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# The Transparent Nucleus

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Background-free Quasi-elastic Scattering of  $^{12}\text{C}$   
in Inverse Kinematics at 4 GeV/c/u

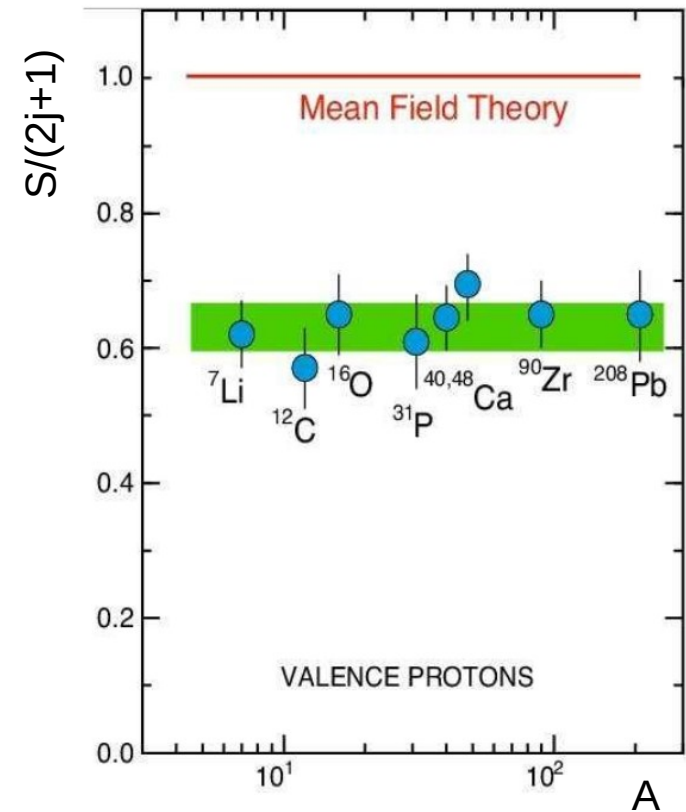
Julian Kahlbow  
for the SRC Collaboration

5<sup>th</sup> BM@N Collaboration Meeting  
April 21<sup>st</sup>, 2020



# Quasi-elastic Scattering

- **A tool to study nuclear structure**
  - successful for many decades in electron scattering
- **Quenching of spectroscopic strength: long and short range correlations missing in meanfield theory**

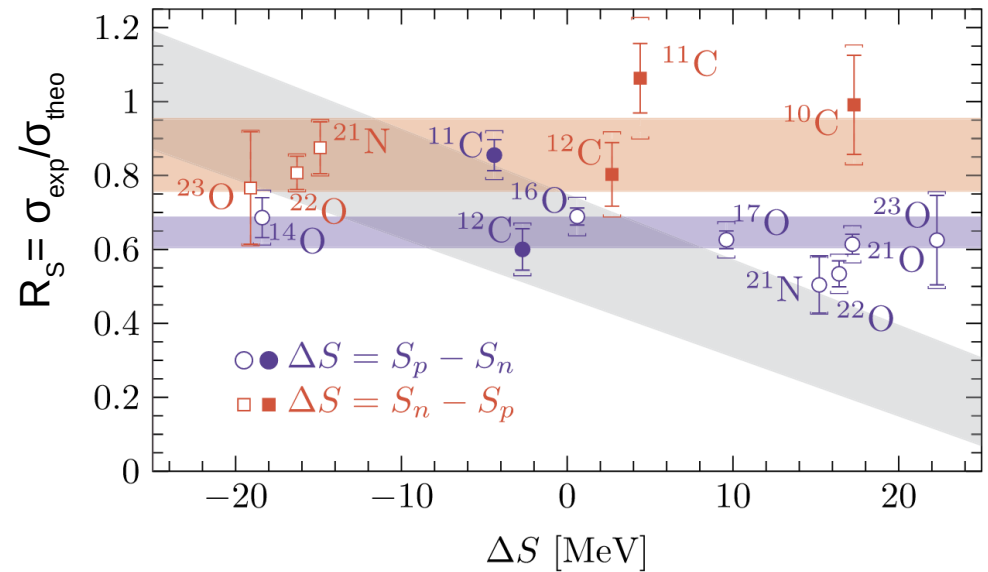


L. Lapikas, NPA 553 (1993)

# Fully-exclusive Quasi-elastic Scattering

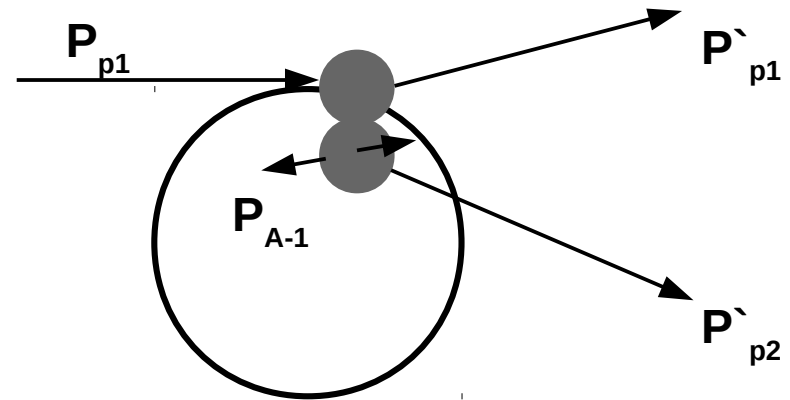
- **Reactions in inverse kinematics**
  - Nuclear beams and hadronic probe
- study exotic nuclei in fully-exclusive way

Quasi-free ( $p,2p$ ) and ( $p,pn$ ) scattering at R<sup>3</sup>B at GSI M. Holl et al., PLB 795 (2019)



# High-energy Quasi-elastic Scattering

- Large momentum transfer, direct nucleon knockout
  - Residual (A-1) system measured in coincidence
  - Selective to nucleons with large momentum:  
strong S dependence in large-angle c.m. elastic scattering
- selective to nucleons in Short-Range Correlated Pairs

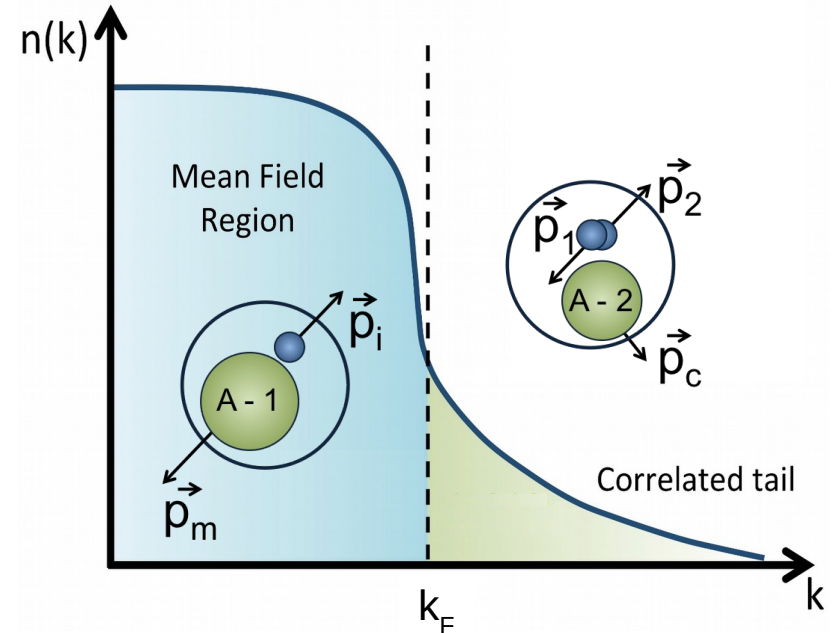
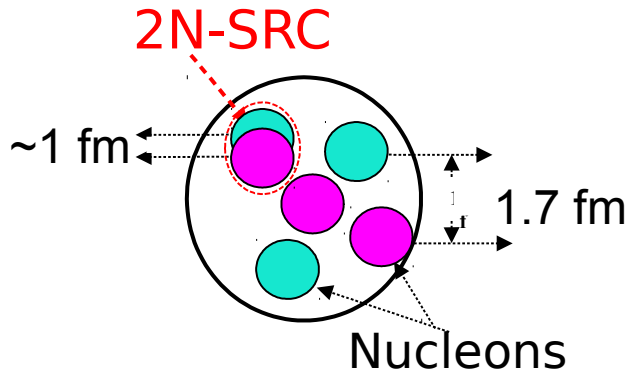


# Short-Range Correlations (SRC) in Nuclei

- SRC pair: 2N in close proximity

In momentum space:

- Large relative momentum ( $> k_F$ )
- Smaller center-of-mass motion
- here:  $^{12}\text{C}(p,2p\ ^{10}\text{B})n$ ,  $^{12}\text{C}(p,2p\ ^{10}\text{Be})p$

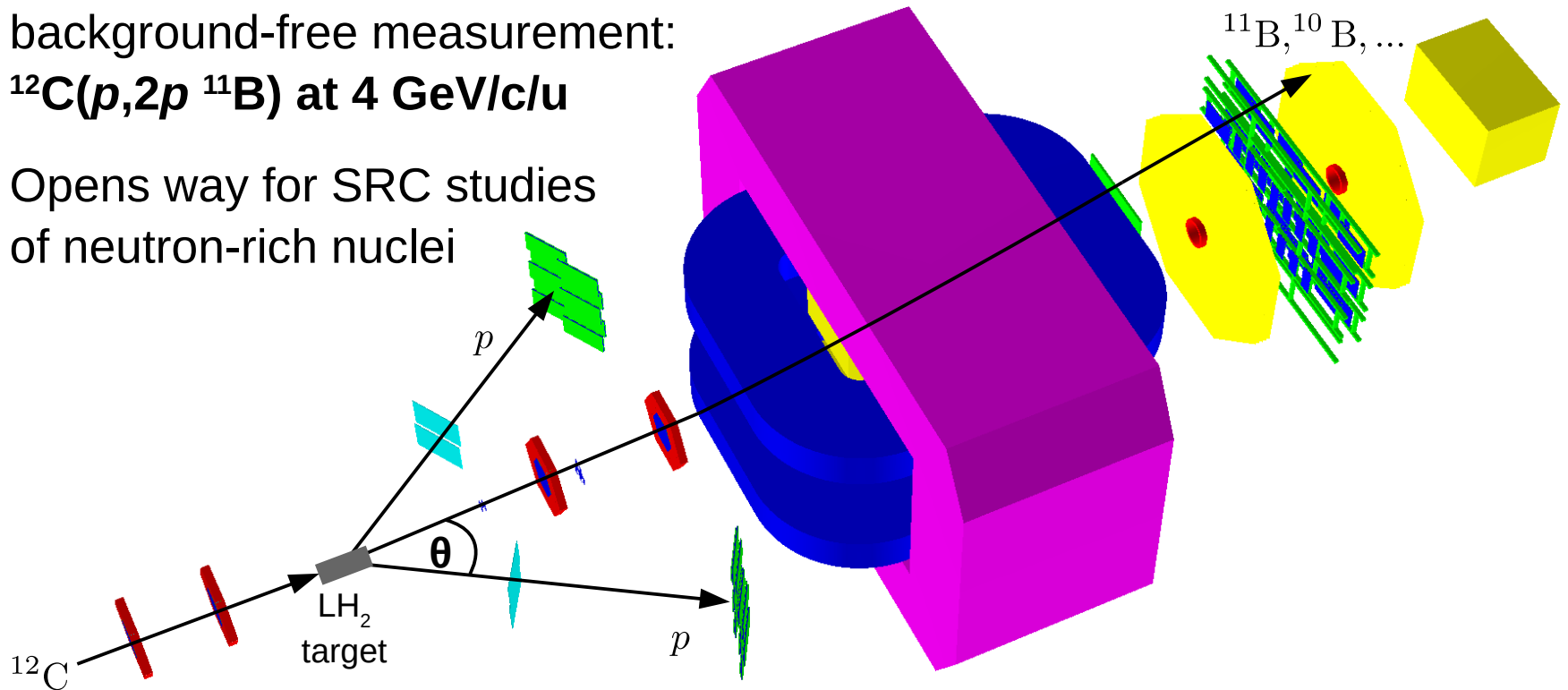


- R. Subedi et al., Science (2008)
- O. Hen et al., Science (2014)
- M. Duer et al., Nature (2018)
- E. Cohen et al., PRL (2018)

