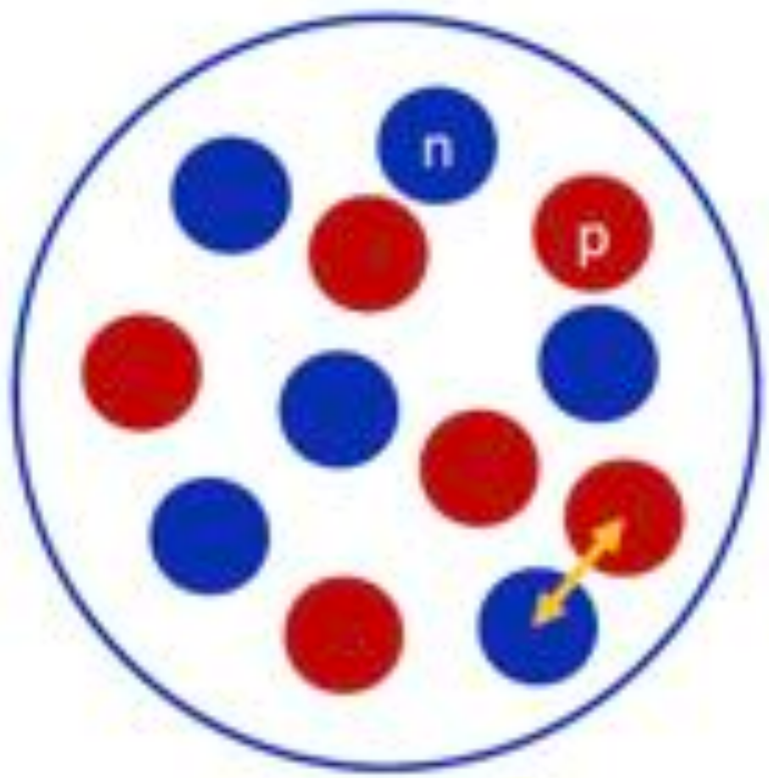
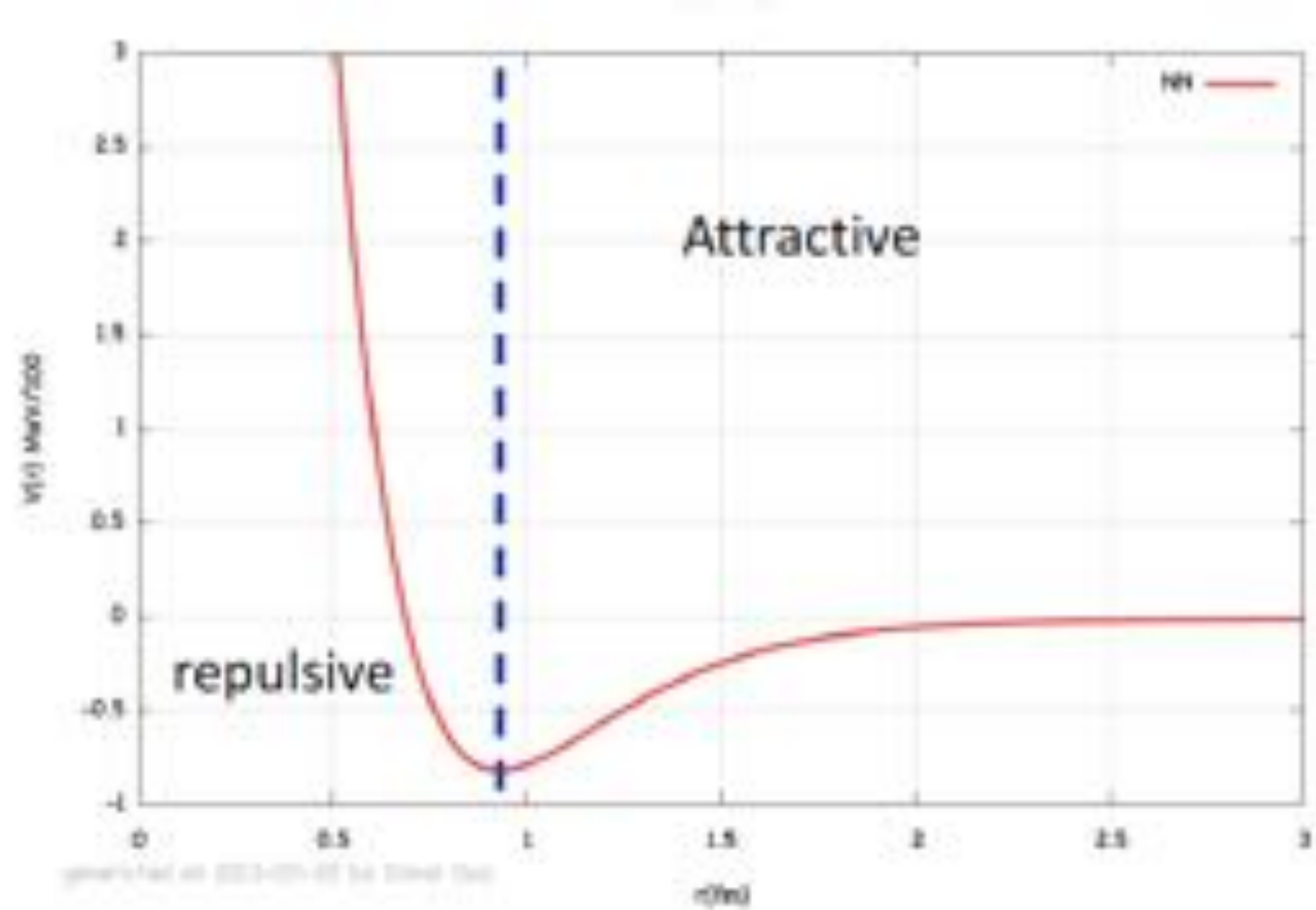
Probing few-body dynamics via ^{3}H and ^{3}He *(e,e'p)*pn cross-section

Dien Nguyen

Nuclear Physics introduction



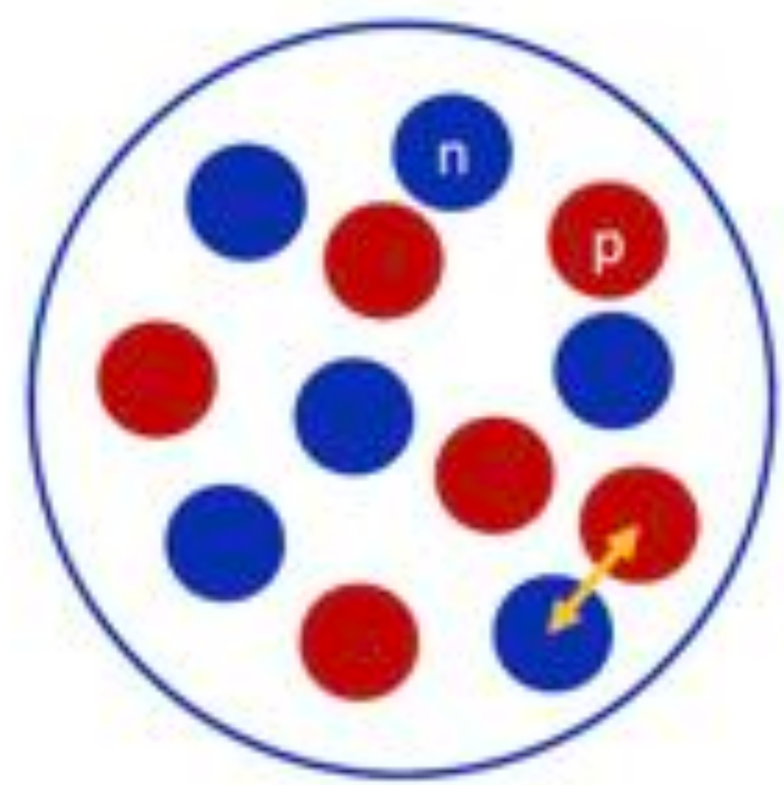
Nucleon-Nucleon (NN) potential



<u>An essential goal of Nuclear physics:</u>

1. Understanding the nature of the interaction between nucleon
2. How these interactions make up atomic nuclei and their property

… In Principle

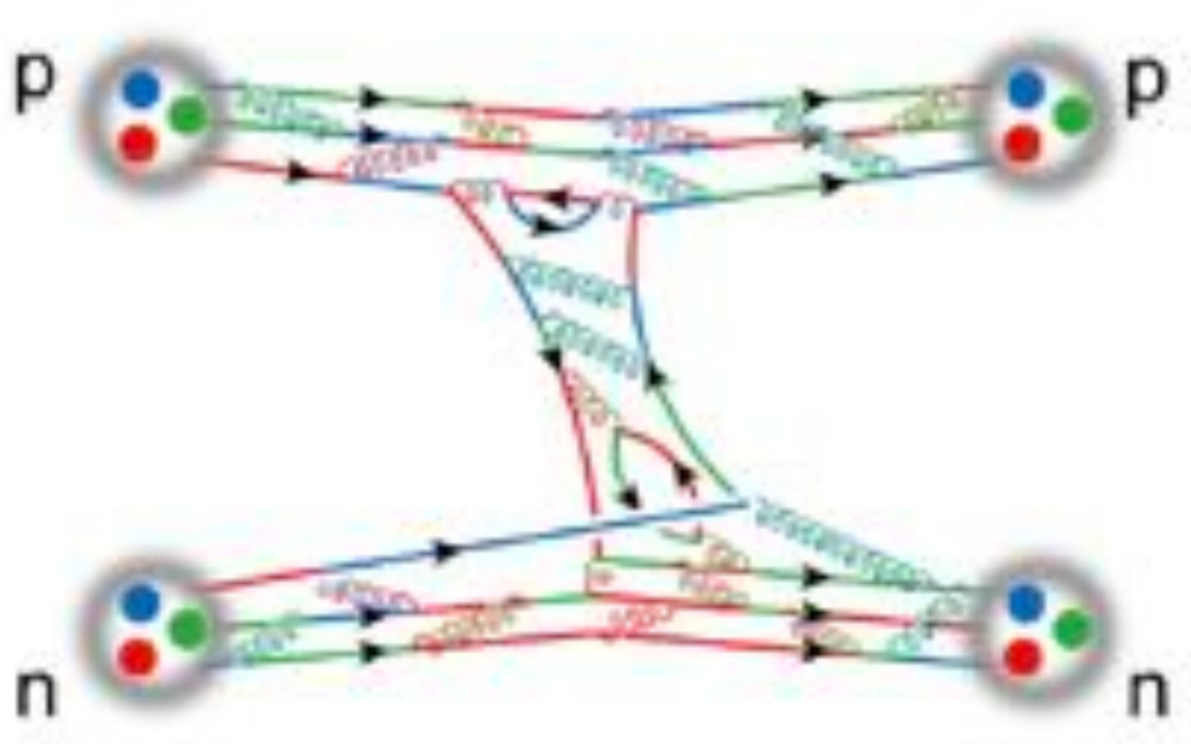


Many-Body Hamiltonian:

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

The Nuclear Challenge

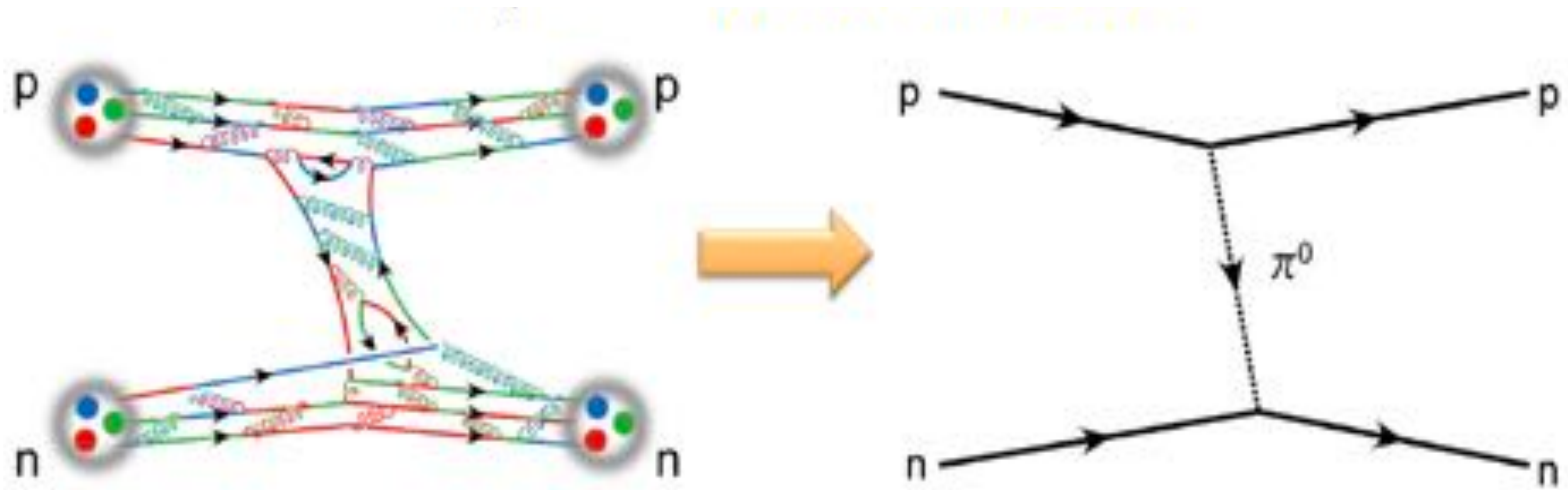
Complex QCD interaction



Strong force, spin, isospin ...

The Nuclear Challenge

Complex QCD -> Effective interaction

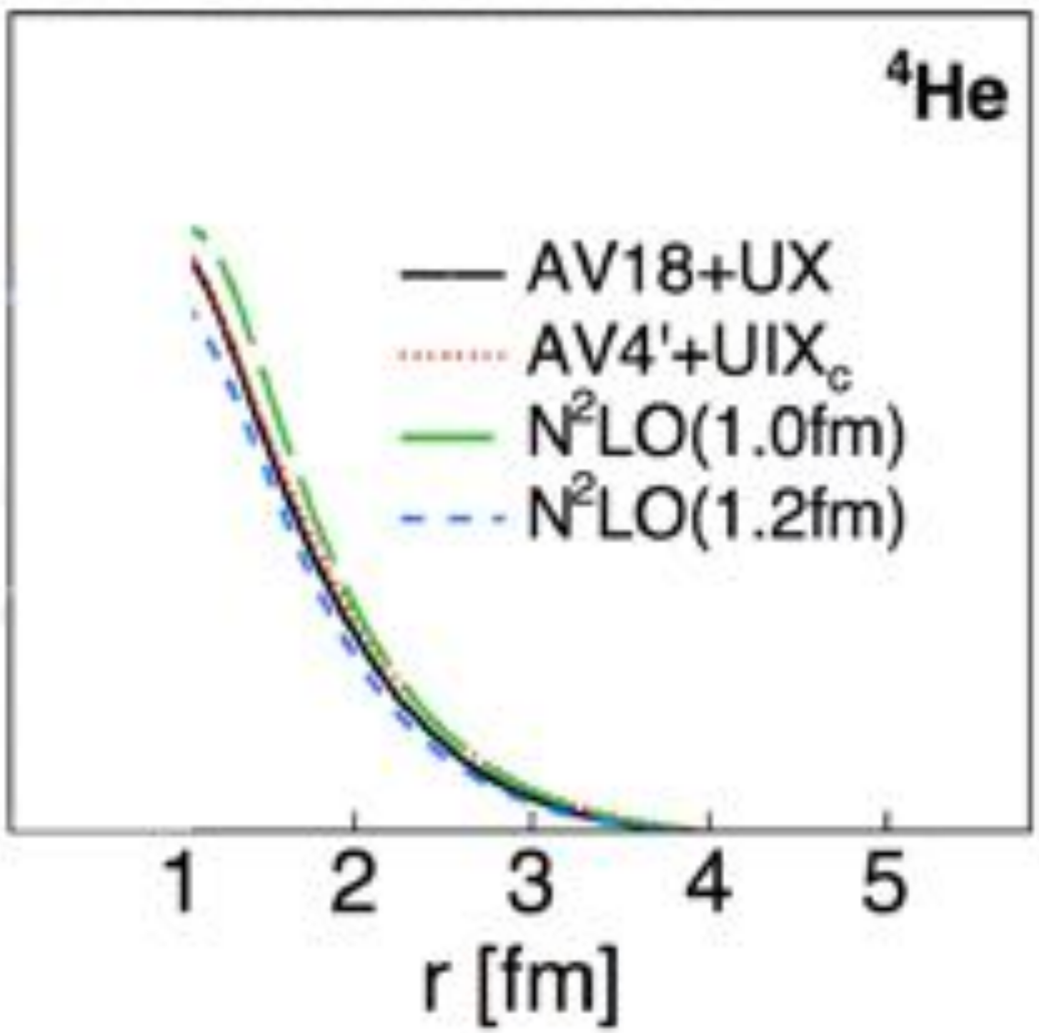


There are many NN potential models…

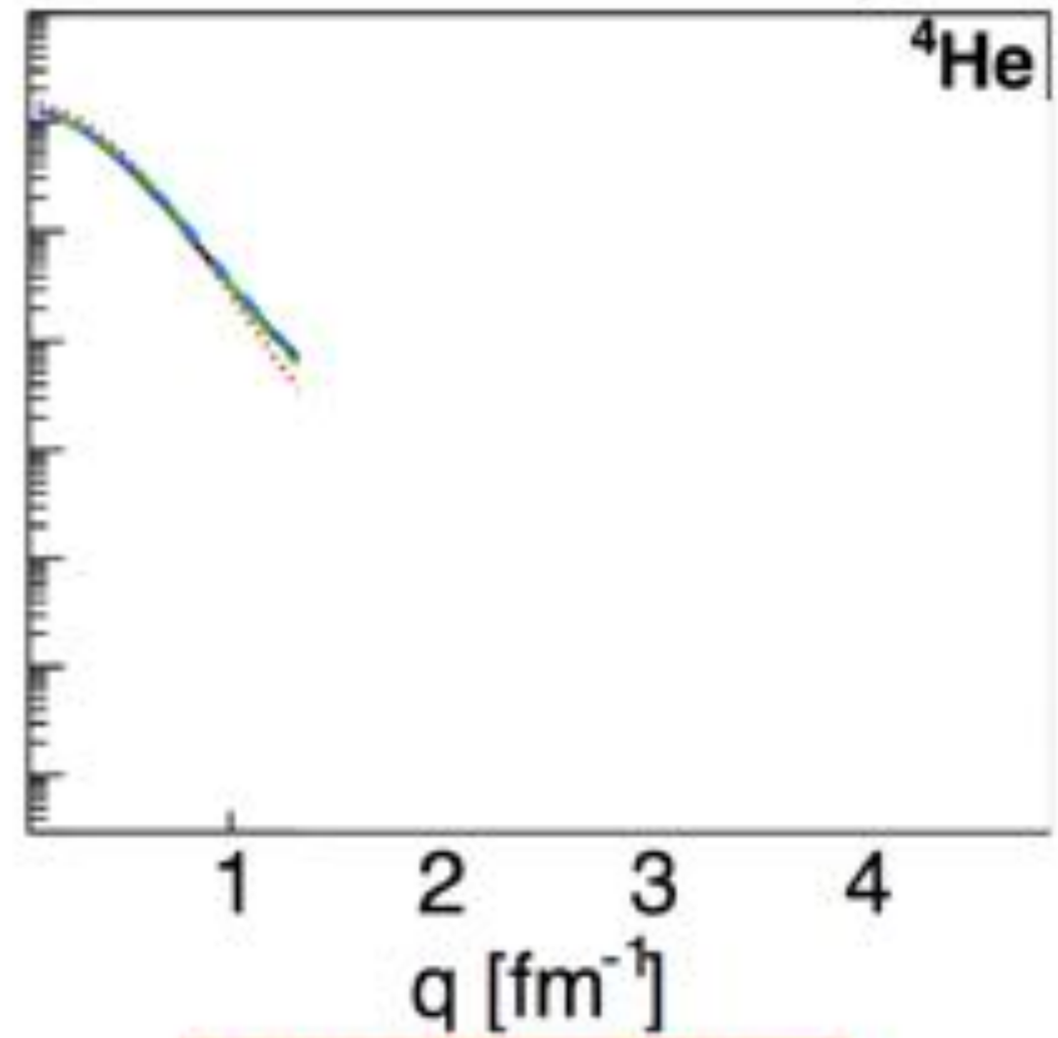
- Hamada-Johnston Potential
- Yale-Group Potential
- Reid68 Potential
- Reid-Day Potential
- Partovi-Lomon Potential
- Paris-Group Potentials
- Stony-Brook Potential
- dTRS Super-Soft-Core Potentials
- Funabashi Potentials
- Urbana-Group Potentials
- Argonne-Group Potentials
  - Argonne V14
  - Argonne 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!**

Overall consistent at long-r/ small-k

Probability to find two nucleons with relative distance r

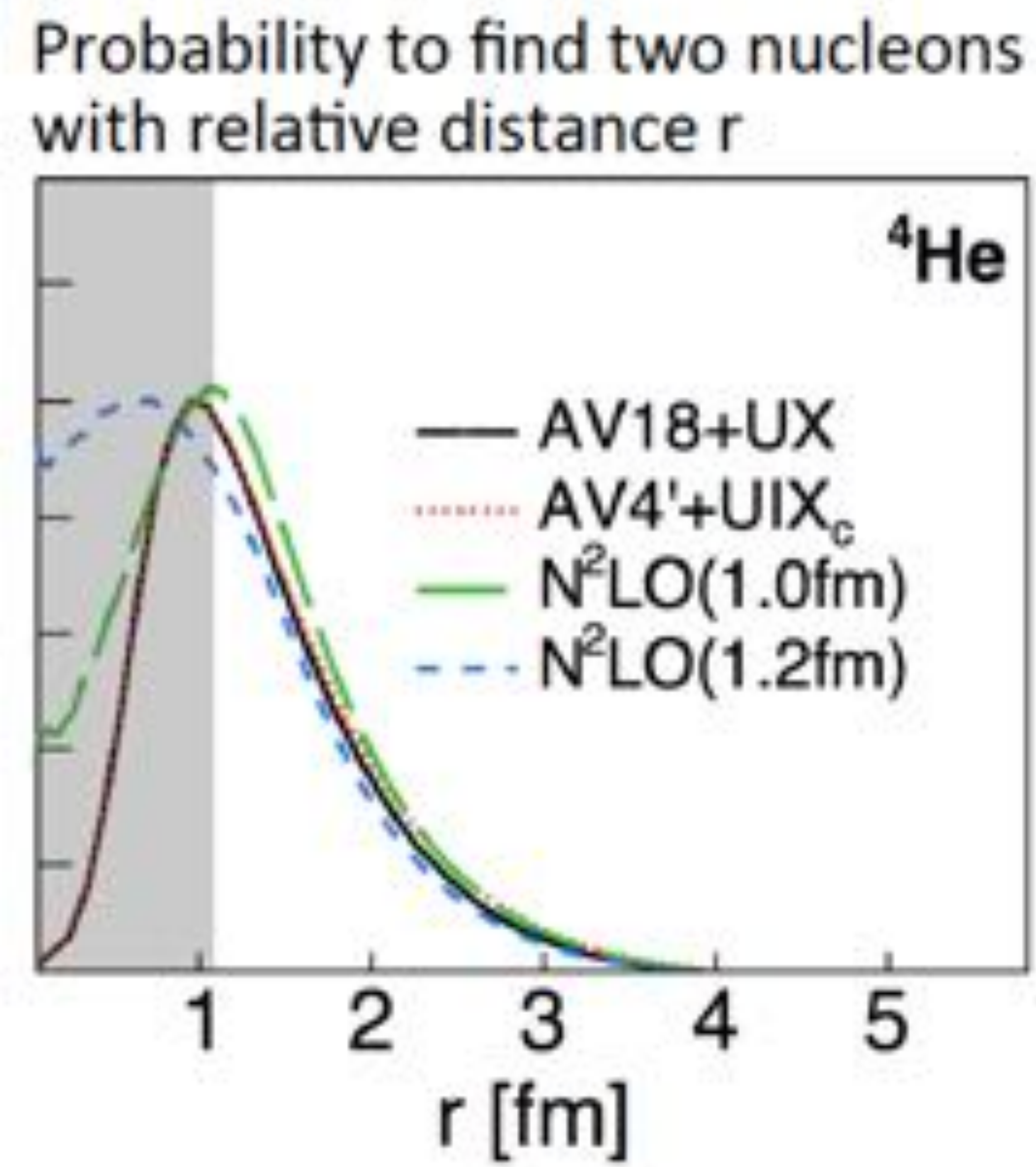


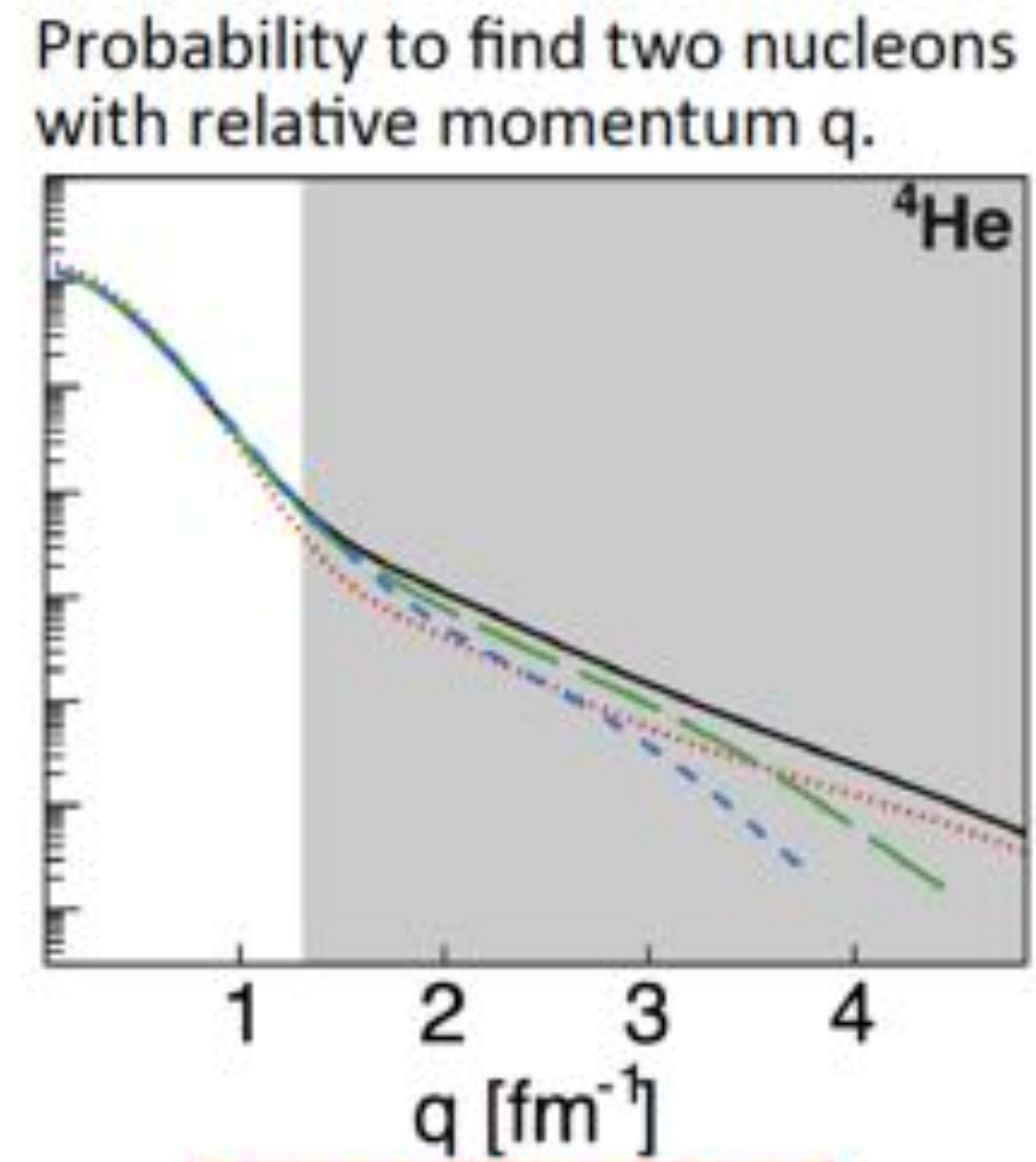
Probability to find two nucleons with relative momentum q.



