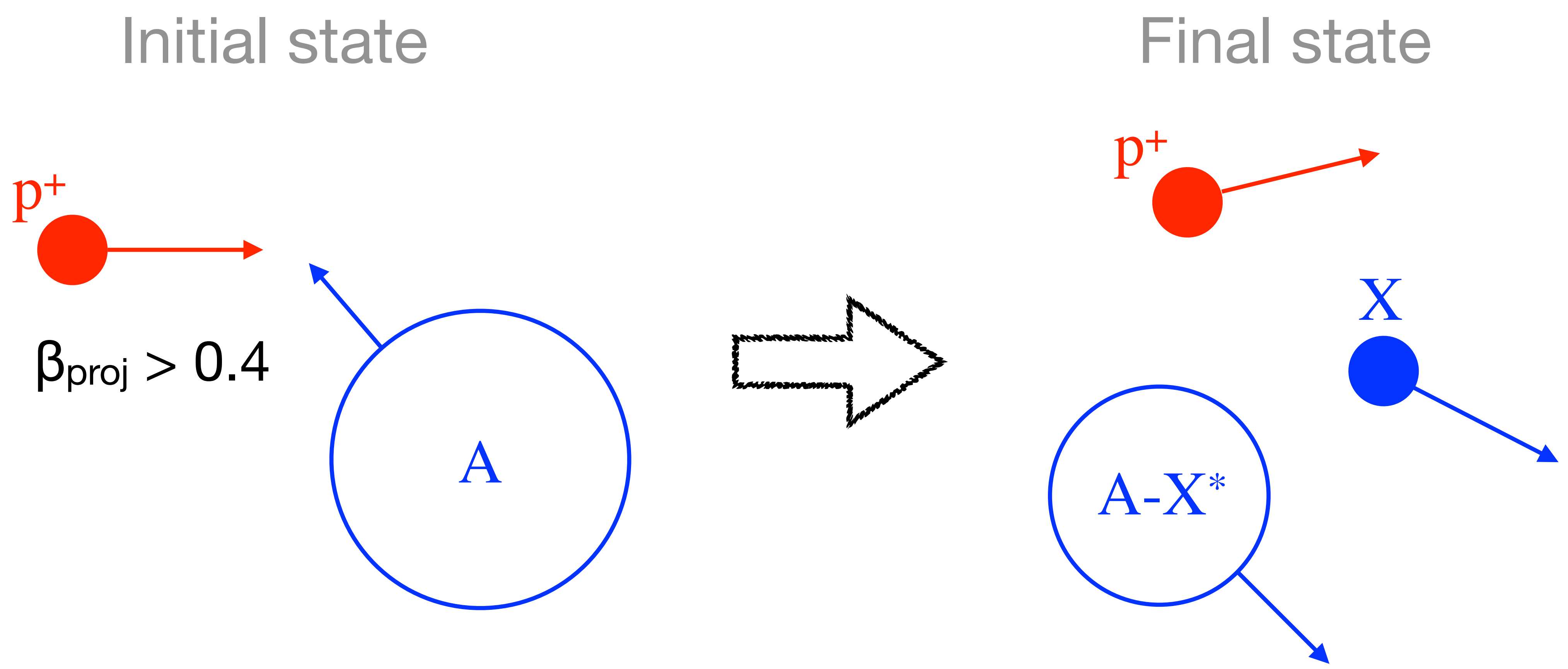
4th International Workshop on Quantitative Challenges in Short-Range Correlations and the EMC Effect Research
CEA Paris-Saclay (Orme des Merisiers)
30 January - 3 February, 2023

Nuclear structure studies with proton-induced QFS reactions

Valerii Panin, GSI Darmstadt

QFS as a proton-induced knockout reaction

What we observe



- Relativistic proton-nucleus collision
- Initial state of A is “destroyed”
- New particle X is generated in the final state
- Complex many-body problem

X = proton, neutron, deuteron, alpha, …

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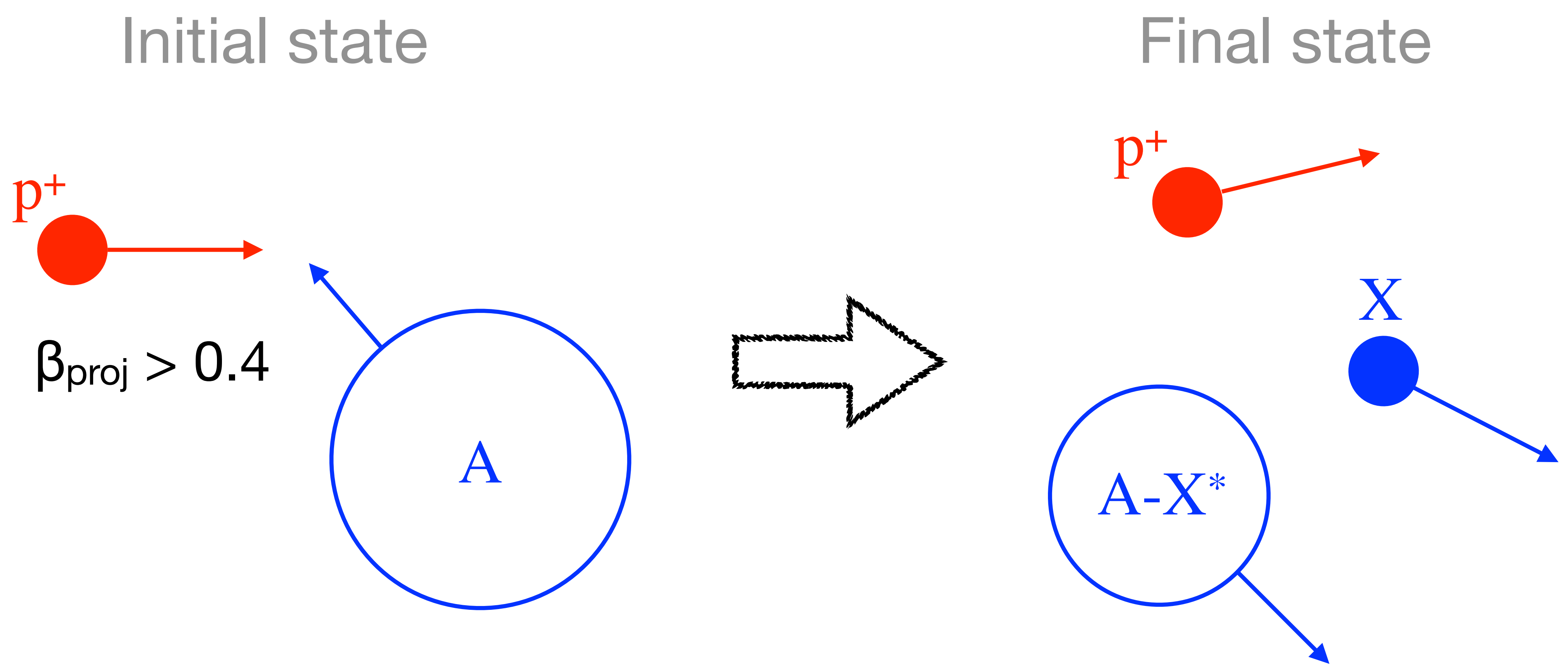

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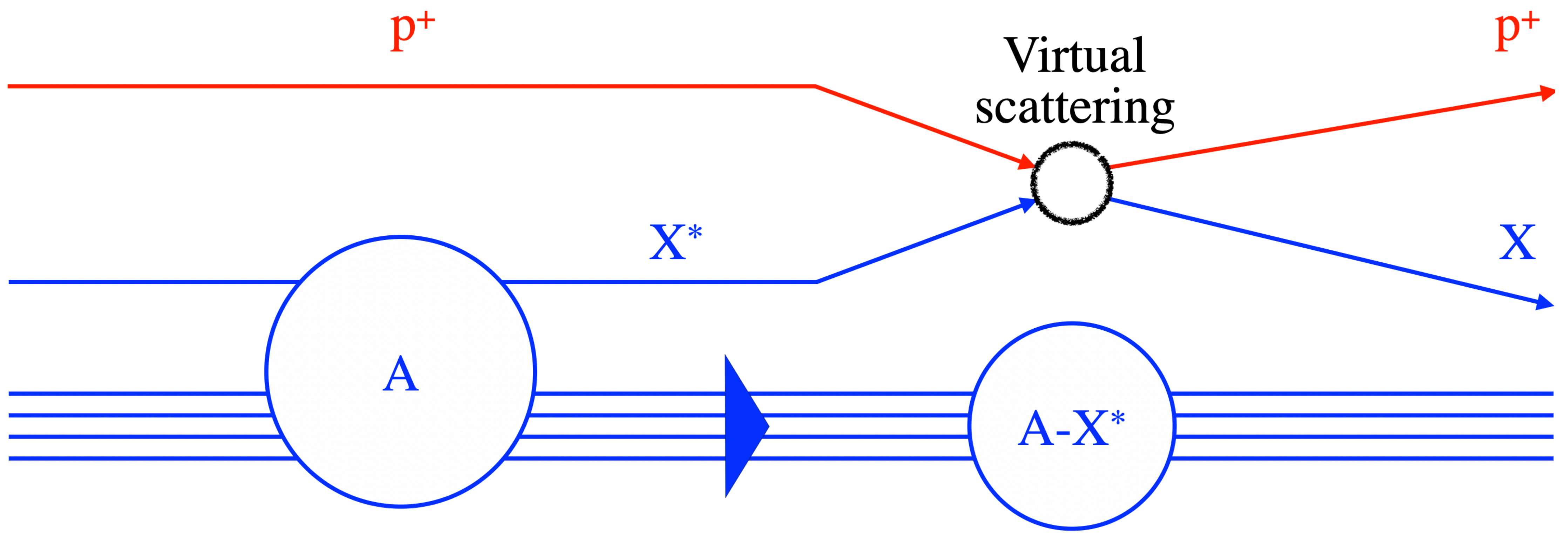
What we think is happening



- Simple 2-body interaction: elastic scattering off a virtual constituent X*
- Proton and X freely escape the nucleus
- (A-X*) spectator with a “hole" → linked to the initial SP state in A

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

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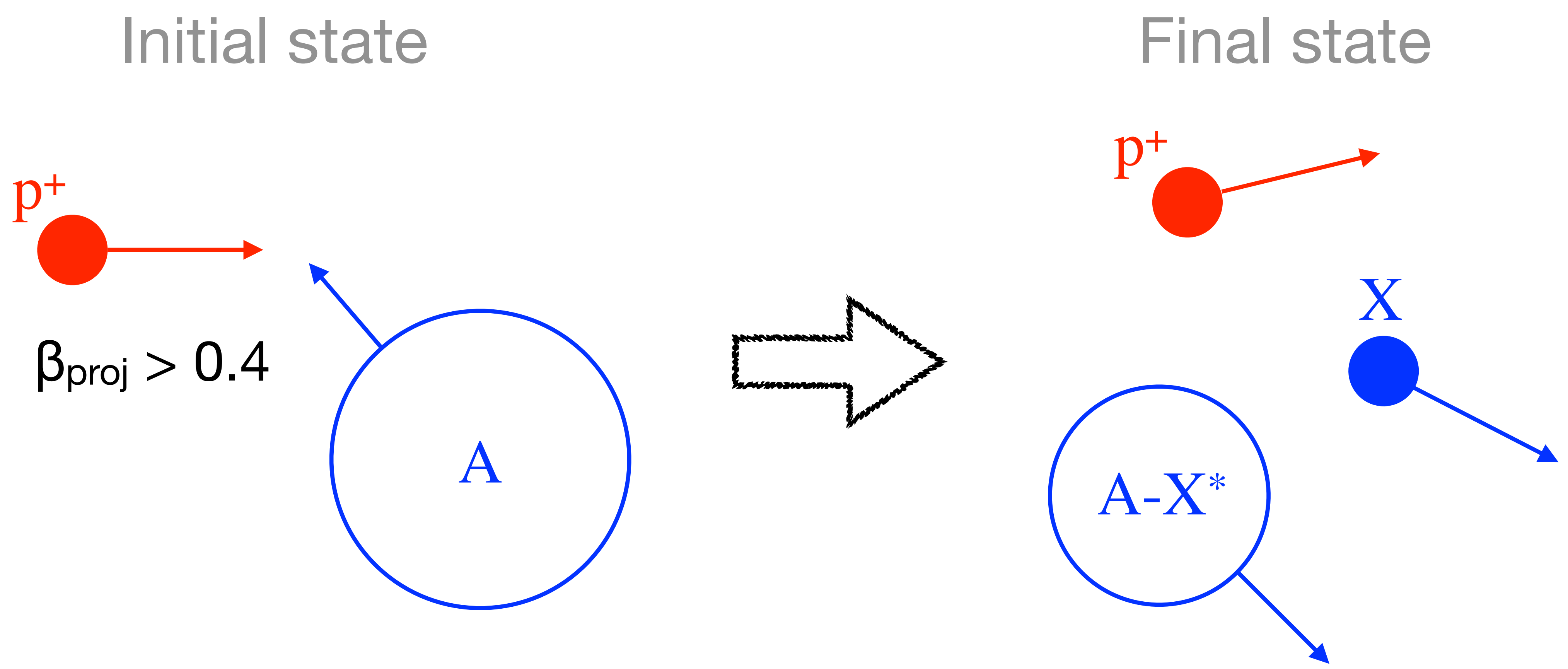

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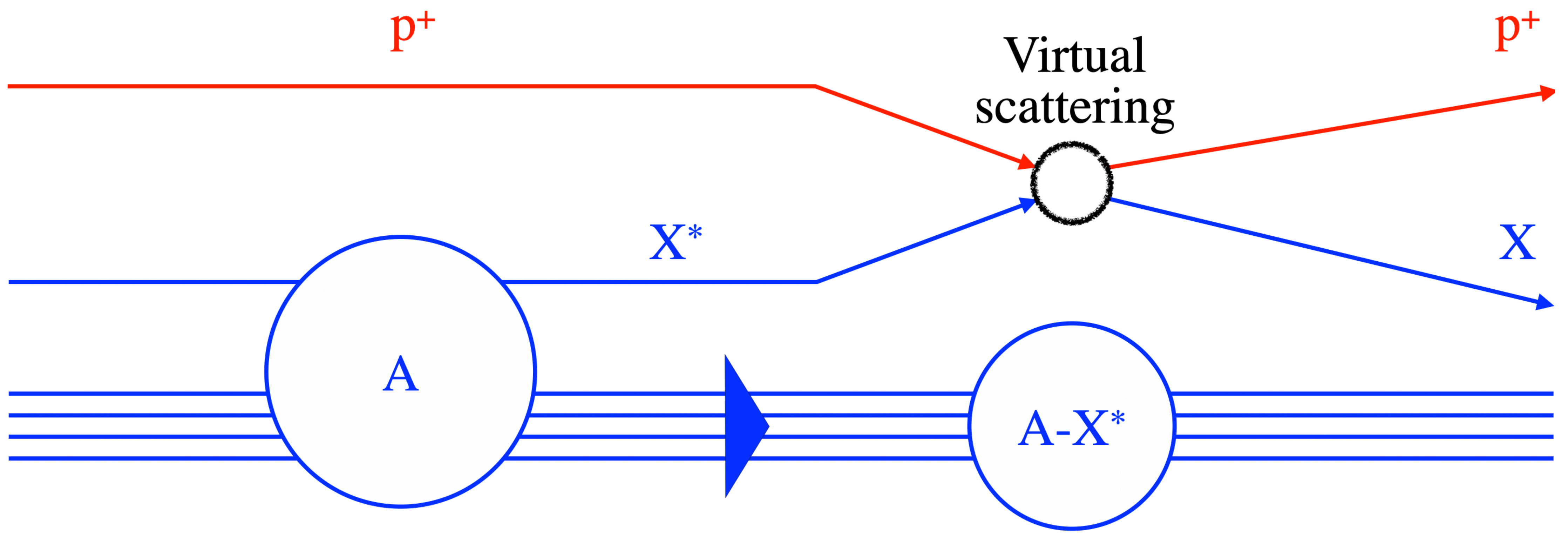

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Kinematical factor

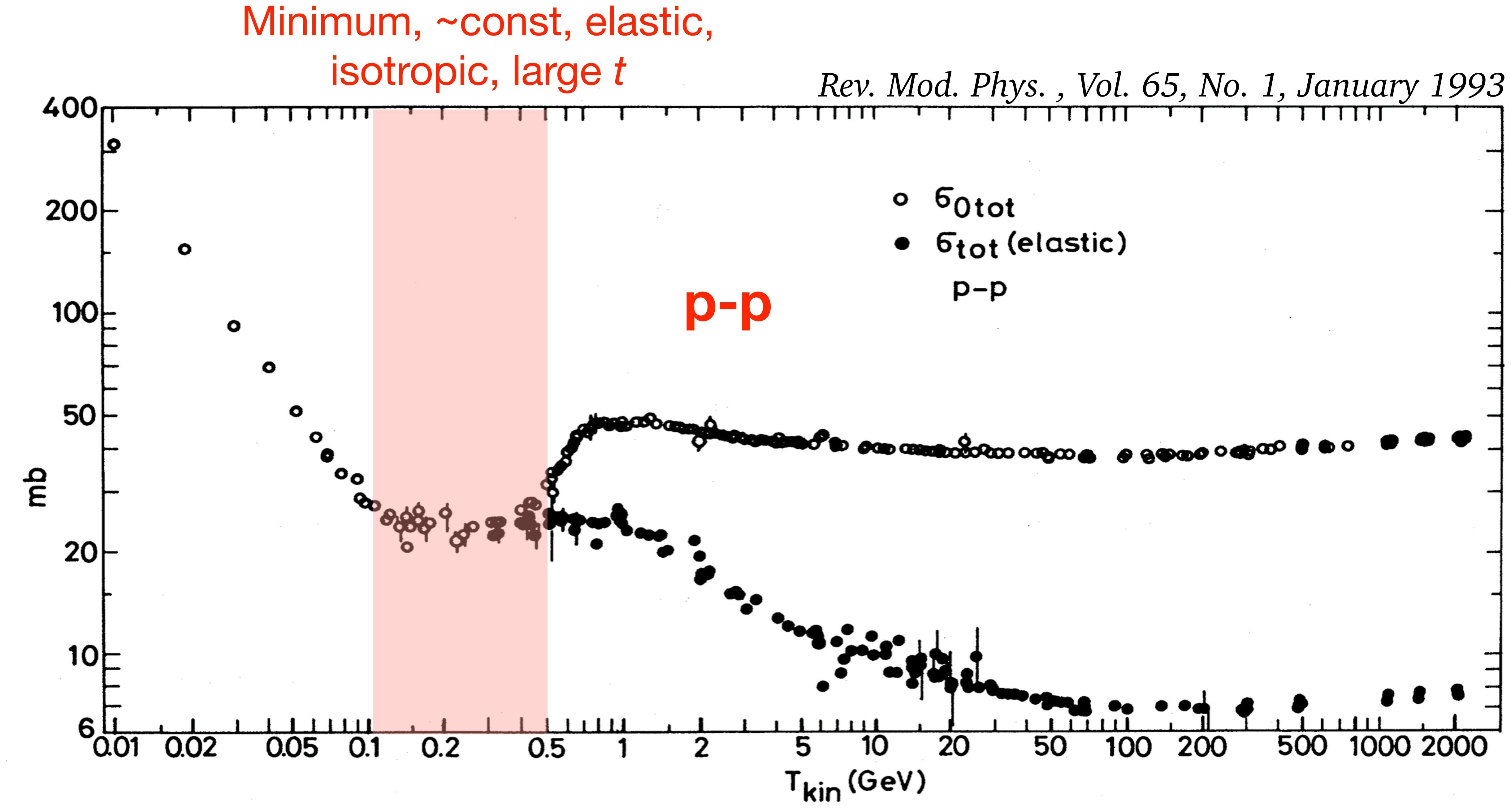
In PWIA: squared Fourier transform of the overlap integral:

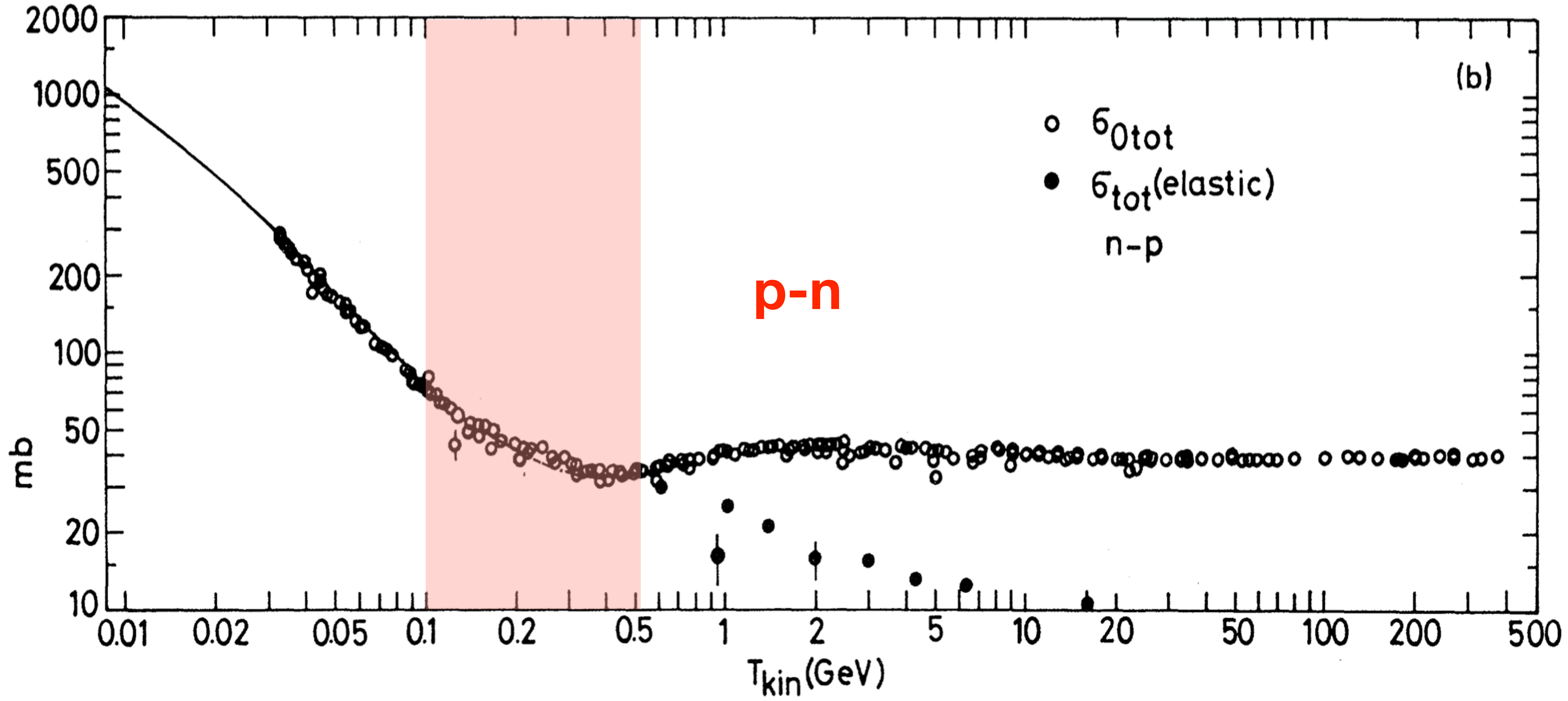
$$\frac{d^4\sigma}{dE_p dE_X d\Omega_p d\Omega_X} = K \frac{d\sigma_{pX}}{d\Omega} S_\epsilon(\mathbf{Q}_X)$$

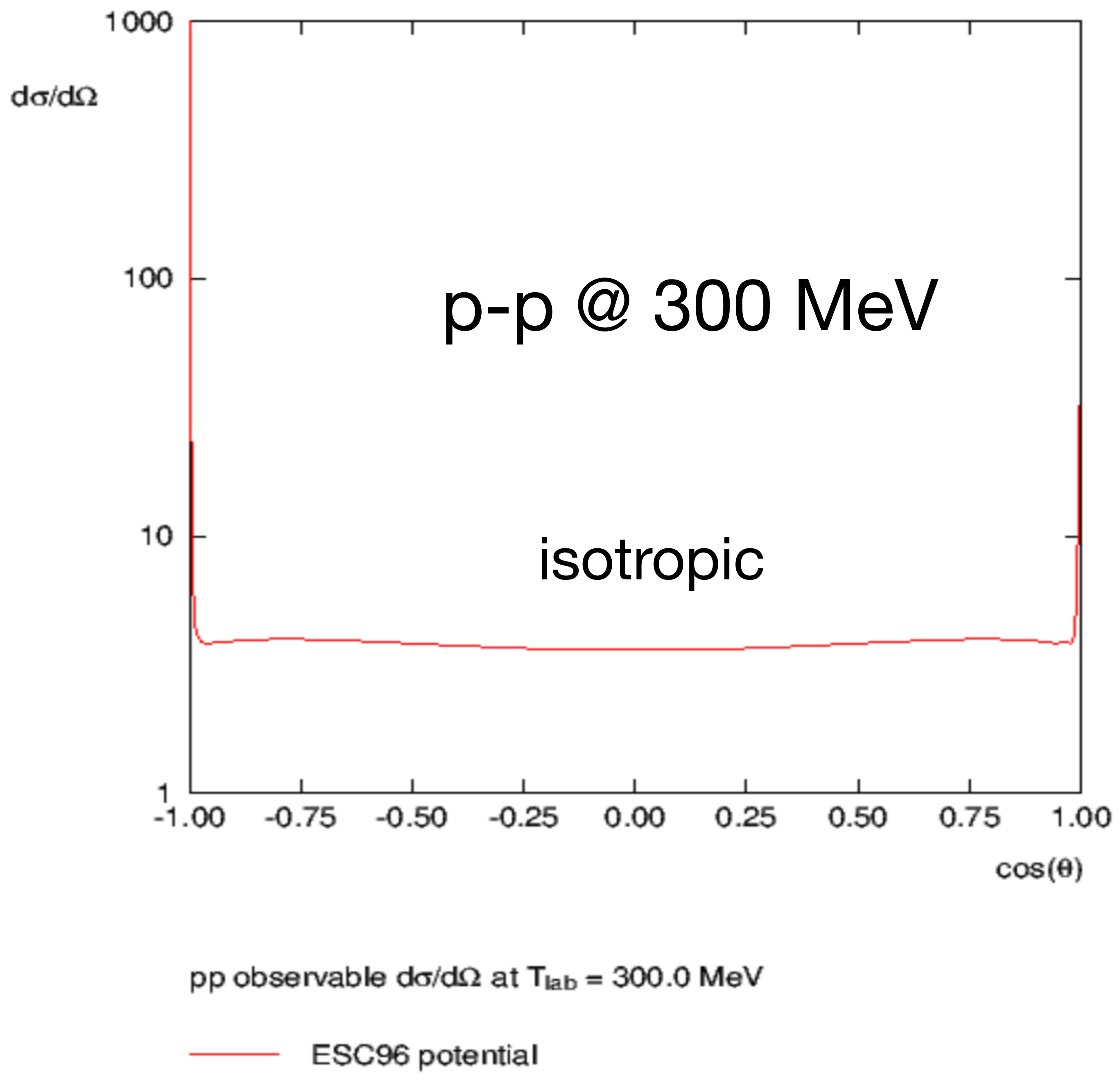
$$< \text{A-X}^* \,|\, a_X \,|\, \text{A} >$$

free c.s.

