Quasi-free scattering experiments in inverse kinematics at GSI

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1. Quasi-free scattering: Reaction mechanism, Treiman-Yang test to validate assumptions

2. The 2-proton halo candidate ^{17}Ne

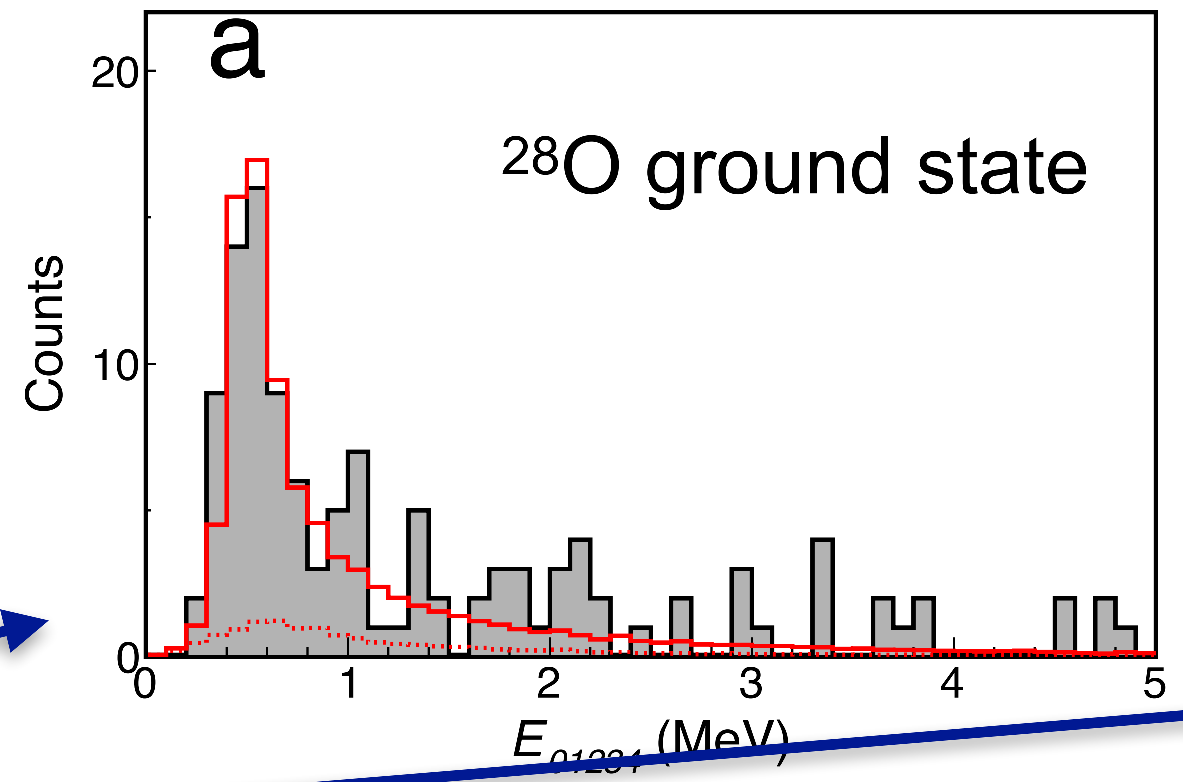
3. Alpha clusters at the surface of heavy nuclei

Physics Programs based on QFS

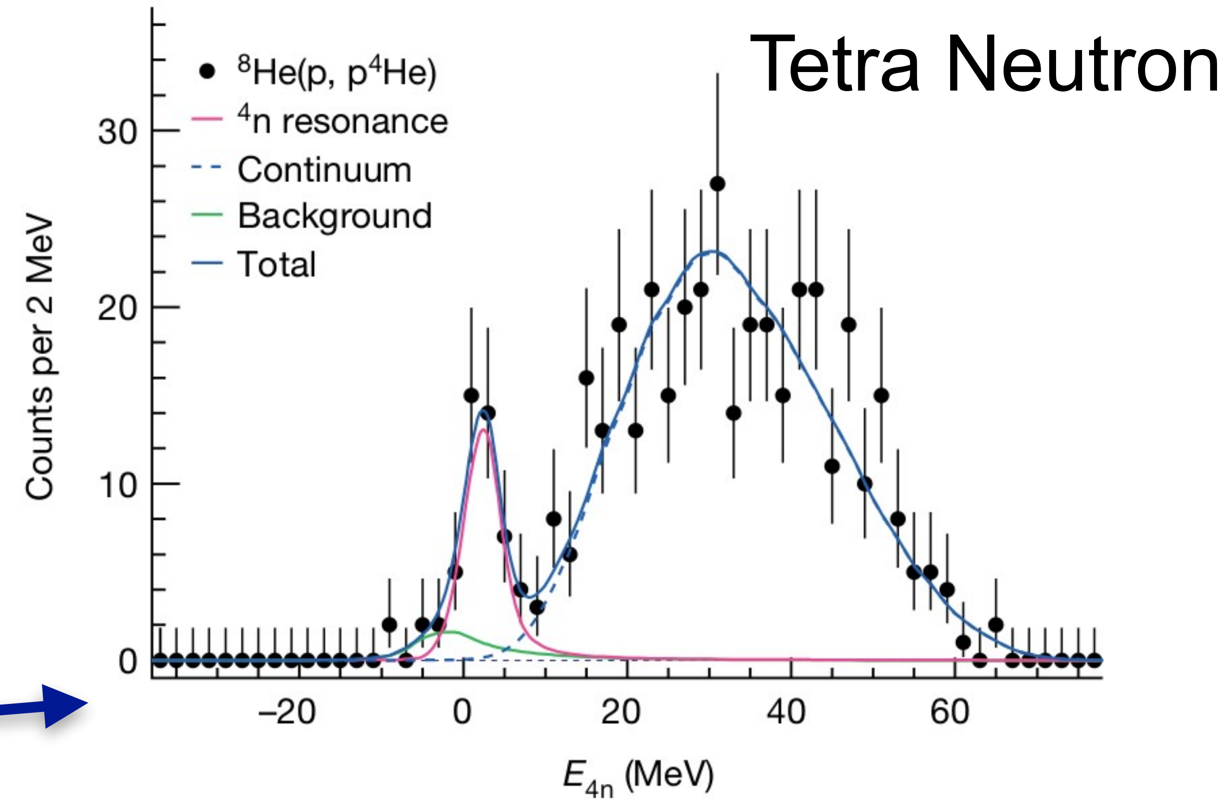
<u>Quasi-free knockout reactions</u>

$(p,2p), (p,pn), (p,2pn), (p,p\alpha), (p,2p)$fission

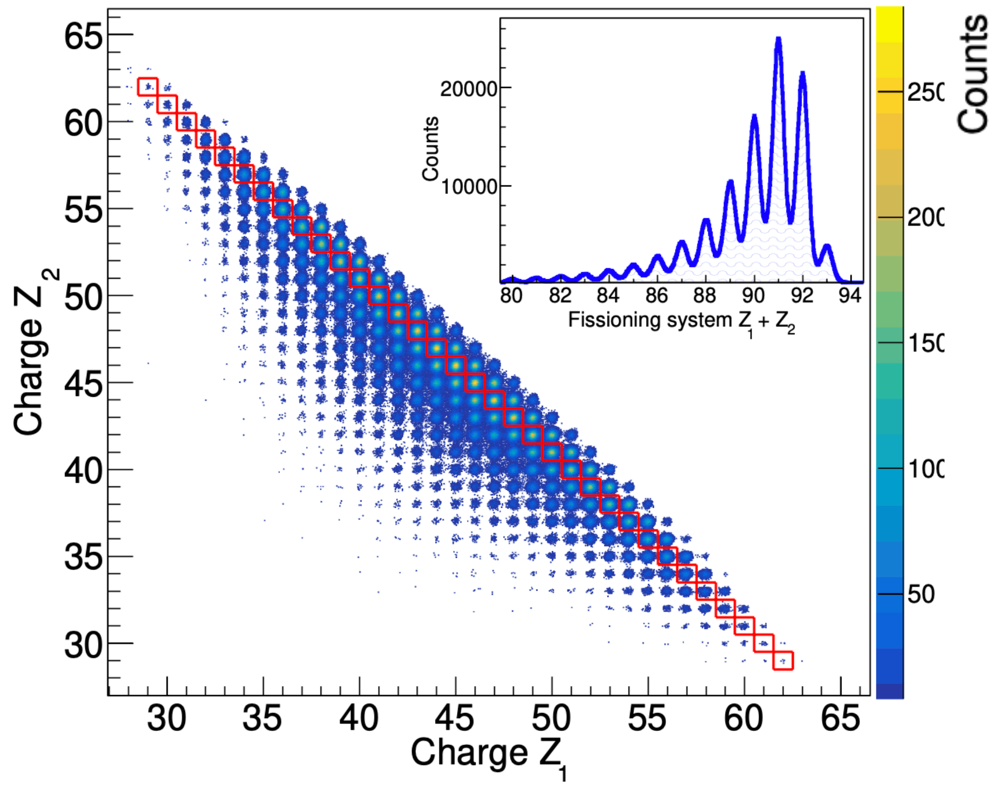
- Single-particle / Shell structure: spectroscopy
- States beyond the drip-lines
- Nucleon-Nucleon short-range correlations
- Cluster structure of nuclei
- Fission studies, dynamics, fission barriers

