TAUP XICHANG

TAUP 2025

19TH INTERNATIONAL CONFERENCE ON TOPICS IN ASTROPARTICLE AND UNDERGROUND PHYSICS

Electronic Recoils in Xenon Detectors Induced by Solar Neutrinos

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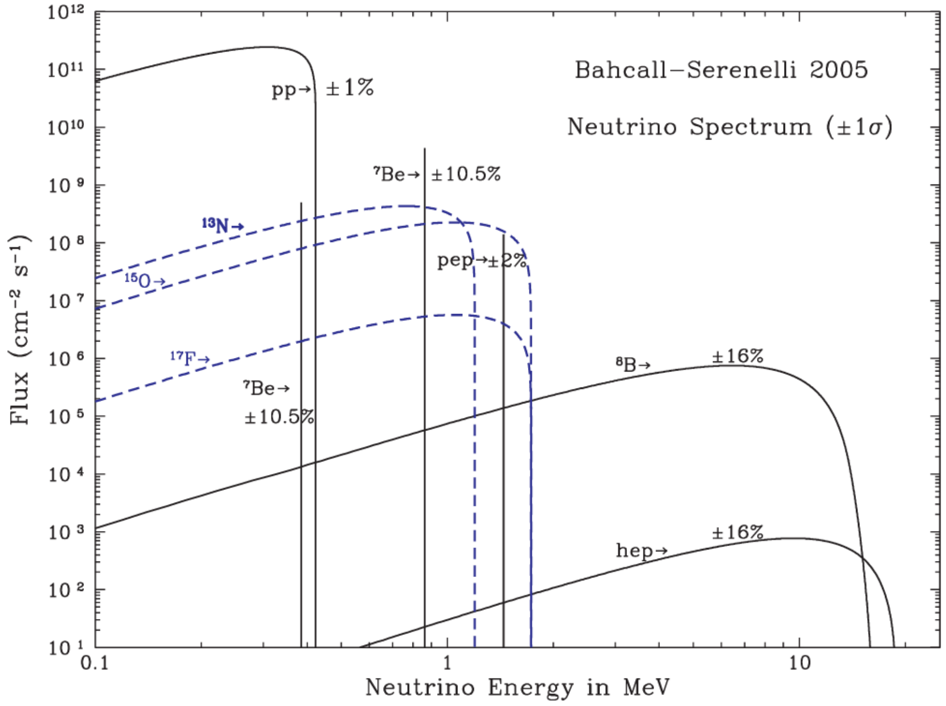
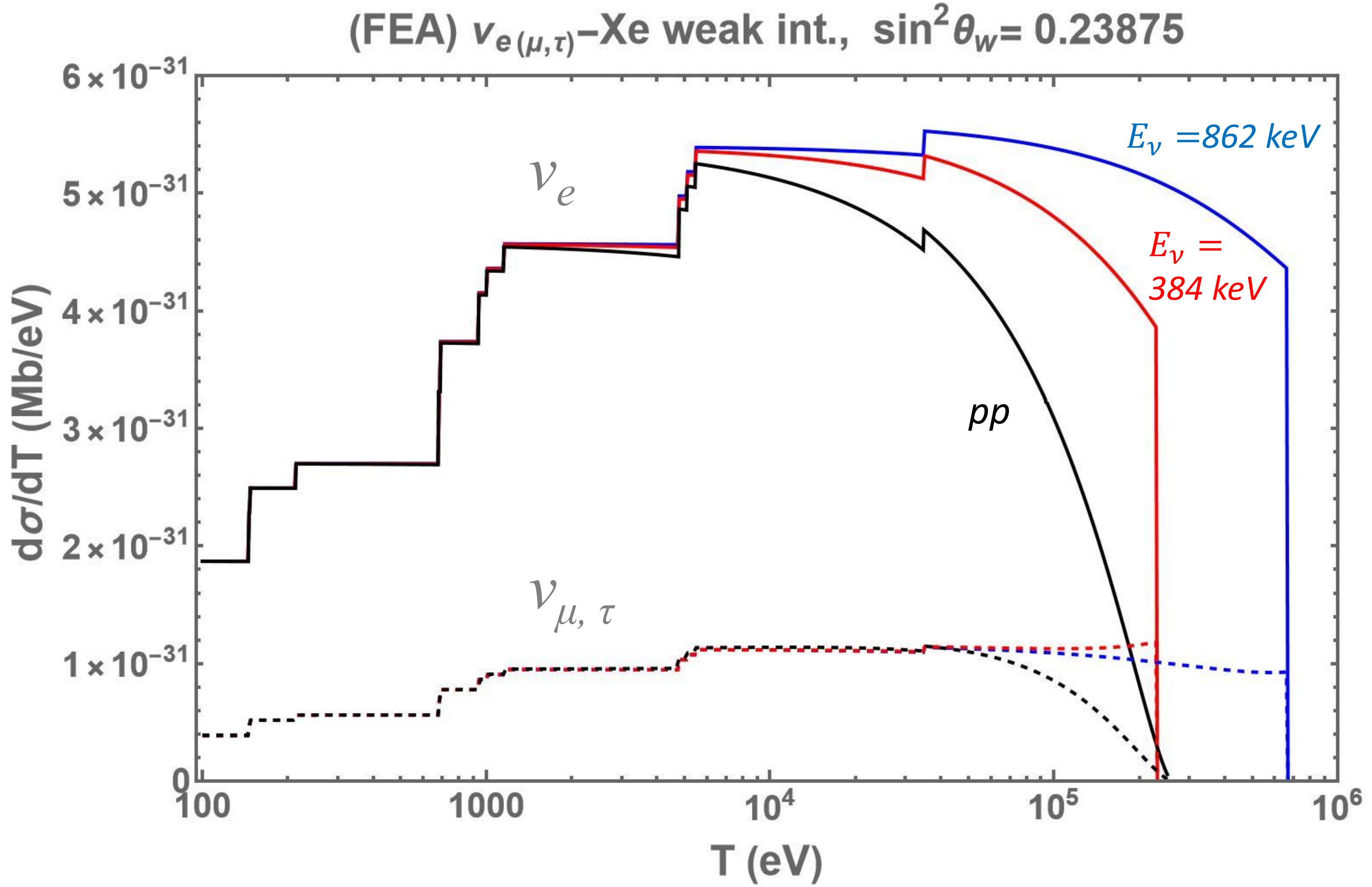
Solar *pp* neutrino & Xenon detector



