Contact extraction from fitting

CLAS Nuclear Physics Working Group Meeting

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This work begins with:

"Ratio of $A(e,e'pp)$ to $A(e,e'p)$ events in SRC kinematics"

- Use short-range correlated nucleons to constrain the NN interaction
- Analysis note approved on May 28
- Paper draft under review by ad hoc committee
  - Preliminary title: "Probing the core of the strong nuclear interaction"

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In my talk today:

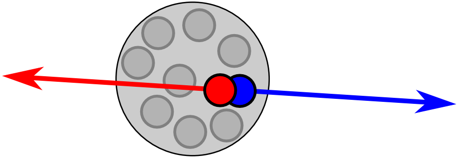
- Review this work, Contact Model
- How can we extend it to infer model parameters
  - $\longrightarrow$ Looking for your feedback

Use short-range correlated nucleons to constrain the *NN* interaction

- What are short-range correlated nucleons?
- What do we want to learn about the *NN* interaction?
  - Repulsive core
- How do we connect the two?
  - Generalized contact formalism (GCF)

Short-range correlations are universal in nuclei.

- Pair with close-proximity high relative momentum



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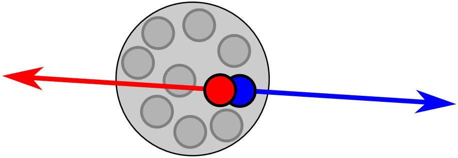

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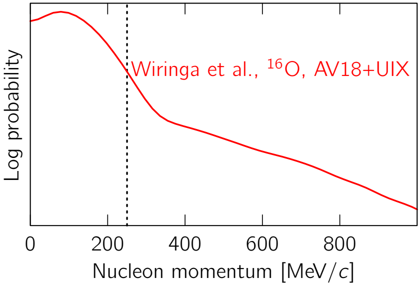
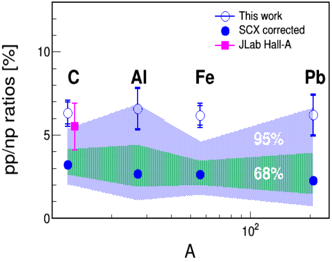
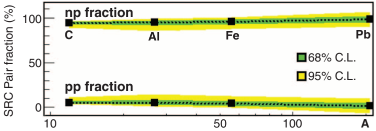
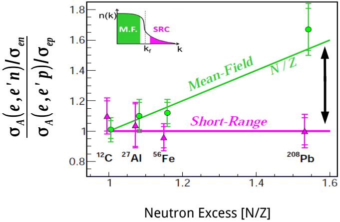
- Lead to high-momentum tails

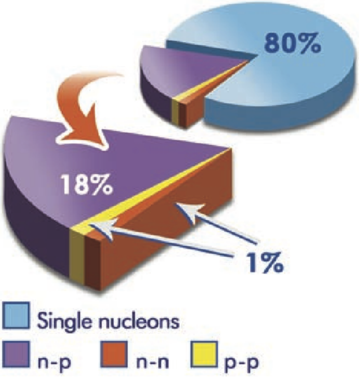


SRC pairs are predominantly neutron-proton.

