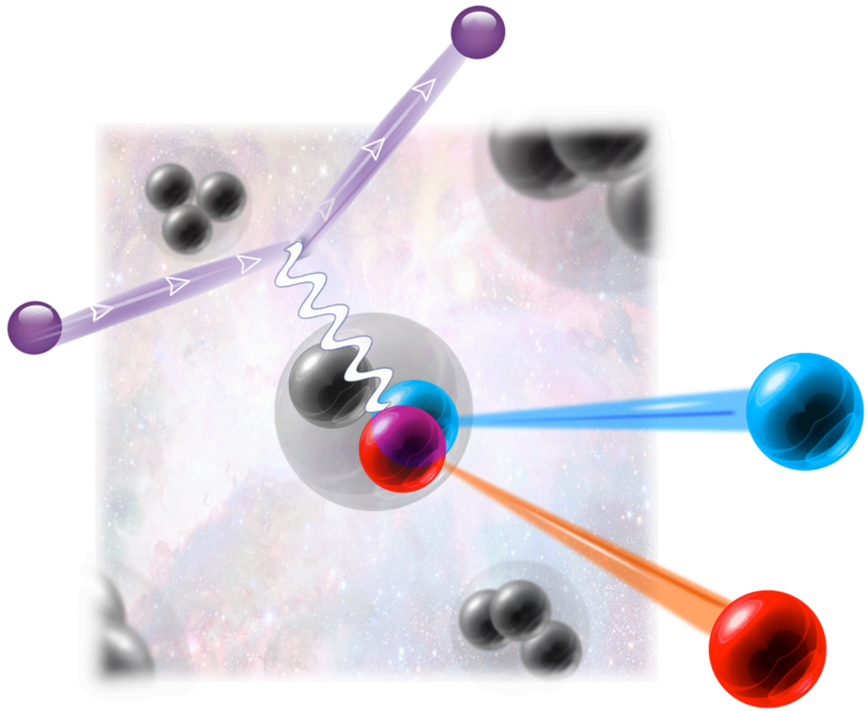
Tritium (e,e'p)

Phys. Lett. B 797, 134890 (2019)

arXiv:2001.07230



Reynier Cruz Torres

Hall A Collaboration Meeting

January 30th, 2020

Hen Lab

Laboratory for Nuclear Science @ MIT

Testing Reaction-Mechanism and NN Models

- Measure nucleon-knockout cross sections.

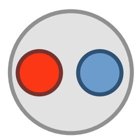
- Compare with calculations using different NN interactions and modeling of reaction.

- See which one works best.

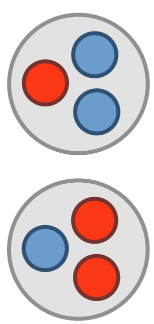
Why light nuclei?

- exactly calculable
- test and benchmark theory

<u>Deuteron</u>



<u>A=3</u>



Why light nuclei?

- exactly calculable
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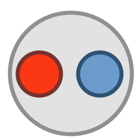
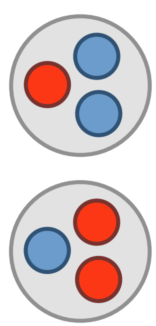
Why A=3?

Deuteron



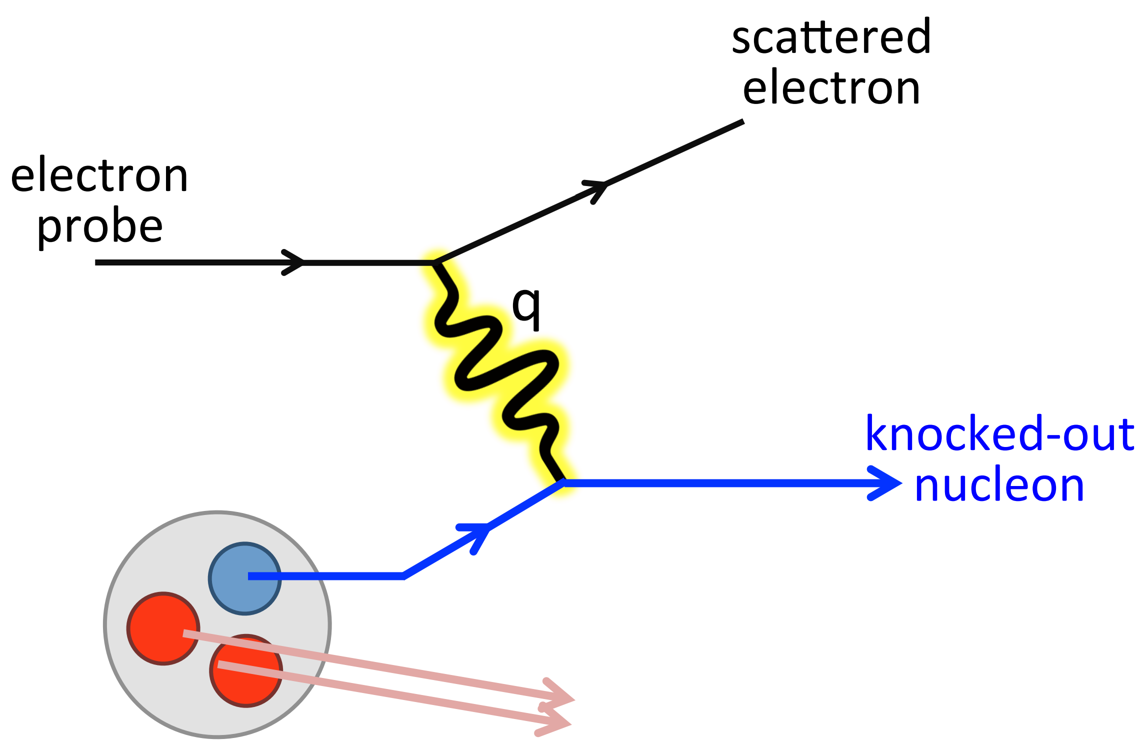
- only pn interaction
- extensively measured

A=3

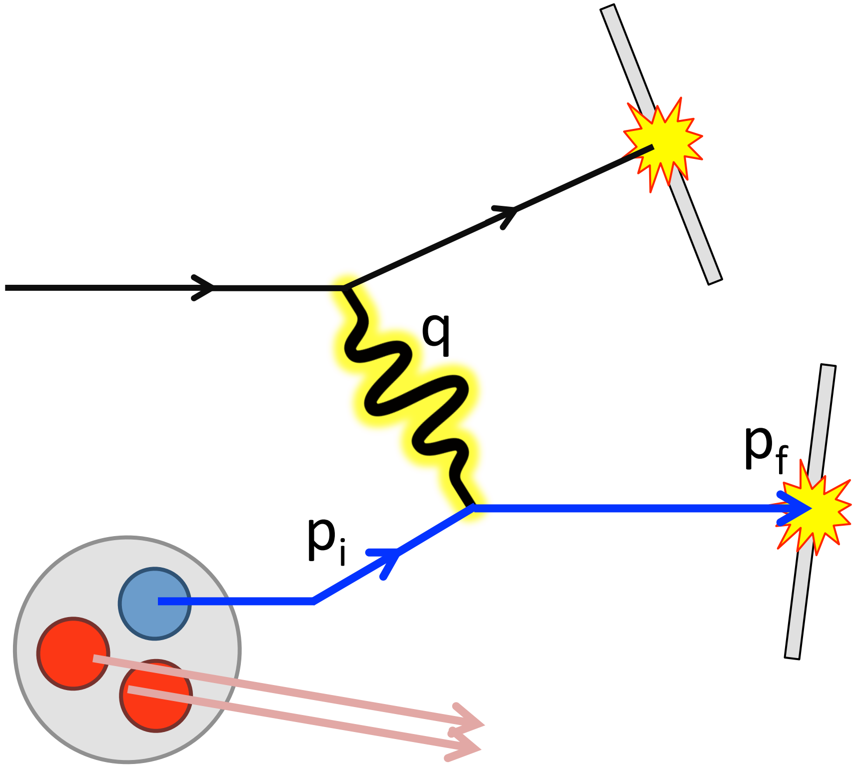


- pp, pn, nn interactions
- ^{3}H targets are uncommon (available once a generation)

Electron-induced Proton Knockout



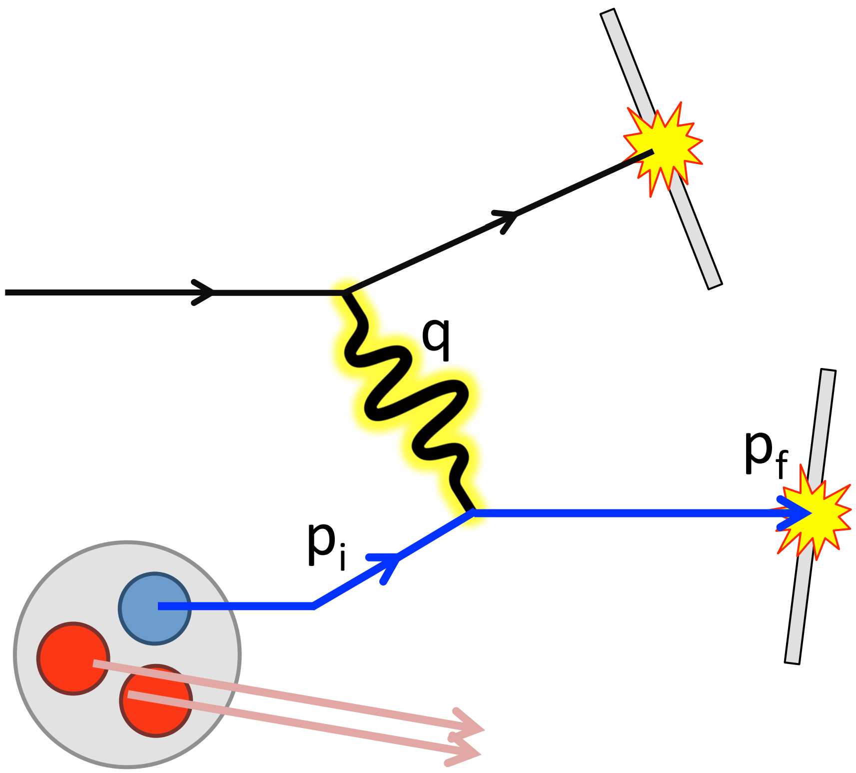
Electron-induced Proton Knockout



Missing momentum

$$\vec{p}_{miss} \equiv \vec{p}_f - \vec{q}$$

Plane-Wave Impulse Approximation (PWIA)



Missing momentum

$$\vec{p}_{miss} \equiv \vec{p}_f - \vec{q}$$

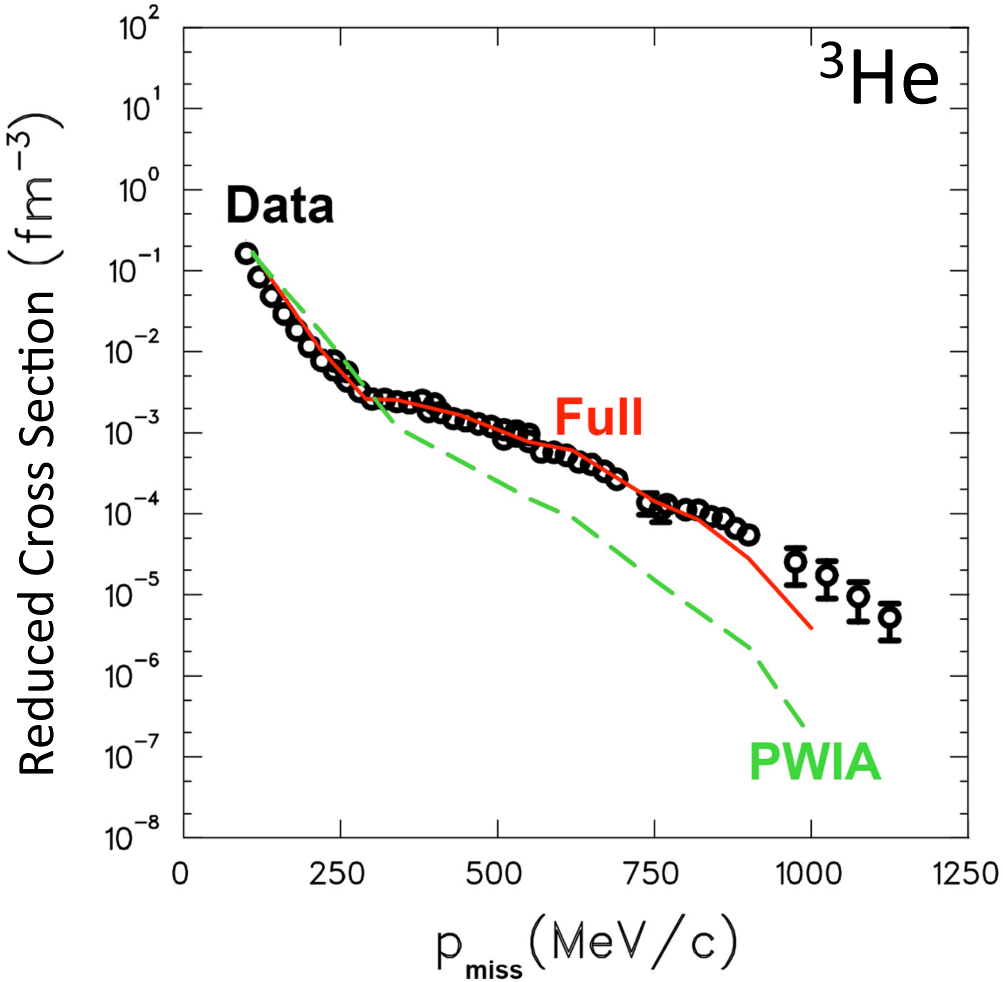
Assuming:

1) momentum transfer absorbed by a single nucleon.

2) knocked-out nucleon did not rescatter as it left the nucleus.

$$\vec{p}_{miss} = \vec{p}_i$$

Previous studies and non-QE mechanisms

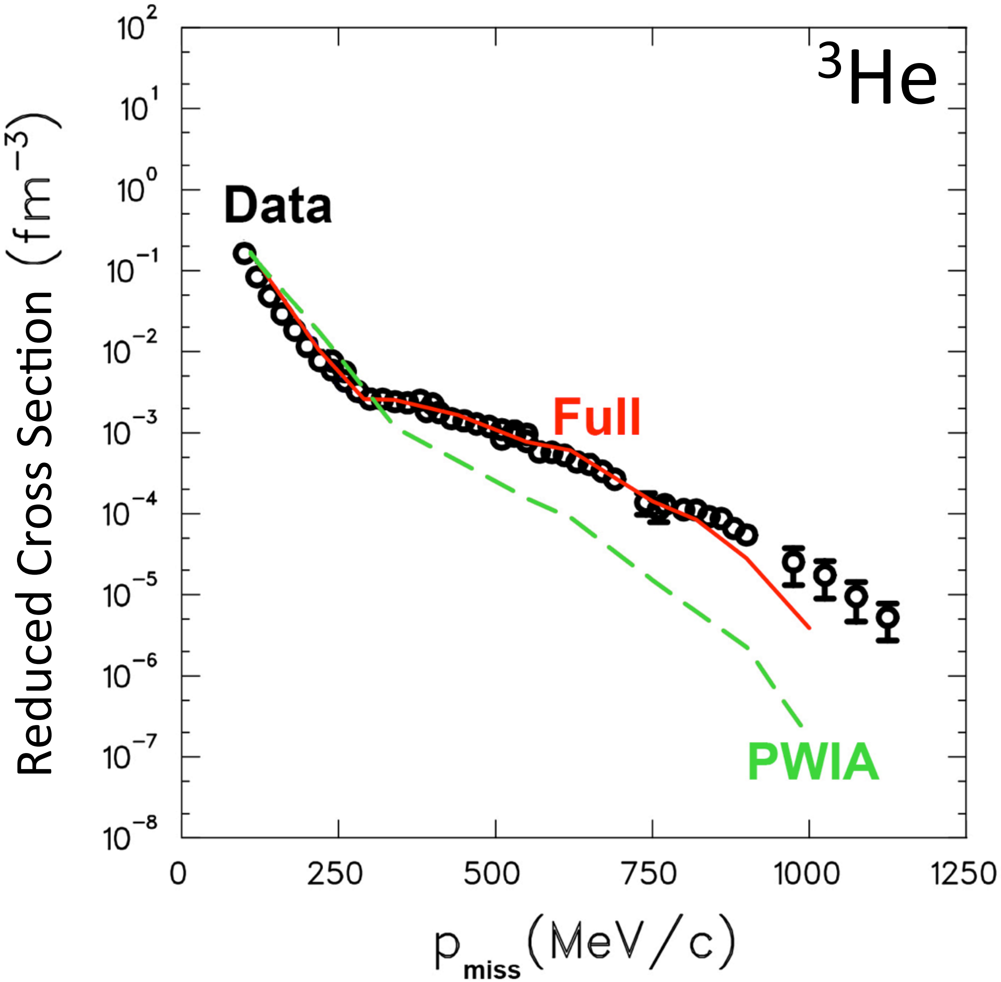


F. Benmokhtar et al., PRL 94, 082305 (2005)

Large differences between data & PWIA

=> Data useful to study reaction mechanism, not nucleon distributions.

Previous studies and non-QE mechanisms



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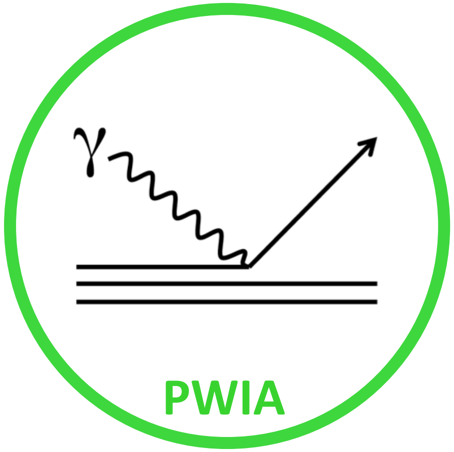
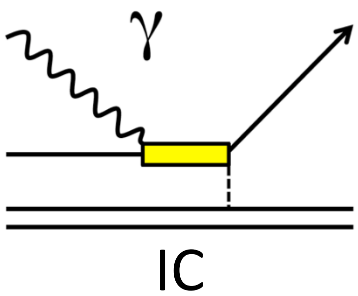
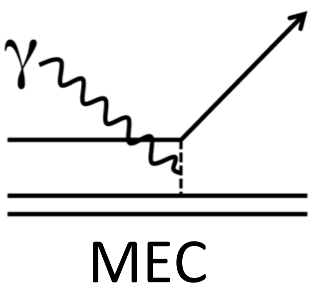
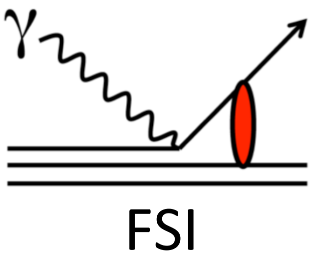




