Using high intensity lasers and laser-wakefield acceleration to explore radiation reaction

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Overview

What is radiation reaction?

Colliding pulse experiments at Gemini

- Experiment A: Cole et al, PRX **8** (2018)
- Experiment B: Poder et al, PRX **8** (2018)

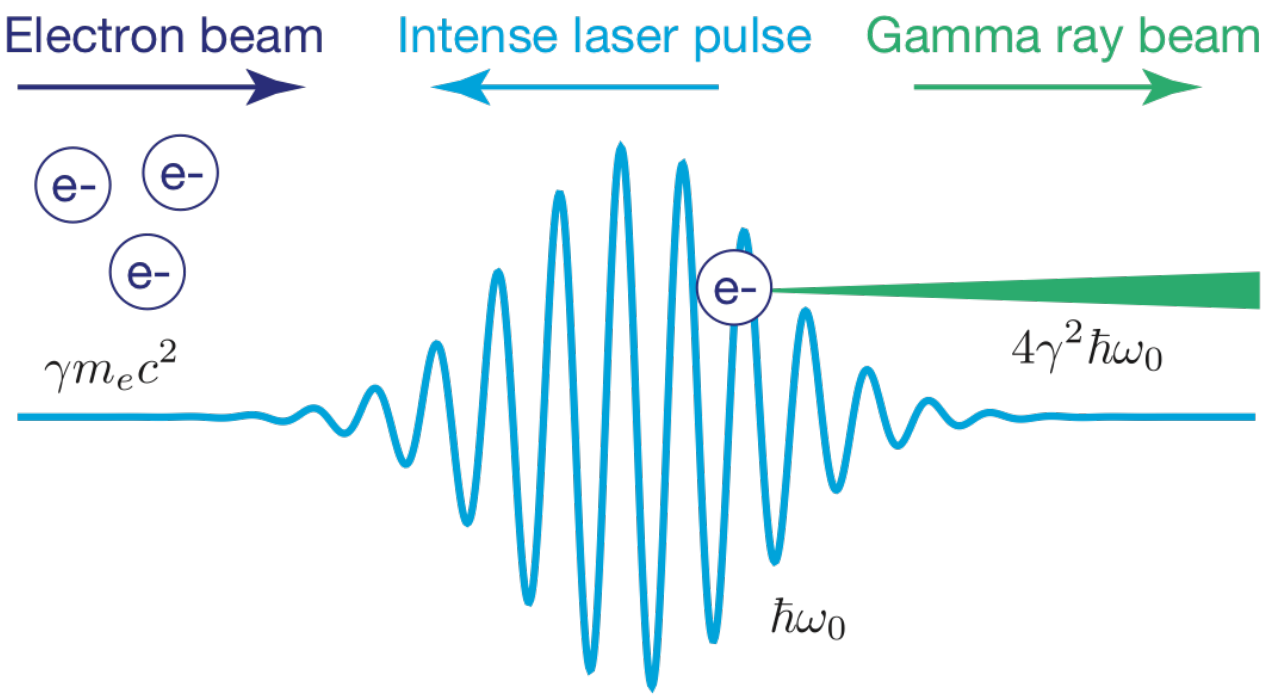
Conclusion

What is radiation reaction?

Radiation reaction is negligible for weak interaction

Lorentz force

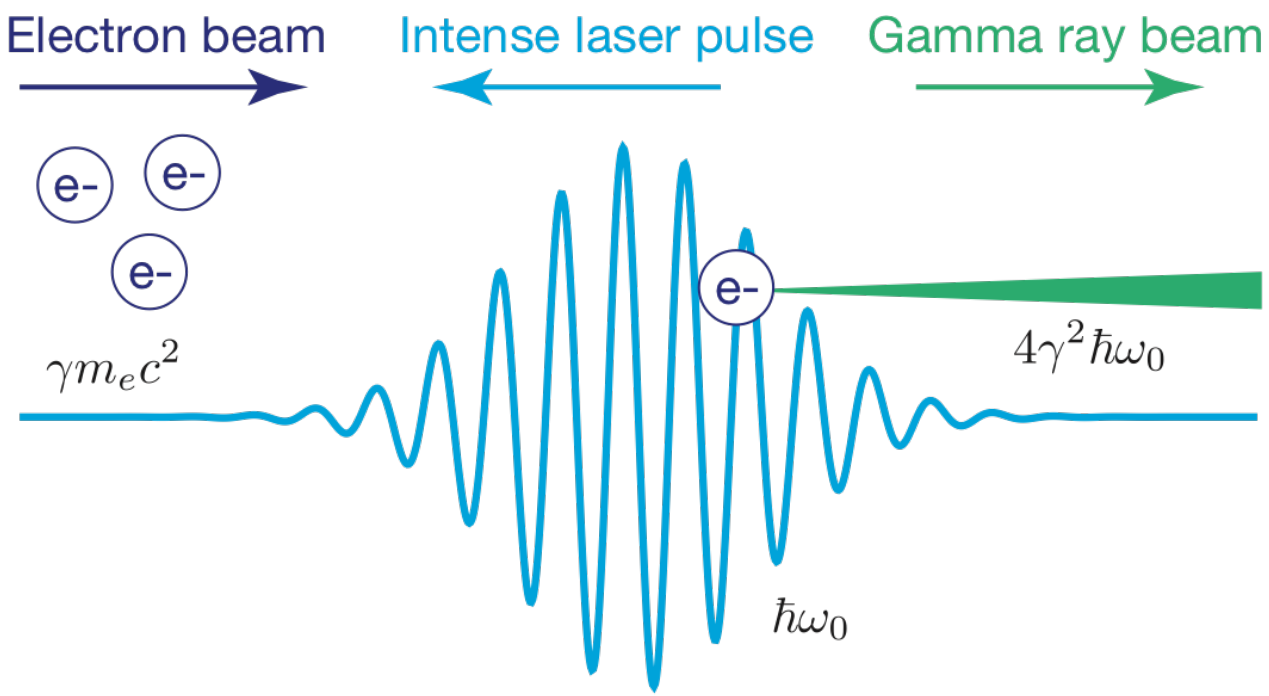
$$\frac{\mathrm{d}\vec{p}}{\mathrm{d}t} = q\left(\vec{E} + \vec{v} \times \vec{B}\right) \tag{1}$$



High energy/intensity lead to significant energy losses

Lorentz force with synchrotron radiation

$$\frac{\mathrm{d}\vec{p}}{\mathrm{d}t} = q\left(\vec{E} + \vec{v}\times\vec{B}\right) + SR\left(\frac{\mathrm{d}\vec{p}}{\mathrm{d}t}\right) \quad (1)$$



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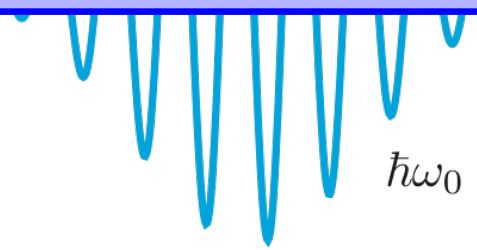
Electron beam Intens[illegible]ulse Gamma ray beam

Caveat

There is no generally accepted solution for the motion of a charge in a field.
$\rightarrow$ This is really a fundamental problem.
All solutions including RR are approximations.

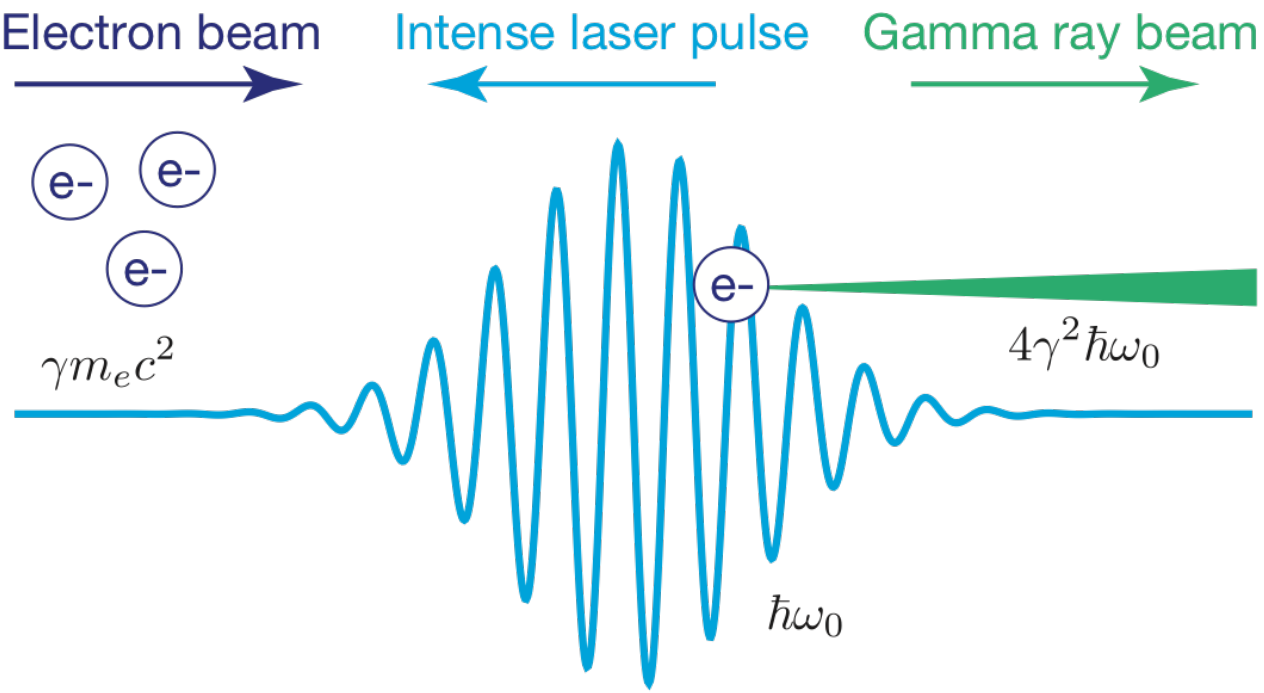


η indicates if classical or quantum description is required

Quantum nonlinearity parameter η for head-on collision

$$\eta = 2\gamma a_0 \hbar\omega_L / m_e c^2 = 2\gamma E_L / E_{crit} \quad (2)$$

e.g. Blackburn *et al.*, *Phys. Rev. Lett.* **112** (2014)



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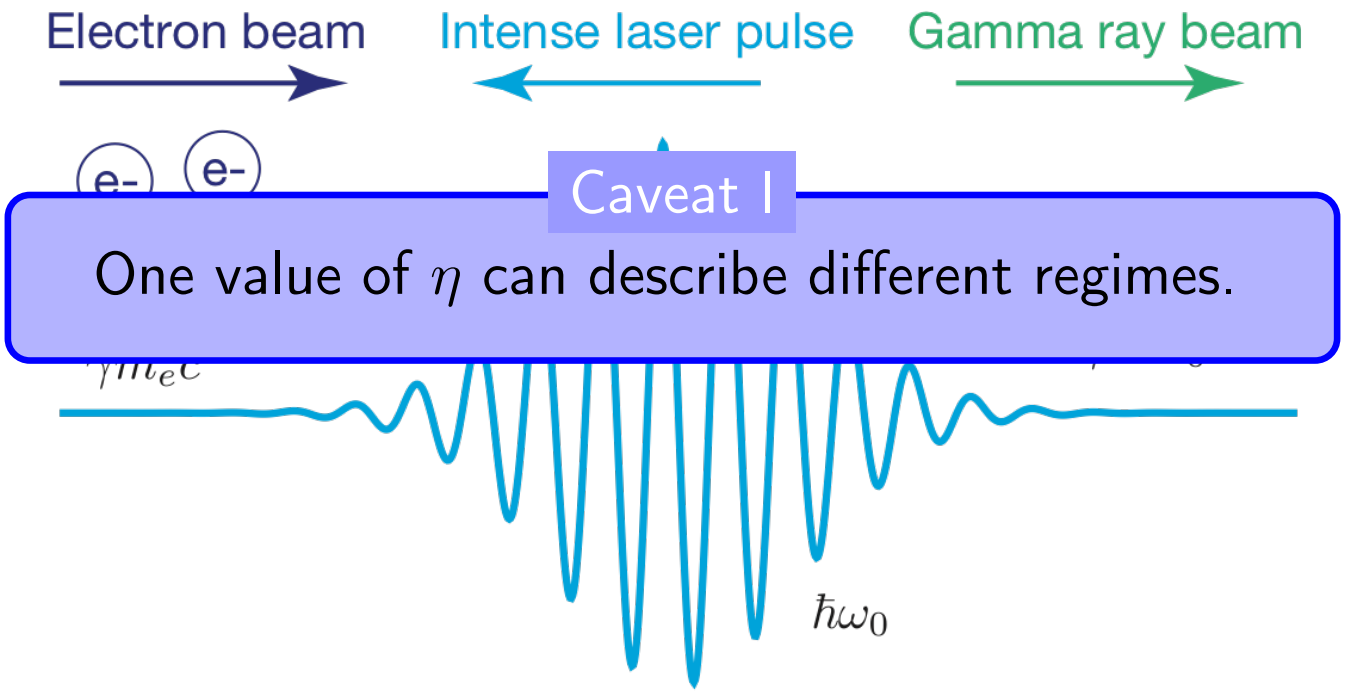

Caveat I

One value of η can describe different regimes.

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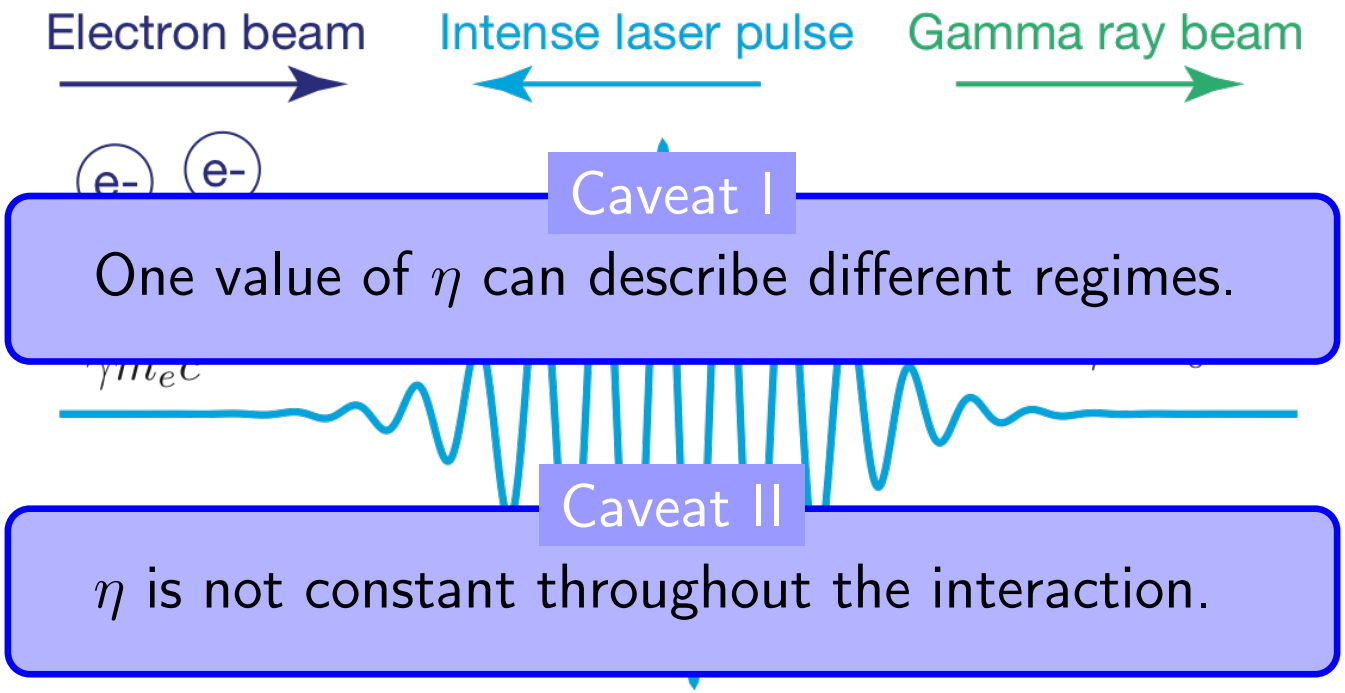
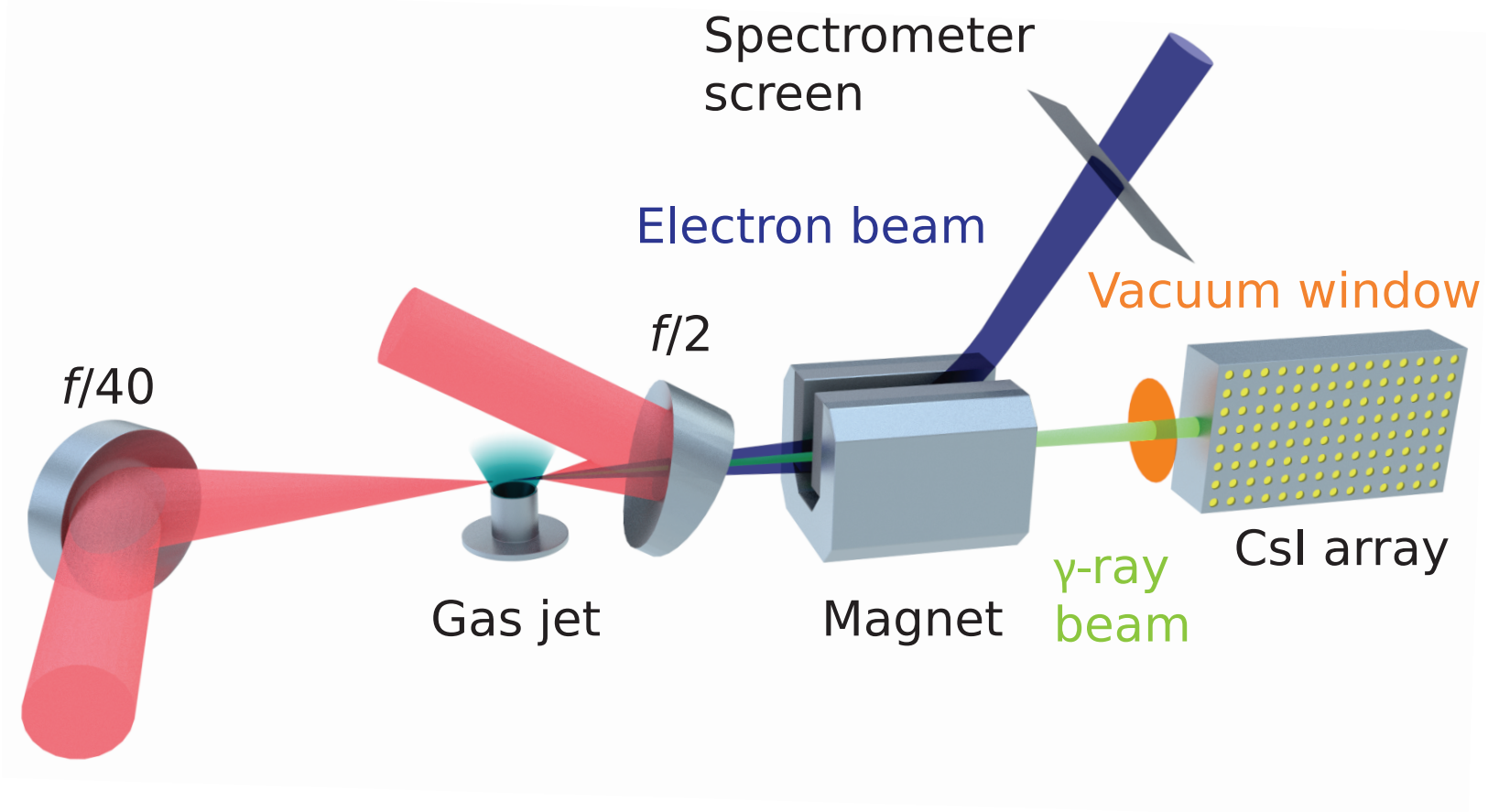


Experimental Setup

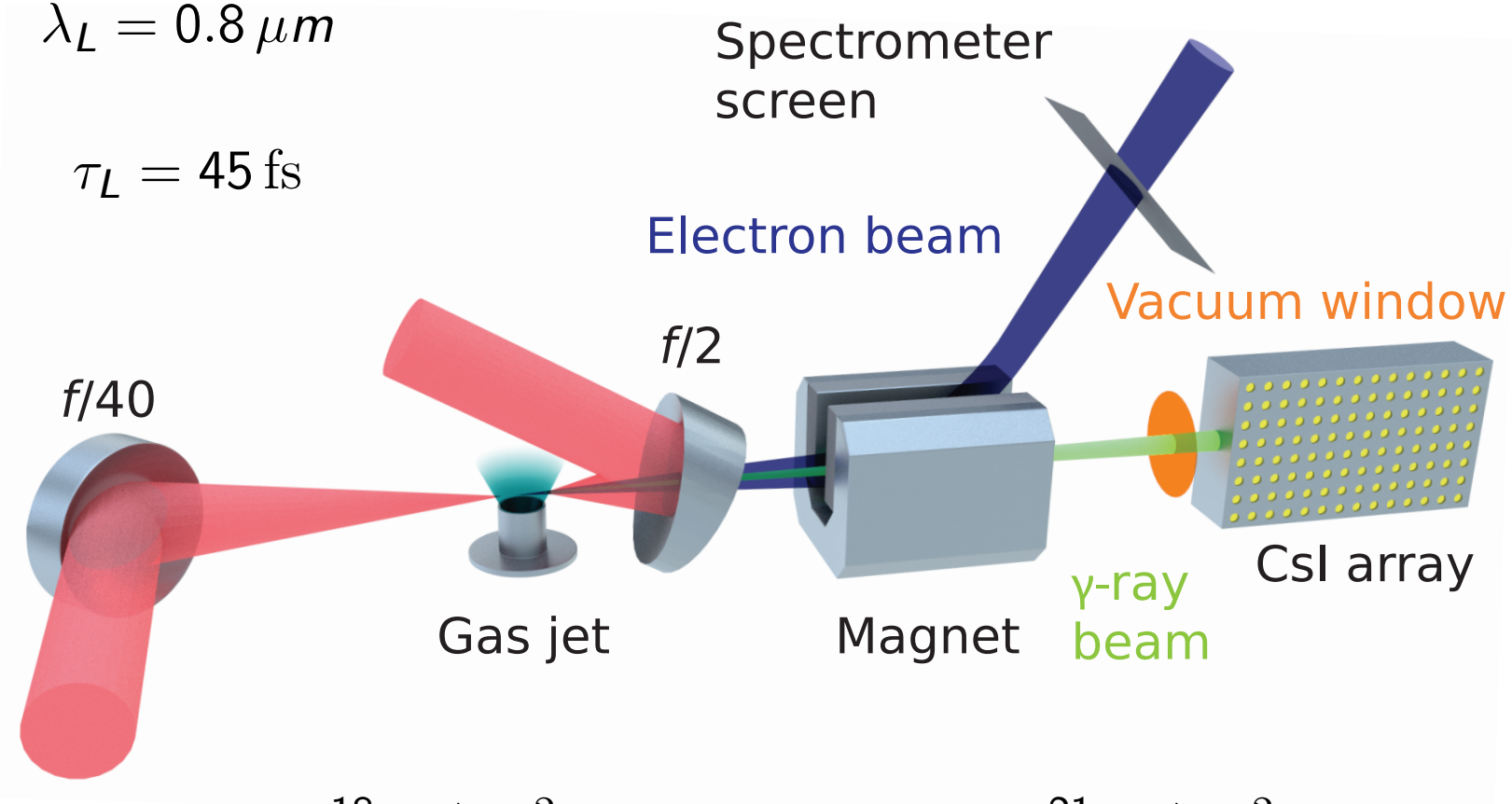
A colliding pulse experiment setup at Astra Gemini



A colliding pulse experiment setup at Astra Gemini

$\lambda_L = 0.8\,\mu m$

$\tau_L = 45\,\mathrm{fs}$



$I_{L,40} = 7.7 \times 10^{18}\mathrm{W/cm^2}$

$a_{0,40} = 1.9$

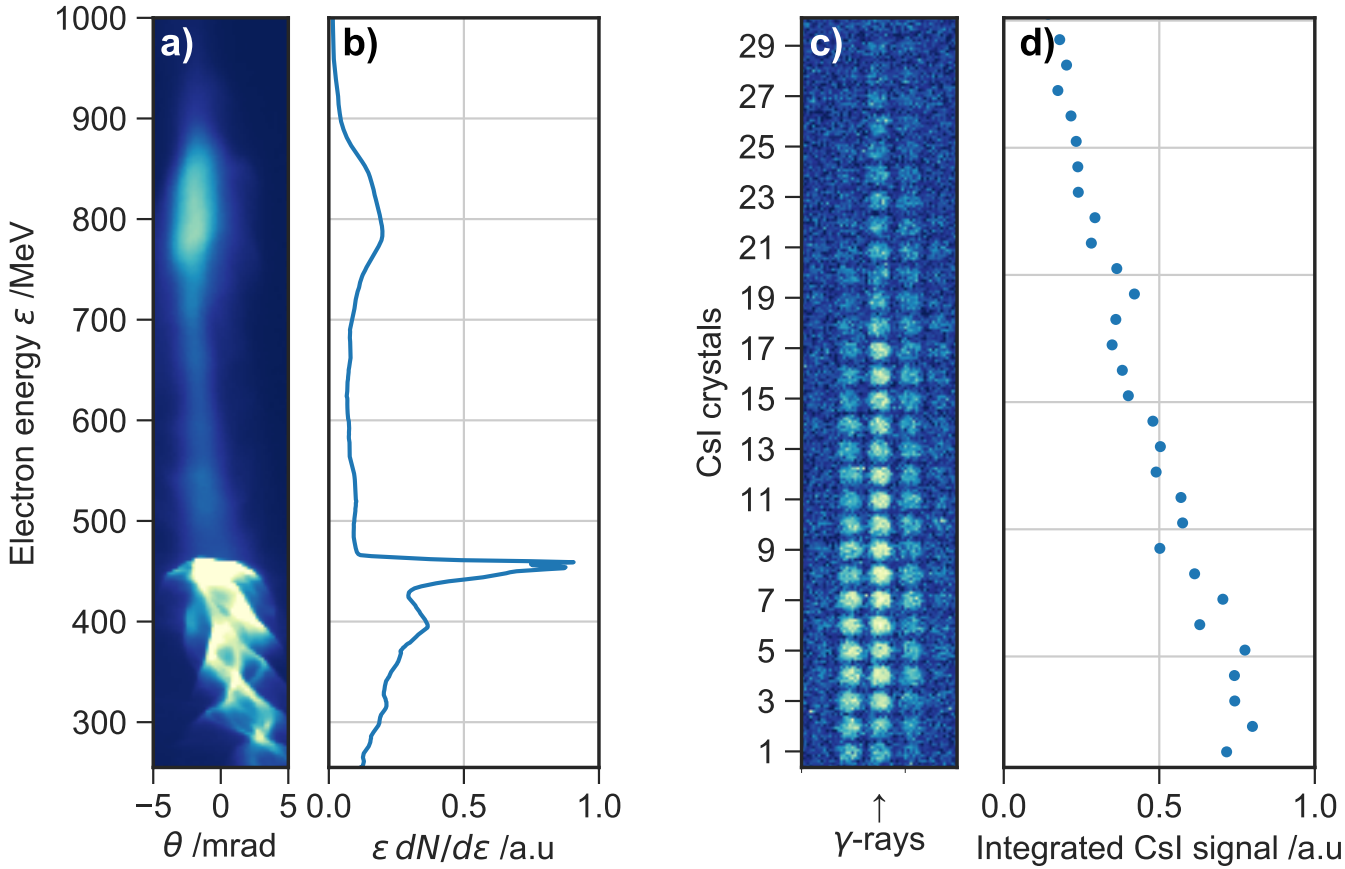
$I_{L,2} = 1.3 \times 10^{21}\mathrm{W/cm^2}$

