# Magnetic fields effects on particle interactions strength in the early unierse

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- In many contexts: lasers, relativistic heavy ion collisions (QCD), compact objects, early universe events
- in presence of different ingredients:
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  weak or strong magnetic field strengths
- through different channels:
  the decay products can be fermions or bosons (scalars or vectors)
  the charged particle can be the progenitor or the products

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- with different methods:
  Schwinger's proper time method
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- Different approximation schemes:
  strong fields → dimensional reduction (LLL)
  weak fields → resummation and some kind of expansion

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This process is enhanced in some cases:

W. Tsai and T. Erber [1974]
L. Urrutia [1978]
A. Kutznetzov, N. Mikheev and L Vassilevskaya [1998]
N. Mikheev and M. Chistyakov [2001]
A. Erdas and M. Lissia [2003]
K. Bhattacharya and S. Sahu [2009]
P. Satunin [2015]
V. Miranski an I. Shovkovy [2015]
A. Bandyopadhyay and S. Mallik [2016]
M. Coppola, D. Dumm, S. Noguera and N. Scoccola [2019]
S. Yang, M. Jin and D. Hou [2022]
G. Piccinelli, A. Sánchez [2022]

# Effect of the magnetic field on the decay process

Sometimes it is inhibited:

K. Sogut, H. Yanar and A. Havare [2017]
M. Kawaguchi and S. Matsuzaki [2017]
G.P. and A. Sánchez [2017]
J. Jaber-Urquiza an A. Sánchez [2023]

# Effect of the magnetic field on the decay process

And in some others it is mixed for different energies:

M. Chistyakov, A. Kutznetzov and N. Mikheev [1998]
S. Ghosh *et al.* [2017]
J. Jaber-Urquiza, G.P. and A. Sánchez [2019]

# Possible application: Warm Inflation

- ”Supercooled models” of inflation assume very little interaction of the inflaton with all other fields until the reheating process, at the end of inflation.
- In warm inflation[1], the inflaton is assumed to interact with other fields in a continuous way.
- A successful implementation of this model is embedded in the framework of supersymmetry.
- It rests on a two-step process of radiation production,

$$\phi \to \chi \to yy,$$

where $\phi$ is the inflaton, $\chi$ an intermediary heavy field and $y$ the light sector, composed of fermions $\psi_y$ and scalars $y$.

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[1] A. Berera, Phys. Rev. D **71**, 023514 (2005).

# Warm Inflation

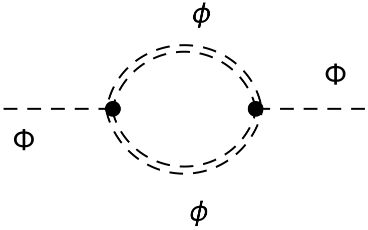
- The model requires a dissipative component $\Gamma$ of sizable strength as compared to the expansion rate of the universe ($\Gamma > 3H$, with $H$ the Hubble parameter).
- This additional dissipation, responsible for producing radiation, modifies the equation of motion for the inflaton $\phi$:

$$\ddot{\phi} + (3H + \Gamma_{\phi})\dot{\phi} + V_{T,\phi} = 0$$

where $V_T$ is the inflaton effective potential at finite temperature.

# The model

$$\mathcal{L}_I = g\Phi\phi^*\phi$$



$$\Pi = (ig)^2 \int \frac{d^4k}{(2\pi)^4} D_B(p-k) D_B(k).$$

# Magnetic field propagators

To include the effect of an external magnetic field, we use Schwinger's proper-time method[2]

$$D_B(k) \quad = \quad \int_0^\infty \frac{ds}{\cos eBs} \exp\left\{ is(k_{||}^2 - k_\perp^2 \frac{\tan eBs}{eBs} - m_\phi^2 + i\epsilon) \right\},$$

where we have adopted the notation $k_{||}^2 = k_0^2 - k_3^2$, $k_\perp^2 = k_1^2 + k_2^2$.

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[2] J. Schwinger, Phys. Rev. **82**, 664-679 (1951).

# Scalar self-energy in presence of magnetic field

$$\Pi = \frac{g^2}{2(4\pi)^2} \int_0^\infty \frac{ds}{s} \int_{-1}^{1} dv \frac{eBs}{\sin(eBs)} e^{-is(m^2 - i\epsilon)} e^{is\left[\frac{1}{4}(1-v^2)p_{||}^2 - \frac{\cos(eBsv)-\cos(eBs)}{2eBs\sin(eBs)} p_\perp^2\right]}$$

where we have integrated over the internal momentum and made the change of variables $s_1 = s\frac{1-v}{2}$ and $s_2 = s\frac{1+v}{2}$

# Decay rate

The decay rate is directly proportional to the imaginary part of the self-energy[3]

$$\Gamma = \frac{\Im(\Pi(p))}{2\omega(p)}$$

with $\Pi(p)$ the self-energy and $\omega(p)$ the dispersion relation of the decaying particle and

$$\Im(\Pi(p)) \equiv \frac{\Pi - \Pi^*}{2i}$$

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[3] R. E. Cutkosky J. of Math. Phys. 1, 429 (1960)

