Quantum physics in intense laser fields

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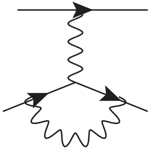
UNIVERSITY OF PLYMOUTH

EPSRC
Engineering and Physical Sciences Research Council

Invitation: perturbative QED

- Quantum field theory of light and matter.
- Coupling $\alpha = e^2/(4\pi) \sim 1/137 \ll 1$: small.
- So use perturbation theory.
- Radiation of photons, pair production etc.
- Well tested regime.
- Lamb shift, $g - 2$, Compton effect...



Few-particle scattering in QED

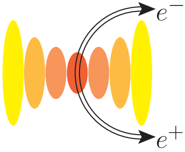
Invitation: Schwinger pair production

- 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

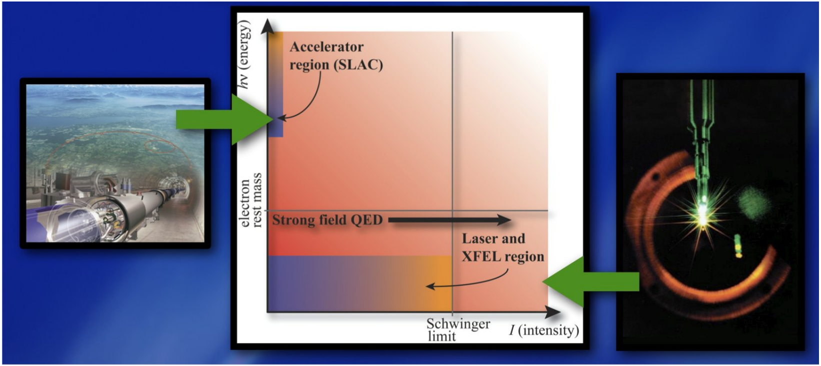
- Work done: $eE_S \times \lambda_C = m$; pair production.

$$N/V = \left(\frac{eE\hbar}{m^2c^3}\right)^2 \exp\left[-\pi\frac{m^2c^3}{eE\,\hbar}\right]$$



- Nonperturbative effects from strong fields.
- Still far from Schwinger ...interesting physics along the way!

Invitation: switching on strong fields



...another parameter to play with. . .

- C.o.M. energy
- Coherent source intensity

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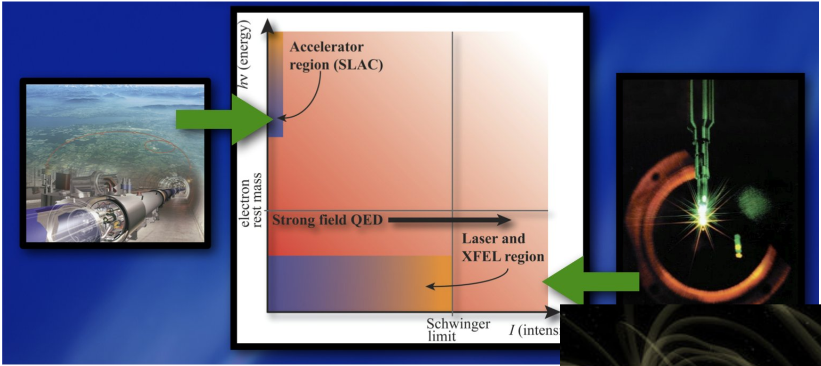

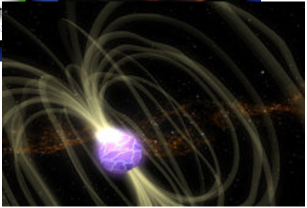

Nasa

...another parameter to play with. . .