- Solar pp neutrino
  - ~90% entire solar flux
  - Up to ~420 keV
- Xenon scintillator:
  - Low detector threshold
  - Backgrounds are well studied
  - keep accumulating exposure

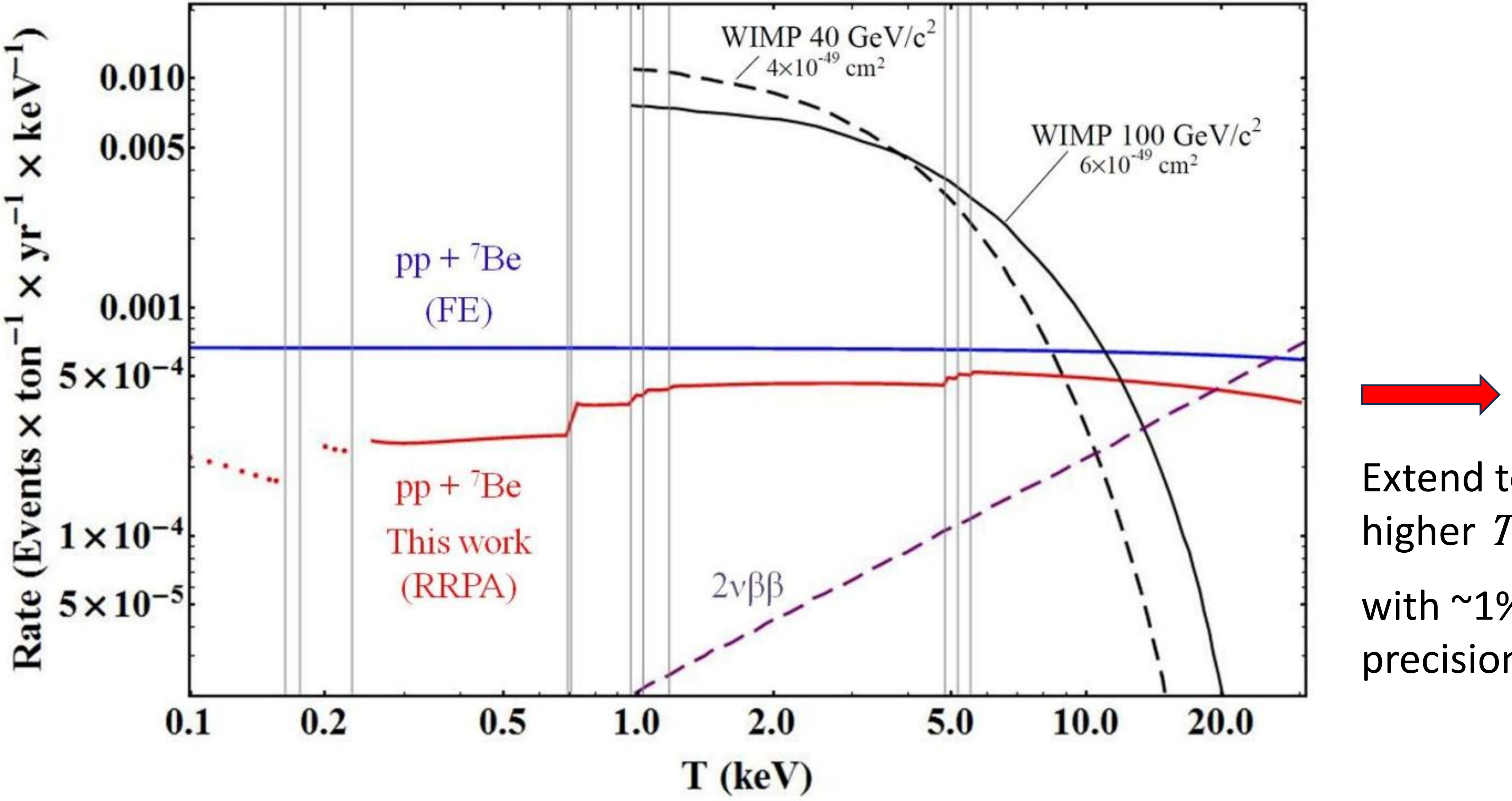
More detail from XENONnT:
Jingqiang Ye's talk on Aug. 26



$$\mathrm{T} \le \frac{2E_\nu^2}{2E_\nu + m_e}$$

$$\frac{d\sigma^{(w)}}{dT} = \frac{G_F^2\, m_e}{2\pi}\left[(g_V+g_A)^2 + (g_V-g_A)^2\left(1-\frac{T}{E_\nu}\right)^2 - (g_V^2-g_A^2)\frac{m_e T}{E_\nu^2}\right],$$

$$g_V = 2\sin^2\theta_w \pm \frac{1}{2}\,,$$
$$g_A = \pm\frac{1}{2}$$



Extend to higher T,

with ~1% precision

Jiunn-Wei Chen, Hsin-Chang Chi, C.-P. Liu, and Chih-Pan Wu, Phys. Lett. B **774** (2017) 656.

