Possible strong field particle physics experiments at XFEL

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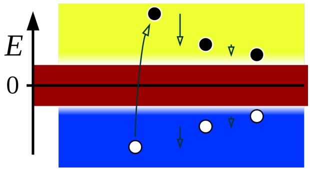
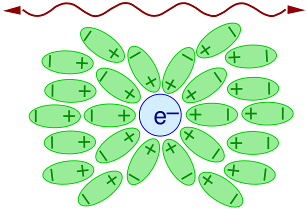
Motivation - physics in strong background fields



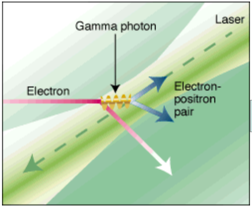
Vacuum polarisation



Bare/Dressed charge

- Heisenberg uncertainty, Casimir force - virtual particles are real!
- Strong background field polarises the vacuum
- The screening charge is rearranged, leading to possibly large effects even at modest field strengths
- At Schwinger critical field strength, vacuum decays into real pairs
- New phenomenology results - odd vertex diagrams, resonant propagators, different manifestations of IR divergences
- Careful studies will allow planned experiments that test strong field theory
- Need to investigate experimental signatures within reach using today's and upcoming technology

How to make a strong field QFT (IFQFT)



Lagrangian of interacting fields (background,Dirac,Maxwell)

Euler-Lagrange equations

Field equations of motion (Dirac+background)

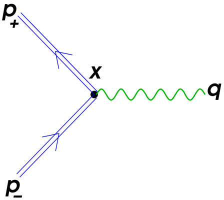
Wavefunction solutions

Quanitsed particles

Matrix Element

Final state integration

Transition Probability



Furry Picture

Furry Picture

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

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

Equations of Motion

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

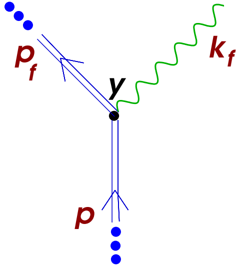
Wavefunction

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

Propagator

$$G^{\text{FP}} = \int \frac{\mathrm{d}^4 p}{(2\pi)^4}\,\mathbf{E}_p(x)\,\frac{p\!\!\!/ + m}{p^2 - m^2}\,\bar{\mathbf{E}}_p(x')\,e^{-ip\cdot x}\,u_p$$

Dressed Furry Picture (FP) vertices



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

$$\gamma_\mu^{\text{FP}} = \int d^4x\, \bar{E}_{p_f}(x)\gamma_\mu E_p(x)\, e^{i(p_f - p + k_f)\cdot x}$$

- Momentum space vertex has contribution nk from external field

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

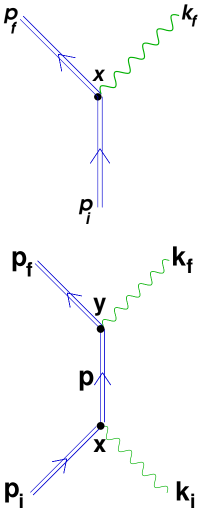
- Fourier transform of circularly polarised field leads to Bessel functions

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

- Transition probabilities built from FP Feynman diagrams/dressed vertices

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

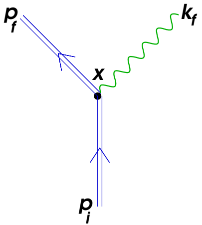
1st and 2nd order Furry picture processes

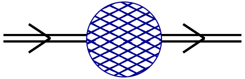


- **1st order intense field process:**
  - High Intensity Compton Scattering (HICS)
  - $p_i + nk \to p_f + k_f$
  - intense laser field included to all orders
  - final state photons can become initial states of second order processes
- **2nd order intense field processes:**
  - Stimulated Compton Scattering (SCS)
  - $p_i + k_i + nk \to p_f + k_f$
  - extra propagator poles leading to physically accessible resonances
  - related to energy level structure of vacuum