NN cross sections and QFS energy regime







Suitable energy for QFS studies:
100 - 500 MeV

T_{kin} = 400 MeV: $\frac{\sigma_{pp}}{\sigma_{pn}} \approx 1.27$

Mean free-path (ρ = 0.15 fm^{-3}, σ_f=25 mb):

$$\Lambda = \frac{1}{\rho\sigma_f} \approx 2.7 \text{ fm}$$

$$R_{rms}(^{12}C) \approx 2.45\text{fm}$$

QFS reactions for nuclear structure studies

(p,2p) and (p,pn)

- Spectroscopy of valence and deeply-bound SP states
- Evolution of shell structure in asymmetric nuclei
- Study of spatial n-n correlations in nuclear halo
- Study of fission barriers in heavy nuclei
- **Probing short-range correlations: e.g. (p,2p+n)**

(p, p ^{4}He):

- Cluster structure of light nuclei
- Alpha-clustering near surface of heavy nuclei
- Study of correlated multi-neutron systems

(p, p ^{2}H)

- Study of p-n pairing and correlations (see talk of Marina Petri)

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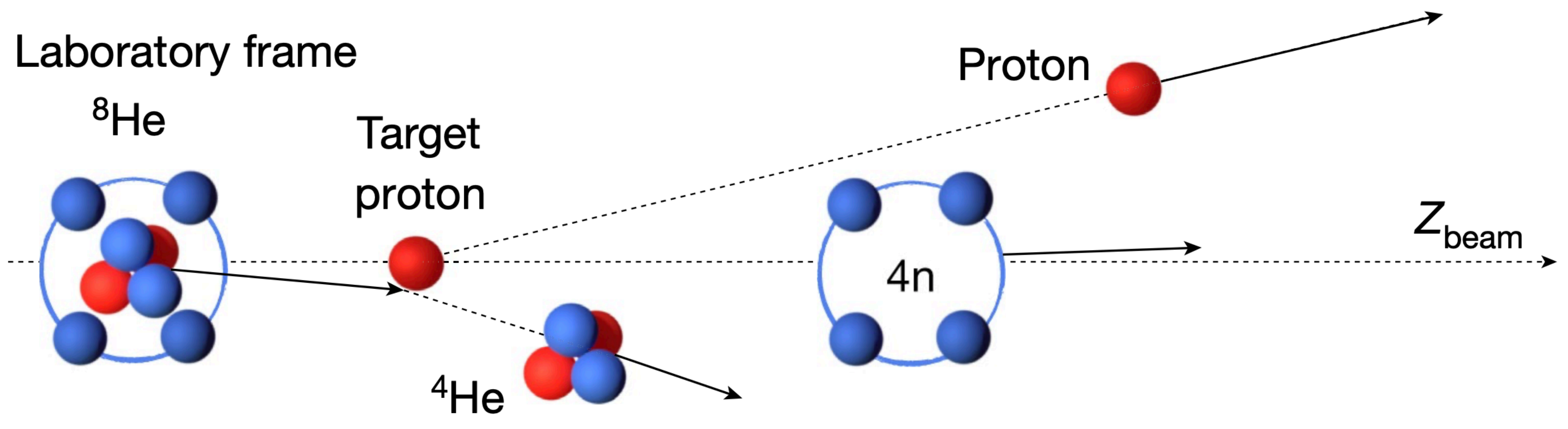
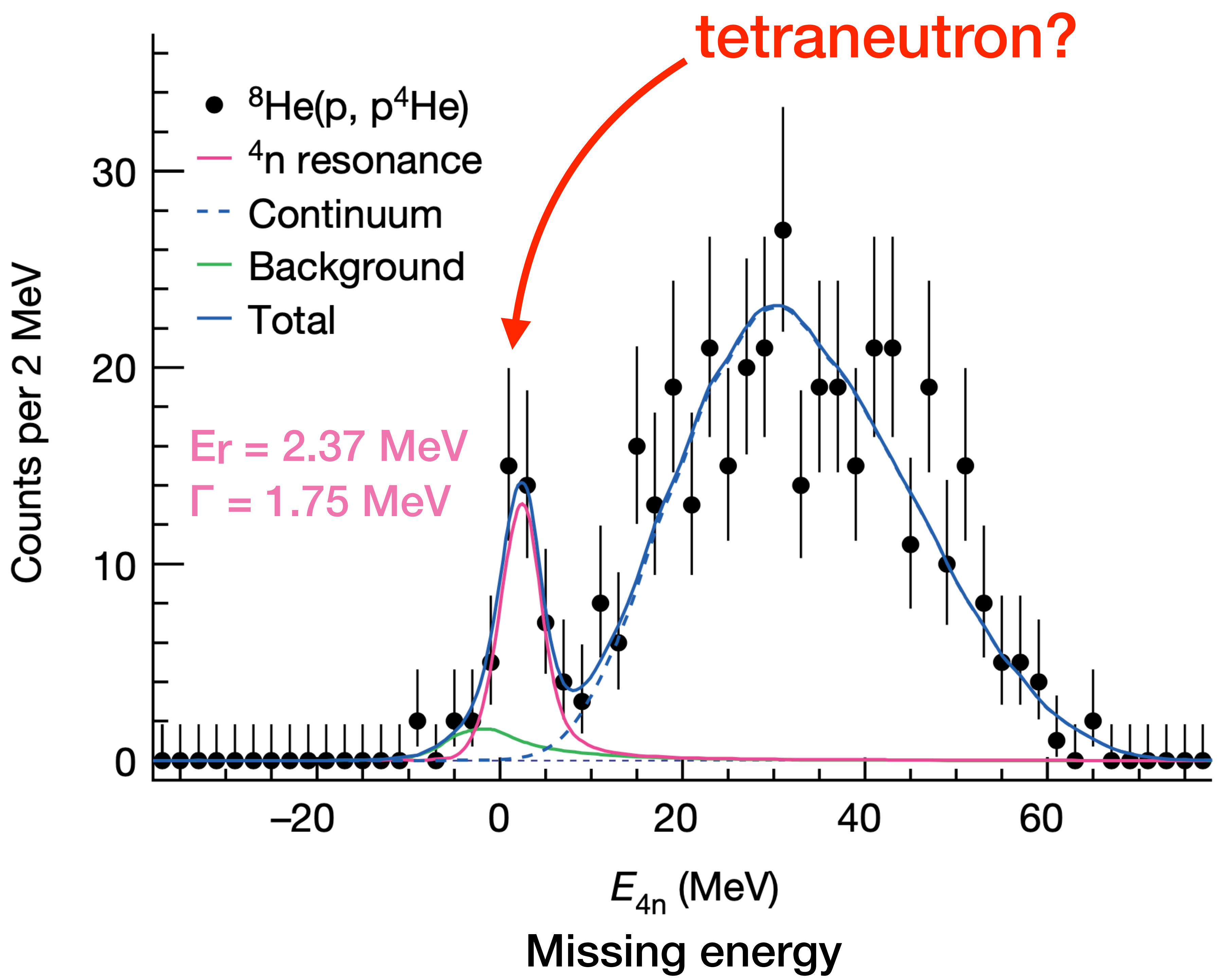


M. Duer et al. Nature 606, 678 (2022)



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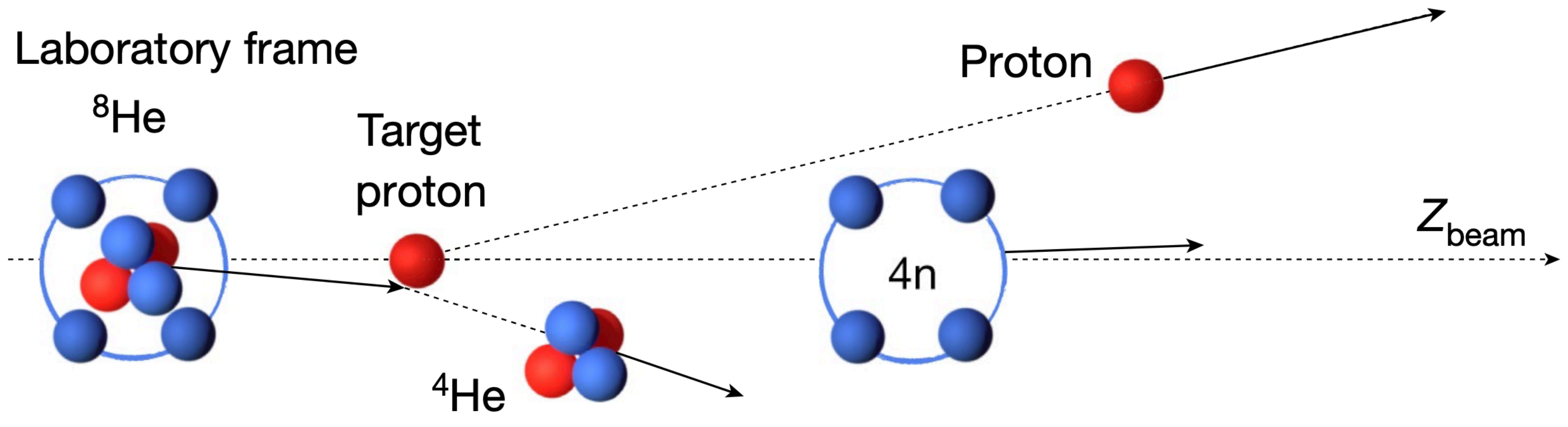

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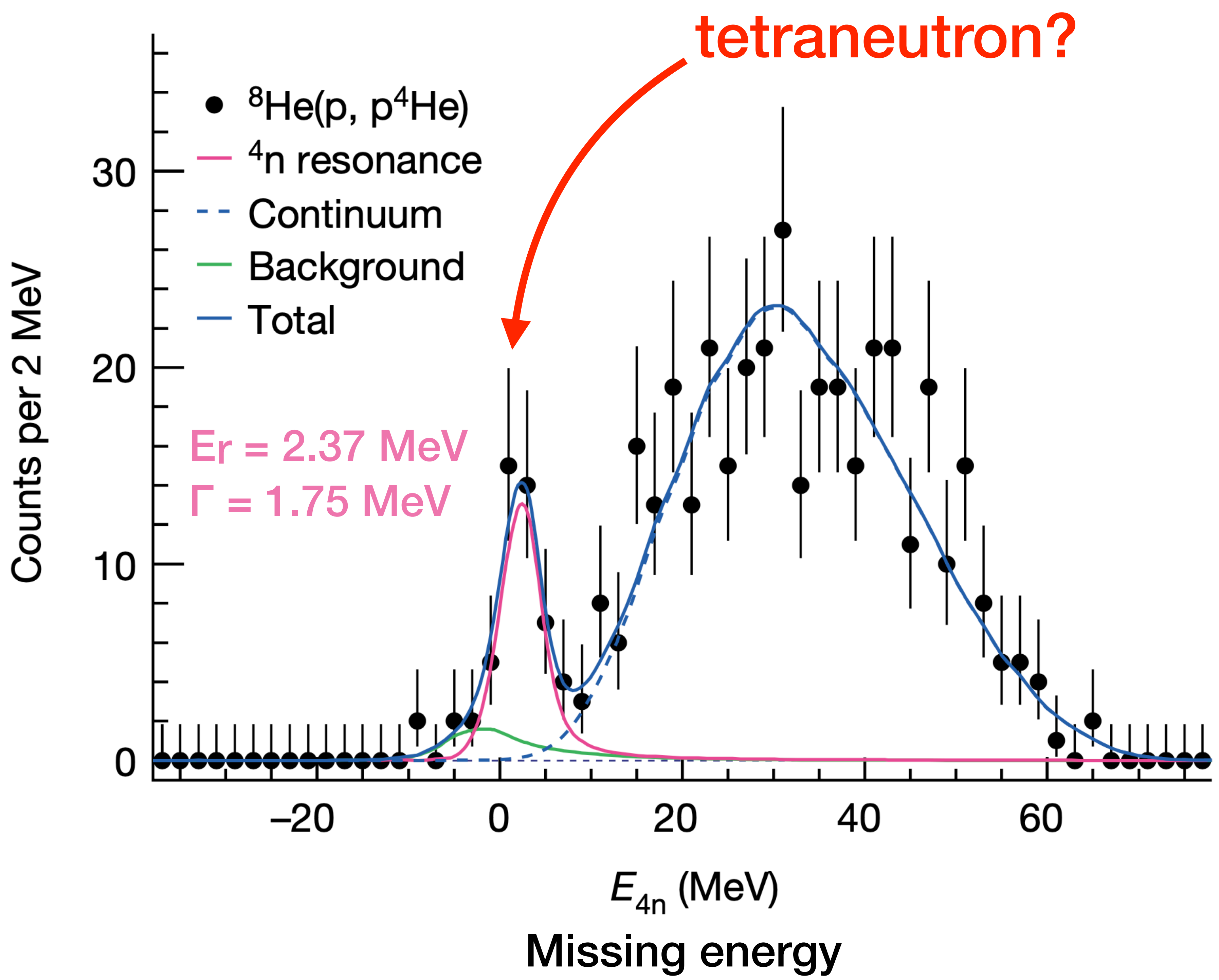

Probing single-particle states in (p,2p) and (p,pn) experiments in direct kinematics

G. Jacob, T.A. Maris, Rev. Mod. Phys. ***38****, 121 (1966)*

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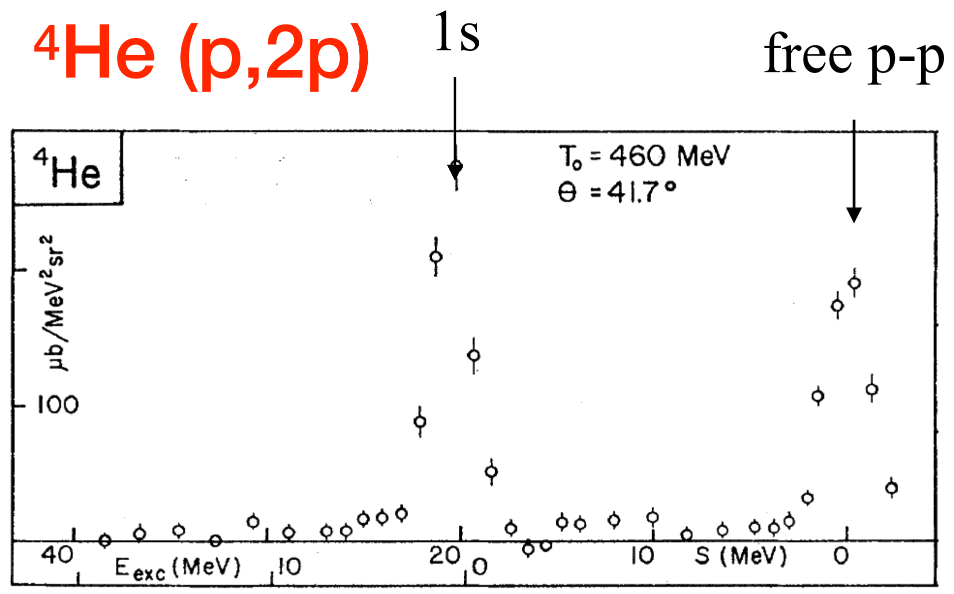

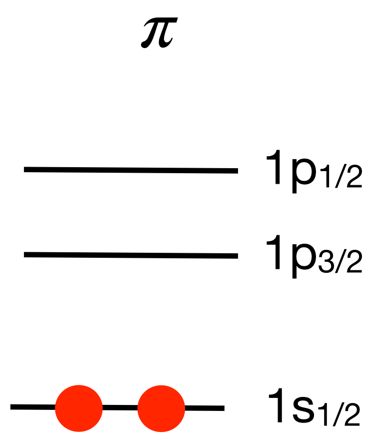

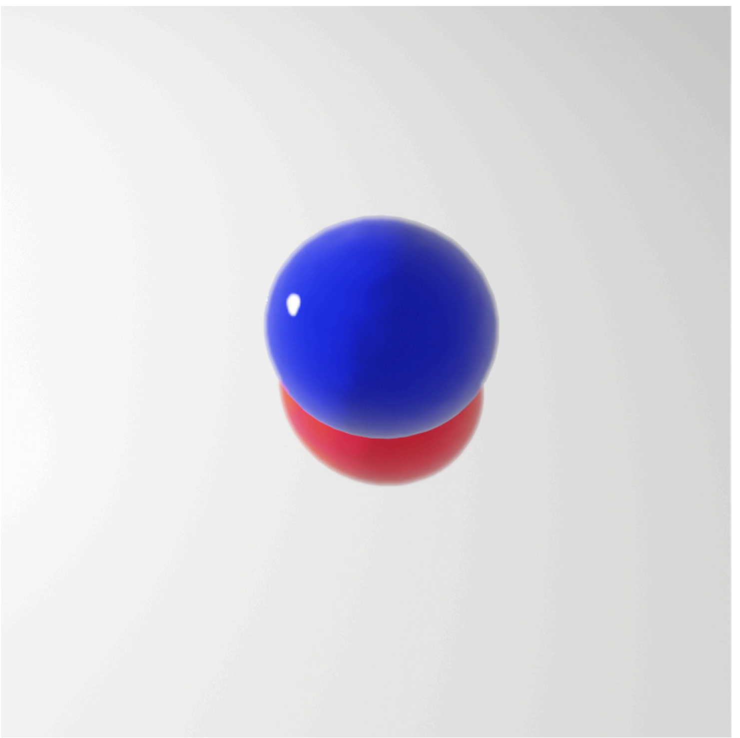

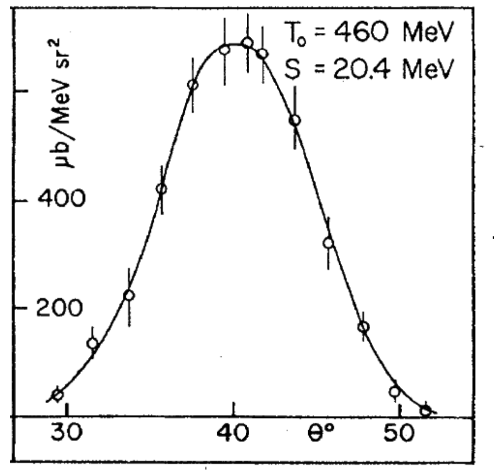

→ pure 1s state!

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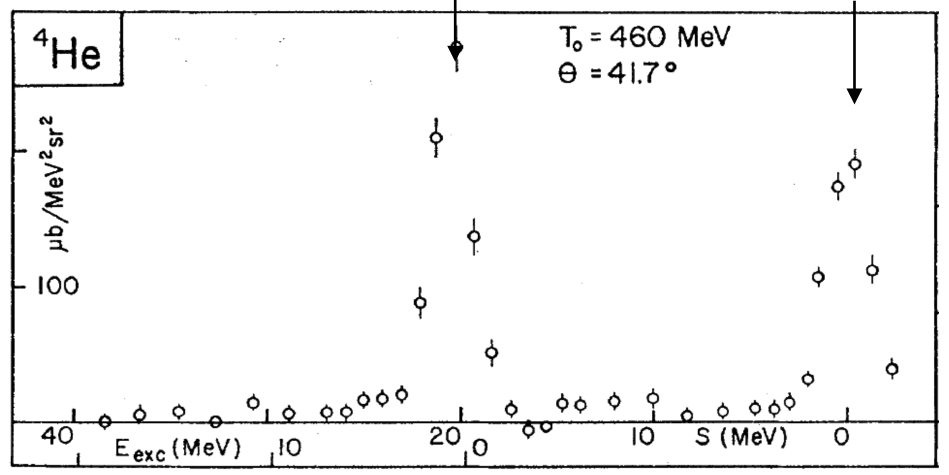
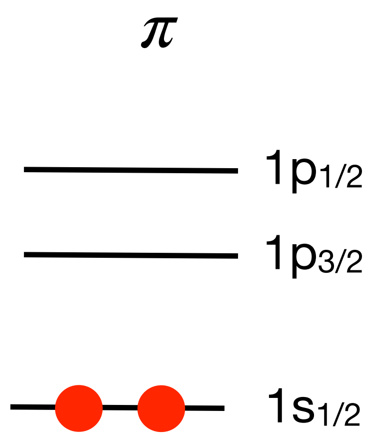
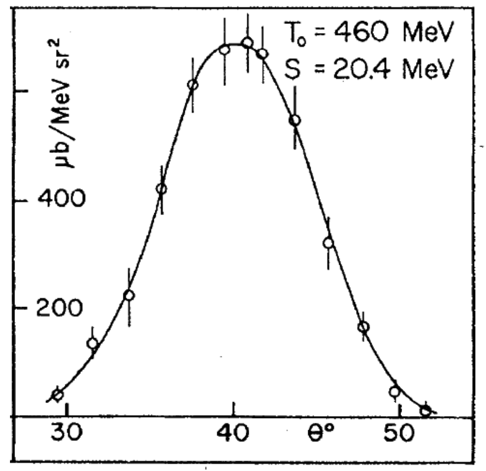
1s

free p-p







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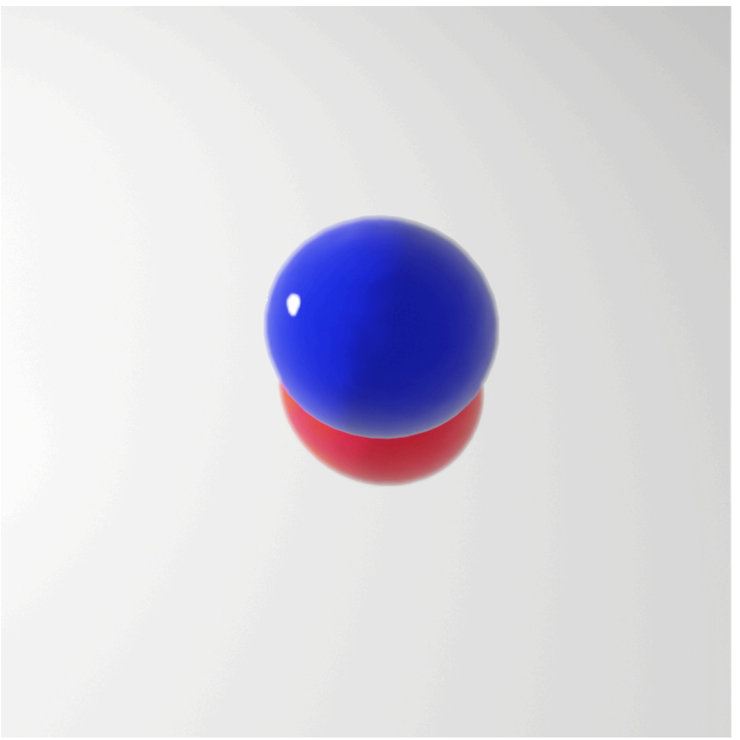
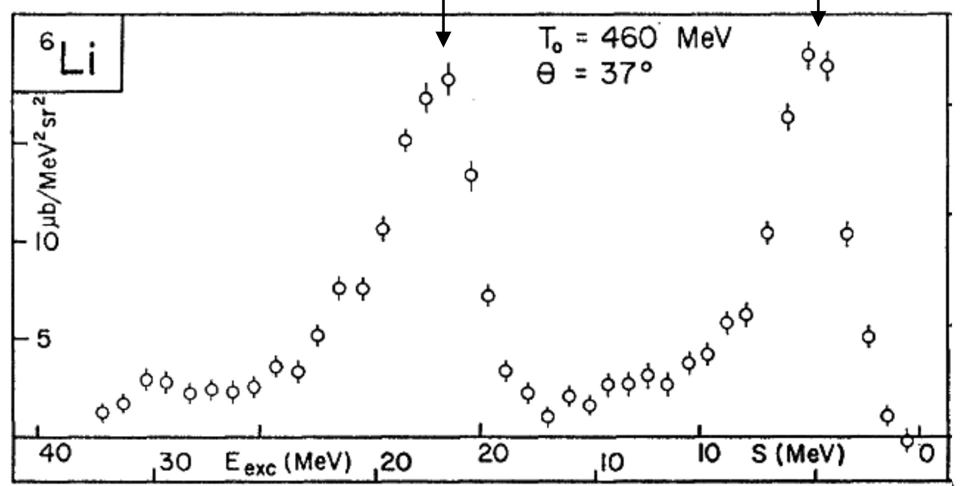
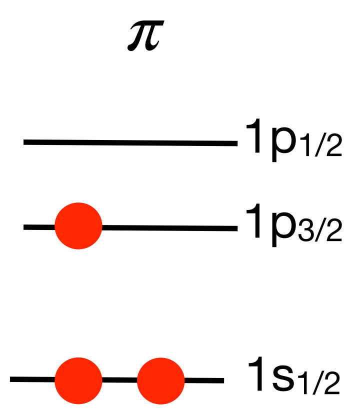


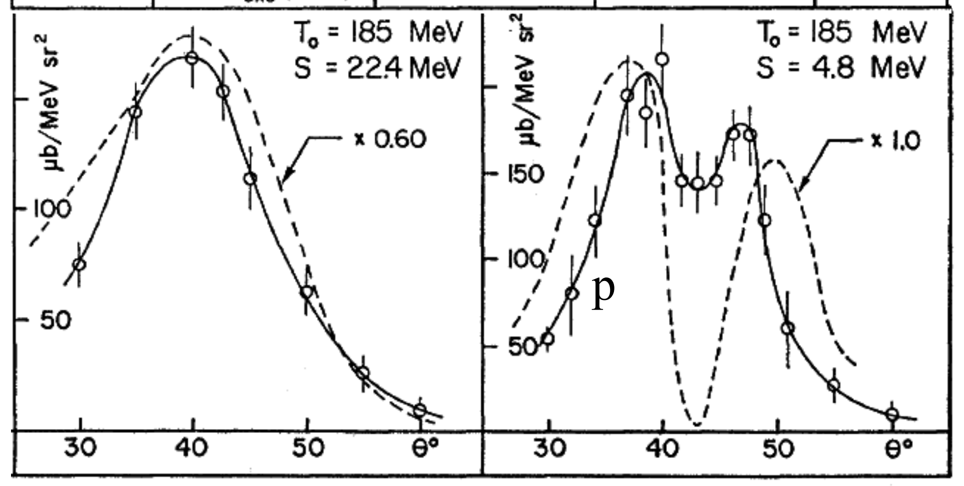
^{6}Li (p,2p)

1s

1p







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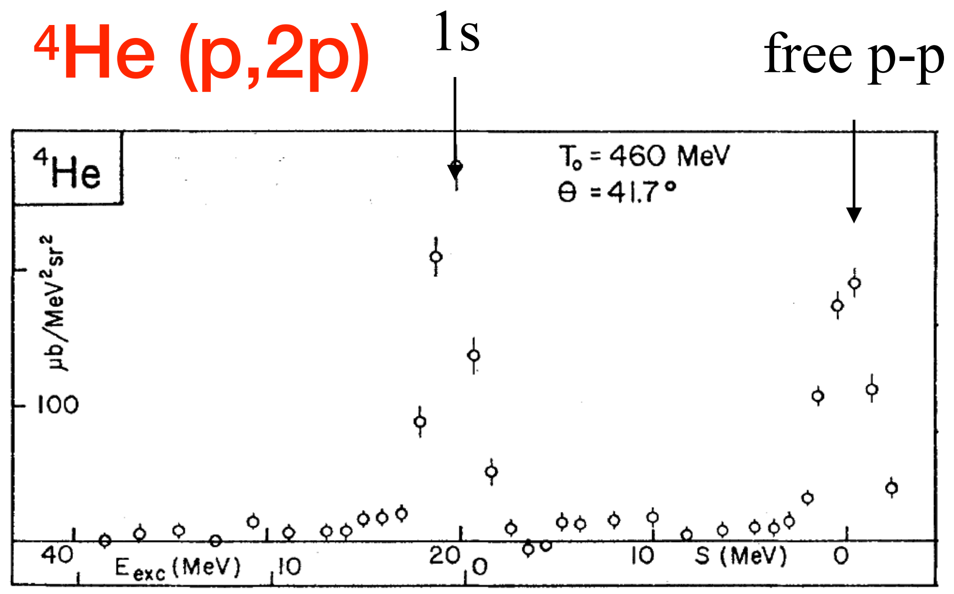

