Science goals in laser-particle interactions

B. King

b.king@plymouth.ac.uk

UNIVERSITY OF PLYMOUTH

RAL Particle Physics Department Seminar

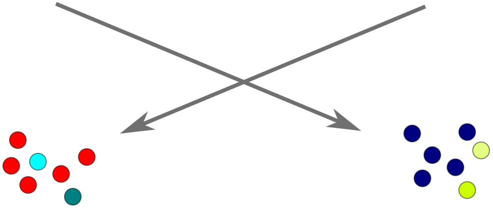
15-07-26

- Summary of some key strong-field QED concepts
- Charge-field coupling in intense electromagnetic backgrounds
- Some example Science Goals and experimental set-ups
- Radiation reaction

Strong-field QED in laser backgrounds

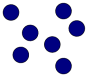
We start with a well-defined 'in' state, $|\mathrm{in}\rangle$

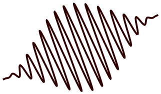
- We measure a well-defined 'out' state, $\langle \mathrm{out}|$



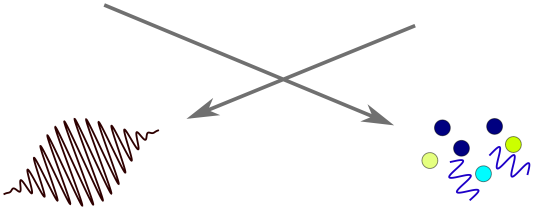
- The probability is then $\sim |\langle \mathrm{out}|\mathrm{in}\rangle|^2$ or $|S_{fi}|^2$.

- We start a well-defined 'in' state, $|\mathrm{in}\rangle$ which includes a laser pulse





- We measure a well-defined 'out' state, $\langle\mathrm{out}|$



- The probability is then $\sim |\langle\mathrm{out}|\mathrm{in}\rangle|^2$ or $|S_{fi}|^2$.

- We are interested in describing QED in coherent EM fields ('intense electromagnetic fields'):

Examples:

- Slowly-varying magnetic fields
- Inter-crystalline fields
- Beam-beam scattering
- Laser pulses (optical, XFEL, etc.)

$\rightarrow$ Coherence implies: $\langle E \rangle \neq 0$

Counter-examples:

- Blackbody radiation
- Bremsstrahlung
- Radiating gas jets

$\rightarrow$ Incoherence implies: $\langle E \rangle \approx 0$

- From QED fundamental parameters:
  - Electron mass: m
  - Positron charge: $e > 0$
  - Speed of light: c
  - Reduced Planck's constant: $\hbar$

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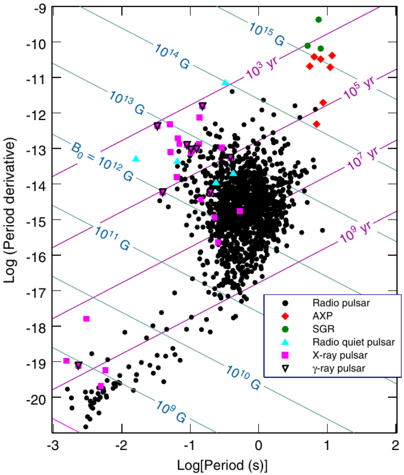
$$\boxed{E_{\rm qed} = \frac{m^2 c^3}{e\hbar}}$$

- Pair creation scale:

$$\underbrace{e \quad E_{\rm qed} \quad \lambda\!\!\!^{-}}_{\text{work done by field over electron wavelength}} \qquad = \qquad \underbrace{mc^2}_{\text{rest energy of electron}}$$

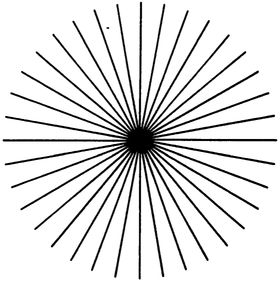
QED Field Scale (Magnetic): $B_{\rm qed} \approx 4.4 \times 10^{13}\,\mathrm{G}$

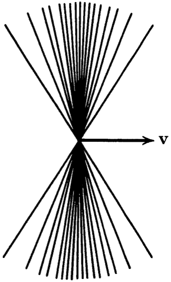


A. Harding, D. Lai, Rep. Prog. Phys. **69** 2631 (2006) [arXiv:astro-ph/0606674]

- Cannot reach E_{qed} in the lab, but...

  ...relativistic enhancement of **rest frame** field for accelerated charges: $E_{\text{r.f.}} \to \gamma(1+\beta)E_{\text{lab}}$:





J. D. Jackson, *Classical Electrodynamics* 3rd. Edition

- Strong-field parameter, χ:

$$\boxed{\chi = \frac{1}{E_{\mathrm{qed}}}\frac{1}{mc^2}\sqrt{-\left(p_\mu F^{\mu\nu}\right)^2}}$$

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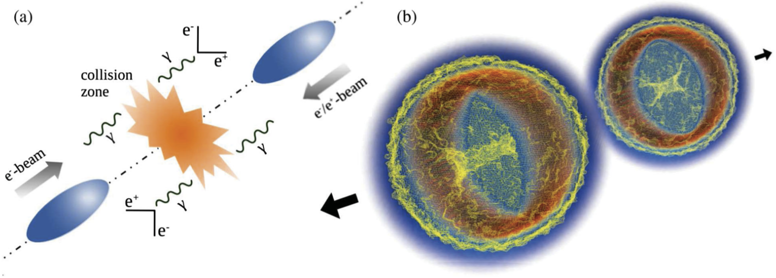
- Strong-field QED when $\chi \sim O(1)$.



Phys. Rev. Lett. **122**, 190404 (2019)

- Simulation of collision of two spherical 10 nm electron beams with 125 GeV energy (blue) producing photon (yellow) and probing $\chi \gtrsim 10^3$ (red).

