Nonlinear interaction-point dynamics for plasma-accelerated beams

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A. Pukhov, A. Caldwell

Talk Structure

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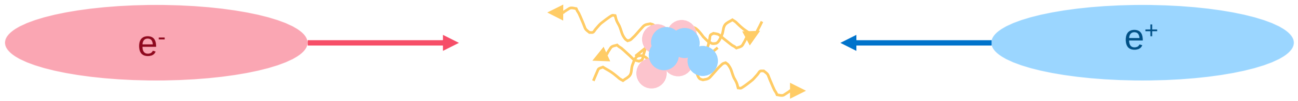
1. **Introduction**
   1. Luminosity and disruption
   2. Plasma accelerators
2. **Plasma-accelerated beams**
   1. Angled beams
   2. Hourglass effect
   3. Plasma-relevant beam profiles
3. **Summary and Further work**

Luminosity



- Particle beams cross each other, and events will occur with some rate

$$\frac{\mathrm{d}R_i}{\mathrm{d}t} = \mathcal{L}\,\sigma_i$$

- Luminosity is the overlap of the two beams. Gaussian beams for instance give;

$$\mathcal{L} = \frac{N_1 N_2}{4\pi\sigma_x\sigma_y}$$

- But beams rarely cross each other without changing shape!

Pinch & disruption

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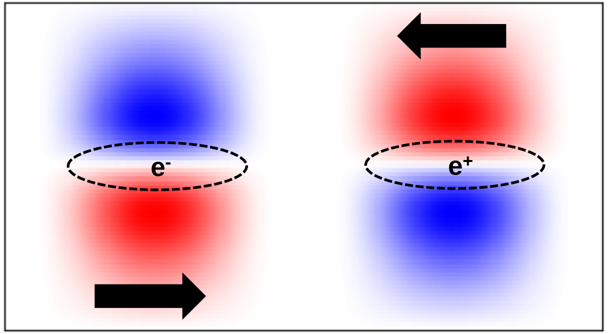
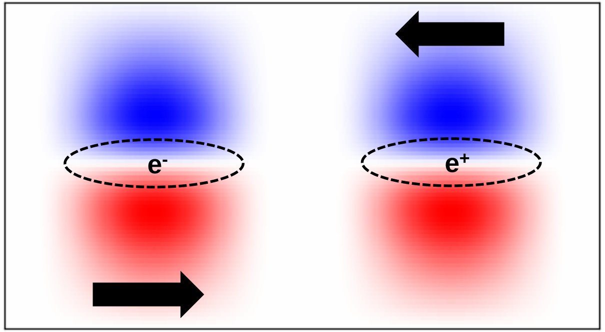
e^-e^+ colliders exhibit pinching at the IP, the reason for this is easy to see

Repelling E_y



Attracting B_z



As the bunches collide, the defocussing E-field is neutralised, and the focussing B-field is enhanced

The amount that the beam pinches is summarised as **disruption**

Conventional colliders mitigate this by making beams **flat**

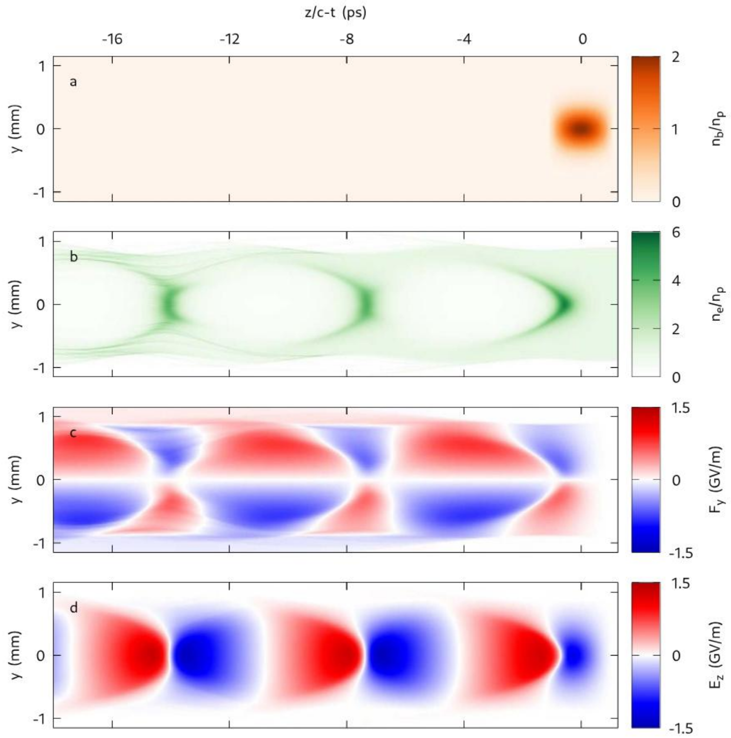
Plasma accelerated beams

- Plasma acceleration offers **high gradients**, which means **shorter accelerators**. Beams are;
  - typically **round**
  - quasimonoenergetic, with **0.1 – 10% energy spread**
  - limited by the size of the plasma wake to around **~100 µm in length**
  - In the case of positrons, typically **high emittance**

Beam parameters:

- $Q = 0.8$ nC
- $\sigma_x = \sigma_y = 20$ nm
- $\sigma_z = 70$ µm
- $\gamma = 370{,}000 \pm 0.3\%$ (190 GeV)
- $\beta_x^* = \beta_y^* = 1$ mm ($\epsilon_n = 150$ nm)

Based on CLIC, adapted to round beams



short-bunch proton-driven wakefield structure
J Farmer *et al* 2024 *New J. Phys.* **26** 113011