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- Coherent source intensity

Outline

- Strong fields in classical & quantum electrodynamics

  "Strong Field QED"

- Electron-laser collisions

  Nonlinear Compton & radiation reaction

- Laser-laser collisions

  Light by light & vacuum birefringence

- Future experiments and open questions

  Cascades & breakdown of Strong Field QED

A limit to perturbative methods

- Start classically
- Motion in electromagnetic fields $\mathbf{E}$ and $\mathbf{B} \to F_{\mu\nu}$
- Consider: laser of amplitude E and frequency ω.

$$m\ddot{x}_\mu = eF_{\mu\nu}\dot{x}^\nu$$

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- Coupling to field / "intensity parameter".

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

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- Interaction is strong when coupling > 1.
- $a_0 > 1$ 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.

Relativistic, nonlinear physics

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   - Nonlinear/'multiphoton' effects.

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2. $a_0 > 1 \iff eE\lambdabar_C > \omega$
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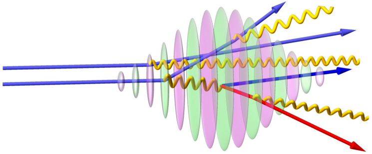
   - Nonlinear/'multiphoton' effects.
3. Strong fields means $a_0 > 1 \implies$ no perturbation in a_0.

   Non-perturbative, nonlinear, relativistic regime.

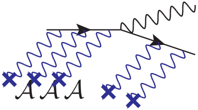
Coherence and intensity



- Laser-particle collisions
- Particles: number state
- Laser: photon coherent state.

$$|\,e^-,\tilde{A}\rangle = |\,e^-\,\rangle \otimes \exp\left[\int \mathrm{d}k\,\tilde{A}(k)a_k^\dagger\right]|\,0\,\rangle$$

! Infinitely many Feynman diagrams for any process.



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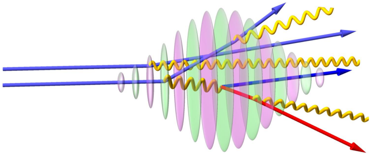

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$$|\, e^-, \tilde{\mathcal{A}} \rangle \simeq |\, e^- \rangle \otimes \left(|\, 0 \rangle + \int \mathrm{d}k\, \tilde{\mathcal{A}}(k) a_k^\dagger |\, 0 \rangle \right)$$

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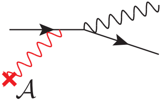

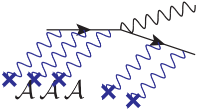

- Perturbation → e.g. Compton, familiar.

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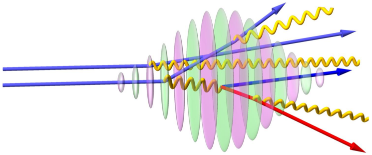

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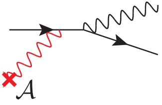
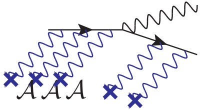
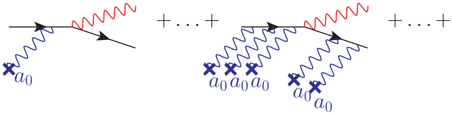




- Perturbation → e.g. Compton, familiar.
- But . . . but what if field is strong?

Strong field QED



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

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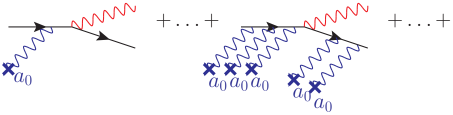

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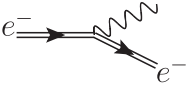
Furry expansion

Furry 1951

- Strong coupling a_0: treated exactly.

  Lorentz force moved into double line.



- Coupling α to dynamical fields: perturbative as usual.

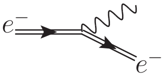
  Radiation of photons, pairs, etc, in vertex as usual.

- "Strong Field QED".

Electron laser collisions: Nonlinear Compton scattering

- Collide electrons & laser pulse.
- Look at emitted radiation.

- $a_0 > 1$
- Nonlinear effects.



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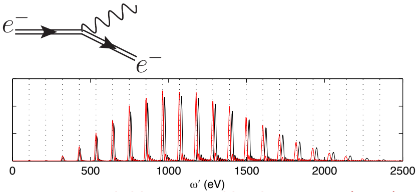
- Typical signatures:

  Harmonics

  Interference patterns.



