Quantum radiation reaction, e^+e^- pair production and acceleration in laser-electron beam scattering configurations

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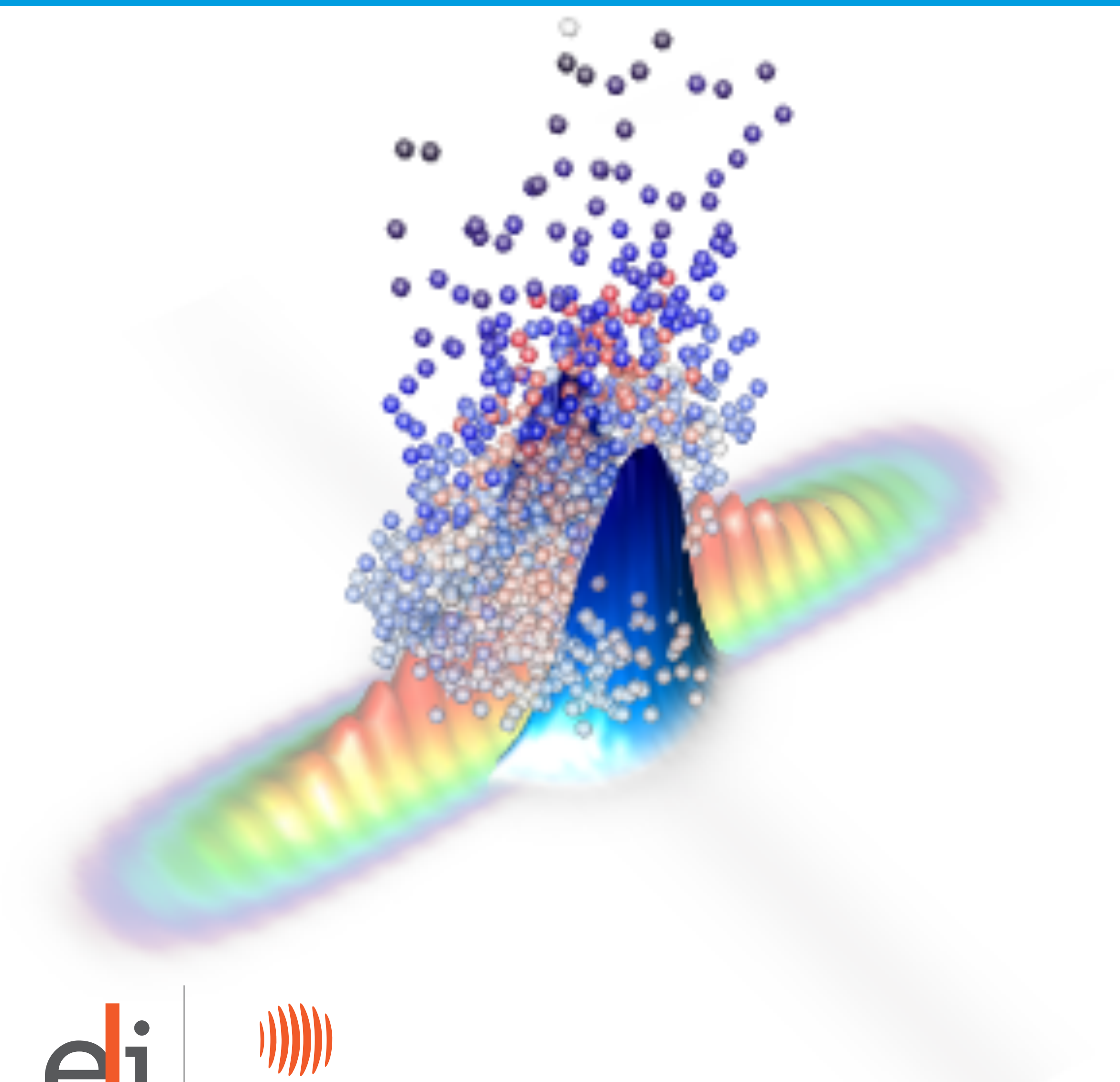

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Acknowledgments

Work in collaboration with:

T. Grismayer, R. A. Fonseca, L. O. Silva (IST)

O. Klimo, G. Korn, S. Weber (ELI Beamlines)

Simulation results obtained at Supermuc (PRACE), Eclipse cluster (ELI) and Salomon cluster (IT4I)

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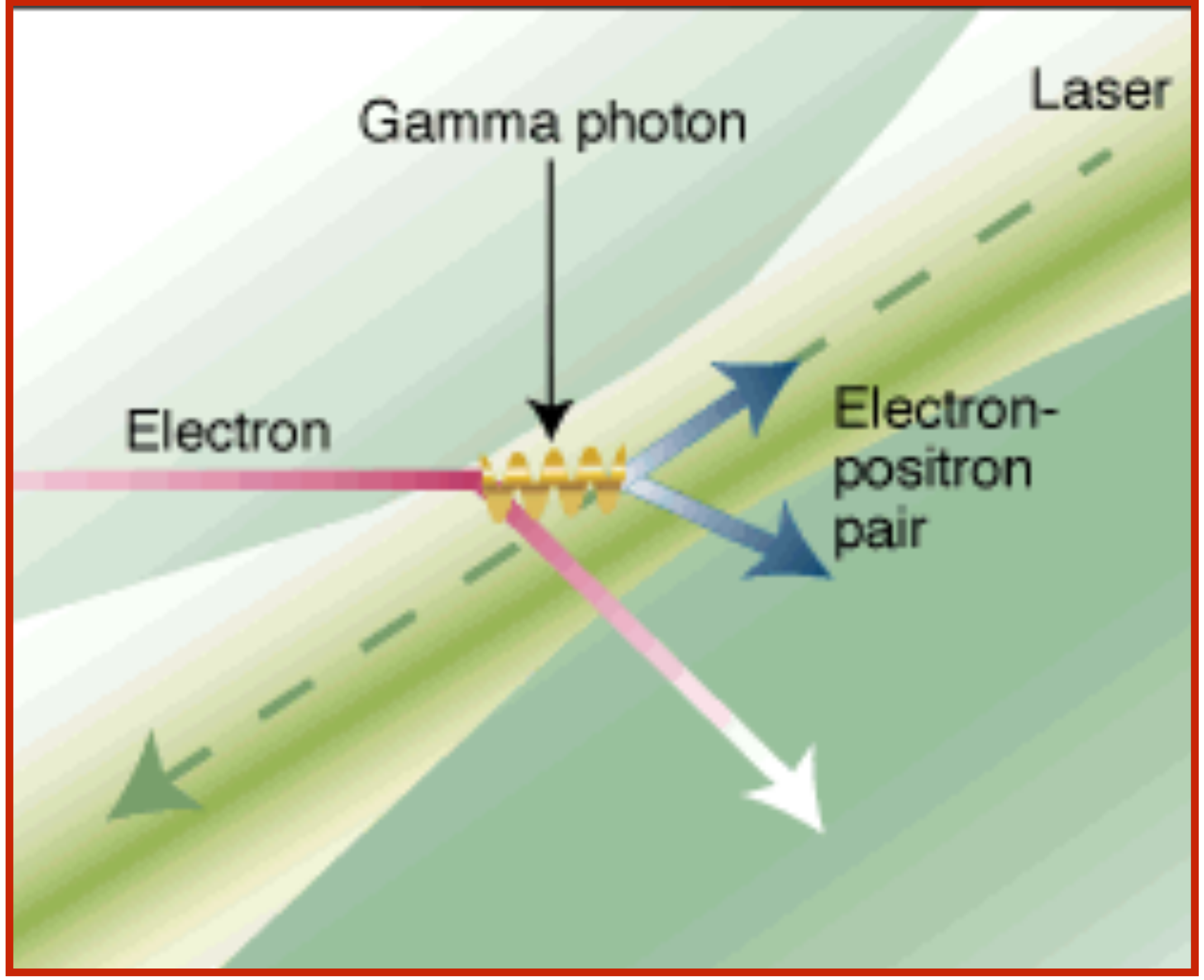
SLAC E-144 experiment, BW process*