# Decay rate

In the weak field limit, the imaginary part has the form[4]

$$\Im(\Pi(p)) = \frac{g^2 p^2}{2(4\pi)^2} \int_0^1 dv \, \frac{4v^2\sqrt{m^2 - \frac{1}{4}(1-v^2)p^2}}{\sqrt{3}|p_\perp|(1-v^2)eB} K_{1/3}(\rho)$$

which is obtained by expanding up to quadratic terms in the argument of the exponential and keeping up to linear term in the coefficient. Here $K_{1/3}(\rho)$ represents the Modified Bessel Function of the Second Kind and

$$\rho \equiv \frac{4}{\lambda} \frac{\left[1 - \frac{1}{4}(1-v^2)\frac{p^2}{m^2}\right]^{3/2}}{(1-v^2)} \qquad \text{with} \quad \lambda \equiv \frac{3}{2}\frac{p_\perp}{m}\frac{eB}{m^2}.$$

In the case of Tsai and Erber $p^2 = 0$ (photons) and in our case $p^2 = M^2$ (massive scalar)

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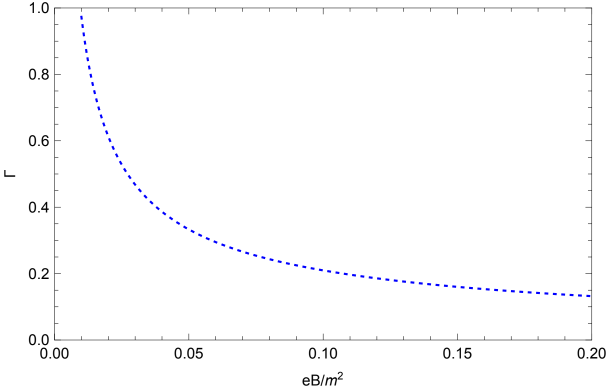
[4] W. Tsai & T. Erber, PRD 10, 472 (1974)

# Results

In this form, we can explore two different kinematical regimes by taking the asymptotical behavior of the Bessel function. [5]

In the region $\lambda \gg 1$ ($p_\perp \gg 1$), $K_{1/3}(\rho) \sim \rho^{-1/3}$, the analytical result is



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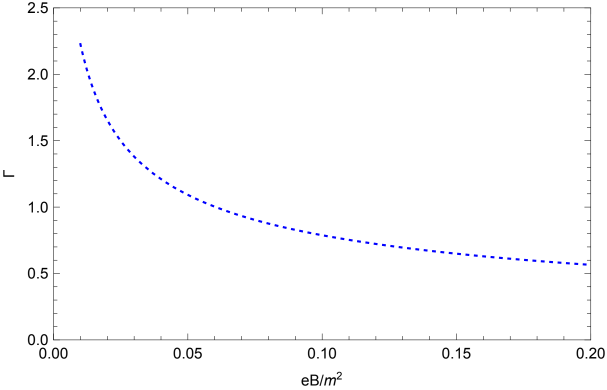
[5] Piccinelli, Sanchez, PRD96 (2017)

# Results

In the region $\lambda \ll 1$ ($p_\perp \ll 1$), $K_{1/3}(\rho) \sim \rho^{-1/2} e^{-\rho}$, the numerical result gives



# Results

In the strong field limit, the calculation is simpler[6],, since we just have to deal with the LLL, that reduces to a Gaussian integration over transverse momentum, $\exp\left(-p_\perp^2/qB\right)$, obtaining:

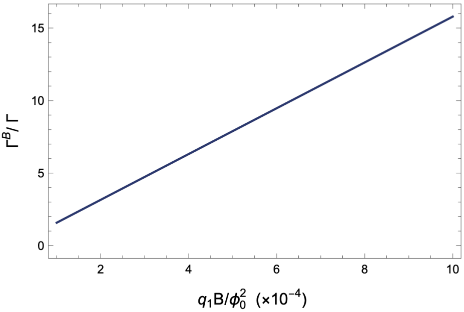


FIG. 2: Decay width ratio $\Gamma^B/\Gamma$, Eqs. (70-71), of a heavy charged scalar into two light charged fermions, for different magnetic field strengths, for $M_s/\phi_0 = 0.05$, $m_1/\phi_0 = 10^{-3}$, $m_2/\phi_0 = 5 \times 10^{-3}$, $g = 0.1$. The magnetic field enhances this process.

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[6] Piccinelli, Sanchez, PRD106 (2022)

# The spin role

Interested in the role of the spin[7], we calculated the decay rate $\Phi -> \Psi\bar{\Psi}$. In the low momentum approximation, we found again a magnetic field suppression, although more pronounced. Through the quantity: $\Delta\Gamma = \Gamma^B/\Gamma_{vac}$, we quantified this effect:

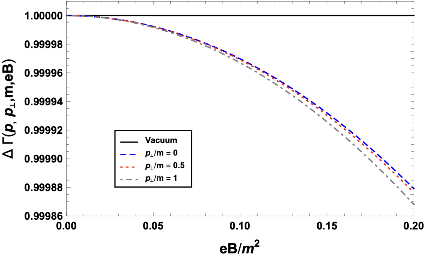

FIG. 4: Decay response to the external magnetic field as a function of the magnetic field strength, for different values of the transverse momentum, for the low momentum approximation, taking $p/m = 5$.

