The fundamental picture of QED vacuum & its implications

Jian-Xin Lu

The Interdisciplinary Center for Theoretical Study (ICTS)
University of Science & Technology of China
&
The Peng Huanwu Center for Fundamental Theory (PCFT)

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The talk is based on the following papers:

- J. X. Lu,"Magnetically-enhanced open string pair production," JHEP **12**, 076 (2017);
- J. X. Lu, "Some aspects of interaction amplitudes of D branes carrying worldvolume fluxes," Nucl. Phys. B **934**, 39 (2018);
- J. X. Lu, "A possible signature of extra-dimensions: The enhanced open string pair production," Phys. Lett. B **788**, 480 (2019);
- Q. Jia and J. X. Lu,"Remark on the open string pair production enhancement," Phys. Lett. B **789**, 568 (2019);
- J. X. Lu, "A note on the open string pair production of the D3/D1 system," JHEP **10**, 238 (2019);
- Q. Jia, J. X. Lu, Z. Wu and X. Zhu, "On D-brane interaction & its related properties,"Nucl. Phys. B 953 (2020)114947;
- J. X. Lu and Nan Zhang, "More on the open string pair production" , Nucl. Phys. B **977** (2022) 115721;
- J. X. Lu, "Understanding the open string pair production of Dp/D0 system", JHEP **11**, 019(2023);
- J. X. Lu, "The open string pair production, its enhancement and the physics behind," PLB 848 (2024)138397;
- J. X. Lu, "The open string pair production revisited" PLB 872 (2026) 140125;
- J. X. Lu, Work in progress.

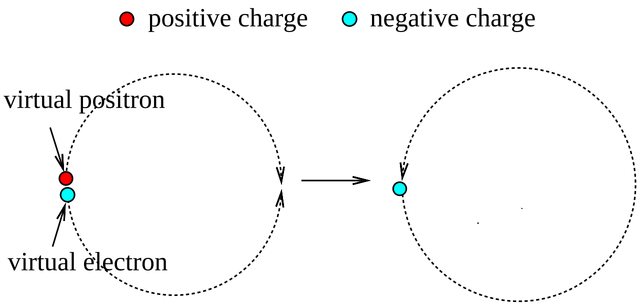
Outline

- Motivation/introduction
- The open string pair production
- The stringy rate vs the QED ones, the underlying implications
- Conclusion and discussion

QED Vacuum Picture

VACUUM QUANTUM FLUCTUATIONS

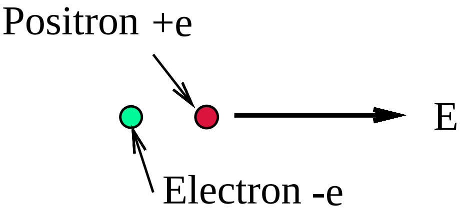
An anti-charge moving forward in time equivalent to a charge moving backward in time



$(\delta t \sim 10^{-21}\, s)$

QED Vacuum Fluctuations

One way to test such QED vacuum picture is to apply a constant electric field to it. There is then certain probability to create real electron and positron pairs from the vacuum virtual fluctuations, called Schwinger pair production (1951).



The rate obtained by Schwinger [PR82(1951)664] is actually the decay one of the QED vacuum in the presence of an electric field E and is

$$\mathcal{W}^{\text{Schwinger}}_{\text{spinor}} = 2\,\frac{(eE)^2}{(2\pi)^3}\sum_{n=1}^{\infty}\frac{1}{n^2}\,e^{-n\pi\frac{m_e^2}{eE}}, \quad (1.1)$$

where m_e is the mass of electron and e is the charge unit or the gauge coupling $g_{\rm YM}$.

