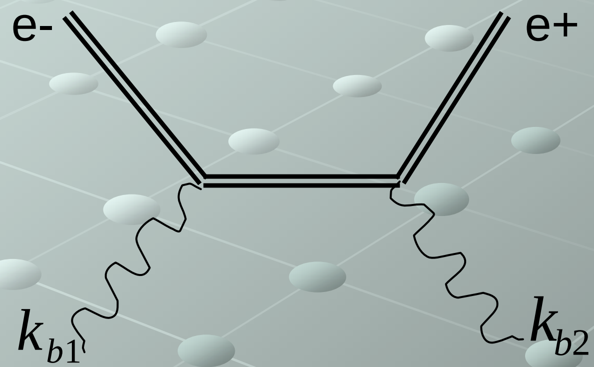
Stimulated Breit-Wheeler process as a source of background pairs



John Adams Institute for Accelerator Science

Tony Hartin

University of Oxford

Outline

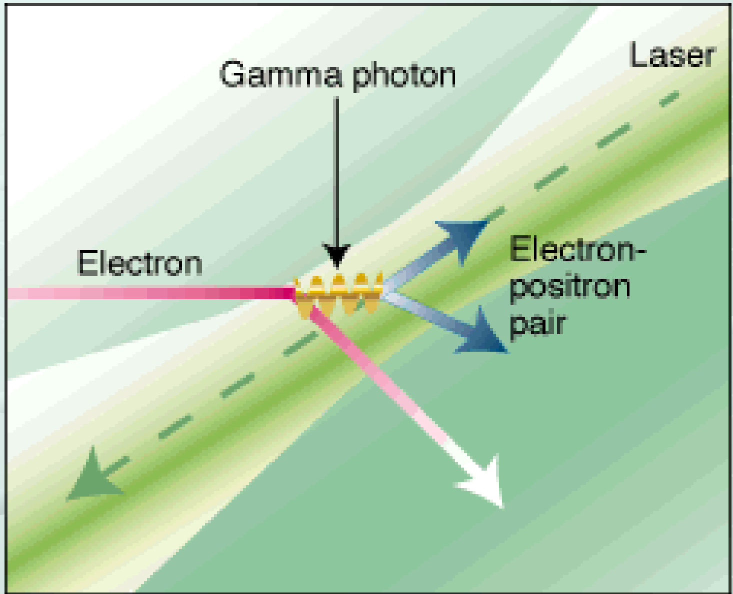
- Have the effect of intense beam fields been fully taken into account?
  - 1st order coherent pair production fully covered but 2nd order not
  - Why consider 2nd order coherent pair production?

- Resonances in the 2nd order IFQED processes
  - Moller process – Oleinik (1967), Bos et al (1979), Panek et al (2003)
  - Stimulated Breit-Wheeler in CIRCULARLY POLARISED field
  - Self Energy calculations in an external field

- The nature of the ILC beam field and its inclusion in QED calculations of stimulated Breit-Wheeler process
  - Constant crossed e-m field
  - 3 different methods

- Preliminary results
  - Only sketch some issues to do with the calculation
  - Separated resonant and non-resonant crossections

Is there another non-linear source of pairs at the IP?



- **Known**: coherent pair production

$$k_b + nk \rightarrow e^- + e^+$$

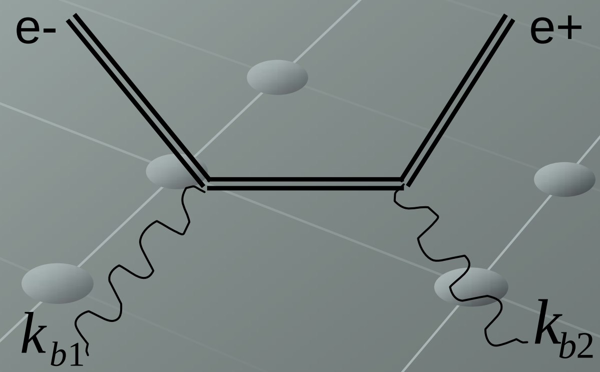
  - rate described by Sokolov-Ternov and onset governed by beam parameter Y=E/E_c~0.3. Scheme1 has Y=0.054, Scheme14 has Y=0.376

