High-intensity quantum electrodynamics in the field of an ultra-intense laser

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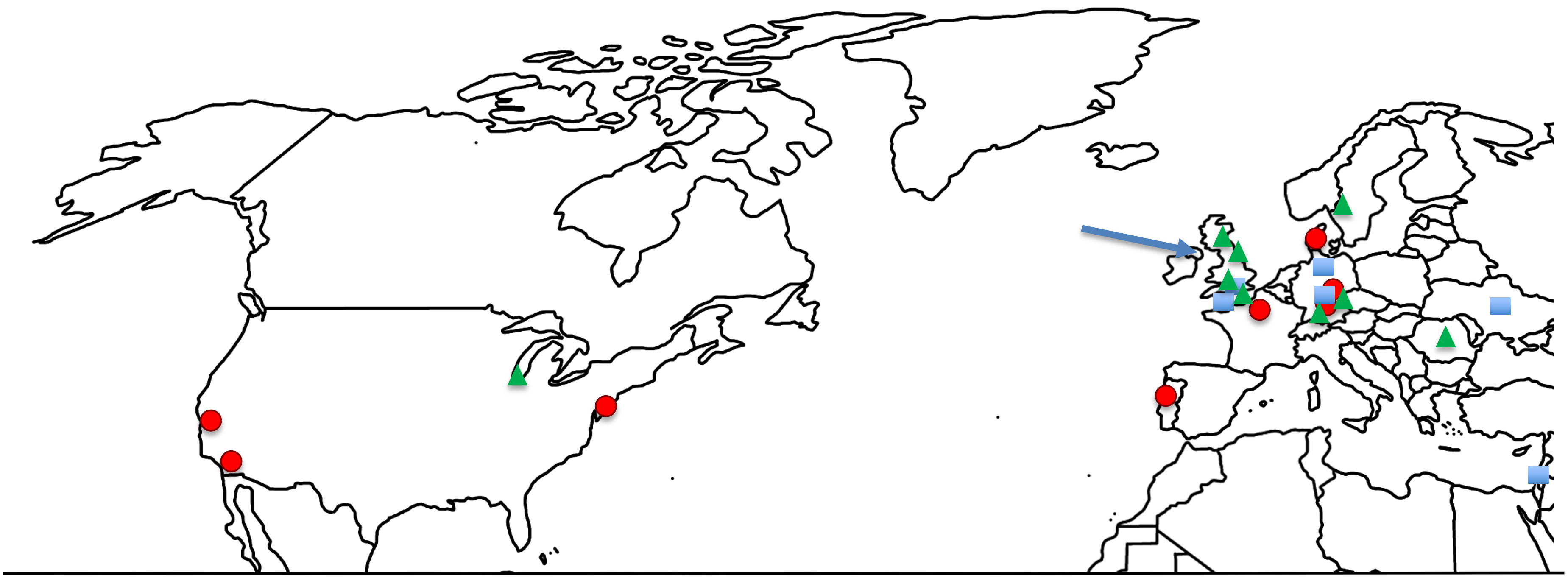
Main Collaborators

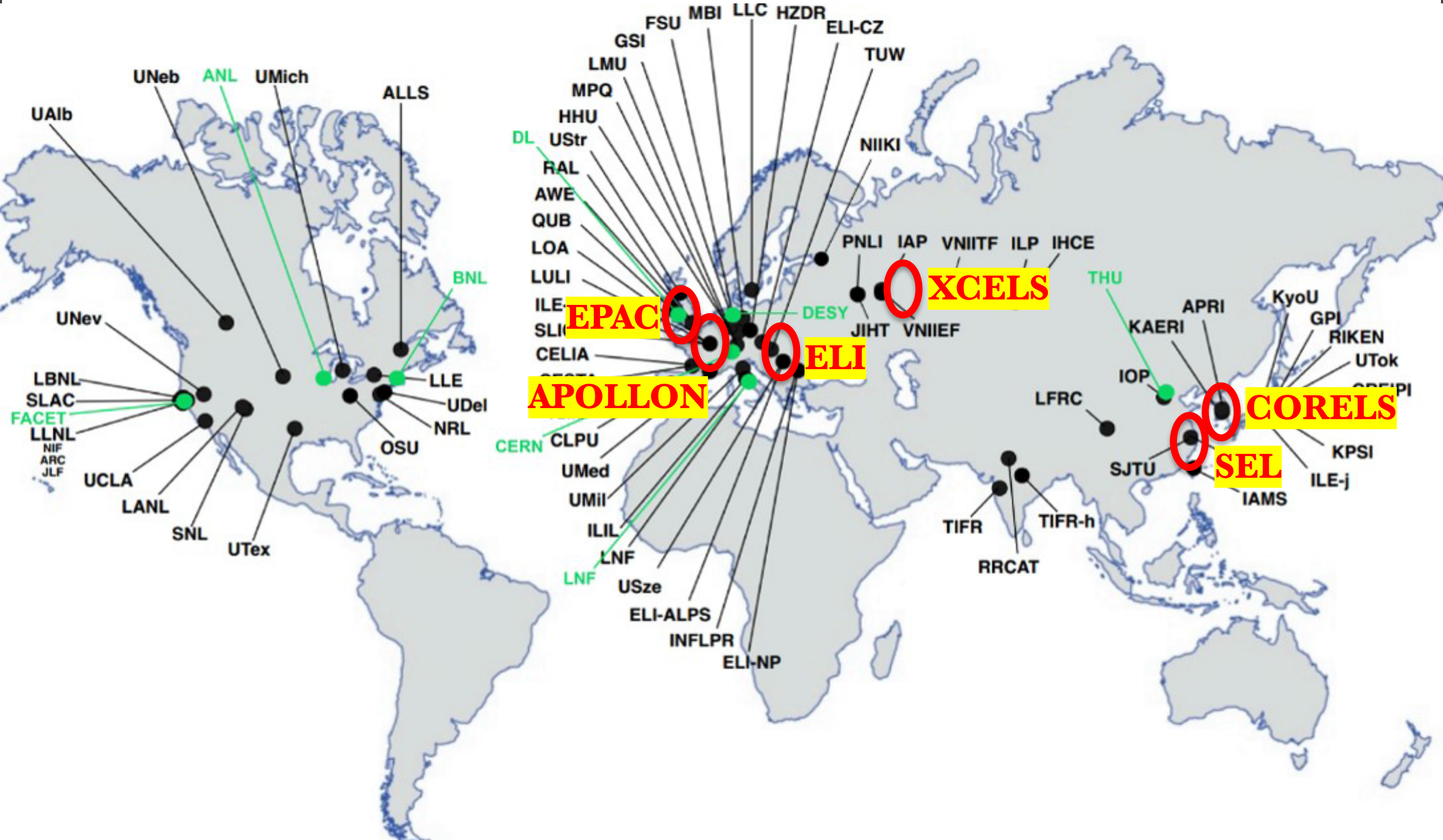


E-320 experiment at FACET-II — SLAC, HI Jena Helmholtz Institute Jena, École Polytechnique Université Paris-Saclay, Princeton University, Técnico Lisboa, UCLA, Aarhus University

LUXE experiment at Eu-XFEL — DESY, European XFEL, University of Plymouth, HI Jena Helmholtz Institute Jena, Weizmann Institute of Science, UCL, KINR, Tel Aviv University

Laser-driven experiments — Central Laser Facility, Imperial College London, University of York, University of Michigan, HI Jena Helmholtz Institute Jena, ELI, Chalmers University of Technology

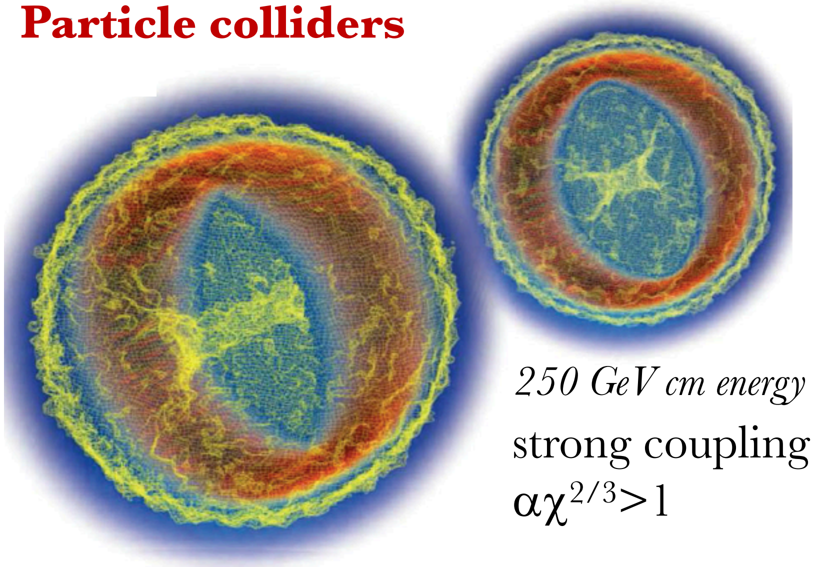
High-power lasers in the world



Part 1
Introduction

High-field QED outside lasers

Particle colliders



250 GeV cm energy

strong coupling

$\alpha\chi^{2/3}>1$

V. Yakimenko et al. PRL 2019

Astrophysics

surface magnetic field of magnetars

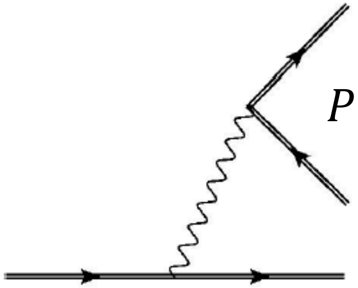
$\sim 10^{-4} - 10\ B_{cr}$

B. Cerutti Space Sci. Rev. 2017

Fundamental physics

perturbative QED: $\alpha << 1$

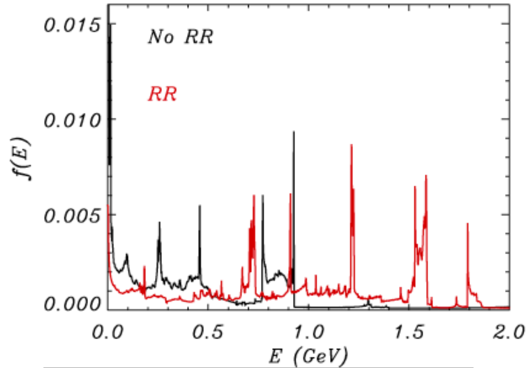
non-perturbative phenomena:



$P \propto \chi_\gamma e^{-8/3\chi_\gamma}$

V. I. Ritus J. Russ. Laser Res. 1985

Plasma physics



M. Tamburini et al. NJP 2010

What happens at the critical field?

⇒ **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

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

X No energy loss

1. LAD Equation

Schott's term

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

✓ Damping force (radiation reaction term)

X Classical renormalisation (point-like electron)

X 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 special relativity

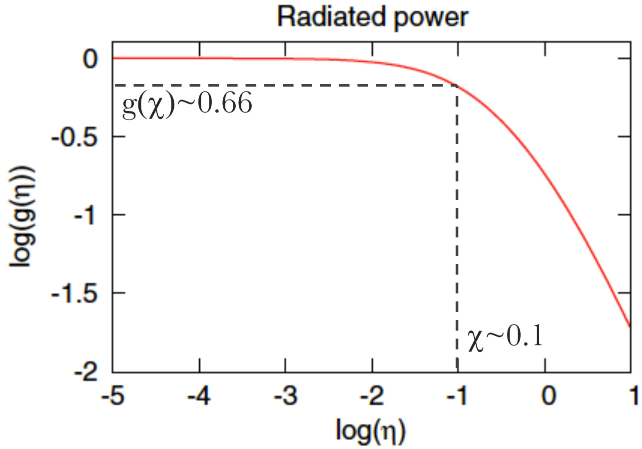
$\lambda >> \alpha\lambda_{C}$ (localised wavefunction)

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

What happens at the critical field?

