Strong Field QED
Current Experiments and Future Possibilites

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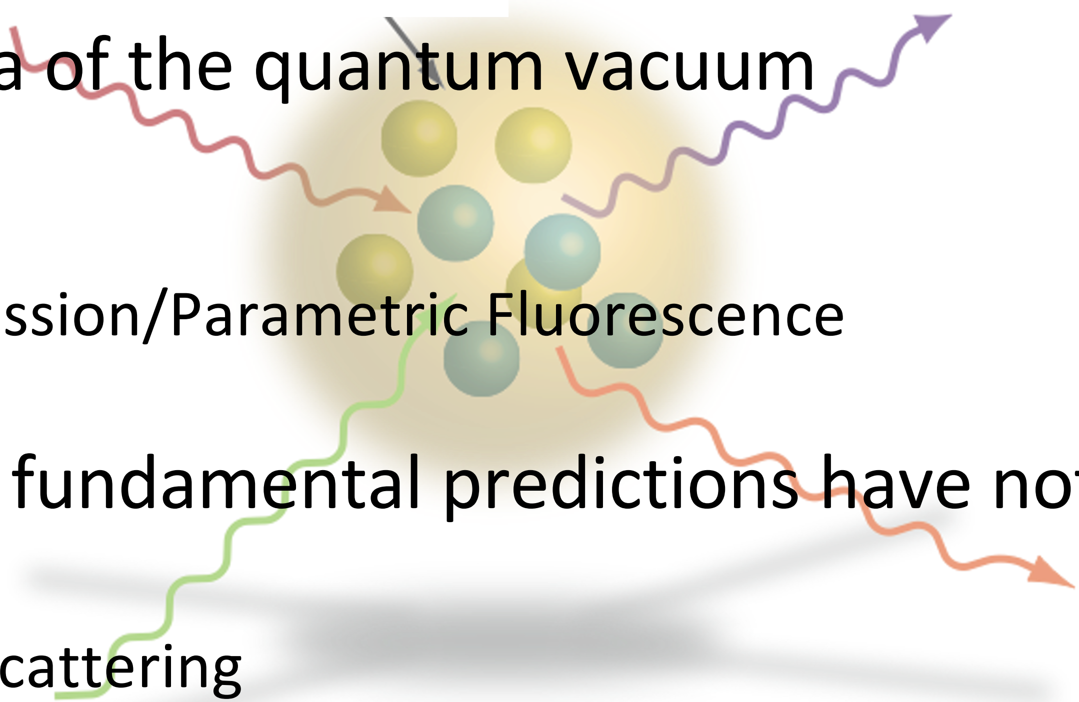
Quantum Vacuum

- What do we mean by the Quantum Vacuum?
  - Fluctuations around a mean of Zero for particles and fields.

- Linear phenomena of the quantum vacuum
  - Lamb Shift
  - Casimir effect
  - Spontaneous Emission/Parametric Fluorescence



- Some of the most fundamental predictions have not been tested
  - Photon/Photon Scattering
    (Violation of the superposition principle)
  - Pair Production in Vacuum
  - Trajectory of an electron in an electromagnetic field

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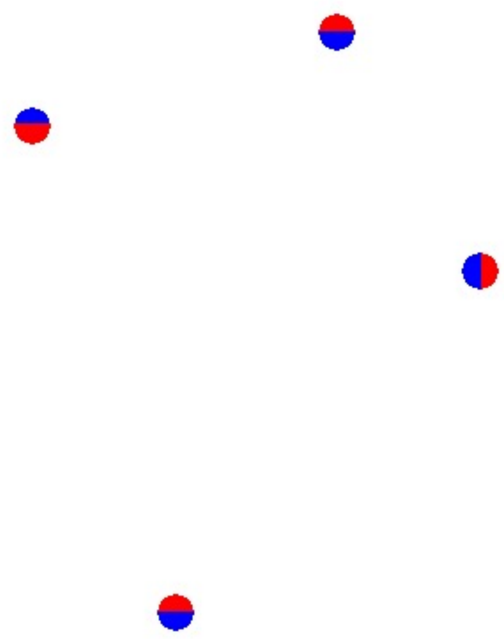
The quantum vacuum – an optical medium

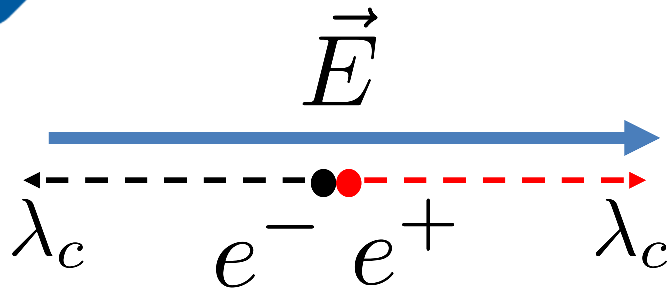
Classical description versus quantum vacuum

vacuum fluctuations



Presence of charged (virtual) particles
=> Coupling between different fields

Effects are very weak

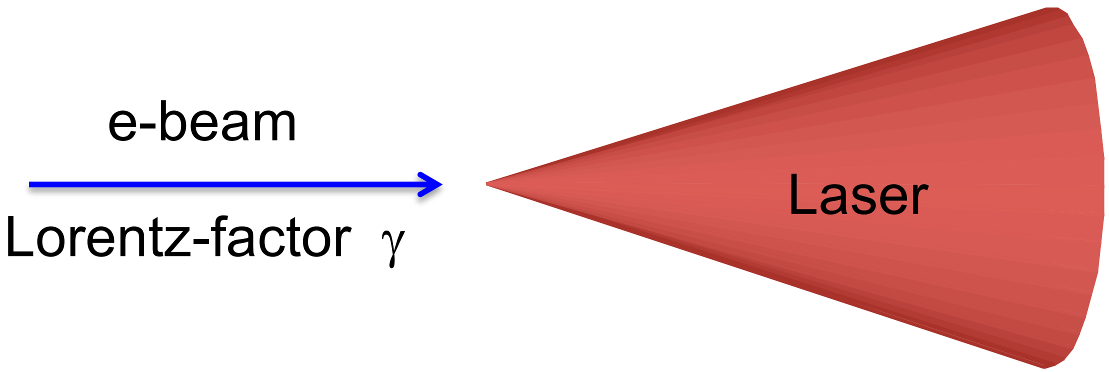


- Work performed on each Lepton over Compton wavelength corresponds to electron restmass

$$W = \lambda_c e E_{cr} = \frac{\hbar}{mc} \times eE_{cr} = mc^2$$

  - At this point our vacuum fluctuations become real
  - Effects become comparable to single electron
- Corresponding Intensity: $I_{cr} \sim 10^{29} Wcm^{-2}$
  - Below this strongly suppressed

Achieving the Critical Field – The Boosted Frame



$$\chi = \frac{E'}{E_{cr}} = \gamma \frac{E}{E_{cr}} (1 - cos\theta)$$

- The strength of electric and magnetic field increases in the boosted frame of reference.
  - Energy is conserved
  - Length contraction leads to higher energy density
    - Field strengths increase
    - Equivalent factor χ_γ for photon/photon collisions
- Critical field can be reached

