Lightfront QED and intense laser fields

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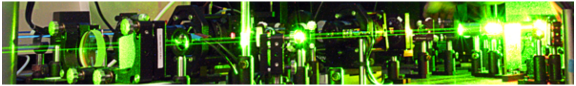
- Chris Harvey, Tom Heinzl, Florian Hebenstreit, Pieter Maris, Mattias Marklund and Greger Torgrimsson, James Vary, Xingbo Zhao

Outline



1. Lasers and prospects.
2. Time-dependent processes.
   - Front form vs. instant form.
   - The mass shift.
   - Pair production: the Wigner formalism.
3. Nonperturbative methods.

Experimental prospects

- Low energy, high intensity.
- Femtosecond duration, 10^{20} photons/ pulse.
- 10^1-10^2 J $\rightarrow$ intensity 10^{22}-10^{23} W/cm^2

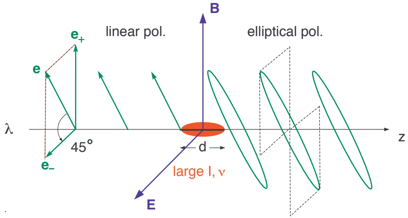
▻ Light-by-light scattering.

▻ Vacuum birefringence.

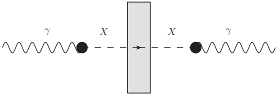
▻ New particle searches:
Light shining through walls

▻ Radiation reaction.

▻ Schwinger pair production.



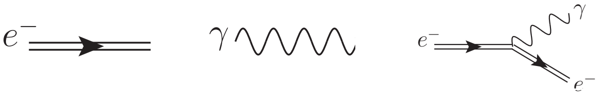
T. Heinzl *et al*, Opt. Commun. **267** (2006) 318



Jaeckel & Ringwald, Ann.Rev.Nucl.Part.Sci. (2010)

Approaches to 'strong field QED'

- Laser → background field.
- Dimensionless field strength $$a_0 \sim \frac{eE}{m\omega} \gg 1.$$
- Cannot be treated perturbatively.
- Treat background exactly: use Furry picture. Furry, 1951

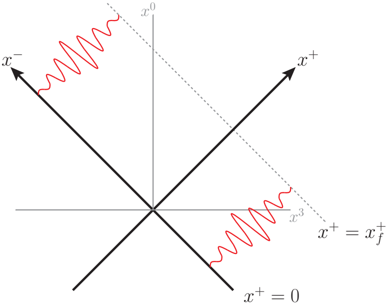


- Fermion propagator: $[i\partial\!\!\!/ - m - eA\!\!\!/_{\text{ext}}]S = \delta^4(x-y)$

→ This talk: Furry picture and simple backgrounds.

Spacetime structure

- Simple field model. $F^{\mu\nu}_{\text{ext}} \equiv F^{\mu\nu}_{\text{ext}}(x^+)$.



1. Plane wave ($\perp$ to lightfront)
2. Longitudinal electric (pairs)

- Compare x^0 and x^+.

- All particles enter at same front times.
- Lorentz orbit: $x^+ = \frac{p^+}{m}\tau$

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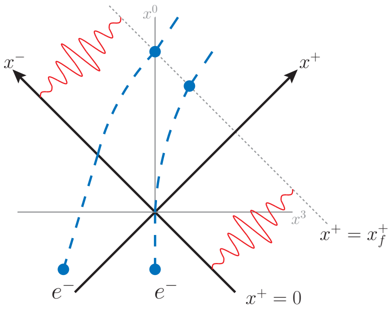

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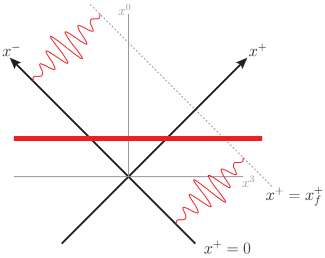
Physics in plane waves: quantum

- Scalar field in a plane wave.

$$\phi = \int \mathrm{d}p \; b_p \varphi_p + d_p^\dagger \varphi_{-p}$$

$$\varphi_p = \exp\Big[-ip.x - i\int^{x^+} \frac{2p.a - a^2}{p^+} \Big]$$

Volkov Z. Phys. 94 (1953)



- Canonical quantisation, instant form:

$$[\phi, \partial_0\phi] = i\delta \implies \ldots ?$$

✘ Orthogonality of φ_p on spacelike hyperplanes?

