From Fully Differential Electron to Ion Impact Studies of Ionization: the Legacy of Don Madison

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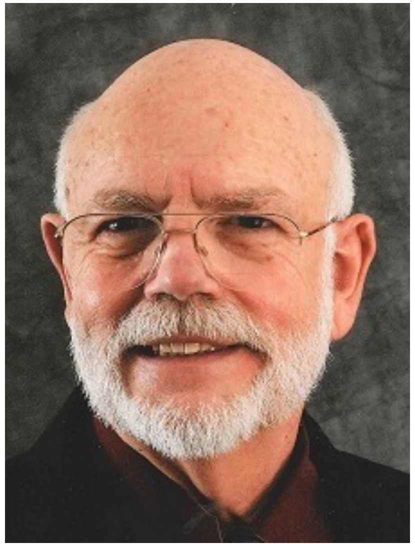

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Most important goal of atomic collision research: study quantum-mechanical few-body problem, one of the most fundamentally important and yet unsolved problems in physics

Essence of FBP: Schrödinger equation not analytically solvable for more than two mutually interacting particles even if forces are precisely known.

Particularly challenging: dynamic few-body systems like e.g. fragmentation processes.

Atomic fragmentation particularly suitable because:

- **underlying interaction (electromagnetic) understood**
- **can select systems with small particle number (≈ 3 – 5)**

Kinematically complete experiments

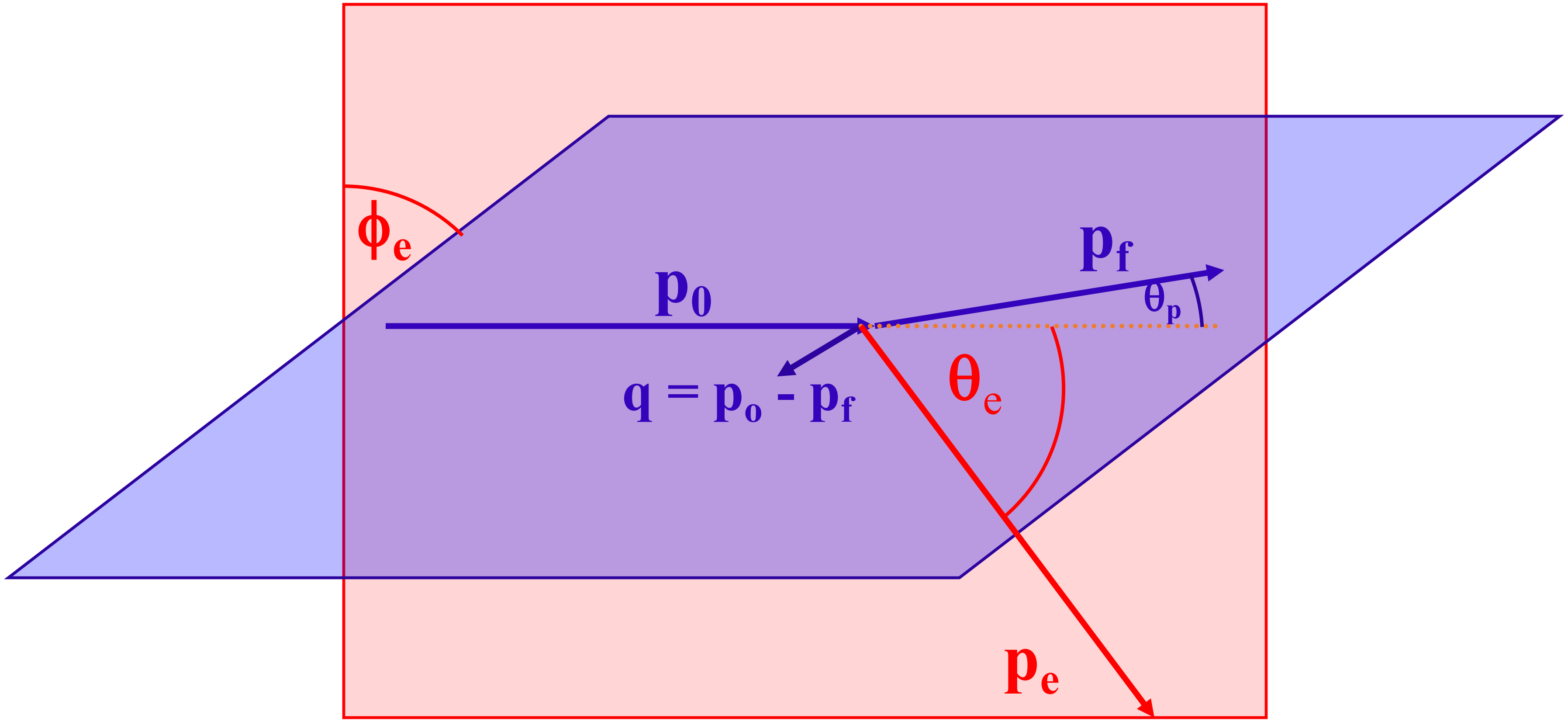
Where Don had to work on me (really hard and persistently): how to present results of a kinematically complete experiment on ionization

Typical <u>e,2e experiment:</u>
energy and angles of both final-state electrons measured in coincidence
⇒ FDCS usually presented as angular distribution of ejected electrons with all other parameters fixed.

Typical <u>ion-impact experiment:</u>
Earlier, either projectile scattering angle or electron spectra measured, but not in coincidence. With advent of COLTRIMS, electrons or projectiles measured in coincidence with recoil ions. ⇒ Usually, momentum distribution of various particles presented.

Advantage of fully differential electron angular distribution: more transparent
Often, structures in FDCS directly reflect interactions underlying reaction dynamics