Harvey Heinzl Ilderton Marklund PRL 109 (2012)

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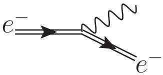
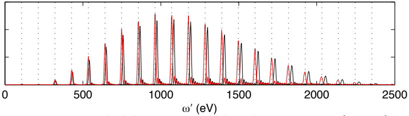
- Observation: $a_0 \simeq 1$

- Classical and quantum.





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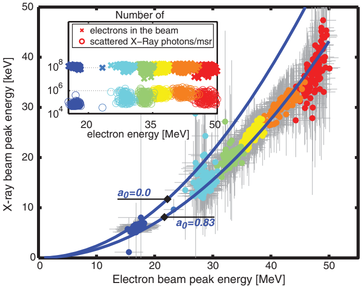
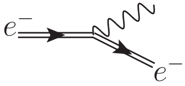


Khrennikov et al PRL 114 (2015)

Nonlinear Compton scattering as ‘radiation reaction’



- Acceleration, radiation, energy loss.
- Measure radiation and e^- spectra
- Recent experiments at Gemini

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

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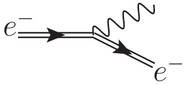

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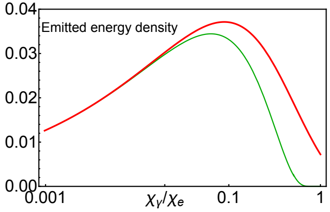
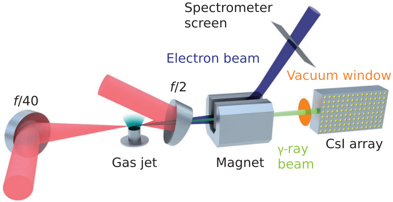


Quantum nonlinearity parameter

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

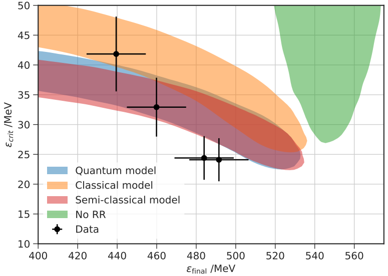
- Quantum effects: $\chi > 0.01$
- $\chi_{\text{gemini}} \sim 0.07$

Nonlinear Compton scattering as ‘radiation reaction’



- $m_e\gamma = 500$ MeV
- $a_0 \simeq 10$
- $\chi \simeq 0.07$

Cole et al, PRX 8 (2018) 011020



× Lorentz (energy not conserved)

× Classical radiation reaction (L.A.D. or L.L.)

✓ QED (PIC + Monte Carlo)

Cole et al, PRX 8 (2018) 011020

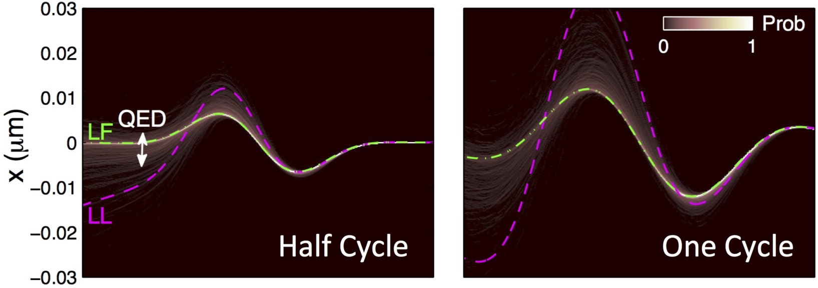
Not yet discussed effects of pulse duration. . .

Quantum quenching

- Classical particle in external field: Lorentz force trajectory.
- Classical particle inc. radiation reaction: L.A.D. → L.L.

Lorentz 1909 Abraham 1905 Dirac 1938, Landau & Lifshitz 1975

- QED...

