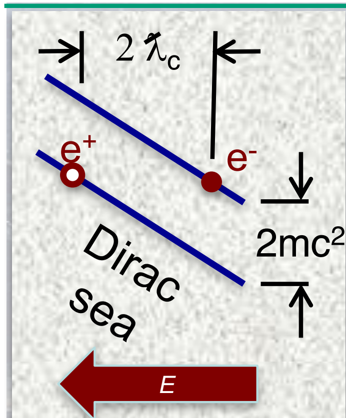
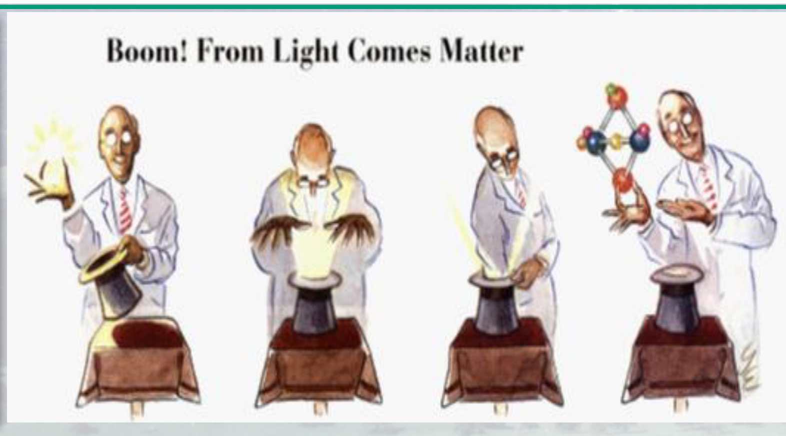


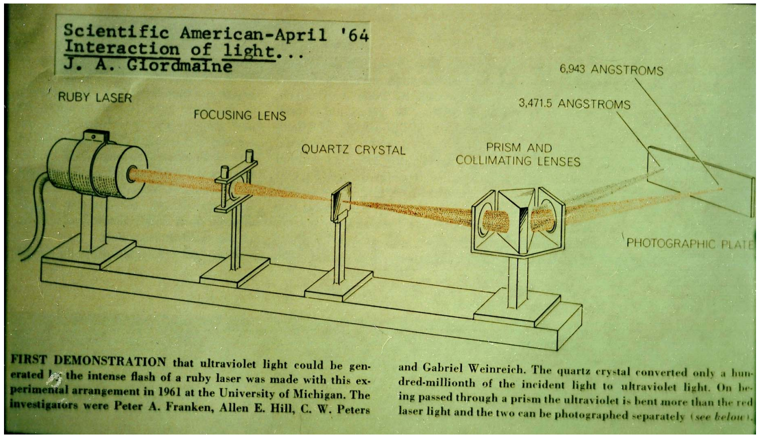


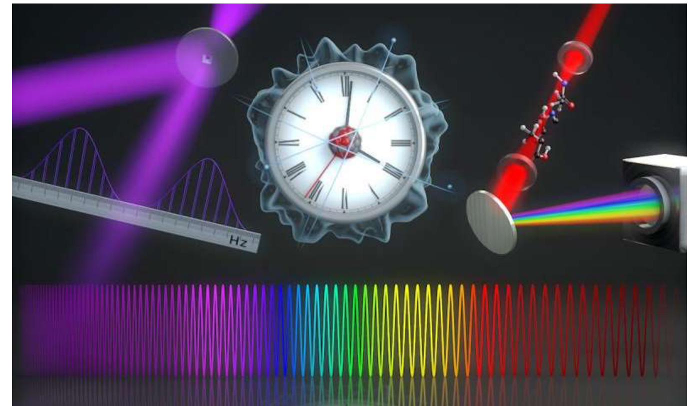
Experiments in Strong-field QED

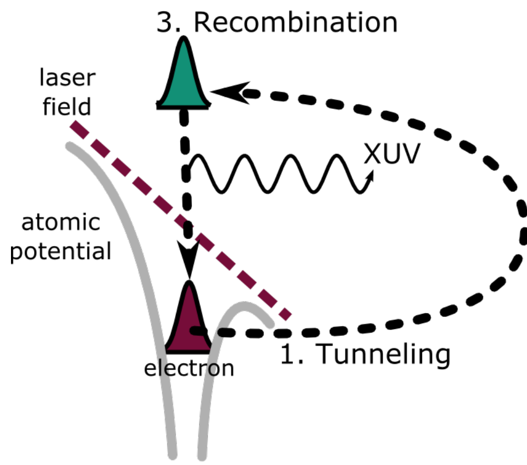
David A. Reis
Stanford PULSE Institute
Departments of Applied Physics and Photon Science

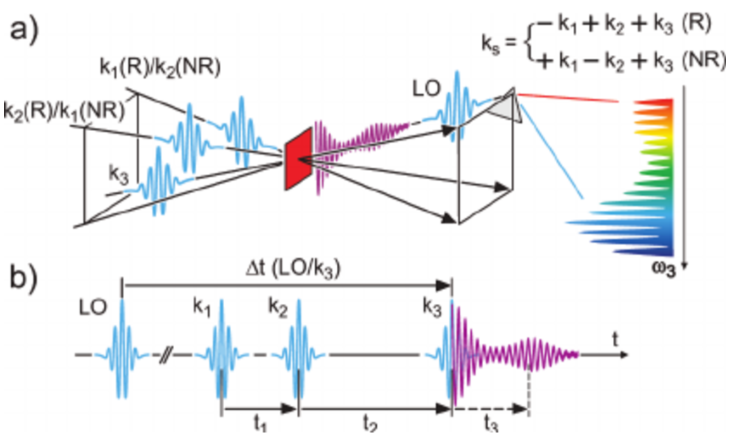
SLAC FPD Experimental Seminar, Tuesday Nov. 13, 2018

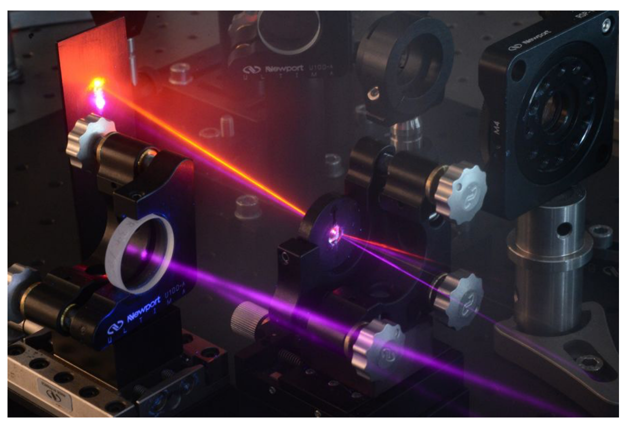
nonlinear optics ubiquitous in matter at long-wavelengths

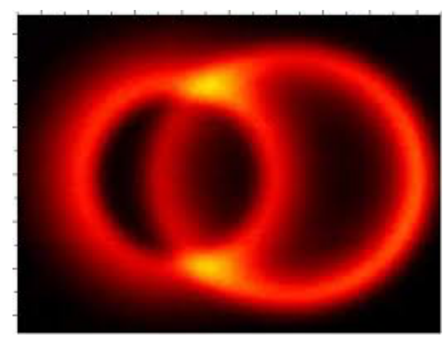












Nonlinear response

$$\chi = \chi(E), \sigma = \sigma(E)$$

Nonrelativistic, perturbative

$$\vec{P} = \epsilon_0 \chi^{(1)} \vec{E} + \chi^{(2)} \vec{E}\vec{E} + \chi^{(3)} \vec{E}\vec{E}\vec{E} + \dots$$

$$\vec{J} = \sigma^{(1)} \vec{E} + \sigma^{(2)} \vec{E}\vec{E} + \sigma^{(3)} \vec{E}\vec{E}\vec{E} + \dots$$

$$E \ll E_a$$

bound-electrons

$$\eta = \frac{eE_{\mathrm{rms}}}{m\omega c} \ll 1$$

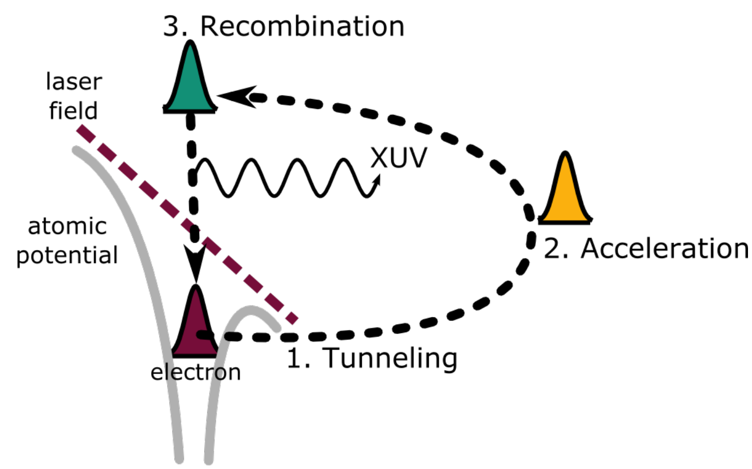
free-electrons/plasma

wave mixing, multi-photon absorption/ionization, self-focusing, …

Nonrelativistic, nonperturbative

$$E \sim E_a$$

$$U_p = \frac{(eE_{\mathrm{rms}})^2}{2m\omega^2} \gtrsim \hbar\omega$$



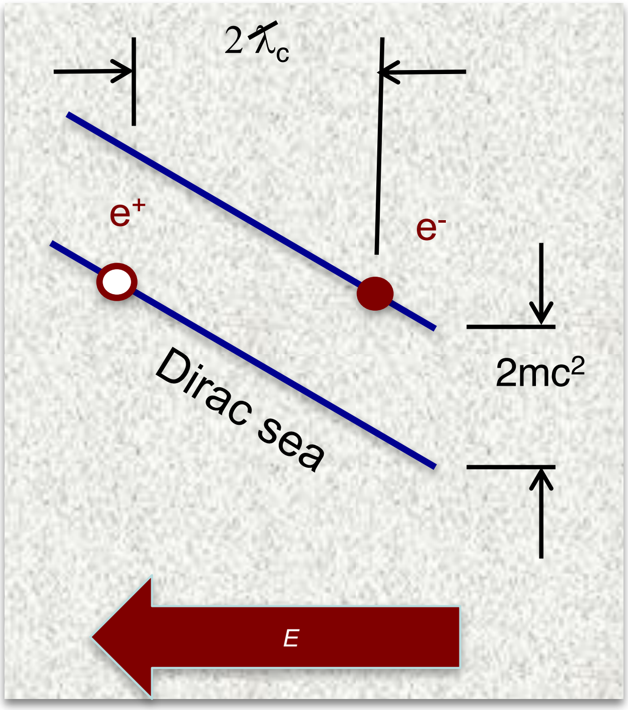
above threshold ionization, high-harmonic generation

Quantum Electrodynamics (QED)

Stanford PULSE Institute

- **Relativistic quantum field theory describing light-matter interaction including quantum vacuum**
- **Most precisely tested theory in weak field regime, perturbative in $\alpha \sim 1/137$**
  - Lamb Shift
  - Anomalous magnetic moment
- **Few tests in multiphoton regime (pair production, birefringence of vacuum…)**
- **strong-field, non-perturbative sector untested and theoretically challenging.**

QED Critical Field ("Schwinger Field")



Photonics Spectra, Nov. 1997

- Materialize pairs when work done in (reduced) Compton wavelength equal rest mass $eE_{cr}\lambda\!\!\!^{-}_c = mc^2$

$$E_{cr} = \frac{m^2c^4}{e\hbar c} = 1.3 \times 10^{16} \mathrm{V/cm}$$

(four orders higher for $\mu^+\mu^-$)

- Exponentially suppressed $E < E_{cr}$
- Critical intensity for EM-field (peak):

$$I_{cr} = 4.6 \times 10^{29} \mathrm{W/cm}^2$$

- Need to also conserve momentum (not possible in single plane-wave)

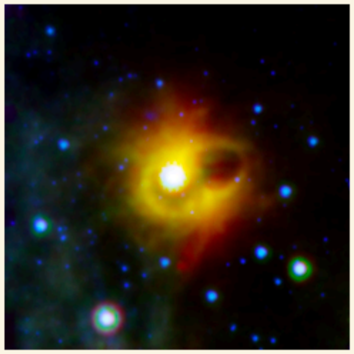
Sauter (1931), Euler, Heisenberg, Schwinger

Why care about strong-field QED

Stanford PULSE Institute

Astrophysics

Magnetar
SGR 1900+14

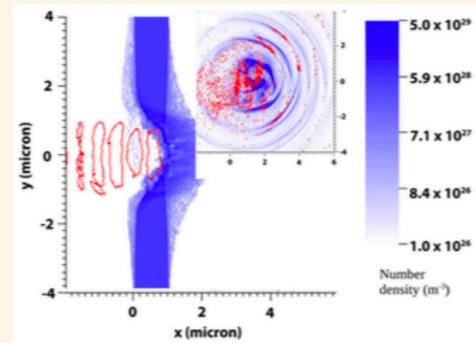


McGILL MAGNETAR CATALOG

Name	B (10^{14} G)
CXOU J010043.1−721134	3.9
4U 0142+61	1.3
SGR 0418+5729	0.061
SGR 0501+4516	1.9
SGR 0526−66	5.6
1E 1048.1−5937	3.9
1E 1547.0−5408	3.2
PSR J1622−4950	2.7
SGR 1627−41	2.2
CXOU J164710.2−455216	<0.66
1RXS J170849.0−400910	4.6
CXOU J171405.7−381031	5.0
SGR J1745−2900	1.6
SGR 1806−20	20
XTE J1810−197	2.1
Swift J1822.3−1606	0.51
SGR 1833−0832	1.6
Swift J1834.9−0846	1.4
1E 1841−045	6.9
SGR 1900+14	7.0
1E 2259+586	0.59

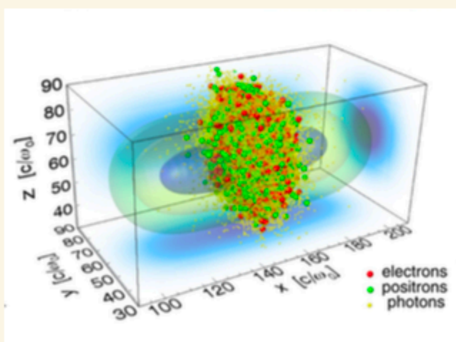
Laser-solid interaction (10 PW)

Ridgers et al. PRL
108, 165006 (2012)

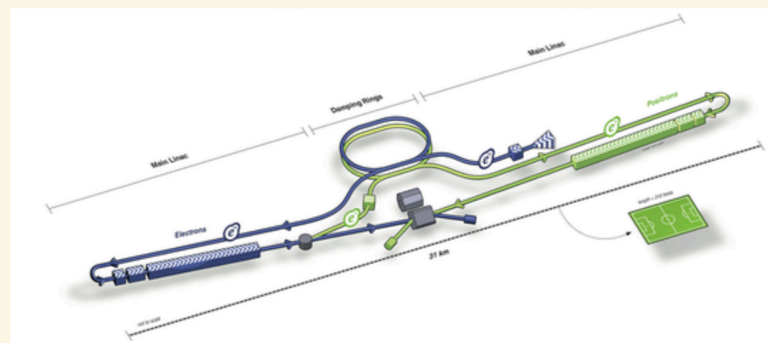


QED cascades (10-100 PW)

Grismayer et al. PRE
95, 023210 (2017)



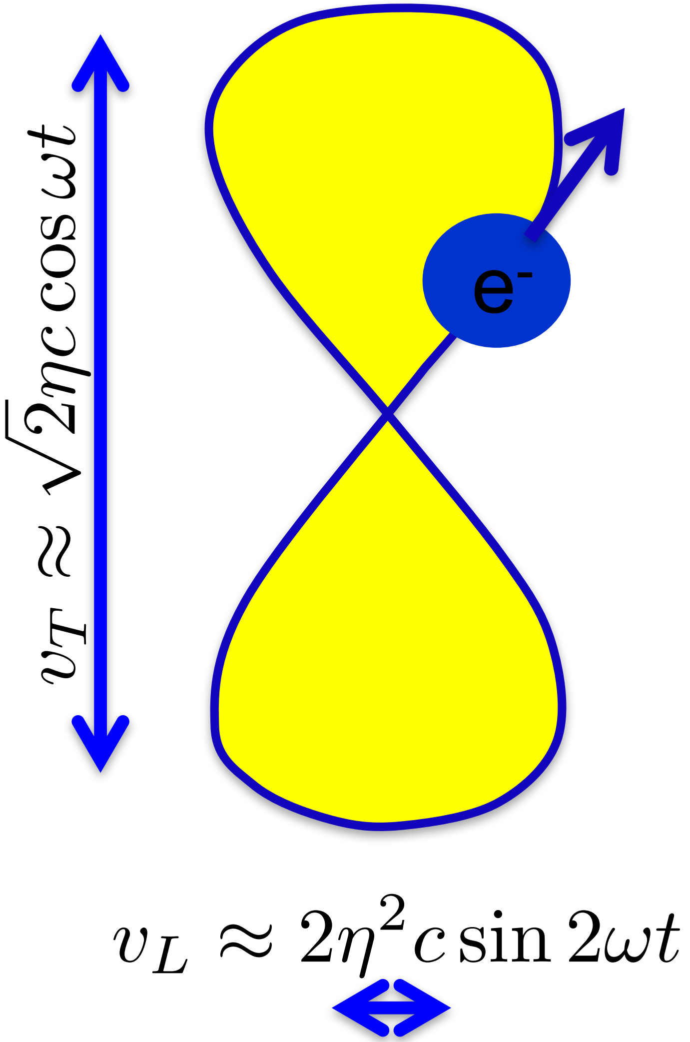
Linear lepton collider



- Astrophysics: magnetic fields $B \gtrsim B_{\mathrm{cr}} = m^2c^2/\hbar e$ ≈ 4.4×10^9 T
- Laboratory laser-plasma and laser-laser collisions: requires 10^{24} W/cm^2
- Future high-luminosity lepton collider (CLIC, ILC): strong space charge

“free” electron in strong (linear pol.) field

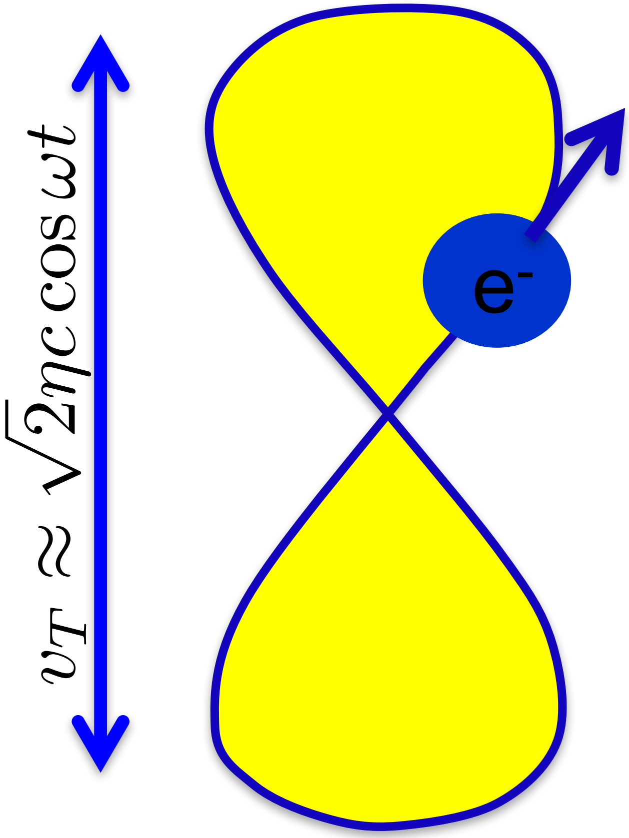
Stanford PULSE Institute



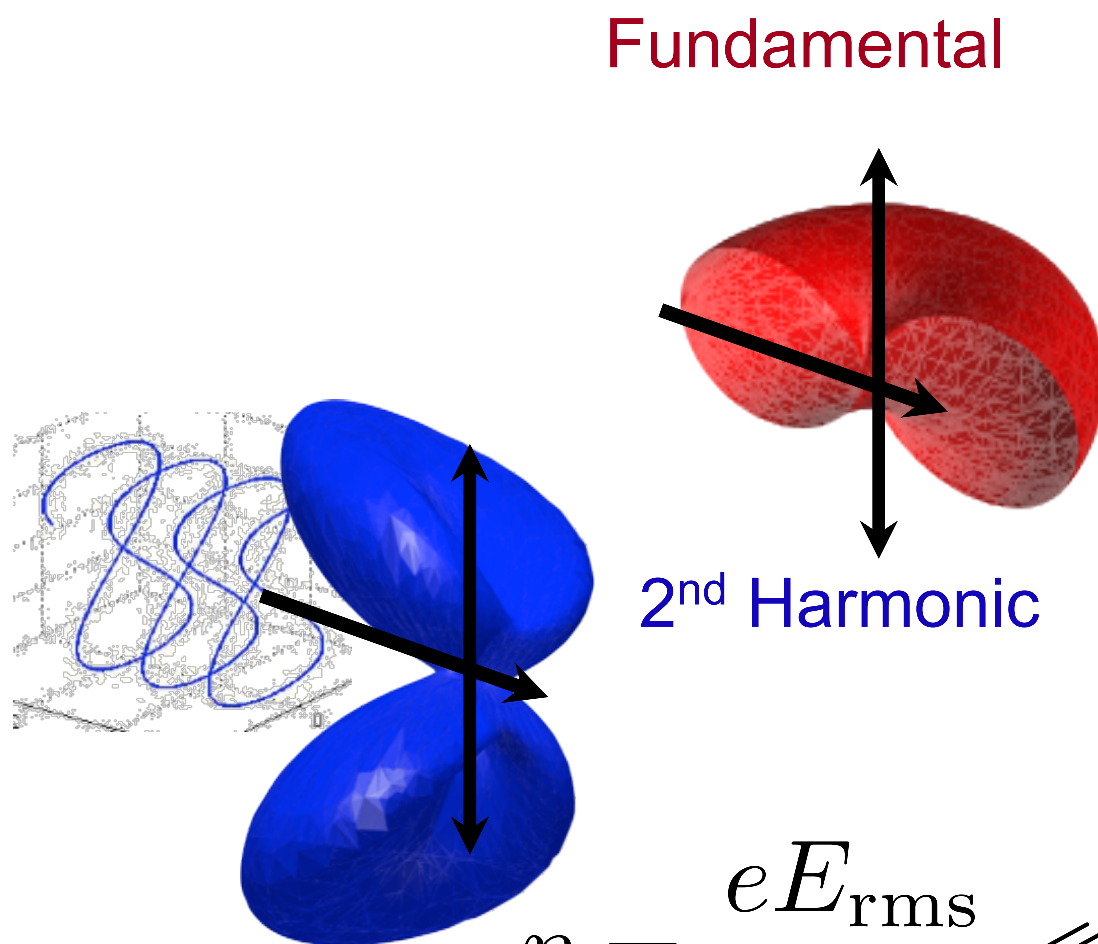
$$\eta = \frac{eE_{\mathrm{rms}}}{m\omega c} \ll 1$$

(10^{20}W/cm^2 @ 9keV:
η~1e-3; E/E_a ~ 200; E/E_{QED}~3e-5)

“free” electron in strong (linear pol.) field



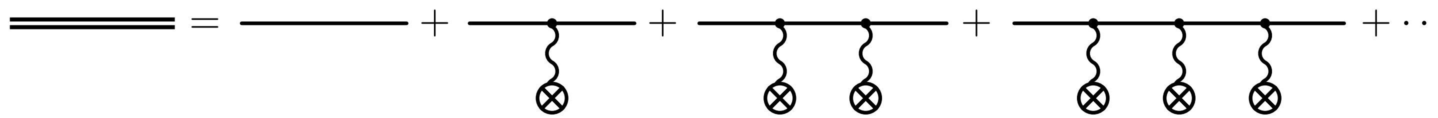
$$v_L \approx 2\eta^2 c \sin 2\omega t$$



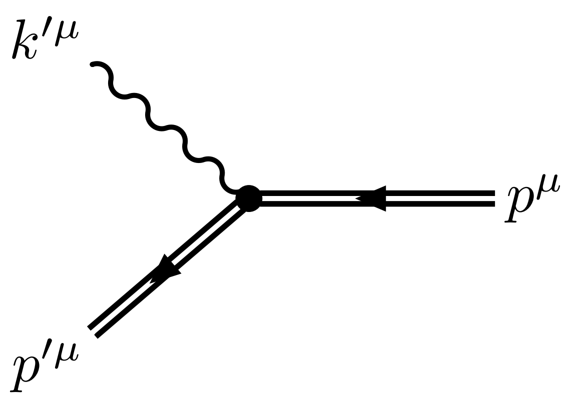
$$\eta = \frac{eE_{\mathrm{rms}}}{m\omega c} \ll 1$$

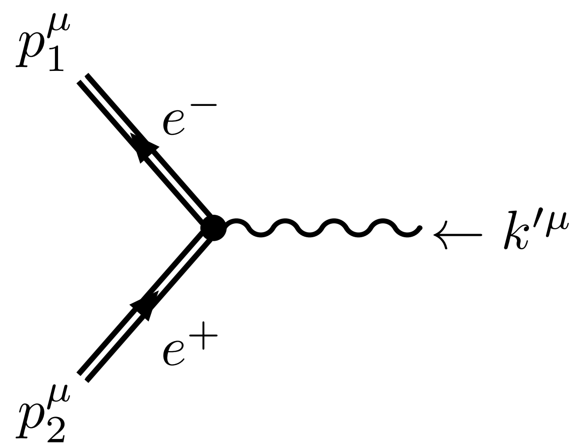
(10^{20}W/cm^2 @ 9keV:
η~1e-3; E/E_a ~ 200; E/E_{QED}~3e-5)

Non-linear/non-perturbative QED



Dressed state (Furry, Volkov, …)





Photon emission

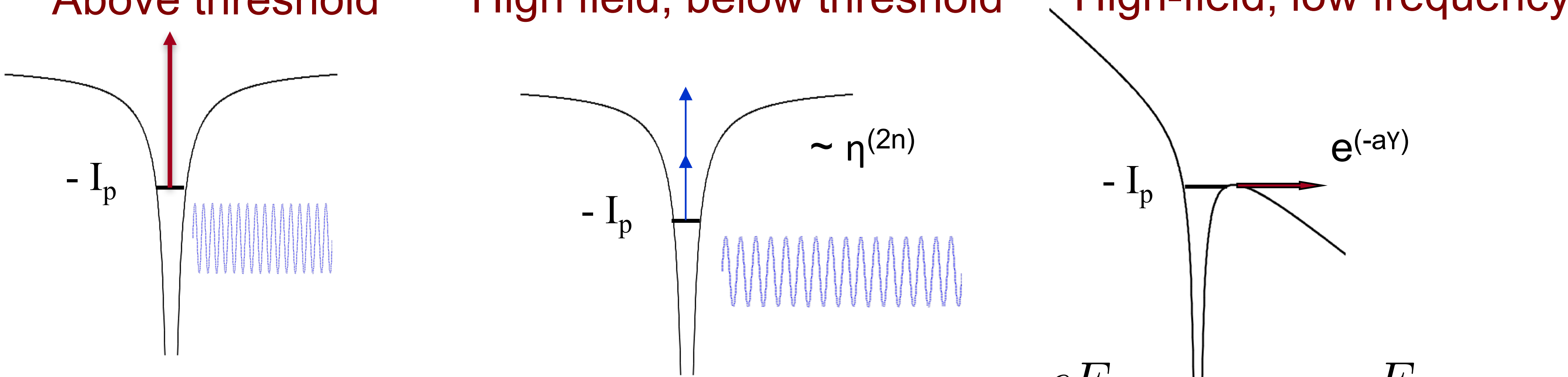
Multi-photon Compton
Quantum radiation reaction
…

Photon decay

Multi-photon Breit-Wheeler Pair production
"Schwinger" pair production
…

Analogy: regimes of atomic ionization

Photoionization/ linear Breit-Wheeler Above threshold	Multi-photon Ionization Nonlinear Breit-Wheeler High field, below threshold	Tunneling Schwinger breakdown High-field, low frequency



$$\eta = \xi = a_0 = \frac{eE}{m\omega c}, \Upsilon = \chi = \frac{E}{E_c}$$

atomic:

