Measuring strong-field QED with the help of ZEUS

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EPS-PP, 3rd July 2026

Engineering and Physical Sciences Research Council

FUSION CDT

UNIVERSITY of York

CLF central laser facility

Thanks to the team!

University of York
- **Owen Lawrence**
- **Chris Murphy**
- Chris Ridgers

Queen's University Belfast
- **Elias Gerstmayr**
- **Conor McAnespie**
- **Hannah Jager**
- Gianluca Sarri
- Matt Streeter

Lancaster University
- **Chris Arran**

Imperial College London
- Brendan Kettle
- Stuart Mangles

University of Oxford
- Eva Los

Thanks to the team!

Strong fields are comparable to the Schwinger field

$$E_{cr} = \frac{m_e^2 c^3}{e\hbar} \approx 1.3 \times 10^{18}\ \mathrm{V/m}$$

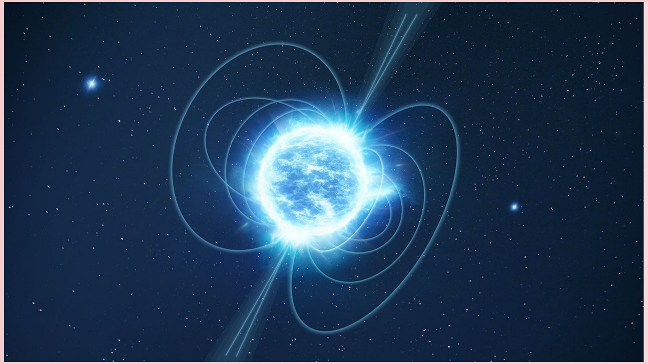
Quantified by the 'quantum parameter':

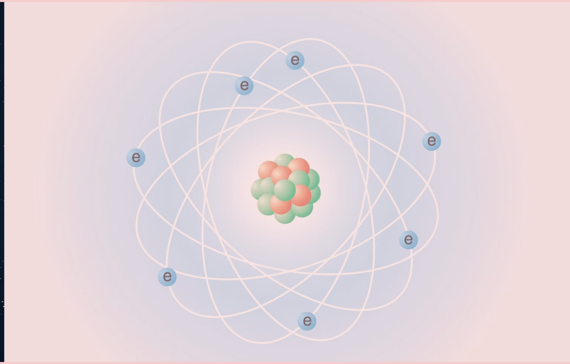
$$\chi_e = \frac{\gamma|\mathbf{E} + \mathbf{v} \times \mathbf{B}|}{E_{cr}}$$

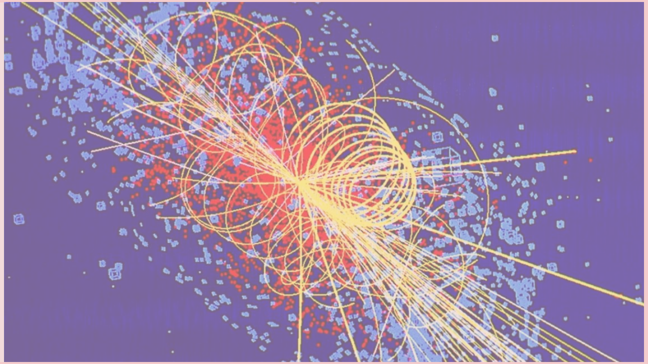
Classical non-linearity parameter:

$$a_0 = \frac{eE_0}{mc\omega}$$

Strong fields arise in a range of environments





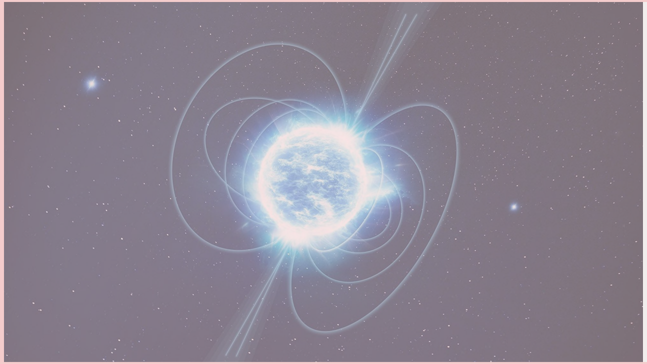


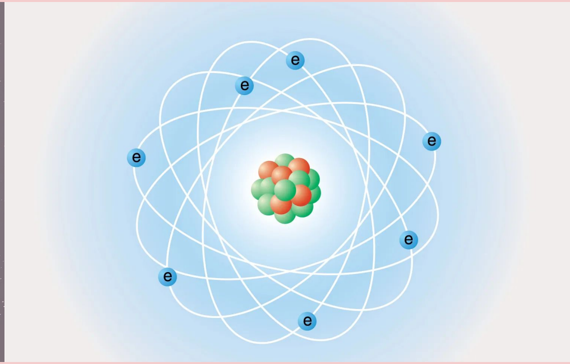
B fields of up to 10^{11} T around certain neutron stars

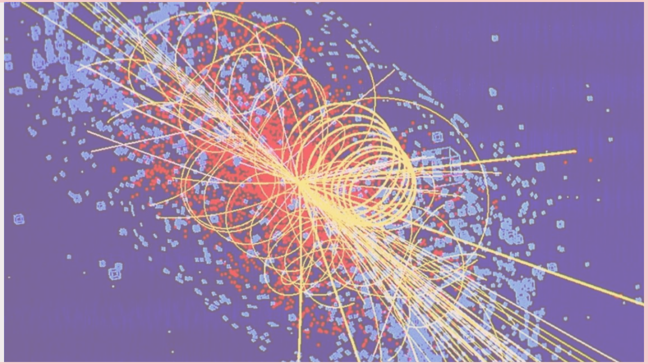
Effects of strong E field are observable close to nuclei with Z>80

