Update on the progress of the E-320 SFQED experiment

A. Knetsch on behalf of the E-320 Collaboration

SLAC National Accelerator Laboratory

SLAC NATIONAL ACCELERATOR LABORATORY

Stanford University

U.S. DEPARTMENT OF ENERGY

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Technical University (TU) of Darmstadt	Stephan Kuschel, Sarah Grimm
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HI Jena and University of Jena, Germany	Harsh, Felipe Salgado, Jannes Wulff, Matt Zepf, Aime Matheron
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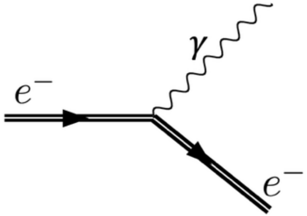
Strong-field QED: The questions we are addressing

$$\chi = \gamma \frac{E}{E_s}$$ $\chi > 1$ marks onset of QED effects

$$a_0 = \frac{e\,E}{m\,\omega}$$ $a_0 > 1$ marks onset of strong-field effects

Non-linear inverse Compton scattering :

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

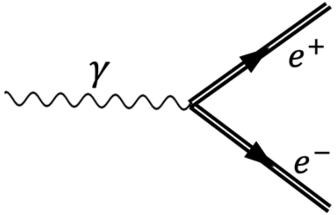


We investigate:

- Relativistic red shift of electron mass
- Quantum radiation reaction

Non linear Breit-Wheeler pair creation :

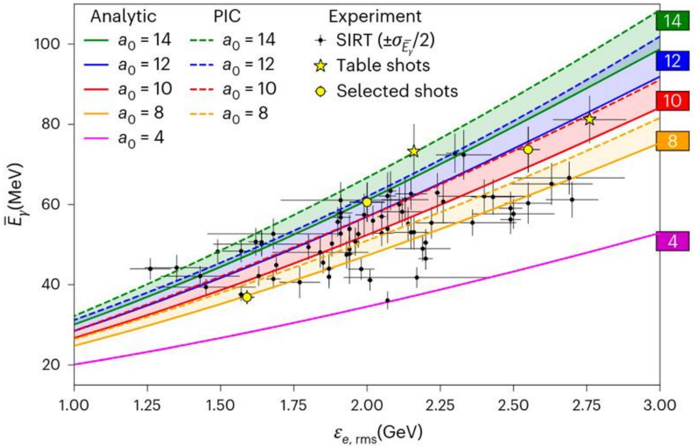
$$\gamma + n\omega \rightarrow e^- + e^+$$



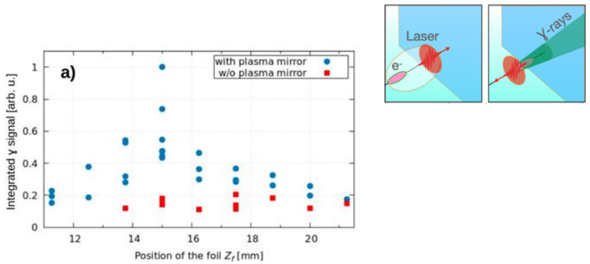
We investigate:

- Pair production from NLBW
- Tunneling regime of pair creation

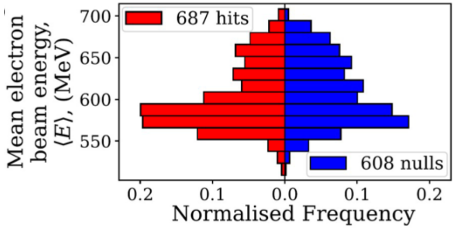
Great progress at PW laser facilities



Mirzaie et al., Nat. Photonics (2024) **~ 80 signal shots**



Matheron et al., arXiv:2412.19337 (2024)
~ 30 signal shots



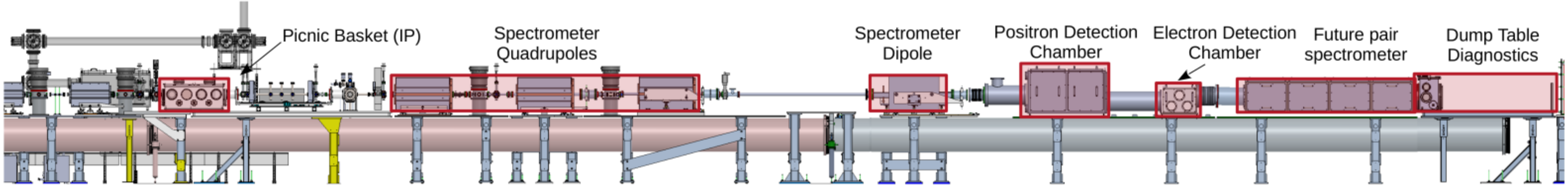
Los et al., Nat. Commun. 17, 1157 (2026)
~ 700 signal shots

