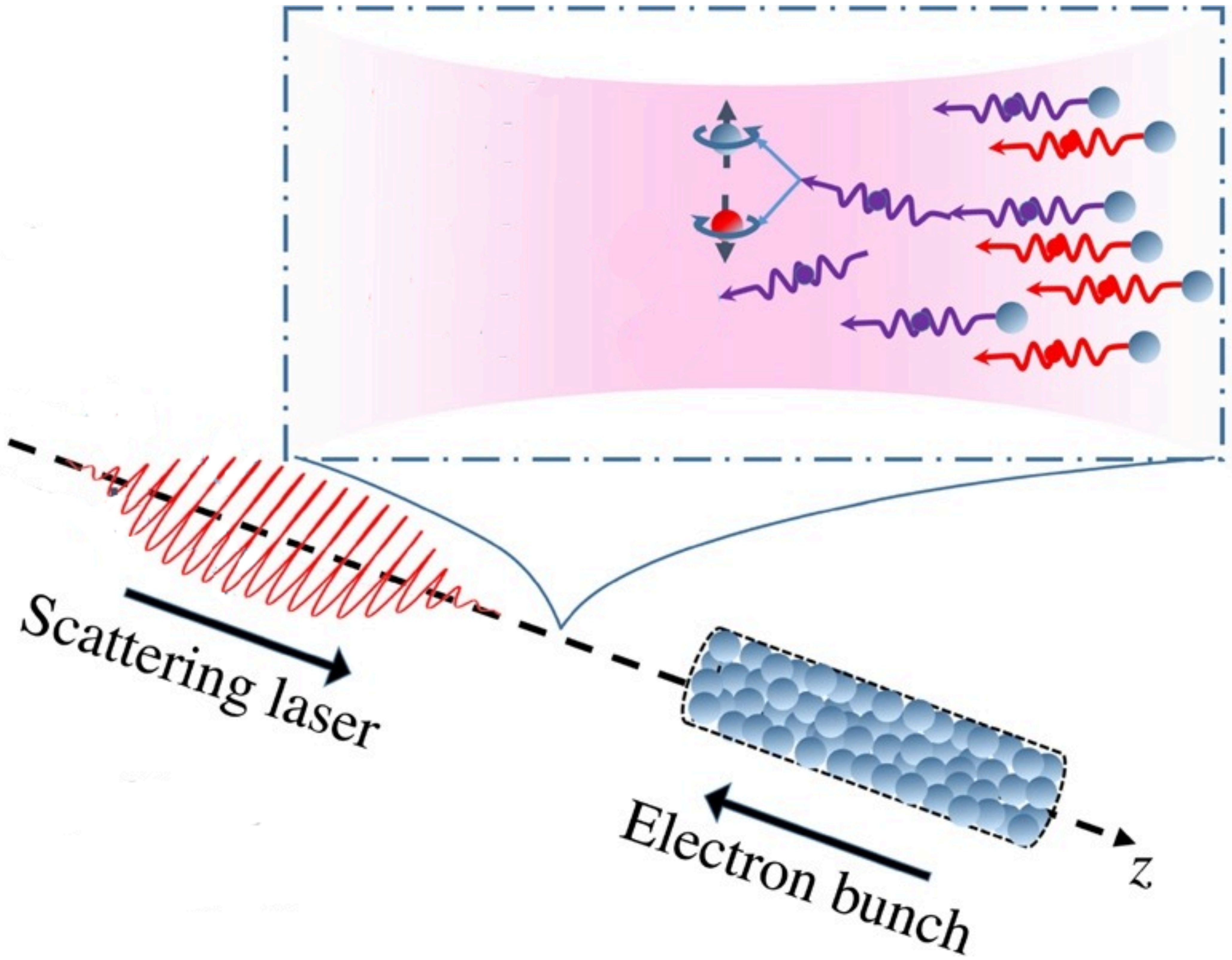
Luminosity for laser-electron colliders

Why and how we should adapt the concept of ‘luminosity’ from the particle colliders

Ou Labun, University of Texas at Austin, July 25, 2024, arXiv:2307.10453

Scope of this work

- **Strong field QED processes**: how electrons interact with coherent intensive electromagnetic field
- **Inverse Compton scattering process**: to produce high energy photons with narrow energy spread, other radiation sources, or to search beyond standard model physics,
  B. Zhao, Phy. Rev. D 106, 115034(2022)



The Question

High magnitude and reliability signal are required to measure and to quantitatively verify the theory of strong field radiation processes.

Does the highest intensity—generally achieved by the shortest possible laser pulse and strongest possible focusing—always lead to larger or more reliable signal?

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M. Lobet, X. Davoine, E. dHumières, and L. Gremillet, Generation of high-energy electron-positron pairs in the collision of a laser-accelerated electron beam with a multipetawatt laser, Physical Review Accelerators and Beams **20**, 043401 (2017).

Previous work

Much previous work has pointed out how various features of the laser fields or electron bunch are imprinted on observables such as the energy or angular distribution of radiation or scattered electrons.