Atomic Response

$$\mathscr{R}_{O_J}(T,q) = \sum_{FJ_F} \overline{\sum_{IJ_I}} \left| \left\langle F, J_F \left\| \hat{O}_J(q) \right\| I, J_I \right\rangle \right|^2 \times \delta(E_{\mathscr{F}} - E_{\mathscr{I}} - T)$$

$$\hat{C}_J^{M_J}(q) = \sum_{i=1}^{Z} j_J(qr_i) Y_J^{M_J}(\Omega_{r_i}) \mathbb{1}_i^{\mathrm{D}} \,,$$

$$\hat{\Sigma}_J^{M_J}(q) = \sum_{i=1}^{Z} j_J(qr_i) \vec{Y}_{JJ}^{M_J}(\Omega_{r_i}) \cdot \vec{\sigma}_i^{\mathrm{D}} \,,$$

$$\hat{\Sigma}_J'^{M_J}(q) = \sum_{i=1}^{Z} \left\{ -\sqrt{\frac{J}{2J+1}} j_{J+1}(qr_i) \vec{Y}_{JJ+1}^{M_J}(\Omega_{r_i}) + \sqrt{\frac{J+1}{2J+1}} j_{J-1}(qr_i) \vec{Y}_{JJ-1}^{M_J}(\Omega_{r_i}) \right\} \cdot \vec{\sigma}_i^{\mathrm{D}} \,,$$

$$\hat{\Sigma}_J''^{M_J}(q) = \sum_{i=1}^{Z} \left\{ \sqrt{\frac{J+1}{2J+1}} j_{J+1}(qr_i) \vec{Y}_{JJ+1}^{M_J}(\Omega_{r_i}) + \sqrt{\frac{J}{2J+1}} j_{J-1}(qr_i) \vec{Y}_{JJ-1}^{M_J}(\Omega_{r_i}) \right\} \cdot \vec{\sigma}_i^{\mathrm{D}} \,,$$

Multipole Expansion

Vector:			
C_J	L_J	E_J	M_J
$\int d^3x\,[j_J(kr)Y_{JM}]\,\hat{\mathcal{J}}^0(\vec{x})$	$\frac{i}{\kappa}\int d^3x\,\vec{\nabla}[j_J(\kappa r)Y_{JM}(\Omega_x)]\cdot\hat{\vec{\mathcal{J}}}(\vec{x})$	$\frac{1}{\kappa}\int d^3x\,\vec{\nabla}\times[j_J(\kappa r)\mathcal{Y}^M_{JJ1}(\Omega_x)]\cdot\hat{\vec{\mathcal{J}}}(\vec{x})$	$\int d^3x\,[j_J(\kappa r)\mathcal{Y}^M_{JJ1}(\Omega_x)]\cdot\hat{\vec{\mathcal{J}}}(\vec{x})$
diagonal $l' + J + l = \text{even}$	Off diagonal $l' + J + l = \text{even}$	Off diagonal $l' + J + l = \text{even}$	Off diagonal $l' + J + l = \text{odd}$
Axial-Vector:			
C_J^5	L_J^5	E_J^5	M_J^5
Off diagonal $l' + J + l = \text{odd}$	diagonal $l' + J + l = \text{odd}$	diagonal $l' + J + l = \text{odd}$	diagonal $l' + J + l = \text{even}$

