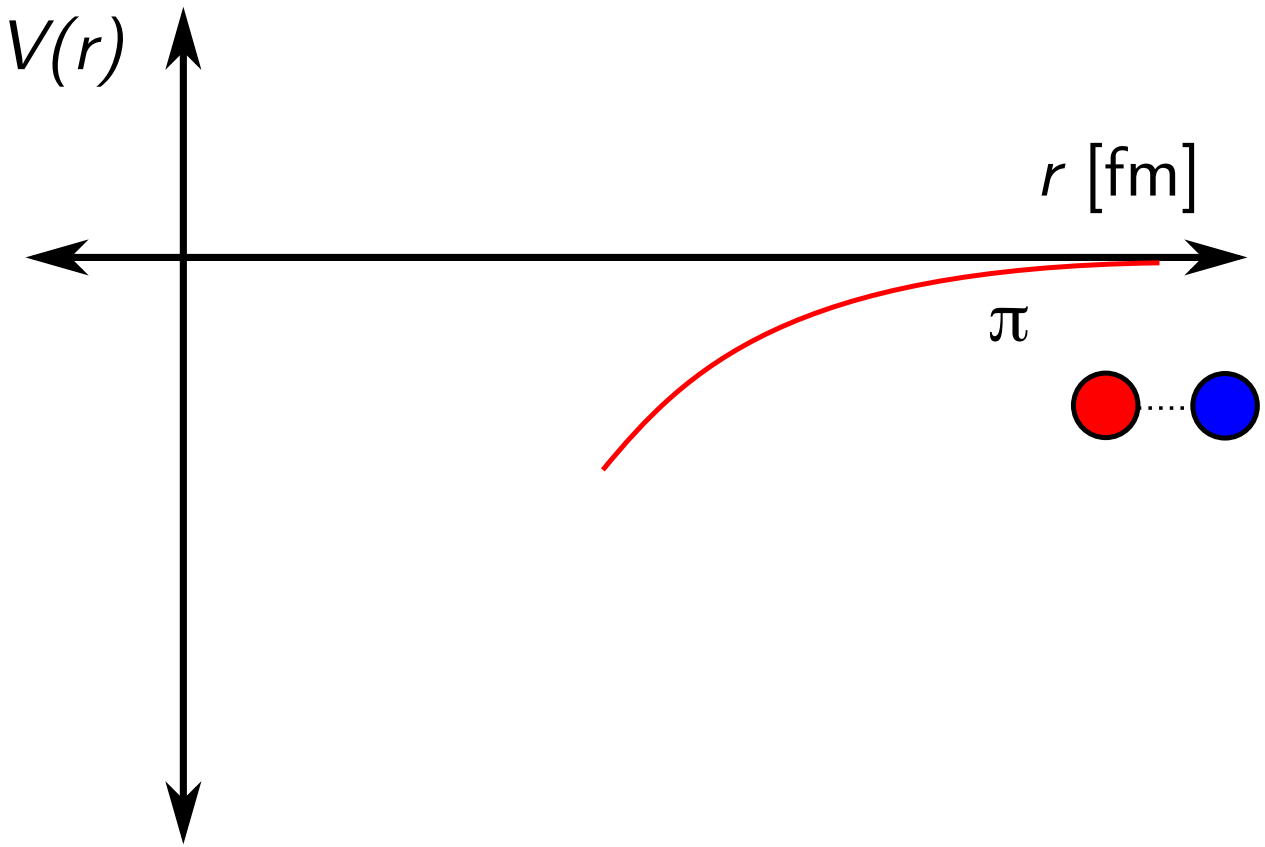
Short-range correlations and the nuclear forces at short distances

Axel Schmidt

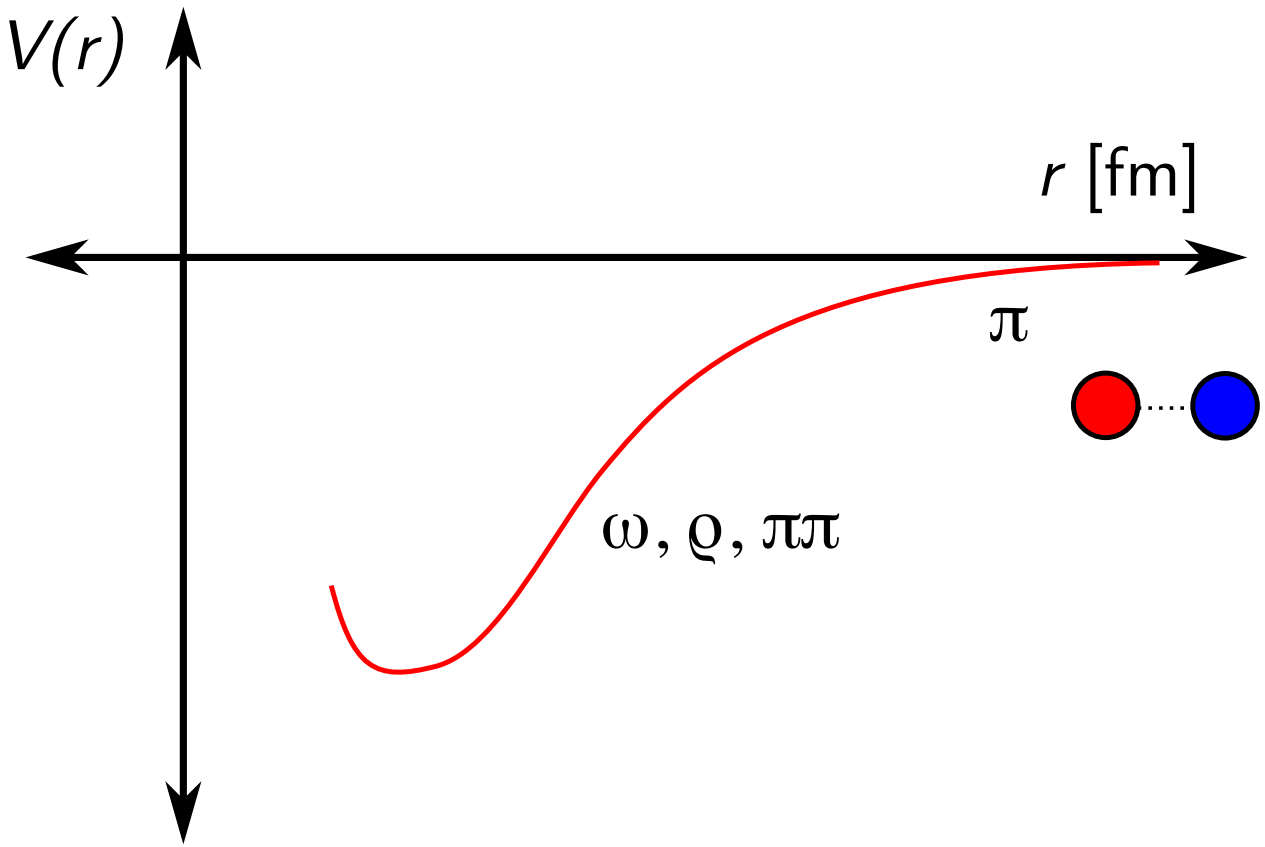
CFNS Seminar

February 28, 2020

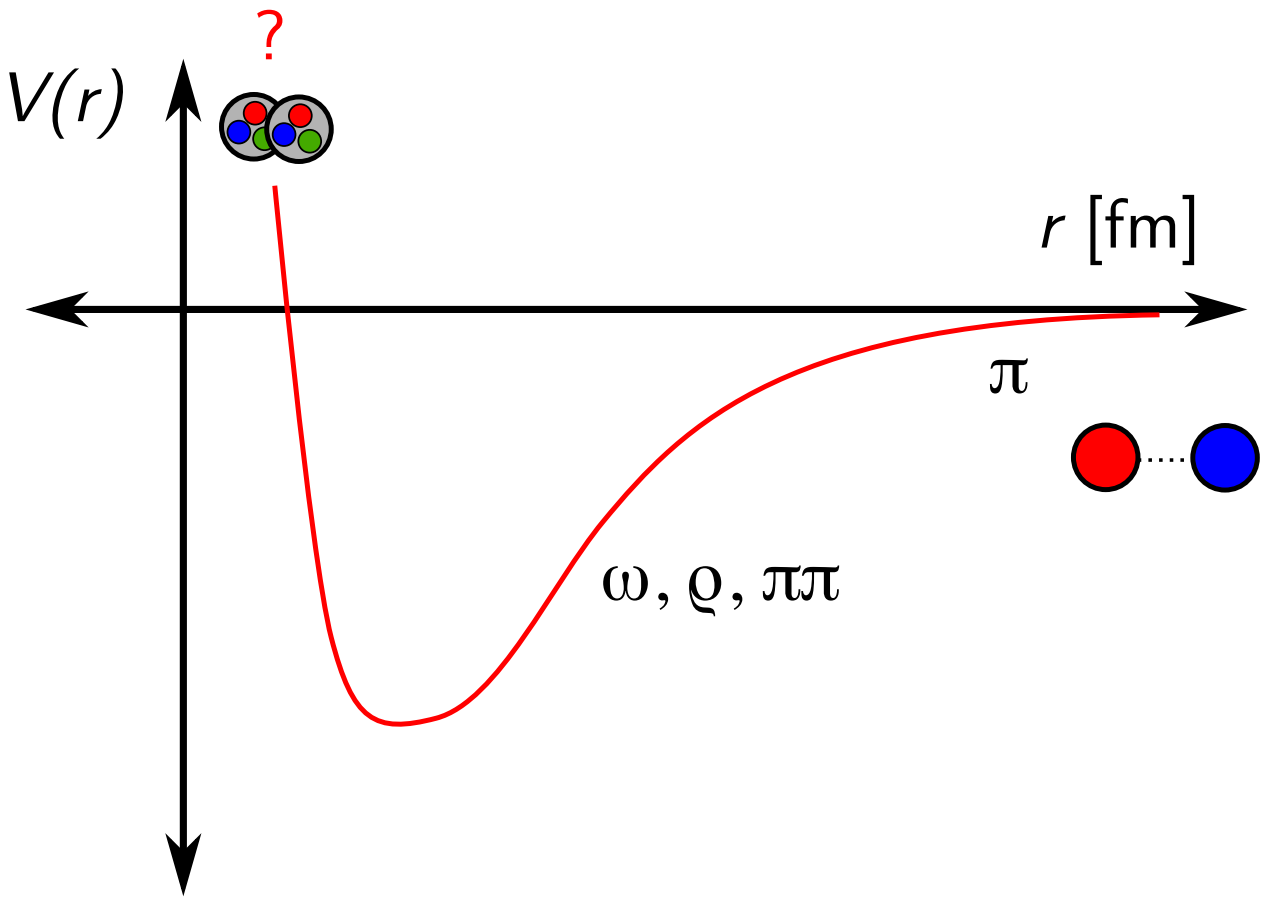
My understanding of the *NN* potential



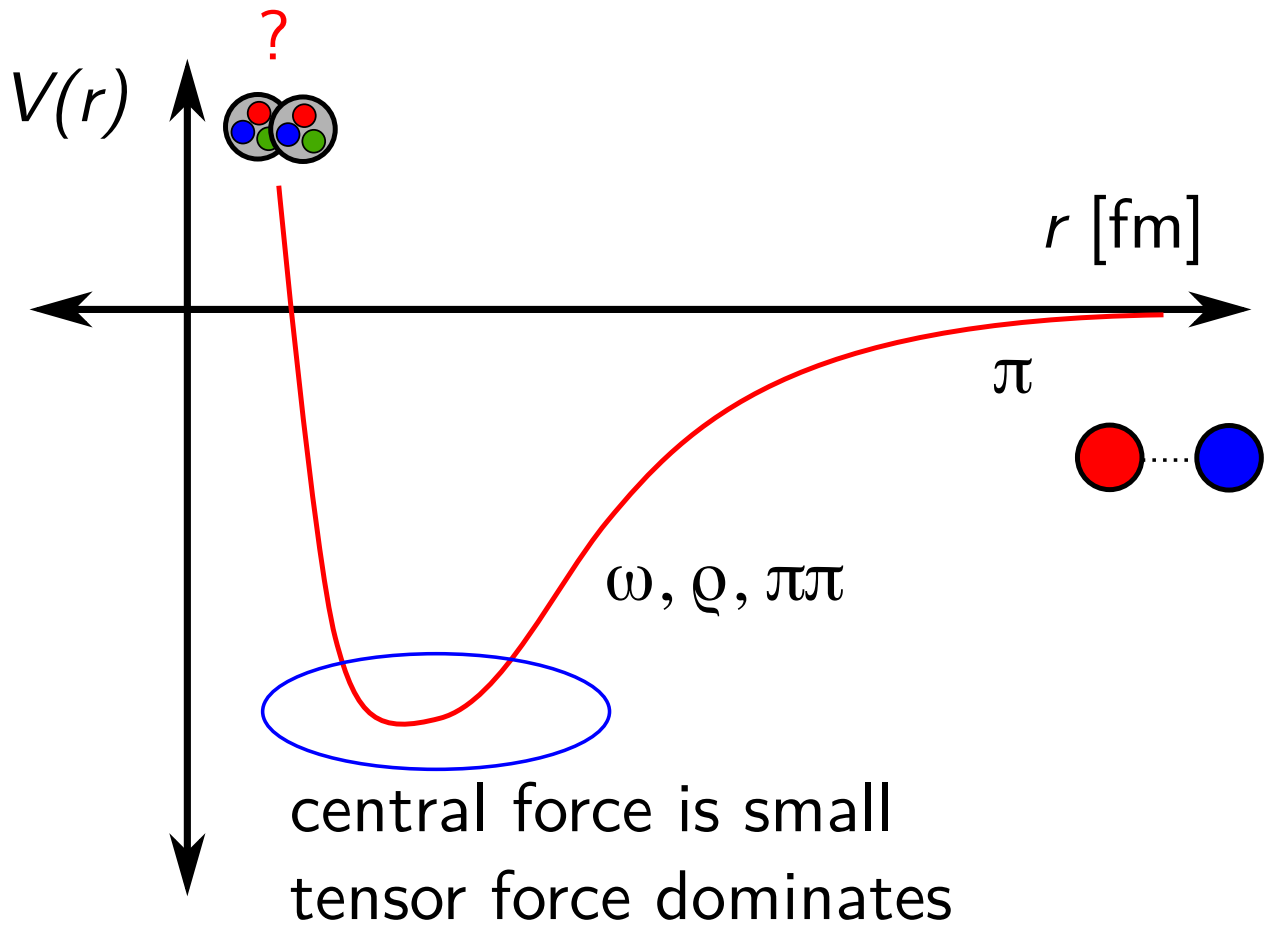
My understanding of the *NN* potential



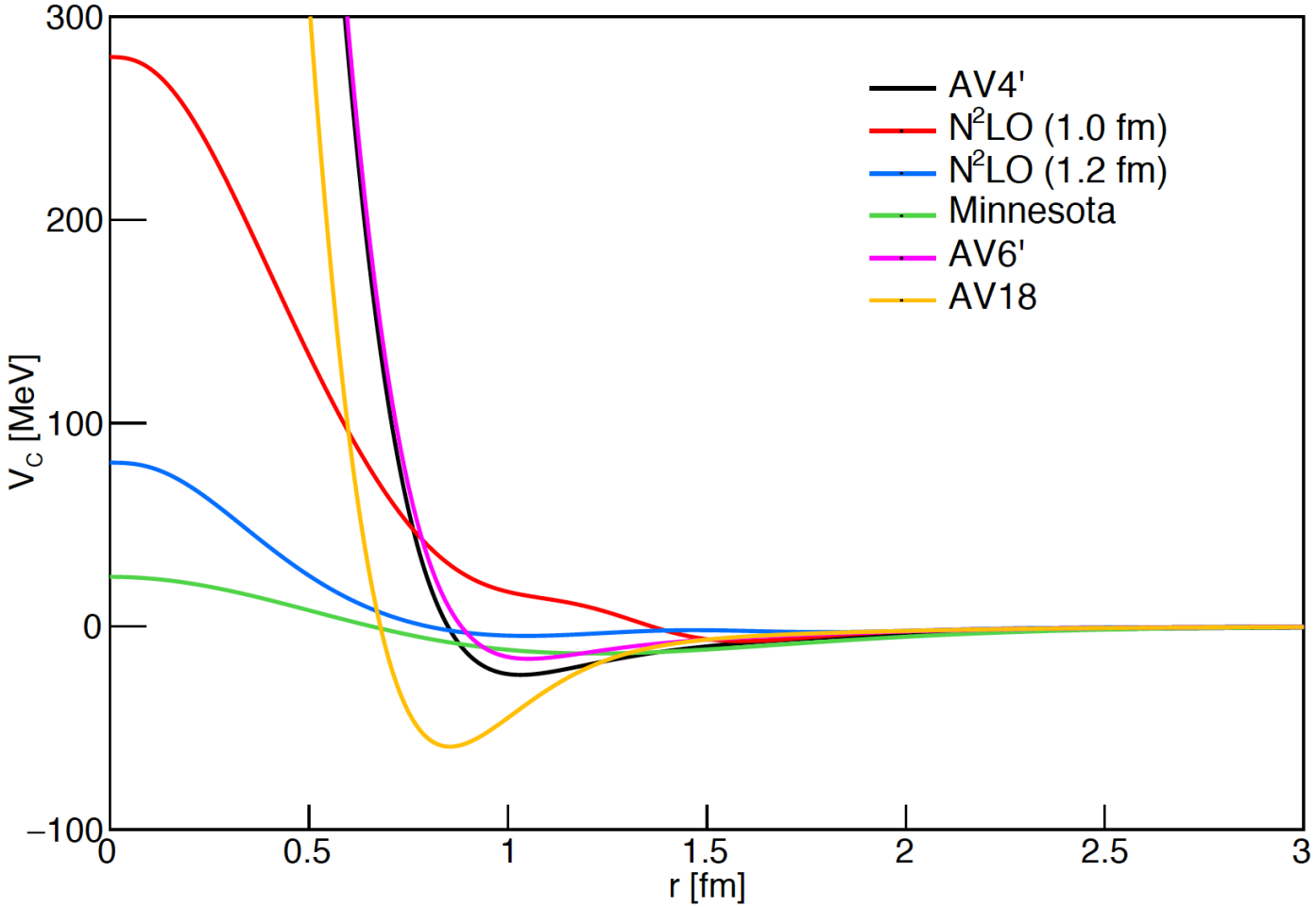
My understanding of the *NN* potential



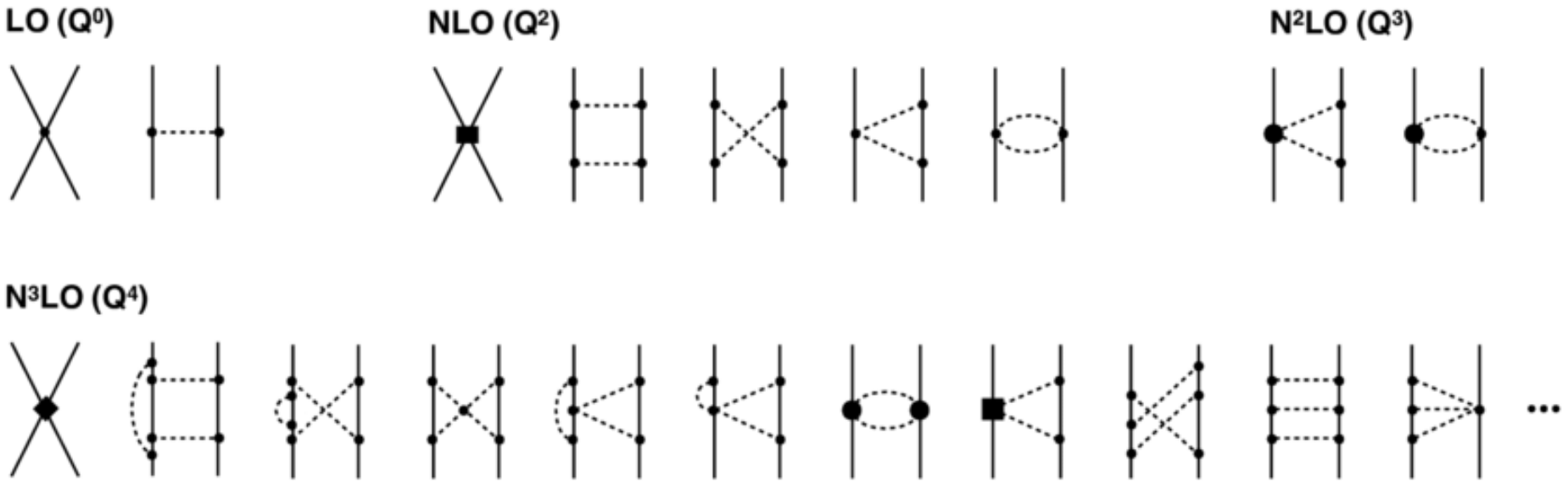
My understanding of the *NN* potential



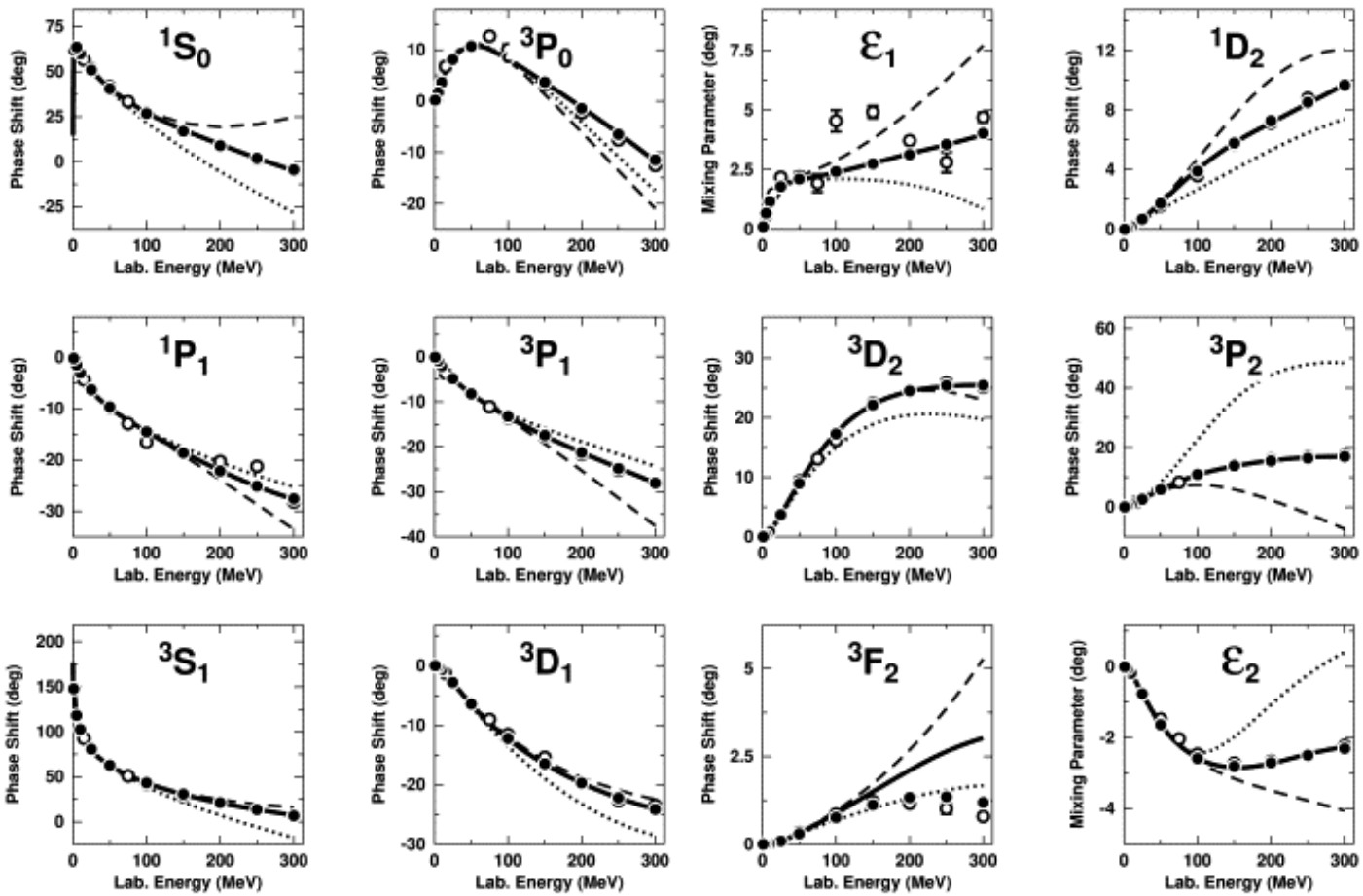
There are a wide variety of *NN* models, all tuned to data.



There are a wide variety of *NN* models,
all tuned to data.

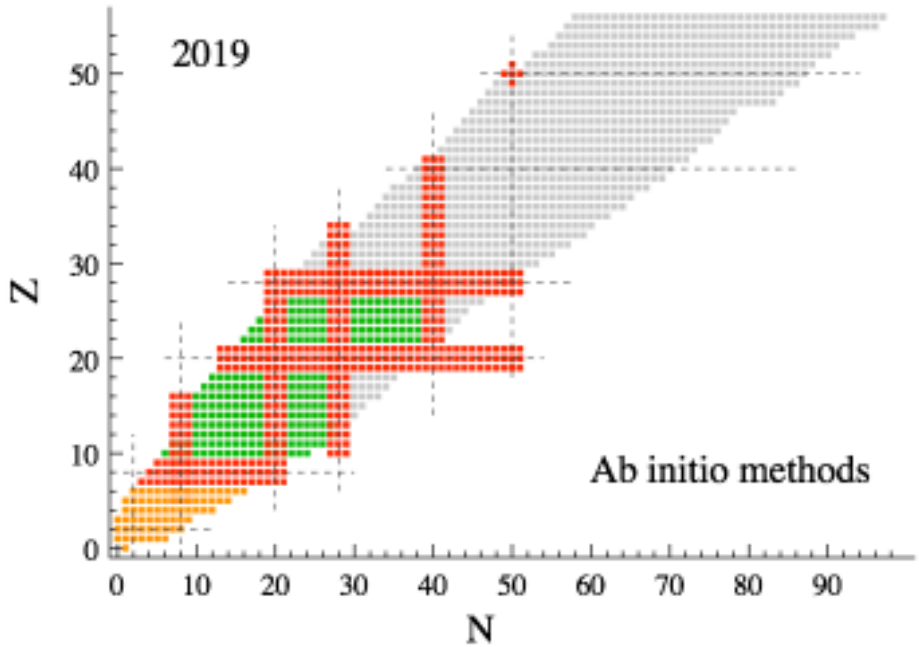


There are a wide variety of *NN* models, all tuned to data.



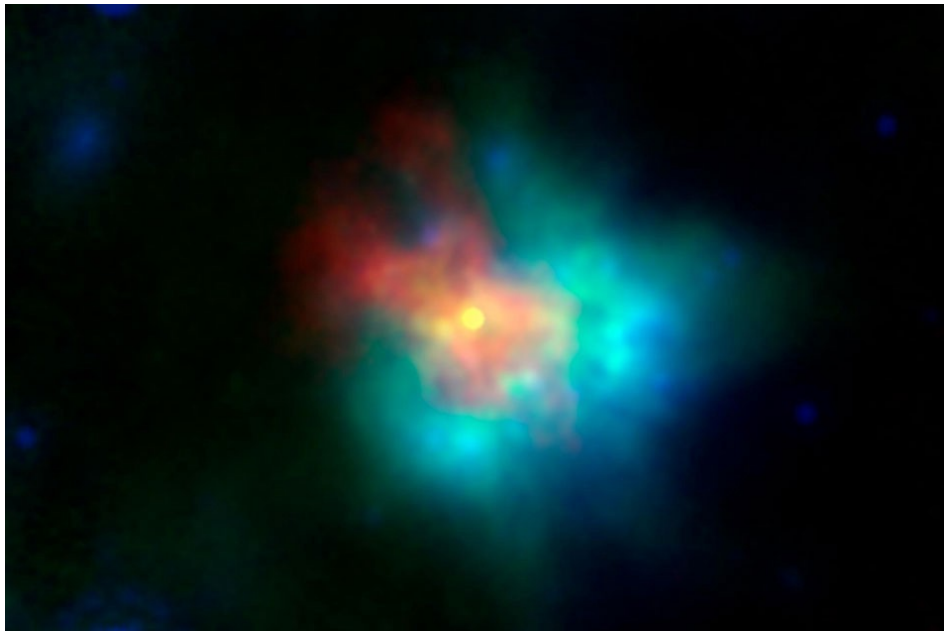
The *NN* force at short-distance matters.

