Vacuum birefringence with X-rays

(Signals of photon-photon scattering using intense lasers.)

Ben King

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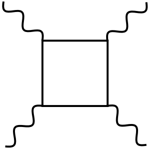
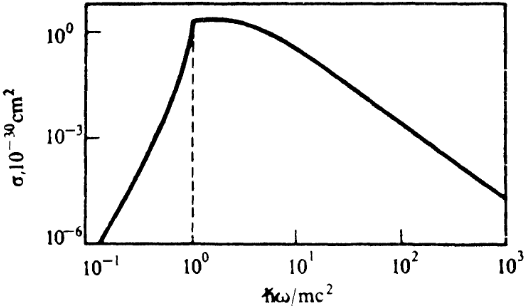
UNIVERSITY OF PLYMOUTH

Club Hotel Marina Beach, Sardinia, 30-04-2019

Photon-photon scattering



$$\sigma_{\gamma\gamma} \approx \frac{973\,\alpha^4\,\lambda_C^2}{10125\pi}\left(\frac{\hbar\omega}{mc^2}\right)^6 \qquad \hbar\omega \ll mc^2$$



V. B. Berestetskii, E. M. Lifshitz, L. P. Pitaevskii, *Quantum Electrodynamics* (1982)

Outline

Overview

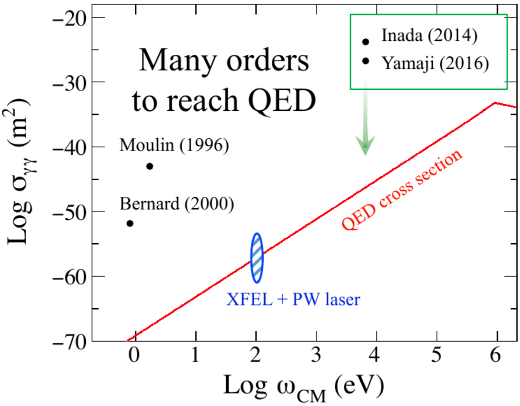
COM energy $\sqrt{s} \sim O(\mathrm{eV})$

Soft x-ray energy $\sqrt{s} \sim O(0.1\,\mathrm{keV})$

Soft γ-ray energy $\sqrt{s} \sim O(10\,\mathrm{keV})$

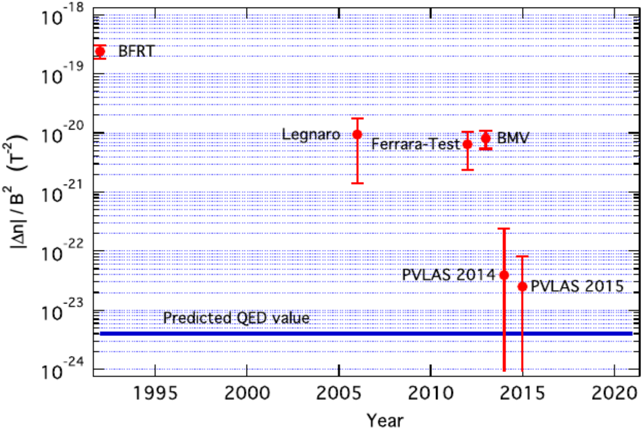
Summary

Photon-photon scattering in laser pulse collisions



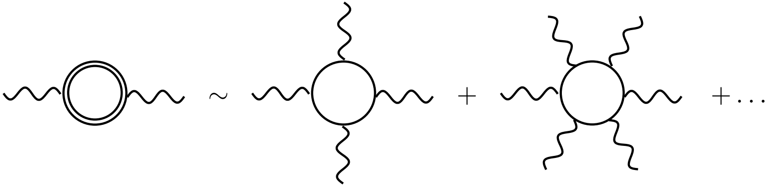
T. Inada, Probing Strong field QED Workshop, DESY 08-2018

Photon-photon scattering in laser pulse collisions



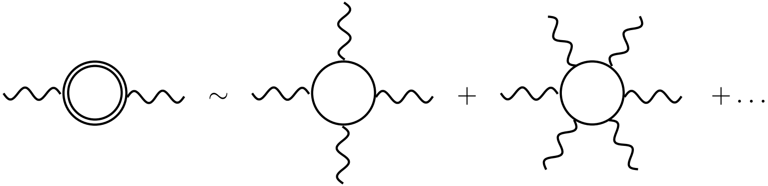
F. Della Valle et al. EPJC **76**, 24 (2016)

Overview



- $E_{QED} = \dfrac{m^2 c^3}{e\hbar}$
- $I_{QED} = 2.3 \times 10^{29}\,\mathrm{Wcm}^{-2}$ $\quad$ $(4.6 \times 10^{29}\,\mathrm{Wcm}^{-2})$

Overview



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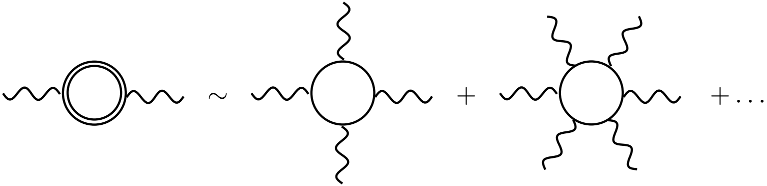
- $I_{QED} = 2.3 \times 10^{29}\,\mathrm{Wcm}^{-2}$ $\quad(4.6 \times 10^{29}\,\mathrm{Wcm}^{-2})$
- $2n$-scattering P $\sim \left(2\gamma_k \dfrac{I}{I_{QED}}\right)^{2(n-1)}$

Overview



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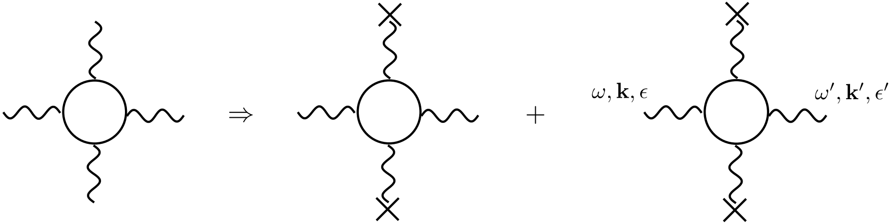
- $I_{QED} = 2.3 \times 10^{29}\,\mathrm{Wcm}^{-2}$ $\quad (4.6 \times 10^{29}\,\mathrm{Wcm}^{-2})$
- $2n$-scattering P $\sim \left(2\gamma_k \frac{I}{I_{QED}}\right)^{2(n-1)}$
- $I_{laser}^{max} = 2 \times 10^{22}\,\mathrm{Wcm}^{-2}$

V. Yanovsky et al., Opt. Express **16**, 2109-2114 (2008)

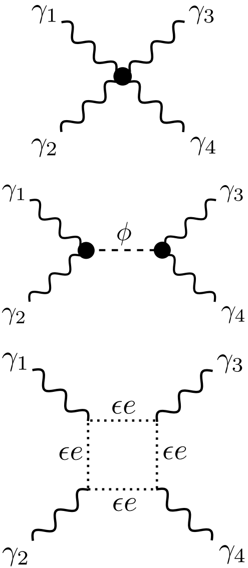
Overview



- Typical "pump-probe" experiment

$$F = \widehat{F}_{probe}(\omega, \mathbf{k}, \varepsilon) + F_{pump}$$

Motivation



- Long-standing prediction of QED

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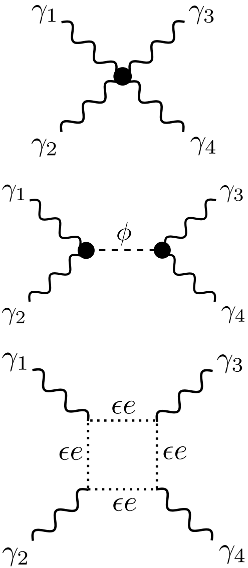
Motivation



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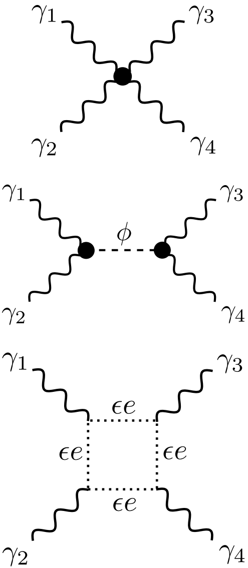
- Exotic astrophysical objects (e.g. magnetars)

Motivation



- Long-standing prediction of QED
- Exotic astrophysical objects (e.g. magnetars)
- Expected feature of very intense laser-matter interactions ($> 10^{25}\,\mathrm{Wcm}^{-2}$).