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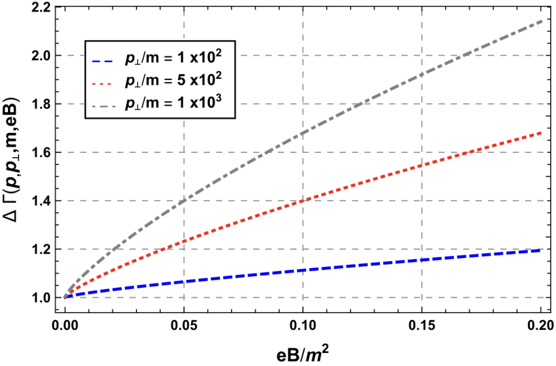
[7] Jaber-Urquiza, Piccinelli, Sanchez, PRD99 (2019)

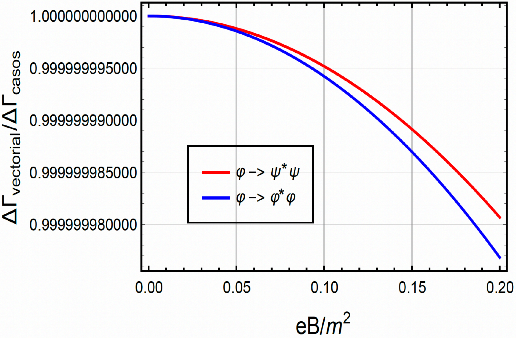
# The spin role

An interesting result of this work is that, with the same approach, the decay rate $\Phi -> \Psi\bar{\Psi}$ presents a different trend in the regime where the momentum of the decaying particle is large:



# The spin role

In another work[8], the decay rate $Z- > \Psi\bar{\Psi}$ was calculated and compared to the previous work, through the quantity: $\Delta\Gamma_{vect}/\Delta\Gamma_{scalar}$, $(\Delta\Gamma \equiv \Gamma_B/\Gamma_{vac})$, giving:



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[8] M.E. Monreal Cancino, Thesis: *Cambios causados por un campo magnético sobre la tasa de decaimiento de un bosón Z a un par de fermiones* (2022)

# Conclusions and Discussion

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- Since the results in the literature can be very different between one situation and another, our interest fells on finding a scheme that could be somehow predictive, once all the physical ingredients are taken into account. We did not fully succeeded since we still face some discrepant results, but we arrived to some preliminary conclusions.

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- Since the analytical calculations require of an approximation approach, it is very important to have a good control on the validity of the different approximation schemes that hold for different well-constrained parameter regimes, in particular for the transferred momentum regime.
- There is a general agreement that strong magnetic fields favor the interaction, with a linear dependence of the decay width on the magnetic field strength, that comes from a gaussian integration (particles confined into LLL)

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- Since the analytical calculations require of an approximation approach, it is very important to have a good control on the validity of the different approximation schemes that hold for different well-constrained parameter regimes, in particular for the transferred momentum regime.
- There is a general agreement that strong magnetic fields favor the interaction, with a linear dependence of the decay width on the magnetic field strength, that comes from a gaussian integration (particles confined into LLL)
- In contrast, for weak magnetic fields, the situation is far from clear: the process is favored in some cases, inhibited in some others, or it can depend on the kinematical regime of the involved particles.

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- Another important ingredient for these differences could be the spin of the particles involved in the interaction. The magnetic field impact was observed to be more pronounced for fermions than for scalars. Although the different results can be traced back to the different analytical structures of the propagators of the particles involved in the interaction, the physical motivation for such behaviors still needs more discussion. In particular, in the case of $\gamma \to e^+e^-$ (Tsai & Erber), and $\nu \to We$ (Erdas & Lissia), the decay rate grows with the magnetic field.

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- The main difference between these behaviors can come from the analytical structure of the self-energy which is associated with the spin. This is supported by the work of Kawaguchi and Matsuzaki (EJPA 2017), where the effect of a magnetic field on the decay rate of a neutral rho meson depends on the polarization modes: The decay of $S_z = 0$ component is suppressed while the decay of $S_z = \pm 1$ is enhanced.

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  The decrease of the decay rate with increasing magnetic field, that emerges in some situations at low-momentum, can be due to the phase space reduction, that is even more pronounced for fermions.

  For high momenta the underlying physical reason is more puzzling. A possible explanation that has been offered is: if we imagine that the (composite) decaying particle were formed by a pair of charged particles, then the Lorentz force would act in opposite directions on each forming particle, promoting the decay process. And this also works for large magnetic fields.

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- Important notice: for the same situation, we have obtained a similar behavior by employing different approaches.

Merci