- **Unknown**: Multiphoton Breit-Wheeler $k_{b1} + k_{b2} + nk \rightarrow e^- + e^+$

•2^{nd} order process rather than 1^{st} order

•Rules for onset are different

•Calculation is complicated, but simplified when the photons are co-linear

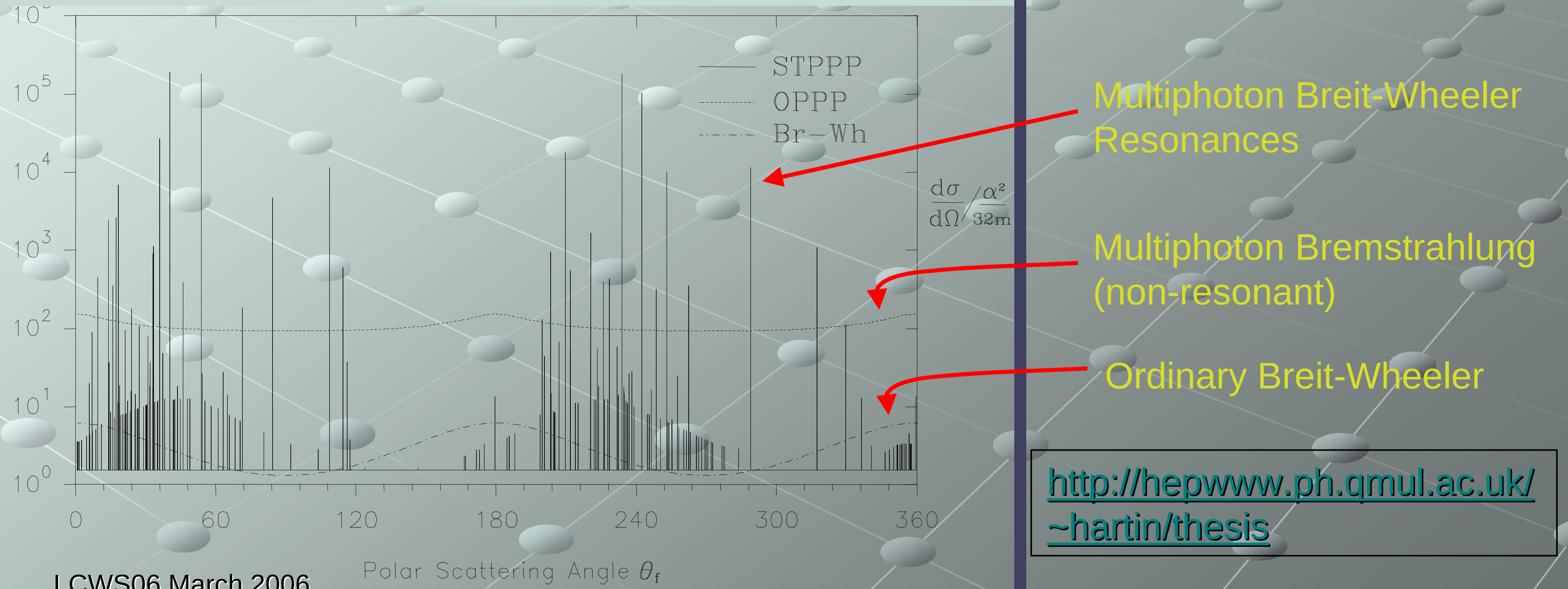


Resonances in 2nd order IFQED processes

- Pairs created in intense e-m field have a quasi-level structure and resonant transitions can occur (Zeldovich, 1967)

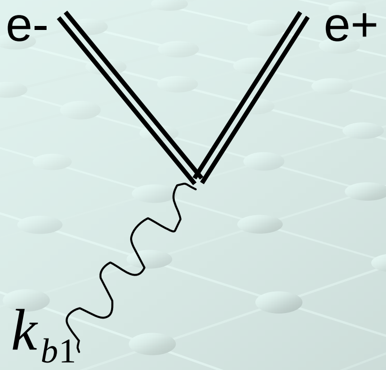
$$(q+nk)^2 = m^2(1+\nu^2)$$

- 2nd order IFQED x-section can exceed normal x-sections by orders of magnitude (Oleinik, JETP 25(4) 697, 1967)
- 2nd order Breit-Wheeler process in CIRCULARLY POLARISED field shows the same feature



