John Adams Institute for Accelerator Science

Imperial College London

Studying QED processes with laser wakefield accelerators

Stuart PD Mangles

erc

Talk Outline

- Can we use Laser Wakefield Accelerators to explore QED physics?
  - » current capabilities of LWFA
  - » What tools do we need to develop?
- QED in extreme X-ray environments
  - » Breit Wheeler pair production
- QED in Extremely high electromagnetic fields
  - » Radiation Reaction

Acknowledgements

Breit Wheeler Experiment:

B Kettle, G Marrero, E Gerstmayr, D Hollatz, C Colgan, A Alejo, C Baird, S Bohlen, M Campbell, D Dannheim, C Gregory, H Harsh, P Hatfield, J Hinojosa, Y Katzir, J Morton, CD Murphy, A Nurnberg, R Pattathil, K Poder, C Roedel, F Roeder, G Sarri, A Seidel, S Spannagel, S Steinke, M Streeter, AGR Thomas, C Underwood, R Watt, M Zepf, S Rose, and SPD Mangles

Radiation Reaction:

JM Cole, KT Behm, E Gerstmayr, TG Blackburn, JC Wood, CD Baird, MJ Duff, C Harvey, A Ilderton, AS Joglekar, K Krushelnick, S Kuschel, M Marklund, P McKenna, CD Murphy, K Poder, CP Ridgers, GM Samarin, G Sarri, DR Symes, AGR Thomas, J Warwick, M Zepf, Z Najmudin, and SPD Mangles

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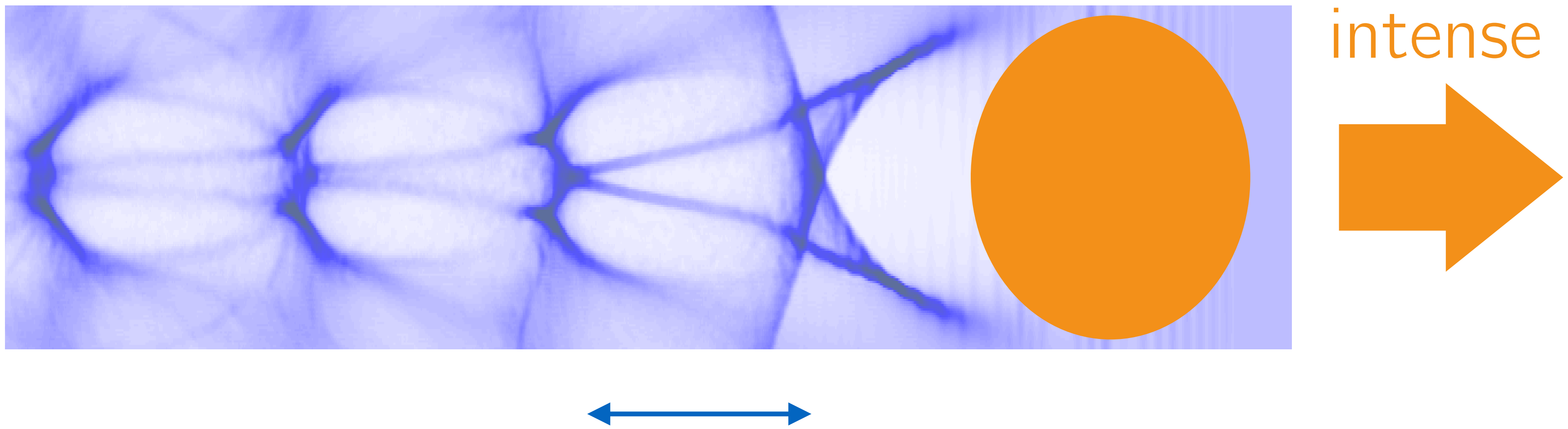
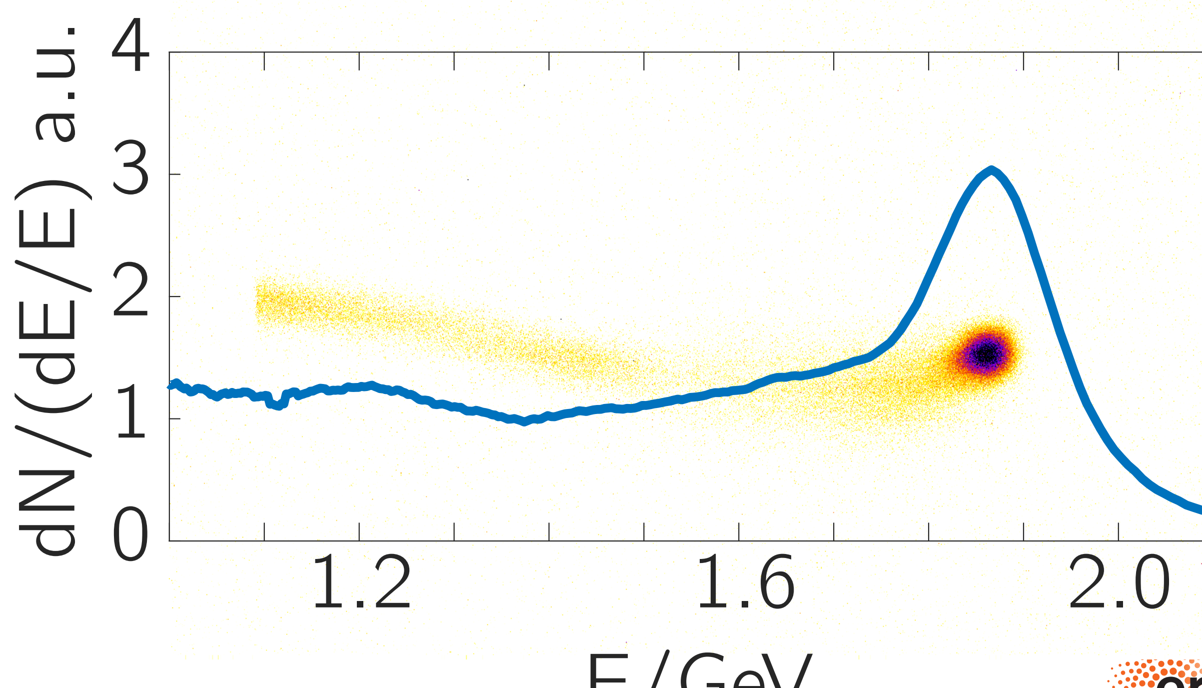
Laser wakefield accelerators are a source of interesting electron beams

electron density of high amplitude plasma wave



$$\lambda_{\mathrm{p}} \simeq \frac{2\pi c}{\omega_{\mathrm{p}}} \approx 20 - 30\ \mu\mathrm{m}$$

- Laser wakefield accelerators produce electron beams
  - high charge (100 pC)
  - high energy (> 1 GeV)
  - short duration (~10 fs)



K Poder et al

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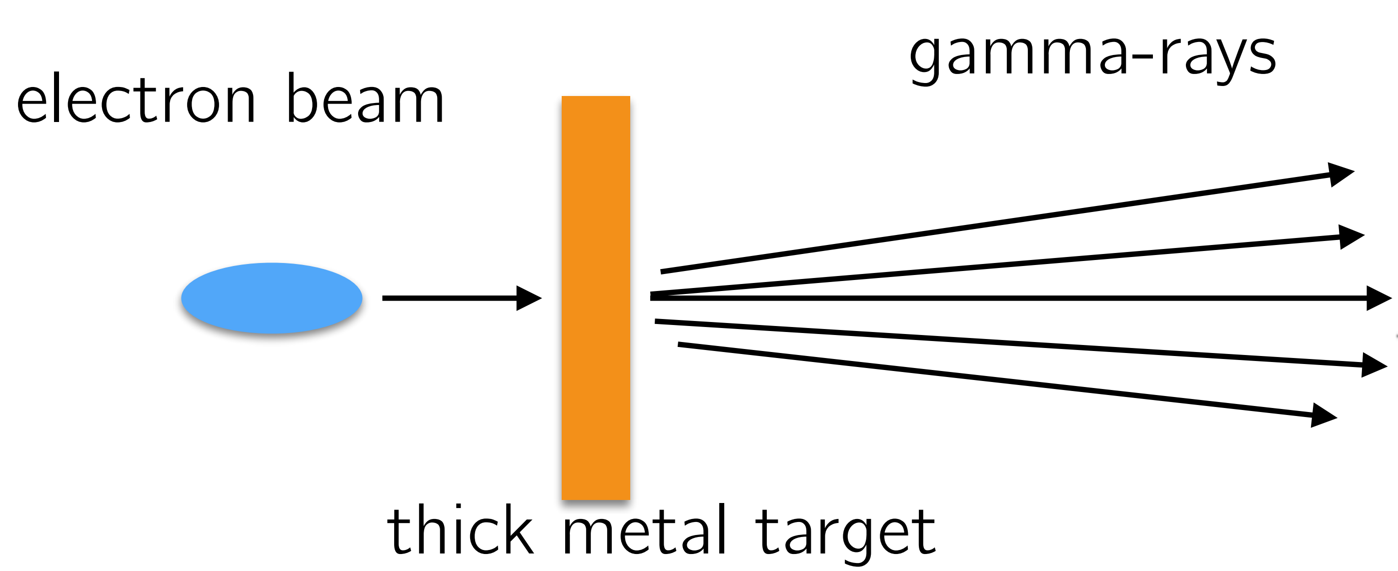
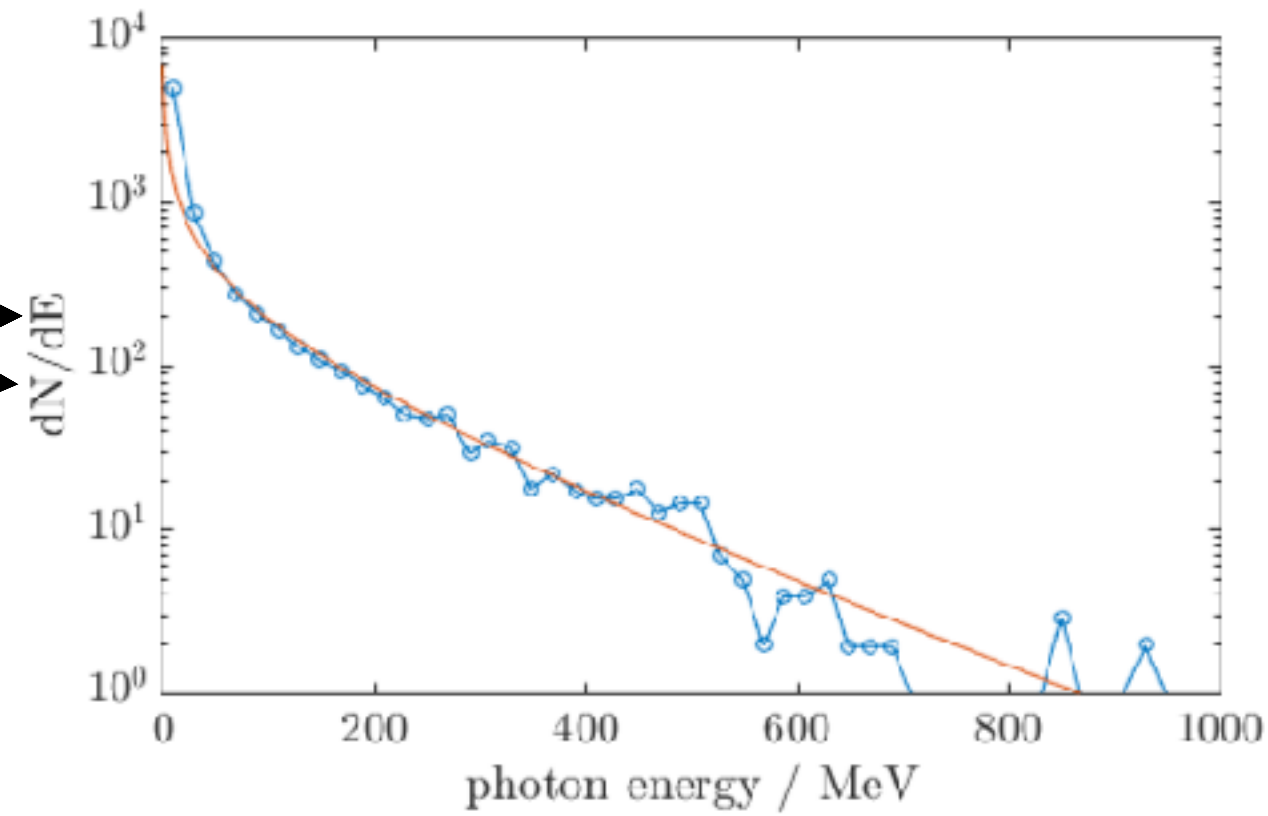
Laser wakefield accelerators are a source of interesting Gamma-ray beams





- Collide GeV electron beam with metal target
  - $E_\gamma > 500$ MeV
    - » (also produces e^+e^-: Sarri et al Nature Comms 2015)

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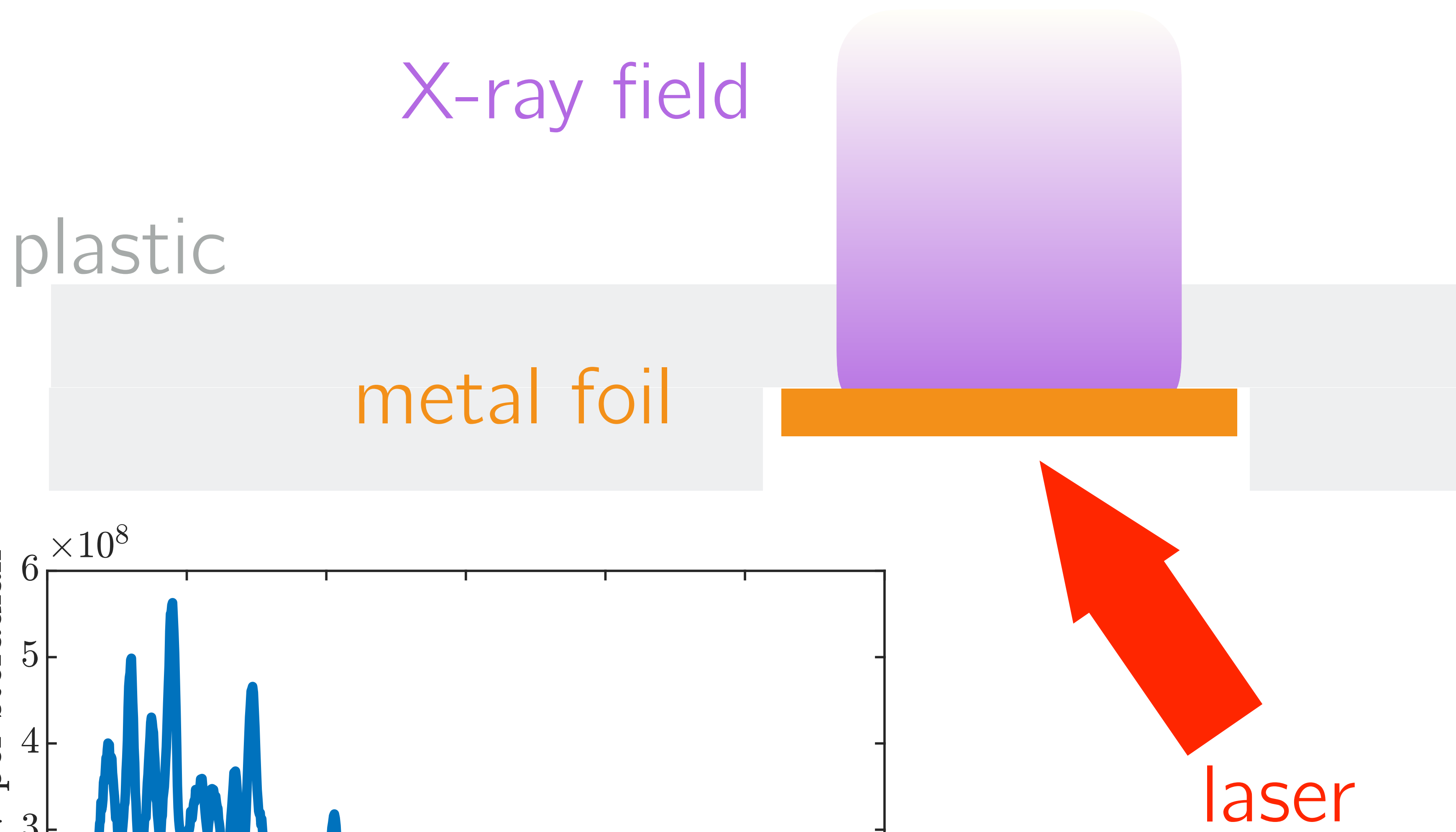
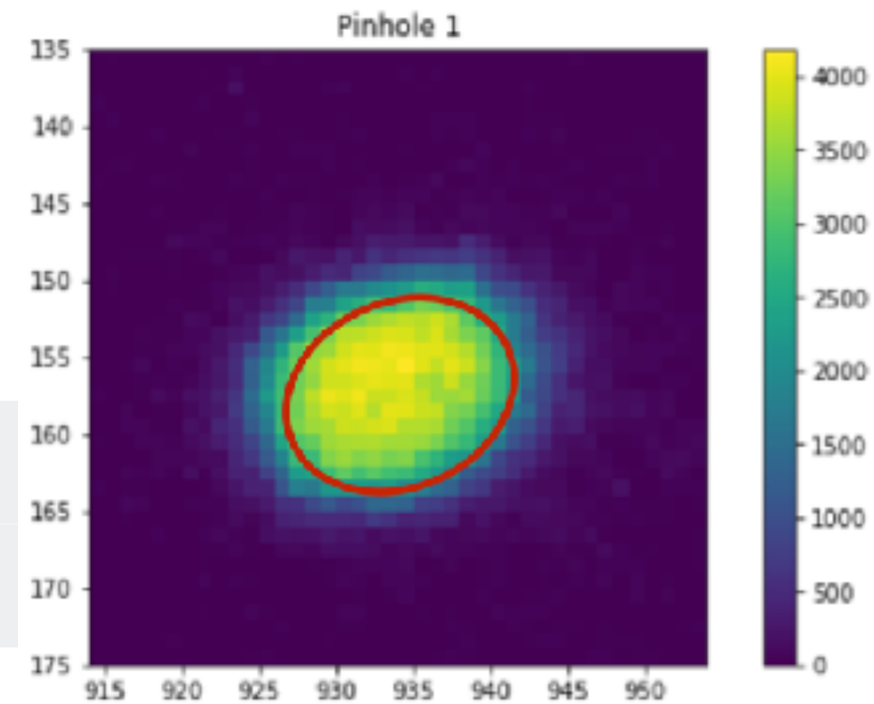
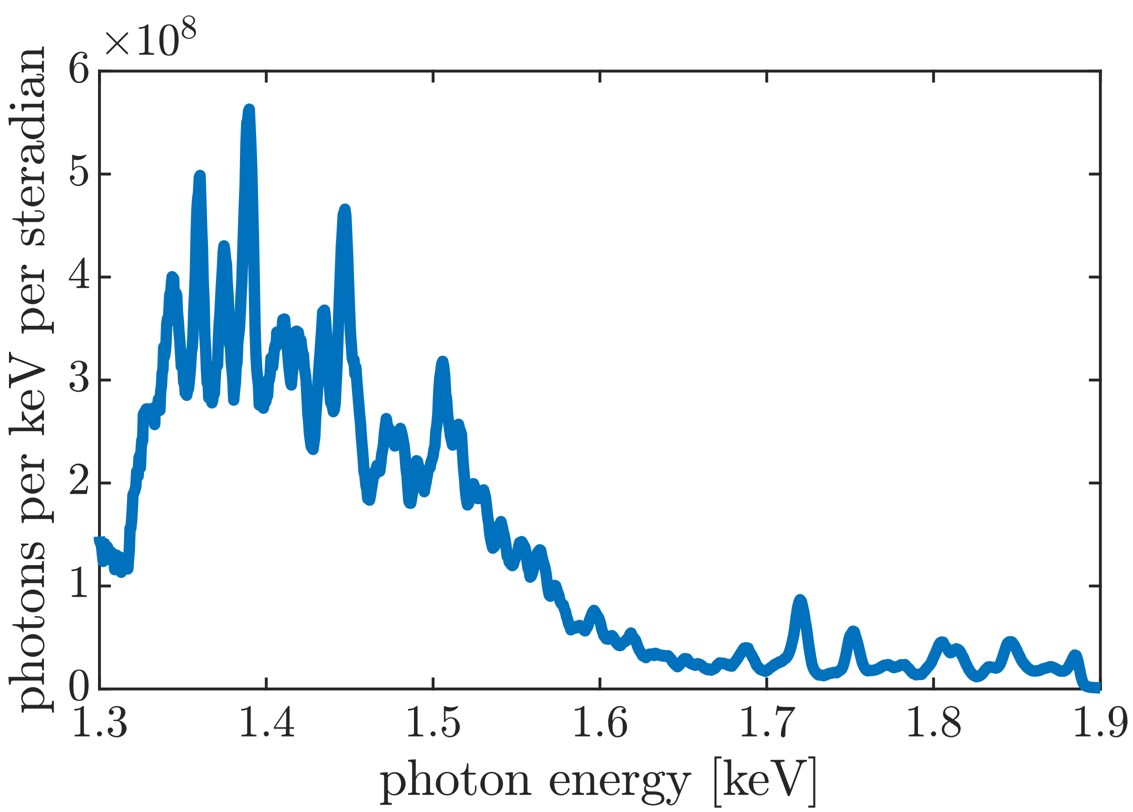
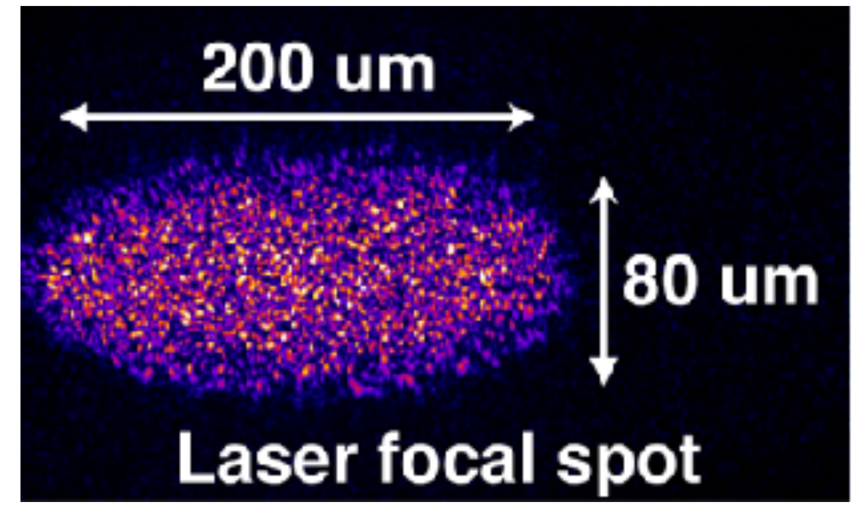
Laser plasma interactions can produce dense X-ray photon fields