Charge-field interaction

- Electromagnetic plane wave 'background': $eA^\mu = a^\mu = m\xi \underbrace{g(\varphi)}_{O(1)} \varepsilon^\mu$

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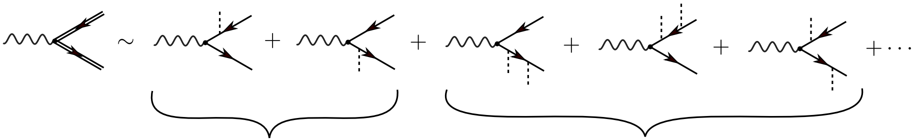
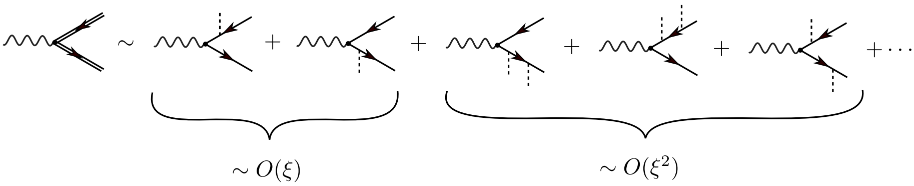
- Example process: $\gamma \to e^{+}e^{-}$ in

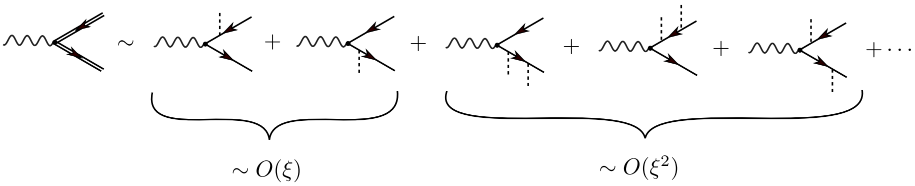


- Charge-background coupling $\boxed{e \to \xi}$



- $\boxed{\textbf{Intensity parameter}}$, ξ:

$$\xi^2 = \alpha \quad \underbrace{4\pi\lambda\!\!\!^{-}_{\text{laser}}\lambda\!\!\!^{-\,2}_{\text{C}}}_{\text{three volume}} \qquad \underbrace{n_{\text{laser}}}_{\text{`photon' number density}} \qquad \sim \alpha\, N_{\text{interacting `laser photons'}}$$



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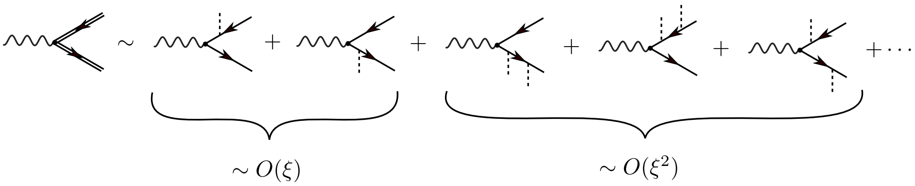
- $\xi \sim O(1)$ 'all-order' / non-perturbativity at small coupling c.f. gluon saturation, Bjorken-$x \to 0$



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- $\xi \sim O(1)$ 'all-order' / non-perturbativity at small coupling c.f. gluon saturation, Bjorken-$x \to 0$
- When $\xi \sim O(1)$, need to resum all order charge-background interaction.

- Split potential into 'background' and 'radiation':

$$\widehat{\mathsf{A}} \to \underbrace{\mathcal{A}}_{\text{classical}} + \underbrace{A}_{\text{radiation}}$$

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$$\mathcal{L}_{\mathrm{QED}} = \underbrace{-\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \bar{\psi}\left(i\partial\!\!\!/ - m\right)\psi}_{\text{'unperturbed'}} \underbrace{-e\bar{\psi}\left(\mathcal{A}\!\!\!/ + A\!\!\!/\right)\psi}_{\text{interaction}},$$

Rearrange:

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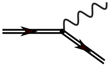
Rearrange:

$$\mathcal{L} = \underbrace{-\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \bar{\psi}\left(iD\!\!\!\!/ - m\right)\psi}_{\text{`unperturbed'}} \underbrace{-e\bar{\psi}A\!\!\!/\psi}_{\text{interaction}},$$

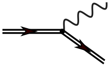
$D_\mu = \partial_\mu + ie\mathcal{A}_\mu$, covariant derivative.

- Leading tree-level processes:

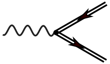


Nonlinear Compton

- Leading tree-level processes:

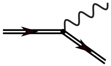


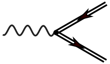
Nonlinear
Compton

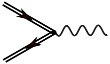


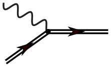
Nonlinear
Breit-Wheeler

- Leading tree-level processes:

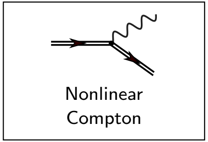

Nonlinear Compton

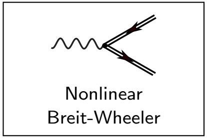

Nonlinear Breit-Wheeler

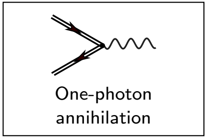

One-photon annihilation

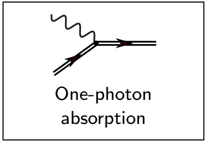

One-photon absorption

- Leading tree-level processes:

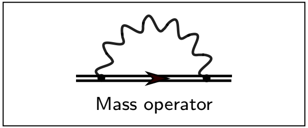


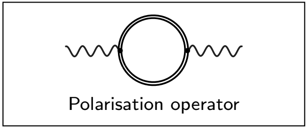


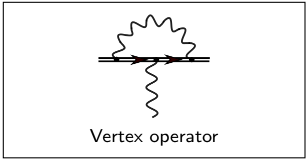




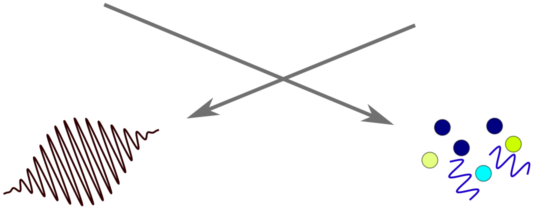
- Leading loop processes:







