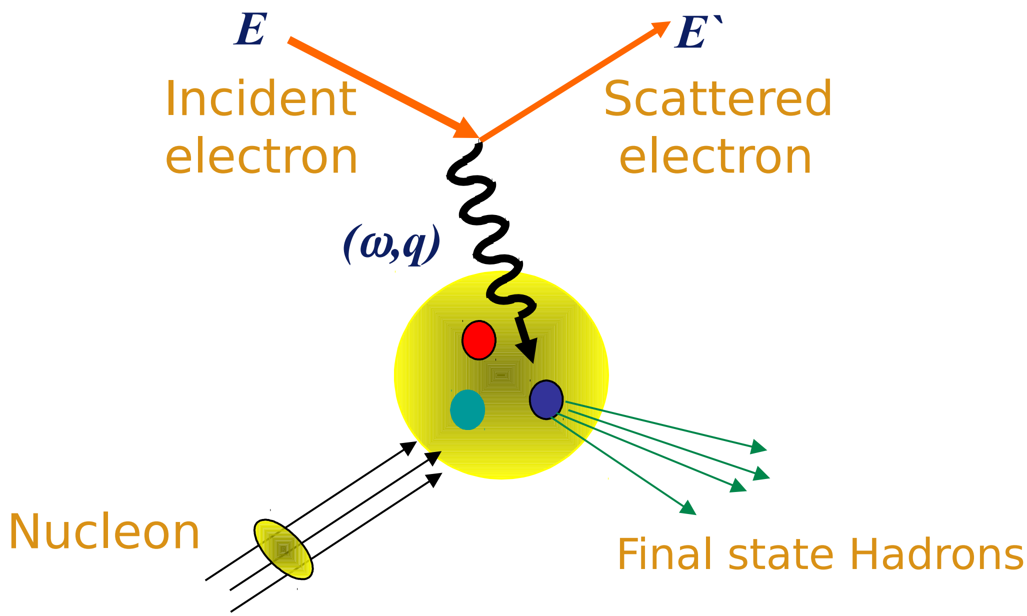
Massachusetts Institute of Technology

Jefferson Lab

EX UMBRA IN SOLEM

UNIVERSIDAD TECNICA FEDERICO SANTA MARIA

# Deep Inelastic Scattering




$$Q^2 = -q_\mu q^\mu = q^2 - \omega^2$$

$$\omega = E' - E$$

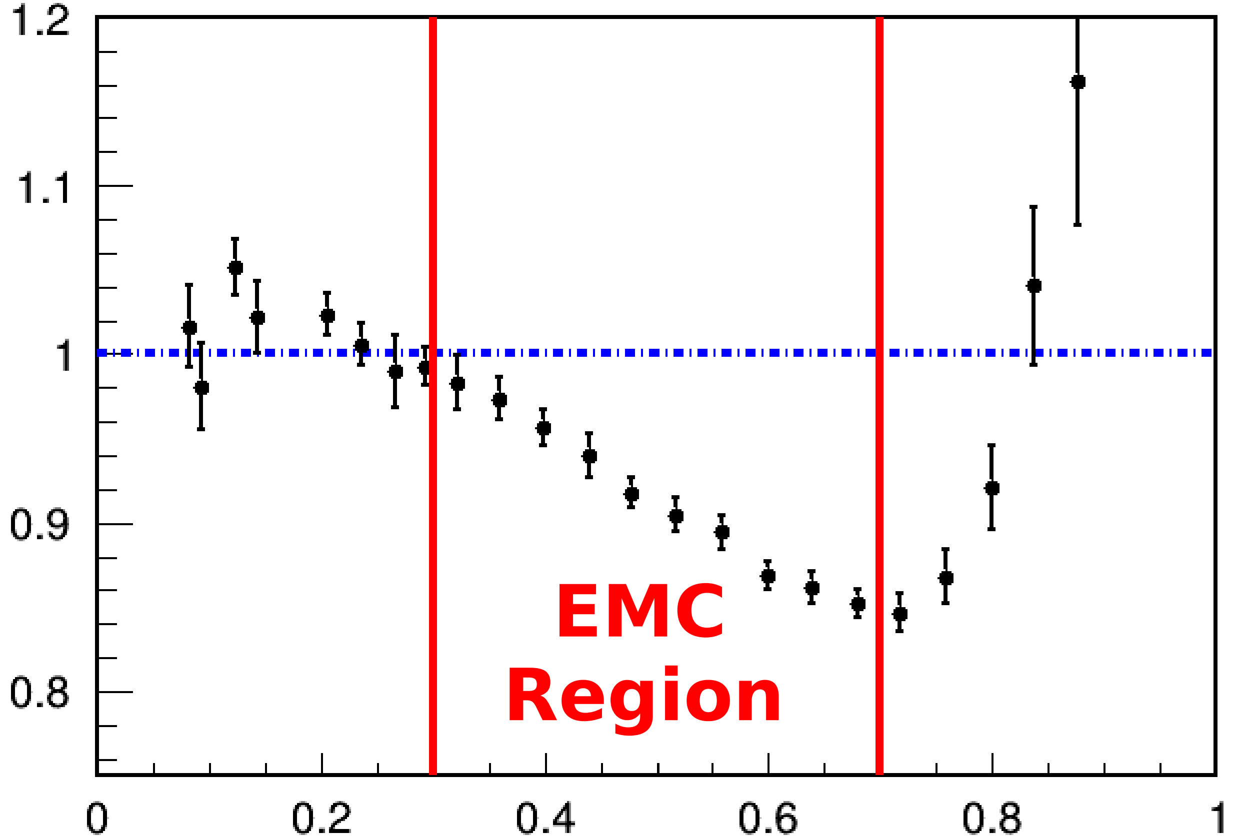
$$x_B = \frac{Q^2}{2m\omega}$$

$$0 \le x_B \le 1$$

**$x_B$ gives the fraction of nucleon momentum carried by the struck parton**

**Experimentally: Inclusive scattering A(e,e')**

# DIS: The EMC Effect



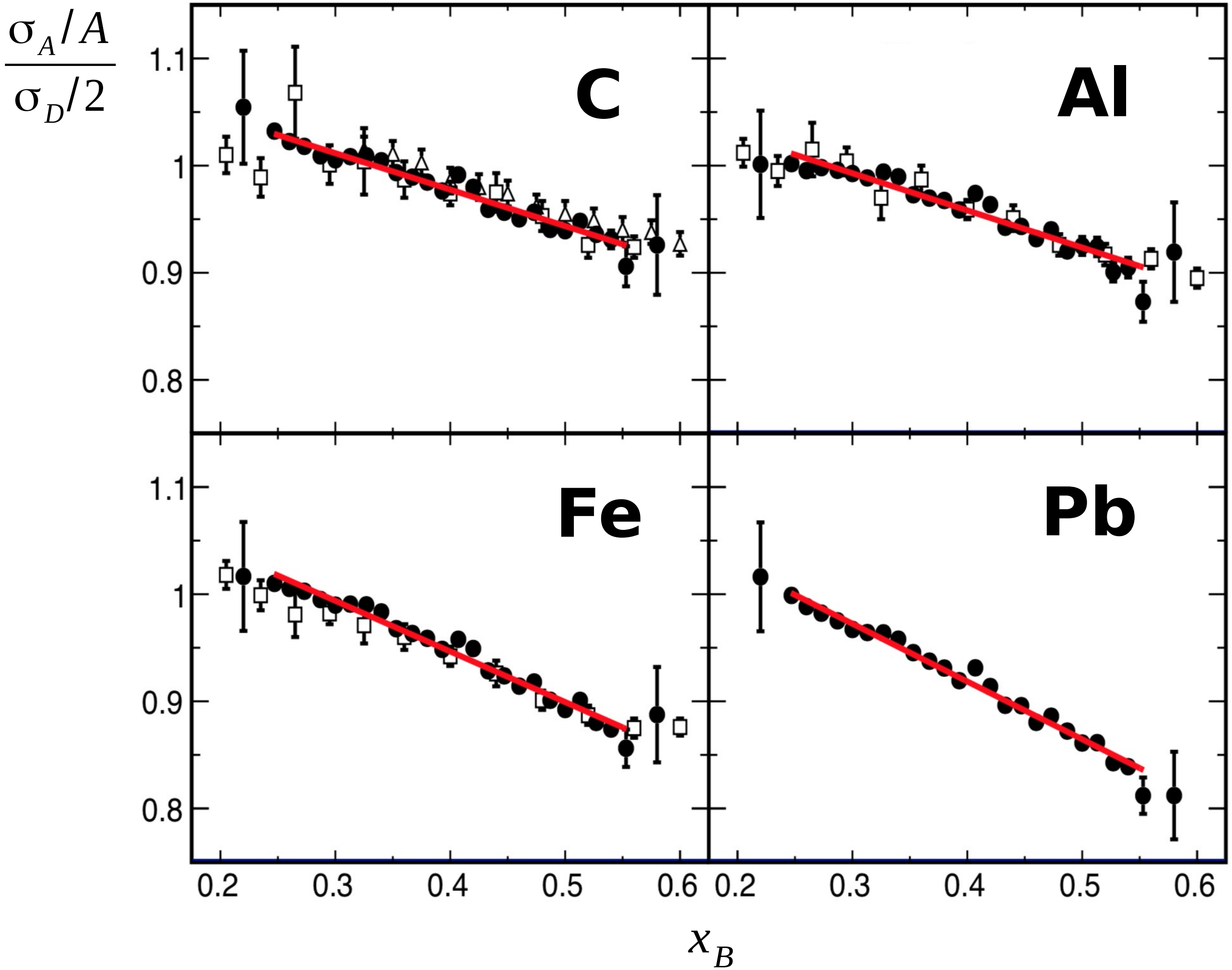

$$\frac{F_2^{Fe}/56}{F_2^D/2}$$

$x_B$

Bound nucleon DIS ≠ free DIS

$$F_2^A \neq Z \cdot F_2^p + N \cdot F_2^n$$

# EMC Effect



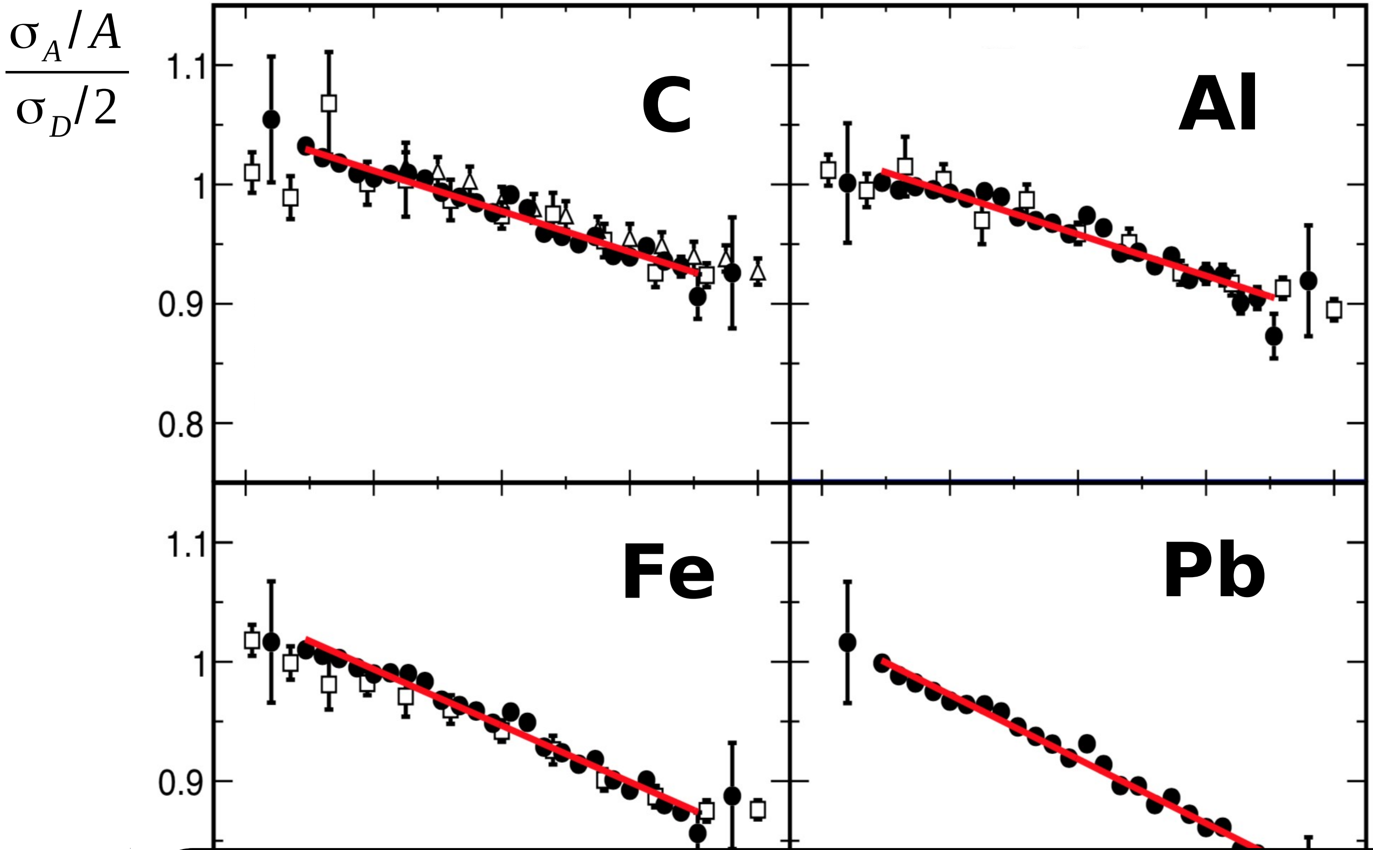

**Size of effect (EMC Slope) increases with A**

Schmoolker, Duer et al. (CLAS Collaboration), Nature 566 (2019)

Previous data:

Arneodo et al., PLB (1988); Allasia et al., PLB (1990); Gomez et al., PRD (1994); Seely et al., PRL (2009)

# EMC Effect




**Size of effect (EMC Slope) increases with A**

- This Work
- Published Data (SLAC)
- Published Data (JLab)

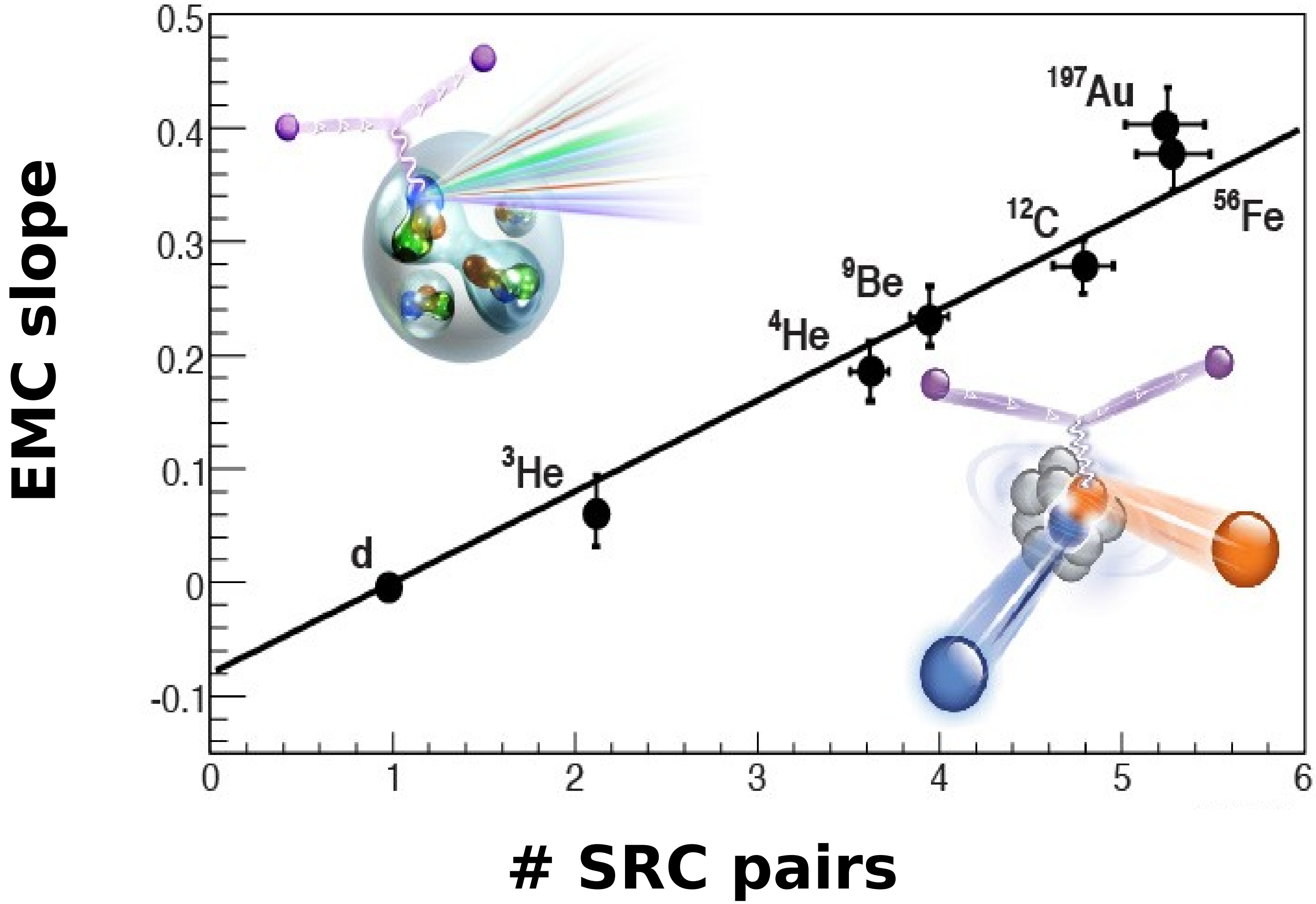
**After 35 years, 1000 papers:**
**no consensus on the cause of EMC effect**

Sc

Previous data:

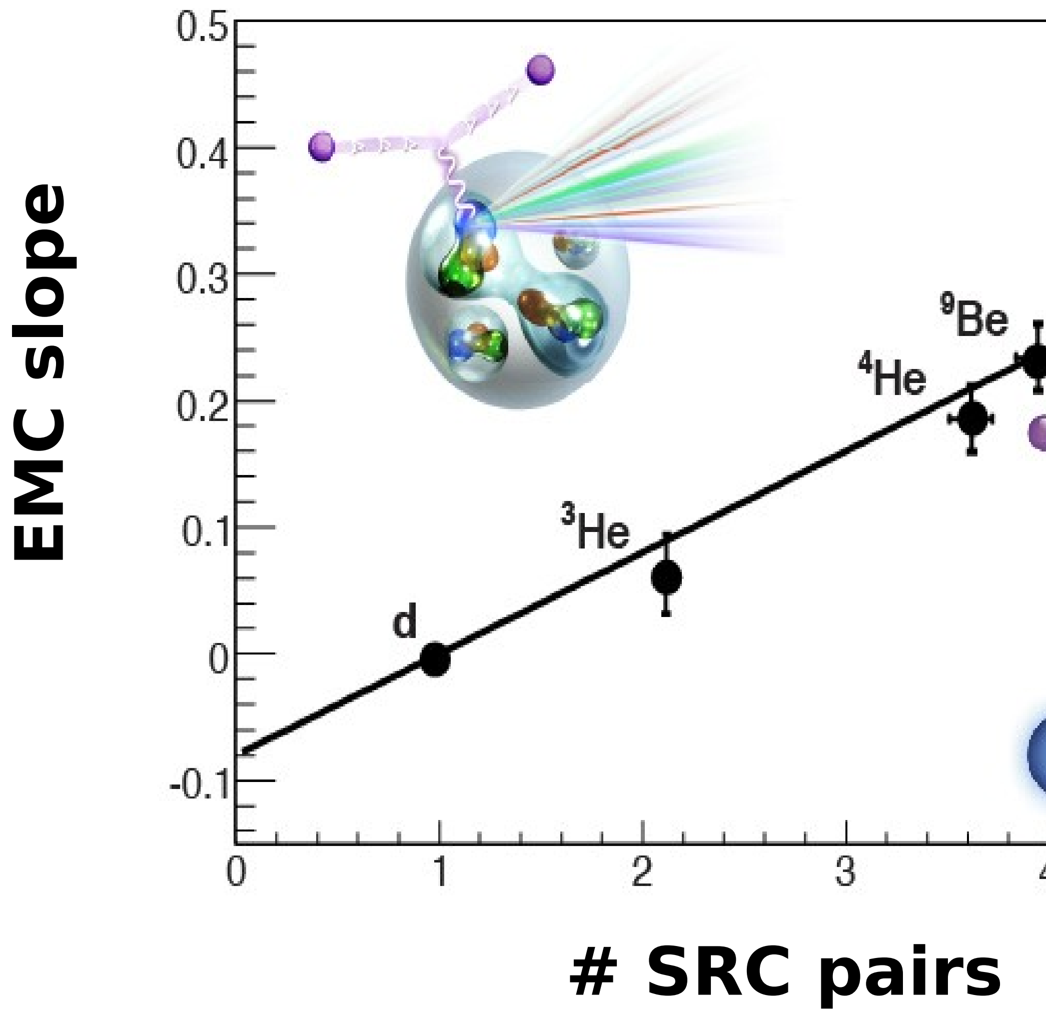
Arneodo et al., PLB (1988); Allasia et al., PLB (1990); Gomez et al., PRD (1994); Seely et al., PRL (2009)

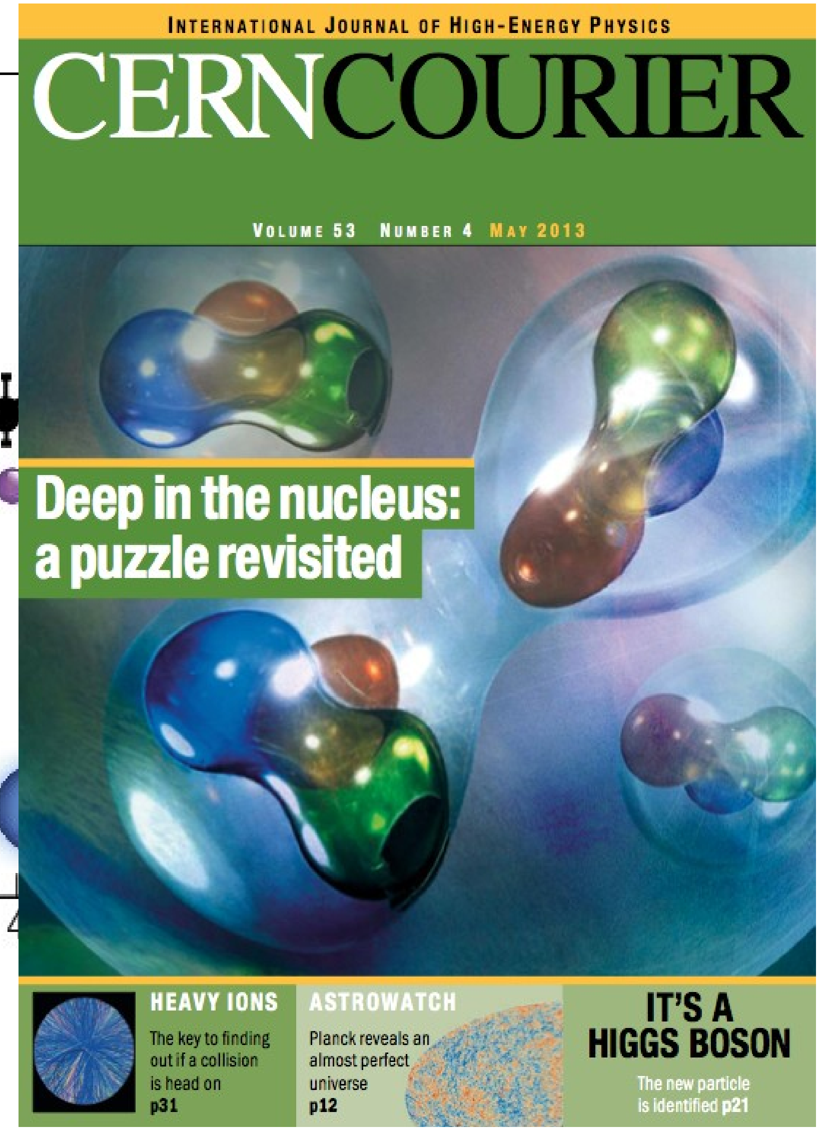
# EMC – SRC Correlation




Weinstein, Piasetzky, Higinbotham, Gomez, Hen, PRL (2011)
Hen et al.: RMP (2017); IJMPE (2013); PRC (2012);

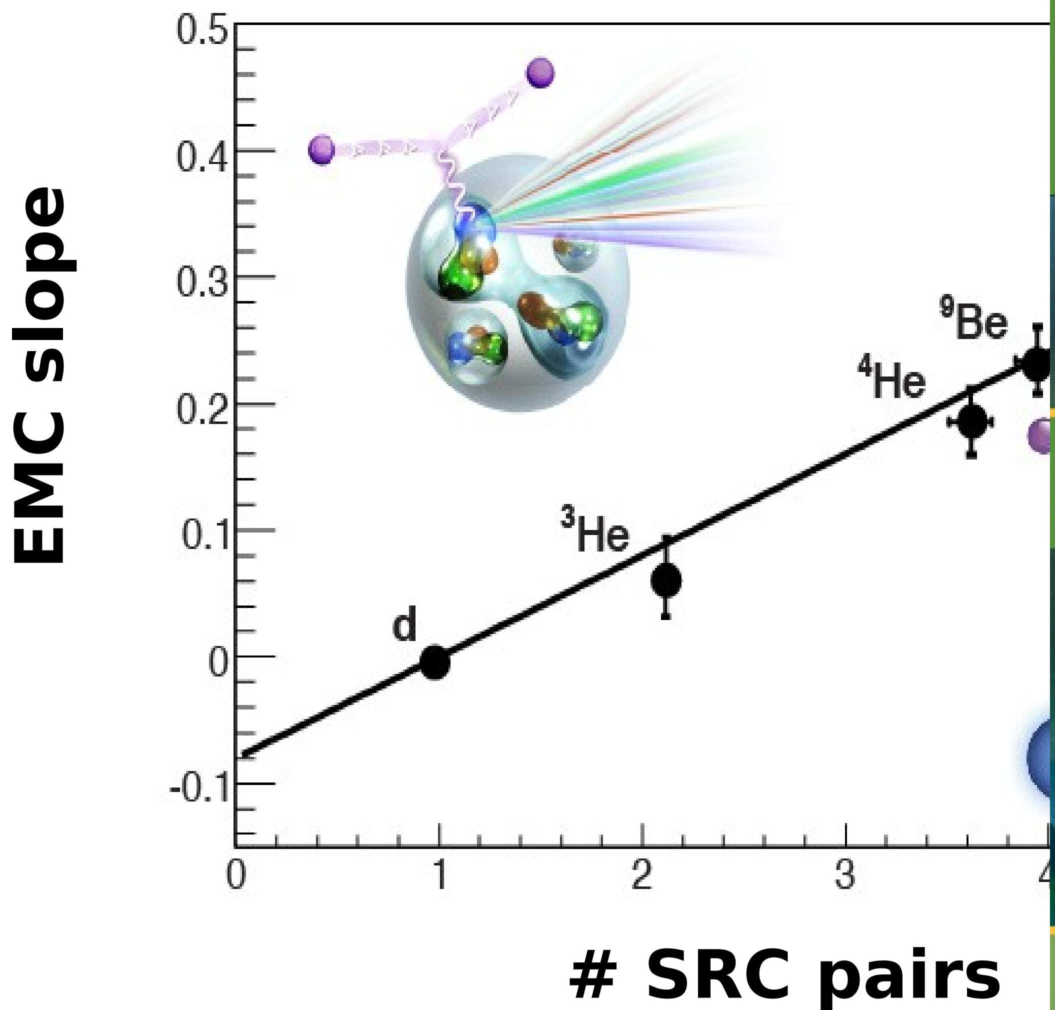
# EMC – SRC Correlation

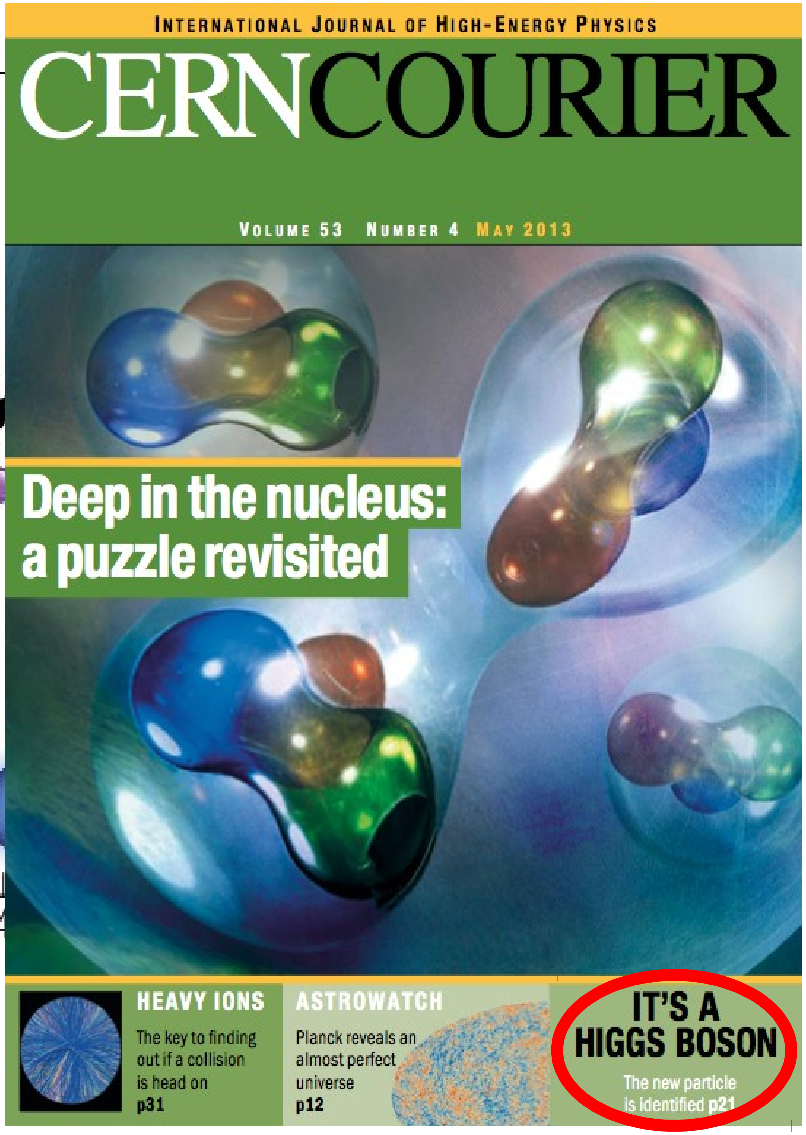



Weinstein, Piasetzky, Higinbotham, Gomez, Hen, PRL (2011)
Hen et al.: RMP (2017); IJMPE (2013); PRC (2012);