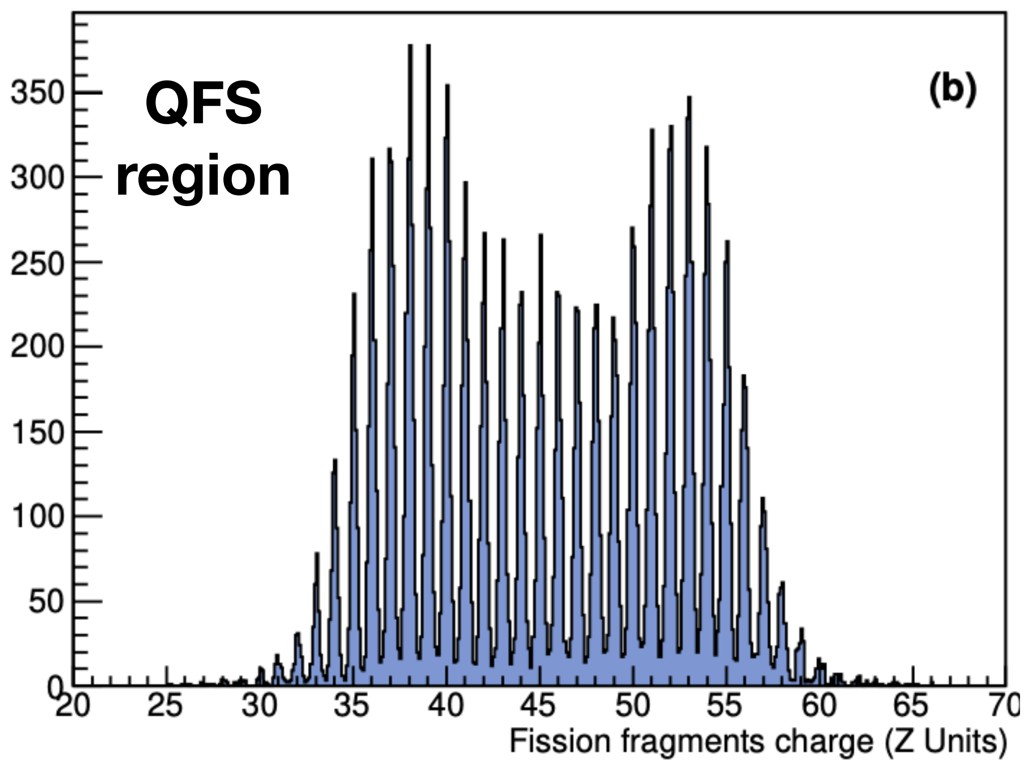


Talk by T. Nakamura



Talk by V. Panin

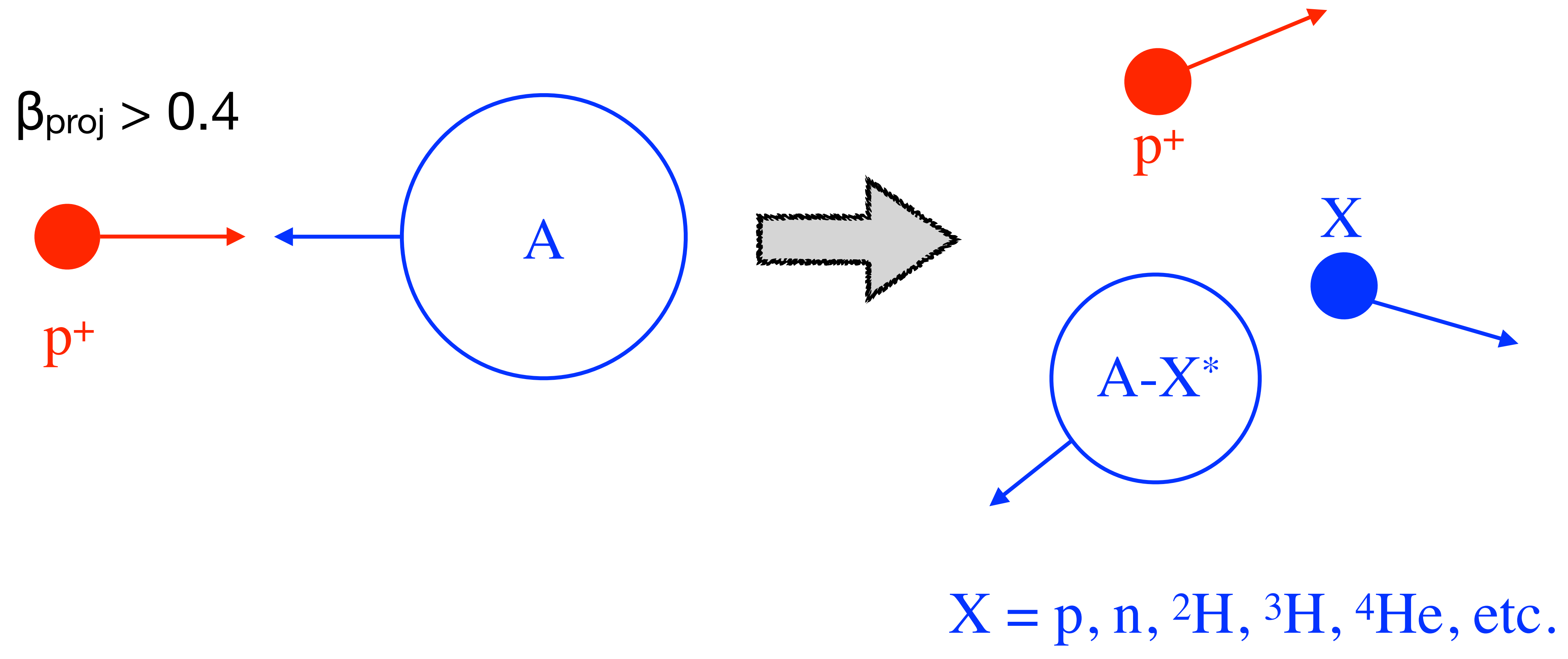




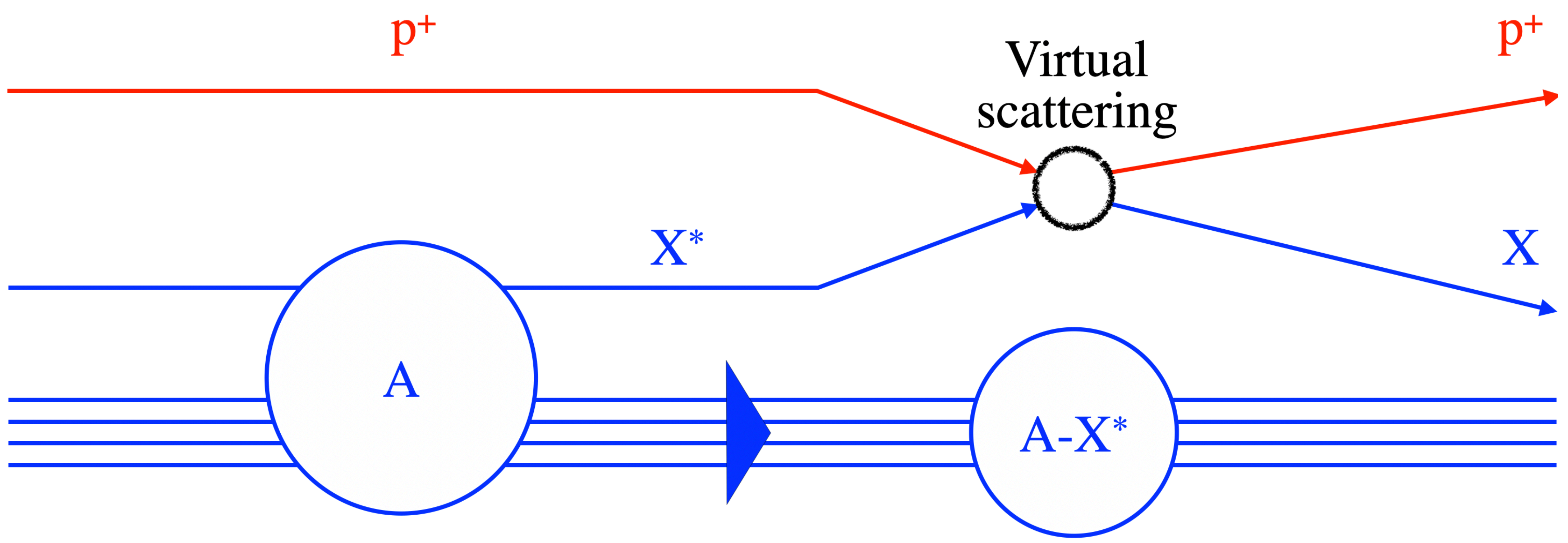
Talk by P. Benlliure

QFS as a proton-induced knockout reaction

What is observed



What we imagine



In PWIA: squared Fourier transform of the overlap integral:

< A-X* | a_X | A >

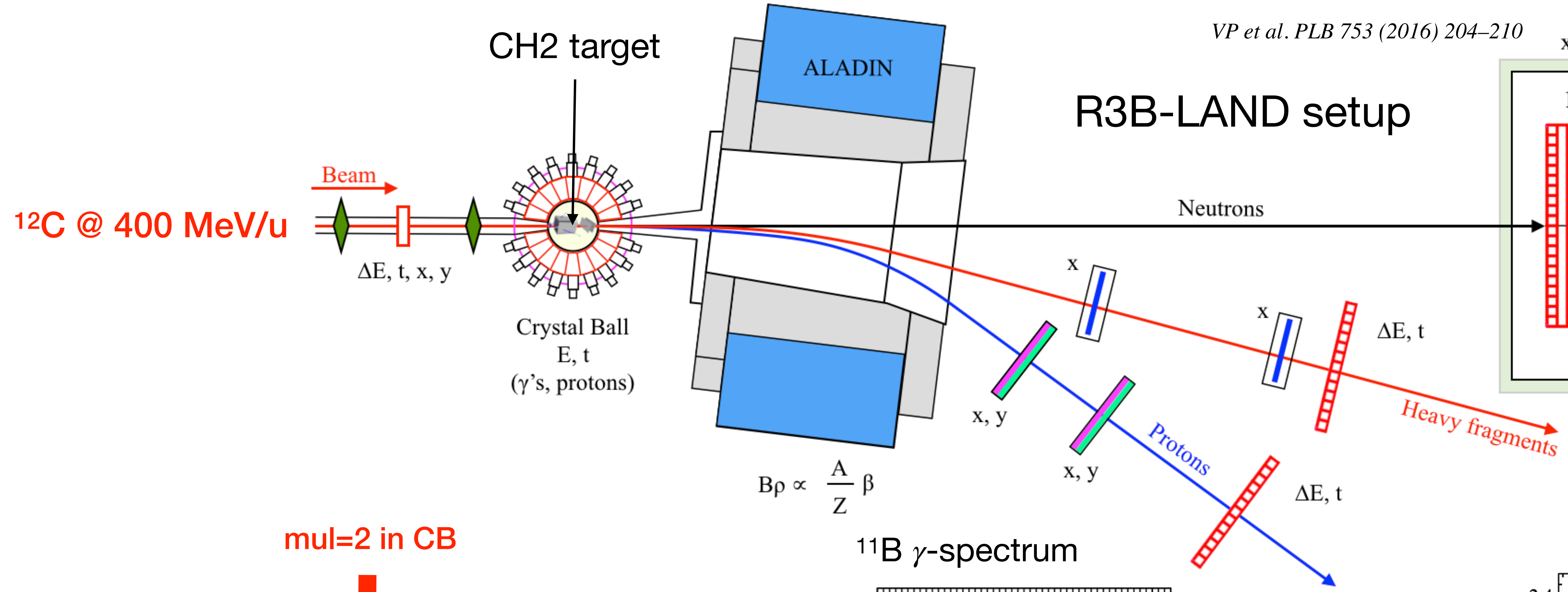
annihilation operator

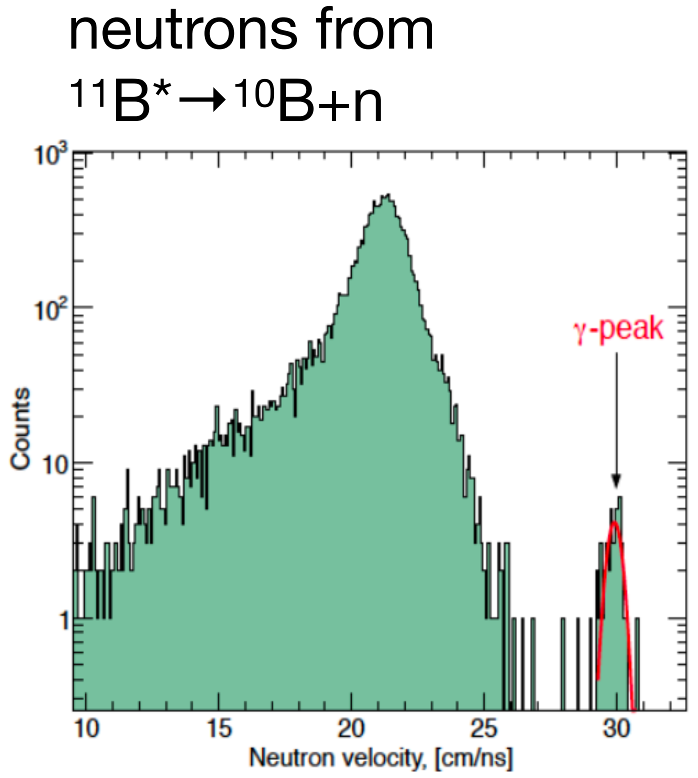
Impulse approximation:

$$\frac{d^4\sigma}{dE_p dE_X d\Omega_p d\Omega_X} = K \frac{d\sigma_{pX}^{free}}{d\Omega} S_\epsilon(\mathbf{Q}_X)$$

V. Panin

Benchmark experiment: $^{12}C(p,2p)^{11}B^*$ (R3B at GSI, 400 MeV/nucleon ^{12}C)





