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Metal Photocathodes: The Influence of Electronic Band Structure on Transverse Emittance

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Brightness: Transverse Emittance

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- Measure of transverse electron beam (or pulse) quality:

$$\varepsilon_T = \frac{\hbar}{mc}\sqrt{\left\langle x^2 \right\rangle \left\langle k_x^2 \right\rangle} = \frac{1}{mc}\Delta x . \Delta p_T$$

… a conserved quantity in a ‘perfect’ system.

- Initial electron source parameters at photocathode:
  - Δx determined by laser spot size & limited by Child’s Law
  - Δp_T is an ***intrinsic*** property of the photocathode material

- ***Standard*** theoretical expressions for transverse rms momentum:
  - Single-photon photoemission: $\Delta p_T = \sqrt{\frac{m(\hbar\omega - \phi_{eff})}{3}}$

D.H. Dowell & J.F. Schmerge, *Phys. Rev. ST – Acc. & Beams* **12** (2009) 074201
K.L. Jensen et al., *J. Appl. Phys.* **107** (2010) 014903

Experiment: Solenoid Scan

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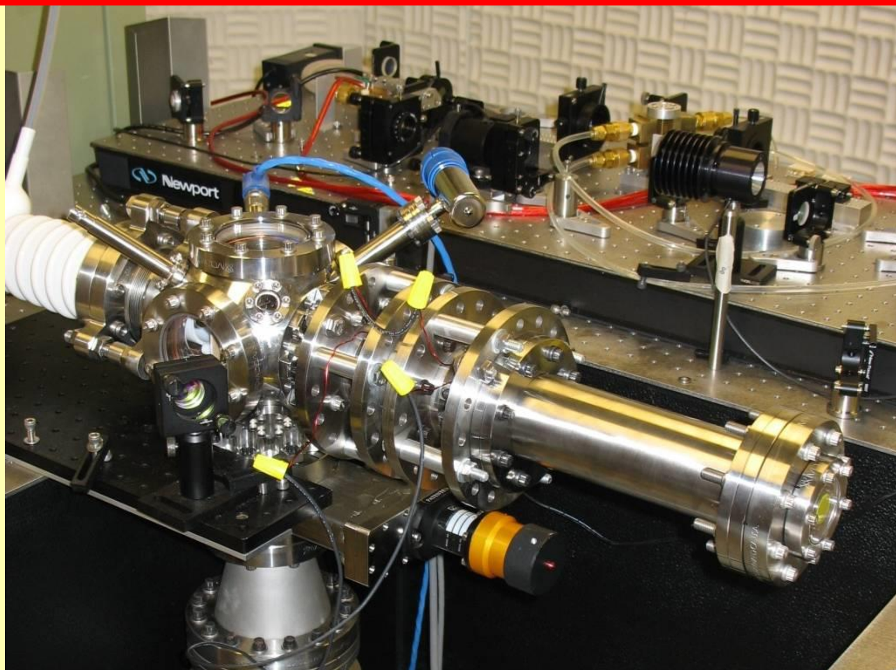
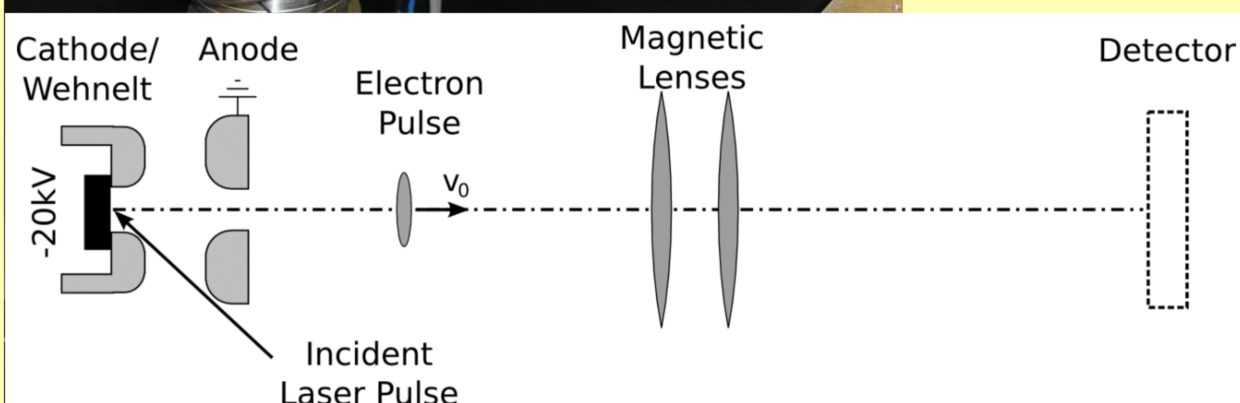


- 2W, 250fs, 63MHz, diode-pumped Yb:KGW laser
  - ~4ps at 261nm ($\hbar\omega = 4.75$eV)
- YAG scintillator optically coupled to CCD camera
  - Beam size vs. magnetic coil (lens) current measured
  - Analytical Gaussian (AG) pulse propagation model to extract Δp_T



J.A. Berger & W.A. Schroeder, *J. Appl. Phys.* **108** (2010) 124905

Results: Polycrystalline Cr

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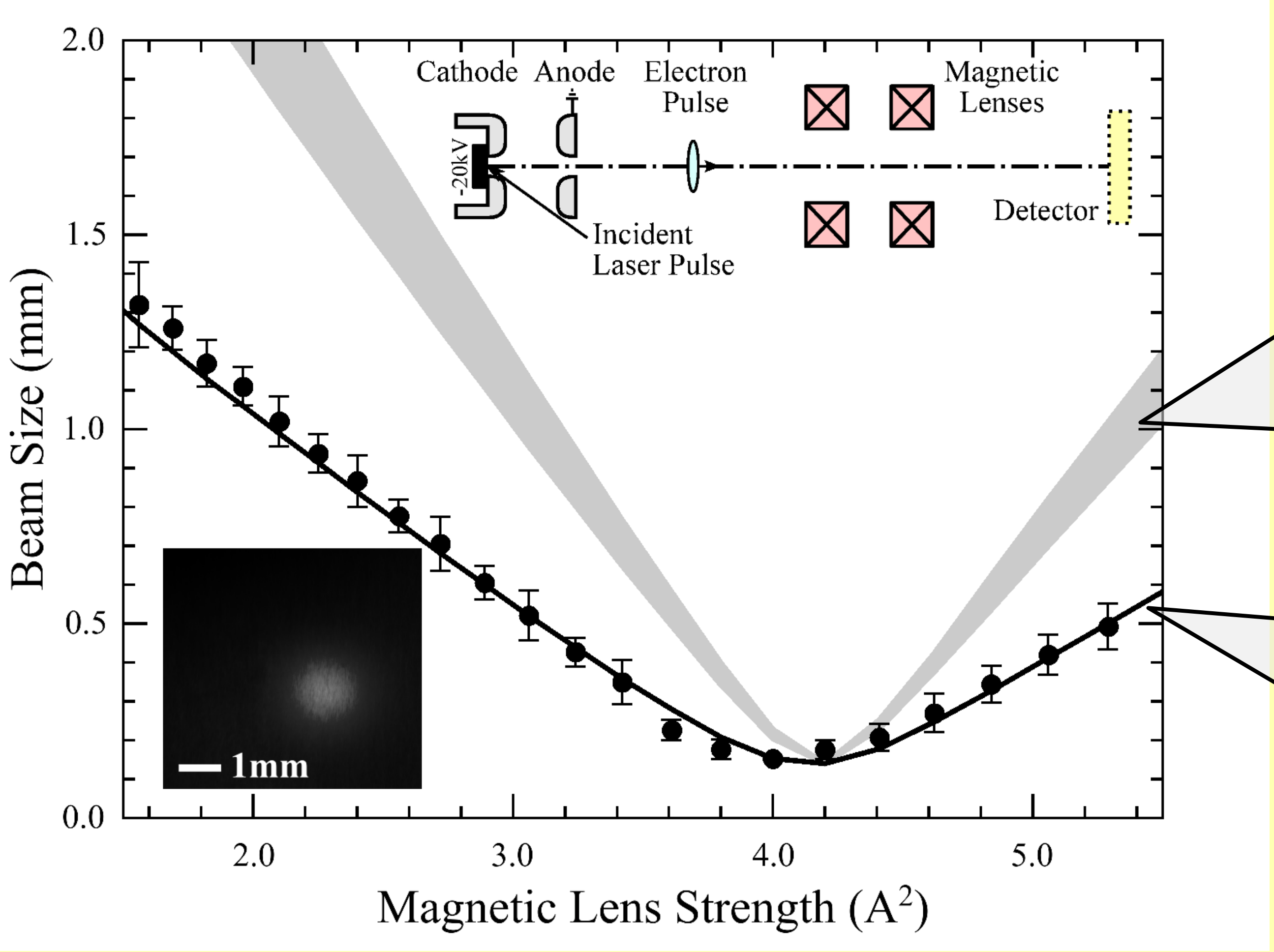
– Solenoid scan measurement



Range for Δp_T from

$$\Delta p_T = \sqrt{\frac{m_0(\hbar\omega - \phi)}{3}}$$

… $\phi = 4.50(\pm 0.05)$eV and $\hbar\omega = 4.75$eV

AG model simulation of experiment gives

$\Delta p_T = 0.155(\pm 0.01)\ (m_0.eV)^{1/2}$

Results: Metals

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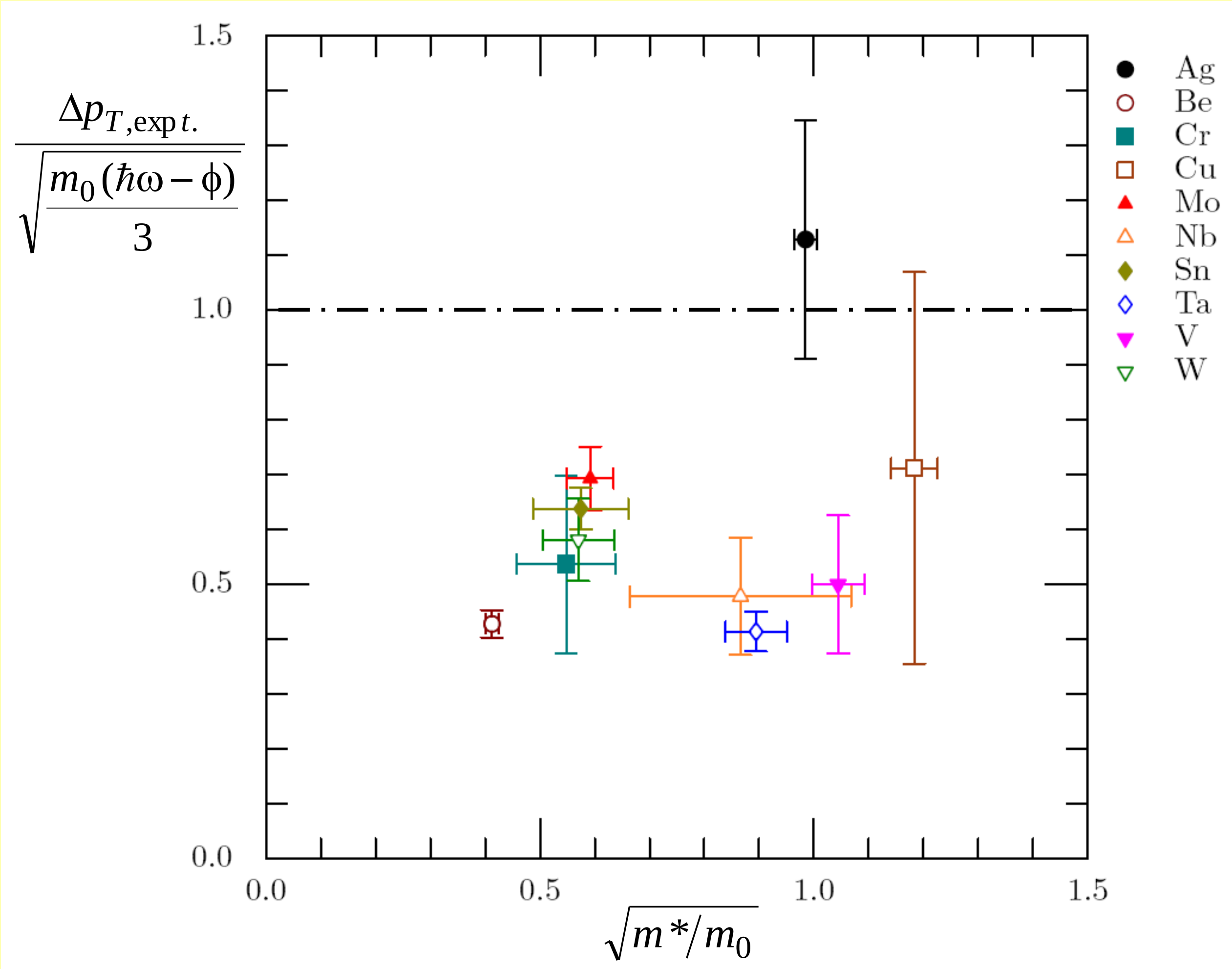
– Effective mass in metal photocathodes: dH-vA, CR, $C_e = \gamma T_e$, optical, …