Predicted at the interaction point of future particle colliders

Strong fields arise in a range of environments







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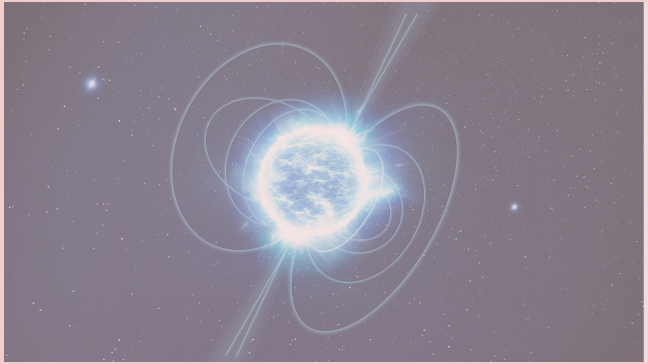
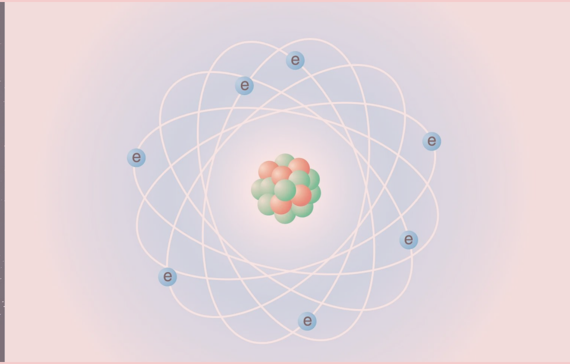
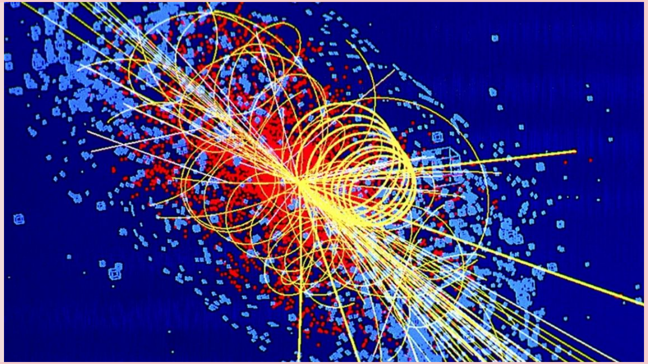






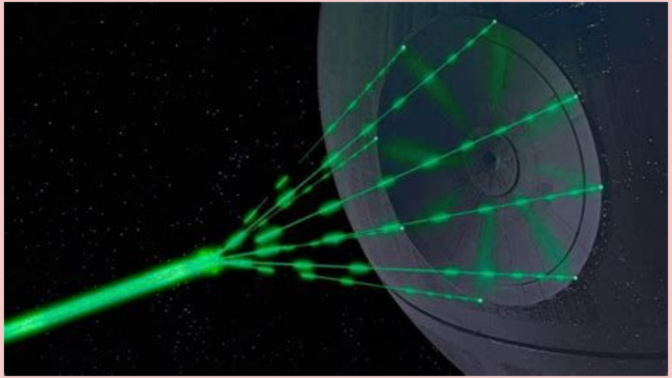
B fields of up to 10^{11} T around certain neutron stars

Effects of strong E field are observable close to nuclei with Z>80

Predicted at the interaction point of future particle colliders

But they are hard to make in controlled experiments

Lasers? Highest powers provide $E_0 = 10^{14}\ \mathrm{V/m} << E_{cr} = 10^{18}\ \mathrm{V/m}$



BUT relativistic particles see upshifted fields!

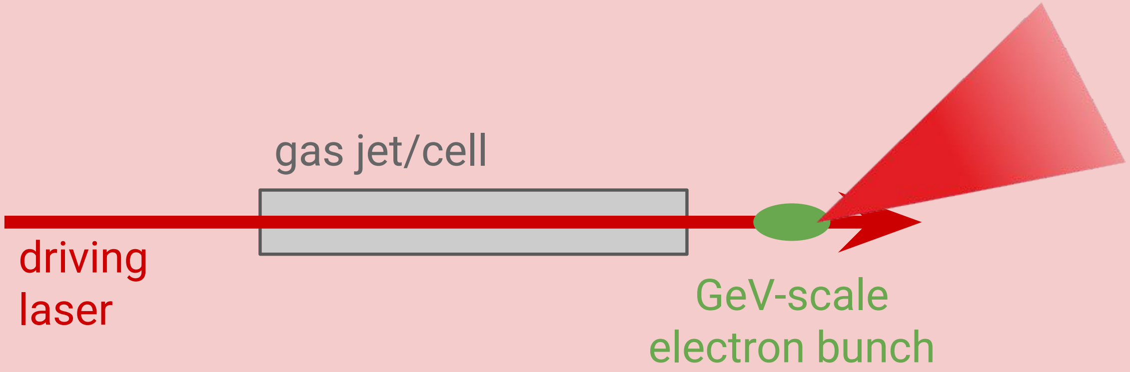
$$\chi_e = \frac{\gamma|\mathbf{E} + \mathbf{v} \times \mathbf{B}|}{E_{cr}}$$

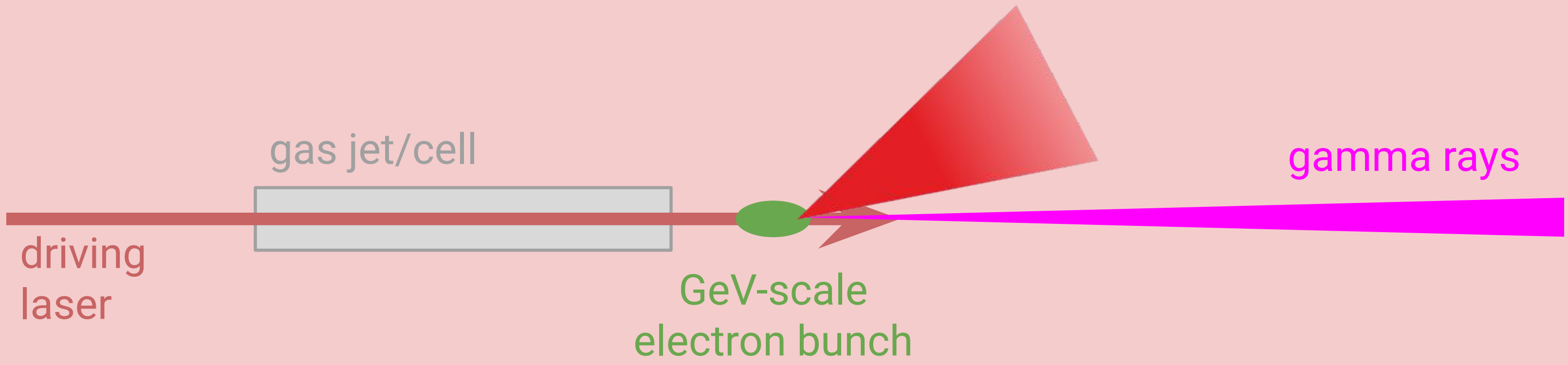
GeV electron

Tightly focused PW-class laser

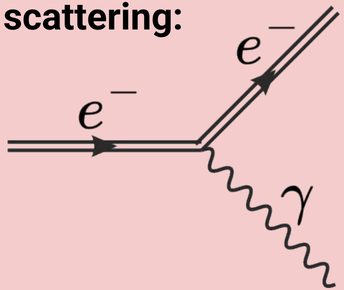
$\chi_e \sim 1$

Laser wakefield acceleration (LWFA) creates GeV electrons

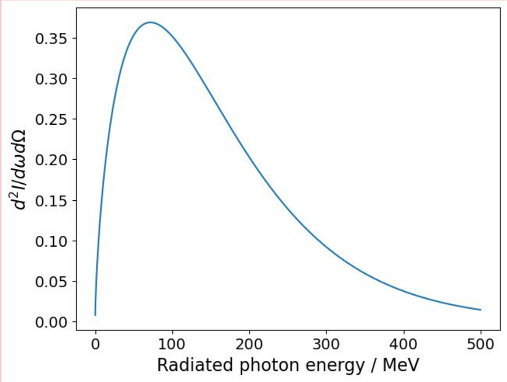




Non-linear Compton scattering:



