Fundamental quantum physics in intense laser fields

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ELI-NP summer school

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Nuclear Physics eli

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European Science Foundation

Links!

Link to my homepage, (extended) presentation and exercises

https://goo.gl/e1Fl7f
https://sites.google.com/site/antonilderton/

Outline

- QED
- Processes
- Strong field QED
- Solvable cases
- Examples

Our group and collaborators

Mattias Marklund

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James Vary
Jonatan Wårdh
Xingbo Zhao

QED

- Field theory: electromagnetic field, electrons, positrons.

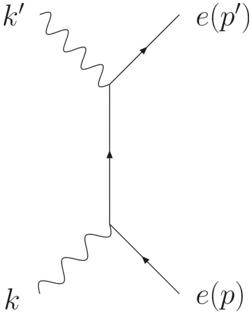
$$\mathcal{L} = -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} + \overline{\psi}(i\partial\!\!\!/ - m)\psi + \text{g.f.} - e\overline{\psi}A\!\!\!/\psi + \text{counterterms}$$

ψ: electrons and positrons. A_μ: photons. Counterterms remove UV ∞'s. Regularisation implicit.

- Tested to ridiculous precision.
- Describes all 'everyday' physics except gravity.
- Perturbation theory in $\alpha = e^2/(4\pi)$: asymptotic expansion.

Example: Compton scattering

- Feynman rules → propagators, correlation functions.

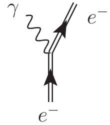


- LSZ → S-matrix, external leg wavefunctions $u_p e^{-ip.x}$

Trees . . .

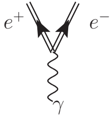
- Nonlinear Compton scattering

  Nikishov and Ritus, Sov.Phys.JETP 19 (1964) 529
  Harvey, Heinzl, Ilderton PRA 79 (2009) 063407
  Boca and Florescu, PRA 80 (2009) 053403
  Seipt, Kämpfer, PRA 83 (2011) 022101
  Mackenroth, Di Piazza, PRA 83 (2011) 032106
  Harvey, Heinzl, Ilderton, Marklund PRL 109 (2012) 100402
  Dinu, Phys.Rev. A87 (2013) 052101



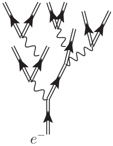
- Stimulated pair production

  Nikishov and Ritus, Sov.Phys.JETP 19 (1964) 529
  Heinzl, Ilderton, Marklund, Phys.Lett. B692 (2010) 250
  Meuren, Keitel and Di Piazza, arXiv:1503.03271
  Nousch, Seipt, Kämpfer, Titov. arXiv:1509.01983



- Cascades

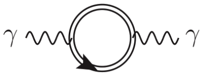
  Fedotov, et al. Phys.Rev.Lett. 105 (2010) 080402
  Sokolov et al. Phys.Rev.Lett. 105 (2010) 195005
  Elkina et al, Phys. Rev. ST Accel. Beams 14 (2011) 054401
  Gonoskov, Ilderton et al., Phys. Rev. Lett. 111 (2013) 060404



... and loops

- Vacuum birefringence

  Toll, PhD thesis, 1952
  Heinzl et al., Opt.Commun. 267 (2006) 318.
  Dinu, Heinzl, Ilderton, Marklund, Torgrimmson PRD 89 (2014) 125003
  Karbstein, Gies, Reuter, Zepf arXiv:1507.01084

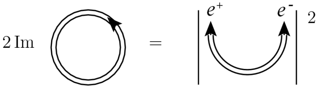


- Photon emission/splitting/scattering

  Adler, Annals Phys. 67 (1971) 599
  Lundström *et al.*, Phys.Rev.Lett. 96 (2006) 083602
  King and Keitel, New J. Phys. 14 (2012) 103002

- Schwinger pair production

  Schwinger, Phys. Rev. 82 (1951) 664
  Dunne, Gies, Schützhold, PRL 101 (2008) 130404
  DiPiazza et al., PRL 103 (2009) 170403
  Bulanov et al., PRL 104 (2010) 22040
  Gonoskov, Ilderton et al., PRL 113 (2014) 014801



QED

- Field theory: electromagnetic field, electrons, positrons.

$$\mathcal{L} = -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} + \overline{\psi}(i\partial\!\!\!/ - m)\psi + \text{g.f.} - e\overline{\psi}A\!\!\!/\psi + \text{counterterms}$$

ψ: electrons and positrons. A_μ: photons. Counterterms remove UV ∞'s. Regularisation implicit.