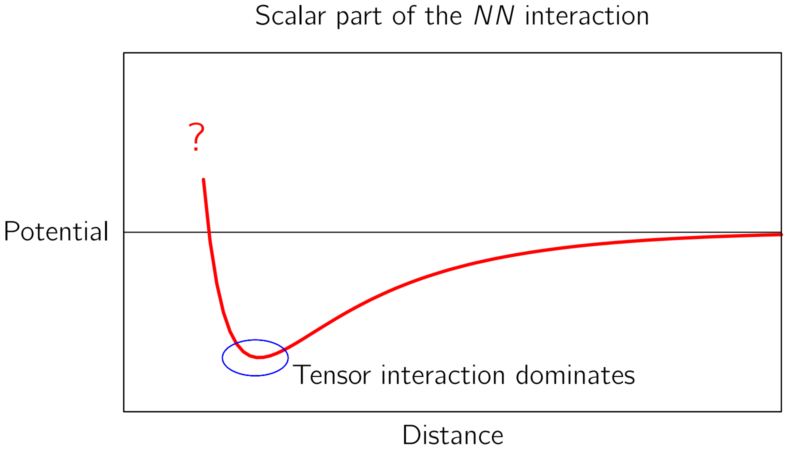




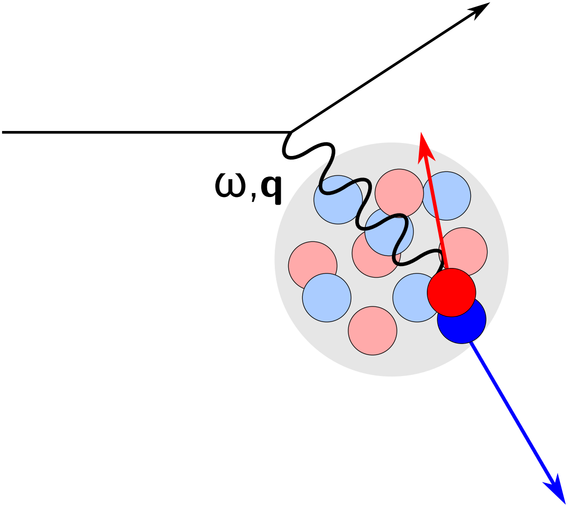




np-dominance arises from the tensor force.



We can study SRCs by breaking them.



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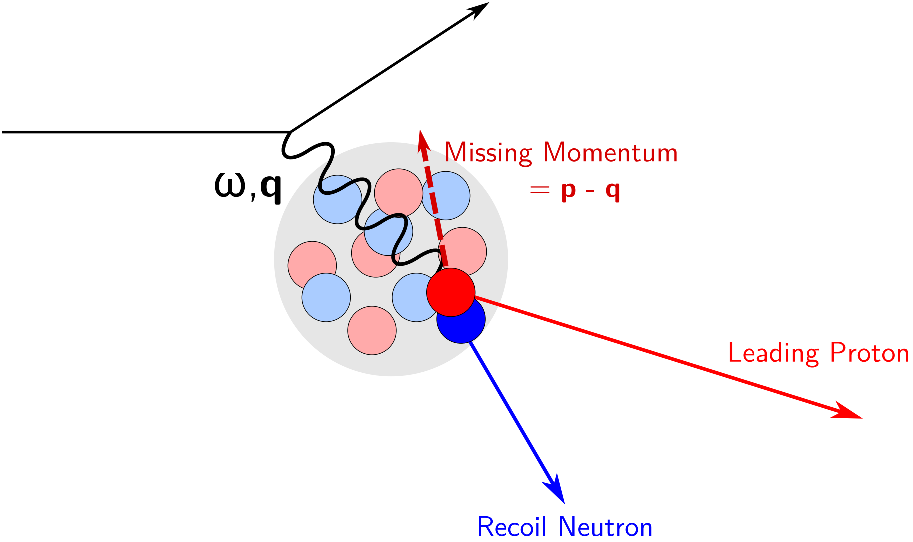