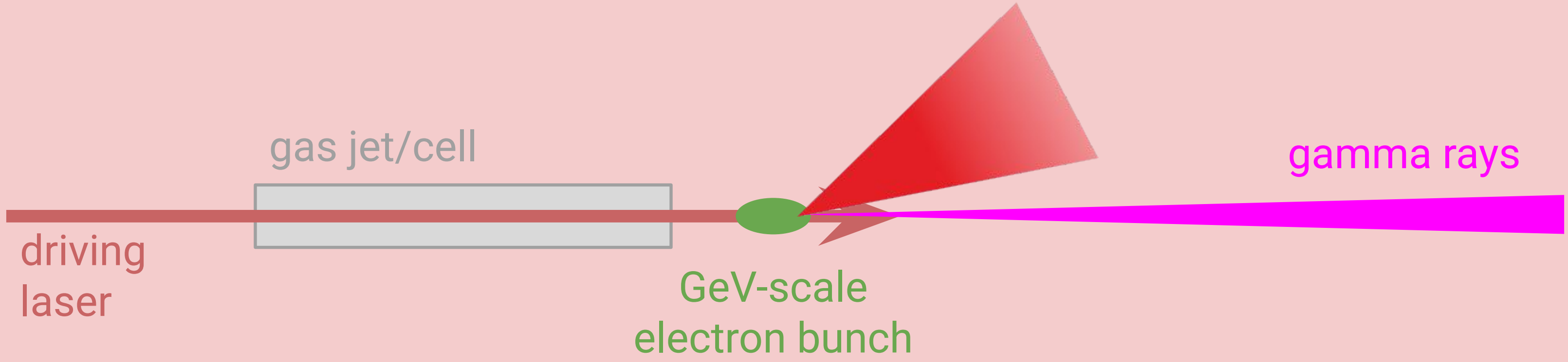
Spectrum:



Synchrotron-like for given electron energy and laser intensity, e.g. shown for

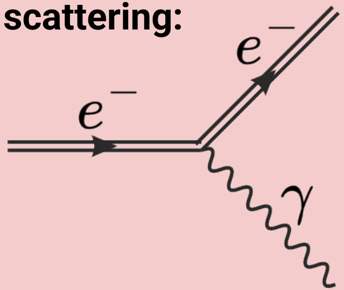
$$a_0 = 5 \quad \gamma = 2000$$

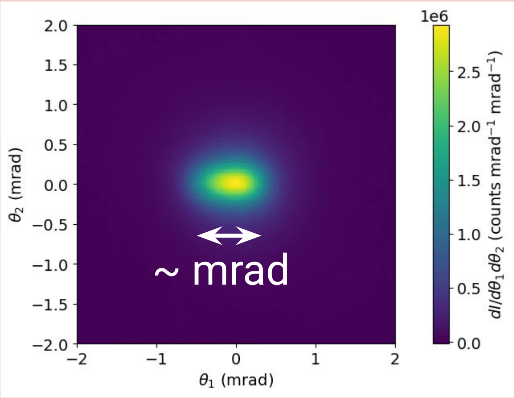
Gamma rays produced by non-linear Compton scattering



Angular distribution:

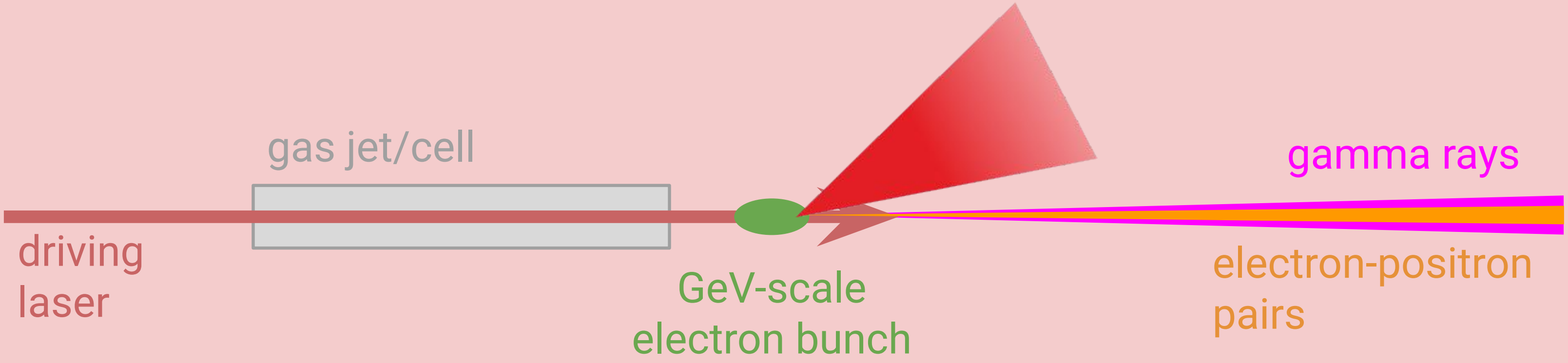
Non-linear Compton scattering:



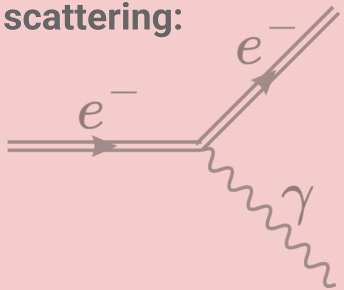


- Relativistically beamed to a few mrad along e^- direction
- Elliptical due to oscillation in linearly-polarised laser field

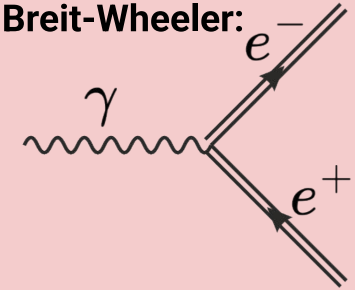
And e$^-$-e$^+$ pairs produced by non-linear Breit-Wheeler



Non-linear Compton scattering:



Non-linear Breit-Wheeler:

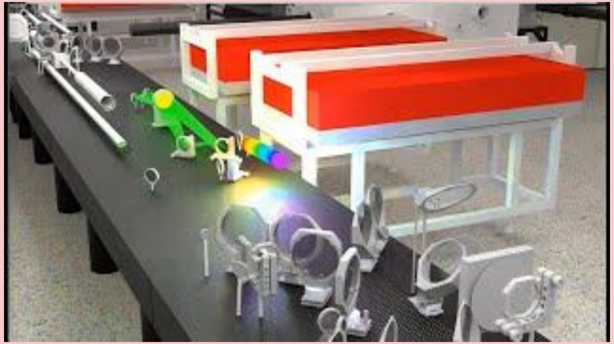


- Exponentially suppressed for $\chi_e < 1$
- Energy ~ 100s MeV

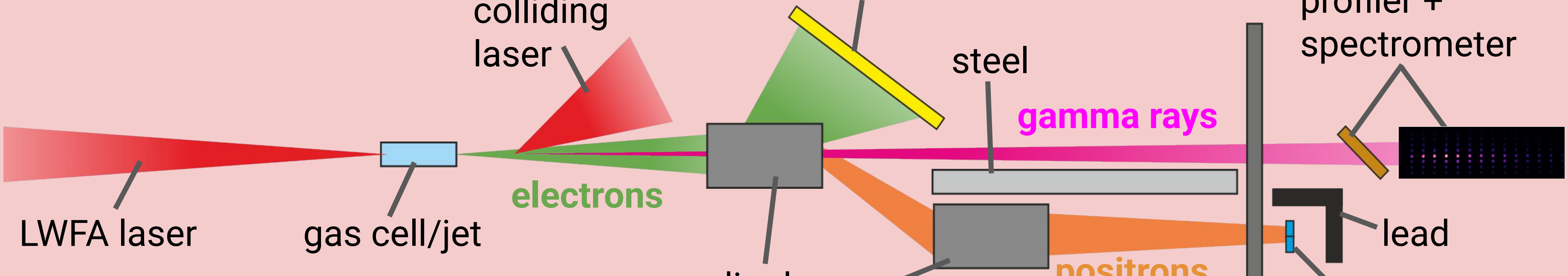
The ZEUS facility → a 2.5 PW + 0.5 PW system

- 2.5 PW LWFA driver allows access to up to ~5 GeV electrons
- 0.5 PW colliding beam focused tightly provides peak a_0 values ~50
- Together, $\chi_e \sim 1$ is achievable
- Still ramping up to above values - we had 1.5 PW + 0.2 PW

Animated fly-through of the laser!

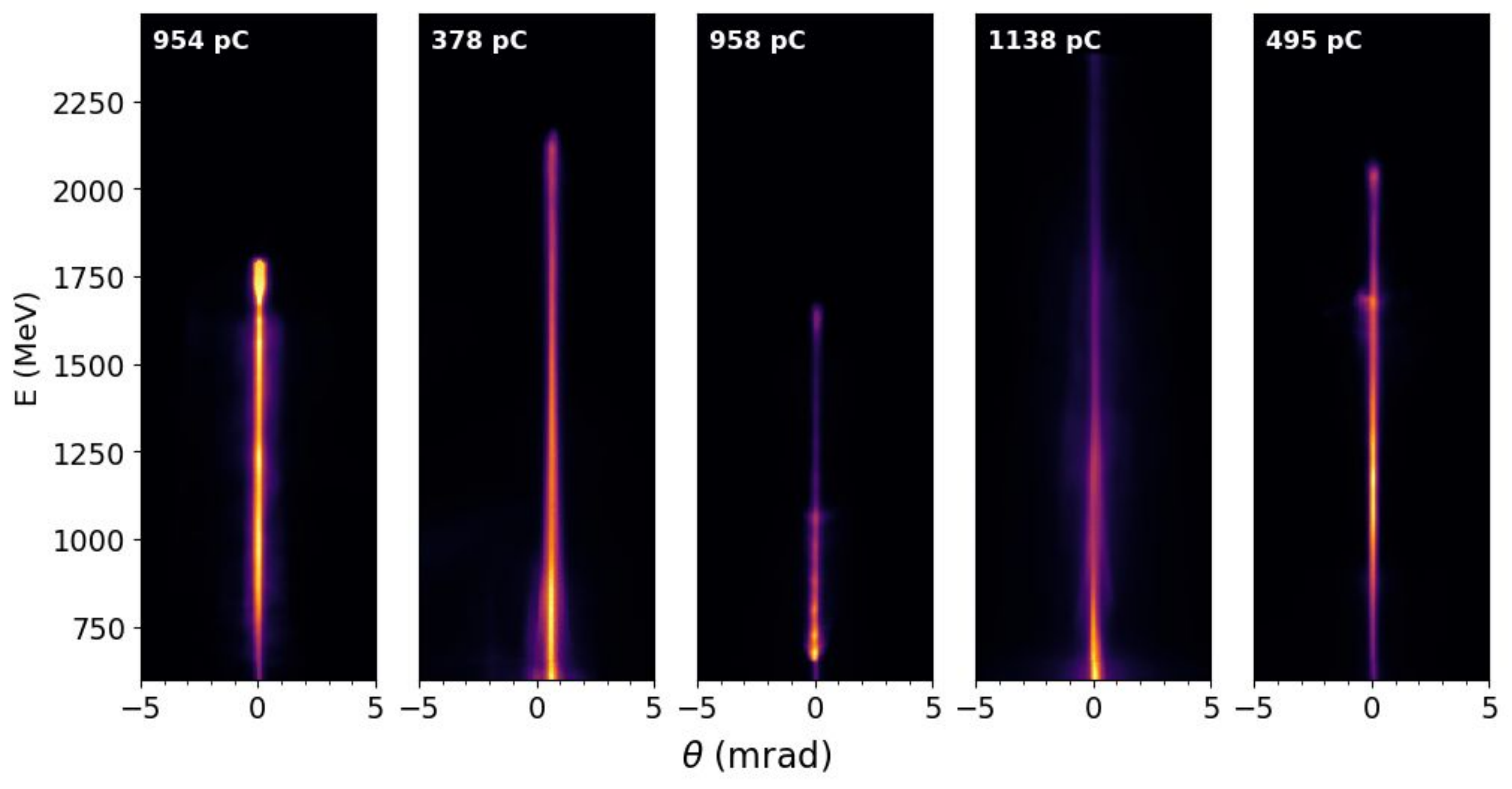


Our set-up



- Observe non-linear Compton scattering via gamma spectrometer
- Observe non-linear Breit-Wheeler via positrons on Timepix3
- Observe radiation reaction via correlated changes to e^- spectra

LWFA results: broad spectrum e^- beams up to 2.3 GeV

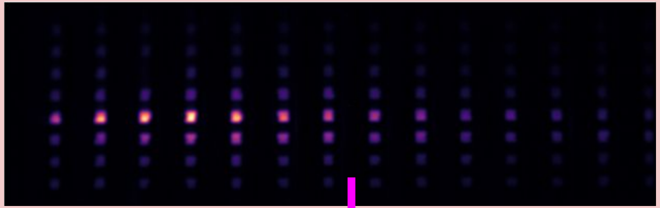


5 shots chosen randomly from one run.