- Our interest: a strong background field is present.

When is a field "strong"?

- What do we mean by a strong field?

When is a field "strong"?

- What do we mean by a strong field?
- Field of "typical" strength E, frequency ω:

$$\text{Lorentz} \quad \longrightarrow \quad x'' \sim \frac{eE}{m\omega} x'$$

- Coupling to the external field is

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

- Relativistic effects: $\eta > 1 \implies eE\lambda > m$
- Nonlinear/'multiphoton' effects: $\eta > 1 \implies eE\lambda_C > \omega$
- Strong fields $\implies \eta > 1 \implies$ no perturbation in η.

Coherent states (how to include a background field)

$$\mathcal{L} = -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} + \overline{\psi}(i\partial\!\!\!/ - m)\psi + \text{g.f.} - e\overline{\psi}A\!\!\!/\psi + \text{counterterms}$$

ψ: electrons and positrons. A_μ: photons. Counterterms remove UV ∞'s. Regularisation implicit.

Scattering in background fields . . .

. . . is scattering between coherent states.

e.g. Compton: $\langle\, e(p'),\, \gamma(k'),\, C\, |\hat{S}_{\text{QED}}|\, e(p),\, \gamma(k),\, C\,\rangle$

- Same state $\implies$ beam depletion neglected!
- Replacement rule: $eA_\mu \to eA_\mu + eA_\mu^{\text{ext}}$.

Strong Field QED

$$\mathcal{L} = -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} + \text{g.f.} + \overline{\psi}(i\not{\mathcal{D}} - m)\psi \\ - e\overline{\psi}\not{A}\psi + \text{counterterms}$$

- $\mathcal{D}_\mu = \partial_\mu + ieA^{\text{ext}}_\mu$: background covariant derivative.

Strong Field QED

$$\mathcal{L} = -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} + \text{g.f.} + \overline{\psi}(i\not{\mathcal{D}} - m)\psi - e\overline{\psi}\not{A}\psi + \text{counterterms}$$

- $\mathcal{D}_\mu = \partial_\mu + ieA_\mu^{\text{ext}}$: background covariant derivative.
- Usual photon propagator.

- Fermion propagator: $(i\not{\mathcal{D}} - m)^{-1}$

Exact treatment of η effects. Describes Lorentz force motion

- Vertex: two fermions, one photon as usual.

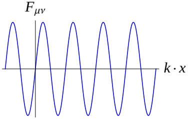
Quantum emission and recoil contained in vertex

- "Furry picture expansion".

Do we know $(i\not{D} - m)^{-1}$? Laser field models

- Monochromatic plane waves.

  Nikishov, Ritus, Narozhny 1964



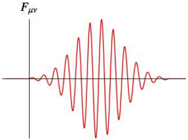
- Pulsed plane waves: finite size effects.

  Boca and Florescu, Phys.Rev. A **80** (2009) 053403

  Heinzl, Ilderton, Marklund, Phys.Lett. B **692** (2010) 250

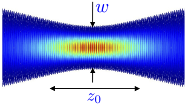
  Heinzl, Seipt and Kämpfer, Phys.Rev. A **81** (2010) 022125

  Mackenroth & Di Piazza, Phys.Rev. A **83** (2011) 032106



- Realistic beams

  No corresponding exact treatment.



▻ Use plane waves...

$$F_{\mu\nu} \equiv F_{\mu\nu}(k.x) \ , \qquad k^2 = 0 \qquad k.x \equiv k_+ x^+ \equiv \omega(x^0 + x^3).$$

- 'One dimensional'. Lightfront. Neville & Rohrlich, Phys. Rev. D **3** 1692 (1971)

Calculations in plane waves: classical

Classical motion: identify momentum π_μ and position x^μ.

Calculations in plane waves: classical

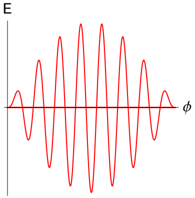
Classical motion: identify momentum π_μ and position x^μ.

