Possibility of pair creation in collision of gamma-ray beams Produced with a high intensity laser

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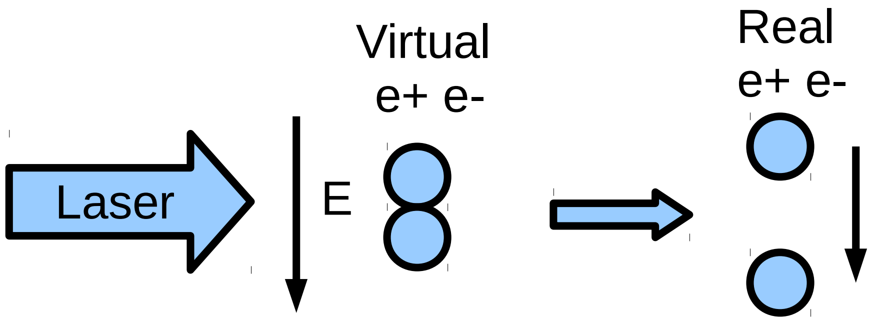
LAPHIA Project : TULIMA

Outlook on Wake Field Acceleration: the Next Frontier 15-16 October 2015

Pairs creation e^+e^- and the Schwinger Limit

It would occur in a strong electric field in vacuum : QED theory

The electric field separates virtual (e^+, e^-) by a distance of compton length and provided 2 m_ec^2 of energy



$$\lambda_c = \frac{h}{m_e c}$$

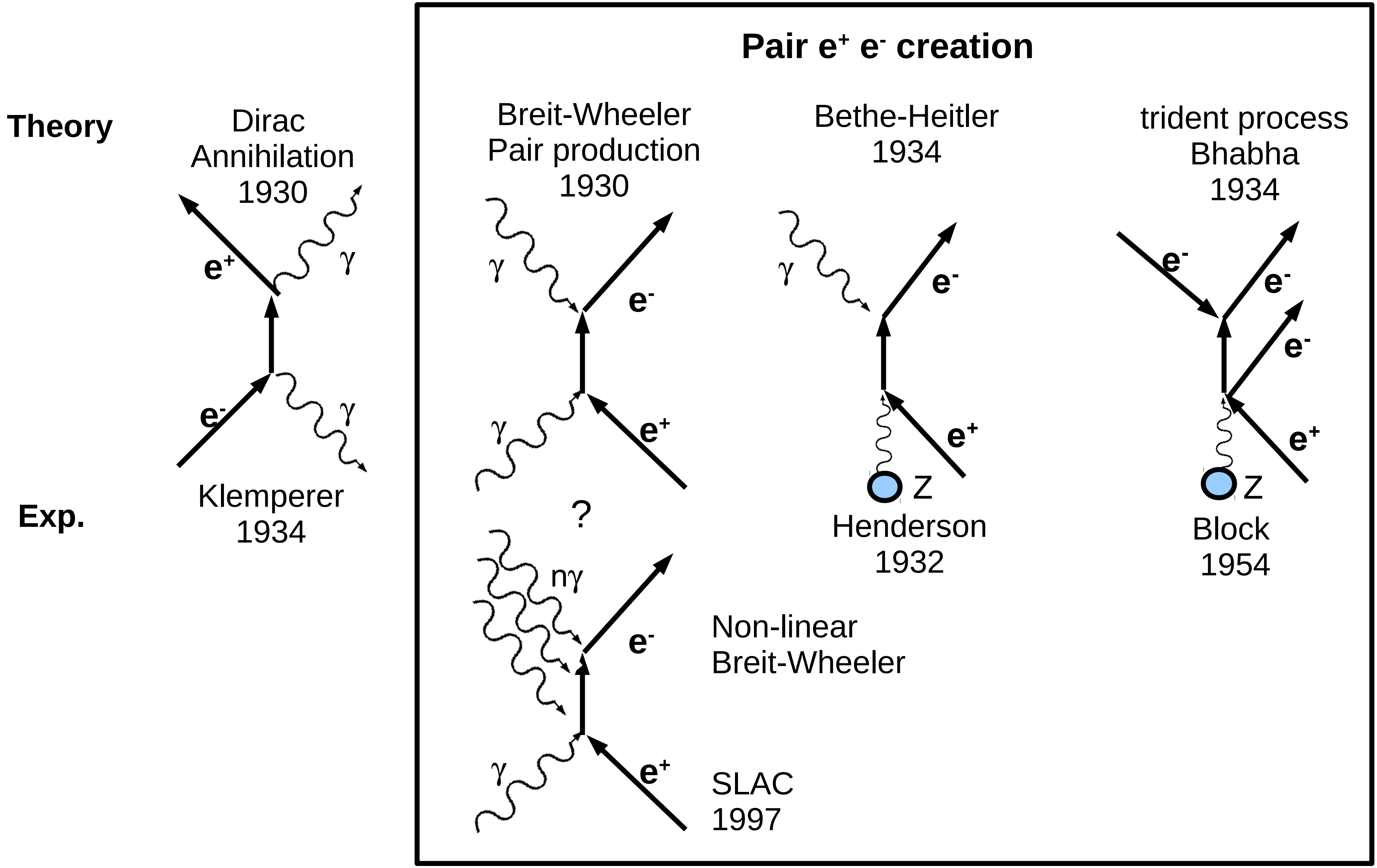
$$\text{Energy} = 2eE\lambda_c = 2m_e c^2 \qquad E = m_e^2 c^3/eh$$

$$E \simeq E_c \equiv \frac{m_e^2 c^3}{e\hbar}$$

Schwinger limit[1] $I_c \simeq 2.3 \times 10^{29} \mathrm{W/cm^2}$

[1]Schwinger J., Phys. Rev, **82**, 664 (1951)

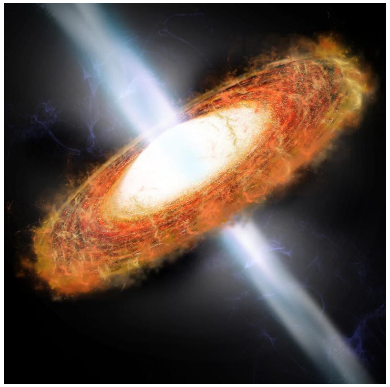
Pairs creation e^+e^- and Quantum ElectroDynamics (QED)



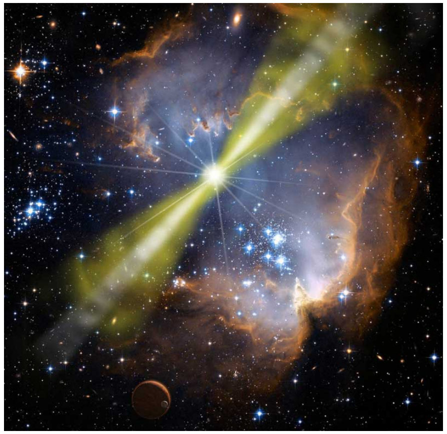
Photon-Photon collision and pair production in astrophysics

Breit-Wheeler process
Collision of two light quanta

$$\gamma + \gamma \longrightarrow e^{+} + e^{-}$$


Artiste composition

- Electron pair production in AGN (Active Galaxy nuclei), Blazar, Quasar[1]
- Absorption of high-energy photon in the Universe[3],
cut-off in high energy gamma rays


Artiste composition

- Electron pair production in
  - GRB[2] (Gamma ray burst), Supernovae, Hypernovae…
  - In pulsar – electron-positron pair plasma
  - Merging neutron start, black hole
  - Accretion disk

[1]Bonometto, S. and Ress, M. J. MNRAS, **152** 21-25 (1971)
[2]Piran, S. Rev. Mod. Phys. 76 (2004)
[3]Nikishov A. I., JETP **14** (1962), Gould, R. J. PRL **155**, 5 part 1, part2 (1967), Kneitske, T.M. et al. A&A 413, 807 (2004)

Pair creation with two real photons has not been observed in laboratory

VOLUME 79, NUMBER 9 PHYSICAL REVIEW LETTERS 1 SEPTEMBER 1997

Positron Production in Multiphoton Light-by-Light Scattering

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(Received 2 June 1997)

A signal of 106 ± 14 positrons above background has been observed in collisions of a low-emittance 46.6 GeV electron beam with terawatt pulses from a Nd:glass laser at 527 nm wavelength in an experiment at the Final Focus Test Beam at SLAC. The positrons are interpreted as arising from a two-step process in which laser photons are backscattered to GeV energies by the electron beam followed by a collision between the high-energy photon and several laser photons to produce an electron-positron pair. These results are the first laboratory evidence for inelastic light-by-light scattering involving only real photons. [S0031-9007(97)04008-8]

PACS numbers: 13.40.−f, 12.20.Fv, 14.70.Bh

The production of an electron-positron pair in the collision of two real photons was first considered by Breit and Wheeler [1] who calculated the cross section for the reaction

$$\omega_1 + \omega_2 \rightarrow e^+ e^- \quad (1)$$

to be of order r_e^2, where r_e is the classical electron radius. While pair creation by real photons is believed to occur in astrophysical processes [2], it has not been observed in the laboratory up to the present.

approaches or exceeds unity. Here the laser beam has laboratory frequency ω_0, reduced wavelength λ_0, root-mean-square electric field $\mathcal{E}_{\rm rms}$, and four-vector potential A_μ; e and m are the charge and mass of the electron, respectively, and c is the speed of light.