Science Goals

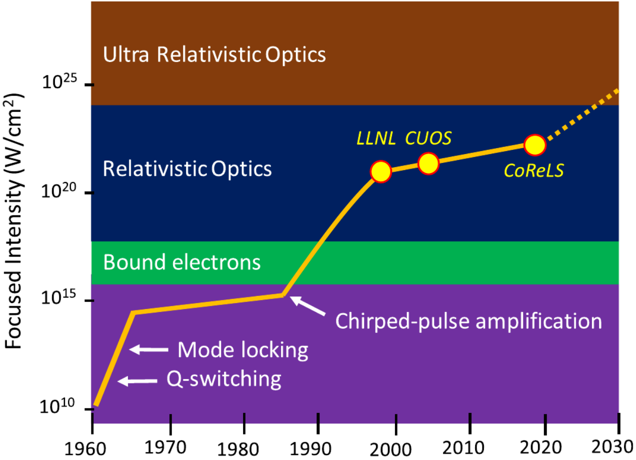


Strong EM fields:

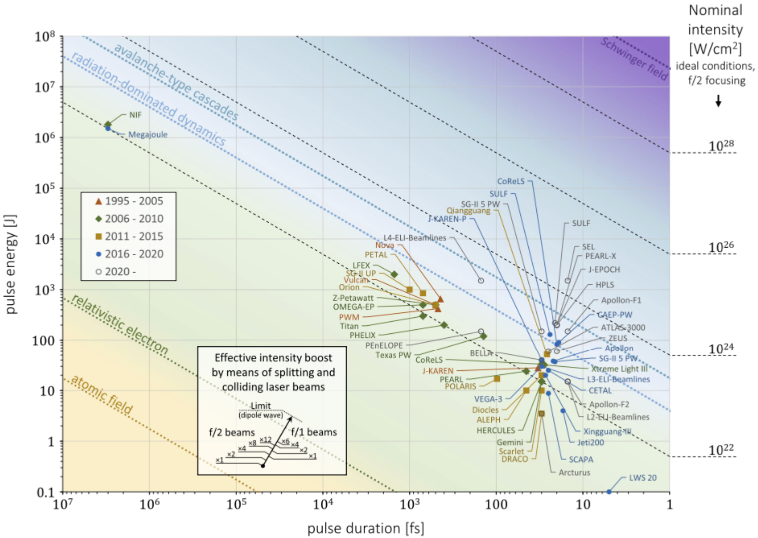
- High Power Laser Facilities (Gemini, EPAC, Vulcan 20-20, ELI, ZEUS, SEL, ...)
- XFELs (EU.XFEL, LCLS, SEL, ...)
- Oriented crystals (NA63)
- High-Z nuclei Coulomb fields
- Beamsstrahlung
- AXPs, Magnetars, ...

Probe beams:

- Laser wakefield accelerated electrons (e.g. gas jets)
- Linac electrons
- Bremsstrahlung photons
- Inverse Compton Scattered source
- Crystal radiators
- Thermal emission

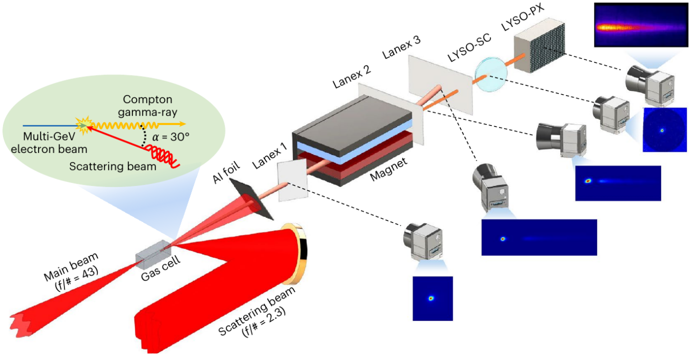


AAPPS Bull. **31**, 4 (2021)



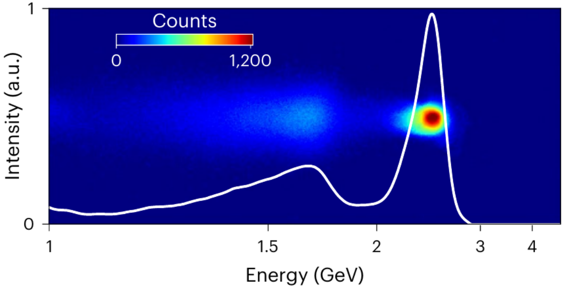
A. Gonoskov et al. Rev. Mod. Phys. 94, 045001 (2022)

- "All-optical" example: CoReLs nonlinear Compton scattering measurement



M. Mirzaie et al. Nature Photon. **18**, 1212–1217 (2024)

- Example LWFA electron spectrum:

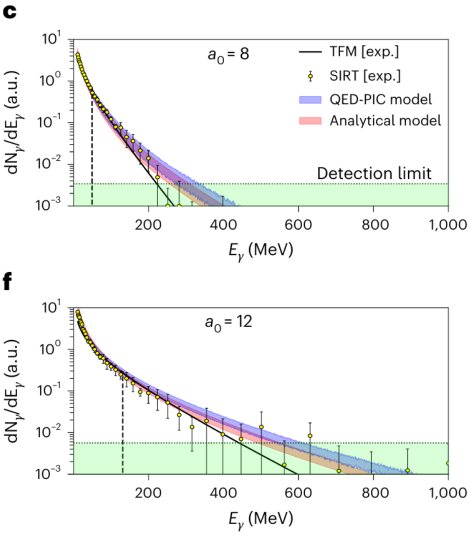


M. Mirzaie et al. Nature Photon. **18**, 1212–1217 (2024)

Photon spectrum:

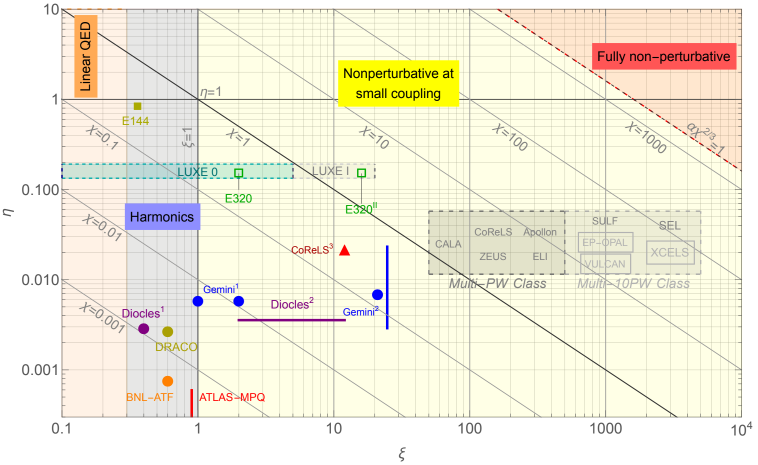
- $1.5\,\mathrm{GeV}$ electrons, $\xi = 8$, $\chi \approx 0.13$