$\omega > 13.6eV(\mathrm{H})$

$\sigma_{\max} \sim a_0^2 \approx 25 \text{ Mb (H)}$

pairs:

$\sqrt{\omega_1\omega_2(1-\cos\theta)} > 2mc^2 = 1 \text{ MeV}$

$\sigma_{\max} \sim r_e^2 \approx 80 \text{ mb}$

Transition depends on both field and frequency

atomic

$E_c = \alpha^4 mc^2/r_e = 2I_P/a_0 = 5\times 10^9 \mathrm{V/cm}$

vacuum

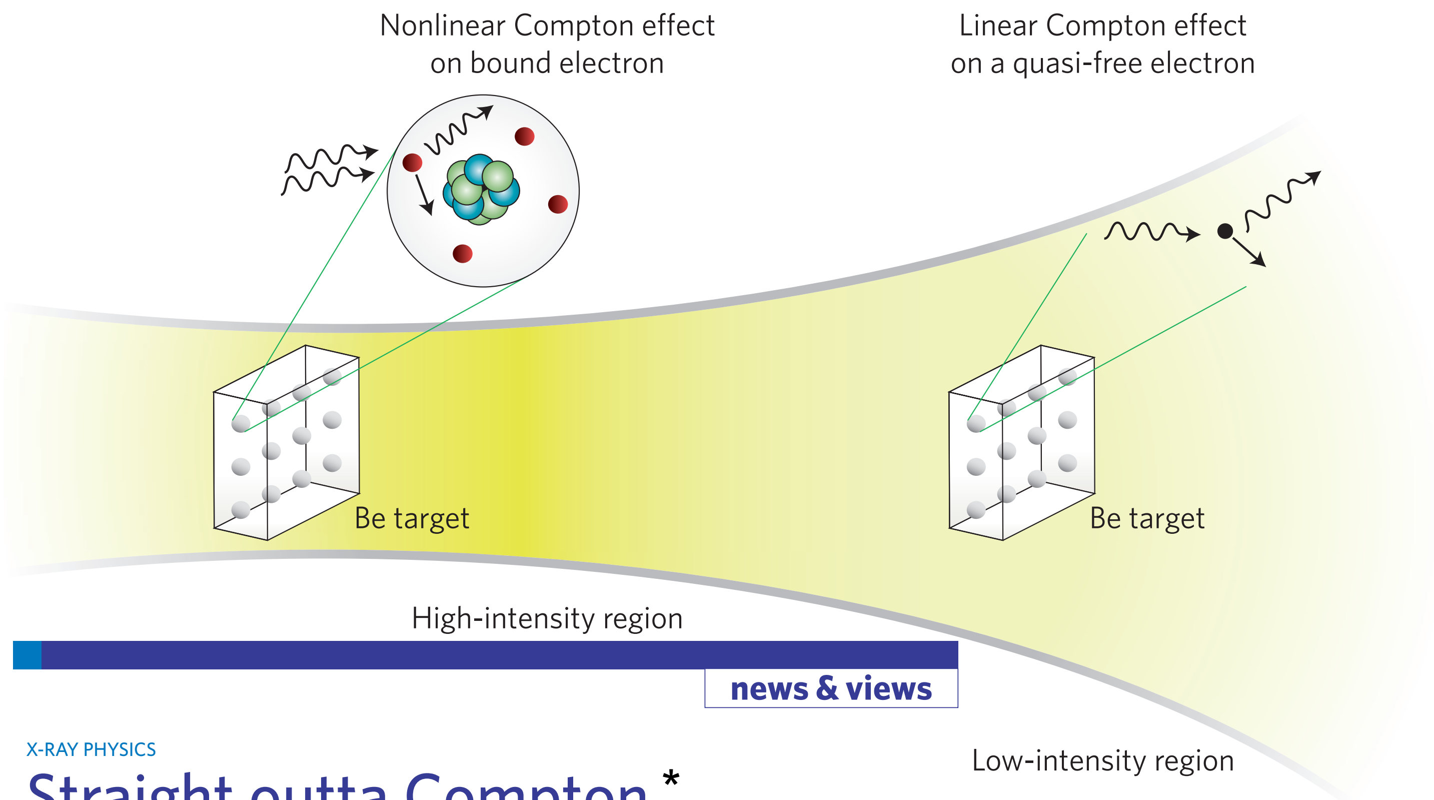
$E_c = \alpha mc^2/r_e = I_P/\lambda_c = 1.3\times 10^{16}\mathrm{V/cm}$

Two-photon Compton Scattering

nature physics
ARTICLES
PUBLISHED ONLINE: 31 AUGUST 2015 | DOI: 10.1038/NPHYS3452

Anomalous nonlinear X-ray Compton scattering

Matthias Fuchs[1,2]*, Mariano Trigo[2,3], Jian Chen[2,3], Shambhu Ghimire[2], Sharon Shwartz[4], Michael Kozina[2,3], Mason Jiang[2,3], Thomas Henighan[2,3], Crystal Bray[2,3], Georges Ndabashimiye[2], Philip H. Bucksbaum[2], Yiping Feng[5], Sven Herrmann[6], Gabriella A. Carini[6], Jack Pines[6], Philip Hart[6], Christopher Kenney[6], Serge Guillet[5], Sébastien Boutet[5], Garth J. Williams[5], Marc Messerschmidt[5,7], M. Marvin Seibert[5], Stefan Moeller[5], Jerome B. Hastings[5] and David A. Reis[2,3]



news & views

X-RAY PHYSICS

Straight outta Compton *

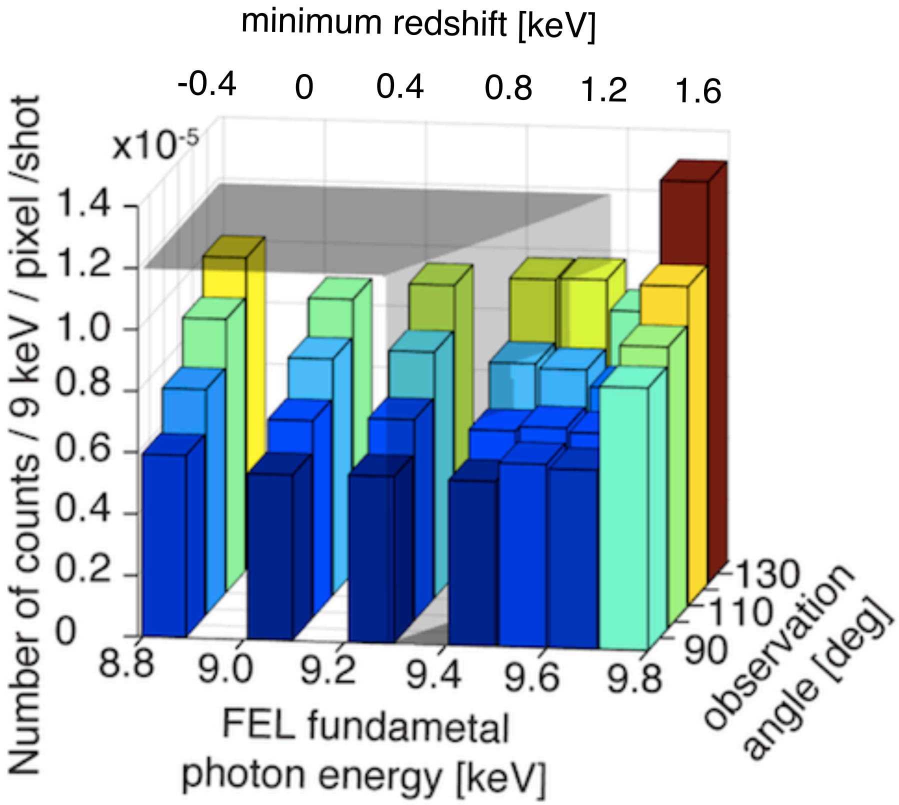
A nonlinear Compton scattering experiment with X-ray photons using an X-ray free-electron laser exhibits an unexpected frequency shift — hinting at the breakdown of standard approximations.

Adriana Pálffy

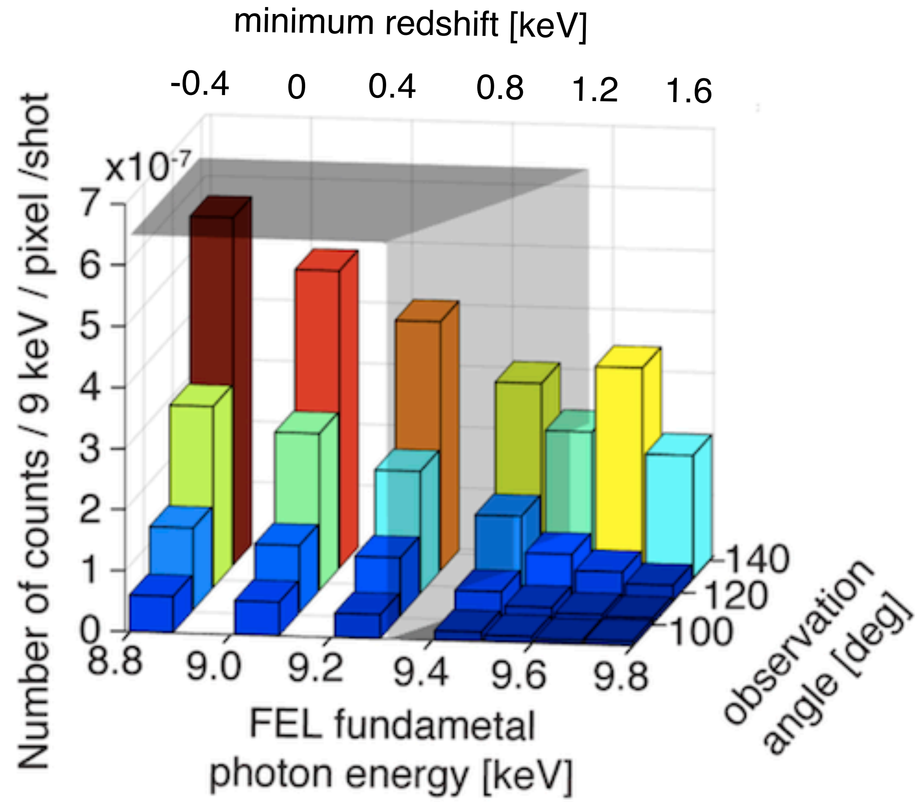
*(on a log-log plot)

Redshift

High Intensity n=2,ω+ω



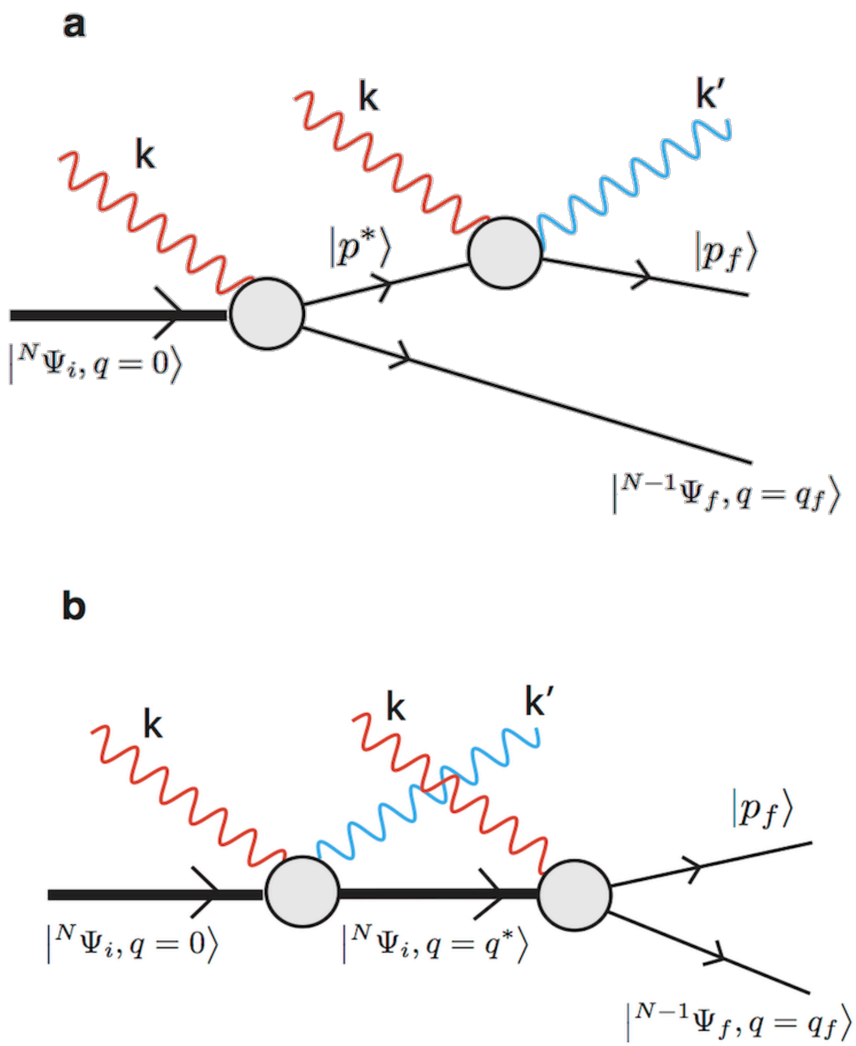
High Intensity n=1, 2ω



$$\omega + \omega \to \omega_K (18 \text{ keV})$$

Fuchs et al., Nature Physics, 2015

Bound-state nonlinear-Compton scattering?



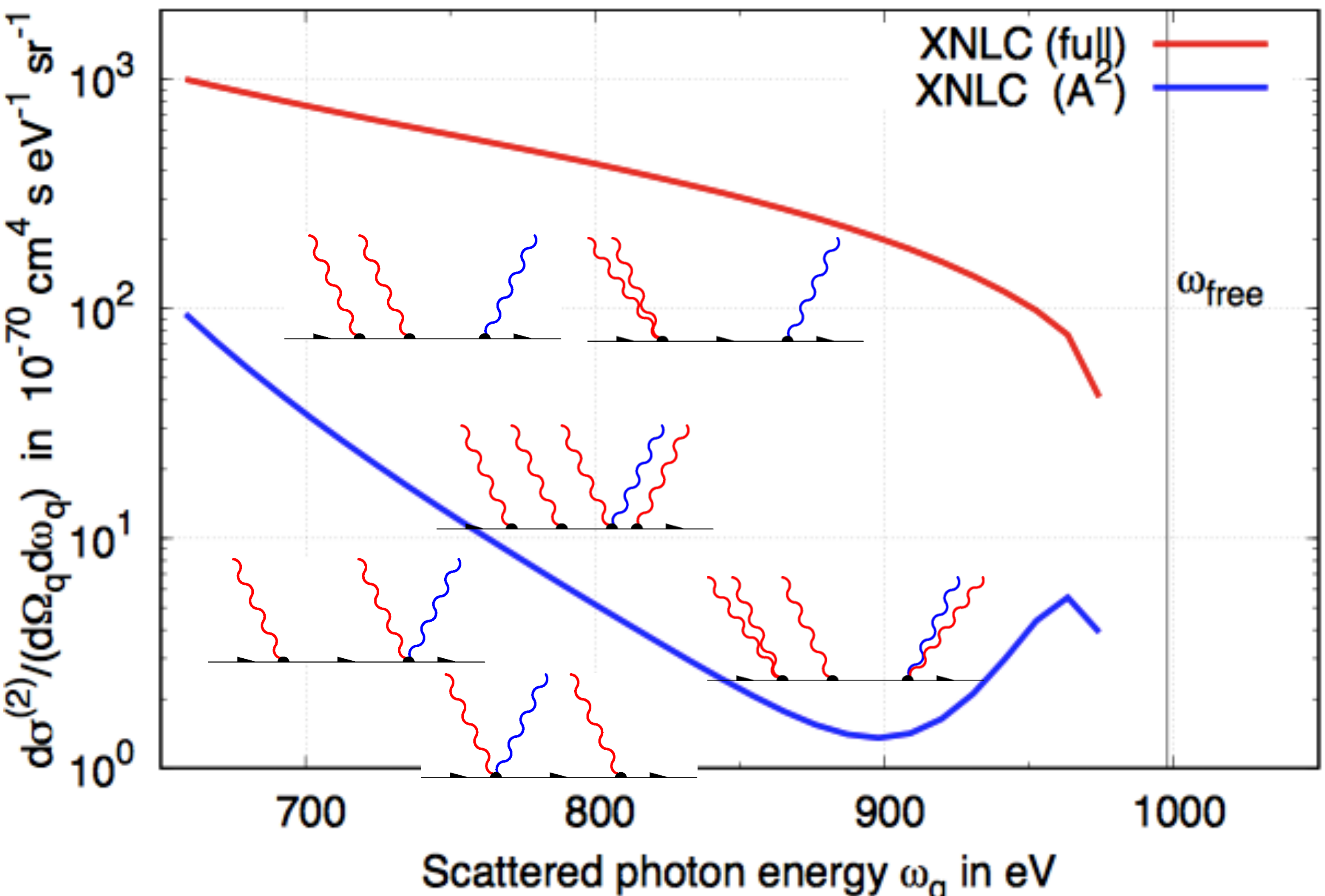
- New mechanism
- second order in (A^2, A•p)
- Atom (solid) takes up missing momentum
- Sensitivity to electronic structure and positions
- Possibility for phase matching

$$\frac{\mathrm{d}\sigma^{(2)}}{\mathrm{d}\Omega} \propto \frac{1}{\omega}\frac{\mathrm{d}\sigma_T}{\mathrm{d}\Omega}\frac{\mathrm{d}\sigma_e}{\mathrm{d}\Omega}$$

Fuchs et al., Nature Physics, 2015

A TDSE-based approach to nonlinear x-ray Compton scattering

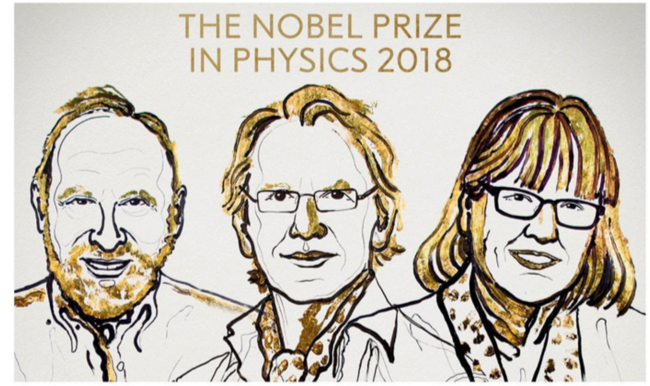
500eV, He

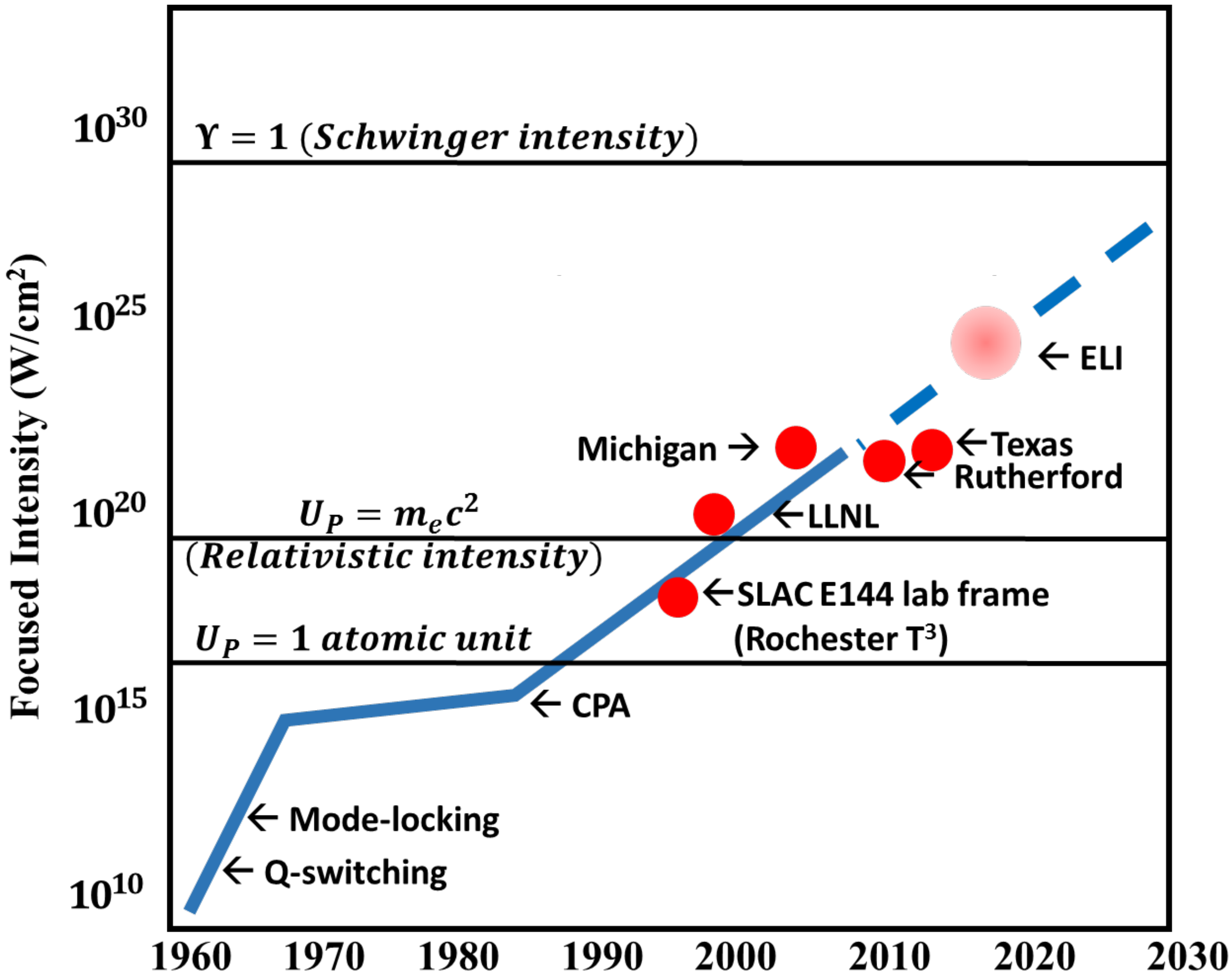


However, cannot reproduce at high energy in Be

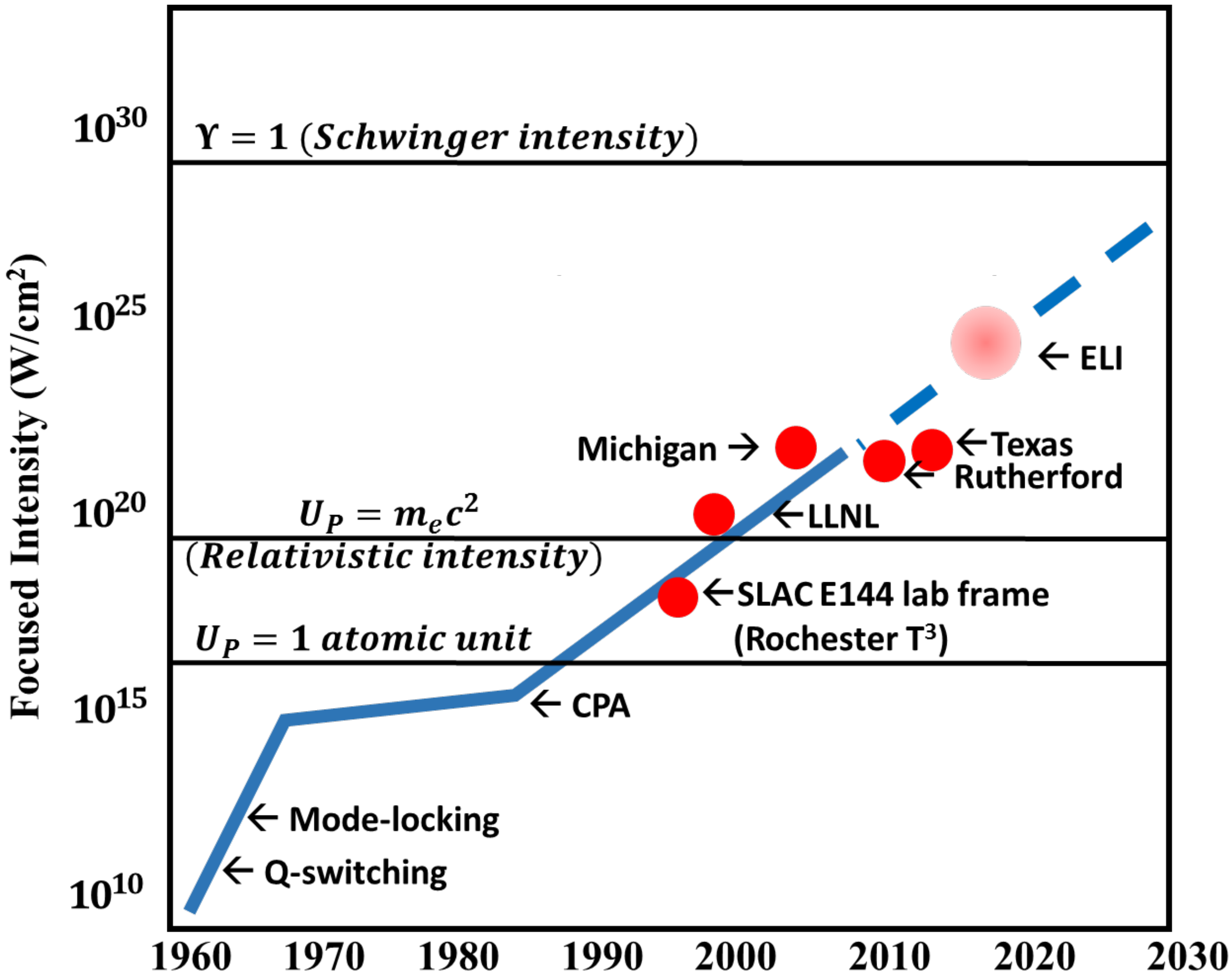
Dietrich Krebs and Robin Santra

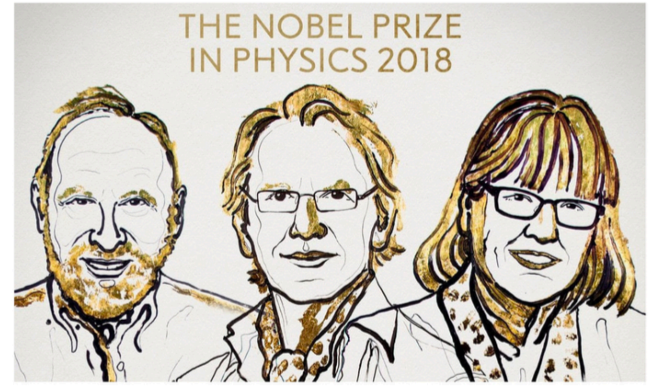
Focused Intensity Frontier





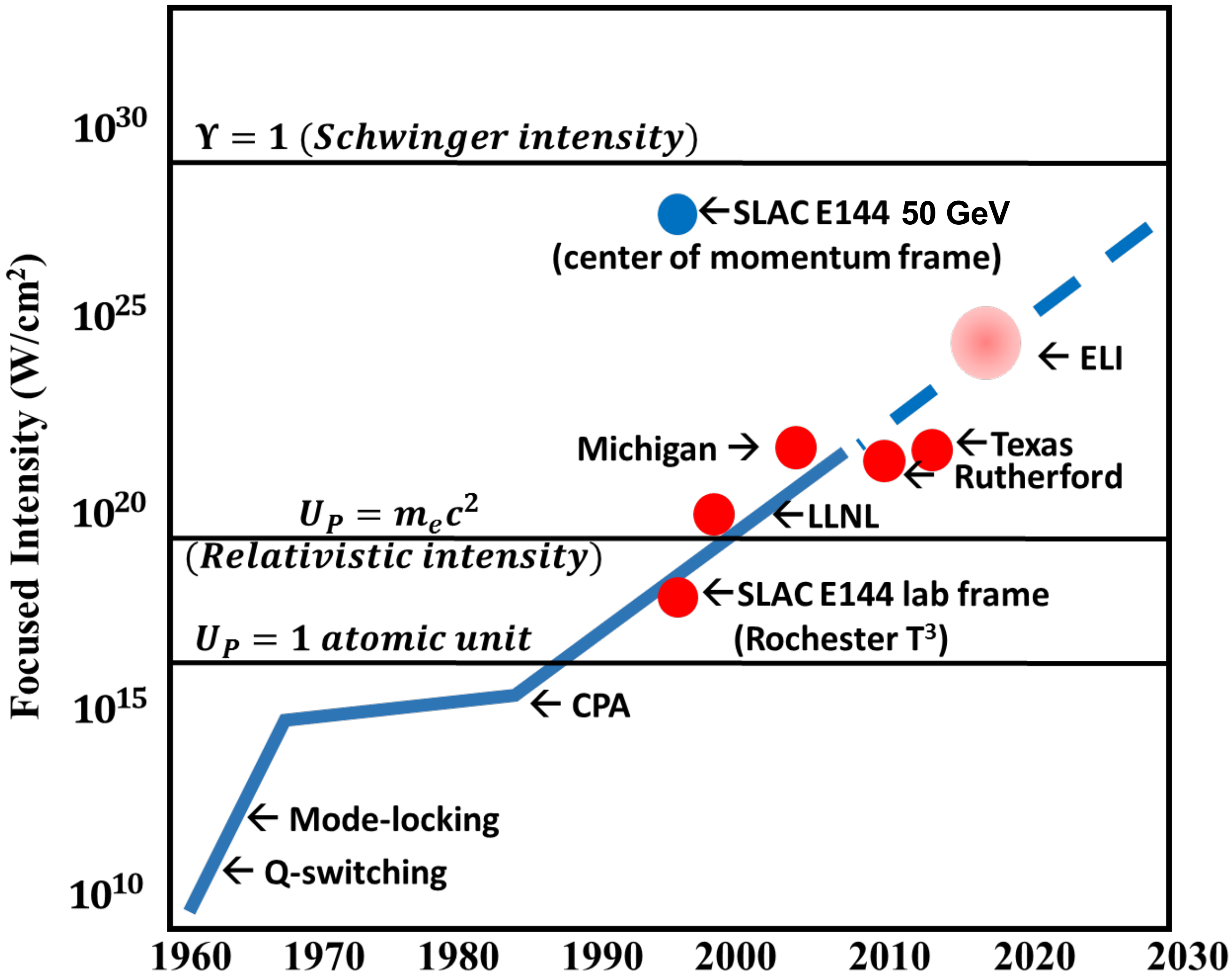
Focused Intensity Frontier

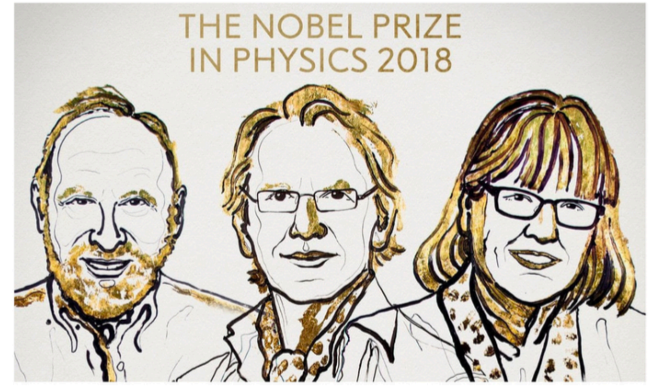




- Strong-field and collective phenomena accessible above QED critical intensity/field
- Current (future) light sources far from this limit in laboratory frame.
- Only possible by combining high energy particles with laser (relativistic boost)
  - $4\gamma^2$ intensity
  - 2γ field

