Multi-particle imaging techniques for studying electron and positron impact ionization

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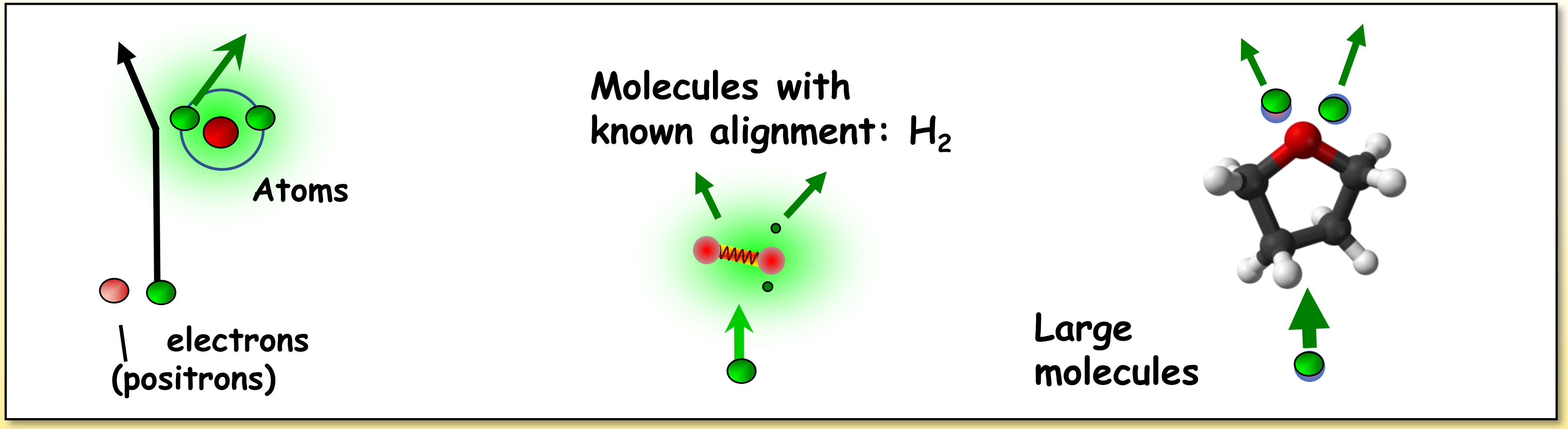
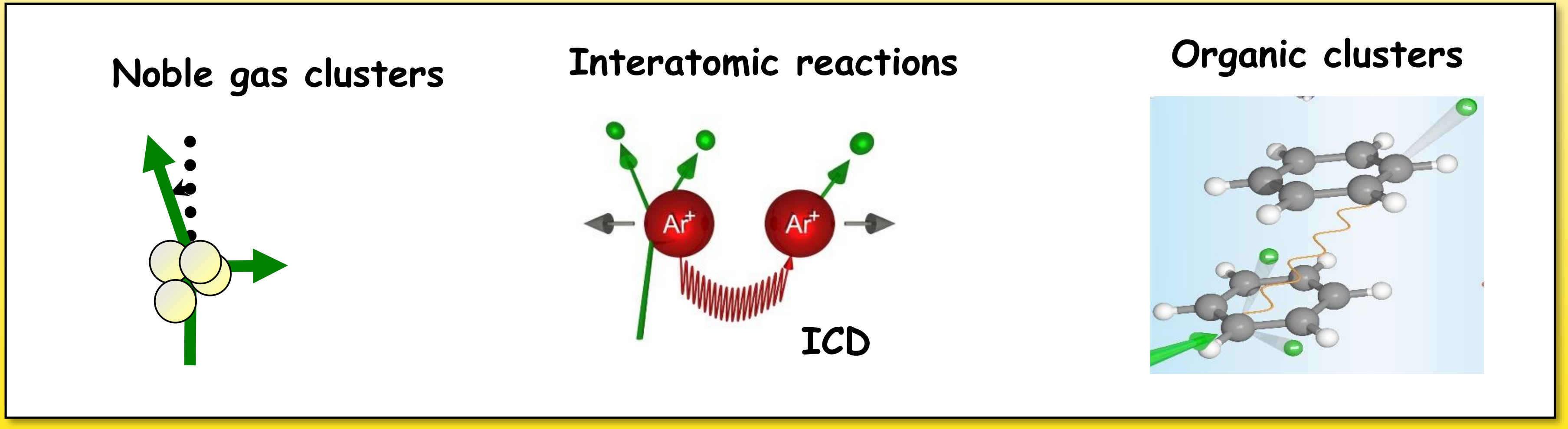
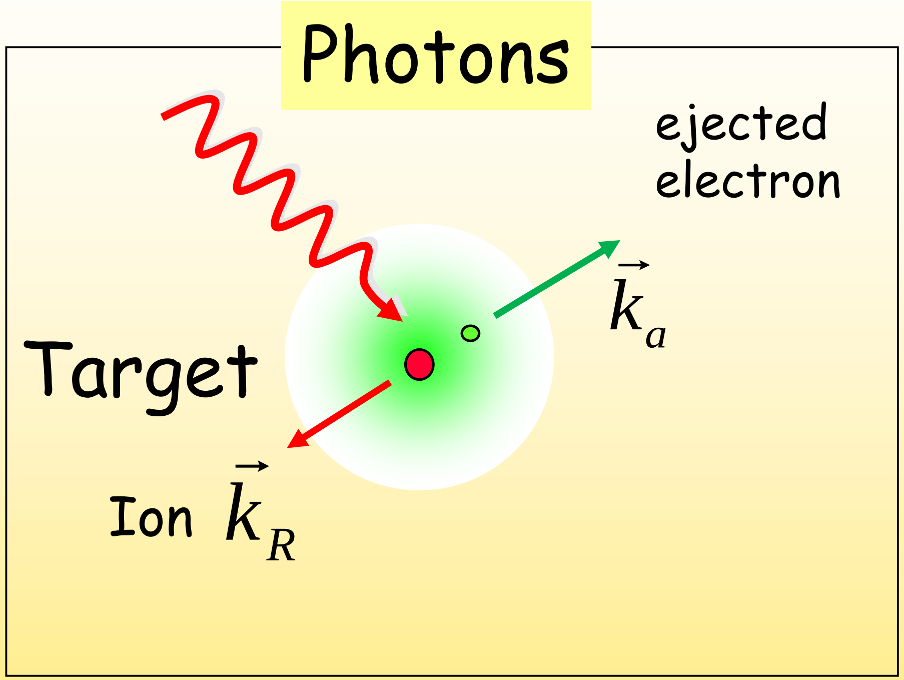
Max–Planck–Institut
für Kernphysik

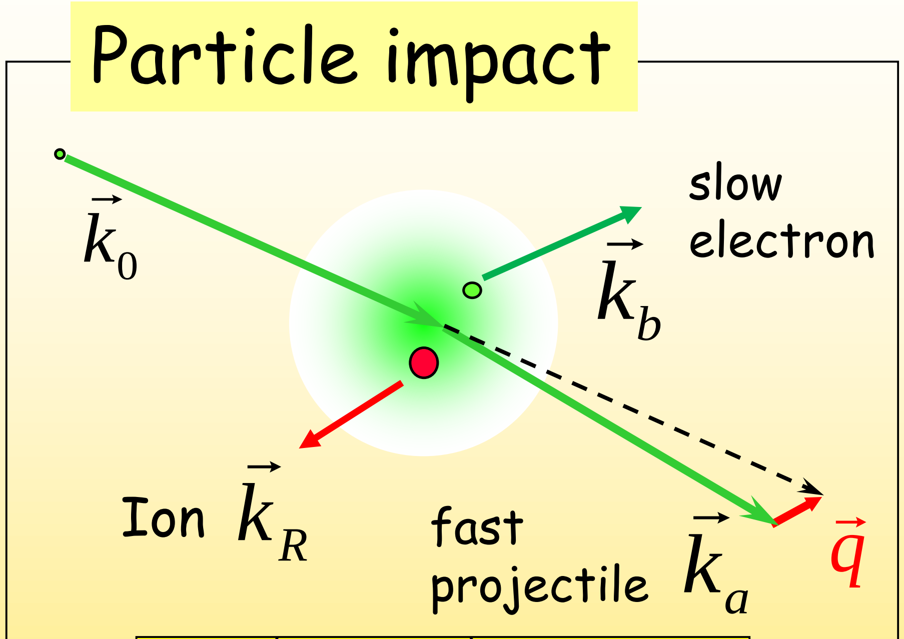
Fundamental ionization reactions





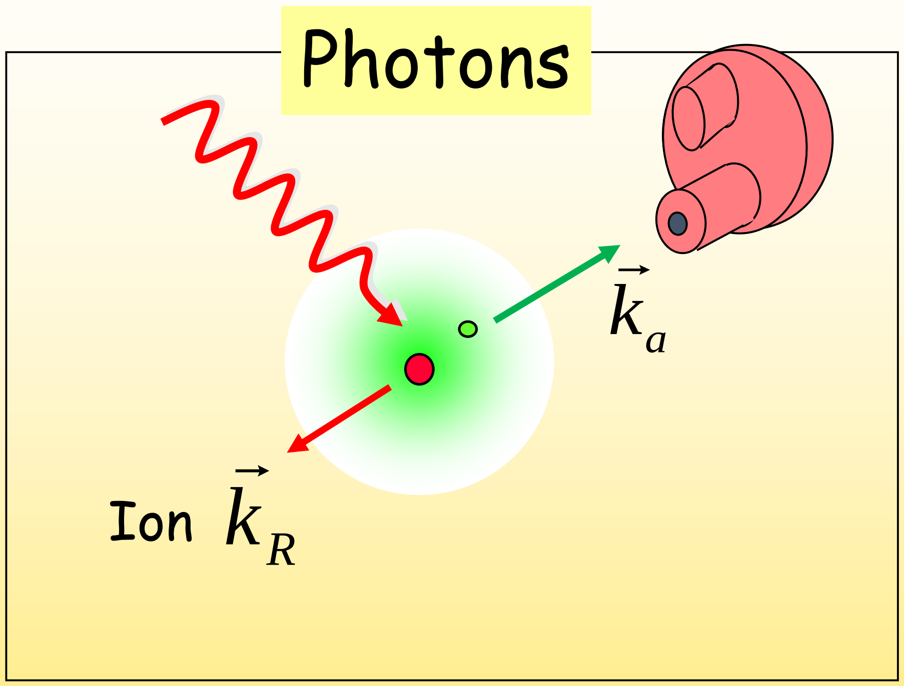
Ideally: Kinematically complete studies

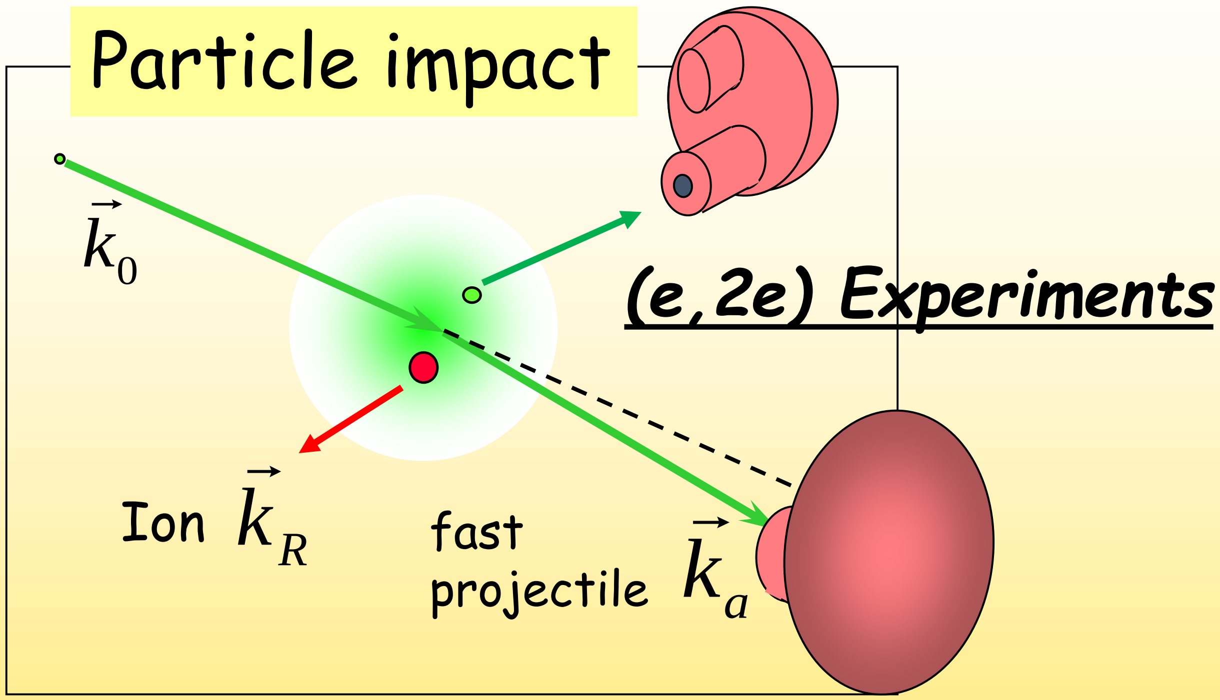




$$\vec{q} = \left(\vec{k}_0 - \vec{k}_a\right) = \vec{k}_R + \vec{k}_b$$

The Experimental Technique



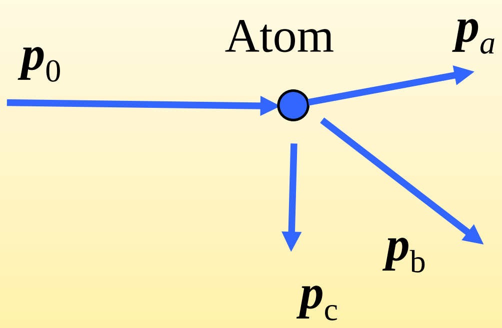


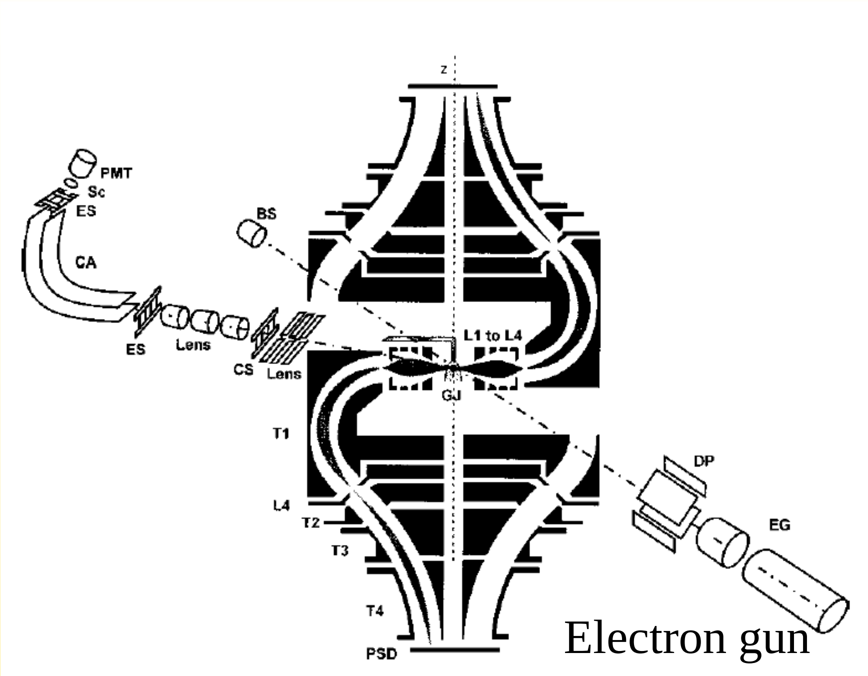
Conventional electron spectrometers:

+ Excellent energy and angular resolution
- Low efficiency. Limitted to 2-particle coincidence.
- For ion impact scattering angles are too small.

Limit: 3-particle coincidences

$$e^- + He \rightarrow He^{2+} + 3e^-$$





Université Paris XI

Azzedine Lahmam-Bennani

Countrate: 1/10 min.

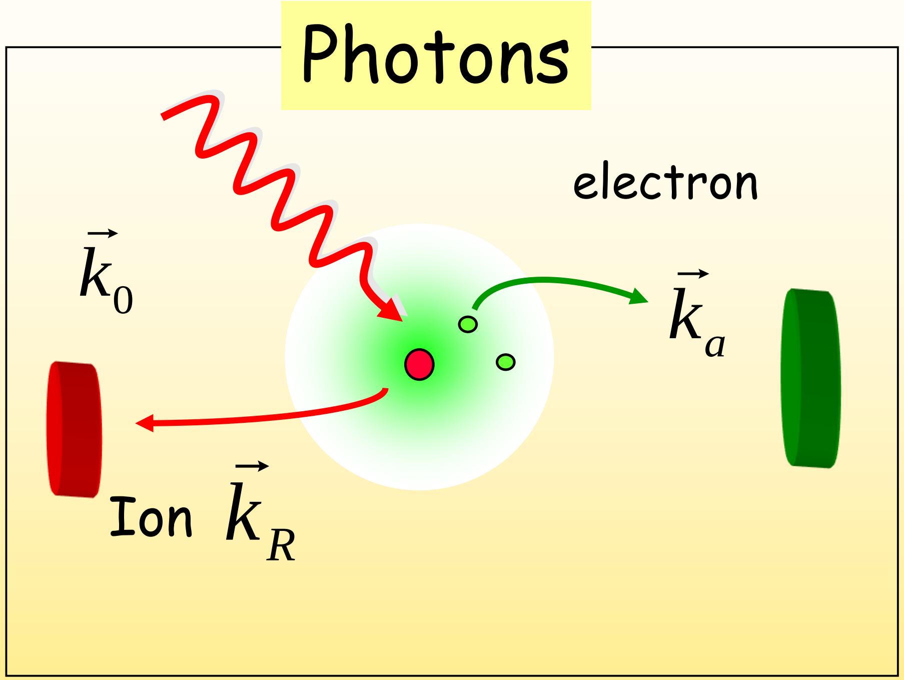
Signal rate

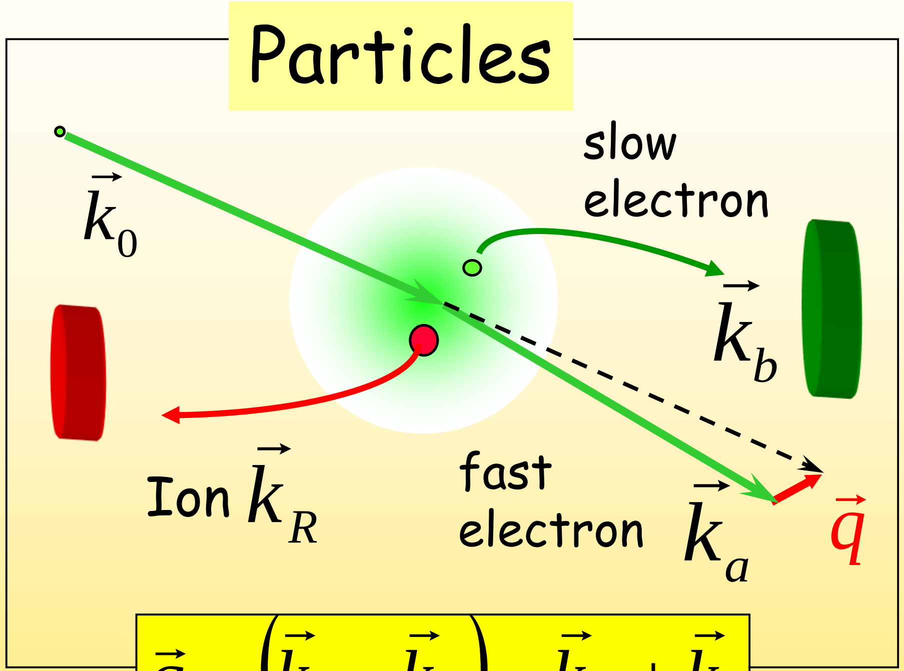
$$\dot{N}_D = \frac{d^5\sigma}{d\Omega_1 d\Omega_2 d\Omega_2 dE_1 dE_2} j_0 N_T \, \Delta\Omega_1 \, \Delta\Omega_2 \, \Delta\Omega_3 \Delta E^{eff} \; \varepsilon_1 \, \varepsilon_2 \, \varepsilon_3$$

$$\dot{N}_D = 10^{-22} \frac{cm^2}{eV^2} \cdot 100 \frac{nA}{mm^2} \cdot 10^{11} \cdot 10^{-6} \cdot 3eV^2 = 0.002 \frac{1}{s}$$

➡ Experiments for coincidences of more than two particles become unfeasible.

The COLTRIMS or Reaction Microscope technique



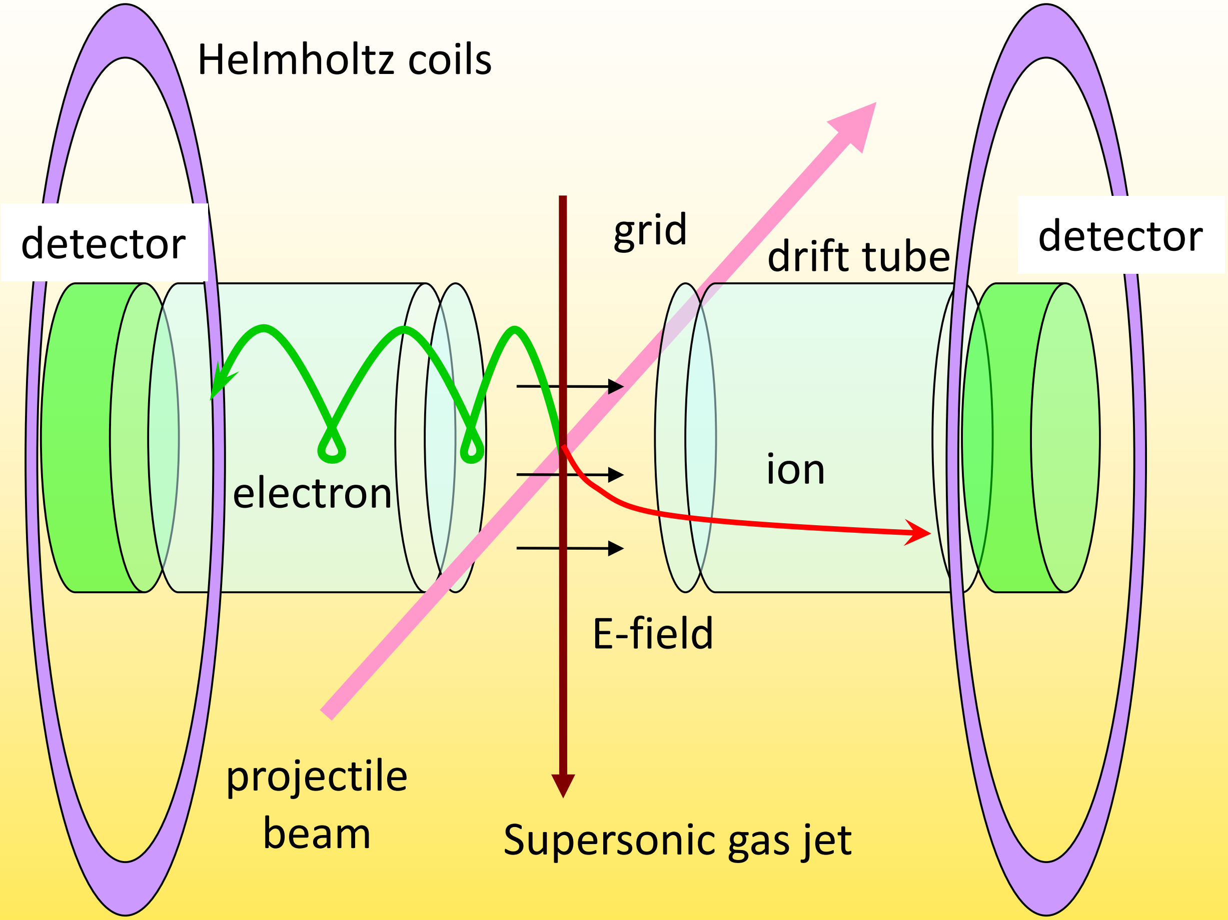


$$\vec{q} = \left(\vec{k}_0 - \vec{k}_a\right) = \vec{k}_R + \vec{k}_b$$

+ Electron and ion detection over the full solid angle
+ Kinematically complete (without projectile detection).
- Ion momentum resolution depends on target temperature and mass.