Collision geometry and coordinate system

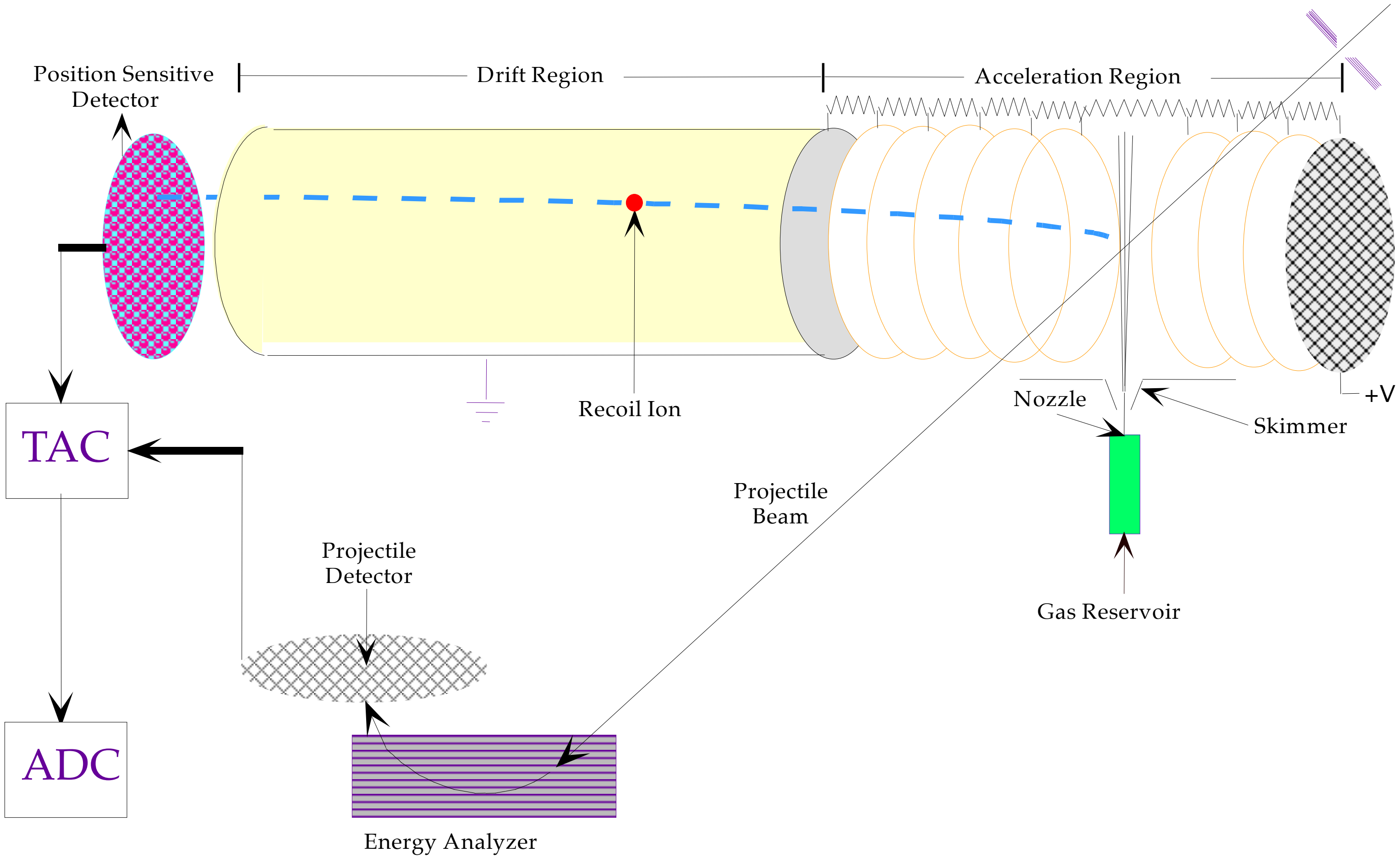


Blue: Scattering plane defined by p_o and p_f

Red: electron emission plane defined by p_o and p_e

Quantities fixed: $\phi_p = 0$, θ_p, $\phi_e = 0$, and E_e, spectra plotted as a fct. of θ_e

Experimental Setup, 75 keV p + He



Complete projectile and recoil-ion momenta measured. Electron momentum from conservation laws ⇒ kinematically complete ⇒ FDCS

Ionization of simple atoms or molecules by ion impact

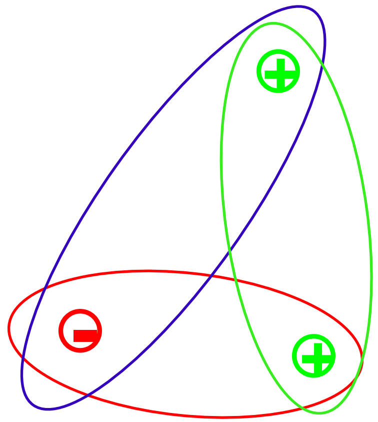
Perturbative treatment: Born series

$$T = \langle e^{ik_f r}\,\varphi_f\,|V|\,e^{ik_i r}\,\varphi_i\rangle + \langle e^{ik_f r}\,\varphi_f\,|VG_0V|\,e^{ik_i r}\,\varphi_i\rangle + \langle e^{ik_f r}\,\varphi_f\,|VG_0VG_0V|\,e^{ik_i r}\,\varphi_i\rangle + \ldots$$

Distorted wave methods

Higher-order contributions treated in wavefunction of system

Break up three-body system into 3 two-body systems:



Continuum eigenstate of each two-body subsystem is a Coulomb-wave.