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The field strength parameter

$$a_0 = \frac{eE}{mc\omega_0}$$

- Familiar in laser physics as normalised vector potential
  - Relativistic threshold:
    Restmass energy gained over one wavelength
  - a0 = ξ => Same paramter, different name
- Strong Field QED:
  - a0 ~ Number of laser photons absorbed per Compton wavelength

$$\Delta\mathcal{E} = eE\lambda_c = a_0\hbar\omega_0$$

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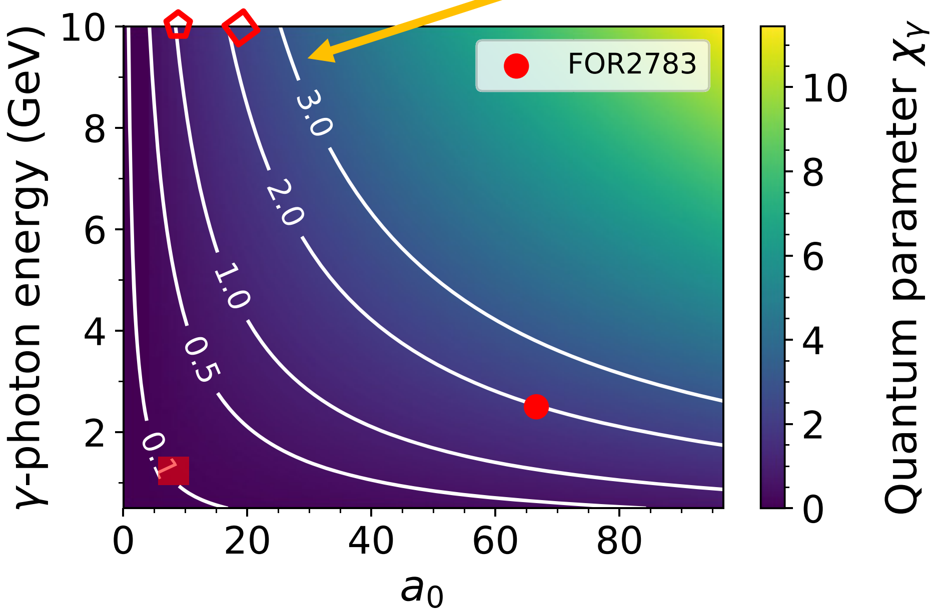
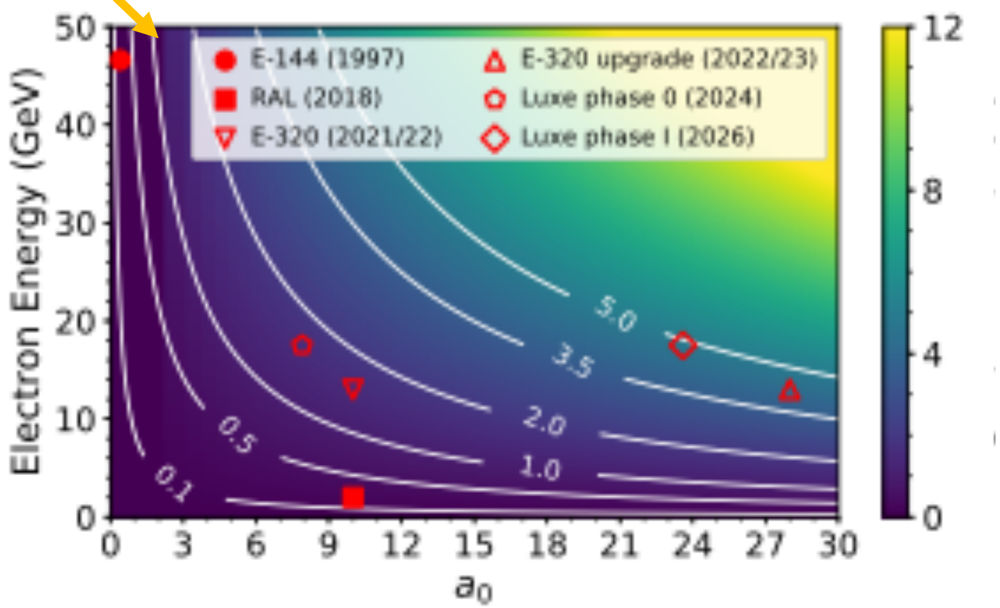
Wide Parameter Range Accessible

χ isocontours





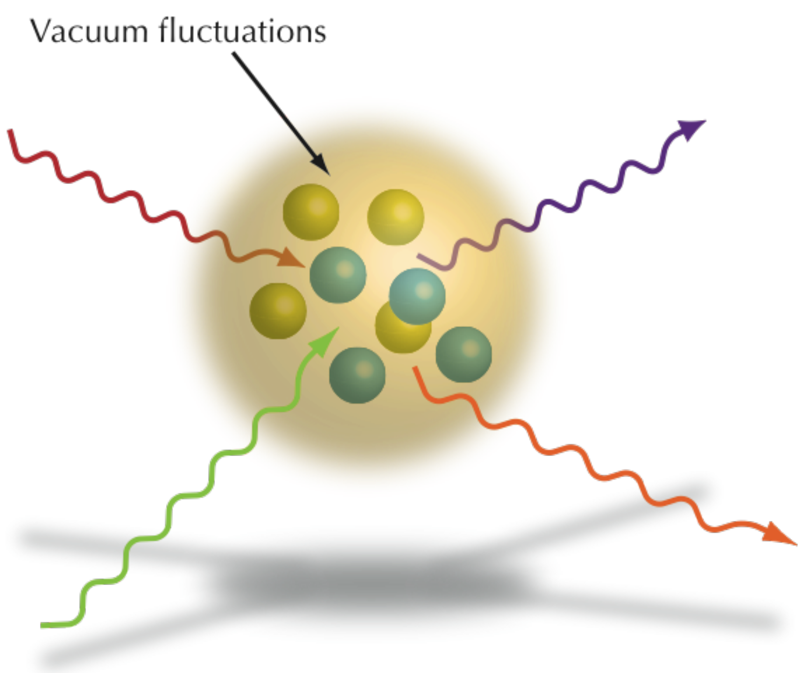
- Currently available e-beam energies: 2-17 GeV
  - 47 GeV at now decomissioned SLAC
- a0 > 100 possible at PW
  - Not (currently) concurrently available

Fundamental phenomena accessible

Accessible phenomena < E_{cr}:

- Vacuum polarisation effects
  - Vacuum Bi-refringence
  - Quantum Reflection
  - 4-Wave mixing

- Non-linear Compton scattering
- Radiation Reaction effects
- Linear Vacuum Pair Production



Accessible phenomena ~ E_{cr}:

- Non-linear Pair Production
- Non-perturbative Compton Scattering

$$E_{cr} = \frac{m^2c^2}{hc} = 1.3\times10^{16}\ \mathrm{V/cm}$$

$$I_{cr} = \frac{cE_{cr}^2}{8\pi} = 2.3\times10^{29}\ \mathrm{W/cm^2}$$

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Radiation Reaction

- What is the correct equation of motion of a charged particle?
  - Without radiation reaction, Lorentz force

$$F = e(\mathbf{E} + \mathbf{v} \times \mathbf{B}) = m\mathbf{a}$$

  - Classical radiation reaction: Lorentz Abraham

$$m\mathbf{a} = \mathbf{F_{rad}} + \mathbf{F_{ext}} = \frac{2}{3}\frac{q^2}{4\pi\epsilon_0 c^3}\frac{\delta\mathbf{a}}{\delta t}$$

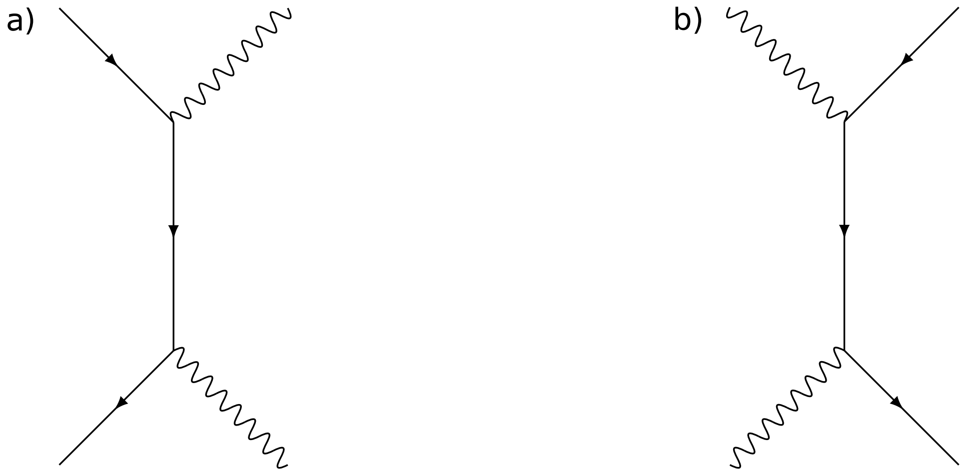
$$\mathbf{F}_{ext} = e(\mathbf{E} + \mathbf{v} \times \mathbf{B}) \qquad \mathbf{F}_{rad} = \frac{2}{3}\frac{q^2}{4\pi\epsilon_0 c^3}\frac{\delta\mathbf{a}}{\delta t}$$

  - At high intensites:
    Quantum Effects - which model is correct?