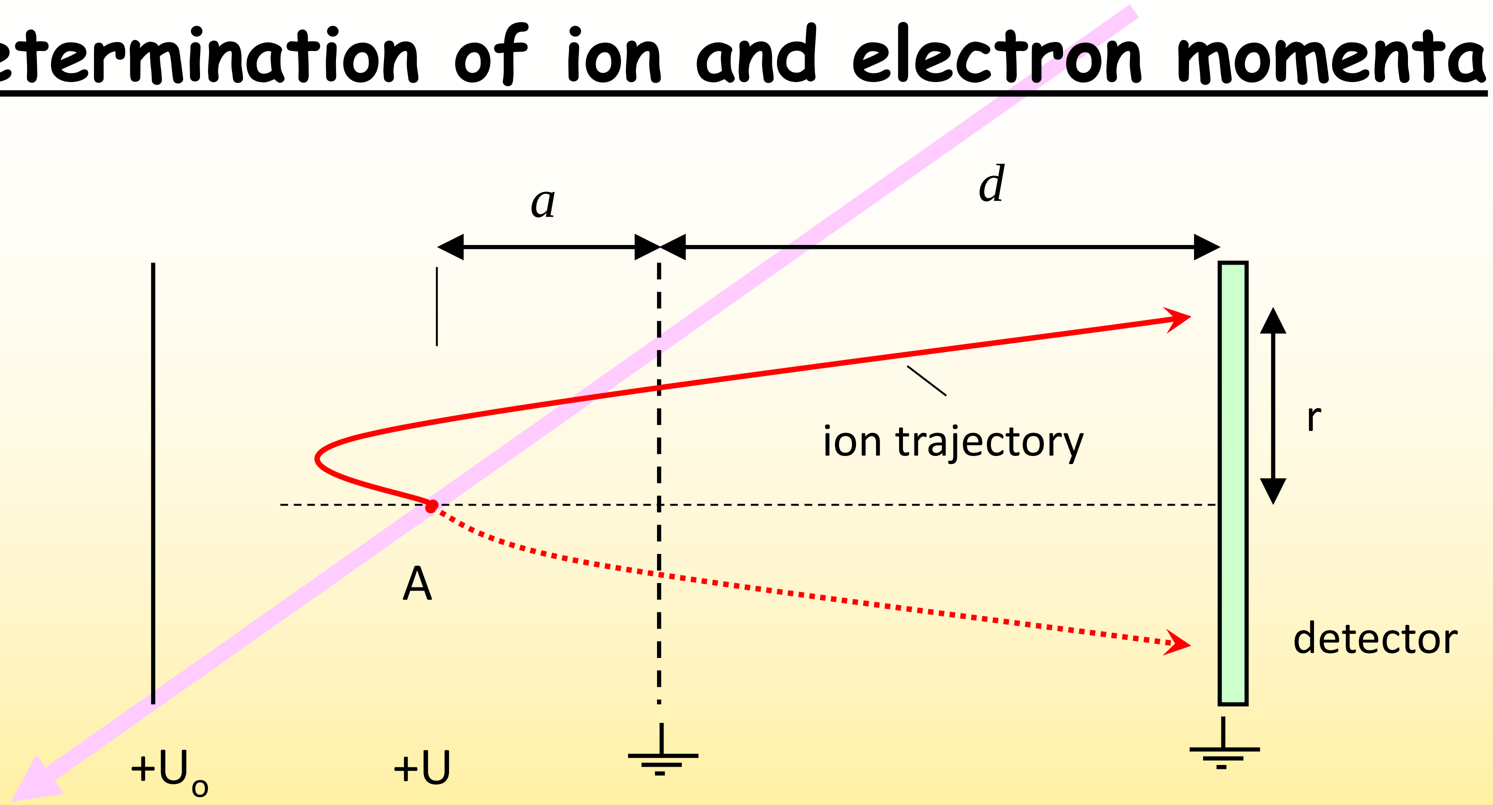
E.g.:
He^+: T = 1°K → Δp = 0.26 a.u.
Ar^+: T = 1°K → Δp = 0.83 a.u

The Reaction Microscope



Universal many-particle coincidence spectrometer for studying
atomic and molecular fragmentation reactions

Determination of ion and electron momenta



Ion/electron time of flight $t_{+/-}(E^{||}) = \sqrt{\frac{m}{2}} \cdot \left[\frac{2a}{\sqrt{E^{||}+qU} \pm \sqrt{E^{||}}} + \frac{d}{\sqrt{E^{||}+qU}} \right]$

$E^{||}$: kinetic energy of ions parallel to spectrometer axis

m : ion mass

q : particle charge

Example: ionization of argon

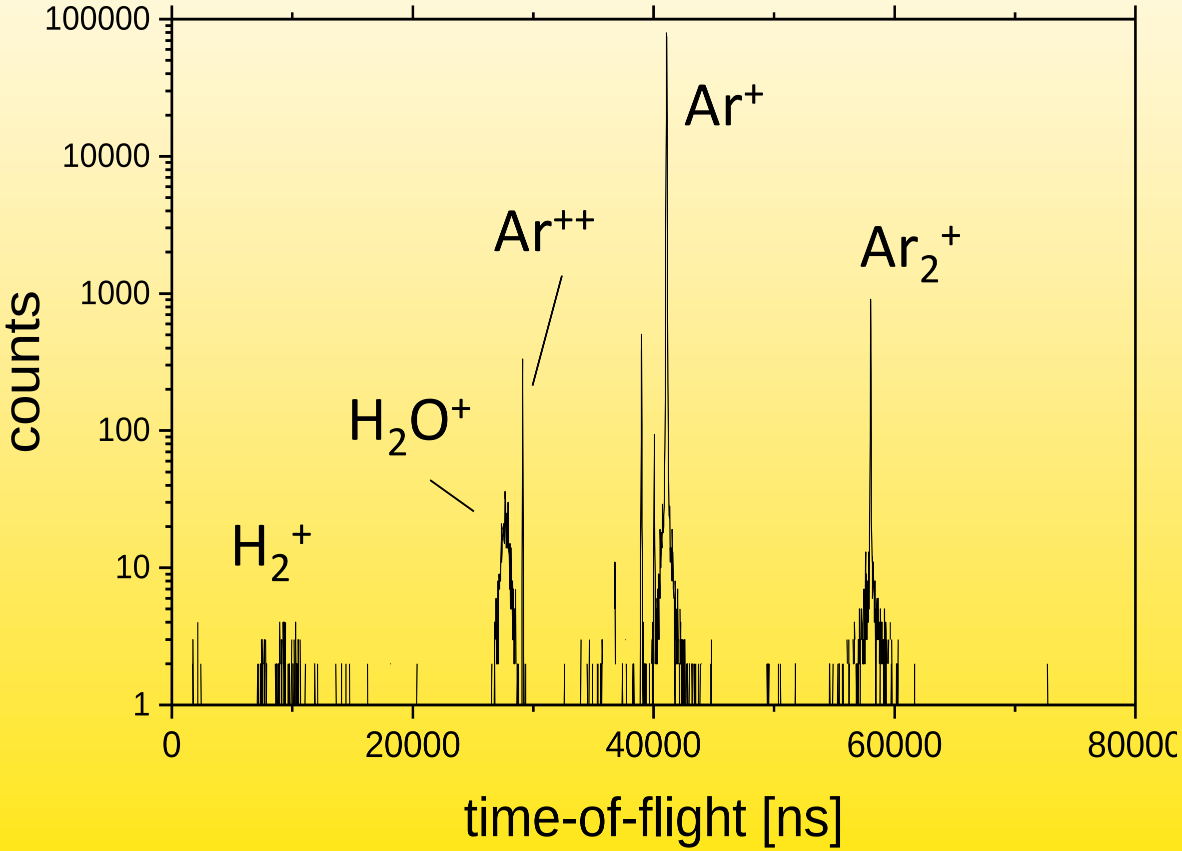
Ion time-of-flight

m = 40 (Ar)
U = 20 eV
a = 10 cm
d = 20 cm
E = 0

$$t_o = \sqrt{\frac{m}{2}}\frac{(2a+d)}{\sqrt{qU}} = 40730\text{ ns}$$

Electrons:
time-of-flight

m = 1/1836
=> $t \approx 150$ ns



$$n\gamma + Ar(3p^6) \rightarrow Ar^+(3p^5) + e^-$$
$$\rightarrow Ar^{2+}(3p^4) + 2e^-$$

→ Mass over charge separation

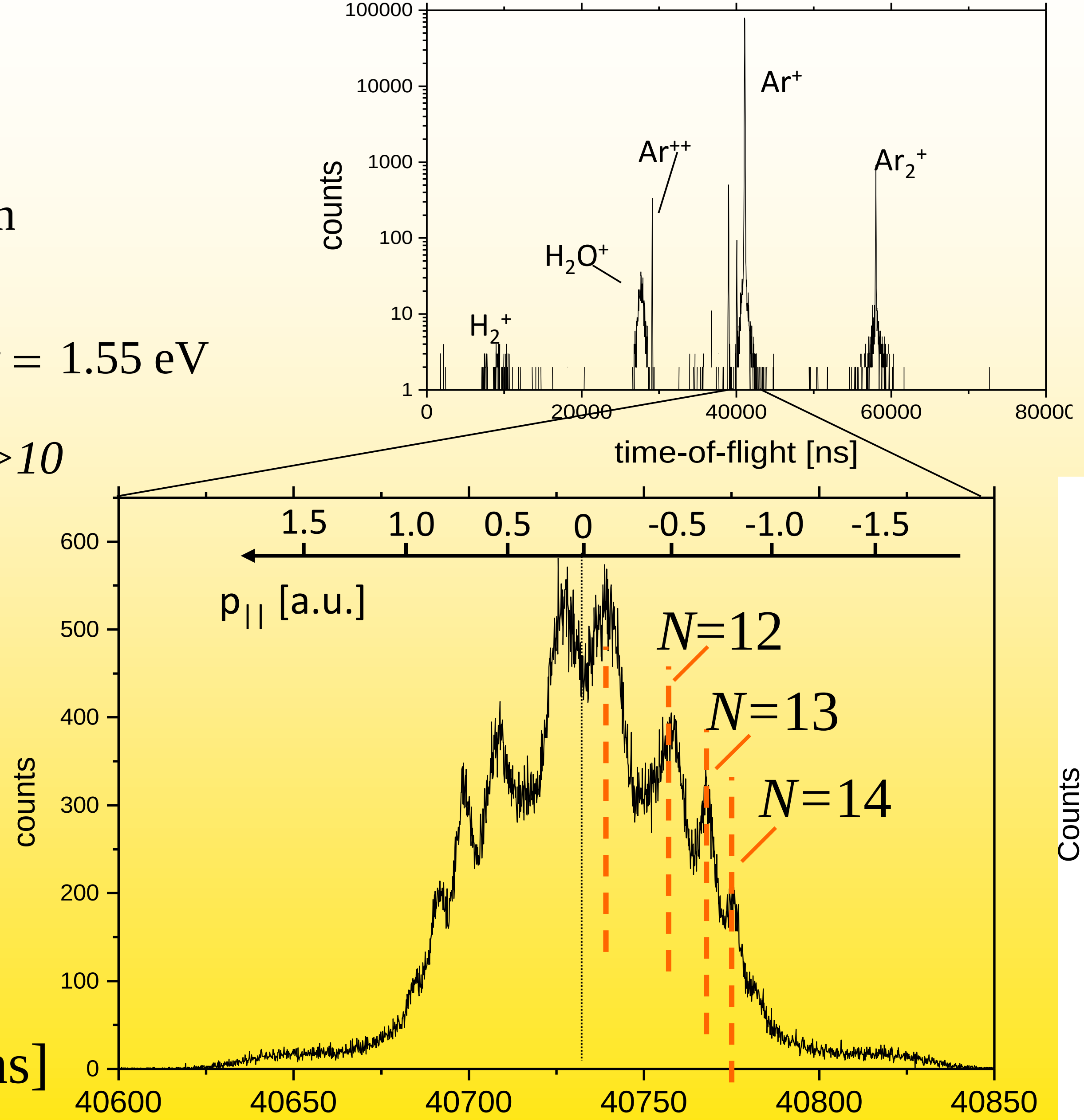
Longitudianal momentum determination

Example:
Ionization of argon

$I_p = 15.7$ eV $h\nu = 1.55$ eV

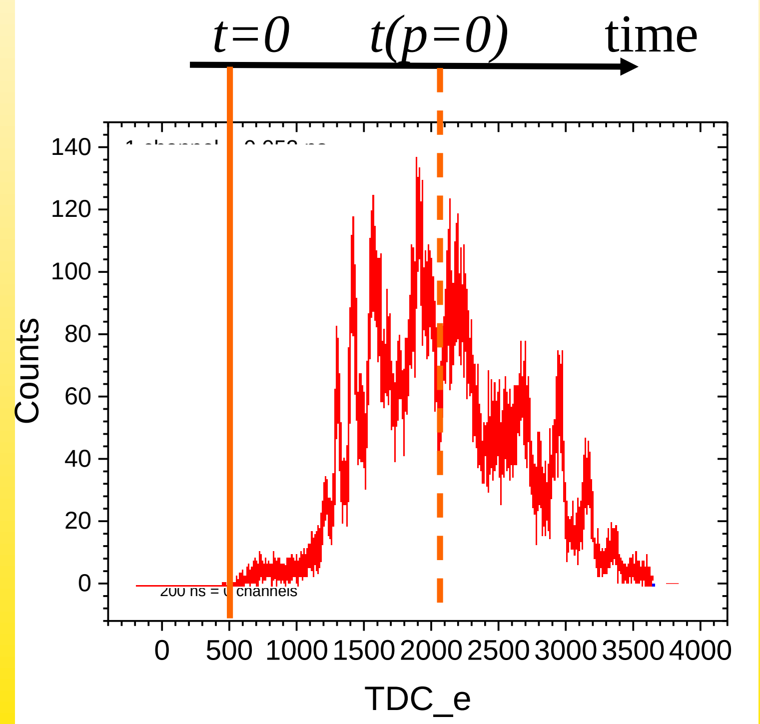
$E_e = N \cdot h\nu - I_p$ $N>10$

$p_e = -p_{ion}$

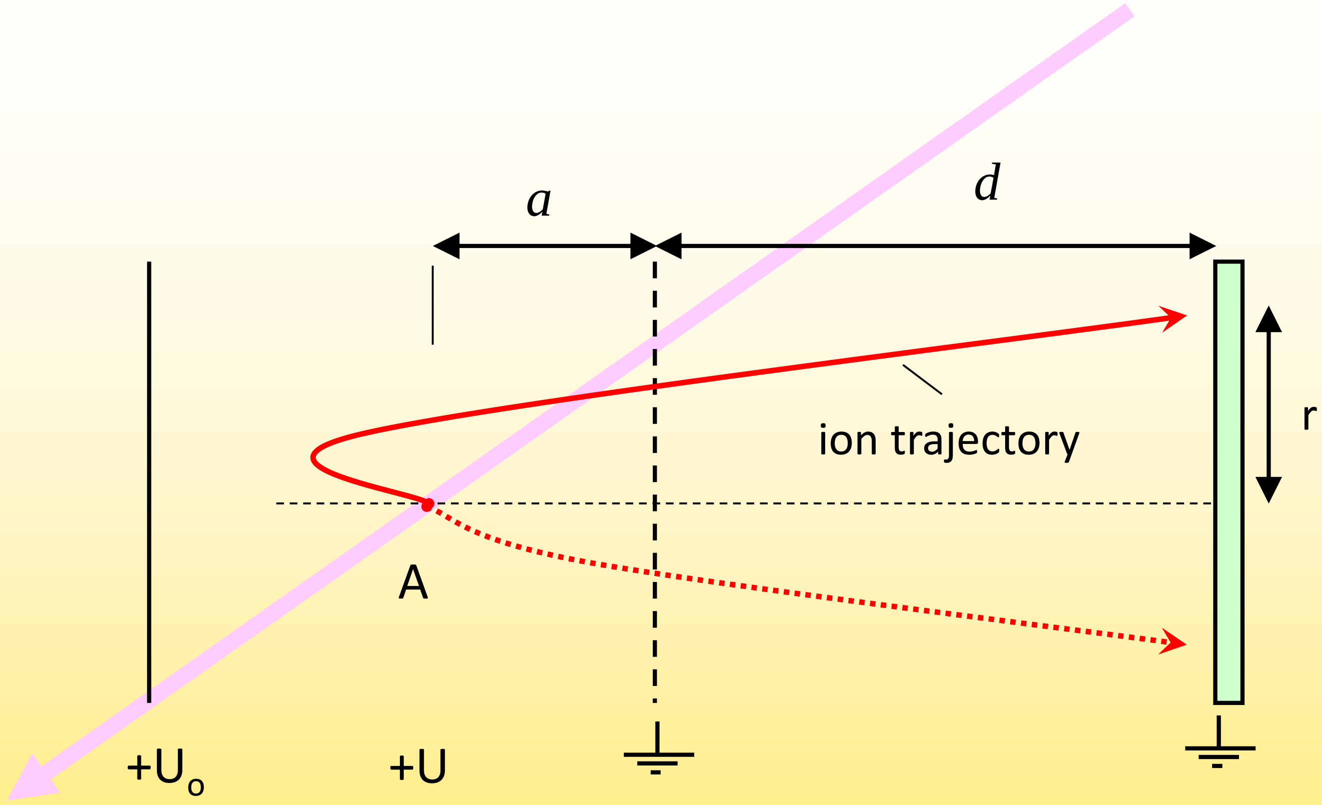


Ion time-of-flight [ns]

Electron time-of-flight



Transversal momentum obtained from detected position

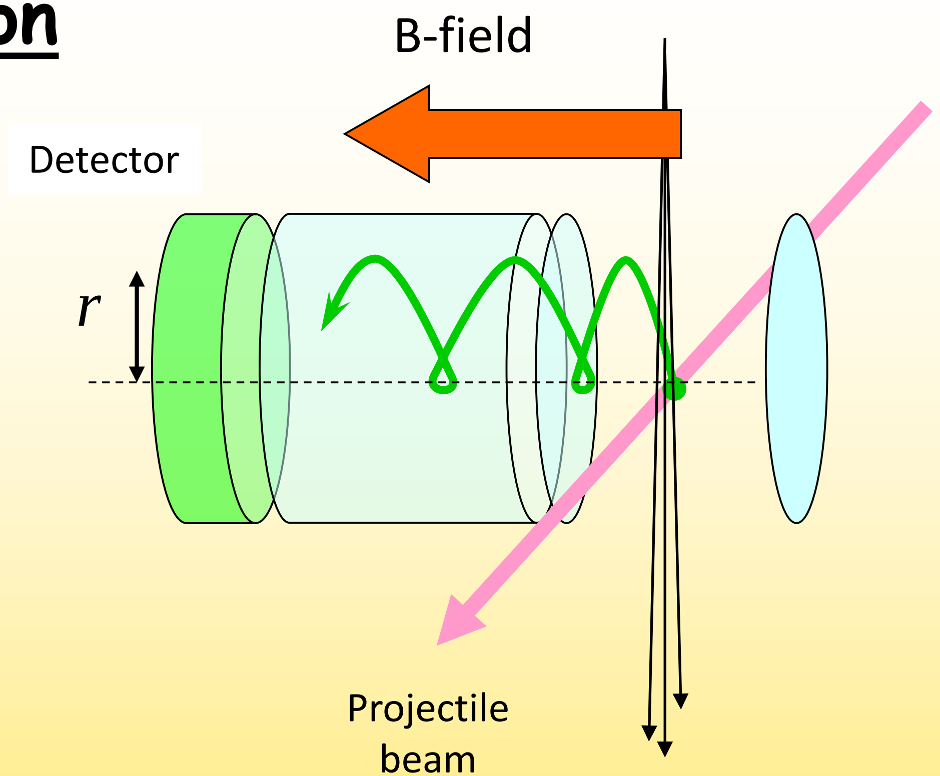


$$t = \sqrt{\frac{m}{2}}\frac{(2a+d)}{\sqrt{qU}}$$

$$v_\perp = \frac{p_\perp}{m}$$

$$r = \frac{p_\perp}{\sqrt{mqU}}\frac{(2a+d)}{\sqrt{2}}$$

The electron transversal motion



Cyclotron motion:

