The scientific interest in strong-field QED & and electron-laser experiments

Anton Ilderton

DESY/LUXE Workshop 22/8/2018

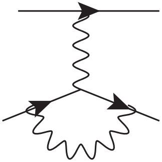
UNIVERSITY OF PLYMOUTH

EPSRC
Engineering and Physical Sciences Research Council

With thanks to T. Blackburn, V. Dinu, T. Hartin & G. Torgrimsson.

Invitation: perturbative QED

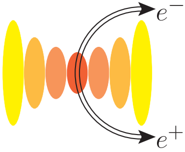
- Best tested quantum field theory.
- Coupling $\alpha = e^2/(4\pi) \sim 1/137 \ll 1$: small.
- So use Perturbation theory.
- Well tested regime.
- Successes: Lamb shift, $g-2$, Compton effect. . .



Invitation: Schwinger pair production

- Fundamental constants: m, e, $\hbar$, c. Make an electric field. . .
- $E_S = \dfrac{m^2c^3}{e\hbar} \simeq 10^{18}$ V/m. Sauter, Schwinger
- Work done: $eE_S \times \lambda_C = m$; pair production.

$$N/V = \left(\frac{E}{E_S}\right)^2 \exp\left[-\pi\frac{E_S}{E}\right]$$



- Nonperturbative effect.
- Still far from Schwinger . . . other pair production processes?

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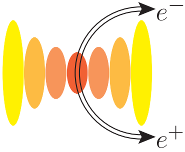

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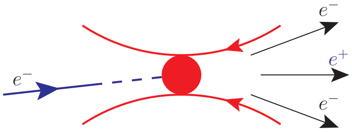
Outline

Today: Trident pair production

1. Throw e^- into a laser.
2. e^- scatters. . .
3. . . . produce pairs.



- LUXE experiment:

  Strongly coupled QFT, all-orders & non-perturbative effects

A limit to perturbative methods

- Interaction is strong when coupling > 1.
- Consider: laser of amplitude E and frequency ω.
- Coupling to field / "intensity parameter".

$$a_0 = \frac{eE}{m\omega}$$

- $a_0 > 1$ now regularly achieved. (10^{18} W/cm^2 optical)

Relativistic, nonlinear physics

A laser of amplitude E and frequency ω.

$$a_0 = \frac{eE}{m\omega}$$

1. $a_0 > 1 \iff eE\lambda\!\!\!^{-} > m$

- Energy gained/ laser wavelength > electron mass.
- Relativistic effects.

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2. $a_0 > 1 \iff eE\lambda\!\!\!^{-}_C > \omega$
   - Energy gained / Compton wavelength > photon energy.
   - Nonlinear/'multiphoton' effects.

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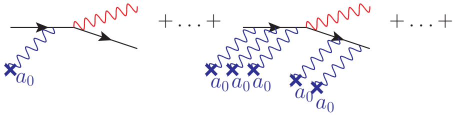
3. Strong fields means $a_0 > 1 \implies$ no perturbation in a_0.

   Non-perturbative, nonlinear, relativistic regime.

Strong field QED

- (Strong) field $\leftrightarrow$ coherent state $|\,\text{laser}\,\rangle \sim \exp(a^\dagger)|\,0\,\rangle$

☹ Infinitely many Feymnan diagrams for any process. . .



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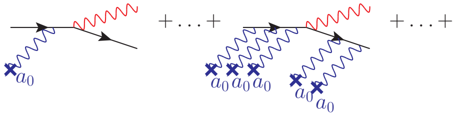

- Resum?

✓ Exactly solvable example

✓ *Non*-pert. approximations.

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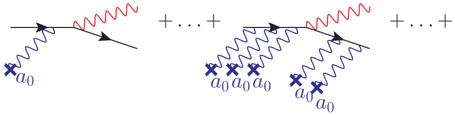
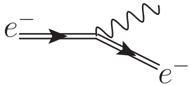


- Resum?
- ✓ Exactly solvable example
- ✓ *Non*-pert. approximations.