Pair Production

e+/e- annihlation: e+/e- pair production:

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



Annihilation a) and it‘s inverse, b) linear **Breit-Wheeler** Pair Production

These processes are analogous to ionisation/recombination in atoms:

Three distinct approaches possible (as in atoms):

1) linear ionisation (photon/photon collision)
2) Static field ionisation
3) Multi-photon/Tunneling processes

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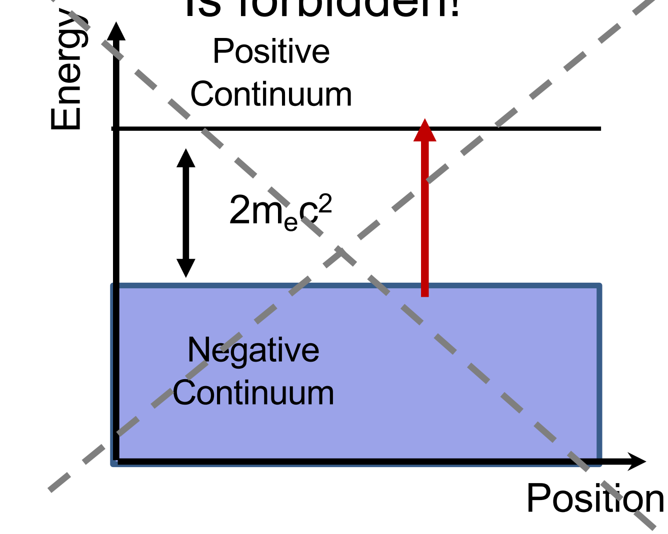
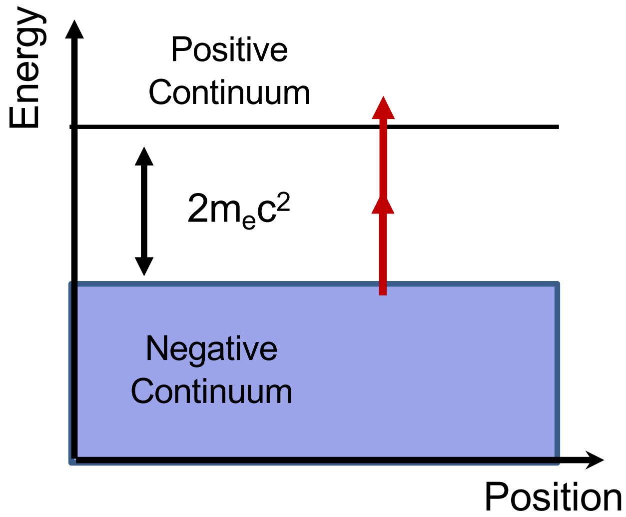
Pair production processes

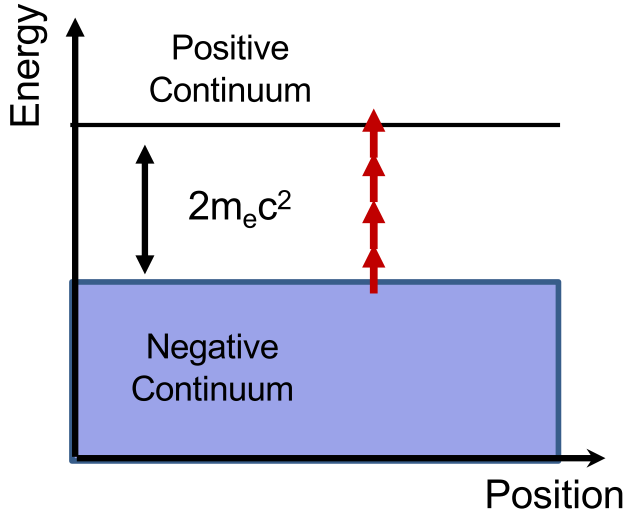
Single photon process
Is forbidden!