$a_{0,2} = 24.7$

@ 500 MeV:

$\eta_{max} \approx 0.15$

This provides us with a set of data for each shot



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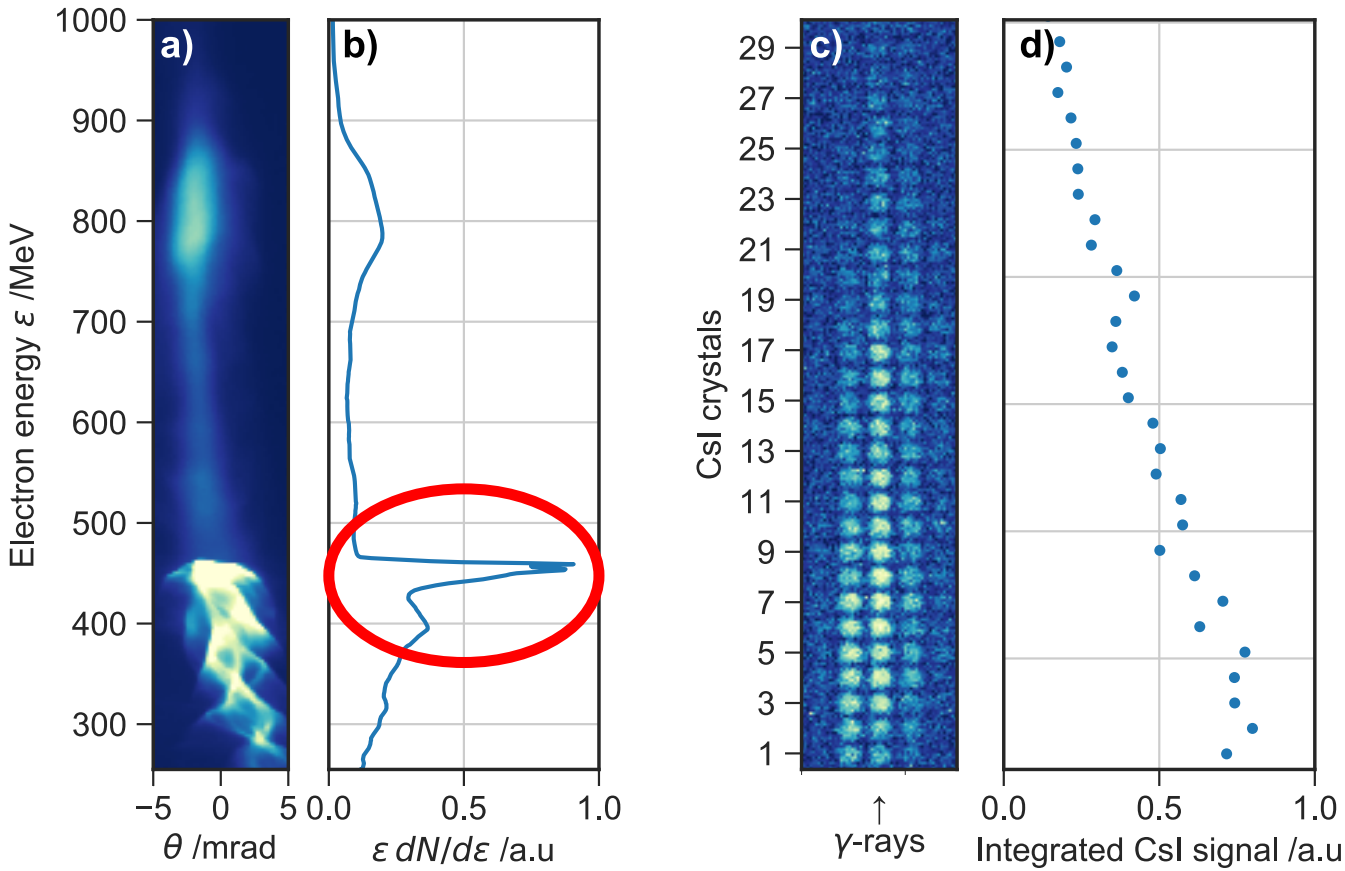
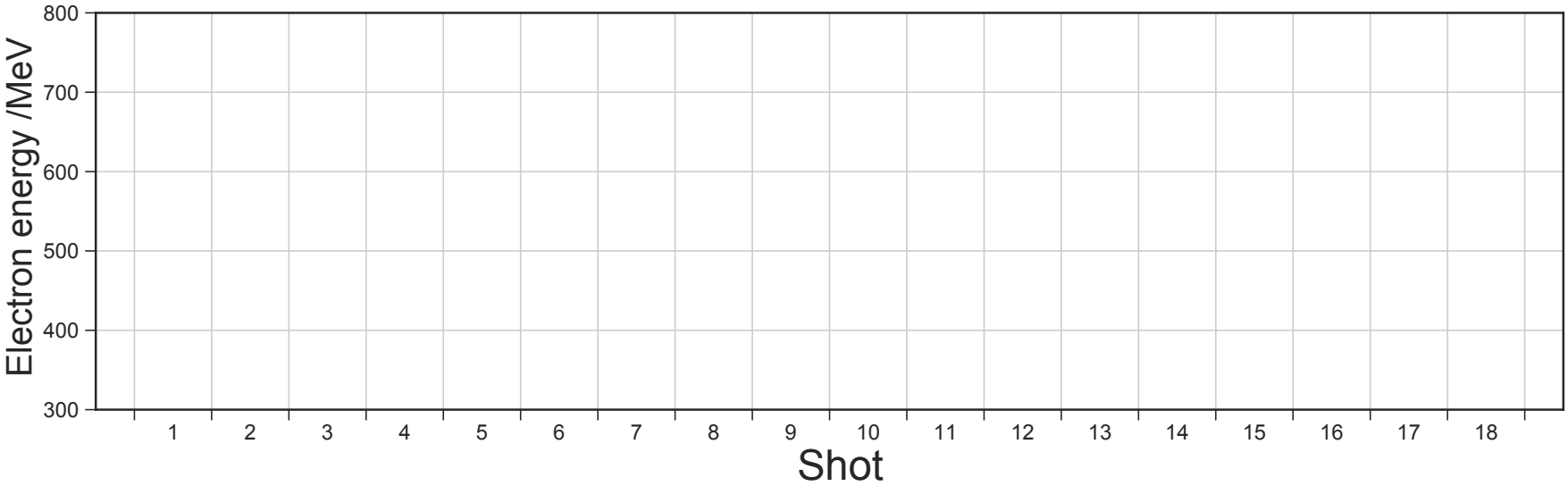


Results

Seeing energy loss in the e-spectrum is not easy



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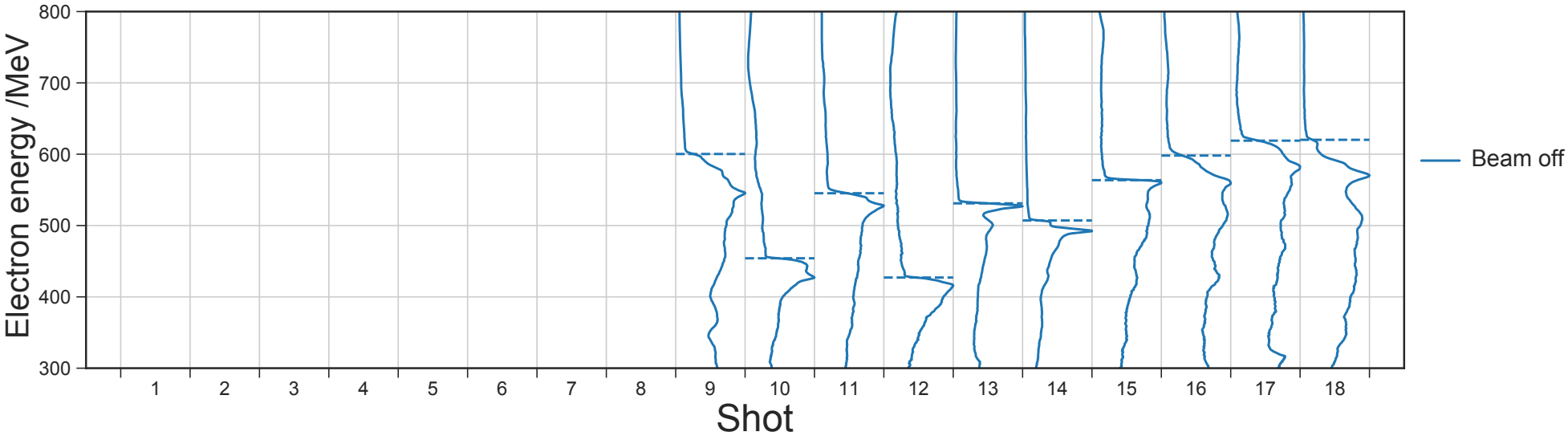

- Shot-to-shot fluctuations of electron energy

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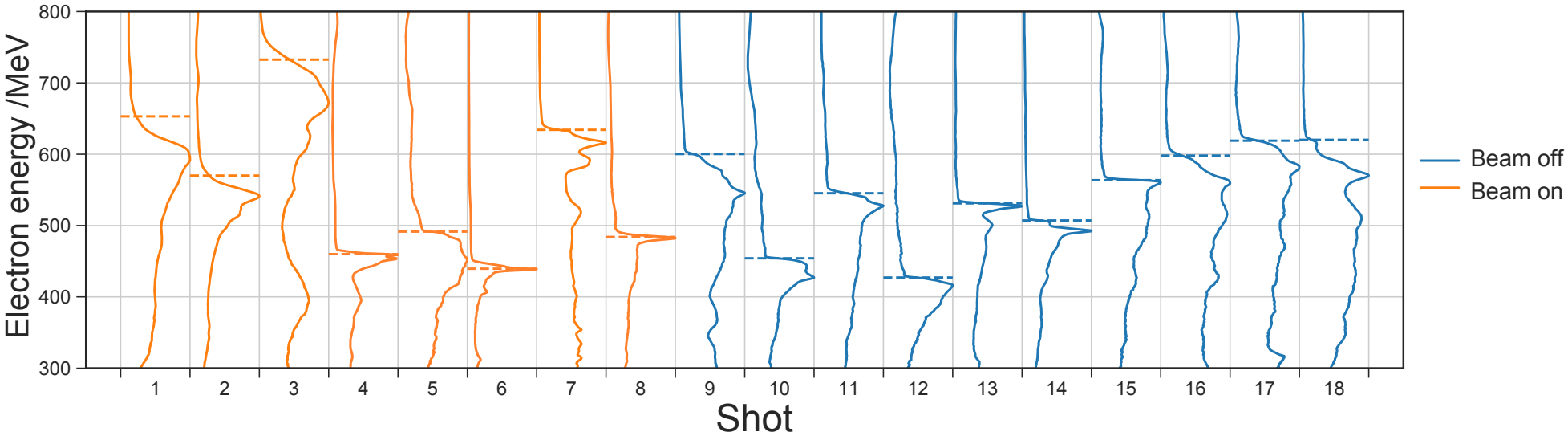
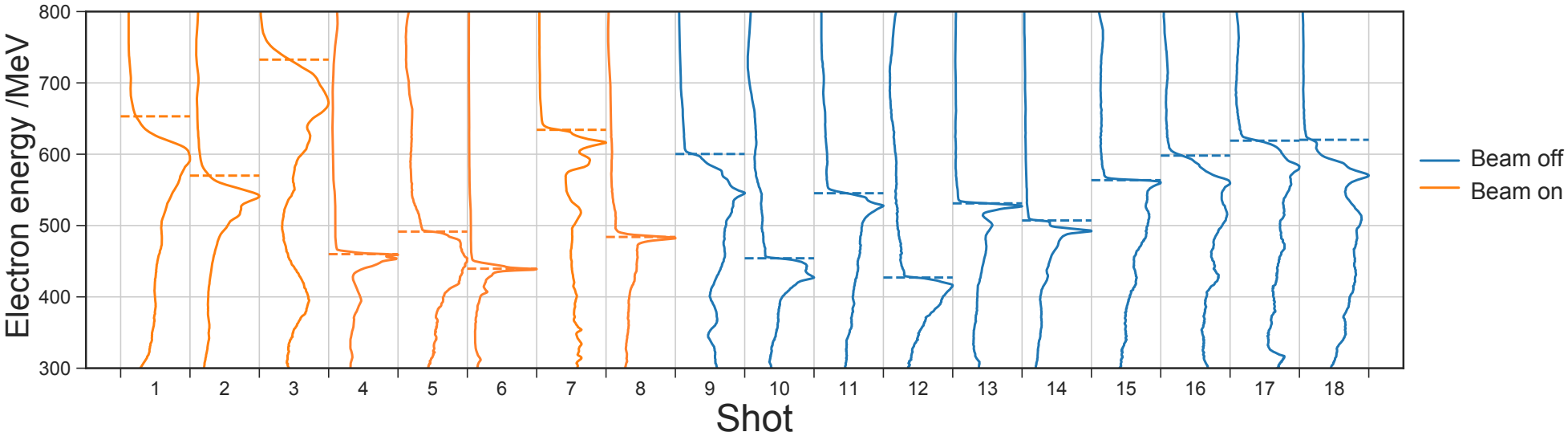


- Shot-to-shot fluctuations of electron energy
- Not all collisions will be successful: considering measured pointing fluctuations $\approx 33\%$ success rate (3 shots) expected

Seeing energy loss in the *e*-spectrum is not easy



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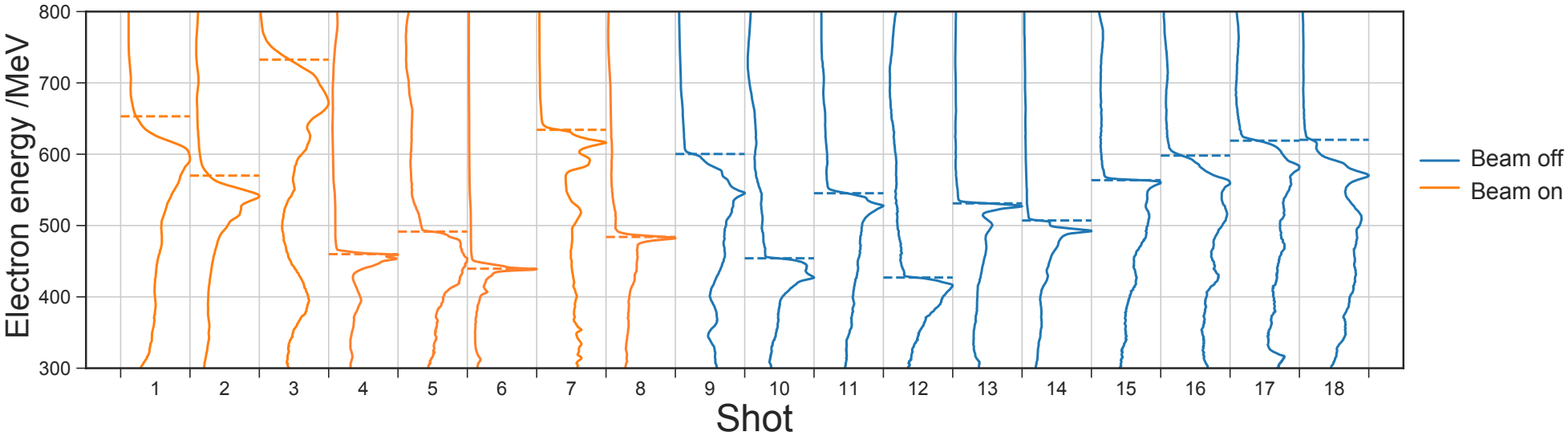
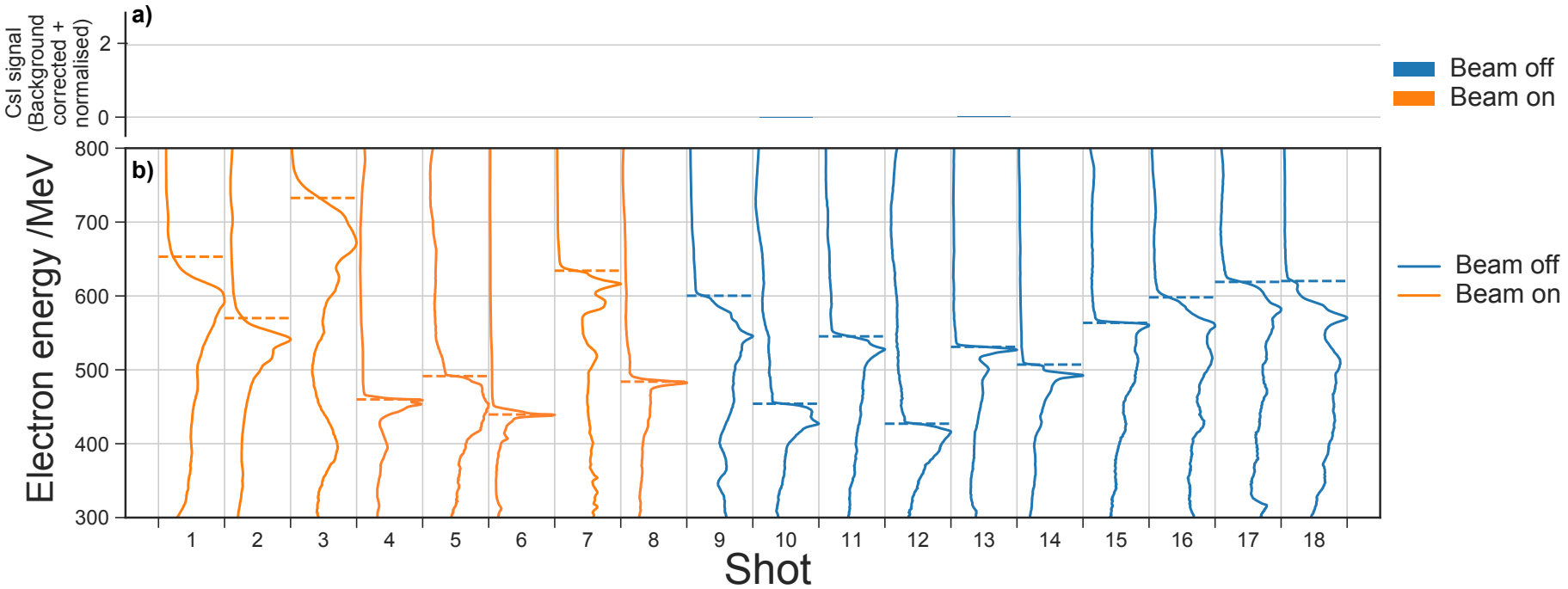


- Shot-to-shot fluctuations of electron energy
- Not all collisions will be successful: considering measured pointing fluctuations $\approx 33\%$ success rate (3 shots) expected
- We need to characterise statistical fluctuations of *e*-energy
- We need a way to identify successful collisions independently

Bright γ signal indicates successful collision



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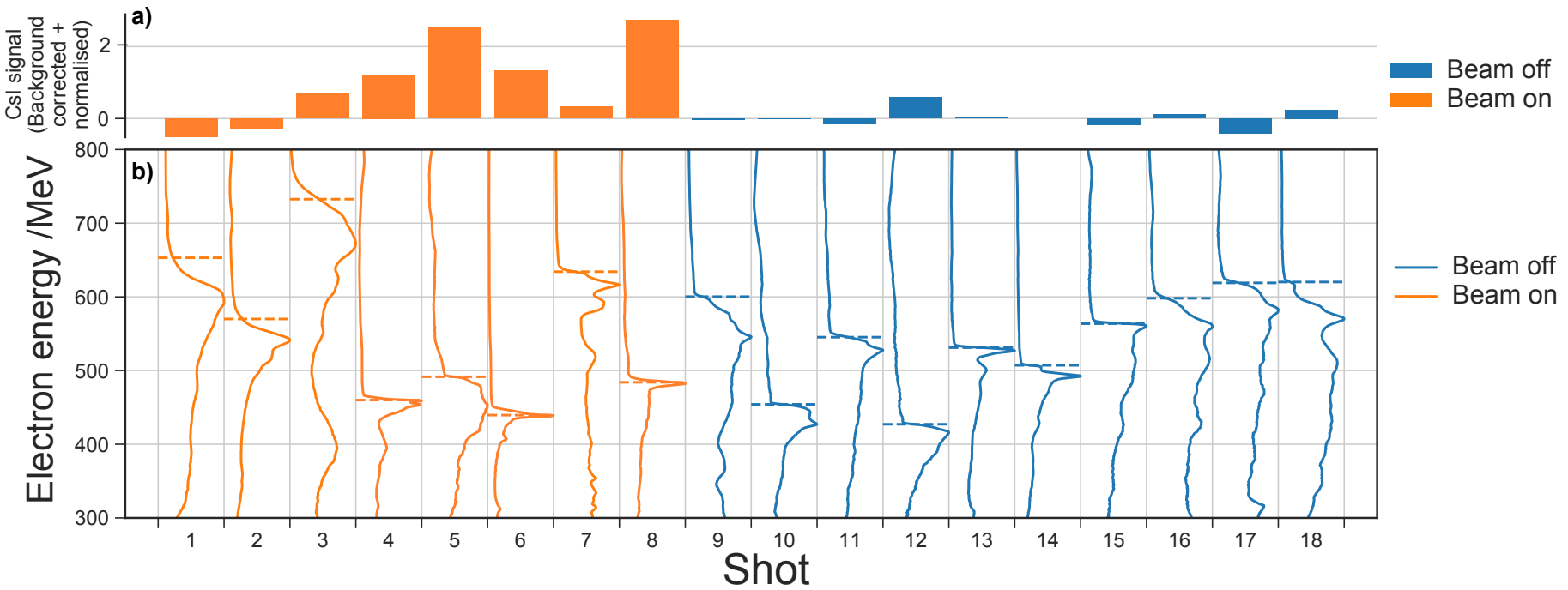

- Total γ signal can be used to identify successful collisions

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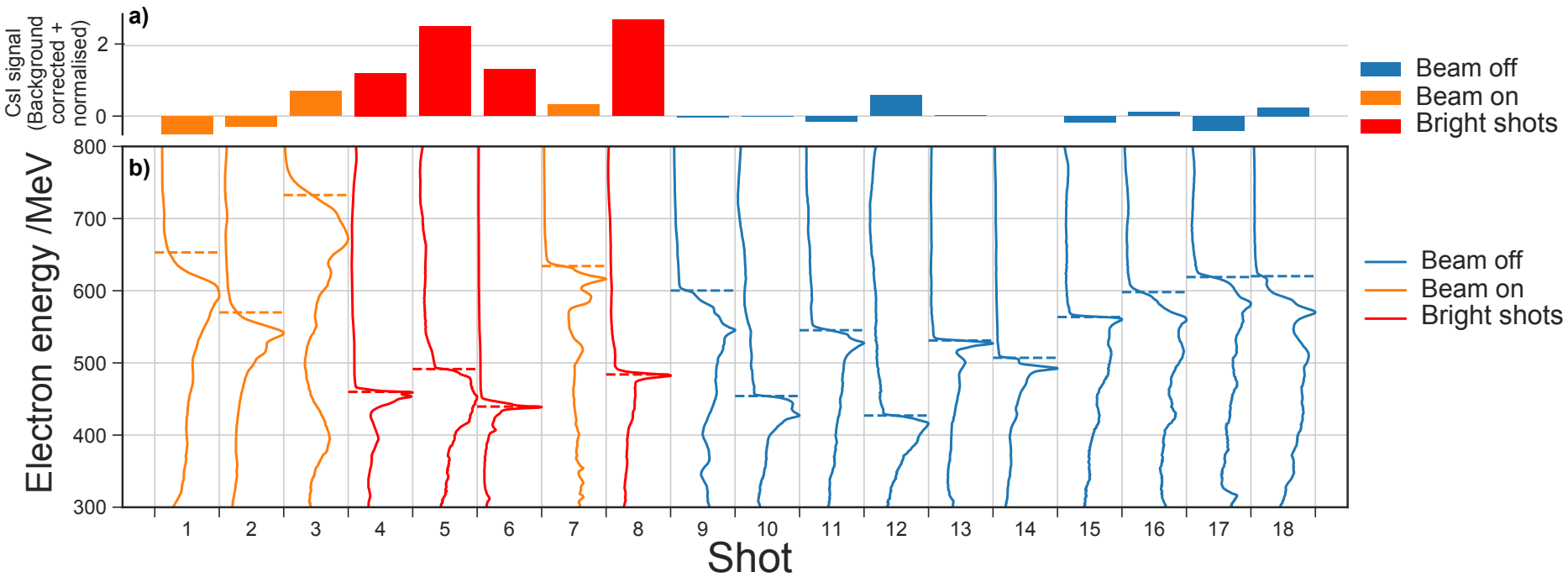