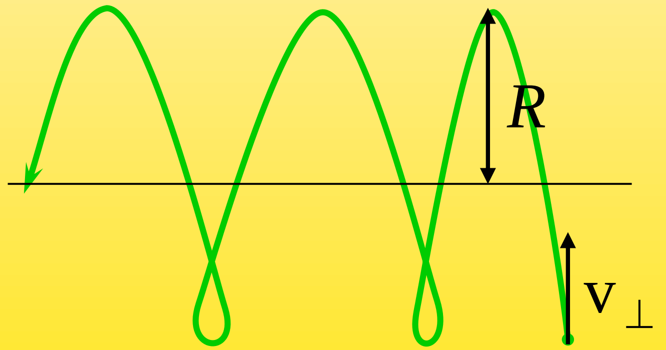
$$F_{Zentrifugal} = F_{Lorentz}$$

$$m v_\perp^2 / R = q \cdot v_\perp \cdot B$$

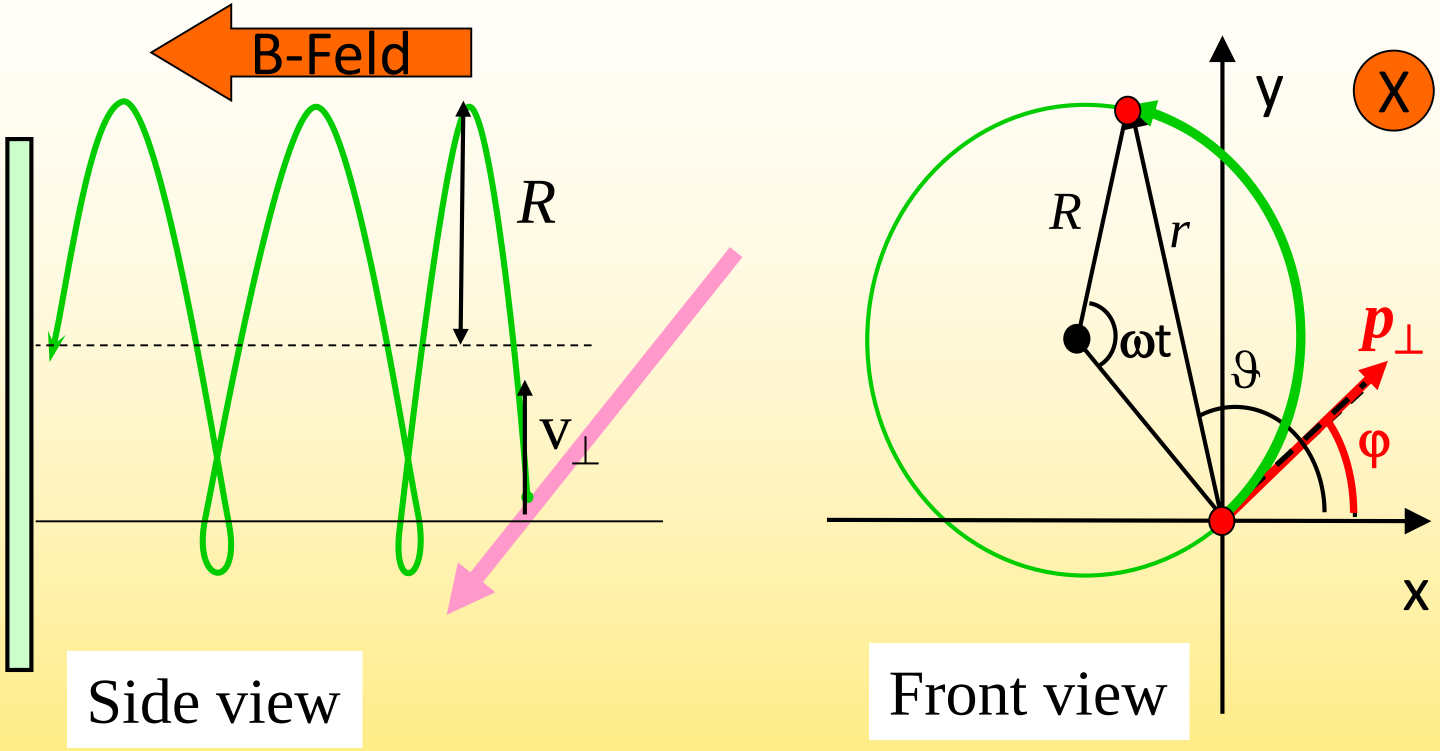
$$p_\perp / R = q \cdot B$$

Radius : $R = p_\perp / (q \cdot B)$

Frequency: $\omega = q \cdot B / m = 2\pi / T$

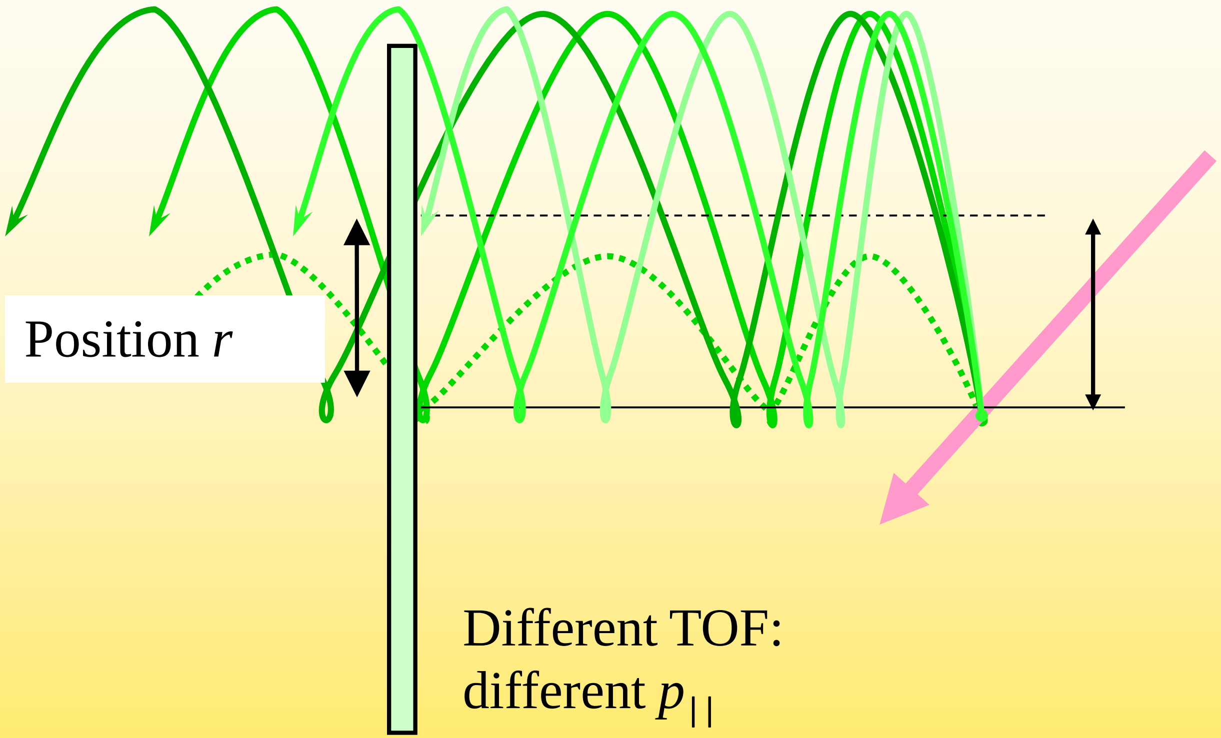


Reconstruction of transversal momentum $p_\perp$



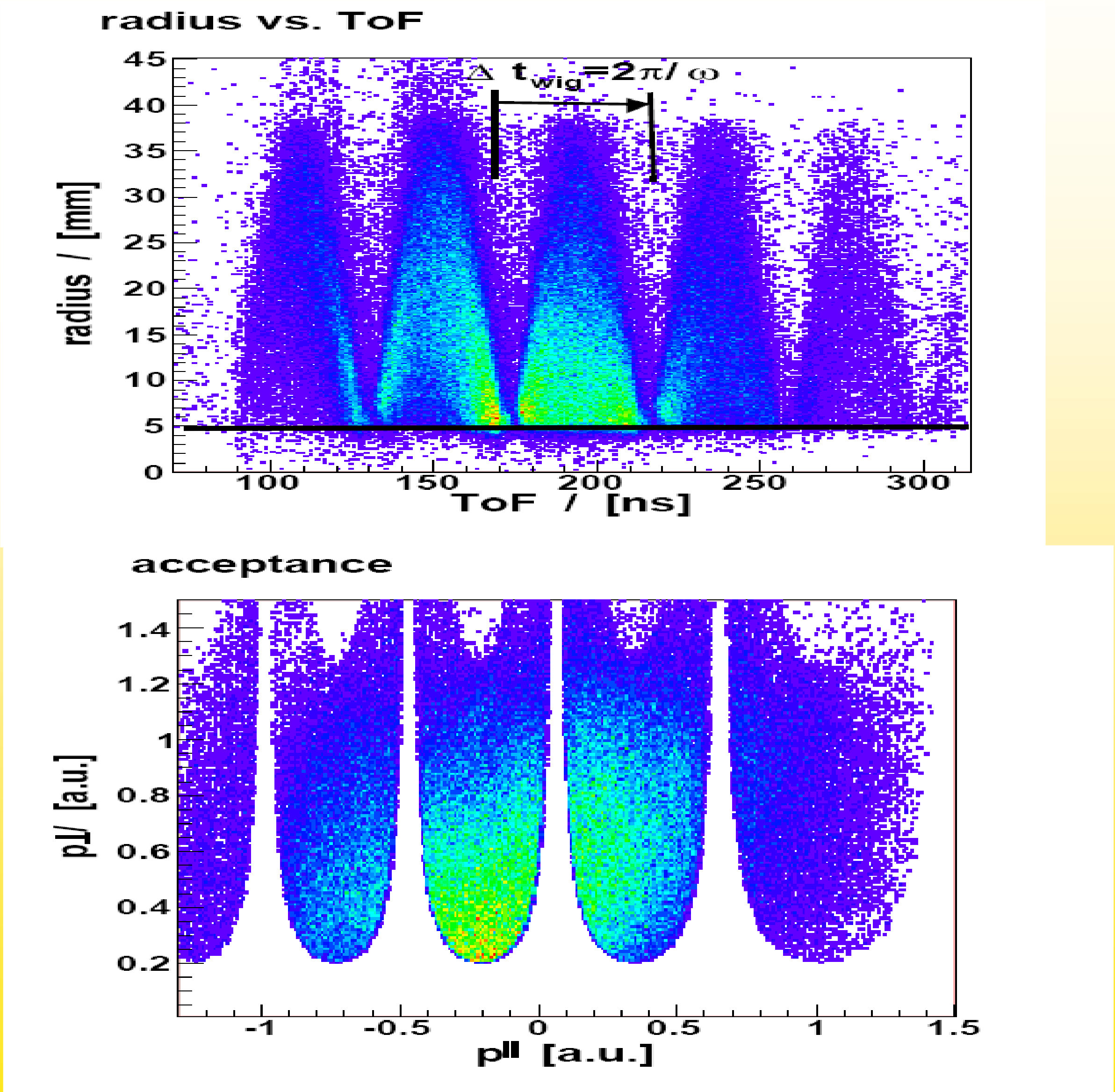
Measured quantities: position (r, ϑ) and TOF t

To be determined: momentum ($p_\perp$) and angel (φ)

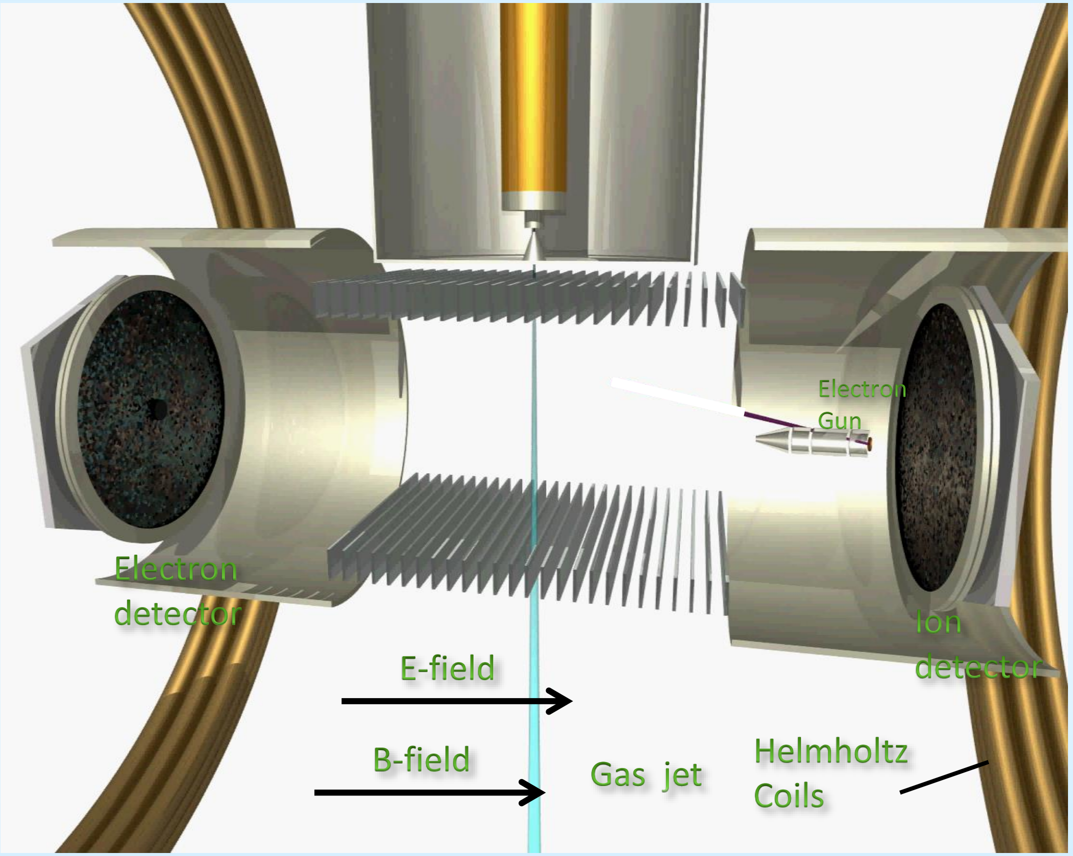


Different TOF:
different $p_{||}$

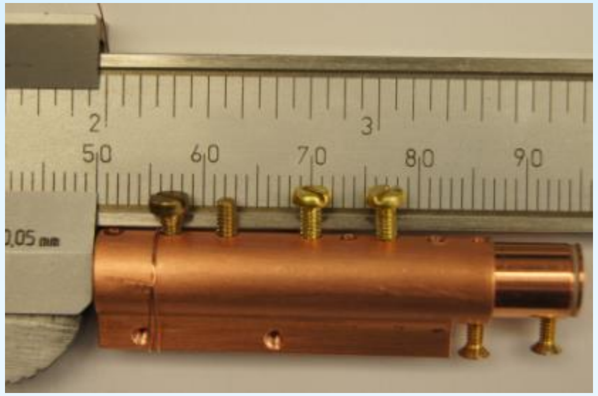
For TOF $t = N \cdot T$ (N = integer number)
The position is $r = 0$ independent of cyclotron Radius R (for all $p_\perp$).

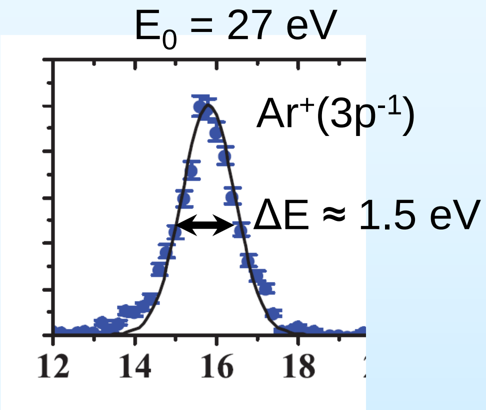


Reaction Microscope/COLTRIMS technique



electron gun with photo-cathode

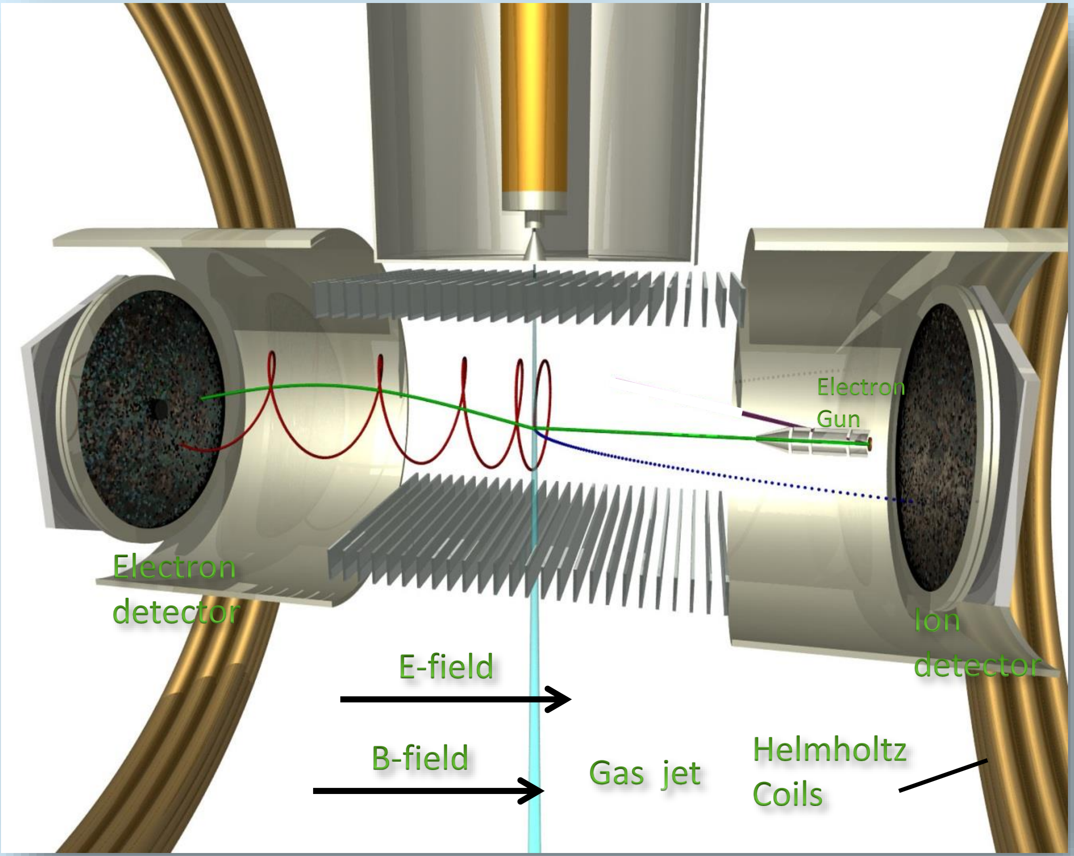




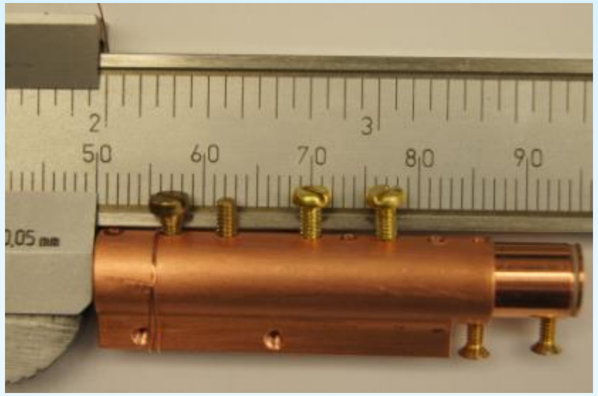
e^--pulse duration $\Delta t \approx 0.5$ ns. Projectile energy resolution $\Delta E \approx 0.3$ eV.

X. Ren et al., J. Chem. Phys. 141, 134314 (2014)

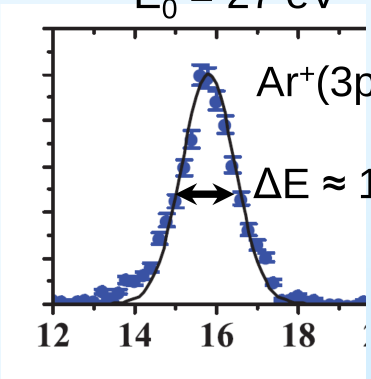
Reaction Microscope/COLTRIMS technique



electron gun with
photo-cathode



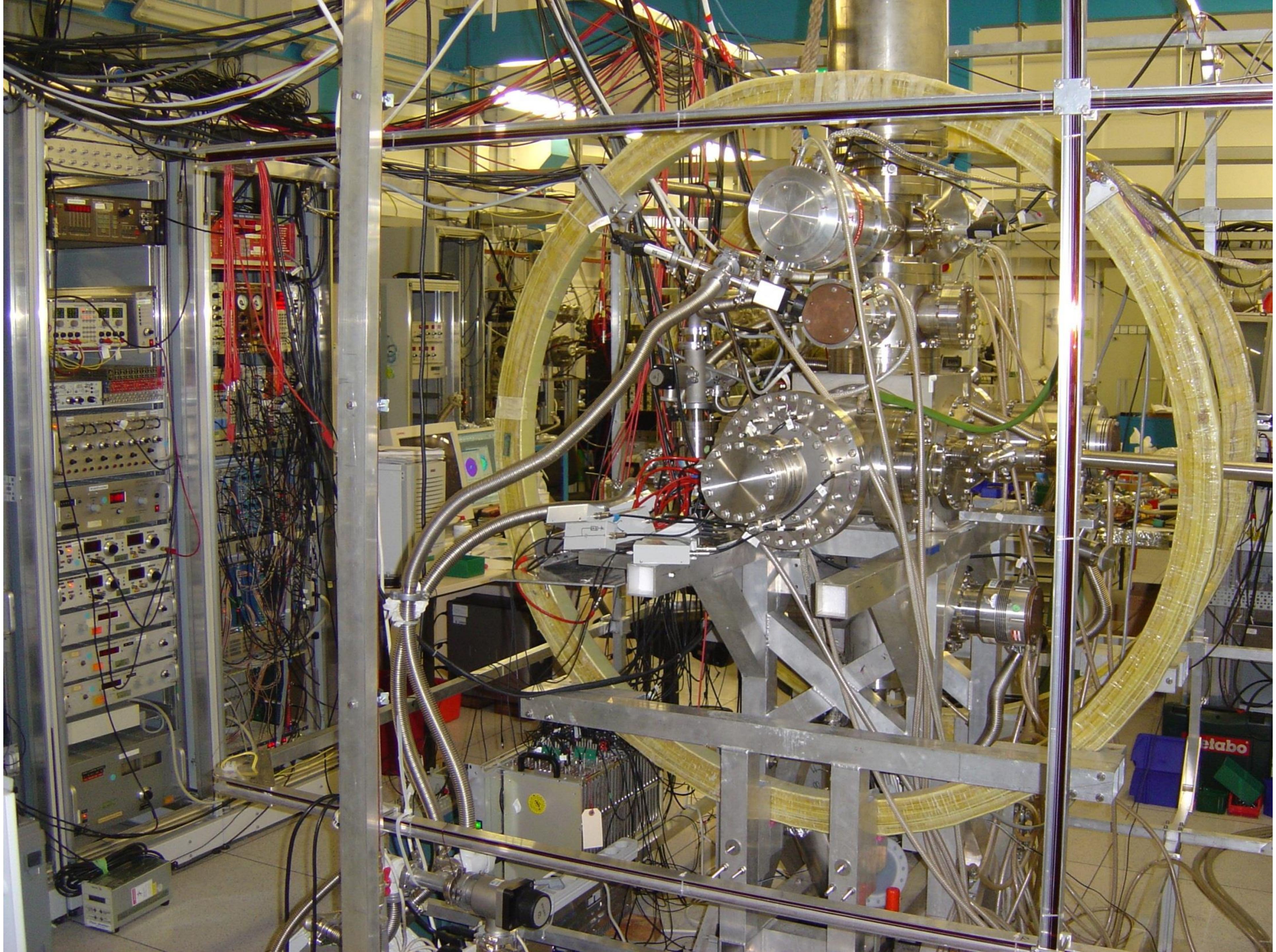
E_0 = 27 eV



Binding energy (eV)

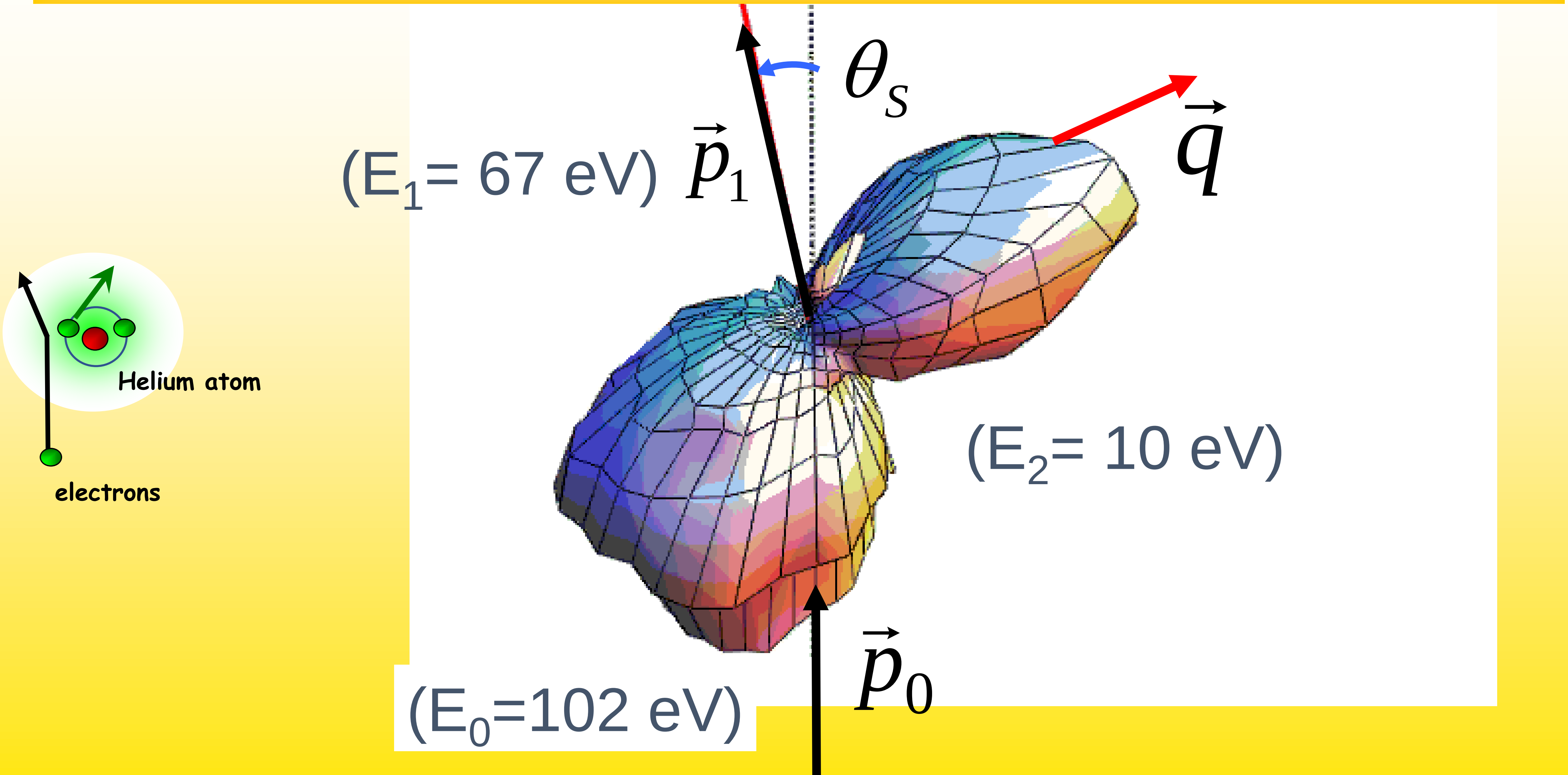
e^--pulse duration $\Delta t \approx 0.5$ ns. Projectile energy resolution $\Delta E \approx 0.3$ eV.