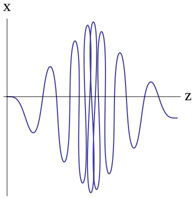
- Transversality of field $\implies$ three conserved quantities.

$\implies$ Use phase $\phi := k.x = \omega(x^0 + x^3)$ to parameterise.

- Initial $p_\mu \to \pi_\mu(\phi)$ depending on

- $a_{1,2} = \int_{-\infty}^{\phi} \mathrm{d}\varphi \, \frac{e}{\omega} E_{1,2}(\varphi)$





Calculations in plane waves: quantum

- LSZ $\implies$ in/out wavefunctions. (Using potential $eA^{\text{ext}}_{\mu} = a_{\mu}$.)

$$e^{-} \text{ in:} \quad \Psi^{-}_{p}(x) = \left[\mathbb{1} + \frac{1}{2k.p}\, \not{k}\not{a}(k.x)\right] u_p \; e^{-ip.x - \frac{i}{2k.p}\int_{-\infty}^{k.x} 2a.p - a^2}$$

- (Solutions of Dirac equation $i\not{D} - m = 0$.)

What does all this mean?

Calculations in plane waves: quantum

- LSZ $\implies$ in/out wavefunctions. (Using potential $eA_\mu^{\text{ext}} = a_\mu$.)

$$e^- \text{ in:} \quad \Psi_p^-(x) = \left[\mathbb{1} + \frac{1}{2k.p}\not{k}\not{a}(k.x)\right] u_p \, e^{-ip.x - \frac{i}{2k.p}\int_{-\infty}^{k.x} 2a.p - a^2}$$

- (Solutions of Dirac equation $i\not{D} - m = 0$.)

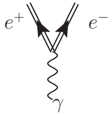
What does all this mean?

$$\text{no background}: \quad u_p \exp\left(-ip.x\right) = u_p \exp\left(-i\partial^{-1}.p\right)$$

$$\text{with background}: \quad u_{\pi(\phi)} \exp\left[-i\mathcal{D}^{-1}.\pi(\phi)\right]$$

- Exact solutions due to conserved quantities
- Simplicity due to vanishing of field invariants: no pairs!

Example: stimulated pair production



- Incoming photon creates a pair.

$$\gamma(k') \underset{\text{laser}}{\longrightarrow} e^-(p) + e^+(p')$$

$$k'_\mu + (\text{background}) = p_\mu + p'_\mu$$

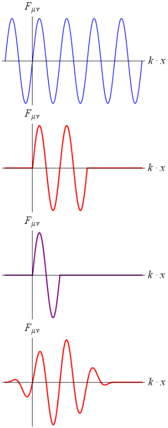
- S-matrix element:

$$S_{fi} = -ie \int \mathrm{d}^4x \; \Psi_p^{\text{out-}}(x)\, e^{-ik'.x} \not{\epsilon}\, \Psi_{p'}^{\text{out+}}(x)$$

- For normalisations, flux factors etc see appendix in:

  Ilderton and Torgrimsson, Phys.Rev.D 87 (2013) 085040 [arXiv:1210.6840]

- Periodic vs. short pulse backgrounds.



Old results: very long pulses.

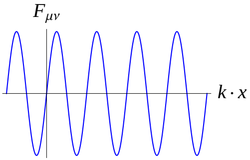
- Periodic waves. Infinite duration.

  Niksihov, Ritus, Sov.Phys.JETP 19 (1964) 529

- Charges: rapid quiver motion.

→ Quasi-momentum q_μ

$$q_\mu = p_\mu + \frac{\eta^2}{2k.p}k_\mu$$



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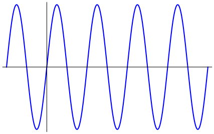


- Charges: rapid quiver motion.