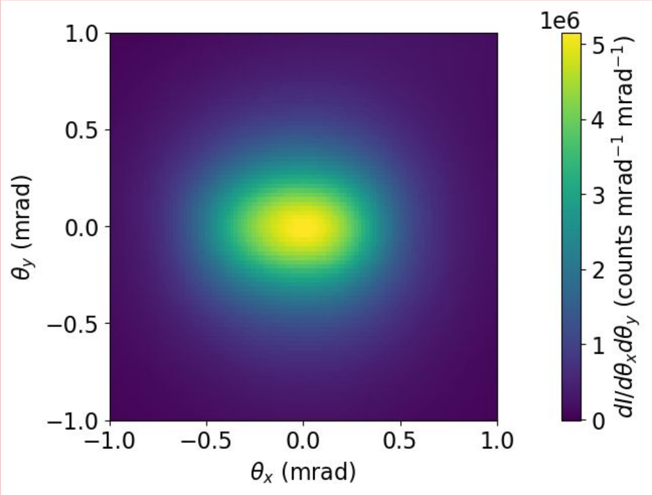
Collisions identified on gamma diagnostics

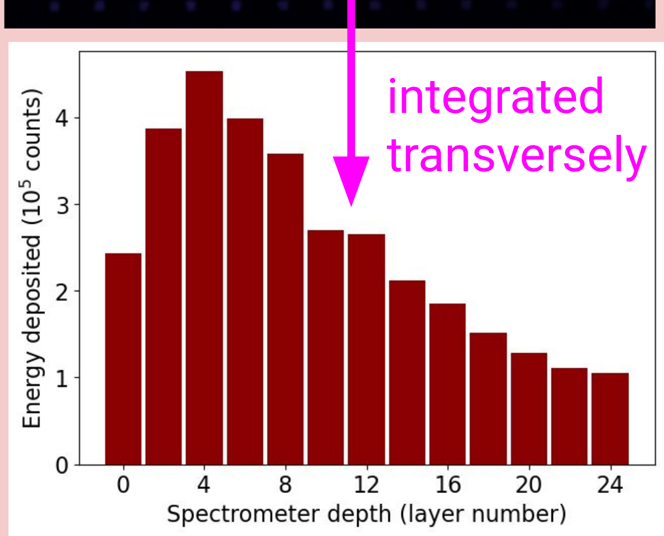
Collisions identified via gamma ray signals with:

- Low divergence
- High penetration into spectrometer

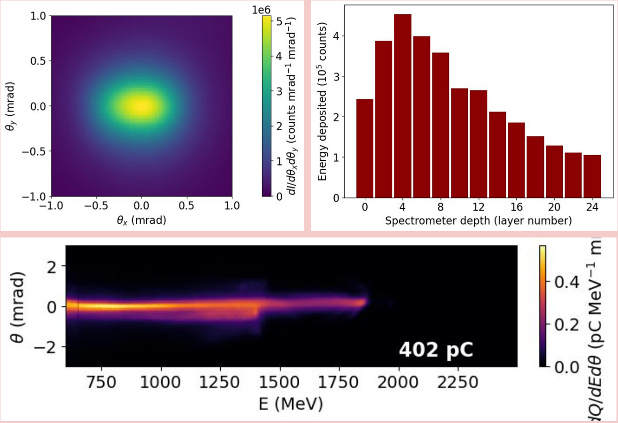


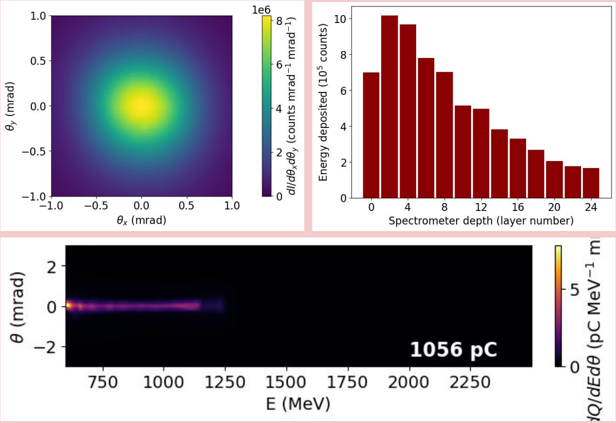
In this run of 105 shots, we estimate 33 successful collisions.
=> 31% hit rate.