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Sample of current Laser facilities with design parameters

Facility	E_l[J]	$\Delta\tau$[fs]	$P_{\rm peak}$ [PW]	$w_0[\mu$m]	$\lambda_l[\mu$m]	$I_{\rm peak}$[W/cm^2]	$a_{\rm peak}$	ϵ_w	ϵ_t	Rep.[Hz]
TPW f/1	150	150	1	1.25	1.054	2.76×10^{22}	142.5	0.127	0.022	10^{-4}
ELI-NP	244	22.5	10.8	2	0.8	1.17×10^{23}	234.6	0.064	0.119	0.02
Arcturus	7	30	0.23	1.1	0.8	8.26×10^{21}	62.34	0.115	0.089	5
ELI-L3 [a]	30	28	1.1	1.9	1.054	1.28×10^{22}	102.38	0.088	0.126	10
CoReLS [b]	50	30	1.67	1.8	0.8	2.22×10^{22}	127.7	0.088	0.111	0.1
OPAL	600	20	30	1.25	0.9	8.28×10^{23}	702.4	0.0839	0.156	10^{-4}

Proper metrics to guide facility/experiment design with all the laser performance parameters?

More carefully defining χ

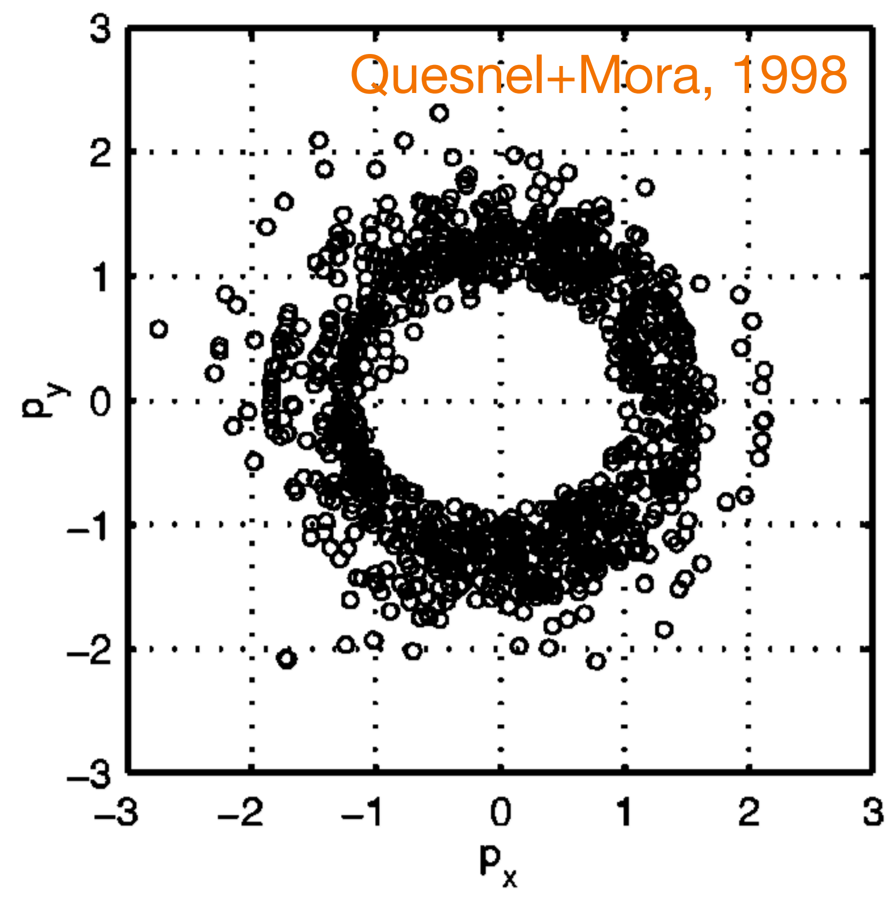
Rate of photon emission increases with χ , therefore the facility should maximize the χ *achieved*.

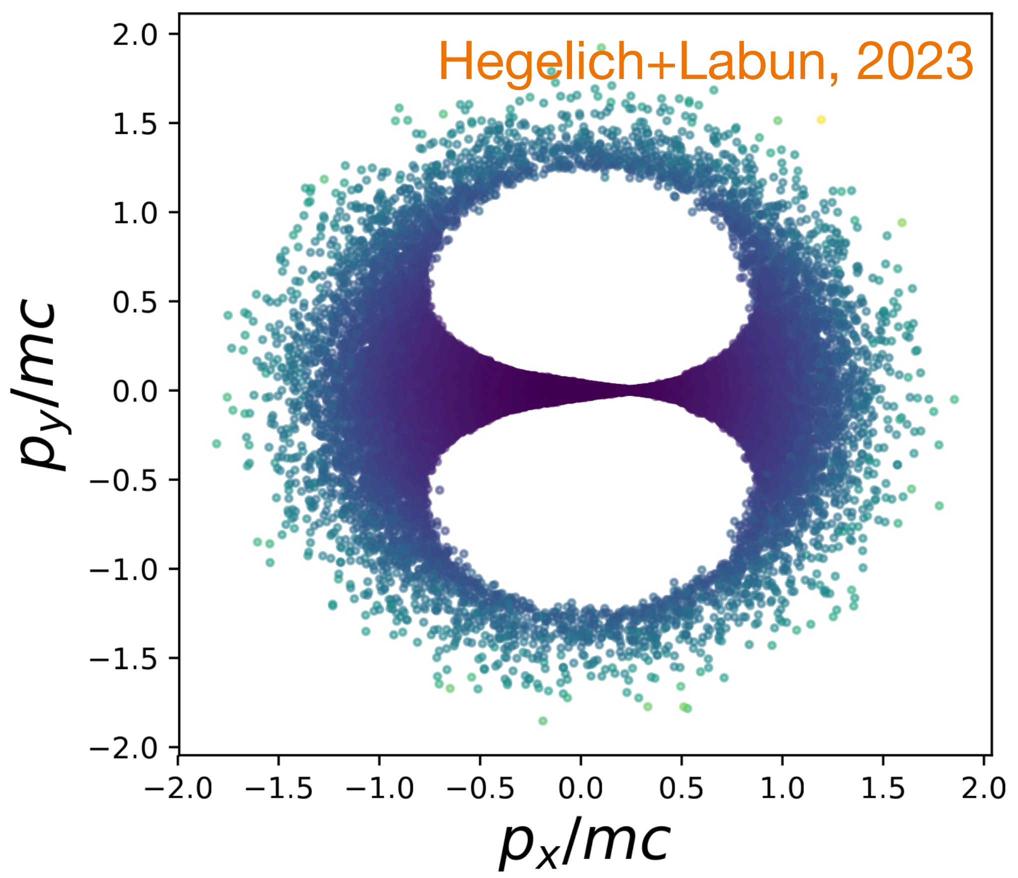
- Conventional definition of χ: obtained by combining the nominal electron energy with the peak electric field

