Resurgence in QED

Probing the Schwinger effect in inhomogeneous fields

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arXiv: 2212.04599

Dunne, Gerald V., and Zachary Harris. "Resurgence of the effective action in inhomogeneous fields." Physical Review D 107.6 (2023): 065003.

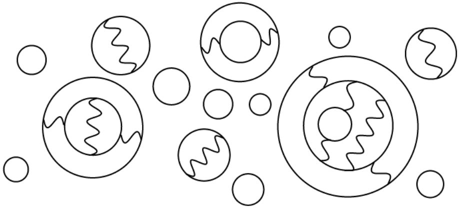
Dunne, Gerald V., and Zachary Harris. "Higher-loop Euler-Heisenberg transseries structure." Physical Review D 103.6 (2021): 065015.

The Schwinger effect

The Schwinger effect

Vacuum bubbles

The vacuum in QED is characterized by virtual fluctuations

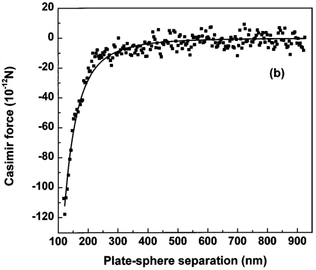


These virtual processes have interesting consequences:

- The Casimir effect
- Light-by-light scattering
- The Schwinger effect

Status of experiments

Casimir effect[1]



Light-by-light scattering: evidence from quasi-real photons[2]

Schwinger effect: related positron production from multi-photon light-by-light scattering[3]

- Upcoming: LUXE at DESY and FACET-II at SLAC (lasers + e^- beams)

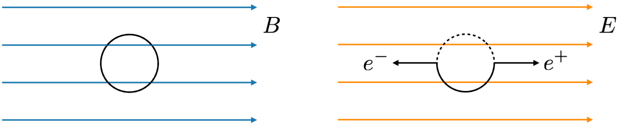
[1] Mohideen, Umar, and Anushree Roy. Physical Review Letters 81.21 (1998)

[2] ATLAS collaboration. Nature physics 13, no. 9 (2017)

[3] Burke, D., et al. Physical Review Letters 79.9 (1997)

The Schwinger effect

The vacuum is unstable in the presence of an electric field



The field strengths required for this are astronomical

$$2eE\frac{\hbar}{mc} \approx 2mc^2 \quad \Rightarrow \quad E \approx 10^{18}\,\text{V/m}$$

- Experimental fields will be strongly inhomogeneous (XFEL facilities at SLAC, DESY), and so the effects of inhomogeneities must be understood.
- Prevailing computational techniques rely on approximations (e.g. LCFA) which are known to be insufficient.

This is an open problem that requires new ideas.

Constant fields

These quantum corrections to Maxwell theory are encoded in the **effective action**, $\Gamma[A]$

$$\langle 0_{\text{out}} | 0_{\text{in}} \rangle = \exp\left(\frac{i}{\hbar} \Gamma[A] \right)$$

The imaginary part gives the pair-production rate

$$P_{e^+e^-} = 1 - |\langle 0_{\text{out}} | 0_{\text{in}} \rangle|^2 \approx \frac{2}{\hbar} \operatorname{Im} \Gamma$$

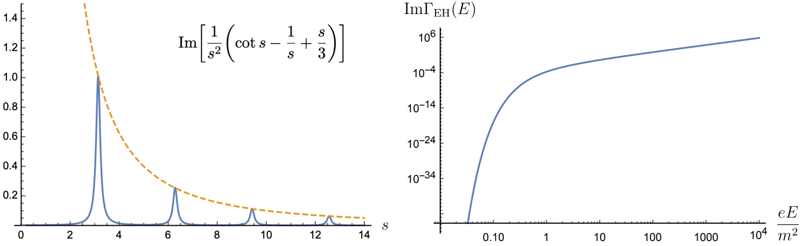
Euler, Heisenberg (1936): constant electromagnetic fields

$$\frac{\Gamma_{\text{EH}}(B)}{V_4} = -\frac{e^2 B^2}{8\pi^2} \int_0^\infty \frac{\mathrm{d}s}{s^2} \left(\coth s - \frac{1}{s} - \frac{s}{3} \right) e^{-m^2 s/(eB)}$$
$$\frac{\Gamma_{\text{EH}}(E)}{V_4} = -\frac{e^2 E^2}{8\pi^2} \int_0^\infty \frac{\mathrm{d}s}{s^2} \left(\cot s - \frac{1}{s} + \frac{s}{3} \right) e^{-m^2 s/(eE)}$$