- Total γ signal can be used to identify successful collisions
- 4 out of 8 shots (50%) were successful

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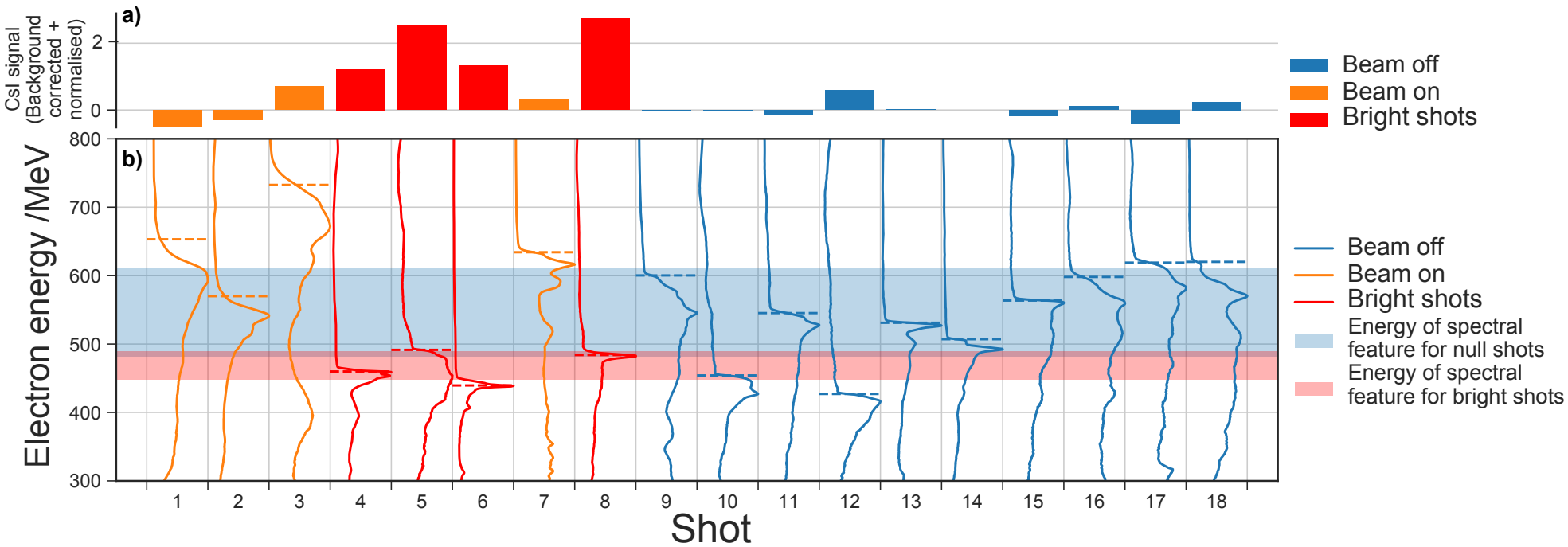
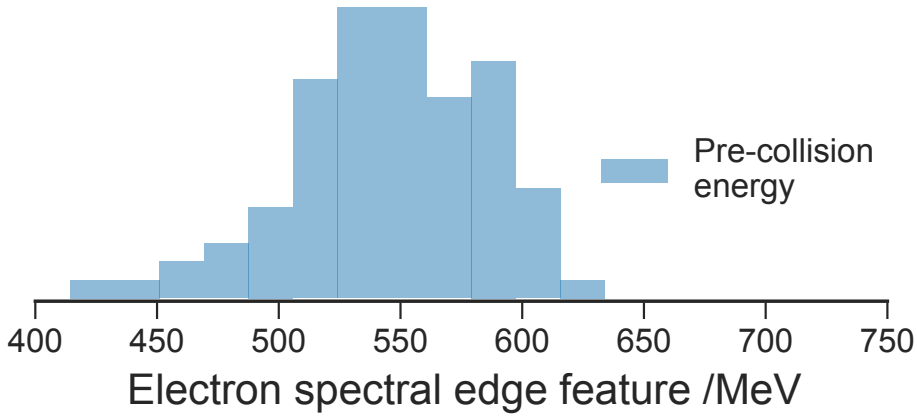


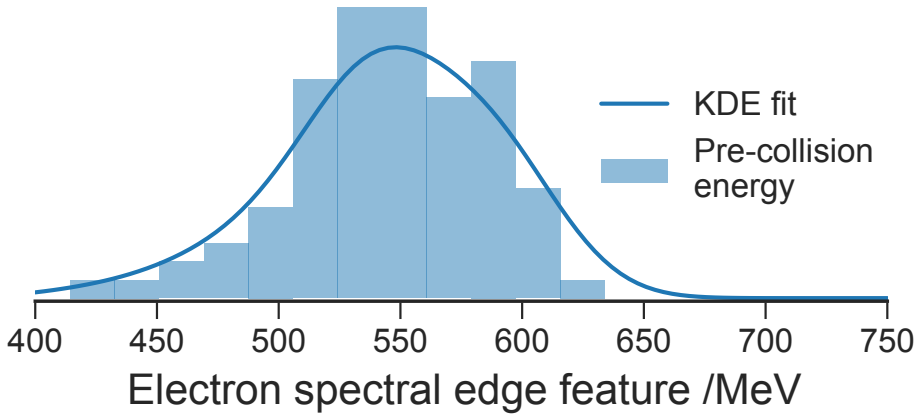
- Total γ signal can be used to identify successful collisions
- 4 out of 8 shots (50%) were successful
- energy is lower in collisions, but is it statistically relevant?

Statistical fluctuation of spectral feature around 550 MeV



Statistical fluctuation of spectral feature around 550 MeV

- The energy of the edge feature follows a normal distribution



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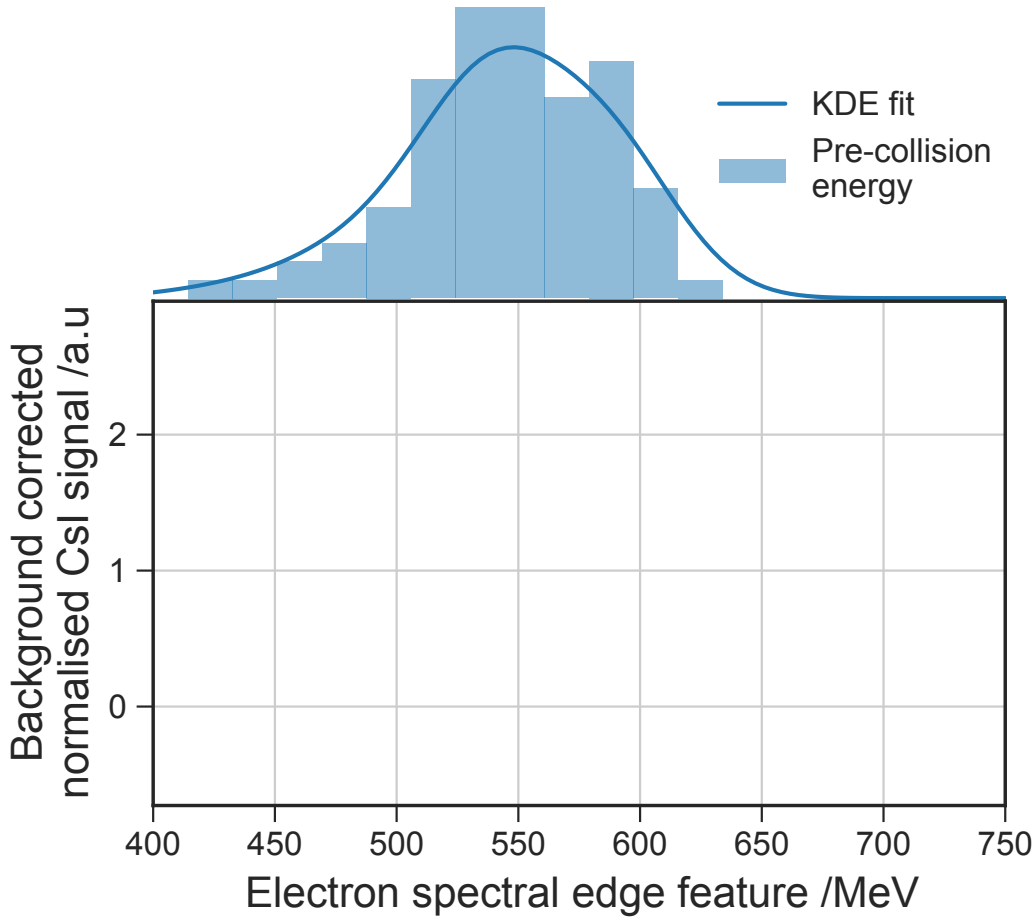

Correlation of the spectral feature and bright γ signal

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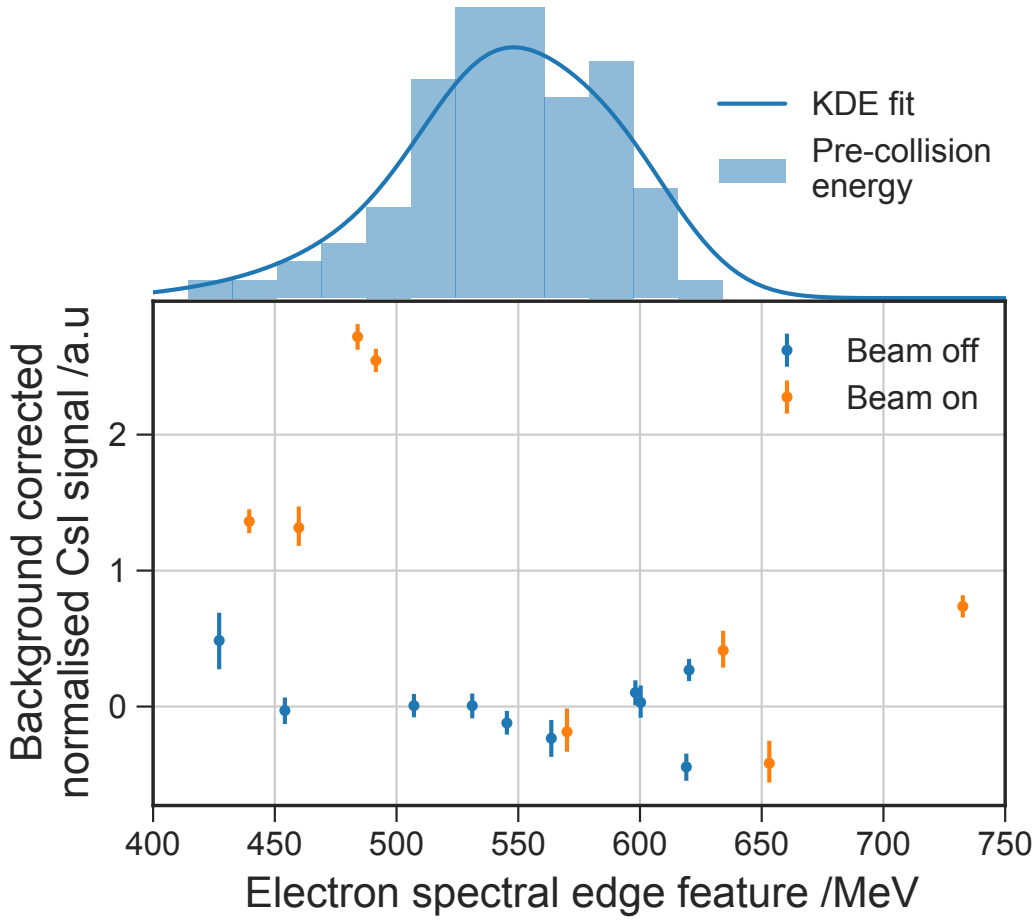
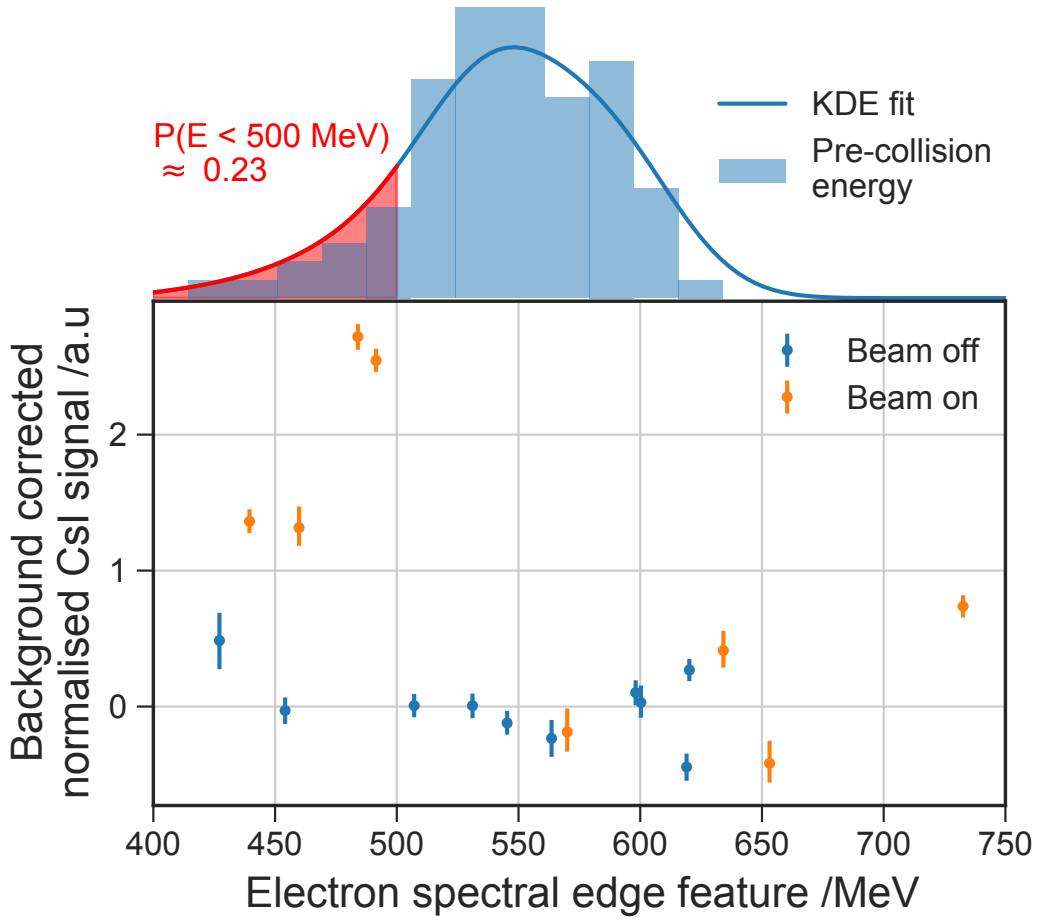


Correlation of the spectral feature and bright γ signal

- The energy of the edge feature follows a normal distribution
- 4 out of 4 successful collisions show $E < 500\,\mathrm{MeV}$
- Probability that this is due to random fluctuations is $P(E < 500\,\mathrm{MeV})^4 \approx 1/350$



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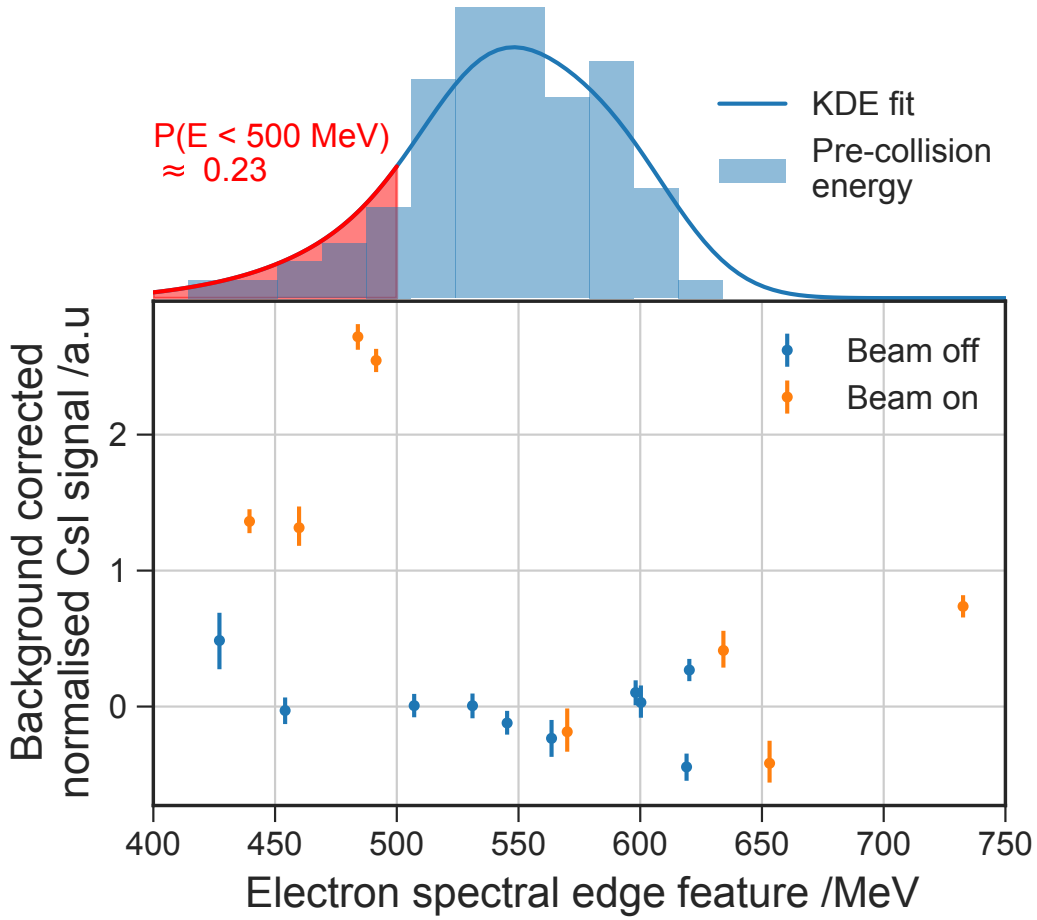
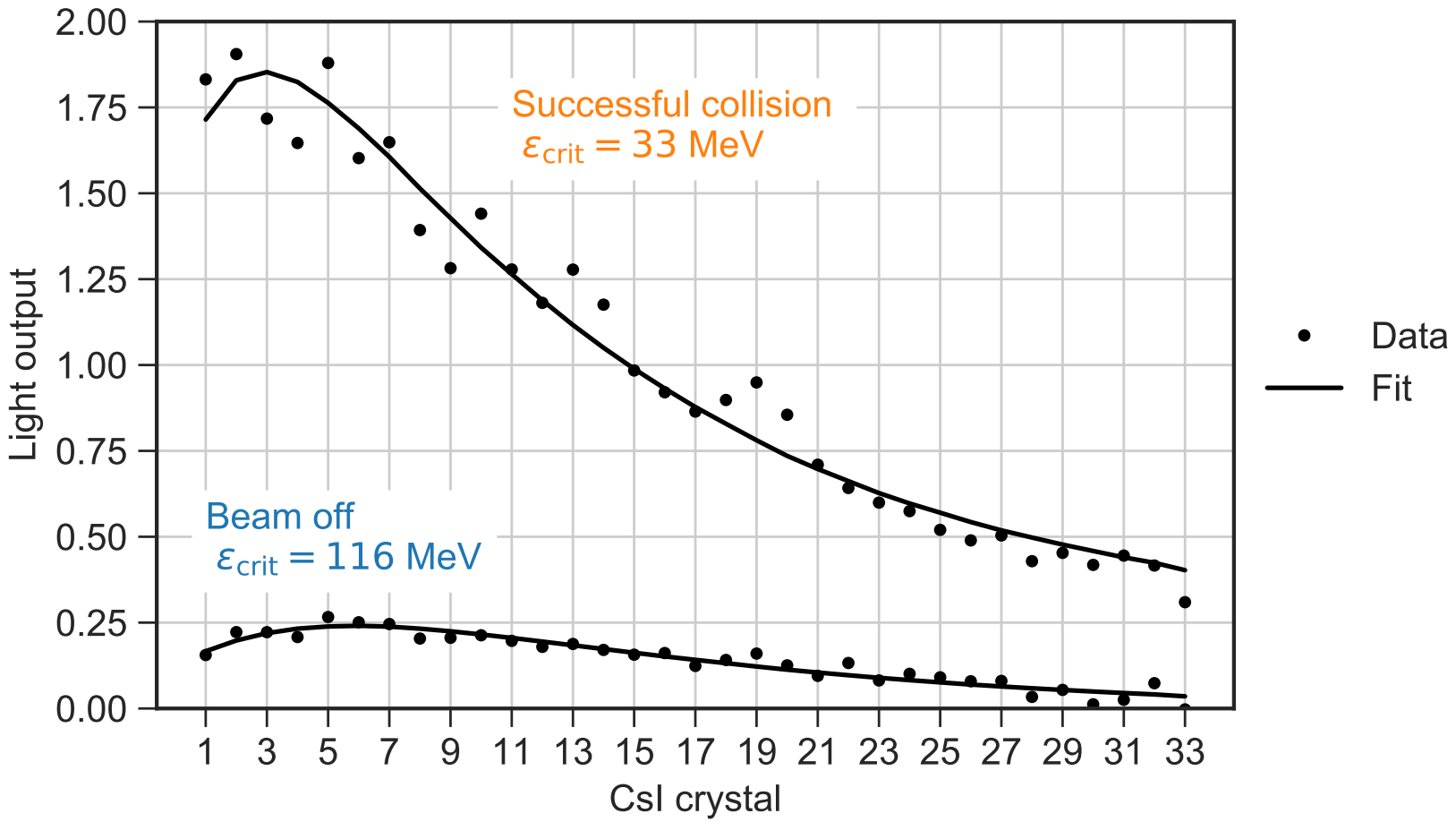
- Probability that this is due to random fluctuations is $P(E < 500\,\mathrm{MeV})^4 \approx 1/350$
- Energy loss (15%) in e spectrum due to emission of radiation
- Consistent with $a_0 \approx 10$, $\eta \approx 0.06$ due to electron-laser offset

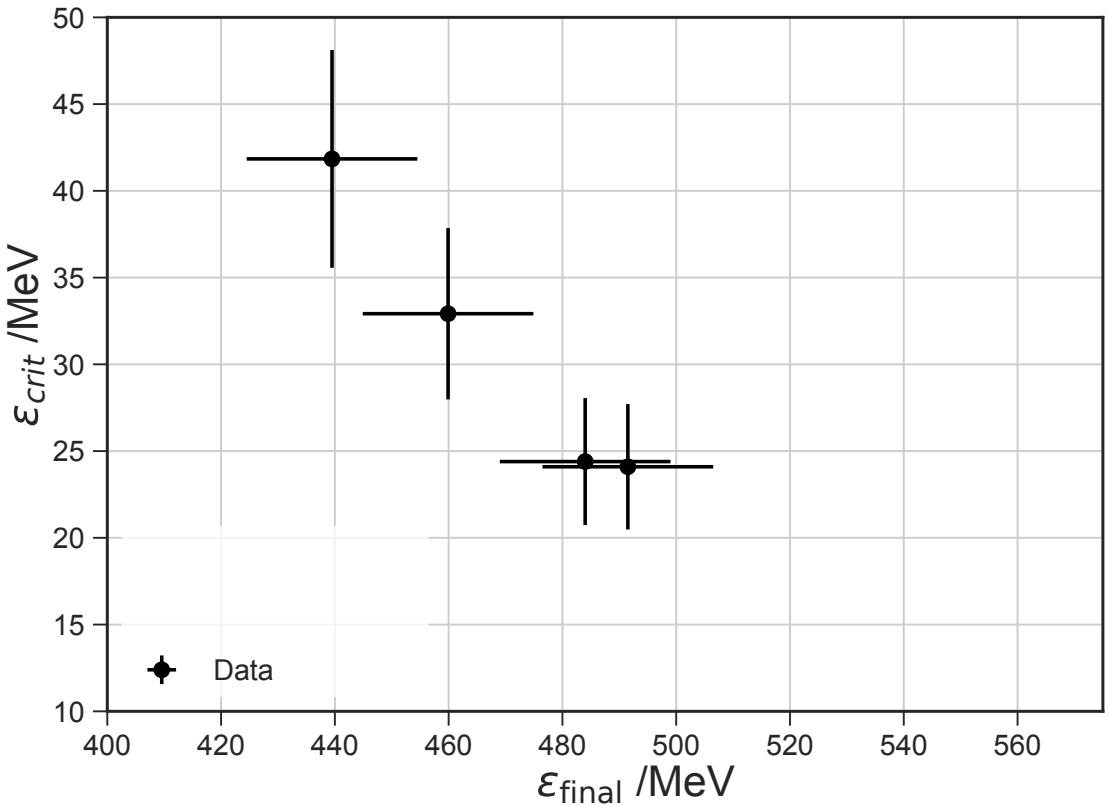


Spectra of bright γ signals differ from those with beam off



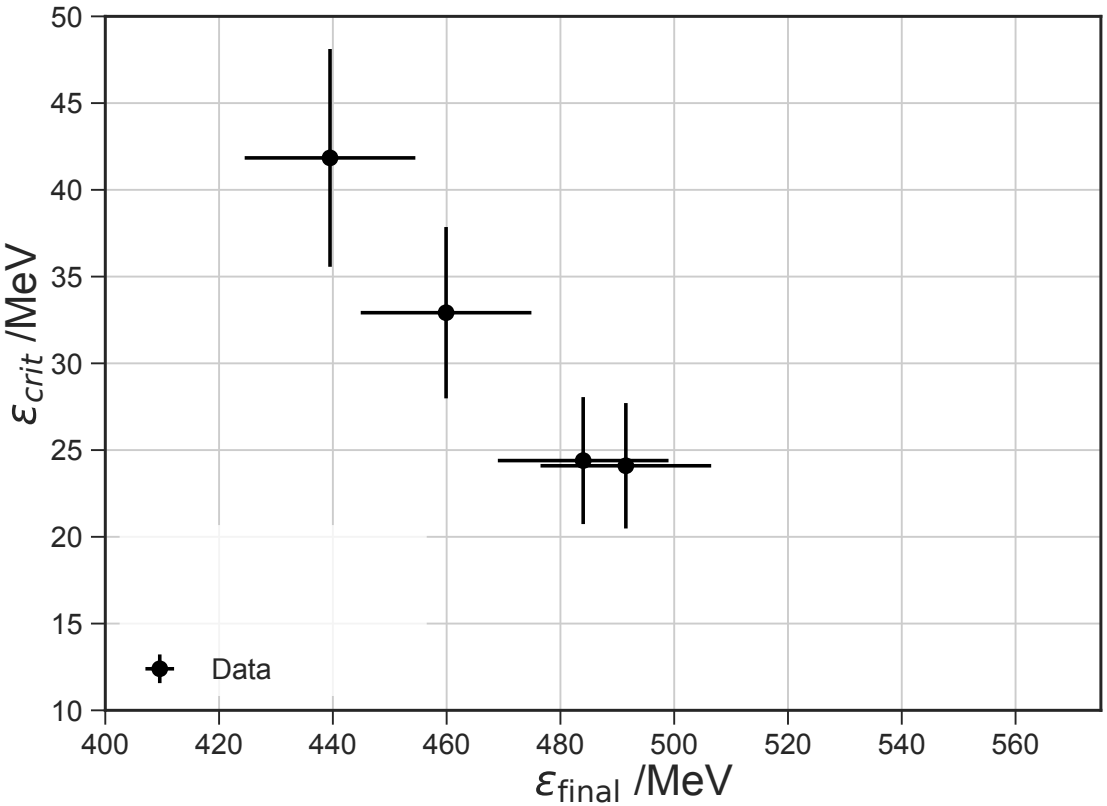
Negative correlation indicates radiation reaction