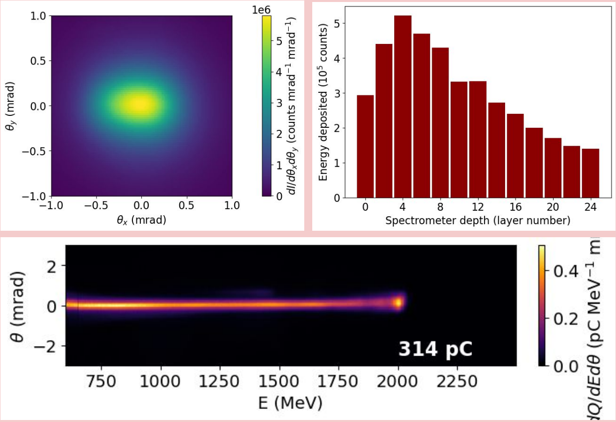




Three of the brightest collisions

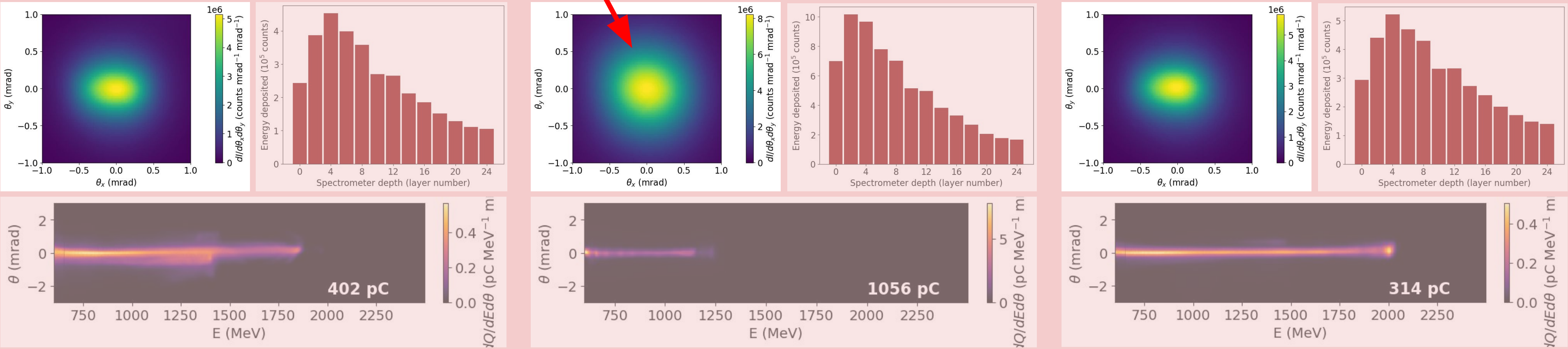






Three of the brightest collisions

Less elliptical profile implies lower a_0



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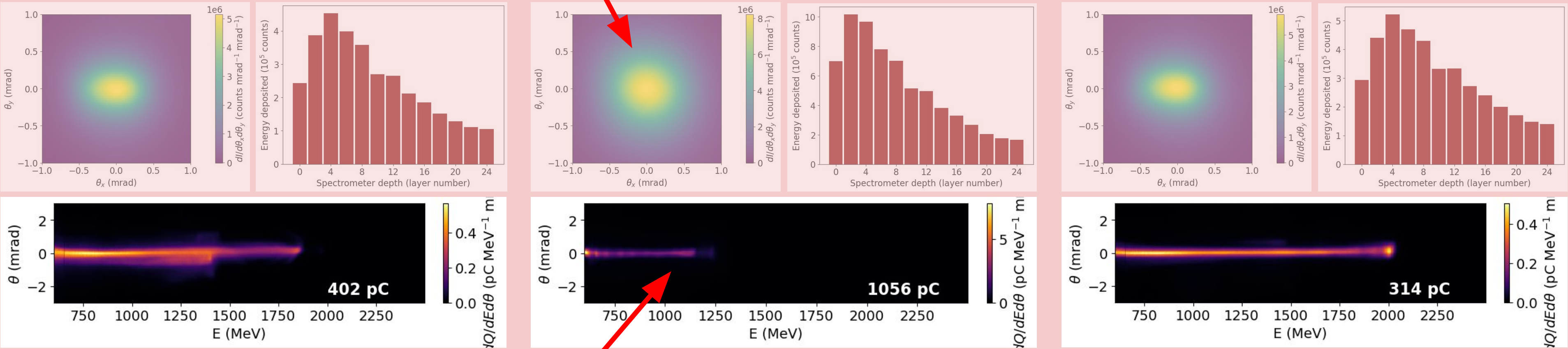
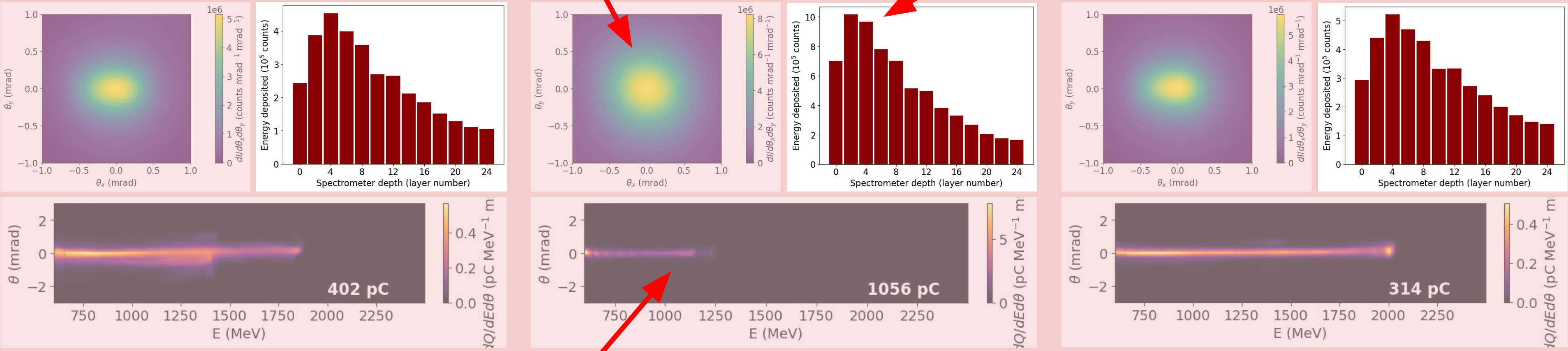


Also colliding with lower
electron energies

Three of the brightest collisions

Less elliptical profile implies lower a_0

Earlier peak means lower photon energies - consistent with lower a_0 and electron energies



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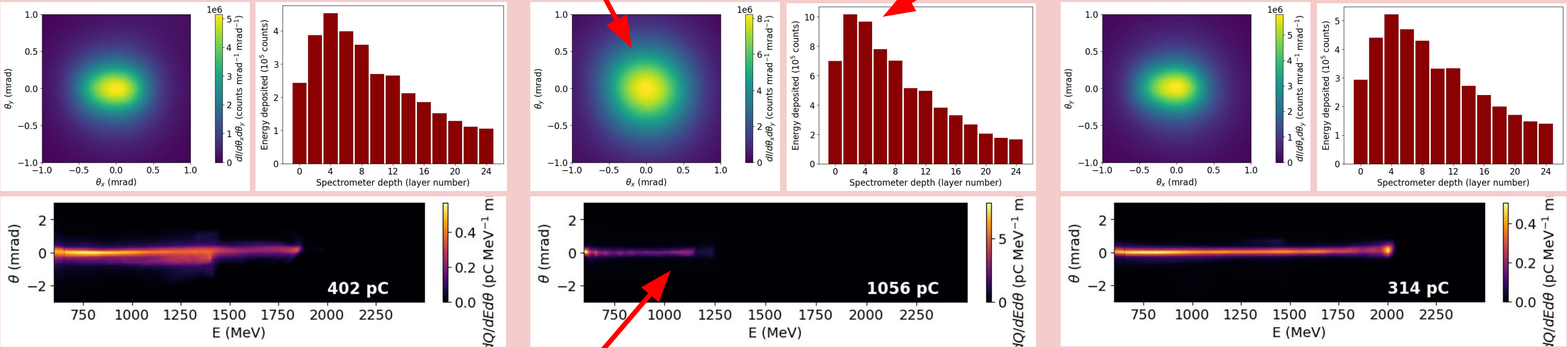
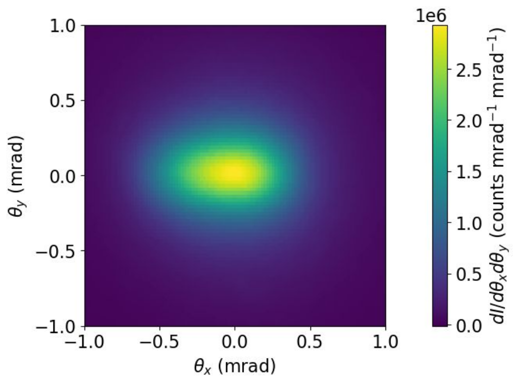
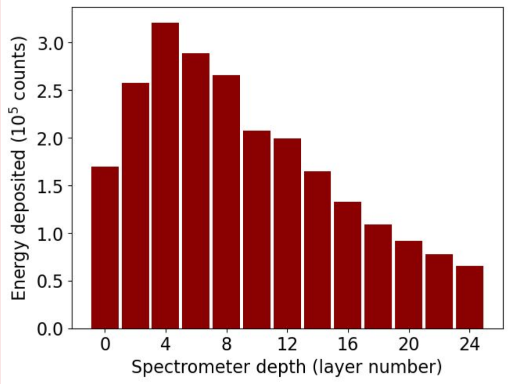