Pair-production rate

The residues at the poles give the imaginary part

$$\frac{\operatorname{Im}\Gamma_{\mathrm{EH}}(E)}{V_4} = \frac{e^2E^2}{8\pi^3}\sum_{k=1}^{\infty}\frac{1}{k^2}\exp\left(-\frac{k\pi m^2}{eE}\right)$$



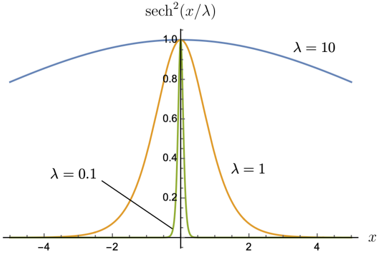
This is a **non-perturbative** phenomenon

Non-constant fields: a single pulse

Exactly solvable *inhomogeneous* field configurations[4]:

$$B(x) = B\,\mathrm{sech}^2\left(\frac{x}{\lambda}\right), \qquad E(t) = E\,\mathrm{sech}^2\left(\frac{t}{\tau}\right)$$

Natural dimensionless parameter: $\gamma = \dfrac{m}{eB\lambda}$ or $\gamma = \dfrac{m}{eE\tau}$



Connected by simultaneous rotations: $B \mapsto \pm iE$ and $\lambda \mapsto \mp i\tau$

[4] Nikishov, A. I. Nuclear Physics B 21.2 (1970)

Standard approximations

The structure of the exact imaginary part is difficult to probe

Locally constant field approximation (LCFA):

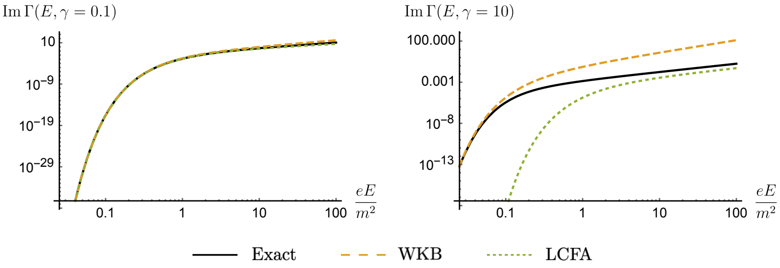
$$\left.\frac{\operatorname{Im}\Gamma}{V_3}\right|_{\text{LCFA}} \sim \tau\frac{e^2E^2}{8\pi^3}\left(\frac{eE}{m^2}\right)^{1/2}\sum_{k=1}^{\infty}\frac{1}{k^{5/2}}\exp\left(-\frac{k\pi m^2}{eE}\right)\sum_{n=0}^{\infty}c_n\left(\frac{eE}{k\pi m^2}\right)^n$$

WKB approximation:

$$\left.\frac{\operatorname{Im}\Gamma}{V_3}\right|_{\text{WKB}} = \tau\frac{e^2E^2}{8\pi^3}\left(\frac{eE}{m^2}\right)^{1/2}(1+\gamma^2)^{5/4}\exp\left(-\frac{\pi m^2}{eE}\frac{2}{\sqrt{1+\gamma^2}+1}\right)$$

It's natural to consider $\operatorname{Im}\Gamma$ at fixed $\gamma = \dfrac{m}{eE\tau}$ ('t Hooft coupling)

Pair-production from perturbation theory



New idea: use resurgence to extract this pair-production rate from a weak-field expansion of the *magnetic* effective action, $\Gamma(B, \lambda)$

$$\frac{\Gamma(B,\lambda)}{V_3} \sim \lambda \frac{m^4}{3\pi^2} \sum_{n=0}^{\infty} a_n(\gamma) \left(\frac{eB}{\pi m^2}\right)^{2n+4} \qquad \left(\frac{eB}{m^2} \to 0\right)$$

Borel summation in physics

Summing divergent series

Series in perturbation theory are generically asymptotic

$$f(g) \sim \sum_{n=0}^{\infty} a_n g^n \quad (g \to 0), \qquad a_n \sim n! \quad (n \to \infty)$$

- Zero radius of convergence

Borel (1899): reconstruct functions from their asymptotic data

$$\sum_{n=0}^{\infty} a_n g^n \quad \to \quad \underbrace{\mathcal{B}(s) = \sum_{n=0}^{\infty} \frac{a_n}{n!} s^n}_{\text{Borel transform}} \quad \to \quad \underbrace{\mathcal{S}[f](g) = \int_0^{\infty} \mathrm{d}s\, e^{-s} \mathcal{B}(sg)}_{\text{Borel sum}}$$