X. Ren et al., J. Chem. Phys. 141, 134314 (2014)

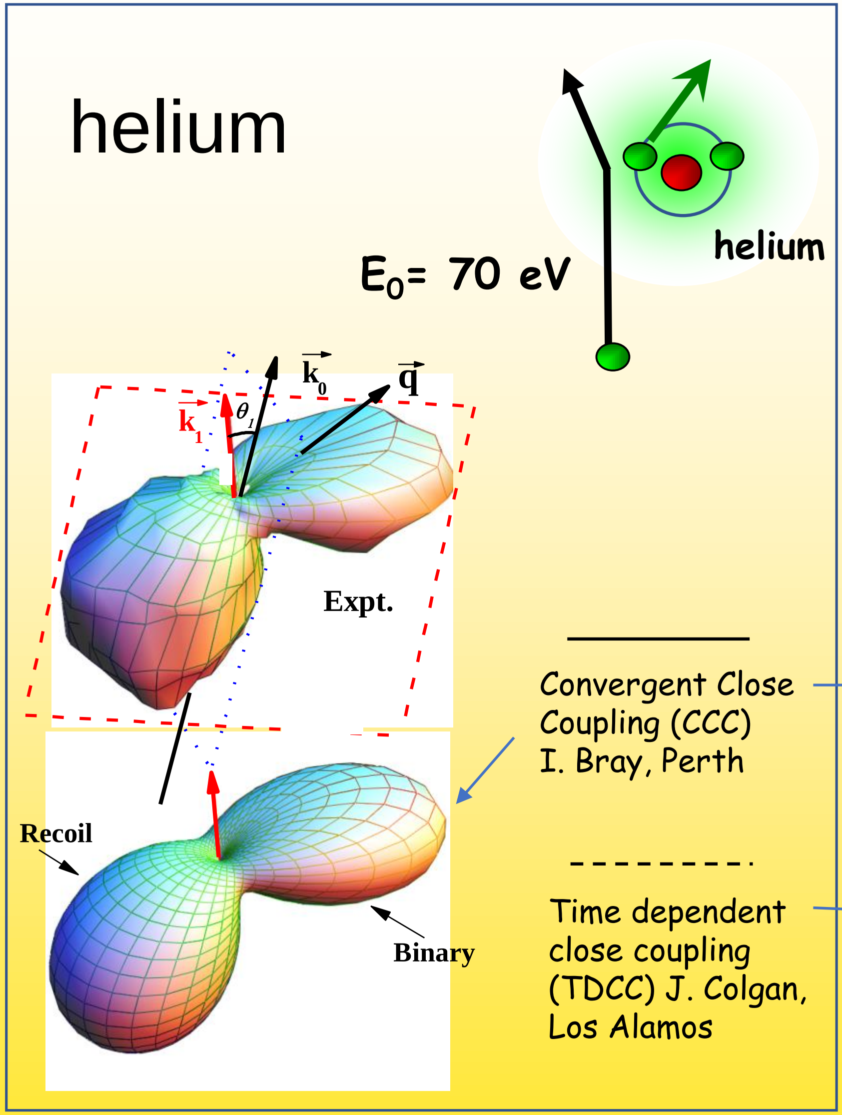


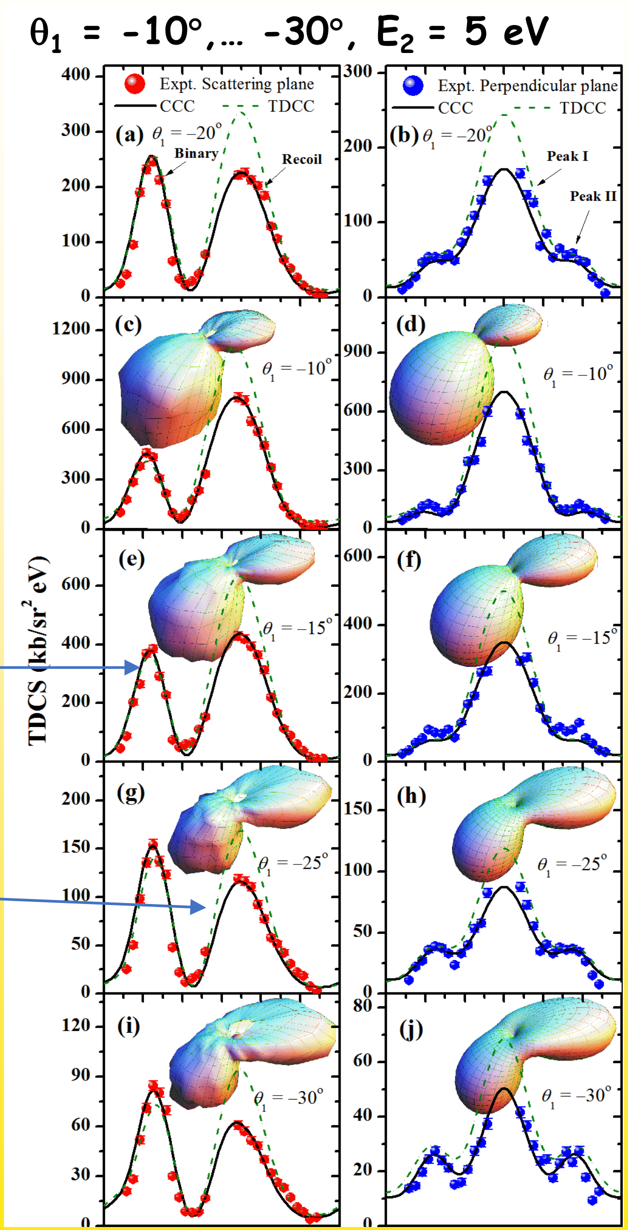
metabo

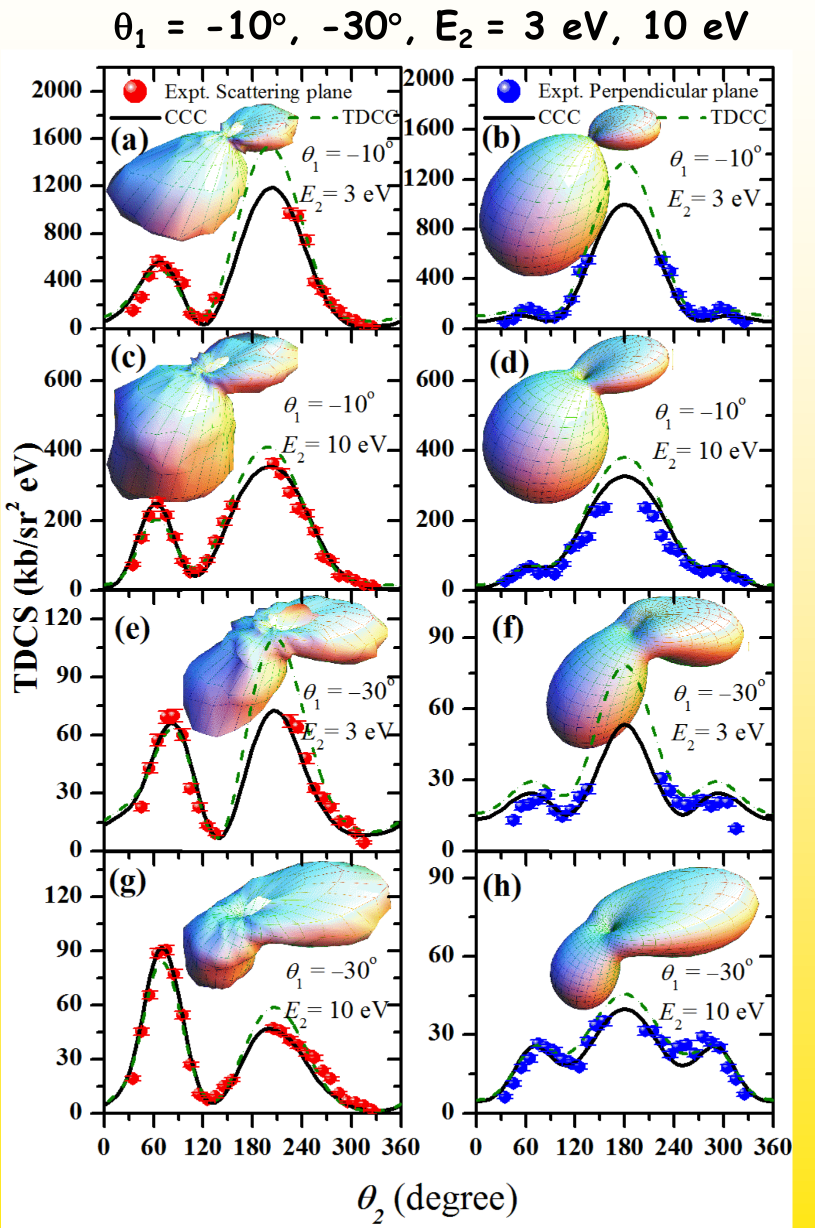
Electron impact on the simple helium atom :
$e^- + He(1s^2) \rightarrow He^+ + 2e^-$



(e,2e): benchmark tests over large phase space

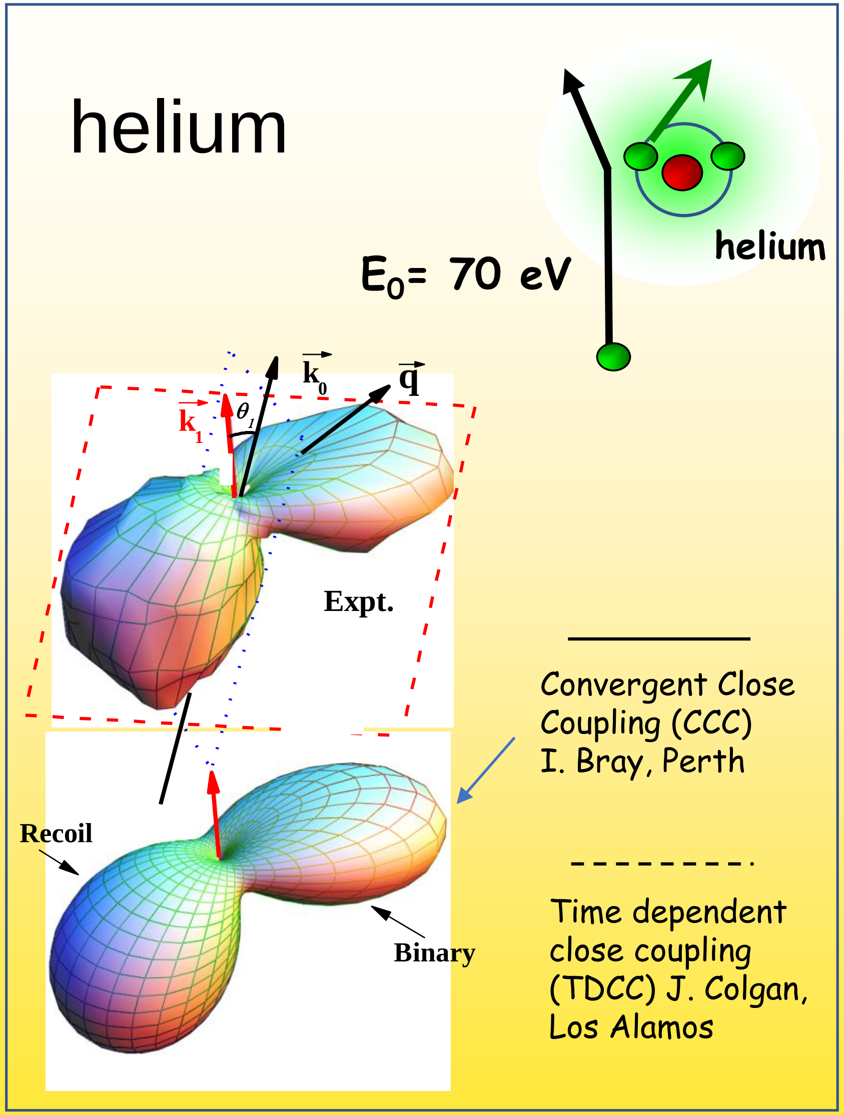


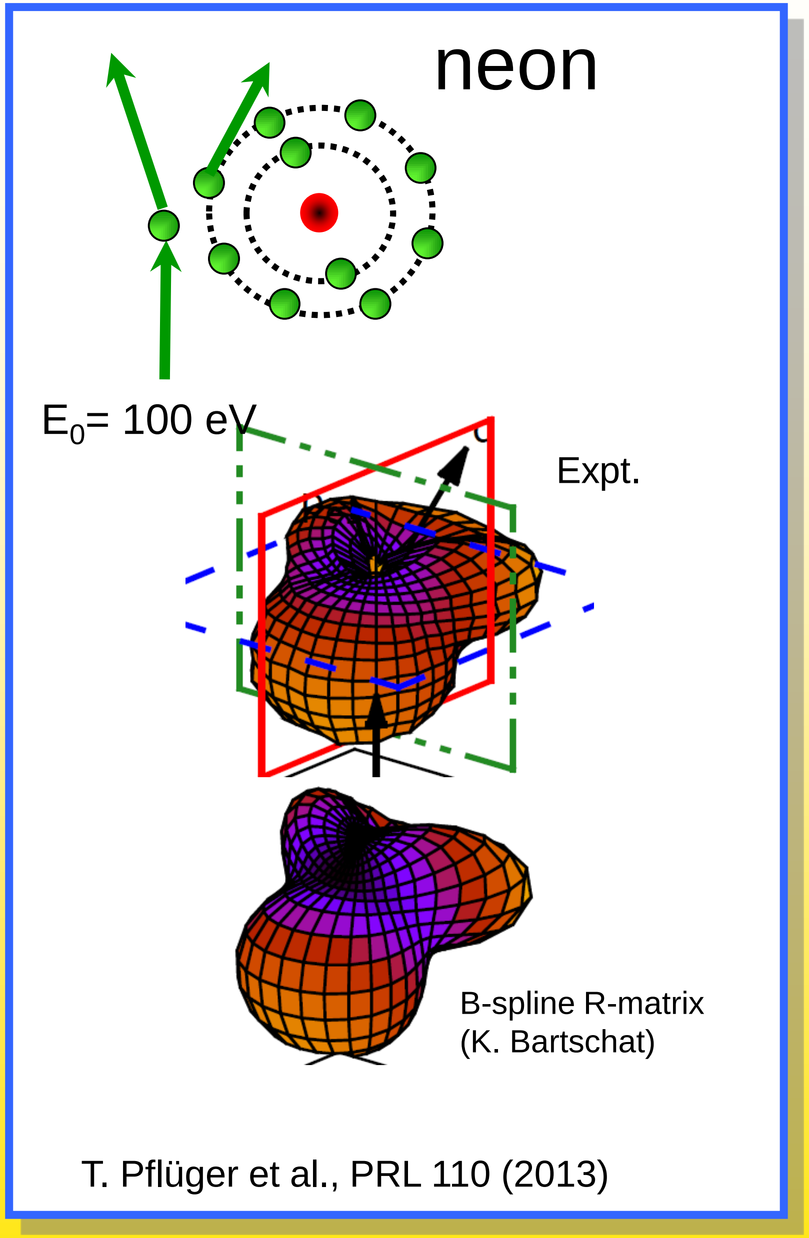




X. Ren, I. Bray, D.V. Fursa, J. Colgan, M.S. Pindzola, T. Pflüger, A. Senftleben, S. Xu, A. Dorn and J. Ullrich, PRA 83, (2011)

(e,2e): benchmark tests over large phase space





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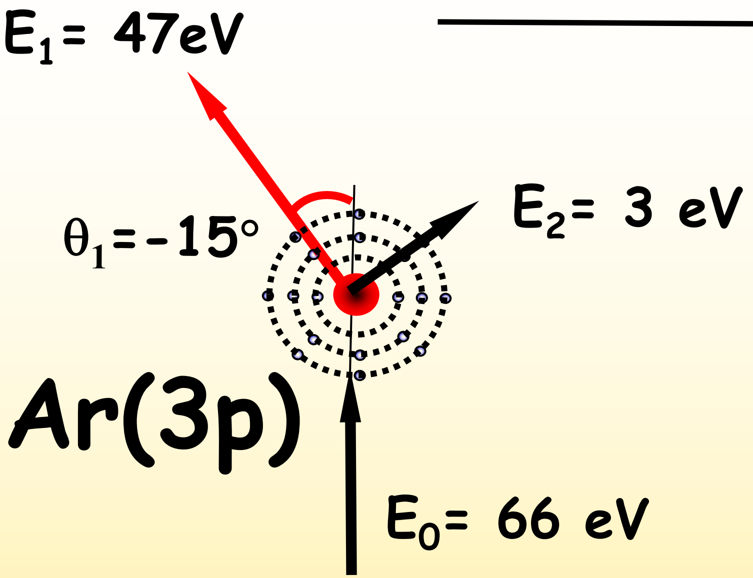
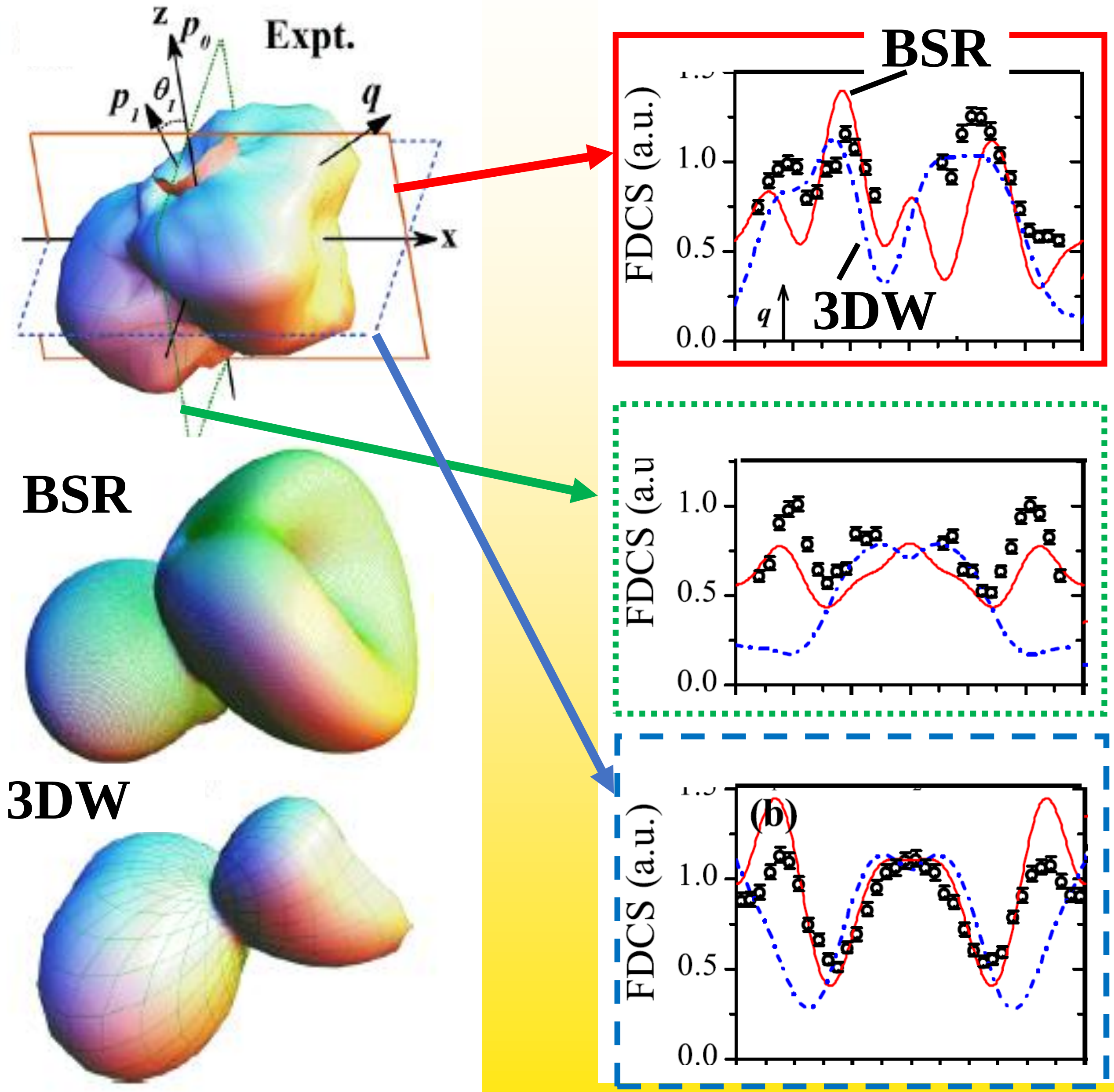
T. Pflüger, A. Senftleben, S. Xu, A. Dorn and J. Ullrich, PRA 83, (2011)

Argon





<u>**B-spline R-matrix (BSR):**</u>

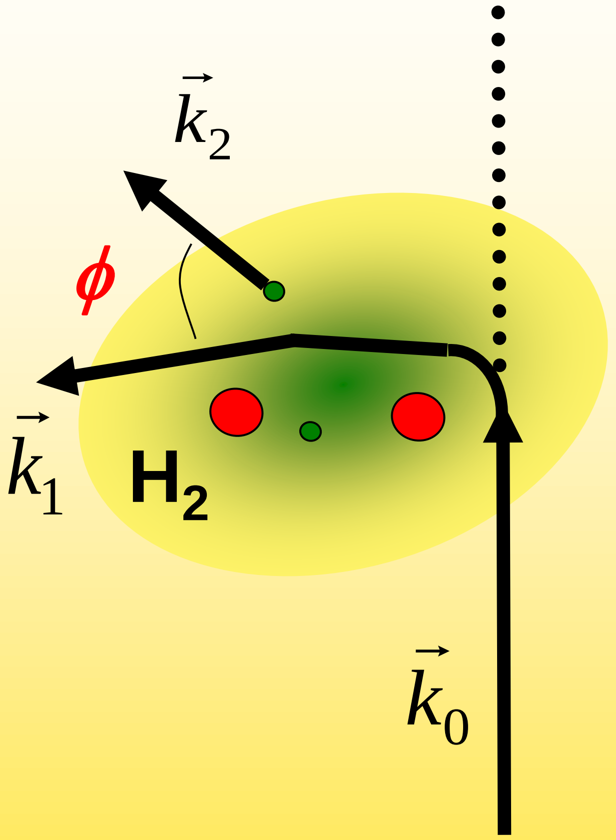
O. Zatsarinni,
K. Bartschat
Des Moins, Iowa

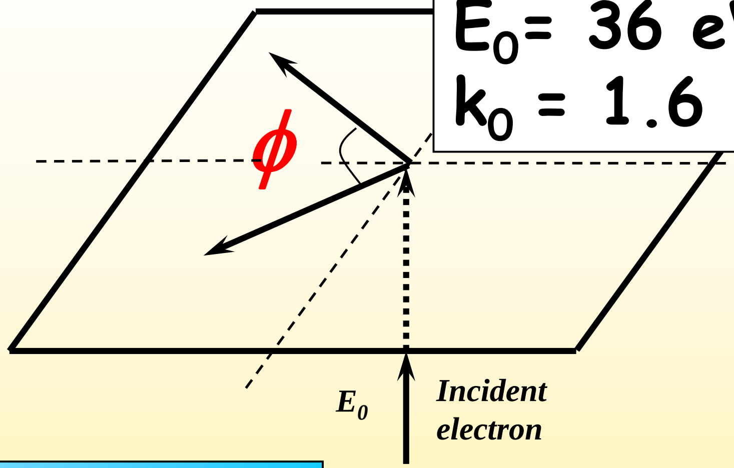
<u>**3 particle distorted wave,(3DW):**</u>