Advantage: High a_0 , high fields
Challenge: Low repetition rate, low repeatability

- Great for exploration
- Difficult for high-precision measurement

How do we measure: The electron beam

FACET-II Facility for Advanced Accelerator Experimental Tests



FACET-II electron beam parameters

- Up to 2 nC bunch charge
- 10 GeV beam energy
- Energy spread 0.1 %
- Bunch length (rms) < 100 µm

IP capabilities

- Final Focusing to typically ~ 20 µm rms
- Control over waist location
- Quadrupole triplet for electrons or positron imaging
- Diagnostics for main-beam, scattered electrons, positrons, and Gamma rays
- Gamma ray spectrometer under development

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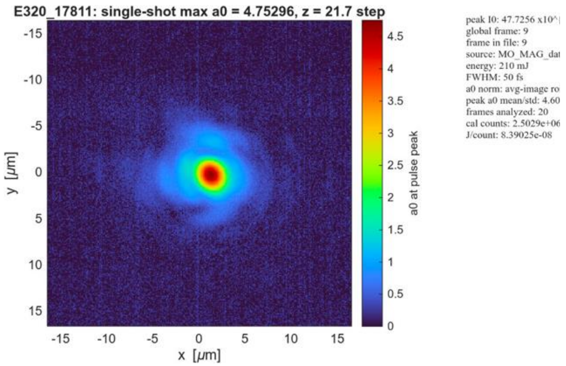
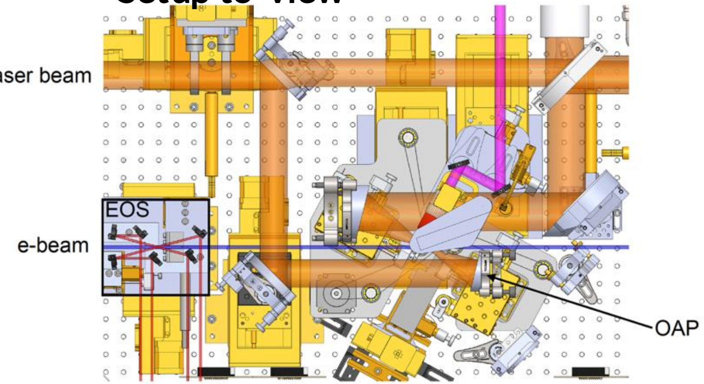
How do we measure: The laser pulse

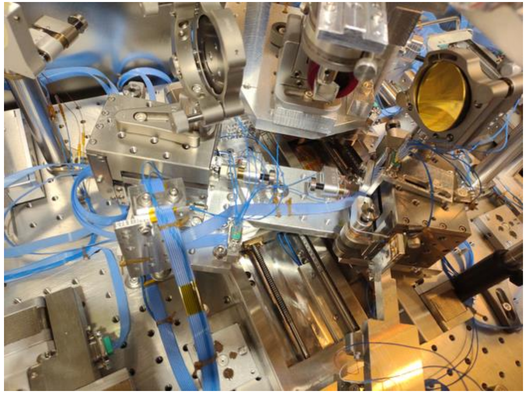
Intensity distribution in focus

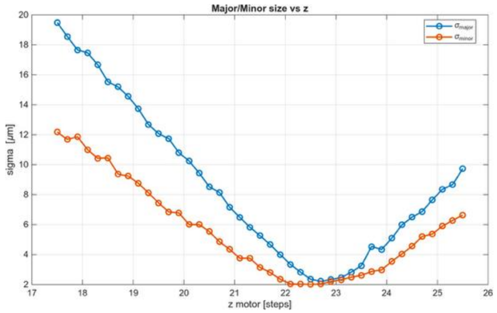
Analysis by Ching-En Lin



Setup to-view







FACET-II laser parameters

- Energy on target: ~ 300 mJ
- Pulse length: 48 fs FWHM
- Collision angle 28.1 deg
- F# 2
- a_0 ~ 4-5
- χ ~ 0.5