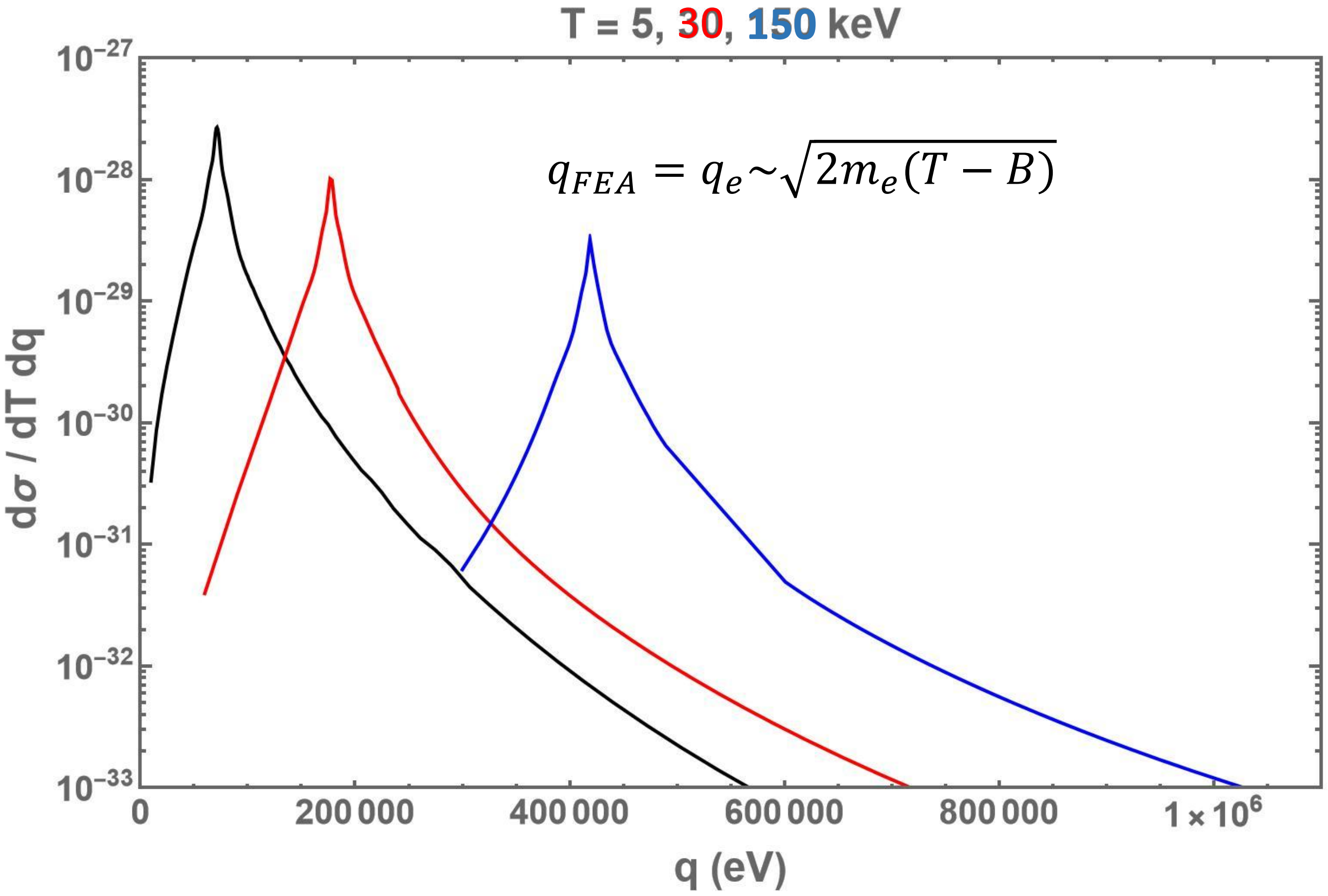
ν-Xe weak scattering cross section

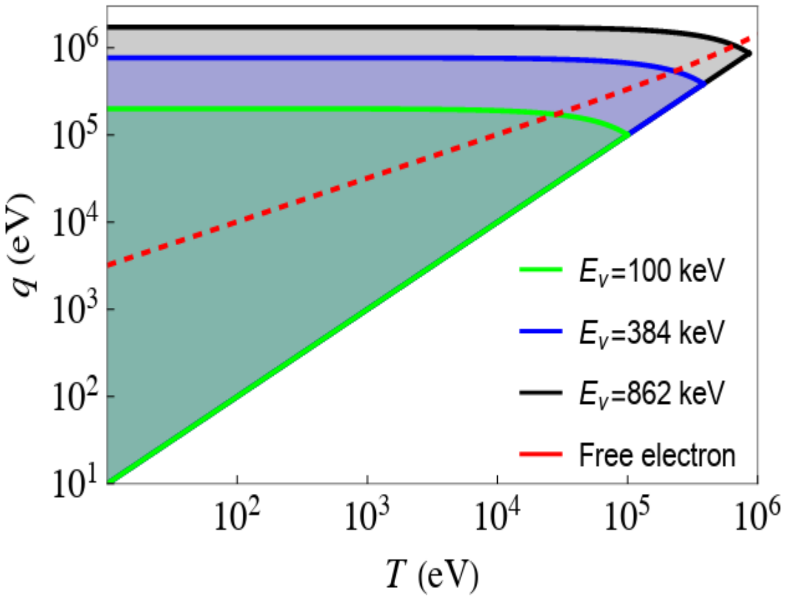
Transition Amplitude of C_J-multipole:

$$\langle j' | \hat{C}_J | j \rangle = \frac{(-1)^{j'+1/2}}{\sqrt{4\pi}} [j'][j][J] \begin{pmatrix} j' & J & j \\ 1/2 & 0 & -1/2 \end{pmatrix} \int dr\, j_J(qr)\, [G'G + F'F]$$

$$\begin{aligned}
\frac{d\sigma^{(i)}}{dT} =& \frac{G_F^2}{\pi}(E_\nu - T)^2 \int d\cos\theta \, \frac{4\pi}{2J_i+1} \sum_F \\
& \Bigg\{ \left(\cos^2\frac{\theta}{2}\right) \left[c_{i,V}^2 \frac{Q^4}{q^4} |\langle J_F \| C_J \| J_I \rangle|^2 + c_{i,A}^2 \left(|\langle J_F \| C_J^5 \| J_I \rangle|^2 + \frac{T^2}{q^2} |\langle J_F \| L_J^5 \| J_I \rangle|^2 - 2\frac{T}{q} \mathrm{Re}\left[\langle J_F \| C_J^5 \| J_I \rangle \langle J_F \| L_J^5 \| J_I \rangle^* \right] \right) \right] \\
& + \left(\sin^2\frac{\theta}{2} - \frac{Q^2}{2q^2|} \cos^2\frac{\theta}{2} \right) \left[c_{i,V}^2 \left(|\langle J_F \| E_J \| J_I \rangle|^2 + |\langle J_F \| M_J \| J_I \rangle|^2 \right) + c_{i,A}^2 \left(|\langle J_F \| E_J^5 \| J_I \rangle|^2 + |\langle J_F \| M_J^5 \| J_I \rangle|^2 \right) \right] \\
& - \left(\sin\frac{\theta}{2} \right) \sqrt{\sin^2\frac{\theta}{2} - \frac{q^2}{|\vec{q}|^2} \cos^2\frac{\theta}{2}} \left[2c_{i,V} c_{i,A} \mathrm{Re}\left[\langle J_F \| M_J \| J_I \rangle \langle J_F \| E_J^5 \| J_I \rangle^* + \langle J_F \| M_J^5 \| J_I \rangle \langle J_F \| E_J \| J_I \rangle^* \right] \right] \Bigg\}
\end{aligned}$$