Quantum Complications

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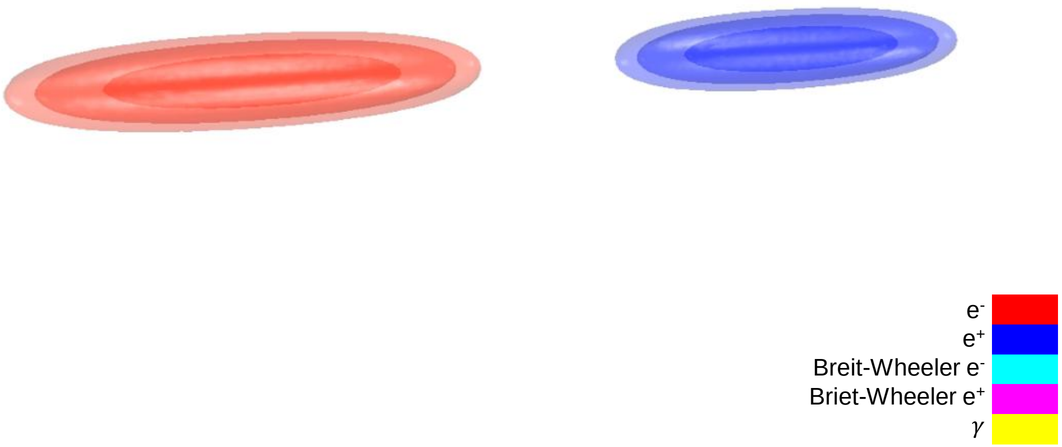
- As the beams pinch, the fields increase in turn, which can lead to strong-field QED effects
- high-energy photons are produced, and in the case of very high disruption, e^-e^+ pairs
- As these secondary particles are produced, the beams lose energy – so called 'beamsstrahlung'
- Pair-production in particular is tricky to model, because new charged particles create fields of their own, which can dramatically affect the interaction
- We need simulations!

VLPL 3D-QED Simulation



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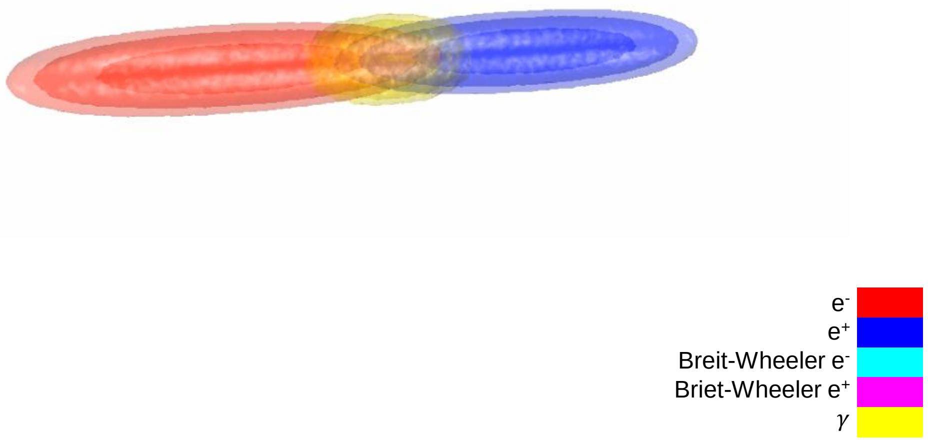

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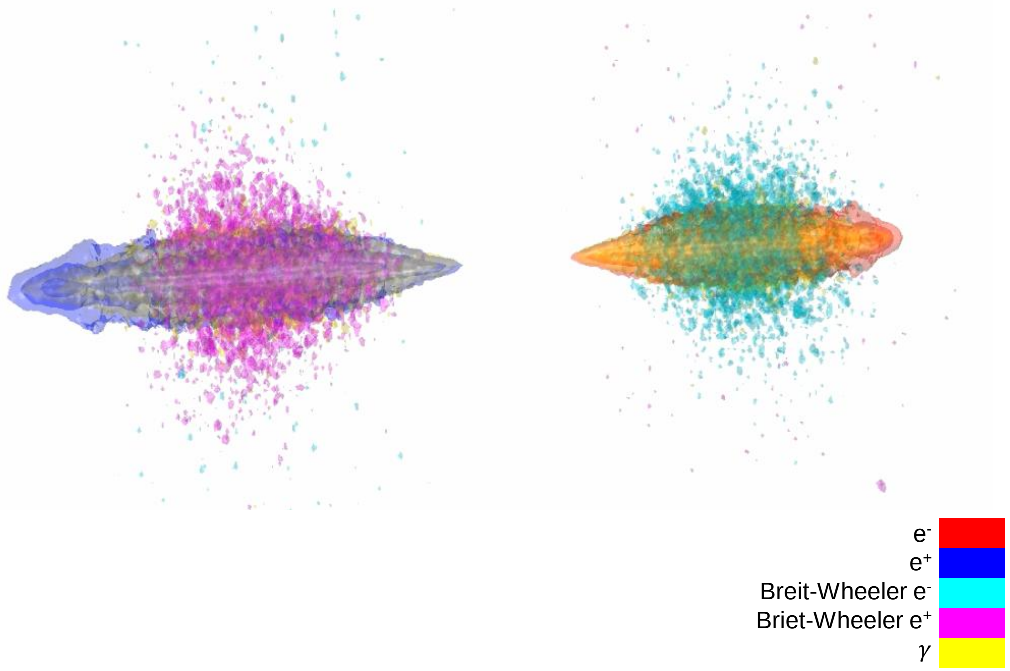