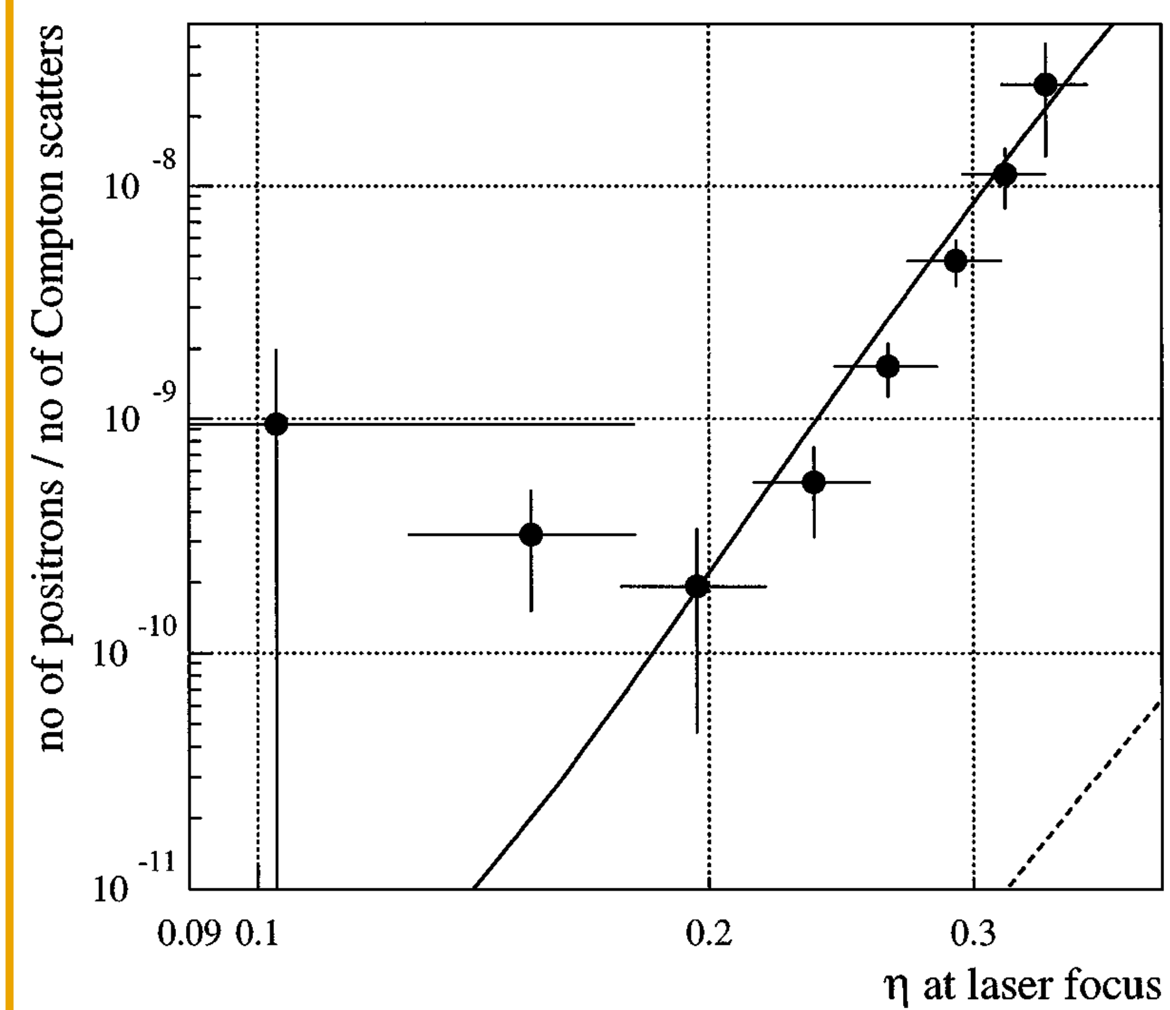
Setup



Laser: 1.6 ps, 1 um, I = 10^{18} W/cm^2

Electron energy: 46.6 GeV

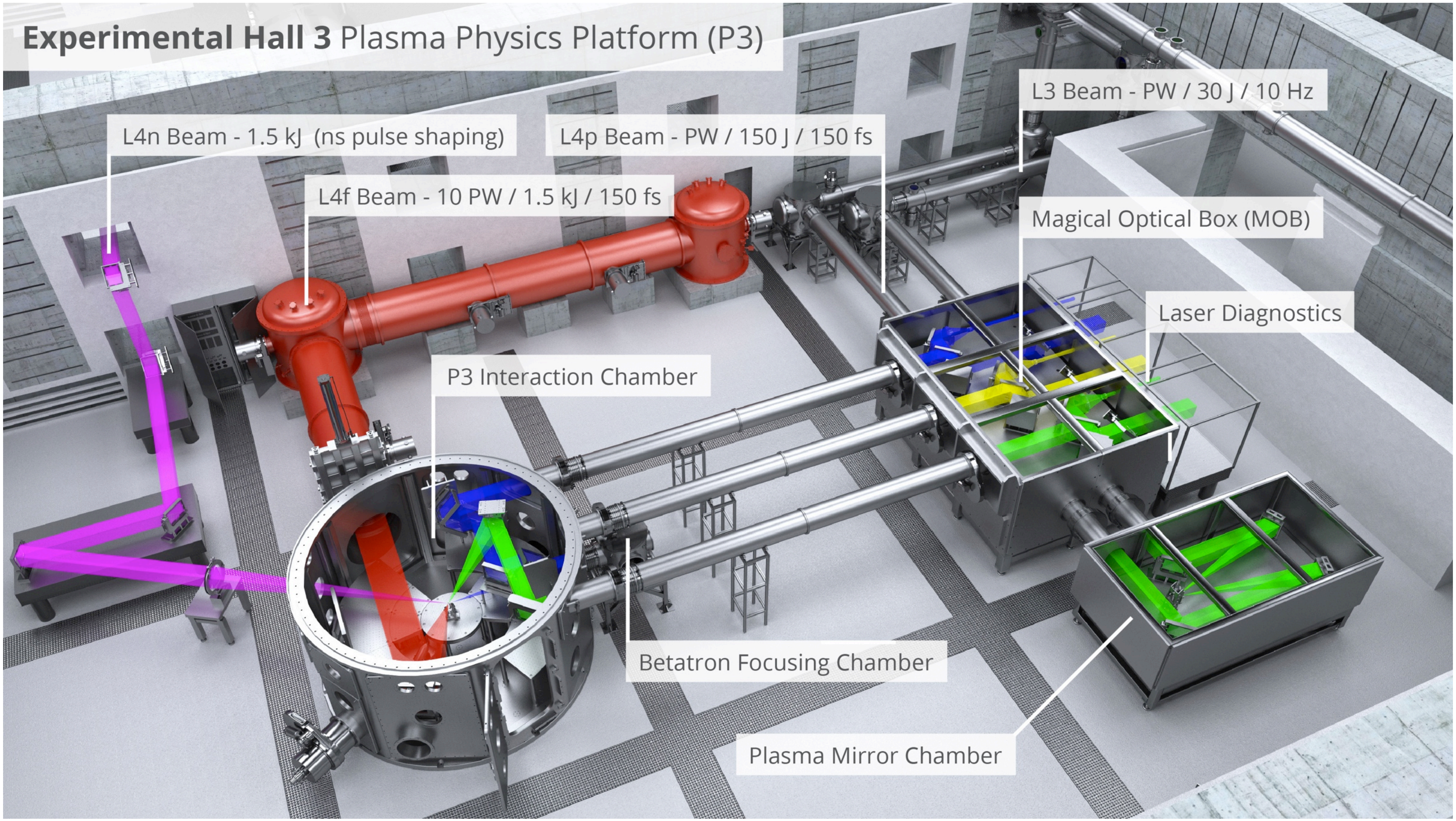
~ 100 positrons



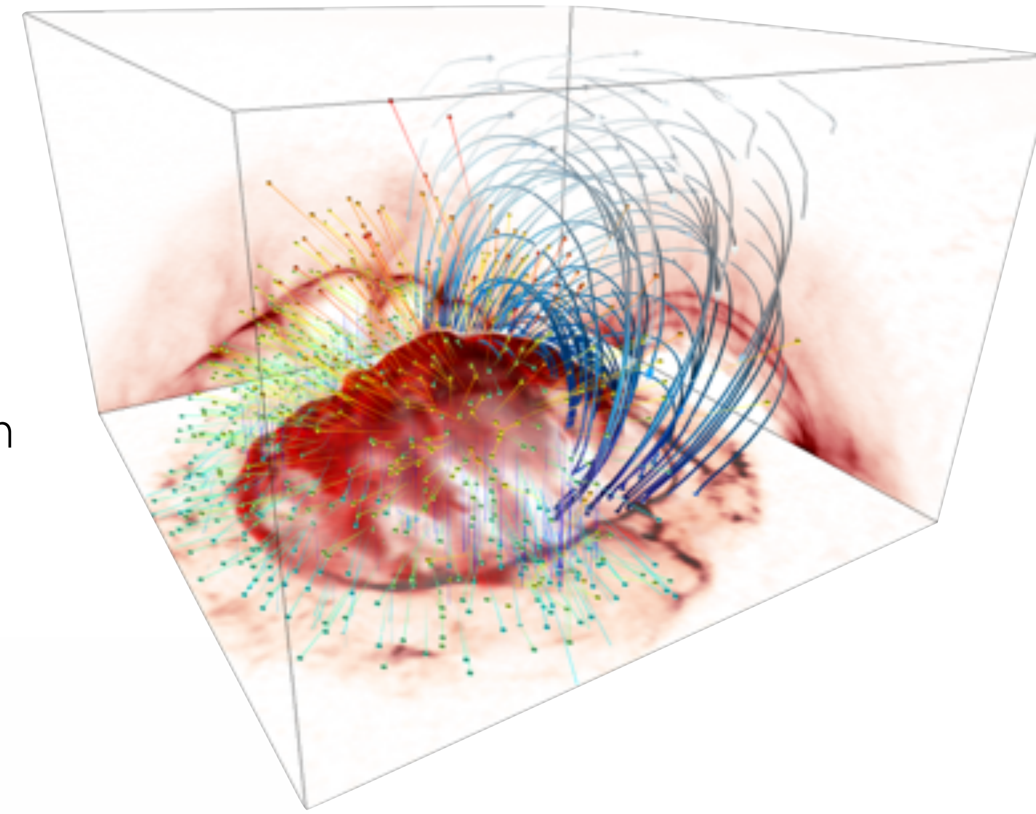
* D.L. Burke et. al., Phys. Rev. Lett.. 79, 1626-1629 (1997)

We expect a 10 PW beam at ELI

L4 will deliver 1.5 kJ in 150 fs (can get a_0~1000), in the same chamber as L3 (30 J, 30 fs)

