Strong-field physics
in
(low-energy) heavy-ion collisions

Hidetoshi TAYA

(RIKEN iTHEMS)

Contents

Purpose

Low-energy HIC might be useful to study strong-(electric-)field phys.

- Review strong-field physics at HIC
- Not to advertise my works, but to stimulate discussions (hopefully…)
- Discuss (or introduce or speculate) implications to low-energy HIC

(• Comments and/or criticisms are very welcome)

1. Review of strong-field physics

- Why is strong-field physics interesting and can be relevant to hadron/QCD ?

2. Strong-field physics in high-energy HIC

3. Strong-field physics in low-energy HIC

- Vacuum (dielectric) polarization
- Electric-field induced birefringence

1. Review of strong-field physics

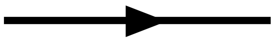
2. Strong-field physics in high-energy HIC

3. Strong-field physics in low-energy HIC

4. Summary

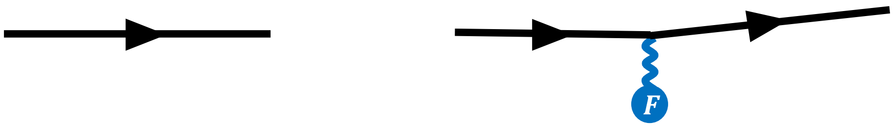
New extreme condition: Strong EM field

New extreme condition: Strong EM field



Vacuum

New extreme condition: Strong EM field



Vacuum **Weak fields ($eF/m^2 \ll 1$)**

Perturbative physics

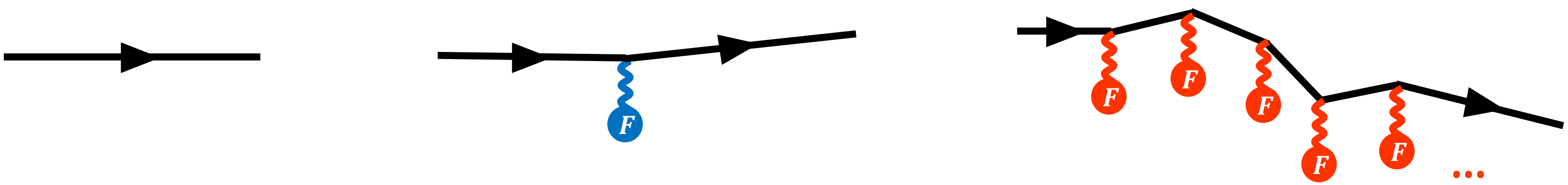
⇒ Very well understood
in both exp.& theor.

ex.) electron anomalous magnetic moment

$\alpha^{-1}(\text{theor.}) = 137.03599914\ldots$ [Aoyama, Kinoshta, Nio (2017)]
$\alpha^{-1}(\text{exp.}) = 137.03599899\ldots$

high-energy processes in accelerator exp.

New extreme condition: Strong EM field



Vacuum → **Weak fields ($eF/m^2 \ll 1$)** → **Strong fields ($eF/m^2 \gg 1$)**

Perturbative physics

⇒ Very well understood
in both exp.& theor.

Non-perturbative physics

⇒ Unexplored in both exp. & theor.

ex.) electron anomalous magnetic moment

$\alpha^{-1}(\text{theor.}) = 137.03599914 \ldots$ [Aoyama, Kinoshta, Nio (2017)]

$\alpha^{-1}(\text{exp.}) = 137.03599899 \ldots$

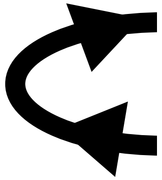
high-energy processes in accelerator exp.

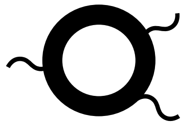
Strong-field phenomena

✔ **Novel QED processes** Review: [Fedotov, Ilderton, Karbstein, King, Seipt, HT, Torgrimsson (2022)]

ex.) Schwinger mechanism, Photon splitting, Vacuum birefringence, ...

