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Current experimental efforts in laser-driven strong-field QED

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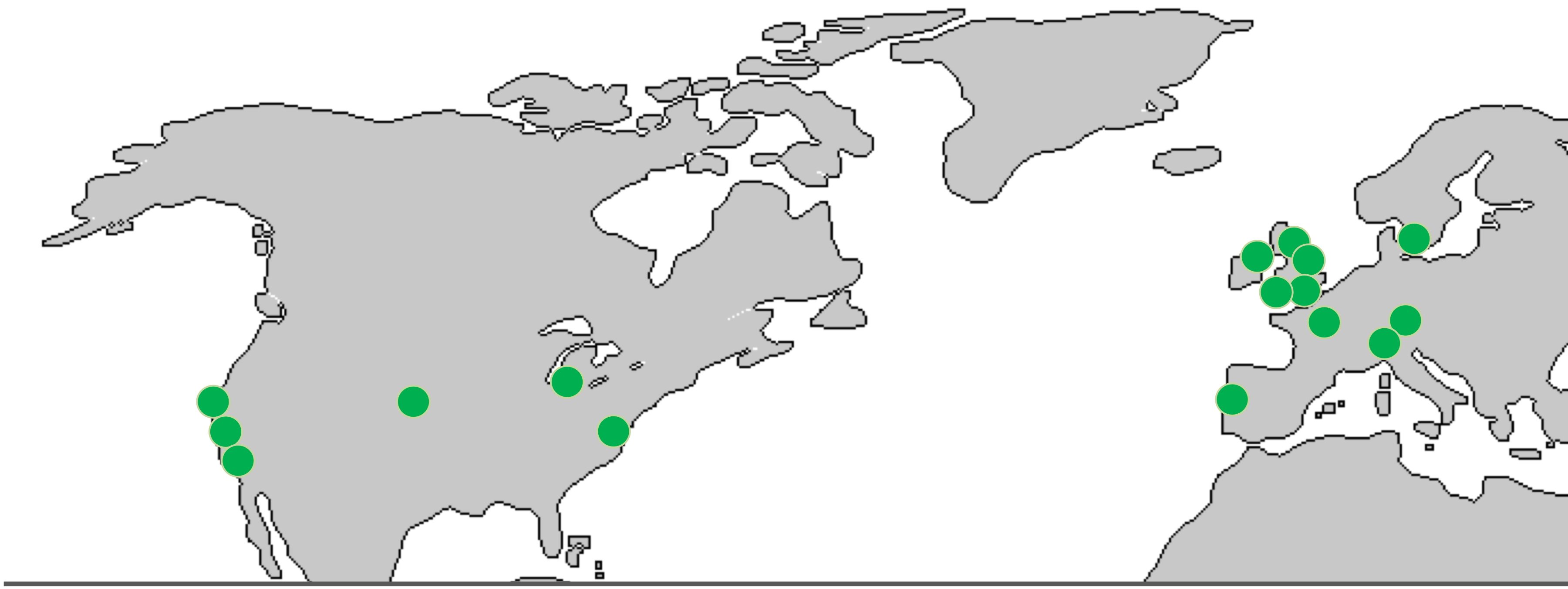
Main Collaborators



UCLA

SLAC

PULSE

UNIVERSITY OF MICHIGAN

central laser facility

UNIVERSITY of York

Imperial College London

l'X ÉCOLE POLYTECHNIQUE UNIVERSITÉ PARIS-SACLAY

HI Jena

Helmholtz Institute Jena

Introduction

Radiation Reaction

⇒ Radiation Reaction is one of the oldest and most fundamental problems in electromagnetism: How do we correctly model the electron dynamics if we include radiative losses?

0. Classical Lorentz force

$$m\frac{du^u}{ds} = eF^{uv}u_v$$

✗ No energy loss

1. LAD Equation

Schott's term

$$m\frac{du^u}{ds} = eF^{uv}u_v + \frac{2}{3}e^2\left(\frac{d^2u^u}{ds^2} + \frac{du^v}{ds}\frac{du^v}{ds}u^u\right)$$

✓ Damping force (radiation reaction term)

✗ Classical renormalisation (point-like electron)

✗ Runaway solutions! (diverging acceleration even without external field)

2. LL Equation

$$m\frac{du^u}{ds} = eF^{uv}u_v + \frac{2}{3}e^2\left(\frac{e}{m}(\partial_\alpha F^{uv})u^\alpha u_v - \frac{e^2}{m^2}F^{uv}F_{\alpha v}u^\alpha + \frac{e^2}{m^2}(F^{\alpha v}u_v)(F_{\alpha\lambda}u^\lambda)u^u\right)$$

✓ No runaway solutions

✓ Valid in classical relativity

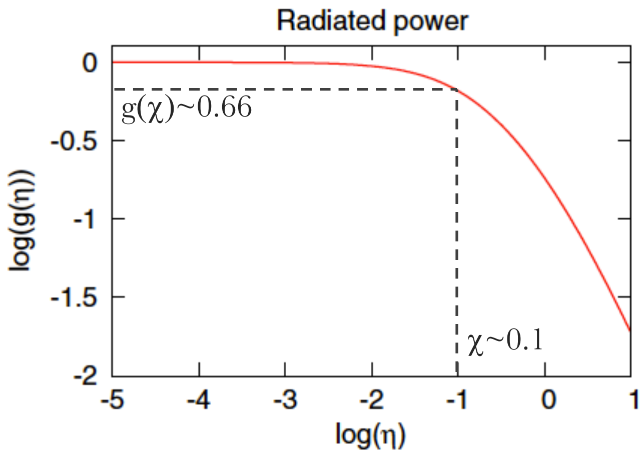
$\lambda >> \alpha\lambda_C$ (localised wavefunction)

$F << F_{cr}/\alpha$ (classical critical field)

Quantum Radiation Reaction

⇒ The classical treatment of radiation reaction neglects three main additional phenomena:

1. The energy of a single emitted photon can not exceed that of the electron



Generally speaking, this leads to a classical overestimate of the total energy loss experienced by the electron $(\chi = \gamma F_L / F_S)$

$$g(\chi) \sim \left(3.7\chi^3 + 31\chi^2 + 12\chi + 1\right)^{-4/9}$$

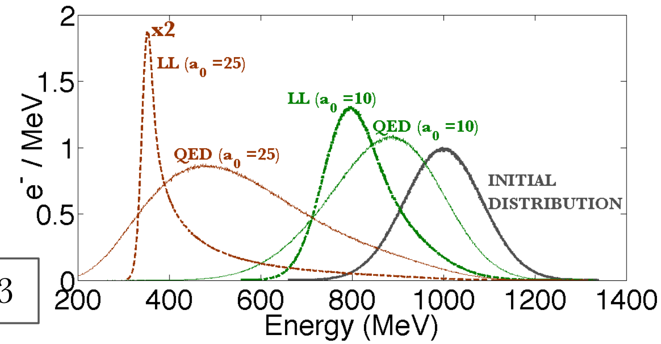
J. G. Kirk et al., PPCF 2013 | A. G. R. Thomas et al., PRX 2012

2. Photon emission is probabilistic

2.a $a_0 >> 1$

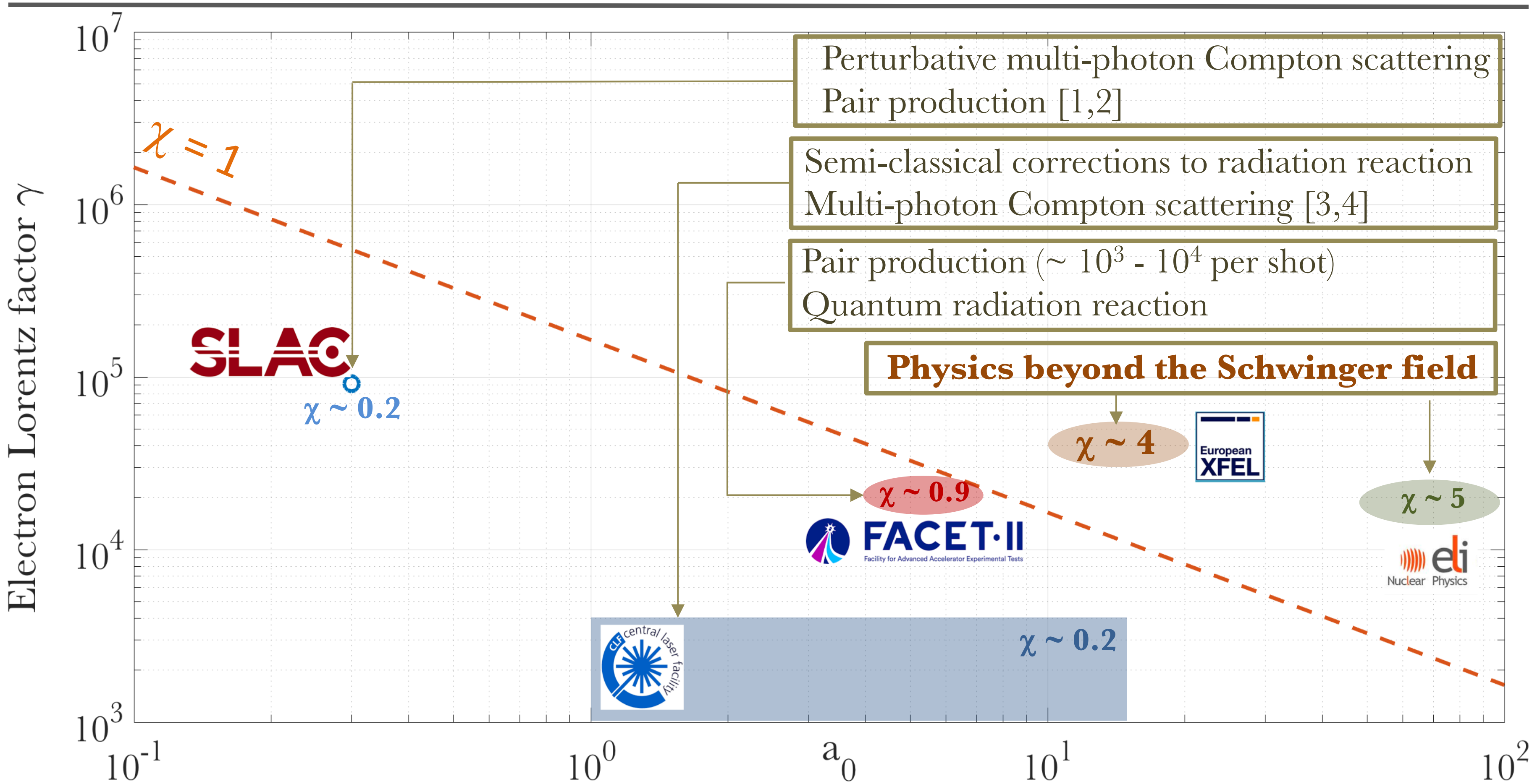
2.b constant cross-field approximation (instantaneous photon emission))

