Non perturbative QED tests at electron/laser facilities

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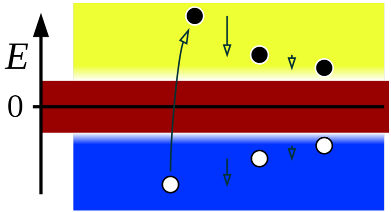
Talk synopsis

1. **The behaviour of the quantum vacuum in the presence of a strong electromagnetic field**
2. **Review some strong field environments - Cosmological, e+e- colliders, laser-electron SQED experiments**
3. **Review non perturbative QFT (Furry picture) and its defining features**
4. **Tour the Furry picture Feynman diagrams and their key phenomenology**
5. **Discuss simulation strategies, custom build monte carlo programs**

Motivation: polarising the vacuum

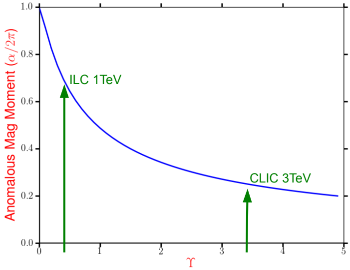
Schwinger limit



- Quantum vacuum becomes more dispersive with field strength
- At Schwinger limit quantum vacuum decays into a real pair
- The Schwinger critical field ($E_{\text{cr}} = m_e^2 c^3/e\hbar = 1.32 \times 10^{18}$ V/m)
- How do we incorporate these vacuum changes into our theories?

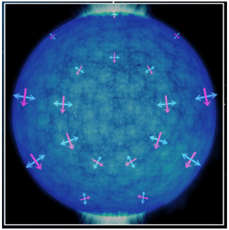
Anomalous magnetic moment

$$\frac{\Delta\mu}{\mu_0} = \frac{\alpha}{2\pi}\int_0^\infty \frac{2\pi\, dx}{(1+x)^3}\left(\frac{x}{\Upsilon}\right)^{1/3} \mathrm{Gi}\left(\frac{x}{\Upsilon}\right)^{1/3}$$

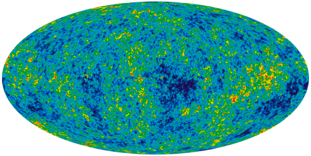


- There is a predicted strong field correction to the AMM. strong field
- $\Upsilon, (\chi_e)$ is the external field strength in electron (muon) rest frame
- Strong field ”running” of the QED coupling. A background field changes the QED vacuum

Strong field Astro/Cosmo arena



Magnetar Vacuum birefringence



CMB signatures

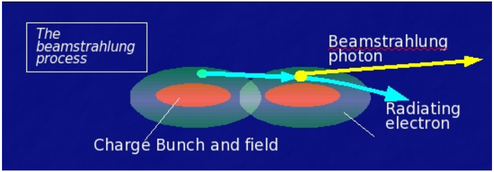
Vacuum birefringence

- Strong field effects in observation of polarised light from Magnetar
- Possible evidence of strong field vacuum birefringence (10^{13} G)
- Polarisation should be correlated with magnetic field relative to Earth
- Reported by arxiv:1610.08323. Rebutted by arxiv:1705.01540

Cosmological Schwinger effect

- Hawking radiation is Schwinger pair creation in strong gravitational field
- Non perturbative QED $\leftrightarrow$ QED in curved space-times (Hollands, Wald arxiv:1401.2026)
- Strong field provided by gravity in early universe (Martin arxiv:0704.3540)
- Two point correlation function linked to CMB fluctuations

Strong fields at the collider Interaction Point



$\Upsilon \approx 1$ sets the strong field scale.

$$\Upsilon = \frac{e|\vec{a}|}{mE_{\text{cr}}}(k \cdot p)$$

- Υ depends on collider bunch parameters and the pinch effect
- Future linear colliders will have "strong" IP fields
- **All** collider processes are potentially "strong field processes"

Machine	LEP2	SLC	ILC	CLIC
E (GeV)	94.5	46.6	500	1500
$N(\times 10^{10})$	334	4	2	0.37
σ_x, σ_y (μm)	190, 3	2.1, 0.9	0.49, 0.002	0.045, 0.001
σ_z (mm)	20	1.1	0.15	0.044
Υ_{av}	0.00015	0.001	0.24	4.9

Strong field effect: IP Depolarisation

Spin precession

Beam field strengths

Spin vector

$$\frac{ds}{dt} = -\left[(a+\gamma^{-1})(\boldsymbol{B} - \boldsymbol{v}\times\boldsymbol{E}) - \boldsymbol{v}\frac{a\gamma}{\gamma+1}\boldsymbol{v}\cdot\boldsymbol{B}\right]\times \boldsymbol{s}$$

Anomalous magnetic moment in external field

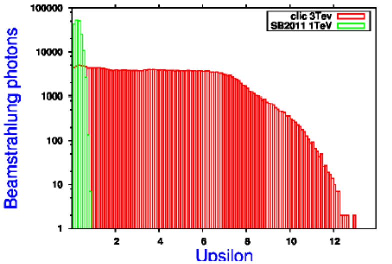
Spin-flip process

Constant crossed field – Airy functions

Spin vector

$$W(\Upsilon,\xi) = \frac{\alpha m_e^2}{\pi\epsilon}\int_0^\infty \frac{du}{(1+u)^3}\left[\frac{e}{m^3}F^{*\mu\nu}p_\mu s_\nu \frac{z\mathrm{Ai}(z)}{1+u} - \mathrm{Ai}_1(z) - \frac{2+2u+u^2}{z\,(1+u)}\mathrm{Ai}'(z)\right]$$