Approximation: Represent total wavefunction as product of three Coulomb terms

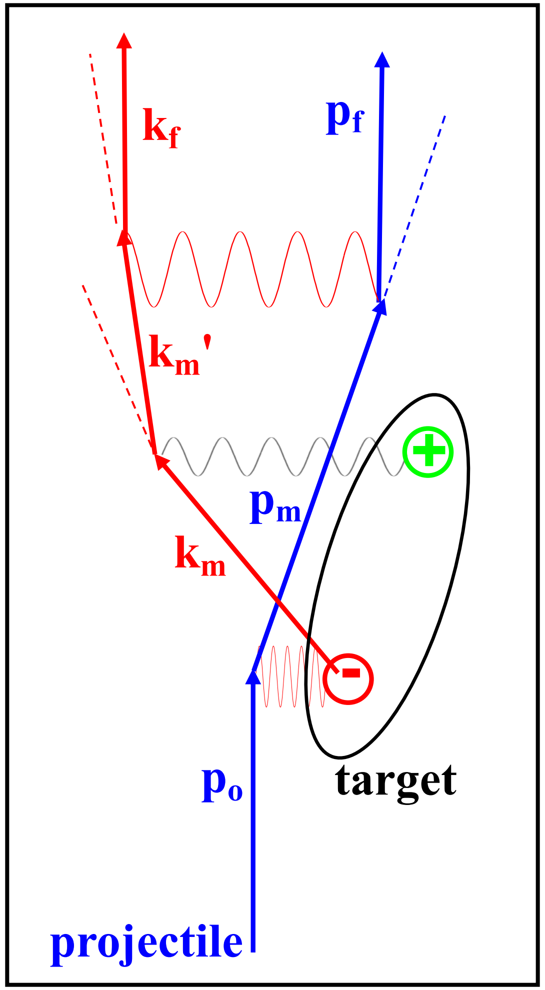
$$\Psi_f = C_{Pe}C_{PT}C_{Te}$$

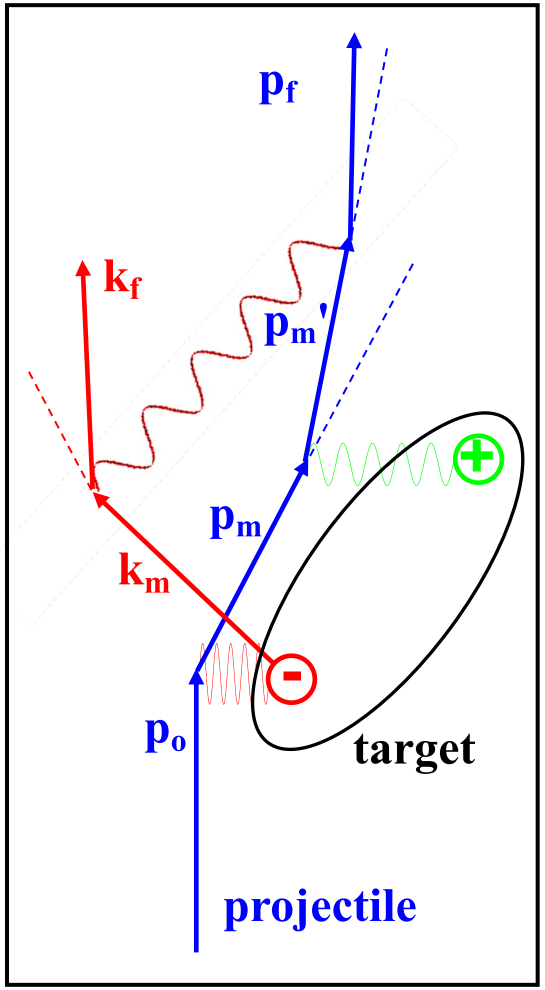
3C wavefunction ignores correlations between particle pairs ⇒ only accurate if one particle far from other two

In perturbation theory understanding few-body dynamics means describing relative importance of higher vs first-order contributions

One important higher-order process: post-collision interaction (PCI)