Plasma-accelerated beams

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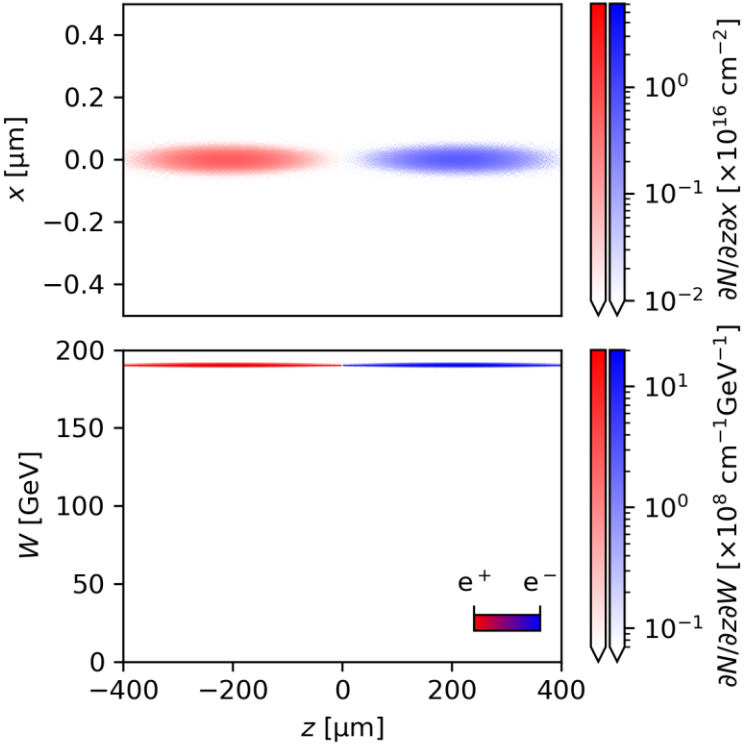
- Colliding two of these beams gives us a starting point



Positional distributions are integrated over any missing axes

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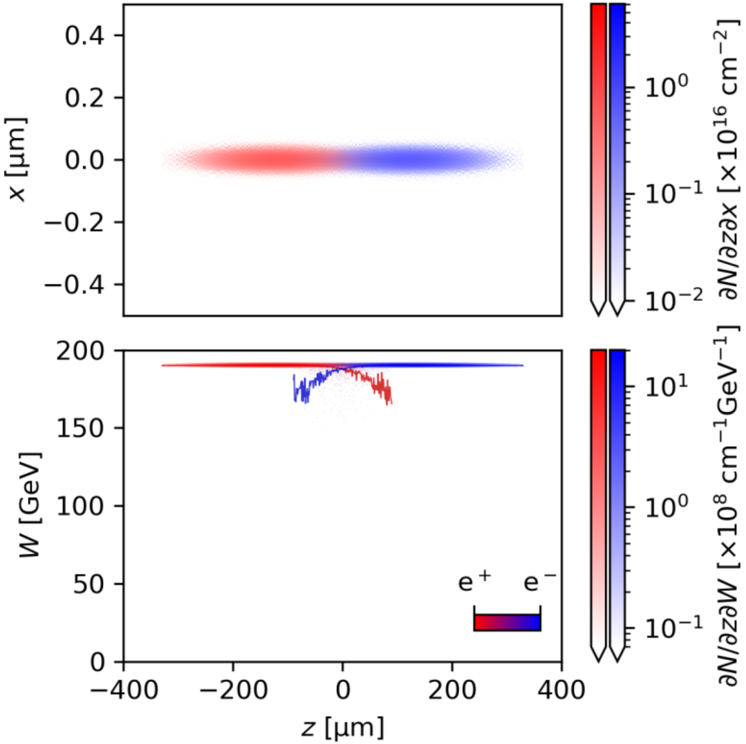

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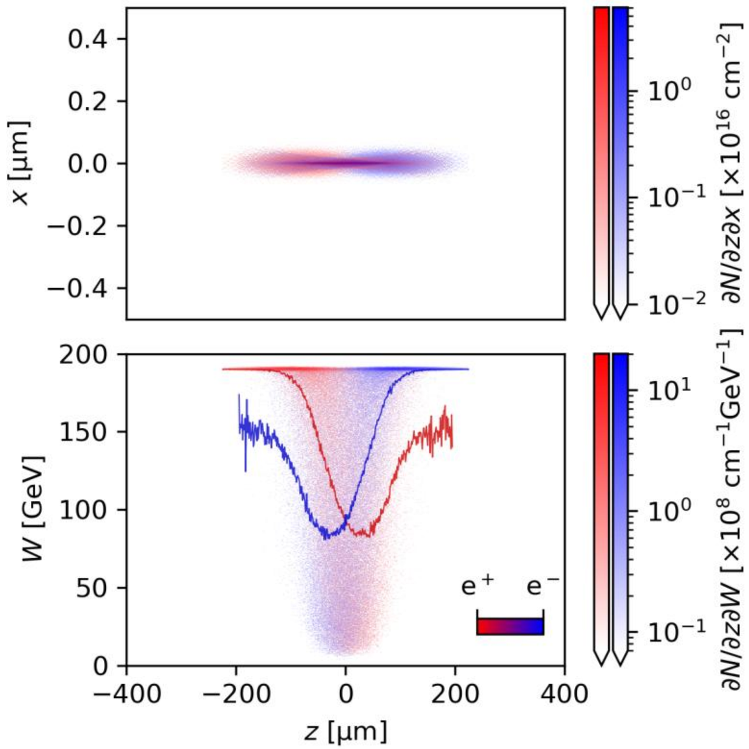