200 MeV/*c* ≈ 1 fm^{-1}

Large model dependence at small-r/high-k





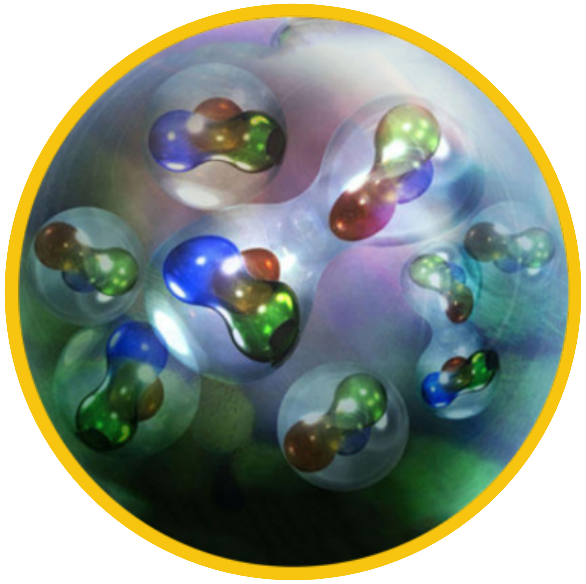
200 MeV/*c* ≈ 1 fm^{-1}

Need to put these to test

Why Nucleon-nucleon interaction?

Crucial for:

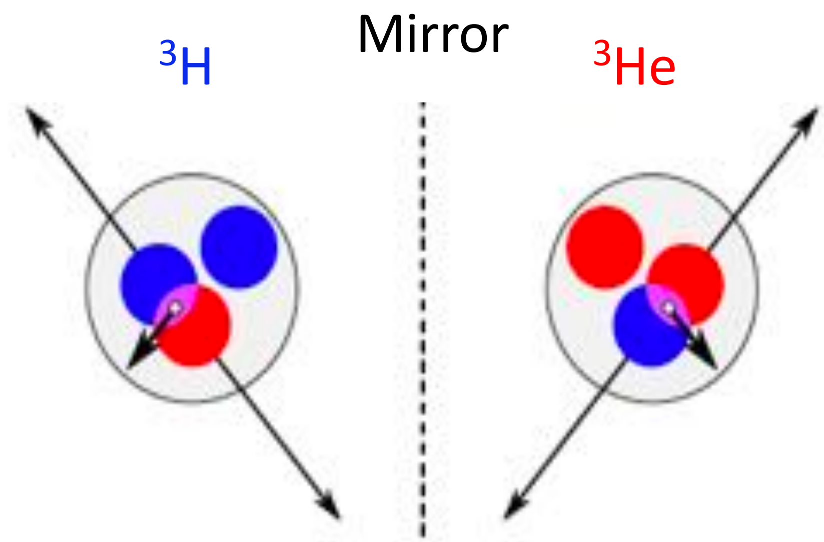
- ❑ Ab-Initio structure & reaction calculations
- ❑ Dense astrophysical objects, e.g. neutron stars
- ❑ Any calculation related to nuclear interaction



Why light nuclei?

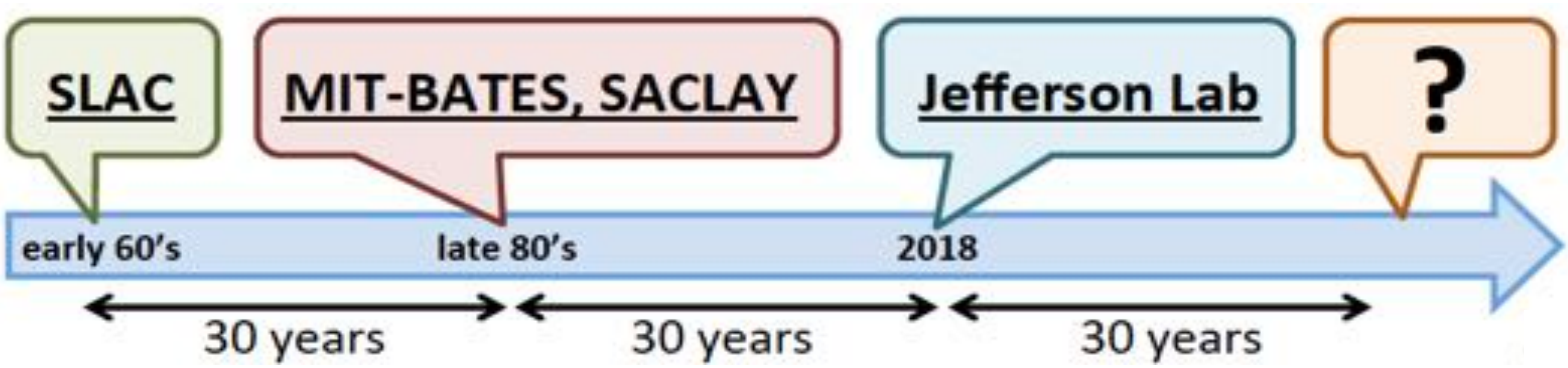
<u>3-Body system</u>:

- Exactly calculatable
- Test & benchmark theory



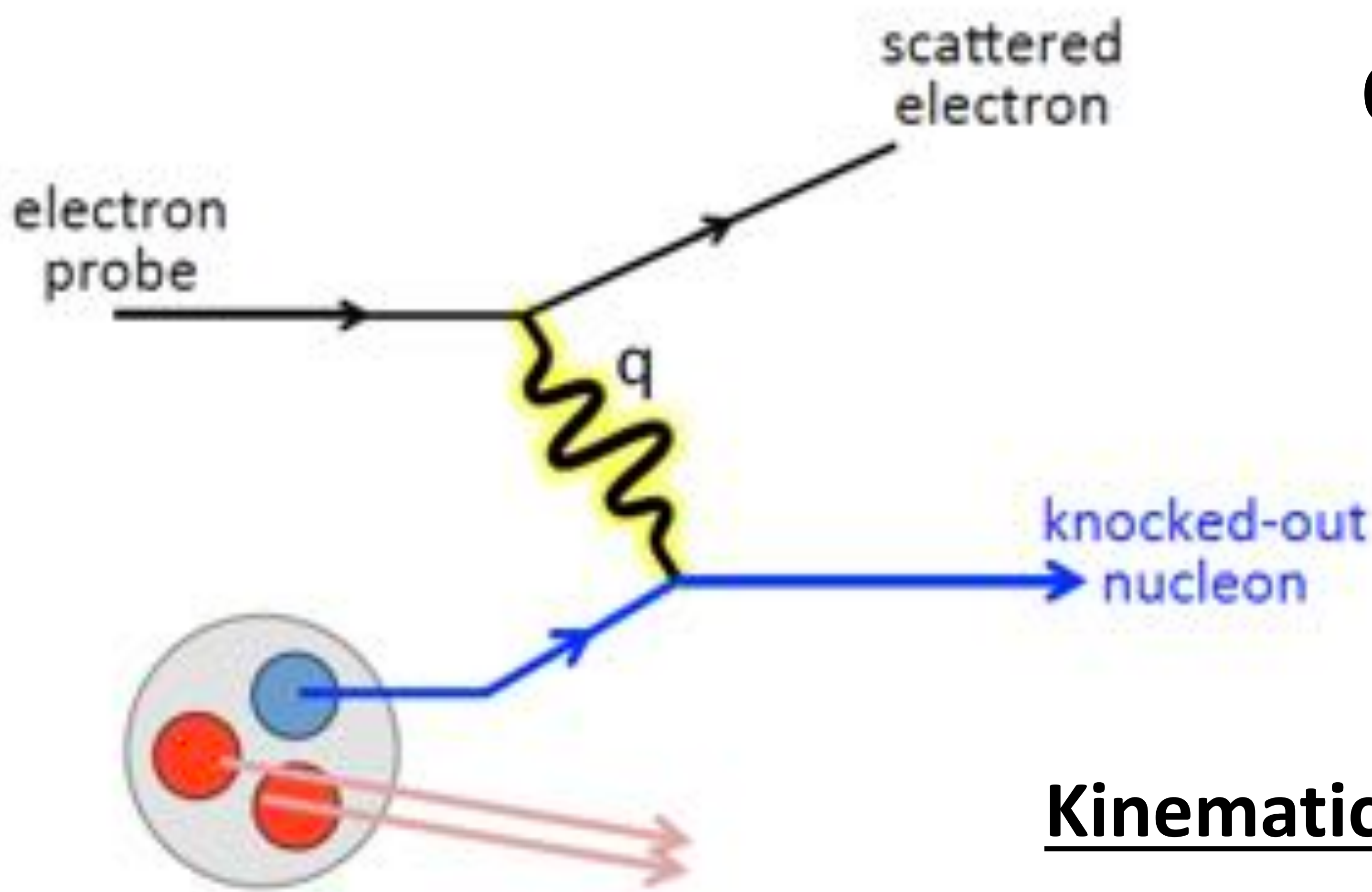
<u>Why Tritium</u>?

- Proton in ^3He = Neutron in ^3H
- Constraint reaction mechanism



Tritium at Jefferson Lab

Electron Scattering



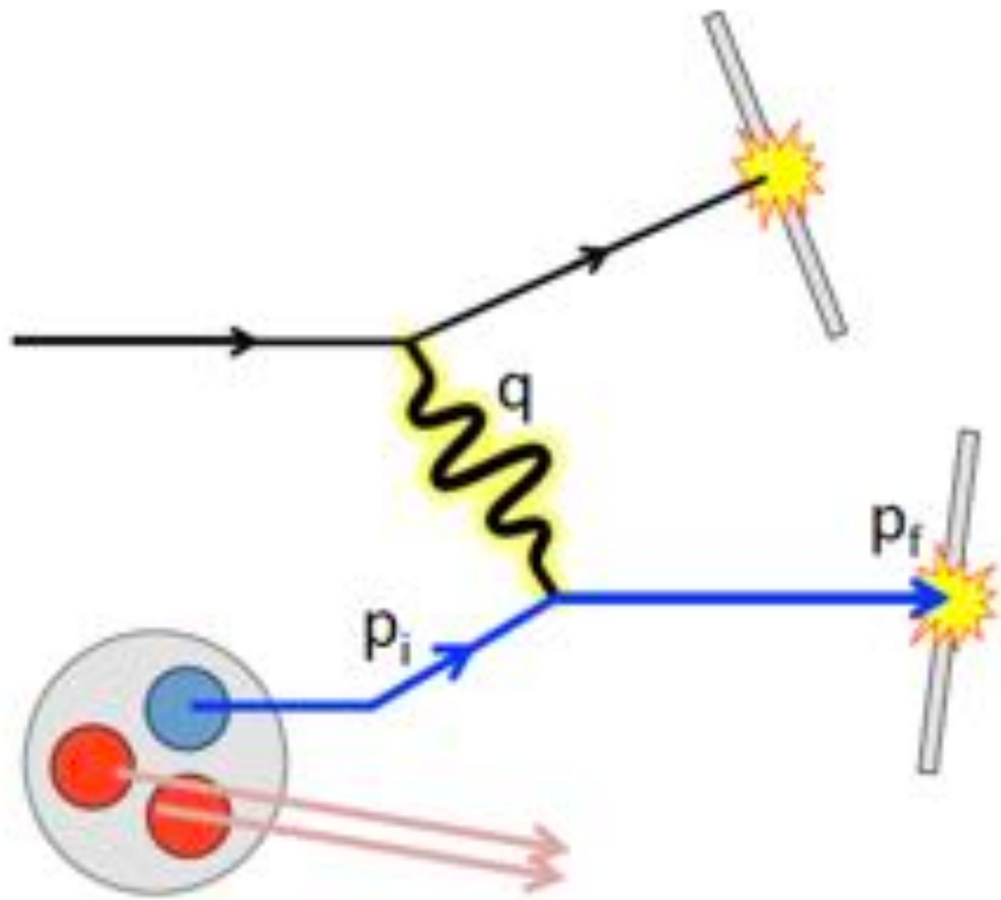
Quasi-elastic (QE) process

Kinematical variables:

$Q^2 = -(p_e - p_e')^2$ Resolution scale

$x_B = Q^2/2m(E - E')$ Dynamic scale

Plane-Wave Impulse Approximation (PWIA)



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

<u>Missing momentum</u>

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

<u>Assumptions:</u>

- ❑ Momentum transfer absorbed by a single nucleon
- ❑ Knocked-out nucleon did not re-scatter as it left the nucleon

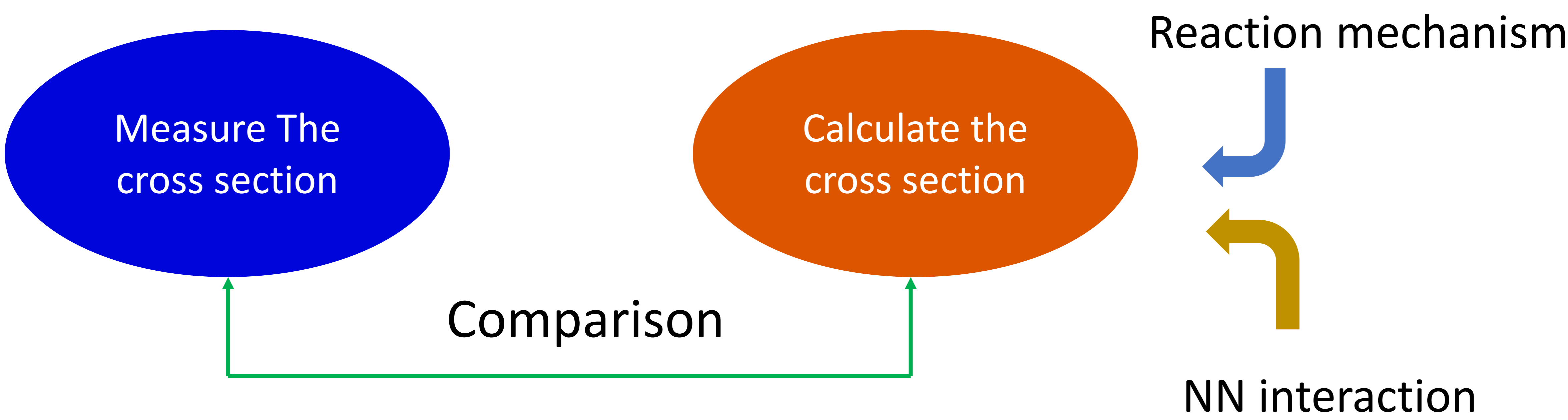
High Q²: PWIA factorized approximation

Cross-section (Observation)   (e,e'p)

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

Experiment:

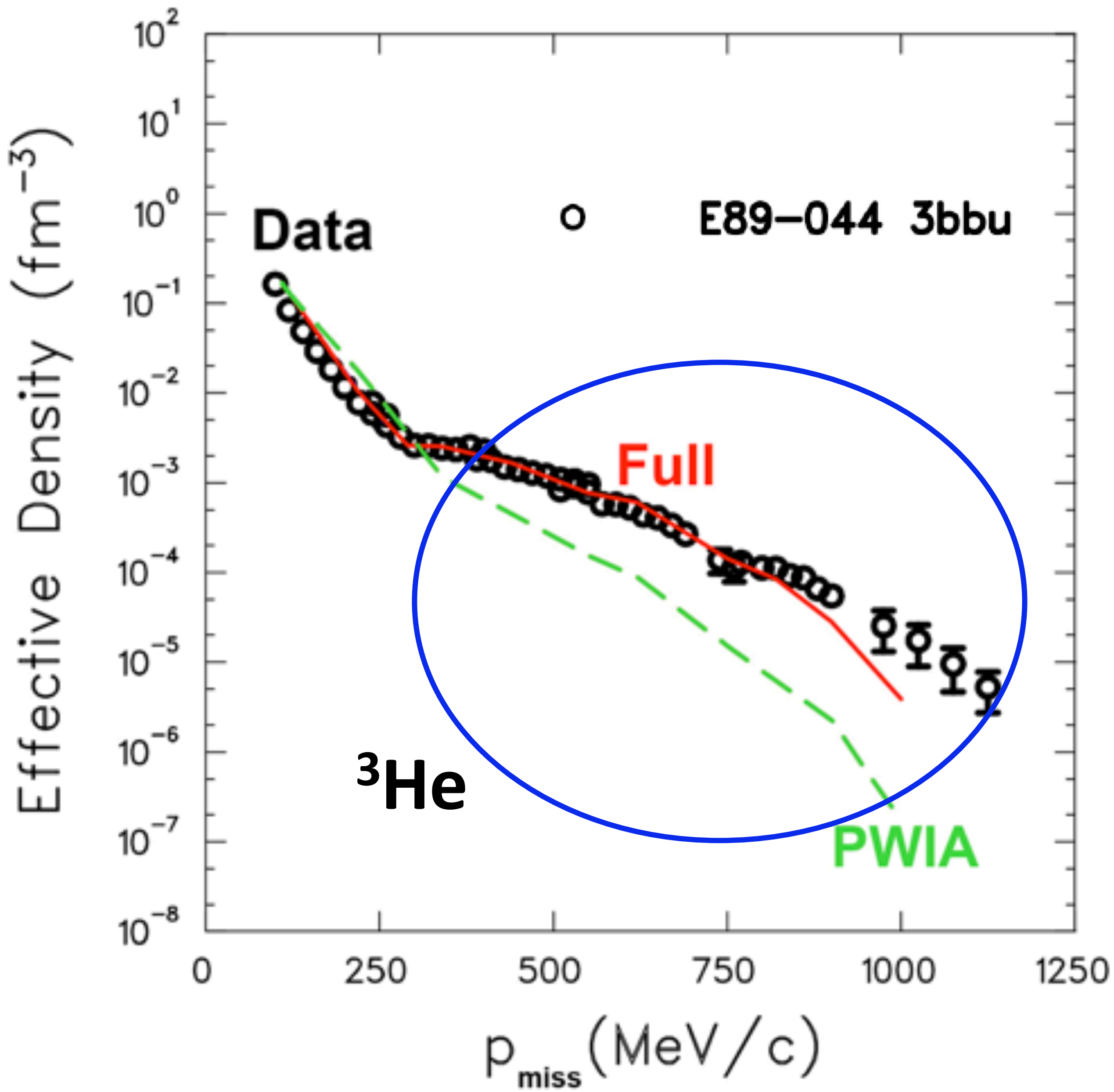
Theory



CD-Bonn NN potential

Previous studies and non-QE mechanisms

F. Benmokhtar et al., PRL (2005)



Large differences between data & PWIA

- ❑ Data is useful to study reaction mechanism, not nucleon distributions.

Previous studies and non-QE mechanisms

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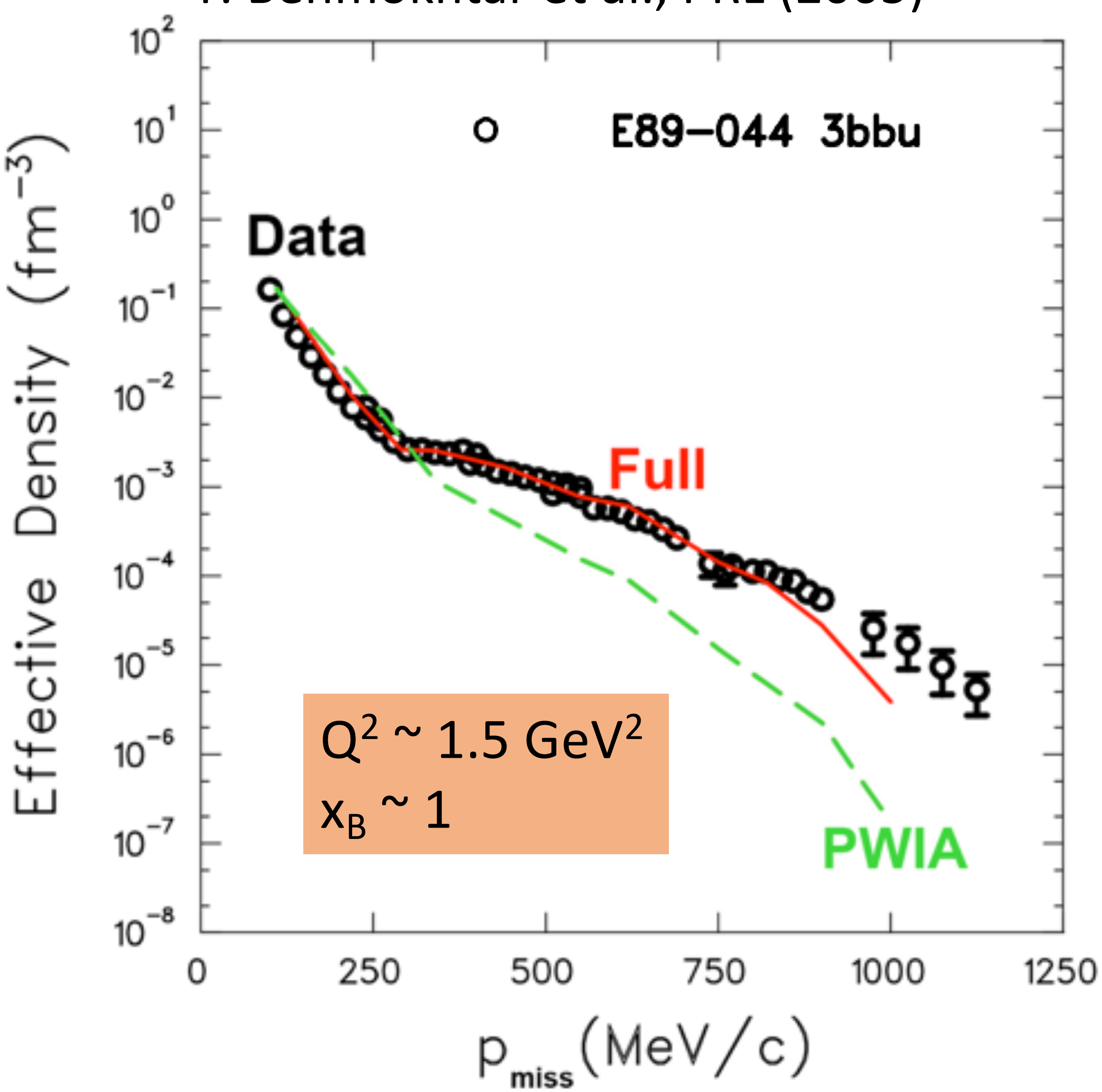
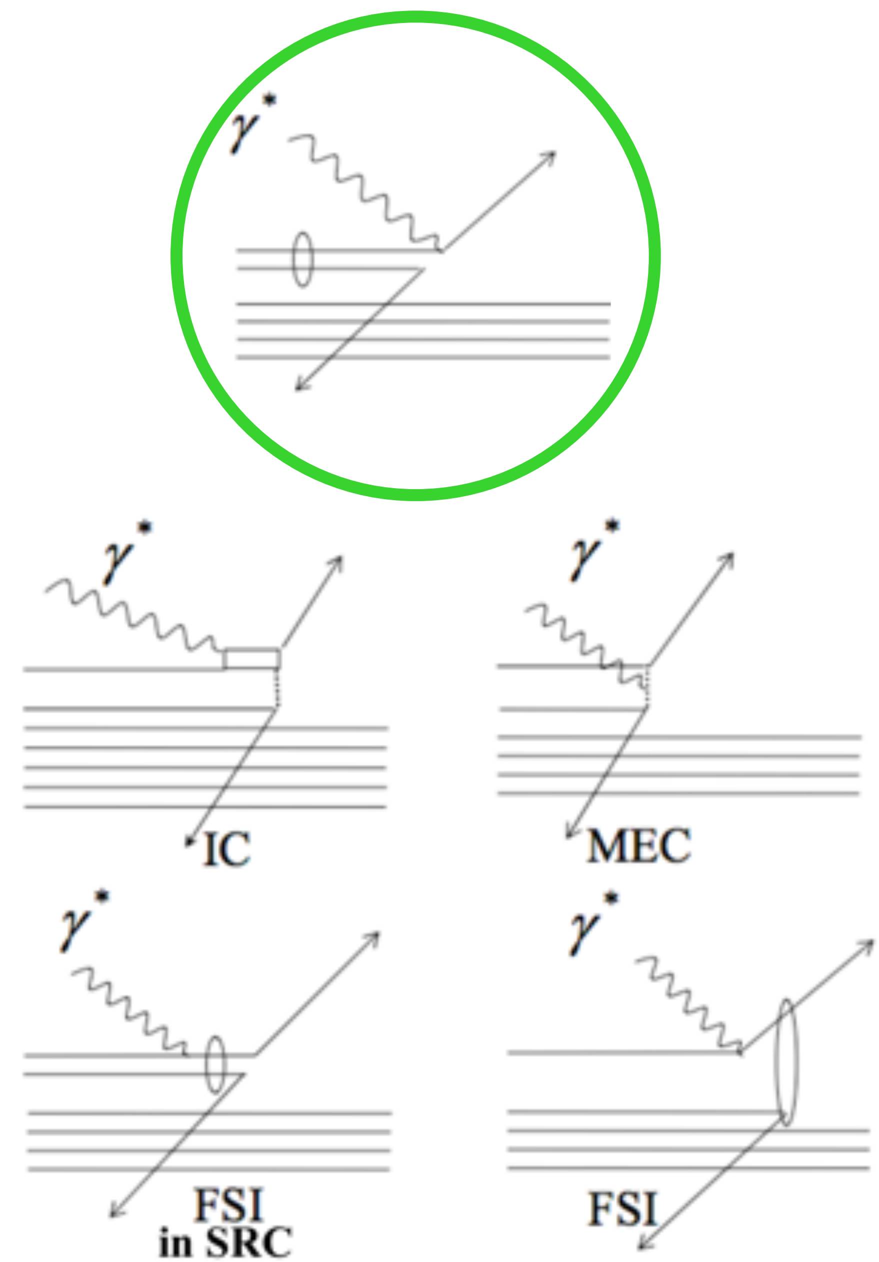




