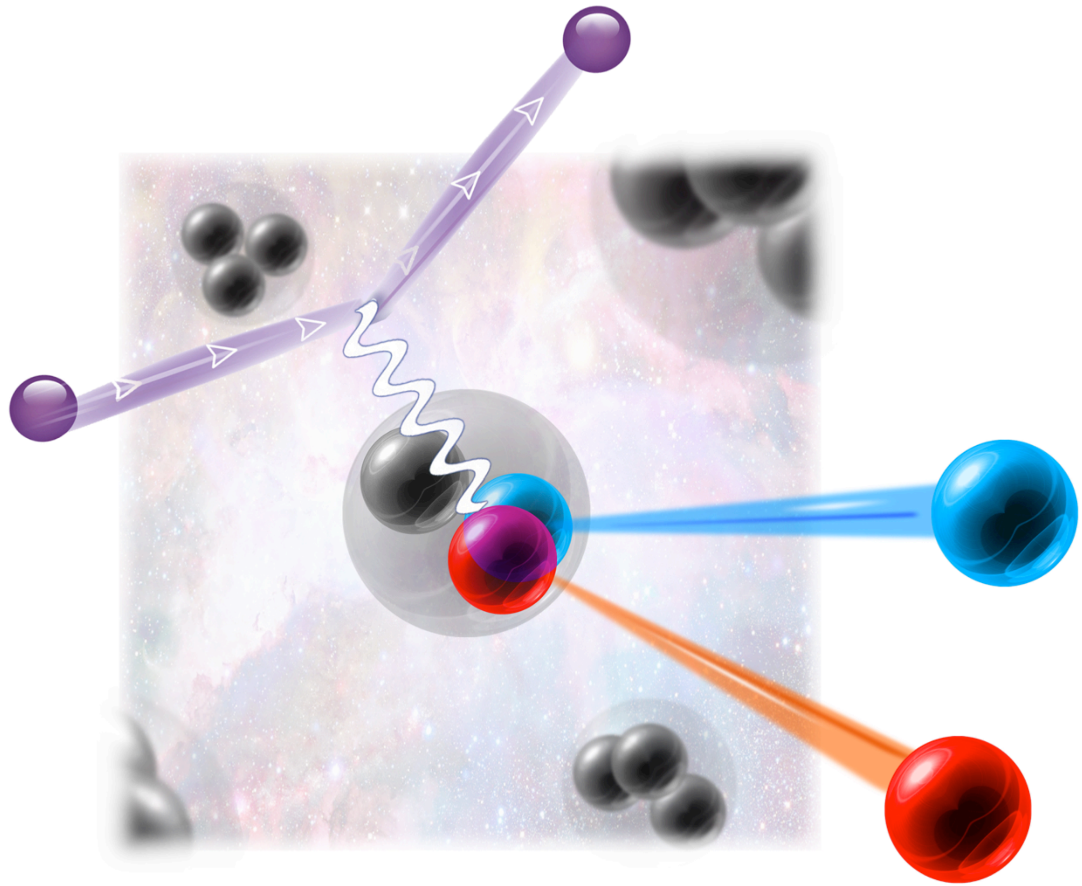
Tritium QE (e,e'p)



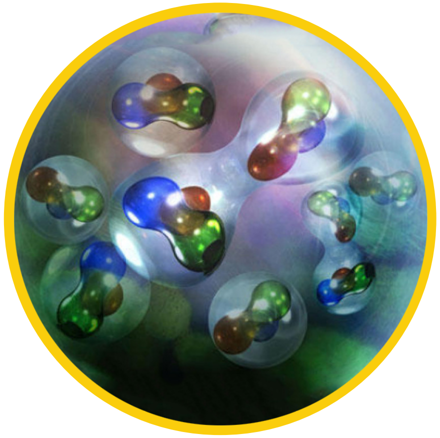
Reynier Cruz Torres
Hall A/C Summer Meeting
June 28th, 2019

Hen Lab
Laboratory for Nuclear Science @ MIT
Jefferson Lab

Nucleon-nucleon interaction

Crucial for:
- Ab-Initio nuclear structure calculations
- understanding dense astrophysical objects such as neutron stars

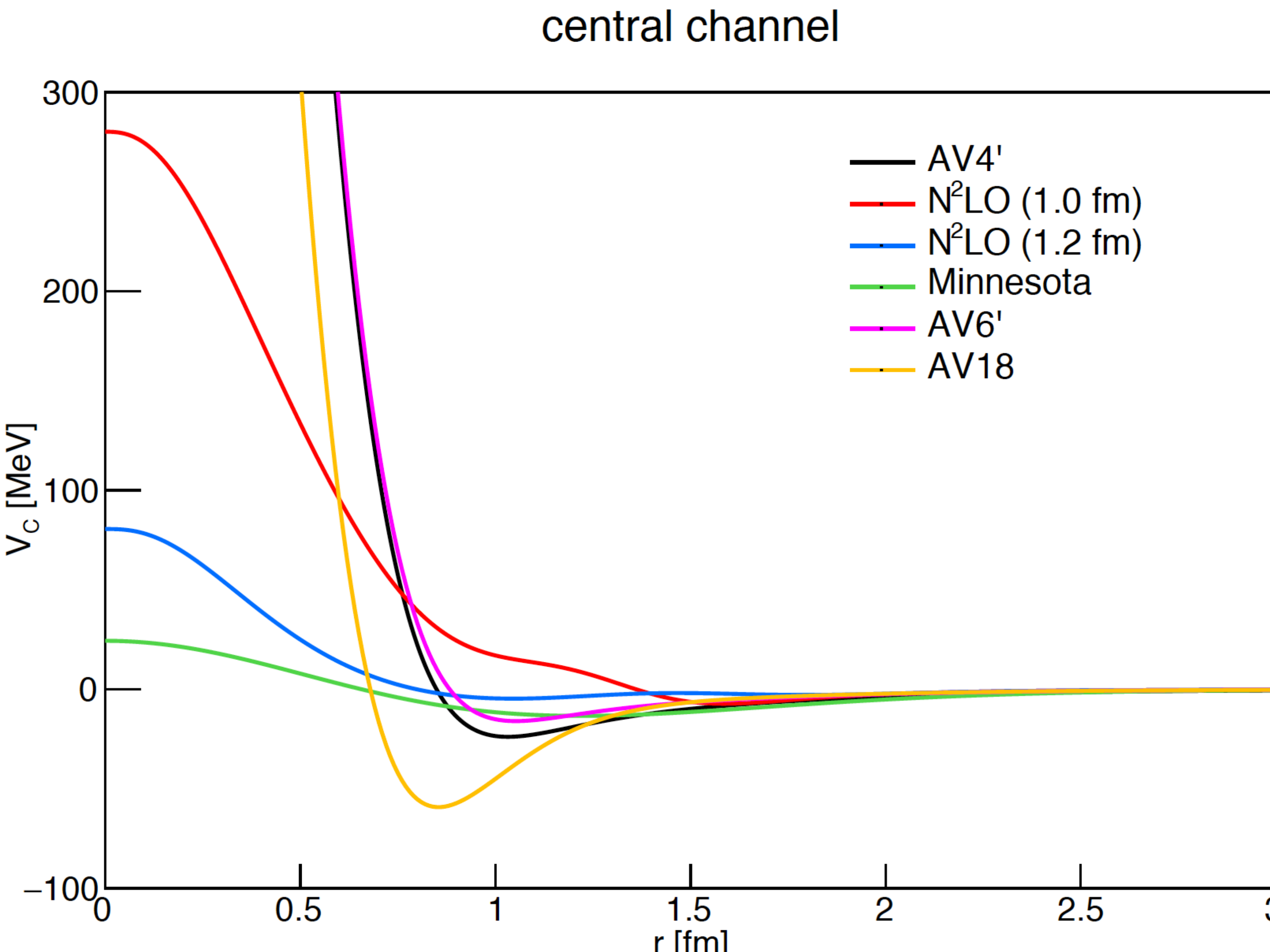
Strong nuclear force, Coulomb force, spins, magnetic moments ...



There are many NN potential models…

- Hamada-Johnston Potential
- Yale-Group Potential
- Reid68 Potential
- Reid-Day Potential
- Partovi-Lomon Potential
- Paris-Group Potentials
- Stony-Brook Potential
- dTRS Super-Soft-Core Potentials
- Funabashi Potentials
- Urbana-Group Potentials
- Argonne-Group Potentials
  - Argonne V14
  - Argonne V28
  - Argonne V18
- Bonn-Group Potentials
  - Full-Bonn Potential
  - CD-Bonn Potential
- Padua-Group Potential
- Nijmegen-Group Potentials
  - Nijm78 Potential
  - Partial-Wave-Analysis
  - Nijm93
  - NijmI
  - NijmII
  - Reid93 Potential
  - Extended Soft-Core
  - Nijmegen Optical Potentials
- Hamburg-Group Potentials
- Moscow-Group Potentials
- Budapest(IS)-Group Potential
- MIK-Group Potential
- Imaginary Potentials
- QCD-Inspired Potentials
- The Oxford Potential
- The First CHPT NN Potentials
- Sao Paulo-Group CHPT Potentials
- Munich-Group CHPT Potentials
- Idaho-Group CHPT Potentials
- Bochum-Julich-Group CHPT Potentials
  - LO Potentials
  - NLO Potentials
  - NNLO Potentials
  - NNNLO Potentials
- **and more!**

…still, short-range behavior in unconstrained

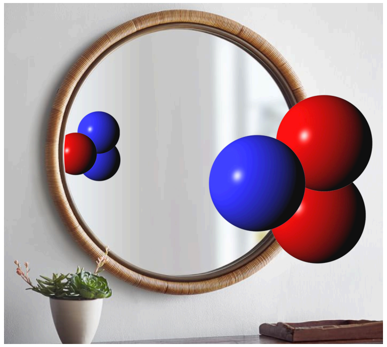


Why light nuclei?

- can be exactly calculated for a given two- and three-nucleon interaction model.

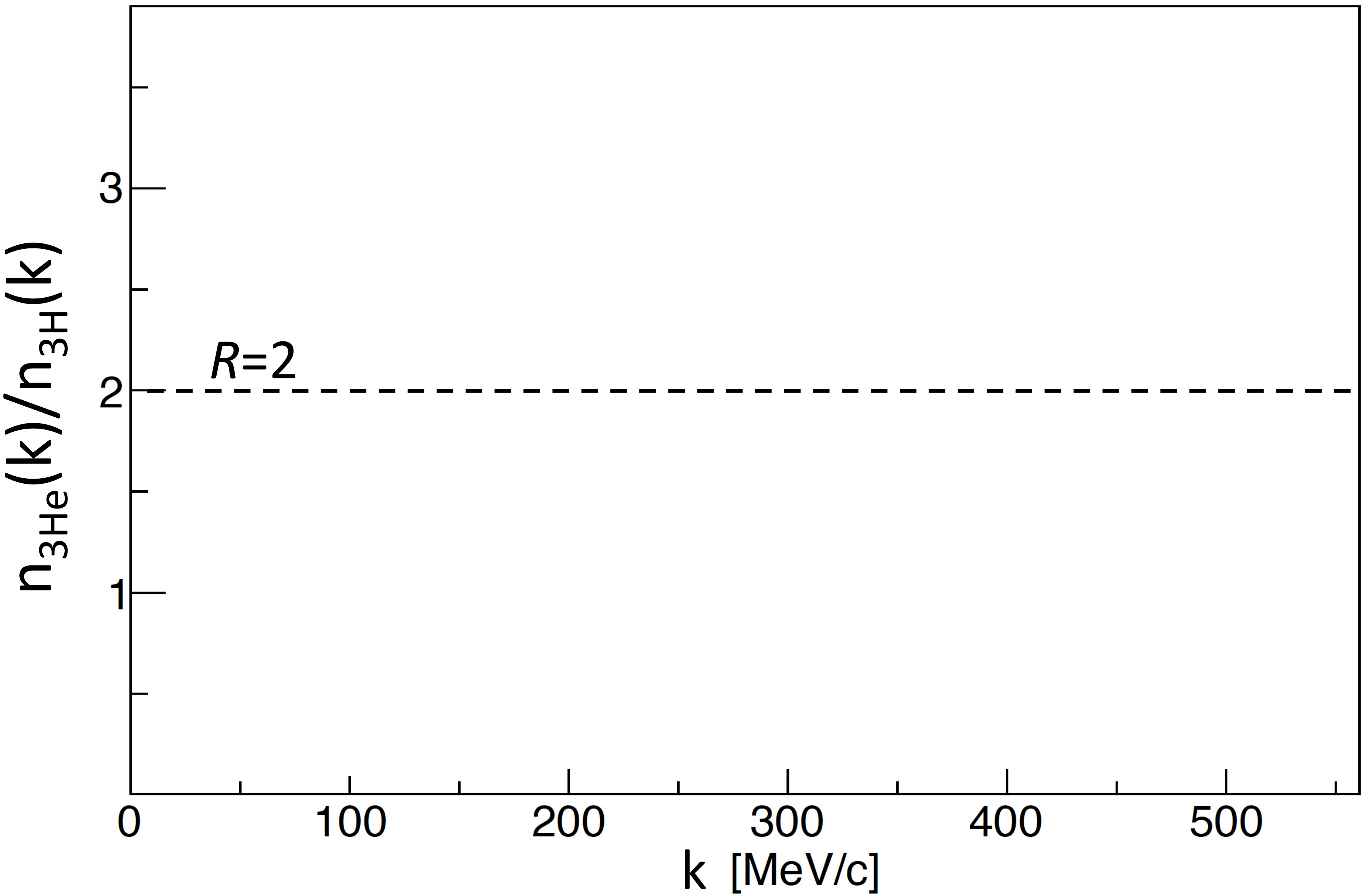
Why Tritium?

- Isospin doublet:
  - ^{3}He is stable mirror nucleus

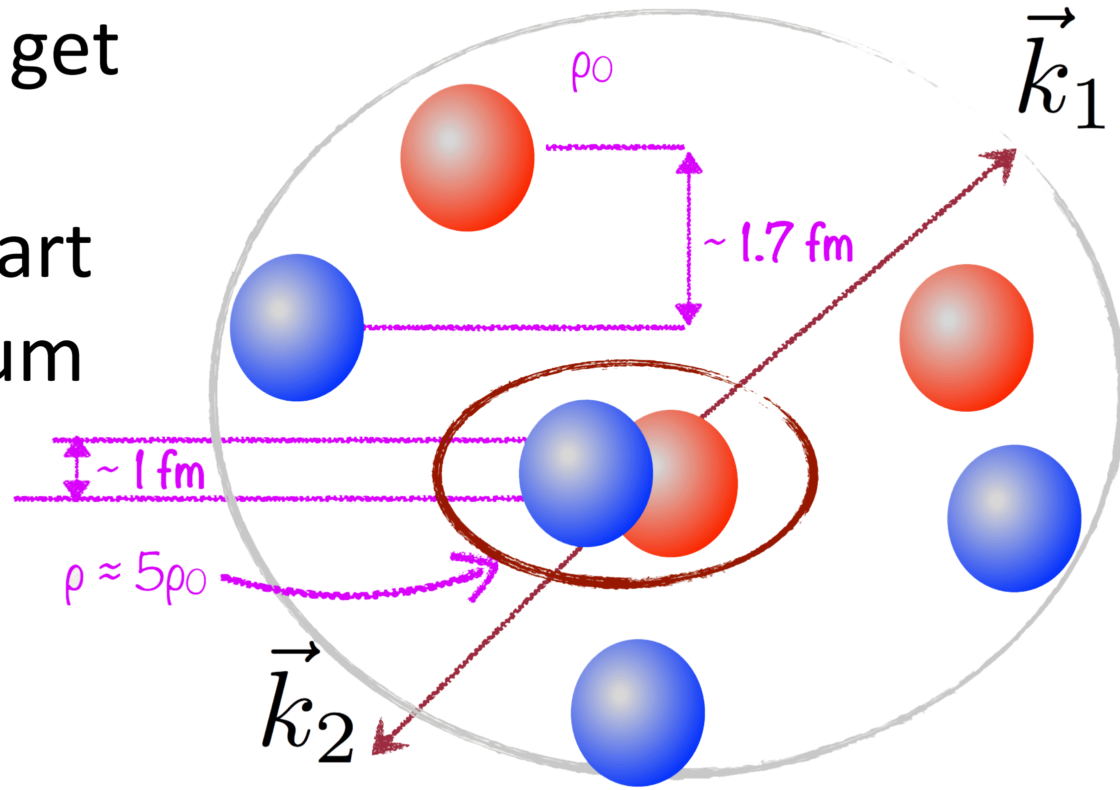


$$\frac{^3\text{He}\ (\mathbf{p})}{^3\text{He}\ (\mathbf{n})} \cong \frac{^3\text{He}\ (\mathbf{p})}{^3\text{H}\ (\mathbf{p})}$$

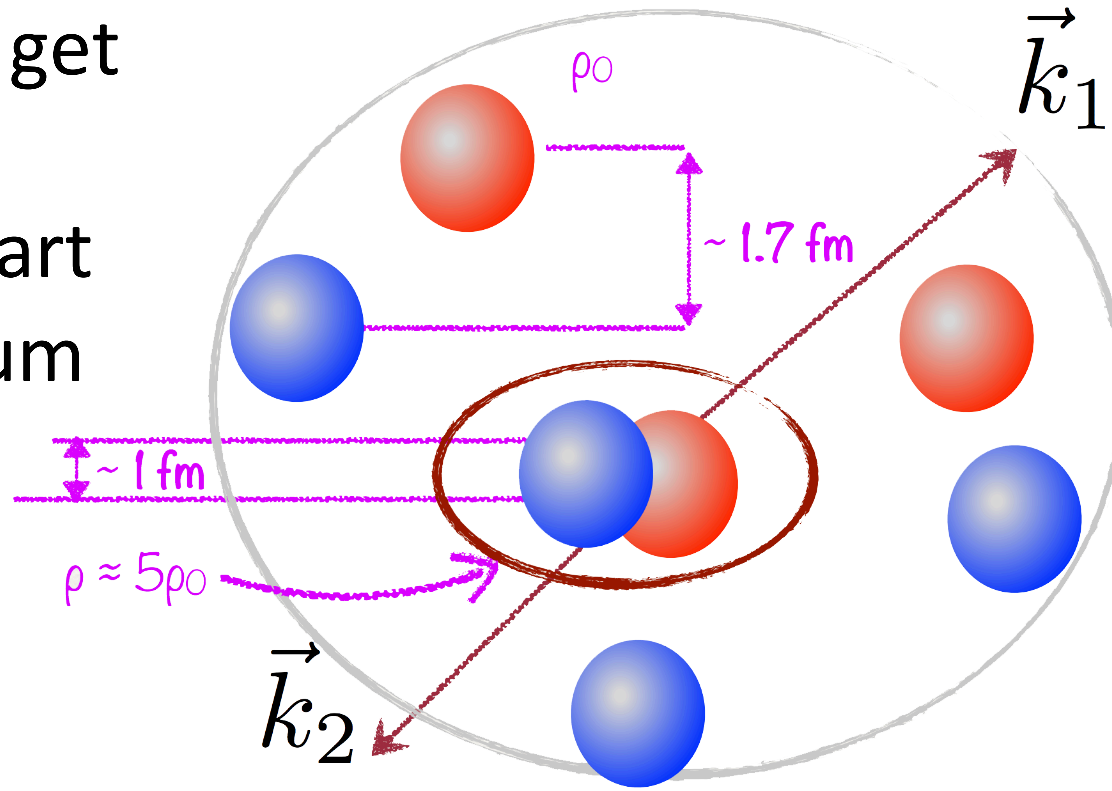
Phenomenological expectations

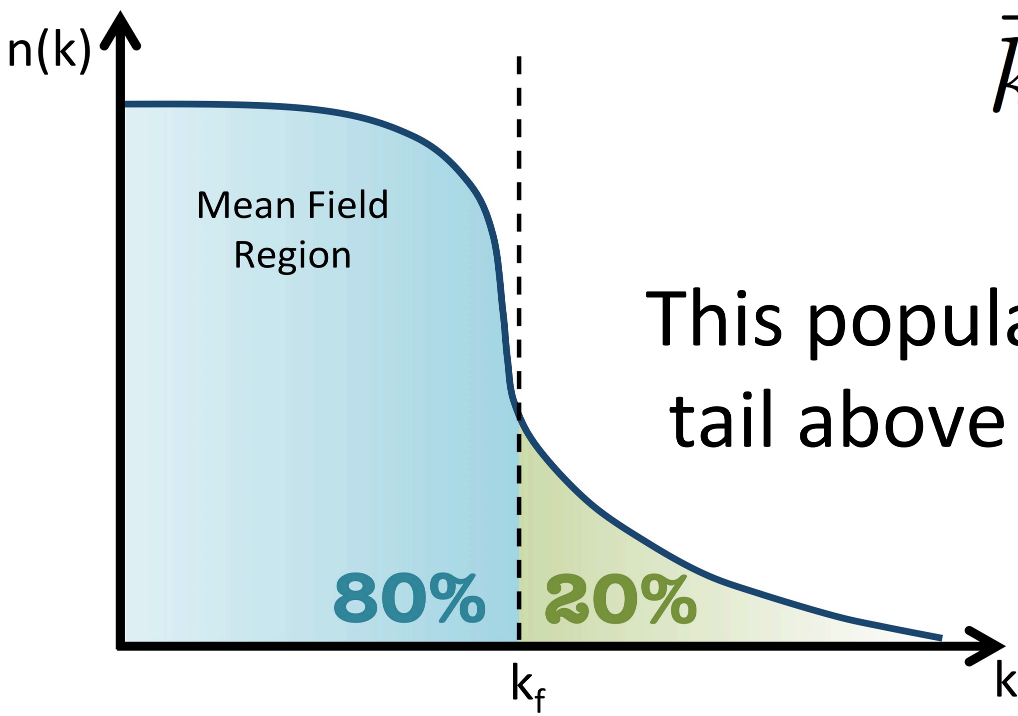


When two nucleons get close inside the nucleus, they fly apart with high momentum