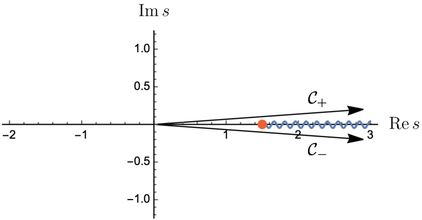
- $\mathcal{B}(s)$ has a non-zero radius of convergence $\to$ singularities
- Borel singularities $\iff$ non-perturbative physics

Borel singularities

If $\mathcal{B}(s)$ has no singularities on the positive real axis, then $f(g)$ is **Borel summable**

$$\mathcal{S}[f](g) = f(g)$$

If $\mathcal{B}(s)$ has singularities on the positive real axis, then $f(g)$ is **non-Borel summable** $\rightarrow$ our resummation is ambiguous



$$\mathcal{S}[f](g) = \frac{1}{2}\left(\int_{\mathcal{C}_+} + \int_{\mathcal{C}_-}\right) \mathrm{d}s\, e^{-s}\mathcal{B}(sg) \pm \frac{1}{2}\left(\int_{\mathcal{C}_+} - \int_{\mathcal{C}_-}\right) \mathrm{d}s\, e^{-s}\mathcal{B}(sg)$$

Resurgence

E.g. a single pole: $a_n \sim \sigma A^{-n} n!$

$$\mathcal{B}(s) = \frac{\sigma}{1-(s/A)} \quad \to \quad \mathcal{S}[f](g) \sim \mathrm{Re}\,\mathcal{S}[f] \pm i\sigma\pi e^{-A/g}$$

E.g. a single branch point: $a_n \sim \sigma A^{-n} n! \left(1 + \frac{b_1}{n} + \frac{b_2}{n(n-1)} + \dots\right)$

$$\mathcal{S}[f](g) \sim \mathrm{Re}\,\mathcal{S}[f] \pm i\sigma\pi e^{-A/g}\left(1 + b_1 g + b_2 g^2 + \dots\right)$$

Large-order growth of g^n $\quad\Longleftrightarrow\quad$ low-order fluctuations of $e^{-1/g}$

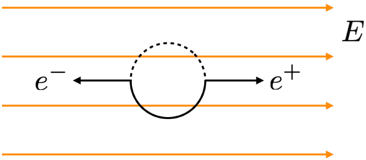
Observables are represented by **resurgent trans-series**

$$f(g) \sim \sum_n a_n g^n \quad \Longrightarrow \quad f(g) = \sum_{nkl} a_{nkl}\, g^n \left(e^{-A/g}\right)^k \left(\ln(-g)\right)^l$$

Resurgence: all non-pert. physics is encoded in the $\{a_n\}$

How to fix an ambiguity?

Idea: use physical knowledge of the system to fix the ambiguity



$$\frac{2}{\hbar}\,\mathrm{Im}\,\Gamma = P_{e^+e^-} > 0$$

Constant fields:

$$\frac{\Gamma_{\mathrm{EH}}(E)}{V_4} = -\frac{e^2E^2}{8\pi^2}\int_0^\infty \frac{\mathrm{d}s}{s^2}\left(\cot s - \frac{1}{s} + \frac{s}{3}\right)e^{-m^2 s/(eE)}$$

Borel sum!

$$\frac{\mathrm{Im}\,\Gamma_{\mathrm{EH}}(E)}{V_4} = +\frac{e^2E^2}{8\pi^3}\sum_{k=1}^{\infty}\frac{1}{k^2}\exp\left(-\frac{k\pi m^2}{eE}\right)$$

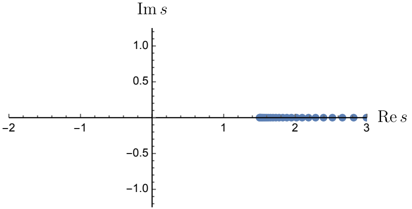
Finite perturbative knowledge

Question: what if we only know the first N perturbative coefficients?

- Ratio tests: $a_n \sim \sigma A^{-n} n!(1+\dots)$ ✓
- Borel transform: $\mathcal{B}_N(s) = \sum_{n=0}^{N-1} \frac{a_n}{n!} s^n$!!! no singularities!
- Borel sum: $\mathcal{S}_N[f](g) \sim \sum_{n=0}^{N-1} a_n g^n$ ✗ no progress