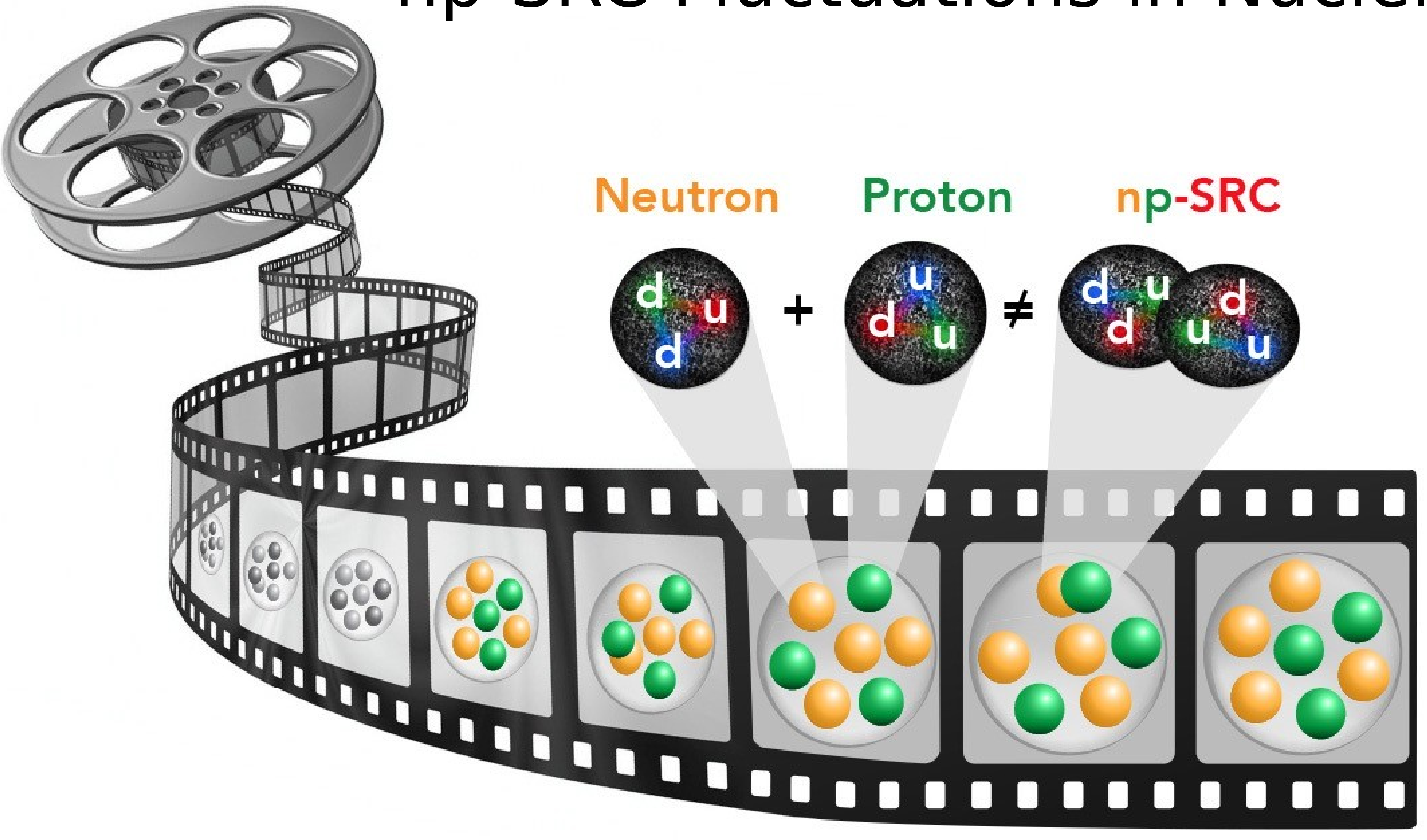
# EMC – SRC Correlation

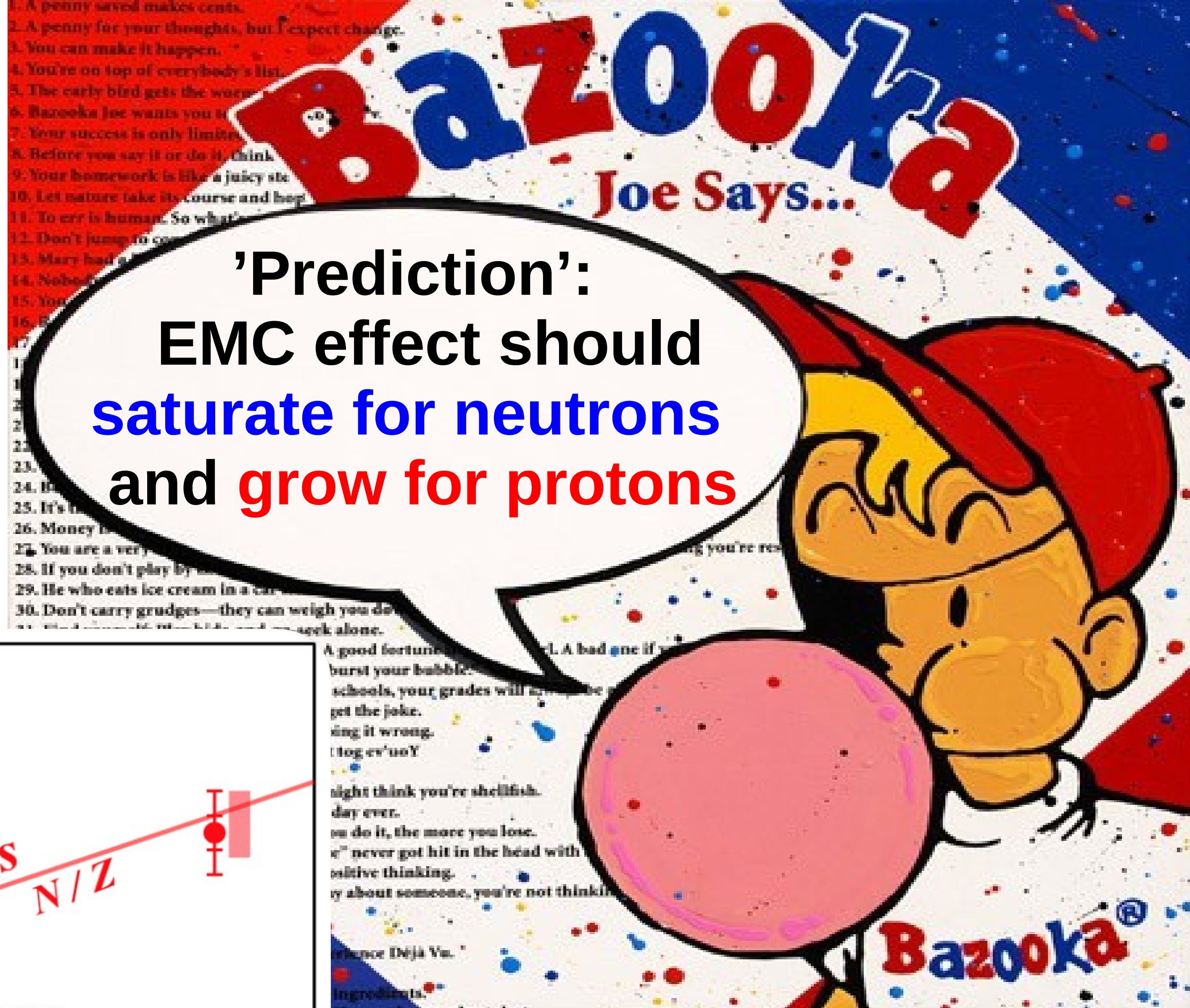


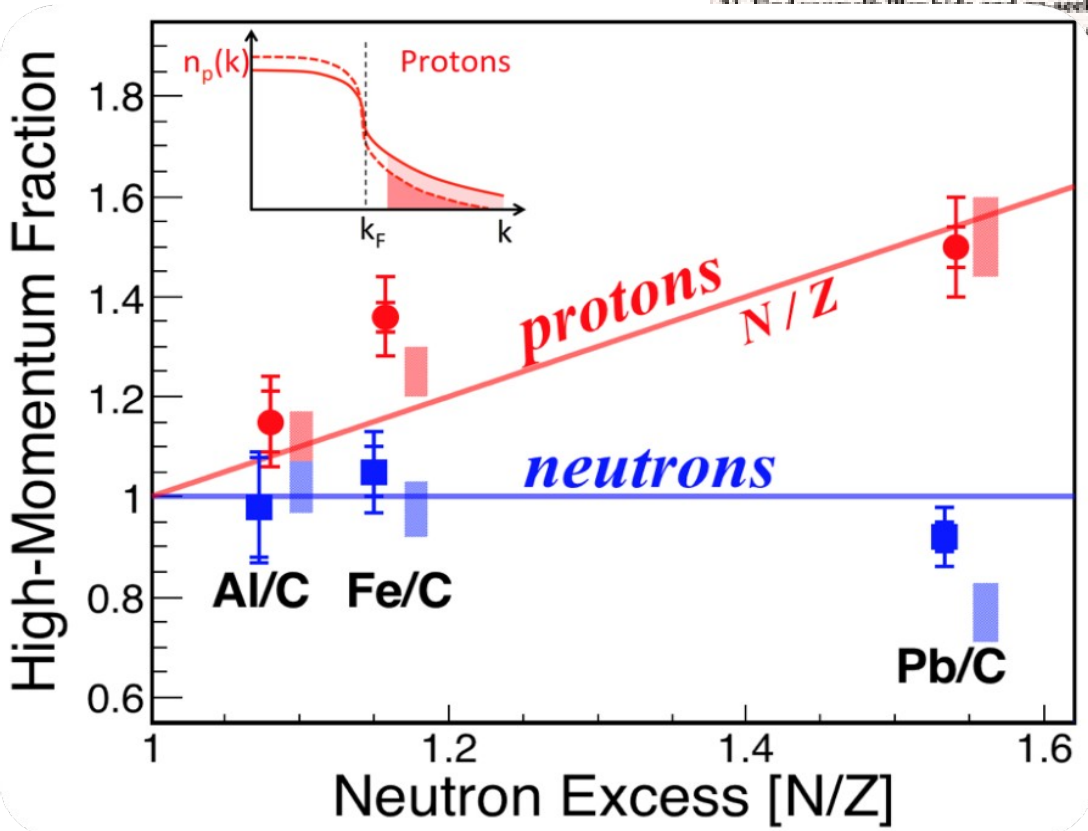



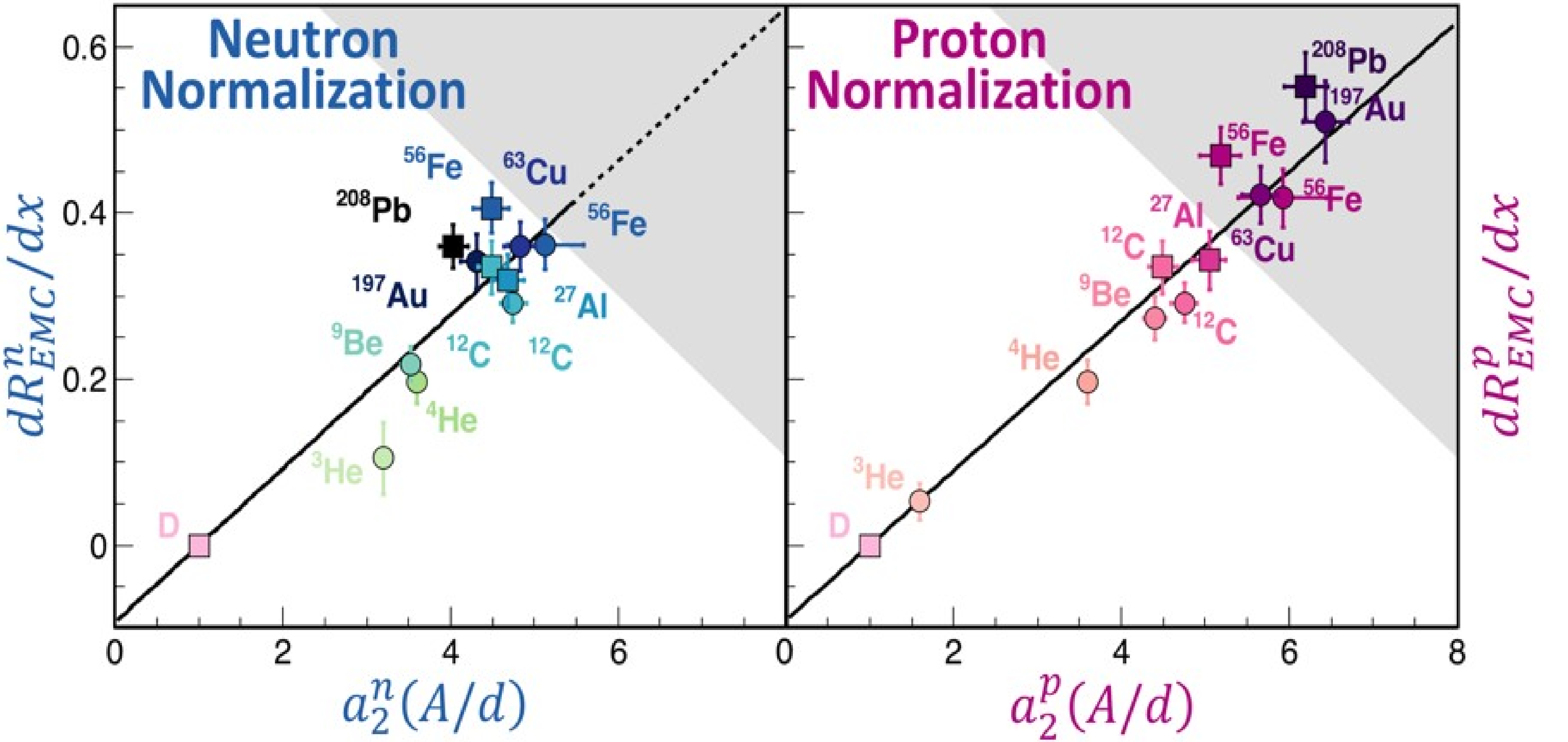

Weinstein, Piasetzky, Higinbotham, Gomez, Hen, PRL (2011)
Hen et al.: RMP (2017); IJMPE (2013); PRC (2012);

# np-SRC Fluctuations in Nuclei



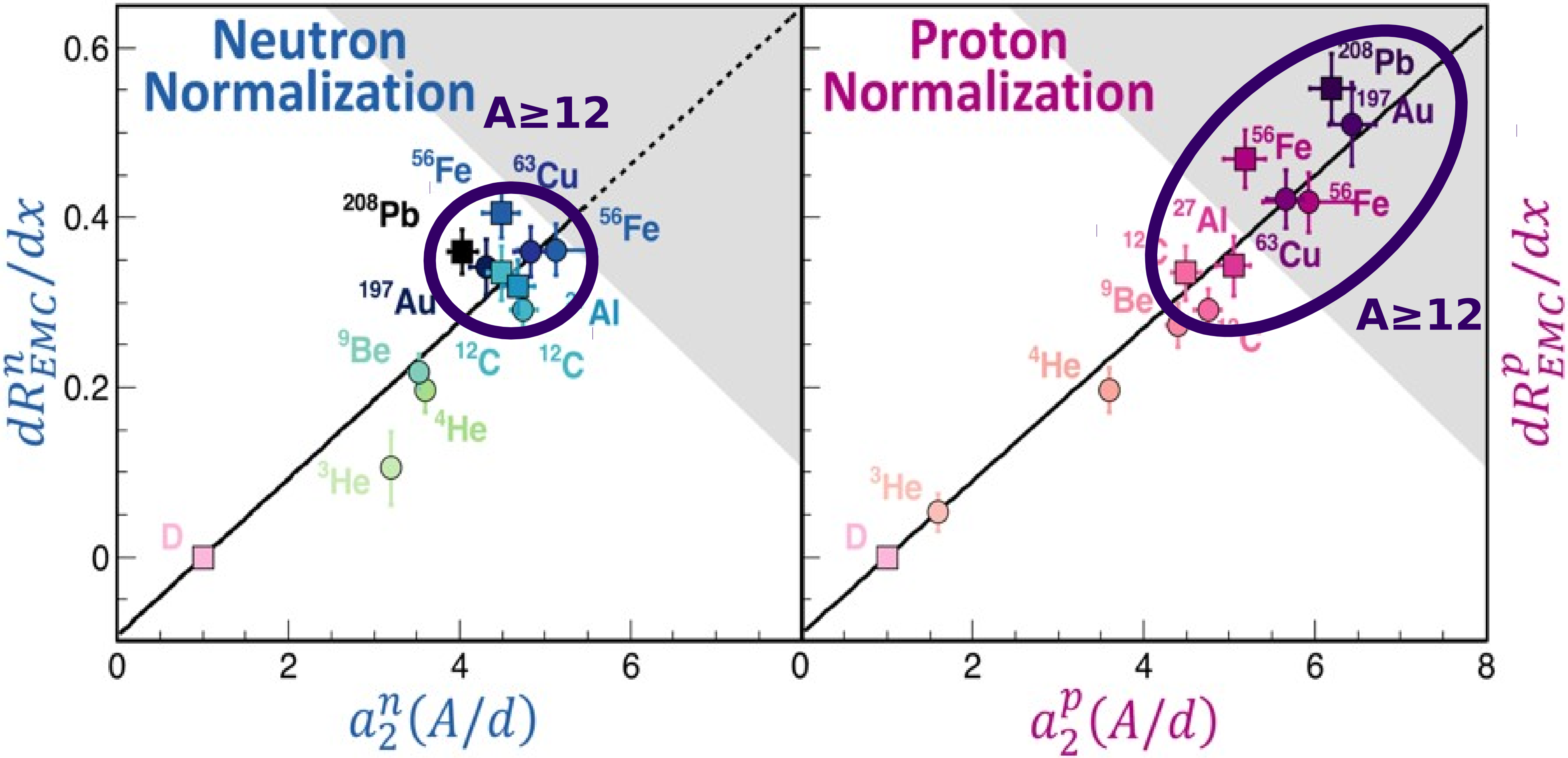

Bazooka
Joe Says...
'Prediction':
EMC effect should
saturate for neutrons
and grow for protons
Bazooka®


$n_p(k)$
Protons
$k_F$
k
protons
N / Z
neutrons
Al/C
Fe/C
Pb/C
High-Momentum Fraction
0.6
0.8
1
1.2
1.4
1.6
1.8
1
1.2
1.4
1.6
Neutron Excess [N/Z]




Schmoolker, Duer et al. (CLAS Collaboration), Nature 566 (2019)

Neutrons saturate Protons grow

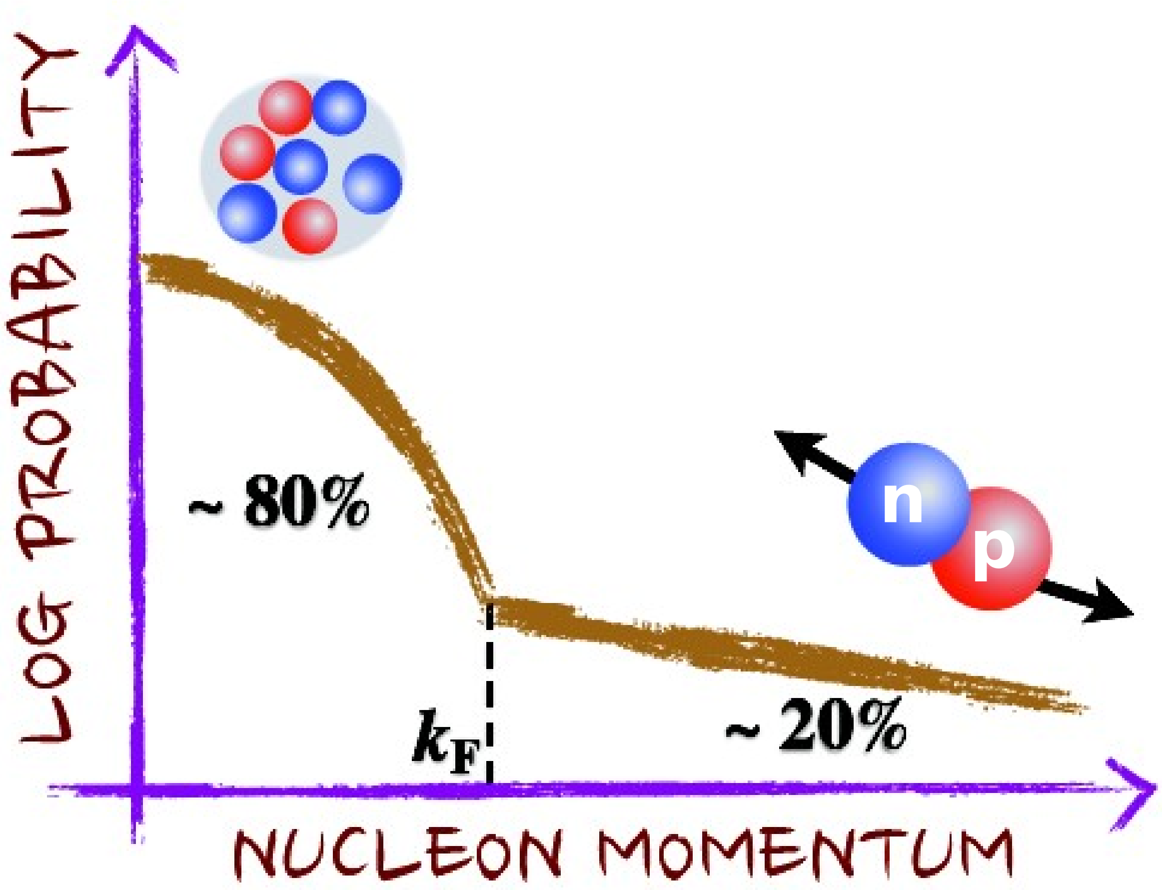



Schmoolker, Duer et al. (CLAS Collaboration), Nature 566 (2019)

# Bound Nucleons

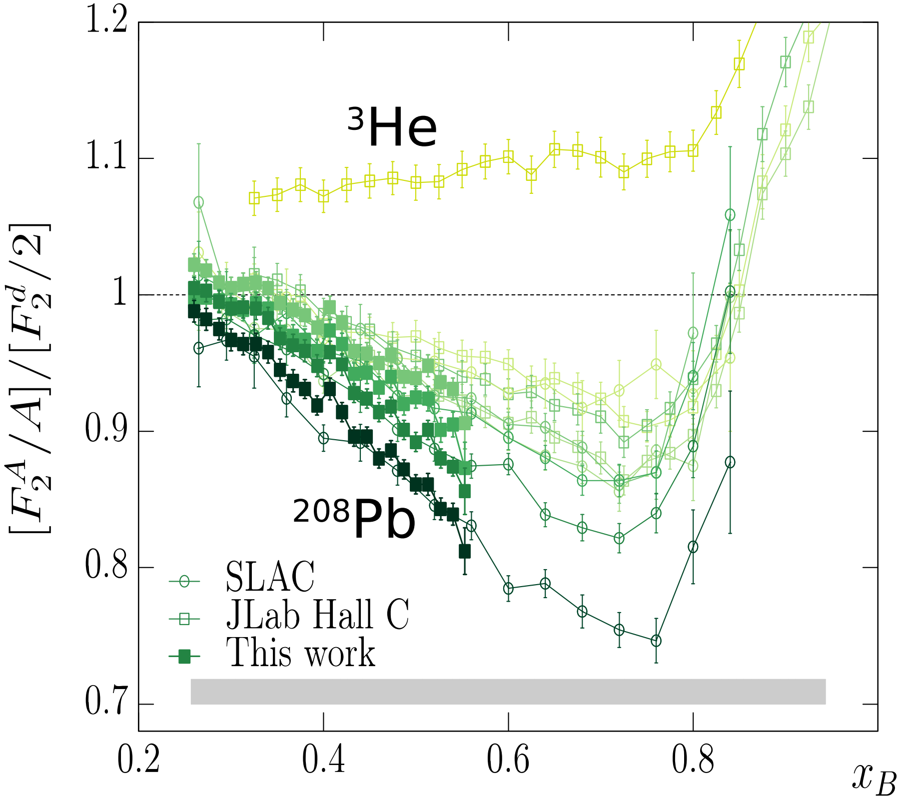
Bound = Free + Modified SRCs

$$F_2^A = Z \cdot F_2^p + N \cdot F_2^n + n_{SRC}^A \left( \Delta F_2^p + \Delta F_2^n \right) \qquad \Delta F_2^N = F_2^{N*} - F_2^N$$



$$F_2^A = Z \cdot F_2^p + N \cdot F_2^n + n_{SRC}^A \left( \Delta F_2^p + \Delta F_2^n \right)$$

## EMC ratios

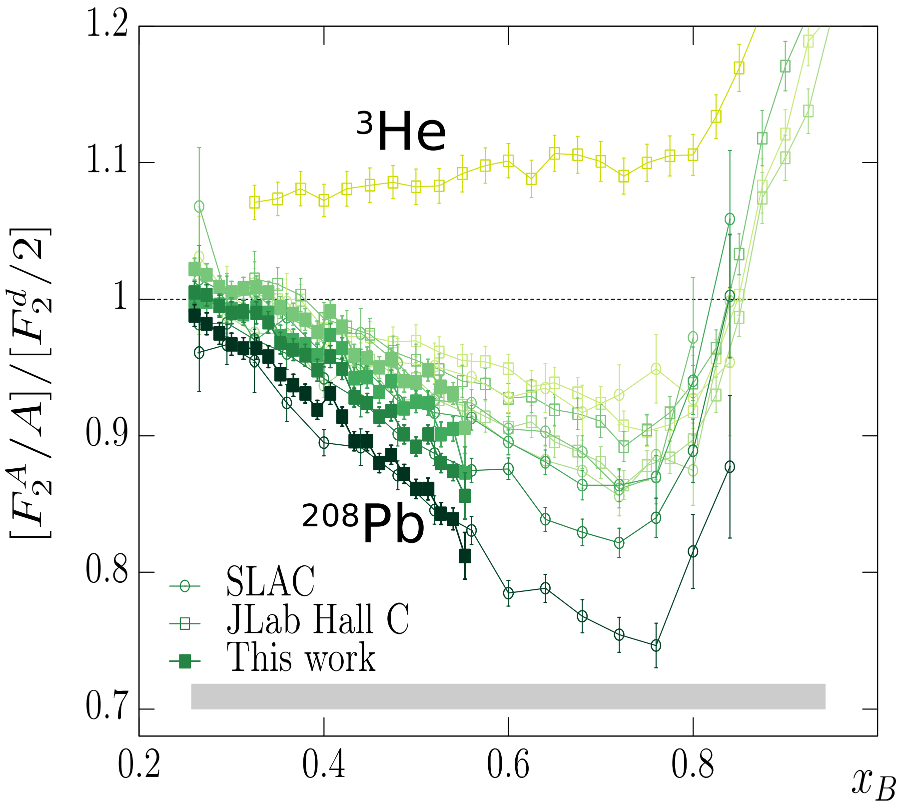



Schmoolker, Duer et al. (CLAS Collaboration), Nature 566 (2019)