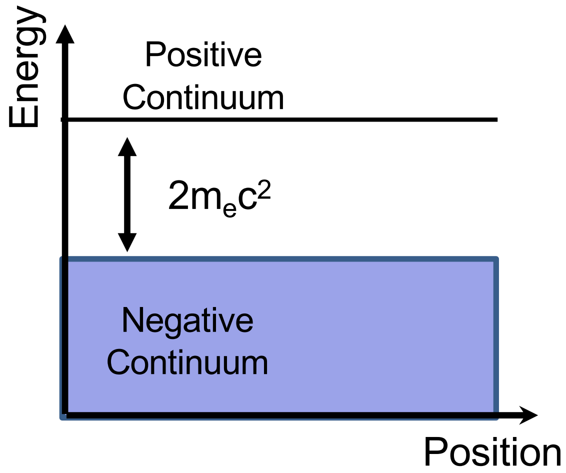


Linear Breit-Wheeler

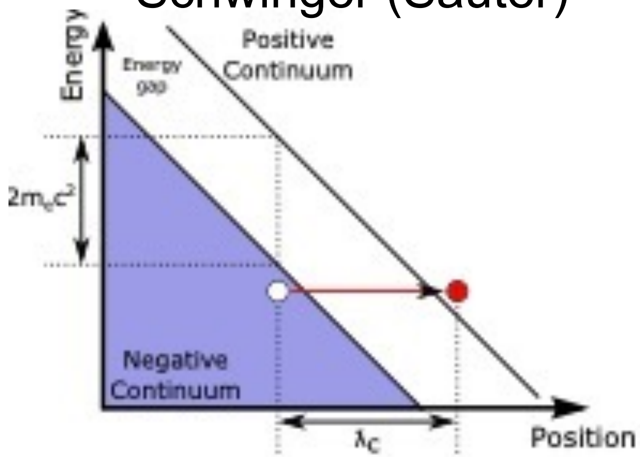


Multi-Photon Breit-Wheeler

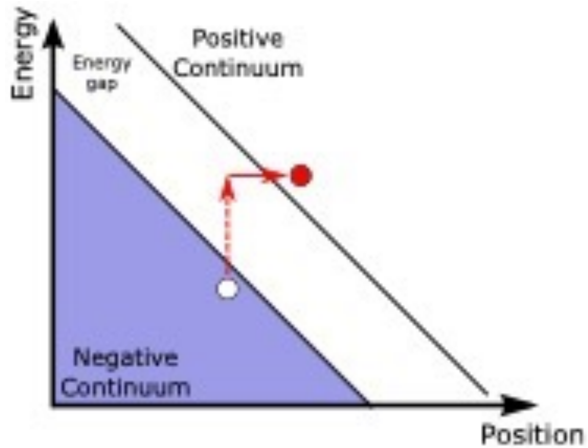




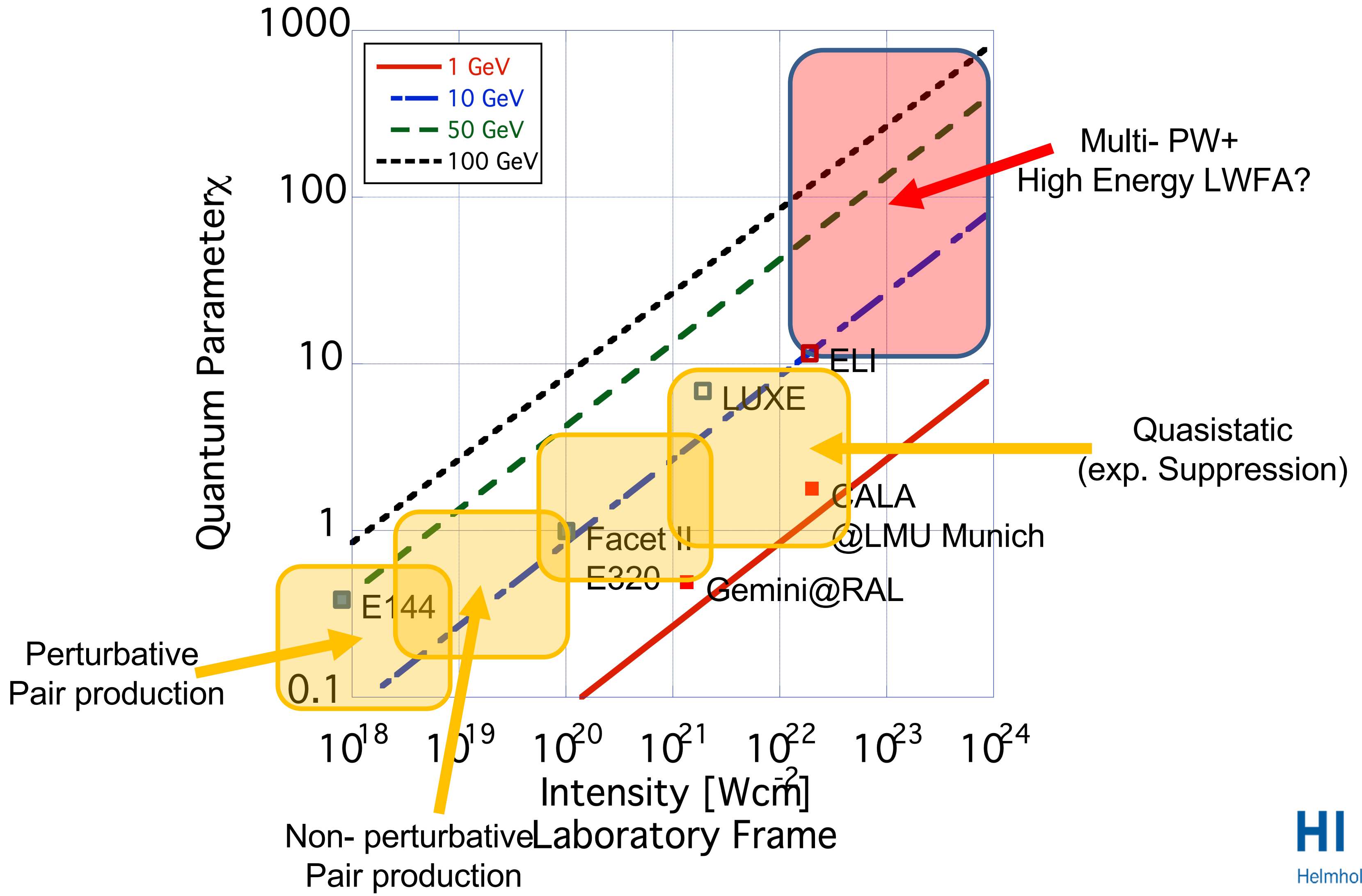
Schwinger (Sauter)



Non-Peturbative, Quasi-Static



Experiments: Past, Present, Future



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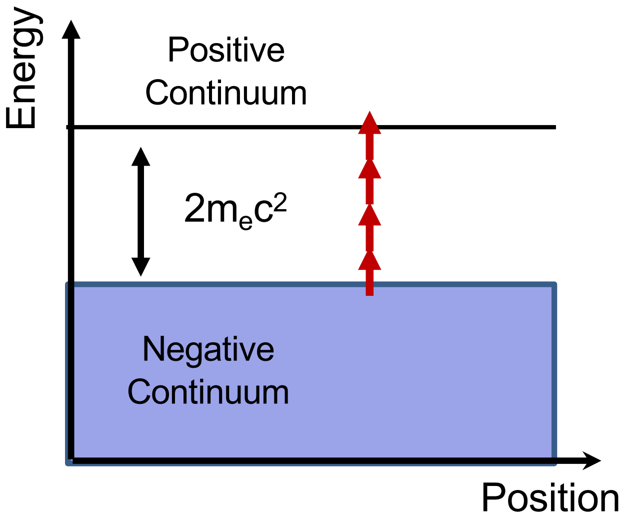
E144 @ SLAC



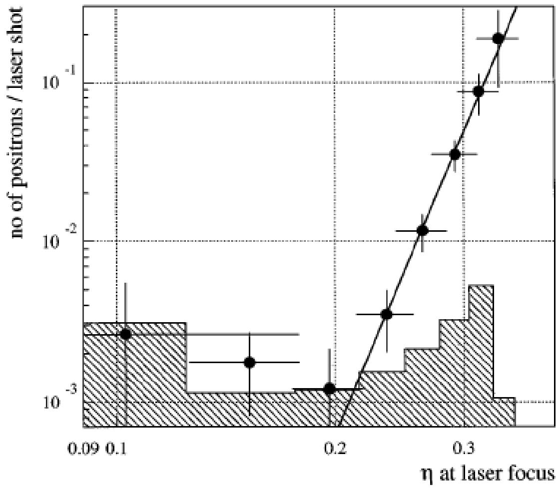
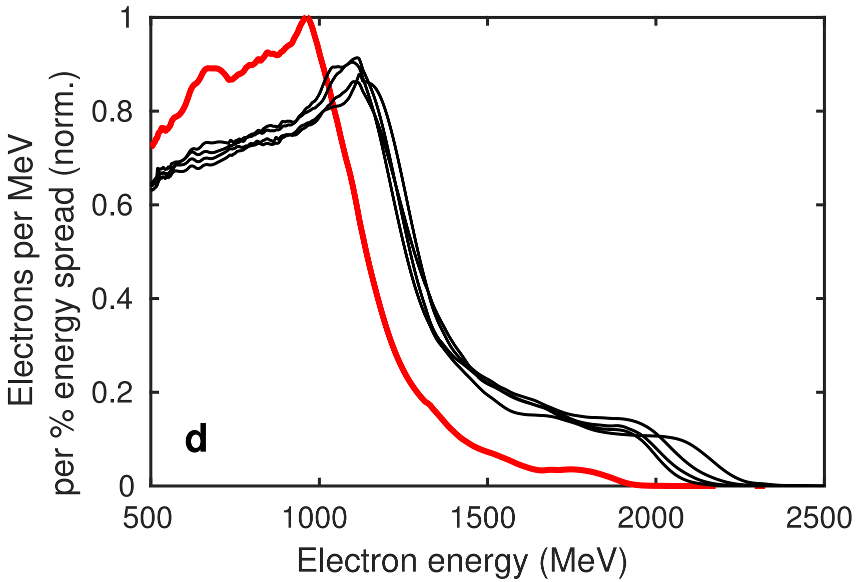
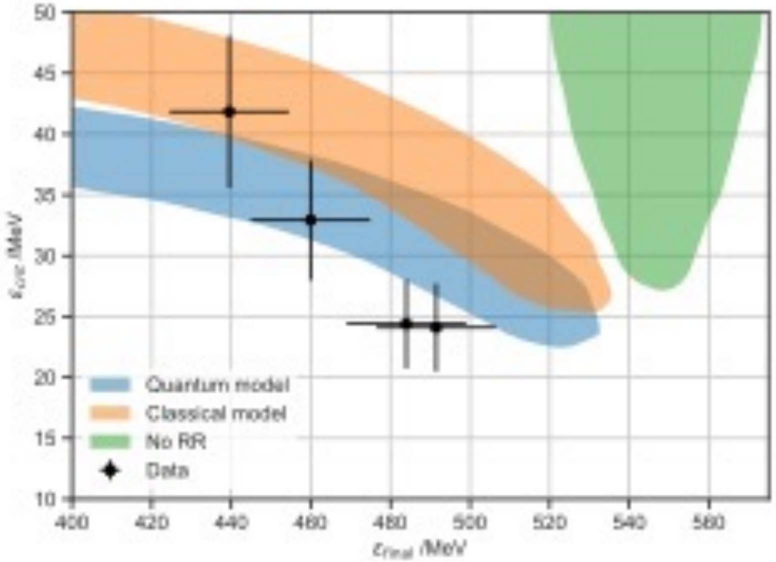


FIG. 4. Dependence of the positron rate per laser shot on the laser field-strength parameter η. The line shows a power law fit to the data. The shaded distribution is the 95% confidence limit on the residual background from showers of lost beam particles after subtracting the laser-off positron rate.