Ten ***polycrystalline*** metal photocathodes

B.L. Rickman et al., *Phys. Rev. Lett.* **111** (2013) 237401

Results: Metals

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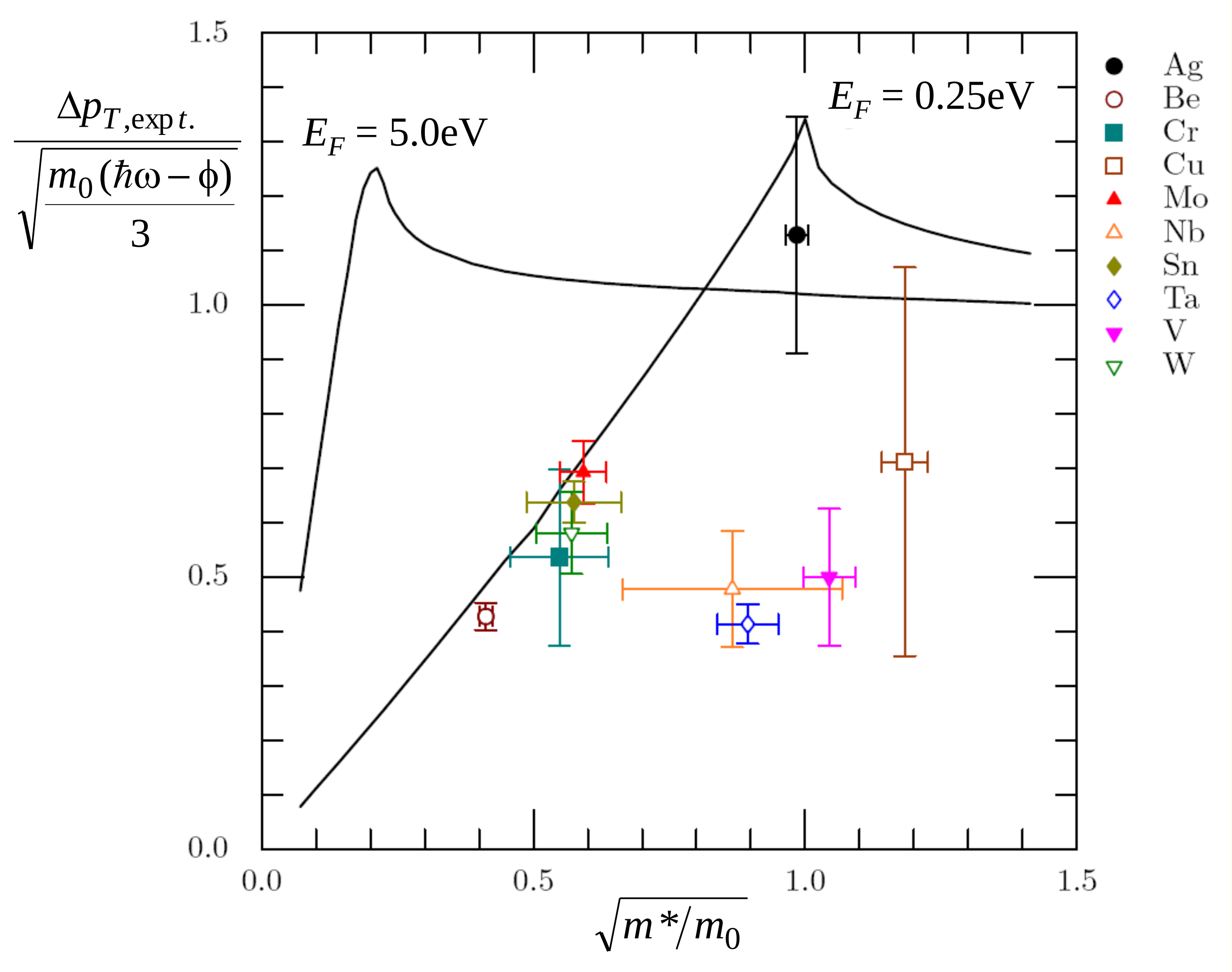
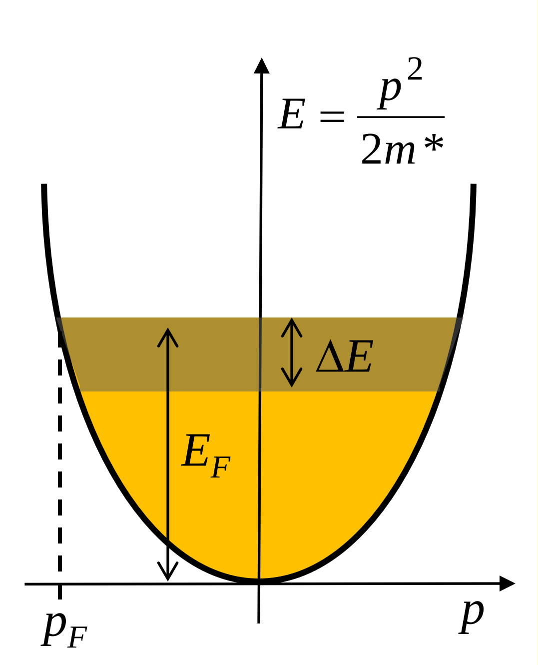
– Spherically symmetric electron-like bands: $\Delta E = \hbar\omega - \phi = 0.25\text{eV}$





Δp_T reduced when

$$p_F = \sqrt{2m^* E_F}$$

is less than

$$p_{T,\mathrm{max.}} = \sqrt{2m_0 \Delta E}$$

B.L. Rickman et al., *Phys. Rev. Lett.* **111** (2013) 237401 (erratum submitted)

Results: Metals

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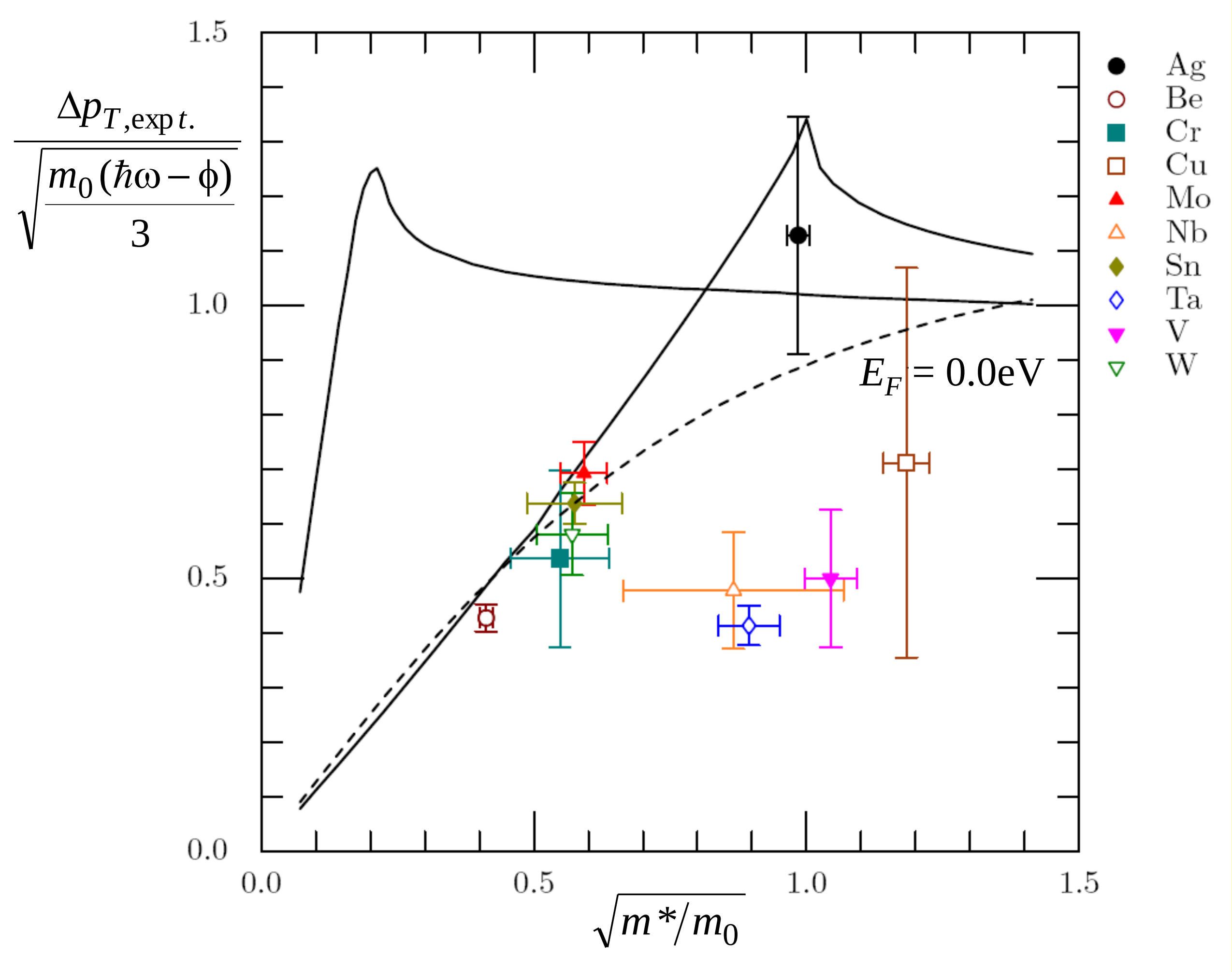
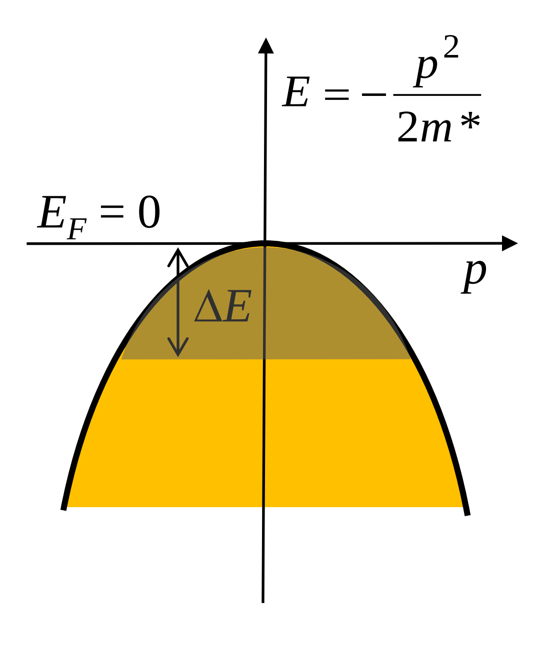
– Hole-like bands (dashed line): $\Delta E = \hbar\omega - \phi = 0.25\text{eV}$