- Starting point for microscopic calculations of nuclei



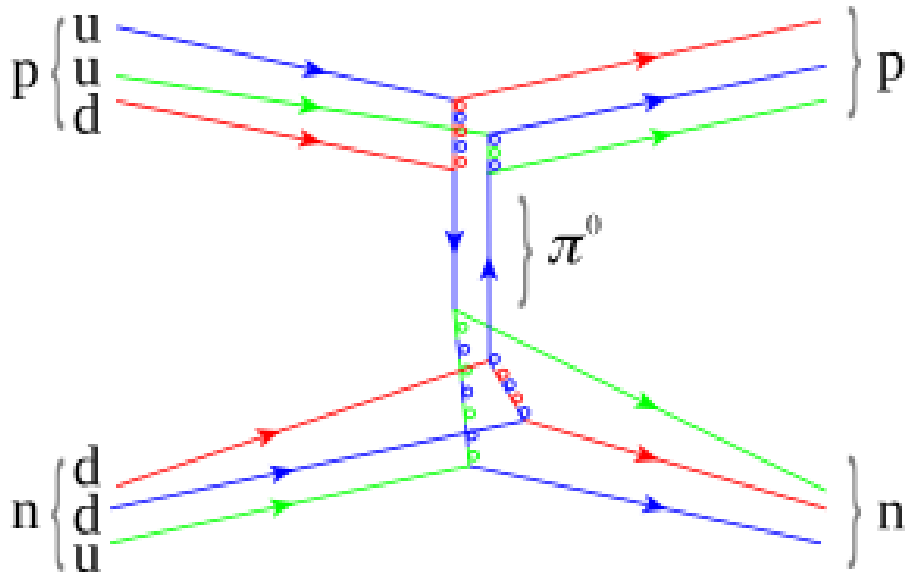
The *NN* force at short-distance matters.

- Starting point for microscopic calculations of nuclei
- Eq. of state of neutron-star matter



The *NN* force at short-distance matters.

- Starting point for microscopic calculations of nuclei
- Eq. of state of neutron-star matter
- How to connect to fundamental QCD?



Short-range correlated nucleon pairs offer a new way to study the *NN* force.

nature

Article | Published: 26 February 2020

Probing the core of the strong nuclear interaction

A. Schmidt, J. R. Pybus, R. Weiss, E. P. Segarra, A. Hrnjic, A. Denniston, O. Hen ✉, E. Piasetzky, L. B. Weinstein, N. Barnea, M. Strikman, A. Larionov, D. Higinbotham & The CLAS Collaboration

Nature **578**, 540–544(2020) | Cite this article

Probing the core of the strong interaction:

- Isolated SRC pair break-up events from Jefferson Lab data
- Developed new theory approach: Generalized Contact Formalism
  - *NN*-potential models $\longrightarrow$ scattering cross sections
- Comparisons revealed:
  - SRC-pair break-up paradigm describes the data well.
  - Non-relativistic *NN* models work *far beyond* where they were tuned.
  - Clear signature of scalar core

Short Range Correlations Collaboration

THE GEORGE WASHINGTON UNIVERSITY
WASHINGTON, DC

- **Axel Schmidt**
- Dr. Holly Szumila-Vance
- Dr. Tyler Kutz

Massachusetts Institute of Technology

- **Prof. Or Hen**
- Dr. Adi Ashkenazi
- Dr. Dien Nguyen
- Dr. Julian Kahlbow
- Rey Cruz-Torres
- Afro Papadopoulou
- Efrain Segarra
- Jackson Pybus
- Andrew Denniston

OLD DOMINION UNIVERSITY

- **Prof. Lawrence Weinstein**
- Dr. Florian Hauenstein
- Dr. Mariana Khachatryan
- Caleb Fogler

TEL AVIV UNIVERSITY

- **Prof. Eli Piasetzky**
- Dr. Igor Korover
- Göran Johansson

Students made big contributions to this work.

Jackson Pybus

Ronen Weiss

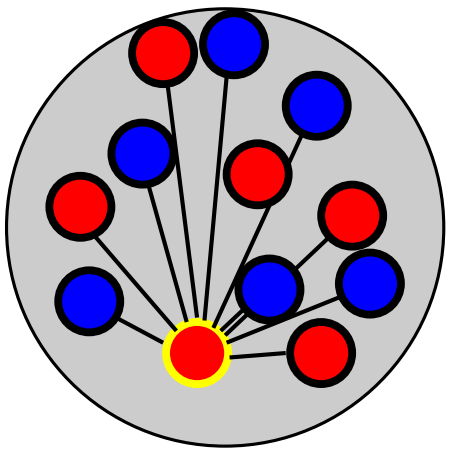
Efrain Segarra

Adin Hrnjic

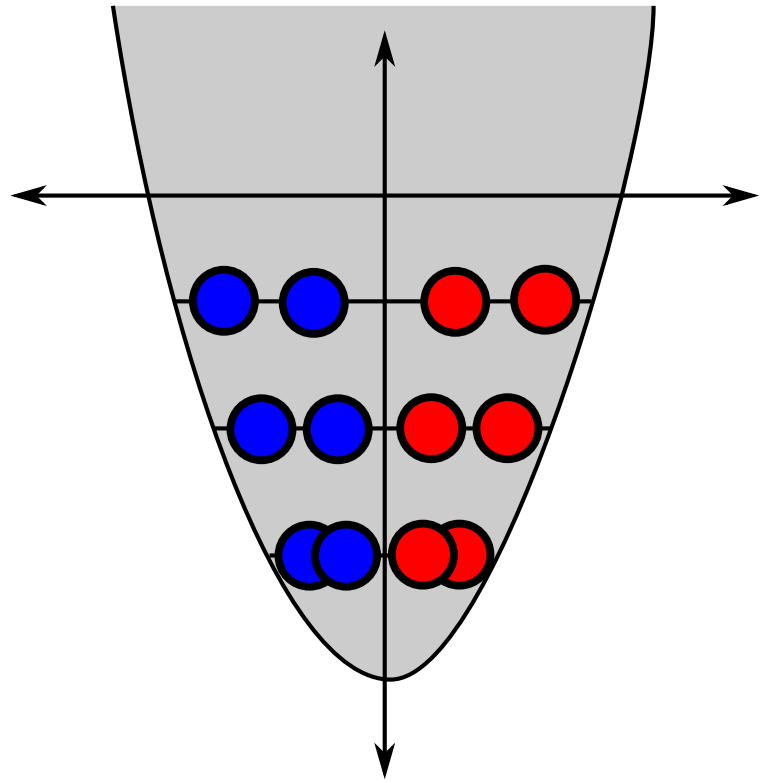
Probing the core of the strong interaction:

- **Isolated SRC pair break-up events from Jefferson Lab data**
- Developed new theory approach: Generalized Contact Formalism
  - *NN*-potential models $\longrightarrow$ scattering cross sections
- Comparisons revealed:
  - SRC-pair break-up paradigm describes the data well.
  - Non-relativistic *NN* models work *far beyond* where they were tuned.
  - Clear signature of scalar core

Mean field models help simplify the picture.

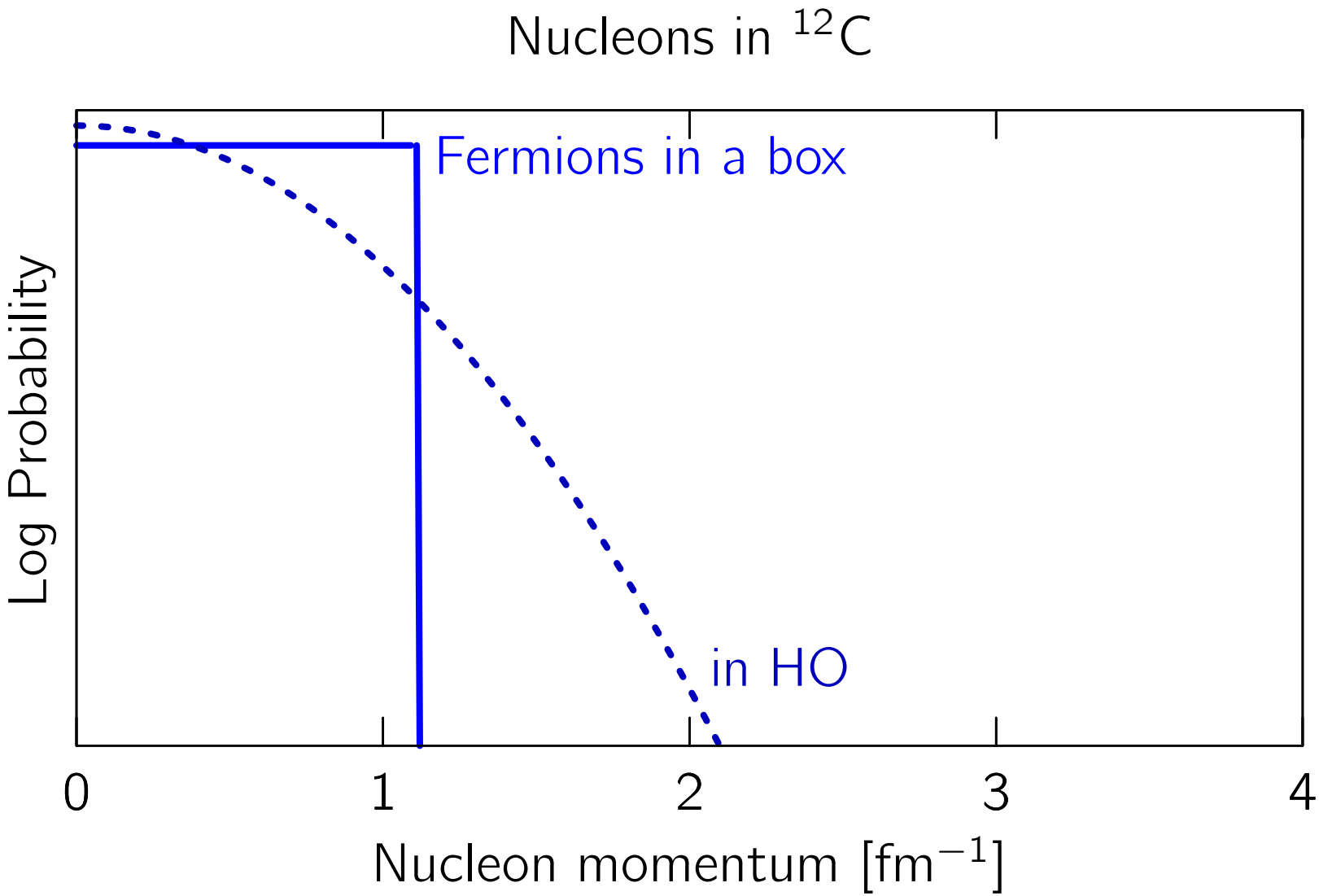


Full microscopic picture

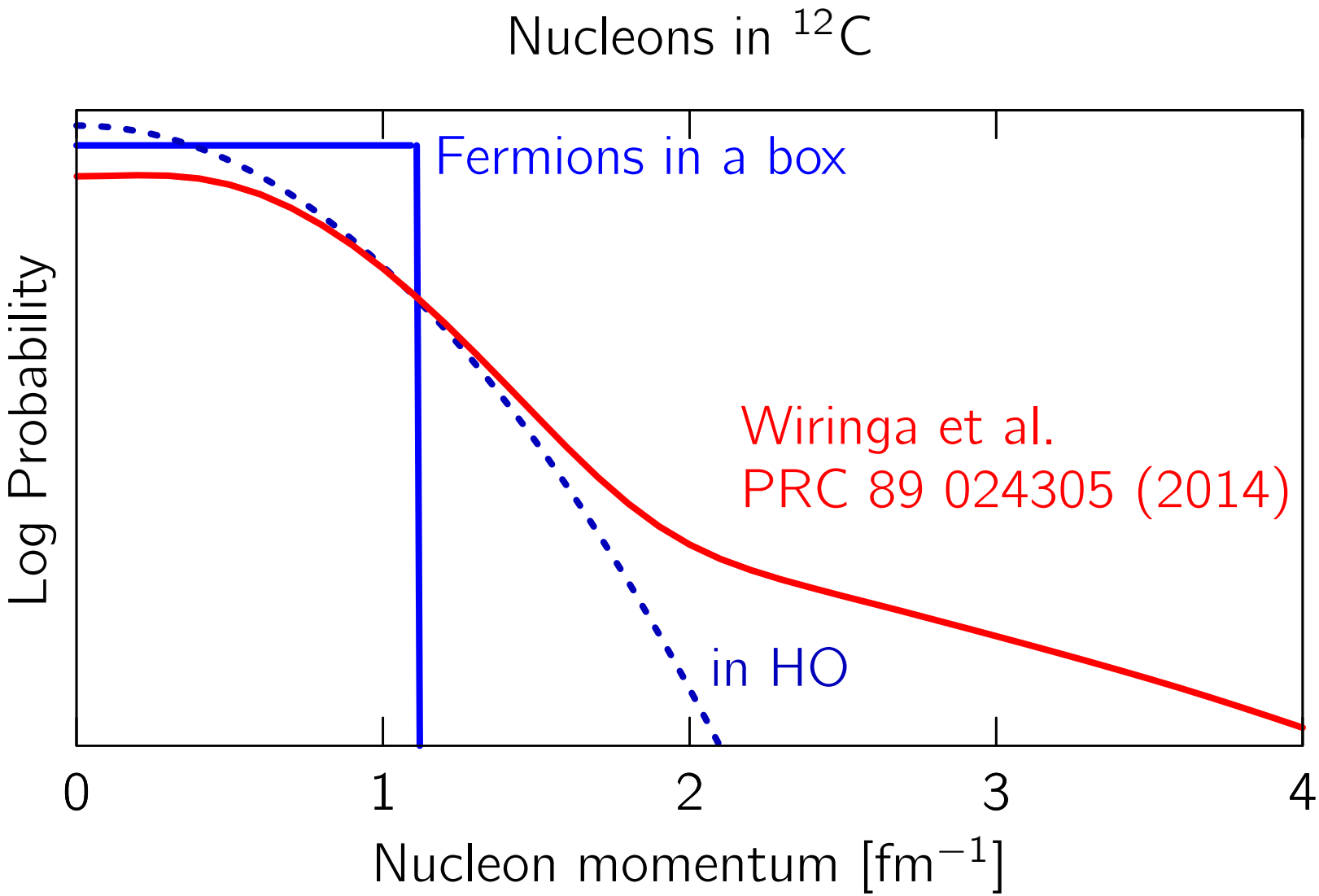


Mean-field approach

The nucleus is like a box of fermions.

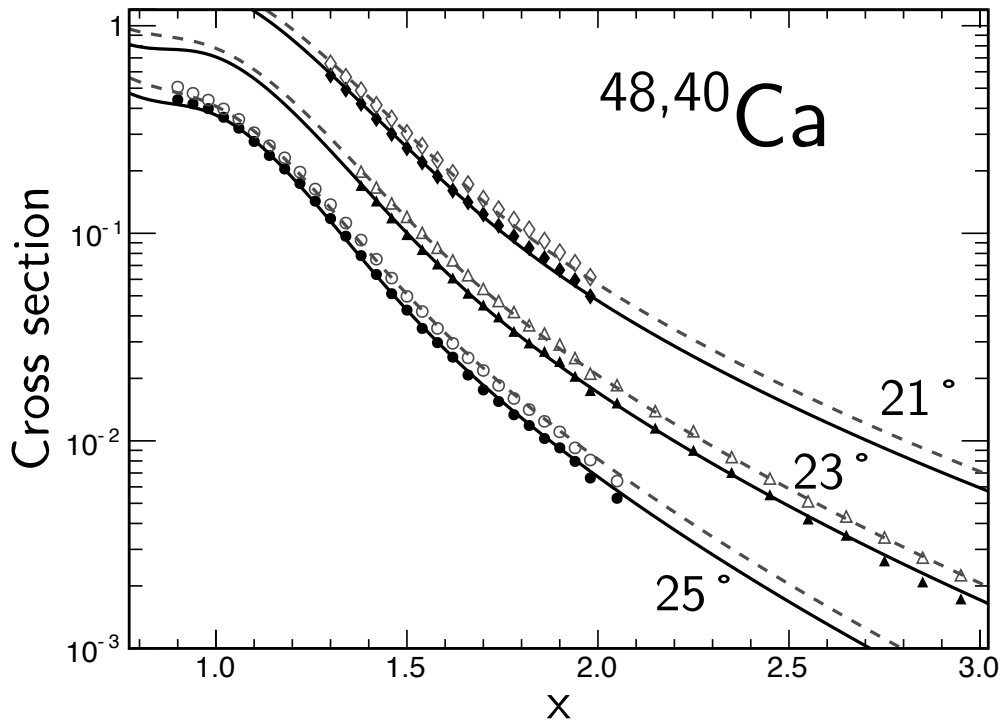


The nucleus is like a box of fermions.



The mean-field picture breaks down.

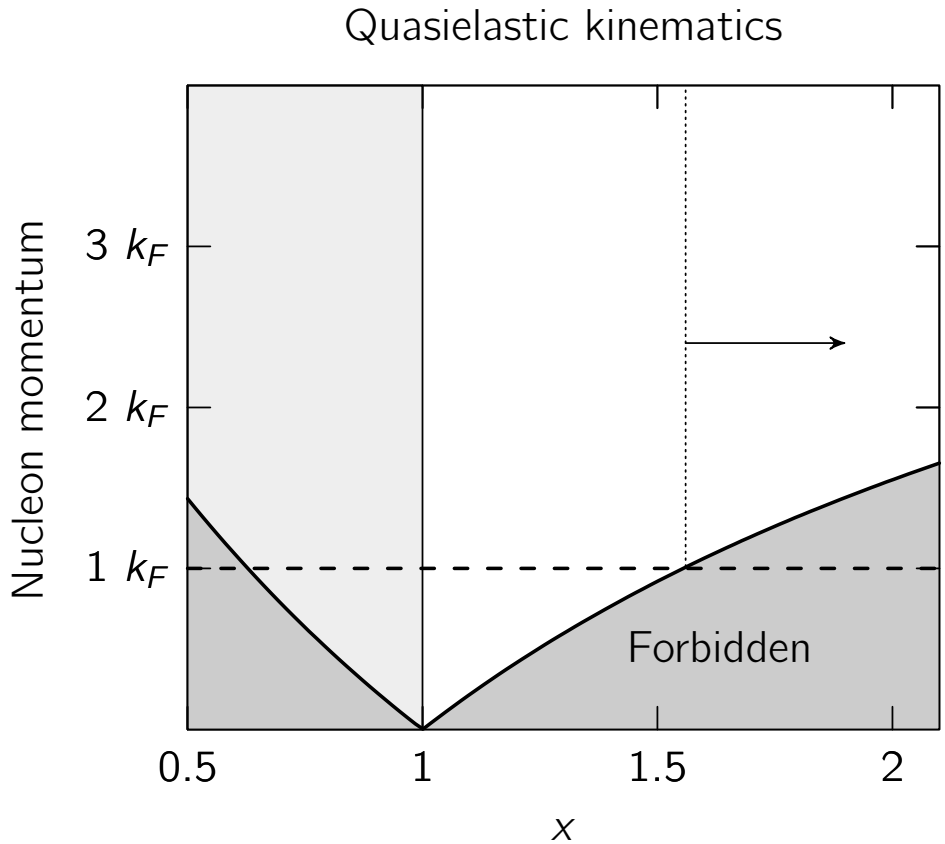
- High-momentum tails



D. Nguyen et al., in preparation

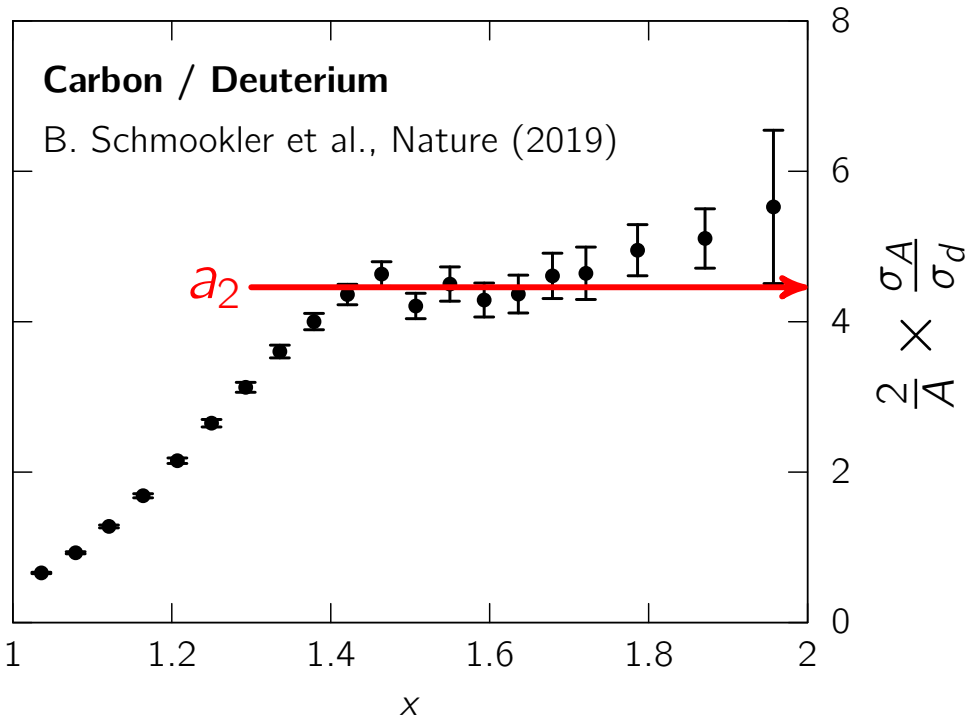
The mean-field picture breaks down.

- High-momentum tails



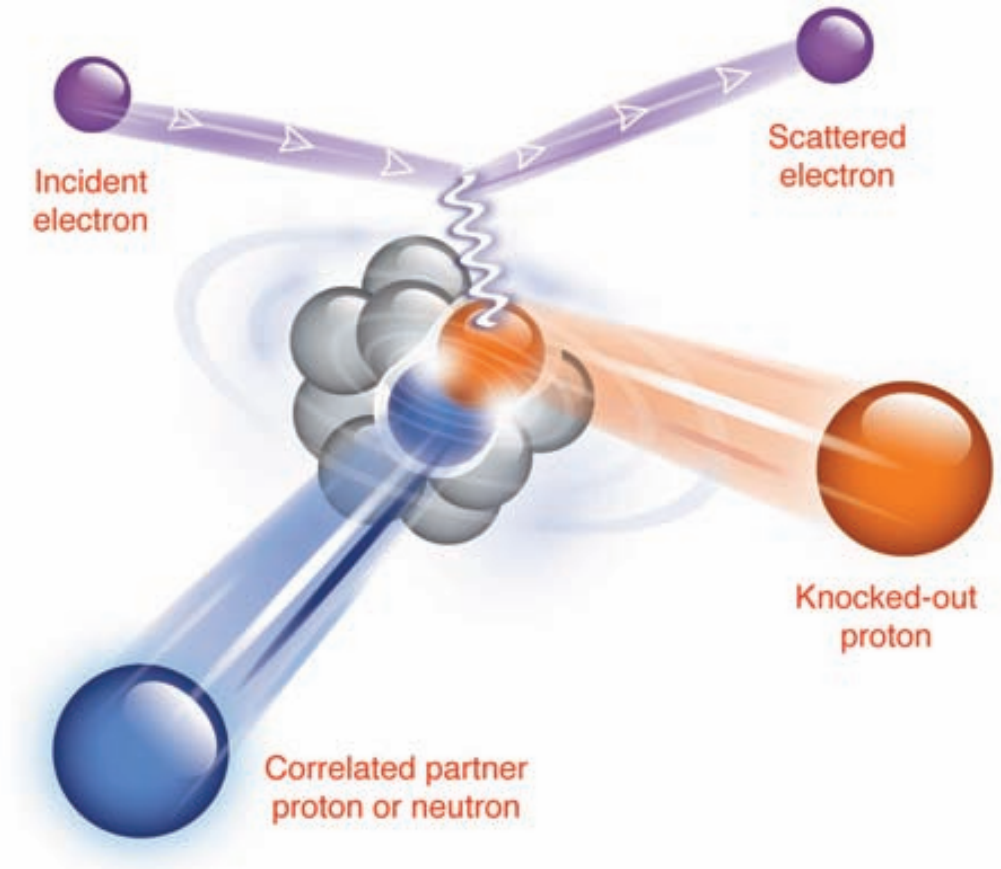
The mean-field picture breaks down.

- High-momentum tails
- Universal shape

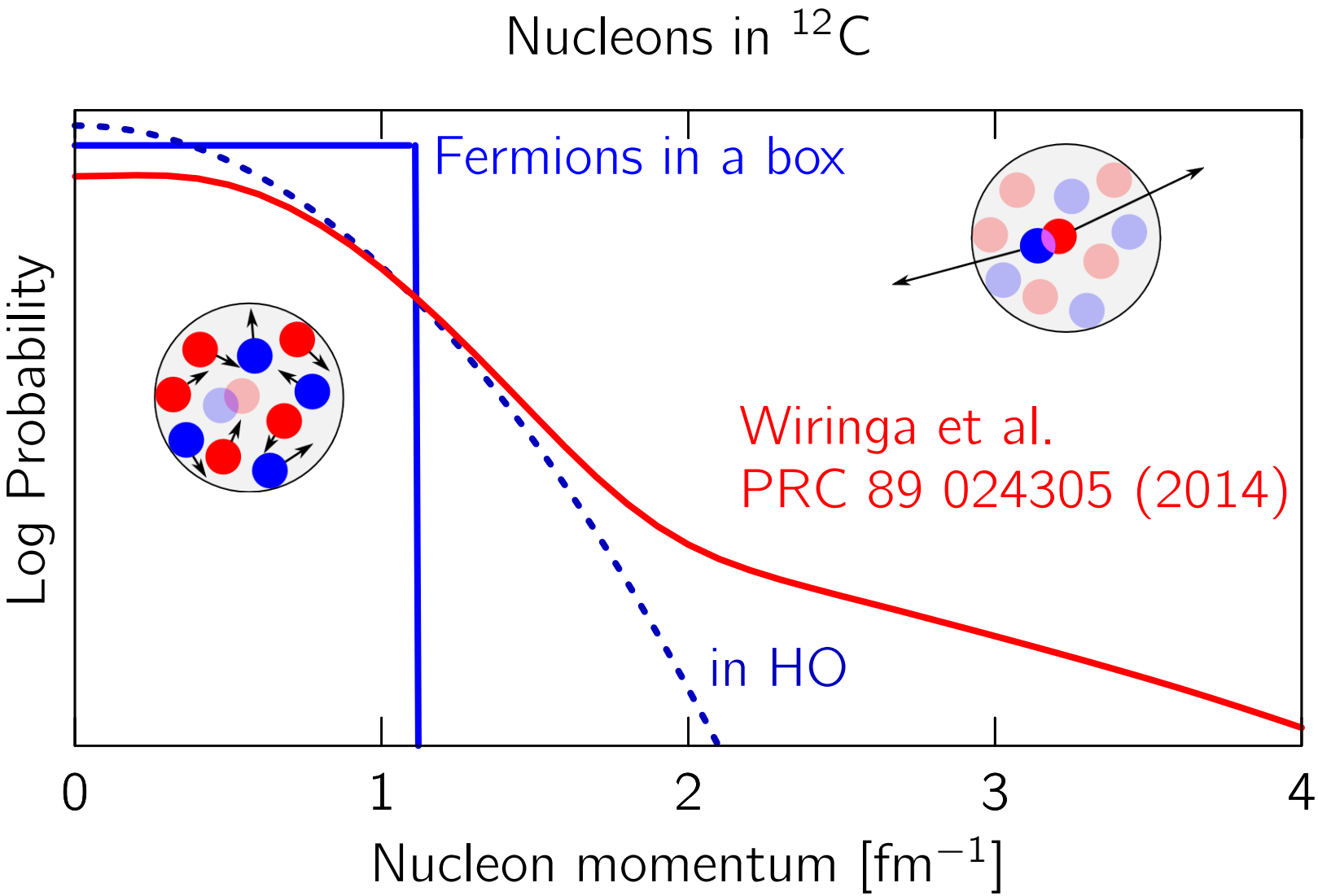


The mean-field picture breaks down.