- $2.4\,\mathrm{GeV}$ electrons, $\xi = 12$, $\chi \approx 0.32$



M. Mirzaie et al. Nature Photon. **18**, 1212–1217 (2024)

Nonlinear Compton: $e^{\pm} \rightarrow e^{\pm} + \gamma$



Eur. Phys. J. P. **140**, 1151 (2025)

Eur. Phys. J. Plus (2025) 140:1151
https://doi.org/10.1140/epjp/s13360-025-07057-7

THE EUROPEAN PHYSICAL JOURNAL PLUS

Review

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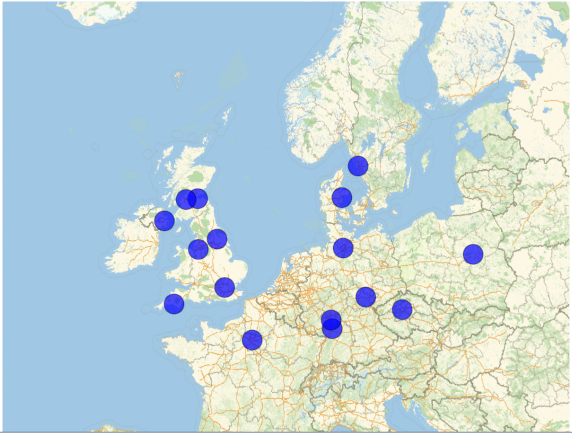
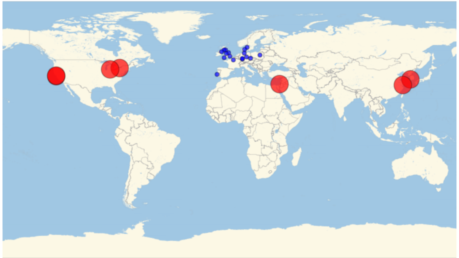
Input to the European strategy for particle physics: strong-field quantum electrodynamics

G. Sarri[1,a], B. King[2], T. Blackburn[3], A. Ilderton[4], S. Boogert[5], S. S. Bulanov[6], S. V. Bulanov[7], A. Di Piazza[8], L. Ji[9], F. Karbstein[10], C. H. Keitel[11], K. Krajewska[12], V. Malka[13], S. P. D. Mangles[14], F. Mathieu[15], P. McKenna[16], S. Meuren[17], M. Mirzaie[18], C. Ridgers[19], D. Seipt[20], A. G. R. Thomas[21], U. Uggerhøj[22], M. Vranic[23], M. Wing[24]



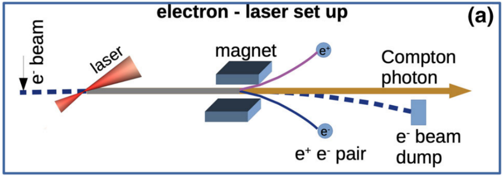


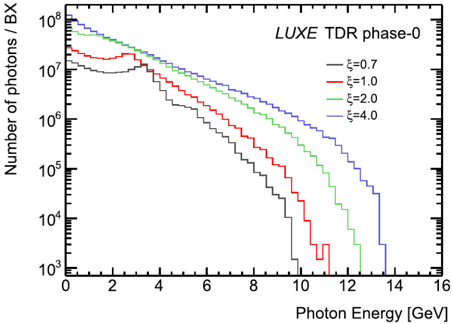
- **LUXE** LUXE - Laser Und Xfel Experiment

...

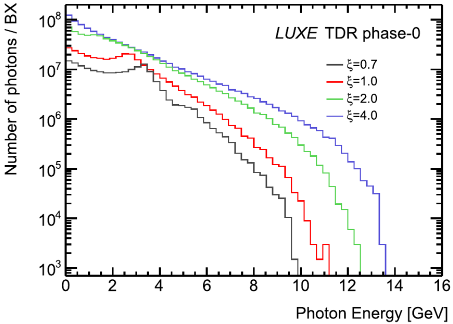
$\sim O(100)$ people, 20 institutions in:
Germany, Israel, UK, Sweden, France, Italy, Poland, Romania, Spain

H. Abramowicz et al. Eur.Phys.J.ST **230** (2021) 11, 2445-2560, H. Abramowicz et al. Eur.Phys.J.ST **233** (2024) 10, 1709-1974





- Position of harmonic edge (lightfront momentum fraction): $$u = \frac{2\eta}{1+\xi^2+2\eta}$$



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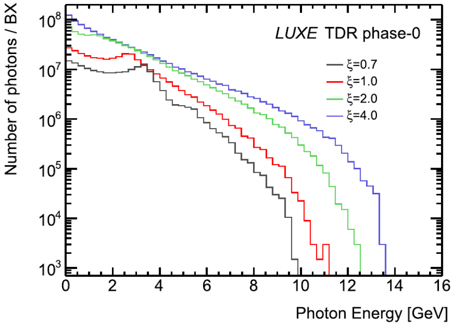
- Correction to 'linear' QED: $$u \approx u^{(\mathrm{QED})}\left[1 - \frac{\xi^2}{1+2\eta} + \left(\frac{\xi^2}{1+2\eta}\right)^2 + \cdots\right]$$