⇒ 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

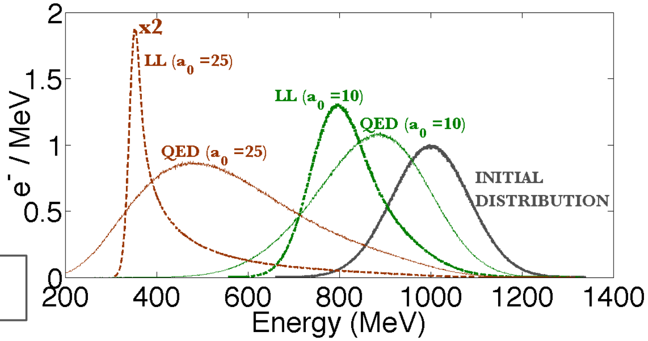
2. Photon emission is probabilistic

2.a $a_0 >> 1$

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

V. I. Ritus, J. Sov. Laser Res. 1985

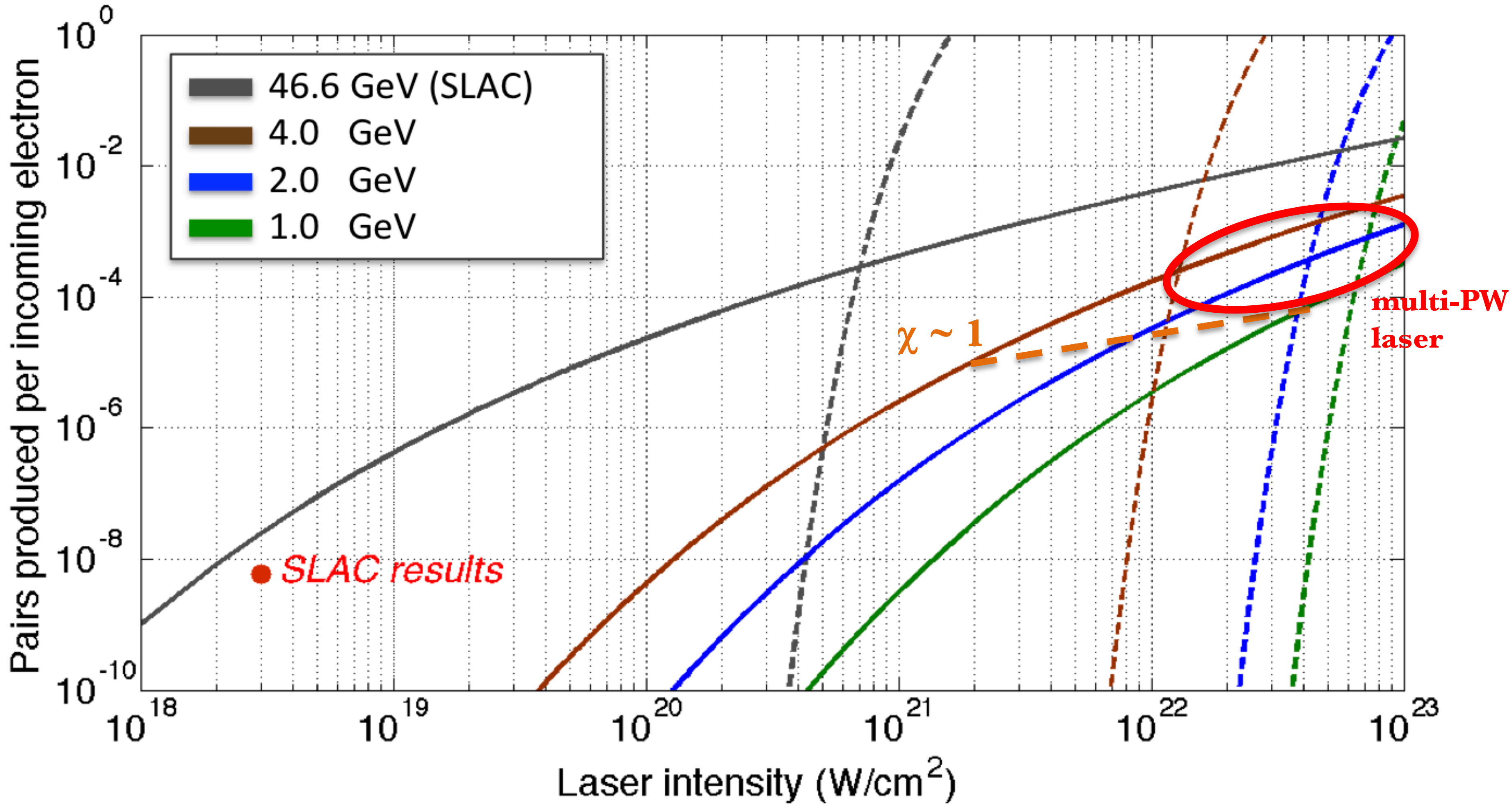
N. Neitz and A. Di Piazza, PRL 2013



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

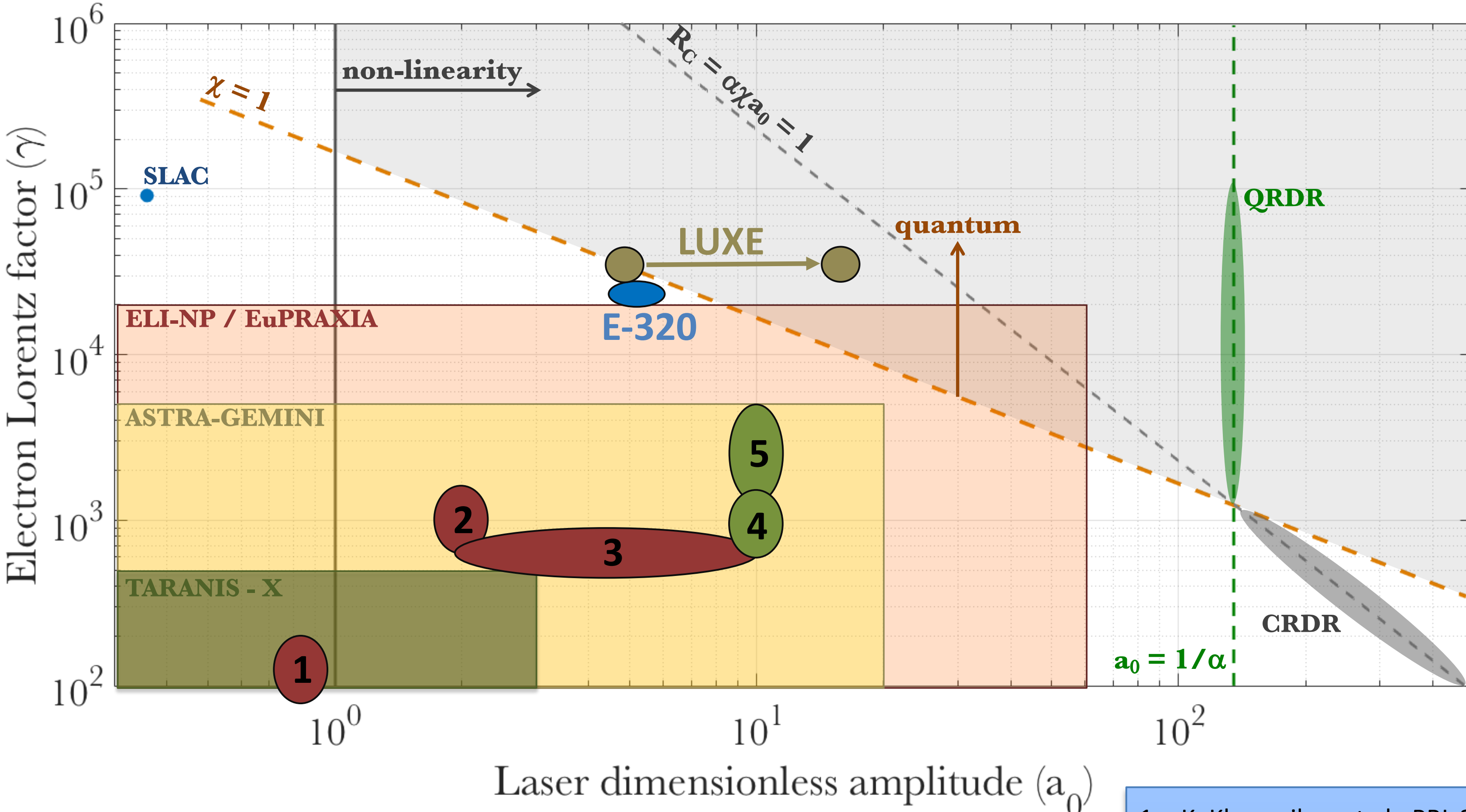
What happens at the critical field?

⇒ Creation of electron-positron pairs becomes significant



Part 2
Recent experiments on quantum radiation reaction

Current status

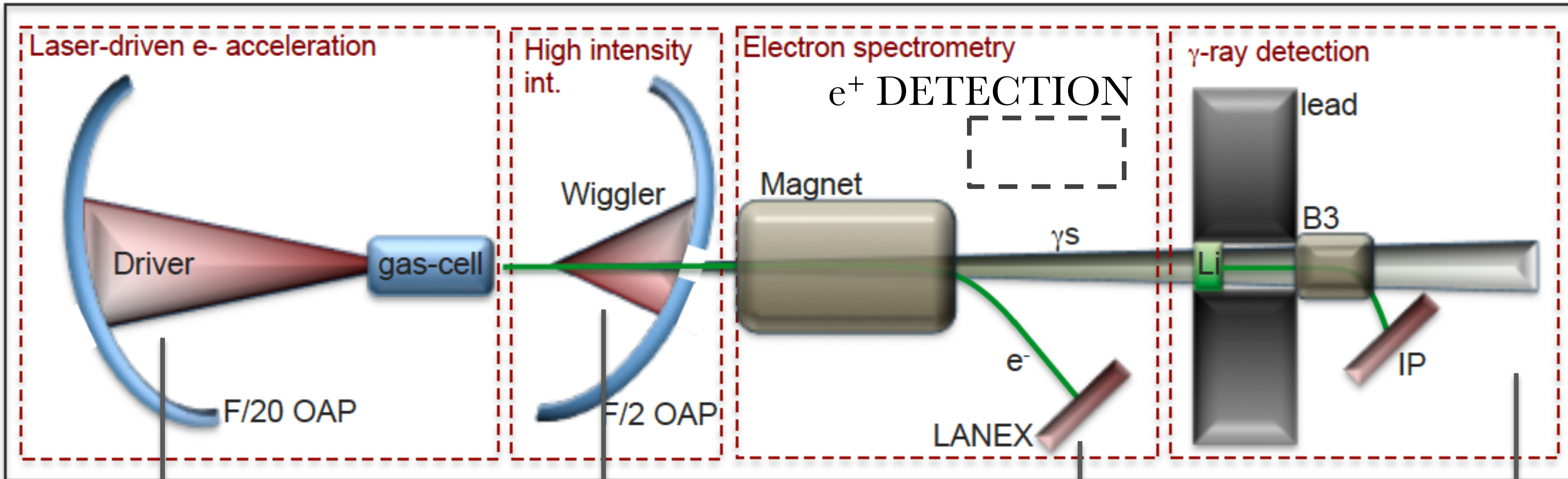


$$a_0 \sim 6\lambda_L[\mu m]\sqrt{I_L[10^{20}\,\mathrm{W/cm^2}]}$$ *Intensity*

$$\chi \sim 6.1\times10^{-6}\gamma_e a_0$$ *Quantum parameter*

1. K. Khrennikov et al., PRL 2015
2. G. Sarri et al., PRL 2014
3. W. Yan et al., Nat. Phot. 2017
4. J. Cole et al., PRX 2018
5. K. Poder et al, PRX 2018

Experiments at the CLF



DRIVER LASER:

- $t_L \sim$ 30-40 fs
- E ~ 1 – 10 J
- Long F# (F/20 – F/40)
- $a_0 \sim$ 1.5 - 2

SCATTERING LASER:

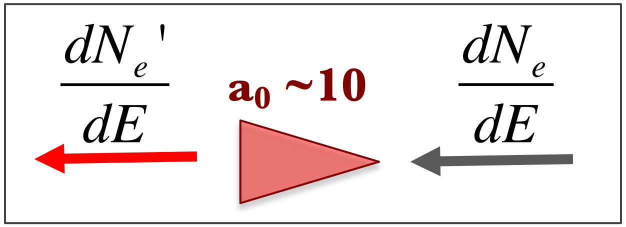
- $t_L \sim$ 30-40 fs
- E ~ 1 – 10 J
- Short F# (F/2)
- $a_0 >> 1$ (~10)

e^- SPECTROMETER

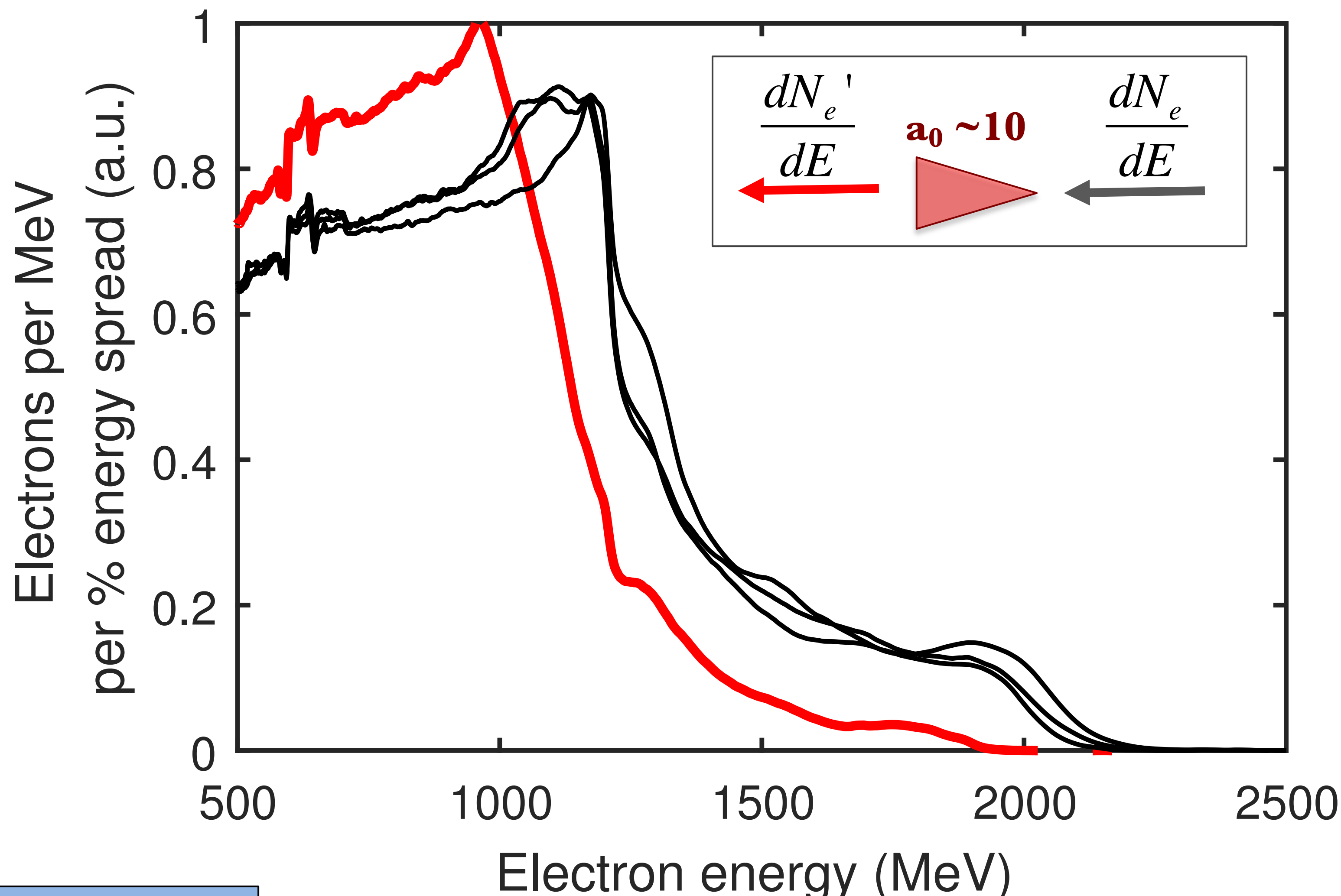
γ-ray SPECTROMETER

✗ 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?