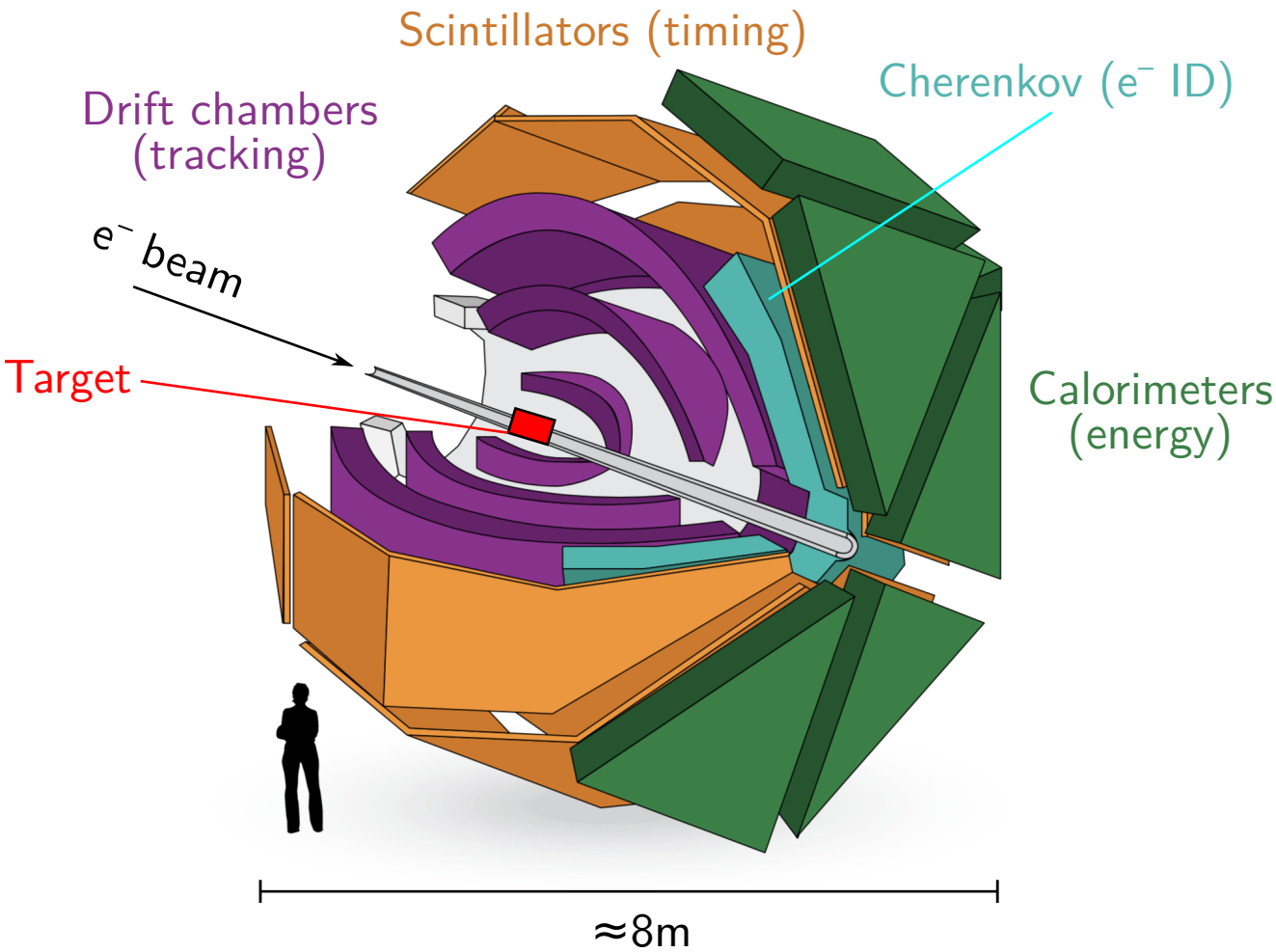
- High-momentum tails
- Universal shape
- Correlated emission of partner



The nucleus is like a box of fermions.



CLAS data-mining has taught us a lot about short-range correlations.



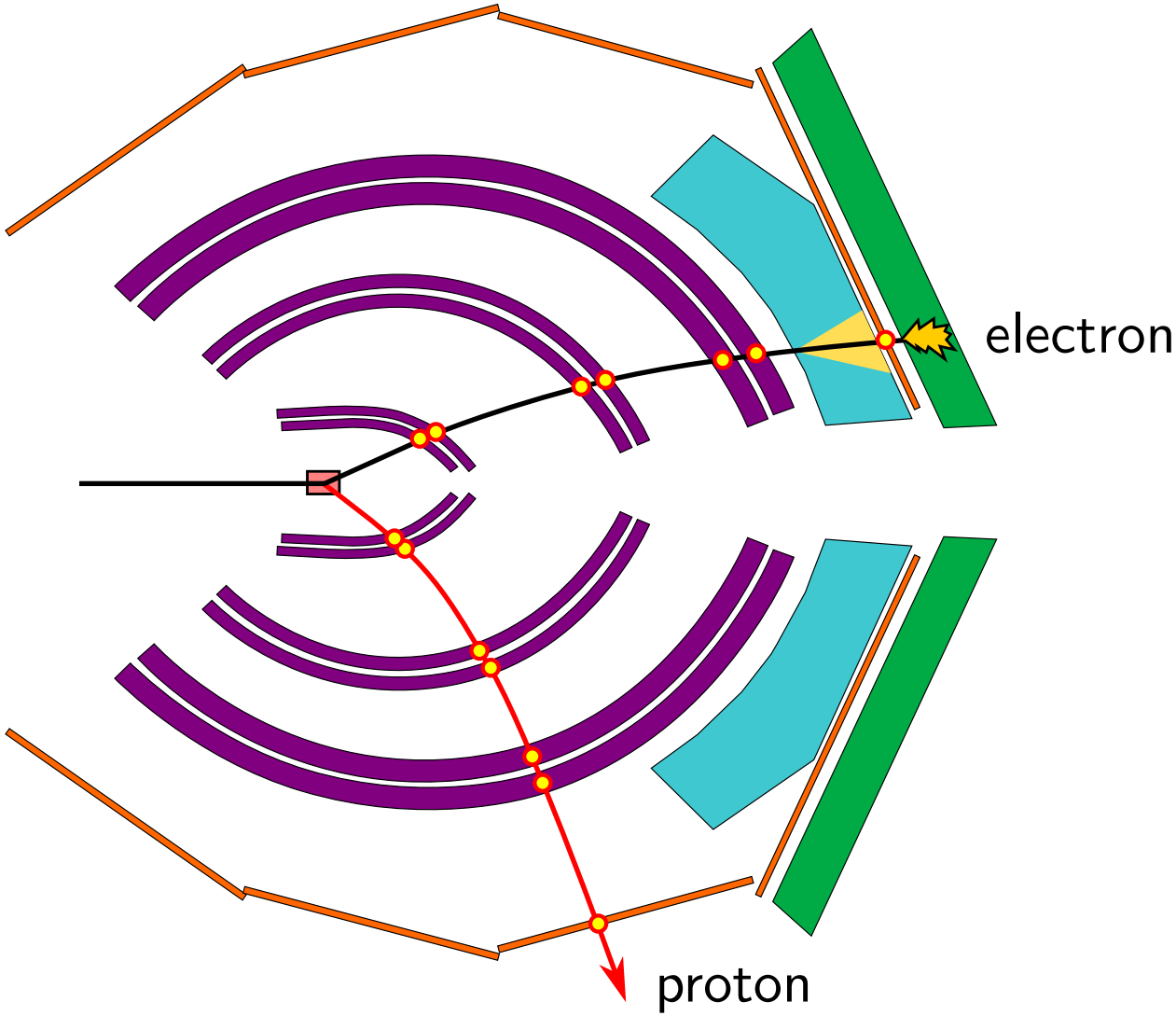
EG2 Experiment

- 5 GeV e^- beam
- C, Al, Fe, Pb

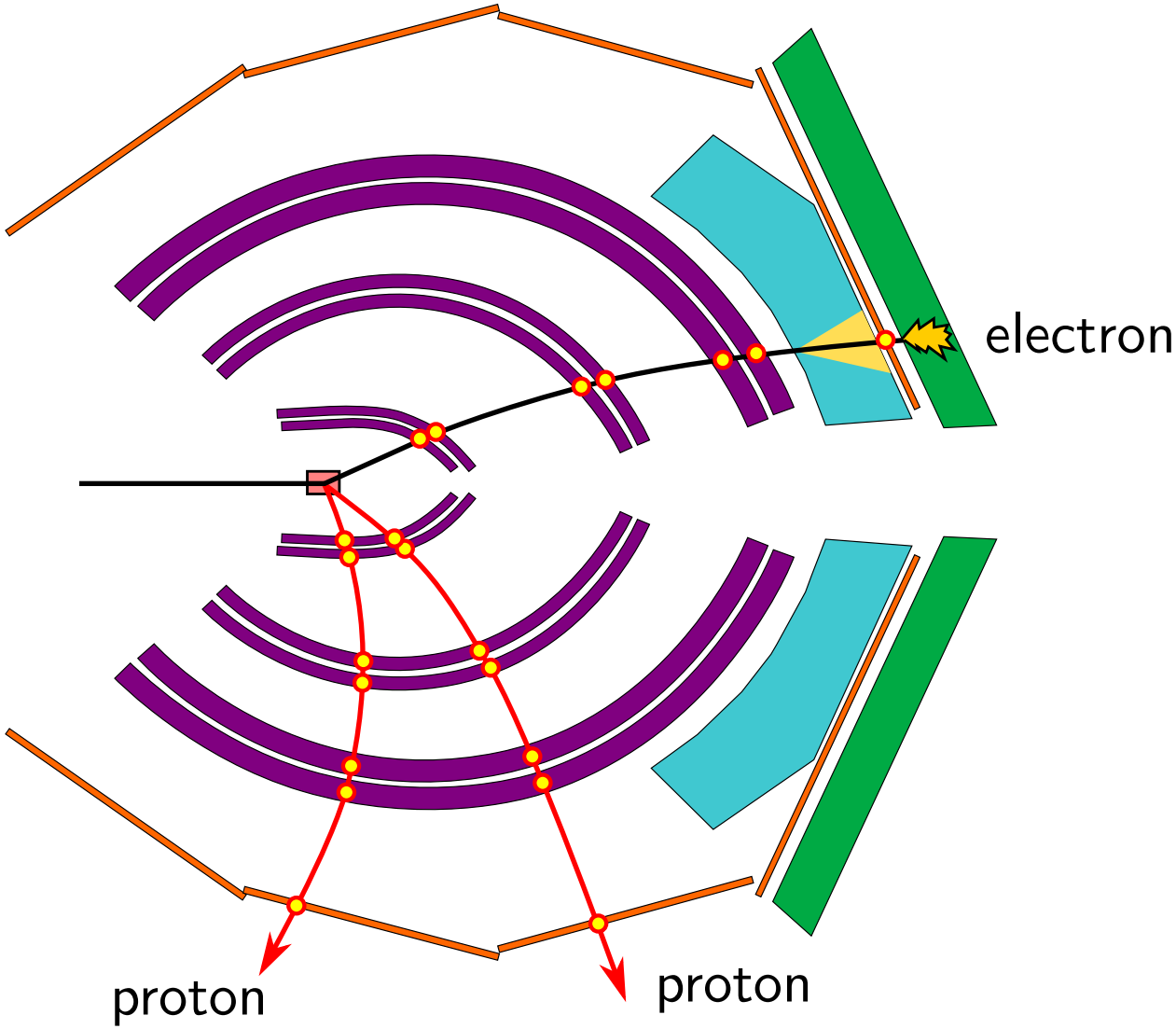
Some publications

- E. O. Cohen et al., PRL 121 092501 (2018)
- M. Duer et al., PRL 122 172502 (2019)
- **A. Schmidt et al., Nature (2020)**

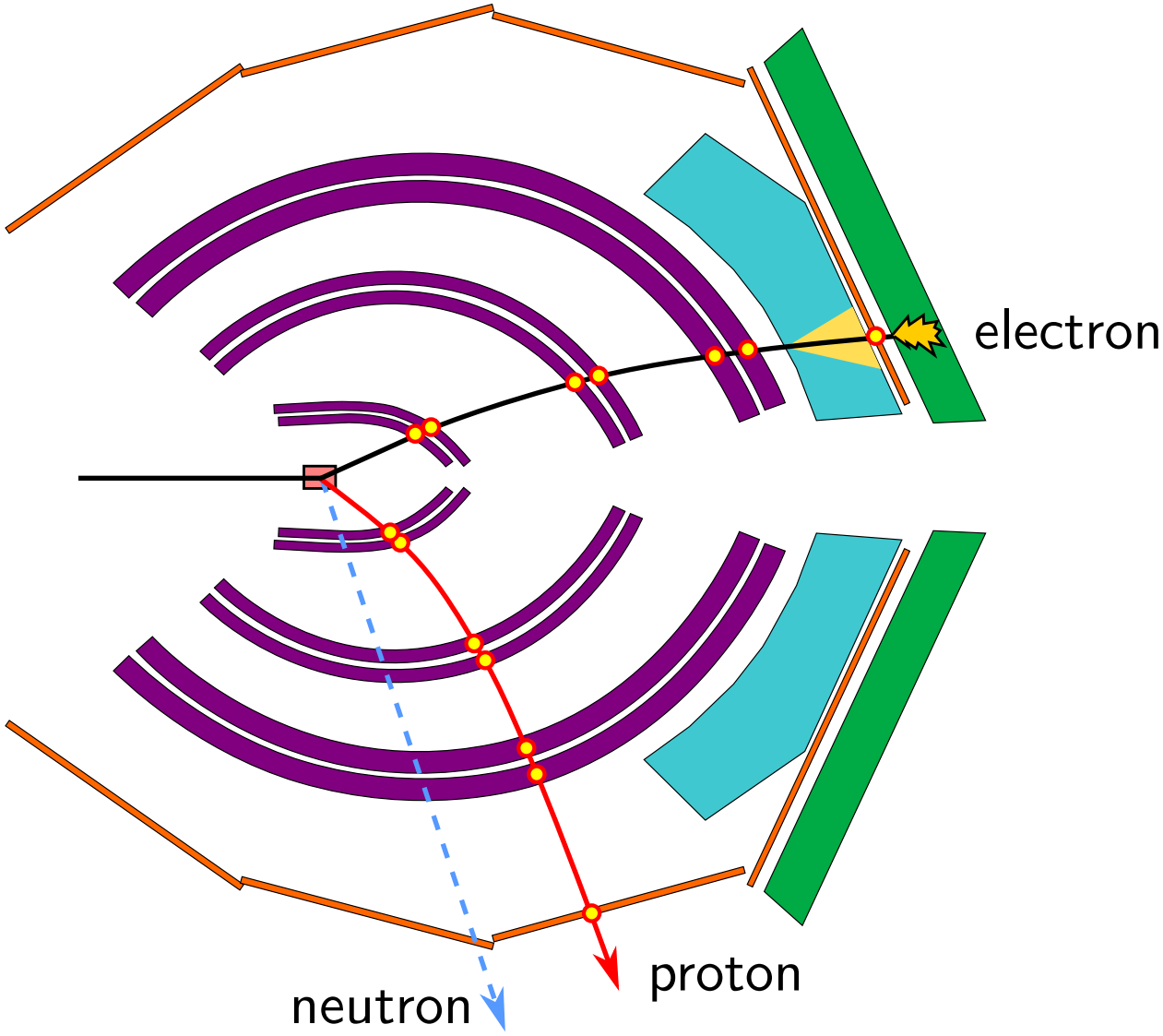
CLAS can measure momenta of charged particles.



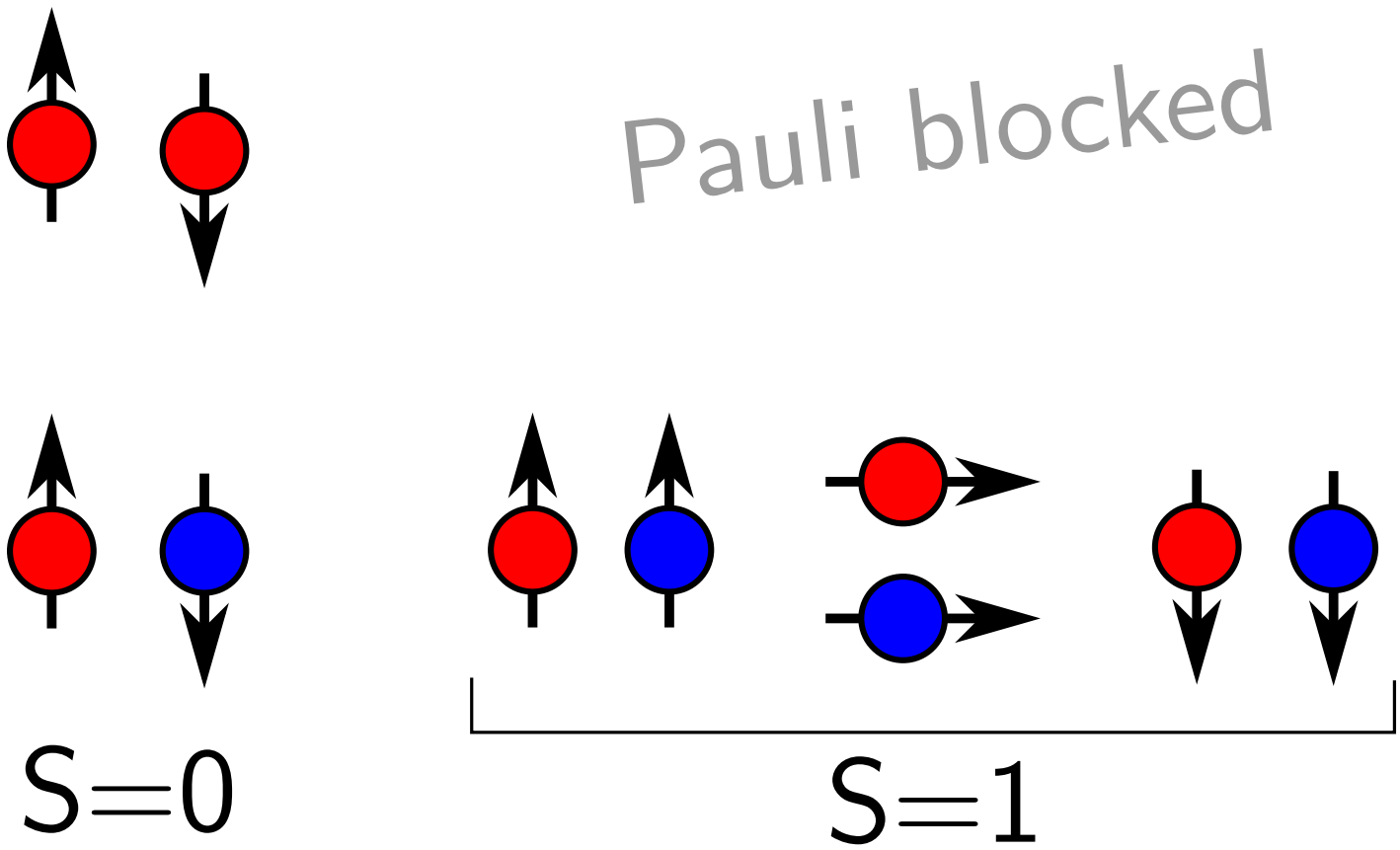
CLAS can measure momenta of charged particles.



CLAS can measure momenta of charged particles.

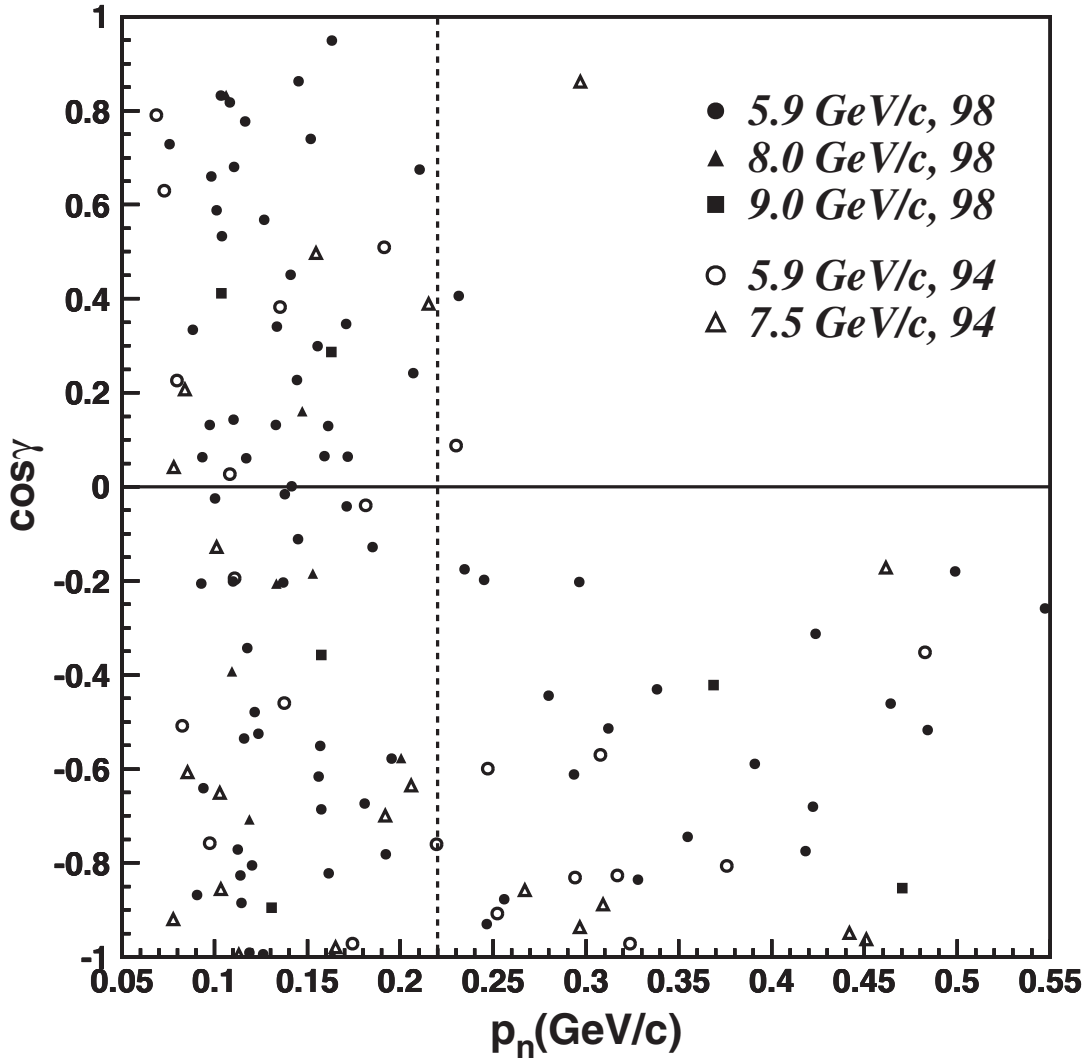


The ratio of *pp*/*np* pairs tells us about the spin-isospin structure of the *NN* force.



Most pairs are *np* spin-1 (in the 300–600 MeV/c range)

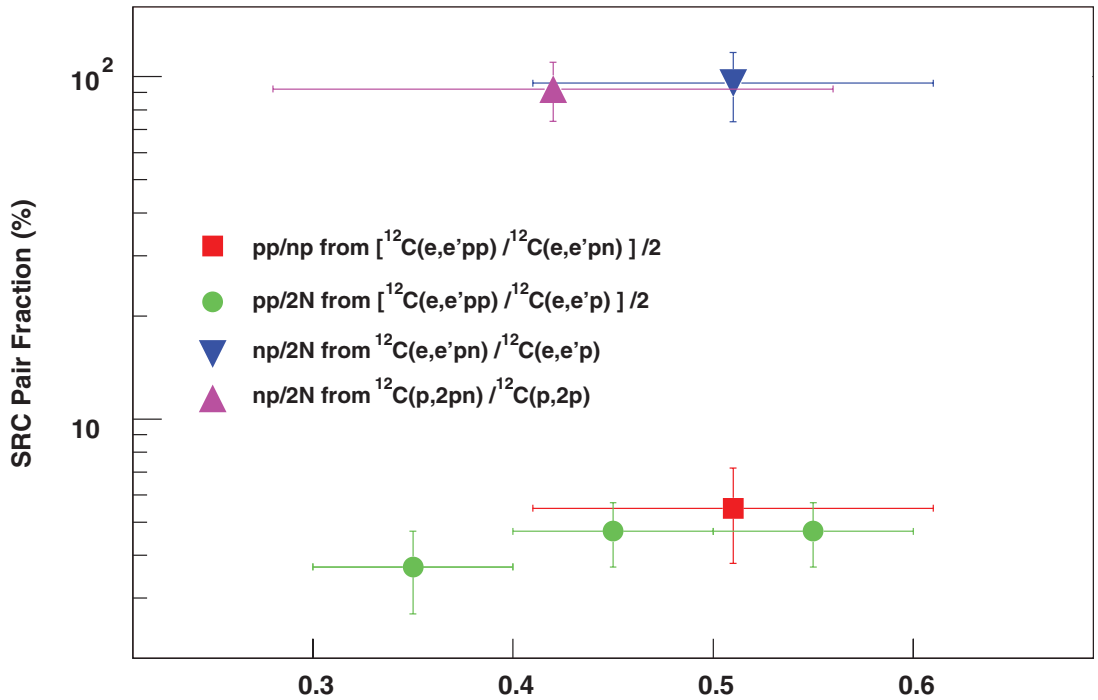
- Brookhaven EVA ('06) (p, ppn) vs (p, ppp)



E. Piasetzky et al., PRL 97, 162504

Most pairs are *np* spin-1 (in the 300–600 MeV/c range)

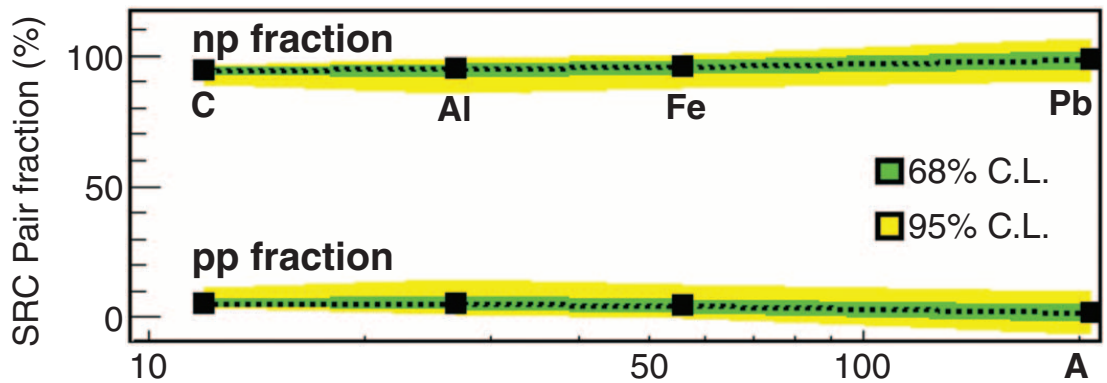
- Brookhaven EVA ('06) (p, ppn) vs (p, ppp)
- JLab Hall A ('08) $(e, e'pn)$ vs $(e, e'pp)$



R. Subedi et al., Science 320, 1476

Most pairs are *np* spin-1 (in the 300–600 MeV/c range)

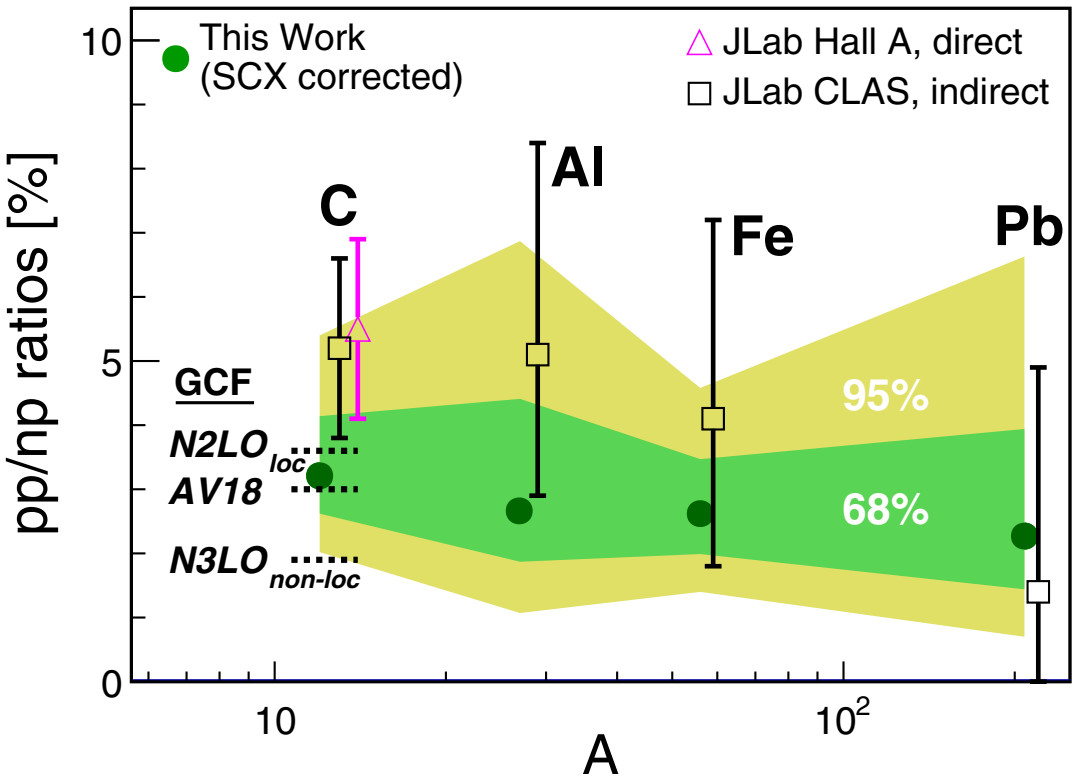
- Brookhaven EVA ('06) (p, ppn) vs (p, ppp)
- JLab Hall A ('08) $(e, e'pn)$ vs $(e, e'pp)$
- JLab CLAS ('14) $(e, e'pp)$ vs $(e, e'p)$