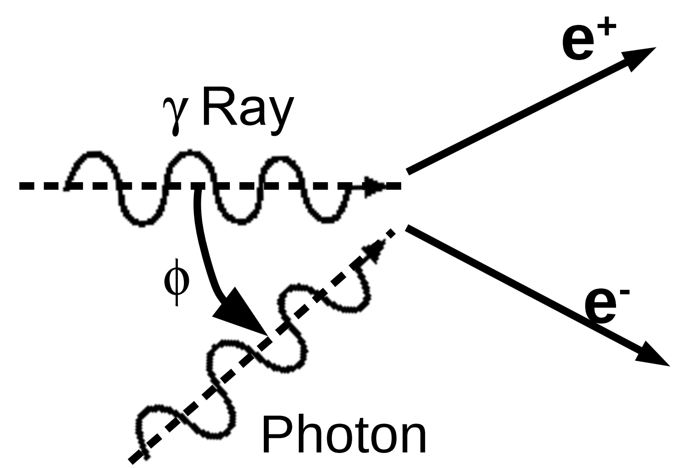
For photons of wavelength 527 nm a value of $\eta = 1$ corresponds to laboratory field strength of $\mathcal{E}_{\rm lab} = 6 \times 10^{10}$ V/cm and intensity $I = 10^{19}$ W/cm^2. Such intensities are now practical in tabletop laser systems based on chirped-pulse amplification [6].

See also Pike et al. Nature Photonics 2014

Minimum energy for the photons for pair creation

$$\gamma + \gamma \longrightarrow e^+ + e^-$$

Energy conservation in the center of mass frame :



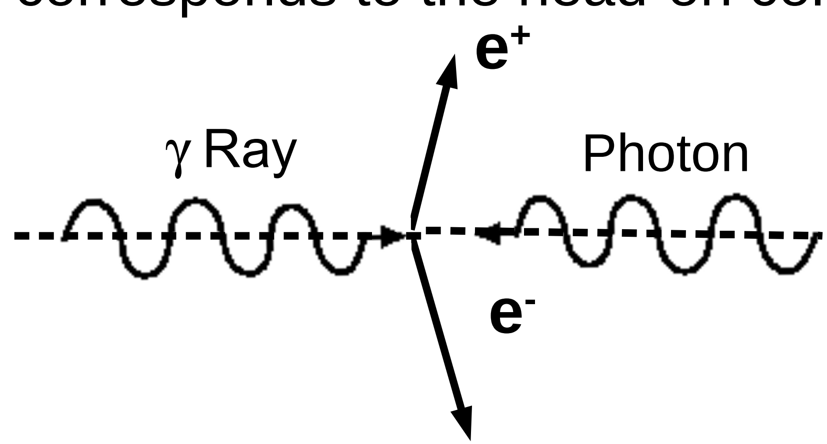
$$E^2-(pc)^2=m_e^2c^4$$

$$E_\gamma = \frac{(2m_e c^2)}{2E_p(1-\cos(\phi))}$$

Minimum for the gamma ray energy corresponds to the head-on collision

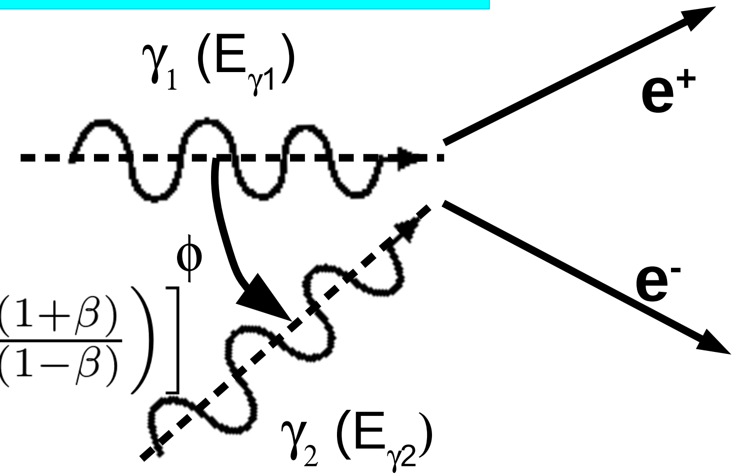
$\phi=180°$

$$E_\gamma = \frac{(m_e c^2)^2}{E_p}$$



Photon-Photon collision and pair production cross section

$$\gamma_1 + \gamma_2 \longrightarrow e^+ + e^-$$



Breit-Wheeler cross section[1] in CM

$$\sigma_{\gamma\gamma}(s) = \frac{\pi r_e^2}{2}(1-\beta^2)\left[2\beta\left(\beta^2-2\right)+(3-\beta^4)\log\left(\frac{(1+\beta)}{(1-\beta)}\right)\right]$$

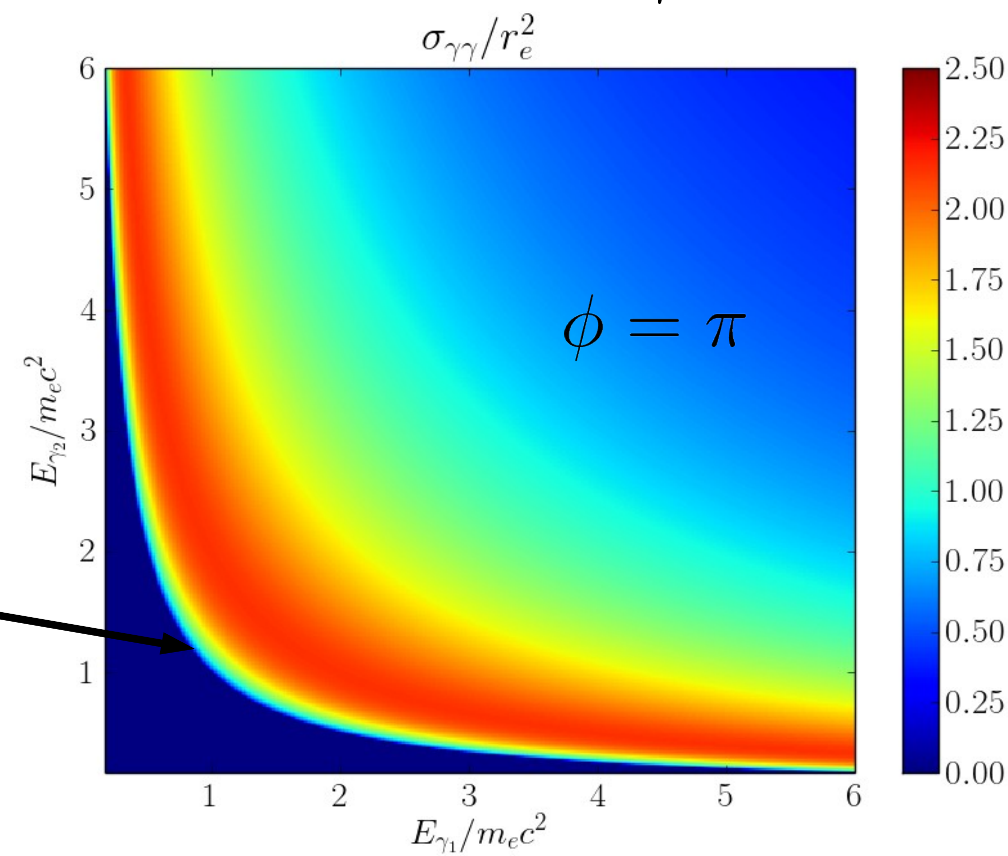
$$\beta = \sqrt{1-\frac{1}{s}} \qquad s = \frac{E_{\gamma_1}E_{\gamma_2}}{2m_e^2c^4}(1-\cos\phi)$$

$$\sigma_{\gamma\gamma} \propto r_e^2$$

Threshold pair
Production : s=1

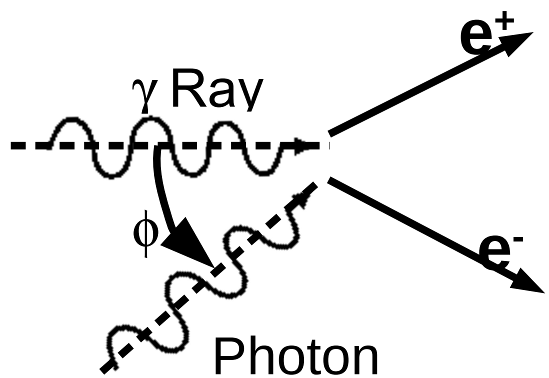
$$\mathrm{E}_{\gamma_1}\mathrm{E}_{\gamma_2} = \mathrm{m_e^2c^4}$$