Additional effect of low barrier transmission $T(p_z,p_{z0})$ for high p_T states

Fermi Surfaces

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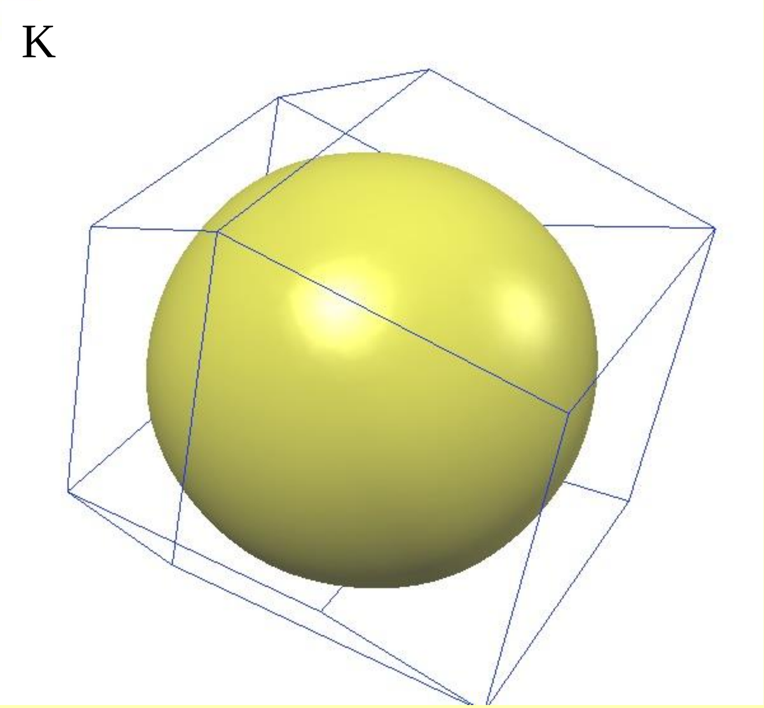

Fermi Surfaces

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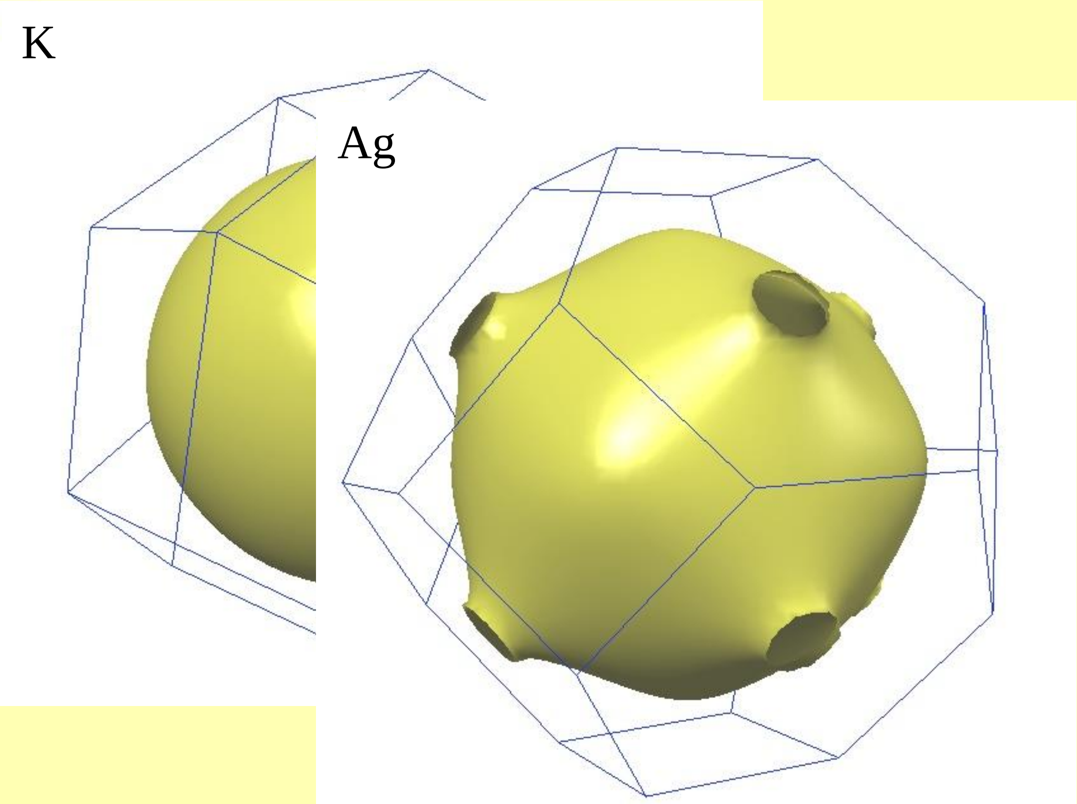

Fermi Surfaces

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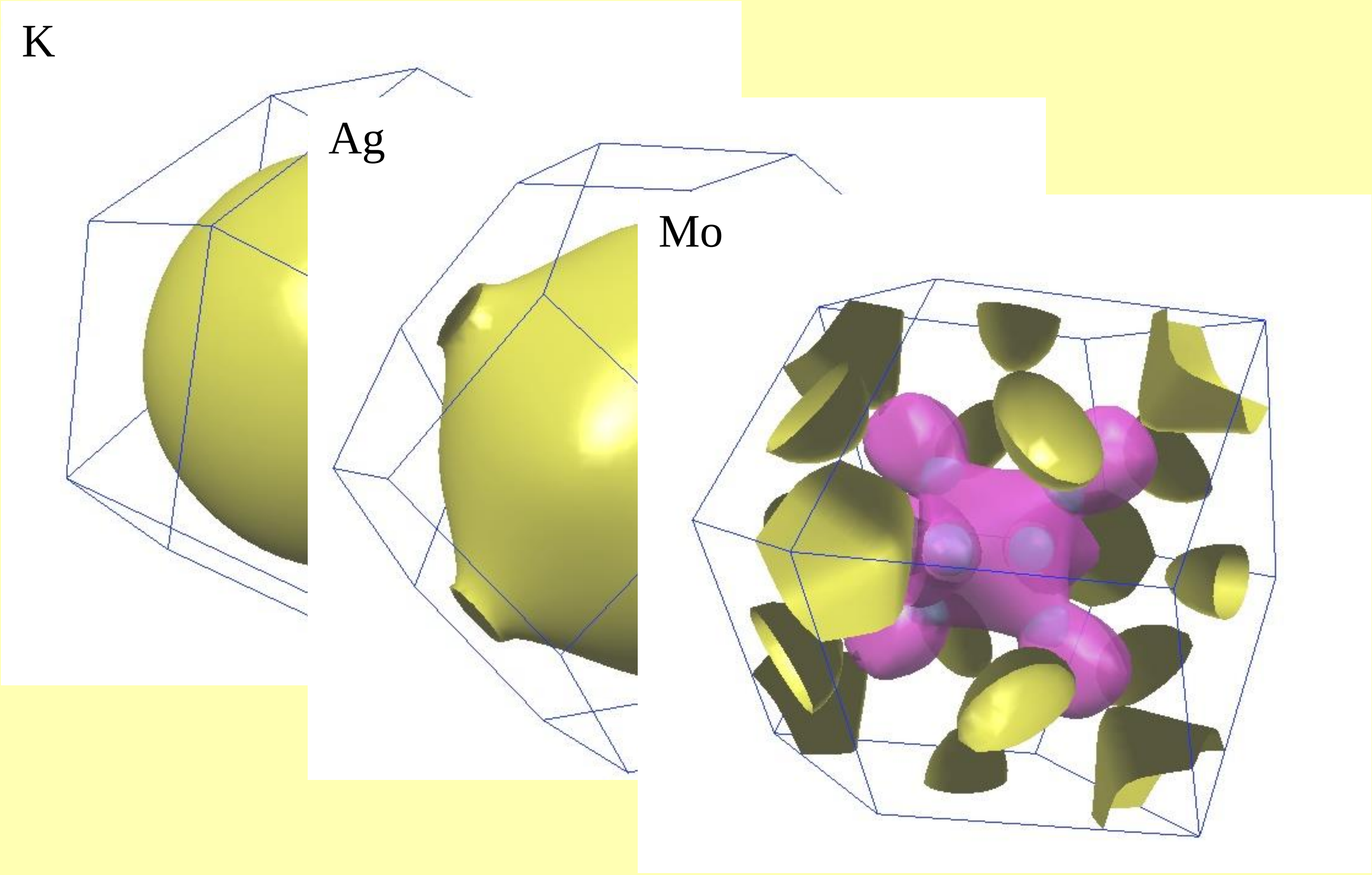

www.phys.ufl.edu/fermisurface/

Fermi Surfaces

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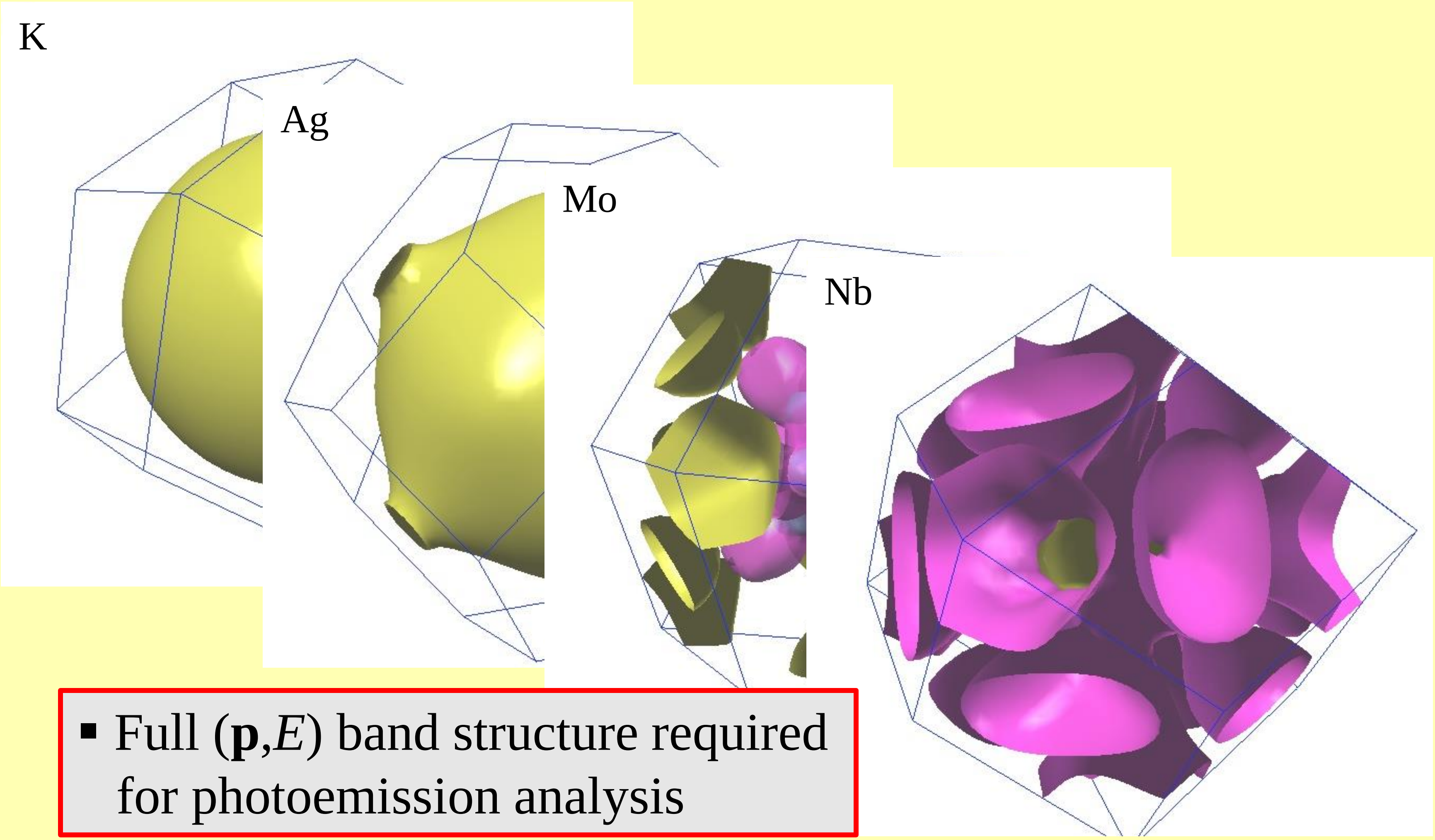