Inverse kinematics

Measurement of scattered protons

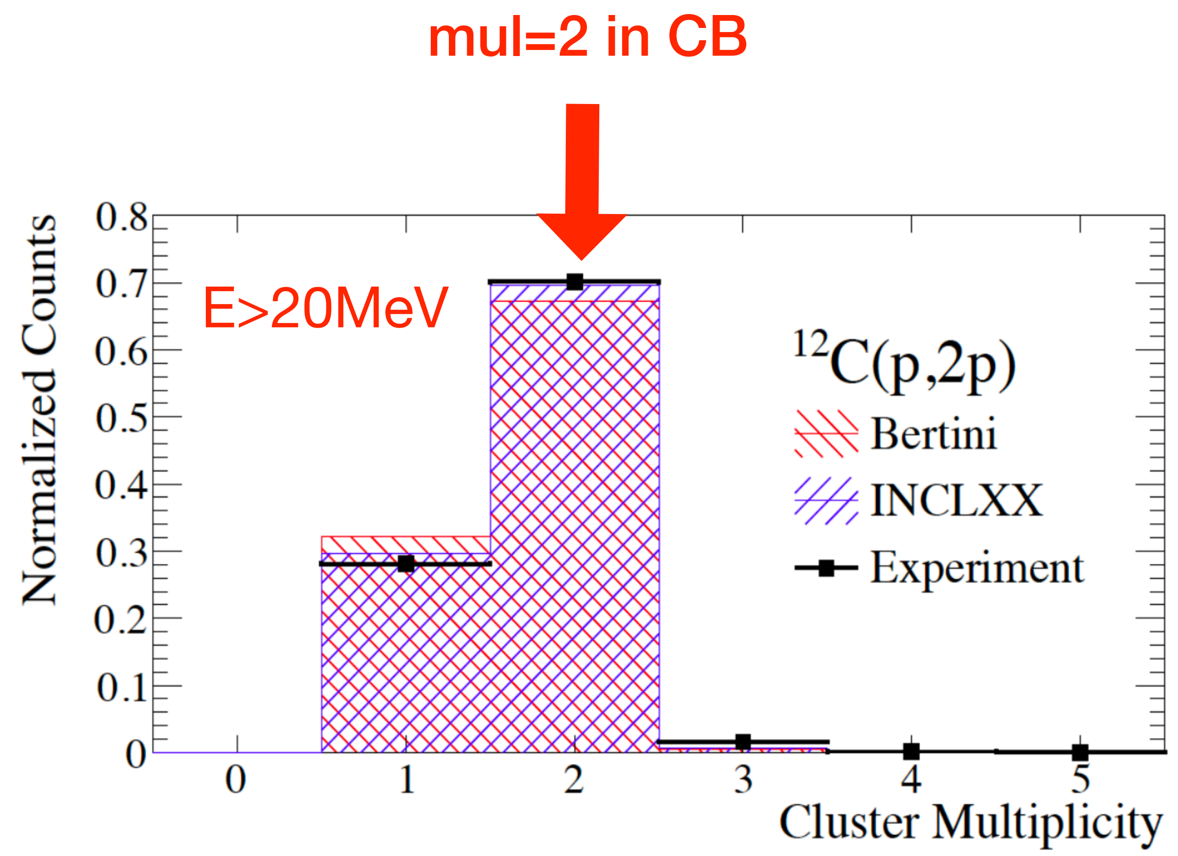
-> missing momentum
-> missing mass

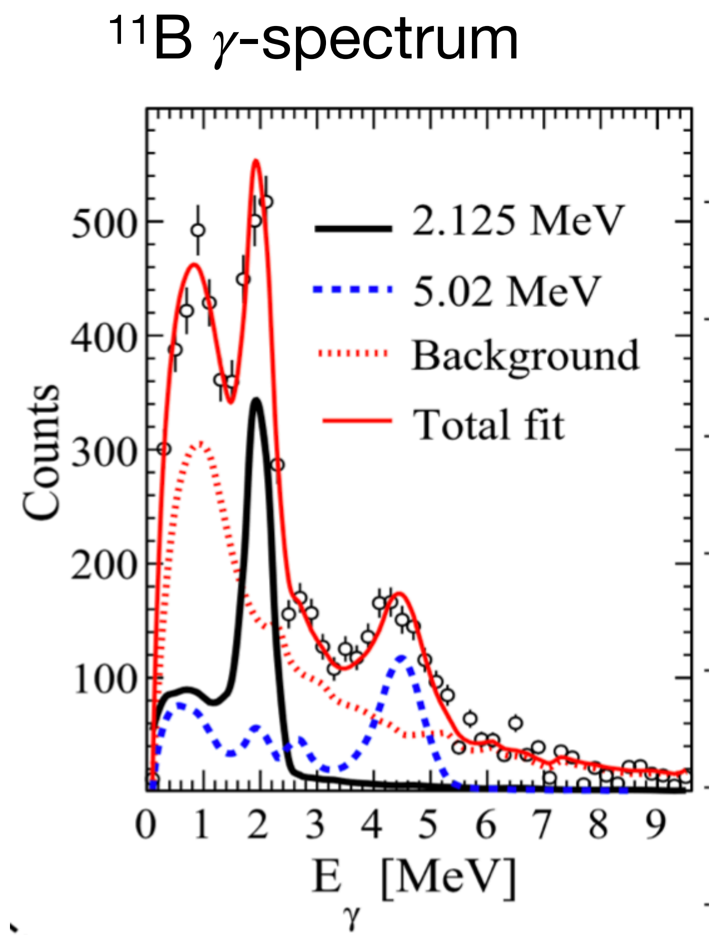
+

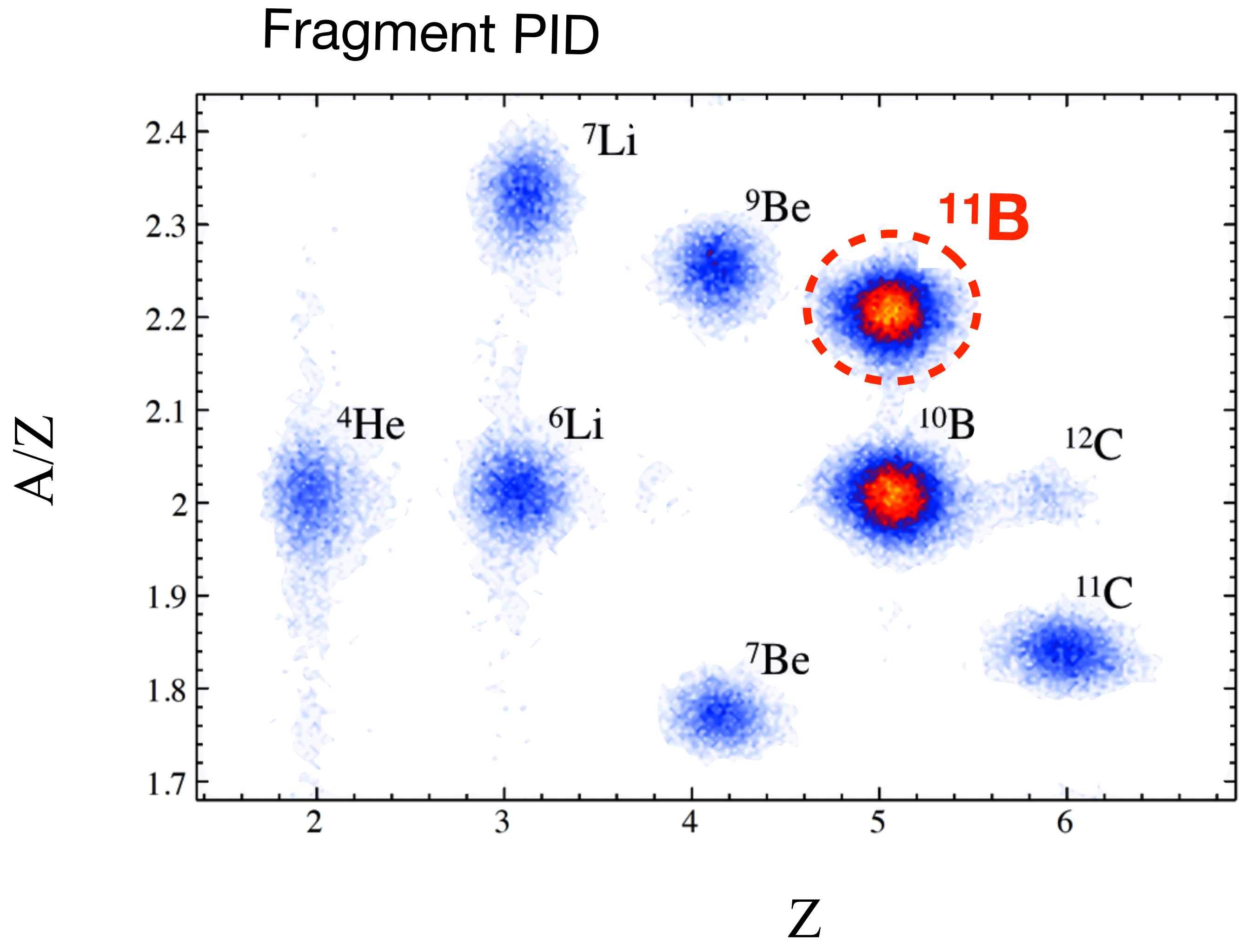
Measurement of produced Fragment A-1 + decay
(γ decay, particle decay)

-> recoil momentum
-> invariant mass

-> suppression of secondary reactions

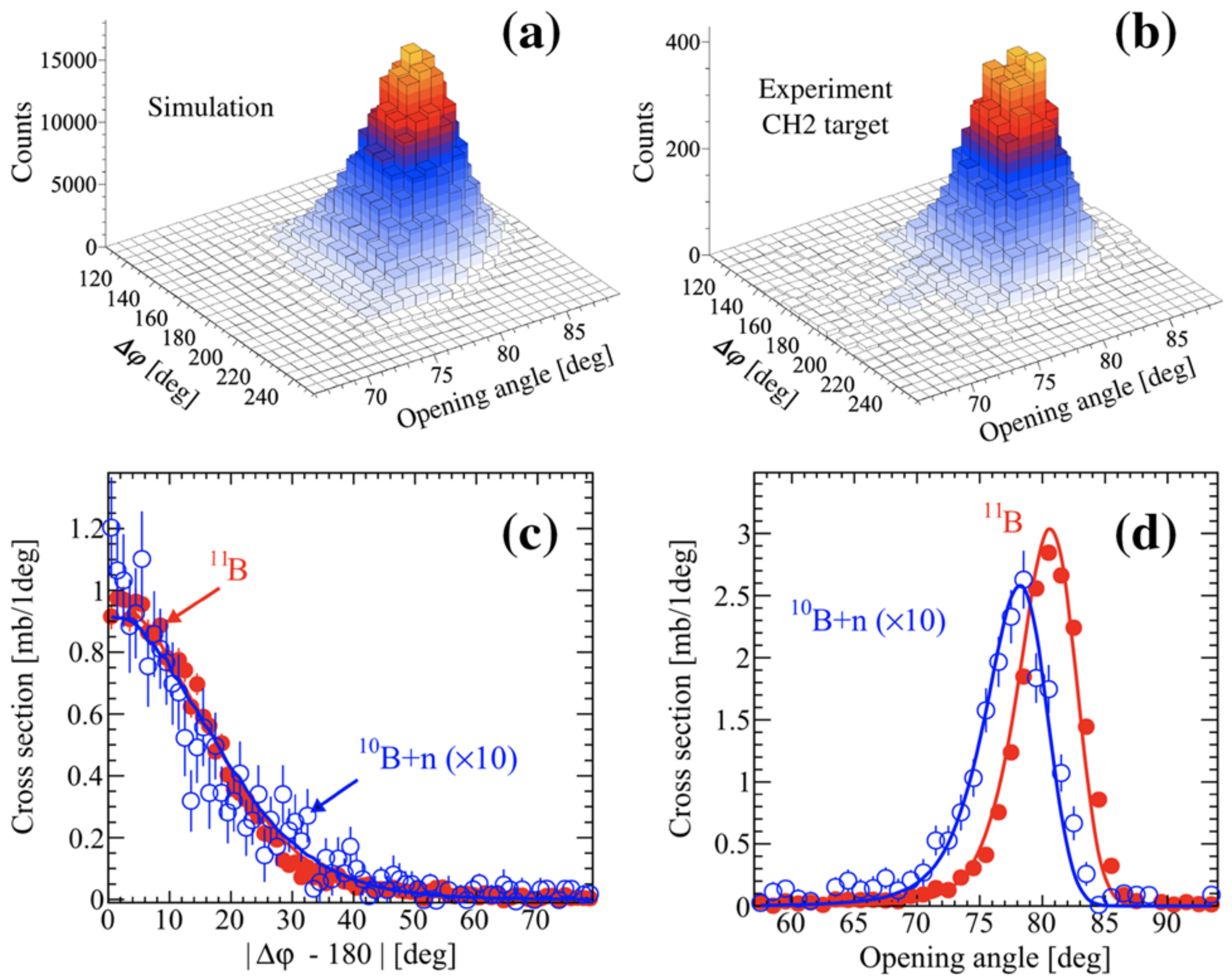






Benchmark experiment: $^{12}C(p,2p)^{11}B^*$

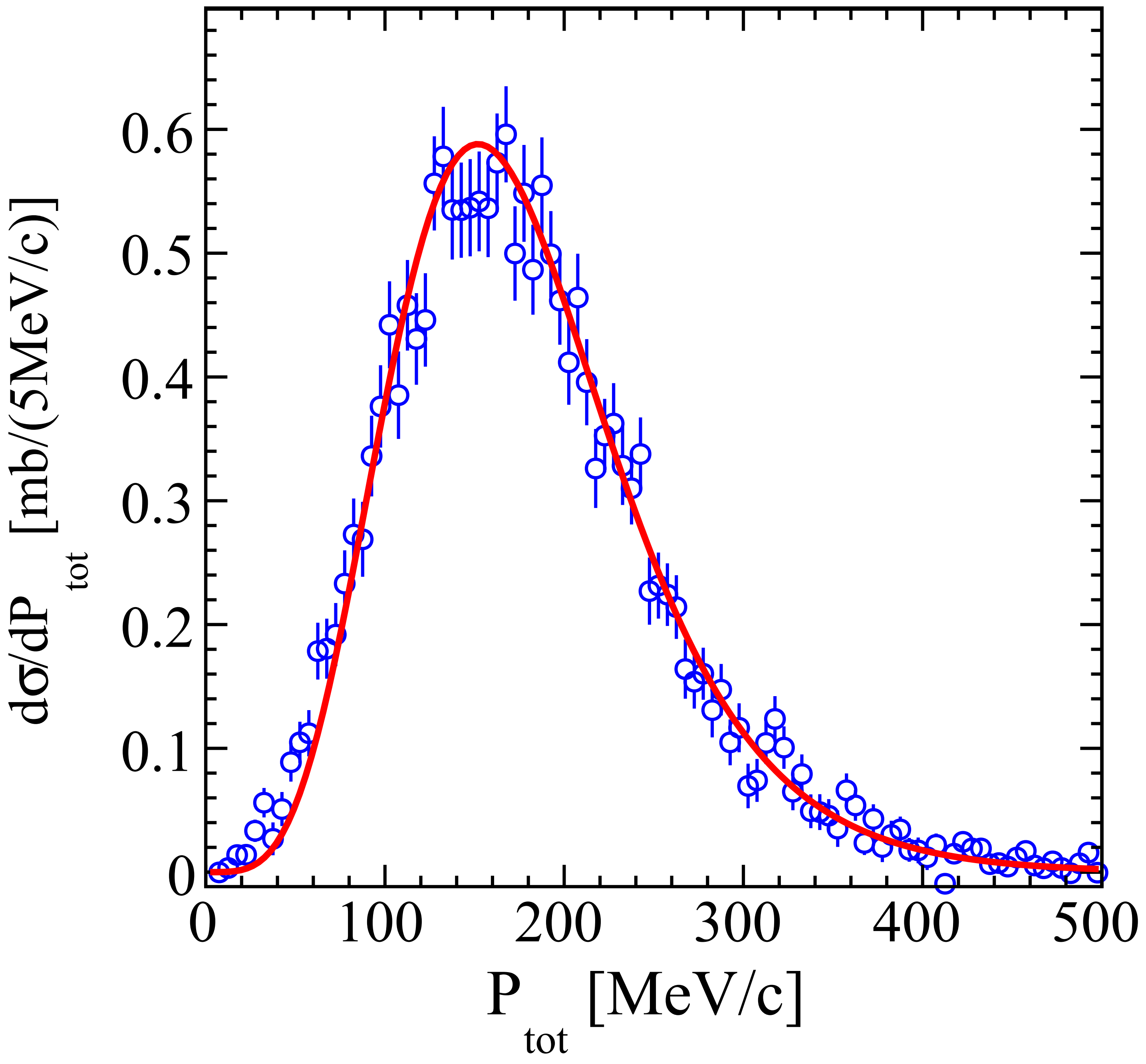
Angular distributions



Momentum distribution

of ^{11}B fragment

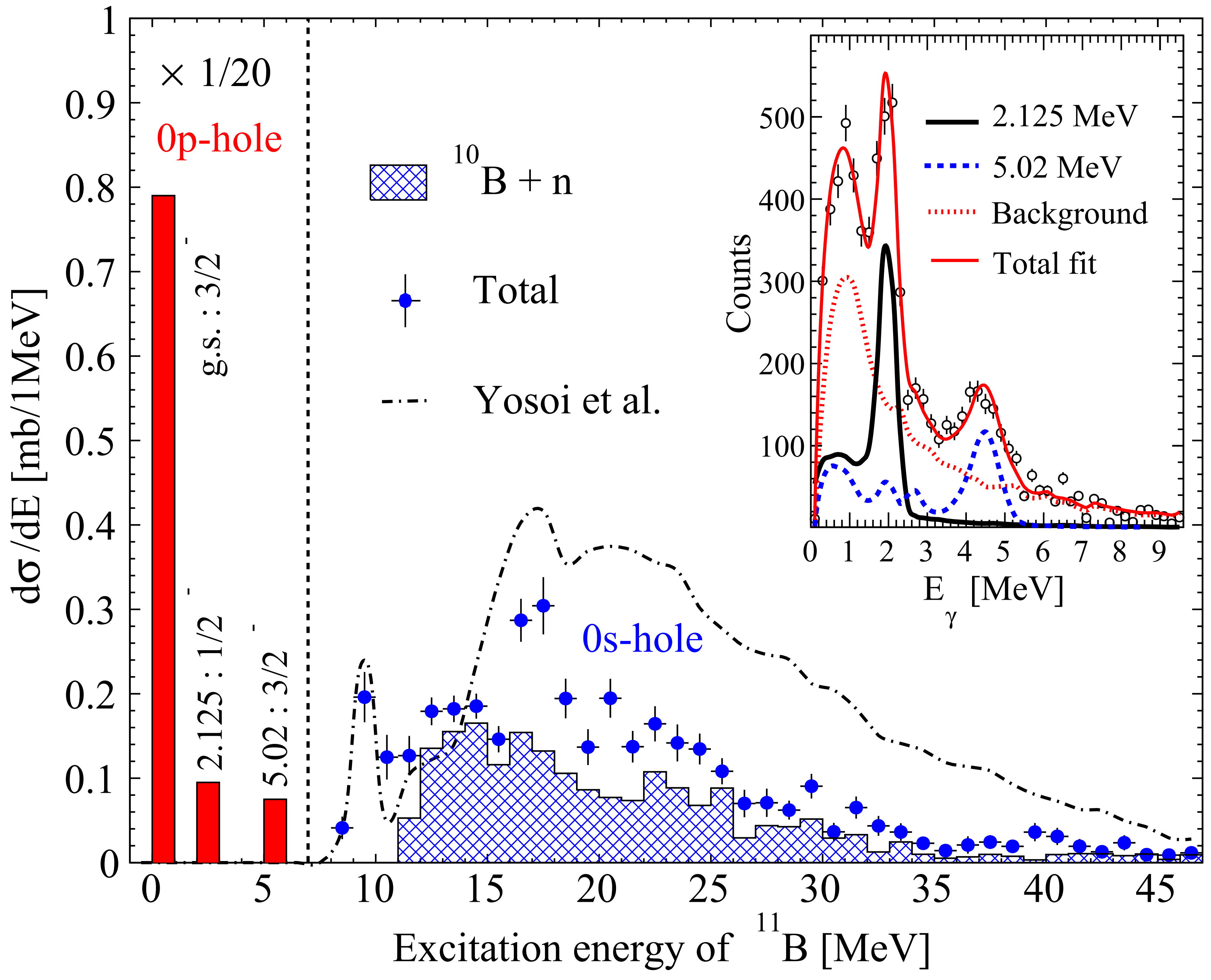
Theory: Glauber, p(3/2) state



Excitation-energy distribution (hole states)