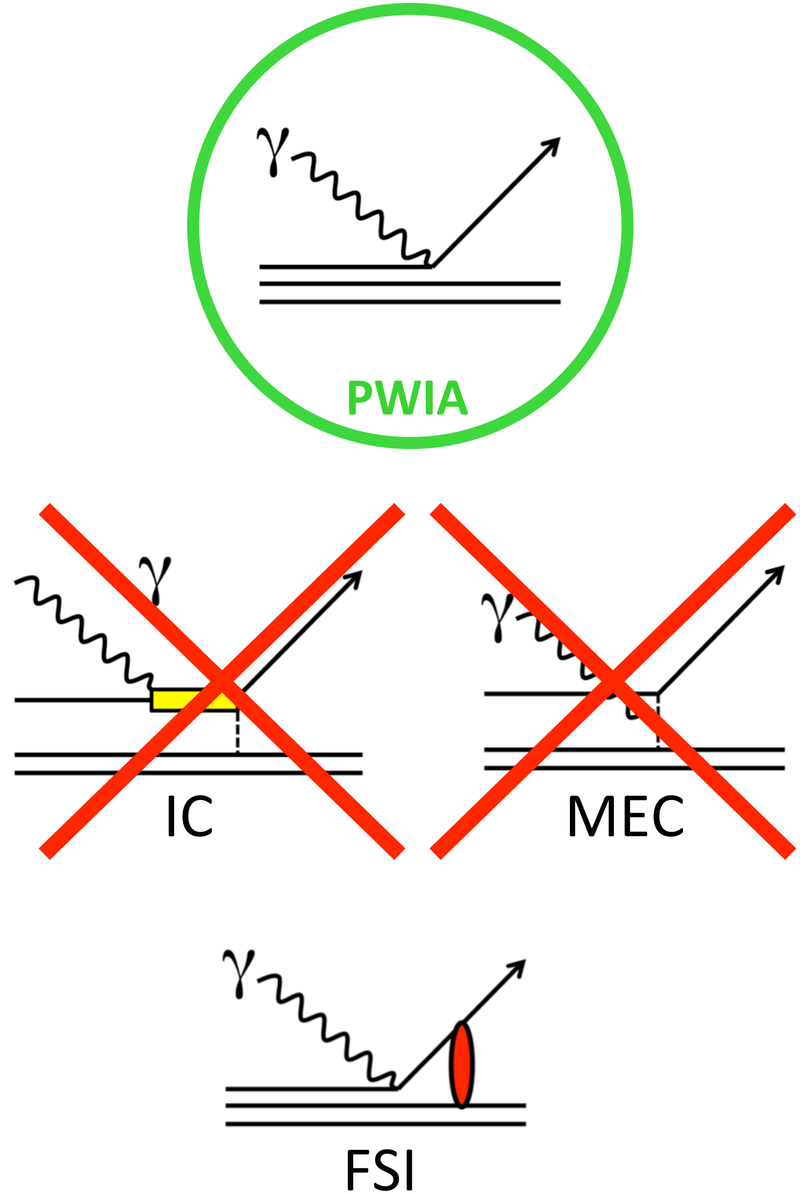




Minimizing non-QE mechanisms

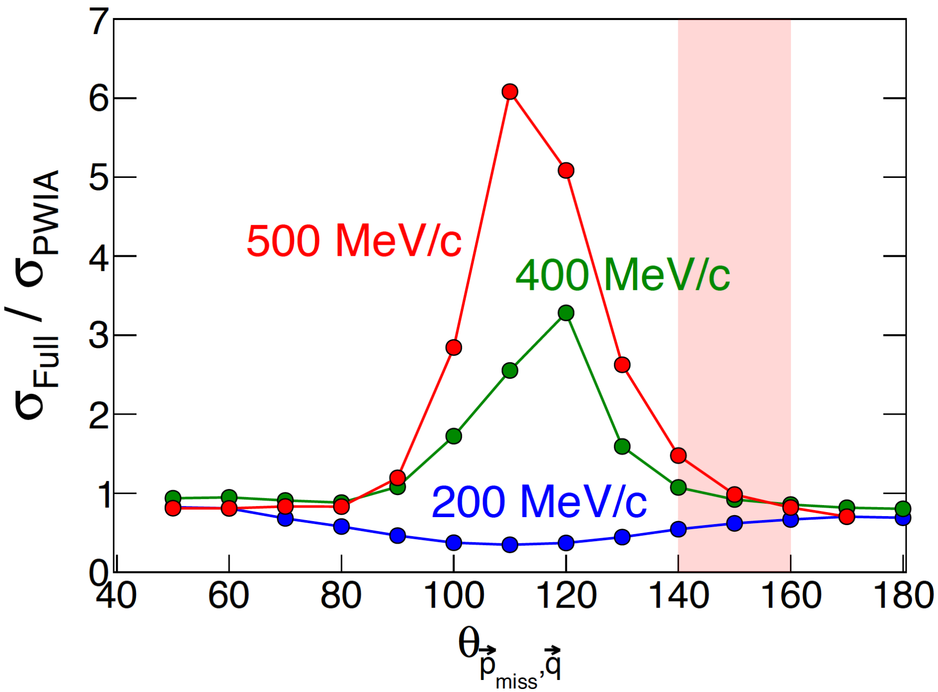
$$Q^2 > 2\ \text{GeV}^2$$

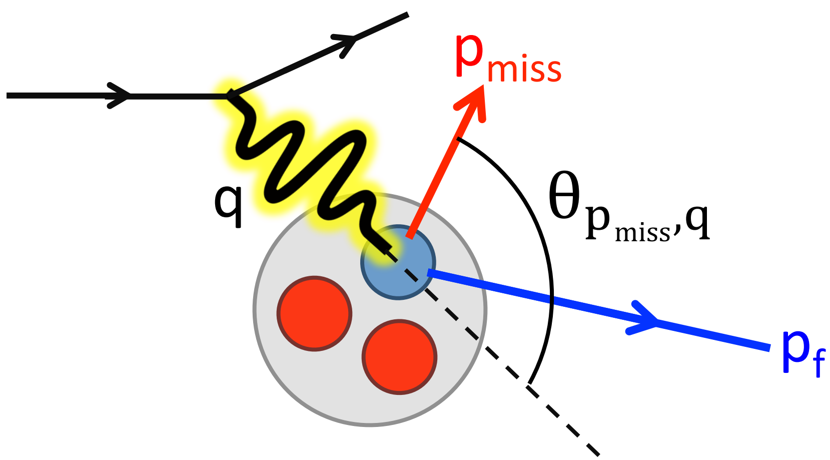
$$x_B = Q^2/2m_p\omega > 1$$

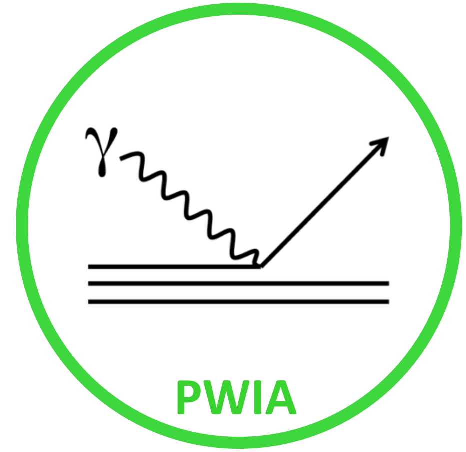


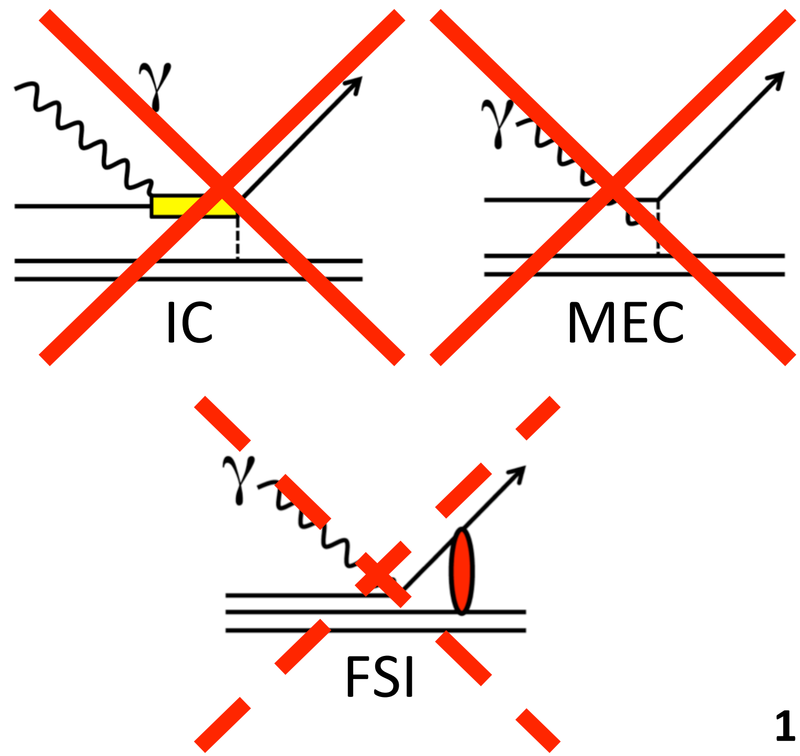
M. M. Sargsian, Int. J. Mod. Phys. E10, 405 (2001)
M. M. Sargsian et al., J. Phys. G29, R1 (2003)

Minimizing non-QE mechanisms









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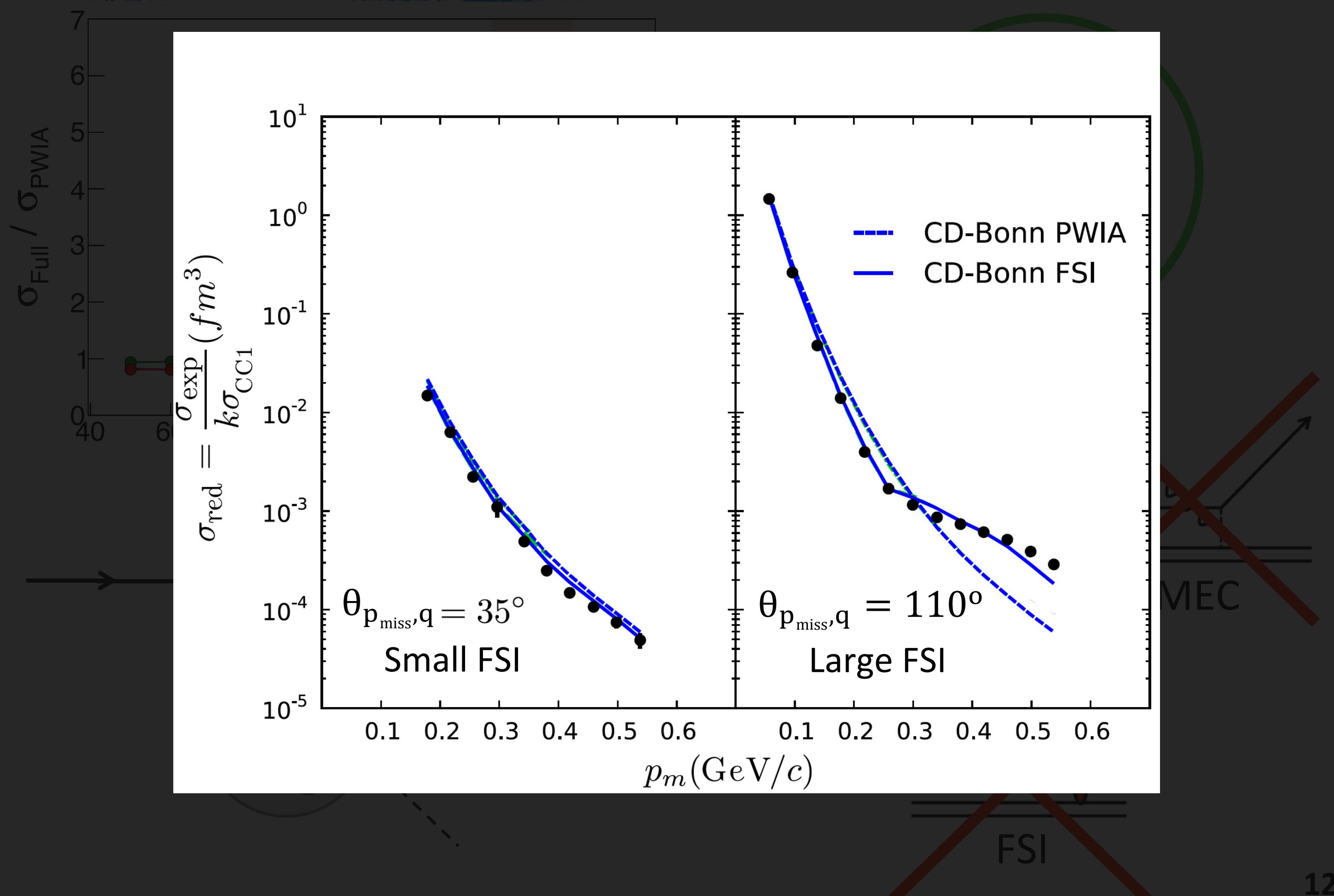
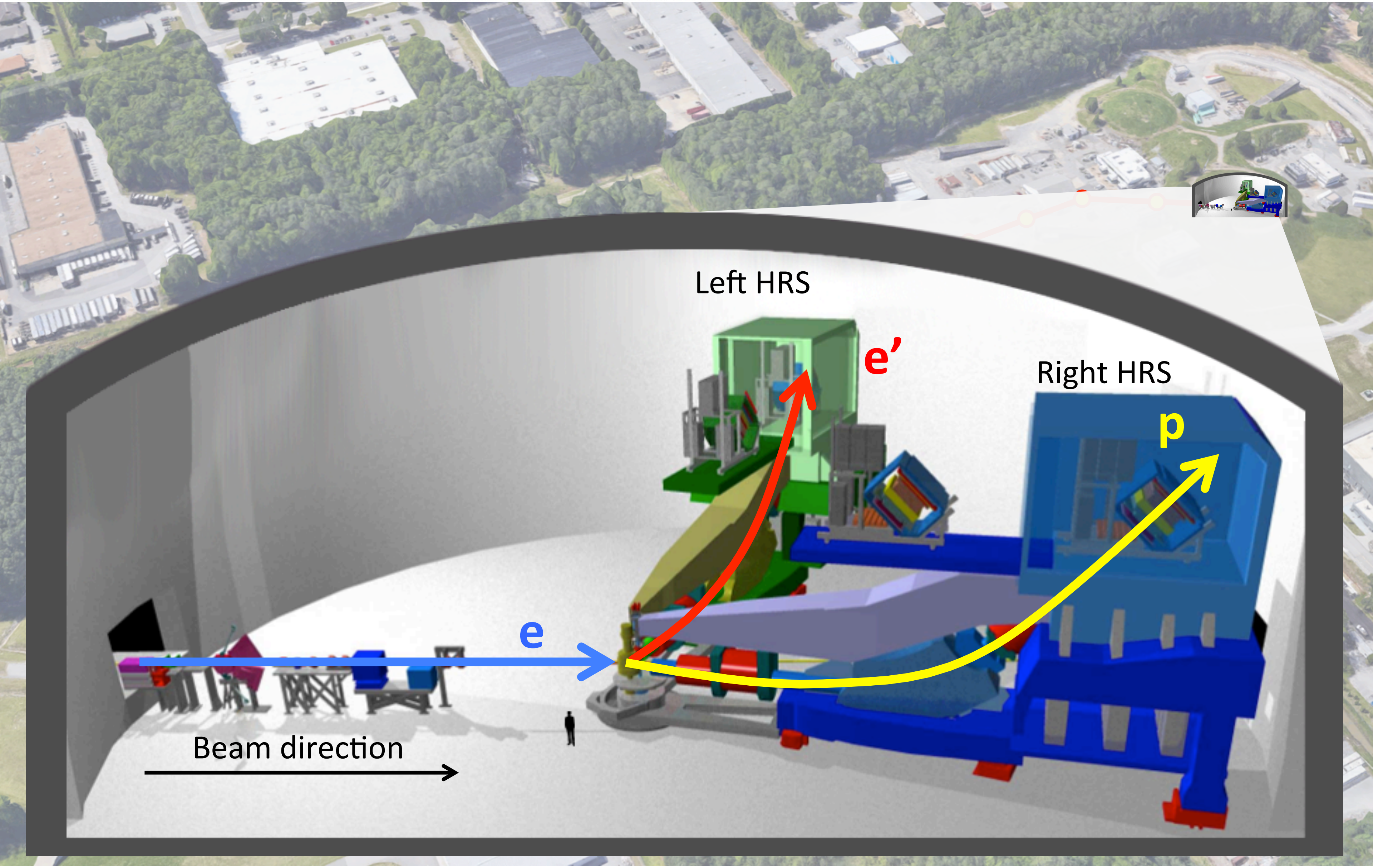
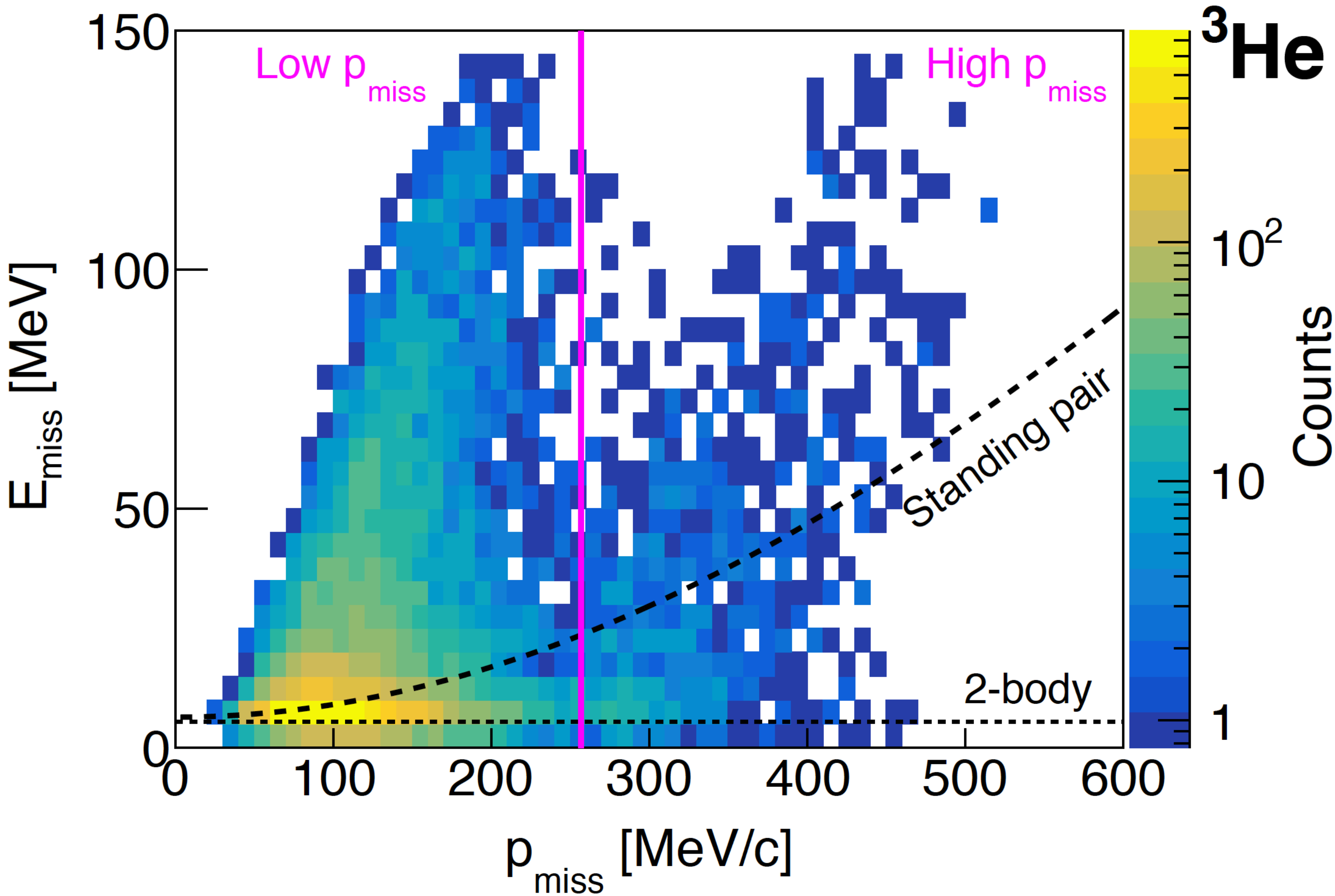


Hall-A of Jefferson Lab



Measured kinematics



Extracting Absolute Cross Sections

$$\frac{d^6\sigma}{dE_e d\Omega_e dE_p d\Omega_p} = \frac{(\text{Counts})}{Q \cdot \left(\frac{\rho}{A}\right) \cdot t_{live} \cdot \varepsilon \cdot V_B} \times C$$

Luminosity

Detector Efficiency
- PID
- tracking
- trigger

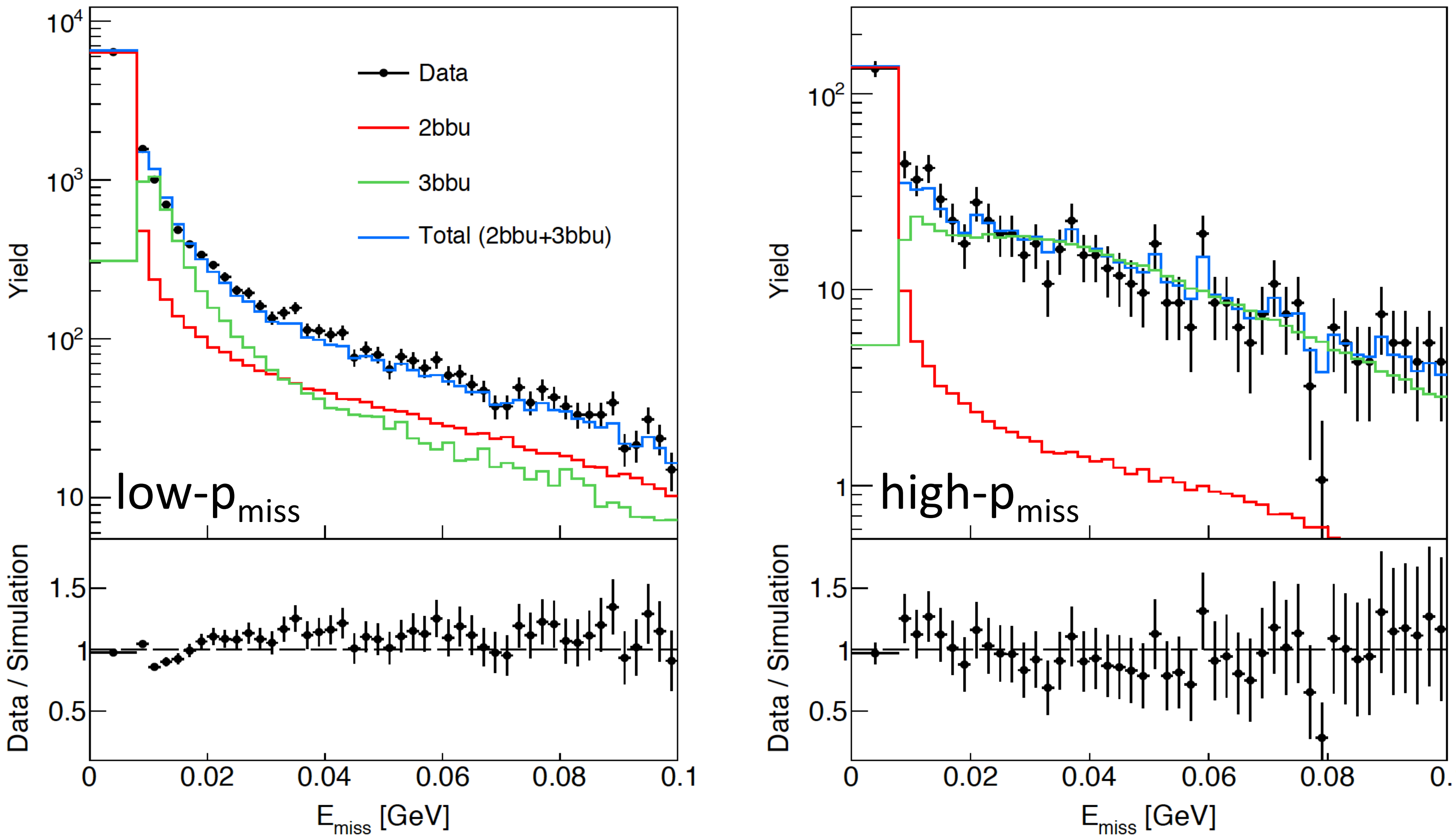
Corrections
- bin migration
- bin centering
- radiation