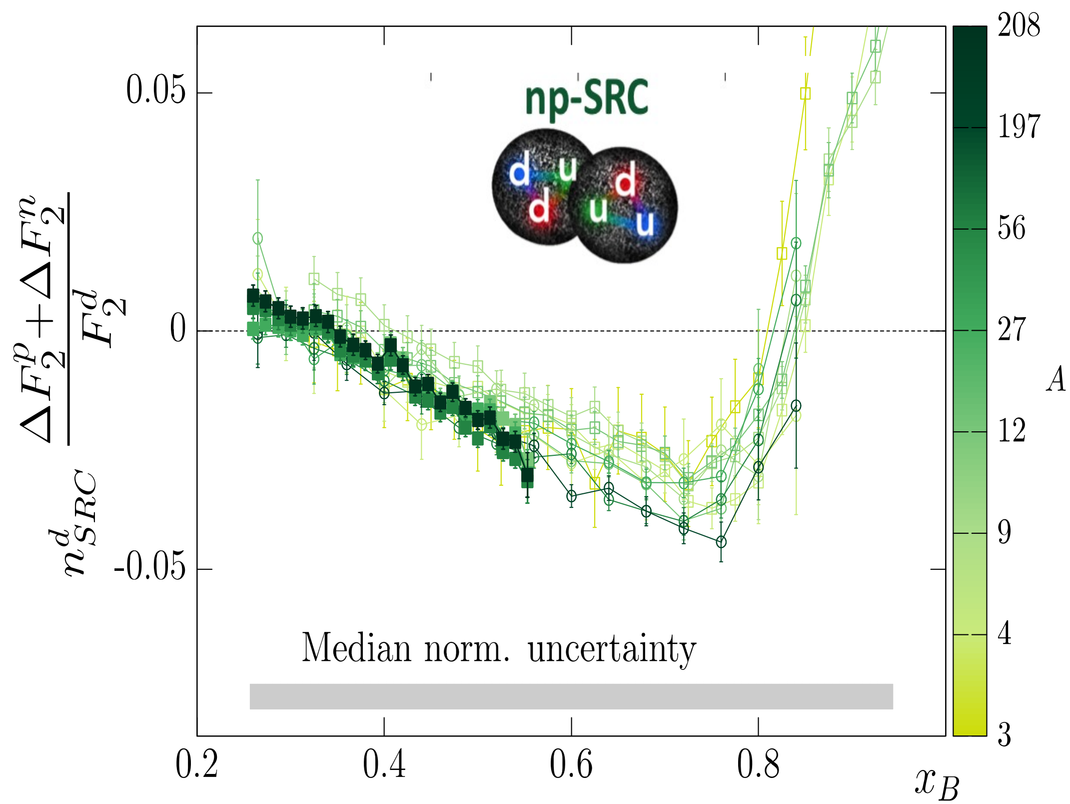
$$\Delta F_2^N = F_2^{N*} - F_2^N$$

$$F_2^A \quad = \quad Z \cdot F_2^p + N \cdot F_2^n \quad + \quad n_{SRC}^A \left( \Delta F_2^p + \Delta F_2^n \right)$$

## EMC ratios




$$\Delta F_2^p + \Delta F_2^n$$




**Universal !**

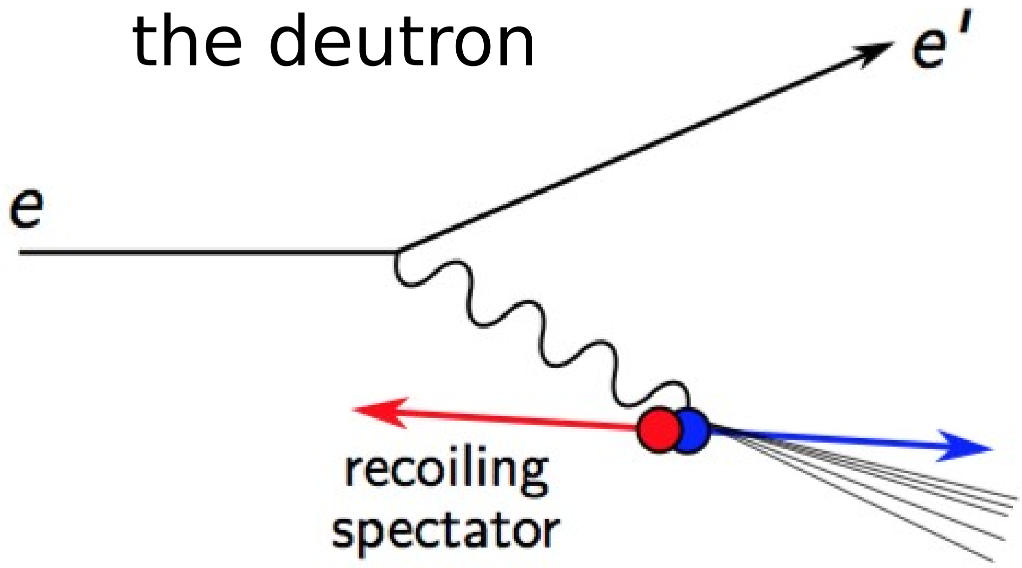
Schmoolker, Duer et al. (CLAS Collaboration), Nature 566 (2019)

$$\Delta F_2^N = F_2^{N*} - F_2^N$$

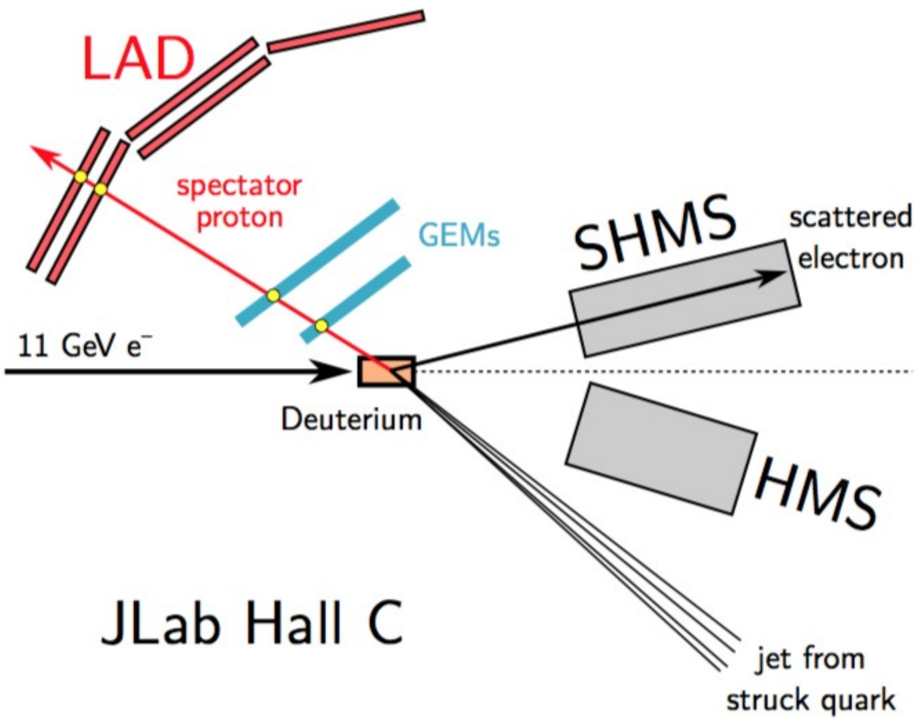
# Is the EMC effect associated with SRC ?

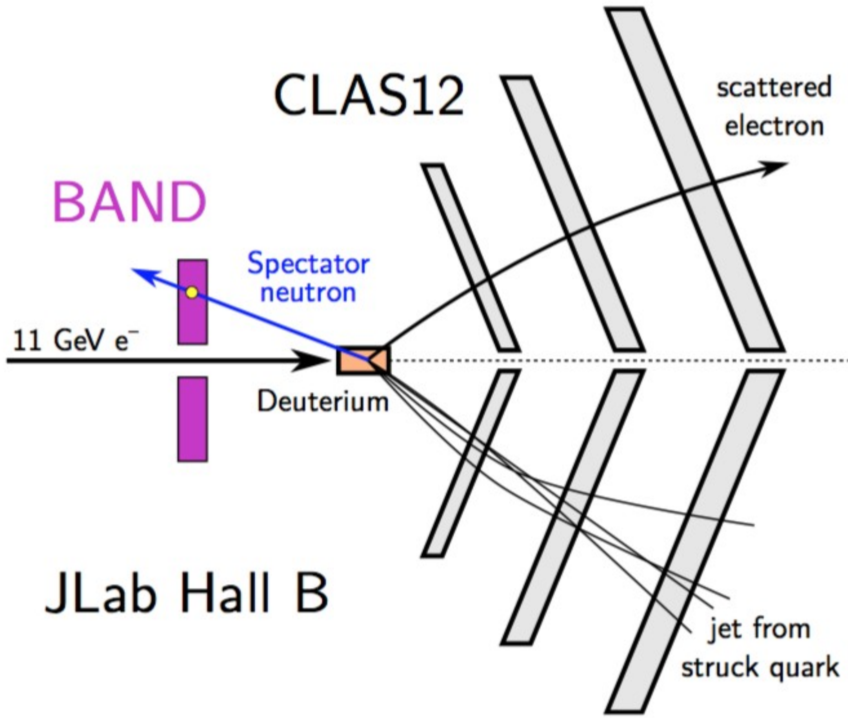
'tagged' high momentum recoil nucleon

Focus on
the deutron

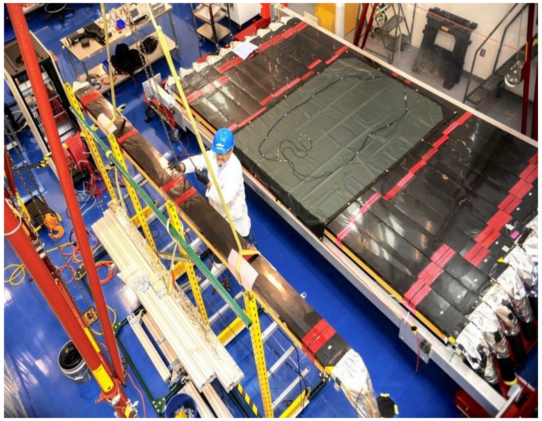


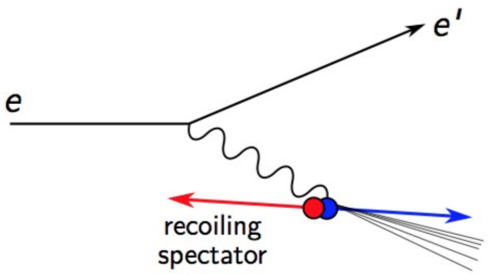
# Nucleon structure function




12 GeV experiments



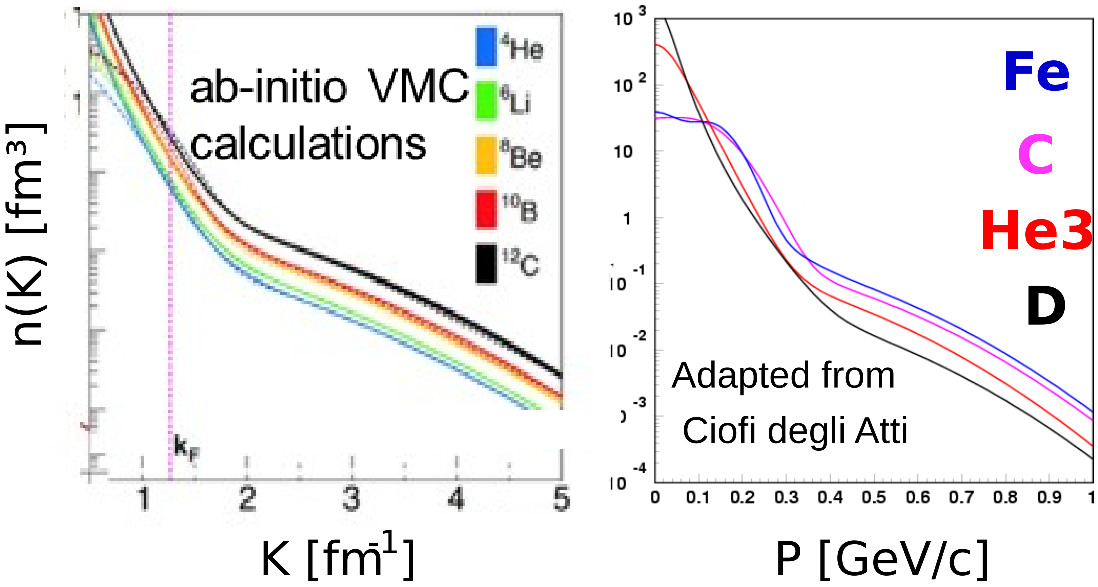



# Backup Slides

# Momentum distribution

**Similar shape for al nuclei: SCALING**

**Can be explained by 2N-SRC dominance**



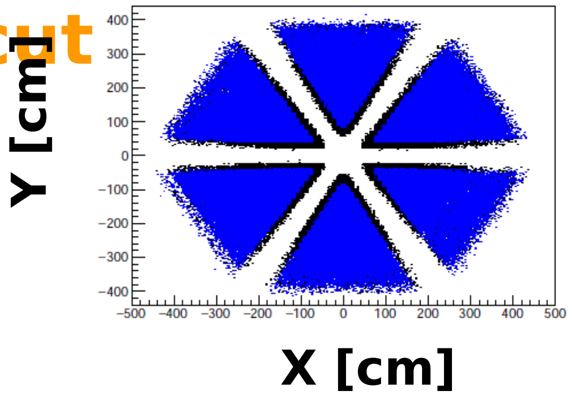

$$n_A(k) \approx C_A \times n_d(k)$$

# Detecting neutrons in CLAS

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

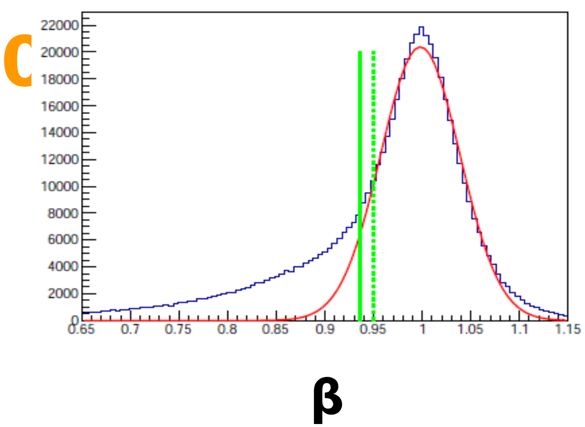
* No signals from Drift-Chambers & Time-Of-Flight Counters
* Hit inside the EC fiducial cut

**Neutral particle**



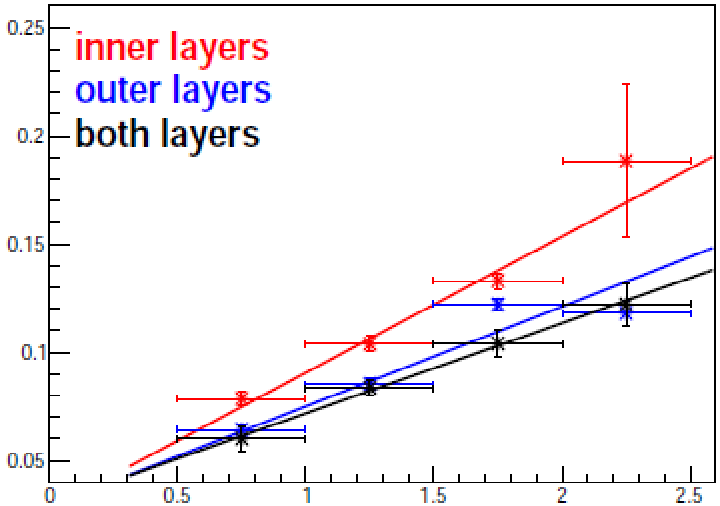

* n/γ separation: β<0.95 (β<0

**Neutron**



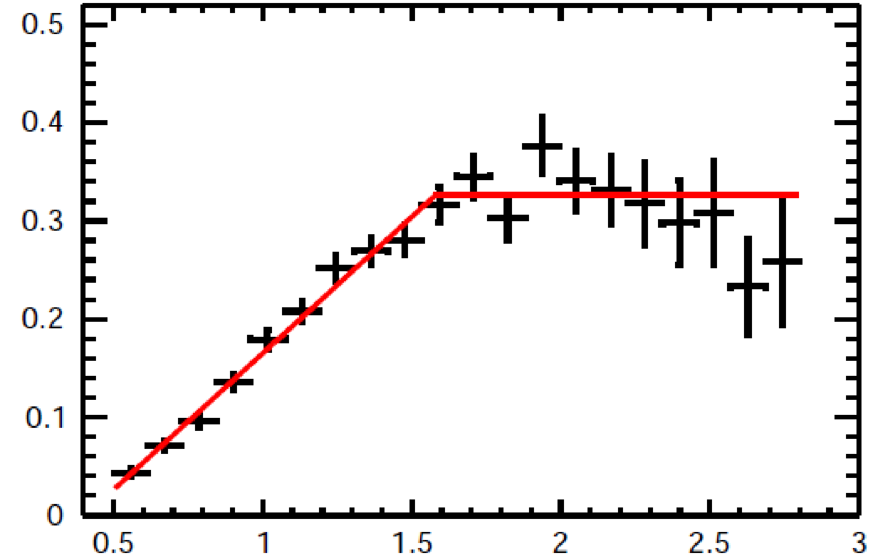
# Neutron resolution & detection efficiency

$\sigma$




$P_n[GeV/c]$

$\epsilon$




$P_n[GeV/c]$

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

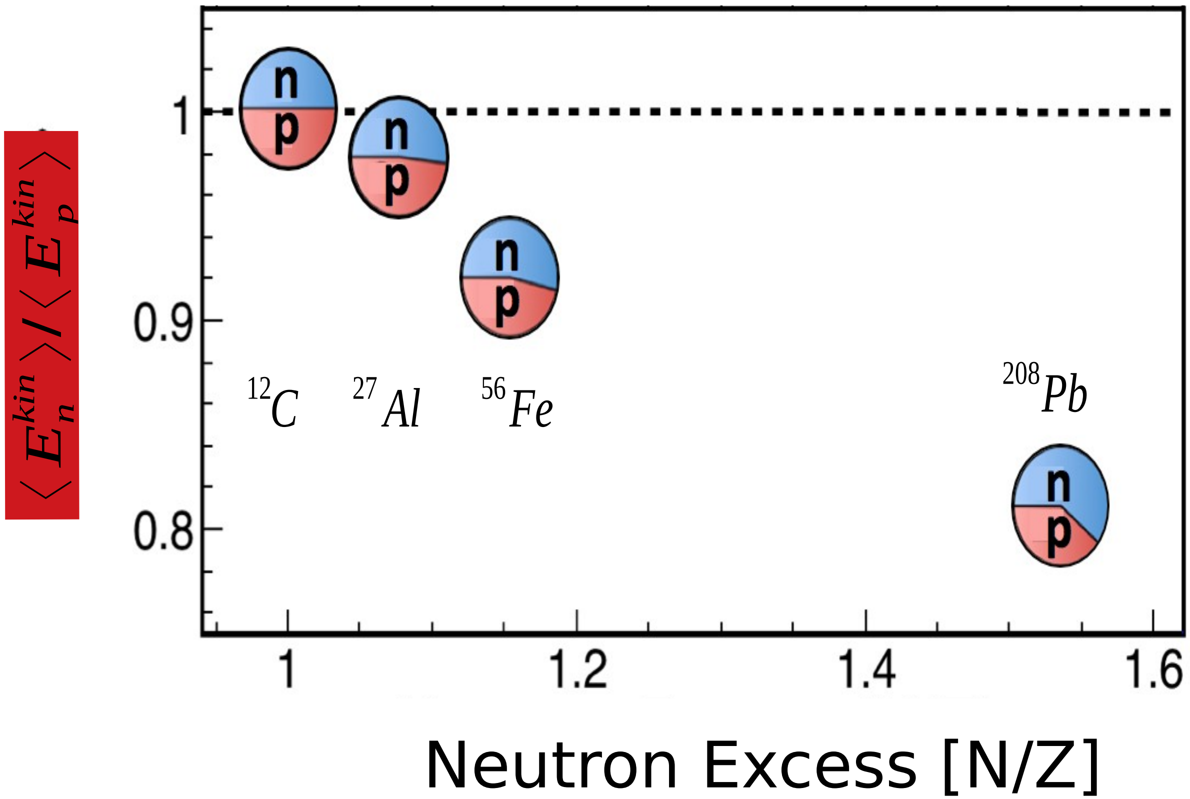
**Using an exclusive reactio** $d(e,e'p\pi^+\pi^-n)$

# 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)



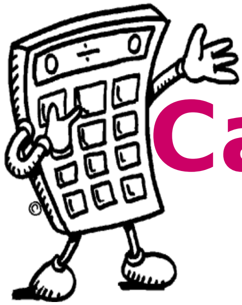

$k_0$: 300 MeV/c, $k_F$

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

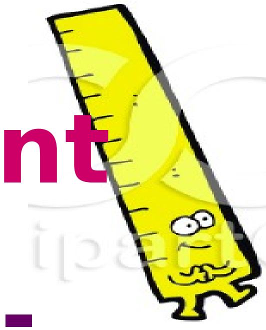
$n_d(k)$: AV18 NN potential

$a_2(A/d)$: Scaling factor

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



# Calculation ⟶ Measurement

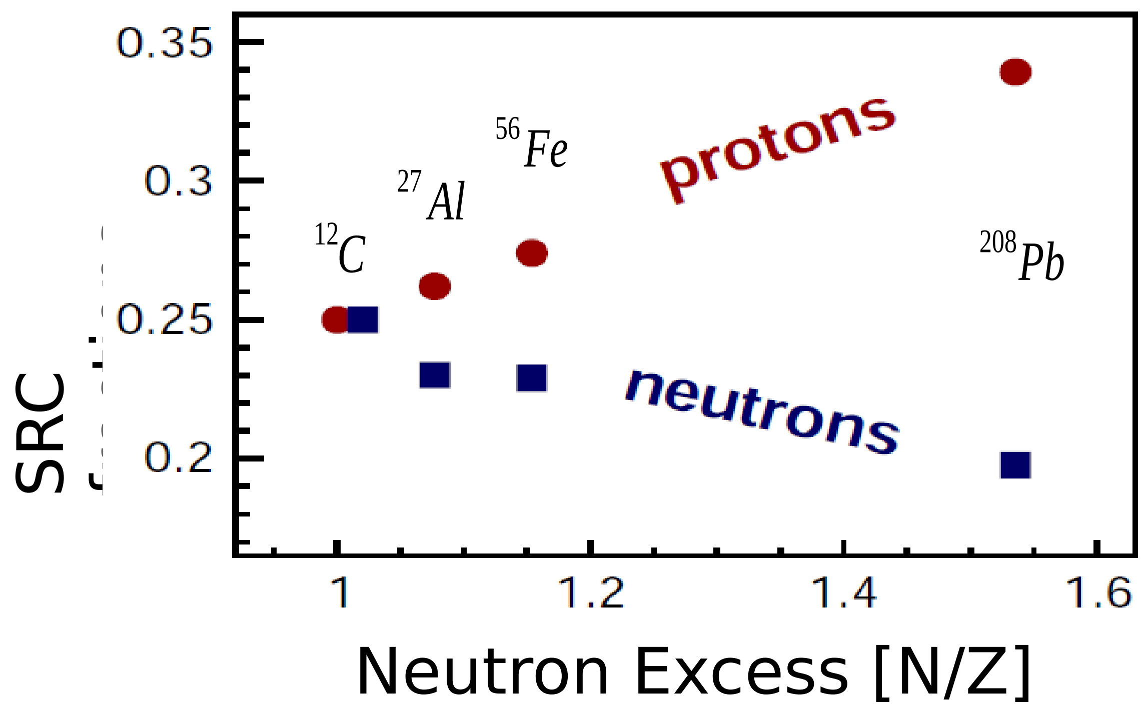


## Simple estimate based on np-dominance

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

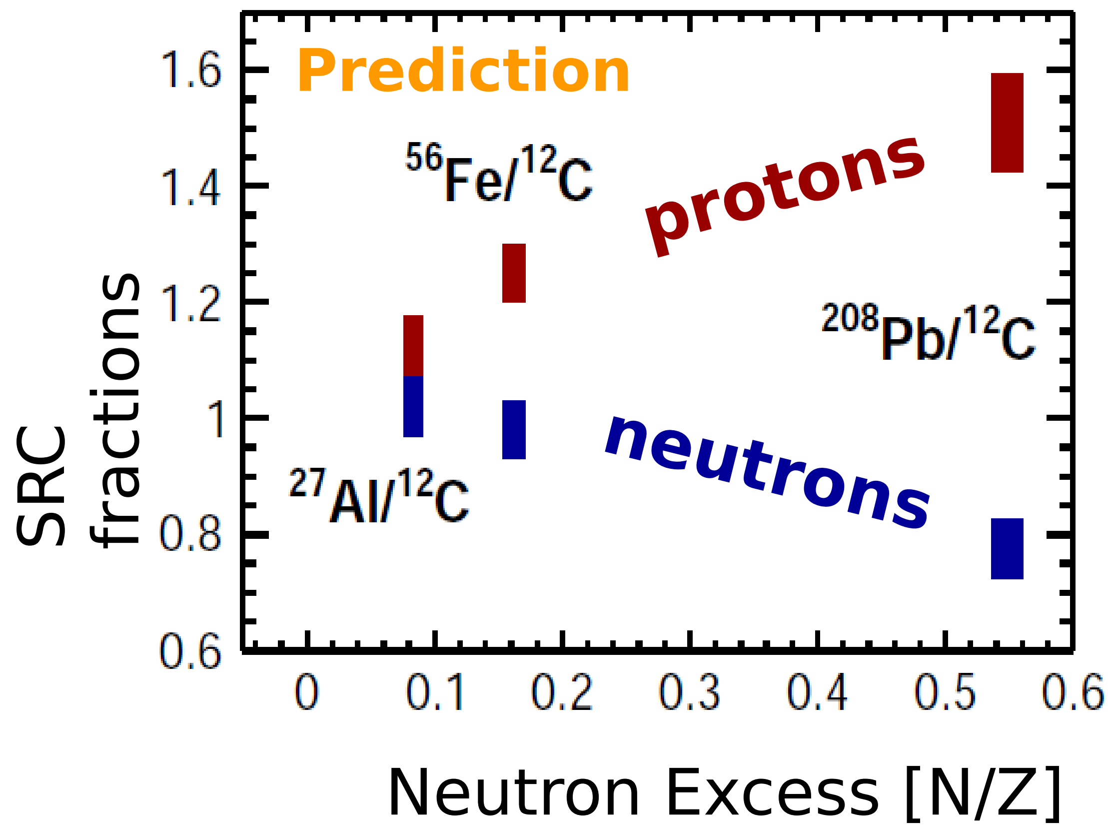
$$R_p=\frac{protons_{k>k_F}}{protons_{k<k_F}}\approx\frac{20}{82-20}=0.32$$

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



# The goal:

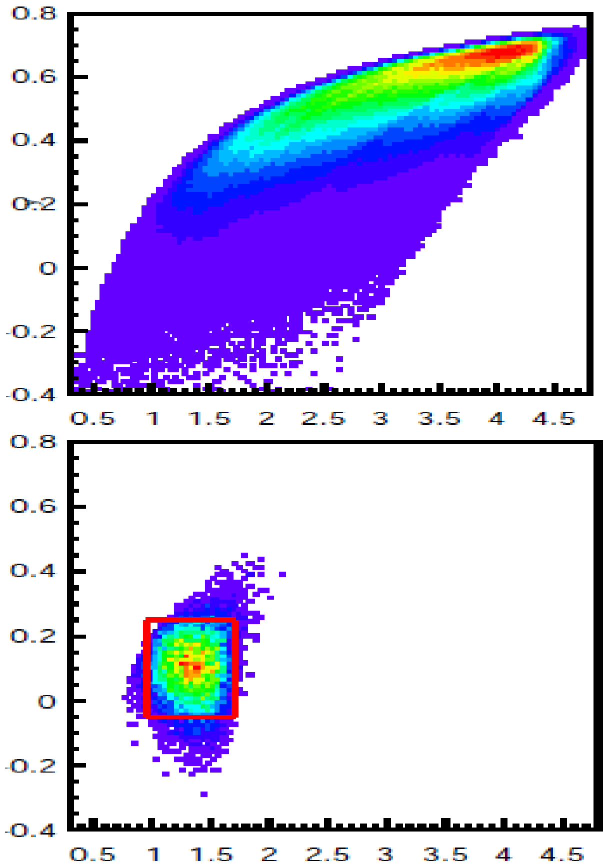
**Extracting** $\frac{A(e,e'N)\ high/low}{^{12}C(e,e'N)\ high/low}$ **ratios** $(N=n/p)$




# Solution I

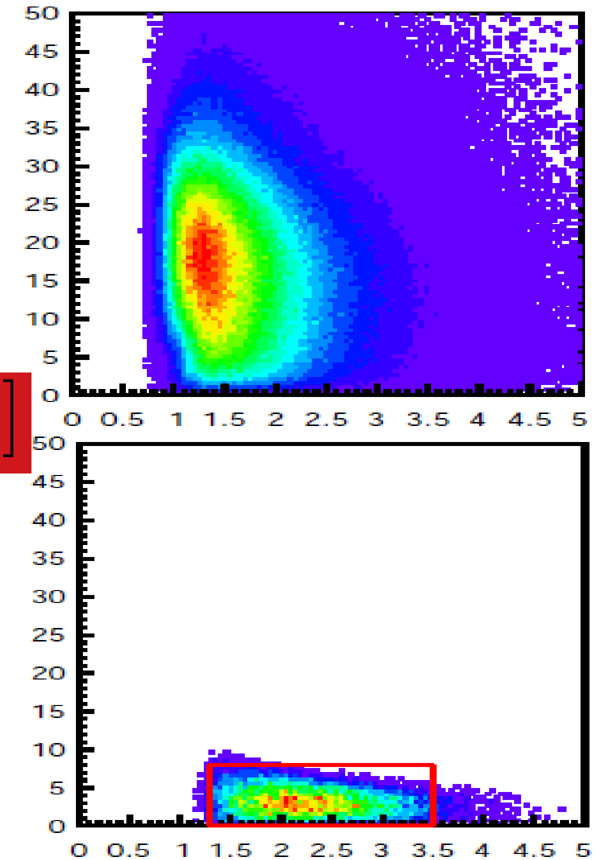
## Using electron & nucleon angular cuts