QED Vacuum Fluctuations

The pair production rate, in a constant applied electric field E, can be computed to give Nikishov [JETP30(1970)660, NPB21(1970)346]

$$\mathcal{W}^{\rm QED}_{\rm spinor} = 2\,\frac{(eE)^2}{(2\pi)^3}\, e^{-\frac{\pi m_e^2}{eE}}\,. \qquad (1.2)$$

The other alternative approach to see this vacuum process or to test the QED vacuum picture is via two slow heavy nuclei collision to form a transient superheavy nucleus with $Z > Z_{\rm critical} \approx 173$ such that its unoccupied 1s state energy $< -m_{\rm e}\, c^2$.

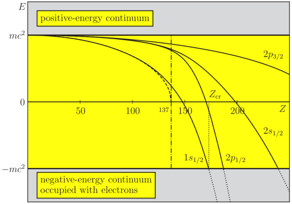


FIG. 1. The low-lying energy levels of a H-like ion as functions of the nuclear charge number Z.

QED Vacuum Fluctuations

The detection of Schwinger pair production requires the applied $E \sim m_e^2/e \sim 10^{18}\, V/m$ while the current lab limit is $\sim 10^{10}\, V/m$, still 8 order of magnitude too small. The test of QED vacuum picture via super heavy nucleus is now on-going in Russia, Germany and also in China (惠州 HIAF) and hope that some positive news comes out soon.

In spite of this, the great success of QED makes nobody doubt its vacuum picture.

Even so, the modern view of QED as merely an effective theory and so its vacuum picture implies that the underlying fundamental picture could teach us lessons about new physics beyond SM, which we will address in what follows.

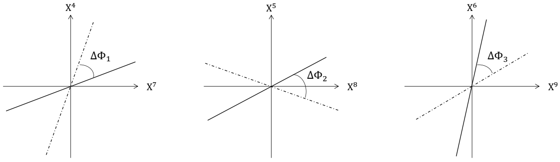
The fundamental QED vacuum picture

- So far, the only known consistent theory unified all known interactions including gravity is string theory. It is expected that particle physics standard model (SM) can be constructed from this theory.
- This is indeed true. For example, the SM with gauge group $SU_C(3) \times SU(2)_{\rm L} \times\ U(1)_{\rm Y}$ can be constructed using intersecting D branes in Type II superstrings.
- The simplest construction Ibanez et al [JHEP11 (2001) 002] begins with 4 stacks of intersecting D6 branes, consisting of 3 D6 in the first stack, 2 D6 in the second, 1 D6 in the third and the other 1 D6 in the fourth, with all D6 along the '$0, 1, 2, 3$' directions, giving the usual 4-dimensional Minkowski flat spacetime and the gauge group $U(3) \times U(2) \times U(1) \times U(1)$ $= U(1) \times SU(3)_{\rm C} \times U(1) \times SU(2)_{\rm L} \times U(1) \times U(1)$,

	0	1	2	3	T^2 (4, 7)	T^2 (5, 8)	T^2 (6,9)
3 D6	x	x	x	x	$\surd$	$\surd$	$\surd$
2 D6	x	x	x	x	$\surd$	$\surd$	$\surd$
1 D6	x	x	x	x	$\surd$	$\surd$	$\surd$
1 D6	x	x	x	x	$\surd$	$\surd$	$\surd$

The fundamental QED vacuum picture

- while each of the three remaining spatial directions of D6's in each stack being along one of three tori $T^2 \times T^2 \times T^2$, respectively, in the compact 6 dimensional space, therefore each of stacks intersecting with the other in the compact directions with angles, for example,



Intersecting D6-branes

- The matter fields arise from the massless open strings in the bi-fundamental connecting different stacks of D6 branes at the intersecting points, therefore also with their ends charged under the respective U(1). Note that the intersecting angles give rise effectively to magnetic fields.