(= polarization dep. reflective index)





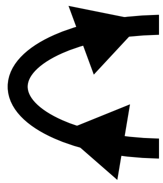
Strong-field phenomena

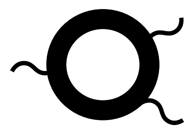
✔ Novel QED processes

Review: [Fedotov, Ilderton, Karbstein, King, Seipt, HT, Torgrimsson (2022)]

ex.) Schwinger mechanism, Photon splitting, Vacuum birefringence, …

(= polarization dep. reflective index)





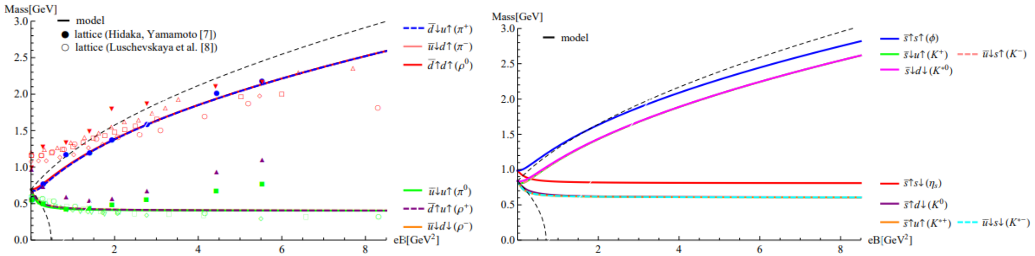
✔ Impacts on hadron physics and QCD

[HT (2015)]

ex. 1) Hadron properties:

⇒ masses, charge dist.,
decay modes, polarization, …

See also recent review [Iwasaki, Oka, Suzuki (2021)]

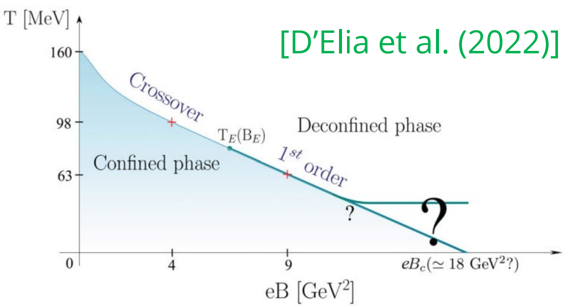


ex. 2) Phase diagram and transition:

[D'Elia et al. (2022)]

⇒ (Inverse) magnetic catalysis, Inhomogeneous phase, …

See also Hattori's talk on Sat.



ex. 3) Others: Anomalous transport phenomena, Glasma, chirality prod., …

Many reviews, e.g., [Kharzeev, Liao, Voloshin, Wang (2016)]
[Hattori, Huang (2017)] …

See Yang's talk on Sat.

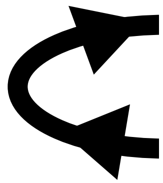
Strong-field phenomena

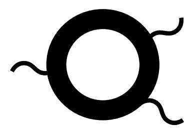
✔ Novel QED processes

Review: [Fedotov, Ilderton, Karbstein, King, Seipt, HT, Torgrimsson (2022)]

ex.) Schwinger mechanism, Photon splitting, Vacuum birefringence, ...

(= polarization dep. reflective index)





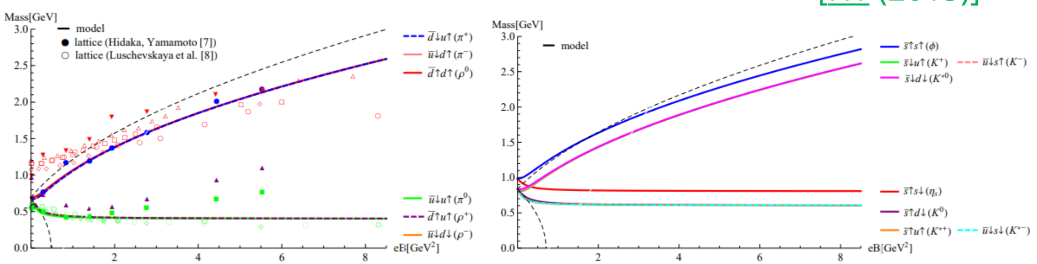
✔ Impacts on hadron physics and QCD

[HT (2015)]

ex. 1) Hadron properties:

⇒ masses, charge dist.,
decay modes, polarization, ...