- First non-linear QED Experiment
  - $\chi<1$
  - Perturbative regime
  - Pair production in electron-laser interactions

Gemini Experiments





- Radiation reaction experiments in $\chi<1$
- First ‚all-optical ‚

K Poder et al. Physical Review X 8 (3), 031004 (2018)
JM Cole, et al, Physical Review X 8 (1), 011020 (2018)

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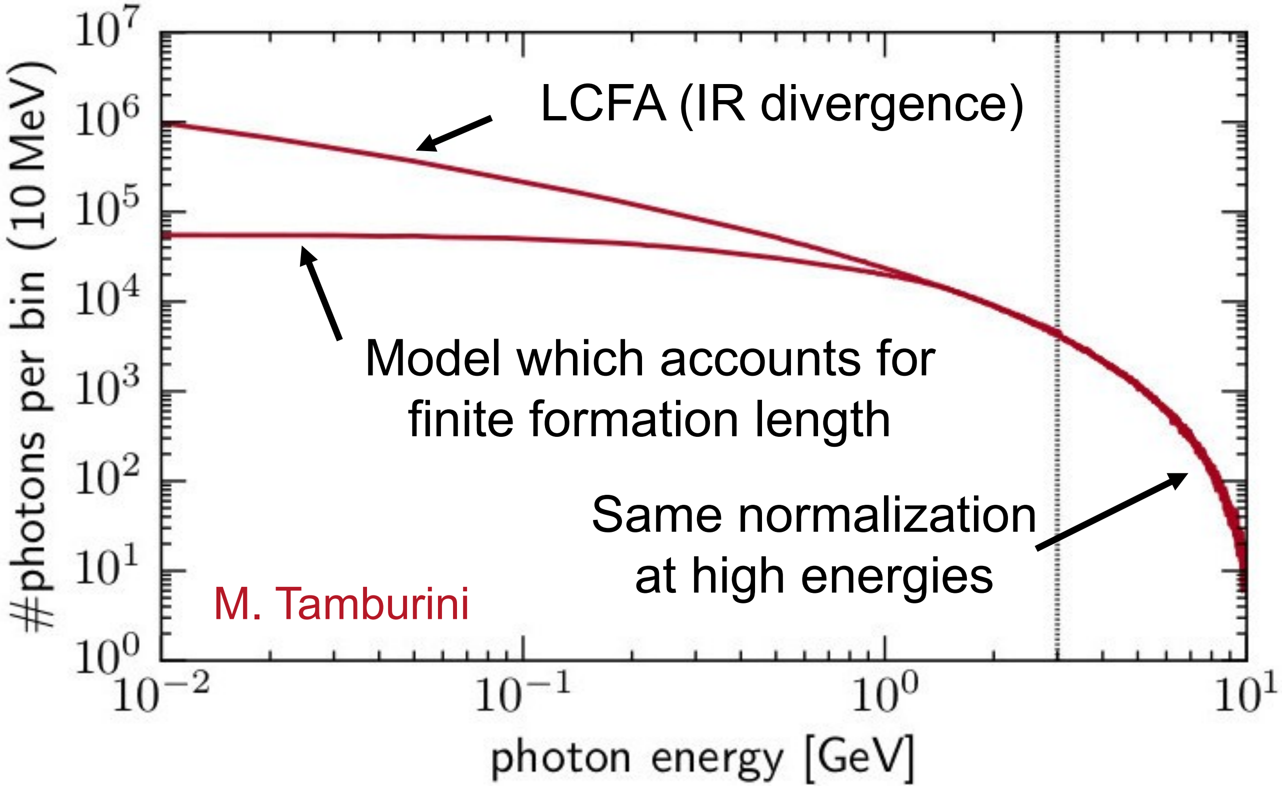
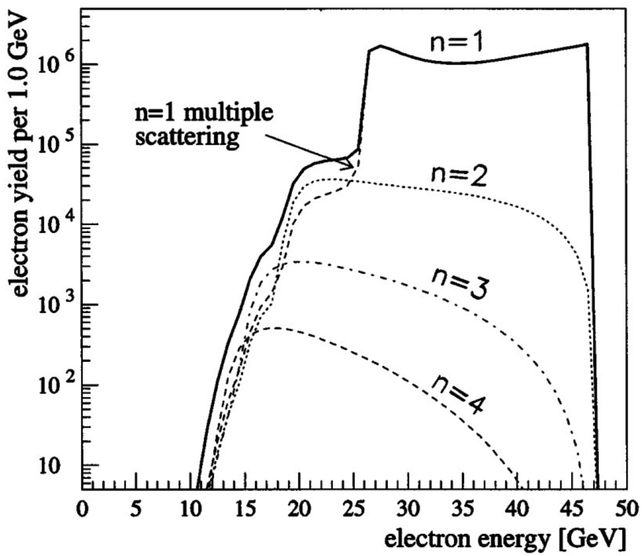
E320 @ FACET II



- Only SFQED facility currently operational
  - χ ~1 -reaches non-perturbative regime
  - electron laser modes
  - Radiation reaction and pair-production
  - Current status: ‚first light' on diagnositics

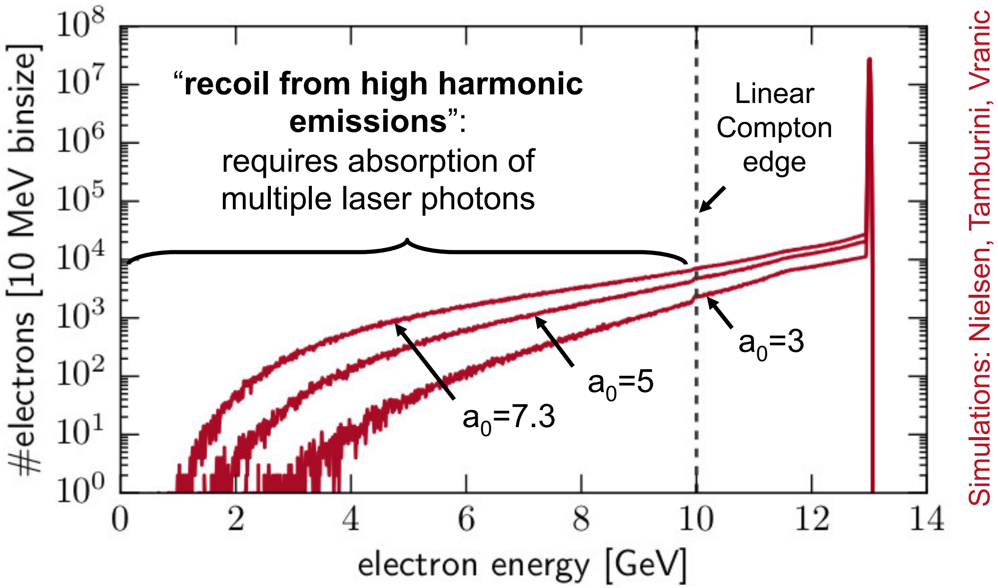
E320 @ FACET

E-144: perturbative multi-photon regime
($a_0 \lesssim 1$, $\chi \lesssim 1$:1990s)



E-144 PRL 76, 3116 (1996)
perturbative scaling: $\sim a_0^{2n}$

E-320: nonperturbative quantum regime
($a_0 \gg 1$,$\chi \gtrsim 1$: 2021)