Bound states: γ spectroscopy

Unbound states: invariant mass

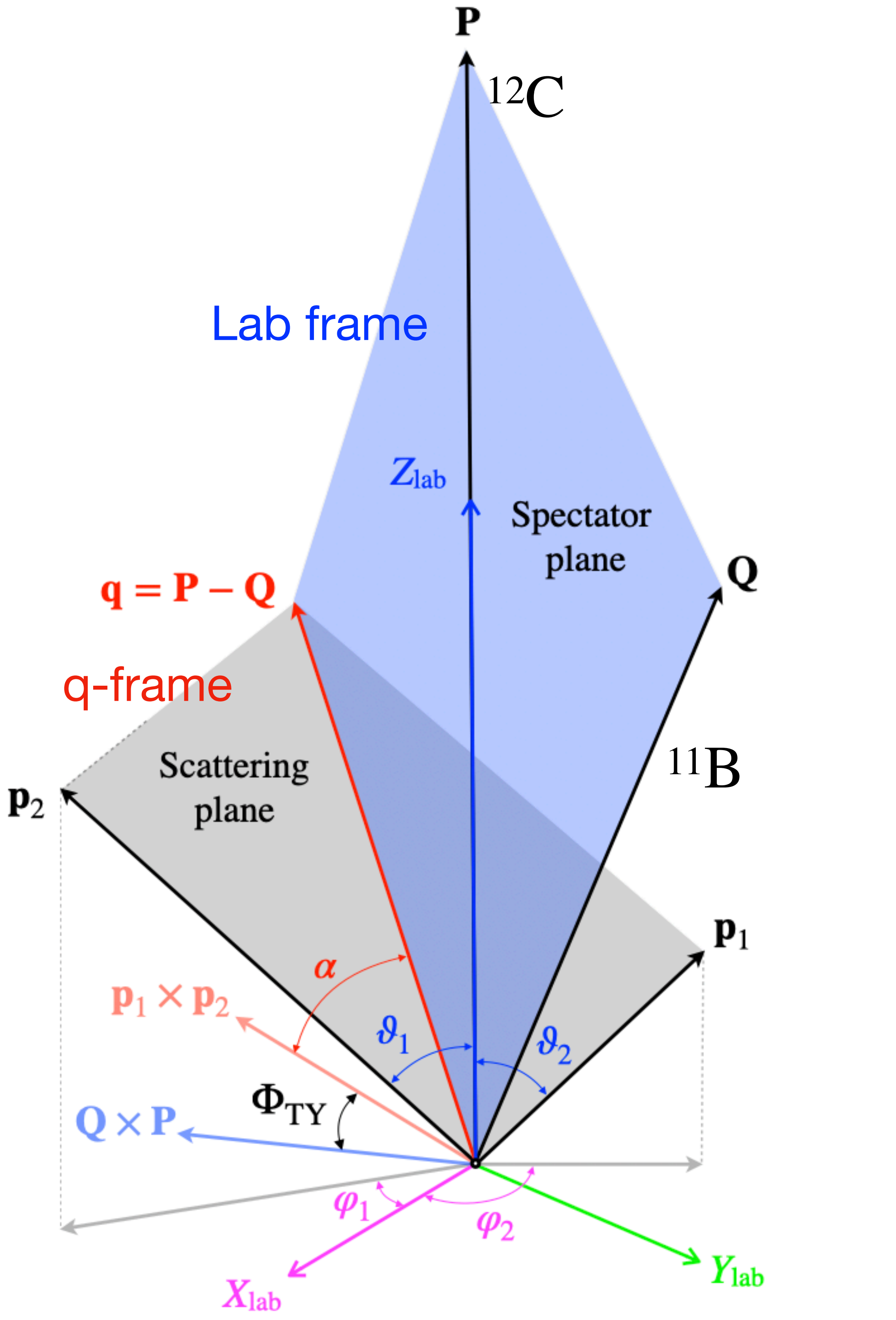


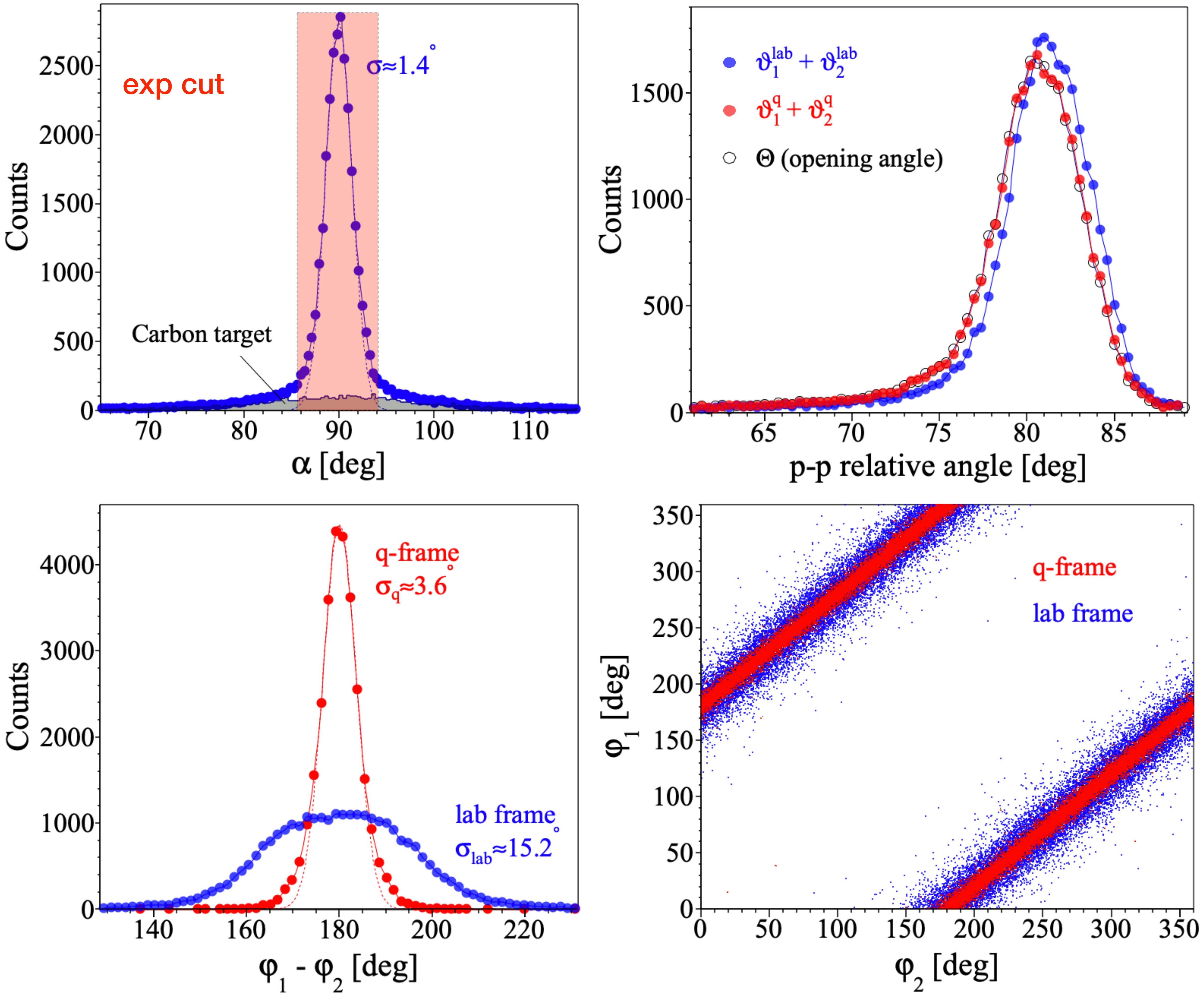
V. Panin et al., PLB 753 (2016) 204

V. Panin et al., EPJA 1014 (2021) 103

Simplest test of the QFS reaction mechanism

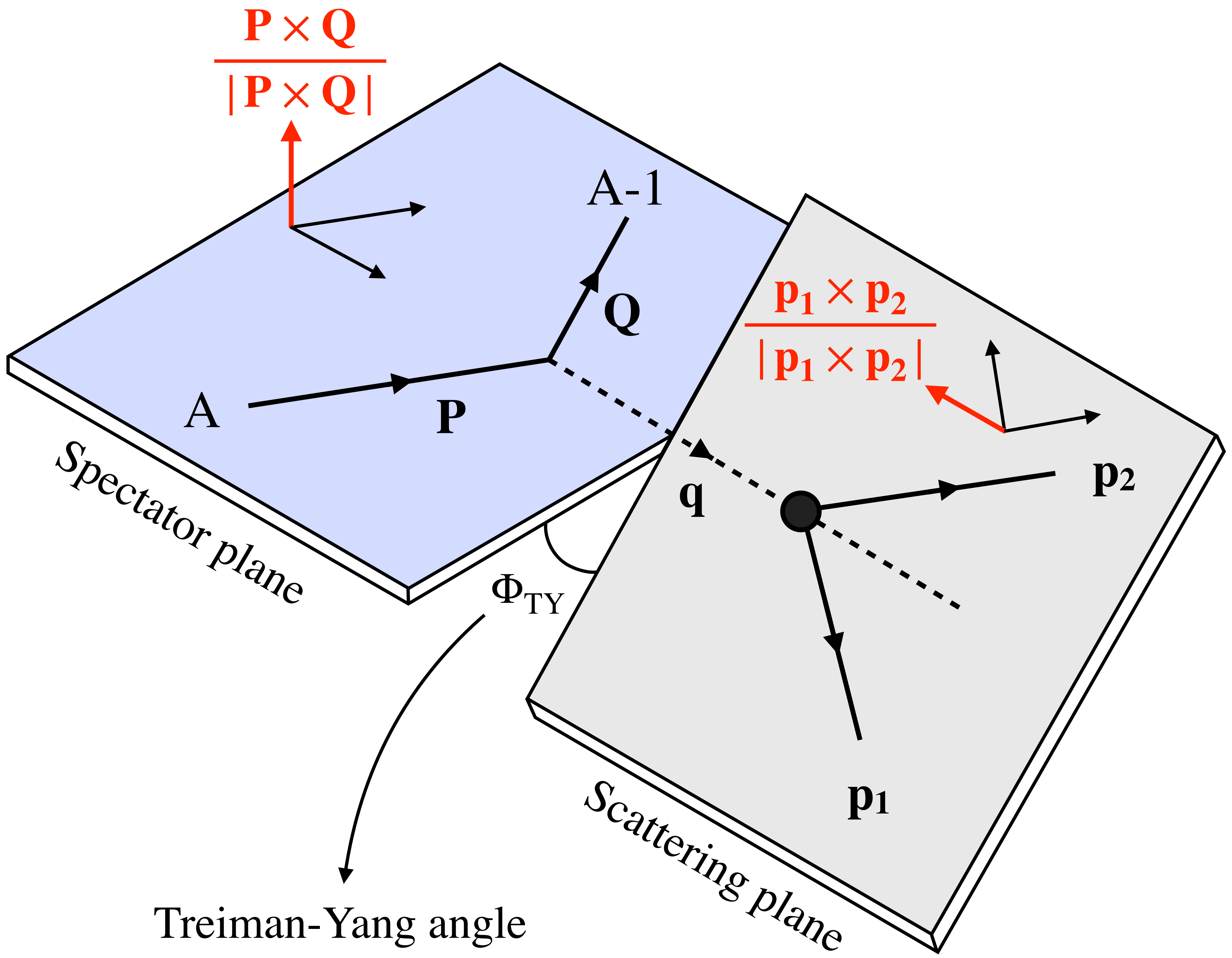
$$\cos\alpha = \frac{\mathbf{p_1}\times\mathbf{p_2}}{|p_1\times p_2|}\cdot\frac{\mathbf{P}-\mathbf{Q}}{|P-Q|}\approx 0$$