Maximum production
for s=2

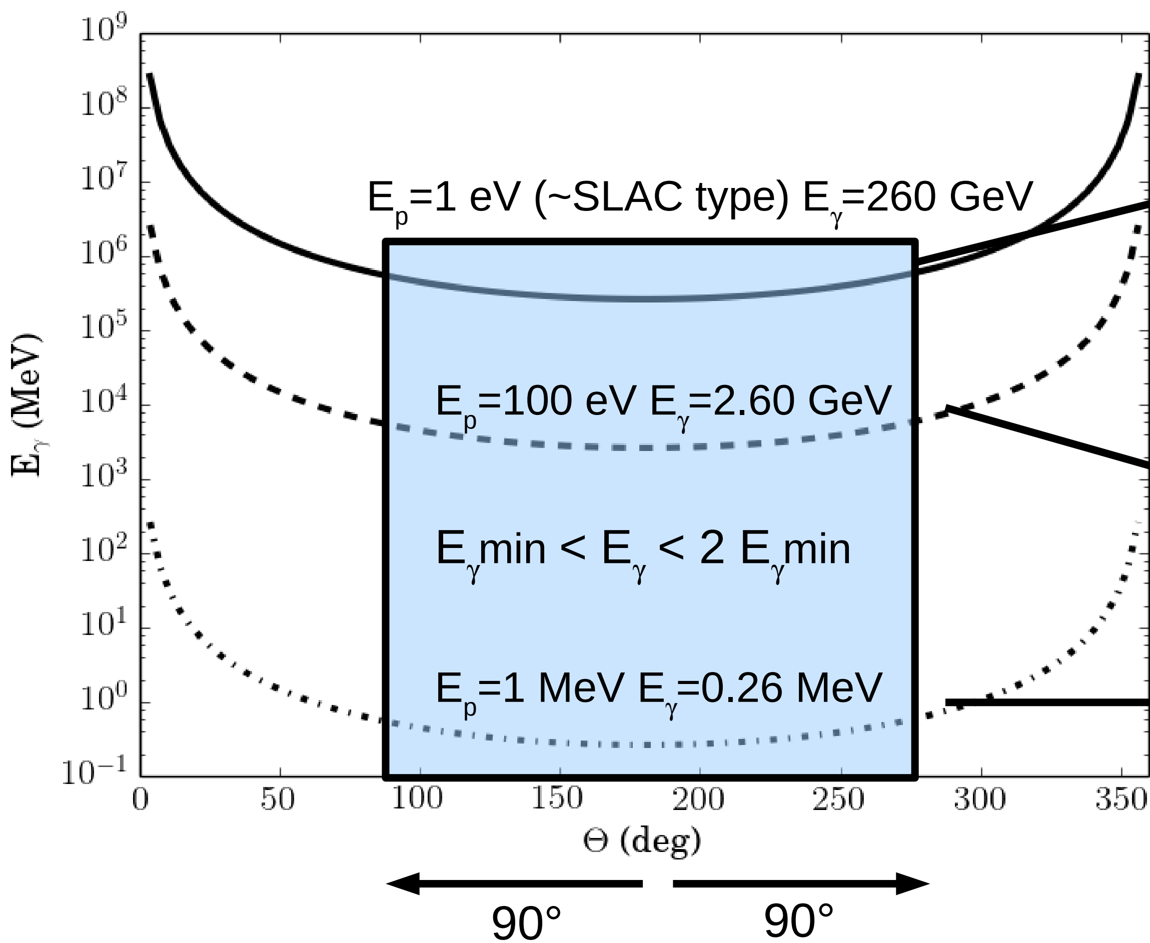


[1]Breit, G. and Wheeler J. A. PRL **15** (1934)

Search for other experimental configurations



$$E_\gamma = \frac{(2m_e c^2)}{2E_p(1-\cos(\phi))}$$



Perturbative regime, i.e.
Non-linear Breit-Wheeler

SLAC E-144 exp

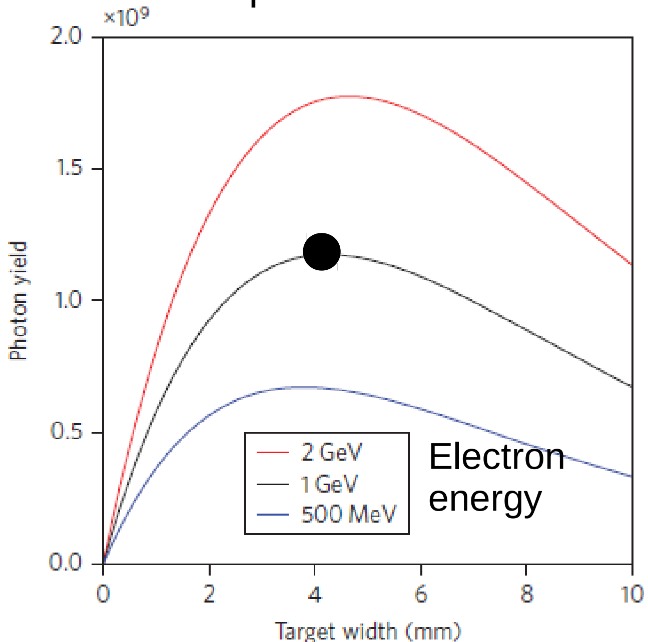
Non-perturbative regime, i.e.
linear Breit-Wheeler
Real photon-photon collision

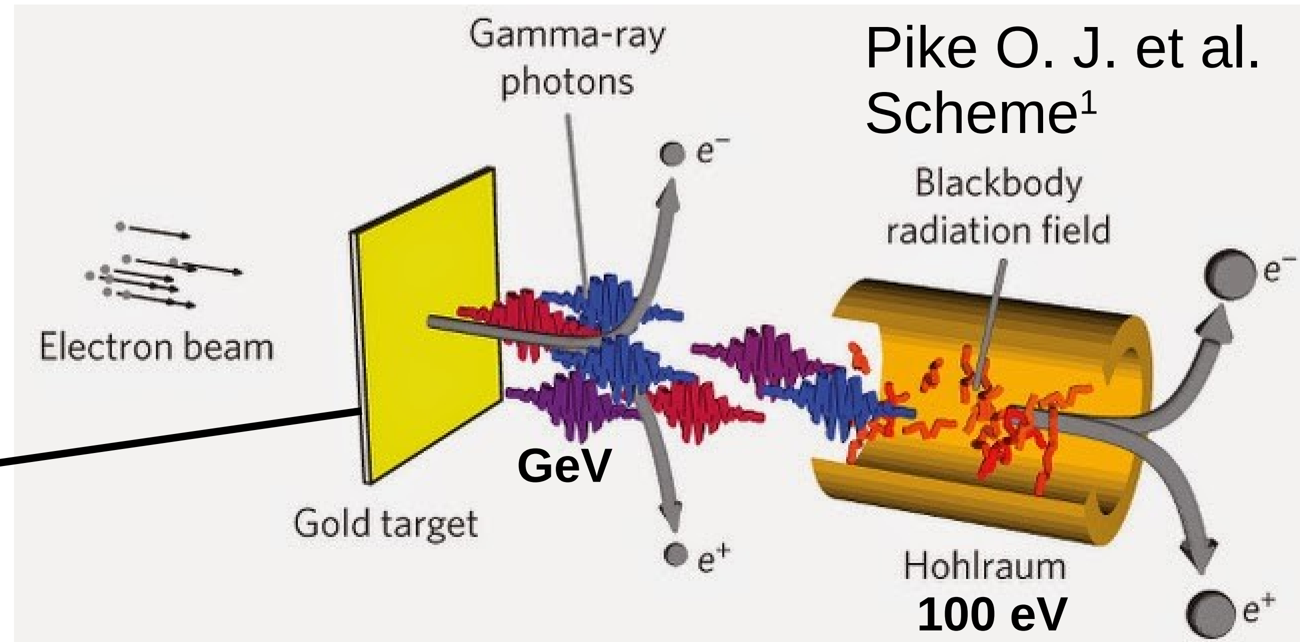
(1) γ photon- photon bath collision

(2) MeV-MeV photon collision

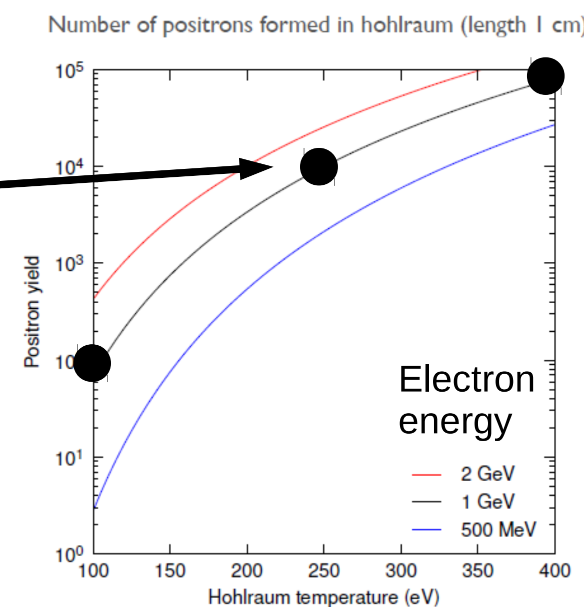
(1) New experimental concept for pair creation