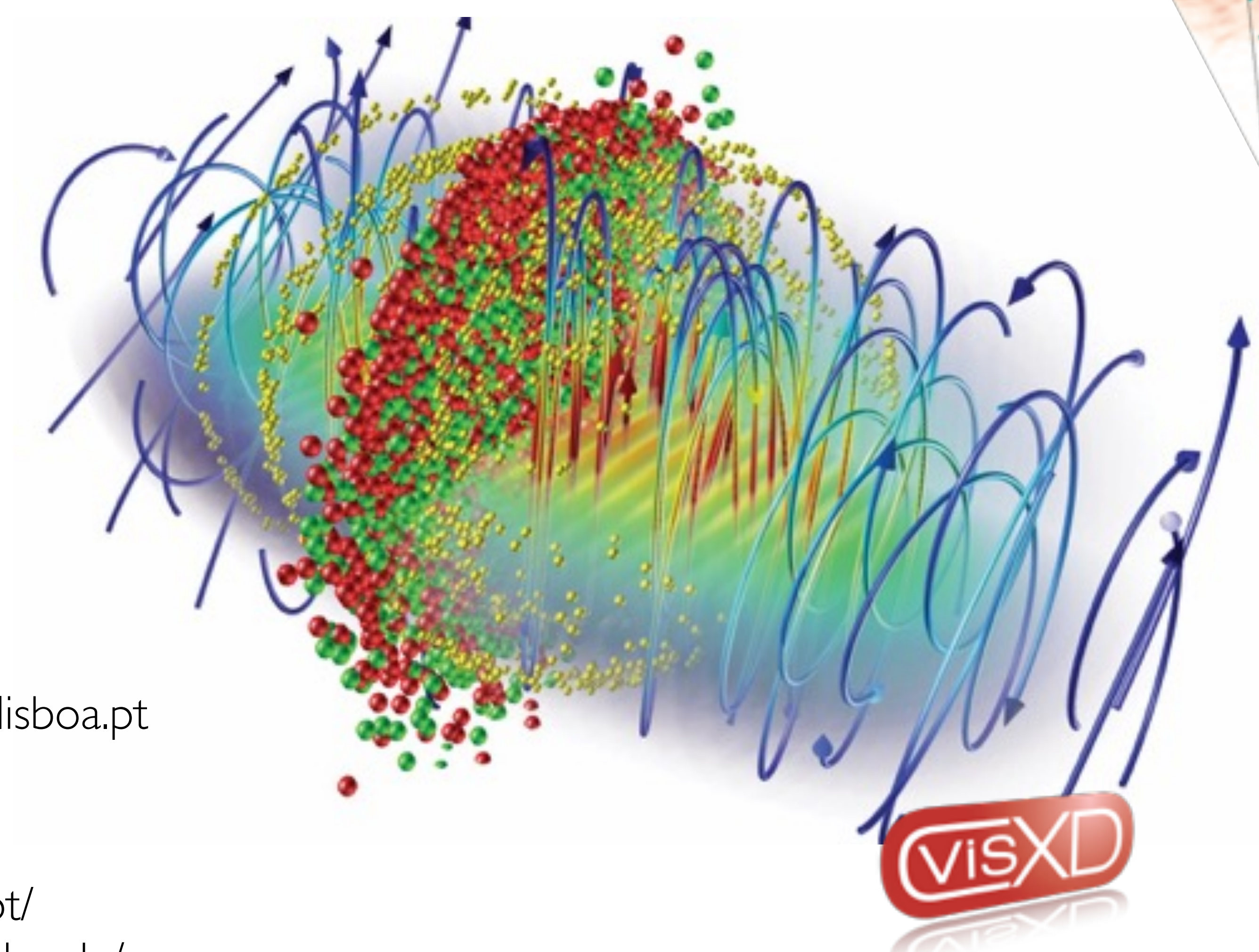


OSIRIS 4.0



osiris framework

- Massivelly Parallel, Fully Relativistic Particle-in-Cell (PIC) Code
- Visualization and Data Analysis Infrastructure
- Developed by the osiris.consortium
  ⇒ UCLA + IST



code features

- Scalability to ~ 1.6 M cores
- SIMD hardware optimized
- Parallel I/O
- Dynamic Load Balancing
- Particle merging
- GPGPU support
- Xeon Phi support
- QED Module

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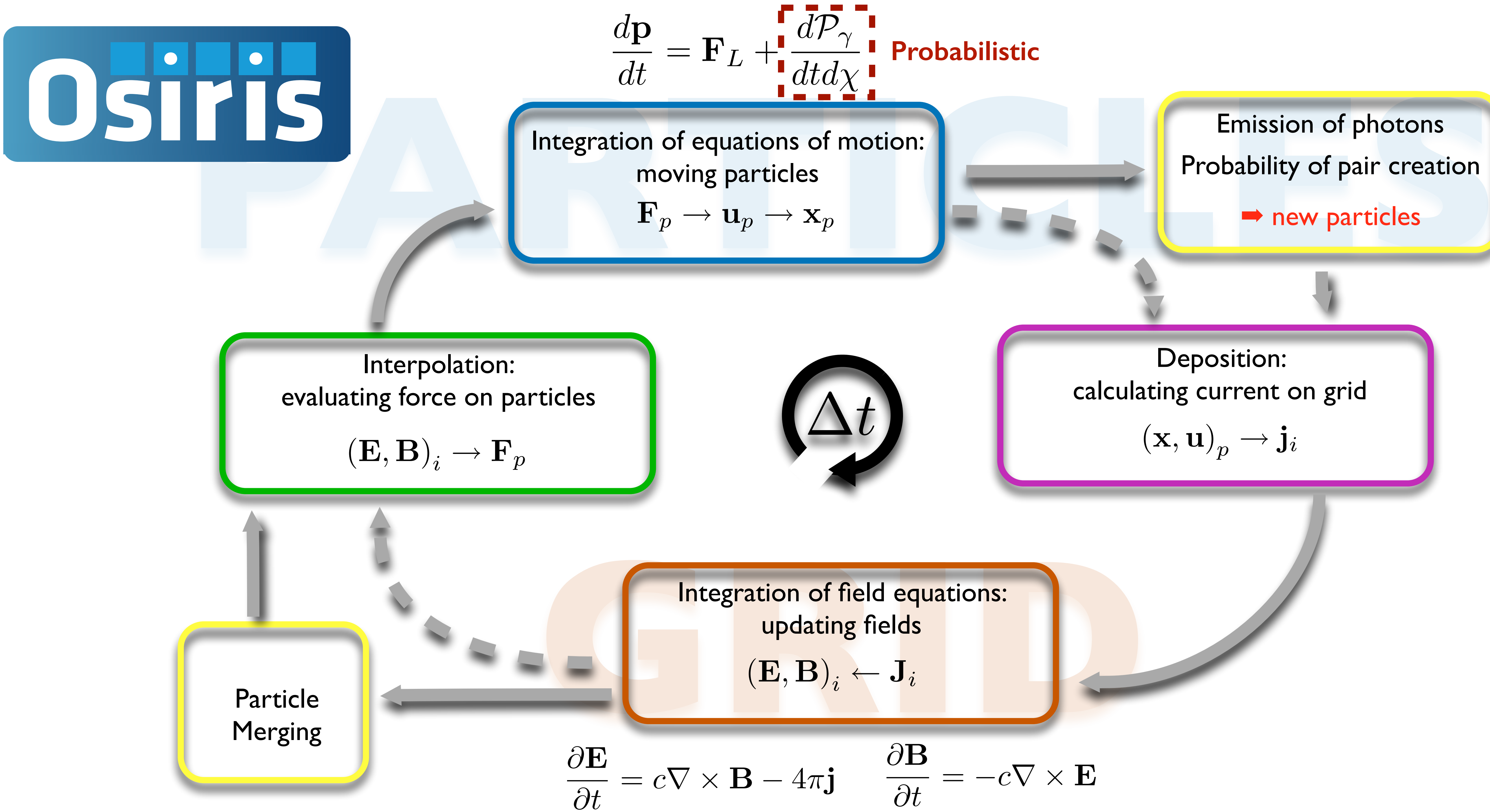
QED loop in OSIRIS

We can take into account the collective effects of laser - plasma interaction

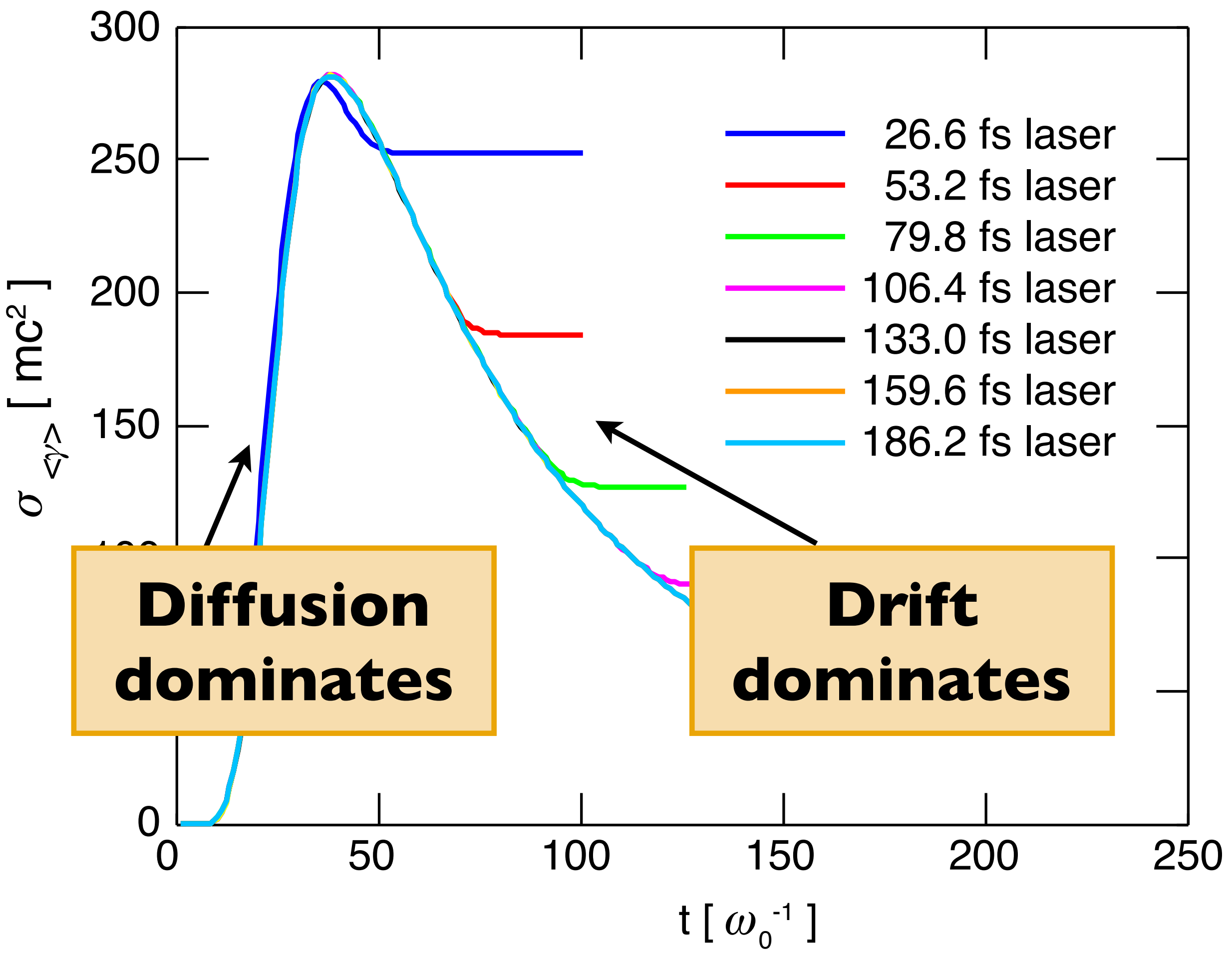


E.N Nerush et al. PRL (2011), C. P. Ridgers et al. , PRL. (2012)
N.V. Elkina et al. PRSTAB (2011), A. Gonoskov et al., PRE (2015)
T. Grismayer et al., POP (2016), T. Grismayer et al., PRE (2017)