Focused Intensity Frontier





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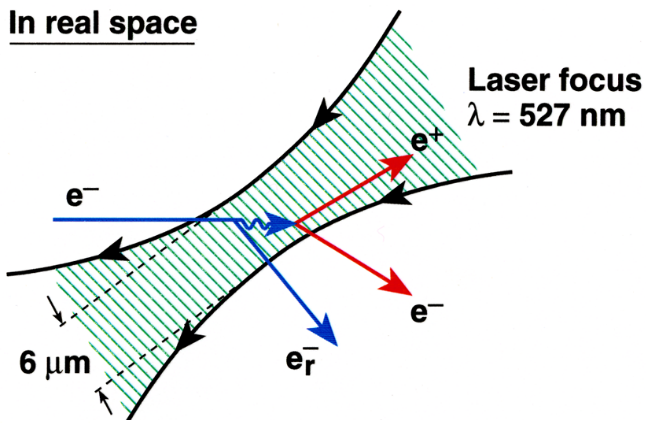
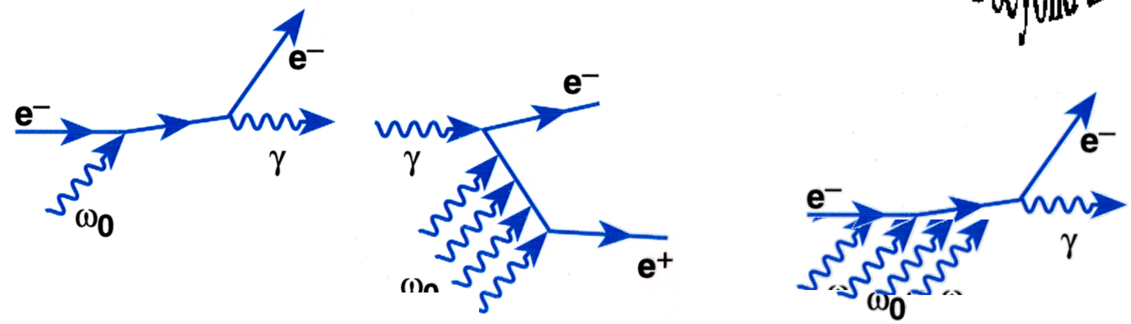
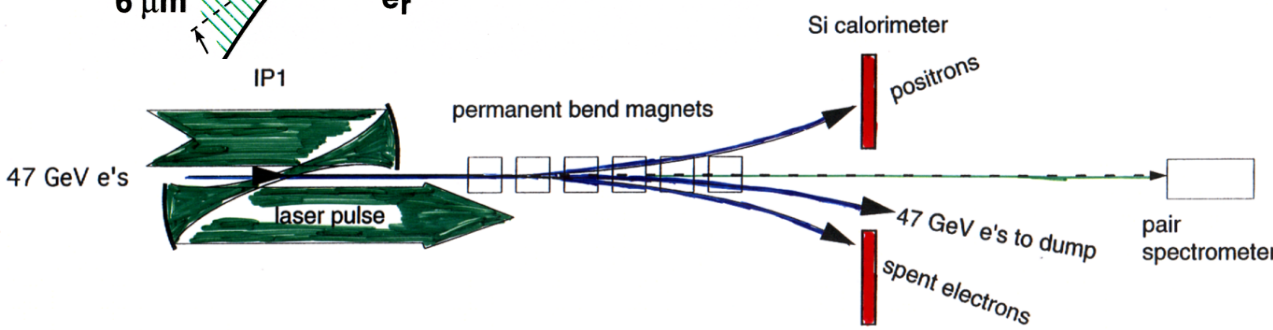
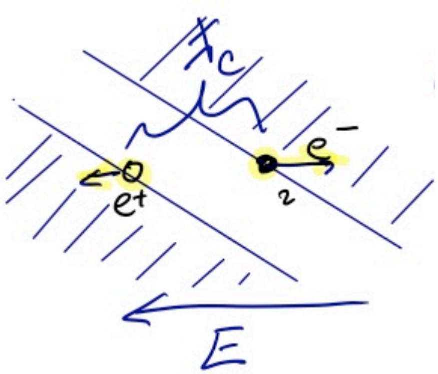
E144 experiment:
nonlinear QED in laser+e- collisions







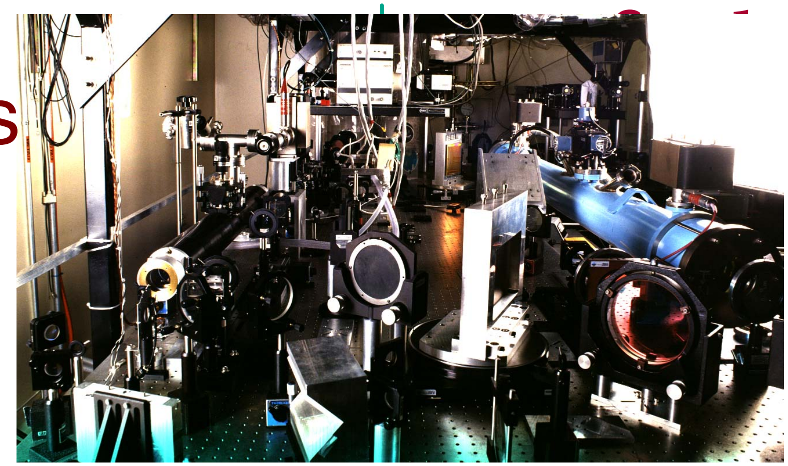


Photonics Spectra, Nov. 1997

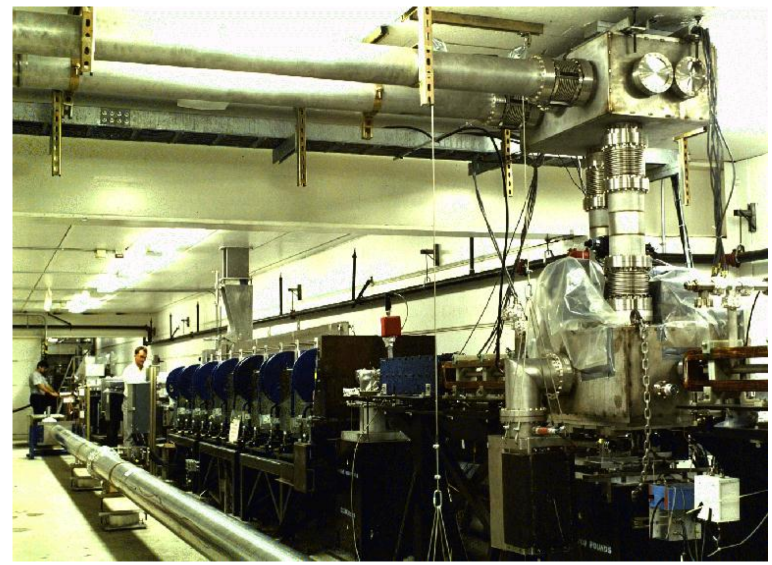
$E_{QED}=E_a/\alpha^3 \sim 1.3\ 10^{16}$ V/cm

Bula et al., PRL 1996,
Burke et al., PRL 1997

E144 experiment:
nonlinear QED in laser+e- collisions

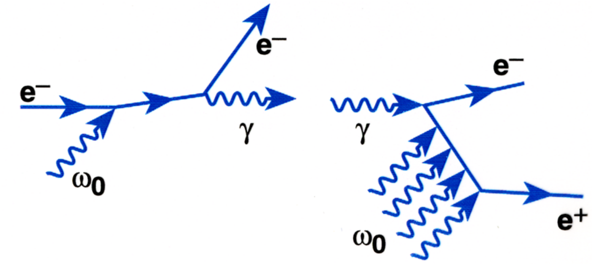


Front row: G. Horton-Smith, Th. Kotseroglou, W. Ragg, S. Boege
Middle row: D. Meyerhofer, W. Bugg, A. Weidemann,
D. Walz, J.Spencer, K.McDonald, A. Melissinos
Last row: K. Shmakov, C. Bamber, U. Haug, D.Burke, C.Bula
Absent: S. Berridge, C. Field, Th. Koffas, E. Prebys, D.Reis



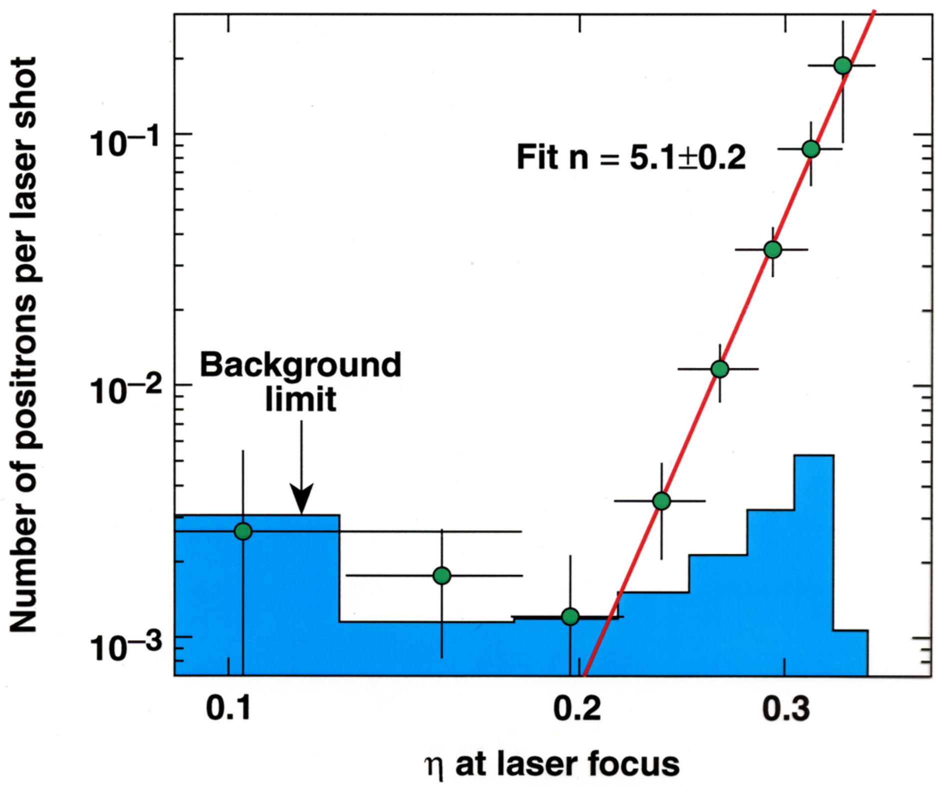
D.L.Burke et al, PRL79 1626(1997)
C.Bamber et al, Phys.Rev. D60 090024(1999)

E144 Measured in transition regime



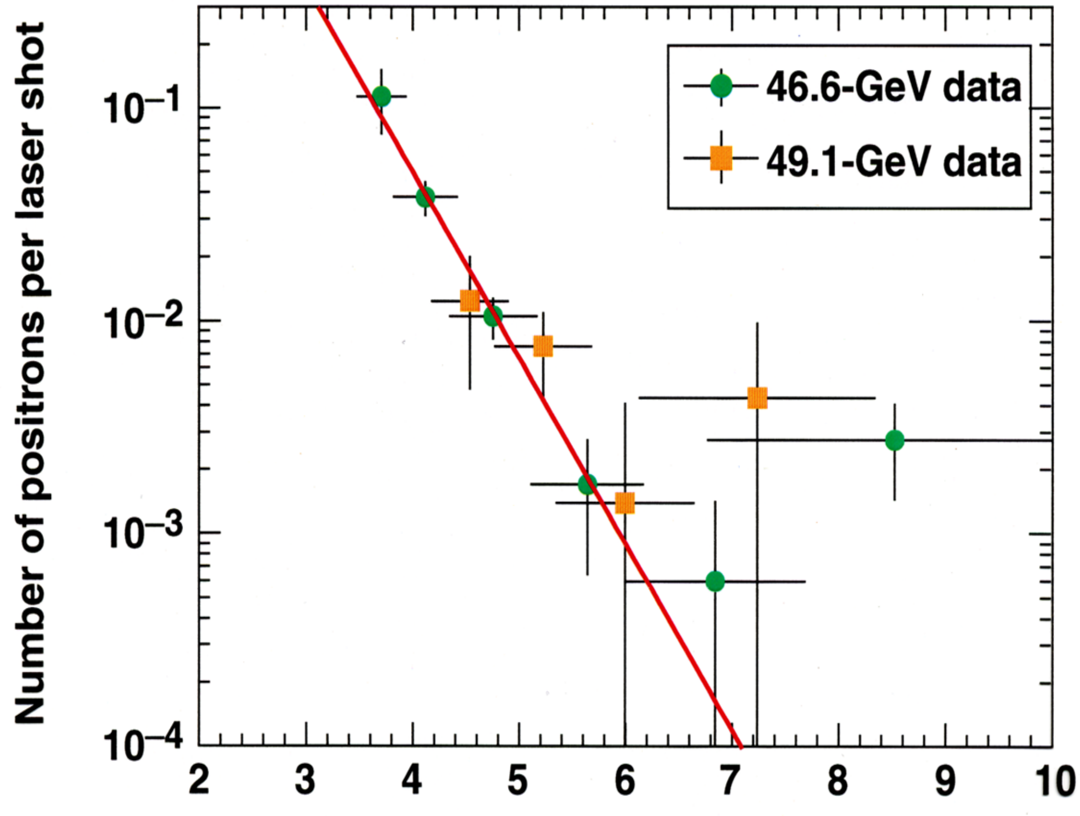
Process involving *n* laser photons has probability

$$P \sim \eta^{2n} \quad \text{where} \quad \eta^2 = \left[\frac{eE}{\omega mc}\right]^2 = \left[\frac{e}{\omega mc}\right]^2 Z_0 I$$



Multi-photon picture

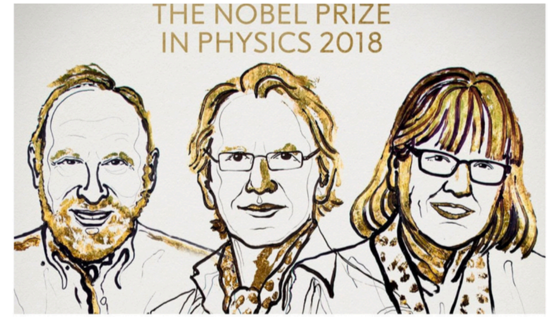
Tunneling Picture (Schwinger)

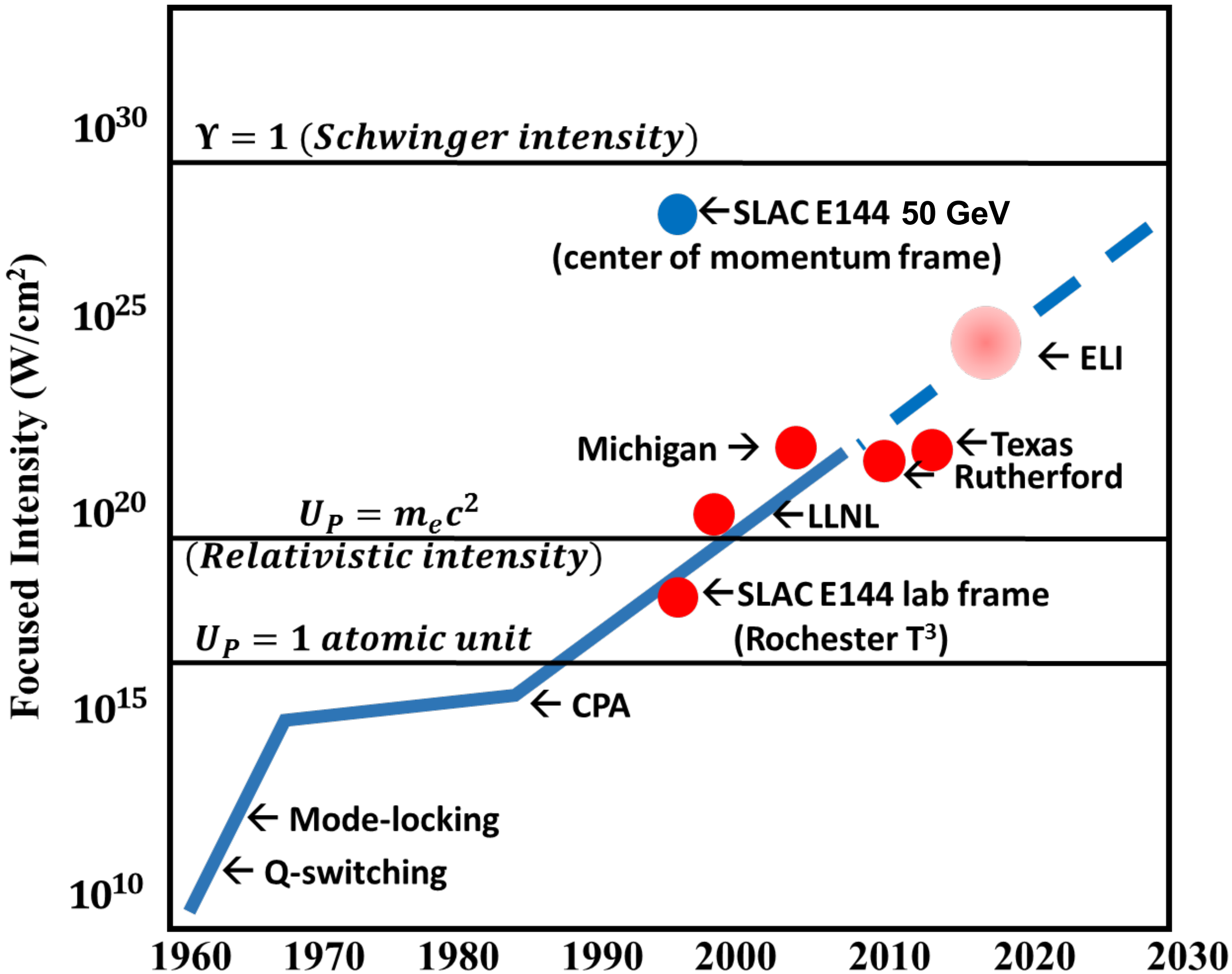


$Y = E/E_c$

Fit to $e^{-\alpha/Y} \rightarrow \alpha = 2.02 \pm 0.12$

Focused Intensity Frontier





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- Current (future) light sources far from this limit in laboratory frame.
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Strong-field QED@SLAC Working group

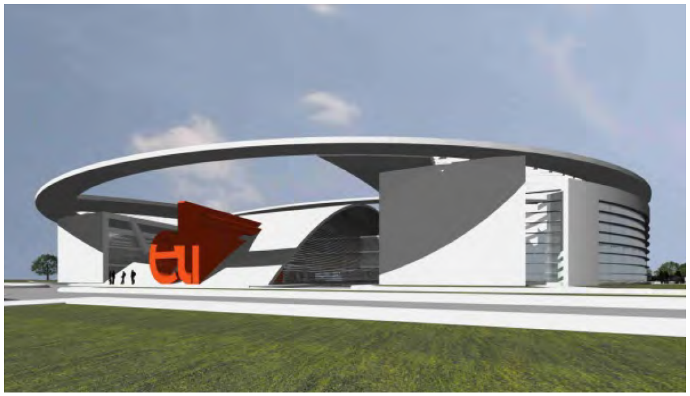
Stanford PULSE Institute

- AMO: Bucksbaum and Reis
- Astrophysics and Cosmology: Abel and Blandford
- HEDS: Fiuza and Glenzer
- Accelerator: Hogan and Yakimenko
- FEL: Huang and Pellegrini
- Laser: Fry
- HEP: Brodsky

- Strong-field QED theory: Meuren (Princeton)

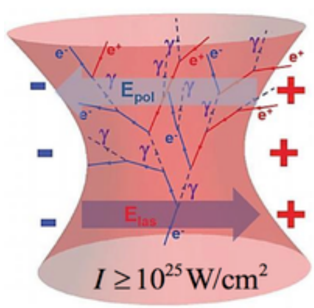
Extreme Light Infrastructure (ELI)

Stanford PULSE Institute



Attosecond Light Pulse Source (Szeged, Hungary)

-Ultrafast light sources, and coherent x-ray sources
-PW drive laser
-Several beam lines, from 10KHz 100 mJ to 0.1 Hz 300J



High Energy Beam-Line Facilitiy (Prague, Czech Republic)

Beam lines from -200mJ to 1.3kJ lasers, including 2 10PW lasers;
Six experimental areas, including exotic physics, acceleration, x-rays, materials science.

10^{23-24} W/cm^2 @Beamlines and NP

Nuclear Physics Facility (Magurele, Romania)

2 multi-petawatt, 200J, 0.1Hz, <30fs lasers
Compton backscatter gamma ray source
Experiments aimed at nuclear physics.

eXtreme light infrastructure

Probing strong-field QED in electron-photon interactions (DESY/PULSE)

Stanford PULSE Institute

DESY.