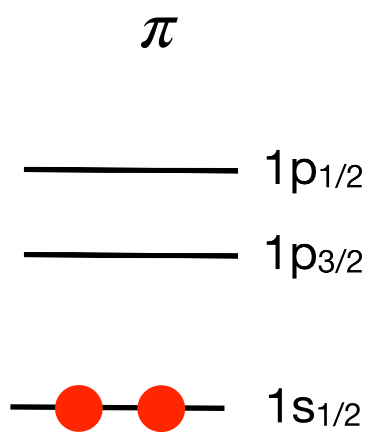

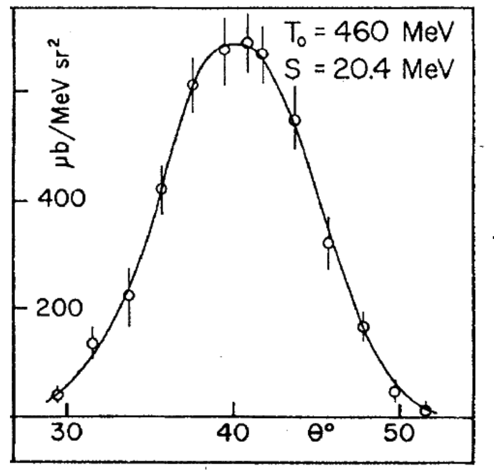

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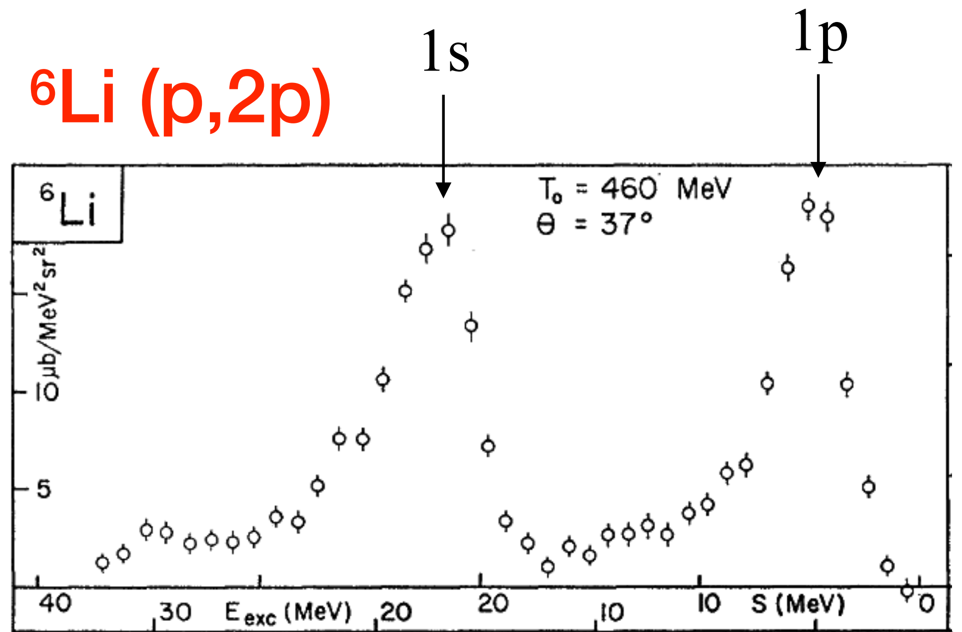
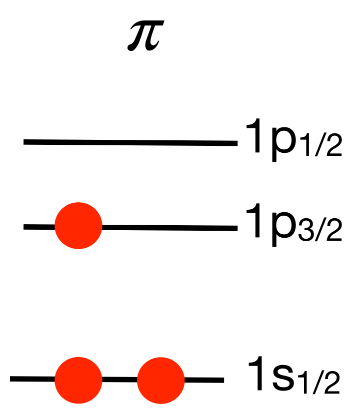
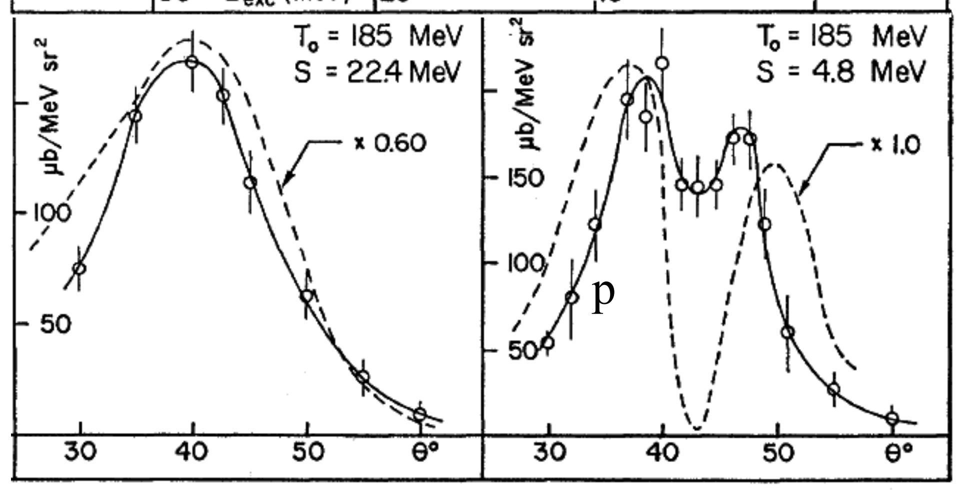
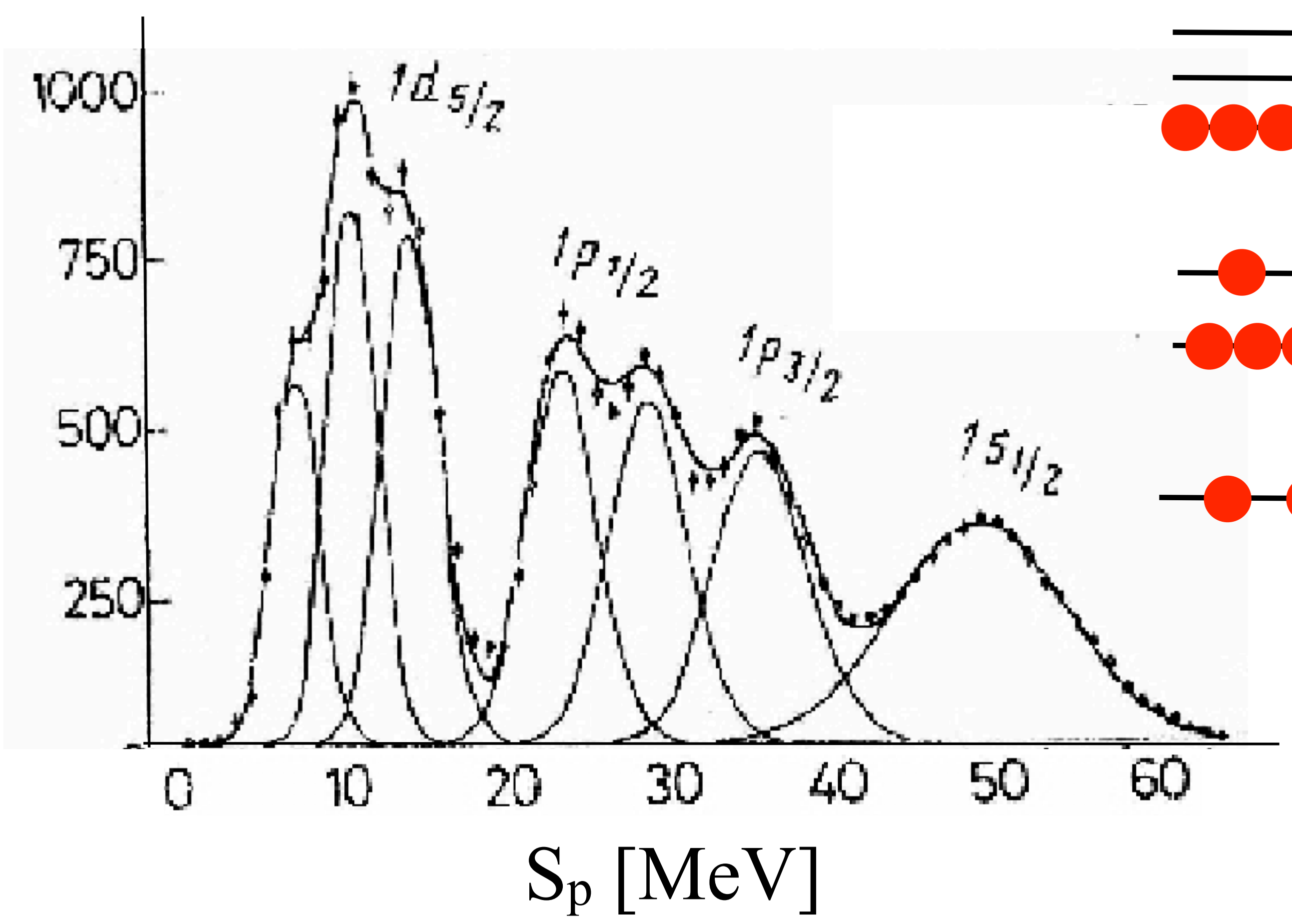
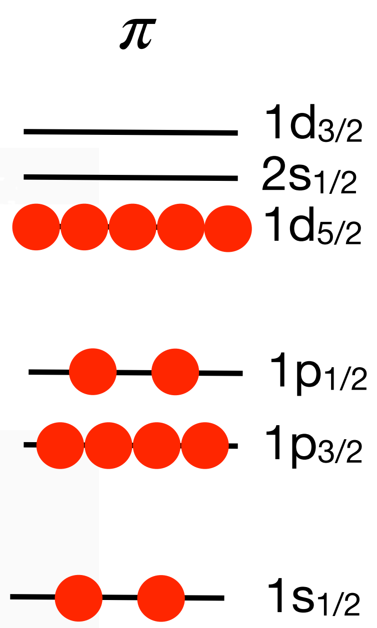






^{27}Al (p,2p) ^{26}Mg





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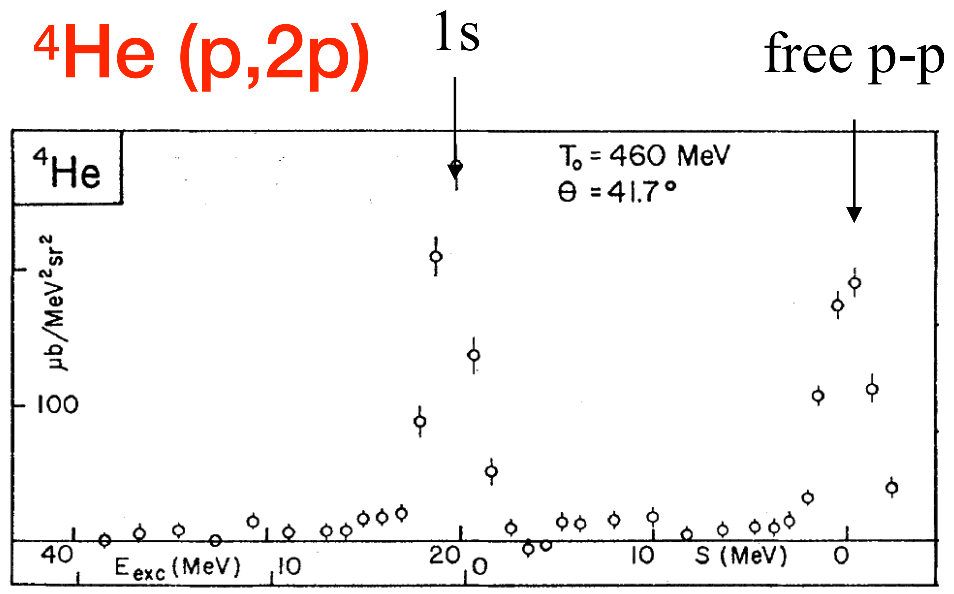

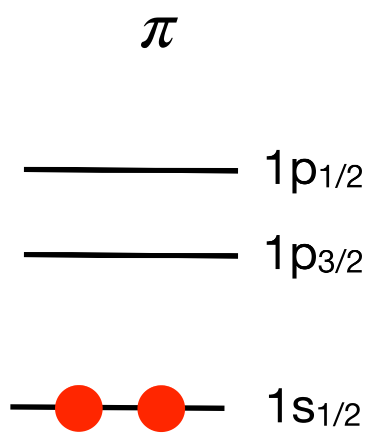

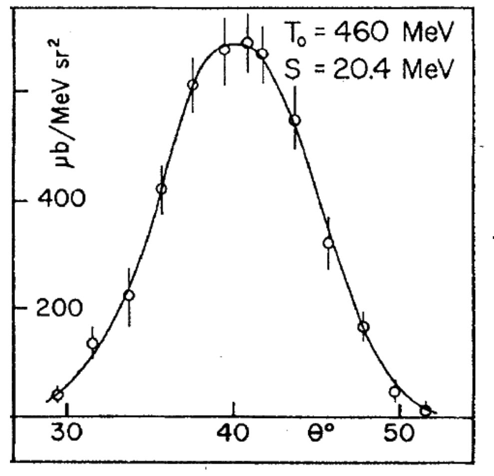

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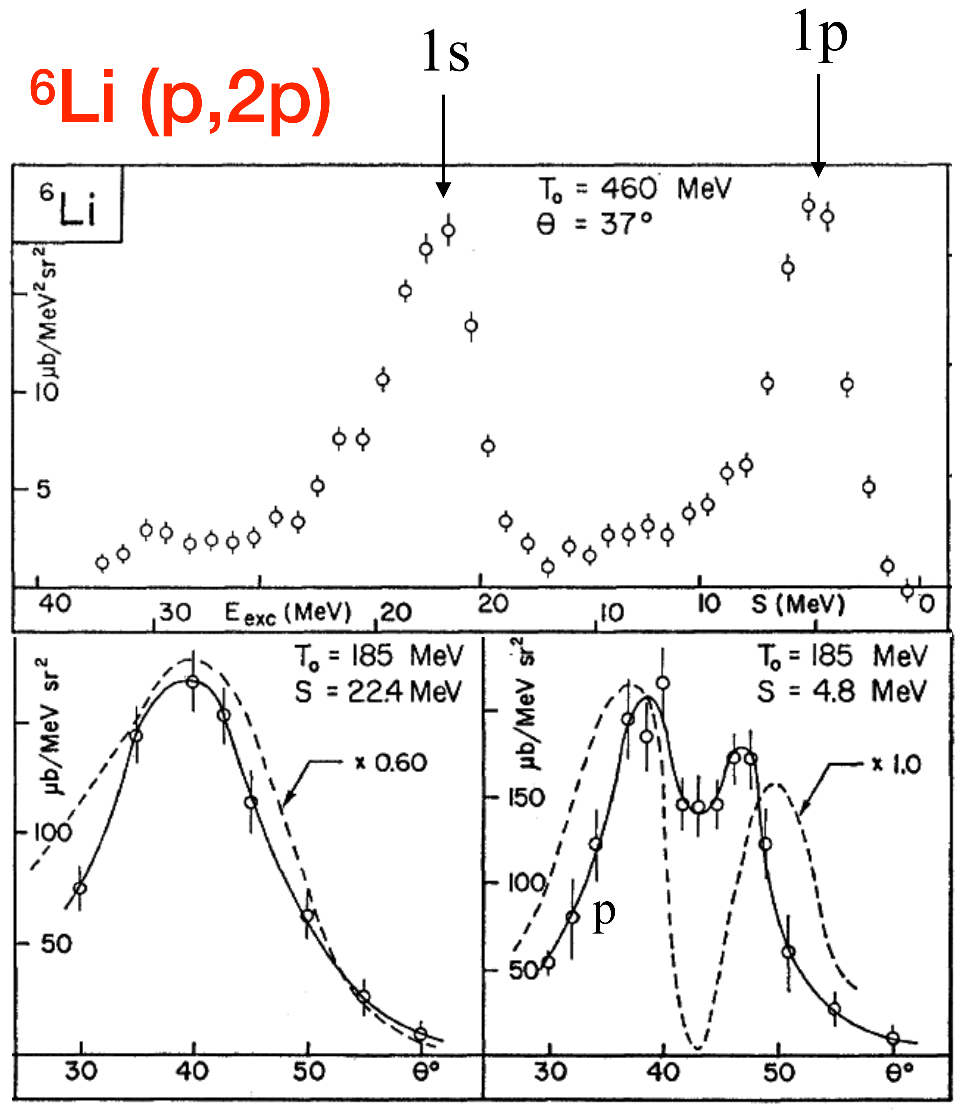

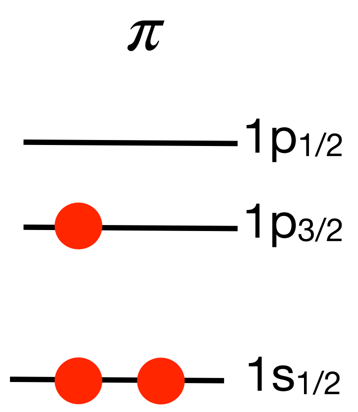

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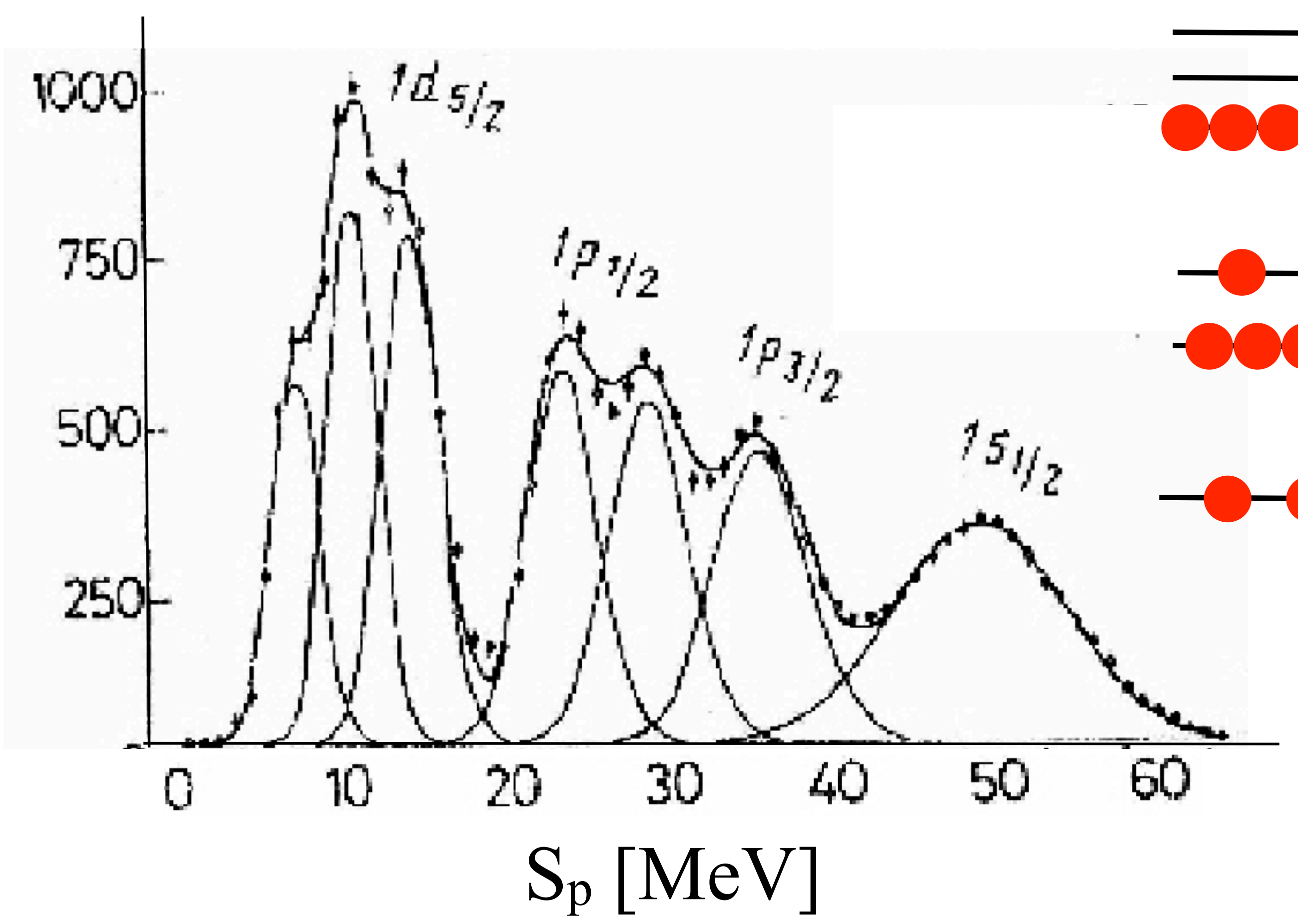
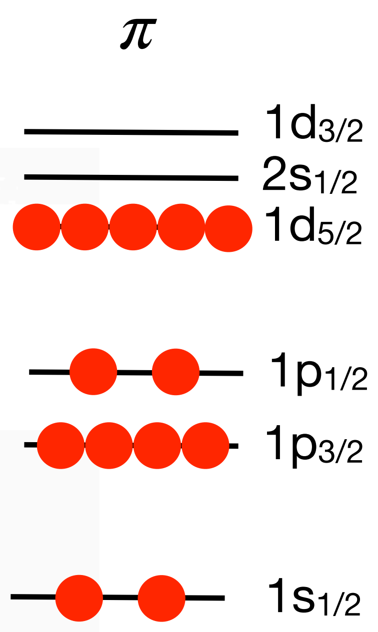
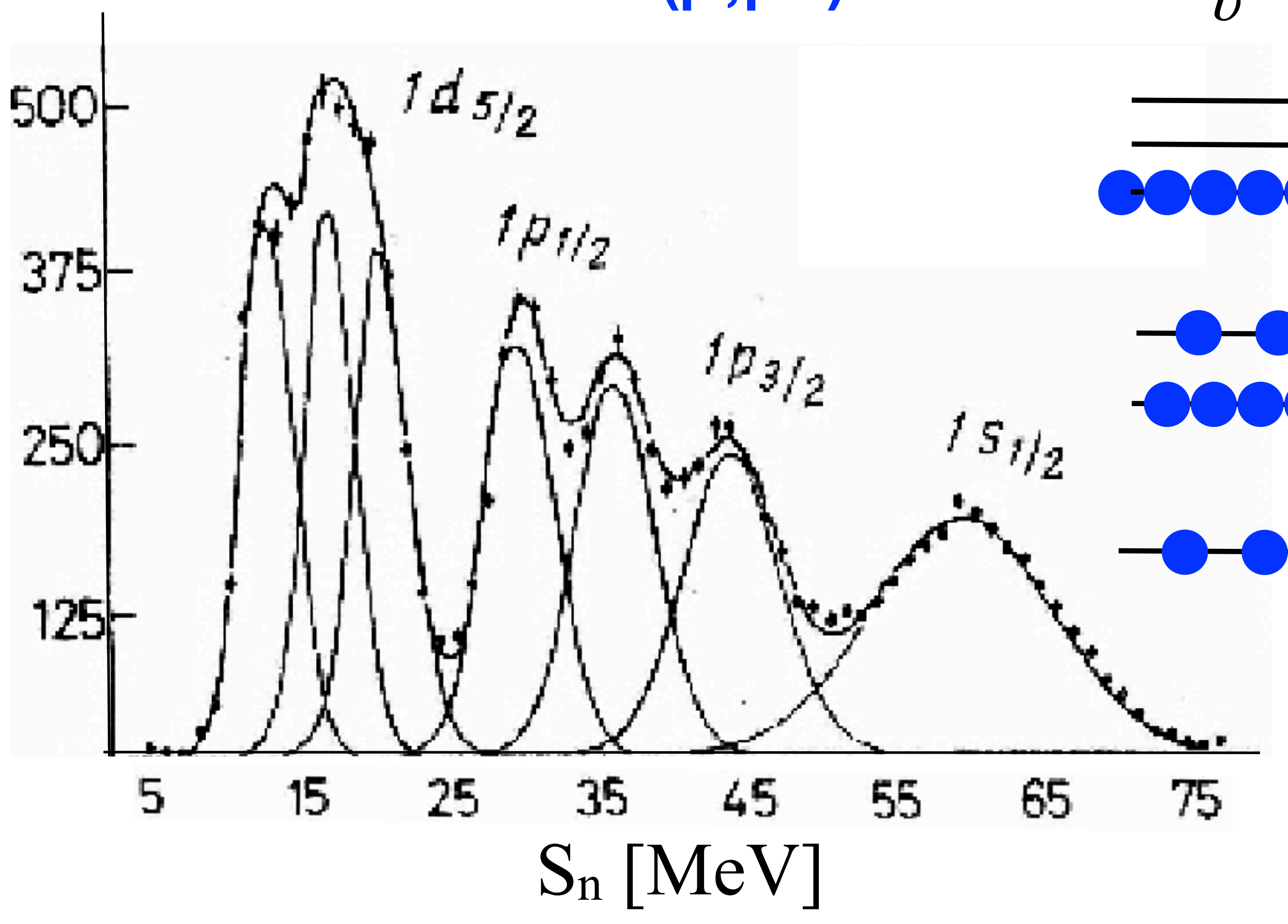
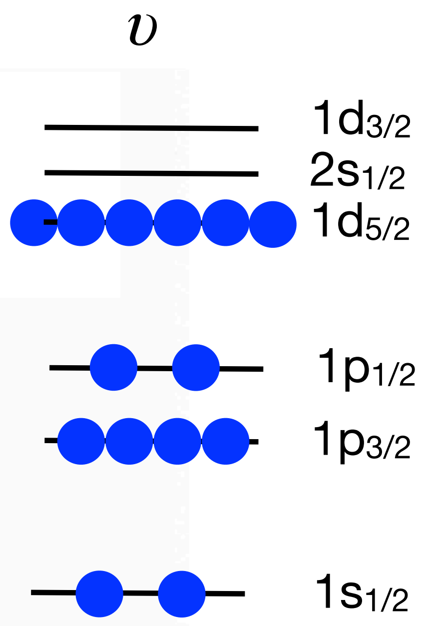