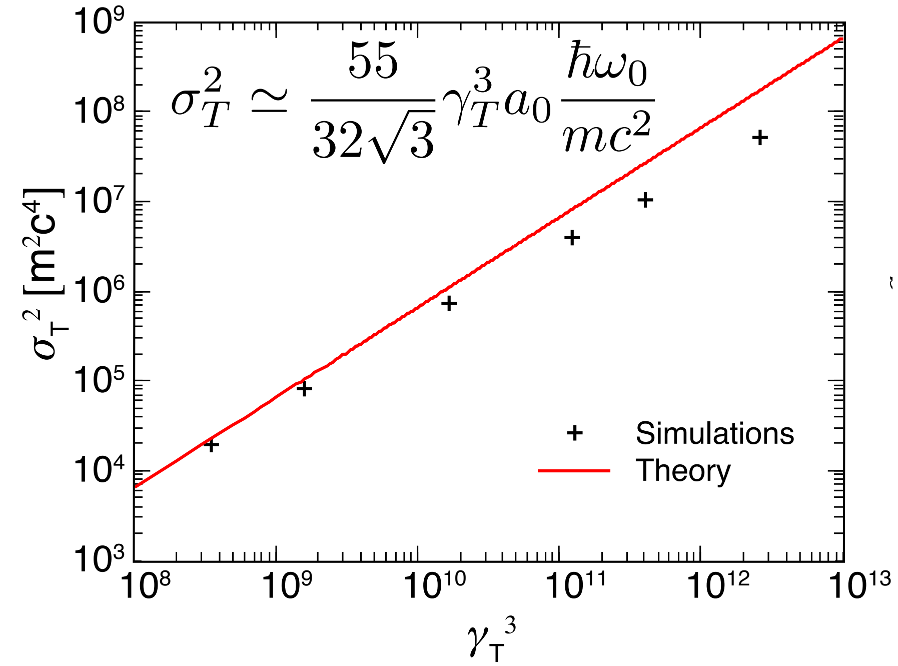
Quantum RR in laser-electron scattering

Fokker-Planck equation for the evolution of e⁻ distribution function

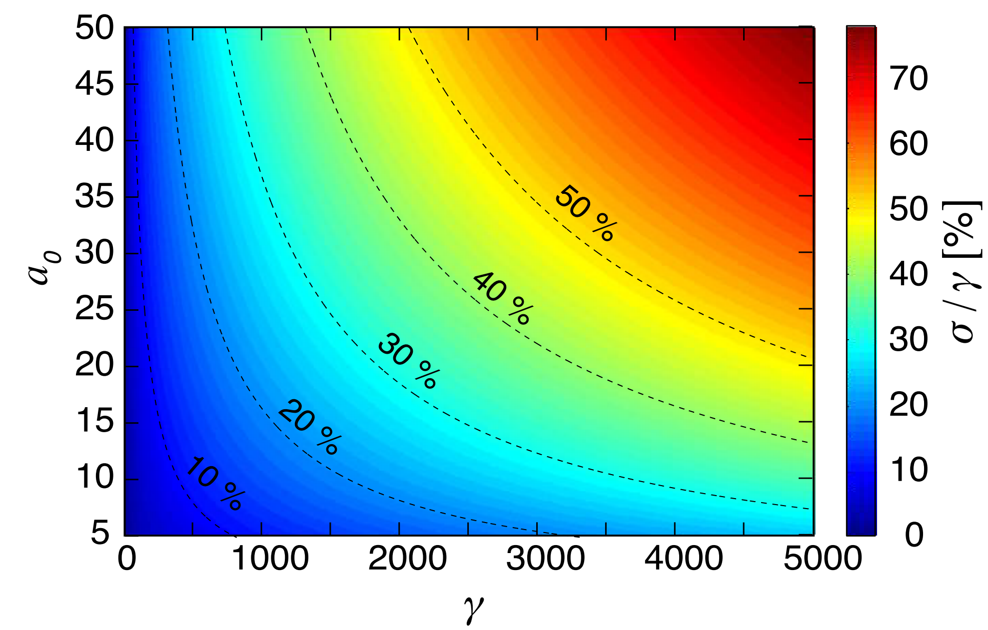
Standard deviation of energy vs. time



Turning point



Maximum attainable energy spread



M. Vranic, T. Grismayer et al., NJP 18, 073035 (2016)
V. N. Baier & V. M. Katkov, PRA 25, 492-493 (1967)
N. Neitz et al., PRL 111, 054802 (2013)
T. G. Blackburn et al., PRL 112, 015001 (2014)
D. G. Green et al., PRL 112, 164801 (2014)
S. Yoffe et al., NJP 17, 053025 (2015)
C. Ridgers et al., JPP 83, 715830502 (2017)
F. Niel et al, PRE 97, 043209 (2018)

Expected value for final energy spread emerges from stochastic diffusion

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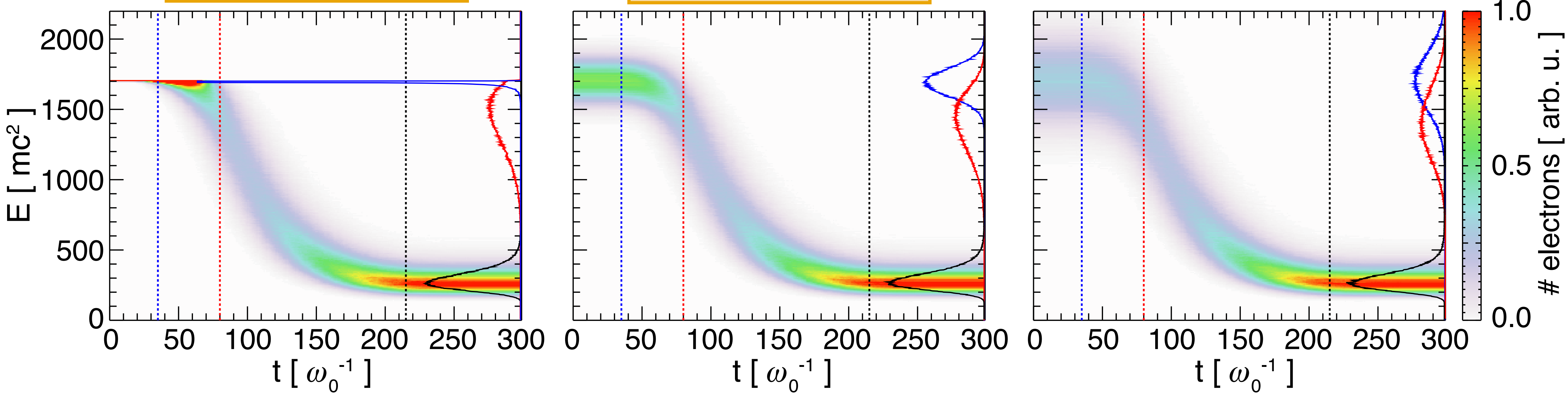
Energy vs. time for interaction with a 150 fs laser

$dE_0 = 2\ mc^2$ | **$dE_0 = 100\ mc^2$** | **$dE_0 = 200\ mc^2$**



$dE_F = 67\ mc^2$

Final energy spread

$$\sigma_F^2 \lesssim 1.455 \times 10^{-4} \sqrt{I_{22}} \frac{\gamma_0^3}{\left(1 + 6.12 \times 10^{-5} \gamma_0\ I_{22}\ \tau_0[\mathrm{fs}]\right)^3}$$

Divergence

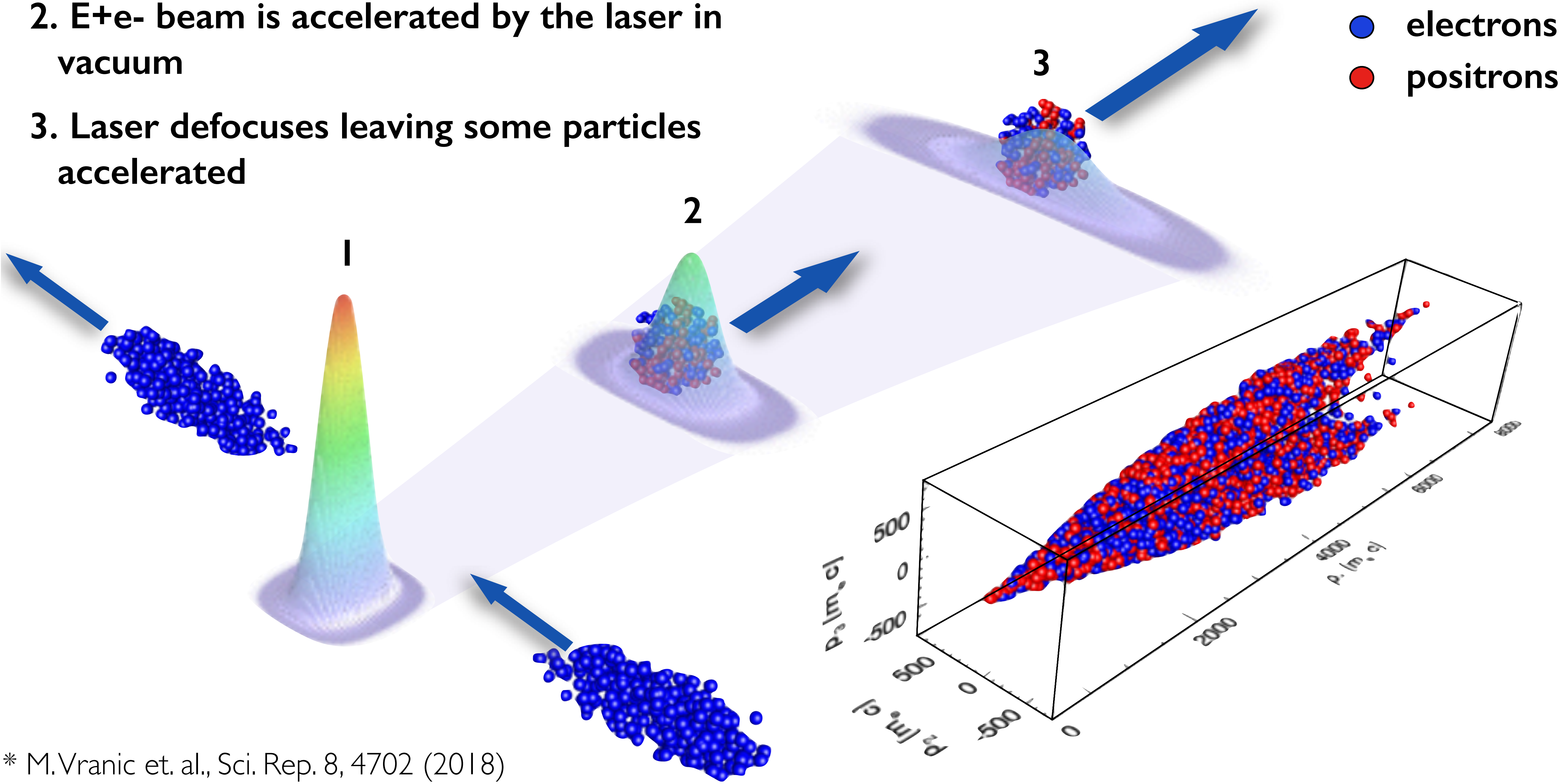
$$\theta_F \simeq \sqrt{\frac{2}{\pi}} \frac{a_0}{\gamma_F^2} \sigma_F$$

* M.Vranic et al., NJP 18, 073035 (2016)

E+e- beam from laser - e- scattering at 90°

1. LWFA electrons collide with the laser; pairs are produced in the highest field region
2. E+e- beam is accelerated by the laser in vacuum
3. Laser defocuses leaving some particles accelerated

Pair creation and acceleration are decoupled!