D. Madison, Rolla, Missouri

Ren *et al*, PRA **93**, 062704 (2016)

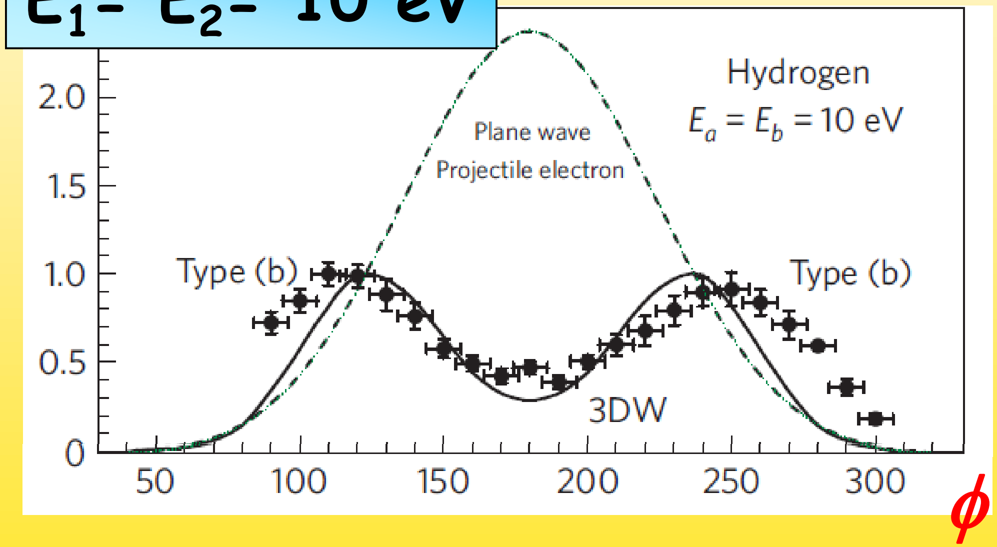
The perpendicular plane





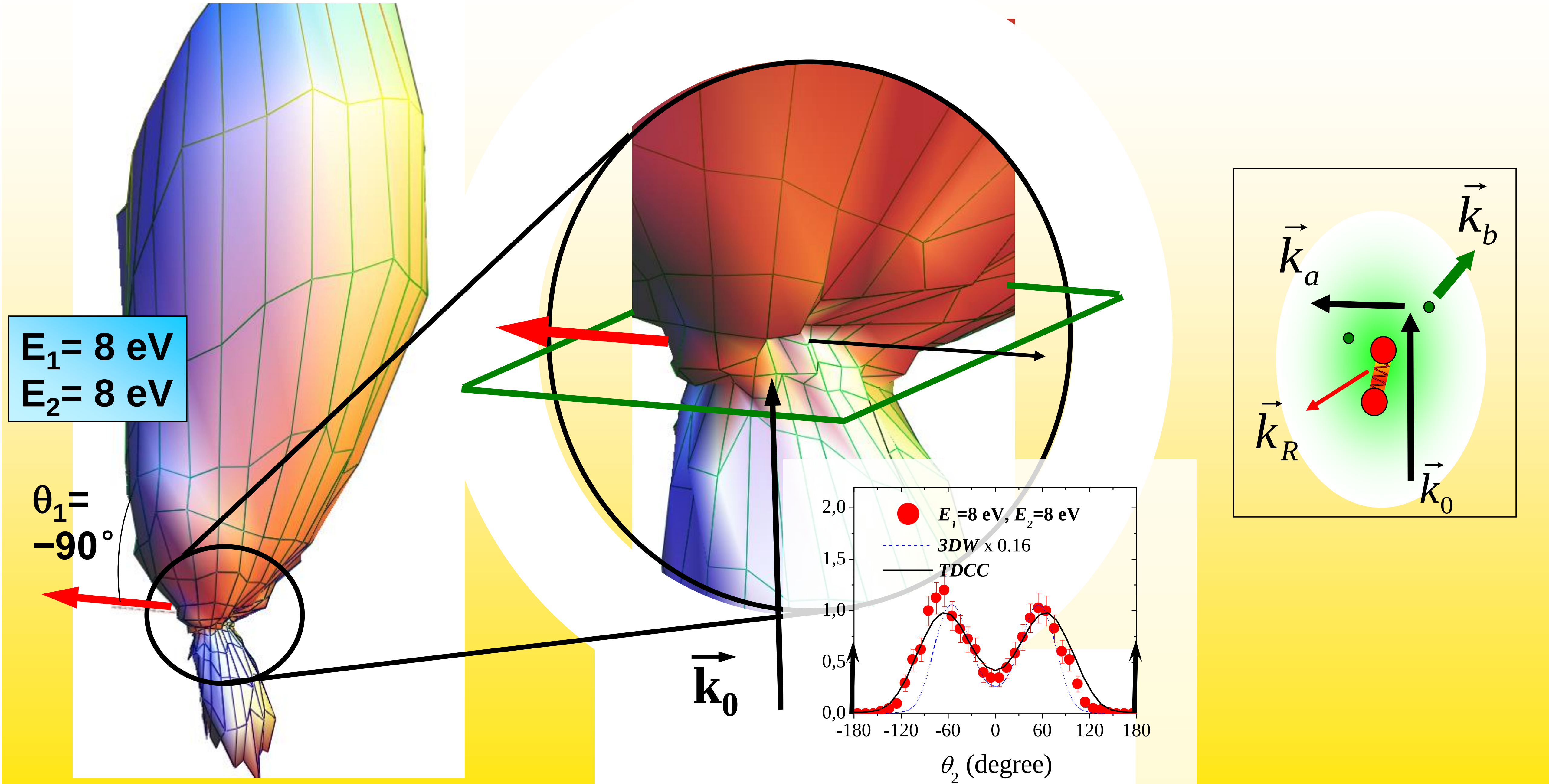
E_0= 36 eV
k_0 = 1.6 a.u.

E_1= E_2= 10 eV

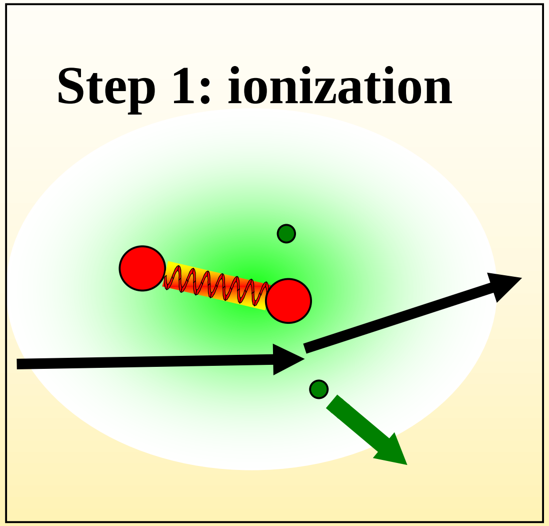


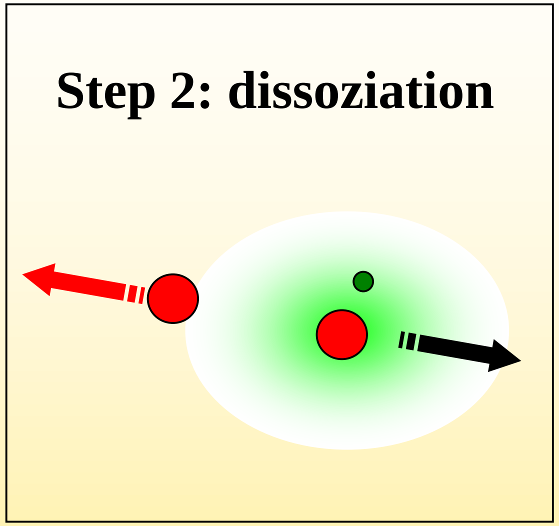
O.Al-Hagan, J.Murray, D.Madison et al., Nature Physics, 5 (2009) 59.

3D emission pattern

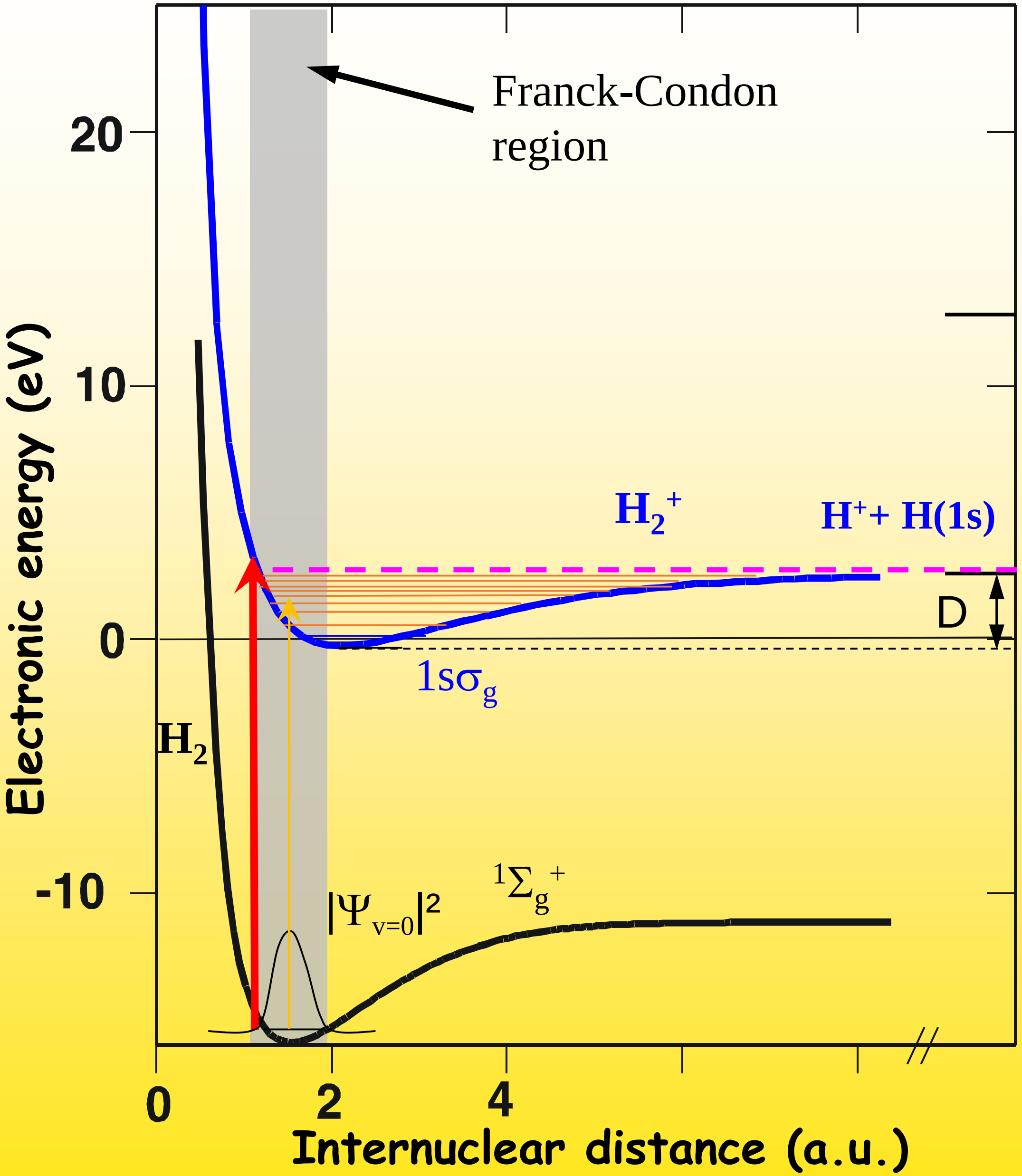


Measurement of the molecular alignment



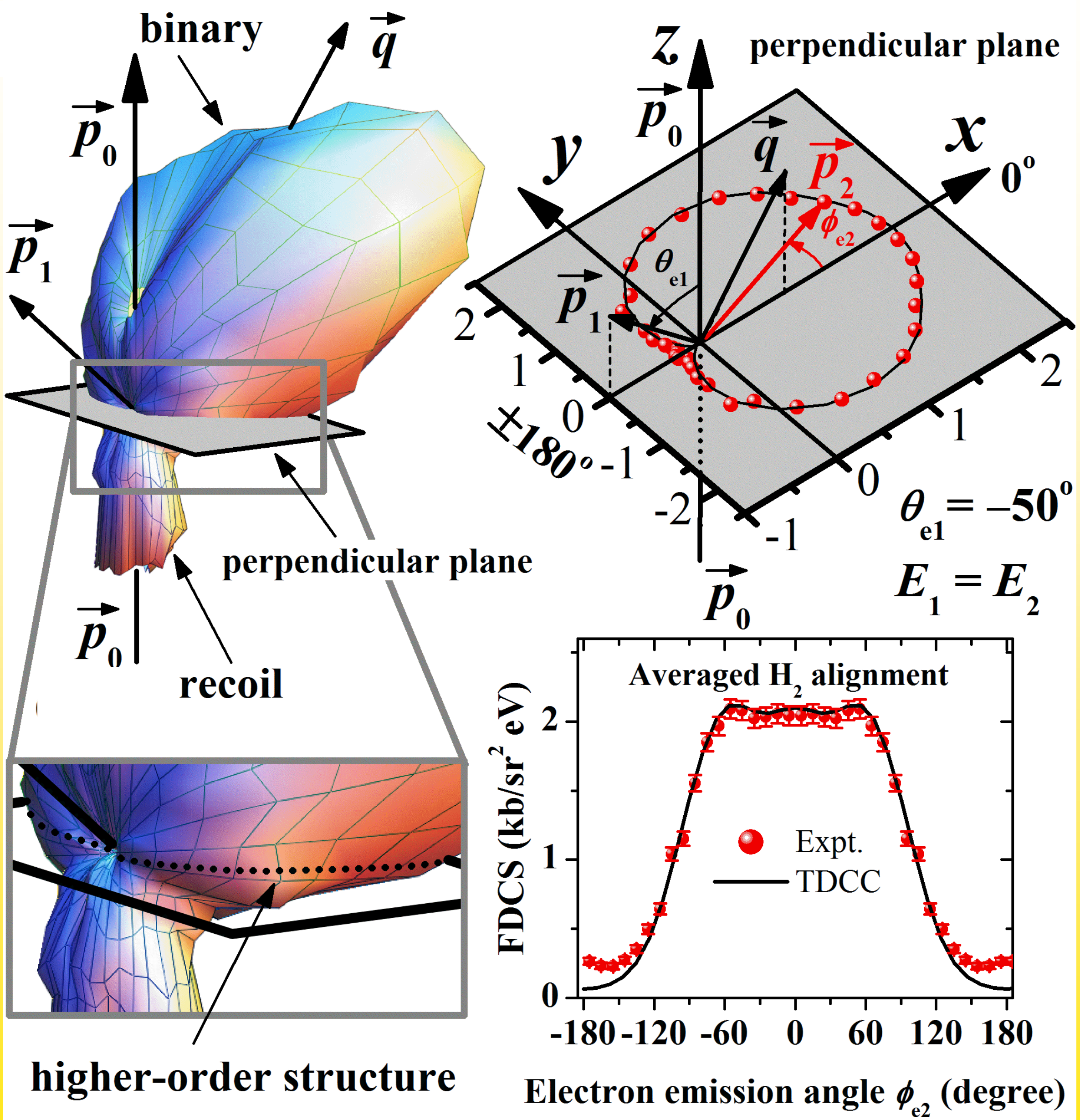


Wang et al., Eur. Phys. J. D 74: 105 (2020)
Ren et al. Phys. Rev. Lett. 109,123202 (2012)
Senftleben et al., J. Phys. B, **43** (2010)
Senftleben, et al., J. Chem. Phys. **133**, 044302 (2010);



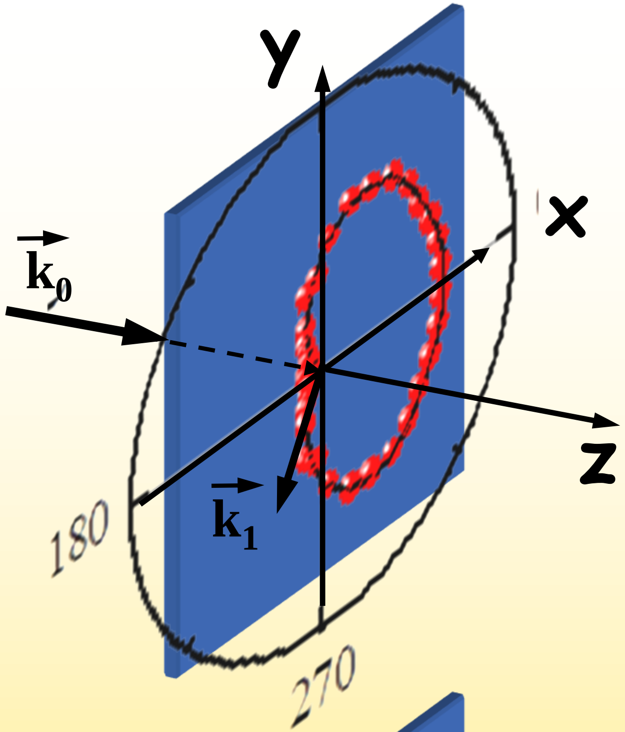
Alignment dependent cross sections

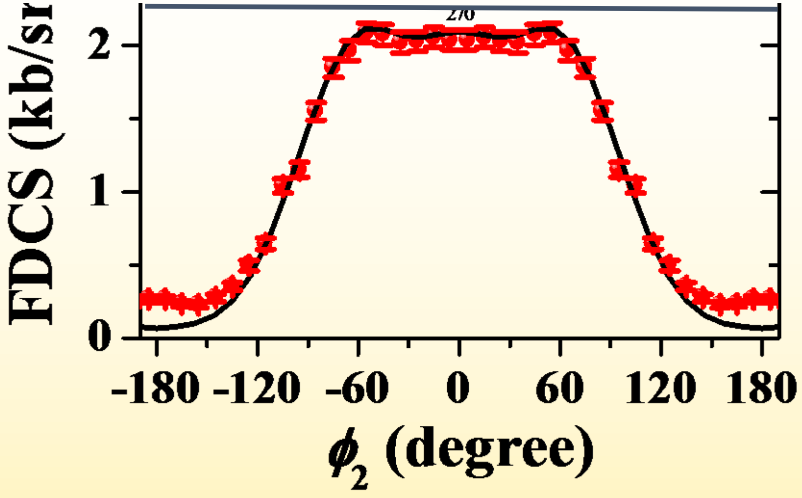
E_0= 54 eV
θ_1= -50°,
E_1= E_2= 18 eV



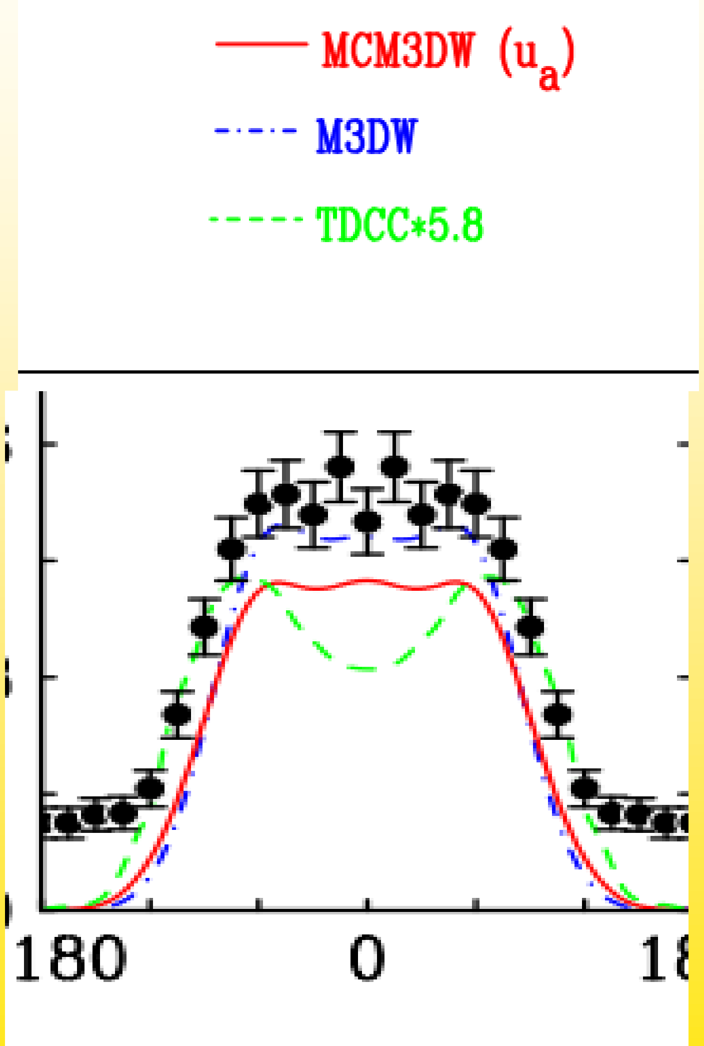
Time dependent close coupling theory (TDCC): J. Colgan, Los Alamos