First step: Padé approximation (poles and zeros accumulate to branch points)

$$\mathcal{P}[\mathcal{B}_N](s) = \frac{P_{N/2}(s)}{Q_{N/2}(s)}$$



Inhomogeneous field: Exact effective action

Single peak magnetic field configuration[5,6]

$$\frac{\Gamma(B,\lambda)}{V_3} = \lambda \frac{m^4}{3\pi^2} \int_0^\infty \frac{\mathrm{d}s}{e^{\pi m^2 s/(eB)} - 1}$$

$$\times \left[\frac{\mathrm{d}z}{\mathrm{d}s} \left(1 - \frac{4z}{3} + \frac{z^2}{5}\, {}_2F_1\left(1,1,\tfrac{7}{2};z\right) \right) - (s \to -s) - \left(\frac{8}{3}s - 2\gamma \left(1 + \frac{\gamma^2}{4}s^2\right)^{3/2} \operatorname{arcsinh}\left(\frac{\gamma}{2}s\right) \right) \right]$$

$$z = -is - \tfrac{\gamma^2}{4}s^2$$

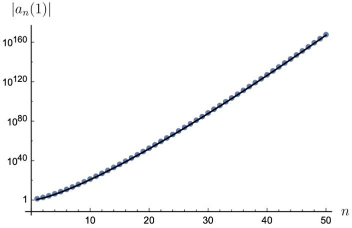
Weak-field expansion:

$$\frac{\Gamma(B,\lambda)}{V_3} \sim \lambda \frac{m^4}{3\pi^2} \sum_{n=0}^{\infty} a_n(\gamma) \left(\frac{eB}{\pi m^2} \right)^{2n+4}$$

$$a_n(\gamma) \sim (-1)^n \left(\frac{2}{\sqrt{1+\gamma^2}+1} \right)^{-2n} \Gamma\left(2n + \tfrac{3}{2}\right)$$

↑

Distance to the leading singularity



[5] Dunne, Gerald, and Theodore M. Hall. Physics Letters B 419.1-4 (1998)

[6] Cangemi, Daniel, Eric D'Hoker, and Gerald Dunne. Physical Review D 52.6 (1995)

Modified Borel transform

Bose-like factor:

$$\frac{1}{e^{\pi m^2 s/(eB)} - 1} = \sum_{k=1}^{\infty} e^{-k\pi m^2 s/(eB)} \qquad \text{“sum over instantons”}$$

Euler-Heisenberg can be written in this form

$$\frac{\Gamma_{\mathrm{EH}}(B)}{V_4} = \frac{e^2 B^2}{4\pi^4} \sum_{k=1}^{\infty} \frac{1}{k^2} \int_0^{\infty} \mathrm{d}s\, e^{-k\pi m^2 s/(eB)} \frac{s}{s^2+1}$$

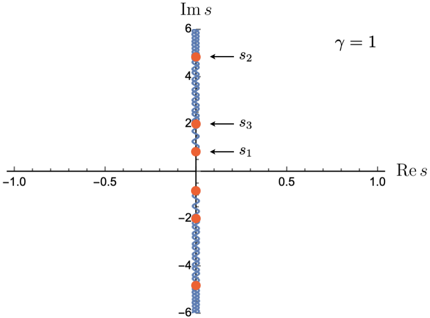
“Modified Borel transform” (only one set of singularities)

Inhomogeneous case:

$$\mathcal{B}(s,\gamma) = \frac{\mathrm{d}z}{\mathrm{d}s}\left(1 - \frac{4z}{3} + \frac{z^2}{5}\, {}_2F_1\!\left(1,1,\tfrac{7}{2};z\right)\right) - (s \to -s) - \left(\frac{8}{3}s - 2\gamma\left(1 + \frac{\gamma^2}{4}s^2\right)^{3/2} \operatorname{arcsinh}\!\left(\frac{\gamma}{2}s\right)\right)$$

Inhomogeneous B field: new Borel singularities

Three pairs of complex conjugate branch points:



$$|s_1| = \frac{2}{\sqrt{1+\gamma^2}+1}$$

$$|s_2| = \frac{2}{\sqrt{1+\gamma^2}-1}$$

$$|s_3| = \frac{2}{\gamma}$$

Growth rate:

$$a_n(\gamma) \sim (-1)^n |s_1|^{-2n} \Gamma\left(2n + \tfrac{3}{2}\right)$$

WKB:

$$\left.\frac{\operatorname{Im}\Gamma}{V_3}\right|_{\text{WKB}} \propto \exp\left(-\frac{\pi m^2}{eE}|s_1|\right)$$

The inhomogeneity causes new singularities to appear!