V. Panin,
to be published

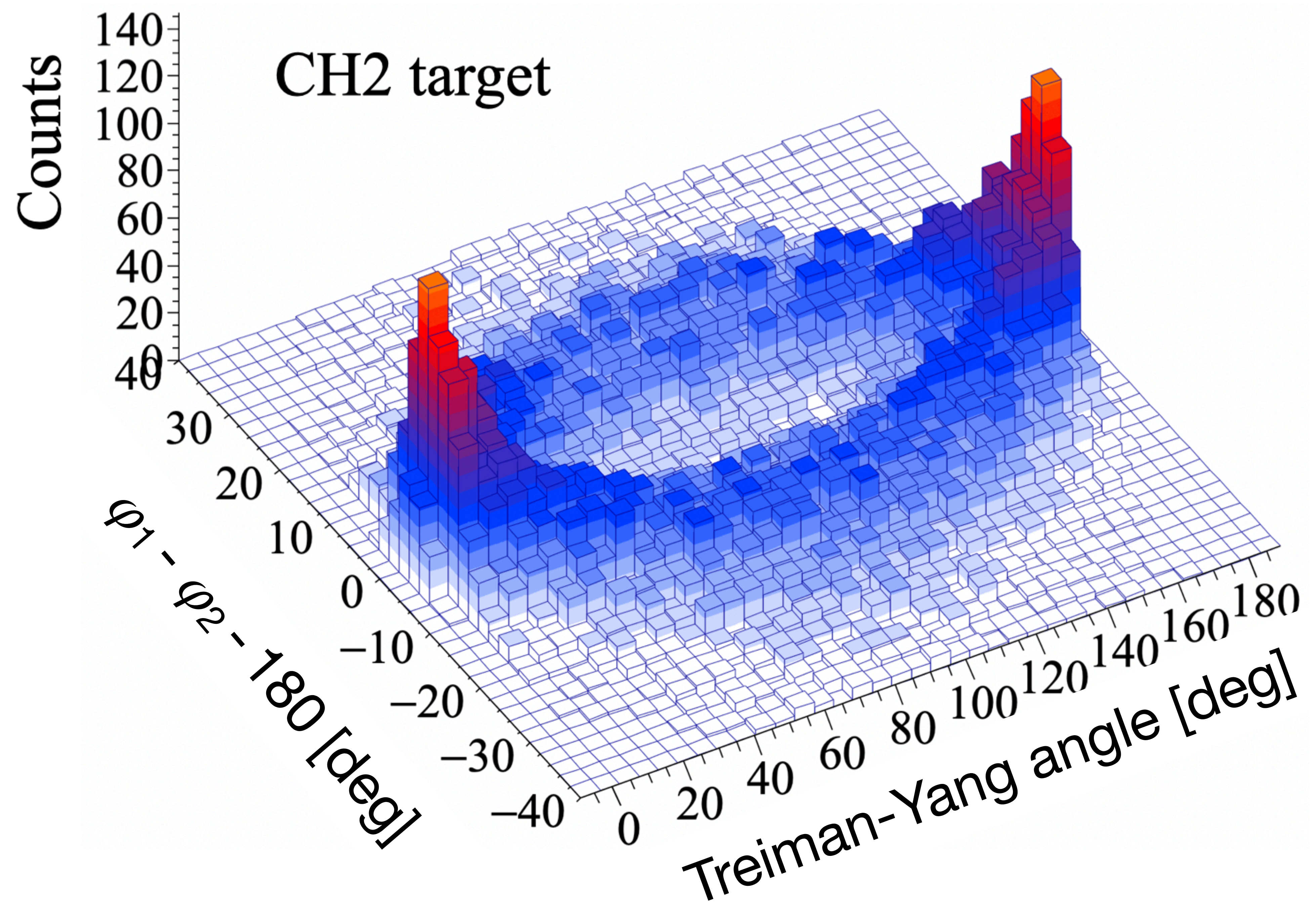
Treiman-Yang test



QFS cross sections should be independent on TY rotations

S. B. Treiman, C. N. Yang, , PRL 8 (1962) 140

Treiman-Yang angle vs azimuthal spread

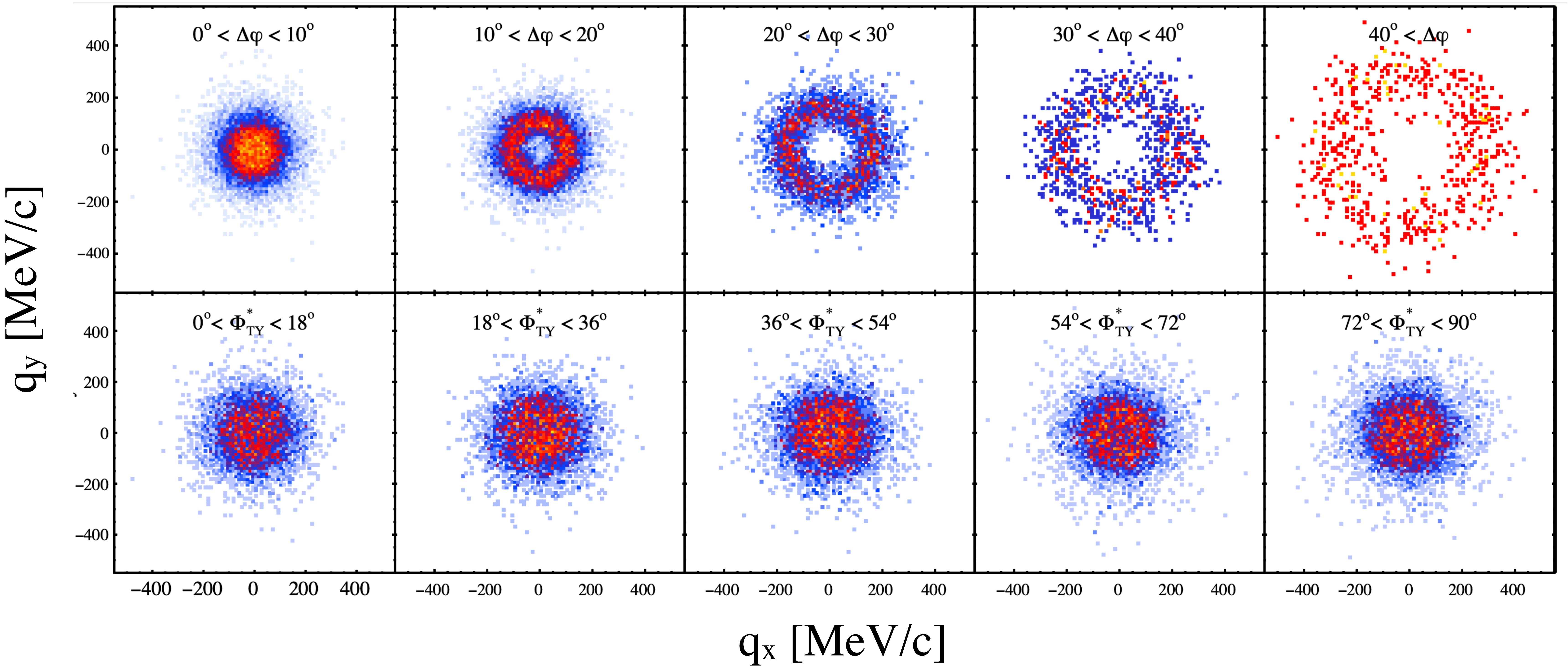


Treiman-Yang test requires large-acceptance measurement -> inverse kinematics

V. Panin, to be published

Transverse momentum and azimuthal spread

Coplanar ⟷ Non-coplanar



$\Delta\varphi = |\varphi_1 - \varphi_2 - 180^\circ|$ - azimuthal spread of two protons

$\Phi^*_{TY} = \pi/2 - |\Phi_{TY} - \pi/2|$ - TY is symmetric around $\pi/2$ —> protons are not distinguishable