- Full ($\mathbf{p}$,E) band structure required for photoemission analysis

Work Function Anisotropy

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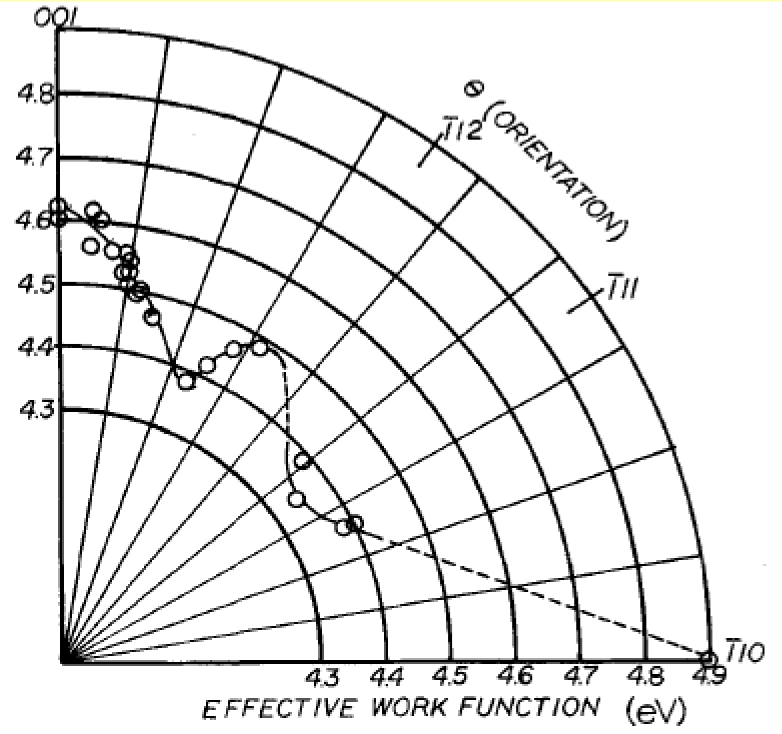
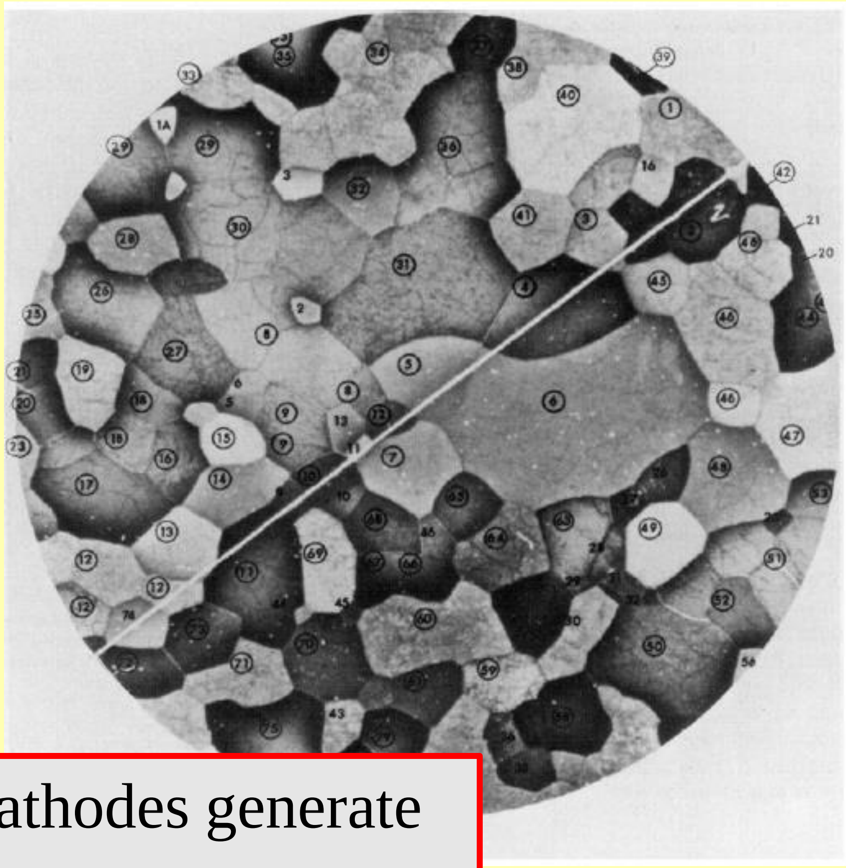
– Example: $\phi_{(ijk)}$ for Mo by electron emission microscopy



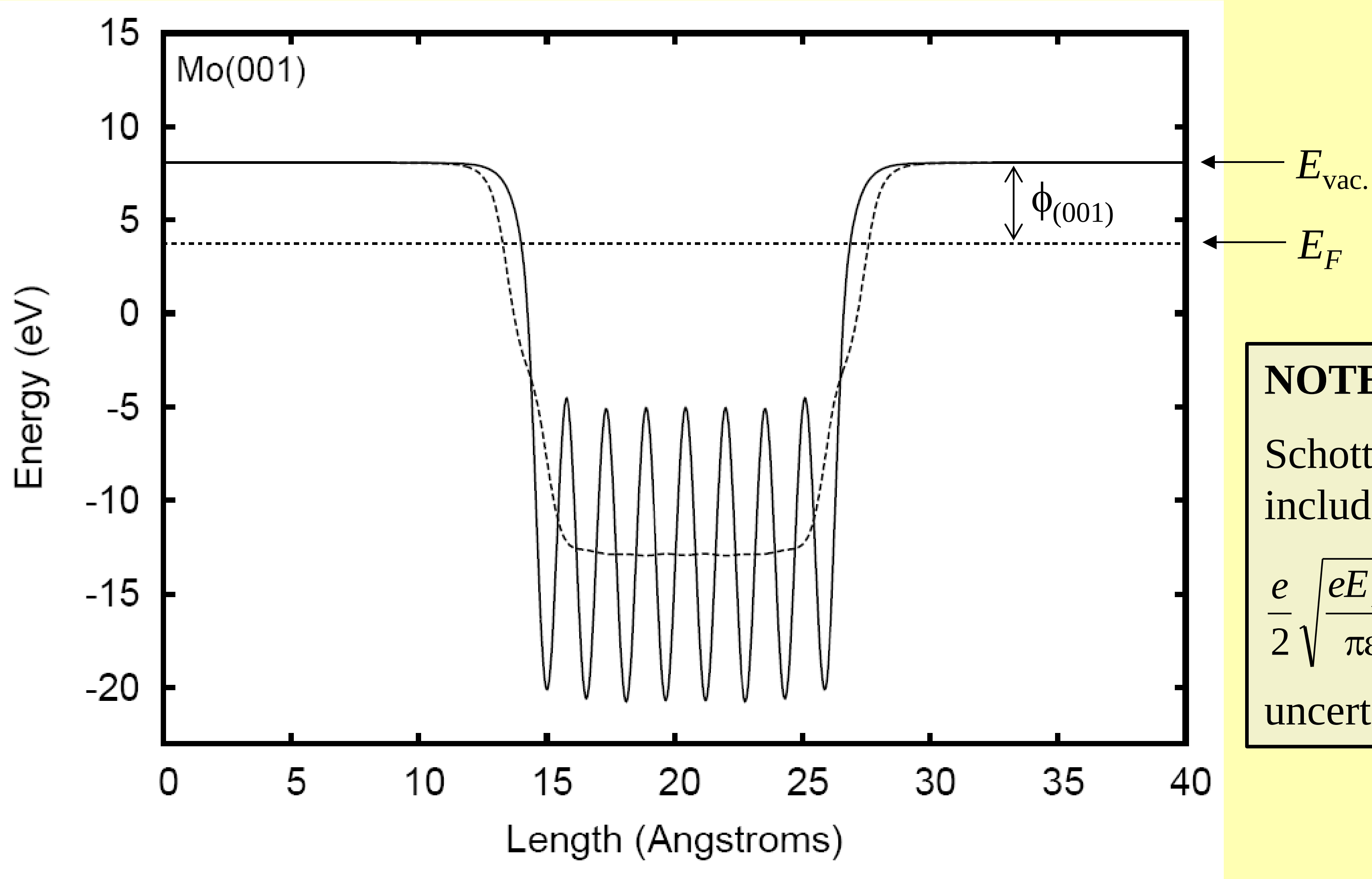


- Polycrystalline metal photocathodes generate *inhomogeneous* electron beams
- Any photoemission analysis ***must*** include $\phi_{(ijk)}$

D. Jacobson & A. Campbell, *Metall. Trans.* **2**, 3063-3066 (1971)

Thin-slab Evaluation of $\phi_{(ijk)}$ UIC

– Example: $\phi_{(001)}$ = 4.53(±0.05)eV for Mo



NOTE

Schottky effect *not* included:

$$\frac{e}{2}\sqrt{\frac{eE_{DC}}{\pi\varepsilon_0}} \approx \pm 50\text{meV}$$

uncertainty in $\phi_{(ijk)}$

C. J. Fall et al., *Journal of Physics: Condensed Matter* **11**, 2689 (1999)

Photoemission Simulation: Ag

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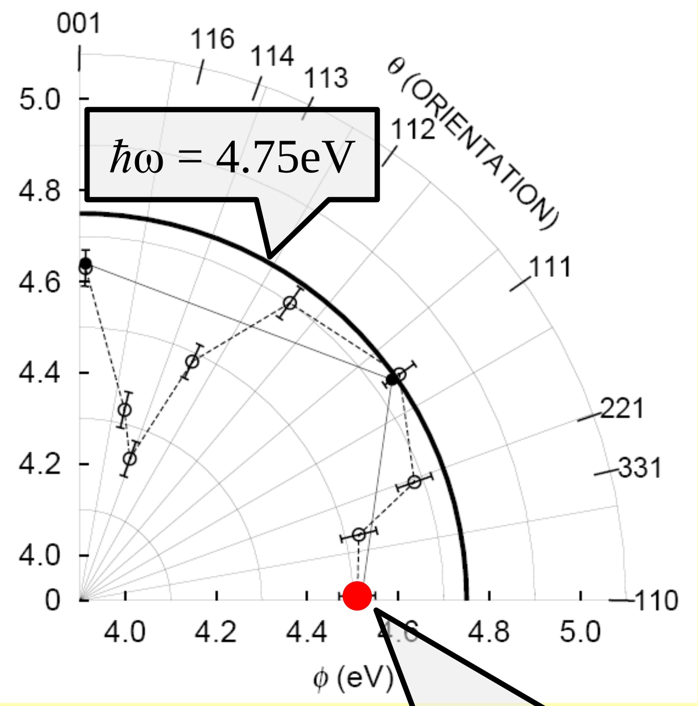
– fcc crystal lattice