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




Before the QE cuts

After the QE cuts




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

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

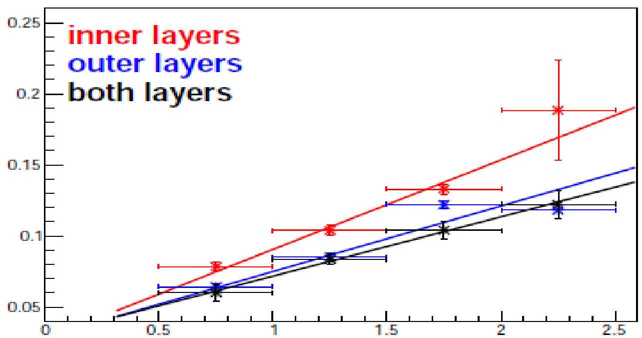

# Solution II

## Using smeared protons to:

* Define and test the cuts

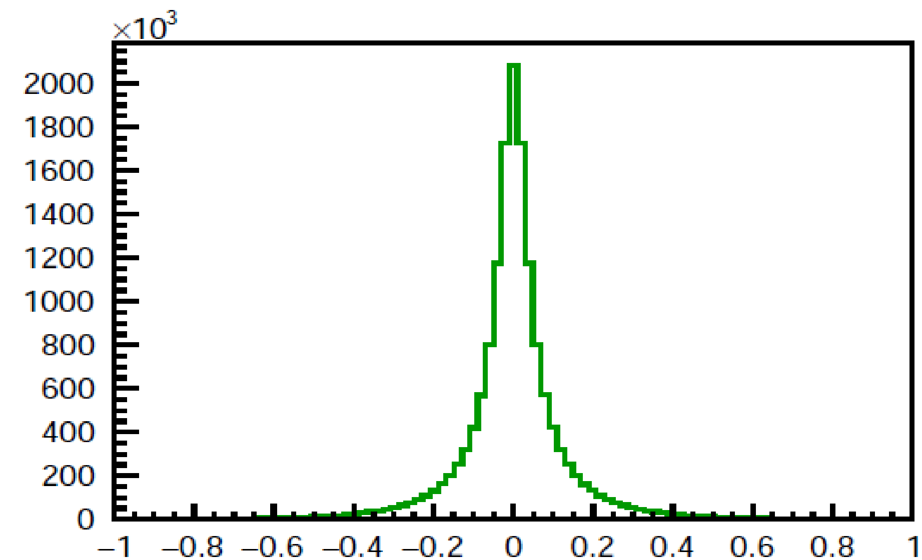
* Study bin mig

$\sigma$



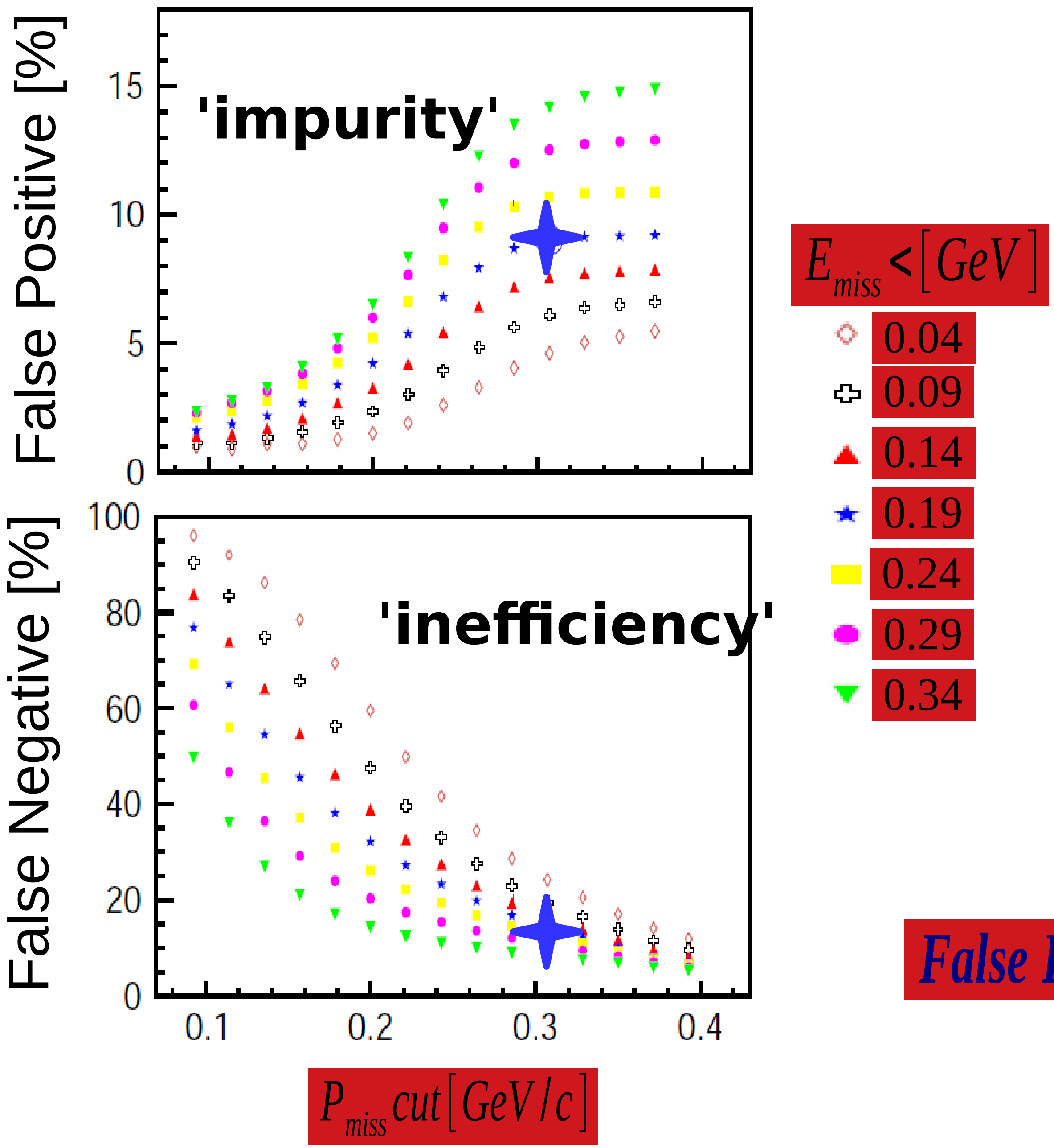

$P_n[GeV/c]$

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




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

# False Positive & Negative probabilities




**smeared p/n cuts:**

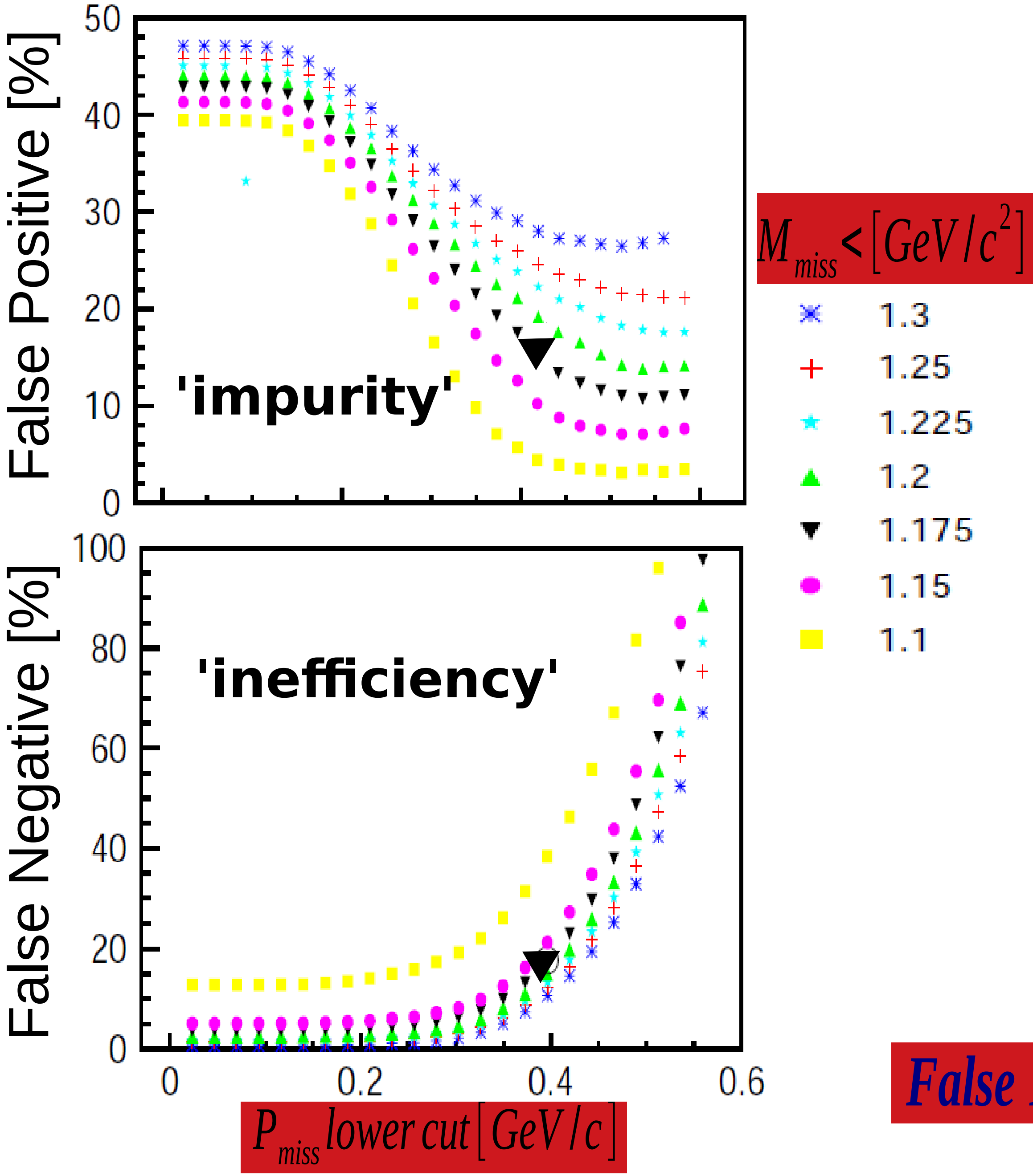
$P_{miss} < 0.3\, GeV/c$, $E_{miss} < 0.19\, GeV$

**un-smeared p cuts:**

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

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

# False Positive & Negative probabilities




**smeared p/n cuts:**

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

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

**un-smeared p cuts:**

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

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

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

# The selected cuts:

| smeared protons | un-smeared protons |
| --- | --- |
| $x_B > 1.1$ | $x_B > 1.2$ |
| $0.62 < \vec{p}/\vec{q} < 1.1$ | $0.62 < \vec{p}/\vec{q} < 0.96$ |
| $\theta_{pq} < 25^o$ | $\theta_{pq} < 25^o$ |
| $0.4 < P_{miss} < 1 GeV/c$ | $0.3 < P_{miss} < 1 GeV/c$ |
| $M_{miss} < 1.175 GeV/c^2$ | $M_{miss} < 1.1 GeV/c^2$ |

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

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

'real' pp SCX

$$A(e,e'pp)=$$

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

'real' np SCX

$$A(e,e'np)=$$

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

(Combinatorial ratio)

# Extracting pp/np ratios

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

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

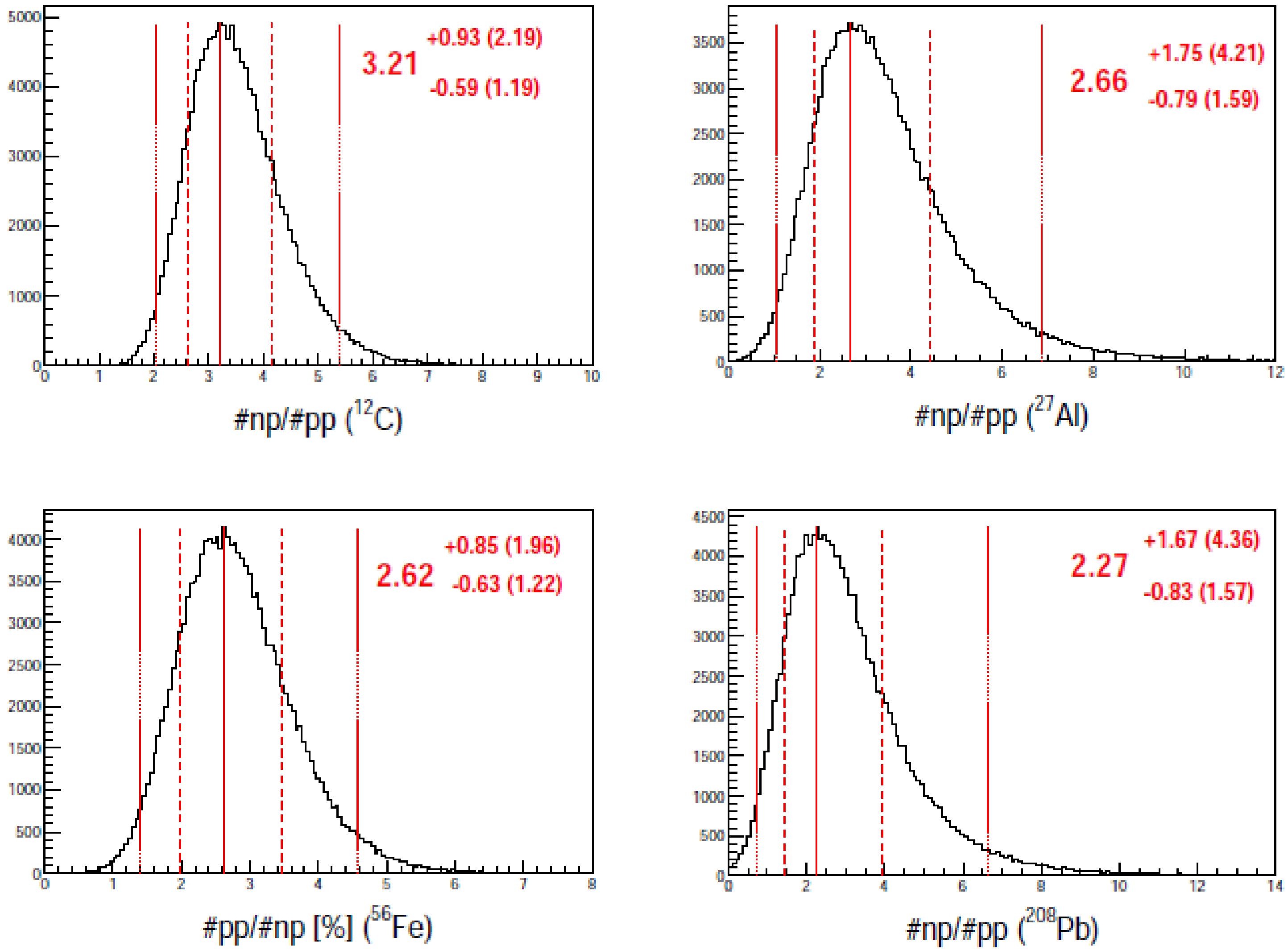
$$R = \frac{A(e,e'pp)/2 \cdot \sigma_{ep}}{A(e,e'np)/\sigma_{en}}$$

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

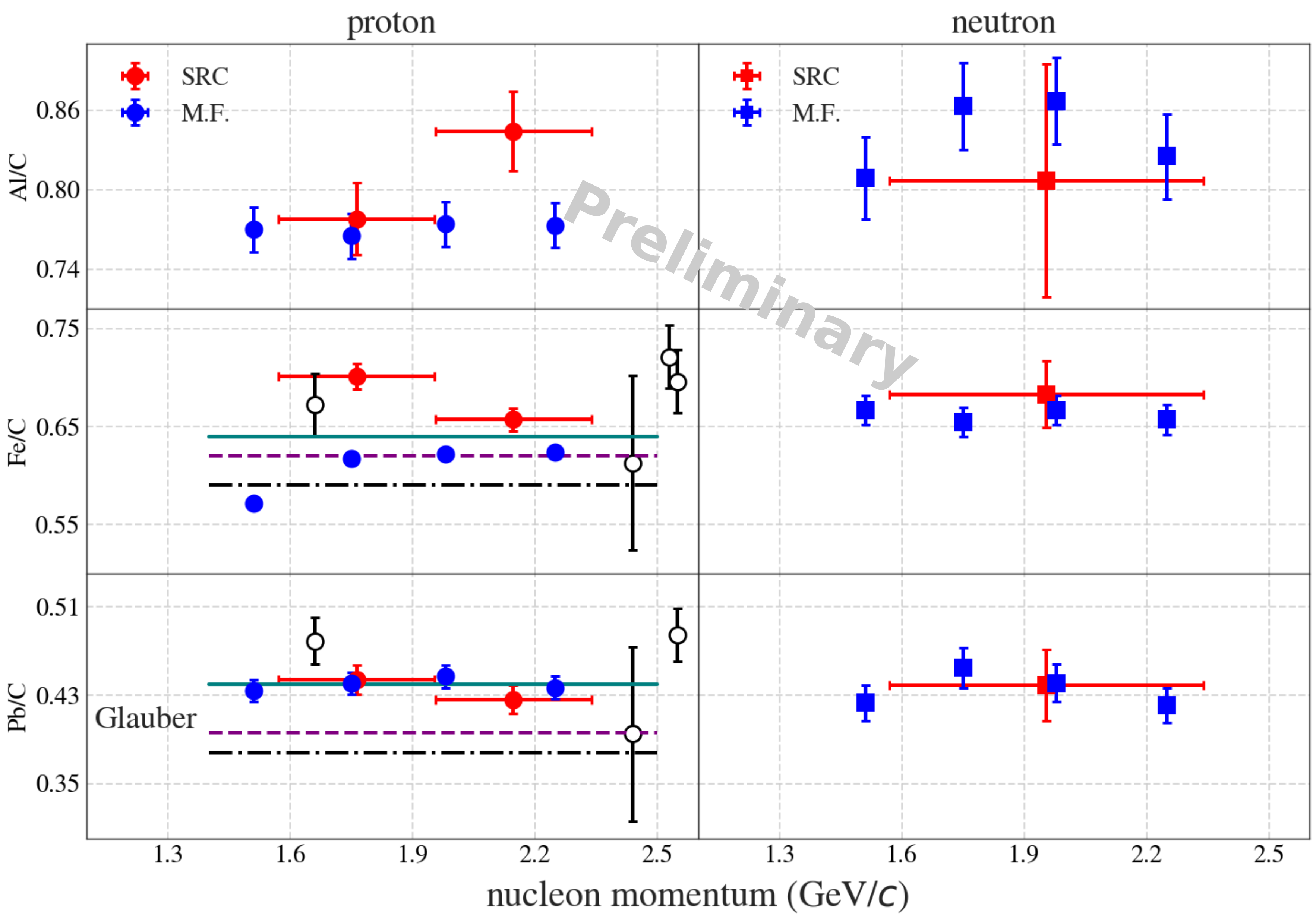
**SCX probabilities, Ref. [1], change between ~ 3 – 7 % from C to Pb**

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

# Extracting pp/np ratios



$T_N(A)/T_N(C)$




**Duer et al., paper under CLAS collaboration review**

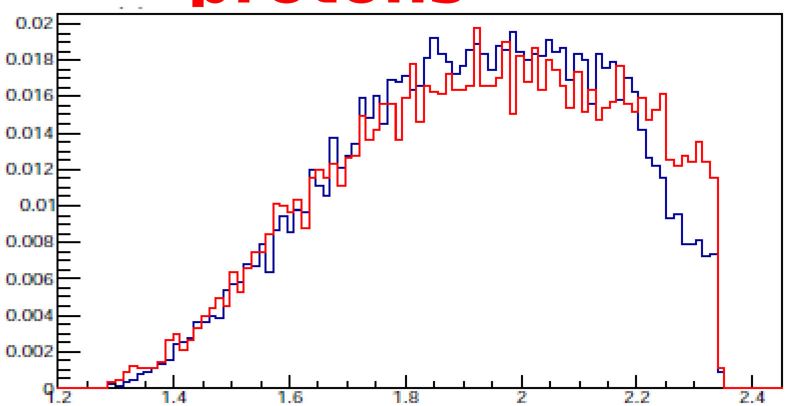


**Glauber calculations:**

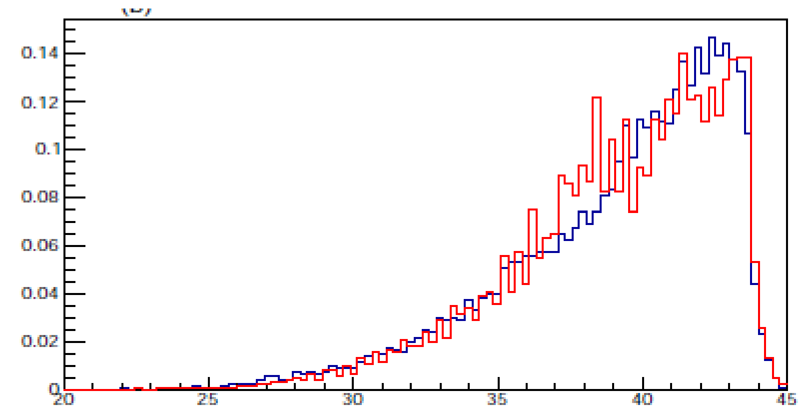
Colle et al., PRC 93, 034608 (2016) Frankfurt et al., PLB. 503, 73 (2001) Pandharipande et al., PRC 45, 791 (19

# Comparing the smeared protons and neutrons

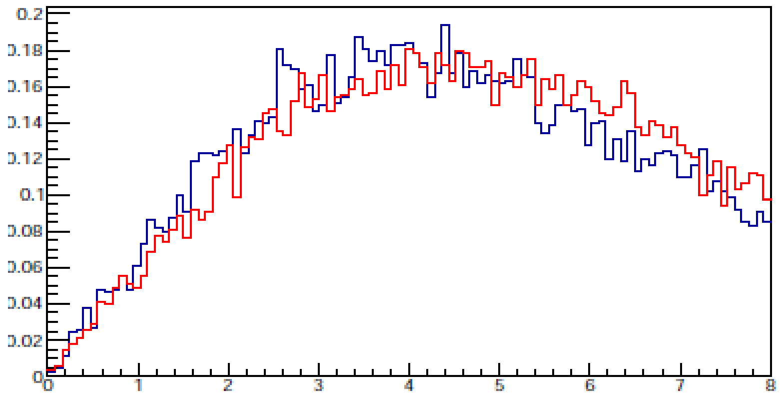
**smeared protons** | **neutrons**



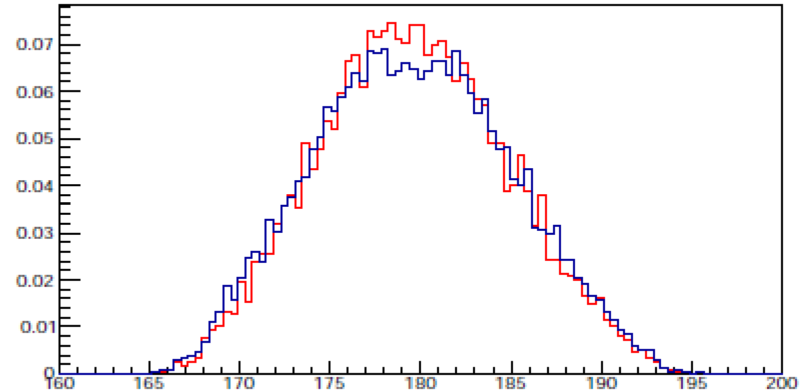

$P_{p/n}[GeV/c]$




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



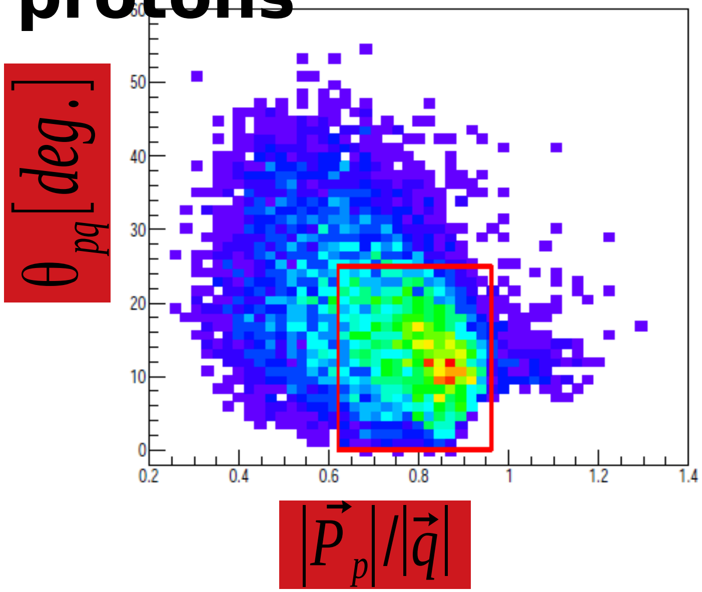

$\theta_{pq/nq}[deg.]$



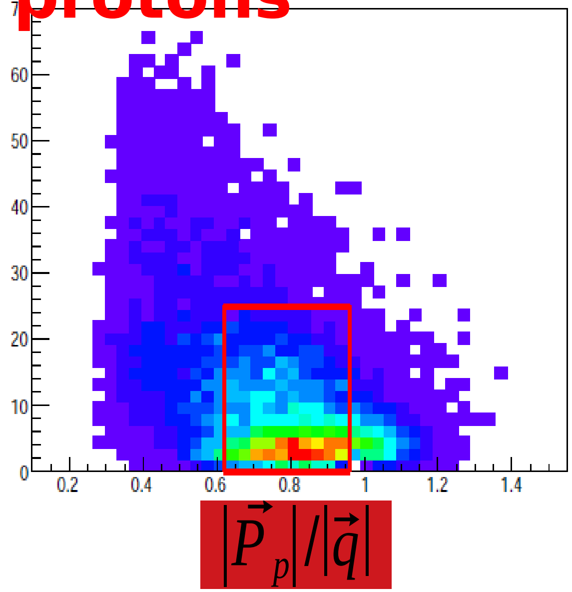

$|\phi_{p/n} - \phi_e|[deg.]$

# Identifying the Leading Nucleon

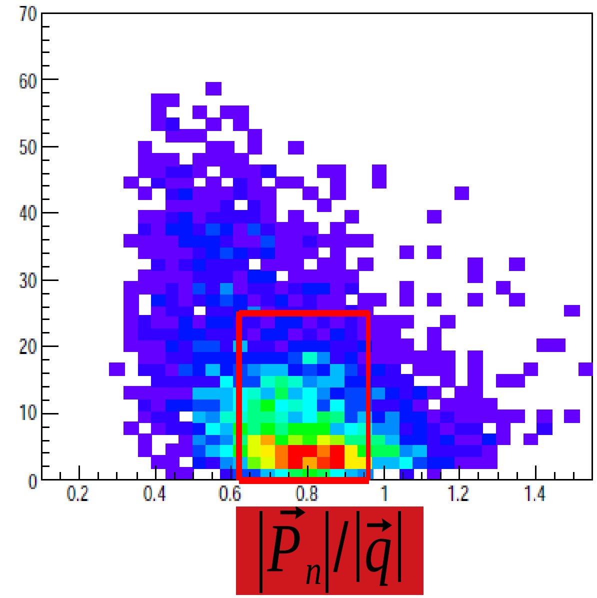
**un-smeared protons**




**smeared protons**




**neutrons**




**We adopted the cuts (O. Hen 2012):**

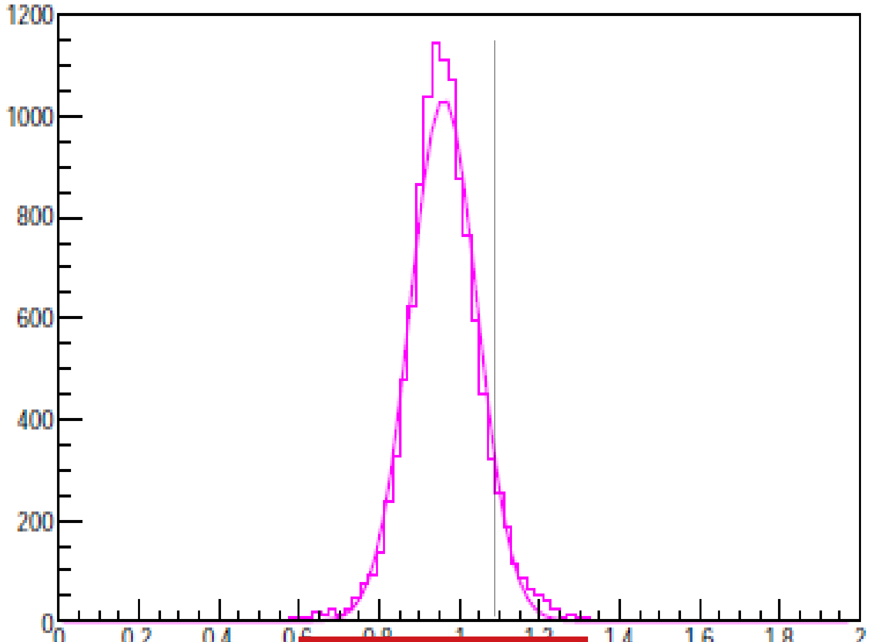
$$0.62 \le \frac{|\vec{P}_N|}{|\vec{q}|} \le 0.96$$