- Non-QE mechanisms can be minimized using selected kinematic region

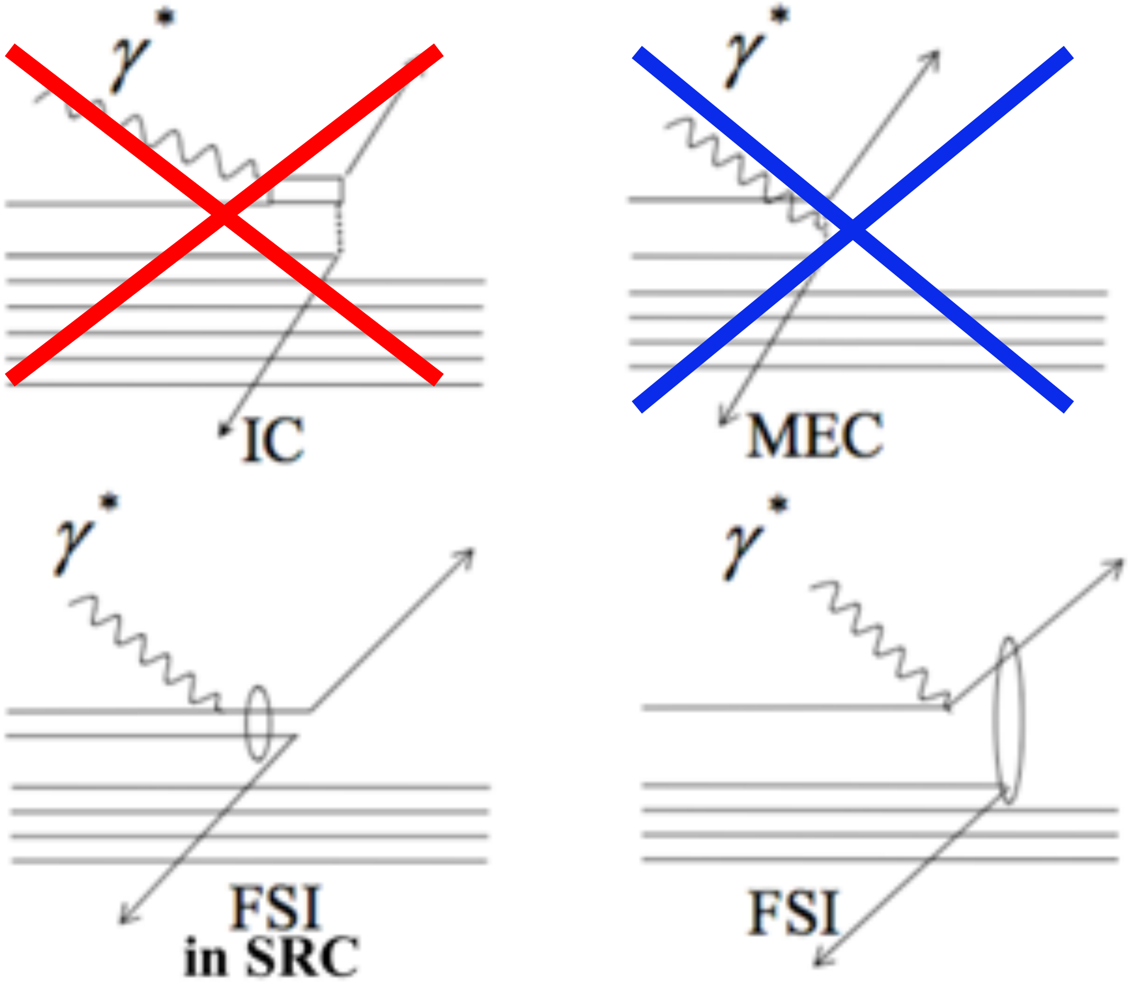
Minimizing non-QE mechanisms

$Q^2 > 2\ GeV^2$

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

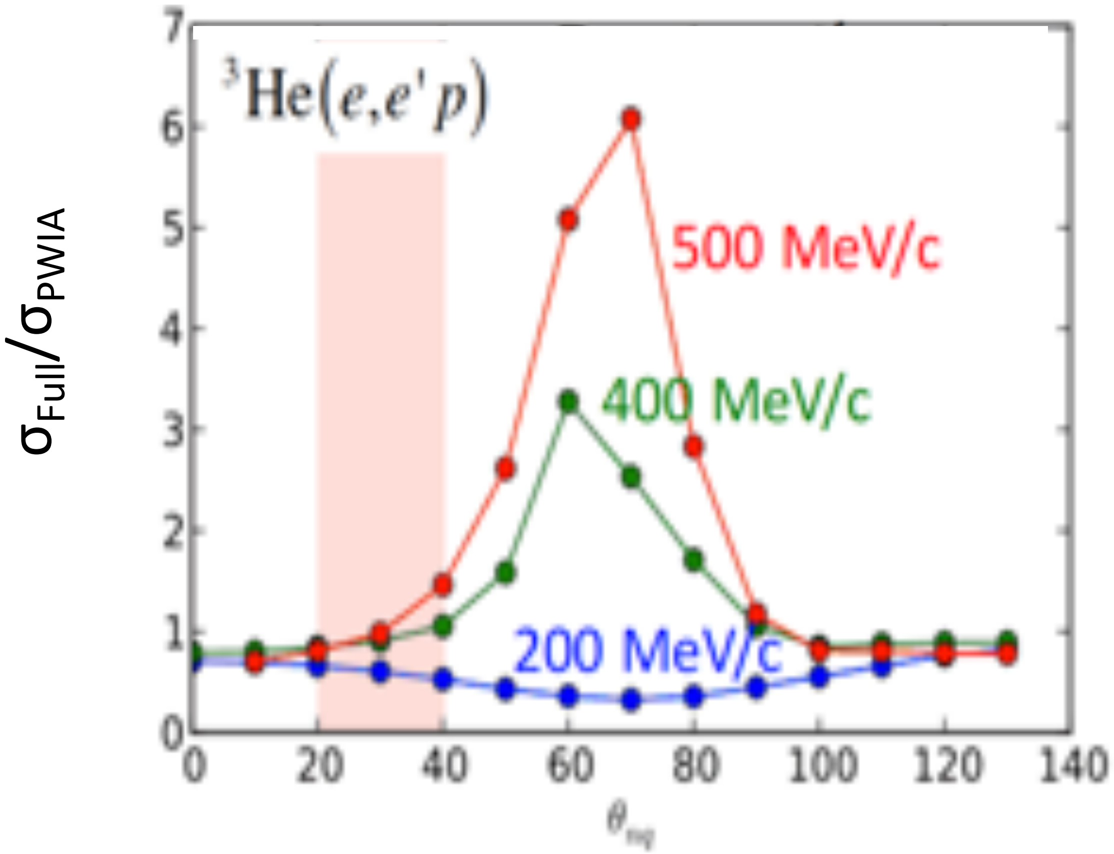
$X_B > 1$

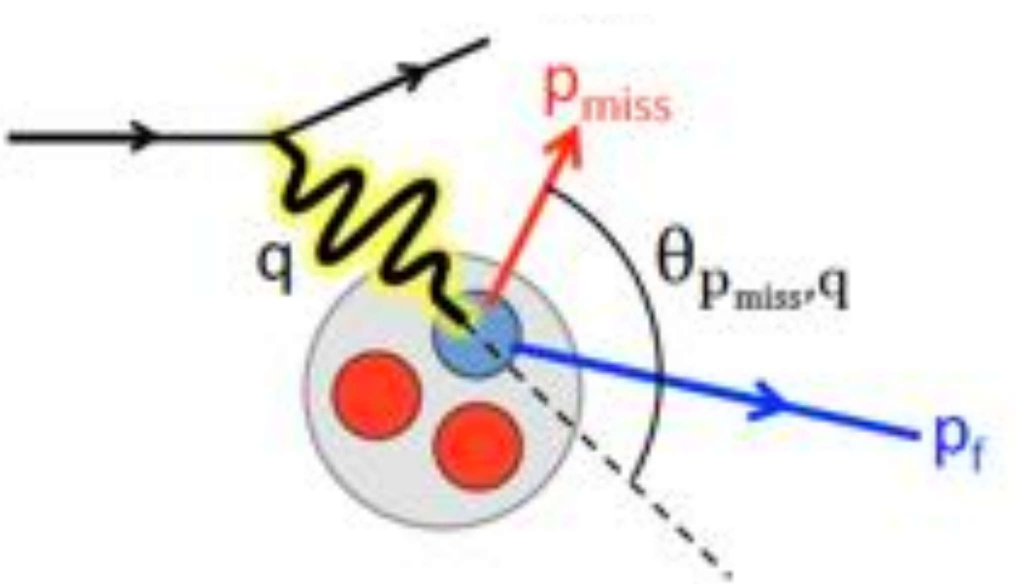
$Q^2 > 2\ GeV^2$

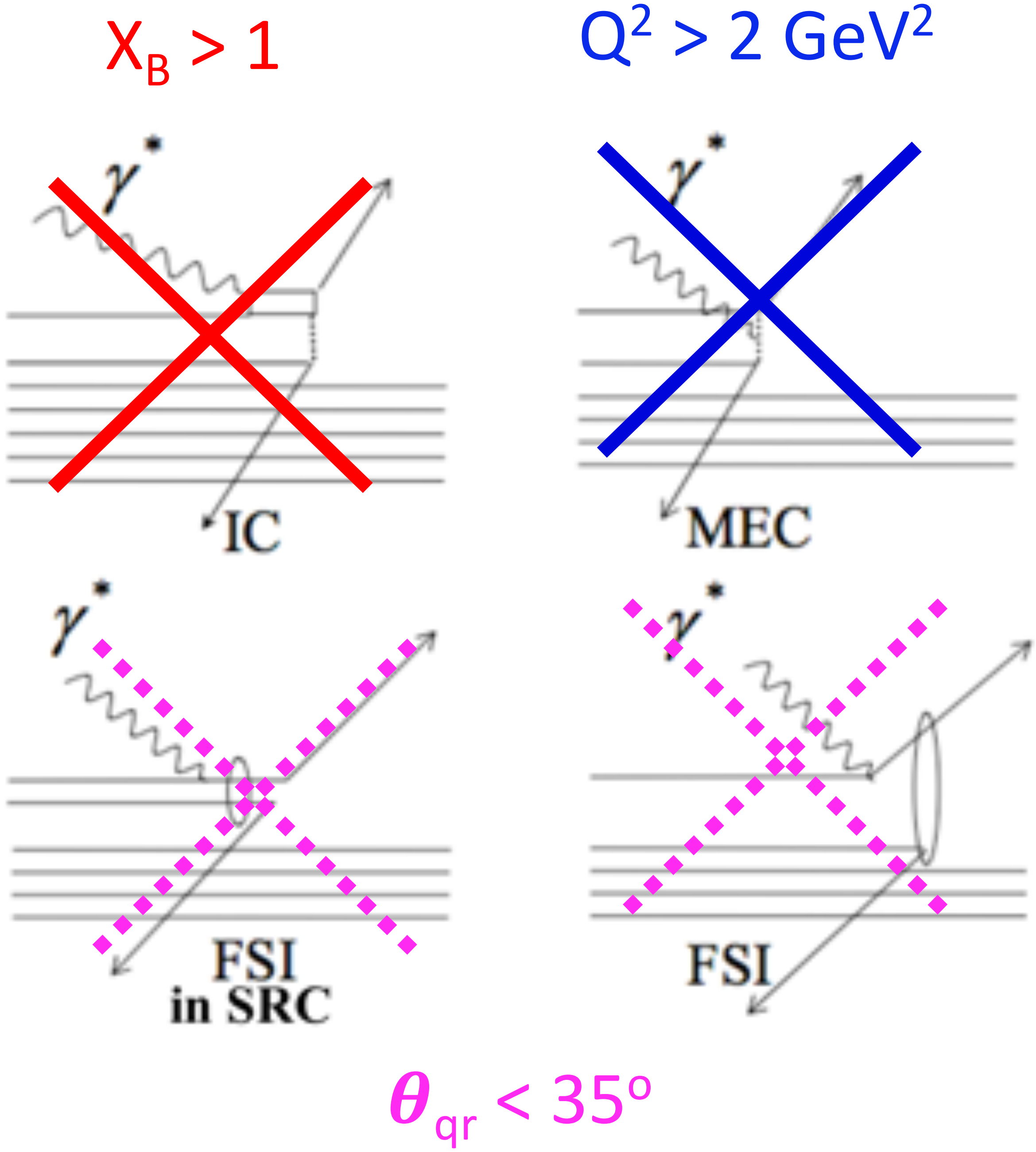


M. M. Sargsian, Int. J. Mod. Phys. E10, 405 (2001)
M. M. Sargsian et al., J. Phys. G29, R1 (2003)

Minimizing non-QE mechanisms



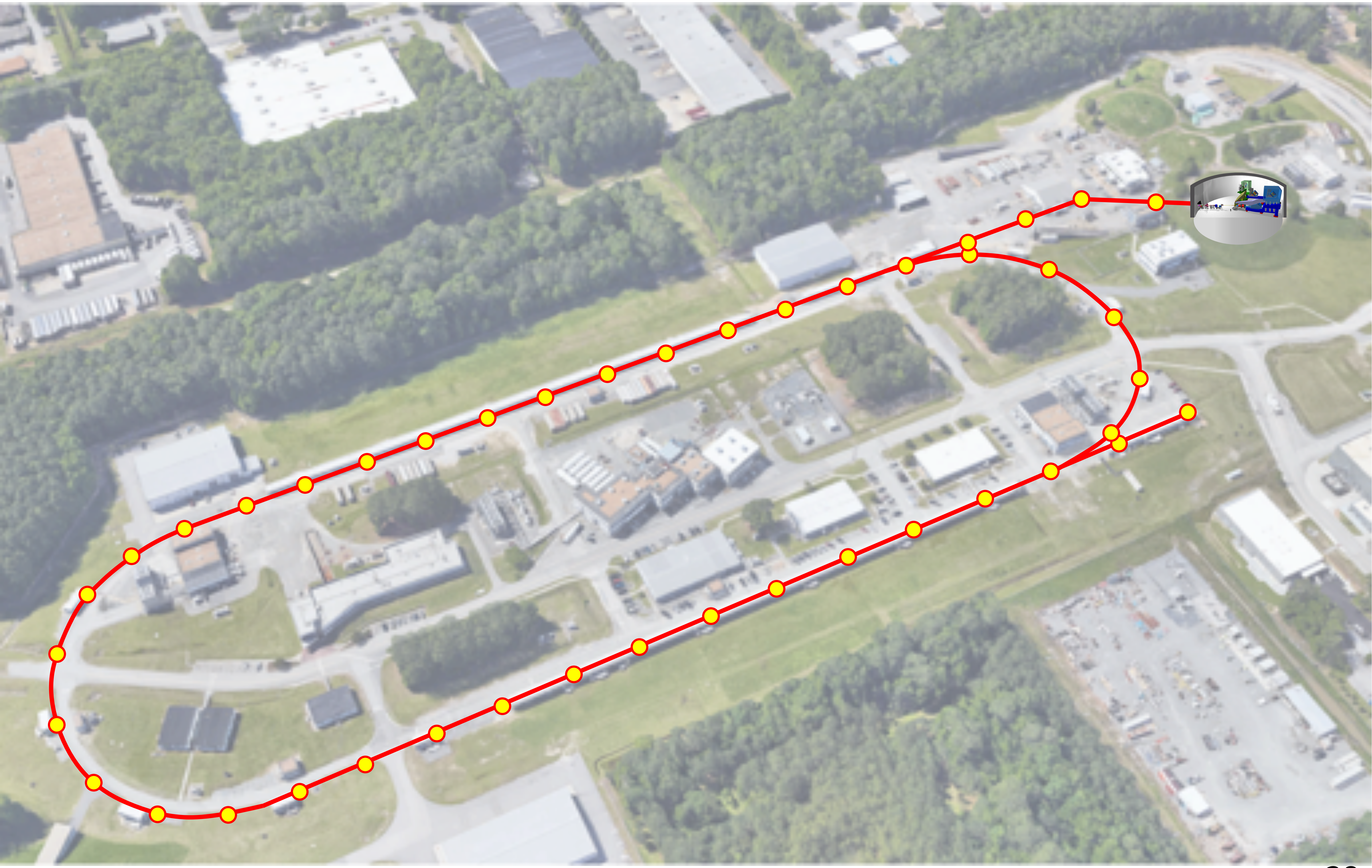




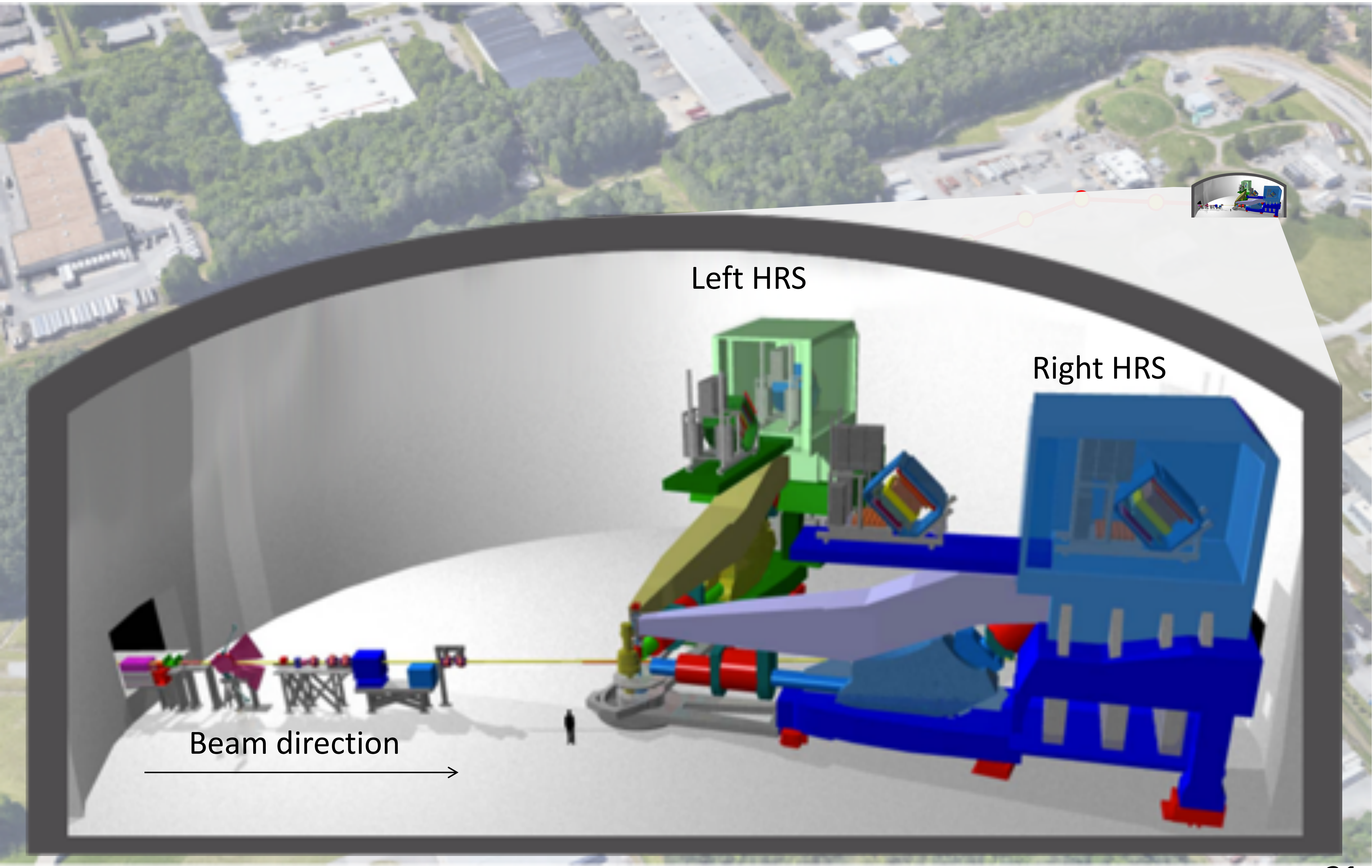
Boeglin et al., PRL 107 (2011) 262501

Jefferson Lab

Jefferson Lab



Hall-A of Jefferson Lab



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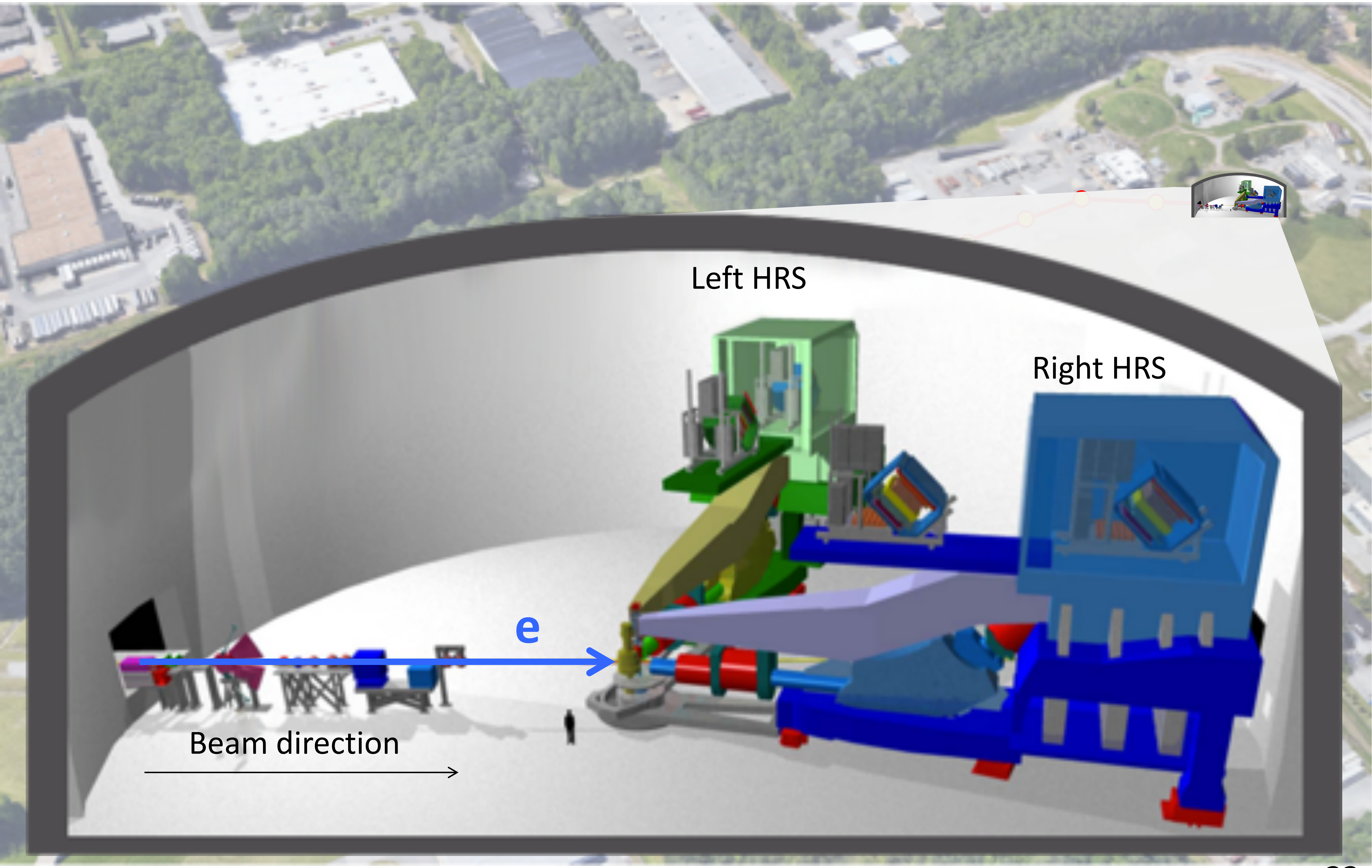