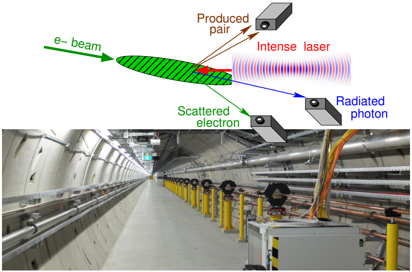
beam field tensor

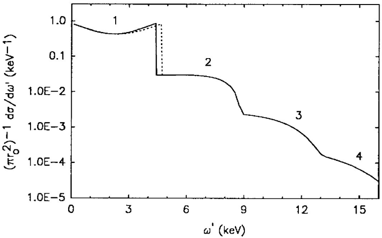


Parameter	ILC 1TeV	CLIC 3 TeV
$\mathcal{L}(\times 10^{34})$	4	3.6
N(incoh)	3.9e5	3.8e5
N(coh)	0	6.8e8
Υ (ave)	0.27	3.34
Υ (max)	0.94	10.9
δE_{bs}	10%	28%
$\langle\text{depol}\rangle_{\text{LW}}$	0.62%	3.5%

- **Precision physics programs requires $\triangle$ LW depolarisation $\leq 0.1\%$**
- **What is the theoretical uncertainty in the LW depolarisation?**

LUXE strong field physics - dimensionless parameters





$\xi (= a_0) = \frac{e|\vec{A}|}{m}$ **intensity parameter**

ξ appears as a mass shift,

$m_* \to m\sqrt{1+\xi}$

$\xi = 3.7 \times 10^{-19} I$ [W/cm^2] λ [micron]

$\xi \approx 1$ reached with a $\sim$1J, focused optical laser pulse

$\chi, \Upsilon = \xi \frac{k \cdot p}{m^2}$ **recoil parameter**

coupling constant conjecture: $\alpha\chi^{2/3}$

$\chi, \Upsilon \approx 1$ Schwinger field in rest frame

Experiment	$\lambda (nm)$	E_{laser} (J)	focus (μm^2)	pulse (fs)	E_{e^-} (GeV)	ξ	χ
SLAC E144	527/1053	2	50	1880	46.6	0.66	2.7
LUXE Phase0	800	0.35	100	35	17.5	1.54	0.29
LUXE Phase1	800	7	100	35	17.5	6.9	1.29
FACET II	800	0.7	64	35	10	2.3	0.29
ELI-NP	1053	2.2	100	22	0.750	6.4	0.04
AWAKE	800	3	64	20	50	7.45	4.0

Furry Picture - a non perturbative, semi classical QFT

- Separate gauge field into external A_μ^{ext} and quantum A_μ parts. Shift A_μ^{ext} into Dirac Lagrangian

$$\mathcal{L}_{\text{QED}}^{\text{Int}} = \bar{\psi}(i\partial\!\!\!/ - m)\psi - \frac{1}{4}(F_{\mu\nu})^2 - e\bar{\psi}(A\!\!\!/^{\text{ext}} + A\!\!\!/)\,\psi$$

$$\mathcal{L}_{\text{QED}}^{\text{FP}} = \bar{\psi}^{\text{FP}}(i\partial\!\!\!/ - eA\!\!\!/^{\text{ext}} - m)\psi^{\text{FP}} - \frac{1}{4}(F_{\mu\nu})^2 - e\bar{\psi}^{\text{FP}}\,A\!\!\!/\,\psi^{\text{FP}}$$

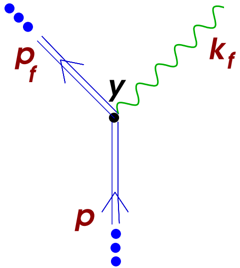
- Lagrangian satisfies Euler-Lagrange equation $\rightarrow$ new equation of motion for the non-pertubative (bound) Dirac field (w.r.t. A^{ext}). New solutions ψ^{FP}

$$(i\partial\!\!\!/ - eA\!\!\!/^{\text{ext}} - m)\psi^{\text{FP}} = 0$$

- For certain classes of external fields (plane waves, Coloumb fields and combinations) exact solutions exist **[Volkov Z Physik 94 250 (1935), Bagrov and Gitman,** *Exact solutions of relativistic wave equations* **(1990)]**

$$\psi^{\text{FP}} = \mathbf{E}_p\, e^{-ipx}\, u_p, \quad \mathbf{E}_p = \exp\left[-\frac{1}{2(k\cdot p)}\left(eA\!\!\!/^{\text{ext}}k\!\!\!/ + i2e(A^e\cdot p) - ie^2 A^{\text{ext}\,2}\right)\right]$$