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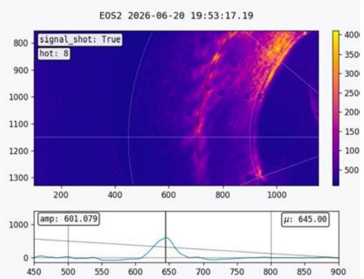
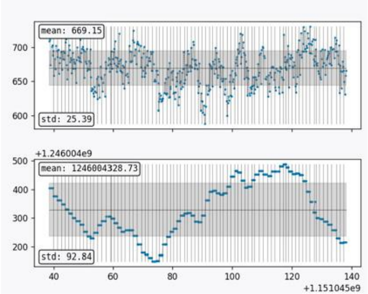
Precision SFQED measurements for 6 consecutive days

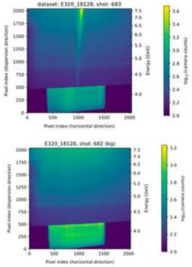
Electro-optical sampling



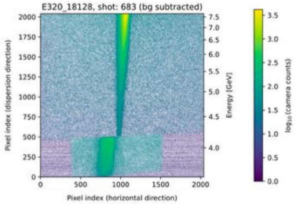


- Calibration: 6 fs/px
- PID feedback keeps timing stable
- Remaining jitter is precisely measured

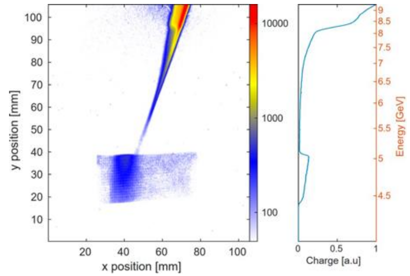
Few-particle electron detection



Signal and background shots

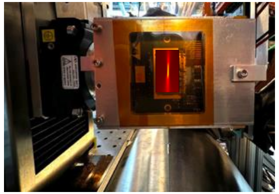


Signal shot with subtracted background



- Charge calibration ~ 15 ct/e$^-$
- Every second shot off-timed (*Goosed*)
- Imaging spectrometer

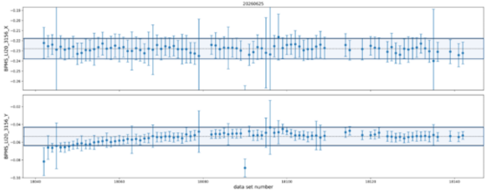
Positron tracker

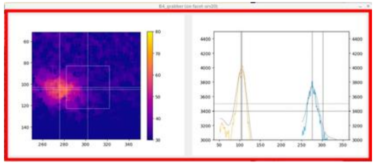


O. Borysov *et al*. (2026), arXiv:2604.23805

- 5 subsequent ALPIDE chips (Group Noam Tal Hod)
- Track reconstruction to identify NLBW positrons
- Very low positron background

Stable laser and electron alignment





- Accelerator feedbacks, beam remains within 10 um
- Feedback on laser alignment

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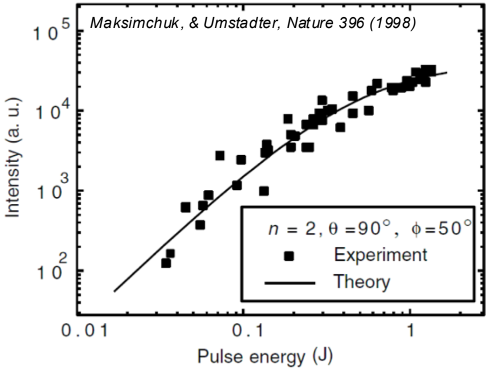
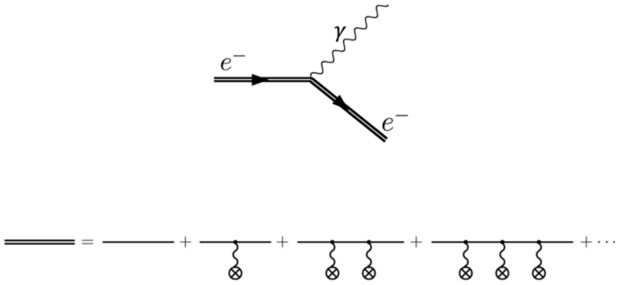
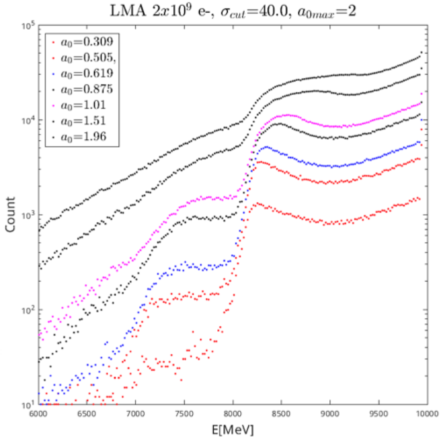
Mass dressing in the strong-field regime