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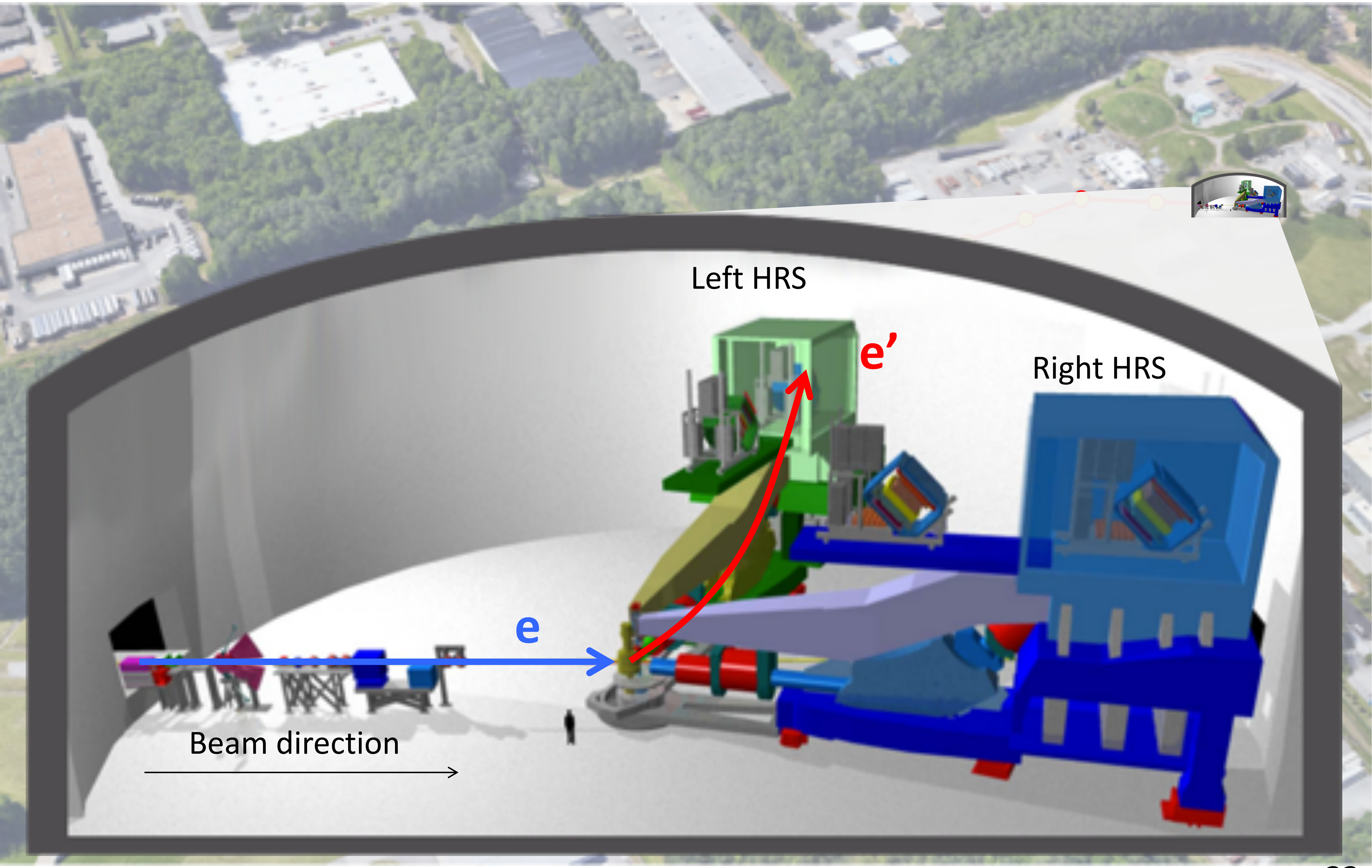

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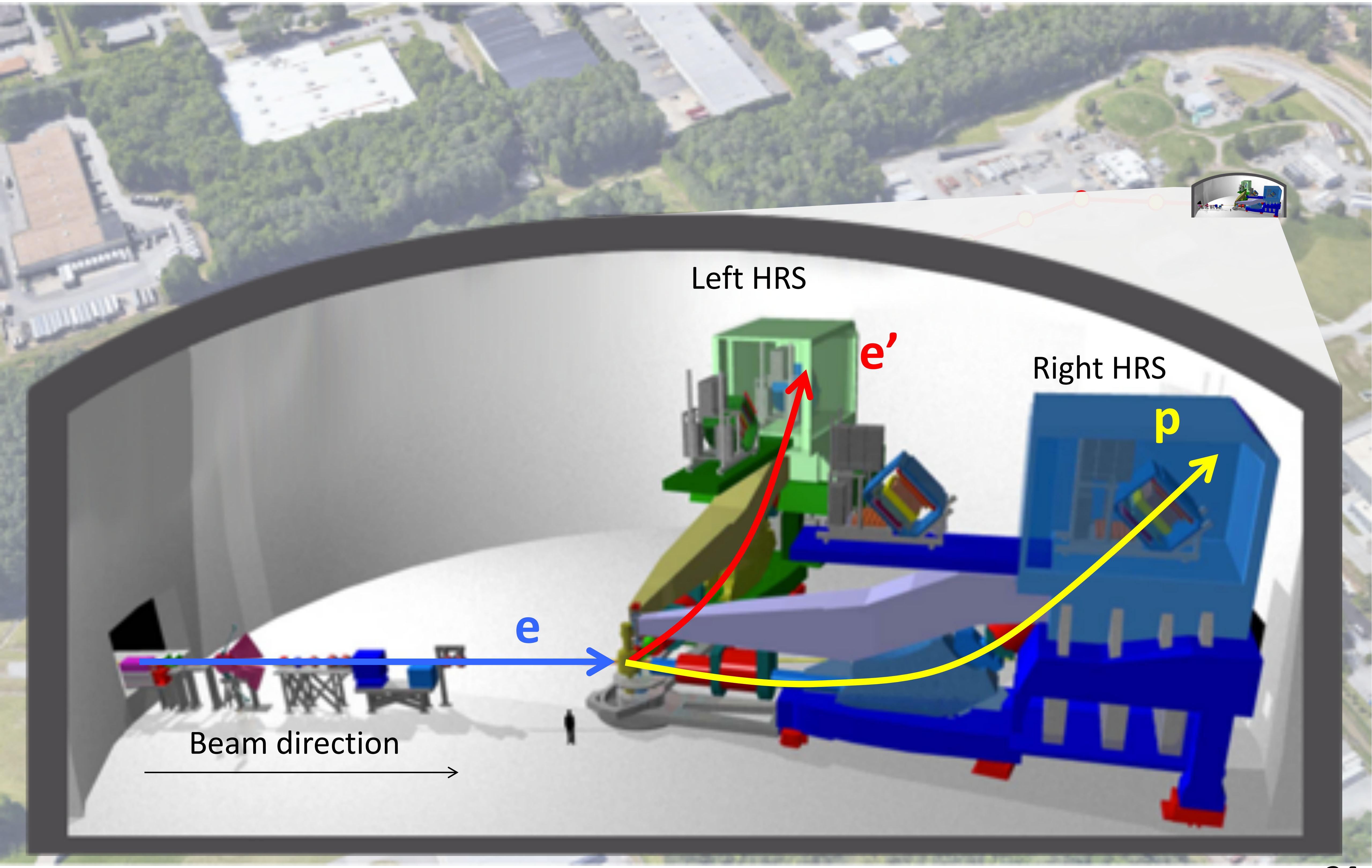

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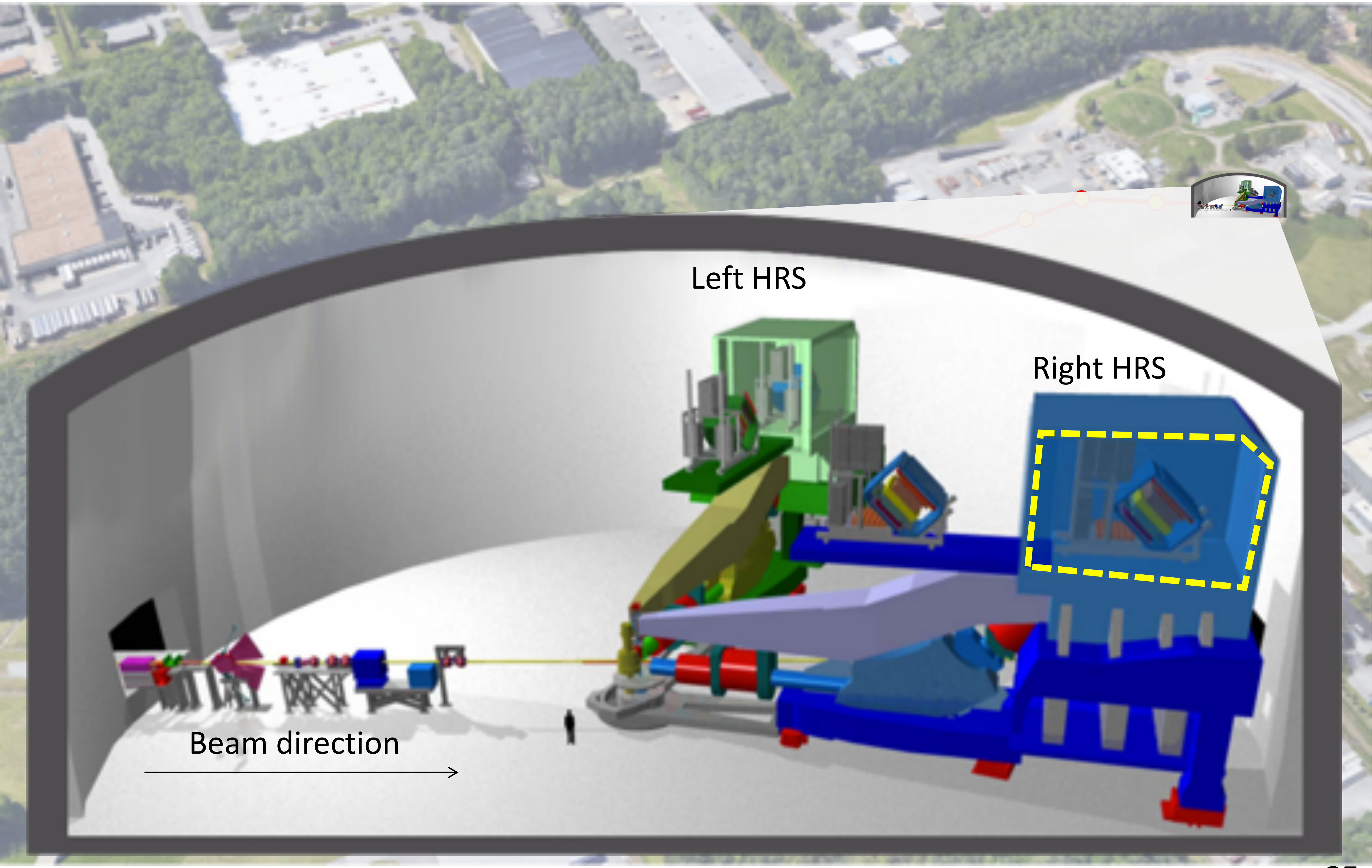
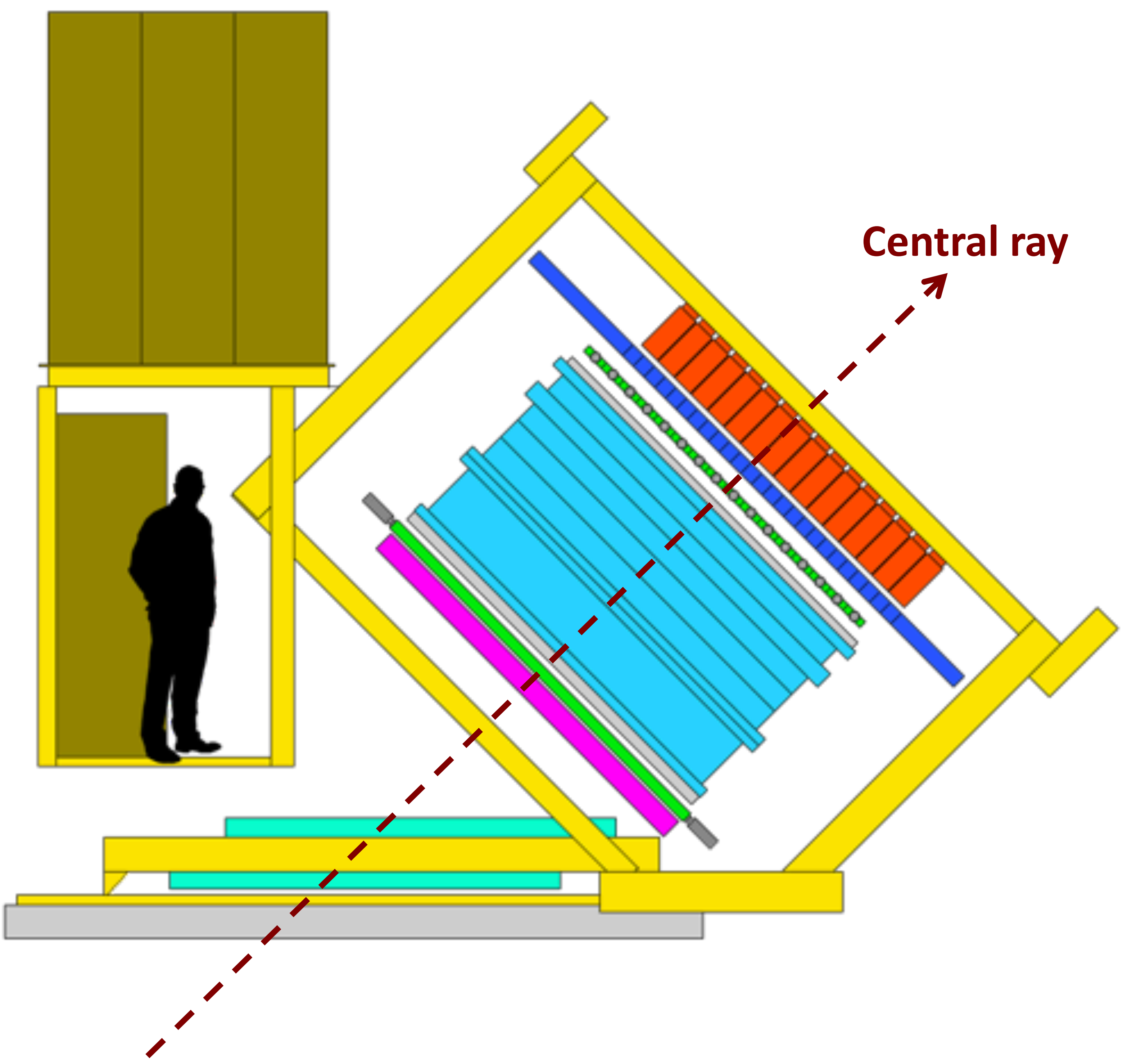
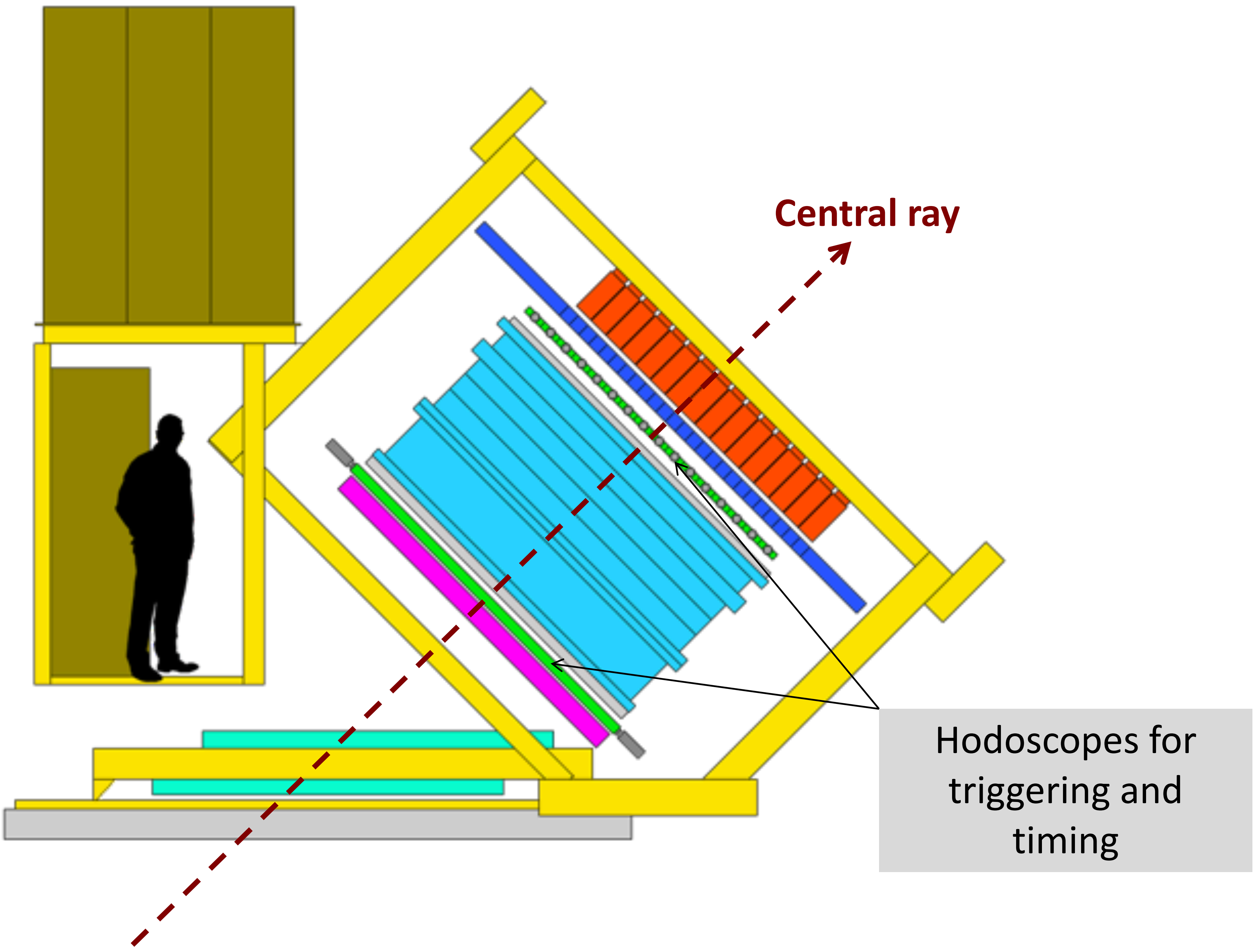


HRS detector package



Allow for excellent momentum reconstruction and particle identification

HRS detector package



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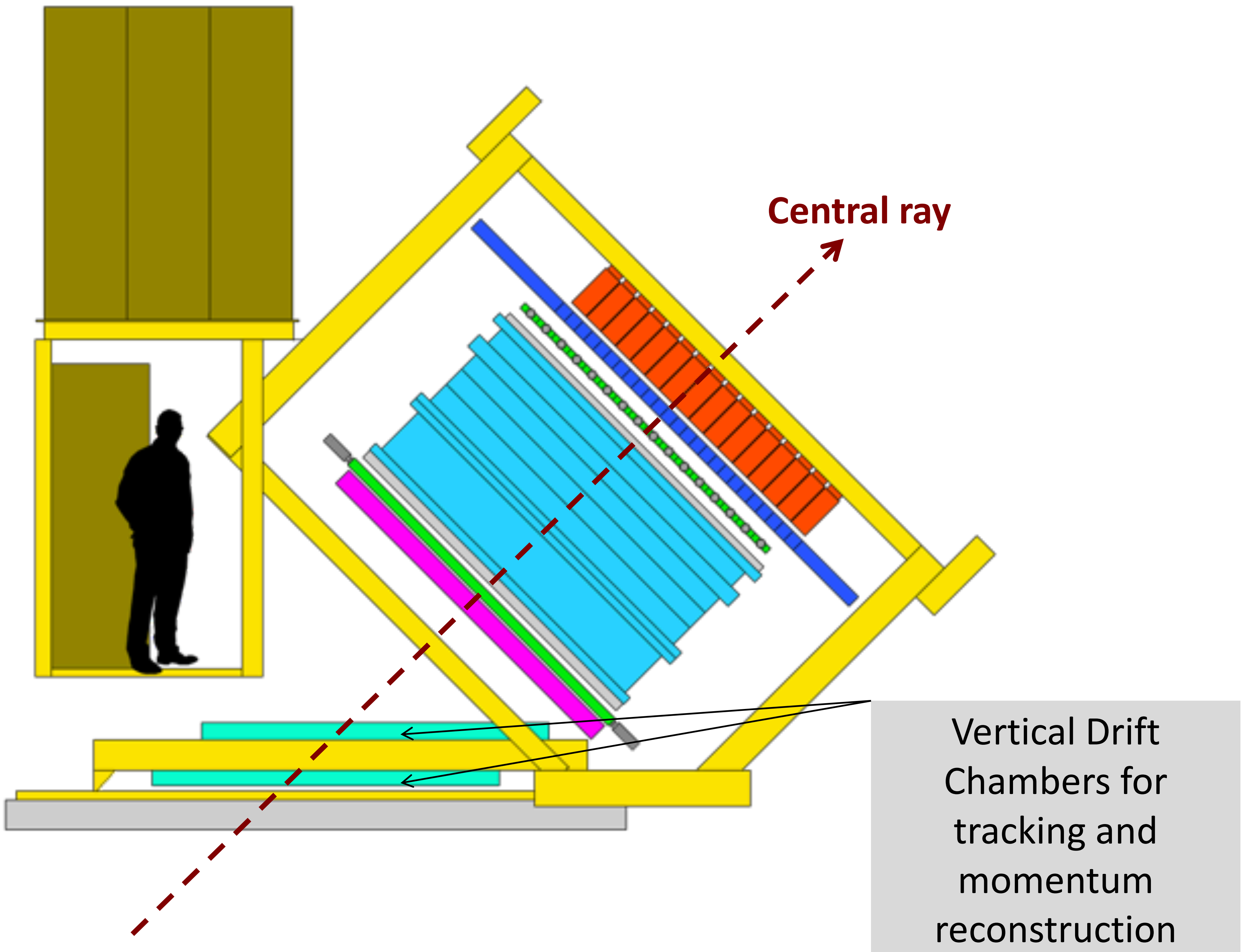