V. I. Ritus, J. Sov. Laser Res. 1985 | N. Neitz and A. Di Piazza, PRL 2013



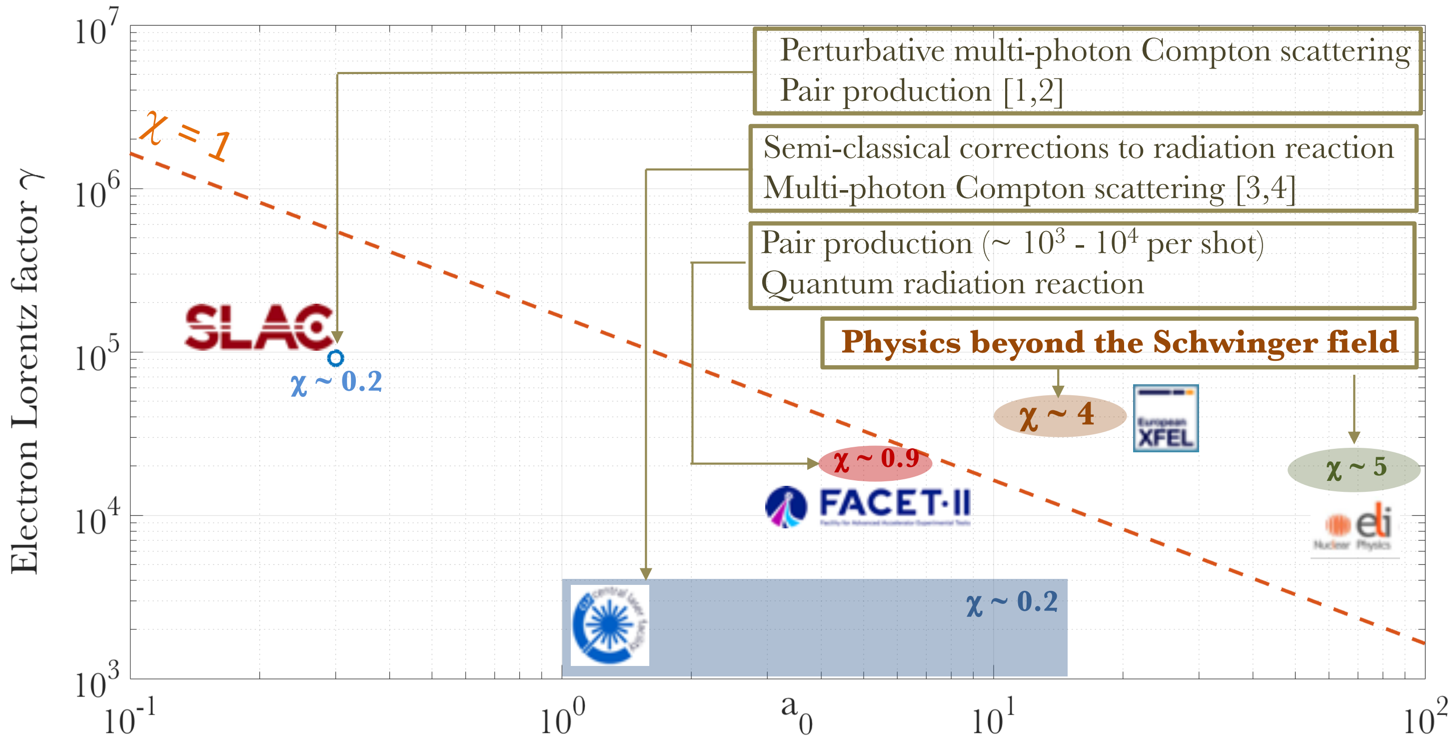
3. Production of electron-positron pairs (important only for $\chi \geq 1$)

A parameter space



[1] C. Bula et al., PRL 76, 3116 (1996).
[2] D. L. Burke et al., PRL 79, 1626 (1997).
[3] K. Poder et al., PRX 8, 031004 (2018).
[4] J. Cole et al., PRX 8, 011020 (2018).

A parameter space



	e⁻ energy (GeV)	ΔE / E	Electron beam charge (pC)	I_L (W/cm²)	a_0	χ	g (χ)
GEMINI	2	10%	100	4×10^{20}	10	0.2	47%
FACET-II	10	< 1%	600	2×10^{20}	1 - 5	0.9	19%
LUXE	17	< 1%	600	10^{21}	1 - 15	4	5%

A fully laser-driven setup

Astra-Gemini experiments

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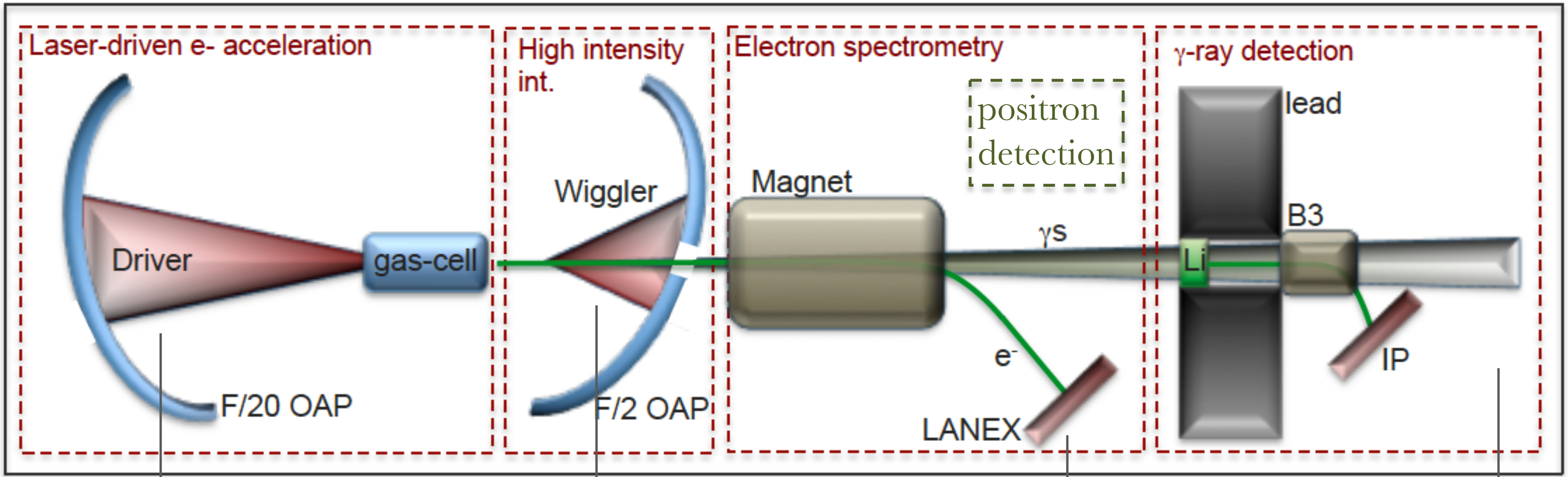
Electron-laser collisions



DRIVER LASER:
- t_L ~ 30-40 fs
- P ~ 0.1 – 1 PW
- Long focal length
- $a_0 > 1$

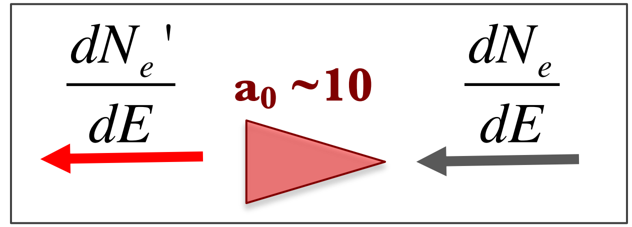
SCATTERING LASER:
- t_L ~ 30-40 fs
- P ~ 0.1 – 1 PW
- Short focal length (holed)
- $a_0 >> 1$