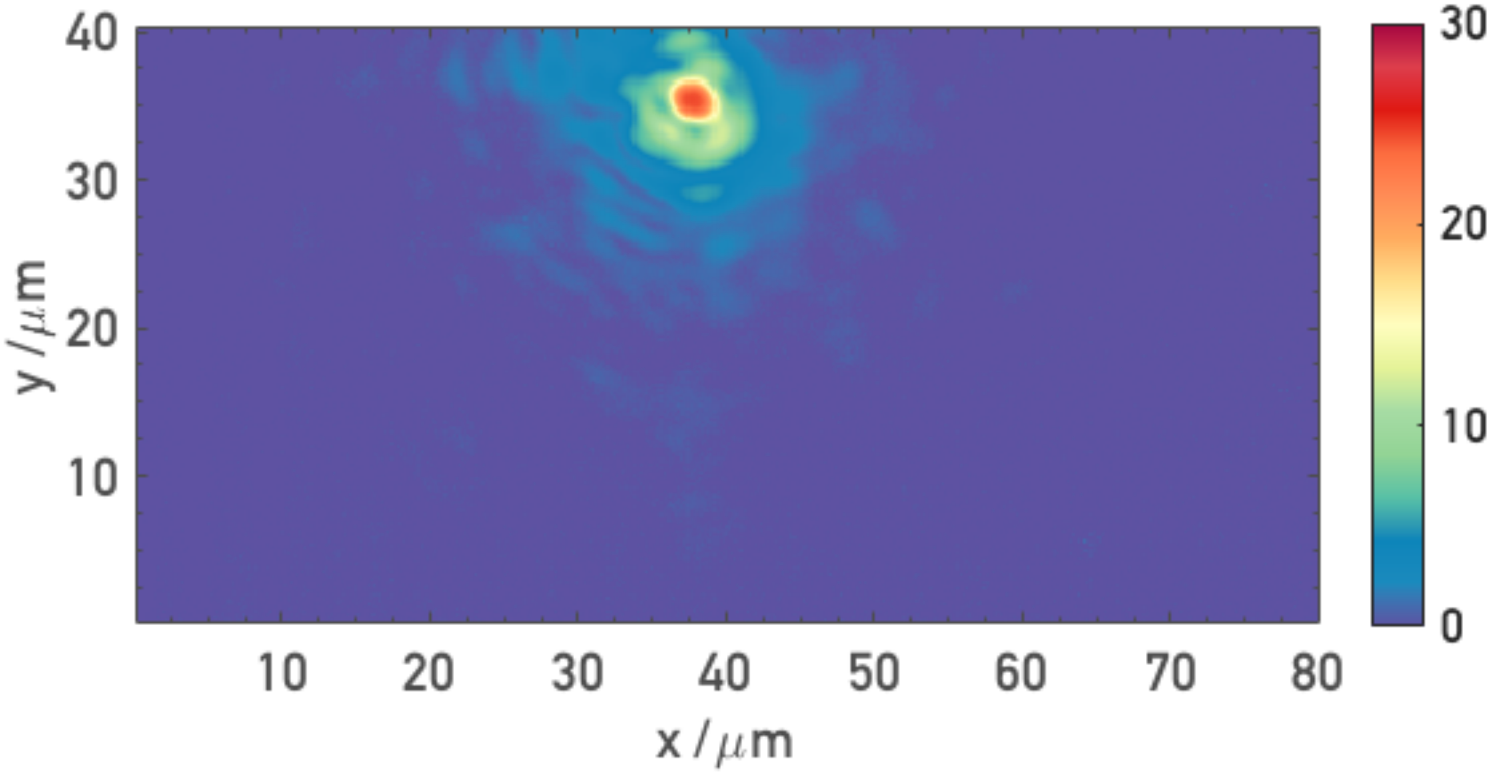


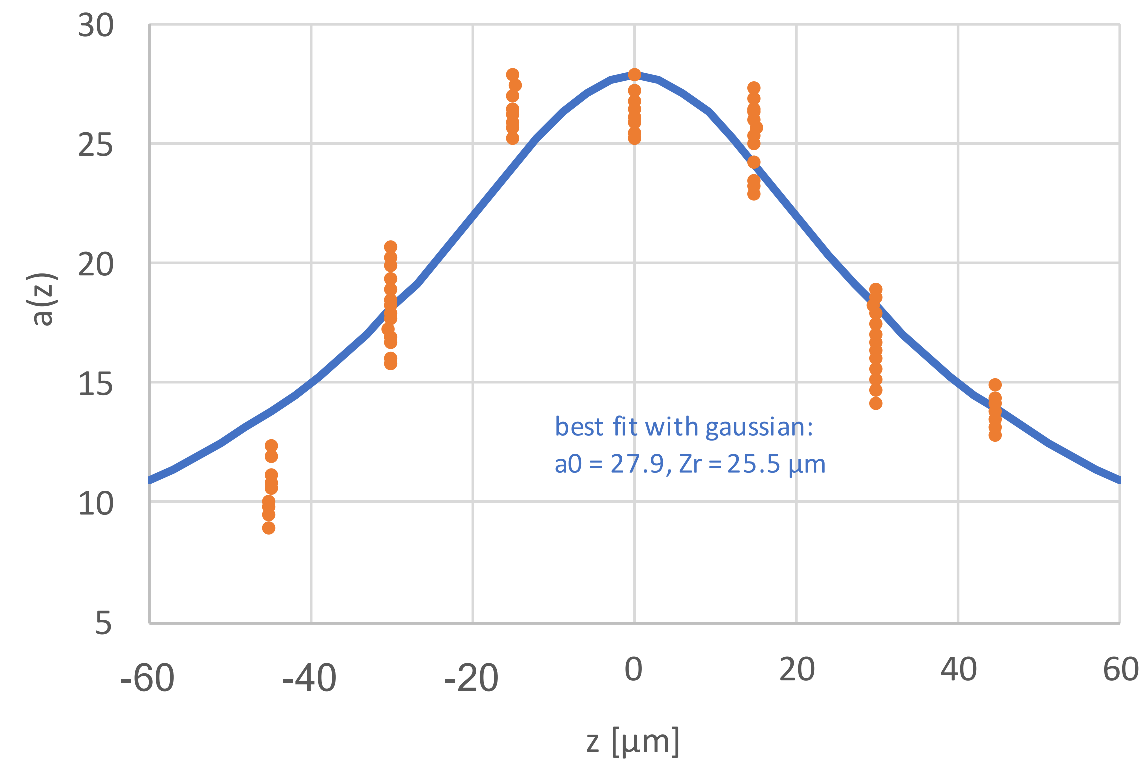






Lasers can produce very high strength electromagnetic fields





- f/2 focusing
  - » 8.6J, 45 fs FWHM, 800nm wavelength.
  - » Intensity: 1.4–2.0 x 10^{21} cm^{-3}
  - » a_0 = 25–30
  - » Electric field: 1.0–1.2 x 10^{14} V m^{-1}

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Probing QED with Laser Wakefield Accelerators

- Co-location of wakefield based sources with other drivers
  - ***femtosecond pulses:*** very strong electromagnetic fields
  - ***picosecond pulses:*** high density X-rays
    - » Good spatial and temporal overlap between sources
    - » 5 μm and 10 fs achievable in principle (but hard in practice)

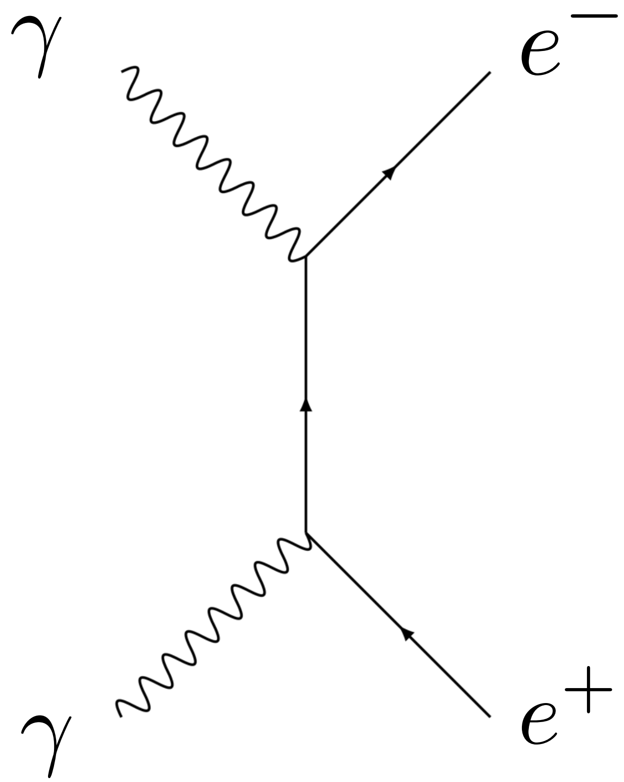
- Can we use laser wakefield accelerators and to probe extreme conditions?
    - » ...where QED physics is important?

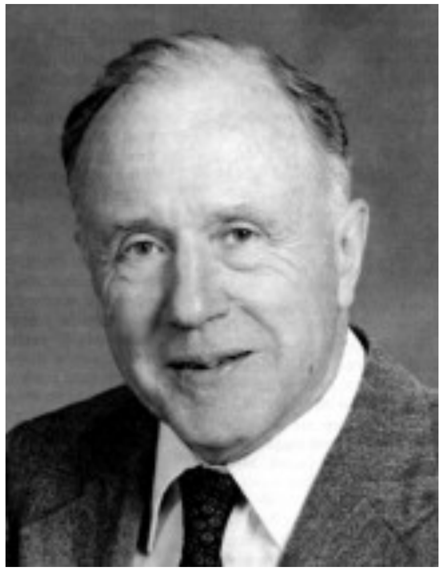
Probing QED with Laser Wakefield Accelerators

- Experiment 1: Breit Wheeler Pair production
- Experiment 2: Radiation Reaction in Extreme electromagnetic fields

Breit Wheeler Pair production

$$\gamma + \gamma \rightarrow e^+ + e^-$$





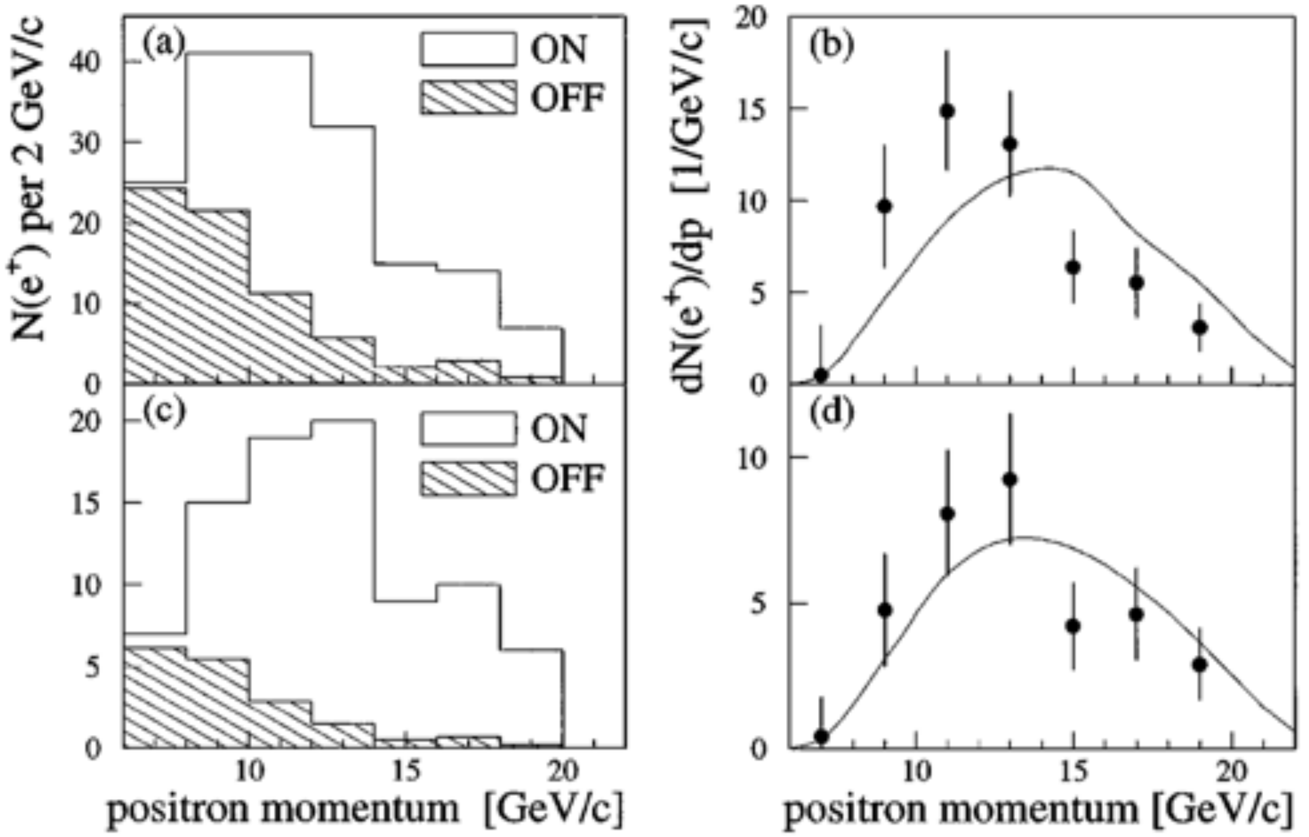
Breit & Wheeler 1934

Breit & Wheeler didn't expect it to be observed in the lab

As has been reported at the Washington meeting, pair production due to collisions of cosmic rays with the temperature radiation of interstellar space is much too small to be of any interest. We do not give the explicit calculations, since the result is due to the orders of magnitude rather than exact relations. It is also hopeless to try to observe the pair formation in laboratory experiments with two beams of x-rays or γ-rays meeting each other on account of the smallness of σ and the insufficiently large available densities of quanta. In the considerations of Williams,

Multi-photon Breit Wheeler observed in 1997

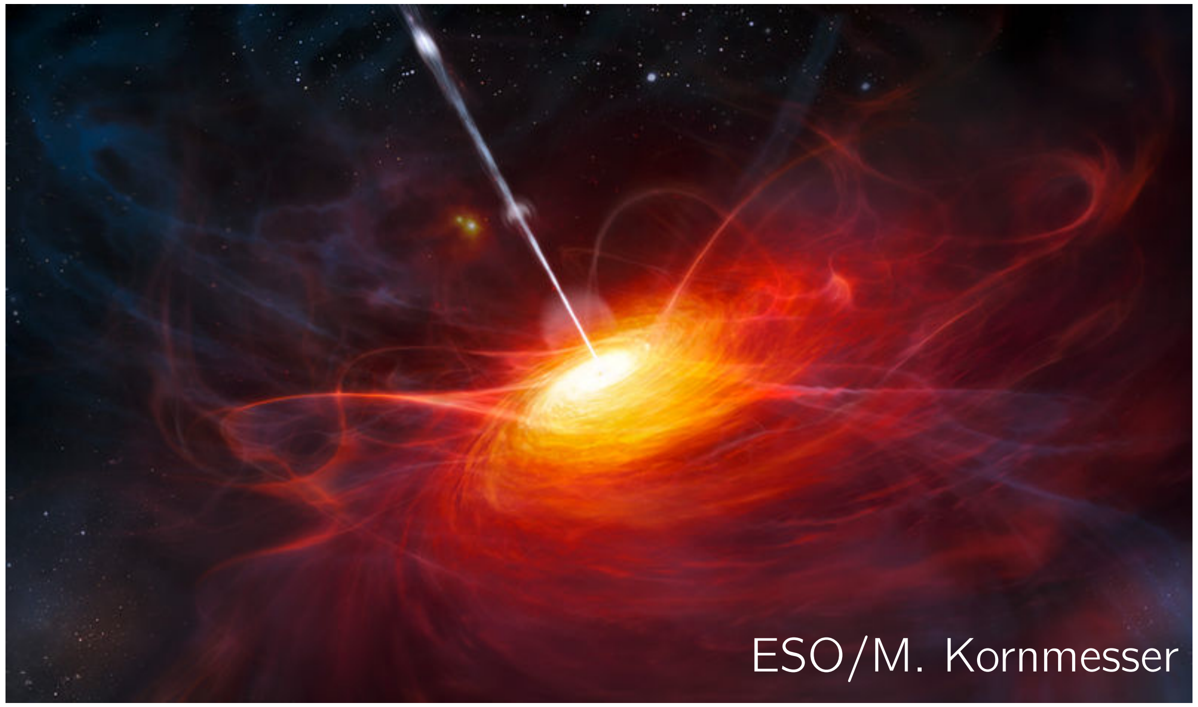
$$\gamma + n\hbar\omega \rightarrow e^+ + e^-$$



- multi-photon BW observed in E144 experiment at SLAC in 1990s

Burke et al PRL 1997

Breit-Wheeler process is important in astrophysics


ESO/M. Kornmesser

- BW pair production affects electron and photon spectrum around compact objects (e.g. black holes)
  - The radiation fields surrounding compact objects can be so hot that an equilibrium between the pair and photon distributions is achieved
    - Bonometto and Rees, MNRAS **152**, 21 (1971)

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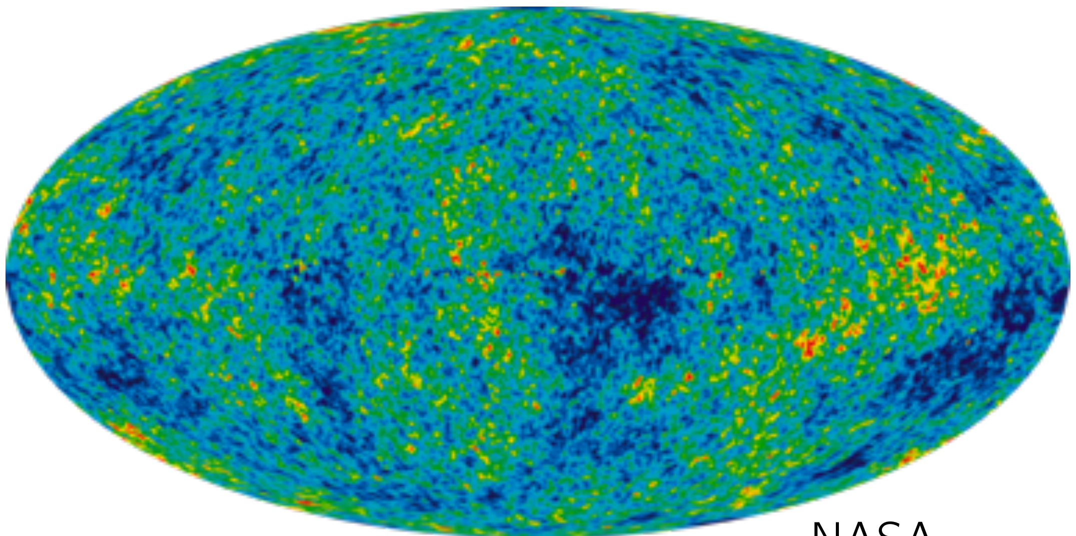
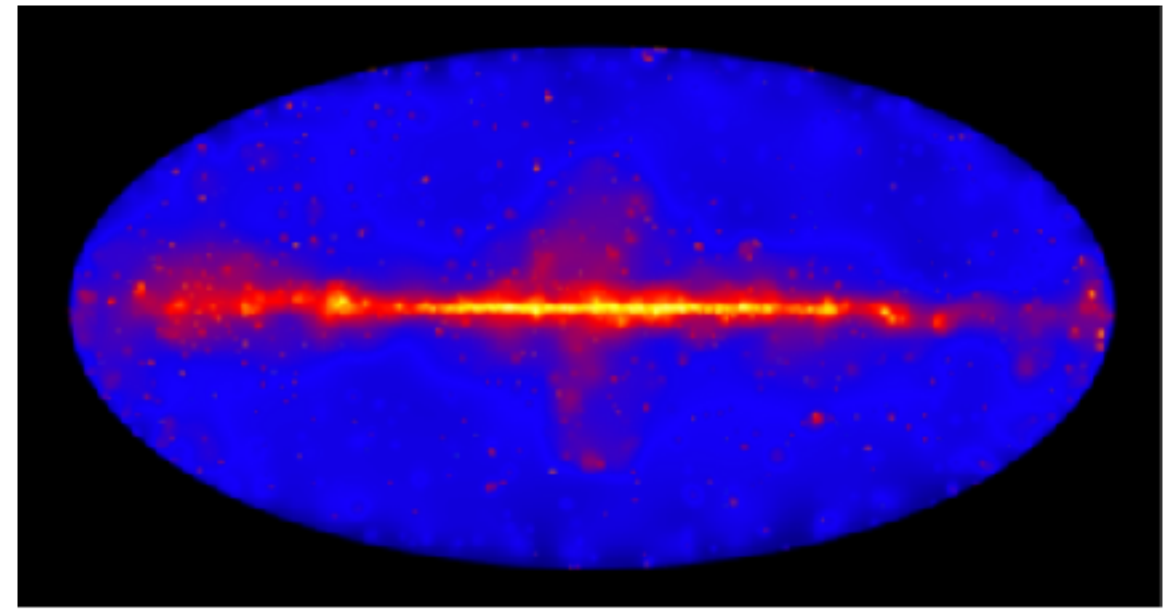
Breit-Wheeler process is important in astrophysics



NASA

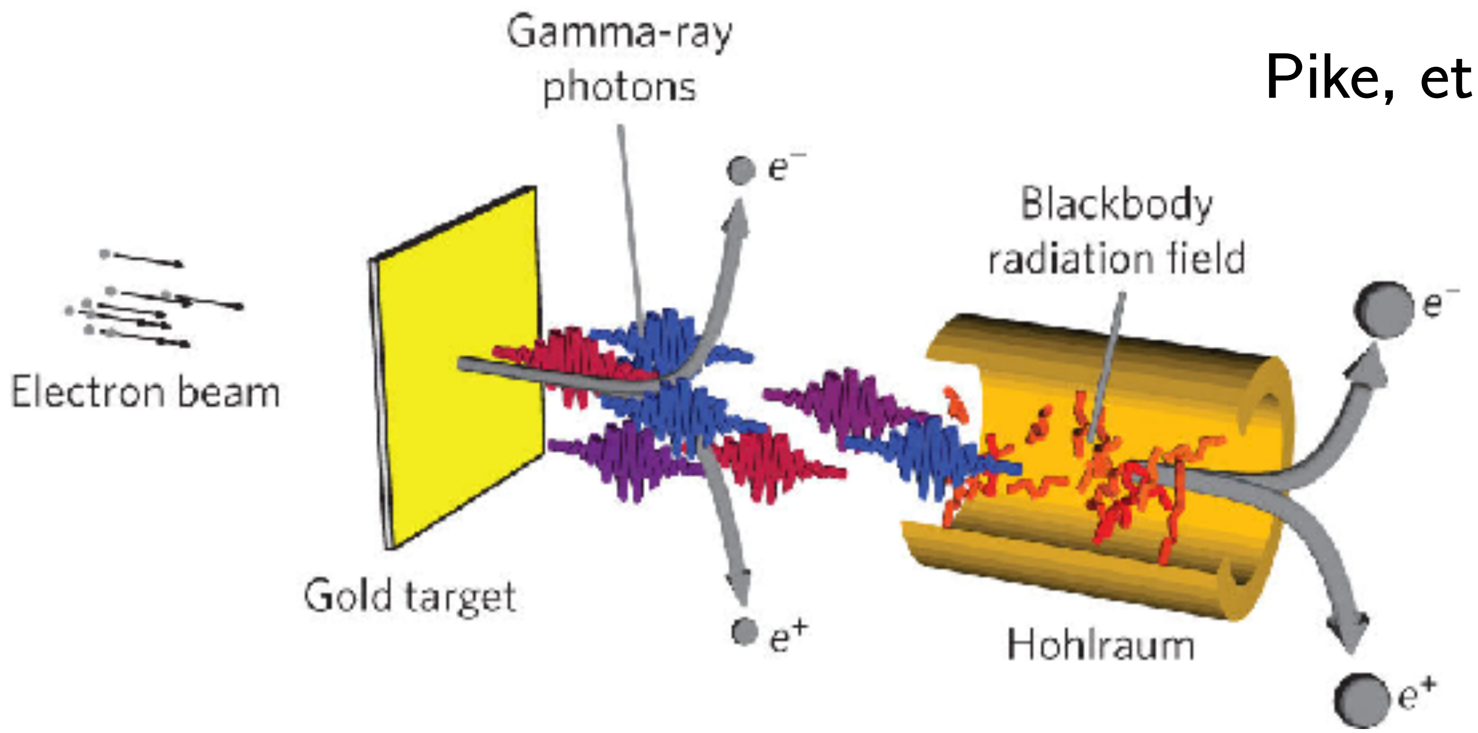


- High-energy gamma-rays should be attenuated as they interact with background radiation
  - Cosmic Microwave Background: Gould and Schréder, PRL 1966
  - Extra Galactic Background Light: Vovk et al ApJ Lett 2012

Observations suggest universe is more transparent than expected...

- "Depending on the distance of the source, the Universe should be opaque to VHE photons above a certain energy. However, indications exist that the Universe is more transparent than previously thought."
  - Meyer, Horns, & Raue, Phys Rev D **87**, 035027 (2013)
- "Recent findings by γ-ray Cherenkov telescopes suggest a higher transparency of the Universe to very-high-energy (VHE) photons than expected from current models of the Extragalactic Background Light."
  - De Angelis, O. Mansutti, M. Persic, & M. Roncadelli, https://arxiv.org/abs/0807.4246

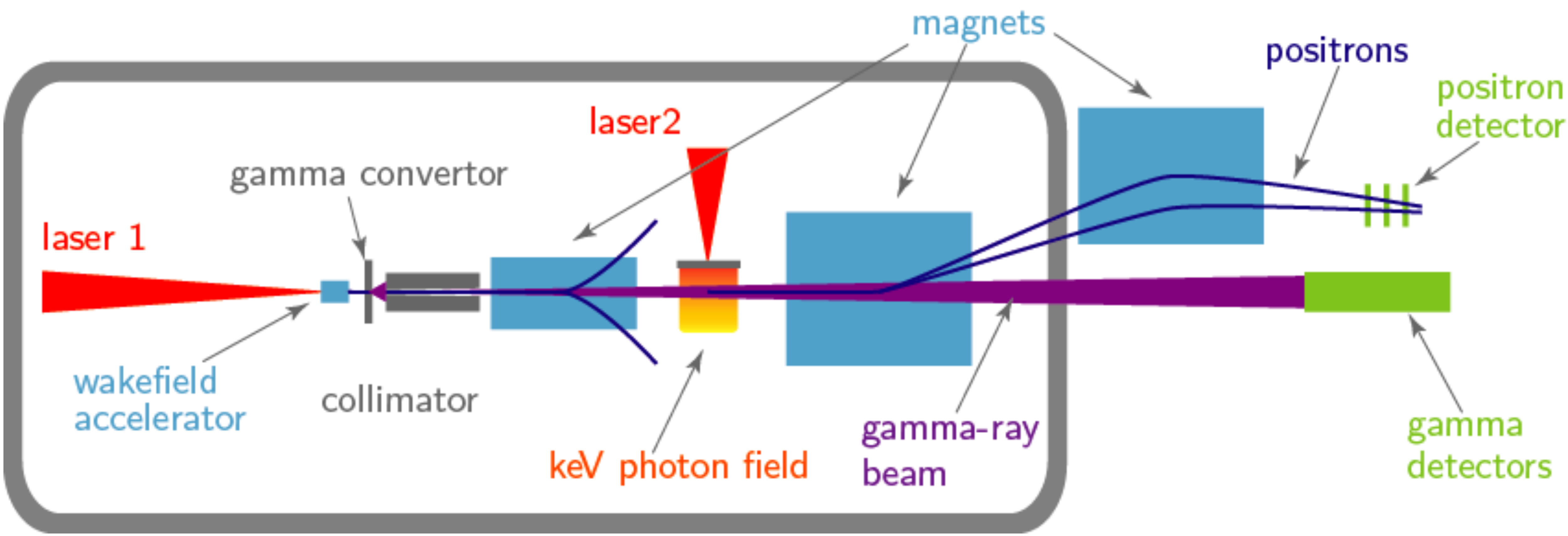
Extreme photon densities



Pike, et al., Nature Photonics 2014

- In 2014 a Pike et al. proposed a method for measuring Breit-Wheeler pair production
  - gamma rays from LWFA electron beam
  - dense X-ray field inside a NIF hohlraum (single shot produces 10^4 pairs)
    - » **Can we do this using a picosecond X-ray source on Gemini?**

Extreme photon densities

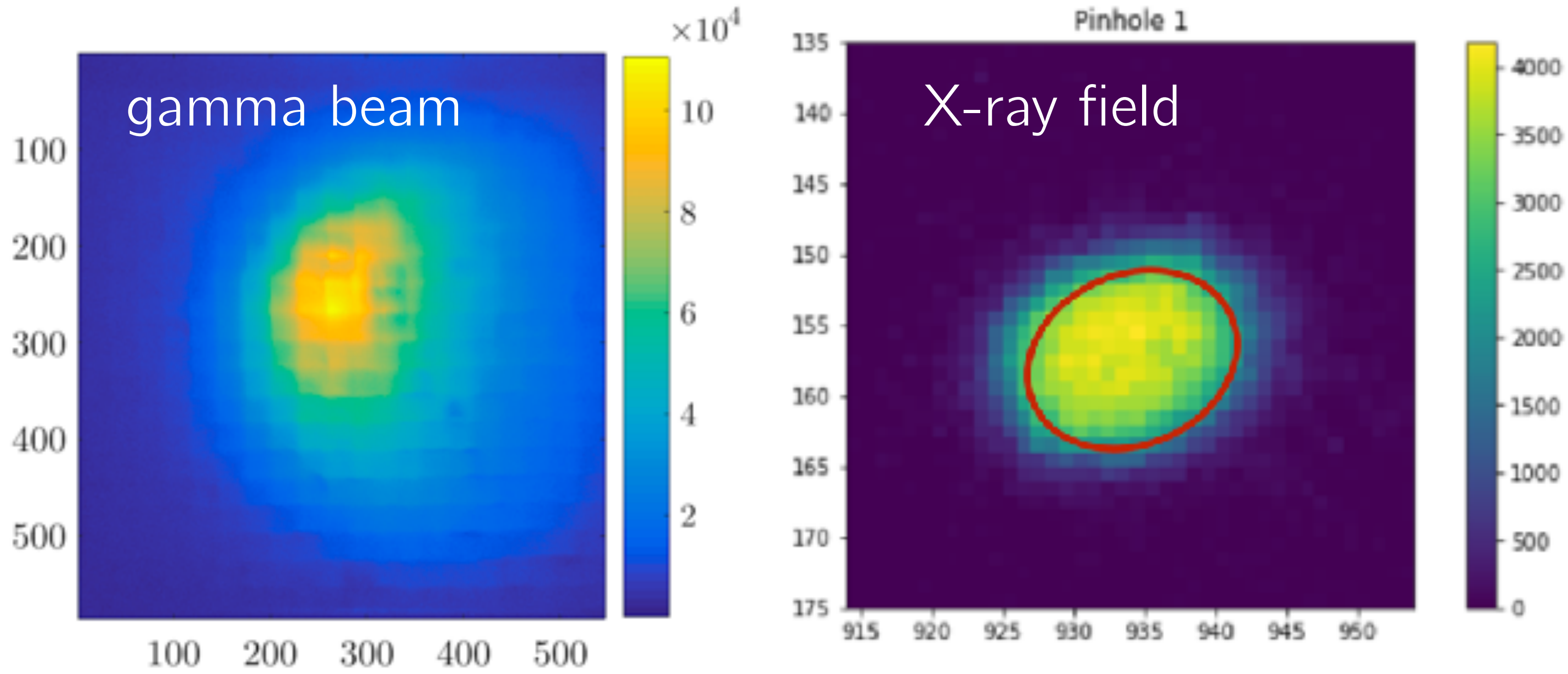


- Breit-Wheeler predictions
  - $\sim$ 1-0.1 pair per shot
  - background: $\sim$ 10 pairs per shot
  - Observation could be possible....