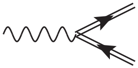


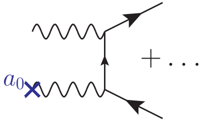
Harvey, Gonoskov, Ilderton, Marklund, PRL 118 (2017) 105004

- Future experiments at higher χ.... what else can happen?

At higher χ: nonlinear Breit-Wheeler

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

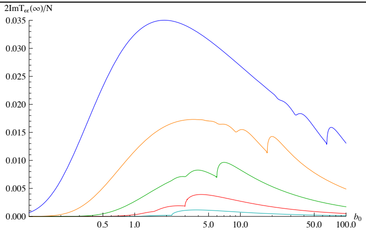




$$P \sim \chi_\gamma \exp\left(-\frac{8}{3\chi_\gamma}\right) \quad \text{for} \quad \begin{matrix} a_0 \gg 1 \\ \chi \ll 1 \end{matrix}$$

SLAC E144 (1998) & ongoing experiments

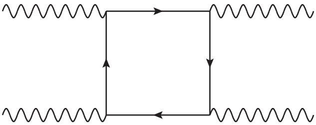
- Optimal: $\chi \sim \mathcal{O}(1)$.
- Nonlinear effects.
- Signature: thresholds & channel opening.



From Dinu Heinzl Ilderton Marklund PRD 89 (2014)

Light-by-light scattering

- Loops mean real photons can scatter:



- Light-by-light scattering ('LBL').

$$\sigma \sim \alpha^4 \frac{\omega^6}{m^8}$$

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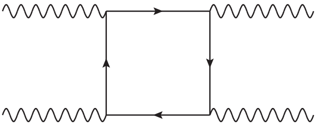

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- Optical photons: $\omega = 1$ eV $\implies \sigma \sim 10^{-66}$ cm^2
- Optical experiments: $\sigma < 10^{-48}$ cm^2. [Bernard et al EPJD 10 (2000) 141]

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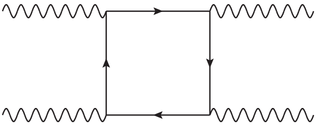

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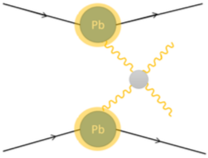
- X-ray photons: $\omega = 1$ keV $\implies \sigma \sim 10^{-46}$ cm^2
- X-ray experiments: $\sigma < 10^{-20}$ cm^2. [Inada et al PLB 732 (2014) 356]

Recent results, scattering and flip. . .

- Heavy ion collisions at ATLAS
  ATLAS, Nat.Phys '17 [1702.01625]
- 'Quasi-real' photons . . .
- Virtuality $Q^2 < 10^{-3}$ GeV^2



From Ellis et al PRL 118 (2017) 261802

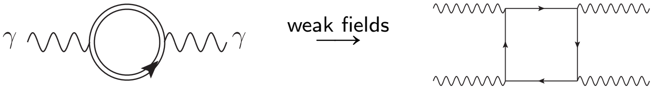
! More physics in the diagram than momentum change!

- Photons carry momentum and helicity ($= \pm 1$, discrete).
- Free photons: momentum and helicity conserved.
- Two photons: helicity can flip.

Microscopic to macroscopic

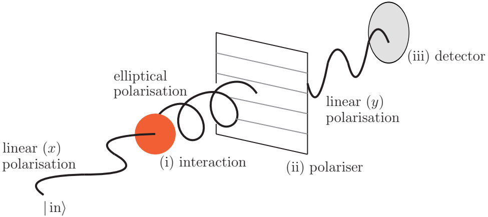
- Consider a beam of light with some polarisation.
- Collide an X-FEL probe with an intense optical laser.

Heinzl et al., Opt.Commun. 267 (2006)



- Helicity flip of photons → change in beam polarisation.

Dinu, Heinzl, Ilderton, Marklund, Torgrimsson PRD 89 (2014) 125003



- Linear → elliptic pol.