e^- SPECTROMETER

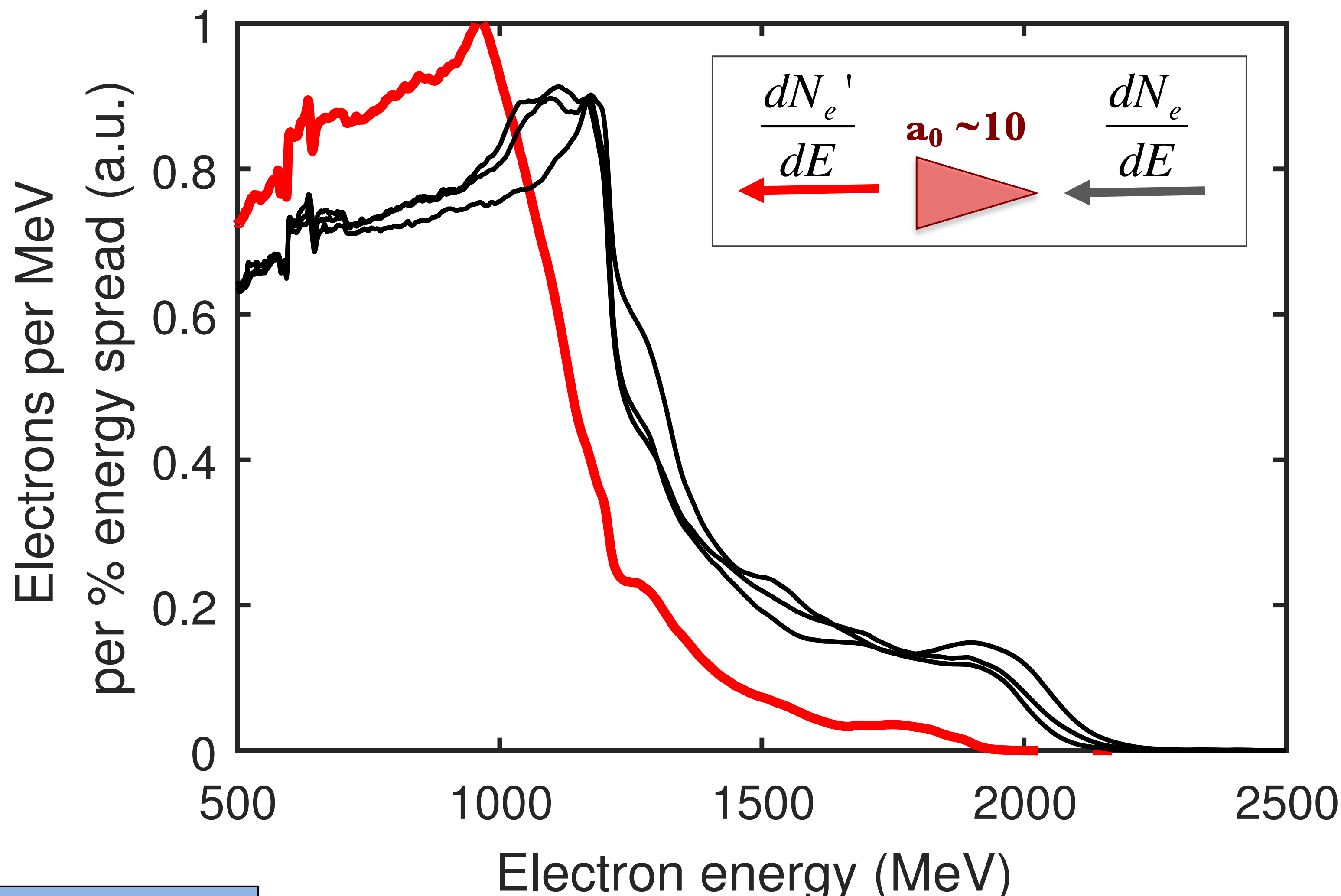
γ-ray SPECTROMETER

✗ Unstable electron beam spectrum — G. Samarin et al., J. Mod. Opt. 65, 1362 (2017)
✗ Pointing fluctuations
✗ fs-scale synchronisation — D. Corvan *et al.*, Opt. Express **24**, 3127 (2016).

What do we see?

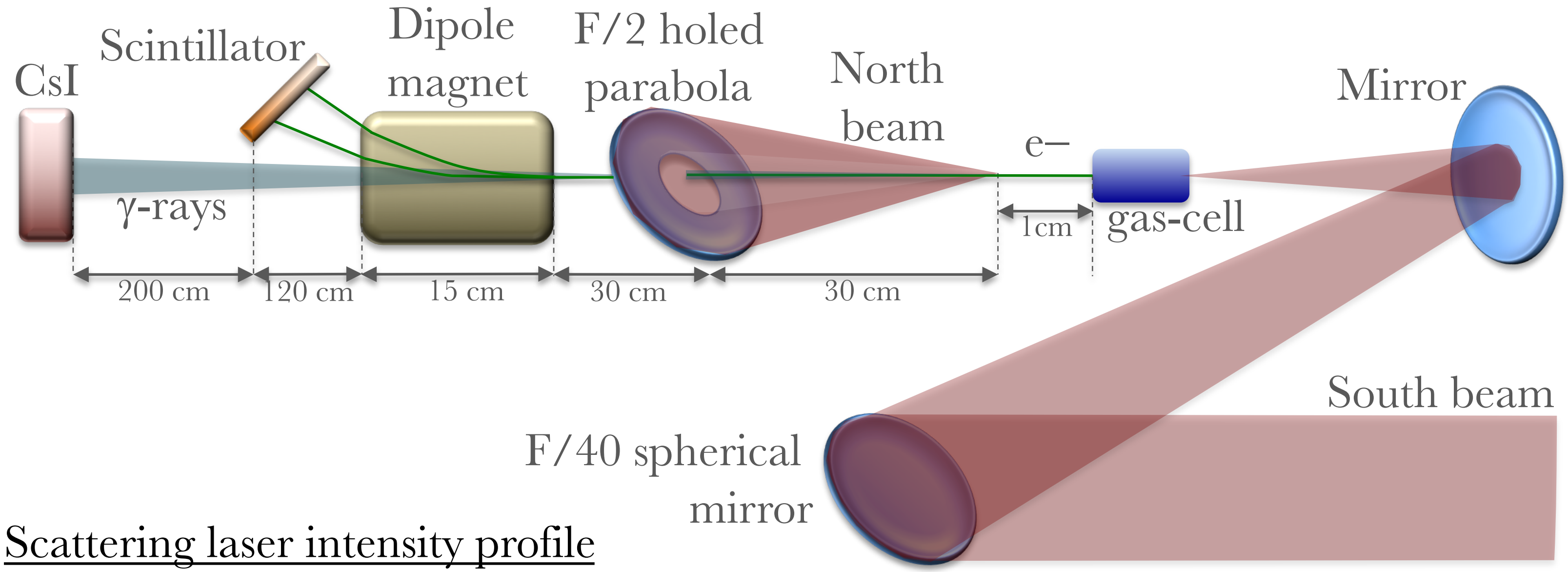


What do we see?

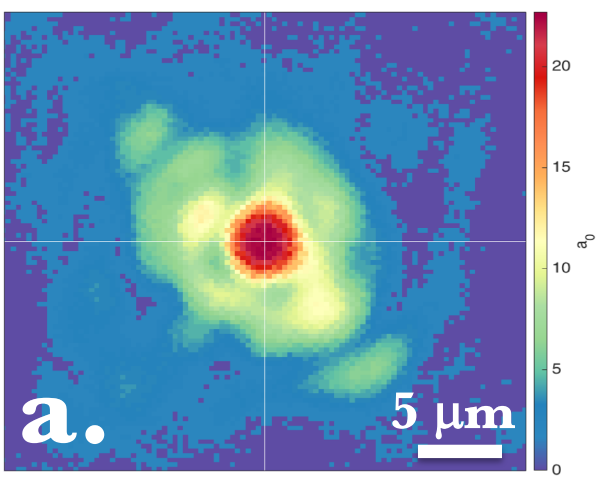


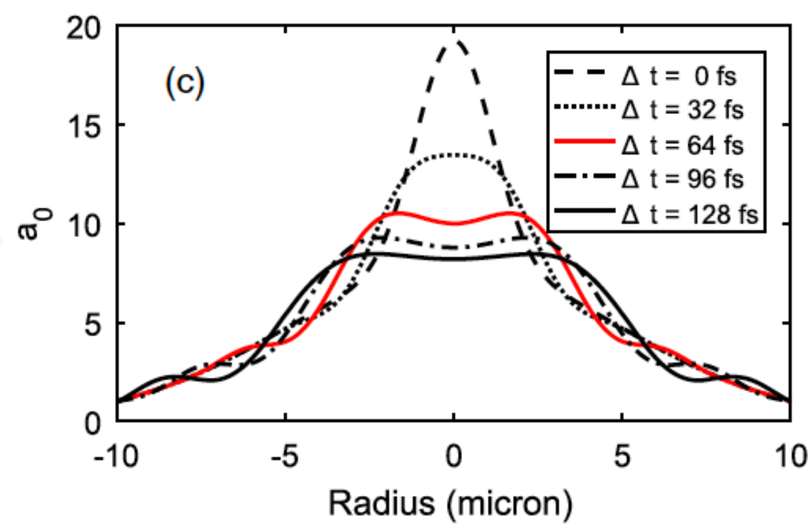
K. Poder *et al.*, Phys. Rev. X (2018)