# Our Pilot Experiment at BM@N

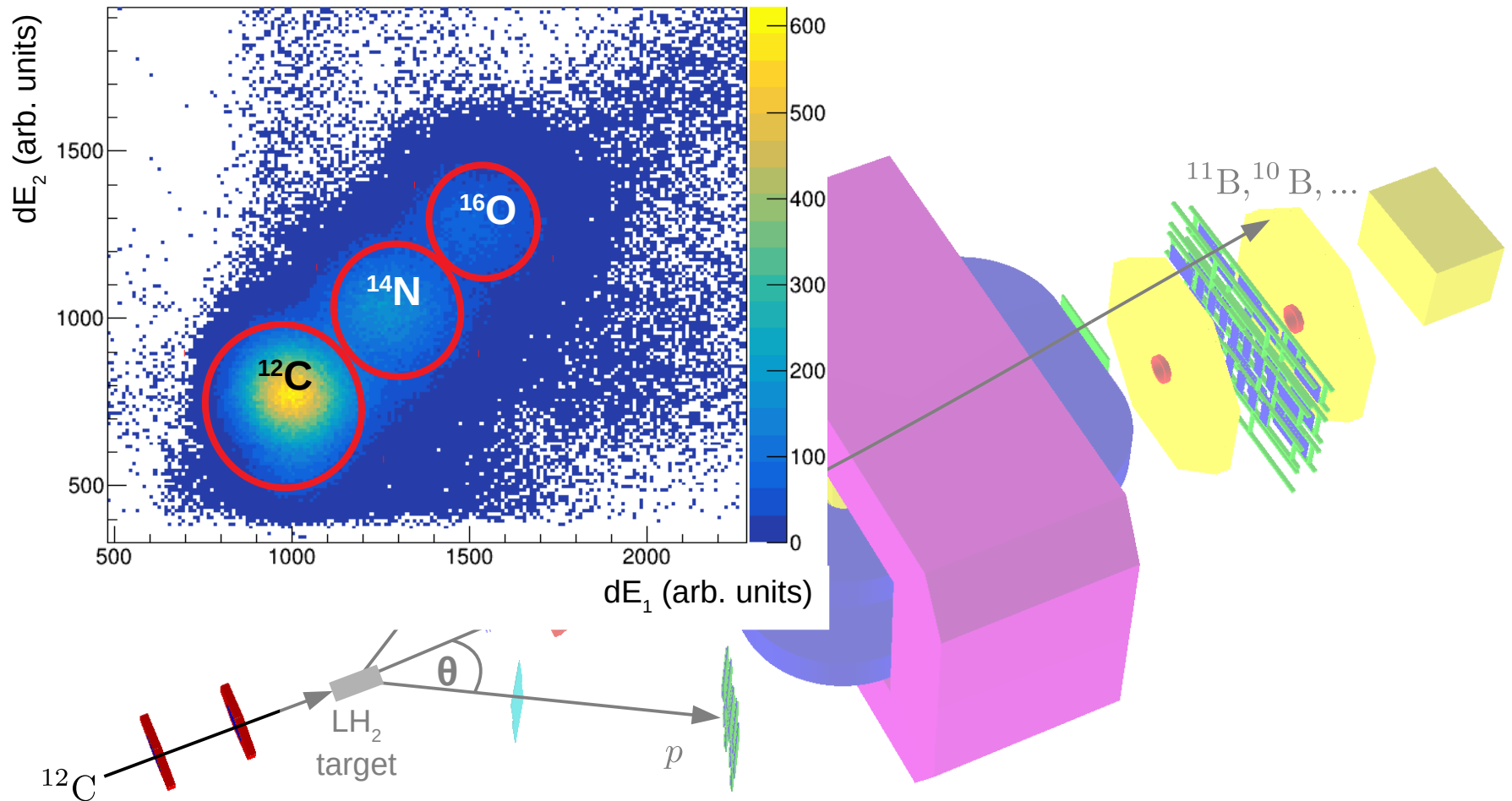
## Combining all these aspects:

- Proof-of-Principle of unique background-free measurement:  
 $^{12}\text{C}(p,2p\ ^{11}\text{B})$  at 4 GeV/c/u
- Opens way for SRC studies of neutron-rich nuclei



# Incoming Particle ID and Tracking

Maria Patsyuk, Göran Johansson, Vasilisa Lenivenko, Timur Atovullaev, et al.

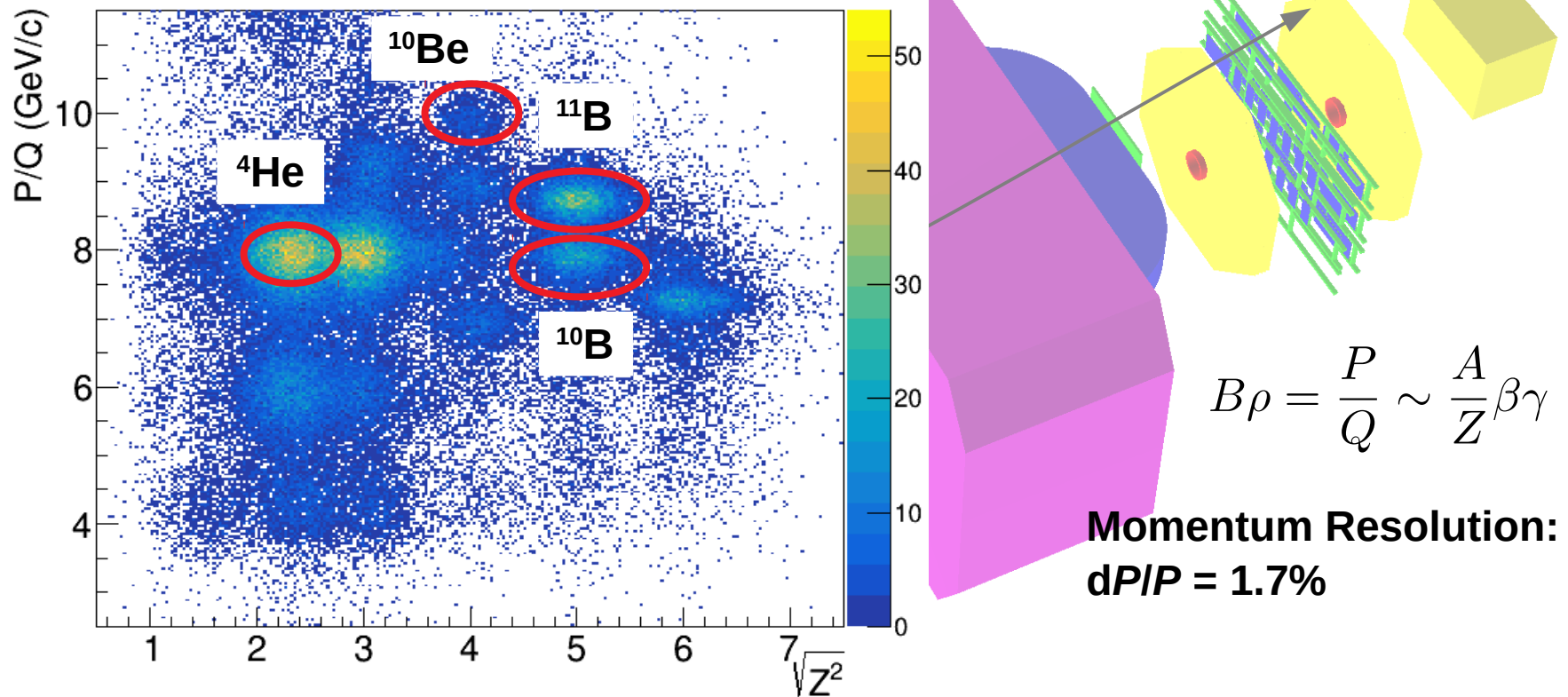


# Fragment ID and Momentum

Valerii Panin, Göran Johansson, Timur et al.

Multi-dimensional Fit

$$P/Q = f(\vec{X}_{in}, \alpha, \vec{X}_{out}, \beta)$$





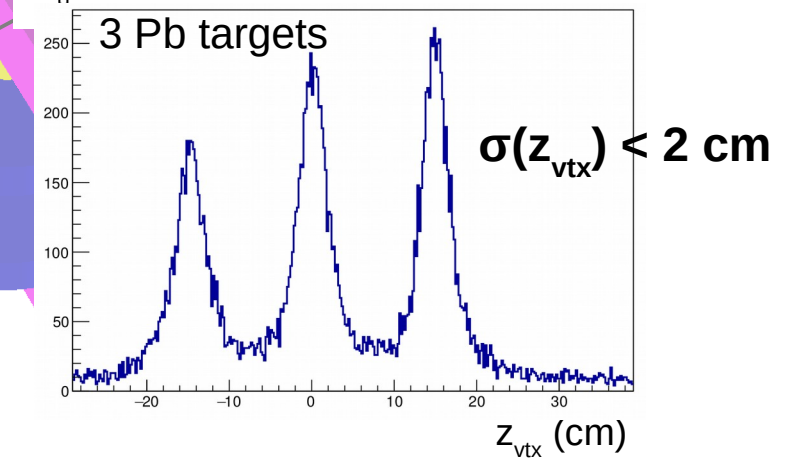
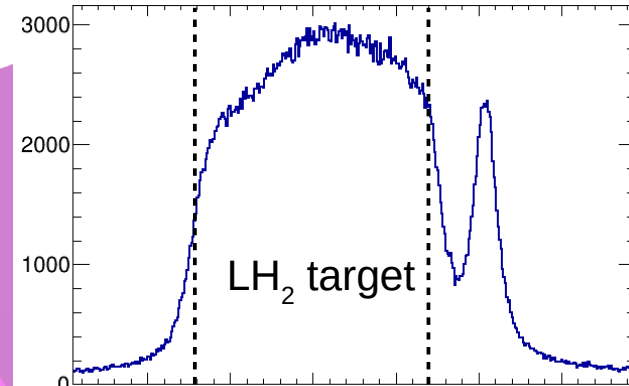
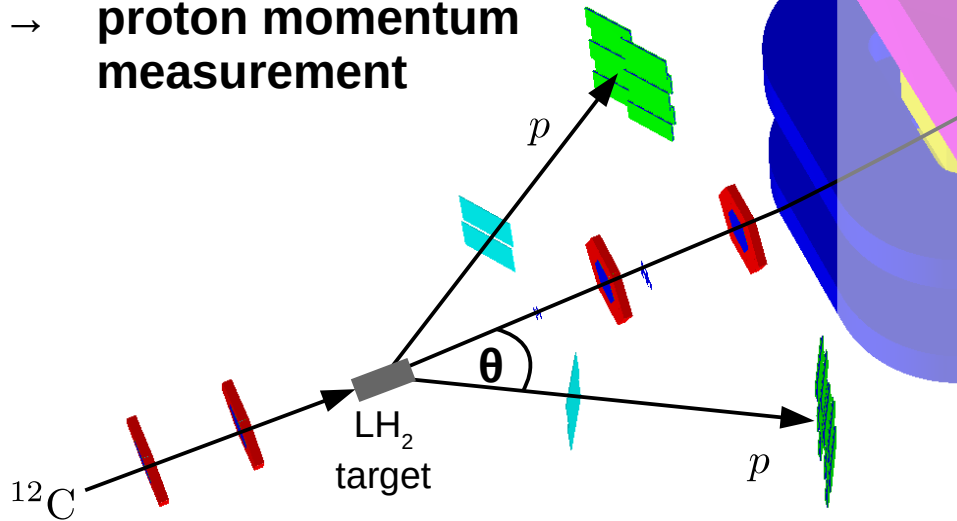
# Knocked-out Proton Momentum

Efrain Segarra et al.

## Charged-Particle Tracking in Proton-Arm Spectrometer

Vertex reconstruction  
from left and right arm track

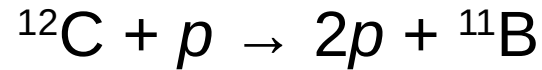
→ **proton momentum  
measurement**



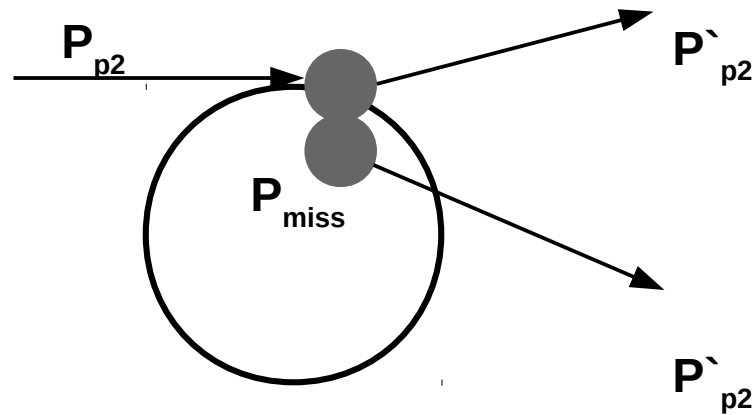
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# Identification of Quasi-elastic Scattering

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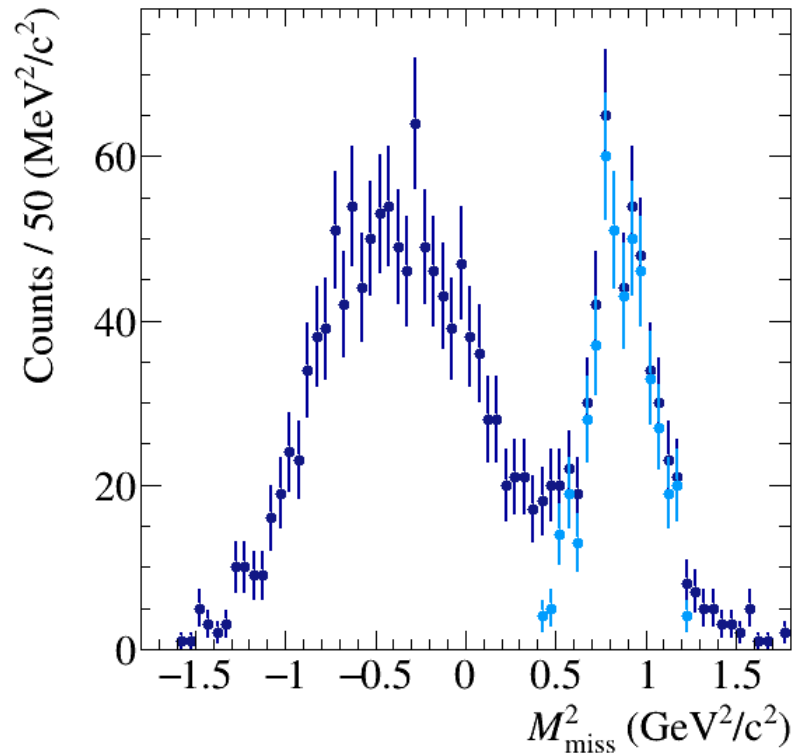
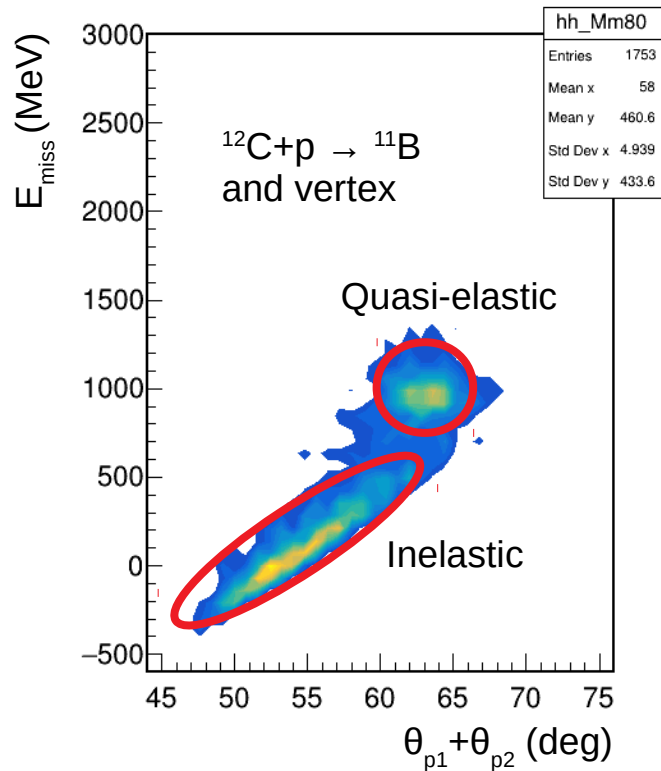
Reconstruct the **proton's initial momentum** in  $^{12}\text{C} = P_{\text{miss}}$



$$(P_{^{11}\text{B}} + P_{p1}) + P_{p2} = P'_{p1} + P'_{p2} + P_{^{11}\text{B}}$$