Number of photons above 100 MeV





Hohlraum Temperature	Nb of positrons
100 eV	10^2
250 eV	**10^4**
400 eV	10^5

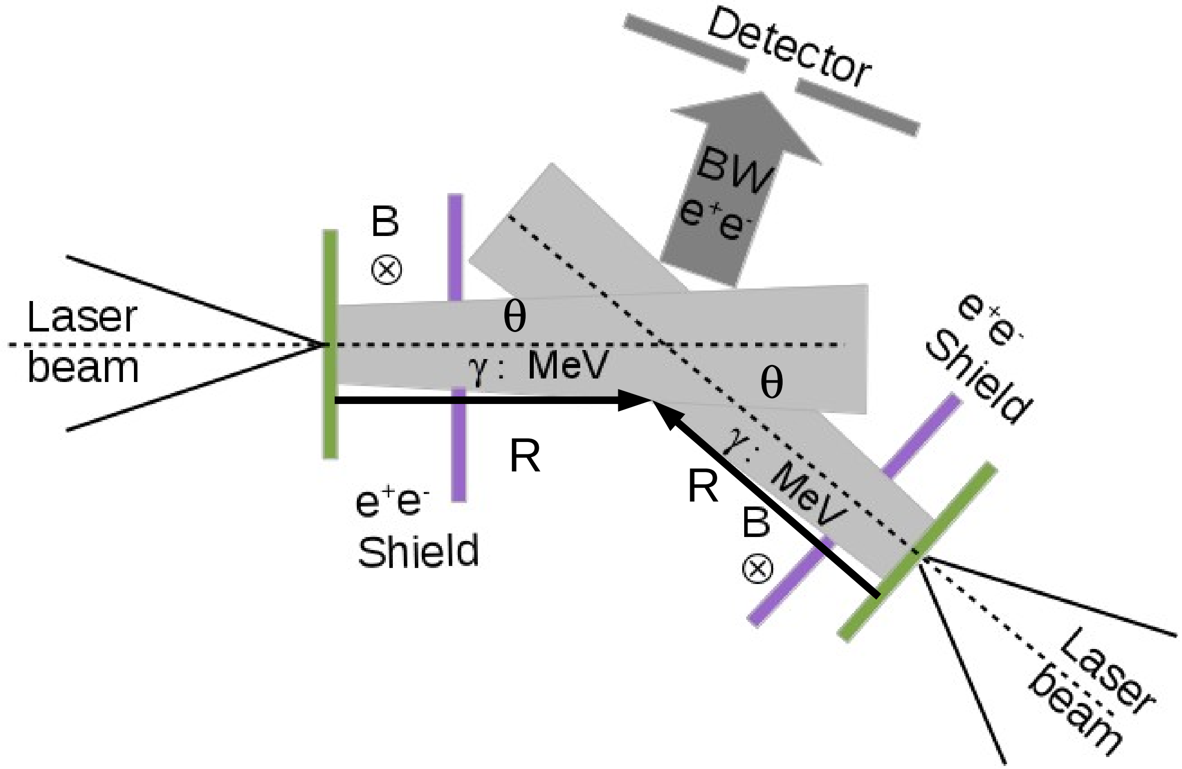


Possible experimentation on LMJ-PETAL facility

Caveat : Noise due to the positrons created with the Bethe-Heitler and Trident processes

[1] Pike, O. J. et al. Nature Photonics, **8**, 434, (2014)

(2) Collision of MeV-MeV photons



θ : γ–beam divergence

R : distance between γ source and photons collision zone

$$N_p = 10^8 E_\mathrm{J}^2 / R_{\mu\mathrm{m}}^2 (1 - \cos(\theta))$$

MeV-MeV photons collision

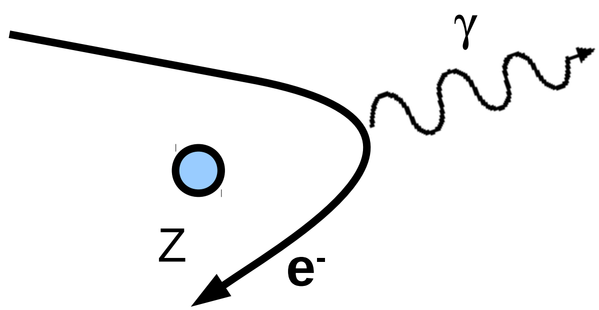
$$\mathrm{E_J} = 1 - 10\,\mathrm{J}\ \text{and}\ \mathrm{R} = 500\,\mu\mathrm{m}\quad \theta = 30°$$

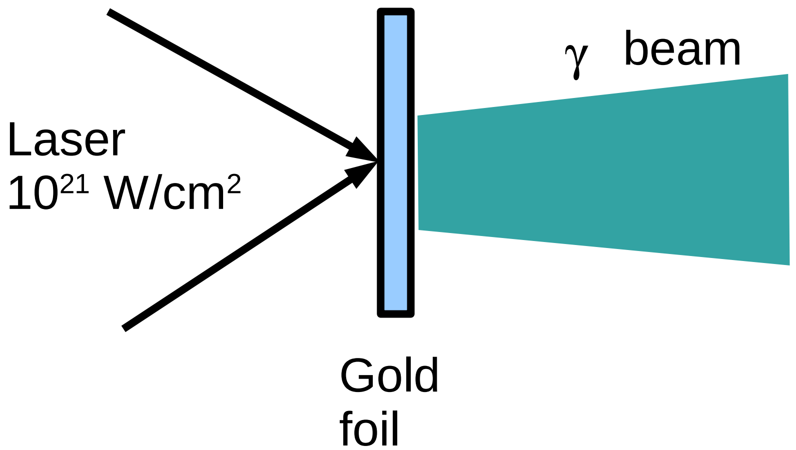
Pair production per Shot : $\mathrm{N}_p = 3 \times 10^3 - 3 \times 10^5$

Need for high-intensity collimated MeV photon beams

γ–ray sources in MeV range (1)

Bremsstralhung source *





Gamma beam characteristics

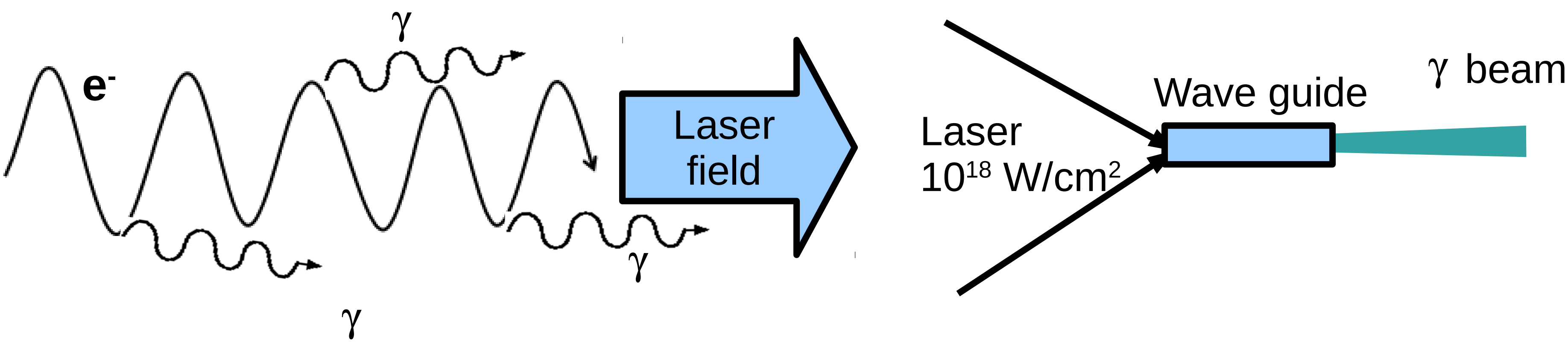
Beam Energy : 1-2 J   γ Energy : 3-50 MeV   Divergence : $\theta=15°$

The beam characteristic are interesting
But because of high-Z target there is lot of pair creation due to BH and Trident process inside the target

*Henderson A. et al. High Energy Density Physics **12**, 46 (2014)

γ–ray sources in MeV range (2)

Betatron source *



Incoherent photon source

Gamma beam characteristics

Beam Energy : 1 μJ

γ Energy : 1-7 MeV

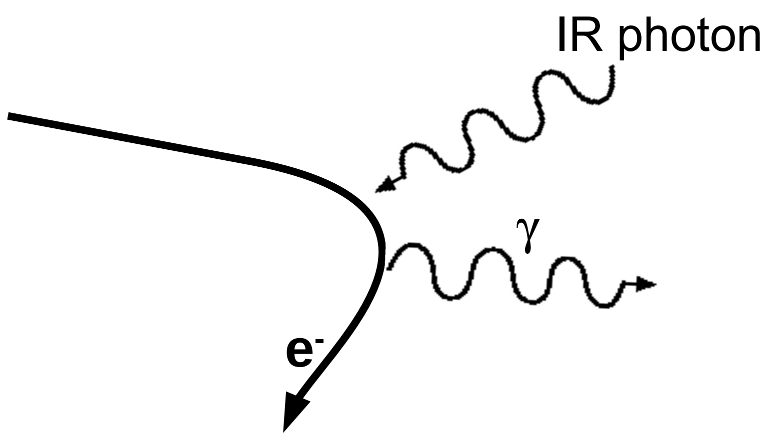
Divergence : $\theta = 1°$

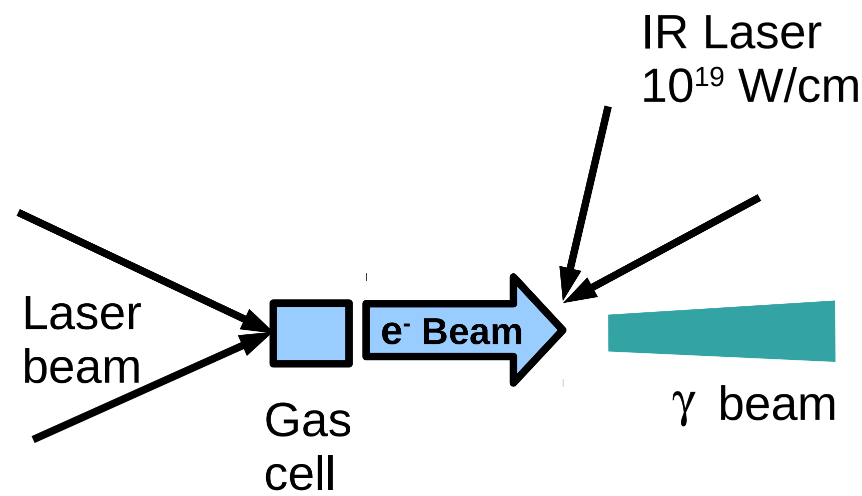
Too low energy beam for efficient pairs production

* Cipiccia S. et al. Nature Physics **7**, 867 (2011)

γ–ray sources in MeV range (3)

Compton source *





Gamma beam characteristics

Beam Energy : 10 µJ

γ Energy : 1-10 MeV

Divergence : $\theta = 1°$

The beam characteristics are interesting
Too low energy for efficient pair production

*Sarri G. et al. PRL **113, 224801** (2014)

γ–ray sources in MeV range (4)