Stanford PULSE Institute

GORDON AND BETTY MOORE FOUNDATION

HELMHOLTZ SPITZENFORSCHUNG FÜR GROSSE HERAUSFORDERUNGEN

FACET-II proposal collaboration

Stanford PULSE Institute

SFQED theory & simulation	A. DiPiazza, F. Fiuza, T. Grismayer, C.H. Keitel, **S. Meuren**, L.O. Silva, D. Del Sorbo, M. Tamburini, M. Vranic
SLAC E144	DR (SF AMO/xray), T. Koffas (HEP)
LWFA SFQED experiments	G. Sarri, M. Zepf
Crystal SFQED experiments	R. Holtzapple, U. I. Uggerhoj
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Accelerator physics	G. White
Detectors	A. Dragone, C. J. Kenney
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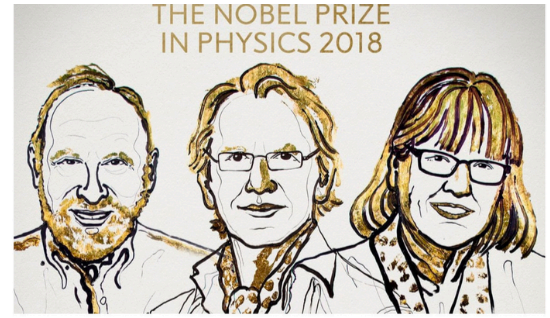
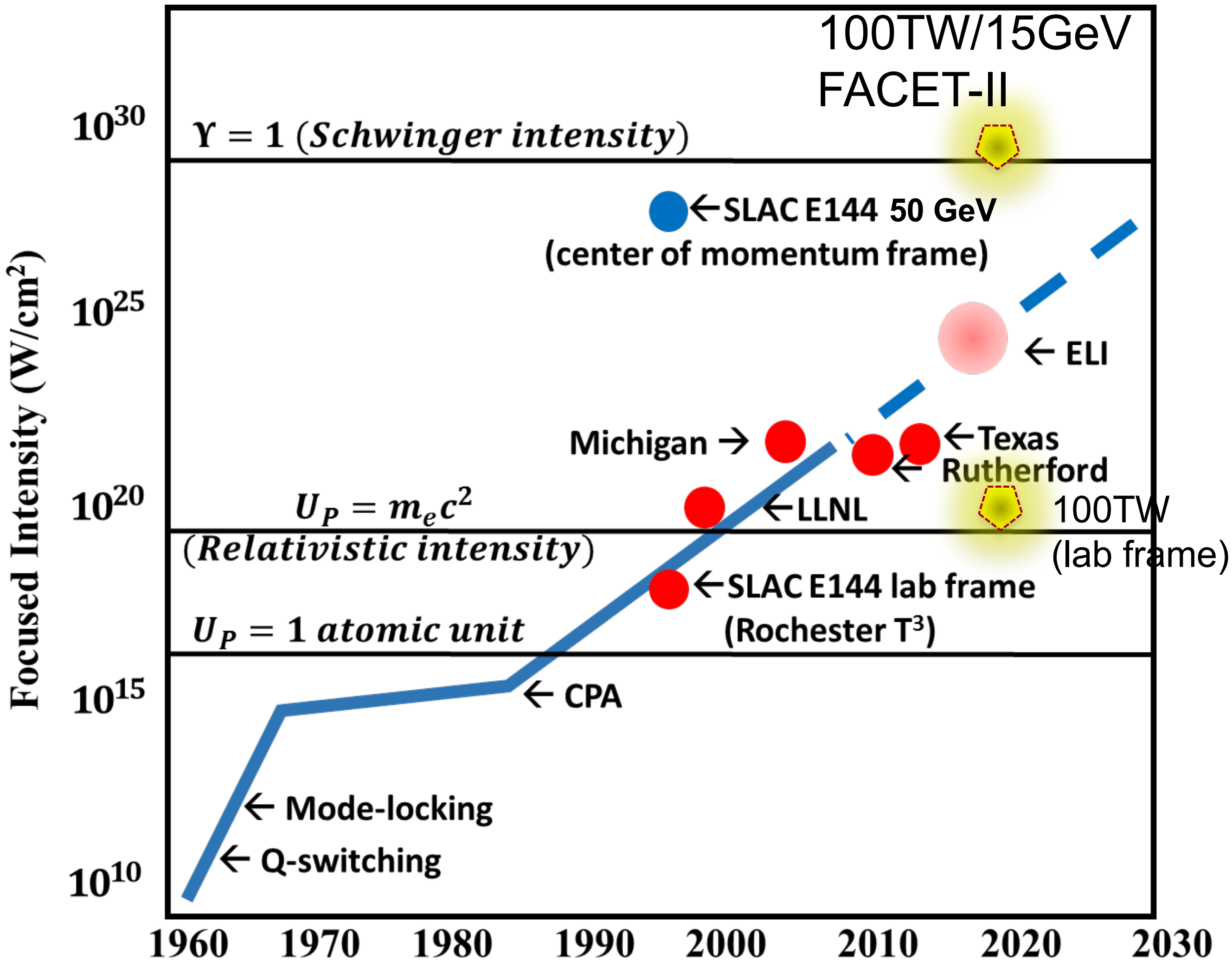
Collaborating Institutions: Carleton University (Canada), Aarhus University (Denmark). Ecole Polytechnique (France) Max-Planck-Institut für Kernphysik (Germany), Helmholtz-Institut Jena (Germany), Friedrich-Schiller-Universität Jena (Germany), Universidade de Lisboa (Portugal), Queen's University Belfast (UK), California Polytechnic State University (CA USA), Lawrence Livermore National Laboratory (CA USA), Princeton University (NJ USA), SLAC National Accelerator Laboratory (CA USA), University of California Los Angeles (CA USA), University of Colorado Boulder (CO USA), University of Nebraska - Lincoln (NE USA)

Focused Intensity Frontier





- Strong-field and collective phenomena accessible above QED critical intensity/field
- Current (future) light sources far from this limit in laboratory frame.
- Only possible by combining high energy particles with laser (relativistic boost)
  - $4\gamma^2$ intensity
  - 2γ field

Good ideas always attract competition

RIKEN SPring8
- two, 500 TW lasers on SACLA (not on e-beam–yet)
- tens nm focus x-ray
- Experiments in elastic light-by-light on SACLA, axion-like-particles on SPring8

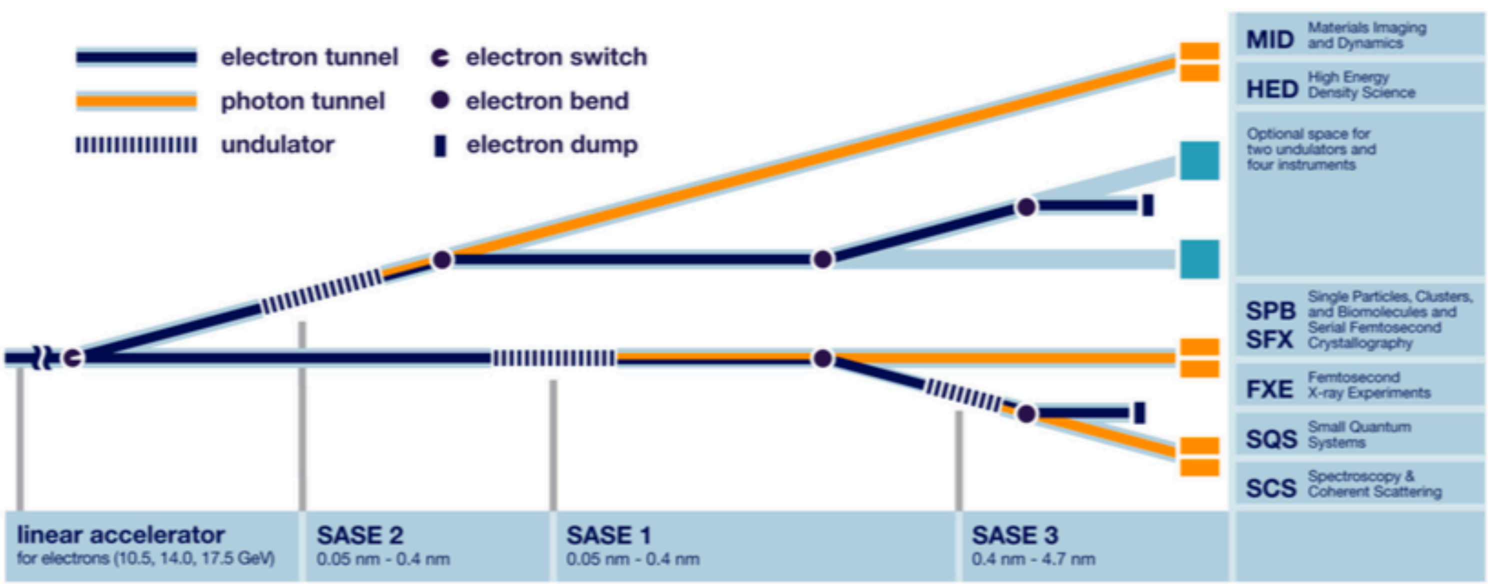
DESY/E-XFEL
- 18 GeV and lots of space.
- Proximity to leading theory groups
- Indication of interest

Shanghai
- 8 GeV SC Linac approved.
- SCLF: .4 to 25 keV x-ray laser now approved
- SEL: a 100PW (NOT a typo) laser approved
- Completion of all in seven years.

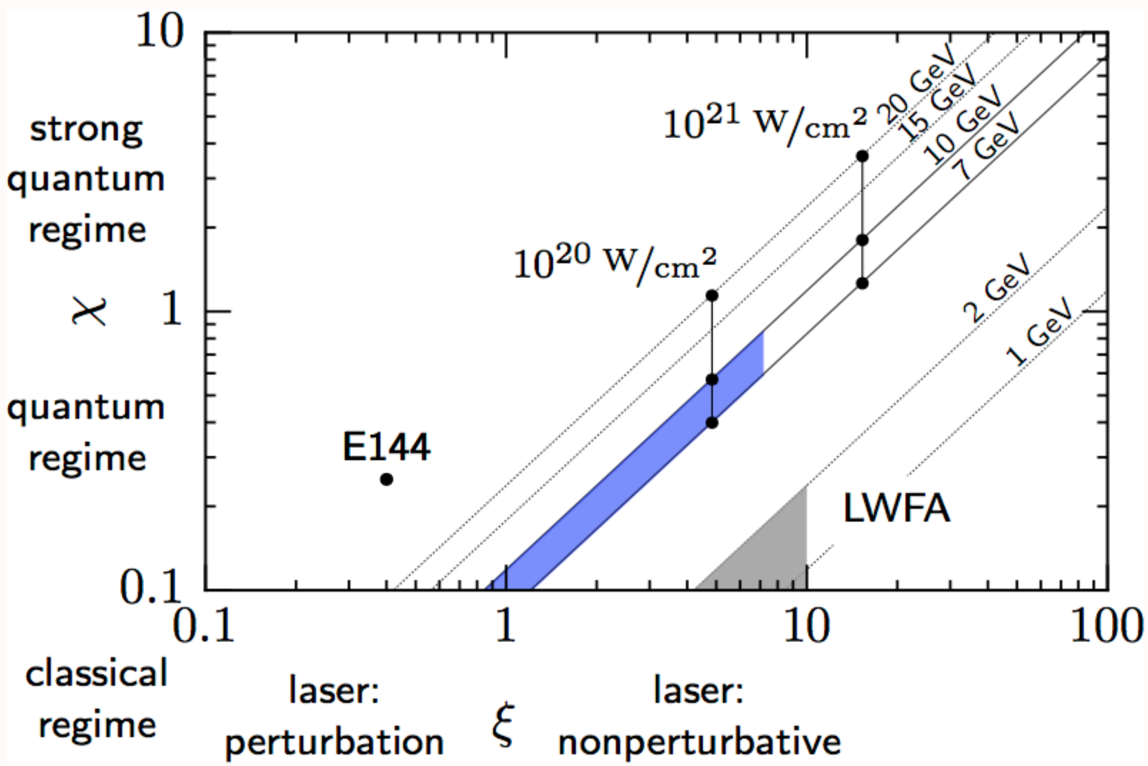
Similar proposal at DESY

LUXE: a new experiment using a laser and XFEL electrons to investigate QED in the strong-field regime

R. Assmann, T. Behnke, W. Decking, B. Heinemann,
J. List, E. Negodin, A. Ringwald (DESY)
M. Altarelli (MPI for structure and dynamics),
A. Hartin (Universität Hamburg), M. Wing (UCL)



Reaching strong-field regime @FACET-II

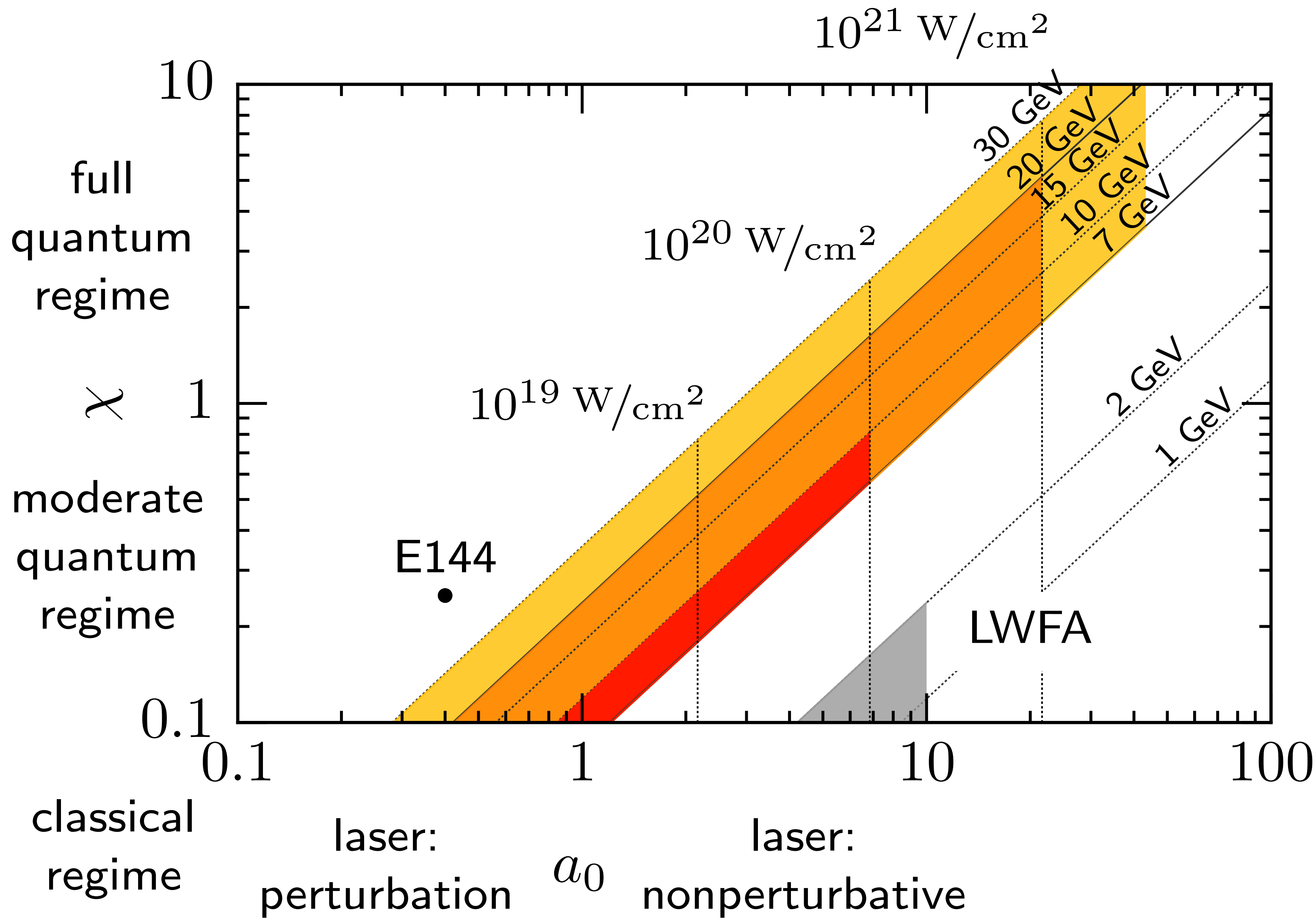


Electron parameters	
Energy	$7-10\,\mathrm{GeV}$
rms Energy Spread	0.5 [%]
rms Bunch Length	$10-100\,\mu\mathrm{m}$
rms Bunch Radius	$3\,\mu\mathrm{m}$
Bunch Charge	$0.6\,\mathrm{nC}$
Peak Current	$2-20\,\mathrm{kA}$

Laser parameters	Baseline
Pulse energy $\mathcal{E}_L$	$0.7\,\mathrm{J}$
Pulse duration (FWHM) τ_0	$35\,\mathrm{fs}$
Power (average) P	$\sim 20\,\mathrm{TW}$
Beam waist w_0	$2.4-5\,\mu\mathrm{m}$
Wavelength λ_L	$0.8\,\mu\mathrm{m}$
Intensity (peak) I_0	$(0.5-2.2)\times10^{20}\,\mathrm{W/cm^2}$

Accessible parameters: $\xi = a_0 = \eta = 3-7; \quad \chi = \Upsilon = 0.4-0.9$

Reaching strong-field regime @FACET-II



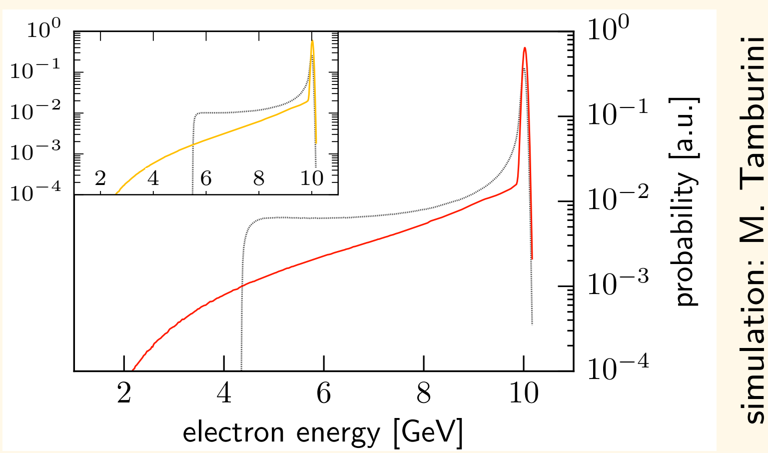
Reaching strong-field regime @FACET-II. 20 TW laser

Stanford PULSE Institute

Major scientific objectives

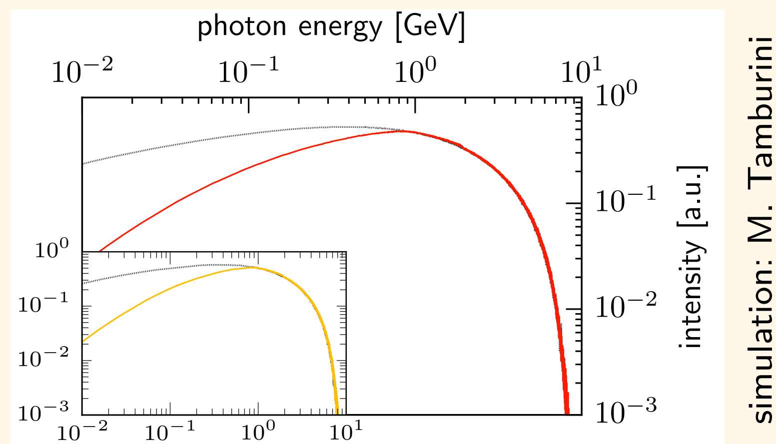
- **Unstable strong-field quantum vacuum**
  $\longrightarrow$ first observation of tunneling pair production ($\sim 10^3$ pairs per shot)
- **Quantum radiation reaction**
  $\longrightarrow$ failure of the classical Landau Lifshitz equation, quantum stochasticity
- **Breakdown of perturbation theory**
  $\longrightarrow$ absorption of $\sim 10^2$ laser photons, emission of ~ 5 photons (per electron)

Electron spectrum



- Quantum radiation reaction: stochasticity
- Deviations from Landau Lifshitz (dotted)

Photon spectrum



- Highly nonlinear Compton scattering
- Local constant field approx. fails (dotted)

Reaching strong-field regime @FACET-II. 20 TW laser

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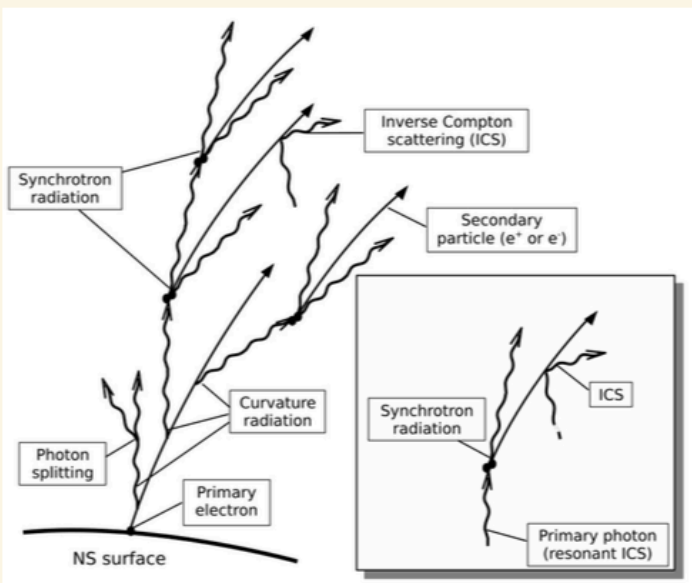
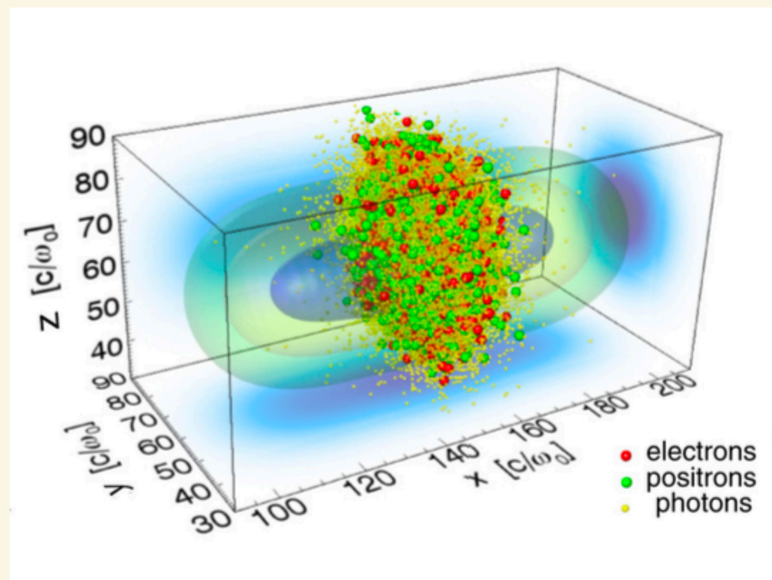
Astrophysics: magnetar/pulsar



Medin and Lai, MNRAS 406, 1379 (2010)

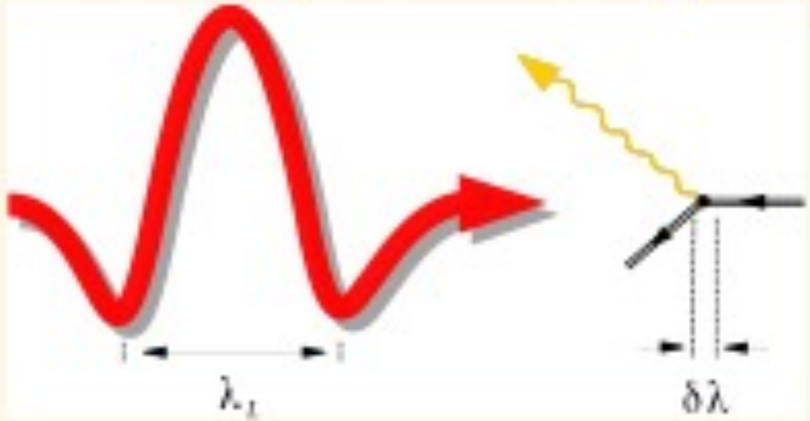
Laser-laser collisions



Grismayer et al. PRE 95, 023210 (2017)

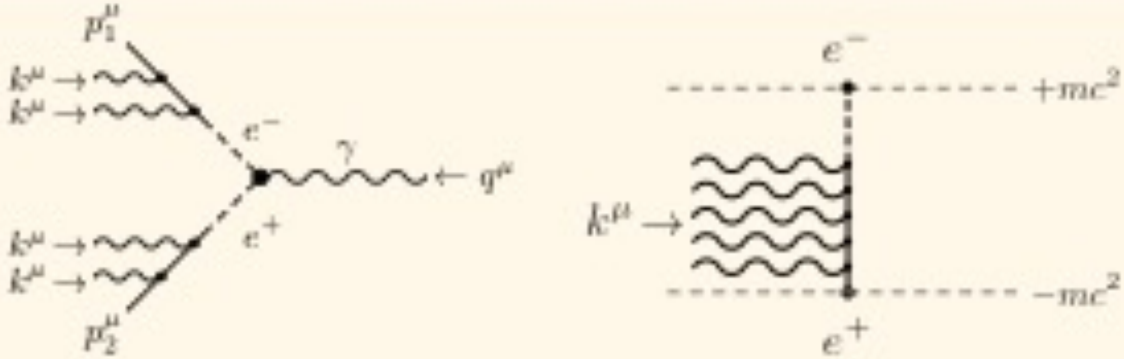
FACET-II: why is the new regime fundamentally different?

Formation length of SFQED processes

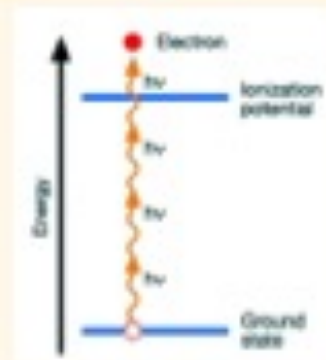


1. λ_L: laser wavelength (scale on which the field changes significantly)
2. $\delta\lambda$: formation region of a fundamental QED processes; $\delta\lambda/\lambda_L \sim 1/\xi$

Multiphoton pair production ($\xi \ll 1$)



Multiphoton ionization

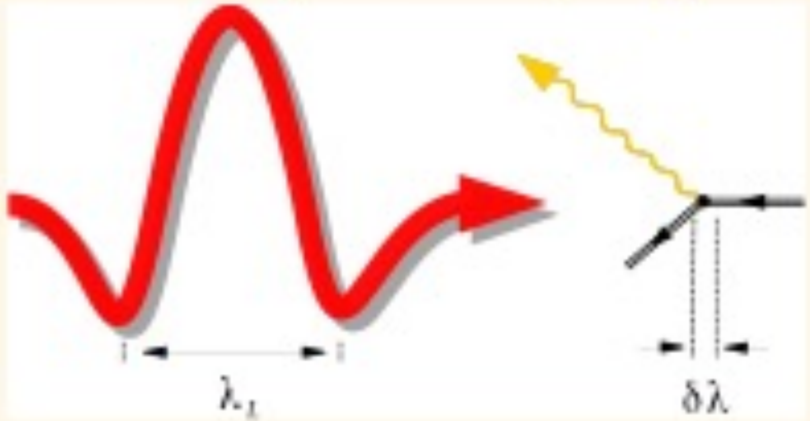


© DESY

- Ionization in atomic physics – Keldysh parameter: $\gamma_K = \omega\sqrt{2mI_p}/(|e|E)$,
- Pair production in SFQED: $\gamma_K(I_p = 2mc^2) \sim 1/\xi = \omega mc/(|e|E)$

FACET-II: why is the new regime fundamentally different?