Experimental setup

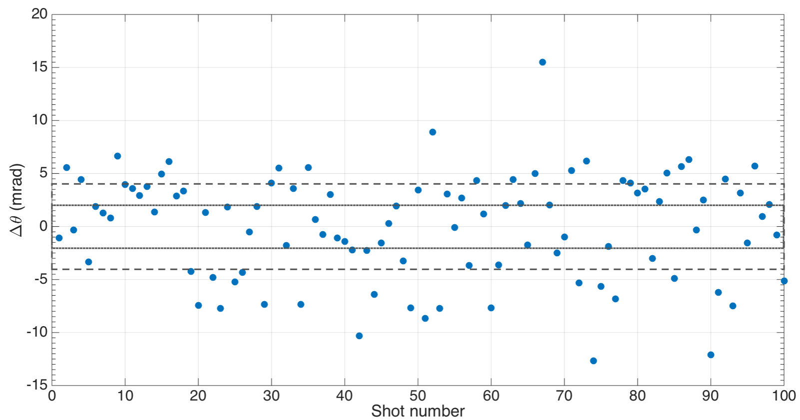


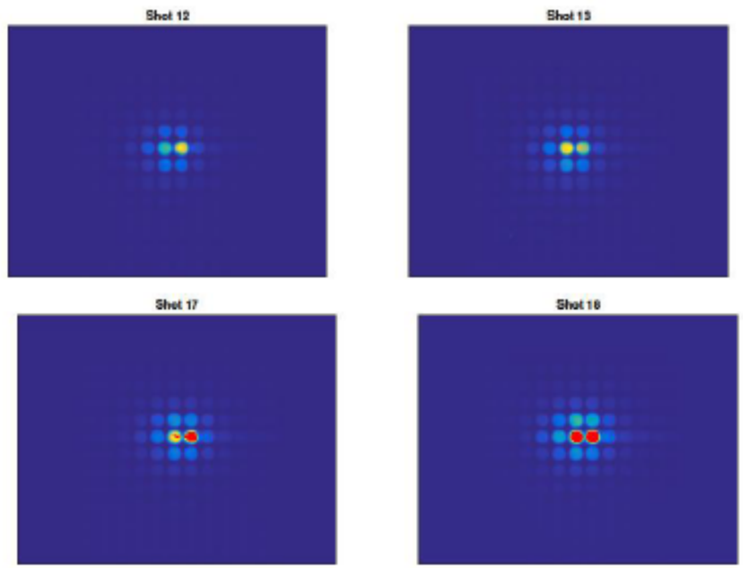
Scattering laser intensity profile

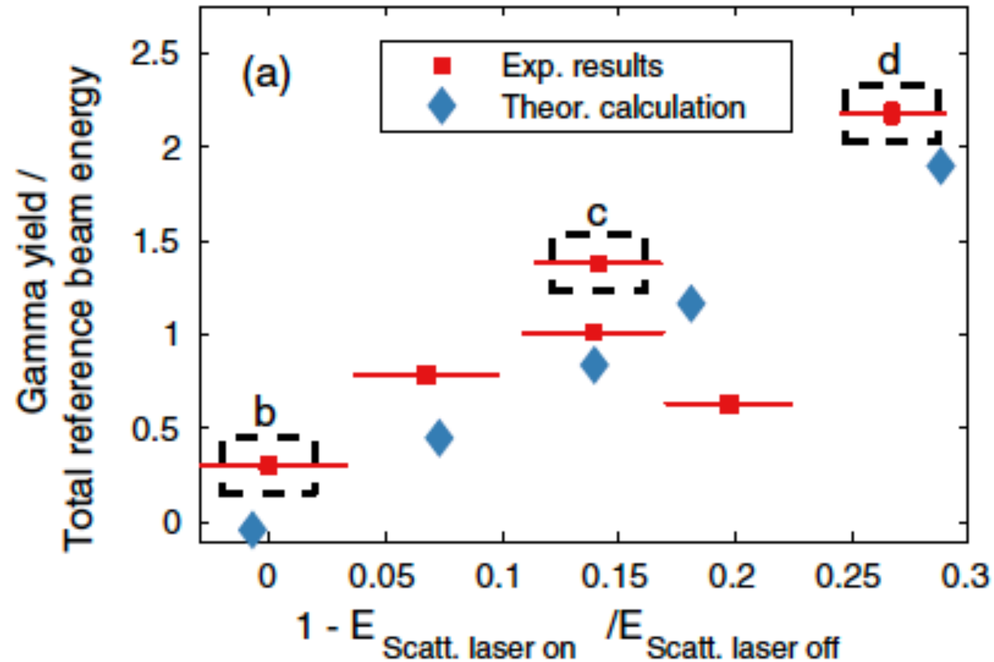




Collision diagnostic



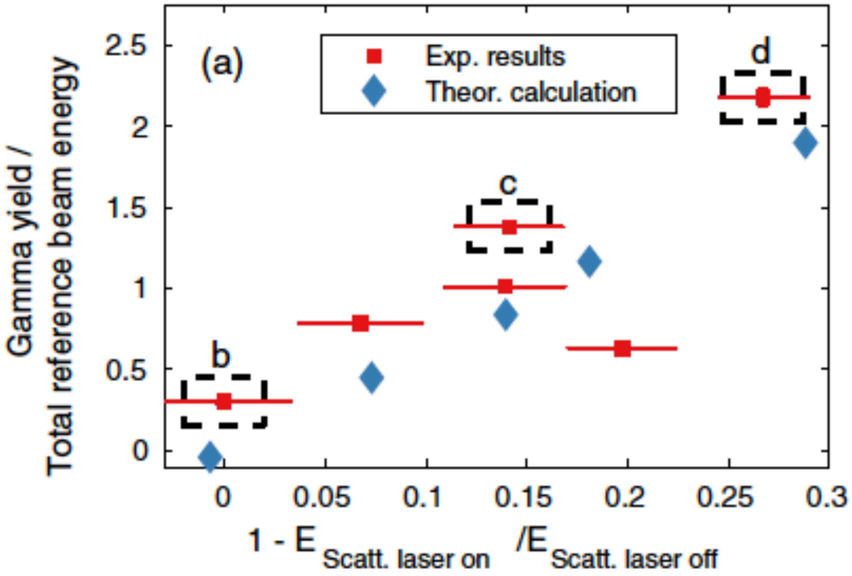




good electron-laser overlap → high photon yield, high energy loss

K. Poder *et al.*, Phys. Rev. X (2018)

Collision diagnostic



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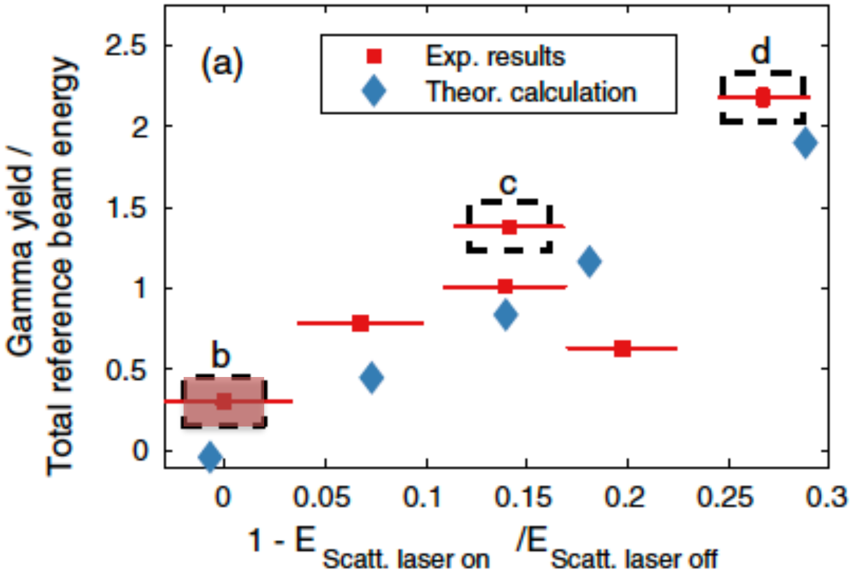