O. Hen et al., Science 346, 614

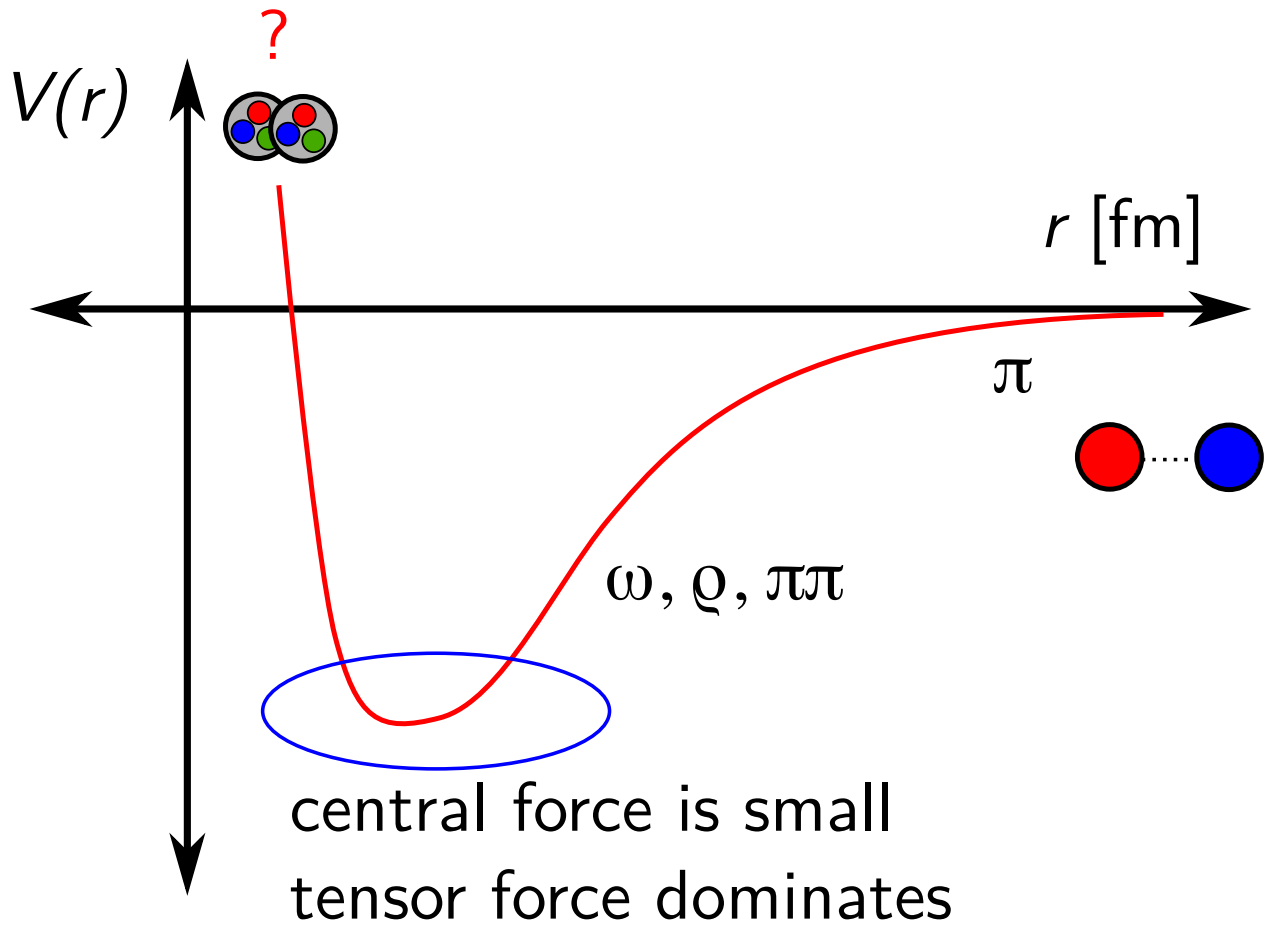
Most pairs are *np* spin-1 (in the 300–600 MeV/c range)

- Brookhaven EVA ('06) (p, ppn) vs (p, ppp)
- JLab Hall A ('08) $(e, e'pn)$ vs $(e, e'pp)$
- JLab CLAS ('14) $(e, e'pp)$ vs $(e, e'p)$
- JLab CLAS ('19) $(e, e'np)$ vs $(e, e'pp)$

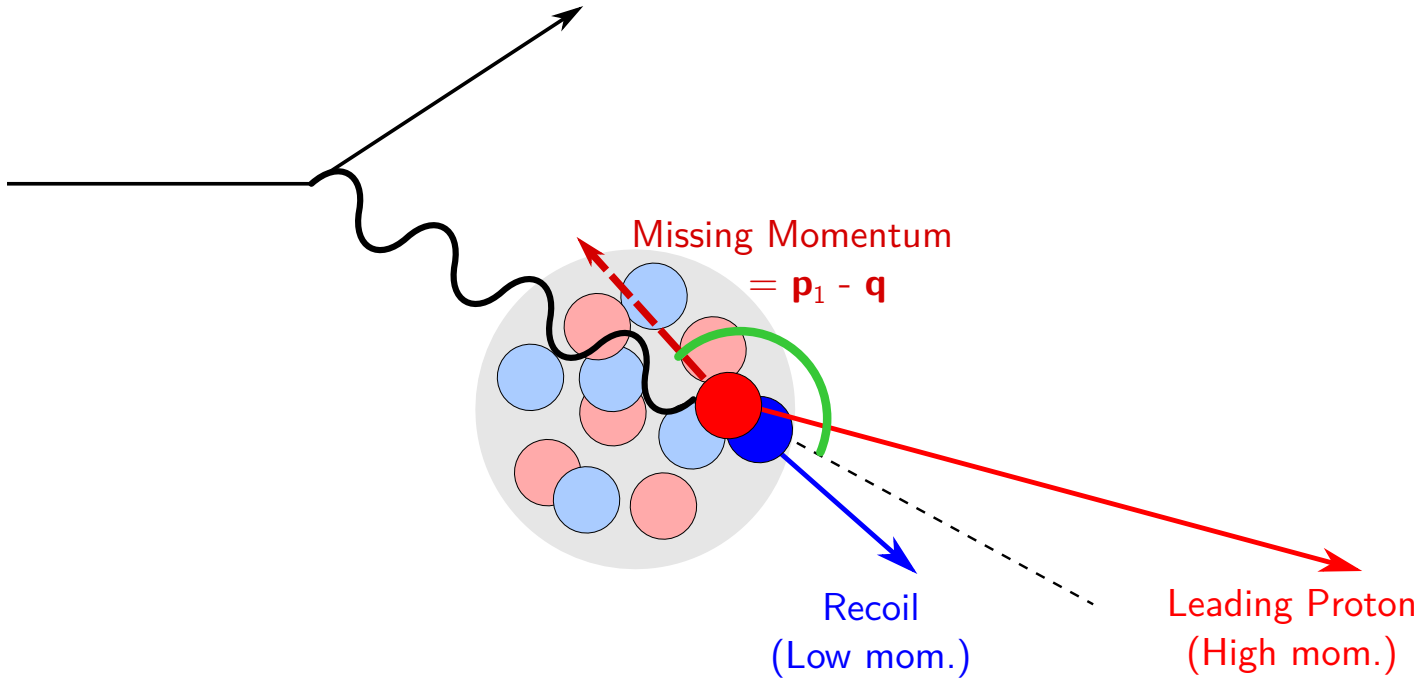


M. Duer et al., PRL 122, 172502

Tensor force dominates at the bottom.
What happens at shorter distances?



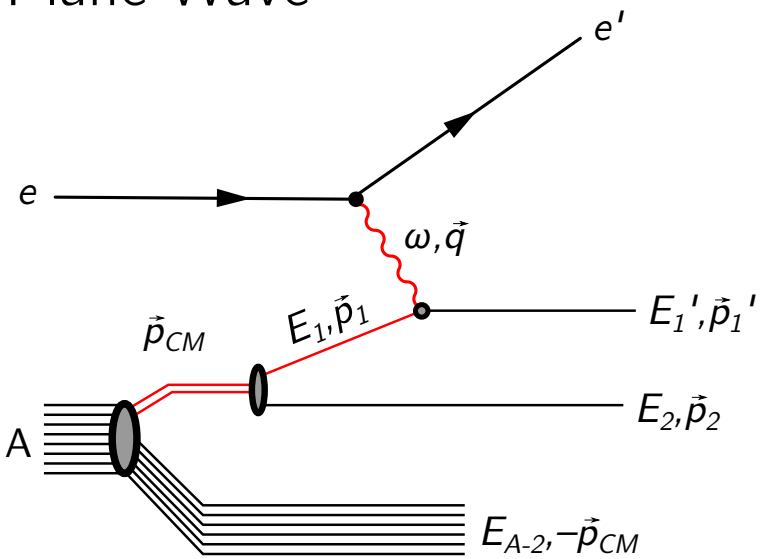
We want $(e, e'p)$ events dominated by the break-up of an SRC proton.



- High missing momentum: $p_{\text{miss}} > 400$ MeV$/c$
- High momentum transfer: $Q^2 > 1.5$ GeV$^2/c^2$
- Proton emitted in $\vec{q}$ direction
- Anti-parallel kinematics: $x_B > 1.2$ and $0.62 < |p_p|/|q| < 0.96$

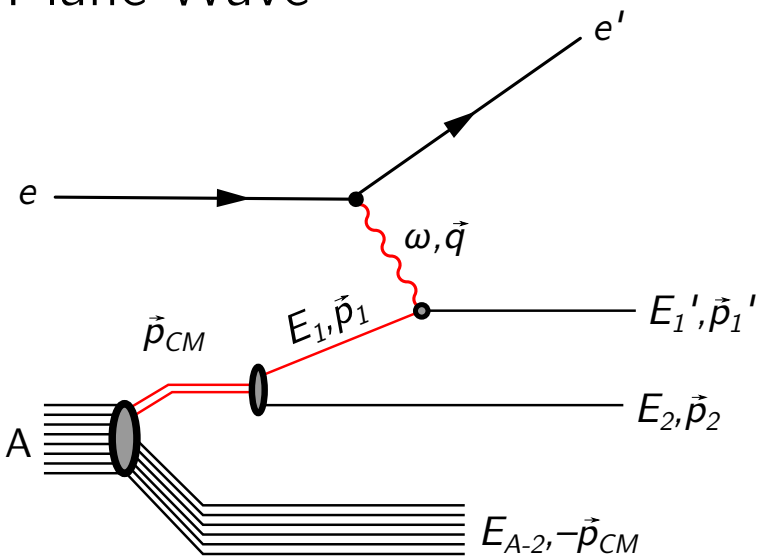
We've selected events to minimize competing reactions.

Plane-Wave

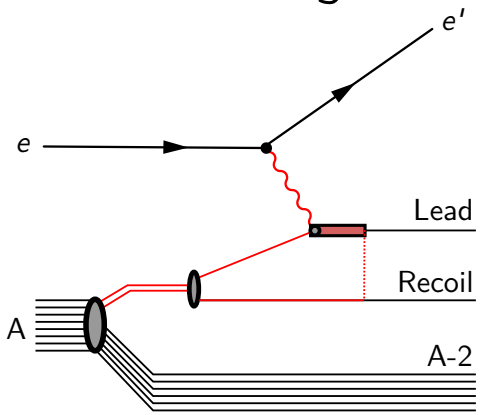


We've selected events to minimize competing reactions.

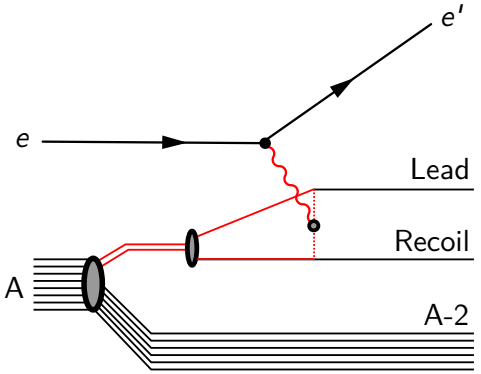
Plane-Wave



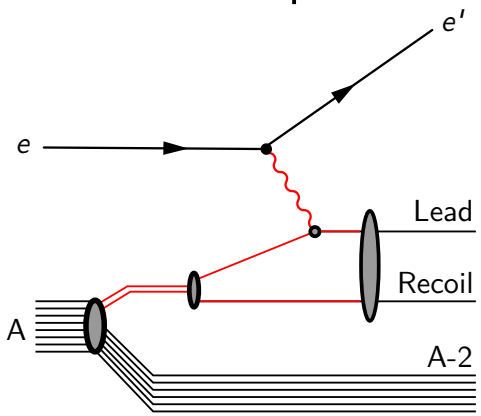
Isobar Config.



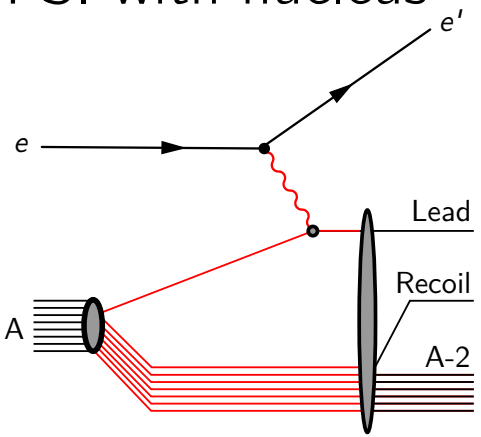
Meson-exchange curr.



FSI within pair



FSI with nucleus



We've selected events to minimize competing reactions.

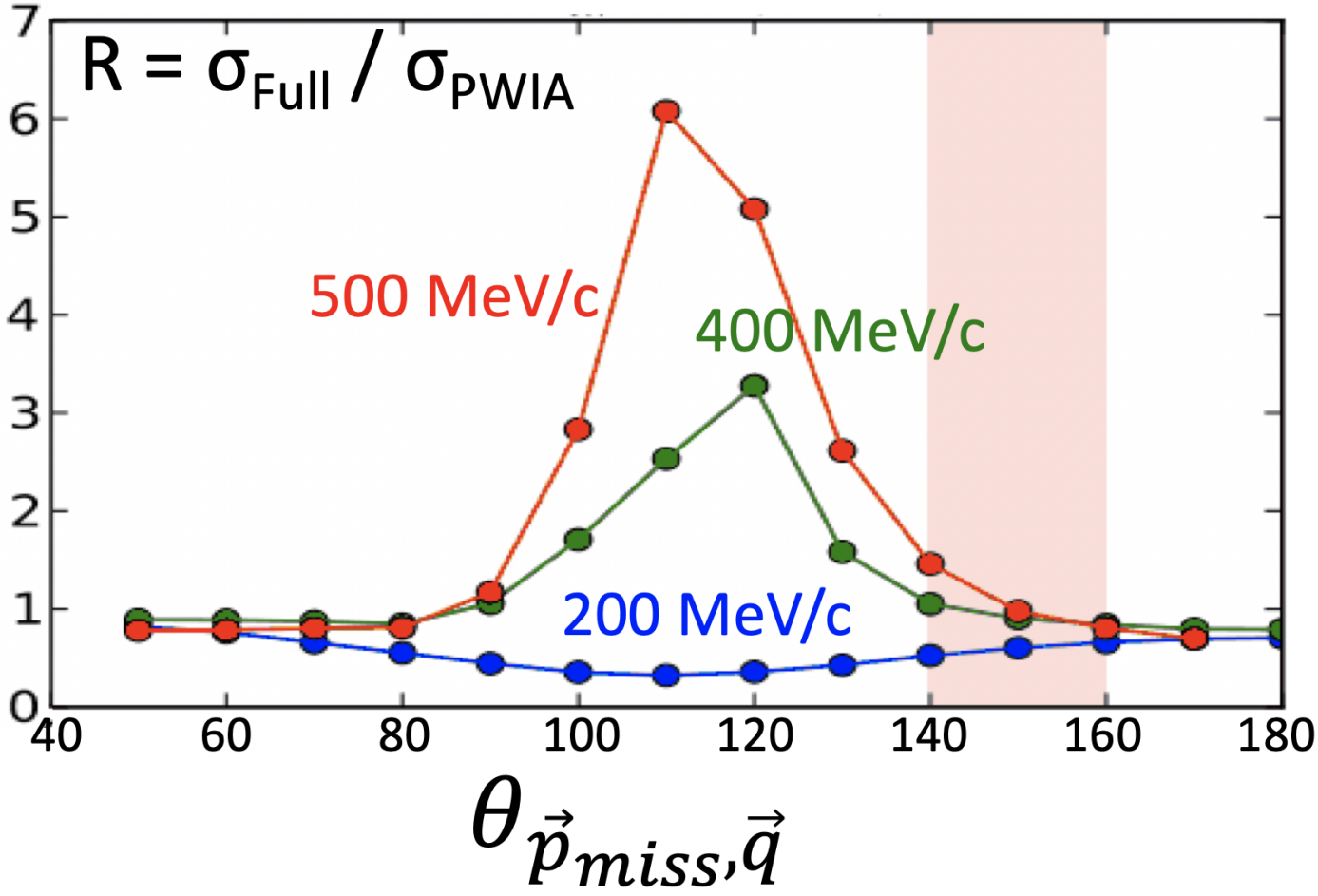
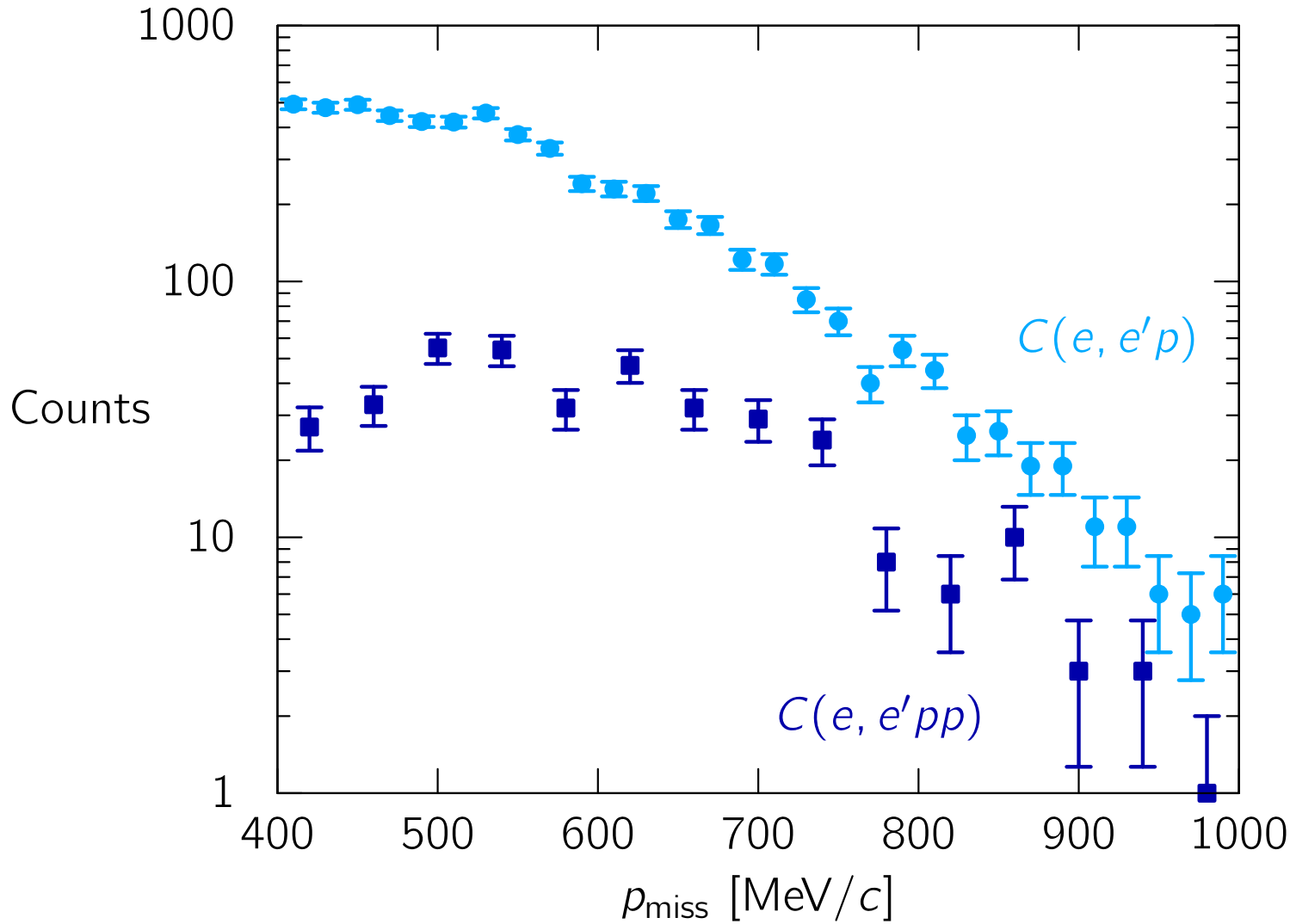
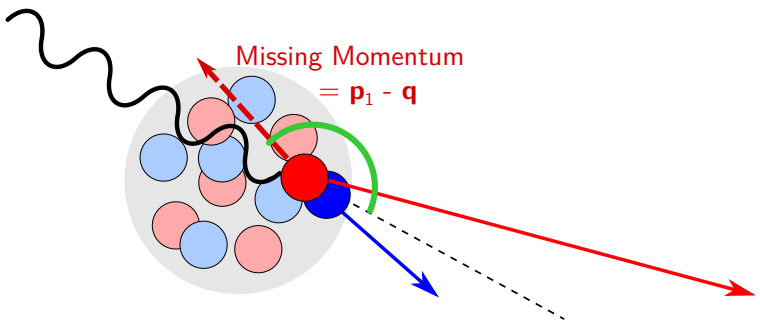


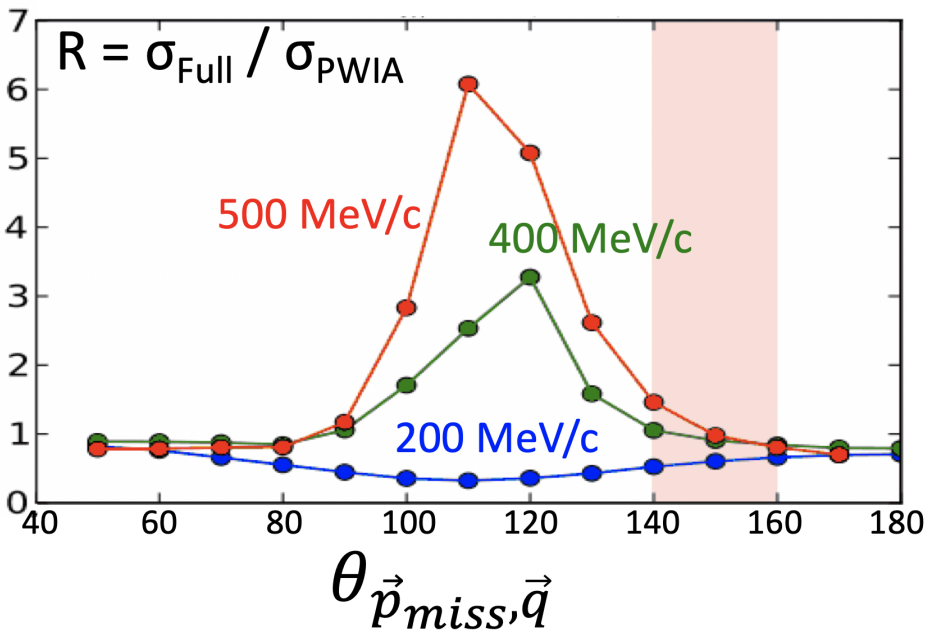
Figure courtesy of Misak Sargsian

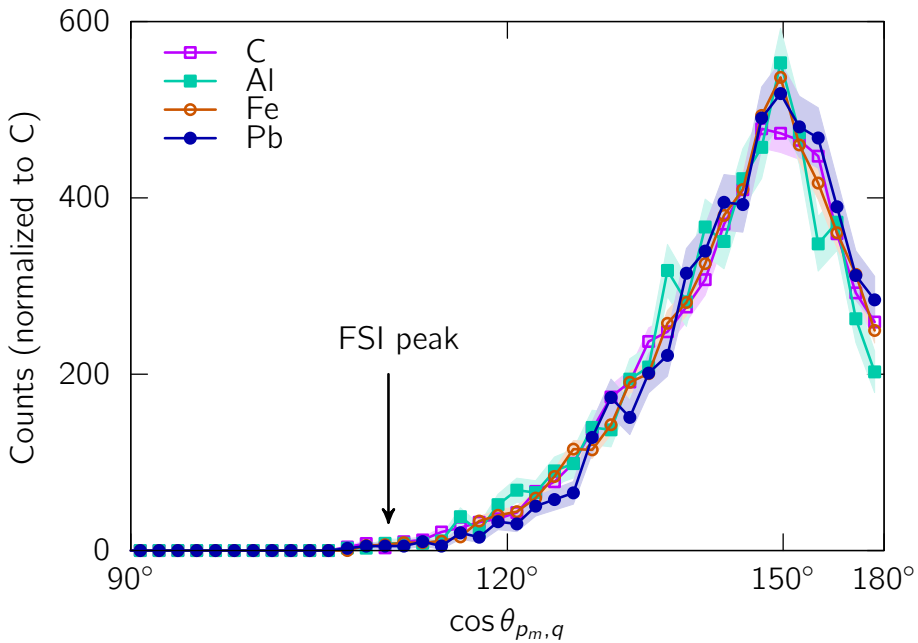
We've selected events to minimize competing reactions.



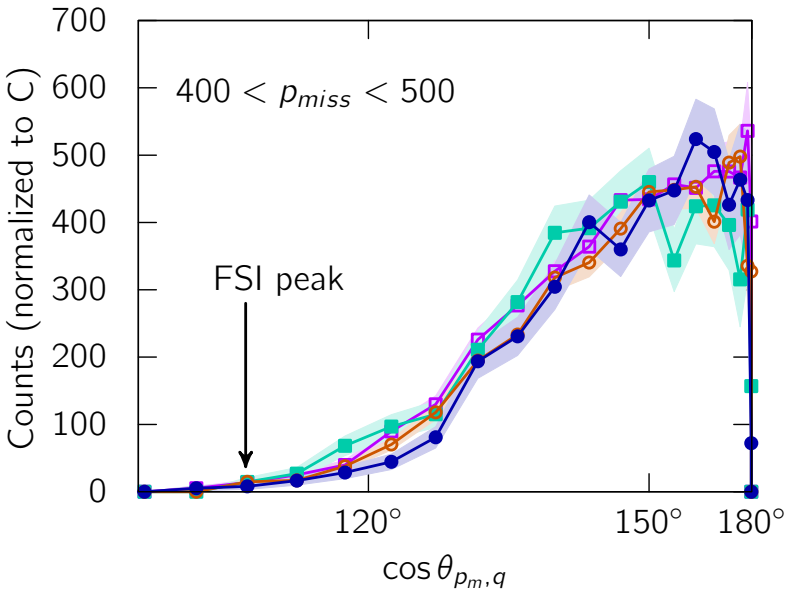
No sign of rescattering peak from C to Pb.

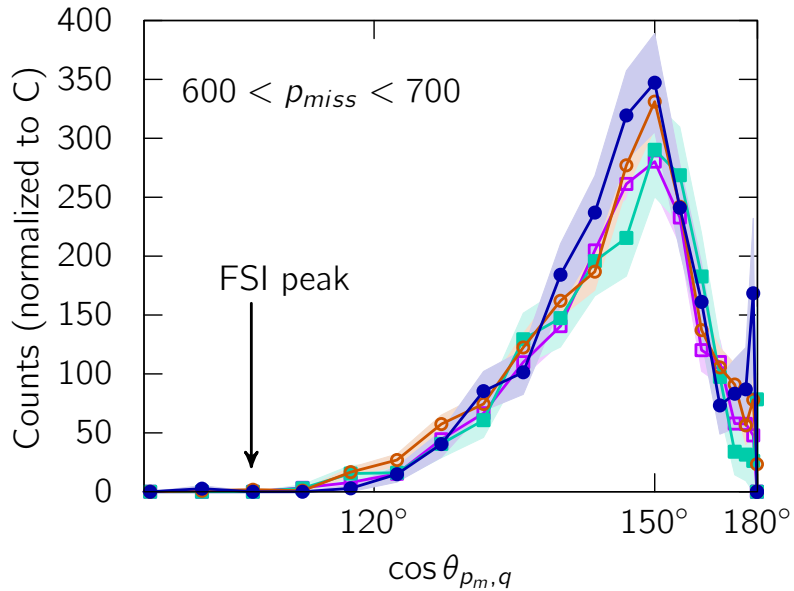


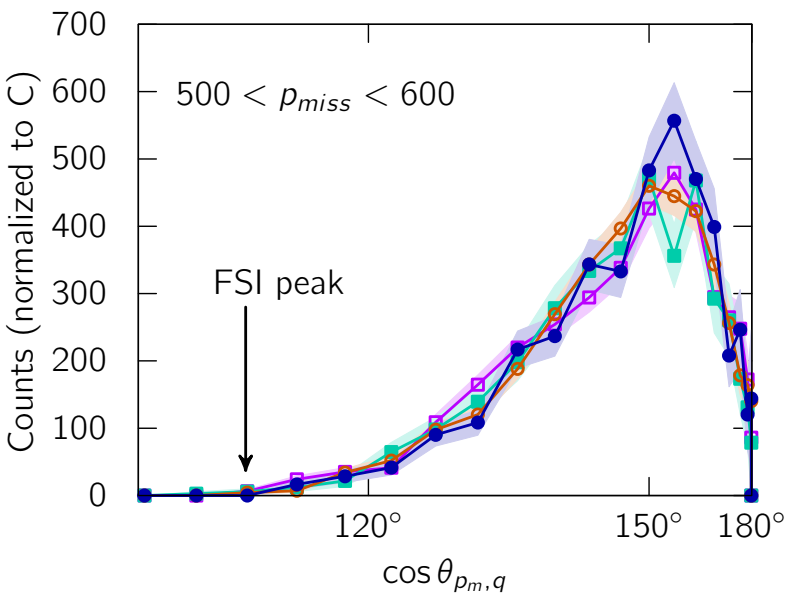


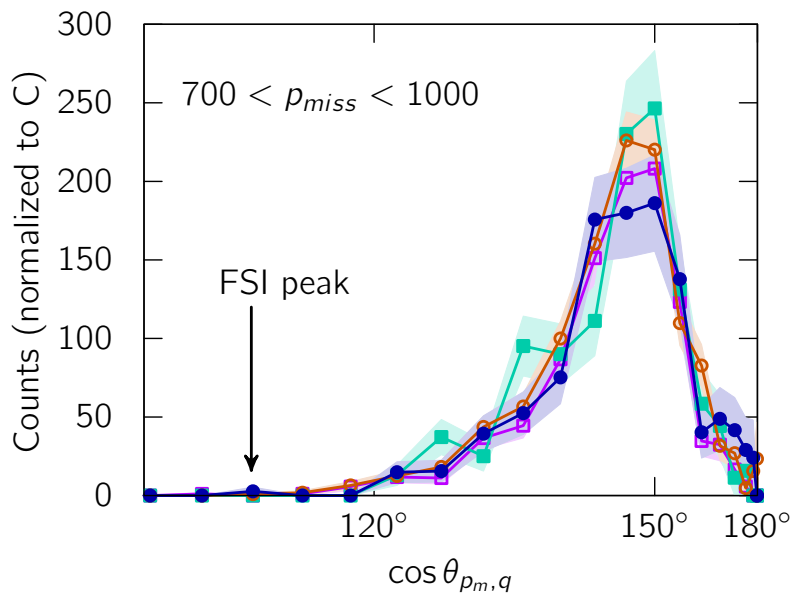


No sign of rescattering over entire p_{miss} range.