PE – ET – PE sequence

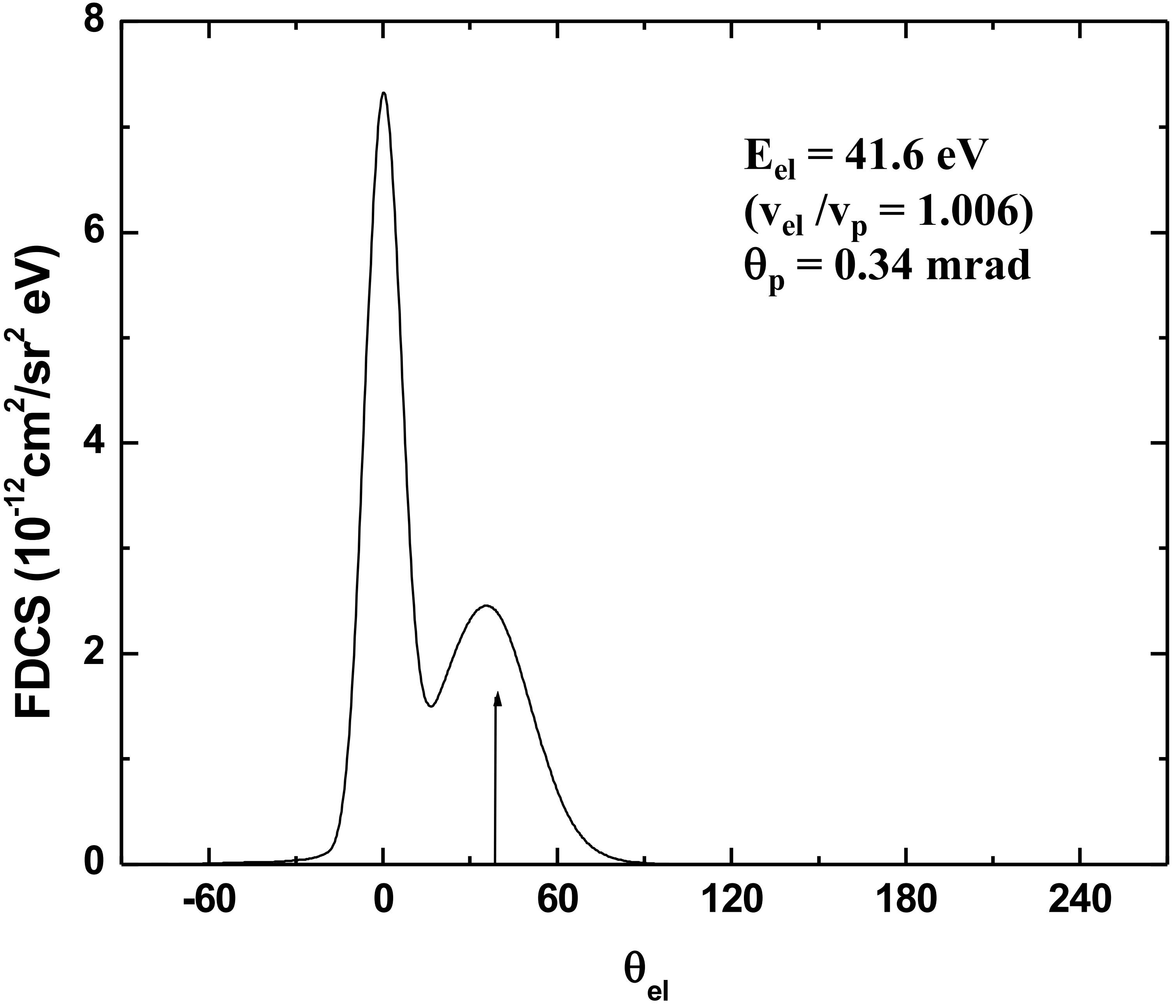




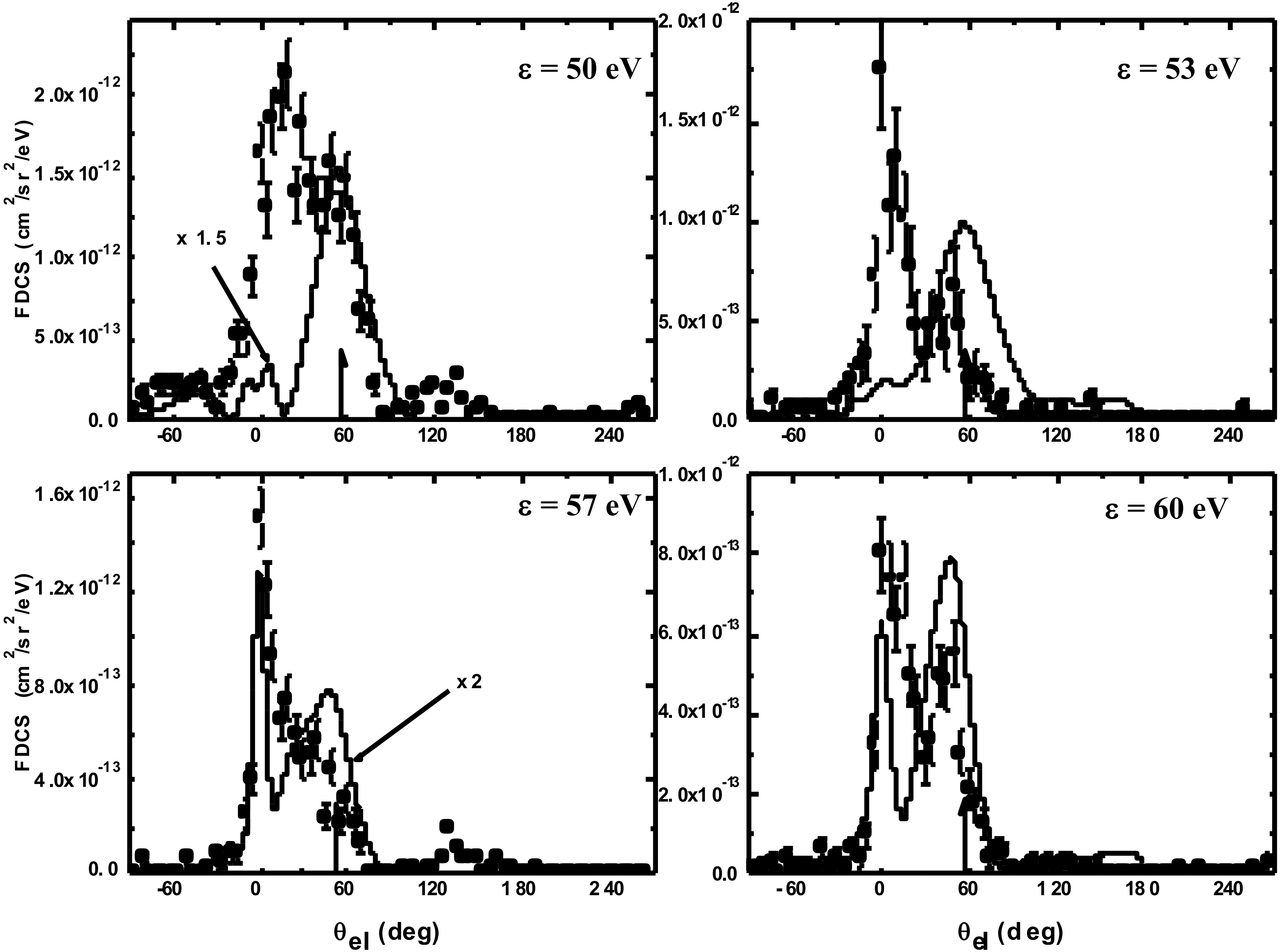
PE – PT – PE sequence

PCI maximizes for $v_{el} = v_p$, for long time no kinematically complete data available!

U. Chowdhury et al.,
Phys. Rev. A 83,
032712 (2011)



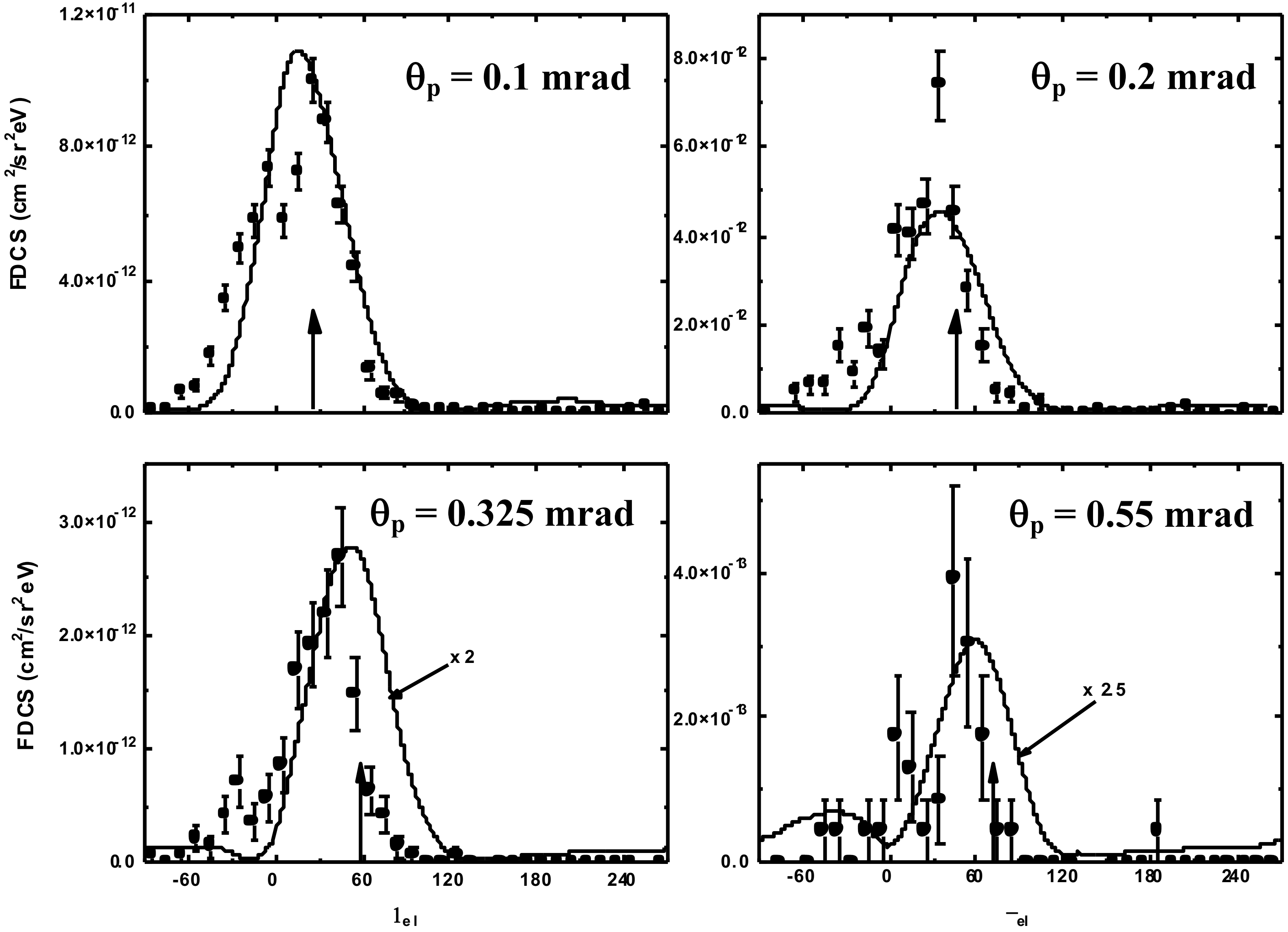
75 keV p + H_2



Electrons ejected into scattering plane
θ_p = 0.55 mrad

M. Dhital et al.
PRA <u>99</u>, 062710 (2019)

75 keV p + H_2



Scattering plane
Electron energy = 30 eV

⇒ Discrepancies between experiment and between two conceptually very similar theoretical models, which appear to maximize near velocity matching and at large θ_p

⇒ In these regions FDCS particulalrly sensitive to details of few-body dynamics!