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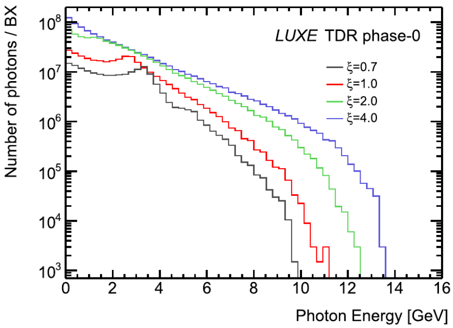
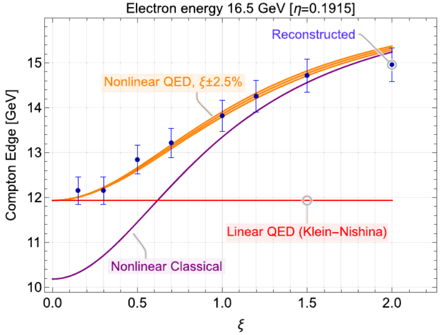
- Correction to classical nonlinear electrodynamics: $$u \approx u^{(\text{classical})}\left[1 - \hbar\frac{2\bar{\eta}}{1+\xi^2} + \hbar^2\left(\frac{2\bar{\eta}}{1+\xi^2}\right)^2 + \cdots\right]$$





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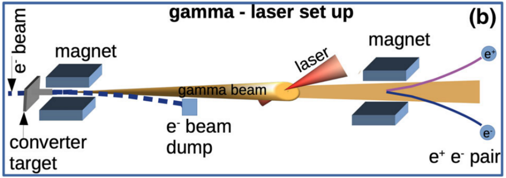
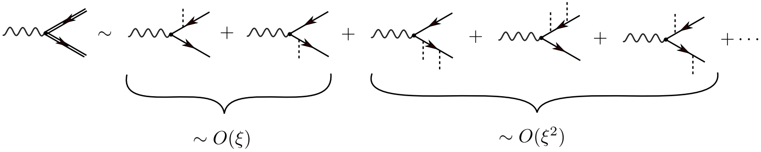
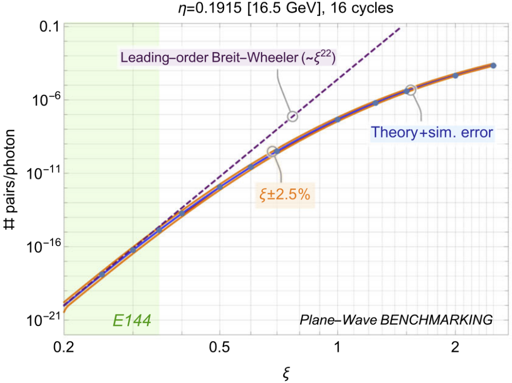
- Correction to 'linear' QED: $$u \approx u^{(\mathrm{QED})}\left[1 - \frac{\xi^2}{1+2\eta} + \left(\frac{\xi^2}{1+2\eta}\right)^2 + \cdots\right]$$
- Correction to classical nonlinear electrodynamics: $$u \approx u^{(\mathrm{classical})}\left[1 - \hbar\frac{2\bar{\eta}}{1+\xi^2} + \hbar^2\left(\frac{2\bar{\eta}}{1+\xi^2}\right)^2 + \cdots\right]$$



- 16.5 GeV electrons, but $\gamma + \mathrm{laser}$ collisions also planned using:

- Bremsstrahlung photons
- Inverse Compton Scattered (ICS) photons: $\sim 8.5\,\mathrm{GeV}$, polarisation grade: $\lesssim 95\%$
- Polarised crystal radiator photons: $\sim 12\,\mathrm{GeV}$, polarisation grade: $\lesssim 80\%$





LUXE TDR, Eur. Phys. J. Spec. Top. **233**, 1709–1974 (2024)

- Approximate higher-order processes by using ‘rate generators’ to iterate first-order processes

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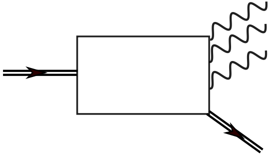
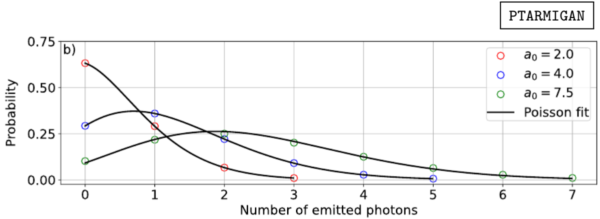
- e.g. Compton showers



Cascade Approximation

- e.g. nonlinear Compton scattering of $8\,\mathrm{GeV}$ electron in $30\,\mathrm{fs}$ pulse:



T. Blackburn et al. PRA **113**, 043109 (2026)

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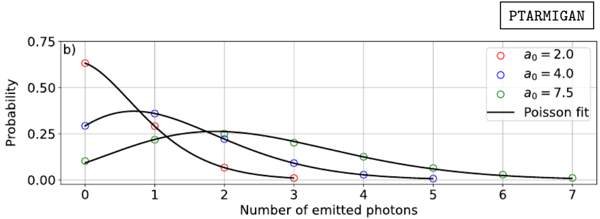
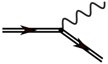


T. Blackburn et al. PRA **113**, 043109 (2026)

- Approximately Poisson distributed, perturbative physics (truncatable)

- In a constant crossed field (CCF) i.e. homogeneous plane wave $\mathcal{S} = \mathcal{P} = \eta = 0$:

As $\chi \to \infty$, $\mathsf{P}\Bigg($  $\Bigg) \sim \alpha\chi^{2/3}$

A. I. Nikishov, V. I. Ritus. JETP **19**, 529 (1964)

(likewise for nonlinear Breit-Wheeler).

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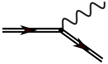
$$\text{As} \ \ \chi \to \infty, \quad \mathsf{P}\left(\right.$$  $$\left. \right) \sim \alpha \chi^{2/3}$$

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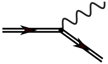
As $\chi \to \infty$, P() $\sim \alpha\chi^{2/3}$

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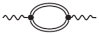
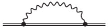
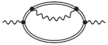
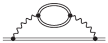
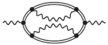
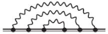
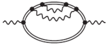
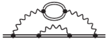
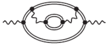
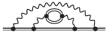
- When $\alpha\chi^{2/3} \sim O(1)$ i.e. $\chi \sim O(10^3)$, perturbation series in (dressed) vertices would break down
- Strong-field QED potentially becomes **strongly-coupled**.