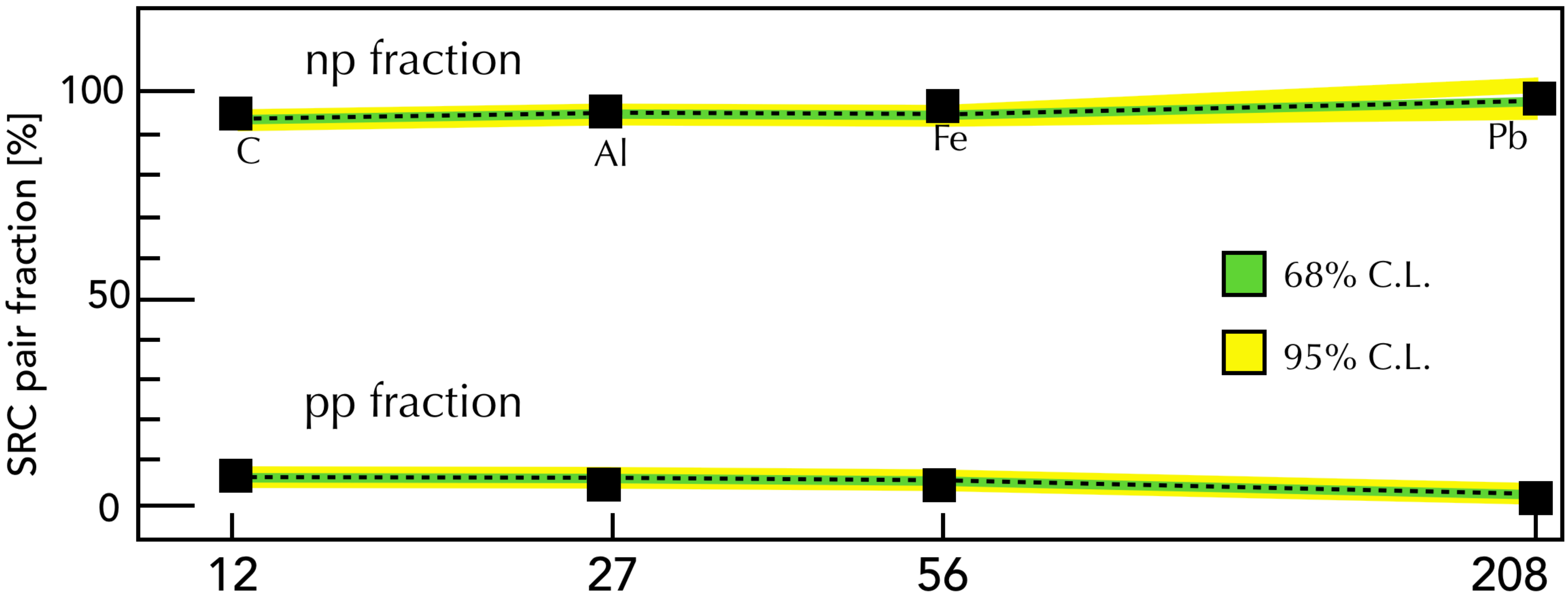
When two nucleons get close inside the nucleus, they fly apart with high momentum





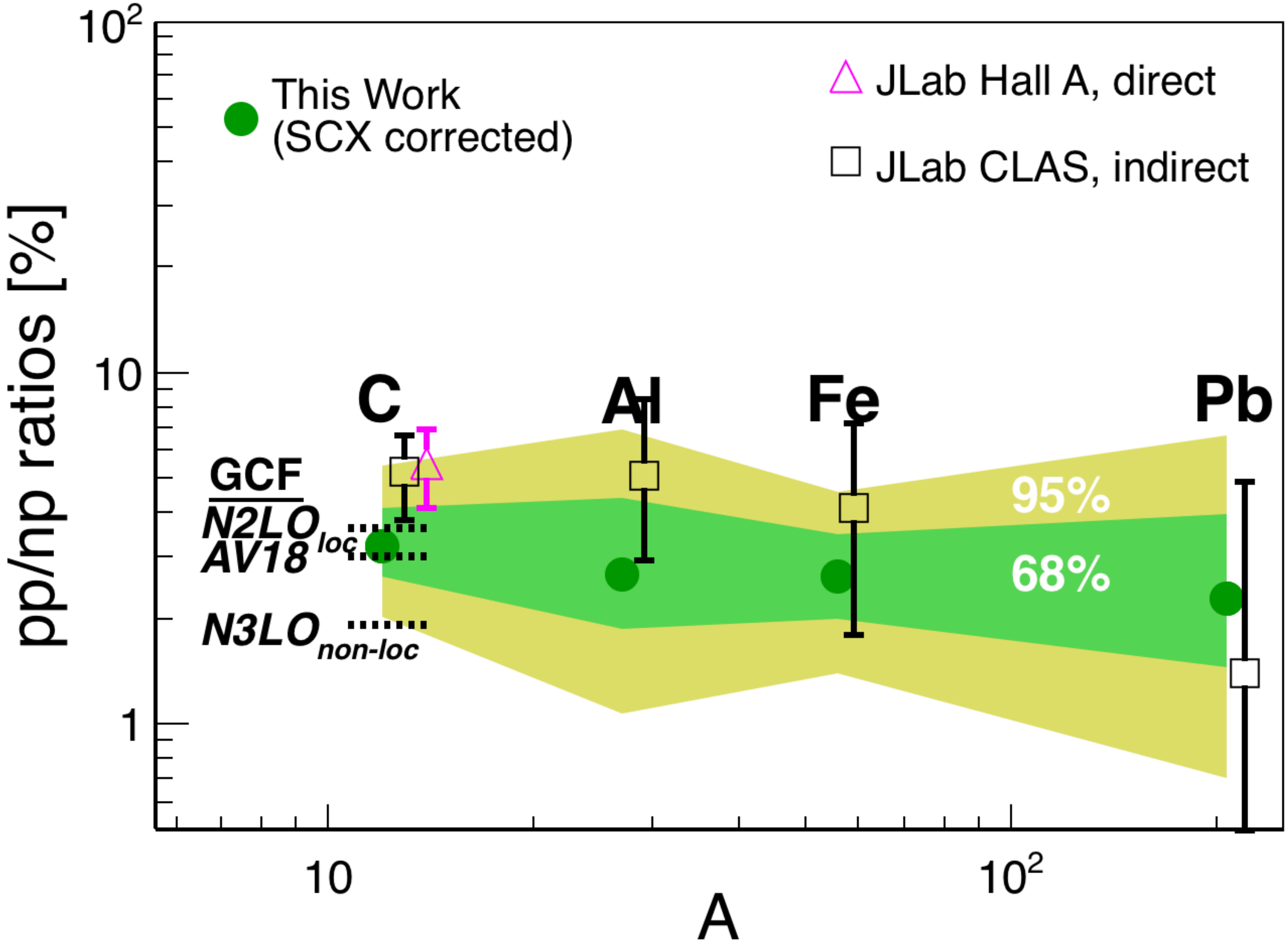
This populates a high-momentum tail above the Fermi momentum

np-dominance



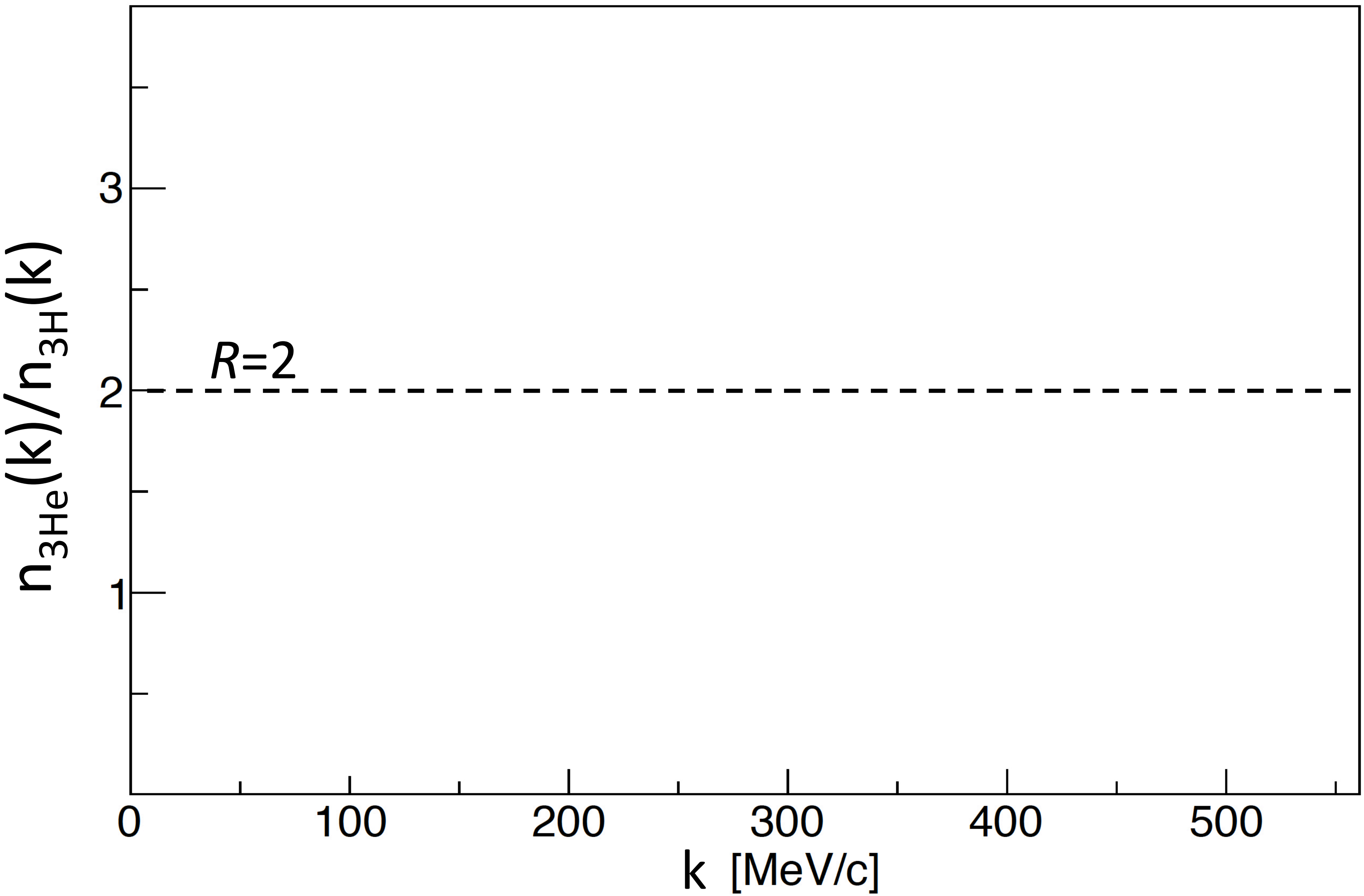
O. Hen et al., Science 346, 614 (2014)