The fundamental picture of QED vacuum

- Note that an electrically charged particle with mass m_S, charge Q and spin S in a magnetic field B background has the energy or effective mass

$$E^2_{(S,S_x)} = (2N+1)|Q|B \mp g_S|Q|\,\mathbf{B}\cdot\mathbf{S} + m_S^2, \quad (1.3)$$

with g_S the gyromagnetic ratio ($g_S = 2$), N the Landau level, '$-$' sign for $Q > 0$ and '$+$' for $Q < 0$. So for the lowest Landau level ($N = 0$), we have the following mass splittings for $Q > 0$ with $m_S = 0$ as

S	0	1/2	1
$E^2_{(S,S_z)}$	$E_{(0,0)} = QB$	$E^2_{(\frac{1}{2},-\frac{1}{2})} = 2QB$ $E^2_{(\frac{1}{2},\frac{1}{2})} = 0$	$E^2_{(1,-1)} = 3QB$ $E^2_{(1,0)} = QB$ $E^2_{(1,1)} = -QB$

- This setup has initially $U(3)\times U(2)\times U(1)\times U(1)$ $= U(1)\times SU(3)_C\times U(1)\times SU(2)_L\times U(1)\times U(1)$ gauge group, giving 4 $U(1)$'s, having various chiral fermions, therefore giving rise to potential anomalies.

The fundamental picture of QED vacuum

- The cancellations of these anomalies require the introduction of various couplings, for examples, arising from the closed string modes to the gauge fields, and these couplings make three of the 4 U(1)'s massive, and the only one remaining massless, giving rise to the SM hypercharge U(1). At the end, we have the precise SM gauge group $SU_C(3) \times SU(2)_{\rm L} \times\ U(1)_{\rm Y}$ with the correct field content.
- This construction spells the origin of standard model matters, indeed coming from the bi-fundamental open strings connecting different stack of D branes, therefore the detection of the Schwinger pair production or the QED quantum fluctuations reveals not only QED vacuum picture but also teach us lessons about the existence of extra dimensions and the non-particle dark matter as we will demonstrate in our following simplified model computations.

The open string pair production

The first natural question is:

Does there exist an analogous process of Schwinger effects in superstring theory?

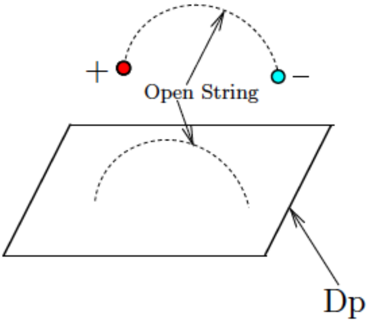
This was answered by Bachas and Porrati [PLB296(1992)77] many years ago in the case of unoriented Type I superstring.

We initiated this study in the oriented Type II superstrings in 2017 and in particular, we will address in this talk

- The open string pair production in Type II superstring theories,
- The relation between the stringy rate and the relevant rates in QED along with some implications of these,
- A possibly complete picture of the QED vacuum.

D-branes in Type II

In the oriented Type II superstring theories, only D-branes have their quantum fluctuations associated with open strings which will be our focus



D-branes in Type II

The point is: unlike in QED, an isolated Dp brane cannot give rise to the pair production even if a large but less than the critical electric field is applied.

In other words, we have

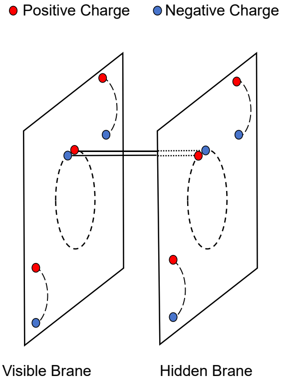
$$\mathcal{W}^{(\mathrm{String})} = 0, \tag{2.1}$$

however, the QED rate

$$\mathcal{W}^{(\mathrm{QED})} \neq 0. \tag{2.2}$$

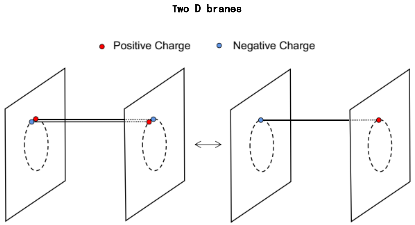
The open string pair production

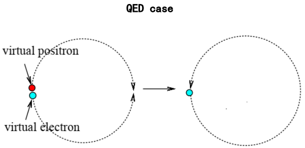
A simple setup for having a non-vanishing stringy rate, giving rise to the fundamental (rather than adjoint) charged matters on the brane, in analogous to the Schwinger pair production in QED, is to consider two D branes in Type II string theories, placed parallel at a separation.