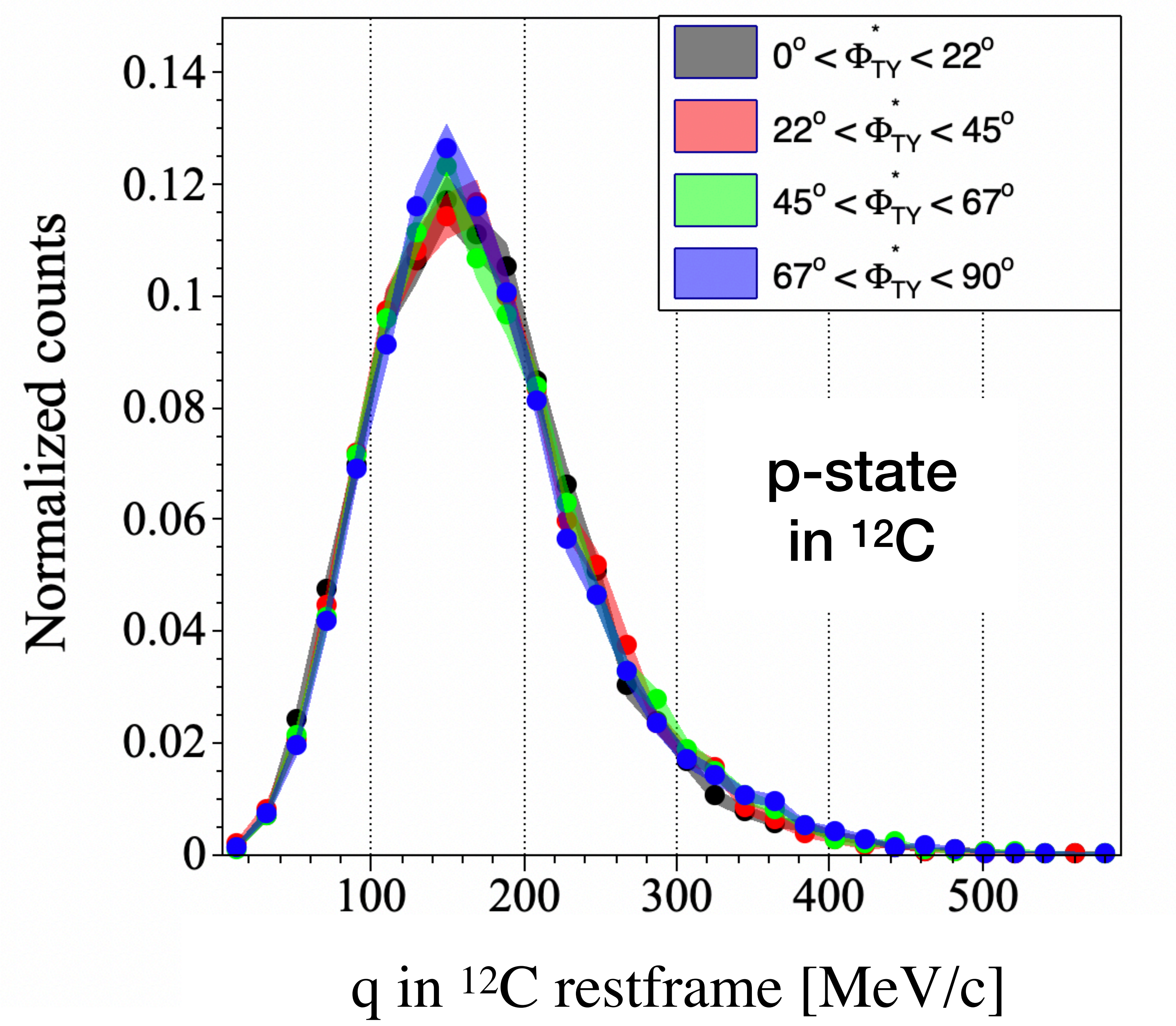
V. Panin, to be published

Momentum distributions and yield dependence

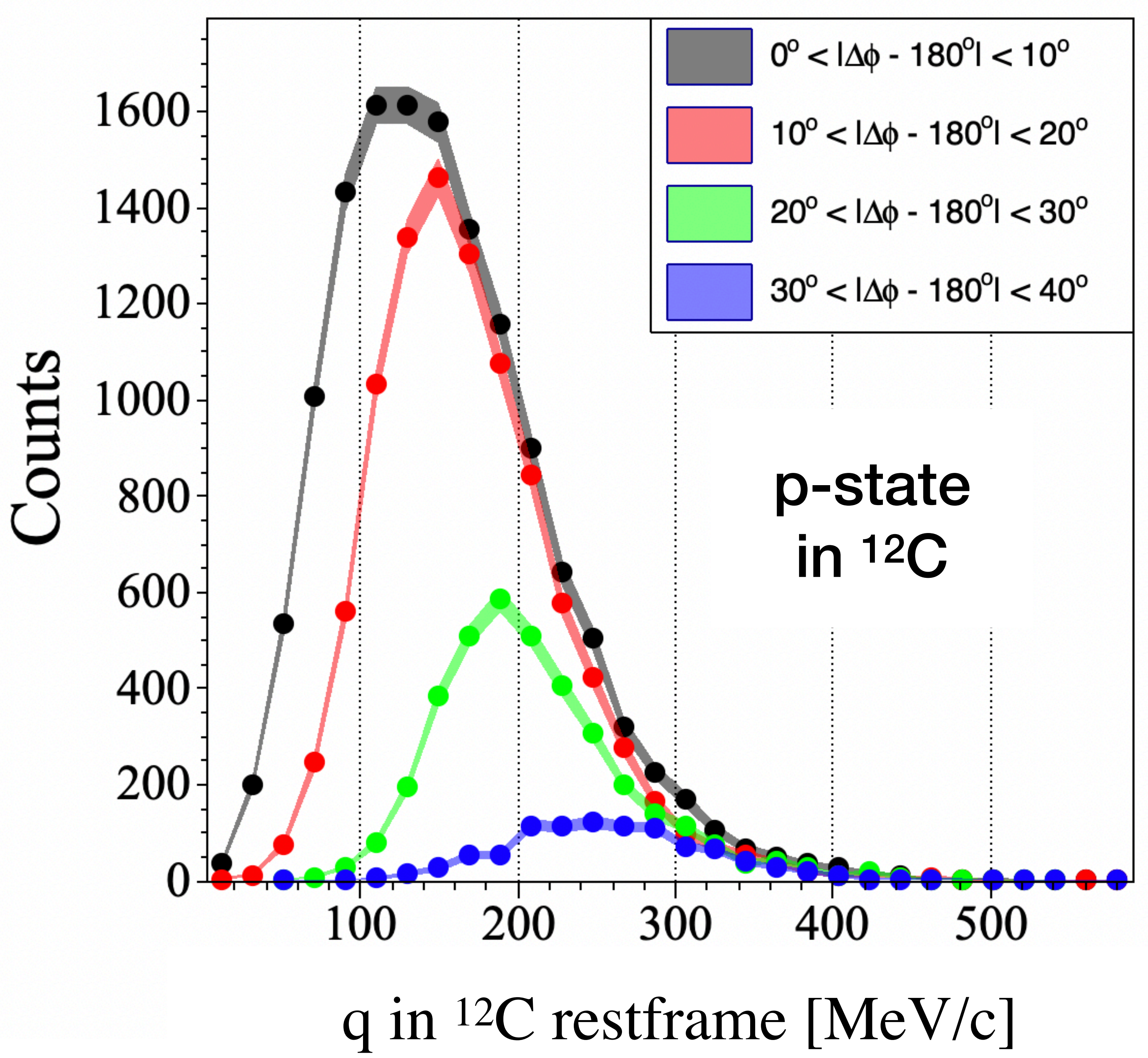
Momentum distributions

Yield

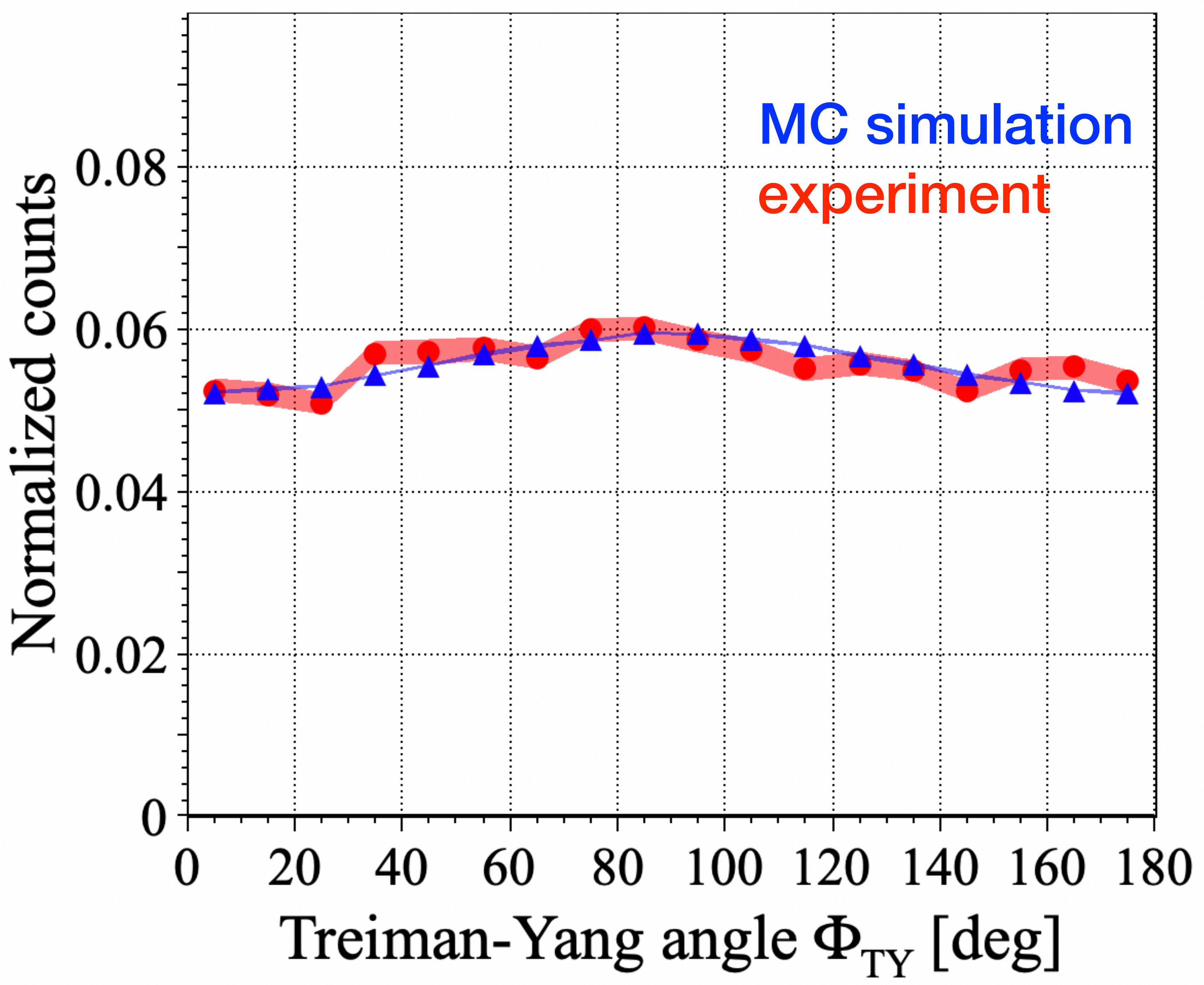
Dependence on Treiman-Yang angle



Dependence on azimuthal spread

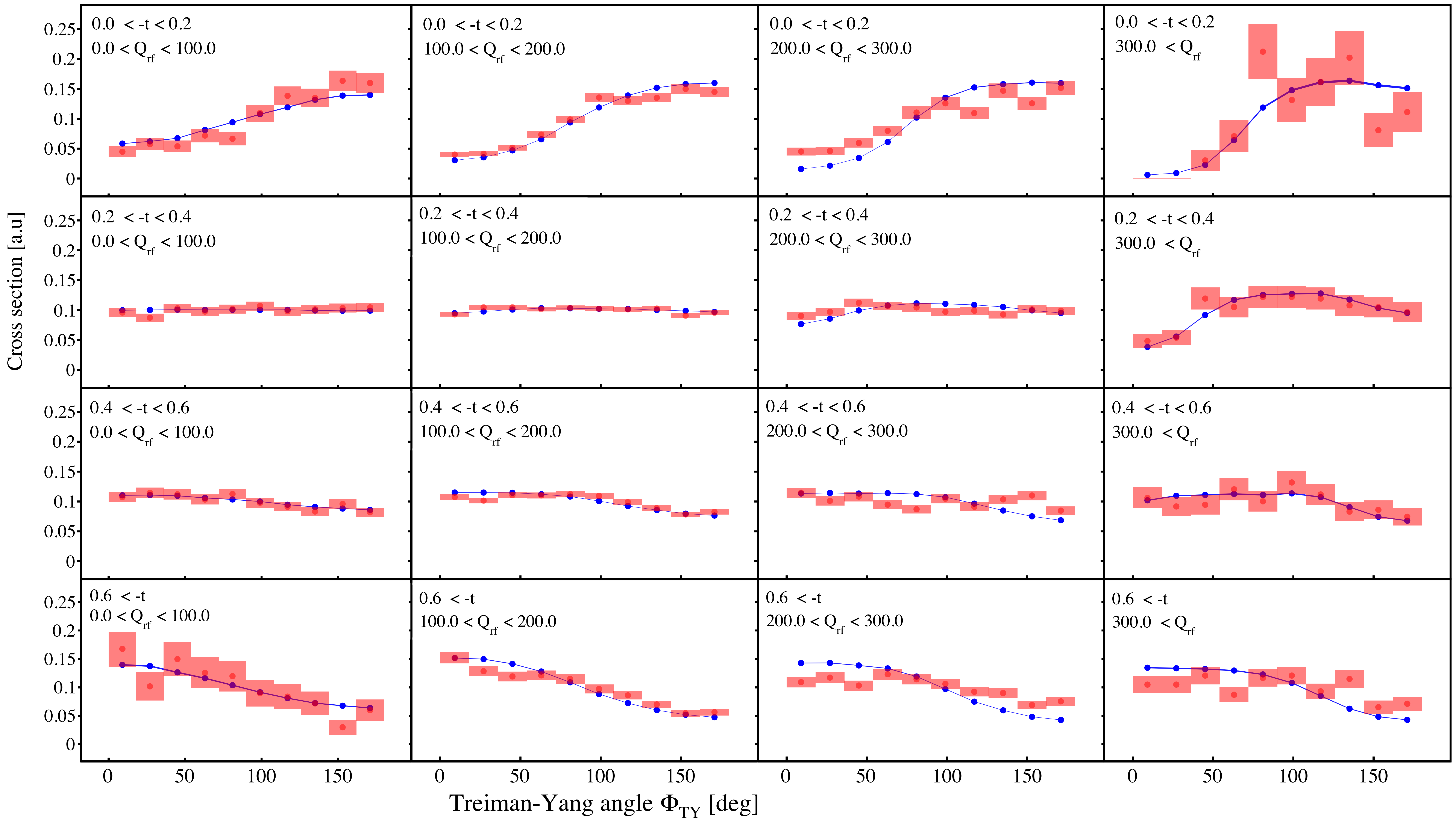


Dependence on Treiman-Yang angle



V. Panin, to be published

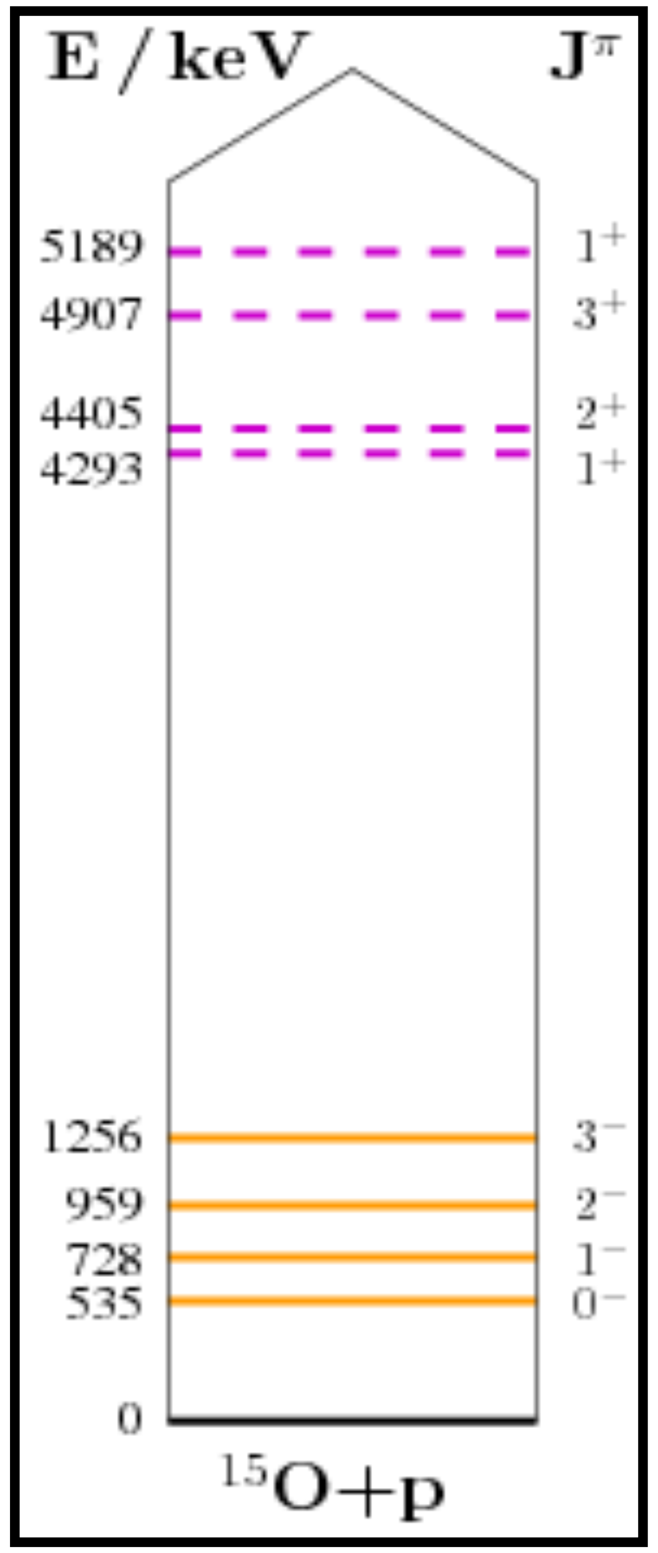
Treiman-Yang angle distribution for different momentum transfers and recoil momenta

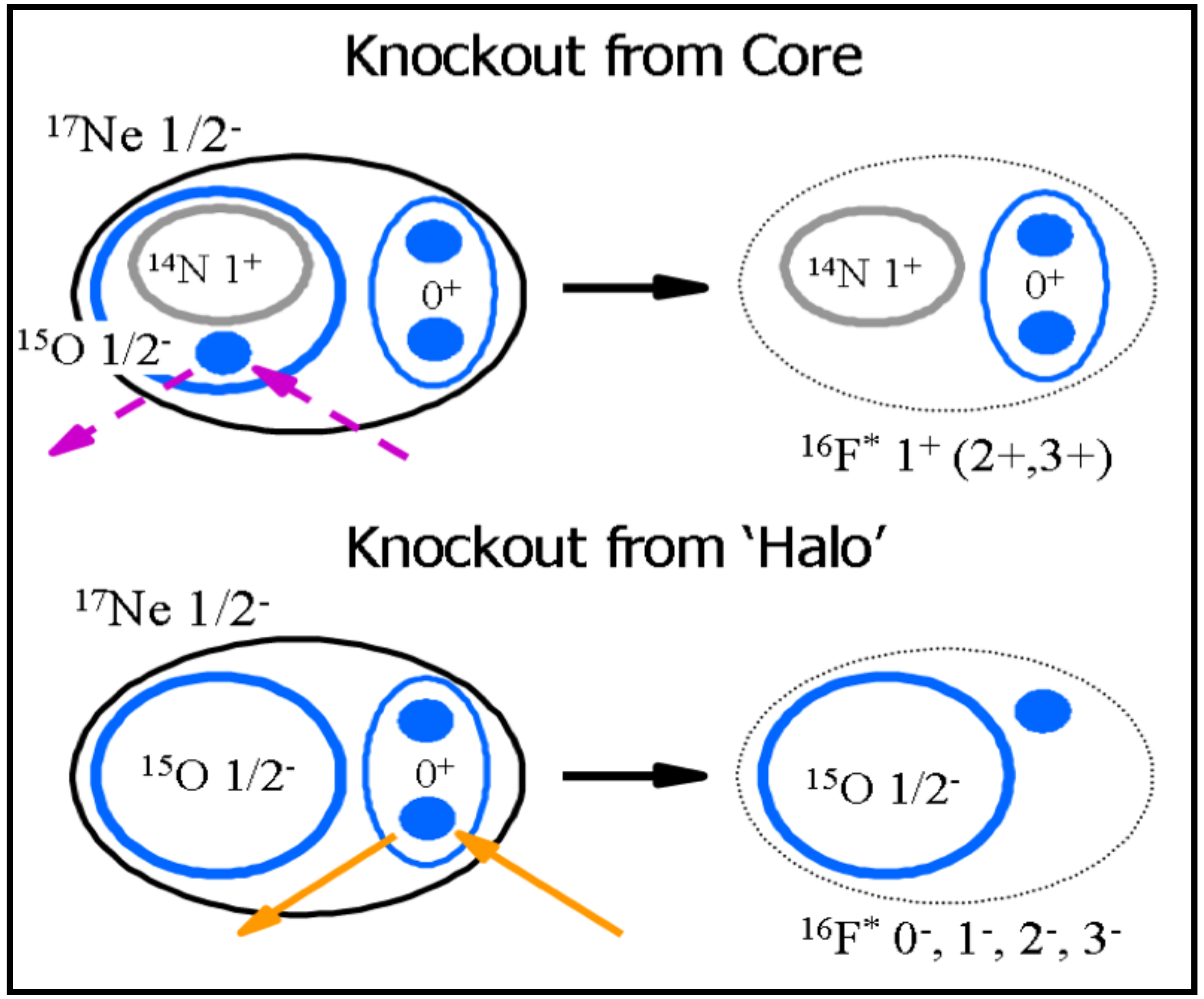


- Simulation based on ideal QFS process
- Excellent agreement with simulation for a wide range of momentum transfer and recoil momentum
- Deviations visible only for very large momentum transfer and recoil momenta
- **Test supports that QFS is a direct one-step process**

V. Panin, to be published

The Halo structure of ^{17}Ne

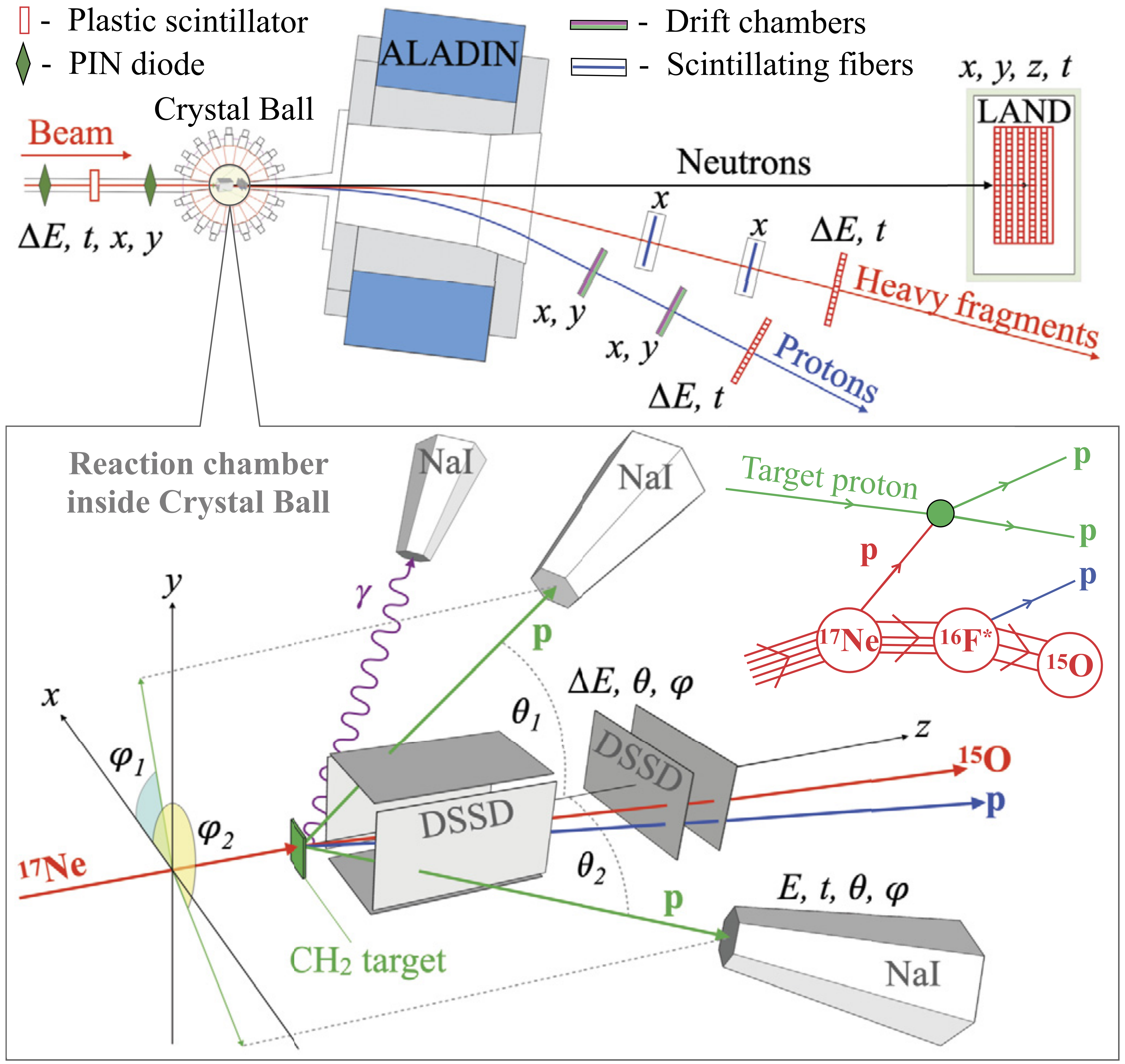




- ^{17}Ne Borromean 3-body structure
- ^{15}O core + 2p
- S_{2p} = 933 keV
- Valence protons in sd shell
- Large s^2 contribution would support halo character
- First exclusive measurement of knockout of halo protons