- Scaling extends to photon and electron propagators

				1 loop			
(1a)		$\alpha\chi^{2/3}$	[12]	(1b)		$\alpha\chi^{2/3}$	[13]
				2 loops			
(2a)		$\alpha^2\chi^{2/3}\log\chi$	[16]	(2b)		$\alpha^2\chi\log\chi$	[14,21]
				(2c)		$\alpha^2\chi^{2/3}\log\chi$	[15]
				3 loops			
(3a)		$\alpha^3\chi^{2/3}\log\chi$	[17]	(3d)		$\alpha^3\chi^{2/3}\log^2\chi$	[17]
(3b)		$\alpha^3\chi^{2/3}\log\chi$	[17]	(3e)		$\alpha^3\chi^{4/3}$	[17]
(3c)		$\alpha^3\chi\log^2\chi$	[18]	(3f)		$\alpha^3\chi\log^2\chi$	[18]
				(3g)		$\alpha^3\chi^{5/3}$	[18]

A. A. Mironov, Phys Rev. D **102**, 053005 (2020)

- Ritus-Narozhny conjecture: In CCF, $\alpha\chi^{2/3}$ is expansion parameter of strong-field QED

For a QED process with n vertices:

- Weak fields ($\xi \ll 1$):

$$\mathsf{P} = \alpha^{n}\left[f_0 + \alpha f_1 + \cdots\right]$$

... perturbative expansion works very well!

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... Furry expansion (to test in experiments)

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- 'High χ' regime ($\alpha\chi^{2/3} \sim O(1)$?):

$$\mathsf{P} = \alpha^n f_n(\alpha, \xi) \text{ ?}$$

Radiation Reaction

- Coupled equations for electron trajectory and radiation:

$$
\begin{aligned}
m\ddot{x} &= e\left[\partial(A\cdot\dot{x}) - A(\partial\cdot\dot{x})\right] \\
\Box A &= e\int \dot{x}
\end{aligned}
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- Expansion in e:

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- Next order:

$$\begin{aligned} m\ddot{x}^{(1)} &= \partial(A_{\text{laser}}\cdot\dot{x}^{(1)}) - A_{\text{laser}}(\partial\cdot\dot{x}^{(1)}) + \partial(A_{\gamma}^{(1)}\cdot\dot{x}^{(0)}) - A_{\gamma}^{(1)}(\partial\cdot\dot{x}^{(0)}) \\ \Box A_{\gamma}^{(2)} &= \int\dot{x}^{(1)} \end{aligned}$$

- Calculating radiation from electron (all-orders RR), Landau-Lifshitz equation:

$$m\ddot{x} = F_{\mathrm{bg}} \cdot \dot{x}(\tau) + \underbrace{\frac{e^2}{6\pi}\left[\dot{F}_{\mathrm{bg}} \cdot \dot{x} + (1 + \dot{x}\dot{x}) \cdot F_{\mathrm{bg}} \cdot F_{\mathrm{bg}} \cdot \dot{x}\right]}_{\text{classical RR}}$$

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- Can be solved in a plane wave background.

A. D. Piazza, Lett. Math. Phys. 83, 305 (2008)

- Ratio of scattered to incident electron energy parameter:

$$\frac{\eta'}{\eta} = \frac{1}{1+\Delta}; \qquad \Delta = \frac{2\alpha\eta}{3}\int \xi'^2(\varphi)d\varphi$$

- Quantum radiation reaction more general...

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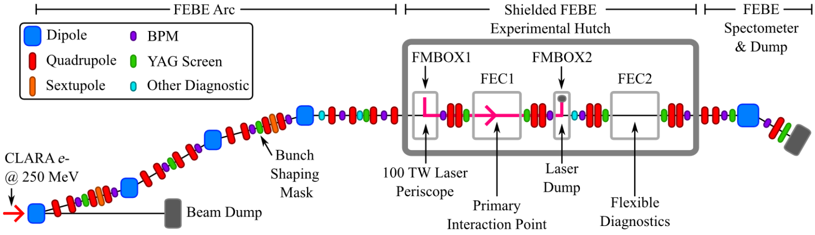
- Classical limit ($\hbar \to 0$) of expected scattered electron momentum of:

... agrees with leading order prediction from Landau-Lifshitz equation:

$$\frac{\eta'}{\eta} \approx 1 - \Delta; \qquad \Delta = \frac{2\alpha\eta}{3}\int \xi'^2(\varphi)d\varphi$$

A. Ilderton and G. Torgrimsson, Phys. Lett. B 481-486, **725** (2013)

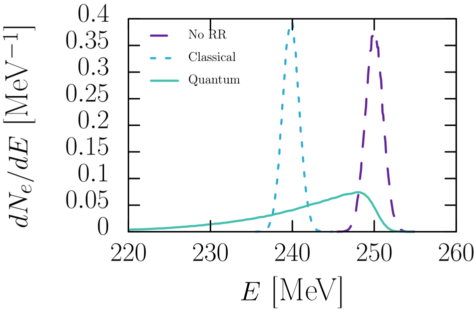
- Full Energy Beam Exploitation (FEBE) at CLARA in Daresbury



E. W. Sneddon et al. Phys. Rev. Accel. Beams **27**, 041602 (2024)

- 250 MeV electron beam, energy spread $\sim 1\%$.
- Laser intensity $\xi \sim O(10)$
- Strong-field parameter $\chi \approx 0.003$
- Radiation reaction parameter $\Delta \approx 0.05$.

- Laser: $\xi = 10$, 25 fs duration (FWHM)
- Electrons: 250 MeV, 1 μm bunch length