* M.Vranic et. al., Sci. Rep. 8, 4702 (2018)

Quantum effects are strongest for the case of counter-propagation

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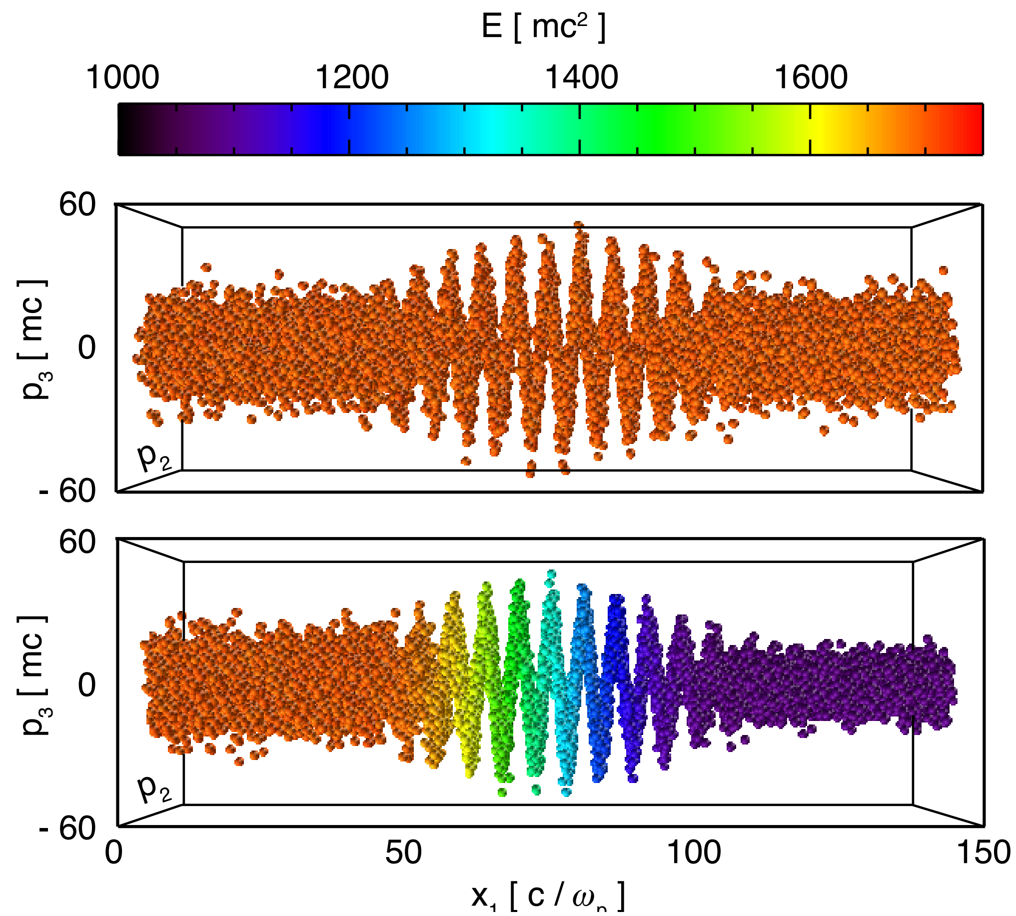
But, the interaction at 90 degrees has only a factor of two lower electron chi



$$\chi = \frac{\sqrt{(p_\mu F^{\mu\nu})^2}}{E_s\, mc}$$

$$\chi_e = \frac{1}{E_s}\sqrt{\left(\gamma\vec{E} + \frac{\vec{p}}{mc}\times\vec{B}\right)^2 - \left(\frac{\vec{p}}{mc}\cdot\vec{E}\right)^2}$$

$$a_0 = 0.8\sqrt{I[10^{18}\ \mathrm{W/cm^2}]}\lambda[\mu\mathrm{m}]$$

Counter-propagation

$$\chi \approx 2\ \gamma_0 a_0 \times 2\times 10^{-6}$$

Co-propagation

$$\chi \approx \frac{a_0}{2\gamma_0} \times 2\times 10^{-6}$$

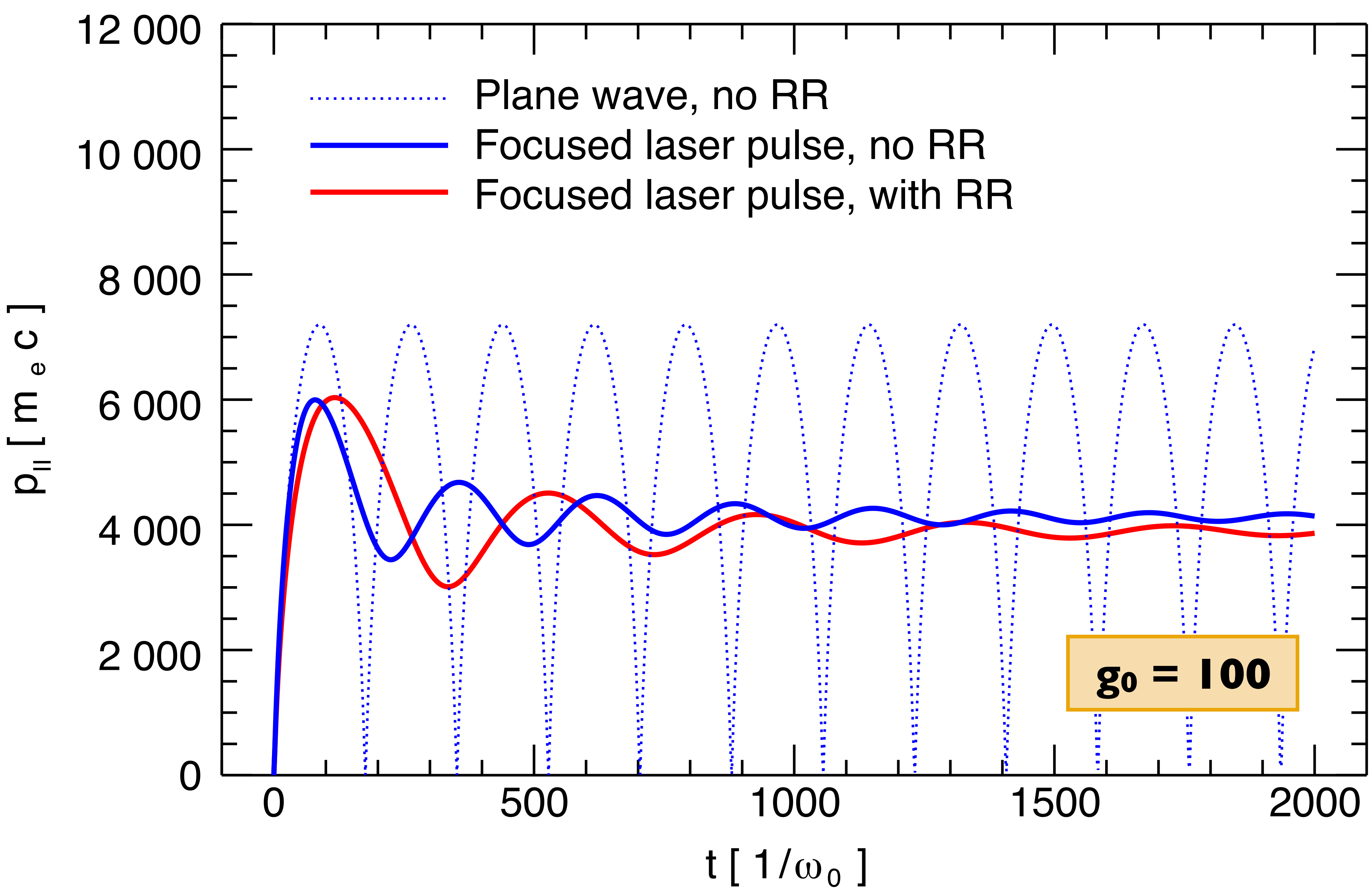
Interaction at 90 deg.

$$\chi \approx \gamma_0 a_0 \times 2\times 10^{-6}$$

* M.Vranic et al., PRL 113, 134800I (2014)

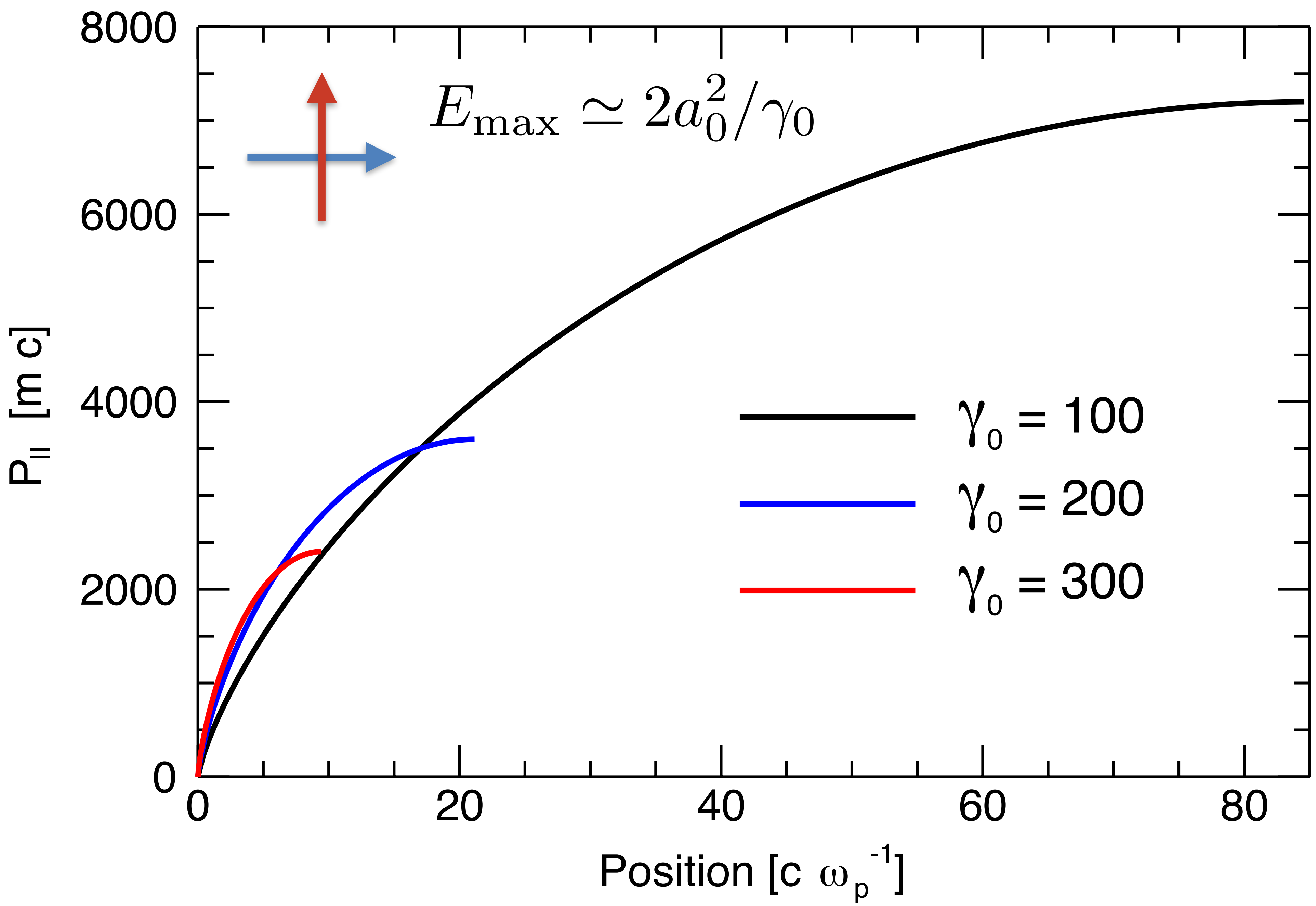
Laser defocusing allows for net acceleration