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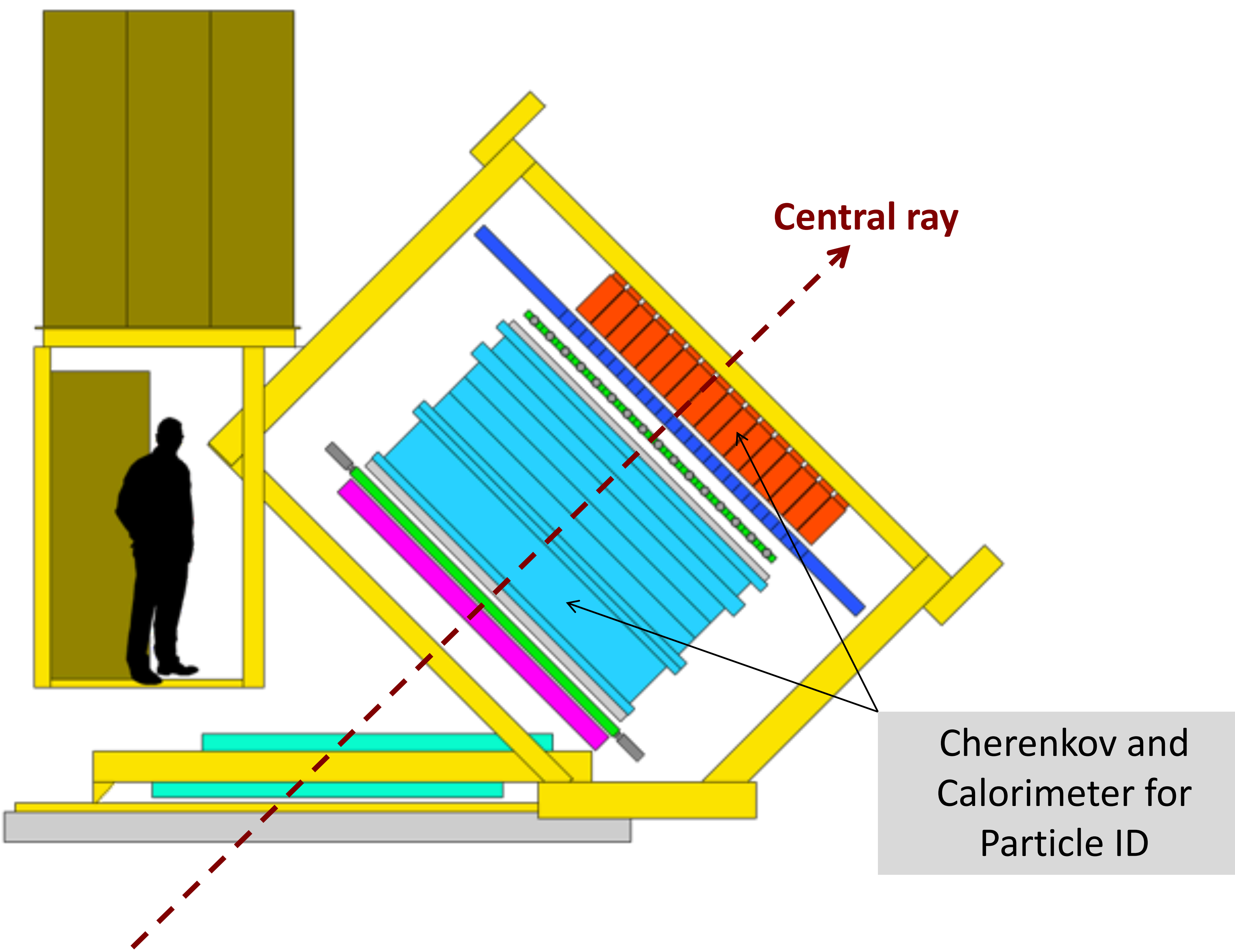


Allow for excellent momentum reconstruction and particle identification

Analysis process

- Data taking
- Calibration
- Data Analysis

Extracting the absolute cross section

$$\frac{d^6\sigma(p_{miss}, E_{miss})}{dE_e dE_p d\Omega_e d\Omega_p} = \frac{Yield(p_{miss}, E_{miss})}{Q * \rho_A * \boldsymbol{\varepsilon} * \boldsymbol{VB} * \boldsymbol{C_{corr}}}$$

Integrated Luminosity

Detected phase space corrected for acceptance

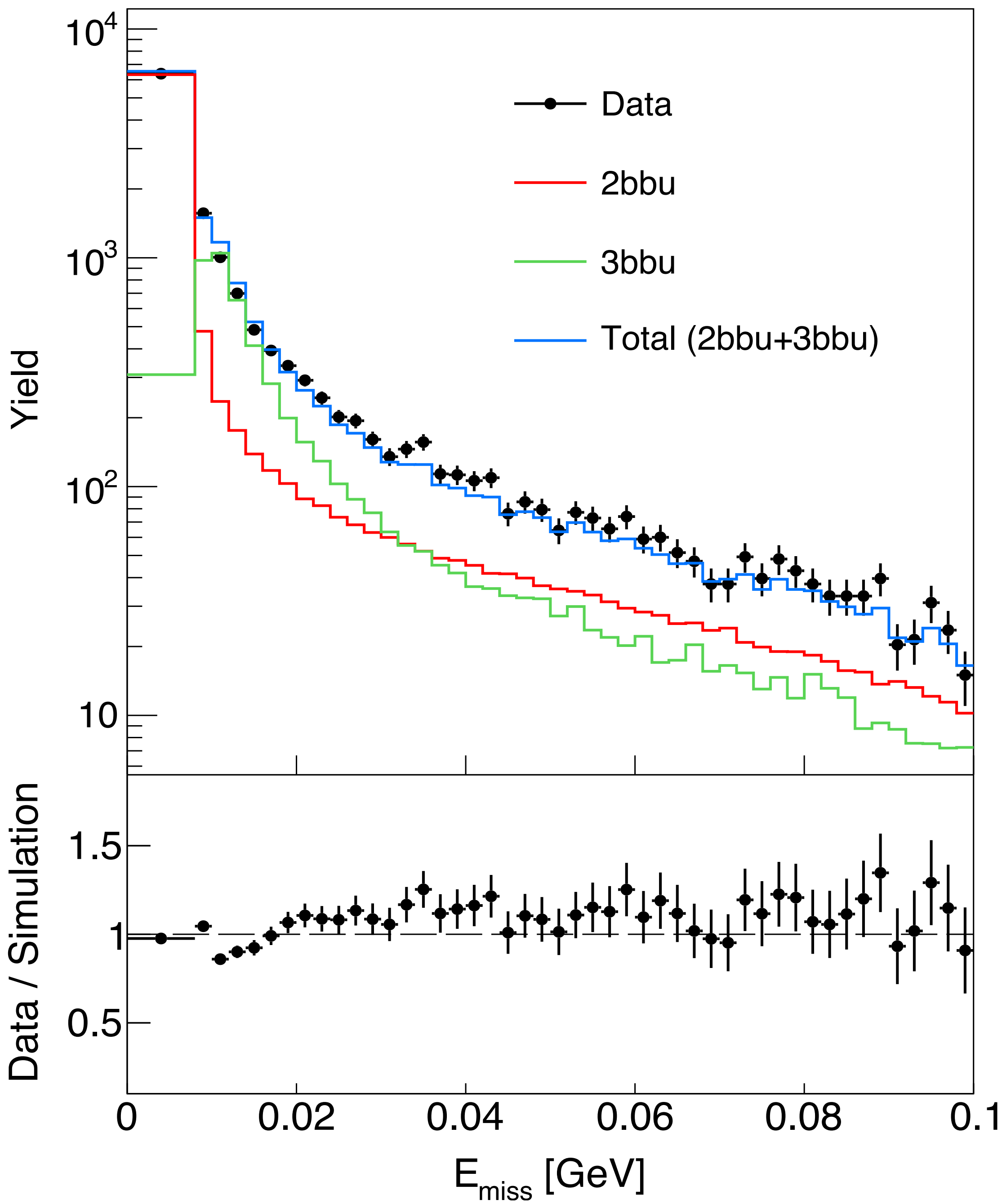
Efficiencies

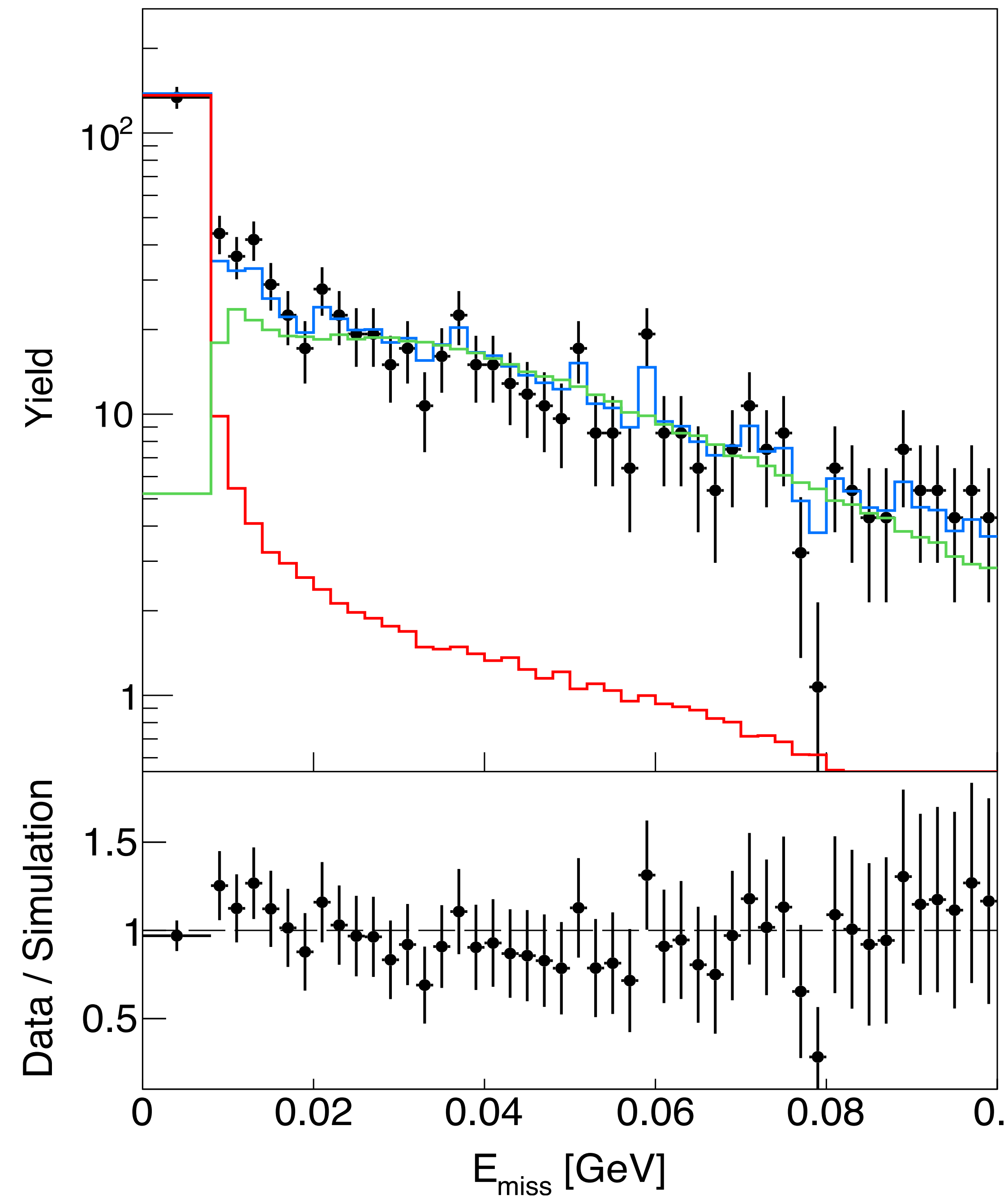
- Detectors
- Trigger
- Live time
- Boiling

Correction factors

- Radiative correction
- Bin migration
- Bin centering
- Tritium Decay

Separating two-body-breakup



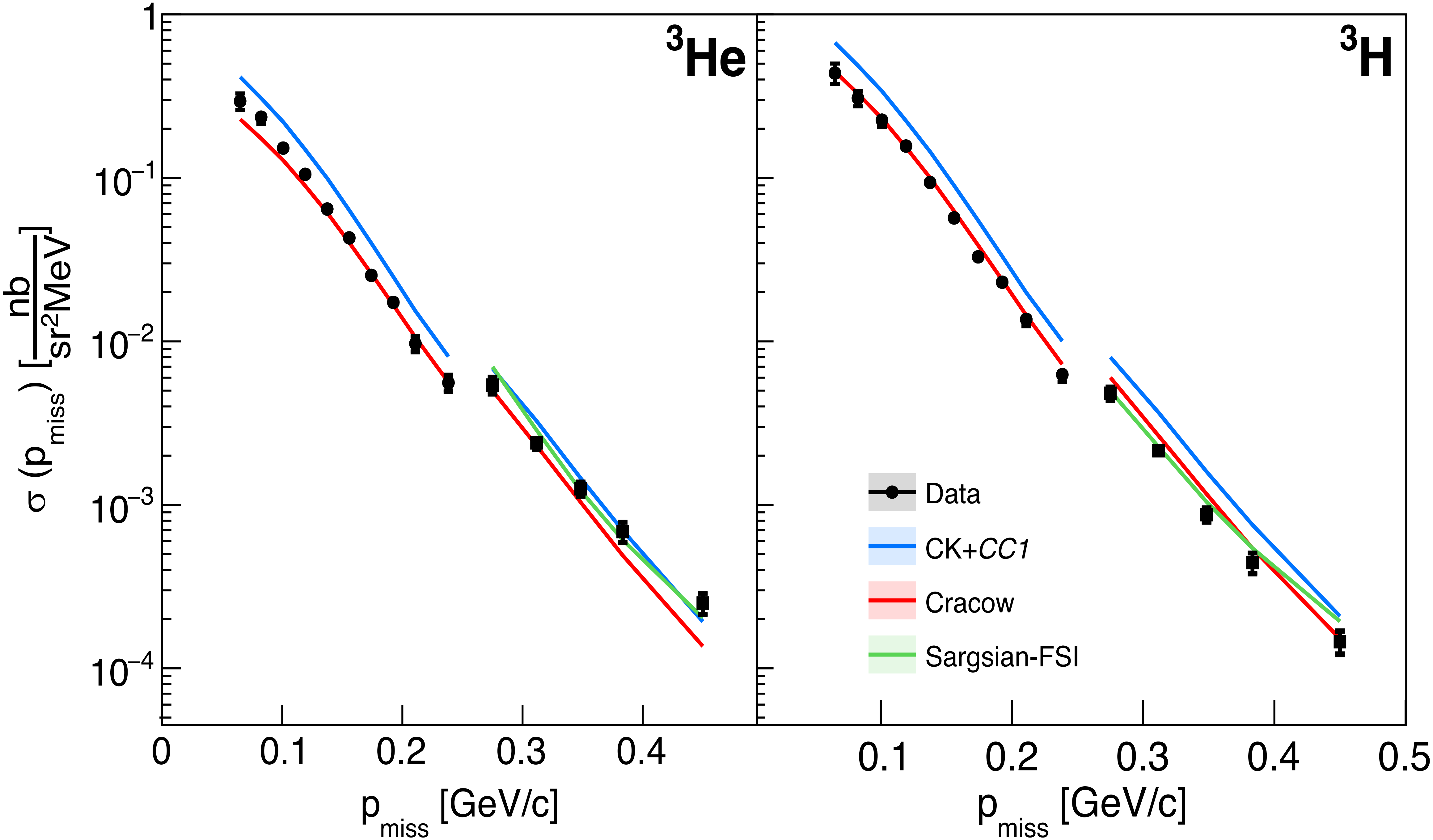


^{3}He -> P + D (2 body break up)

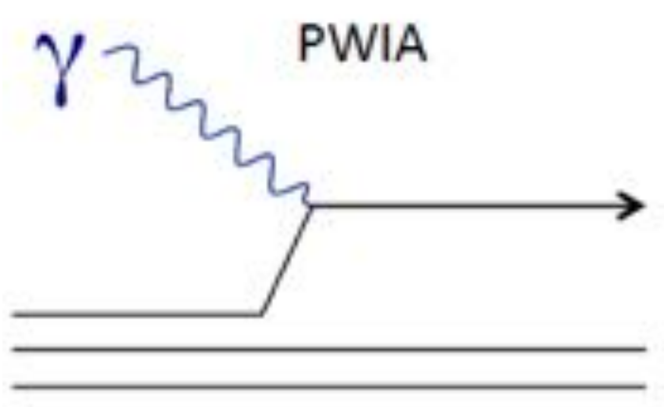
^{3}He -> P + N + P (3 body break up)

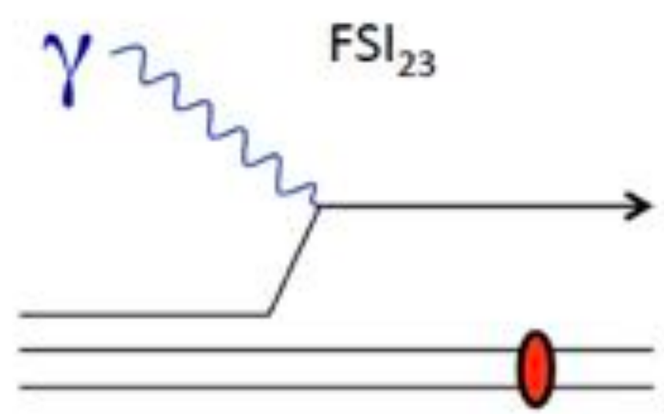
3H -> P + N + N (3body break up)

Extracted Absolute cross-section



Compare to different theory calculation

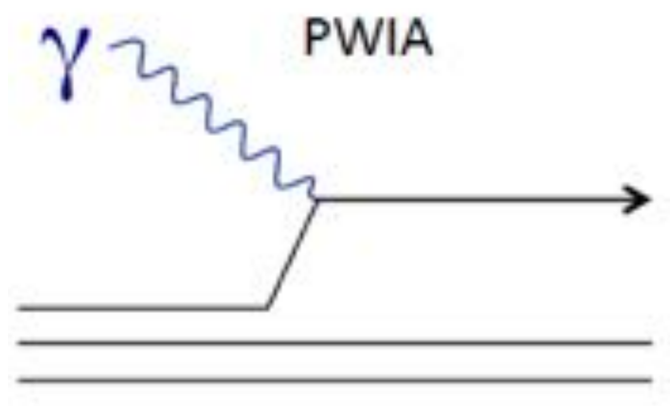


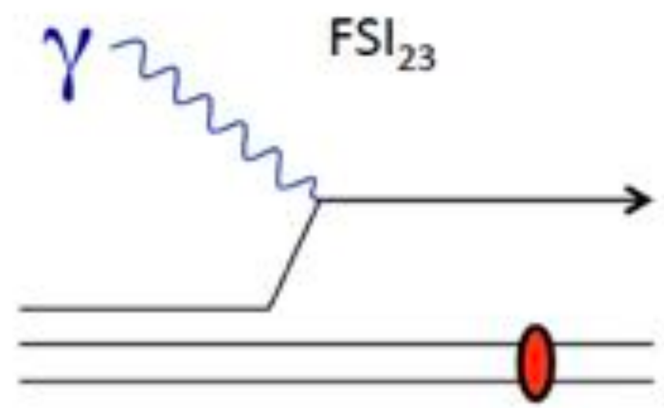


Cracow:

- ❑ Faddeev-formulation-based calculations
- ❑ Continuum interaction between two spectator nucleons (FSI_{23})

Compare to different theory calculation





Cracow:

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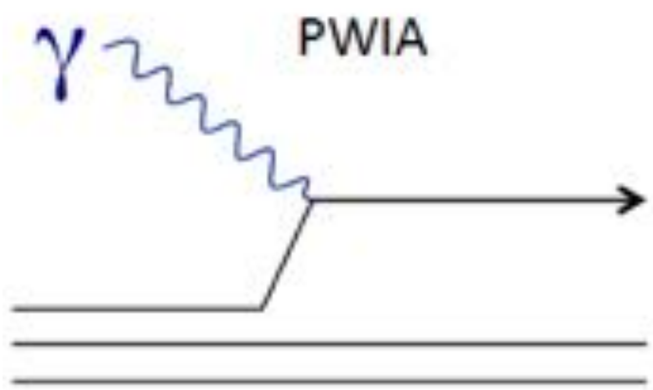
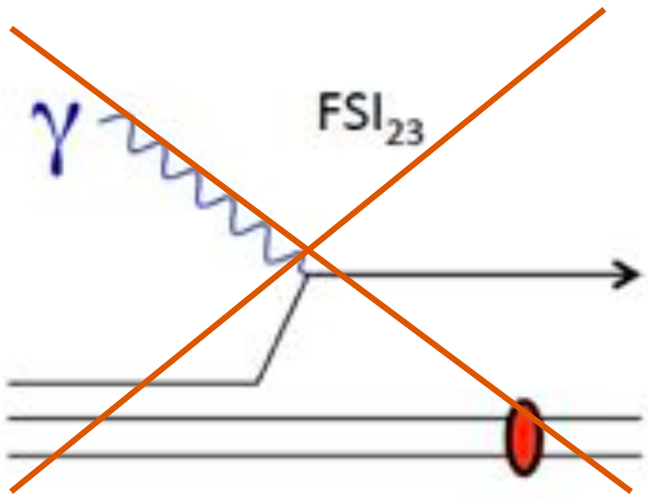
- Continuum interaction between two spectator nucleons (FSI_{23})

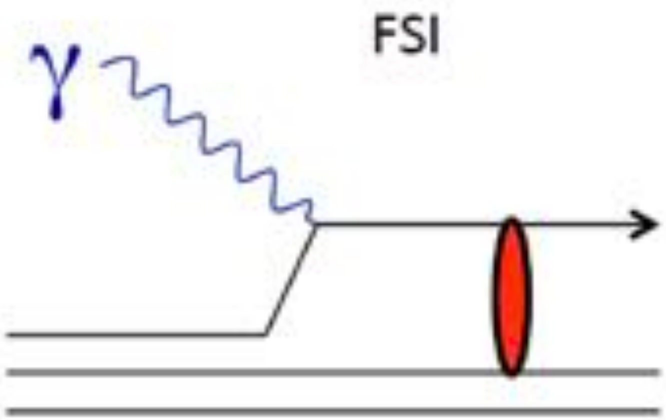
***CK + CC1*:**

- ^{3}He spectral function of C. Cio degli Atti and L. P. Kaptari and electron off-shell nucleon cross-section
- Including FSI_{23}

Compare to different theory calculation







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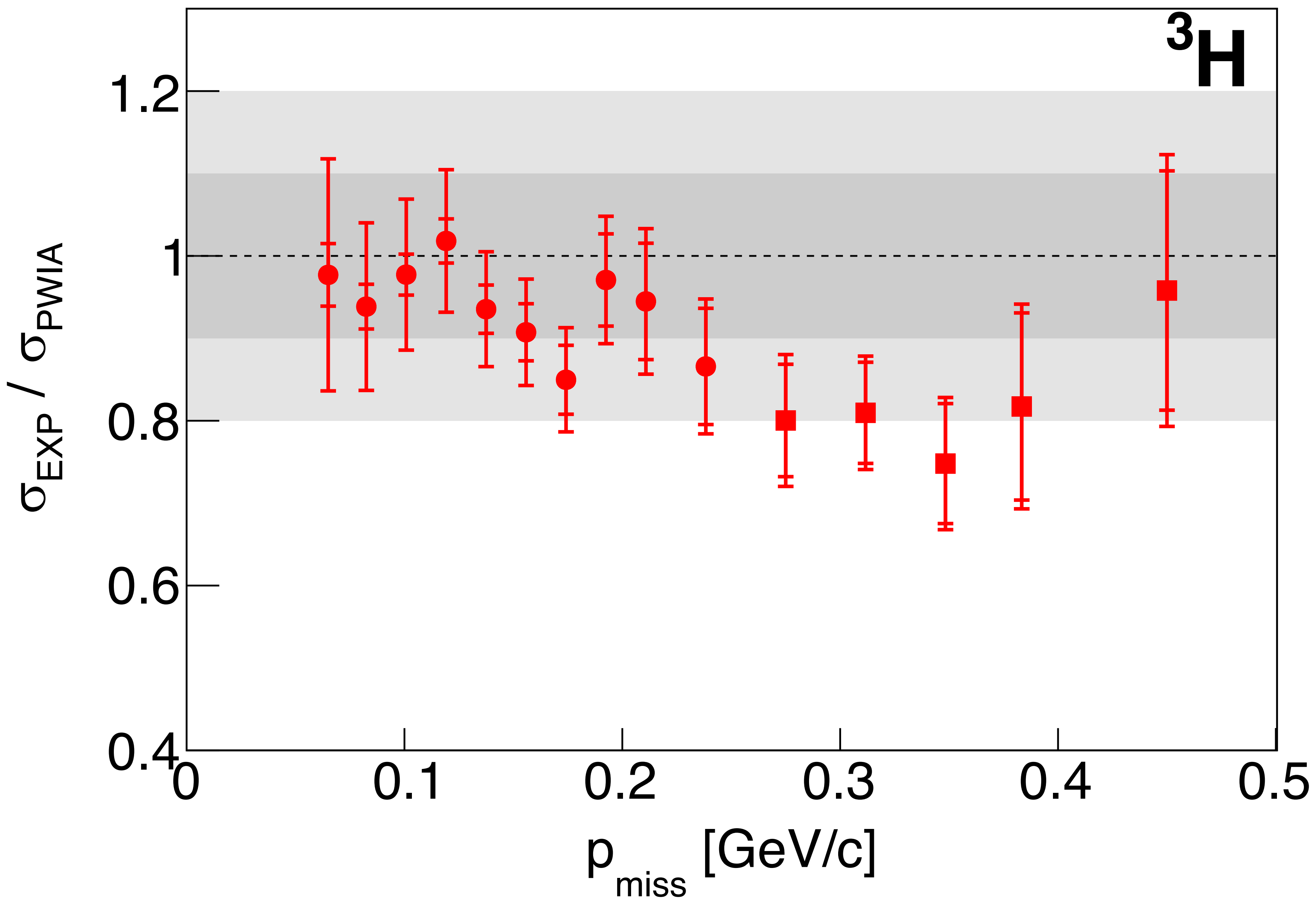
- ❑ ^{3}He spectral function of C. Cio degli Atti and L. P. Kaptari and electron off-shell nucleon cross-section
- ❑ Including FSI_{23}