Live time

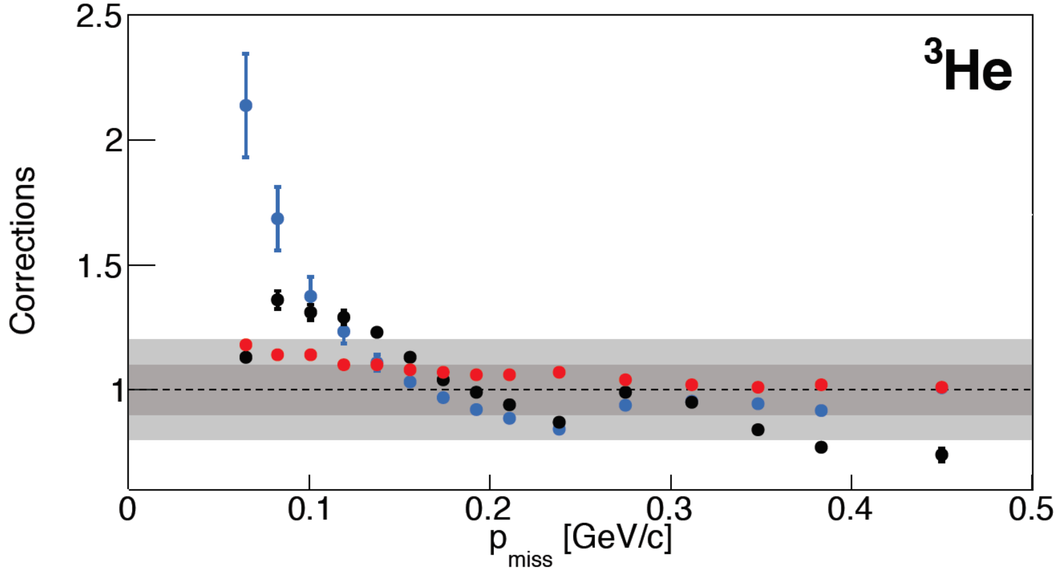
Phase-space volume and acceptance correction

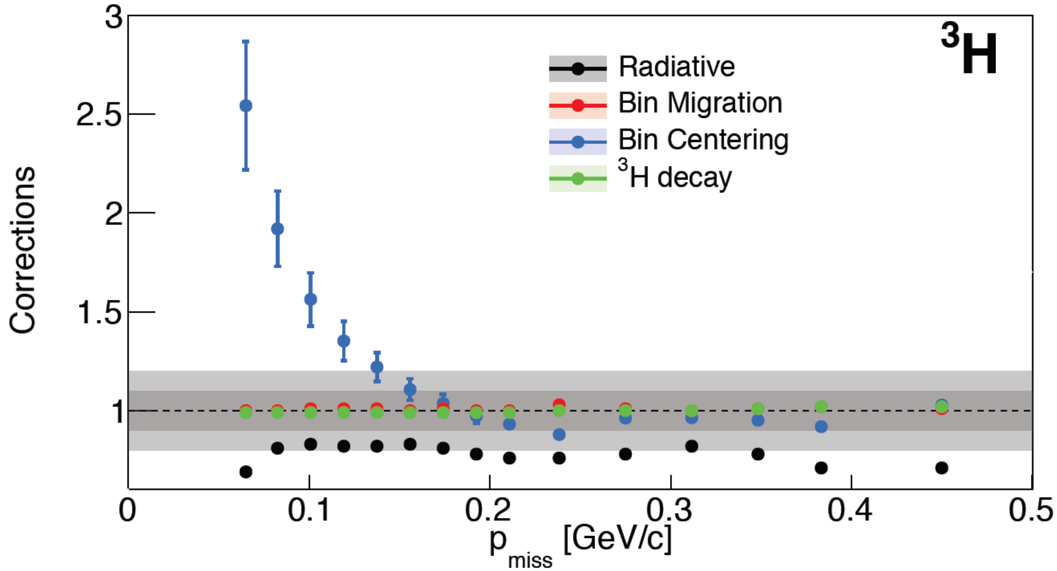
Isolating the ^{3}He 3bbu channel

- ^{3}He(e,e'p) final state can be 2bbu (pd) or 3bbu (ppn)
  - ^{3}H(e,e'p) does not have a 2bbu channel



Corrections





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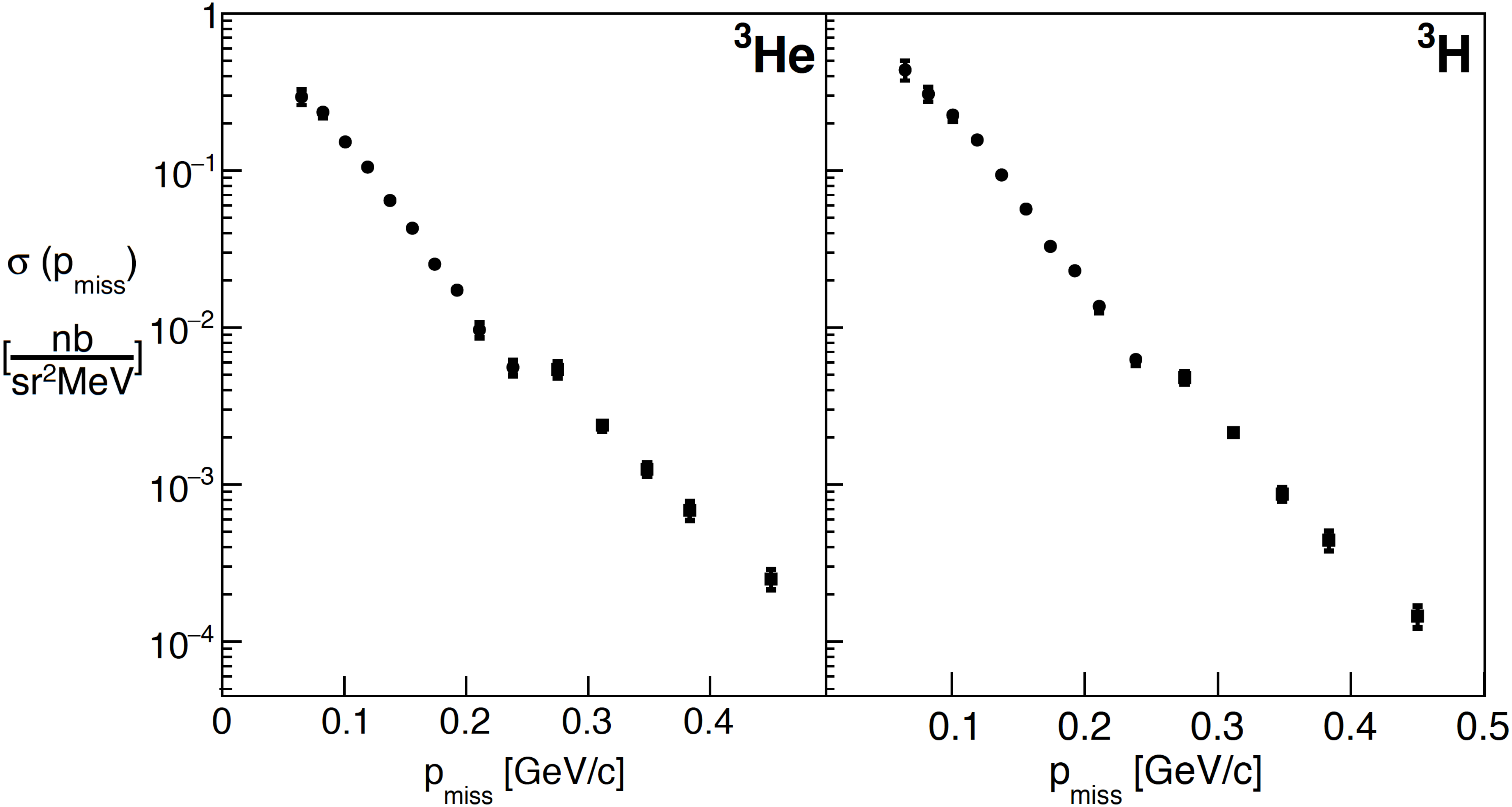
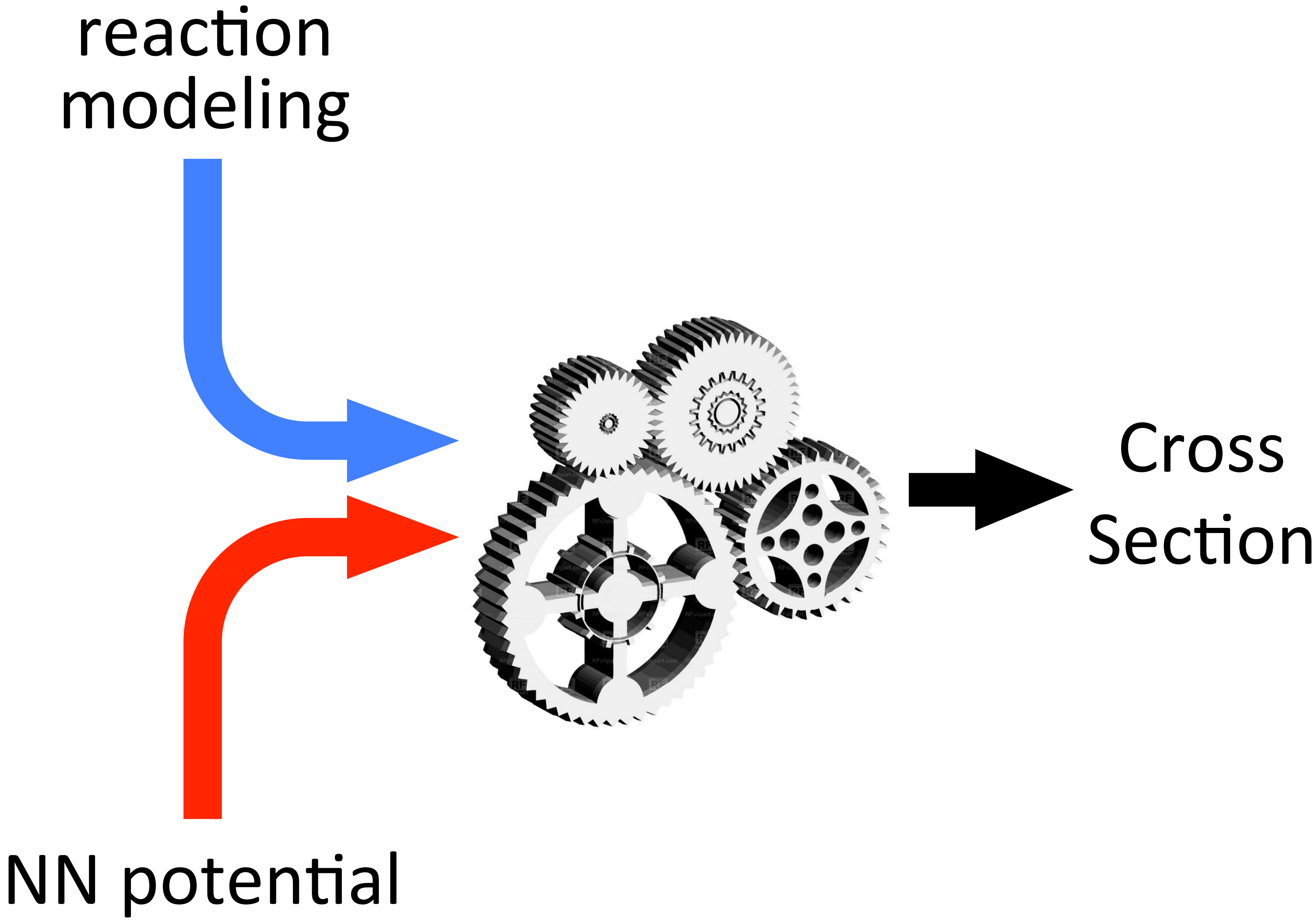
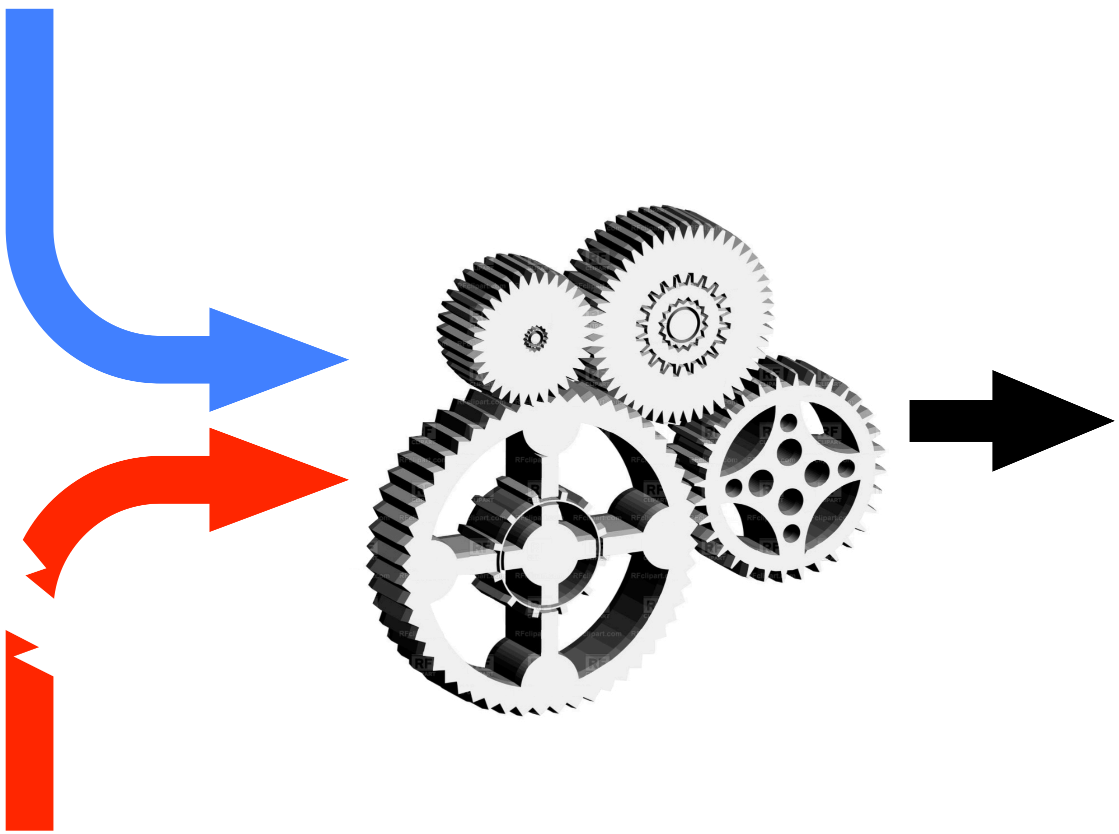


Theory Calculations



We have fixed the NN potential

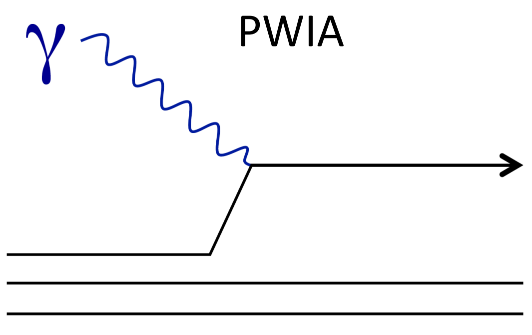
reaction modeling

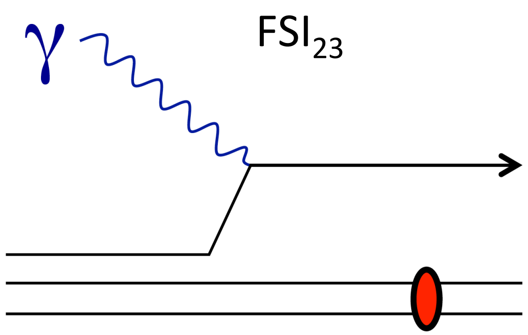


Cross Section

~~NN potential~~ → CD-Bonn

Theory Calculations





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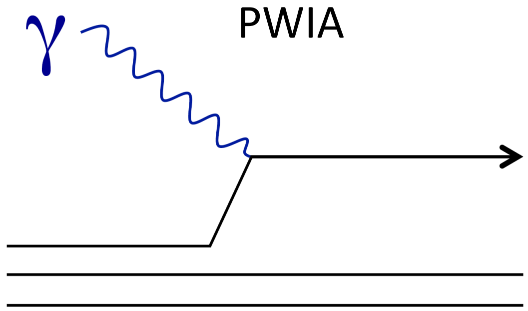
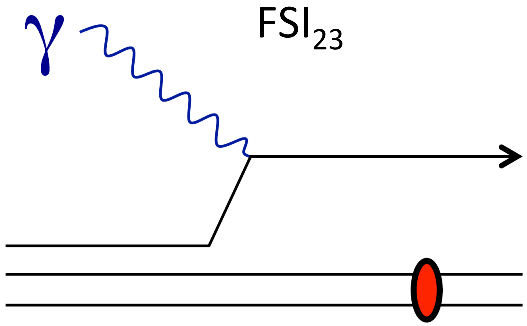
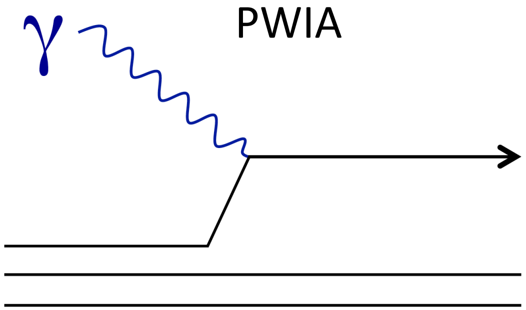


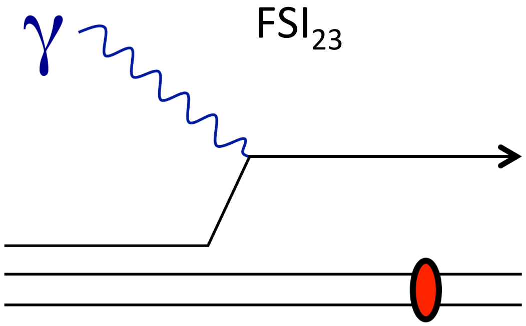


Cracow

- Faddeev-formulation based calculations
- Unfactorized
- Includes FSI_{23}

Theory Calculations





Cracow

- Faddeev-formulation based calculations
- Unfactorized
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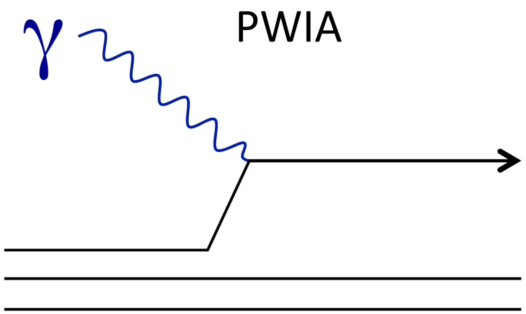
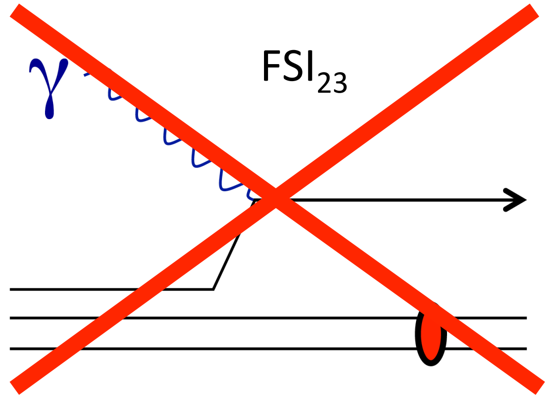
CK+*CC1*

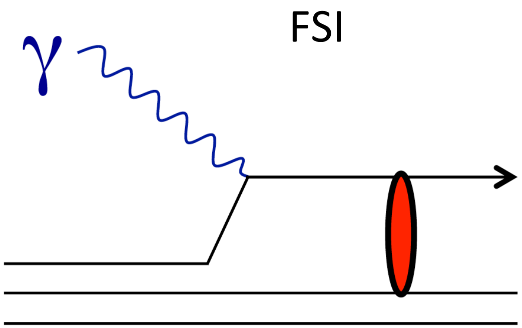
$$\sigma = \sigma_{ep} \cdot S(p_i, E_i)$$

- Spectral function: C. Ciofi degli Atti and L.P. Kaptari
- ep off-shell cross section: CC1
- Includes FSI_{23}