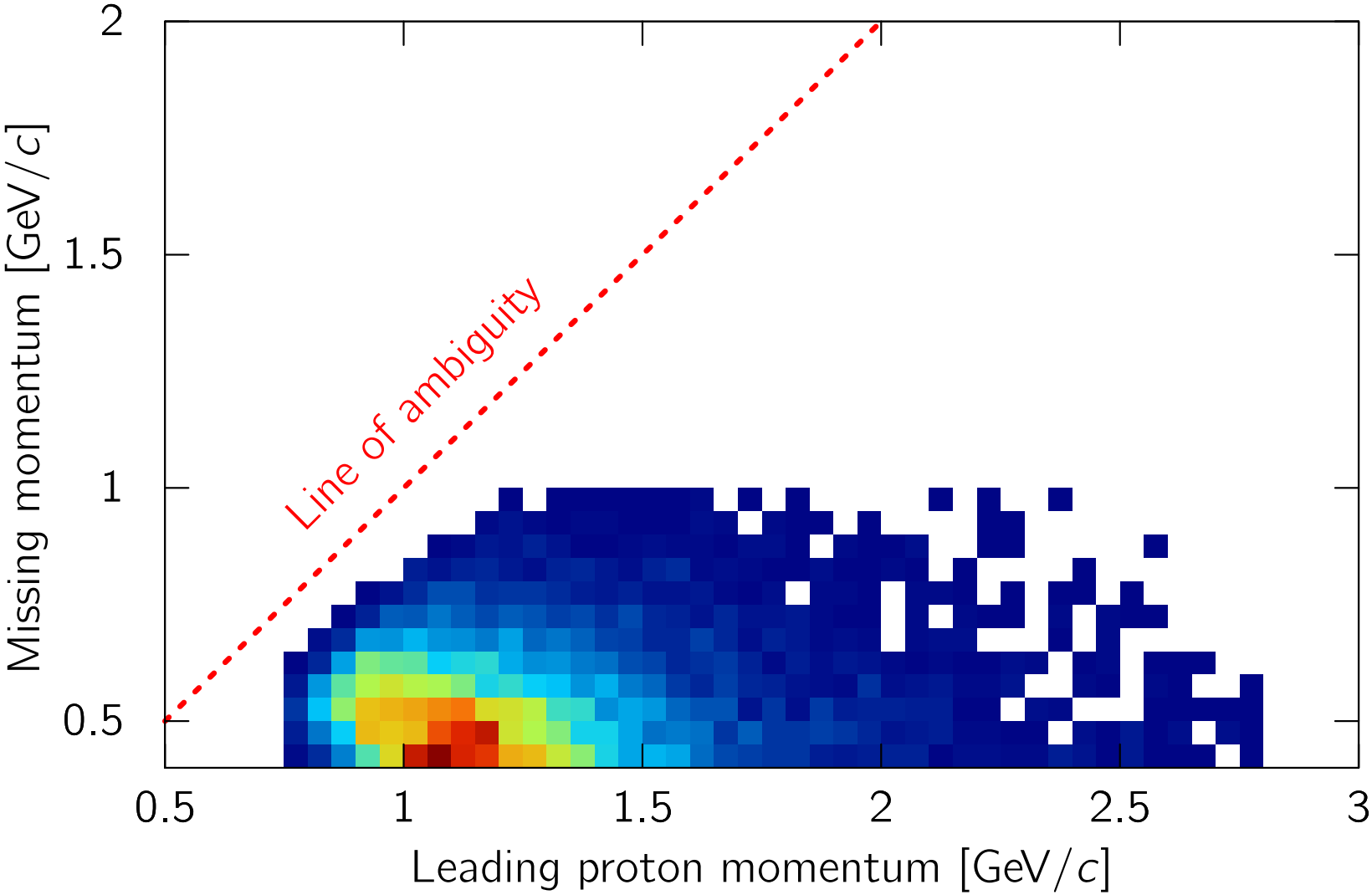








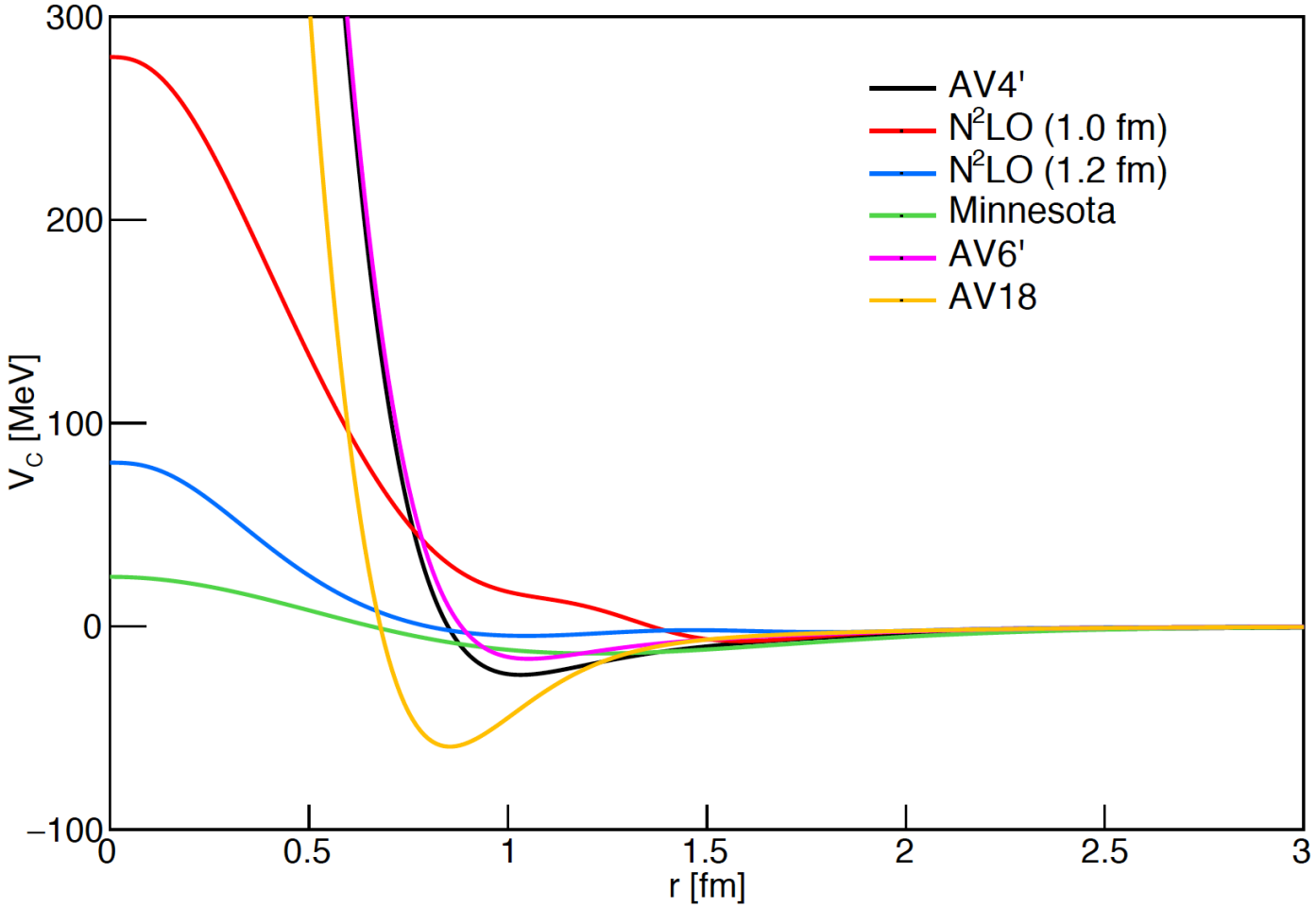
Leading and recoil protons are distinct.



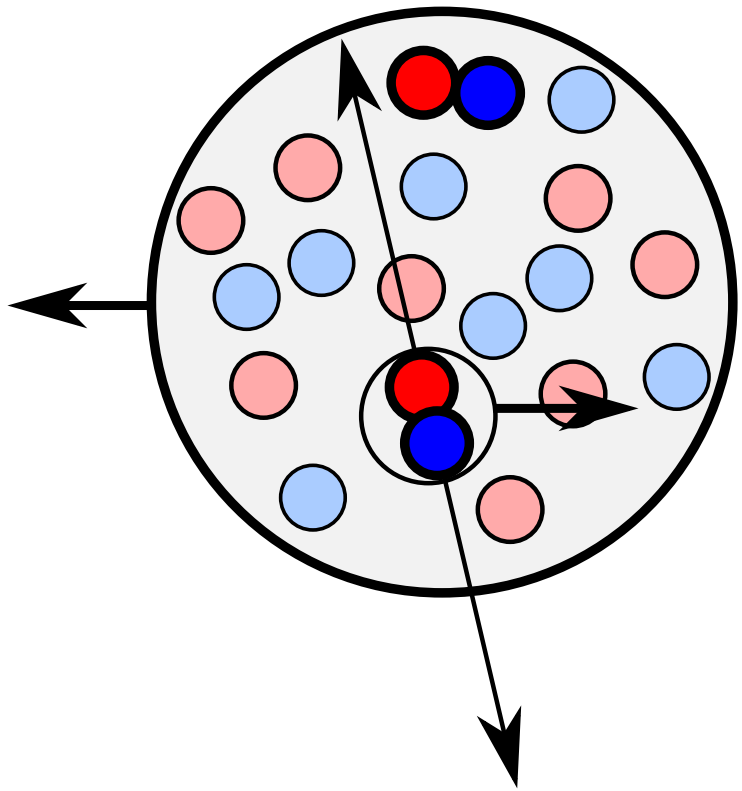
Probing the core of the strong interaction:

- Isolated SRC pair break-up events from Jefferson Lab data
- **Developed new theory approach: Generalized Contact Formalism**
  - *NN*-**potential models** $\longrightarrow$ **scattering cross sections**
- Comparisons revealed:
  - SRC-pair break-up paradigm describes the data well.
  - Non-relativistic *NN* models work *far beyond* where they were tuned.
  - Clear signature of scalar core

To learn about the *NN* interaction we need to connect it to $(e, e'pp)$ cross sections.

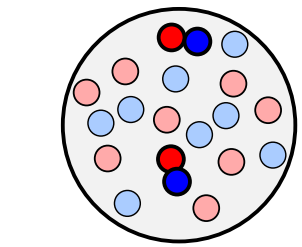


Short-range correlations produce
a complicated picture.

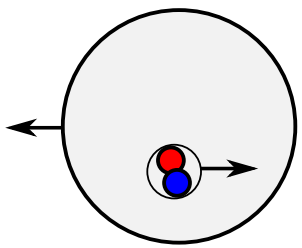


Generalized Contact Formalism exploits scale-separation.

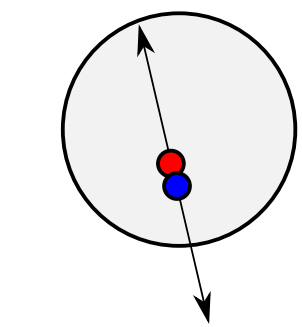
Three important properties:



Pair abundances



Pair CM motion



Pair relative motion

Generalized Contact Formalism exploits scale separation.

When two particles are in close proximity:

$$\Psi(r_{ij} \to 0) \longrightarrow \varphi^{\alpha}(r_{ij}) \times A(R_{ij}, \vec{r}_{k \neq i,j})$$

Generalized Contact Formalism exploits scale separation.

When two particles are in close proximity:

$$\Psi(r_{ij} \to 0) \longrightarrow \varphi^{\alpha}(r_{ij}) \times A(R_{ij}, \vec{r}_{k \neq i,j})$$

$$\rho_2(r_{ij}) \longrightarrow \sum_{\alpha} C_{\alpha} |\varphi^{\alpha}(r_{ij})|^2$$

Generalized Contact Formalism exploits scale separation.

When two particles are in close proximity:

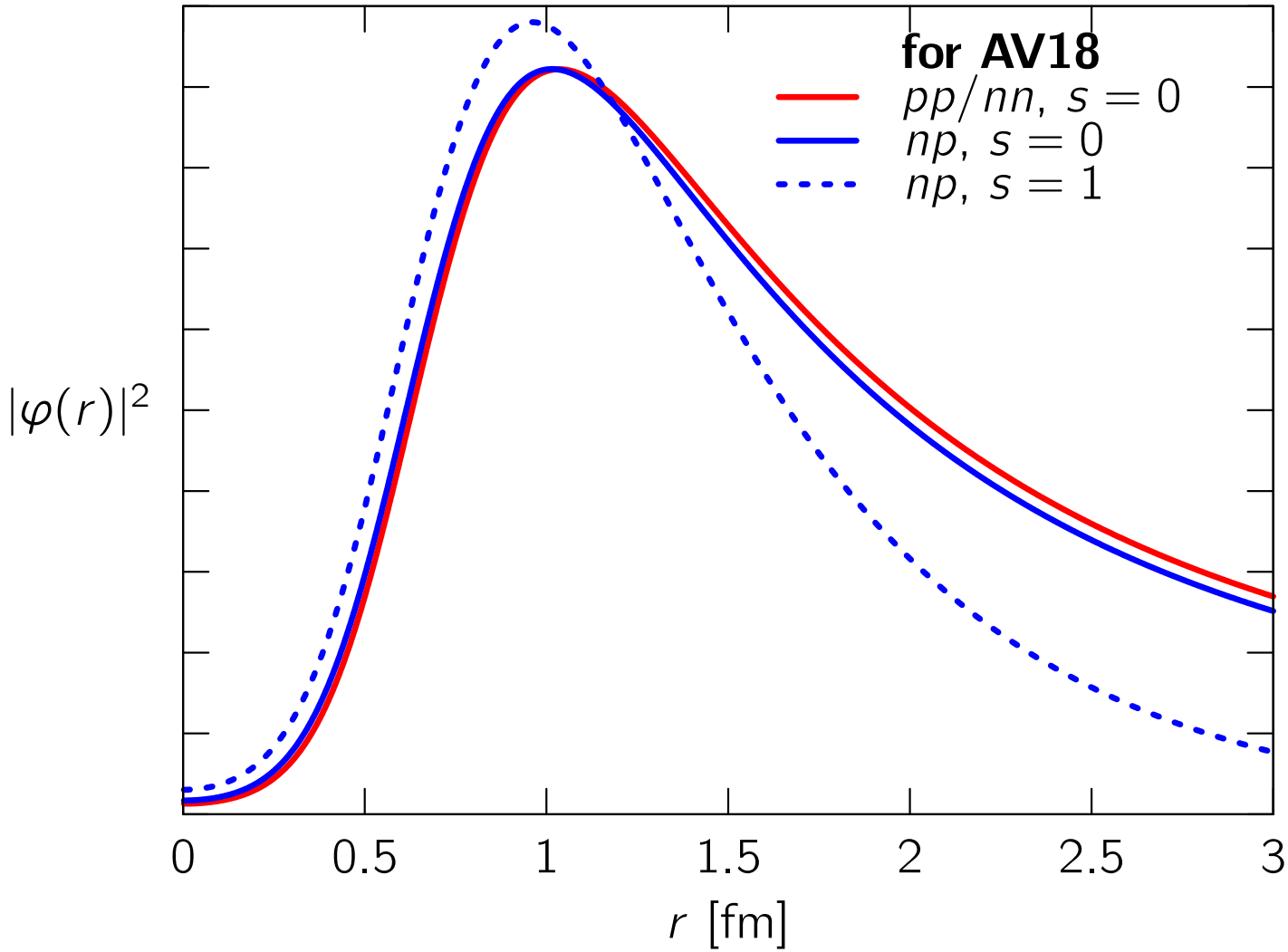
$$\Psi(r_{ij} \to 0) \longrightarrow \varphi^{\alpha}(r_{ij}) \times A(R_{ij}, \vec{r}_{k \neq i,j})$$

$$\rho_2(r_{ij}) \longrightarrow \sum_{\alpha} C_{\alpha} |\varphi^{\alpha}(r_{ij})|^2$$

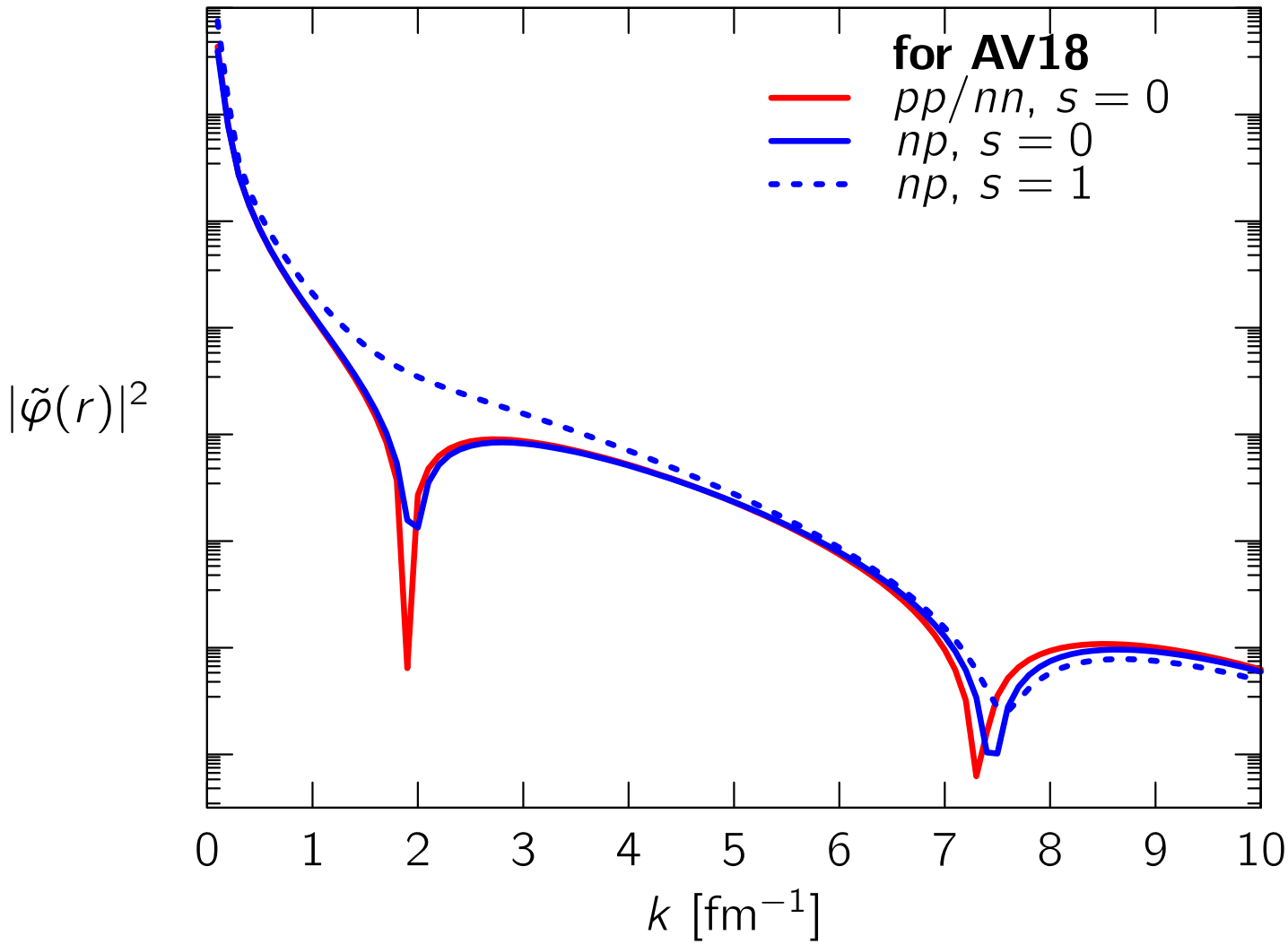
When two particles have high relative momentum:

$$\tilde{\rho}_2(k_{ij}) \longrightarrow \sum_{\alpha} C_{\alpha} |\tilde{\varphi}^{\alpha}(k_{ij})|^2$$

Universal φ^α functions are Schrödinger solutions for a given NN potential.



Universal φ^α functions are Schrödinger solutions for a given NN potential.



Generalized Contact Formalism exploits scale separation.

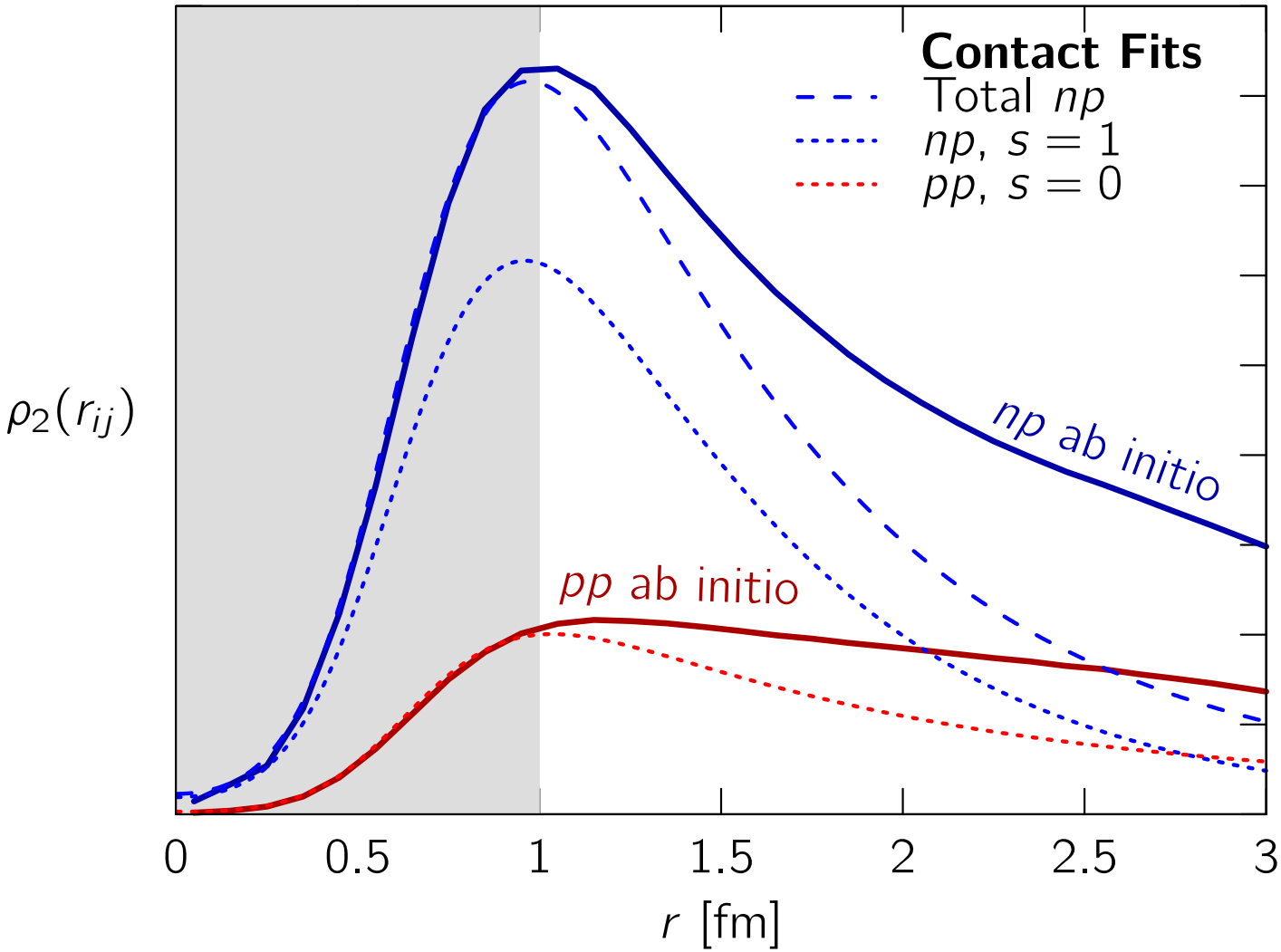
When two particles are in close proximity:

$$\rho_2(r_{ij}) \longrightarrow \sum_\alpha C_\alpha |\varphi^\alpha(r_{ij})|^2 \quad \checkmark$$

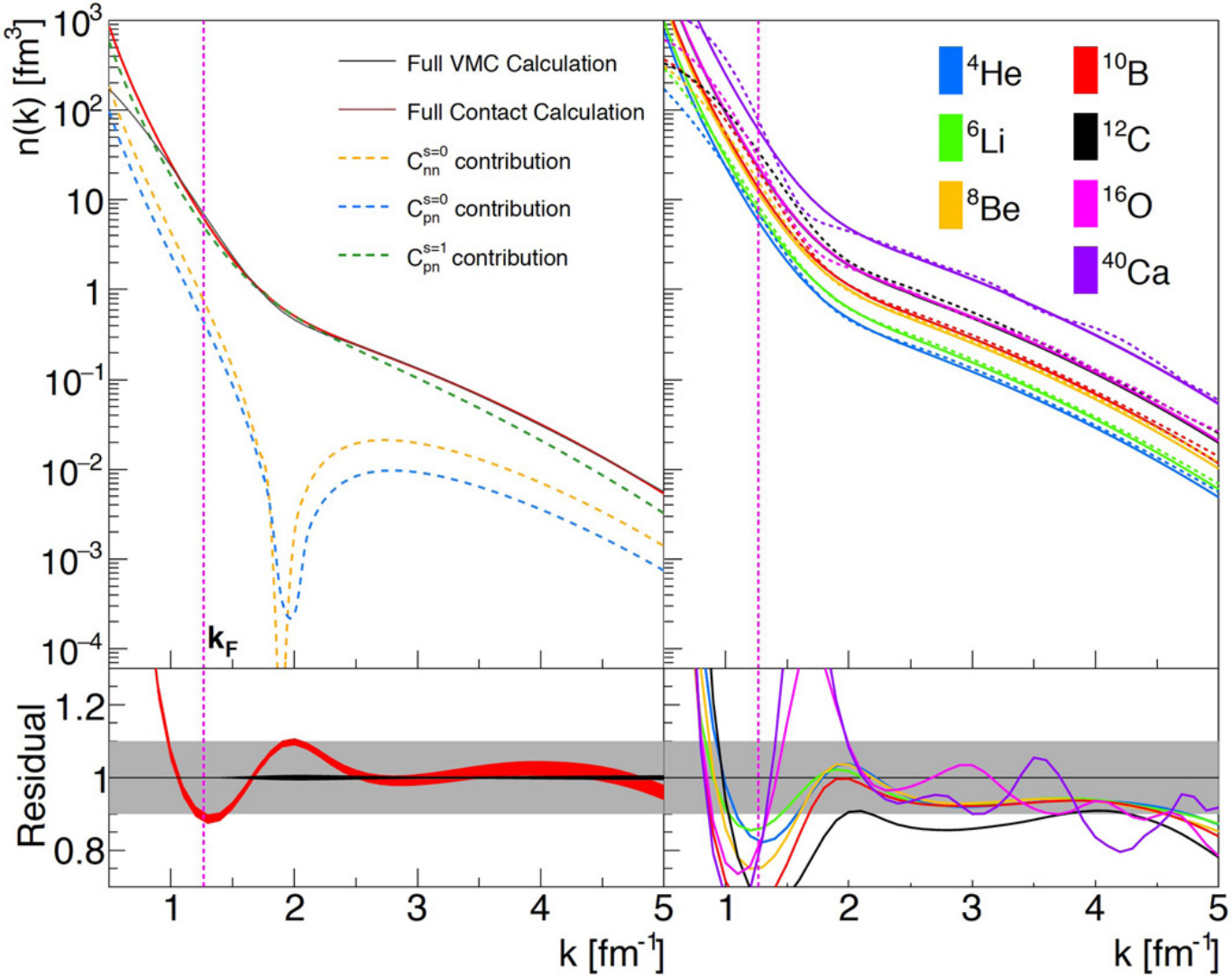
When two particles have high relative momentum:

$$\tilde{\rho}_2(k_{ij}) \longrightarrow \sum_\alpha C_\alpha |\tilde{\varphi}^\alpha(k_{ij})|^2 \quad \checkmark$$

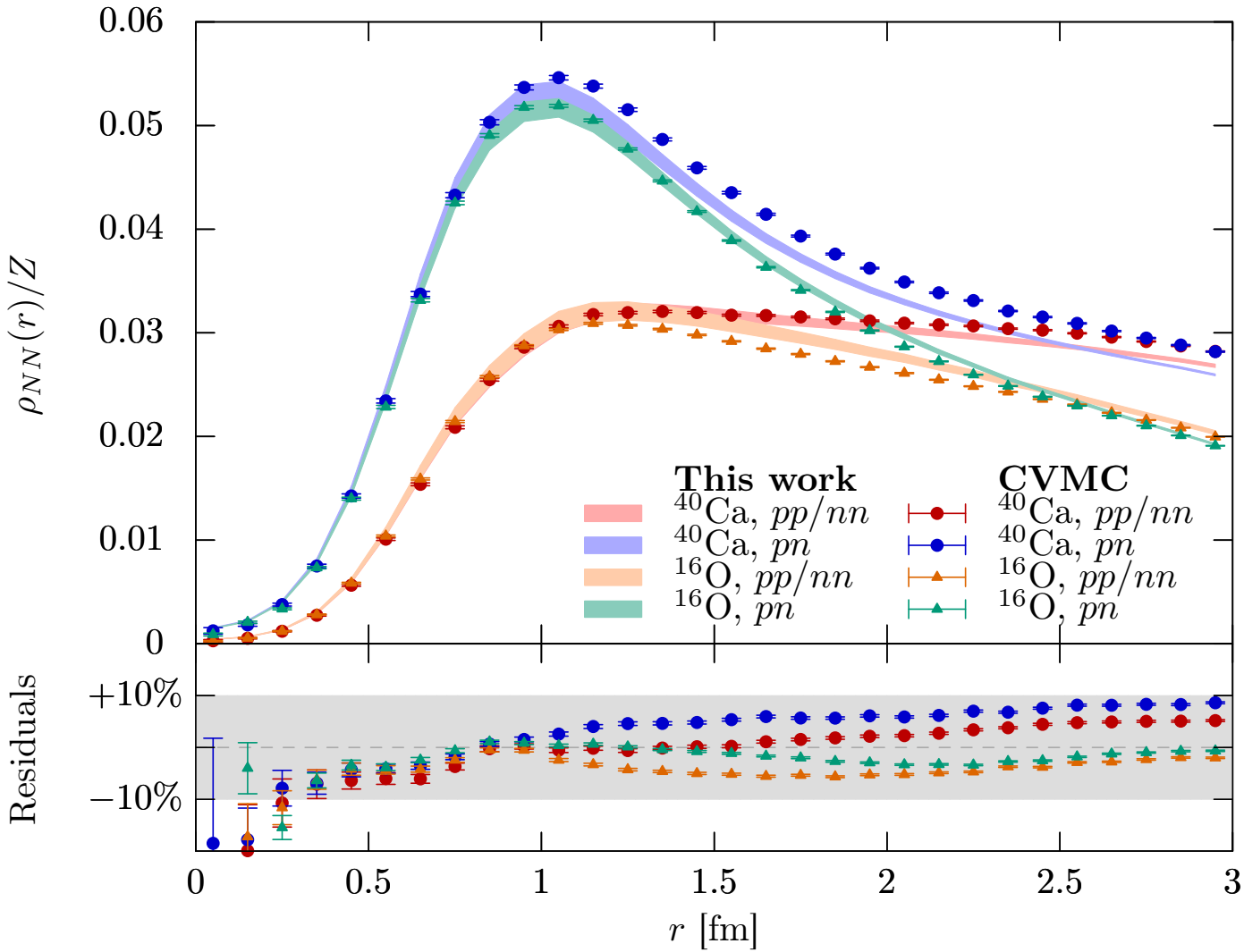
Contacts can be determined from fits to ab initio calculations.