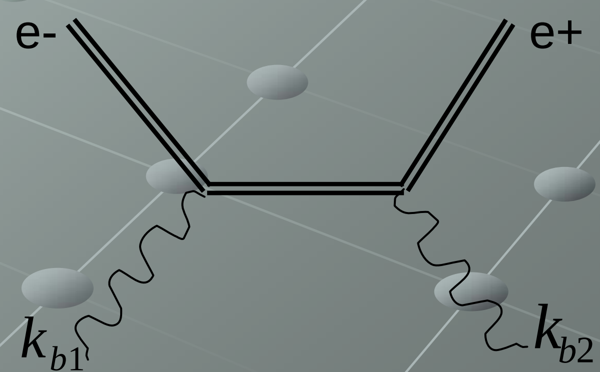
http://hepwww.ph.qmul.ac.uk/~hartin/thesis

Experimental evidence for the IFQED processes



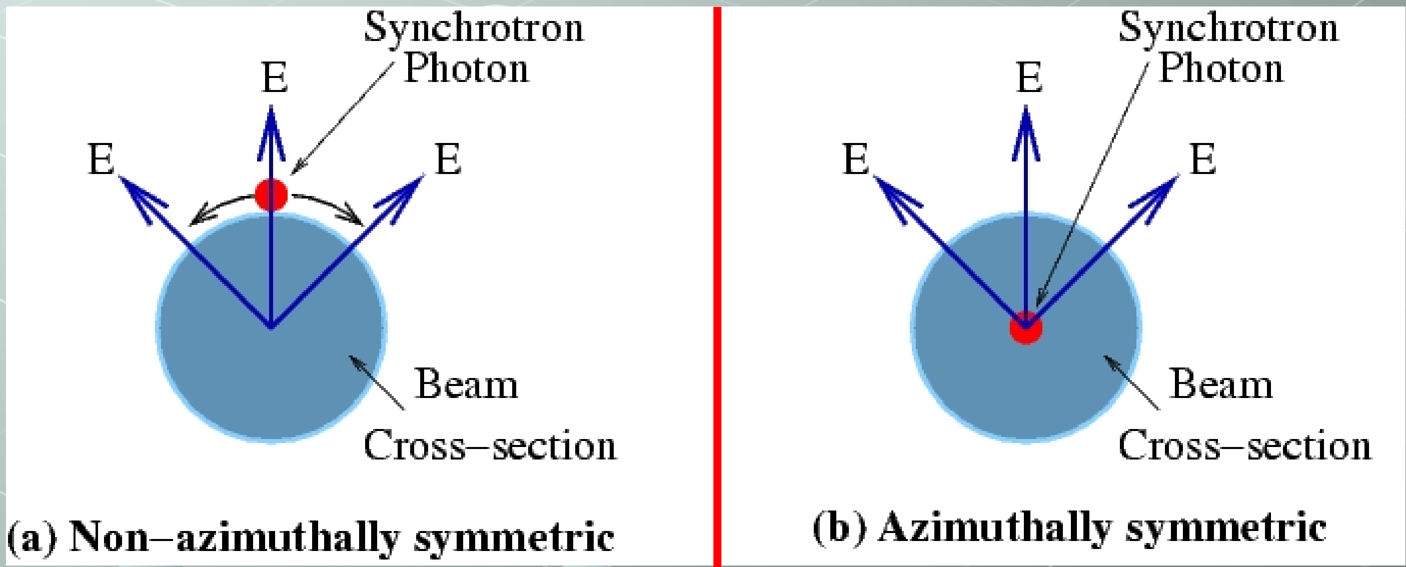
- **1st order:** One photon pair production
- Experiment E144 SLAC. 46 GeV beam with Nd:glass laser peak intensity 0.5×10^{18} Wcm^{-2}. Up to 4 photons contributed to each event
- Meyerhofer et al (1996) other non-linear phenomena such as electron mass shift observed