Schlenvoigt et al, Phys. Scripta 91 (2016)

Vacuum birefringence

QED relates probabilities to observables:

$$P_{\text{flip}} = \delta^2$$

← beam ellipticity squared

- Approximate form: $$\delta \sim a_0\, \chi_x \sim \frac{2\alpha}{15} \frac{E^2}{E_S^2} \frac{L}{\lambda_X} \quad (1)$$

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Optics

- Birefringent medium → ellipticity. $$\delta = \pi(\mathrm{n}_{\parallel} - \mathrm{n}_{\perp}) \frac{L}{\lambda_X} \quad (2)$$

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Euler-Heisenberg

- Low energy effective QED: $$\mathrm{n} = 1 + \frac{2\alpha}{45\pi}\left\{\begin{matrix}7\\4\end{matrix}\right\}\frac{E^2}{E_S^2} \quad (3)$$
- Plug (3) into (2) ...

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- Plug (3) into (2) . . . recovers (1).

The quantum vacuum, exposed to intense light, is birefringent.

Toll, PhD thesis, 1952

Experimental scenarios

- Flagship experiment @ European XFEL.
- Needs accurate X-ray polarimetry: $\delta \sim 2 \times 10^{-6}$

Marx et al PRL 110 (2013), Della-Valle et al EPJC 76 (2016)

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- Generate gamma-rays from backscattering.
- Collide with $10PW$ laser.

  Nakamiya et al, PRD 96 (2017)

  Ilderton & Marklund J.Plasma Phys. 82 (2016)

- Challenge: gamma ray pair polarimetry.

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- High degree of linear pol. in emission from Neutron Stars.

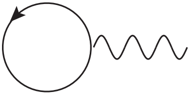
Mignami et al 1610.08323, Capparelli et al 1705.01540, Turolla et al 1706.02505

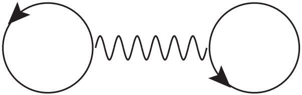
- Disputed! What is the B-field and initial photon distribution?

Tadpoles and bubbles: still learning about QFT

- Usually: drop tadpoles and vacuum bubbles.

Tadpoles and bubbles: still learning about QFT





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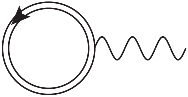
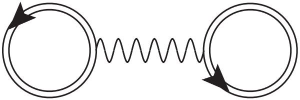

$\neq 0!$


$\neq 0!$

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), Ahmadiniaz, Edwards & Ilderton, to appear.

- New info. on QFT. Richer physics.

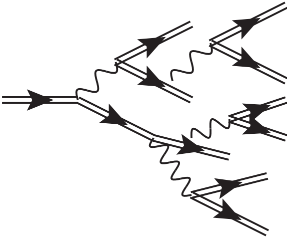
Motivation: observing cascades

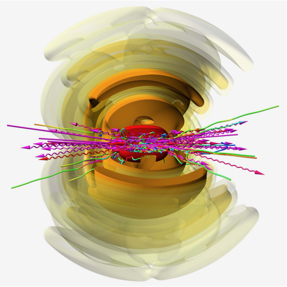
- $I \simeq 10^{23} - 10^{24}$ W/cm^2 or $a_0 \simeq 300 - 10^3$
- Acceleration → emission → pairs ↺
- Avalanche/cascade of particle production.

  Bell & Kirk, PRL 101 (2008)
- Application of cascade control: gamma source. Gonoskov et al, Phys.Rev. X7 (2017)
- Reduces field; inhibits Schwinger

  Fedotov et al, PRL 105 (2010), S.S.Bulanov et al, PRL 105 (2010)

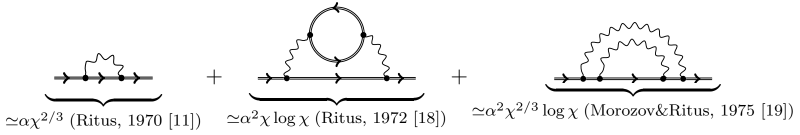
  Gonoskov PRL 111 (2013) 060404





Motivation: the fully nonperturbative regime?