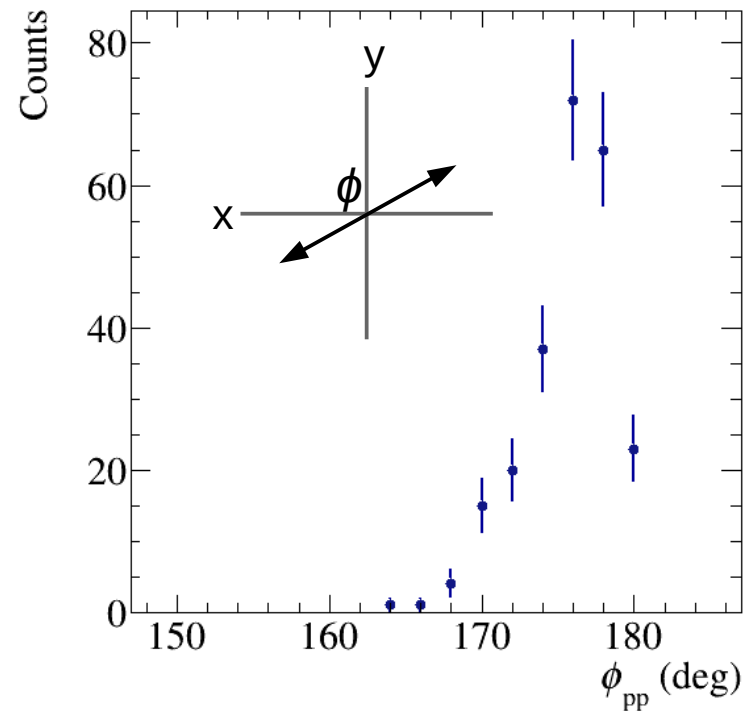
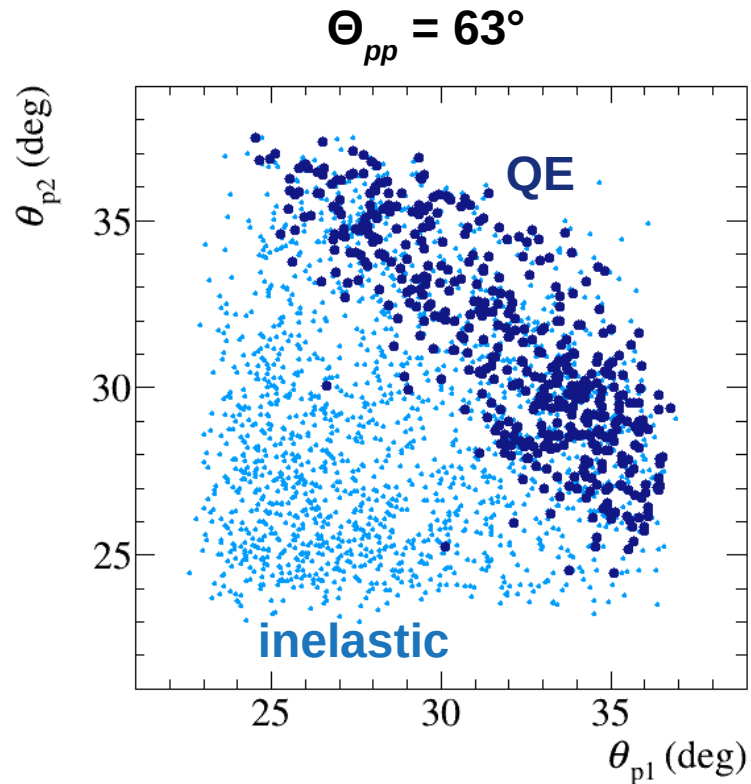
$$\downarrow$$
$$P_{\text{miss}} = P'_{p1} + P'_{p2} - P_{p2}$$

# Identification of Quasi-elastic Scattering



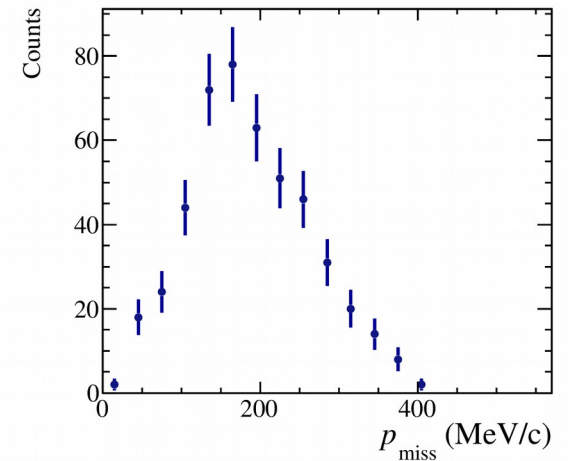
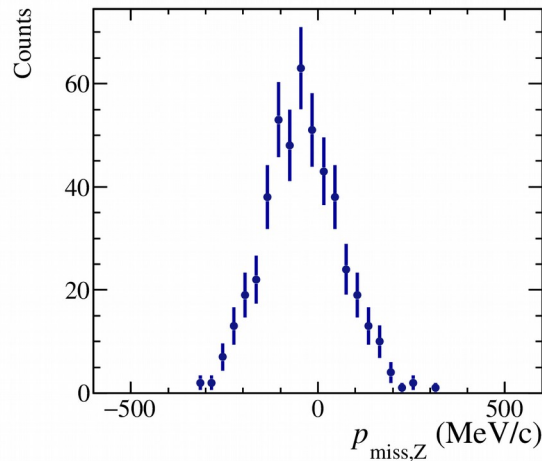
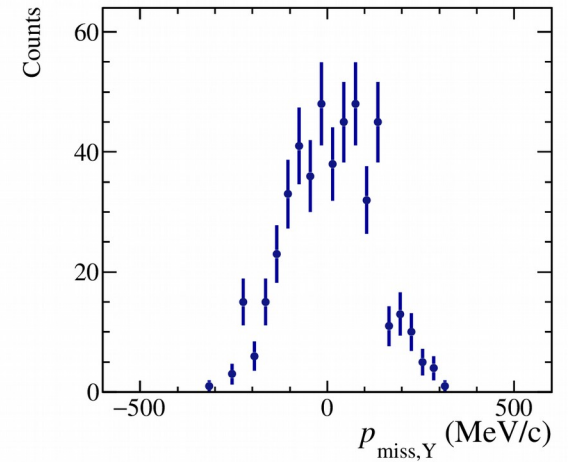
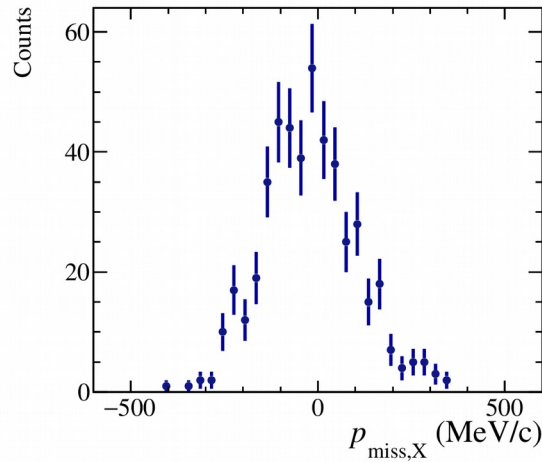
# Signatures of Quasi-elastic Scattering

Proton Angular Correlations  $^{12}\text{C}(p,2p\ ^{11}\text{B})$



# Knocked-out Proton Initial Momentum $P_{miss}$

$$P_{miss} = P'_{p1} + P'_{p2} - P_{p2}$$



# Meanfield ( $p,2p$ ) MonteCarlo

Compare to meanfield ( $p,2p$ ) MonteCarlo:

- $pp$  scattering in inverse kinematics
- Initial proton-momentum sampled from Woods-Saxon meanfield momentum distribution for  $^{12}\text{C}$
- Cross section parametrization

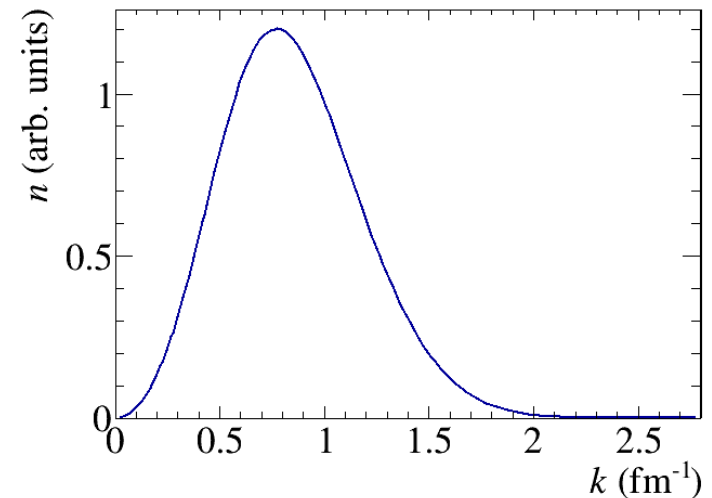
$$\frac{d\sigma}{dt} \sim S^{-10} (1 - \cos^2(\theta_{c.m.}))^{-4.0.9}$$

S.J. Brodsky and G.R. Farrar, PRL 31 (1973)

V.A. Matveev, R.M. Muradyan, A.N. Tavkhelidze, Lett. Nuvo Cim. 7 (1973)

D. Sivers, S.J. Brodsky, and R. Blankenbecler, Phys. Rep. 23 (1976)

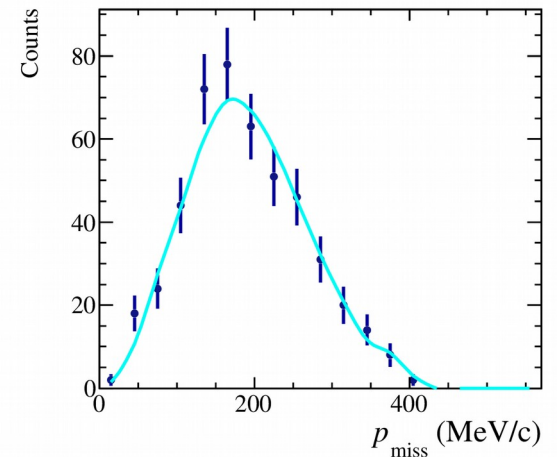
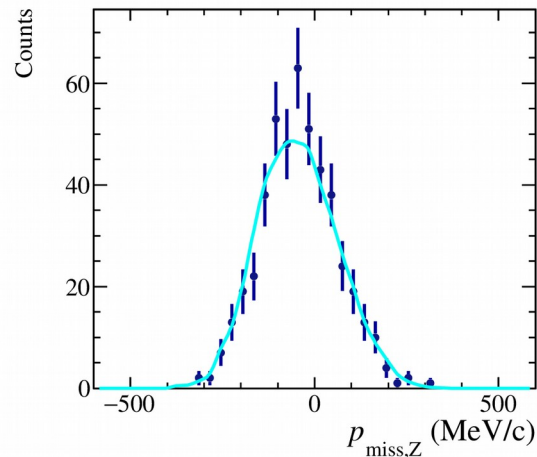
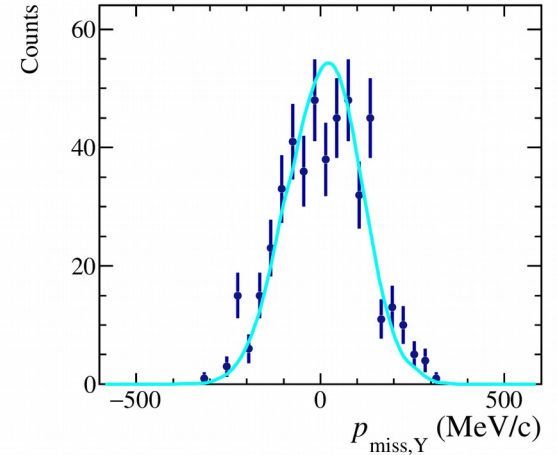
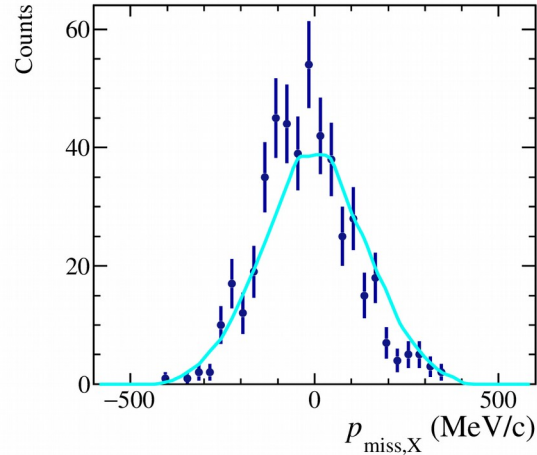
- Detector acceptances and resolutions included