- **2nd order:** Substantial theoretical studies but no experimental efforts yet!
- **BUT** potentially more detectable because of resonances



The field of the relativistic charge beams

- With low disruption, approximate to a constant crossed e-m field perpendicular to direction of propagation
- SIMPLIFICATION: Beamsstrahlung photons k_1 and k_2 emitted forward. Assume they are collinear
- COMPLICATION: Symmetry of the field seen by the synchrotron photons



$$AiJ(P,n) = \int_0^\infty J_0(Pt^2)\cos(nt + t^3/3)\,dt$$

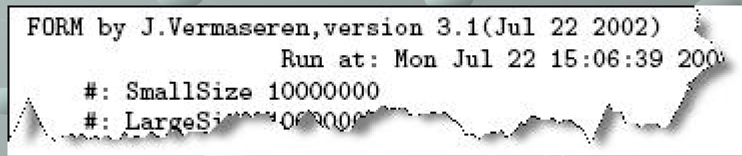
$$Ai(n) = \int_0^\infty \cos(nt + t^3/3)\,dt \equiv K_{1/3}$$

Including the external field in IFQED calculations

- **'Operator Method':** quantum interaction of electron and external field photons but electron trajectory is considered classical. Due to Baier et al (JETP 28(4) p.807, 1969)

$$U_{fi} = \left\langle f \left| \int e^{i\omega t} M_{fi}(t)\,dt \right| i \right\rangle$$

- **Full quantum treatment:** Horrendously complex but potentially doable with Vermaseren's FORM



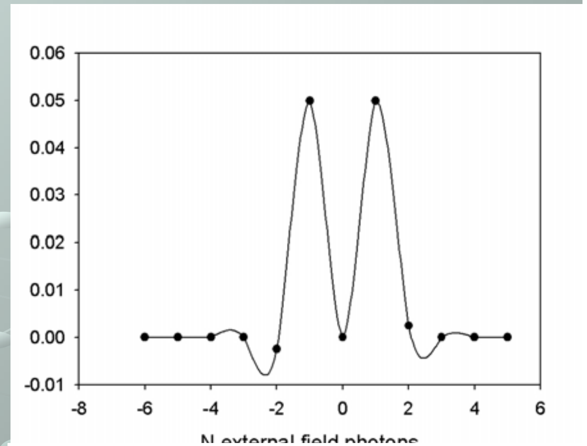
- **'Semi-classical method':** Dirac equation is solved exactly for interaction with a classical plane-wave e-m field. Most common method. Used originally by Narozhnyii, Nikishov and Ritus in the mid 1960s

IFQED – Dirac Equation Solution

- Exponential dependency on external field 4-potential

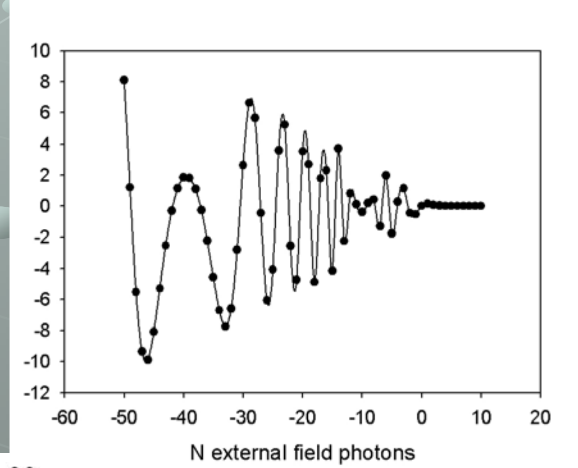
$$\exp\left\{\int d\phi\left[i(A^e p) - i(A^e)^2\right]\right\}$$

- Fourier Expansion in contributions of n external field photons



- Different external field polarisations lead to different “form factor” functions