Dressed Furry Picture (FP) vertices



- Double fermion lines are Volkov-type solutions
- Volkov E_p functions "dress" the vertex

$$\gamma_\mu^{\mathsf{FP}} = \int d^4x\, \overline{\mathbf{E}_f}(x)\gamma_\mu \mathbf{E}_p(x)\, e^{i(p_f - p + k_f)\cdot x}$$

- Momentum space vertex has contribution nk from external field

$$\gamma_\mu^{\mathsf{FP}}(x) = \sum_{n=-\infty}^{\infty} \int_{-\pi L}^{\pi L} \frac{d\phi}{2\pi L} \exp\left(i\frac{n}{L}[\phi - (kx)]\right) \gamma_\mu^{\mathsf{FP}}(\phi)$$

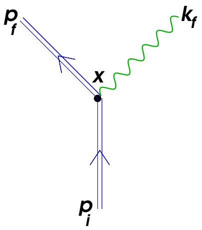
- Fourier transform of circularly polarised field leads to Bessel functions

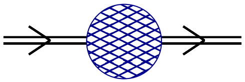
$$\int_{-\pi}^{\pi} \frac{d\phi_v}{2\pi} \exp\left[ir\phi_v - z\sin\phi_v\right] = \mathrm{J}_r(z)$$

- Transition probabilities built from FP Feynman diagrams/dressed vertices

$$M_{\mathsf{fi}}^{\mathsf{HICS}} = \int \mathrm{d}^4x\ \bar{u}_{\mathsf{fr}}\, \gamma^{\mathsf{FP}}\, u_{\mathsf{is}}\, e^{-i(p_f + k_f - k_i)}, \quad W = \int \frac{\mathrm{d}\vec{p}_{\mathsf{f}}}{2\epsilon_{\mathsf{f}}} \frac{\mathrm{d}\vec{k}_{\mathsf{f}}}{\omega_{\mathsf{f}}} \left| M_{\mathsf{fi}}^{\mathsf{HICS}} \right|^2$$

Unstable Strong field particles & resonant transitions





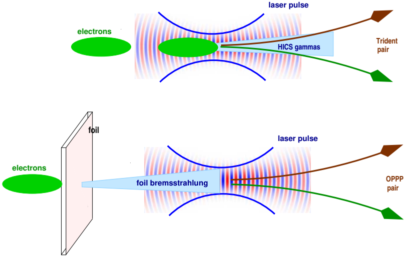
- **Electrons decay in strong field Furry picture**
  - Background field renders vacuum a dispersive medium
  - new effects: Lamb shift, vacuum birefringence, resonant transitions
  - electron has a finite lifetime, Γ and probability of radiation, W
- **Resonant transitions in propagator**
  - required by S-matrix analyticity
  - Optical theorem $W = \text{Im}(\Sigma)$
  - extra propagator poles leading to physically accessible resonances
  - related to energy level structure of vacuum

Similar decay (one photon pair production) and lifetime for photons

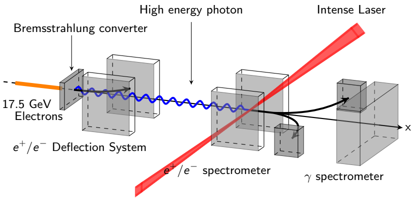
Isolating the main processes at LUXE

- Three main processes at LUXE - HICS gamma production, One photon pair production (OPPP), Trident process (HICS gammas + strong field) pair production
- There are compelling reasons to study the three processes separately
- HICS shows mass shift - strong field leads to increase in electron rest mass
- Trident leads to rare resonance processes, related to dispersive vacuum
- OPPP pair production at ultra high intensity - non-perturbative physics
- PROBLEM: Trident process pair production limited by laser intensity (suppressed already at $\xi \sim 3$)
- SOLUTION: Use foil to convert electrons to gammas upsteam of the strong field IP with high intensity laser further upstream

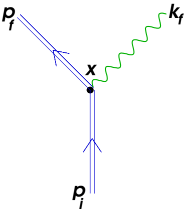
Strong field IPs



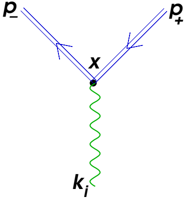
Strong field + foil, experimental setup



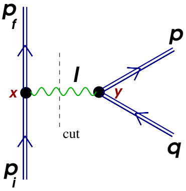
Tour of LUXE processes



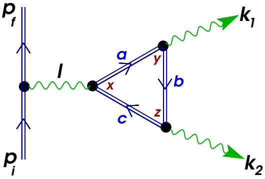
High intensity Compton scatttering (HICS)



One photon pair production (OPPP)



Trident process (one step and two step)

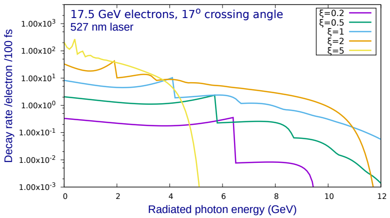


Photon splitting (vacuum birefringence)

HICS - High Intensity Compton scattering

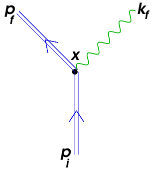
- Created inidicative parameter sets with different laser intensity
- Increasing ξ increases the HICS rate, but suppresses the photon energy (the mass shift)
- Optimise ξ - need energetic enough photons for pair production, trade off between photon rate and photon energy
- The energy of the radiated photons also dependent on initial electron energy
- HICS vanishes as field disappears
  the electron becomes stable again

