High intensity laser driven positron source

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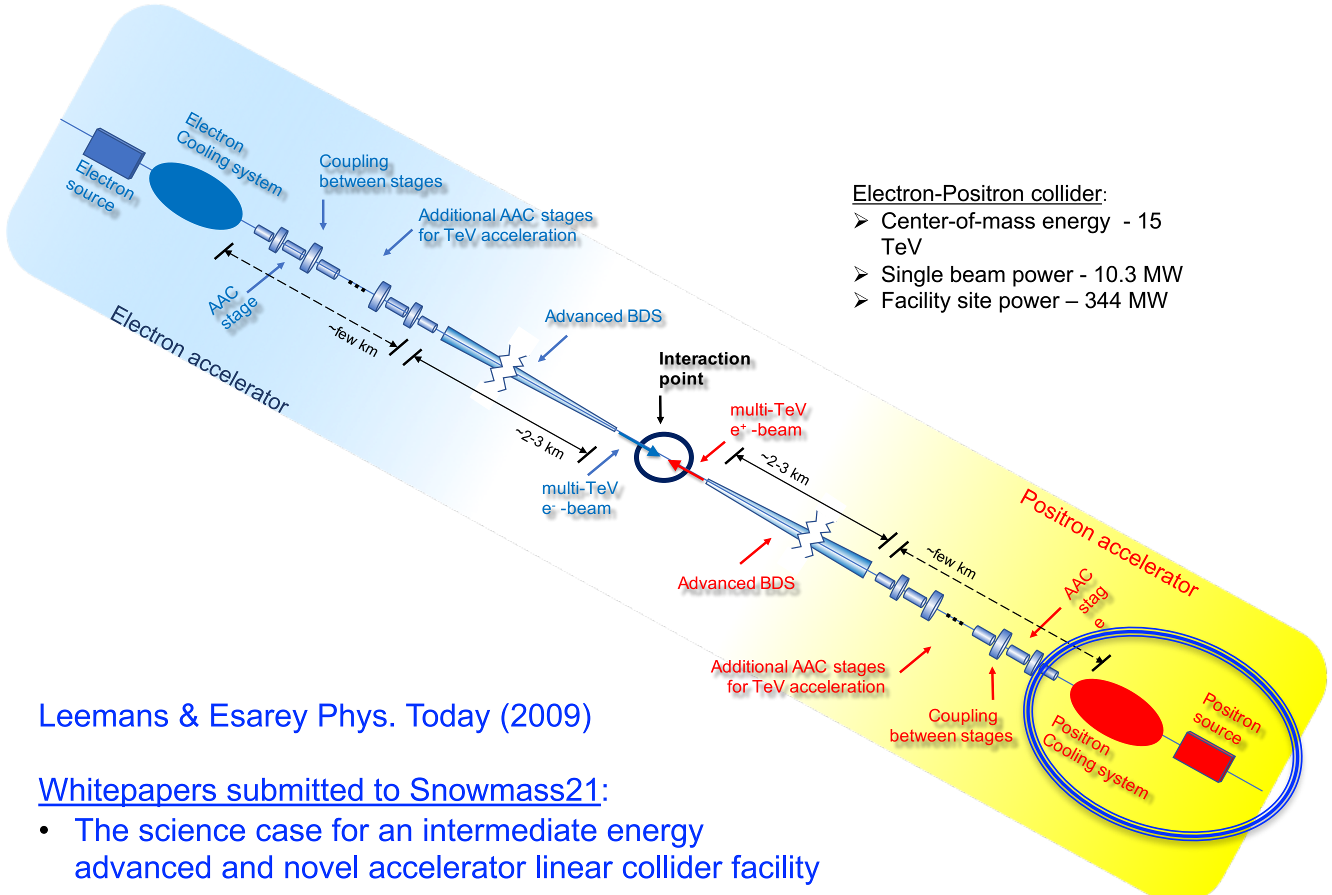
A Path Towards TeV-scale Lepton Collider:
Basic configuration of a laser-plasma linear collider



Electron-Positron collider:

- Center-of-mass energy - 15 TeV
- Single beam power - 10.3 MW
- Facility site power – 344 MW

Leemans & Esarey Phys. Today (2009)

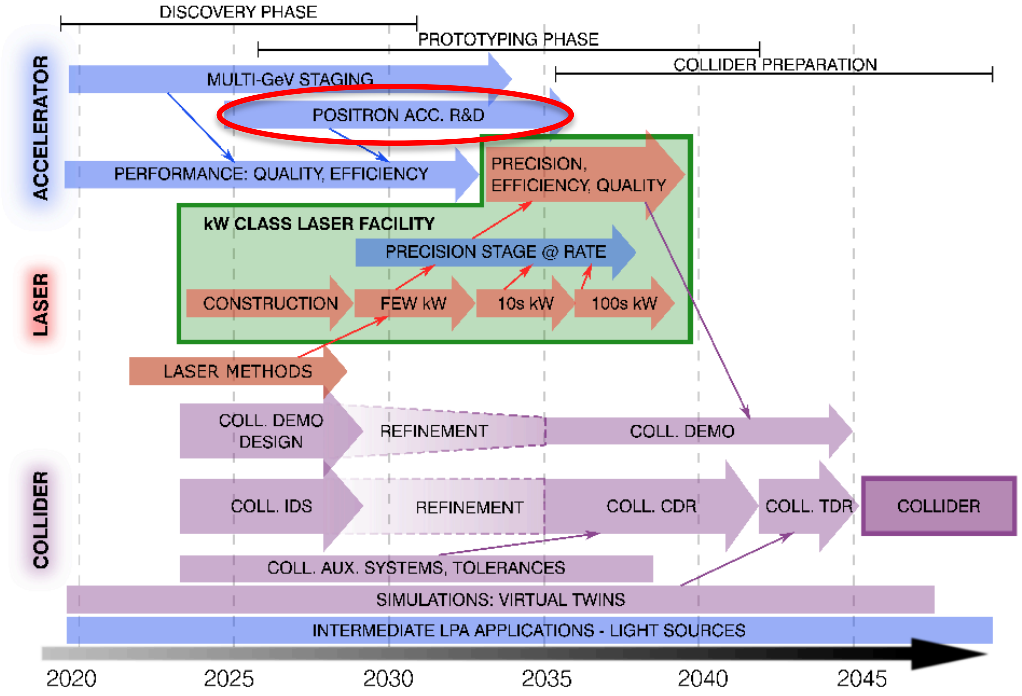
Whitepapers submitted to Snowmass21:

- The science case for an intermediate energy advanced and novel accelerator linear collider facility
  S. S. Bulanov, et al., JINST, 2023
- Linear collider based on laser-plasma accelerators,
  C.B. Schroeder, et al., JINST, 2023

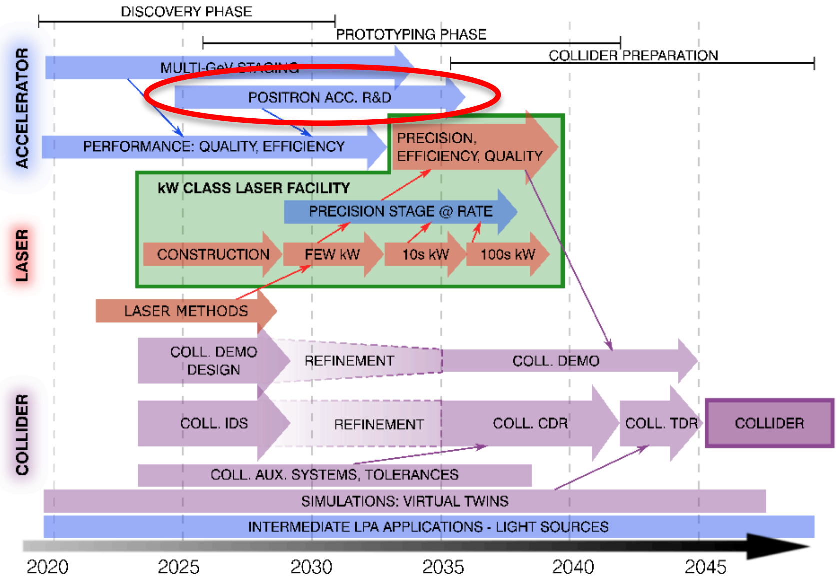
Report of snowmass 21 accelerator frontier topical group 6 on advanced accelerators
C. Geddes, M. Hogan, P. Musumeci, and R. Assmann, arXiv:2208.13279

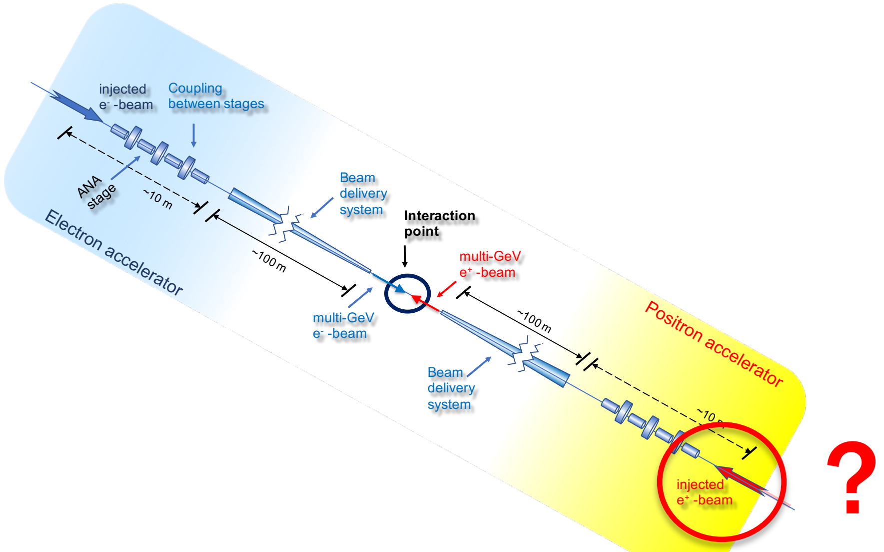
- **Plasma density optimization: n ~ 10^{17} cm^{-3}**
- Staging & laser coupling into plasma channels:
  - J-class laser energy/stage required
  - multi-GeV energy gain/stage
- 10s of kHz rep. rate to achieve luminosity (100s kW)
- High laser efficiency required (tens %)

?