Sub-leading singularities would give rise to sub-dominant exponential contributions

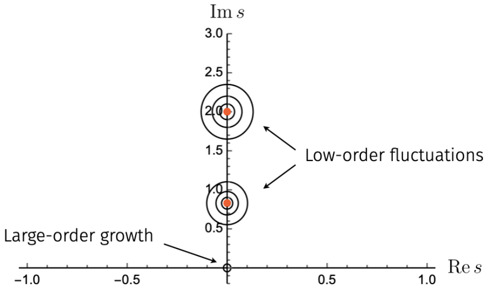
$$\frac{\operatorname{Im}\Gamma(E,\tau)}{V_3} \sim \sum_{i=1}^{3} \sigma_i(\gamma) \left[\sum_{n=0}^{\infty} \sum_{k=1}^{\infty} c_{nk}^{(i)}(\gamma) \left(\frac{eE}{\pi m^2} \right)^{n+\delta} \left(e^{-\pi m^2 |s_i|/(eE)} \right)^k \right]$$

How to determine $\sigma_i(\gamma)$, $c_{nk}^{(i)}(\gamma)$, and δ? $\Longrightarrow$ Darboux's theorem

$$\mathcal{B}(s \to 0, \gamma)$$

$$\Updownarrow$$

$$\mathcal{B}(s \to s_i, \gamma)$$



Exact large-order growth

Expansion about the origin:

$$\mathcal{B}(s,\gamma) = \sum_{n=0}^{\infty} \frac{a_n(\gamma)}{\Gamma(2n+4)\zeta(2n+4)} s^{2n+3}$$

Expansion about each singularity:

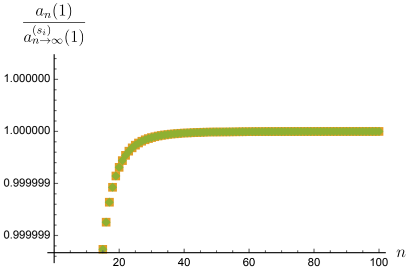
$$\mathcal{B}(s,\gamma) = \left(1 - \frac{s}{s_i}\right)^{3/2} \sum_{n=0}^{\infty} b_n^{(i)}(\gamma)(s-s_i)^n + \text{analytic}$$

Large-order growth of coefficients: (non-trivial function of γ !)

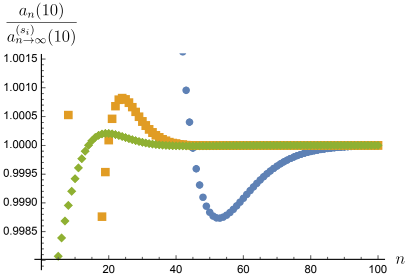
$$\boxed{\frac{a_n(\gamma)}{\Gamma(2n+4)\zeta(2n+4)} \sim 2\sum_{l=0}^{\infty}(-1)^l \binom{2n+\frac{1}{2}-l}{-\frac{5}{2}-l} \left(\frac{b_l^{(1)}(\gamma)}{s_1^{2n+3-l}} + \frac{b_l^{(2)}(\gamma)}{s_2^{2n+3-l}} + \frac{b_3^{(1)}(\gamma)}{s_3^{2n+3-l}} \right)}$$

Do these new singularities really contribute?

Small γ



Large γ



● $$\frac{a_n(\gamma)}{2\,\Gamma(2n+4)\zeta(2n+4)\binom{2n+\frac{1}{2}}{-\frac{5}{2}}\frac{b_0^{(1)}(\gamma)}{s_1^{2n+3}}}$$

■ $$\frac{a_n(\gamma)}{2\,\Gamma(2n+4)\zeta(2n+4)\binom{2n+\frac{1}{2}}{-\frac{5}{2}}\left[\frac{b_0^{(1)}(\gamma)}{s_1^{2n+3}}+\frac{b_0^{(3)}(\gamma)}{s_3^{2n+3}}\right]}$$

◆ $$\frac{a_n(\gamma)}{2\,\Gamma(2n+4)\zeta(2n+4)\binom{2n+\frac{1}{2}}{-\frac{5}{2}}\left[\frac{b_0^{(1)}(\gamma)}{s_1^{2n+3}}+\frac{b_0^{(3)}(\gamma)}{s_3^{2n+3}}+\frac{b_0^{(2)}(\gamma)}{s_2^{2n+3}}\right]}$$