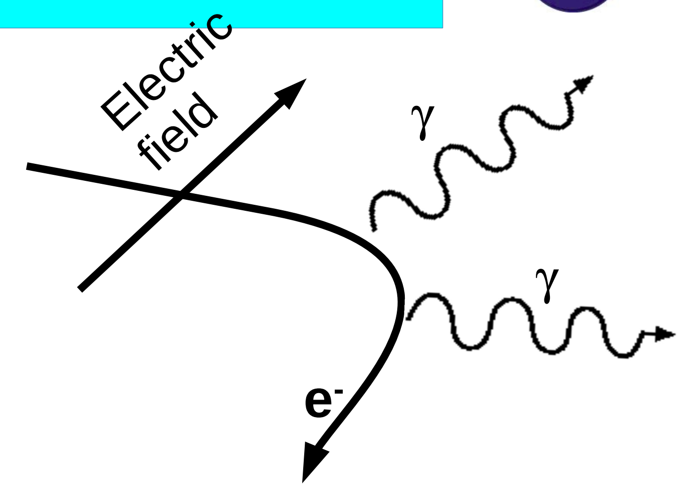
Synchrotron emission[1,2]

Reaction force[1]

$$\frac{d\vec{P}}{dt} = -e(\vec{E} - \frac{\vec{v}}{c} \times \vec{B}) - \vec{R}$$

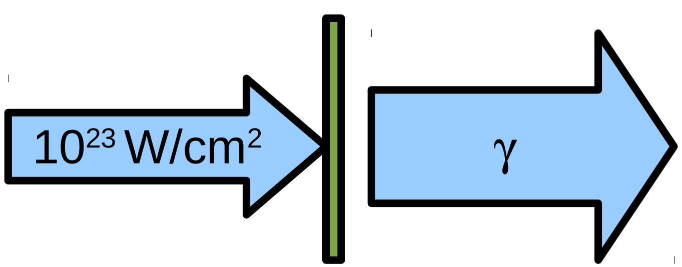
Lorentz force

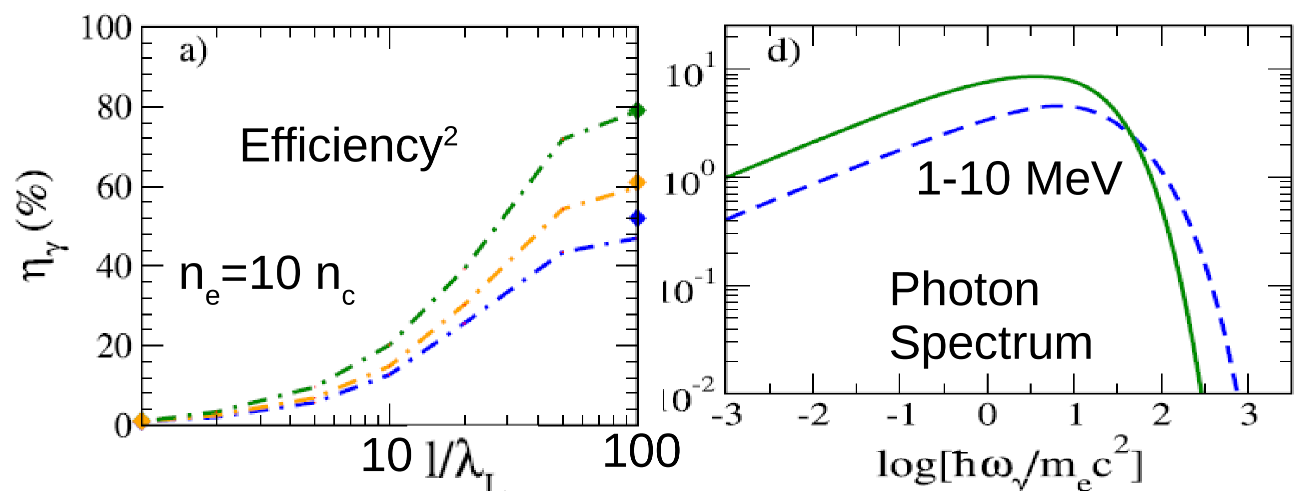
Radiation reaction force (self force)



$$I > 10^{23}\mathrm{W/cm}^2$$

Radiated energy during acceleration is close to its kinetic energy, it yields, radiation reaction is important





Gamma beam characteristics

Beam Energy : 1-10 J   γ Energy : 1-10 MeV   Divergence : θ=30°

[1] Landau and E. Lifschitz, The Classical Theory of Fields (1994); Sokolov I. V., J. Exp. Theor. Phys. 109 207 (2009)

[2] Capdessus, R. et al. PRL **110** (2013), Capdessus, R. PoP **21** (2014)

γ–ray sources in MeV range

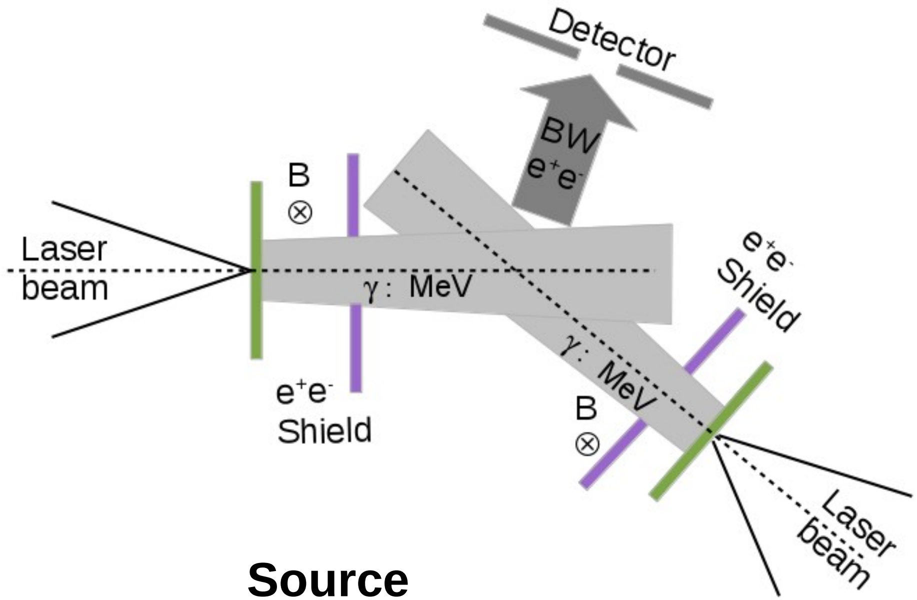
Performances comparison between different γ–ray sources

Sources	Bremss.	Betatron	Compton	Synch.
γ energy	3–50 MeV	1–7 MeV	6–18 MeV	1–10 MeV
Beam energy	1–2 J	1 μJ	1 μJ	1–10 J
Efficiency	$1\text{–}2\times10^{-2}$	10^{-6}	10^{-7}	10^{-1}
Divergence (θ)	$\sim15^\circ$	$\sim 1^\circ$	$\sim1^\circ$	$\sim 30^\circ$
Reference	[23]	[29]	[32]	[30]
N_p from Eq.(3) at $R = 500$ μm	$\sim 10^4$	$\sim 10^{-5}$	$\sim 10^{-5}$	$\sim 10^4$

Synchrotron radiation sources seems a good choice for pair production
Possibility to use gas target (low noise source)

[23]Henderson A. et al. High Energy Density Physics **12**, 46 (2014)
[29]Cipiccia S. et al. Nature Physics **7**, 867 (2011)
[32]Sarri G. et al. PRL **113, 224801** (2014)
[30]Capdessus, R. et al. PRL **110** (2013), Capdessus, R. PoP **21** (2014)

Collision of MeV-MeV photons from PIC simulations



Source

- Conversion 10-20 % of laser energy
- 10^{13} photons up to 1 MeV
- 10^{12} photons in 1-3 Mev range
  Forward emitted [0, π]

Pair production with pure BW process

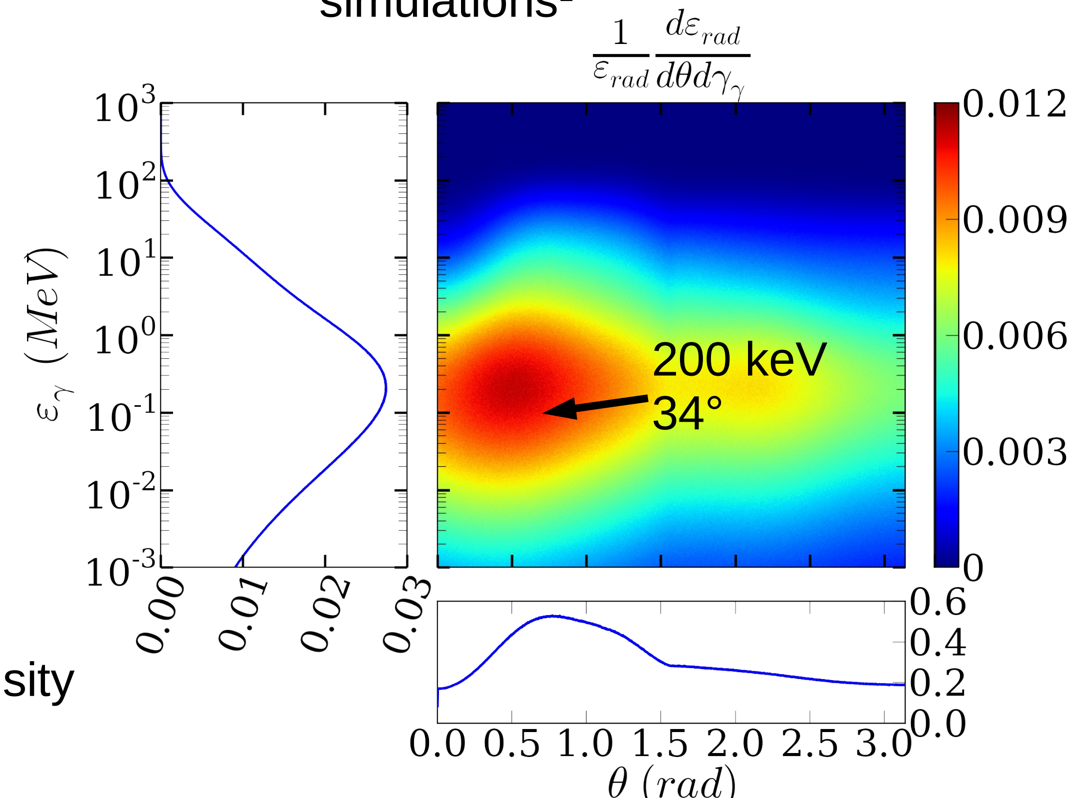
- Head on collision : **10^8 pairs**
- At R=500 µm distance : **10^4 pairs**
- the pair production decrease with photon density