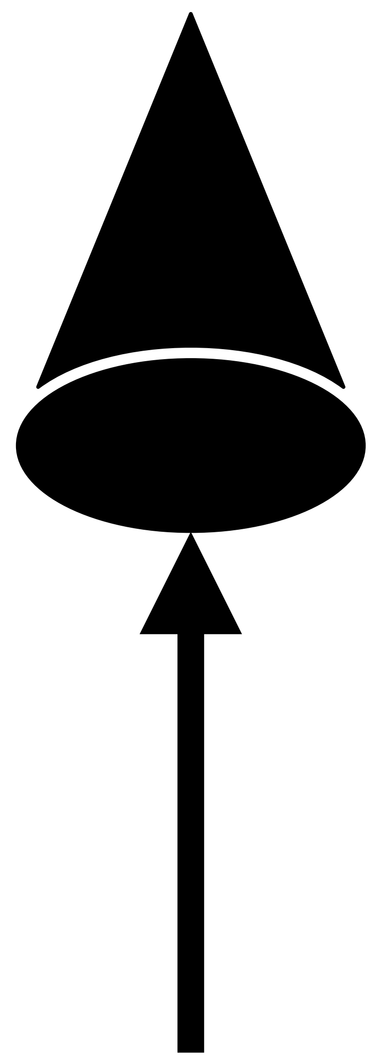
$$\chi_b \equiv \frac{\hbar}{c^4} \frac{|p_\mu^{(0)} e F^{\mu\nu}_{\mathrm{peak}}|}{m_e^3} \simeq \frac{2E_e}{m_e} |e\vec{E}_{\mathrm{peak}}| m_e^2 = \frac{2E_e}{m_e} \sqrt{\frac{I_{\mathrm{peak}}}{I_c}}$$

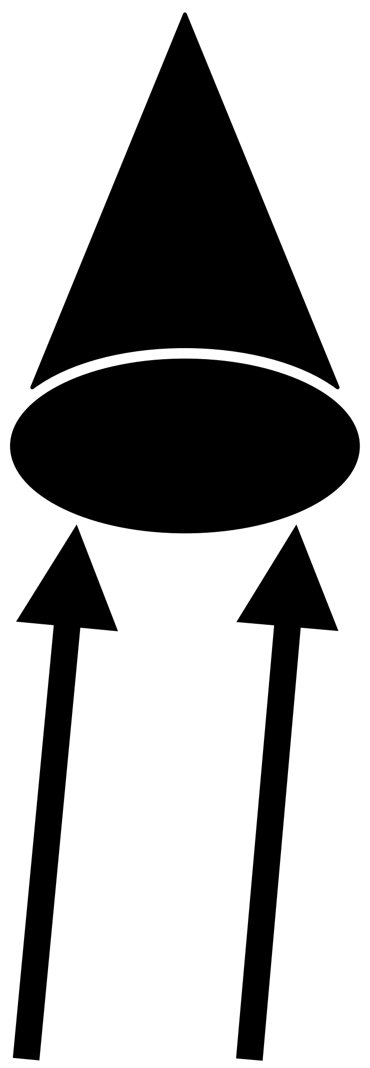
- Local definition of χ: varies with time and space for each electron, characterize the entire collision dynamics, similar to the center of mass energy in particle physics

$$\chi_{\mathrm{max}} \equiv \max_\tau \chi\left(x^\mu(\tau)\right)$$









Introducing Electron-Laser Luminosity

The analog of luminosity to quantify and optimize the efficiency as well as estimate the facility requirements

- Particle colliders:

$$\frac{dN}{dt} = \int d^3x d^3p_1 d^3p_2 f_1(\vec{x}, \vec{p}_1, t) f_2(\vec{x}, \vec{p}_2, t) v_{12} \sigma($$