# Knocked-out Proton Initial Momentum $P_{miss}$

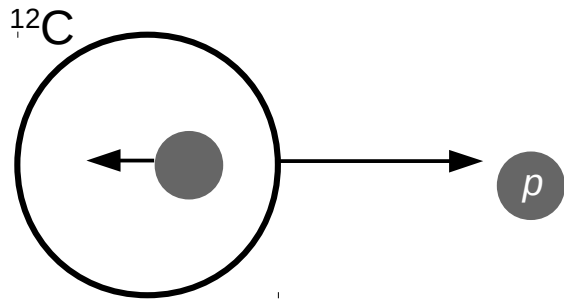
$$P_{miss} = P'_{p1} + P'_{p2} - P_{p2}$$

In comparison to Simulation



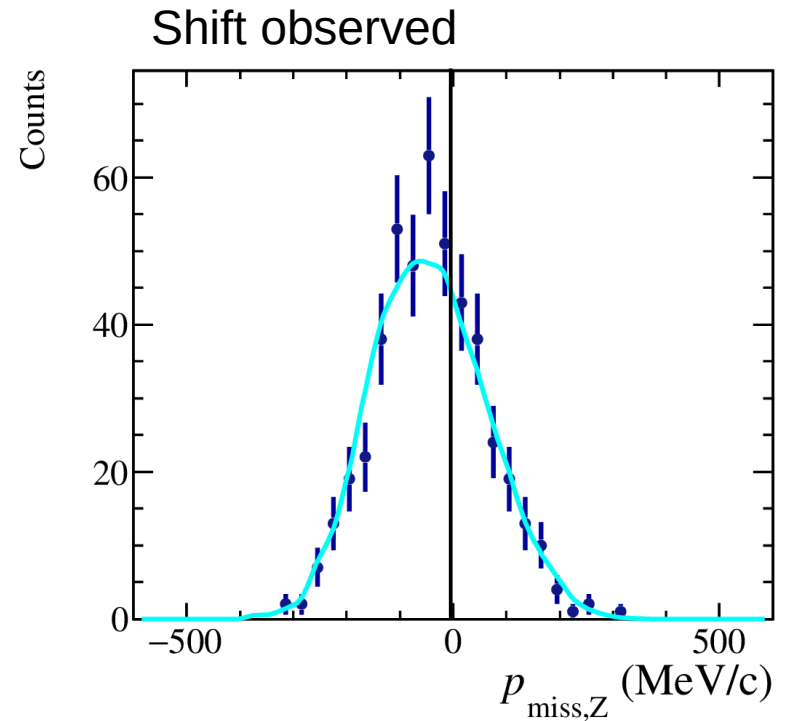
# Sensitivity to $S$ Scaling

$$\frac{d\sigma}{dt} \sim S^{-10} \quad \text{for fixed c.m. scattering angle in free } pp \text{ scattering}$$



Maximized cross section in anti-parallel direction

→ longitudinal momentum is sensitive

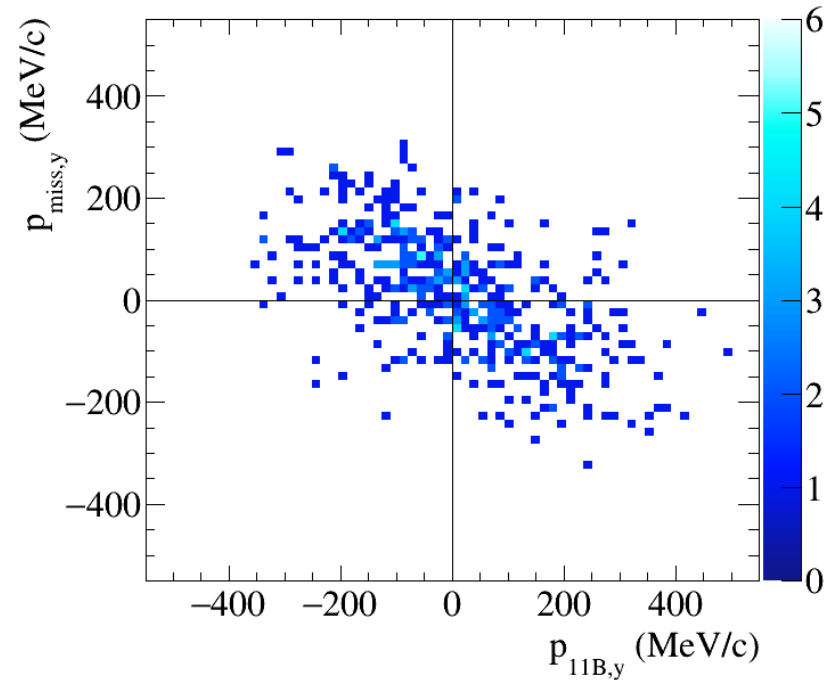
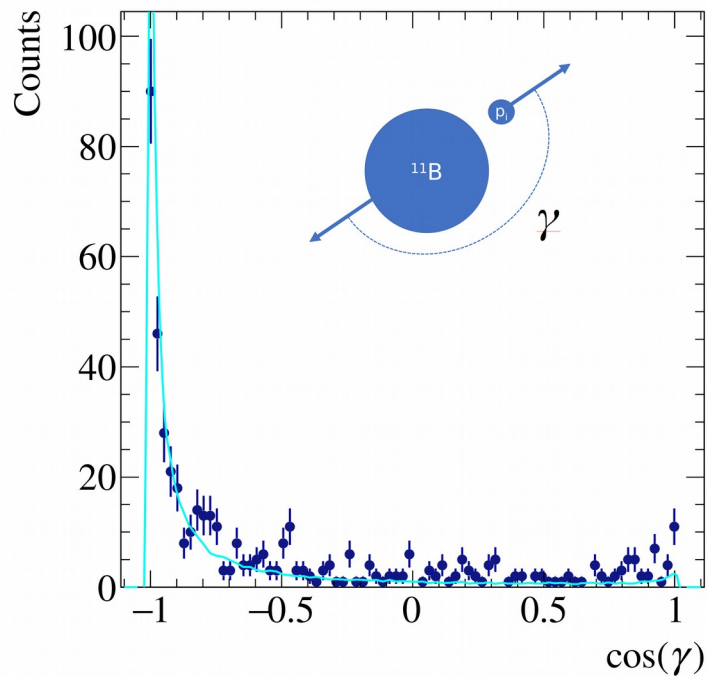




# Fragment – Proton Correlation

QE knockout reaction, in spectator assumption:  $\vec{p}_{A-1} = -\vec{p}_{p1}$

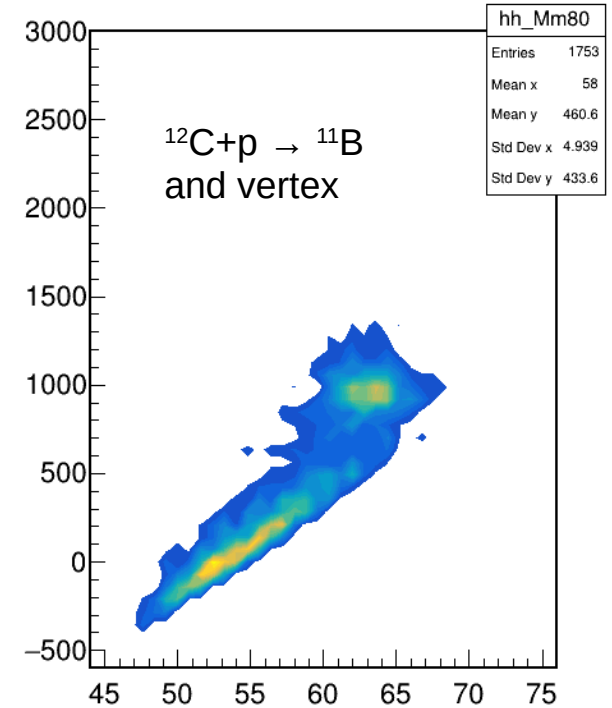
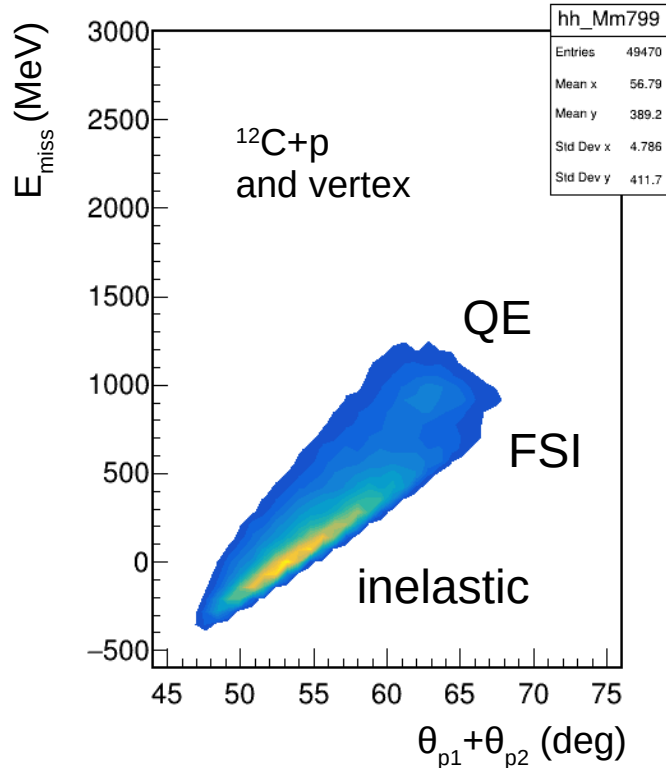
Opening angle in transverse plane  
→ back-to-back emission



# Quasi-elastic Scattering, Inelastic Scattering, and Final-State Interaction

Meytal Duer et al.

Fragment Selection  
rejects FSI,  
study e.g. only bound  
states

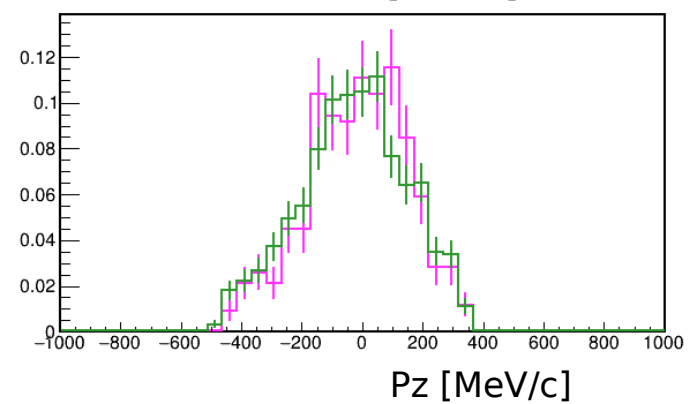
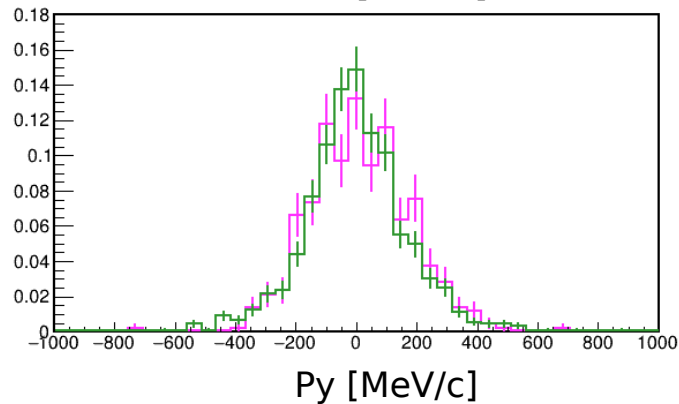
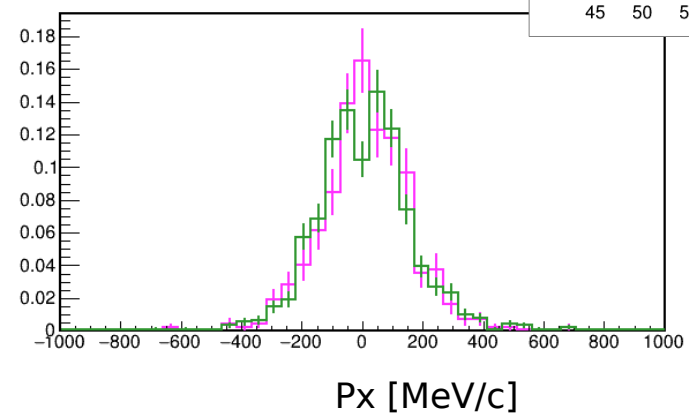
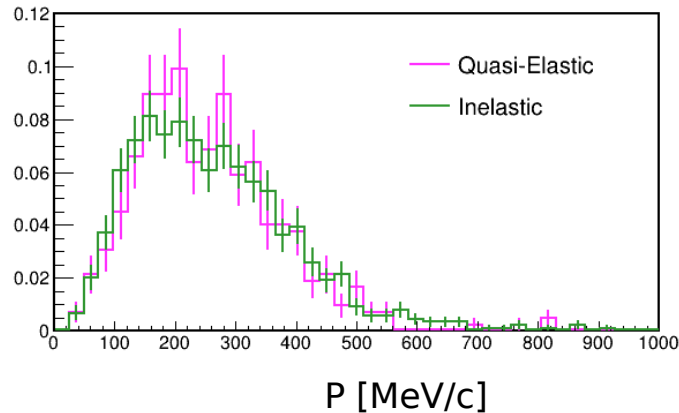
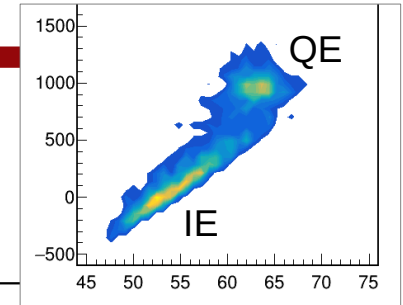