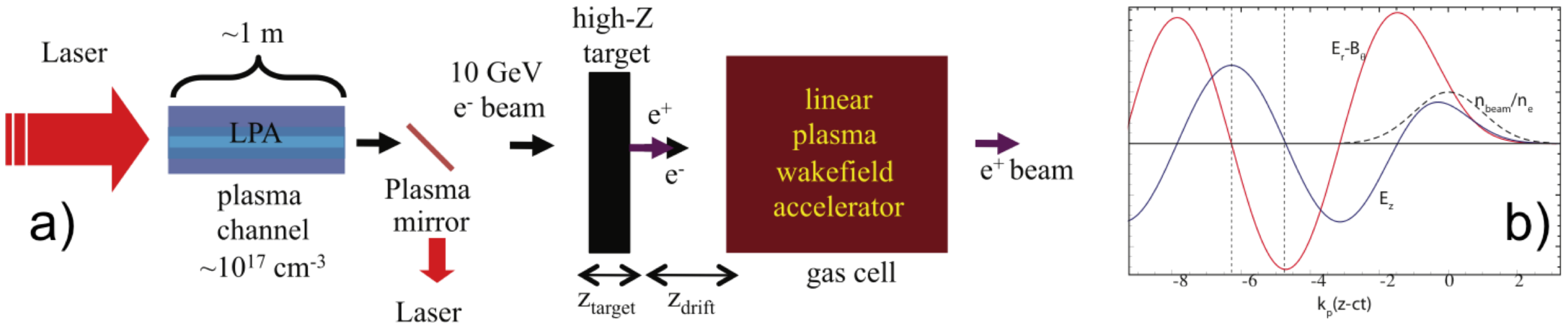


LPA based collider needs a compact positron source. How positron creation, capture, and acceleration can be achieved?

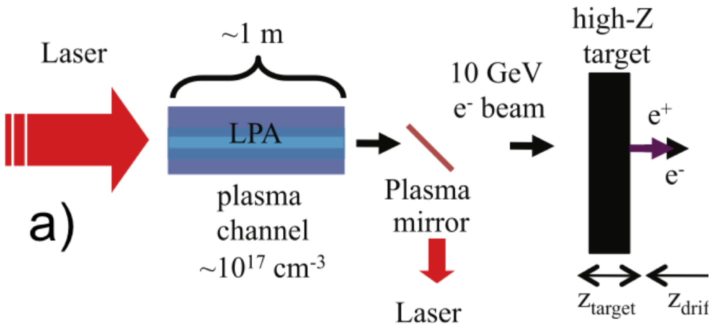




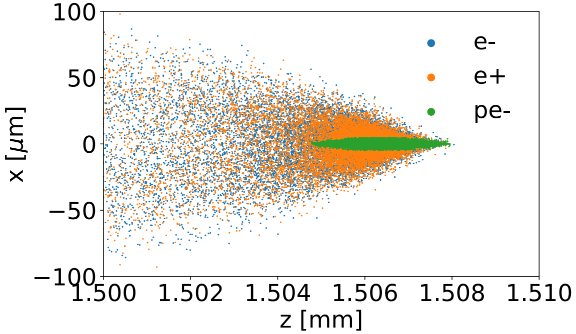
positron creation, capture, and acceleration

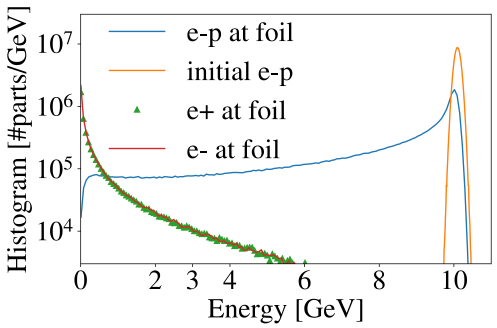


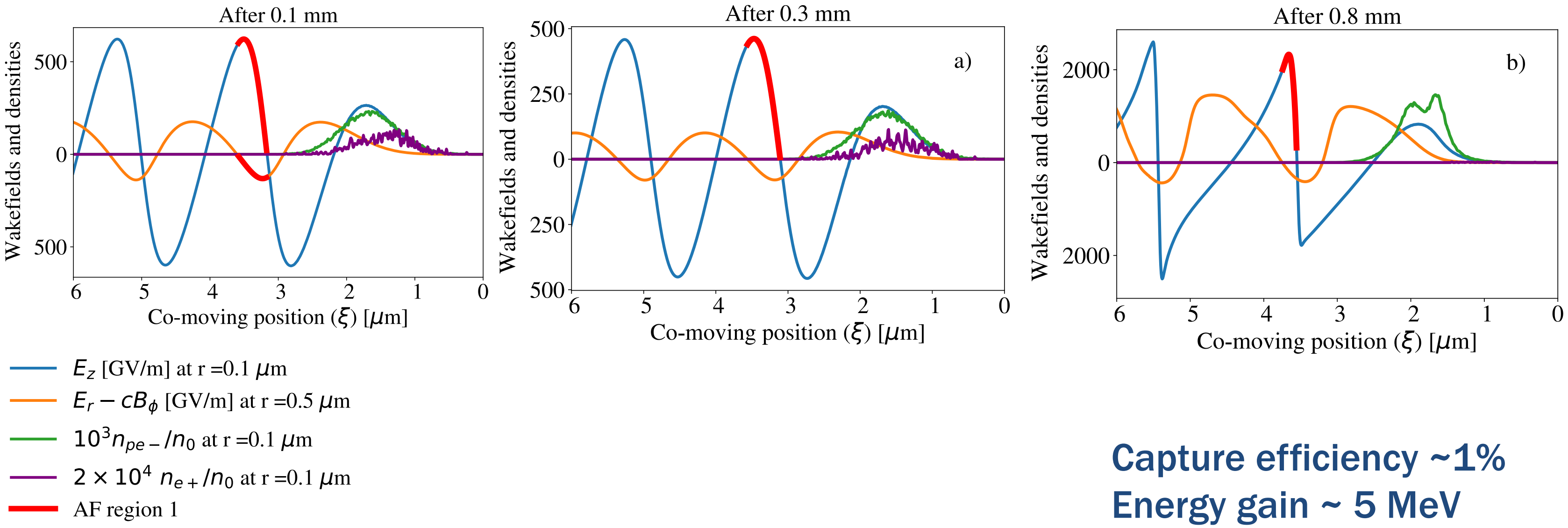
Single LWFA beam is used to produce, capture, and accelerate positrons