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

# Missing Mass cut

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

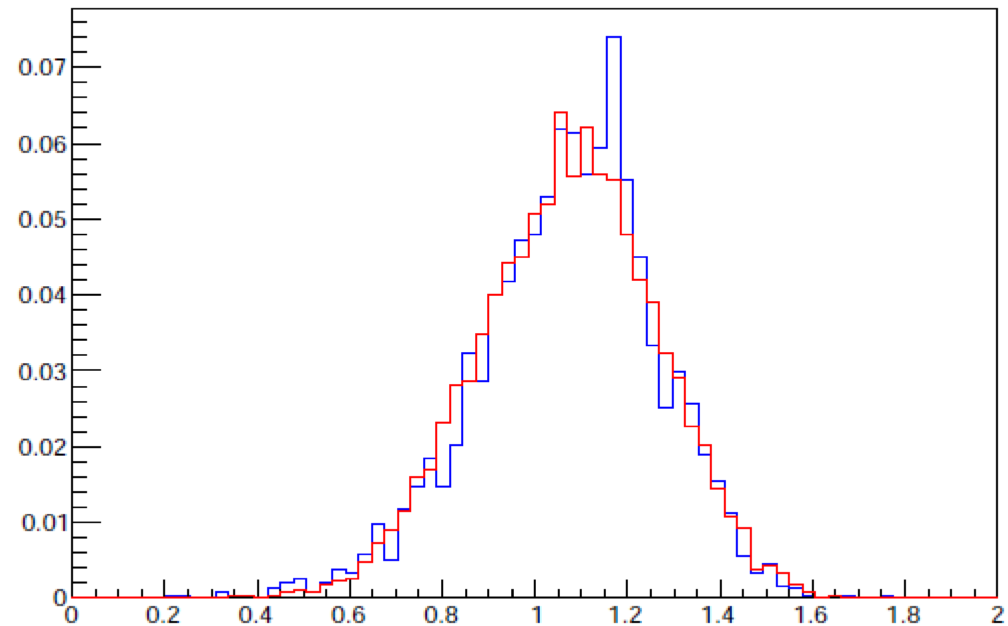
**un-smeared**




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

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

**smeared** **neutrons**




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

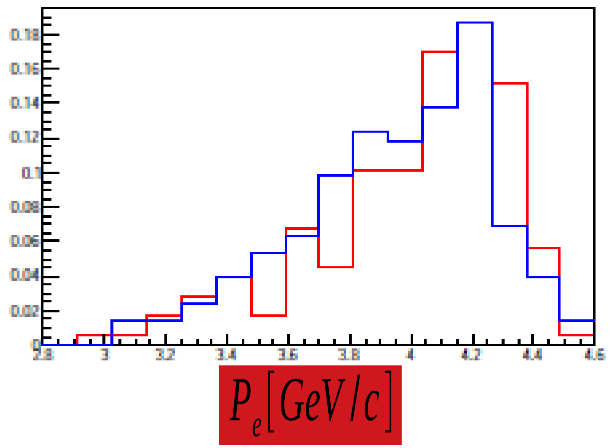
$$M_{miss} < ?$$

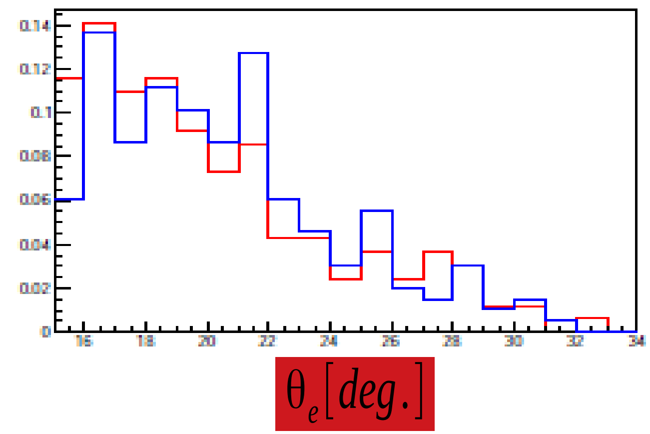
# The selected events:

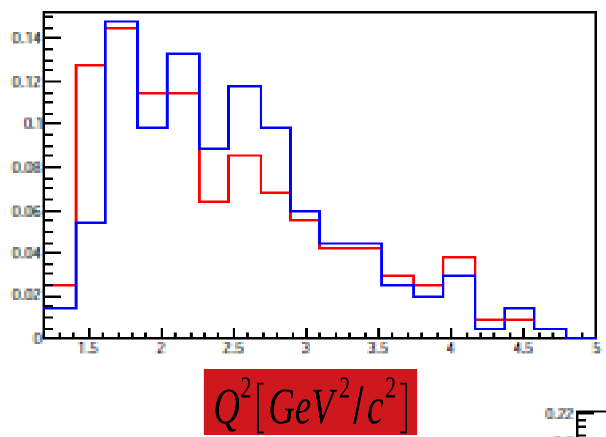
| This analysis (smeared protons & neutrons) | Proton analysis (O. Hen et al.) |
| --- | --- |
| $x_B > 1.1$ | $x_B > 1.2$ |
| $0.62 < p/q < 1.1$ | $0.62 < p/q < 0.96$ |
| $\theta_{pq} < 25^o$ | $\theta_{pq} < 25^o$ |
| $M_{miss} < 1.175\, GeV/c^2$ | $M_{miss} < 1.1\, GeV/c^2$ |
| $0.4 < P_{miss} < 1\, GeV/c$ | $0.3 < P_{miss} < 1\, GeV/c$ |

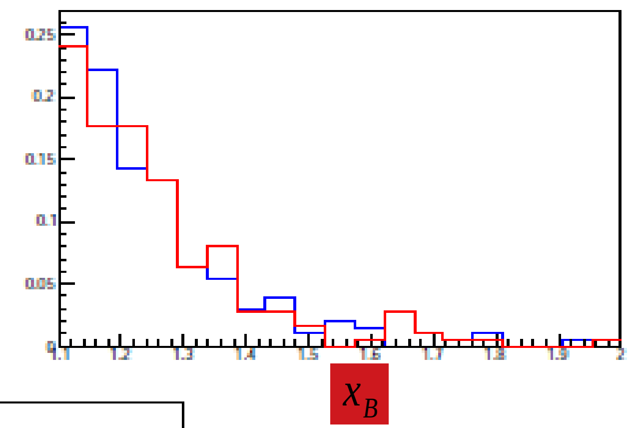
# Electron kinematics

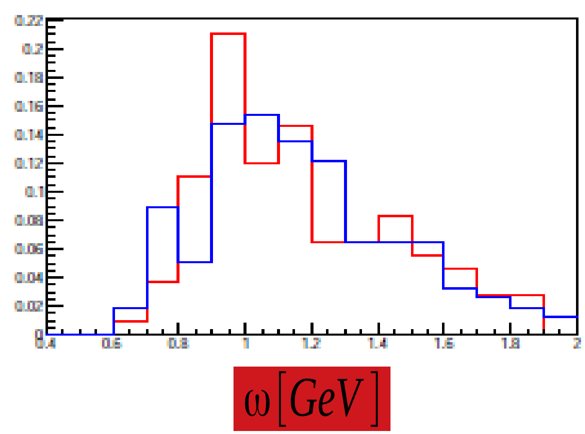
## smeared protons neutrons



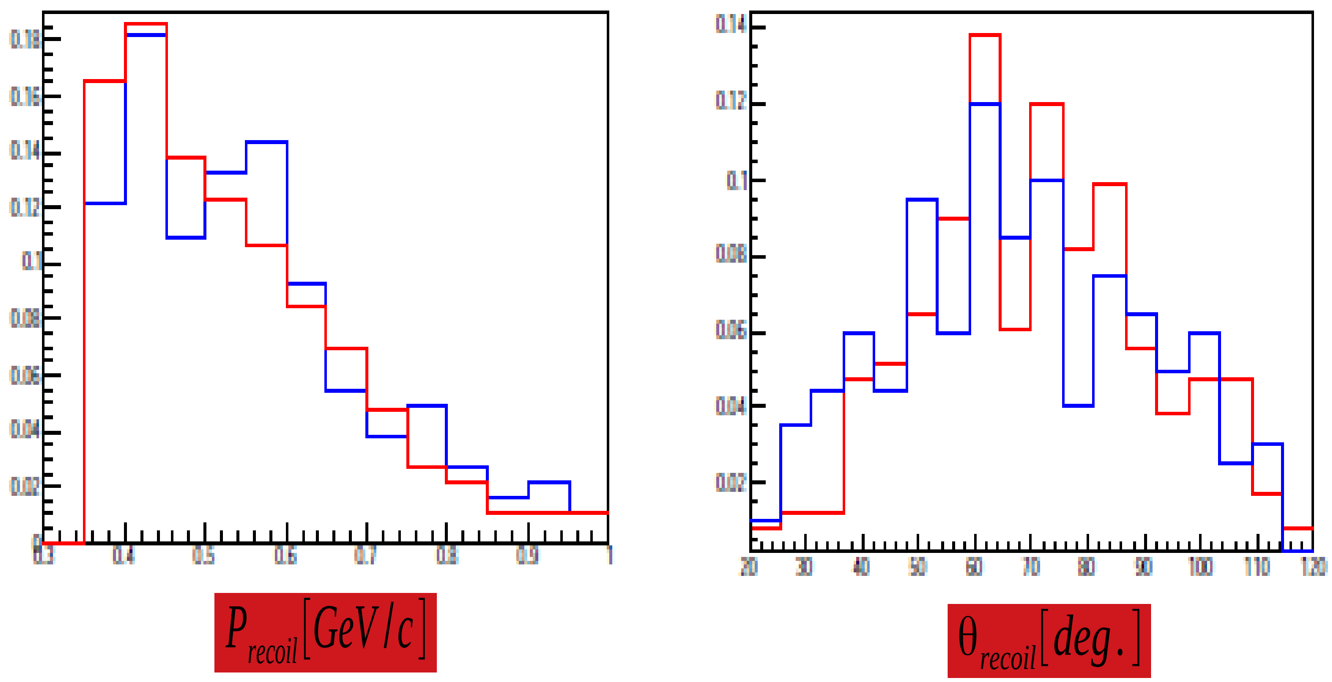



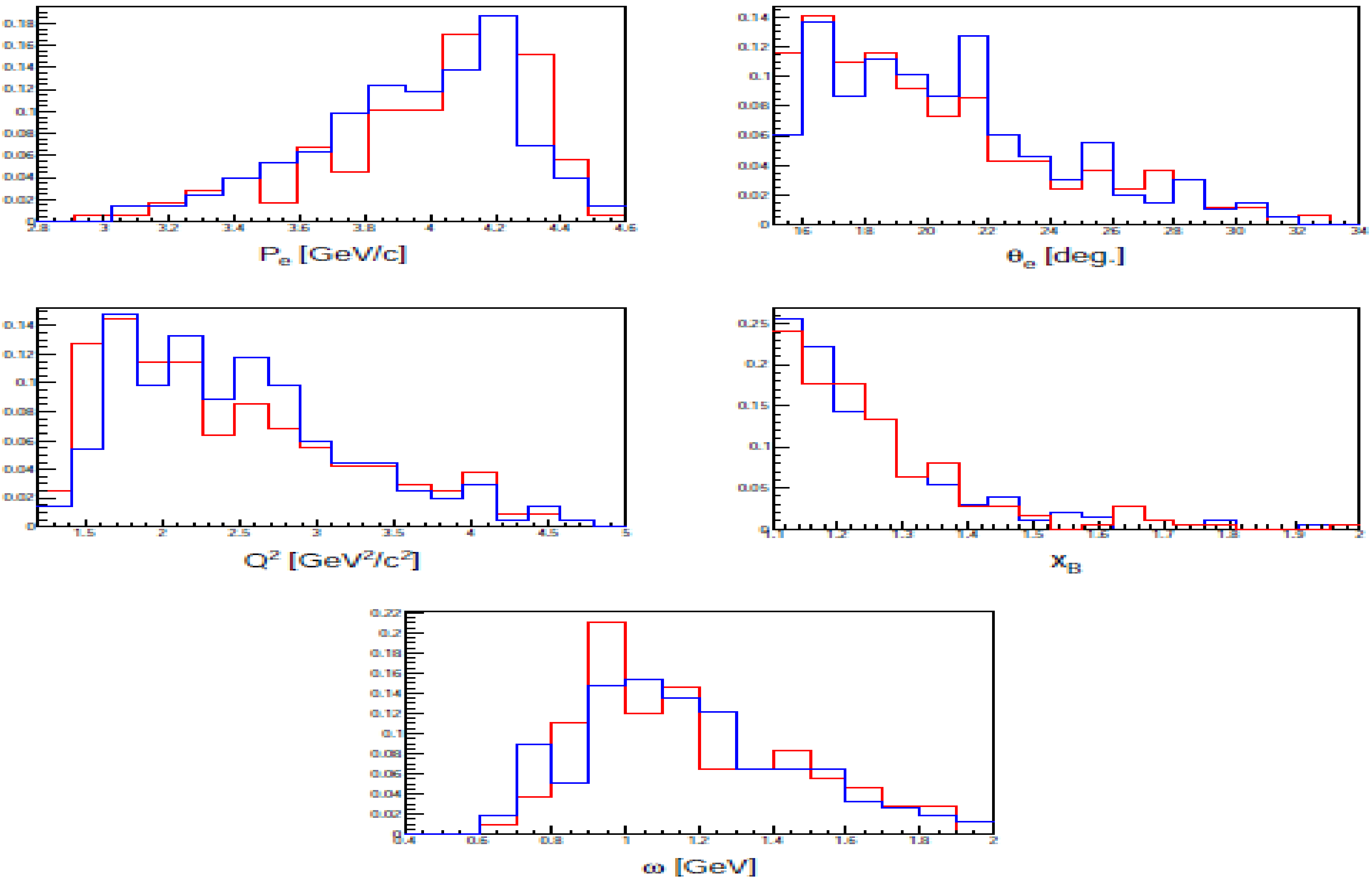



# Recoil proton kinematics

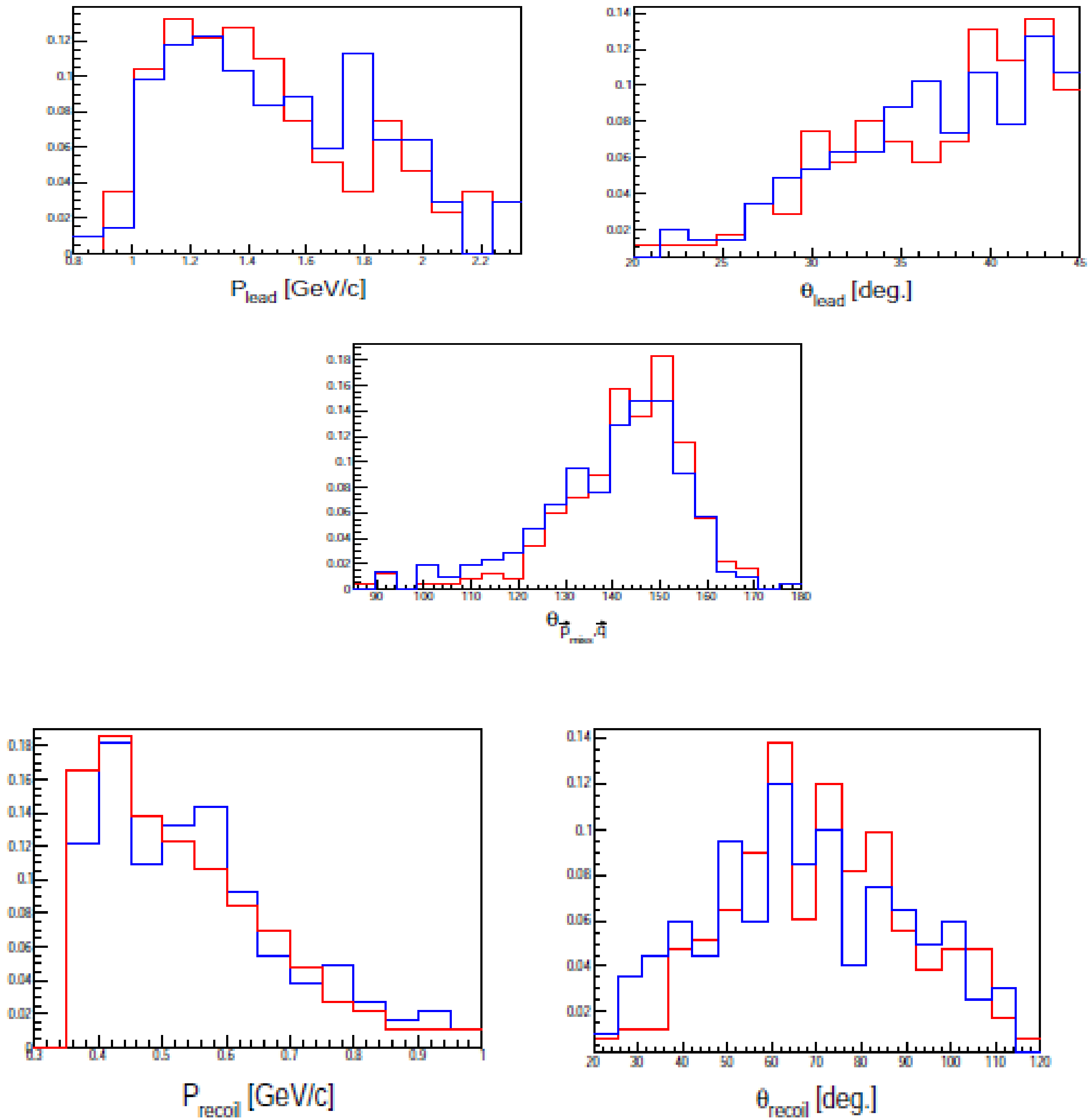
**smeared protons** **neutrons**



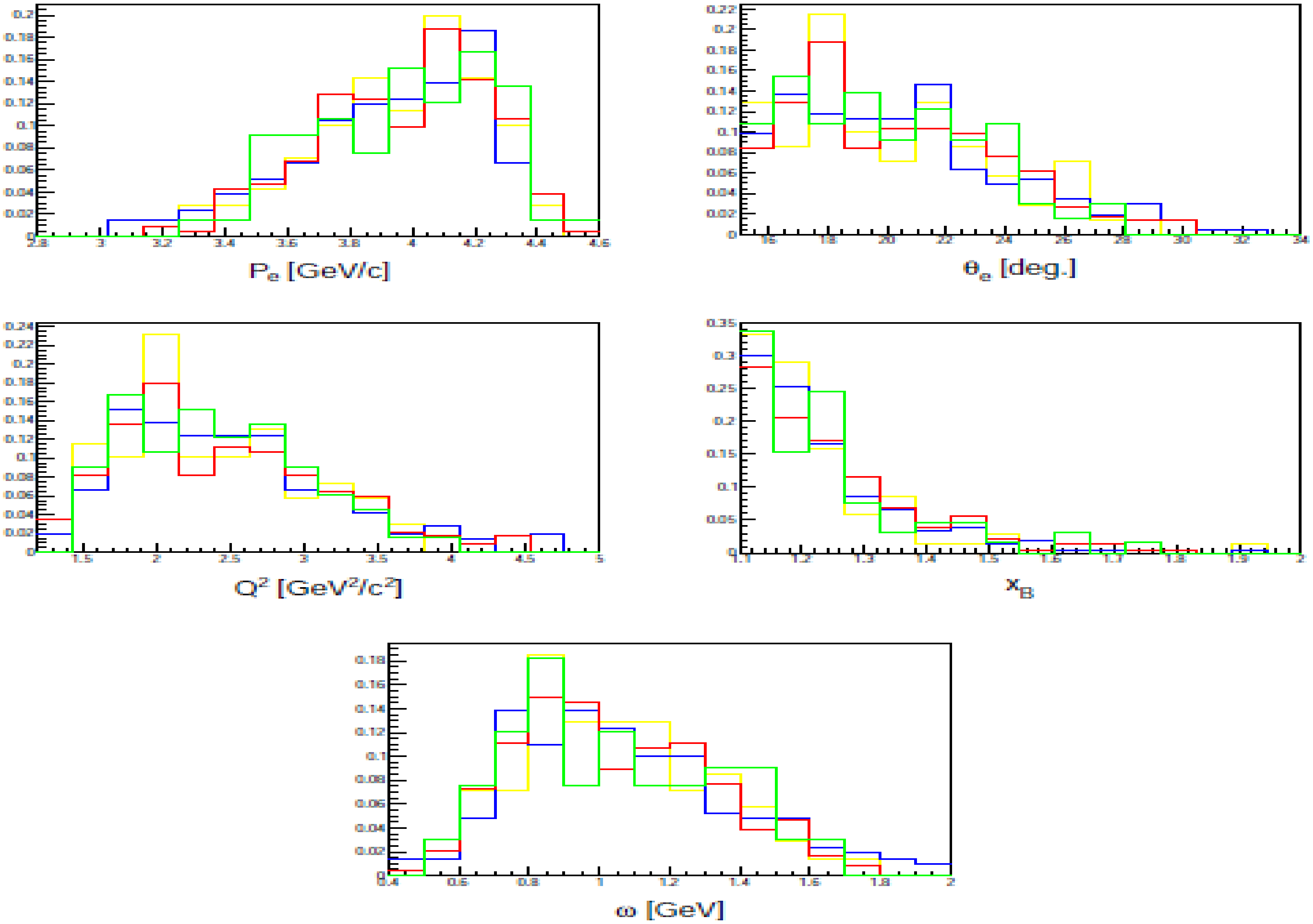
# np-pp smeared & neutrons



# np-pp smeared & neutrons

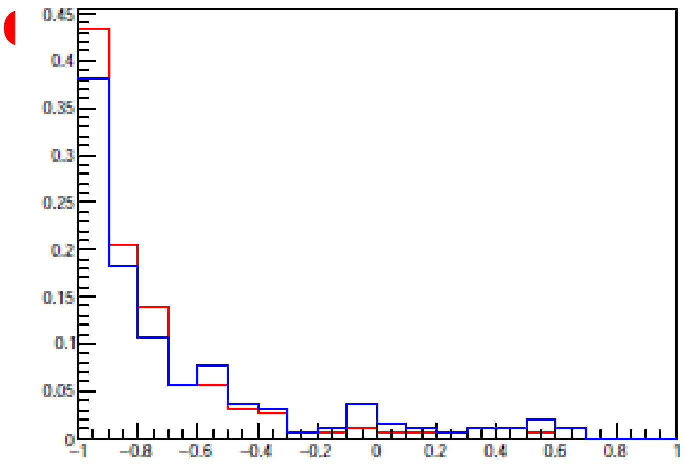


# np-pp neutrons

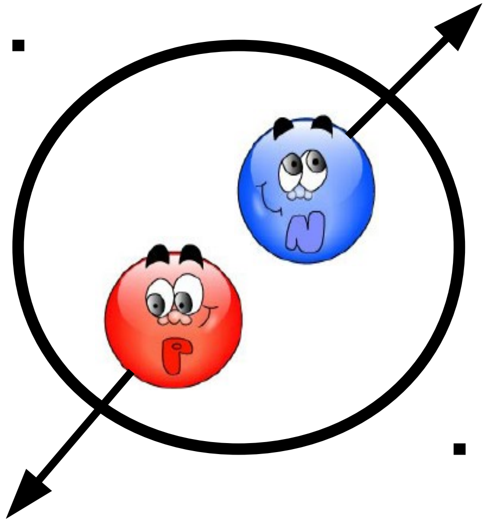


# Opening angle distribution

**smeared protons** **neutrons**




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

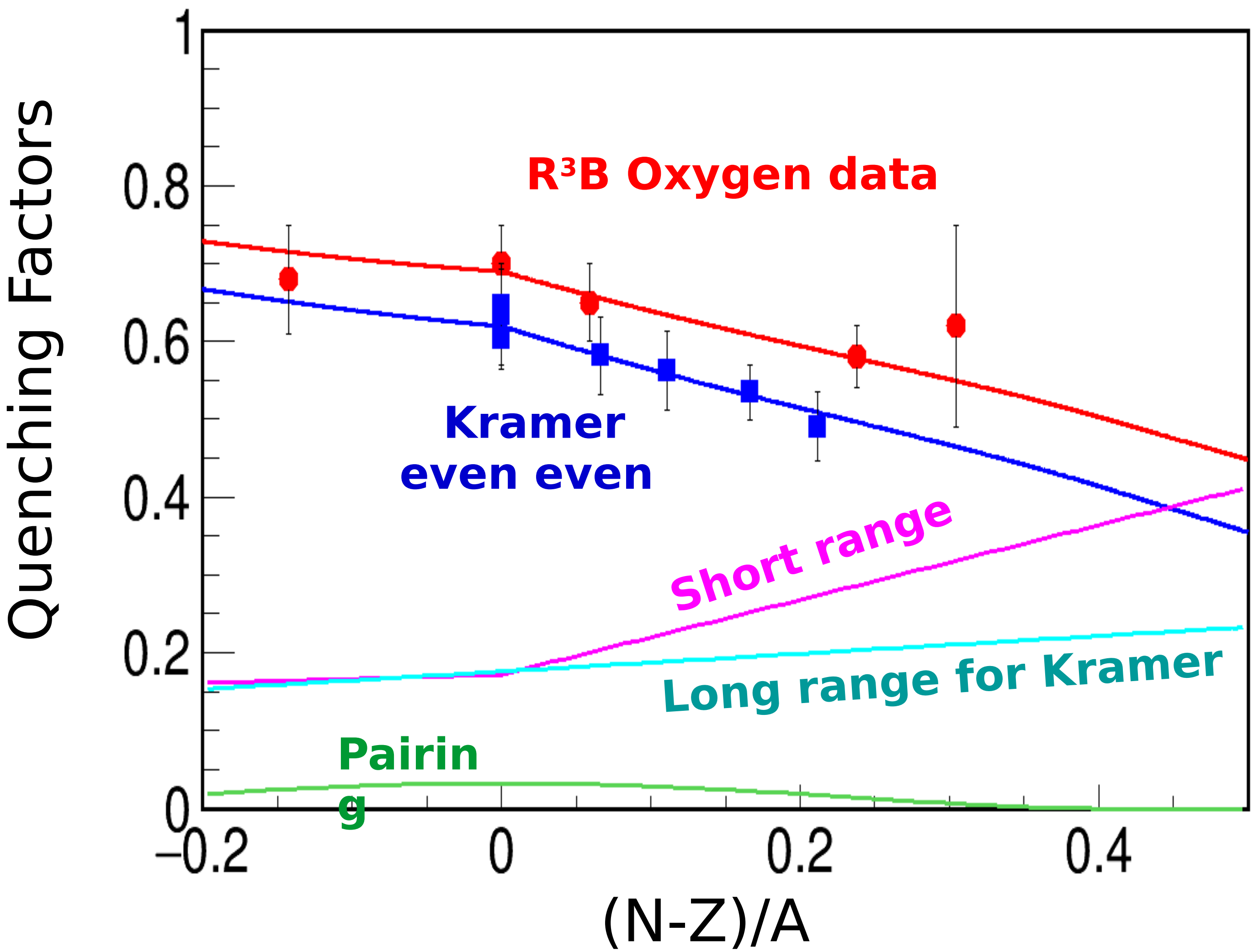


$$\frac{T(A)}{T(C)} = \frac{1}{a_2(A/C)} \cdot \frac{\sigma_A(e,e'N)/A}{\sigma_C(e,e'N)/12} = \frac{1}{a_2(A/C)} \cdot \frac{12}{A} \cdot R$$

$$\frac{T_A}{T_C} = \frac{\sigma_A(e,e'p)/Z/{}_0\int^{k_0} n^p_{A,M.F.}(k) \cdot kdk}{\sigma_C(e,e'p)/6/{}_0\int^{k_0} n^p_{C,M.F.}(k) \cdot kdk} = \frac{6}{N_1} \cdot \frac{{}_0\int^{k_0} n^p_{C,M.F.}(k) \cdot kdk}{{}_0\int^{k_0} n^p_{A,M.F.}(k) \cdot kdk} \cdot R$$

**Isospin dependence of nucleon-nucleon correlations and the reduction of the single-particle strength in atomic nuclei**