  Circular polarisation
  Bessel functions ⟶ **n Jn(Q)**

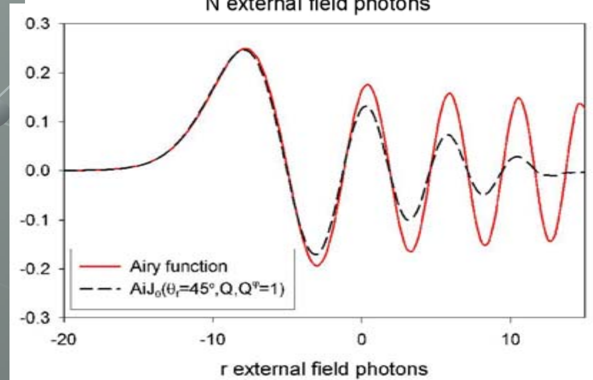


  Linear polarisation
  Generalised Bessel–type functions

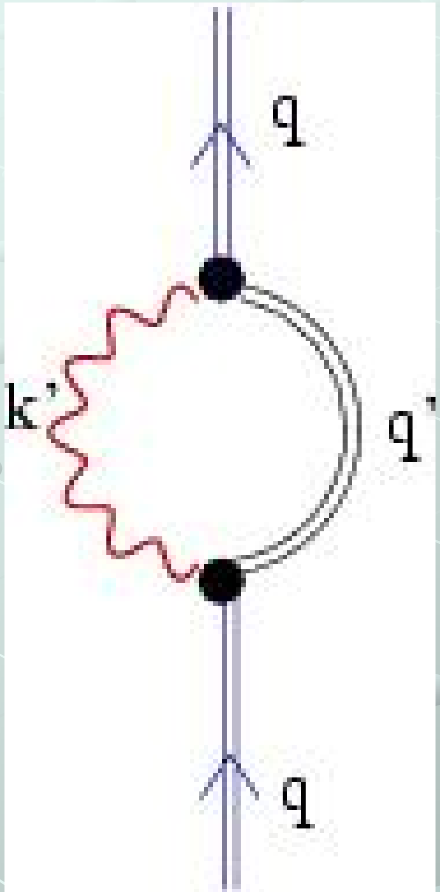
-

  Constant crossed field-Azimuthally symmetric
  Airy functions ⟶ **n Ai(n Q)**

- **Constant crossed field –Nonazimuthally symmetric**
  New ‘AiJ’ functions ⟶ **n AiJn(Q)**