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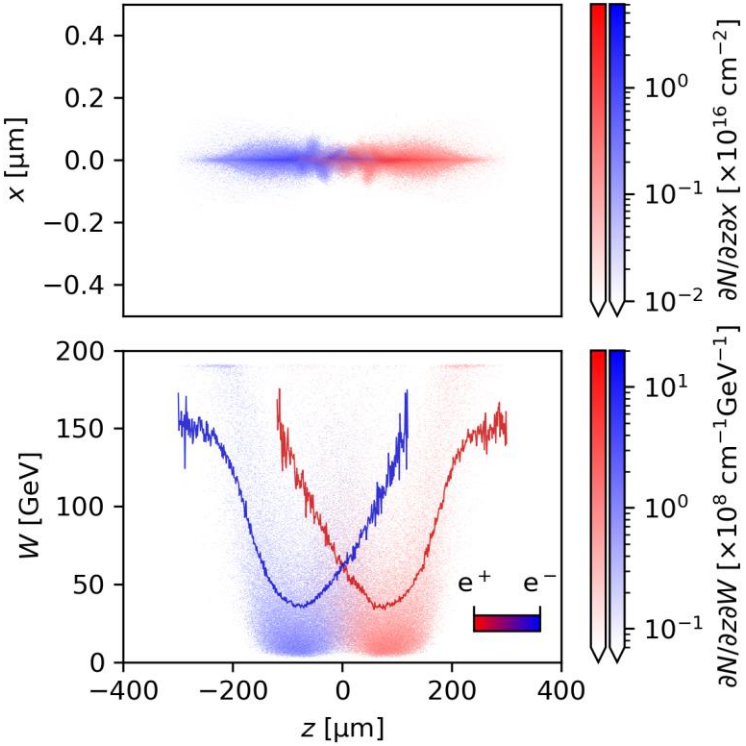

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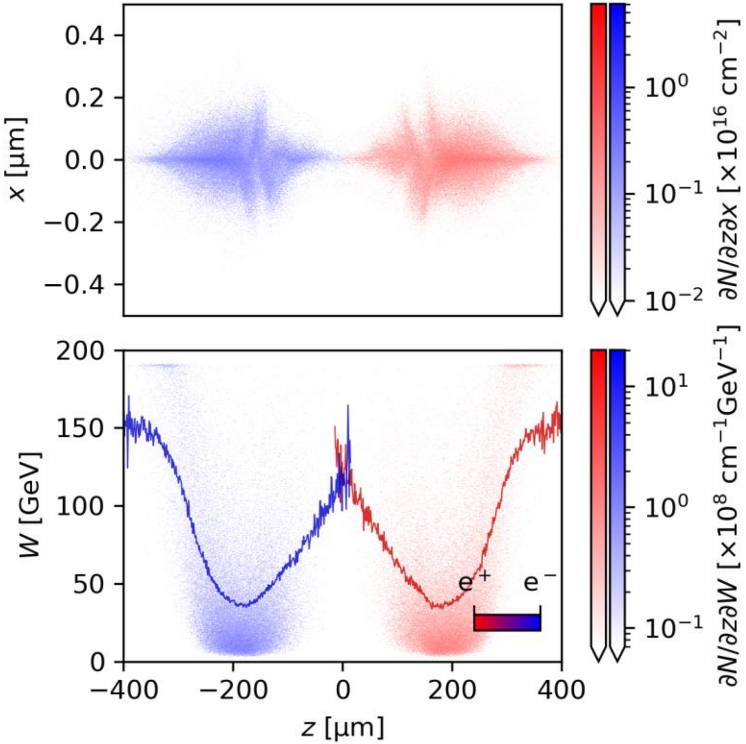

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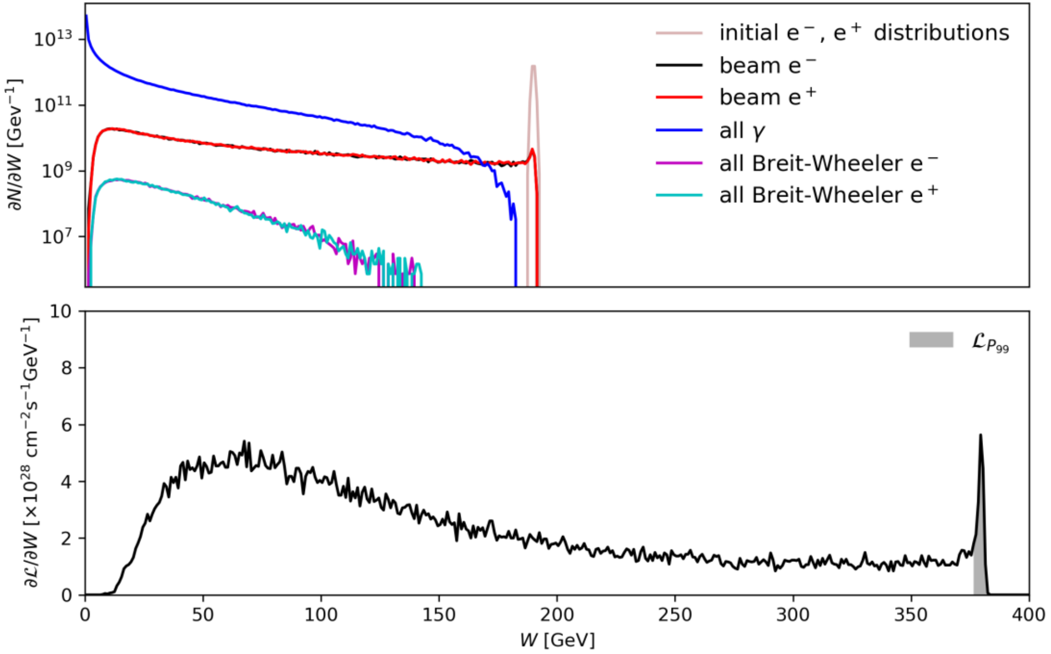