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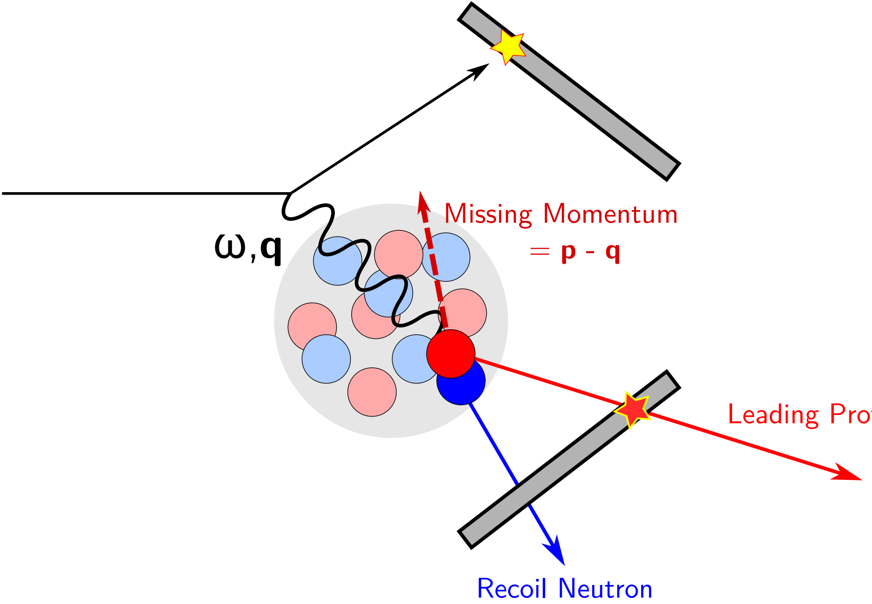

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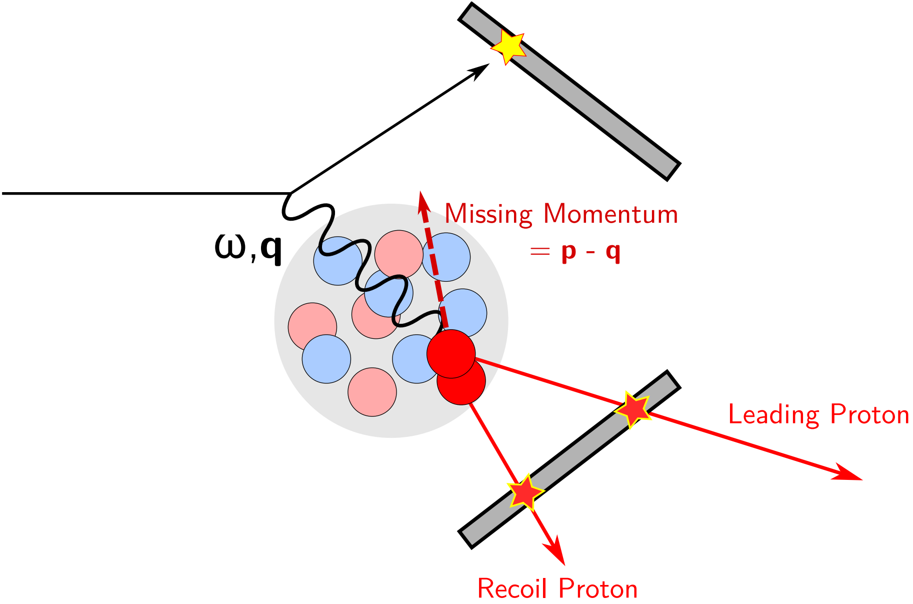

Several previous EG2 analyses have identified SRC pair break-up events.

- Or Hen (2012):
  $(e, e'pp)/(e, e'p)$ confirms *np*-dominance in heavy nuclei
- Meytal Duer (2017):
  Direct confirmation of *np*-dominance by detecting neutrons in ECal
- Erez Cohen (2018):
  CM motion in *pp* pairs is Gaussian, $\sigma \approx 150$ MeV/c
- Igor Korover (*next talk!*):
  Detection of recoil neutrons in ToFs