Breit Wheeler Experiment: Challenges

- Successful collisions
  - » Relatively easy as X-ray field is millimetre scale,
  - » Relatively easy few picosecond timing much easier
- Single particle detection
  - » CsI detectors
  - » TimePix3 detectors
- Background signal
  - – Bethe Heitler
  - – Signal and background both depend on gamma yield
    - » a few high gamma yield shots in the collision shots could skew results

Extreme photon densities



- First BW experiment on Gemini in 2018
  - » gamma beam
  - » X-ray field

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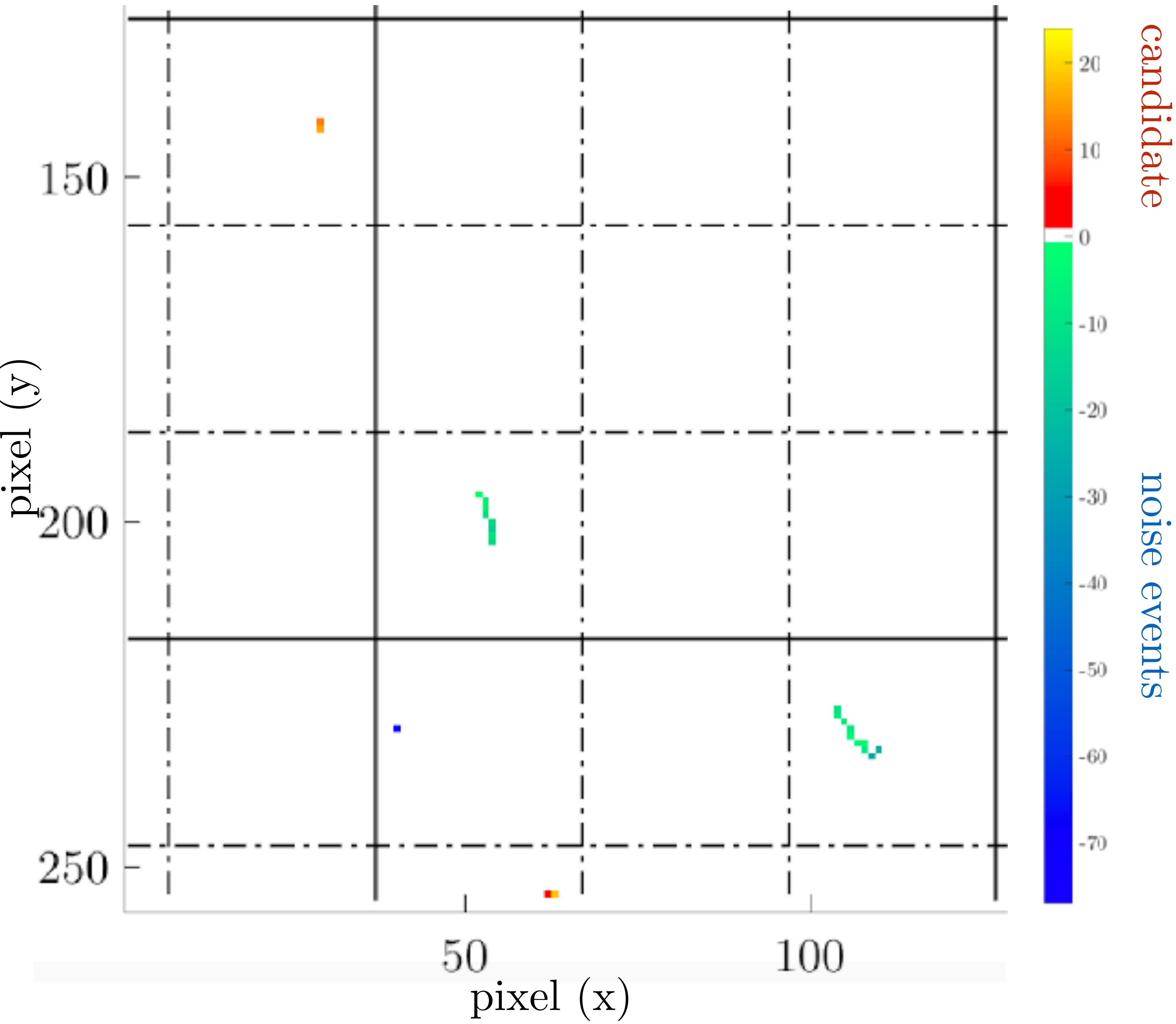
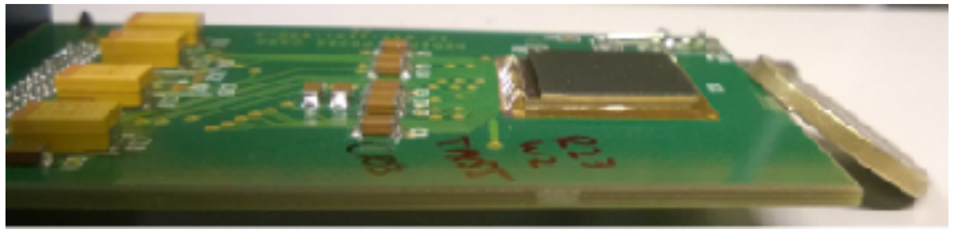
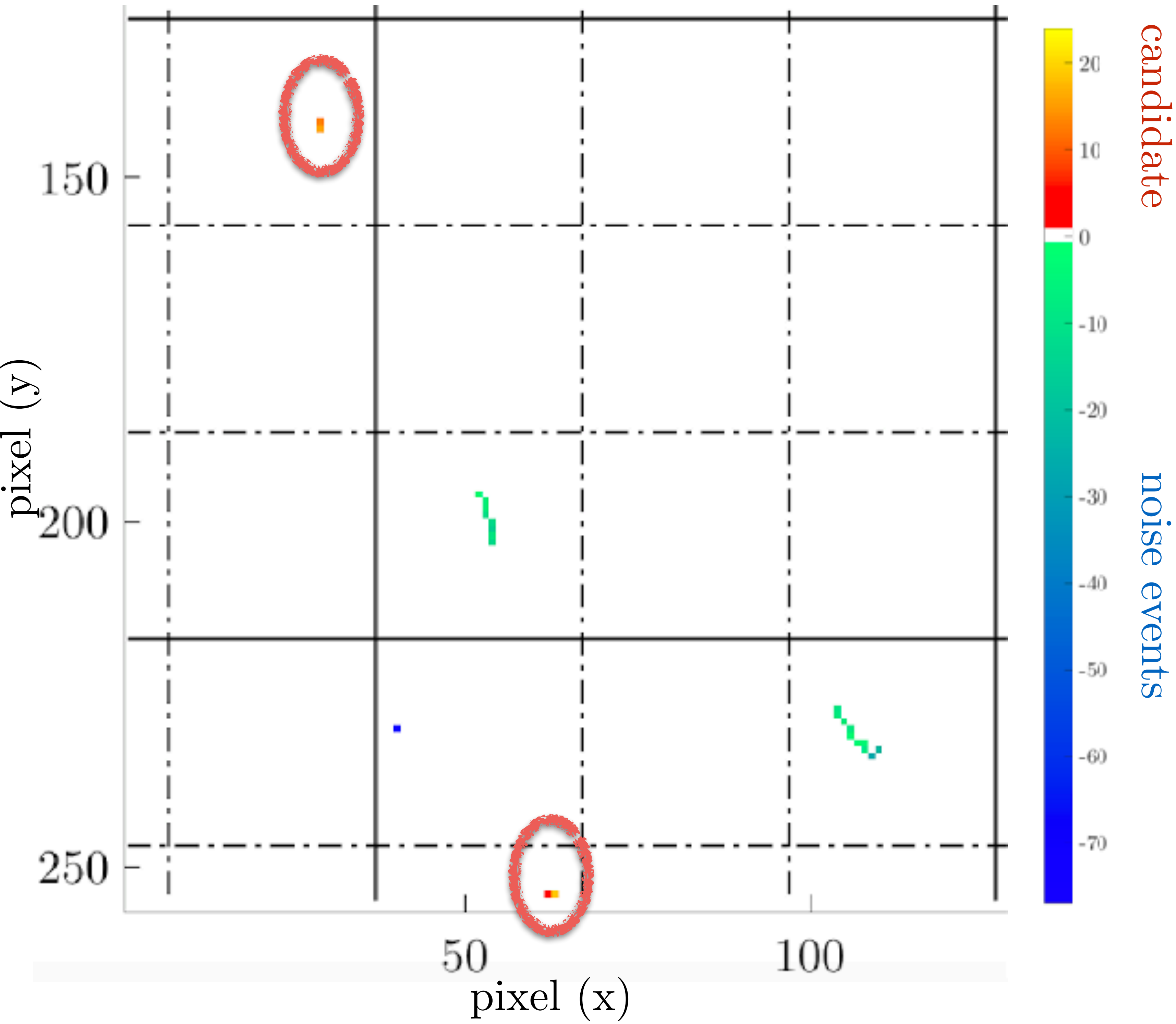
TimePix3 detector

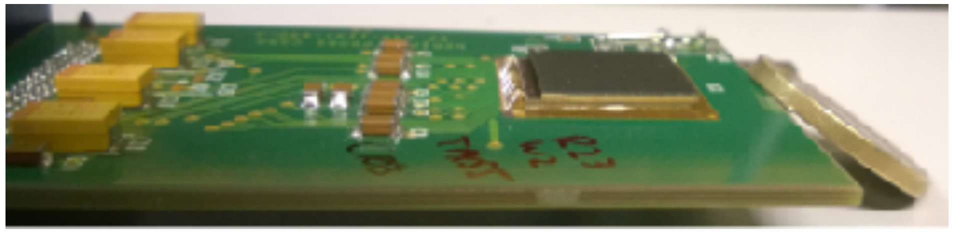




- Track shape on TimePix3 helps discriminate between candidate events and noise events

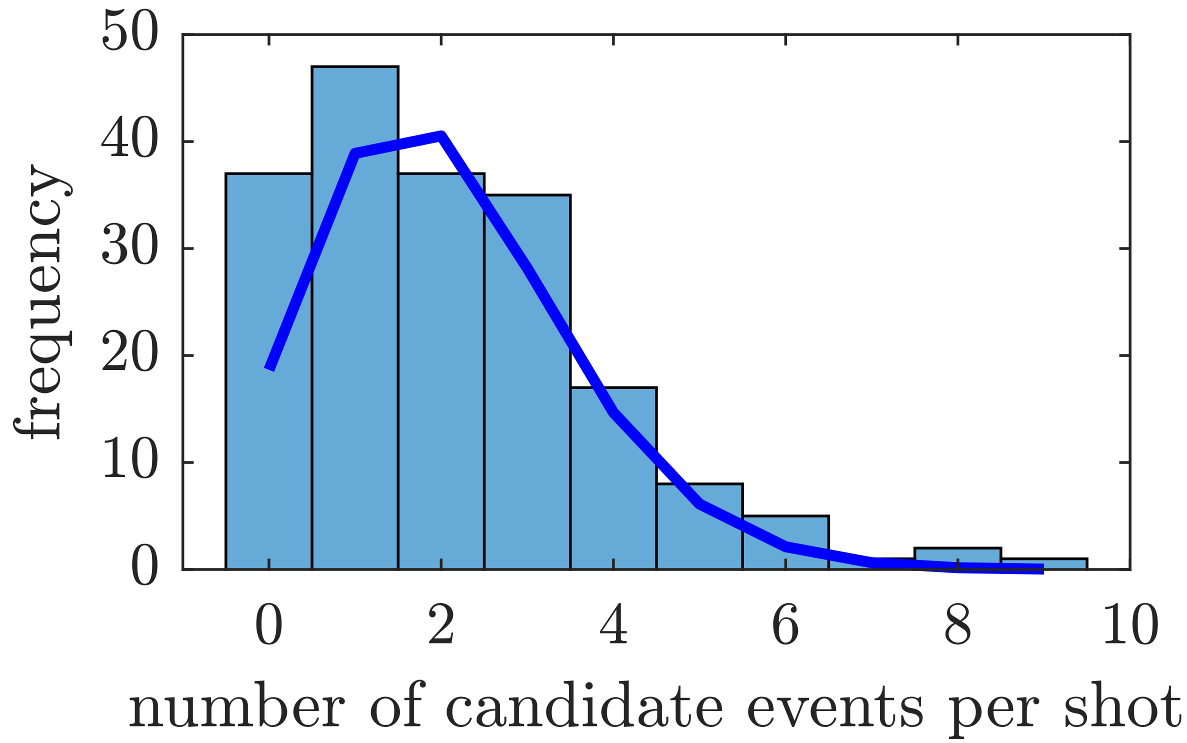
TimePix3 detector





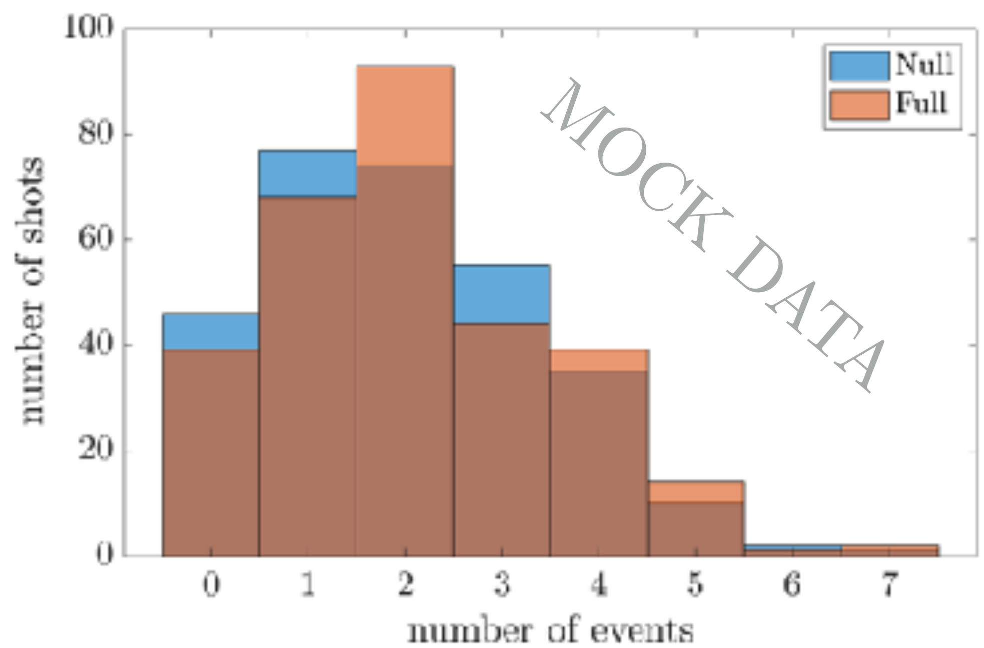
- Track shape on TimePix3 helps discriminate between candidate events and noise events

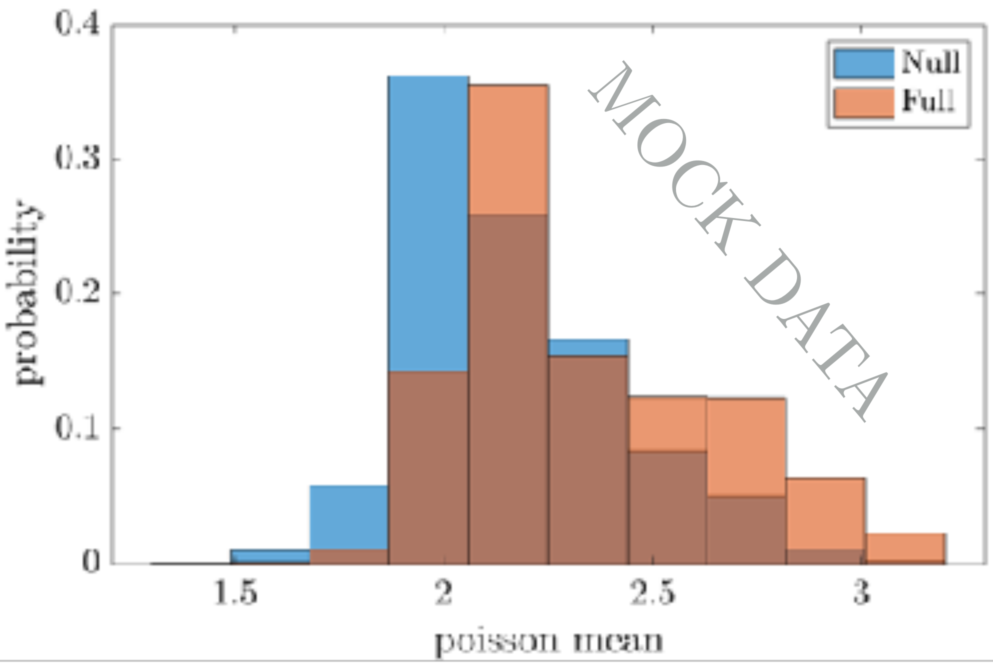
Small number of background events per shot



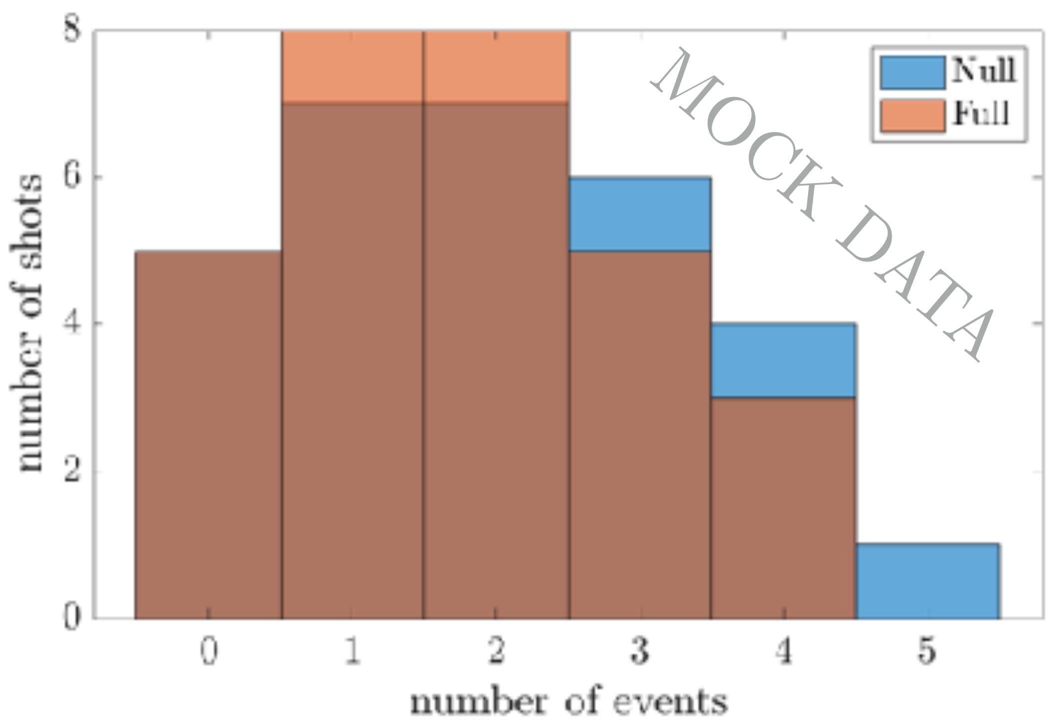
- Series of Null shots (gamma beam only) to measure background
  - » mean number of candidate events is 2 per shot
  - » (approximately poisson distributed)

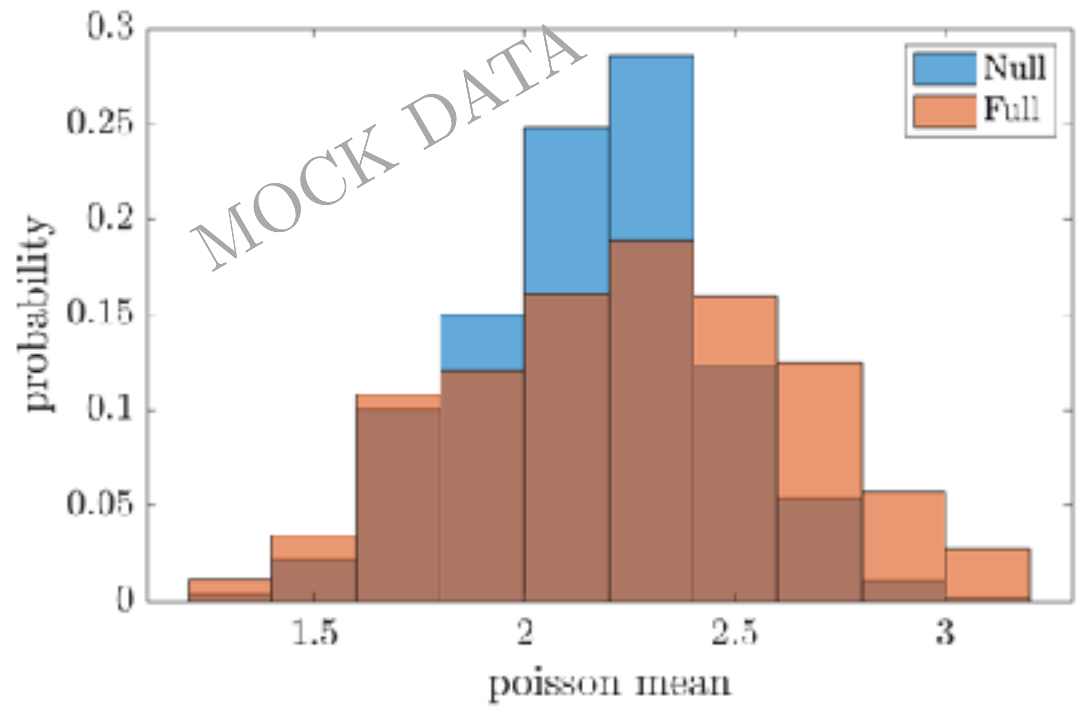
- How might we go about extracting a small signal ~ 0.1 from a background of 2 in a reasonable number (300) of shots?
    - test ideas using mock data
        - » null shots have poisson distribution with mean 2,
        - » full shots are sum of two poisons (mean 2 and mean 0.1)
        - » fit poisson distribution to Null and Full shots