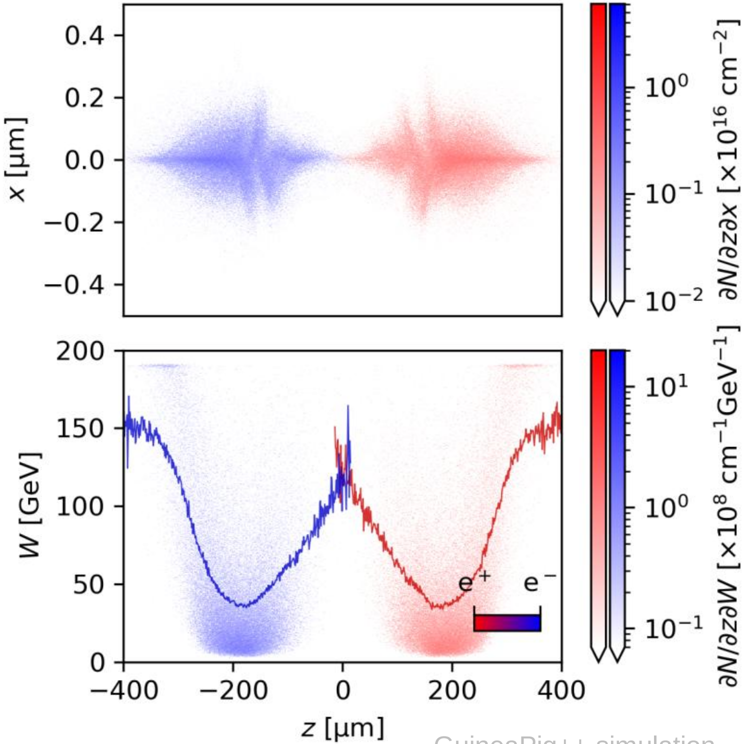

GuineaPig++ simulation

Positional distributions are integrated over any missing axes

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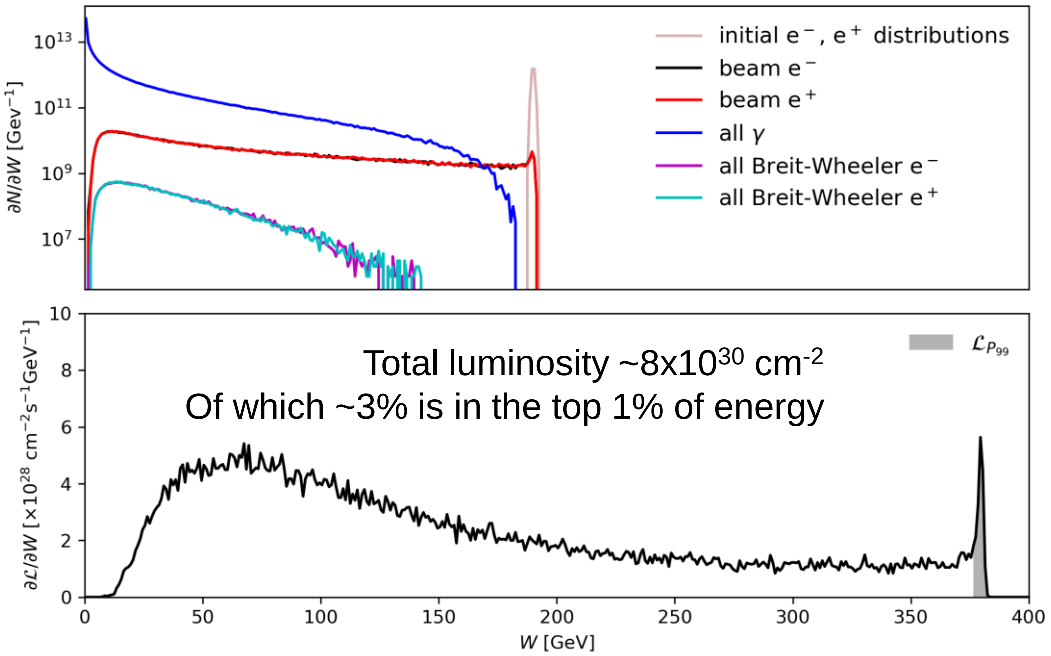