<u>Possible causes for discrepancies:</u>

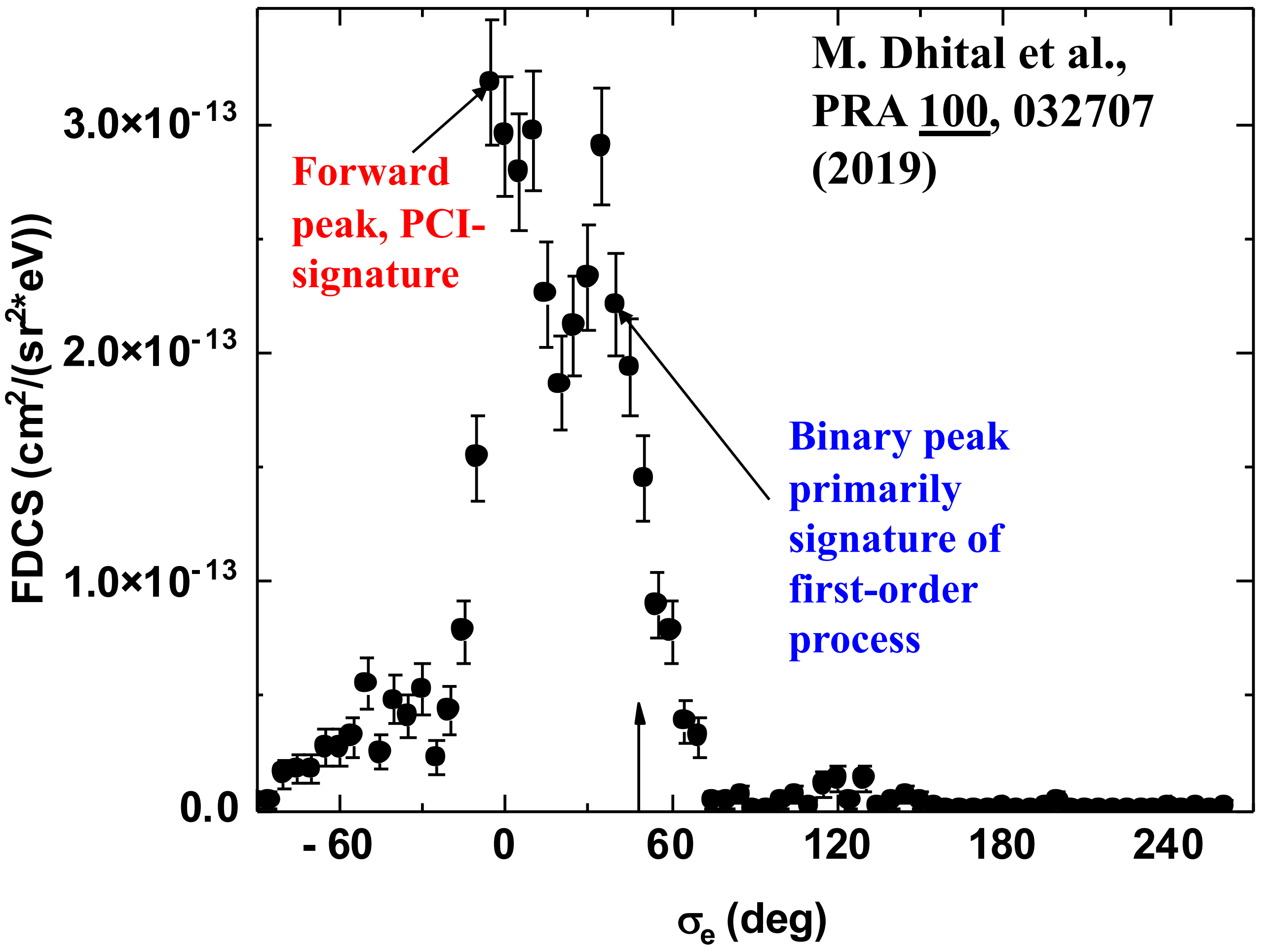
a) 3C wavefunction inaccurate if all particles close together. PE – PT – PE sequence selects such events.

b) Capture channel not included in theory ⇒ due to unitarity capture is erroneously counted as ionization in transition amplitude

Both problems addressed by non-perturbative approaches such as WP-CCC. Calculations currently in progress ⇒ Alisher Kadyrov

p + He

ε = 65.5 eV (v_{el}/v_p = 1) , θ_p = 0.5 mrad



2 signatures of PCI:

a) **forward peak**

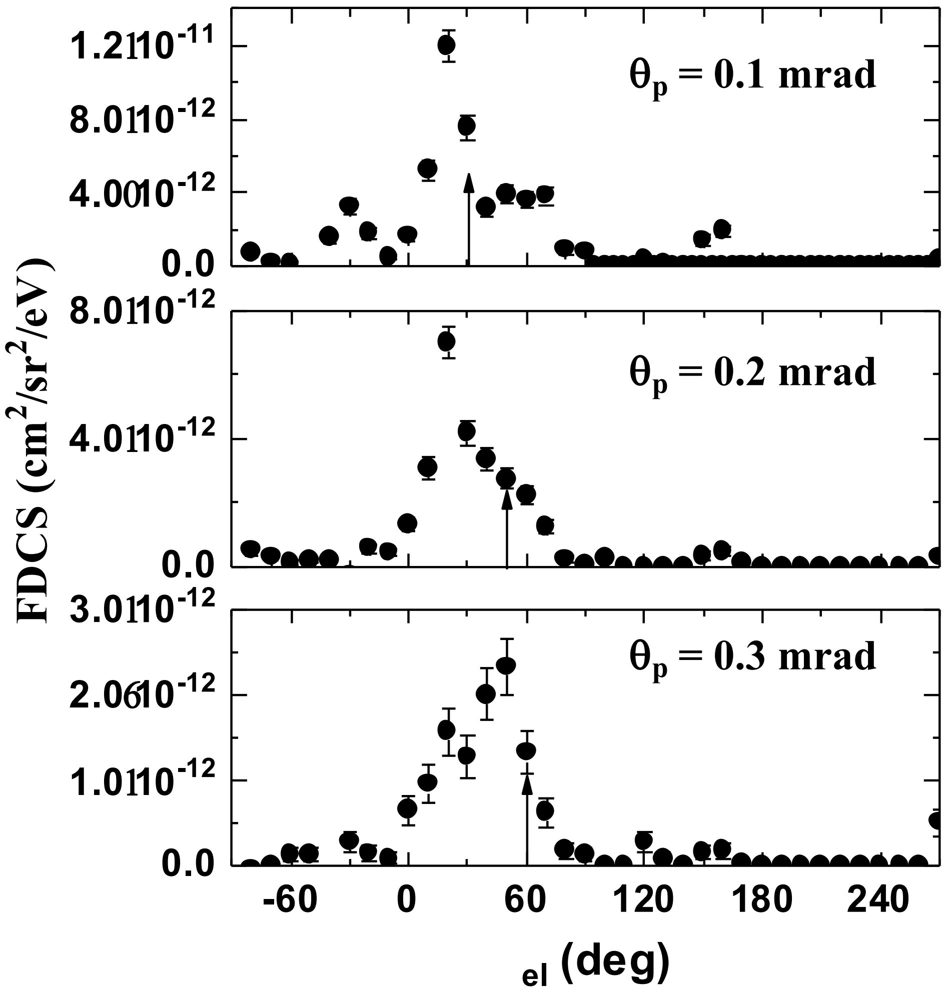
b) **forward shift of binary peak**

Next project: go as far away as possible from v_{el}/v_p = 1 in order to <u>suppress PCI</u>.