# Tagged Quasi-elastic vs. Inelastic

## $^{11}\text{B}$ Fragment Momentum Distributions

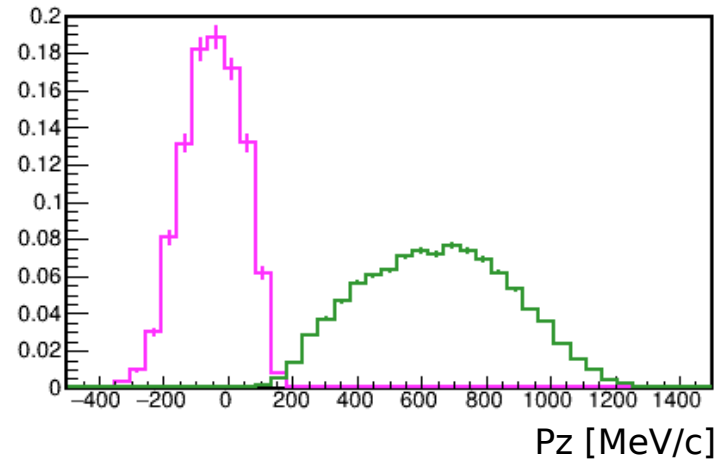
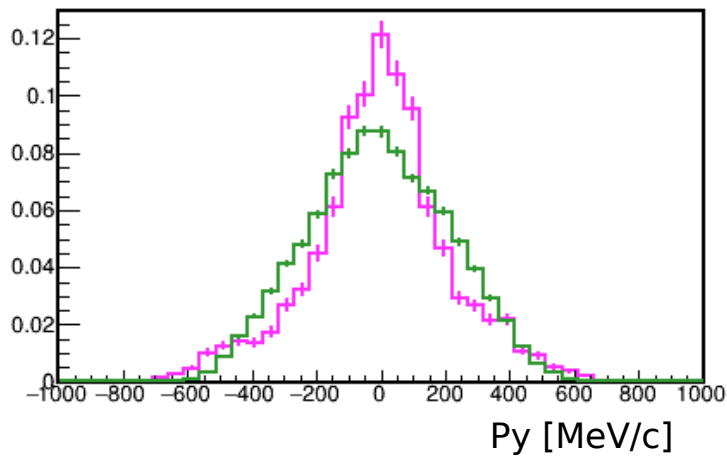
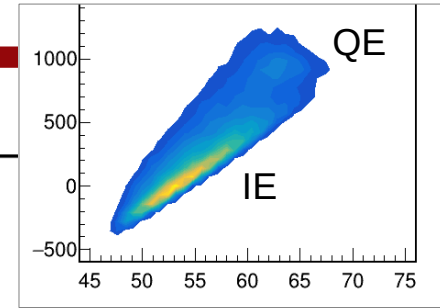
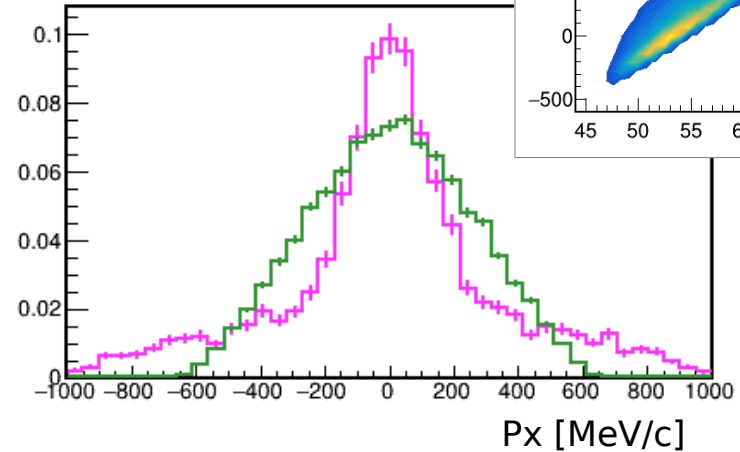
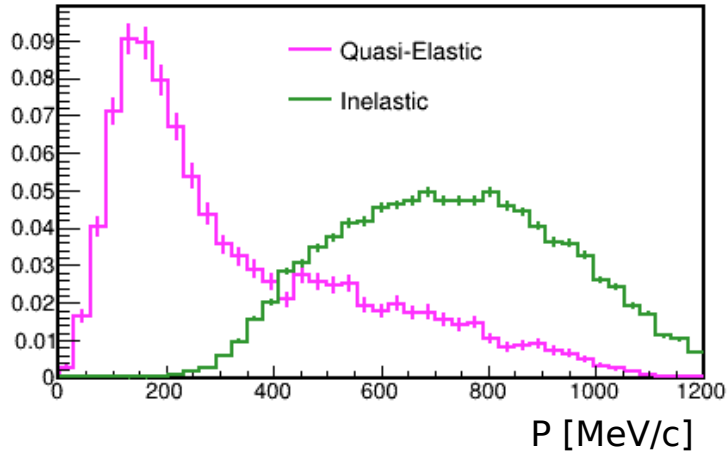
Fragment Exclusiveness:  $^{11}\text{B}$  carries only information from knockout process:

FSI background below inelastic scattering removed



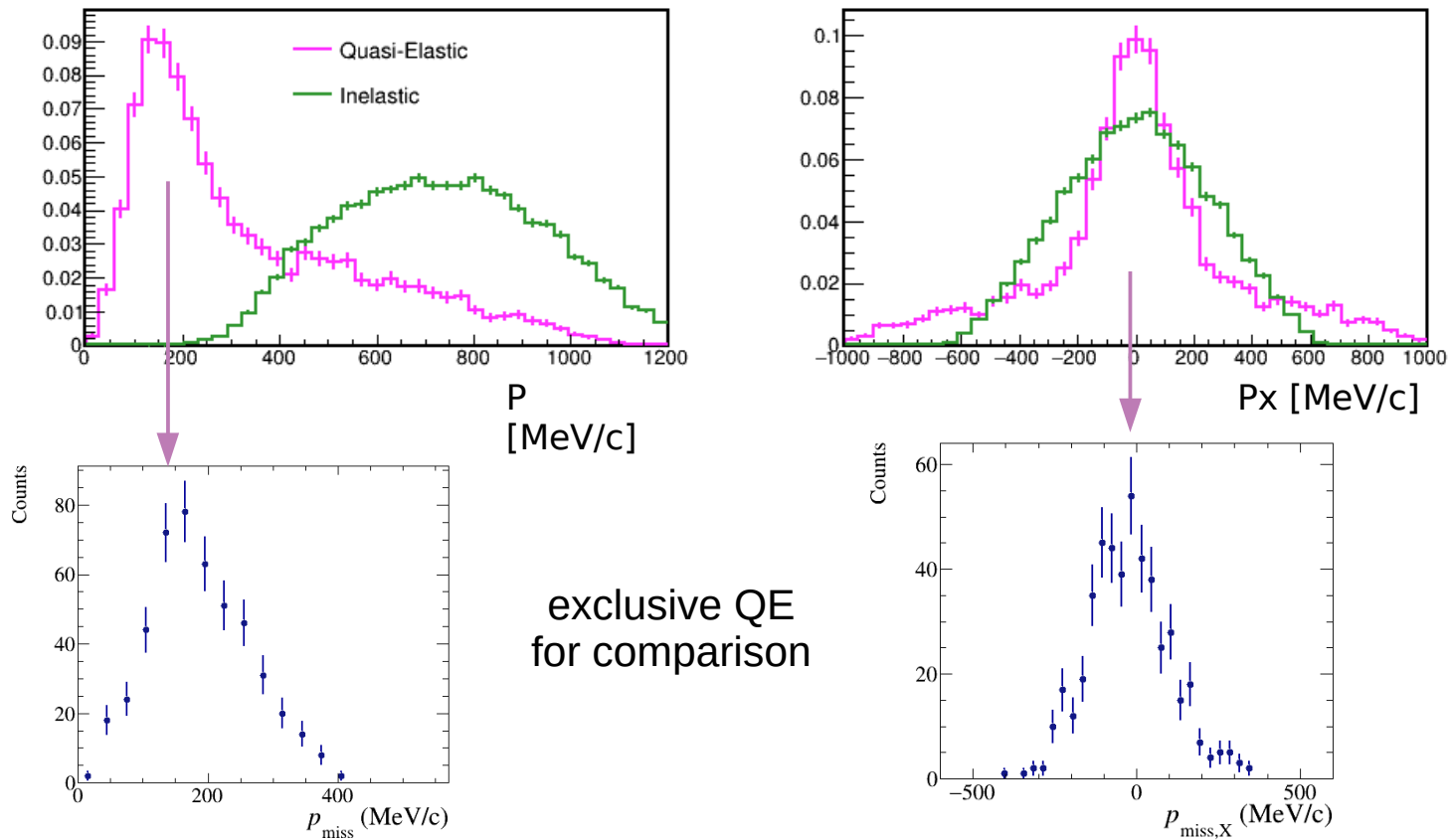
# Inclusive Quasi-elastic vs. Inelastic

$P_{\text{miss}}$  for Inclusive Reaction

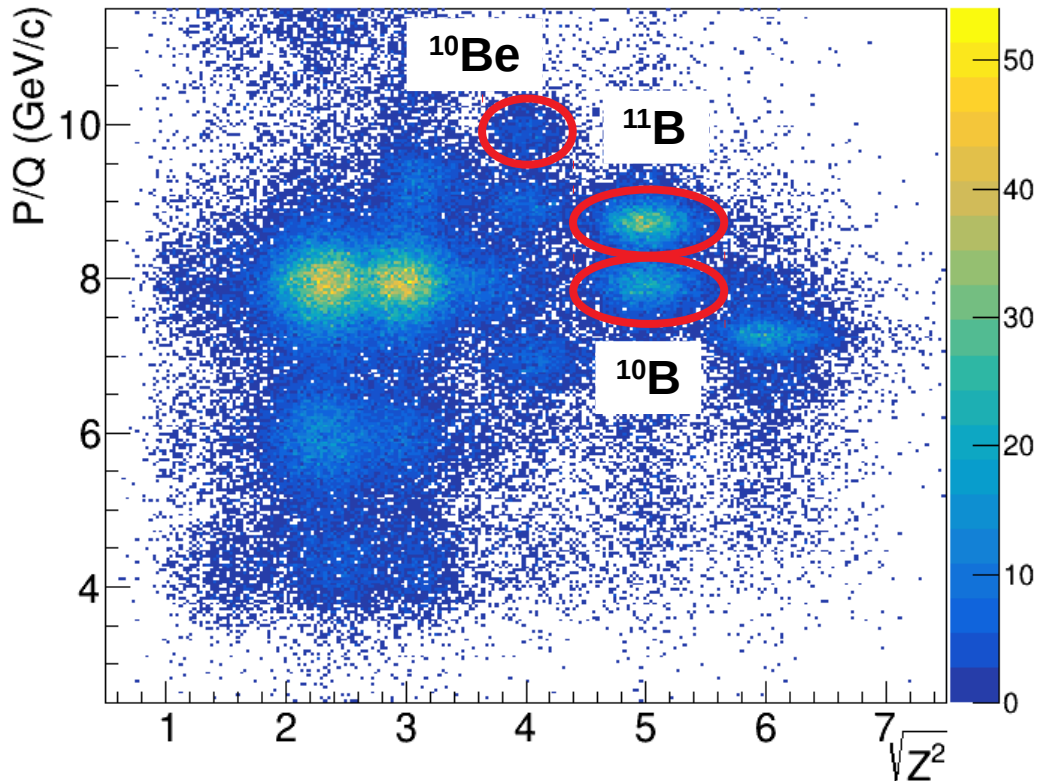


# Tagged vs. Inclusive Quasi-elastic

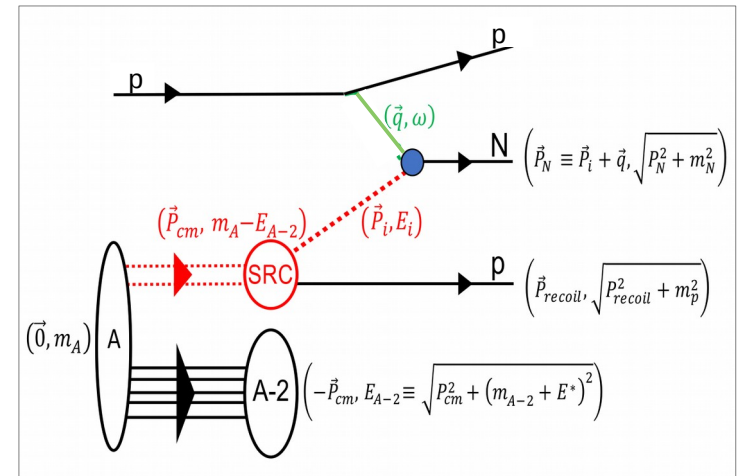
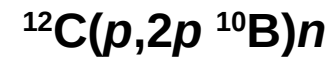
$P_{\text{miss}}$  is disturbed by FSI,  
confirms the robustness and cleanliness by tagging the fragment