Interaction with n~100 laser photons

$$a_0 = \frac{|e|E}{mc\omega} \approx 0.75\,\frac{\text{eV}}{\hbar\omega}\sqrt{\frac{I}{10^{18}\,\text{W/cm}^2}}$$

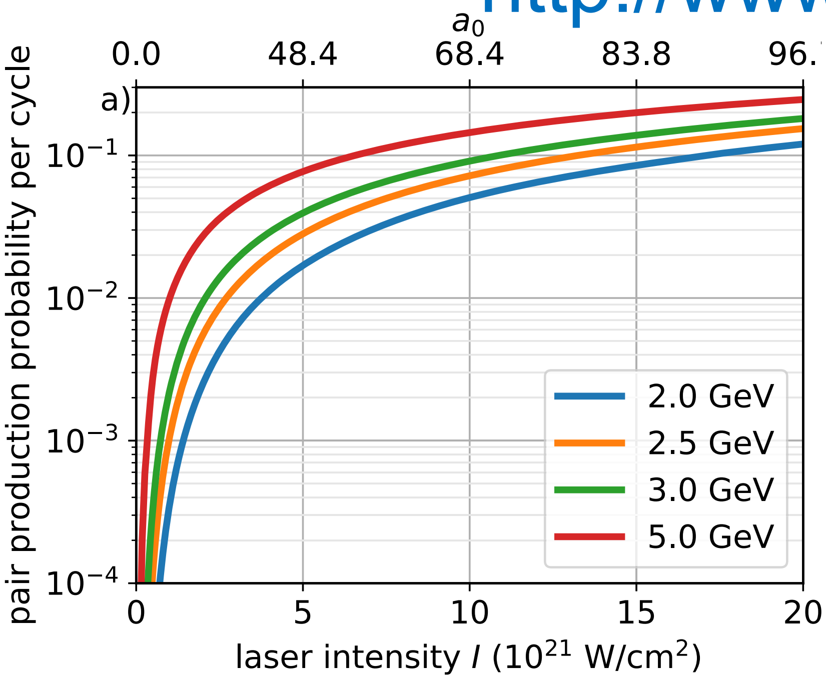
$$\chi = \frac{2\gamma a_0 \hbar\omega}{mc^2} = \frac{2\gamma E_L}{E_{crit}} \approx 0.057\frac{\epsilon}{\text{GeV}}\sqrt{\frac{2I_0}{10^{20}\,\text{W/cm}^2}}$$

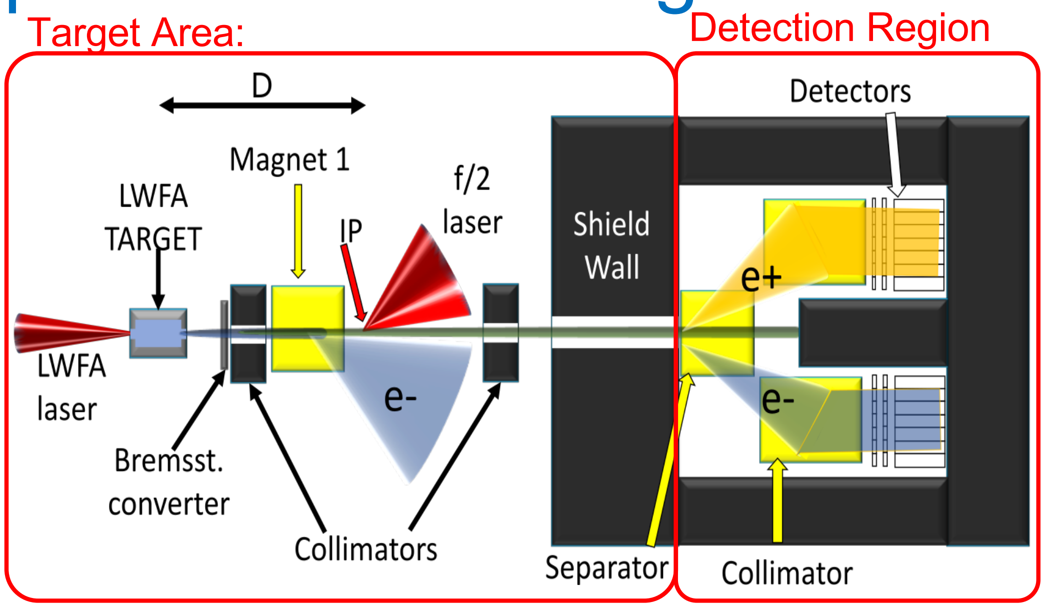
- First runs underway, first data on detectors!

CALA (LMU/Jena/Düsseldorf)

DFG research group 2783

http://www.quantumvacuum.org/





- γ-LASER and laser-laser experiments
- First vacuum pair experiment

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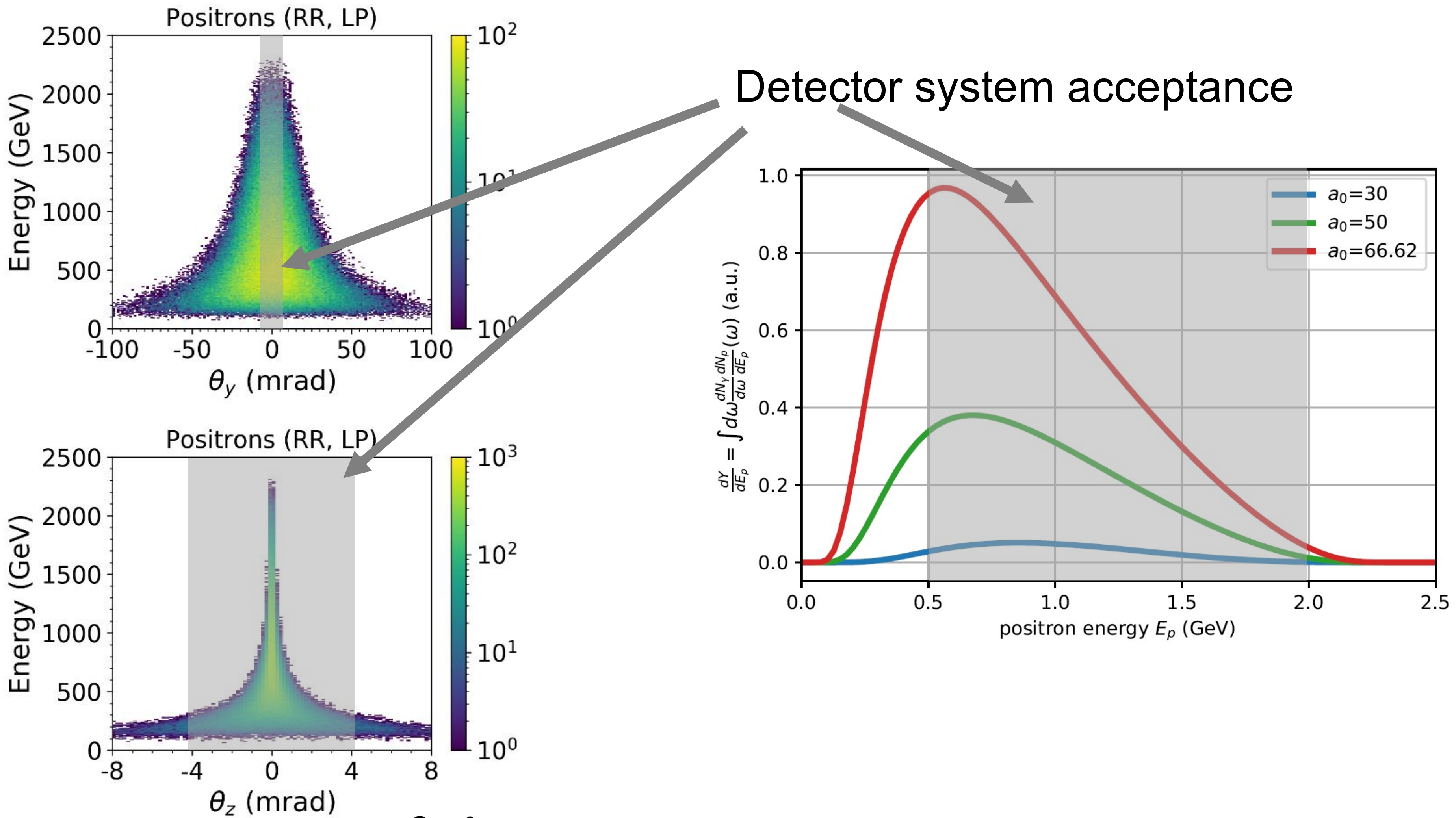
Effective Pair Rate@0.1 Hz