Theory Calculations







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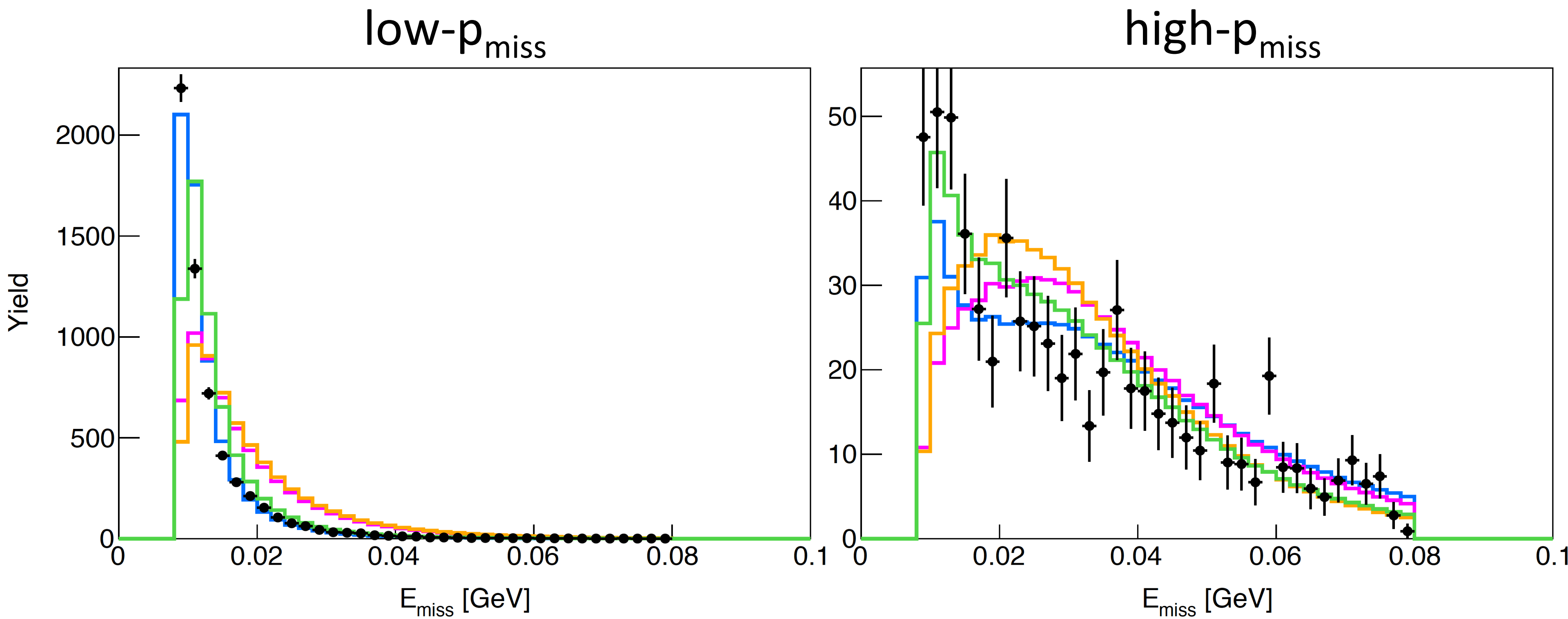
- Spectral function: C. Ciofi degli Atti and L.P. Kaptari
- ep off-shell cross section: CC1
- Includes FSI_{23}

Sargsian-FSI

- FSI calculation based on the Generalized Eikonal Approximation
- Does NOT include FSI_{23}

FSI_{23} is more important at low-p_{miss}

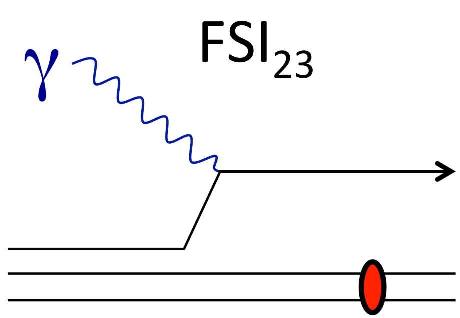


- CK+*CC1*
- Cracow

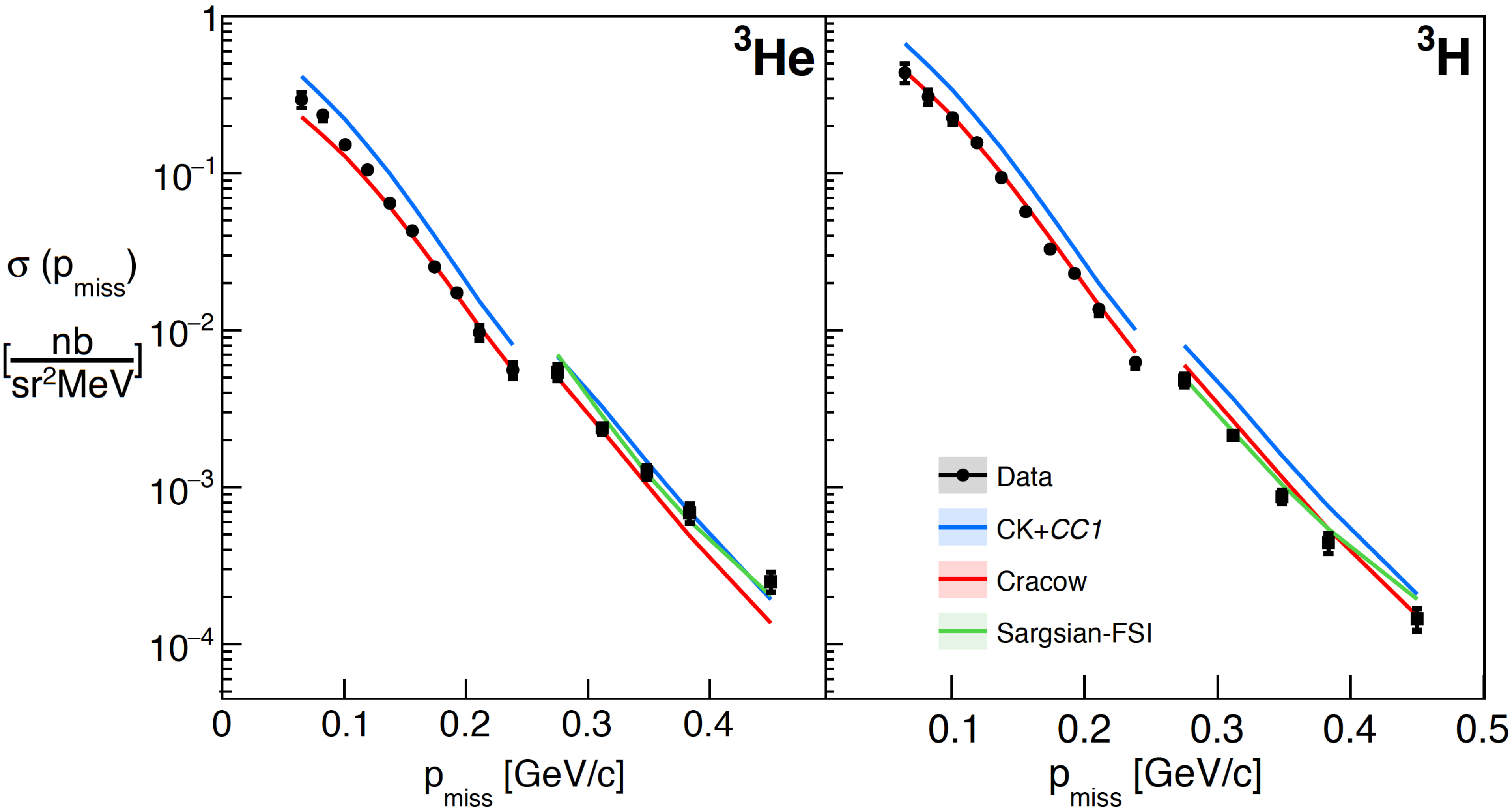
PWIA + FSI_{23}

- Cracow-PW
- Sargsian-PW

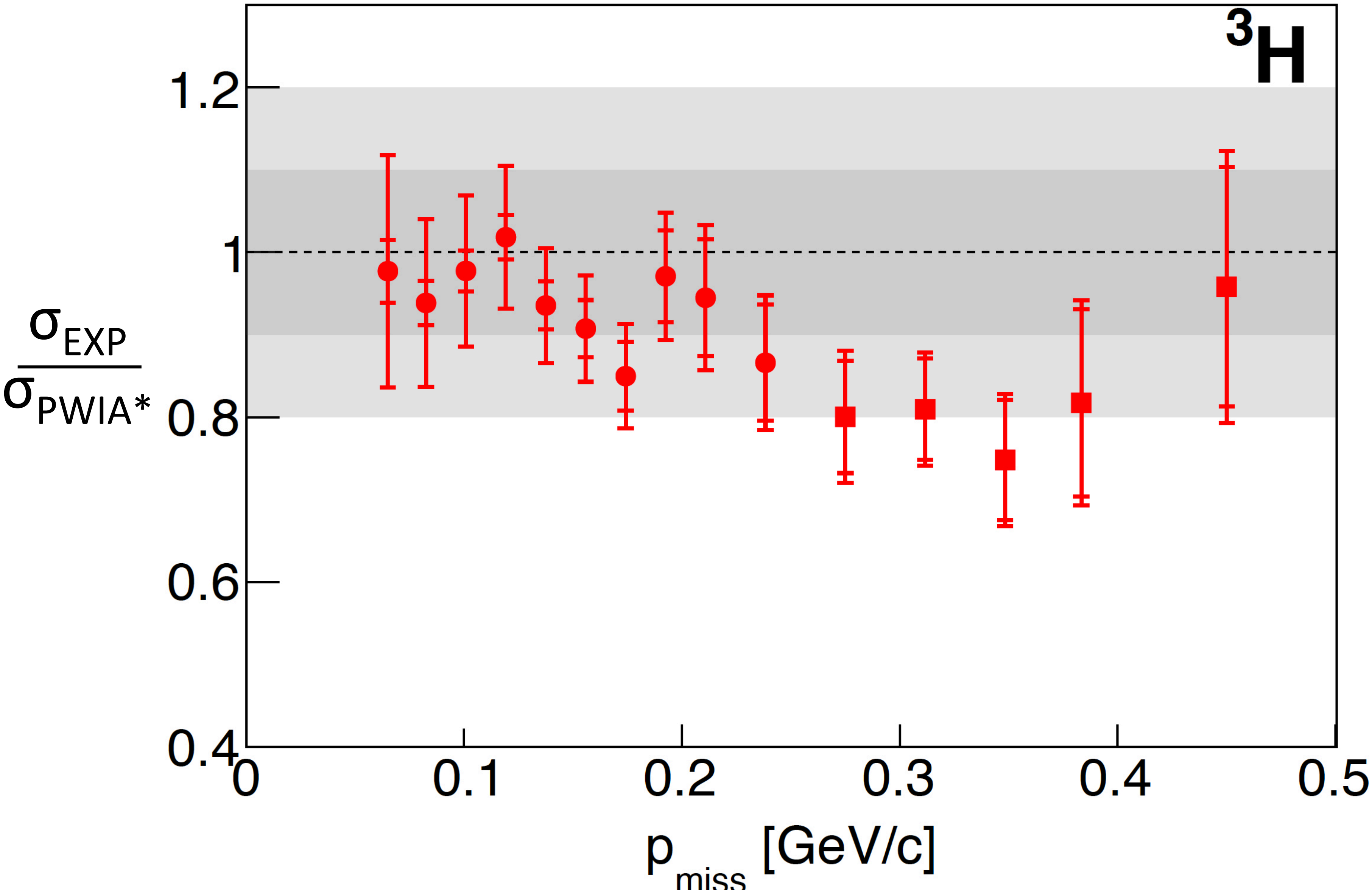
PWIA only



Comparison to theory

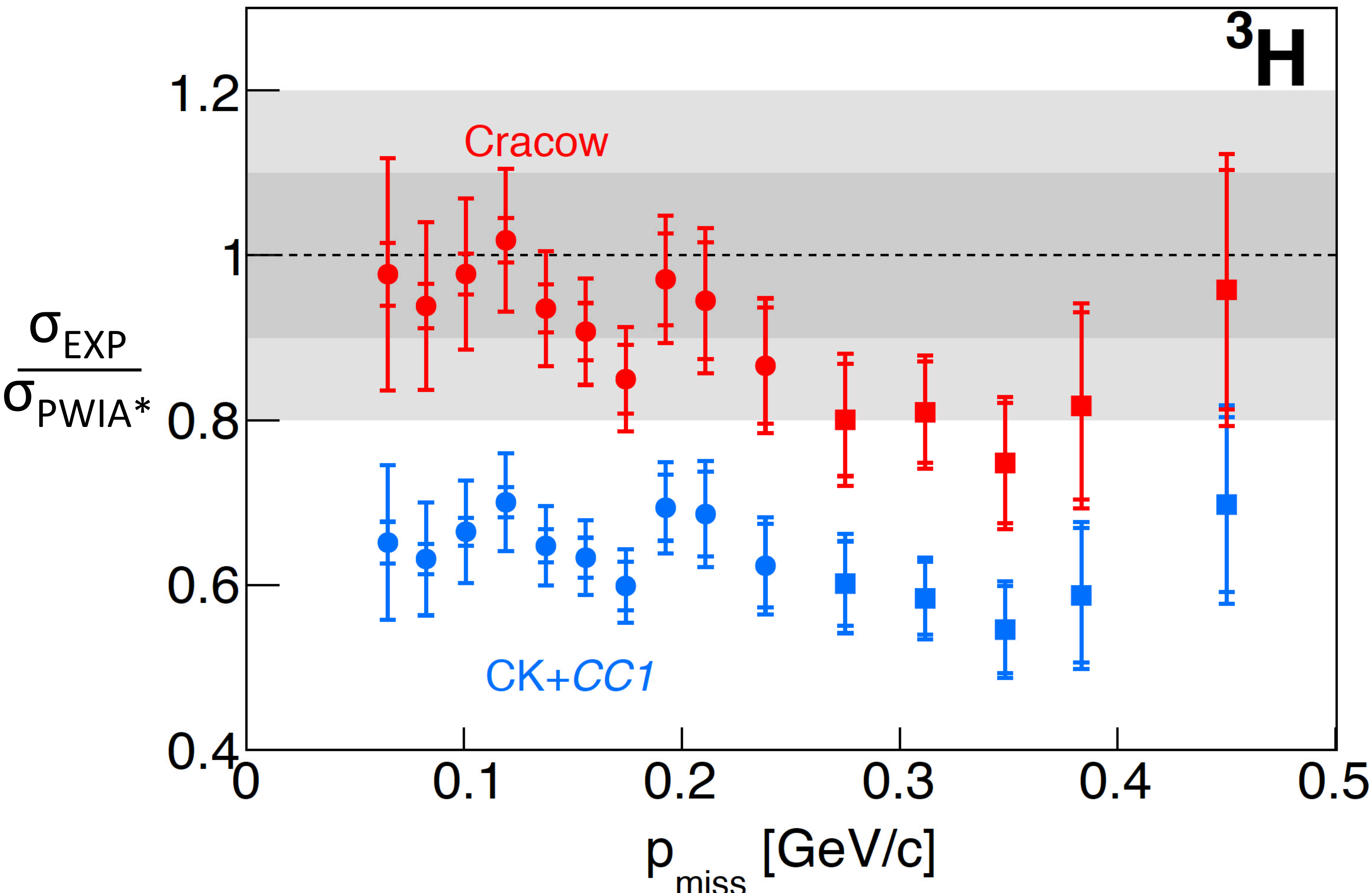


^{3}H Data, Cracow agree within 10-20%!!!