- **ALL** processes are in effect ”strong field” processes

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

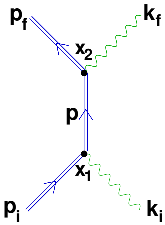
Resonant Compton Scattering

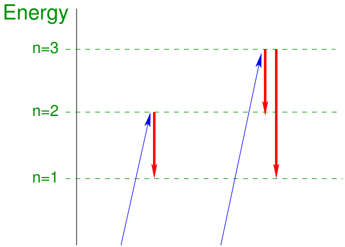
2nd order strong field QFT process

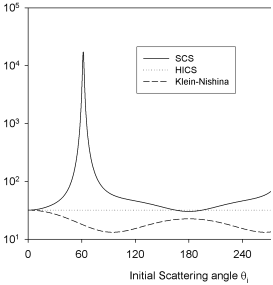
Resonant transitions between quasi energy levels in 2nd order processes

$$(q + nk)^2 = m_*^2$$

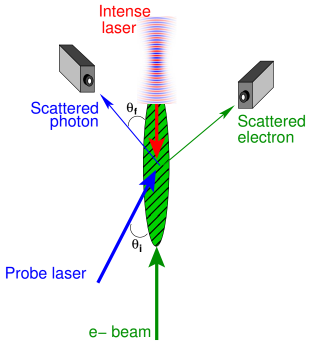
q = effective electron momentum
n = nth energy level
m_* = effective electron mass
k = LASER 4-momentum

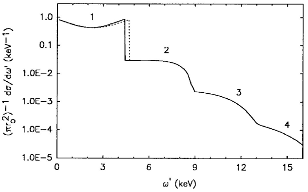






Strong field physics - dimensionless parameters





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

a_0 appears as a mass shift, $m_* \to m\sqrt{1+a_0^2}$

$a_0 = 3.7 \times 10^{-19} I$ [W/cm^2] λ [micron]

$$\chi = 2a_0 \frac{k \cdot p}{m^2}$$ **recoil parameter**

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

$$\Upsilon = \frac{\gamma E}{E_{\text{crit}}}$$ **strong field parameter**

field strength seen by particle:
$E_{\text{crit}} = 1.32 \times 10^{18}$ V/m

$$Q_n \approx \frac{\omega_i}{\omega}(1 - \cos\theta_i)$$ **resonance parameter**

Resonant cross-sections as $Q_n = 1, 2, 3...$

Bound states of electron in intense laser

Probe laser tunes the resonance

strong field regime, $a_0, \Upsilon, \chi \geq 0.1$

Strong field QED historical timeline

1935 Dirac equation in external field (Volkov solution)

1950 Lamb shift (vacuum polarisation)
AMM, spontaneous pair prod (Schwinger)
Furry picture (strong field QED)

1960 1st order FP theory (mass shift, multiphoton)

2nd order FP theory (resonant transitions)

1970 AMM/Lamb shift in strong field

1990 Exp: 1st order FP experiment (SLAC E144)

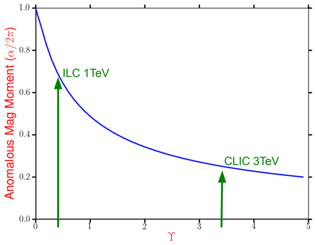
Exp: AMM/Lamb shift in strong field

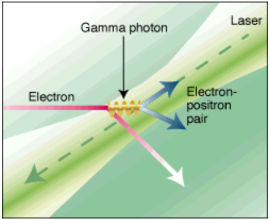
2010 Theory: Simple FP tran prob, FP renormalisation

Exp: 2nd order FP experiment (proposed)

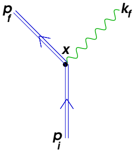
2 Year DESY/Uni-HH Seed project funding for experimental proposal, 2016-2017

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



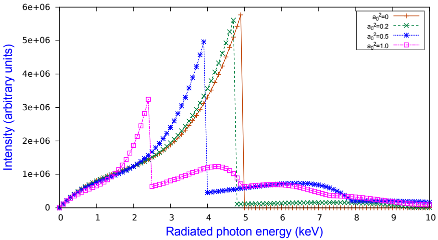


1st order FP - Radiated x-ray photons



$$\frac{dW}{\Delta t} = \frac{r_e m^2 \rho_\omega}{\omega \epsilon_i} \sum_{n=1}^{\infty} \int_0^{u_n} \frac{du}{(1+u)^2} \left[\frac{4}{a_0^2} J_n^2 - \frac{2+2u+u^2}{(1+u)} \left(J_{n-1}^2 + J_{n+1}^2 - 2 J_n^2 \right) \right]$$

