Pair creation in PTARMIGAN

Tom Blackburn
Department of Physics, University of Gothenburg

11 May 2021
LUXE Simulation and Analysis Task Force

Pair creation in PTARMIGAN

Theory and simulation milestones

- Theory and simulation milestones:
  - NBW in a CP laser pulse in simulation and theory-benchmarked [May 2021]
  - Approximate Trident in CP laser pulse (no photon polarisation) [July 2021]
- Implement LMA and LCFA pair creation rates, as well as "perturbative (leading order) LMA"
- Benchmark simulation against theory for pulsed plane waves
- Simulate gamma-laser collisions with approximate photon spectrum, phase 0 and 1
- Simulate electron-laser collisions, phase 0 and 1
- Simulate ICS gamma-laser collisions assuming monoenergetic photons/using Daniel's simulation results, reading HDF5 formatted data

Pair creation in PTARMIGAN

Rates

The pair creation rate of a photon with momentum k'. embedded in a CP plane wave of normalized, root-n square amplitude a and wavevector k, is given by [2]

$$\frac{\mathrm{d}W_n}{\mathrm{d}s} = \frac{\alpha m}{\gamma} \left\{ J_n^2(z) - \frac{a^2}{2} \left[\frac{1}{2s(1-s)} - 1 \right] \left[2J_n^2(z) - J_{n-1}^2(z) - J_{n+1}^2(z) \right] \right\}$$

where the argument of the Bessel functions, z, and auxiliary variables are

$$z^2 = \frac{4n^2a^2}{1+a^2} \frac{1}{s_n s(1-s)} \left[1 - \frac{1}{s_n s(1-s)} \right], \qquad s_n = \frac{2n\eta}{1+a^2}, \qquad \eta = \frac{k.k'}{m^2}, \qquad \gamma = \frac{k'^0}{m}.$$

The lightfront momentum fraction $s = k.q/k.k'$ is restricted to

$$\frac{1}{2}\left[1 - (1 - 4/s_n)^{1/2}\right] < s < \frac{1}{2}\left[1 - (1 - 4/s_n)^{1/2}\right],$$

and therefore the rate is non-zero only for $s_n > 4$, or equivalently, harmonic orders $n_\star > 2(1+a^2)/\eta$.

In the limit that $a \ll 1$, eq. (1) becomes

$$\frac{\mathrm{d}W_n}{\mathrm{d}s} = \frac{\alpha m}{\gamma} \frac{(a\zeta/2)^{2n}}{\Gamma(n)^2} \left[\frac{1}{\zeta^2 s(1-s)} - \frac{2}{\zeta^2} + \frac{1}{n^2} + O(a^2) \right], \qquad \zeta^2 = \frac{4n^2}{s_n s(1-s)} \left[1 - \frac{1}{s_n s(1-s)} \right], \qquad s_n = 2n\eta.$$

Pair creation in PTARMIGAN
Rates

The pair creation rate of a photon with momentum k'. embedded in a CP plane wave of normalized, root-n square amplitude a and wavevector k, is given by [2]

$$\boxed{\frac{\mathrm{d}W_n}{\mathrm{d}s} = \frac{\alpha m}{\gamma}\left\{J_n^2(z) - \frac{a^2}{2}\left[\frac{1}{2s(1-s)} - 1\right]\left[2J_n^2(z) - J_{n-1}^2(z) - J_{n+1}^2(z)\right]\right\}}$$

LMA

where the argument of the Bessel functions, z, and auxiliary variables are

$$z^2 = \frac{4n^2a^2}{1+a^2}\frac{1}{s_n s(1-s)}\left[1 - \frac{1}{s_n s(1-s)}\right], \qquad s_n = \frac{2n\eta}{1+a^2}, \qquad \eta = \frac{k.k'}{m^2}, \qquad \gamma = \frac{k'^0}{m}.$$

The lightfront momentum fraction $s = k.q/k.k'$ is restricted to

$$\frac{1}{2}\left[1 - (1-4/s_n)^{1/2}\right] < s < \frac{1}{2}\left[1 - (1-4/s_n)^{1/2}\right],$$

and therefore the rate is non-zero only for $s_n > 4$, or equivalently, harmonic orders $n_\star > 2(1+a^2)/\eta$.