A. J. Macleod (private communication)

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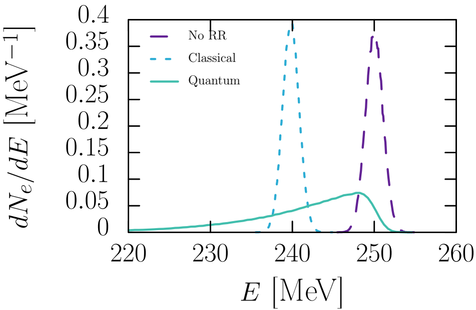
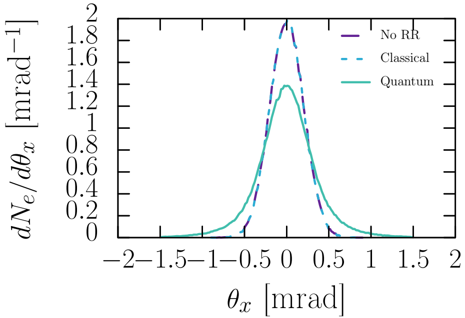
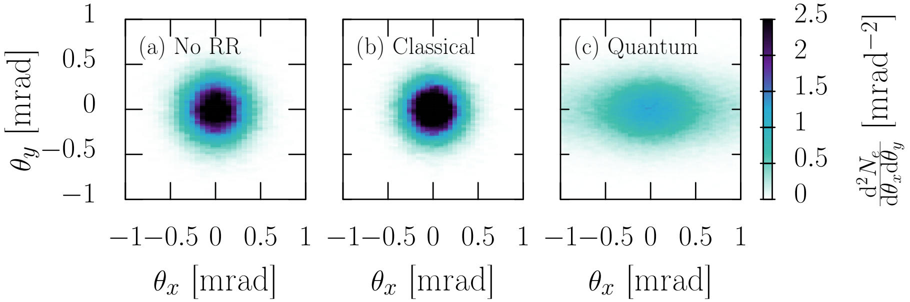




A. J. Macleod (private communication)



A. J. Macleod (private communication)

- Collaboration forming between particle/accelerator and laser physicists

Summary

- High power lasers can be used to study fundamental physics (QED, electroweak, BSM,...)

- Recent Theory Review: *Advances in QED with intense background fields*, A. Fedotov et al. Phys. Rep. **1010**, 1-138 (2023)
- LUXE CDR: *Conceptual design report for the LUXE experiment*, H. Abramowicz et al. Eur. Phys. J. S. T. **230**, 2445-2560 (2021)
- Possible future directions: G. Sarri et al. Eur. Phys. J. P. **140**, 1151 (2025)

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- At high χ, QED predicted to become strongly coupled - no methods available to calculate in this regime
- Precision experimental tests of radiation reaction at CLARA, LUXE (DESY) and elsewhere can provide much needed input.

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Backup Slides

- QED is a relativistic theory: observables should be expressed as Lorentz invariants

- Electromagnetic (EM) invariants:

$$\begin{aligned}\mathcal{S} &= -\frac{1}{E_{\text{qed}}^2}\frac{1}{4}F_{\mu\nu}F^{\mu\nu} = \frac{\mathbf{E}^2-\mathbf{B}^2}{2\,E_{\text{qed}}^2};\\ \mathcal{P} &= -\frac{1}{E_{\text{qed}}^2}\frac{1}{4}F_{\mu\nu}F^{*\,\mu\nu} = \frac{\mathbf{E}\cdot\mathbf{B}}{E_{\text{qed}}^2}\end{aligned}$$

- Probability P for QED processes in *constant* and *homogeneous* EM field:

$$\mathrm{P} = \mathrm{P}\,(\mathcal{S},\mathcal{P})\,.$$

- For EM fields in the lab:

$$\mathrm{P} \approx \mathrm{P}\,(0,0)$$

- Analytical solutions to:

$$\left(i\not{D} - m\right)\psi = 0$$

exist for: constant fields; Coulomb field... and plane-wave backgrounds

- Plane-wave background solution (Volkov wavefunction):

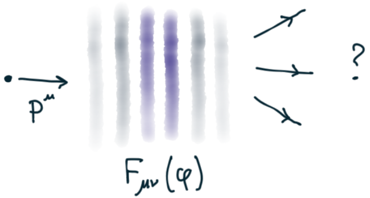
$$\psi_p = \left[1 + \frac{\not{n}\not{a}(\varphi)}{2\,n\cdot p}\right]\frac{u_p}{\sqrt{2p^0V}}\,\mathrm{e}^{-ip\cdot x - i\int_{-\infty}^{\varphi}\frac{2p\cdot a(\phi) - a^2(\phi)}{2\omega\,n\cdot p}\,d\phi}$$

D. M. Wolkow, Z. Phys. 94 250-260 (1935)

(Shorthand: $a(\varphi) = eA(\varphi)$, $\varphi = \omega n\cdot x$.)

  - Spin-dependent pre-factor describing spin precession
  - Nonlinear phase describing all-order interaction with background.

- Semiclassical (WKB) *exact*: $-ip\cdot x - \int_{-\infty}^{\varphi}\frac{2p\cdot a(\phi) - a^2(\phi)}{2\omega n\cdot p}d\phi \equiv -iS_{\mathrm{classical}}$



- Plane wave: $F^{\mu\nu} = F^{\mu\nu}(\varphi)$ where phase $\varphi = \omega n \cdot x$ and $n \cdot n = 0$.
- Vacuum no longer translational invariant: four-momentum no longer conserved (Noether's theorem)!
- 'Perpendicular momentum', $p^\perp$, and 'lightfront momentum' (projection onto wavevector n) are conserved.

  e.g. if $n = (1, 0, 0, 1)$ i.e. laser propagating down z axis, then:

$$p^x, \quad p^y, \quad \text{and} \quad p^- = p^0 - p^z \qquad \text{are conserved,}$$

whereas $p^+ = p^0 + p^z$ is **not** conserved.

Schwinger:

$$\frac{dP_{\text{Sch.}}}{dt} \propto \exp\left[-\frac{\pi E_{\text{qed}}}{E}\right]$$

- EM field: constant, homogeneous, $F^{\mu\nu}$.

$$\frac{dP_{\text{Sch.}}}{dt} \propto \exp\left[-\pi\frac{m^2}{\sqrt{4\pi\alpha_{\text{QED}}}\,E}\right].$$

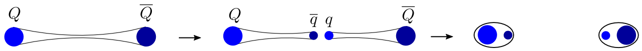
Nonlinear Breit-Wheeler:

$$\frac{dP_{\text{nbw}}}{d\varphi} \sim \exp\left[-\frac{8}{3\chi(\varphi)}\right]$$

- EM field: photon plus plane wave: $F^{\mu\nu} = F^{\mu\nu}(\varkappa\cdot x)$;

$$\frac{dP_{\text{nbw}}}{d\varphi} \sim \exp\left[-\frac{8}{3}\frac{m}{\omega_\gamma(1+\cos\theta)}\frac{m^2}{\sqrt{4\pi\alpha_{\text{QED}}}\,E}\right]$$