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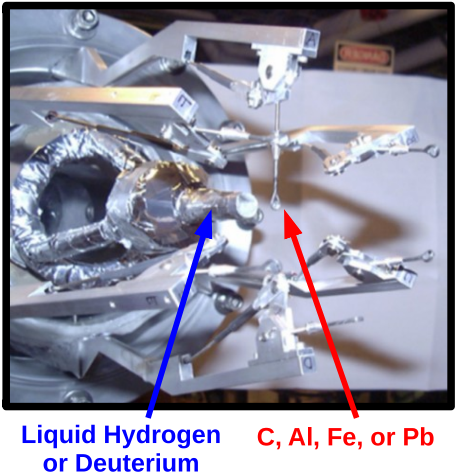
EG2 Experiment

- Data taking in 2004
- 5.016 GeV beam energy
- *d*, C, Al, Fe, Pb targets



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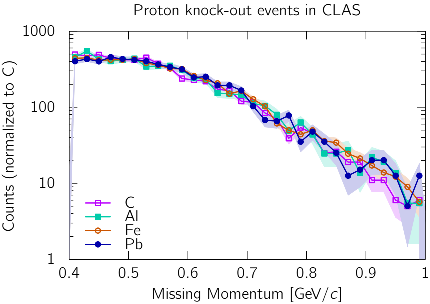

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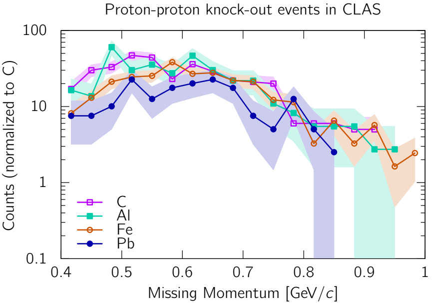
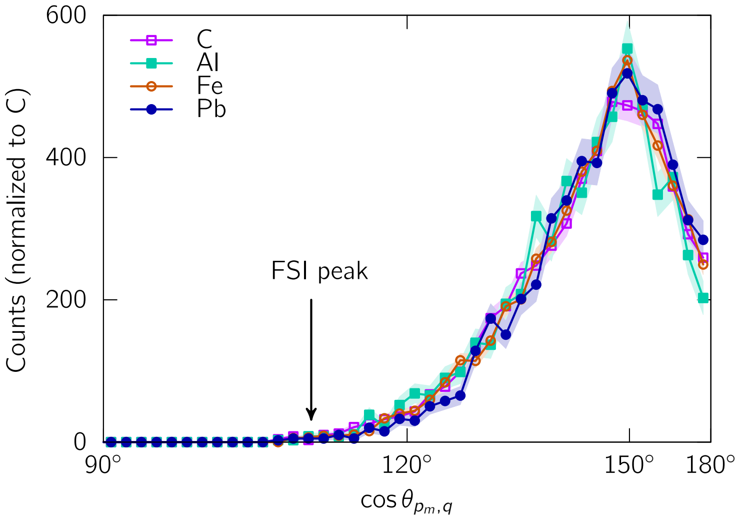
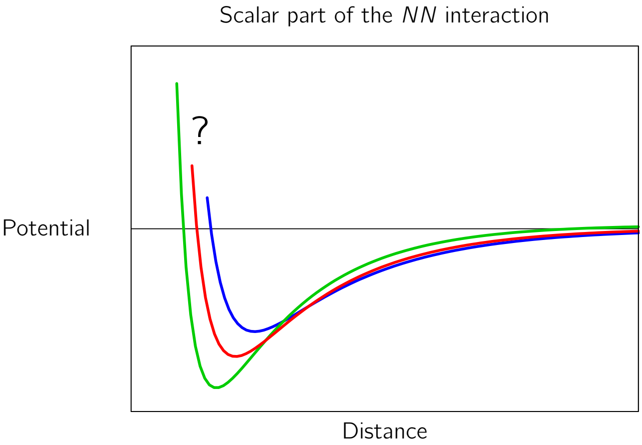


Similar distributions from C to Pb show that FSIs are suppressed.



The *NN* interaction is poorly constrained at short-distance.