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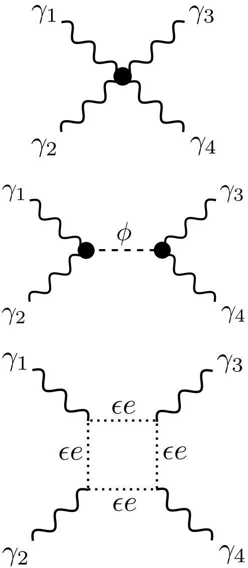
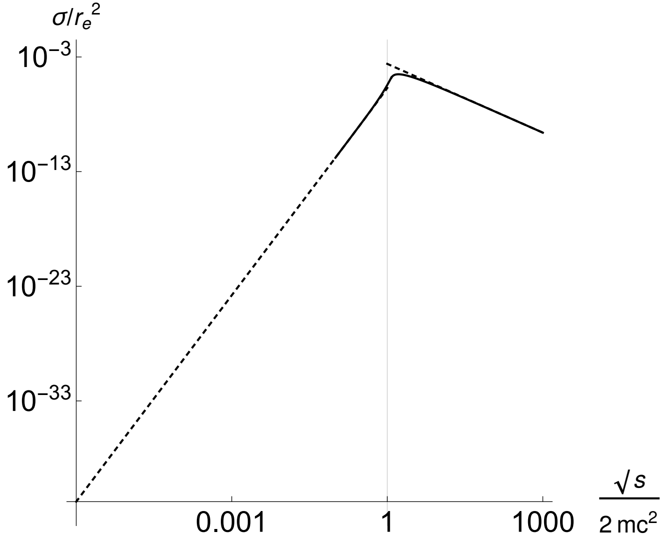
Motivation



- Long-standing prediction of QED
- Exotic astrophysical objects (e.g. magnetars)
- Expected feature of very intense laser-matter interactions ($> 10^{25}\,\mathrm{Wcm}^{-2}$).
- Places limits on dark matter candidates

$\sqrt{s} = O(\mathrm{eV})$: Optical laser pulse collisions



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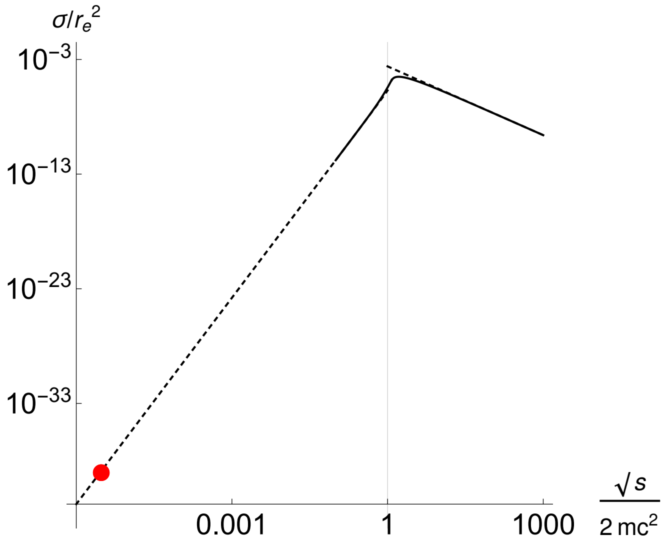
$\sqrt{s} = O(\mathrm{eV})$: Optical laser pulse collisions



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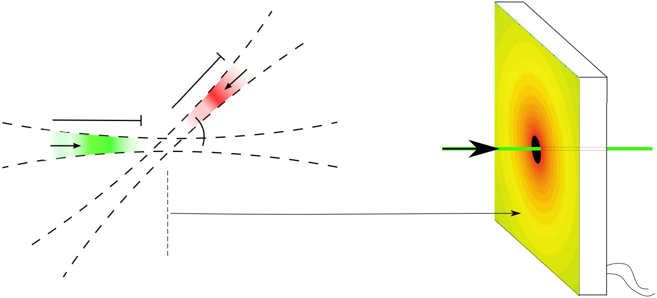
$\sqrt{s} = O(\mathrm{eV})$: High power optical lasers

Laser	Power	N_γ	Completion
Diocles	$0.1\,\mathrm{PW}$	7×10^{19}	
Hercules	$0.3\,\mathrm{PW}$	2×10^{20}	
Astra-Gemini	$2 \times 0.5\,\mathrm{PW}$	7×10^{20}	
Vulcan	$1\,\mathrm{PW}$	7×10^{20}	
ELI-Beamlines	$10\,\mathrm{PW}$, $2 \times 1\,\mathrm{PW}$	8.4×10^{20}	2020?
ELI-NP	$2 \times 10\,\mathrm{PW}$	1.4×10^{22}	2020-21?
SULF	$4 \times 25\mathrm{PW}$	7×10^{22}	2023

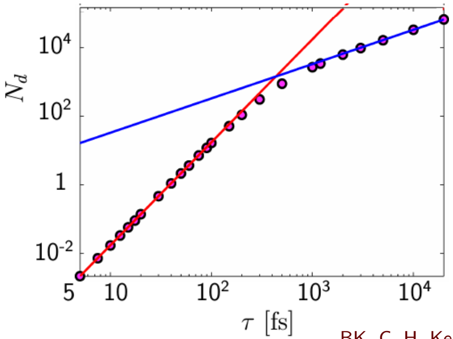
$\sqrt{s} = O(\mathrm{eV})$: Optical pulses: **Momentum** signal



BK, A. Di Piazza, C. H. Keitel, Nature Photon. **4**, 92–94 (2010)

E. Lundström et al., PRL **96**, 083602 (2006)
A. Di Piazza, K. Z. Hatsagortsyan, and C. H. Keitel, PRL **97**, 083603 (2006)
A. Ferrando et al., PRL **99**, 150404 (2007)
BK, A. Di Piazza, and C. H. Keitel, PRA **82**, 032114 (2010)
D. Tommasini and H. Michinel, PRA (R) **82**, 011803 (2010)
G. Y. Kryuchkyan and K. Z. Hatsagortsyan, PRL **107**, 053604 (2011)
Y. Monden and R. Kodama, PRL **107**, 073602 (2011)
BK and C. H. Keitel, NJP **14**, 103002 (2012)
F. Karbstein, et al., PRD **92**, 071301 (2015)

$\sqrt{s} = O(\mathrm{eV})$: Optical pulses: **Momentum** signal



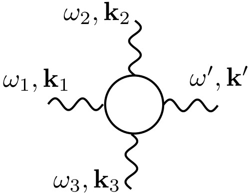
BK, C. H. Keitel, NJP **14**, 103002 (2012)

$10\,\mathrm{PW}(5\,\mathrm{PW}$ per beam); $\lambda = 910\,\mathrm{nm}$; $w_{pump} = \lambda_{pump}$; $w_{probe} = 100\lambda_{probe}$

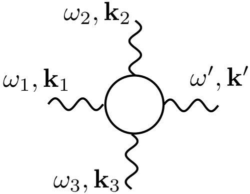
$6.7\,\mathrm{PW}$ pump $3.2\,\mathrm{PW}$ probe; $w_{pump} = w_{probe} = 5\lambda$; 25% loss