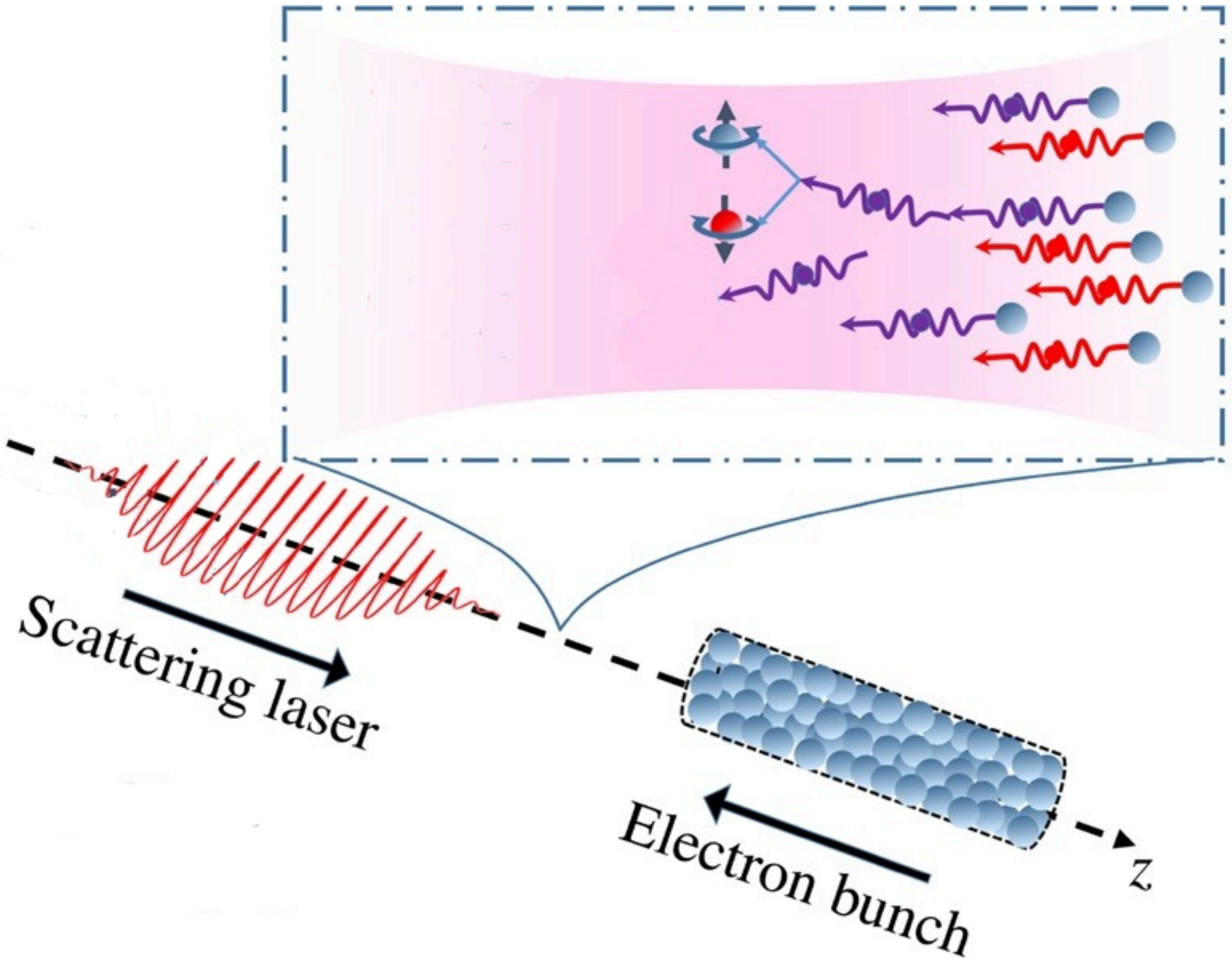
$$\frac{dN}{dt} = \sigma(E_{cm}) v_{12} \int d^3x n_1(\vec{x}, t) n_2(\vec{x}, t) \equiv \sigma L.$$

(monoenergetic beams)

- Electron-laser colliders:

$$P[e \to X] = \int \frac{d^3p d^3x}{(2\pi)^3} f_e(\vec{x}, \vec{p}, t) \Gamma(E_e, \chi(\vec{x}, \vec{p})) dt$$

$$L_{e\ell} = \frac{1}{\Gamma_b} \frac{dN}{dt} = \frac{1}{\Gamma_b} \nu_c P[e \to X]$$