Lowest index face
with lowest $\phi_{(ijk)}$

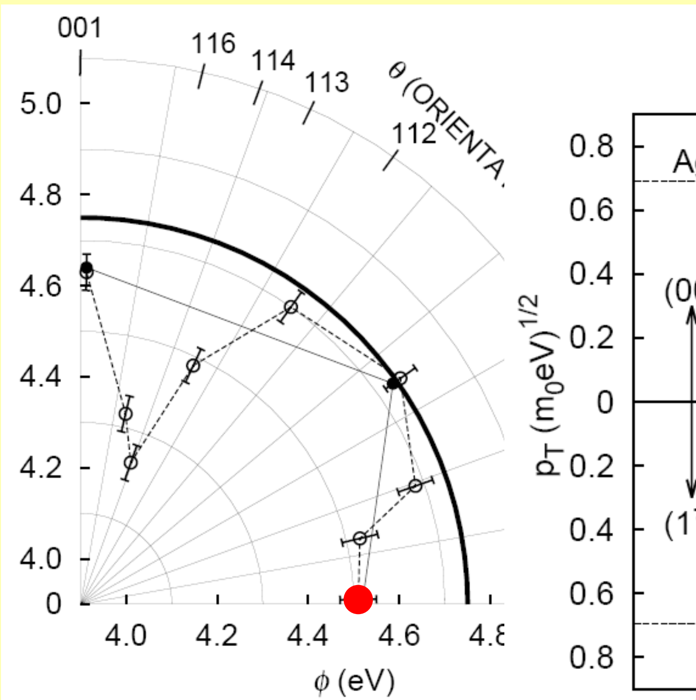
$\Delta E = \hbar\omega - \phi_{(110)} = 0.23\text{eV}$

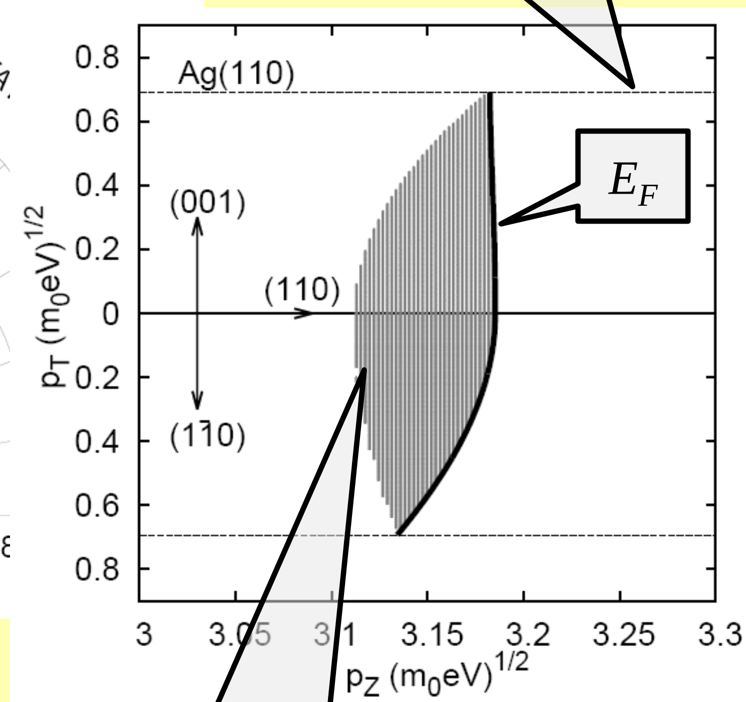
… ±50meV error in $\phi_{(ijk)}$

Photoemission Simulation: Ag

UIC

– fcc crystal lattice





$p_{T,\max.} = \sqrt{2m_0 \Delta E}$

E_F

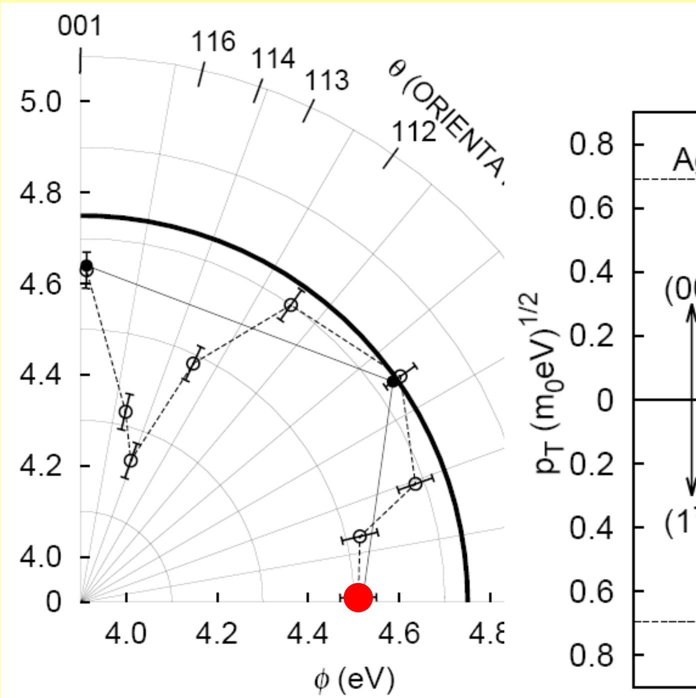
Photoemitting electron-like states for $\hbar\omega = 4.75\text{eV}$ ($\mathbf{p}_T$ and E conserved)

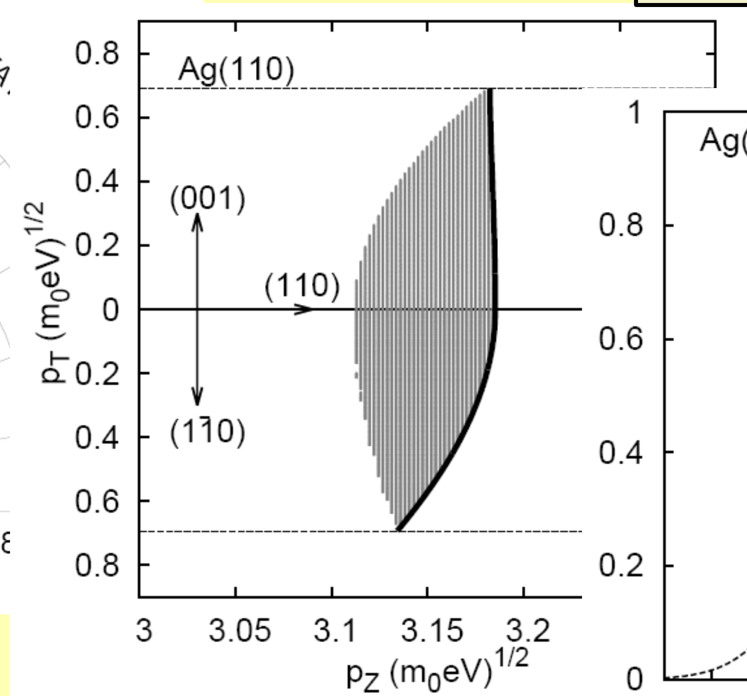
Photoemission Simulation: Ag

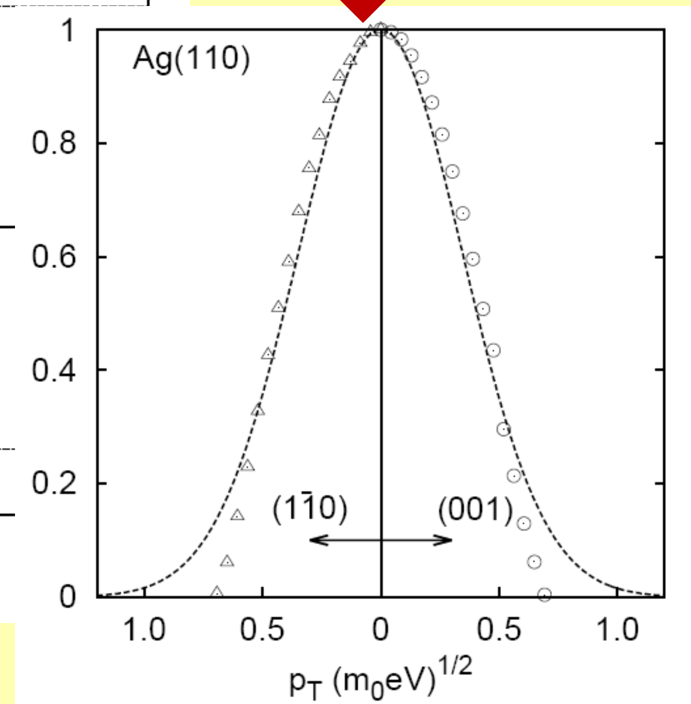
UIC

– fcc crystal lattice

E, $\mathbf{p}_T$ conservation
PLUS
Barrier transmission, $T(p_z,p_{z0})$







Spatially-averaged
$\Delta p_T = 0.267\ (m_0.eV)^{1/2}$

Photoemission Simulation: Mo

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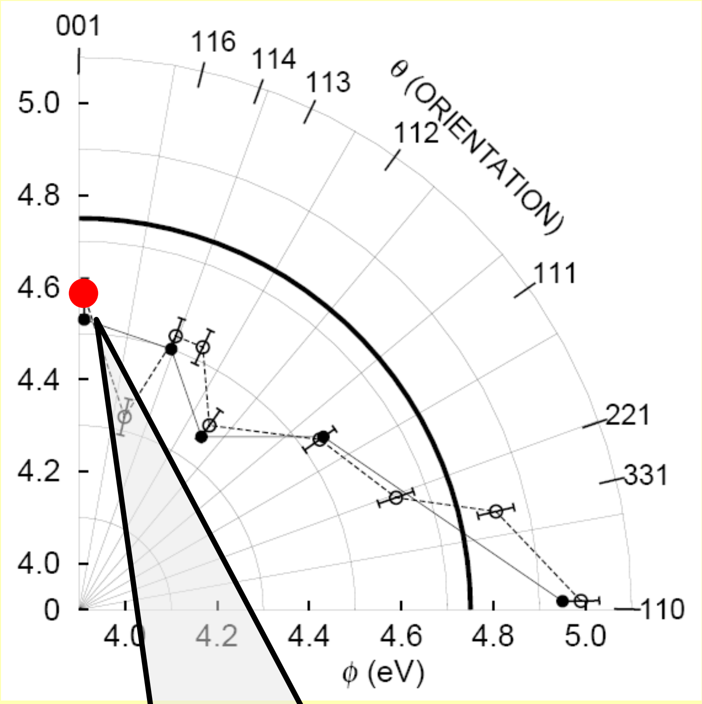
– bcc crystal lattice