$\sqrt{s} = O(\mathrm{eV})$: Optical pulses: **Momentum** signal

$\sqrt{s} = O(\mathrm{eV})$: Optical pulses: **Momentum** signal

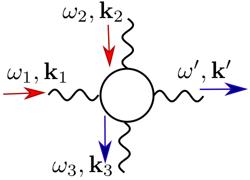


$\sqrt{s} = O(\mathrm{eV})$: Optical pulses: **Momentum** signal



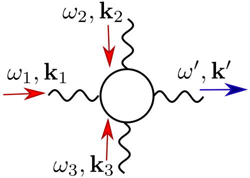
$$\left.\begin{aligned} \omega' &= \omega_1 + \omega_2 + \omega_3 \\ \mathbf{k}' &= \mathbf{k}_1 + \mathbf{k}_2 + \mathbf{k}_3 \end{aligned}\right\} \quad \text{Require:} \quad \omega'^2 = \mathbf{k}' \cdot \mathbf{k}'$$

$\sqrt{s} = O(\mathrm{eV})$: Optical pulses: **Momentum** signal



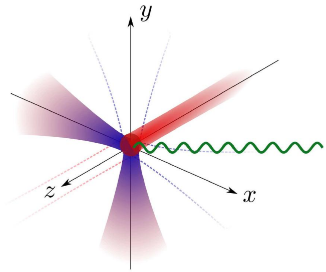
$$\left.\begin{aligned} \omega' &= |\omega_1| + |\omega_2| - |\omega_3| \\ \mathbf{k}' &= \mathbf{k}_1 + \mathbf{k}_2 + \mathbf{k}_3 \end{aligned}\right\} \quad \text{Require:} \quad \begin{aligned} &(|\omega_1| + |\omega_2| - |\omega_3|)^2 \\ &= (\mathbf{k}_1 + \mathbf{k}_2 + \mathbf{k}_3)^2 \end{aligned}$$

$\sqrt{s} = O(\mathrm{eV})$: Optical pulses: **Momentum** signal



$$\left.\begin{aligned} \omega' &= |\omega_1| + |\omega_2| + |\omega_3| \\ \mathbf{k}' &= \mathbf{k}_1 + \mathbf{k}_2 + \mathbf{k}_3 \end{aligned}\right\} \quad \text{Require:} \quad \begin{aligned} &(|\omega_1| + |\omega_2| + |\omega_3|)^2 \\ &= (\mathbf{k}_1 + \mathbf{k}_2 + \mathbf{k}_3)^2 \end{aligned}$$

$\sqrt{s} = O(\mathrm{eV})$: Optical pulses: **Frequency** signal

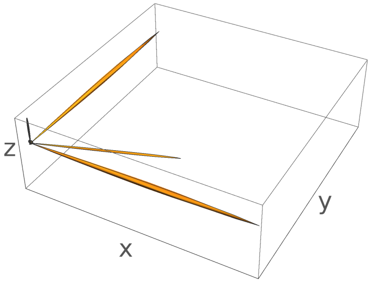


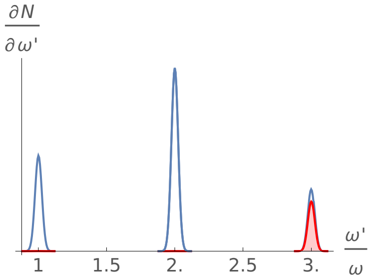
$$\begin{pmatrix} 2\omega \\ 2\omega \\ 0 \\ 0 \end{pmatrix} + \begin{pmatrix} 2\omega \\ 0 \\ 2\omega \\ 0 \end{pmatrix} - \begin{pmatrix} \omega \\ 0 \\ 0 \\ \omega \end{pmatrix} = \begin{pmatrix} 3\omega \\ 2\omega \\ 2\omega \\ -\omega \end{pmatrix}$$

F. Moulin and D. Bernard, Optics Comm. **164**, 137-144 (1999)
E. Lundström et al., PRL **96**, 083602 (2006)
BK, A. Di Piazza, and C. H. Keitel, PRA **82**, 032114 (2010)

H. Gies et al., PRD **97**, 076002 (2018)
BK, H. Hu and B. Shen, PRA **98**, 023817 (2018)

Lundström set-up



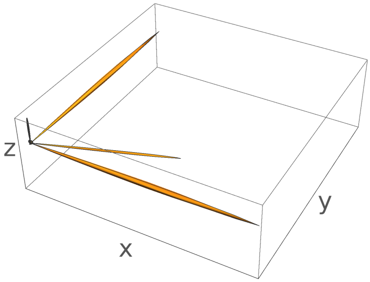


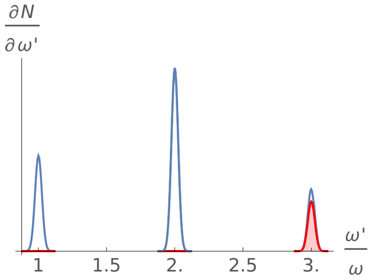
BK, H. Hu and B. Shen, PRA **98**, 023817 (2018)

SULF: three 25 PW optical lasers @ 1.365 eV(910 nm)

Frequency	$\varepsilon'^{\parallel}$ photons	$\varepsilon'^{\perp}$ photons
ω	1180	0.7
$2\,\omega$	4460	0.7
$3\,\omega$	150	610

Lundström set-up



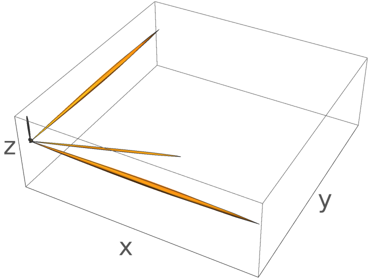


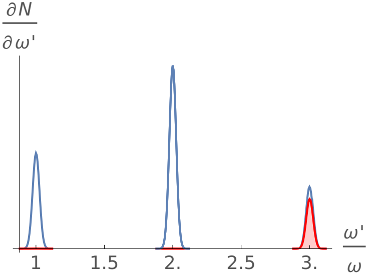
BK, H. Hu and B. Shen, PRA **98**, 023817 (2018)

Total $20\,\mathrm{PW}$ optical lasers @ $1.365\,\mathrm{eV}(910\,\mathrm{nm})$

Frequency	$\varepsilon'^{\parallel}$ photons	$\varepsilon'^{\perp}$ photons
ω	22.4	0.01
$2\,\omega$	84.6	0.01
$3\,\omega$	2.8	11.6

Lundström set-up



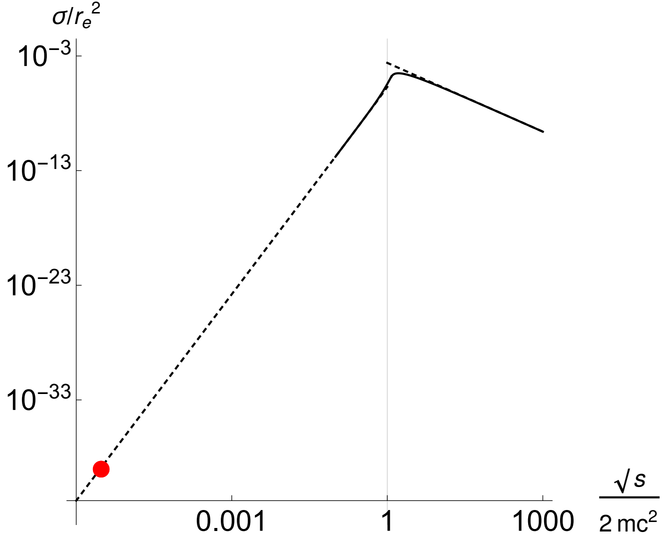


BK, H. Hu and B. Shen, PRA **98**, 023817 (2018)