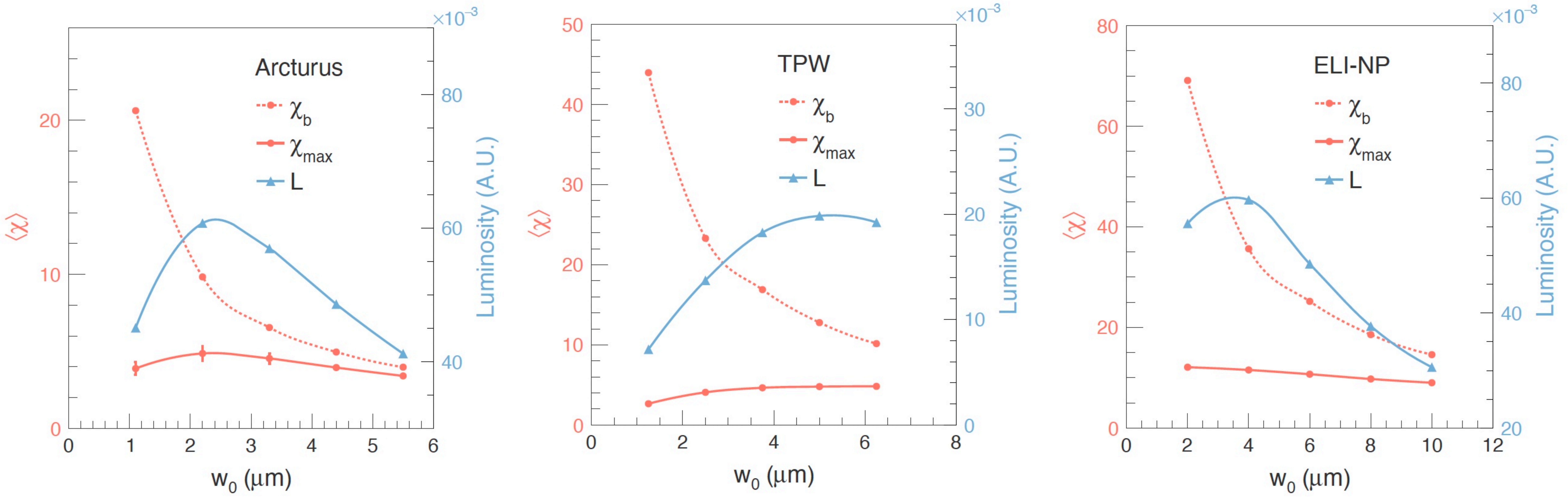


$\Gamma_b \equiv \Gamma(E_e^{(0)}, \chi_b)$ is the event rate evaluated at nominal beam collision parameters

ν_c is the frequency of beam crossing

Focal spot, χ, and luminosity

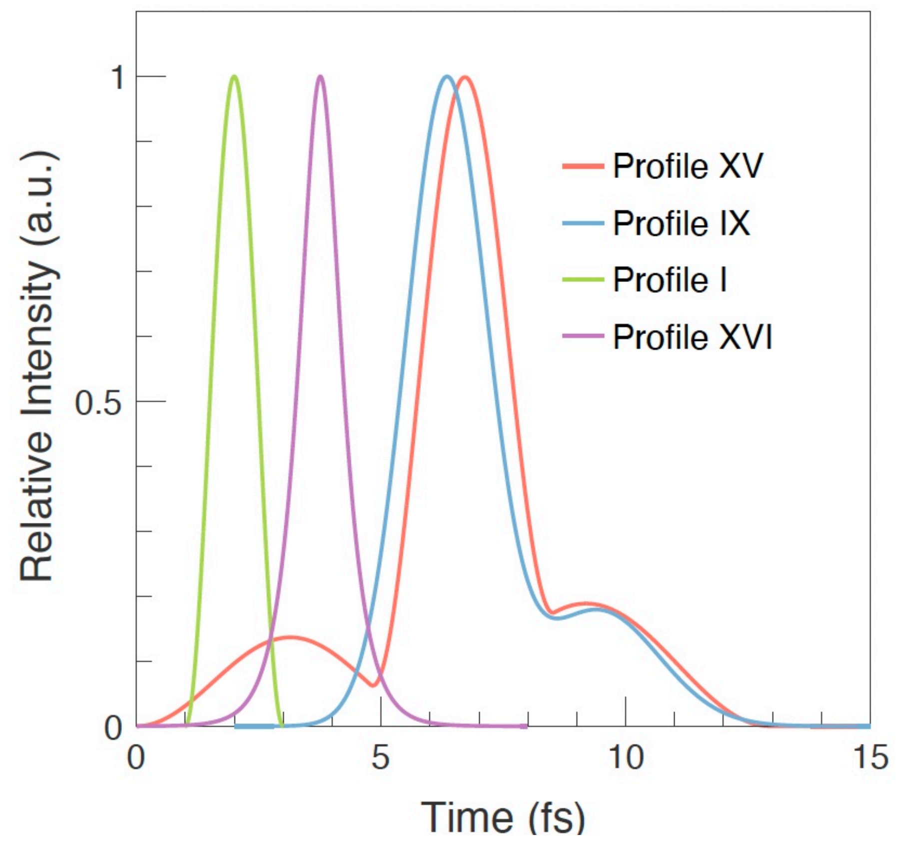
Smaller spot size increases field strength but decreases cross sectional area that overlapping with electron beam