Double differential cross section v.s. q





Relativistic Random Phase Approximation (RRPA)

Advantage:

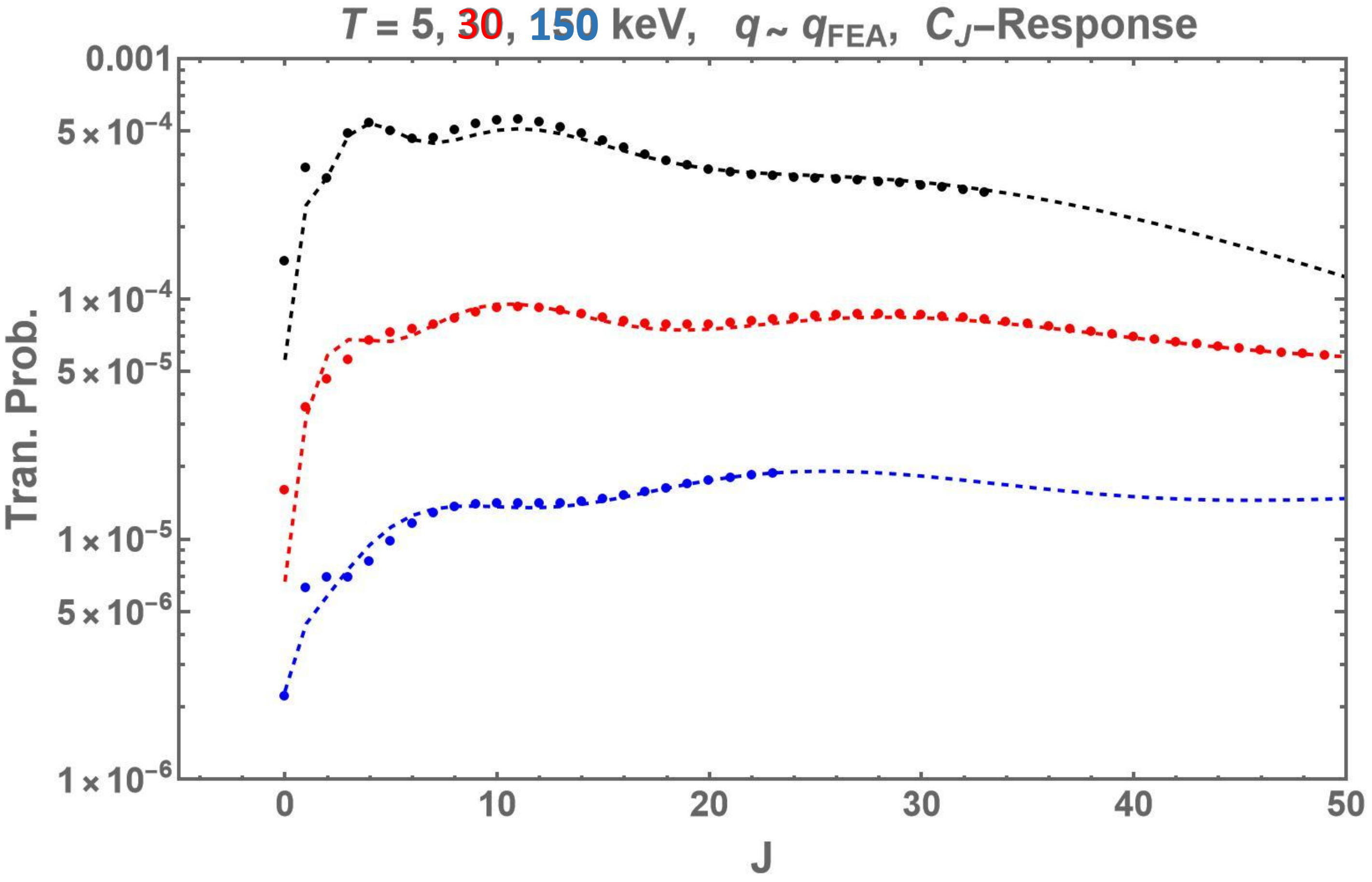
- Self-consistent many-body approach
- benchmarked by photoabsorption data
- orthogonality of the orbitals wave function with good quantum numbers

Challenge:

- Iterations take a lot of time
- When energy transfer T increases:
  - Multipole convergence is very slow at specific $q \sim q_{FEA} = \sqrt{2m_e T}$
  - Numerical simulation needs more precision

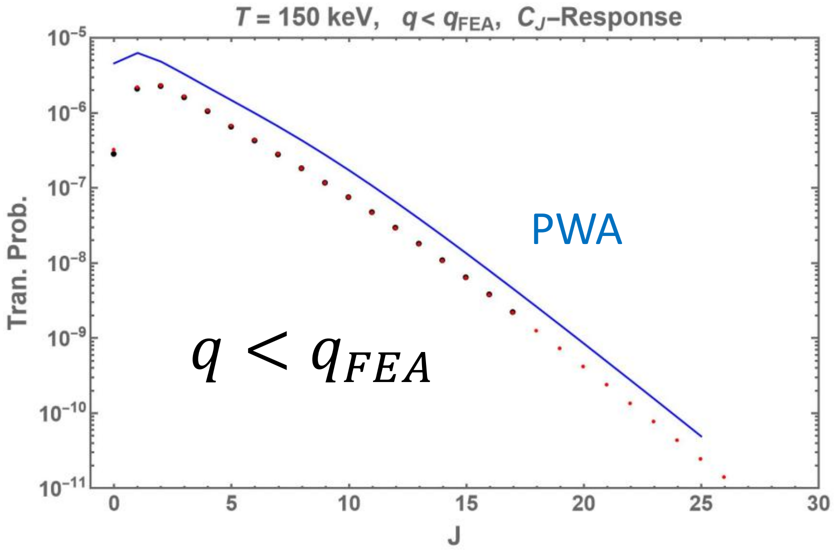
More detail:
Cheng-Pang Liu's talk on Aug. 25