These fits faithfully reproduce high-momentum tails.



. . . and short-distance two-body densities.



R. Cruz-Torres, **A. Schmidt** et al., PLB 785 p.304 (2018)

Different *NN* interactions can lead to very different two-body densities.

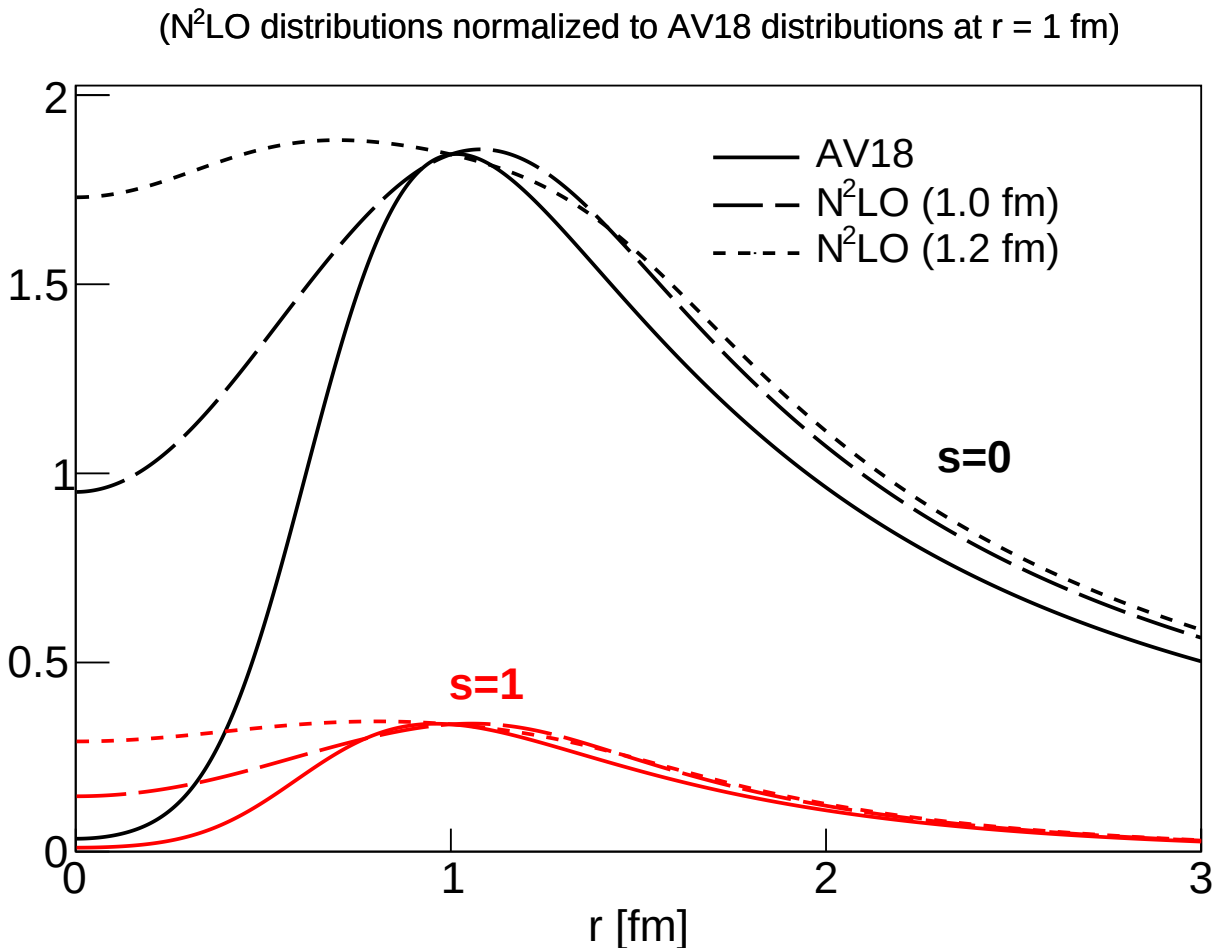


Figure courtesy of Reynier Cruz-Torres

Different *NN* interactions can lead to very different two-body densities.

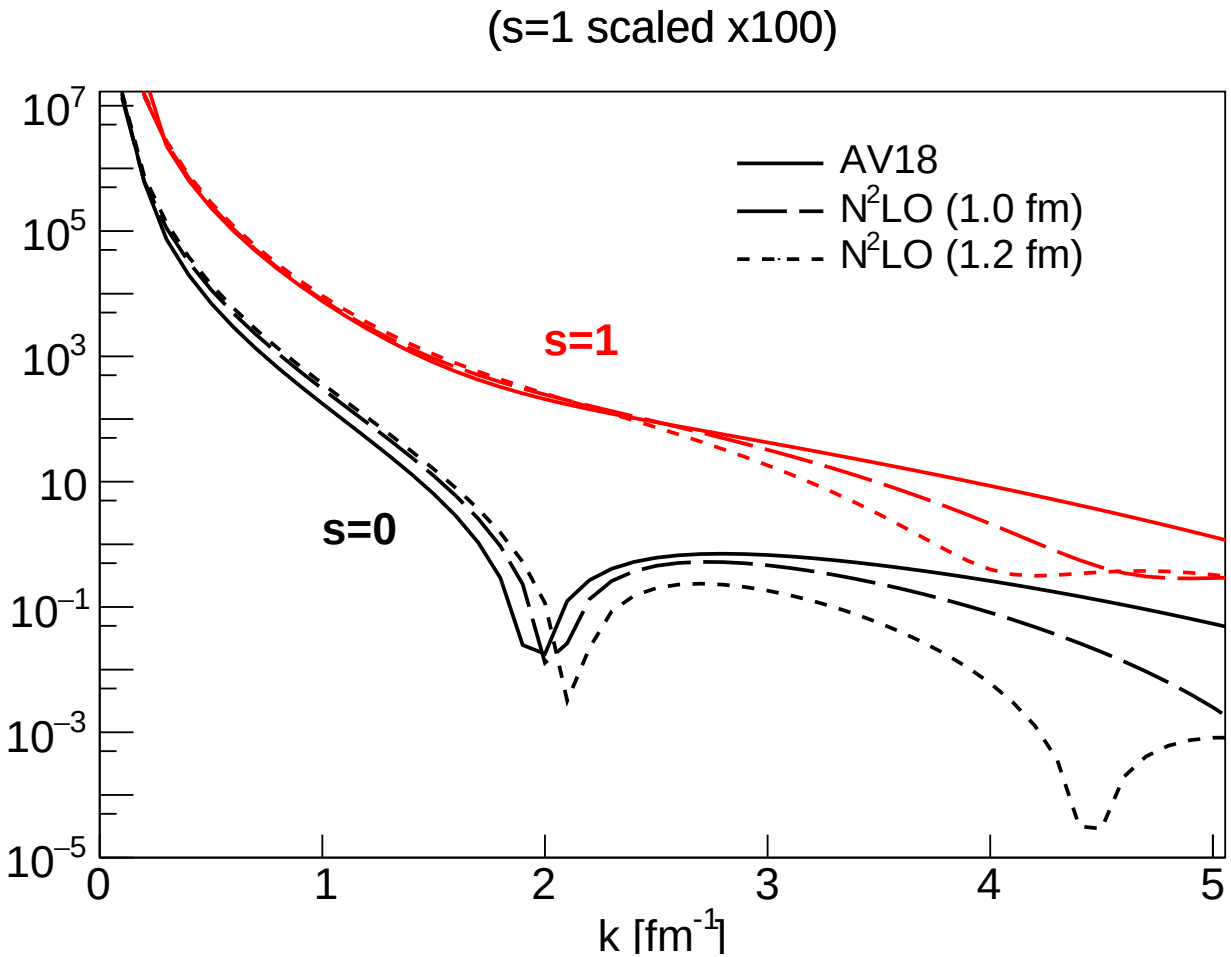
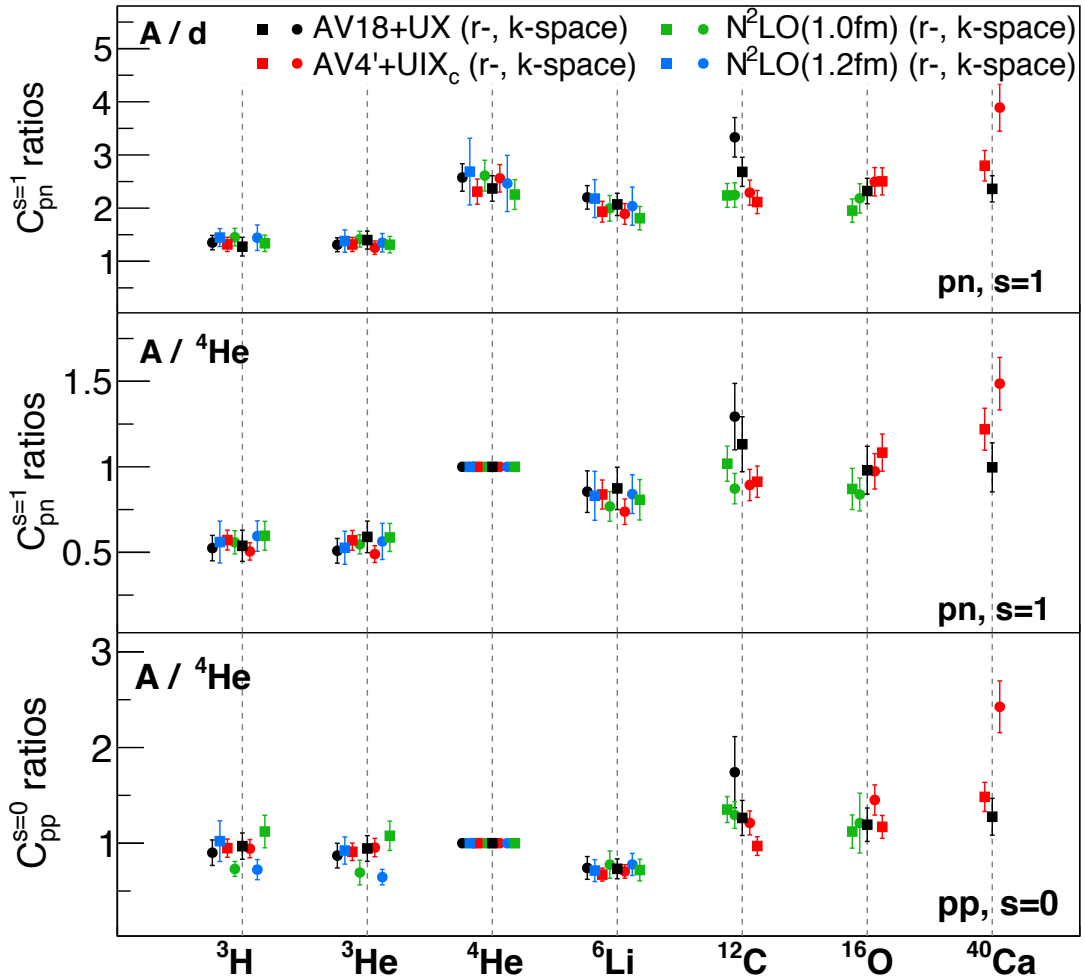


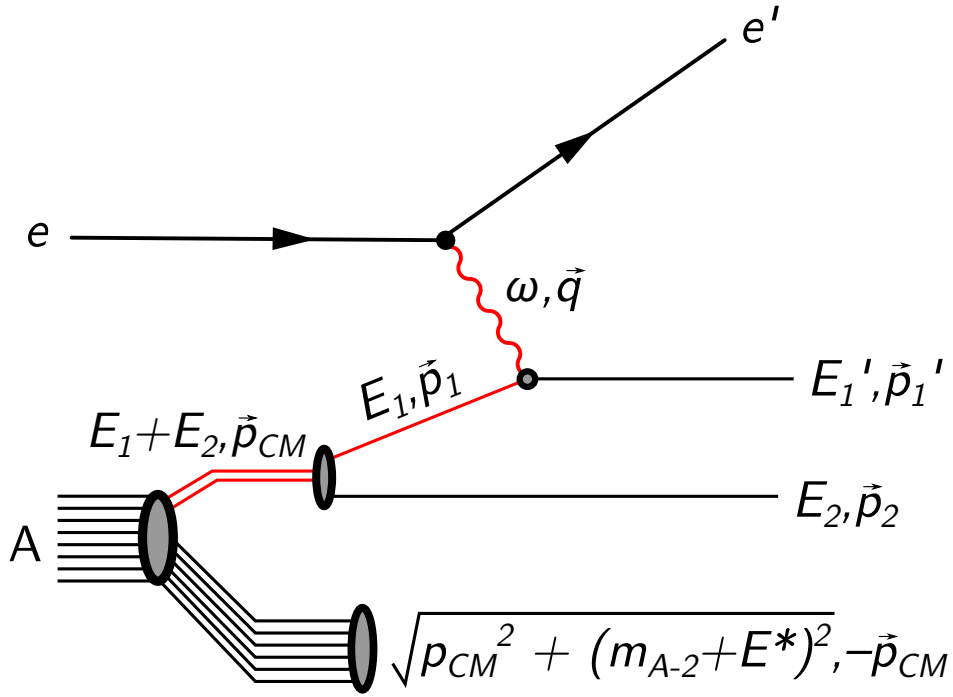
Figure courtesy of Reynier Cruz-Torres

Relative SRC pair abundances are largely scale and scheme independent.

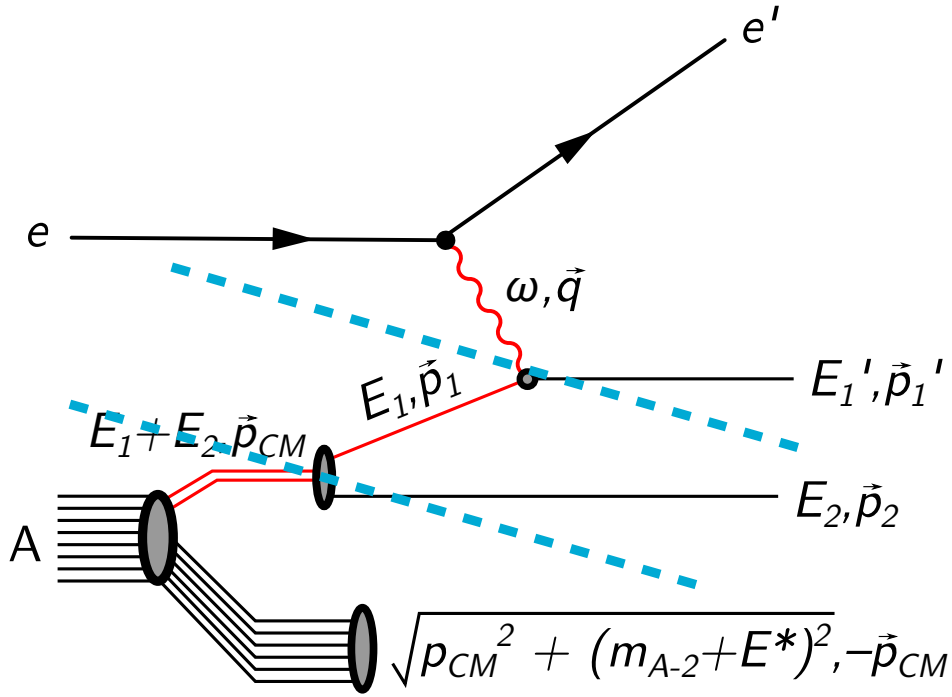


R. Cruz-Torres, D. Lonardoni, R. Weiss et al., arXiv:1907.03658 (2019)

We can use GCF to calculate this plane-wave reaction.



We can use GCF to calculate this plane-wave reaction.



$$p_{CM} \ll p_{rel} \ll q$$

GCF allows us to calculate a spectral function or a decay function.

R. Weiss et al., PLB 790 p 241 (2019)

Two-nucleon knockout:

$$D(E_1, p_1, p_2) = \sum_{\alpha} C_\alpha |\varphi^\alpha(p_{rel})|^2 n(p_{CM}) \delta(E_i - E_f)$$

GCF allows us to calculate a spectral function or a decay function.

R. Weiss et al., PLB 790 p 241 (2019)

Two-nucleon knockout:

$$D(E_1, p_1, p_2) = \sum_{\alpha} C_\alpha |\varphi^\alpha(p_{rel})|^2 n(p_{CM}) \delta(E_i - E_f)$$

Single-nucleon detection:

$$S(E_1, p_1) = \sum_{\alpha} C_\alpha \int \frac{d^3\vec{p}_2}{(2\pi)^3} |\varphi^\alpha(p_{rel})|^2 n(p_{CM}) \delta(E_i - E_f)$$

GCF allows us to calculate a spectral function or a decay function.

R. Weiss et al., PLB 790 p 241 (2019)

Two-nucleon knockout:

$$D(E_1, p_1, p_2) = \sum_{\alpha} C_\alpha |\varphi^\alpha(p_{rel})|^2 n(p_{CM}) \delta(E_i - E_f)$$

Single-nucleon detection:

$$S(E_1, p_1) = \sum_{\alpha} C_\alpha \int \frac{d^3\vec{p}_2}{(2\pi)^3} |\varphi^\alpha(p_{rel})|^2 n(p_{CM}) \delta(E_i - E_f)$$

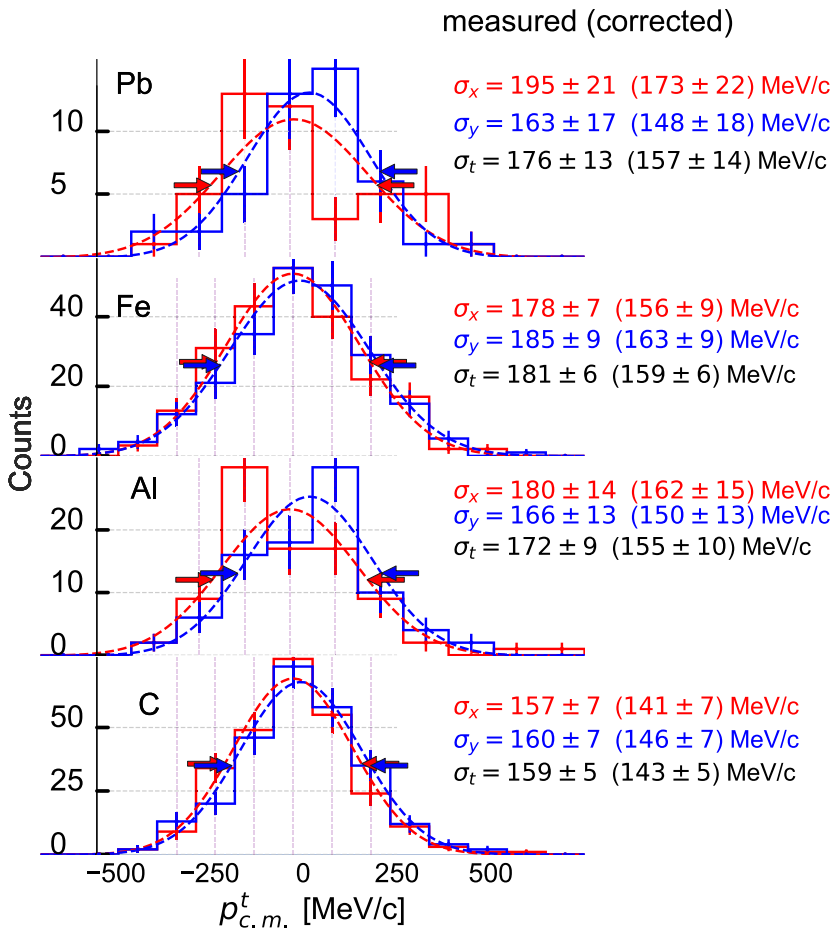
$$d\sigma \propto \sigma_{eN} \cdot S(E_1, p_1)$$

Ingredients to the GCF cross section

- Relative momentum $\longrightarrow$ *NN* interaction
- SRC pair abundances $\longrightarrow$ estimate from ab initio calcs.
- Pair center-of-mass motion

We measured the CM momentum distribution and confirmed its width is small.

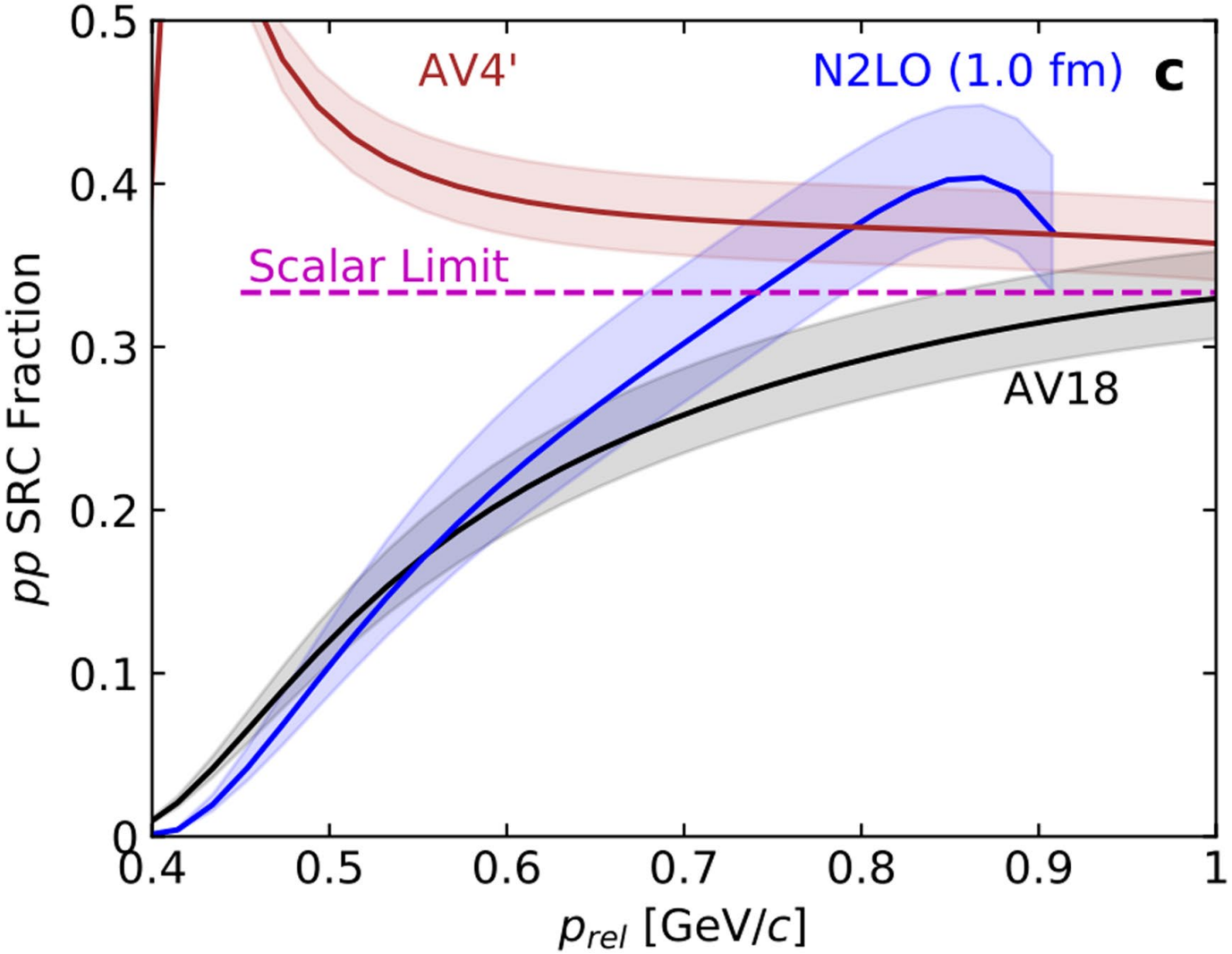
E.O. Cohen et al., PRL 121 092501 (2018)



Ingredients to the GCF cross section

- Relative momentum $\longrightarrow$ NN interaction
- SRC pair abundances $\longrightarrow$ estimate from ab initio calcs.
- Pair center-of-mass motion $\longrightarrow$ measured!