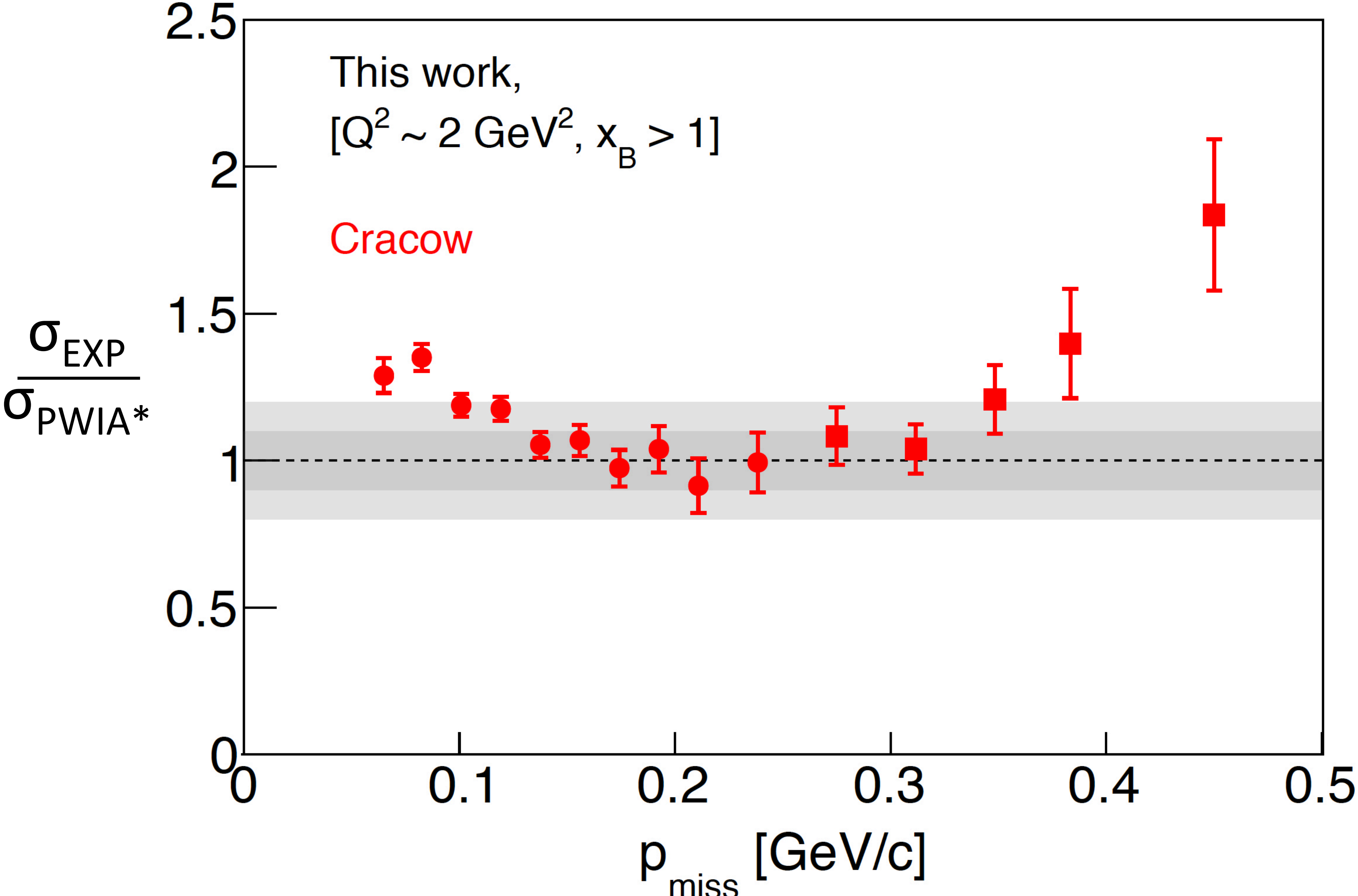
* including FSI_{23}

^{3}H Data, PWIA*-calculation comparison



* including FSI_{23}

^{3}He agreement is limited



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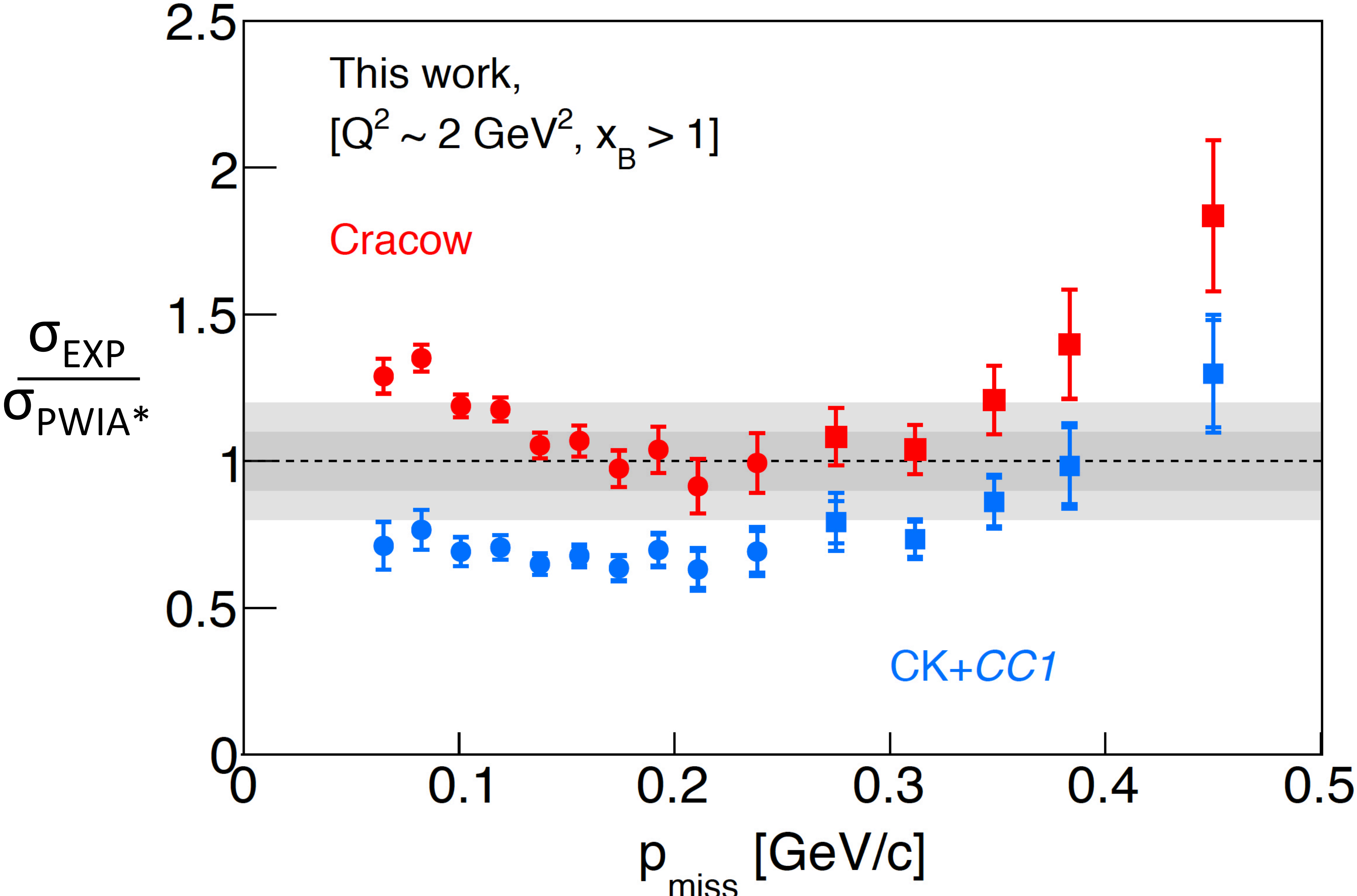
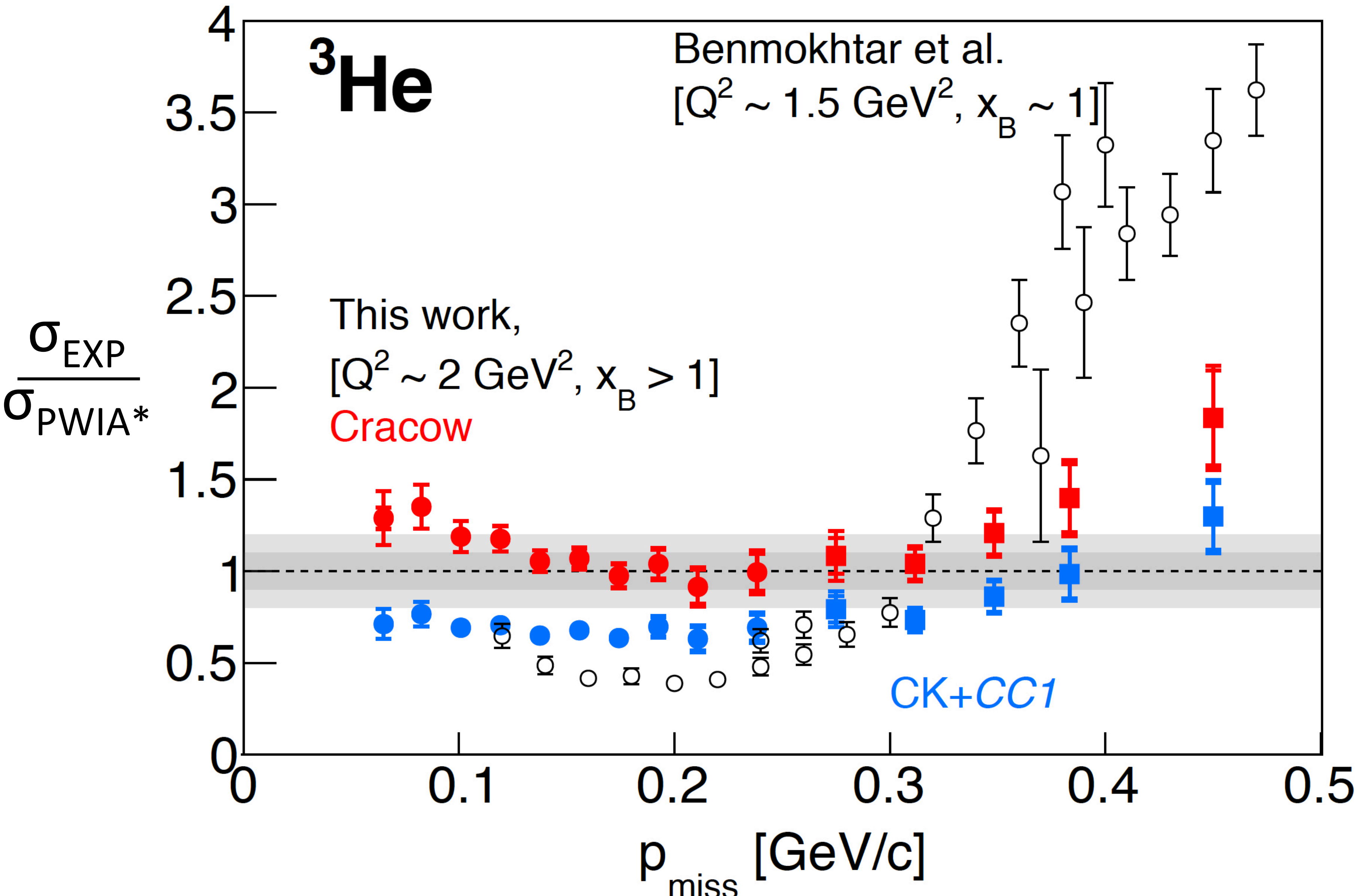


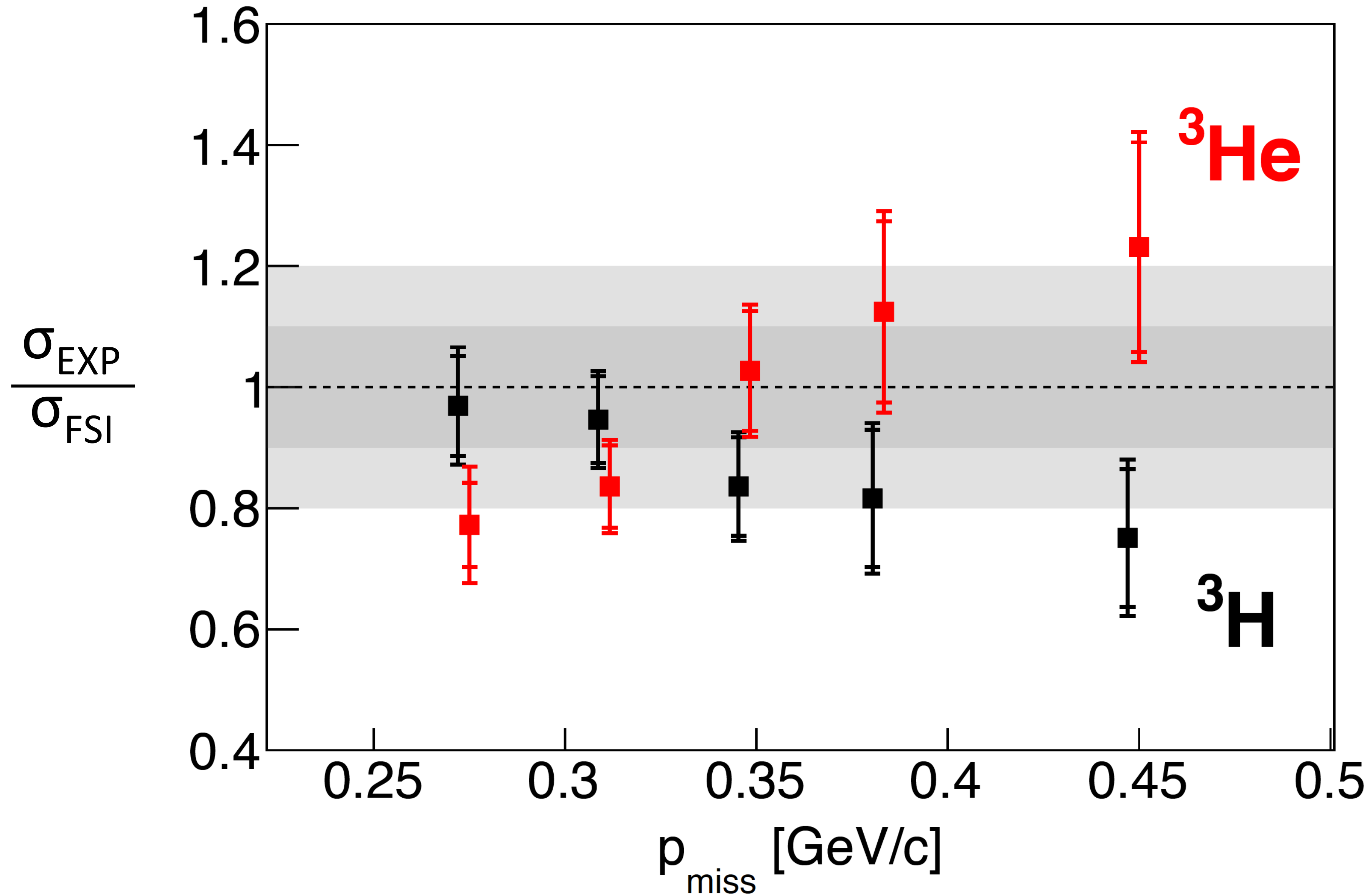
* including FSI_{23}

Still better agreement than previous data

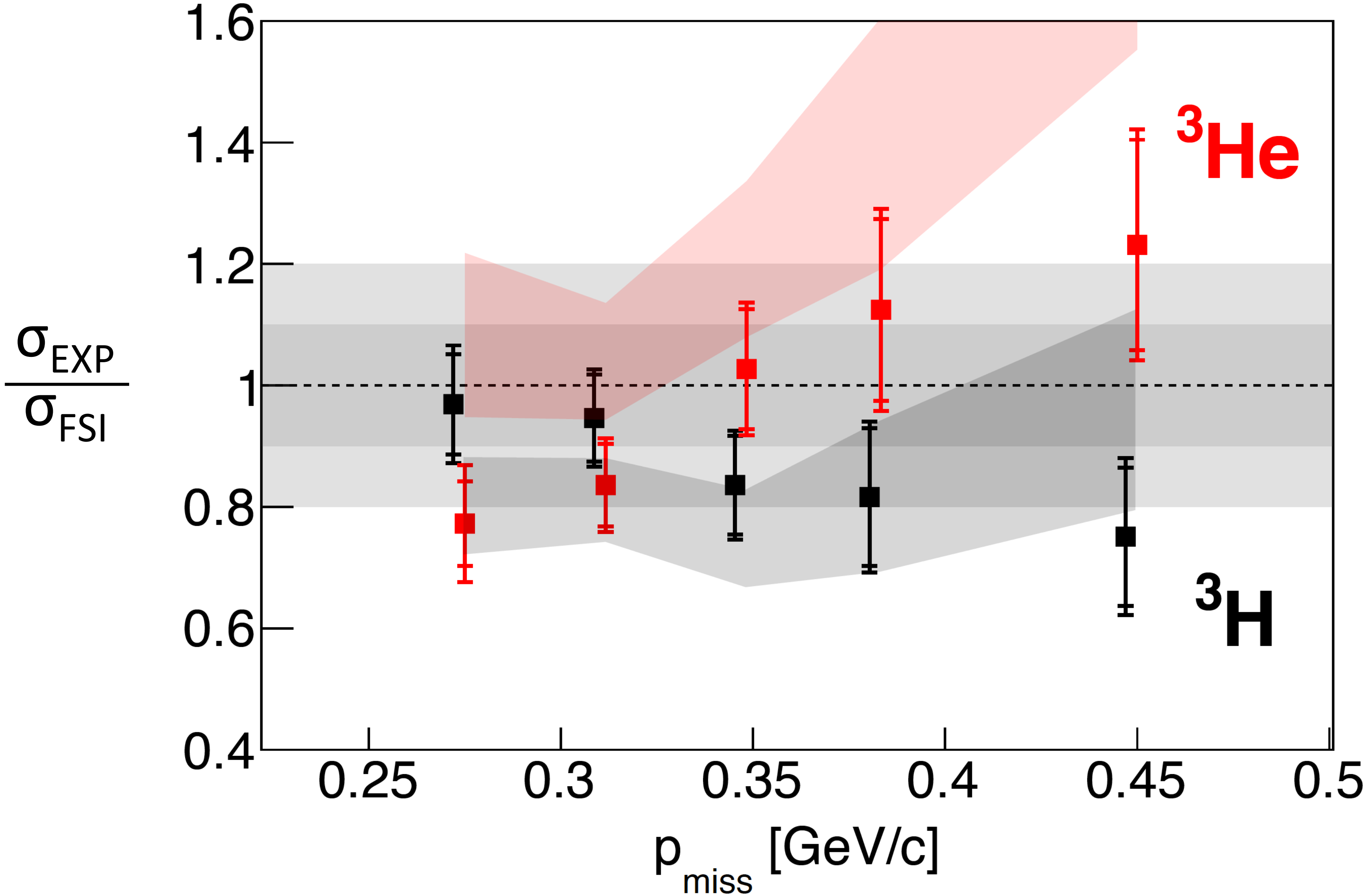


* including FSI_{23}

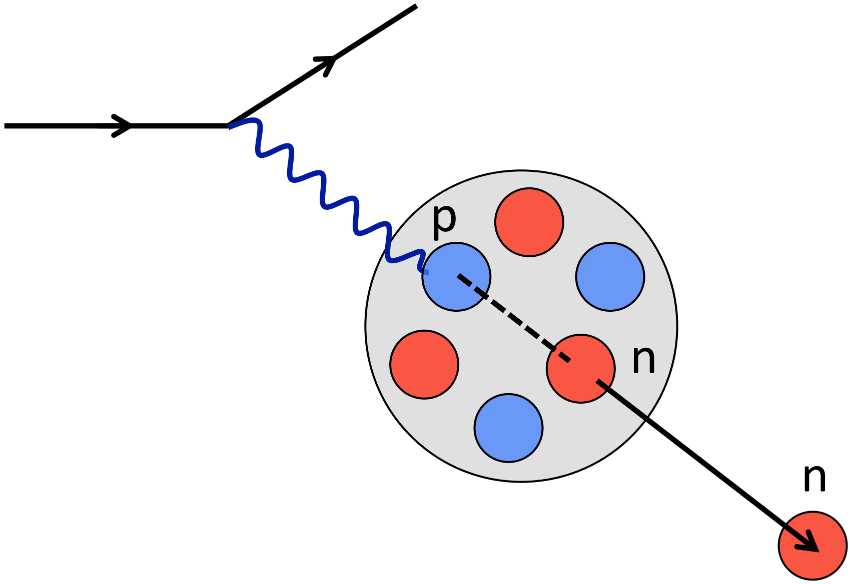
Struck-nucleon FSI at high-p_{miss}



FSI small, but improves the agreement



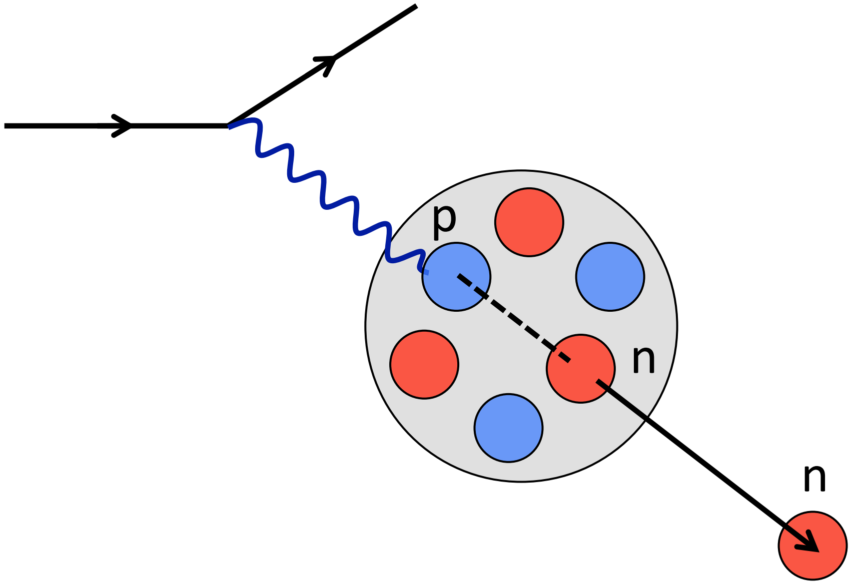
Single-Charge Exchange (SCX)



pn-SCX

(e,e’p) -> (e,e’n)
decreases σ(e,e’p)

Single-Charge Exchange (SCX)



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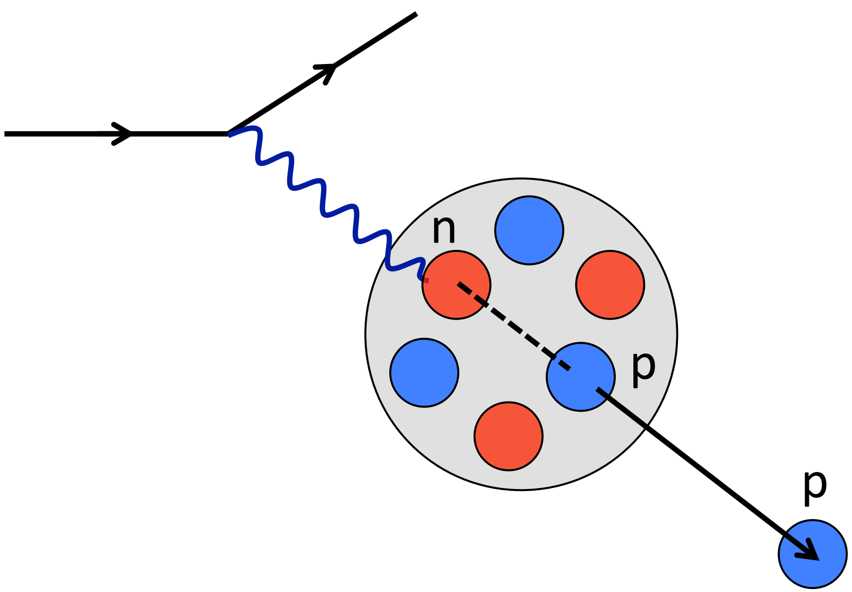
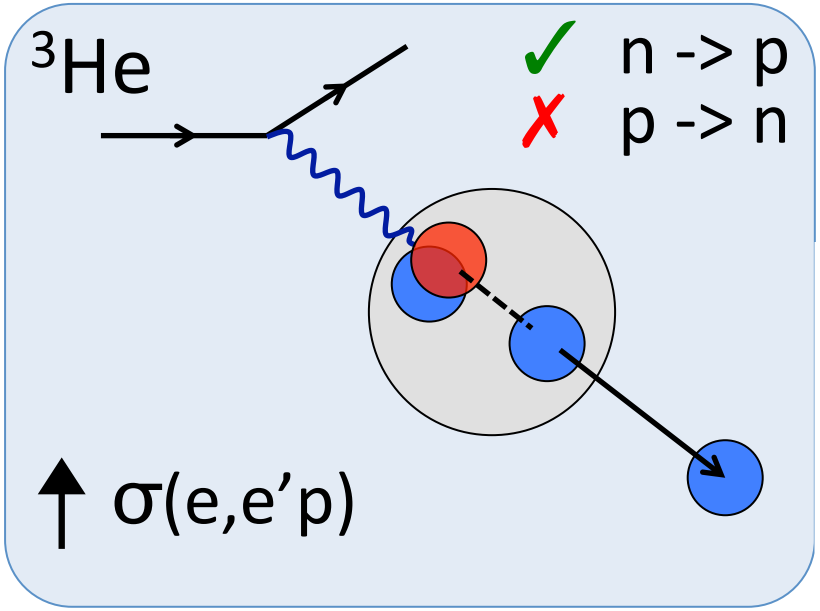
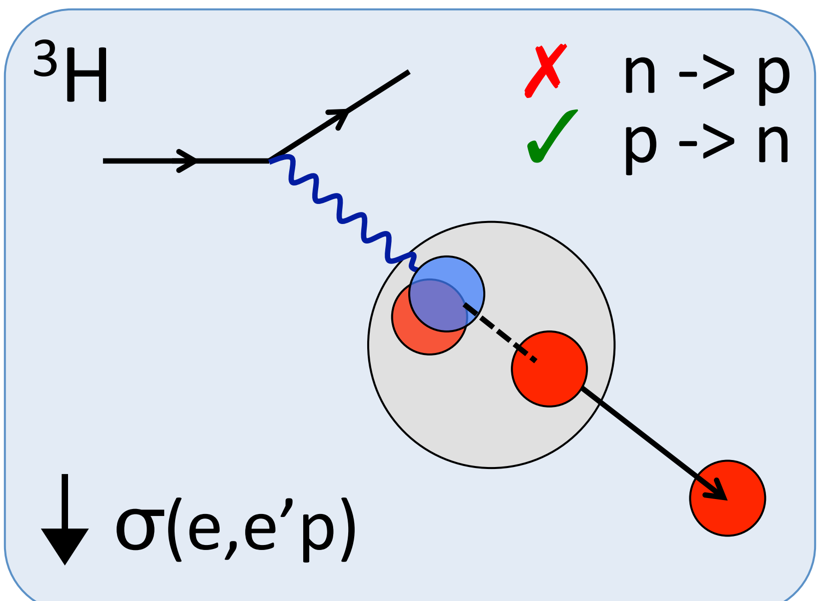