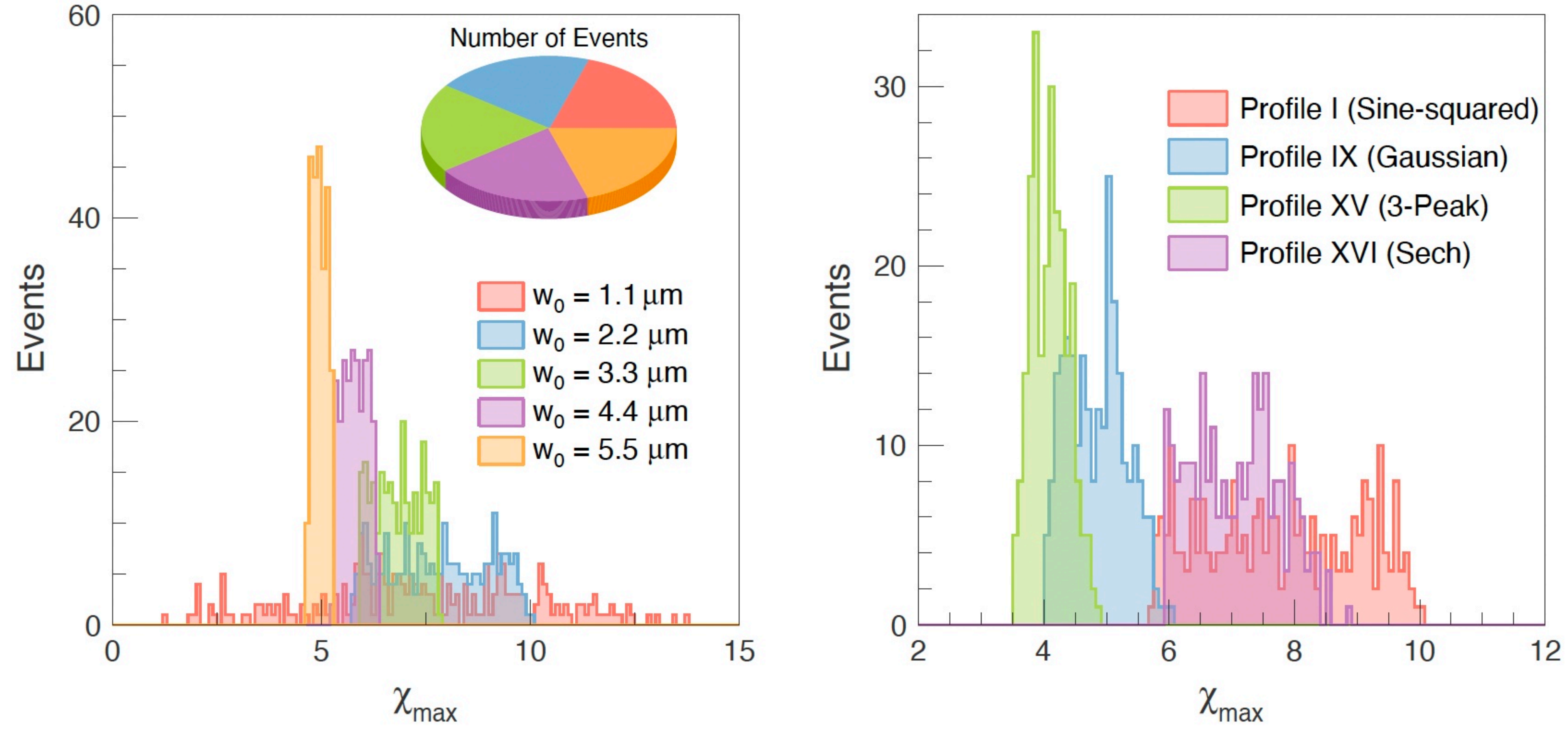
400 MeV 2 micron radius electron beam

Temporal profile, χ, focal spot, and luminosity

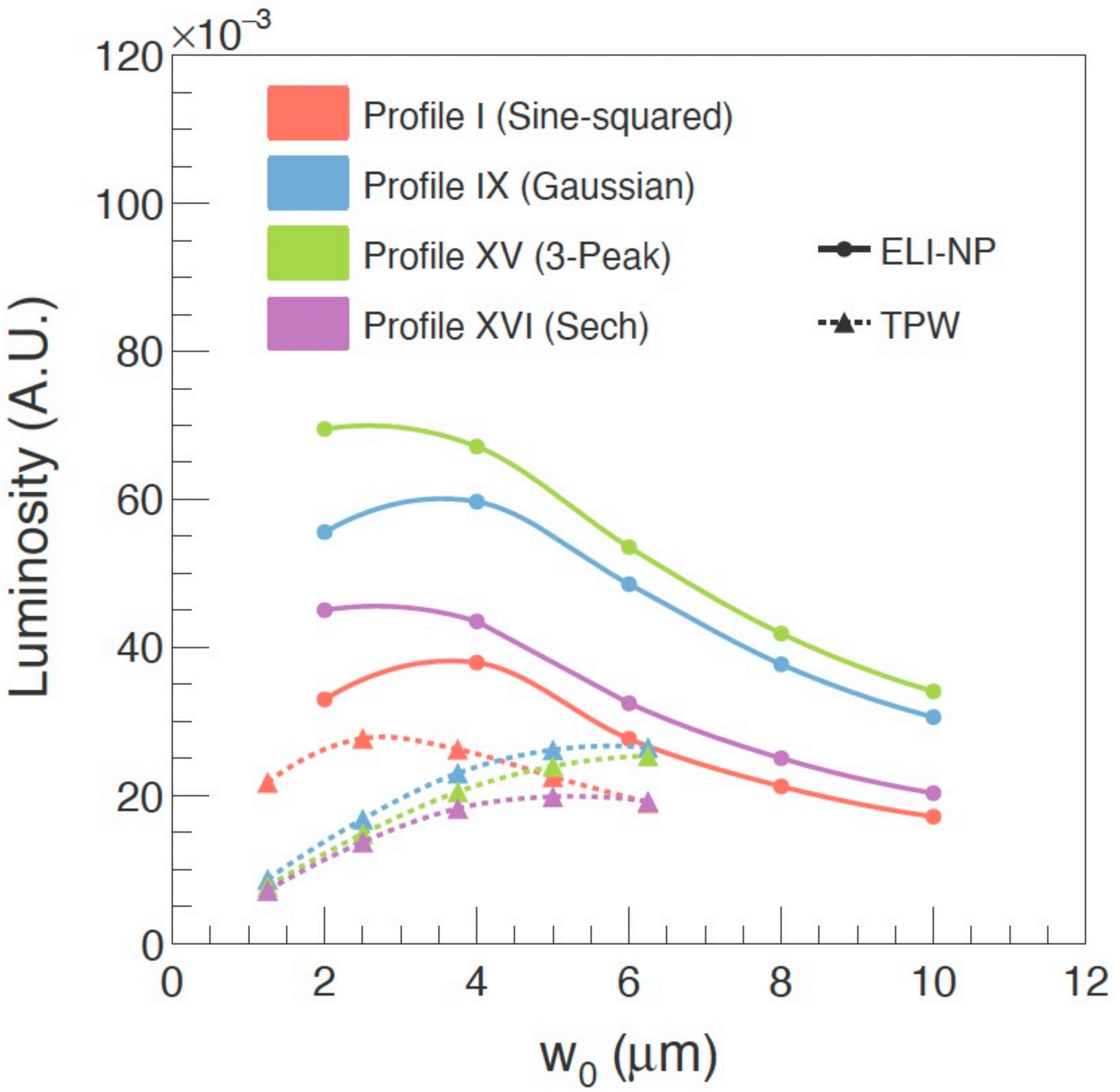
Recognized approach to modulating photon emission in SFQED, yet the impact is never systemically investigated