Particle distribution after the high−Z target



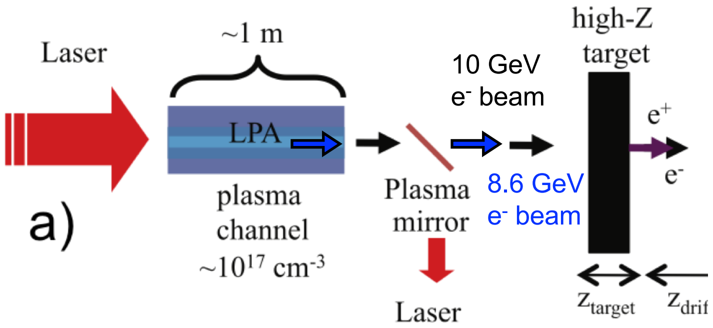


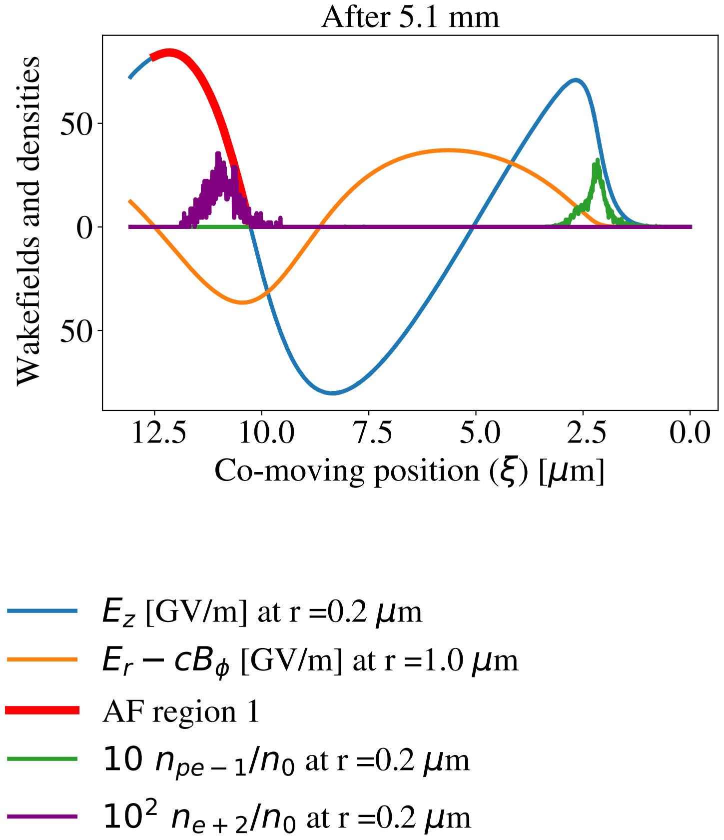


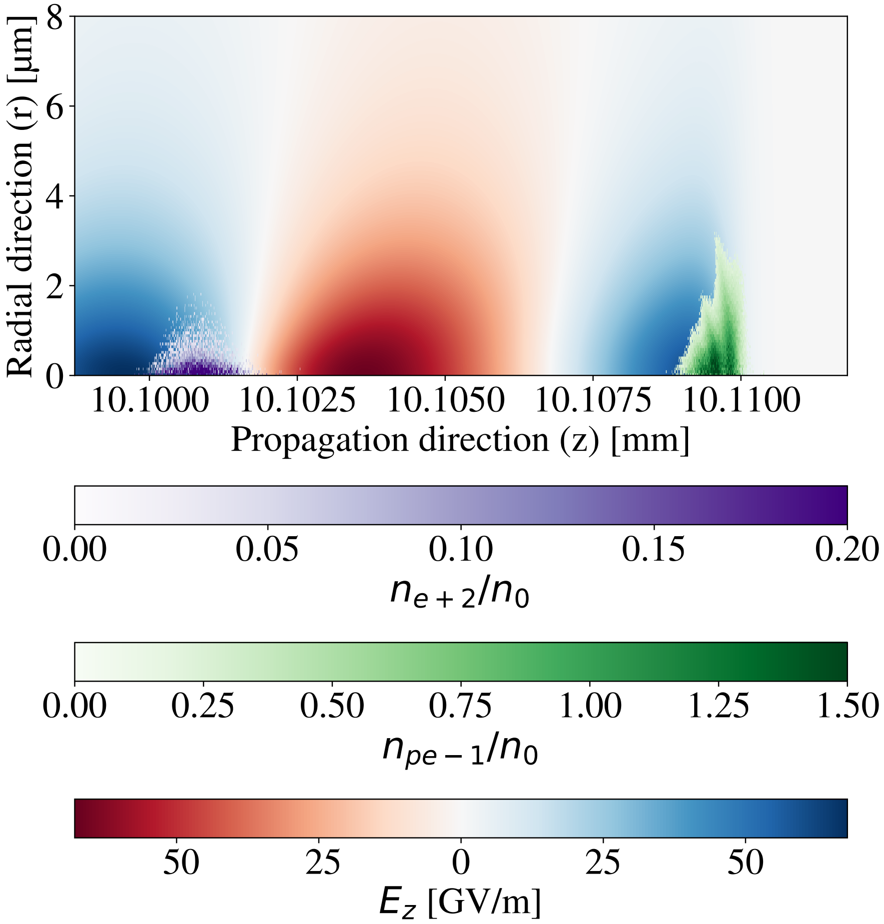
Capture efficiency ~1%

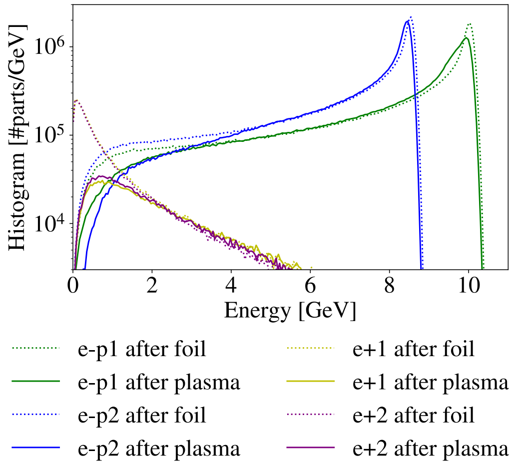
Energy gain ~ 5 MeV

Two LWFA beams are used to produce, capture, and accelerate positrons





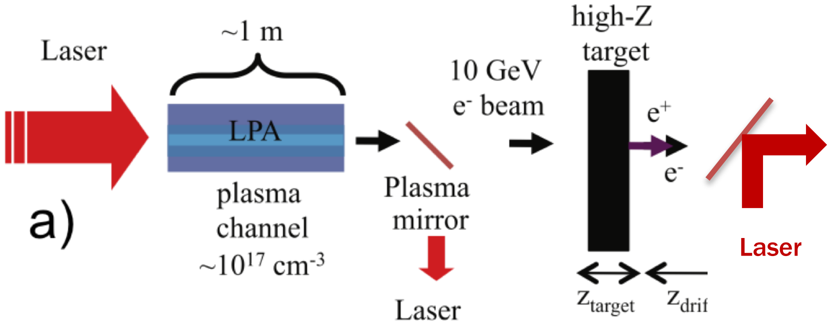


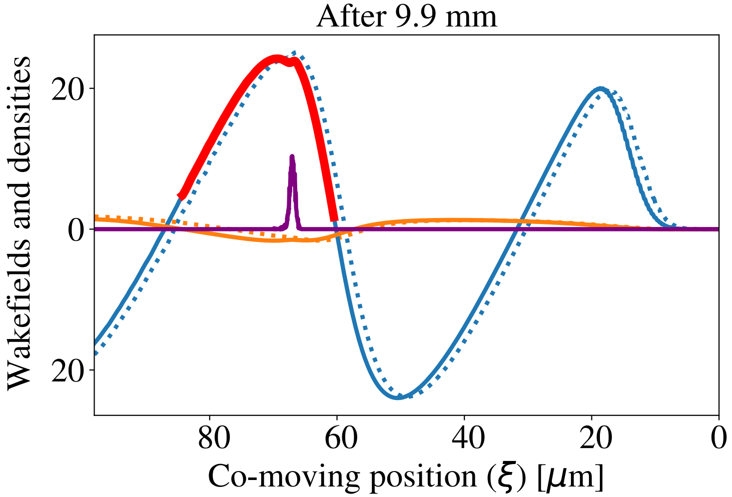


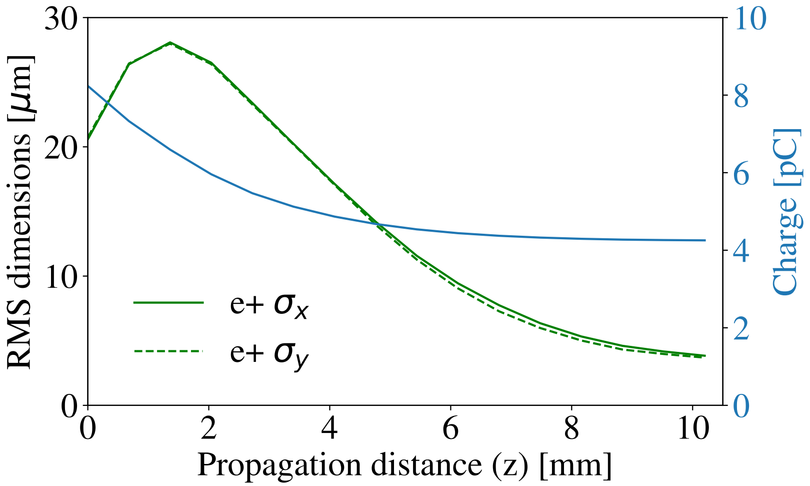
This two beam configuration is similar to PRAB 22, 091301 (2019)

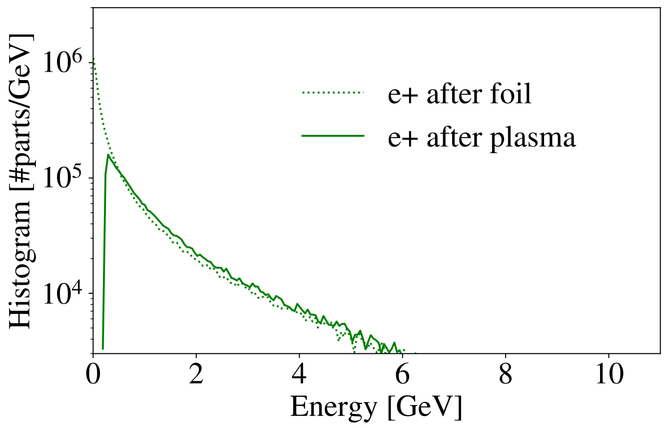
Capture efficiency ~25%
Energy gain ~ 1 GeV

Single LWFA beam is used to produce positrons, which are captured and accelerated by the laser driven wakefield









E_z [GV/m] at r =0.4 μm after 1.7 mm

$E_r - cB_\phi$ [GV/m] at r =0.9 μm after 1.7 mm

E_z [GV/m] at r =0.4 μm after 9.9 mm

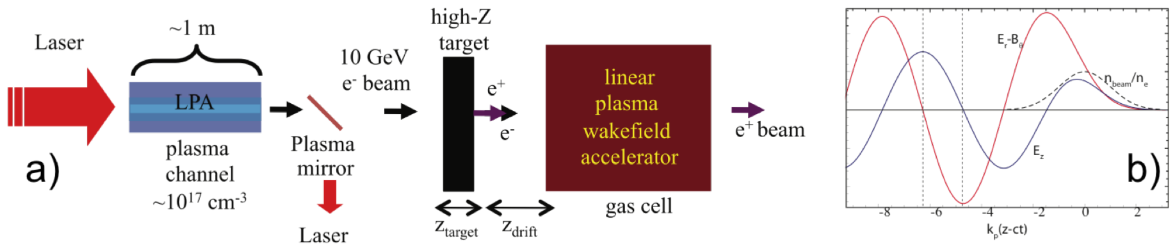
$E_r - cB_\phi$ [GV/m] at r =0.9 μm after 9.9 mm

AF region 1

$2\ n_{e+}/n_0$ at r =0.4 μm

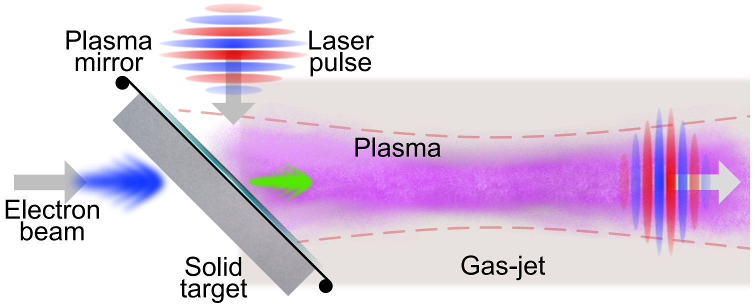
Capture efficiency ~49%
Energy gain ~ 0.8 GeV

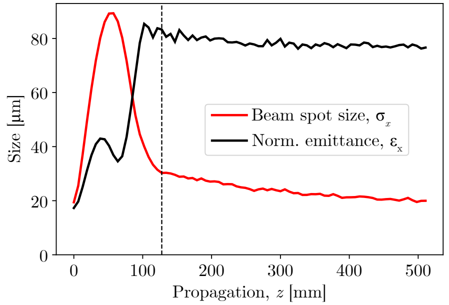
LPA based collider needs a compact positron source. How positron creation, capture, and acceleration can be achieved?