HICS for 17 GeV electrons, intensity sweep



$$\Gamma_{\text{HICS}} = -\frac{\alpha m^2}{\epsilon_{\text{i}}} \sum_{n=1}^{\infty} \int_0^{u_n} \frac{du}{(1+u)^2} \left[\mathrm{J}_n^2(z_u) - \frac{\xi^2}{4} \frac{1+(1+u)^2}{1+u} \left(\mathrm{J}_{n+1}^2 + \mathrm{J}_{n-1}^2 - 2\,\mathrm{J}_n^2 \right) \right]$$

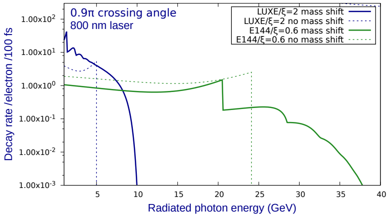
$$z_{\text{u}} \equiv \frac{m^2 \xi \sqrt{1+\xi^2}}{k \cdot p_i} [u(u_n - u)]^{1/2}, \quad u_n \equiv \frac{2(k.p_i)\,n}{m^2(1+\xi^2)}, \quad \xi \equiv \frac{e|A|}{m}$$



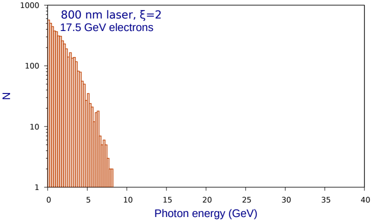
HICS - effective rest mass shift (SQED effect)

- Decay rate proportional to
$$\sum_n \delta^{(4)}\left[p_i + k\frac{\xi^3}{2\chi_i} + nk - p_f - k\frac{\xi^3}{2\chi_f} - k_f\right]$$
- Momentum conservation is a sum over external field photon contributions, nk
- Even for $n=0$ there is an irreducible contribution
$$p_i + k\frac{\xi^3}{2\chi_i} \rightarrow p_i^2 = m^2(1+\xi^2)$$
- Manifests in Compton edge shift
$$\frac{\omega_f}{\epsilon_i - \omega_f} \leq \frac{2nk\cdot p_i}{m^2(1+\xi^2)} \quad \text{c.f.} \quad \frac{2nk\cdot p_i}{m^2}$$
- Significant part of electron energy taken up by electron motion in the field/dispersive vacuum. Less energy available for radiated photon
- Edge shift in comparison to normal Compton scattering
- Real bunch collision smears the edge - recover with cuts?
- Edge easier to see at modest ξ
A LUXE phase 0 precision test?

HICS with mass shift for LUXE and E144



IPstrong monte-carlo, HICS for LUXE/ξ2



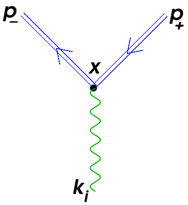
OPPP - one photon pair production

- Assuming that the initial state photon energy is known..
- The produced positron spectra is smooth, maximum at about half the photon energy
- Total OPPP rate is much better with higher laser intensity (and higher photon energy)
  - Pair must be created with the mass shift

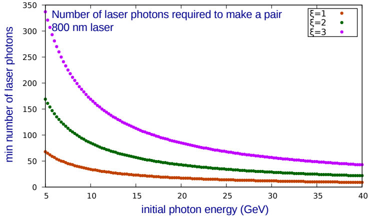
$$n \geq \frac{m^2(1+\xi^2)}{k \cdot k_{\mathrm{i}}}$$

...so another way to detect mass shift?

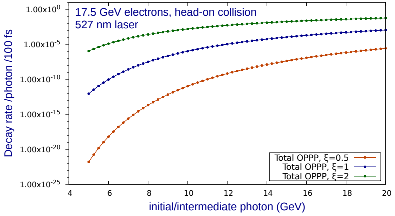
One photon pair production



Minimum laser photons needed for OPPP

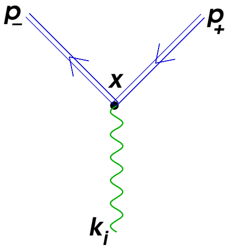


Total OPPP rate for LUXE with different ξ

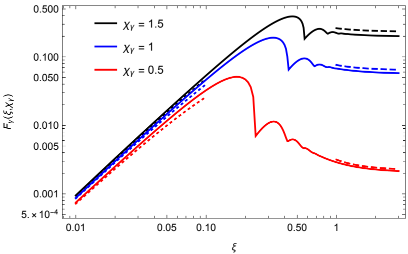


OPPP and Schwinger critical field measurement

One photon pair production (OPPP)