- Negative correlation of ϵ_{final} and ϵ_{crit}
  $\rightarrow$ RR (would be opposite for Bremsstrahlung)



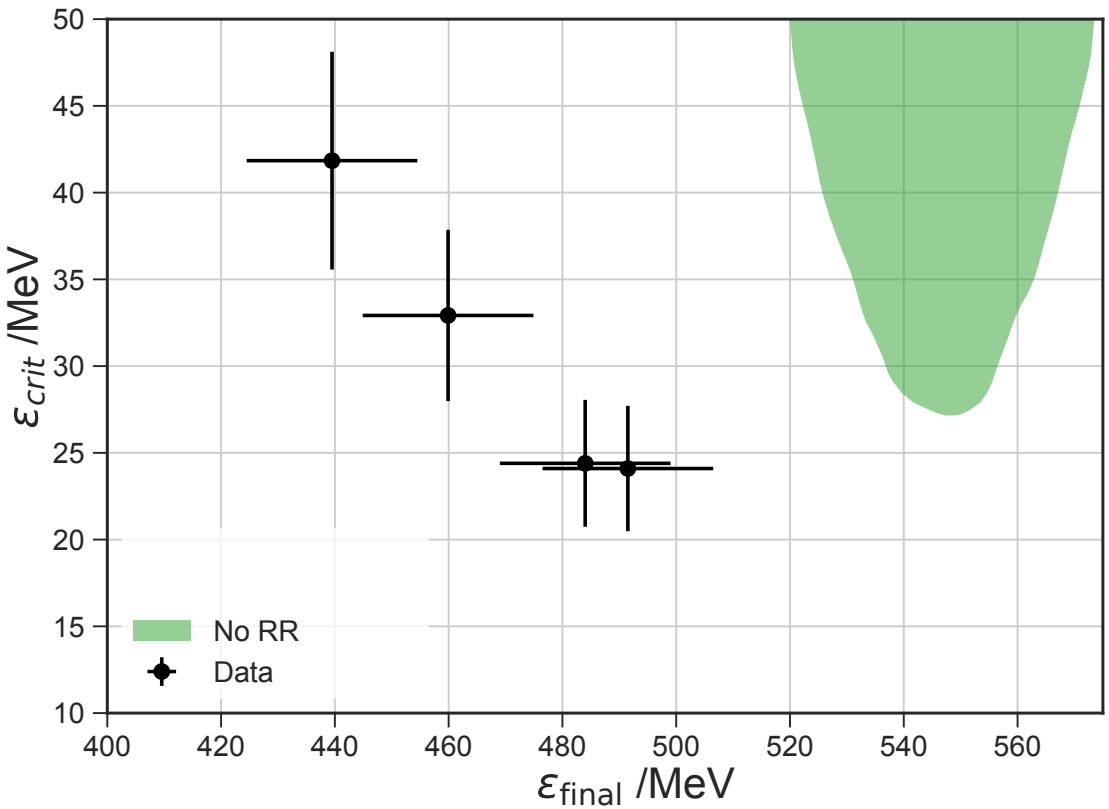
Negative correlation indicates radiation reaction

- Negative correlation of ϵ_{final} and ϵ_{crit} $\rightarrow$ RR (would be opposite for Bremsstrahlung)
- Probability that the 4 successful shots are low in energy and correlated by chance is 1/4000



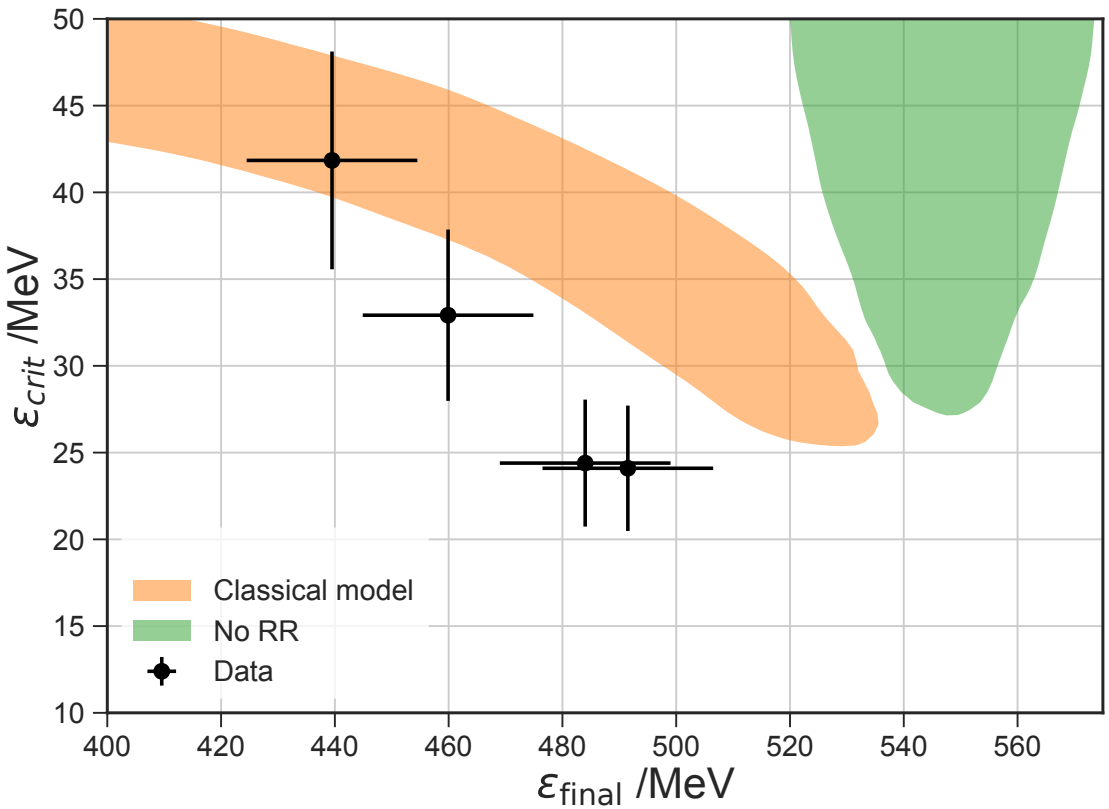
Measurements not consistent with a model without RR

- Contours indicate expected theoretical correlation based on the shot-to-shot fluctuation of the edge and a range of laser intensities
- no radiation reaction (green)



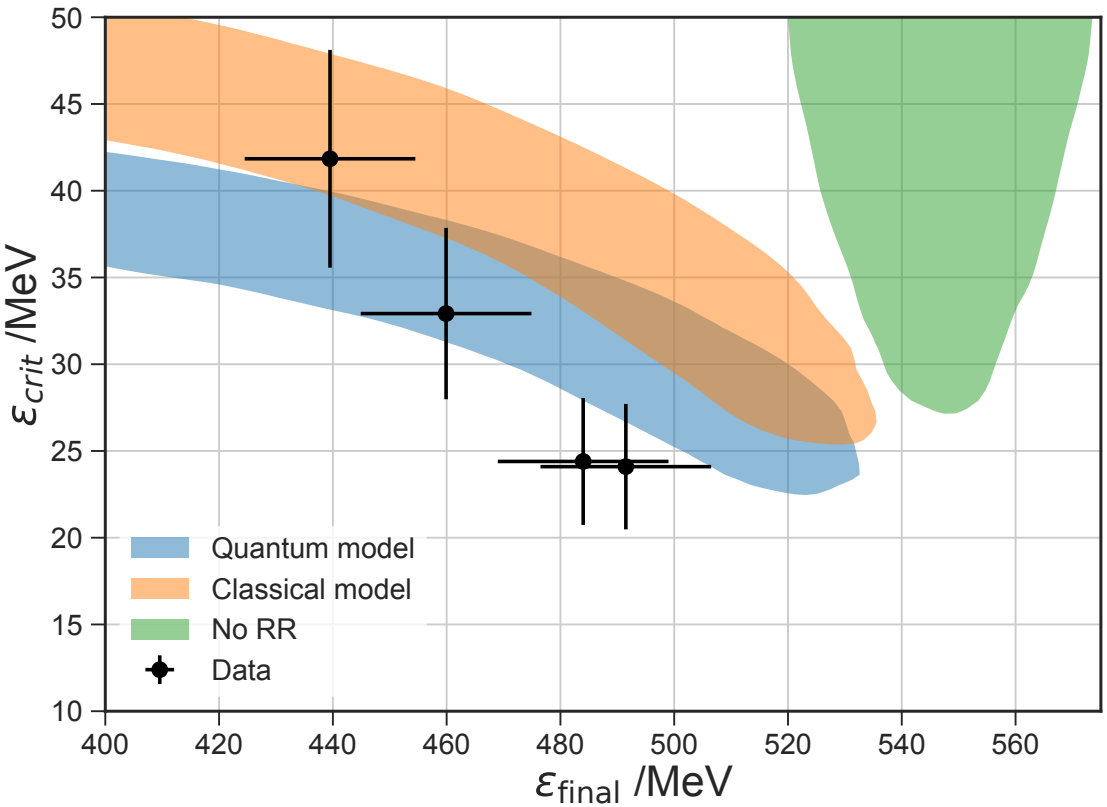
Classical description seems to overestimate emission slightly

- Contours indicate expected theoretical correlation based on the shot-to-shot fluctuation of the edge and a range of laser intensities
- no radiation reaction (green), a classical (orange)



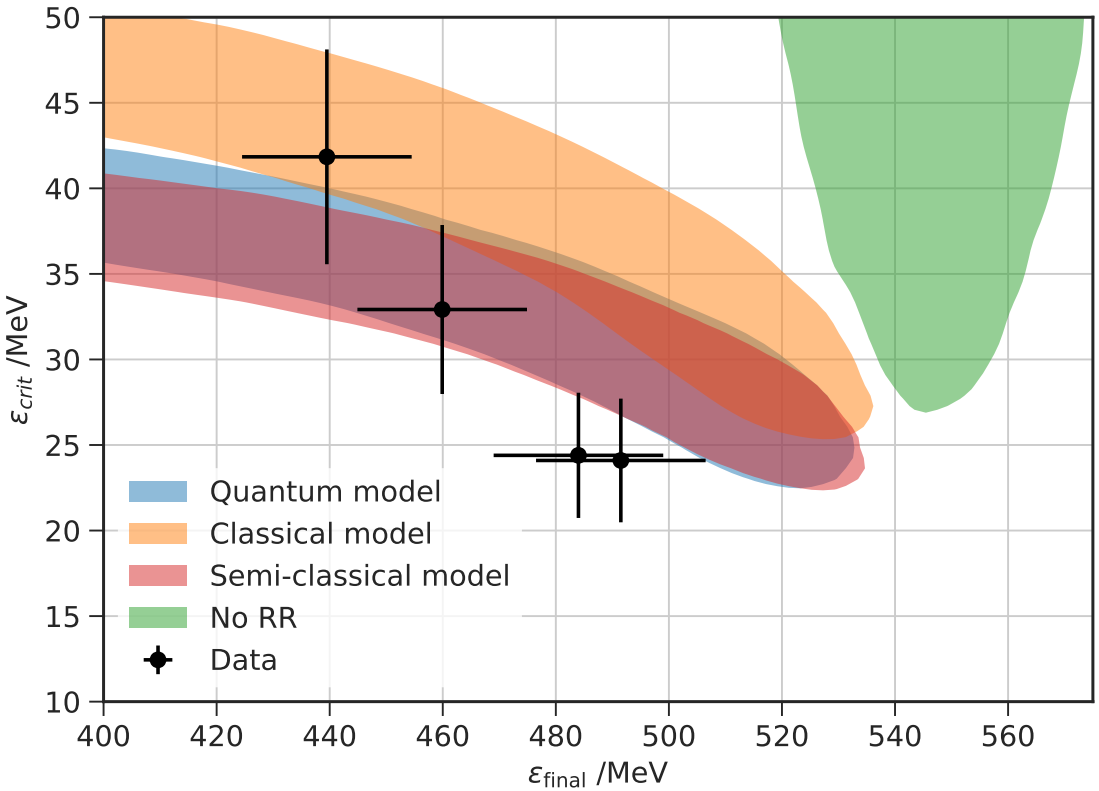
Consistency with quantum description of radiation reaction

- Contours indicate expected theoretical correlation based on the shot-to-shot fluctuation of the edge and a range of laser intensities
- no radiation reaction (green), a classical (orange) and a quantum radiation reaction model (blue)



Semi-classical and quantum description agree in this regime

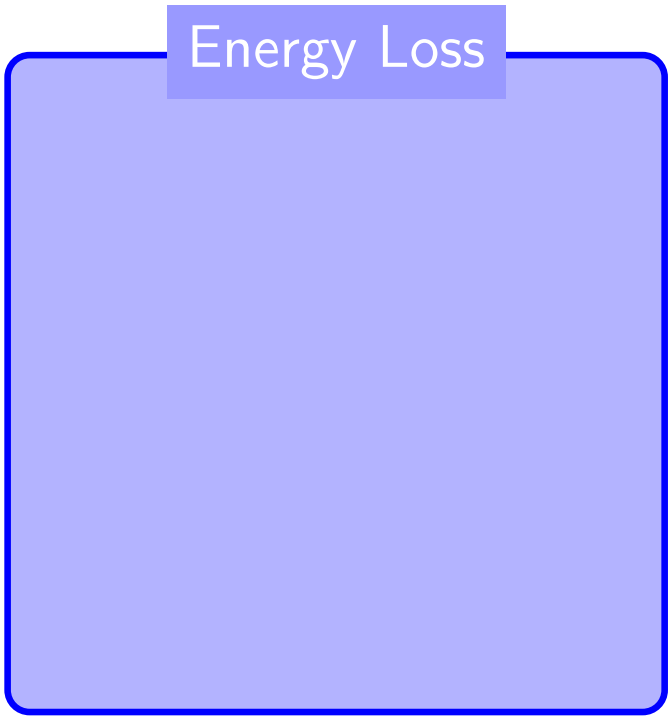
- Contours indicate expected theoretical correlation based on the shot-to-shot fluctuation of the edge and a range of laser intensities
- no radiation reaction (green), a classical (orange) and a quantum radiation reaction model (blue)
- a semi-classical model (red) agrees well with the quantum description (blue)



Another look at our observables...

- e observable is shift of spectral feature from reference mean
- shift is due to radiation reaction (statistically relevant)

Another look at our observables...



Another look at our observables...

Energy Loss

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Another look at our observables...

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Measuring only energy loss might not be sensitive enough

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- mean energy loss expected to be identical for SC and QED

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Variance

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Variance

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- mean energy loss expected to be identical for SC and QED
- measuring variance, i.e. shape of the spectrum will be more sensitive to distinguish the SC and full QED model

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- mean energy loss expected to be identical for SC and QED
- measuring variance, i.e. shape of the spectrum will be more sensitive to distinguish the SC and full QED model
- when increasing η change in spectral shape needs to be considered as well $\rightarrow$ high stability of spectral shape required

An improved experiment should address...

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- Improved stability of the electron spectrum

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- Improved stability of the electron spectrum
  - In terms of energy

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  - In terms of energy
  - In terms of overall spectral shape

An improved experiment should address...

- Improved stability of the electron spectrum
  - In terms of energy
  - In terms of overall spectral shape
- Higher value for η

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- Improved stability of the electron spectrum
  - In terms of energy
  - In terms of overall spectral shape
- Higher value for η
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...which brings us to the second part of this talk!

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See Poder et al., PRX **8** (2018)

...which brings us to the second[‡] part of this talk!

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  - In terms of overall spectral shape ✓
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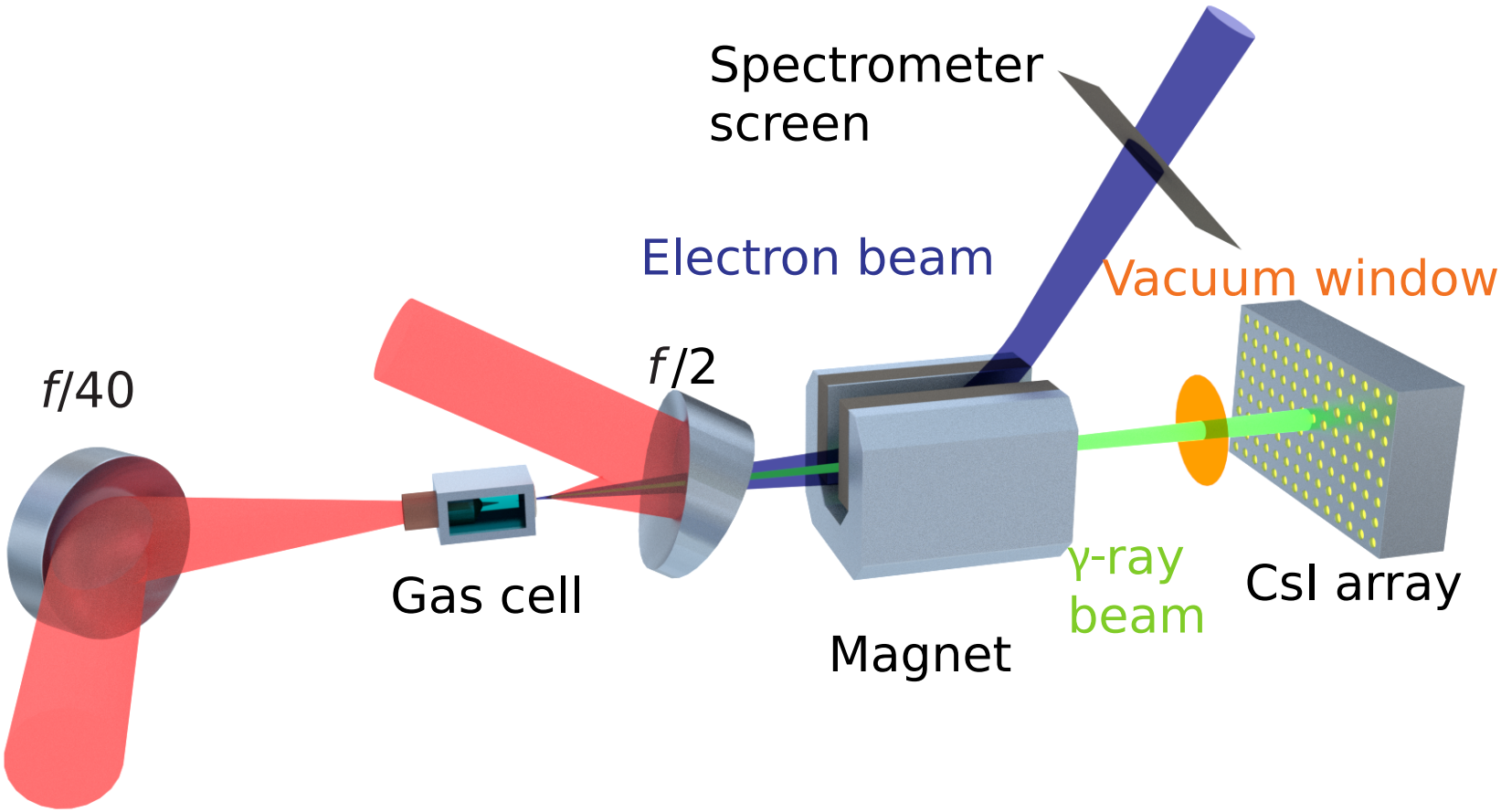
- More collision shots

See Poder et al., PRX **8** (2018)

[†] This experiment was actually performed first.

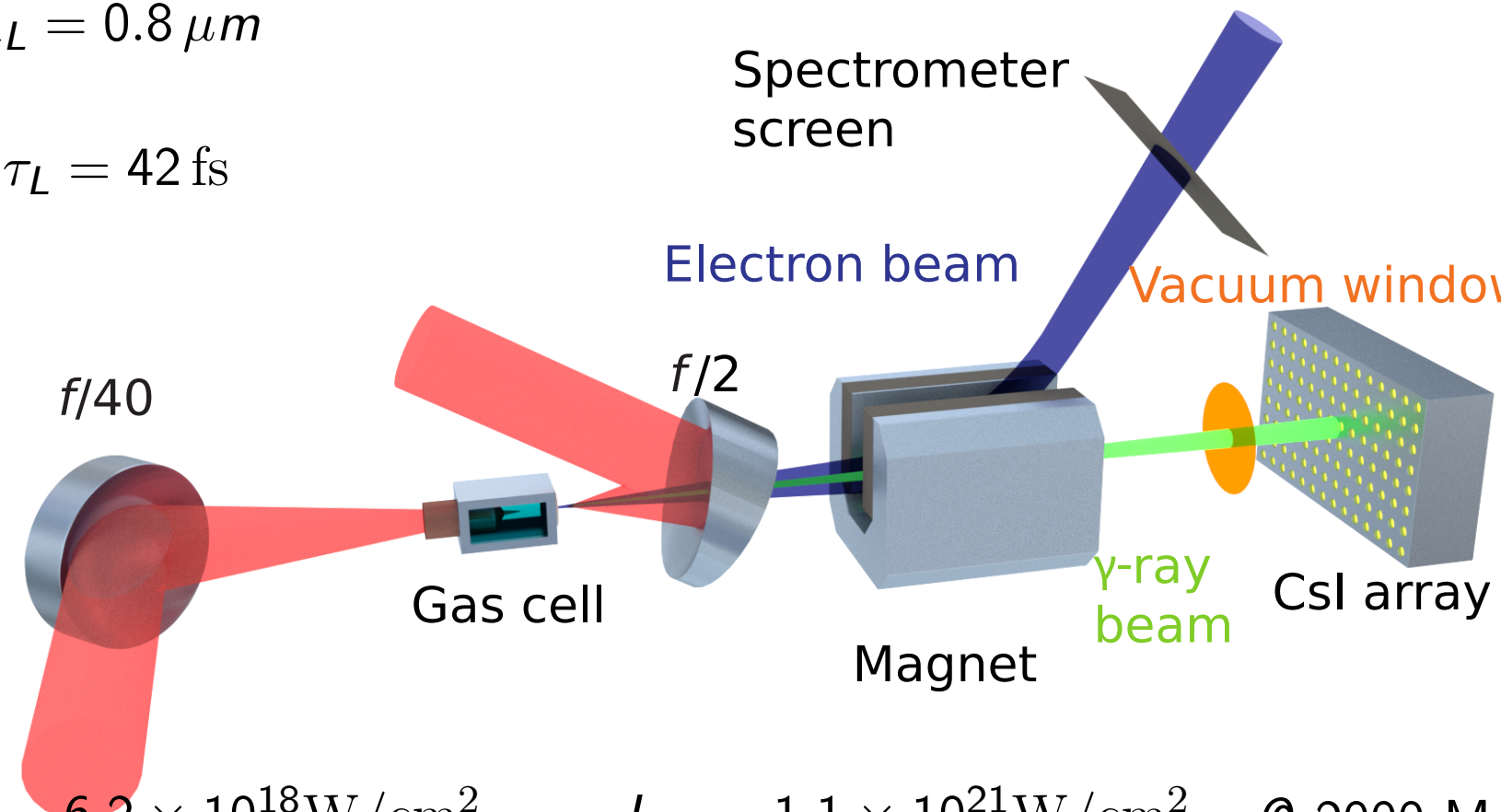
Colliding pulse setup at Gemini using a gas cell