→ Quasi-momentum q_μ

$$q_\mu = p_\mu + \frac{\eta^2}{2k.p} k_\mu$$

- S-matrix supported on:

$$k'_\mu + n k_\mu = q_\mu + q'_\mu$$

$$\boxed{q^2 = m_*^2 \equiv m^2(1+\eta^2).}$$

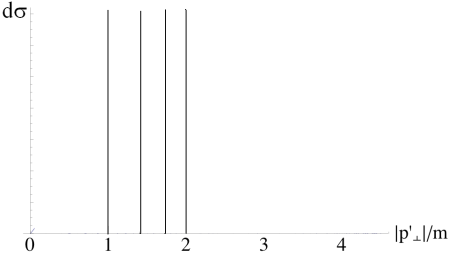
Sengupta, 1952

? Pair production threshold: $n > \dfrac{2m_*^2}{k.k'}$

- ELI optical laser: $m_* \sim 10^2 m$!

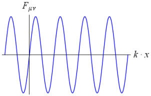
Extreme Light Infrastructure

The role of the shifted mass



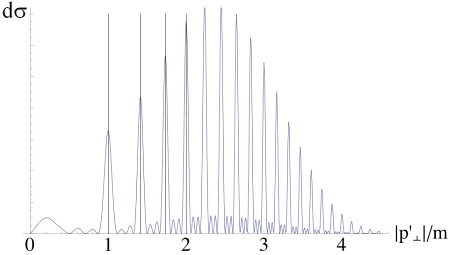
- Differential cross-section.
- (arb. units)
- Energies: $0 \sim m$ and $1 \sim m_*$.

Periodic wave:

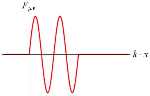


- Line spectrum.
- Shifted threshold.
- $k.k' > 2m^2(1 + \eta^2)$

The role of the shifted mass



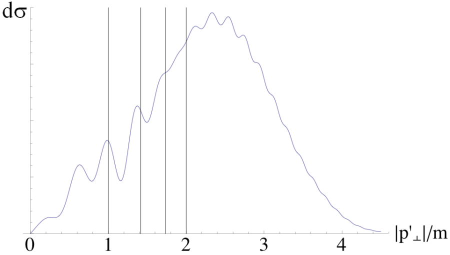
Wavetrain:
few cycles

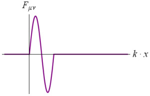


- Substructure.
- Sub-threshold behaviour
- Peaks = resonances.

- Lightfront momentum transfer:
- Peaks when average = multiple of driving frequency ω.
- Resonances! Just looks like energy to produce m_* pairs.
- Identifies $q_\mu = \langle \pi_\mu \rangle$

The role of the shifted mass



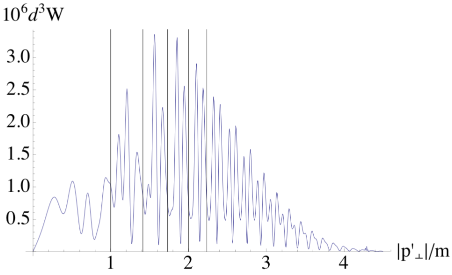


- Different structure.
- Clear signal between m and m_*.

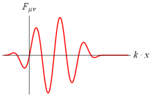
$\Longrightarrow$ Mass $\leftrightarrow$ shifted mass dominance.

- m_* not 'in control'.
- The emission spectrum reflects the pulse shape.

The role of the shifted mass



Smooth pulse



- Different structure.
- Shifted peaks.
- Messy!

- $m_* \to M(k.x, k.y)$. Kibble, Salam, Strathdee, NPB **96** (1975) 255
- Different pulse shape: there exist other effective masses m_*!

Harvey, Heinzl, Ilderton, Marklund Phys.Rev.Lett. 109 (2012) 100402

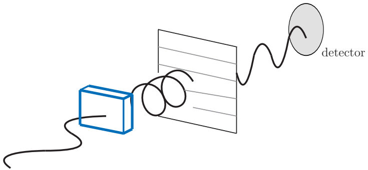
Optics: birefringence

- A birefringent medium (length L).
- Refractive indices $\mathrm{n}_{\|}$ and $\mathrm{n}_{\perp}$.
- A beam of light (wavelength λ').

$\Longrightarrow$ Effective probe velocity depends on polarisation.