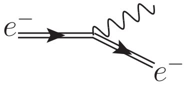
Furry expansion Furry 1951

- Strong coupling a_0: treated exactly.
  Lorentz force moved into double line.



- Coupling α to dynamical fields: perturbative as usual.
  Radiation of photons, pairs, etc, in vertex as usual.

Electron laser collisions: Nonlinear Compton scattering



- Acceleration, radiation, energy loss.
- Recent experiments at Gemini

  Cole et al. PRX 8 (2018), Poder et al. PRX 8 (2018)

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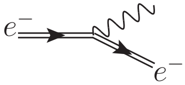

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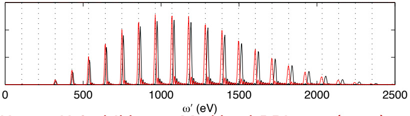
- $a_0 > 1$; nonlinear effects.
- Signature: harmonics,

  Khrennikov et al PRL 114 (2015)

  and interference patterns.



Harvey Heinzl Ilderton Marklund PRL 109 (2012)

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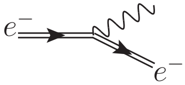

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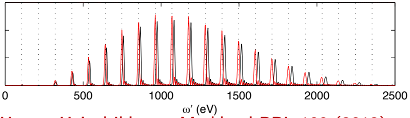

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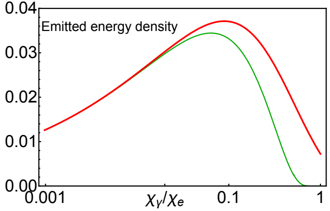


Quantum nonlinearity parameter

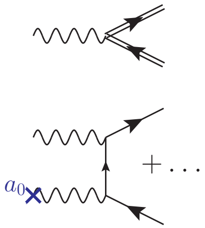
$$\chi = \frac{e}{m^3}\sqrt{p \cdot F^2 \cdot p} = \frac{E_{\text{r.f.}}}{E_S} \simeq \gamma \frac{E}{E_S}$$

- Quantum effects: $\chi > 0.01$
- $\chi_{\text{gemini}} \sim 0.1 \ldots \chi_{\text{LUXE}}$ higher...

At higher χ: nonlinear Breit-Wheeler

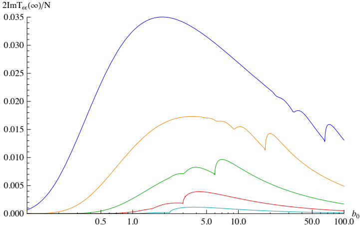
- Photon can be converted to pairs.
- Nonlinear Breit-Wheeler.
- Non-perturbative in incoming photon χ_γ.

$$P \sim \chi_\gamma \exp\left(-\frac{8}{3\chi_\gamma}\right) \quad \text{for} \quad \begin{matrix} a_0 \gg 1 \\ \chi \ll 1 \end{matrix}$$



SLAC E144 & talk by K. McDonald

- Optimal: $\chi \sim \mathcal{O}(1)$.
- Nonlinear effects.
- Signature: thresholds & channel opening.



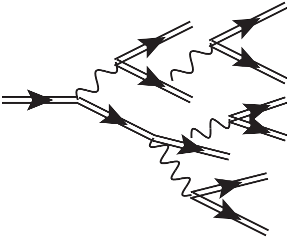
From Dinu Heinzl Ilderton Marklund PRD 89 (2014)

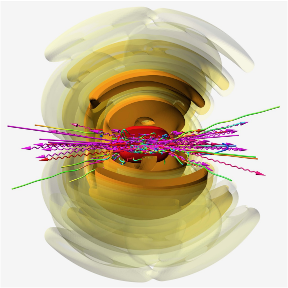
Motivation: observing cascades

- $I \simeq 10^{23} - 10^{24}$ W/cm^2 or $a_0 \simeq 300 - 10^3$
- Acceleration → emission → pairs ↻
- Avalanche/cascade of particle production.