M. Sargian (FSI):

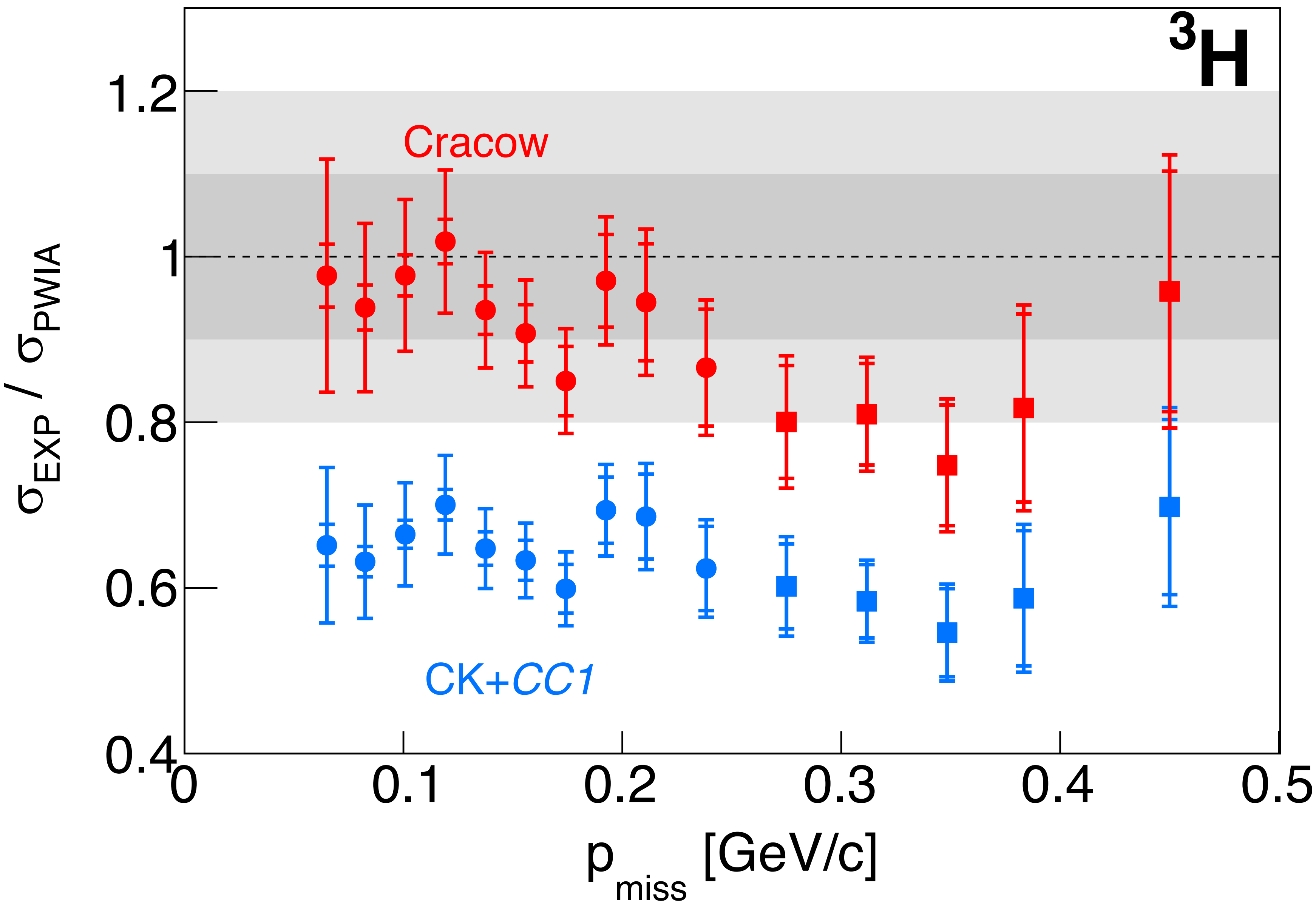
- ❑ FSI calculation based on generalized Eikonal approximation
- ❑ Does not include FSI23

^{3}H Exp/Cracow$_{PWIA}$ *agree* to ~20%



R. Cruz-Torres*, D. Nguyen* et al., Under PRL review

^{3}H Exp/CK+CC1$_{PWIA}$ *disagree* by ~40%



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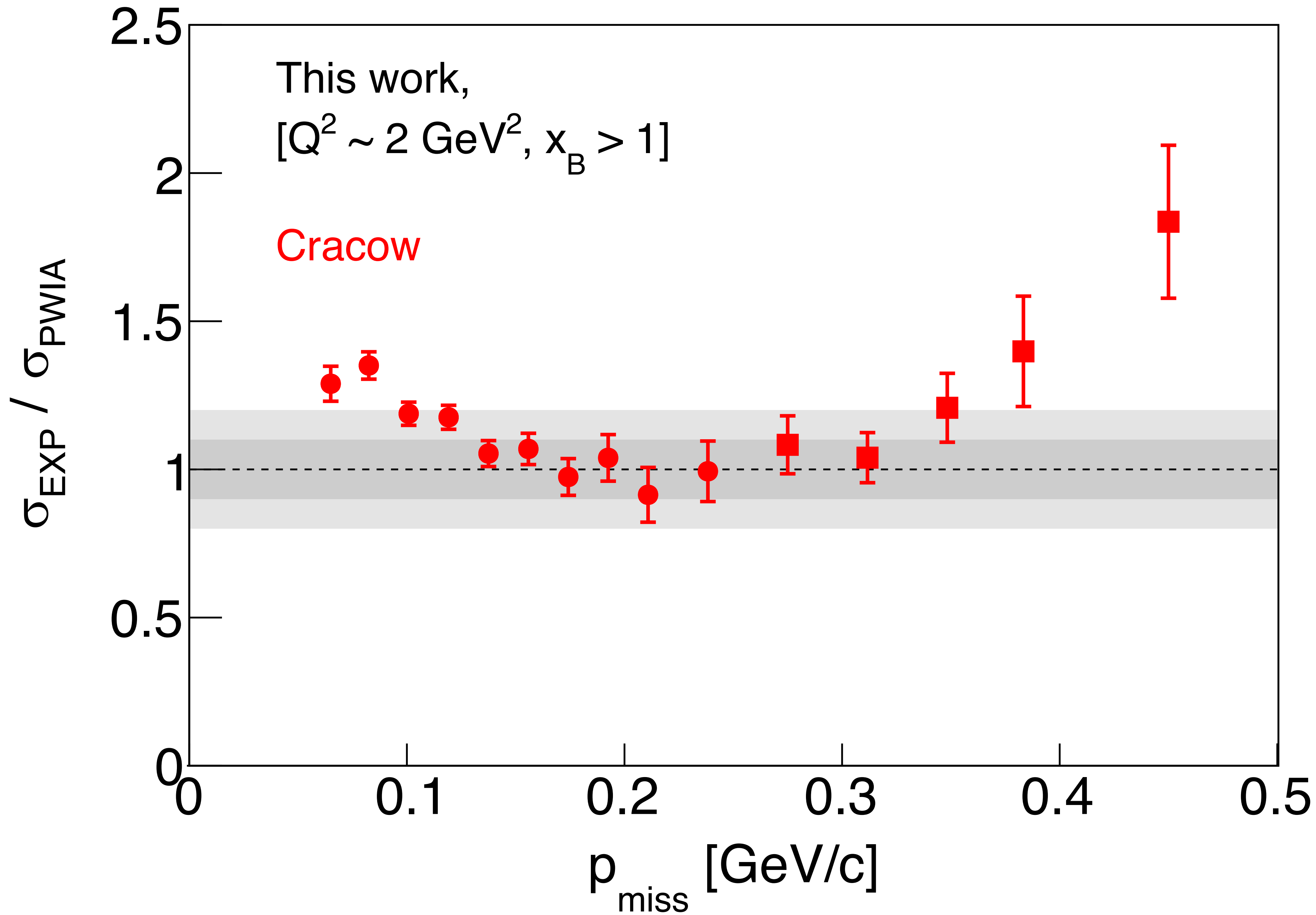
^{3}He Exp/Cracow



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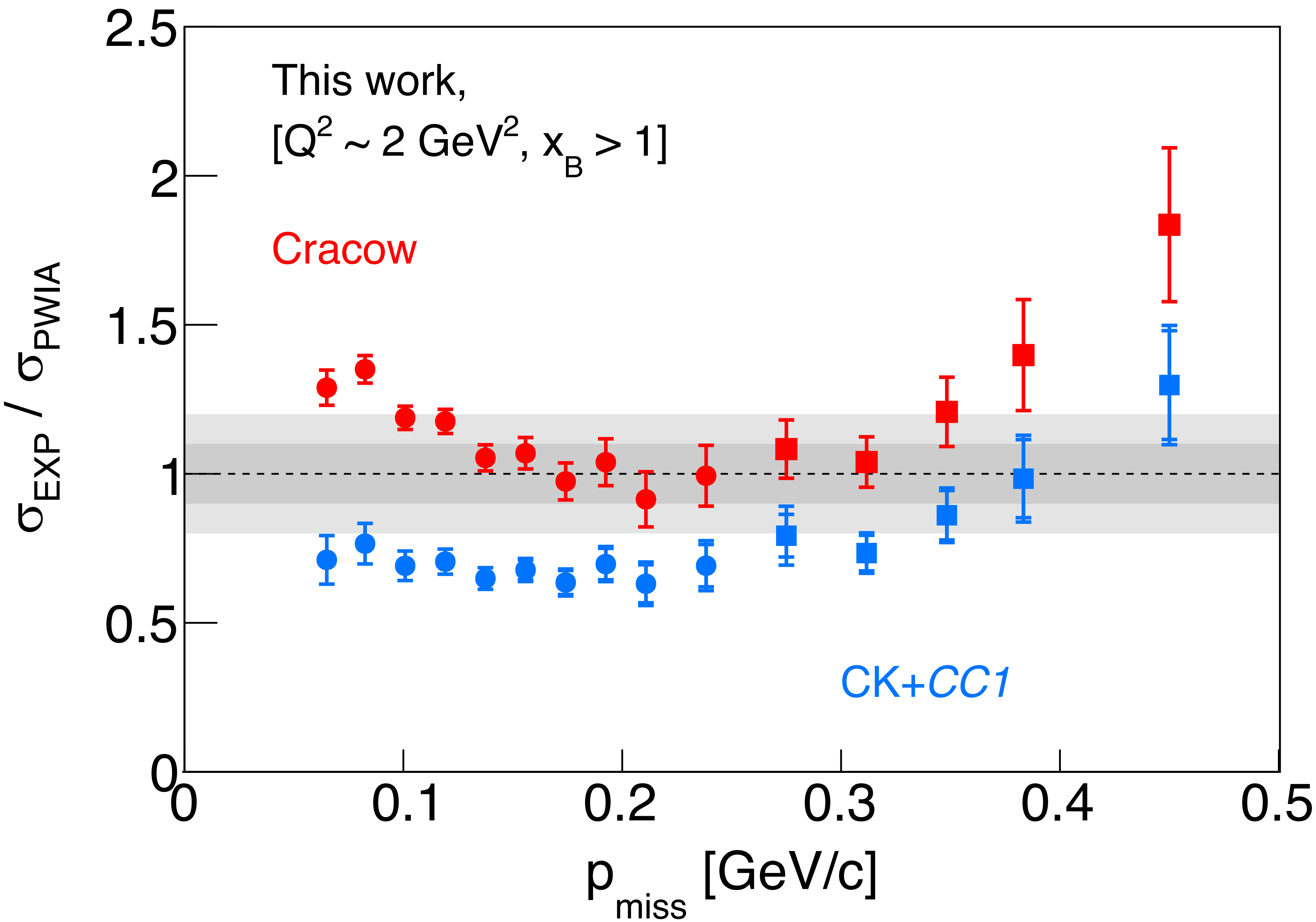
^{3}He Exp/Cracow & CK+CC1



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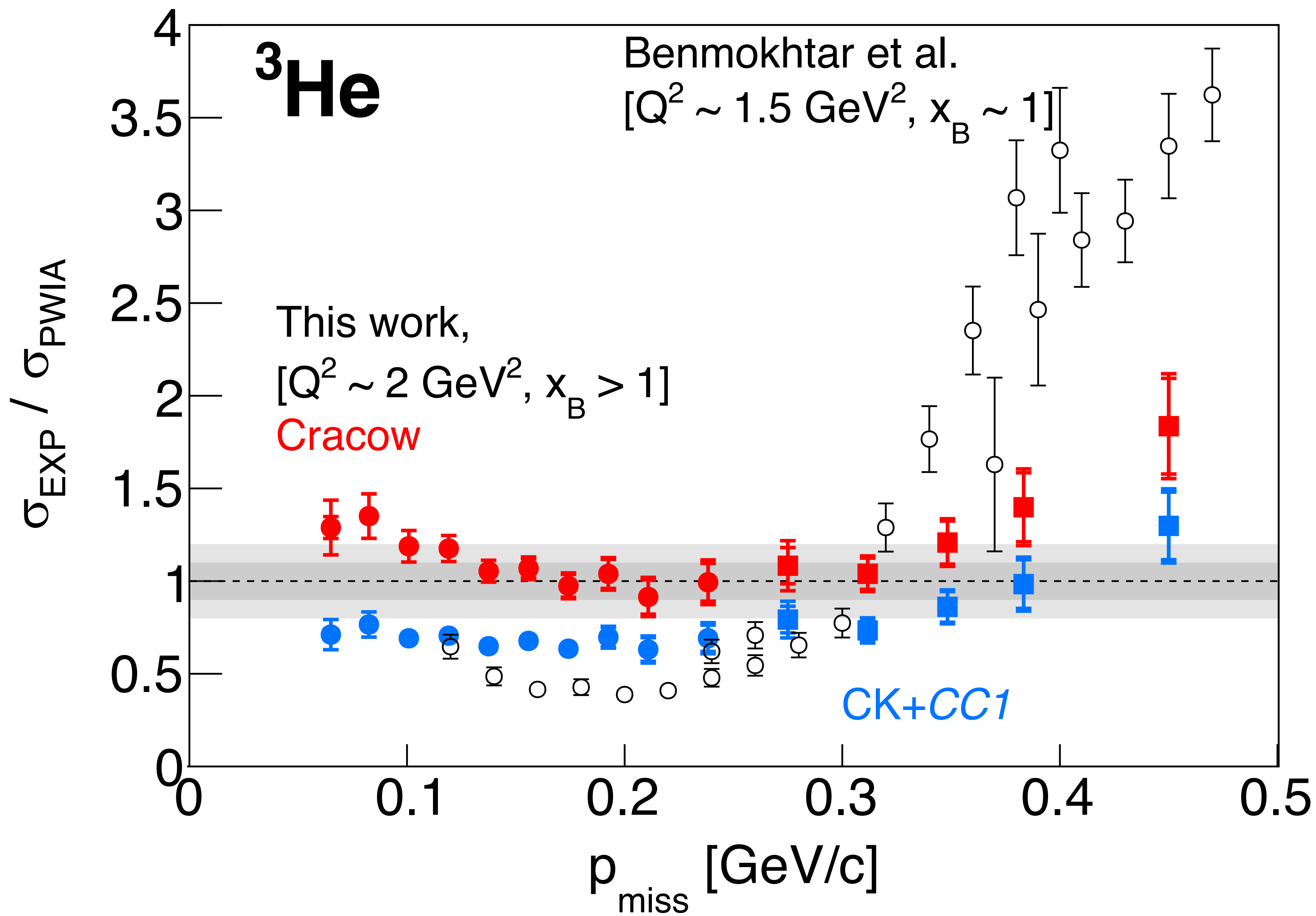
Much better than previous data!



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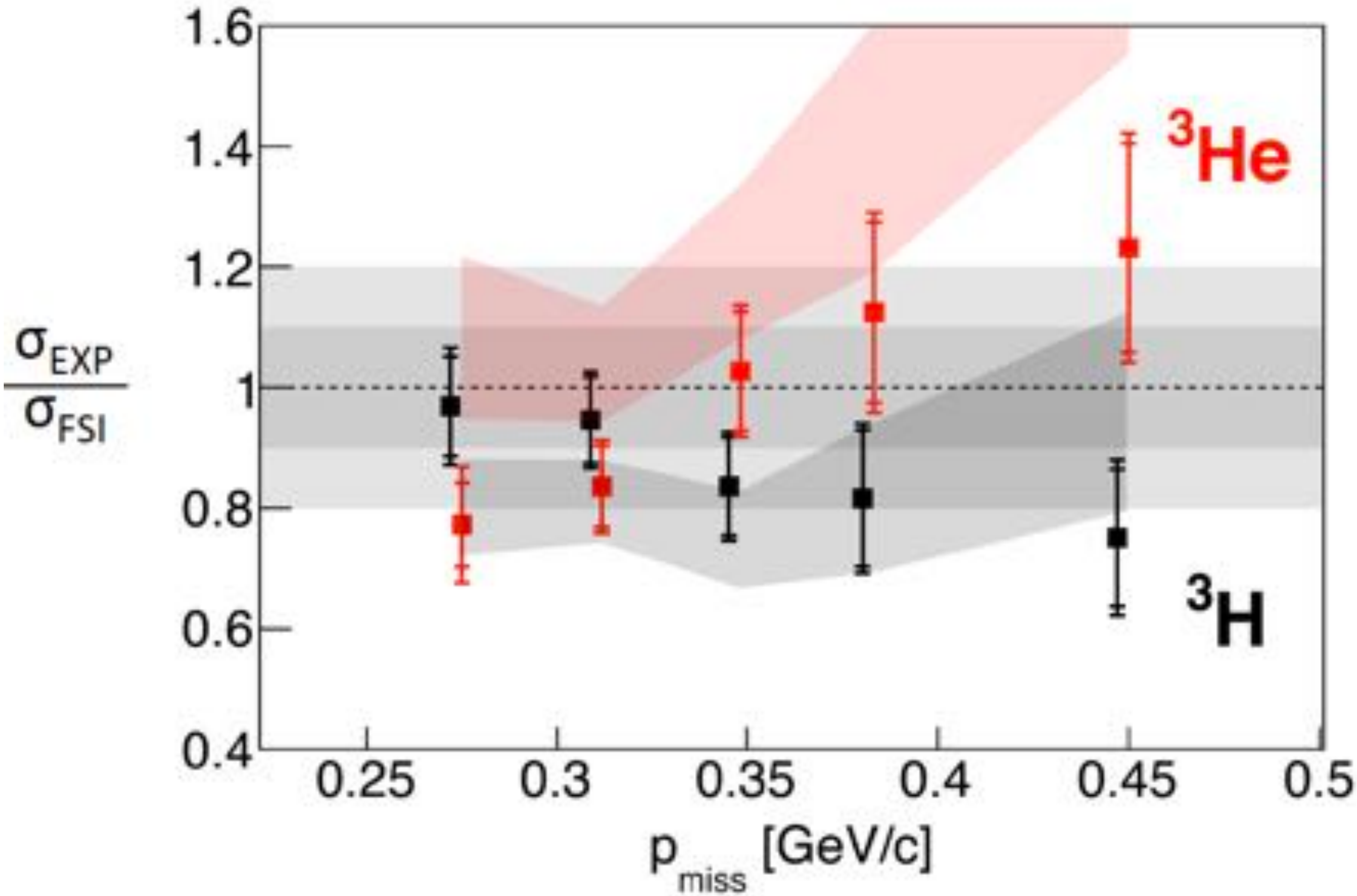
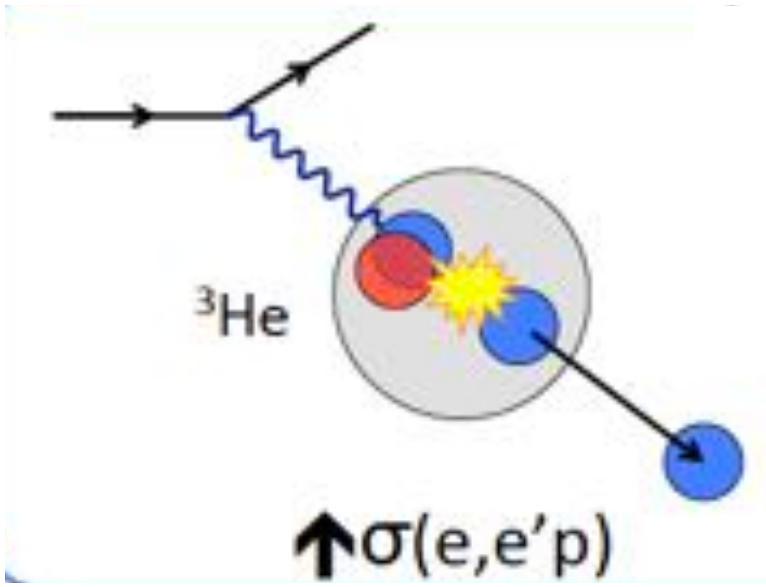
Leading Nucleon FSI: Small but improve things!



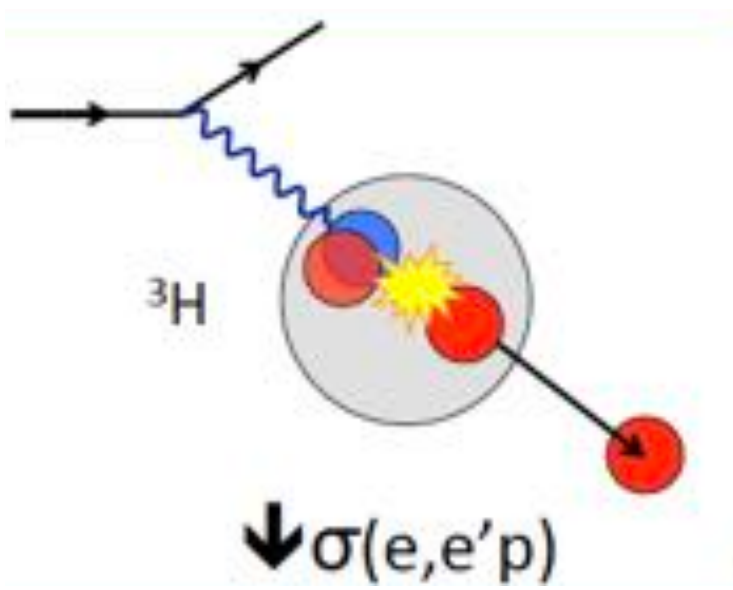
Single charge exchange!



np-SCX

(e,e'n) -> (e,e'p)

increases σ(e,e'p)



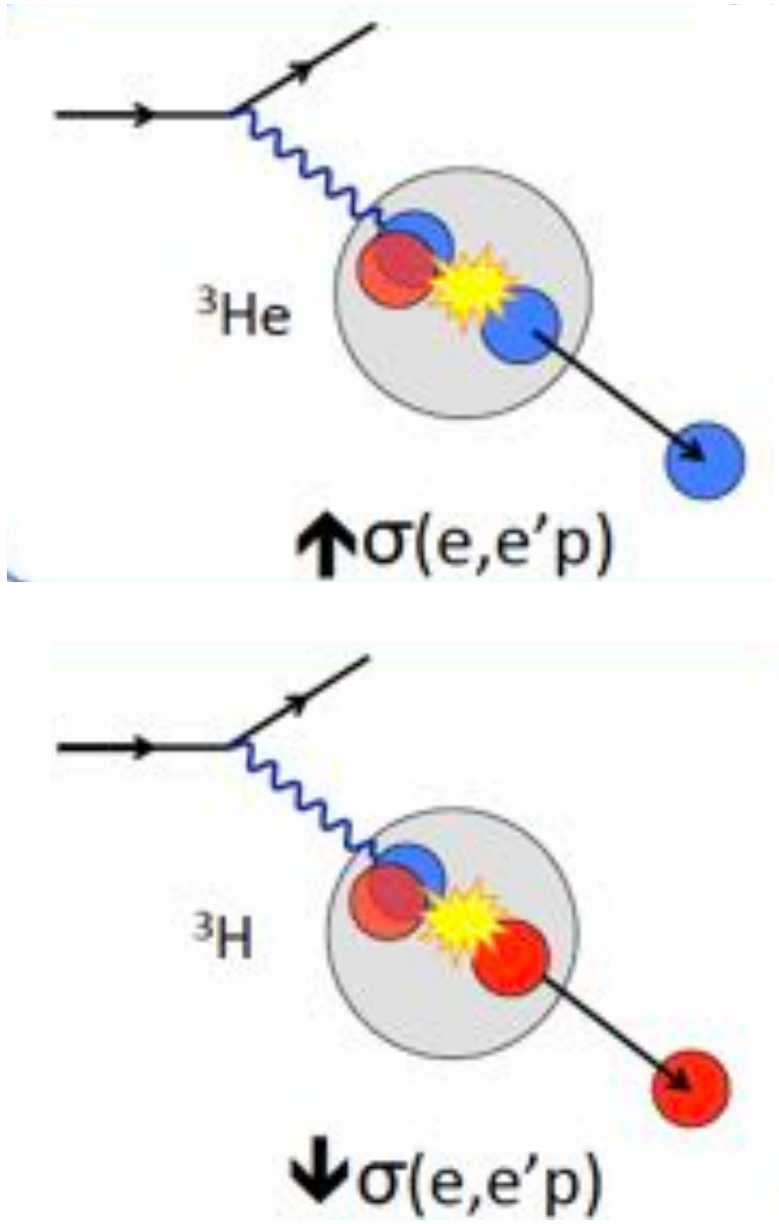
pn-SCX

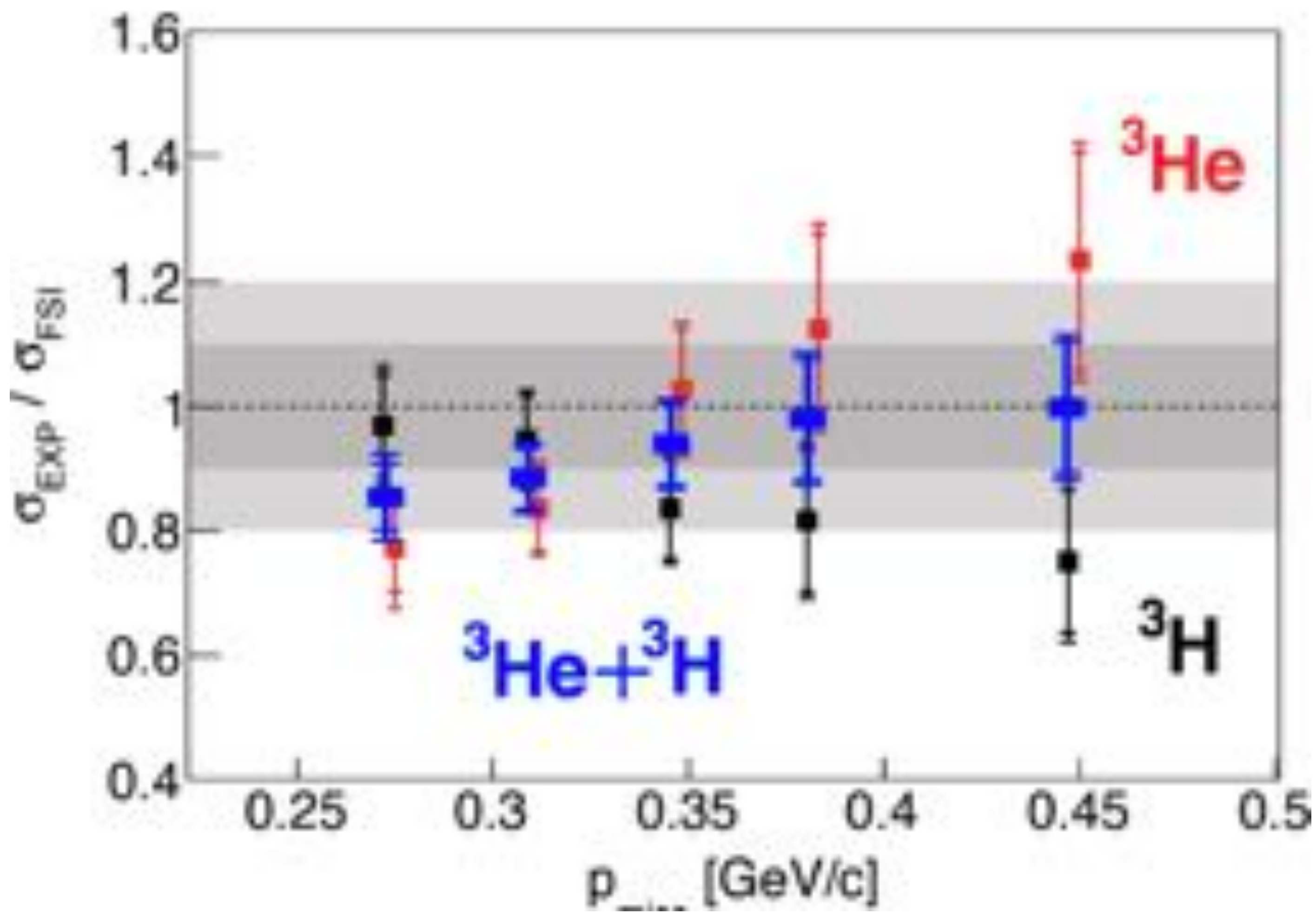
(e,e'p) -> (e,e'n)

decreases σ(e,e'p)

High-pmiss and np-doninant

Single charge exchange!