- Linear → elliptic, ellipticity δ:

$$\delta = \pi(\mathrm{n}_{\|} - \mathrm{n}_{\perp})\frac{L}{\lambda'}$$



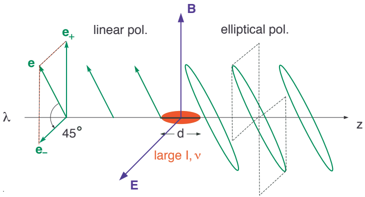
Vacuum birefringence

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

Toll, PhD thesis, 1952

- Intense optical laser
- Send in X-ray probe: linear pol
- Probe emerges: elliptical pol
- Needs accurate X-ray polarimetry

Marx et al PRL 110 (2013)

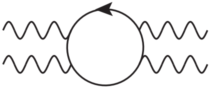


T. Heinzl *et al*, Opt. Commun. **267** (2006) 318

- Virtual loops → refractive indices.
- First measurement of light-by-light?

Halpern, Phys.Rev. 44 (1934), HIBEF, ELI-NP

- Beyond the SM? What runs the loop?



Scattering → observables

- Beam ellipticity: photons flipping helicity-state.
- Ellipticity: $\delta^2 = \mathbb{P}(\text{flip}) = |S_{flip}|^2$
- Much simpler then going 'via indices'.

Dinu, Ilderton, Heinzl, Marklund, Torgrimsson, PRD **90** (2014) & PRD **89** (2014)

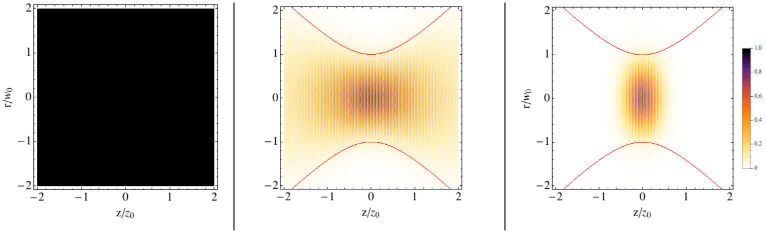
- Look at impact of realistic pulse geometry.

! Precision expt.

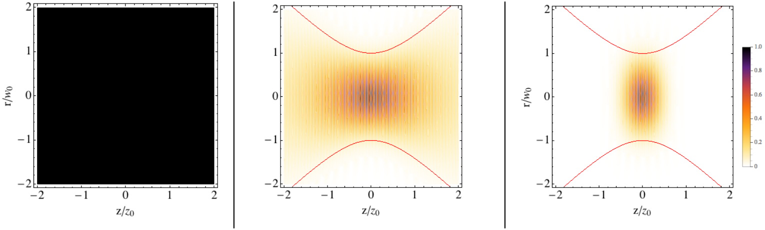
! Need to do better than plane waves.

- Build up complexity.

Impact of pulse geometry

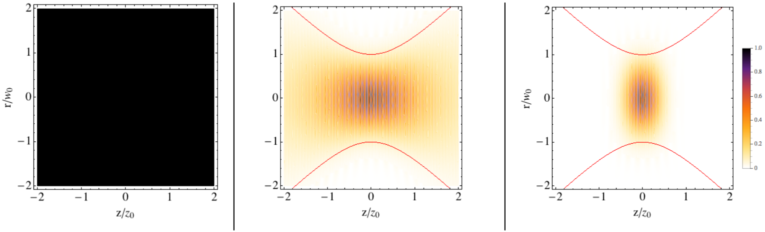


Impact of pulse geometry



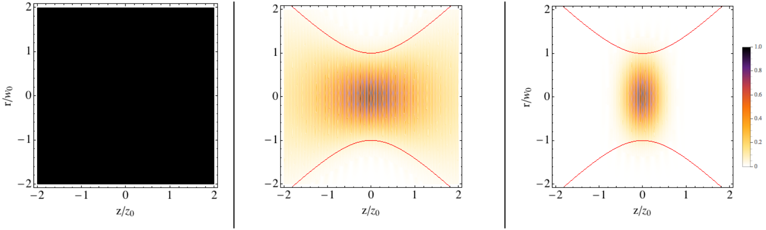
$$\delta = \frac{2\alpha}{15}\frac{E^2}{E_S^2}\frac{2z_0}{\lambda'}$$