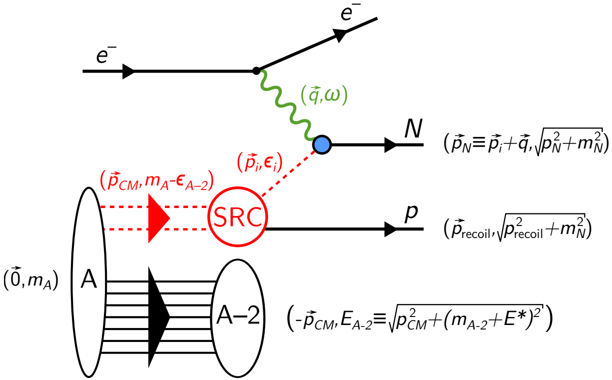
π-production complicates the interpretation of phase-shifts at high-momentum.



Generalized Contact Formalism:

Use scale separation to calculate PWIA cross section

For pairs with high relative momenta:



$$d\sigma \sim \sigma_{eN} \cdot n(\vec{p}_{CM}) \cdot \sum_{\alpha} C_{\alpha} |\tilde{\varphi}_{\alpha}(k)|^2$$

Contact Formalism Ingredients

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- $n(\vec{p}_{CM})$: Pair CM distribution (3D Gaussian)
- $\tilde{\varphi}_\alpha(k)$: Schrödinger Eq. solution for *NN*-potential model
- C_α: Contacts, abundances of pairs in with quantum numbers α

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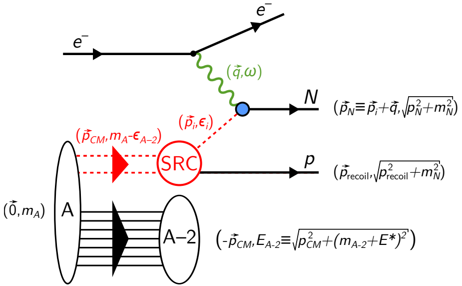
+ several other nuisance (and expt.) parameters.

Vary all parameters within sensible bounds to estimate systematics

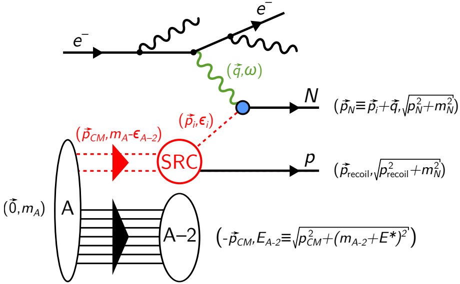
In order to compare to data:

- Generate MC Events



In order to compare to data:

- Generate MC Events
- Other effects
  - Radiation



In order to compare to data:

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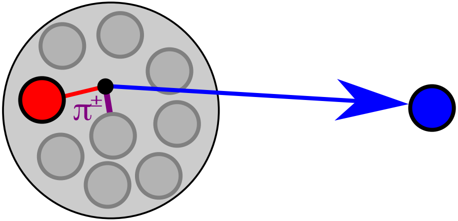
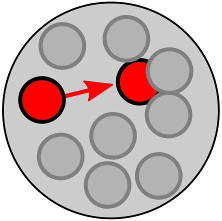
  - Radiation
  - SCX



In order to compare to data:

- Generate MC Events
- Other effects
  - Radiation
  - SCX
  - Transparency



In order to compare to data:

- Generate MC Events
- Other effects
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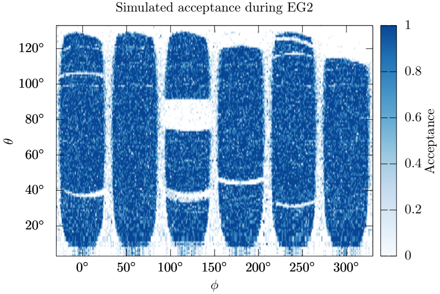
  - Transparency
- Acceptance using Fast MC



In order to compare to data:

- Generate MC Events
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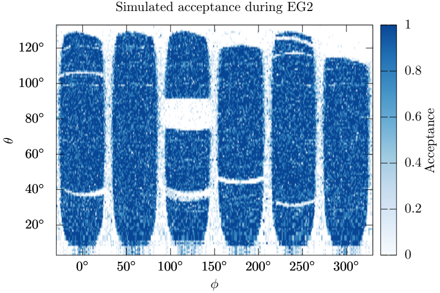
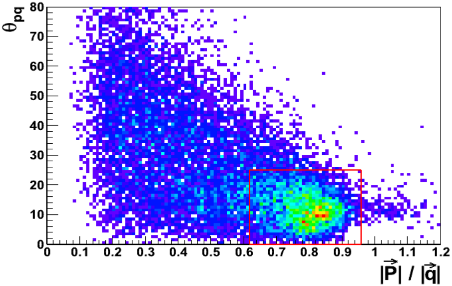
- Acceptance using Fast MC
- Smear e^- and p momenta



In order to compare to data:

- Generate MC Events
- Other effects
  - Radiation
  - SCX
  - Transparency
- Acceptance using Fast MC
- Smear e^- and p momenta
- SRC event selection

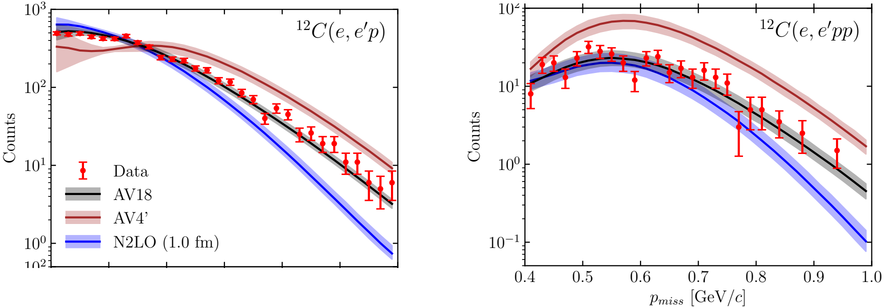


In the following plots:

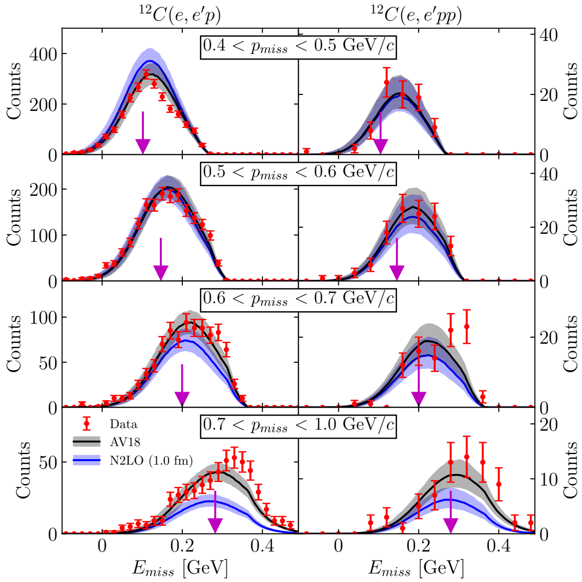
- Comparisons to carbon data: C$(e, e'p)$ and C$(e, e'pp)$ reactions
  - Contacts (C_α) extracted from ab initio calculations

- Three model *NN* interactions
  - AV18: top-of-the-line phenomenological potential
  - AV4$'$, simplified, *no tensor*
  - χEFT N2LO (1.0 fm cut-off)