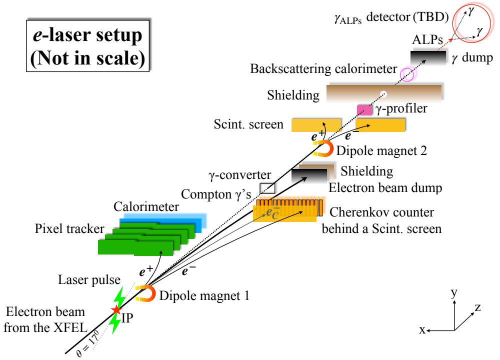
- c.f. "string-breaking" in QCD:



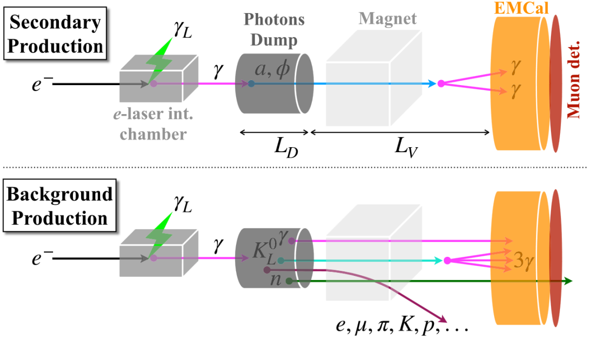
A. Casher, H. Neuberger, S. Nussinov, PRD **20**, 179 (1979)

- Non-analytic / 'non-perturbative' in α_{QED}: Can we measure this 'tunneling-like', 'Schwinger-like' pair creation in experiments?

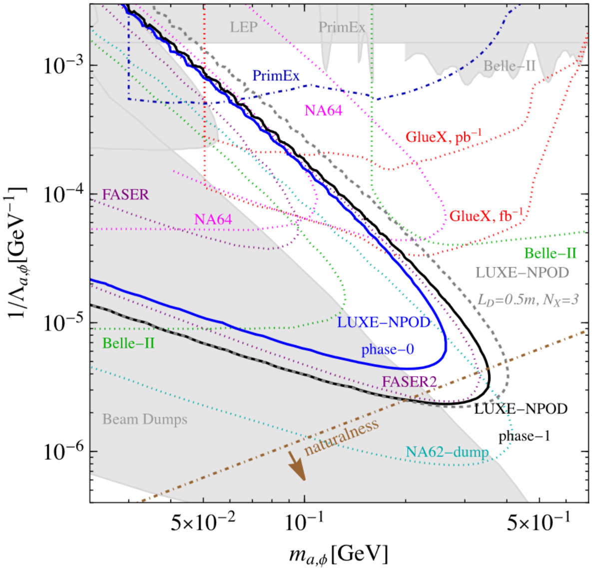
- Synergy of particle and high intensity laser physics allows for more precise measurements.



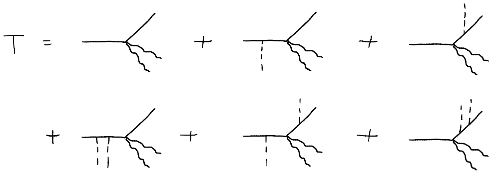
- LUXE-NPOD 'New Physics search with Optical Dump'



Z. Bai et al. Phys. Rev. D **106**, 115034 (2022)


LEP
PrimEx
Belle–II
PrimEx
NA64
GlueX, pb^{-1}
FASER
NA64
GlueX, fb^{-1}
Belle–II
LUXE–NPOD
L_D=0.5m, N_X=3
LUXE–NPOD
phase–0
Belle–II
FASER2
LUXE–NPOD
phase–1
Beam Dumps
naturalness
NA62–dump
10^{-3}
10^{-4}
10^{-5}
10^{-6}
$1/\Lambda_{a,\phi}[\mathrm{GeV}^{-1}]$
5×10^{-2}
10^{-1}
5×10^{-1}
$m_{a,\phi}[\mathrm{GeV}]$

- In *weak fields* ($\xi \ll 1$), we can perturbatively expand S_{fi} up to $O(\xi^2)$



- In a *plane wave* pulse of *finite extent*, one finds:

$$\mathsf{T}_{\mathsf{fi}} = \underbrace{(\cdots\cdots)\,\delta^4(\Delta p)}_{\text{Vacuum term}} + \underbrace{(\cdots\cdots)\,\delta^{\perp,-}(\Delta p)}_{\text{Laser pulse term}},$$

where $\Delta p = p_{\mathrm{out}} - p_{\mathrm{in}}$ is the momentum change.

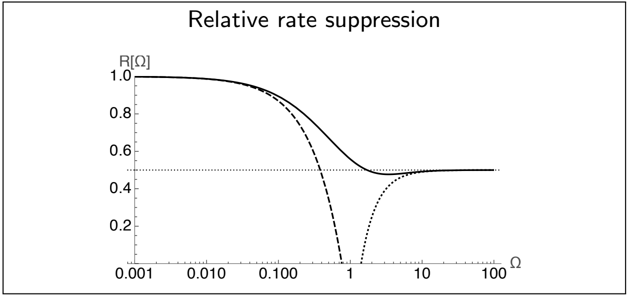
- Since:

$$\mathrm{Prob}_{vac} \propto VT; \qquad \mathrm{Prob}_{\mathrm{pulse}} \propto V\tau,$$

and $T \gg \tau$ (pulse duration), probability is **dominated by vacuum term**.

- Total vacuum decay rate:

$$W_{\mathrm{vac}}(\xi) = \mathcal{R}\left[\Omega(\xi)\right] W_{\mathrm{vac}}(0)$$



$$\mathcal{R}[\Omega] \quad \approx \quad \begin{cases} 1 - \dfrac{5\pi\Omega}{12} + \dfrac{\Omega^2}{18}\left(19 - 15\gamma - 15\log\Omega\right), & (\Omega \ll 1) \\ \dfrac{1}{2} - \dfrac{1}{\Omega^2} + \dfrac{20}{\Omega^4} & (\Omega \gg 1) \end{cases}$$

BK and D.Liu, Phys. Rev. Lett. **135**, 251802 (2025)