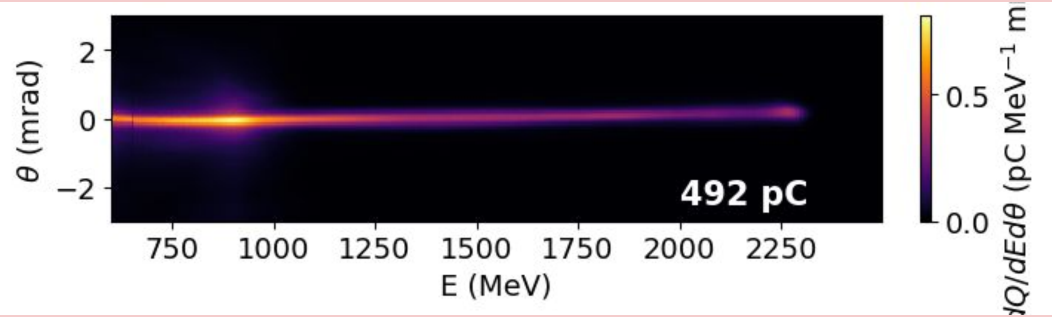
Also colliding with lower electron energies

Higher counts on gamma diagnostics explained by higher charge in electron beam

‘Focusing’ on one good shot - 17/09 run 7 shot 63







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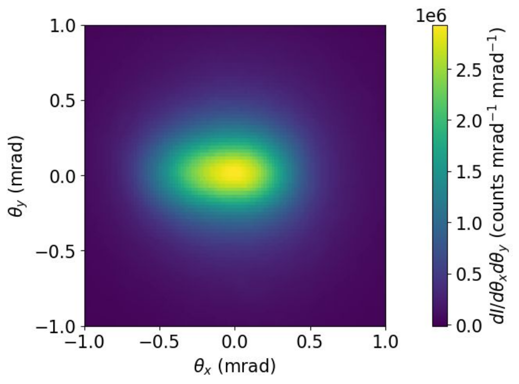
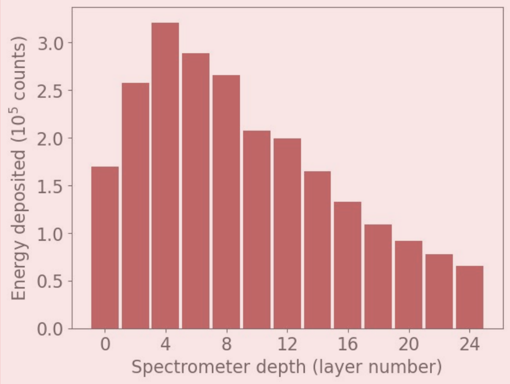
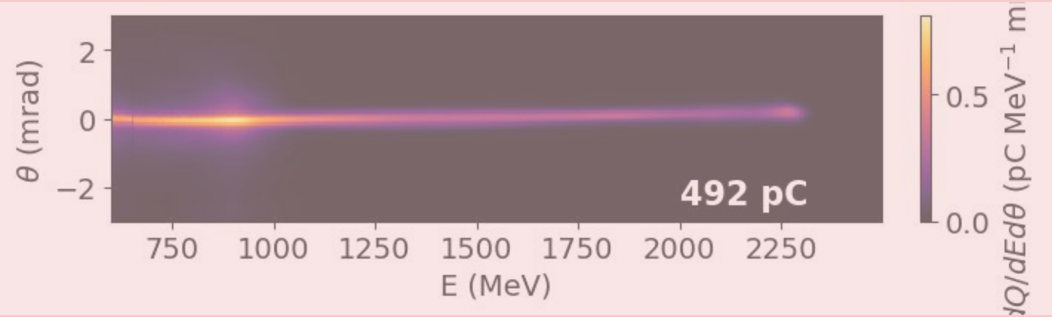
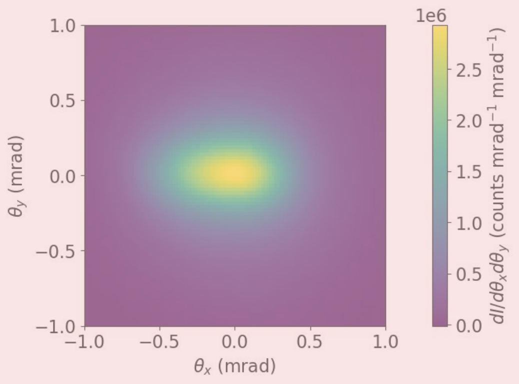


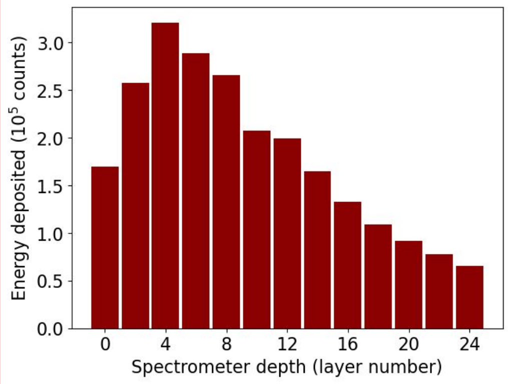




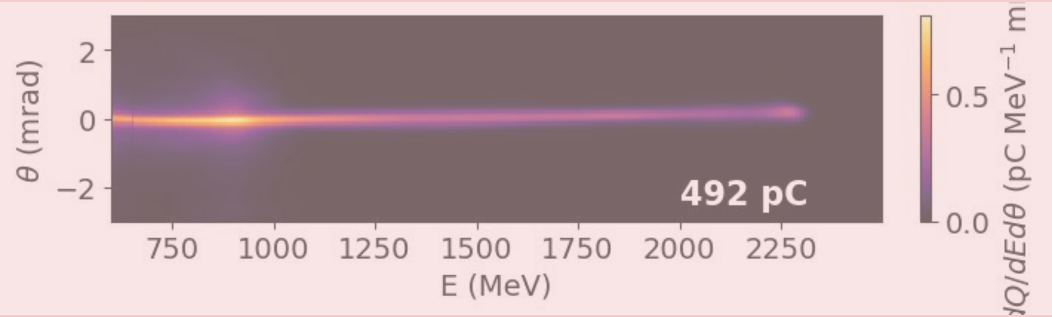
Using equations from [Fleck et al (2024)](#), we can use the elliptical shape to estimate the collision peak a_0~5.3 (but requires many assumptions).