D. Amorim et al., PPCF, 2023

1. Single e-beam → Capture efficiency ~1%, Energy gain ~ 5 MeV
2. Two consecutive e-beams → Capture efficiency ~25%, Energy gain ~ 1 GeV
3. Single e-beam + LWFA → Capture efficiency ~49%, Energy gain ~ 0.8 GeV

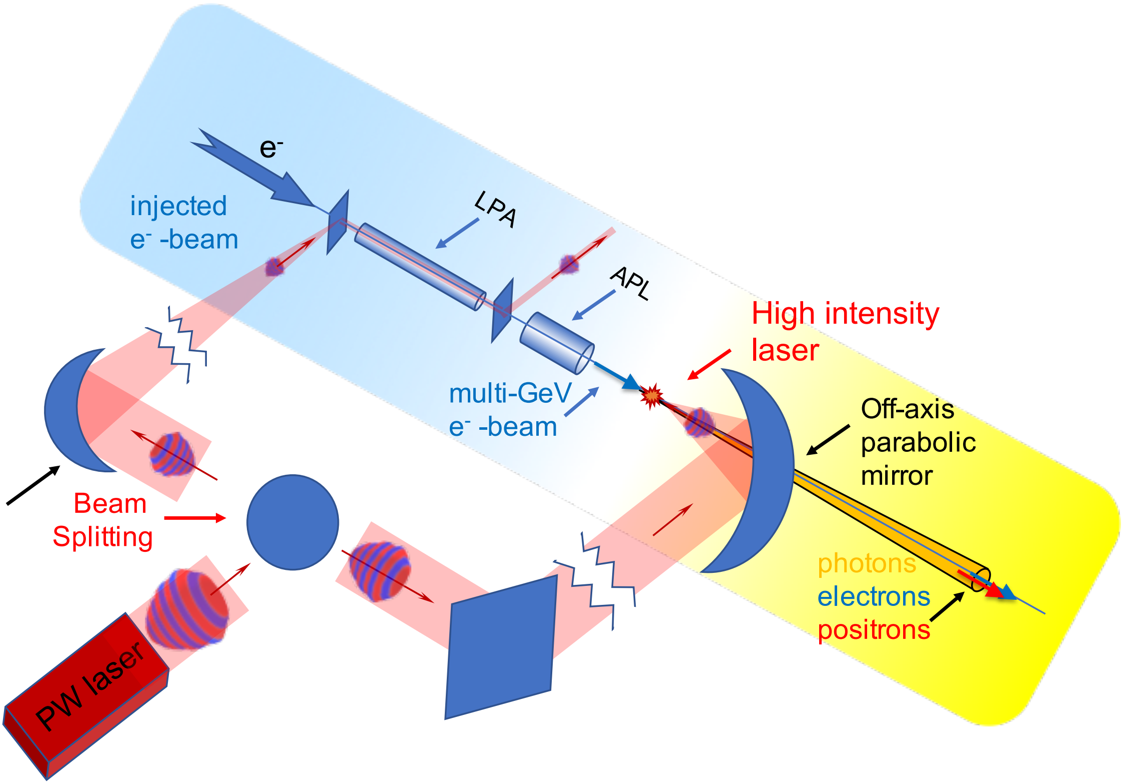


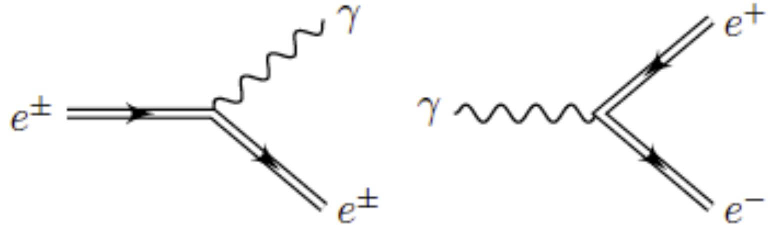


Single e-beam + LWFA → Capture efficiency ~50%, Energy gain ~ 1 GeV

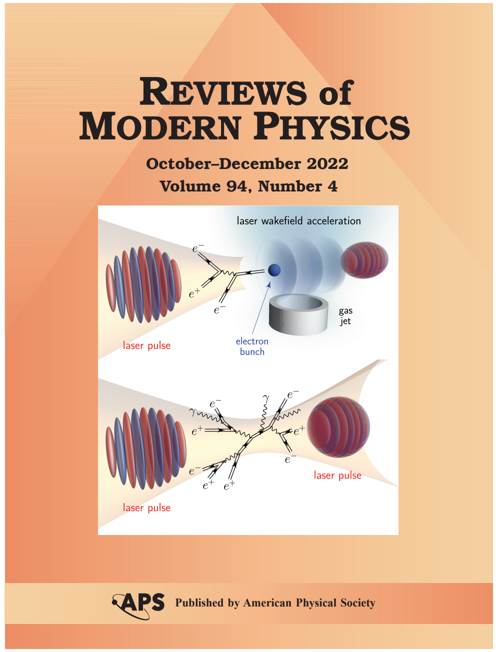
D. Terzani et al., PRAB, 2023

Will the interaction of a multi-GeV electron beam with a PW class laser pulse produce enough positrons?





The Feynman diagrams of the Compton ($e \to e\gamma$) and Breit-Wheeler ($\gamma \to ee$) processes. Double fermion lines indicate that the process occurs in an external field.



REVIEWS of MODERN PHYSICS

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Volume 94, Number 4

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Extremely high-intensity laser interactions with fundamental quantum systems
A. Di Piazza, C. Muller, K. Z. Hatsagortsyan, and C. H. Keitel, Reviews of Modern Physics 84, 1177 (2012).

Charged particle motion and radiation in strong electromagnetic fields
A. Gonoskov, T. G. Blackburn, M. Marklund, and S. S. Bulanov, Reviews of Modern Physics 94, 045001 (2022).

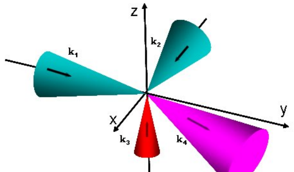
Advances in QED with intense background fields
A. Fedotov, A. Ilderton, F. Karbstein, B. King, D. Seipt, H. Taya, G. Torgrimsson, Phys. Rep. 1010, 1 (2023)

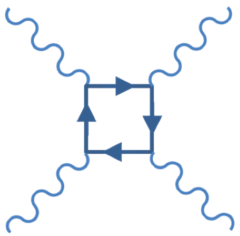
Strong Field QED describes the phenomena in strong EM fields in the environments where the field strength is large relative to the QED critical field

Laser fields may provide both strong electromagnetic fields and generate high-energy particles and therefore represent a particularly interesting environment for studying a number of High Intensity Particle Physics effects.

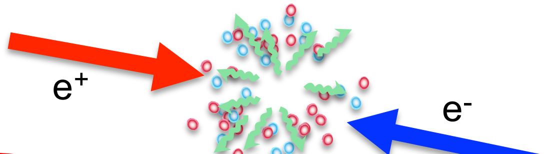
4-wave mixing

(Lundström et al, 2006)

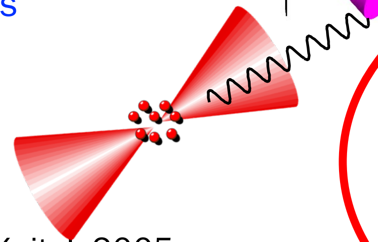




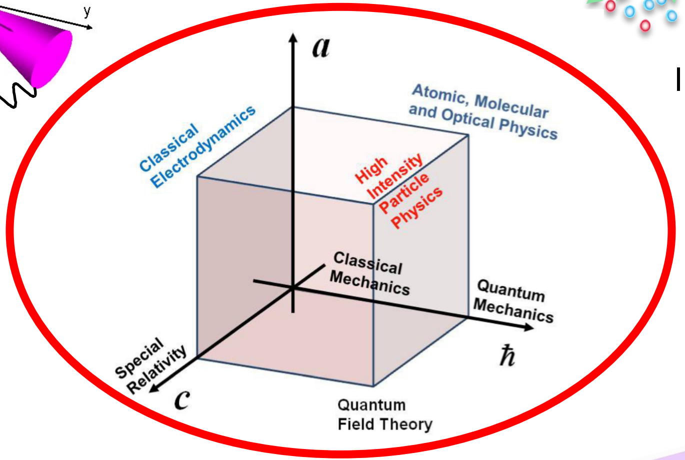
Photon-photon scattering via relativistic mirrors (Koga et al (2012))