Colliding pulse setup at Gemini using a gas cell

$\lambda_L = 0.8\,\mu m$

$\tau_L = 42\,\mathrm{fs}$



$I_{L,40} = 6.2 \times 10^{18}\mathrm{W/cm^2}$

$a_{0,40} = 1.7$

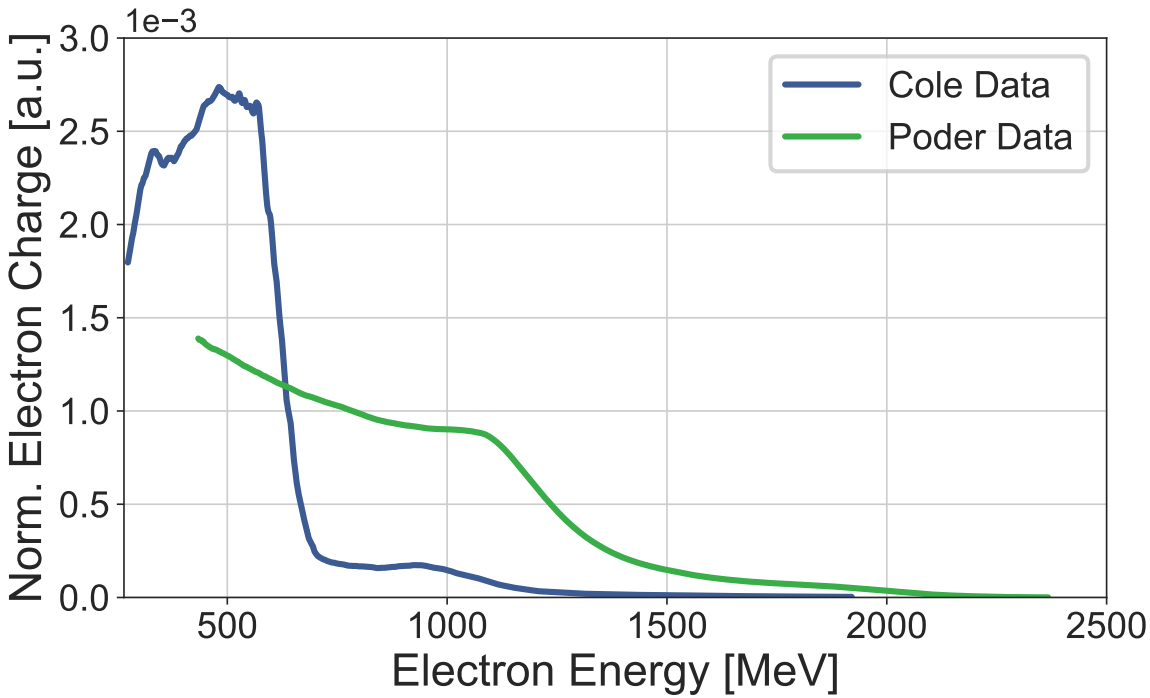
$I_{L,2} = 1.1 \times 10^{21}\mathrm{W/cm^2}$

$a_{0,2} = 22.5$

@ 2000 MeV:

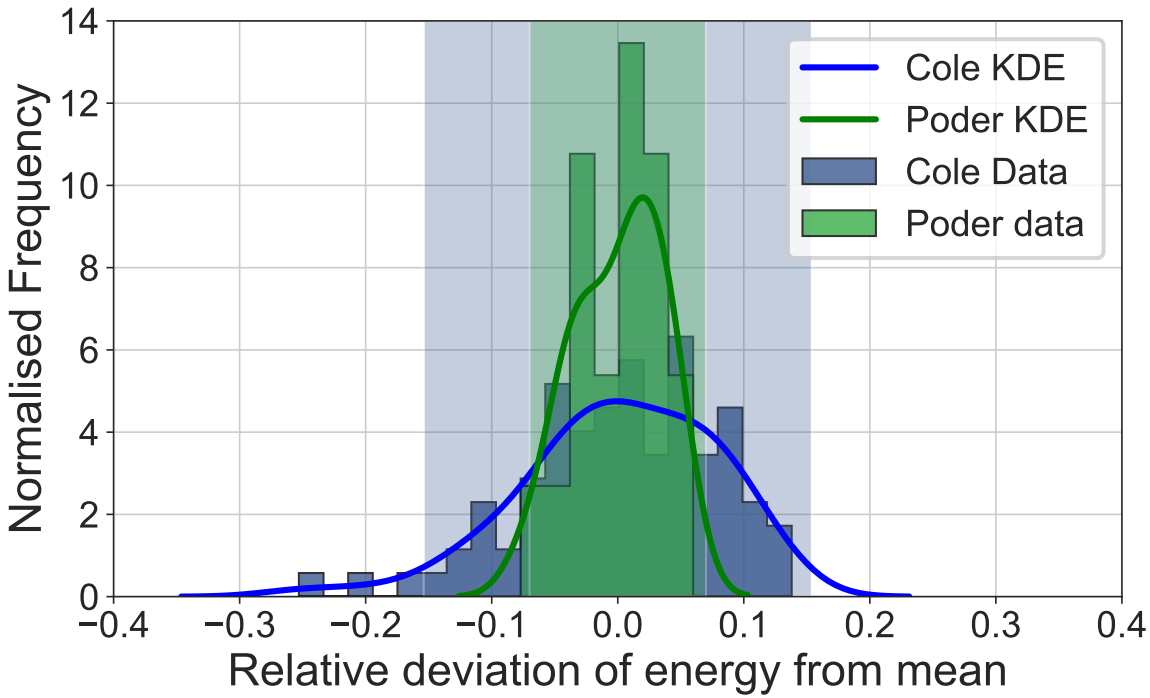
$\eta_{max} \approx 0.55$

Increased electron energy of the beam at similar a_0: higher η



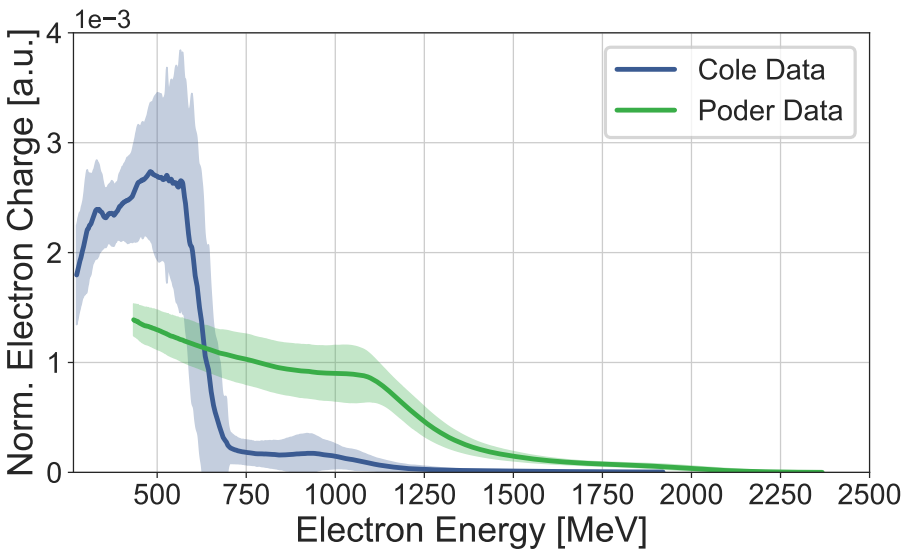
- Mean reference electron spectra normalised by total charge
- Drifts and fluctuations of the laser energy are accounted for
- Significant increase in electron energy: η more than doubled

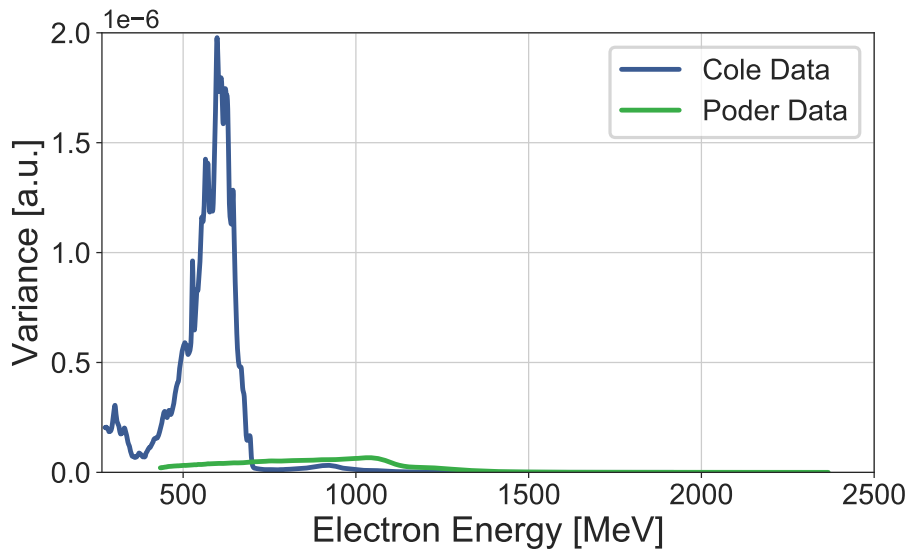
Increased energy stability for spectra



- normalised histograms of deviations from mean energy
- width of distribution is narrower: standard deviation halved

Increased stability of the spectral shape





- error bars in spectra show energy dependent variance
- total and differential variance decreased by a factor of 10
- variance is very localised around the peaks for Cole data

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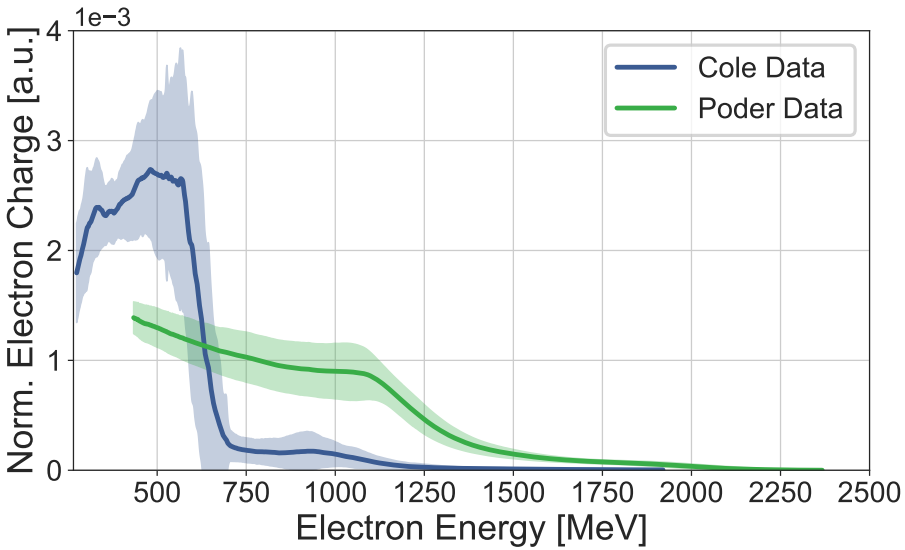

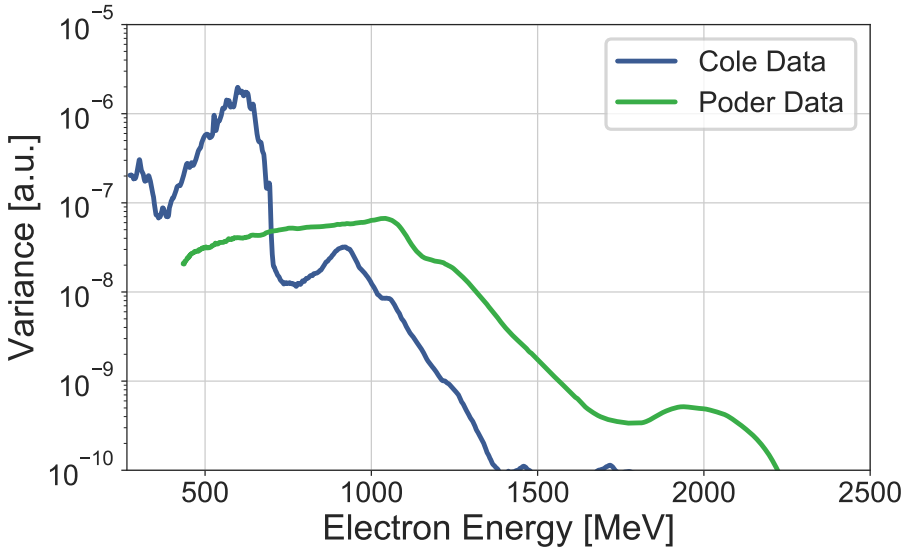

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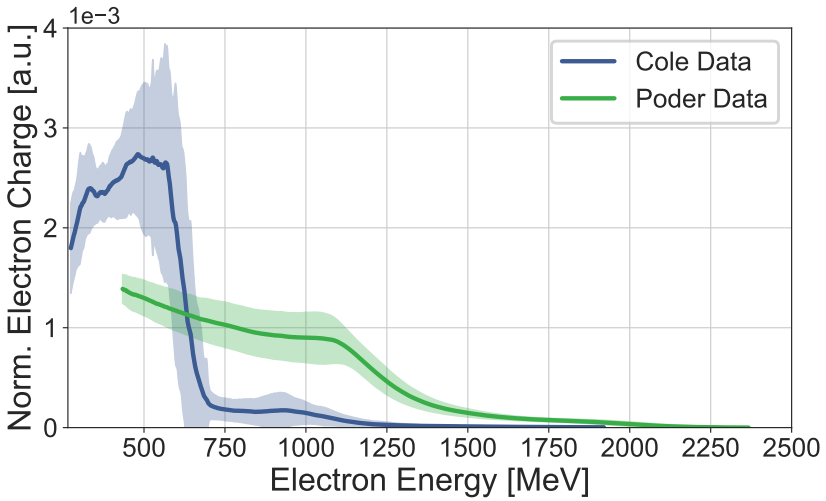
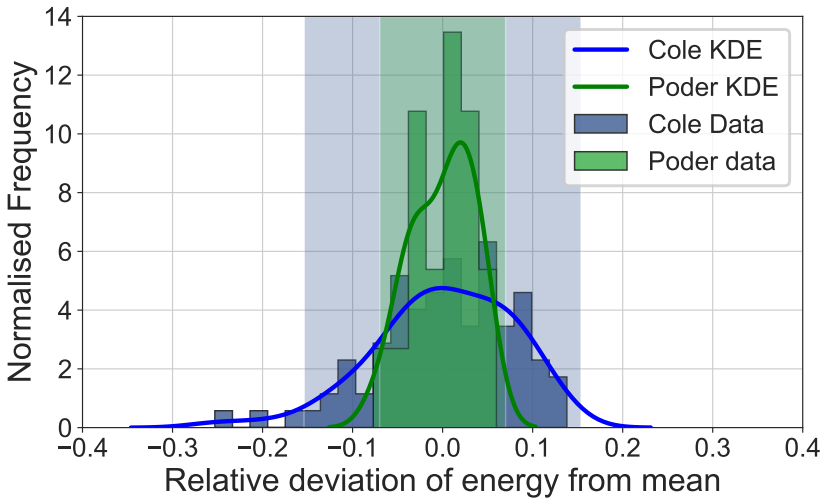
Increased η and stability: can we see signatures?





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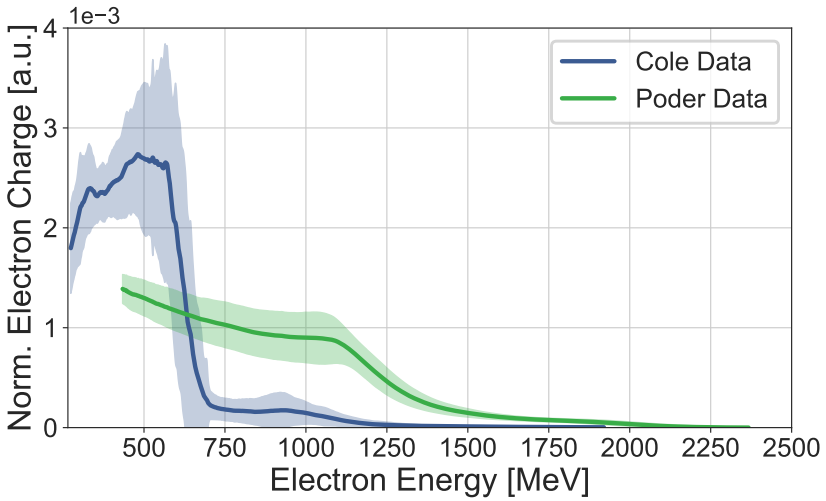

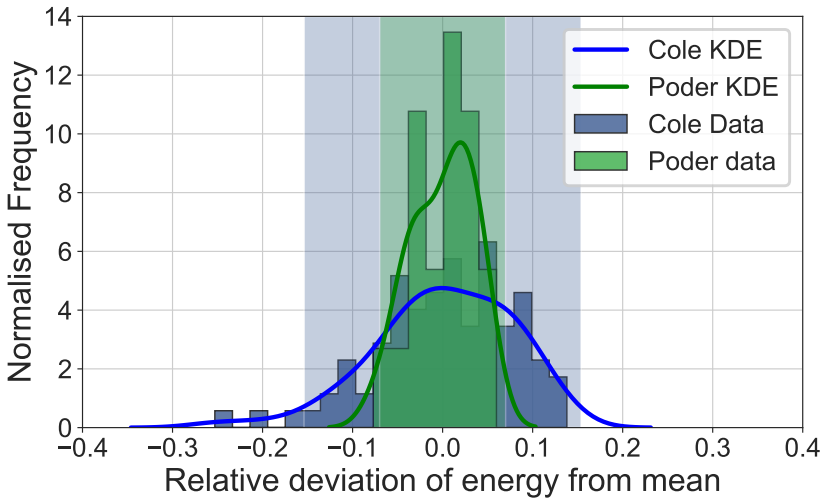

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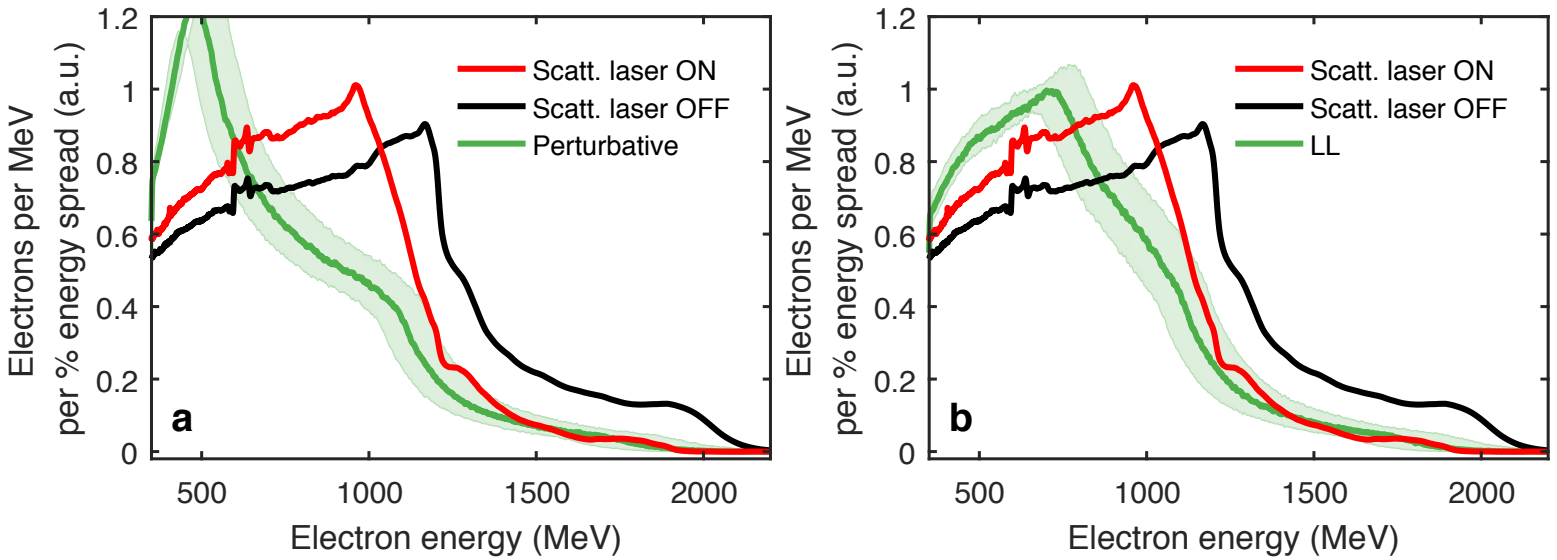
Can we see signatures of the models more clearly now?

Classical RR model overestimates energy loss



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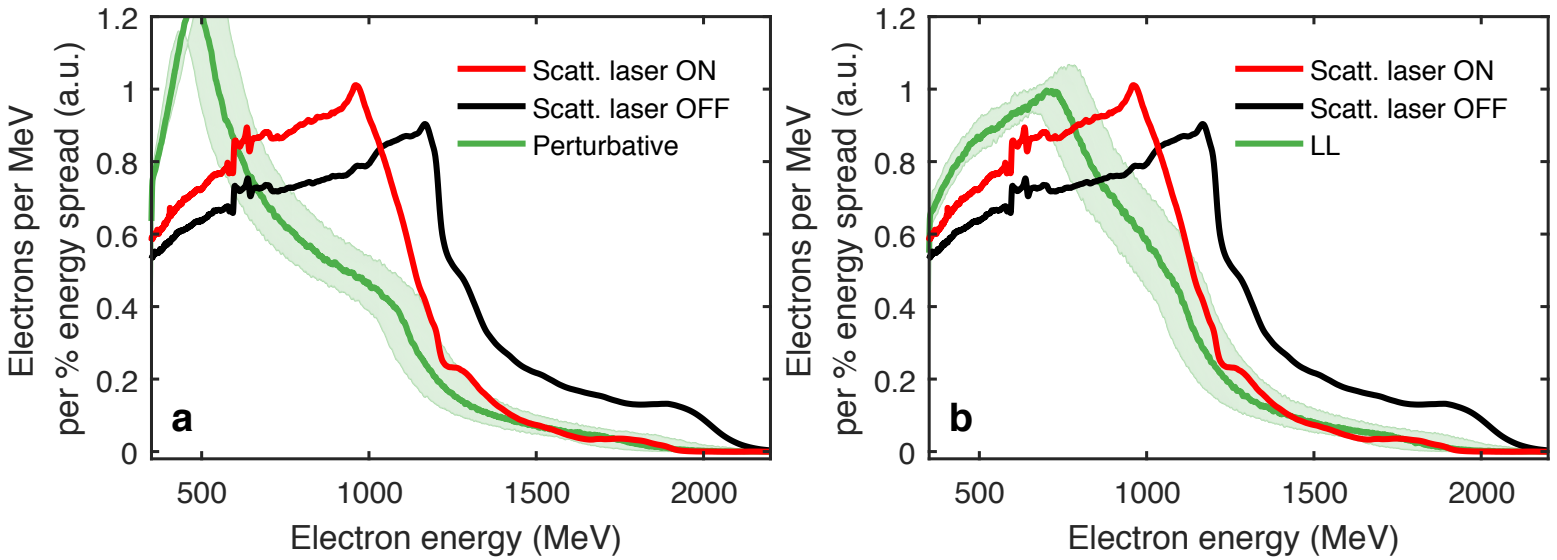

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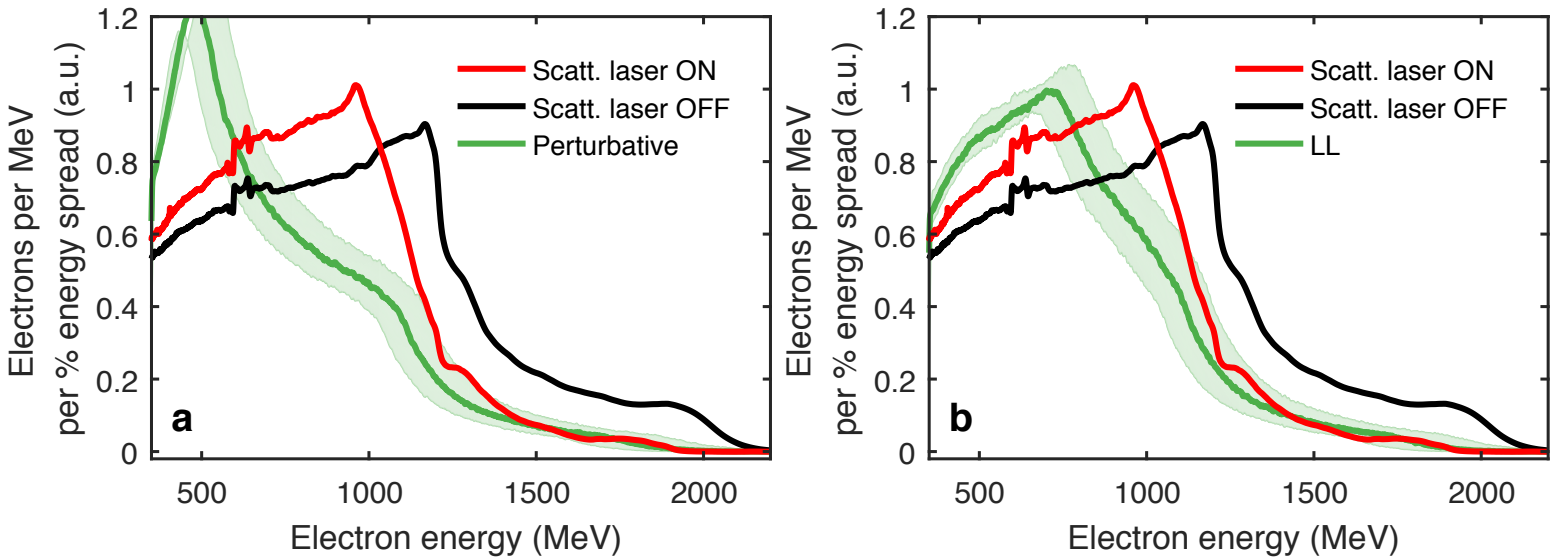