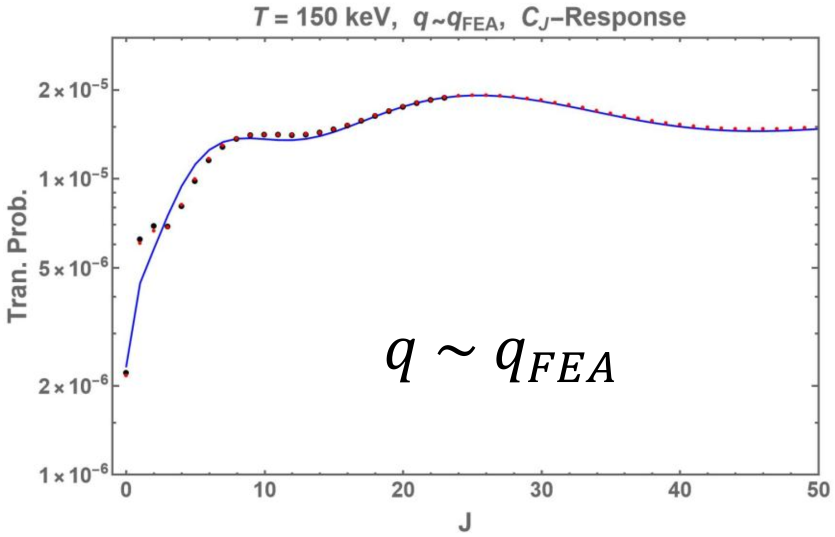
Convergence problem of J

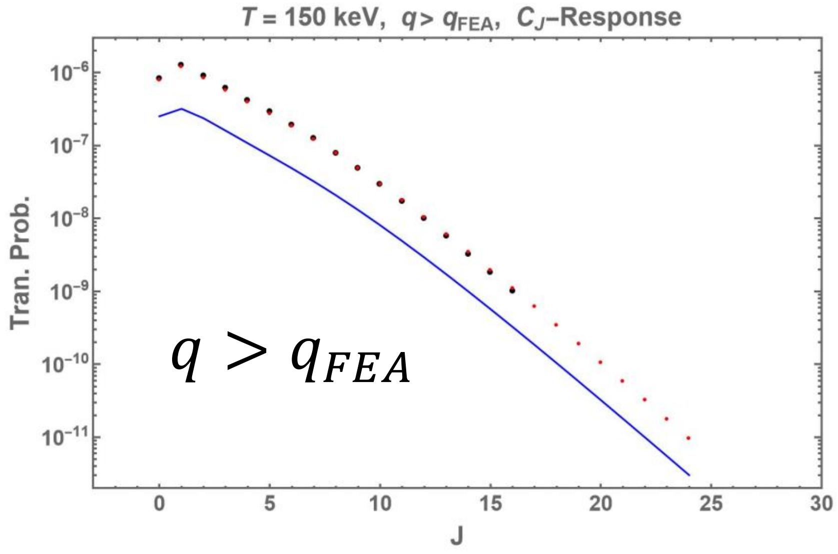


Plane-wave & partial wave analysis

Replace ionized (final) electron WF by $e^{i\mathbf{k}\cdot\mathbf{r}} = 4\pi \sum_{\ell=0}^{\infty} \sum_{m=-\ell}^{\ell} i^{\ell} j_{\ell}(kr) Y_{\ell}^{m}(\hat{\mathbf{k}}) Y_{\ell}^{m*}(\hat{\mathbf{r}})$