  Bell & Kirk, PRL 101 (2008)
- Reduces field; inhibits Schwinger

  Fedotov et al, PRL 105 (2010), S.S.Bulanov et al, PRL 105 (2010)
- Application of cascade control: gamma source. Gonoskov et al, Phys.Rev. X7 (2017)





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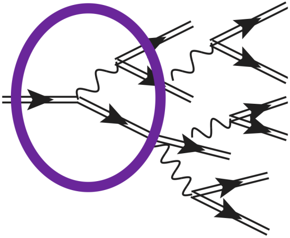
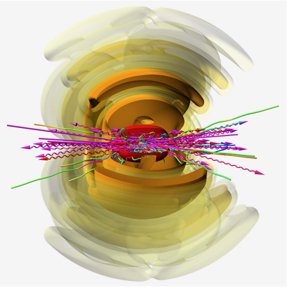
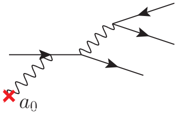
- First step is trident.





Trident pair production: ideal testing ground for SFQED.

- Weak fields $a_0 < 1$



- Virtual photon.

Mork, Phys.Rev. 160 (1967)

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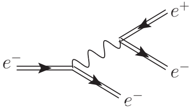

- Real or virtual. . .

K. McDonald's "loose ends"

☺ Contains both NLC & NBW, first step of cascade. . .

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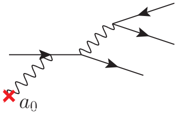

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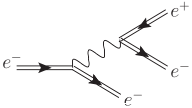

- Real or virtual...

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- For $a_0 \ll 1$ virtual channel dominant. (Power counting.) SLAC: "Virtual channel negligible"...but $a_0 \simeq 0.4 < 1$
- a_0 not $\ll 1$? Pulse length effects and power counting? Weizsäcker Williams approx? Neglects interference...

King & Ruhl PRD 88 (2013)

Trident: unanswered questions and LUXE

- Improved trident results?
- Can we study SFQED at LUXE?
- Interesting regime?
- Can we study trident?
- How many pairs could be created?
- Other processes?

✓ Recent work.

✓ $a_0 > 1$.

✓ Highest χ.

- $\rightarrow$ Sims.
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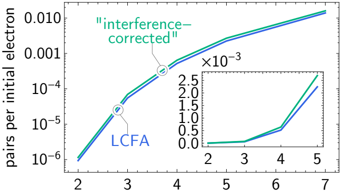
Simulation results

Experiment	$\lambda(nm)$	E_{laser}	focus	pulse	E_{e^-} (GeV)	ξ	χ
LUXE/ξ2	**527**/1053	2 J	100 μm^2	0.05 ps	17.5	2	0.63

- Particle in Cell simulations.
- Step particle through field
- LCFA + Monte Carlo/timestep.
- $a_0 \simeq 2 \implies 10^{-6}$ pairs/ electron.



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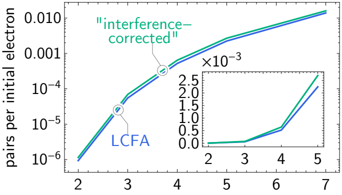
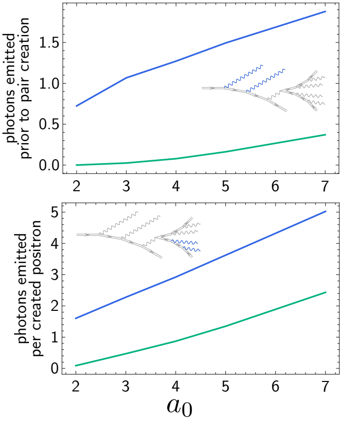


Nonlinear Compton at $a_0 \gtrsim 5$

- Corrections to positron spectrum.
- Must account for in $\not\subset$ trident.