np-dominance

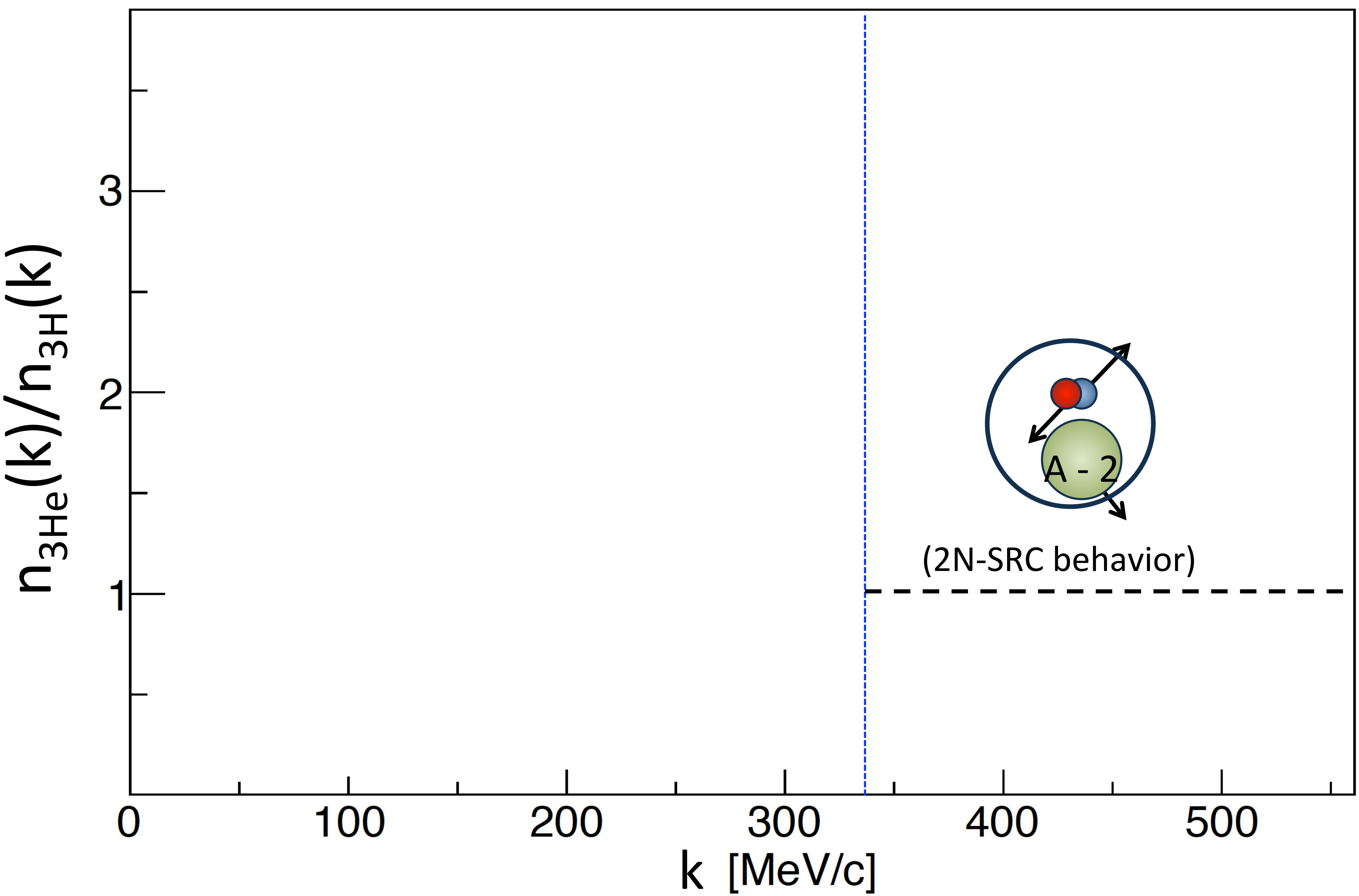


M. Duer et al., (Jefferson Lab CLAS Collaboration)
Phys. Rev. Lett. 122, 172502 (2019)

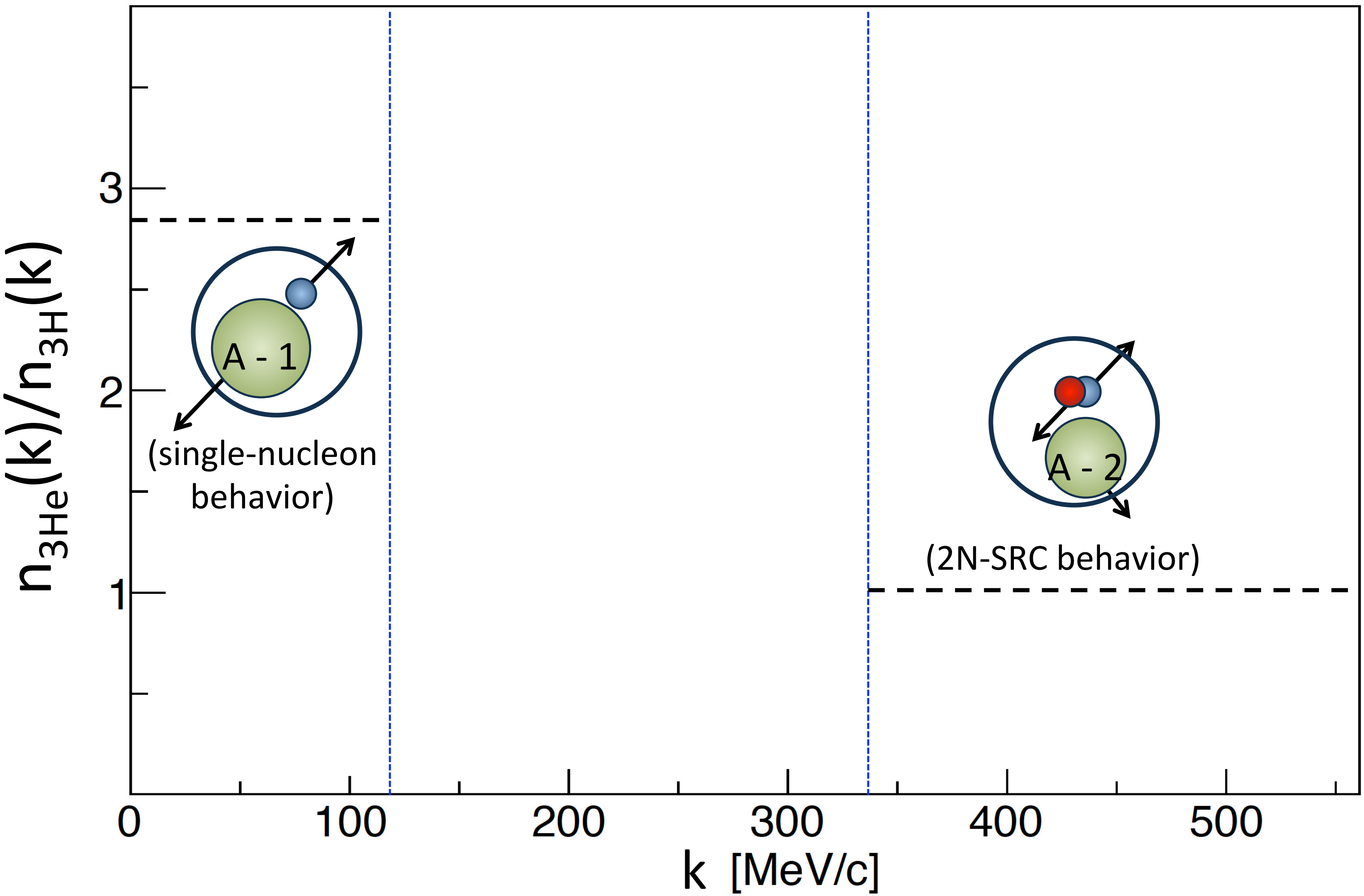
Phenomenological expectations



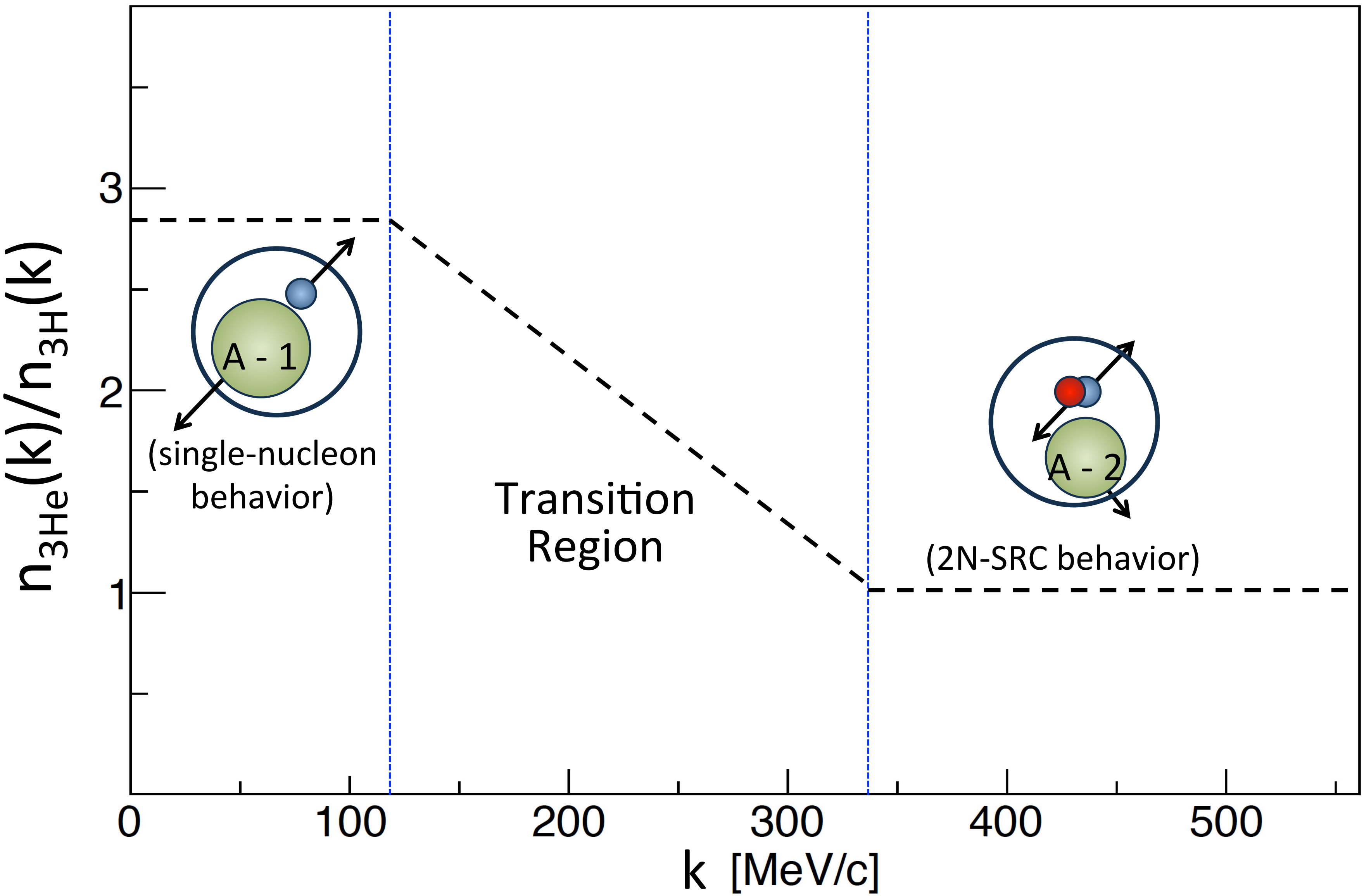
Phenomenological expectations



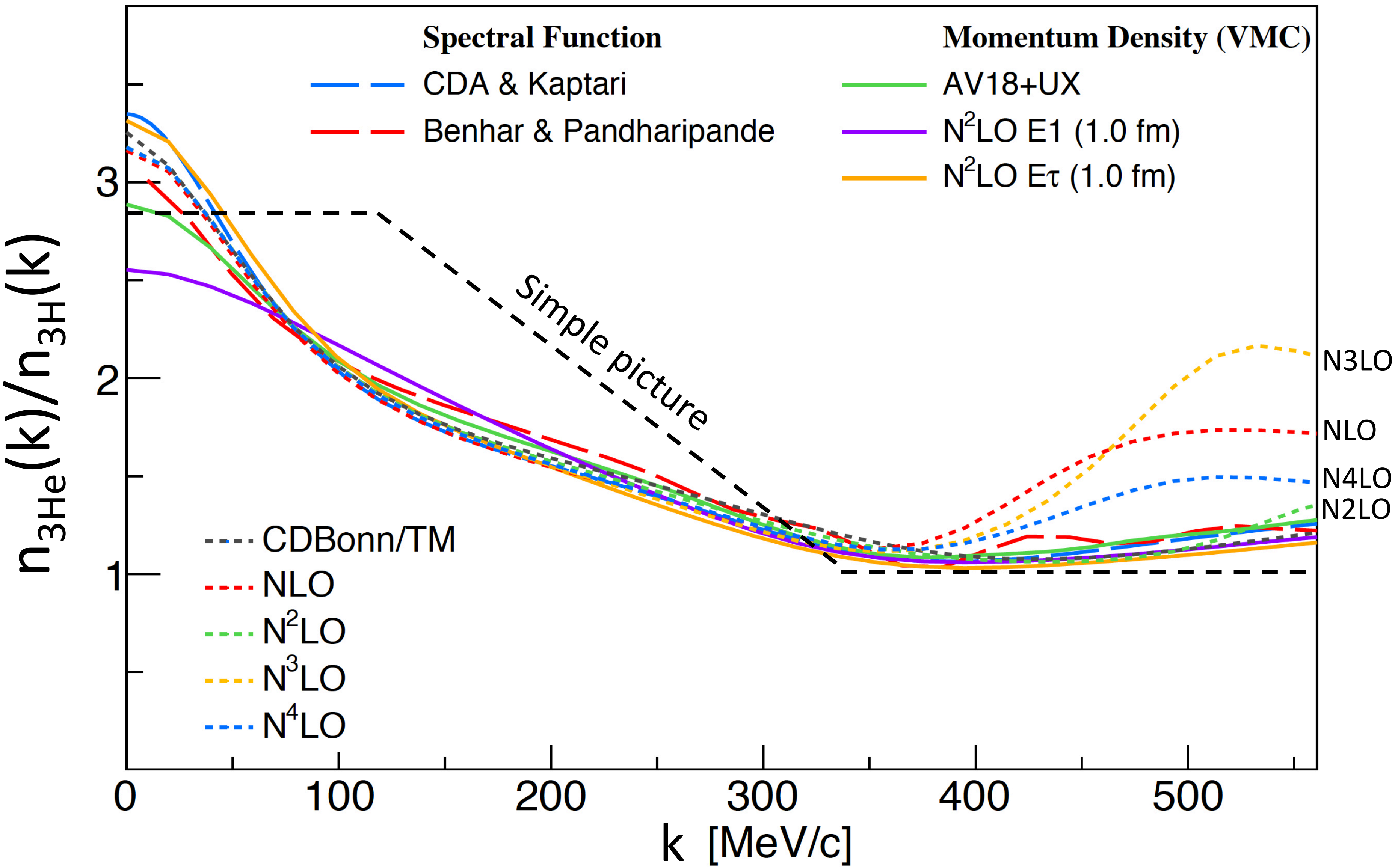
Phenomenological expectations



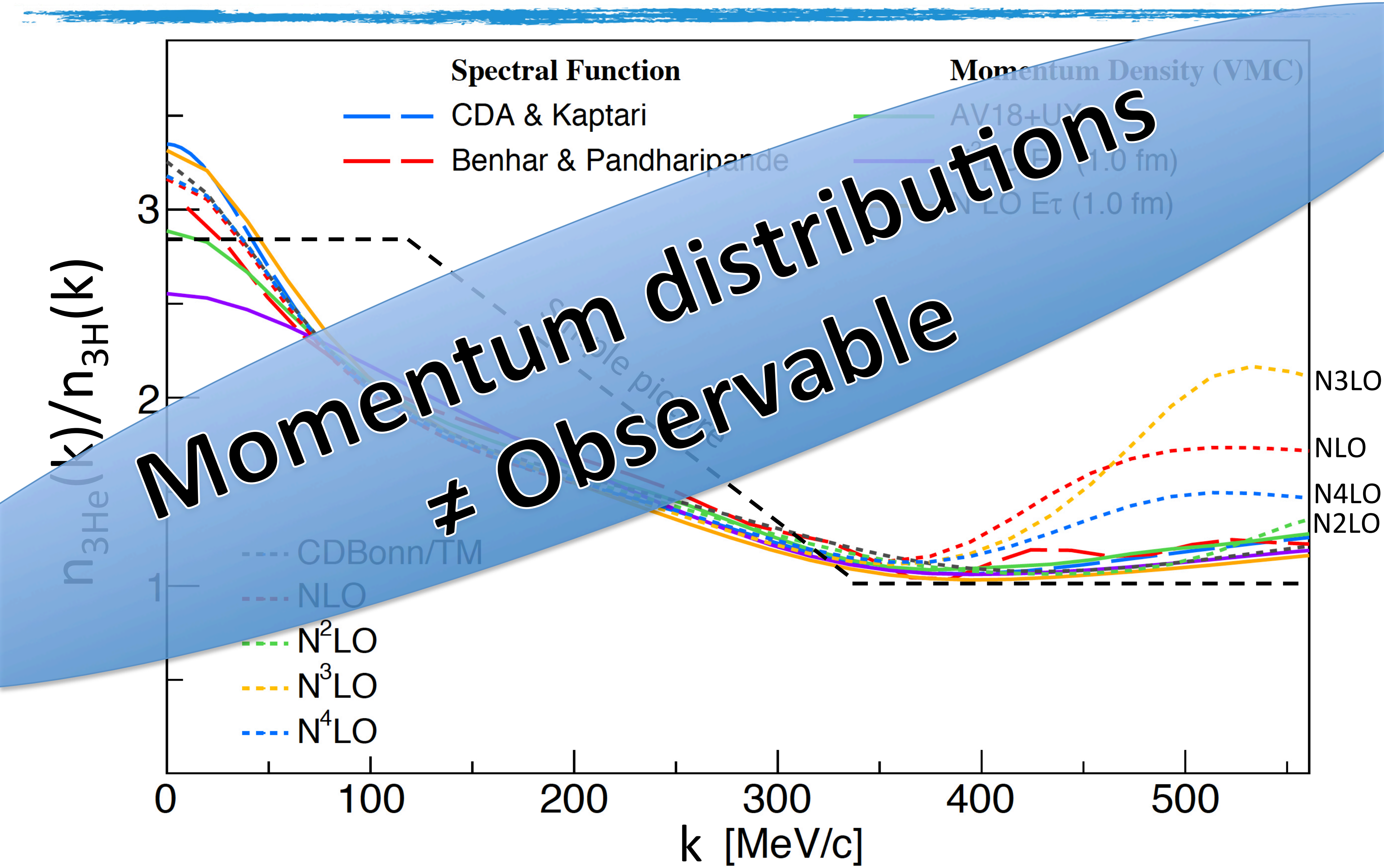
Phenomenological expectations



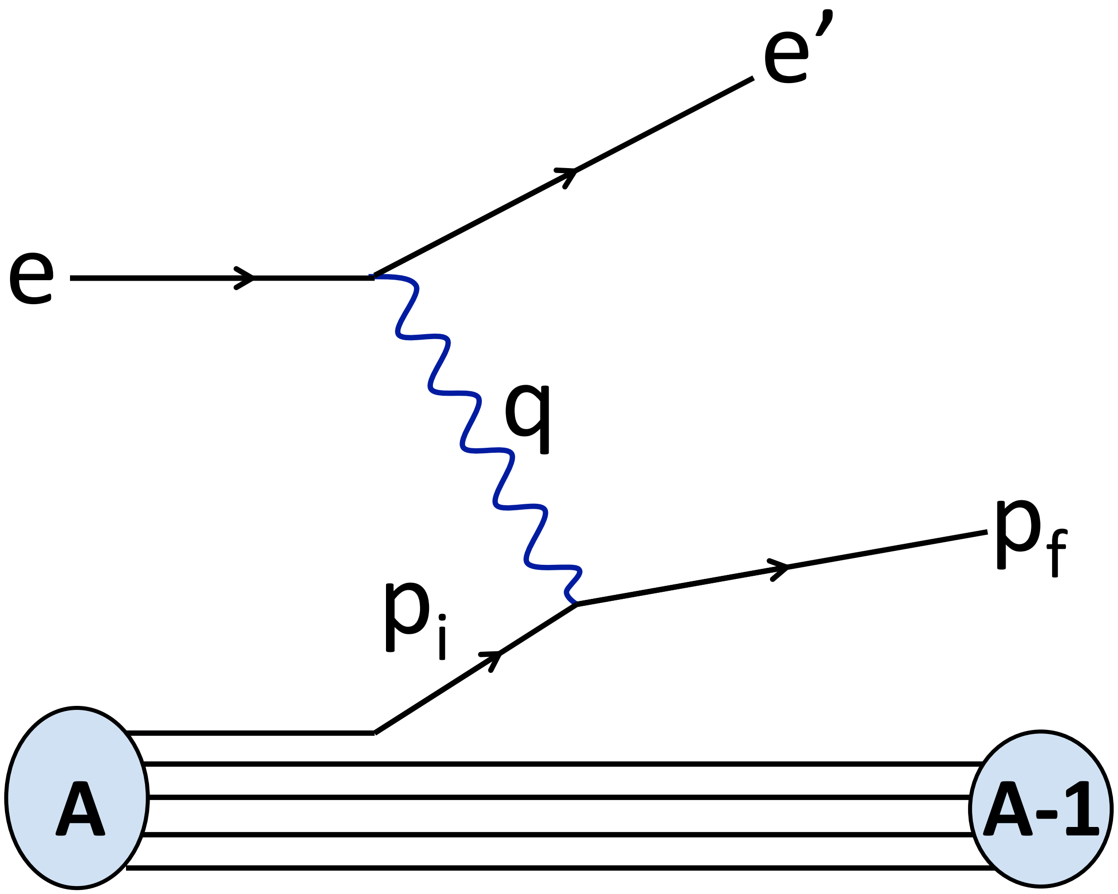
Theory predictions



Theory predictions

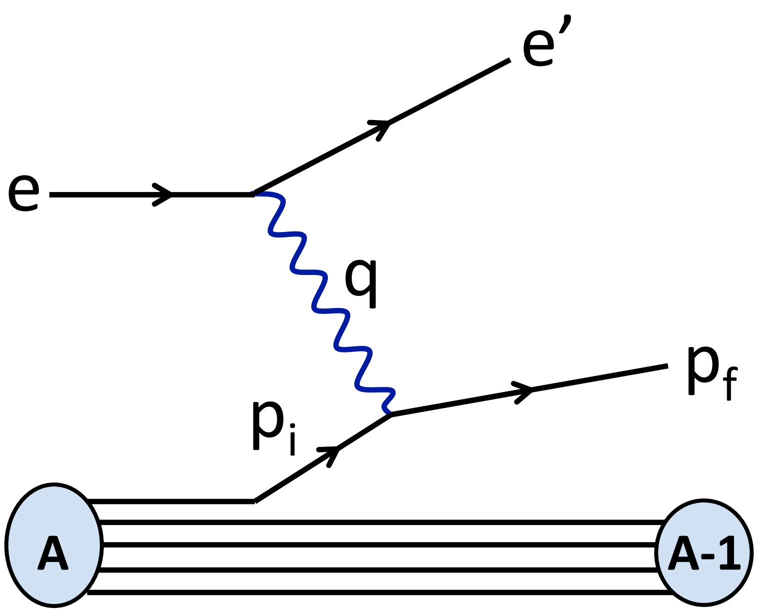


Electron scattering 101



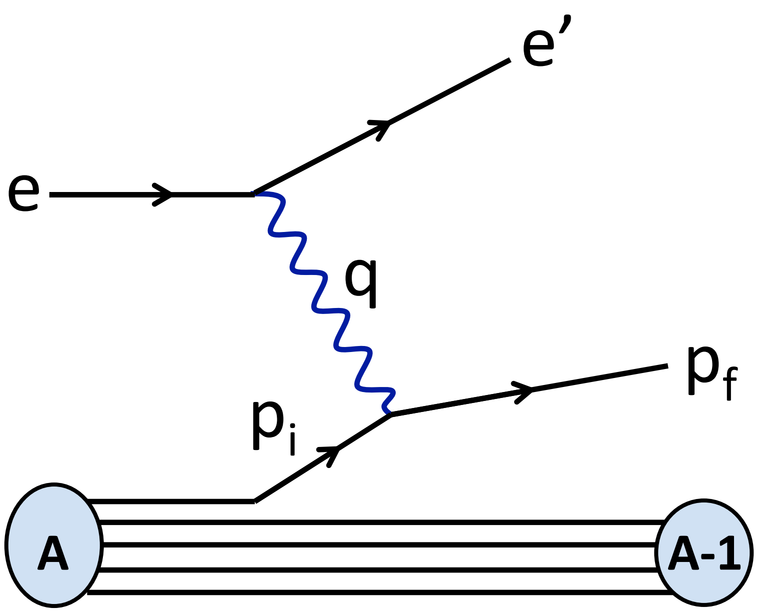
High Q^2: PWIA factorized approximation

$$\frac{d^6\sigma}{d\omega dE_p d\Omega_e d\Omega_p} = K\sigma_{ep} S(|\vec{p}_i|, E_i)$$



High Q^2: PWIA factorized approximation

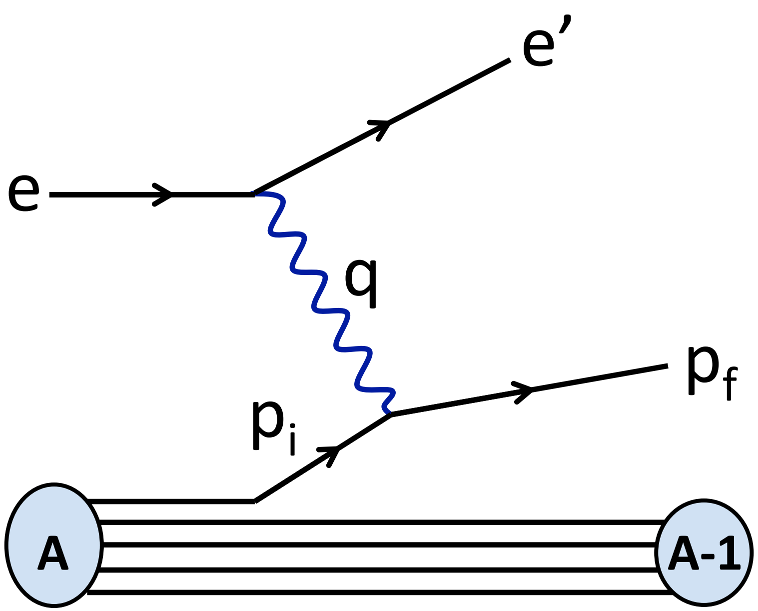
$$\frac{d^6\sigma}{d\omega dE_p d\Omega_e d\Omega_p} = K\sigma_{ep} S(|\vec{p}_i|, E_i)$$



Calculation requires a spectral function…

High Q^2: PWIA factorized approximation

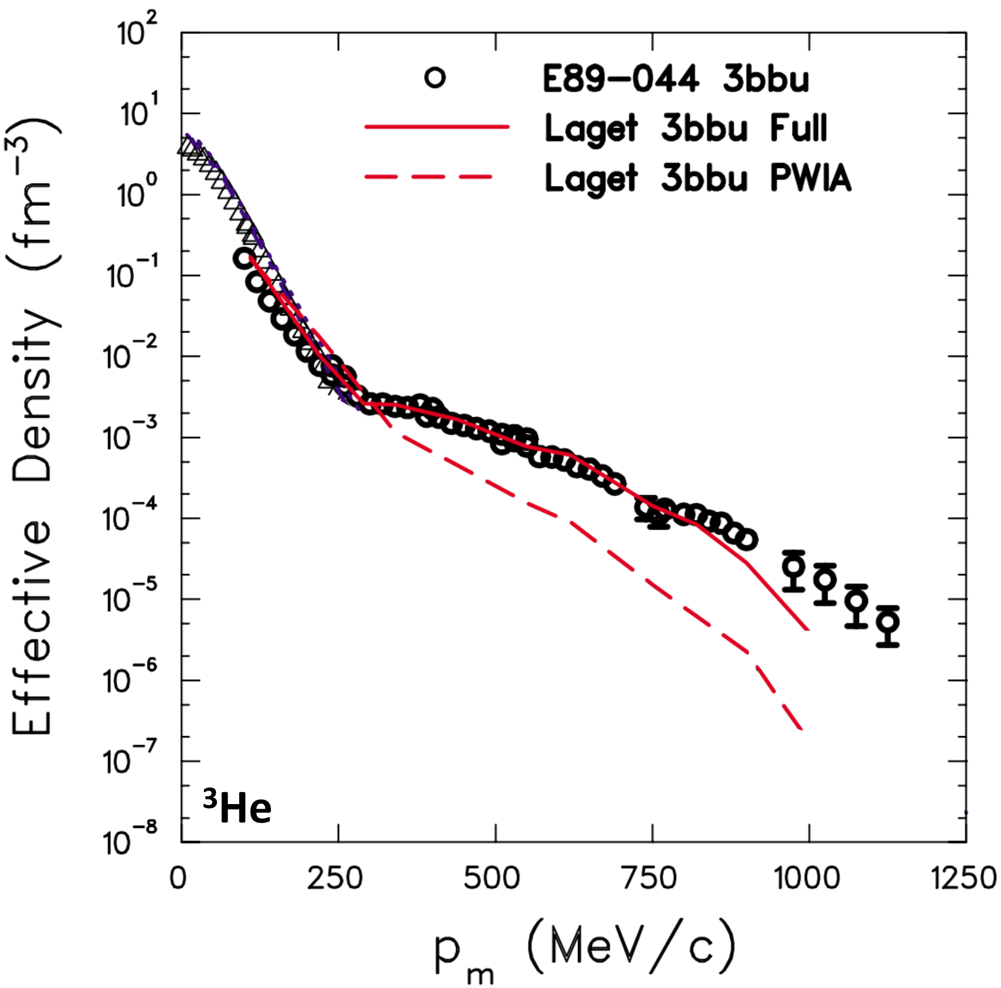
$$\frac{d^6\sigma}{d\omega dE_p d\Omega_e d\Omega_p} = K\sigma_{ep} S(|\vec{p}_i|, E_i)$$

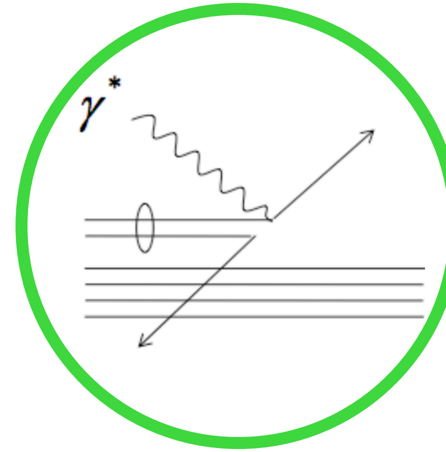


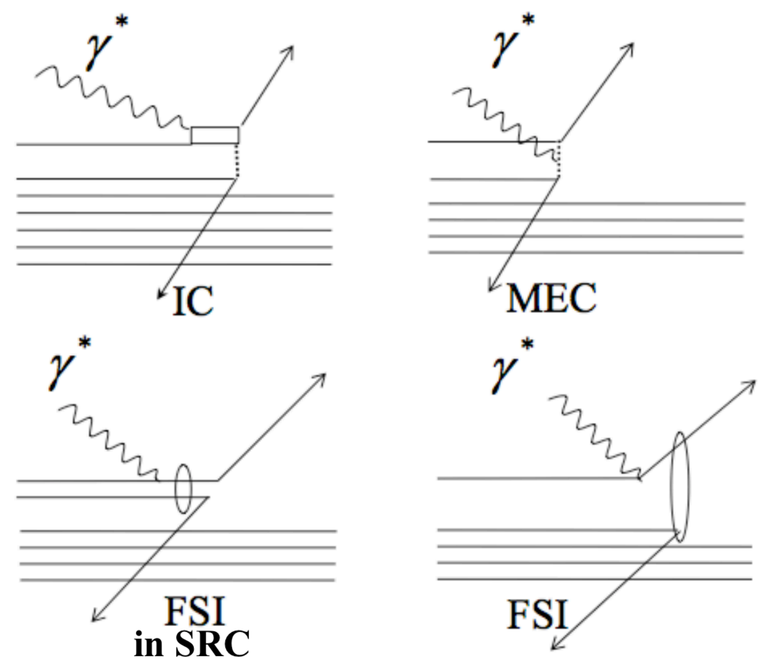
Assuming the q vector was absorbed by a single nucleon:

$$\vec{p}_i = \vec{p}_{miss} = \vec{p}_f - \vec{q}$$

Previous studies and non-QE mechanisms





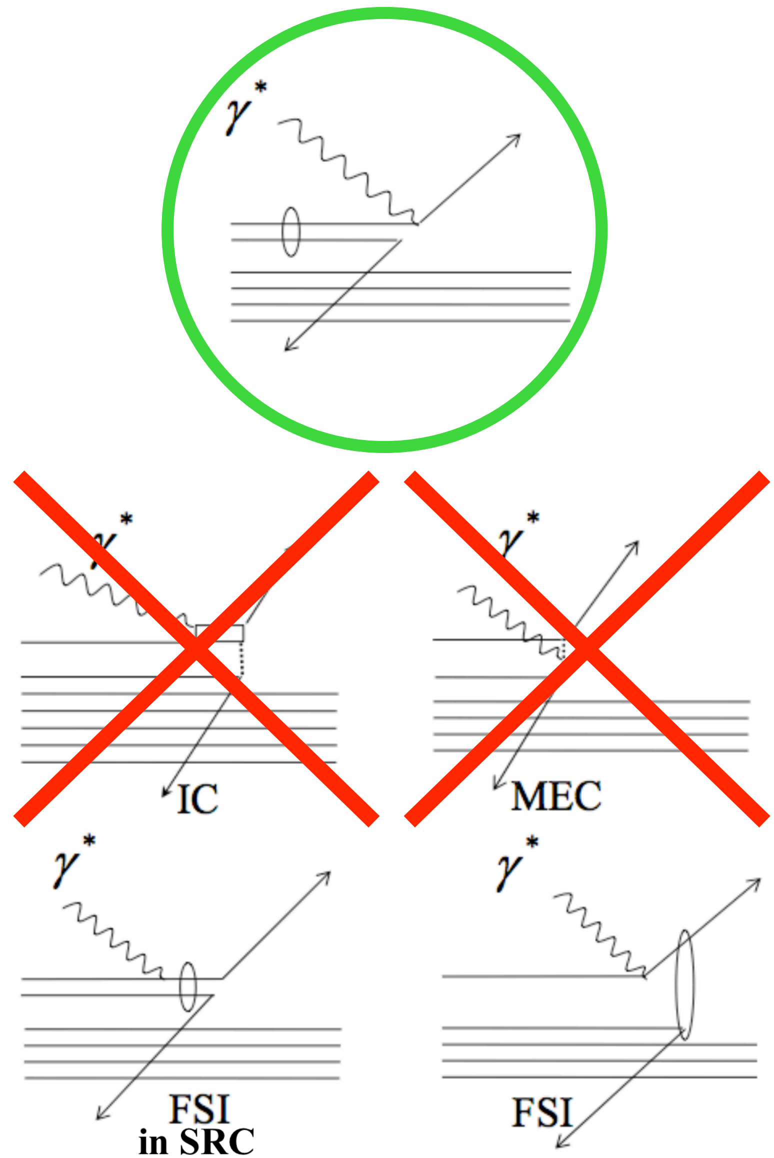


F. Benmokhtar et al., PRL 94, 082305 (2005)

Minimizing non-QE mechanisms

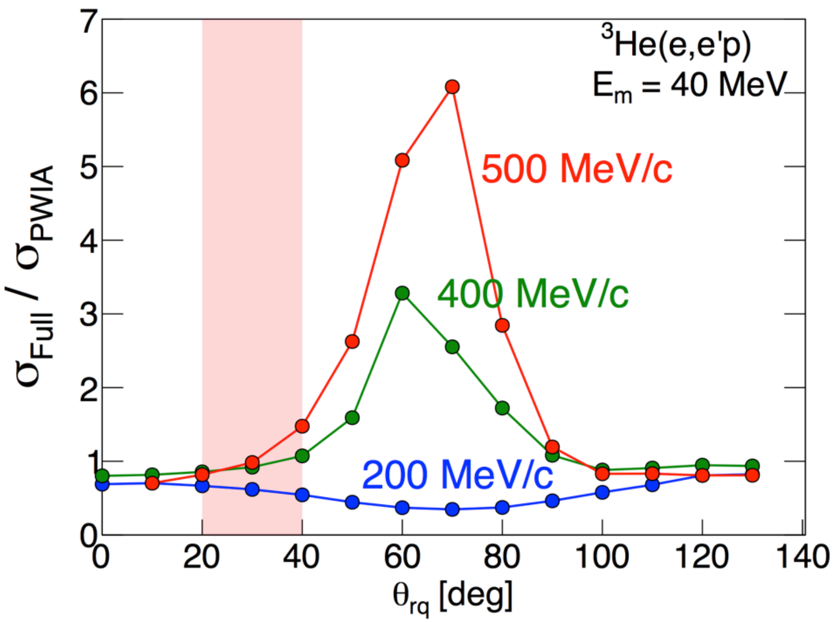
$Q^2 > 2\ GeV^2$

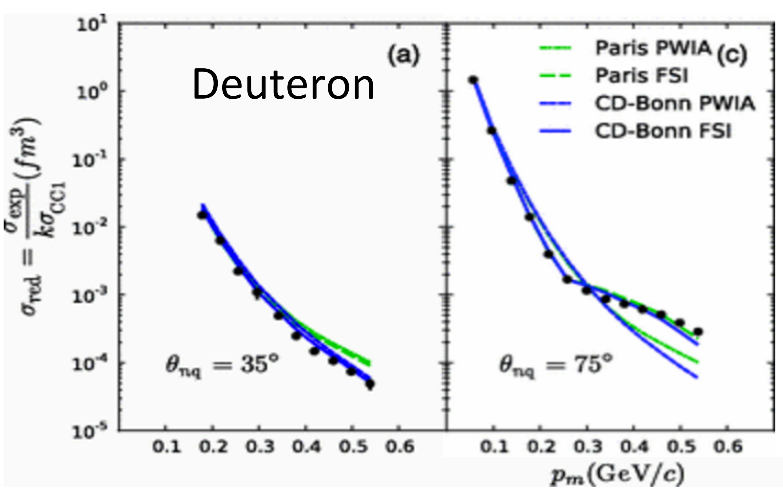
$x_B > 1$



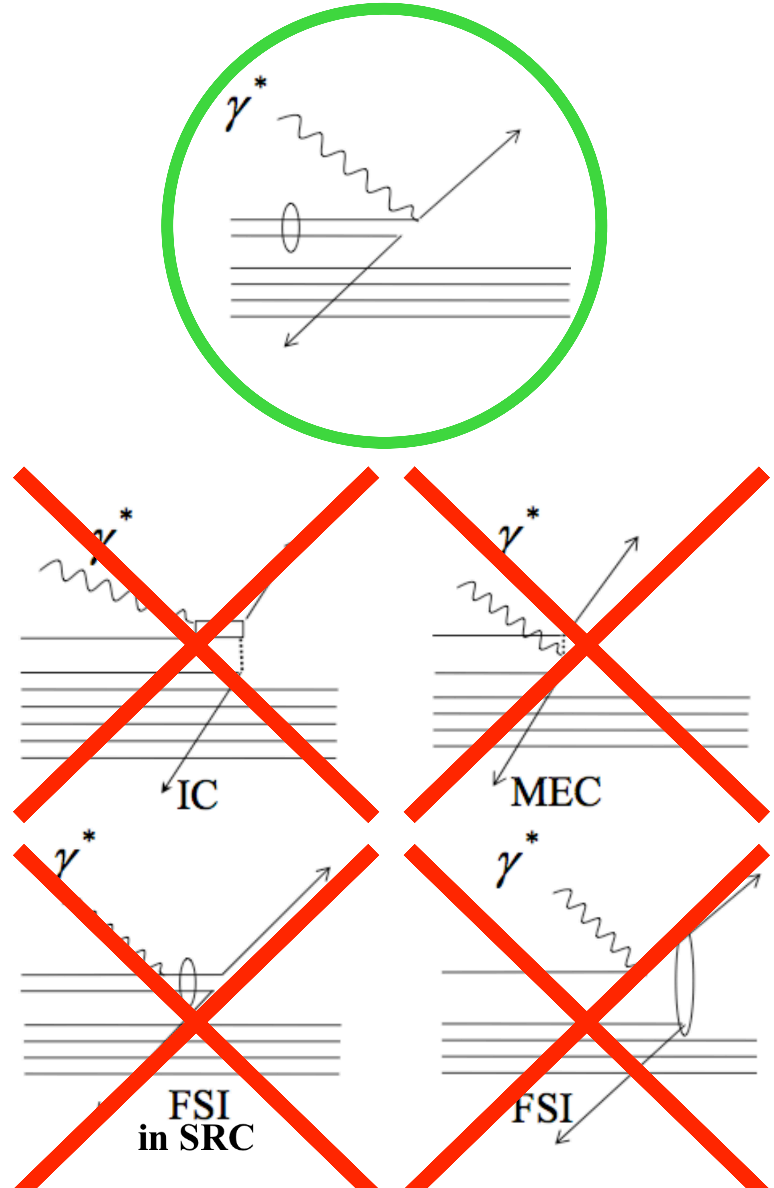
M. M. Sargsian, Int. J. Mod. Phys. E10, 405 (2001)
M. M. Sargsian et al., J. Phys. G29, R1 (2003)

Minimizing non-QE mechanisms





Boeglin et al., PRL 107 (2011) 262501



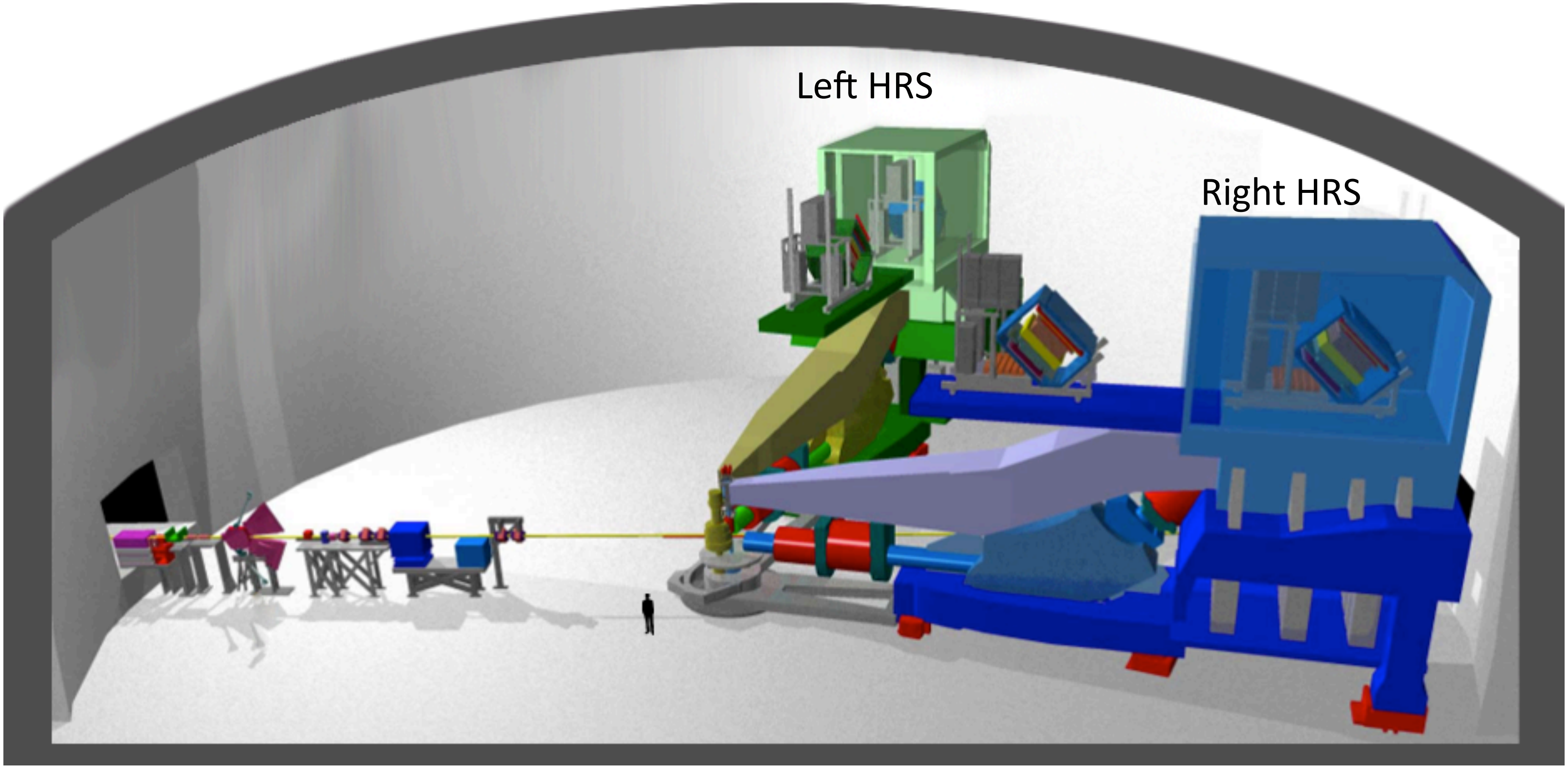
High Q^2: PWIA factorized approximation

$$\frac{d^6\sigma}{d\omega dE_p d\Omega_e d\Omega_p} = K\sigma_{ep} S(|\vec{p}_i|, E_i)$$

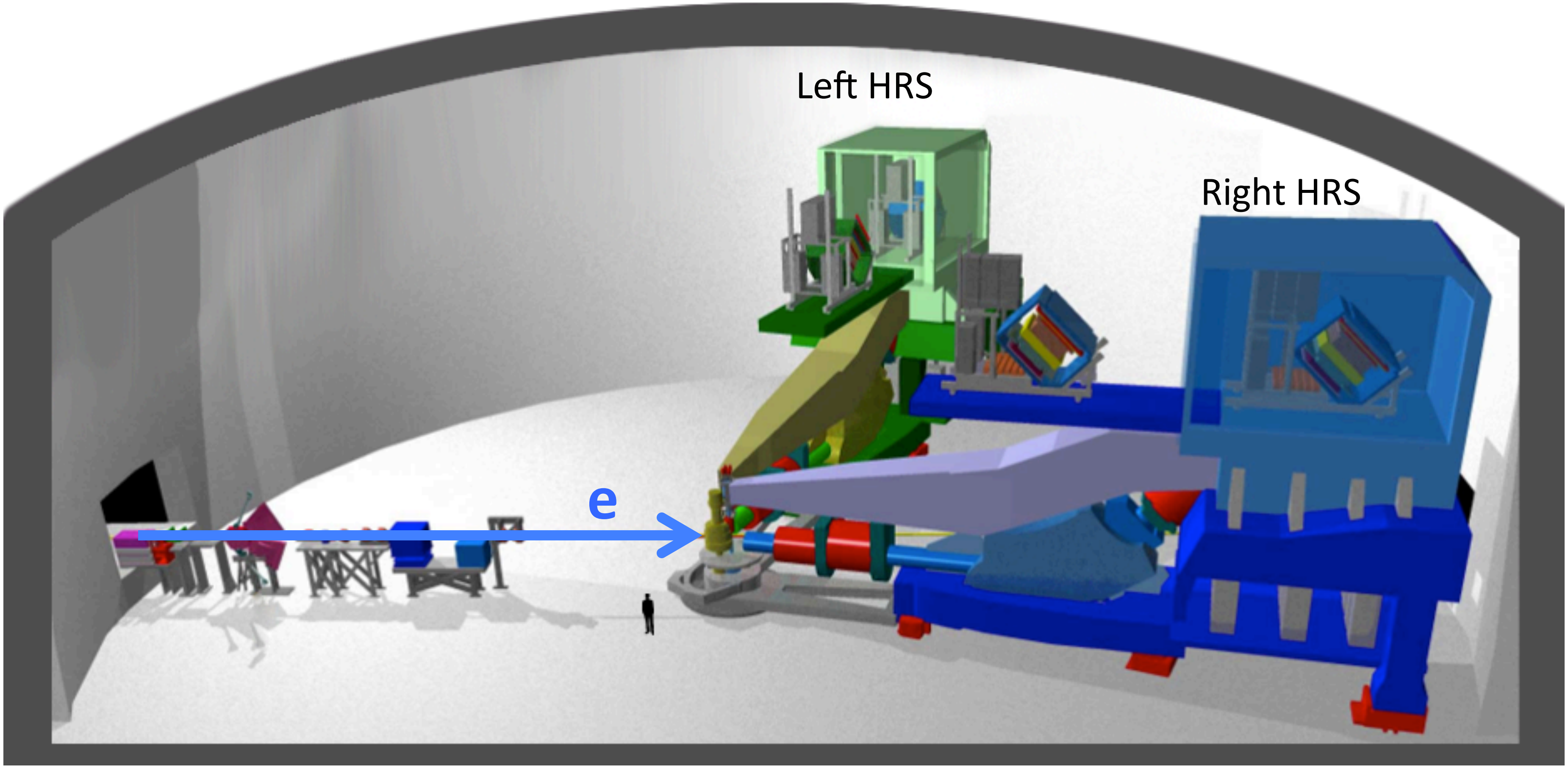
thus:

$$\frac{\sigma_{3He(e,e'p)}}{\sigma_{3H(e,e'p)}} \cong \frac{S_{3He}(|\mathbf{p}_i|,E_i)}{S_{3H}(|\mathbf{p}_i|,E_i)}$$