I: Sin^2; II: Gaussian; III:Hyperbolic Secant; IV: with repulse consisting of 15% secondary maximum and 1.5 pulse duration ahead



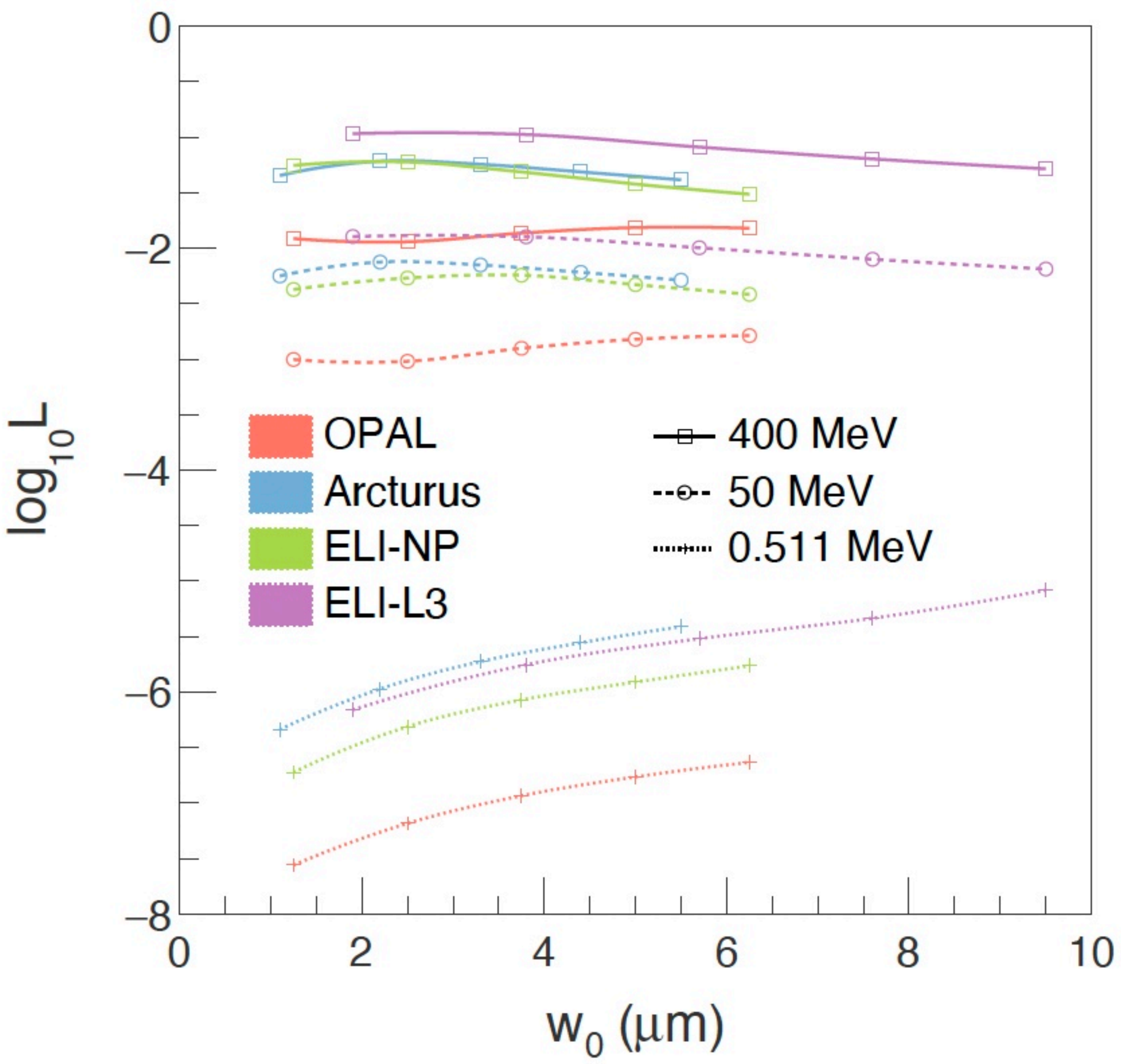
Fixed Sin^2 profile v.s. fixed 2.2 micro focal spot



Trading intensity for repetition rate

A lower-intensity laser operating at higher repetition rate can produce an equal or greater number of events than a higher-intensity laser at lower repetition rate.