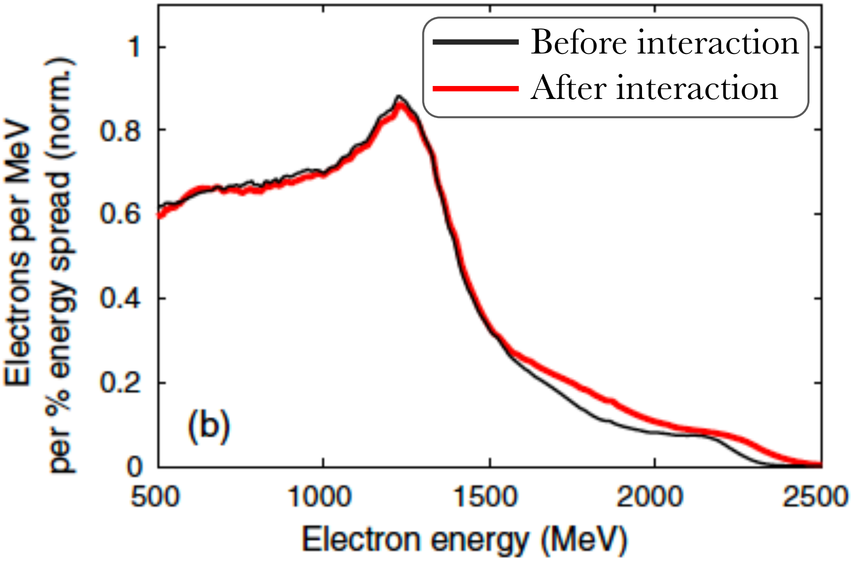

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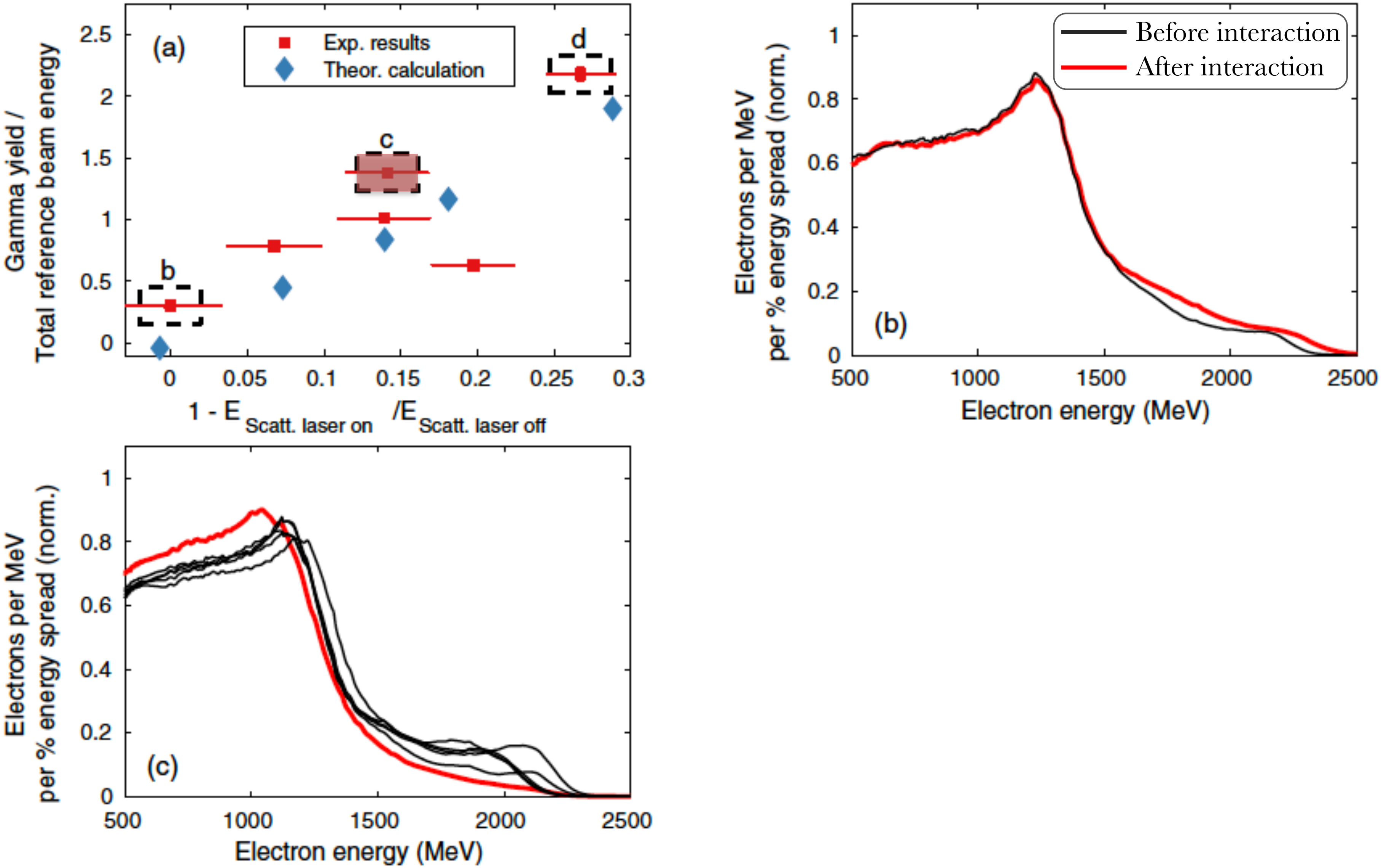

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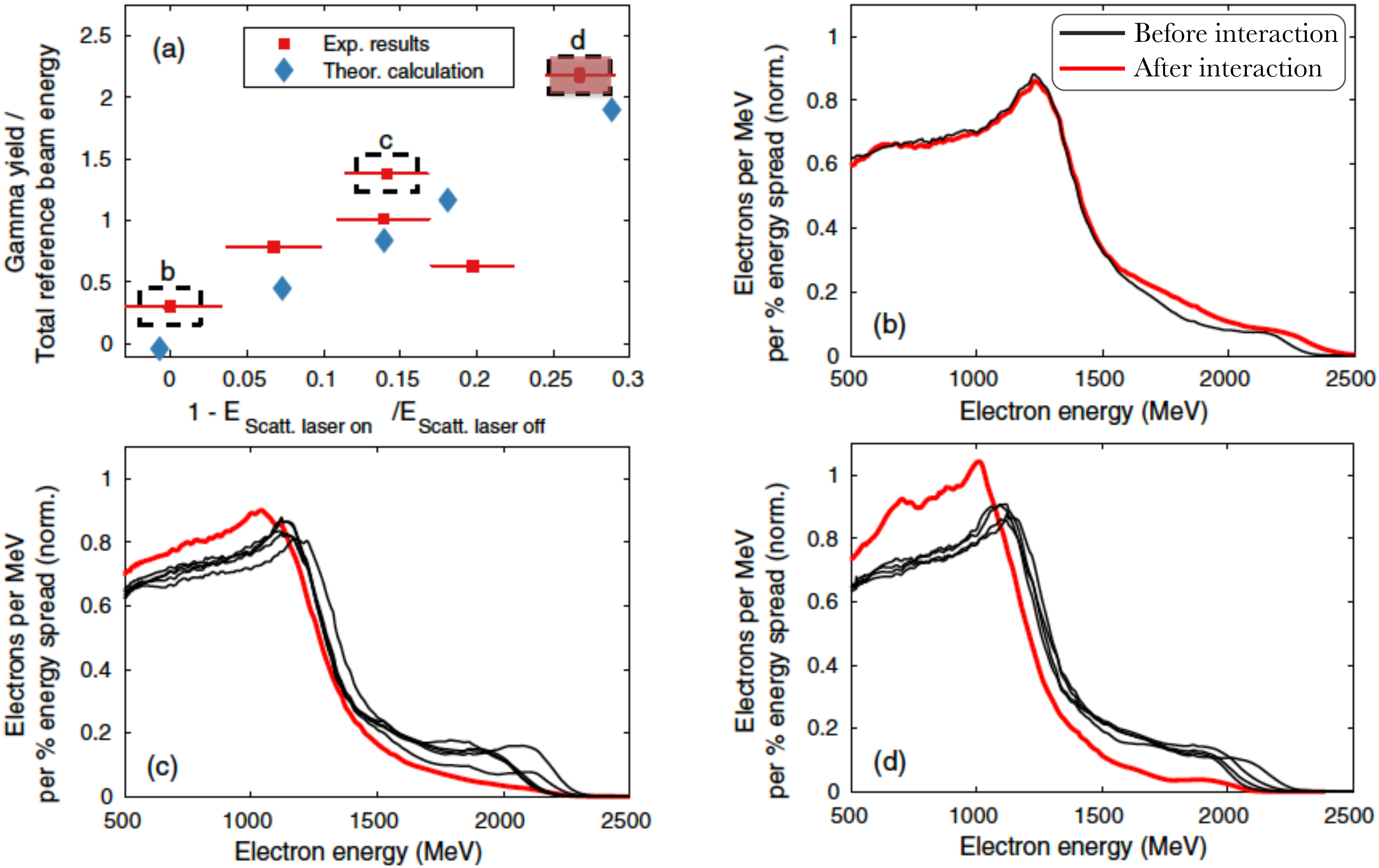
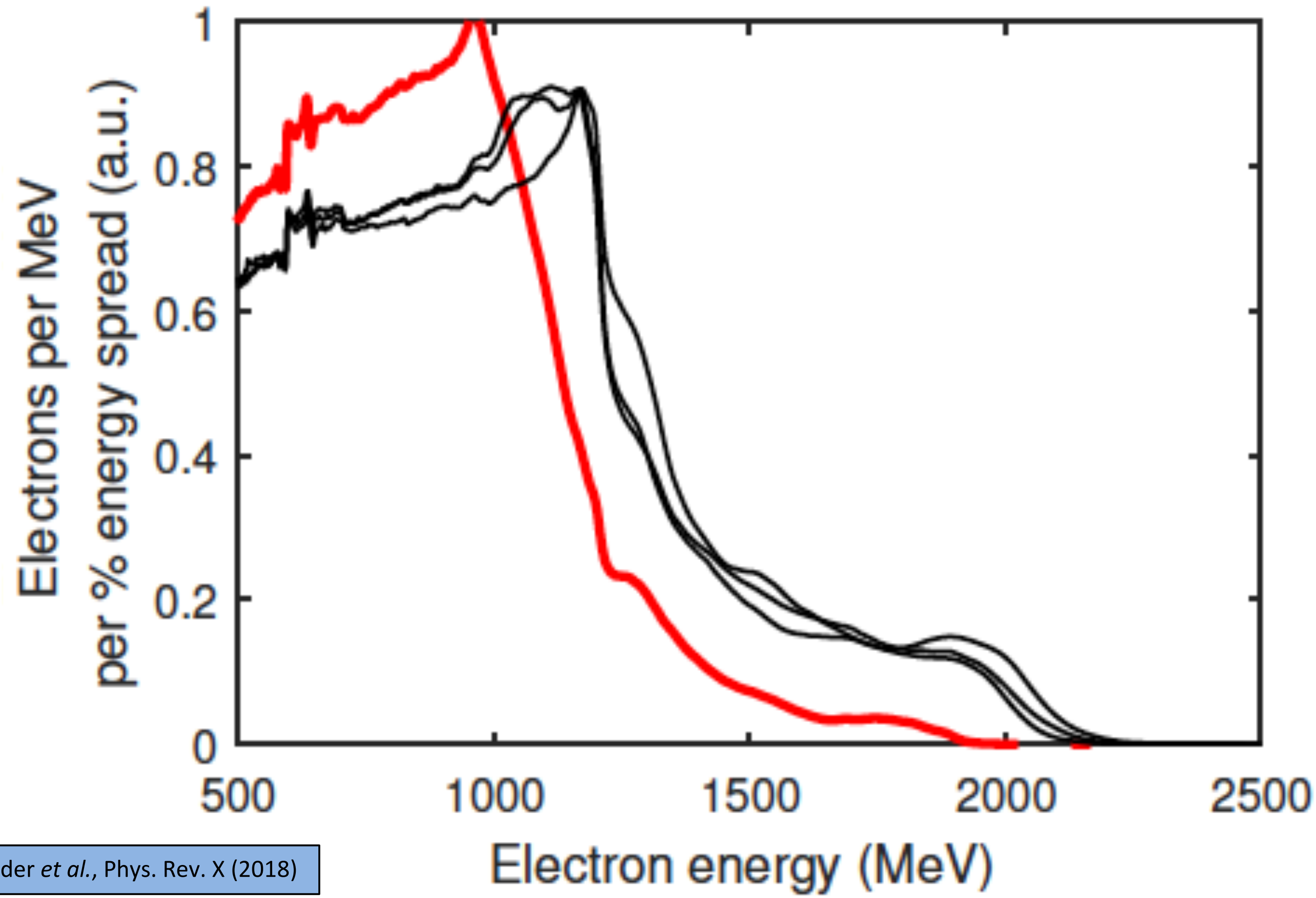