-Laser parameters (ELI Facility)

λ_L=0.8 µm, τ_L=15 fs,
150 J, 10 PW   I =10^{23} W/cm^2
Φ_L=3 µm, 0.05 Hz

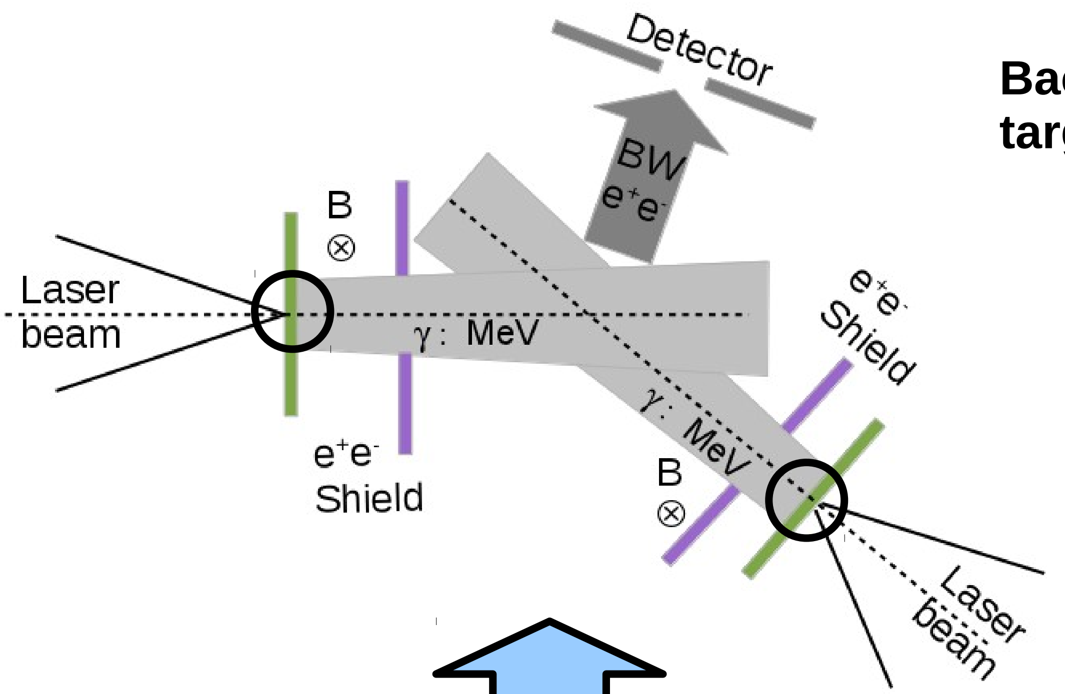
-Target properties Aluminium
(1.7 g/cc, n_{Al}=60 n_c)

Normalized spectrum of photon source from PIC simulations[1]



[1]Lobet, M. et al. ArXiV:1311.1107 (2013)

Other e⁺e⁻ pair production can perturb the detection of BW pairs



Background pairs production during laser target interaction from PIC simulations

- Non-linear BW pairs : **10^5**
- Trident pairs : **10^7**
- Bethe-Heitler pairs : **10^9**

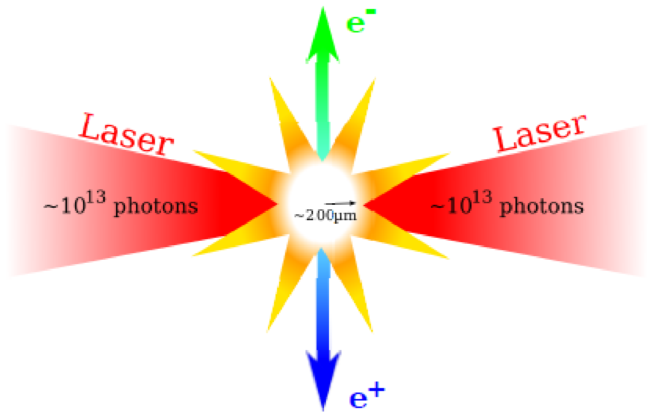
The Bethe-Heitler ten time than
Breit-Wheeler pairs
if we collide photon right near the target foil

For the pure BW pair production in vacuum we need to separate the source from the collision zone

[1]Capdessus, R. et al. PRL **110** (2013), Capdessus, R. PoP **21** (2014)

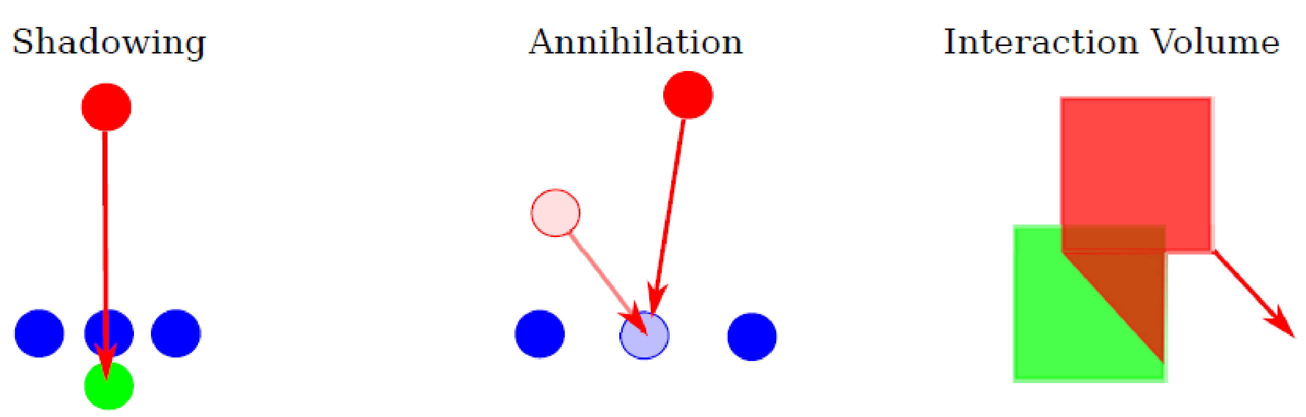
Photon-Photon beam collision simulations (1)

Physical situation



Large number of photons collide. Regular *PIC* approaches would lead to massive particles. Simply computing collision rates of photons of two macro-particles leads to problems:

Three non-physical artefacts of a statistical approach, that change collision rates.



Also, any probabilistic aspect of the phenomenon is gone.

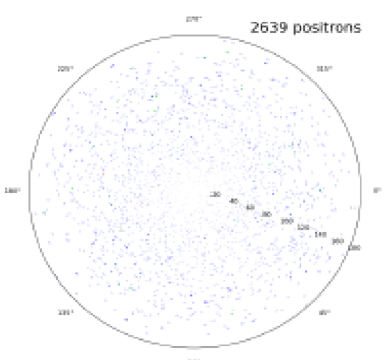
Photon-Photon beam collision simulations (2)

Results from three different methods :
All simulations were done on a modern desktop PC

Bounding volume hierarchies

Using 100.000 macro particles, $N_{total} = 1Mio.$.

Runtime about 1hrs.

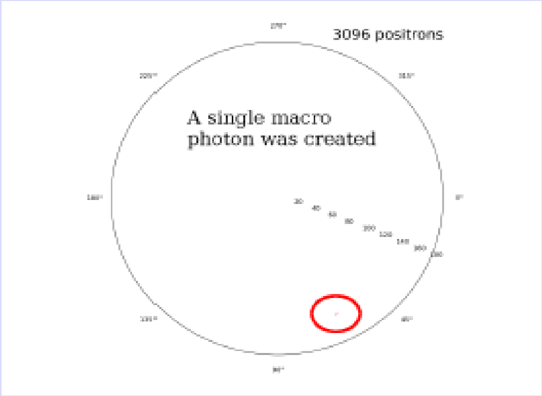


2639 BW-Pairs

Statistical collision rates

Using 1 macro particle, $N_{total} = 1Mio.$.

Runtime less than 1 min.



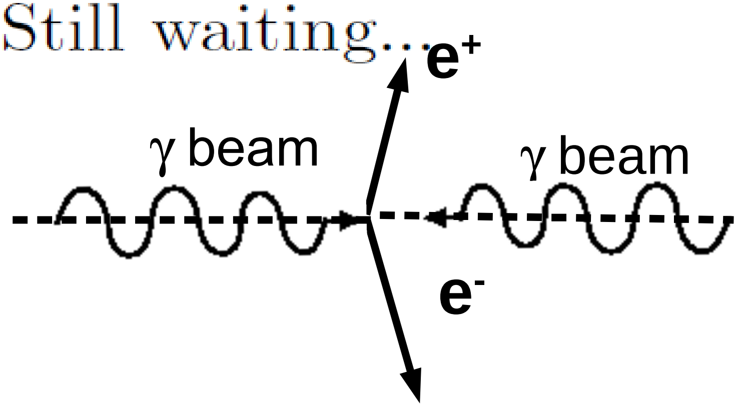
3096 BW-Pairs

Classical PIC

Using 100.000 macro particles, $N_{total} = 1Mio.$.