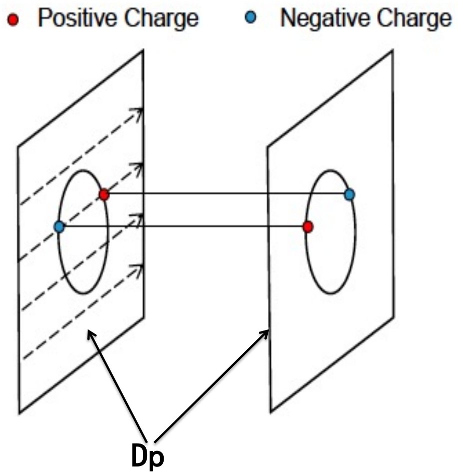
The open string pair production

A visible-brane observer, who can only sense the charged ends of the open strings attached on the brane, will have the same vacuum quantum fluctuation picture as in QED, shown below





The open string pair production



The most significant and relevant case is for $p = 3$, the one mimicking our own $(1+3)$-dimensional world.

So in what follows we will focus on this special D3/D3 system, as a concrete illustration, in this talk

	0	1	2	3	4	5	6	7	8	9
Visible D3	x	x	x	x	0	0	0	0	0	0
Hidden D3	x	x	x	x	y_1	y_2	y_3	y_4	y_5	y_6

with $y^2 = \sum_{i=1}^{6} y_i^2$.

The D3/D3 rate

Consider the electric/magnetic tensor $\hat{F}^1$ on one D3 brane and the $\hat{F}^2$ on the other D3 brane, respectively, as

$$\hat{F}^a_{\alpha\beta} = \left(\begin{array}{cccc} 0 & \hat{f}_a & 0 & 0 \\ -\hat{f}_a & 0 & 0 & 0 \\ 0 & 0 & 0 & \hat{g}_a \\ 0 & 0 & -\hat{g}_a & 0 \end{array}\right), \qquad (2.3)$$

where $\hat{f}_a$ denotes the dimensionless electric field ($|\hat{f}_a| < 1$) while g_a the dimensionless magnetic one ($|\hat{g}_a| < \infty$) with $a = 1, 2$. Note $\hat{F}_{\mu\nu} = F_{\mu\nu}/T$ with $T = 1/(2\pi\alpha')$ the fundamental string tension. Note $[T] = 2$, $[F] = 2 \rightarrow [\hat{F}] = 0$.

The D3/D3 rate

The open string one-loop annulus amplitude can be computed to give Lu'17

$$\Gamma = \frac{4\,V_4|\hat f_1 - \hat f_2||\hat g_1 - \hat g_2|}{(8\pi^2\alpha')^2}\int_0^\infty \frac{dt}{t}\, e^{-\frac{y^2 t}{2\pi\alpha'}}\,\frac{(\cosh\pi\nu_0'\,t - \cos\pi\nu_0\,t)^2}{\sin\pi\nu_0\,t\,\sinh\pi\nu_0'\,t}\prod_{n=1}^{\infty} Z_n, \qquad (2.4)$$

where (note $|z| = e^{-\pi t}$)

$$Z_n = \frac{\prod_{j=1}^{2}[1 - 2\,e^{(-)^j\pi\nu_0' t}|z|^{2n}\cos\pi\nu_0\,t + e^{(-)^j 2\pi\nu_0' t}|z|^{4n}]^2}{(1-|z|^{2n})^4(1 - 2\,|z|^{2n}\cos 2\pi\nu_0\,t + |z|^{4n})\prod_{j=1}^{2}(1 - e^{(-)^{(j-1)}2\pi\nu_0' t}|z|^{2n})}. \qquad (2.5)$$