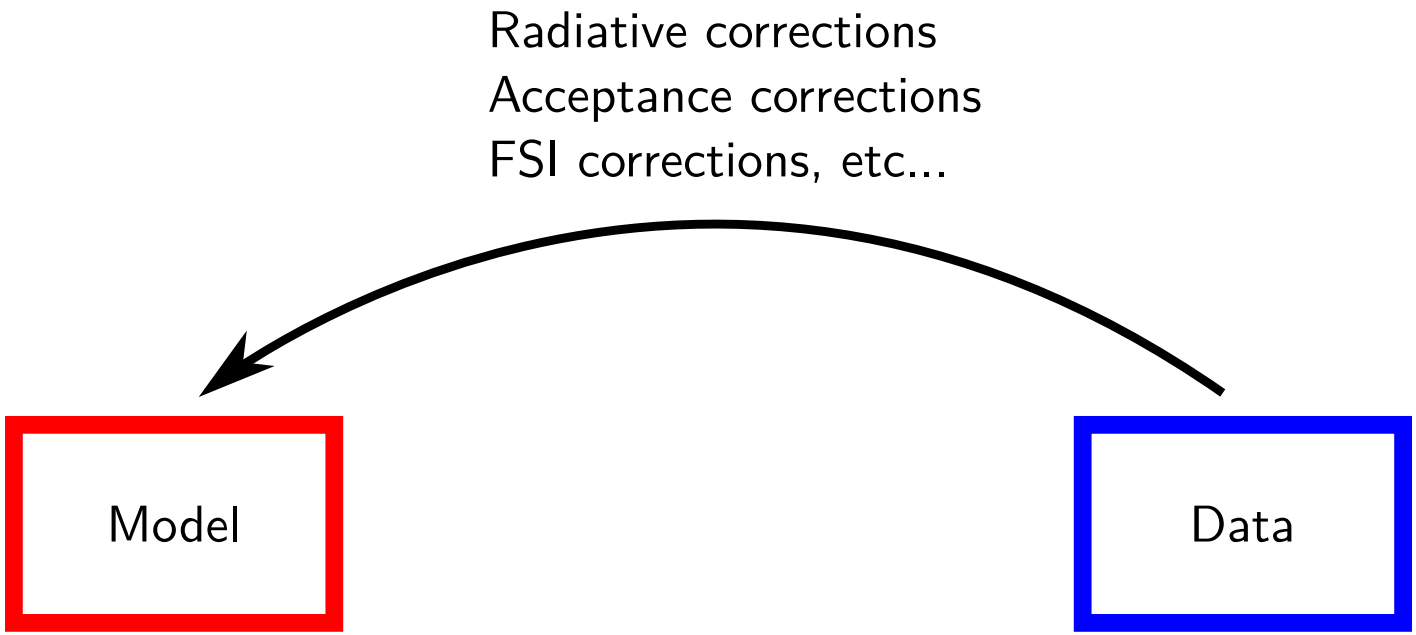
Under the hood, models have scalar core.



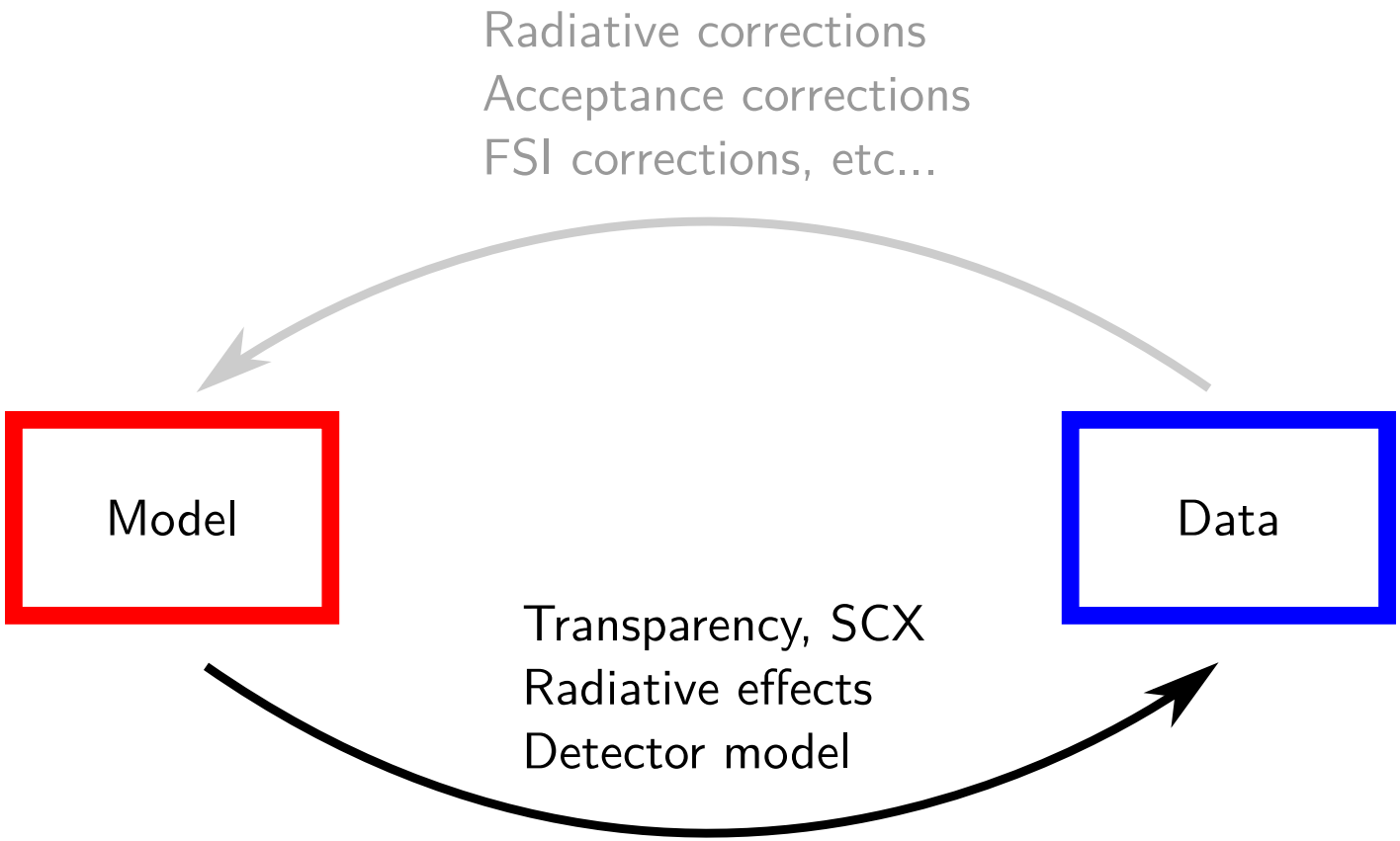
Probing the core of the strong interaction:

- Isolated SRC pair break-up events from Jefferson Lab data
- Developed new theory approach: Generalized Contact Formalism
  - *NN*-potential models $\longrightarrow$ scattering cross sections
- **Comparisons revealed:**
  - SRC-pair break-up paradigm describes the data well.
  - Non-relativistic *NN* models work *far beyond* where they were tuned.
  - Clear signature of scalar core

Connecting the model to data

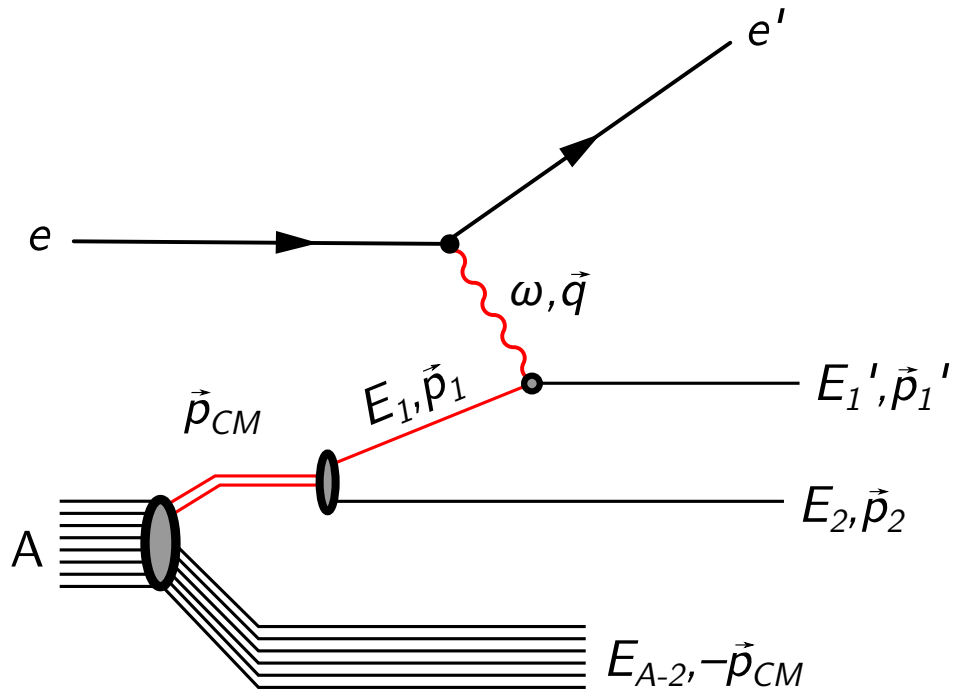


Connecting the model to data



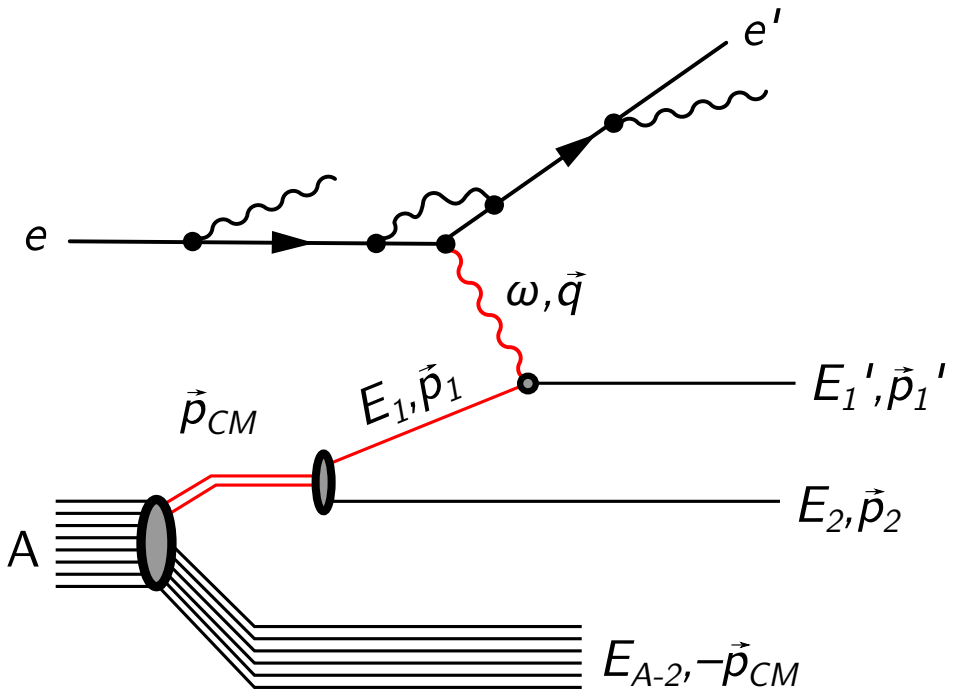
We forward propagate the model to the data.

1. Generate events according to model



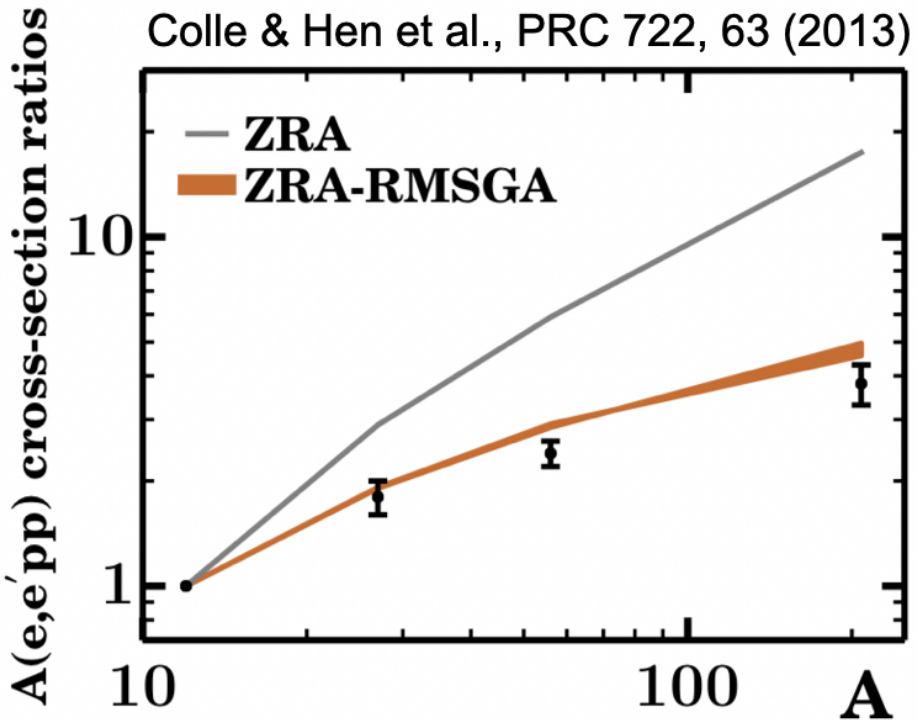
We forward propagate the model to the data.

1. Generate events according to model
2. Radiative effects



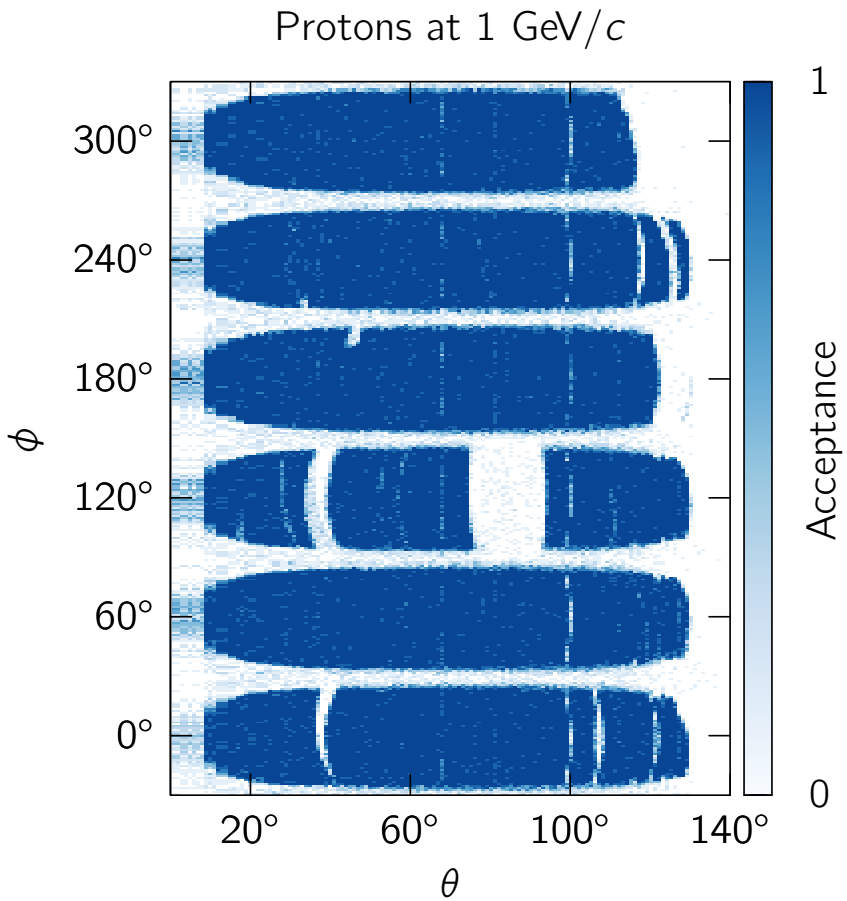
We forward propagate the model to the data.

1. Generate events according to model
2. Radiative effects
3. Transparency/SCX using Glauber



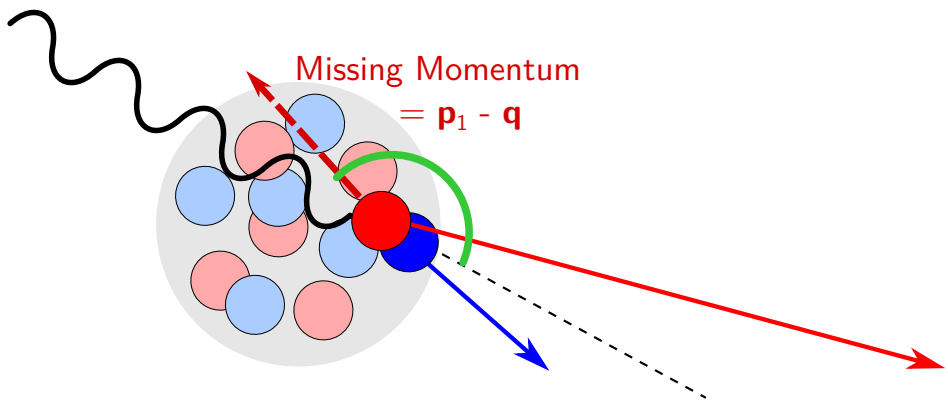
We forward propagate the model to the data.

1. Generate events according to model
2. Radiative effects
3. Transparency/SCX using Glauber
4. Detect



We forward propagate the model to the data.

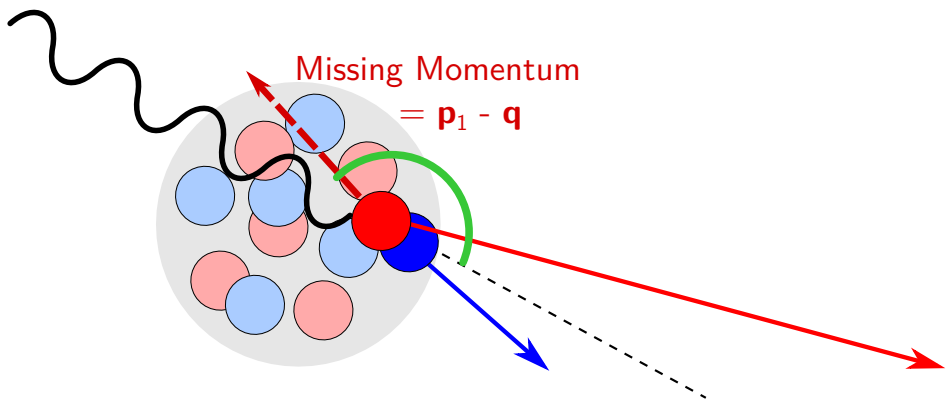
1. Generate events according to model
2. Radiative effects
3. Transparency/SCX using Glauber
4. Detect
5. Same event selection as data



We forward propagate the model to the data.

1. Generate events according to model
2. Radiative effects
3. Transparency/SCX using Glauber
4. Detect
5. Same event selection as data

6. Vary model parameters



Comparison to ^{12}C$(e, e'p)$ and ^{12}C$(e, e'pp)$

- Carbon data only
  - Contacts determined from fits to ab initio VMC

Comparison to ^{12}C$(e, e'p)$ and ^{12}C$(e, e'pp)$

- Carbon data only
  - Contacts determined from fits to ab initio VMC
- *NN* interactions
  - AV18
  - AV4′ (no tensor force)
  - Local χPT N2LO (1 fm, 1.2 fm cut-offs)

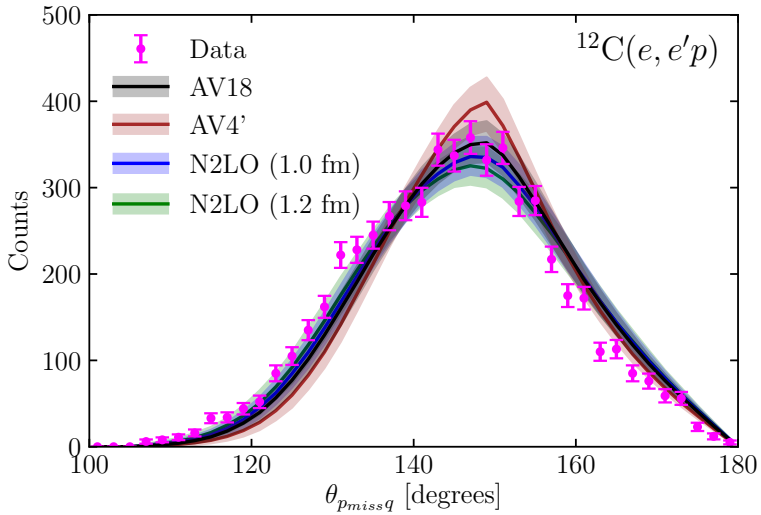
Comparison to $^{12}C(e, e'p)$ and $^{12}C(e, e'pp)$

- Carbon data only
  - Contacts determined from fits to ab initio VMC
- *NN* interactions
  - AV18
  - AV4′ (no tensor force)
  - Local χPT N2LO (1 fm, 1.2 fm cut-offs)
- Model uncertainty from:

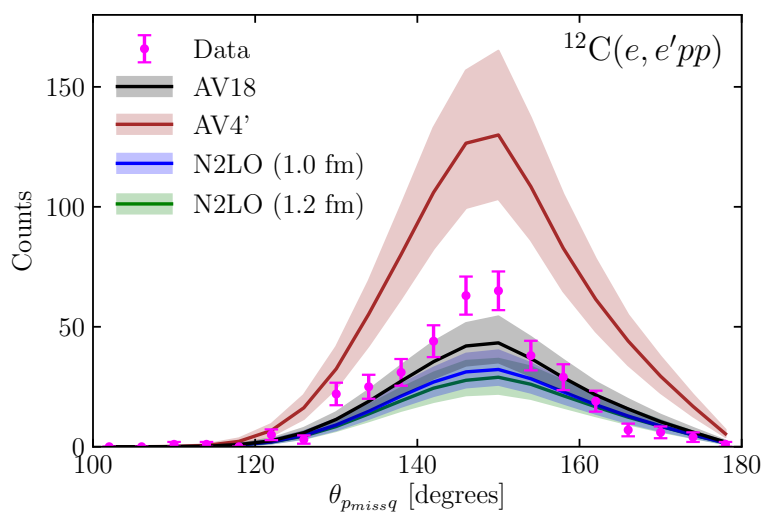
- Contacts
- σ_{CM}
- SCX prob.
- Transparency
- $A-2$ excitation E^*
- $p_{\text{rel.}}$ cut-off
- e^- res.
- p res.

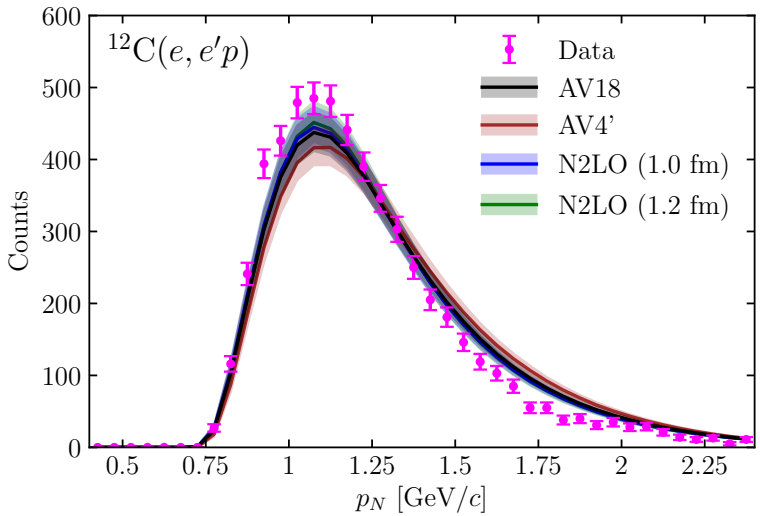
The model accurately predicts kinematics.

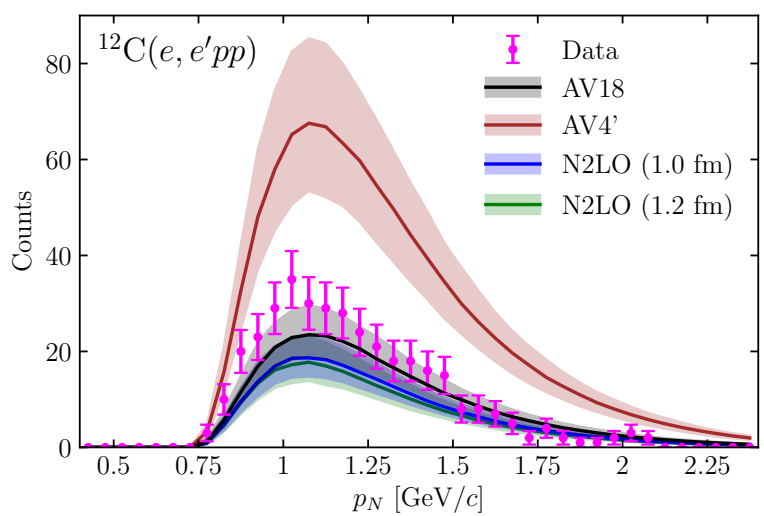
C$(e, e'p)$



C$(e, e'pp)$

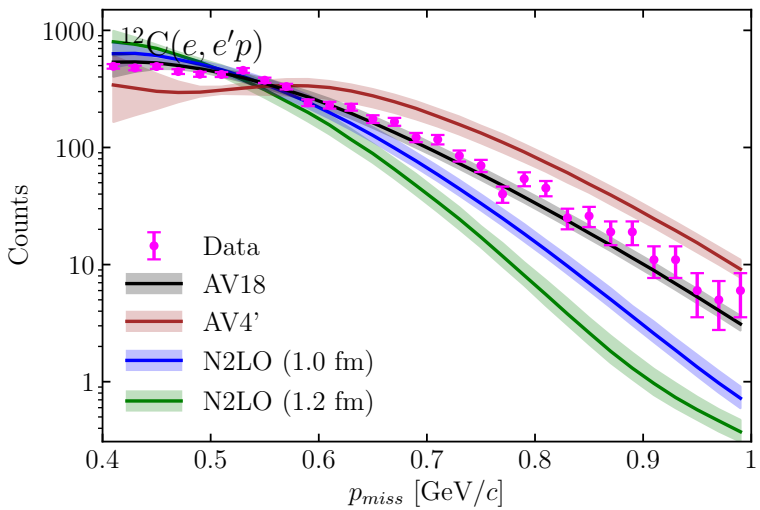




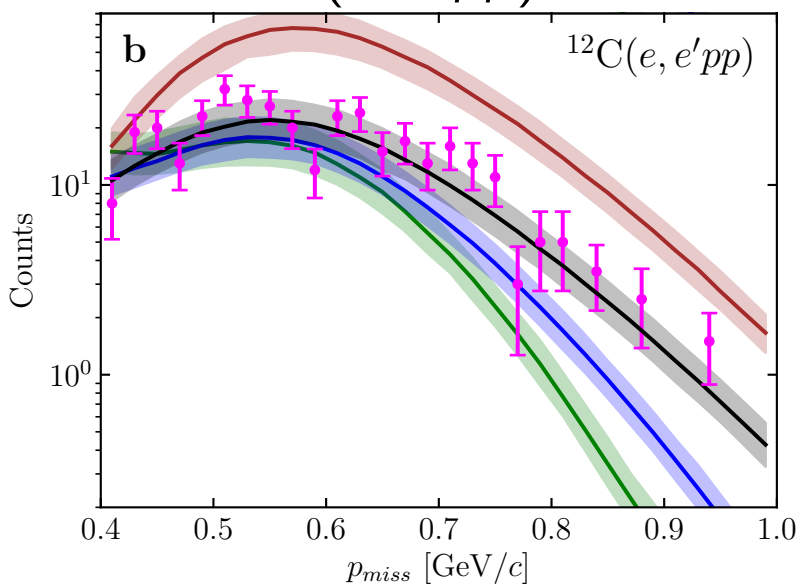


Missing momentum distributions show sensitivity to the *NN* interaction.