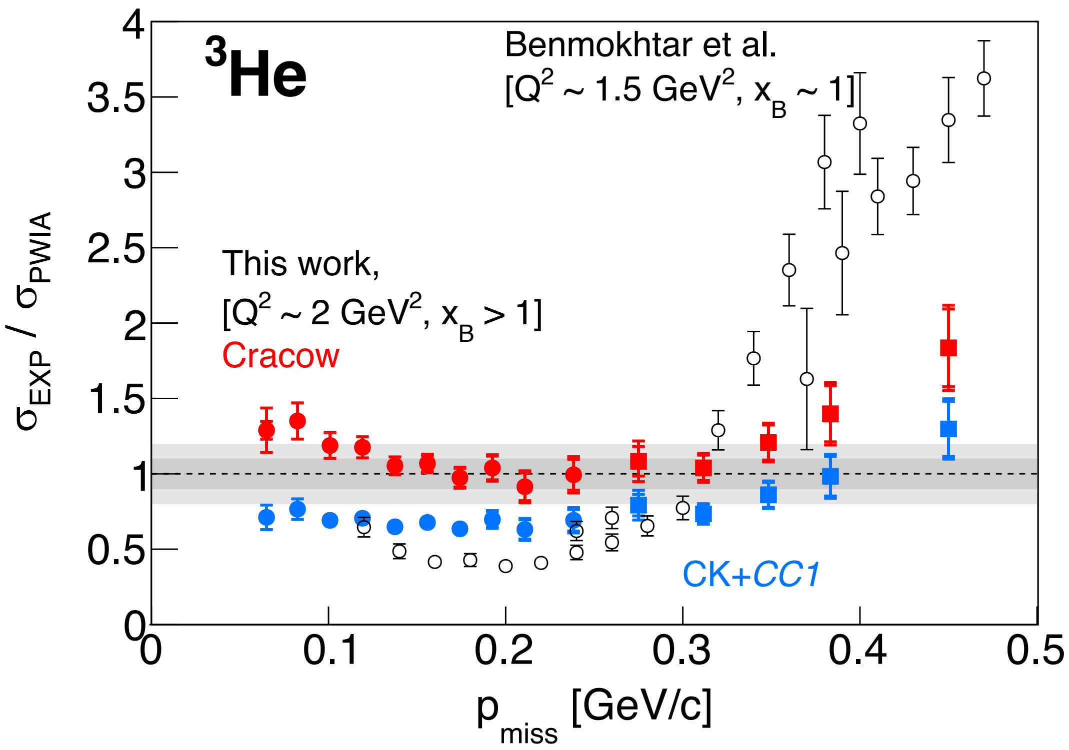




High-pmiss and np-doninant

Summary and Conclusion

- Much Smaller Non-QE contribution compared to previous measurements



Summary and Conclusion

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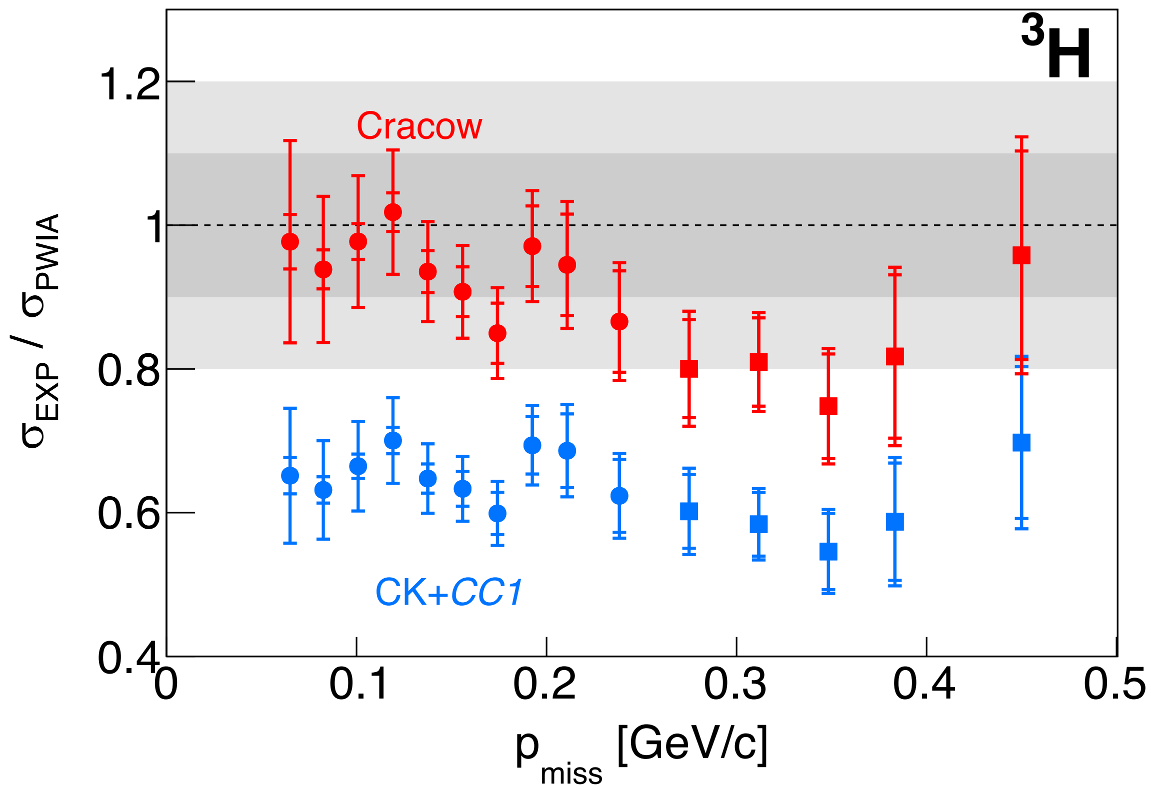

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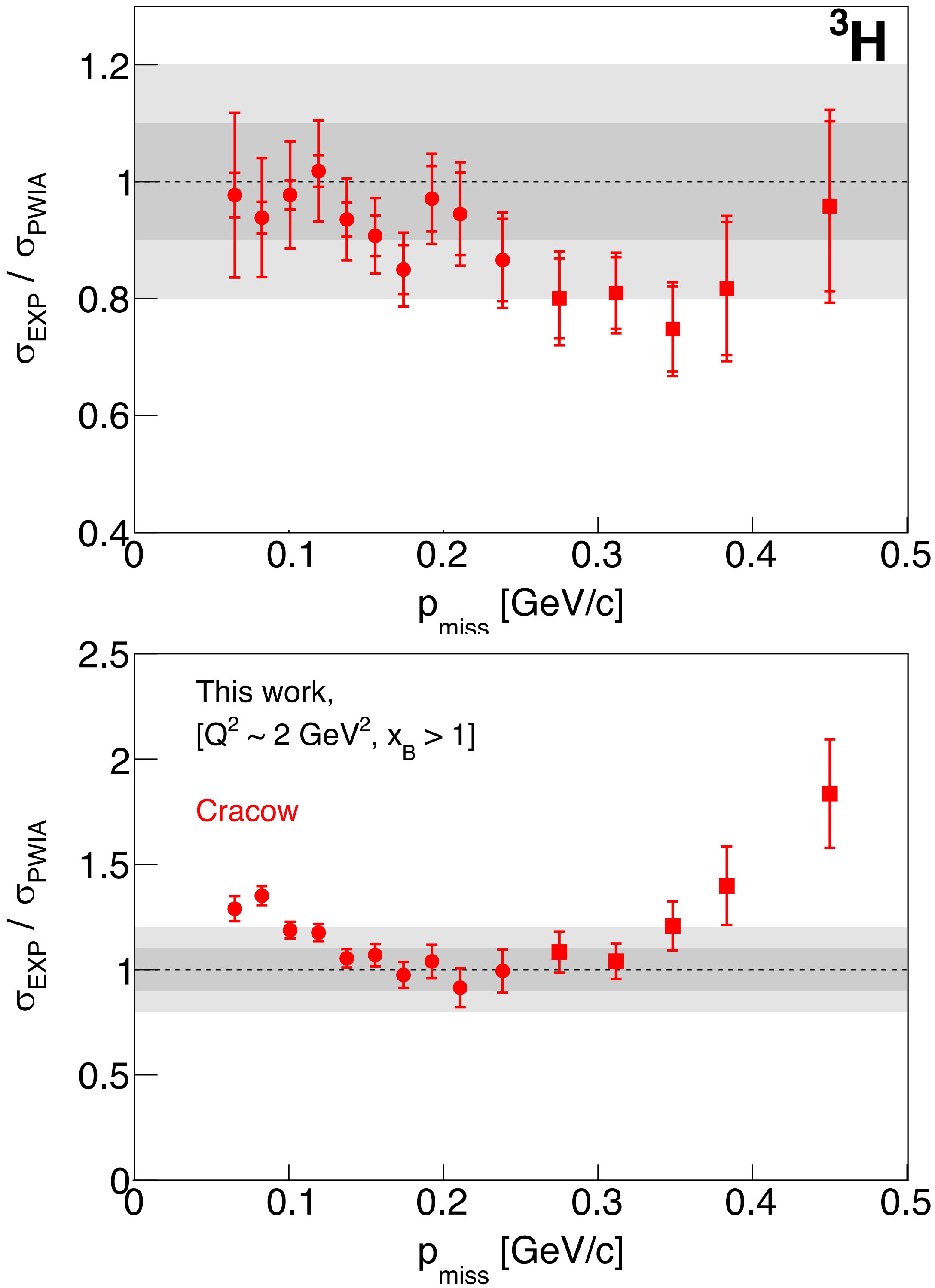
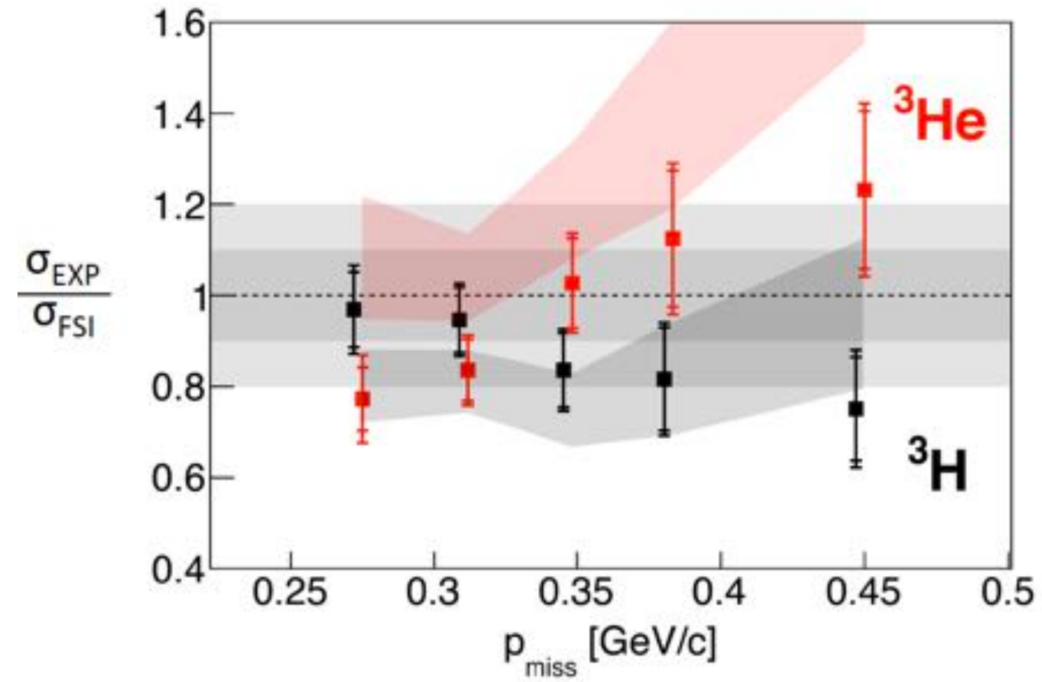


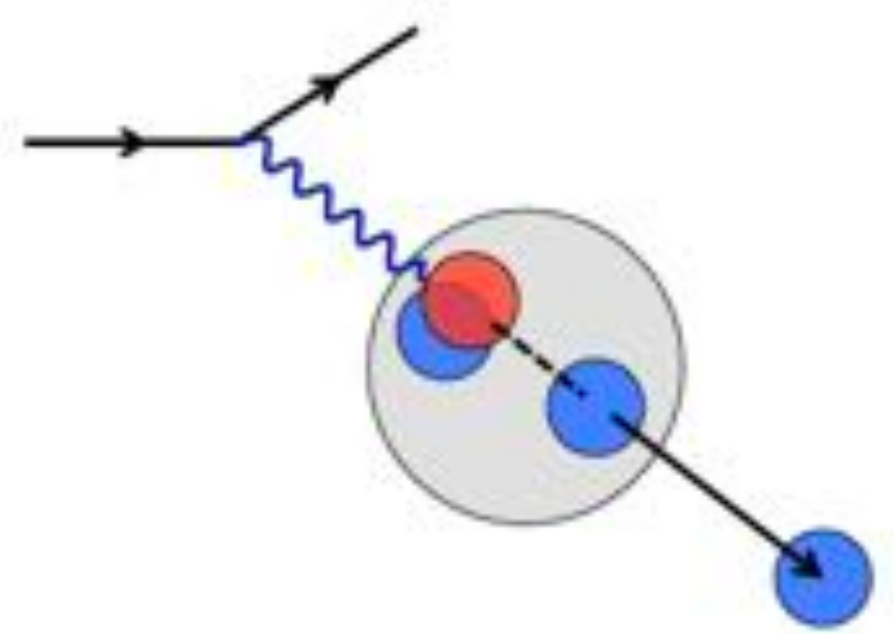
Summary and Conclusion

- Much Smaller Non-QE contribution compared to previous measurements
- Better agreement with Cracow than with CK+CC1
- Better agreement with ^3H than ^3He
- including of leading nucleon FSI improve the agreement



Summary and Conclusion

- Much Smaller Non-QE contribution compared to previous measurements
- Better agreement with Cracow than with CK+CC1
- Better agreement with ^3H than ^3He
- Including of leading nucleon FSI improve the agreement
- The remaining disagreement could be explained by SCX



Summary and Conclusion

- ❑ Much Smaller Non-QE contribution compared to previous measurements
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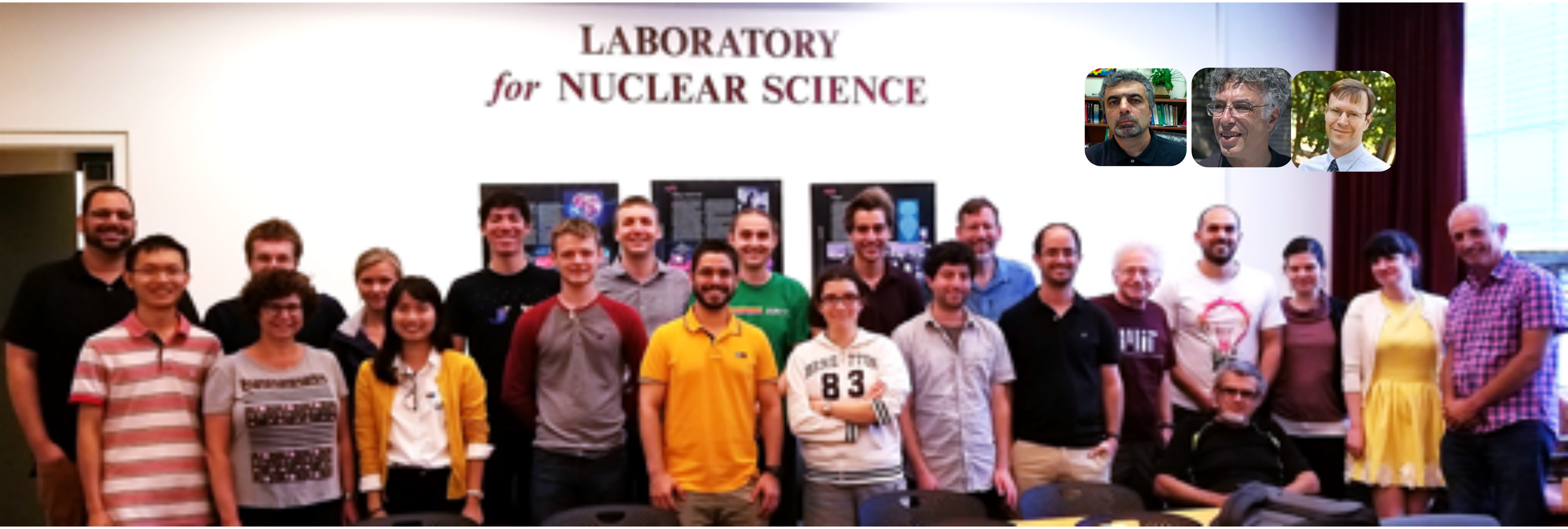
These data are a crucial benchmark for few-body nuclear theory

PRL. 124, 212501 (2020)

Thank you !



Support Slides

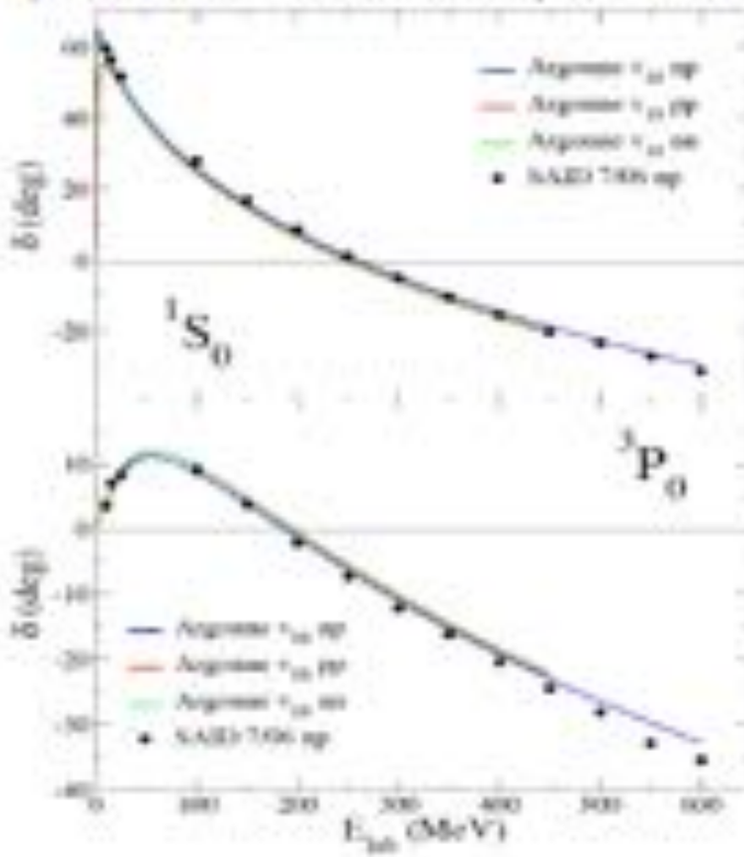
NN potentials

Long range (r > 2 fm): one-π exchange
Medium and short range (r < 2 fm):

Phenomenological ⟵ ⟶ **χEFT**

Phenomenological

- parametrized (~45 parameters) with (Wood-Saxon or Yukawa-like) functions
- Fit to NN scattering <u>**data**</u> up to π-production threshold (~350 MeV)



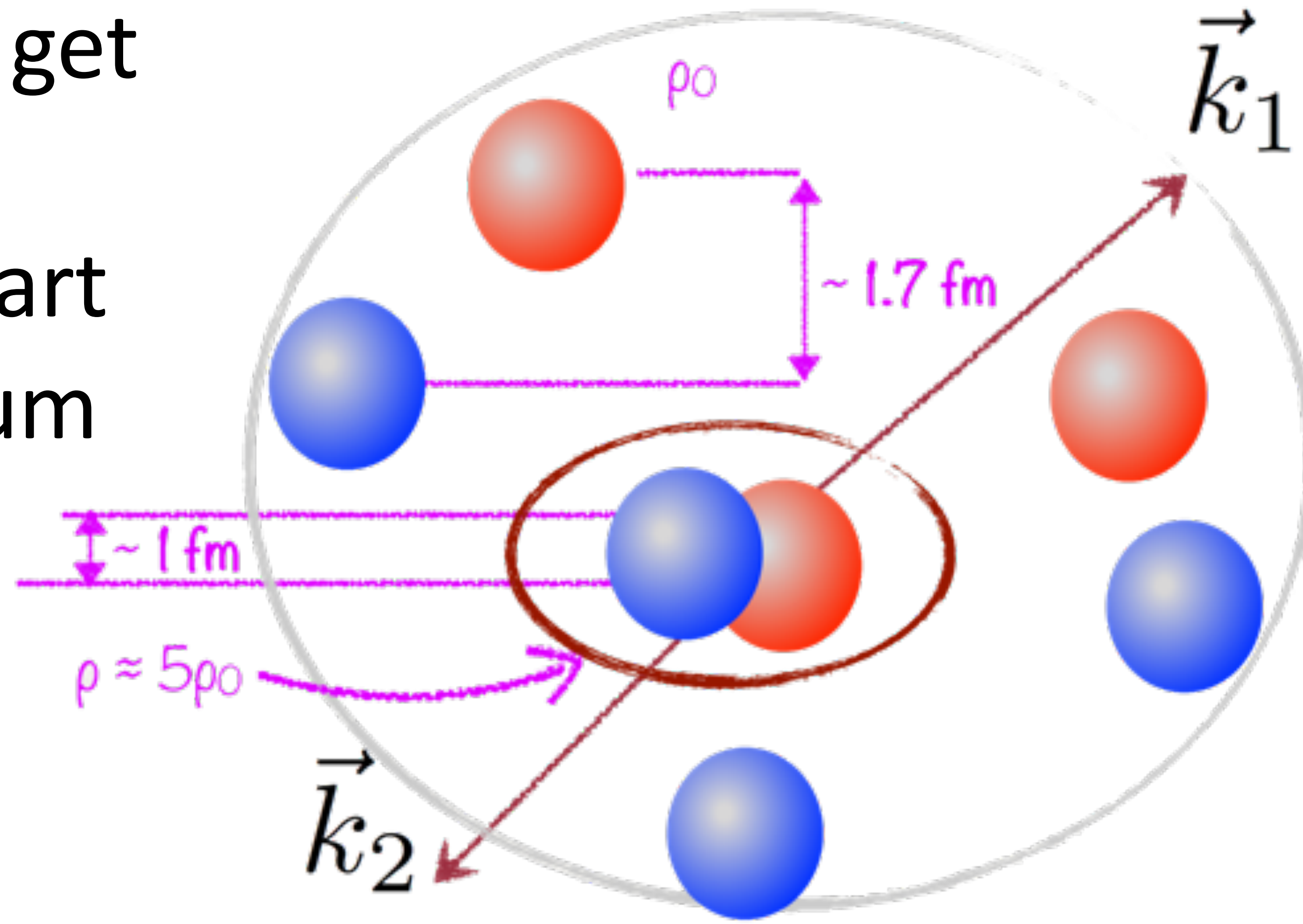
χEFT

- Systematic expansion ~ $(Q/\Lambda)^n$
- Q: generic for momentum
- Λ (χ symmetry breaking scale) ≈ 1 GeV
- DOF: hadrons and mesons
- LEC constrained from <u>**data**</u>