In the above, y is the separation between the two D3, the parameters $\nu_0 \in [0,\infty)$ and $\nu_0' \in [0,1)$ are

$$\tanh\pi\nu_0 = \frac{|\hat f_1 - \hat f_2|}{1 - \hat f_1\hat f_2}, \quad \tan\pi\nu_0' = \frac{|\hat g_1 - \hat g_2|}{1 + \hat g_1\hat g_2}. \qquad (2.6)$$

The integrand of the above amplitude has an infinite many of simple poles along the t-axis, occurring at $\sin\pi\nu_0\,t = 0$, i.e.

$$\pi\nu_0\,t_k = k\pi \to t_k = \frac{k}{\nu_0}, \quad k = 1, 2, \cdots, \qquad (2.7)$$

signaling the open string pair production at these poles.

The D3/D3 rate

The decay rate of the underlying system per unit worldvolume is the imaginary part of the above amplitude which can be obtained as the sum of the residues of the poles of the integrand in (2.4) times π following Bachas and Porrati'92 and is given as

$$\begin{aligned} \mathcal{W} &= -\frac{2\,\mathrm{Im}\Gamma}{V_4} \\ &= \frac{8|f_1 - f_2||g_1 - g_2|}{(8\pi^2\alpha')^2} \sum_{k=1}^{\infty} (-)^{k-1} \frac{\left[\cosh\frac{\pi k \nu_0'}{\nu_0} - (-)^k\right]^2}{k \sinh\frac{\pi k \nu_0'}{\nu_0}} e^{-\frac{k y^2}{2\pi\alpha' \nu_0}} Z_k(\nu_0, \nu_0') \end{aligned} \tag{2.8}$$

where

$$Z_k(\nu_0, \nu_0') = \prod_{n=1}^{\infty} \frac{\left[1 - (-)^k e^{-\frac{2nk\pi}{\nu_0}\left(1 - \frac{\nu_0'}{2n}\right)}\right]^4 \left[1 - (-)^k e^{-\frac{2nk\pi}{\nu_0}\left(1 + \frac{\nu_0'}{2n}\right)}\right]^4}{\left(1 - e^{-\frac{2nk\pi}{\nu_0}}\right)^6 \left[1 - e^{-\frac{2nk\pi}{\nu_0}(1 - \nu_0'/n)}\right] \left[1 - e^{-\frac{2nk\pi}{\nu_0}(1 + \nu_0'/n)}\right]}. \tag{2.9}$$

The D3/D3 rate

The non-perturbative open string pair production rate can be computed Lu'17,19,24 as

$$\mathcal{W}^{(\mathrm{String})} = \frac{8\,|\hat{f}_1 - \hat{f}_2||\hat{g}_1 - \hat{g}_2|}{(8\pi^2\alpha')^2}\, e^{-\frac{y^2}{2\pi\nu_0\alpha'}} \frac{\left[\cosh\frac{\pi\nu_0'}{\nu_0} + 1\right]^2}{\sinh\frac{\pi\nu_0'}{\nu_0}} Z_1(\nu_0, \nu_0'), \quad (2.10)$$

where

$$\begin{aligned} Z_1(\nu_0, \nu_0') &= \prod_{n=1}^{\infty} \frac{\left[1 + 2e^{-\frac{2n\pi}{\nu_0}}\cosh\frac{\pi\nu_0'}{\nu_0} + e^{-\frac{4n\pi}{\nu_0}}\right]^4}{\left[1 - e^{-\frac{2n\pi}{\nu_0}}\right]^6 \left[1 - e^{-\frac{2\pi}{\nu_0}(n-\nu_0')}\right]\left[1 - e^{-\frac{2\pi}{\nu_0}(n+\nu_0')}\right]}. \\ &= 1 + 4\left[1 + \cosh\frac{\pi\nu_0'}{\nu_0}\right]^2 e^{-\frac{2\pi}{\nu_0}} + \cdots \quad (2.11) \end{aligned}$$