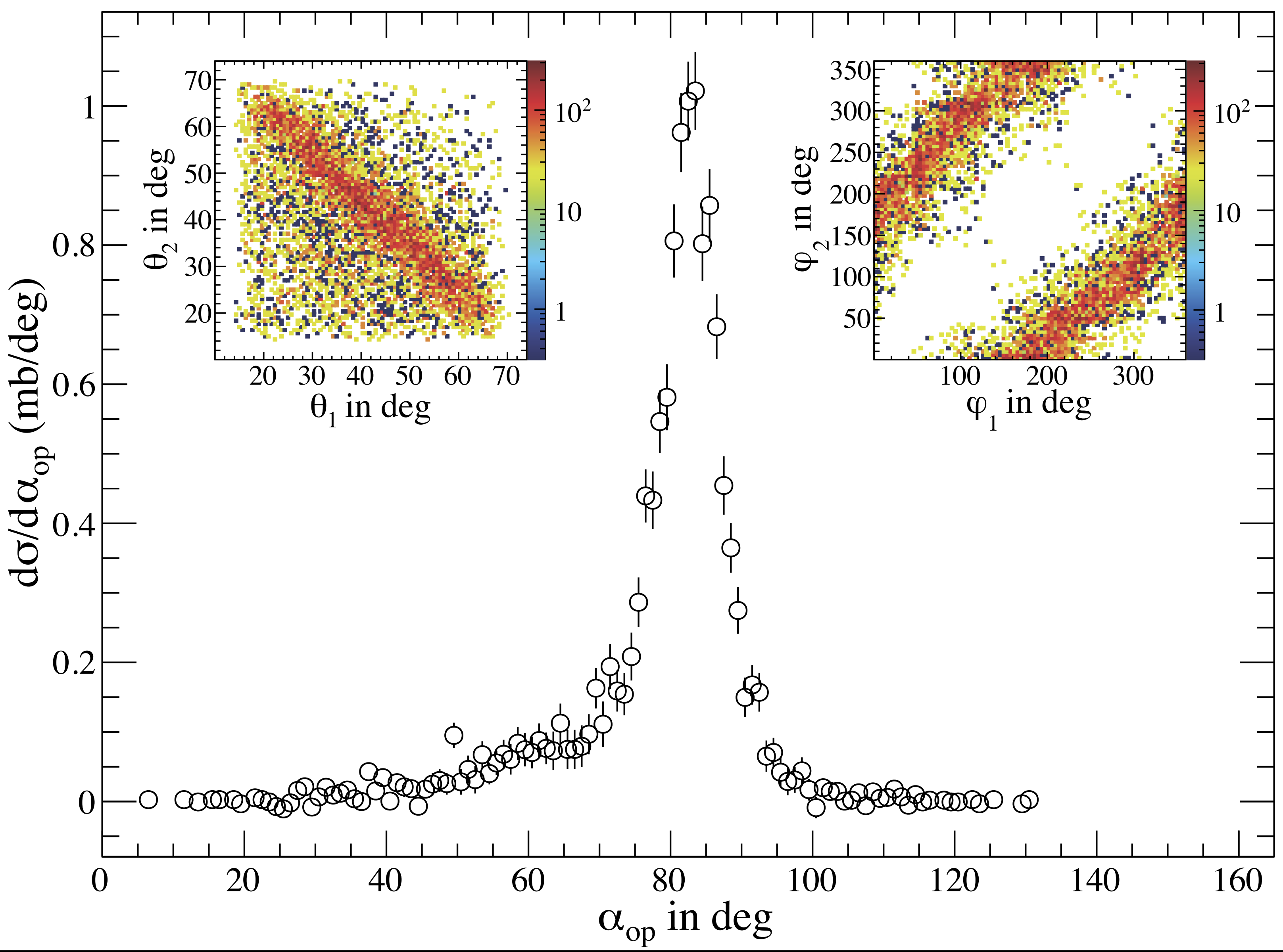
  → s^2/d^2 configuration ratio

^{17}Ne (p,2p)^{16}F → ^{15}O+p: Experiment at GSI



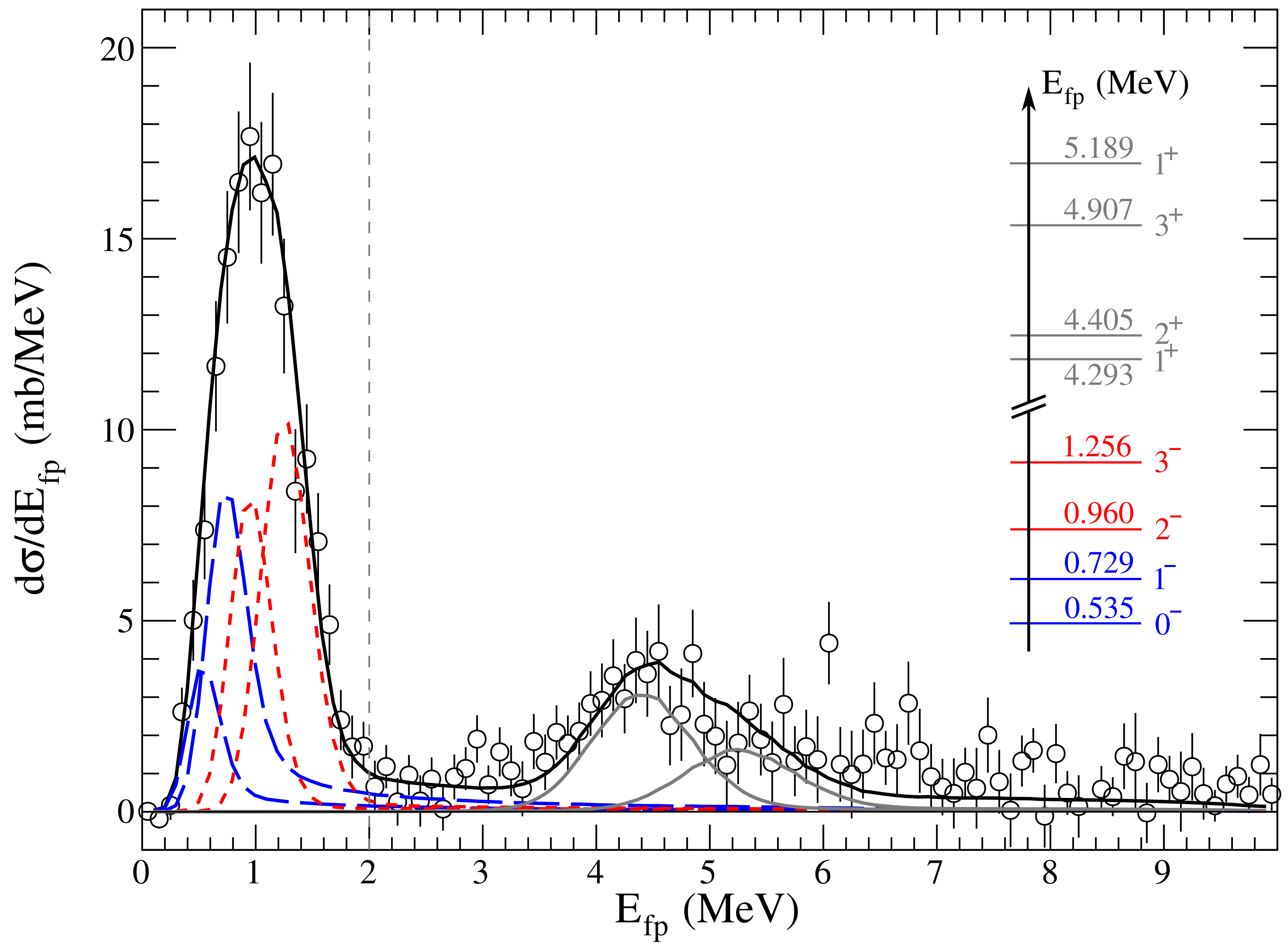
- Kinematically complete measurement
- 500 MeV/u beam energy
- C and CH_2 targets

Correlations of scattered protons

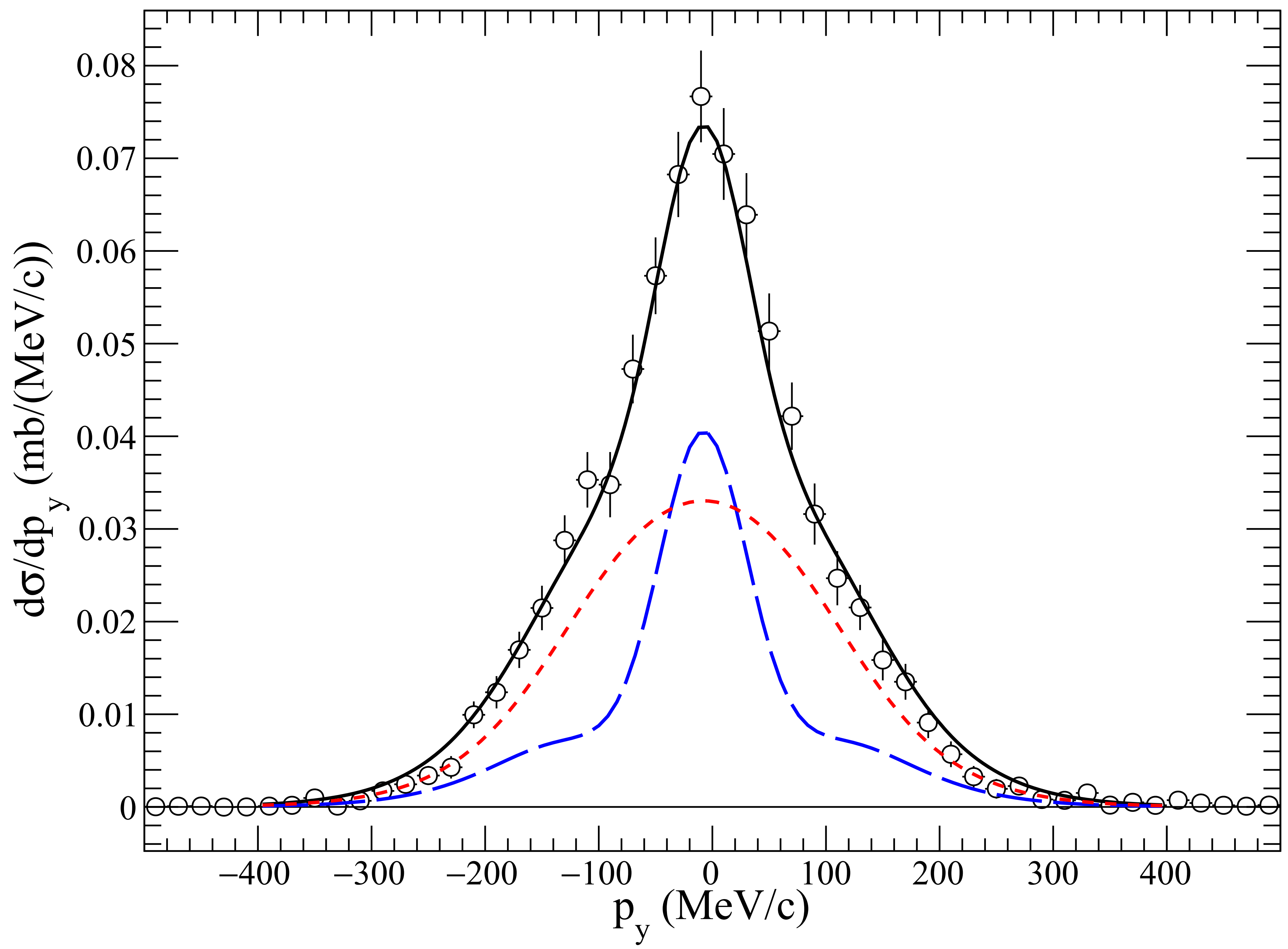


^{17}Ne (p,2p): energy and momentum distributions

^{15}O+p: relative-energy distribution



^{16}F: momentum distribution



— Independent determinations of s^2/d^2 ratio from energy spectrum and momentum distributions consistent
→ **only 35(3)% s^2 component** ! → ^{17}Ne is not a pronounced Halo nucleus

— Spectroscopic factor for valence protons (s^2+d^2): C^2S = 1.8(2) → only small or no quenching