Formation length of SFQED processes



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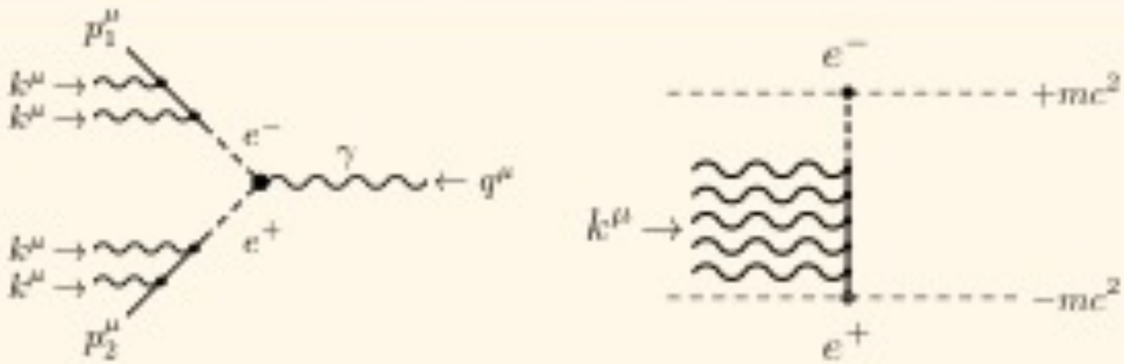
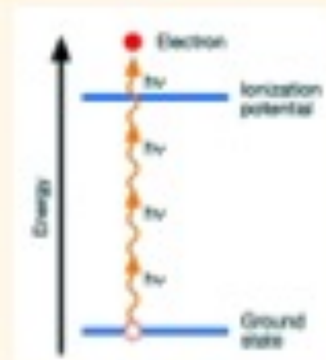


Multiphoton ionization



© DESY

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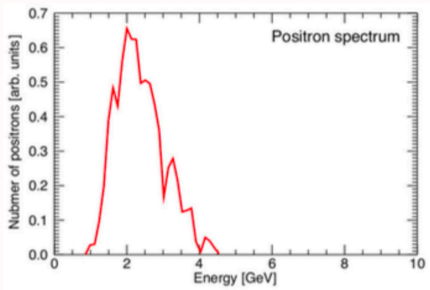
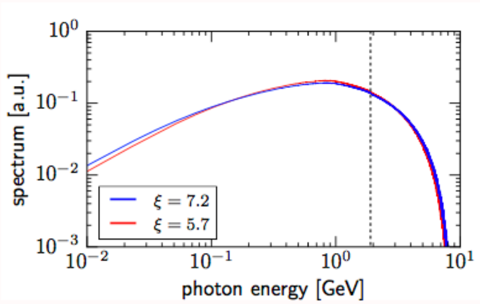
- Pair production in SFQED: $\gamma_K(I_p = 2mc^2) \sim 1/\xi = \omega mc/(|e|E)$

FACET-II will test various aspects of SFQED



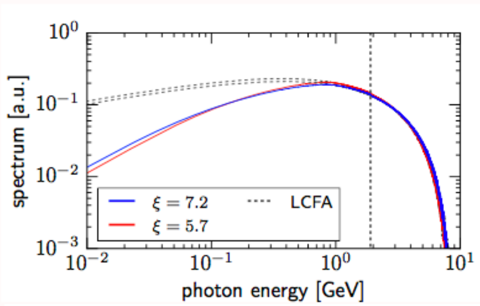
Tunneling pair production/vacuum breakdown

- Pair production inside quasi-static field
- Nonperturbative tunneling exponent
- Much higher statistics: $\sim 10^4$ positrons/shot



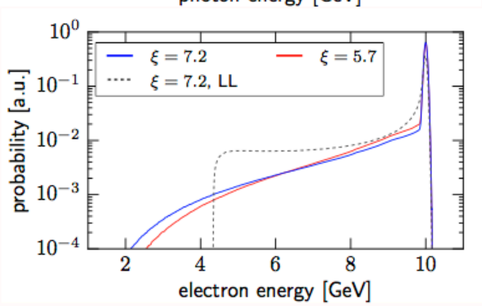
Strong-field synchrotron radiation

- Reduced radiation probability, spectrum: redshift
- Coherent interaction with $\sim 10^2$ laser photons
- Emission of high harmonics (up to 8 GeV photons)



Breakdown of the LCFA

- Applicability of the LCFA: vital for numerical codes
- Formation region depends on photon frequency
- LCFA fails: suppression of low-frequency radiation



Quantum radiation reaction (QRR) – energy

- Stochasticity: broadening of the energy distribution
- Quenching: some electrons don't radiate at all
- Quantum corrections to Landau-Lifshitz

Status

- **SLAC has narrow opportunity to lead the field**
- **FACET-II proposal reviewed, waiting for official feedback. Would test vacuum breakdown, strong-field effects in radiation, validity of codes**
- **Lots of laser, detector, beamline and other work to do**
- **Already thinking of upgraded laser and e-beam to well exceed Schwinger**
- **Plans for PW laser at SLAC, but so far just on MEC (LCLS)**

Backup, from SM talk to FACET-II PRC

Probing Strong-field QED at FACET-II

FACET-II Program Advisory Committee Meeting

October 9, 2018

Sebastian Meuren

for the SFQED collaboration

GORDON AND BETTY MOORE FOUNDATION   DFG   PRINCETON UNIVERSITY   PPPL PRINCETON PLASMA PHYSICS LABORATORY

Department of Astrophysical Sciences, Princeton University (New Jersey, USA)

The strong-field QED (SFQED) collaboration:

SFQED theory & simulation	A. Di Piazza, F. Fiuza, T. Grismayer, C. H. Keitel, SM, L. O. Silva, D. Del Sorbo, M. Tamburini, M. Vranic
SLAC E144 experiment	D. A. Reis (SF AMO/xray), T. Koffas (HEP)
LWFA SFQED experiments	G. Sarri, M. Zepf
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Synergy with other FACET-II proposals

- Laserwire for Sector 20 IP Transverse Beam Diagnostics (PI: G. White)
- Beam filamentation and bright Gamma ray Burst (PI: S. Corde)
- Energy Doubling of Narrow Energy Spread Witness Bunch (PI: C. Joshi)
- Thin plasma lens experiment (PI: M. Litos)
- Beam-Driven Ion Channel Laser experiment & thin plasma lense (PI: M. Litos)

If our proposal is approved, the detailed design of the experimental setup will be worked out in close collaboration with those experiments

Motivation: QED critical field is a fundamental scale

Important scales of QED

Energy	$\mathcal{E} = mc^2$	$10^6\,\mathrm{eV}$	relativistic effects
Length	$\lambda\!\!\!^{-}_C = \hbar c/(mc^2)$	$10^{-13}\,\mathrm{m}$	quantum fluctuations
Field strength	$E_{\mathrm{cr}} = (mc^2)^2/(\lvert e\rvert\,\hbar c)$	$10^{18}\,\mathrm{V/m}$	nonperturbative effects

Electron/positron mass (m) and charge ($e < 0$) determine fundamental scales

Relativity: Dirac equation

- Changed dispersion relation: $\epsilon = mv^2/2$ vs. $\epsilon = \gamma mc^2$
- Spin degree of freedom
- Antiparticles

Quantum fluctuations: QFT

- Virtual particles
- Lamb shift of atomic levels
- Anomalous magnetic moment
- Running coupling constant

- At each fundamental scale the theory changes qualitatively
- Nature surprised us whenever we tested a fundamental scale

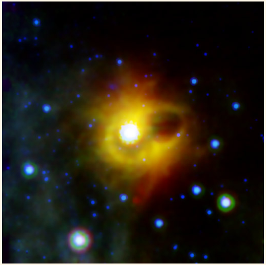
The strong-field regime $E \gtrsim E_{\mathrm{cr}}$ is largely unexplored

We use natural units from now on $\epsilon_0 = \hbar = c = 1$ (often restored for clarity)

Motivation: strong-field QED in astrophysics

Extreme magnetic fields: magnetars

Magnetar SGR 1900+14



THE McGILL MAGNETAR CATALOG

Name	B (10^{14} G)
CXOU J010043.1−721134	3.9
4U 0142+61	1.3
SGR 0418+5729	0.061
SGR 0501+4516	1.9
SGR 0526−66	5.6
1E 1048.1−5937	3.9
1E 1547.0−5408	3.2
PSR J1622−4950	2.7
SGR 1627−41	2.2
CXOU J164710.2−455216	<0.66
1RXS J170849.0−400910	4.6
CXOU J171405.7−381031	5.0
SGR J1745−2900	1.6
SGR 1806−20	20
XTE J1810−197	2.1
Swift J1822.3−1606	0.51
SGR 1833−0832	1.6
Swift J1834.9−0846	1.4
1E 1841−045	6.9
SGR 1900+14	7.0
1E 2259+586	0.59

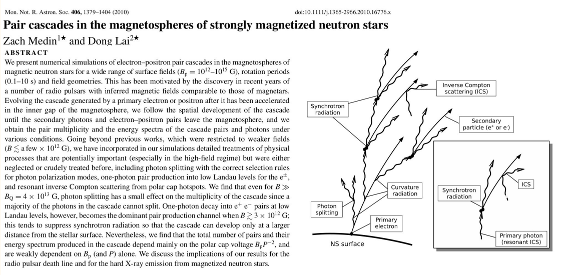
Ultrastrong electromagnetic fields + highly energetic particles: SFQED

- **Interior of neutron stars**
- **Magnetospheres of magnetars**: $B \gtrsim B_{\rm cr}$ $\quad [B_{\rm cr} = m^2c^2/(\hbar e) \approx 0.4 \times 10^{14}\,\mathrm{G}]$
  vacuum birefringence, electromagnetic cascades
- Central engines of supernovae and gamma ray bursts
- Black holes: energy extraction via the Blandford–Znajek process

Uzdensky and Rightley, Plasma physics of extreme astrophysical environments
Rep. Prog. Phys. **77**, 036902 (2014)

Motivation: strong-field QED in astrophysics

Magnetosphere: electromagnetic cascades



Mon. Not. R. Astron. Soc. **406,** 1379–1404 (2010) doi:10.1111/j.1365-2966.2010.16776.x

Pair cascades in the magnetospheres of strongly magnetized neutron stars

Zach Medin[1★] and Dong Lai[2★]

ABSTRACT

We present numerical simulations of electron–positron pair cascades in the magnetospheres of magnetic neutron stars for a wide range of surface fields ($B_p = 10^{12}$–10^{15} G), rotation periods (0.1–10 s) and field geometries. This has been motivated by the discovery in recent years of a number of radio pulsars with inferred magnetic fields comparable to those of magnetars. Evolving the cascade generated by a primary electron or positron after it has been accelerated in the inner gap of the magnetosphere, we follow the spatial development of the cascade until the secondary photons and electron–positron pairs leave the magnetosphere, and we obtain the pair multiplicity and the energy spectra of the cascade pairs and photons under various conditions. Going beyond previous works, which were restricted to weaker fields ($B \lesssim$ a few $\times 10^{12}$ G), we have incorporated in our simulations detailed treatments of physical processes that are potentially important (especially in the high-field regime) but were either neglected or crudely treated before, including photon splitting with the correct selection rules for photon polarization modes, one-photon pair production into low Landau levels for the $e^{\pm}$, and resonant inverse Compton scattering from polar cap hotspots. We find that even for $B \gg B_Q = 4 \times 10^{13}$ G, photon splitting has a small effect on the multiplicity of the cascade since a majority of the photons in the cascade cannot split. One-photon decay into $e^+ e^-$ pairs at low Landau levels, however, becomes the dominant pair production channel when $B \gtrsim 3 \times 10^{12}$ G; this tends to suppress synchrotron radiation so that the cascade can develop only at a larger distance from the stellar surface. Nevertheless, we find that the total number of pairs and their energy spectrum produced in the cascade depend mainly on the polar cap voltage $B_p P^{-2}$, and are weakly dependent on B_p (and P) alone. We discuss the implications of our results for the radio pulsar death line and for the hard X-ray emission from magnetized neutron stars.

Ultrastrong electromagnetic fields + highly energetic particles: SFQED

– **Interior of neutron stars**
– **Magnetospheres of magnetars**: $B \gtrsim B_{cr}$ $\quad [B_{cr} = m^2c^2/(\hbar e) \approx 0.4 \times 10^{14}\,\mathrm{G}]$
  vacuum birefringence, **electromagnetic cascades**
– Central engines of supernovae and gamma ray bursts
– Black holes: energy extraction via the Blandford–Znajek process

Uzdensky and Rightley, Plasma physics of extreme astrophysical environments
Rep. Prog. Phys. **77**, 036902 (2014)

Motivation: strong-field QED in astrophysics

Gamma ray bursts, black holes

artist's view – quarkmag.com

Ultrastrong electromagnetic fields + highly energetic particles: SFQED

- Interior of neutron stars
- Magnetospheres of magnetars: $B \gtrsim B_{cr}$ $[B_{cr} = m^2c^2/(\hbar e) \approx 0.4 \times 10^{14}\,\mathrm{G}]$
  vacuum birefringence, electromagnetic cascades
- **Central engines of supernovae and gamma ray bursts**
- **Black holes**: energy extraction via the Blandford–Znajek process

Uzdensky and Rightley, Plasma physics of extreme astrophysical environments
Rep. Prog. Phys. **77**, 036902 (2014)

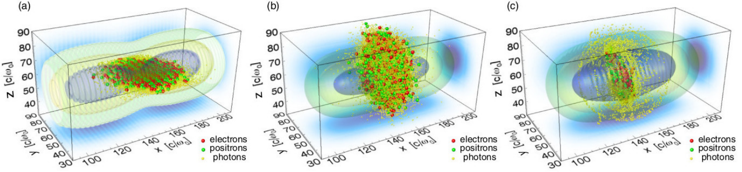
Motivation: plasma physics, benchmarking QED-PIC codes

PHYSICAL REVIEW E **95**, 023210 (2017)

Seeded QED cascades in counterpropagating laser pulses

T. Grismayer,[1,*] M. Vranic,[1] J. L. Martins,[1] R. A. Fonseca,[1,2] and L. O. Silva[1,†]

These results show that relativistic pair plasmas and efficient conversion from laser photons to γ rays can be observed with the typical intensities planned to operate on future ultraintense laser facilities such as ELI or Vulcan.

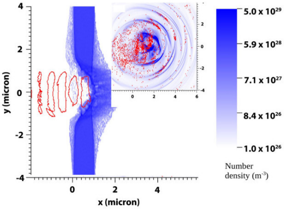


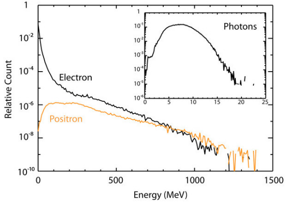
PRL **108,** 165006 (2012) PHYSICAL REVIEW LETTERS week ending 20 APRIL 2012

Dense Electron-Positron Plasmas and Ultraintense γ rays from Laser-Irradiated Solids

C. P. Ridgers,[1,2] C. S. Brady,[3] R. Duclous,[4] J. G. Kirk,[5] K. Bennett,[3] T. D. Arber,[3] A. P. L. Robinson,[2] and A. R. Bell[1,2]

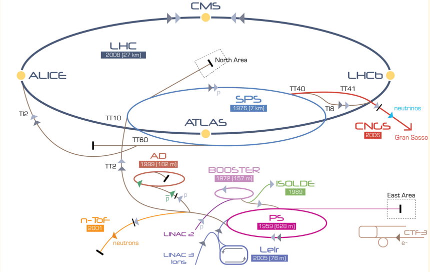
In simulations of a 10 PW laser striking a solid, we demonstrate the possibility of producing a pure electron-positron plasma by the same processes as those thought to operate in high-energy astrophysical environments.



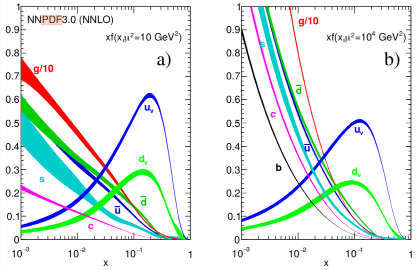


Motivation: beamstrahlung in future linear colliders

Hadron collider (proton-proton)



Parton distribution functions

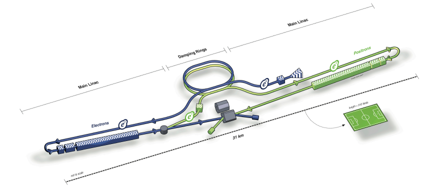


- **Problems of protron-proton collider:**
  - Nontrivial initial state: protons are not elementary particles
  - PDFs: smaller effective energy, complicated background
- Problems of linear electron-positron collider:
  - High luminosity $\to$ high charge density $\to$ strong fields $\to$ beamstrahlung
  - Stochastic photon emission + large recoil: nontrivial energy distribution, modified transverse beam structure (beam broadening $\to$ focusing quality)

Understanding of beamstrahlung is crucial

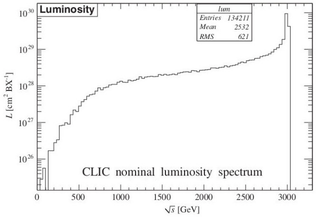
Motivation: beamstrahlung in future linear colliders

Lepton collider (electron-positron)



ILC $E^*/E_{\text{cr}} = 0.1 - 0.3$ $(0.25 - 0.5\,\text{TeV})$
CLIC $E^*/E_{\text{cr}} = 1.5 - 12$ $(0.2 - 1.5\,\text{TeV})$

Stochastic beamstrahlung



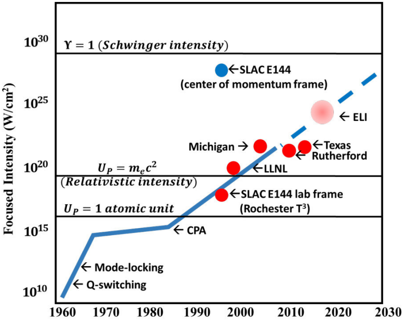
SFQED determines energy/luminosity

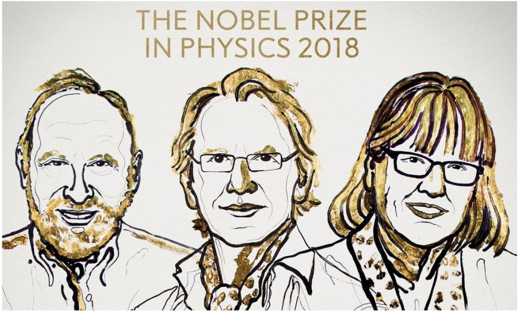
Esberg et al., PRSTAB **17**, 051003 (2014)

- Problems of protron-proton collider:
  - Nontrivial initial state: protons are not elementary particles
  - PDFs: smaller effective energy, complicated background
- **Problems of linear electron-positron collider:**
  - High luminosity $\to$ high charge density $\to$ strong fields $\to$ beamstrahlung
  - Stochastic photon emission + large recoil: nontrivial energy distribution, modified transverse beam structure (beam broadening $\to$ focusing quality)

Understanding of beamstrahlung is crucial

Reaching the QED critical field with lasers





QED critical field:

$$E_{cr} \approx 1.3 \times 10^{18}\,\mathrm{V/m}$$
$$I_{cr} \approx 4.6 \times 10^{29}\,\mathrm{W/cm^2}$$

Volume 56, number 3 OPTICS COMMUNICATIONS 1 December 1985

COMPRESSION OF AMPLIFIED CHIRPED OPTICAL PULSES ☆

Donna STRICKLAND and Gerard MOUROU

We have demonstrated the amplification and subsequent recompression of optical chirped pulses. A system which produces 1.06 μm laser pulses with pulse widths of 2 ps and energies at the millijoule level is presented.

		facility	current	future
optical	$1\,\mathrm{eV}$	APOLLON, ELI,...	$10^{22}\,\mathrm{W/cm^2}$	$10^{24-25}\,\mathrm{W/cm^2}$
x-ray	$10\,\mathrm{keV}$	LCLS-II, XFEL,...	$10^{21}\,\mathrm{W/cm^2}$	$10^{27}\,\mathrm{W/cm^2}$ (if focused)

We need the Lorentz boost of ultra-relativistic particles to probe the QED critical field!

Reaching the QED critical field with lasers

- QED critical field: $E_{cr} \approx 1.3 \times 10^{18}\,\mathrm{V/m} \longleftrightarrow I_{cr} \approx 4.6 \times 10^{29}\,\mathrm{W/cm^2}$ is not reachable in the laboratory rest frame (with existing technology)
- Fortunately, the electric/magnetic field is not Lorentz invariant:

$$\boldsymbol{E}' = \gamma(\boldsymbol{E} + \boldsymbol{\beta} \times \boldsymbol{B}) - \frac{\gamma^2}{\gamma+1}\boldsymbol{\beta}(\boldsymbol{\beta E}), \quad \boldsymbol{B}' = \gamma(\boldsymbol{B} - \boldsymbol{\beta} \times \boldsymbol{E}) - \frac{\gamma^2}{\gamma+1}\boldsymbol{\beta}(\boldsymbol{\beta B})$$

Quantum parameter

Decisive measure: electric field in the electron rest frame (E^*):

$$\chi = \Upsilon = \frac{\sqrt{pF^2p}}{E_{cr}mc^2} = \frac{E^*}{E_{cr}} \approx 0.57\,\frac{\epsilon}{10\,\mathrm{GeV}}\sqrt{\frac{I}{10^{20}\,\mathrm{W/cm^2}}}$$

I: laser intensity ϵ: electron energy (last relation: head-on electron-laser collision)

Strong field universality

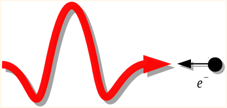
- For ultra-relativistic particles χ is the only relevant field invariant:
- **Same fundamental probabilities for processes in a laser field, static magnetic field (astrophysics), and linear lepton colliders**

$\longrightarrow$ Suggested experiment is relevant for different research areas

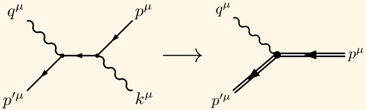
Ritus, J. Sov. Laser Res. **6**, 497–617 (1985); Di Piazza et al., Rev. Mod. Phys. **84**, 1177 (2012)

The fundamental (strong-field) QED processes

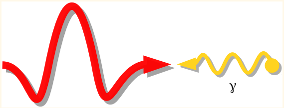
Photon emission



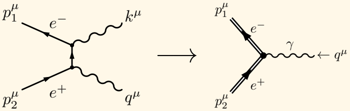
photon emission by an electron/positron



Pair production



photon decay into a lepton pair

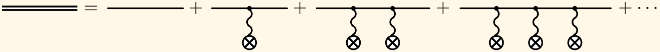


Dressed states

- Perturbative treatment of the laser field breaks down if $\xi \gtrsim 1$

$$\xi = a_0 = \eta = \frac{|e|E}{mc\omega} \approx 0.75 \, \frac{\mathrm{eV}}{\hbar\omega} \sqrt{\frac{I}{10^{18}\ \mathrm{W/cm^2}}}$$

- Dressed states include the classical background field exactly:

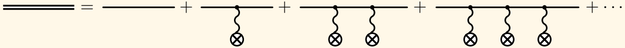


Ritus, J. Sov. Laser Res. **6**, 497–617 (1985); Di Piazza et al., Rev. Mod. Phys. **84**, 1177 (2012)

Different types of nonperturbative effects in SFQED

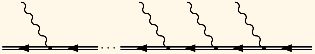
1st breakdown of perturbation theory: background field

FACET-II, $\xi \gtrsim 1$: interaction with laser becomes nonperturbative:



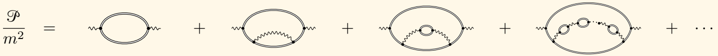
2nd breakdown of perturbation theory: higher-order processes

FACET-II: tree-level processes with many vertices become important:

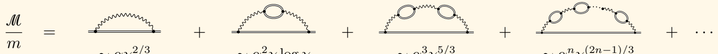


3rd breakdown of perturbation theory: radiative corrections

Future: if $\alpha\chi^{2/3} \gtrsim 1$ radiative corrections become nonperturbative:



$\sim \alpha\chi^{2/3}$ (Narozhny, 1968); $\sim \alpha^2\chi^{2/3}\log\chi$ (Morozov, 1977); $\sim \alpha^3\chi\log^2\chi$ (Narozhny, 1980); $\sim \alpha^n\chi^{(2n-3)/3}$ ($n>3$, conjecture)



$\sim \alpha\chi^{2/3}$ (Ritus, 1970); $\sim \alpha^2\chi\log\chi$ (Ritus, 1972); $\sim \alpha^3\chi^{5/3}$ (Narozhny, 1980); $\sim \alpha^n\chi^{(2n-1)/3}$ ($n>3$, conjecture)

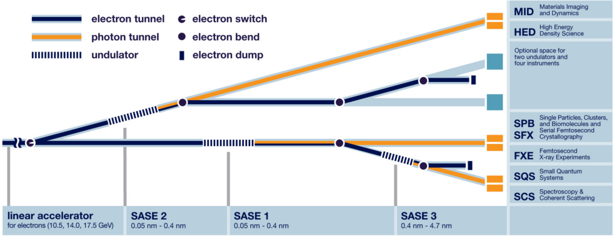
Community interest & competitors

LUXE: a new experiment using a laser and XFEL electrons to investigate QED in the strong-field regime

R. Assmann, T. Behnke, W. Decking, B. Heinemann,
J. List, E. Negodin, A. Ringwald (DESY)
M. Altarelli (MPI for structure and dynamics),
A. Hartin (Universität Hamburg), M. Wing (UCL)

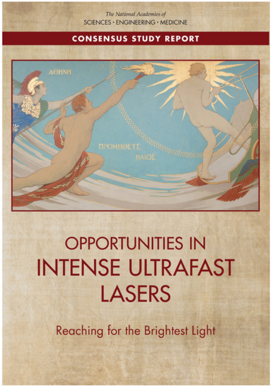
European XFEL

DESY.



- Strong interest in SFQED experiments with conventional GeV electron beams
- Recent PULSE/DESY workshop was dedicated to this topic
- We could get there first (similar ideas at DESY – not started *yet*)

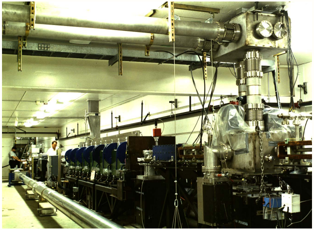
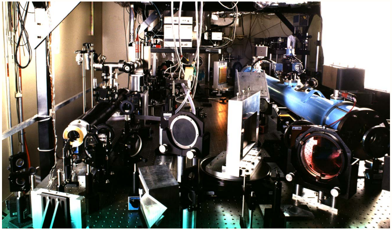
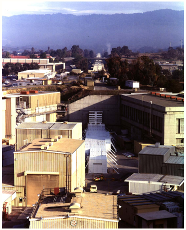
Community interest & competitors



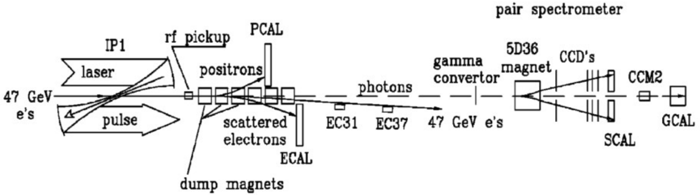
Suggested Citation: National Academies of Sciences, Engineering, and Medicine. 2018. *Opportunities in Intense Ultrafast Lasers: Reaching for the Brightest Light*. Washington, DC: The National Academies Press. doi: https://doi.org/10.17226/24939.

- Strong interest in SFQED experiments with conventional GeV electron beams
- Recent PULSE/DESY workshop was dedicated to this topic
- We could get there first (similar ideas at DESY – not started *yet*)

The seminal SLAC E-144 experiment (1990s)

- First laser experiment which probed the QED critical field
- Electron energy: $\epsilon = 46.6\,\mathrm{GeV}$, laser intensity: $I \sim 10^{18}\,\mathrm{W/cm^2}$
  $\longrightarrow$ Onset of nonlinear effects: $\xi = a_0 = \eta \lesssim 0.4$, $\chi = \Upsilon \lesssim 0.25$



C. Bamber et al. "Studies of nonlinear QED in collisions of 46.6 GeV electrons with intense laser pulses." Phys. Rev. D **60**, 092004 (1999).

The seminal SLAC E-144 experiment (1990s)

VOLUME 76, NUMBER 17 PHYSICAL REVIEW LETTERS 22 APRIL 1996

Observation of Nonlinear Effects in Compton Scattering

Nonlinear Compton scattering has been observed in the collision of a low-emittance 46.6-GeV electron beam with terawatt pulses from a Nd:glass laser at 1054 and 527 nm wavelengths in an experiment at the Final Focus Test Beam at SLAC. Peak laser intensities of 10^{18} W/cm^2 have been achieved, corresponding to a value of 0.6 for the parameter $\eta = e\mathcal{E}_{\rm rms}/m\omega_0 c$. Results are presented for multiphoton Compton scattering in which up to four laser photons interact with an electron, in agreement with theoretical calculations. [S0031-9007(96)00012-9]

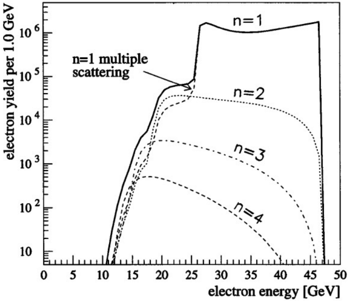


FIG. 1. Calculated yield of scattered electrons from the collision of 5×10^9 46.6-GeV electrons with a circularly polarized 1054-nm laser pulse of intensity parameter $\eta = 0.5$.

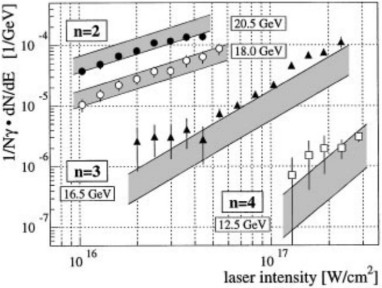


FIG. 5. The normalized yield of scattered electrons of energies corresponding to $n = 2$, 3, and 4 infrared laser photons per interaction versus the intensity of the laser field at the interaction point. The bands represent a simulation of the experiment, including 30% uncertainty in laser intensity and 10% uncertainty in N_γ.

The seminal SLAC E-144 experiment (1990s)

VOLUME 79, NUMBER 9 PHYSICAL REVIEW LETTERS 1 SEPTEMBER 1997

Positron Production in Multiphoton Light-by-Light Scattering

A signal of 106 ± 14 positrons above background has been observed in collisions of a low-emittance 46.6 GeV electron beam with terawatt pulses from a Nd:glass laser at 527 nm wavelength in an experiment at the Final Focus Test Beam at SLAC. The positrons are interpreted as arising from a two-step process in which laser photons are backscattered to GeV energies by the electron beam followed by a collision between the high-energy photon and several laser photons to produce an electron-positron pair. These results are the first laboratory evidence for inelastic light-by-light scattering involving only real photons. [S0031-9007(97)04008-8]

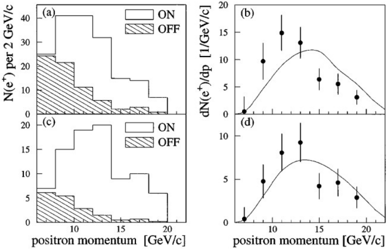


FIG. 3. (a) Number of positron candidates vs momentum for laser-on pulses and for laser-off pulses scaled to the number of laser-on pulses. (b) Spectrum of signal positrons obtained by subtracting the laser-off from the laser-on distribution. The curve shows the expected momentum spectrum from the model calculation. (c),(d) Same as (a) and (b) but with the requirement that $\eta > 0.216$.

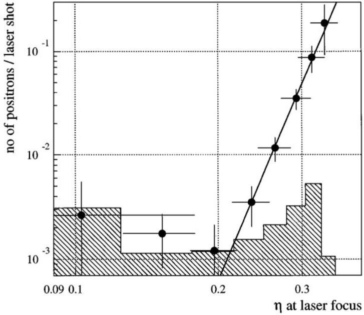


FIG. 4. Dependence of the positron rate per laser shot on the laser field-strength parameter η. The line shows a power law fit to the data. The shaded distribution is the 95% confidence limit on the residual background from showers of lost beam particles after subtracting the laser-off positron rate.