^{27}Al (p,pn) ^{26}Al





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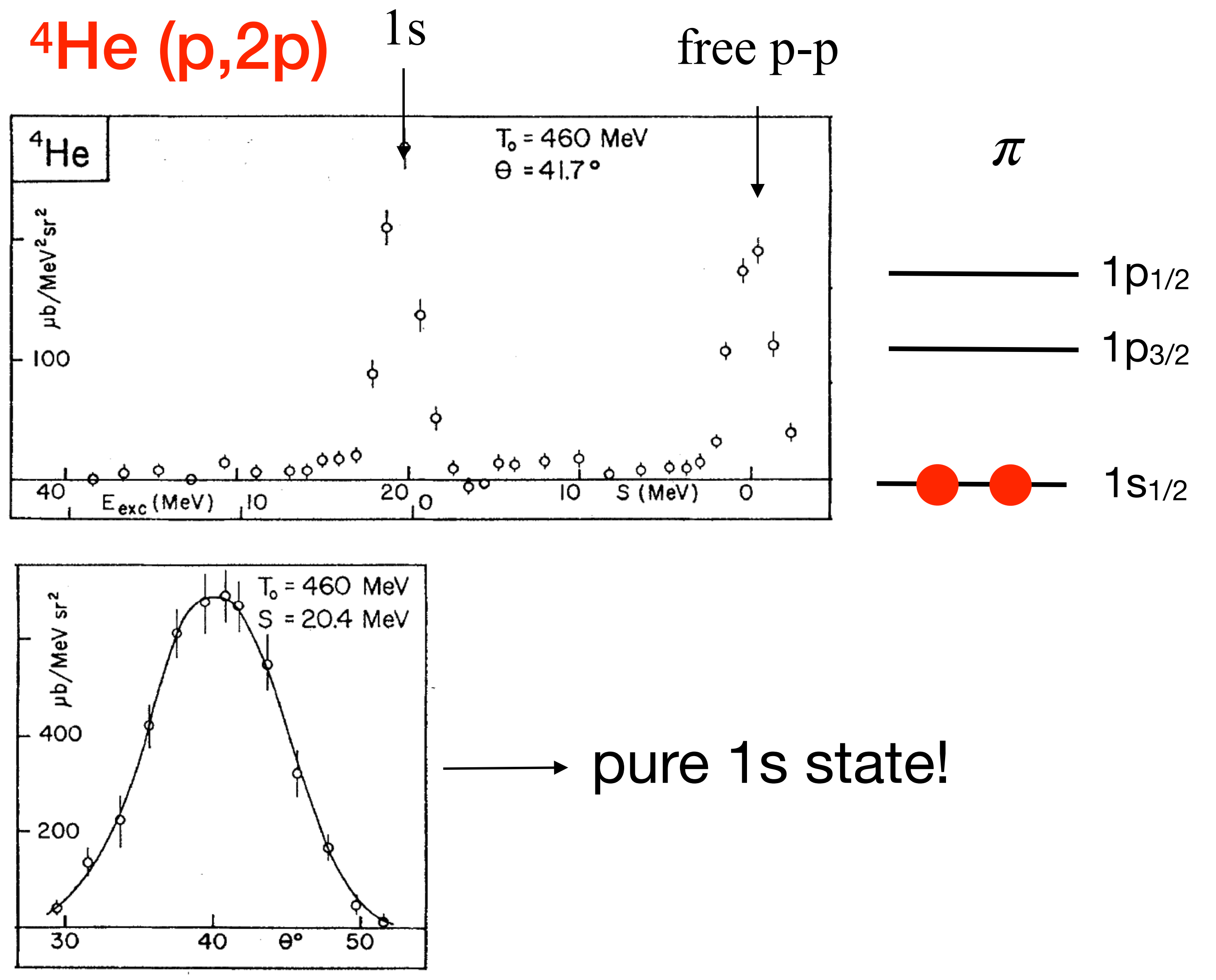

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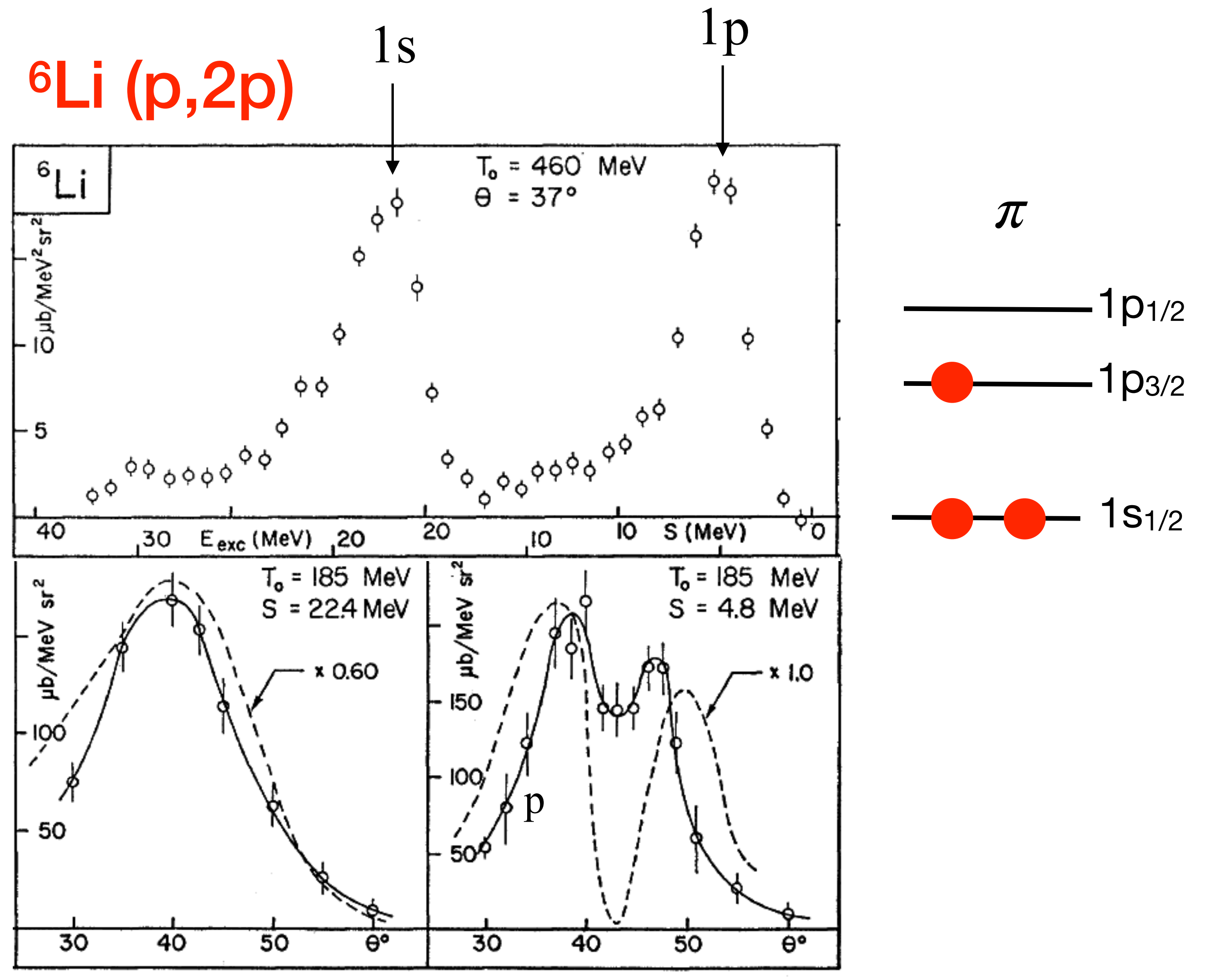

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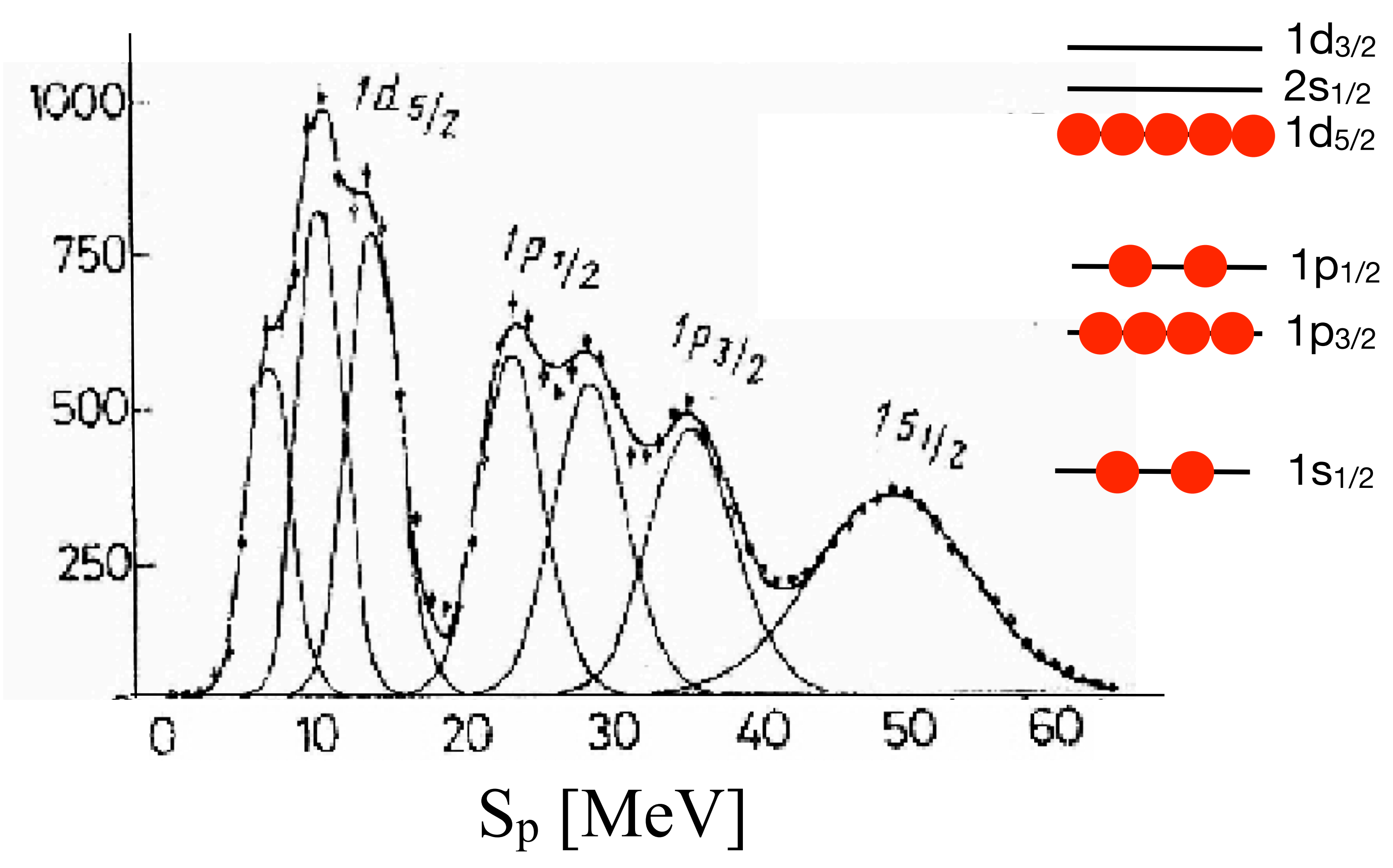
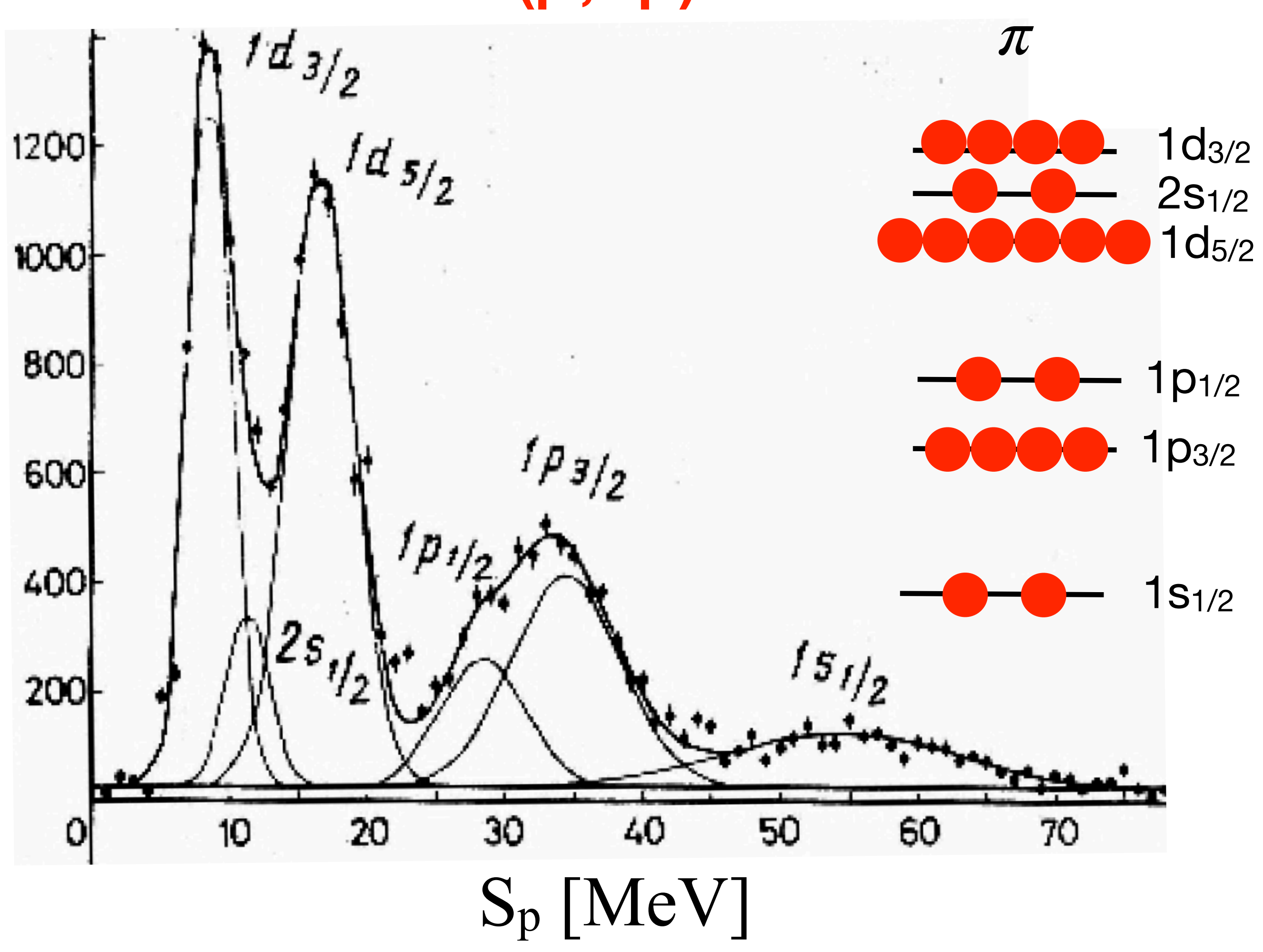


^{40}Ca (p,2p) ^{39}K



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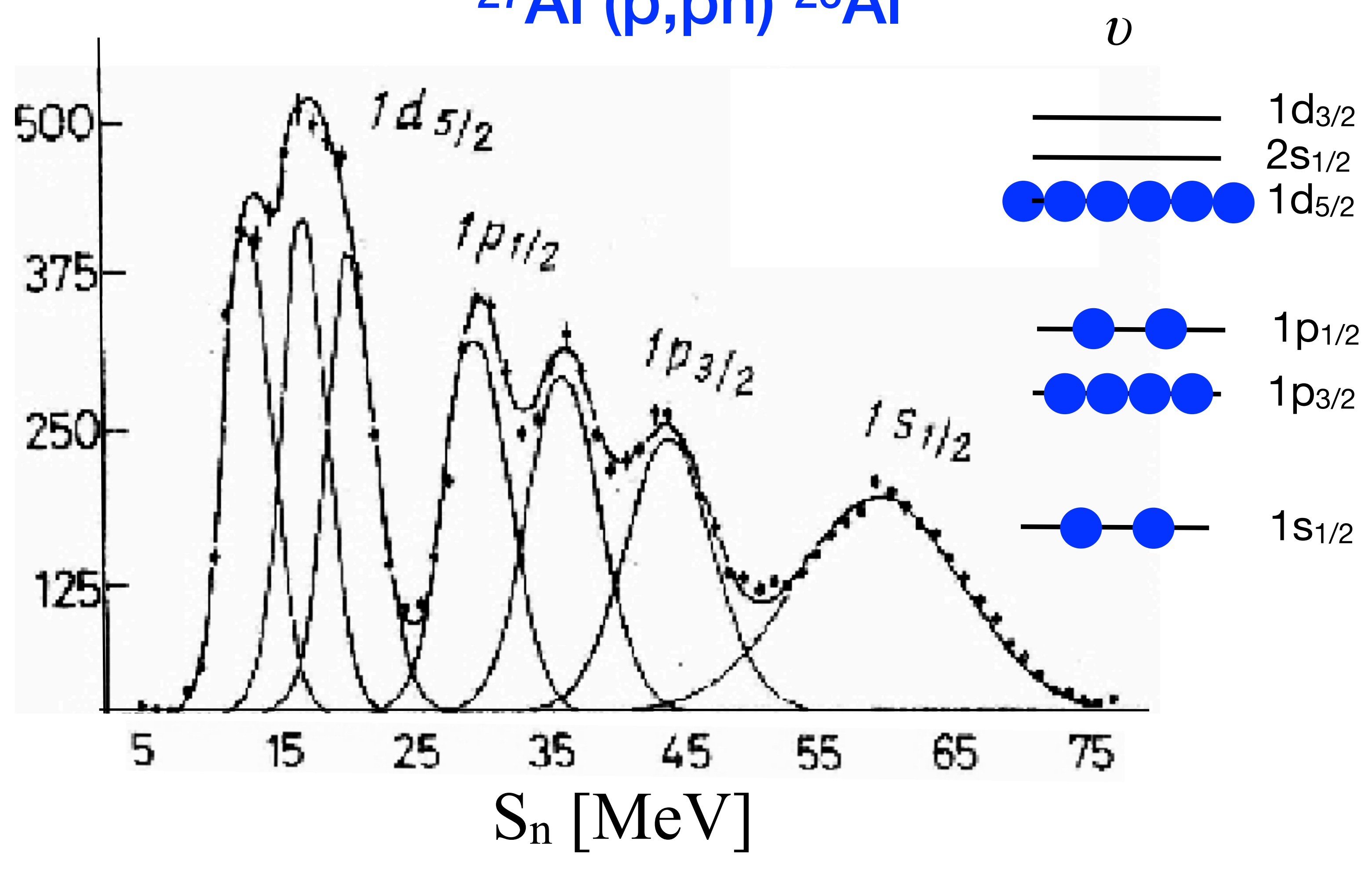
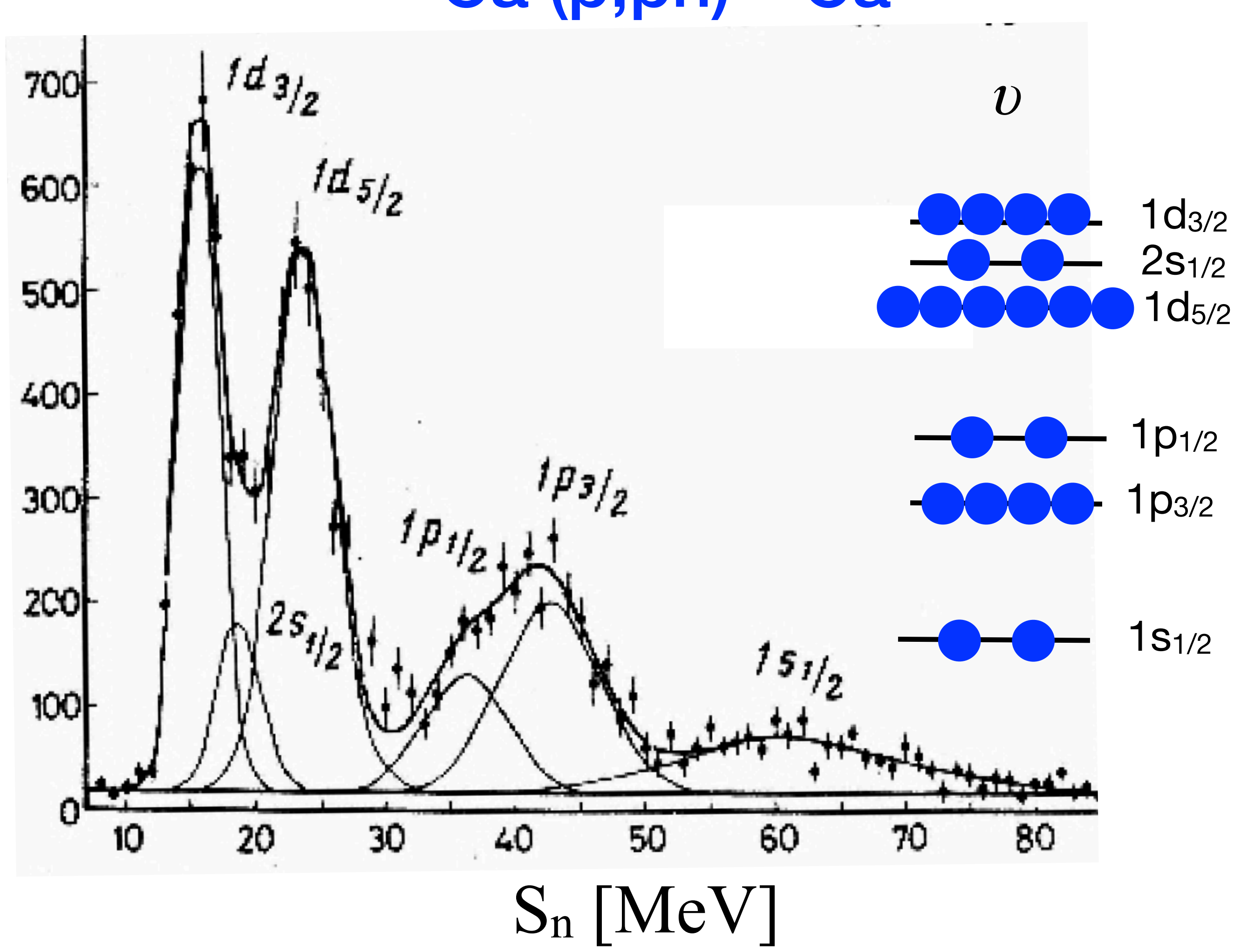
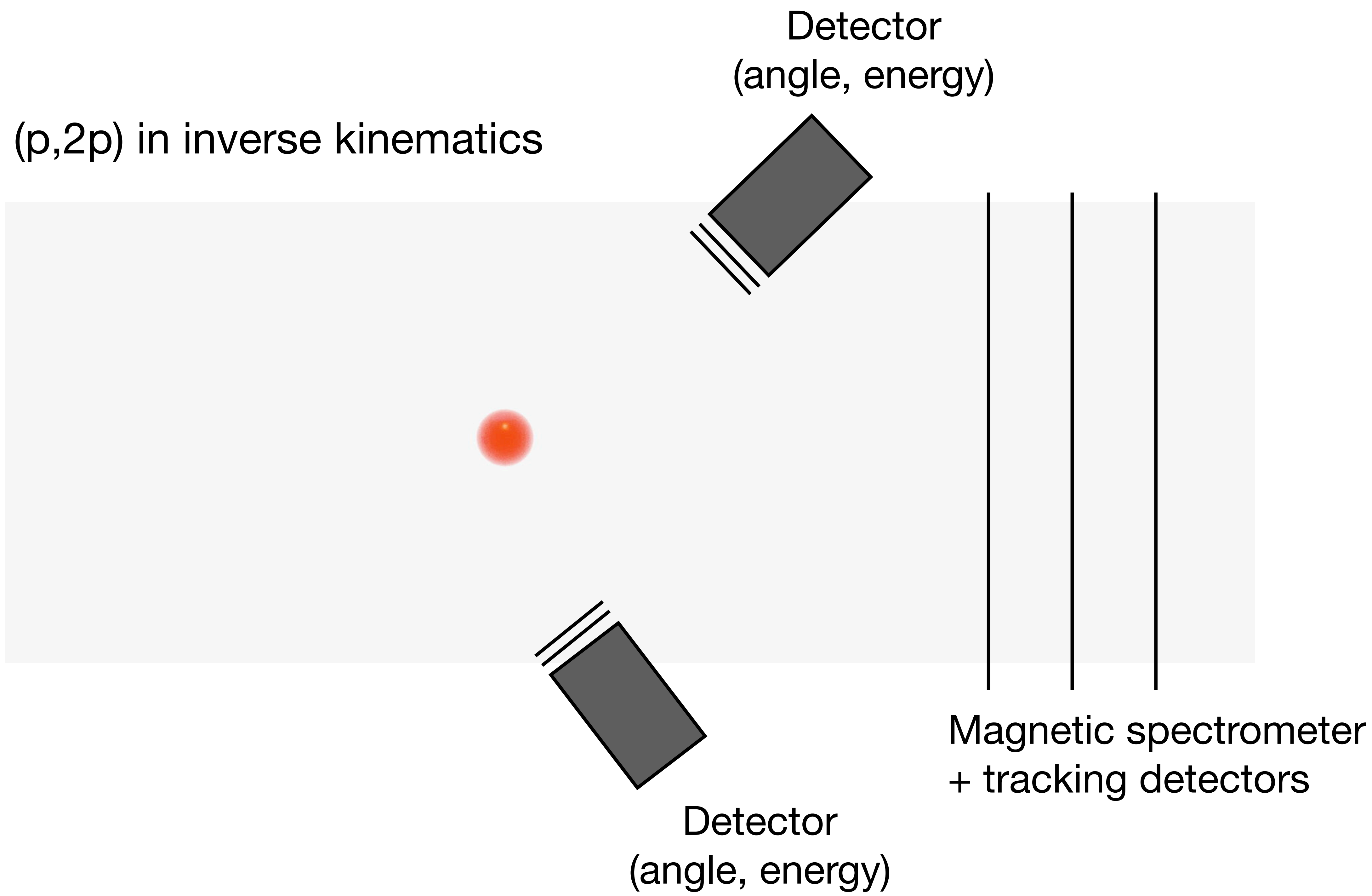
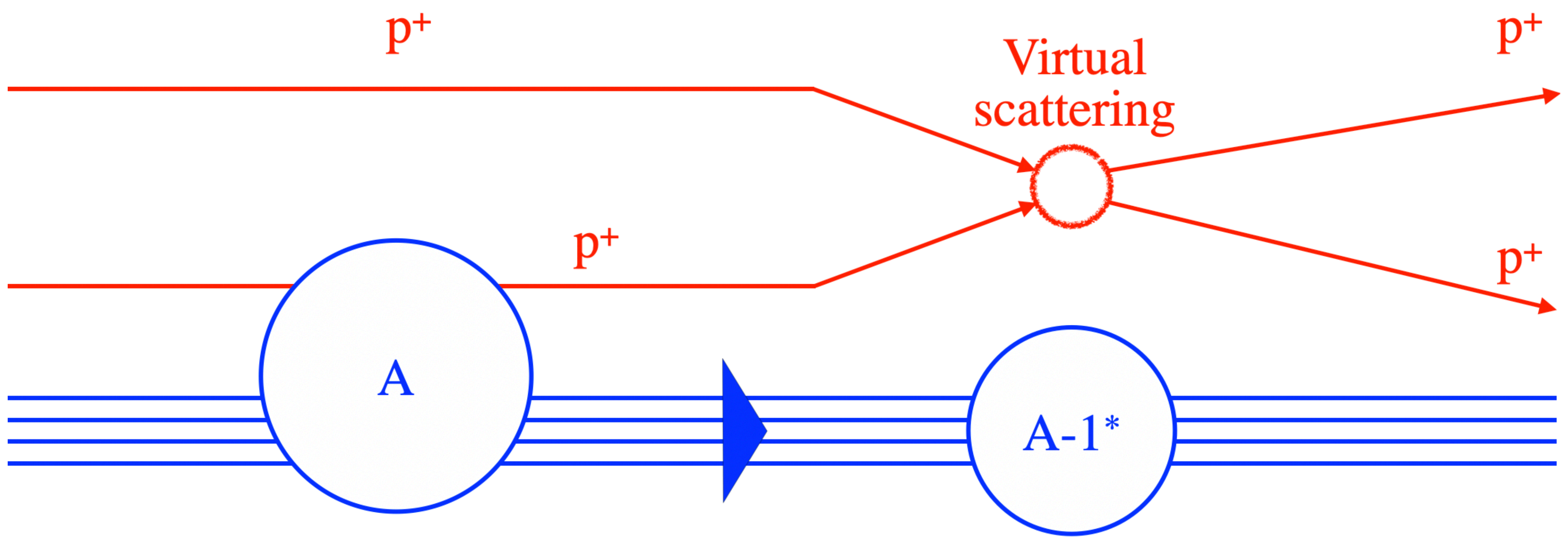