Comparison with theoretical models

Comparison with theory



K. Poder *et al.*, Phys. Rev. X (2018)

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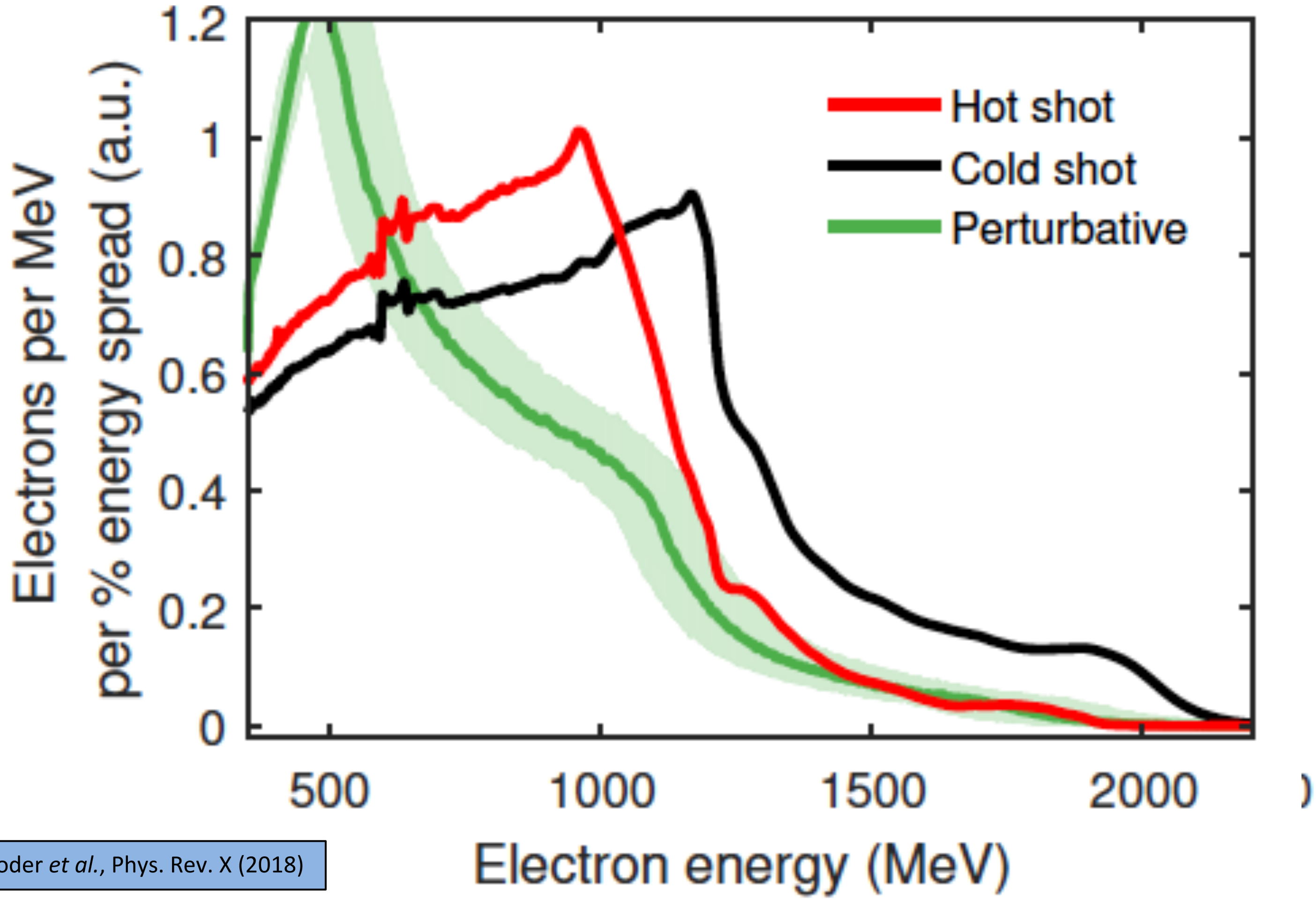
Comparison with theory



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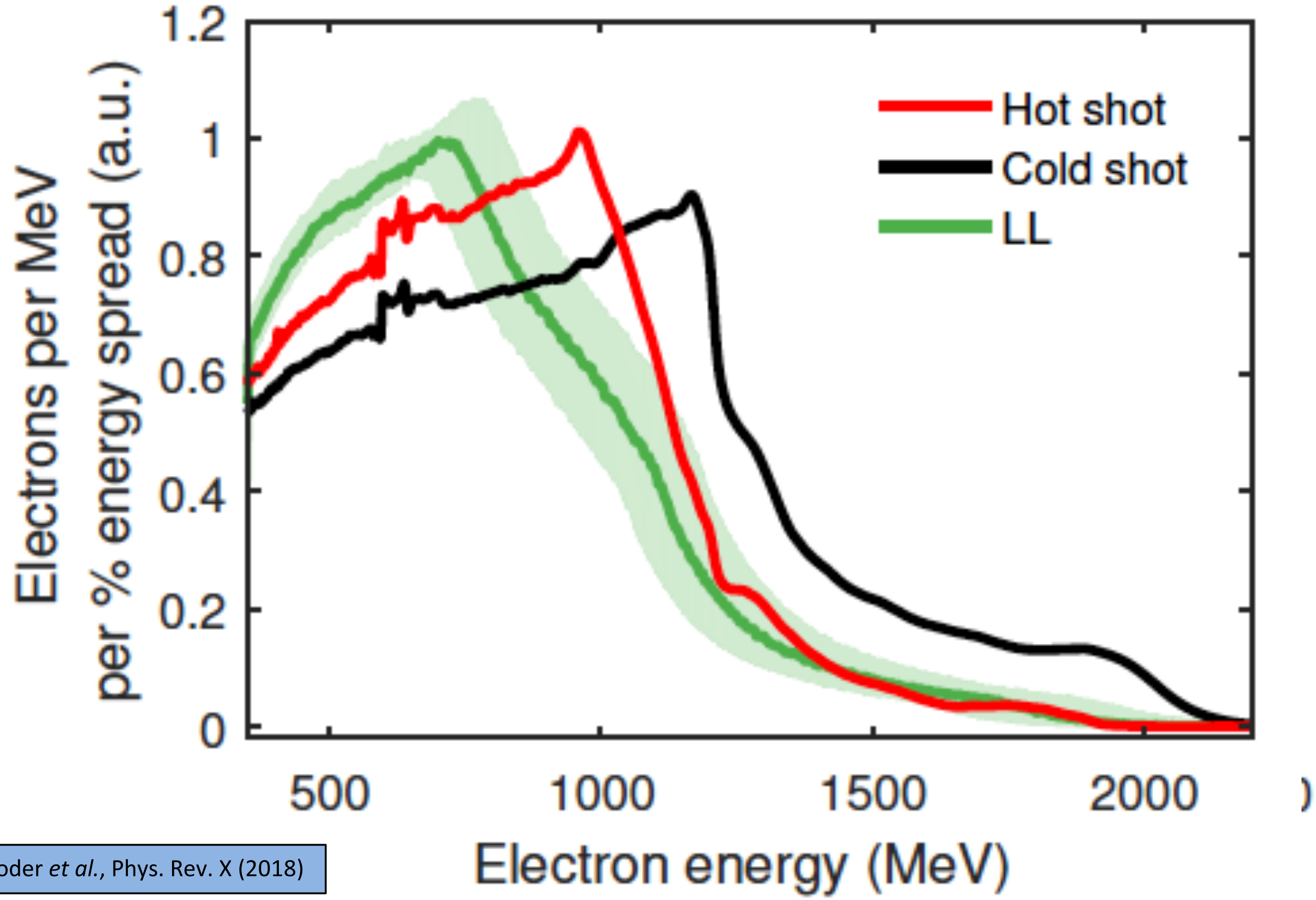