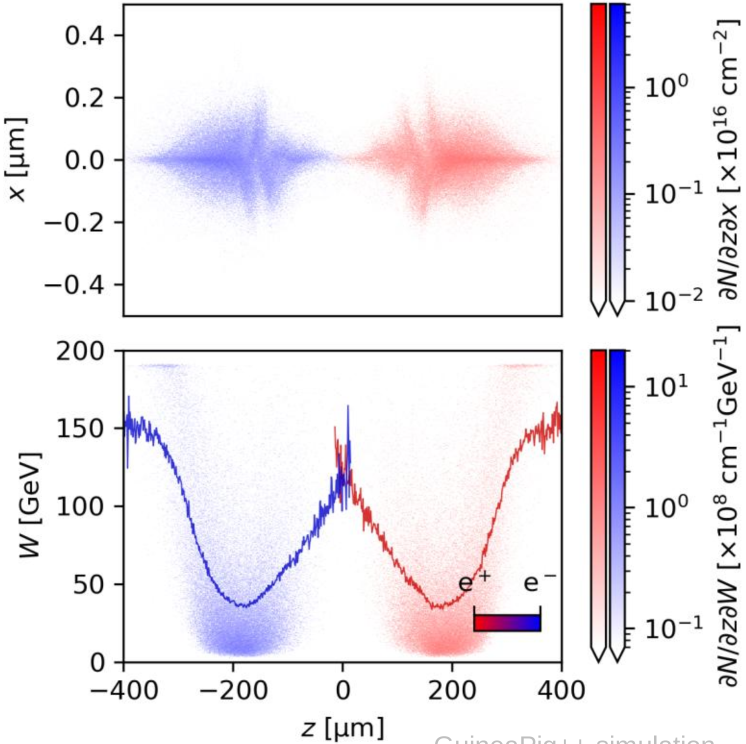

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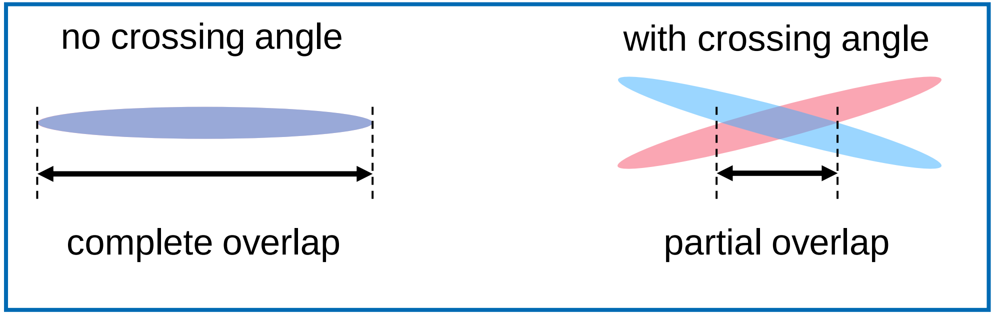
Crossing Angles



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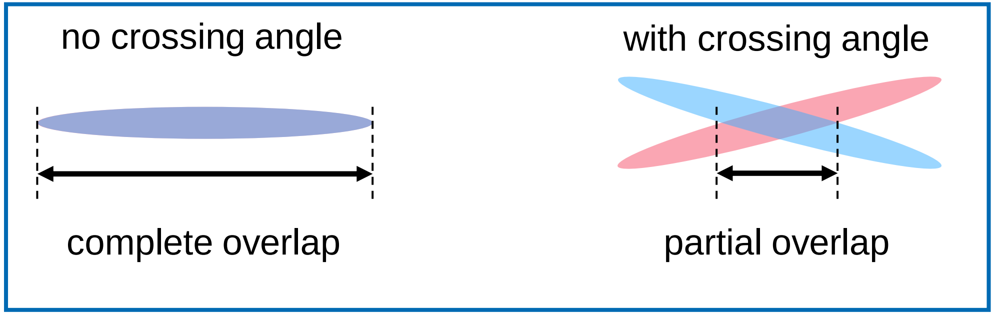
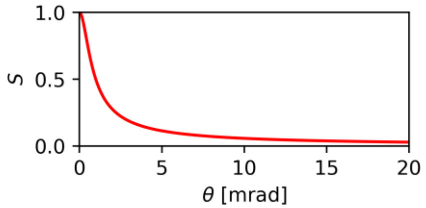


- Crossing angles modify the luminosity by a factor

$$S = \left[1 + \left(\frac{\sigma_z}{\sigma_x} \tan\frac{\theta}{2}\right)^2\right]^{-\frac{1}{2}}$$



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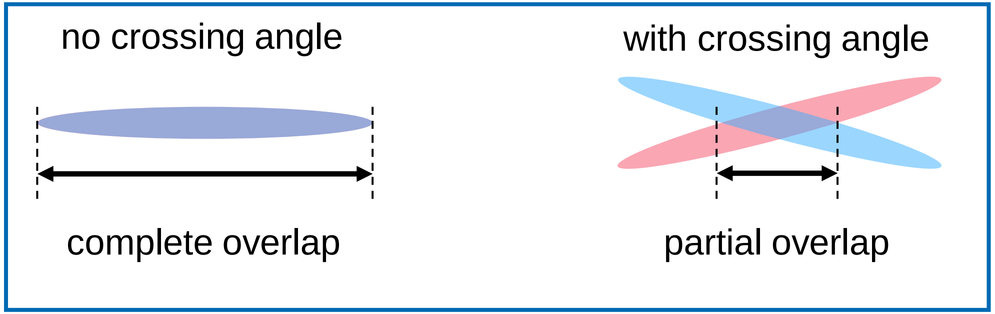

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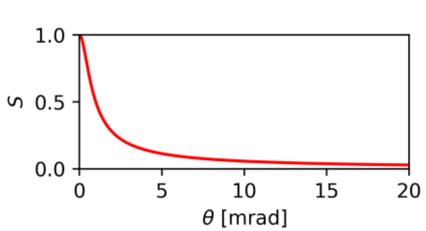
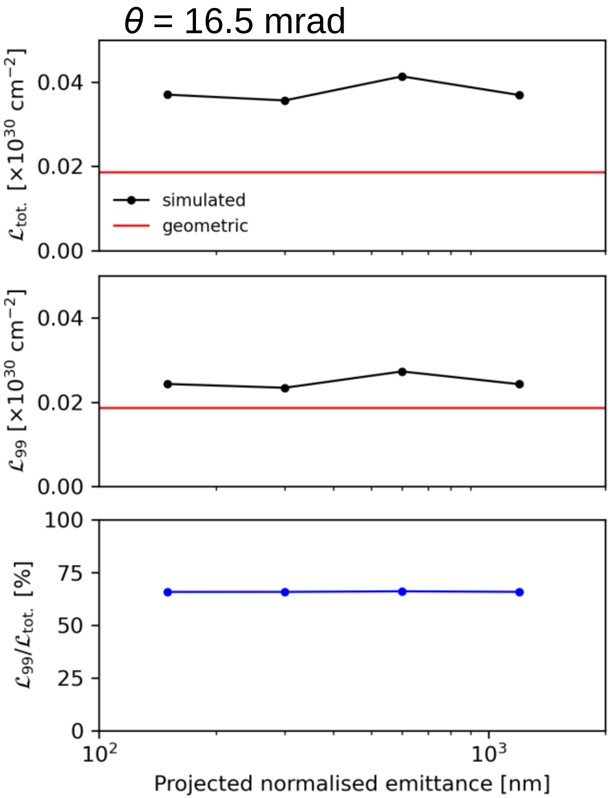


- Directly reducing the overlap between the two beams reduces both disruption and the attainable luminosity, but the interaction becomes insensitive to beam quality