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



- 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

How many pairs?

- Return to Schwinger effect.

  Start with light. End up with matter.
- What's happening in between?

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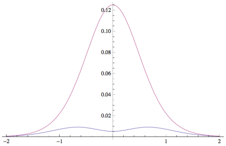

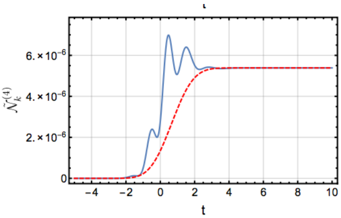

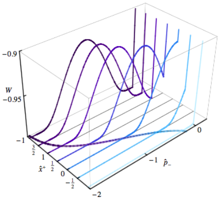

Inclusive/exclusive	Choice of basis	Quantisation surface
Vlasov	Schrödinger	Wigner
Kim, Schubert PRD84 (2011)	Dunne, Dabrowski PRD94 (2016)	Hebenstreit, Ilderton PRD84 (2011)

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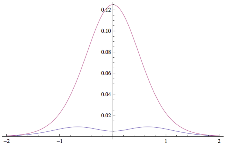

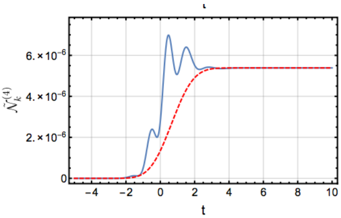

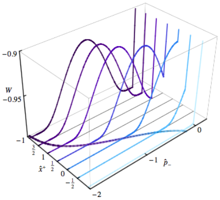

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- Non-asymptotic results seem heavily basis dependent.

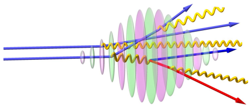
Conclusions

Strong fields give access to new phenomena.

- Birefringence of the vacuum, electromagnetic cascades . . .
- New era of experiments has begun.
- Many interesting theory questions remain.

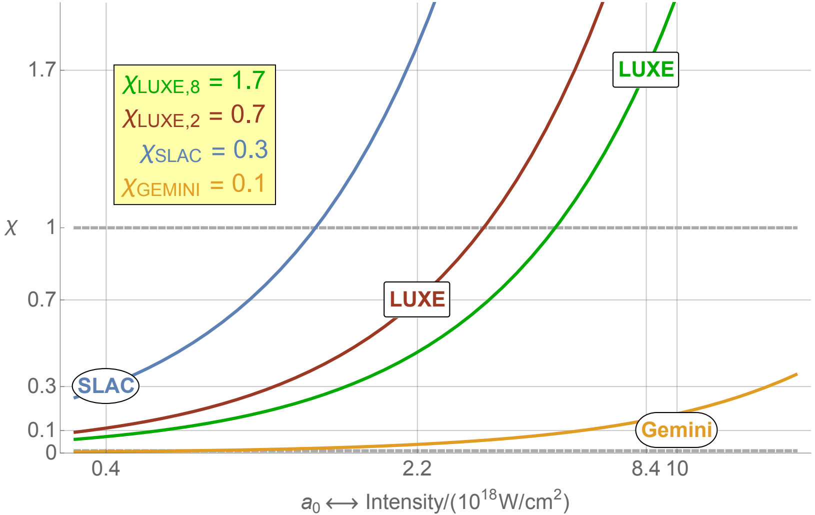
A chance to investigate:

- Strongly coupled QFT
- All-orders & non-perturbative effects
- Non-equilibrium processes



extra slides

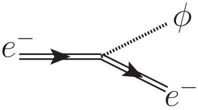
Past, present and future experiments



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

Motivation: intense lasers for BSM physics

- Lab based probes of Beyond Standard Model physics.



  - e.g. electron–scalar ALP coupling