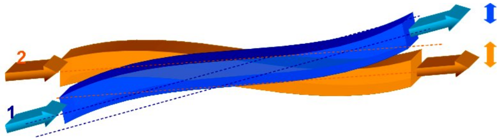
- Nonperturbative Quantum Field Theory
- Matter in Extreme conditions
- Next generation lasers
    - Day-to-day operation
    - New applications
- Future lepton colliders
- Future $\gamma\gamma$ colliders
- Various astrophysical phenomena



High order harmonic generation (Di Piazza, Hatsagortsyan, C. H. Keitel, 2005 Fedotov & Narozhny, 2006)

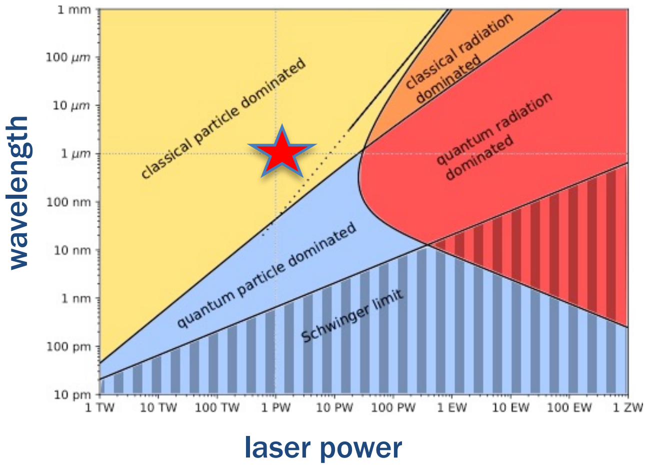


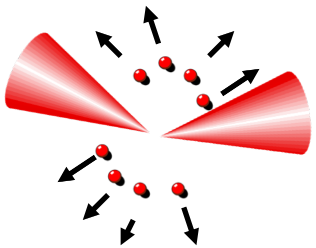
Interaction point physics at future TeV- class lepton colliders (Yakimenko et al, 2019)



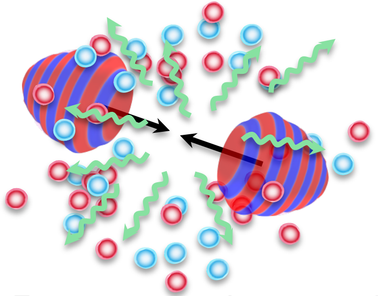
Birefringent e.m. vacuum

(Rozanov, 1993)

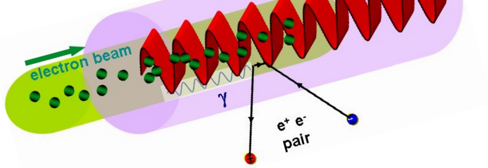




Electron positron pair production from vacuum (Schwinger, 1951)



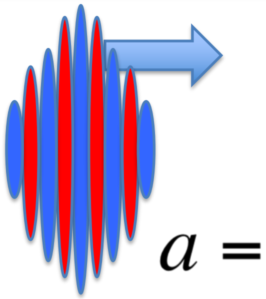
- Electromagnetic avalanches
- Electromagnetic cascades (Bell&Kirk, 2008)



Mulitphoton Compton and Breit-Wheeler processes
A. I. Nikishov, V. I. Ritus (1964);
Bula et al (1996); Burke et al (1997)
Cole et al (2018); Poder et al (2018)

Behavior of particles and fields is characterized by Lorentz invariant parameters

Classical nonlinearity parameter



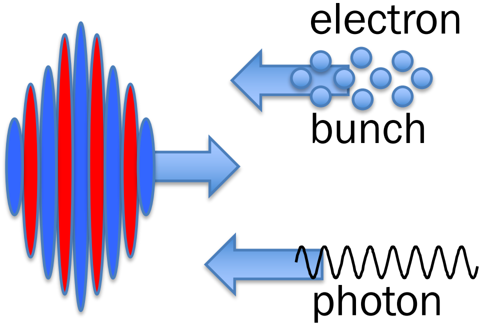
$$a = \frac{eE}{m\omega c}$$ Electron energy gain over laser wavelength in units of *mc*²

$$a = 1 \rightarrow$$ Relativistic regime of interaction $\lambda = 1\ \mu m$

Critical QED field can create an electron-positron pair at Compton length, $\lambda_C = 3.86 \times 10^{-11}$ cm

$$E_S = \frac{m^2c^3}{e\hbar} = 1.32\times10^{16}\ V/cm \quad \rightarrow \quad a_s = \frac{\hbar\omega}{mc^2} = 4.1\times10^5$$

Quantum Effects



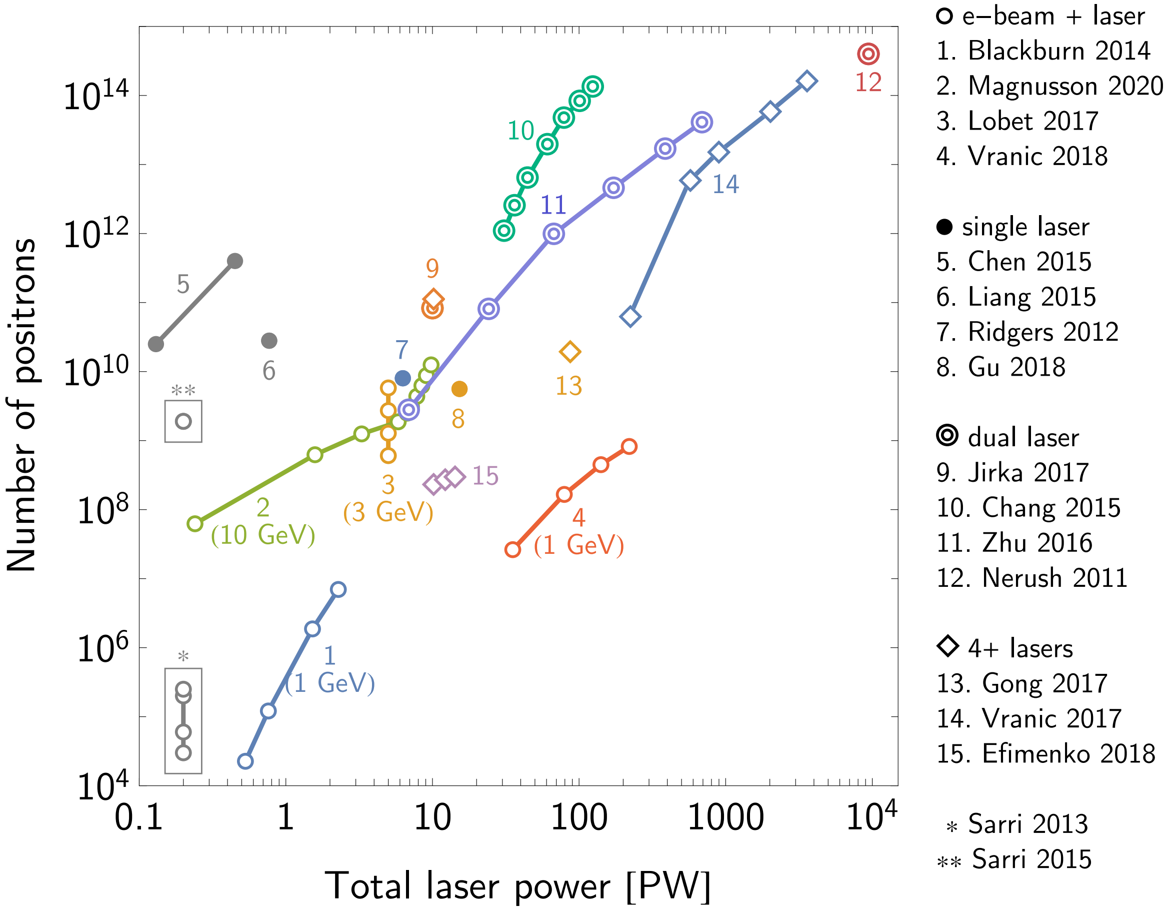
$$\chi_e = \frac{e\hbar\sqrt{(F_{\mu\nu}p^\nu)^2}}{m^3c^4}$$

$$\chi_\gamma = \frac{e\hbar\sqrt{(F_{\mu\nu}k^\nu)^2}}{m^3c^4}$$

counter-propagating laser and electron/photon

$$\chi_e = 2\gamma\frac{E}{E_S}, \chi_\gamma = 2\frac{\hbar\omega}{mc^2}\frac{E}{E_S}$$

What can be expected in terms of positron production by high intensity lasers?

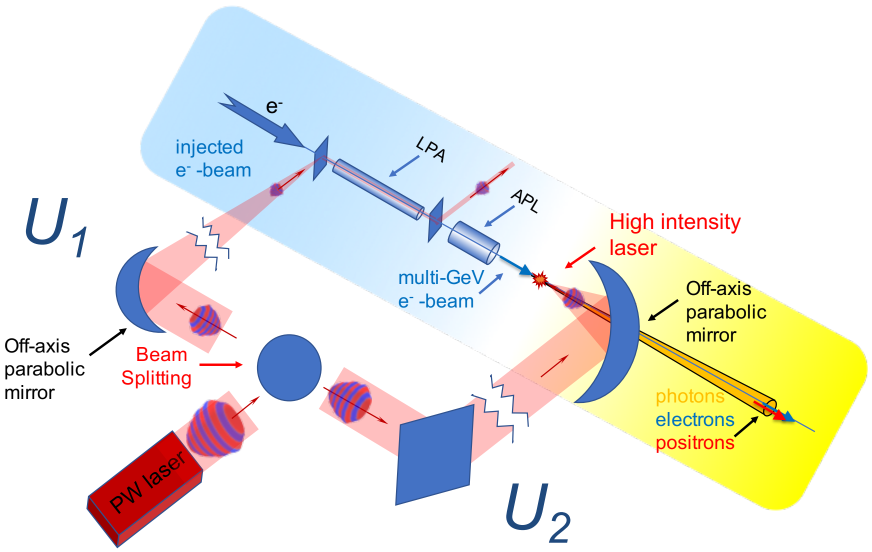


Number of positrons produced in high-intensity laser-plasma interactions. For laser-electron beam interactions (open circles), the energy of the electron beam is noted in brackets. Points marked with asterisks indicate experimental results from LPA electron-beam interactions with high-Z foils; in these cases the laser power is not indicated.