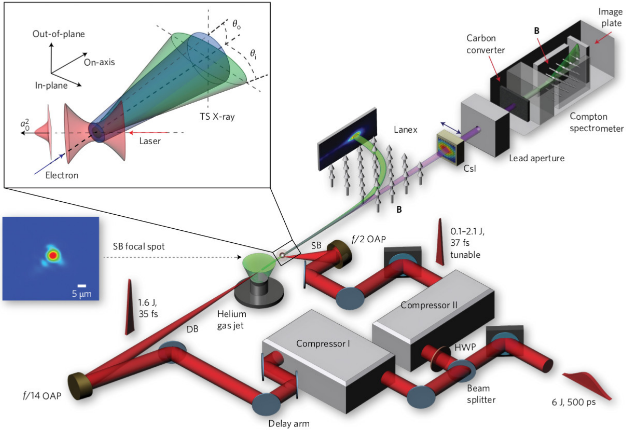
Recent all-optical LWFA experiments (2017-2018)

ARTICLES
PUBLISHED ONLINE: 26 JUNE 2017 | DOI: 10.1038/NPHOTON.2017.100
nature photonics

High-order multiphoton Thomson scattering

Wenchao Yan[1], Colton Fruhling[1], Grigory Golovin[1], Daniel Haden[1], Ji Luo[2,3], Ping Zhang[1], Baozhen Zhao[1], Jun Zhang[1], Cheng Liu[1], Min Chen[2,3], Shouyuan Chen[1], Sudeep Banerjee[1] and Donald Umstadter[1]*

we made the first measurements of high-order multiphoton scattering, in which more than 500 near-infrared laser photons were scattered by a single electron into a single X-ray photon.



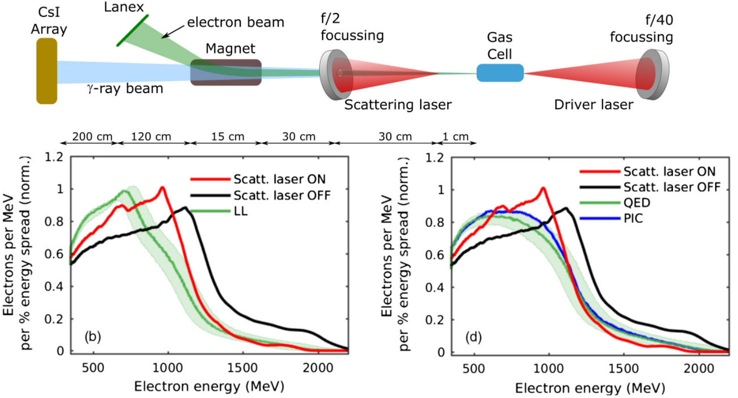
Recent all-optical LWFA experiments (2017-2018)

PHYSICAL REVIEW X **8,** 031004 (2018)

Experimental Signatures of the Quantum Nature of Radiation Reaction in the Field of an Ultraintense Laser

K. Poder,[1,†] M. Tamburini,[2] G. Sarri,[3,*] A. Di Piazza,[2] S. Kuschel,[4,5] C. D. Baird,[6] K. Behm,[7] S. Bohlen,[8] J. M. Cole,[1] D. J. Corvan,[3] M. Duff,[9] E. Gerstmayr,[1] C. H. Keitel,[2] K. Krushelnick,[7] S. P. D. Mangles,[1] P. McKenna,[9] C. D. Murphy,[6] Z. Najmudin,[1] C. P. Ridgers,[6] G. M. Samarin,[3] D. R. Symes,[10] A. G. R. Thomas,[7,11] J. Warwick,[3] and M. Zepf[3–5]

We report here on the experimental evidence of strong radiation reaction, in an all-optical experiment, during the propagation of highly relativistic electrons (maximum energy exceeding 2 GeV) through the field of an ultraintense laser (peak intensity of 4×10^{20} W/cm^2).



Recent all-optical LWFA experiments (2017-2018)

PHYSICAL REVIEW X **8,** 011020 (2018)

Featured in Physics

Experimental Evidence of Radiation Reaction in the Collision of a High-Intensity Laser Pulse with a Laser-Wakefield Accelerated Electron Beam

J. M. Cole,[1,*] K. T. Behm,[2] E. Gerstmayr,[1] T. G. Blackburn,[3] J. C. Wood,[1] C. D. Baird,[4] M. J. Duff,[5] C. Harvey,[3] A. Ilderton,[3,6] A. S. Joglekar,[2,7] K. Krushelnick,[2] S. Kuschel,[8] M. Marklund,[3] P. McKenna,[5] C. D. Murphy,[4] K. Poder,[1] C. P. Ridgers,[4] G. M. Samarin,[9] G. Sarri,[9] D. R. Symes,[10] A. G. R. Thomas,[2,11] J. Warwick,[9] M. Zepf,[8,9,12] Z. Najmudin,[1] and S. P. D. Mangles[1,†]

We present evidence of radiation reaction in the collision of an ultrarelativistic electron beam generated by laser-wakefield acceleration ($\varepsilon > 500$ MeV) with an intense laser pulse ($a_0 > 10$). We measure an energy loss in the postcollision electron spectrum that is correlated with the detected signal of hard photons (γ rays), consistent with a quantum description of radiation reaction.

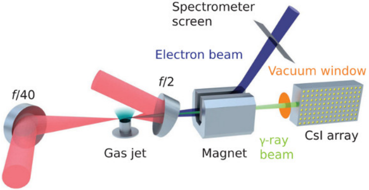
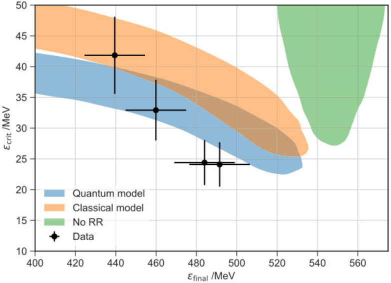


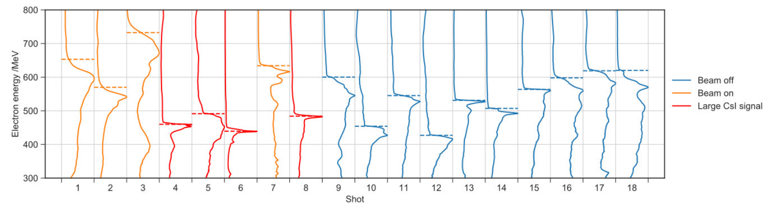
FIG. 1. Schematic of the experimental setup. All components are inside a vacuum chamber except for the CsI array.



Why strong-field QED at FACET-II?

Disadvantages of LWFA electron beams

- Parameters fluctuate severely from shot to shot:



J. M. Cole et al. Phys. Rev. X **8**, 011020 (2018)

- Electron energy: far from monochromatic, limited to $\lesssim 1 \ldots 5\,\mathrm{GeV}$
- Pointing instabilities: effective laser field strength changes

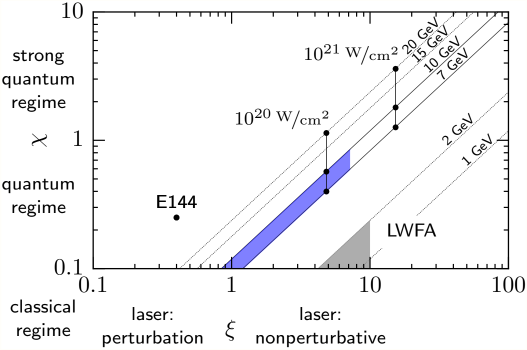
Parameter uncertainties: complicate analysis, large systematic errors

Advantages of FACET-II

- Well defined parameters (monoenergetic electrons, small beam jitter)
- High repetition rate + shot-to-shot stability $\longrightarrow$ high precision

World-wide unique opportunity for scrutinizing the theoretical framework and state-of-the-art approximations used in SFQED

Why strong-field QED at FACET-II?



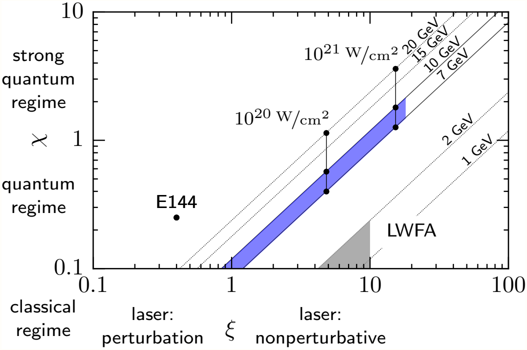
PWFA "afterburner":
energy doubling
(10 GeV $\rightarrow$ 20 GeV)

Electron parameters	
Energy	$7 - 10\,\mathrm{GeV}$
rms Energy Spread	0.5 [%]
rms Bunch Length	$10 - 100\,\mu\mathrm{m}$
rms Bunch Radius	$3\,\mu\mathrm{m}$
Bunch Charge	$0.6\,\mathrm{nC}$
Peak Current	$2 - 20\,\mathrm{kA}$

Laser parameters	Baseline
Pulse energy $\mathcal{E}_L$	$0.7\,\mathrm{J}$
Pulse duration (FWHM) τ_0	$35\,\mathrm{fs}$
Power (average) P	$\sim 20\,\mathrm{TW}$
Beam waist w_0	$2.4 - 5\,\mu\mathrm{m}$
Wavelength λ_L	$0.8\,\mu\mathrm{m}$
Intensity (peak) I_0	$(0.5 - 2.2) \times 10^{20}\,\mathrm{W/cm^2}$

Accessible parameters: $\xi = a_0 = \eta = 3 - 7; \quad \chi = \Upsilon = 0.4 - 0.9$

Why strong-field QED at FACET-II?



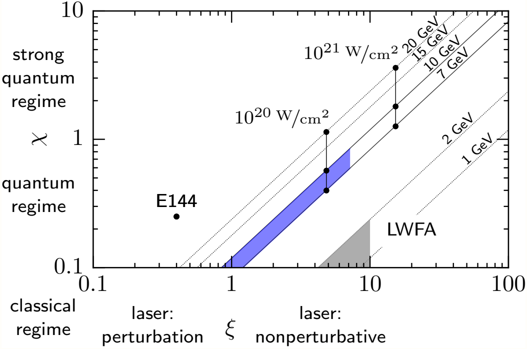
PWFA "afterburner": energy doubling (10 GeV → 20 GeV)

Electron parameters	
Energy	$7 - 10\,\mathrm{GeV}$
rms Energy Spread	0.5 [%]
rms Bunch Length	$10 - 100\,\mu\mathrm{m}$
rms Bunch Radius	$3\,\mu\mathrm{m}$
Bunch Charge	$0.6\,\mathrm{nC}$
Peak Current	$2 - 20\,\mathrm{kA}$

Laser parameters	Laser upgrade
Pulse energy $\mathcal{E}_L$	$8\,\mathrm{J}$
Pulse duration (FWHM) τ_0	$40\,\mathrm{fs}$
Power (average) P	$\sim 200\,\mathrm{TW}$
Beam waist w_0	$3-6\,\mu\mathrm{m}$
Wavelength λ_L	$0.8\,\mu\mathrm{m}$
Intensity (peak) I_0	$(0.4-1.4)\times 10^{21}\,\mathrm{W/cm^2}$

Accessible parameters: $\xi = a_0 = \eta = 9-18; \quad \chi = \Upsilon = 1.1-2.2$

Why strong-field QED at FACET-II?



PWFA "afterburner": energy doubling (10 GeV → 20 GeV)

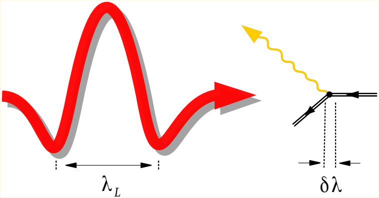
Reaching a novel regime

- For the first time $\xi \gg 1$, $\chi \sim 1$ will become accessible
- Regime $\xi \gg 1$ is qualitatively different from $\xi \lesssim 1$ (next slides)
- Beamstrahlung: parameters expected for ILC accessible:
  ILC: $\chi = 0.15$ ($\chi_{\text{av}} = 0.06$); **CLIC**: $\chi = 12$ ($\chi_{\text{av}} = 5$)

Accessible parameters: $\xi = a_0 = \eta = 3{-}7$; $\chi = \Upsilon = 0.4{-}0.9$

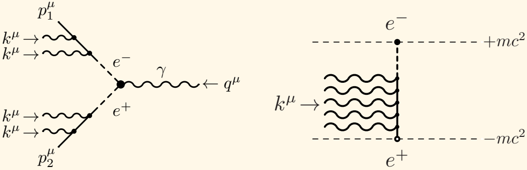
FACET-II: why is the new regime fundamentally different?

Formation length of SFQED processes

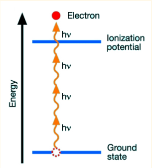


1. λ_L: laser wavelength (scale on which the field changes significantly)
2. $\delta\lambda$: formation region of a fundamental QED processes; $\delta\lambda/\lambda_L \sim 1/\xi$

Multiphoton pair production ($\xi \ll 1$)



Multiphoton ionization

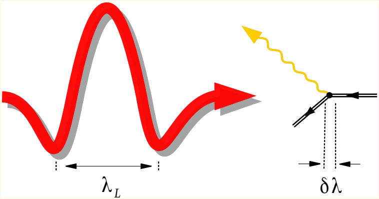


© DESY

- Ionization in atomic physics – Keldysh parameter: $\gamma_K = \omega\sqrt{2mI_p}/(|e|E)$,
- Pair production in SFQED: $\gamma_K(I_p = 2mc^2) \sim 1/\xi = \omega mc/(|e|E)$

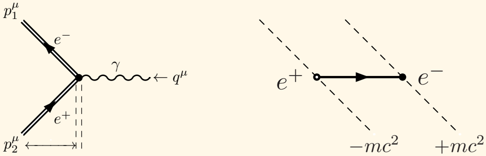
FACET-II: why is the new regime fundamentally different?

Formation length of SFQED processes

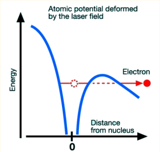


1. λ_L: laser wavelength (scale on which the field changes significantly)
2. $\delta\lambda$: formation region of a fundamental QED processes; $\delta\lambda/\lambda_L \sim 1/\xi$

Tunneling pair production ($\xi \gg 1$)



Tunnel ionization

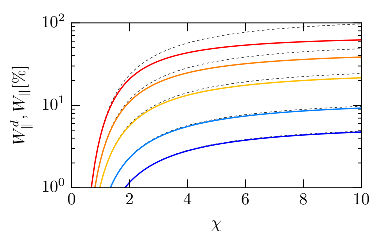


©DESY

- Ionization in atomic physics – Keldysh parameter: $\gamma_K = \omega\sqrt{2mI_p}/(|e|E)$,
- Pair production in SFQED: $\gamma_K(I_p = 2mc^2) \sim 1/\xi = \omega mc/(|e|E)$

FACET-II: why is the new regime fundamentally different?

Total pair production probability



$\xi = 10, 20, 50, 100, 200$

laser pulse with 5 cycles ($13\,\mathrm{fs}$)

- Pair production probability: $P \sim \exp[-8/(3\chi)]$ (note that $1/\chi \sim 1/e$)
- Nonperturbative tunneling exponent (expansion around $e = 0$ vanishes)

(χ: incoming photon) SM, Hatsagortsyan, Keitel, Di Piazza, PRD **91**, 013009 (2015)

FACET-II: probing a new regime of light-matter interaction

- The regime $\xi \gg 1$ is qualitatively different from $\xi \lesssim 1$
- Quantum corrections become important if $\chi \gtrsim 0.1$
  $\longrightarrow$ the regime $\xi \gg 1$, $\chi \gtrsim 1$ is exciting and unexplored

Simulations for FACET-II

- Numerical simulations with two independent codes have been carried out
  - Heidelberg group (M. Tamburini, A. Di Piazza, and C. H. Keitel): Monte-Carlo QED code
  - Lisbon group (M. Vranic, T. Grismayer, and L. O. Silva): fully relativistic particle-in-cell (PIC) code OSIRIS with QED module
- Realistic 3D simulations of the actual FACET-II parameters: focussed Gaussian laser, electron beam with Gaussian charge and energy distribution

Osiris

osiris framework

- Massively Parallel, Fully Relativistic Particle-in-Cell (PIC) Code
- Visualization and Data Analysis Infrastructure
- Developed by the osiris.consortium ⇒ UCLA + IST

code features

- Scalability to ~ 1.6 M cores
- SIMD hardware optimized
- Parallel I/O
- Dynamic Load Balancing
- Particle merging
- GPGPU support
- Xeon Phi support
- QED Module

Ricardo Fonseca
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http://plasmasim.physics.ucla.edu/

T. Grismayer et al., POP (2016), T. Grismayer et al., PRE (2017)

OPEN

Laser-pulse-shape control of seeded QED cascades

Matteo Tamburini, Antonino Di Piazza & Christoph H. Keitel

Methods

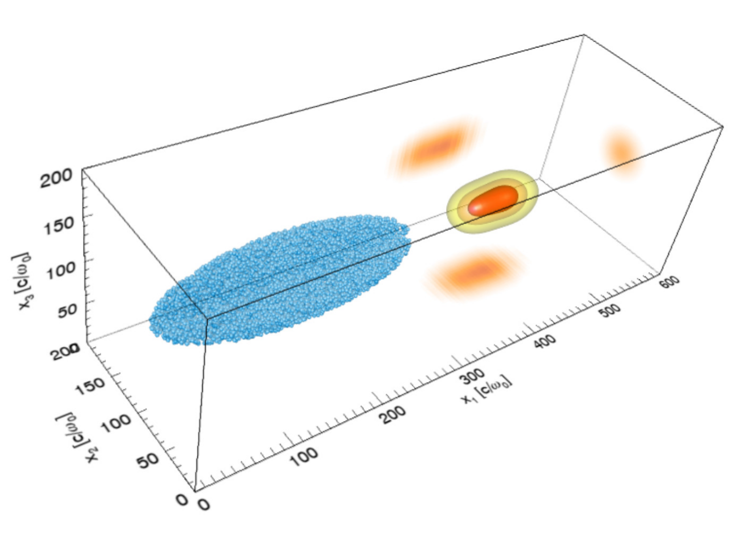
Numerical Modelling. All our simulations were performed employing both a standard Boris pusher[53] with a time-step much smaller than the laser period $\Delta t = 1/(10^5\omega)$ where $\omega = 2\pi/T$, and an adaptive fourth order Runge-Kutta integrator with time step chosen such that $\Delta t < T/(10\xi_M)$, where $\xi_M = eE_M/m_e\omega c$ is the normalized field amplitude and E_M is the maximum of the local value of the electric and magnetic field at the particle's position. For both integrators, stochastic photon emission by electrons and positrons and electron-positron pair creation from high-energy photons was taken into account by employing a standard Monte Carlo technique[18]. The small time step renders negligible the probability of multiple photon emission events during each time step. No significant difference was found between the two different integrators. Further details on the Monte Carlo technique, and benchmarks of the code against published results on the formation of a seeded QED cascade are reported in the Supplementary Information. For photons with energy less than 2.5 MeV and in the regions where $\chi_\gamma < 0.3$ photon conversion into pairs was neglected because for these photons the mean free path for pair conversion is much longer than the considered laser pulse duration.

In all our simulations a fully three-dimensional description of the laser pulse fields with terms up to the fifth order in the diffraction angle $\varepsilon = \lambda/\pi w_0$ was employed[54].

SCIENTIFIC REPORTS | 7: 5694 | DOI:10.1038/s41598-017-05891-z

Head-on collision of a FACET-II electron bunch and a 20 TW Gaussian laser pulse. Electrons: Gaussian charge distribution (10 μm rms length, 3 μm rms radius), Gaussian energy distribution (10 GeV mean, 100 MeV FWHM), and Gaussian transverse momentum distribution (zero mean, 0.1 mrad FWHM). Gaussian laser pulse: linear polarization, 0.8 μm central wavelength, 35 fs duration (intensity FWHM).

Simulation with OSIRIS-QED – M. Vranic



FACET-II measurements: pair production (tunneling regime)

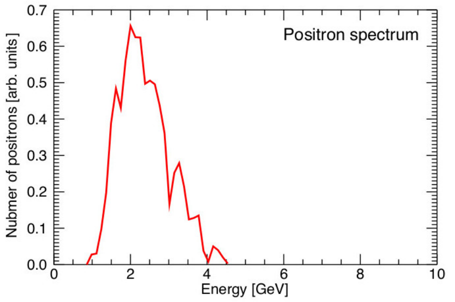
Comparison with E144

- Already with the 20 TW laser: $\sim 10^2 \ldots 10^4$ positrons per shot!
  - $\longrightarrow$ Significant reduction of statistical and systematic errors with respect to E144 (100 positrons in total)
    [see T. Koffas, PhD thesis (SLAC-Report-626) for details]
  - $\longrightarrow$ Positron yield: sensitive laser intensity measurement
- **First observation of vacuum breakdown in strong fields** (measurement of the nonperturbative tunneling exponent)

Total number of positrons & their spectrum

w_0	ξ	# positrons per electron	Simulation
3 μm 2.4 μm	5.7 7.2	1.2×10^{-7} 0.9×10^{-6}	M. Tamburini
4 μm	5.0 8.0	1.9×10^{-7} 1.7×10^{-5}	M. Vranic

FACET-II beam: 0.6 nC, i.e., 3.7×10^9 electrons
w_0: laser focus spot size

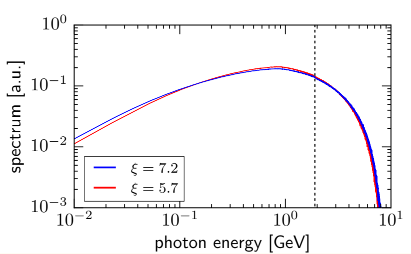


simulated by M. Vranic

FACET-II measurements: emitted gamma photon spectrum

Comparison with (linear) Compton scattering

- Laser is clearly nonperturbative (linear CS cutoff: 1.9 GeV)
- Absorbed laser photons $\sim \xi^3$
- Spectrum extends to very high harmonics ($\sim 8\,\mathrm{GeV}$ photons)



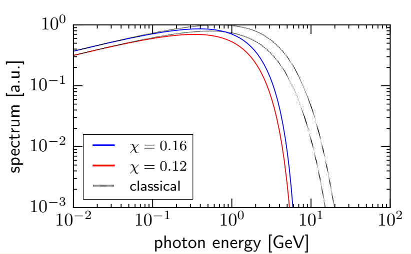
simulated by M. Tamburini

Comparison with synchrotron radiation

- $\chi \gtrsim 0.1$: classical electrodynamics violates energy conservation (photons with energy $> 10\,\mathrm{GeV}$)
- Recoil of individual photons:

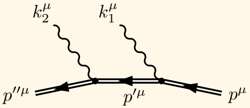
$\longrightarrow$ Redshift of the spectrum

$\longrightarrow$ Reduced total probability



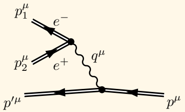
FACET-II measurements: validity of the LCFA

Higher-order processes



Multiple emissions per particle

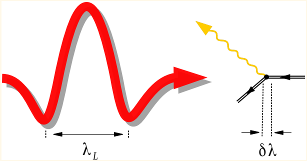
QED cascade



Trident: simplest QED cascade

State-of-the-art numerical approach

Strong fields ($\xi \gg 1$) $\longrightarrow$ small formation region ($\delta\lambda = \lambda_L/\xi$):



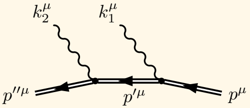
$\longrightarrow$ Background field is approximately constant during transition: the "Local Constant Field Approximation" (LCFA) is applied

$\longrightarrow$ Separation of scales: macroscopic fields / quantum processes particles propagate classically between quantum transitions

Classical propagation + Monte Carlo event generator

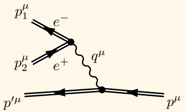
FACET-II measurements: validity of the LCFA

Higher-order processes



Multiple emissions per particle

QED cascade



Trident: simplest QED cascade

The validity of the LCFA is vital for all numerical methods

- Codes for calculating beamstrahlung, e.g., CAIN and GUINEA-PIG

User's Manual of **CAIN**

- Particle-in-cell codes with QED modules for laser-plasma interactions

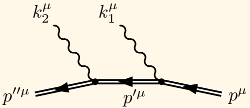
EPOCH — An open source PIC code for high energy density physics

Osiris

Smilei

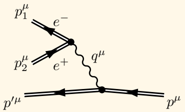
FACET-II measurements: validity of the LCFA

Higher-order processes



Multiple emissions per particle

QED cascade



Trident: simplest QED cascade

Importance of higher-order processes at FACET-II

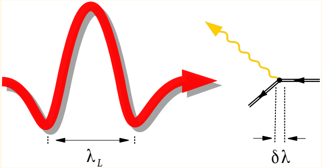
On average each electron emits more than one photon:
(radiation field no longer a perturbation)

Laser spot size (w_0)	ξ	electrons included in average	# photons per electron	Simulation
$3\,\mu\text{m}$	5.7	all	1.4	M. Tamburini
$2.4\,\mu\text{m}$	7.2	all	1.3	
		focus only	4.8	
$4\,\mu\text{m}$	5.0	all	1.6	M. Vranic
		focus only	1.9	
	8.0	all	2.9	
		focus only	3.3	

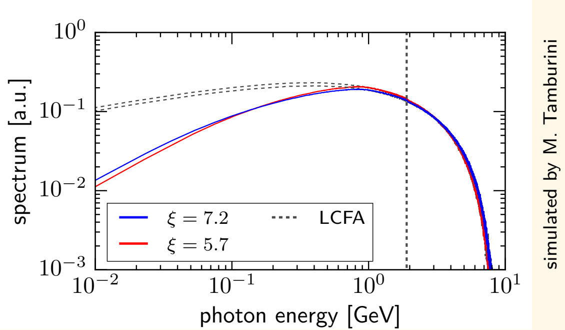
FACET-II measurements: breakdown of the LCFA

Validity of LCFA depends on photon energy

- Formation region $\delta\lambda$ depends on photon energy
- LCFA breaks down for "low-energy" photons



Observable: "low-energy" photons



FACET-II measurements: classical radiation reaction

Lorentz force

$$\frac{du^\mu}{d\tau} = \frac{e}{m} F^{\mu\nu} u_\nu$$

Acceleration by an electromagnetic field

Larmor formula

$$\mathcal{P} = -\frac{2}{3}\alpha \frac{du^\mu}{d\tau}\frac{du_\mu}{d\tau}$$

Radiation emitted due to acceleration

- Energy loss due to radiation must change the trajectory
- Self-consistent solution within classical electrodynamics: LAD

Lorentz-Abraham-Dirac (LAD) equation

$$\frac{du^\mu}{d\tau} = \frac{e}{m} F^{\mu\nu} u_\nu + \frac{2}{3}\frac{\alpha}{m}\left[\frac{d^2 u^\mu}{d\tau^2} + u^\mu \frac{du^\nu}{d\tau}\frac{du_\nu}{d\tau}\right]$$

- The LAD equation results in unphysical solutions
  $\longrightarrow$ The radiation reaction problem is unsolvable classically
- Assuming that RR effects are "small": perturbative expansion

Landau Lifshitz (LL) equation

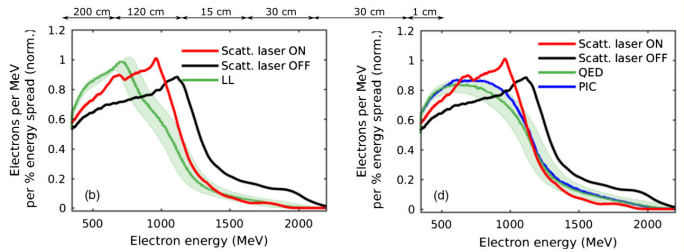
$$\frac{du^\mu}{d\tau} = \frac{e}{m} F^{\mu\nu} u_\nu + \frac{2}{3}\frac{\alpha}{m}\left[\frac{e}{m}(\partial^\rho F^{\mu\nu}) u_\rho u_\nu + \frac{e^2}{m^2} F^{\mu\nu} F_{\nu\rho} u^\rho - \frac{e^2}{m^2} u^\mu (uF^2 u)\right]$$