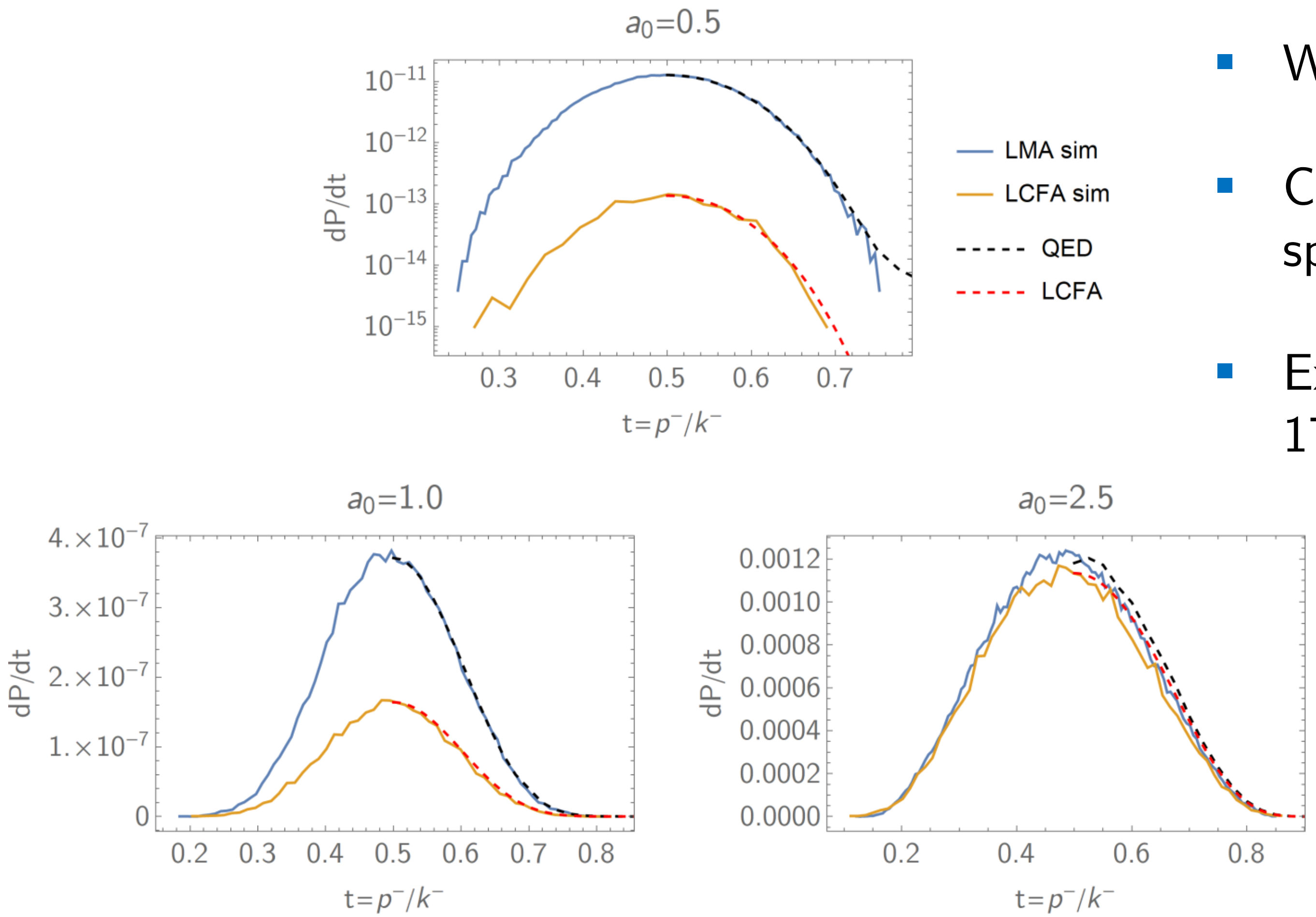
In the limit that $a \ll 1$, eq. (1) becomes