Thanks to Tony Hartin for the above

Gonoskov et al PRE 92 (2015)



Thanks to Tom Blackburn.
Blackburn, Ilderton, Marklund, *to appear*

Simulation results

Experiment	$\lambda(nm)$	E_{laser}	focus	pulse	E_{e^-} (GeV)	ξ	χ
LUXE/HIξ	800	5 J	100 μm^2	0.02 ps	17.5	7.7	1.6

Trident

$a_0 \simeq 8 \implies 10^{-4}$ pairs/ electron.

(Multiple) Nonlinear Compton

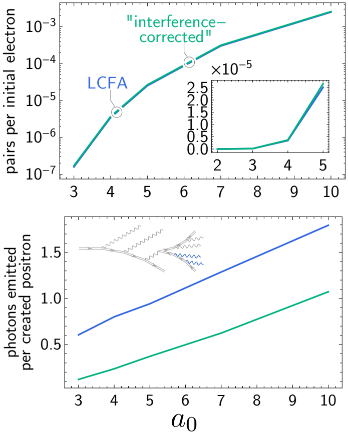
- Some contribution.

Summary

- First approximation only.

Trident is a primary process at LUXE.

- Virtual channel neglected.
- Closer investigation of trident. . .



Trident Calculations: the state of the art

Ritus NPB 44 (1972), Hu et al PRL 105 (2010) , Ilderton PRL 106 (2011), King& Ruhl PRD 88 (2013)
Fedotov & King PRD 98 (2018), Mackenroth & DiPiazza 2018

✓ All terms now included. (× Early results neglected exchange.)

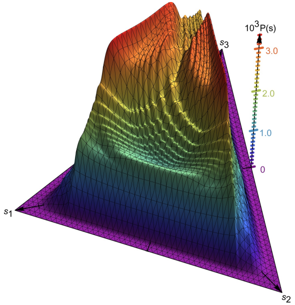
Dinu & Torgrimsson PRD 97 (2018) arXiv:1711.04344 & Talk by Greger Torgrimsson

- Compact analytics in various limits, e.g.:

$$\mathbb{P} \sim \exp\left[-\frac{4a_0}{\chi}\left((2+a_0^2)\Lambda - \sqrt{1+a_0^2} \right) \right]$$

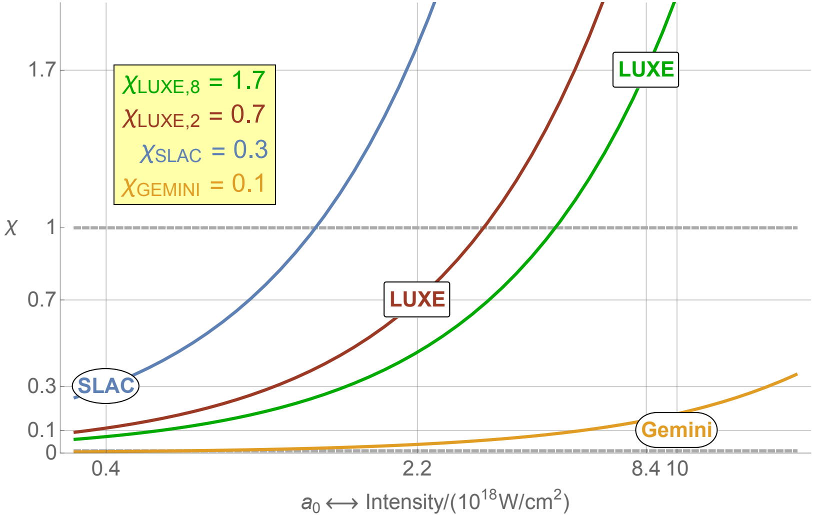
$a_0 \simeq 1,\ \chi \ll 1,\ \Lambda = \sinh^{-1} 1/a_0.$

- Detailed numerical spectra ⟶
- Lots of information to uncover.



$a_0 = 1$, long pulse.
Three outgoing $e^{\pm}$.
Momenta constrained: △

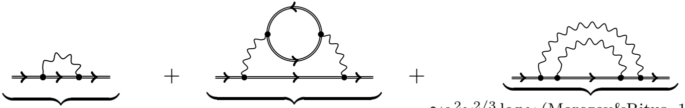
Past, present and future experiments



Curves: lines of constant c.o.m. energy $s/m^2 \sim 1 + 2\gamma\omega/m \sim 1 + 2\chi/a_0$

Motivation: the fully nonperturbative regime?