Landau & Lifshitz, "The Classical Theory of Fields"; Di Piazza et al., RMP **84**, 1177 (2012)

FACET-II measurements: classical radiation reaction

FACET-II: testing the LL equation

- The applicability range of the LL equation is not clear
  $\longrightarrow$ questions raised during recent LWFA-based experiments
- FACET-II: precision test of classical radiation reaction ($\chi \lesssim 0.1$)



K. Poder et al. Phys. Rev. X **8**, 031004 (2018)

Landau Lifshitz (LL) equation

$$\frac{du^\mu}{d\tau} = \frac{e}{m} F^{\mu\nu} u_\nu + \frac{2}{3}\frac{\alpha}{m}\left[\frac{e}{m}(\partial^\rho F^{\mu\nu}) u_\rho u_\nu + \frac{e^2}{m^2} F^{\mu\nu} F_{\nu\rho} u^\rho - \frac{e^2}{m^2} u^\mu (uF^2 u)\right]$$

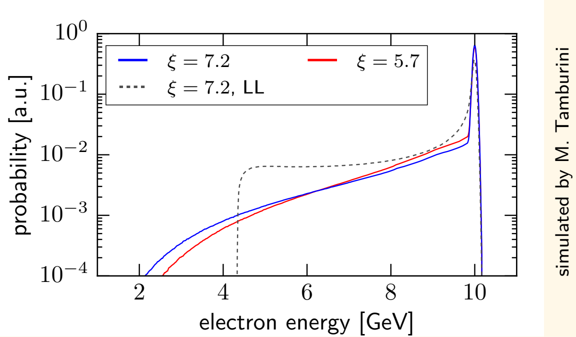
Landau & Lifshitz, "The Classical Theory of Fields"; Di Piazza et al., RMP **84**, 1177 (2012)

FACET-II measurements: quantum radiation reaction

Classical vs. quantum radiation reaction

- Classical radiation reaction represents a “frictional force”
  $\longrightarrow$ sharp cutoff of the electron energy spectrum
- $\chi \gtrsim 0.1$: stochastic photon emission leads to “diffusion”
  $\longrightarrow$ edge of the spectrum is smeared out (higher losses!)
- Clean signature of the quantum regime

Observable: electron energy distribution

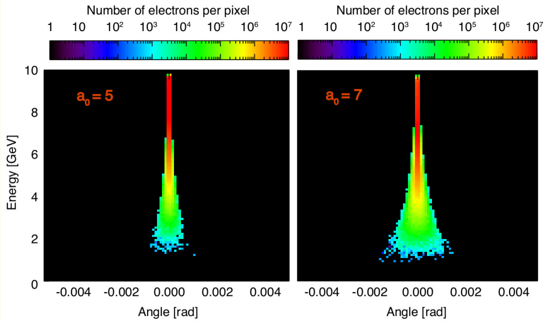


FACET-II measurements: quantum radiation reaction

Classical vs. quantum radiation reaction

- Classically (LL): continuous energy/momentum loss
- Quantum regime ($\chi \gtrsim 0.1$): instantaneous recoil
  $\longrightarrow$ symmetry breaking: transverse acceleration by laser
  $\longrightarrow$ electron beam "broadens" due to quantum effects
- Transverse momentum: $\sim m\xi \longrightarrow$ angle: $\sim m\xi/\epsilon$

Observable: transverse momentum distribution



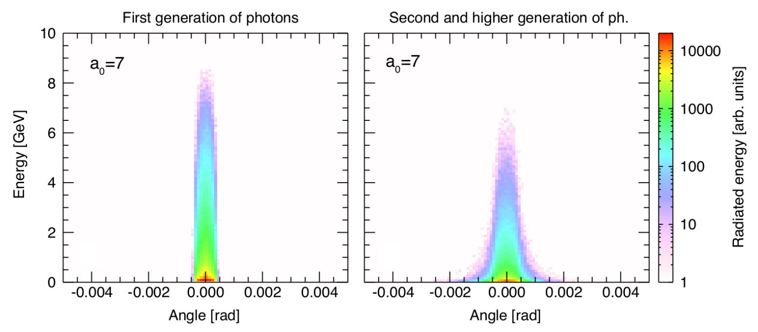
simulated by
M. Vranic

FACET-II measurements: quantum radiation reaction

Recoil induced correlations between emissions

- High-energy photon changes trajectory instantaneously
  $\longrightarrow$ due to energy loss the transverse excursion increases
  $\longrightarrow$ subsequent photons can be emitted into a wider cone
- Gamma photons cover a broader angular range
  $\longrightarrow$ electron energy loss affects radiation spectrum

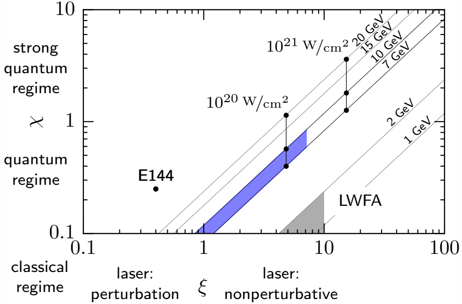
Observable: angular photon distribution



simulated by M. Vranic

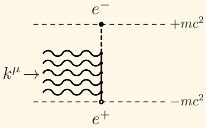
Summary: FACET-II 10 GeV electrons + 20 TW laser pulses

Exploring light-matter interaction in a novel regime



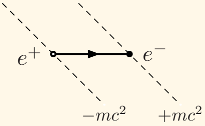
- E144: $\xi < 1$ vs. FACET-II: $\xi \gg 1$
- Important qualitative changes
- Important test of state-of-the art theory framework/approximations
- Highly relevant for future linear colliders (stochastic beamstrahlung)
- Many phenomena could be observed for the first time:

Perturbative regime ($\xi \lesssim 1$, E144)



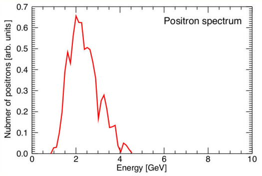
Laser is perturbation, pairs produced by multi-photon absorption

Tunneling regime ($\xi \gg 1$, FACET-II)



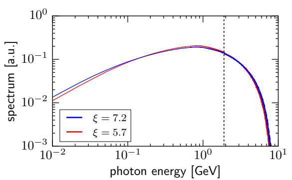
"Vacuum breakdown" in static field, afterward pair propagates classically (LCFA)

Summary: FACET-II 10 GeV electrons + 20 TW laser pulses



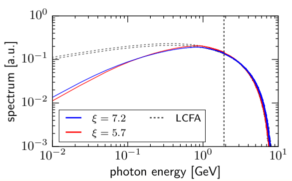
Tunneling pair production/vacuum breakdown

- Pair production inside quasi-static field
- Nonperturbative tunneling exponent
- Much higher statistics: $\sim 10^4$ positrons/shot



Strong-field synchrotron radiation

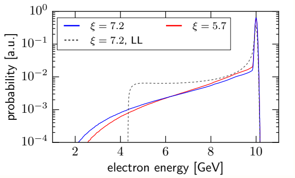
- Reduced radiation probability, spectrum: redshift
- Coherent interaction with $\sim 10^2$ laser photons
- Emission of high harmonics (up to 8 GeV photons)



Breakdown of the LCFA

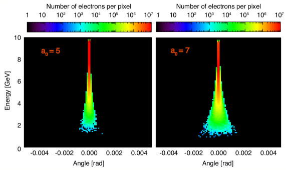
- Applicability of the LCFA: vital for numerical codes
- Formation region depends on photon frequency
- LCFA fails: suppression of low-frequency radiation

Summary: FACET-II 10 GeV electrons + 20 TW laser pulses



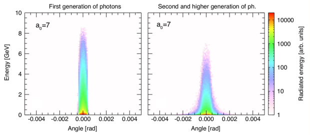
Quantum radiation reaction (QRR) – energy

- Stochasticity: broadening of the energy distribution
- Quenching: some electrons don't radiate at all
- Quantum corrections to Landau-Lifshitz



QRR – transverse beam broadening

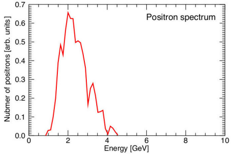
- Photon emission: transverse recoil
- Energy and momentum broadening: important for linear collider (severe impact on Luminosity)

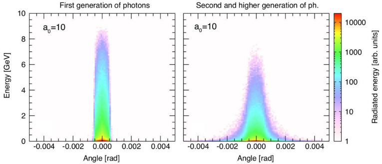


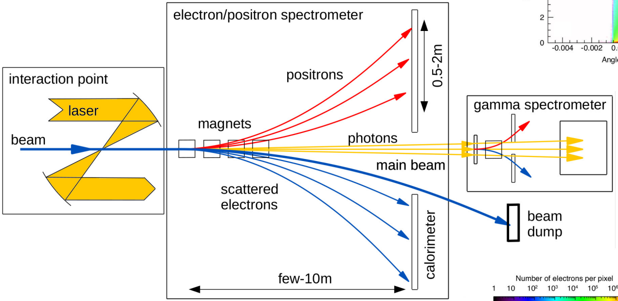
QRR – impact on photon phase space

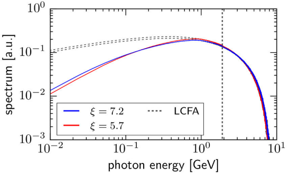
- Recoil of hard gamma emissions:
  $\longrightarrow$ instantaneous change of electron trajectories
- Subsequent emissions have broader angular range

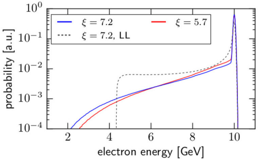
Summary: FACET-II 10 GeV electrons + 20 TW laser pulses

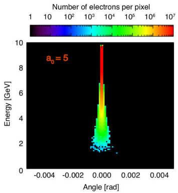












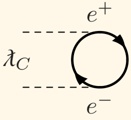
- **Tunneling pair production**
- **Strong-field synchrotron radiation (nonlinear CS)**
- **Breakdown of the LCFA**
- **Classical & quantum radiation reaction**

Backup slides

Intuitive explanation: vacuum breakdown

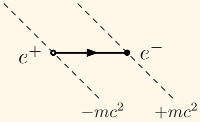
- According to quantum mechanics (Heisenberg uncertainty principle) the vacuum contains virtual electron-positron pairs (pictorial model)
- Spatial scale of these quantum fluctuations: $\lambda\!\!\!^{-}_C = \hbar/(mc)$
- If an electric field is able to transfers the rest energy $2mc^2$ to these pairs within their lifetime, they become real: $E_{\mathrm{cr}} = mc^2/(|e|\,\lambda\!\!\!^{-}_C)$

Vacuum fluctuations



Instead of being empty, the vacuum is filled with quantum fluctuations

Heuristic tunneling picture



"Tilted" energy levels $\longrightarrow$ tunneling
Probability: $\sim \exp\left(-\pi E_{\mathrm{cr}}/E\right)$

Critical field correspons to critical (laser) intensity $I_{\mathrm{cr}} = 4.6 \times 10^{29}\ \mathrm{W/cm^2}$:

	$\sim \hbar\omega$	Future facilities	I (intensity)	current
optical	$1\,\mathrm{eV}$	APOLLON, ELI,...	$10^{24-25}\ \mathrm{W/cm^2}$	$10^{22}\ \mathrm{W/cm^2}$
x-ray	$10\,\mathrm{keV}$	LCLS-II, XFEL,...	$10^{27}\ \mathrm{W/cm^2}$ (if focused)	$10^{21}\ \mathrm{W/cm^2}$

Community interest & competitors: 10 PW lasers

ELI - Extreme Light Infrastructure

Research Program 6: High-field physics

The principal goal of this research program is to explore specific themes of the ultra-relativistic regime of laser-matter interaction, with focused intensities exceeding 10^{23} Wcm^{-2}, which is sometimes also referred to as exotic physics. This intensity territory, which is experimentally inaccessible at present, will provide an unprecedented tool for testing fundamental predictions of quantum electrodynamics in external strong electromagnetic (laser) fields and will involve several fields such as atomic physics, plasma physics, particle physics, nuclear physics, quantum field theory, ultra-high-pressure physics, astrophysics and cosmology, and possibly others. The "exotic" candidate experiments to be developed in Research Program 6 include, for example, electron-positron plasmas, vacuum four-wave mixing, vacuum polarization and vacuum birefringence, and QED cascades (experimental tests on all-optical inverse Compton scattering will be performed on a preliminary basis in Research Program 3).

Strong Field Physics and QED Experiments with ELI-NP 2x10PW Laser Beams

I.C.E. Turcu[1, a)], S. Balascuta[1], F. Negoita[1], D. Jaroszynski[2], P. McKenna[2]

Abstract. The ELI-NP facility will focus a 10 PW pulsed laser beam at intensities of ~10^{23} W/cm^2 for the first time, enabling investigation of the new physical phenomena at the interfaces of plasma, nuclear and particle physics. The electric field in the laser focus has a maximum value of ~10^{15} V/m at such laser intensities. In the ELI-NP Experimental Area E6, we propose the study of Radiation Reaction, Strong Field Quantum Electrodynamics (QED) effects and resulting production of Ultra-bright Sources of Gamma-rays which could be used for nuclear activation. Two powerful, synchronized 10 PW laser beams will be focused in the E6 Interaction Chamber on either gas or solid targets. One 10 PW beam is the Pump-beam and the other is the Probe-beam. The focused Pump beam accelerates the electrons to relativistic energies. The accelerated electron bunches interact with the very high electro-magnetic field of the focused Probe beam. The layout of the experimental area E6 will be presented with several options for the experimental configurations.

- Several ~10 PW laser facilities will become operational soon
- GeV electrons are obtainable using laser wakefield acceleration (LWFA)
- This approach has decisive disadvantages: electron beam quality is not sufficient to achieve the necessary precision (main talk)

FACET-II measurements: breakdown of the LCFA

PHYSICAL REVIEW A **98**, 012134 (2018)

Implementing nonlinear Compton scattering beyond the local-constant-field approximation

A. Di Piazza,[1,*] M. Tamburini,[1,†] S. Meuren,[2,1,‡] and C. H. Keitel[1,§]

Here, we scrutinize the validity of the LCFA in the case of nonlinear Compton scattering focusing on the role played by the energy of the emitted photon on the formation length of this process.

we obtained an improved approximation for the photon emission probability, implemented it numerically, and showed that it amends the inaccurate behavior of the LCFA in the infrared region, such that it is in qualitative and good quantitative agreement with the full strong-field QED probability also in the infrared region.

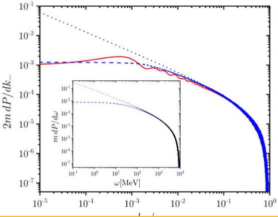
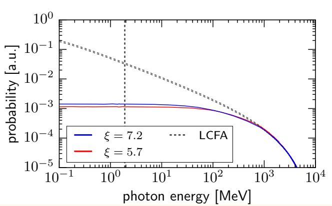
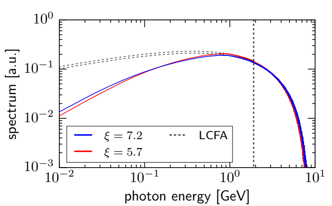


FIG. 1. Exact (solid red curve) vs local-constant-field approximated (dotted black curve) differential photon emission probability for an electron with initial energy of 10 GeV colliding head-on with a plane-wave pulse of 5 fs FWHM duration and 4.4×10^{20} W/cm^2 peak intensity. The dashed blue curve shows the same probability obtained via the numerical code presented in [54], with the improved emission model as described in the text. The inset shows the corresponding probabilities with the same color code and calculated via the numerical code in [54] in the case of an electron beam with 10 GeV average energy and 10% energy spread colliding head-on with a focused Gaussian laser beam with 30 fs FWHM duration, 4.4×10^{20} W/cm^2 peak intensity, and 8 μm waist radius.

FACET-II measurement: "low-energy" photons

simulated by M. Tamburini





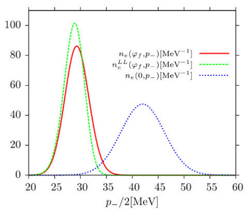
FACET-II measurements: quantum radiation reaction

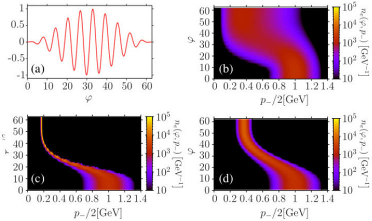
PRL **111,** 054802 (2013) PHYSICAL REVIEW LETTERS week ending 2 AUGUST 2013

Stochasticity Effects in Quantum Radiation Reaction

N. Neitz and A. Di Piazza*

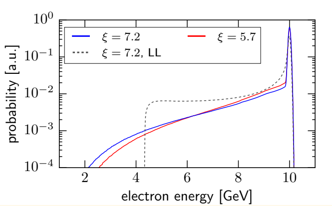
Here we show that when quantum effects become important, radiation reaction induces the opposite effect; i.e., the energy distribution of the electron beam spreads out after interacting with the laser pulse. We identify the physical origin of this opposite tendency in the intrinsic stochasticity of photon emission, which becomes substantial in the quantum regime.



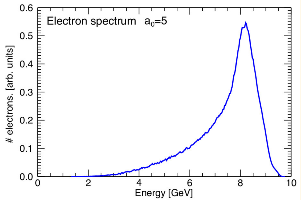


Electron energy distribution (after interaction)

simulated by M. Tamburini



simulated by M. Vranic



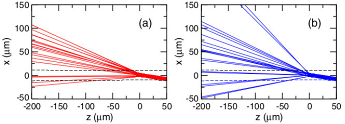
FACET-II measurements: quantum radiation reaction

PRL **112,** 164801 (2014) PHYSICAL REVIEW LETTERS week ending 25 APRIL 2014

Transverse Spreading of Electrons in High-Intensity Laser Fields

D. G. Green* and C. N. Harvey†

We show that for collisions of electrons with a high-intensity laser, discrete photon emissions introduce a transverse beam spread that is distinct from that due to classical (or beam shape) effects.



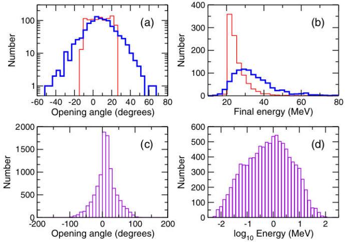
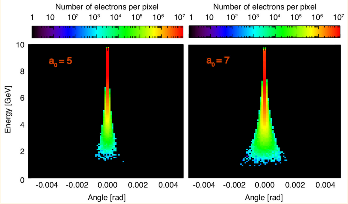


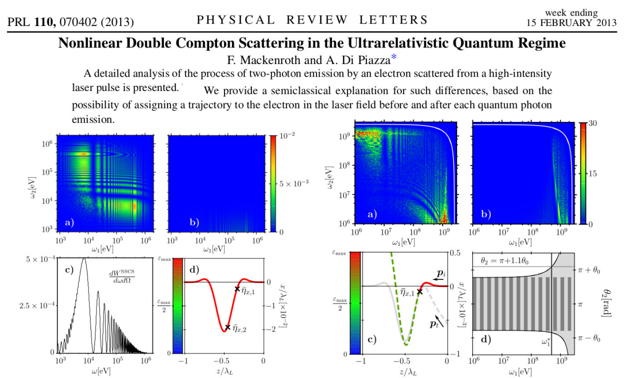
FIG. 2 (color online). Sample of 20 simulated electron trajectories in a paraxial Gaussian laser beam of intensity $a_0 = 150$ (9.5×10^{22} W cm^{-2}), wavelength of 800 nm, waist radius of 10 μm and duration 35 fs (dashed line shows laser profile). Initial electron energies distributed around 255 MeV ($\gamma_0 = 500$) according to a Gaussian of FWHM 0.52 MeV. Electrons incident at 10 degree angle. (a) classical (LL); (b) QED electrons.

Transverse electron momentum distribution

simulated by M. Vranic



FACET-II measurements: multiple emissions & QRR



PRL **110,** 070402 (2013) PHYSICAL REVIEW LETTERS week ending 15 FEBRUARY 2013

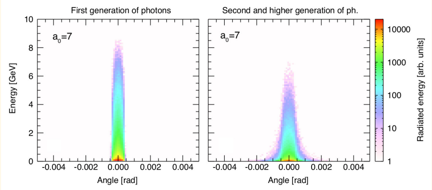
Nonlinear Double Compton Scattering in the Ultrarelativistic Quantum Regime

F. Mackenroth and A. Di Piazza*

A detailed analysis of the process of two-photon emission by an electron scattered from a high-intensity laser pulse is presented. We provide a semiclassical explanation for such differences, based on the possibility of assigning a trajectory to the electron in the laser field before and after each quantum photon emission.

FACET-II measurement: angular-resolved gamma photon spectrum

simulated by M. Vranic



- Recoil: change in trajectory
  - → Signature of rad. reaction
  - → Larger emission range
- Requires measuring the angular photon distribution

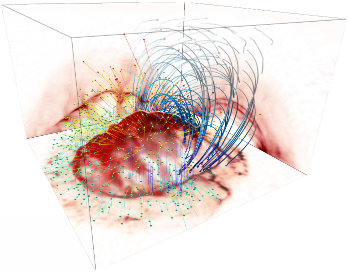
OSIRIS 4.0

TÉCNICO LISBOA

Osiris

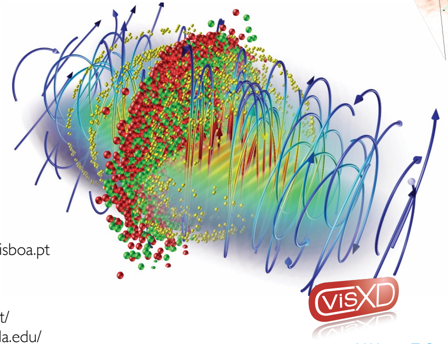
osiris framework

- Massivelly Parallel, Fully Relativistic Particle-in-Cell (PIC) Code
- Visualization and Data Analysis Infrastructure
- Developed by the osiris.consortium
  $\Rightarrow$ UCLA + IST



TÉCNICO LISBOA

UCLA



Ricardo Fonseca
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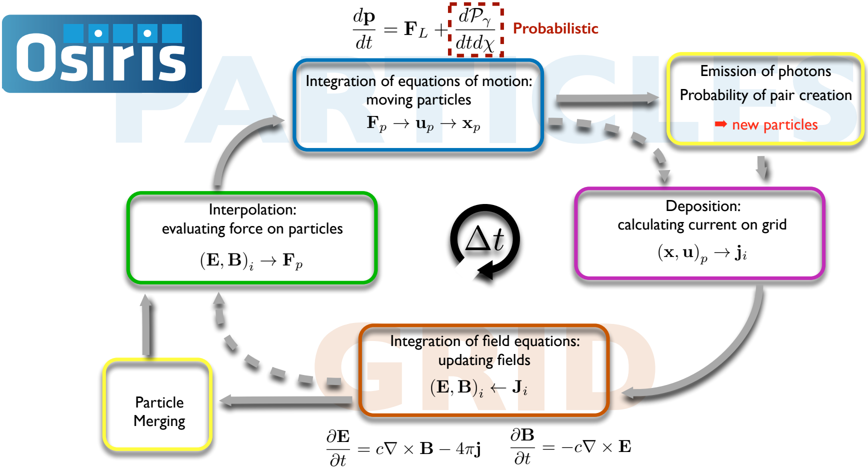
http://plasmasim.physics.ucla.edu/

code features

- Scalability to ~ 1.6 M cores
- SIMD hardware optimized
- Parallel I/O
- Dynamic Load Balancing
- Particle merging
- GPGPU support
- Xeon Phi support
- QED Module

M.Vranic, T. Grismayer, L. O. Silva | IST, UTL, Lisbon, Portugal

QED loop in OSIRIS



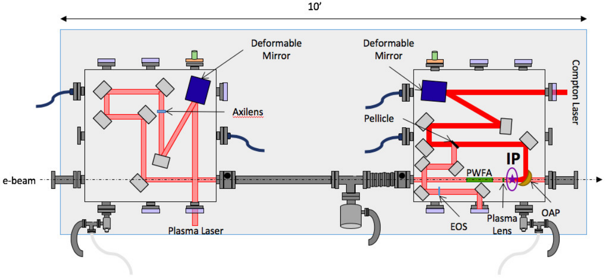
T. Grismayer et al., POP (2016), T. Grismayer et al., PRE (2017)

M. Vranic, T. Grismayer, L. O. Silva | IST, UTL, Lisbon, Portugal

Future possibilities

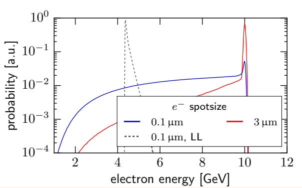
Future upgrade: beam focusing with thin plasma lens

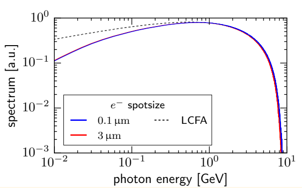
Thin plasma lens experiment (PI: M. Litos)



Simulation: compressed FACET-II electron beam + 20TW laser

simulated by M. Tamburini

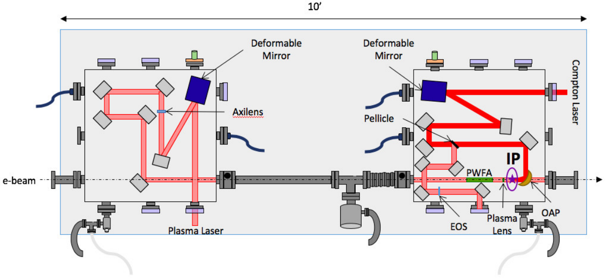




photons emitted: 1.3 (3μm), 4.8 (0.1μm); pairs produced: 9×10^{-7} (3μm), 2×10^{-5} (0.1μm) – (per electron)

Future upgrade: beam focusing with thin plasma lens

Thin plasma lens experiment (PI: M. Litos)



Bringing all electrons into the strong field

- Electron and laser focus of the same order: intensity distribution
  $\longrightarrow$ we have to determine the spatial laser distribution
- Electron focus much smaller: only one free parameter (peak intensity)
- The average intensity increases:
  $\longrightarrow$ photons emitted (average per e^-): $1.3\,(3\mu\mathrm{m})$ vs. $4.8\,(0.1\mu\mathrm{m})$
  $\longrightarrow$ pairs produced (average per e^-): $\sim 10^{-6}\,(3\mu\mathrm{m})$ vs. $\sim 10^{-5}\,(0.1\mu\mathrm{m})$

Future upgrade: energy doubling + PW-class laser: CLIC

PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS **17,** 051003 (2014)

Strong field processes in beam-beam interactions at the Compact Linear Collider

J. Esberg,[1,2] U. I. Uggerhøj,[1] B. Dalena,[2] and D. Schulte[2]

The demand for high luminosity in the next generation of linear e^+e^- colliders necessitates extremely dense beams, giving rise to strong fields at the collision point, and therefore the impact of the field on the physical processes occurring at the interaction point must be considered. These processes are well described by the interaction of the individual lepton with the field of the oncoming bunch, and they depend strongly on the beamstrahlung parameter Υ which expresses the field experienced by the lepton in units of the critical field. In this paper, we describe calculations and simulations of strong field processes—also of higher order—at the interaction point.

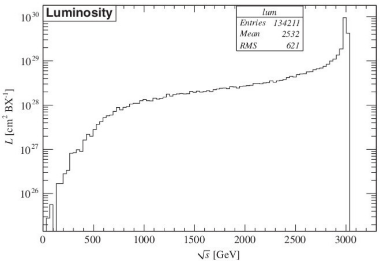


FIG. 13. CLIC nominal luminosity spectrum at ideal conditions; the spectrum includes contributions from coherent pairs and initial state radiation.

	CLIC 3 TeV	CLIC 500 GeV	ILC 500 GeV	ILC 1 TeV
E_{cm} [GeV]	3000	500	500	1000
$\langle\Upsilon\rangle$	4.9	0.21	0.062	0.20

The deciding parameter for strong field effects in a collider is approximately given by [7]

$$\langle\Upsilon\rangle = \frac{5}{6}\frac{\gamma N r_e^2}{\alpha\sigma_z(\sigma_x+\sigma_y)}, \qquad (3)$$

in this context known as the beamstrahlung parameter, with r_e being the classical electron radius, and σ_z the length of the beams at the IP.