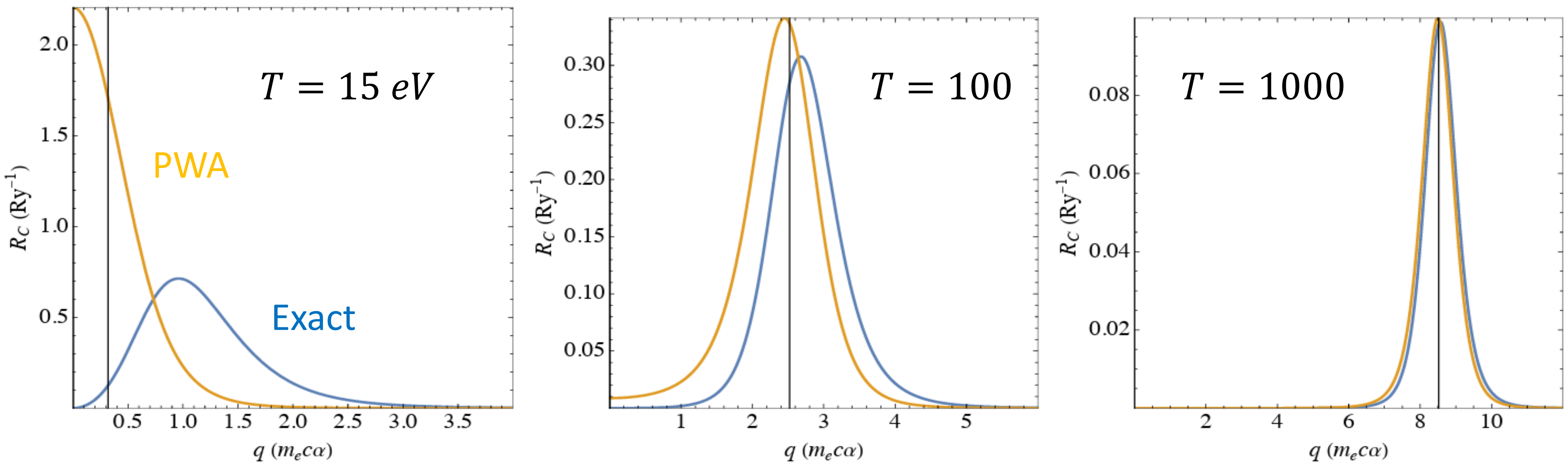




Hydrogen analysis (Exact WF)

$$\tilde{R}_C = \int \frac{d^3p_r}{(2\pi)^3} |{}^{(-)}\langle \vec{p}_r|e^{i\vec{q}\cdot\vec{r}}|1s\rangle|^2 \delta\left(T - B_{1s} - \sqrt{m_e^2+p_r^2} + m_e\right)$$
$$= \frac{2^8 Z^6 \sqrt{1+\frac{p_r^2}{m_e^2}}\,\bar{q}^2(3\bar{q}^2+\bar{p}_r^2+Z^2)\,\exp\left[-2\eta\tan^{-1}\left(\frac{2Z\bar{p}_r}{\bar{q}^2-\bar{p}_r^2+Z^2}\right)\right]}{3m_e\alpha^2((\bar{q}+\bar{p}_r)^2+Z^2)^3((\bar{q}-\bar{p}_r)^2+Z^2)^3\,(1-e^{-2\pi\eta})},$$

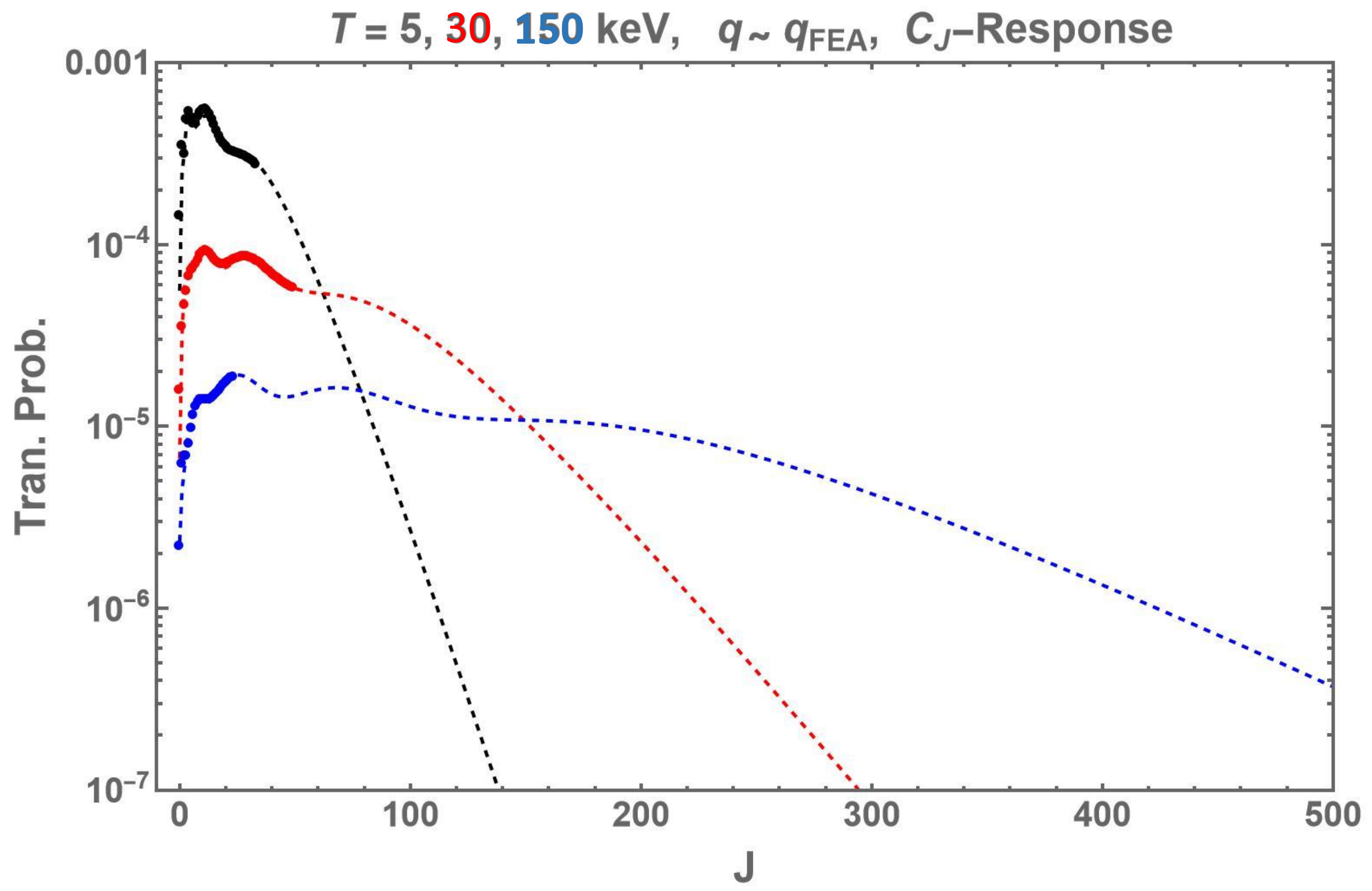
$$\tilde{R}_C^{(\mathrm{PWA})} = \int \frac{d^3p_r}{(2\pi)^3} |\langle \vec{p}_r|e^{i\vec{q}\cdot\vec{r}}|1s\rangle|^2 \delta\left(T - B_{1s} - \sqrt{m_e^2+p_r^2} + m_e\right)$$
$$= \frac{8Z^5\sqrt{1+\frac{p_r^2}{m_e^2}}}{3\pi m_e\alpha^2\bar{q}}\left(\frac{1}{((\bar{q}-\bar{p}_r)^2+Z^2)^3} - \frac{1}{((\bar{q}+\bar{p}_r)^2+Z^2)^3}\right)$$