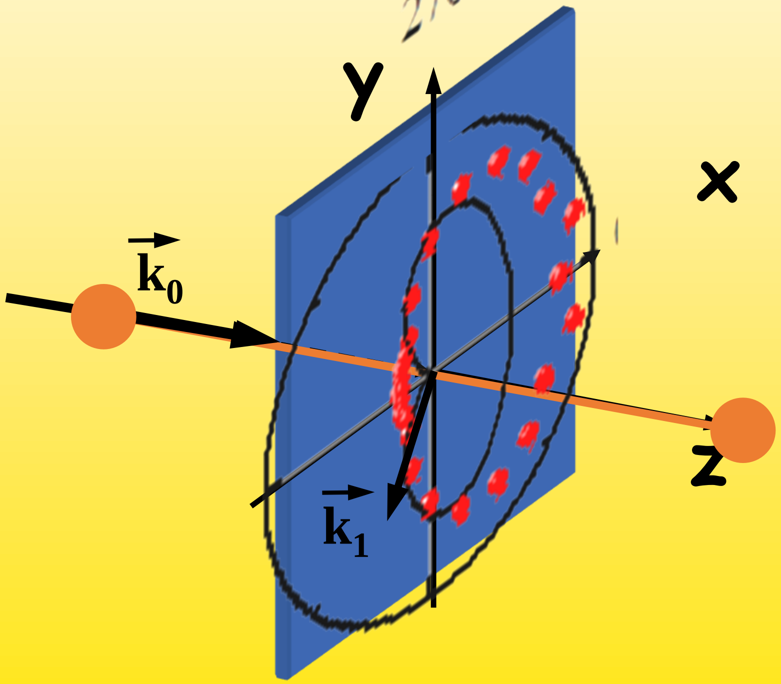
Averaged alignment

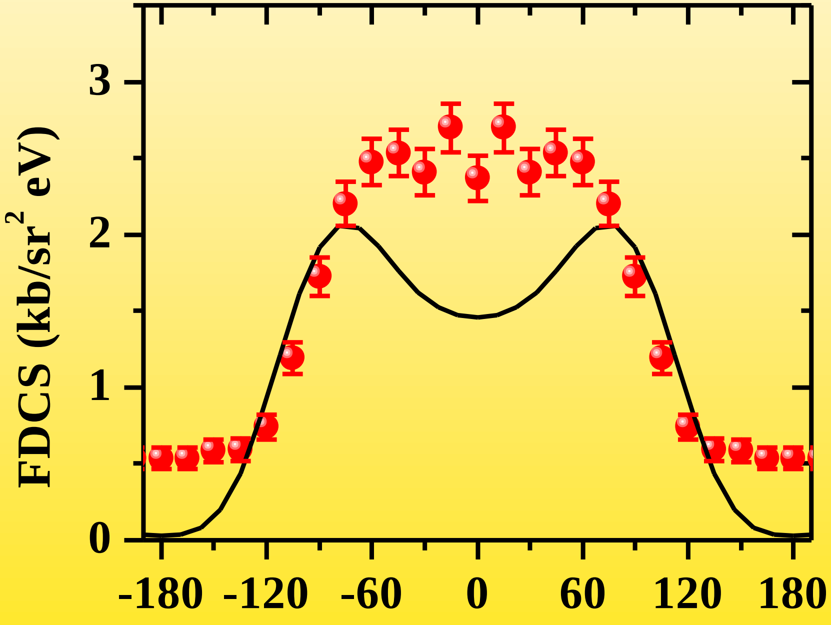




Esam Ali and Don Madison
PRA **100**, 012712, 2019

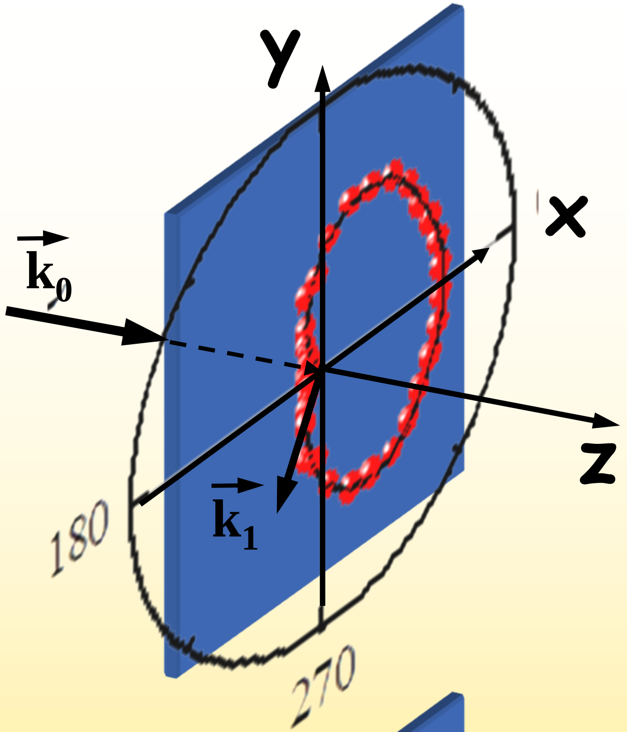


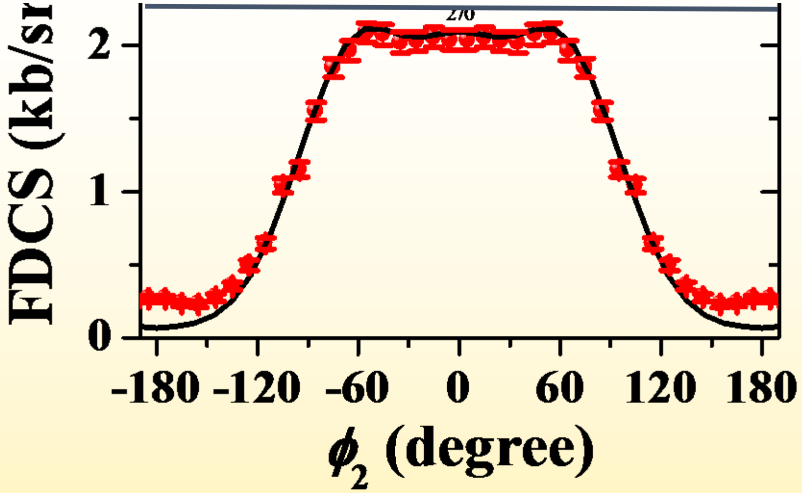




TDCC theory: J. Colgan

Averaged alignment





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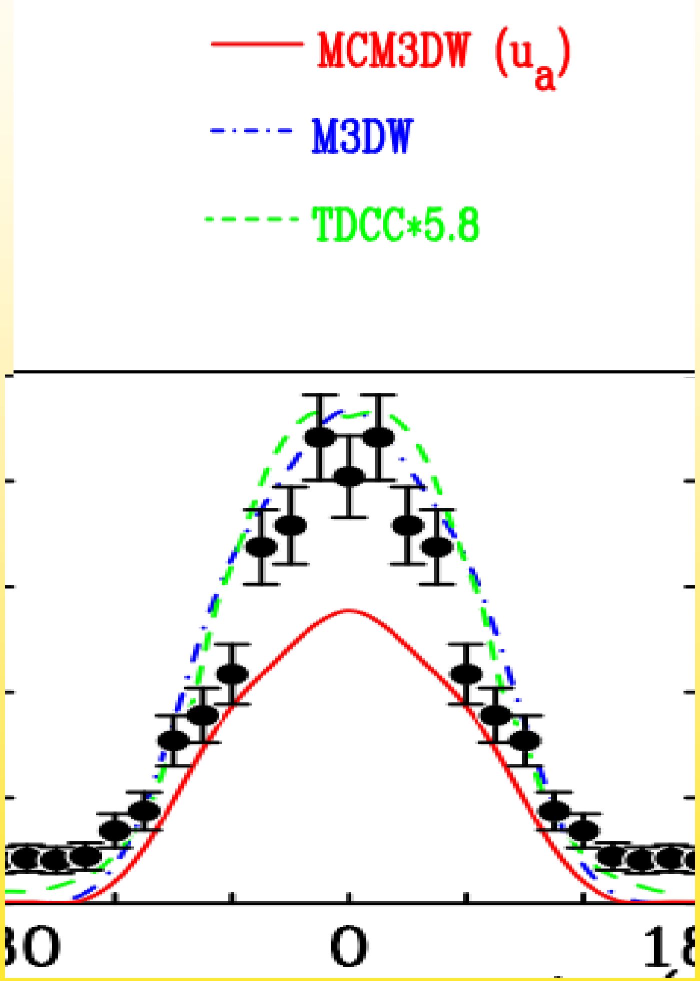
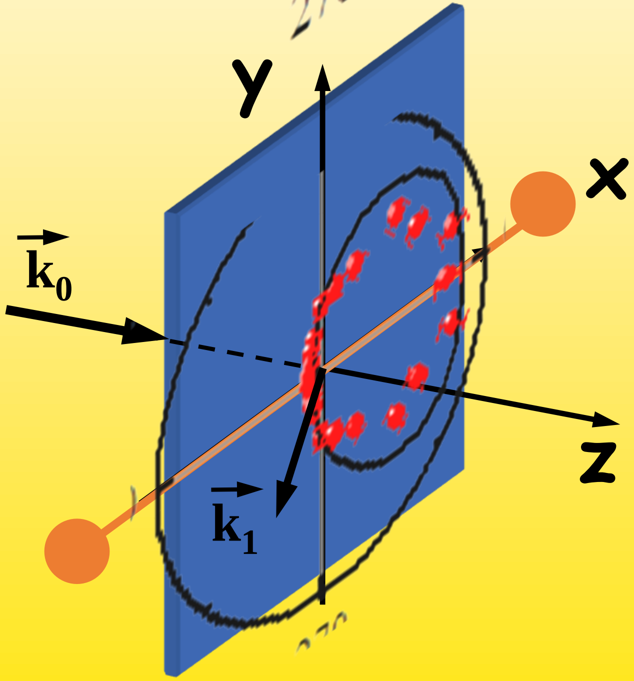
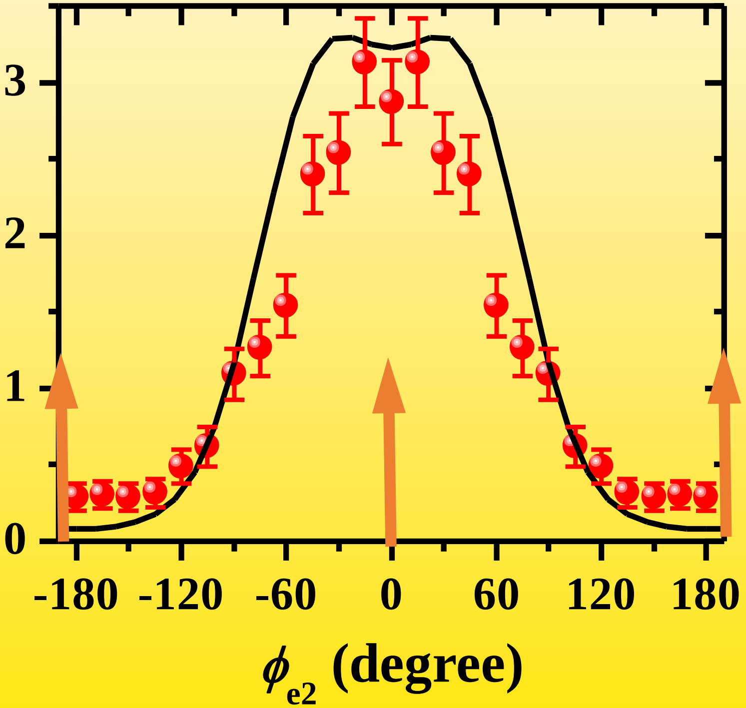
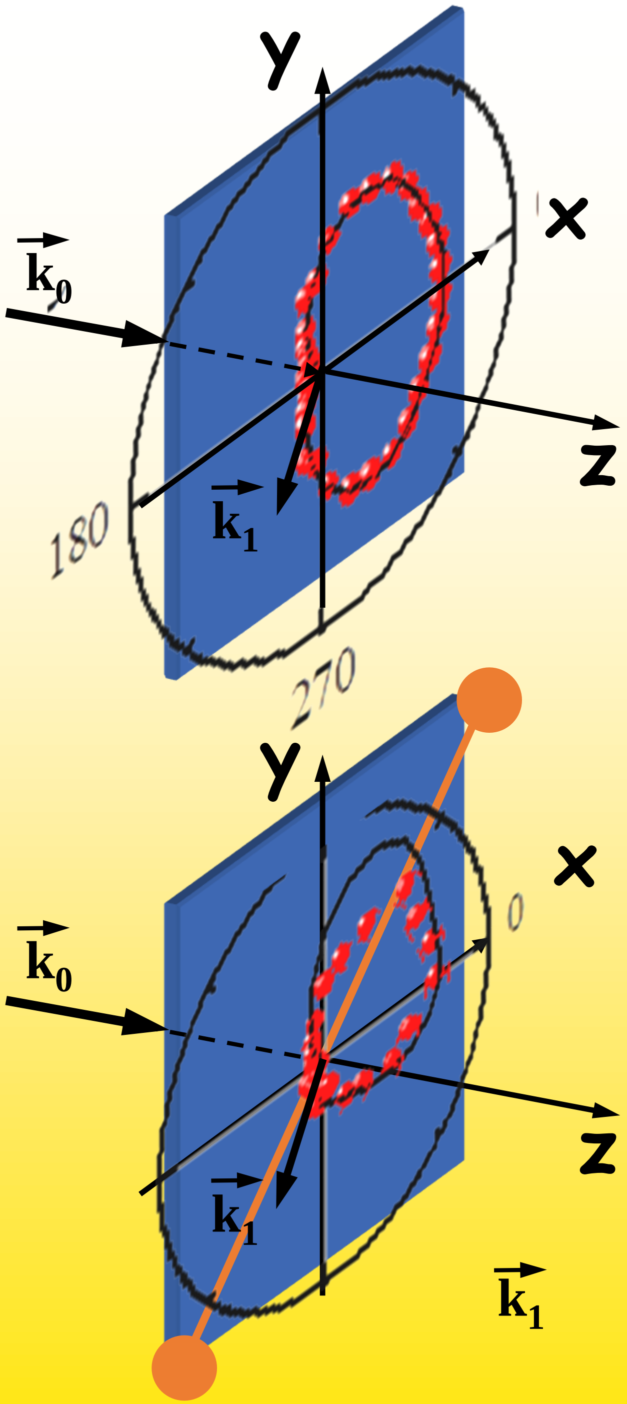
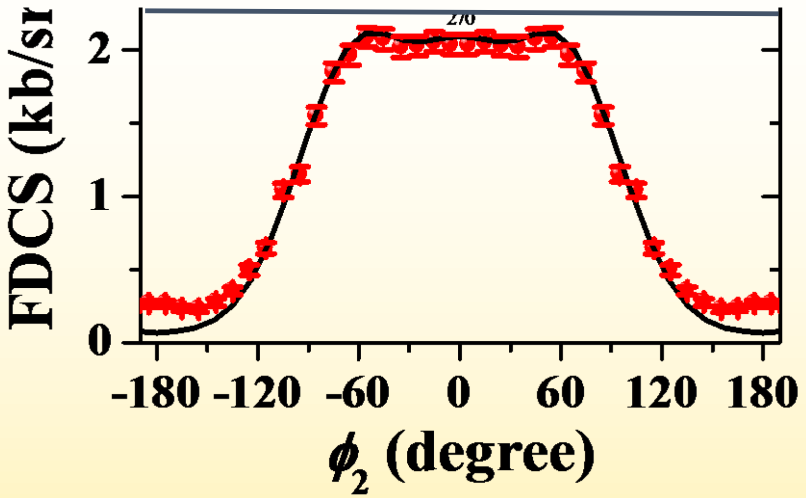


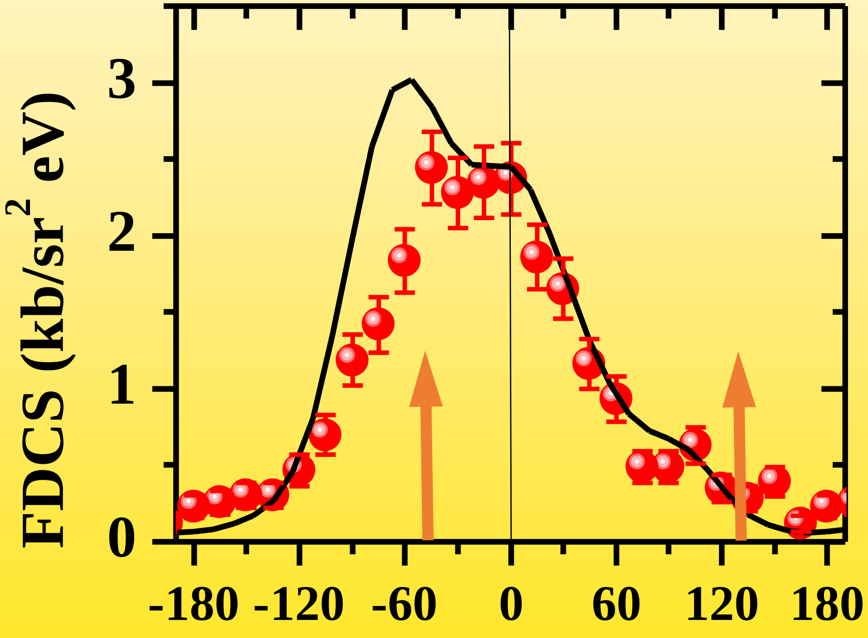




Averaged alignment







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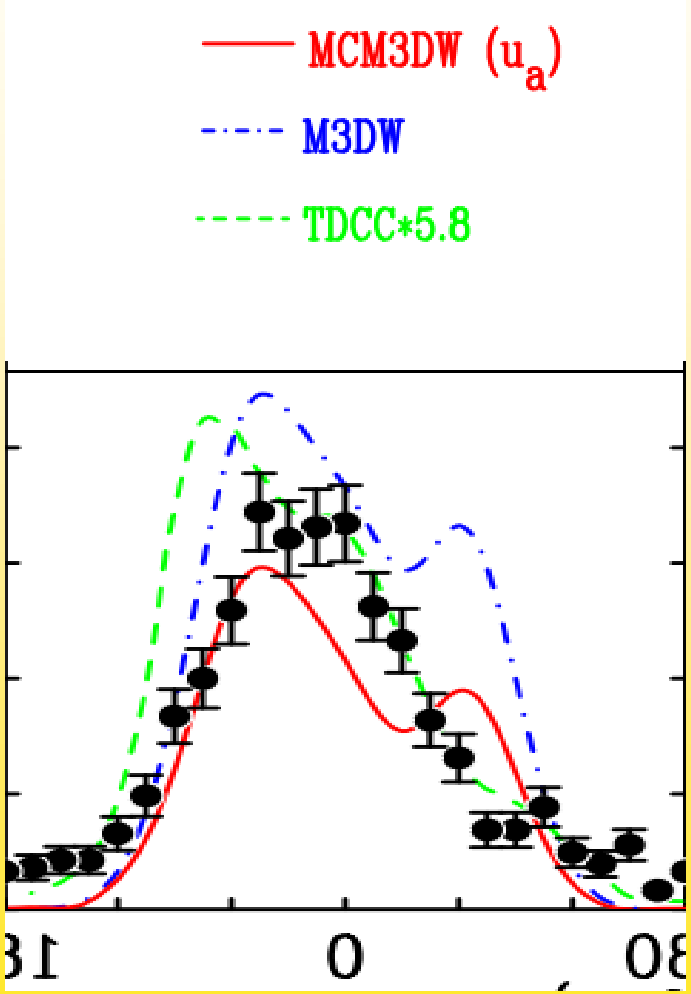
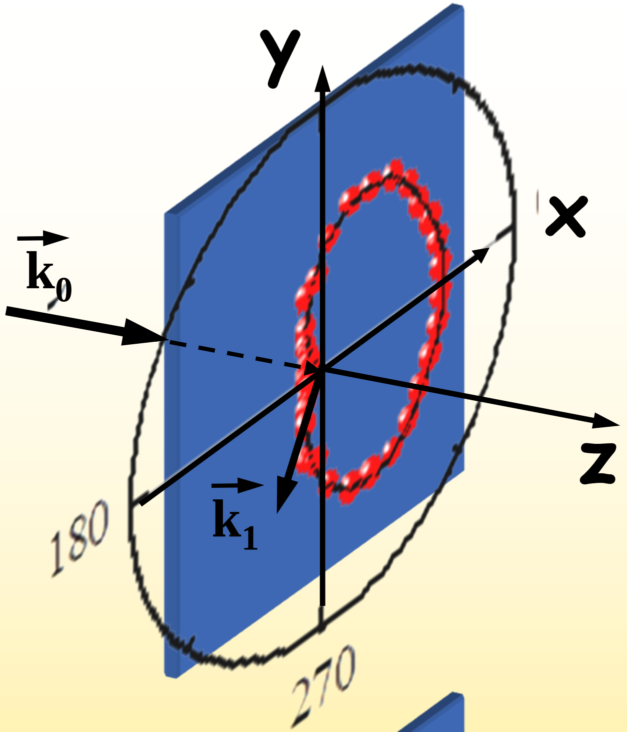
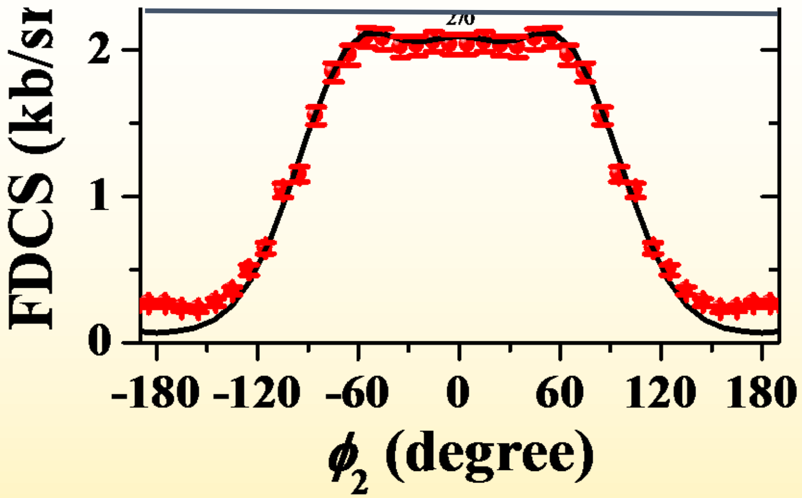
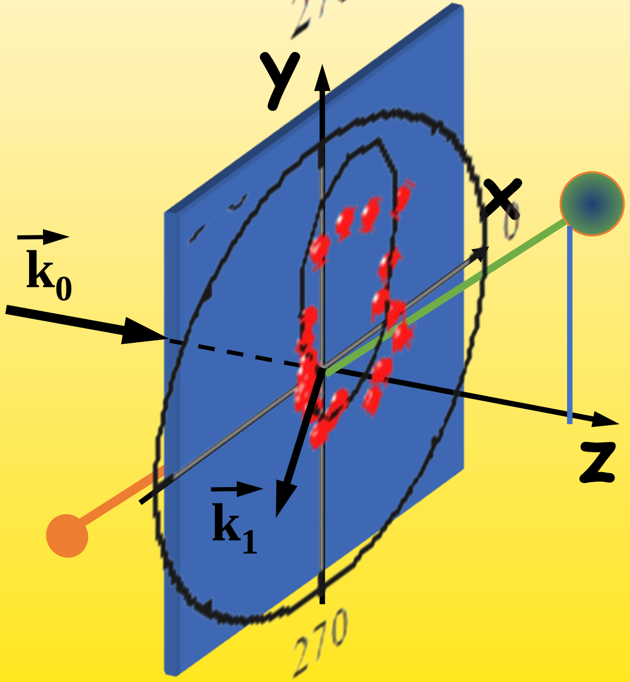
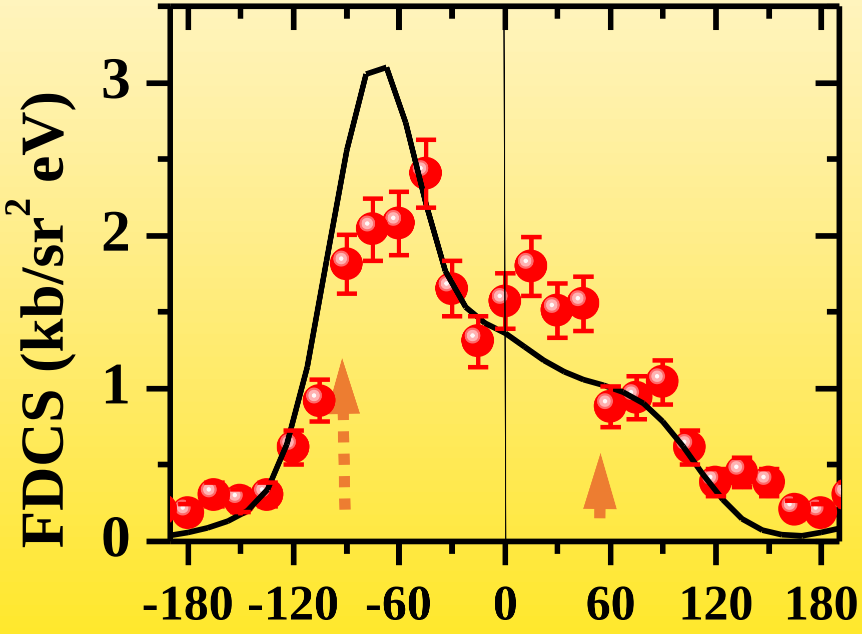


Averaged alignment









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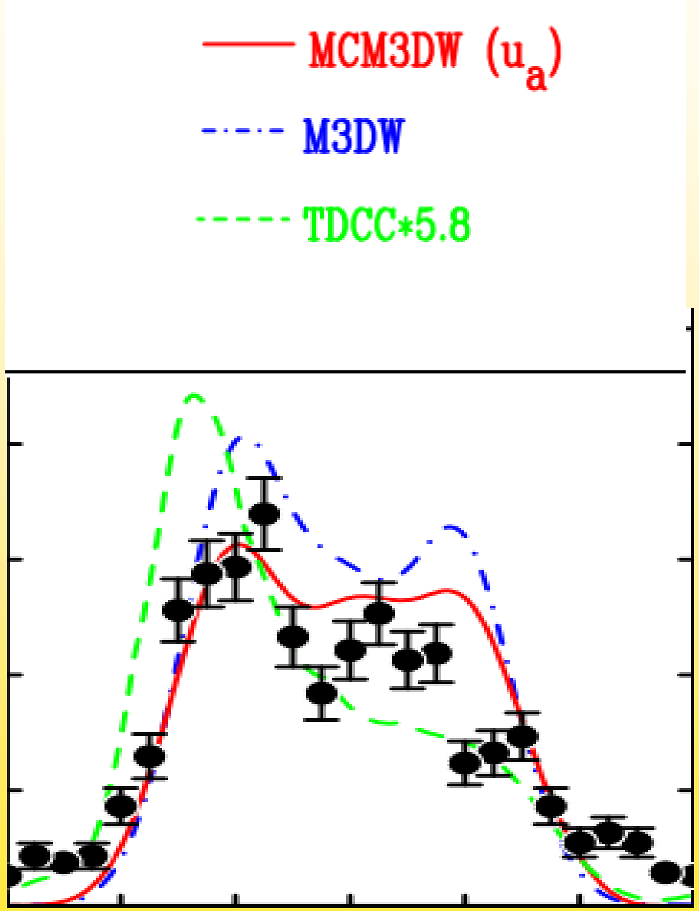