S. Paschalis,[1] A. O. Macchiavelli,[2] M. Petri,[1] O. Hen,[3] and E. Piasetzky[4]




SRC fraction - 20%

LRC (gs → gs) - 18%

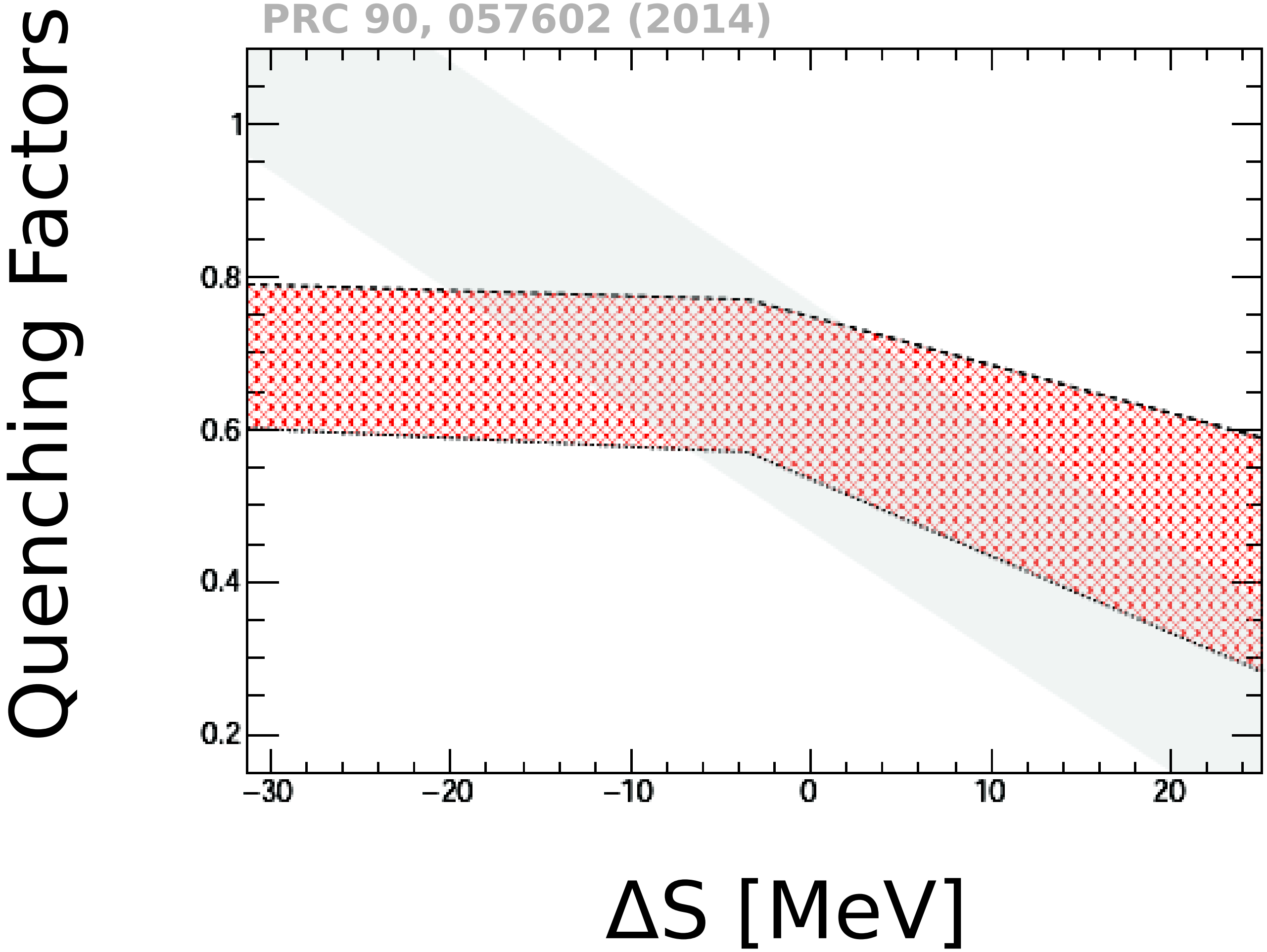
LRC (gs → all) - 11%

Pairing - small

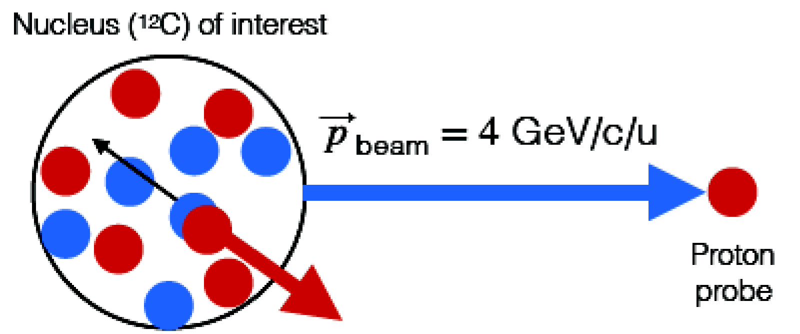
G. Kramer, H. Blok, and L. Lapikas, NPA, 679, 267 (2001)

J. Lee et al., PRC 73, 044608 (2006); L. Atar, Phys. Rev. Lett. 120 (5) (2018) 052501

**Tostevin & Gade,**
**PRC 90, 057602 (2014)**



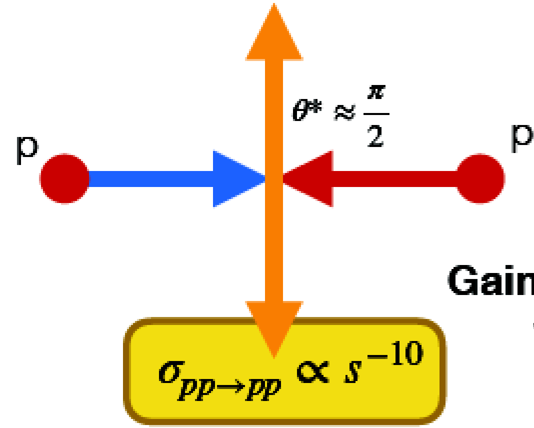
Lab Frame:




To study SRC pairs: $|p_{\text{miss}}| \geq 250$ MeV/c

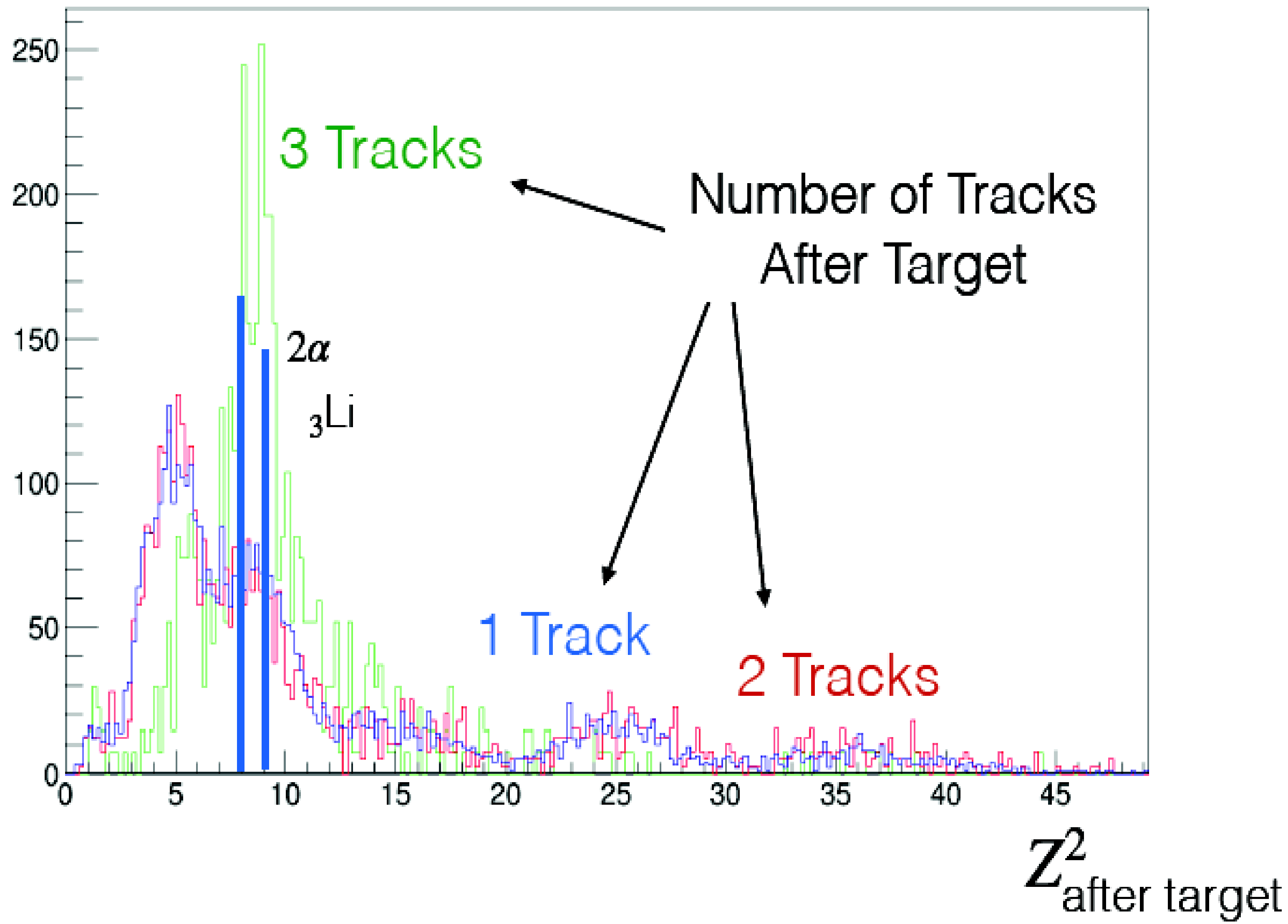
$|s,t,u| > 2\ (\text{GeV/c})^2$ (Hard process)

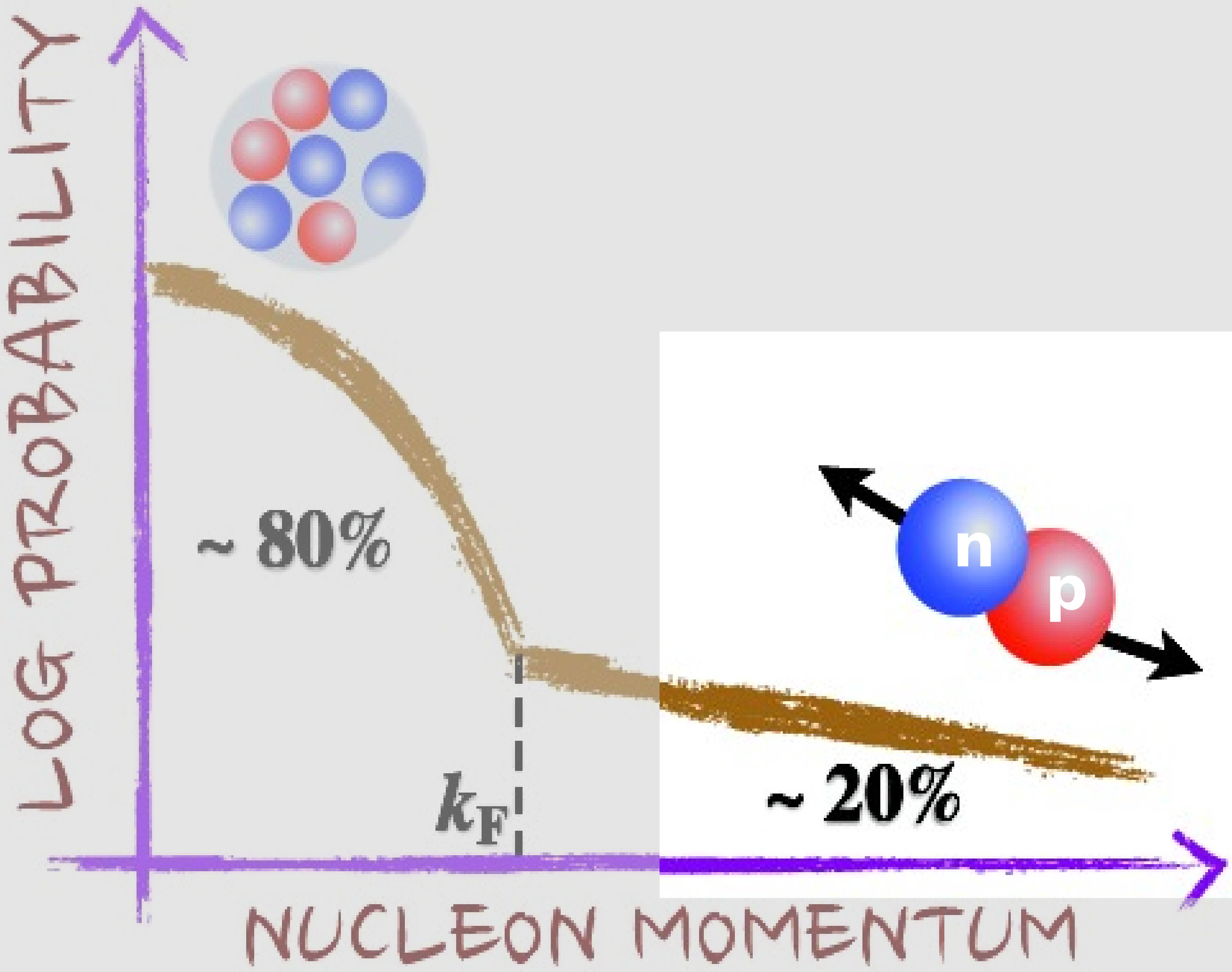
CM Frame:




**Gain higher SRC statistics with proton probe**

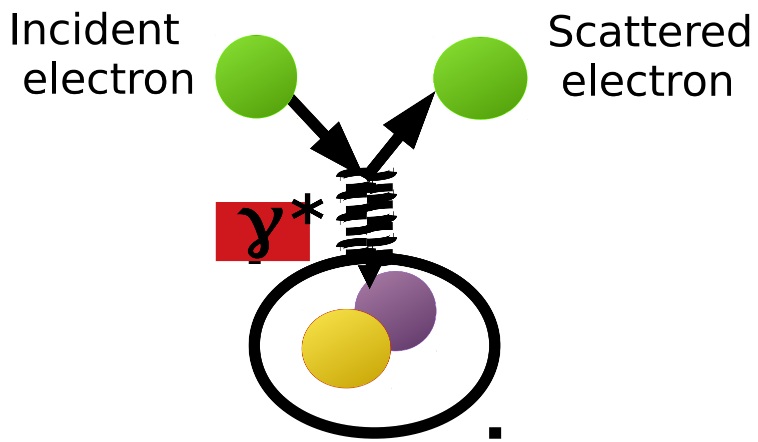
$$p + C \rightarrow p^? + p^? + X$$



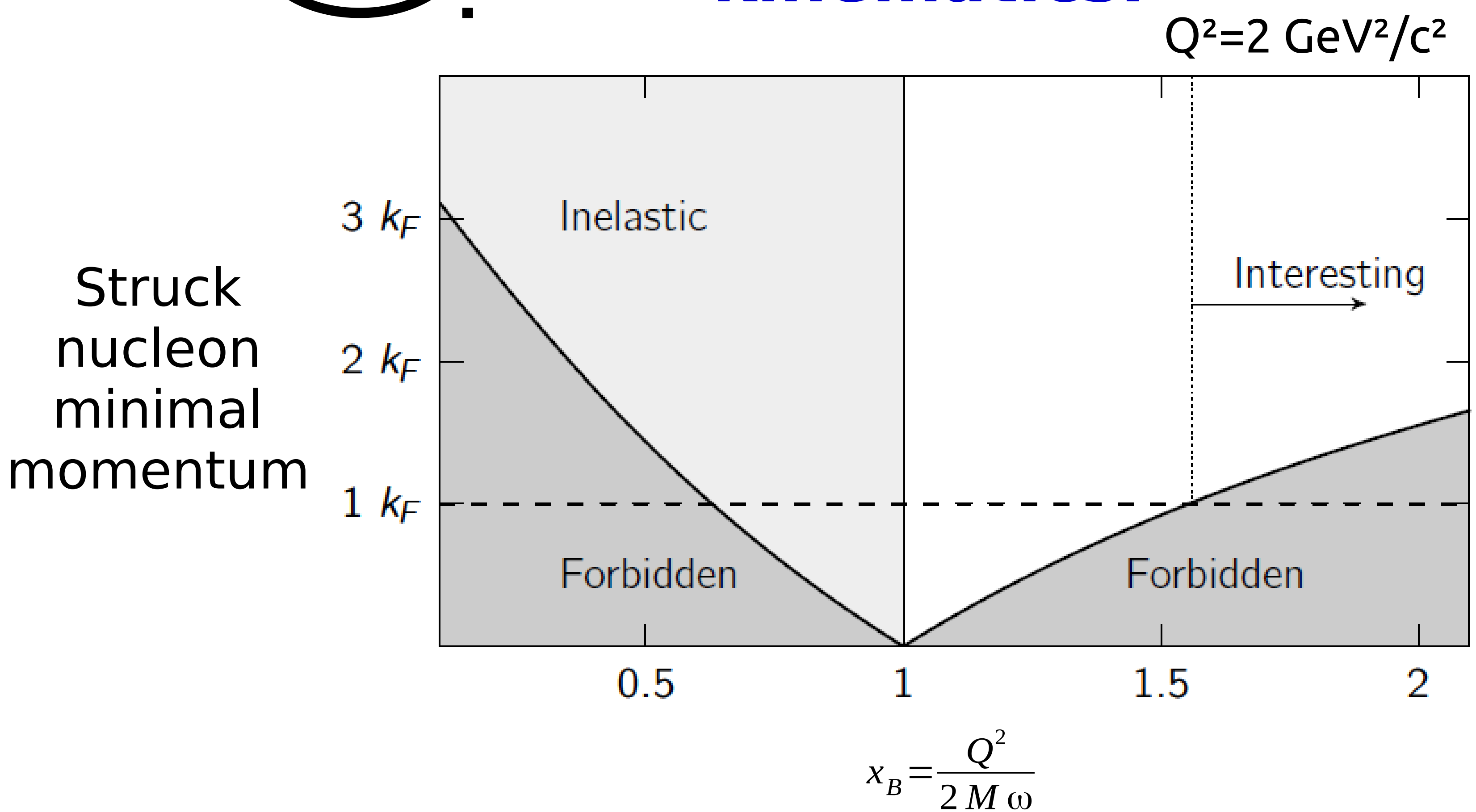



How do we get 20% ?

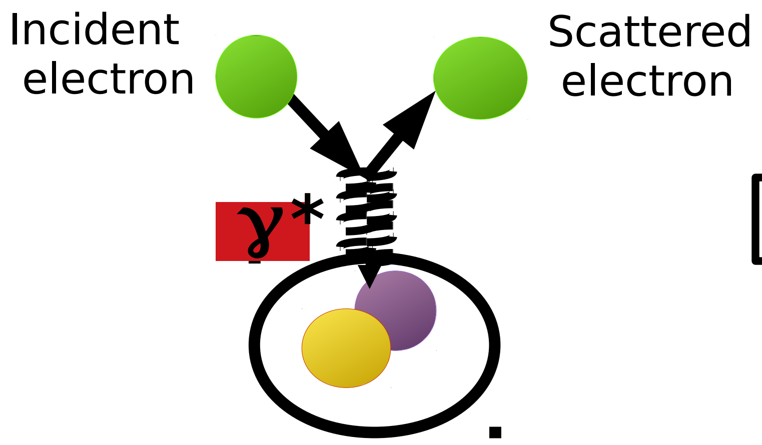
# (e,e') & high-momentum nucleons



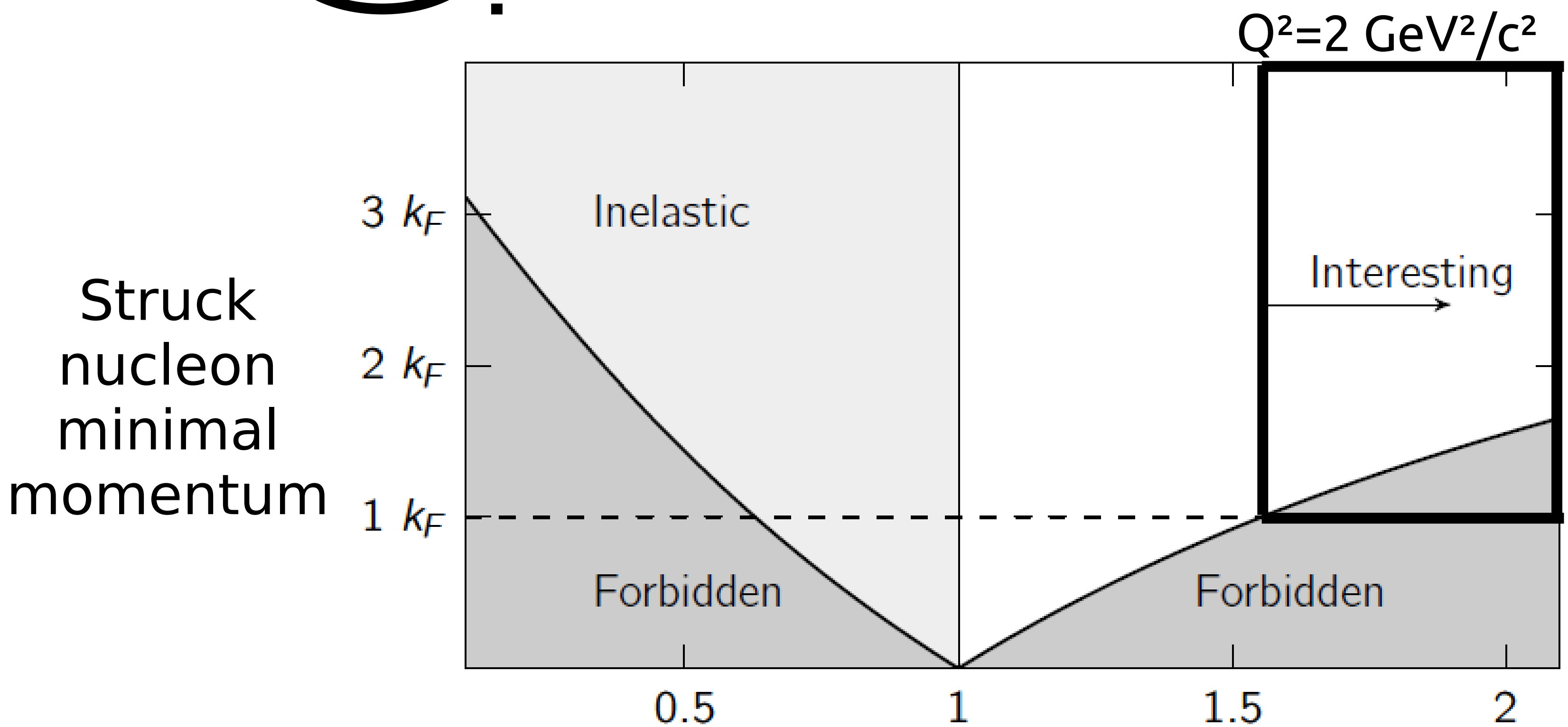

**High-momentum nucleons can be selected by the e kinematics.**



# High $x_B$ ↔ High initial momentum

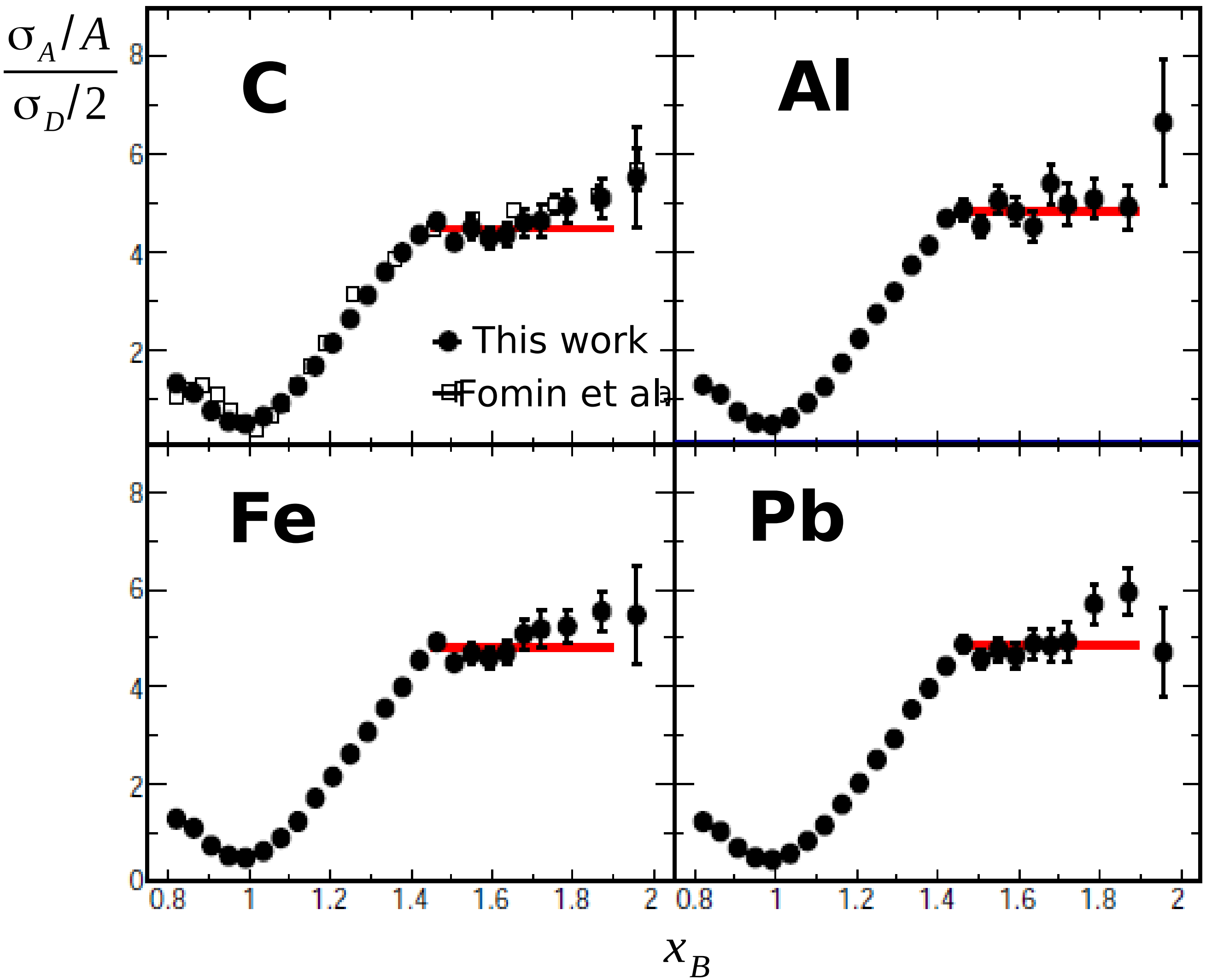



**High-momentum nucleons can be selected by the e kinematics.**




$$x_B = \frac{Q^2}{2M\omega}$$

# Counting high-momentum pairs




Schmoolker, Duer et al. (CLAS Collaboration), Submitted (2018)

Observed scaling for $x_B > 1.4$

$$n_A(k>k_F) = a_2(A) \times n_d(k)$$

More data: Day et al. PRL 59,427(1987) Fomin et al., PRL 108, 092502 (2012) Egiyan et al. PRL. 96, 082501 (2006) Egiyan et al. PRC 68, 014313 (2003)

# Counting high-momentum pairs

$$n_A(k>k_0) = a_2(A) \times n_d(k>k_0)$$

$K_0 \sim 275$ MeV/c

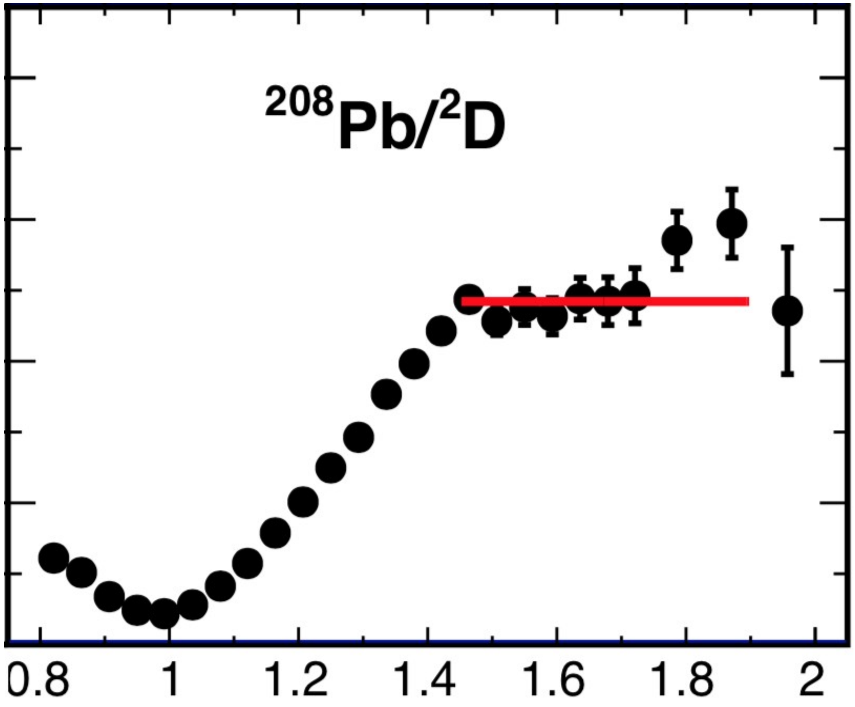
( $x_B > 1.4$ )