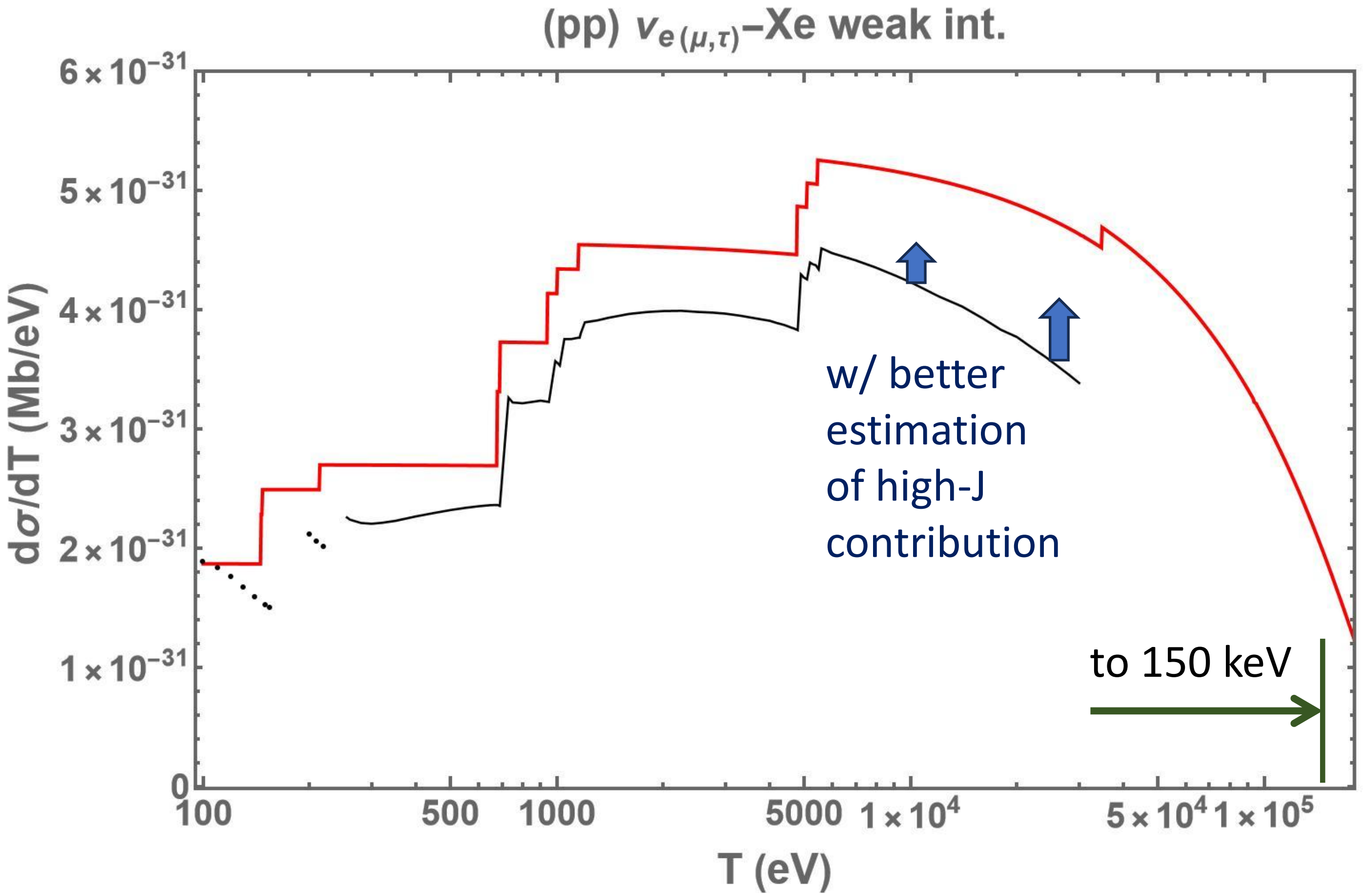
$$R_C^{(\mathrm{FEA})} = \delta(T - B_{1s} - \sqrt{m_e^2+q^2} + m_e)$$

For $B_{1s} < T < T_{Max}^{(FEA)}$, $\int_0^\infty dq\, q\, R_C^{(\mathrm{FEA})} = \int_0^\infty dq\, q\, \tilde{R}_C^{(\mathrm{PWA})} = \sqrt{m_e^2+p_r^2}$

Convergence of higher *J*



Projected Result



Thanks for your attention!

& Stay tuned!!