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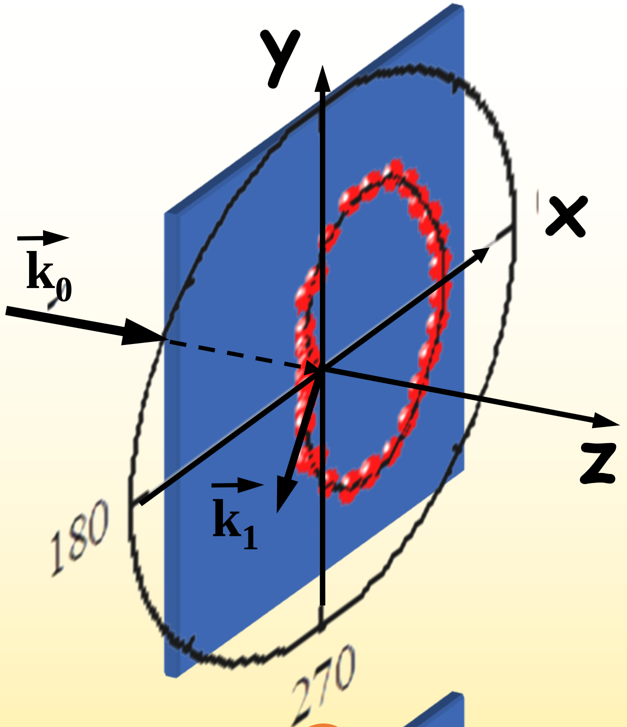
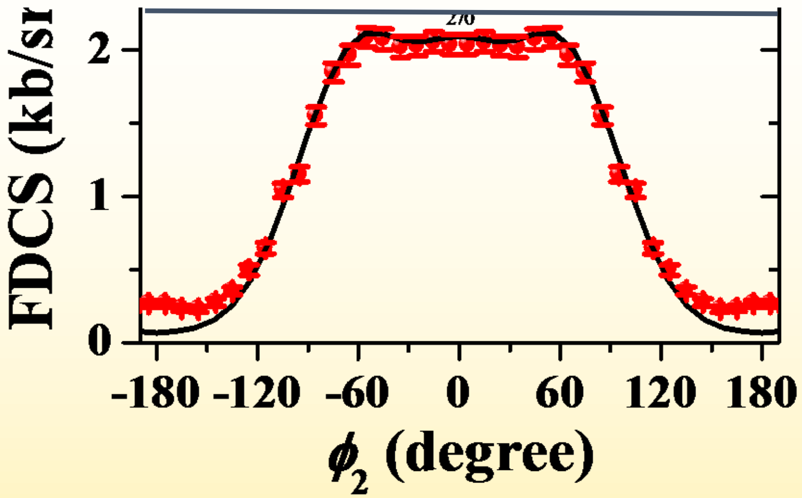
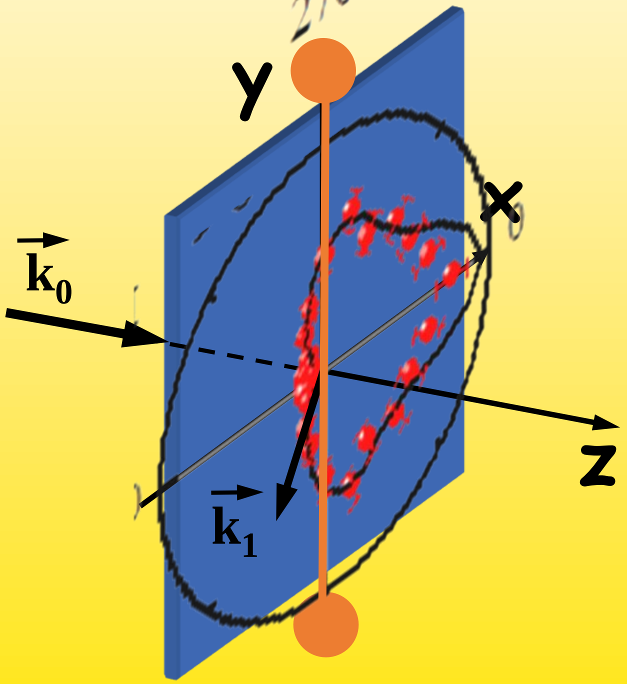
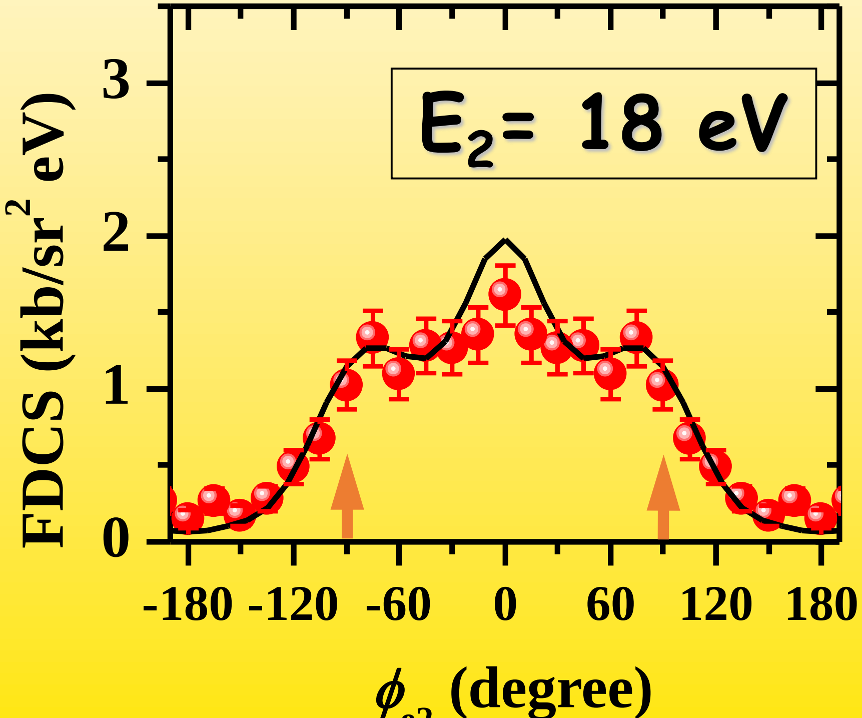
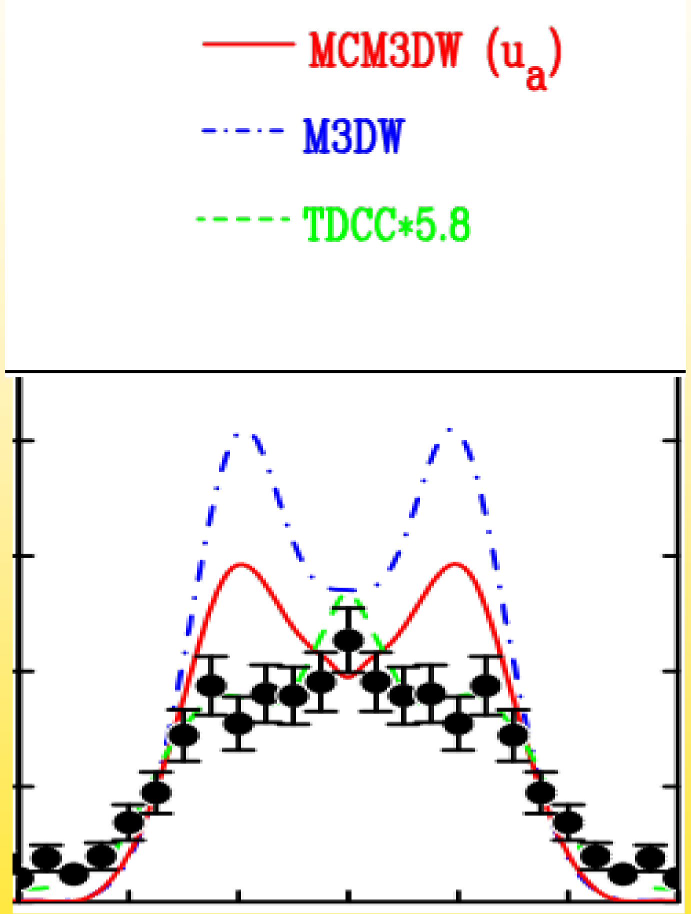




Esam Ali and Don Madison
PRA **100**, 012712, 2019







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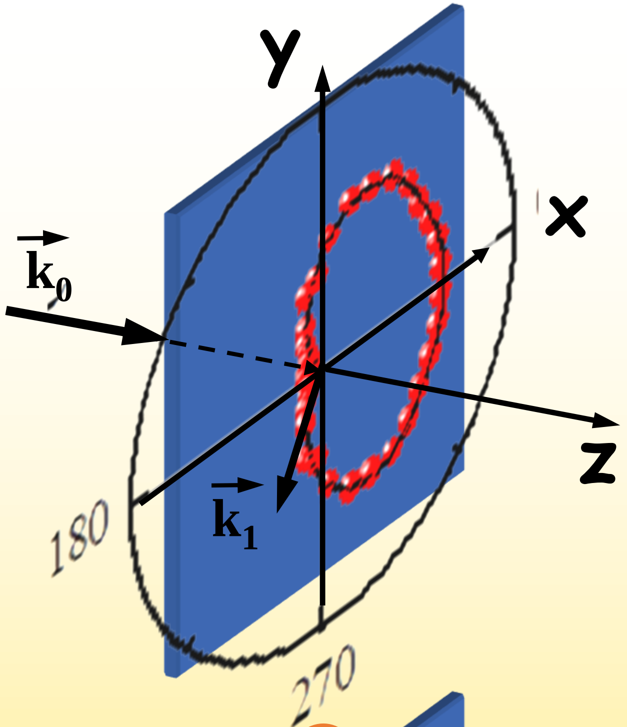
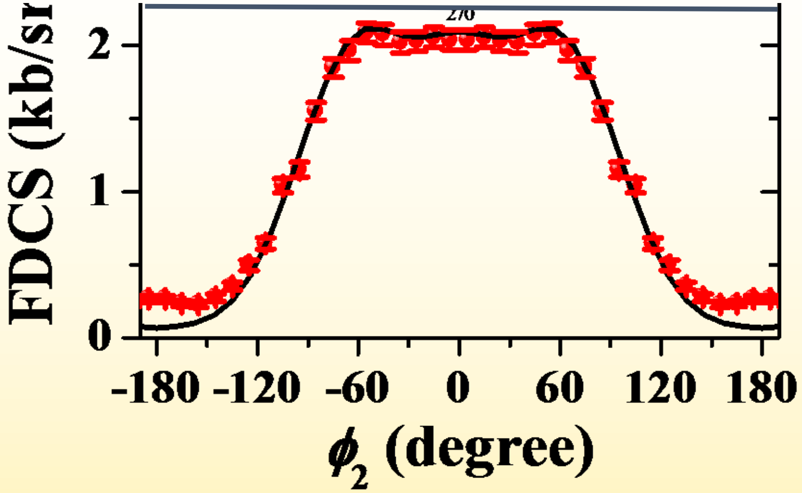
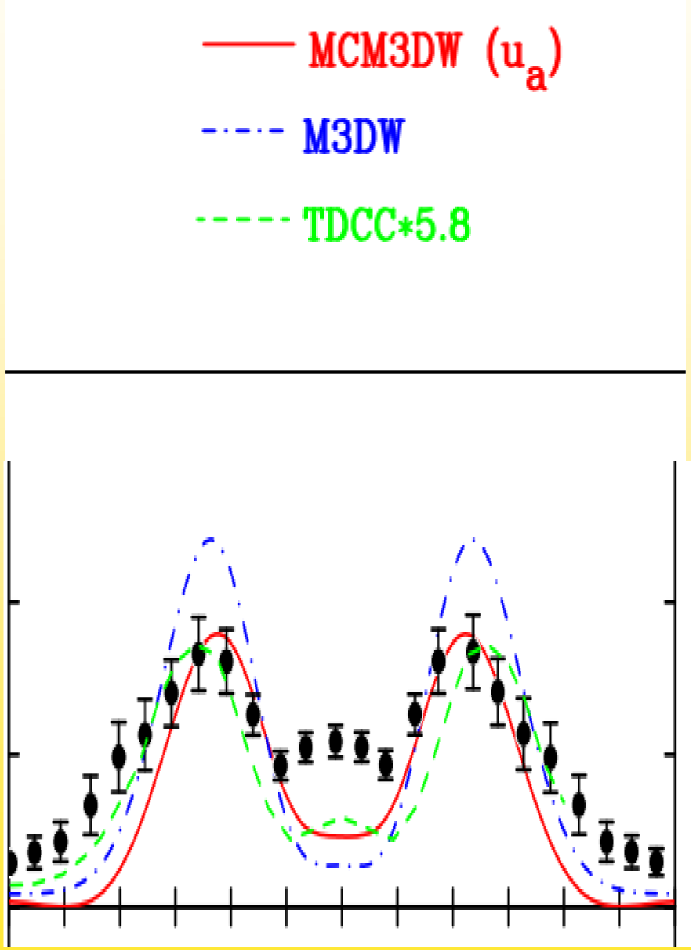
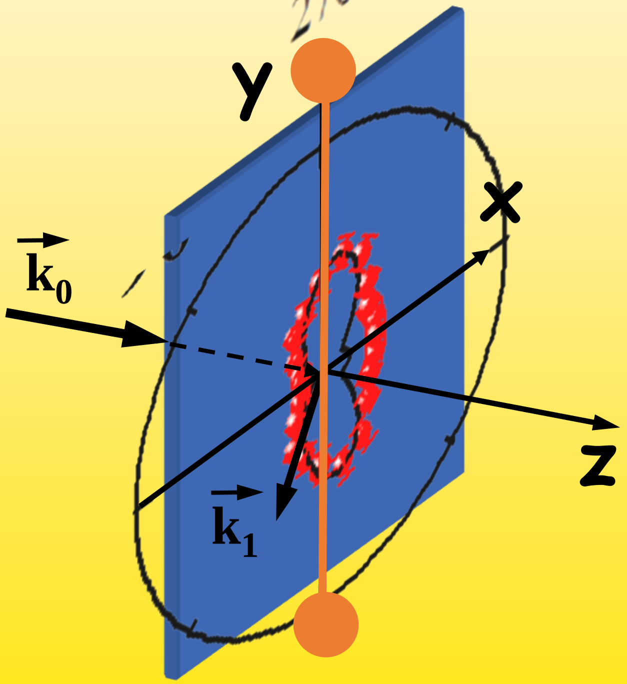
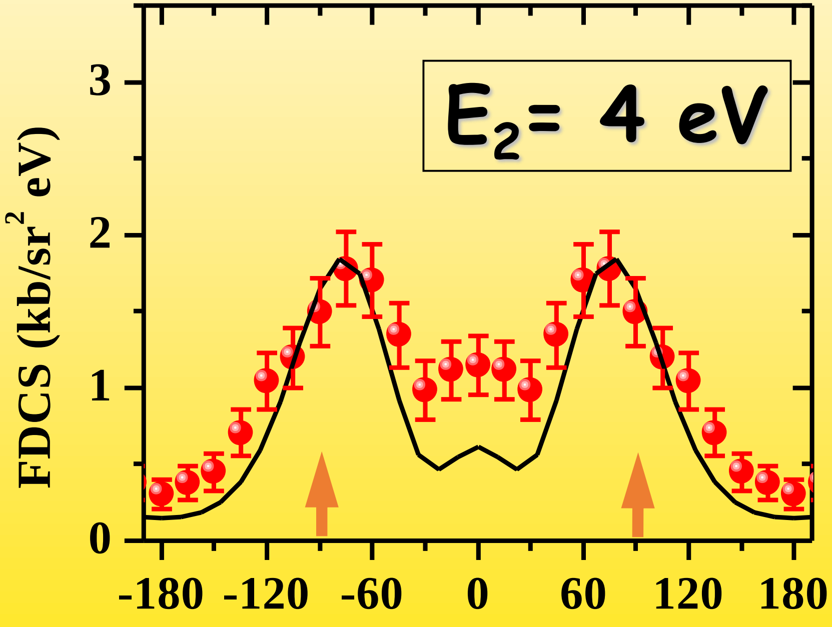




Esam Ali and Don Madison
PRA **100**, 012712, 2019







Summary H2

- Fully differential cross sections can be obtained for spatially fixed moelcular axis

-Strong influence of molecular axis. Which can be reproduced by theory.

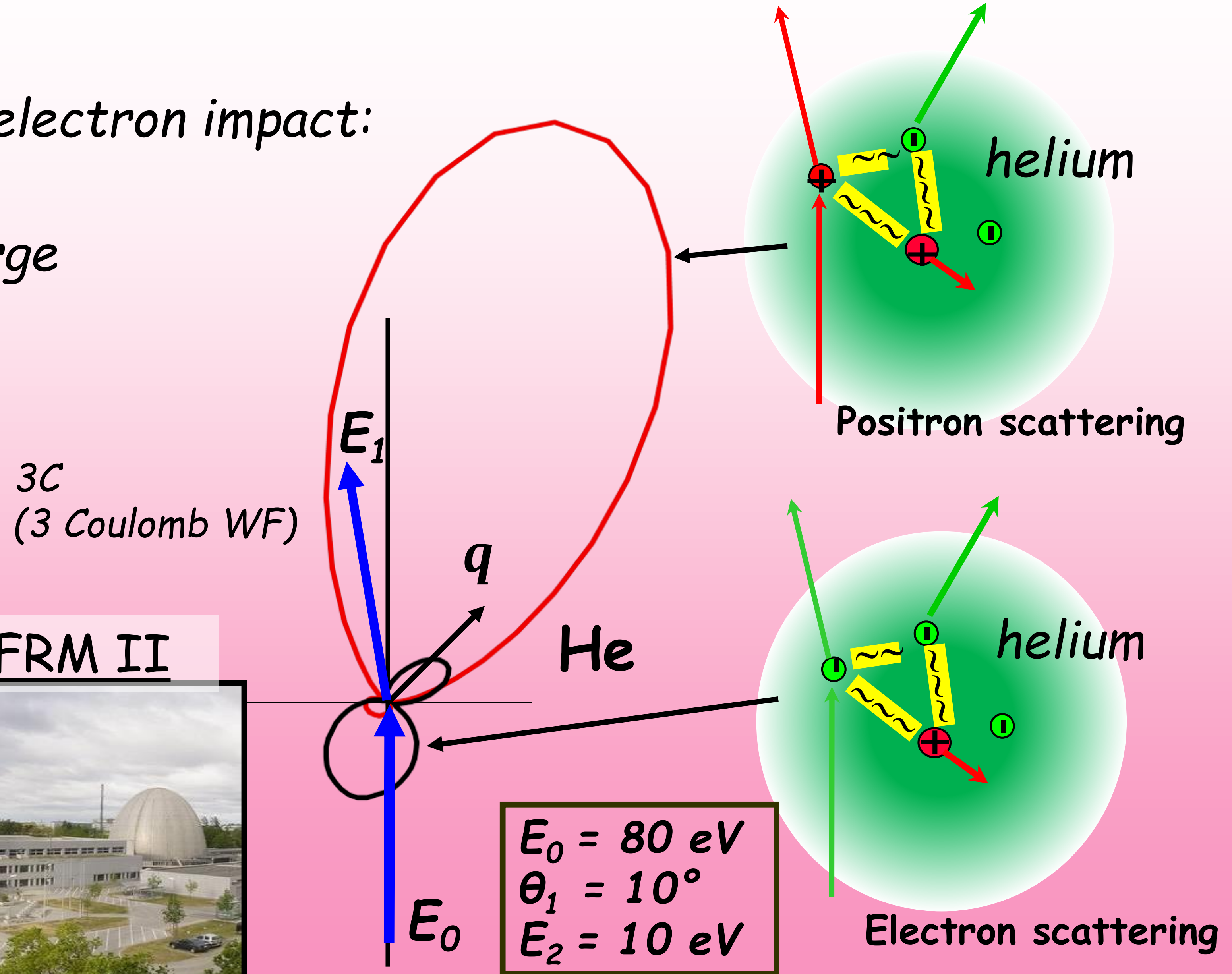
-Distorted waves in the final state not decisive for emission pattern. Other reasons:
A) anisotroy of bound molecular wave function.
B) distorted projectile wave in the inital state.

From electrons to positrons

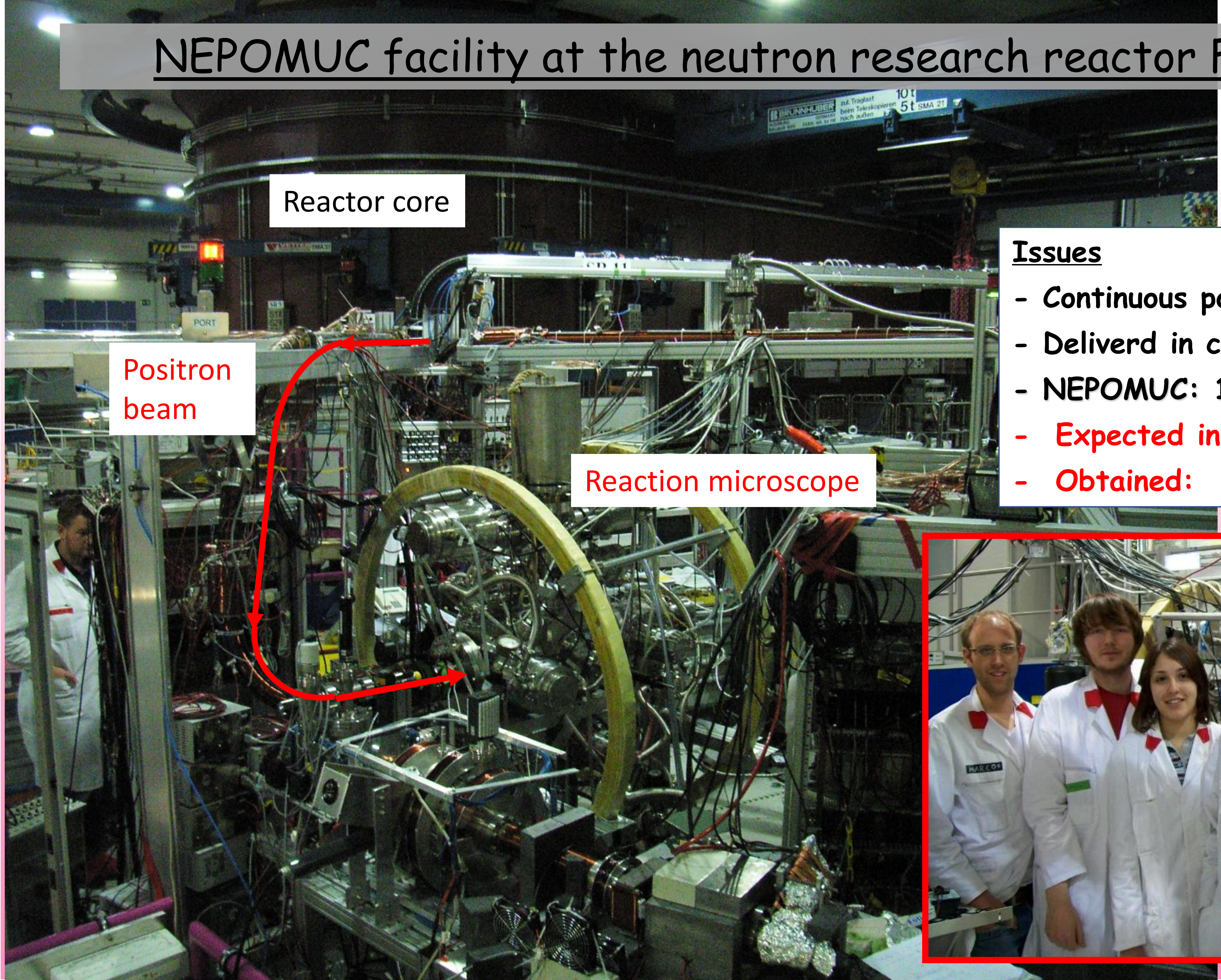
Differences compared to electron impact:

+ Reversed projectile charge
+ No exchange effects
+ Capture channel (Ps)

Neutron Research Reactor FRM II

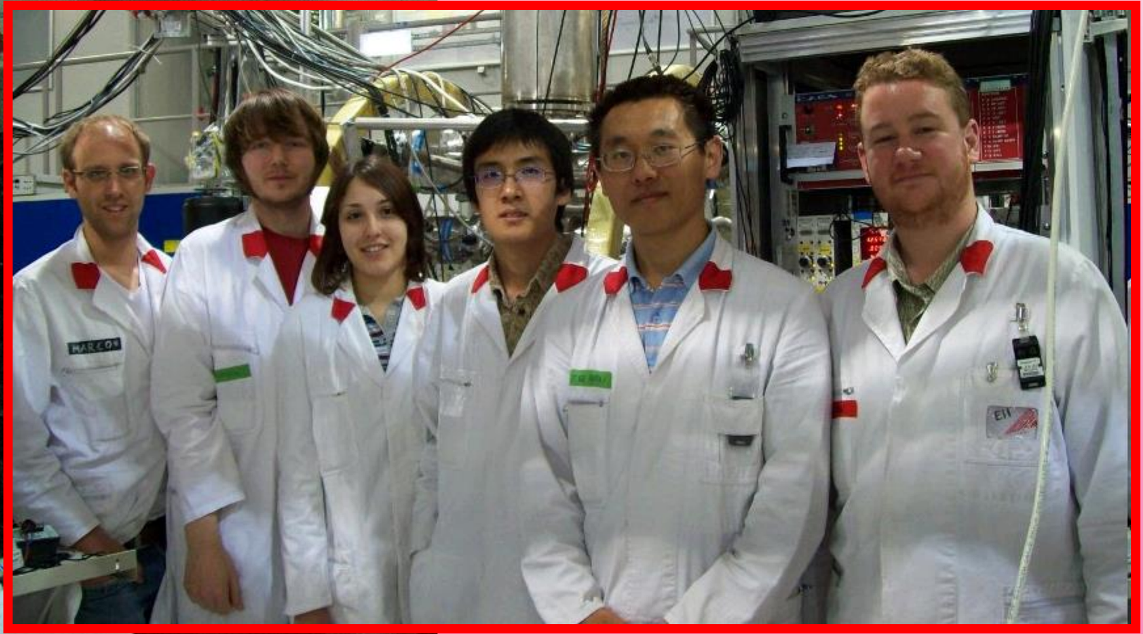


NEPOMUC facility at the neutron research reactor FRM II. Garching.