OPPP rate, non perturbative regime



OPPP Rate at constant χ reaches non perturbative asymptote for $\xi \geq 1$

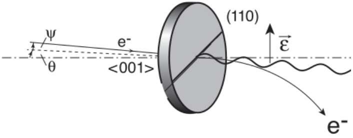
$$\Gamma_{\text{OPPP}} = \frac{\alpha m^2}{2\omega_{\text{i}}} \sum_{s>s_0}^{\infty} \int_1^{v_s} \frac{dv}{v\sqrt{v(v-1)}} \left[\mathrm{J}_s^2 + \frac{\xi^2}{2}(2v-1)\left(\mathrm{J}_{s+1}^2 + \mathrm{J}_{s-1}^2 - 2\,\mathrm{J}_s^2\right) \right] \propto \frac{\alpha m^2}{2\omega_{\text{i}}} \frac{E}{E_c} \exp\left[-\frac{8mE_c}{3\omega_i E} \right]$$

Theory: $E_c = \dfrac{m^2}{e}$. Experiment: $E_c =$ .... It can now be measured in the lab

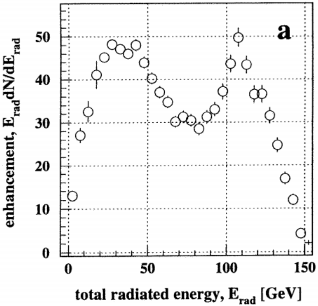
Polarized bremsstrahlung photons

- We plan to use a foil to produce high energy photons
- As well as a foil (amorphous structure), use oriented crystal (Si, Ge, Diamond)
- Energetic, linearly polarised photons produced by unpolarised electrons
- Coherent bremsstrahlung, resonance from lattice planes in phase with photon energy
- Order of magnitude enhancement of photon rate
- Crystal oriented so that electron path is 5 mrad from (001) axis and 70 μrad from (110), 150 GeV e- [CERN-SPSC98-17]
- 10-60% polarisation possible
- OPPP is polarisation dependent
- Schwinger field polarisation dependent?

Polarised bremsstrahlung from oriented crystal



Enhancement of bremsstrahlung

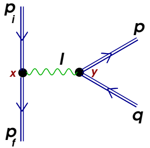


Trident process and its resonant spectrum

- **One step trident** has a virtual photon propagating through a dispersive vacuum.
- Additional propagator poles due to contributions from the strong field, $\sum_n (\mathbf{nk})$
- Including lifetime of the unstable state produces quasi-particle resonances
- Resonances manifest as peaks in the positron spectrum

$$M_{fi}^{\text{Trid}} = \sum_{rn} \int \frac{\text{d}^4 l}{(2\pi)^4} \gamma_{pq}^{\text{FP}} \frac{g_{\mu\nu}}{l^2 + i\Gamma} \gamma_{fi}^{\text{FP}} \, \delta(p_\text{f} + l - p_\text{i} + rk) \delta(p + q - l + nk)$$

pole condition: $(p_\text{i} + q_\text{i} + nk)^2 = m^2$



- Resonance conditions in centre of mass frame:

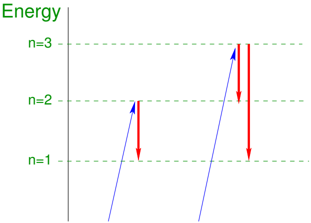
$$n = \frac{\epsilon_q}{\omega} = \frac{\text{positron energy}}{\text{laser photon energy}}$$

- Narrow resonance width:

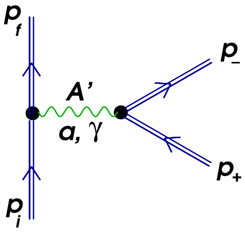
$\Gamma \propto \Im \Pi_{\mu\nu} \propto \Gamma_{\text{OPPP}}$, by the Optical theorem

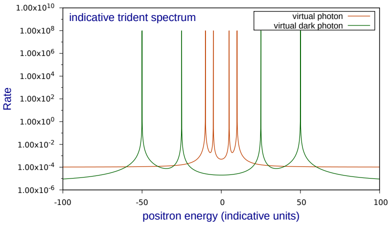
- Resonance height (narrow width approximation):

$|M_{\text{trident}}|^2 \approx |M_{\text{HICS}}|^2$ at resonance



Resonant dark photon trident spectrum



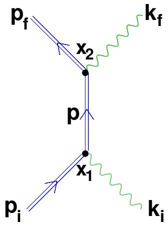


$$\mathcal{L} = g' e \bar{\psi} \gamma \psi A'$$

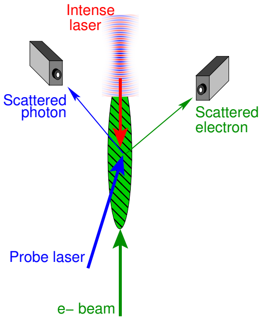
$$\mathcal{L} = \frac{1}{f_a} \bar{\psi} \gamma \gamma^5 \psi \partial_\mu a$$

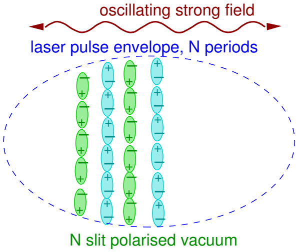
- Dark (massive) photon: BSM mechanisms to explain dark matter
- The trident process may proceed via a virtual **Dark** photon
- Given that resonant trident spectra exist (and are detectable), then...
- Resonances shift, depending on the mass of the virtual particle
- Given that these resonances are narrow this maybe a fine discriminator of the dark photon mass
- Full calculations are in progress