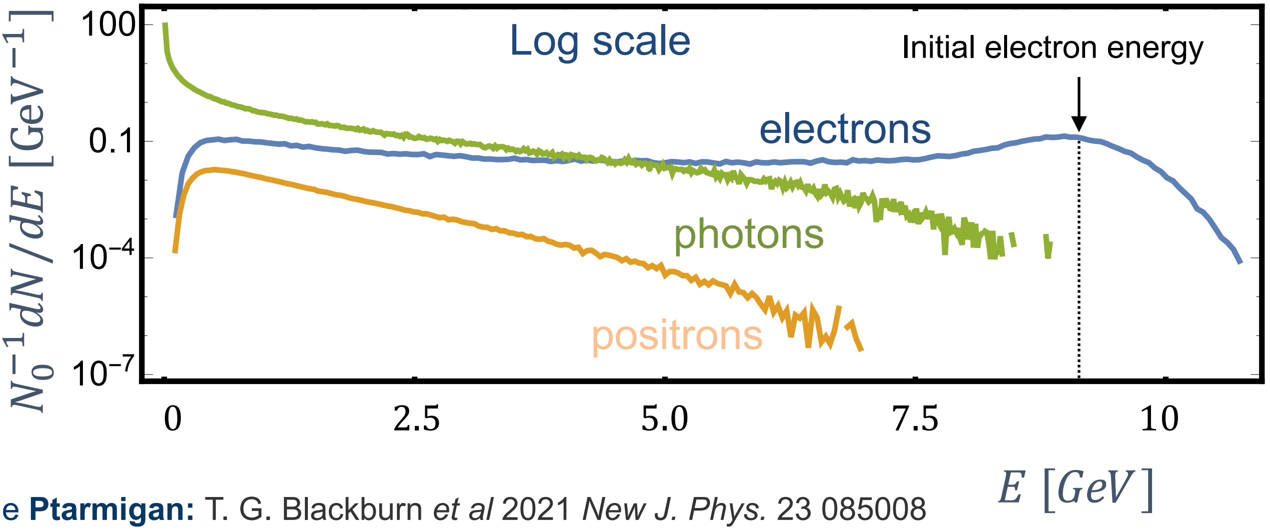
Charged particle motion and radiation in strong electromagnetic fields

A. Gonoskov, T. G. Blackburn, M. Marklund, and S. S. Bulanov, Reviews of Modern Physics 94, 045001 (2022).

PW laser needs to be split into two beams for one of them to accelerate electrons via LPA and the other to provide high-intensity electromagnetic field



Particle spectra



code **Ptarmigan:** T. G. Blackburn *et al* 2021 *New J. Phys.* 23 085008

Simulation input:

- laser peak a_0 = 40
- laser pulse focal spot size w_0 = 2.5 um
- laser duration = 30 fs
- electron beam energy = 9.1 GeV (+-5%)
- electron bunch size = 2.5 um
- electron beam charge = 120 pC

$\chi_e = 3.7$

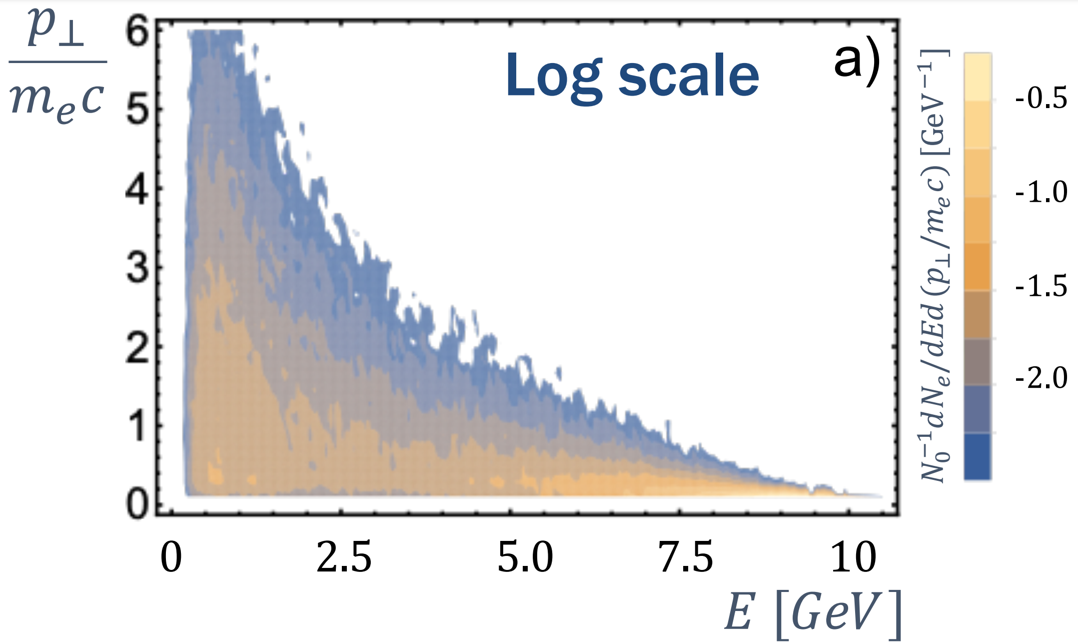
Guided LPA (quasi-linear regime)

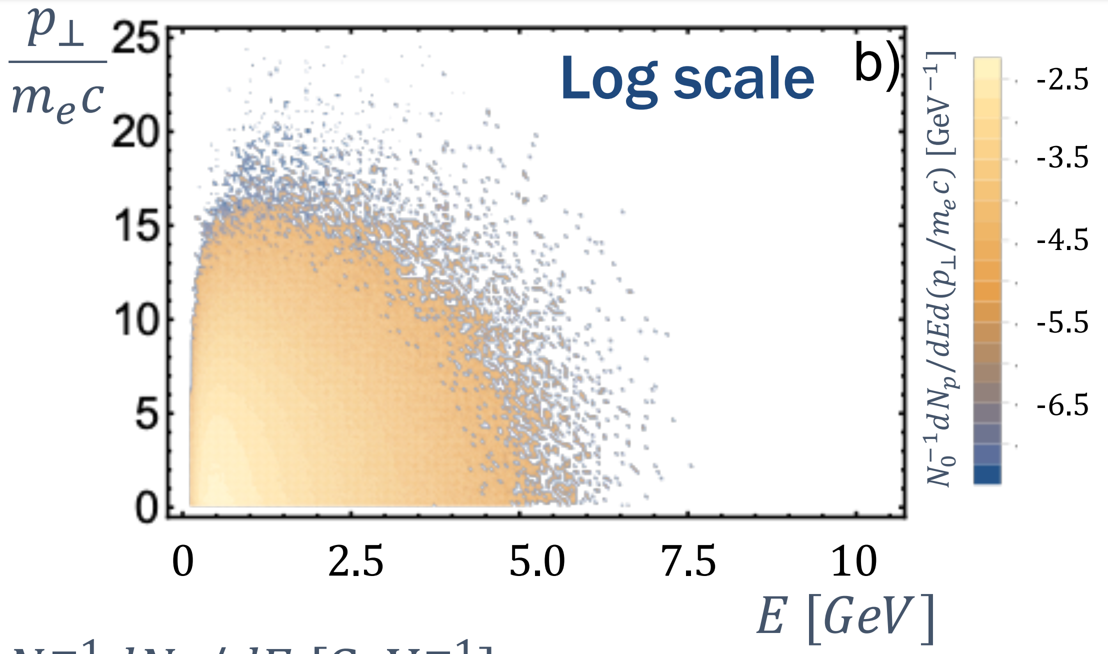
Simulation results:

- electron beam energy loss = 42%
- positron beam charge = 5 pC
- positron energy at peak = 500 MeV
- number of photons per electron ~ 10

Electron and positron beams demonstrate broad distributions as a result of interaction