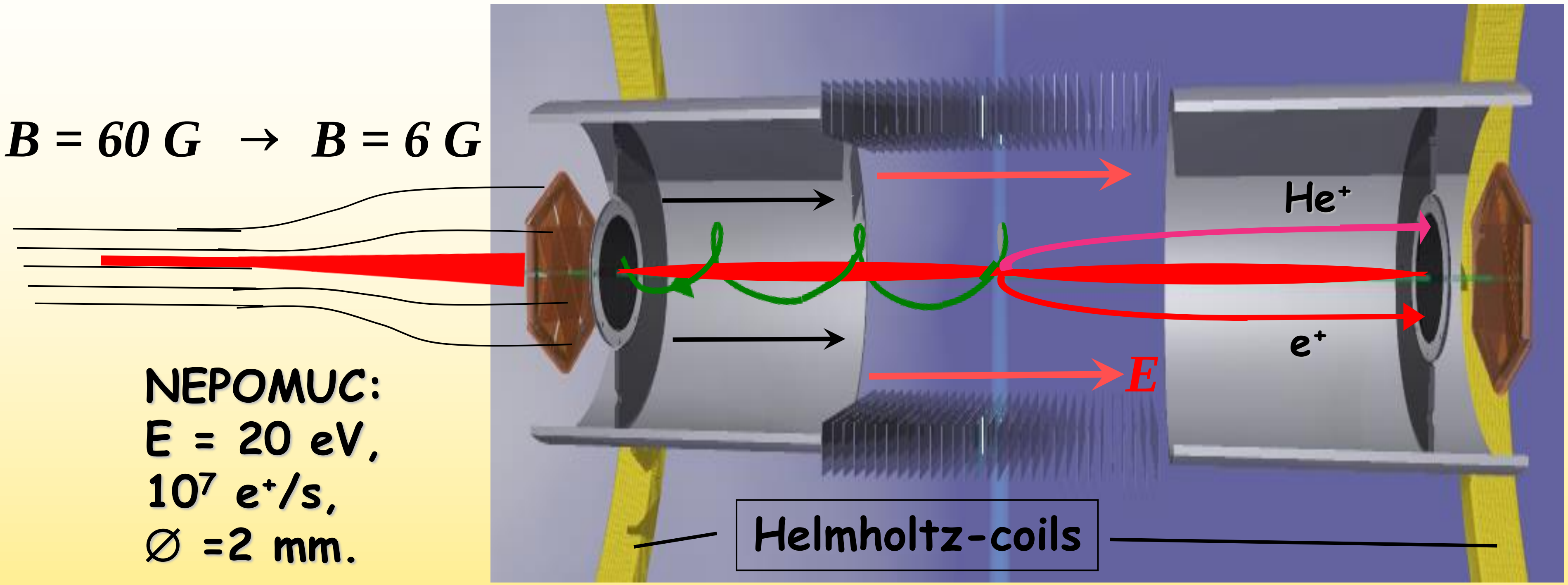


Issues

- Continuous positron beam (triple coincidence).
- Deliverd in comparatively high B-field (60 G).
- NEPOMUC: 10^7 e^+/s, E = 20 eV, ∅ = 2 mm.
- Expected in Remi: 10^6 e^+/s, ∅= 2 mm
- Obtained: 10^5 e^+/s, ∅= 5 mm



The Positron Reaction Microscope

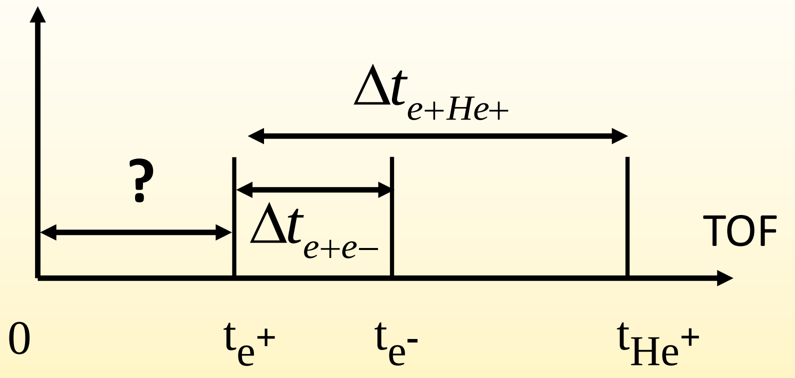


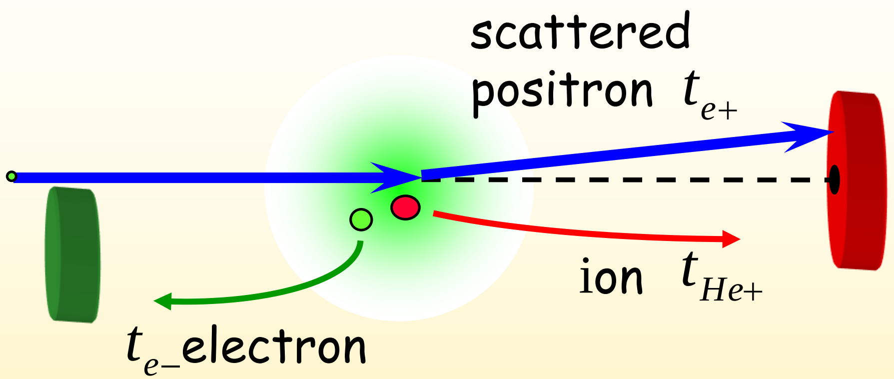
NEPOMUC:
E = 20 eV,
10^7 e^+/s,
∅ =2 mm.

Challenges

- Reversed charge → Positron/Ion detector.
- Continuous positron beam (TOF measurement?).
- Deliverd in comparatively high B-field.
- Expected: 10^6 e^+/s, ∅= 2 mm ☺ - Obtained: 10^5 e^+/s, ∅= 5 mm ☹

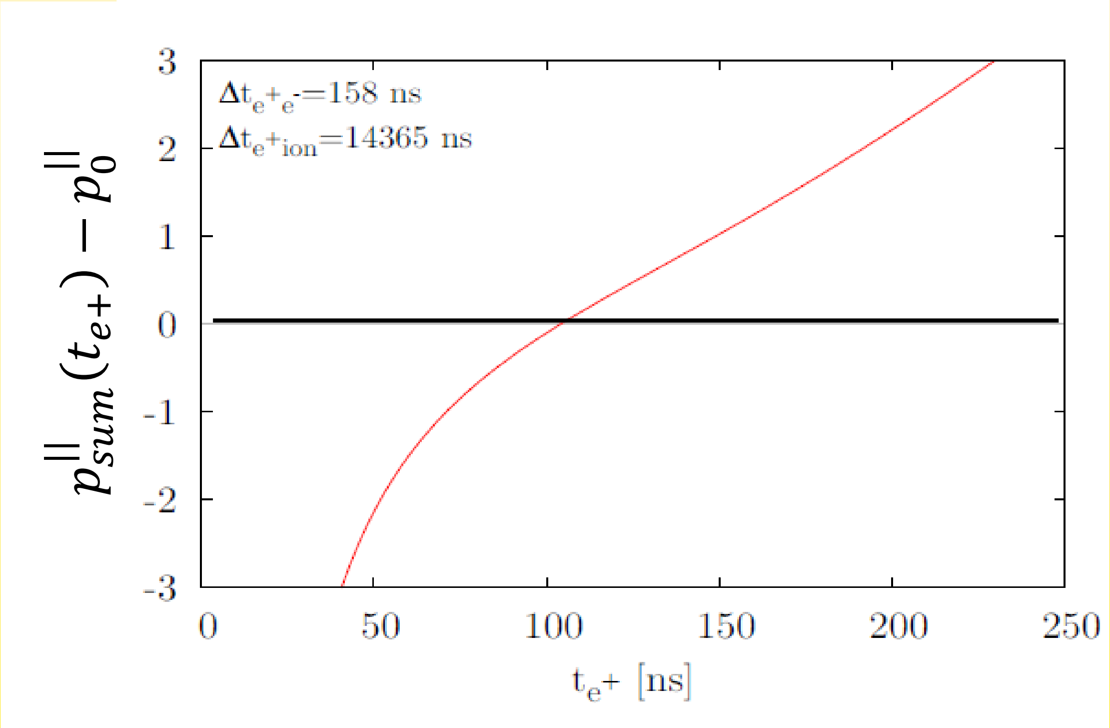
TOF and Momentum Determination





Exploit momentum conservation:

$$p^{||}_{sum}(t_{e+}) - p^{||}_0 = 0$$

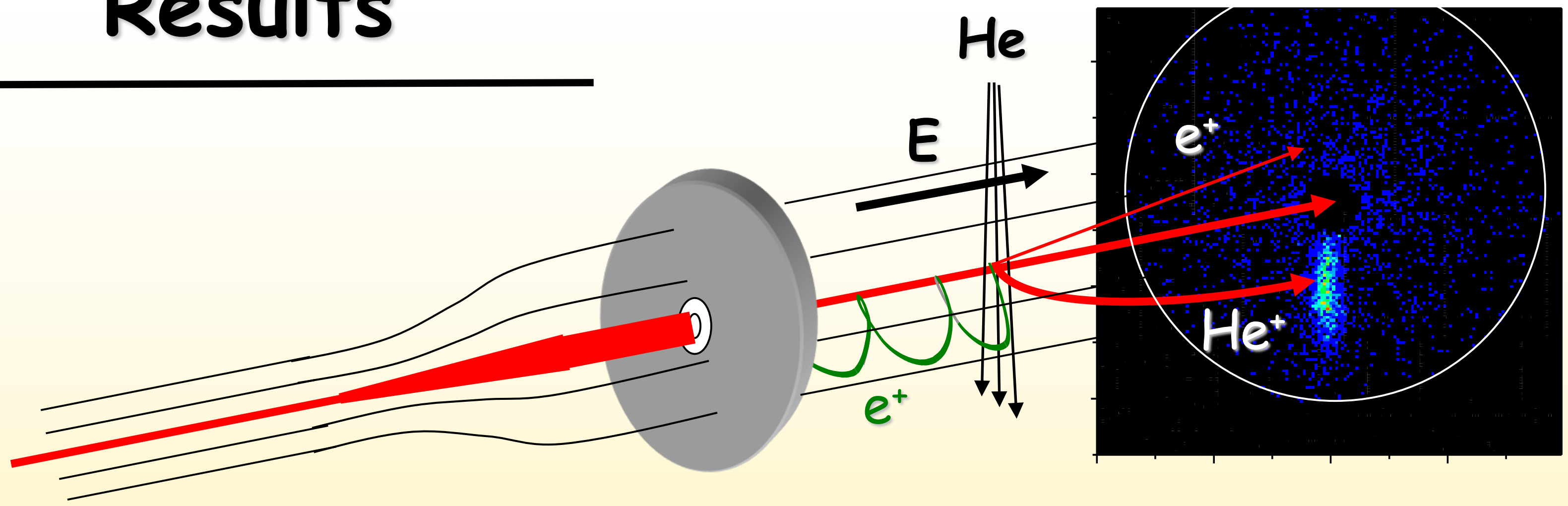


$$p^{||}_{e+} = f(t_{e+})$$

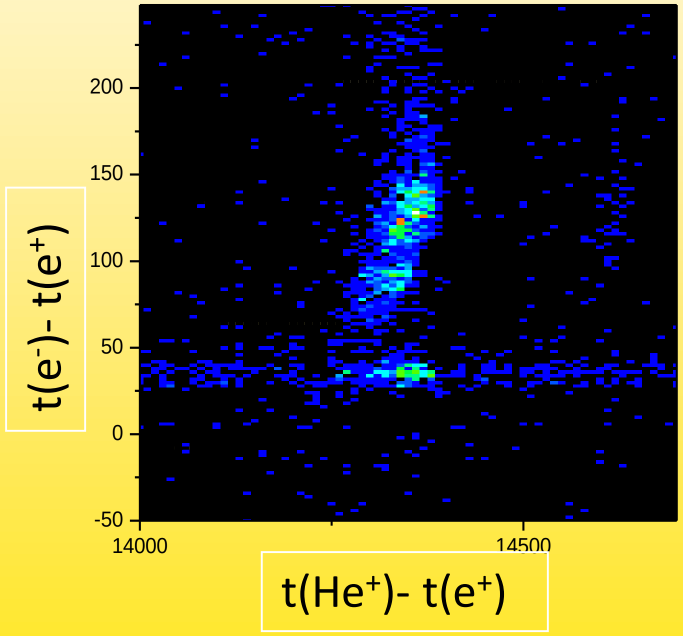
$$p^{||}_{e-} = g(t_{e-}) = g(t_{e+} + \Delta t_{e+e-})$$

$$p^{||}_{He+} = h(t_{He+}) = h(t_{e+} + \Delta t_{e+He+})$$

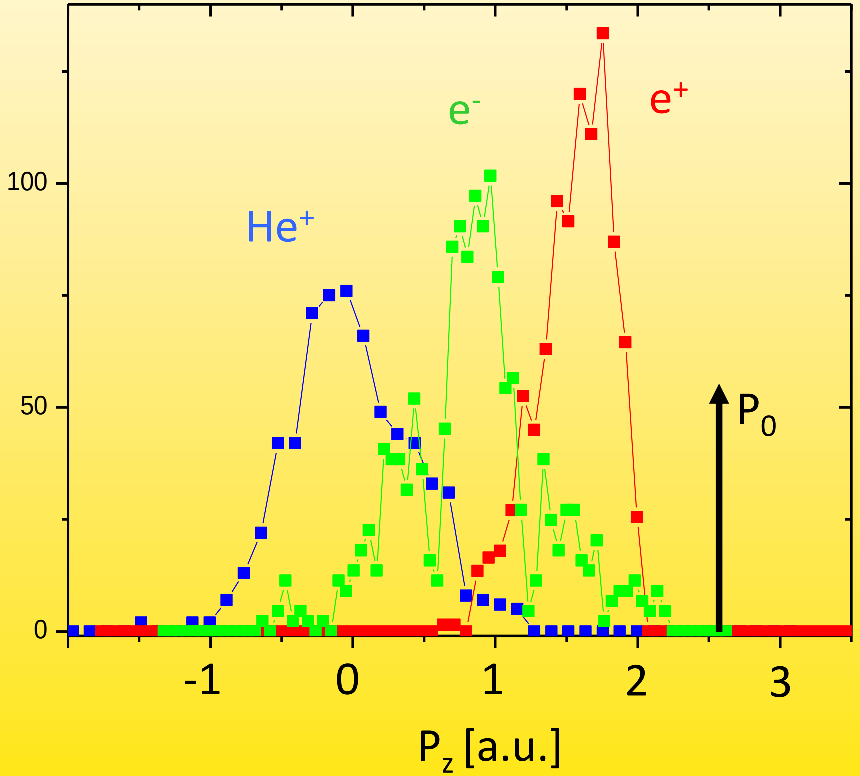
Results



He
E
e+
He+
e+



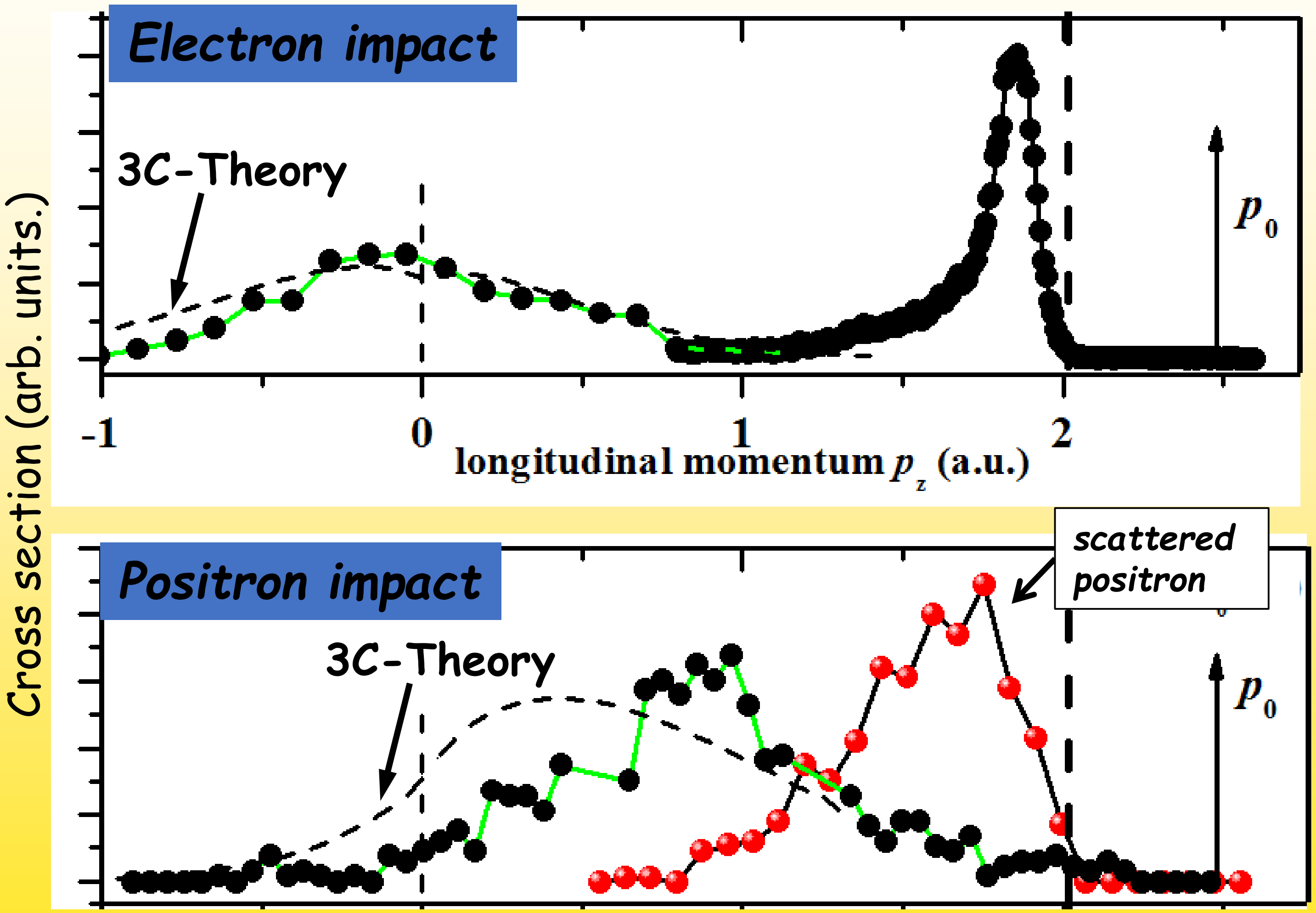
200
150
100
50
0
-50
14000
14500
t(e-)- t(e+)
t(He+)- t(e+)

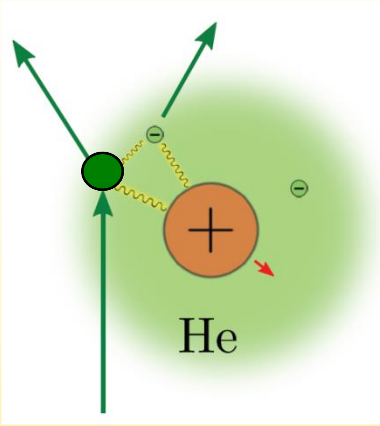


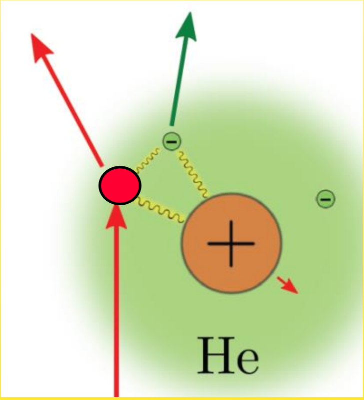
e-
e+
He+
100
50
0
P0
-1
0
1
2
3
Pz [a.u.]

Comparison: Electron v.s. Positron

E_0 = 80 eV, target: helium







Theory: 3-Coulomb wave function calculation.

Summary positron impact

- Kinematically complete study of low energy positron impact successful
  (triple coincidences, TOF reconstruction, …)

- Longitudinal momentum spectra strongly different from respective electron impact data. Theory qualitatively in agreement.

Thanks to

Electron impact

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Mareike Dinger

Positrons

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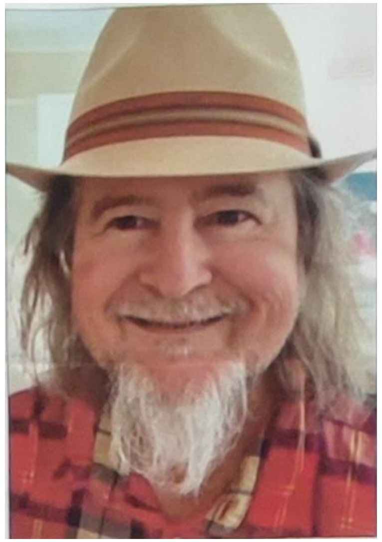
Steve Buckman	ANU, Canberra
Dan Slaughter	Berkley

And more …

In memory of our friends and collaborators

Don H. Madison
1945 - 2022

Oleg Zatsarinny
1953 - 2021



Michael Brunger
1960 - 2022