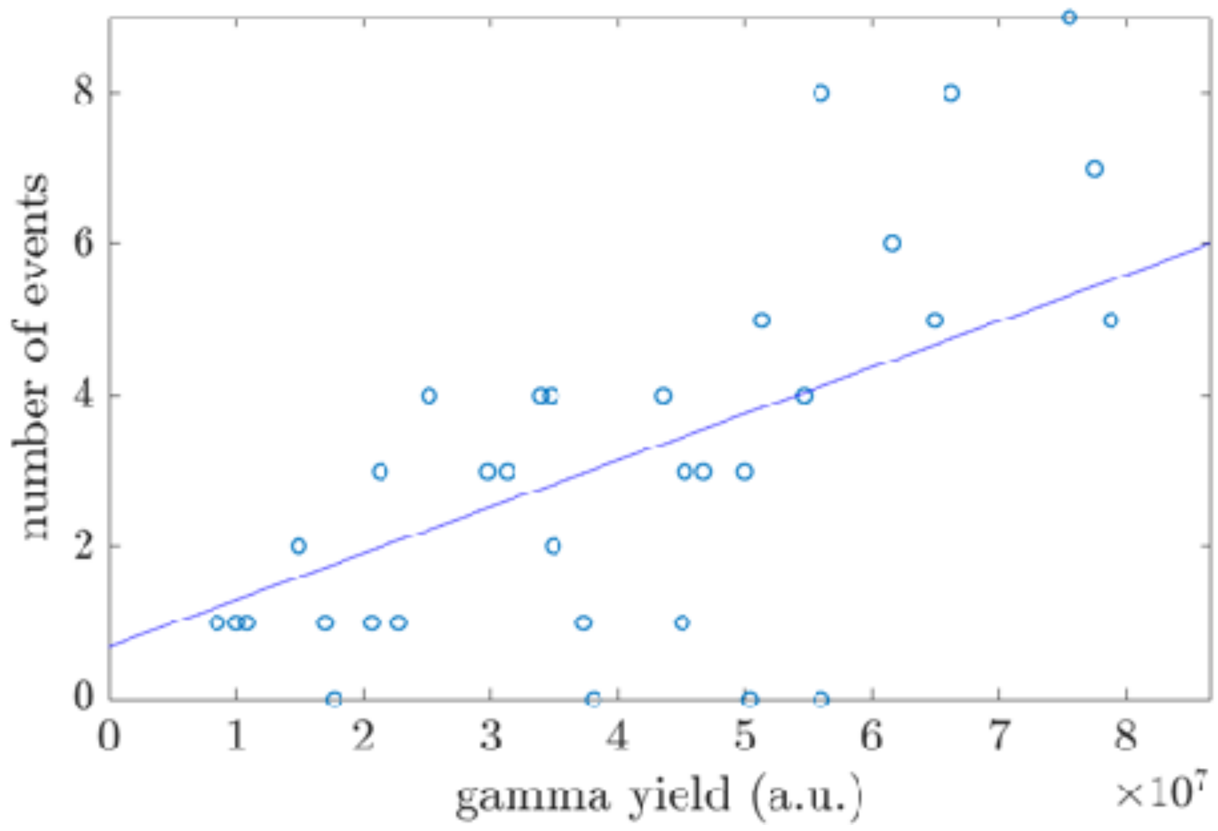


- How might we go about extracting a small signal ~ 0.1 from a background of 2 in a limited number (30) of shots?
  - test ideas using mock data
    - » null shots have poisson distribution with mean 2,
    - » full shots are sum of two poisons (mean 2 and mean 0.1)
    - » fit poisson distribution to Null and Full shots



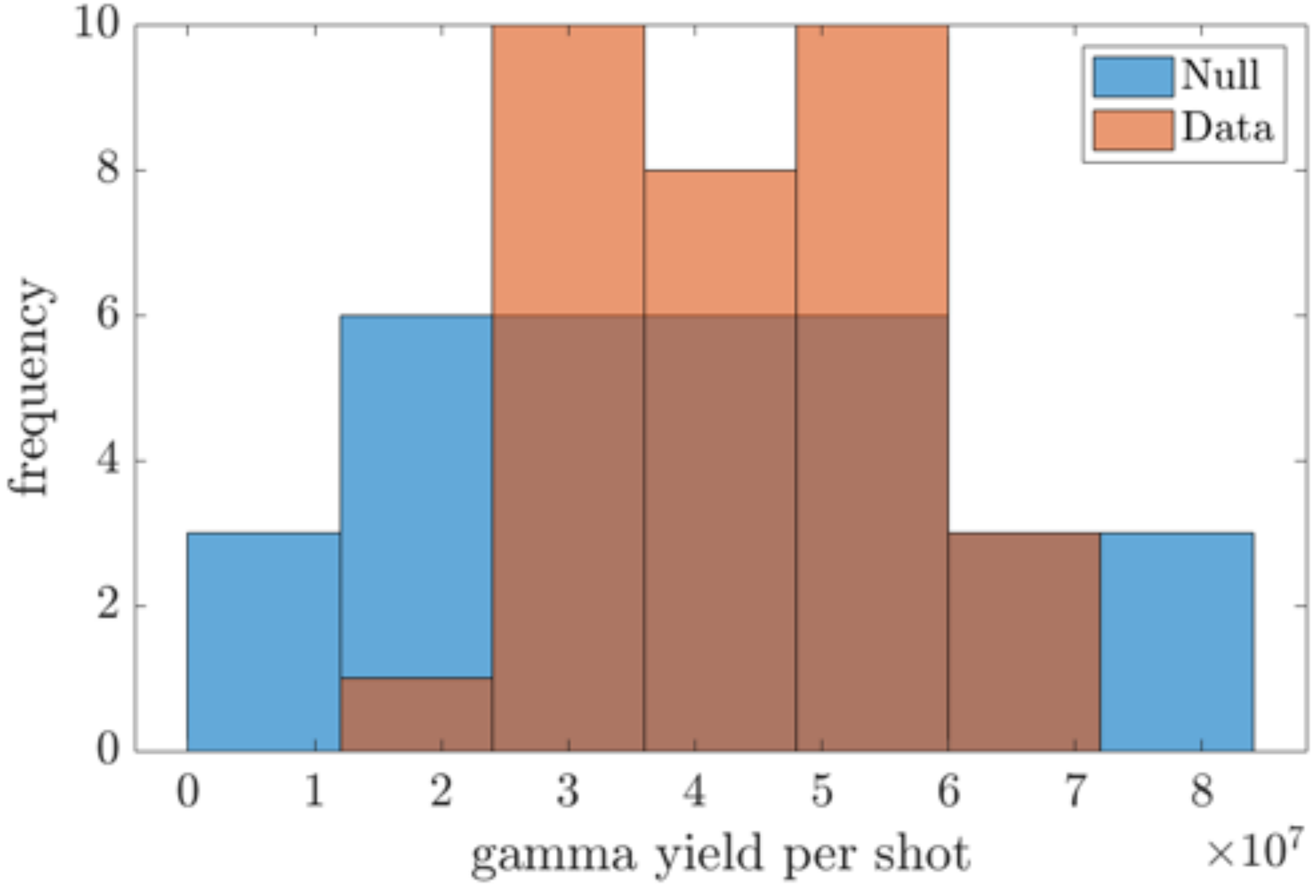


Background events are correlated with gamma yield



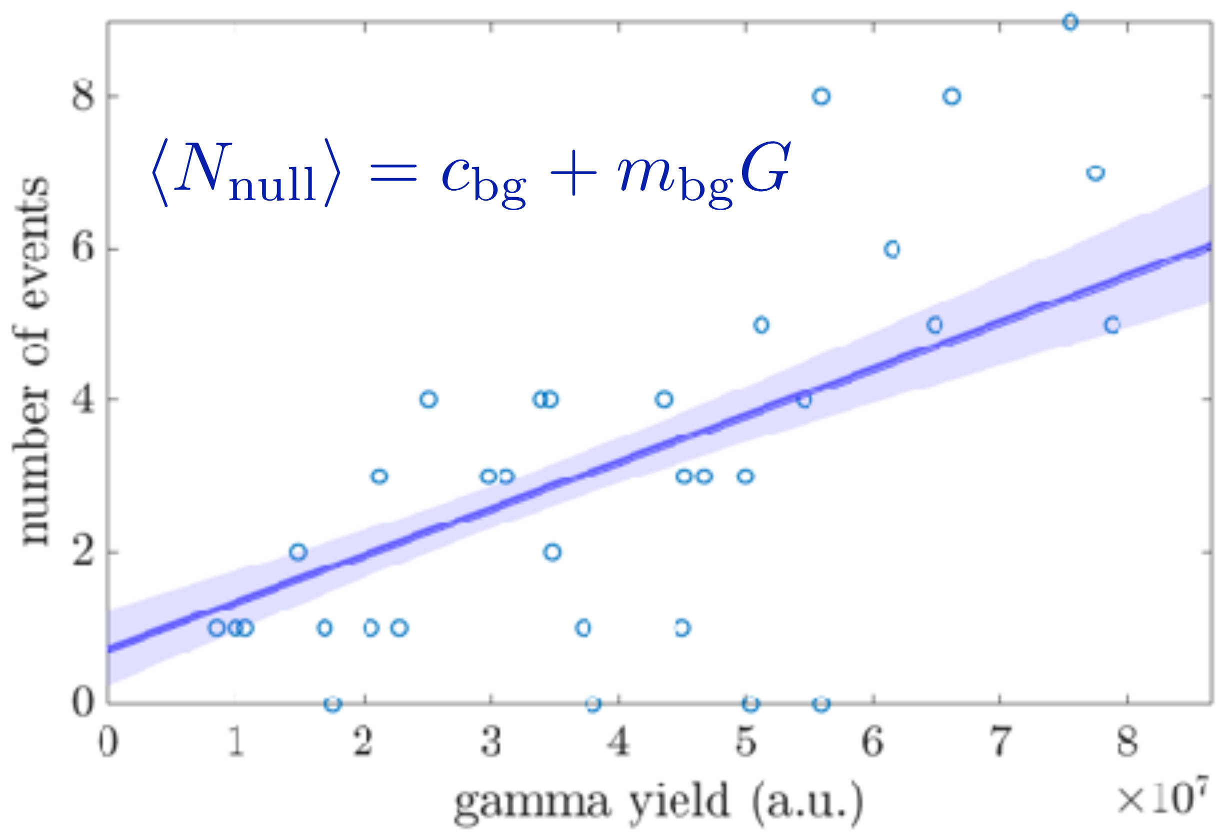
- The gamma yield, G, varies from shot-to-shot
- Correlation between background events N_{null} and gamma yield

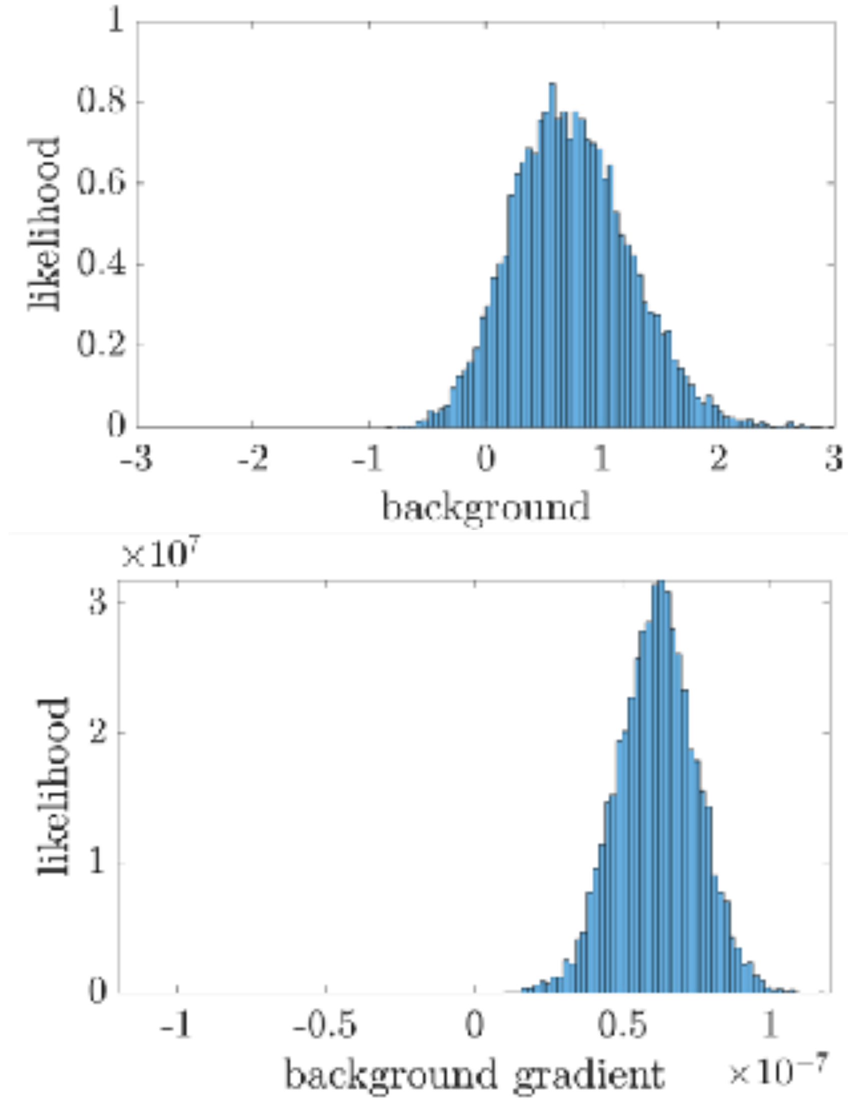
Background events are correlated with gamma yield



- Correlation between gamma yield and number of events
  - we are sensitive to small differences in the gamma yields on null and full shots

Background events are correlated with gamma yield





- A Bayesian analysis shows background is consistent with the (poisson) mean number of events varying with gamma yield

Do we see more events on full shots?

- We expect signal events to follow similar behaviour

$$\langle N_{\mathrm{null}}\rangle = c_{\mathrm{bg}} + m_{\mathrm{bg}}G$$
$$\langle N_{\mathrm{full}}\rangle = c_{\mathrm{bg}} + (m_{\mathrm{bg}} + m_{\mathrm{signal}})G$$

Do we see more events on full shots?

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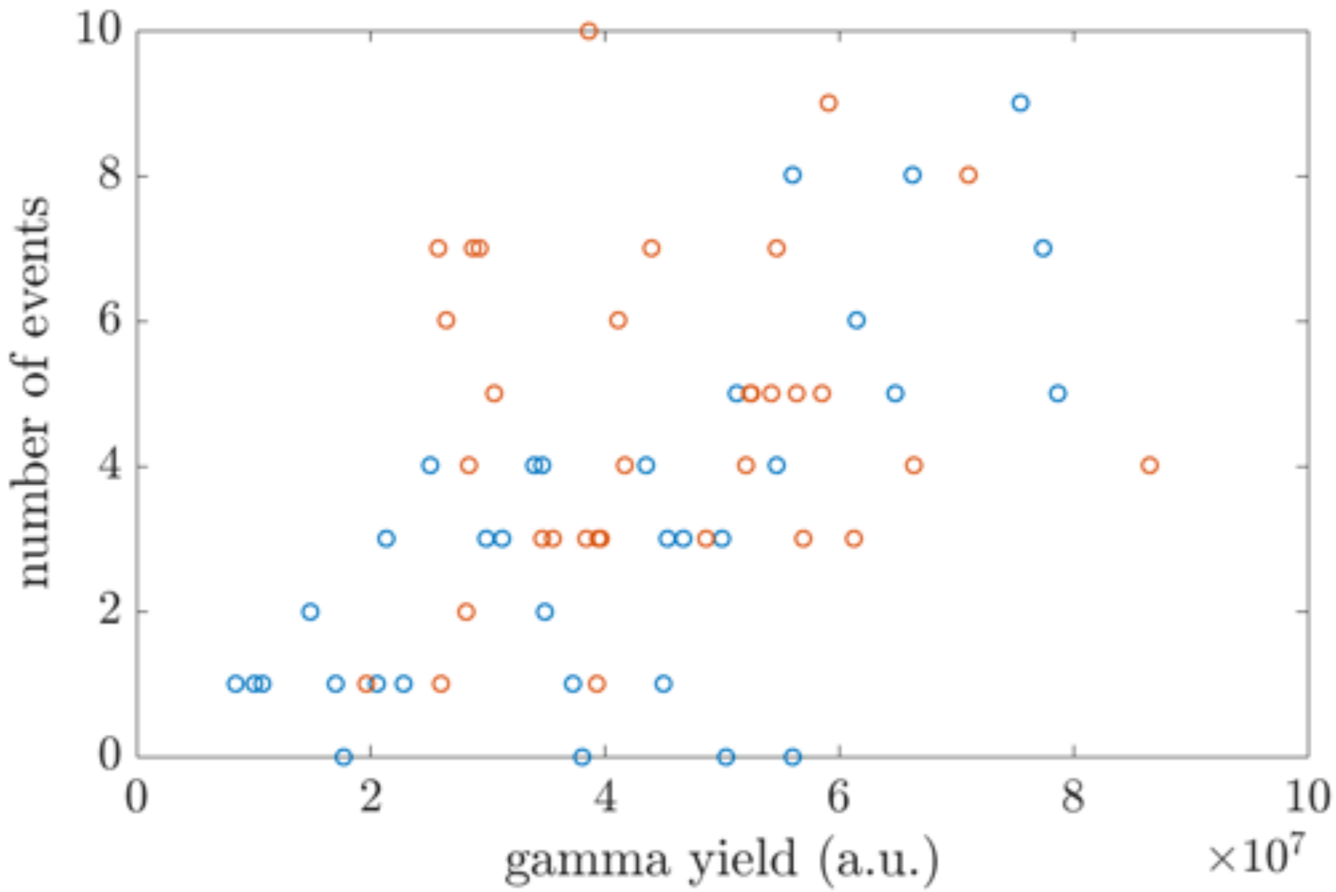

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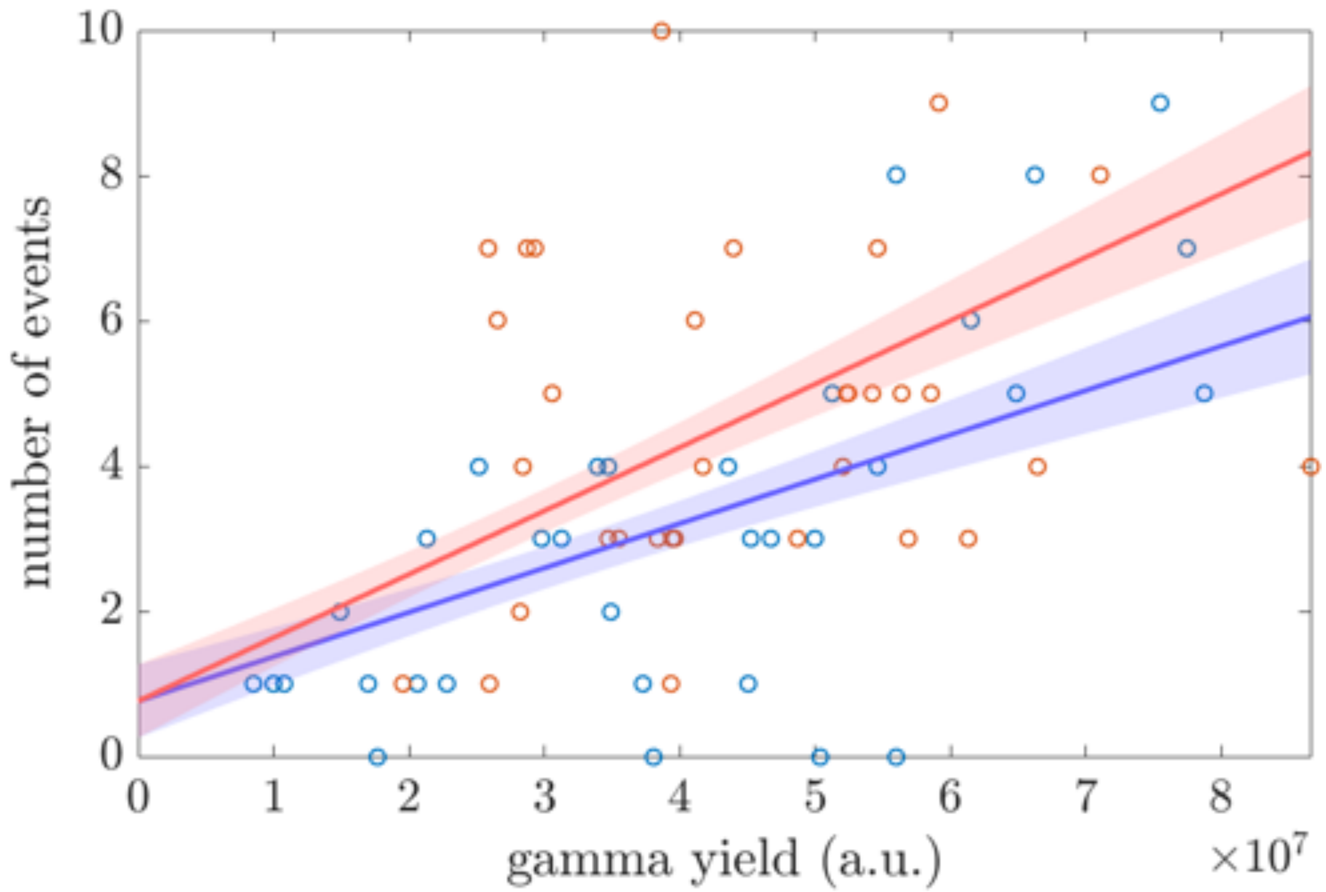

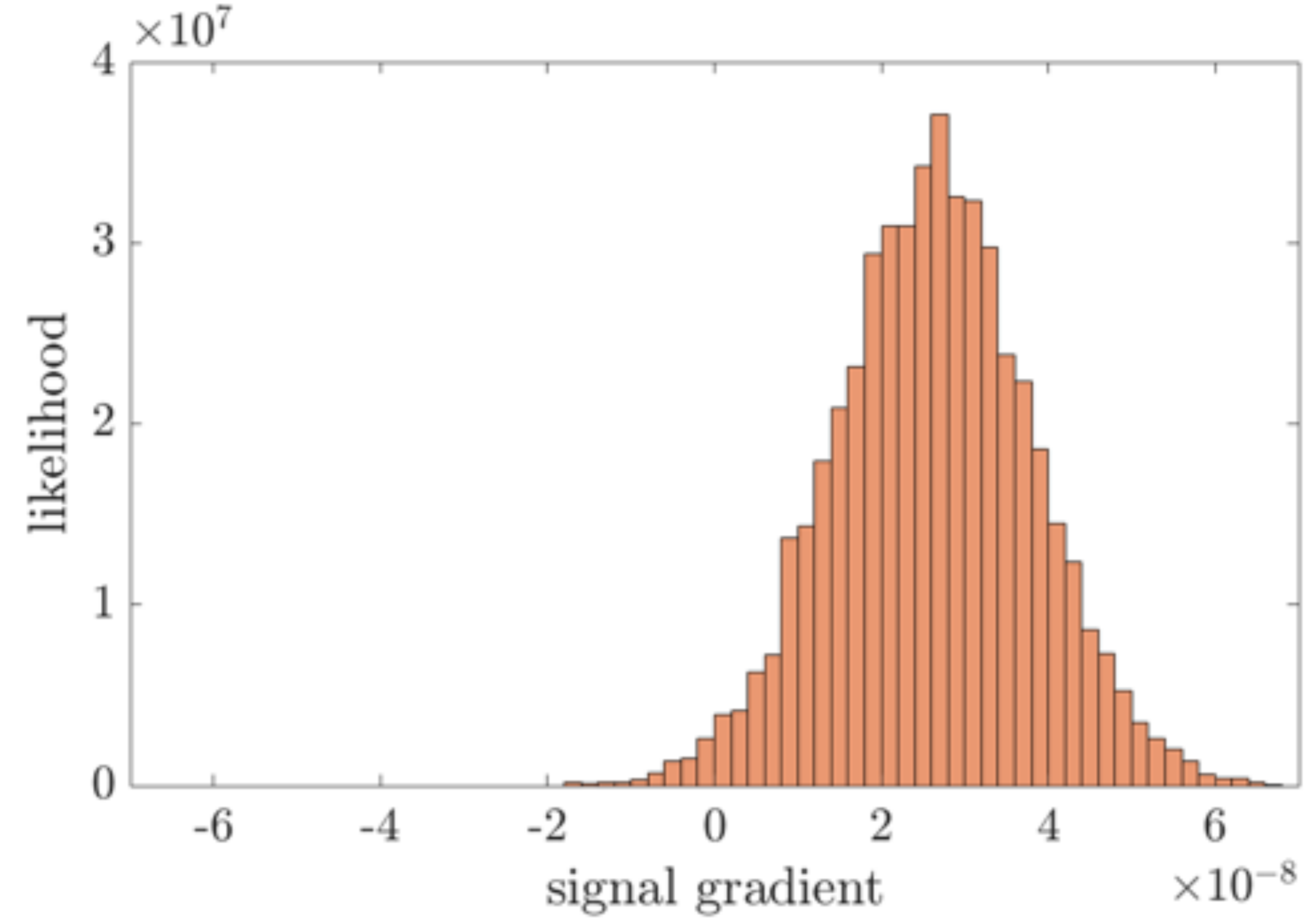

- Data favours signal > 0 (p ≈ 0.01)

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Next steps

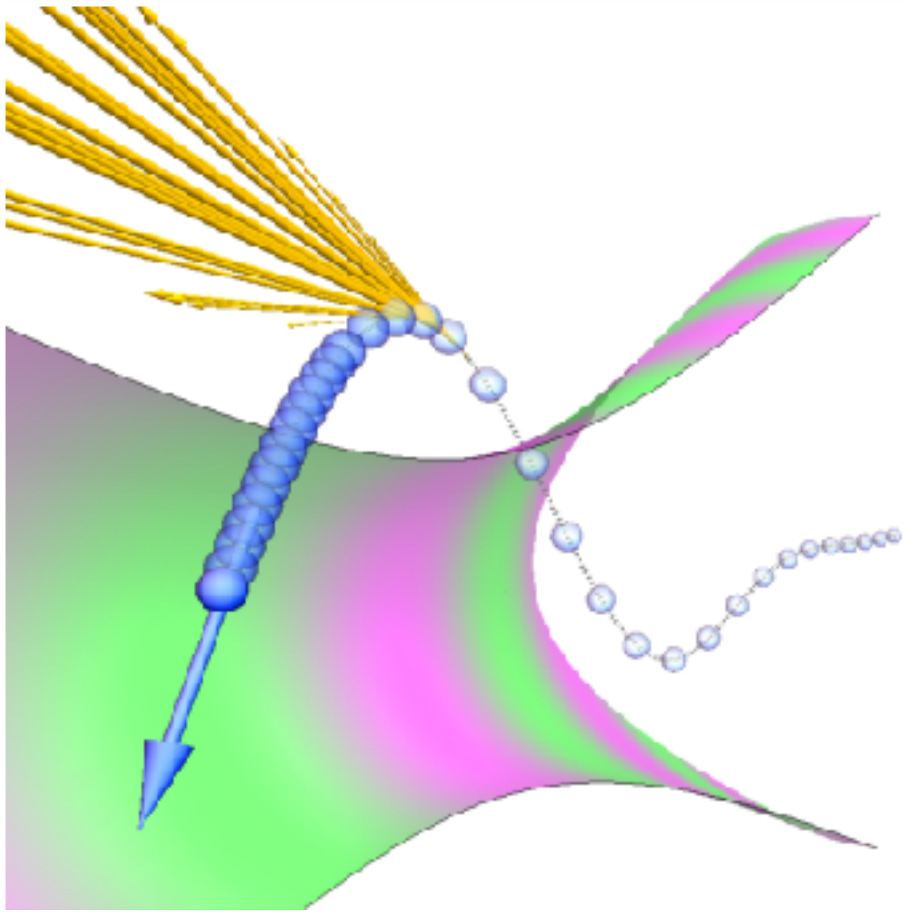
- What is next?
  - similar under analysis is underway for other particle detectors
    - » a second TimePix3
    - » combining both TimePix3s
    - » Single event CsI
    - » combining all diagnostics together
    - » Comparing results with BW theory

- CAUTION significance can go down as well as up when more data is included.