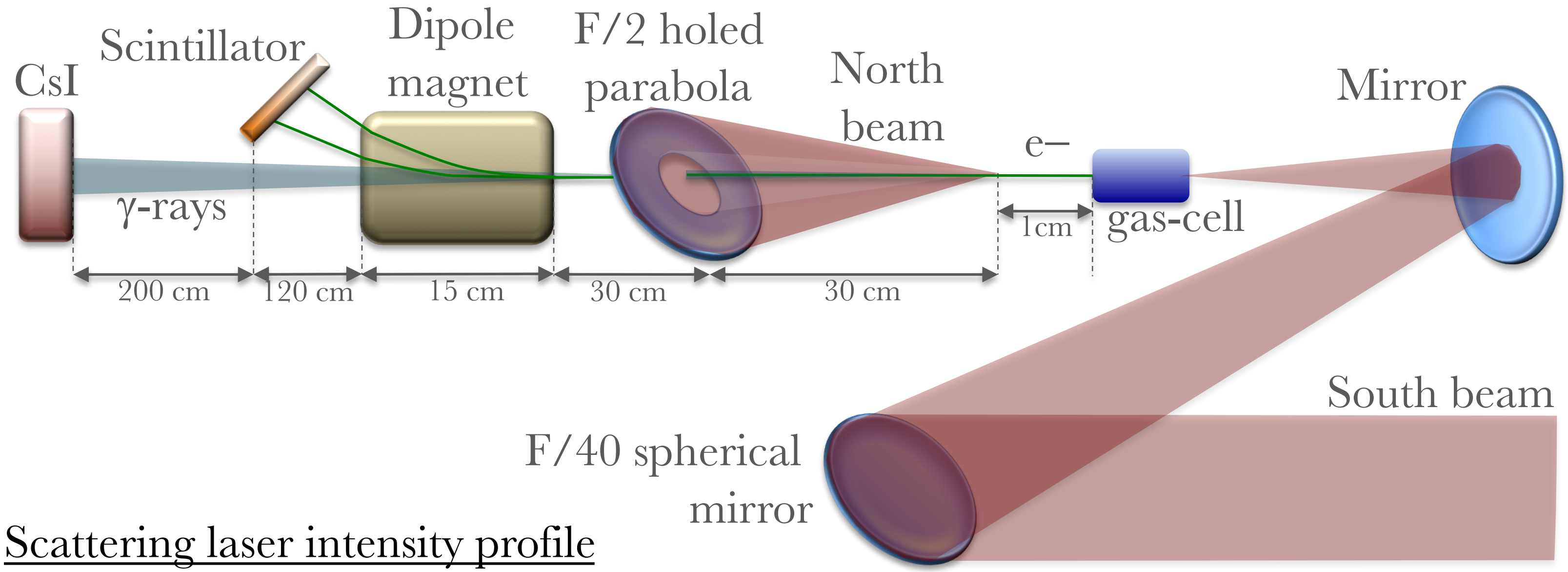


What do we see?

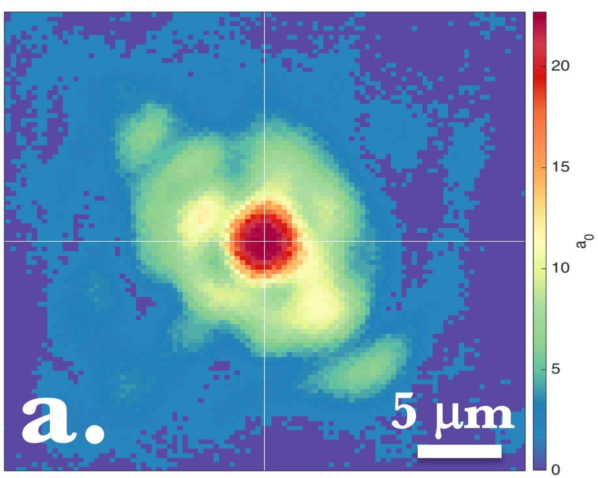


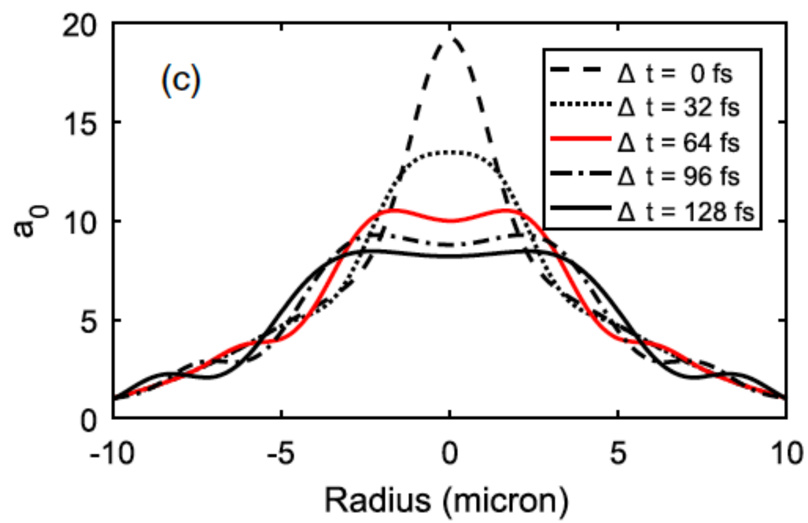
K. Poder *et al.*, Phys. Rev. X (2018)

Experimental setup

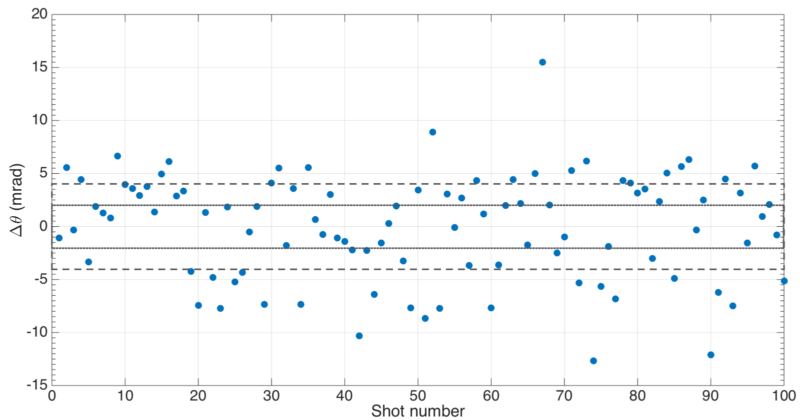


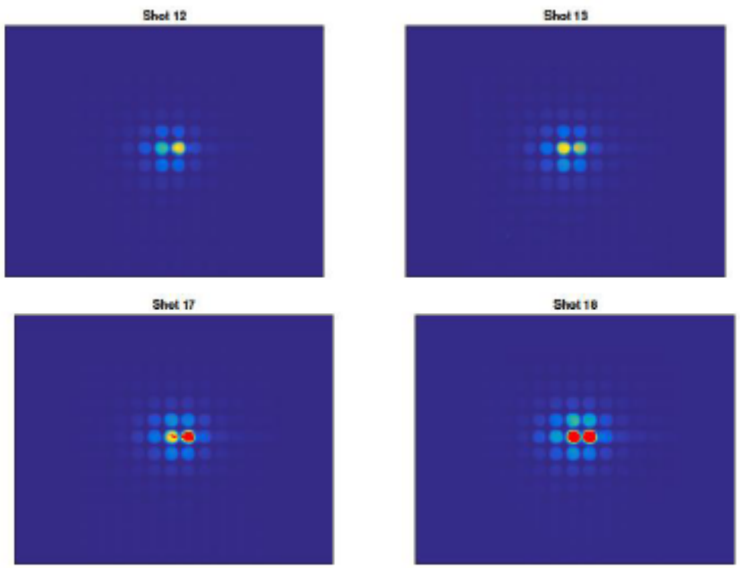
Scattering laser intensity profile

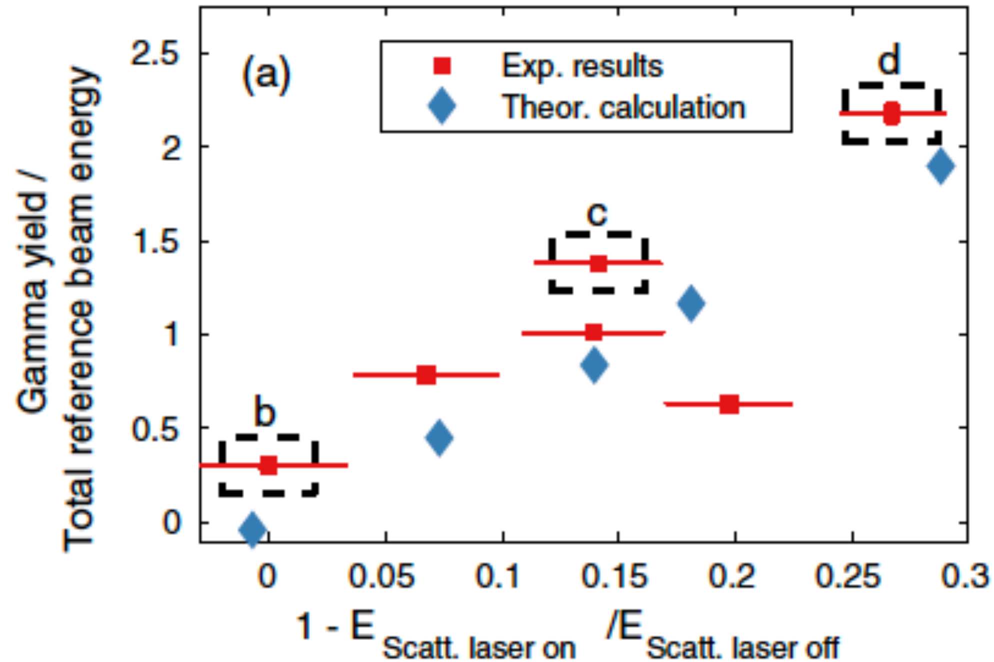




Collision diagnostic



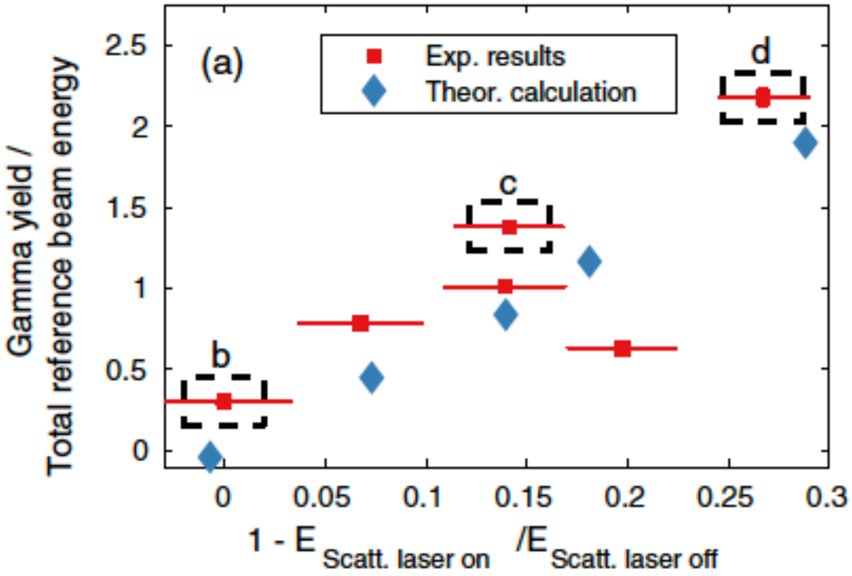




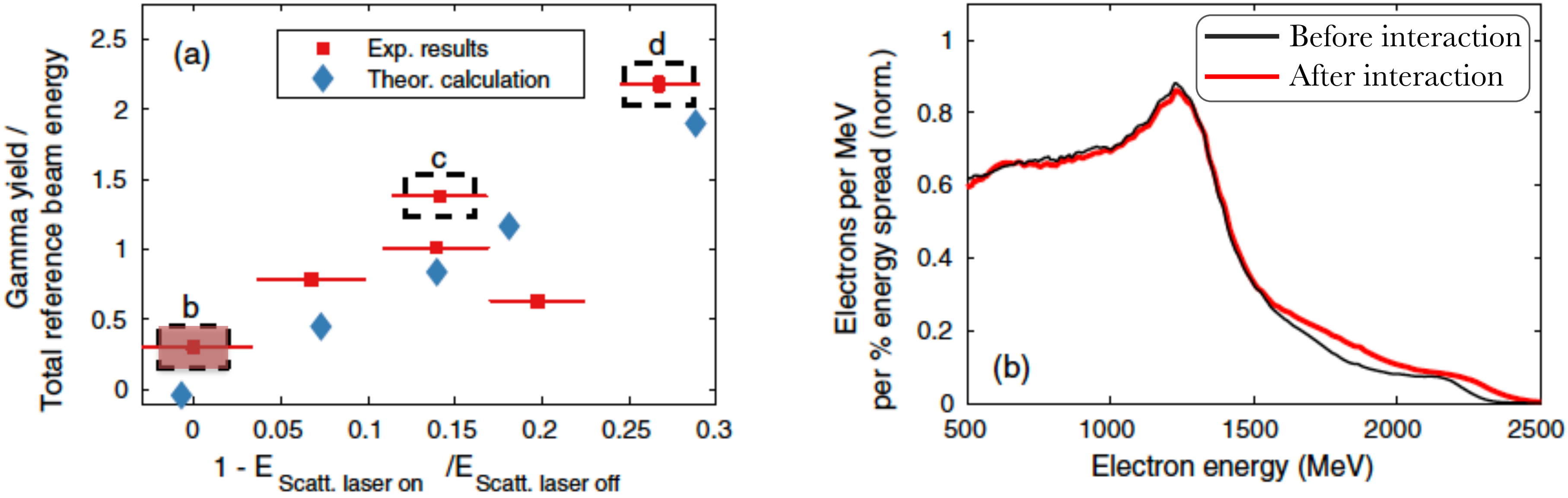
good electron-laser overlap → high photon yield, high energy loss