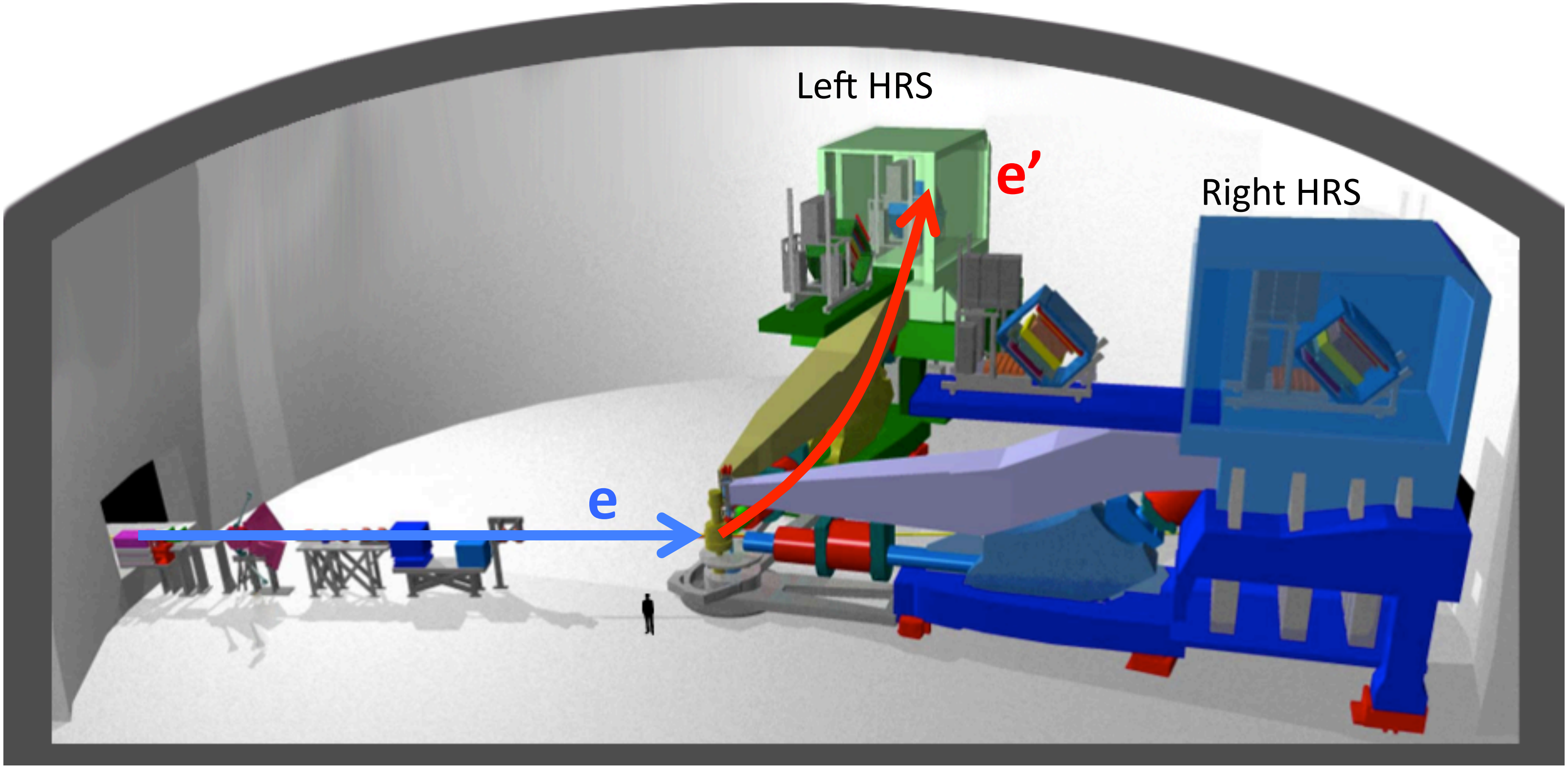
Hall-A of Jefferson Lab



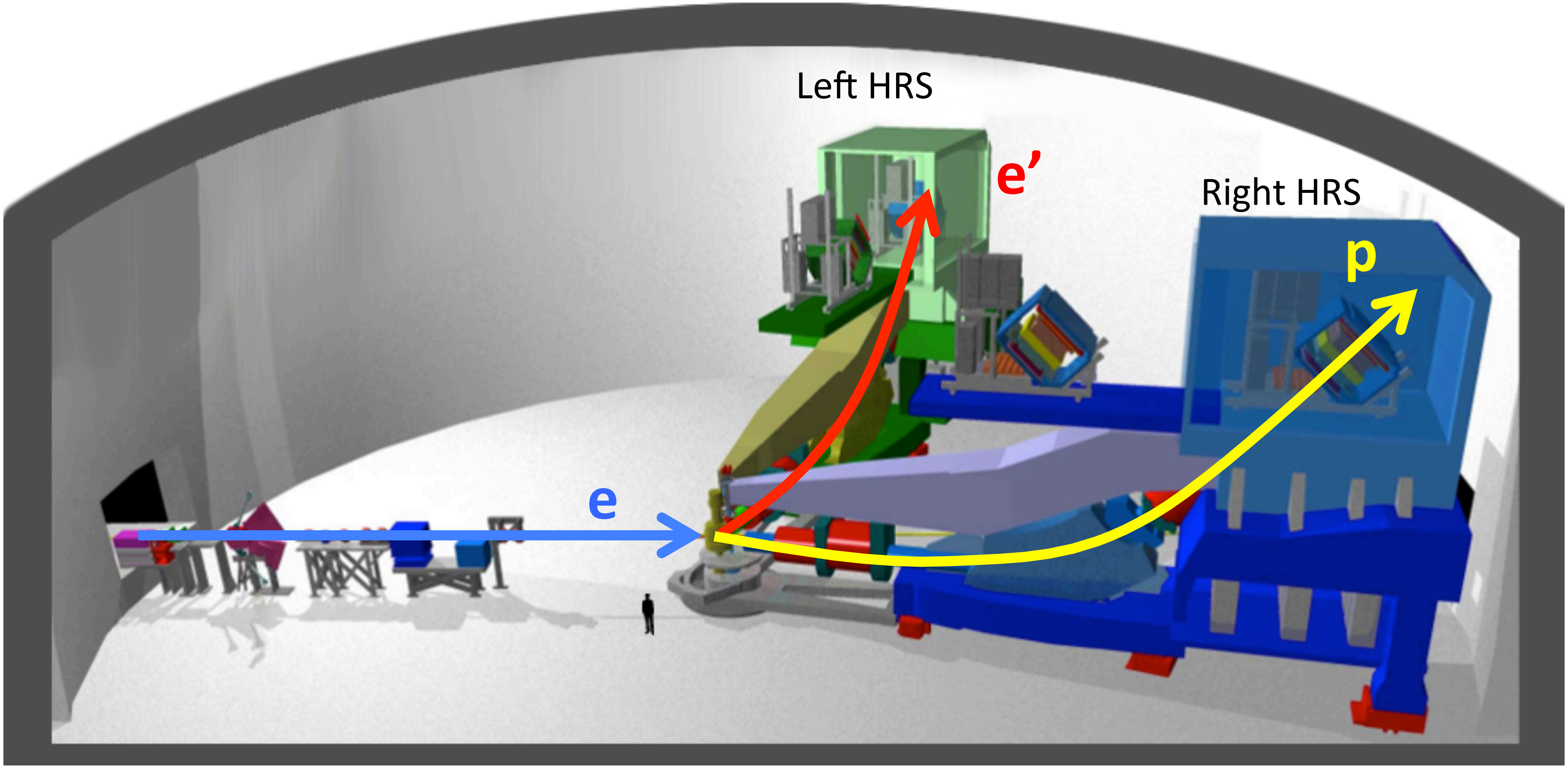
Hall-A of Jefferson Lab



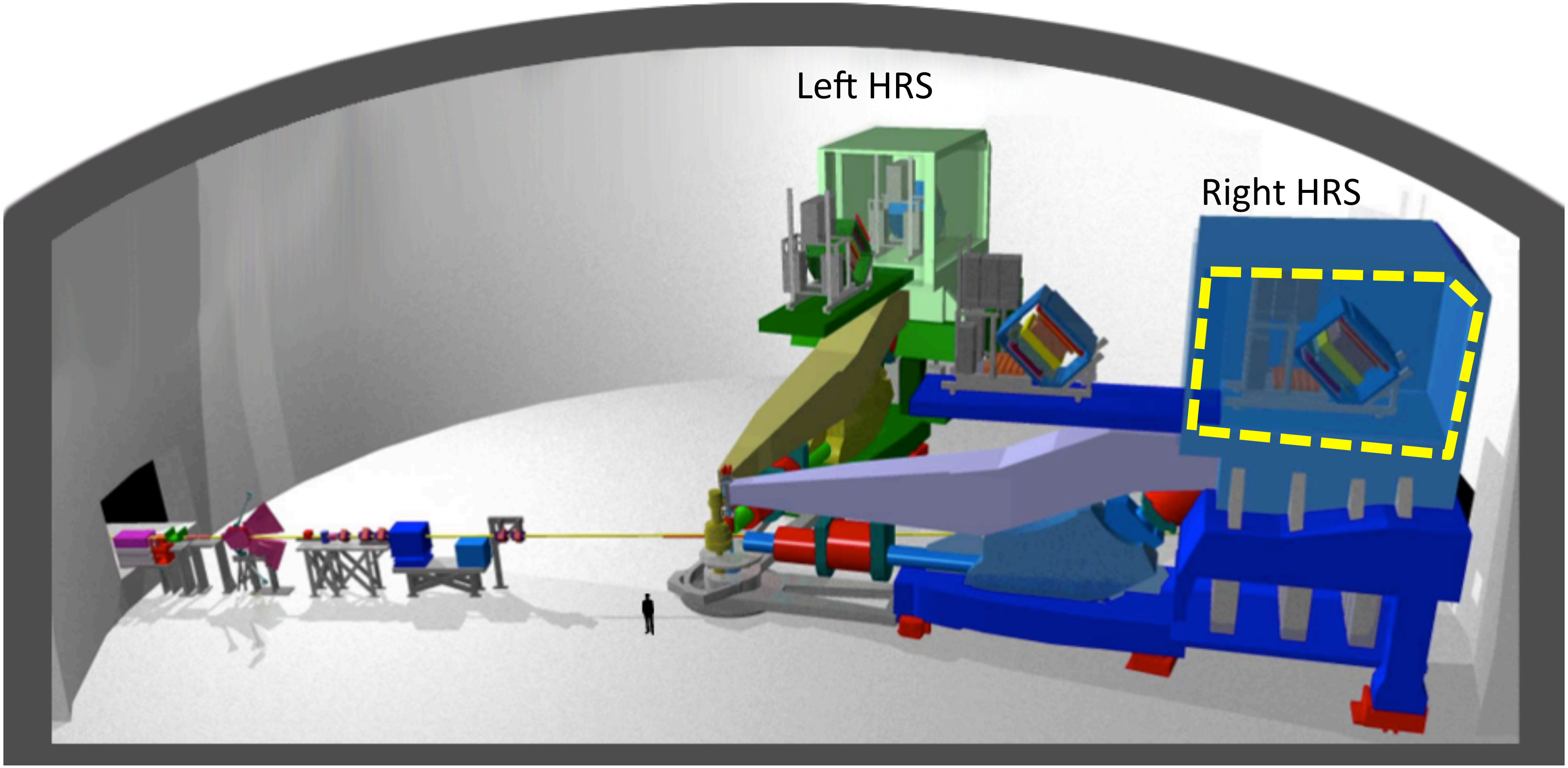
Hall-A of Jefferson Lab



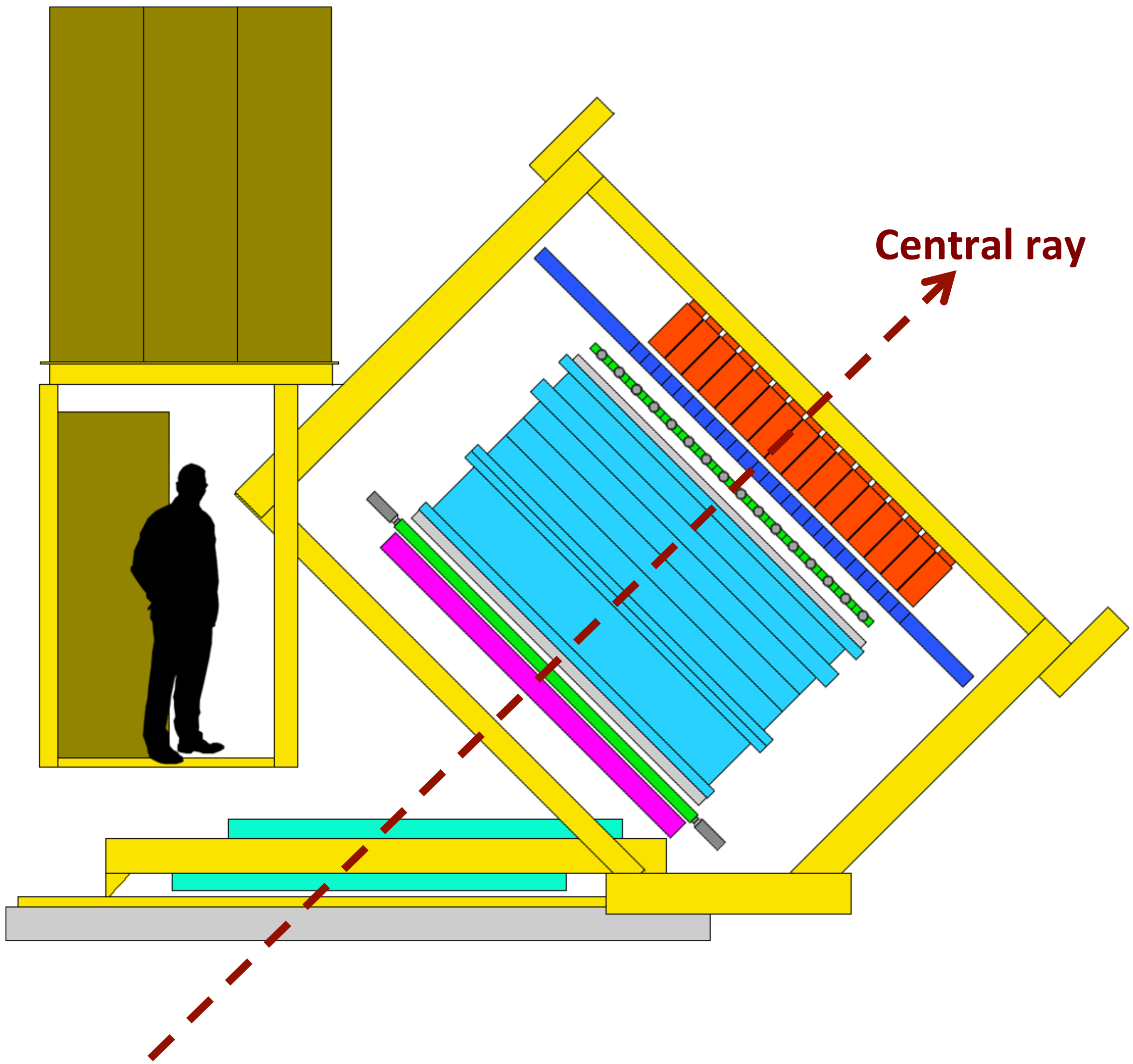
Hall-A of Jefferson Lab



Hall-A of Jefferson Lab

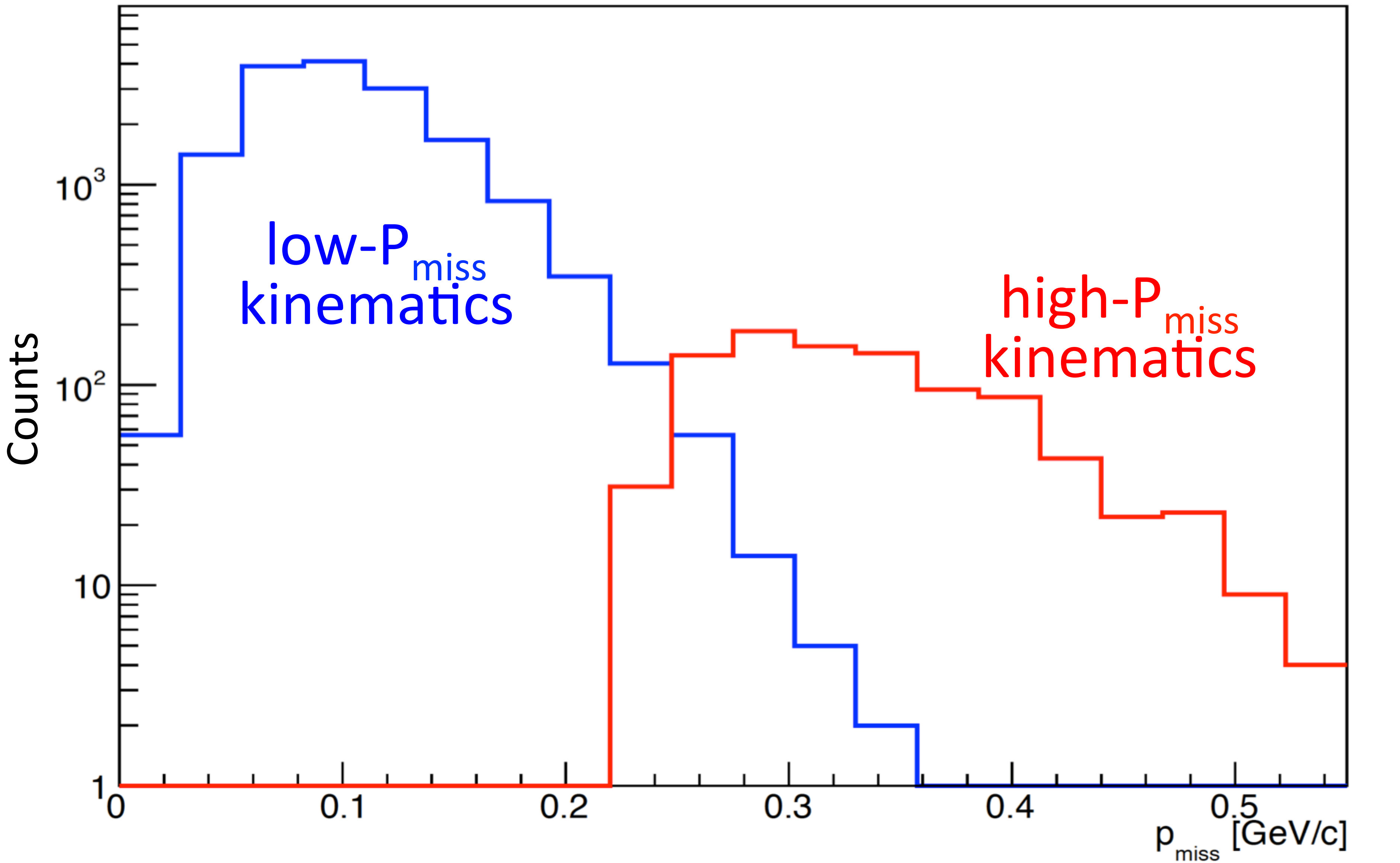


HRS detector package



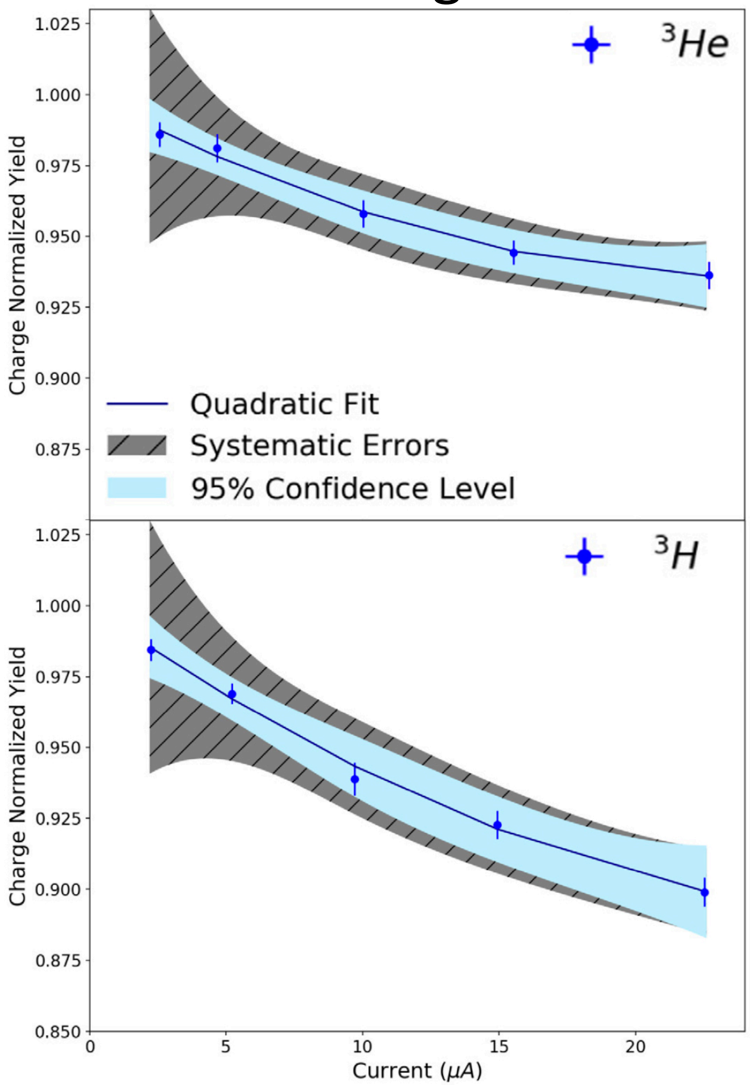
Allow for excellent momentum reconstruction and particle identification

Kinematical settings



Yield corrections

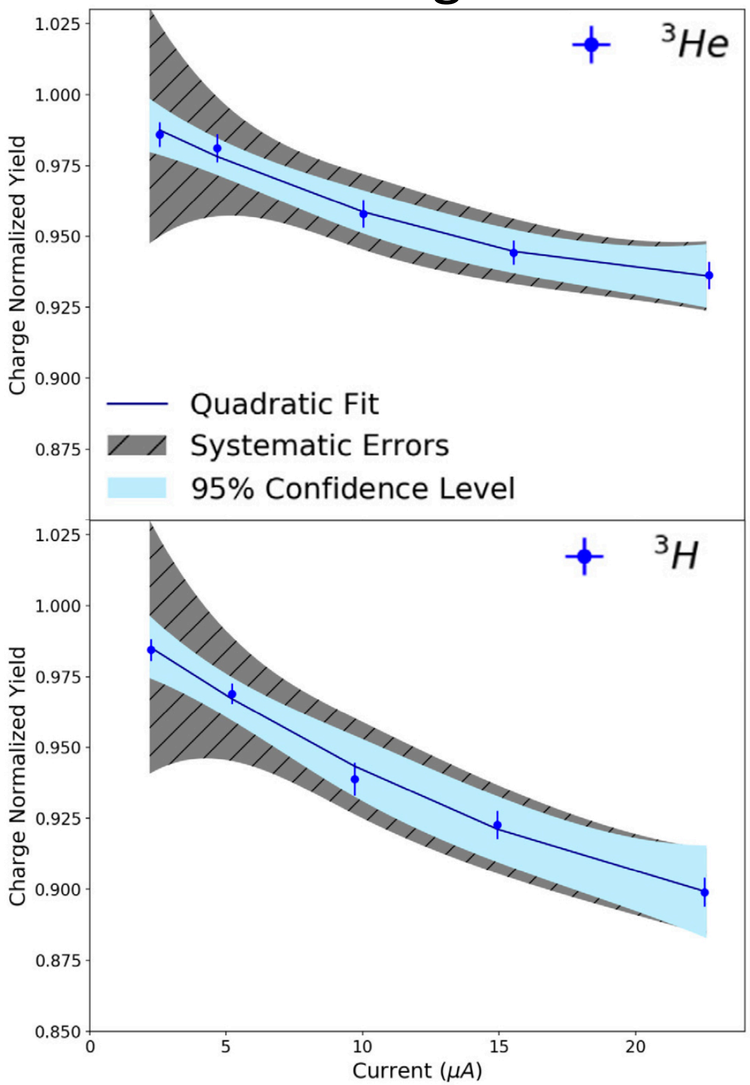
"Boiling"



Nuc. Instrum. Meth. **A940**, 351 (2019)

Yield corrections

"Boiling"



Nuc. Instrum. Meth. **A940**, 351 (2019)

$$^3H \rightarrow {}^3He + e^- + \bar{\nu}_e$$

$t_{1/2}$ = (4500 ± 8) days

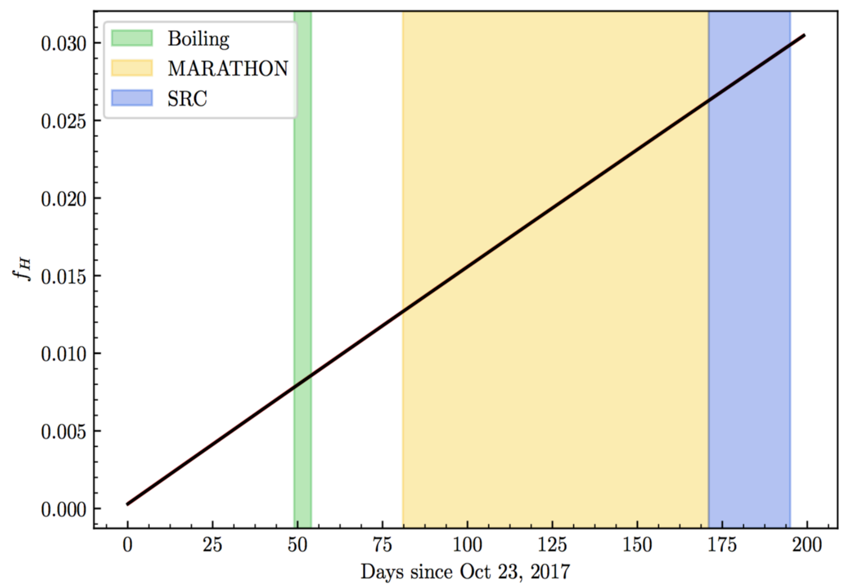
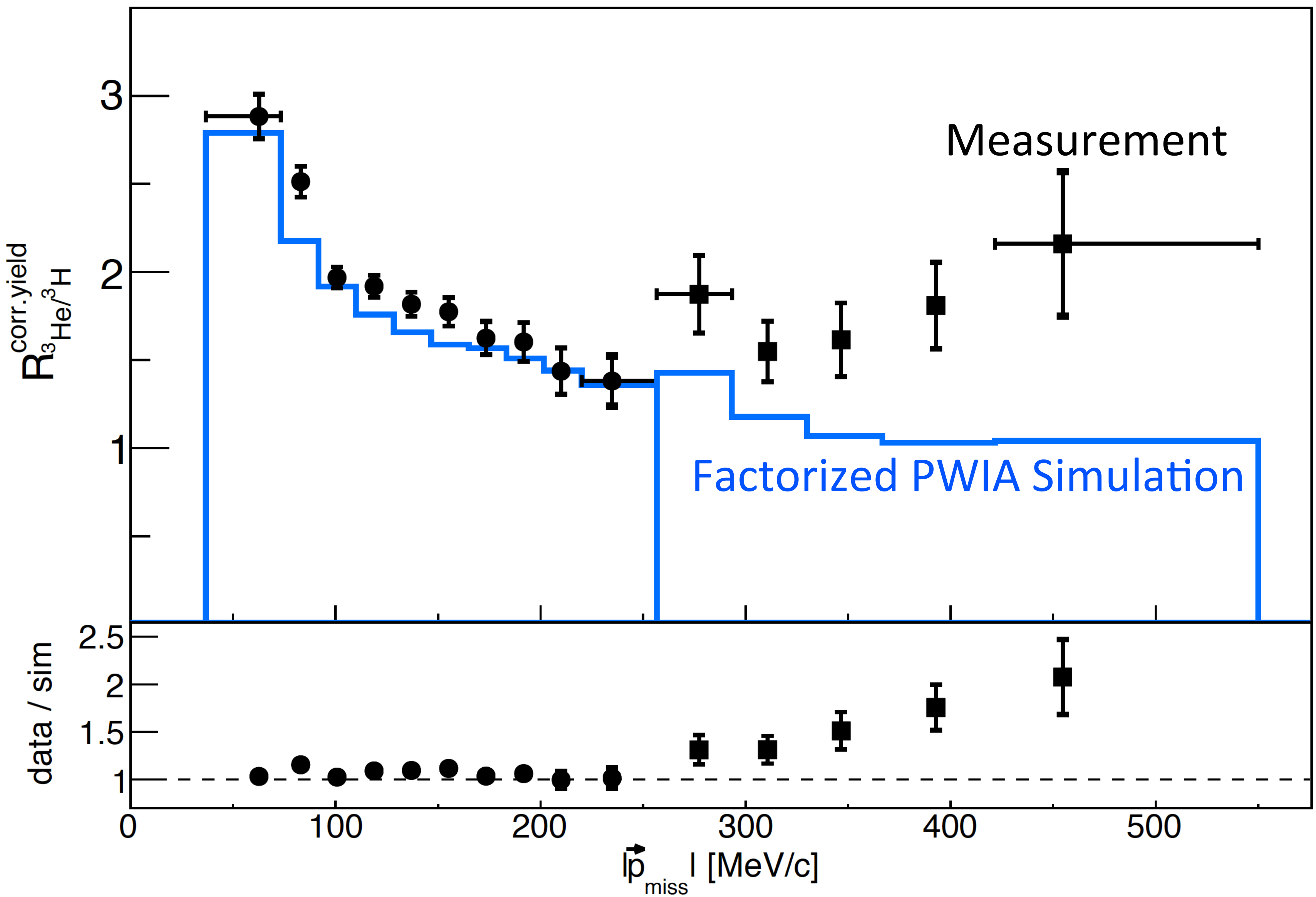