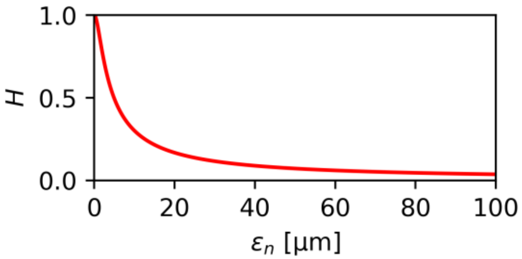


The hourglass effect

- The emittance of a beam cause the size of the beam to vary with distance from its focus, much like a laser. This effect also causes a reduction in crossover and hence luminosity

$$H = \sqrt{\pi}\, u_x \exp(u_x^2)\, \mathrm{erfc}(u_x)$$

$$u_x = \frac{\beta_x^*}{\sigma_z}$$



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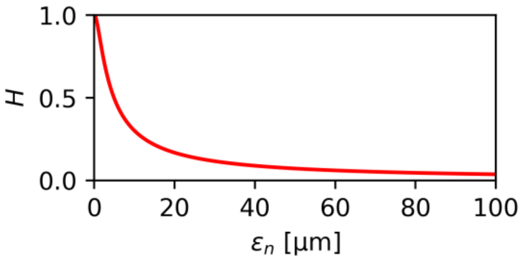
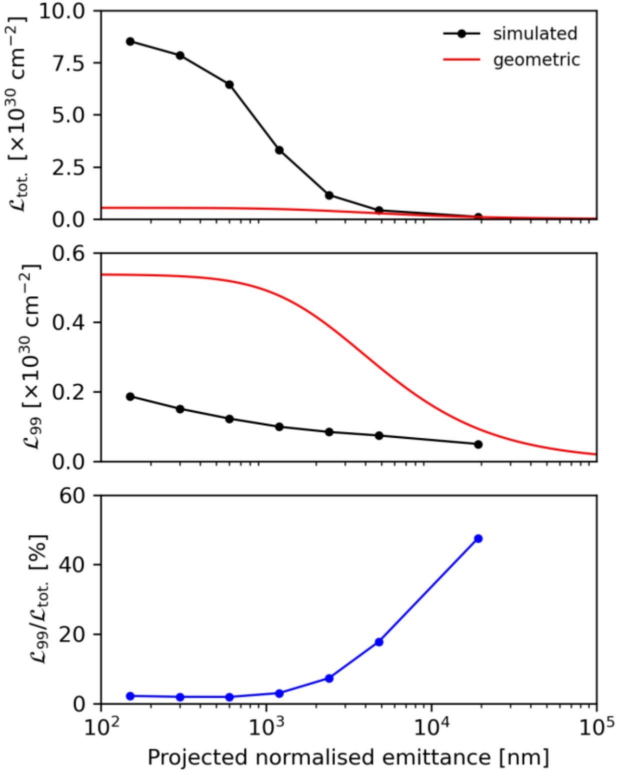
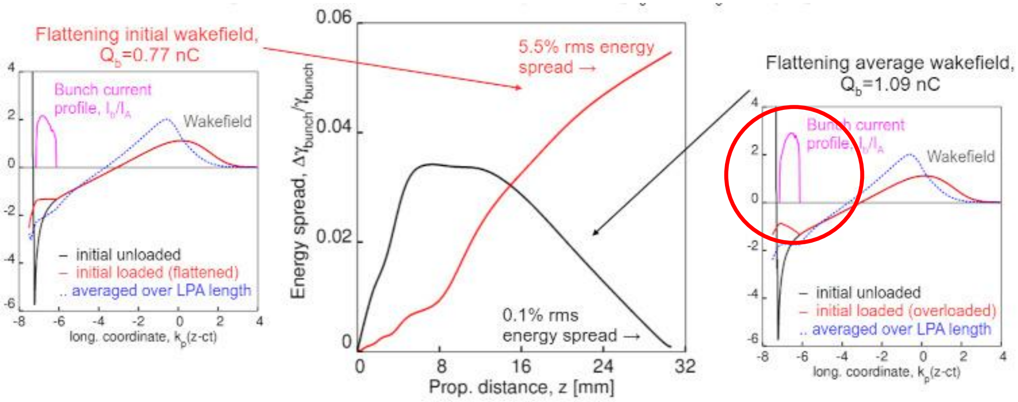


- The reduction in disruption causes a large drop in total luminosity, but quality of the signal improves as beam quality degrades, leaving the top 1% fraction relatively insensitive

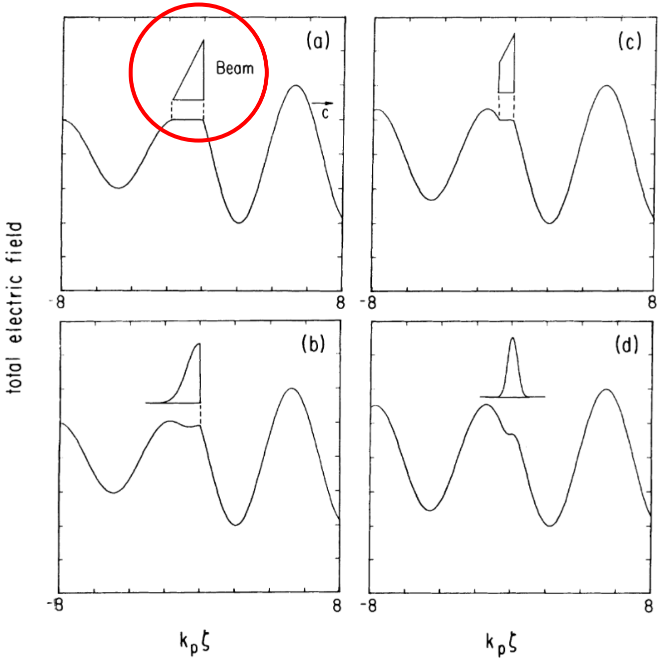


What might we be colliding?