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

Collision diagnostic



Collision diagnostic



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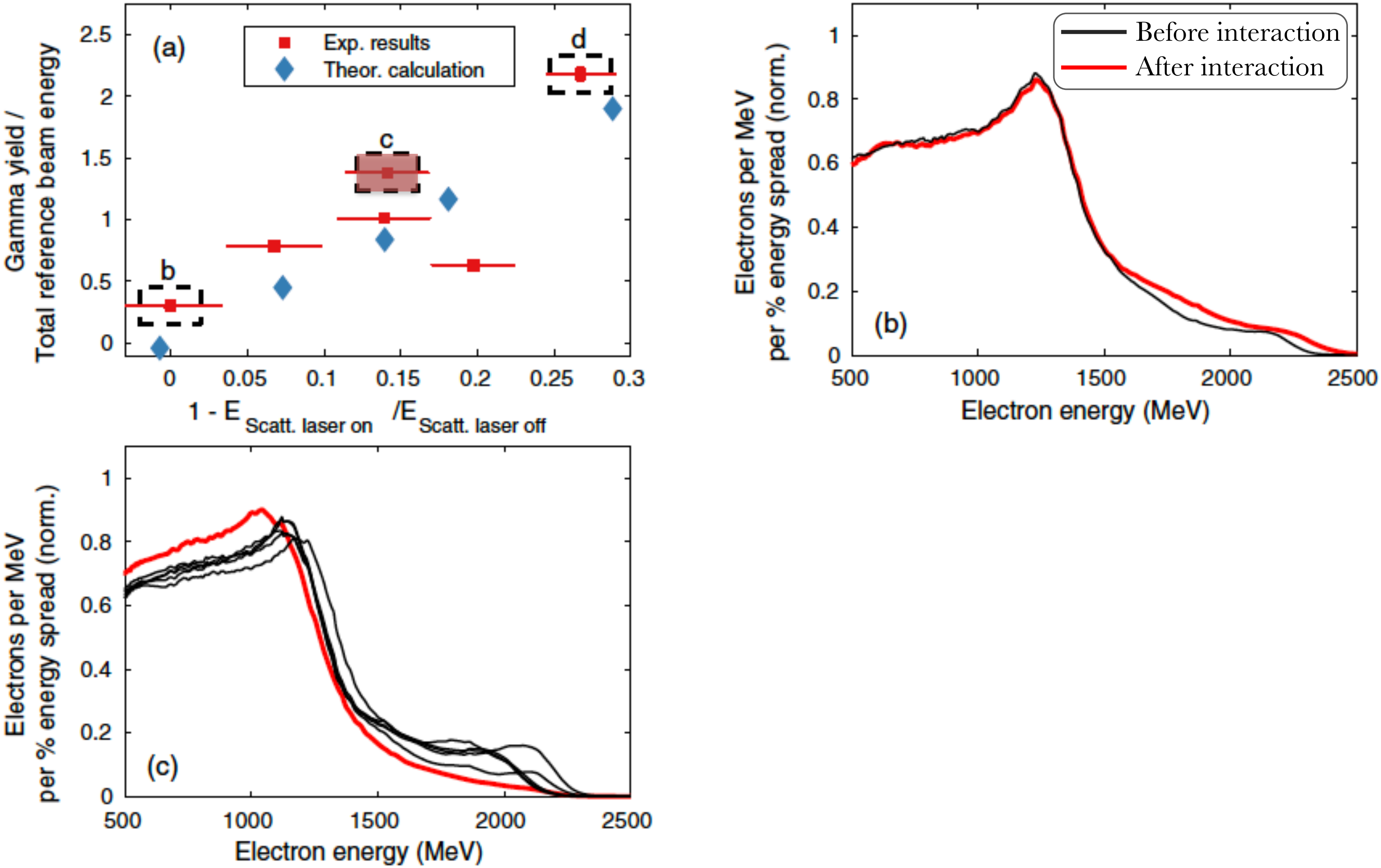
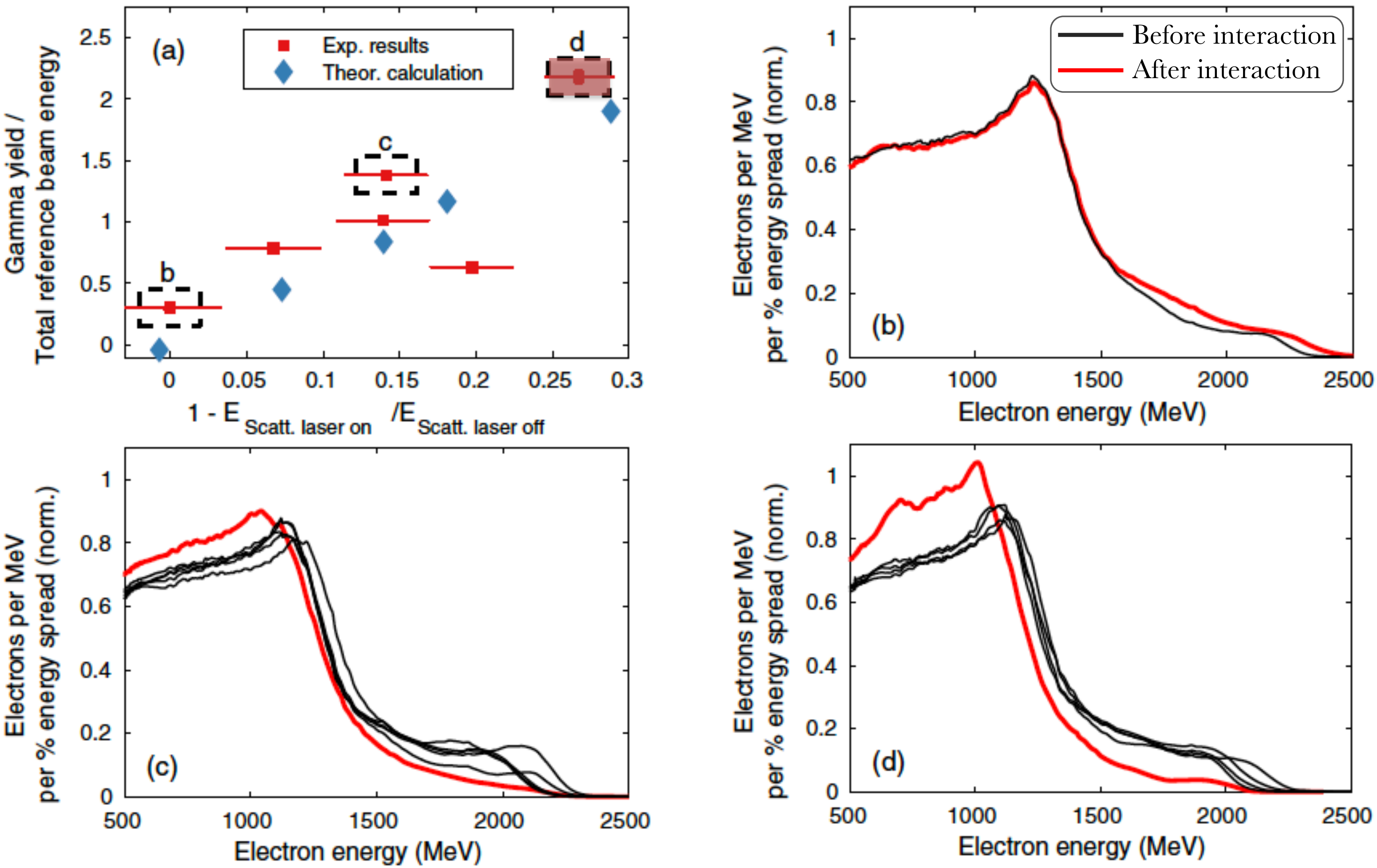
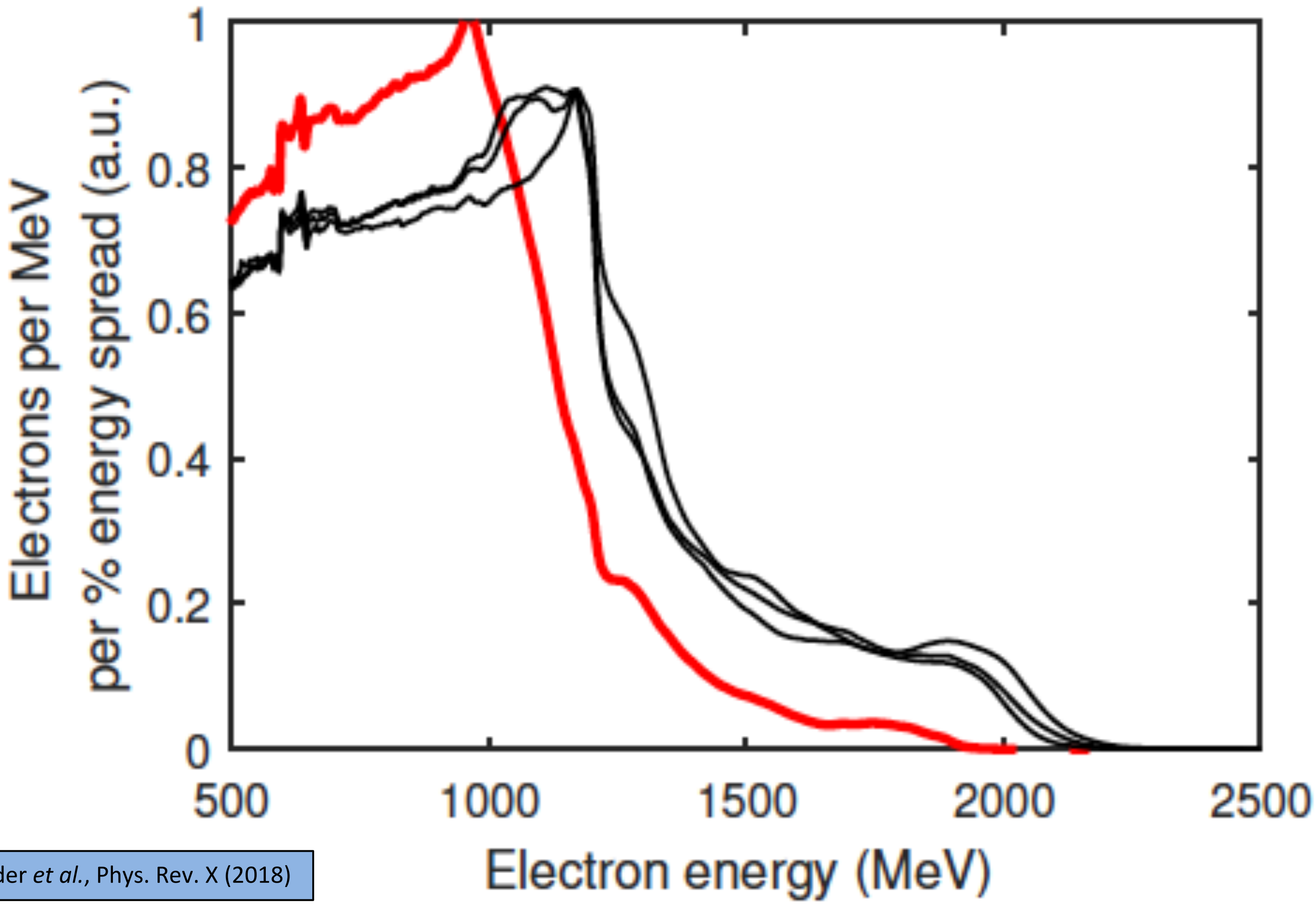