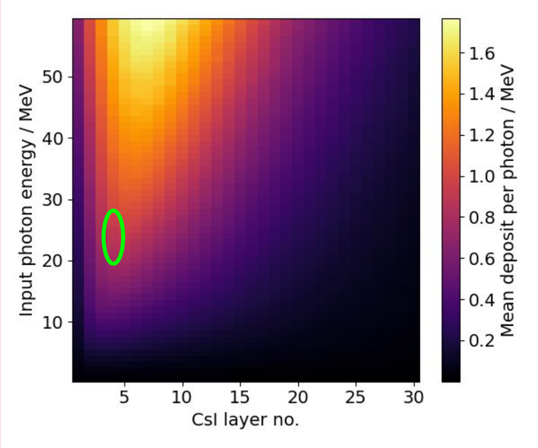
‘Focusing’ on one good shot - 17/09 run 7 shot 63





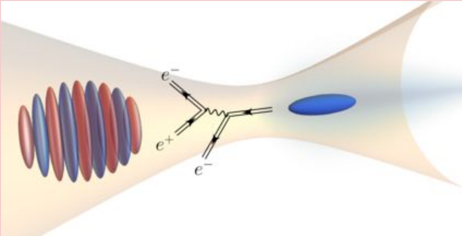
By comparison to spectrometer response matrix, we can see that deposits peaking at layer 4 implies photons of energy ~25 MeV, but extracting full spectrum requires an assumption of shape.





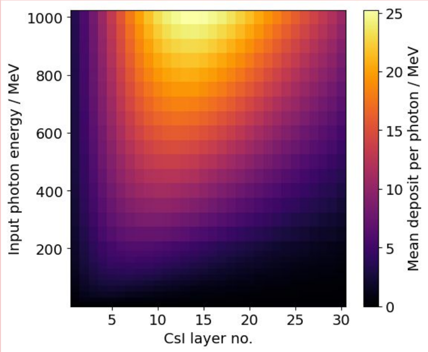
Let's find consistent Monte-Carlo simulations

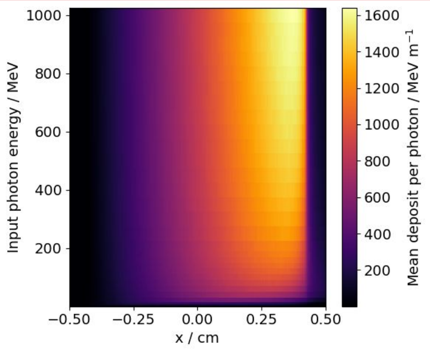
1. Ptarmigan - Monte-Carlo SFQED simulations for particle-laser collisions
Vary four unknowns: spatial and temporal offset of colliding beams, electron bunchlength, and peak a_0
Outputs: full gamma ray distribution



Ptarmigan: Blackburn, King, Tang (2023)

2. Topas - Monte-Carlo simulations of detector responses





OpenTOPAS: Faddegon et al (2020), Shin et al (2012)

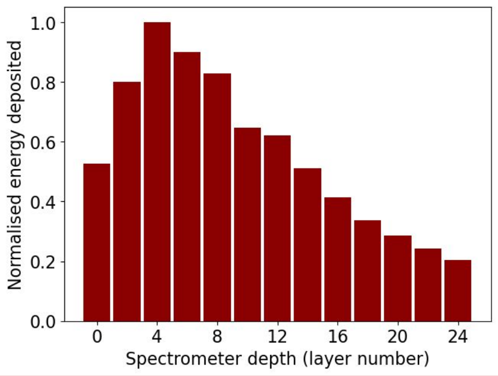
3. Compare to experimental data and update estimates

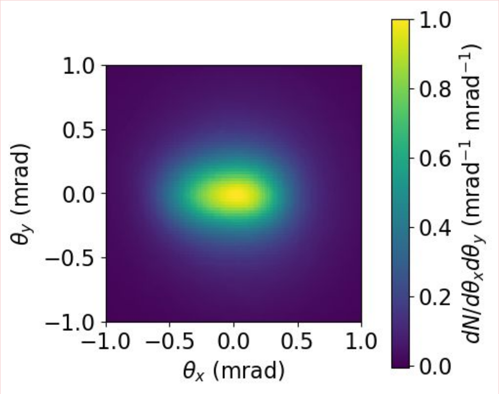
In summary...

- ZEUS provides access to previously unexplored regimes of SFQED, via LWFA + colliding laser beam experiments
- Presented one such experiment with 30% collision rate, identified via low divergence, high energy gamma rays
- Quantitative analysis is difficult due to many unknown collision parameters => so proposed finding these by optimisation of a forward model
- Thanks for listening :)

Optimum parameters found by Bayesian optimisation

Experiment





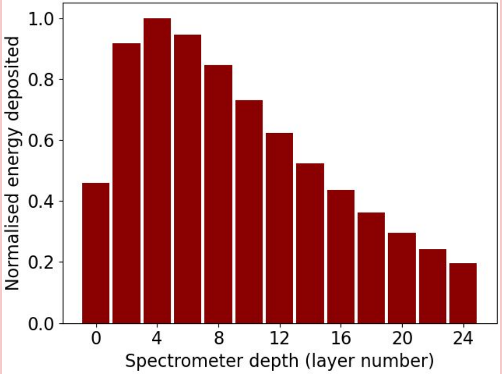
a_0 : 2.59

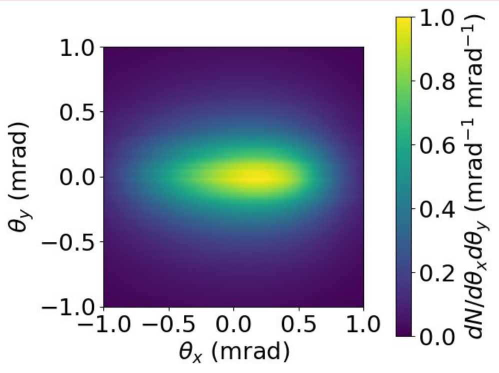
Spatial offset : -48.3 um

Temporal offset : -11.5 um

Bunchlength : 2.65 um *

Best simulation





* very low dependence

Resulting gamma ray distributions

a_0 : 2.59
Spatial offset : -48.3 um
Temporal offset : -11.5 um
Bunchlength : 2.65 um