$\sim$4-5 $\times$ $\sim$4% = **~20%**

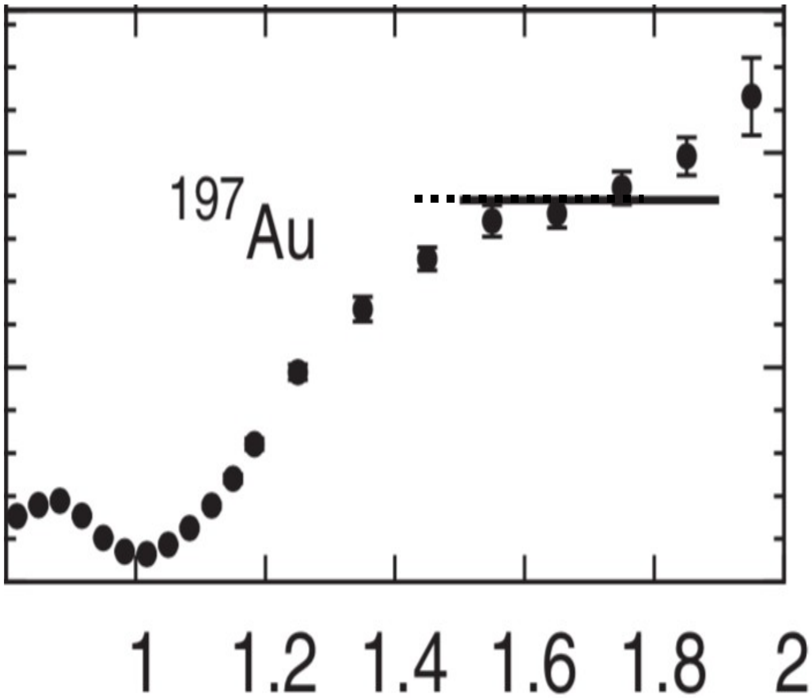
AV18

# 2018 High-Momentum Scaling

Schmookler

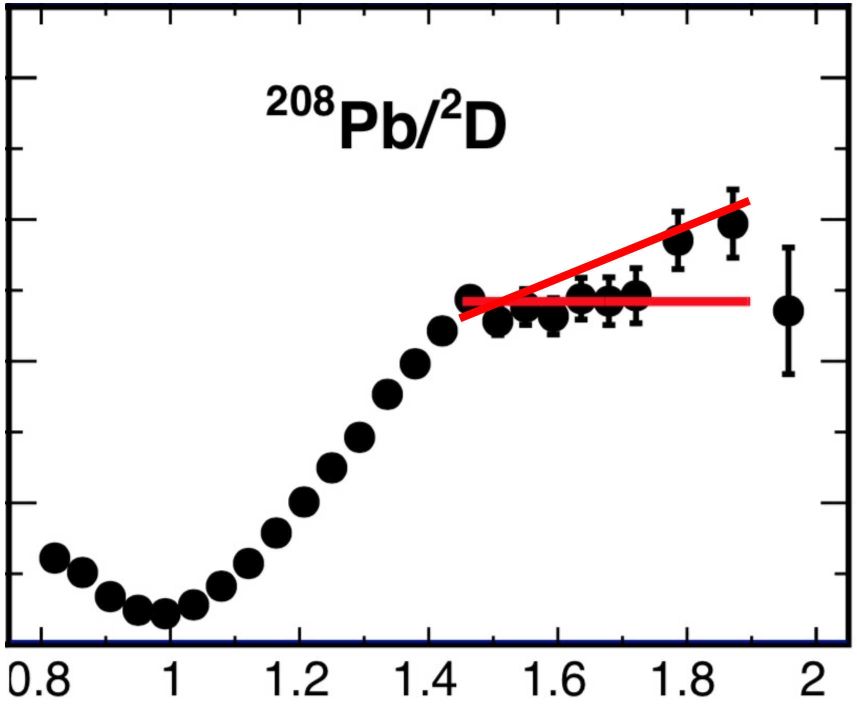



Fomin

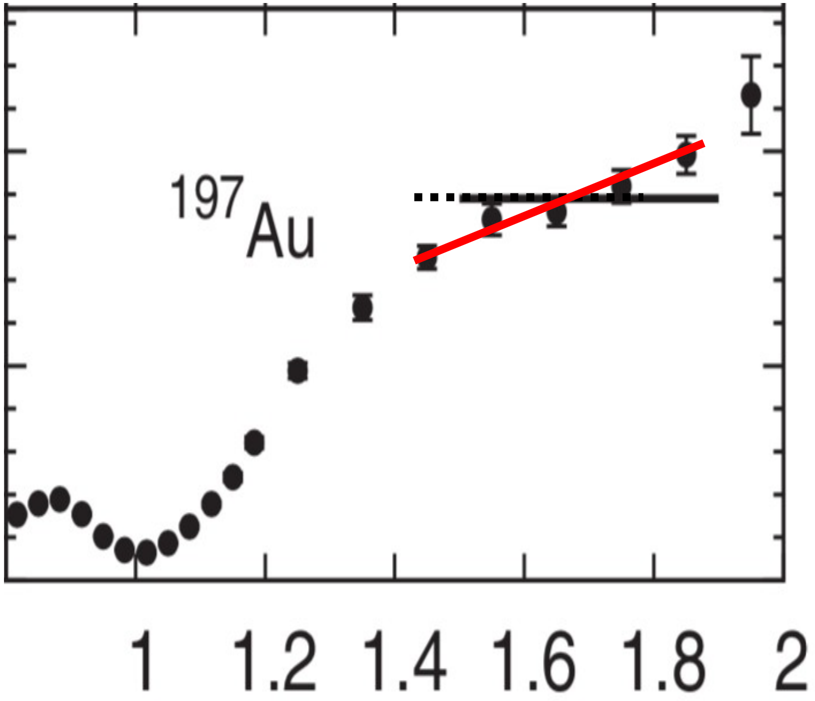


# 2018 High-Momentum Scaling

Schmookler

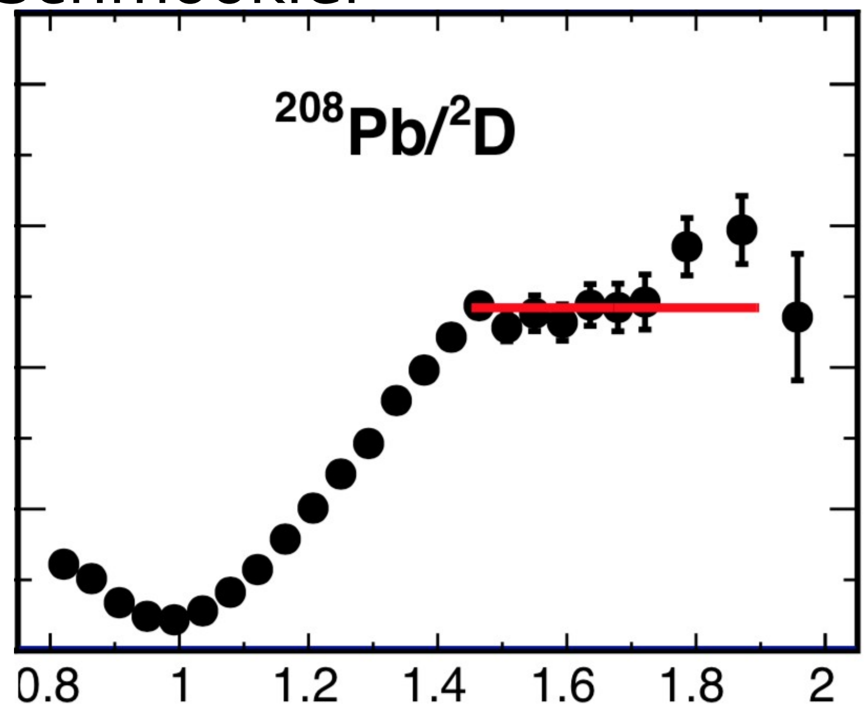



Fomin

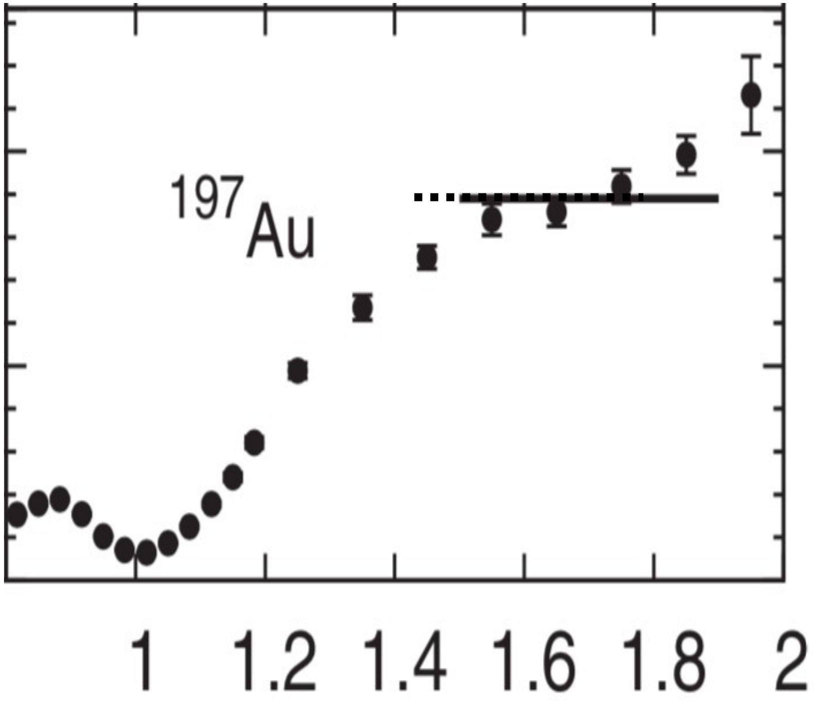


# 2018 High-Momentum Scaling

Schmookler




Fomin

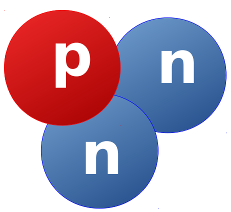


# Present & Future @ Jefferson Lab

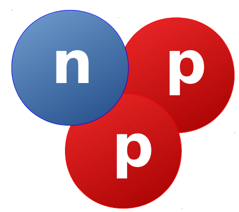
E12-14-011, Hall-A
run @ April 2018

CaFe Experiment, Hall-C
will run @ 2019

$^{3}H$

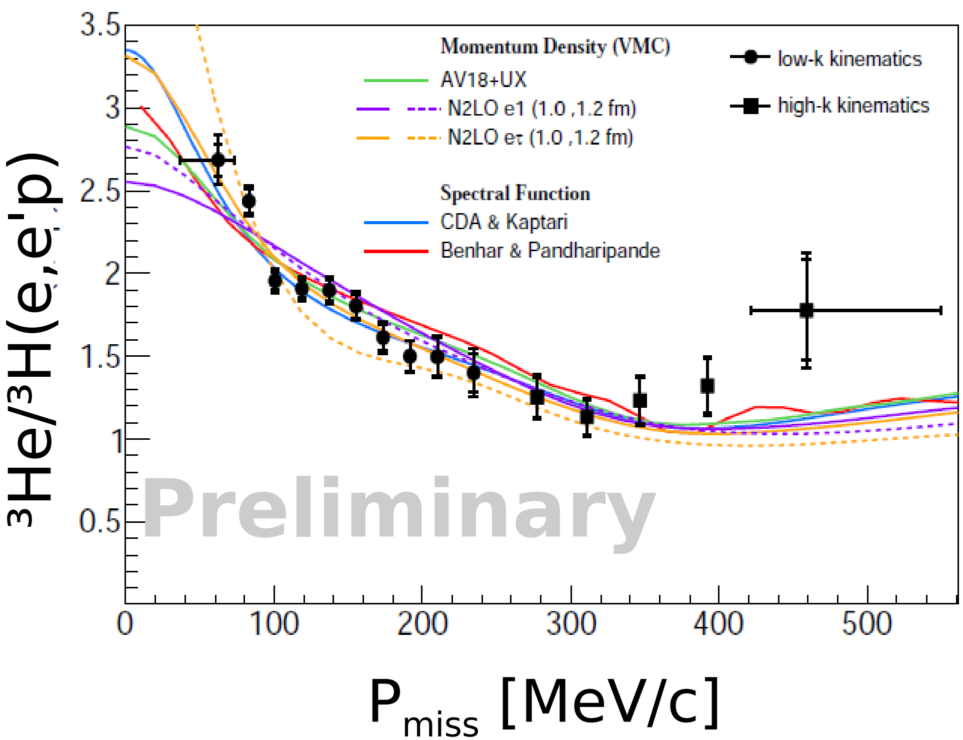


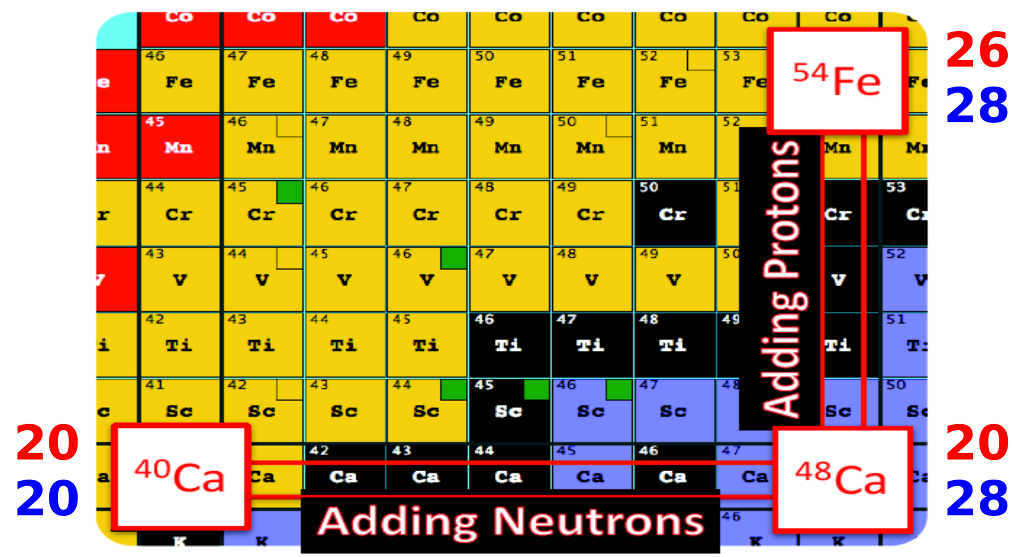

$^{3}He$



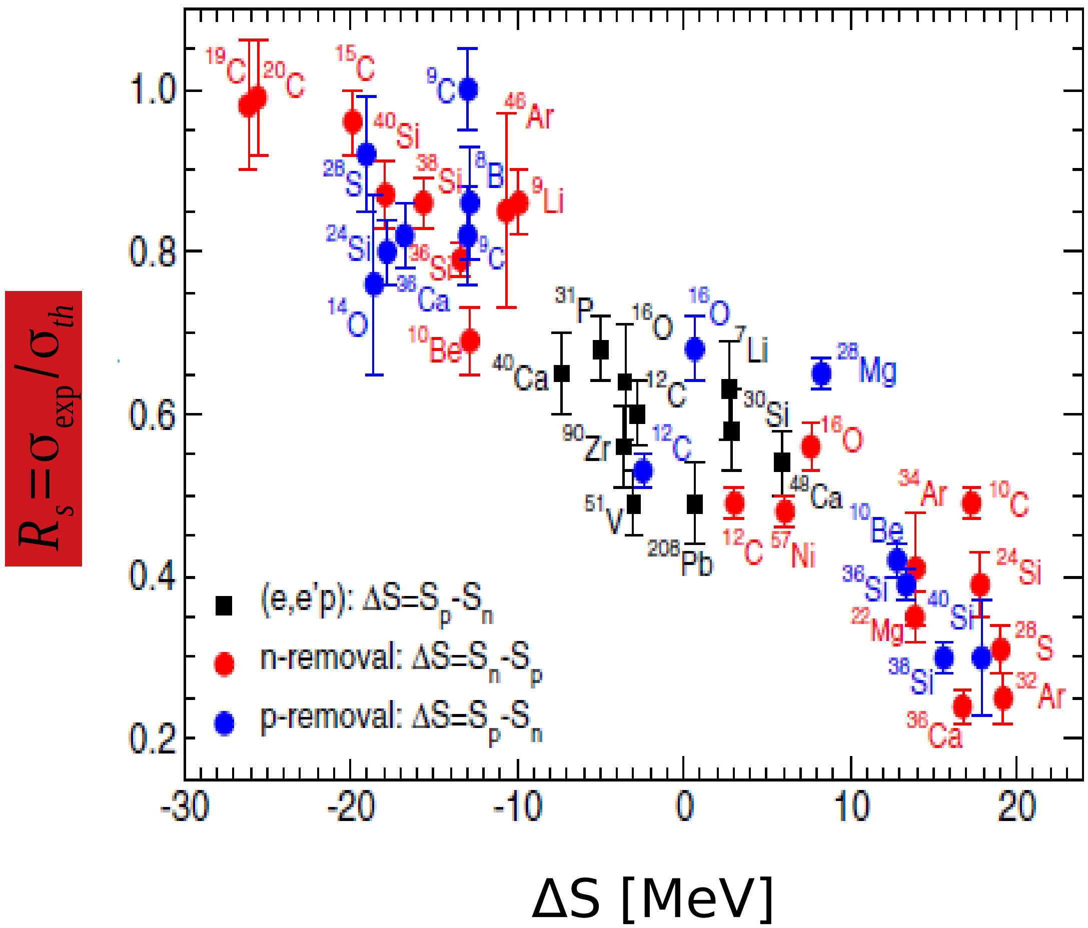

**Dynamics of pairing with asymmetry**

R. Cruz-Torres



# Single particle strength



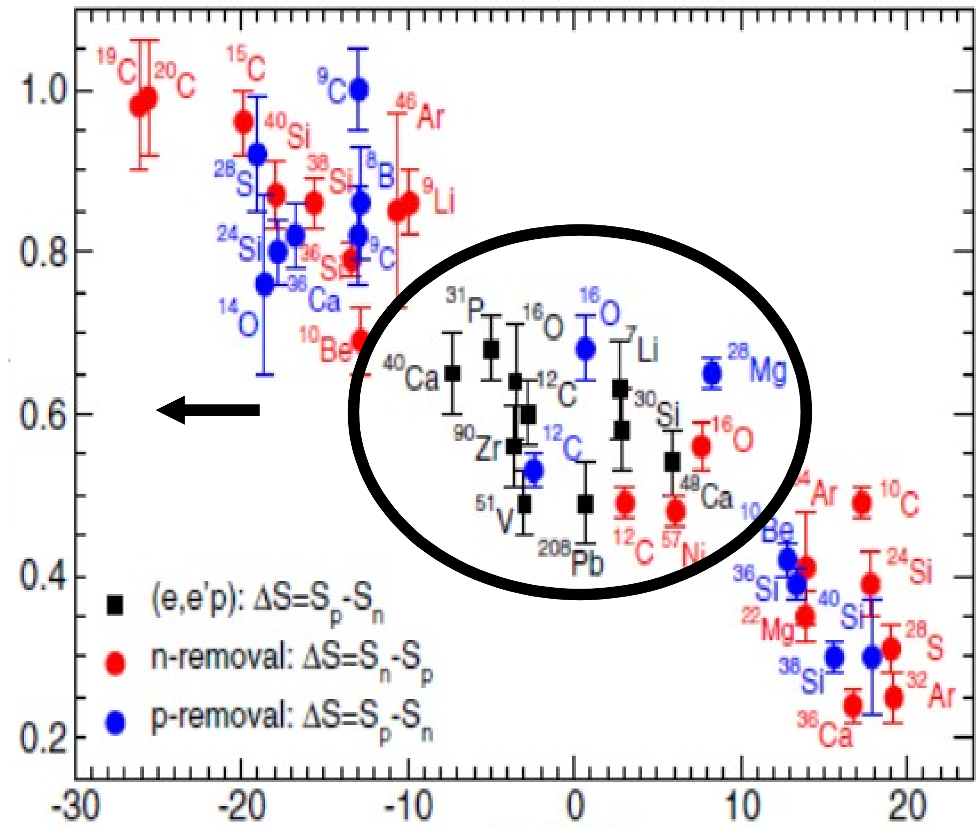

J. A. Tostevin and A. Gade, PRC **90**, 057602 (20

# Single particle strength

Spectroscopic factors for (e,e'p) reactions

Only 60-70% of expected single-particle strength

$R_s = \sigma_{exp}/\sigma_{th}$



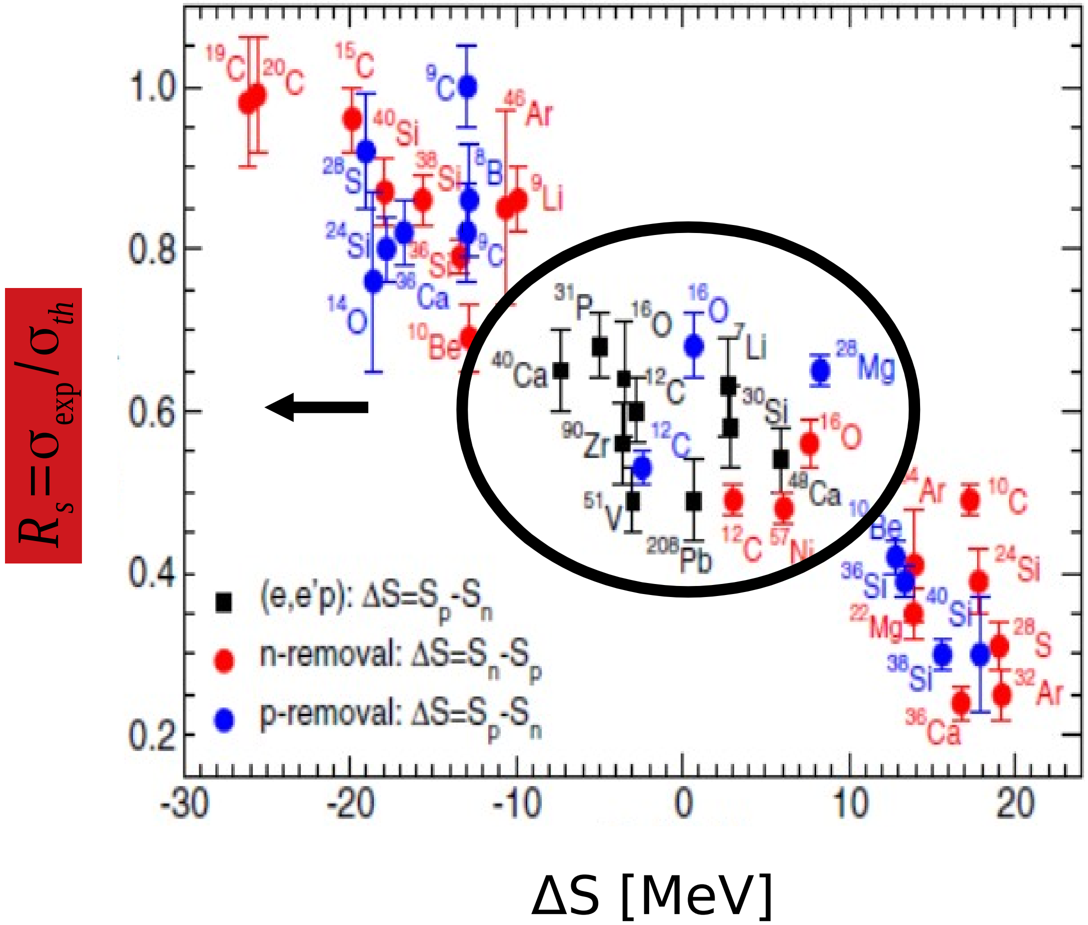

ΔS [MeV]

J. A. Tostevin and A. Gade, PRC **90**, 057602 (20

# Single particle strength

Spectroscopic factors for (e,e'p) reactions

Only 60-70% of expected single-particle strength

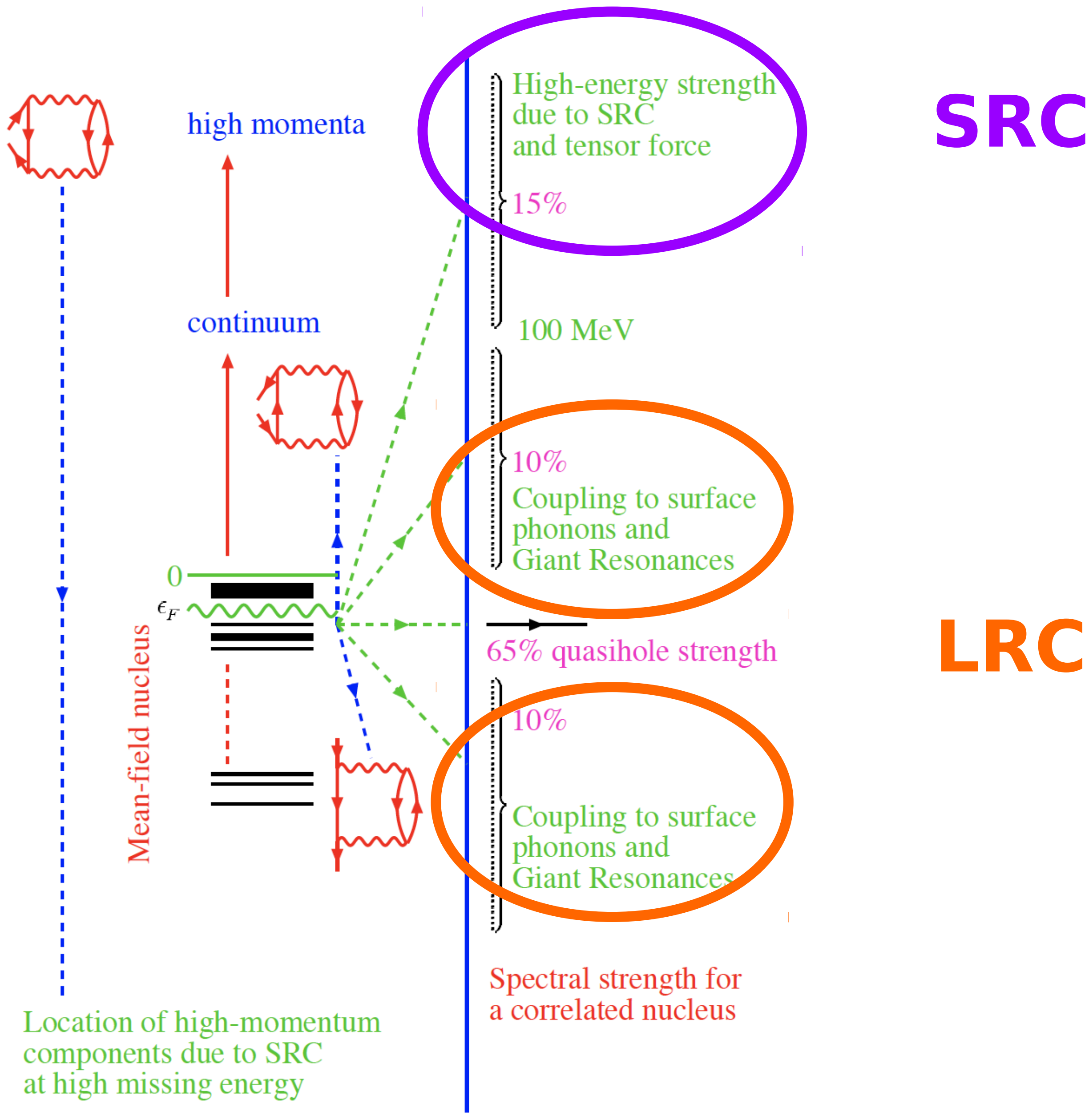



**MISSING:**

**SRC LRC**

J. A. Tostevin and A. Gade, PRC **90**, 057602 (20

# Single particle strength




W.H. Dickhoff, C. Barbieri, Progress in Particle and Nuclear Physics 52 (2004) 377–496

Single particle

Missing strength

$$QF = 1 - \left( QF_{PVC} + QF_{Pairing} + QF_{SRC} \right)$$

Long-Range Correlations

Short-Range Correlations

**Single particle**

**Missing strength**

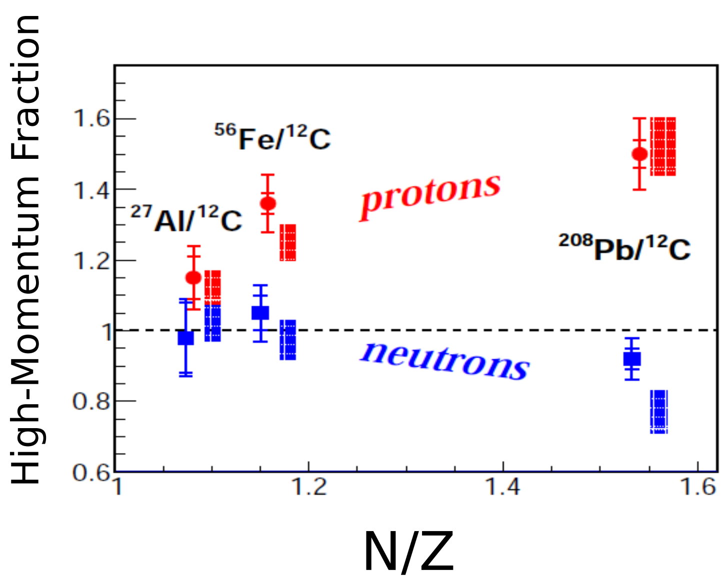
$$QF = 1 - \left( QF_{PVC} + QF_{Pairing} + QF_{SRC} \right)$$