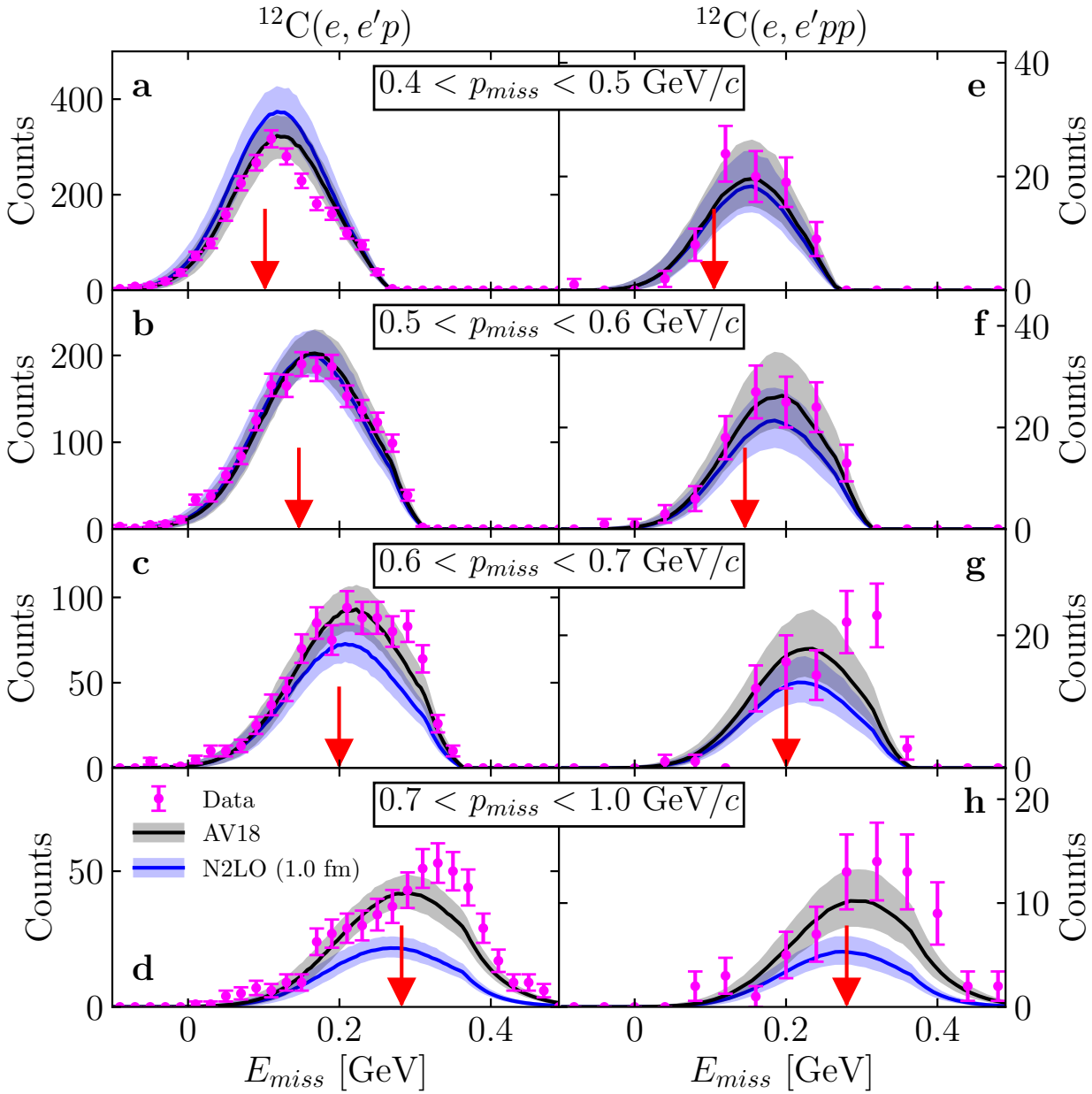
C($e, e'p$)



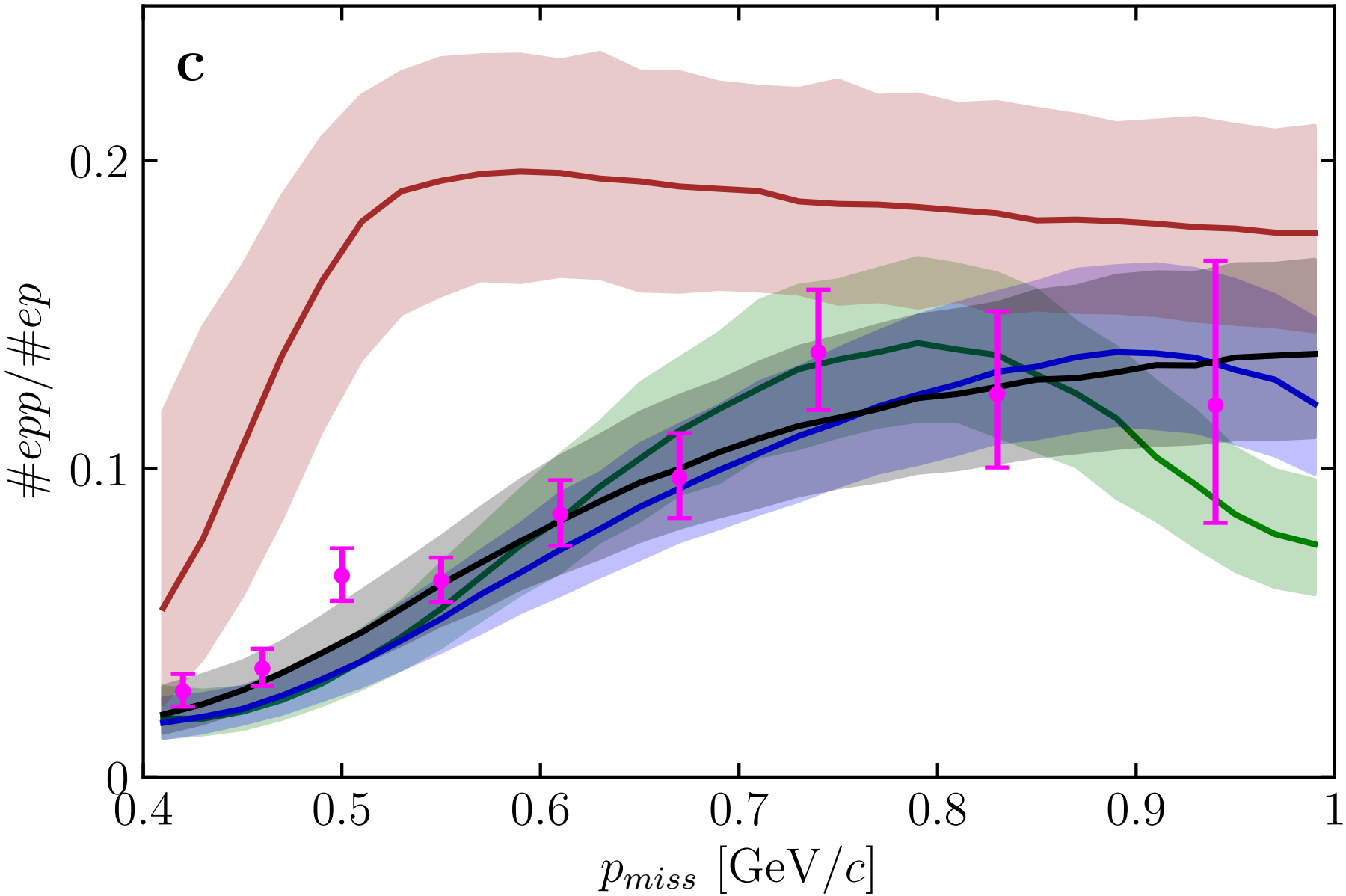
C($e, e'pp$)



Missing-momentum and missing-energy

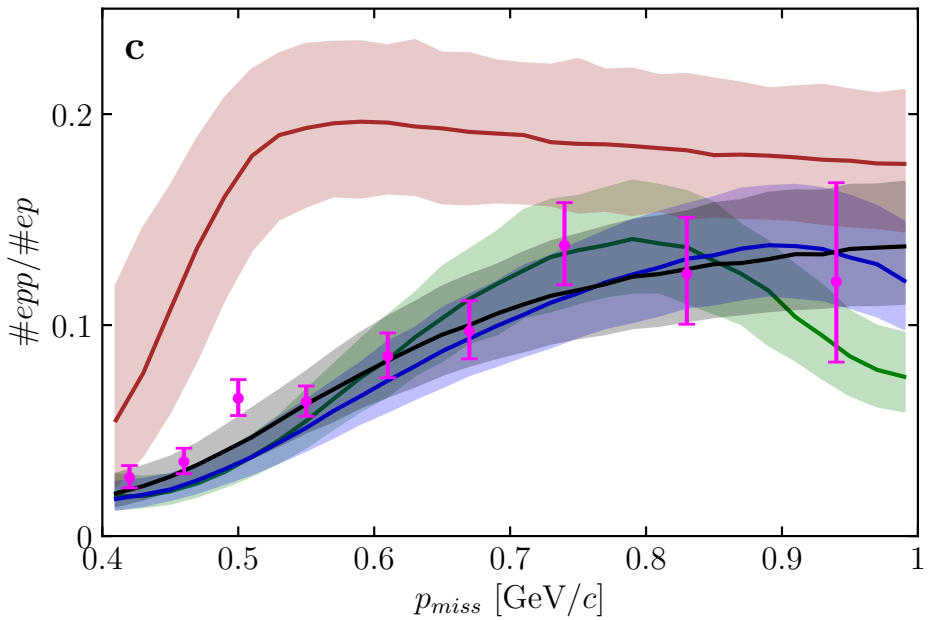


$(e, e'pp)/(e, e'p)$ ratio



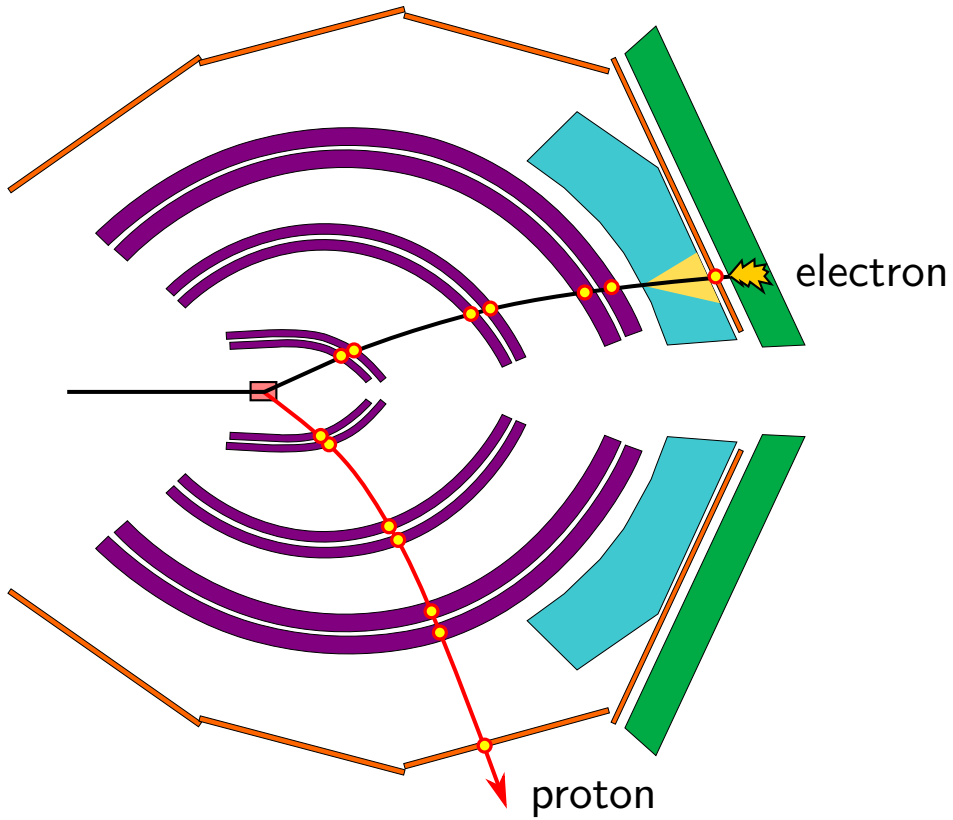
A very simple theory seems to work well.

- Point-like nucleons
- On-shell *NN* potentials
- Factorized cross section
- Evidence of a tensor-to-scalar transition



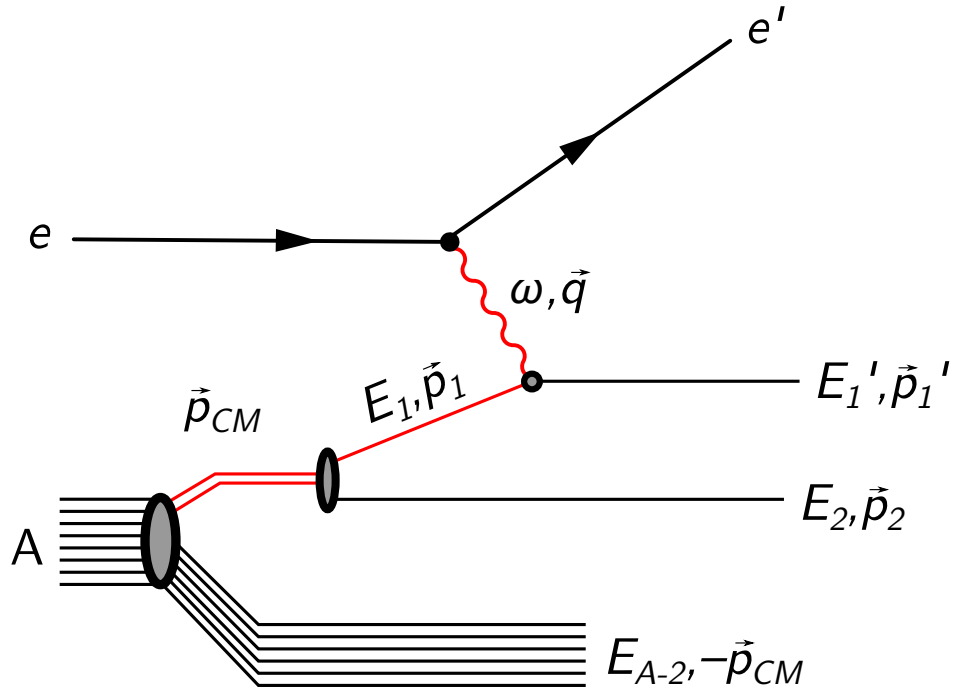
To recap:

- Isolated SRC break-up events in CLAS data



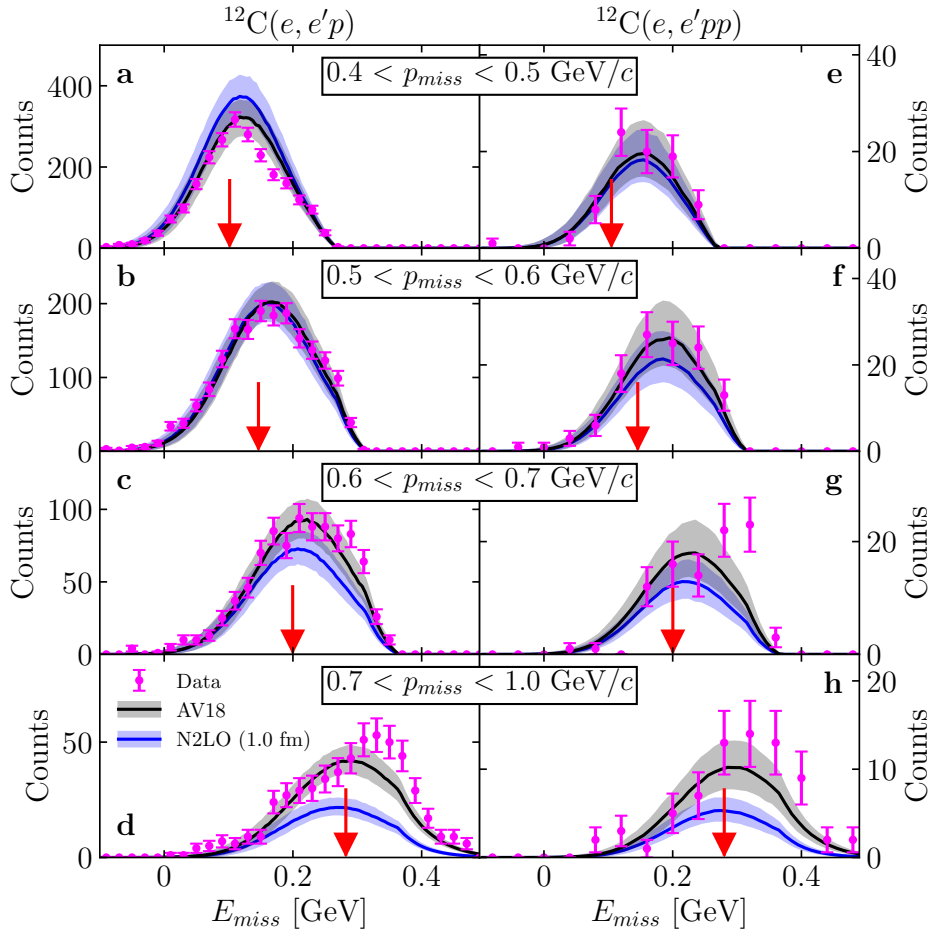
To recap:

- Isolated SRC break-up events in CLAS data
- Generalized Contact Formalism *NN*-model $\leftrightarrow$ cross-sections



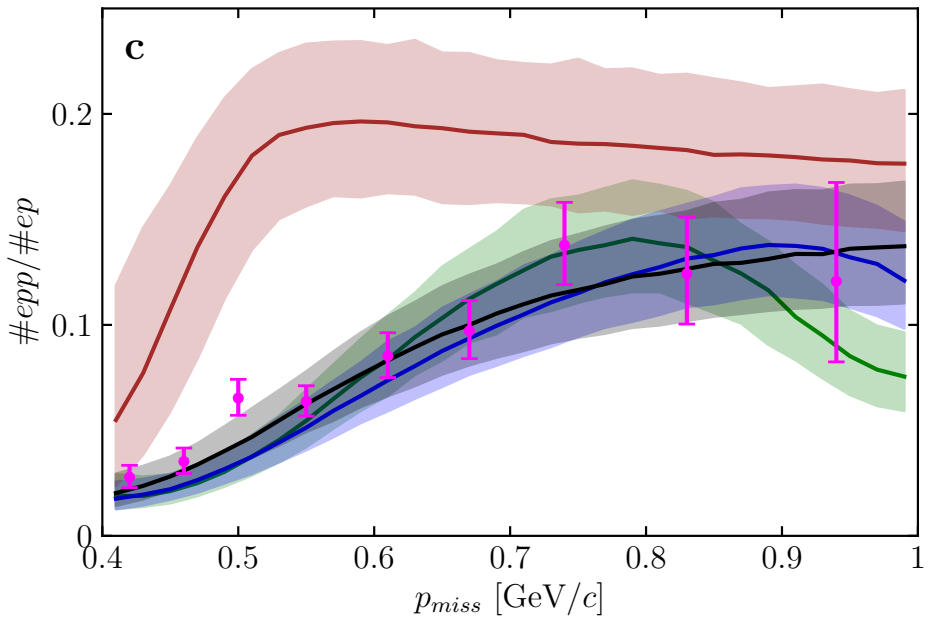
To recap:

- Isolated SRC break-up events in CLAS data
- Generalized Contact Formalism *NN*-model $\leftrightarrow$ cross-sections
- GCF matches data superbly.

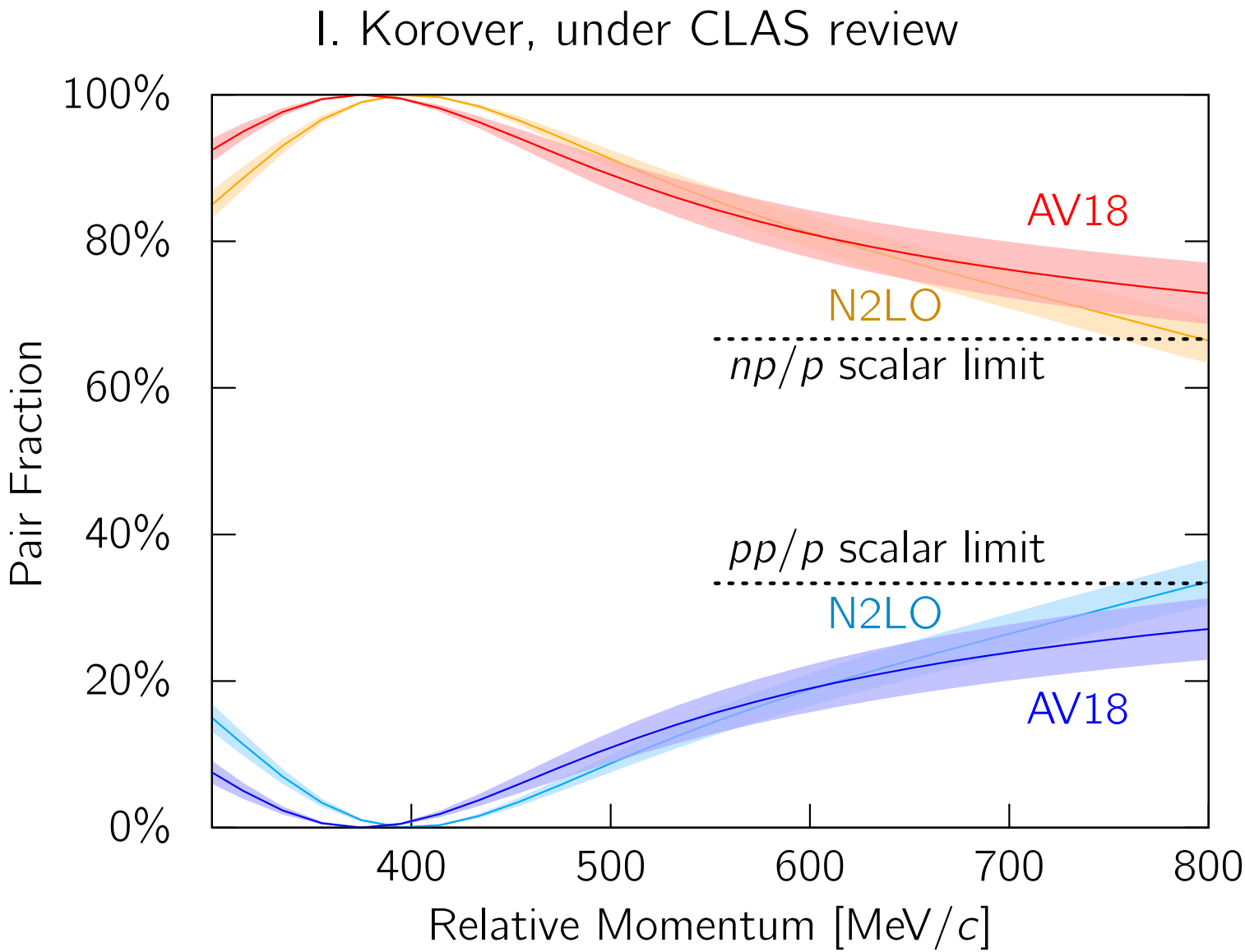


To recap:

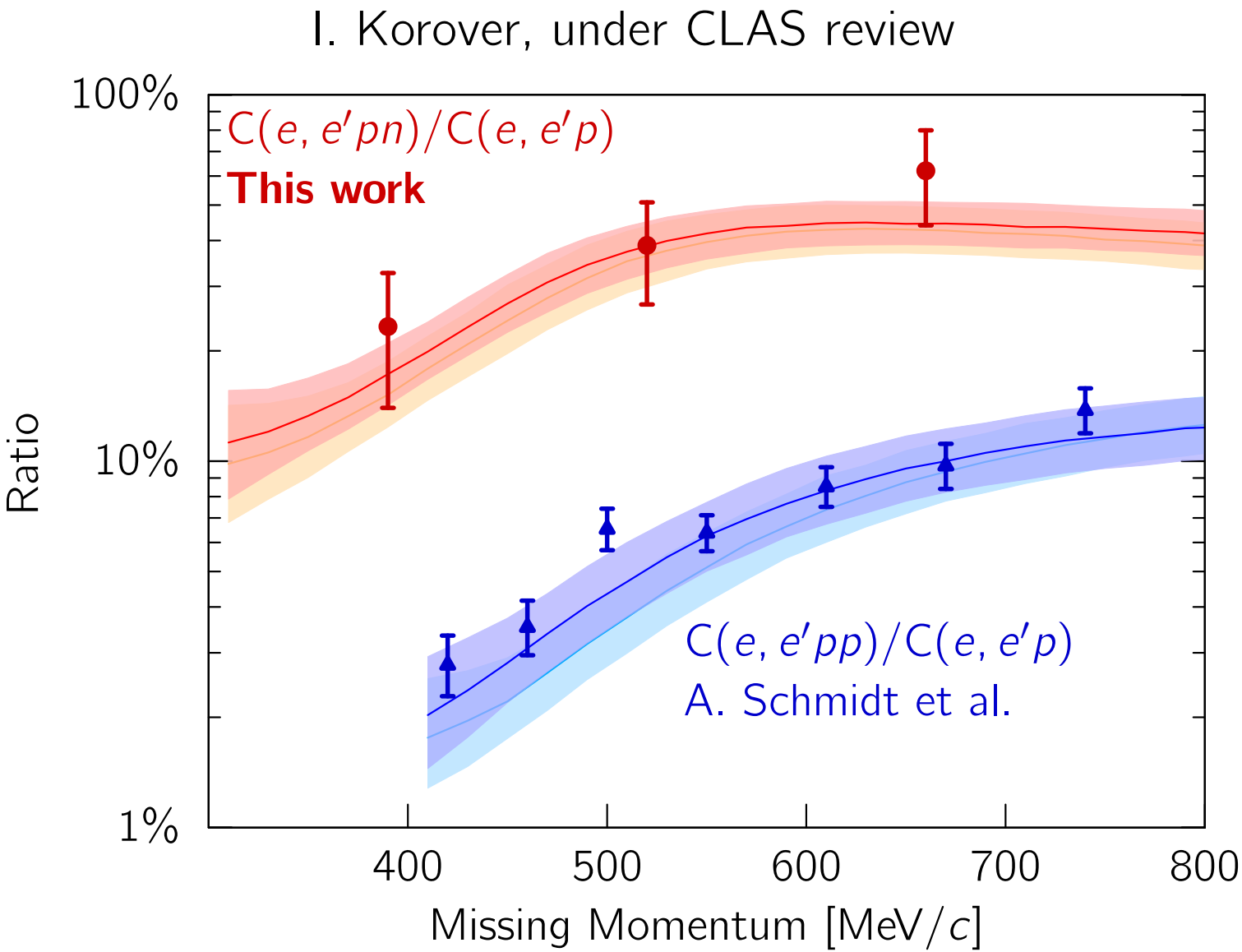
- Isolated SRC break-up events in CLAS data
- Generalized Contact Formalism *NN*-model $\leftrightarrow$ cross-sections
- GCF matches data superbly.
- Tensor-to-scalar transition



We can close the loop with $(e, e'pn)$

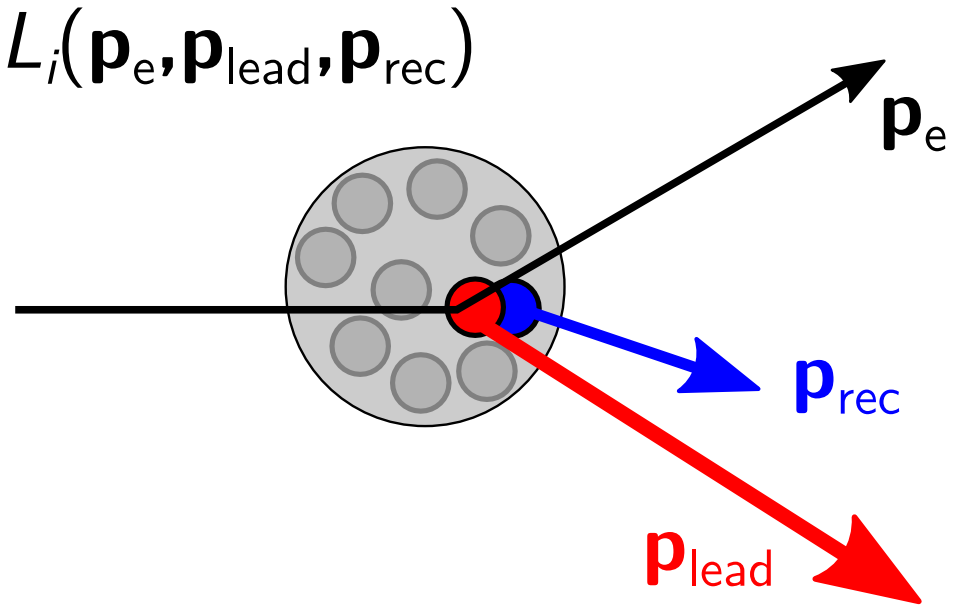


We can close the loop with $(e, e'pn)$



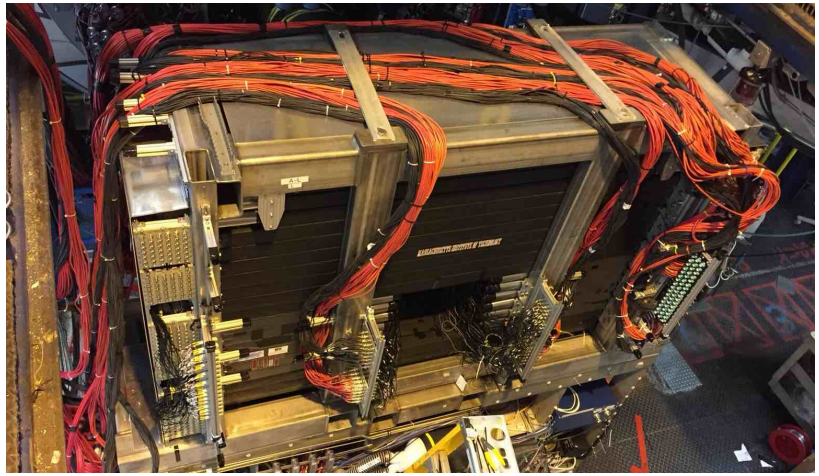
We can do inference on model parameters.

J. Pybus, T. Kutz

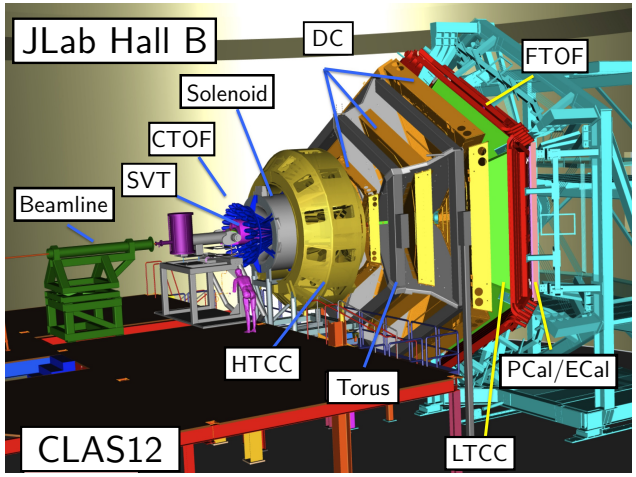


Three big new measurements

BAND: Testing the SRC-EMC Connection



CLAS-12 Run Group M



SRCs at GlueX