Runtime >> 1 hrs.

Still waiting...



Conclusions

Pure Breit-Wheeler pairs creation :

- Never been observed experimentally
- Great interest for fundamental physics and astrophysics

Three experimental schemes

- **250 GeV - eV Photons** collider : SLAC experiment:
  0.01-0.2 pair per shot : Non-linear BW process

- **GeV - 100 eV Photons** collider
  until **10^4** pair per shot (1 shot per day)
  Possible experiment on **LMJ-PETAL** facility
  Need high brilliance GeV electron and photon beam
  Pairs created inside Hohlraum

- **MeV - MeV Photons** collider **10^4** pair per shot[1]
  (laser repetition rate > **1 shot per min**)
  Possible experiment on **ELI** or **APOLLON** facilties
  Need a separation between photons source and photons collision zone

Further Studies : - Source optimisation : PIC simulations of MeV synchrotron photon source
- Monte Carlo simulations of pairs production during Photon-Photon collision[2]
- Toward experimental proposal

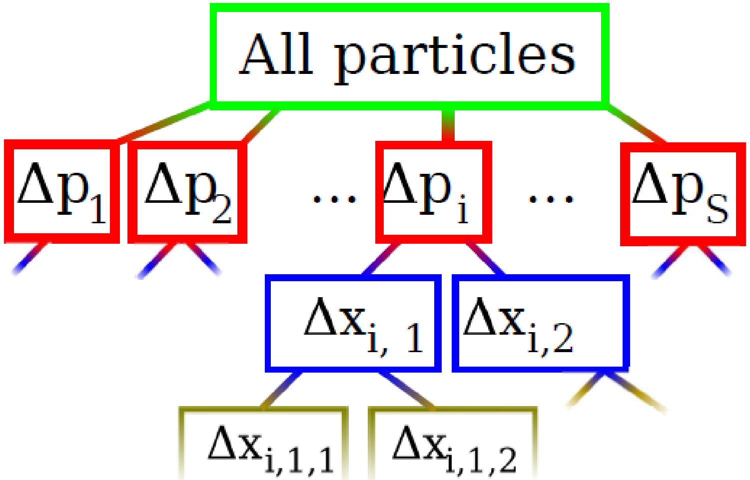
[1] Ribeyre X. et al. arXiv:1504.07868v1, 29 Apr 2015

[2] Oliver Jansen et al. Paper In preparation

Photon-Photon beam collision simulations

Bounding volume hierarchies

Creating more particles in order to have a better statistic leads to numerical challenges. Collision detections between all N particles involved lead to N^2 queries.
Bounding volumes (BVs) can reduce N by orders of magnitude. A bit like particles-in-particles-in-particles-in...



Phase space is divided into co-moving particles and then spatially.
On high levels only a small number of BVs exist. Descent deeper into the tree only occurs, if higher level BVs collide.
Thus, each particle is only checked against a small number of possible collision partners.

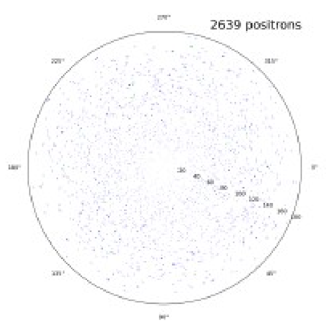
Photon-Photon beam collision simulations

Direct comparison

Three simulations with different angle, but otherwise the same parameter:

2639 BW-Pairs

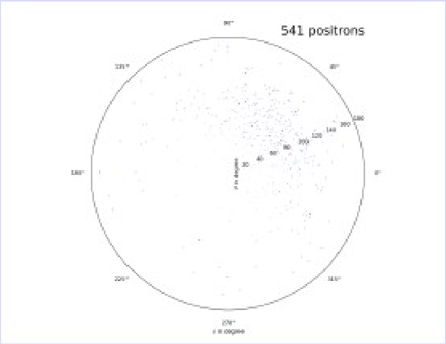
180°



Uniform distribution of pairs.

541 BW-Pairs

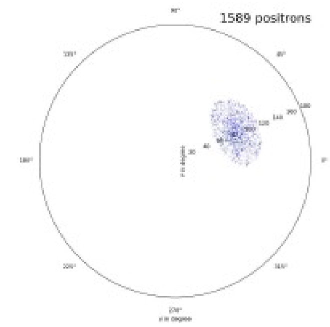
90°



Significantly less particles, slightly more focussed.

1589 BW-Pairs

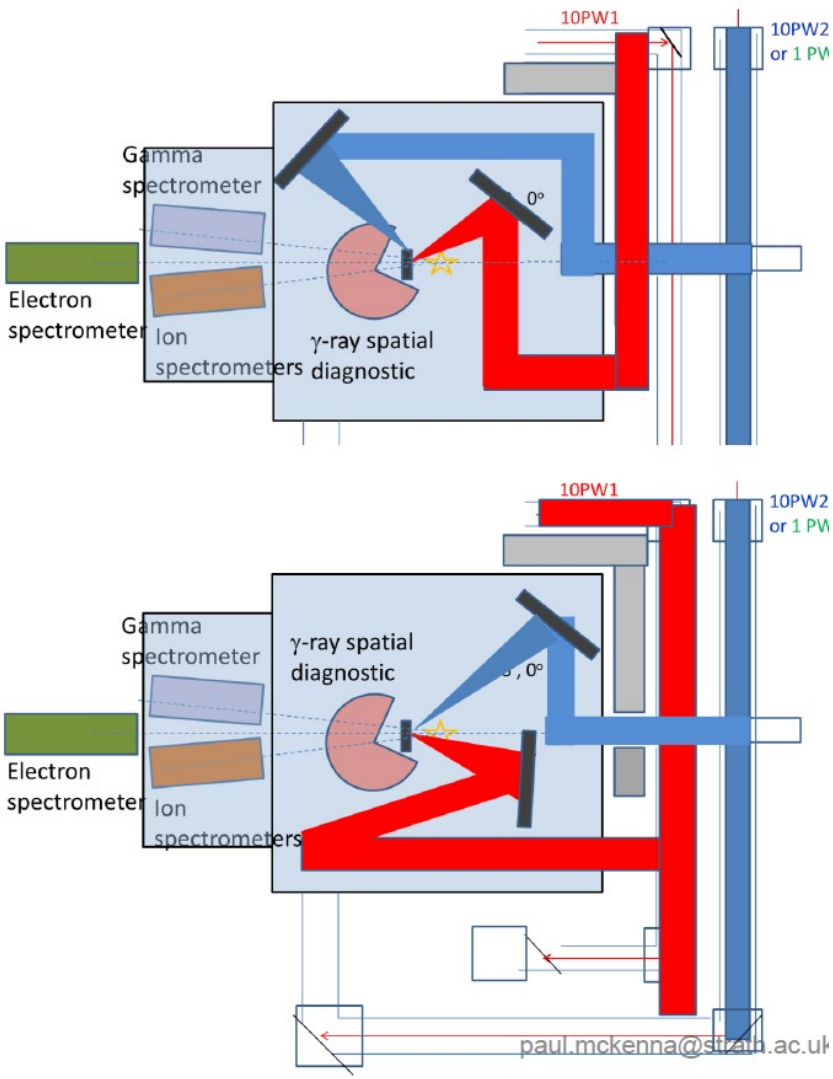
45° (co-propagating)



Somewhat fewer particles, but well collimated.

Beam geometry on ELI -NP laser facility

Laser-based Nuclear Physics pillar of ELI
that will focus on high-intensity laser-based nuclear physics (Bucharest-Magulrel Romania).



Two 10 PW beams (100 J, 15 fs)
Intensity on target
10^{23} – 10^{24} W/cm²
0.1 Hz

With different beams Interaction angles (operational 2017)

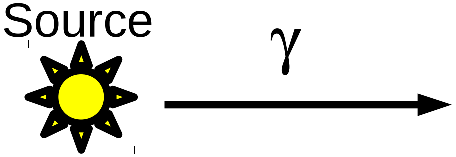
Photon-Photon collision and pair production in astrophysics[1]

Breit-Wheeler process[2]
Collision of two light quanta

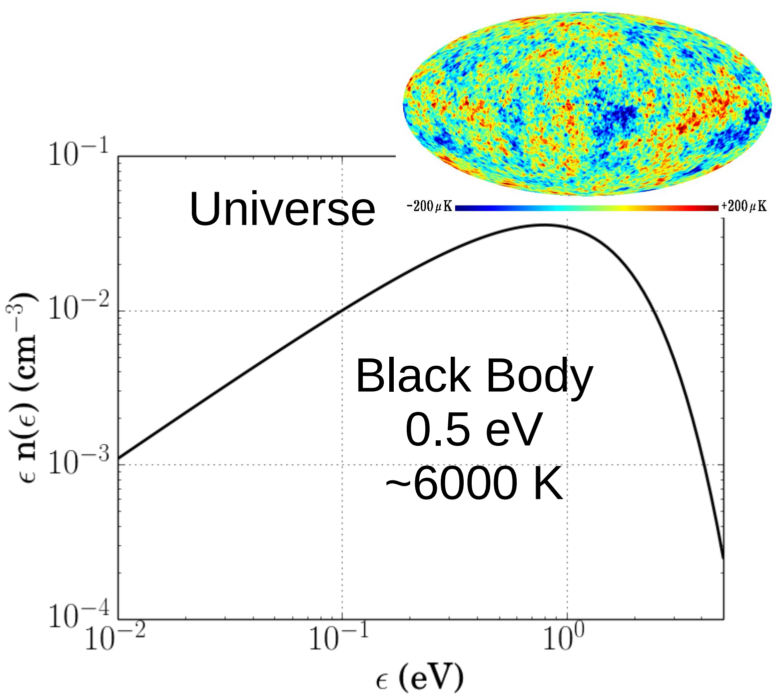
$$\gamma + \gamma \longrightarrow e^+ + e^-$$