Lowest index face
with lowest $\phi_{(ijk)}$

$\Delta E = \hbar\omega - \phi_{(001)} = 0.22\text{eV}$

… $\pm 50\text{meV}$ error in $\phi_{(ijk)}$

Photoemission Simulation: Mo

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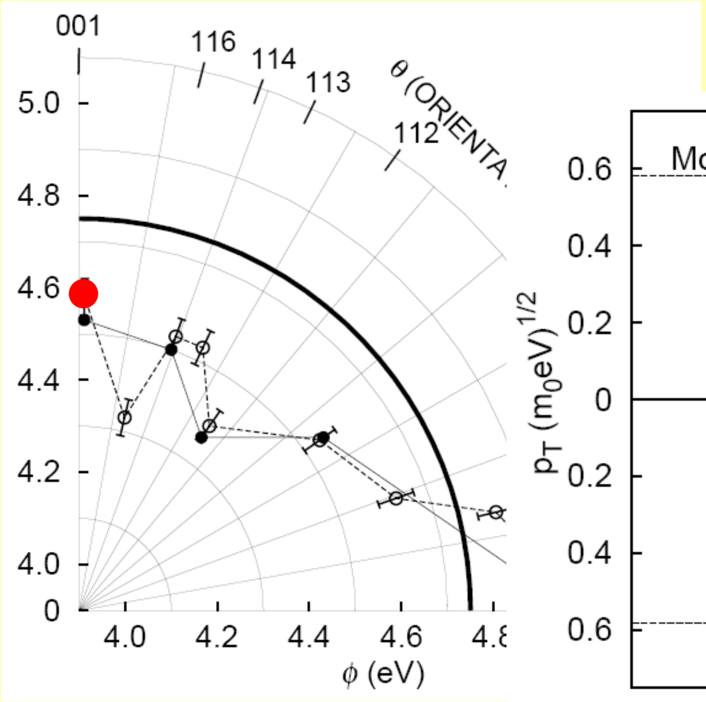
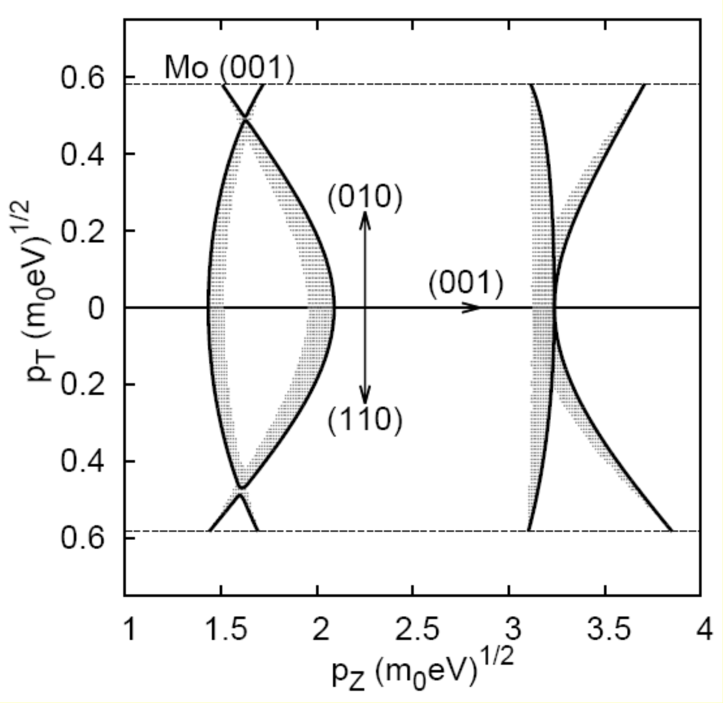
– bcc crystal lattice



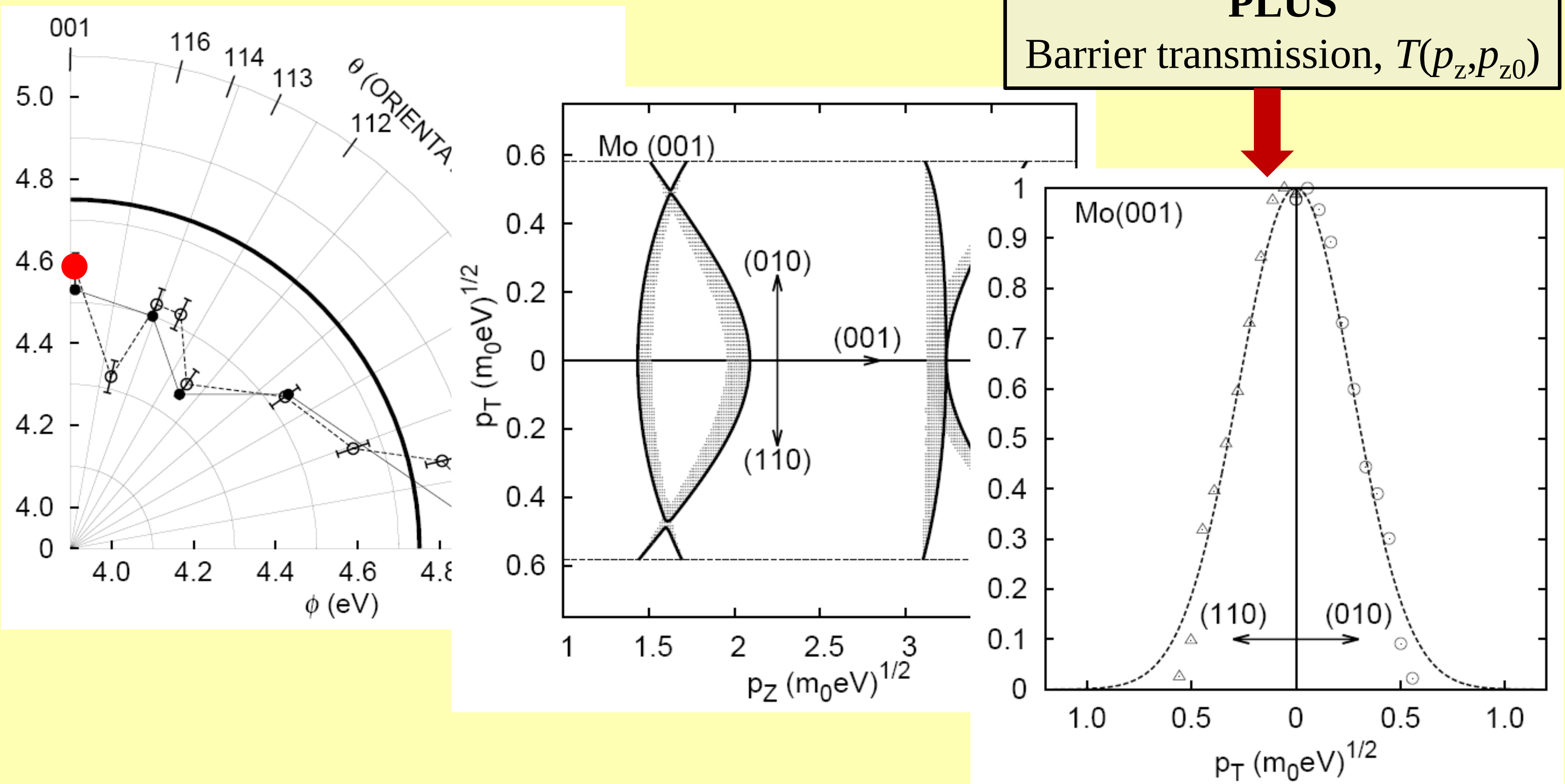


Both electron- and hole-like states contribute to photoemission

Photoemission Simulation: Mo

– bcc crystal lattice

E, $\mathbf{p}_T$ conservation
PLUS
Barrier transmission, $T(p_z,p_{z0})$



Spatially-averaged
$\Delta p_T = 0.219\ (\mathrm{m_0.eV})^{1/2}$

Photoemission Simulation: Nb

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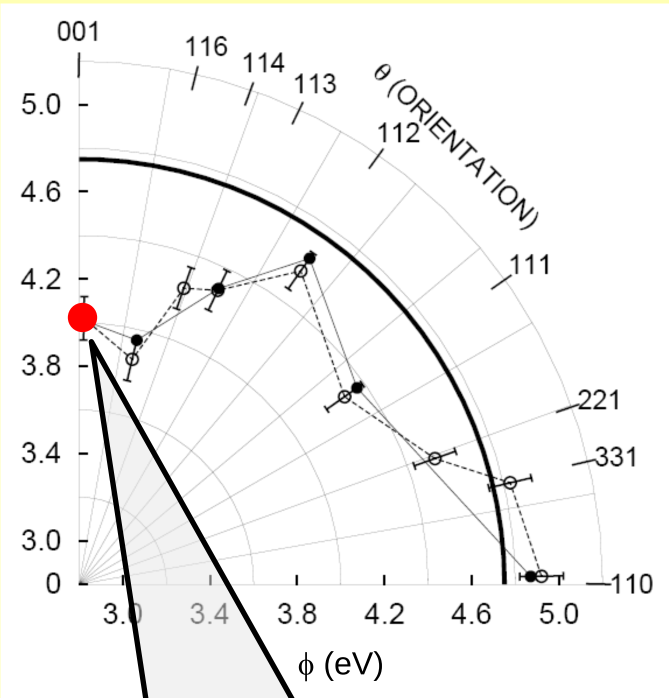
– bcc crystal lattice



Lowest index face
with lowest $\phi_{(ijk)}$

$\Delta E = \hbar\omega - \phi_{(001)} = 0.73\text{eV}$

… ±50meV error in $\phi_{(ijk)}$

Photoemission Simulation: Nb

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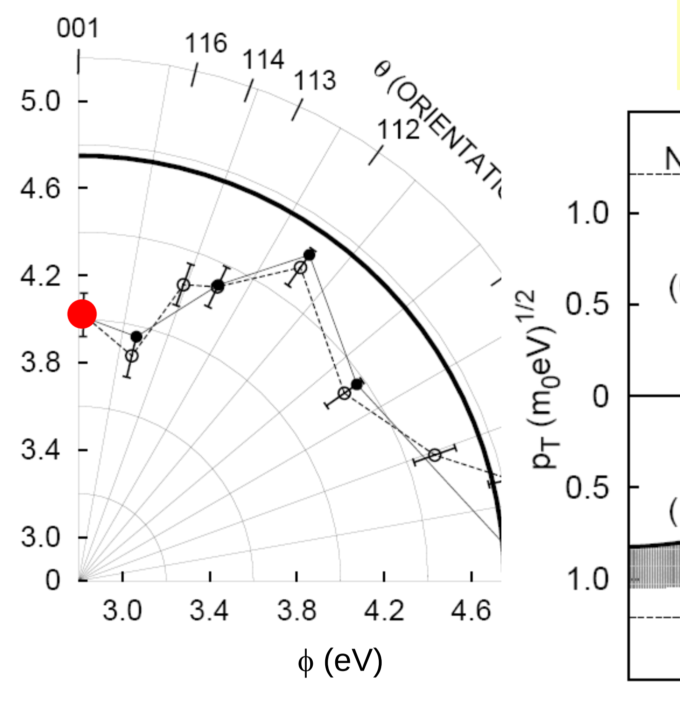
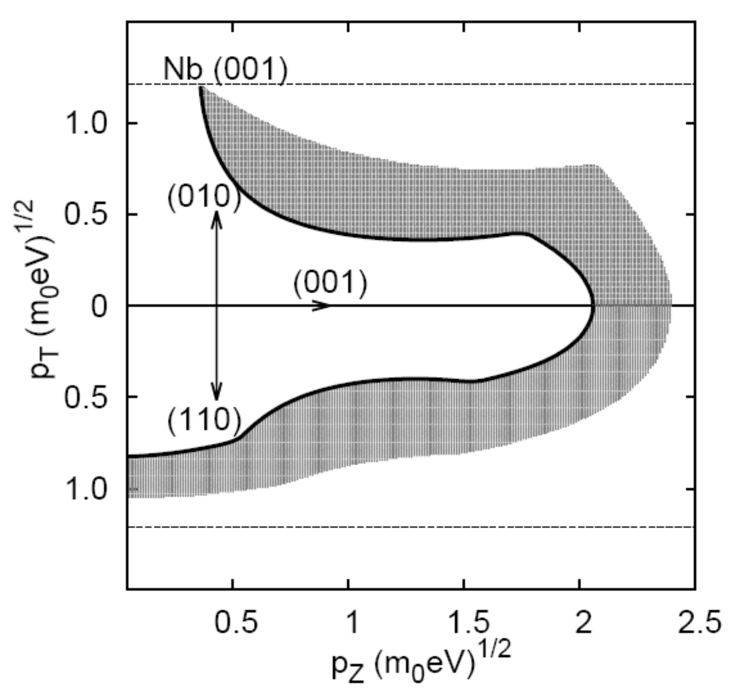
– bcc crystal lattice