Figure by T. Kutz

Measured $^3He/^3H$ ratio

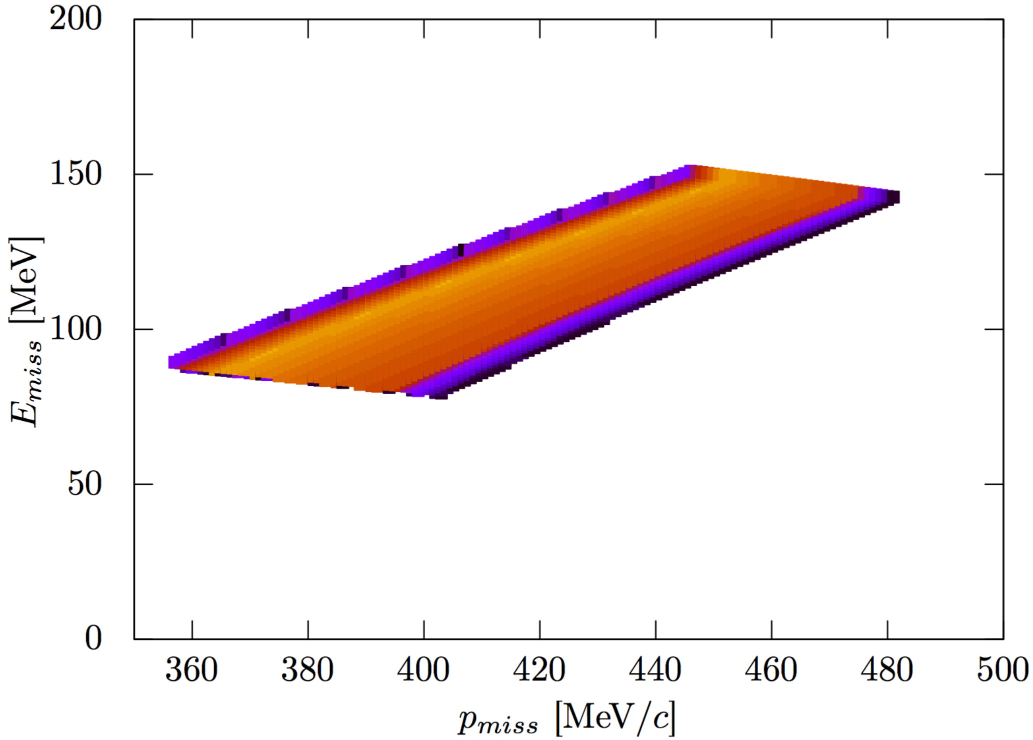


R.Cruz-Torres et al. Submitted for publication. arXiv:1902.06358 (2019)

Corrections

$$R_{n(p)}^{\mathrm{meas.}}(p_{miss}) \neq R_{^3\mathrm{He}/^3\mathrm{H}}^{corr.yield}(p_{miss})$$

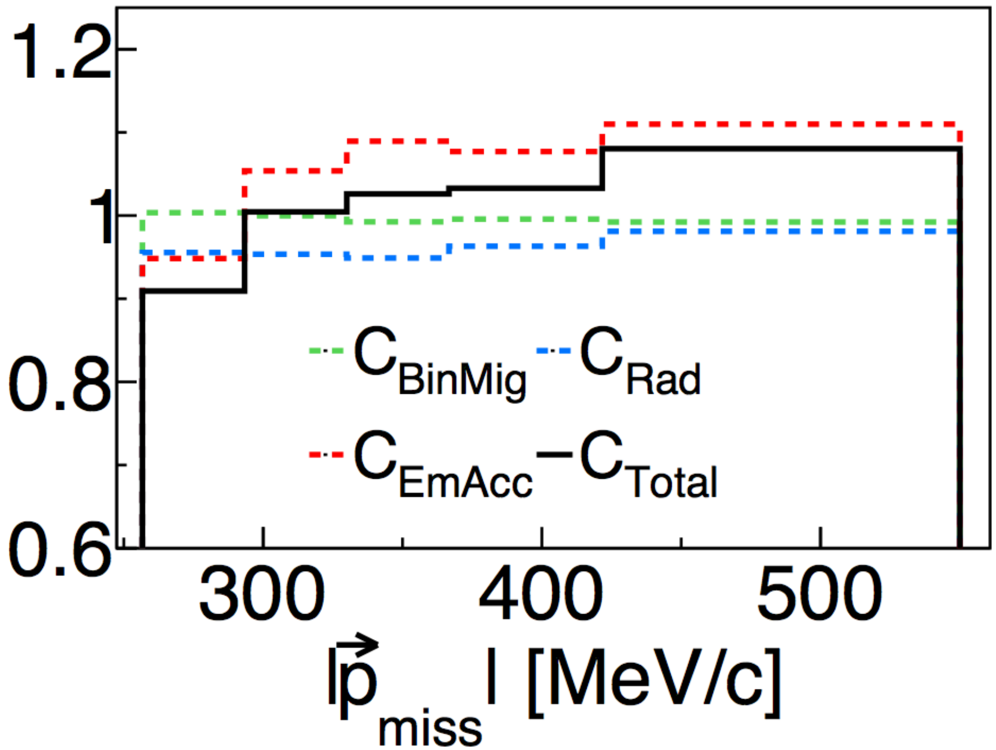
High missing momentum setting
(toy model by A. Schmidt)



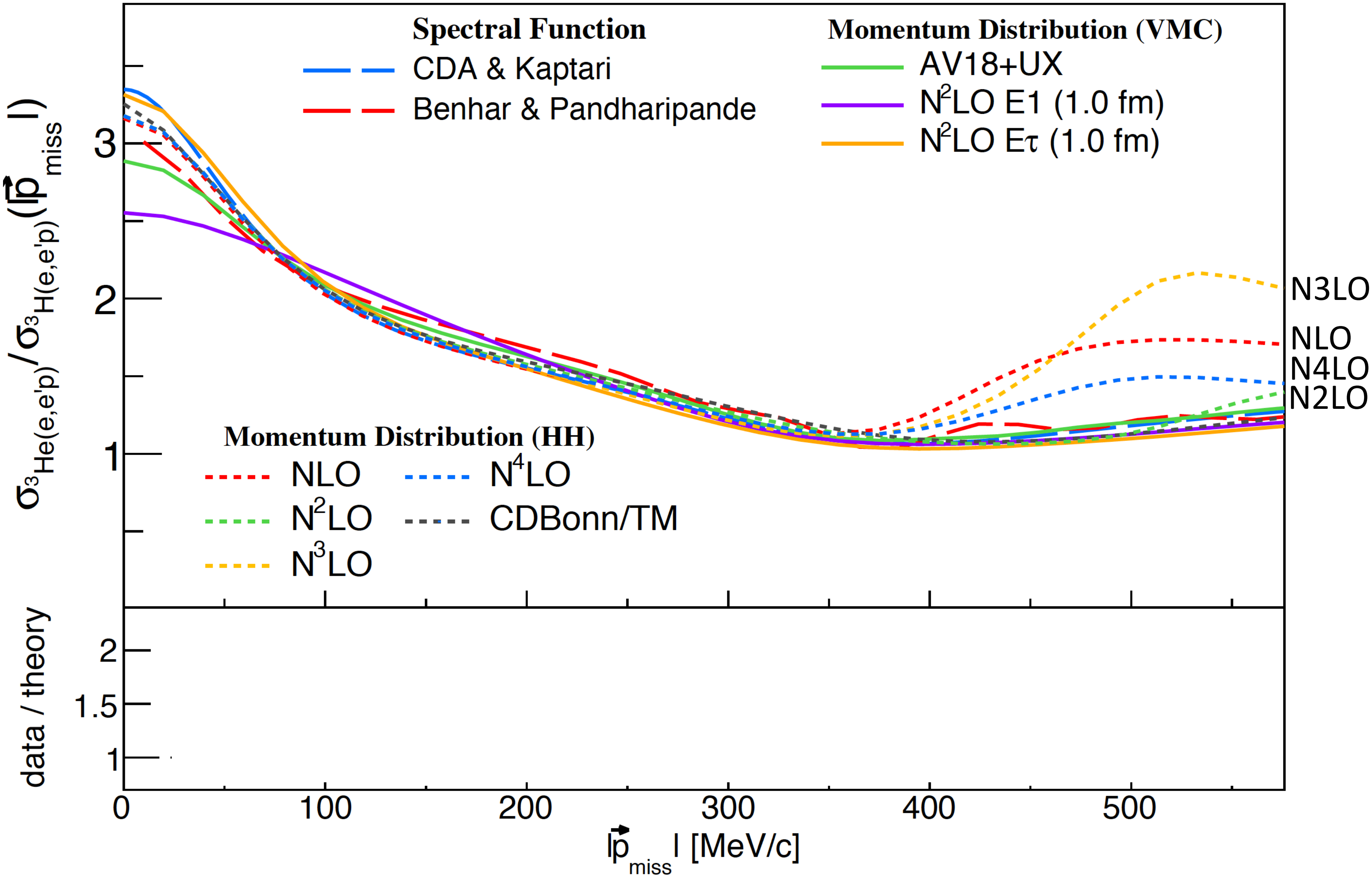
Corrections

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

High missing momentum setting

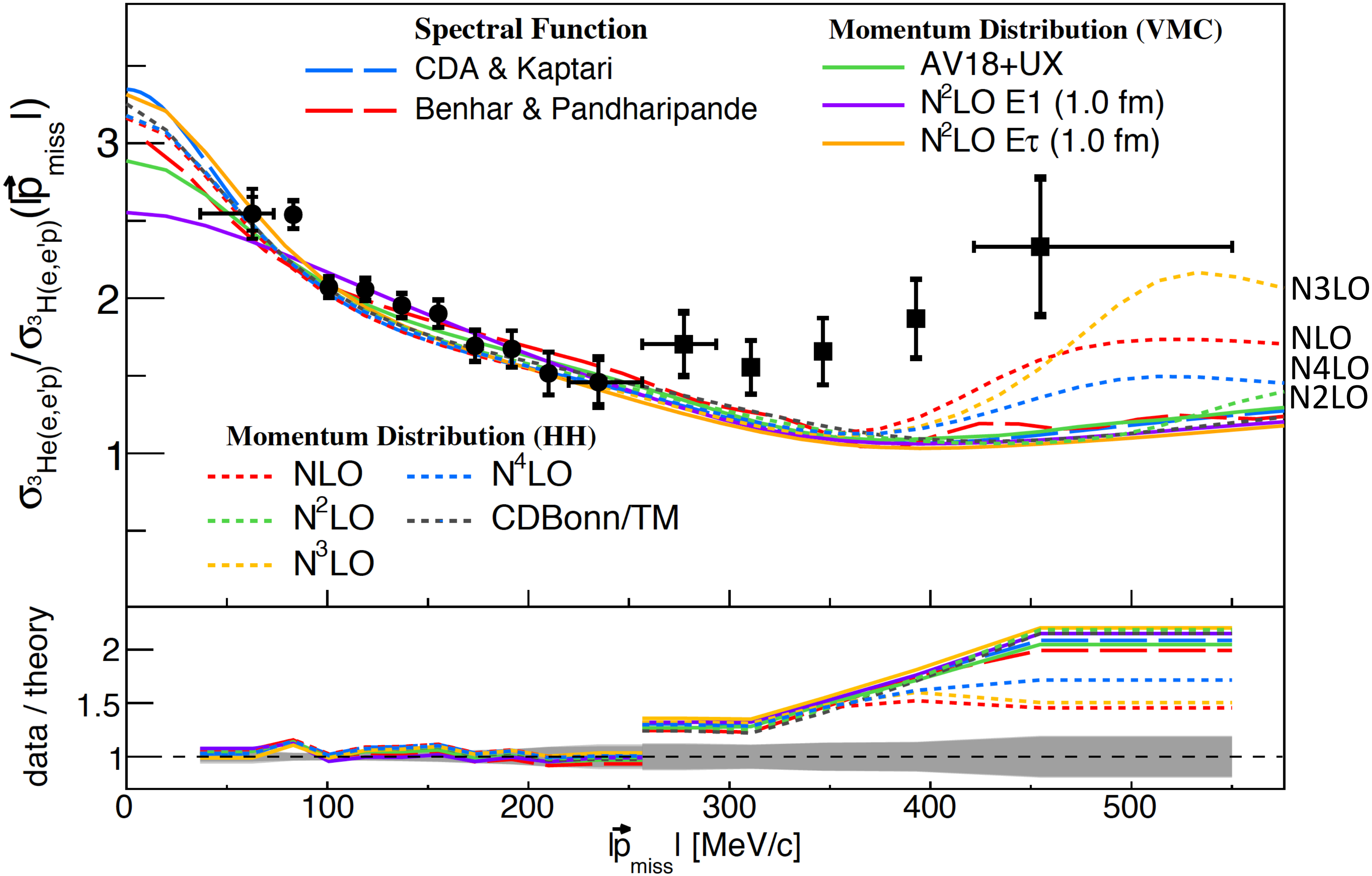


Final results



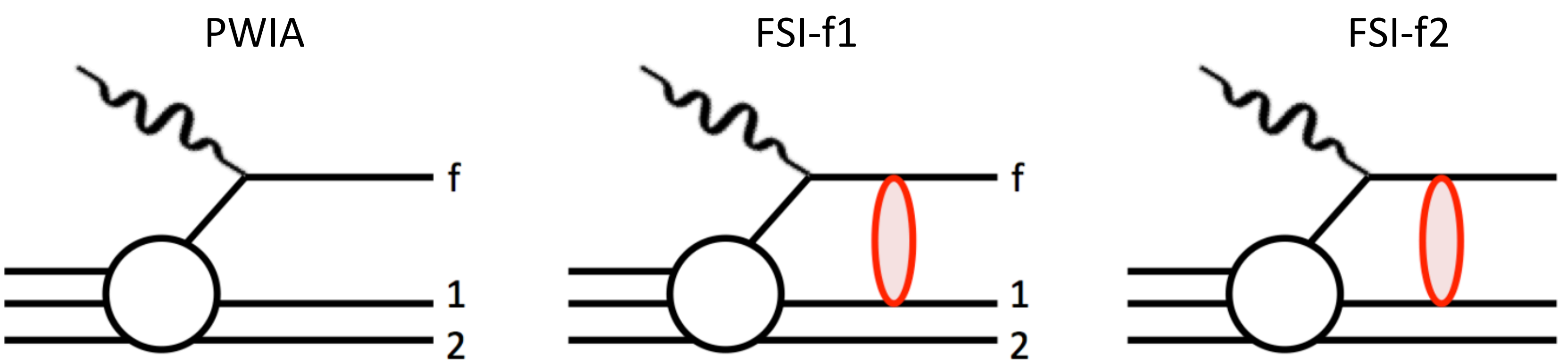
R.Cruz-Torres et al. Submitted for publication. arXiv:1902.06358 (2019)

Final results



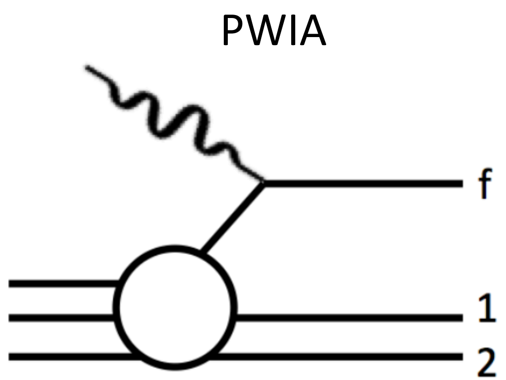
R.Cruz-Torres et al. Submitted for publication. arXiv:1902.06358 (2019)