Simulation: R. Holtzapple (CalPoly)

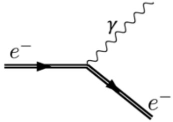
- Electron mass relativistically increased in laser field to $m^* = m\sqrt{1 + a_0^2/2}$
- Increased electron mass shifts Compton-edge to higher energies
- Mass-dressing well-known in classical regime, not in strong-field regime

Nonlinear Thomson scattering (classical ED)

Meyerhofer, Knauer, McNaught, & Moore, JOSA (1996)
Chen, Maksimchuk, & Umstadter, Nature 396 (1998)

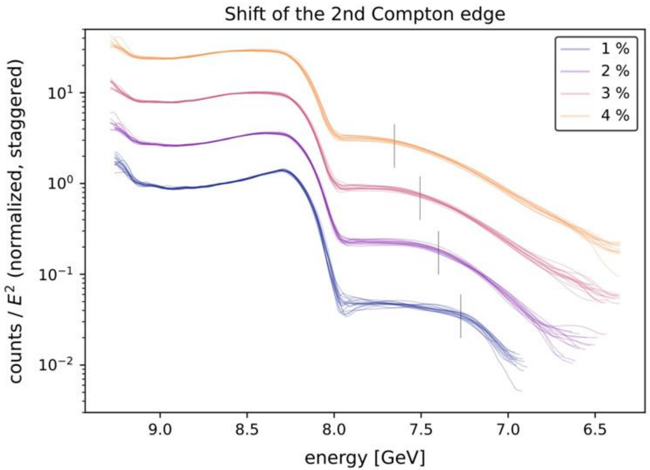
Dressed state / semiclassical picture in QFT

Volkov (1935), Furry (1951), Schwinger (1951), Glauber (1963), Nikishov & Ritus (1964), Brown & Kibble (1964), Baier, Katkov & Strakhovenko (1975)



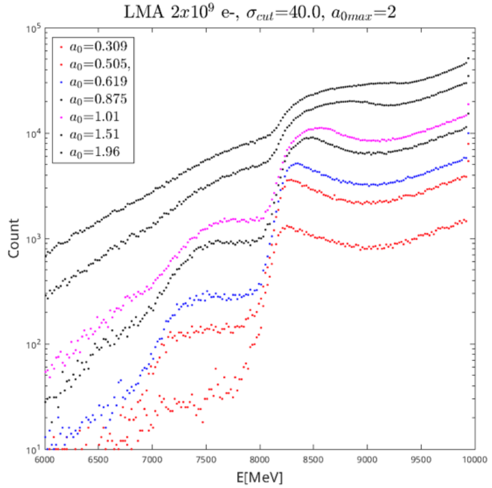
Mass dressing in the strong-field regime

Experiment



Analysis: T. Smorodnikova (Stanford)

Simulation



Simulation: R. Holtzapple (CalPoly)

- 5000 shots per energy setting, 1000 analyzed
- Down-sampled for best time-of-arrival and spatial overlap → 15 shots each
- Most precise measurement of mass dressing in SFQED regime so far