Stimulated Compton scattering (SCS)



- Make a virtual non perturbative electron propagator with a probe laser
- Virtual electron sees a periodically dispersive vacuum. Momentum matched probe photon $\rightarrow$ resonant transitions
- Resonances related to strong laser intensity, scattering angles, initial photon energy
- Scanning probe photon angles, energies $\rightarrow$ resonance scans



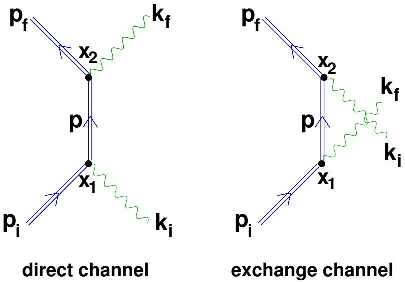


SCS transition probability calculation sketch

$$M_{fi} = ie\int d^4p\ d^4x_1\ d^4x_2\ \bar{u}_{p_f}\left[\gamma^{\mathsf{FP}\mu}\ \frac{\not{p}+m}{p^2-m^2}\gamma^{\mathsf{FP}}_{\mu} + \text{x.c.}\right] u_{p_i}$$

$$\to -e^2\sum_{rs}\ \bar{u}_{p_f}\left[\gamma^{\mathsf{FP}\mu}\ \frac{\not{p}_r+m}{p_r^2-m^2}\ \gamma^{\mathsf{FP}}_{\mu} + \text{x.c.}\right] u_{p_i}\ \delta^4[q_f+k_f+(r-s)k-q_i-k_i],\ \ q_r = q_i+k_i+rk$$

- Spin/polarisation sums can be performed as normal to produced usual projection opers
- two dressed vertices γ^{FP} lead to an internal sum r and overall contribution $l=r-s$
- product of delta functions reduces 4 summations to 2 internal $(r,\bar{r})$ and 1 overall (l)
- all terms in $|M_{fi}|^2$ have coproducts of 4 Bessel functions



$$\frac{|M_{fi}|^2}{VT} = -e^2\sum_{r\bar{r}l}\int \mathrm{Tr}\left[\frac{..r..\bar{r}..}{(q_r^2\text{-}m_*^2)(q_{\bar{r}}^2\text{-}m_*^2)}\right]\ \frac{d\mathbf{k_f}\ d\mathbf{q_f}}{4\omega_f\epsilon_{q_f}}\delta(q_f+k_f+lk-q_i-k_i)$$

SCS propagator poles at tree level

Poles have a complicated structure due to infinite summation over r

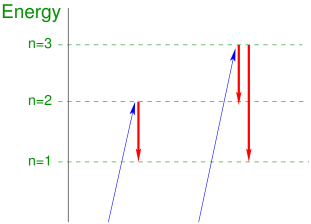
$$(q_\mathrm{i} + k_\mathrm{i} + r k)^2 = m^2(1+\xi^2) \qquad \text{SCS direct channel}$$
$$(q_\mathrm{i} - k_\mathrm{f} + \bar{r} k)^2 = m^2(1+\xi^2) \qquad \text{SCS exchange channel}$$

- Resonance conditions:

$$\frac{\omega_i}{\omega} = r\,\frac{1+\beta+\omega(1-\cos\theta_i)/\gamma}{1+\beta\cos\theta_i+\xi^2(1-\cos\theta_i)/2\gamma^2(1+\beta)}$$

$r = 0 \implies \omega_i = 0$ "normal" IR divergence

- interpretation in terms of Zeldovich energy levels
- The IR divergence is the base energy level



1. Calculate the width of the energy levels (avoids poles)
2. Include other processes with same pole structure

We need to calculate Furry Picture loop diagrams

Resonance width via self energy insertion

The electron decays in dispersive vacuum with resonance width Γ

$$G^{\text{FP}}_{\text{y,x}} = \int \frac{\mathrm{d}^4 p}{(2\pi)^2}\; E_{\text{py}} \frac{\not{p} + m}{p^2 - m^2 - i\Gamma}\, \bar{E}_{\text{px}}$$

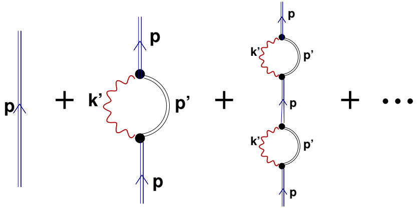
Γ is sum of 1PI diagrams, self energy to leading order

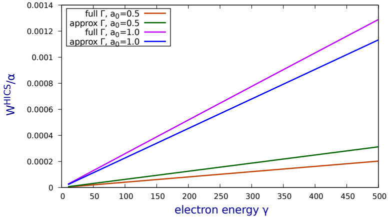
$$\Gamma = \Im \Sigma^{\text{FP}}(p) + \ldots$$