Collision diagnostic

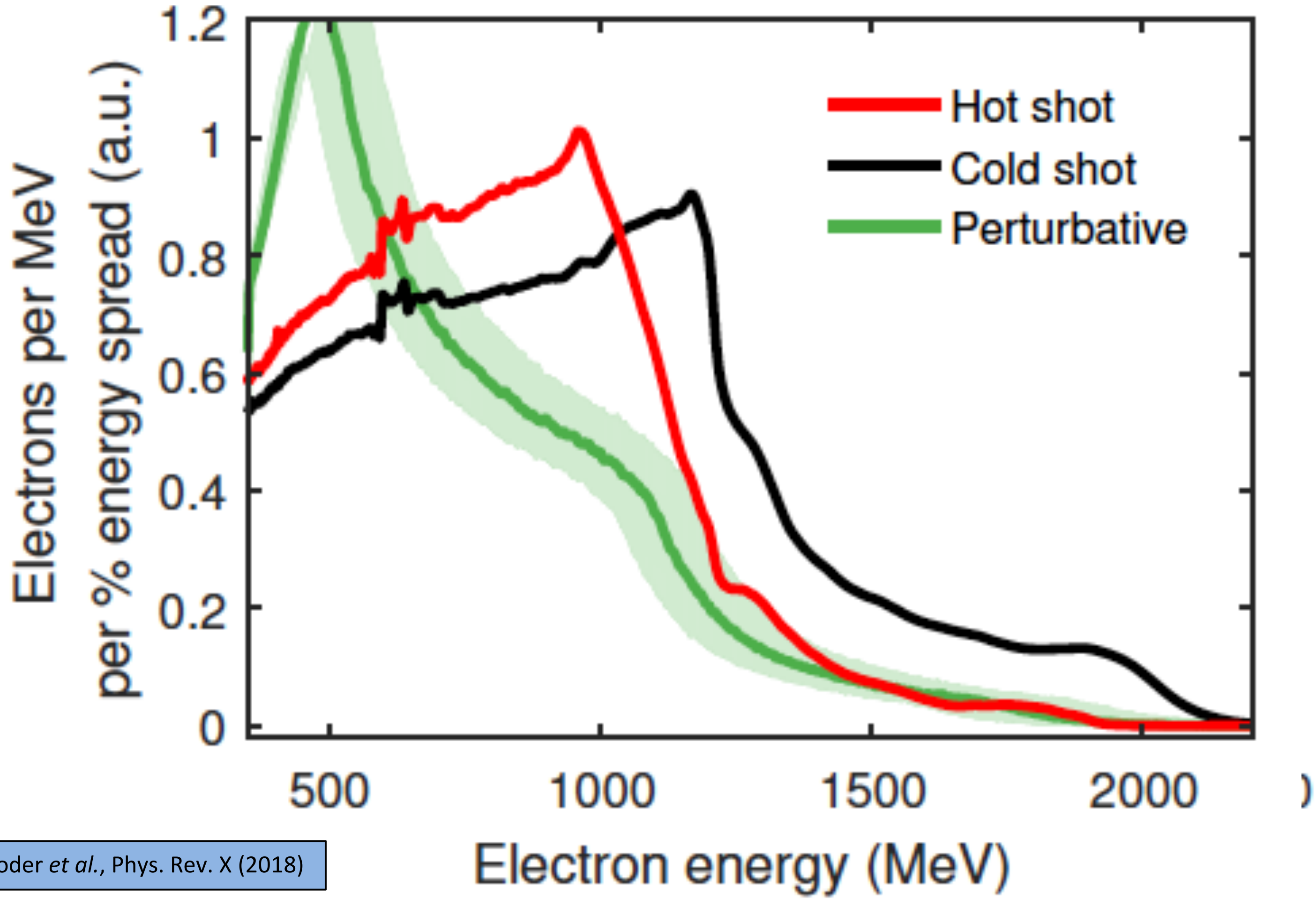


Comparison with theory



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

Comparison with theory



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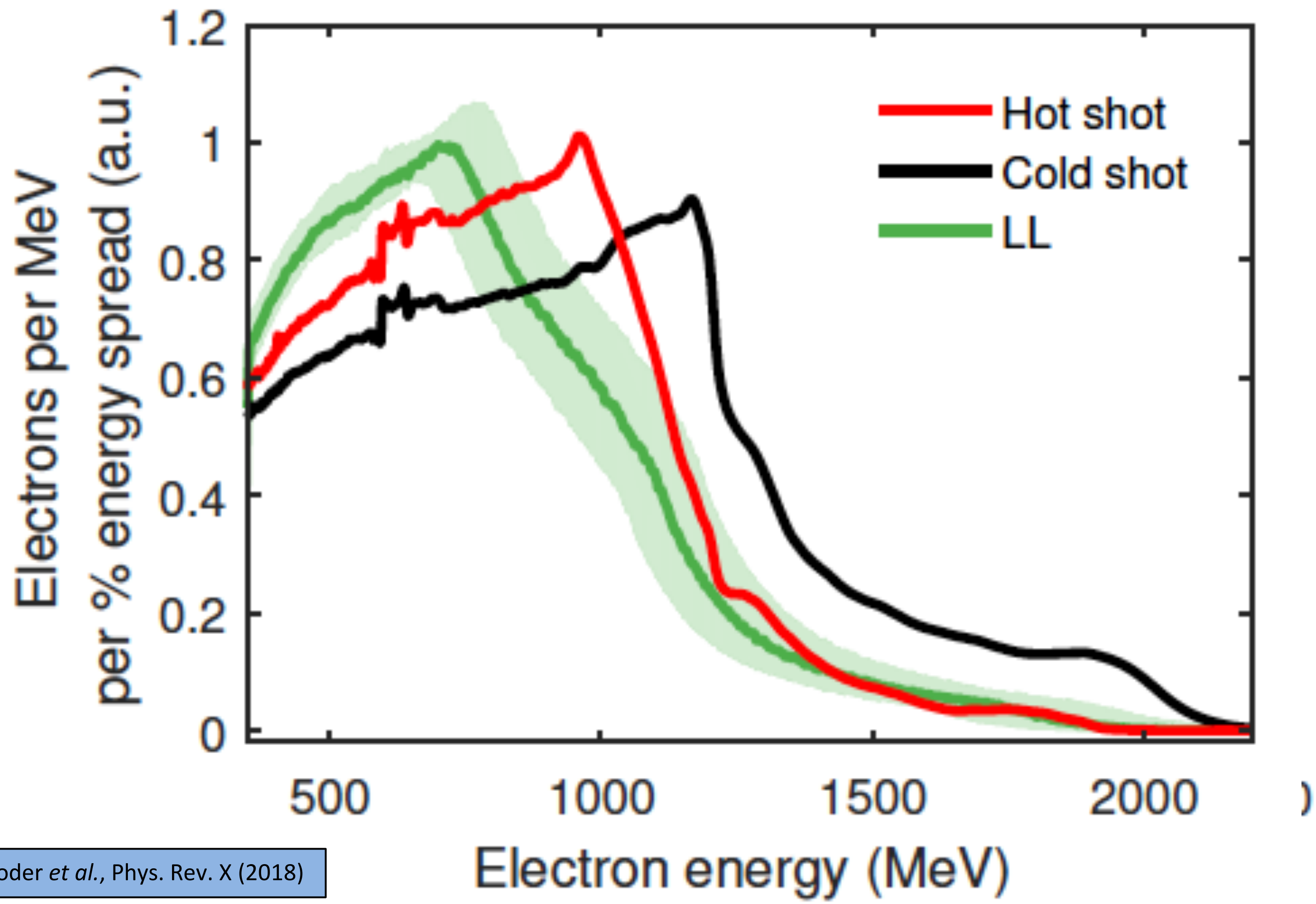

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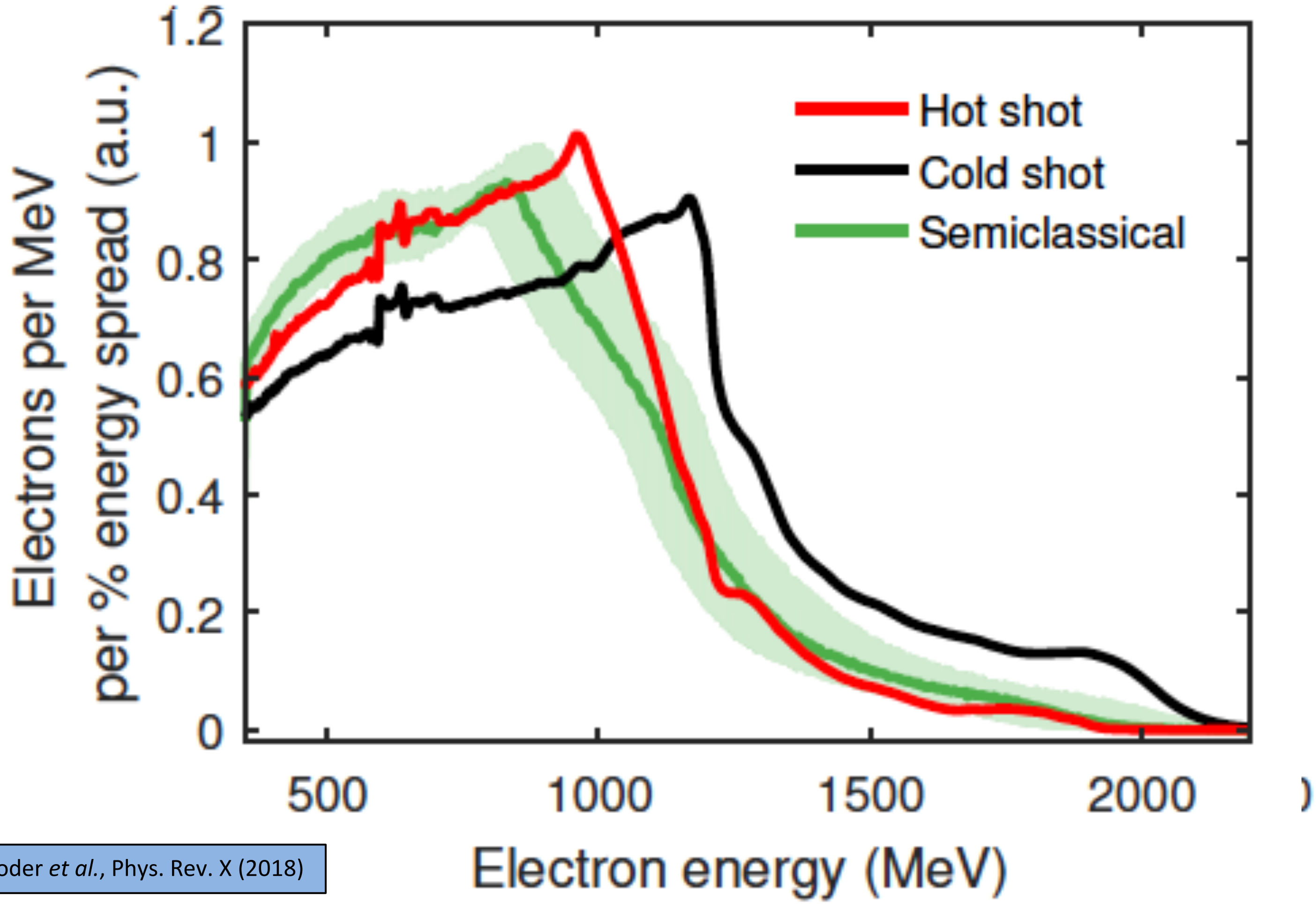
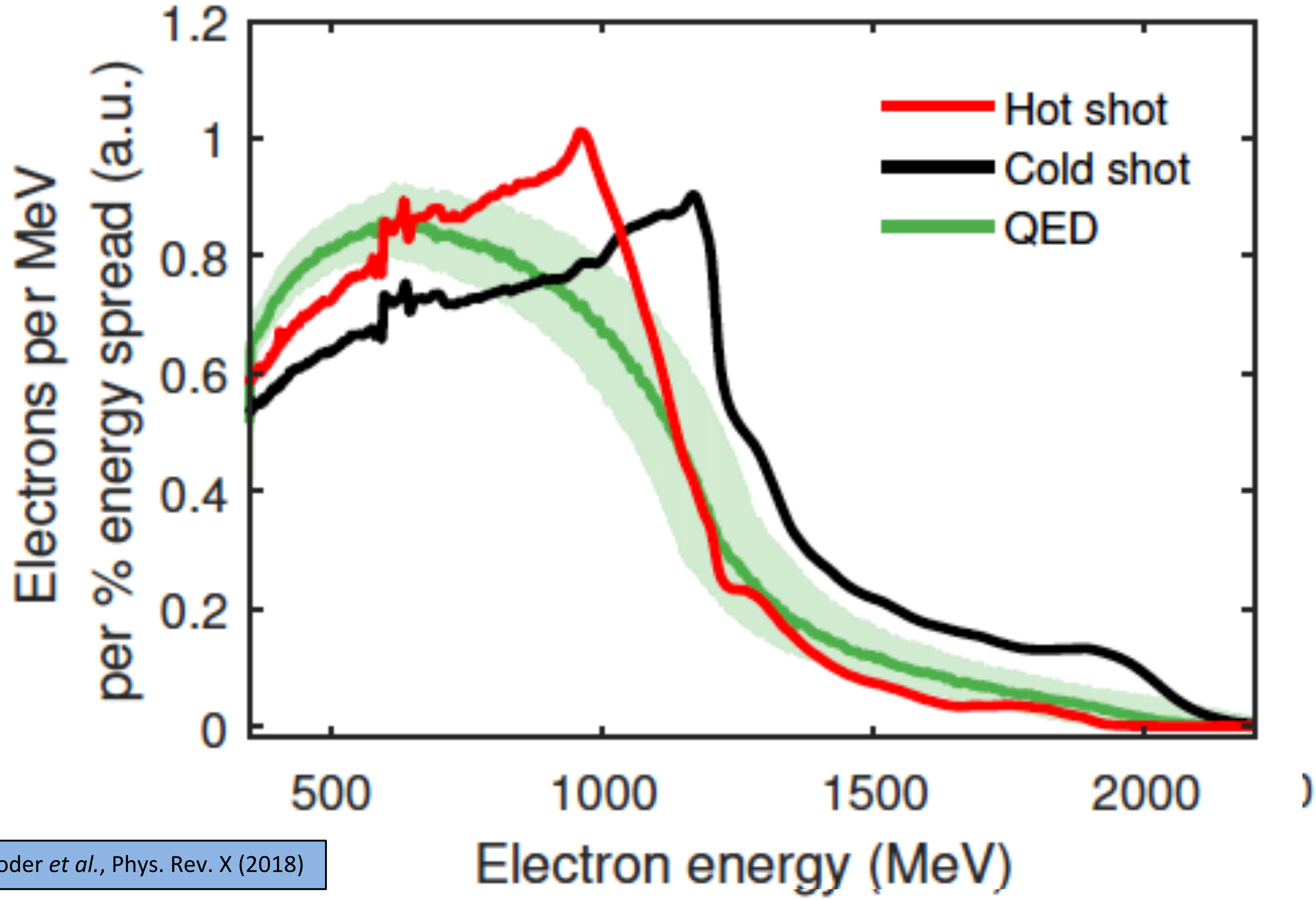


K. Poder *et al.*, Phys. Rev. X (2018)

Comparison with theory



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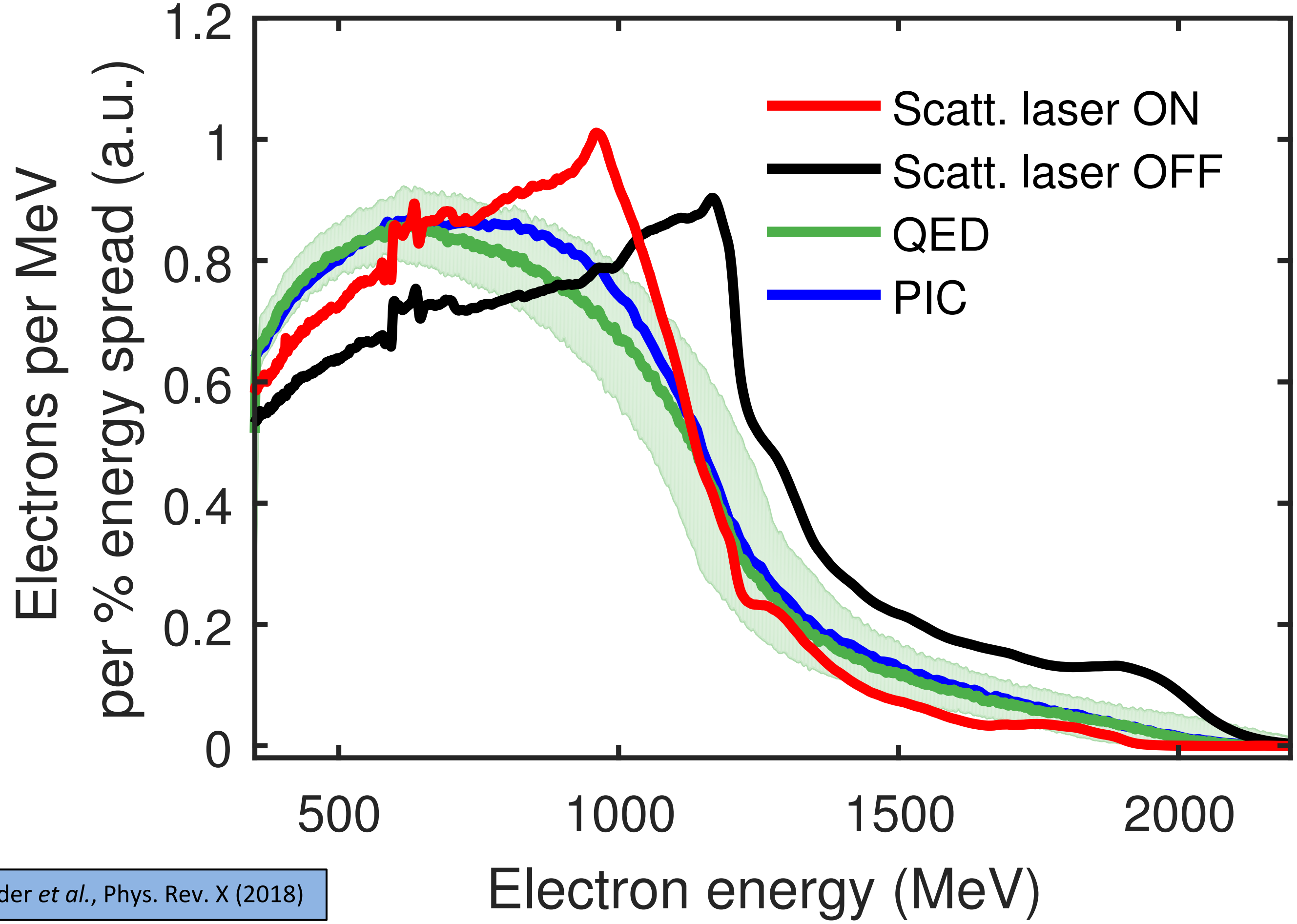
Comparison with theory



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

CCF approximation

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

Several possibilities:

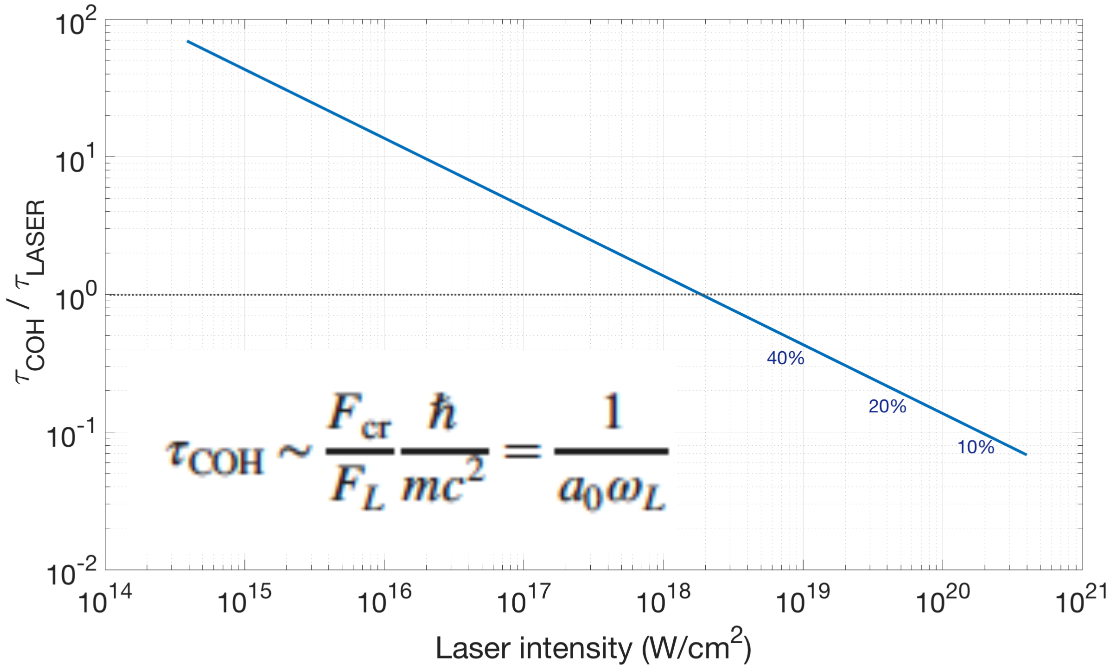
- **Incomplete knowledge of laser spectral phase**
- **Incomplete knowledge of longitudinal laser distribution**
- **…**

CCF approximation

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**
- ...

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



$$\tau_{COH} \sim \frac{F_{cr}}{F_L} \frac{\hbar}{mc^2} = \frac{1}{a_0 \omega_L}$$

This approximation is used to calculate

$g(\chi)$ in the semiclassical model

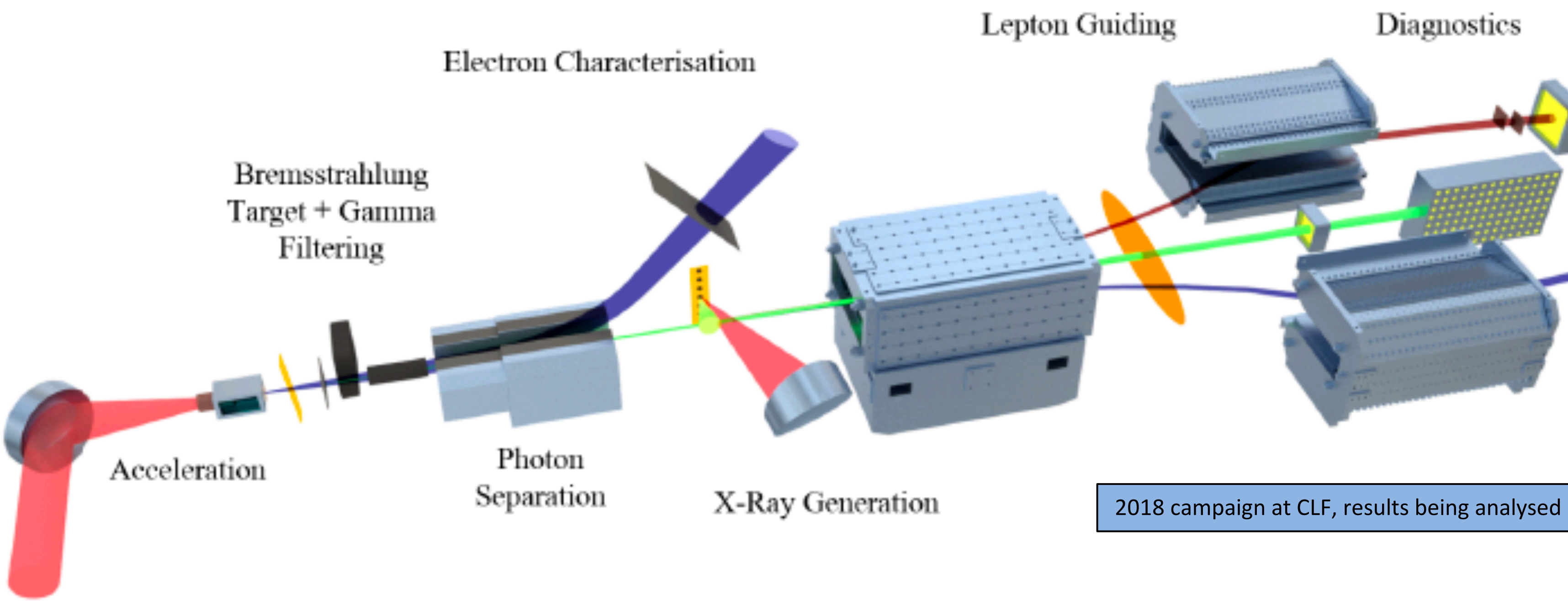
Photon emission probability in the QED model

Part 3
Recent experiments on pair production

Above-threshold pair production

For an electron-positron pair to be produced during the collision of two photons of energy E_1 and E_2, we need a centre of momentum energy of $\sqrt{E_1 E_2} > mc^2$: **Breit-Wheeler pair production**

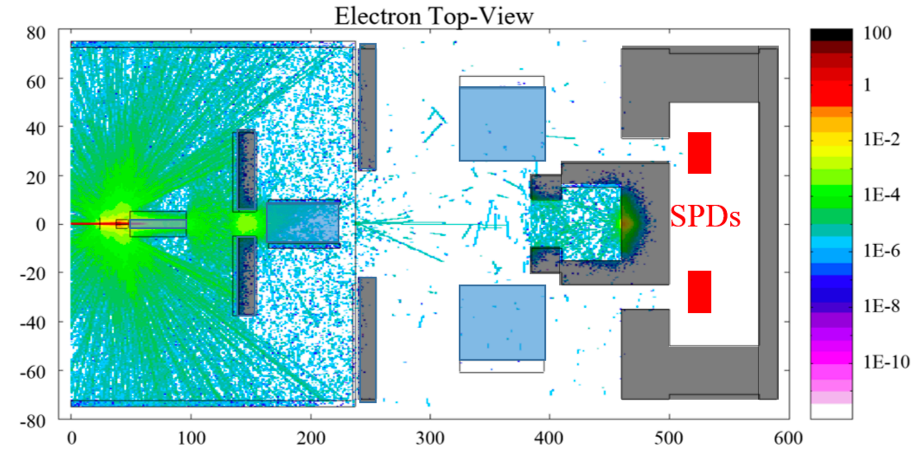
If we start with E_1 = 1.5 eV (laser photon) this means E_2 = 174 GeV (forget about it…)
but, with E_1 = 1.5 keV (X-ray photon) this means E_2 = 174 MeV!

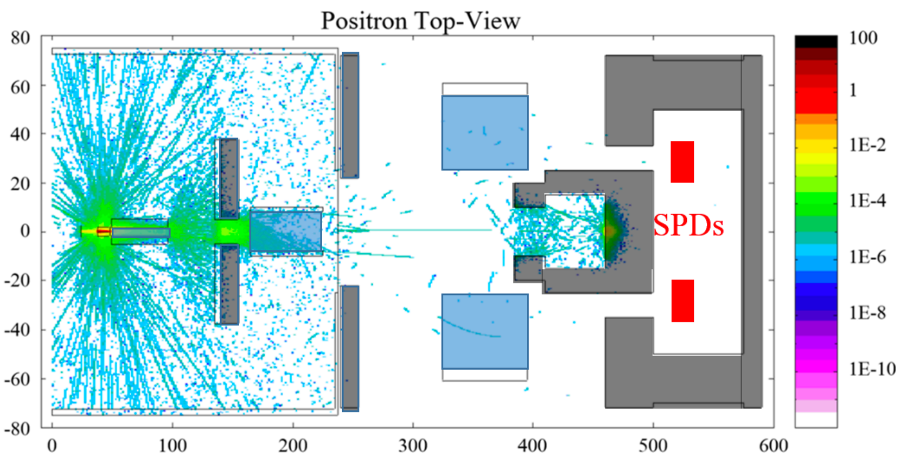


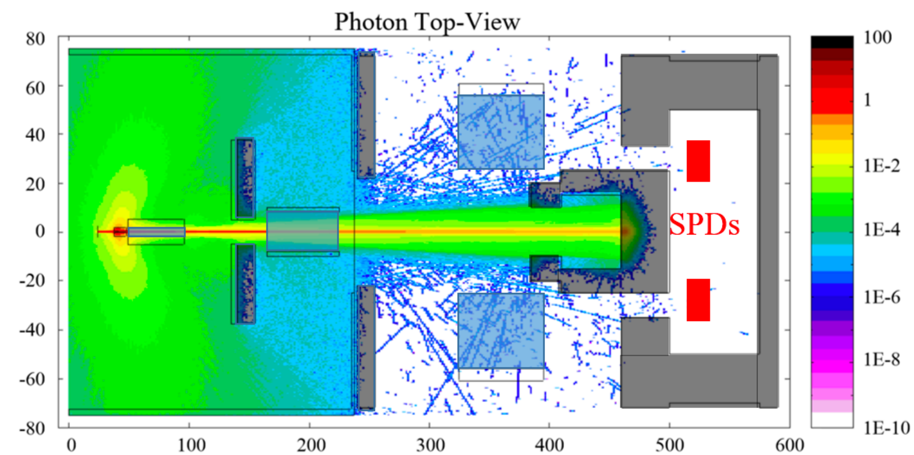
2018 campaign at CLF, results being analysed

Above-threshold pair production

A major issue in these experiments is that you require incredibly high signal-to-noise.
You want to measure a single particle (indeed, a fraction of a particle per shot) in an area flooded with secondary particles!

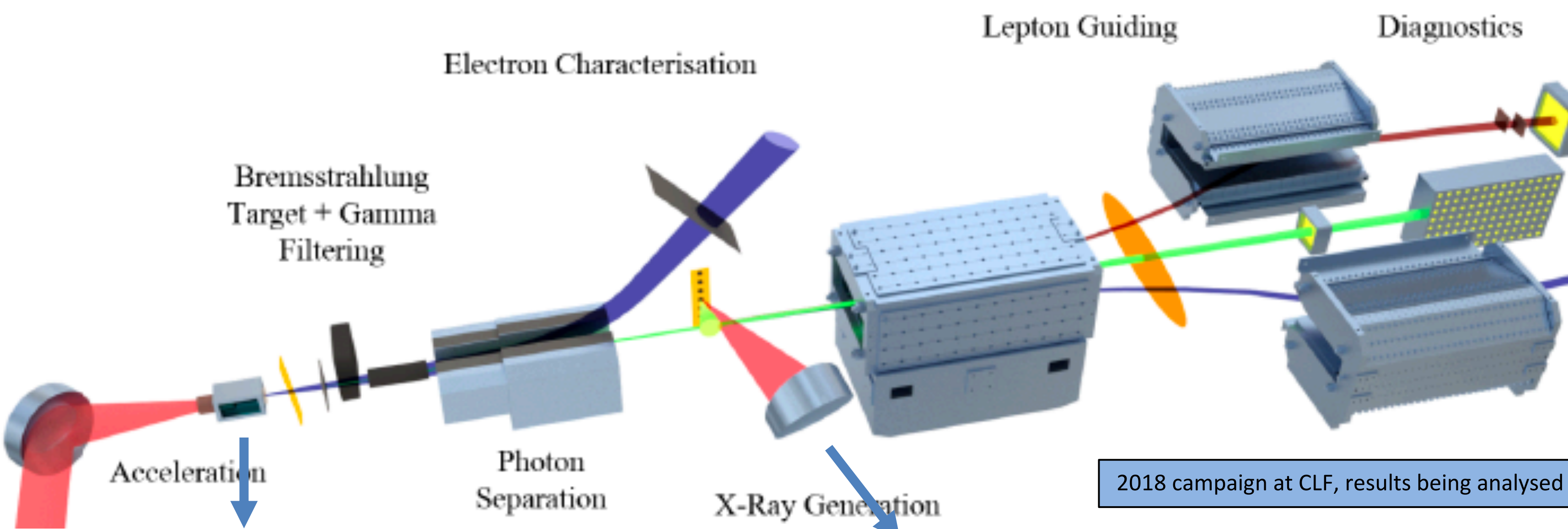




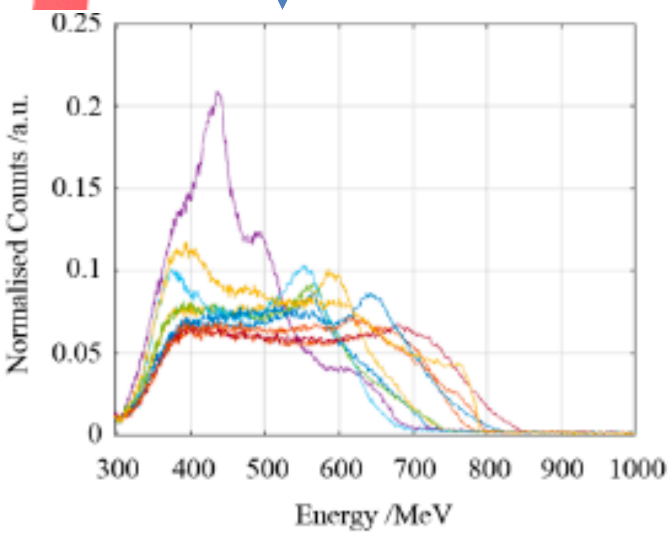


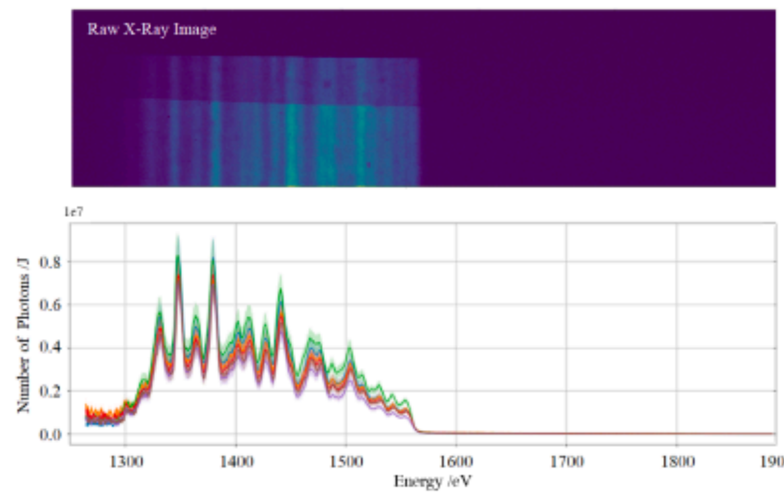
2018 campaign at CLF, results being analysed