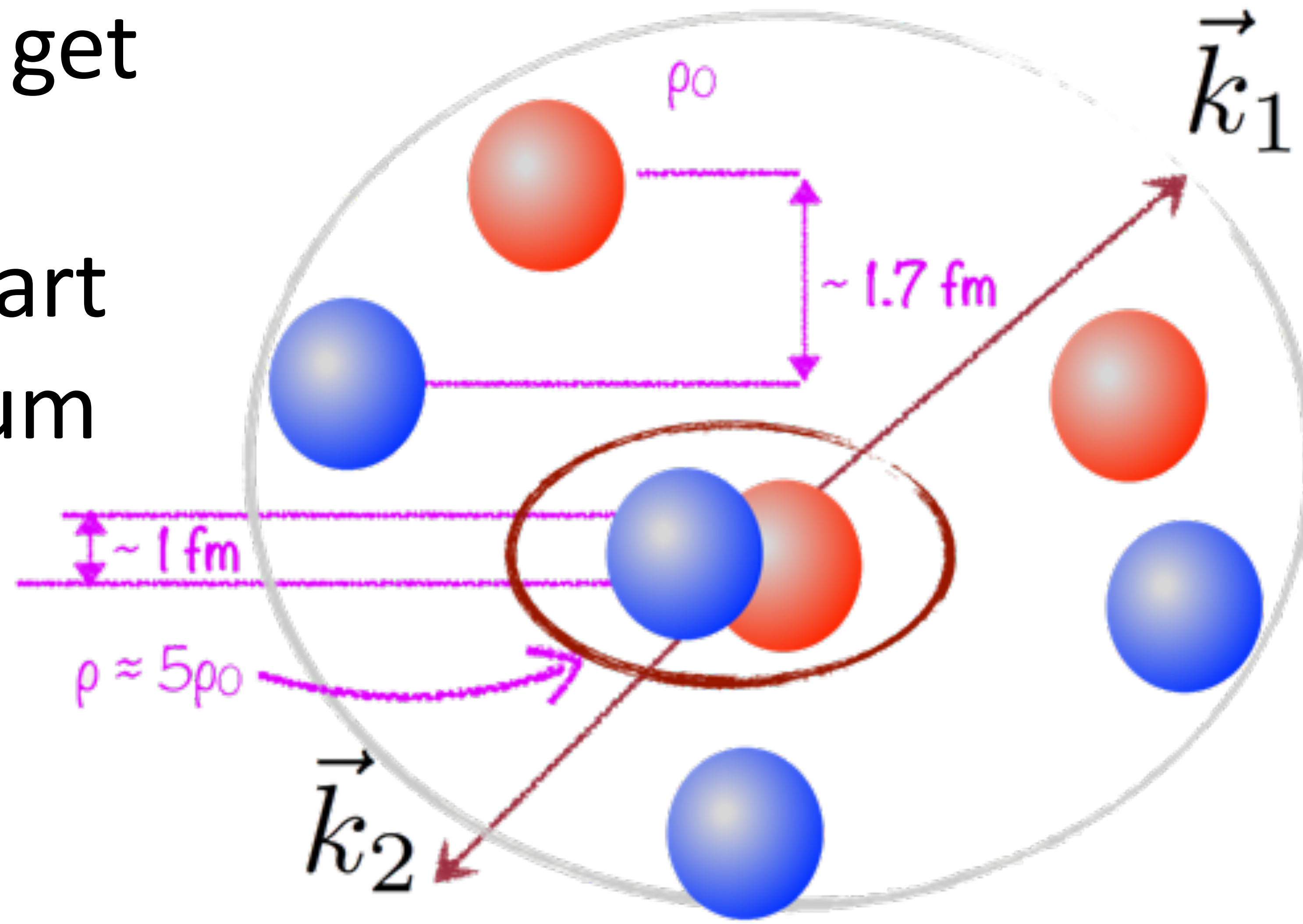
		NN	*NNN*
LO	$O\left(\frac{Q}{\Lambda}\right)^0$		—
NLO	$O\left(\frac{Q}{\Lambda}\right)^2$		—
N^2LO	$O\left(\frac{Q}{\Lambda}\right)^3$		

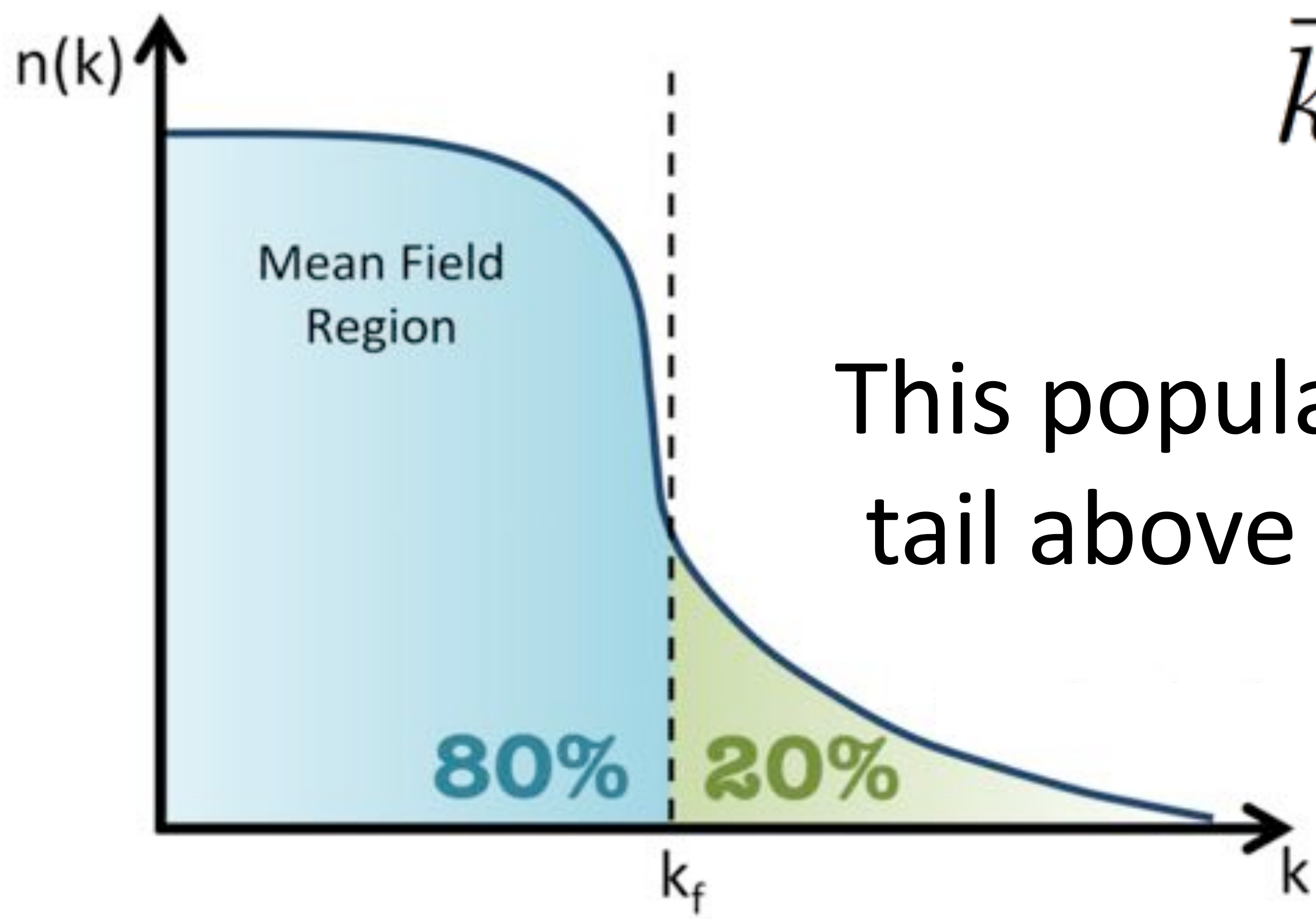
Short range interaction: Brief introduction

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



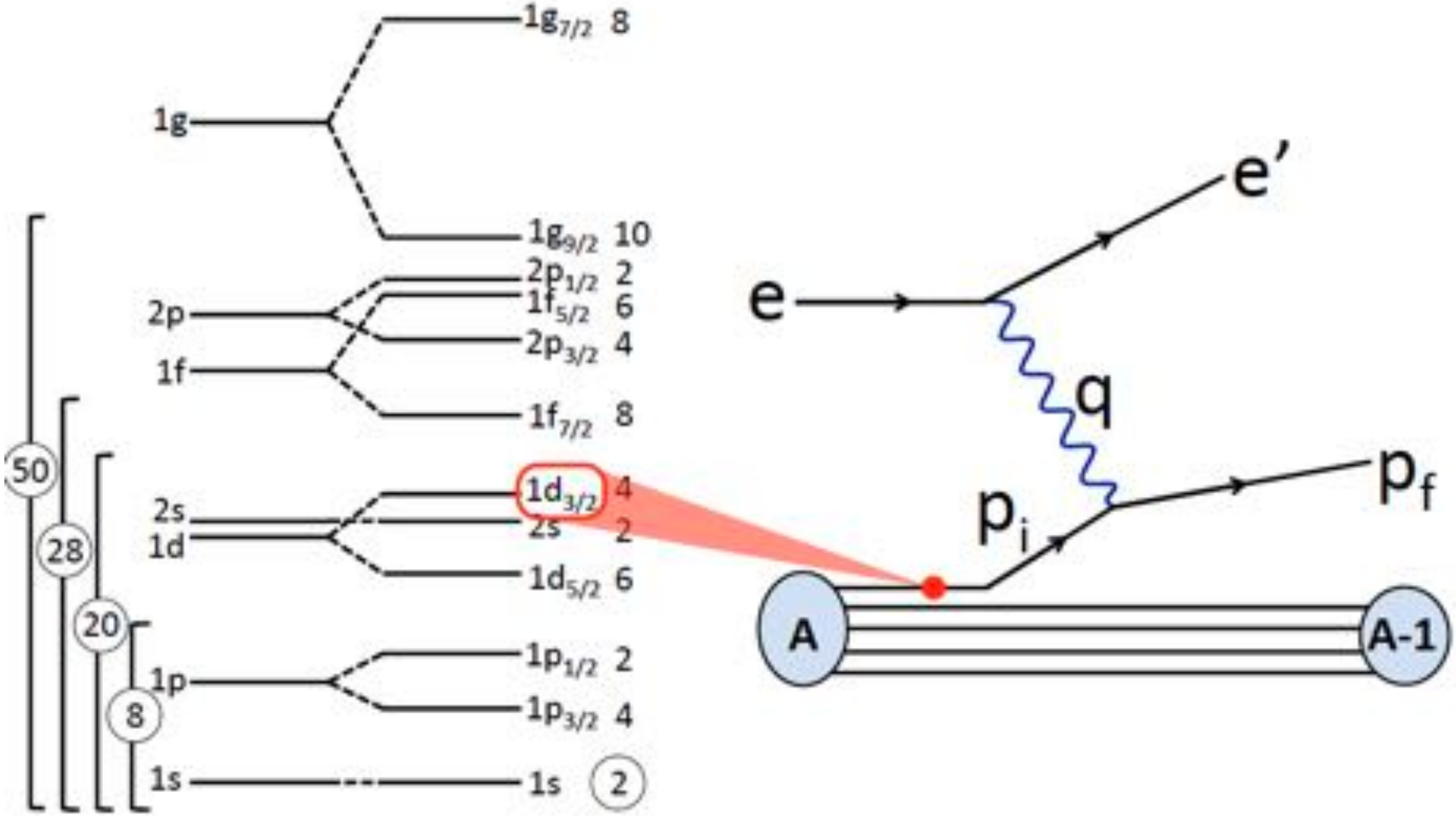
When two nucleons get close inside the nucleus, they fly apart with high momentum





This populates a high-momentum tail above the Fermi momentum

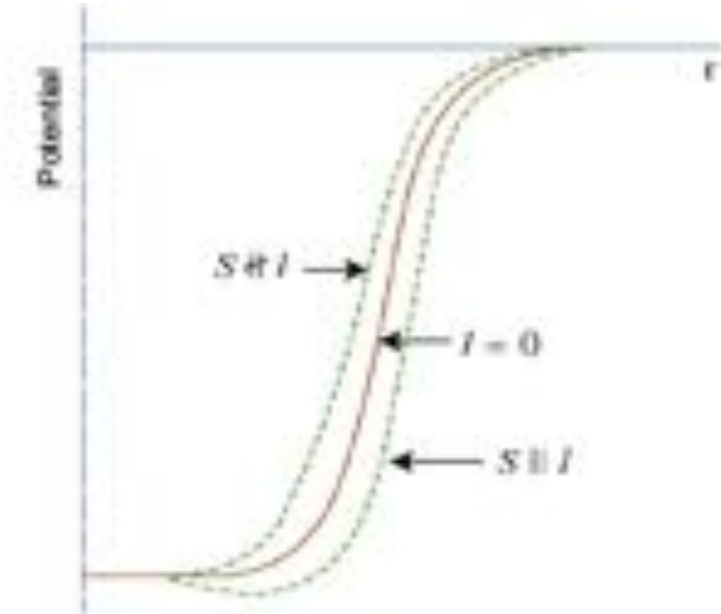
(e,e'p) scattering off shell orbitals



Independent particle shell model

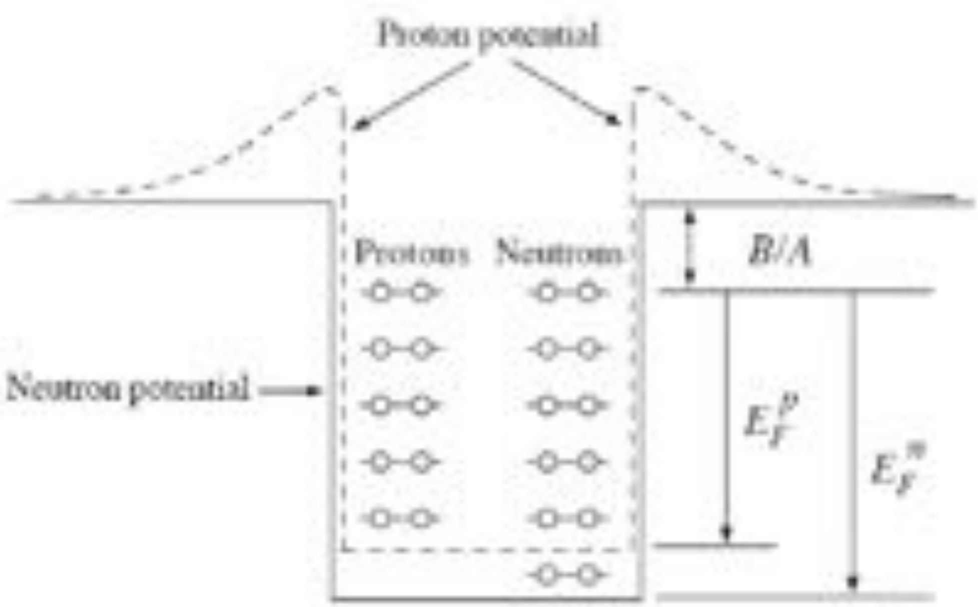
$$H = \underbrace{[T + V_M]}_{\text{IPSM}} + \underbrace{[V_{2-body} + V_{3-body} + ... - V_M]}_{\text{neglected in IPSM}}.$$

$$V_M = \underbrace{\left[\frac{-V_0}{1 + exp[(r-R)/a]}\right]}_{\text{Woods-Saxon potential}} + \underbrace{\left[V_{ls}(r)\mathbf{L}\cdot\mathbf{S}\right]}_{\text{Spin-orbit interaction term}}$$



Assumptions:

- Nucleon moves in a mean field created by surrounding nucleons
- No interaction at a short distance
- Nucleons fill up distinct energy levels defined by quantum number, highest energy level is called Fermi energy, corresponds to fermi momentum k_f



Pauli principle:

- Forbids nucleon scattering to occupied shell. Suppresses the nucleon interaction.

IPSM is very successful in:

- Describing the shell structure of nuclei
- Explaining magic number, spin, angular momentum

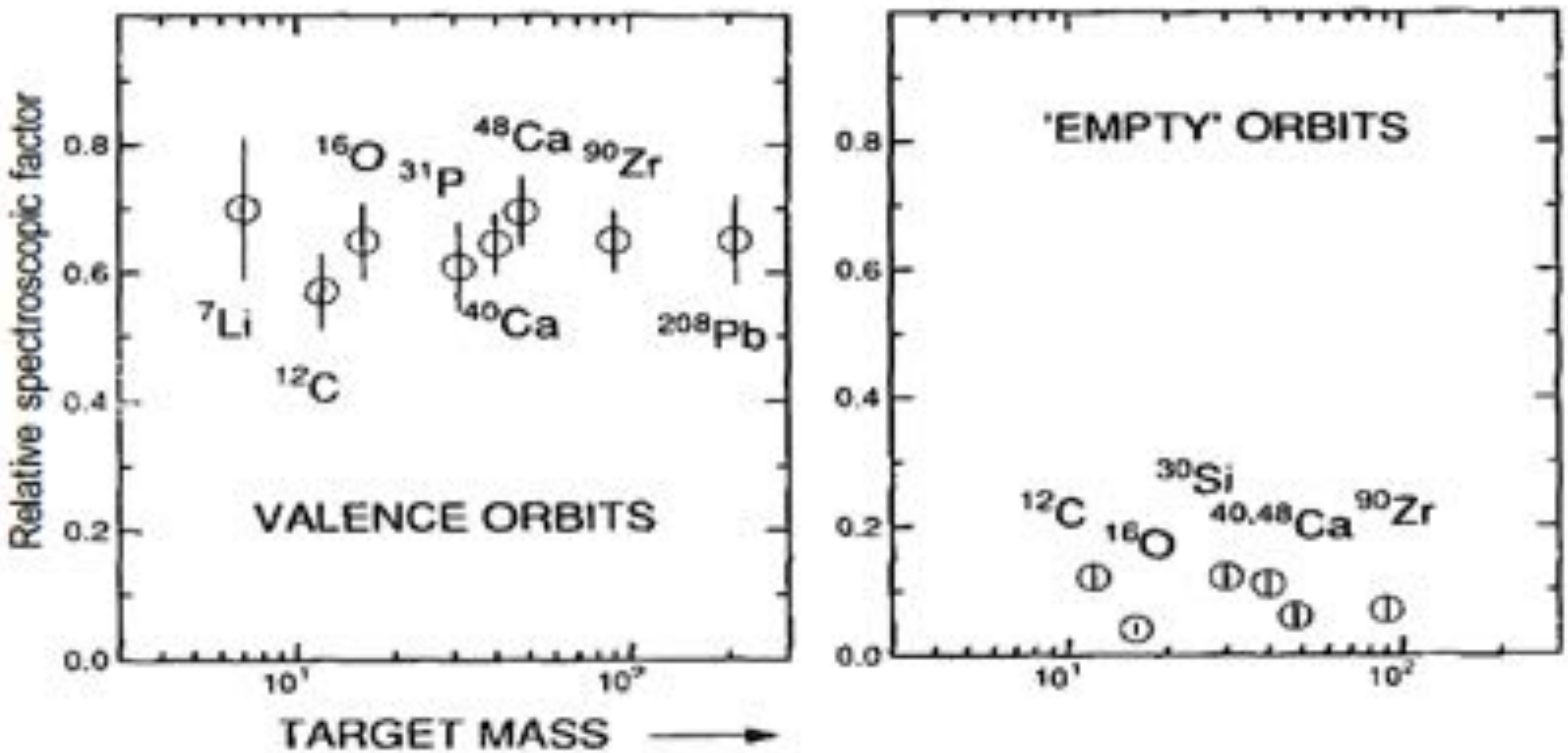
IPSM's limitations

- Due to mean field approximation

Missing strength of proton at valence shell

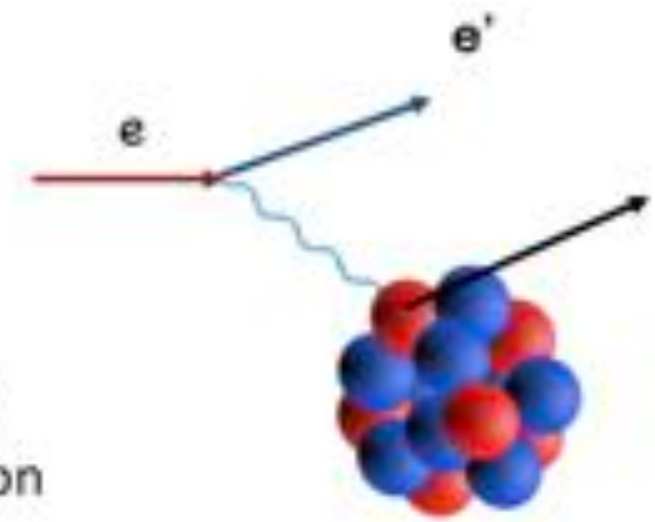
- Spectroscopic factor is only ~65 % for valence shell over big range of A
- Some strength was detected in the shell above fermi edge which is empty in ISPM

Lapikas, Nucl. Phys. A553 (1993)



Possible solution: Including Short range Correlations (SRCs)

Inclusive electron scattering



Kinematic variables:

$\nu = E_0 - E$ → Transfer energy

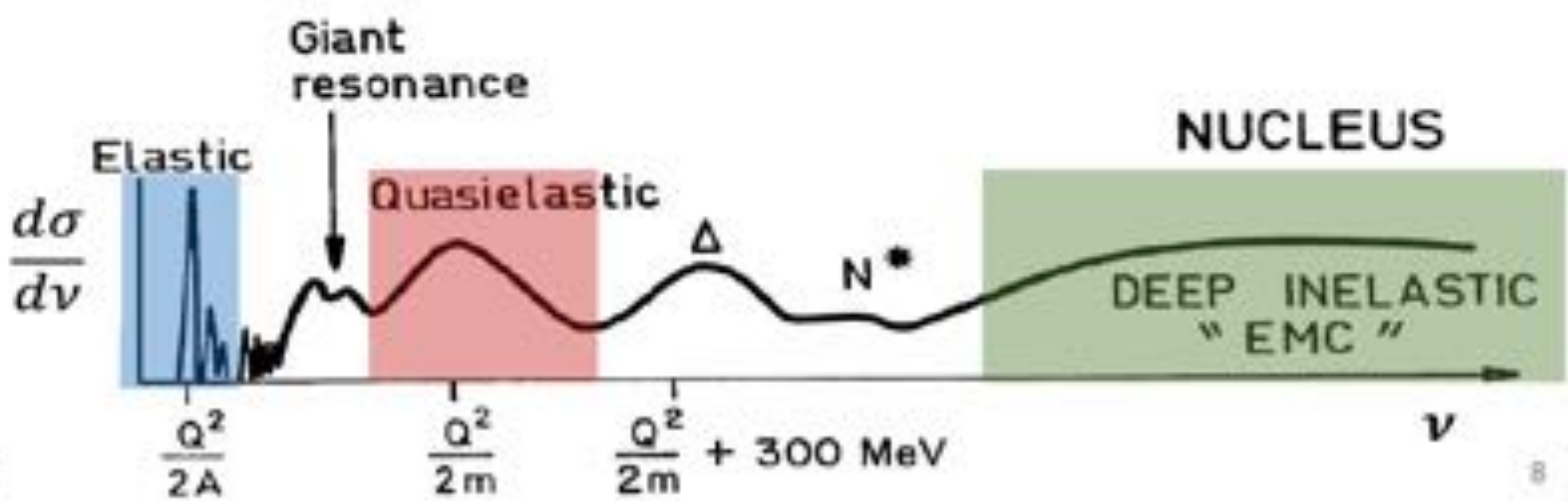
$Q^2 = 4E_0 E \sin^2(\theta/2)$ → 4-momentum transfer squared

$x_{bj} = \dfrac{Q^2}{2m\nu}$ → Momentum fraction of a nucleon shared by the struck quark.

$y \approx -q/2 + m\upsilon/q$ → Momentum of struck nucleon parallel to q vector

e-p elastic scattering: x = 1, Quasi-elastic scattering x ≈ 1

Motion of nucleon in the nucleus broadens the peak to x~ 1.3



(e,e'p) scattering off shell orbitals

Missing energy spectrum shows shells occupancy