$$\boxed{\frac{\mathrm{d}W_n}{\mathrm{d}s} = \frac{\alpha m}{\gamma}\frac{(a\zeta/2)^{2n}}{\Gamma(n)^2}\left[\frac{1}{\zeta^2 s(1-s)} - \frac{2}{\zeta^2} + \frac{1}{n^2} + O(a^2)\right]}, \qquad \zeta^2 = \frac{4n^2}{s_n s(1-s)}\left[1 - \frac{1}{s_n s(1-s)}\right], \qquad s_n = 2n\eta.$$

perturbative LMA

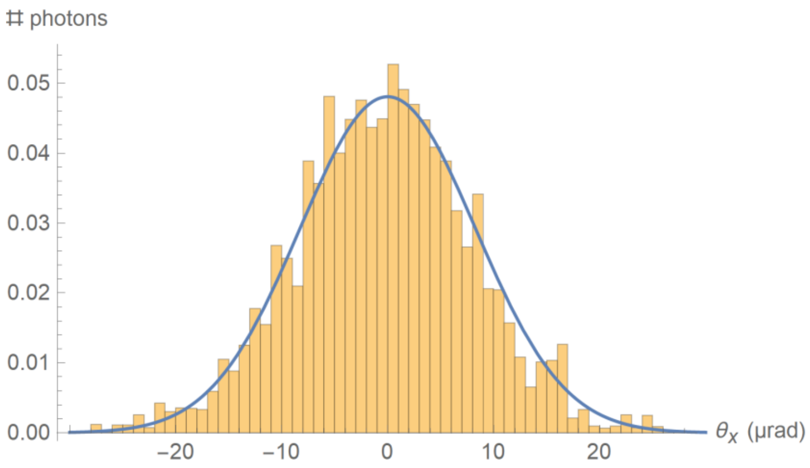
Pair creation in PTARMIGAN

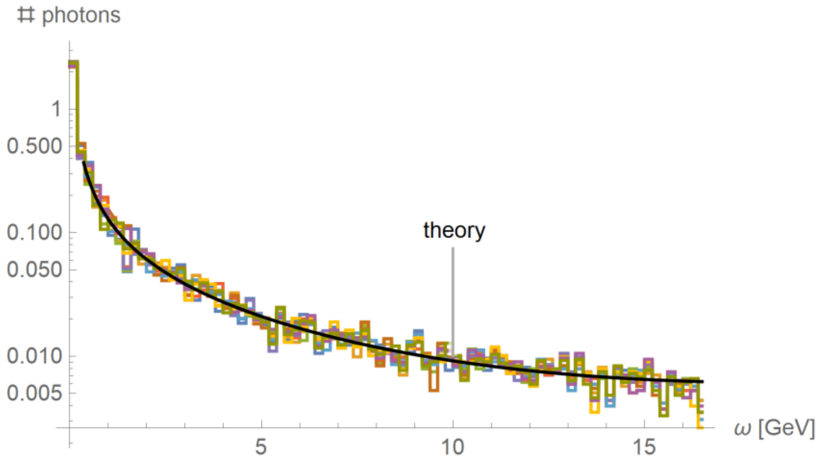
Benchmarking with theory



- WIP with Ben King
- Comparing simulation results for positron spectrum and yield.
- Example for $\eta_\gamma = 0.2$ (close to 16.5 GeV @ 17.2 degree collision angle) and $N = 16$