- Acceptance of detector: O~15%
  - Effective rate: 20-140 \h (50-350µm conv. target)

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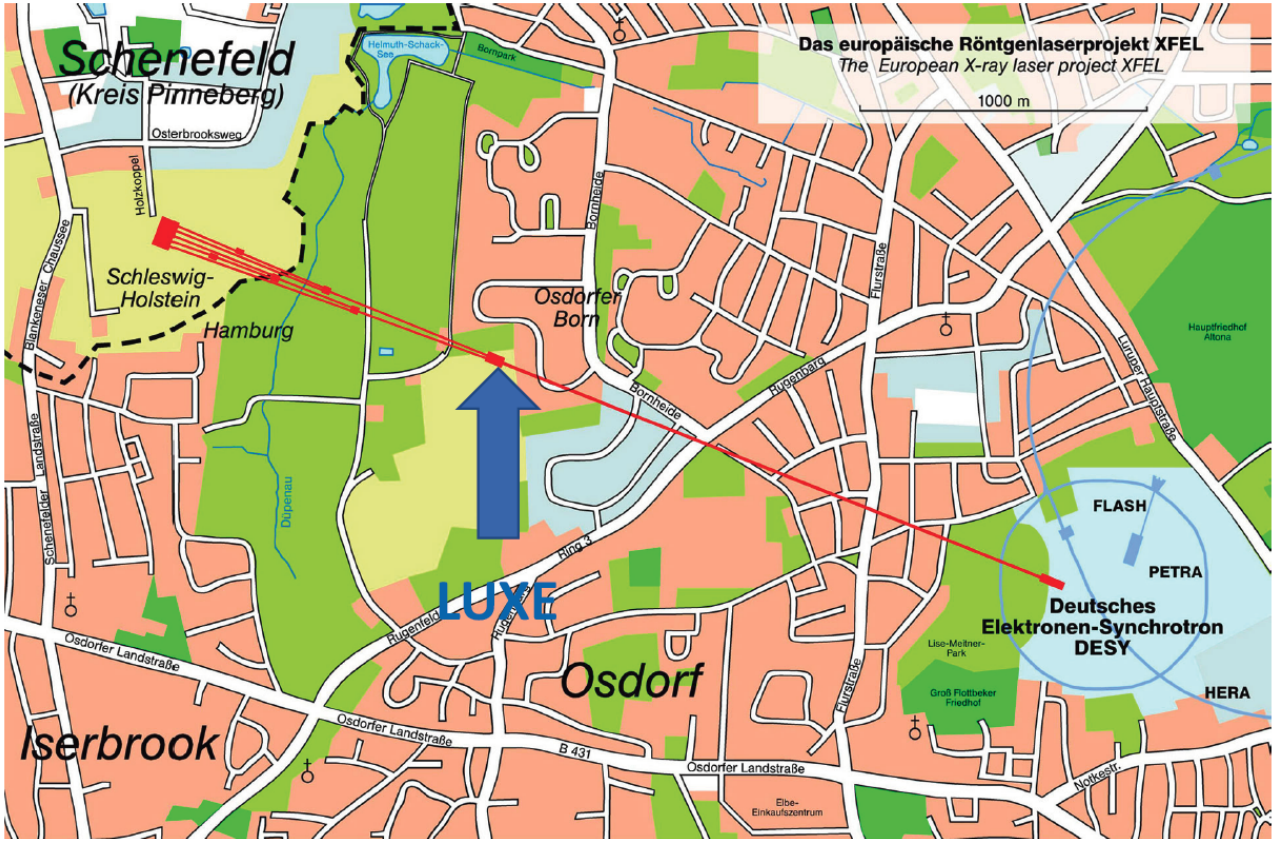
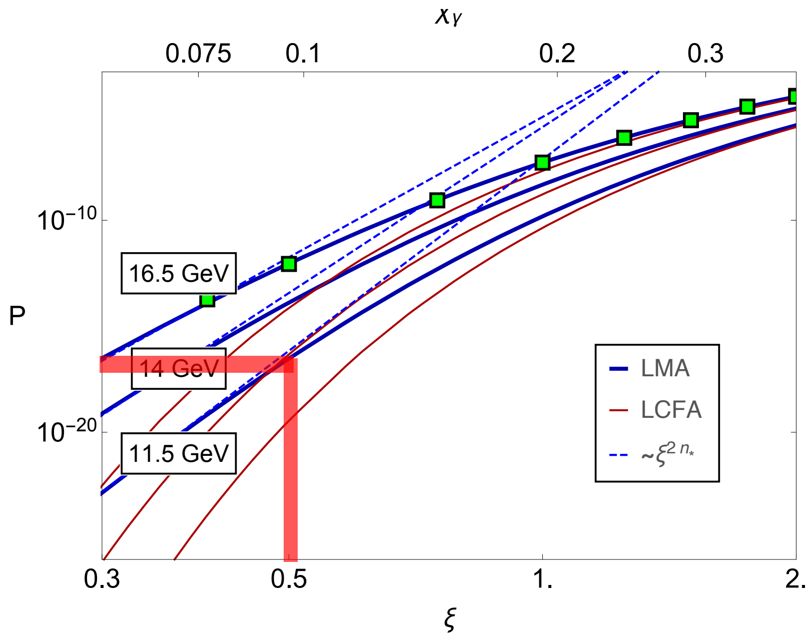
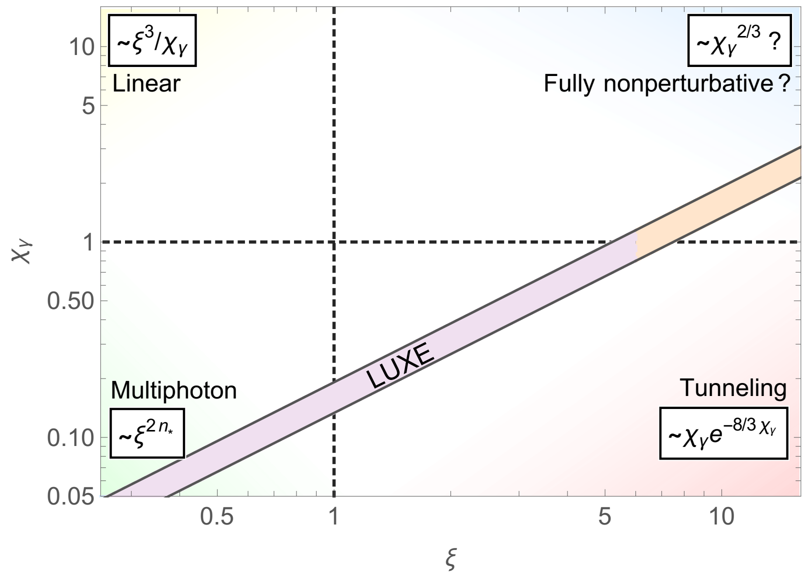
LUXE



- Located at EU XFEL
  - 300TW, 17 GeV
  - a0>20, χ>4

LUXE (Laser Und XFEL Experiment)





- High precision experiment in the non-perturbative regime
  - χ >>1
  - γ-laser and electron laser modes
  - 10Hz, 24 Hour data taking
  - XFEL linac performance
  - Currently awaiting funding decision