Full trans-series

Exact large-order growth $\rightarrow$ full trans-series structure of $\operatorname{Im}\Gamma(E,\tau)$

$$\frac{\operatorname{Im}\Gamma(E,\tau)}{V_3} \sim \sum_{i=1}^{3} \sigma_i(\gamma) \left[\sum_{n=0}^{\infty} \sum_{k=1}^{\infty} c_{nk}^{(i)}(\gamma) \left(\frac{eE}{\pi m^2} \right)^{n+\delta} \left(e^{-\pi m^2 |s_i|/(eE)} \right)^k \right]$$

$$\sigma_1(\gamma) = \sigma_2(\gamma) = \frac{\tau m^4}{8\sqrt{\pi}} (1+\gamma^2)^{5/4}, \qquad \sigma_3(\gamma) = -\frac{\tau m^4}{4\sqrt{\pi}} \gamma^{5/2}$$

$$c_{nk}^{(j)}(\gamma) = \frac{i^n}{k^{n+5/2}} \frac{\Gamma\left(n+\frac{5}{2}\right)}{\Gamma\left(\frac{5}{2}\right)} \left(\frac{b_n^{(j)}(\gamma)}{b_0^{(j)}(\gamma)} \right)$$

$$\delta = \frac{5}{2}$$

Resurgence confirmed to all orders!

- Perturbative coefficients encode **all** non-perturbative physics

LCFA and WKB approximations

$$\frac{\operatorname{Im}\Gamma(E,\tau)}{V_3} \sim \sum_{i=1}^{3} \sigma_i(\gamma) \left[\sum_{n=0}^{\infty} \sum_{k=1}^{\infty} c_{nk}^{(i)}(\gamma) \left(\frac{eE}{\pi m^2} \right)^{n+5/2} \left(e^{-\pi m^2 |s_i|/(eE)} \right)^k \right]$$

LCFA: set $\gamma = 0 \implies s_1(0) = 1, \quad s_2(0), s_3(0) \to \infty$

$$\tau \frac{e^2 E^2}{8\pi^3} \left(\frac{eE}{m^2} \right)^{1/2} \sum_{k=1}^{\infty} \frac{1}{k^{5/2}} \exp\left(-\frac{k\pi m^2}{eE} \right) \sum_{n=0}^{\infty} c_{nk}^{(1)}(0) \left(\frac{eE}{k\pi m^2} \right)^n \quad \checkmark$$

WKB: consider only the closest singularity and its leading fluctuation

$$\tau \frac{e^2 E^2}{8\pi^3} \left(\frac{eE}{m^2} \right)^{1/2} (1+\gamma^2)^{5/4} \exp\left(-\frac{\pi m^2}{eE} \frac{2}{\sqrt{1+\gamma^2}+1} \right) \quad \checkmark$$

Full perturbative knowledge $\rightarrow$ full non-perturbative knowledge

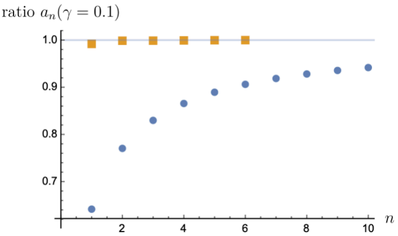
Finite order extrapolation

How much of this can be seen?

Assuming no knowledge of the exact effective action, we start with N terms in perturbation theory

$$\frac{\Gamma(B,\lambda)}{V_3} \sim \lambda \frac{m^4}{3\pi^2} \sum_{n=0}^{N-1} a_n(\gamma) \left(\frac{eB}{\pi m^2}\right)^{2n+4}$$

With ~ 10 terms, we can deduce the exact leading growth



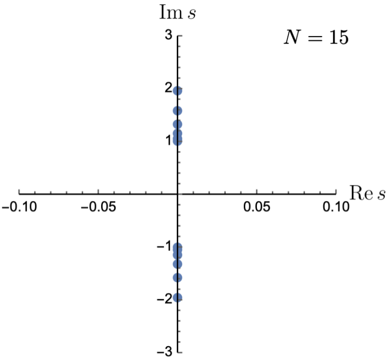
$$a_n(\gamma) \sim (-1)^n \frac{3\sqrt{\pi}}{4}(1+\gamma^2)^{5/4} \frac{\Gamma\left(2n+\frac{3}{2}\right)}{|s_1|^{2n+3/2}}$$

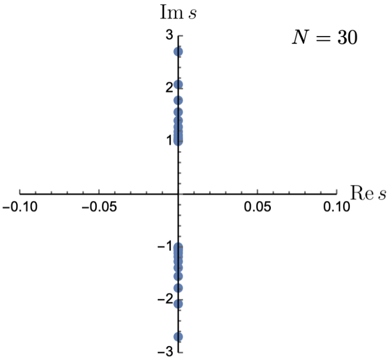
4th order Richardson

Singularity structure

Borel transform: $$\mathcal{B}_N(s,\gamma) = \sum_{n=0}^{N-1} \frac{a_n(\gamma)}{\Gamma(2n+2)} (|s_1| s)^{2n+2}$$

Padé-approximant: $$\mathcal{P}[\mathcal{B}_N](s,\gamma) = \frac{P_N(s,\gamma)}{Q_N(s,\gamma)} \qquad (\gamma = 1)$$