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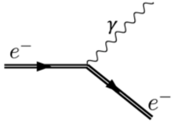
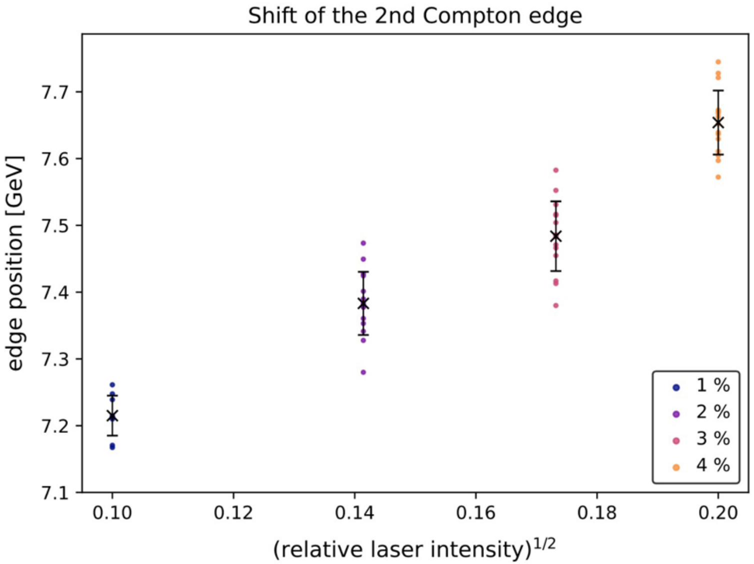
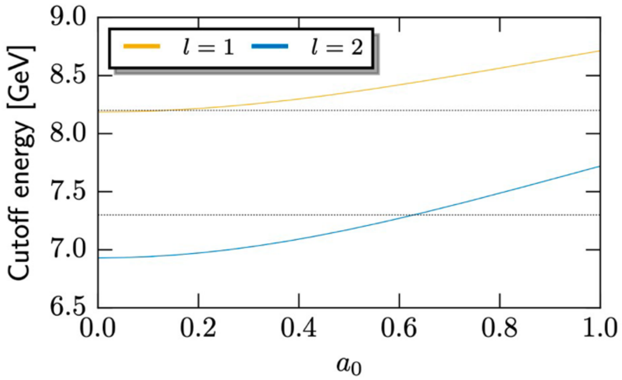
Mass dressing in the strong-field regime







$$m^* = m\sqrt{1 + a_0^2/2}$$

- Clear mass shift of about 0.5 GeV (from ~ 7.2 to ~ 7.7 GeV)
- Compatible with a_0 ~ 0.4-0.5 for 1% laser intensity, implying a maximum a_0 ~ 4-5
- Preliminary analysis, much more data to go through
- Simulations ongoing. **Goal: precisely compare mass increase scaling**

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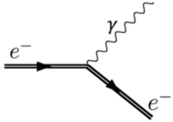
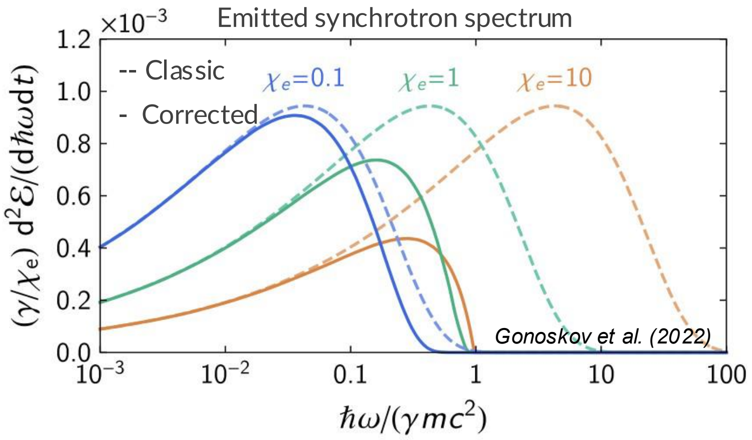
From classical to quantum synchrotron radiation





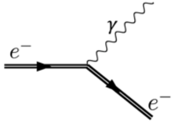
E320 parameters

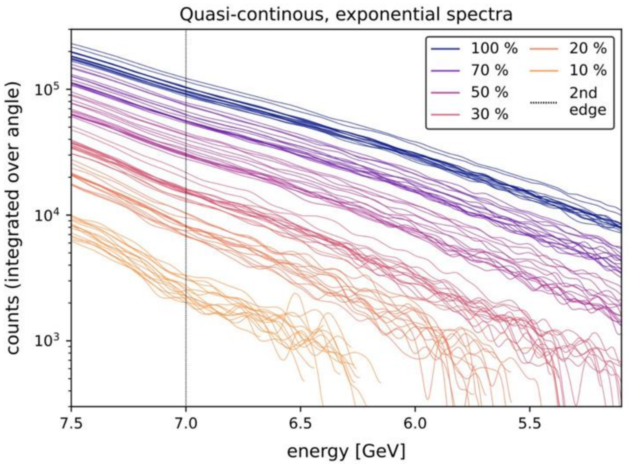
a0 ~ 4.5
χ ~ 0.5

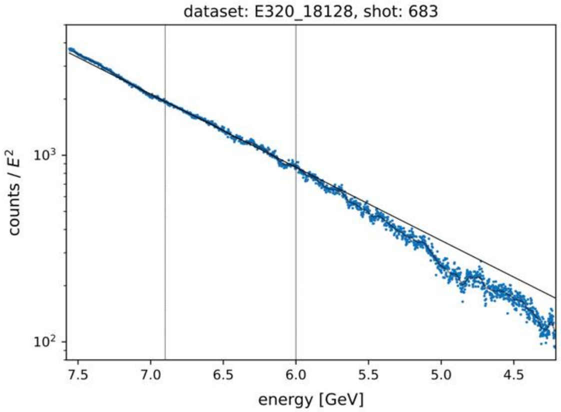
- In classical electrodynamics photons are not quantized, therefore only the emitted power is meaningful
- At χ> 0.1 quantum corrections are required
- E-320 is testing the validity of one of the most fundamental effects in accelerator science