- Progress only in recent years.

Lavelle, McMullan, Raddadi, PRD 87 (2013) 085024

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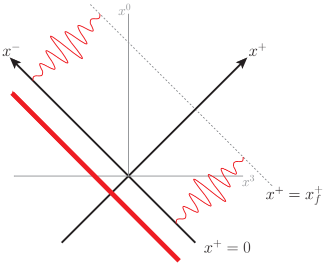

✓ Front form: as in free theory.

$$[b_p, b_q^\dagger] = 2p^+ (2\pi)^3 \delta^{\perp,+}(q-p)$$

✓ Usual particle interpretation.

✓ Time dependent processes in lightfront QED.

Neville & Rohrlich PRD 8 (1971) 1692, Ilderton & Torgrimsson PRD 87 (2013) 085040

Poles in the propagator

- Monochromatic plane wave, frequency ω.
- Volkov propagator G: infinite series of poles $(n \in \mathbb{Z})$

$$(p_\mu - nk_\mu)^2 = m_*^2$$
$$m_*^2 = m^2(1 + a_0^2)$$

$$k_\mu = \omega n_\mu$$
$$k.x = \omega x^+$$
$$k.p = \omega p^+$$

- 'Shifted mass' in a plane wave, intensity a_0. Sengupta 1952
- Discrete spectrum? Zel'dovich 1967, Oleinik 1967

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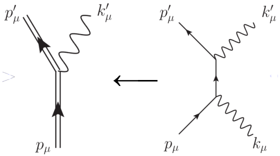
Debate

Divergences? Oleinik 1967	Higher loops? Becker & Mitter 1976	No mass shift! Fried & Eberly 1964	Mass shift is there Kibble 1965
Finite mass reform. Reiss 1966	Non-pert. effect Reiss 1966	Pert. effect Lavelle 2012	What about pulses? Corson & Peatross PRA 85 (2012) Mackenroth & Di Piazza PRA 85

The shifted mass: osbervation

1. Compton Scattering.
2. 'Nonlinear Compton'.



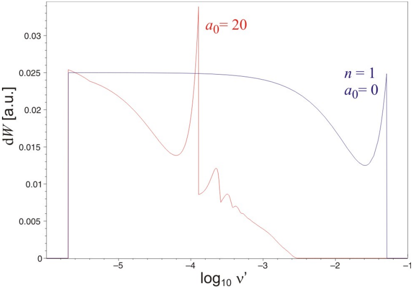
- $m_* \implies$ frequency shift.

Kibble 1965

→ Spectrum ($\nu' = \omega'/m$)

⍨ Never observed.

(N.B. undulators!)

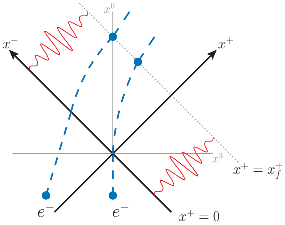


Answers from lightfront quantisation

- Llightcone quantisation:

$$P^-(x^+)|\,p_\mu\,\rangle = \pi^-(x^+)|\,p_\mu\,\rangle$$

- Particle content of free theory.



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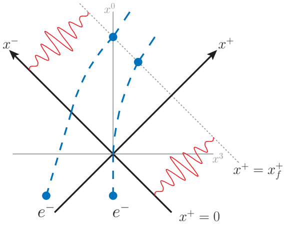


- Particle content of free theory.
- Time dependence $\implies$ no explicit Lorentz invariance.
- All poles contribute. Resum contributions

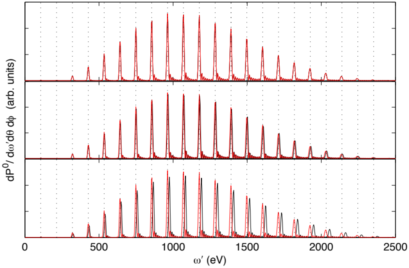
$$G \sim \int \mathrm{d}p\ \delta(p^2 - m^2)\varphi_p(x)\varphi_p^*(y)$$

- Off shell poles = going onto ordinary mass-shell.
- Källén-Lehmann in a background field.