Should enable us to study non-PCI higher-order effects.

Use signatures of PCI as monitor for residual PCI contributions

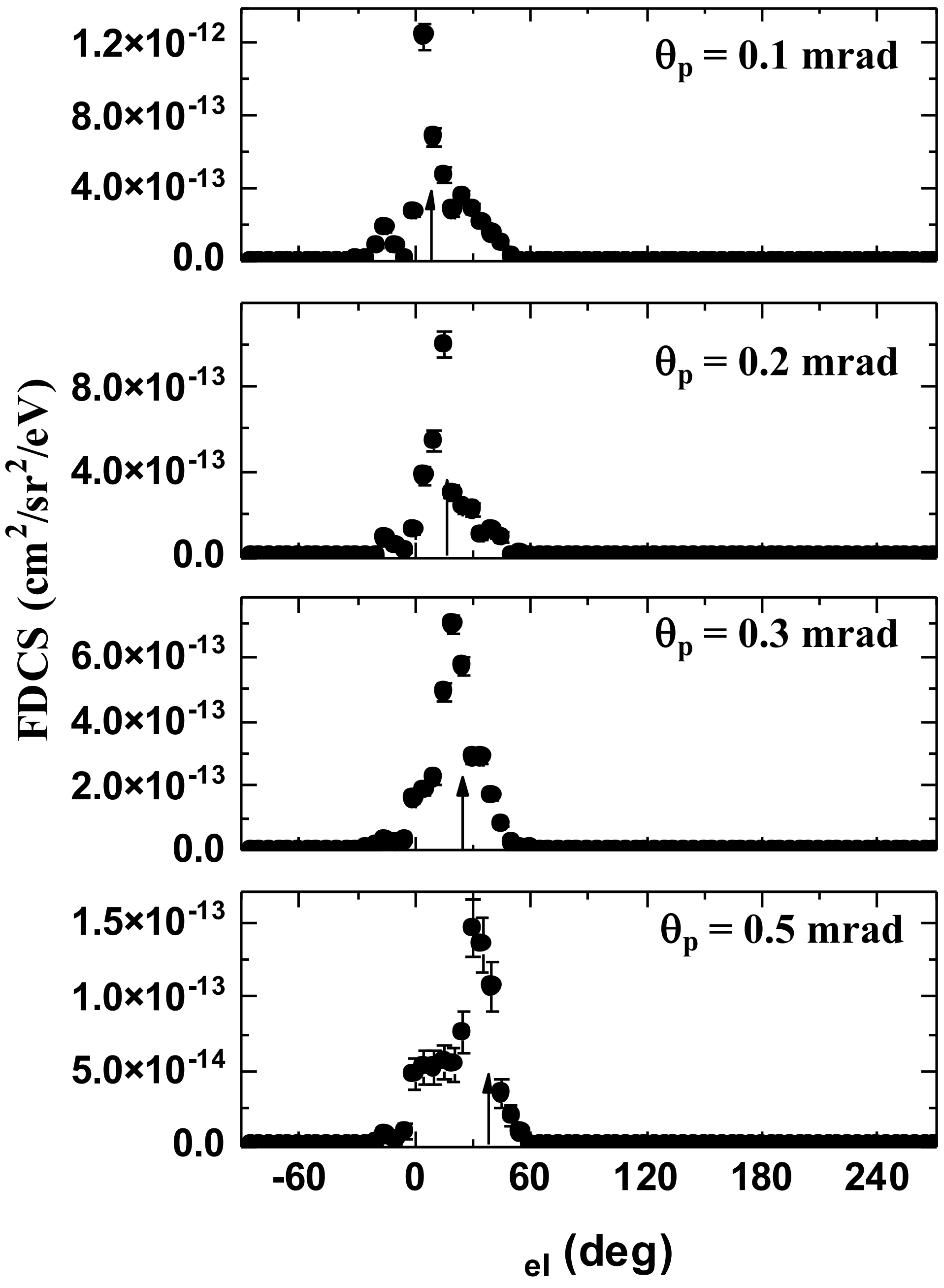
ε = 25.6 eV



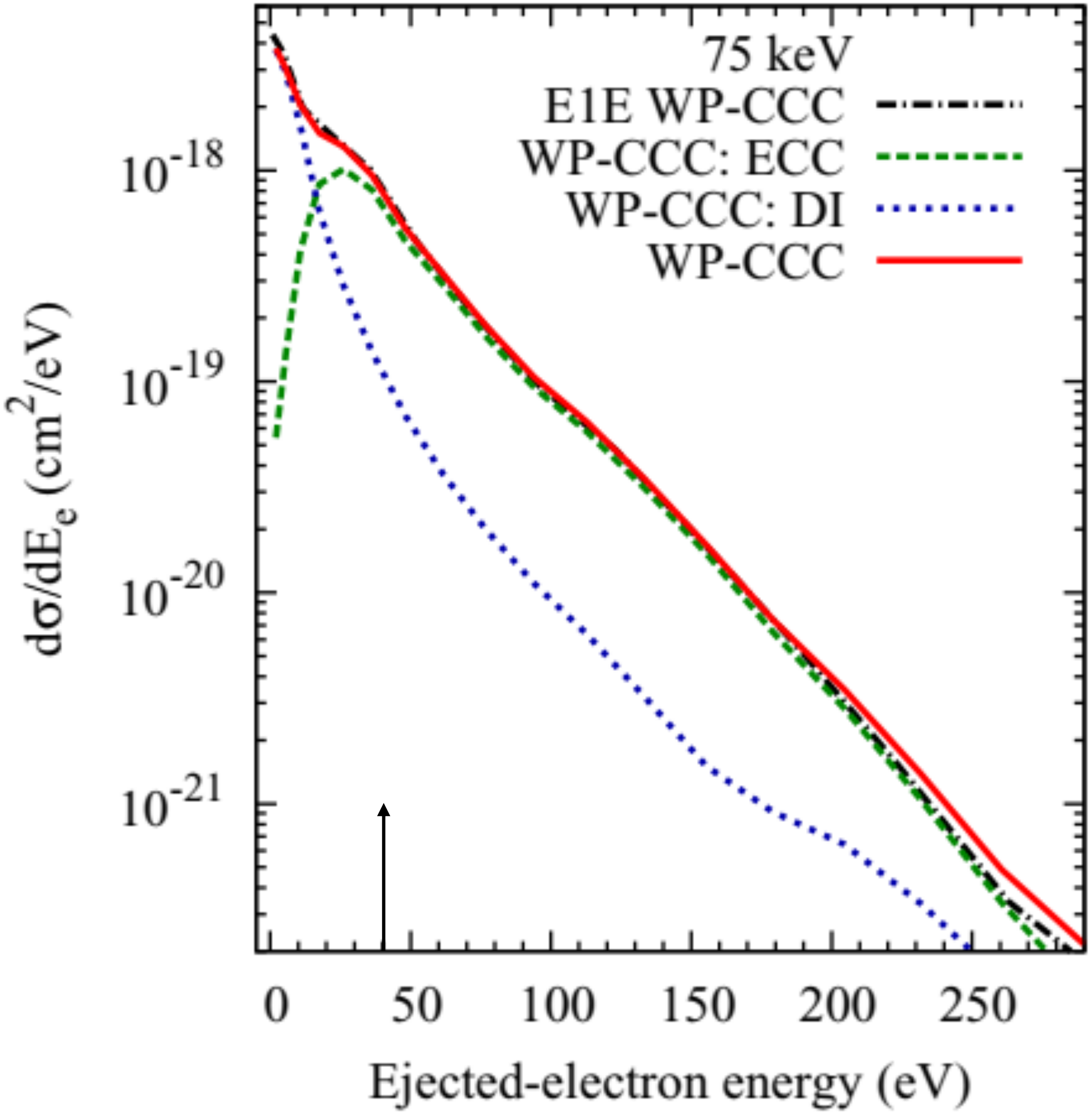
One PCI signature, forward peak, completely absent