Probing QED with Laser Wakefield Accelerators

- Experiment 1: Breit Wheeler Pair production
- Experiment 2: Radiation Reaction in Extreme electromagnetic fields

Extreme electromagnetic fields



$$\frac{\mathrm{d}\mathbf{p}}{\mathrm{d}t} = e(\mathbf{E} + \mathbf{v} \times \mathbf{B}) + \mathrm{R.R.}$$

- Accelerating charges radiate, and so must lose energy
  - an outstanding problem in classical electrodynamics
- How this occurs in very strong fields is not well understood
  - fields approaching critical field of QED (Schwinger field)

Radiation Reaction models

Classical | Semi-classical | Strong field QED

Classical

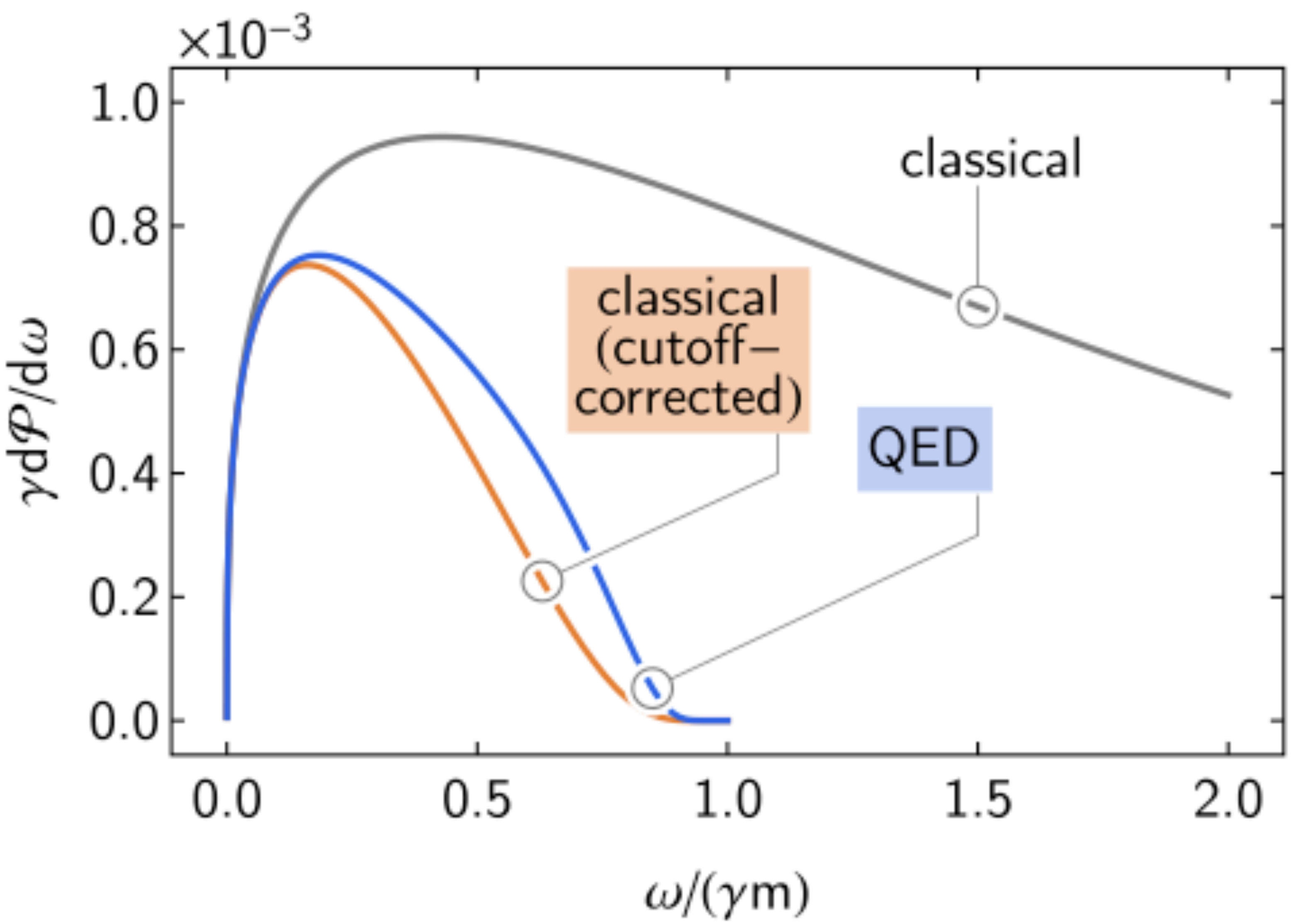
- emission is continuous
- emission rate determined by Larmor formula
- no maximum emission frequency

Semi-classical

- emission is continuous
- maximum photon energy

Strong field QED

- emission is discrete (photons)
- Maximum photon energy



Blackburn Rev Mod Plas Phys https://doi.org/10.1007/s41614-020-0042-0

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Radiation Reaction is important in astrophysics

- Powerful and variable gamma-ray sources (pulsar winds, active galactic nuclei, gamma-ray bursts)
  - Gamma rays generated by charged particles accelerated to very high energy due to rapid dissipation of EM energy from plasma
  - Particle energies and fields are high enough for RR to play an important role

Yuan *et al* 2016 *ApJ* **828** 92 https://doi.org/10.3847/0004-637X/828/2/92

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Extreme electromagnetic fields

$$E_{cr} = \frac{m_e^2 c^3}{\hbar e} = 1.3 \times 10^{18}\ \mathrm{V\,m^{-1}}$$

$$\frac{E_{\mathrm{Gemini}}}{E_{\mathrm{cr}}} \approx 0.00001$$

- Electric fields at focus of intense laser are some of strongest on Earth
  - But they are still well below the critical field of QED

Extreme electromagnetic fields

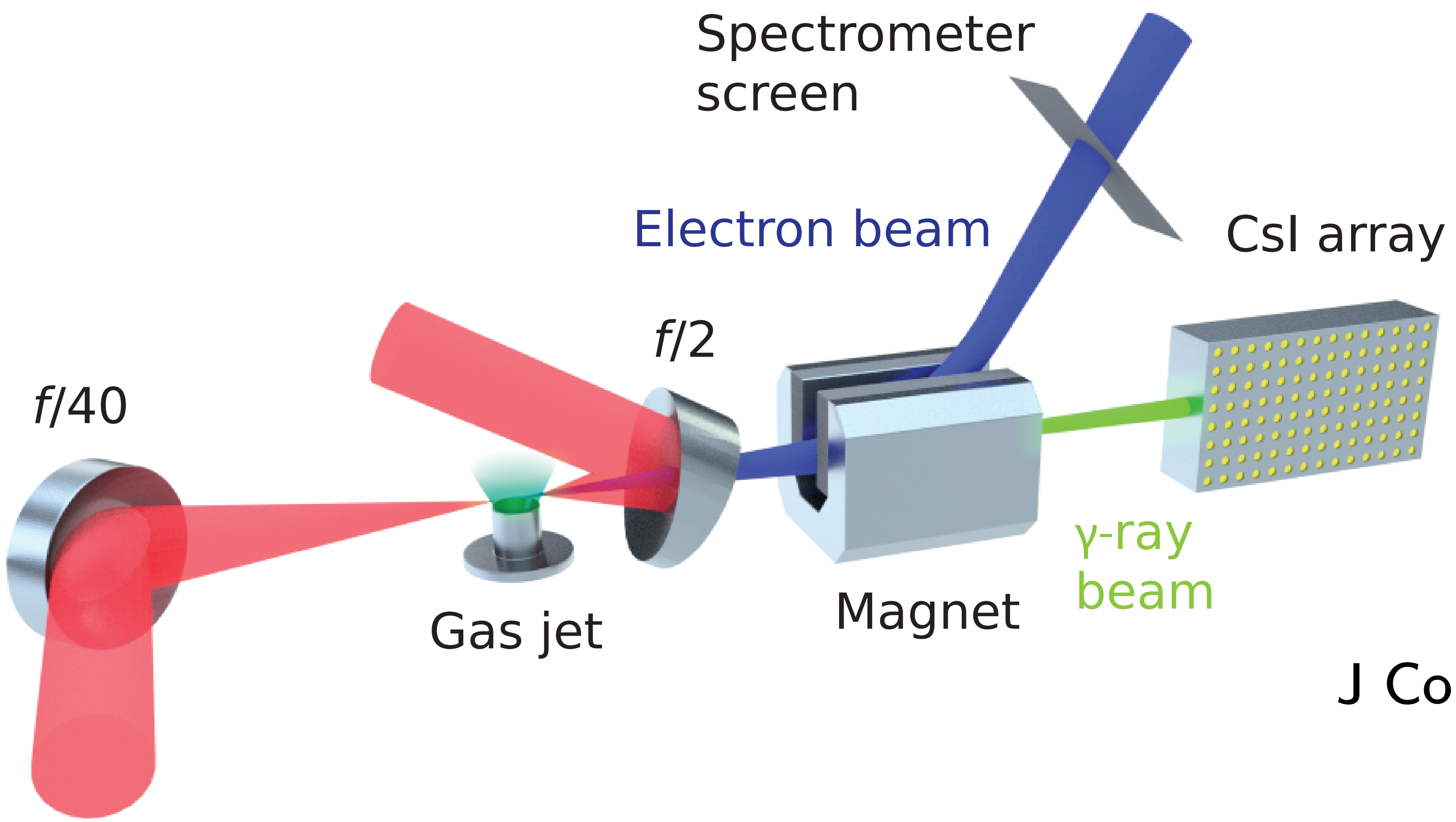
$$E_{cr} = \frac{m_e^2 c^3}{\hbar e} = 1.3 \times 10^{18}\ \mathrm{V\,m^{-1}}$$

$$\frac{E_{\mathrm{Gemini}}}{E_{\mathrm{cr}}} \approx 0.00001$$

$$\frac{\gamma E_{\mathrm{Gemini}}}{E_{\mathrm{cr}}} \approx 0.1$$

- Electric fields at focus of intense laser are some of strongest on Earth
  - But they are still well below the critical field of QED
- Can access strong fields fields in frame of relativistic beam
  - collide high intensity laser pulse with relativistic electron beam

Extreme electromagnetic fields



J Cole et al PRX 2018

- Can access strong fields fields in frame of relativistic beam
  - collide high intensity laser pulse with relativistic electron beam

Radiation Reaction Experiments: Challenges

- Successful collisions
  » shot-to-shot pointing and timing jitter
- Unknown laser intensity profile at the collision
  » mitigate these by colliding when electron beam is smaller than the laser beam
- Unknown electron beam properties at the collision
  » mitigate these by focusing on energy loss of main feature
- Shot-to-shot variation in electron beam

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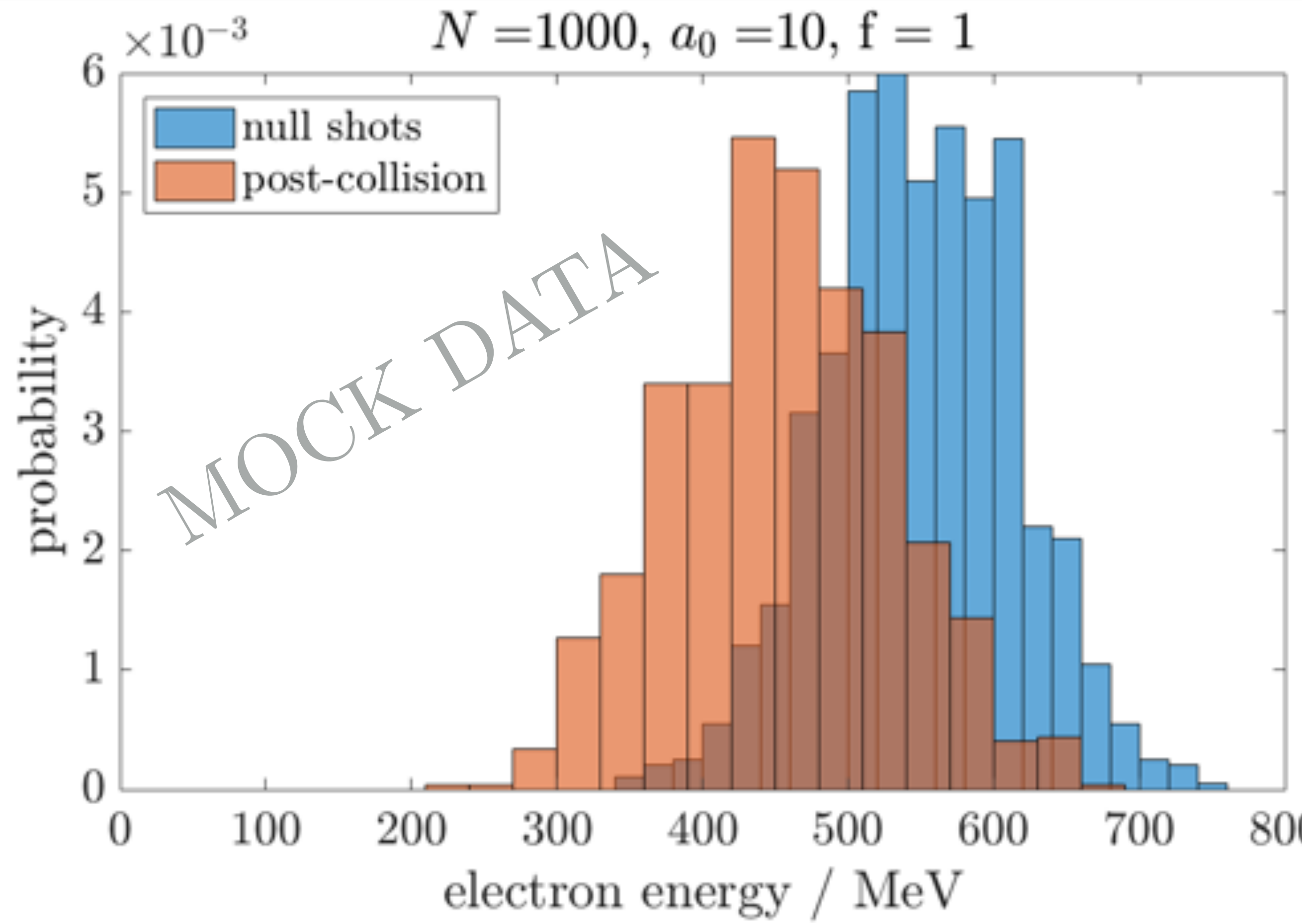
With 100% successful collisions small effects are observable

- electron beam energy,
  - » E = 550 ± 65 MeV
- number of shots,
  - » N = 1000
- fraction of successful collisions,
  - **» f = 1**
- peak laser intensity possible,
  - » a_0 = 10 ± 5



- mean energy of null shots
  - » 547 ± 2 MeV
- mean energy of collision shots
  - » 456 ± 2 MeV
- energy "loss" in collision shots
  - » 91 ± 3 MeV (30 sigma)

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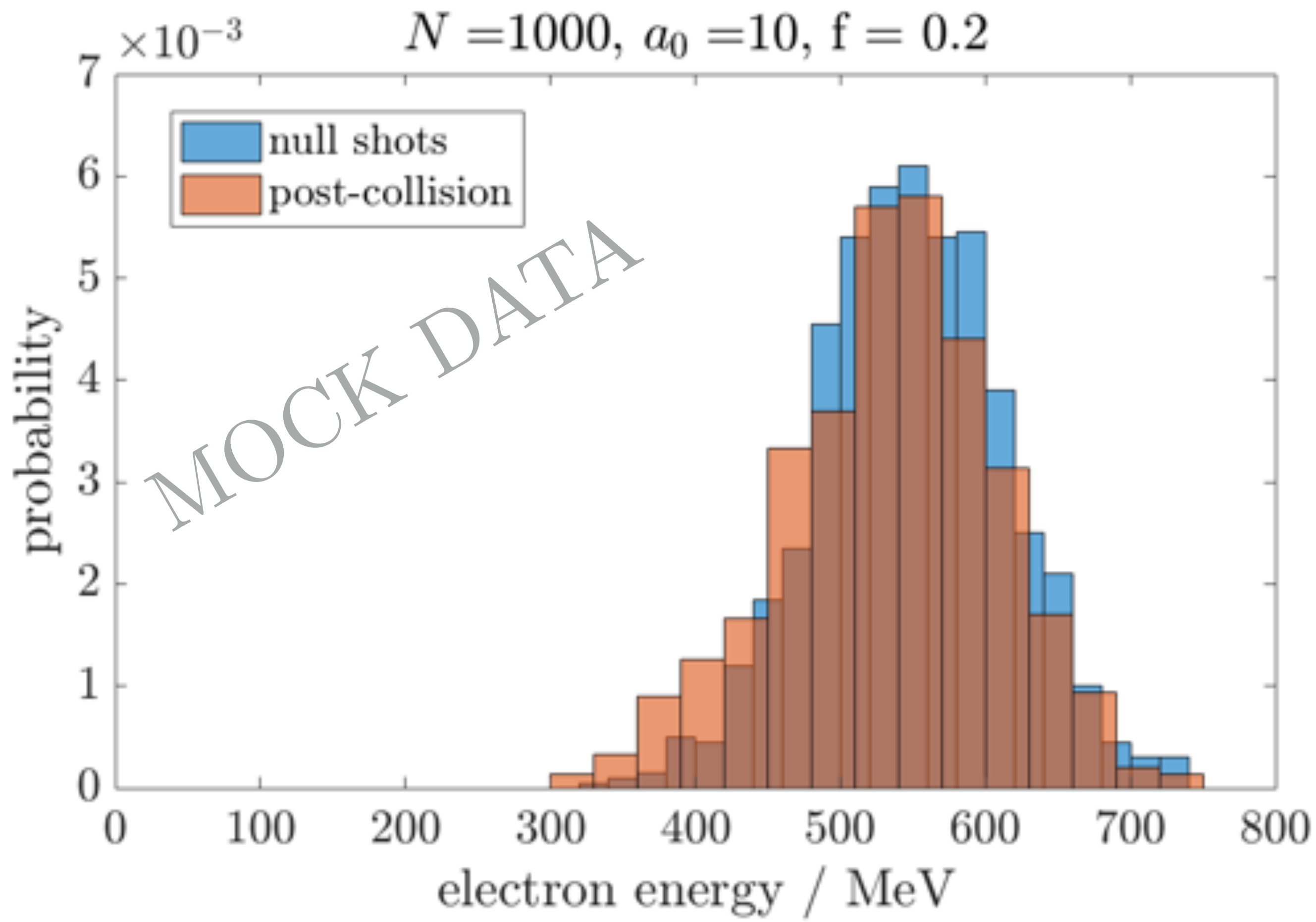
Sometimes the laser and electron beam will miss

- electron beam energy,
  - » E = 550 ± 65 MeV
- number of shots,
  - » N = 1000
- fraction of successful collisions,
  - » f = 0.2
- peak laser intensity possible,
  - » a_0 = 10 ± 5



- mean energy of null shots
  - » 548 ± 2 MeV
- mean energy of collision shots
  - » 534 ± 2 MeV

- energy "loss" in collision shots
  - » 14 ± 3 MeV (4.6 sigma)

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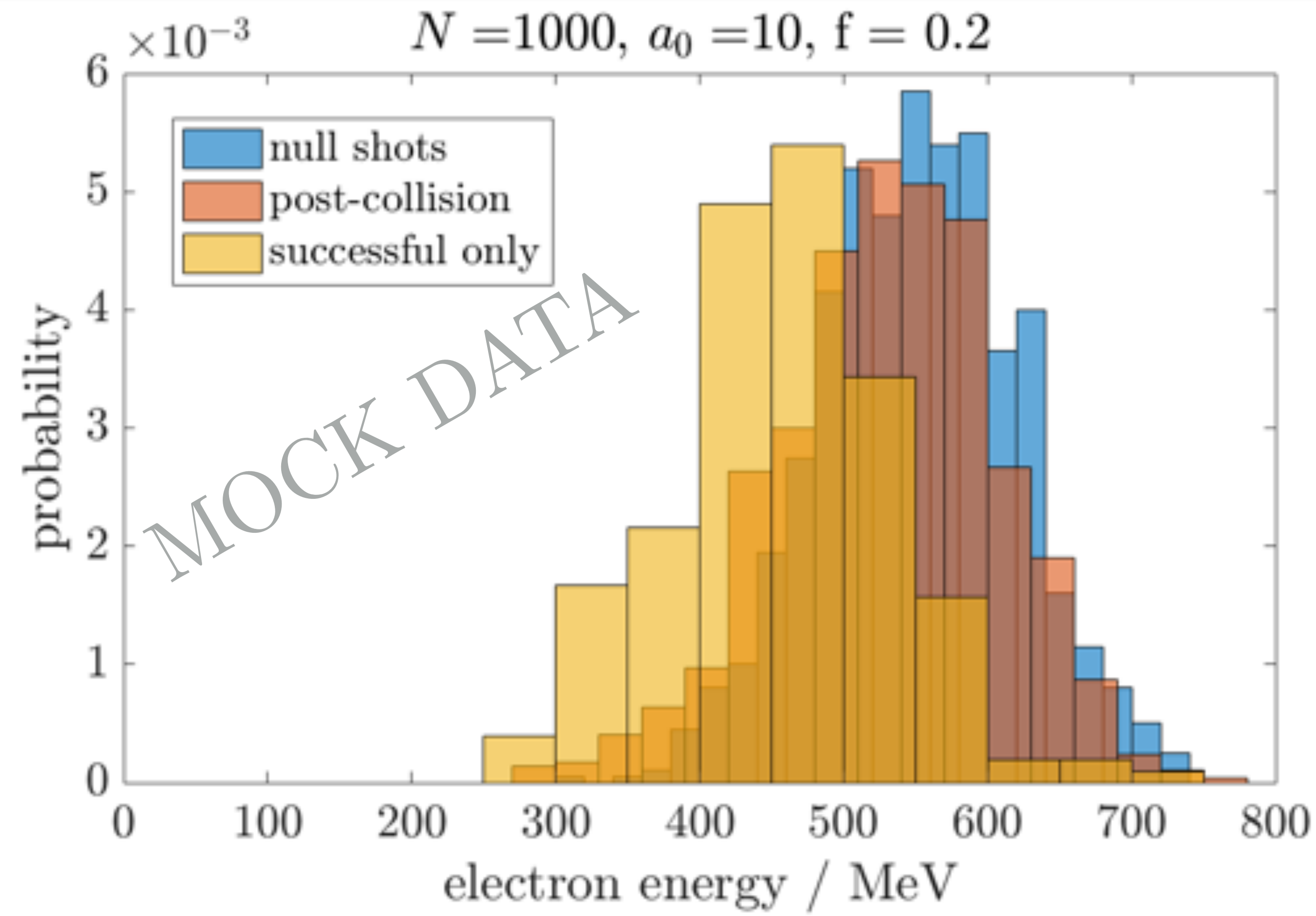
Identifying which collisions are successful is key to observing radiation reaction

- electron beam energy,
  - » E = 550 ± 65 MeV
- number of shots,
  - » N = 1000
- fraction of successful collisions,
  - » f = 0.2
- peak laser intensity possible,
  - » a_0 = 10 ± 5



- mean energy of null shots
  - » 552 ± 2 MeV
- mean energy of successful collisions
  - » 458 ± 5 MeV
- energy "loss" in collision shots
  - » 94 ± 6 MeV (15 sigma)

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The number of shots is important
(but maybe not as important as you might think)