^{40}Ca (p,pn) ^{39}Ca



Inverse kinematics QFS experiments





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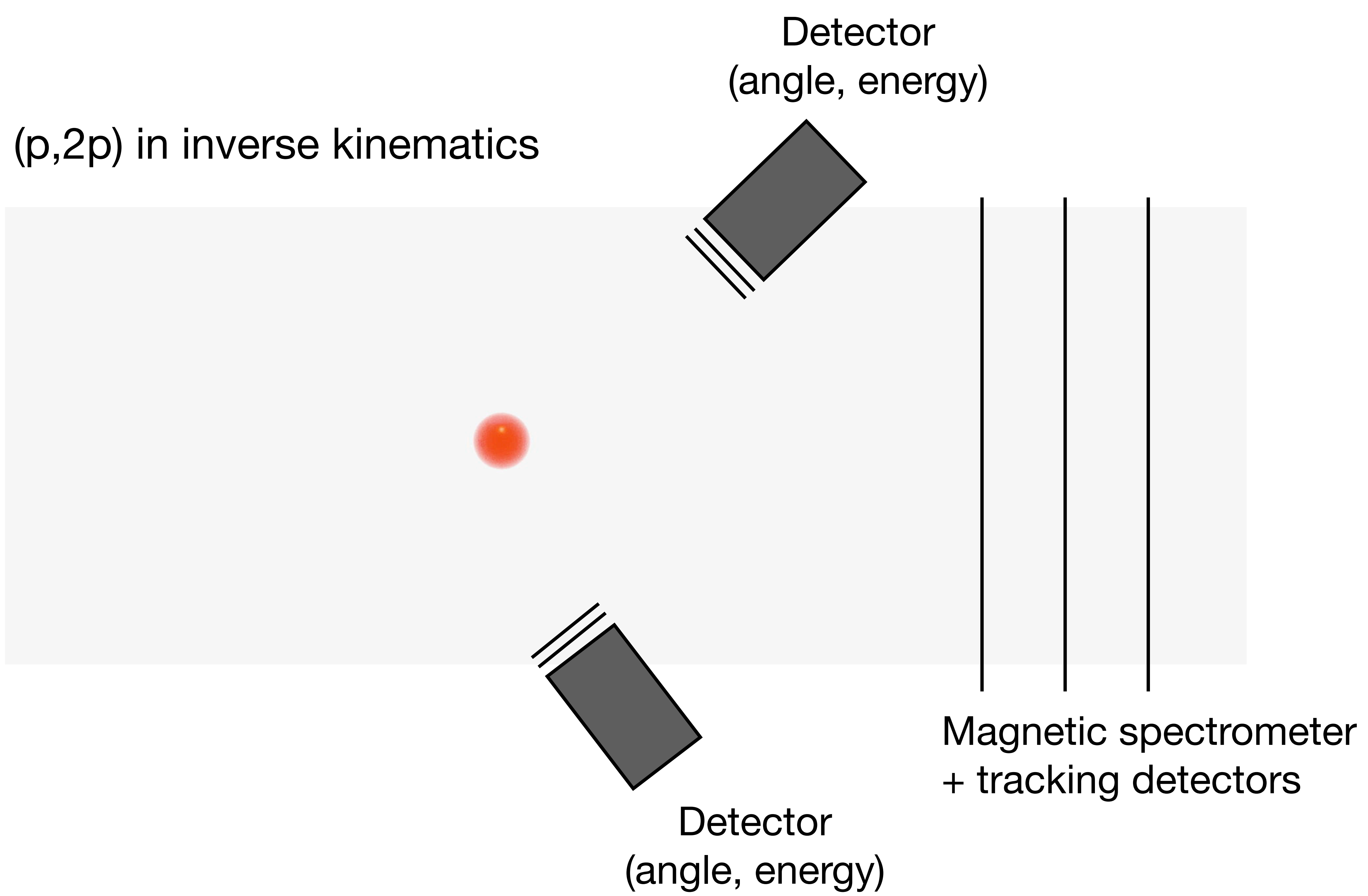
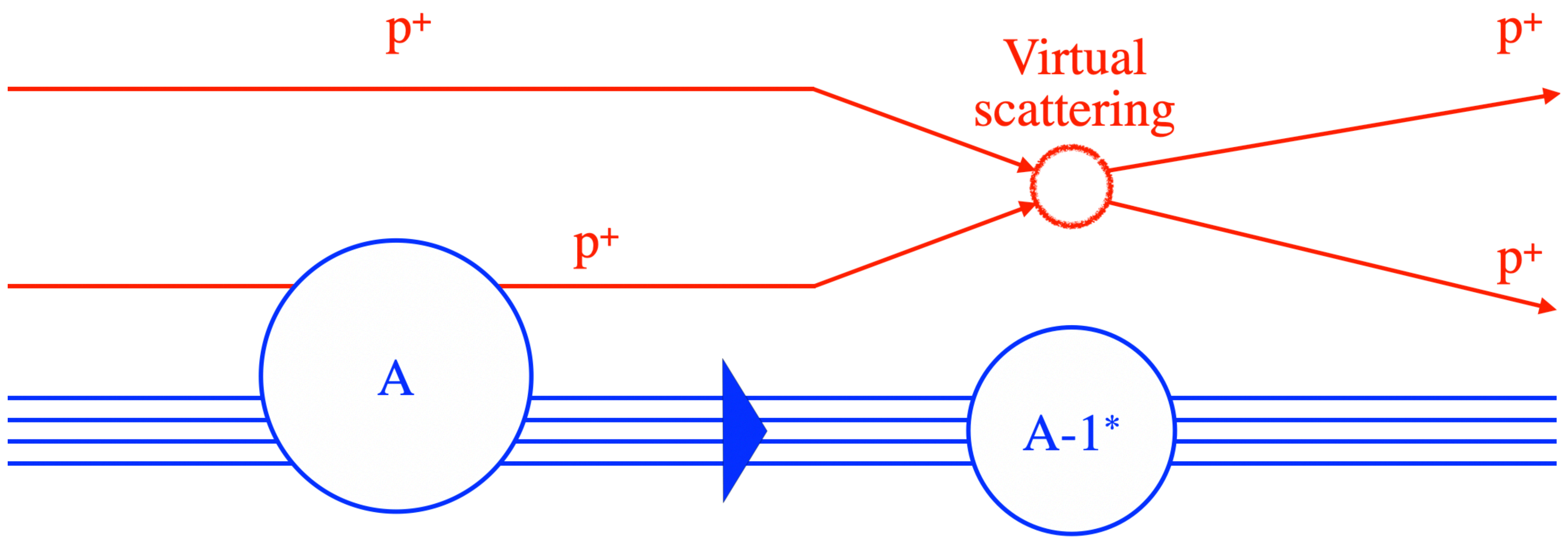
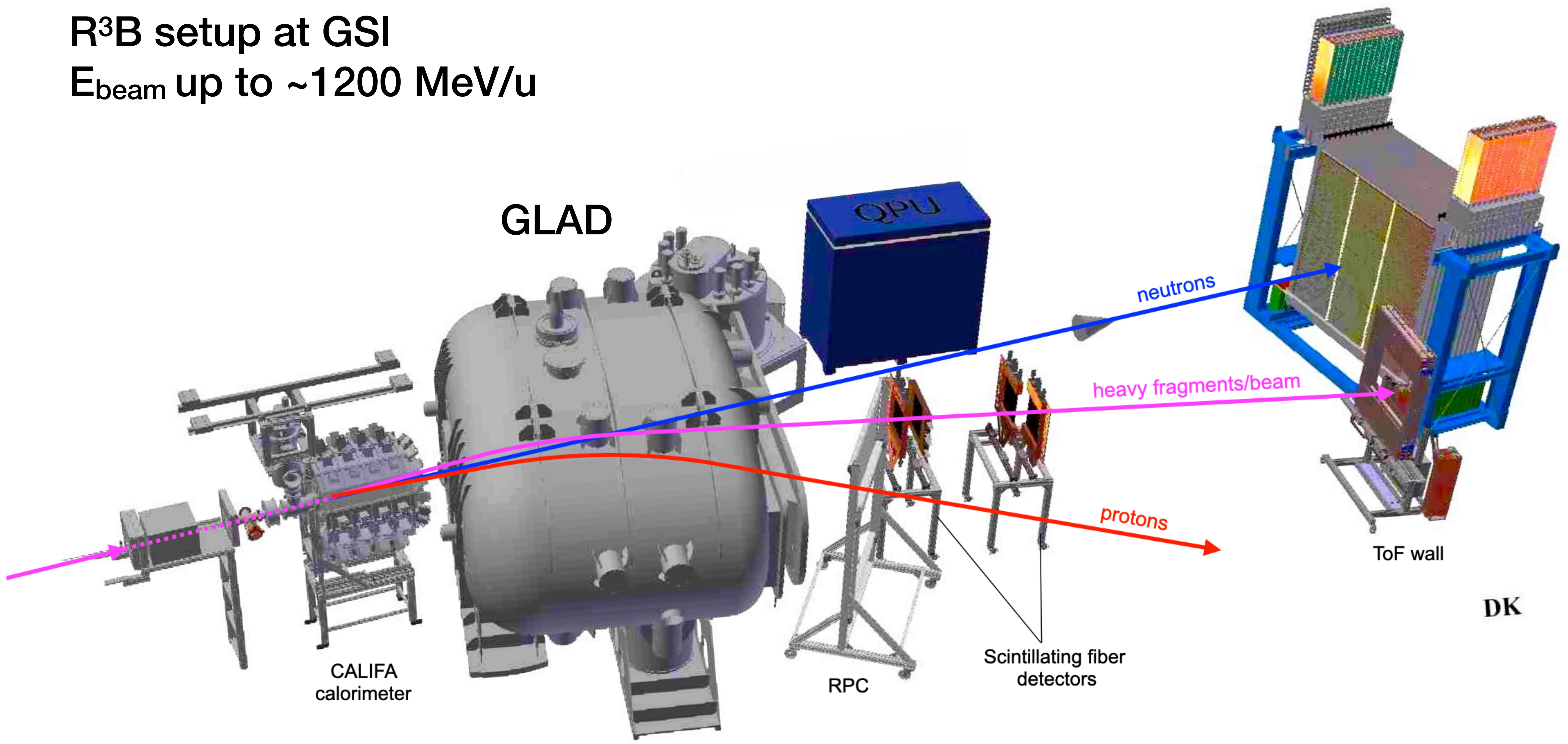
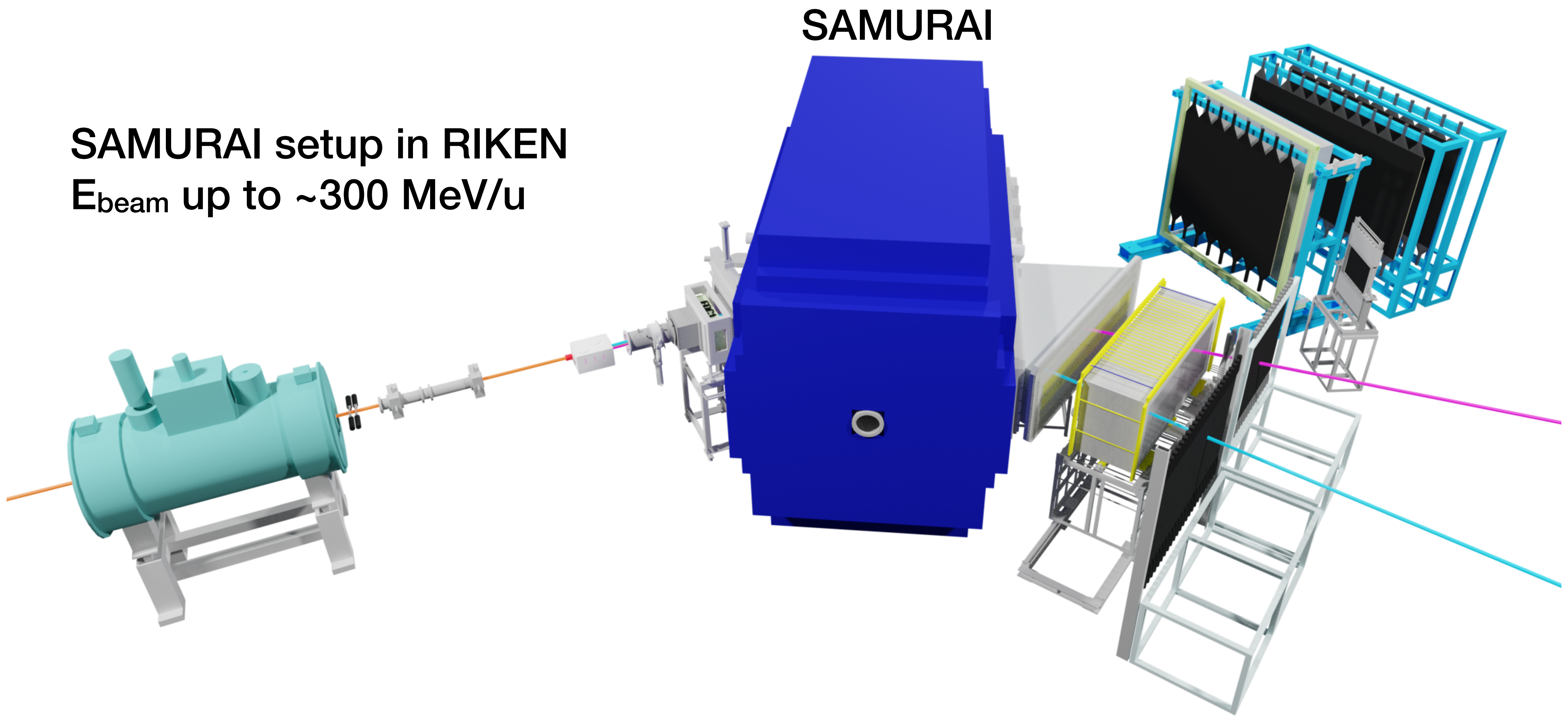




R^{3}B setup at GSI
E_{beam} up to ~1200 MeV/u



SAMURAI setup in RIKEN
E_{beam} up to ~300 MeV/u



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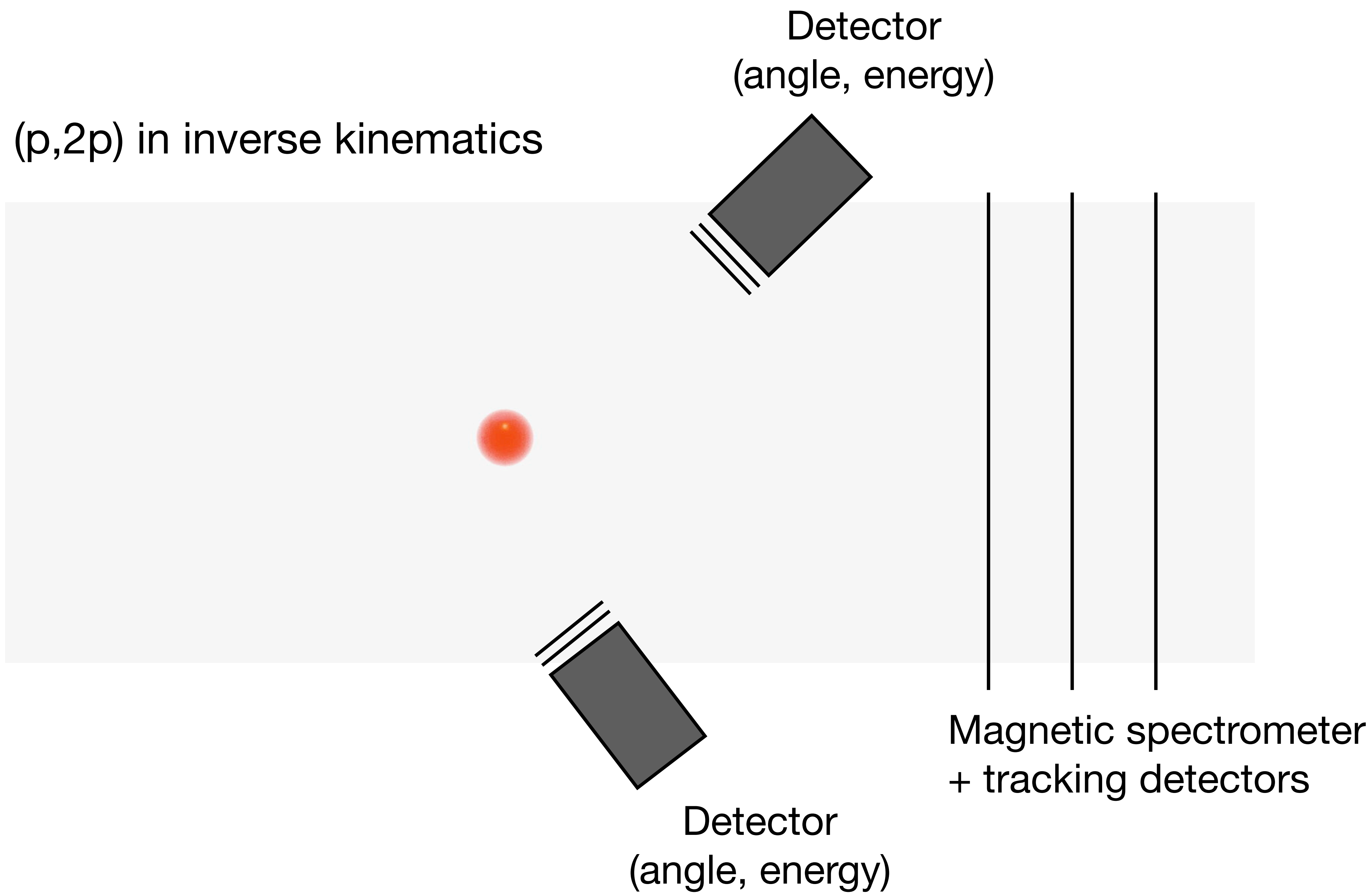
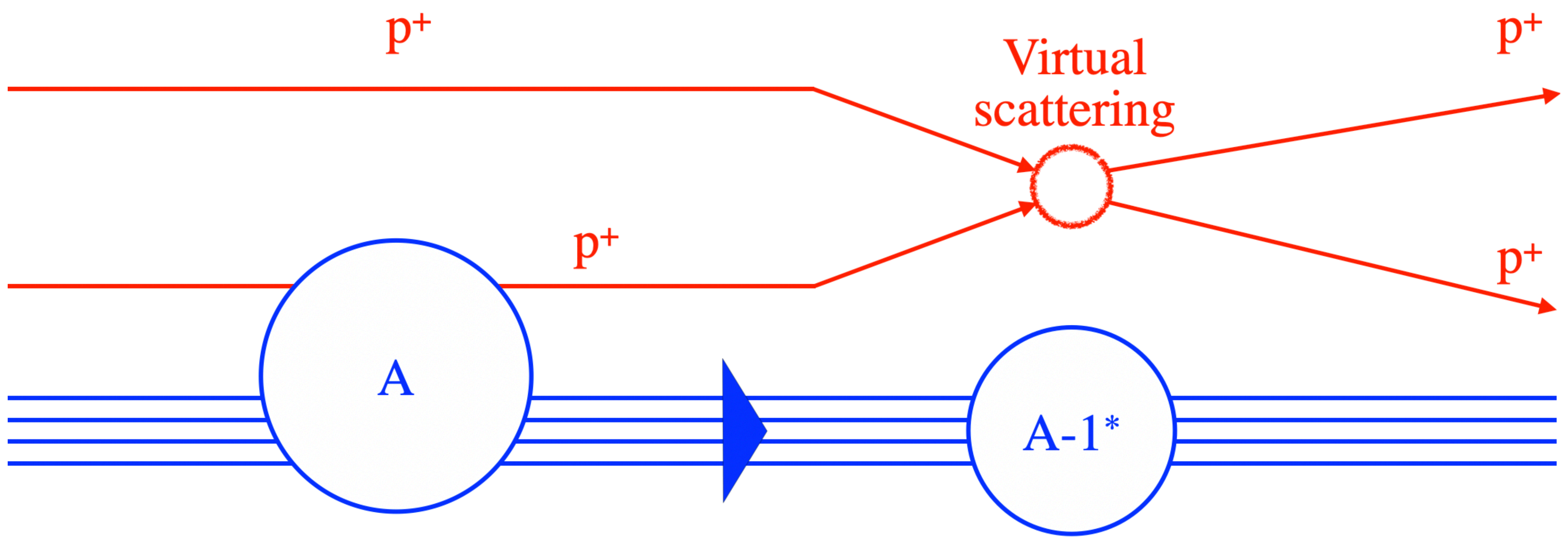
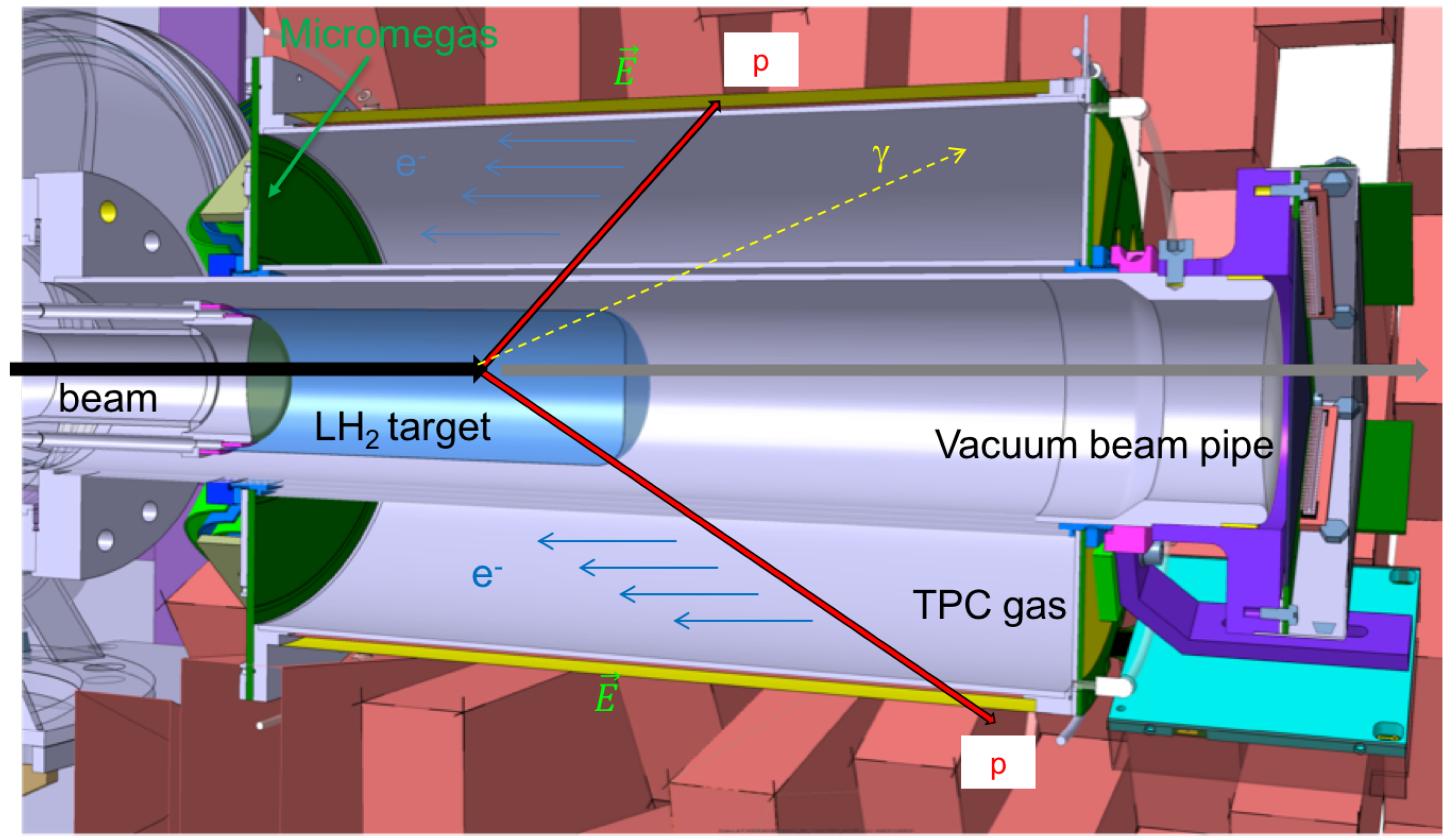


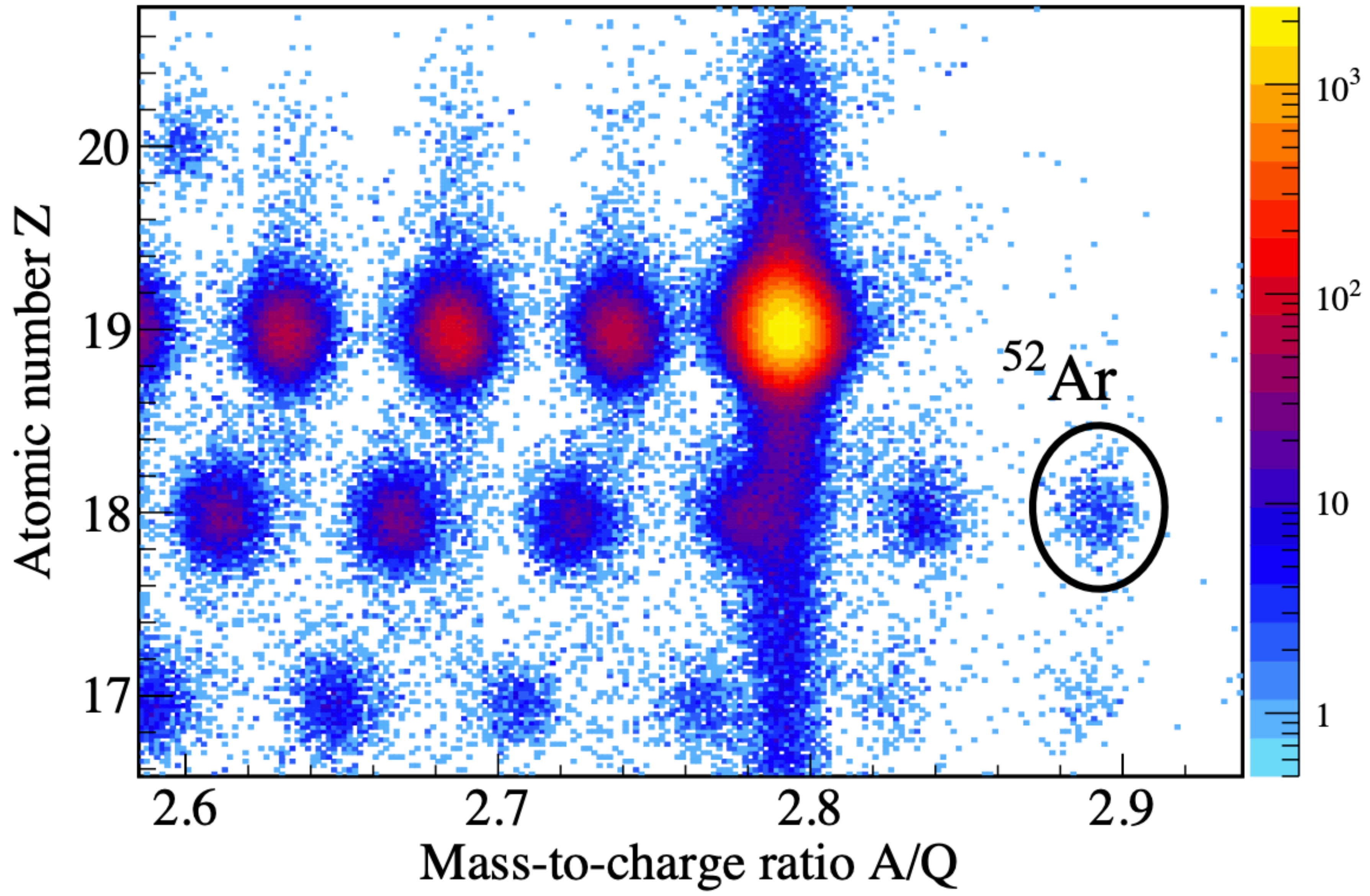


- Suitable for stable and exotic nuclei:
  - ➡ (p,2p), (p,pn) etc.
- Momentum transfer: $t = -2m_p T_{kin}$
- Direct observation of the residual fragment:
  - ➡ redundant information on the missing momentum
- Measuring excitation of the residual fragment (gammas, neutrons, etc.)
  - ➡ redundant information on the missing energy
  - ➡ structure of the residual hole-state
  - ➡ better control of FSI
- Possibility to use thick LH_2 targets
  - ➡ maximizing reaction yields for low-intensity beams