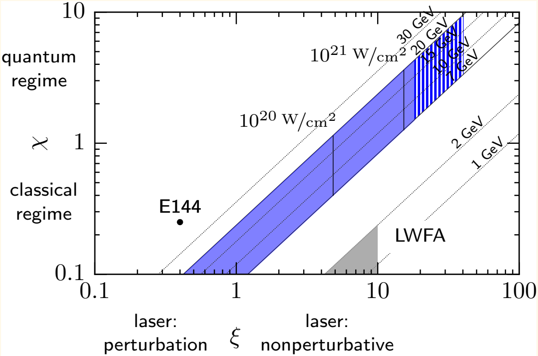
When Eq. (3) is compared to the expression for the luminosity Eq. (2), one sees that high luminosity and high beamstrahlung parameter are intimately connected.

Future upgrade: energy doubling + PW-class laser: CLIC

PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS **17,** 051003 (2014)

Strong field processes in beam-beam interactions at the Compact Linear Collider

Reaching the regime $\chi \sim 10$



- Laser upgrade: 200 TW (solid blue) – 1 PW (hatched blue)
- Electron beam energy doubling: 10 GeV $\rightarrow$ 20 GeV

$\longrightarrow$ CLIC parameters accessible: $\chi = 12$ ($\chi_{av} = 5$)

Future measurements: electron-positron recollisions

PRL 114, 143201 (2015) PHYSICAL REVIEW LETTERS week ending 10 APRIL 2015

High-Energy Recollision Processes of Laser-Generated Electron-Positron Pairs

Sebastian Meuren,* Karen Z. Hatsagortsyan,† Christoph H. Keitel,‡ and Antonino Di Piazza§

By investigating the laser-dressed polarization operator, we identify a new contribution describing high-energy recollisions experienced by an electron-positron pair generated by pure light when a gamma photon impinges on an intense, linearly polarized laser pulse. The energy absorbed in the recollision process over the macroscopic laser wavelength corresponds to a large number of laser photons and can be exploited to prime high-energy reactions.

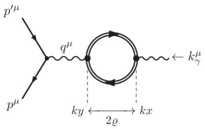


FIG. 1. Depending on the distance 2ϱ of the two polarization-operator vertices, this Feynman diagram describes either radiative corrections to the photon propagator or laser-induced recollision processes. The wavy lines denote photons, the double lines the laser-dressed electron (positron) propagators, and the straight solid lines indicate the particles produced in the secondary reaction. The meaning of the other symbols is explained in the text (time increases from right to left).

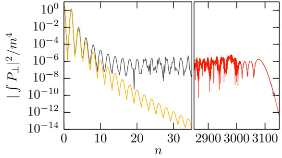


FIG. 3 (color online). Left side: Comparison of the quasistatic contribution (lower yellow curve) with the full numerical calculation (upper gray curve). Right side: Plateau-region, analytical (red curve) and numerical calculation coincide [$\chi = 1$, $\xi = 10$, $N = 5$, see Eq. (3)].

Analogous to high-harmonic generation in atomic physics

- Electron-Atom recollisions & HHG: important signature of the strong-field regime
- Oscillating laser field: e^+e^- trajectories intersect periodically
  $\longrightarrow$ possibility for coherent scattering/annihilation
- Cross section (electron radius) is much lower than in atomic physics (Bohr radius)
  $\longrightarrow$ qualitatively different physics but difficult to observe

Future possibility: combining optical, x-ray, and gamma photons

Spectral caustics in laser assisted Breit–Wheeler process

Physics Letters B 755 (2016) 162–167

T. Nousch [a,b,*], D. Seipt [c], B. Kämpfer [a,b], A. I. Titov [d]

A B S T R A C T

Electron–positron pair production by the Breit–Wheeler process embedded in a strong laser pulse is analyzed. The transverse momentum spectrum displays prominent peaks which are interpreted as caustics, the positions of which are accessible by the stationary phases. Examples are given for the superposition of an XFEL beam with an optical high-intensity laser beam. Such a configuration is available, e.g., at LCLS at present and at European XFEL in near future.

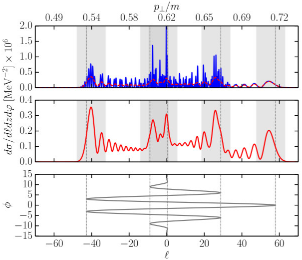


Fig. 2. Spectra for the laser assisted Breit–Wheeler process with the parameters mentioned in the Introduction which translate into $\sqrt{s_{X'X}} = 1.2$ MeV, $\eta = 1/600$, $a_X = 10^{-5}$, $\tau_X = 2\tau/(\pi\eta)$, $a_L = 0.1$, and $\tau_L = 4\pi$ in the field (2). Upper panel: $d\sigma/d\ell dz d\varphi$ at $z = 0$ and $\varphi = \pi$ as a function of ℓ (lower axis; the corresponding values of $p_\perp$ are given at the upper axis). The calculated spectrum according to (12) (blue, with 20,000 meshes) is smoothed by a Gaussian window function with width $\delta\ell = 0.8$ to get the red curve. Middle panel: smoothed spectrum separately. Lower panel: phase ϕ as a function of ℓ from Eq. (26) (only the "+" solution applies here). The vertical dotted lines depict the positions of diverging $d\phi/d\ell$, where two branches of $\phi(\ell)$ merge. The gray bands depict the estimated widths of caustic regions. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Three-wave mixing experiment

- X-ray photons available at LCLS and LCLS-II could be used to prime reaction
- Both "assisted" pair production and nonlinear Compton scattering accessible
  $\longrightarrow$ Several new degrees of freedom (relative intensity, phase, etc.)
  $\longrightarrow$ X-ray photon: reduction of the tunneling barrier for pair production
- Photon science at SLAC: unique possibilities: from eV via keV to GeV photons

Future upgrade: 100 TW laser – radiation reaction

PRL **113**, 134801 (2014) PHYSICAL REVIEW LETTERS week ending 26 SEPTEMBER 2014

All-Optical Radiation Reaction at 10^{21} W/cm^2

M. Vranic,[1,*] J. L. Martins,[1] J. Vieira,[1] R. A. Fonseca,[1,2] and L. O. Silva[1,†]

Using full-scale 3D particle-in-cell simulations we show that the radiation reaction dominated regime can be reached in an all-optical configuration through the collision of a ~1 GeV laser wakefield accelerated electron bunch with a counterpropagating laser pulse.

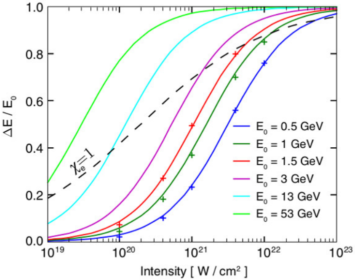


FIG. 3 (color online). Electron beam energy loss. Parameter scan based on *ab initio* full scale PIC simulations for different experimental conditions that correspond to 0.5, 1, and 1.5 GeV—class LWFA electron beams, coupled with a scattering laser with intensity in the range 10^{20}–10^{22} W/cm^2. Curves represent the theoretical prediction of Eq. (3), and each cross represents one simulation result. For reference, the theoretical curves for higher energy electron beams from Ref. [29] are also given; the dashed black line corresponds to the value $\chi_e = 1$.

Transition from classical to quantum radiation reaction

- Classical RR: emission of many photons with small recoil
  $\longrightarrow \chi \lesssim 0.1$, long laser pulses
- Quantum RR: stochastic emission of photons with large recoil
  $\longrightarrow \chi \gtrsim 0.1$, short laser pulses
- $\sim$100 TW laser: broader range of parameters accessible

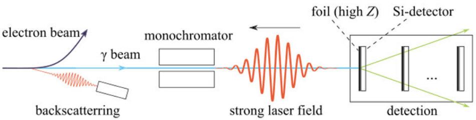
Future upgrade: 100 TW laser – vacuum birefringence

PRL **119,** 250403 (2017) PHYSICAL REVIEW LETTERS week ending 22 DECEMBER 2017

High-Energy Vacuum Birefringence and Dichroism in an Ultrastrong Laser Field

Sergey Bragin, Sebastian Meuren,* Christoph H. Keitel, and Antonino Di Piazza

A long-standing prediction of quantum electrodynamics, yet to be experimentally observed, is the interaction between real photons in vacuum. As a consequence of this interaction, the vacuum is expected to become birefringent and dichroic if a strong laser field polarizes its virtual particle–antiparticle dipoles. the feasibility of quantitatively confirming the prediction of nonlinear QED for vacuum birefringence at the 5σ confidence level on the time scale of a few days is demonstrated



Note that for FACET-II a hundred-TW-class laser ($\omega_L = 1.55\,\text{eV}$, PRR = 10 Hz) and $\eta = 10^{-3}$ could be sufficient. Assuming 10-GeV electrons, $N_e = 10^9$, $\theta_{\max} = 6 \times 10^{-6}$ rad (i.e., $\omega = 1.9\,\text{GeV}$, $\sigma_{bs} = 0.113 r_e^2$, $\sigma_1/\sigma_0 = 0.077$) the measurement time is 3 hours if using a 200 TW laser (20 J in 100 fs, $I = 5 \times 10^{20}\,\text{W/cm}^2$) and 12 days if using a 100 TW laser (4 J in 35 fs, $I = 2.3 \times 10^{20}\,\text{W/cm}^2$).

FIG. 3. (a) Experimental setup. Polarized highly energetic gamma photons (produced via Compton backscattering) propagate through a strong laser field, which induces vacuum birefringence and dichroism. Afterward, the gamma photons are converted into electron-positron pairs. From their azimuthal distribution, the polarization state is deduced.

Vacuum birefringence & dichroism

- Interaction of real photons has never been observed
  $\longrightarrow$ several experiments have searched for vacuum birefringence (unsuccessful)
  $\longrightarrow$ recent claim that VB is important to understand radiation from magnetars
- With a 100-200 TW laser it could be measured at FACET-II for the first time
  $\longrightarrow$ IP1: polarized gamma photons, IP2: $\sim$100 TW laser to polarize vacuum

Future upgrade: electron radiative self polarization

PRL **107,** 260401 (2011) PHYSICAL REVIEW LETTERS week ending 23 DECEMBER 2011

Quantum Electron Self-Interaction in a Strong Laser Field

S. Meuren and A. Di Piazza*

The quantum state of an electron in a strong laser field is altered if the interaction of the electron with its own electromagnetic field is taken into account. On the other hand, the electron self-interaction induces a distinct dynamics of the electron spin, whose effects are shown to be measurable in principle with available technology.

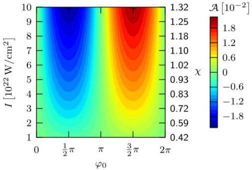


FIG. 2 (color online). Asymmetry $\mathcal{A}$ for numerical parameters given in the text below Eq. (14).

We introduce the asymmetry $\mathcal{A} \equiv (P_\uparrow - P_\downarrow)/(P_\uparrow + P_\downarrow) = -\sin(2\mathrm{Re}(\Phi_s))/\cosh(2\mathrm{Im}(\Phi_s))$ as a convenient observable.

In Fig. 2 we show the asymmetry $\mathcal{A}$ as a function of the laser intensity I and of the laser carrier-envelope phase (CEP) φ_0 for the following numerical parameters: $\omega = 1.55$ eV, $N = 3$ (corresponding to a pulse duration $\tau \approx 8$ fs) and $\epsilon = 500$ MeV.

At an intensity of $I_0 = 4 \times 10^{22}$ W/cm^2, for example, we find $\exp[2\mathrm{Im}(\Phi_0)] \approx 9 \times 10^{-4}$ and a maximal asymmetry $\mathcal{A}_0 \sim 1\%$

Assuming a Gaussian laser beam focused to one wavelength (spot radius $w_0 = \lambda$ and Rayleigh length $l_r = \pi w_0^2/\lambda = \pi\lambda$) [23], about $\mathcal{N}^* \sim \mathcal{N} \exp[2\mathrm{Im}(\Phi_0)]2l_r/l_e \sim 10^5$ electrons pass through the strong-field region without radiating. Thus, the absolute difference of the expected electrons with opposite spin is $\sim \mathcal{A}_0 \times \mathcal{N}^* \sim 10^3$.

Radiative self polarization of the electron beam

- Magnetic field: prefered direction in short pulses (for nonlinear effects)
- Due to vacuum fluctuations (radiative corrections): non-trivial spin dynamic
- Emission probability for photon with large recoil depends on spin orientation
  $\longrightarrow$ possibility for Sokolov-Ternov self polarization
  $\longrightarrow$ possibility for stochastic self polarization

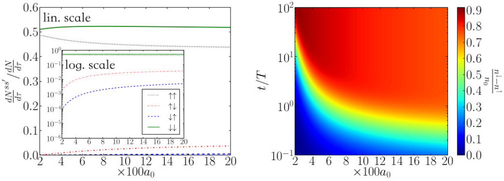
Future upgrade: electron radiative self polarization

PHYSICAL REVIEW A **96**, 043407 (2017)

Spin polarization of electrons by ultraintense lasers

D. Del Sorbo,[1] D. Seipt,[2,3] T. G. Blackburn,[4] A. G. R. Thomas,[3,2] C. D. Murphy,[1] J. G. Kirk,[5] and C. P. Ridgers[1]

Electrons in plasmas produced by next-generation ultraintense lasers ($I > 5 \times 10^{22}$ W/cm^2) can be spin polarized to a high degree (10%–70%) by the laser pulses on a femtosecond time scale. This is due to electrons undergoing spin-flip transitions as they radiate γ-ray photons, preferentially spin polarizing in one direction. Spin polarization can modify the radiation reaction force on the electrons, which differs by up to 30% for opposite spin polarizations. Consequently, the polarization of the radiated γ-ray photons is also modified: the relative power radiated in the σ and π components increases and decreases by up to 30%, respectively, potentially reducing the rate of pair production in the plasma by up to 30%.



(a) (b)

FIG. 1. (a) The rates in Eq. (3), summed over photon polarization and normalized to the unpolarized rate $dN/d\tau$, as functions of the strength parameter of the laser electromagnetic waves a_0. (b) Degree of electron spin polarization antiparallel as a function of a_0 and of time normalized to the laser period $T \approx 3.33$ fs.

Radiative self polarization of the electron beam

- Magnetic field: prefered direction in short pulses (for nonlinear effects)
- Due to vacuum fluctuations (radiative corrections): non-trivial spin dynamic
- Emission probability for photon with large recoil depends on spin orientation
  $\longrightarrow$ possibility for Sokolov-Ternov self polarization
  $\longrightarrow$ possibility for stochastic self polarization

Future upgrade: few-cycle laser pulses (CEP effects)

PRL **105,** 063903 (2010) PHYSICAL REVIEW LETTERS week ending 6 AUGUST 2010

Determining the Carrier-Envelope Phase of Intense Few-Cycle Laser Pulses

F. Mackenroth, A. Di Piazza,* and C. H. Keitel

The electromagnetic radiation emitted by an ultrarelativistic accelerated electron is extremely sensitive to the precise shape of the field driving the electron. We show that the angular distribution of the photons emitted by an electron via multiphoton Compton scattering off an intense ($I > 10^{20}$ W/cm^2), few-cycle laser pulse provides a direct way of determining the carrier-envelope phase of the driving laser field.

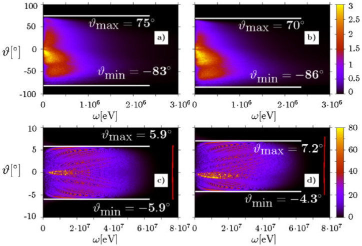


FIG. 2 (color online). Energy emission spectra $dE/d\Omega d\omega'$ in sr^{-1} via Eq. (66.9) in [10] [parts (a) and (b)] and via Eq. (2) [parts (c) and (d)] for the two sets of parameters described in the text. In parts (a) and (b) quantum effects are negligible and it is $\phi_0 = -\pi/10$ [part (a)] and $\phi_0 = -\pi/5$ [part (b)]. In parts (c) and (d) quantum effects are important and it is $\phi_0 = 0$ [part (c)] and $\phi_0 = \pi/4$ [part (d)] (the almost vertical red line indicates here the quantum cutoff frequency $\omega'_M = (\epsilon + p)/(1 + \cos\vartheta)$). The horizontal white lines indicate the boundary of the emission range determined analytically from Eq. (3) generalized to the case of a Gaussian beam for parts (a) and (b).

Detailed test of the semiclassical description (LCFA)

- For short laser pulses the CEP strongly affects the electron trajectories
- Dependence of the final momentum on the CEP tests semiclassical description
- Current state-of-the-art numerical approach for strong fields ($\xi \gg 1$):

Classical propagation + quantum transitions (Monte Carlo)

Future upgrade: few-cycle laser pulses (CEP effects)

PHYSICAL REVIEW D **93**, 085028 (2016)

Semiclassical picture for electron-positron photoproduction in strong laser fields

The nonlinear Breit-Wheeler process is studied in the presence of strong and short laser pulses. We show that for a relativistically intense plane-wave laser field many features of the momentum distribution of the produced electron-positron pair like its extension, region of highest probability and carrier-envelope phase effects can be explained from the classical evolution of the created particles in the background field.

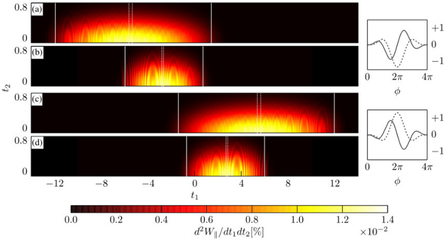


FIG. 3. Left side: Numerically calculated differential pair-production probability as a function of the transversal momentum parameters t_1 and t_2

Detailed test of the semiclassical description (LCFA)

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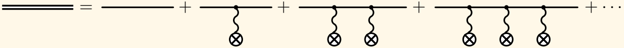
Long-term perspective

Different types of nonperturbative effects in SFQED

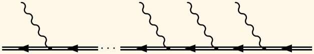
1st breakdown of perturbation theory: background field

FACET-II, $\xi \gtrsim 1$: interaction with laser becomes nonperturbative:



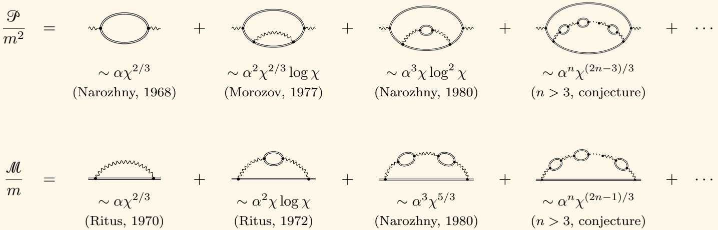
2nd breakdown of perturbation theory: higher-order processes

FACET-II: tree-level processes with many vertices become important:



3rd breakdown of perturbation theory: radiative corrections

Future: if $\alpha\chi^{2/3} \gtrsim 1$ radiative corrections become nonperturbative:

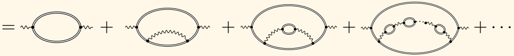


Different regimes of strong-field QED:

1. $\chi \ll 1$: **classical regime**
   Quantum effects are very small, pair production is exponentially suppressed
2. $\chi \gtrsim 1, \alpha\chi^{2/3} \ll 1$: **quantum regime**
   Recoil and pair production are important, but the radiation field is a perturbation
3. $\alpha\chi^{2/3} \gtrsim 1$: **fully nonperturbative regime**
   "Radiative corrections" become nonperturbative, strong-coupling regime of QED

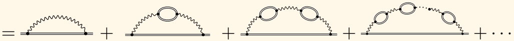
Scaling of diagrams considered so far

$\frac{\mathscr{P}}{m^2} =$



$\sim\alpha\chi^{2/3}$	$\sim\alpha^2\chi^{2/3}\log\chi$	$\sim\alpha^3\chi\log^2\chi$	$\sim\alpha^n\chi^{(2n-3)/3}$
Narozhny 1968	Morozov 1977	Narozhny 1980	conjecture

$\frac{\mathscr{M}}{m} =$

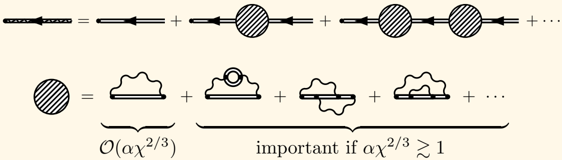


$\sim\alpha\chi^{2/3}$	$\sim\alpha^2\chi\log\chi$	$\sim\alpha^3\chi^{5/3}$	$\sim\alpha^n\chi^{(2n-1)/3}$
Ritus 1970	Ritus 1972	Narozhny 1980	conjecture

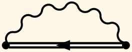
A. M. Fedotov, J. Phys.: Conf. Ser. **826**, 012027 (2017); N. B. Narozhny, Phys. Rev. D **21**, 1176–1183 (1980); V. I. Ritus, Ann. Phys. **69**, 555–582 (1972)

Dynamical mass generation: electrons/positrons

Radiative corrections



Field-induced mass shift



$$\frac{\delta m^2}{m^2} = \frac{\alpha}{\pi}\int_0^\infty \frac{du}{(1+u)^3}\,\frac{5+7u+5u^2}{3z}\,f'(z),$$

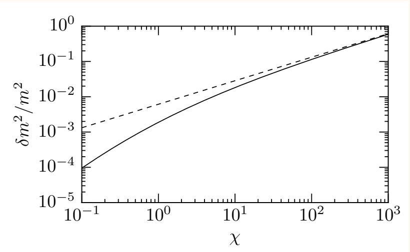
$$\Re(\delta m^2) \approx 0.84\alpha\chi^{2/3} m^2 \;(\chi \gg 1)$$

$f(z) = \pi[\mathrm{Gi}(z) + i\,\mathrm{Ai}(z)]$, $z = (u/\chi)^{2/3}$

$\longrightarrow$ If $\alpha\chi^{2/3} \gtrsim 1$ $\delta m \approx m$!

$\longrightarrow$ higher-order diagrams important

Increase of the fermion mass



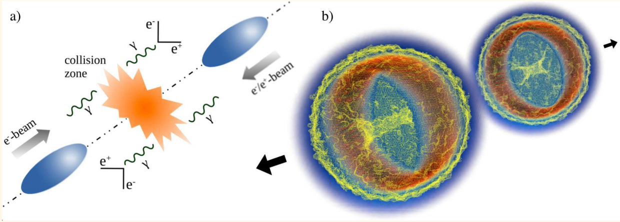
dashed line: $\chi \gg 1$ asymptotics

Strong indications that the dressed loop expansion breaks down if $\alpha\chi^{2/3} \gtrsim 1$

Ritus, Sov. Phys. JETP **30**, 1181 (1970); SM and Di Piazza, PRL **107**, 260401 (2011)

Probing fully nonperturbative QED: beam-beam collisions

Nonperturbative QED (NpQED) collider

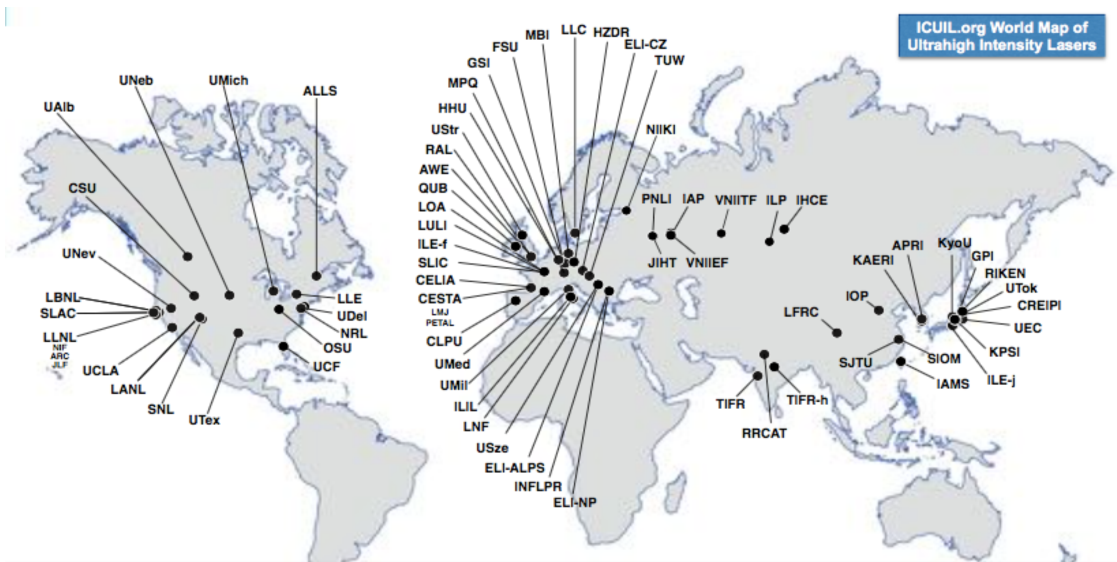


Collider parameters

Parameter	[Unit]	NpQED Collider	FACET-II	ILC	CLIC
Beam Energy	[GeV]	125	10	250	1500
Bunch Charge	[nC]	1.4	1.2	3.2	0.6
Peak Current	[kA]	1700	300	1.3	12.1
rms Energy Spread	[%]	0.1	0.85	0.12	0.34
rms Bunch Length	[μm]	0.1-0.01	0.48	300	44
rms Bunch Size	[μm]	0.01	3	0.47	0.045
		0.01	2	0.006	0.001

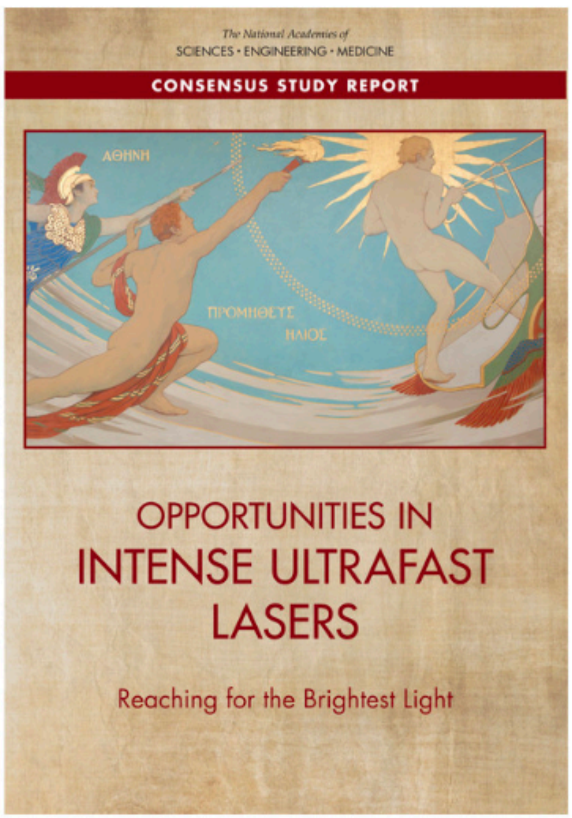
Parameter	[Unit]	NpQED Collider	FACET-II	ILC	CLIC
Beamstrahlung	χ_{av}	969	–	0.06	5
Parameter	χ_{max}	1721	–	0.15	12
Disruption	$D_{x,y}$	0.001	–	0.3	0.15
Parameters		0.001	–	24.4	6.8
Peak electric field	[TV/m]	4500	3.2	0.2	2.7
Beam Power	[MW]	10^{-3}	10^{-4}	5	14
Luminosity	$[\mathrm{cm}^{-2}\mathrm{s}^{-1}]$	10^{30}	–	10^{34}	10^{34}

On the Prospect of Studying Nonperturbative QED with Beam-Beam Collisions (2018)



- The pursuit of ultrahigh intensity laser science & applications is now a world wide activity
- Capabilities have evolved beyond the single PI scale to that of international user facilities
- Ultrahigh intensity laser projects now total more than $4B and involve > 1500 FTE's

Stanford PULSE Institute



Suggested Citation: National Academies of Sciences, Engineering, and Medicine. 2018. *Opportunities in Intense Ultrafast Lasers: Reaching for the Brightest Light.* Washington, DC: The National Academies Press. doi: https://doi.org/10.17226/24939.