Arrows indicate direction of momentum transfer

$\varepsilon = 100$ eV

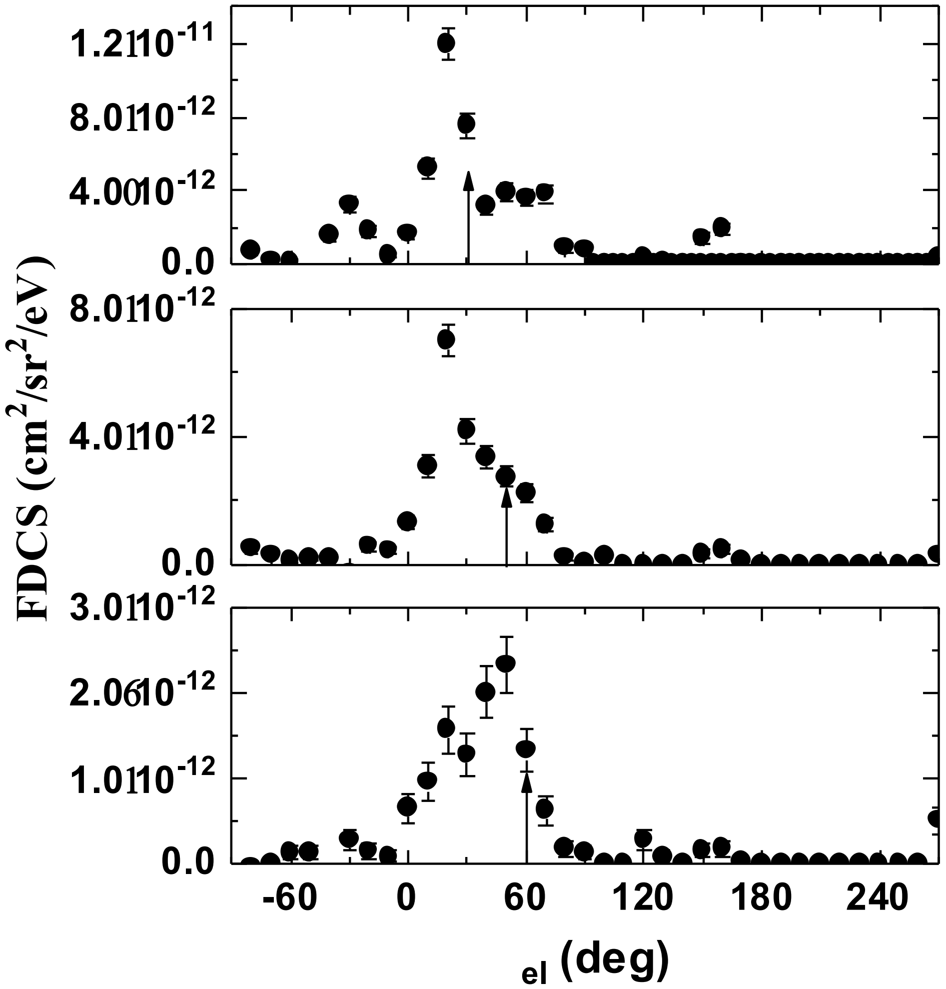


Compared to $v_{el}/v_p = 1$, forward peak strongly suppressed, but compared to $v_{el}/v_p \ll 1$ a significant residue remains