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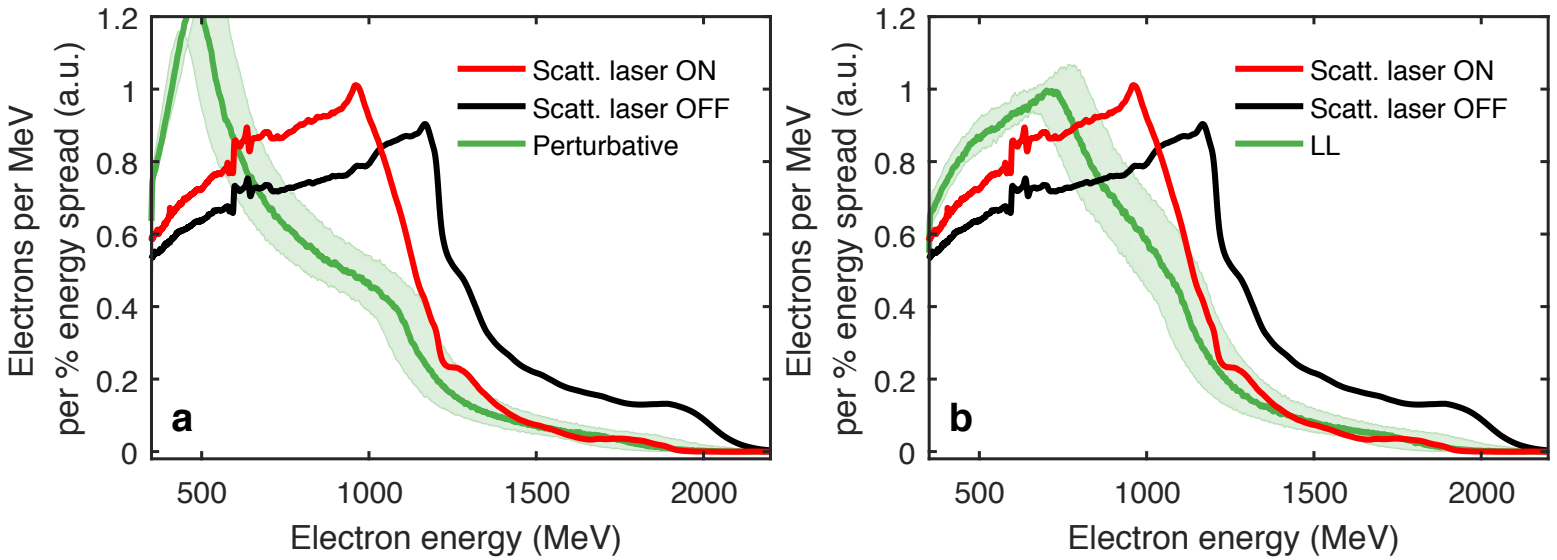

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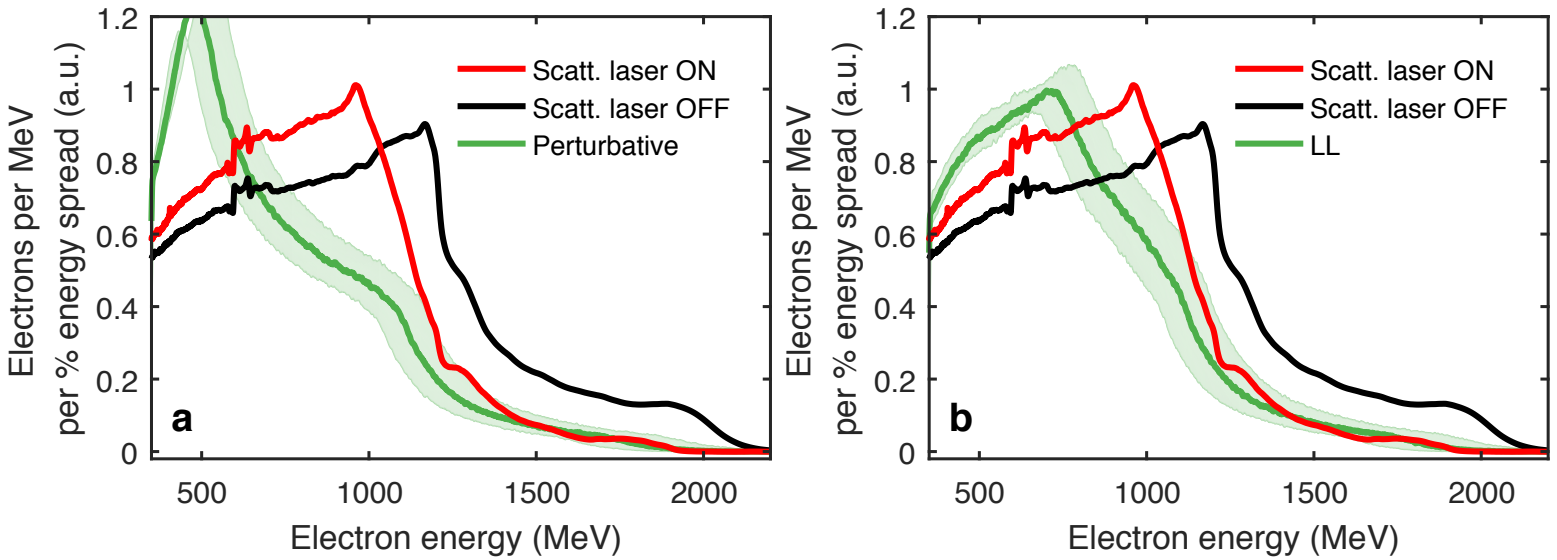

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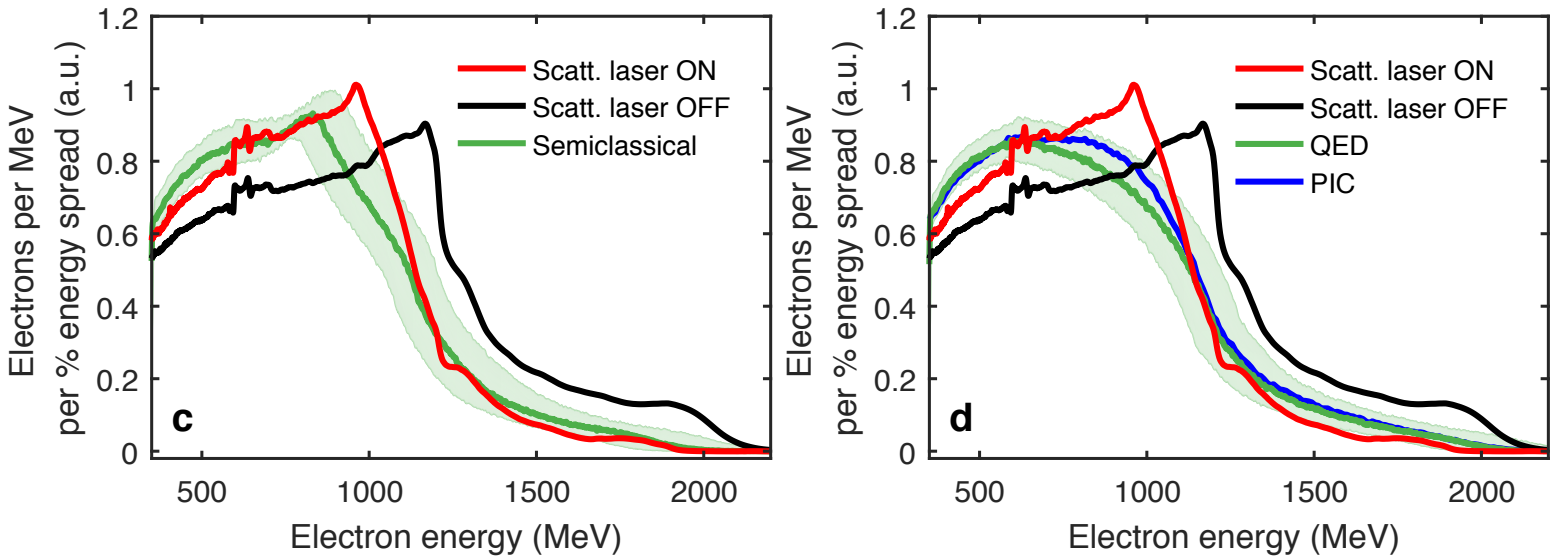
- the classical LL model (right) overestimates the energy loss

Semi-classical and QED model match better



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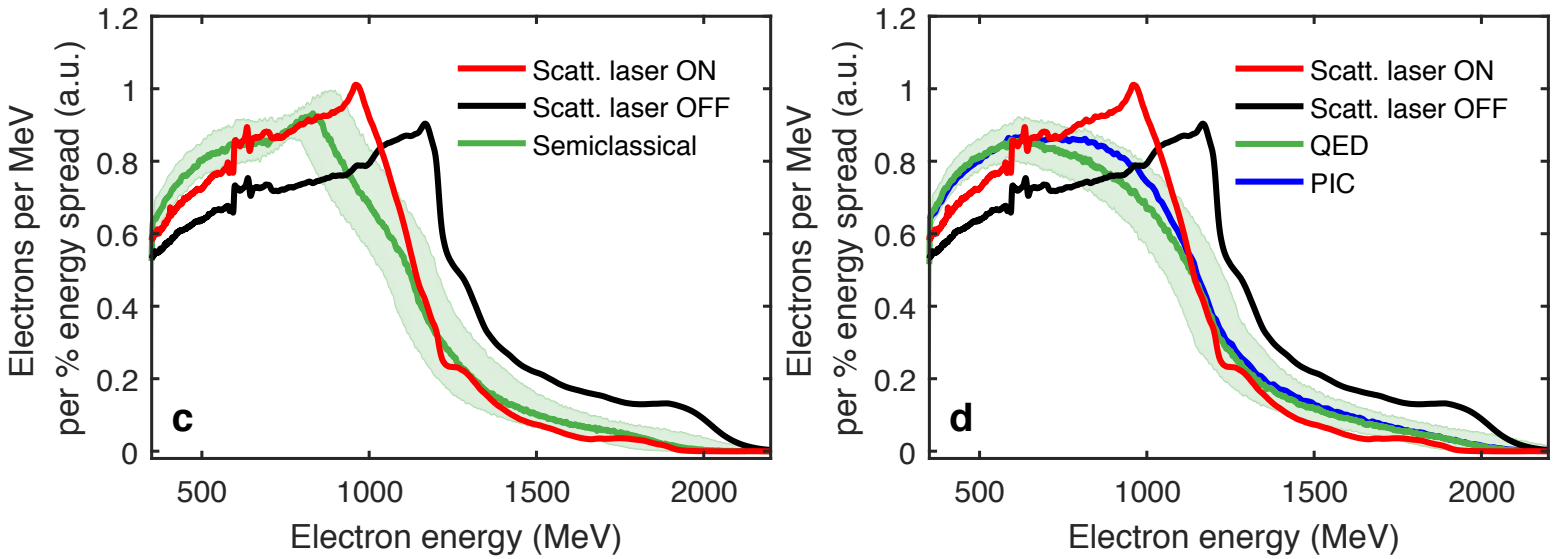

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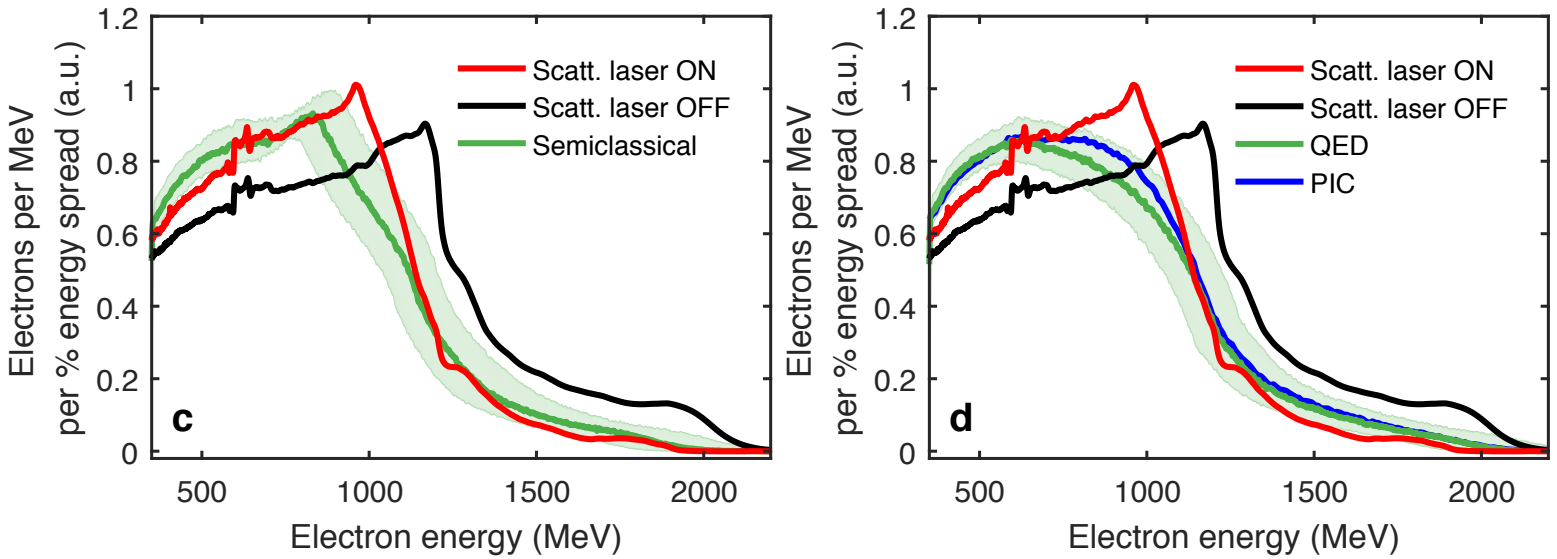

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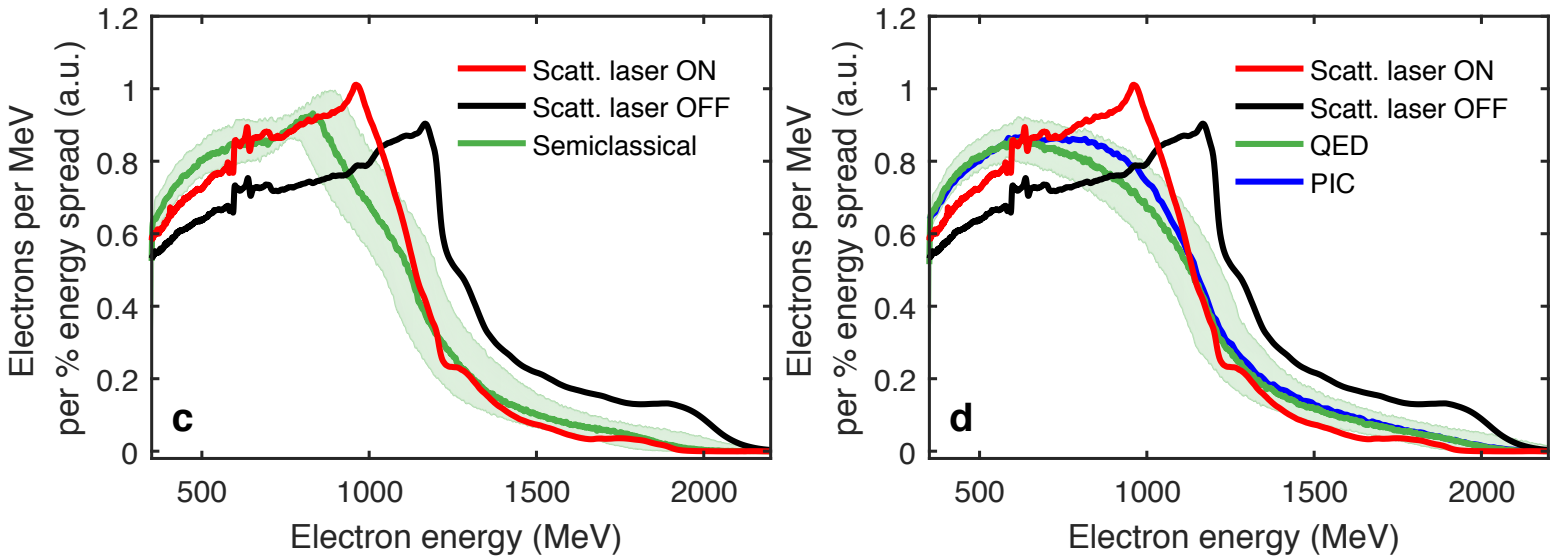

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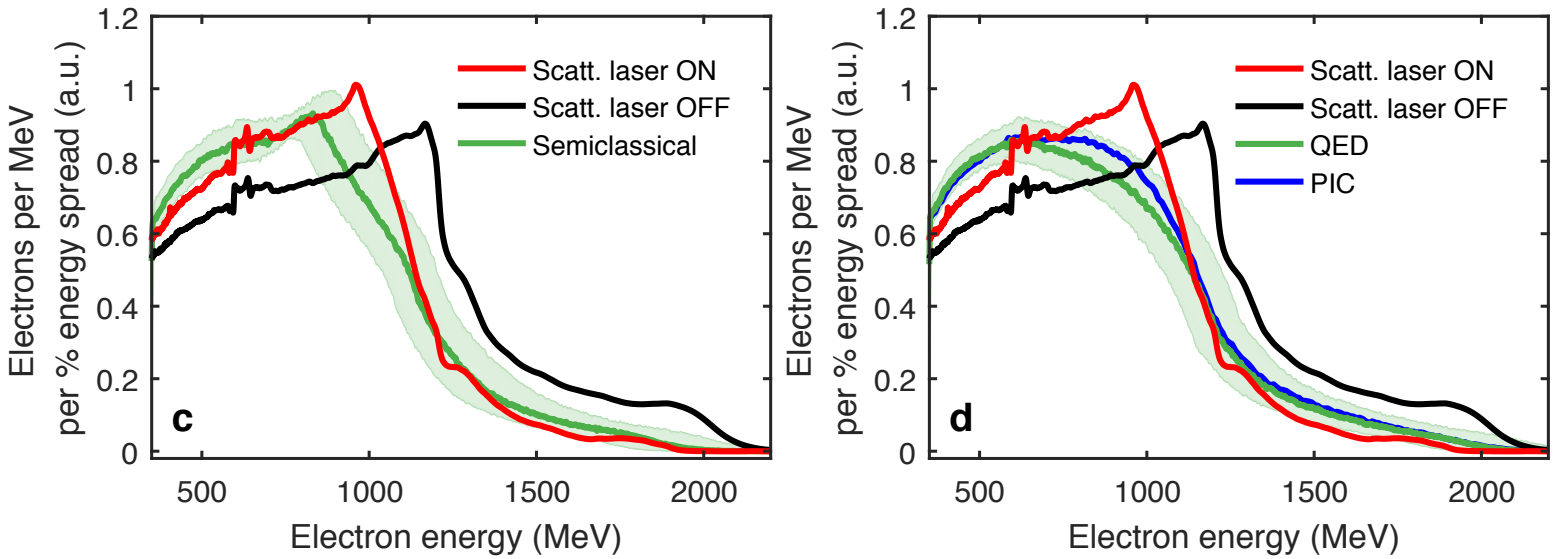

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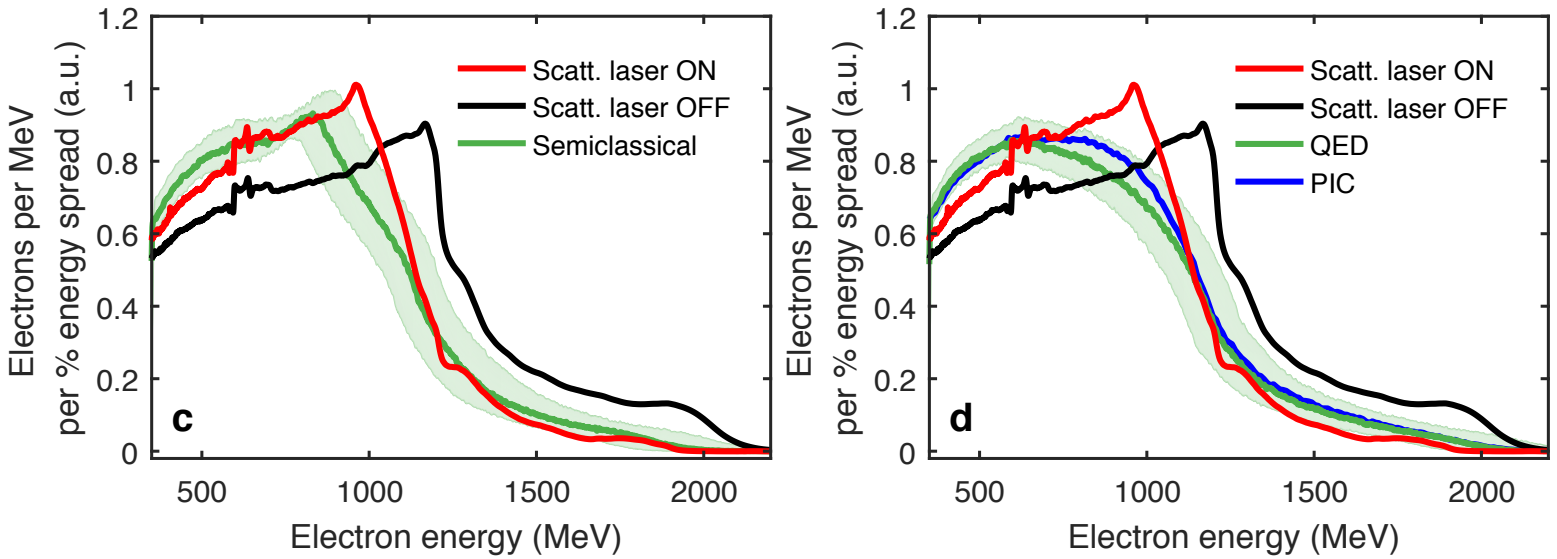

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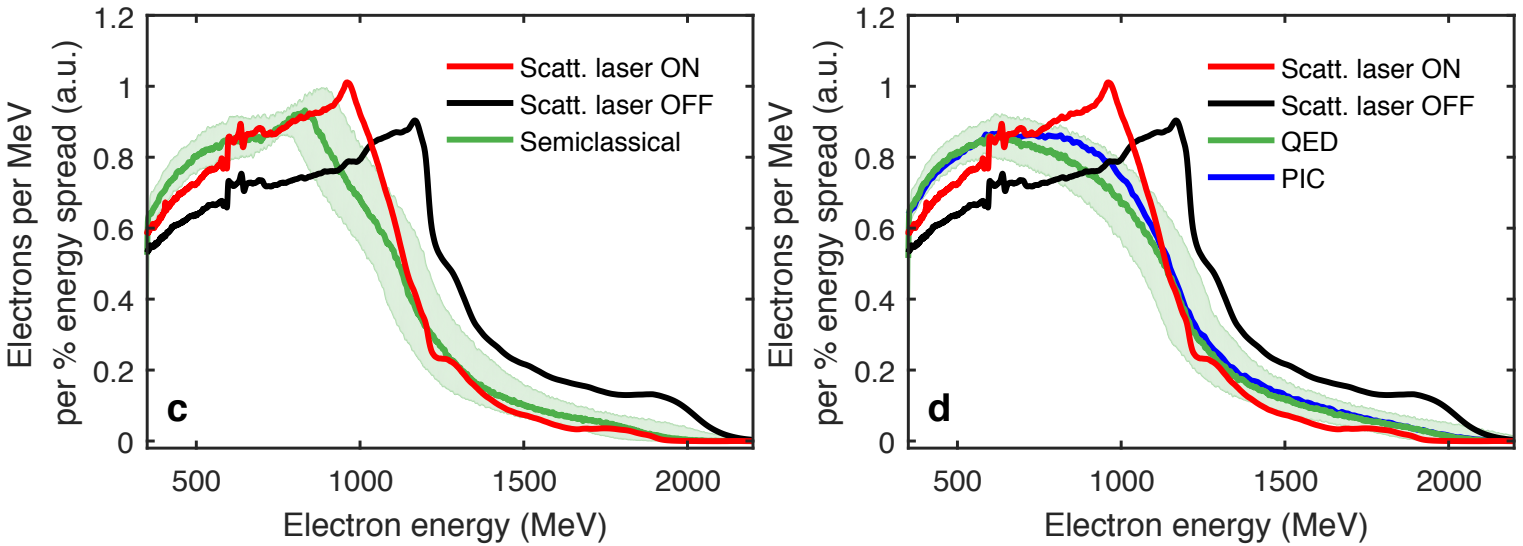
- both models still overestimate the energy loss
- why do neither of the models match perfectly?

Option 1: deviations could be of experimental origin...