Classic Synchrotron spectrum
Schott (1912), Schwinger (1949)
Quantum-corrected synchrotron spectrum
Sokolov, Klepikov, & Ternov (1952, 1968), Schwinger (1954)
Gonoskov et al. (2022), Blackburn (2020), Di Piazza et al. (2012)

From classical to quantum synchrotron radiation







- Simultaneous interaction with ~ a_0^3/χ >100 photons → Clearly non-perturbative regime
- 20K shots including 6 laser energy settings and 3 spectrometer imaging condition
- Clear observation of contiguous exponential spectrum

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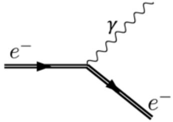
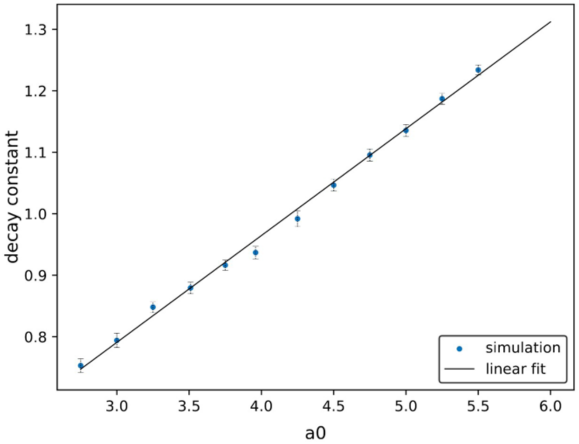
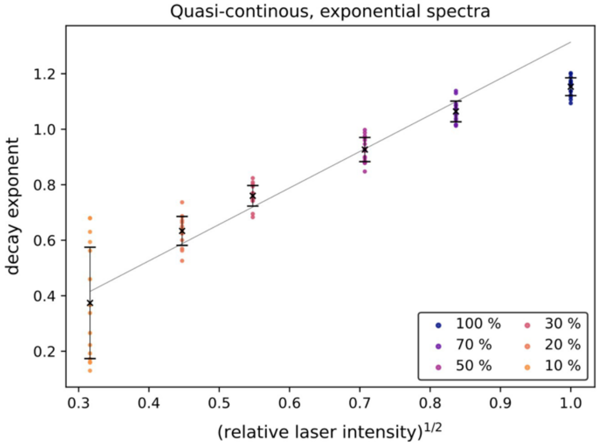