Calculation of Resonance widths

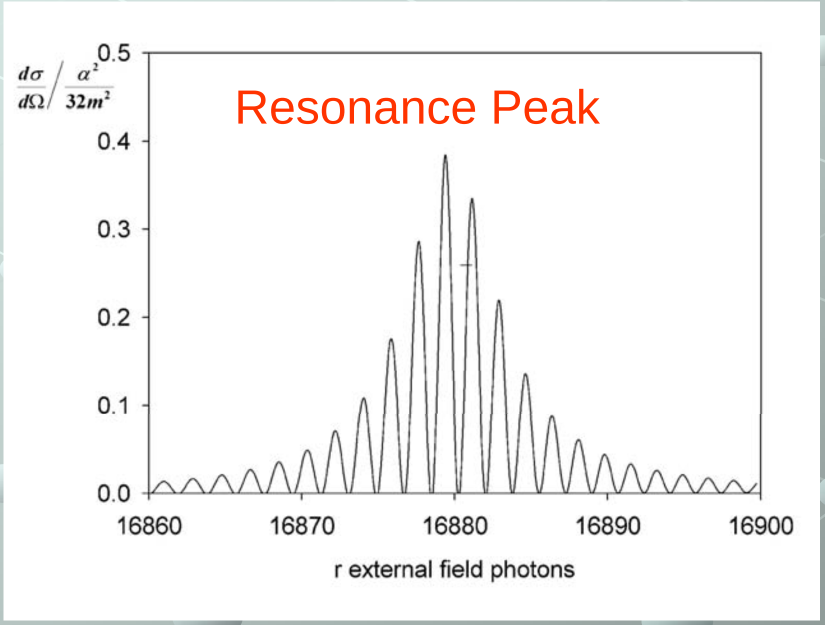


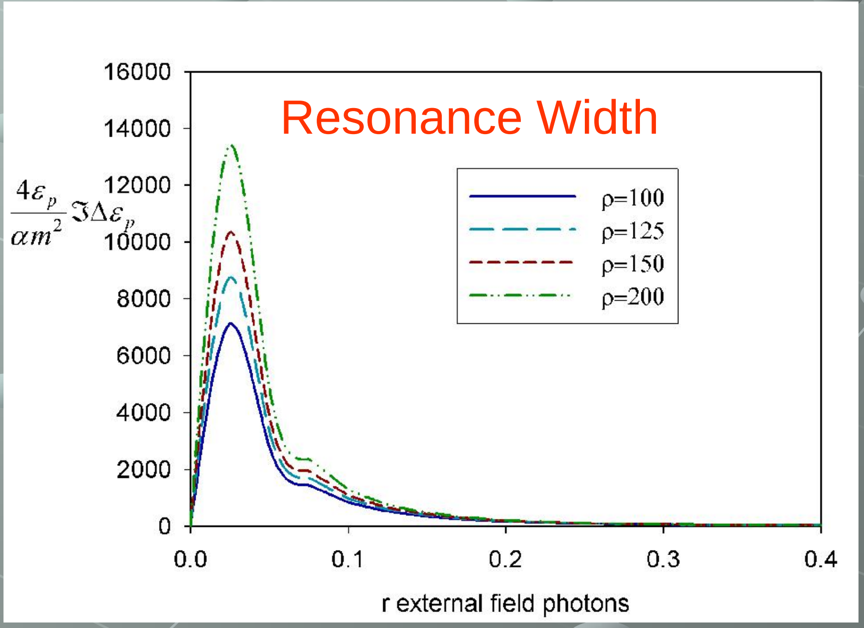
- The Electron Self Energy must be included in the Multiphoton Breit-Wheeler process
- This is a 2nd order IFQED process in its own right.
- Renormalization/Regularization reduces to that of the non-external field case
- The Electron Self Energy in external CIRCULARLY POLARISED e-m field originally due to Becker & Mitter 1975 for low field intensity parameter $\nu=(ea/m)^2$. Has been recalculated for general ν
- ESE in external CONSTANT CROSSED field is due to Ritus, 1972
- Optical theorem: the imaginary part of the ESE is the same form as the Sokolov-Ternov equations

Where do the resonances occur?

- Beamsstrahlung photon $E_S >> 0.511$ MeV
- Beam photon $E_B < 0.511$ MeV
- Processes which give/take energy to the field allowed and mass shell can be reached for physical values
- For collinear beamstrahlung photons, resonance condition is

r (external field photons) ~ E_S/E_B





Notes on the cross-section calculation

- Full trace contains ~ 100,000 terms

$$\sum_{i,f} |S^{e}_{fi}|^2 = -\frac{e^2}{16m^2} \sum_{l} \delta^4(k_1 + k_2 + lk - q_- - q_+)\, \mathrm{Tr}\, Q_{\mathrm{STPPP}}$$

$$\text{where} \quad \mathrm{Tr}\, Q_{\mathrm{STPPP}} = \sum_{rr'} [\mathrm{Tr}\ Q_1(\bar{p}_r, \bar{p}_{r'}) + \mathrm{Tr}\ Q_1(\bar{\bar{p}}_r, \bar{\bar{p}}_{r'}) + \mathrm{Tr}\ Q_2(\bar{p}_r, \bar{\bar{p}}_{r'}) + \mathrm{Tr}\ Q_2^{\ddagger}(\bar{p}_r, \bar{\bar{p}}_{r'})]$$

$$\text{and} \quad Q_1(\bar{p}_r, \bar{p}_{r'}) = (\not{p}_- + m) B(\gamma_\mu, \bar{N}_r, \bar{p}, p_-) \left[\frac{\bar{\not{p}}_r + m}{\bar{p}_r^2 - m^2}\right] B(\gamma_\nu, \bar{M}_r, -p_+, \bar{p})$$