Note that in practice, $|\hat{f}_a|,\ |\hat{g}_a| \ll 1 \to \nu_0,\ \nu_0' \ll 1 \Rightarrow Z_1(\nu_0, \nu_0') \approx 1$

$$\tanh\pi\nu_0 = \frac{|\hat{f}_1 - \hat{f}_2|}{1 - \hat{f}_1\hat{f}_2}, \quad \tan\pi\nu_0' = \frac{|\hat{g}_1 - \hat{g}_2|}{1 + \hat{g}_1\hat{g}_2}. \quad (2.12)$$

The D3/D3 rate

For simplicity, we consider the case $\hat{f}_2 = \hat{g}_2 = 0$ on the hidden D3 while on our own D3, in terms of the lab. field E and B via

$$\hat{f}_1 = 2\pi\alpha' eE \ll 1, \qquad \hat{g}_1 = 2\pi\alpha' eB \ll 1, \tag{2.13}$$

the pair production rate (2.10) for D3 brane is now (with $Z_1(\nu_0, \nu'_0) = 1$)

$$\mathcal{W}^{(\text{String})} = \frac{2(eE)(eB)}{(2\pi)^2} \frac{\left[\cosh \frac{\pi B}{E} + 1\right]^2}{\sinh \frac{\pi B}{E}} e^{-\frac{\pi m^2(y)}{eE}}, \tag{2.14}$$

where we have introduced the mass for the lowest modes of the open string connecting the two D3

$$m(y) = T_f y = \frac{y}{2\pi\alpha'}. \tag{2.15}$$

Keep in mind, we need to have a nearby hidden D3 brane for this rate!

The D3/D3 rate

Let us now understand which are those pairs to contribute to the rate (2.14).

- From the visible D3 view, for either the open string or the anti open string, these are 5 scalars, 4 spinors and 1 vector, all of which are massive with the same mass as given by (2.15) and charged under the visible U(1).
- For the open string, these modes each carries a positive charge while for the anti open string, they each carries a negative charge. So we have 5 scalar charged/anti-charged pairs, 4 spinor charged/anti-charged pairs and 1 vector charged/anti-charged pair to contribute to the rate (2.14).
- Since in 4D each massive vector has 3 polarizations while a spinor has 2, so we have 8 bosonic polarization pairs and 8 fermionic polarization pairs, giving a total of 16 polarization pairs. In other words, there are 16 charged/anti-changed pairs to contribute to the rate (2.14).

The D3/D3 rate

Let us check if the $B = 0$ rate is the one expected.

For this, let us take $B \to 0$ limit from (2.14) and we have

$$\mathcal{W}^{(\mathrm{string})}(B=0) = \frac{8(eE)^2}{\pi(2\pi)^2}\, e^{-\frac{\pi m^2}{eE}} = 16\, \frac{(eE)^2}{(2\pi)^3}\, e^{-\frac{\pi m^2}{eE}}, \qquad (2.16)$$

indeed the expected result, giving the contribution of 16 charge/anti charge pairs.

The stringy rate vs the QED rate

For convenience, we rewrite the weak-field stringy rate (2.14) here again

$$\mathcal{W}^{(\mathrm{String})} = \frac{2(eE)(eB)}{(2\pi)^2} \frac{\left[\cosh\frac{\pi B}{E} + 1\right]^2}{\sinh\frac{\pi B}{E}} e^{-\frac{\pi m^2(y)}{eE}}, \tag{3.1}$$

which, as discussed earlier, includes the contributions of 5 massive charged scalar pairs, 4 massive charged spinor pairs and one massive vector pair from our visible D3 brane perspective.