Living on the edge

- Poles/mass shift: fingerprint of beam shape.
- Requires fine tuning.

Harvey, Heinzl, Ilderton, Marklund PRL 109 (2012)



Laser

- 40μm spot radius.
- $a_0 \simeq 2$, 800nm.

Electron beam

- 5Mev, 8μm radius.
- e^- see a plane wave.

REGAE at DESY

- Plane wave vs. Gaussian beam.
- Peaks = mass-shift signals.

Radiation reaction from QED

- Classical radiation reaction: LAD $\implies$ runaways.

→ Different classical equations.

- Measurable at 10^{23} W/cm^2?

  Di Piazza et al. Rev. Mod. Phys. 84 (2012), Heinzl Int. J. Mod. Phys. A27 (2012), Harvey, Heinzl, Marklund PRD 84 (2011), Di Piazza, Hatsagortsyan, Keitel, PRL 102 (2009), Bulanov *et al.* PRE 84 (2011)

- Radiation Reaction from QED?
- Progress using lightfront quantisaton. Ilderton & Torgrimsson (2013)

See talk by Greger Torgrimsson

Pair production → zero modes

- Dirac-Heisenberg-Wigner function $W(x,p)$.

  Wigner Phys.Rev.40 (1932), Heisenberg Z.Phys.90 (1934), Dirac Proc.Camb.Phil.Soc.30 (1934)

- Phase space (quasi) probability distribution.
- Instant and front forms:

$$W_I = \int \mathrm{d}^3\mathbf{y} e^{ip.y} \langle 0 | \psi(x+\tfrac{y}{2})\, e^{ie\int \mathrm{d}z.A(z)}\, \psi^\dagger(x-\tfrac{y}{2}) | 0 \rangle \Big|_{y^0=0}$$

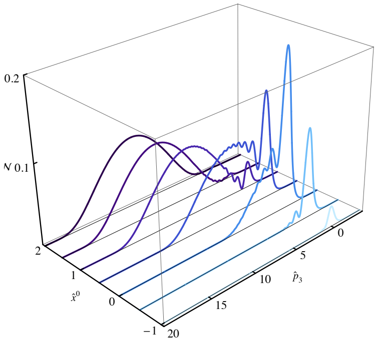
$$W_F = \int \mathrm{d}^2 y^\perp \mathrm{d}y^- e^{ip.y} \langle 0 | \psi_+(x+\tfrac{y}{2})\, e^{ie\int \mathrm{d}z.A(z)}\, \psi_+^\dagger(x-\tfrac{y}{2}) | 0 \rangle \Big|_{y^+=0}$$

- $W(x,p) \sim$ prob. momentum p at time/position x.

Compare: instant vs. front form

- In a pair producing background
- W = momentum (p) distribution at time x.

Instant form.



- Oscillations: transient effects.
- Virtual particles.

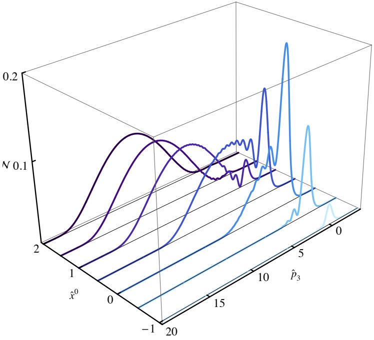
  Bialynicki-Birula, Gornicki, Rafelski, PRD (1991),

  Bialynicki-Birula and Rudnicki (2011)
- Bump moving out: real particles

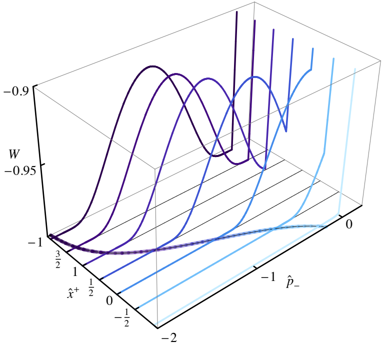
Compare: instant vs. front form

- In a pair producing background
- W = momentum (p) distribution at time x.