From classical to quantum synchrotron radiation

Simulation

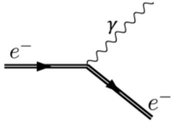


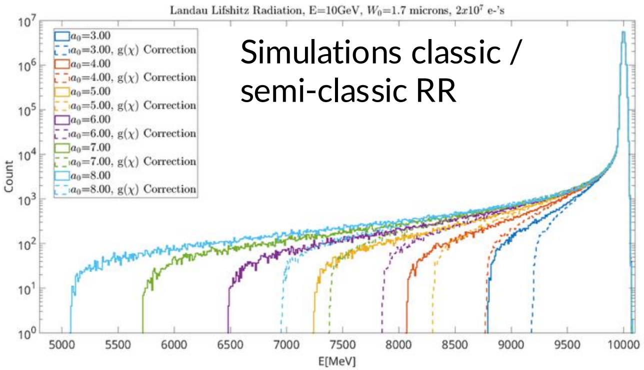
Experiment

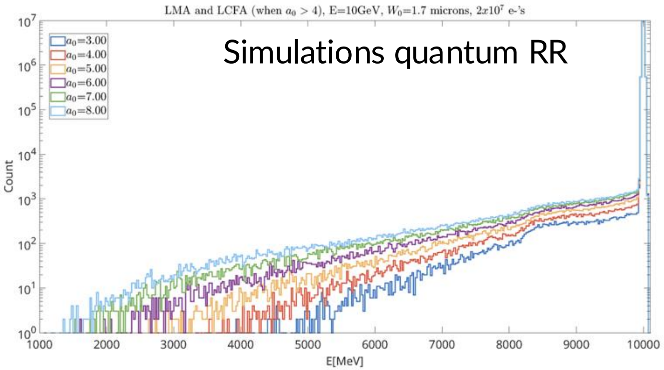


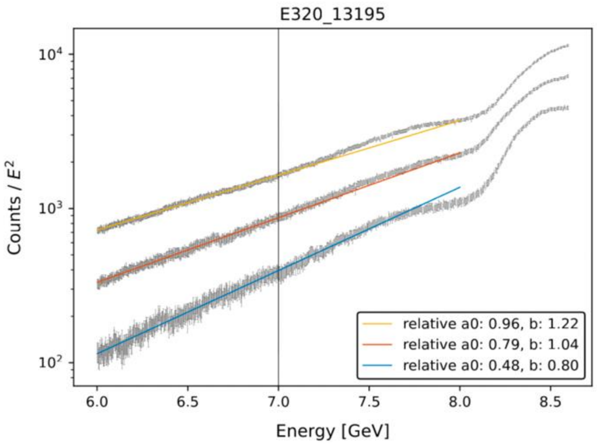
- Simulation in Local monochromatic Approximation
- Decay constant in electron spectrum can be compared with simulations

A note on classical versus quantum radiation reaction









Quantum-corrected Landau Lifshitz fail to describe prominent observed spectral features:

- No mass dressing
- Unphysical cutoff towards lower energies

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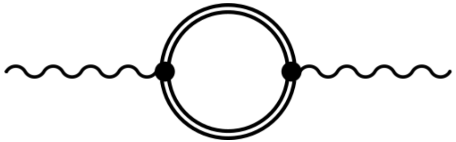
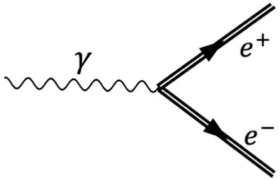
Simulation plots by R. Holtzapple, analysis by T. Smorodnikova

Nonlinear Breit-Wheeler pair creation



Vacuum polarization

Photon temporarily decays into virtual e^+ e^- pair



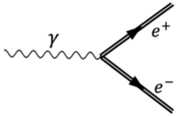
Pair production

At critical field virtual pair becomes separated into real pair

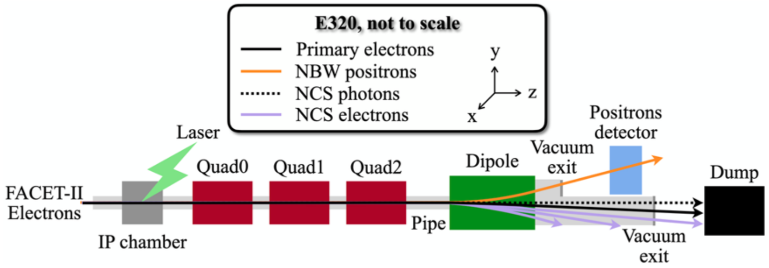
- E-144 showed NLBW pair creation in perturbative regime
- E-320 aims to measure NLBW pair creation in non-perturbative regime

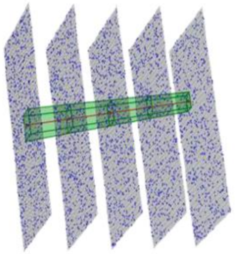
QED vacuum instability

Klein paradox (1929), Sauter (1931), Euler/Heisenberg (1936) Schwinger (1951)

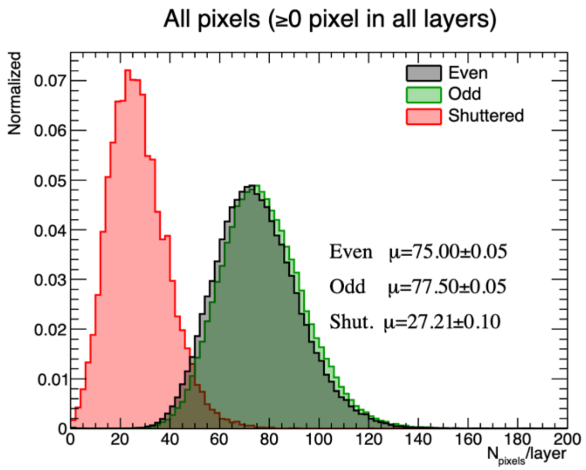


Nonlinear Breit-Wheeler pair creation

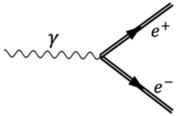




	Shots	Tracks	Rate	Error
background	123739	15	1.21E-04	3.13E-05
collisions	137388	21	1.53E-04	3.34E-05