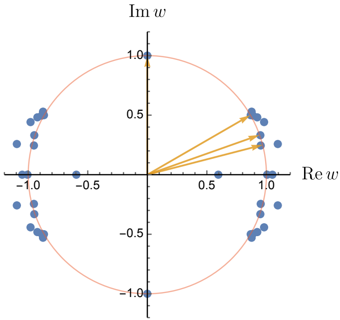


Conformal map: looking under the cut(s)

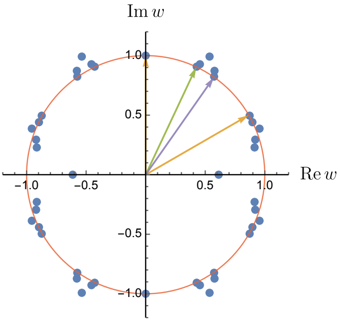
Conformal map: separate out branch cuts[7]

$$s = \frac{2w}{1-w^2} \quad \Longleftrightarrow \quad w = \frac{s}{\sqrt{1+s^2}+1}$$

At large γ we see the new singularities $(N = 50)$



$\gamma = 0.1$



$\gamma = 10$

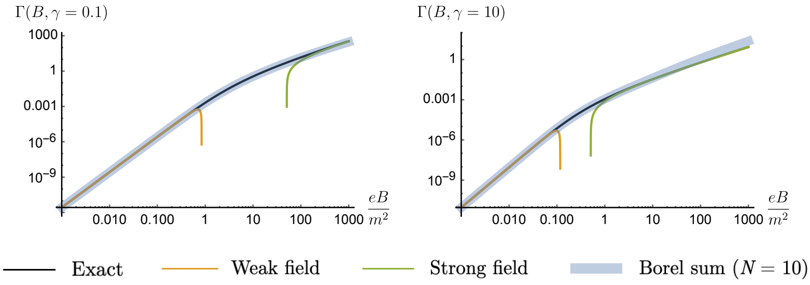
[7] Costin, Ovidiu, and Gerald V. Dunne. Physics Letters B 808 (2020).

Extrapolation from weak field to strong field

Weak field: $\dfrac{\Gamma(B,\lambda)}{V_3} \sim \lambda \dfrac{m^4}{3\pi^2} \displaystyle\sum_{n=0}^{\infty} a_n(\gamma) \left(\dfrac{eB}{\pi m^2}\right)^{2n+4} \qquad \left(\dfrac{eB}{m^2} \to 0\right)$

Strong field: $\dfrac{\Gamma(B,\lambda)}{V_3} \sim \lambda \dfrac{m^4}{3\pi^2} \cdot \dfrac{1}{3} \left(\dfrac{eB}{m^2}\right)^2 \left[\ln\left(\dfrac{eB}{m^2}\right) + \ln(2\gamma) - 12\ln A + \dfrac{2}{3}\right] \qquad \left(\dfrac{eB}{m^2} \to \infty\right)$

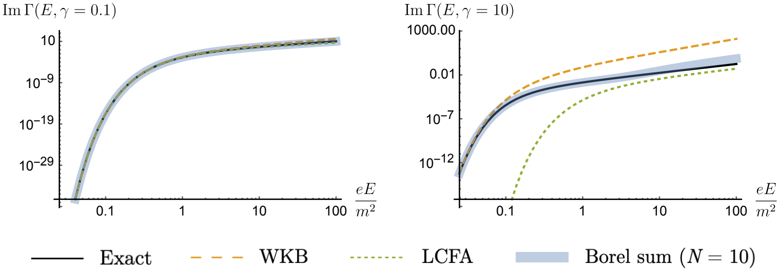
Borel sum: $\dfrac{\mathcal{S}[\Gamma_N](B,\lambda)}{V_3} = \lambda \dfrac{m^4}{3\pi^2} \left(\dfrac{eB}{\pi m^2}\right)^2 \displaystyle\int_0^{\infty} \dfrac{\mathrm{d}s}{s} e^{-\pi m^2 |s_1| s/(eB)} \mathcal{P}[\mathcal{B}_N](s,\gamma)$



Pair-production rate

Borel sum: $\frac{\mathcal{S}_\theta[\Gamma_N](E,\tau)}{V_3} = -\tau \frac{m^4}{3\pi^2}\left(\frac{eE}{\pi m^2}\right)^2 \int_0^{\infty e^{i\theta}} \frac{\mathrm{d}s}{s} e^{-\pi m^2 |s_1| s/(eE)} \mathcal{P}[\mathcal{B}_N](-is,\gamma)$

$$\operatorname{Im}\mathcal{S}[\Gamma_N](E,\tau) = \frac{1}{2}\Big(\mathcal{S}_{0^+}[\Gamma_N](E,\tau) - \mathcal{S}_{0^-}[\Gamma_N](E,\tau)\Big)$$