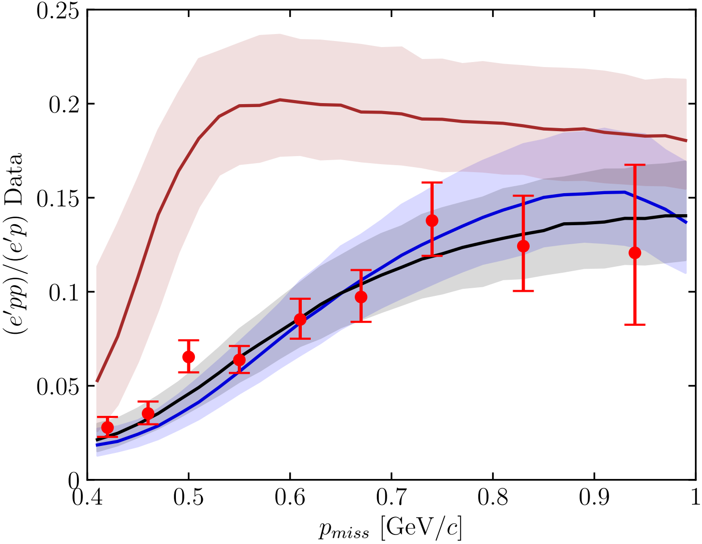
Missing momentum distribution



E_{miss}-p_{miss} correlations



C(e, e′pp)/C(e, e′p): tensor to scalar transition



How can we extract parameters from the data?

Main parameters of interest:

- Contacts (pair abundances)
- Pair CM gaussian width
- Residual excitation $\langle E^* \rangle$

Other parameters:

- SCX, Transparency
- CLAS resolution
- $p_{\mathrm{rel.}}$ Cut-off

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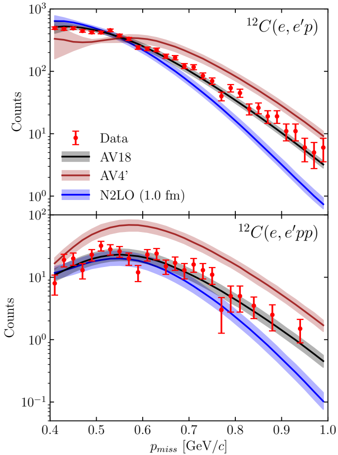
This is an *inference* problem.

Possible approaches

1. Compare several binned distributions
   - Run generator for each param. value



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1. Compare several binned distributions
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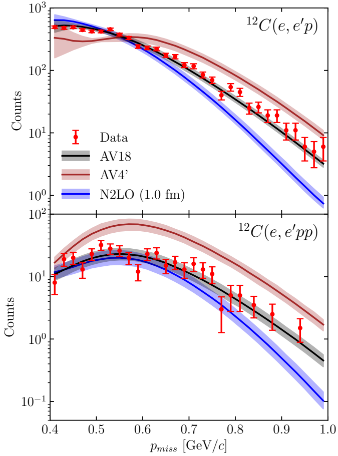
   - Ignores full dimensionality
   - Limited by statistics



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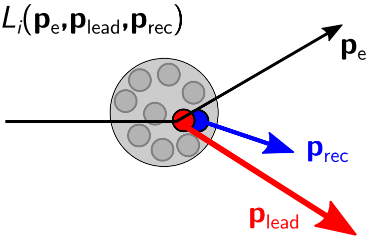

2. Unbinned Likelihood

Possible approaches

1. Compare several binned distributions
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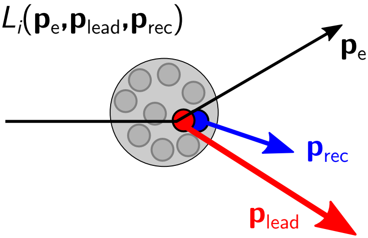
2. Unbinned Likelihood
   - Likelihood each event
   - Full dimensionality
   - The generator is the wrong tool



Unbinned Likelihood

$$\log \mathcal{L} = \sum_i \log L_i$$

$(e, e'pp)$:

$$L_i(\vec{p}_e^{\text{meas.}}, \vec{p}_{\text{lead}}^{\text{meas.}}, \vec{p}_{\text{rec.}}^{\text{meas.}}) \sim \int \frac{d^8\sigma}{d^3\vec{p}_e d^3\vec{p}_{\text{lead}} d\Omega_{\text{rec.}}} \cdot G^3(\Delta p)\delta(\Delta E) d^3\Delta p$$

$(e, e'p)$:

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These are very different integrals than $d^8\sigma$!