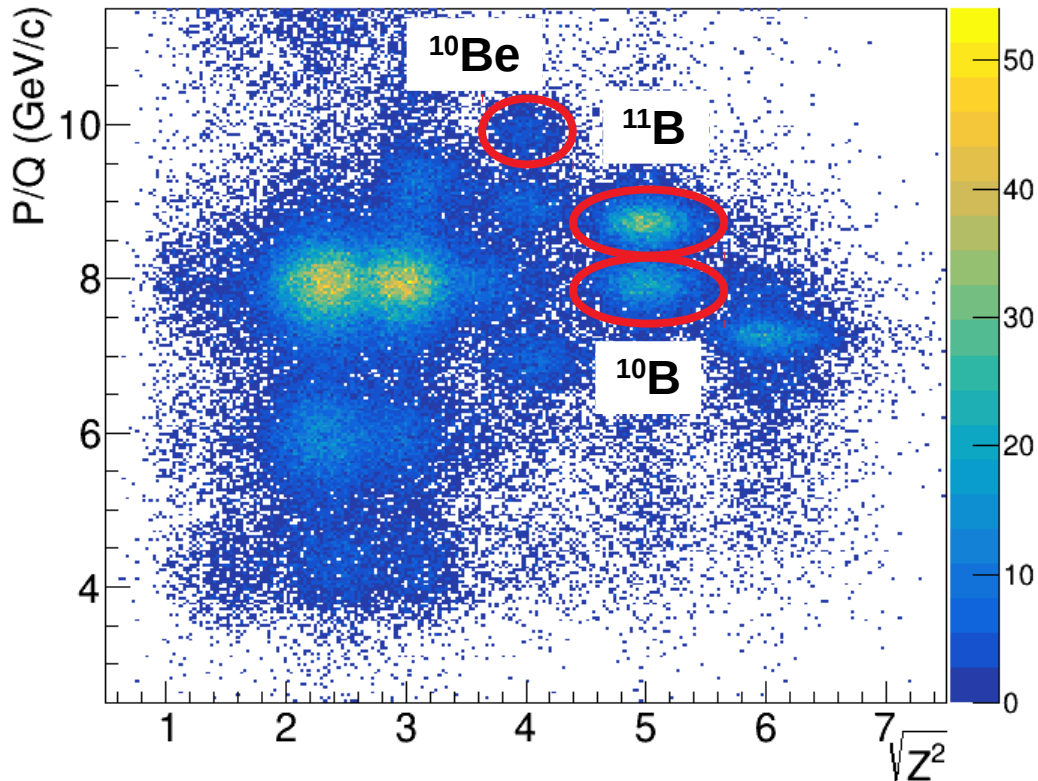
# Looking for High-Momentum Nucleons



Breakup of SRC  $pn$  pair



# Looking for High-Momentum Nucleons

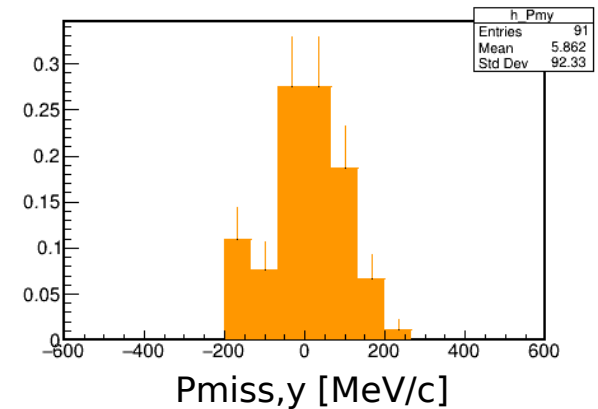
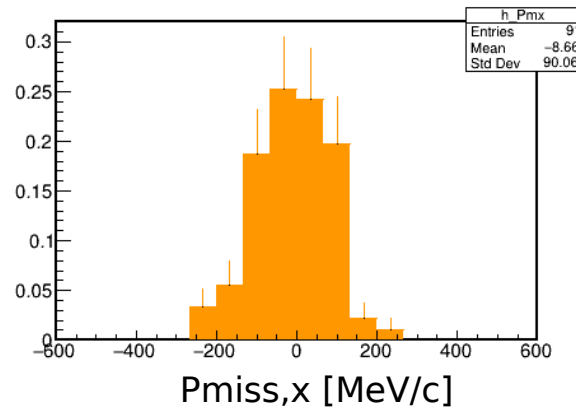
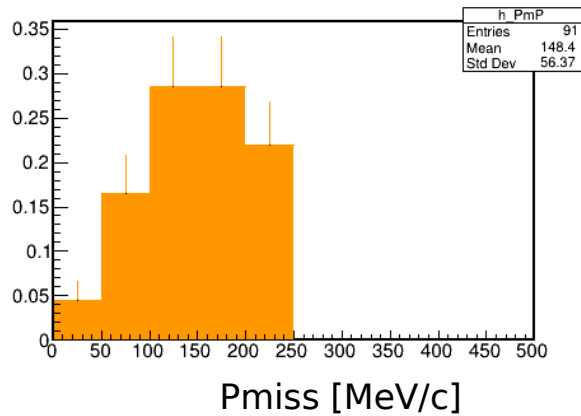
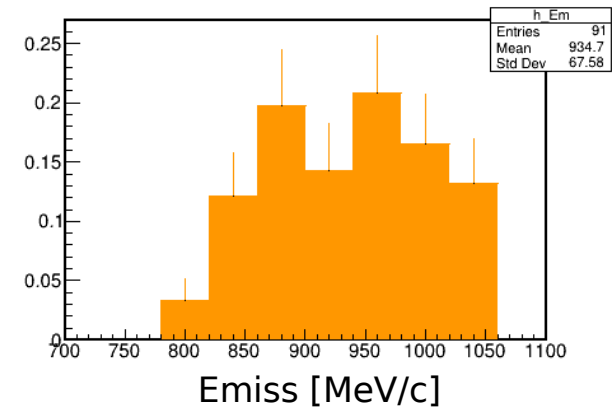
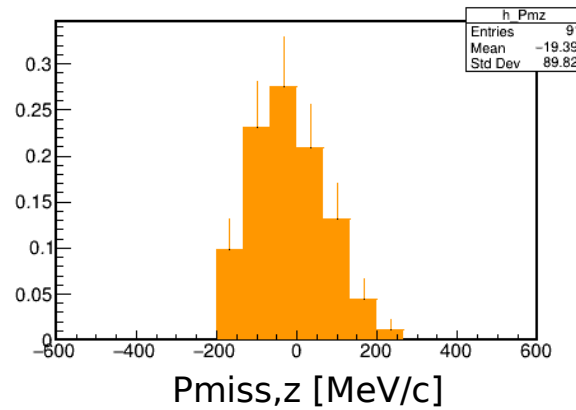
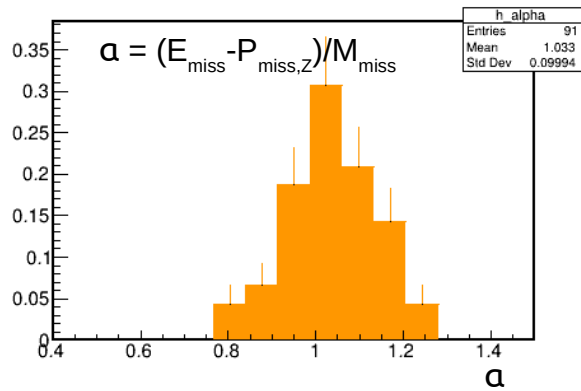


Breakup of SRC  $pn$  pair  
 $^{12}\text{C}(p,2p\ ^{10}\text{B})n$

$^{10}\text{B}$  can be produced in

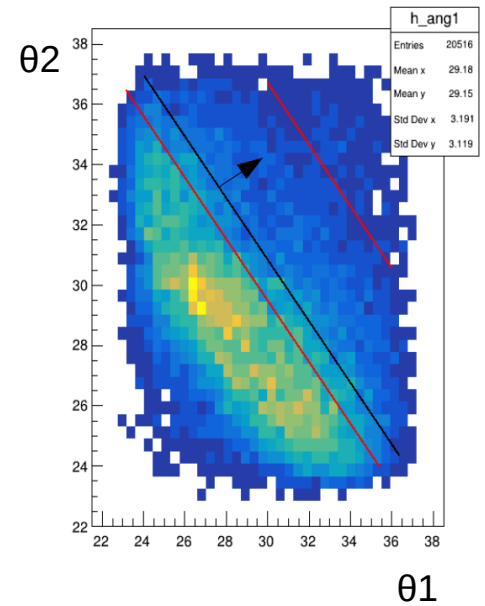
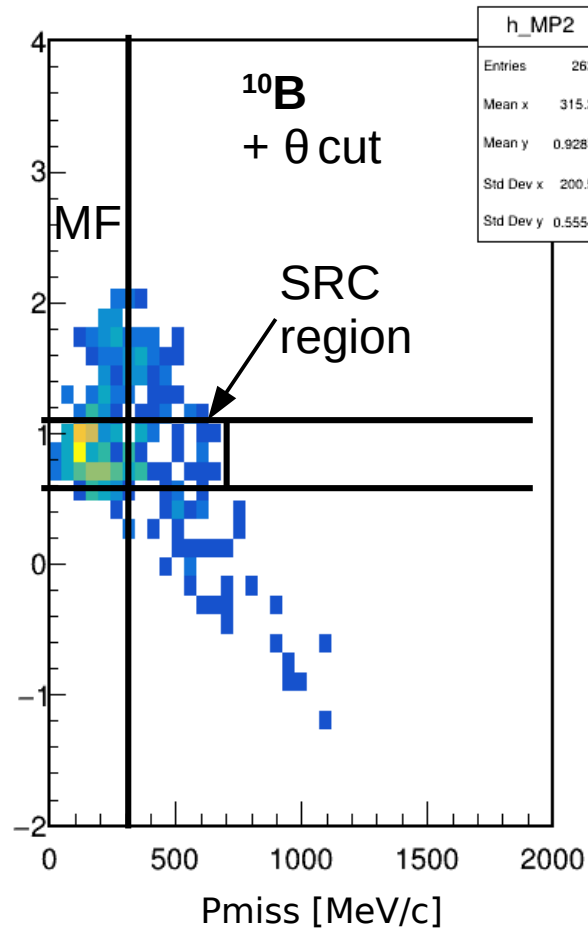
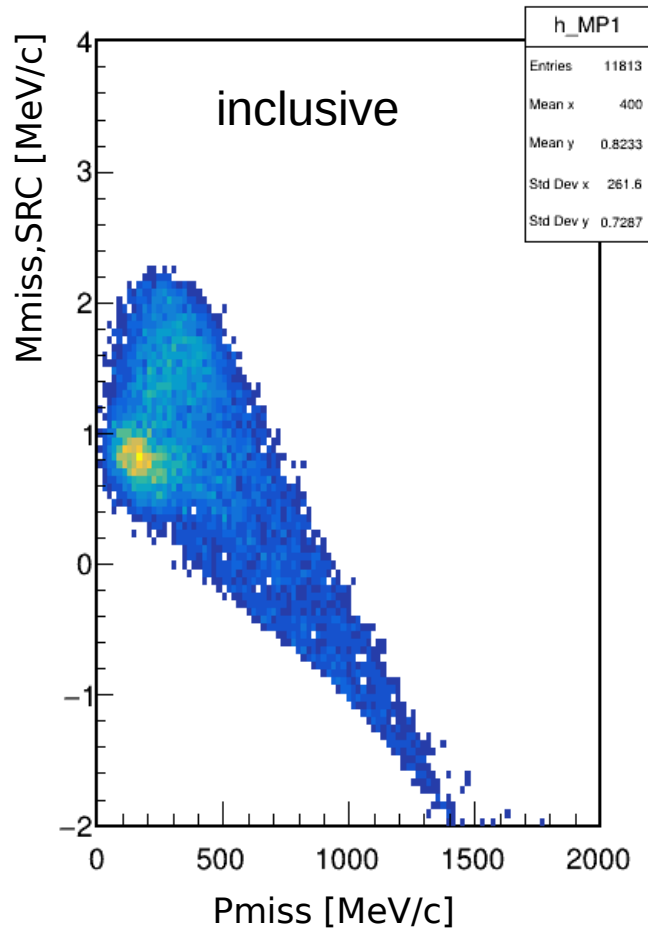
- $^{11}\text{B}^*$  neutron decay
- SRC breakup
- Proton-fragment FSI

# $^{10}\text{B}$ QE Meanfield

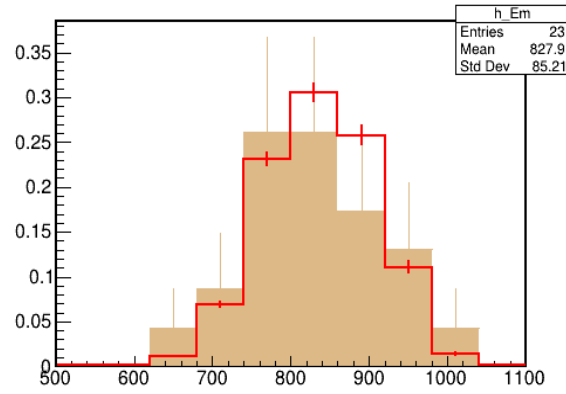
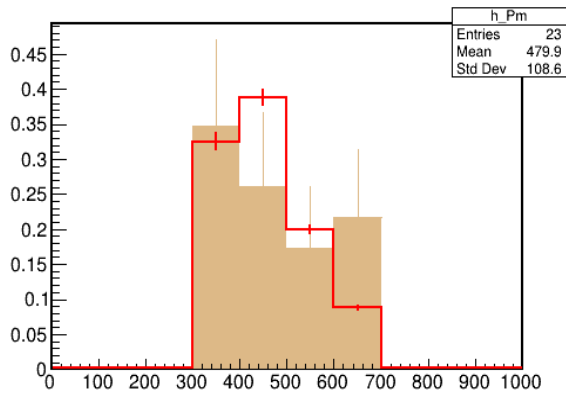