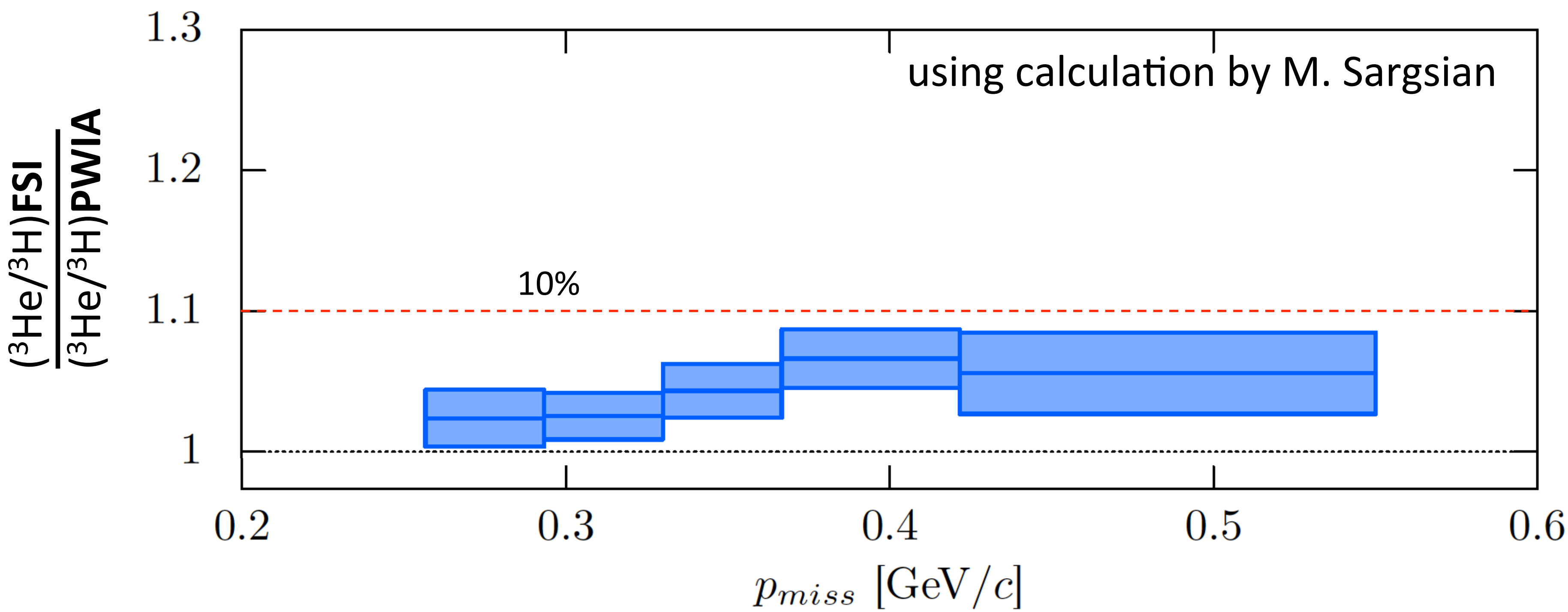
Effect of Final-State Interactions



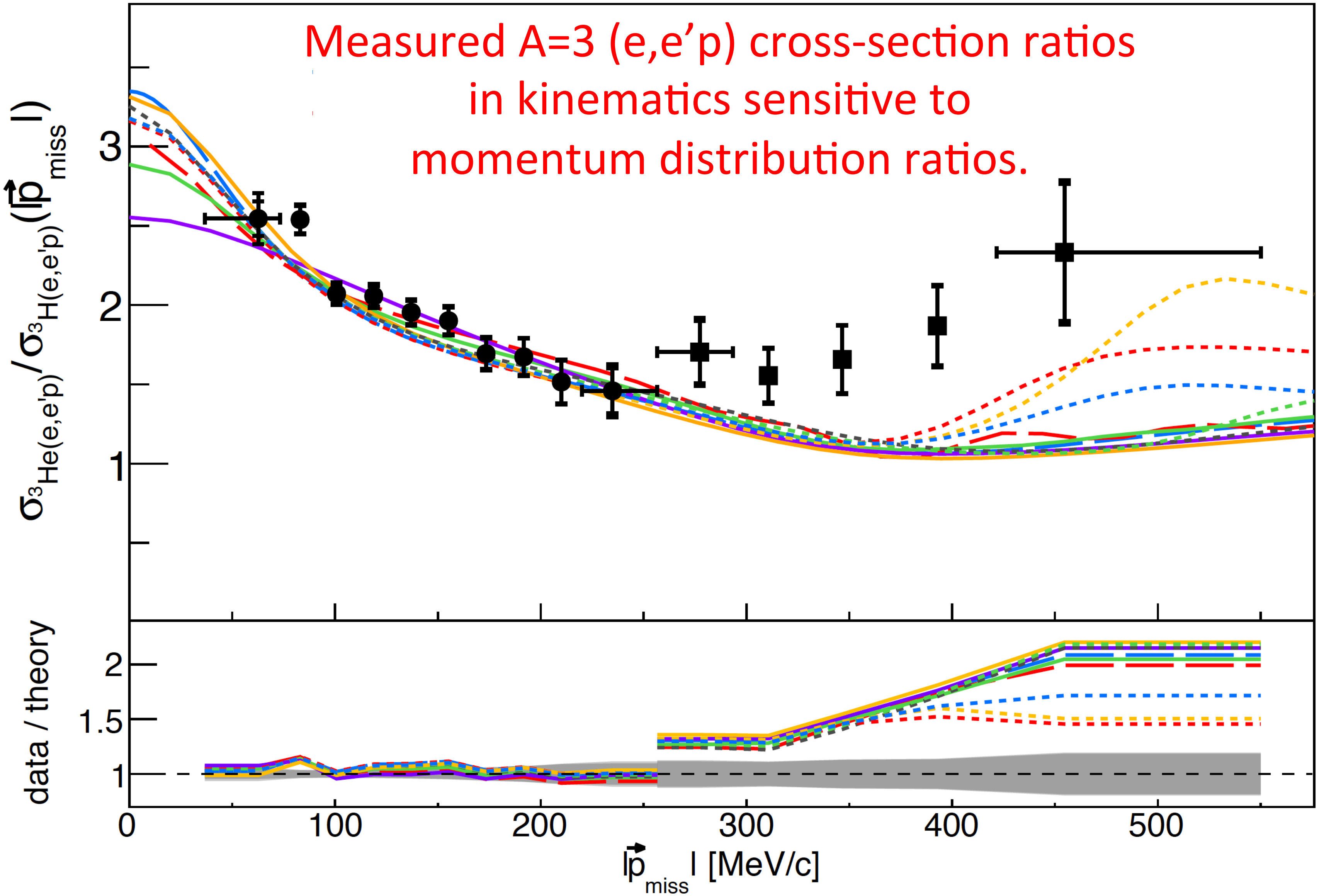
using calculation by M. Sargsian

Effect of Final-State Interactions



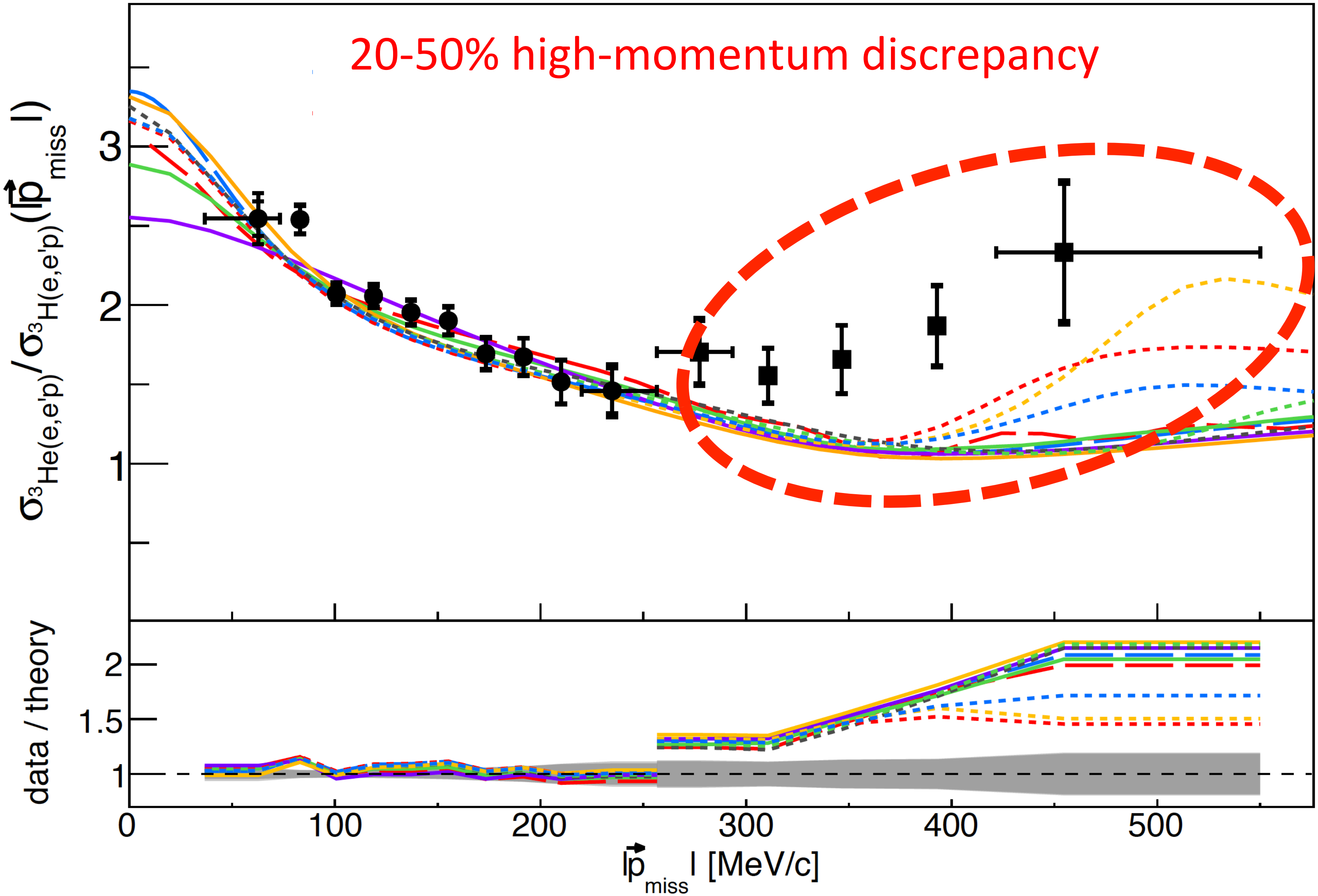


To Recap:



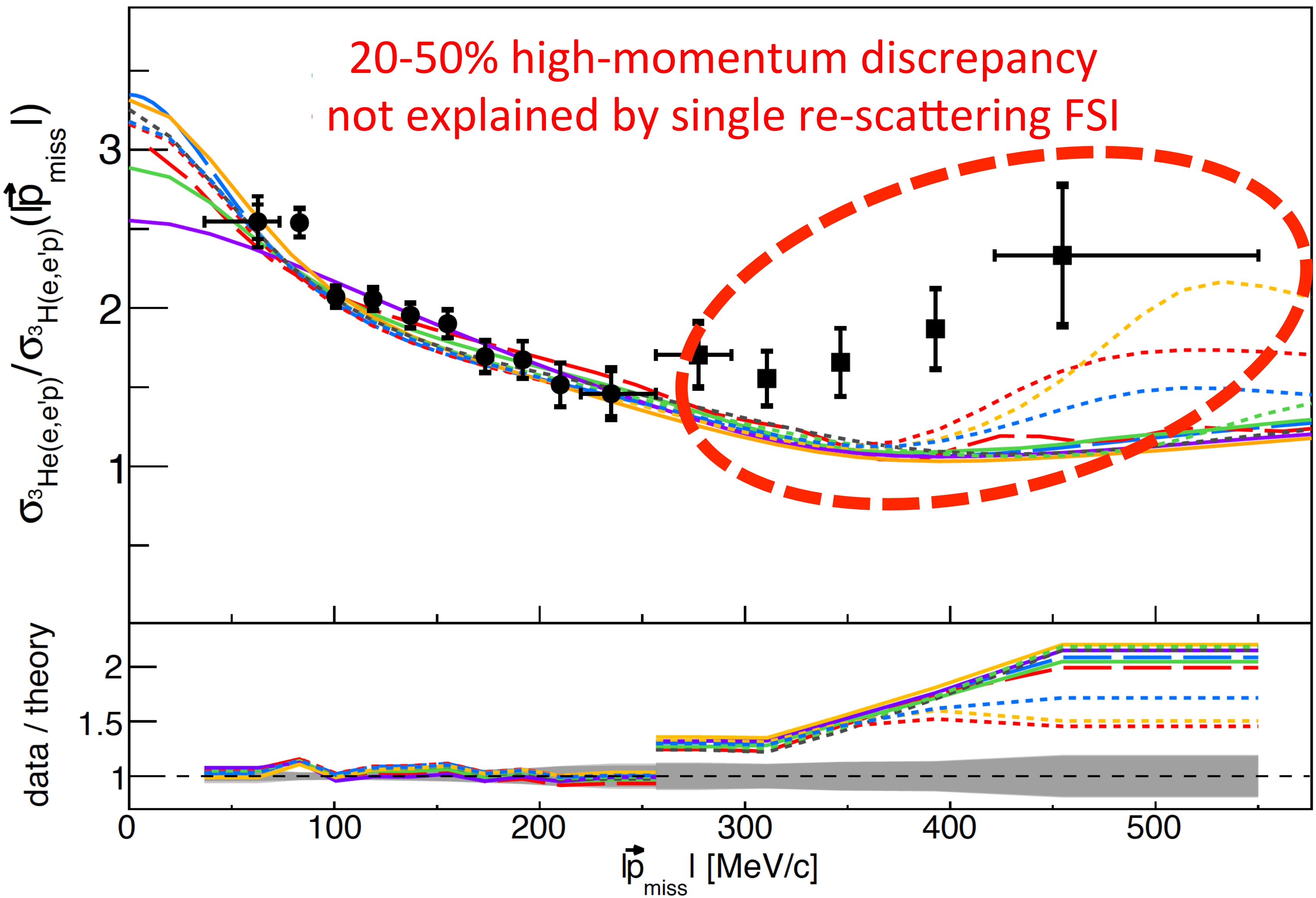
R.Cruz-Torres et al. Submitted for publication. arXiv:1902.06358 (2019)

To Recap:



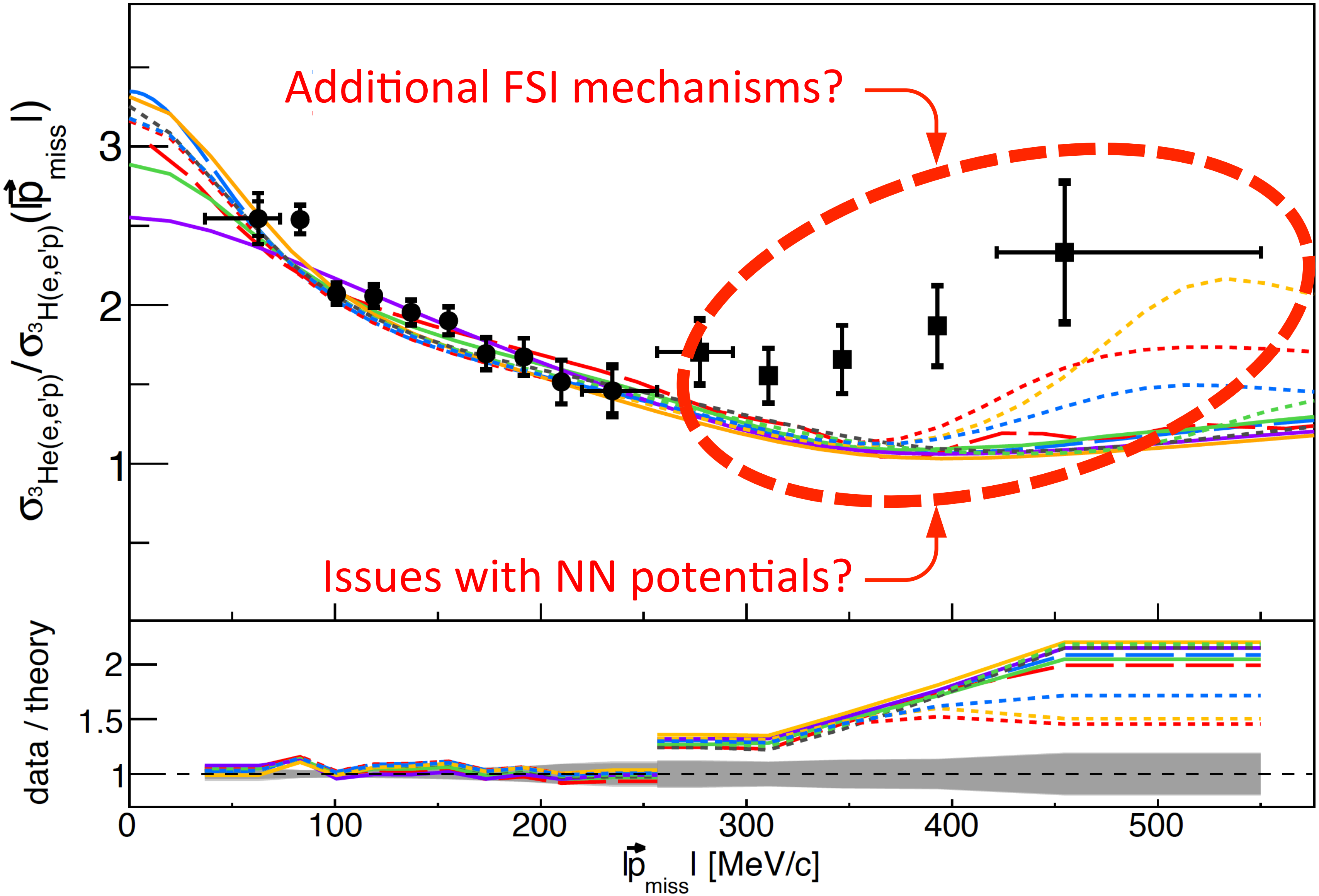
R.Cruz-Torres et al. Submitted for publication. arXiv:1902.06358 (2019)

To Recap:



R.Cruz-Torres et al. Submitted for publication. arXiv:1902.06358 (2019)

To Recap:



R.Cruz-Torres et al. Submitted for publication. arXiv:1902.06358 (2019)

Outlook:

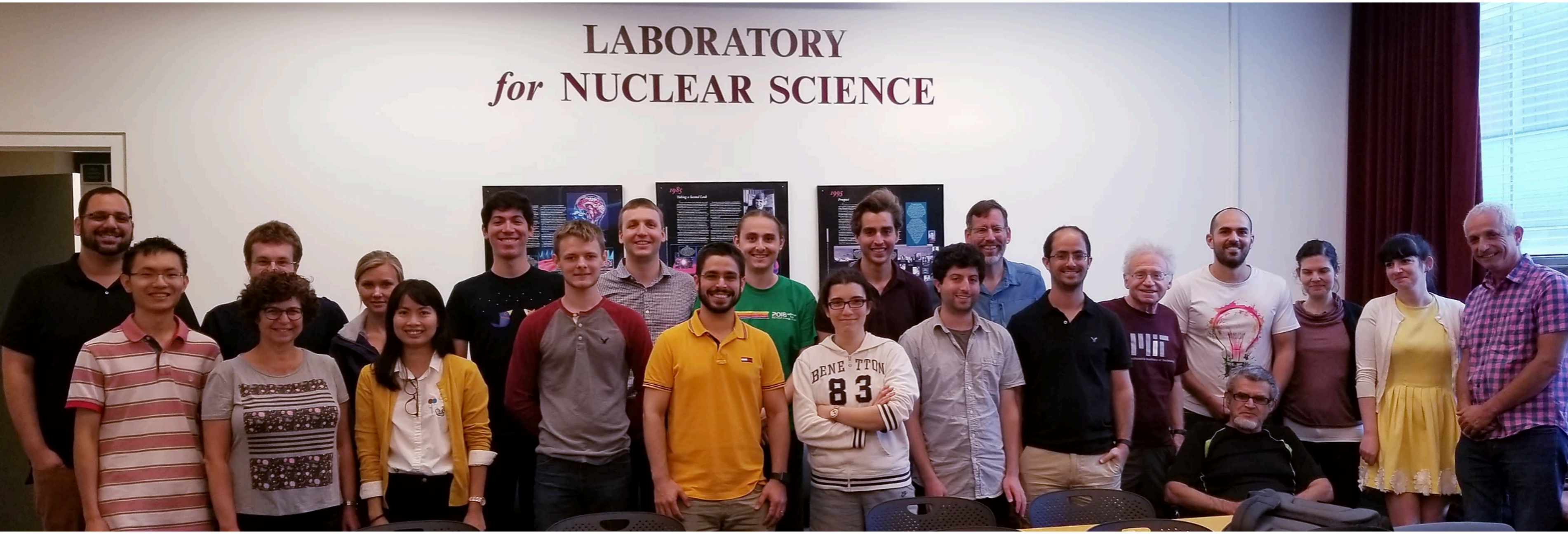
Path forward to understanding high-p_{miss} discrepancy:

- Study additional calculations with other effects
- Absolute cross section extraction

D. Nguyen

R.Cruz-Torres et al. Submitted for publication. arXiv:1902.06358 (2019)

Thank you!



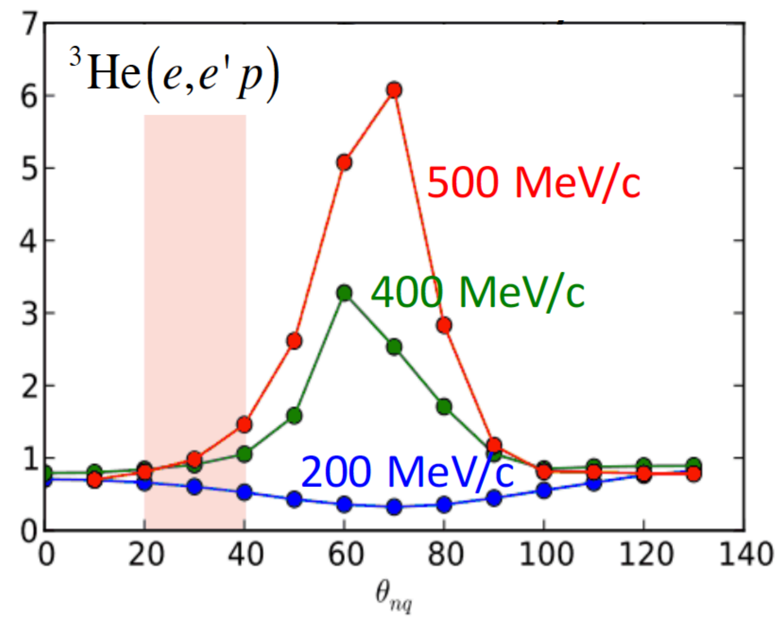
Backup slides

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



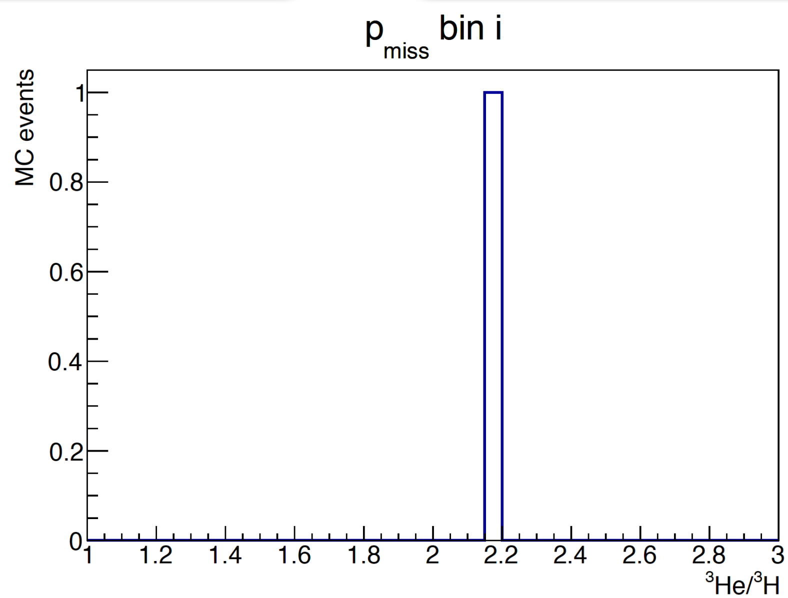
non-QE events: xB > 1.3
(high-Pmiss kinematics)

Systematic Uncertainties

From event selection

Determined as follows: for a given p_{miss} bin:

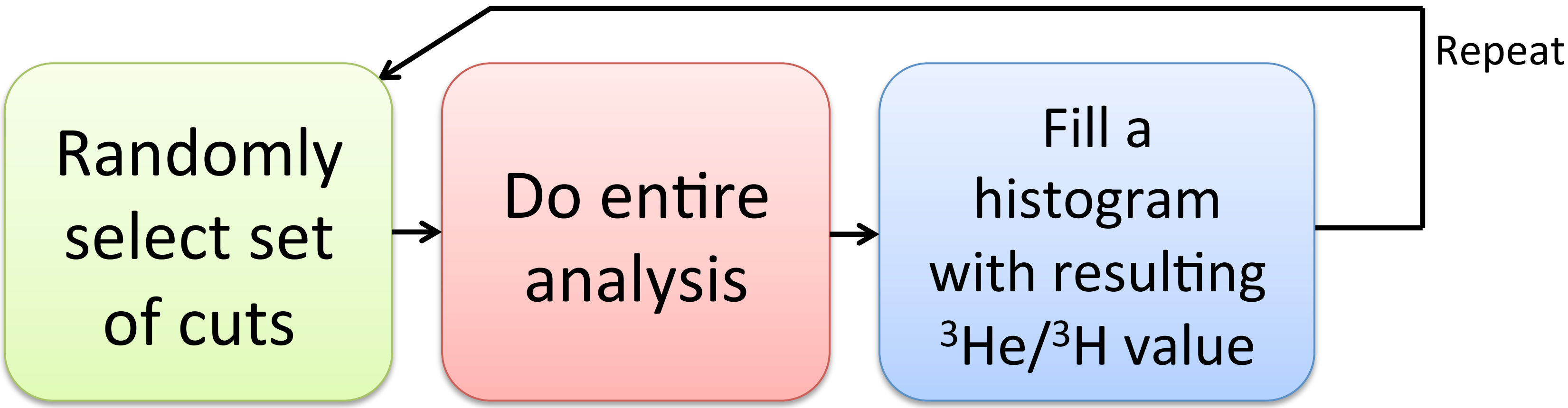
Randomly select set of cuts → Do entire analysis → Fill a histogram with resulting $^3He/^3H$ value

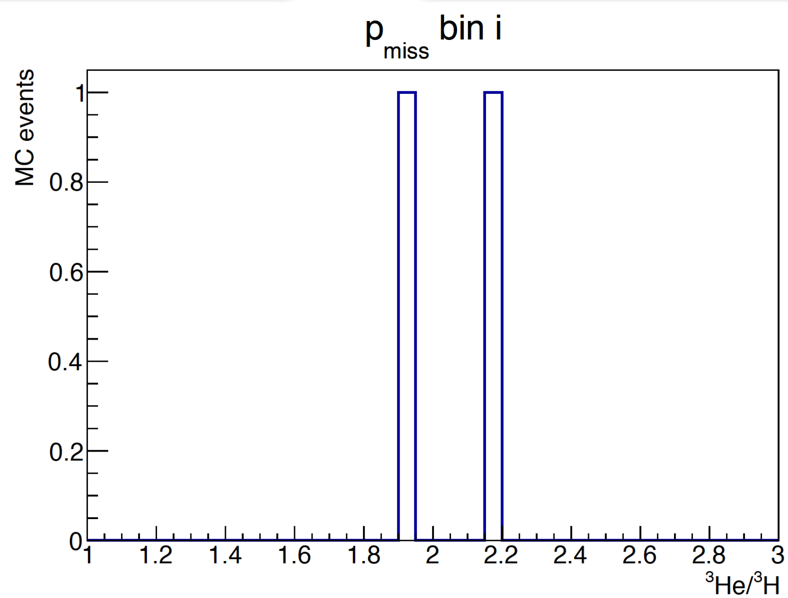


Systematic Uncertainties

From event selection

Determined as follows: for a given p_{miss} bin:

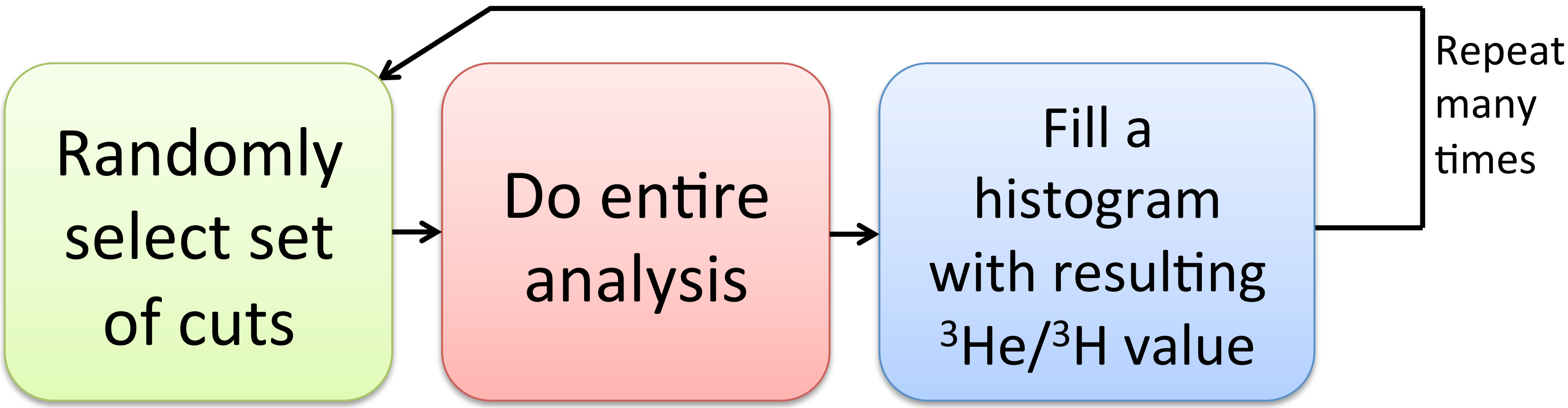


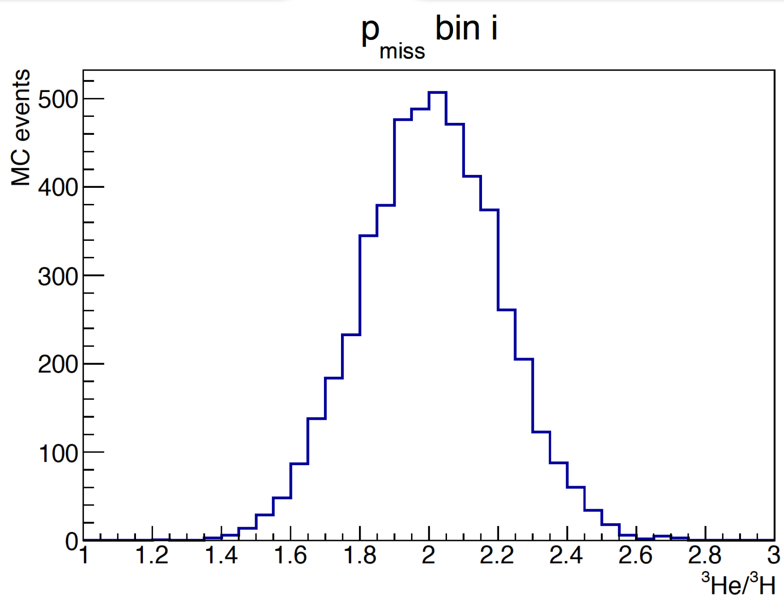


Systematic Uncertainties

From event selection

Determined as follows: for a given p_{miss} bin:



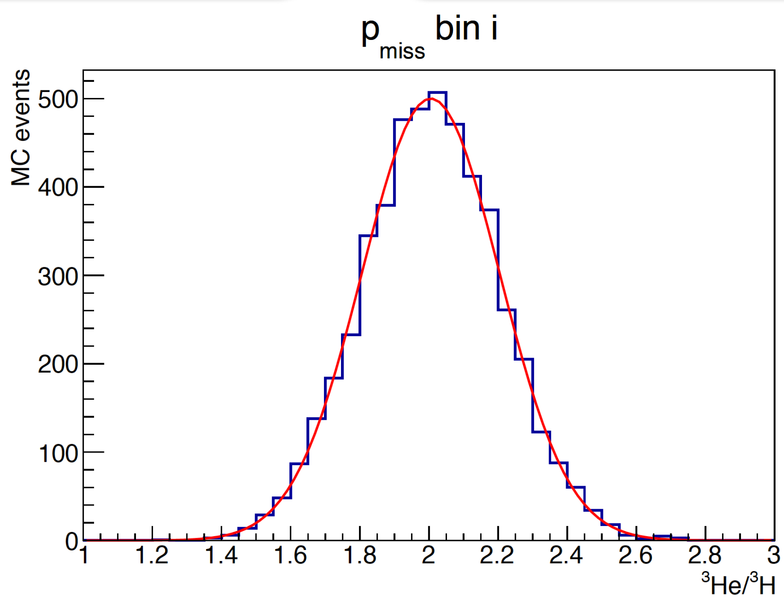


Systematic Uncertainties

From event selection

Determined as follows: for a given p_{miss} bin:

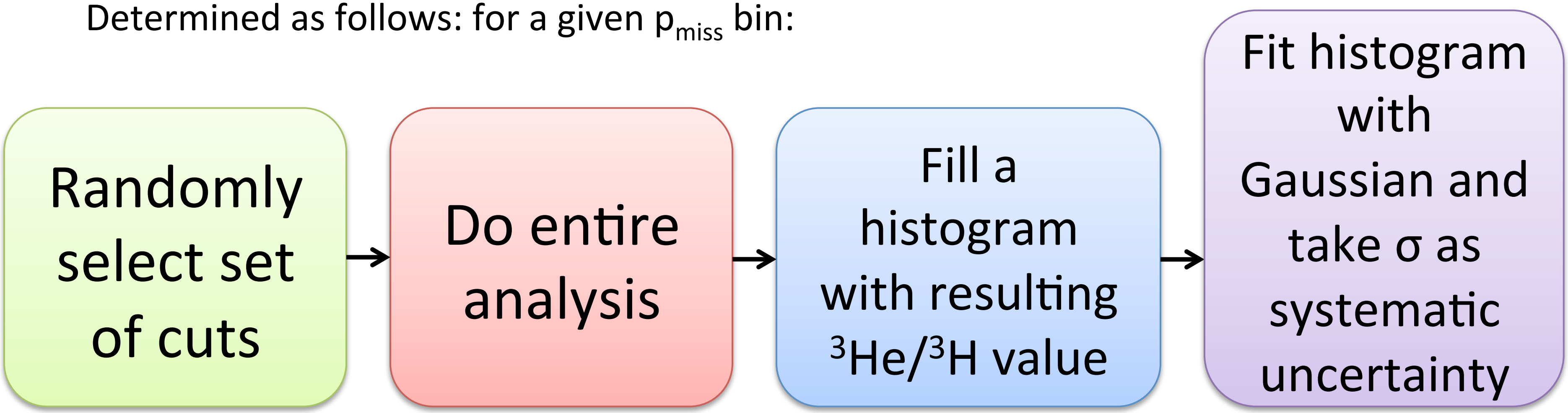
Randomly select set of cuts → Do entire analysis → Fill a histogram with resulting $^3He/^3H$ value → Fit histogram with Gaussian and take σ as systematic uncertainty



Systematic Uncertainties

From event selection

Determined as follows: for a given p_{miss} bin:



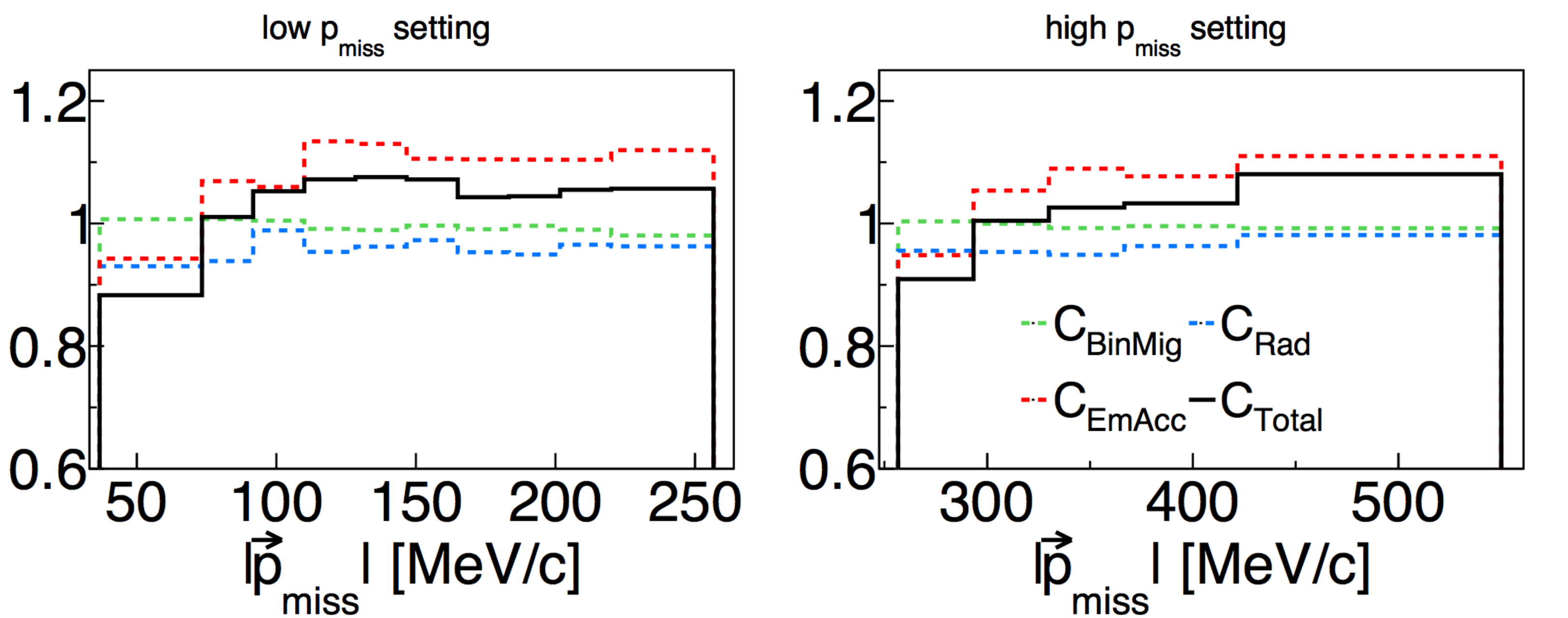
Others:

	Overall	Point-to-point
Target Walls	$\ll 1\%$	
Target Density	1.5%	
Beam-Charge and Stability	1%	
Tritium Decay	0.18%	
spectral function isospin symmetry	3%	
Cut sensitivity		1% - 8%
Simulation Corrections (bin-migration, radiation, E_m acceptance)		1% - 2%

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

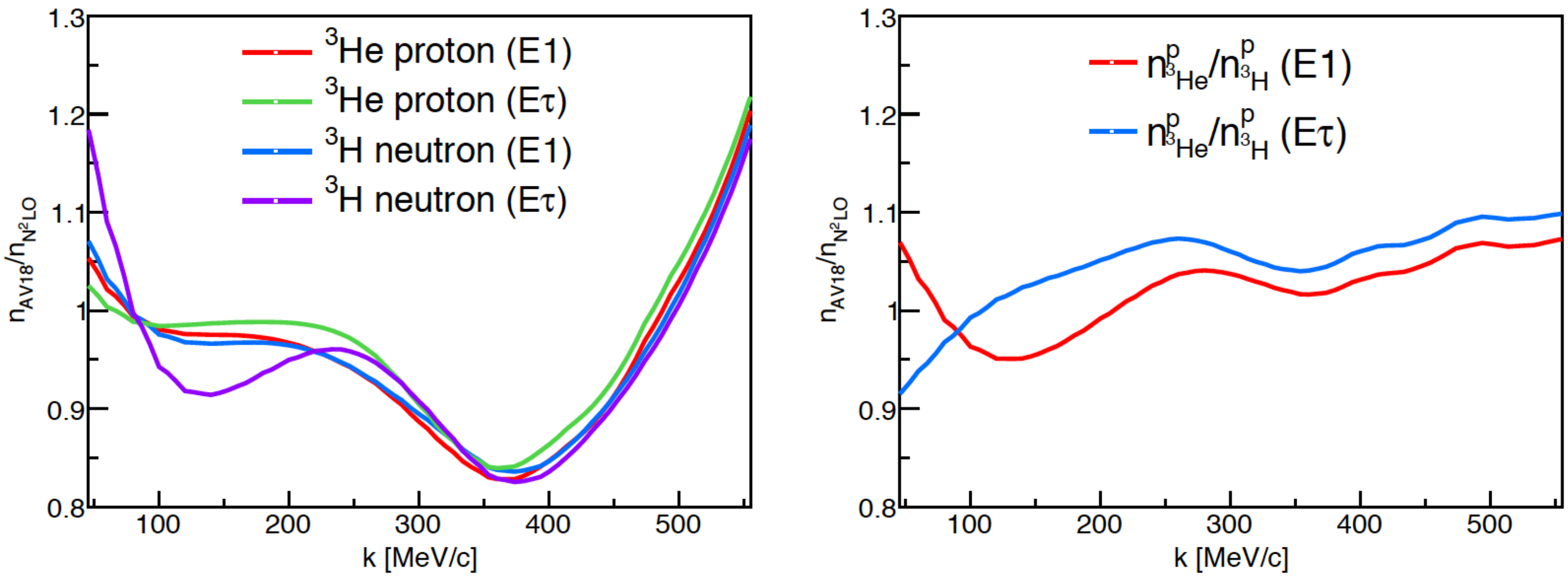
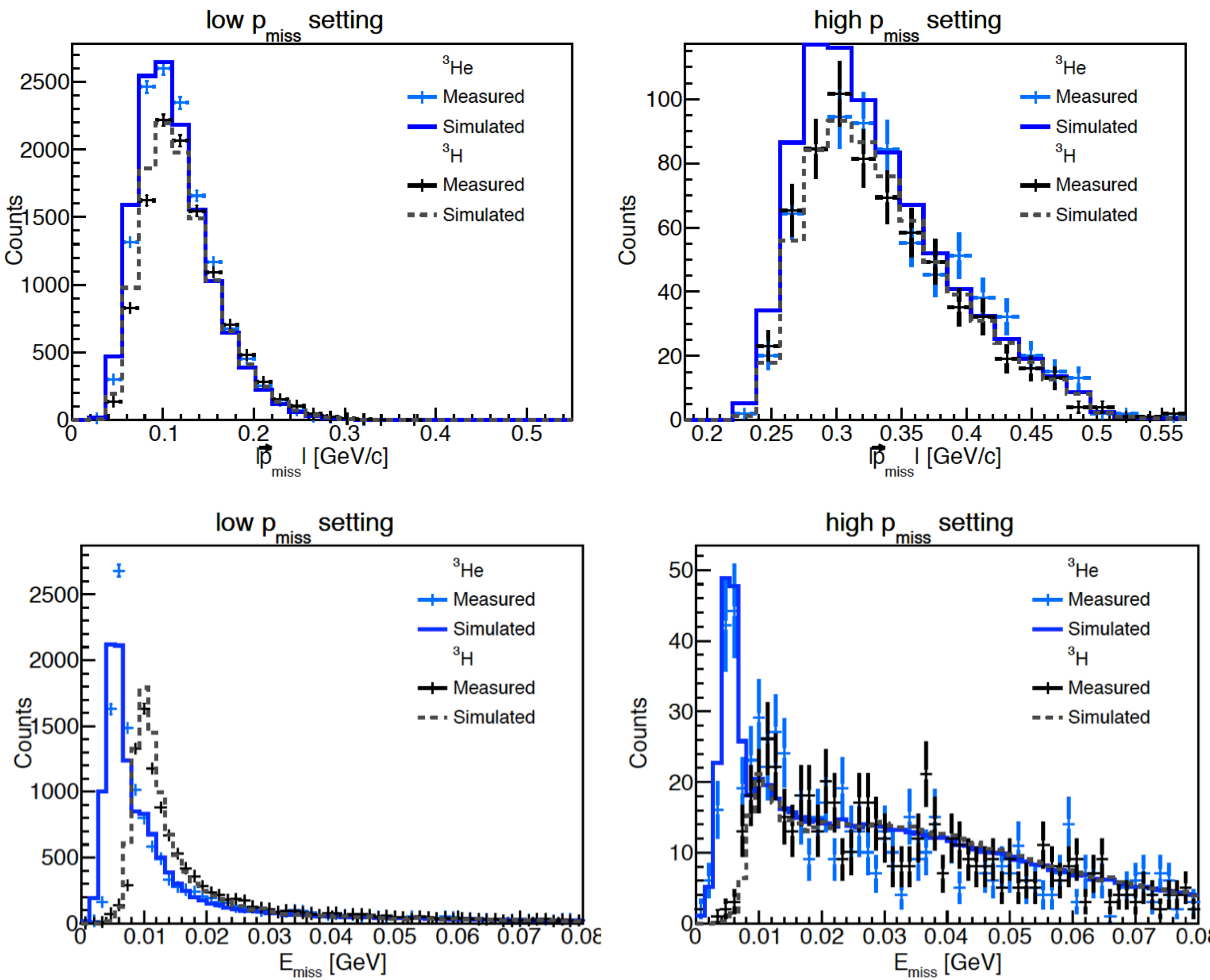
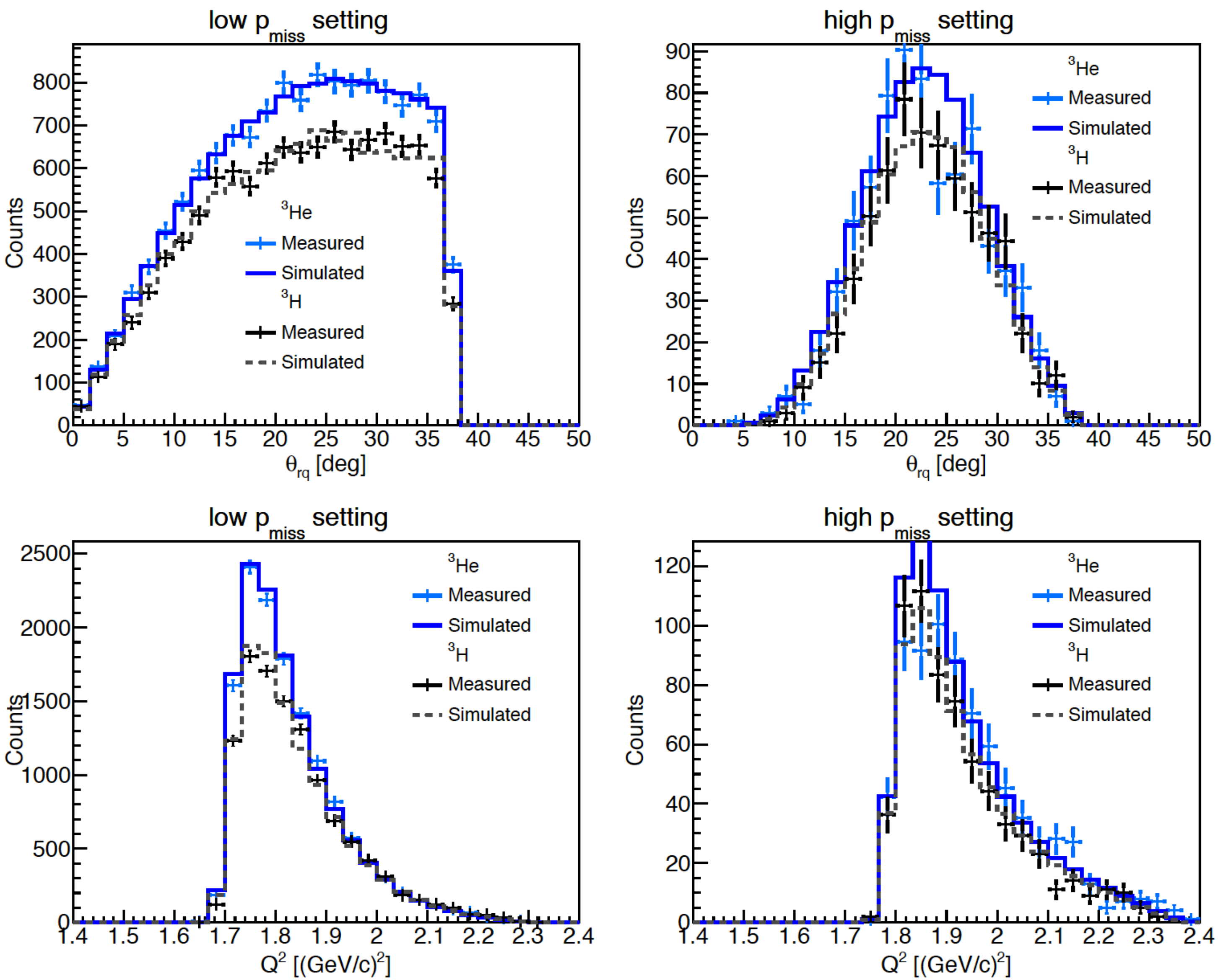


FIG. 2: Ratio of different distributions obtained using the AV18 and N^{2}LO potentials. The left figure shows the $(n_{A=3})_{AV18}/(n_{A=3})_{N^2LO}$, where $n_{A=3}$ refers to the ^{3}He proton and ^{3}H neutron momentum distributions. The right figure shows the double ratio $(n^p_{^3He}/n^p_{^3H})_{AV18}/(n^p_{^3He}/n^p_{^3H})_{N^2LO}$.

Measurement-simulation comparison



Measurement-simulation comparison



2- and 3-body breakups in ^{3}He