Only hole-like states contribute
to photoemission

Photoemission Simulation: Nb

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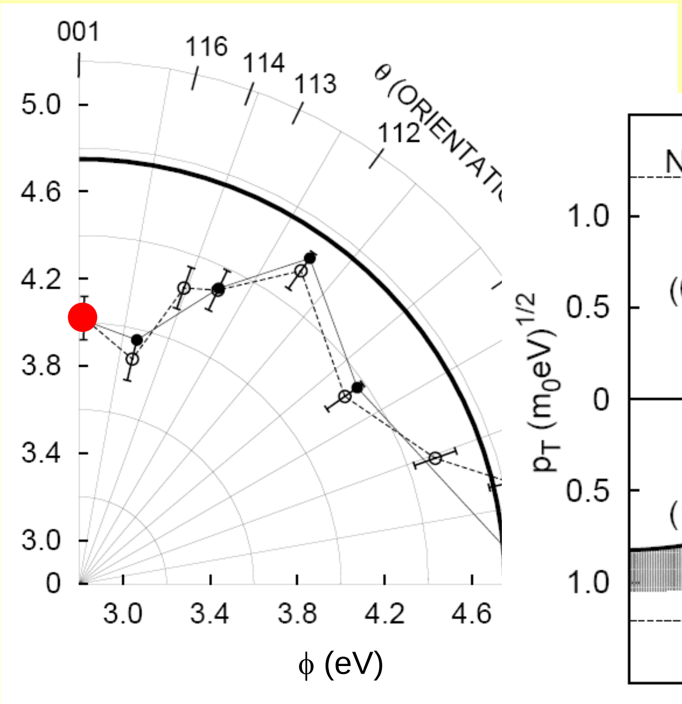
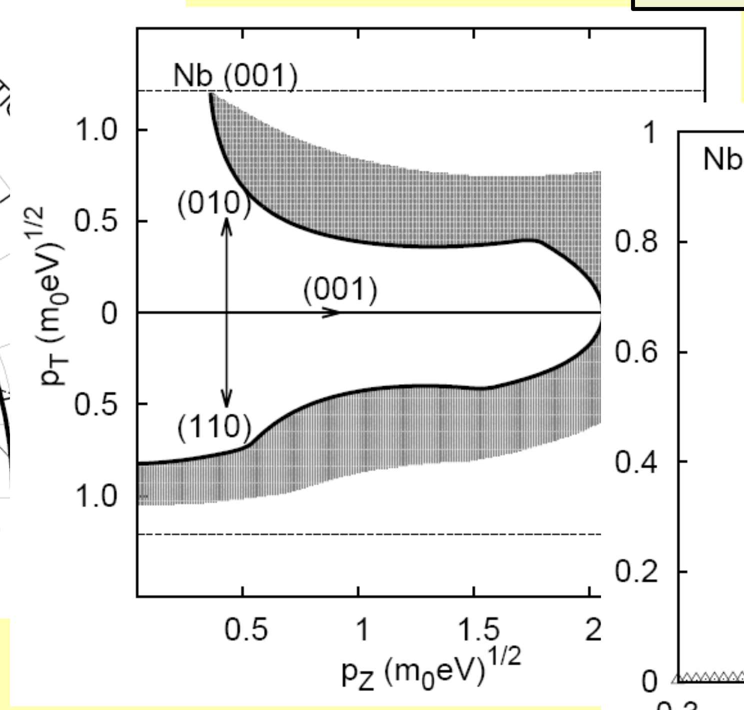
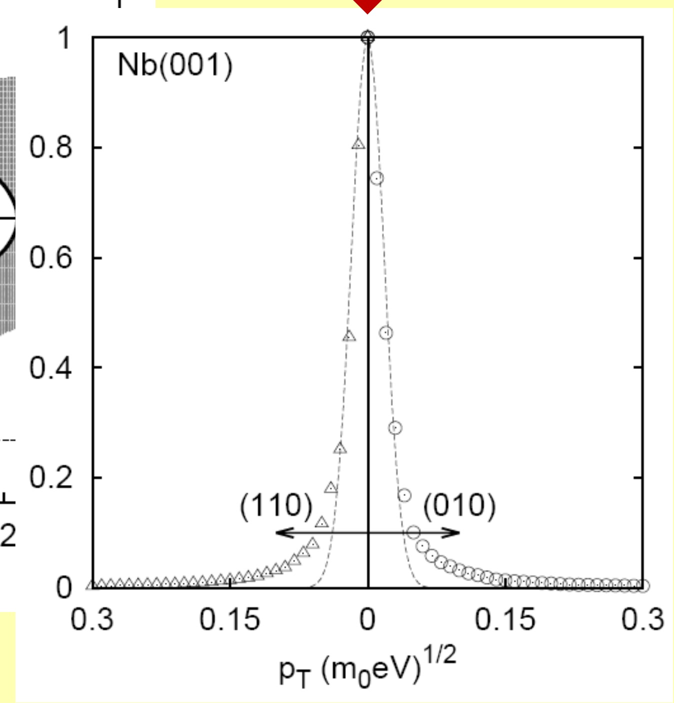
– bcc crystal lattice

E, $\mathbf{p}_T$ conservation
PLUS
Barrier transmission, $T(p_z,p_{z0})$







Spatially-averaged
$\Delta p_T = 0.196\ (\mathrm{m_0.eV})^{1/2}$

Experiment vs. Theory

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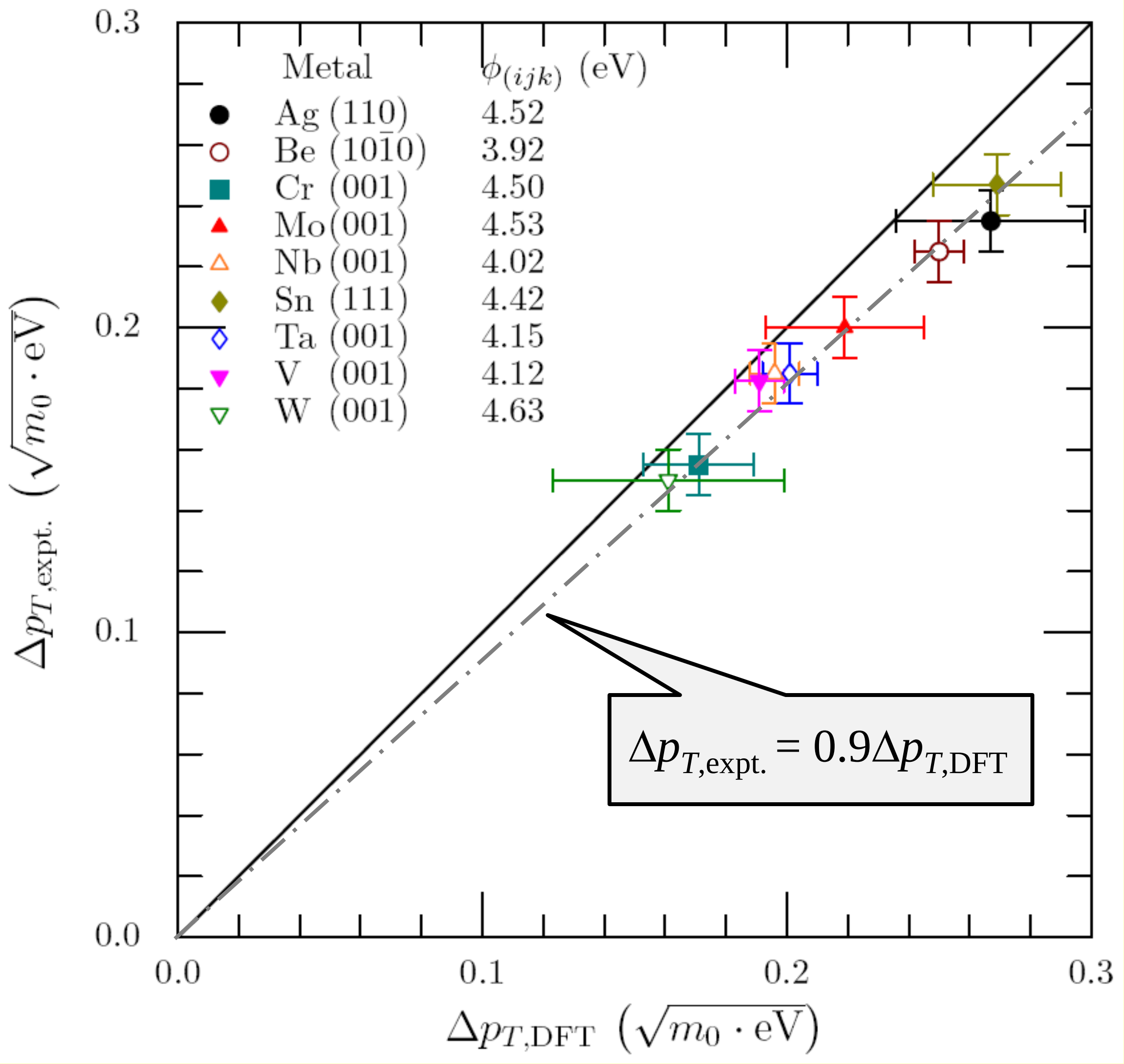

NOTE

$\Delta p_{T,DFT} \geq \Delta p_{T,\text{expt.}}$

is ***expected***:

Other crystal faces with smaller $\Delta E = \hbar\omega - \phi_{(ijk)}$ contribute with lower Δp_T thereby reducing $\Delta p_{T,\text{expt.}}$ for polycrystalline metal photocathodes.