- Absorption of hight energy photon in the universe[3], **cut-off in high energy gamma rays**

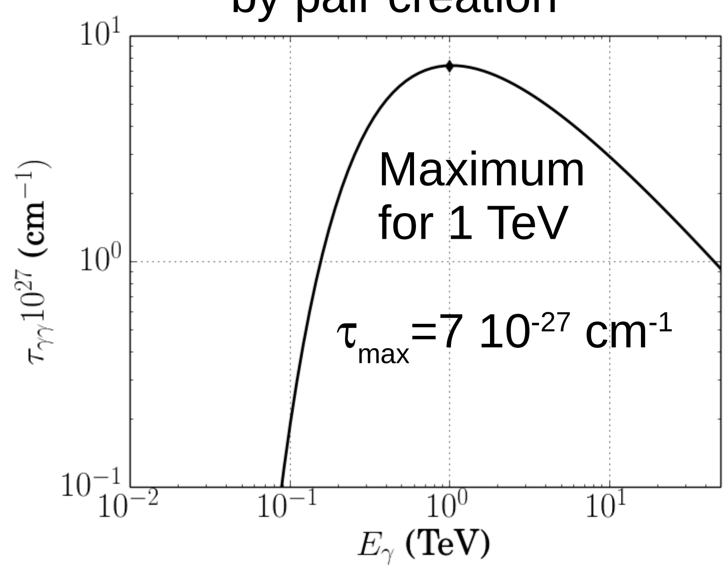
Nikishov[3] (1962) first showed that the maximum of absorption in universe is around 1 TeV



R_c= distance
Source-observateur
(Cygnus A)



Absorption (opacity)
by pair creation



Attenuation : $\eta=\exp(\tau R_c)$

R_c=6.6 10^{26} cm = 213 Mpc $\eta=\exp(4.6)$

[1]Ruffini, R. et al. Physics Reports, 487, 1-140 (2010)
[2]Breit, G. and Wheeler J. A. PRL **15** (1934)
[3]Nikishov A. I., JETP **14** (1962), Gould, R. J. PRL **155**, 5 part 1, part2 (1967), Kneitske, T.M. et al. A&A 413, 807 (2004)

e^+e^- pair cross sections

Signal : Pure BW

-Linear BW pairs: $\gamma + \gamma \longrightarrow e^+ + e^-$ $\sigma \propto r_e^2$

Noise : Main pairs production process during laser target interaction[1]

- **Non-linear BW pairs:** $\gamma + n\omega \longrightarrow e^+ + e^-$
  less probable than pure BW

- **Trident pairs** : $e^- + Z \longrightarrow Z + e^- + e^+ + e^-$ $\sigma \propto Z^2 \alpha^2 r_e^2$

- **Bethe-Heitler pairs** : $\gamma + Z \longrightarrow Z + e^+ + e^-$ $\sigma \propto Z^2 \alpha \, r_e^2$

$$\mathrm{r}_e = 2.8 \times 10^{-13} \mathrm{cm}$$
$$\alpha = 1/137$$

[1] Landau and Lifshitz, Quantum electrodynamics

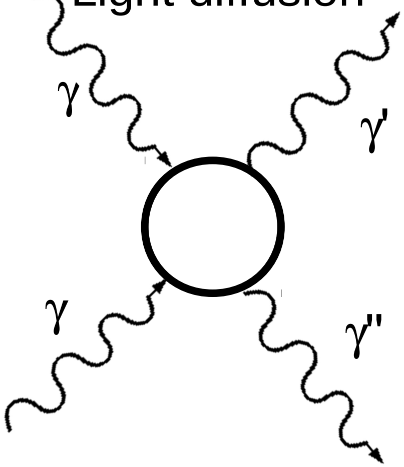
Pure photon-photon collision

Light-light scattering does not occurs in classical electrodynamic (Maxwell equ. are linear)

In QED theory

$$\hbar\omega \leq m_e c^2$$

Light diffusion



$$\sigma_{\gamma\gamma} \simeq 3 \times 10^{-2} \alpha^2 r_e^2 \left(\frac{\hbar\omega}{m_e c^2} \right)^6$$

$$\hbar\omega = 400\,\mathrm{keV}$$

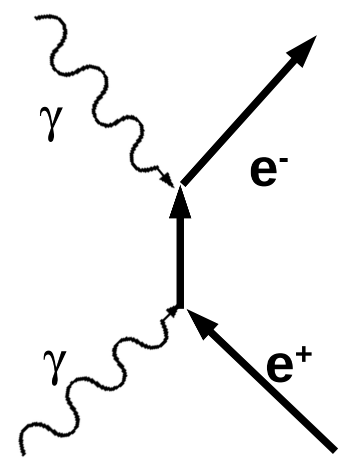
$$\sigma_{\gamma\gamma} \simeq 3.7 \times 10^{-7} r_e^2$$

$$\sigma_{\gamma\gamma} = 3 \times 10^{-32} \mathrm{cm}^2$$

$$\ll$$

$$\hbar\omega \geq m_e c^2 = 511\,\mathrm{keV}$$

Breit-Wheeler process



$$\sigma_{\gamma\gamma} \simeq r_e^2$$

$$\sigma_{\gamma\gamma} \simeq 8 \times 10^{-26} \mathrm{cm}^2$$

Photon-Photon collision and pair production in laboratory (SLAC)

Non-linear Breit-Wheeler process[1]

$\gamma + n\omega \longrightarrow e^+ + e^-$

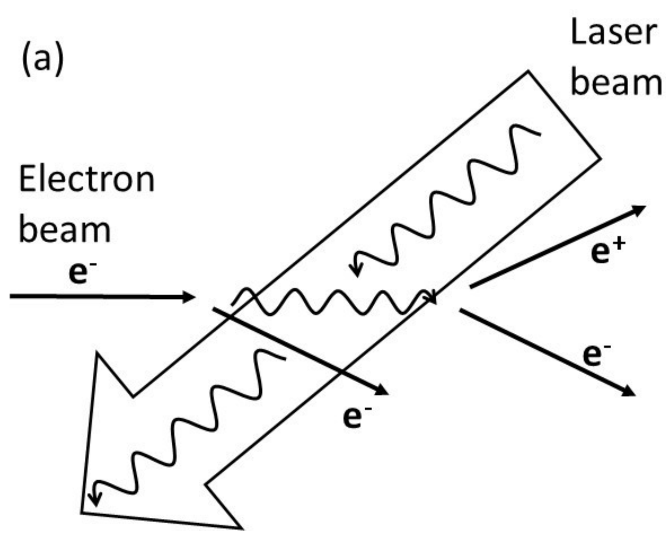
Two steps process

Laser ω 2.35 eV

1- Non-linear Compton scattering

$e\ (46\ \mathrm{GeV}) + n\omega \longrightarrow e' + \gamma\ (29\ \mathrm{GeV})$

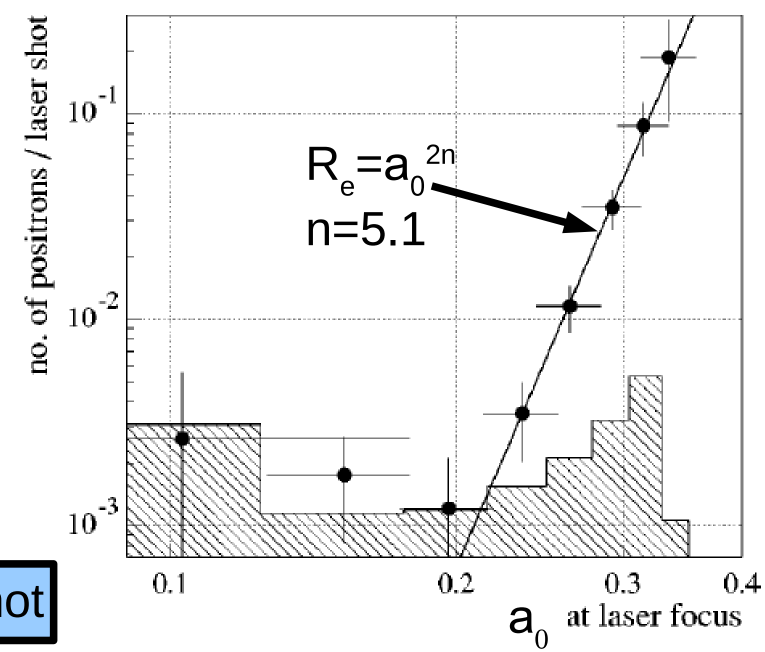
SLAC electrons γ 46.6 GeV



First observation of non-linear Breit-Wheeler pair production with real photons[2] (with n>4)

2- Non-linear Breit-Wheeler pair

$\gamma + n\omega \longrightarrow e^+ + e^-$



$R_e = a_0^{2n}$

n=5.1

Nb of interacting photon becomes large if $a_0>1$

$a_0 = e\,E/m\omega_0$

0.01 - 0.2 pair per laser shot

[1]Bamber, C. et al. PRD, 60 092004 (1999)

[2]Burke, D. L. et al. PRL 79, 9 (1997)