Above-threshold pair production



2018 campaign at CLF, results being analysed



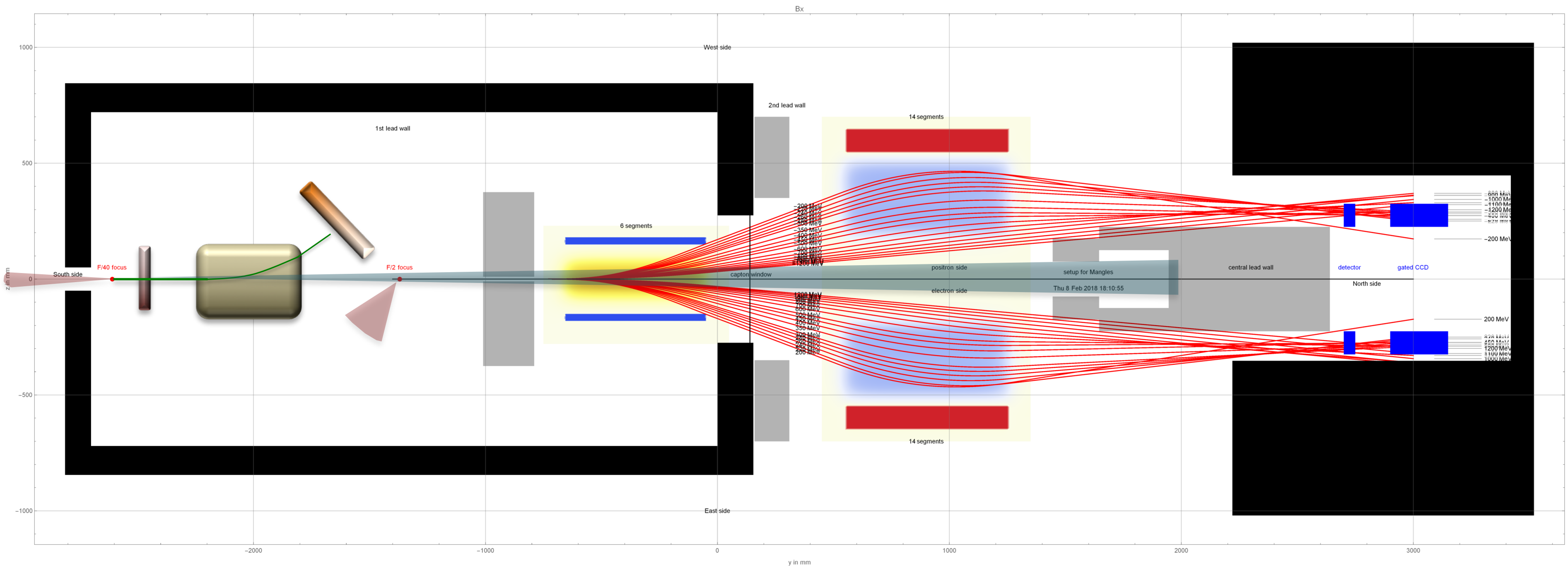


Below-threshold pair production

However, what if I can get N photons involved in one event? Then my threshold becomes

$$\sqrt{NE_1E_2} > mc^2$$ **Non-linear Breit-Wheeler pair production**

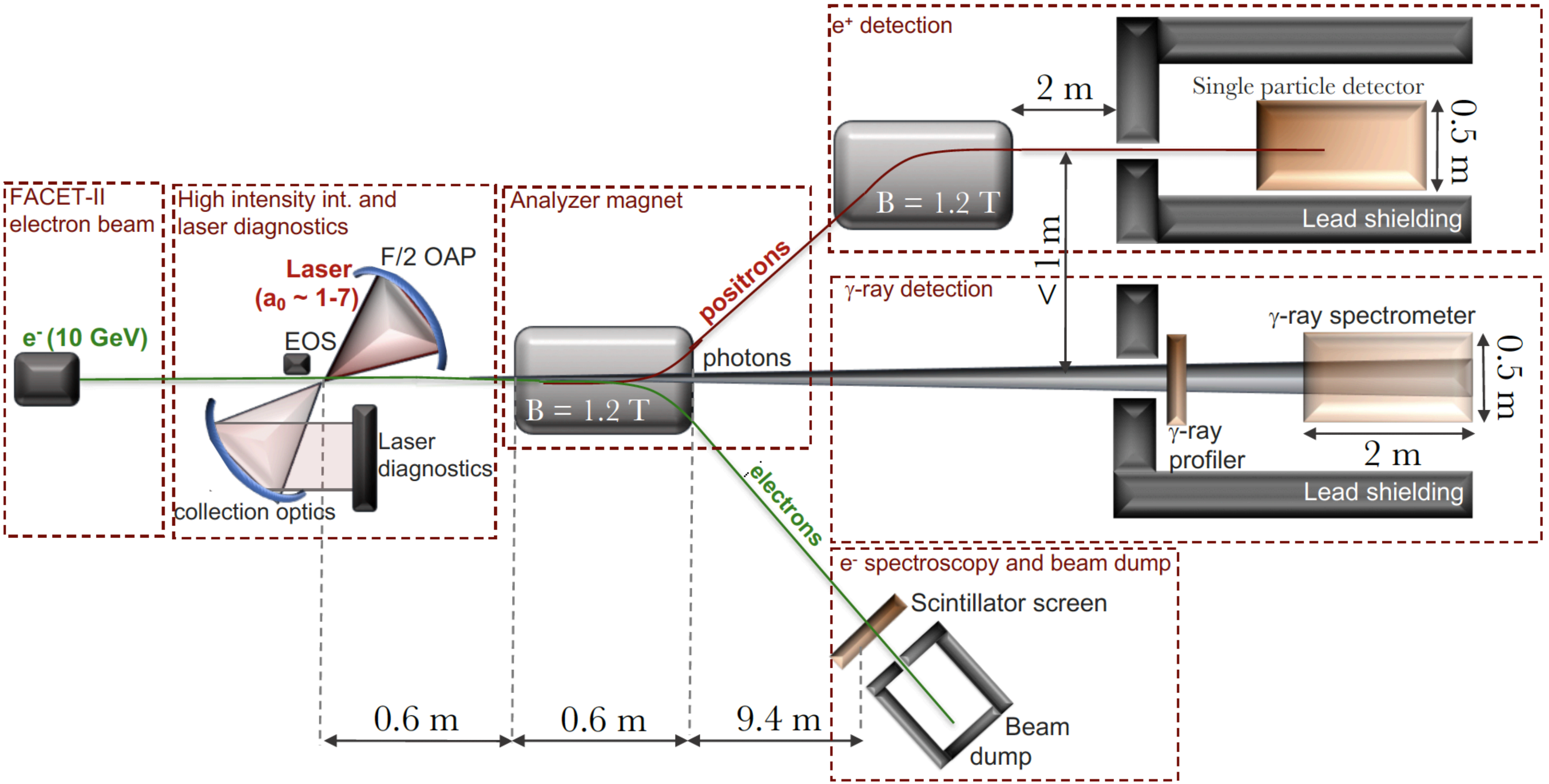
If we start with E_1 = 1.5 eV (laser photon) and E_2 =1 GeV (bremsstrahlung), then N ~ 170.



Part 4
Next experiments
E-320 at FACET-II

The E-320 experiment

FACET-II provides 13 GeV electron beams, which are already coupled with a low-power laser beam (20 TW)

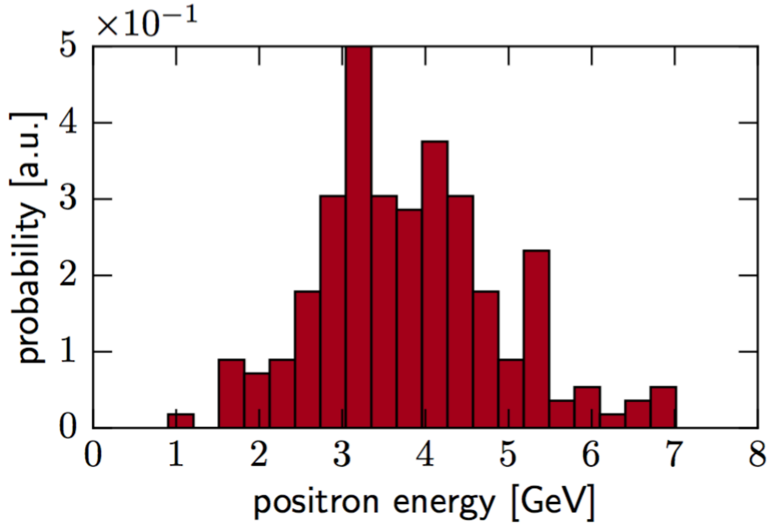


The E-320 experiment

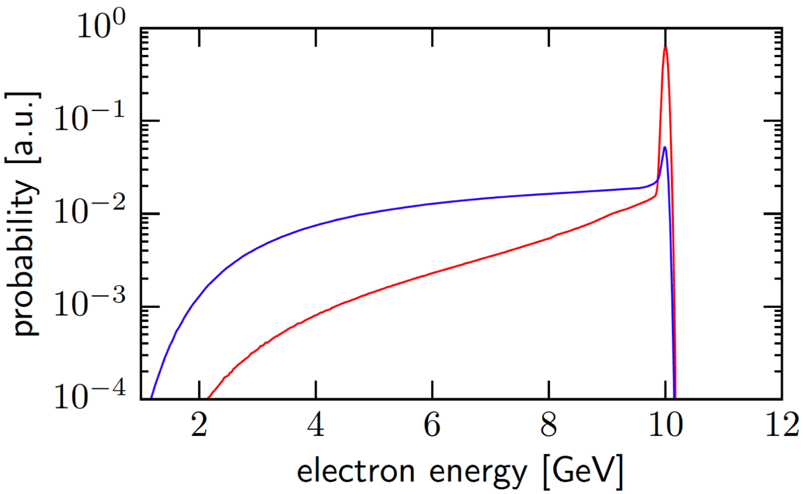
At FACET-II we aim (first shots in 2020) at measuring:

1. pair production in the laser field
2. quantum corrections to radiation reaction
3. non-linear Compton scattering (photon emission above the Compton edge)
4. breakdown of the LCFA

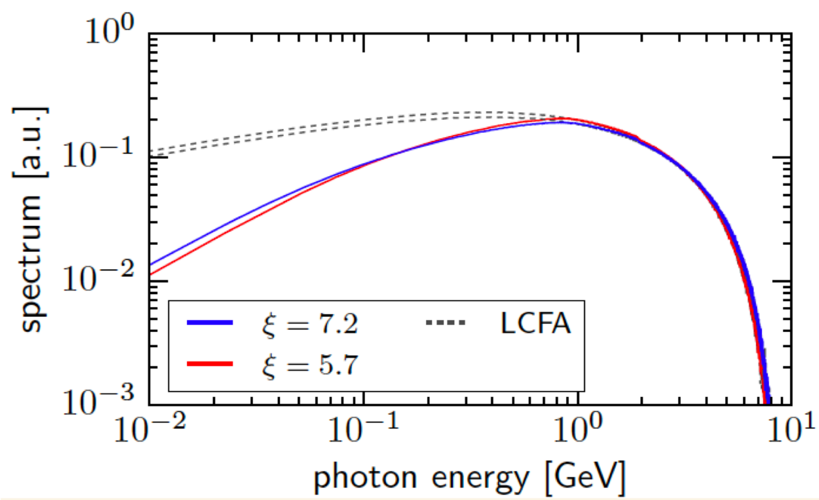
Pair production



Quantum Radiation Reaction



Non-linear Compton scattering



Part 5
Next experiments
LUXE at the EuXFEL

The LUXE experiment

The EuXFEL generates high-quality electron beams with the following characteristics:

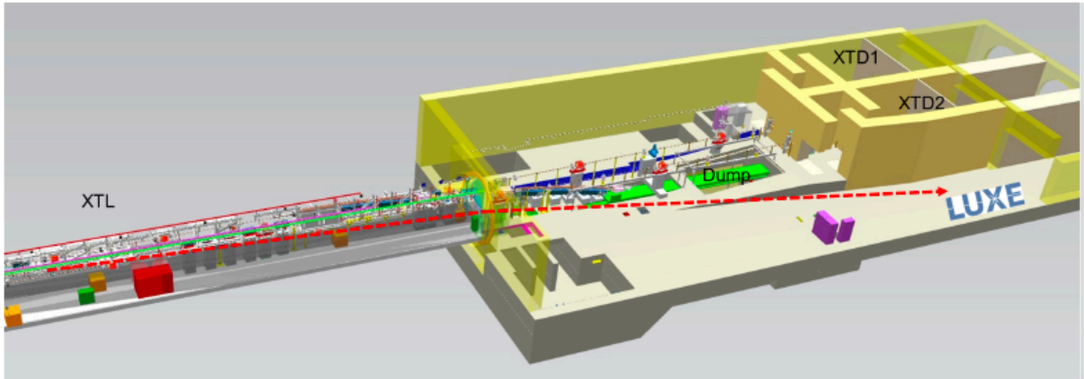
$E = 17.5$ GeV

$\Delta E/E = 2\text{x}10^{-4}$

$N = 10^9$

$f = 10$ Hz

What if we couple a high-intensity laser to it?