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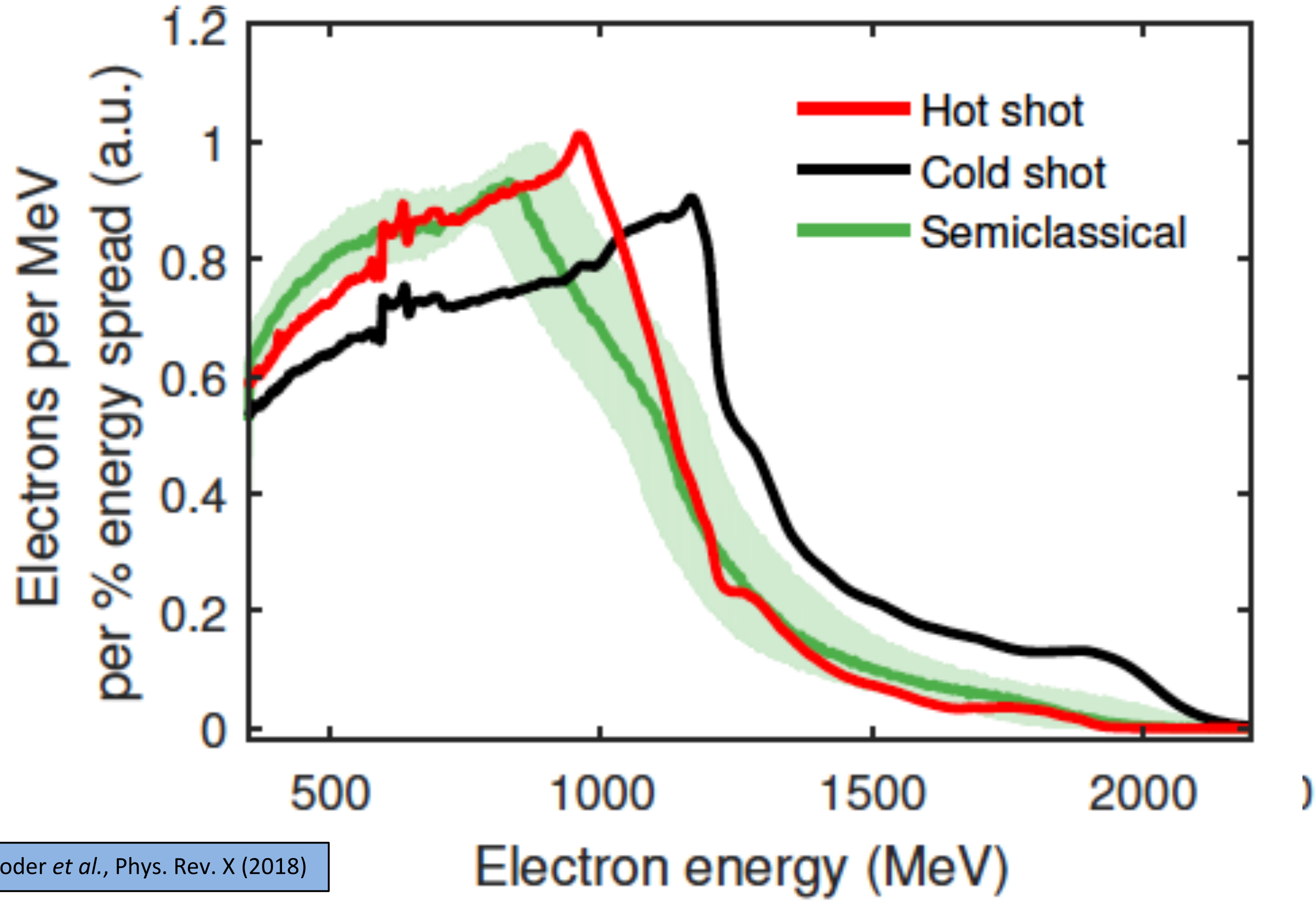

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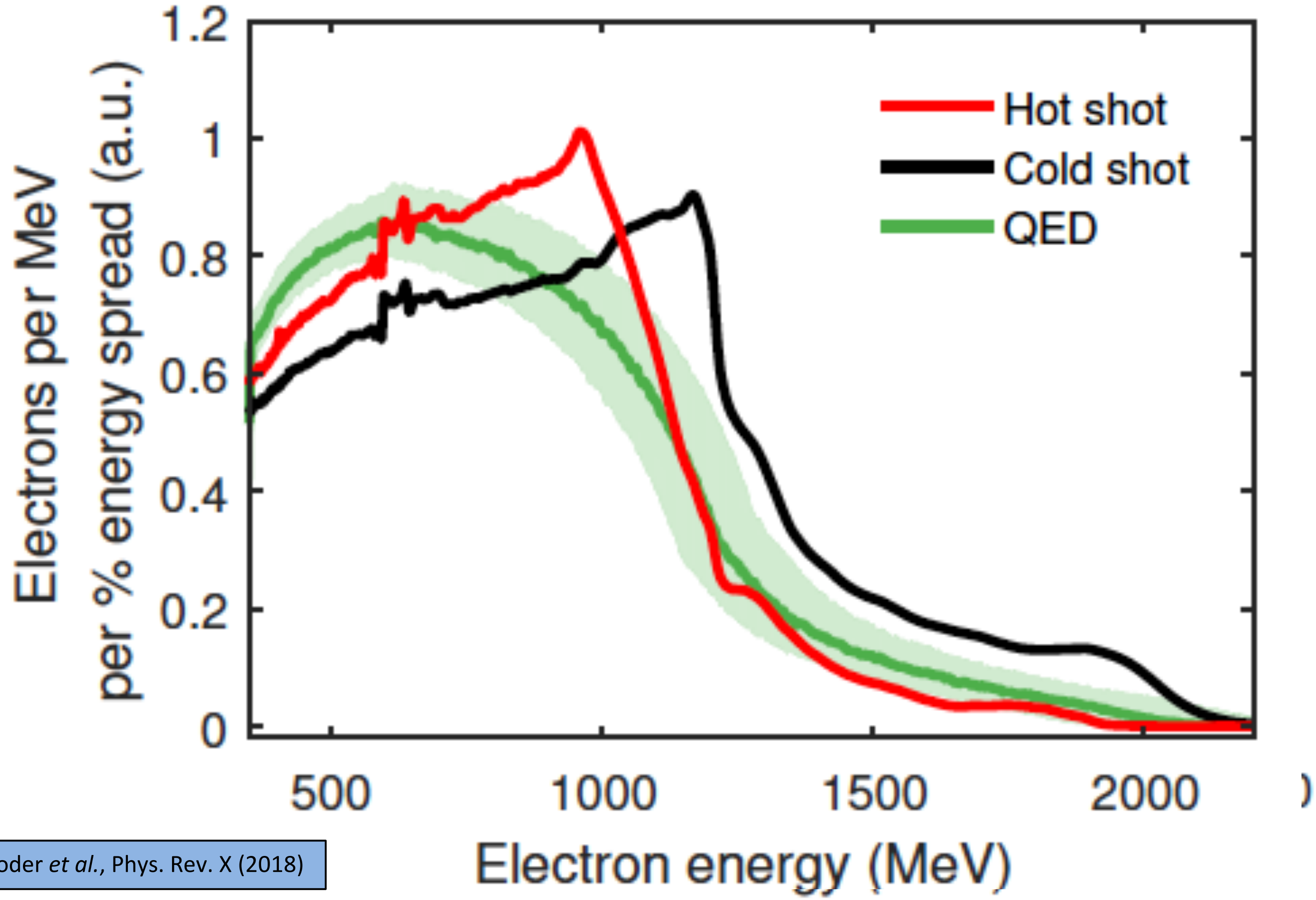

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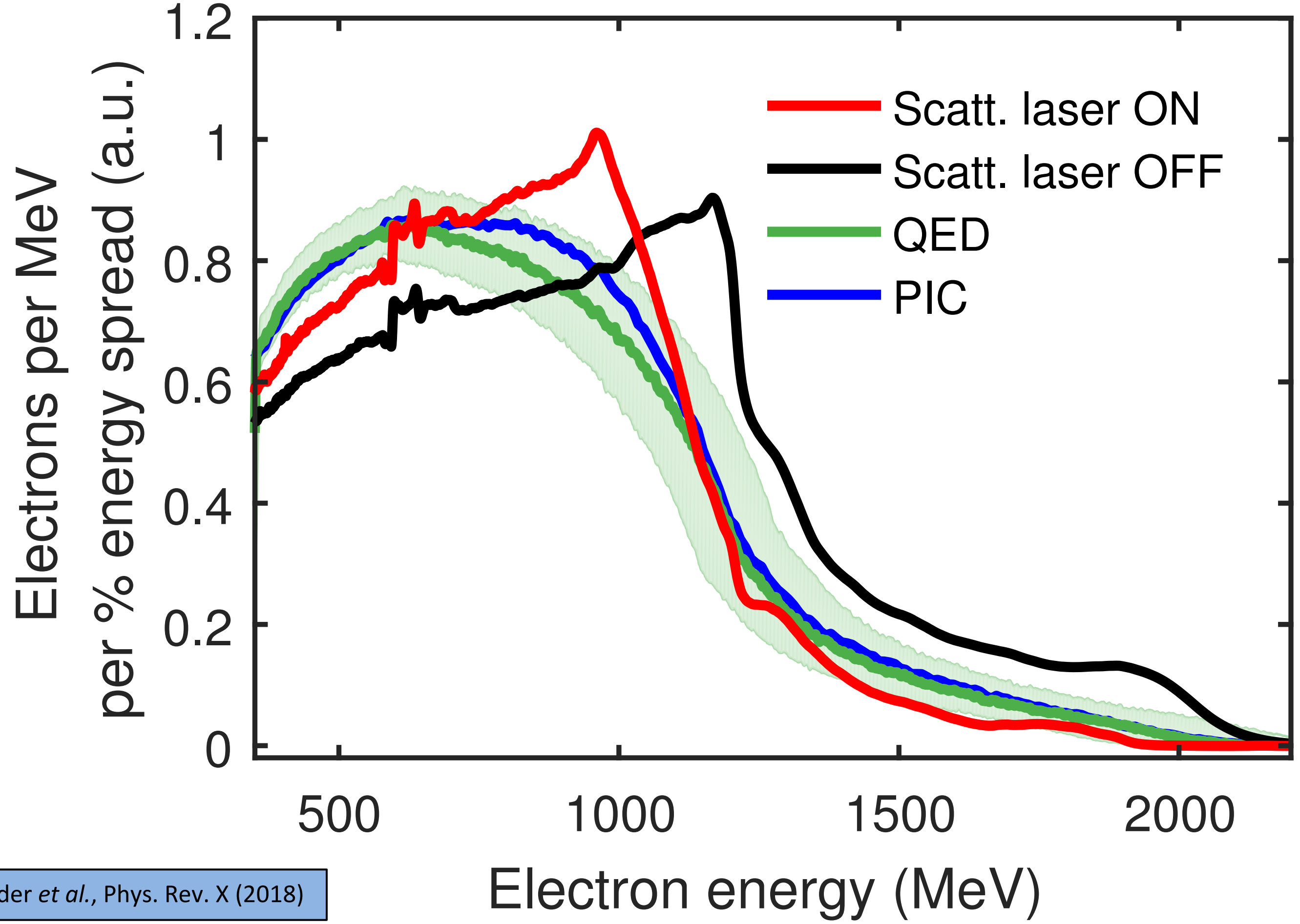

K. Poder *et al.*, Phys. Rev. X (2018)

CCF approximation

Why are the semiclassical and QED model not reproducing the data exactly?