We therefore expect physically the following relation Lu'24

$$\mathcal{W}^{(\mathrm{String})} = \mathcal{W}^{\mathrm{QED}}, \tag{3.2}$$

where

$$\mathcal{W}^{\mathrm{QED}} \equiv 5\, W^{\mathrm{QED}}_{\mathrm{scalar}} + 4\, W^{\mathrm{QED}}_{\mathrm{spinor}} + W^{\mathrm{QED}}_{\mathrm{vector}}. \tag{3.3}$$

with $W^{\mathrm{QED}}_{\mathrm{scalar}}$, $W^{\mathrm{QED}}_{\mathrm{spinor}}$ and $W^{\mathrm{QED},}_{\mathrm{vector}}$ the respective QED rates if our computations are indeed consistent and correct.

The stringy rate vs the QED rate

We happily find that the above relation (3.2) holds indeed true given the following known QED rates

$$\mathcal{W}^{\rm QED}_{\rm scalar} = \frac{(eE)(eB)}{2(2\pi)^2} {\rm csch}\left(\frac{\pi B}{E}\right) e^{-\frac{\pi m^2}{eE}}, \quad \mathcal{W}^{\rm QED}_{\rm spinor} = \frac{(eE)(eB)}{(2\pi)^2} \coth\left(\frac{\pi B}{E}\right) e^{-\frac{\pi m^2}{eE}}, \tag{3.4}$$

for a scalar pair and a spinor pair Nikishov'70, and

$$\mathcal{W}^{\rm QED}_{\rm vector} = \frac{(eE)(eB)}{2(2\pi)^2} \frac{2\cosh\frac{2\pi B}{E} + 1}{\sinh\frac{\pi B}{E}} e^{-\frac{\pi m^2}{eE}} \tag{3.5}$$

for a vector pair Kruglov [EPLC22(2001)89].

In the above, the scalar, spinor and vector masses in the respective QED rates are all set the same as the m given by (2.15), i.e.

$$m = T_f y = \frac{y}{2\pi\alpha'}. \tag{3.6}$$

The stringy rate vs the QED rate

The confirmed weak-field relation

$$\mathcal{W}^{(\mathrm{String})} = \mathcal{W}^{\mathrm{QED}} (\equiv 5\, W^{\mathrm{QED}}_{\mathrm{scalar}} + 4\, W^{\mathrm{QED}}_{\mathrm{spinor}} + W^{\mathrm{QED}}_{\mathrm{vector}}) \tag{3.7}$$

is remarkable in the following sense

- The stringy rate $\mathcal{W}^{(\mathrm{String})}$ and the QED rate $\mathcal{W}^{(\mathrm{QED})}$ are computed completely independently, the former is computed non-perturbatively from string theory while the latter is computed non-perturbatively from QFT, but both are happily found to agree with each other in the weak field limit;
- The stringy rate $\mathcal{W}^{(\mathrm{String})}$ needs the presence of a nearby hidden D3, relating to the existence of extra dimensions and to a potential source of dark matter (the hidden D3), while the QED rate $\mathcal{W}^{\mathrm{QED}}$ needs only the $(1+3)$-dimensional world and the underlying QED quantum fluctuations, having nothing to do with the hidden D3.
- The above clearly demonstrates the difference between the fundamental description (here D-brane one) and the low energy effective QED one.

Summary and discussion

- Unlike in QED, we need at least two separate D branes to give rise to the open string pair production, with the pairs coming from the virtual ones connecting the two D branes, therefore along the extra dimensions.

- We show a remarkable weak-field relation between the non-perturbative stringy pair production rate and the QED rate as

$$\mathcal{W}^{(\text{String})} = \mathcal{W}^{\text{QED}}. \tag{4.1}$$

  The former needs the presence of a second or hidden D3, while the QED (QFT) computations say nothing about this, therefore reflecting the incomplete QED vacuum picture.

Summary and discussion

- Given the intersecting D brane construction of particle physics standard model, our study of the open string pair production indicates the significance of detecting the QED Schwinger pair production: it gives not only a test of QED vacuum picture, but also provides potentially a means to detect the existence of extra dimension(s) and hints a source of dark matter (hidden D3) not in the form of particles Lu'26.

THANK YOU!