# Select kinematical Region for SRC

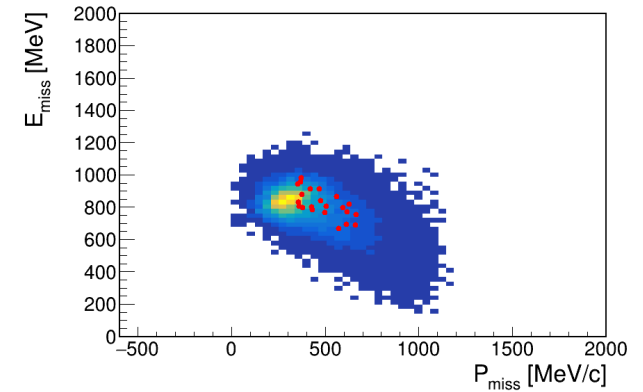
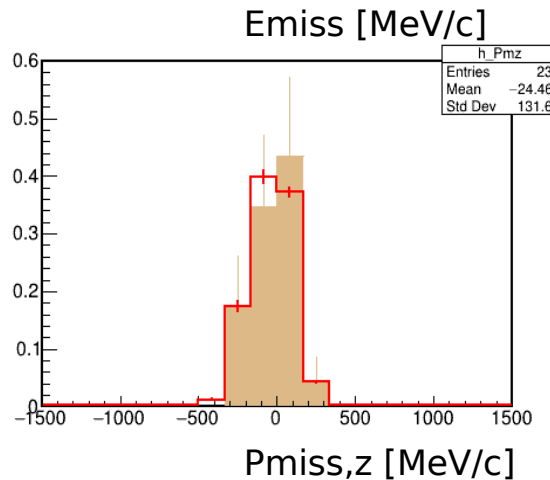
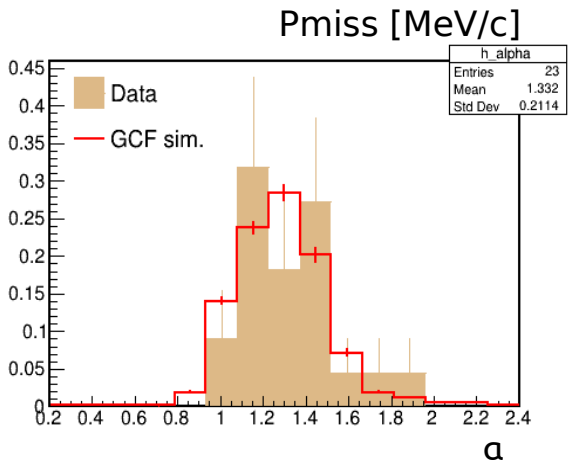


# Search for SRCs

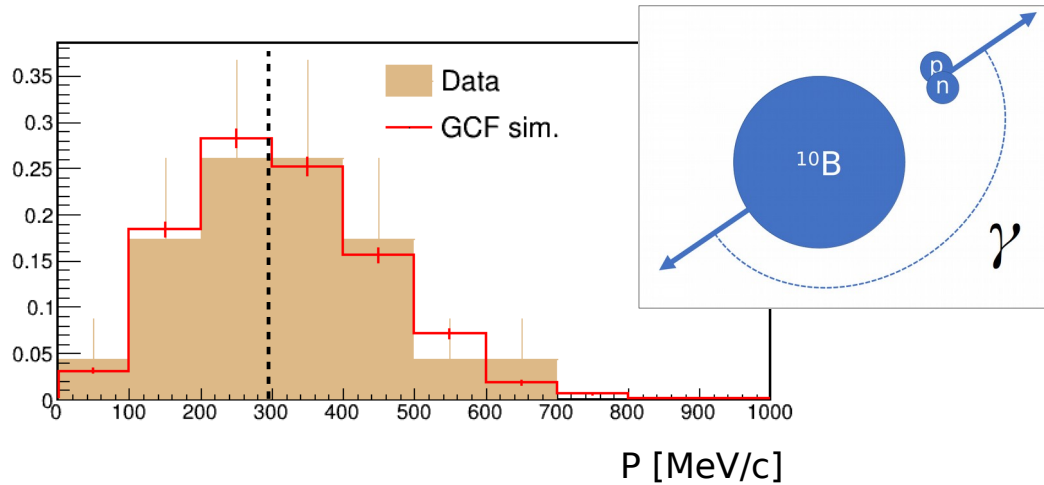


Comparison to SRC  
Generalized Contact  
Formalism

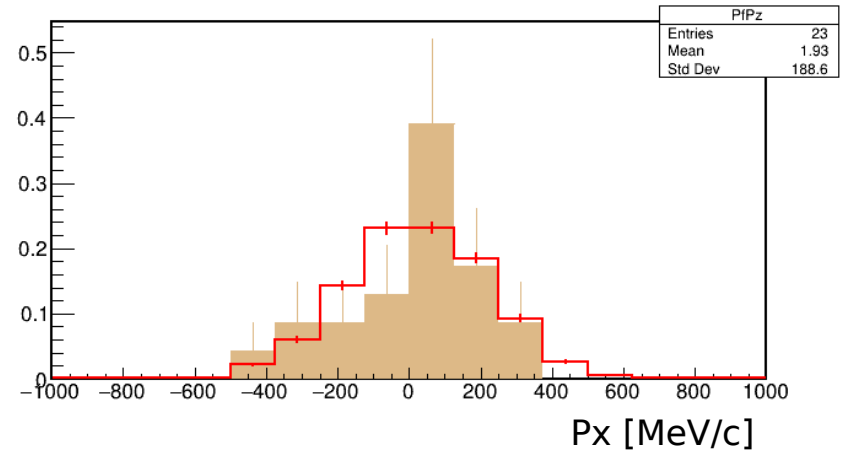
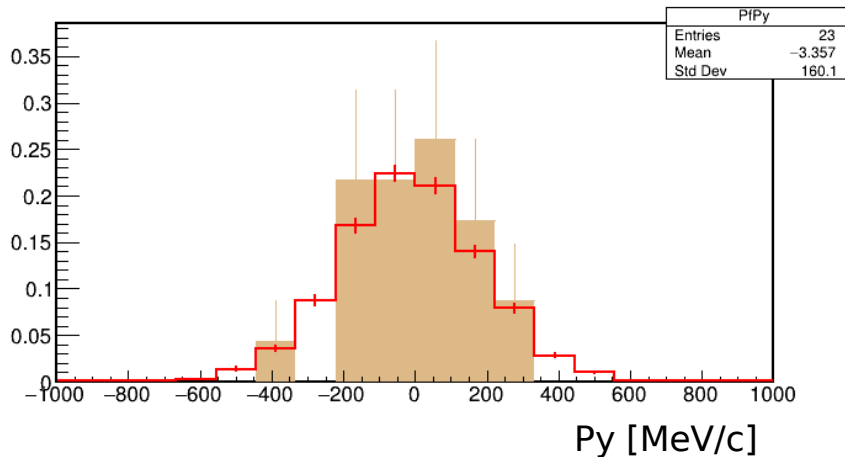
A. Schmidt et al., Nature 578 (2020)



# C.M. Momentum Distribution of $^{10}\text{B}$ with SRC Selection

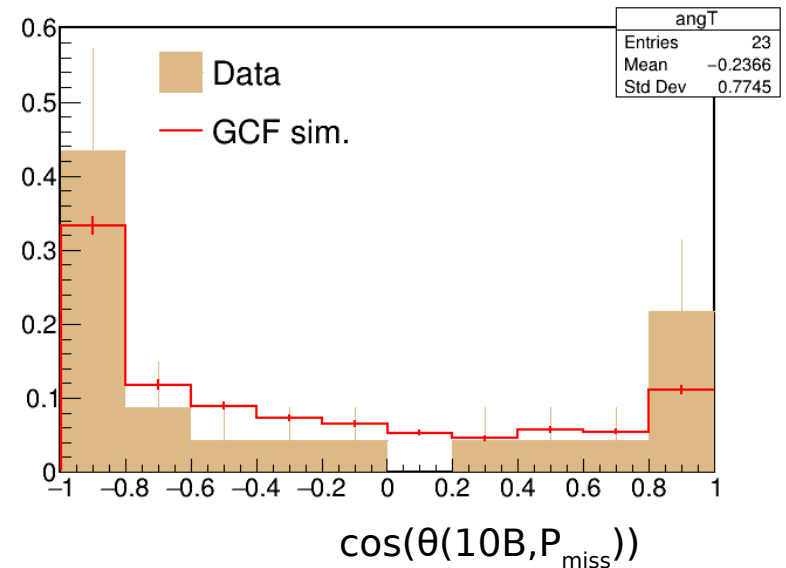


These new observables confirm result from SRC studies at JLab  
E. Cohen et al., PRL (2018)



# SRC Signal

- Data consistent with our understanding of SRCs
- Fragment ratio  $^{10}\text{B}/^{10}\text{Be} \sim 5$ :
  - If FSI:  $^{10}\text{B} \sim ^{10}\text{Be}$  due to similar  $pn$  and  $pp$  cross section with  $^{11}\text{B}$
  - If SRC:  $^{10}\text{B} > ^{10}\text{Be}$  due to  $np$  pair dominance
- Pair recoil will give additional insight

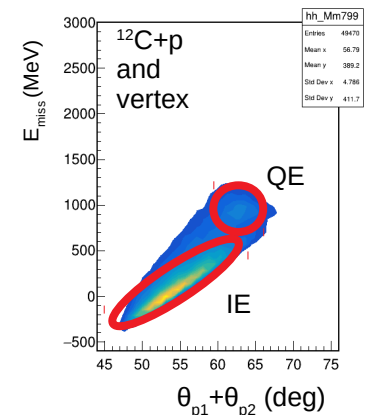
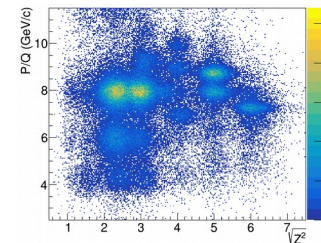
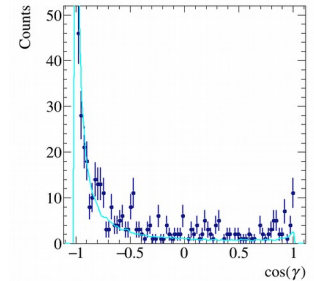
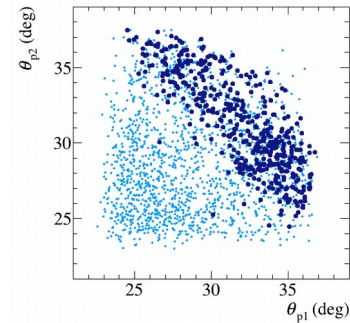


# New Results from our successful Pilot Experiment

Fully-exclusive QE scattering at high energy  
**performed for first time**  $^{12}\text{C}(p,2p\ ^{11}\text{B})$ :

- QE proton and fragment kinematics observed
- Fragment Tagging allows to suppress FSI
- Direct selection of QE scattering

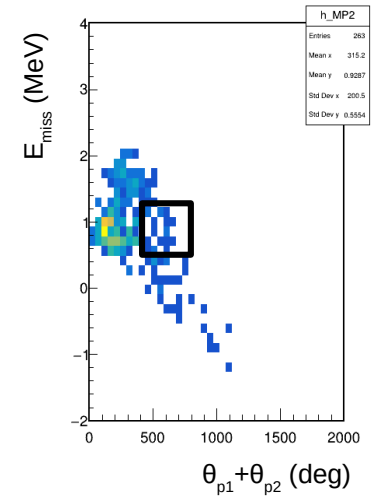
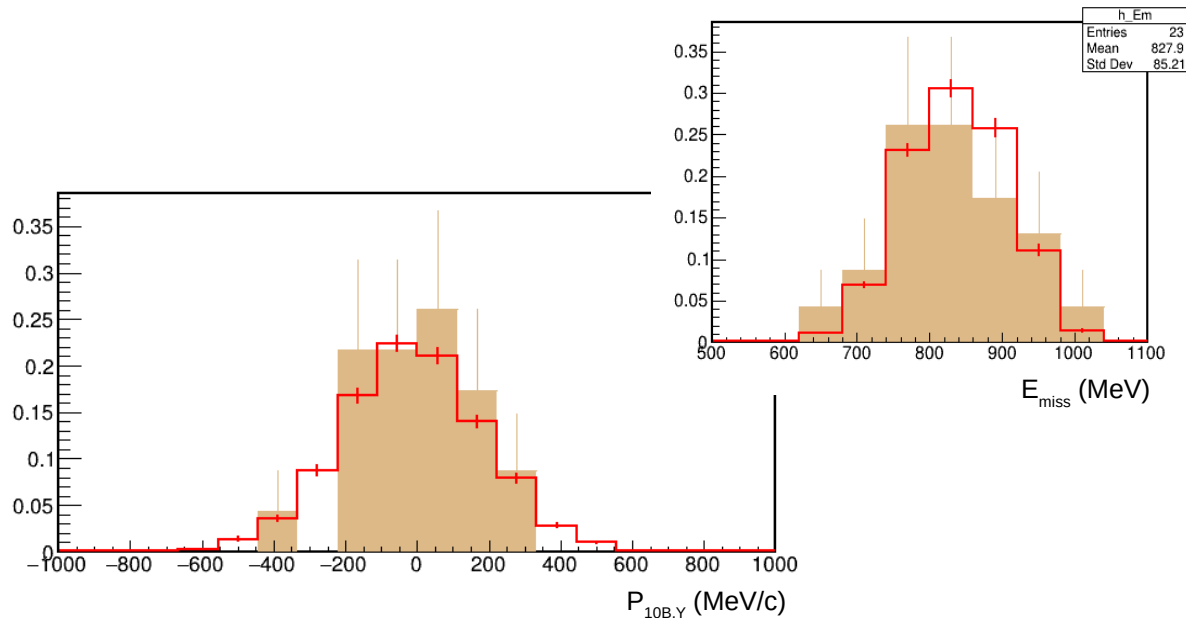
→ QE scattering at high energy in inverse kinematics is pure 1-step, single knockout process:  
**“Transparent Nucleus“**