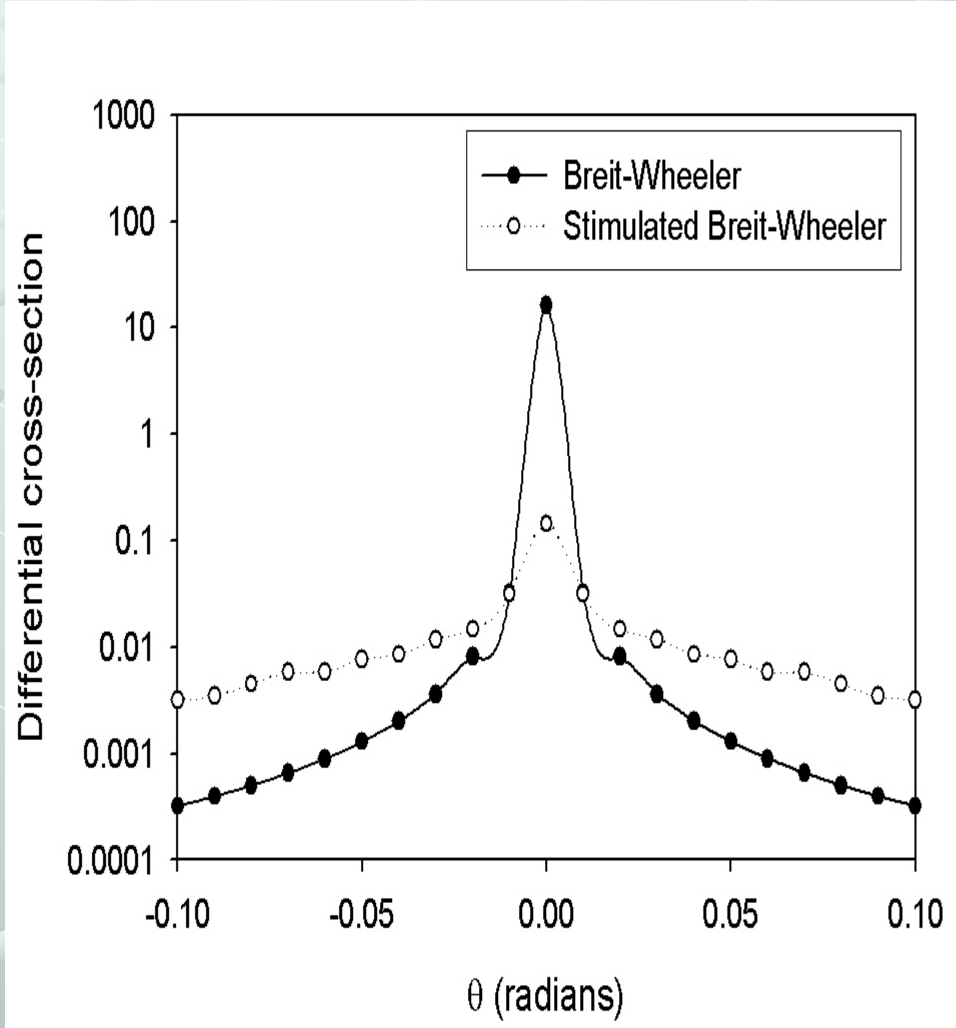
- Dramatically simplified by
  - Special "centre of mass-like" reference frame

$$\underset{\rightarrow}{k}_1 + \underset{\rightarrow}{k}_2 = \underset{\rightarrow}{q}_- + \underset{\rightarrow}{q}_+ - r\underset{\rightarrow}{k} = 0$$

  - Assume beamsstrahlung photons and beam field photons are collinear
  - Only insert Imaginary part of self energy to get resonance width