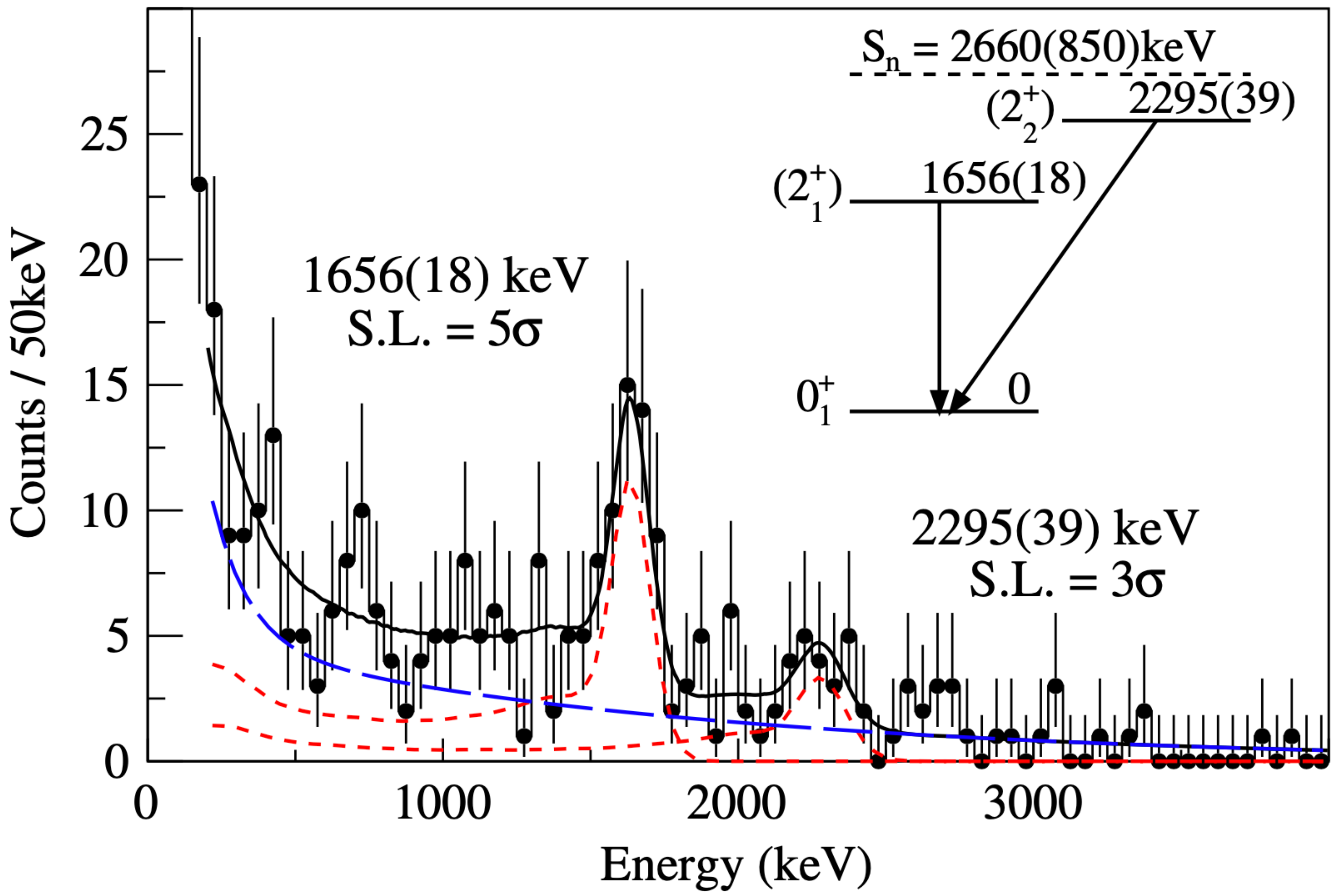
SEASTAR / MINOS experiment SAMURAI: ^{53}K (p,2p) ^{52}Ar @ 210 MeV/u

H.N. Liu et al., Phys. Rev. Lett. ***122***, *072502 (2019)*

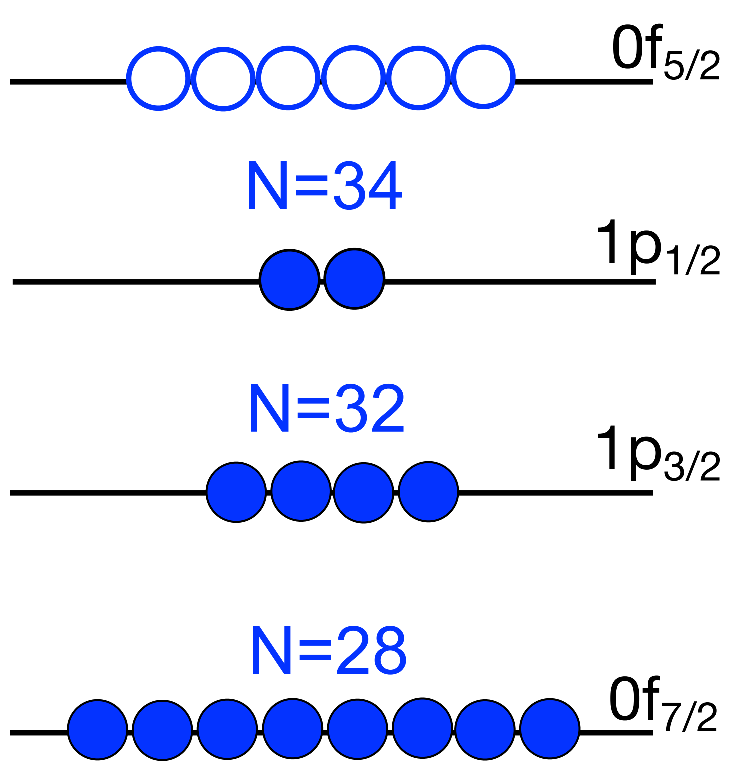




Doppler-corrected gamma spectrum from ^{53}K (p,2p) ^{52}Ar



Neutrons

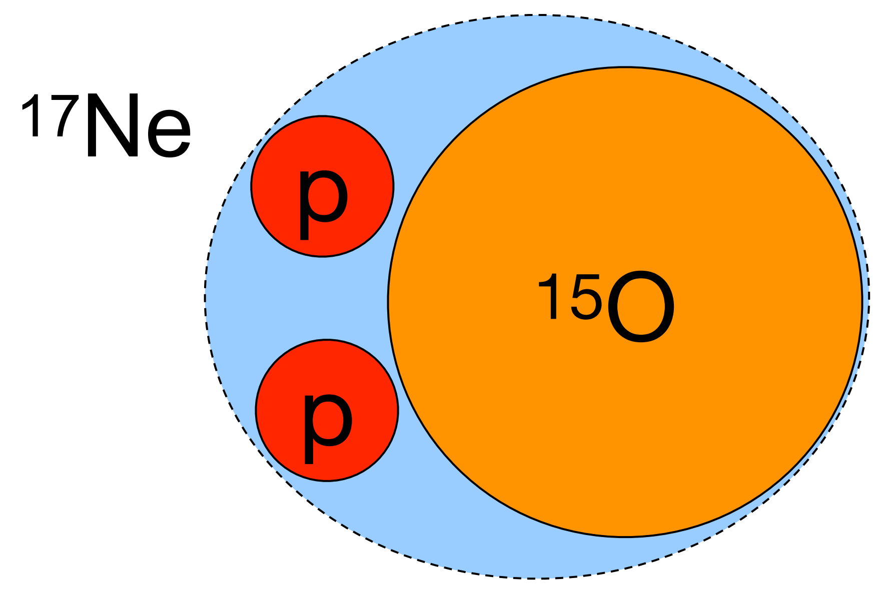


- Beam energy: @ 210 MeV/u
- 15 cm LH2 target
- **Beam intensity: ~ 1particle per second!**
- Highest 2_1^+ state in Ar isotopes with N>20

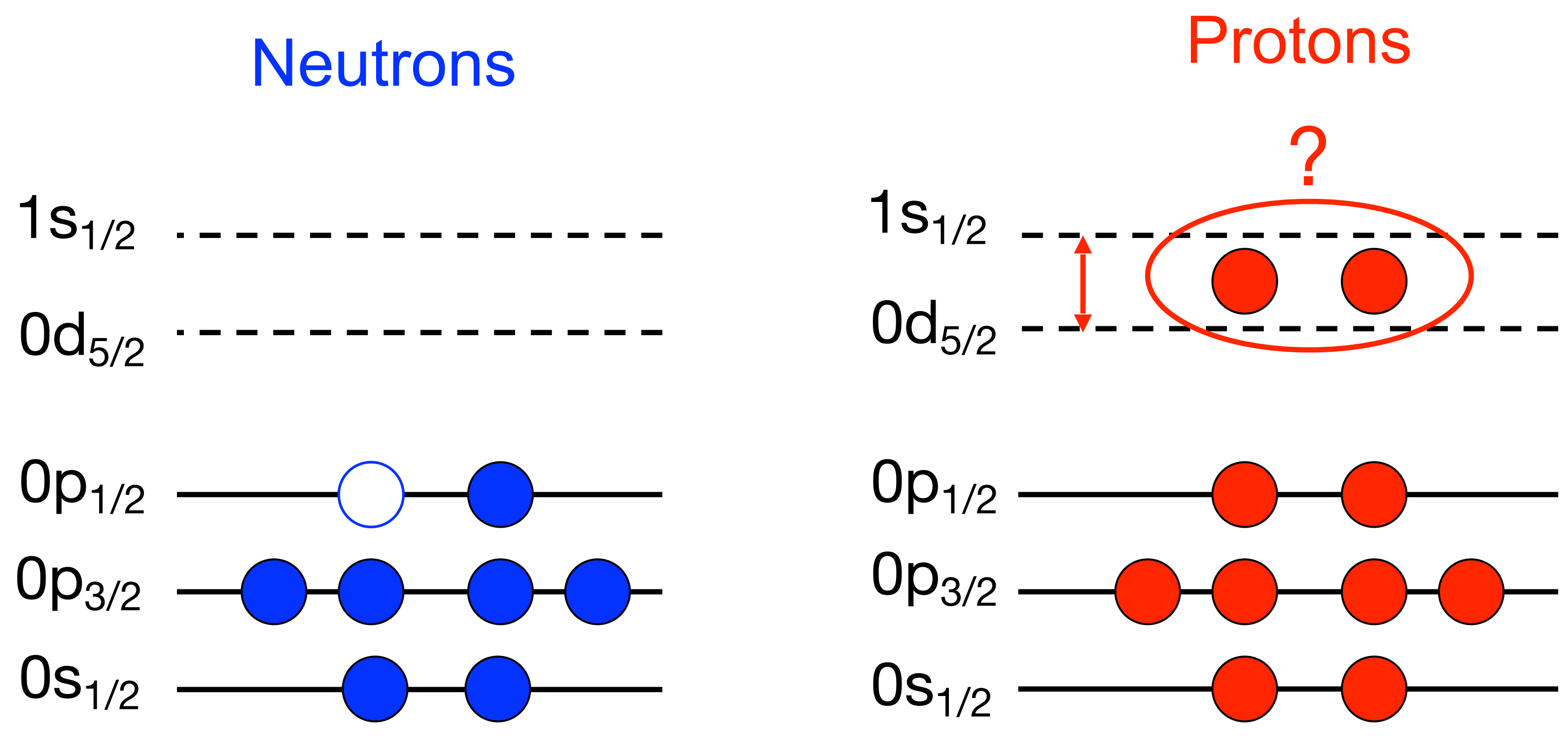
➡ **Persistence of N=34 sub-shell closure below Z=20**

GSI experiment: $^{17}Ne\,(p,2p)^{16}F^* \rightarrow {}^{15}O+p$ @ 500 MeV/u

is ^{17}Ne a real 2p-halo system at the proton dripline?



Shell model view of ^{17}Ne



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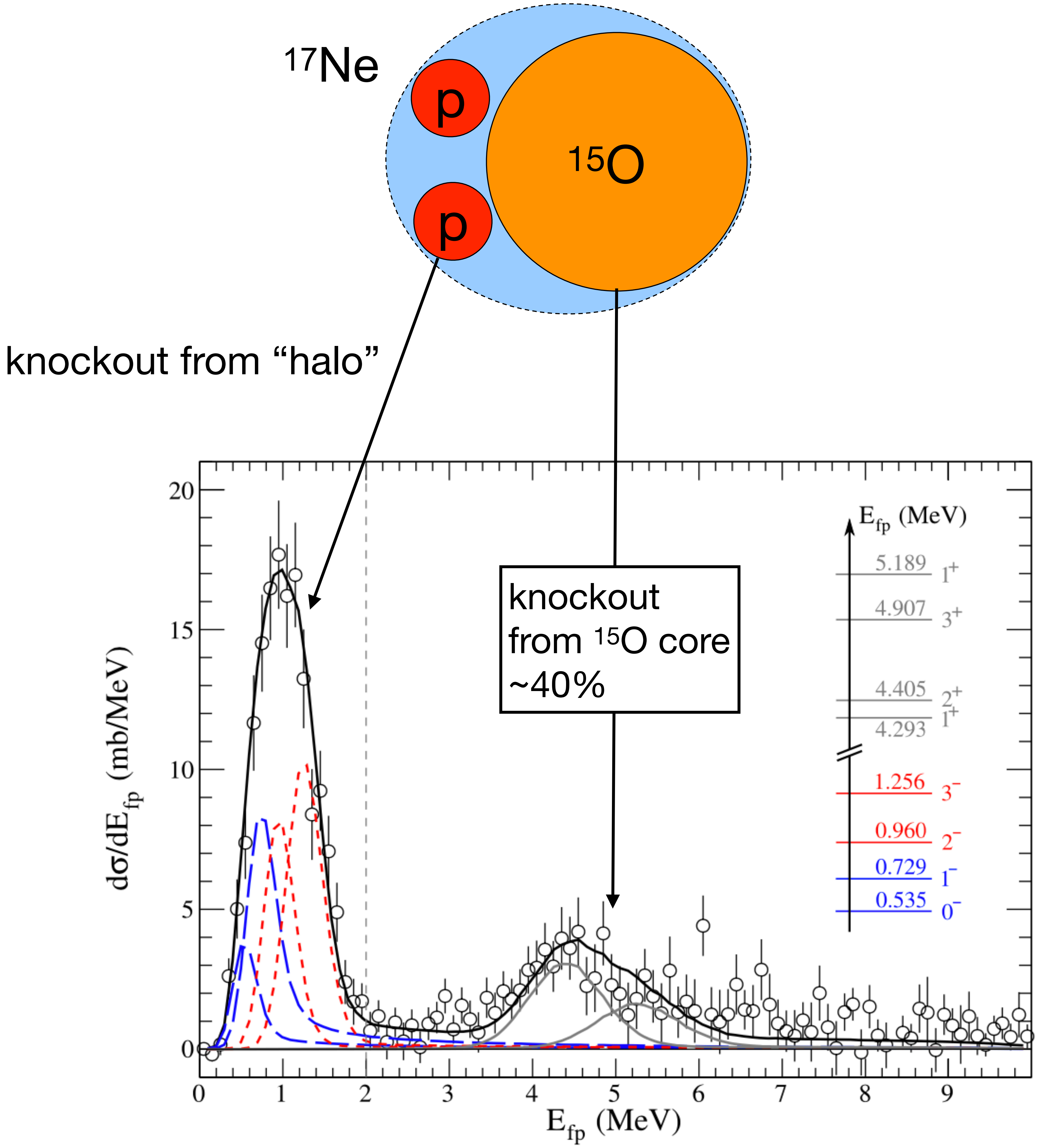
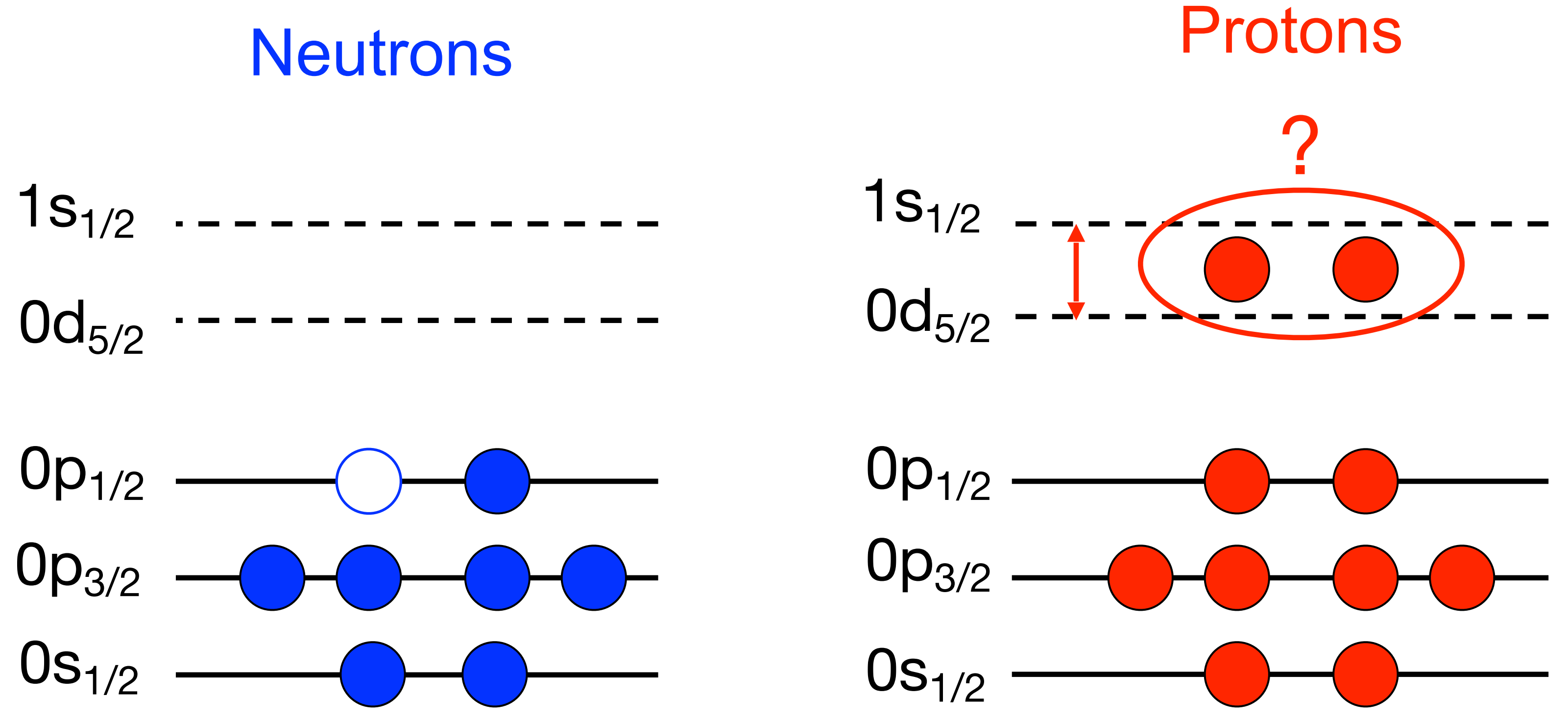
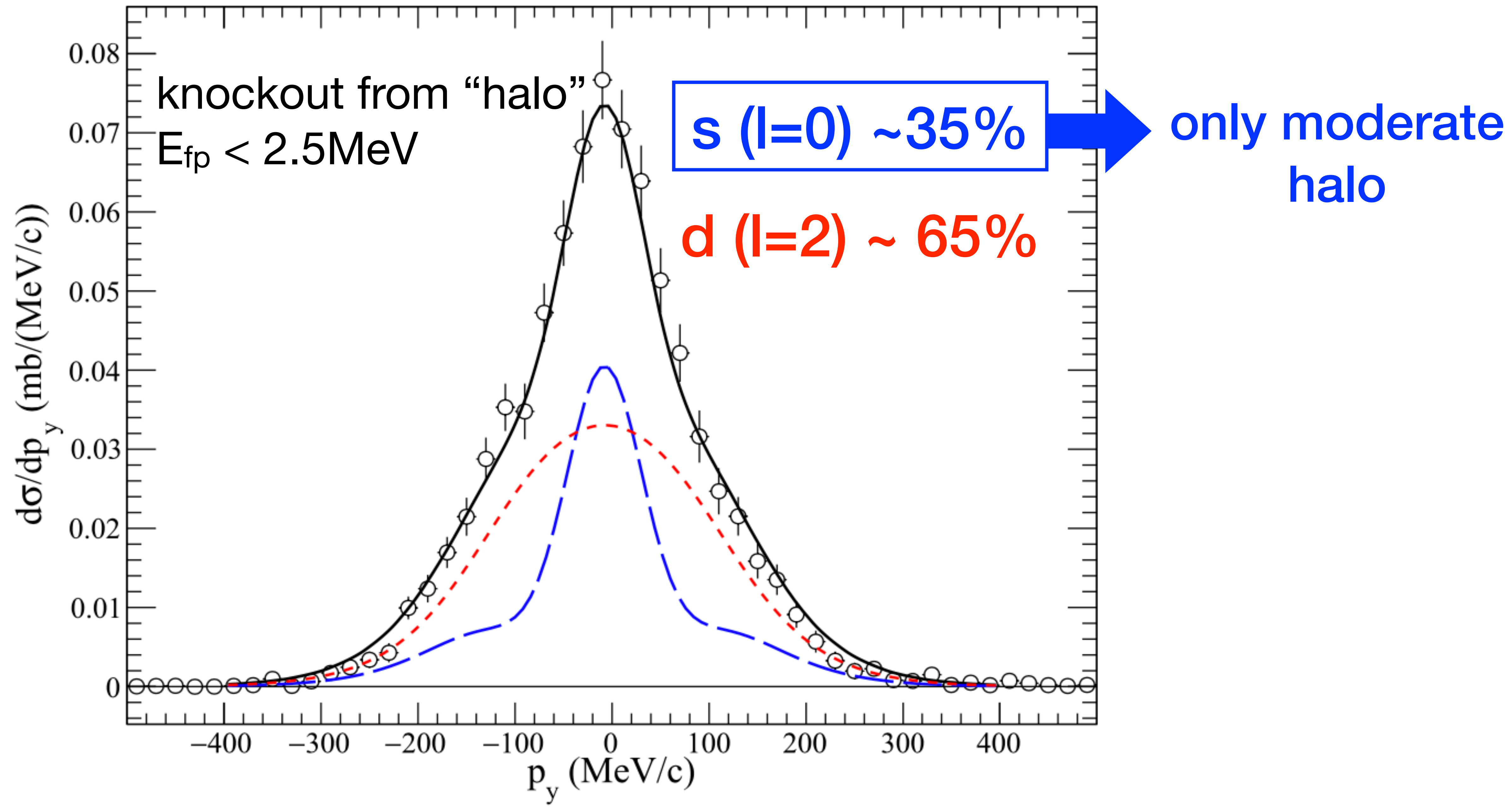