With only 10 terms, we recover the exact pair-production rate with remarkable precision

Conclusion

Conclusion

- The Schwinger effect is a non-perturbative phenomenon which is difficult to probe for inhomogeneous fields even at one-loop order.
- Resurgence predicts that this information is encoded within the divergence of weak field expansions of the effective action. ✓
- Using only a modest amount of perturbative data, we can efficiently extract the strong field behavior and the pair-production rate with a higher precision than both the LCFA and WKB approximation.
- This technique offers a new approach to understand more general field configurations in QED, higher loop contributions, pair-production in dS/AdS backgrounds, etc.

Questions?

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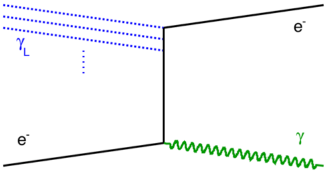
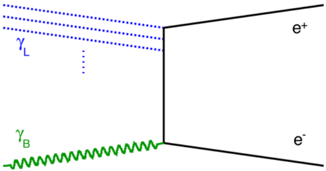
Additional slides

Scattering processes

Nonlinear inverse Compton scattering (NICS)

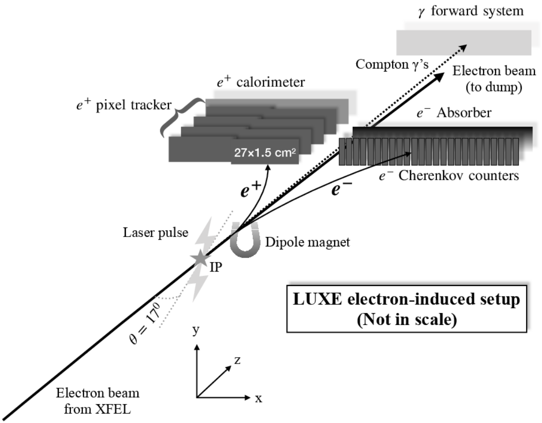


Nonlinear Breit-Wheeler



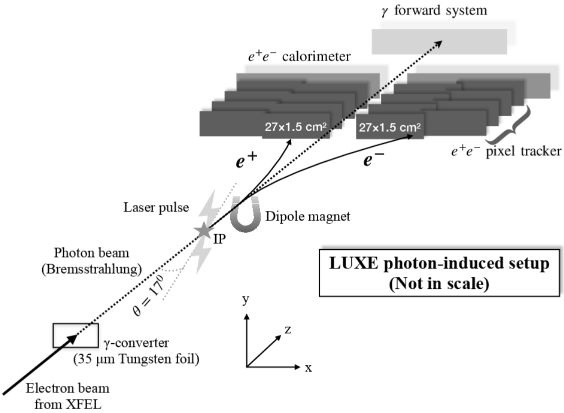
LUXE (Laser Und XFEL Experiment) at DESY[8]

Sketch of experimental set-up for NICS



[8] Abramowicz, H., et al. "Letter of intent for the LUXE experiment." arXiv preprint arXiv:1909.00860 (2019).

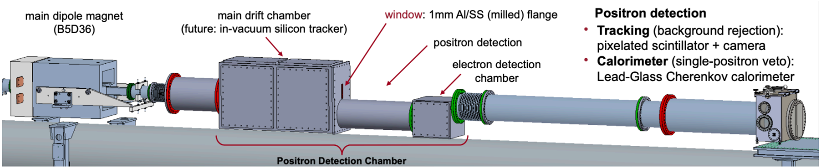
Sketch of experimental set-up for nonlinear Breit-Wheeler



$$E_e = 17.5\,\mathrm{GeV}, \quad P_\gamma = 30 - 300\,\mathrm{TW}, \quad I = 10^{21}\,\mathrm{W/cm}^2, \quad 30\,\mathrm{fs\ pulses}$$

FACET-II at SLAC[9]

Experimental set-up for NICS



$$E_e = 13\,\mathrm{GeV}, \quad P_\gamma = 10\,\mathrm{TW}, \quad I = 10^{20}\,\mathrm{W/cm^2}, \quad 30\,\mathrm{fs\ pulses}$$

[9] Meuren, Sebastian. "Probing strong-field qed at facet-ii (slac e-320)." Third conference on extremely high intensity laser physics (exhilp). Vol. 7. 2019.