C. Lehr et al.,
Phys. Lett. B **827** (2022) 136957)

Alpha Clusters at the surface of heavy nuclei

Theoretical prediction:

nuclear clusters appear in low-density nuclear matter

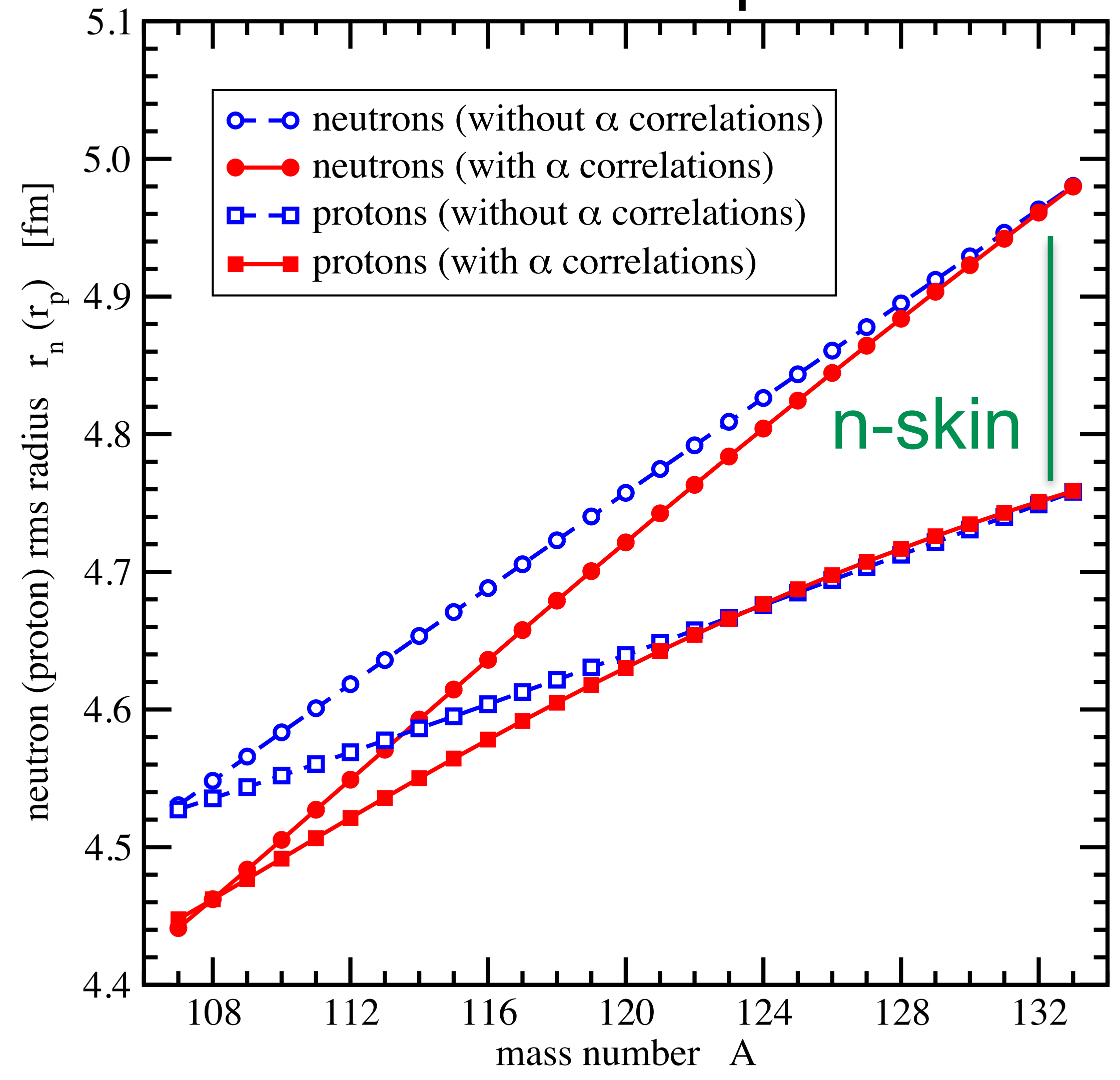
+

alpha clusters can form at the very surface of heavy nuclei at densities well below saturation

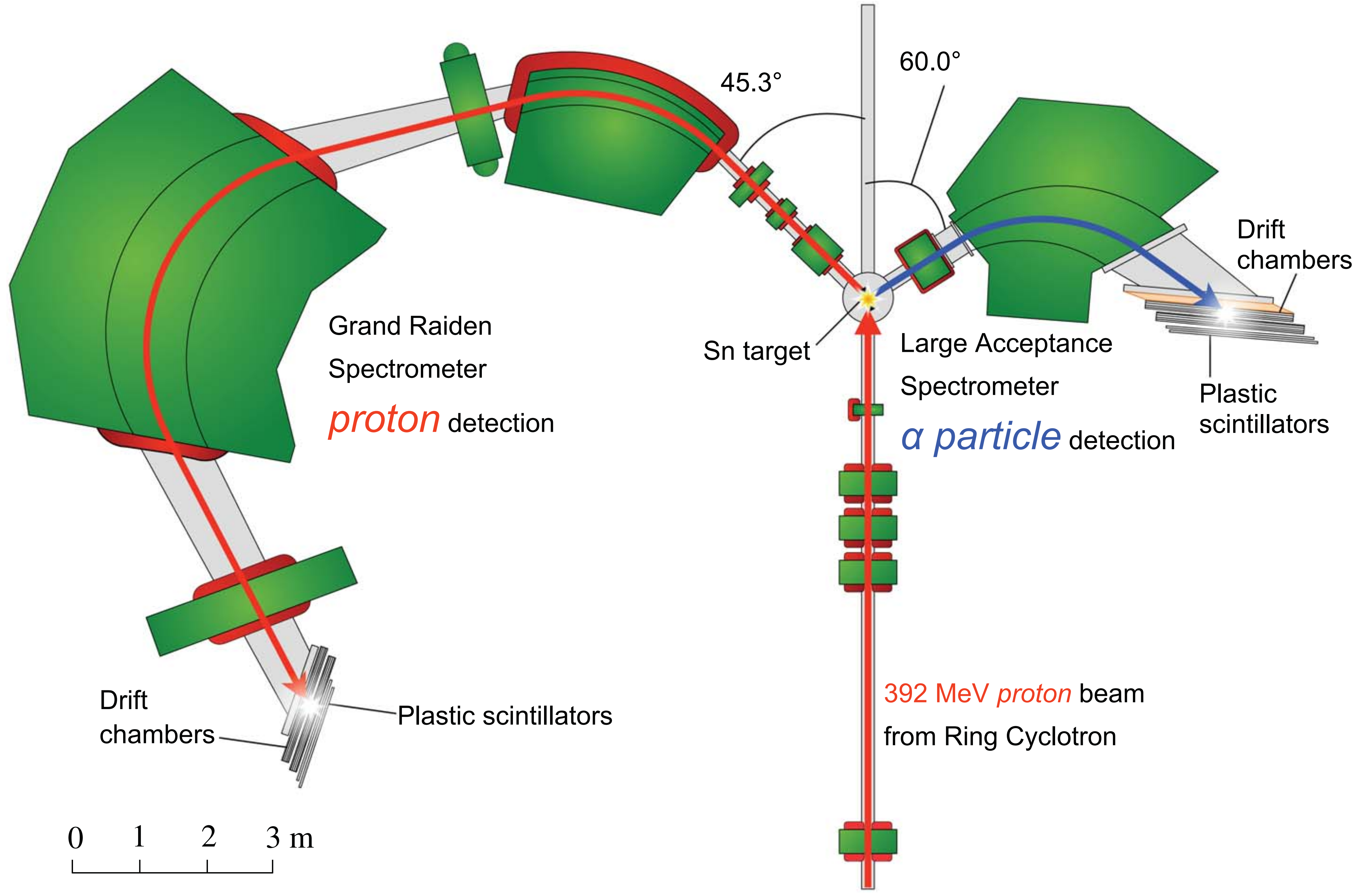
Dependence of neutron/proton density profiles

-> dependence on neutron skin

-> prediction for Sn isotopes



S. Typel, generalized relativistic mean-field model (gRMF)



Experiment at RCNP, Osaka University

$^{112,...,124}$Sn$(p, p\alpha)$X (enriched targets, 392 MeV protons)

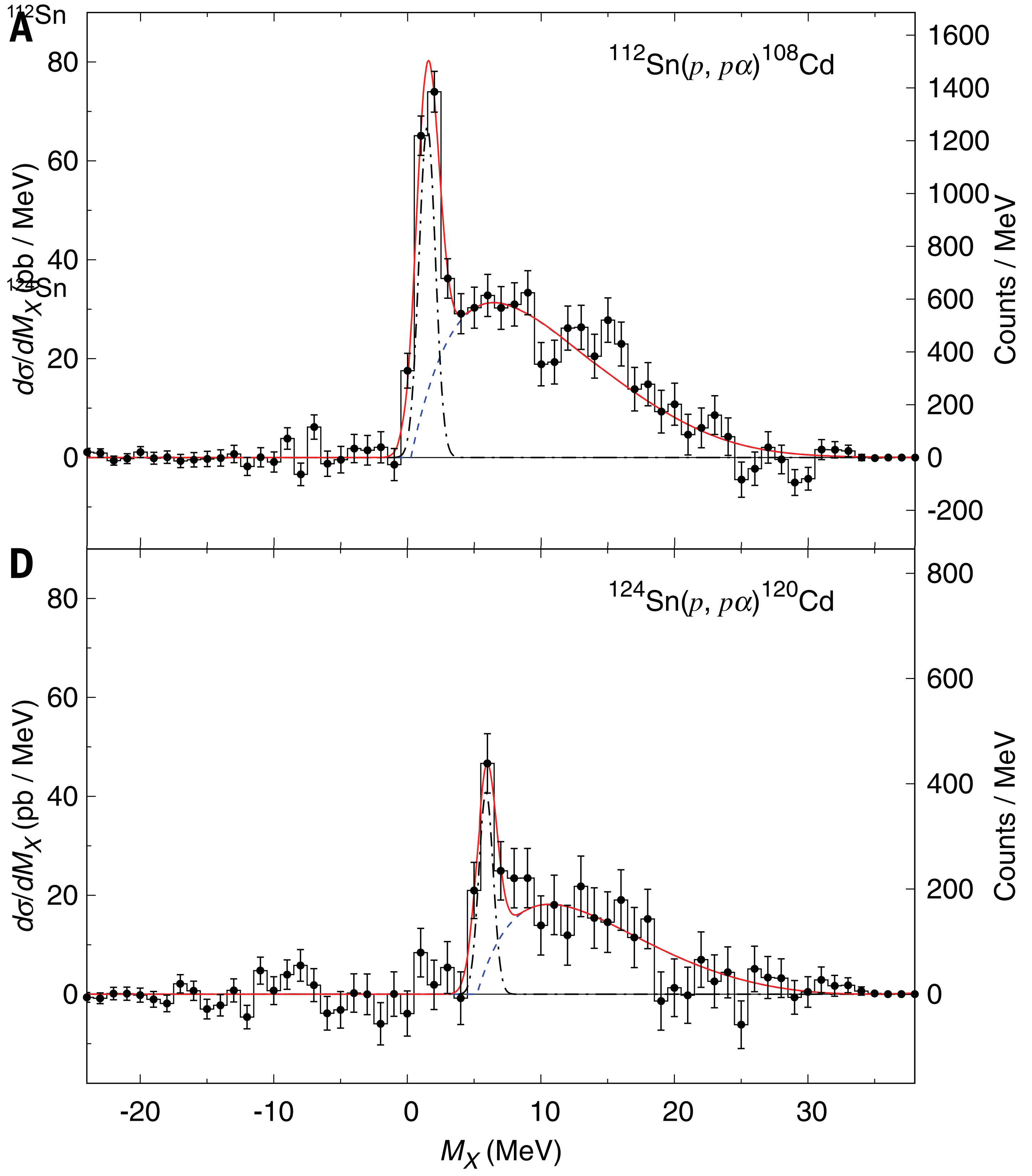
Measurement of p and alpha in quasi-free kinematics

-> cross section dependence on A

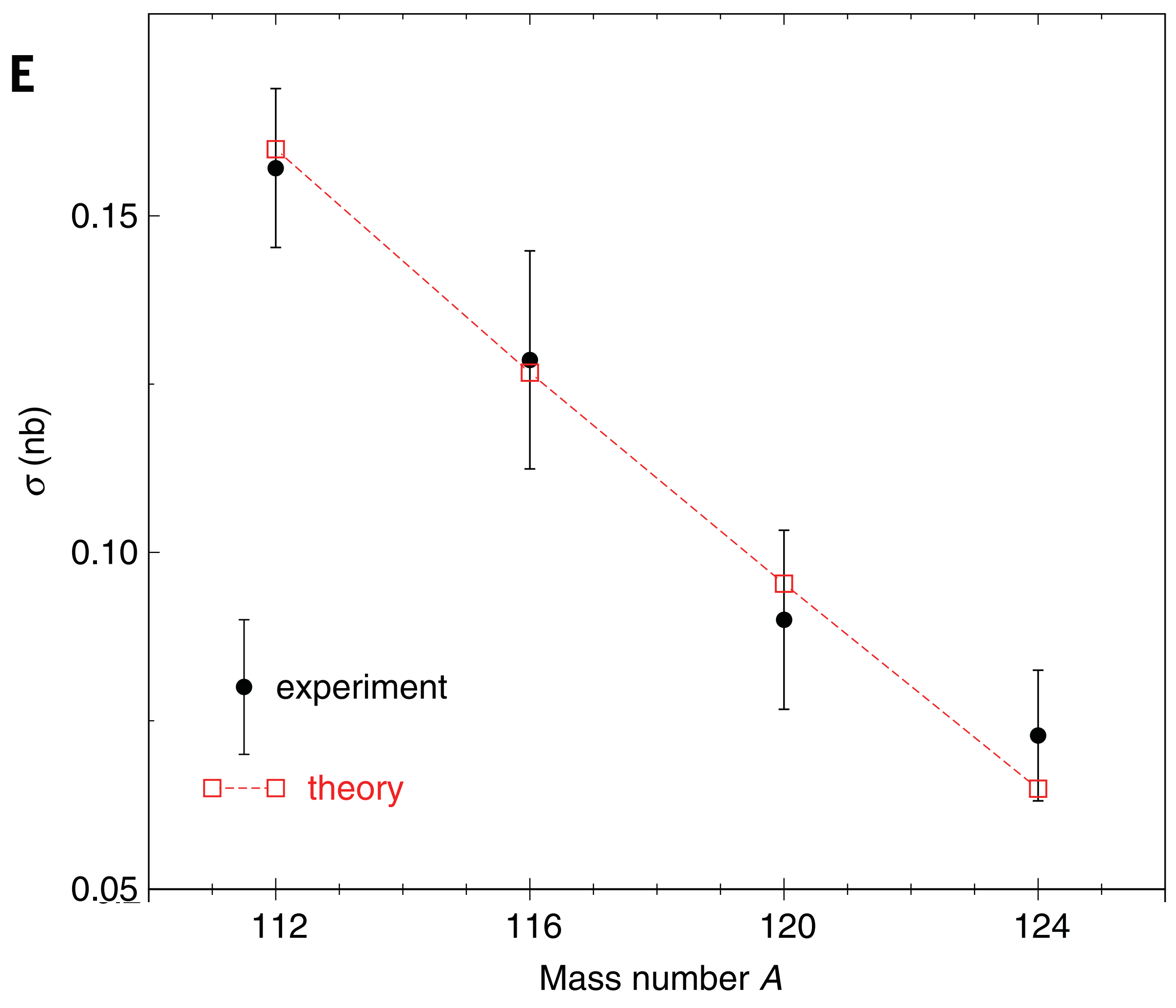
J. Tanaka et al., Science **372**, 260 (2021)

^{A}Sn(p,pα) cross sections

missing mass



Dependence on mass A



-> dependence on mass / neutron-skin thickness as predicted by gRMF (S. Typel)

-> consequence on Esym - n-skin relation ?

-> relation to alpha decay ?

-> future experiments with RIBs at RIBF and R3B at FAIR

J. Tanaka et al., Science **372**, 260 (2021)

Conclusion

- Quasi-free scattering has proven to be a versatile and clean reaction to study short-lived nuclei in inverse kinematics at relativistic energies
    Large-acceptance experiment allowed for Treiman-Yang test over the full phase space
- $^{17}Ne(p,2p)$: halo size suppressed due to dominant l=2 configuration
- Alpha clusters observed at the surface of Sn nuclei

- R3B FAIR Phase-0 experiments in analysis:

  - short range correlations vs. neutron excess: (p,2pN) and (p,pd) -> talk by D. Cortina

  - (p,2p)fission -> talk by J. Benlliure

Thank you