Electron trajectories in plane wave vs. defocusing laser at a_0=600



Initial e+e- energy plays a vital role in the final acceleration - the lower the better

Longitudinal momentum vs. position (90° incidence, a_0=600)*



* Analytical solution: Di Piazza, Lett. Mat. Phys. 83, 305–313(2008)

We can estimate the maximum energy as a function of the spot size and the laser intensity

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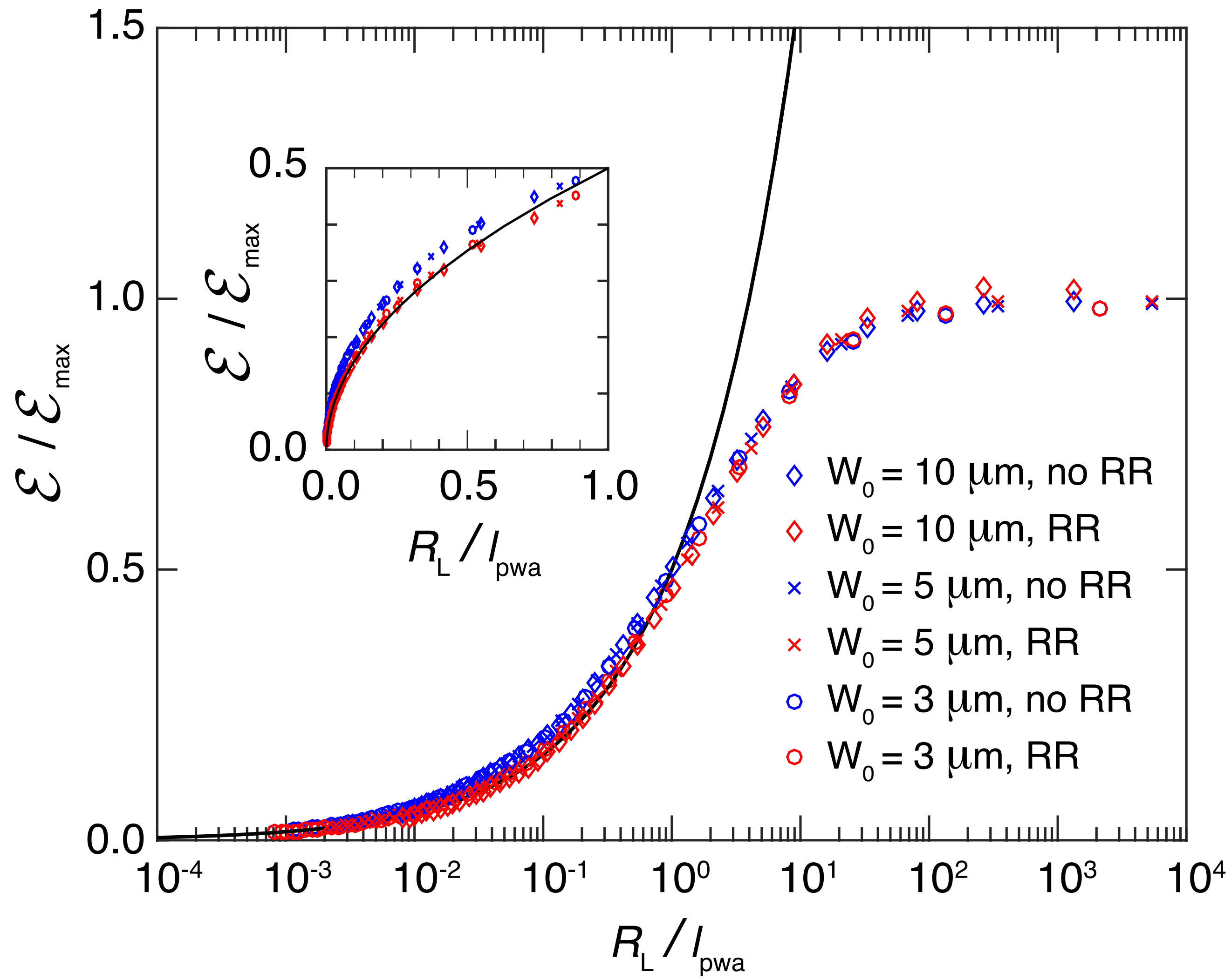
Extending the plane wave estimate for focused pulses*



$$\frac{\mathcal{E}}{\mathcal{E}_{\max}} = 0.5\sqrt{\frac{R_L}{l_{\rm pwa}}}$$

$$R_L = \pi W_0^2/\lambda_0$$

$$l_{\rm pwa} = 3\pi a_0^2/(4\gamma_0^2)$$

Test particle simulations:

particles born with the most favourable initial phase exactly in the laser focus!

General 3D cutoff (e+e- born anywhere)

$$\frac{\mathcal{E}}{\mathcal{E}_{\max}} = 0.5\sqrt{\frac{2R_L}{l_{\rm pwa}}}$$

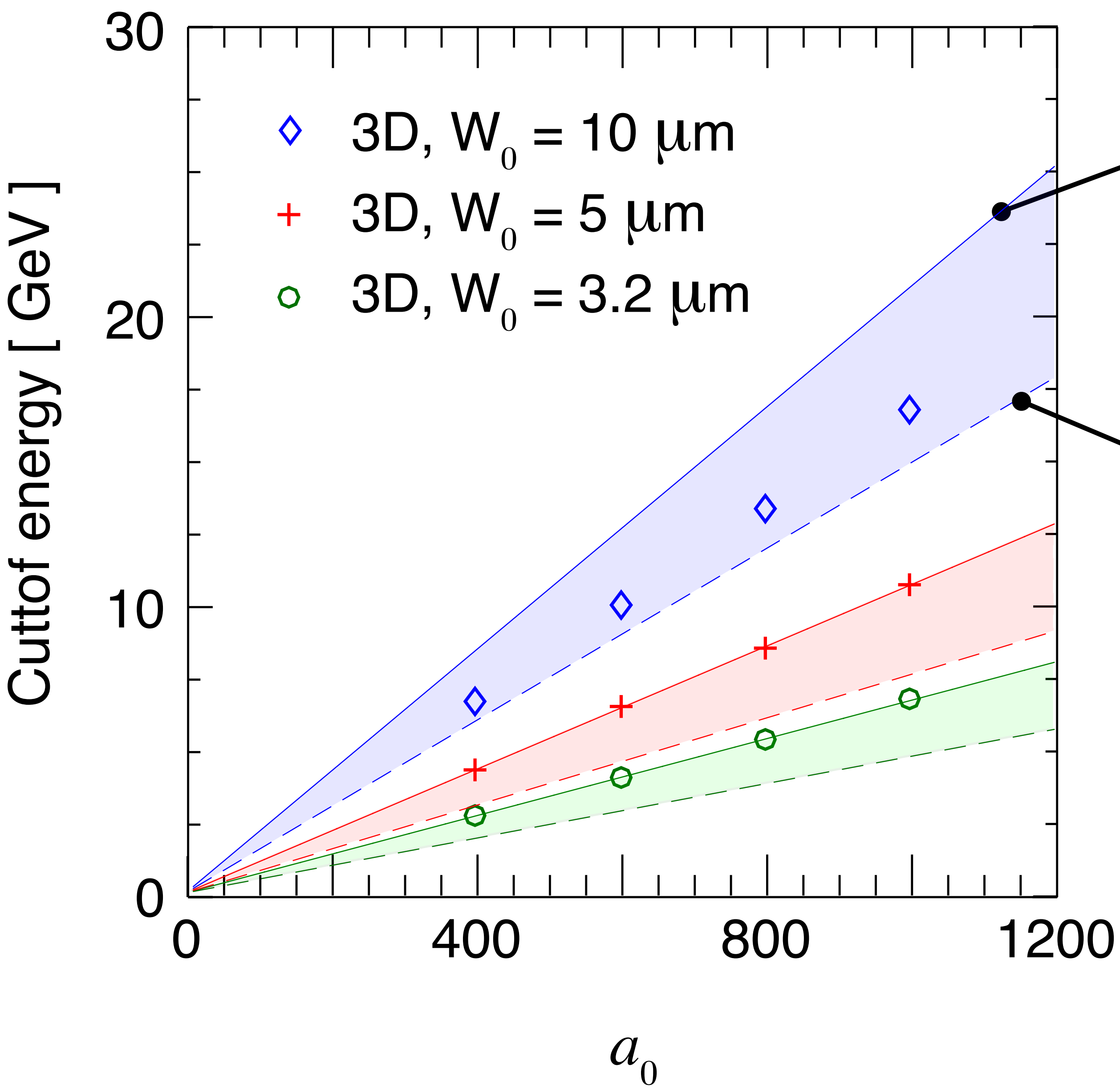
for 1 um laser:

$$\mathcal{E}_{\rm cutoff}\ [\rm MeV] \simeq 2a_0\ W_0\ [\mu m]$$

* Pulse description by Quesnel & Mora, Phys. Rev. E, 58,3719– 3732 (1998)