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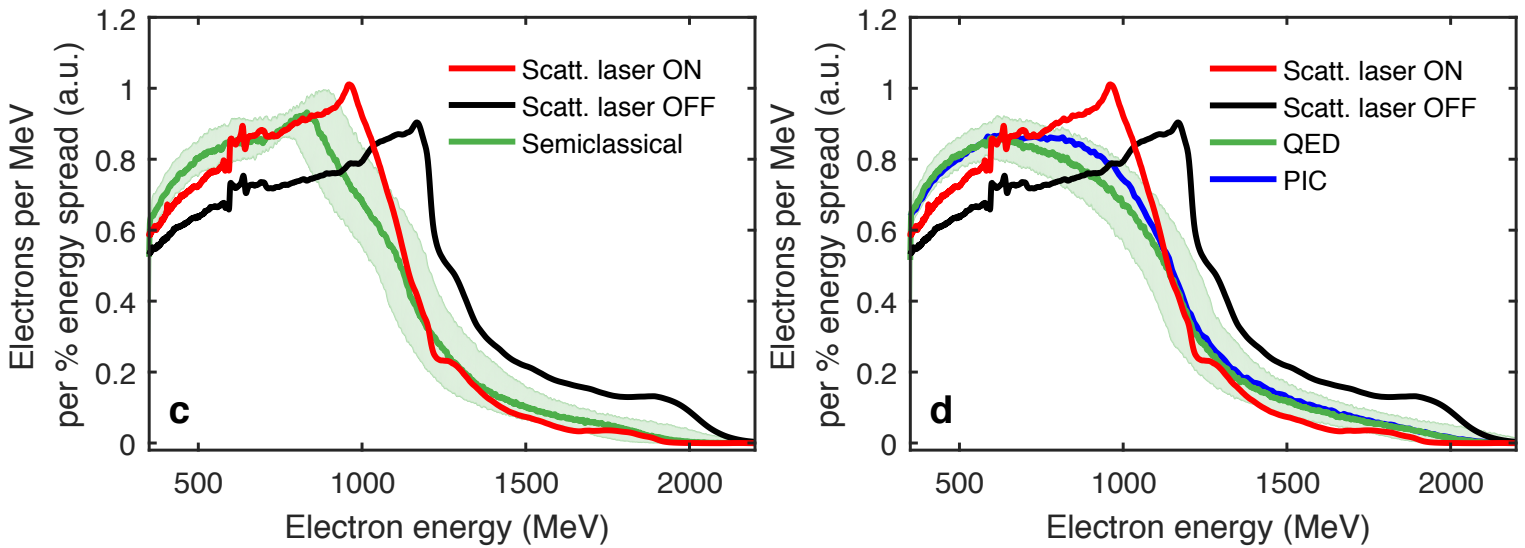

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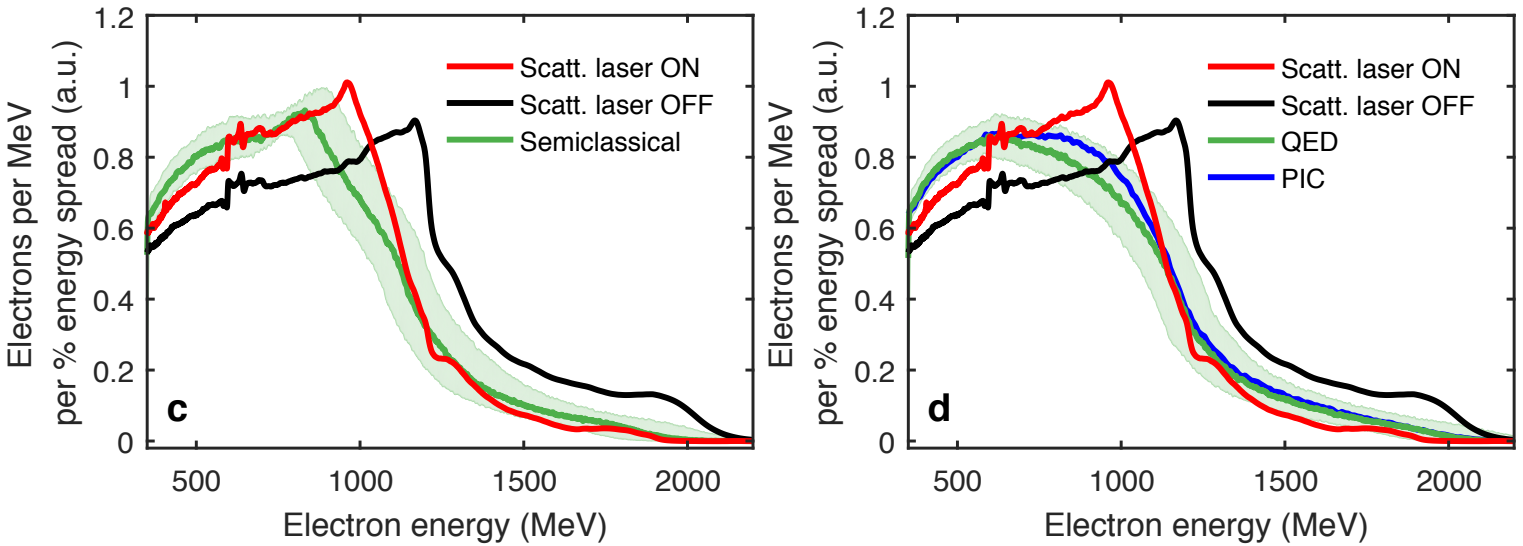

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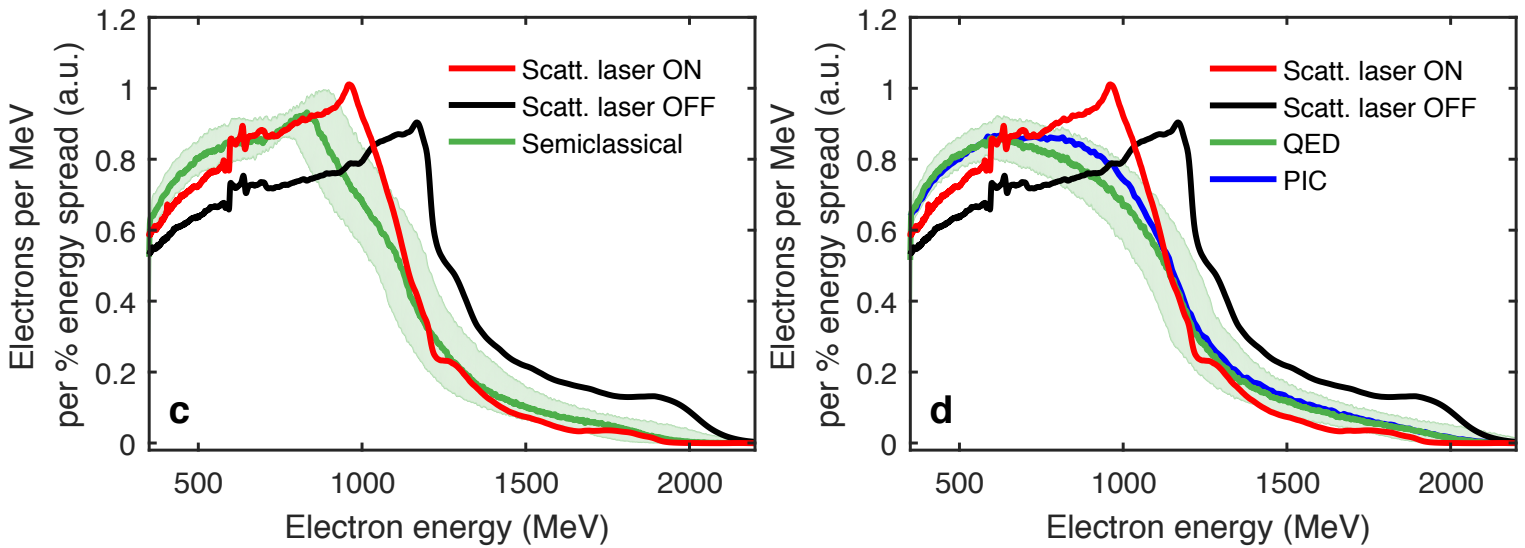

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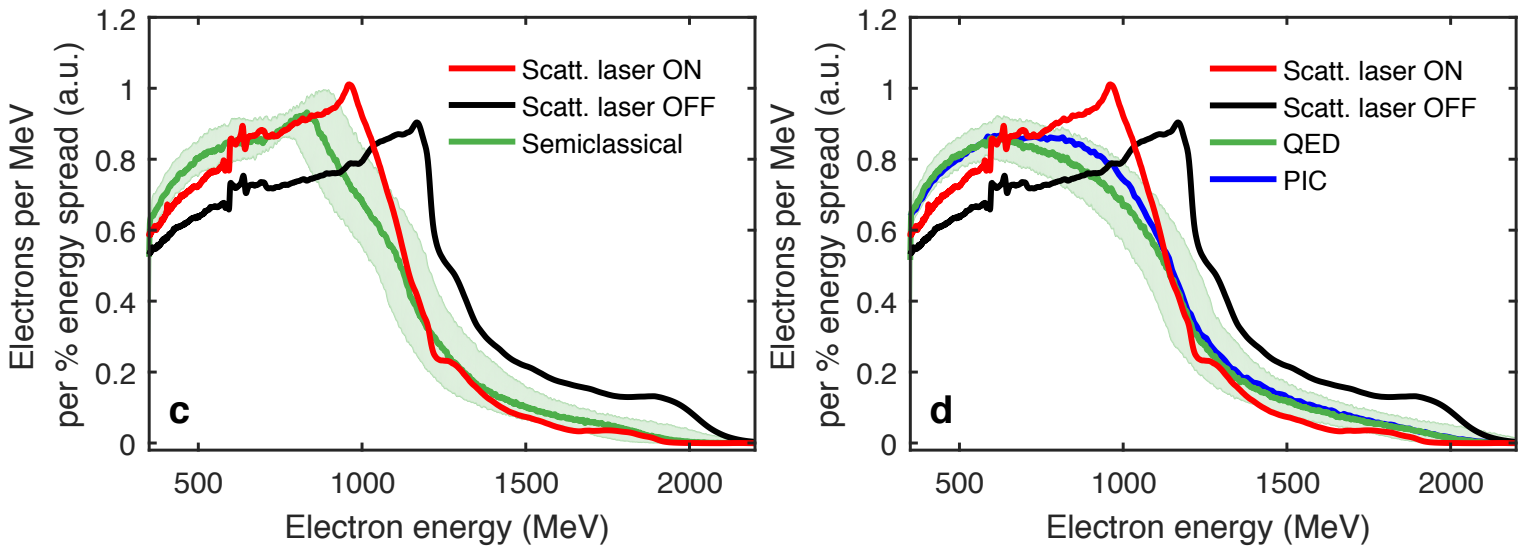

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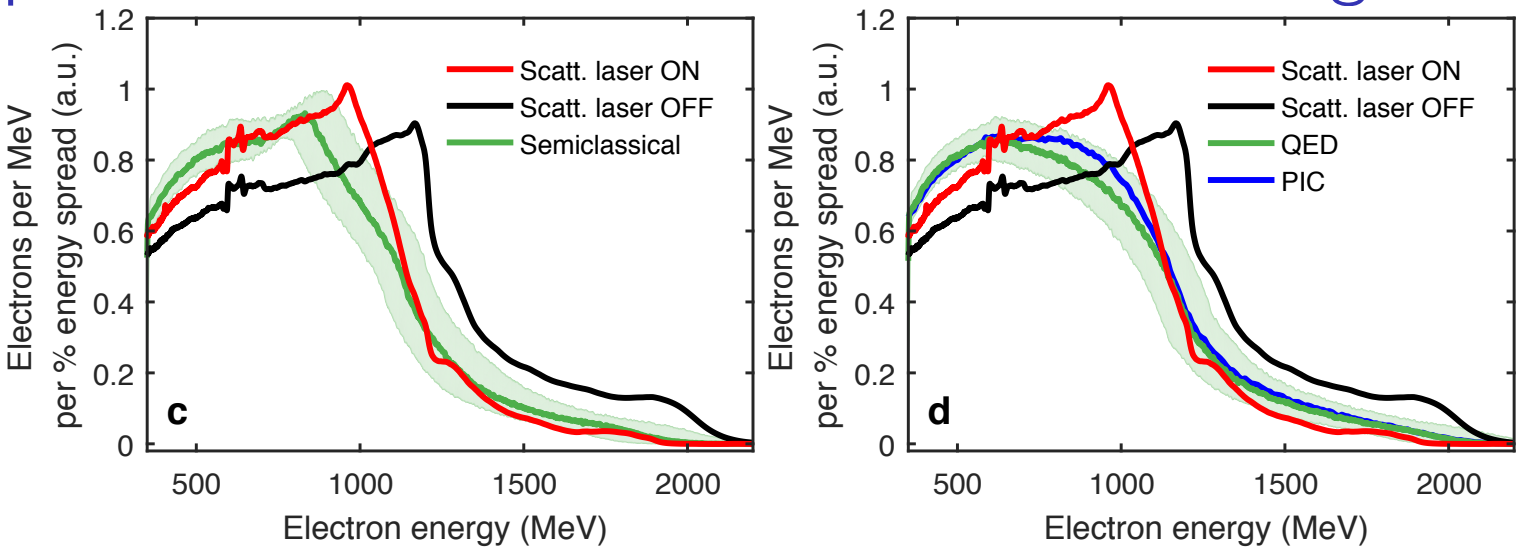

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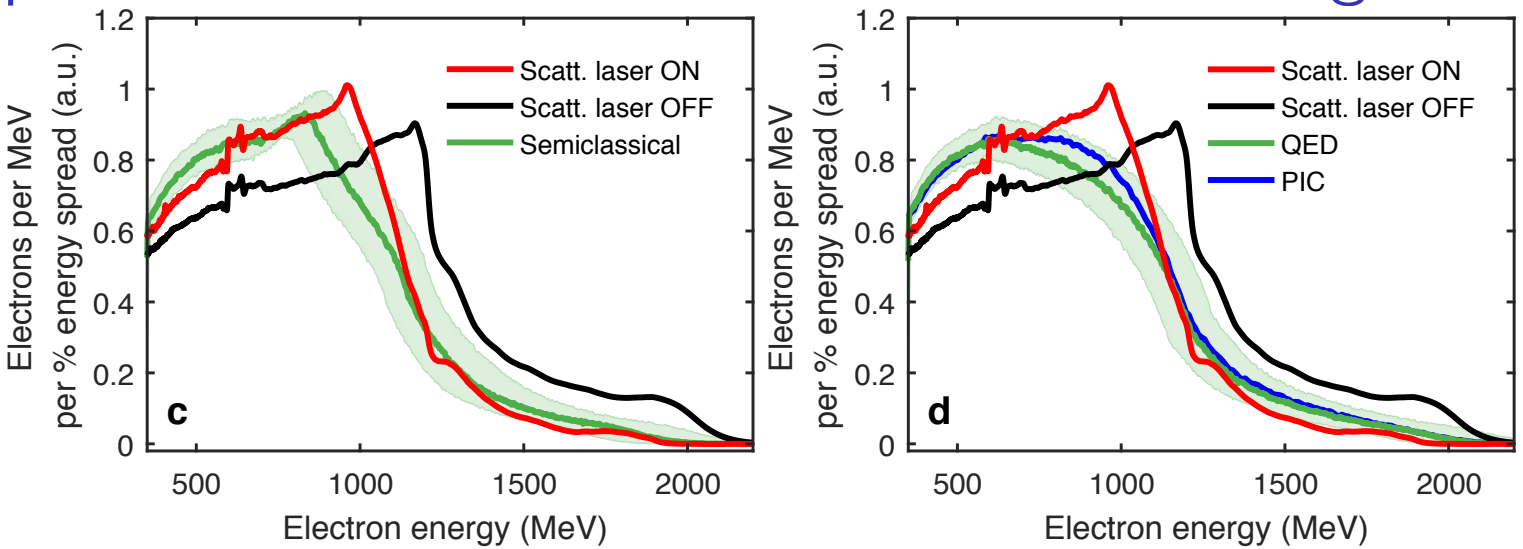

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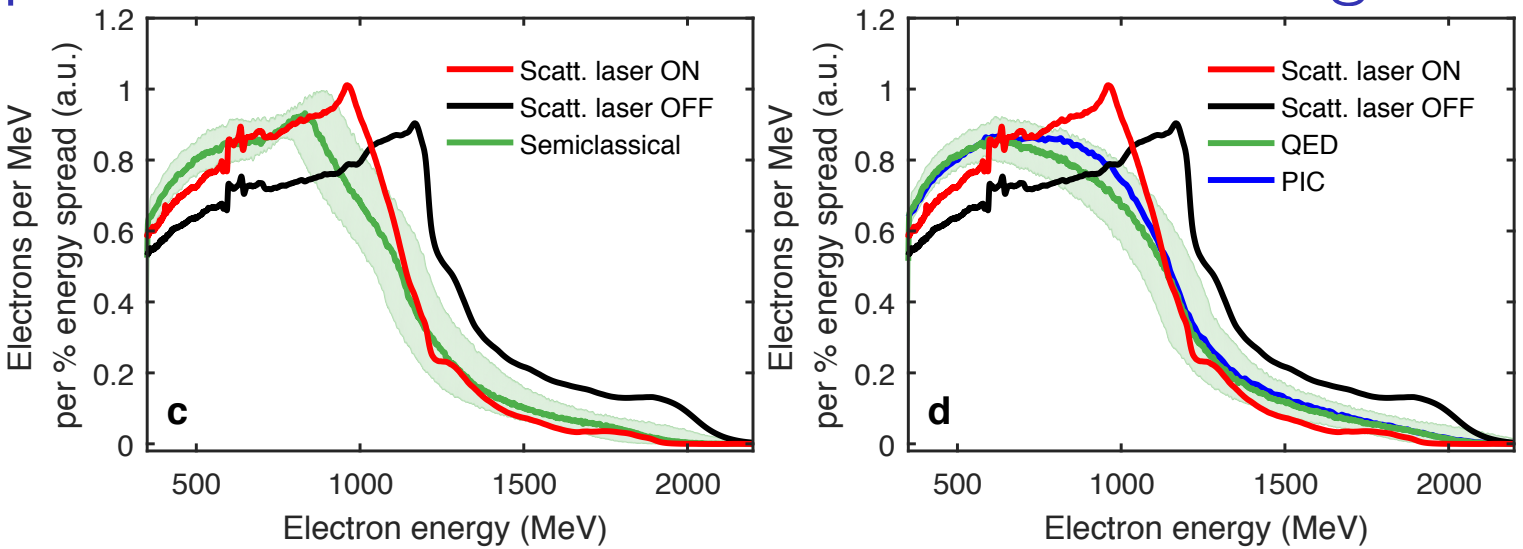

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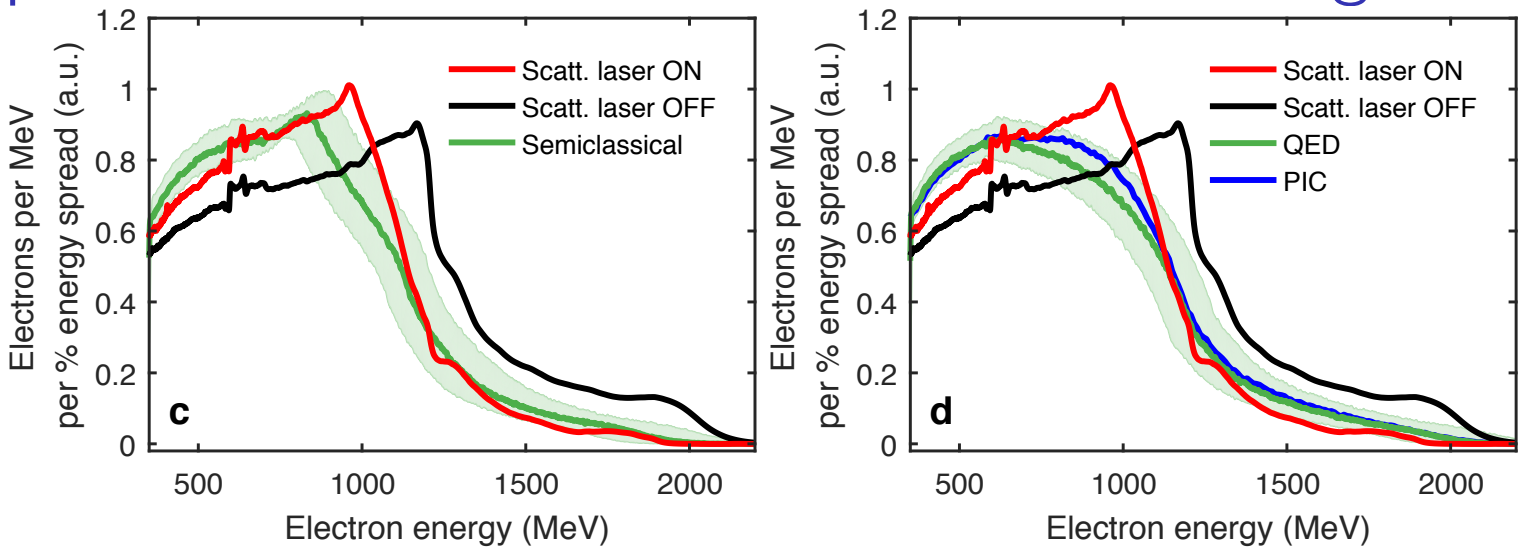

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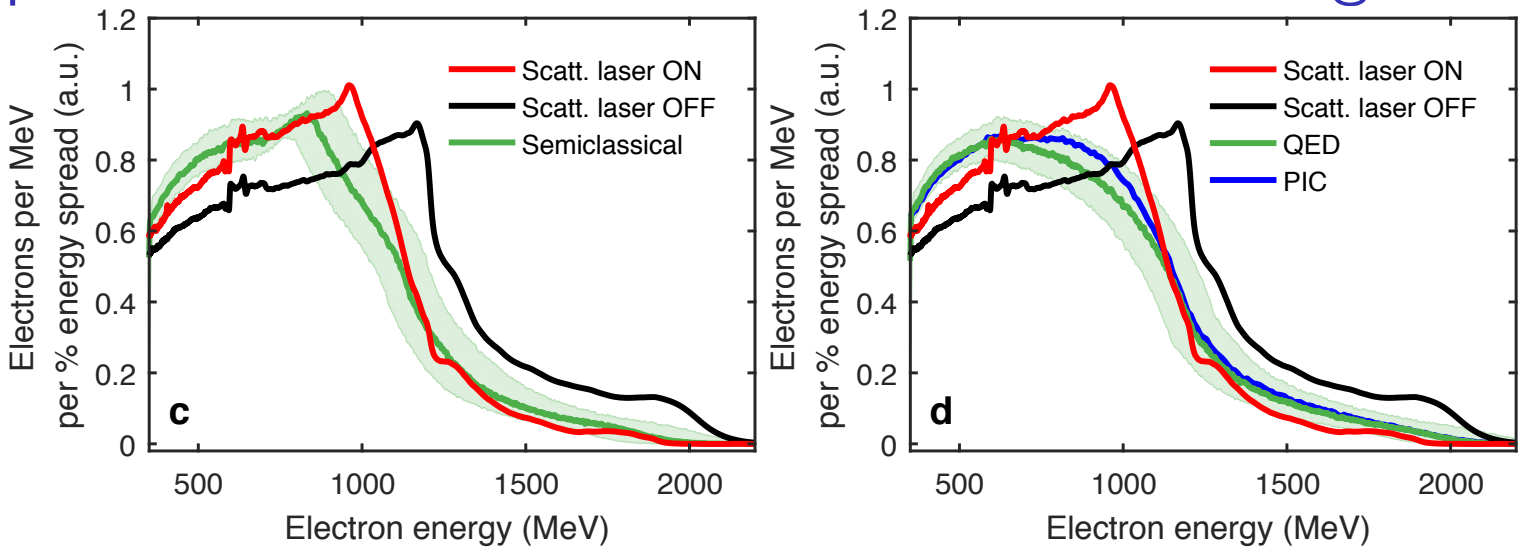

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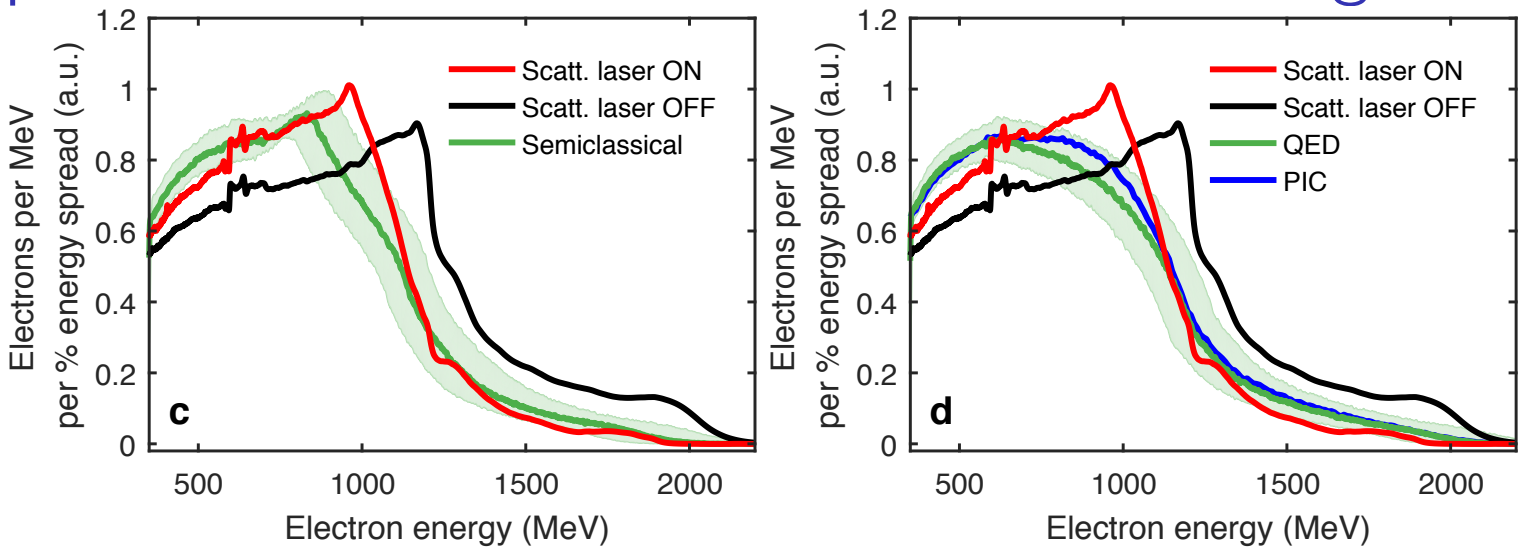