Luminosity enables direct comparison.



Generalizing to radiation efficiency

How the particle dynamics as determined by choices on the laser design side affect the number of observed events

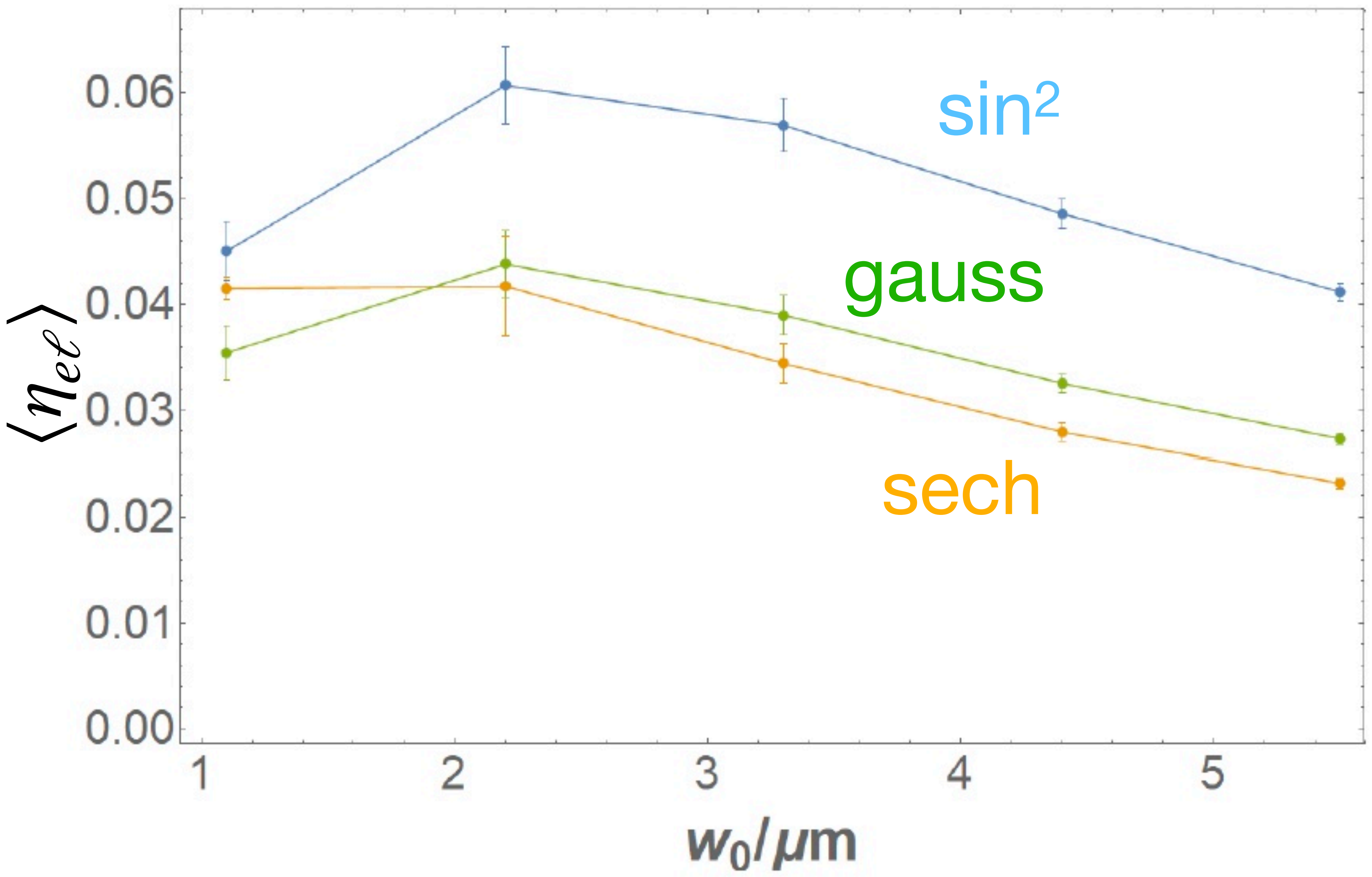
For some applications, we may want greater control and more uniformity in the electron response.

Per-particle luminosity:

$$L_{e\ell} \equiv N_e \langle \eta_{e\ell} \rangle,$$

Measure efficiency of the laser pulse in causing the particle to emit a photon:

$$\eta_{e\ell} = \frac{1}{\Gamma_b} \nu_c \int \Gamma(E_e, \chi(\vec{x}, \vec{p})) dt,$$



Comparison of radiation efficiency and its width for the 200-TW Arcturus laser for different temporal profile functions. Error bars show variance over bunch.

Take-away: there exists a nontrivial optimum in the trade-off between beam-overlap, ponderomotive dynamics and peak intensity.

To find this optimum, we need an appropriate metric: the analog of luminosity

Definitions here generalize to intense beam-beam collisions where sfQED effects start to become relevant