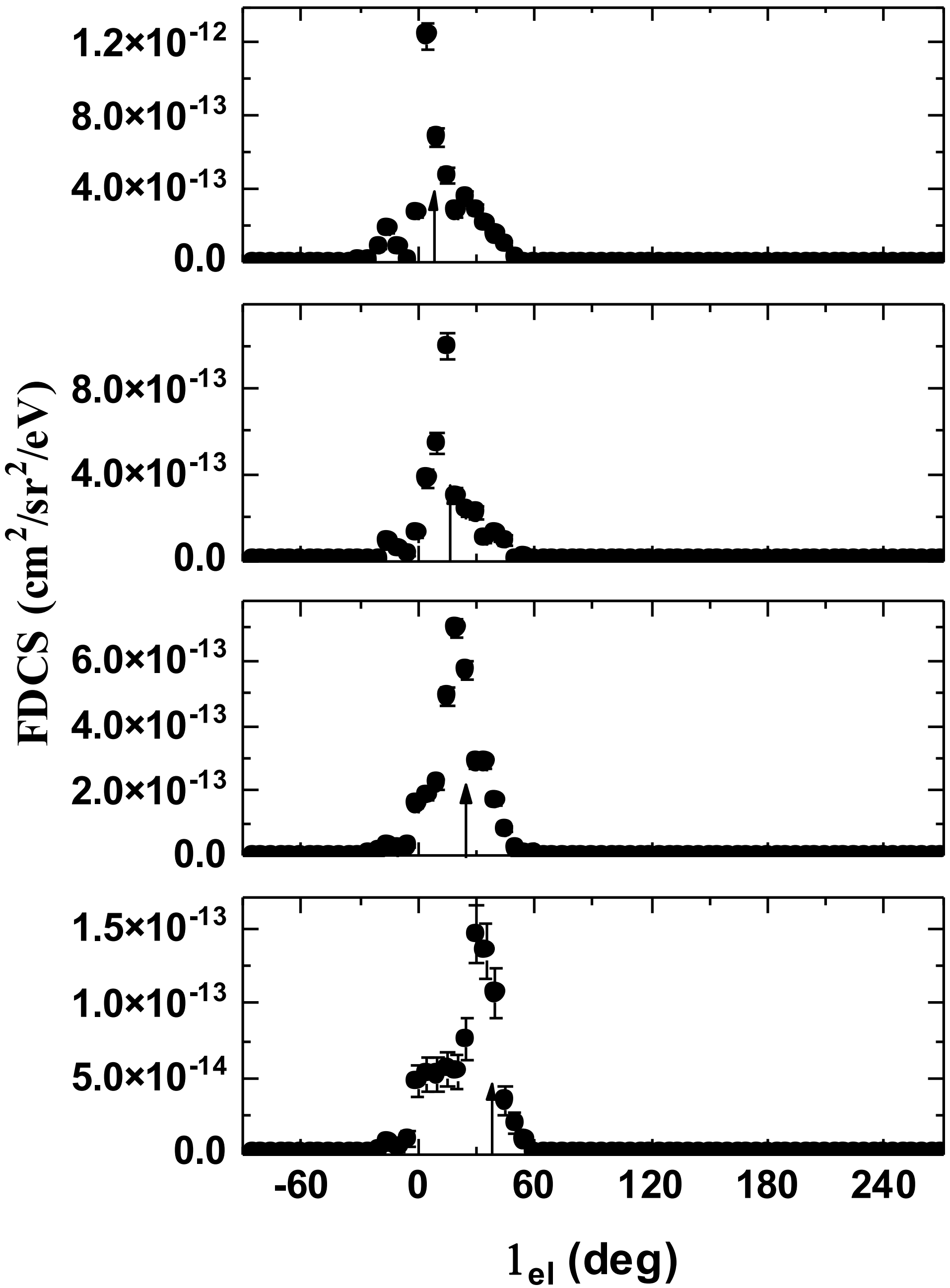


K.H. Spicer et al., PRA 104, 052815 (2021)

ε = 25.6 eV

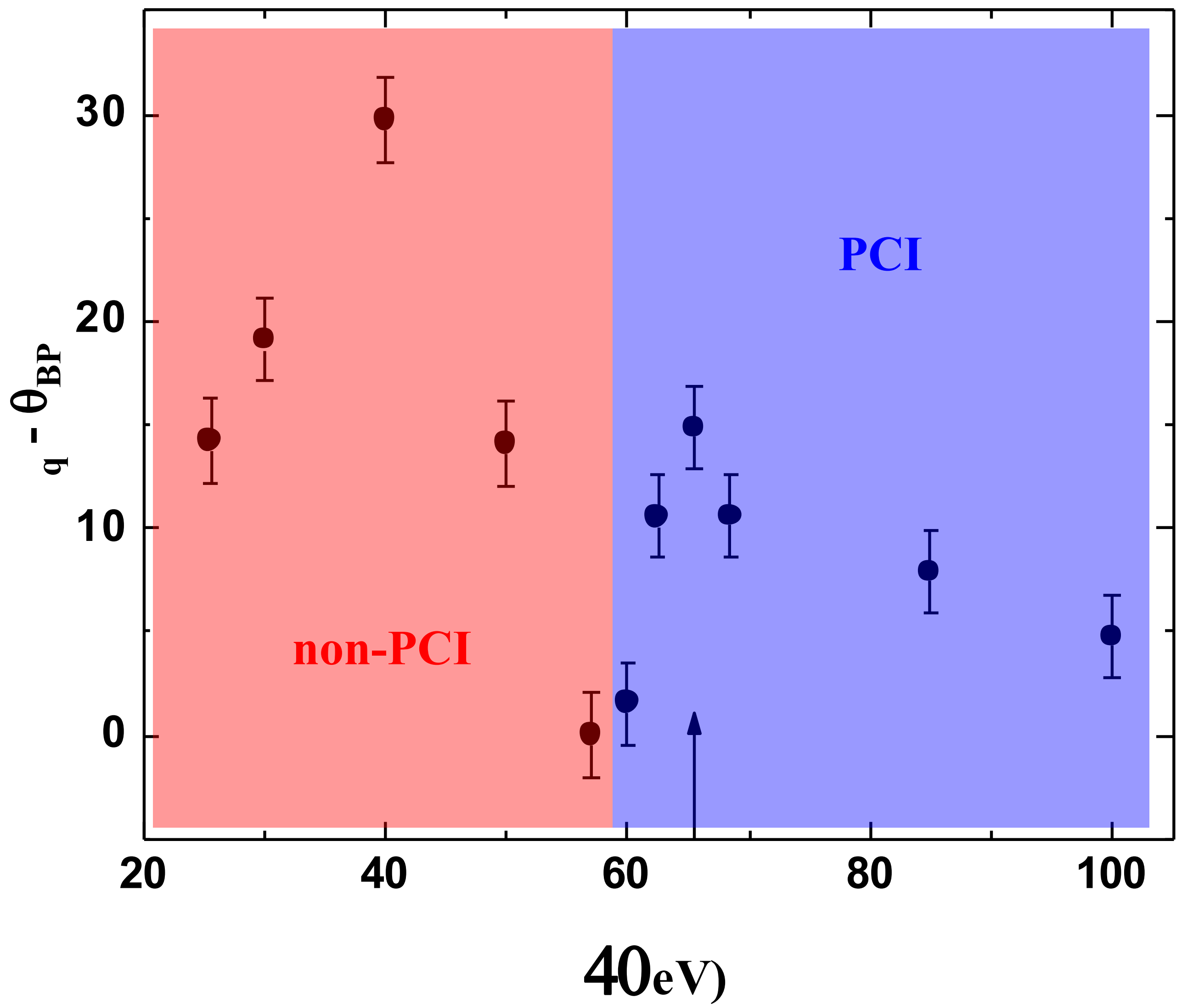


ε = 100 eV



Forward shift is larger at
ε = 25.6 eV,
BUT …

… Schulz et al. PRA 88, 022704 (2013): projectile – target nucleus interaction can also lead to forward shift



2 components to forward shift, one contributes only at $v_{el}/v_p < 1$, the other only near and above $v_{el}/v_p = 1$.

Forward shift for ε = 100 eV caused mostly by PCI, but for ε = 25.6 eV mostly due to non-PCI effects?

Conclusions

- **FDCS for ionization measured for a broad range of electron energies**
- **Near velocity matching PCI signatures: a) forward peak b) forward shift of binary peak**
- **Forward peak absent far below, but residue remains far above matching velocity**
- **Not every forward shift of binary peak is signature of PCI**
  - **far below matching velocity non PCI higher-order effects**
  - **above matching velocity mostly due to PCI**
- **Without Don Madison and his distorted wave calculations we would not be where we are. But now non-perturbative calculations needed.**