■ Instant form.



■ Front form.



Compare: instant vs. front form

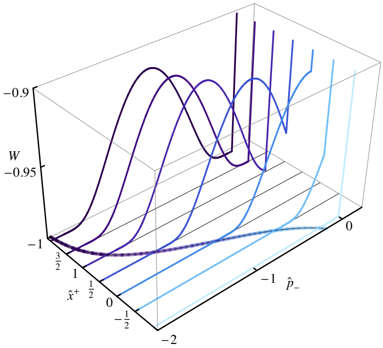
- In a pair producing background
- W = momentum (p) distribution at time x.

■ Front form.

- Only real particles.
- W supported on classical worldlines.
- Zero modes essential!

Tomaras et al. JHEP 0111 (2001),

Woodard, Nucl.Phys.Proc.Suppl 108 (2002)



Hebenstreit, Ilderton, Marklund, Phys.Rev. D84 (2011) 125022

Pair production?

→ Phenomenology.

☹ Very far from Sauter-Schwinger limit $E_S \sim 10^{18}$ V/m.

Heisenberg and Euler 1936; Sauter 1931; Schwinger 1951

- Next generation: $E < 10^{-2} E_S$.
- Many ways to 'lower' the threshold.

Schutzhold, Gies, Dunne PRL 101 (2008), PRD 80 (2009)

- Geometry helps. Simple illustration:

$$\text{Number of pairs} \simeq \frac{\text{Vol}}{\lambda_c^4}\frac{E^2}{E_S^2}\exp\left(-\pi\frac{E_S}{E}\right)$$

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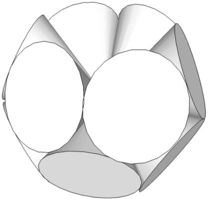
- Focal Vol $\sim 1\mu\text{m}^4$, 1 pair $\implies E \sim 0.06 E_S$.

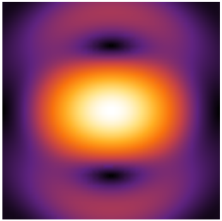
Focussed fields

- Multiple colliding pulses.

Bulanov et al, PRL 104 (2010)



→ near optimal focusing →
Gonoskov et al, 2013



- Nonperturbative calculations in real fields? / in general?

→ Numerical approaches.

- PIC Codes + Monte-Carlo modules?
- Would like to retain quantum and lightfront approach.

A non-perturbative approach

- Time dependent Basis Light-Front Quantisation.
  - For explicitly time-dependent problems in QFT.

Xingbo Zhao, Anton Ilderton, Pieter Maris, James Vary (2013)

$$P^- = P^-_{\mathsf{QED}} + V_{\mathsf{ext}}(x^+)$$

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$$P^- = P^-_{\text{QED}} + V_{\text{ext}}(x^+)$$

1.) Solve QED. :)

$$\hat{P}^-_{\text{QED}} |\, \beta \,\rangle = E_\beta |\, \beta \,\rangle$$

2.) Transitions due to V_{ext}:

$$|\, \beta \,\rangle \rightarrow |\, \beta' \,\rangle$$

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1.) Fock space truncation.

$$| e_{\text{phys}} \rangle = | e \rangle + | e\gamma \rangle + \ldots$$

2.) Time step discretisation.

$$\mathcal{T}_+ e^{-\frac{i}{2}\int P^+} \to (1 - \tfrac{i}{2} P^+(x_n^+) \delta x^+) \cdots$$

- Fully quantum, real time.

See talk by Xingbo Zhao.

Conclusions

- Intense laser fields offer prospects for
  - testing QED
  - new particle searches
- Old problems: lightfront provides answers.
  - Effective mass — Ilderton & Torgrimsson PRD (2012)
  - Radiation reaction — Ilderton & Torgrimsson (2013)
- Nonperturbative methods.

Talk by Xingbo Zhao