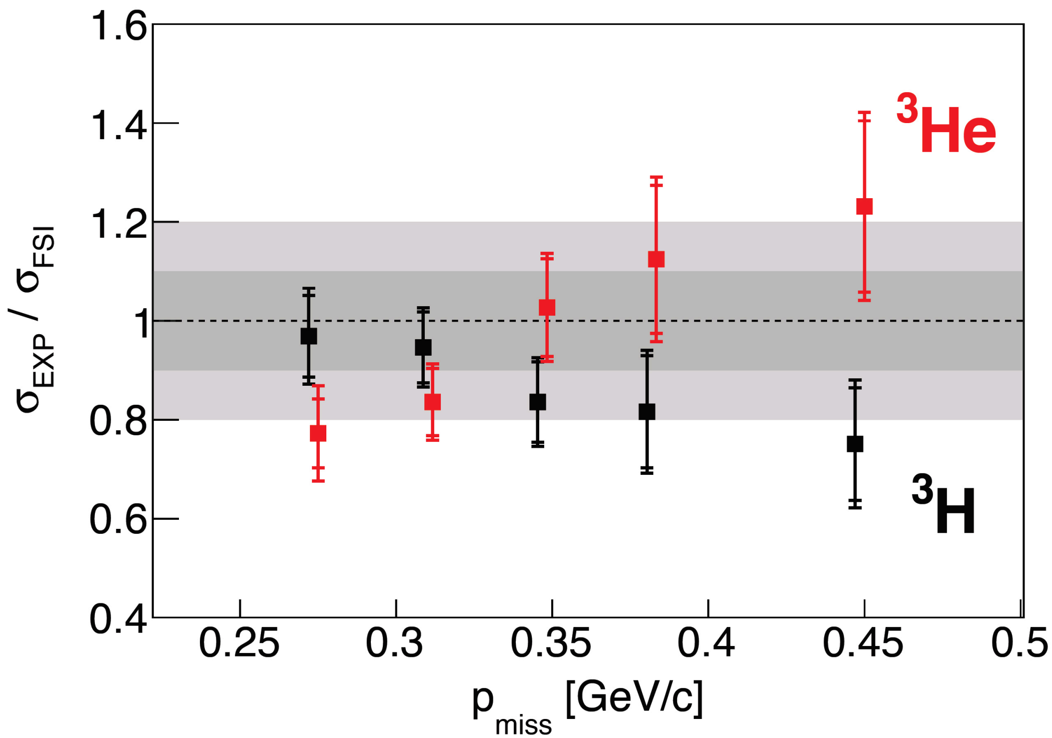
np-SCX

(e,e’n) -> (e,e’p)
increases σ(e,e’p)

SCX in A=3 at high-p_{miss}







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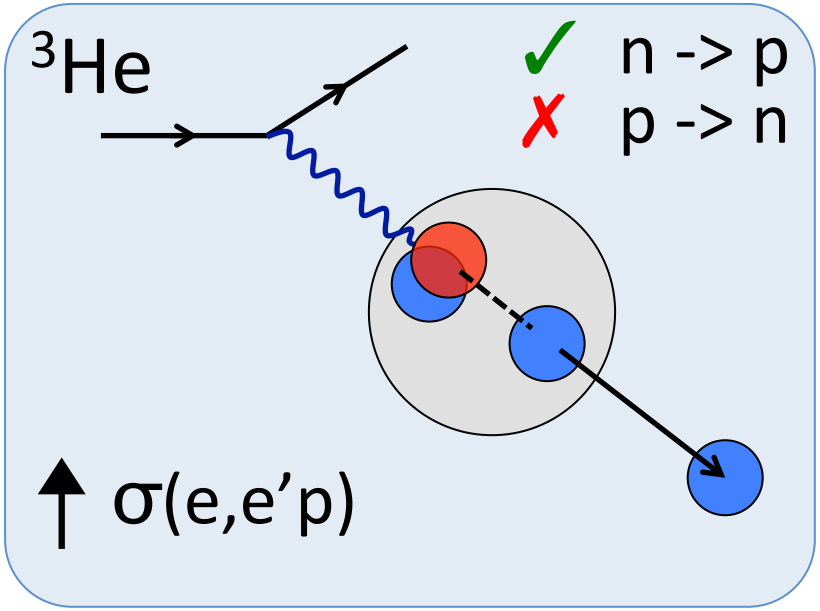
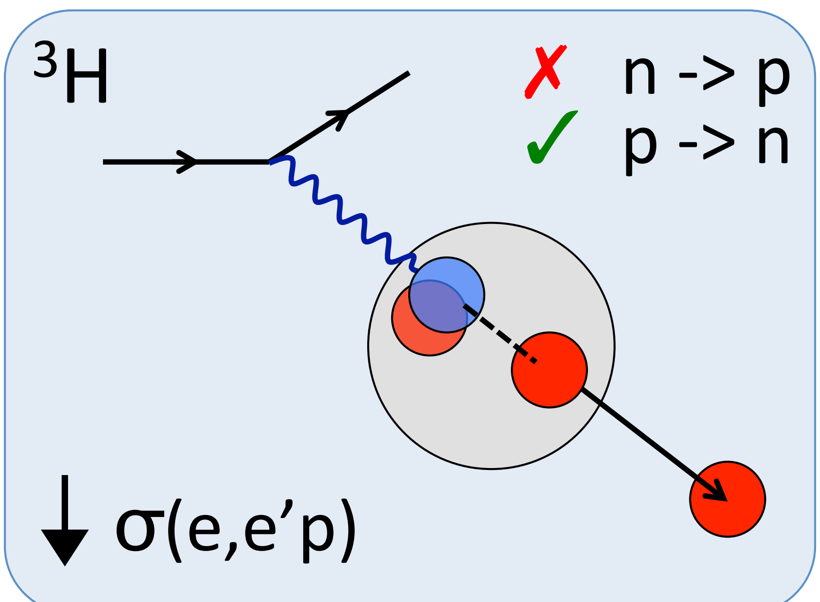
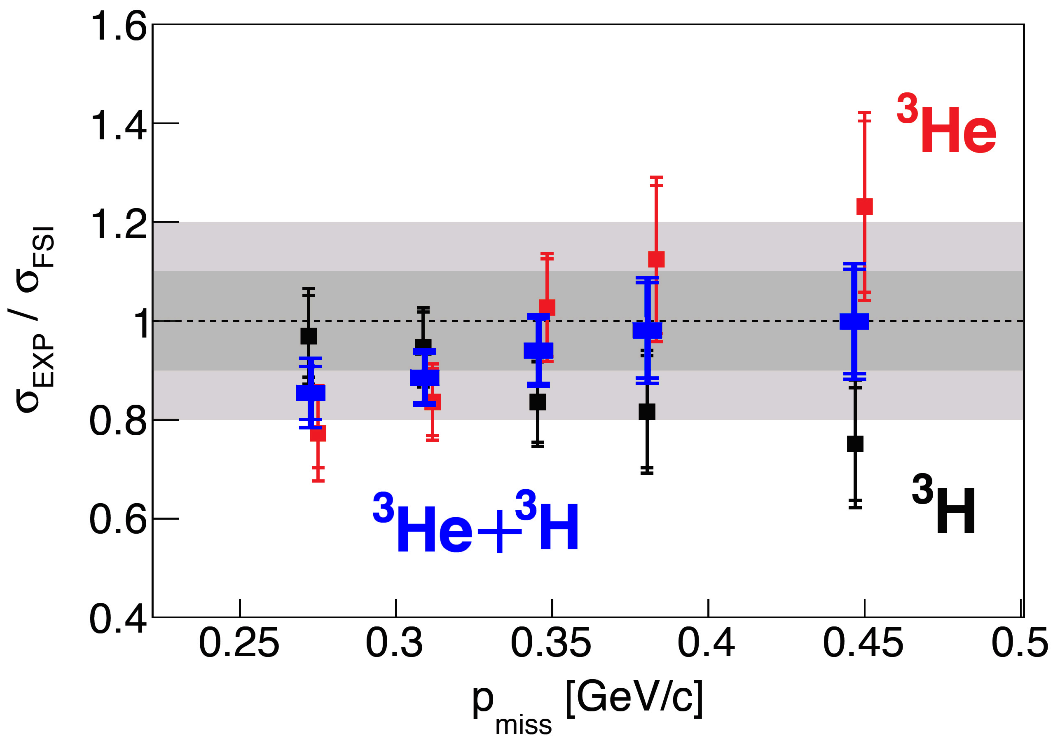


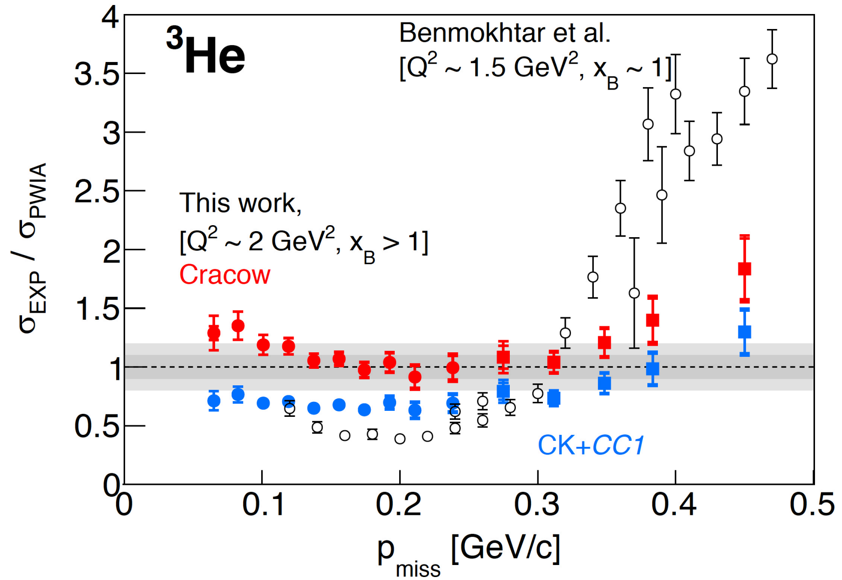




Summary and Conclusions

arXiv:2001.07230

- Smaller Non-QE contribution compared to previous measurements



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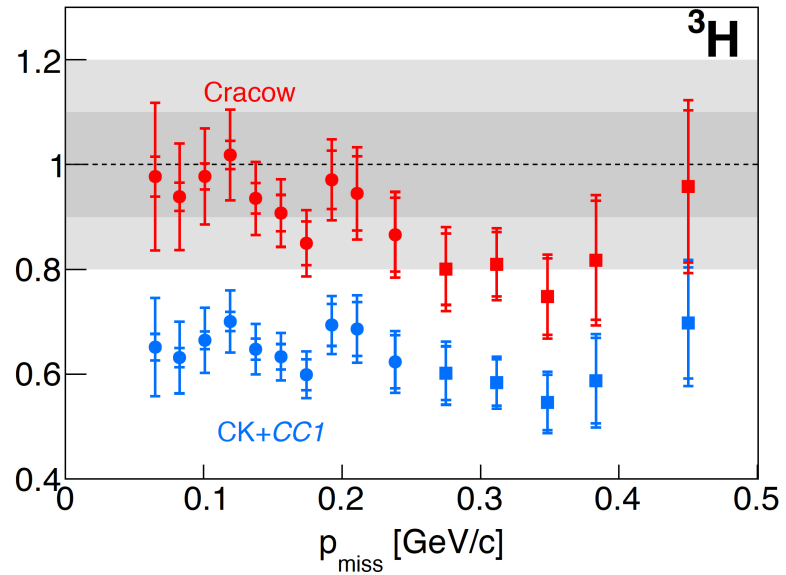

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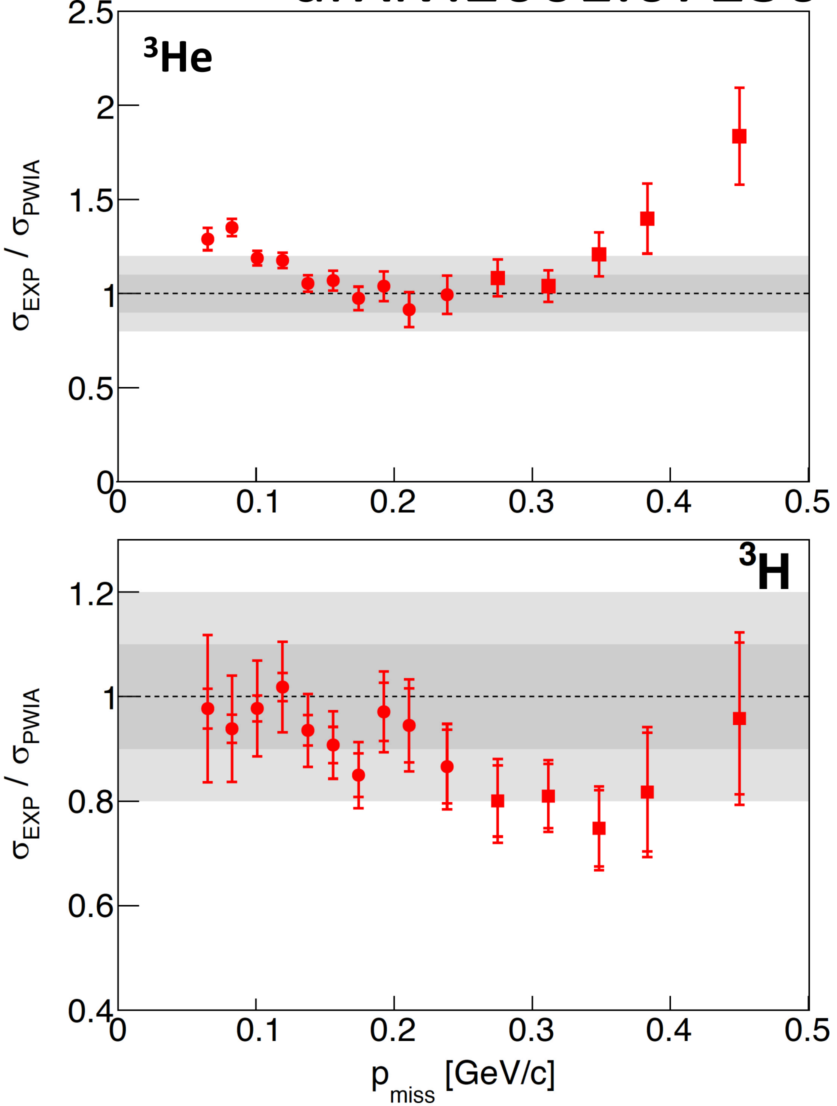

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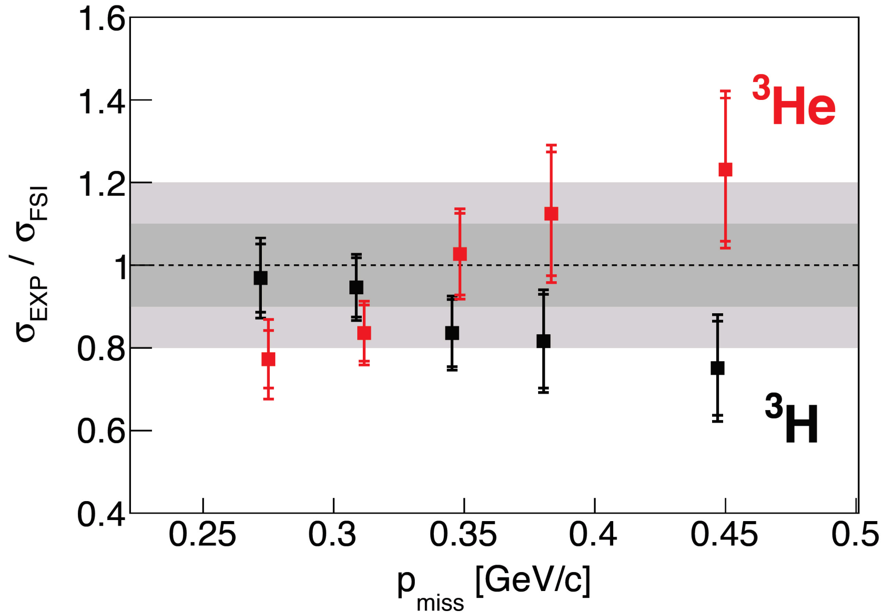

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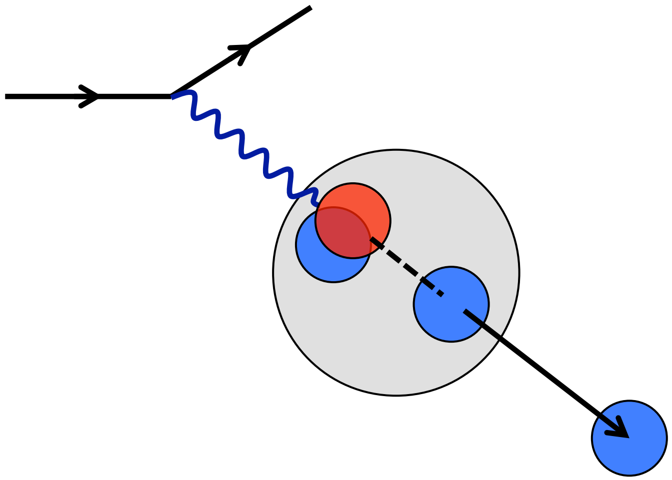
- High-p_{miss} disagreement could be explained by SCX in an np-SRC dominated regime.



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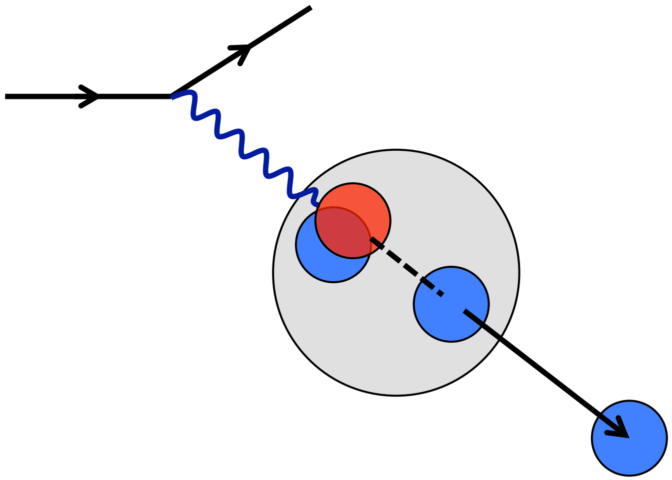
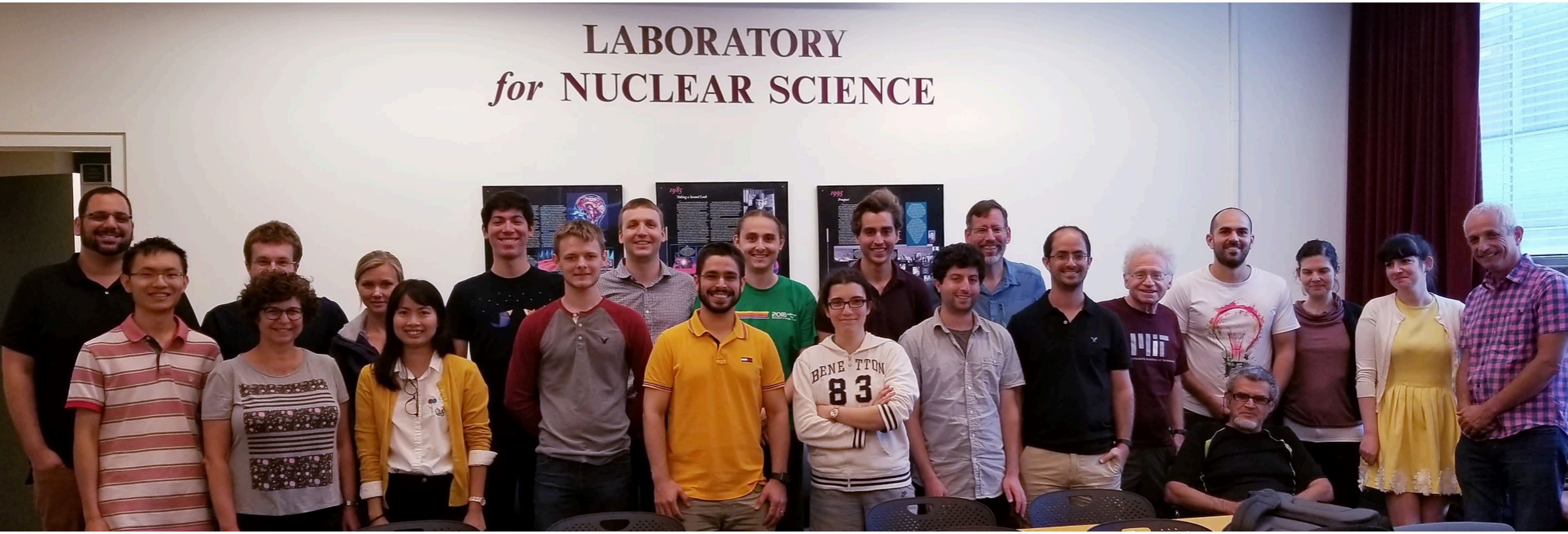
arXiv:2001.07230

- Smaller Non-QE contribution compared to previous measurements
- Better agreement with Cracow than with CK+*CC1*
- Better agreement of PWIA calculations with ^3H than with ^3He
- Inclusion of leading nucleon FSI enhances the agreement
- High-p_{miss} disagreement could be explained by SCX in an np-SRC dominated regime.