Total $10\,\mathrm{PW}$ optical lasers @ $1.365\,\mathrm{eV}(910\,\mathrm{nm})$

Frequency	$\varepsilon'^{\parallel}$ photons	$\varepsilon'^{\perp}$ photons
ω	2.80	0.002
$2\,\omega$	10.57	0.002
$3\,\omega$	0.36	1.45

$\sqrt{s} = O(100\,\mathrm{eV})$: Optical + x-ray laser pulse collisions



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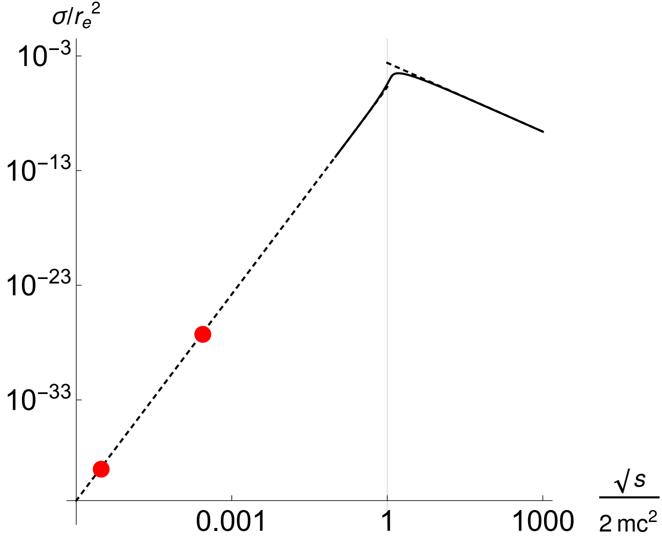

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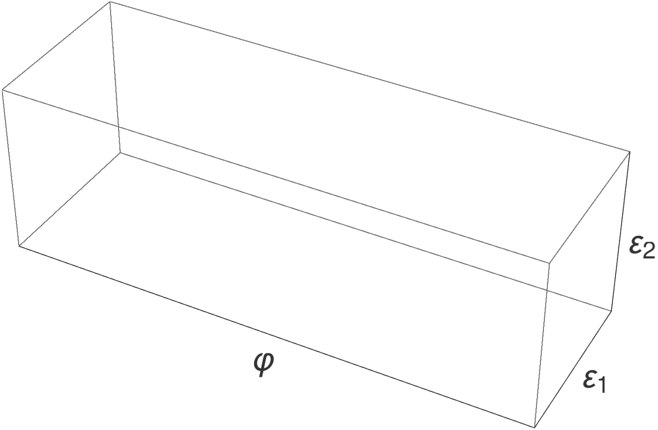

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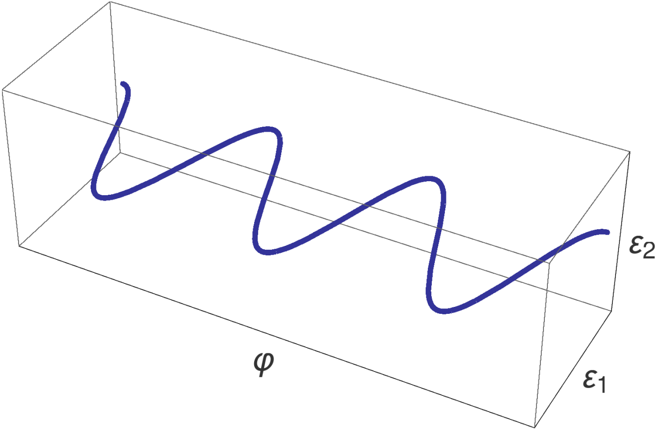

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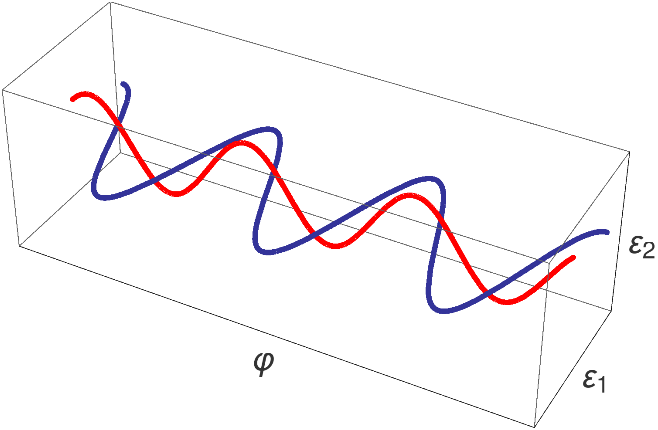

$$n_{vac} = 1 + c(\varepsilon_p)\,\alpha\frac{I}{I_{\text{QED}}}$$

$$c(\varepsilon_p^{\parallel}) \sim \frac{8}{45\pi}, \quad c(\varepsilon_p^{\perp}) \sim \frac{14}{45\pi}$$

$\sqrt{s} = O(100\,\mathrm{eV})$: Optical + x-ray laser pulse collisions

$$\mathbf{E}_{probe}^{classical} = \mathbf{E}_{probe}^{classical}(\varphi)$$

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$\sqrt{s} = O(100\,\mathrm{eV})$: Optical + x-ray laser pulse collisions

$$\mathbf{E}^{QED}_{probe} = \mathbf{E}^{QED}_{probe}(\varphi + \delta\varphi^{QED}); \qquad \delta\varphi^{QED} = \delta n^{QED}\,\omega L$$

$\sqrt{s} = O(100\,\mathrm{eV})$: Optical + x-ray laser pulse collisions

$$\mathbf{E}^{QED}_{probe} \;=\; \mathbf{E}^{QED}_{probe}(\varphi + \delta\varphi^{QED}); \qquad \delta\varphi^{QED} = \delta n^{QED}\,\omega L$$

$$\delta\varphi^{QED} \ll \varphi^{classical}, 1$$

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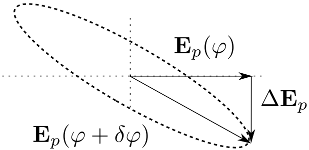
$$\mathbf{E}^{QED}_{probe} \quad = \quad \mathbf{E}^{QED}_{probe}(\varphi + \delta\varphi^{QED}); \qquad \delta\varphi^{QED} = \delta n^{QED}\ \omega L$$

$$\delta\varphi^{QED} \ll \varphi^{classical}, 1$$

$$\mathbf{E}^{QED}_{probe} = \mathbf{E}^{classical}_{probe}(\varphi) + \underbrace{\delta\varphi^{QED}\mathbf{E}^{QED\,\prime}_{probe}(\varphi)}_{\Delta\mathbf{E}^{QED}_{probe}} + \ldots$$



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$\sqrt{s} = O(100\,\mathrm{eV})$: HiBEF experiment

- European XFEL x-ray probe ($12.9\,\mathrm{keV}$)

$\sqrt{s} = O(100\,\mathrm{eV})$: HiBEF experiment

- European XFEL x-ray probe ($12.9\,\mathrm{keV}$)
- Dipole optical pump ($400\,\mathrm{TW}$)

HiBEF – User Consortium

Spokesman: T.E. Cowan (*HZDR*); **Management Board***: E. Weckert (DESY), J. Wark (Oxford), R.Redmer (Rostock);* **Coordinator:** *C. Baehtz (HZDR*). **Laser Director:** *T. Toncian (HZDR).*

Germany: 29

CFEL, DESY, FZJ, GFZ, **GSI, HI-Jena,** HZB, **HZDR,** MBI, MPIC, MPIK, MPI-S, MPQ, MPSD, **Bayreuth**, HU Berlin, TU Darmstadt, **TU Dresden**, Duisburg, Erlangen, Frankfurt, Freiburg, Hamburg, **FSU-Jena**, Kiel, LMU-Munich, TU München, **Rostock, Siegen**