- Very large quantum nonlinearity $\chi \gg 1$ . . . what happens?
- Constant field scalings: Narozhny, Morozov, Ritus 1968 – 1981



$\simeq \alpha\chi^{2/3}$ (Ritus, 1970 [11]) + $\simeq \alpha^2\chi \log\chi$ (Ritus, 1972 [18]) + $\simeq \alpha^2\chi^{2/3} \log\chi$ (Morozov&Ritus, 1975 [19])

- Breakdown of Furry expansion at $\alpha\chi^{2/3} \simeq 1$?
- $\chi \simeq 1600 \implies$ laser $a_0 = 2000$ for 100 GeV electrons.
- Many open questions . . . intriguing.

Fedotov, J. Phys.: Conf. Ser. 826 (2017) 012027, & talk by Alexander Fedotov

More physics motivation

I ran out of time for . . .

- Light-by-light and vacuum birefringence — Talk by H. Gies
- Using intense lasers to probe BSM physics. — Talks by Selym Villalba-Chavez & Ben King
- New input to QFT; tadpoles, bubbles and effective actions.

Conclusions

A trident experiment at $a_0 > 1$ and $\gamma \gg 1$

- ✓ Nonlinear effects.
- ✓ Quantum effects.
- ✓ Further into strong-field quantum regime ($\chi \simeq 1$).
- ✓ Can probe e.g. NLC as well as trident.
- ✓ All-orders, *non*-perturbative effects.
- ✓ Challenge for theory and simulations.
- ✓ First step toward cascades and high χ.

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Jobs: 2×2 year EPSRC-funded postdocs available.

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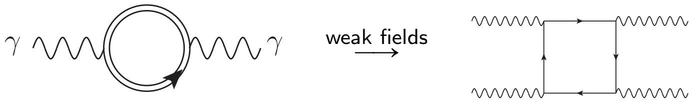
Extra slides

Light-by-light → vacuum birefringence

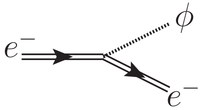


- Light by light scattering. ATLAS, Nat.Phys '17 [1702.01625]
- Internal d.o.f. can change: helicity flip Toll, PhD Thesis 1952
  Dinu, Heinzl, Ilderton, Marklund PRD 89 (2014), arXiv:1312.6419
- Vacuum birefringence: induced probe ellipticity in strong field.
  Heinzl et al, Opt.Commun. 267 (2006)
  King et al NJP 14 (2012), Karbstein et al PRD 92 (2015)
  Talk by Holger Gies

Motivation: intense lasers for BSM physics

- Lab based probes of Beyond Standard Model physics.

Talk by Selym Villalba-Chavez



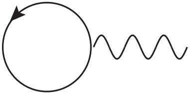
- e.g. electron–scalar ALP coupling

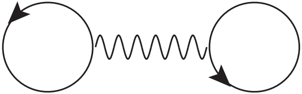
Talk by Ben King, poster by Barry Dillon

Tadpoles and bubbles: still learning about QFT

- Usually: drop tadpoles and vacuum bubbles.

Tadpoles and bubbles: still learning about QFT





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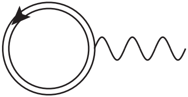
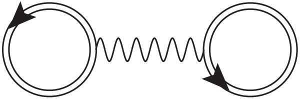
 $\neq 0!$

 $\neq 0!$

Gies, Karbstein & Kohlfürst PRD 97 (2018)

- New corrections to Euler-Heisenberg Gies & Karbstein JHEP 1703 (2017)
- Tadpole diagrams contribute Edwards & Schubert NPB 923 (2017) Karbstein JHEP 1710 (2017)
- Point is: new info. on QFT! Richer physics . . .