Impact of pulse geometry



$$\delta = \frac{2\alpha}{15}\frac{E^2}{E_S^2}\frac{2z_0}{\lambda'} \qquad \times \frac{\pi}{4}$$

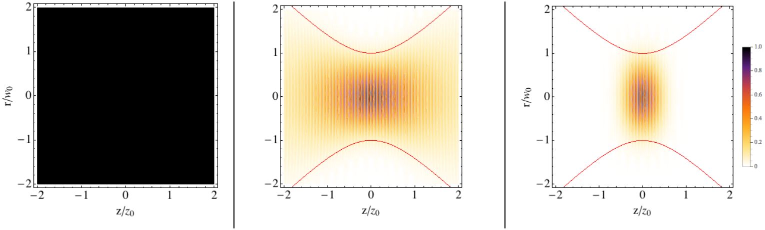
Impact of pulse geometry



$$\delta = \frac{2\alpha}{15}\frac{E^2}{E_S^2}\frac{2z_0}{\lambda'} \qquad \times \frac{\pi}{4} \qquad \times \frac{1}{4\sqrt{\pi\log 2}}\frac{\tau}{z_0}$$

- Hibef @ European X-FEL:
  En. $= 30$J, $\lambda = 800$nm, $w_0 = 2\mu$m, $\tau = 30$fs & $\lambda' = 0.1nm$

Impact of pulse geometry



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$$\delta = 2.2 \times 10^{-5}$$

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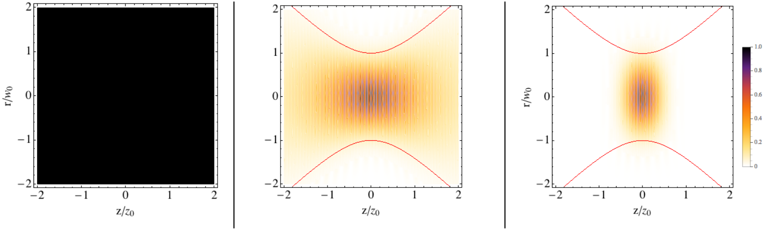

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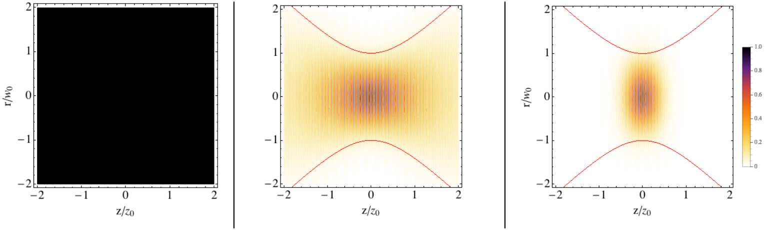
$\delta = 2.2 \times 10^{-5}$ $\rightarrow 1.7 \times 10^{-5}$

Impact of pulse geometry



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- Hibef @ European X-FEL:
  En. $= 30$J, $\lambda = 800$nm, $w_0 = 2\mu$m, $\tau = 30$fs & $\lambda' = 0.1nm$

$\delta = 2.2 \times 10^{-5}$ $\rightarrow 1.7 \times 10^{-5}$ $\rightarrow 2.0 \times 10^{-6}$

- Only slightly beyond what can be measured today...

Birefringence at ELI-NP

- Pump/target: an intense (PW) optical laser
- Probe: synchrotron emission from laser-electron collisions.

$$\delta = \frac{2\alpha}{15}\frac{E^2}{E_S^2}\frac{2z_0}{\lambda'}$$

- ☺ Strong laser fields (E/E_S is 'large')
- ☺ Synchrotron radiation: gamma rays (λ' small)
- ☹ Messy environment, lose precision.
- ☹ Gamma ray spectroscopy is challenging!

Conclusions

- If quantum and relativistic effects are important:

  QFT is the theory to use.

- Interested in theory?

  All-orders and nonperturbative physics

  Back-reaction, realistic fields...

- Interested in experiment?

  Unobserved standard model processes

  Beyond the standard model

Links!

Link to my homepage, (extended) presentation and exercises

https://goo.gl/e1Fl7f

https://sites.google.com/site/antonilderton/