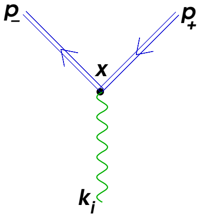
$$u_n = \frac{2n\, k \cdot p}{m^2(1+a_0^2)} \quad \text{and Bessel fn arguments } z = \frac{2\, n\, a_0}{\sqrt{1+a_0^2}} \sqrt{\frac{u}{u_n}\left(1 - \frac{u}{u_n}\right)}$$



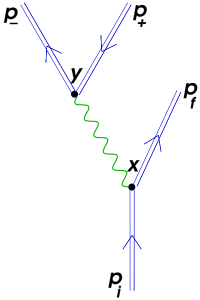
- dW probability in a time slice Δt
- sum over n describes harmonic generation
- momentum conservation $q_i + nk = q_f + k_f$
- radiated photon, ω_f

$$\omega_f = \omega \frac{n\gamma^2(1+\beta)^2}{\gamma^2(1+\beta)(1-\beta\cos\theta) + (a_0^2/2 + n\omega\gamma(1+\beta))(1+\cos\theta)}$$

OPPP and Trident processes



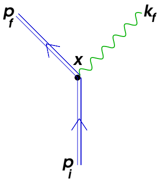
- **One photon pair production:**
  - initial state produced by photon radiation
  - Onset is $\frac{4n\omega\omega_i}{m^2} \geq 2m_*^2$
  - $k_i + \color{red}{nk} \rightarrow p_+ + p_-$
  - Observed with 46.6 GeV primary electrons at SLAC E144 (30 Gev photon, $n \geq 4$)

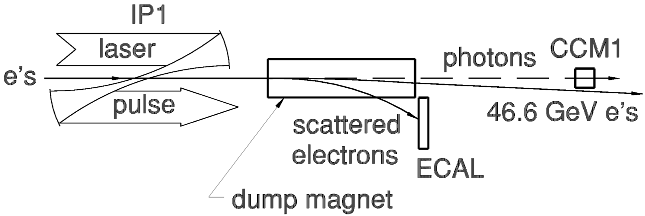


- **Trident process:**
  - One step rather than two step process
  - $p_i + \color{red}{nk} \rightarrow p_f + p_+ + p_-$
  - Resonant propagator poles/Breit-Wigner resonances due to bound states
  - Nominally suppressed by 1 order of α
  - Resonant differential x-section can exceed that of 1st order process

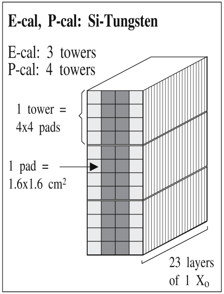
SLAC E144 electron/strong laser experiment, 1990s

[*Bamber et al, PRD 60 092004, 1999*]

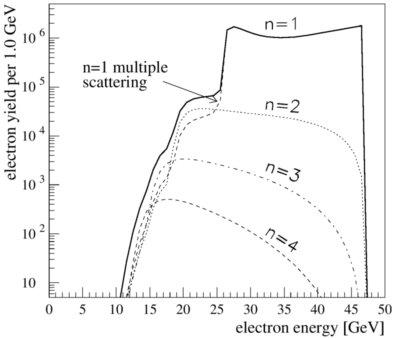


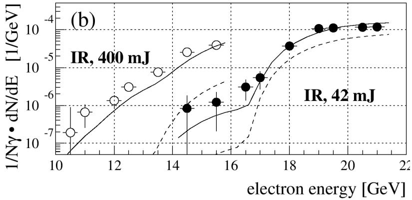


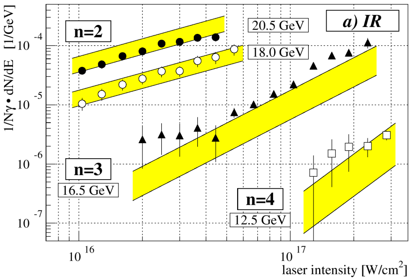
- 46.6 GeV e- beam collides with focussed ND:YAG laser at $\theta = 17^o$
- measurements made of pulse width, spot size and laser energy to get Intensity $\approx 10^{18}$ W/cm^2
- electrons with $E \lesssim 30$ GeV detected by Si-Tungsten ECAL, $\frac{\sigma}{E} \approx \frac{0.25}{\sqrt{E\text{(GeV)}}}$
- photons converted in 0.2 X_0 Al and detected in gas Cherenkov, $\Delta N_\gamma = 10\%$