Relevance/Future Experiments

- Future Linear Collider
  - χ>10
  - Radiation Reaction critical to accurate modelling
  - Beamstrahlung losses
- QED cascades
  - Pair plasmas resulting from high χ
  - Astrophysical objects
- χ>>>1 => $\alpha\chi^{2/3}$>1
  - Ritus/Narozhny conjecture
    (see Fedotov, Ilderton, King, Karbstein, Seipt, Taya, Torgirmson, Phys. Rep 2023m Fedotov J. Phys.: Conf. Ser. 826, 012027 (2017))
  - Full breakdown of perturbative approach
  - Loop corrections no longer small

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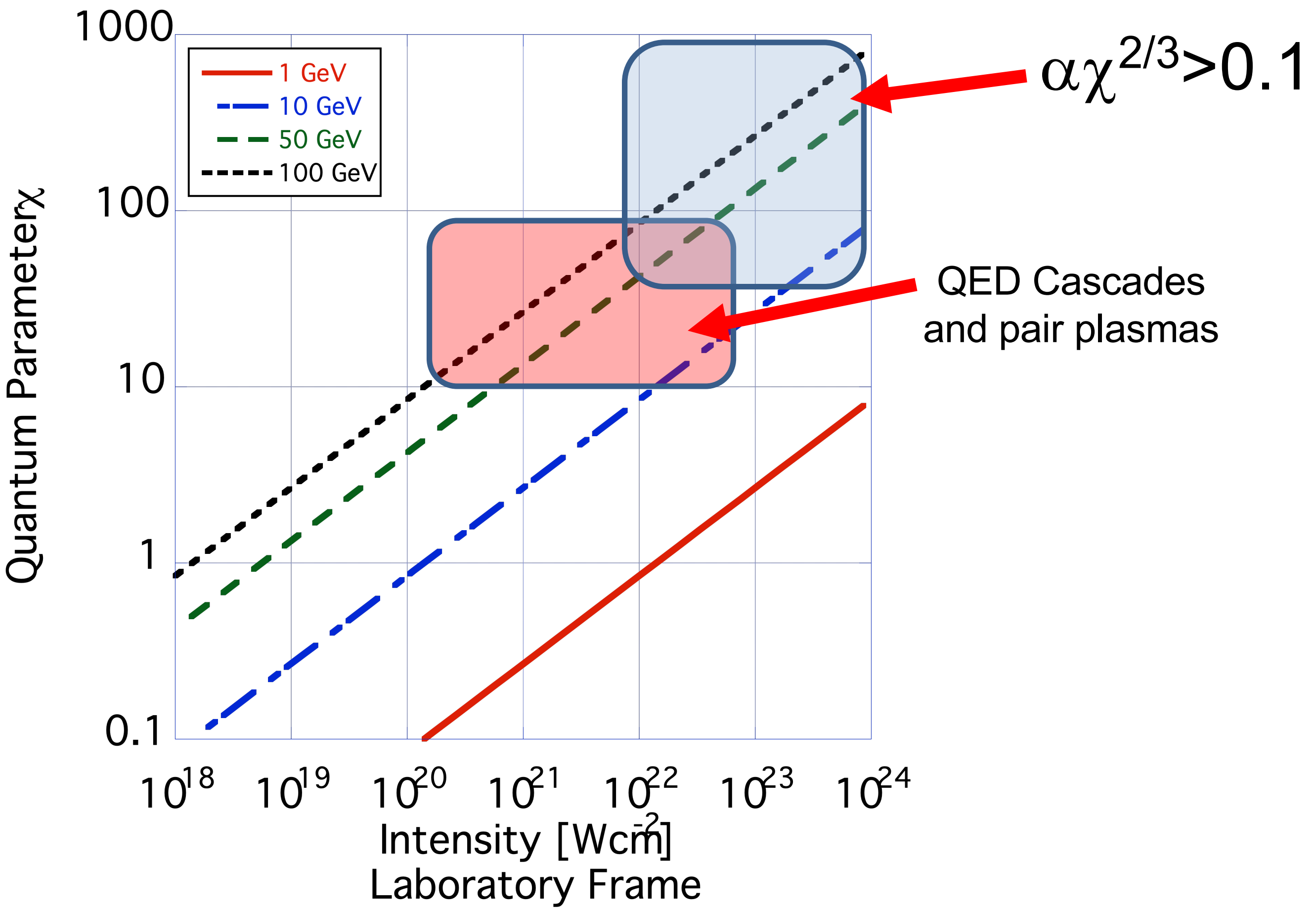
Plasma wakes can reach new regimes



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Summary

- SFQED is experimentally accessible with current generation of lasers and particle beams
  - Experimentally not tested
  - Collider and Astrophysically important
- Competing Experiments in χ~1 regime
  - RF-Accelerator + laser
  - ‚All-optical‘
- LUXE – a SFQED precision experiment
  - requires large number of beam crossings
- χ>>>1
  - Unexplored regime – theoretically challenging

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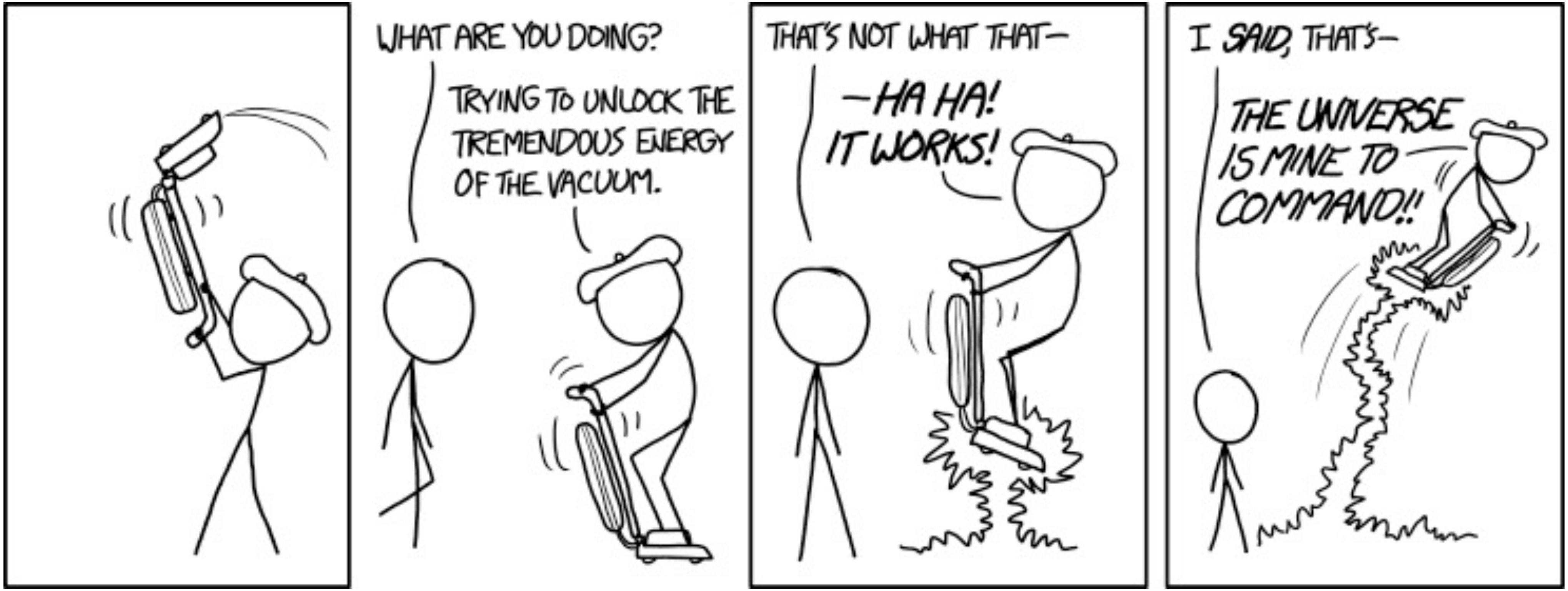

Thanks to XKCD&Pooyan