Analytical cutoff agrees with 3D QED PIC

The cutoff for a_0=1000 with a spotsize W_0=3 um becomes ~ 7 GeV



$$\mathcal{E}_{\mathrm{cutoff}}\ [\mathrm{MeV}] \simeq 2 a_0\ W_0\ [\mu\mathrm{m}]$$

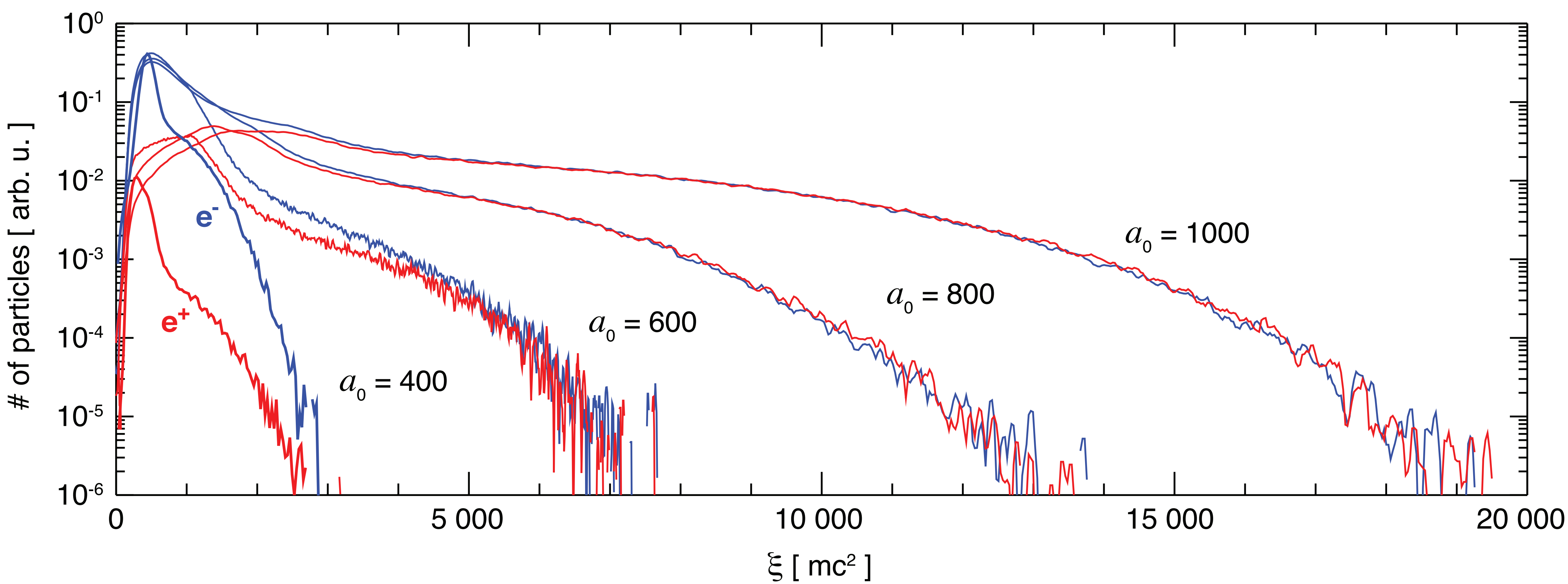
For particles born in the centre of the focus

* M.Vranic et. al., Sci. Rep. 8, 4702 (2018)

At energies > 2 GeV, we obtain the same number of e- and e+ in the spectrum

50 % of the positrons are above 2 GeV for a_0=1000

E+e- spectra at 50 um distance from focal plane for W_0=3.2 um

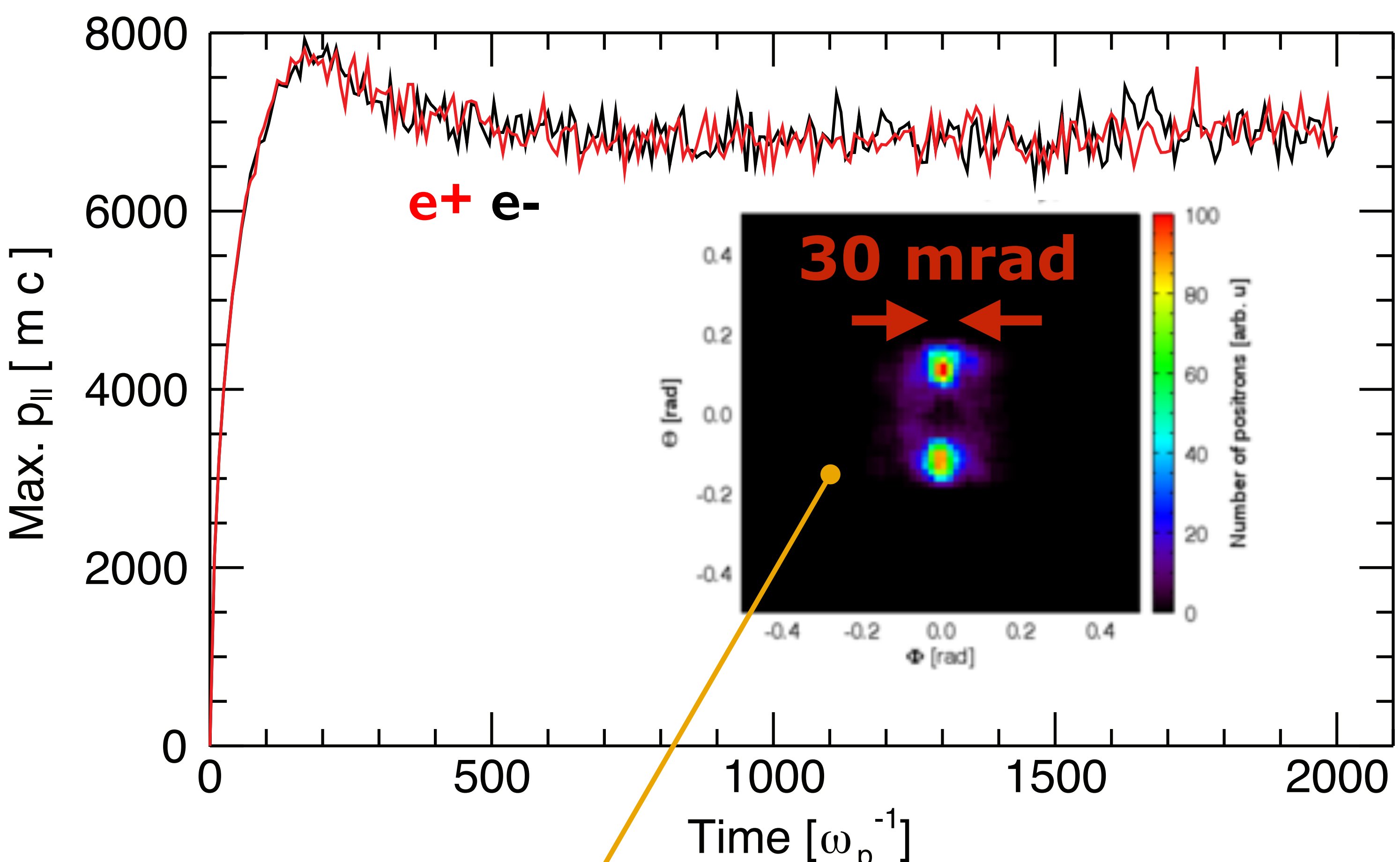


~ 10 GeV e+e- beam can be obtained with a_0=1000

* M.Vranic et. al., Sci. Rep. 8, 4702 (2018)

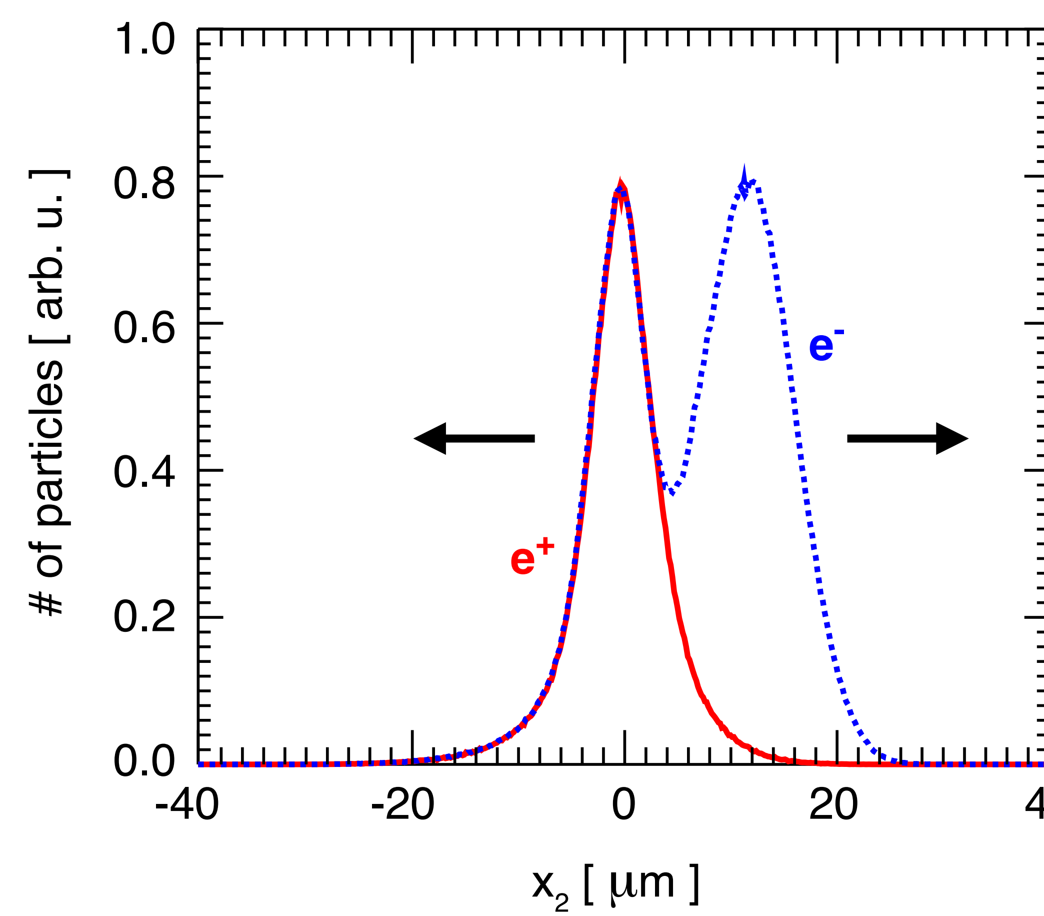
Low divergence for the final e+e- beam

~ 30 mrad beam divergence on detector for laser a_0 = 600



Virtual detector after 200 um propagation

Initial e- and new pairs do not “mix”: possible to collect a beam with 50% e+ and 50% e-.