$\Delta p_T(T_e)$ for V(001) emission

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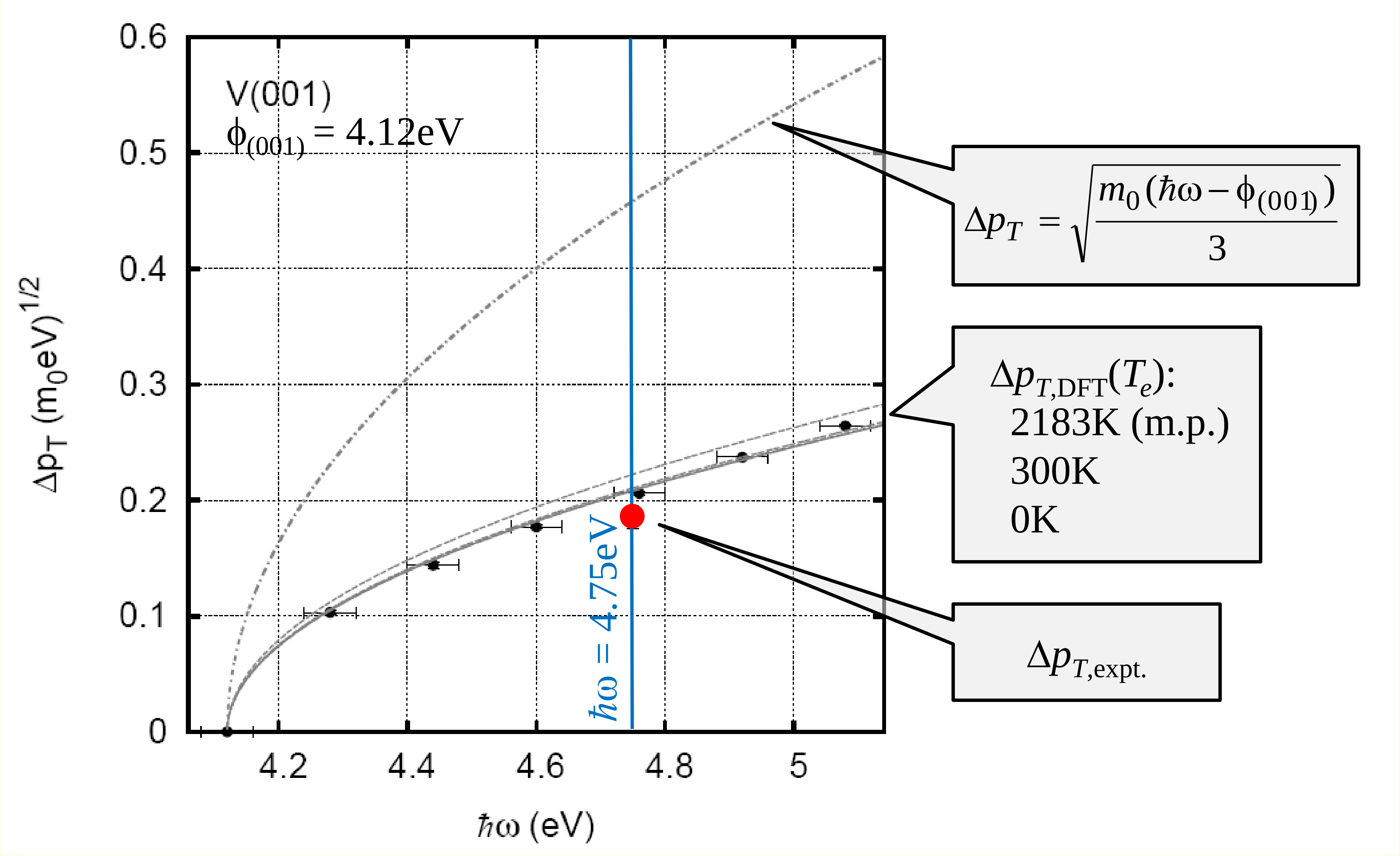
– DFT band structure with Fermi-Dirac distribution for electrons



Summary

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- Work function anisotropy $\phi_{(ijk)}$

  $\Rightarrow$ Intrinsically inhomogeneous electron beam
  from polycrystalline photocathodes

- Band structure complexity (non-spherical Fermi surface)

  $\Rightarrow$ DFT-based photoemission analysis for evaluation of Δp_T
  (knowledge of electronic state ($\mathbf{p}$,E)-distribution is fundamental)

- Future work: Single-crystal photocathodes

  – Direct comparison with theory
  – Homogeneous electron beams (higher η_{PE} possible)
  – Bi-metal crystal alloys to 'tune' photocathode properties ?
  – Semiconductors …

Finally …

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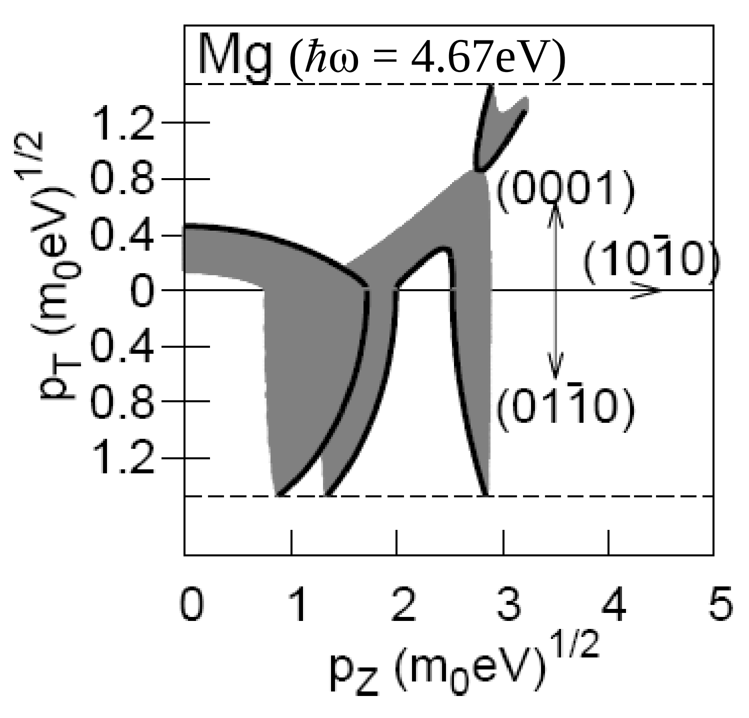
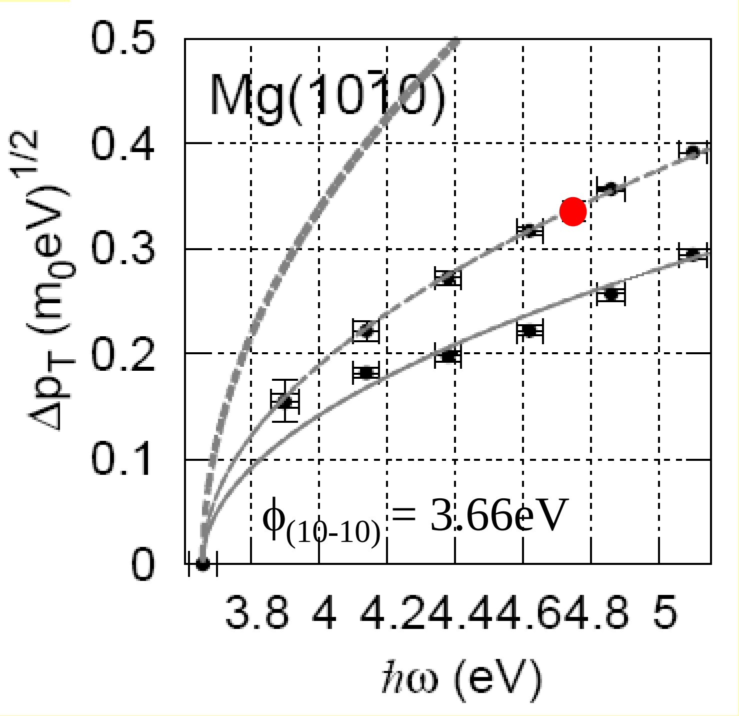
Calculating Δp_T(ijk) for ***all*** elemental metals

– Results will be available on-line to research community in early 2015





… data presentation ?

X.J. Wang et al., *Proceedings of LINAC2002*, Gyeongju, Korea.

Thank you!

Copper Photocathode

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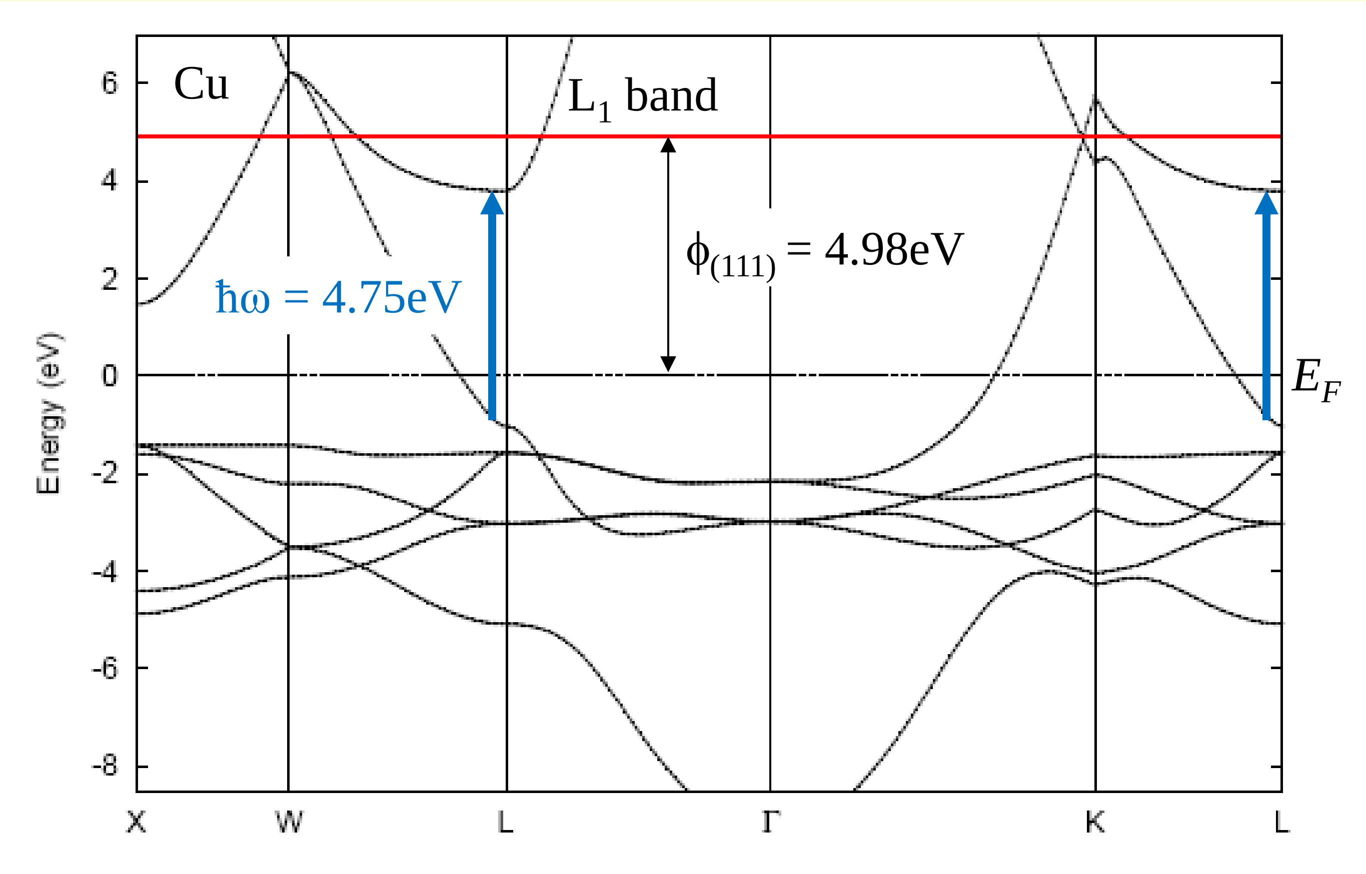
– Possible excited state emission process for Cu(111)



R. Courths et al., *J. Phys. F: Met. Phys.* **14**, 1559-1572 (1984)