These data are a crucial benchmark for few-body nuclear theory

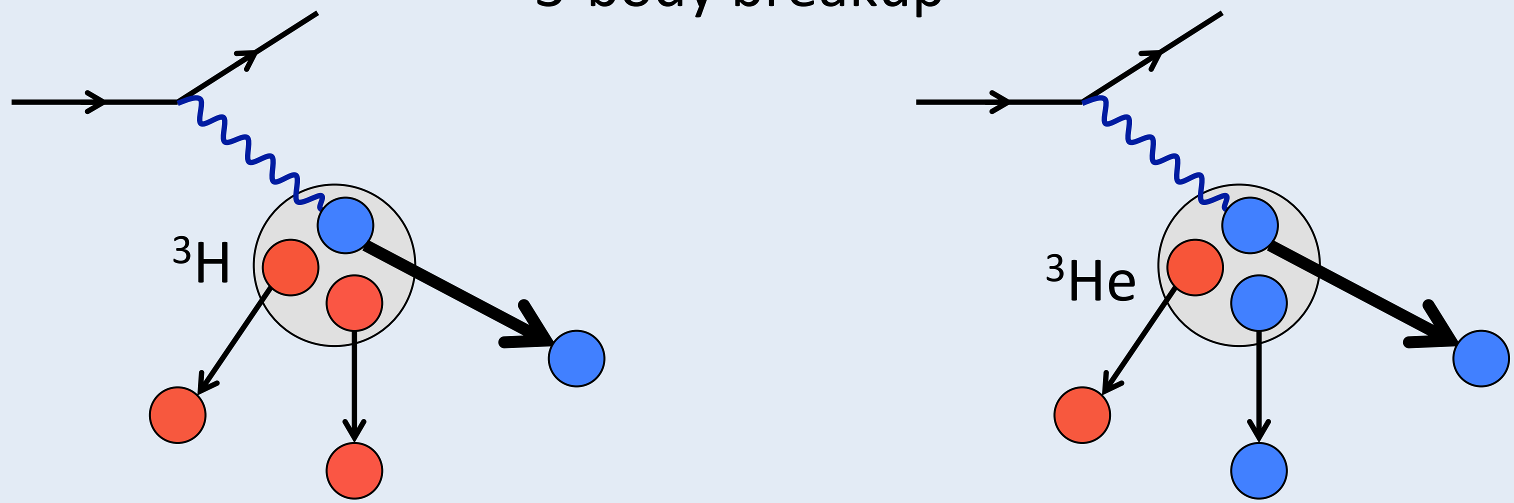
Thank you!



Backup slides

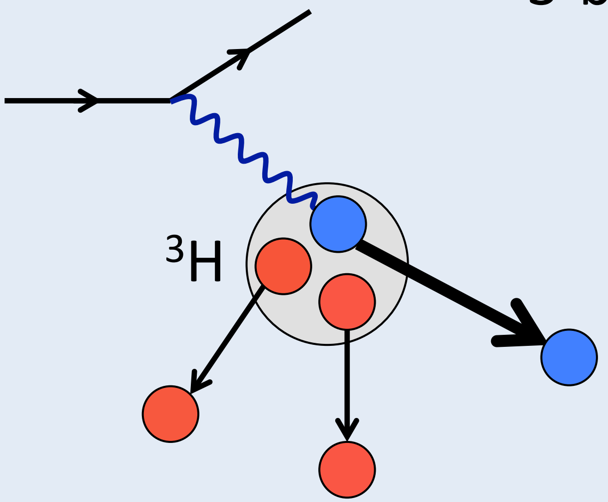
A=3 (e,e'p) channels

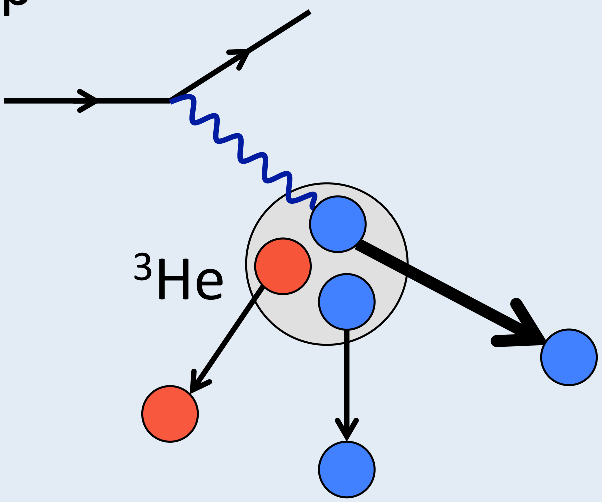
3-body breakup



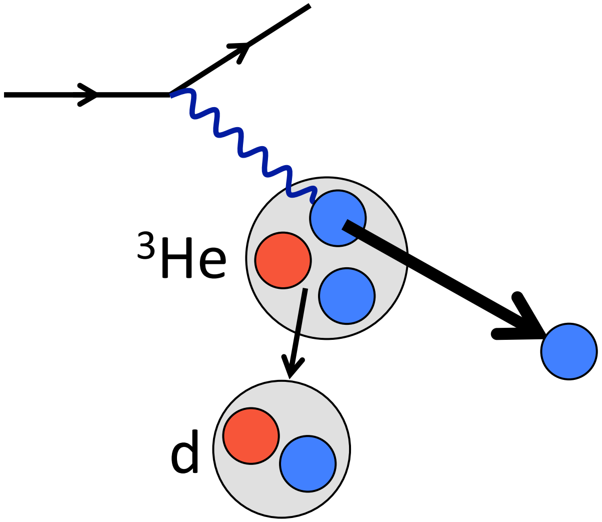
A=3 (e,e'p) channels

3-body breakup





2-body breakup



Trigger Efficiencies

LHRS triggers:

T1: (S0& S2)

T2: (S0& S2) & Cer

T3: (S0||S2) & Cer

$$\epsilon_{T1} = 1 - \frac{\text{T3 \& [! (T1||T2)]}}{\text{T1 \& T2 \& T3}}$$

RHRS & Coincidence triggers:

T4: T1 & (S0 & S2) $|_{\text{RHRS}}$

T5: T1 & S0 $|_{\text{RHRS}}$

T6: T1 & S2 $|_{\text{RHRS}}$

T7: (S0 & S2) $|_{\text{RHRS}}$

$$\epsilon_{\text{S2}_{\text{RHRS}}} = \frac{\text{T4}}{\text{T5}}, \qquad \epsilon_{\text{S0}_{\text{RHRS}}} = \frac{\text{T4}}{\text{T6}}$$

$$\epsilon_{\text{T7}} = \epsilon_{\text{S2}_{\text{RHRS}}} \times \epsilon_{\text{S0}_{\text{RHRS}}}$$

Coincidence timing: T1 – T7

$$\epsilon_{\text{coincidence}} = \epsilon_{\text{T1}} \times \epsilon_{\text{T7}}$$

Phase Space Factor and Acceptance Correction

$$\sigma = \frac{\text{(Normalized yield)}}{V_B}$$

- Simulate N_{tot} events by uniformly sampling in the ranges ΔE_e, ΔE_p, $\Delta\Omega_e$, $\Delta\Omega_p$.
- Out of N_{tot}, $N(p_{miss},E_{miss})$ are generated in that (p_{miss},E_{miss}) bin.
- Out of $N(p_{miss},E_{miss})$, $N_{acc}(p_{miss},E_{miss})$ pass the acceptance cuts.

Phase Space volume of the bin:

$$\Phi = \frac{N(p_{miss},E_{miss})}{N_{tot}} \times (\Delta E_e \Delta E_p \Delta\Omega_e \Delta\Omega_p)$$

Acceptance Correction:

$$A = \frac{N_{acc}(p_{miss},E_{miss})}{N(p_{miss},E_{miss})}$$

$$V_b = A\Phi = \frac{N_{acc}(p_{miss},E_{miss})}{\cancel{N(p_{miss},E_{miss})}} \times \frac{\cancel{N(p_{miss},E_{miss})}}{N_{tot}} \times (\Delta E_e \Delta E_p \Delta\Omega_e \Delta\Omega_p)$$

$$V_b = \frac{N_{acc}(p_{miss},E_{miss})}{N_{tot}} \times (\Delta E_e \Delta E_p \Delta\Omega_e \Delta\Omega_p)$$

Corrections

- **Bin Centering Correction**

$$C_{bc}(p_{miss}) = \frac{\sigma^{model}_{point}(p_{miss})}{\sigma^{model}_{mean}(p_{miss})}$$

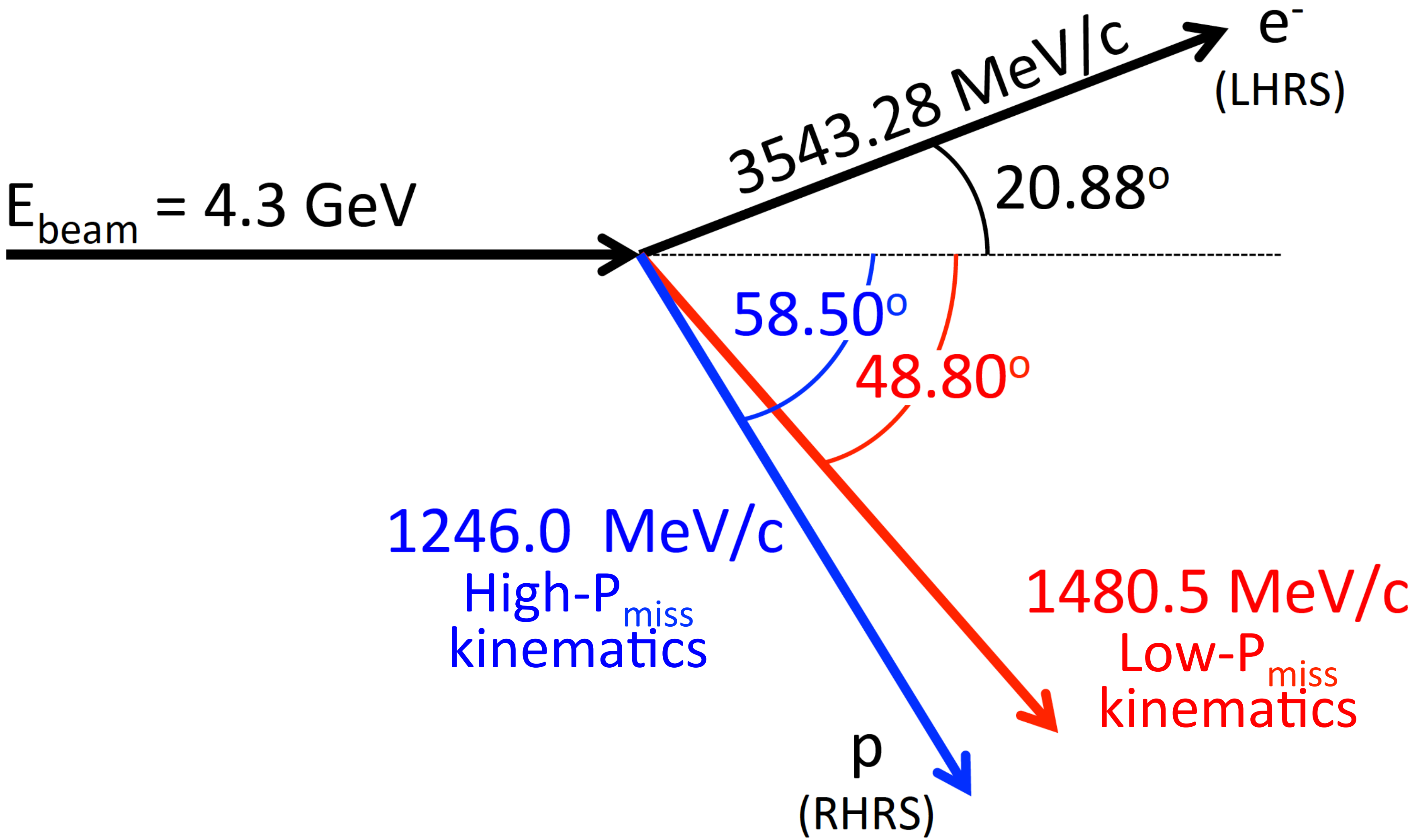
- **Bin Migration Correction**

$$C_{bm}(p_{miss}, E_{miss}) = \frac{\sigma^{generated}_{Born}(p_{miss}, E_{miss})}{\sigma^{reconstruc}_{Born}(p_{miss}, E_{miss})}$$

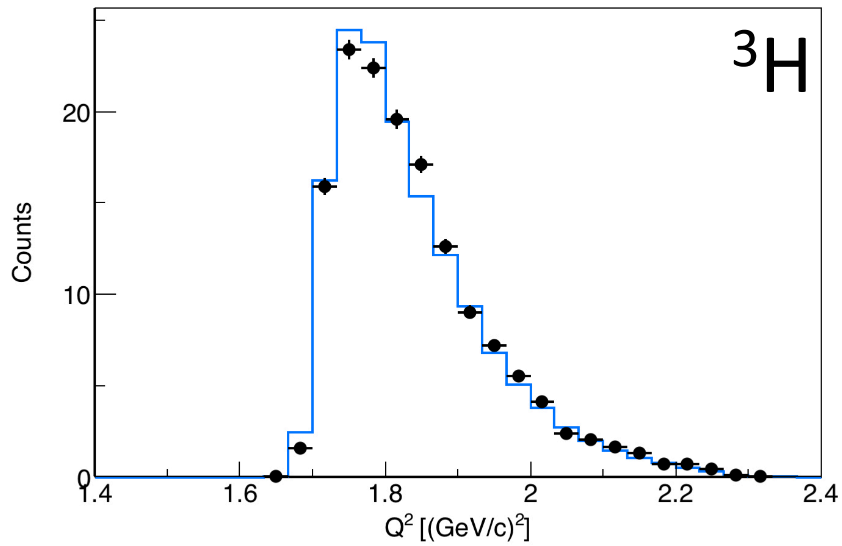
- **Radiative Correction**

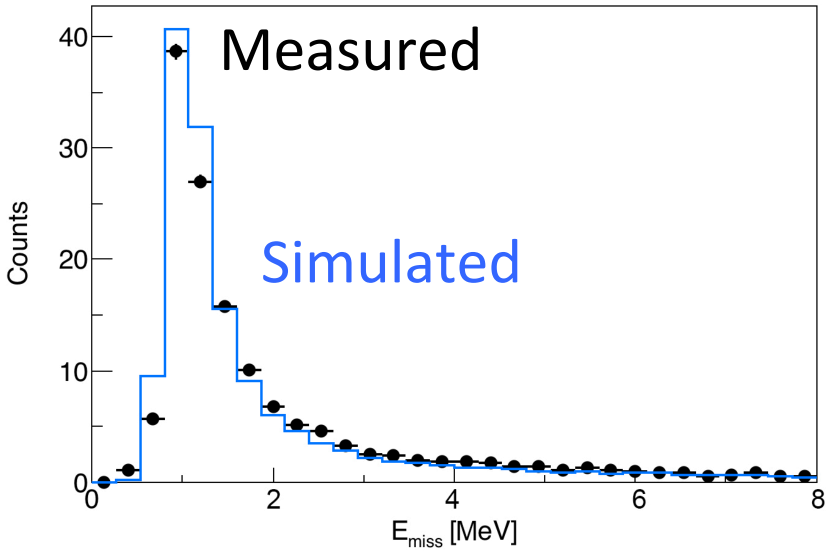
$$C_{Rad}(p_{miss}, E_{miss}) = \frac{\sigma^{model}_{Born}(p_{miss}, E_{miss})}{\sigma^{model}_{Rad}(p_{miss}, E_{miss})}$$

Kinematical settings



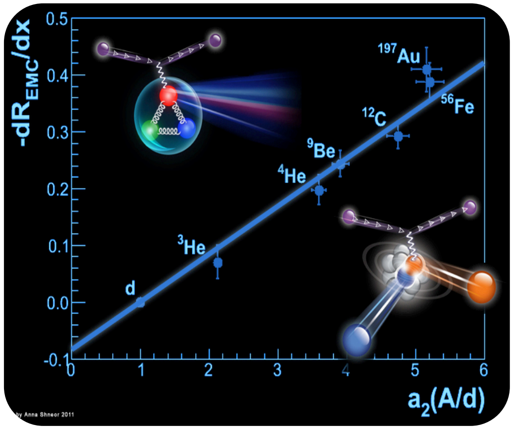
Simulations



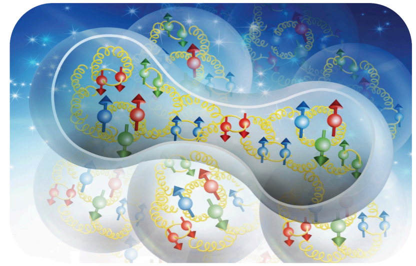


- Hall-A Monte Carlo event generator
- Emulates experiment setup (detector resolution, optics, acceptance, …)
- Includes radiative effects, energy loss, …
- ^{3}He, ^{3}H cross section model not properly implemented

Significance of SRC research

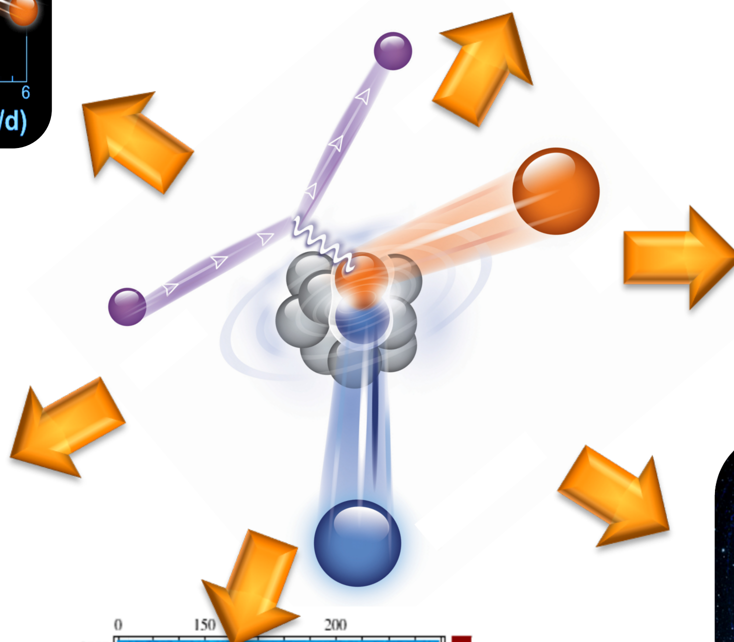


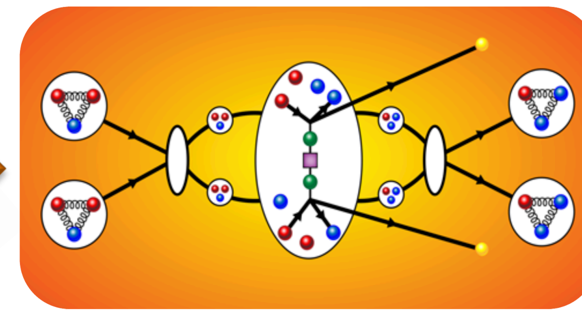
EMC

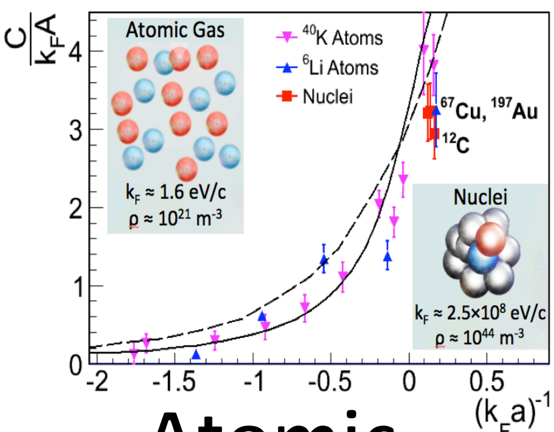


QCD effects in nuclei

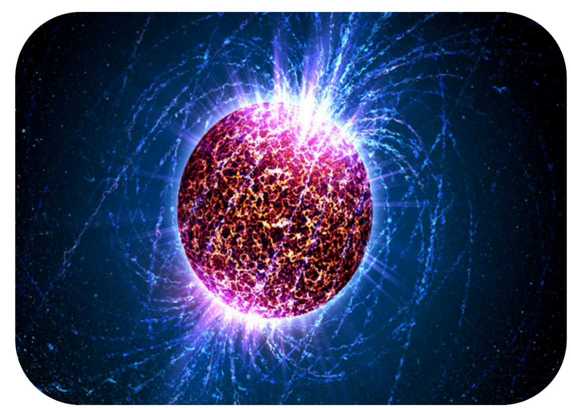
high-q processes





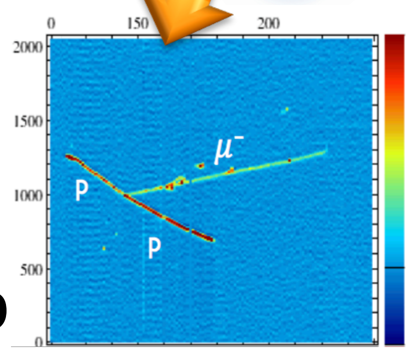


Atomic



High-density systems

Neutrino



Unitary interlude

- Interpretation of missing-momentum in PWIA relies on *single nucleon* interaction operators.

- Unitary transforms simplifies calculations of heavy nuclei at the expense of forming many-body operators.