SLAC E144 results



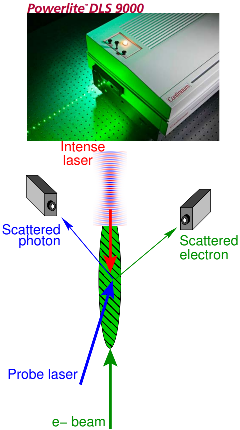




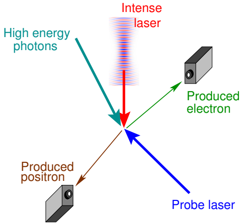
- Compton edge shifted by multiphoton effects
- Multiple Compton scattering vs nonlinear Compton scattering
- n=1 edge should also be mass shifted $m \to \sqrt{m^2 + e^2a^2}$
- yellow band - uncertainty in I, N_γ

Experimental detection today (XFEL dump line)

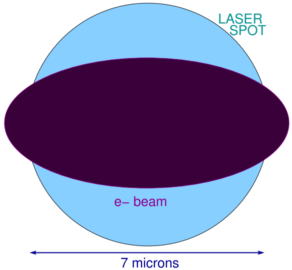
Experiment	$\lambda(\mu m)$	E_{laser}	focus	pulse	I(W/cm^2)	E_{e-} (GeV)	a_0^2
1990s E144 (SLAC)	1	2 J	60 μm^2	1.5 ps	$\approx 10^{18}$	46.6	0.4
2010s (PL 9000)	1	3 J	40 μm^2	0.5 ps	6.75×10^{18}	18	2.7



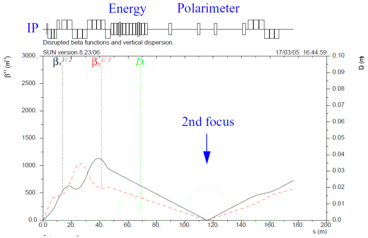
- Strong field mass shift still to be detected
- 2nd order resonant strong field effects should be in reach
- Electrons dont necessarily have to be ultra-relativistic
- Resonant pair production, with probe and gammas



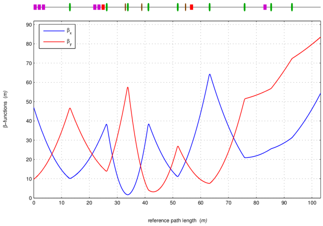
Potential location in the extraction line



- Need overlap of laser and e-beam - spot and Rayleigh length
- ILC had a second focus in downstream polarimeter chicane
- minimize backgrounds - situation of ECAL, PCAL, GCAL



ILC extraction line



XFEL extraction line

Beam parameters for 1st order processes

Parameter	Configuration		
	Nonlinear Compton	Beamstrahlung	$\gamma + \omega \to e^+e^-$
N_e	10^9	10^9	10^{10}
σ_x, σ_y (μm)	2000	20	100
$\sigma_{x'}, \sigma_{y'}$ (rad)	10^{-6}	10^{-4}	10^{-5}
σ_z (μm)	500	500	500
λ_L (nm)	1054	351	351
Δt_L (ps)	1.2	1.2	1.2
U_L (Joule)	0.16	0.4	0.4 (at IP1) 0.4 (at IP2)
f/D	3	3	100 (at IP1) 3 (at IP2)

E144 parameters

XFEL parameters

$E_{\text{beam}} = 17.5 \pm 0.001$ GeV

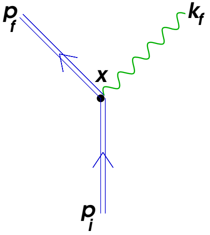
Bunch Charge = 1 nC (6×10^9)