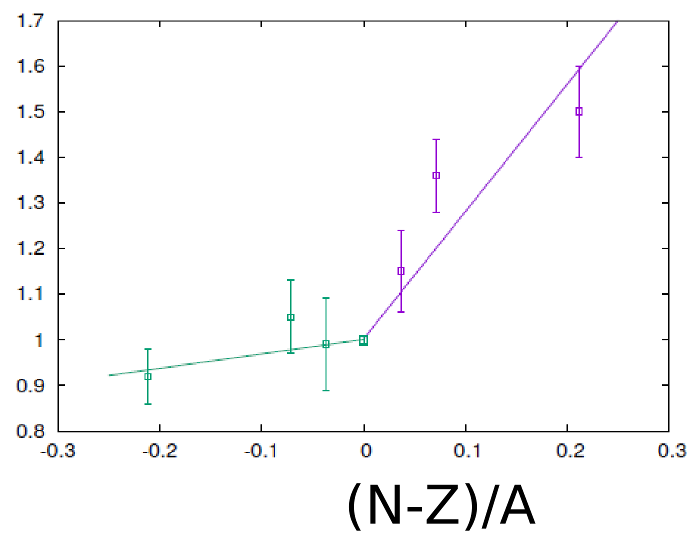
**Long-Range Correlations**

**Short-Range Correlations**

$$N > Z: \quad QF_{SRC} = \gamma \left( 1 + SL^{p}_{SRC} \frac{(N-Z)}{A} \right)$$

$$N < Z: \quad QF_{SRC} = \gamma \left( 1 + SL^{n}_{SRC} \frac{(N-Z)}{A} \right)$$



Single particle

Missing strength

$$QF = 1 - \left(QF_{PVC} + QF_{Pairing} + QF_{SRC}\right)$$

Long-Range Correlations

Short-Range Correlations

$$N > Z: \quad QF_{SRC} = \gamma\left(1 + SL^{p}_{SRC}\frac{(N-Z)}{A}\right)$$

$$N < Z: \quad QF_{SRC} = \gamma\left(1 + SL^{n}_{SRC}\frac{(N-Z)}{A}\right)$$

$$QF_{PVC} = \alpha\left(1 + \frac{33}{51}\left(\frac{(N-Z)}{A}\right)^{2}\right)$$

Particle Vibration Coupling

$$QF_{Pairing} = 0.0324\left(1 - 6.07\left(\frac{(N-Z)}{A}\right)^{2}\right)^{2}$$

Nuclear Physics **A431** (1984) 393-418

**Single particle**

**Missing strength**

$$QF = 1 - \left(QF_{PVC} + QF_{Pairing} + QF_{SRC}\right)$$

**Short-Range Correlations**

**Long-Range Correlations**

$$N > Z: \quad QF_{SRC} = \gamma \left(1 + SL_{SRC}^{p} \frac{(N-Z)}{A}\right)$$

$$N < Z: \quad QF_{SRC} = \gamma \left(1 + SL_{SRC}^{n} \frac{(N-Z)}{A}\right)$$

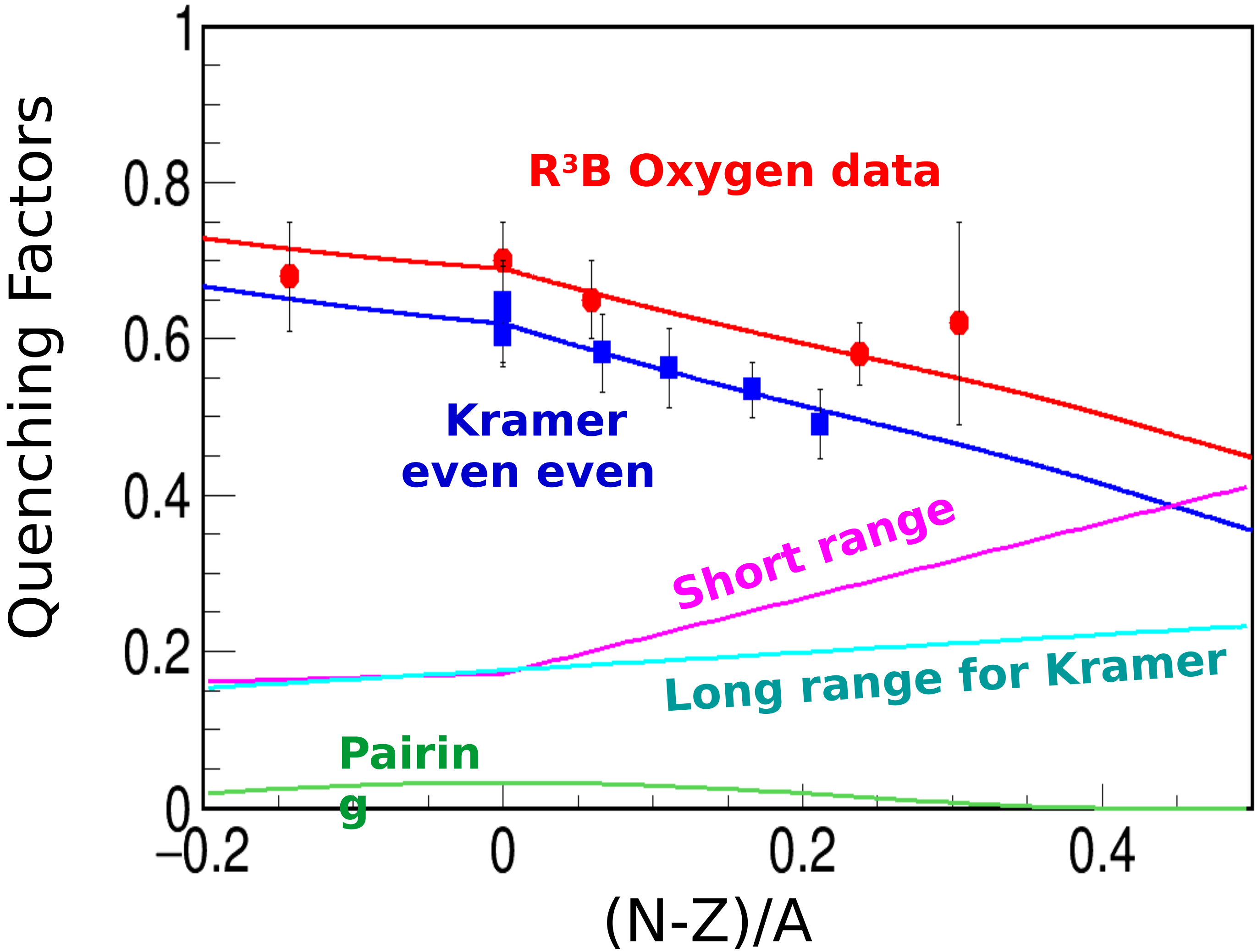
$$QF_{PVC} = \alpha \left(1 + \frac{33}{51} \frac{(N-Z)}{A}\right)^{2}$$

Particle Vibration Coupling

$$QF_{Pairing} = 0.0324 \left(1 - 6.07 \left(\frac{(N-Z)}{A}\right)^{2}\right)^{2}$$

Nuclear Physics **A431** (1984) 393-418

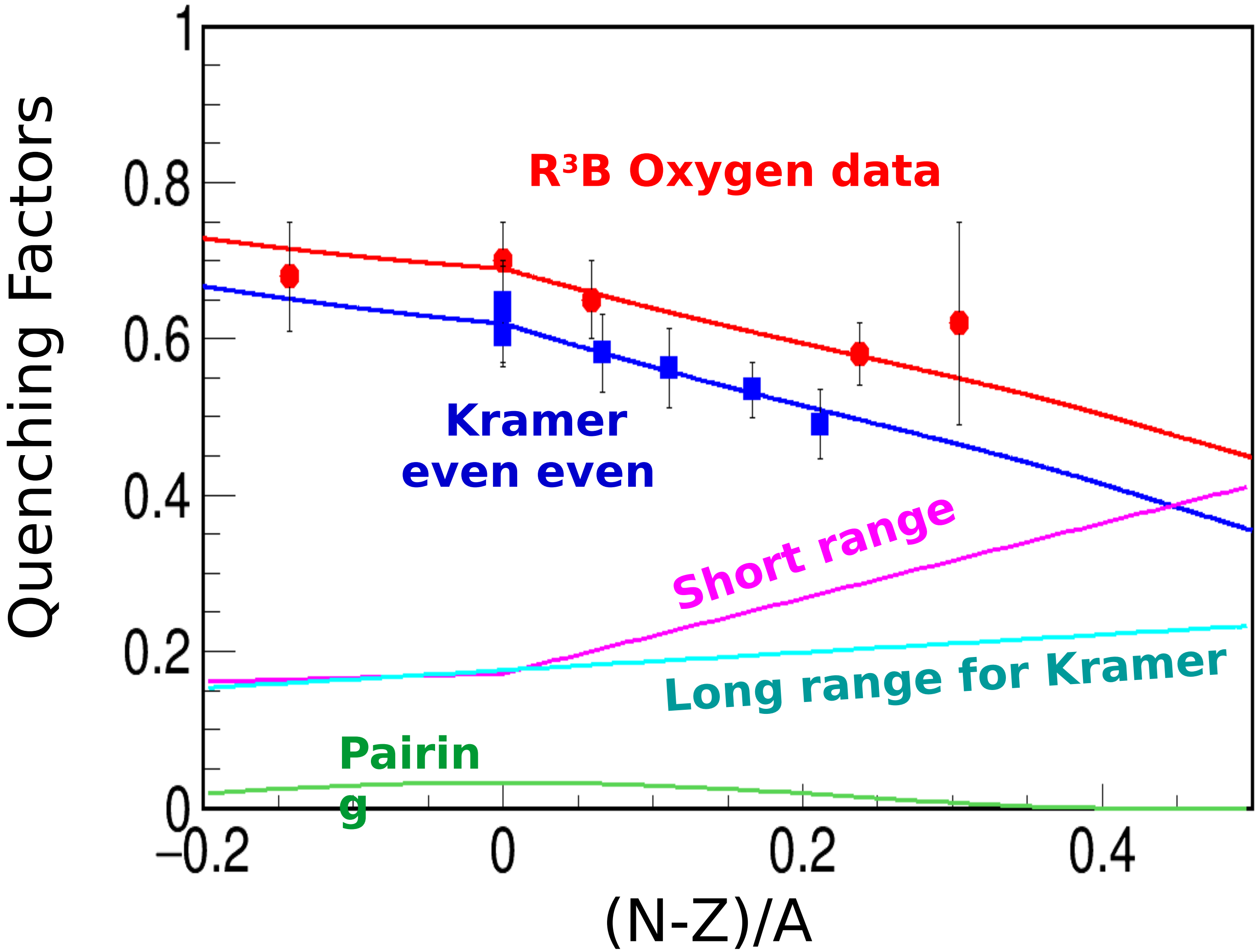
**Use data to determine the amplitudes**




SRC fraction - 20%

gs → gs: G. Kramer, H. Blok, and L. Lapikas, NPA, 679, 267 (2001)

gs → all: Lee et al., PRC 73, 044608 (2006); L. Atar, Phys. Rev. Lett. 120 (5) (2018) 052501




For neutron matter:

$A \to \infty$

$(N-Z)/A \to 1$

⇩

$$QF = 1 - \gamma - \gamma\, SL^{p}_{SRC} = 0.2$$

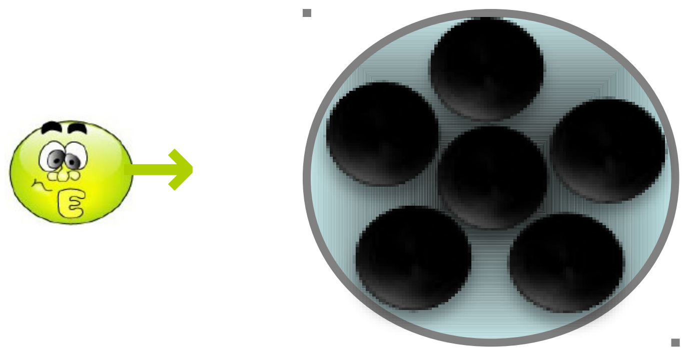
$SL^{p}_{SRC} \simeq 3$

gs → gs: G. Kramer, H. Blok, and L. Lapikas, NPA, 679, 267 (2001)

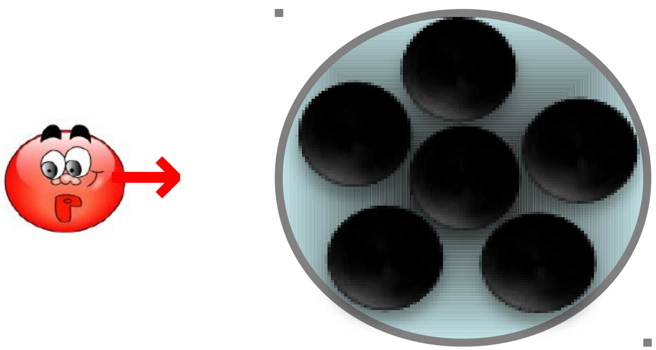
gs → all: Lee et al., PRC 73, 044608 (2006); L. Atar, Phys. Rev. Lett. 120 (5) (2018) 052501

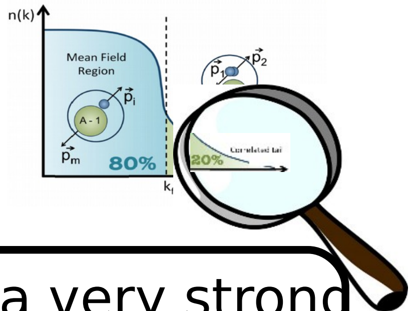
# Present & Future directions

## Lepton scattering



## Hadron scattering



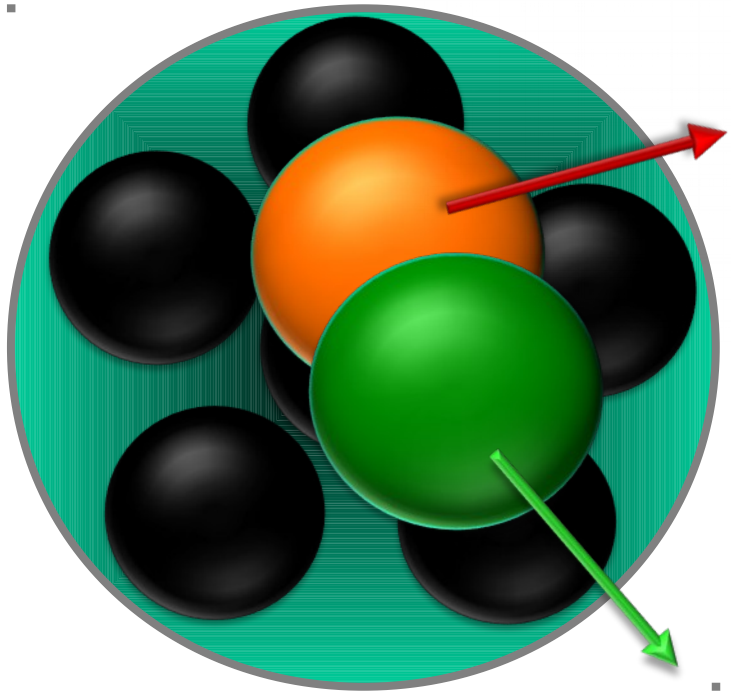



QE pp scattering have a very strong preference for reacting with forward going high-momentum nuclear protons

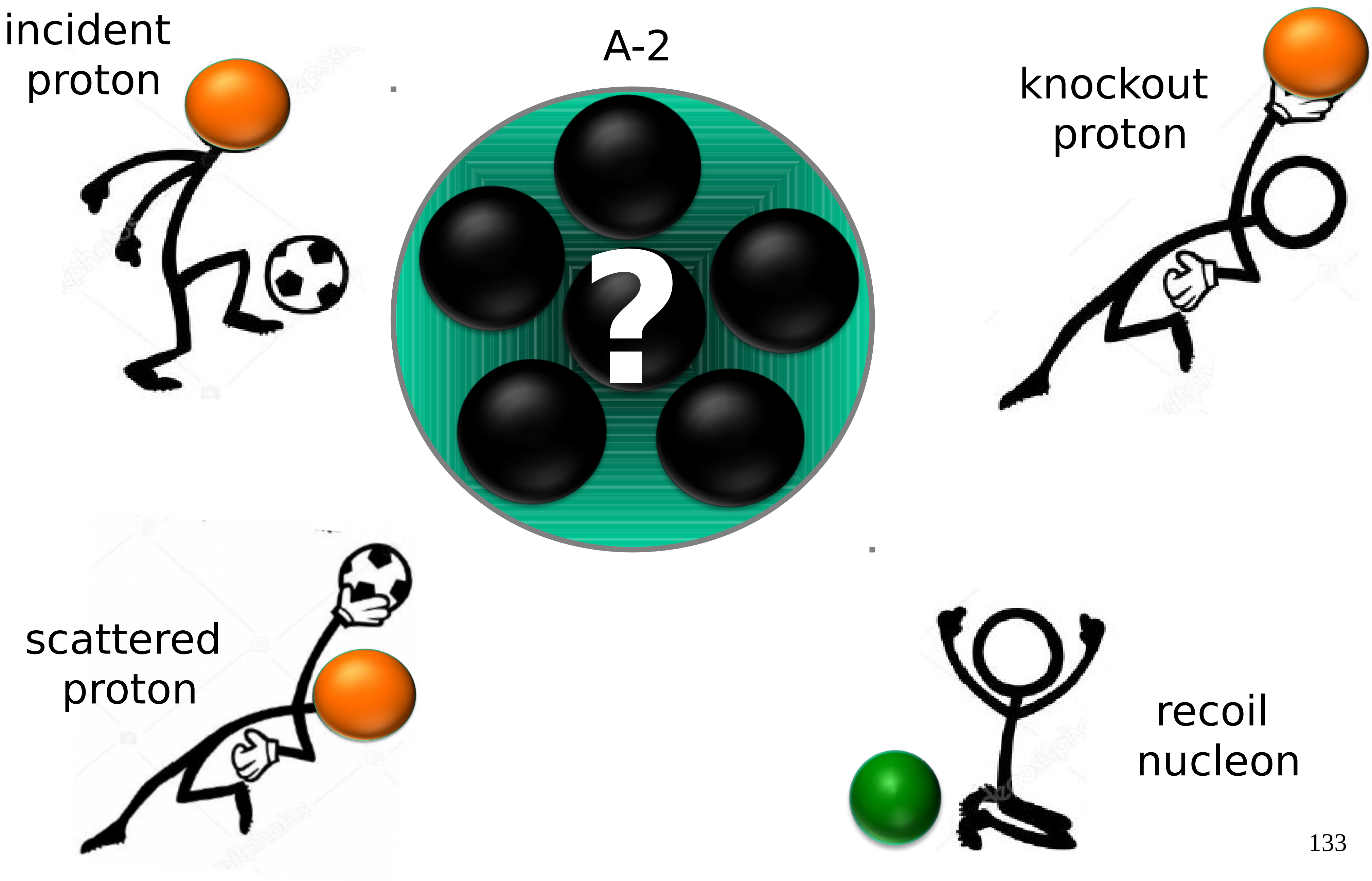
# Direct kinematics

incident
proton

target
nucleus



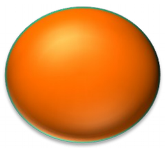
# Direct kinematics



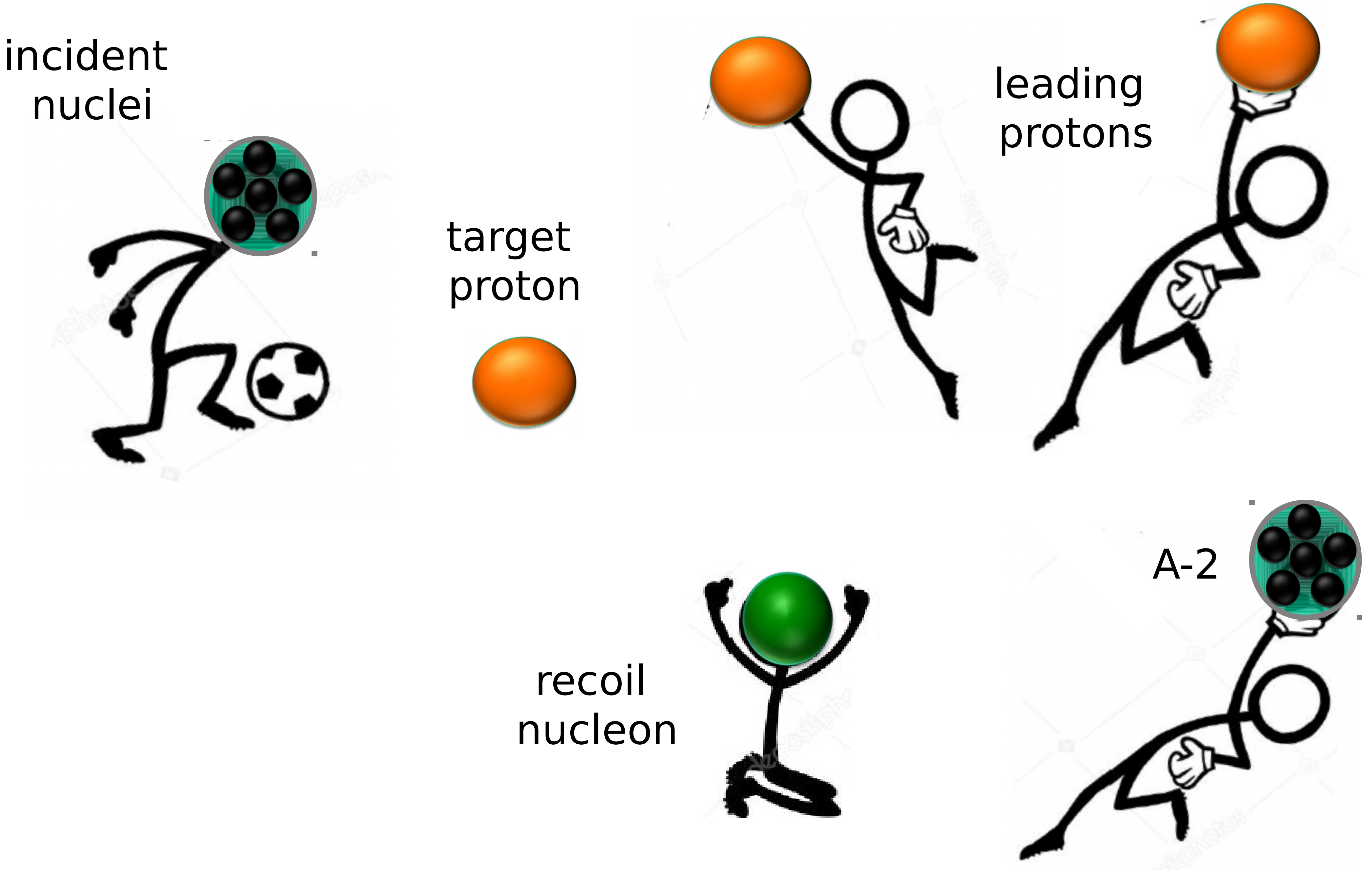
# Inverse kinematics

incident
nucleus

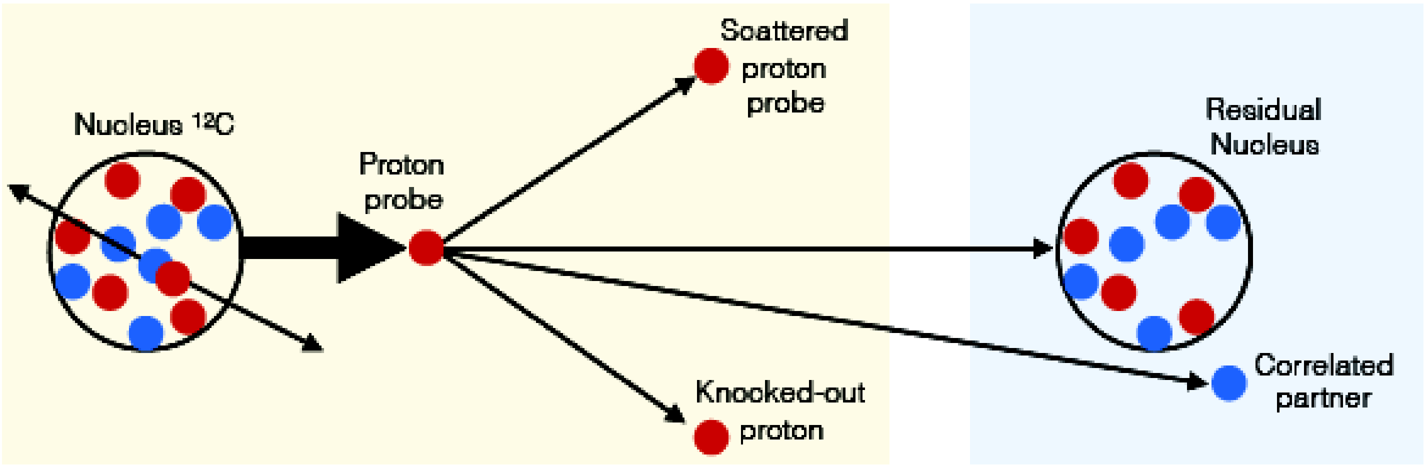
target
proton



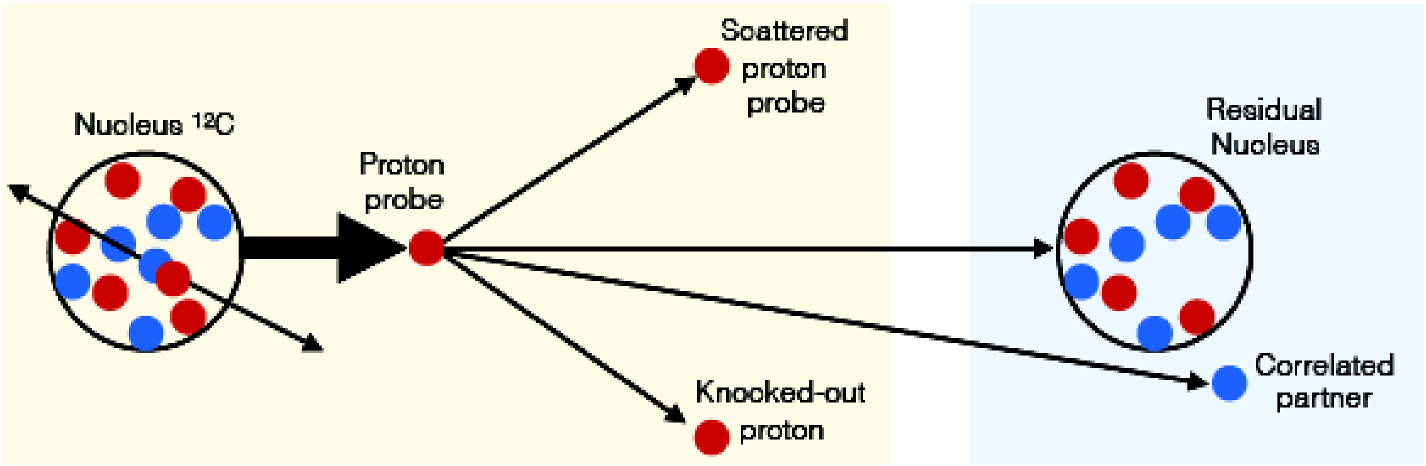
# Inverse kinematics

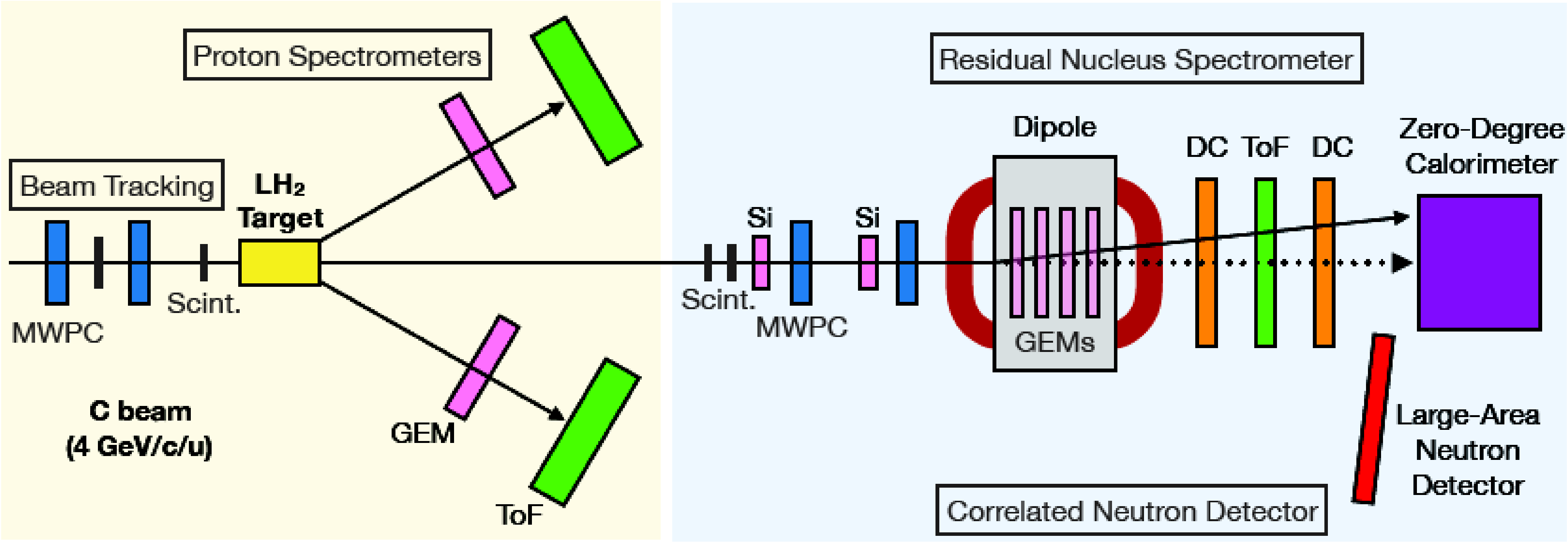


# Inverse kinematics @ JINR



# Inverse kinematics @ JINR



# A-2 System

## 1st run @ March 2018

$$p + C \rightarrow p^? + p^? + X$$