Pair creation in PTARMIGAN
Bremsstrahlung γ-laser

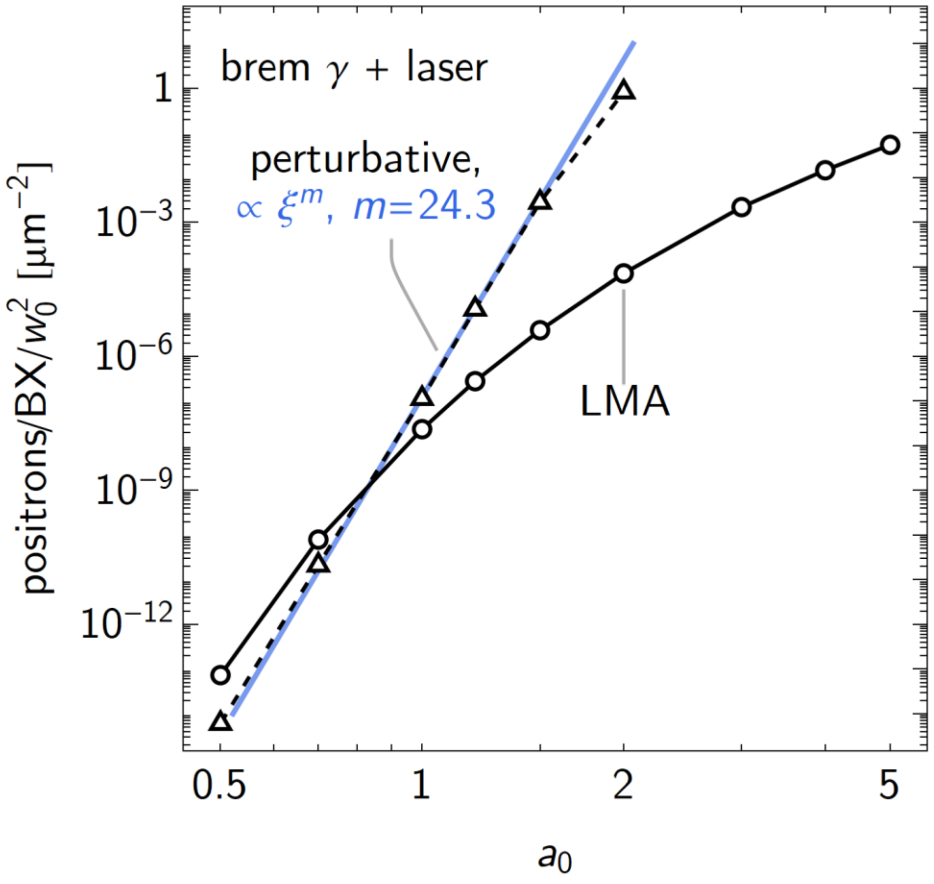




- Using approximate photon spectrum and sampling analytically.
- From Sasha's Geant4 results, photon flux in the transverse plane at the IP is 41 photons/μm^2 ($>$ 2 GeV). Photon beam inherits duration and angular divergence of source electron beam (24 μm/c, 8.7 μrad).
- Energy spectrum between 2 and 16.5 GeV a close match to expected analytical result for thin-target bremsstrahlung [Tsai et al, RMP 46, 815 (1974)].

Pair creation in PTARMIGAN

Bremsstrahlung γ-laser



- Photons assumed to be uniformly distributed in IP across an area much larger than focal spot (seems accurate up to a radius of 25 μm)
- Positron yield is proportional to w_0^2, the focal spot area, which is scaled out in this plot.
- Perturbative (leading order) results follow a power-law scaling unless $a_0 > 2$, probably because rate is so large than positrons decay in the leading edge of the pulse.
- Extend to higher a_0

Pair creation in PTARMIGAN

Theory and simulation milestones

- Theory and simulation milestones:
  - NBW in a CP laser pulse in simulation and theory-benchmarked [May 2021]
  - Approximate Trident in CP laser pulse (no photon polarisation) [July 2021]
- Implement LMA and LCFA pair creation rates, as well as "perturbative (leading order) LMA"
- Benchmark simulation against theory for pulsed plane waves
- Simulate gamma-laser collisions with approximate photon spectrum, phase 0 and 1
- Simulate electron-laser collisions, phase 0 and 1
- Simulate ICS gamma-laser collisions assuming monoenergetic photons/using Daniel's simulation results, reading HDF5 formatted data