Norm emittance = 1.4 mm mrad

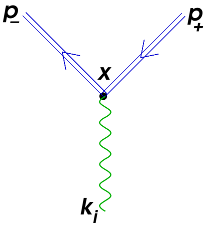
$N_{\text{bunchs}} = 3250$

$\sigma_{x,y} = 35\ \mu$m

$\sigma_z = 20\ \mu$m

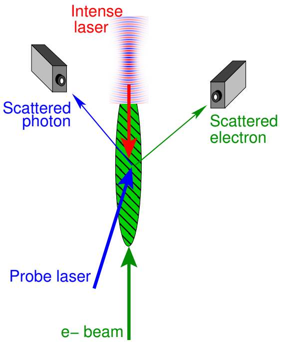


1 vertex photon radiation



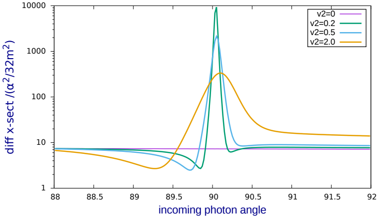
1 photon pair production

Resonances in probe laser angle scan

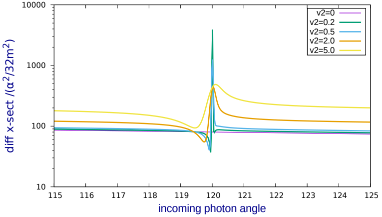


- key ratio for resonance is $\frac{\omega_i}{\omega} \in \mathbb{Z}$
- resonances broadened by larger a_0
- resonances suppressed by large electron energy

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



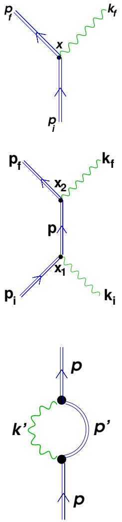
Enhanced rate of photon radiation at resonance

Estimate the rate of vacuum resonance x-ray production

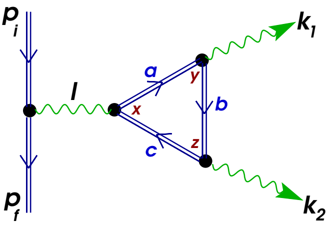
- 3 processes:
  - **ICS**, inverse Compton scattering
  - **SCS**, resonant Compton scattering
  - **ESE**, self energy, resonance width
- Probability proportional to

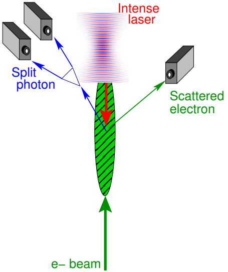
  fine structure constant $\times$ no. of vertices
- ICS $\propto \frac{1}{137}$, SCS $\propto \frac{1}{137^2}$, $\Gamma \equiv$ESE $\propto \left[\frac{0.29}{137}\right]^2$
- At resonance, $\propto \frac{\text{SCS}}{\text{ESE}} \propto \frac{1}{0.29^2}$

> - **x-ray rate at vacuum resonance $10^3 \times$ ICS**
> - **probe laser tunes for resonance**
> - **probe laser pulse length is a factor**



Stimulated photon splitting rate at resonance





- At resonance, photon propagator on-shell, multiply differential rates of separate processes

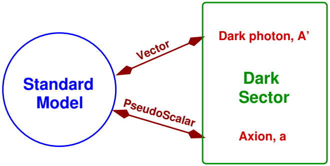
$$\mathrm{d}W_{P_\mathrm{S}} = \mathrm{d}W^{\mathrm{HICS}} \frac{1}{\Gamma^2} \mathrm{d}\Pi^{(3)\mathrm{FP}}$$

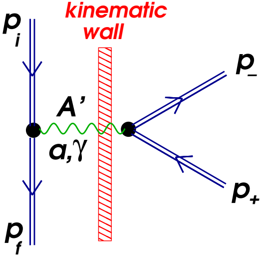
- Assume N=10^{10} electrons per bunch, 50 keV (split) photons

$$\mathrm{d}W_{P_\mathrm{S}} \approx 1 \text{ event per 2 bunch collisions}$$

- Order of magnitude estimate
- Without resonance,
  1 event per 10^4 bunches
- Doable at resonance?
  experimental considerations
- Need detailed calculation