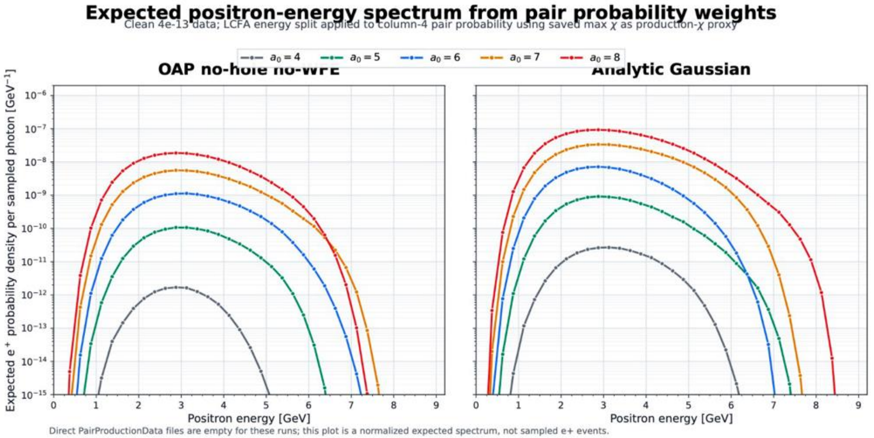
- 11 h continuous data acquisition at 10 Hz
- Very stable conditions, Very low noise
- **First hint of NLBW positrons in non-perturbative regime**



Nonlinear Breit-Wheeler pair creation: Outlook for 2027

Laser intensity (current: a_0~4.5)	e+ /shot	Bg shots	Timed shots	Positrons	S/√B
$a_0 = 5.0$	0.01	50 %	10 %	6.1	14.3
$a_0 = 5.5$	0.05	50 %	10 %	**30**	71.6
$a_0 = 6.0$	0.2	50 %	10 %	120	286.4

detector acceptance: 30 %, tracking efficiency: 10 %; assumption: 10h run



Path towards clear NLBW positrons:

- Increase a_0 from 4.5 to 5.5
- Improve imaging and transport
- Improve laser-to-beam timing drifts
- Change background-to-signal ratio

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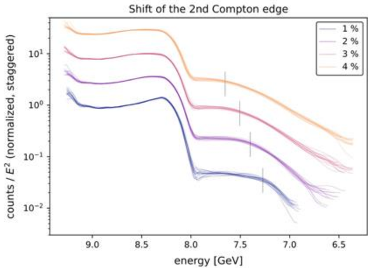
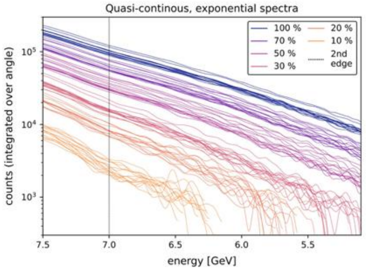
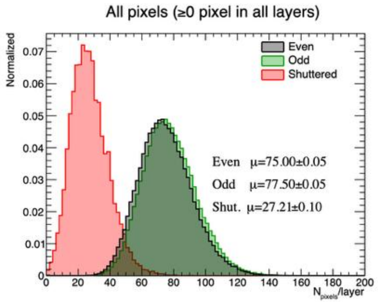
Summary

- Relativistic mass dressing
  - Very clean data, no doubt on positive observation
  - Precise modeling ongoing for quantitative statements
- Quantum radiation reaction
  - Very clean electron spectral data
  - Gamma spectrum to be analyzed
  - a_0-dependent divergence to be analyzed
- NLBW positrons
  - First hint at positron detection
  - Improve detection efficiency
  - Improve production rate



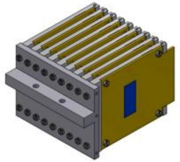




E320 branching out

Detector development and testing

- LUXE Cherenkov detector (see Athanassiadis, Antonios, et al. *NIM-A* 1080 (2025): 170777)
- ALPIDE detector (see O. Borysov *et al.* (2026), arXiv:2604.23805)



Experiments

- E-330 Strong-field laser wire experiment led by Junzhi Wang
- E-343 Laser control and collimation of particle beams for Higgs factories
    - Poster by Ching-En Lin

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Thank you for your attention