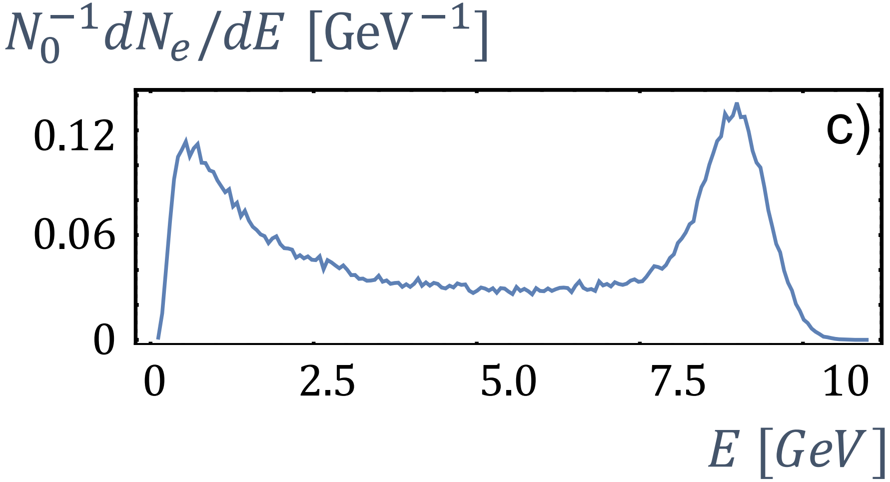
final electron beam distribution

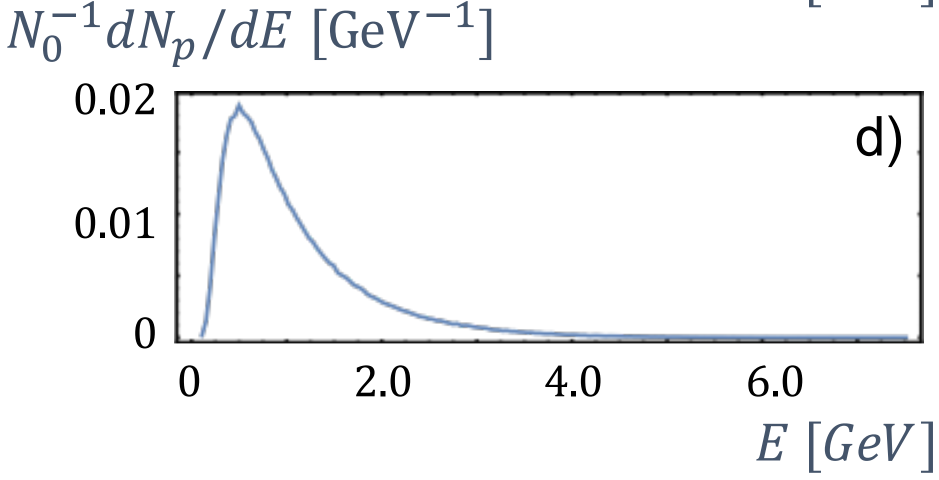




final positron beam distribution

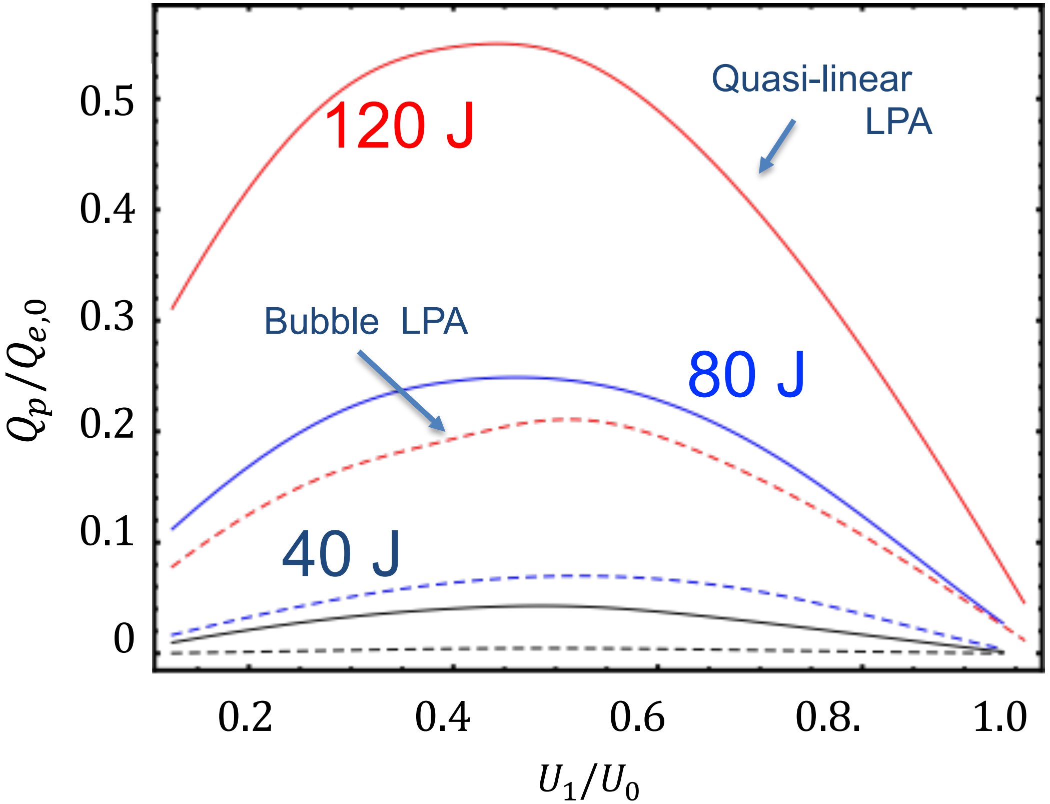
Electron spectrum



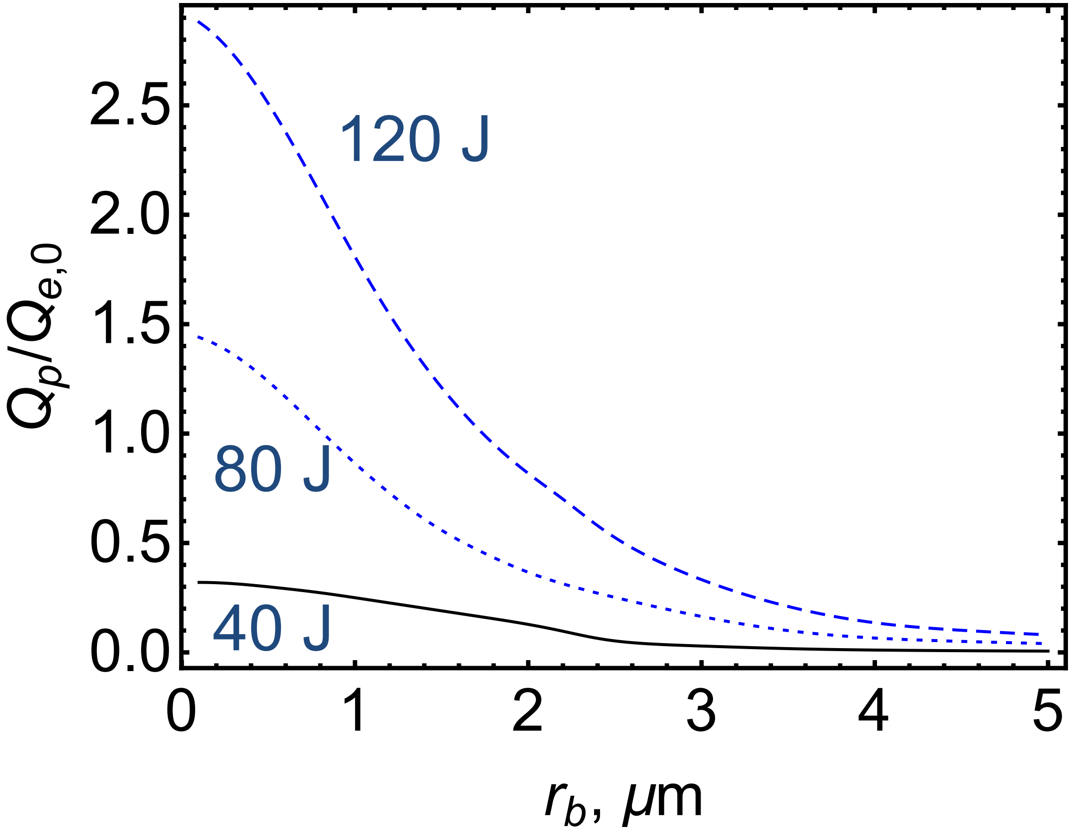


Positron spectrum

Positron beam charge depends strongly on the total laser energy and electron beam radius