Resonant Dark Photon/Axion searches





- BSM mechanisms to explain dark matter
- Spontaneously broken U(1) symmetry - Dark photon (vector, ϵ mixing) or Peccei-Quinn (axion, f_a breaking scale) or

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

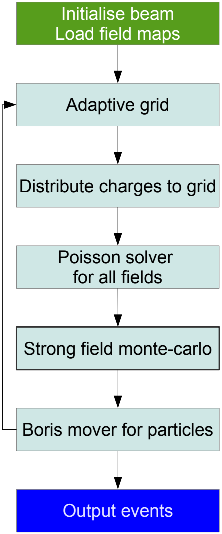
$$\mathcal{L} = \frac{1}{f_a} \bar{\psi} \gamma \gamma^5 \psi \partial_\mu a$$

- Strong field QFT allows resonant production of dark bosons. Rate is increased by order of $1/\Gamma^2 \approx 10^5$ at resonant peak

$$dW = dW^{\text{HICS}} \frac{1}{\Gamma^2} dW^{\text{PPROD}}$$

- Strong field interaction permits a kinematic wall which suppresses photon exchange and allows massive dark photon exchange

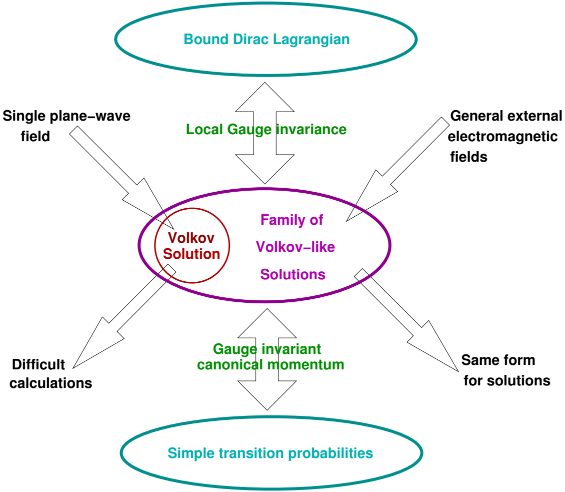
IPstrong - IFQFT monte carlo in a PIC el-mag solver



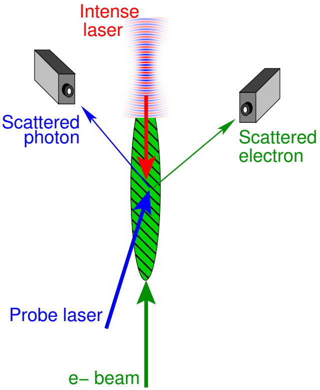
- Fortran 2003 with openMPI (Fortran 2008 has inbuilt GPU libraries)
- 3D poisson solver (PSPFFT, MPI)
- HICS photon radiation, resonant higher order SCS by Strong field QFT monte carlo
- Internally generated bunches or externally loaded
- Cross-check with
  - CAIN (KEK, strong field QFT, no FEL)
- e-/laser, e+e-, higher order interactions, FEL
- new processes can be added as modules

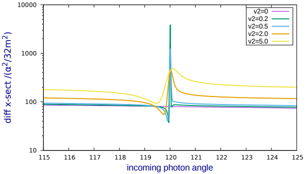
Beyond the Volkov solution (for realistic laser pulses)

- **bound Dirac Lagrangian** for electrons in external fields
- **Volkov solution** (one plane wave external field) ensures local gauge invariance
- There is a whole family of **locally gauge invariant** solutions
- **Rotational symmetry** allows solutions in two external fields propagating in any direction
- **New studies**, further solutions possible



Summary: Intense field physics in the lab!





- 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
- Goal is experimental studies at particular facilities (XFEL, plasma accelerator) leading to experiments
- **Discover new quantum effects and perform new tests of QFT in background fields**
- **Theory development - divergence handling/renormalisation in Furry picture, unstable vacuum, analogy with QFT in curved space-time**