Recipe

To evaluate a guess for $C_{s=0}$, $C_{s=1}$, σ_{CM}, ...:

1. Evaluate normalization integral: $\int d^8\sigma A(\vec{p}_e, \vec{p}_{\text{lead}})$
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This method:

- Normalization: 1M samples
- Likelihood: 10k events $\times$ 10k samples $=$ 100M total

We may even get a speed-up!

Each L_i can be evaluated in parallel

Complications I have glossed over. . .

- Detector acceptance
    - $\longrightarrow$ Weight integrals using maps (Fast MC)

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- Single charge exchange
  - $\longrightarrow$ Sum all contributing channels:
  - $\longrightarrow \sigma_{pp} = \sigma_{pp}(1 - P_{\mathrm{SCX}}) + \sigma_{pn} P_{\mathrm{SCX}} + \sigma_{np} P_{\mathrm{SCX}} + \dots$

Method to exploring likelihood space will depend on speed and dimensionality.

Some options:

- Metropolis-Hastings MCMC
  - Explore *entire* space using random walk
  - Good for complicated topologies
  - Bad for high-dimensionality

- Maximum-Likelihood Estimation
  - Find most-likely parameters (e.g. with gradient descent)
  - Explore space around maximum, parameterize curvature
  - Bad for complicated topologies

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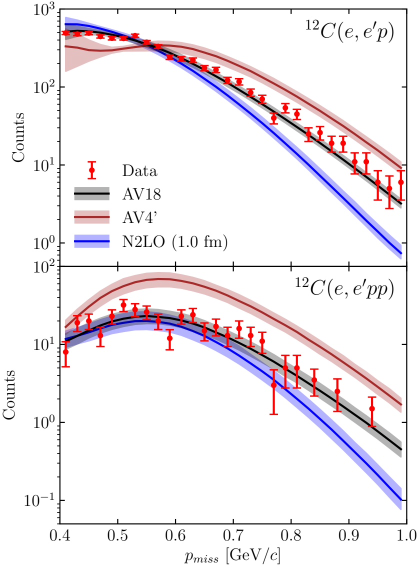

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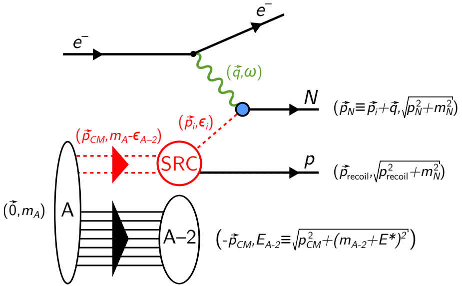

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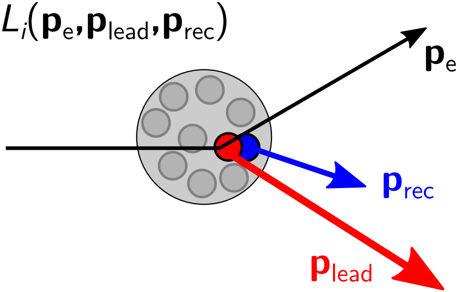

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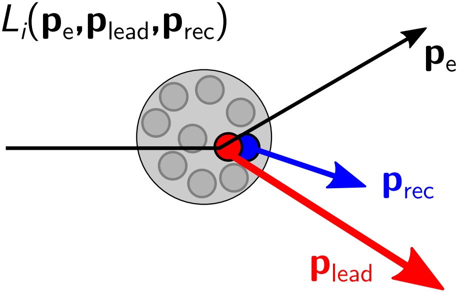

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