Europe & Assoc. Countries: 46

Graz, TU Wien (AT); PSI, EP-Lausanne, **ETH-Zurich**(CH); IOP-ASCR, CTU-Prague (CZ); Salamanca, UPM-Madrid (ES); IRAMIS-CEA, CEA-Arpajon, CELIA-Bordeaux, ESRF, Jussieu, **LULI, UPMC,** LNCMI, U Toulouse (FR); U Pecs, U Szeged (HU); Weizmann (IS); Politecnico-Milano, Sapienza-Rome (IT); MUT-Warsaw, NCBJ-Swierk, U Wroclaw (PL); IST-Lisbon (PO); JIHT-RAS (RU); Chalmers, Stockholm, Umea, Uppsala (SE); **Cambridge, Edinburgh, Imperial, QUB, UCL, Oxford, Plymouth, STFC, SUPA, Strathclyde, Warwick, York (UK)**; Eu-XFEL, ELI-DC, EMFL (EU);

Asia: 11

CAEP, IOP-CAS, PKU, **SIOM, SJTU (CN)**; Tata IFR, RRCAT (IN); GSE Osaka, ILE-Osaka, KPSI, Uni Kyoto (JP);

North America: 17

Alberta (CA), BNL, **UC Berkeley**, Carnegie Inst. Wash., Gen At, **LANL**, **LBL, LLNL**, Michigan, ORNL, **Ohio State**, U Penn, Rockefeller, **SLAC, UC San Diego**, UNR, UT Austin, **WSU** (US)

Major funding & In-kind contributions:

	HGF, HZDR, DESY:	28 M€	TW laser, DAC, PM, AGIPD,...
	UK (STFC, Oxford):	11 M€	DiPOLE Laser
Planned:	China (CAEP):	12 M€	kJ laser + operations *(approved)*
	US (6 inst.):	4-5 M€	*instrumentation (in planning)*

Operations (HZDR): + 3.5 M€ / year

HI JENA
Helmholtz Institute Jena

$\sqrt{s} = O(100\,\mathrm{eV})$: HiBEF experiment

- European XFEL x-ray probe ($12.9\,\mathrm{keV}$)
- Dipole optical pump ($400\,\mathrm{TW}$)
- Observable: ellipticity, ε

$$\varepsilon = \frac{S_{\varepsilon'\varepsilon}}{S_{\varepsilon\varepsilon}} = \frac{\text{amplitude of photon polarisation flip}}{\text{amplitude of no polarisation flip}}$$

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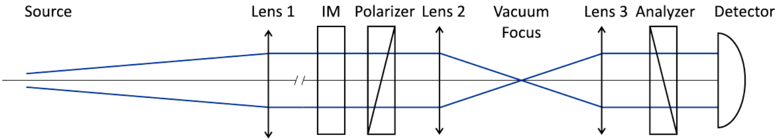

H.-P. Schlenvoigt et al., Phys. Scr. **91**, 023010 (2016).

$\sqrt{s} = O(100\,\mathrm{eV})$: HiBEF experiment

$$N_{\text{det}}^{QED} = \underbrace{N_X}_{\text{No. x-rays}} \cdot \underbrace{T_X}_{\text{Transmission}} \cdot \underbrace{\varepsilon}_{\text{QED ellipticity}}$$

$\sqrt{s} = O(100\,\mathrm{eV})$: HiBEF experiment

$$\mathsf{N}_{\mathsf{det}}^{QED} = \underbrace{\mathsf{N}_X}_{\text{No. x-rays}} \cdot \underbrace{\mathsf{T}_X}_{\text{Transmission}} \cdot \underbrace{\varepsilon}_{\text{QED ellipticity}}$$

$$\mathsf{N}_{\mathsf{bg}}^{QED} = \underbrace{\mathsf{N}_X}_{\text{No. x-rays}} \cdot \underbrace{\mathsf{T}_X}_{\text{Transmission}} \cdot \underbrace{\beta_{\mathsf{pol}}}_{\text{polariser}}$$

H.-P. Schlenvoigt et al., Phys. Scr. **91**, 023010 (2016)

$\sqrt{s} = O(100\,\mathrm{eV})$: HiBEF experiment

$$N_{\mathrm{det}}^{QED} = \underbrace{N_X}_{\text{No. x-rays}} \cdot \underbrace{T_X}_{\text{Transmission}} \cdot \underbrace{\varepsilon}_{\text{QED ellipticity}}$$

$$N_{\mathrm{bg}}^{QED} = \underbrace{N_X}_{\text{No. x-rays}} \cdot \underbrace{T_X}_{\text{Transmission}} \cdot \underbrace{\beta_{\mathrm{pol}}}_{\text{polariser}}$$

$$\nu = \frac{N_{\mathrm{det}}^{QED}}{N_{\mathrm{bg}}^{QED}} = \frac{\varepsilon}{\beta} \lesssim 10^{-3} \qquad \varepsilon \sim \alpha^2 \left(\frac{L}{\lambda}\right)^2 \frac{I}{I_{QED}} \sim O(10^{-12})$$

$$\beta \approx 6 \times 10^{-10}$$

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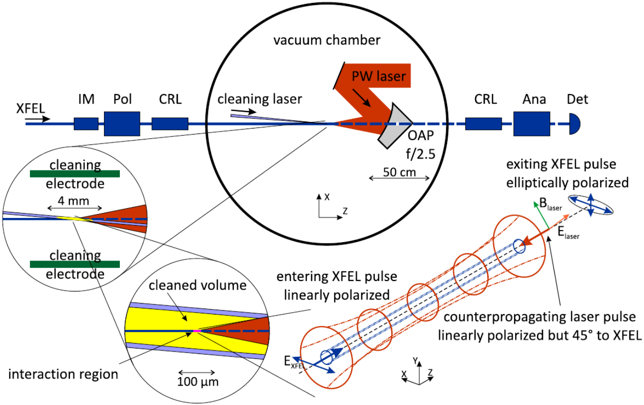
- Example background: Cotton-Mouton effect

$$\omega_{\mathrm{plasma}} \approx 10^8\,\mathrm{s}^{-1}; \quad 12\,\mu\mathrm{m}, \quad 10^6\,\mathrm{T} \quad \Rightarrow \quad \varepsilon \sim O(10^{-9})\,!!$$

H.-P. Schlenvoigt et al., Phys. Scr. **91**, 023010 (2016)

$\sqrt{s} = O(100\,\mathrm{eV})$: HiBEF experiment

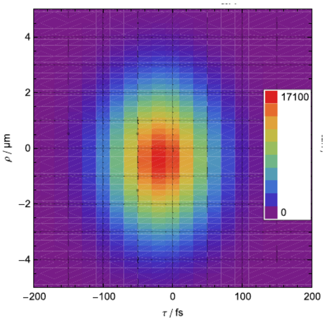


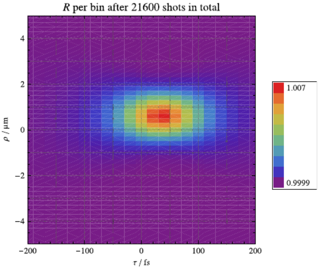
$$v_0 \sim \sqrt{\frac{3RT}{M}} \sim 2000\,\mathrm{ms}^{-1}; \quad \text{cleaned volume: } \sim 100\,\mu\mathrm{m}, \quad \text{delay: } \sim 10\,\mathrm{ns}$$

$$100\,\mathrm{mJ}, \quad 1\,\mathrm{ps}, \quad f/40 \text{ focus}, \quad 30\,\mu\mathrm{m}\,\text{radius}, \quad I > 10^{15}\,\mathrm{Wcm}^{-2}$$

H.-P. Schlenvoigt et al., Phys. Scr. **91**, 023010 (2016)