Approximate value for Γ available (Becker, Mitter 1976)

$$\Gamma \approx 0.29\, \alpha\, \rho\, a_0^{1.86}, \qquad \rho = 2k \cdot p$$

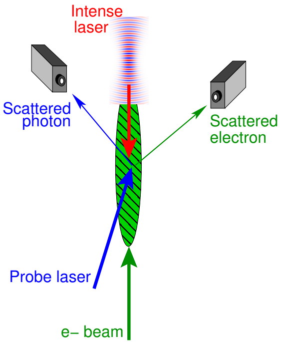
$$\Gamma \equiv \Im \Sigma^{\text{FP}}_{\text{p}} \equiv W^{\text{HICS}} \quad \text{(optical theorem)}$$





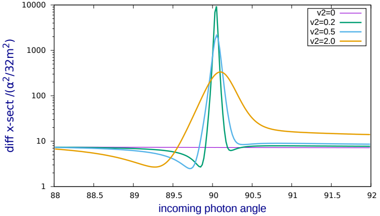
$$W^{\text{HICS}} = \frac{\alpha}{2} \sum_{n=1}^{\infty} \int_0^{u_n} \frac{du}{(1+u)^2} \left[\frac{4}{\xi}\, \mathrm{J}_n^2 - \frac{2 + 2u + u^2}{(1+u)} \left(\mathrm{J}_{n-1}^2 + \mathrm{J}_{n+1}^2 - 2\, \mathrm{J}_n^2 \right) \right]$$

SCS resonances in probe laser angle scan

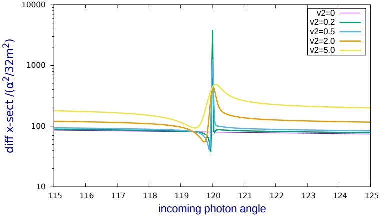


- key ratio for resonance is $\frac{\omega_i}{\omega} \in \mathbb{Z}$
- resonances broadened by larger strong laser intensity, $\xi \; (\nu^2)$
- resonances suppressed by large electron energy

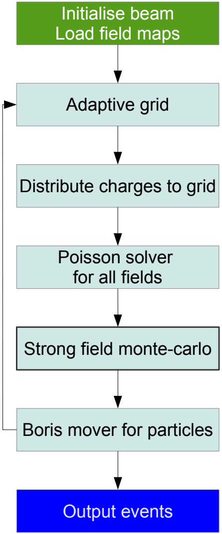
Probe laser 2 eV, intense laser 1 eV
electrons 10 MeV, detector at 160^o

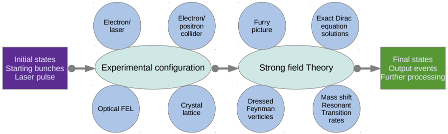


Probe laser 4 eV, intense laser 1 eV
electrons 40 MeV, detector at 175^o



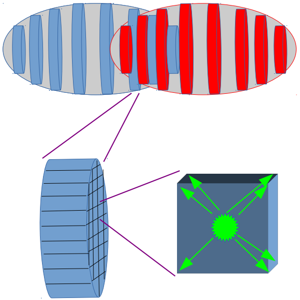
IPstrong - SQED monte carlo PIC simulation code

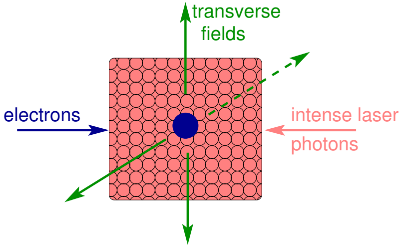




- Furry picture SQED interactions, via monte carlo, embedded in a 3D PIC electromagnetic solver
- e-/laser, e+e-, higher order interactions, optical FEL, crystal lattices
- Internally generated or externally loaded bunches
- Fortran 2003 with openMPI (Fortran 2008/GPU)
- 3D poisson solver (PSPFFT, MPI)
- Currently contains - HICS, OPPP, BPPP, 2 step trident, circularly polarised lasers
- Coming soon - resonant trident, Compton scattering, linear pol, constant crossed fields

Charge bunch/laser/undulator interaction





- Interacting bunches divided into overlapping transverse slices
- Slices divided into voxels
- Charges within each voxel distributed to voxel vertices

Solve for the potential $\Phi(x)$ from the charge density $S(x)$ via FFTW

$$\nabla^2\Phi(x) = S(x)$$

- Get the field strength at each macroparticle
- longitudinal electrons & photons
- transverse electric/magnetic fields
- ponderomotive force at cell edges
- electron momentum & position via leapfrog method
- Lorentz invariant particle pusher

Modelling the strong field - IPW,LCFA,Envelope

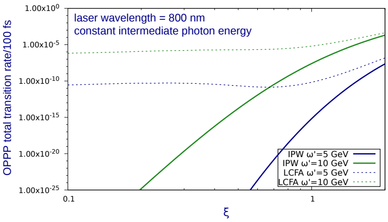
- LUXE strong laser - 800 nm, 35 fs gaussian pulse, linearly or circularly polarised, 10 micron spot, $0.1 < \xi < 5$
- Full SQED calculations in a pulse can be challenging, so approximations are attractive
- Locally constant field approx (LCFA) assumes $\xi \gg 1$. Not appropriate for LUXE
- Finite pulse smears out momentum transfer