  $\langle \Psi | \hat{O} | \Psi \rangle = \langle \Psi\, U^{\dagger} | U\, \hat{O}\, U^{\dagger} | U\, \Psi \rangle$

  – Transforms “high momentum” to “short range”

    Win: Simpler wave functions

    Lose: Complicated interaction operators

    Trick: Transform wave-function but not the operators 😬😬

  – No calculations for e-scattering off heavier nuclei, yet.

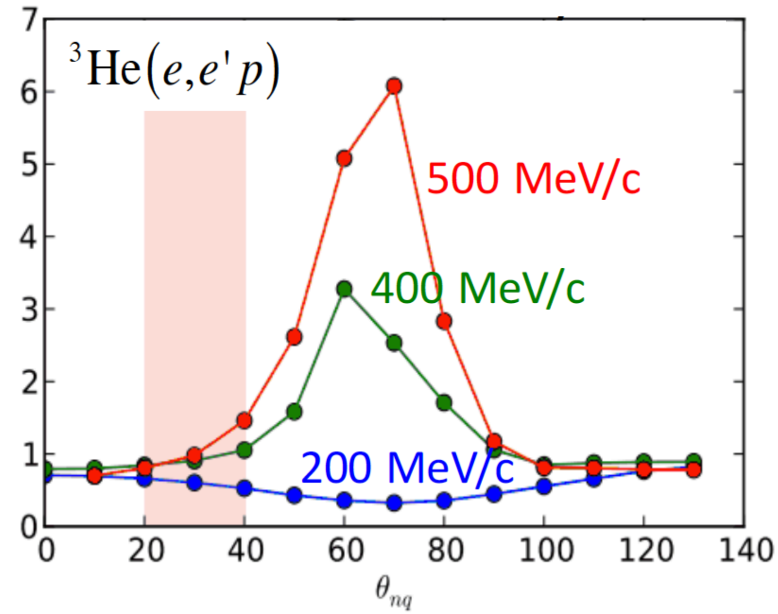
- Complete physical equivalent.
  – Same cross sections
  – Different interpretations

Event selection cuts

electron-PID: $E_{cal}/|\mathbf{p}| > 0.5$
proton in coincidence: $\Delta t_{e\text{-}p} < 3\sigma$
target wall cut: $|vz| < 9.5$ cm
$\Delta vz_{e\text{-}p} < 1.2$ cm ($< 3\sigma$)

Acceptance:
$\delta < 4\%$
ϕ (horizontal) < 25.5 mrad
θ (vertical) < 55.0 mrad

FSI: $\theta_{rq} <$ 37.5 deg →

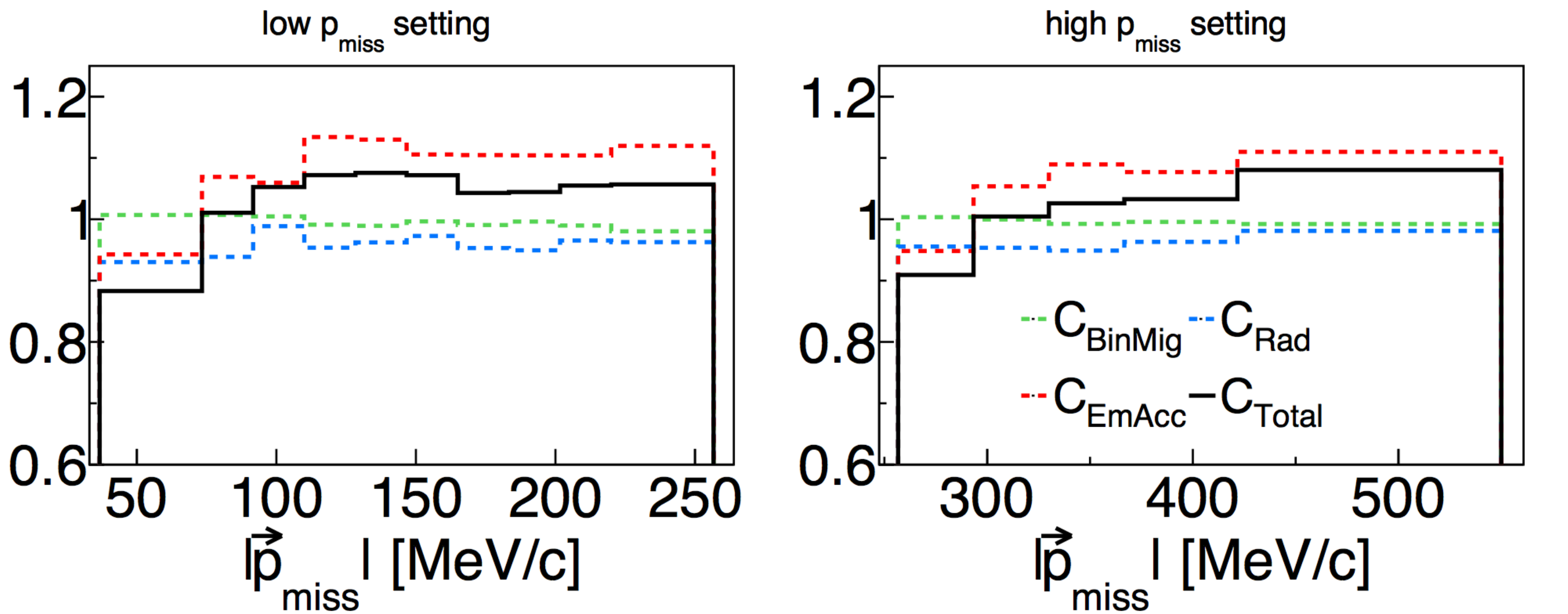


non-QE events: xB > 1.3
(high-Pmiss kinematics)

Corrections

$$R^{\text{meas.}}_{n(p)}(p_{miss}) = R^{corr.yield}_{^3\text{He}/^3\text{H}}(p_{miss}) \times C_{\text{BinMig}} \times C_{\text{Rad}} \times C_{E_m\text{Acc}}$$

$$\begin{aligned} C_{\text{BinMig}} &= R^{\sigma_{\text{Rad}}}_{\text{Sim}}(p^{\text{gen}}_{miss}) \;/\; R^{\sigma_{\text{Rad}}}_{\text{Sim}}(p^{\text{rec}}_{miss}), \\ C_{\text{Rad}} &= R^{\sigma_{\text{Born}}}_{\text{Sim}}(p^{\text{gen}}_{miss}) \;/\; R^{\sigma_{\text{Rad}}}_{\text{Sim}}(p^{\text{gen}}_{miss}), \\ C_{E_m\text{Acc}} &= n_{^3\text{He}/^3\text{H}}(p^{\text{gen}}_{miss}) \;/\; R^{\sigma_{\text{Born}}}_{\text{Sim}}(p^{\text{gen}}_{miss}) \end{aligned}$$



Ratios of AV18/N^{2}LO momentum distributions

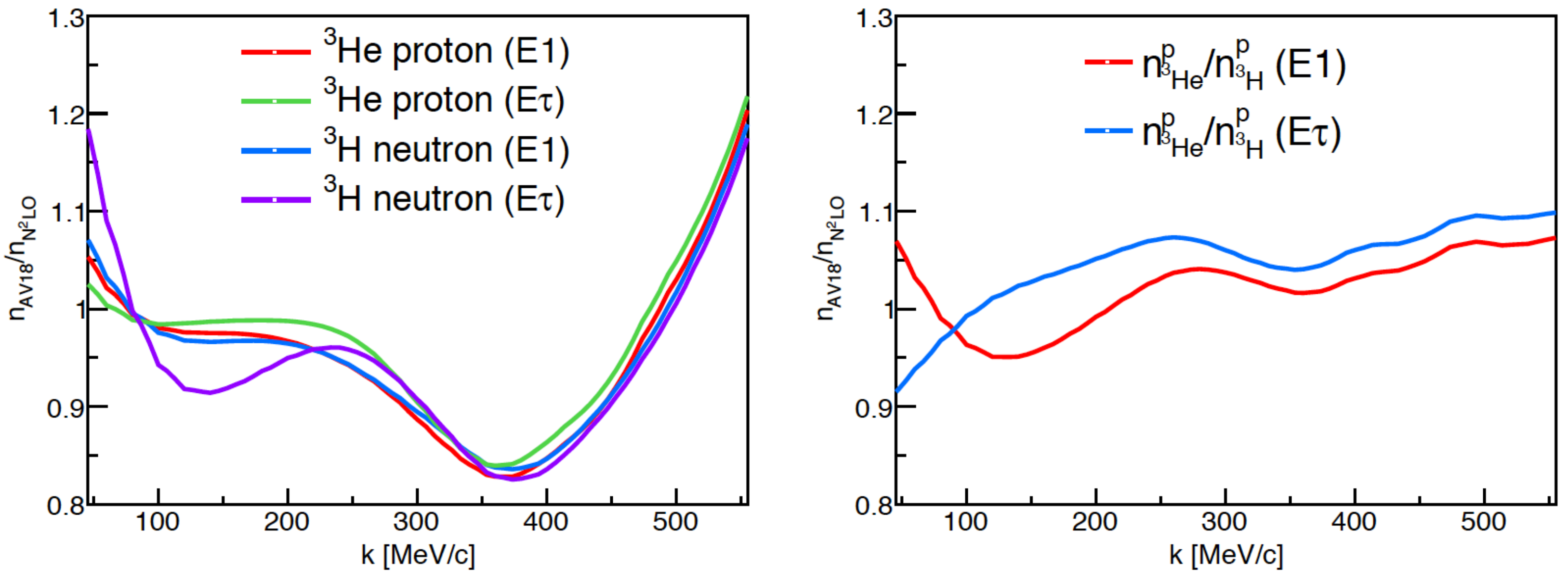
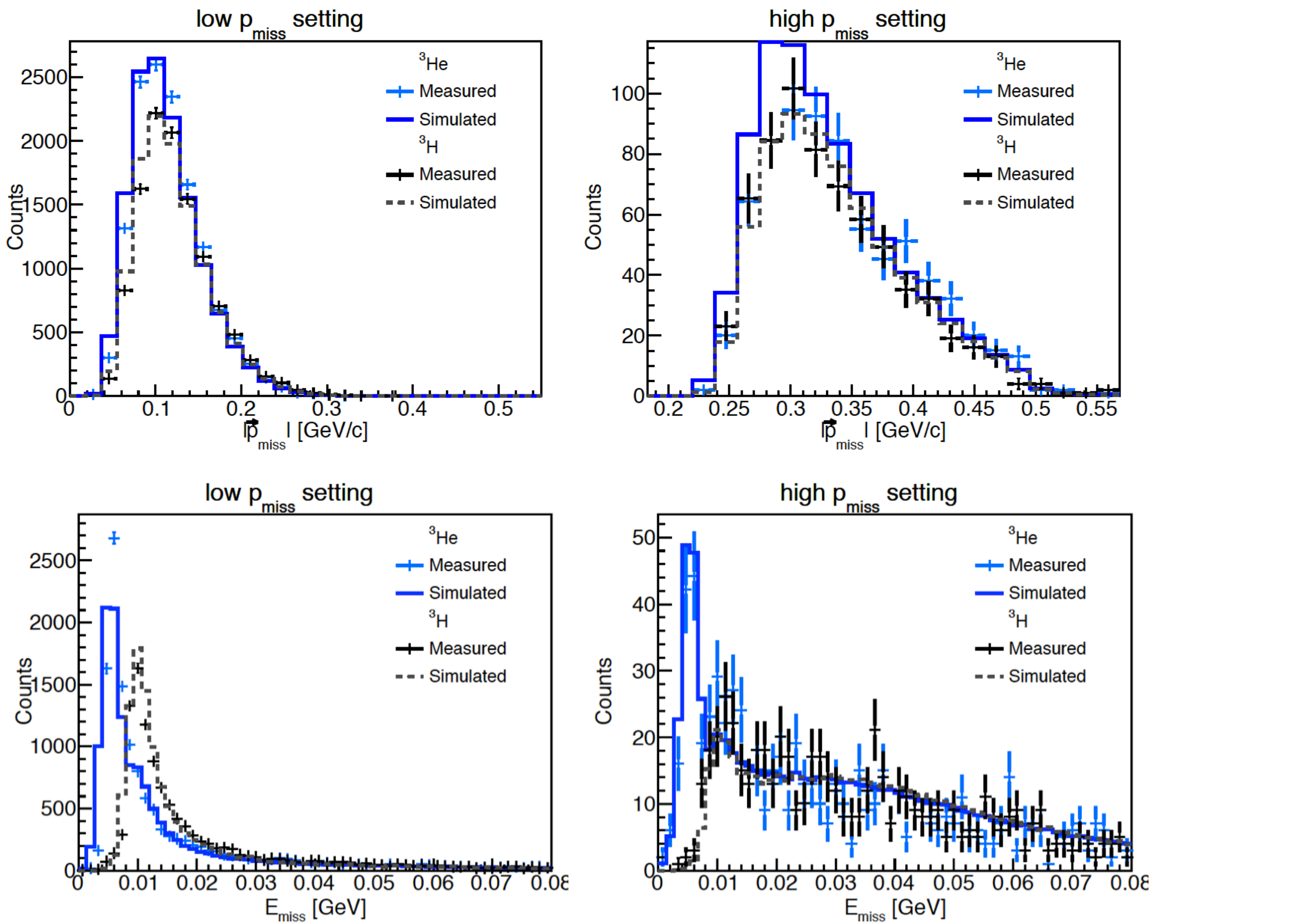
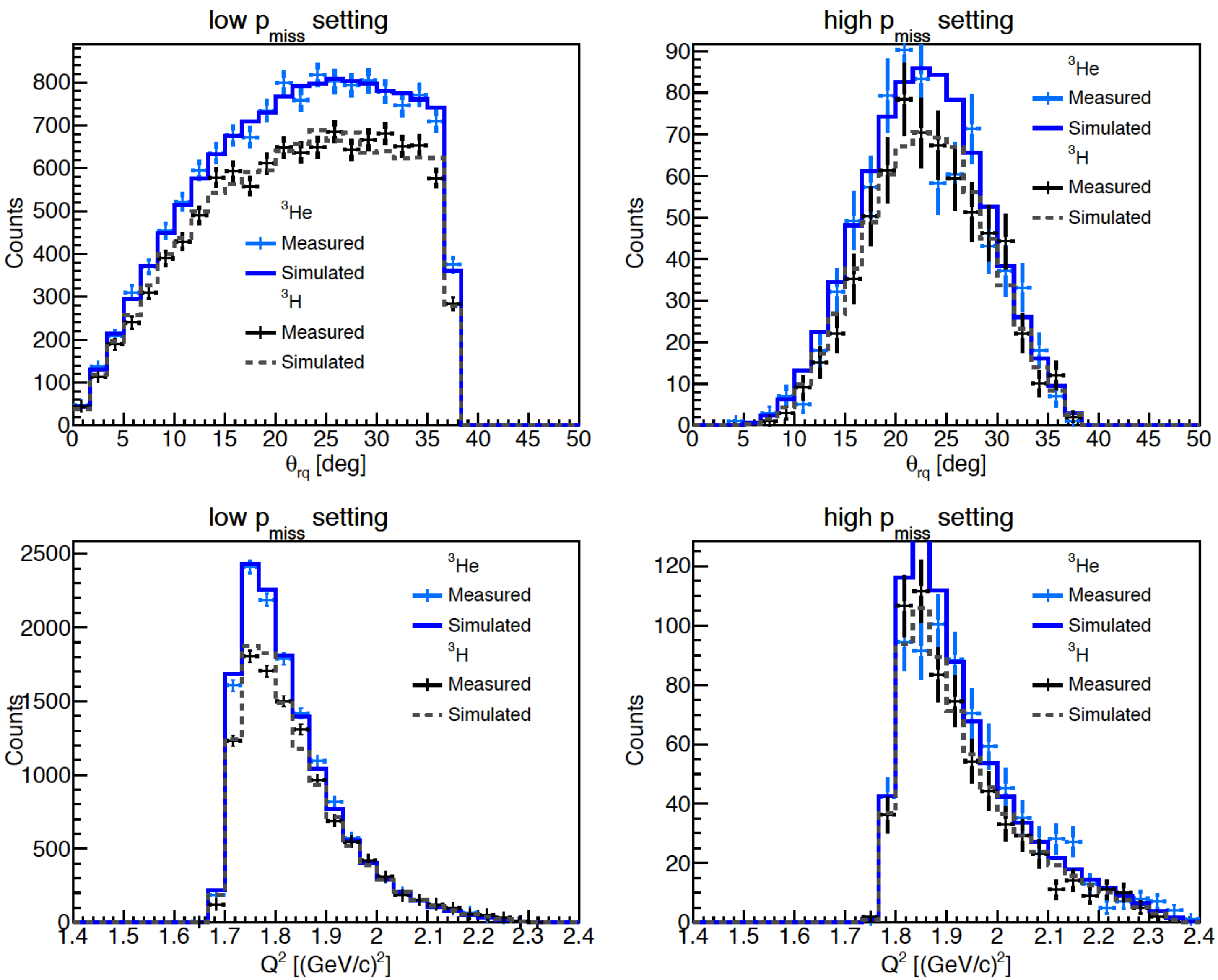


FIG. 2: Ratio of different distributions obtained using the AV18 and N^{2}LO potentials. The left figure shows the $(n_{A=3})_{AV18}/(n_{A=3})_{N^2LO}$, where $n_{A=3}$ refers to the ^{3}He proton and ^{3}H neutron momentum distributions. The right figure shows the double ratio $(n^p_{^3He}/n^p_{^3H})_{AV18}/(n^p_{^3He}/n^p_{^3H})_{N^2LO}$.

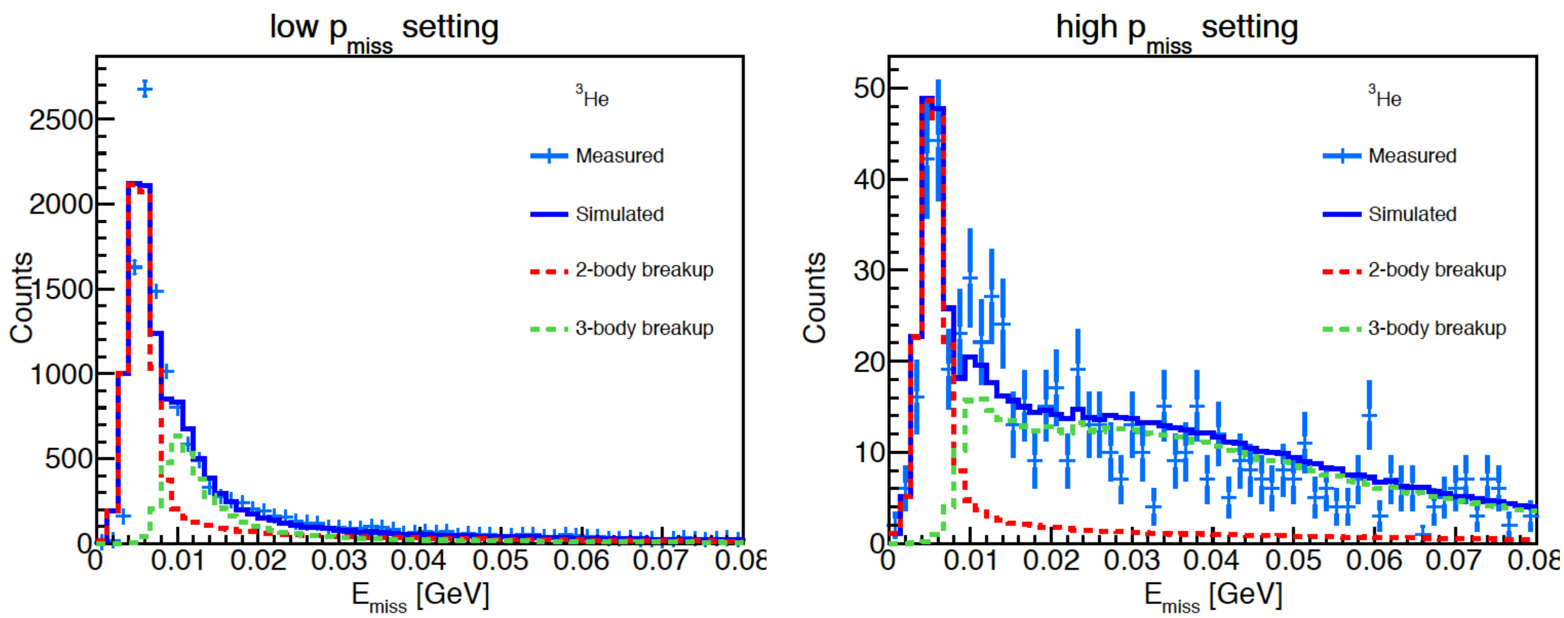
Measurement-simulation comparison



Measurement-simulation comparison



2- and 3-body breakups in ^3He



Cross Section Models

Unfactorized Calculation

$$\sigma = \sigma_{\mathrm{Mott}} \hat{l}^{\mu\nu} W_{\mu\nu}^{A}$$

- J. Golak, M. Sargsian

Factorized Approximation

$$\sigma = \sigma_{\mathrm{ep}} \cdot \mathrm{S}(\mathrm{p_i}, \mathrm{E_i})$$

- σ_{ep}: T. De Forest, S: CDA, Kaptari

Systematic Uncertainties

	Overall	Point-to-point
Target Walls	$\ll 1\%$	
Target Density	1.5%	
Beam-Charge and Stability	1%	
Tritium Decay	0.18%	
Cut sensitivity		1% - 8%
Simulation Corrections (bin-migration, radiation, E_m acceptance)		1% - 2%