– electron beam energy,

» E = 550 ± 65 MeV

– number of shots,

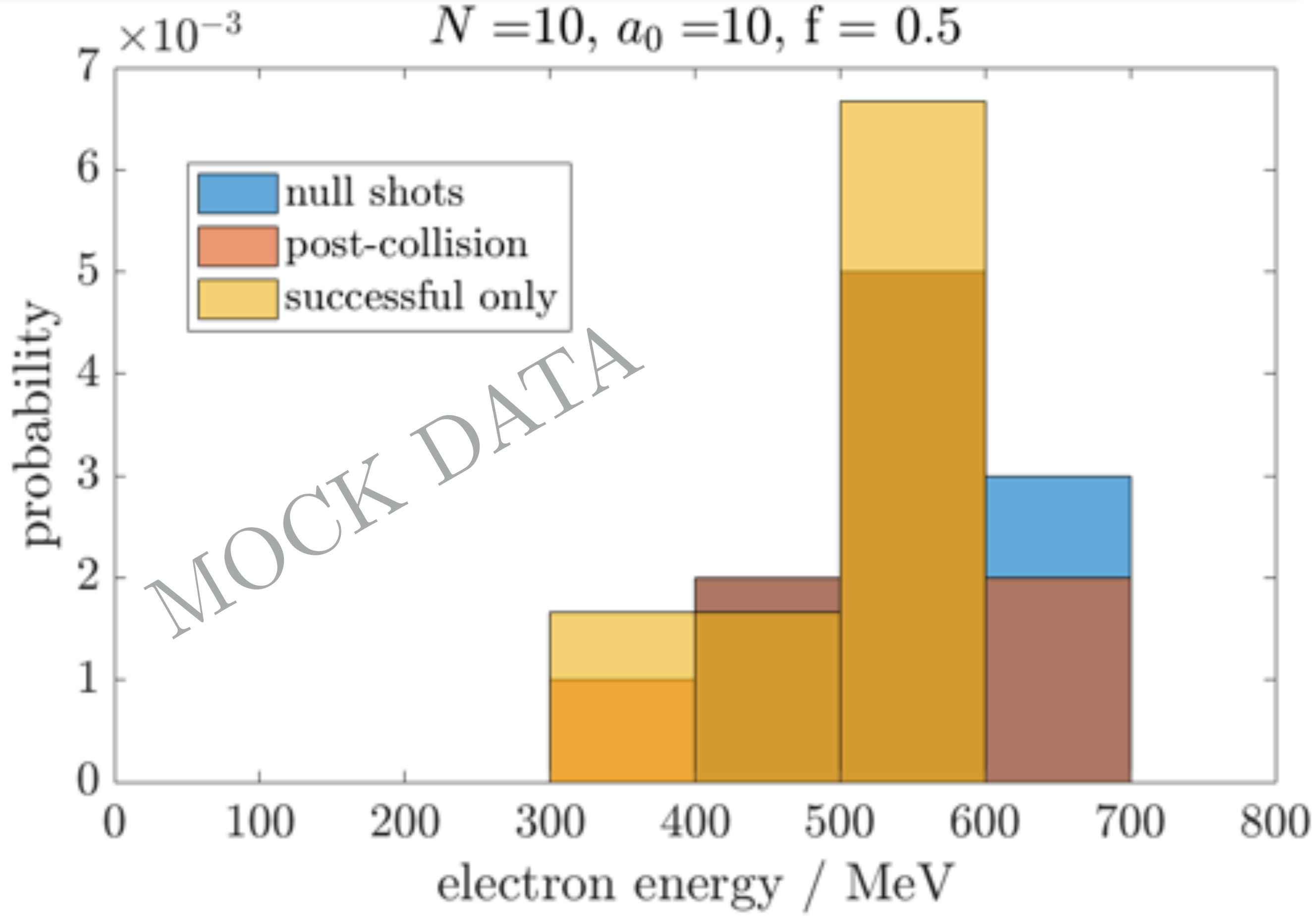
» N = 10

– fraction of successful collisions,

» **f = 0.5**

– peak laser intensity possible,

» a_0 = 10 ± 5



- mean energy of null shots

  » 550 ± 20 MeV

- mean energy of successful collisions

  » 482 ± 25 MeV

- energy “loss” in collision shots

  » 68 ± 32 MeV (2 sigma)

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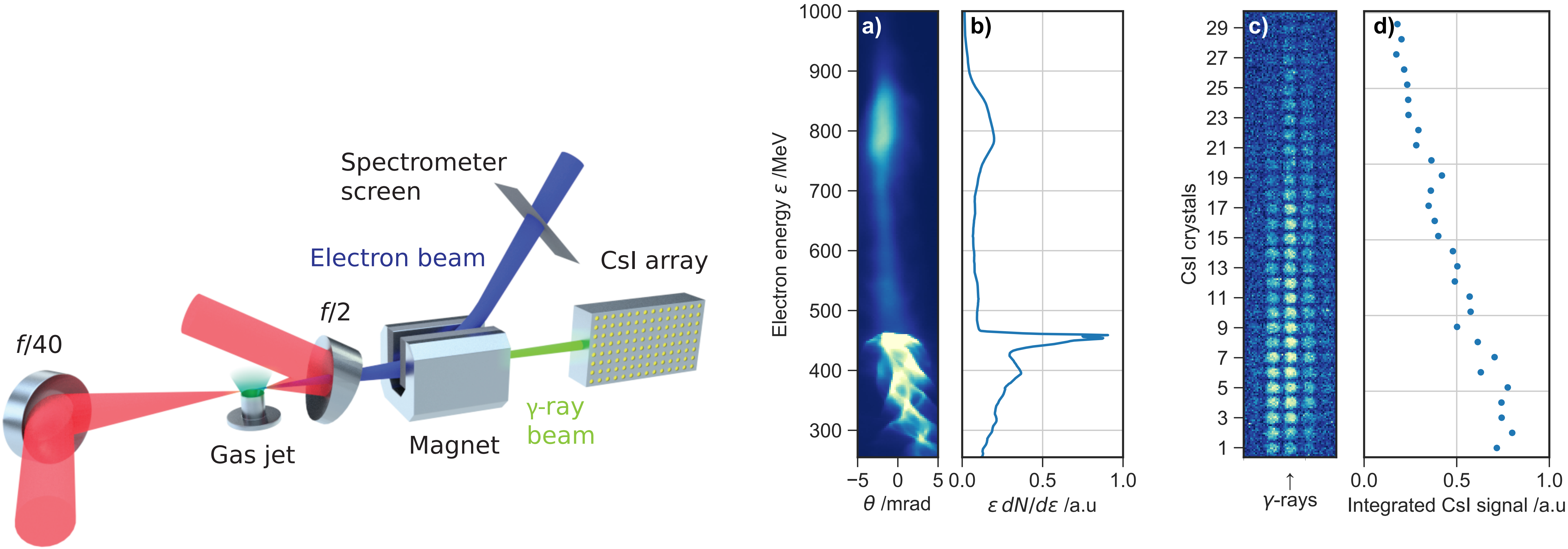
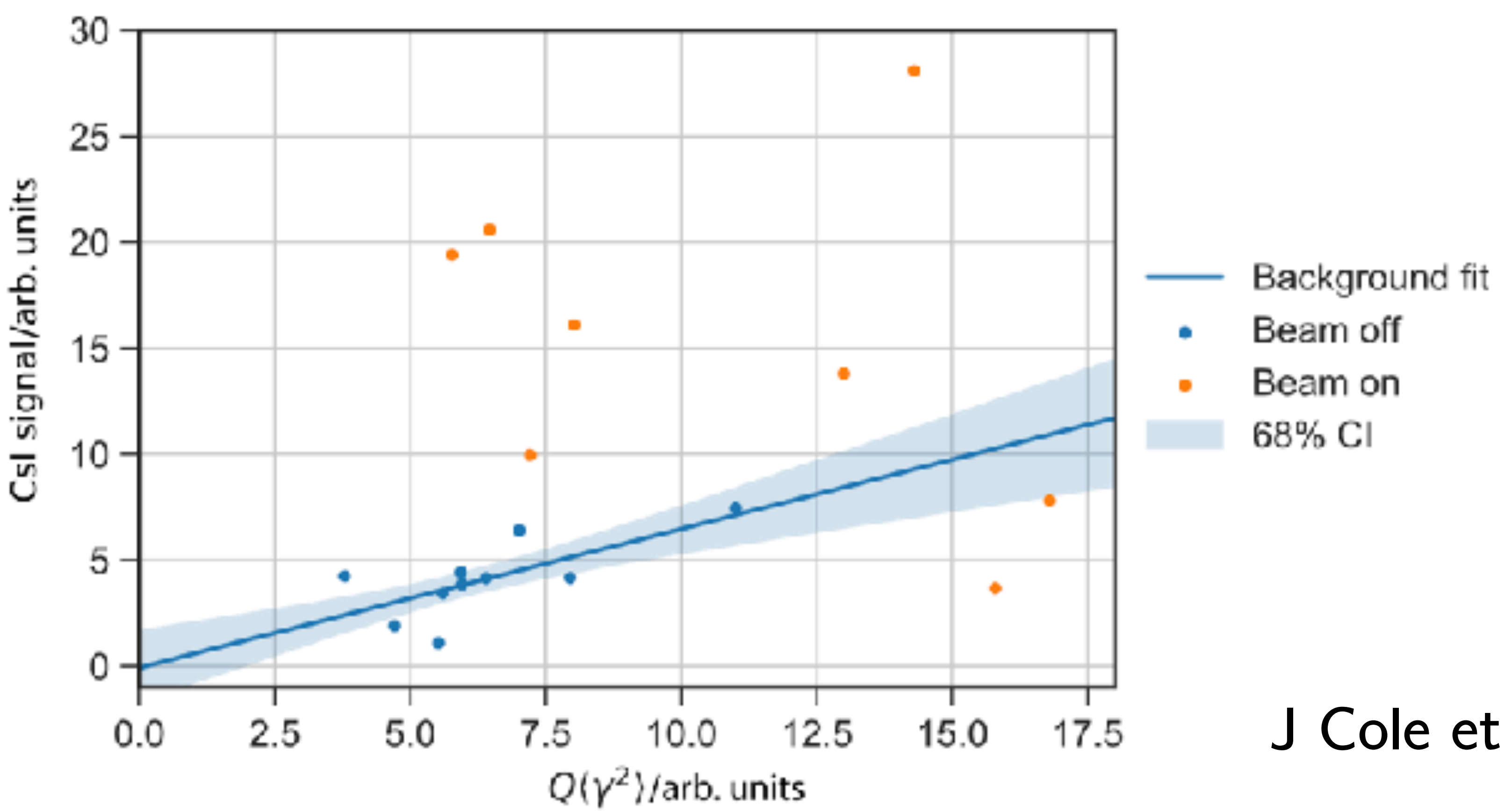
Radiation Reaction Experiment at Gemini

J Cole et al PRX 2018



K Behm et al RSI 2018

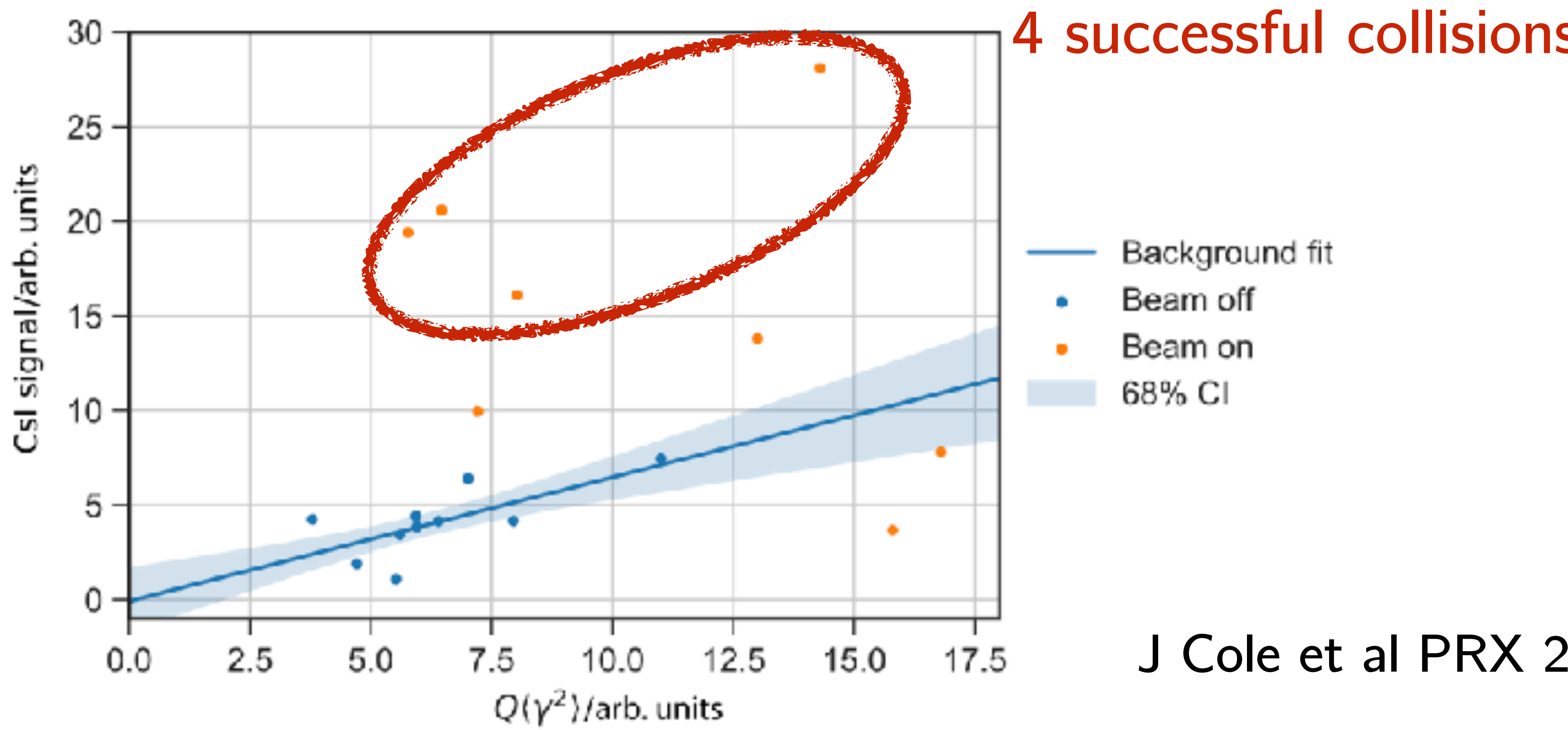
Identifying successful collisions



J Cole et al PRX 2018

- Successful collisions will produce bright Gamma-ray signal
  - Background gamma-ray signal on null shots is correlated with electron spectrum $Q\langle\gamma^2\rangle$
  - Successful collisions need to be significantly above this

Identifying successful collisions



J Cole et al PRX 2018

- Successful collisions will produce bright Gamma-ray signal
  - Background gamma-ray signal on null shots is correlated with electron spectrum $Q\langle\gamma^2\rangle$
  - Successful collisions need to be significantly above this

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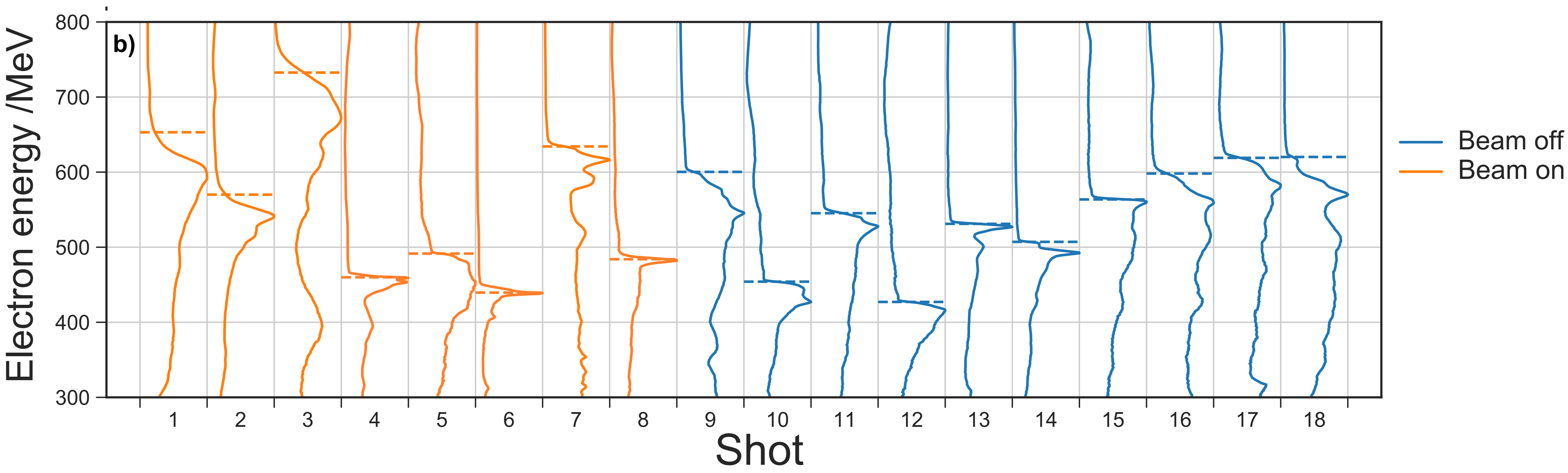
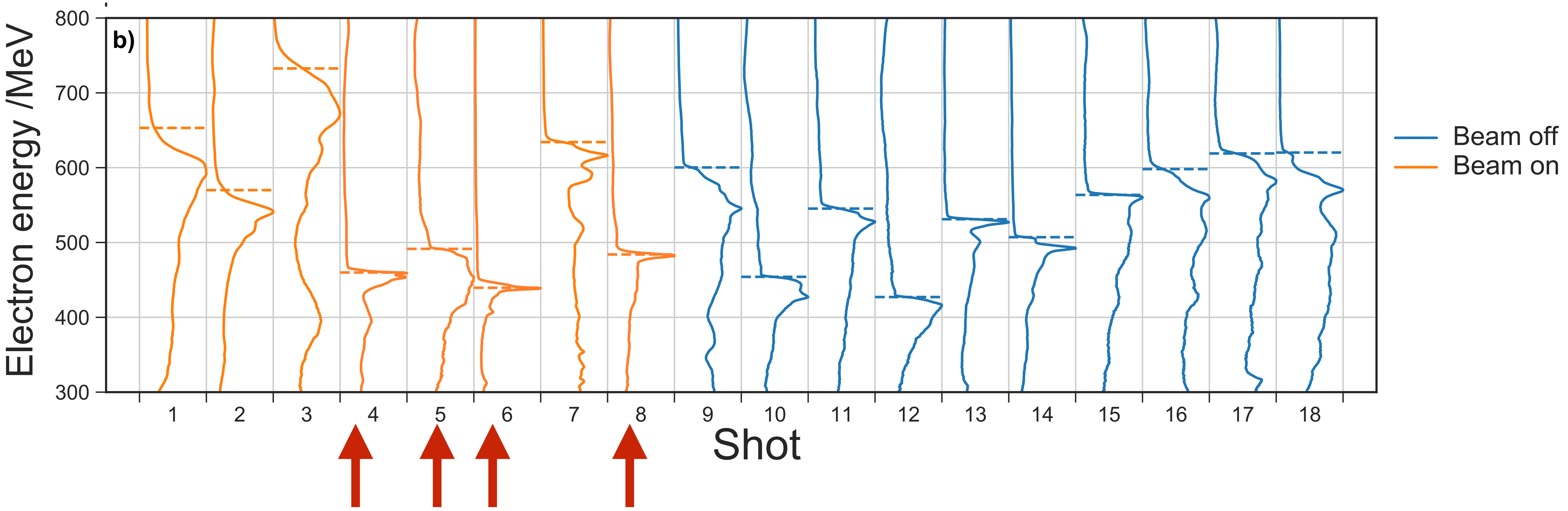
Fluctuations of electron beam make RR signal far from obvious



All successful collisions show electron energy below 500 MeV



- The 4 successful collisions are all at low (< 500 MeV) energy.
  - » How significant is this?

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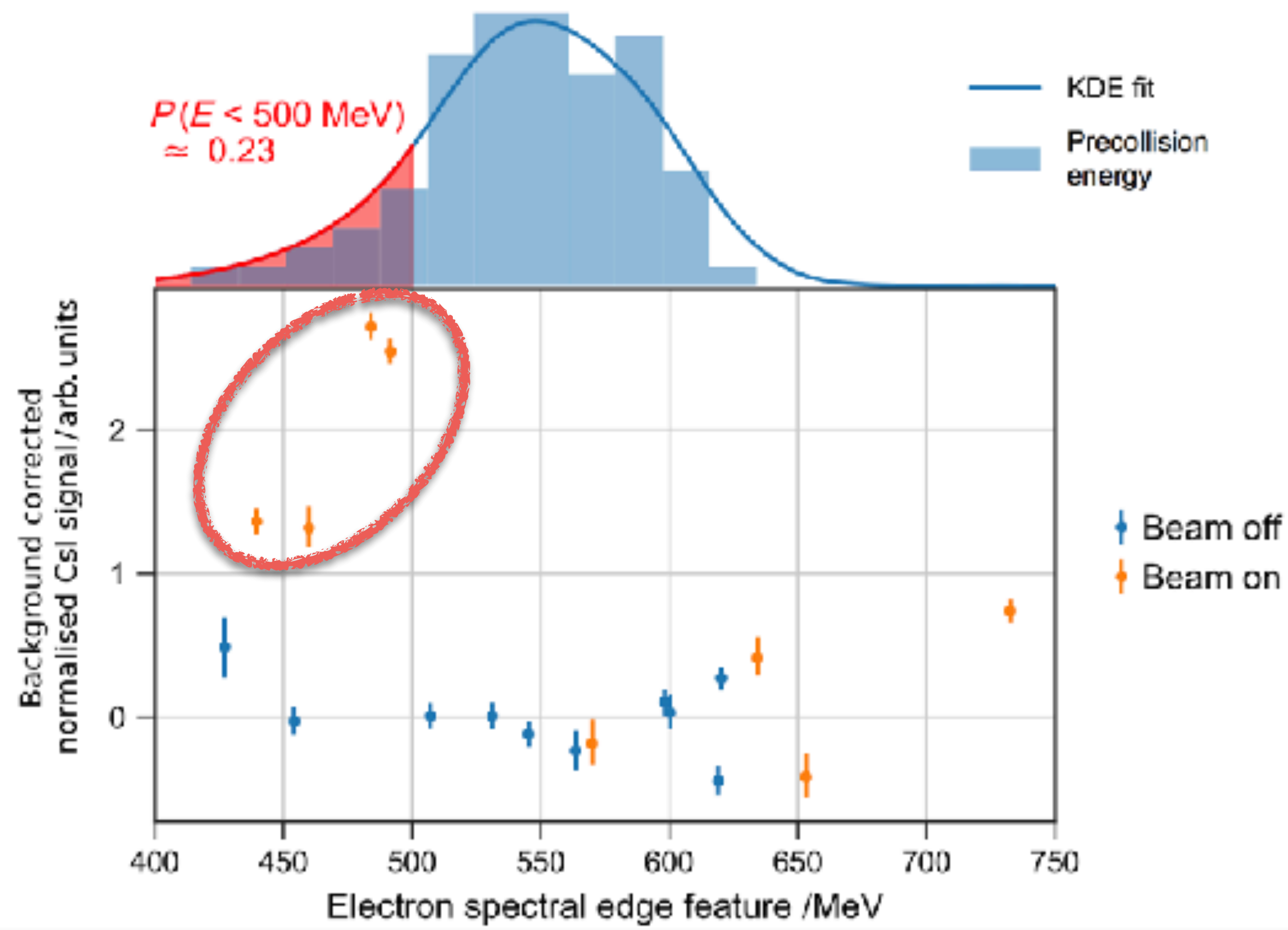
All successful collisions show electron energy below 500 MeV

- Null shots distribution:
  - mean 550 ± 20 MeV
  - standard deviation 63 ± 14 MeV
- All successful collisions have E < 500 MeV
  - For 1 shot with E < 500 MeV by chance
    - » $p = 0.23$ (1 in 4)
- For 4 out of 4 shots with E < 500 MeV by chance
  - » $p = (0.23)^4$
  - » $p < 0.003$ (1 in 350)

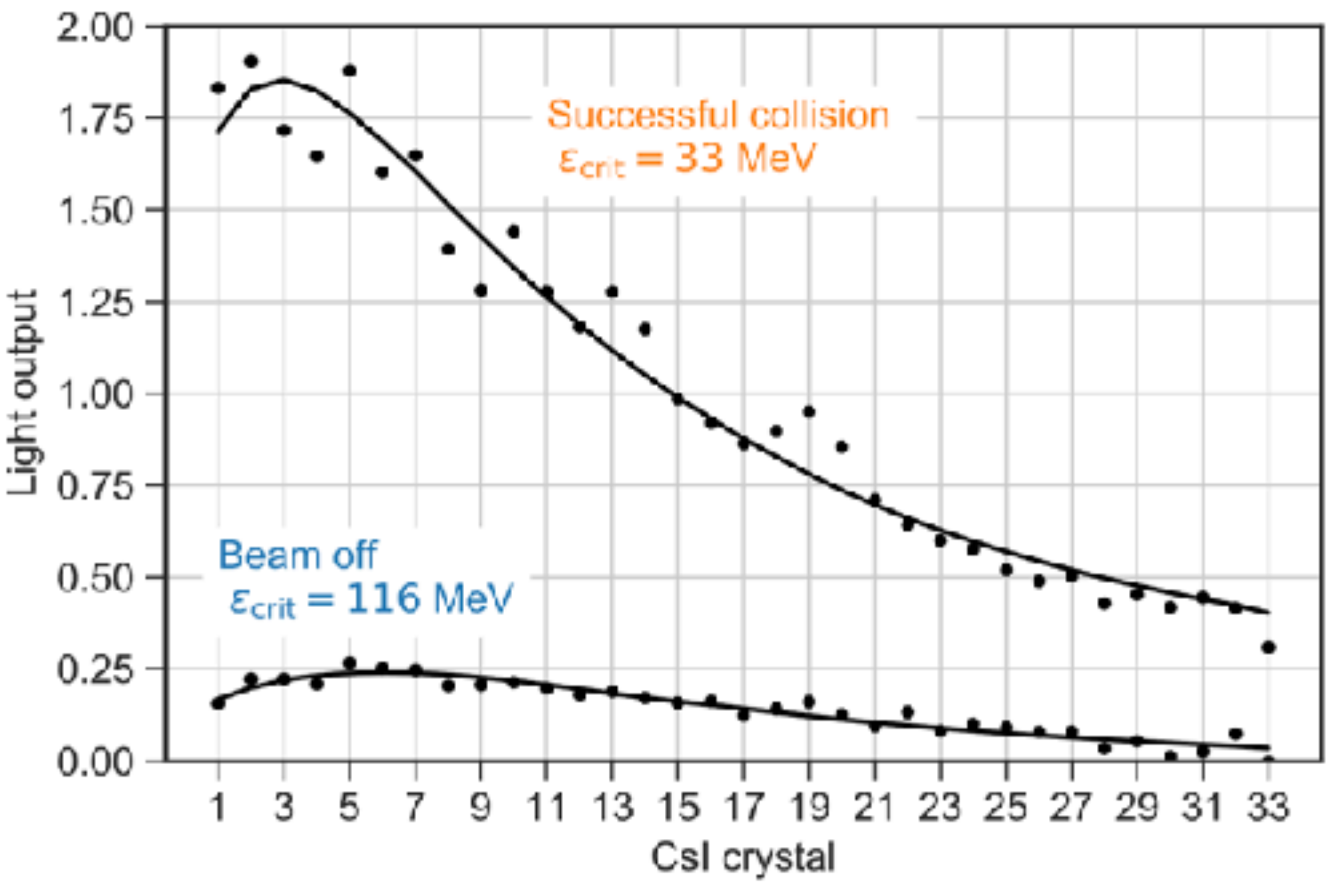


J Cole et al PRX 2018

Additional information from Gamma ray spectrum

- We expect energy loss to be correlated with gamma ray spectrum
  - lower energy beams (more energy loss) will make higher energy gammas
  - Without Radiation Reaction, we would expect correlation the other way round

$$\frac{dN_\gamma}{d\epsilon} \propto \epsilon^{-2/3} \exp(-\epsilon_\gamma/\epsilon_{crit})$$