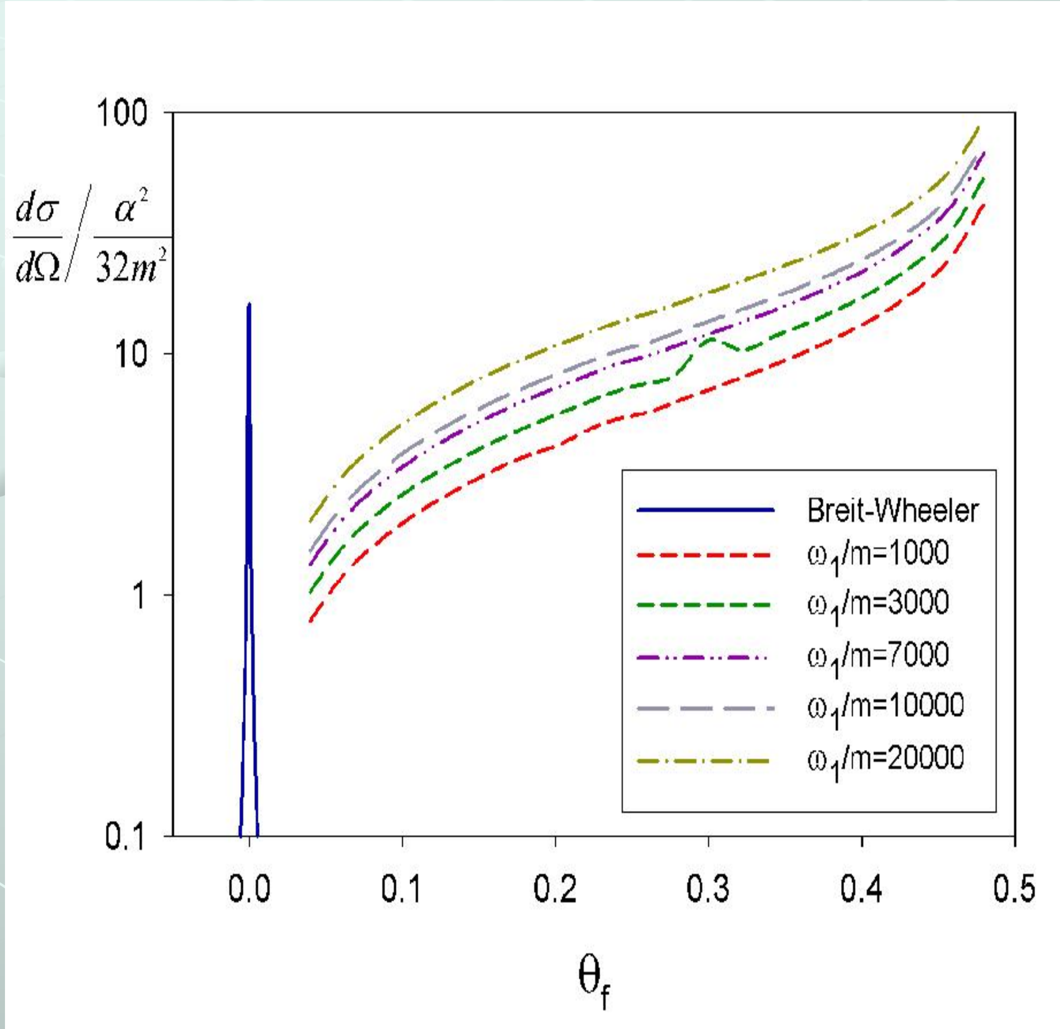
And the PRELIMINARY results…..?

Results: Stimulated Breit-Wheeler (Non-Resonant)



- Compare Stimulated Breit-Wheeler process with ordinary Breit-Wheeler process
- Examine the resonant and non-resonant contributions to the cross-section separately
- Nonresonant Stimulated Breit-Wheeler cross-section only a few percent of the ordinary Breit-Wheeler cross-section
- Can be neglected as a source of extra pairs

Results: Stimulated Breit-Wheeler (Resonant)



- Differential cross-section can exceed the ordinary Breit-Wheeler process
- Stimulated Breit-Wheeler Cross-section up to 2 orders of magnitude greater than ordinary breit-wheeler
- Transverse production of pairs seems favoured

PROVISO – calculation for special reference frame. Need to generalise the case!

Summary

- 2nd order, nonlinear interactions of beamsstrahlung photons with the beam fields should be taken into account because the cross-sections are potentially resonant and can exceed 1st order and "linear" ordinary cross-sections – established by substantial theoretical work by several groups
- Preliminary calculations of the Stimulated Breit-Wheeler process (simplified case) suggests that this will be an issue at the ILC
- Calculations need to be completed for the general case and predictions made of numbers, angular spread and energy spectrum of the additional background pairs
- Searches of unexplained pair backgrounds at other experiments