Several possibilities:

- **Incomplete knowledge of laser spectral phase**
- **Incomplete knowledge of longitudinal laser distribution**
- **…**

CCF approximation

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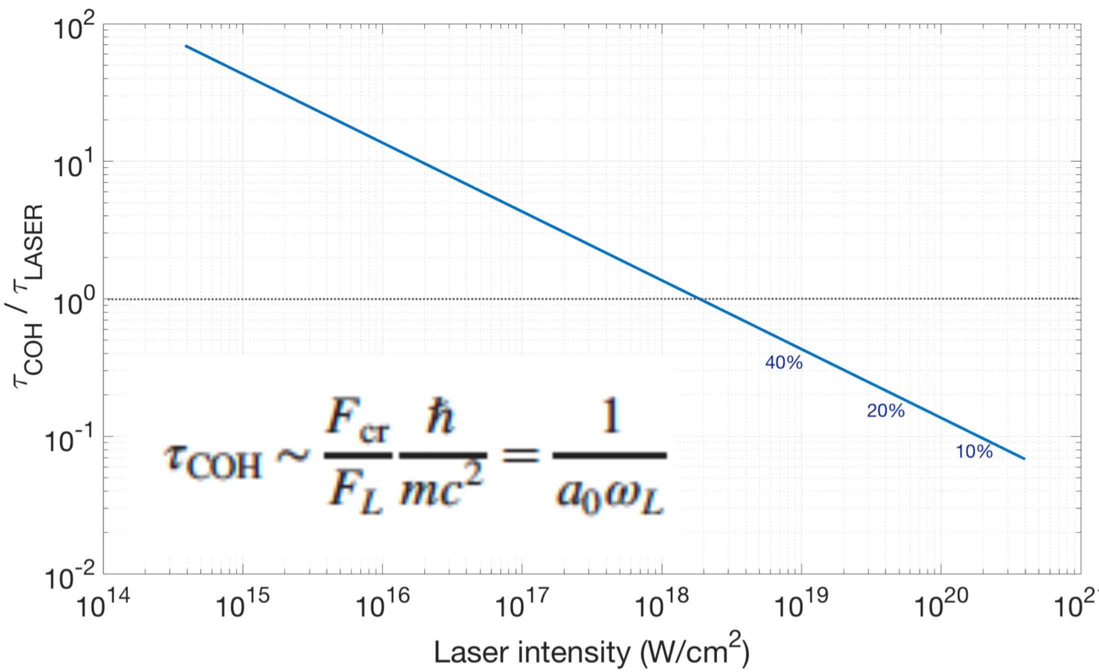
OR, we could be in a situation where the **constant cross-field approximation** is not strictly valid



This approximation is used to calculate

g(χ) in the semiclassical model

Photon emission probability in the QED model

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The SFQED experiment at FACET-II

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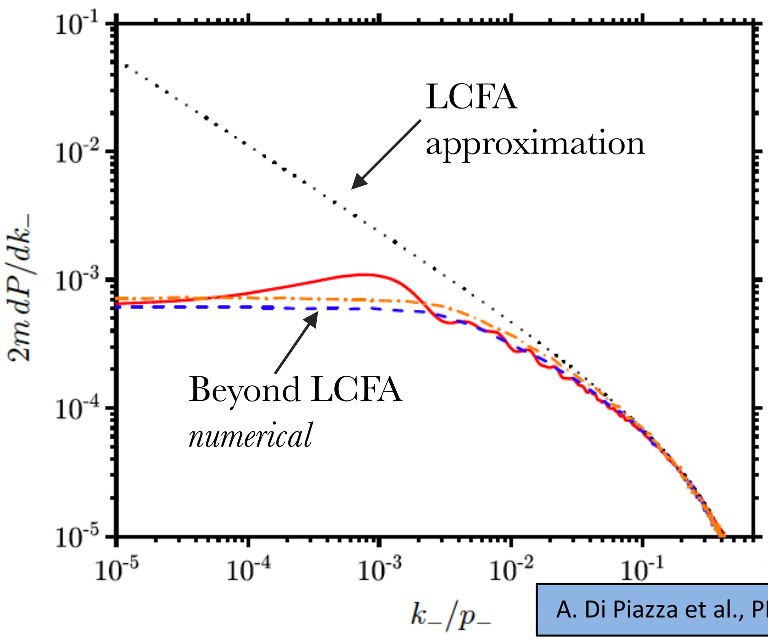
Measurables

Series of experimental campaigns approved at SLAC – FACET II, to study face-on collisions (10 GeV e⁻ beam and a 20 TW laser)

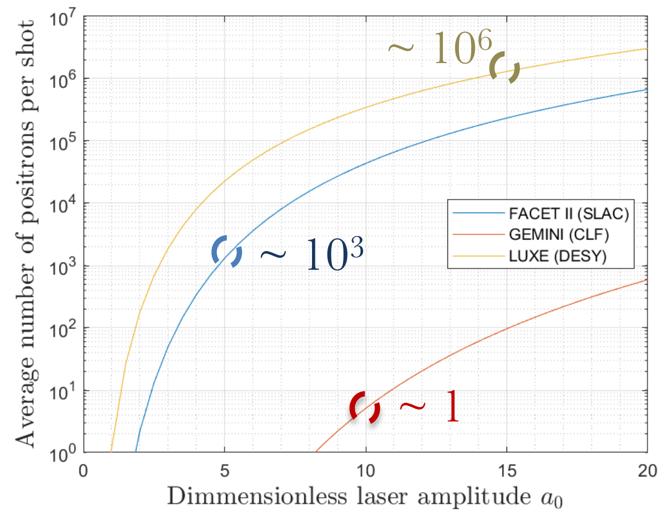
Main diagnostics:
- γ-ray spectrometer
- γ-ray beam profiler
- electron spectrometer
- positron spectrometer

Breakdown of LCFA *10 GeV, $a_0 \sim 8$*

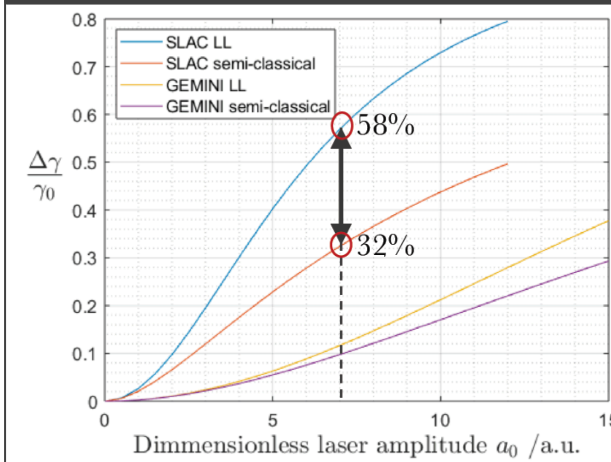


A. Di Piazza et al., PRA (2019)

Pair production



Quantum radiation reaction



Conclusions and Outlook

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- First experimental observation of high-field QED phenomena in a fully optical setup **obtained at the Central Laser Facility**

- For the next steps we need: A. Higher laser intensities
  B. Improved pointing and spectral stability of electron beams
  C. Higher electron energy

Conclusions and Outlook

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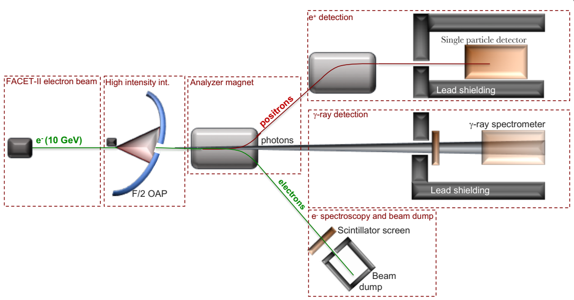
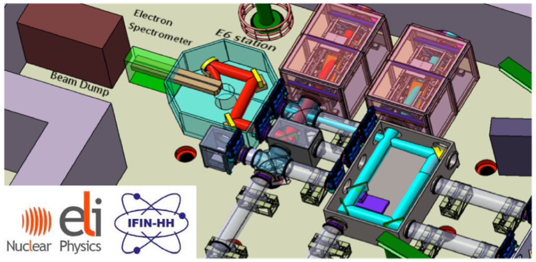


- SFQED experimental campaigns approved at FACET-II (SLAC)
- E ~ 10 GeV, a_0 ~ 5



- Extreme-Light Infrastructure Nuclear Pillar
- 2 x 10 PW laser beams
- First commissioning experiments early 2020

EuPRAXIA

- European consortium for a plasma-based accelerator of 5 GeV electron beams of industrial quality
- High-field QED studies proposed as a pilot application

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Thanks for your attention!

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