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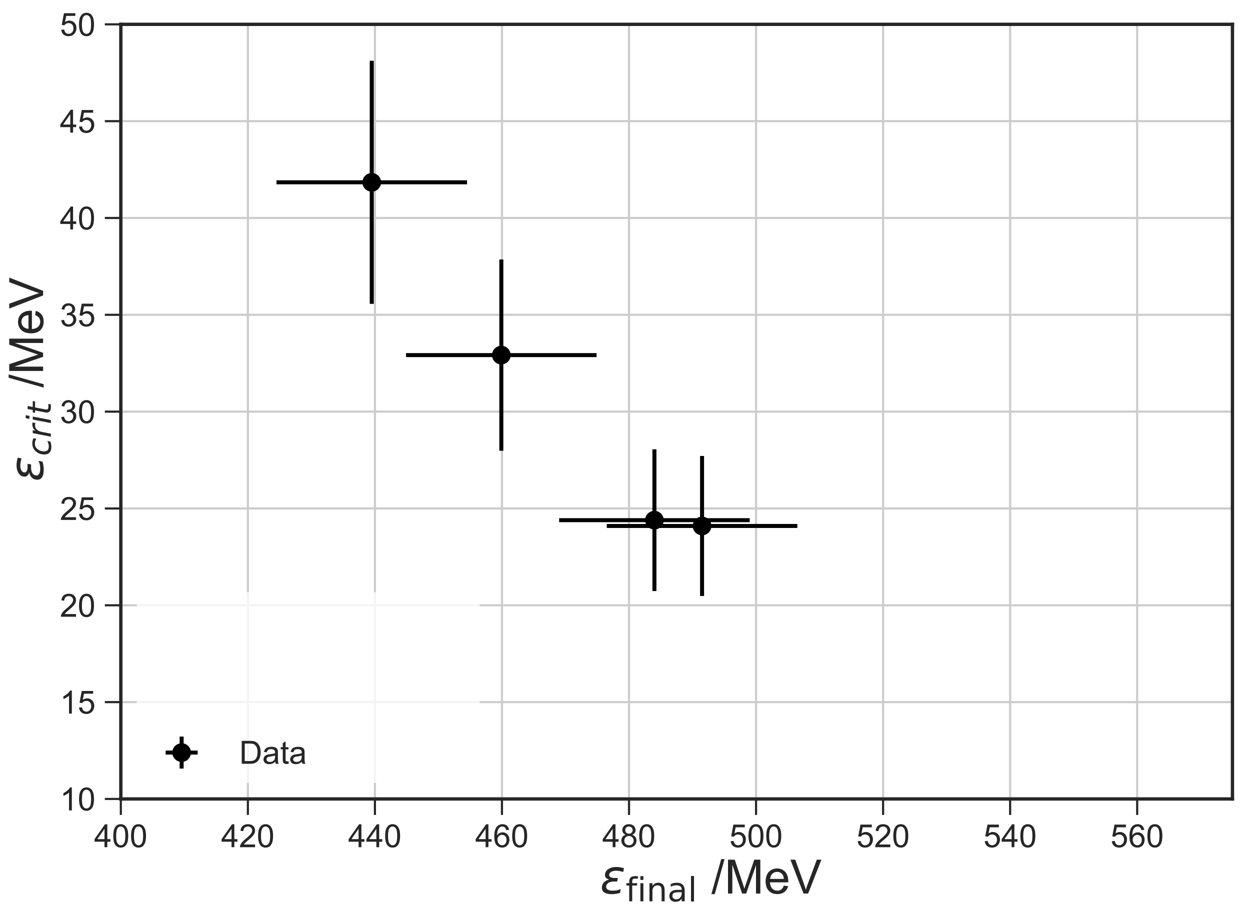
Correlation of gamma spectrum and electron energy

- We do observe a negative correlation
  - probability that we observe negative correlation ***and*** E < 500 MeV on 4/4 successful collision shots by chance is
    - p < 0.0003 (1/3000)
      - » 3–4 sigma



Experimental ***evidence*** for radiation reaction

J Cole et al PRX 2018

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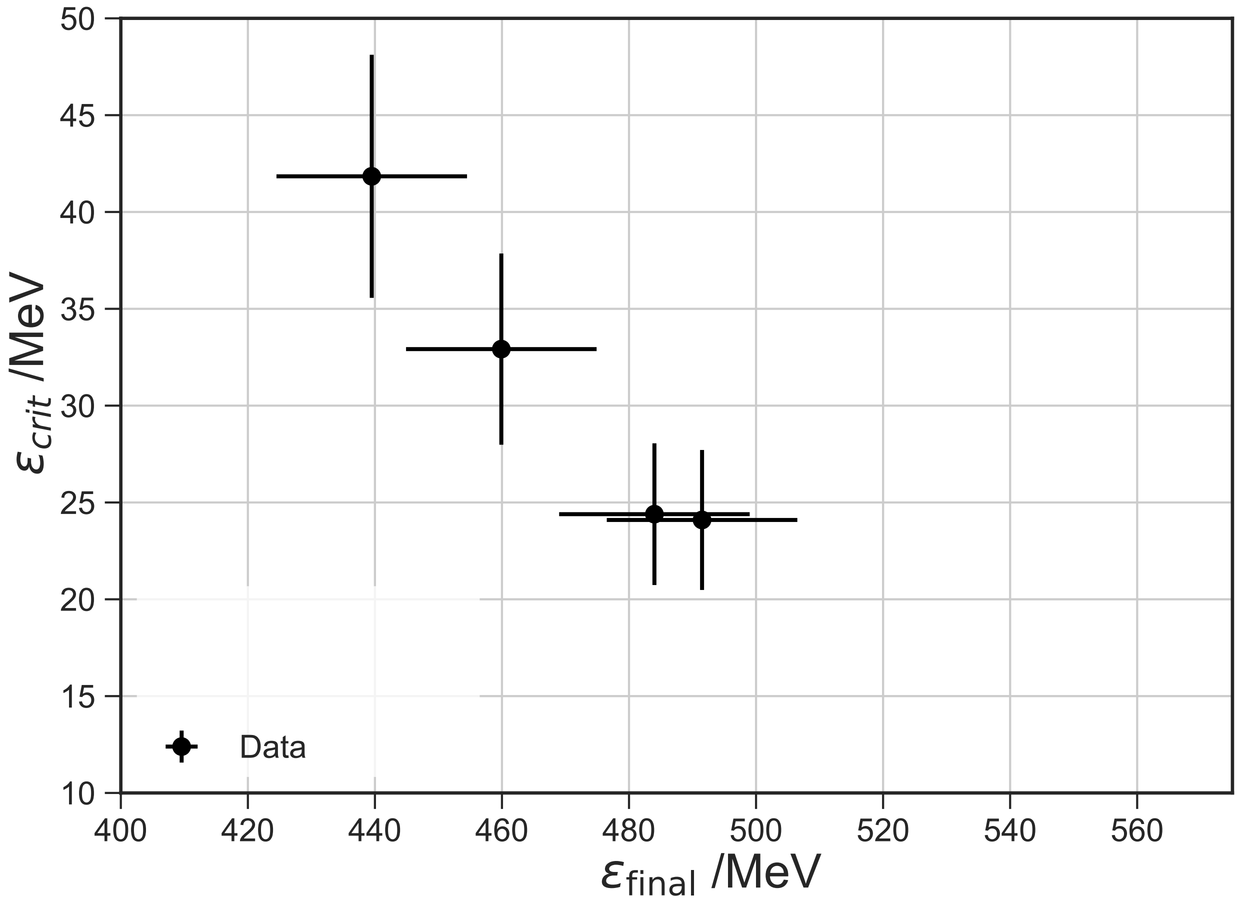
Comparing data to theoretical models

- Variation of energy loss and gamma spectrum due to a_0 fluctuations at the collision
  - If we had more data it would map out a curve parameterised by a_0
  - Different models map out different curves
  - curves will be broadened to include experimental fluctuations
  - We can build up these curves using MC modelling (including measured shot-shot variations etc)



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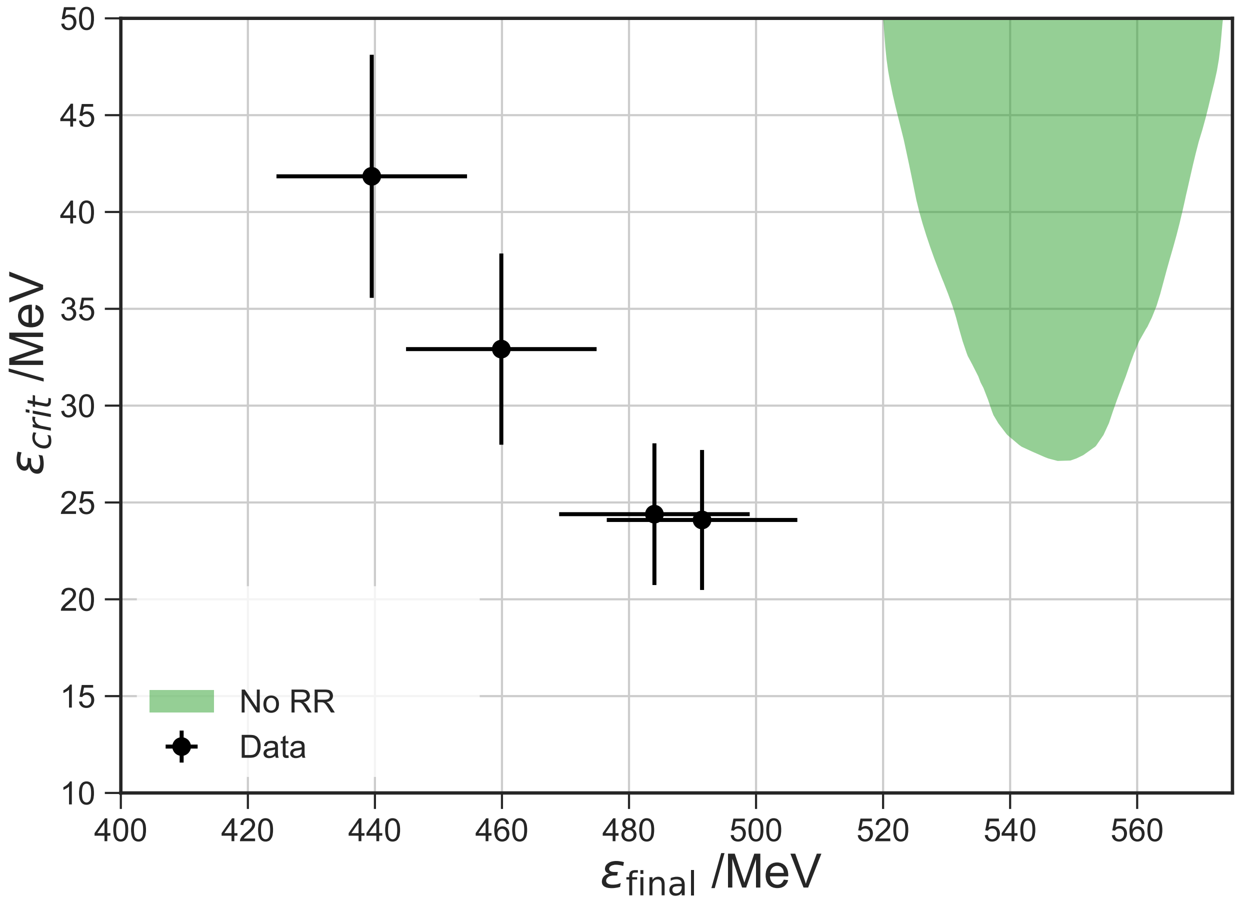
Comparing data to theoretical models

- No radiation reaction
  - excluded



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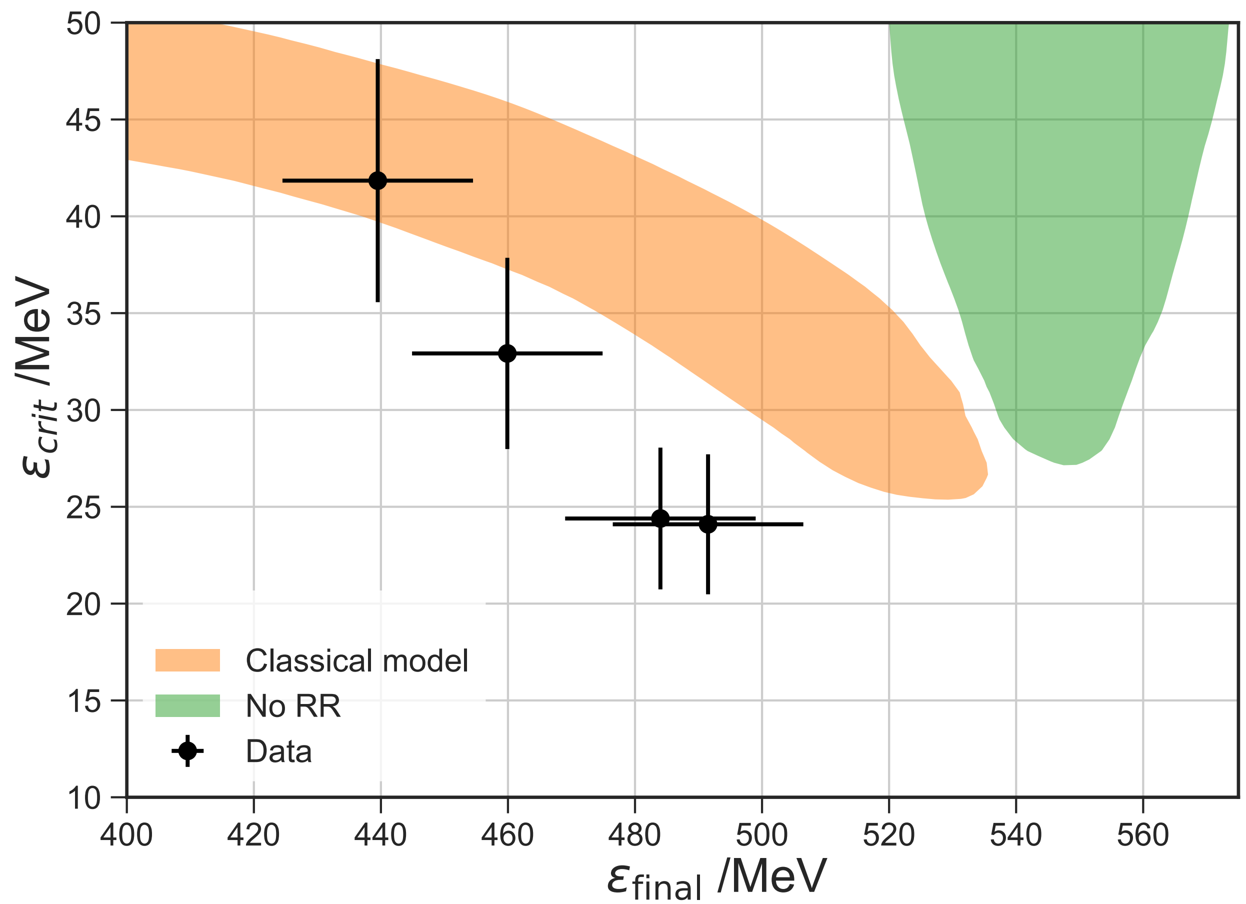
Comparing data to theoretical models

- No radiation reaction
  - excluded
- Classical (LL)
  - overestimates emission for small energy loss



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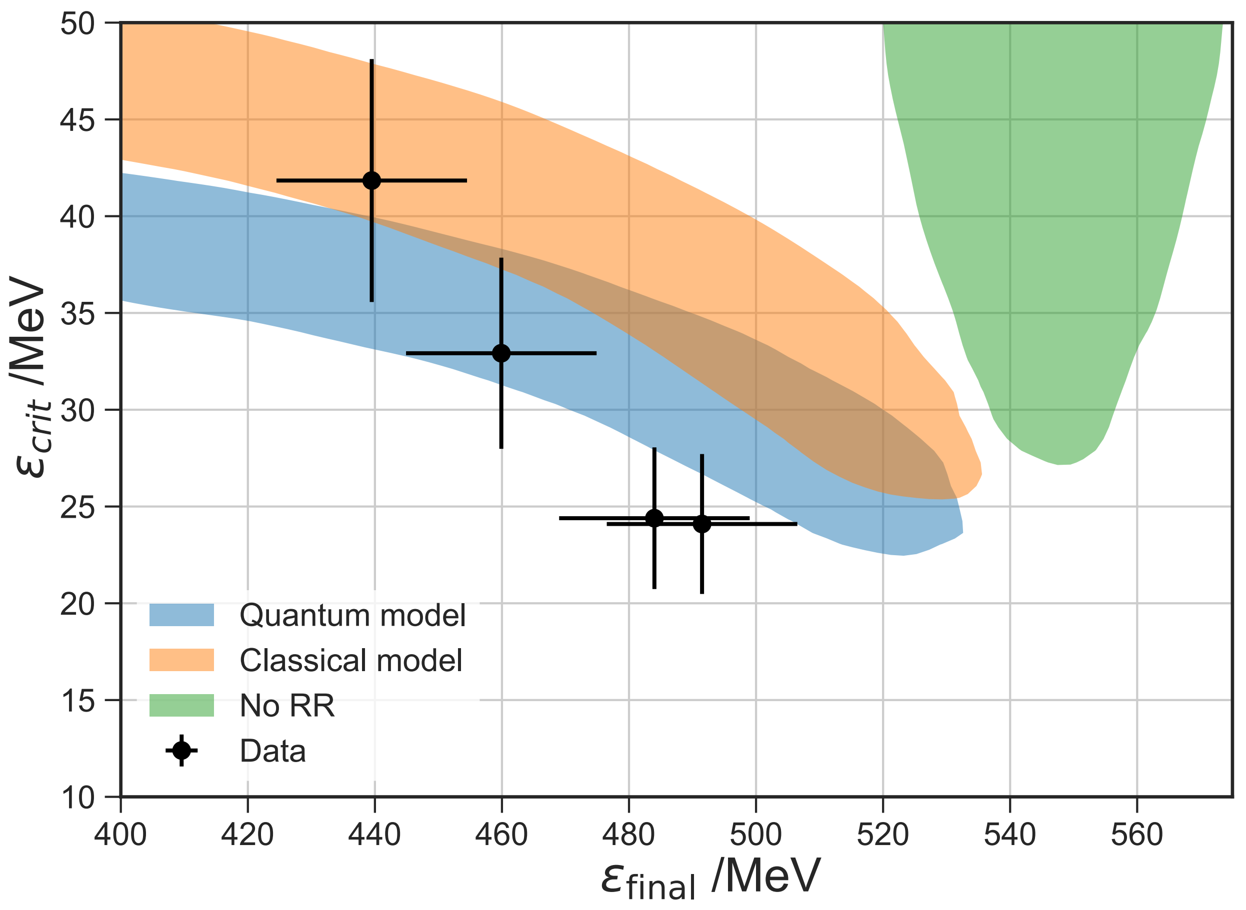
Comparing data to theoretical models

- No radiation reaction
  - excluded
- Classical (LL)
  - overestimates emission for small energy loss
- Quantum stochastic
  - agreement at 1 sigma level with all data points



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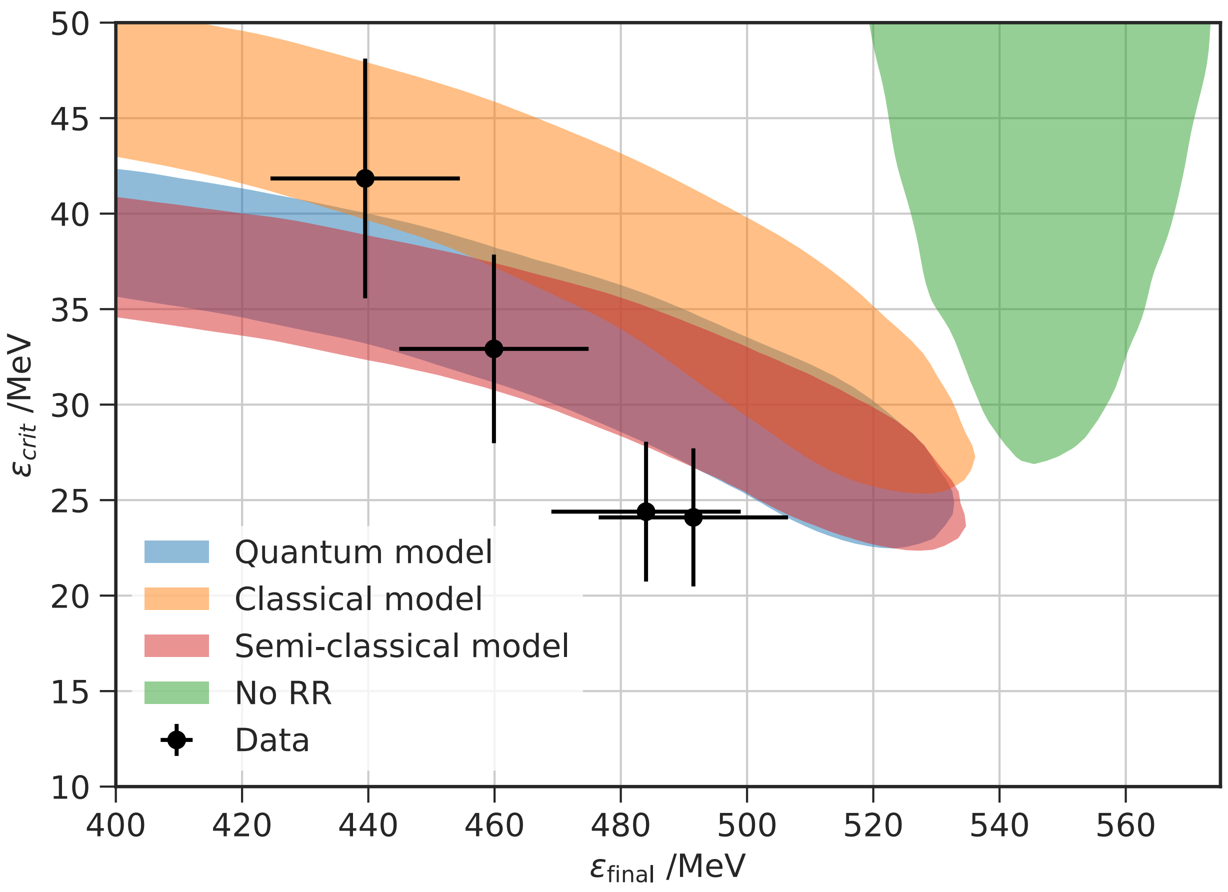
Comparing data to theoretical models

- No radiation reaction
  - excluded
- Classical (LL)
  - overestimates emission for small energy loss
- Quantum stochastic
  - agreement at 1 sigma level with all data points
- Semi-classical
  - for η ≈ 0.1 no difference from stochastic emission model
    - mean energy loss v gamma spectrum



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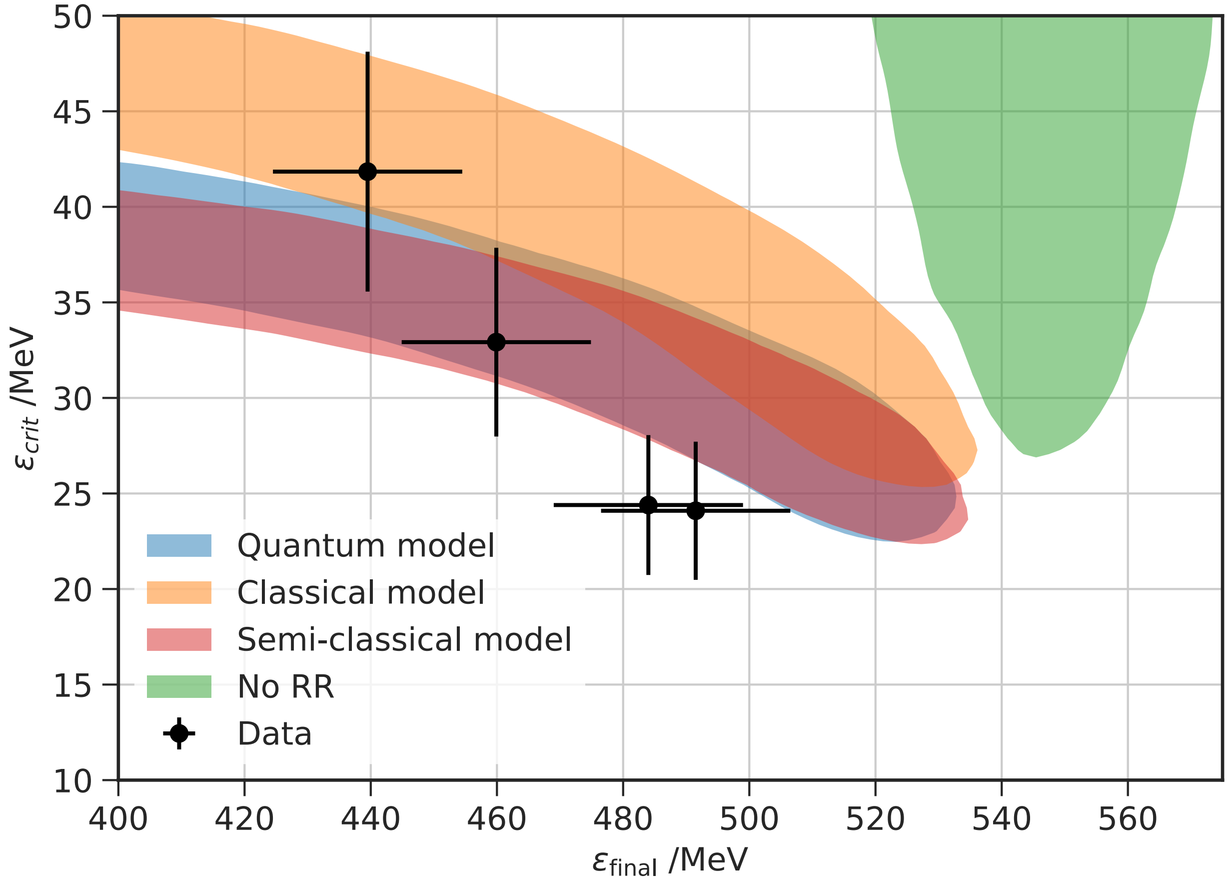
Comparing data to theoretical models