$\sqrt{s} = O(100\,\mathrm{eV})$: HiBEF: momentum + polarisation





$$\beta = 6 \times 10^{-10}; \quad 6\,\mathrm{h}, \quad 21600\ \mathrm{shots}:$$

$$N_{\mathrm{det}} = 2.37 \times 10^{6}, \qquad N_{\mathrm{det}}^{QED} = 3803 \pm 1776 \qquad (1:886)$$

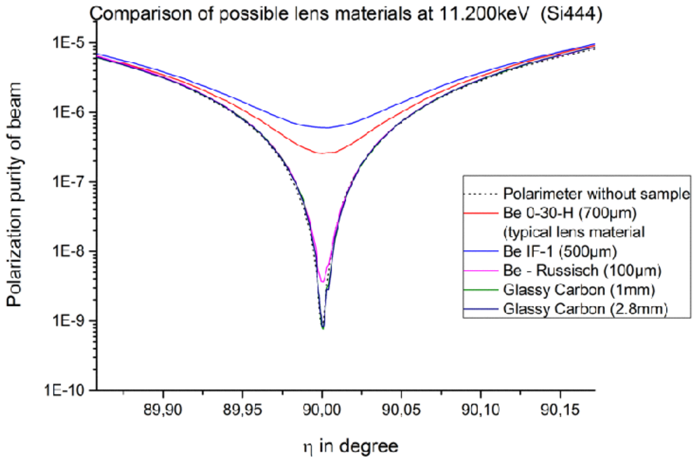
H.-P. Schlenvoigt et al., Phys. Scr. **91**, 023010 (2016)

$\sqrt{s} = O(100\,\mathrm{eV})$: HiBEF: momentum + polarisation

Update on issues identified in H.-P. Schlenvoigt et al., Phys. Scr. **91**, 023010 (2016):

(i) *the impact of CRL lenses on the effective polarimeter suppression* β

Question 3: Can we focus w/o spoiling purity?

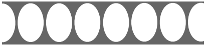


Question 3: Can we focus w/o spoiling purity?

f = 1 m
r = 50 μm

Beryllium

glassy Carbon



	Beryllium		glassy Carbon	
E_{photon}	lenses	transmission	lenses	transmission
6.4 keV	3	> 89%	3	> 68%
9.0 keV	6	> 92%	7	> 74%
12 keV	11	>93%	12	> 80%
14 keV	15	>93%	17	> 82%
17 keV	21	>93%	25	> 83%

Beryllium:

+ less absorption
– birefringence is a show stopper
? amorph metal instead of polycrystalline

glassy Carbon:

+ radiation hard
+ no birefringence @ 10^{-10}
+ can be polished and molded

$\sqrt{s} = O(100\,\mathrm{eV})$: HiBEF: momentum + polarisation

Update on issues identified in H.-P. Schlenvoigt et al., Phys. Scr. **91**, 023010 (2016):

(i) *the impact of CRL lenses on the effective polarimeter suppression* β

- Alternative material: Be $\rightarrow$ glassy carbon (amorphous), solves issue

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(ii) *the effects of combining the channel-cut crystals of the polarimeter with a short and self-seeded x-ray pulse*

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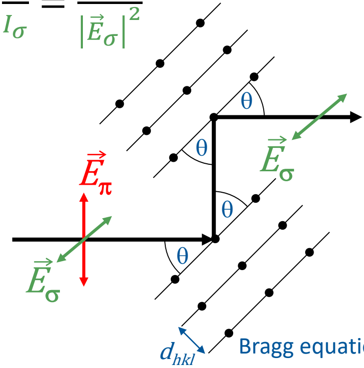
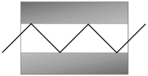
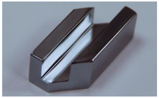
- Polarimeter test experiment @ XFEL 05/19.

How?

$$\frac{I_\pi}{I_\sigma} = \frac{|\vec{E}_\pi|^2}{|\vec{E}_\sigma|^2}$$







improved polarization purity with channel cut crystal

Bragg equation

$$n\lambda = 2d_{hkl} \sin\theta$$

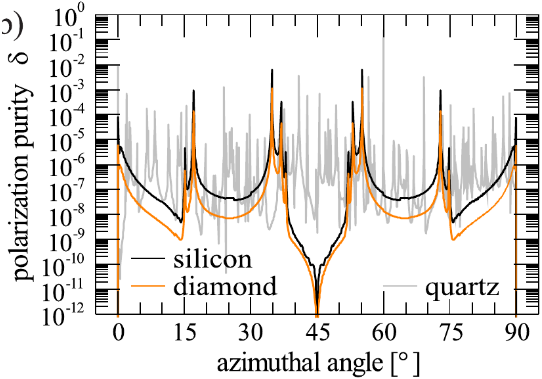
+

θ = 45.000°

	d_{hkl} [Å]	λ [Å]	E_{photon} [keV]
Si400	1.36	1.92	6.46
C400	0.89	1.26	9.84

HI JENA
Helmholtz Institute Jena

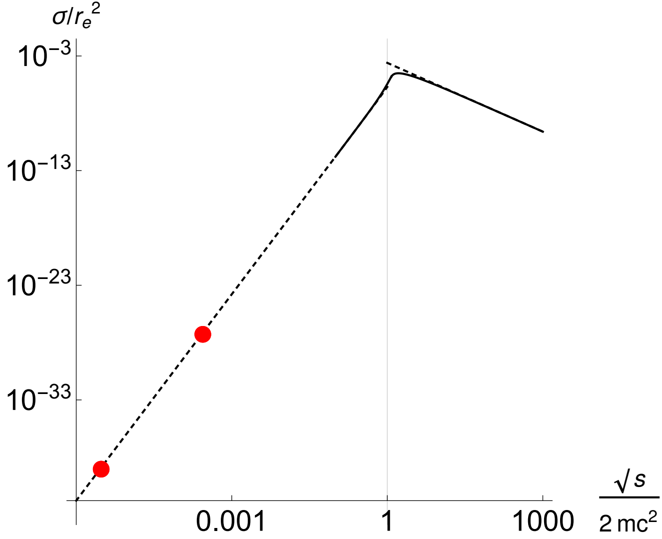
$\sqrt{s} = O(100\,\mathrm{eV})$: HiBEF experiment



K. S. Schulze, APL Photonics **3**, 126106 (2018)

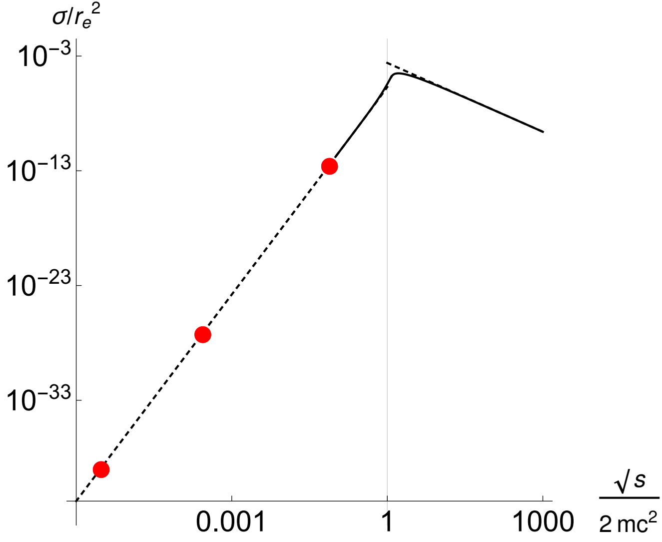
"Under ideal experimental conditions, the current limit that is possible to realize is a polarization purity of 2×10^{-12} free- electron lasers with a divergence of $1\,\mu rad$."