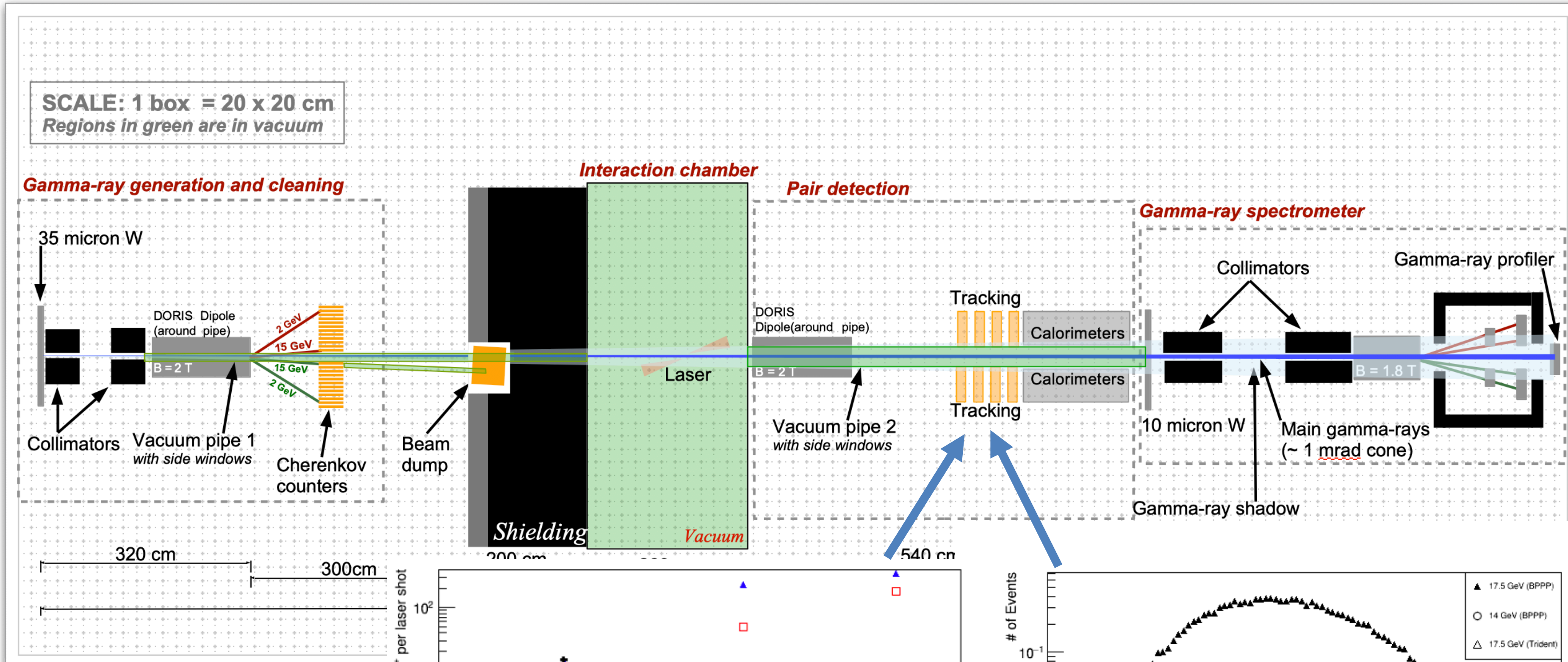
	30 TW, 8μm	300 TW, 8μm	300 TW, 3μm
Laser energy after compression (J)	0.9	9	9
Percentage of laser in focus (%)	40	40	40
Laser energy in focus (J)	0.36	3.6	3.6
Laser pulse duration (fs)	30	30	30
Laser focal spot FWHM (μm)	8	8	3
Peak intensity in focus (Wcm^{-2})	1.6×10^{19}	1.6×10^{20}	1.1×10^{21}
Dimensionless peak intensity, ξ	2	6.2	16
Laser repetition rate (Hz)	1	1	1
Electron-laser crossing angle (rad))	0.35	0.35	0.35

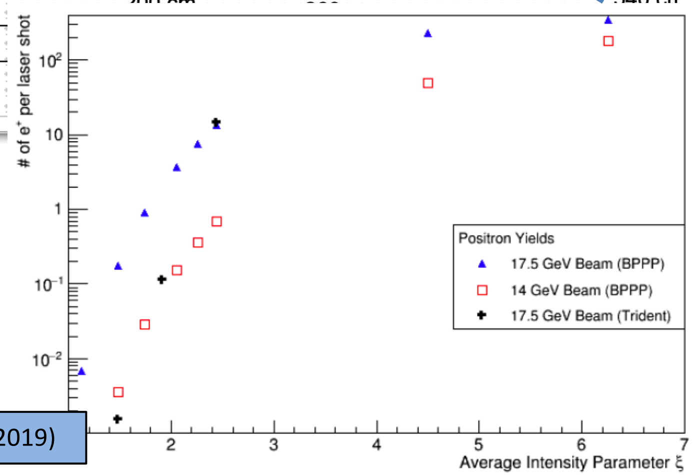
17.5 GeV electrons

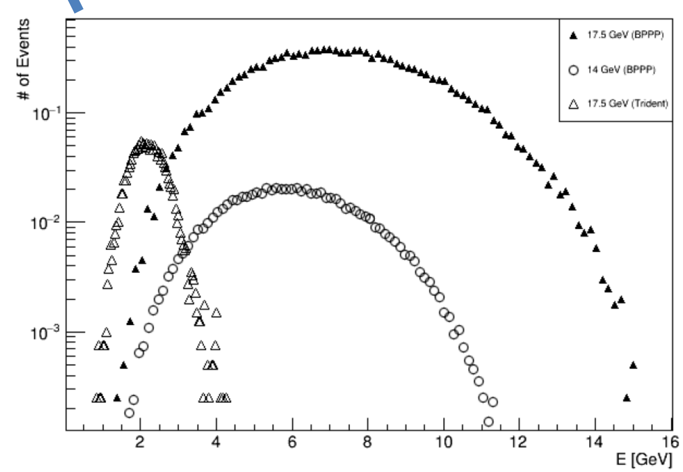
Electron Lorentz factor	3.4×10^4	3.4×10^4	3.4×10^4
Quantum parameter χ	0.41	1.26	3.26

LUXE collaboration ArXiv:1909.00860 (2019)

The LUXE experiment







LUXE collaboration ArXiv:1909.00860 (2019)

The LUXE experiment

What is unique about the LUXE experiment?

The only experiments in the area are the E-144 at SLAC and the Gemini experiments

E – 144 and Gemini	**LUXE**
X **$\chi \sim 0.2$**	✓ **$\chi \sim 1$** even for a 30 TW laser
X the E-144 still operated in a quasi-linear regime ($a_0 \sim 0.3$) ***perturbative non-linearities in Compton scattering***	✓ high a_0 implies ***strong non-linearities*** in Compton scattering and pair production
X ***lack of parametric studies in intensity***	✓ systematic and precision ***parametric studies***
X ***no direct photon-photon studies***	✓ ***pure non-linear Breit-Wheeler*** above and below threshold
X ***difficult to secure sustained access***	✓ easily upgradable → sustained campaigns
	✓ exotic physics at the ***intensity frontier!***

Equipment cost for phase 1 ~ 30 M€
input from European and national funding agencies

LUXE collaboration ArXiv:1909.00860 (2019)

Part 6
Next experiments
E6 area at ELI-NP

QUEEN'S UNIVERSITY BELFAST

The E6 area at ELI-NP

LaserFocusWorld

World's most powerful laser, developed by Thales and ELI-NP, achieves record power level of 10 PW

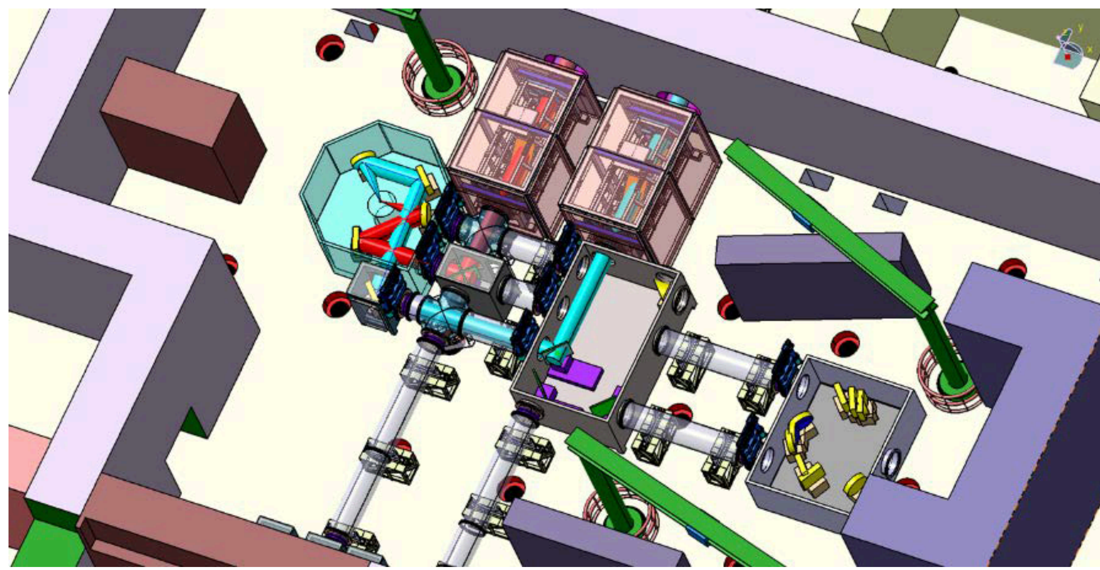
After delivering pulses of 7 PW for more than 4 h continuously, the Thales system reached 10 PW on 7 March 2019.

Assuming 60% of it in a 3μm FWHM focal spot, we get

$I = 6x10^{22}$ Wcm^{-2} ($a_0 > 100$)

If we couple it with a 5 GeV electron beam, **$\chi \sim 7$!**

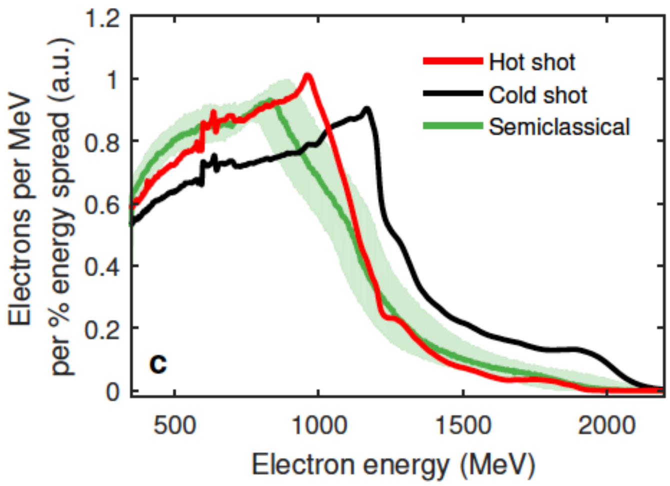
First commissioning experiments end 2020



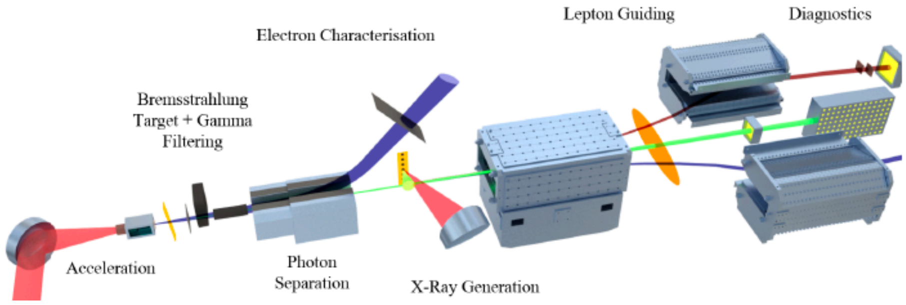
Conclusions

Conclusions

First experiments in CLF showed hints of the quantum nature of radiation reaction ($\chi \sim 0.2$)

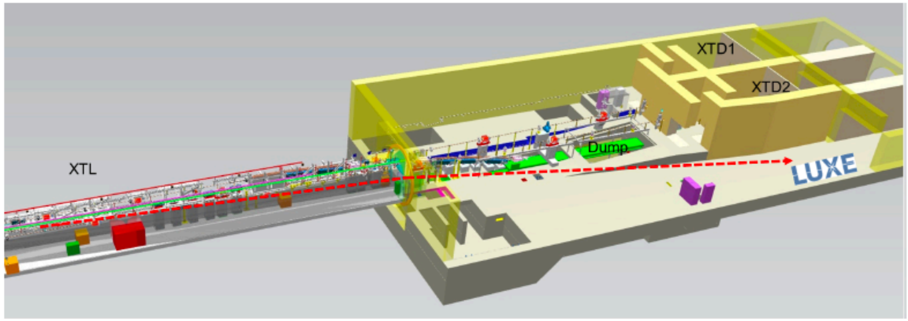


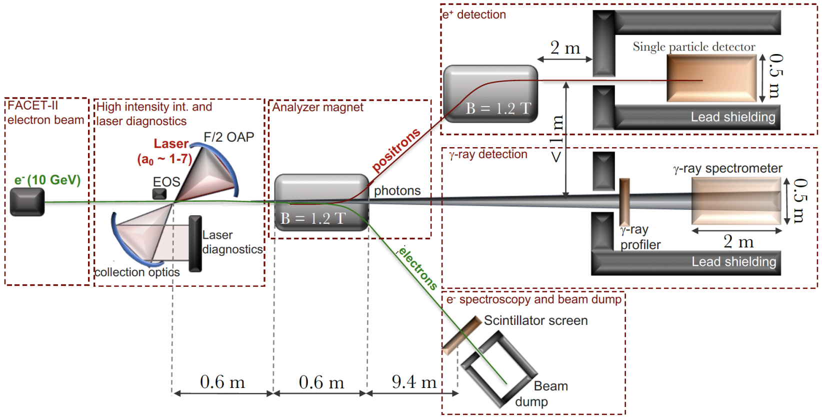
First attempts at studying pair production from photon-photon collisions (**Breit Wheeler**)



E-320 experiment at FACET-II
(13 GeV electrons and 20 TW laser)

LUXE experiment at EuXFEL
(17.5 GeV electrons and 30 - 300 TW laser)





Thanks for your attention!

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Main publications
[1] D. J. Corvan et al., Rev. Sci. Instrum. 85, 065119 (2014)
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[3] D. J. Corvan et al., Optics Express 24, 3127 (2016)
[4] K. T. Behm et al., Rev. Sci. Instrum 89, 113303 (2018)
[5] K. Poder et al., Phys. Rev. X 8, 031004 (2018)
[6] J. Cole et al., Phys. Rev. X 8, 011020 (2018)
[7] LUXE collaboration ArXiv:1909.00860 (2019