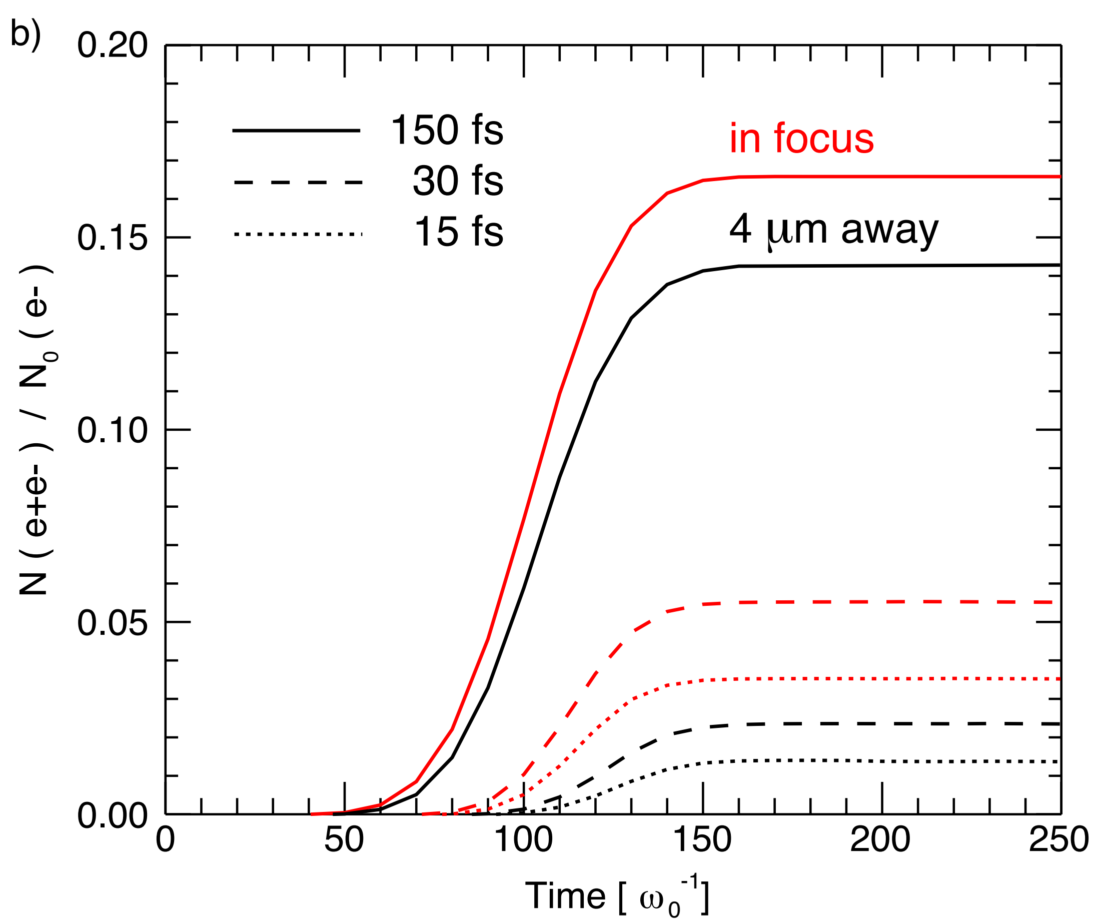


* M. Vranic et. al., Sci. Rep. 8, 4702 (2018)

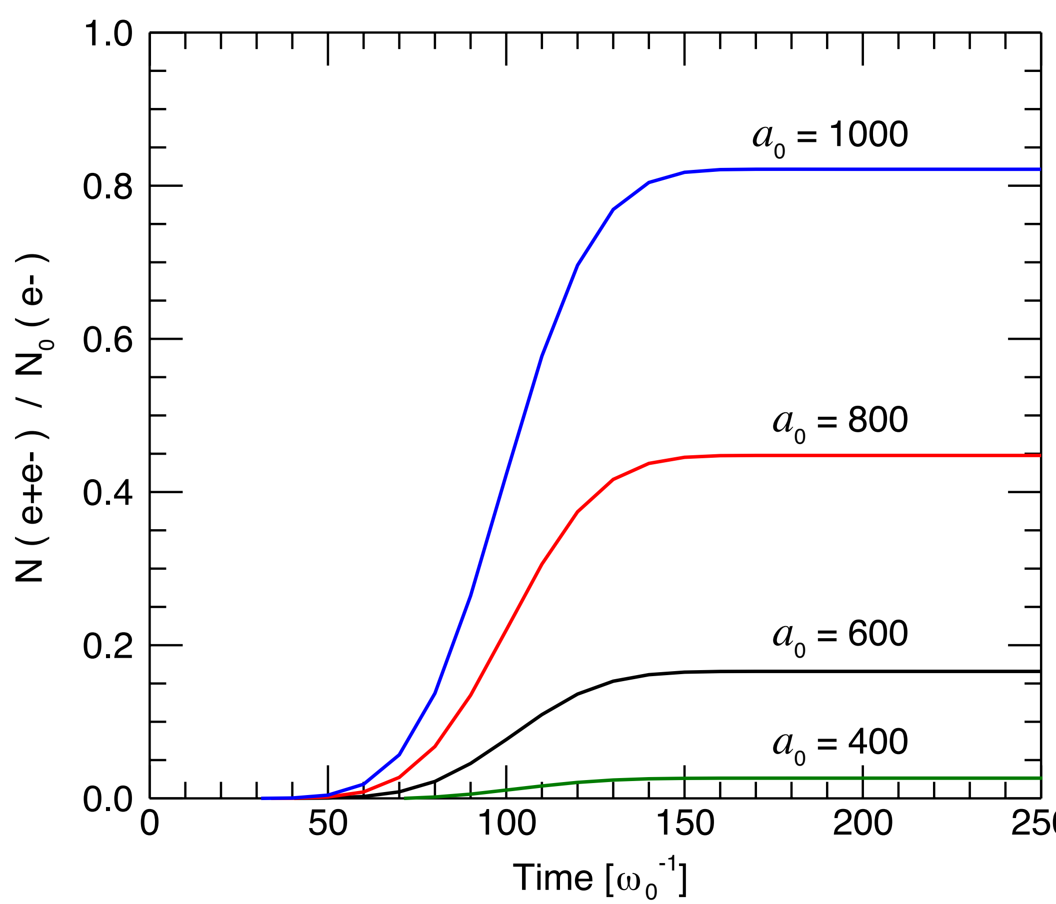
Charge in the e+e- beam can be comparable to the charge of the initial e- beam

For long laser pulses the total number of pairs is higher and less sensitive with respect to spatio-temporal synchronisation

a_0 = 600 -> a pair per 17 % of e-



85 % for a_0 = 1000 and 1 GeV e-



If you start with a 2 GeV e- beam, you can get a pair per e- at a_0=600

If you start with a 4 GeV e- beam, you can get a pair per e- at a_0=400

* M. Vranic et. al., Sci. Rep. 8, 4702 (2018)

Conclusions

- We can predict the electron energy spread and divergence as a function of a_0, pulse duration and initial e- energy.

- Laser-electron scattering at 90º can produce pairs and accelerate them to multi-GeV energies.

- Vacuum acceleration is possible due to the laser defocusing.

- Energy cutoff can be predicted as a function of the spot size and the laser intensity.

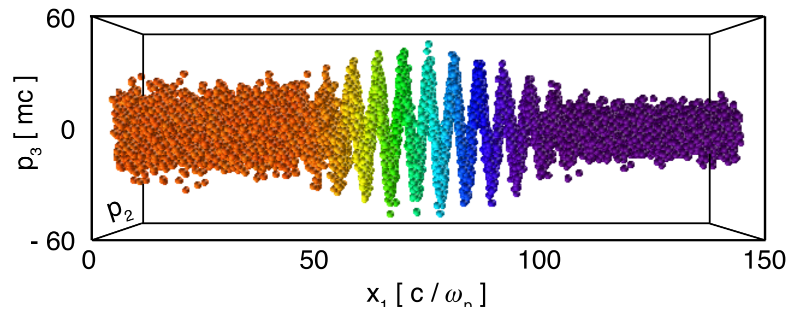
- Quasi neutrality - equal number of e+ and e- for particles with energies > 2 GeV.

Our publications

Adding classical radiation reaction

- Modelling electron beam slowdown in scattering configurations
- Modeling other configurations where only a fraction of electrons may be subject to RR but where this can alter qualitative behaviour

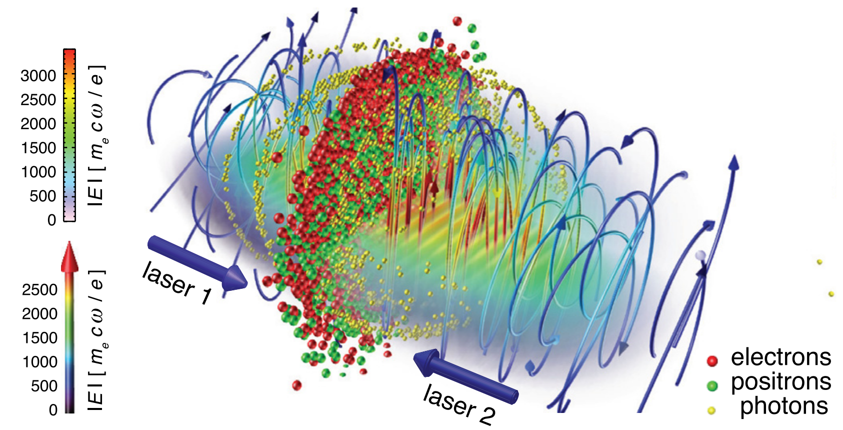
M.Vranic et al., PRL (2014); M.Vranic et al., CPC (2016); M.Vranic et al, PPCF (2018)



Adding quantum processes

- Modelling the onset of QED, RR from quantum perspective
- Modelling e+e- pair production
- QED cascades, nonlinear regimes where many particles are created and collective plasma dynamics can alter the background fields

M.Vranic et al, NJP (2016); T. Grismayer et al, POP (2016); T. Grismayer et al, PRE (2017); J. L. Martins et al, PPCF (2016); M.Vranic et al, PPCF (2017); M.Vranic et al, SciRep (2018);



Adding performance improvements (particle merging, advanced load balancing schemes)

- Essential for all the projects with strong QED effects

M.Vranic et al., CPC (2015)