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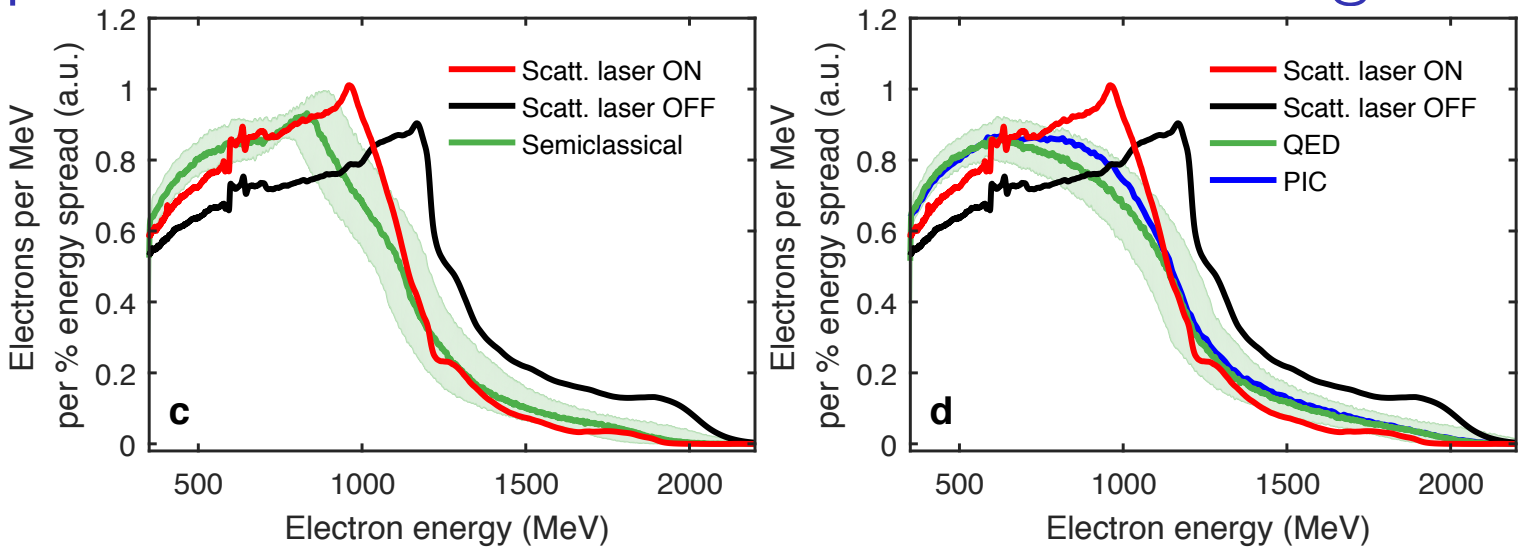

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- full QED is more sensitive which could explain worse match

Summary

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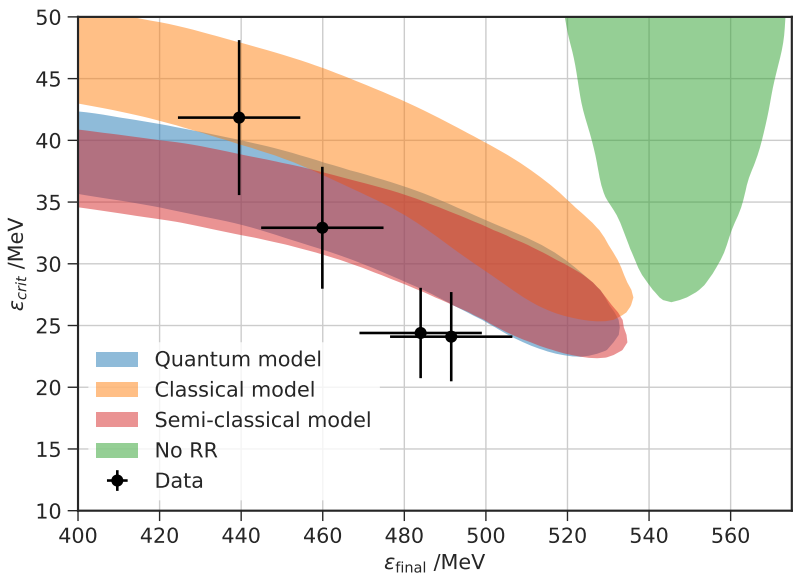
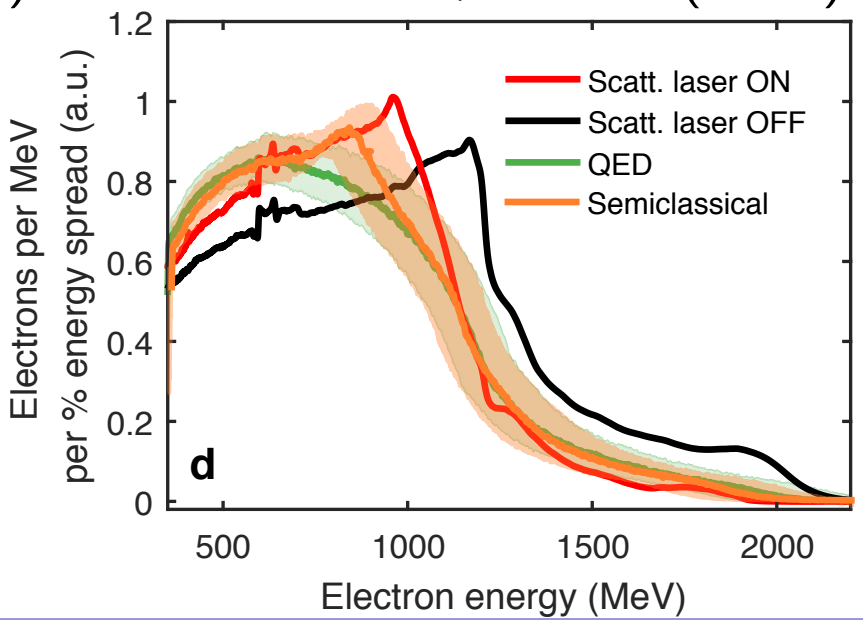
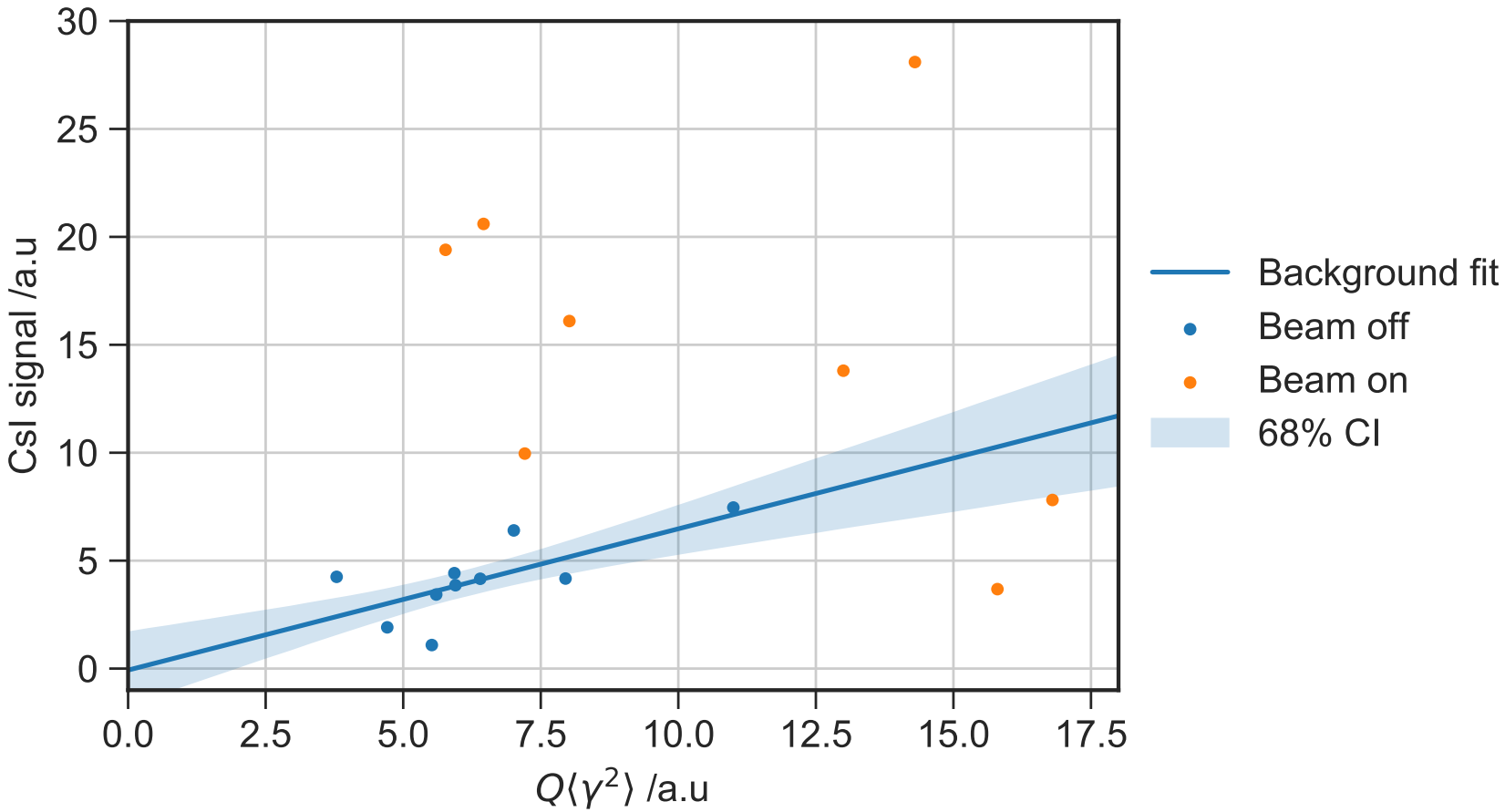
- see Cole et al., PRX **8** (2018) and Poder et al., PRX **8** (2018)



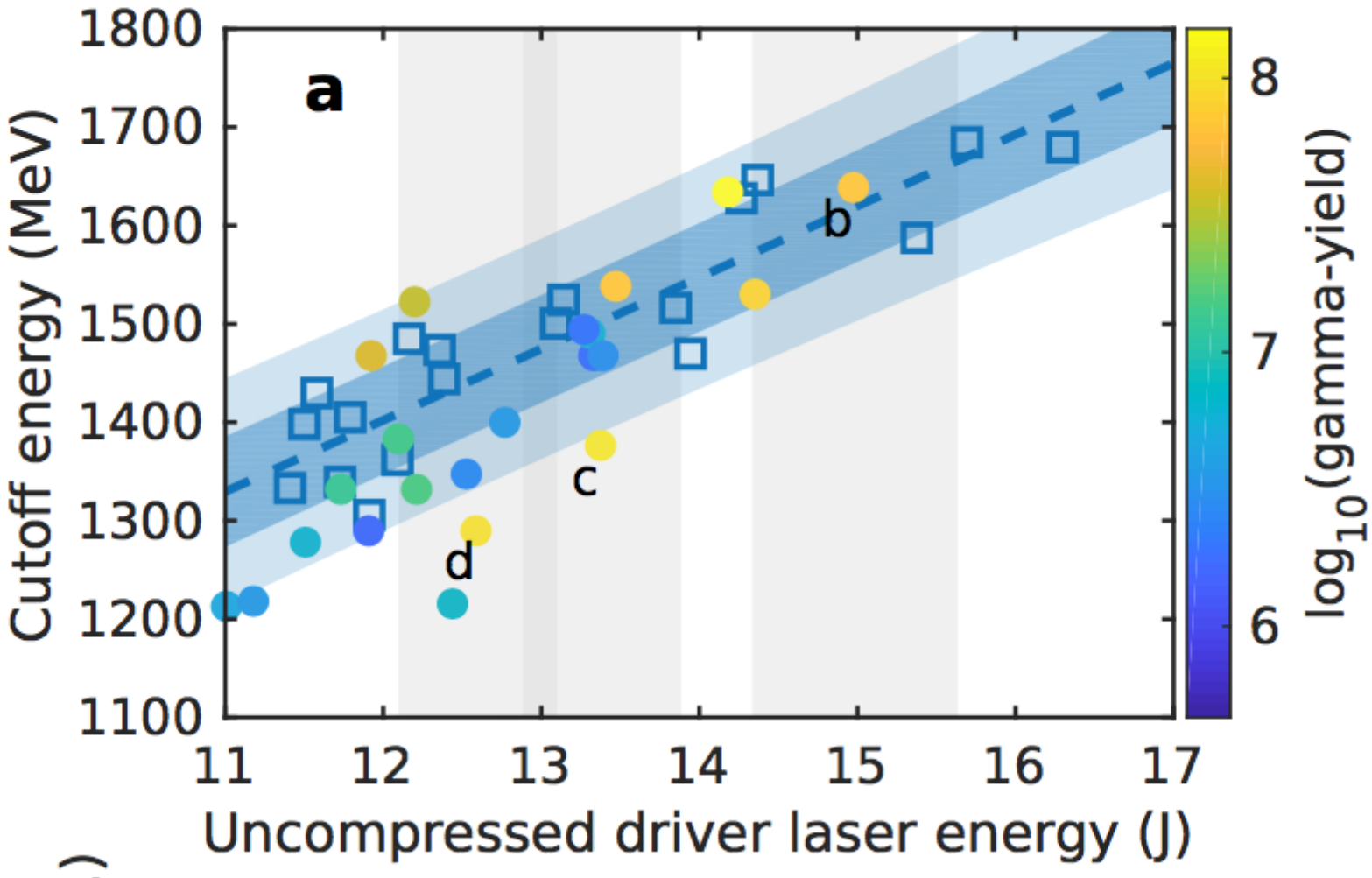


Backup Slides

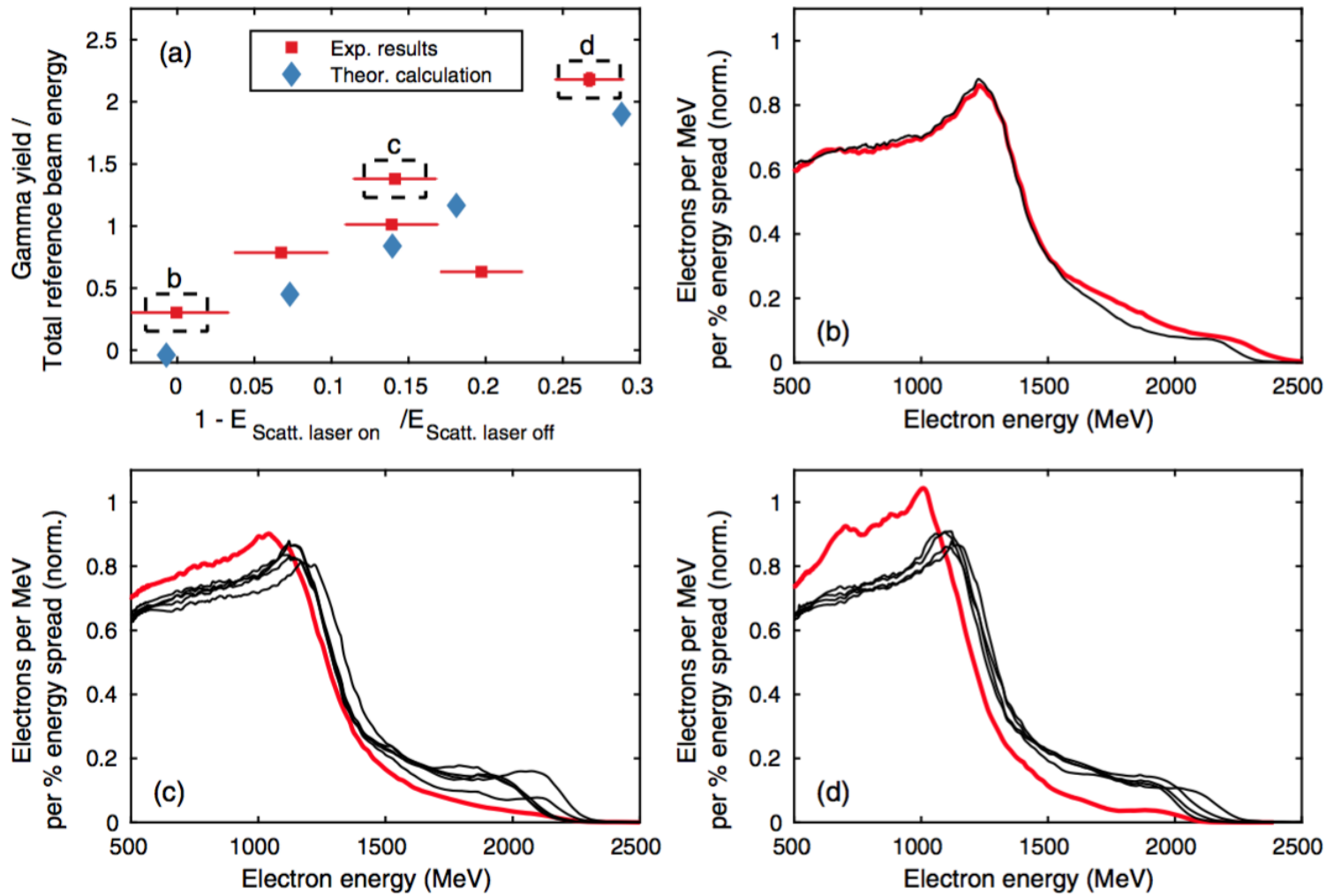
Background radiation scales well with e energy squared



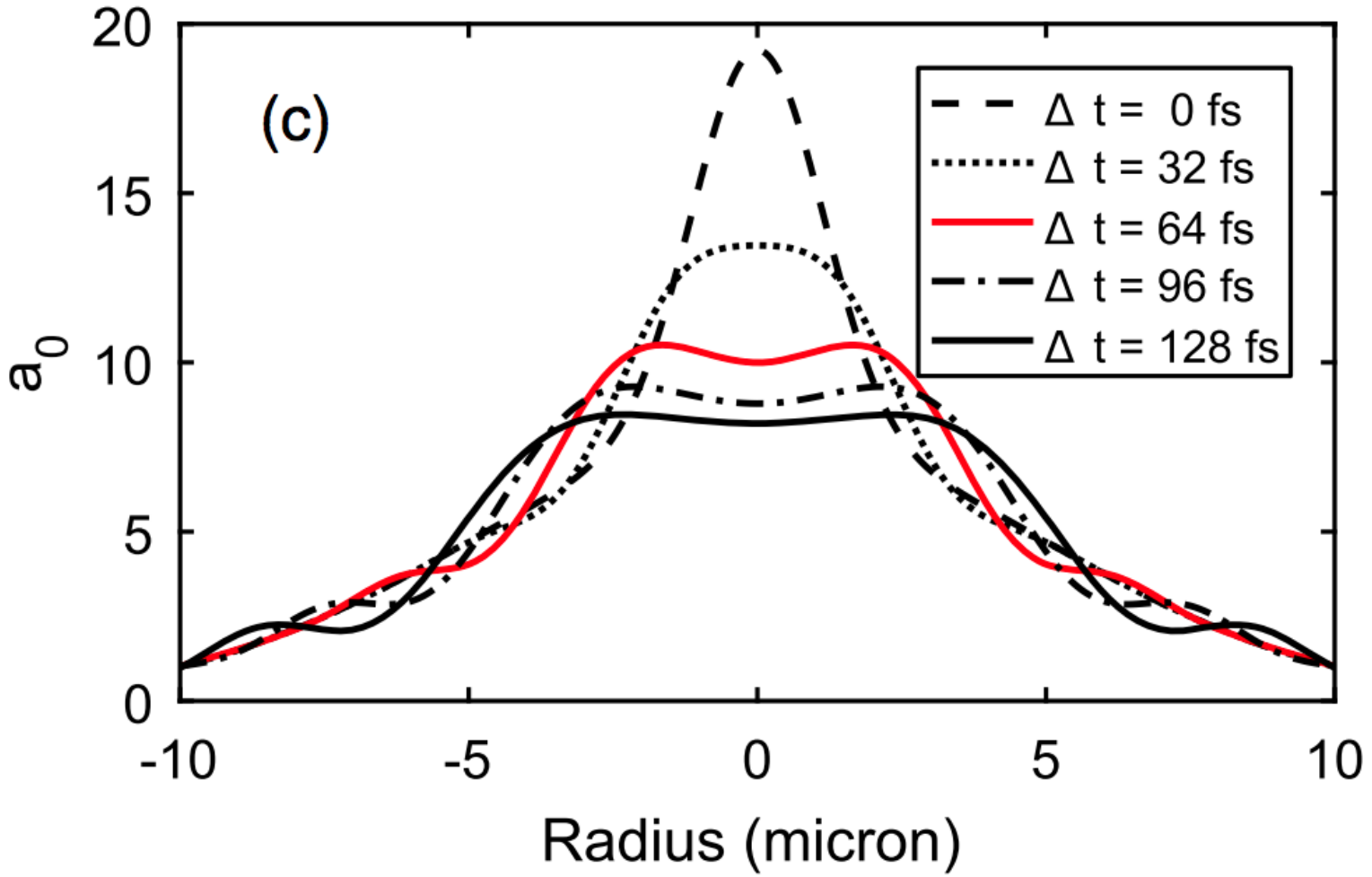
Scaling of electron energy to laser energy



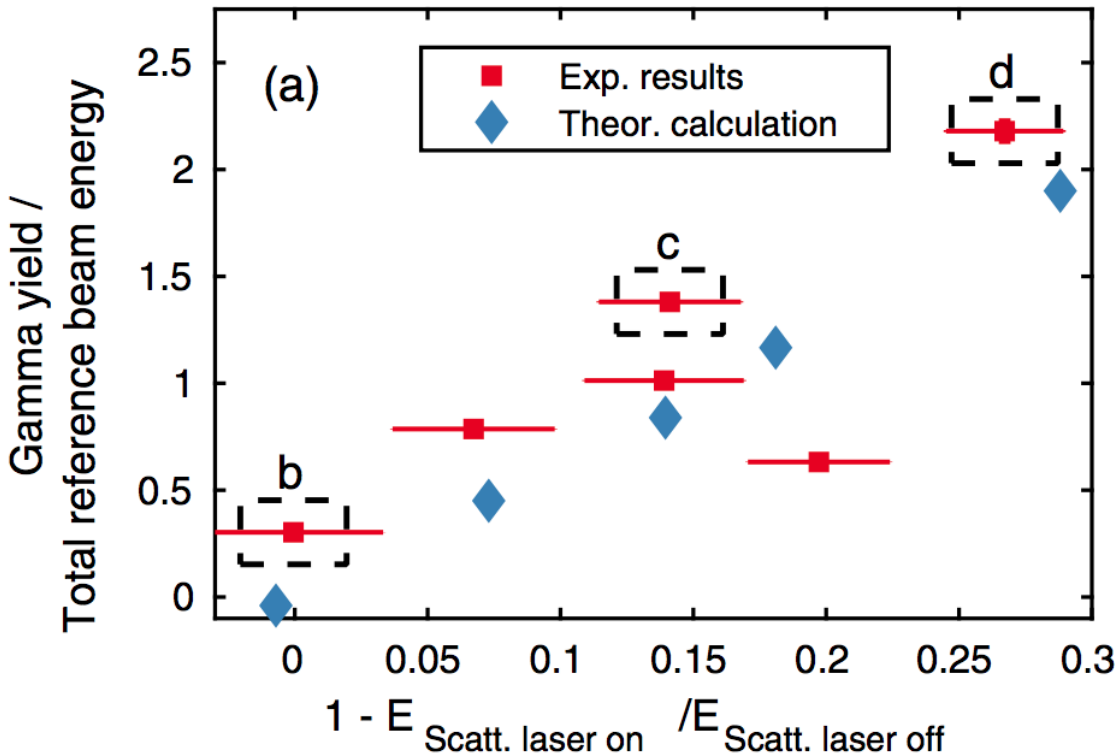
Variation in γ yield indicates different regimes of η



Laser intensity distribution for different relative timings

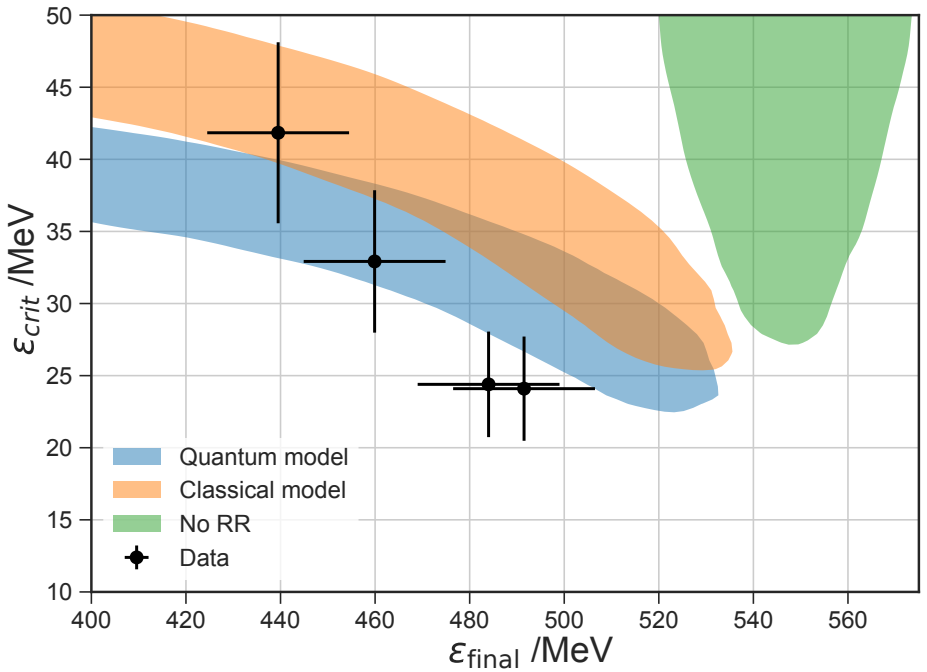


Gamma yield above background indicates successful collision



- the integrated gamma yield above the background indicates successful collisions and different levels of overlap
- we will now only consider the best overlap (highest γ and η)

Summary Part A



- Statistically significant evidence of radiation reaction was observed in a colliding pulse experiment at Astra Gemini
- Analysis shows that the results are in agreement with models of radiation reaction that include quantum corrections
- A discrimination between the classical model (LL) and the quantum models beyond the 1σ level requires more data
- Differences between the semi-classical and the full quantum model only expected at higher η: see second part of the talk
- Results published in Cole et al., PRX **8** (2018)

Summary Part B

- Evidence of energy loss in the electron spectrum
- Purely classical LL model overestimates losses
- Semi-classical model shows right signature (peak preserved)
- Quantum model with stochasticity shows worse alignment
- Remaining deviations could be due to experimental errors...
- ...or indicate a departure from the validity of the constant cross field approximation used to derive the quantum corrections