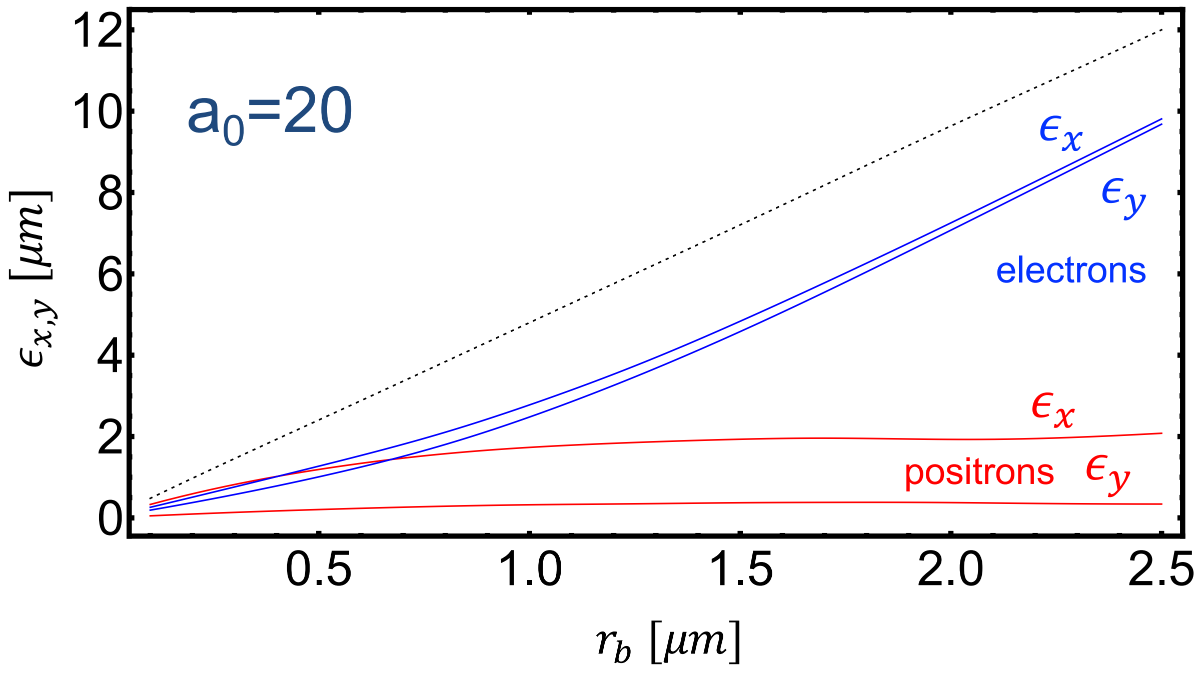


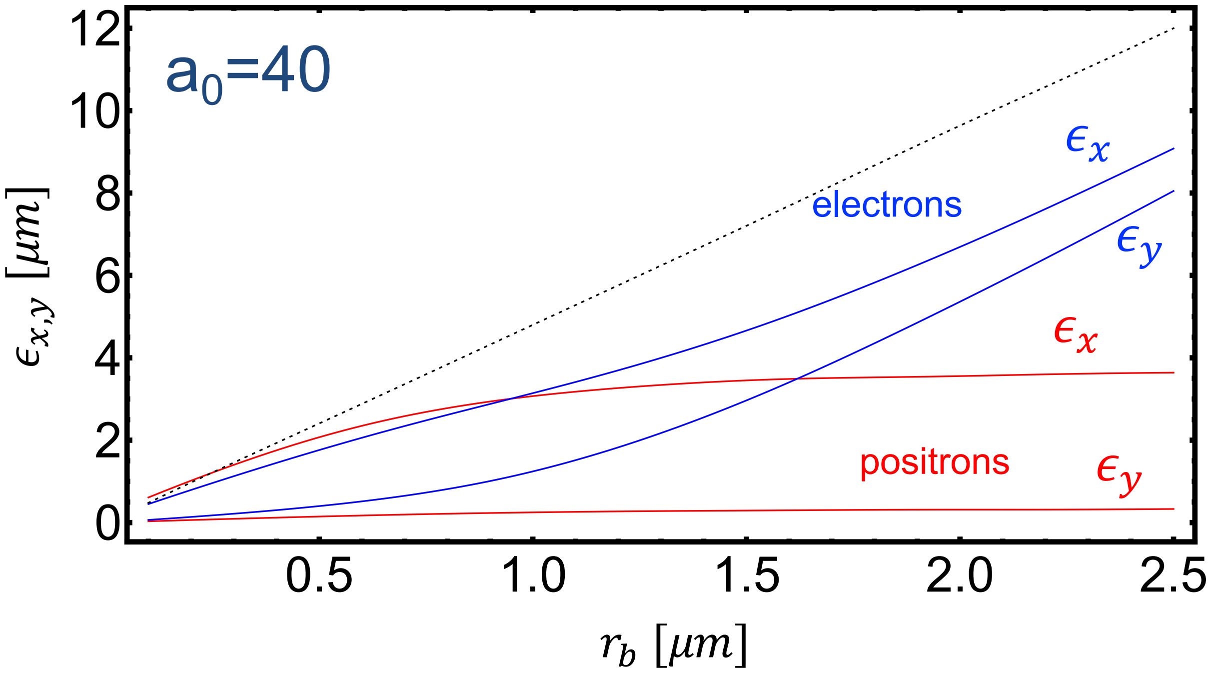
Positron beam charge produced in the electron beam collision with a laser pulse for 40 J, 80 J, and 120 J of total laser energy.



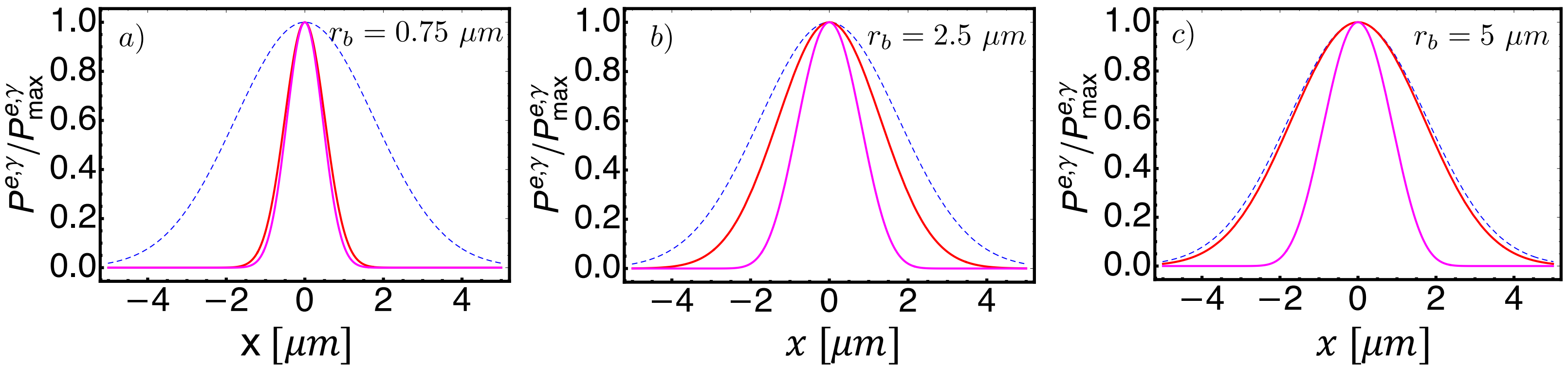
Dependence of the positron beam charge on the initial radius of the 9.1 GeV electron beam for 40 J (solid curve), 80 J (dotted curve), and 120 J (dashed curve) total laser energy

Positron beam emittance can be reduced by employing small radius electron beams





The dependence of the Compton (red curves) and Breit-Wheeler (black curves) process probabilities on the transverse profile of the laser EM field for different initial radii of the electron beam

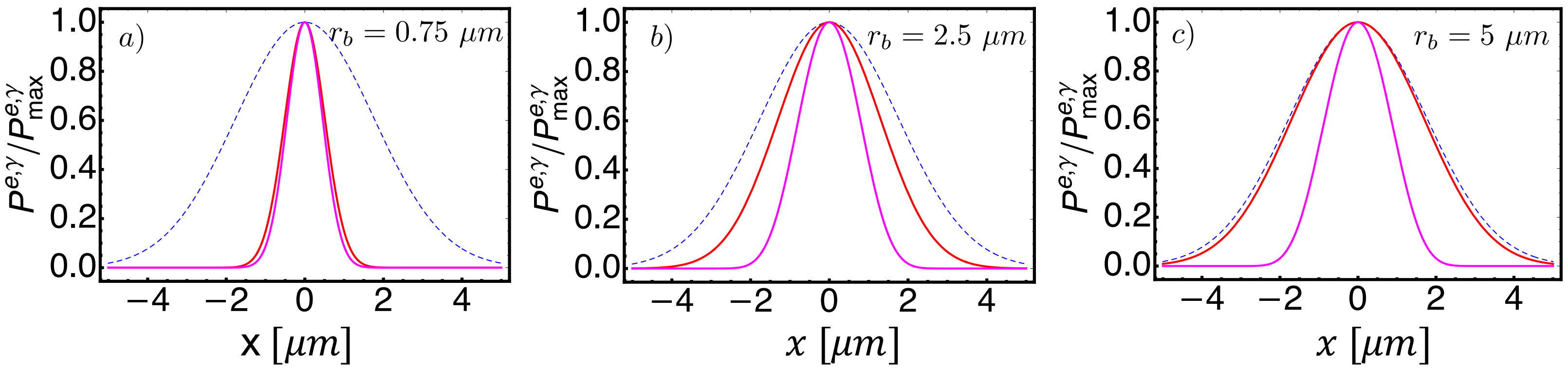


Higher frequency laser pulses offer a way to produce positron beams with collider-relevant emittances.

$\epsilon_x \vert \epsilon_y$ [μm]	$a_0 = 20, \omega = \omega_0$				$a_0 = 40, \omega = \omega_0$			
	electron		positron		electron		positron	
$\theta = 0.1, \quad \epsilon_0 = 0.1\ \mu m$	0.18	0.038	0.32	0.025	0.44	0.02	0.61	0.02
$\theta = 0.25, \quad \epsilon_0 = 0.2\ \mu m$	0.2	0.089	0.33	0.05	0.46	0.03	0.61	0.03
$\theta = 0.5, \quad \epsilon_0 = 0.48\ \mu m$	0.26	0.2	0.34	0.1	0.45	0.07	0.62	0.06

θ $- initial\ electron\ beam\ divergence\ in\ mrad;\ \epsilon_0$ $- initial\ electron\ beam\ normalized\ emittance\ in\ [\mu m]$

The dependence of the Compton (red curves) and Breit-Wheeler (black curves) process probabilities on the transverse profile of the laser EM field for different initial radii of the electron beam



Higher frequency laser pulses offer a way to produce positron beams with collider-relevant emittances.

$\epsilon_x \vert \epsilon_y$ [μm]	$a_0 = 5, \omega = 4\omega_0$				$a_0 = 10, \omega = 4\omega_0$			
	electron		positron		electron		positron	
$\theta = 0.1$, $\epsilon_0 = 0.1\ \mu m$	0.06	0.04	0.08	0.026	0.1	0.02	0.13	0.02
$\theta = 0.25$, $\epsilon_0 = 0.2\ \mu m$	0.11	0.096	0.095	0.05	0.1	0.016	0.13	0.016
$\theta = 0.5$, $\epsilon_0 = 0.48\ \mu m$	0.2	0.2	0.13	0.1	0.13	0.1	0.13	0.016

θ $-$ *initial electron beam divergence in mrad*; ϵ_0 $-$ *initial electron beam normalized emittance in* [μm]

Conclusions

- Positron creation, capture, and acceleration is one of the key missing components on the way to the plasma based collider.
- High intensity laser driven positron source is a feasible option for the collider design.
- Present day PW-class laser facilities can be used for proof-of-principle experiments on positron production.
- Higher frequency laser pulses offer a way to produce positron beams with collider-relevant emittances (~100 nm) using the interaction of a small radius electron beam with a high intensity laser pulse.

Thank you!