$\sqrt{s} = O(10\,\mathrm{keV})$: Optical + γ-ray laser pulse collisions



B. King
UNIVERSITY OF PLYMOUTH

$\sqrt{s} = O(10\,\mathrm{keV})$: Optical + γ-ray laser pulse collisions



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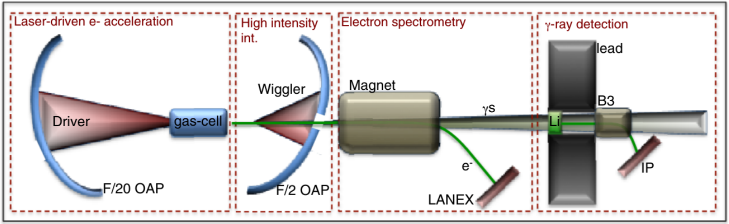
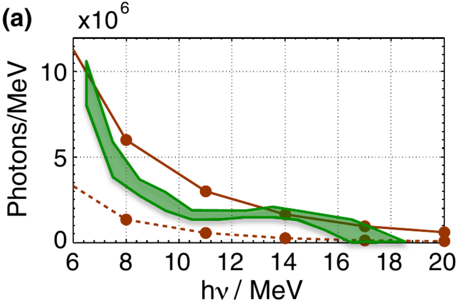
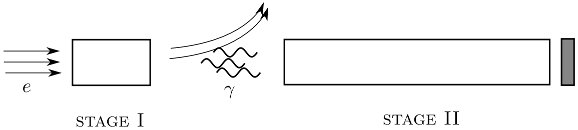




G. Sarri et al. PRL **113**, 224801 (2014)

Vacuum birefringence in laser-electron collisions



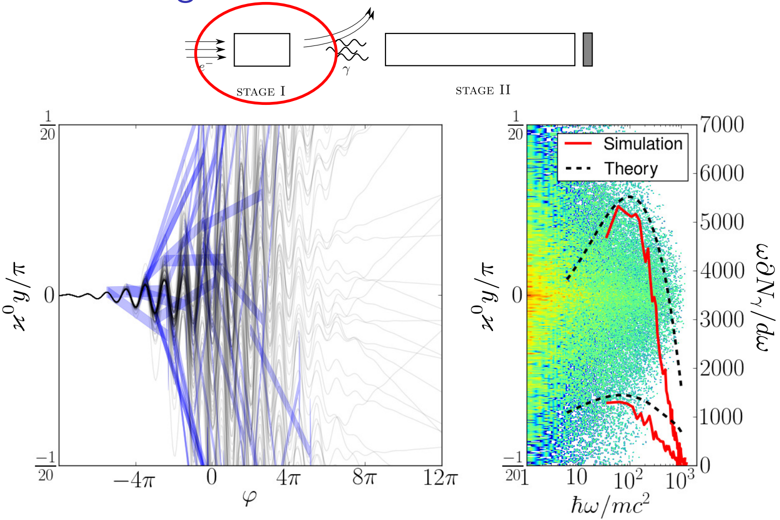
Y. Nakamiya, K. Homma, PRD **96**, 053002 (2015)

A. Ilderton, M. Marklund J. Plasma Phys. **82** (02), 655820201 (2016)

BK, N. Elkina, PRA **94**, 062102 (2016)

S. Bragin, et al., PRL **119**, 250403 (2017)

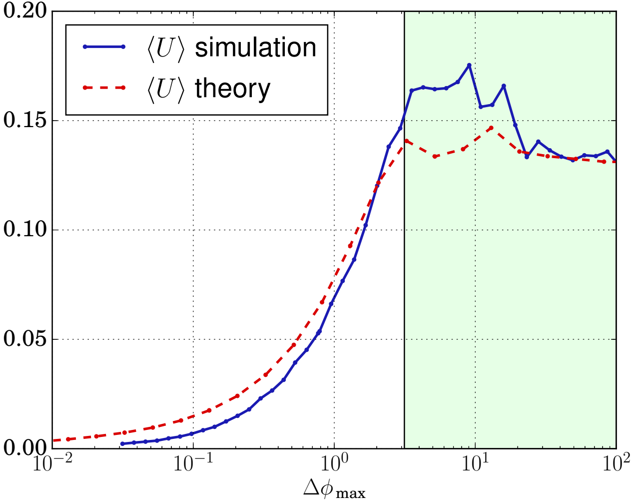
Vacuum birefringence in laser-electron collisions



- 2 GeV e^-, $\xi = 100$ ($I = 4 \times 10^{22}\,\mathrm{Wcm}^{-2}$), $\tau = 10\,\mathrm{fs}$, $\lambda = 800\,\mathrm{nm}$

BK, N. Elkina, PRA **94**, 062102 (2016)

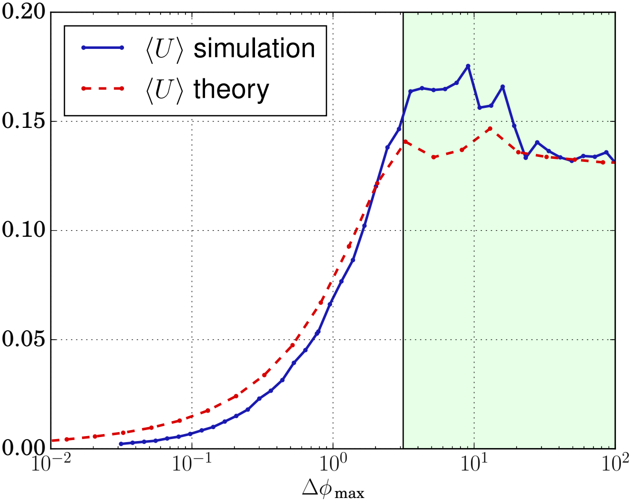
Vacuum birefringence in laser-electron collisions



$$\Delta\phi = \frac{\alpha}{15\pi}\gamma_p \int \frac{d\varphi}{\omega_l}\ I(\varphi)$$

BK, N. Elkina, PRA **94**, 062102 (2016)

Vacuum birefringence in laser-electron collisions

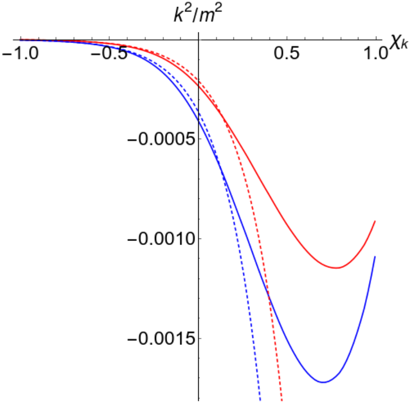


$\Delta\phi = \frac{\alpha}{15\pi}\gamma_p \int \frac{d\varphi}{\omega_l}\; I(\varphi)$

Stage II: $\xi = 25$ ($I = 2.5 \times 10^{21}\,\mathrm{Wcm}^{-2}$), 800 nm, 40fs, $\Delta\phi_{\max} \approx 1.5$.

BK, N. Elkina, PRA **94**, 062102 (2016)

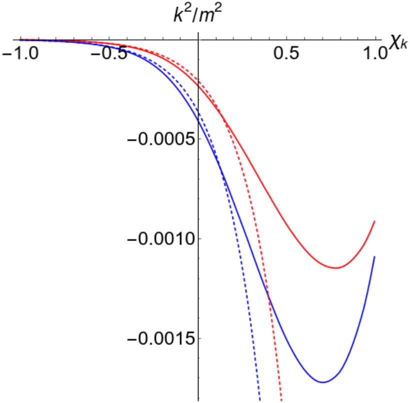
Vacuum birefringence in laser-electron collisions



- 2n-scattering P $\sim \left(2\gamma_k \dfrac{I}{I_{QED}}\right)^{2(n-1)}$

B. King

Vacuum birefringence in laser-electron collisions



- $2n$-scattering $\mathrm{P} \sim \left(2\gamma_k \frac{I}{I_{QED}}\right)^{2(n-1)}$
- FACET-II, LUXE experiments, $\gamma_k \approx 3 \times 10^5$

Summary

Summary

- Many signatures of photon-photon scattering possible using intense optical pump lasers and different probes:

  in i) momentum, ii) polarisation and iii) frequency signal.