Relative energy spectrum of ^{15}O+p

Shell model view of ^{17}Ne

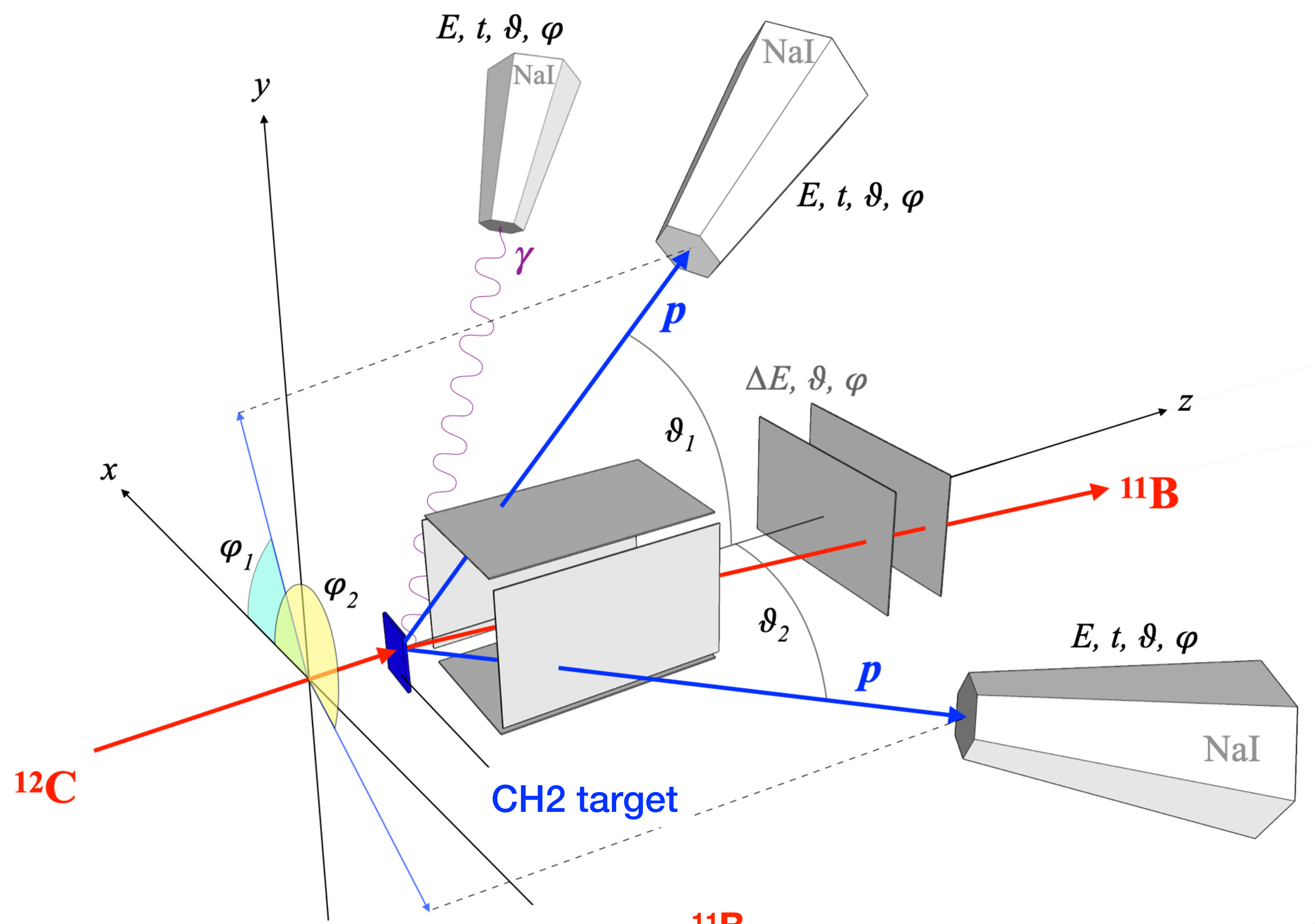


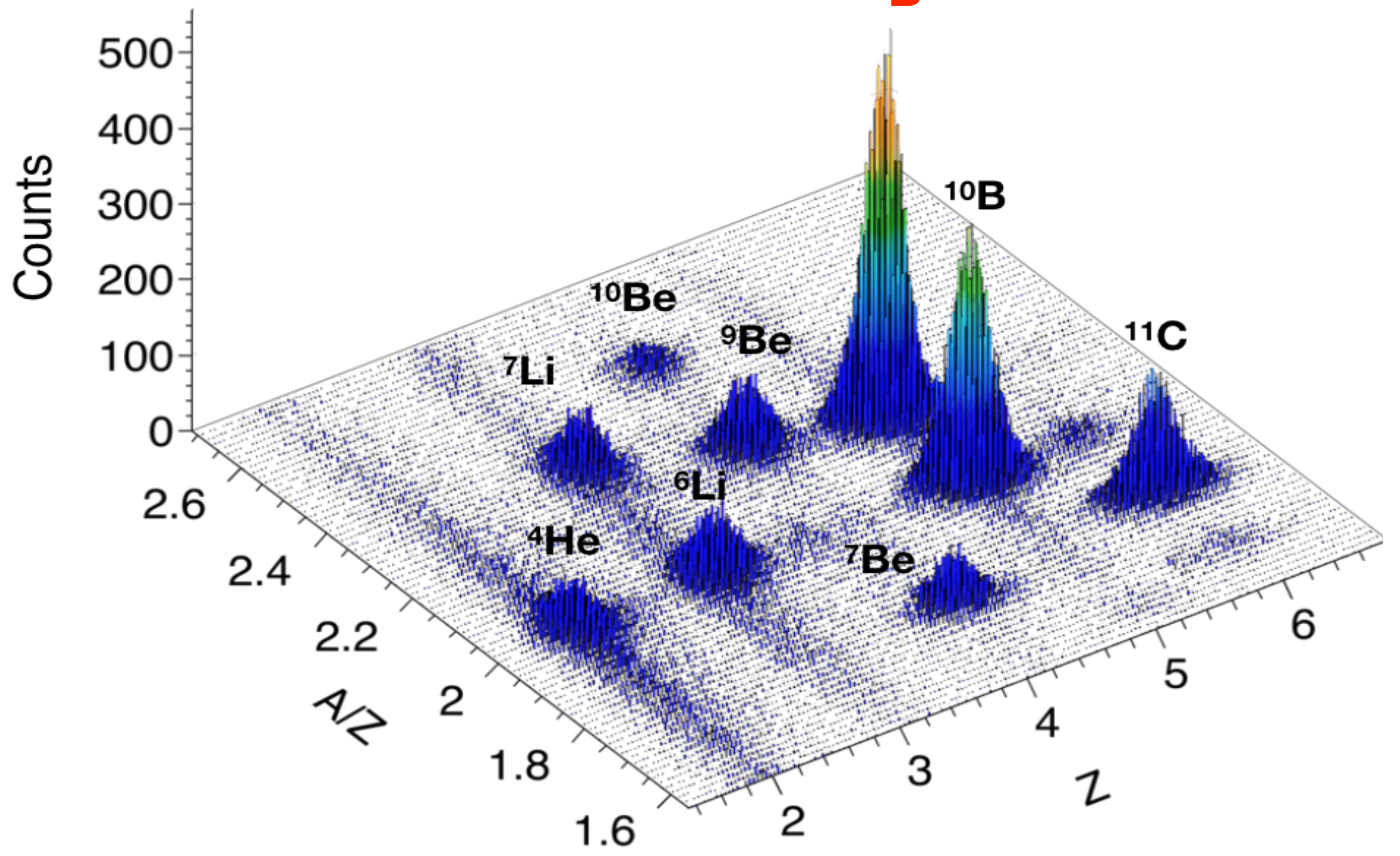
*C. Lehr et al. Phys. Lett. B **827**, 136957 (2022)*



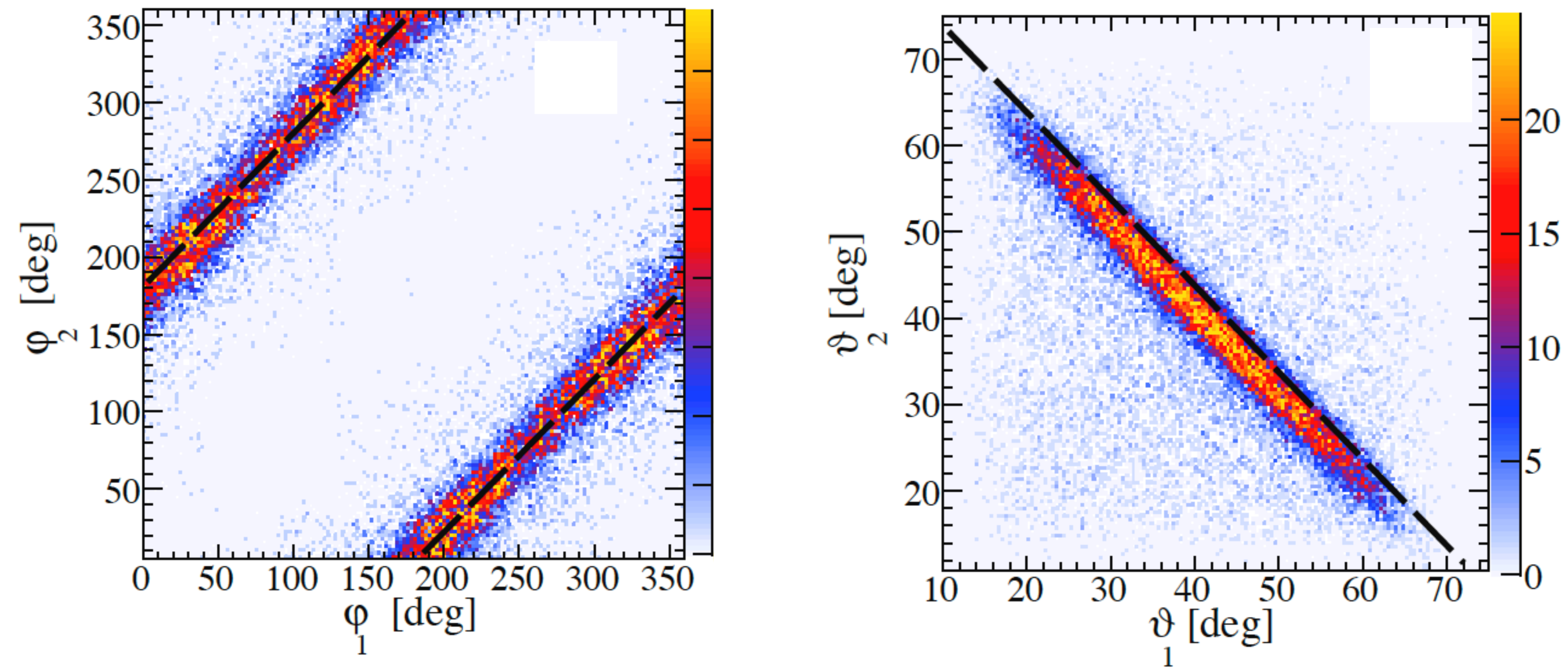
Transverse momentum of ^{16}F

GSI experiment: $^{12}C\ (p,2p)^{11}B$ @ 400 MeV/u in inverse kinematics

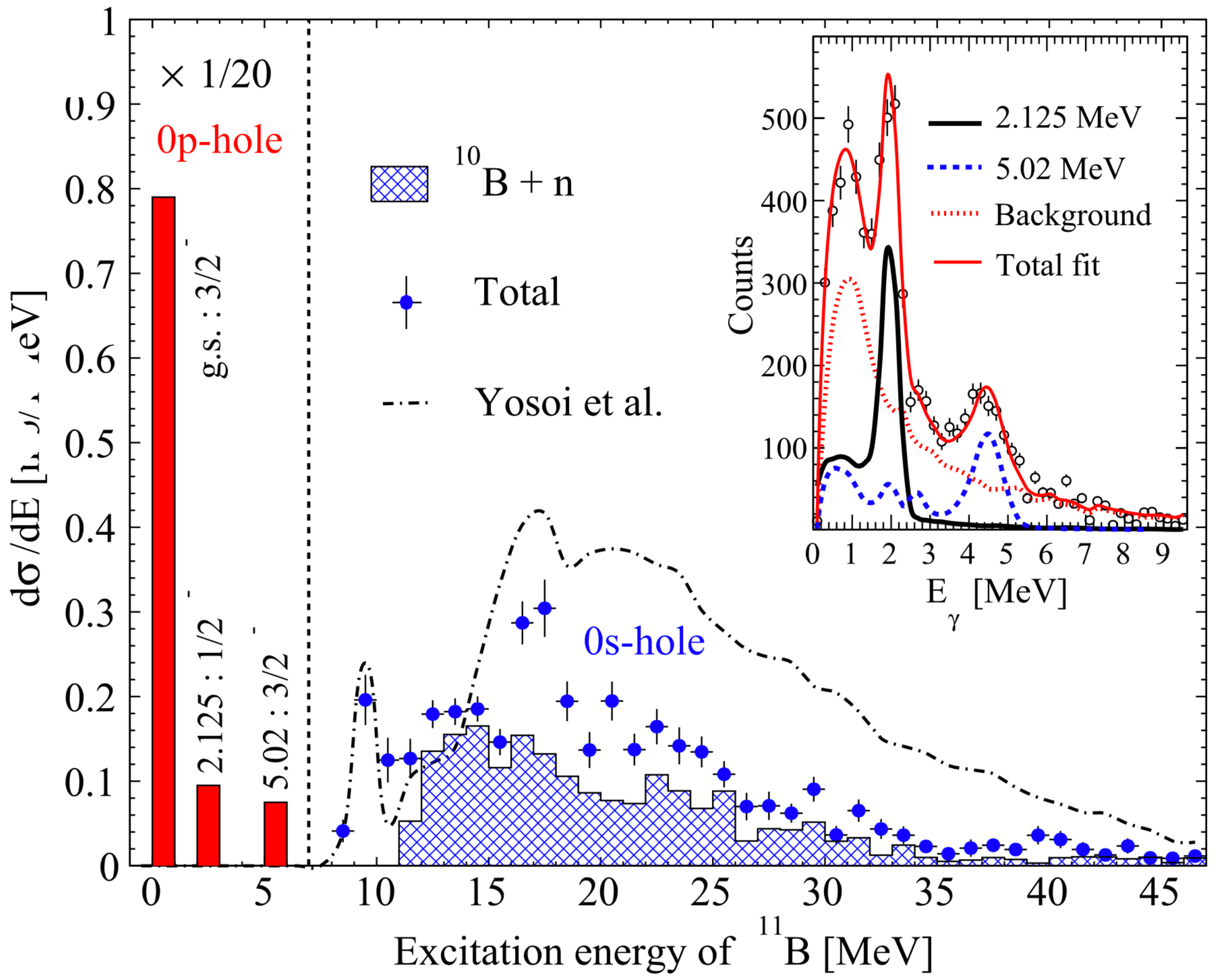




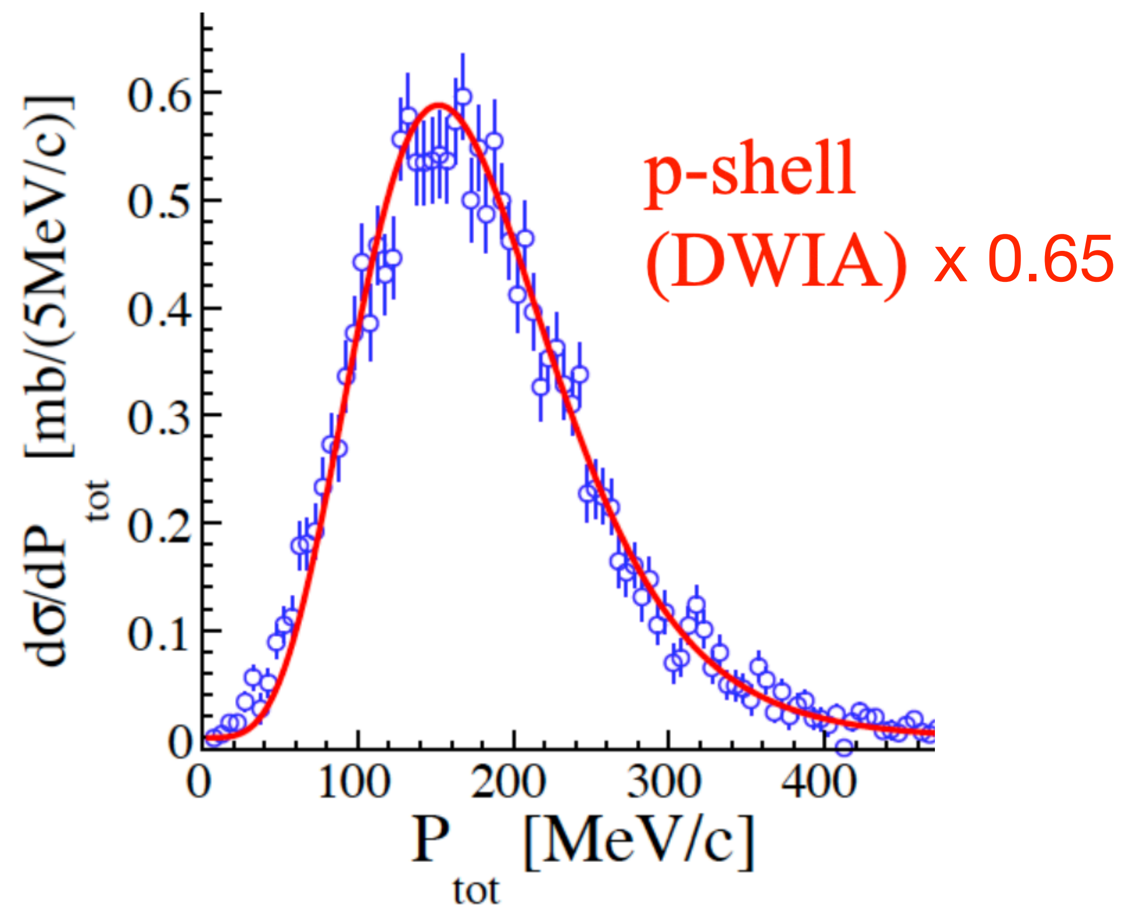
Two-proton angular correlations



gammas + particle evaporation

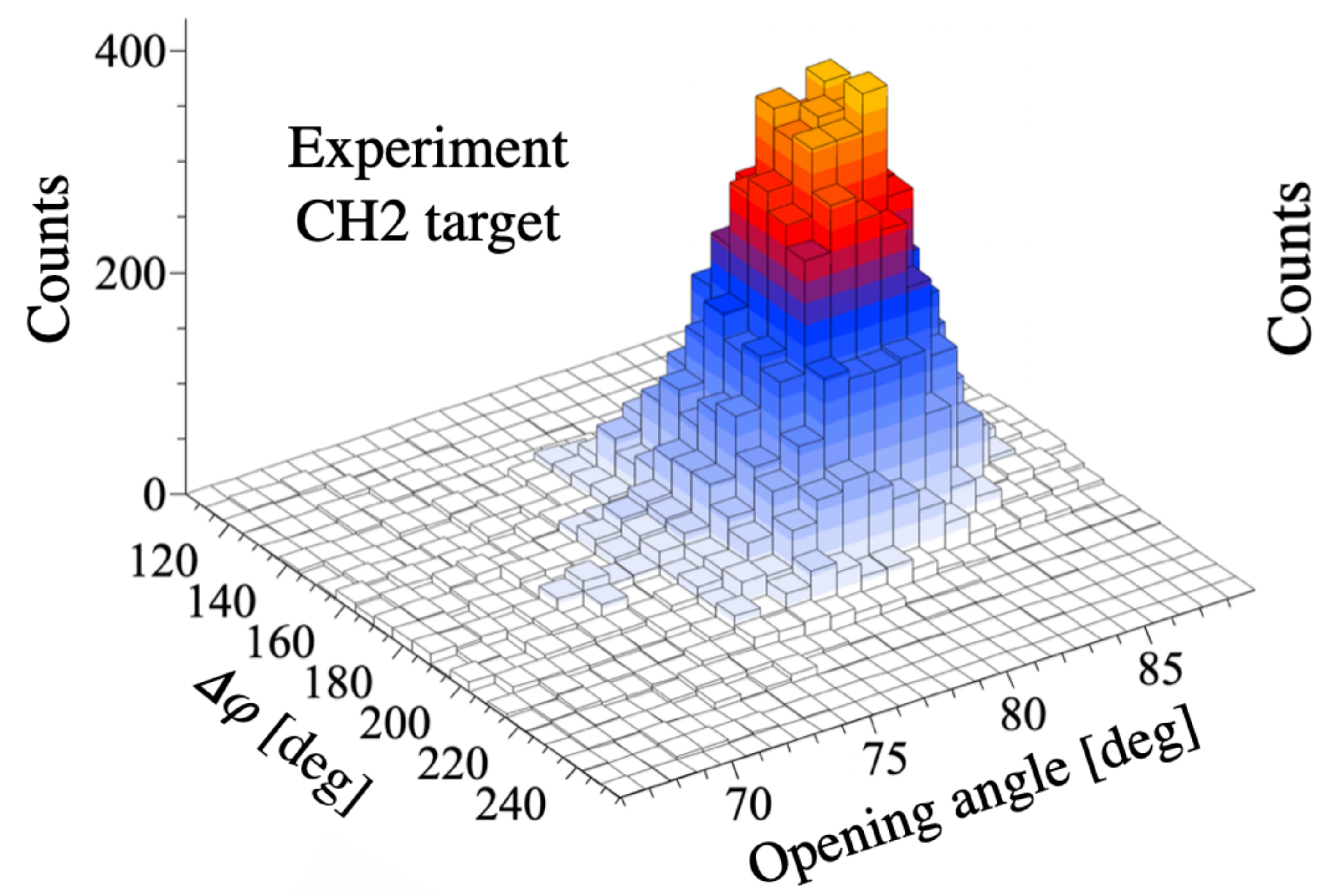


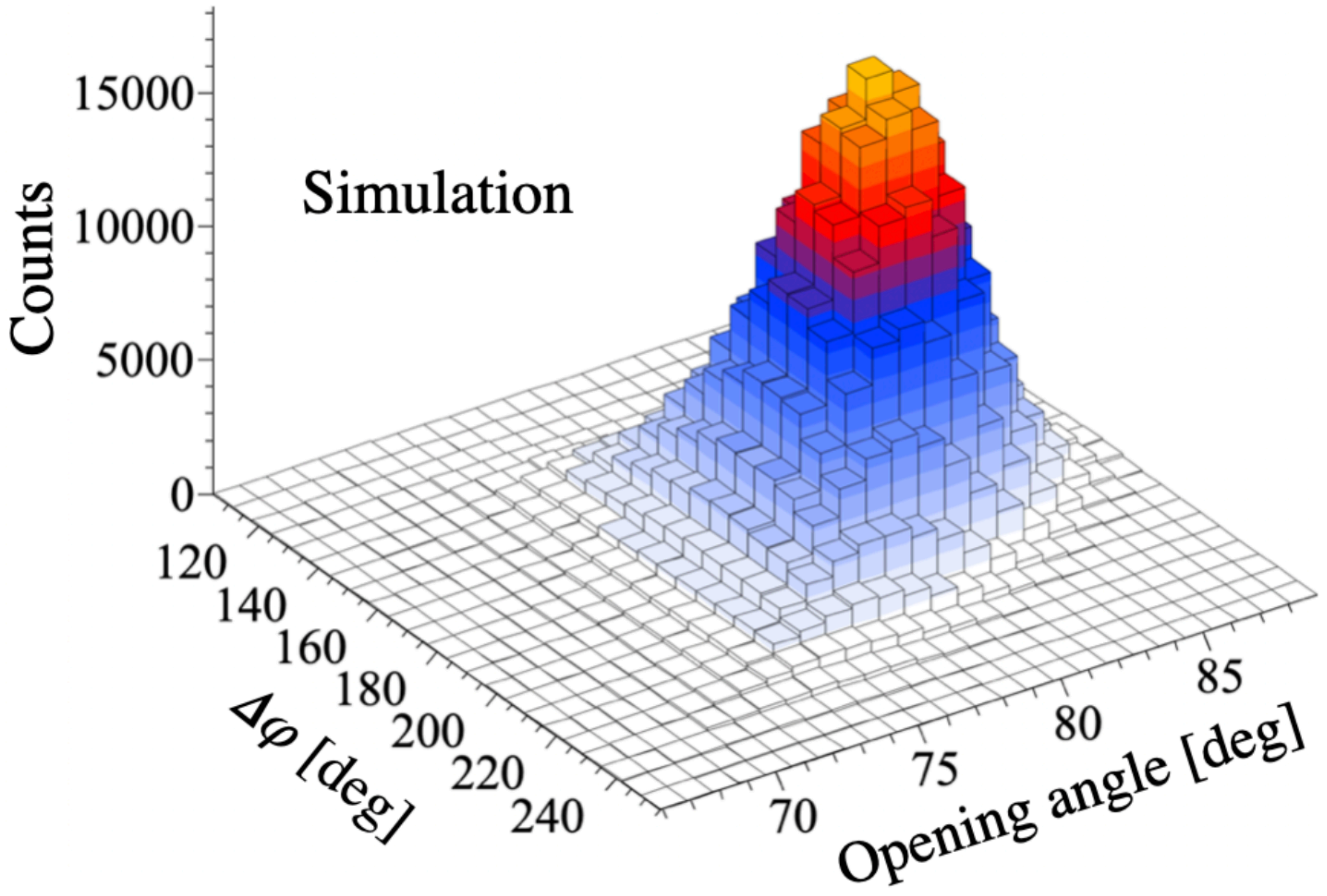
^{11}B momentum in ^{12}C restframe



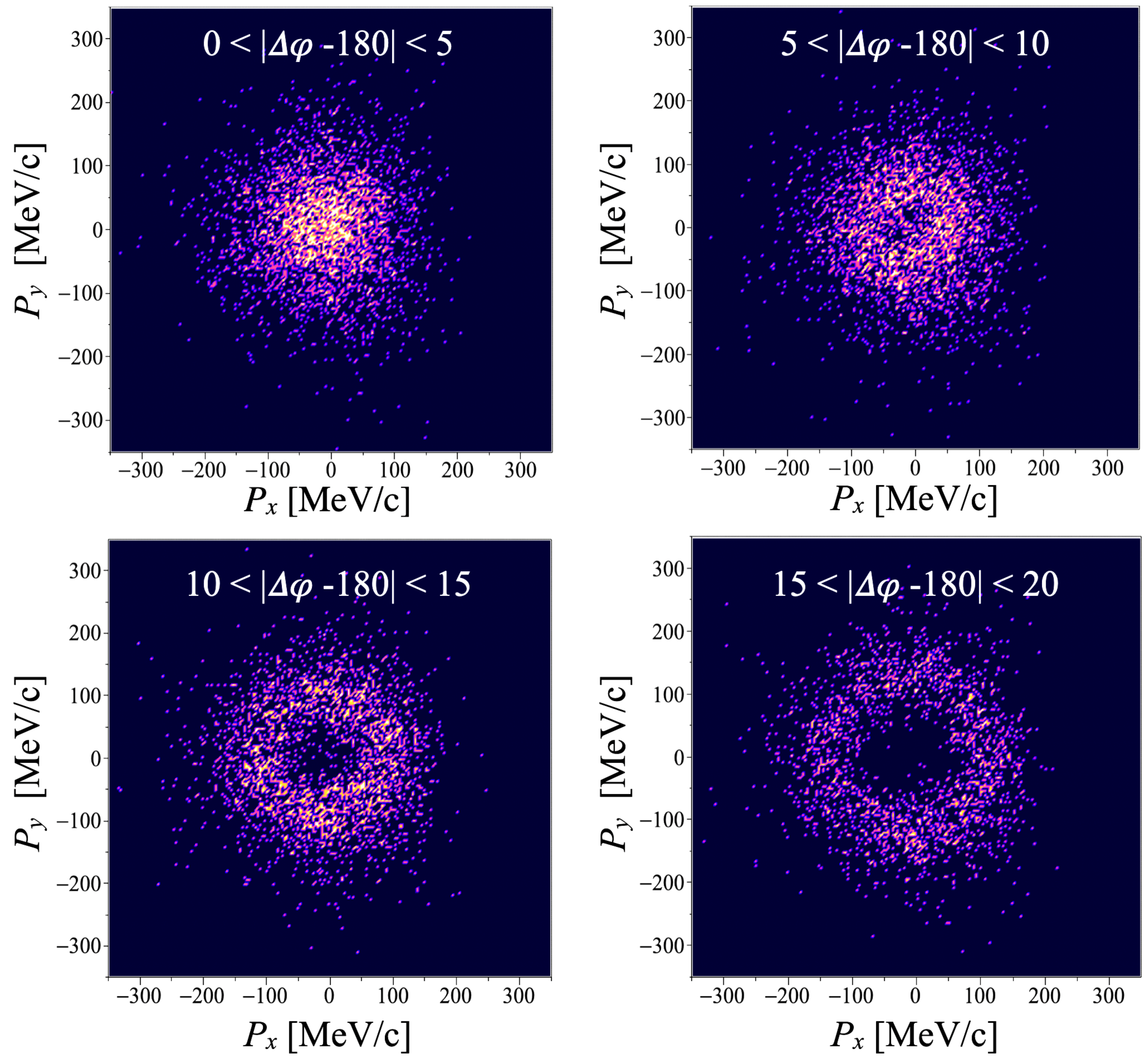
GSI experiment: $^{12}C\,(p,2p)^{11}B$ @ 400 MeV/u in inverse kinematics

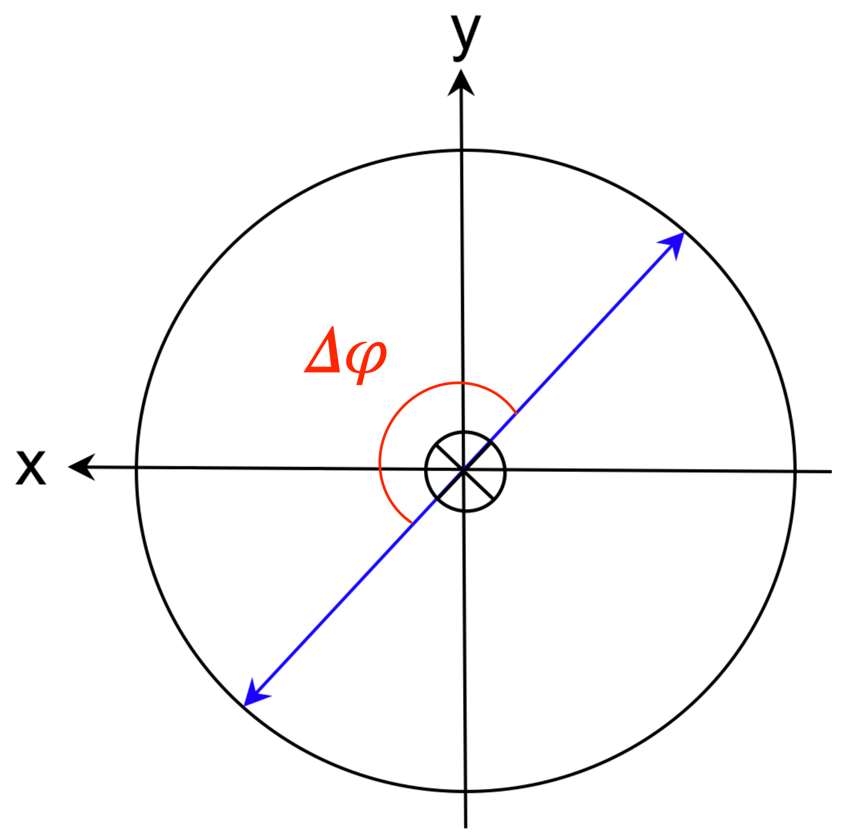
Narrow peak in polar-azimuthal space —> distinct QFS signature