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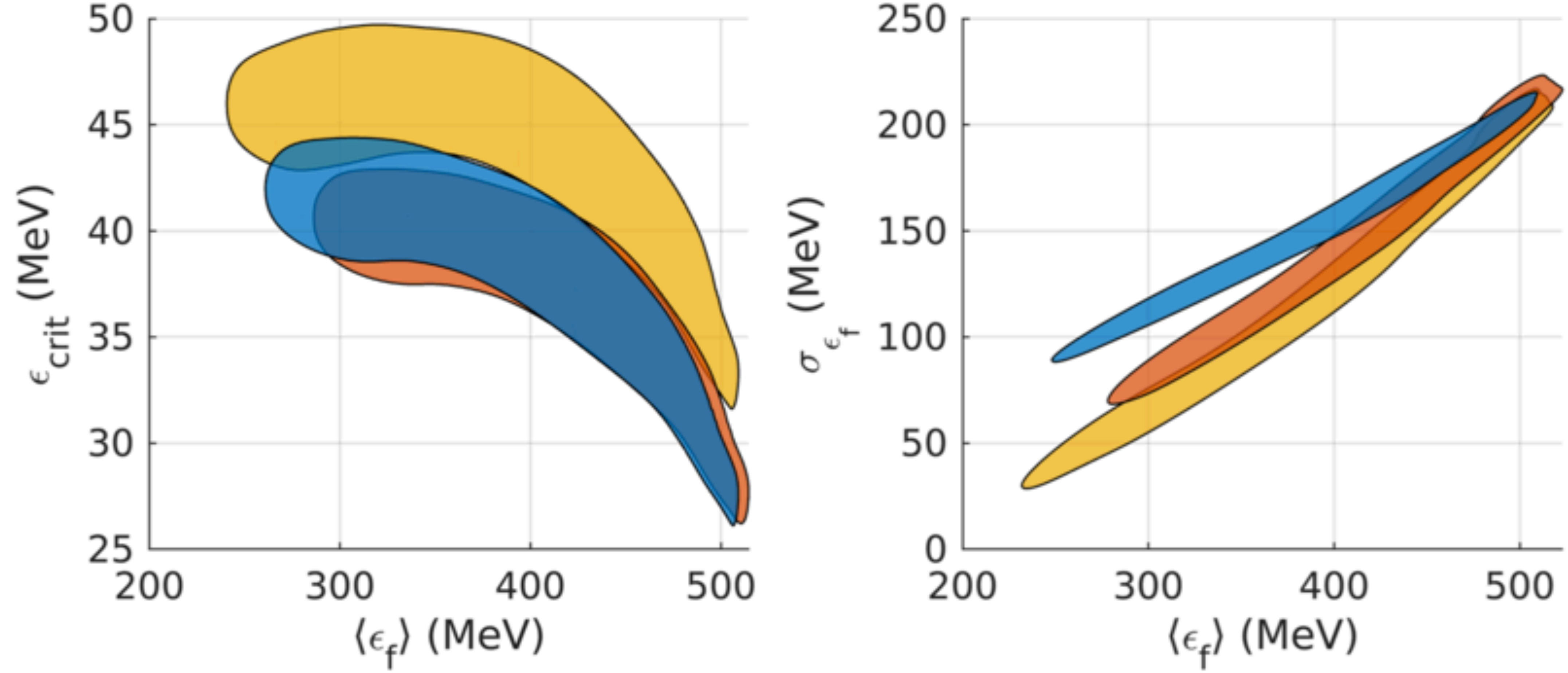
Data consistent with RR occurring

BUT it cannot not distinguish between models

*it does favour quantum/semi-classical over classical, but not significantly

Distinguishing between Radiation Reaction models

C Arran PPCF 2019



- Easier to distinguish if we look at change in shape of electron beam, not just energy loss
- Easier to distinguish at higher electron energy / laser intensity

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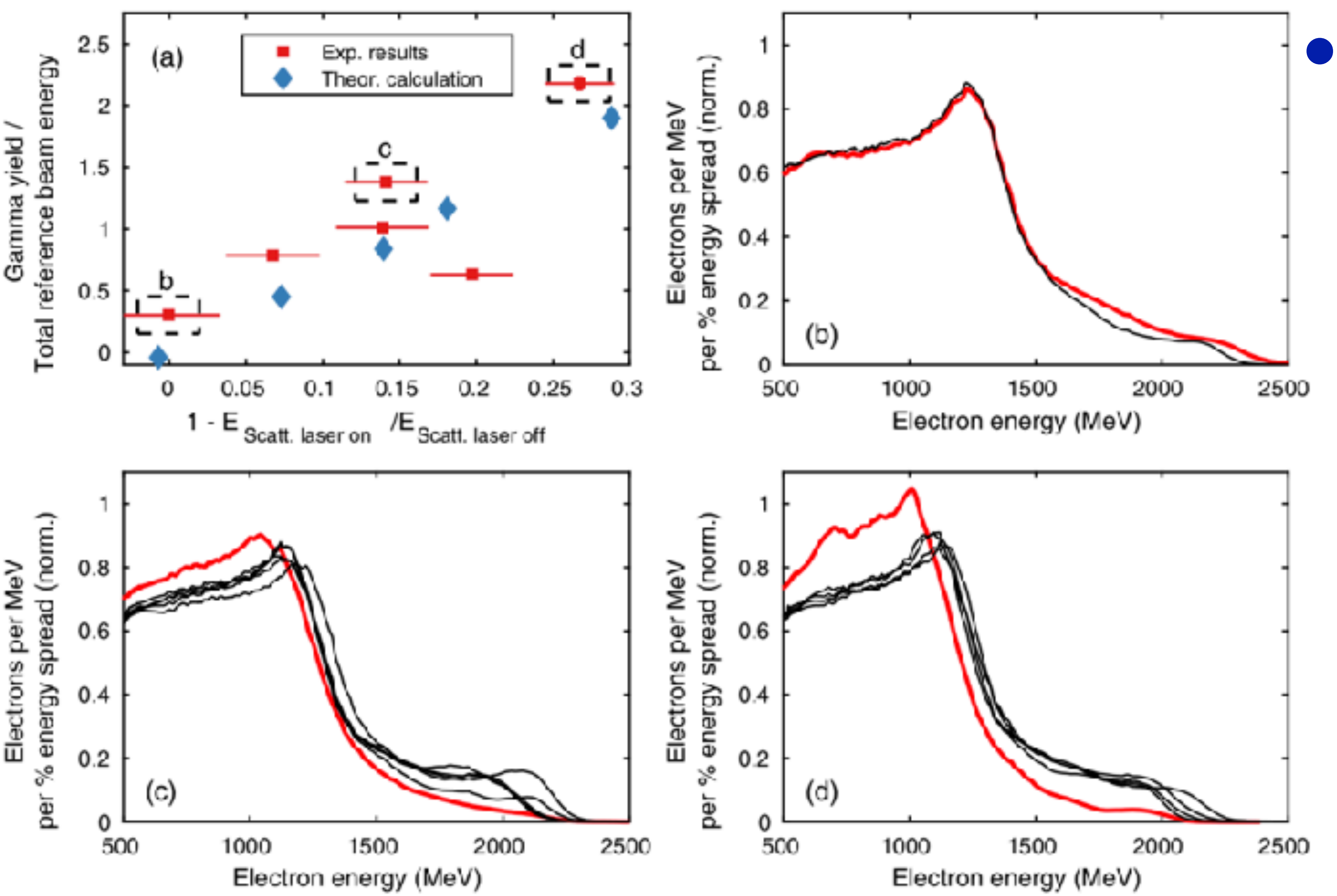
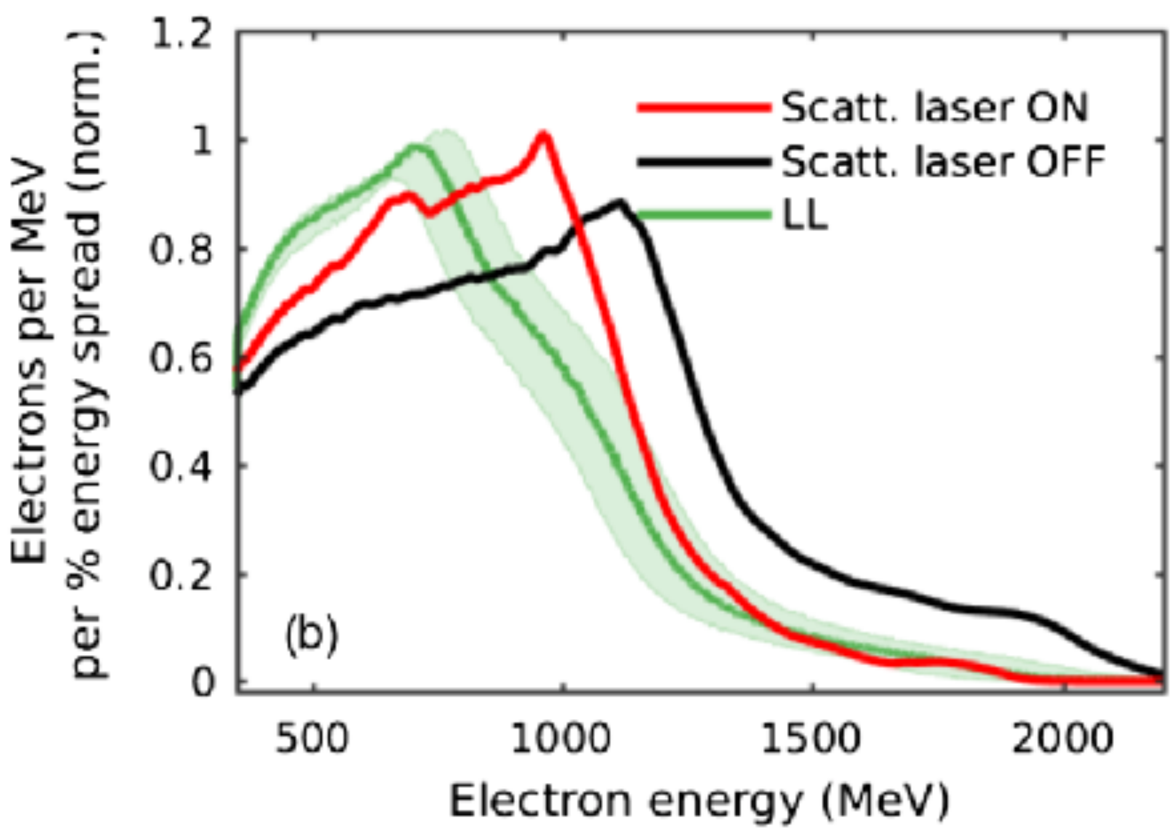
Distinguishing between Radiation Reaction models



K Poder et al PRX 2018

- Higher energy beams, broad energy spread
  - stable shape from gas cell target on Gemini
  - allows comparison of collision shots with nulls under same conditions

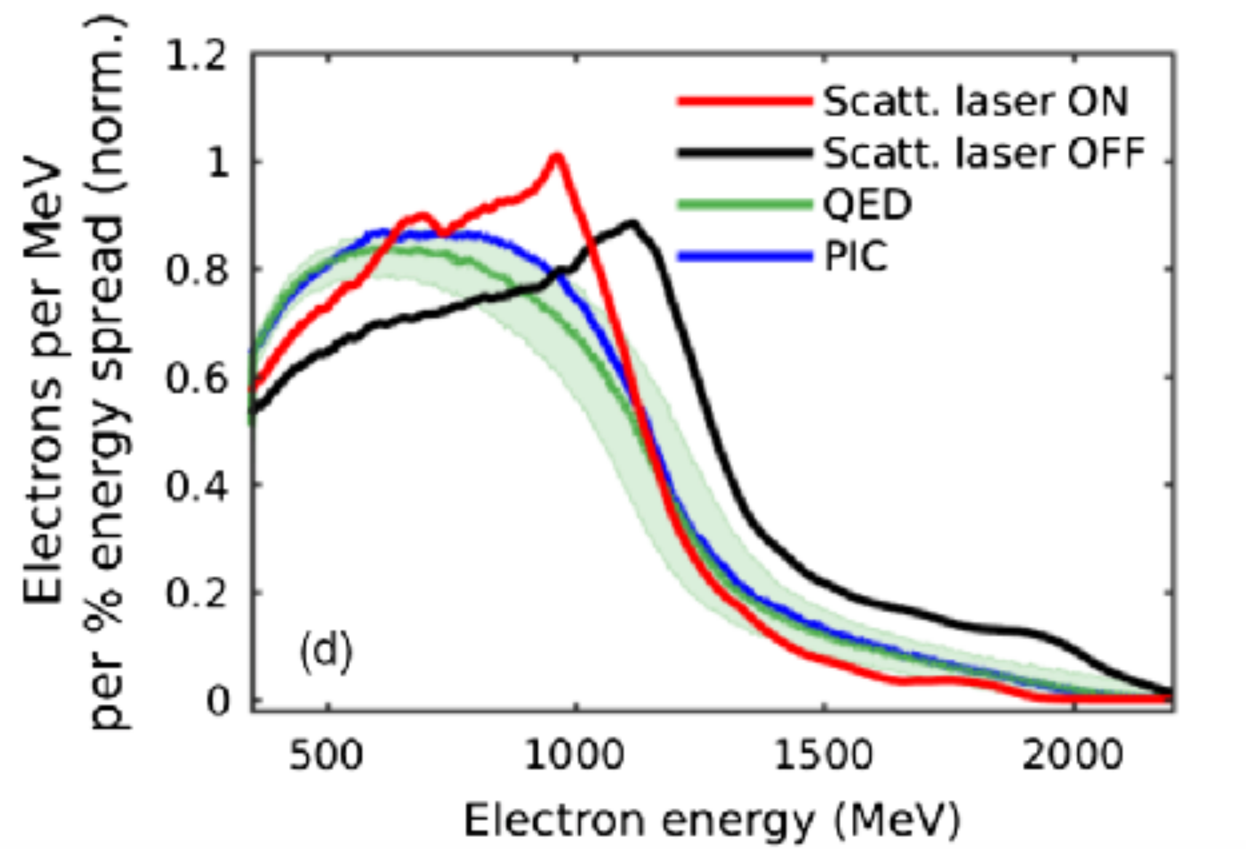
Distinguishing between Radiation Reaction models



K Poder et al PRX 2018

- Calculate change in spectral shape for highest intensity collision
  - Classical (Landau Lifshitz) model doesn't agree

Distinguishing between Radiation Reaction models



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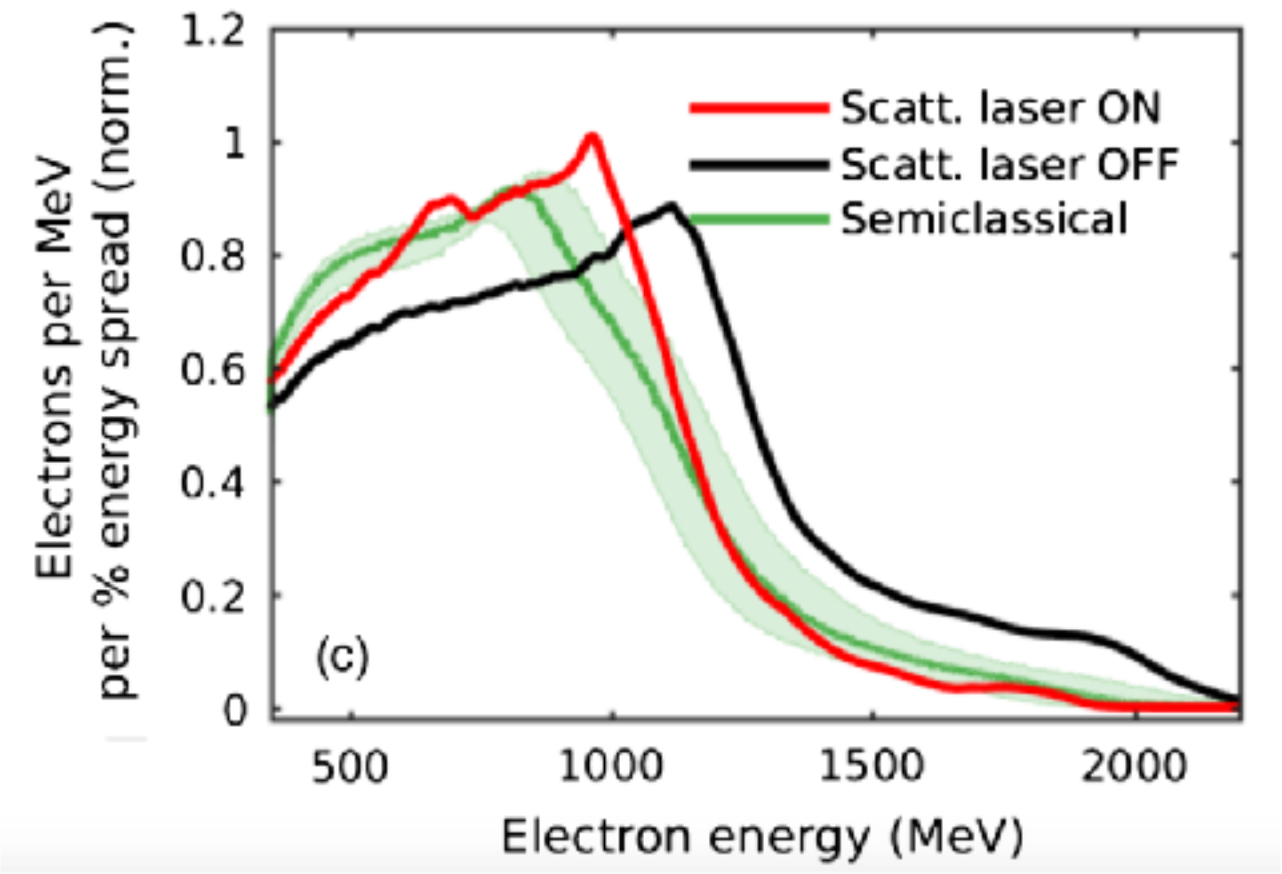
- Calculate change in spectral shape for highest intensity collision
  - » Quantum (stochastic) does better

Distinguishing between Radiation Reaction models



K Poder et al PRX 2018

- Calculate change in spectral shape for highest intensity collision
  - » semi-classical model does best
  - » This is unexpected, the quantum stochastic model is more complete...

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Next steps

- What is next?
  - Definitive determination of quantum nature of strong field radiation reaction
    - Follow-up experiment scheduled in 2021
      - On shot determination of collision intensity
      - More successful collisions
  - Attempt to measure non-linear BW process (gamma ray emitted by RR interacts with the strong laser field)

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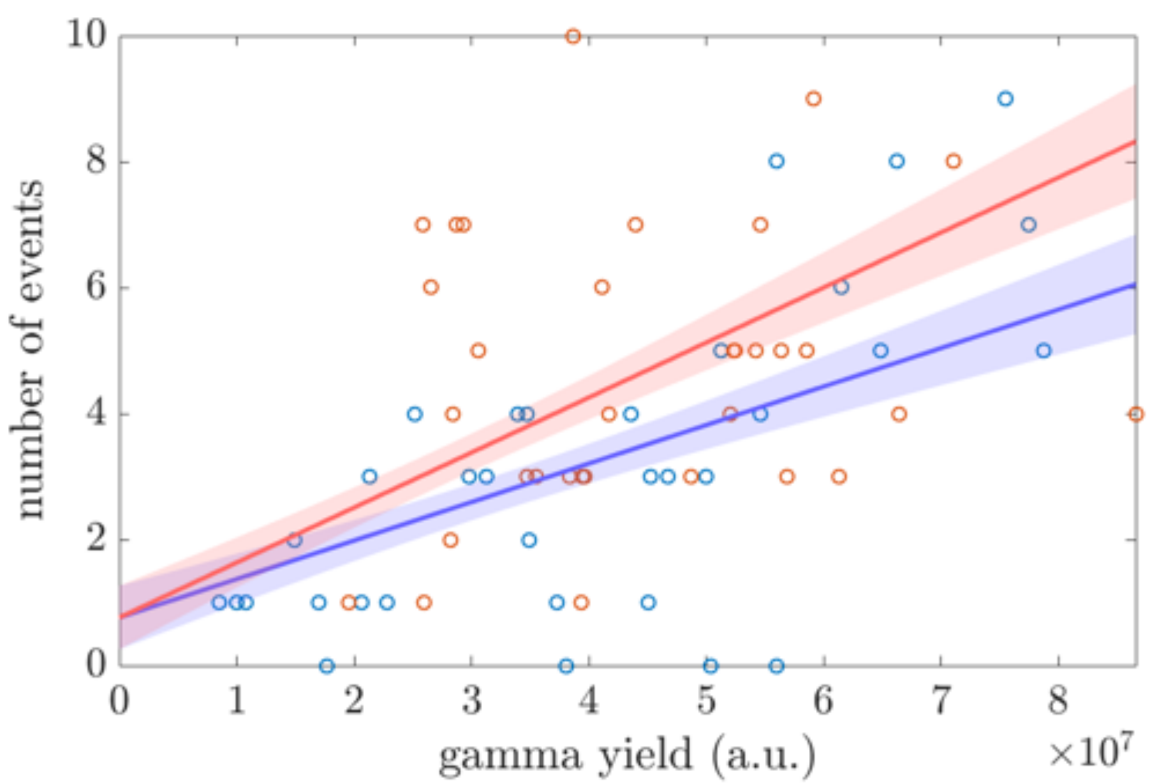
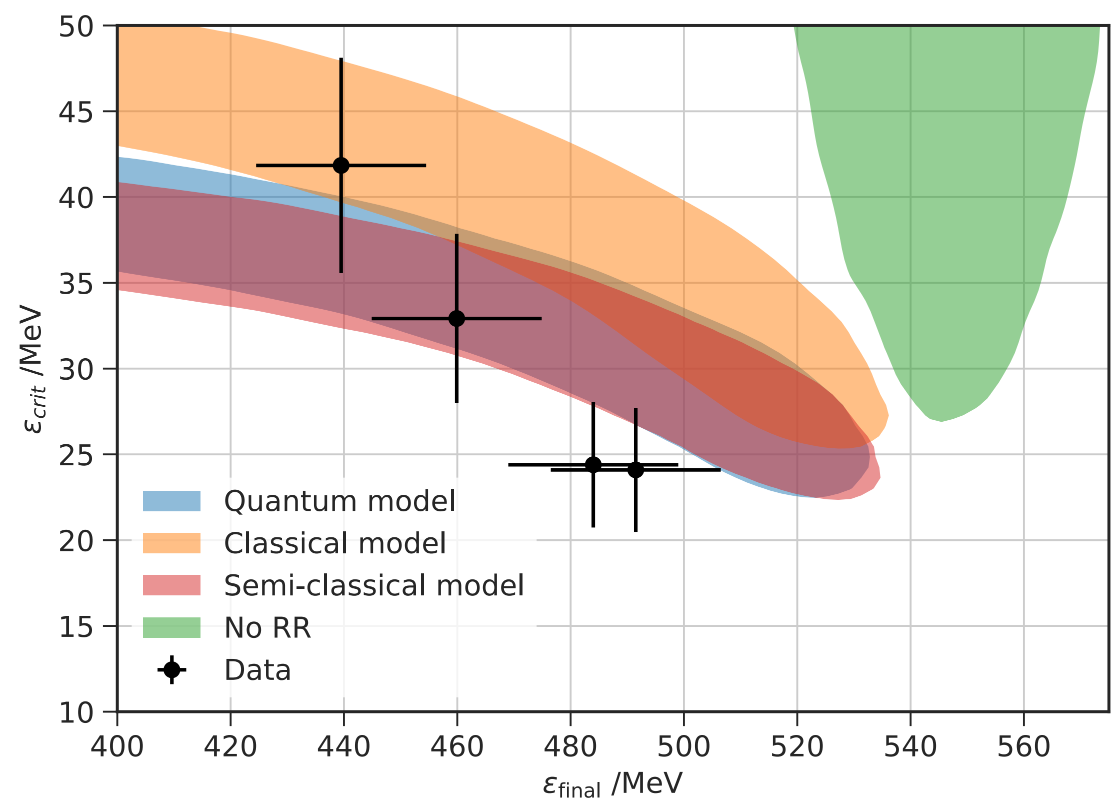
Laser wakefield accelerators as probe of QED physics

- Radiation Reaction experiments with laser-plasma accelerators

- Breit-Wheeler Experiment





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