- Beamloading in plasma accelerators traditionally calls for downramp (fat-end first) bunches
- Optimal profiles for acceleration over very long distances take on weird and wonderful shapes
- If the beams require focussing after leaving the plasma, the eventual shape may be different again



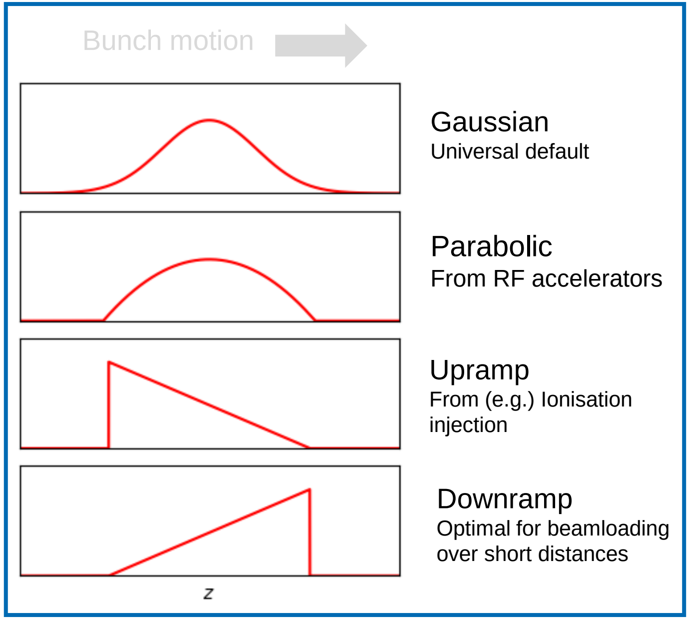
https://indico.slac.stanford.edu/event/9734/



T. Katsouleas et al., *Particle Accelerators,* **22,** 81-99, 1987

Longitudinal shape factors

- It makes sense to scan several different shapes to see how different the results are



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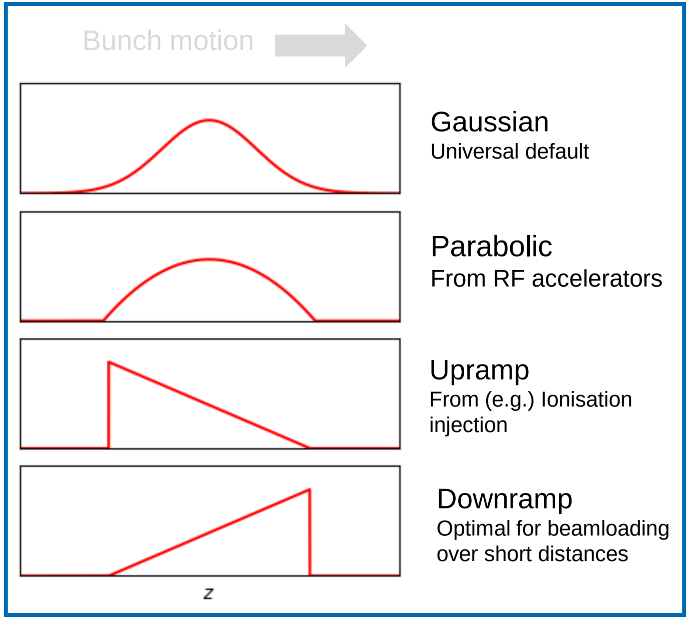
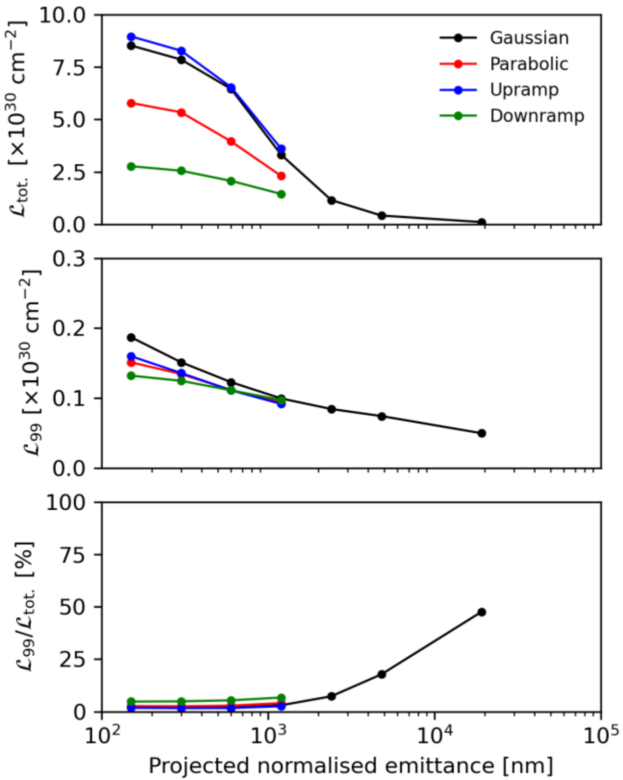


- Large variations in the total luminosity are all smoothed out when looking at the top 1%
- The overwhelming factor for the high-energy fraction is the projected emittance
- All profiles converge towards similar values at high emittance



Summary

- The kinds of bunch profiles typical of plasma accelerators offer similar performance to those of conventional accelerators
- The high disruption of round beams can be mitigated with increased emittance, trading off absolute luminosity for quality of signal
- The effect of signal to noise ratio should be evaluated with start-to-end (system) codes and detector simulation
- As we move towards higher-energy colliders, scanning broad range of collision energies becomes a useful property, so figures of merit may change

Thank you for your attention