  Prob $=$ sinc$N\pi\,(I - F + nk)\,M(I, F, nk)$

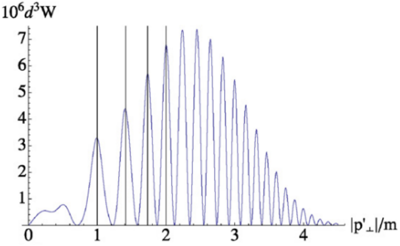
  N is the number of wavelengths in the pulse

  LUXE has $N \approx 12$: well described by delta comb (discrete external field photons)
- So infinite plane wave (IPW) is suitable. Well understood Volkov solutions can be employed
- The **transverse** pulse shape will be flat top. To the extent it is not, leading order behavious is local ξ value
- So, in (my) simulation the local intensity of the laser pulse, voxel by voxel, is used as the amplitude of the IPW calculation

LCFA approximation in OPPP



Momentum transfer in a laser pulse



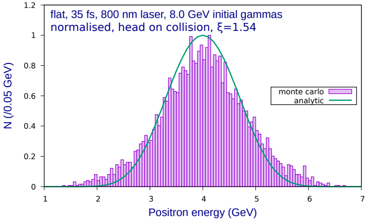
IPstrong, one photon pair prod (OPPP) monte-carlo

- IPstrong tabulates and interpolates total rate. Calculates decay energies, angles on the fly

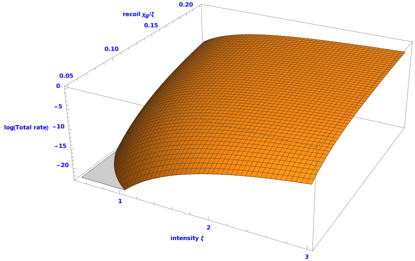
$$\Gamma_{\mathrm{OPPP}}=\frac{\alpha m^2}{2\omega_{\mathrm{i}}}\sum_{s>s_0}^{\infty}\int_1^{v_s}\frac{\mathrm{d}v}{v\sqrt{v(v\text{-}1)}}\ldots,\quad v=\frac{(k\cdot k_i)^2}{4k\cdot qk\cdot p}$$

- $v=1$ corresponds to $\epsilon_q,\epsilon_p=\omega_i/2$
- Differential rate sharply peaked at v=1. Not good for monte carlo
- So change $\frac{\mathrm{d}v}{v\sqrt{v(v\text{-}1)}}\to\frac{\mathrm{d}k\cdot q}{k\cdot k_i/4}$
- **Validation:** interact flat laser pulse (with ramps) with 8 GeV gammas (HICS artificially turned off)
- Fine gridding for OPPP total rate lookup table ($<1\%$ variation between looked up and true rate)

OPPP positron spectrum

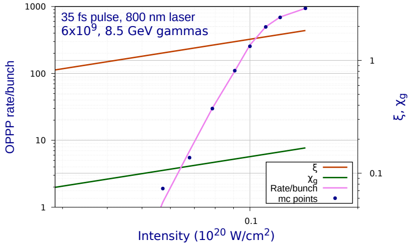


OPPP total rate rate



Ongoing SQED preparation

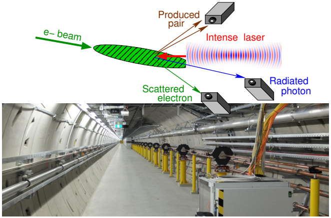
- **Further IPstrong validation**

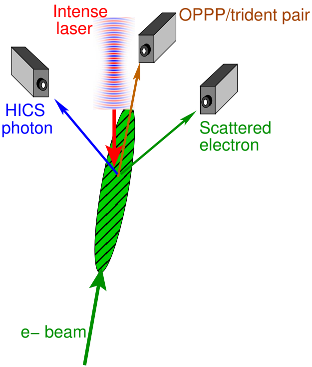


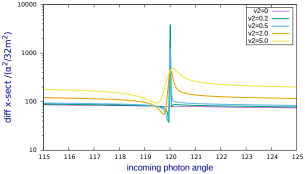
- **Monte carlo datasets**
  - initial and final states of beam as well as stdhep events
  - BPPP : 5m and 12m foil to IP
  - HICS + OPPP : gaussian pulse, 17.2^o crossing angle
  - Ideal, flat laser pulses, head on collisions

/afs/desy.de/user/h/hartin/public/IPstrong

- **Papers**
  - ”Strong field QED in lepton colliders and electron/laser interactions”
    A. Hartin
    IJMPA **33**, no. 13, 1830011 (2018), arXiv:1804.02934
  - ”Measuring the boiling point of the vacuum of quantum electrodynamics”
    A. Hartin, A. Ringwald and N. Tapia.
    PRD **99**, No. 3, 036008 (2019), arXiv:1807.10670, DESY-18-128







- Quantum vacuum polarises in a strong electromagnetic field $\rightarrow$ new physical features
- QFT with background field predicts multiphoton events, mass shift, resonant cross-sections, electron/photon decays
- Experimental facilities can already perform tests of the theory
- First signature experiment at SLAC 20 years ago, new experiments being planned
- **Discover new quantum effects and perform new tests of QFT in background fields**
- **New types of BSM searches can be designed utilising strong field QFT phenomena**
- **Theory development - divergence handling/renormalisation in Furry picture, unstable vacuum, analogy with QFT in curved space-time**