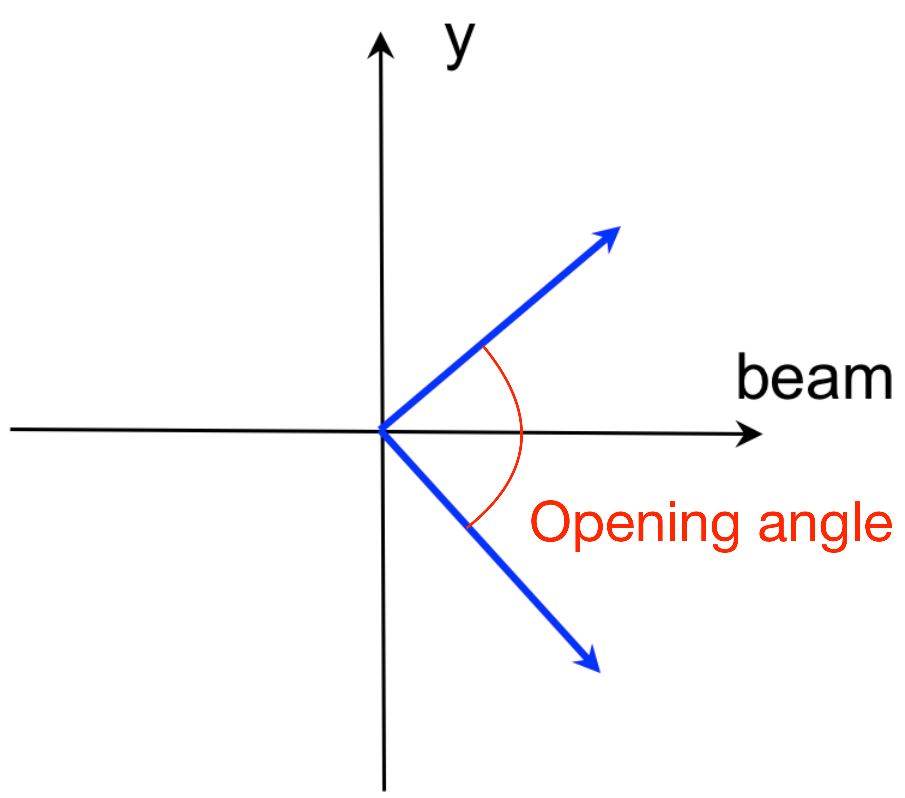




Transverse momentum components of ^{11}B (experiment)



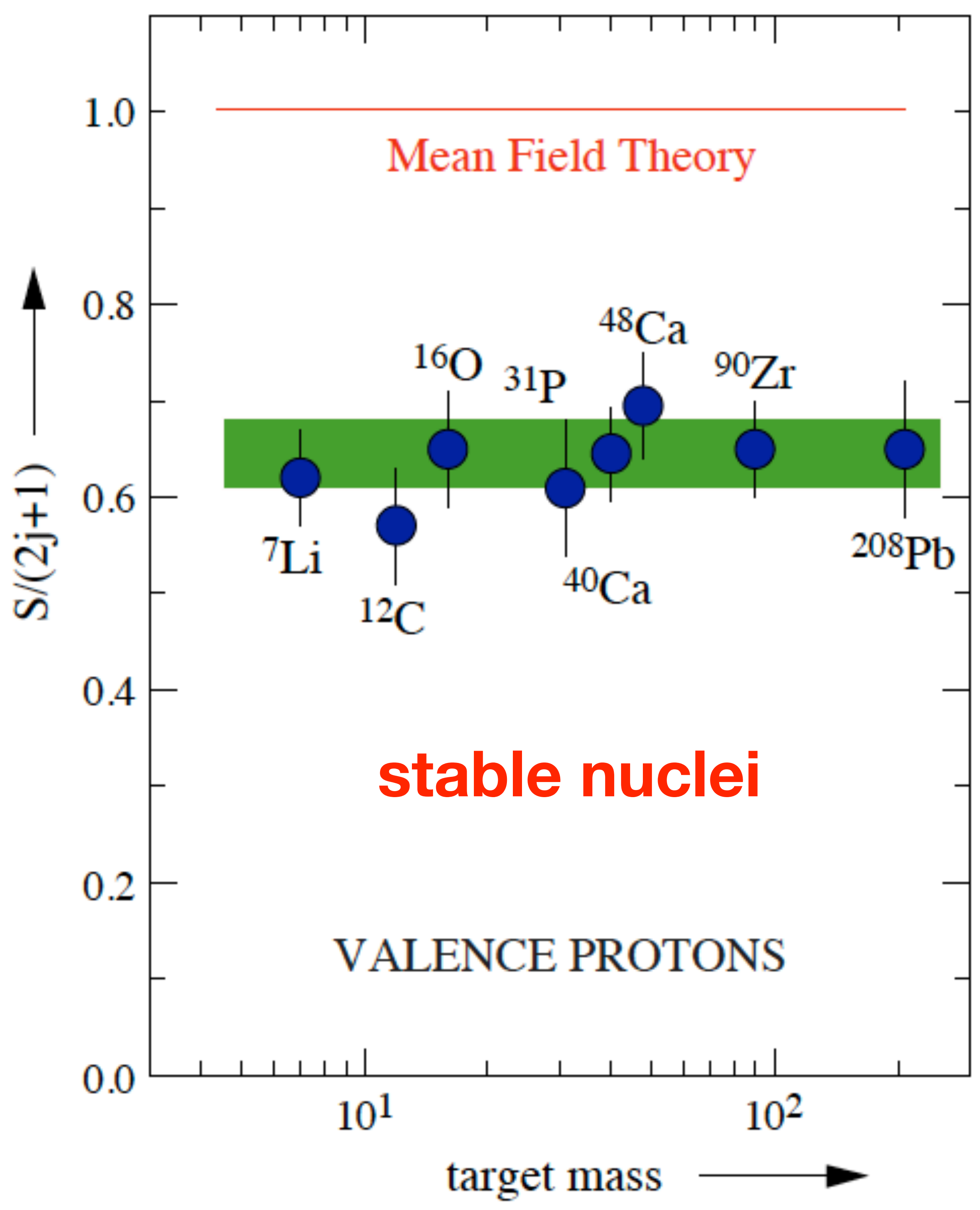




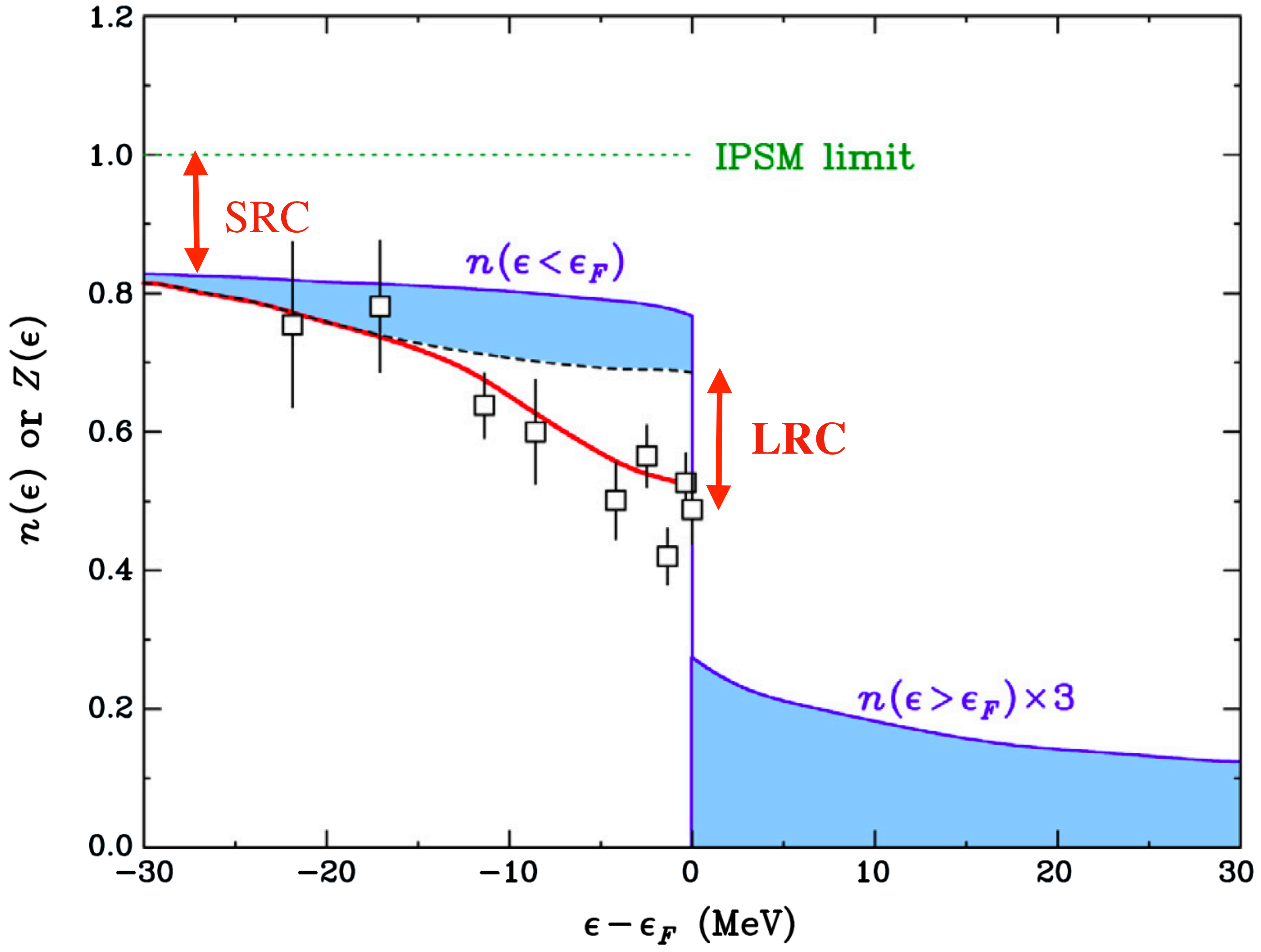
$$\cos\theta_o = \sin\vartheta_1 \sin\vartheta_2 \cos\left(\varphi_2 - \varphi_1\right) + \cos\vartheta_1 \cos\vartheta_2$$

Quenching of the single-particle strength

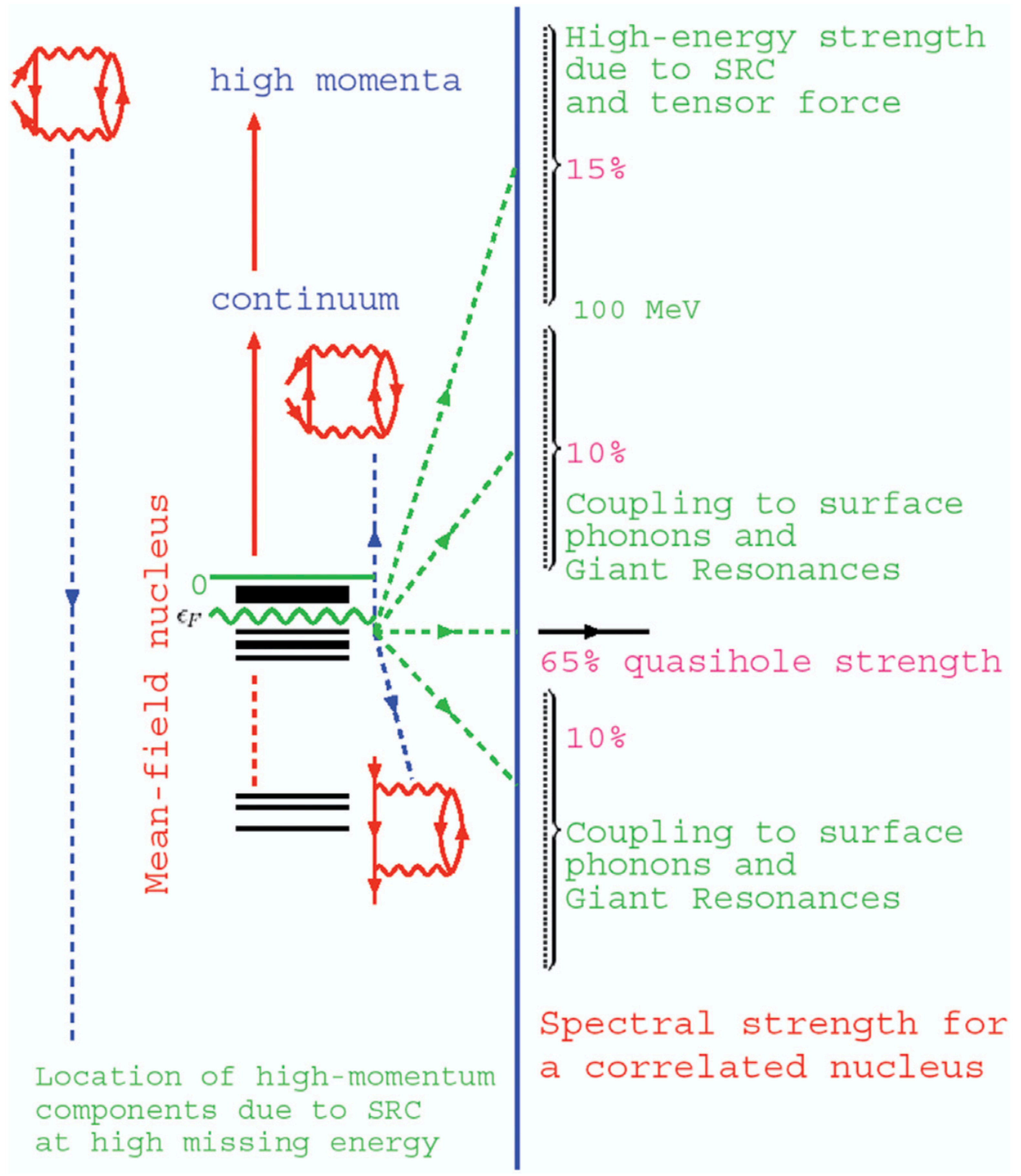
Prog. in Part. and Nucl. Phys. 52 (2004) 377–496



Prog. in Part. and Nucl. Phys. 96 (2017) 32–87



Prog. in Part. and Nucl. Phys118 (2021) 103847



“Experimental” SP strength:

$$S^{\exp} = \frac{\sigma^{\exp}}{\sigma^{\mathrm{th}}}$$

Sum rule from independent-particle model:

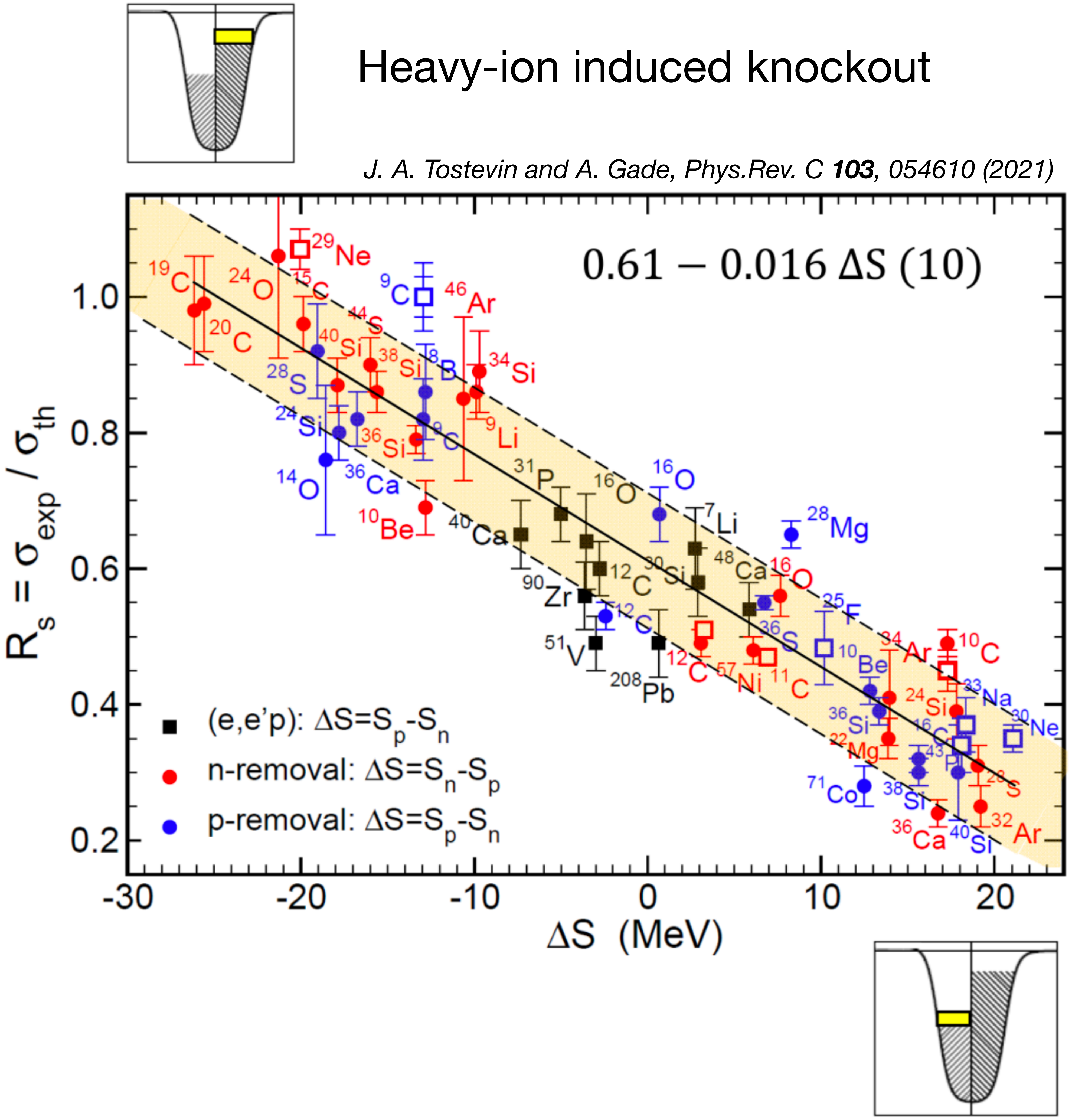
$$\boxed{\sum S_j^{\exp} \leq S_j^{\mathrm{IPSM}} = 2j+1}$$

Indirect approach to study SRC content of nuclear w.f.

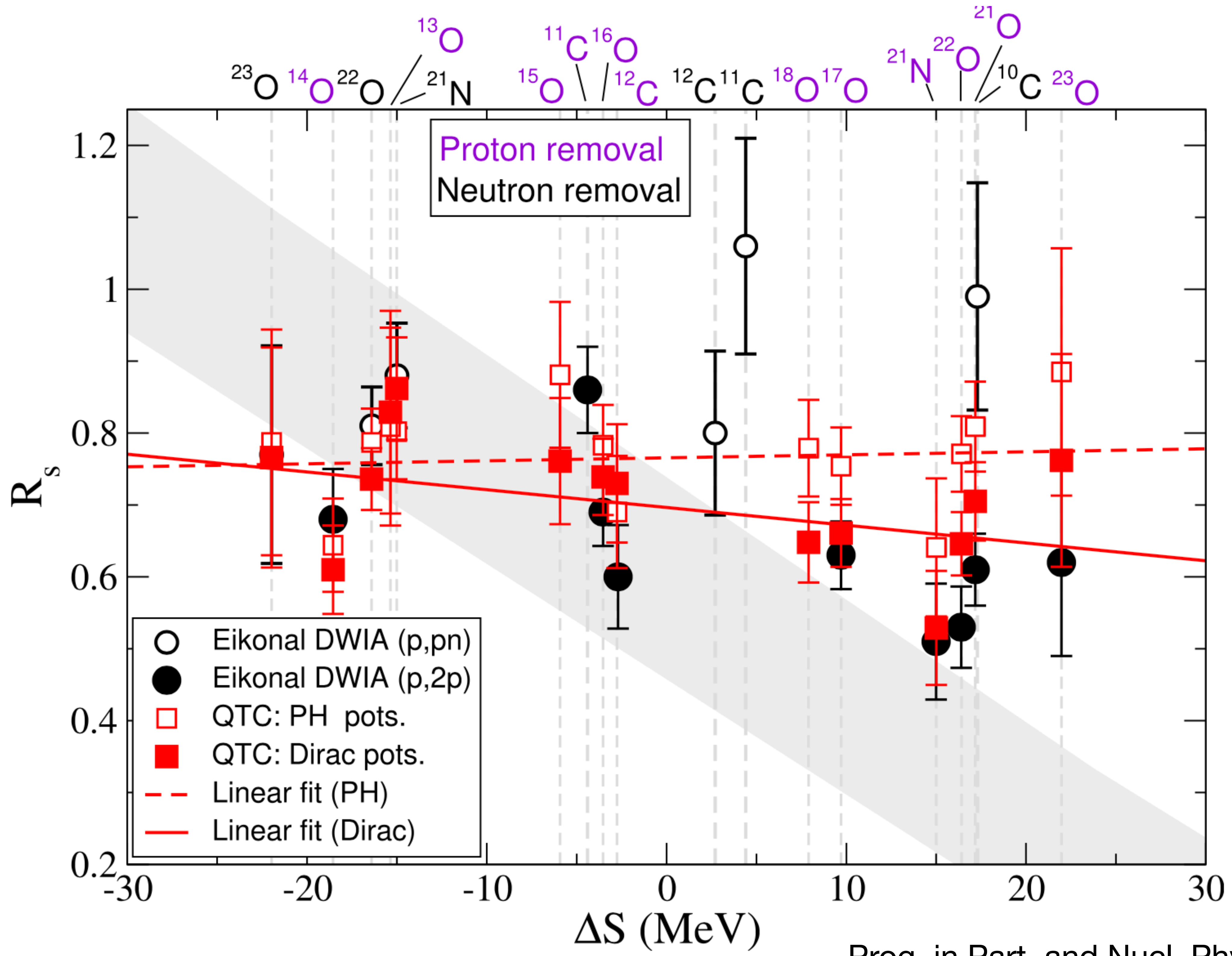
Quenching of the single-particle strength

Heavy-ion induced knockout

J. A. Tostevin and A. Gade, Phys.Rev. C **103**, 054610 (2021)



(p,2p) and (p,pn) reactions



Prog. in Part. and Nucl. Phys118 (2021) 103847

- **No dependence on isospin asymmetry in QFS reactions**
- (p,pn) values are systematically larger:

  Rs = 0.85(10) vs Rs = 0.65(4)

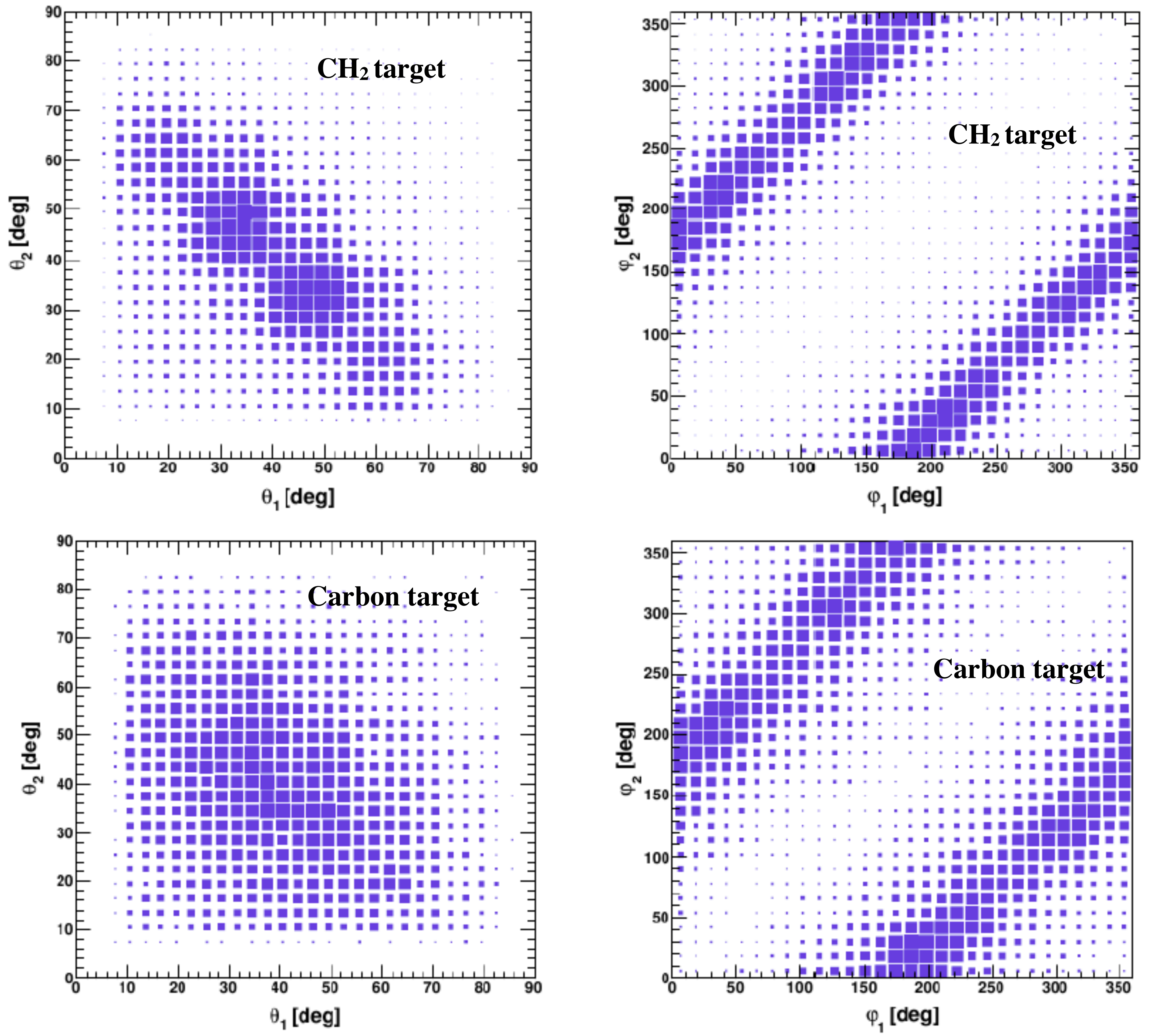
Summary

- QFS provides unique access to the single-particle structure of nuclei
- Elementary scattering process as a knockout mechanism
- Inverse-kinematics approach: asymmetric nuclei and additional kinematic observables
- Need for accurate reaction models and experimental data
- Reaction and structure part have to be treated within the same many-body theory

Thank you!

$^{12}C(p,pn)^{11}C$ reaction

Angular correlations via CB measurements



M. Holl et al. Phys. Lett. B 795 (2019) 682