# New Results from our successful Pilot Experiment

## SRC signal $^{12}\text{C}(p,2p\ ^{10}\text{B})$

- Results agree with known SRC properties
- First direct observation of pair c.m. motion
- Opens the way for studies in neutron-rich nuclei



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# Thank You for Your Attention. Many Thanks to the Collaborators

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## The Analysis Team

Maria Patsyuk (JINR)

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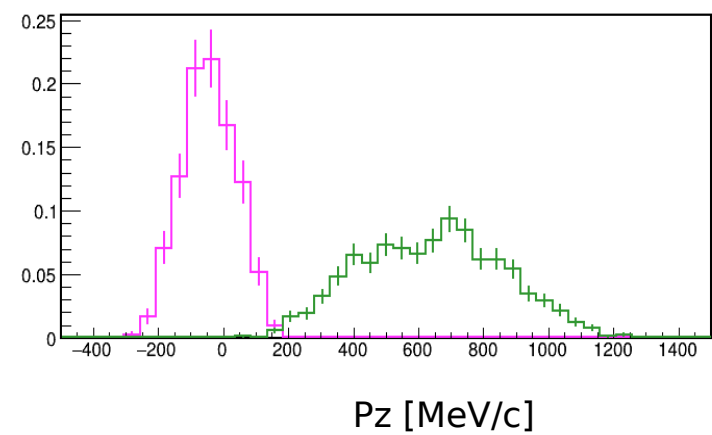
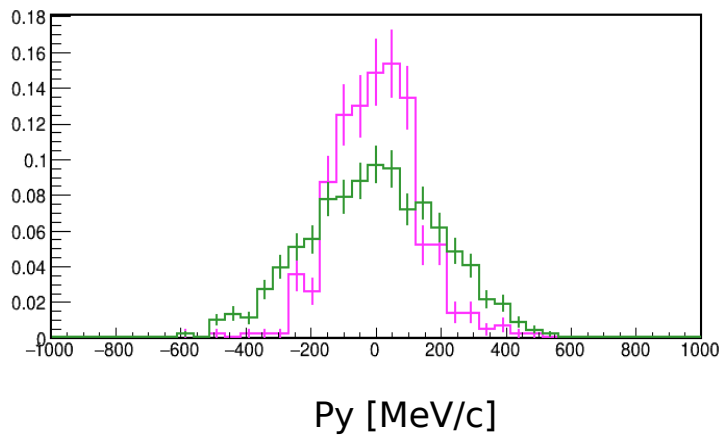
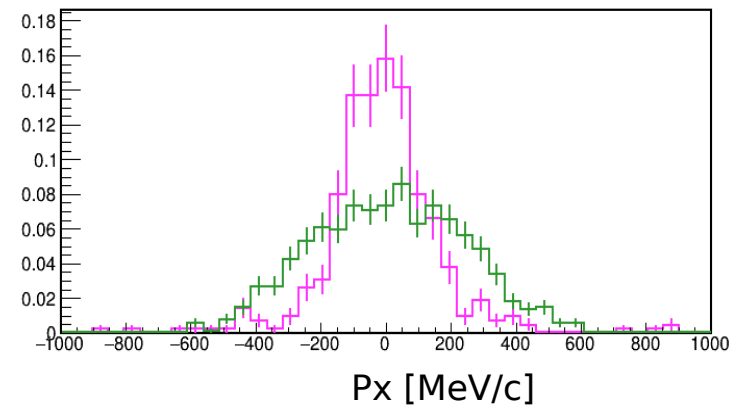
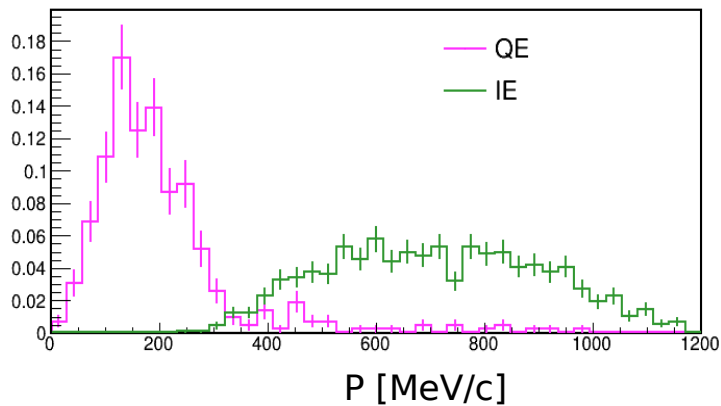
Meytal Duer (TU Darmstadt)

Valerii Panin (GSI)



# $P_{\text{miss}}$ for Inclusive

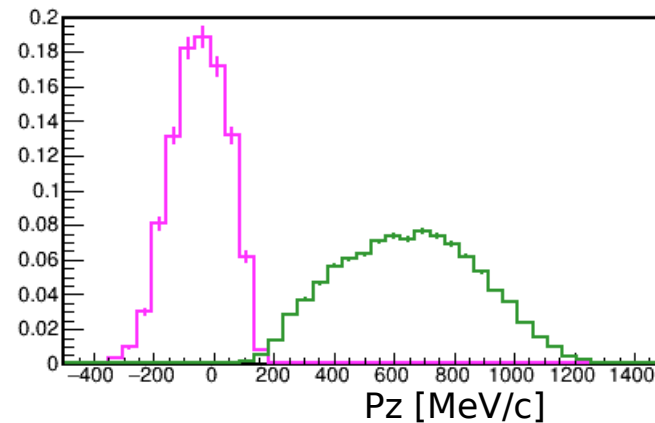
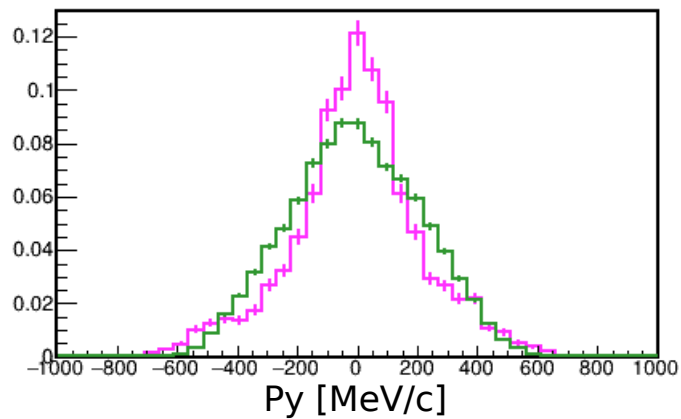
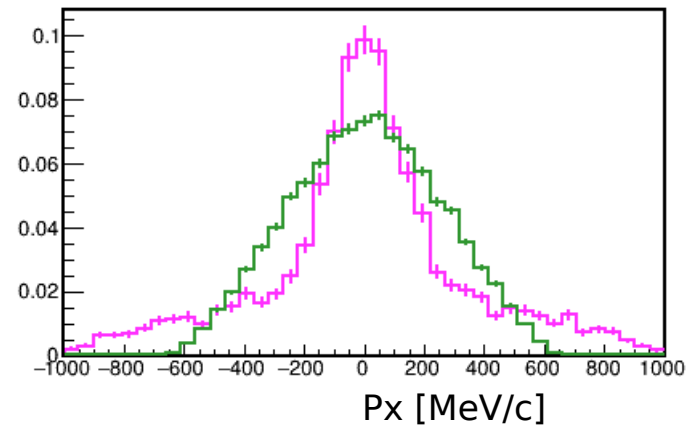
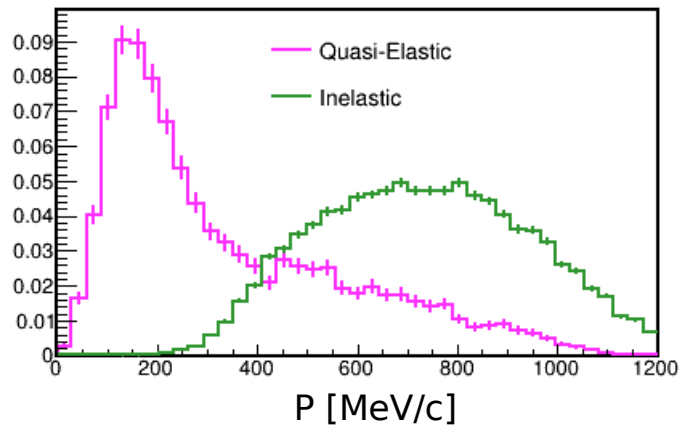
$^{11}\text{B}$  carries only information from knockout process  
But not  $P_{\text{miss}}$





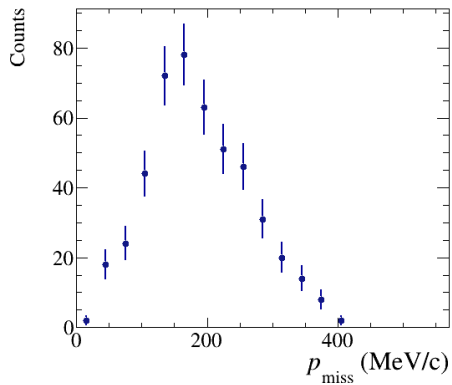
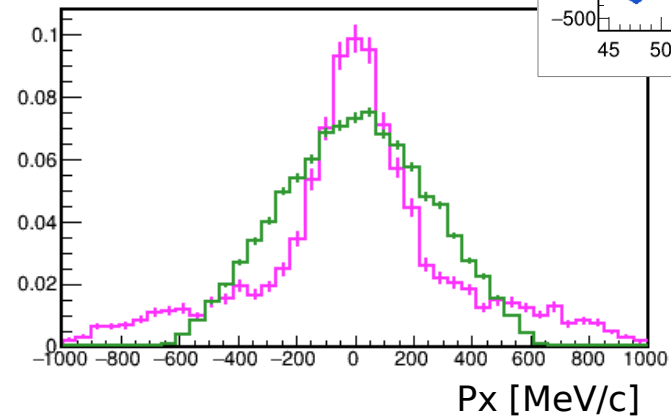
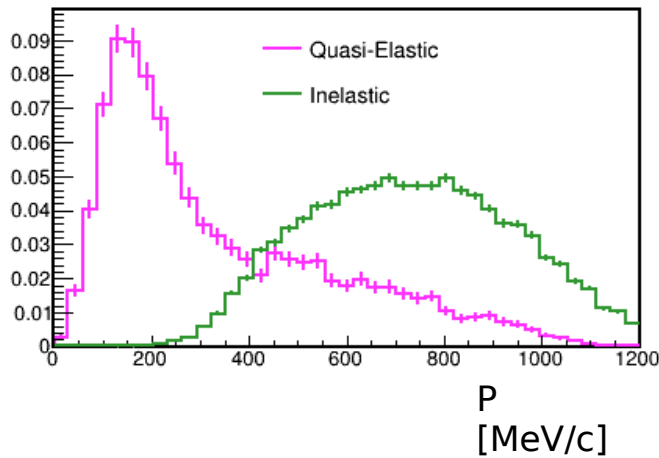
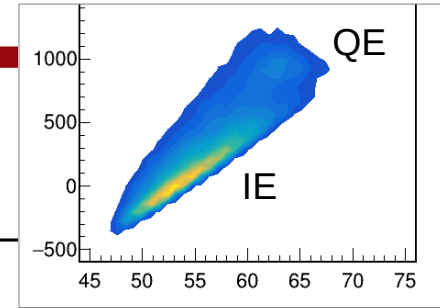
# $P_{\text{miss}}$ for Inclusive Reaction

$P_{\text{miss}}$  is disturbed by FSI,  
confirms the robustness and cleanliness of tagging the fragment

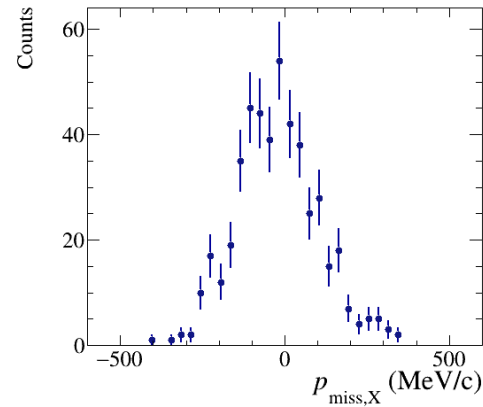


# $P_{\text{miss}}$ for Inclusive Reaction

$P_{\text{miss}}$  is disturbed by FSI,  
confirms the robustness and cleanliness by tagging the fragment



exclusive QE  
for comparison



# $P_{\text{miss}}$ for Inclusive Reaction