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- Many signatures of photon-photon scattering possible using intense optical pump lasers and different probes:

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- Next generation of lasers (being commisioned) could measure real photon-photon scattering using $O(100)\,\mathrm{MeV}$ photons.

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BK, T. Heinzl, High Power Laser Sci. Eng. **4**, e5 (2016)

A. Di Piazza et al., RMP **84** 1177 (2012)

M. Marklund, P. Shukla, RMP **78**, 591 (2006)

HI Jena Helmholtz Institute Jena — N. Elkina

CARDC — H. Hu

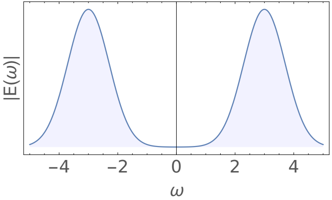
UNIVERSITY OF PLYMOUTH — T. Heinzl

SIOM — B. Shen

MAX-PLANCK-GESELLSCHAFT — A. Di Piazza, C. H. Keitel

Extra Slides

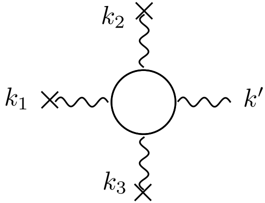
Why three pulses?



$$|E(\omega)| \sim \left| \int dt\ \mathrm{e}^{i\omega t}\ \mathrm{e}^{-\left(\frac{\varphi}{\Phi}\right)^2} \cos(\varphi) \right|$$

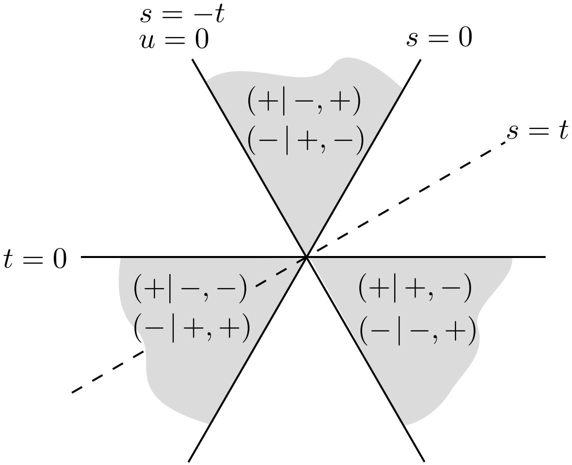
$$\begin{aligned} s &= (\delta_{j_1} k_1 + \delta_{j_2} k_2)^2 \\ t &= (\delta_{j_1} k_1 + \delta_{j_3} k_3)^2 \\ u &= (\delta_{j_2} k_2 + \delta_{j_3} k_3)^2 \end{aligned}$$

$$\delta_{j_i} \in \{-1, 1\}$$



$$s + t + u = 0; \qquad s\,t\,u \geq 0$$

Why three pulses?



Three pulses

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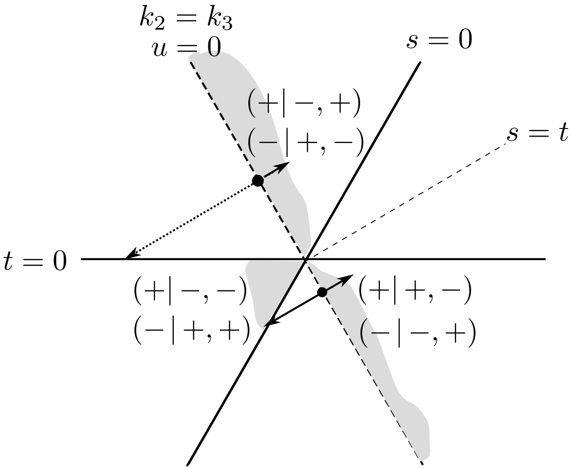
UNIVERSITY OF PLYMOUTH

Why three pulses?



Two pulses

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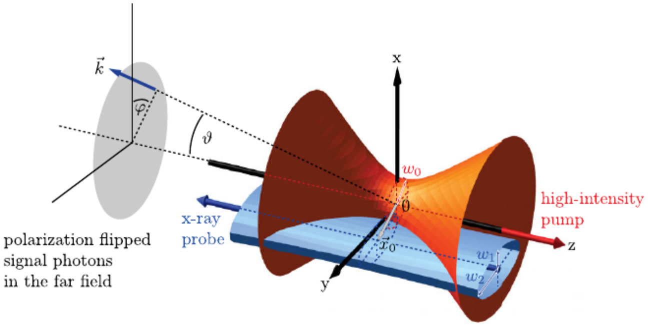
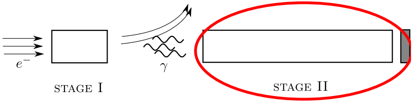
$\sqrt{s} = O(100\,\mathrm{eV})$: HiBEF: momentum + polarisation



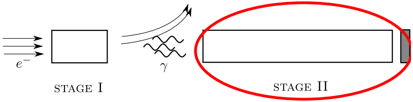
F. Karbstein PRD **98**, 056010 (2018)

Vacuum birefringence in laser-electron collisions



$$\tau = 10\text{ps} \quad \xi = 50(I = 10^{22}\,\text{Wcm}^{-2}), \lambda = 800\,\text{nm}$$

Vacuum birefringence in laser-electron collisions



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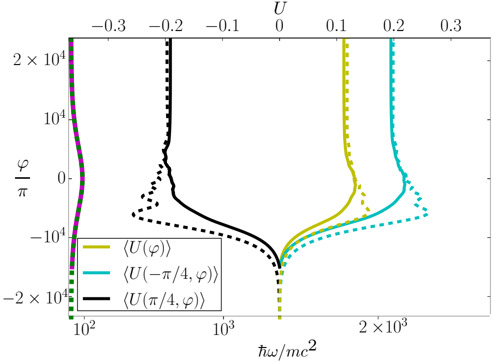
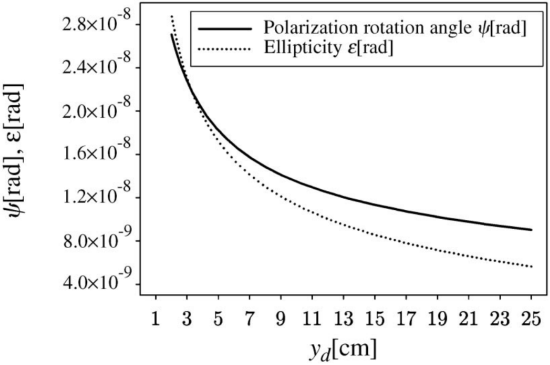


$$\mathsf{P}_+ - \mathsf{P}_- = U = \sin\Delta\phi$$

BK, N. Elkina, PRA **94**, 062102 (2016)

$\sqrt{s} = O(100\,\mathrm{eV})$: Optical + x-ray laser pulse collisions



$$\omega_{\text{probe}} = 3.1\,\mathrm{keV}, \quad I_{\text{probe}} = 10^{23}\,\mathrm{Wcm}^{-2}, \quad w_{\text{pump}} = \lambda_{\text{pump}} = 0.745\,\mu\mathrm{m}$$

A. Di Piazza, K. Z. Hatsagortsyan, C. H. Keitel, PRL **97**, 083603 (2006)

T. Heinzl et al., Opt. Commun. **267**, 318 (2006)
BK, A. Di Piazza, C. H. Keitel, PRA **82**, 032114 (2010)
H. Gies, F. Karbstein, N. Seegert, NJP **15**, 083002 (2013)
V. Dinu et al., PRD **89**, 125003 (2014)
V. Dinu et al., PRD **90**, 045025 (2014)
H. Hu and J. Huang, PRA 90, 062111 (2014)
H. Schlenvoigt, et al., Phys. Scr. **91**, 023010 (2016)