See also recent review [Iwasaki, Oka, Suzuki (2021)]

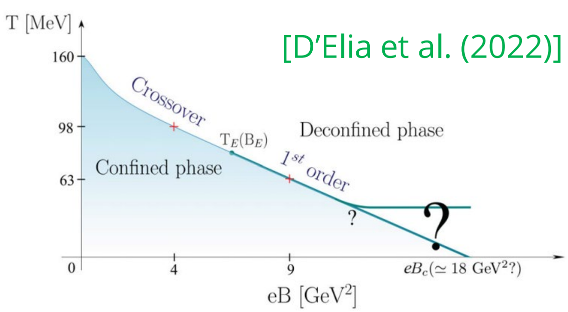


ex. 2) Phase diagram and transition:

[D'Elia et al. (2022)]

⇒ (Inverse) magnetic catalysis, Inhomogeneous phase, ...

See also Hattori's talk on Sat.



ex. 3) Others: Anomalous transport phenomena, Glasma, chirality prod., ...

Many reviews, e.g., [Kharzeev, Liao, Voloshin, Wang (2016)]
[Hattori, Huang (2017)] ...

See Yang's talk on Sat.

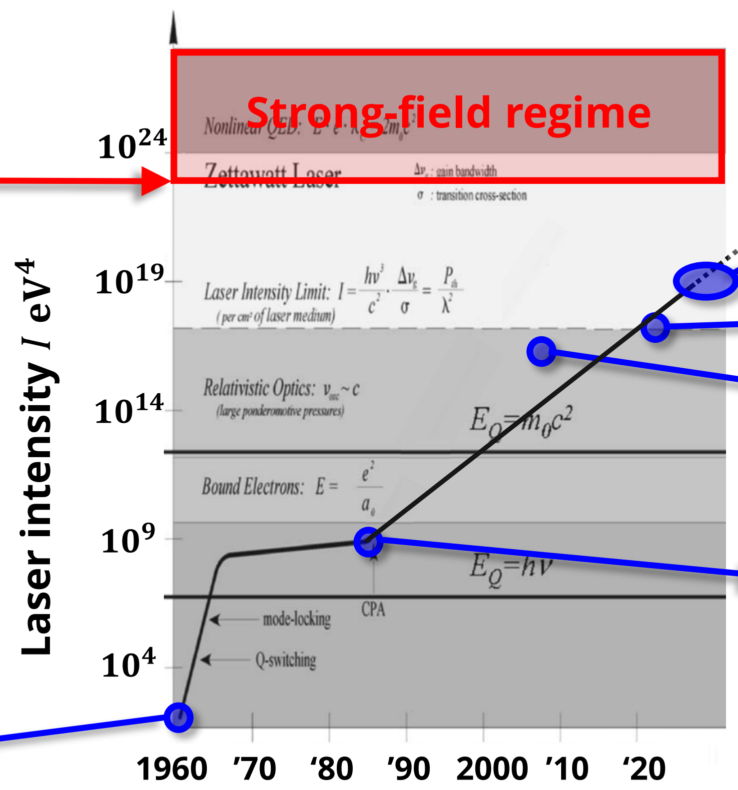
✔ Experimentally, however (almost) NONE of them has been verified

Development of intense laser

✔ Experimental progress is mainly lead by laser physics

Adapted from [Mourou, Tajima, Bulanov (2006)]

Critical field for electrons
$eE, eB \sim (511\ \mathrm{keV})^2$

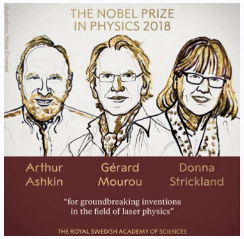


Near-future laser
$I > 10^{18}\ \mathrm{eV}^4$
e.g., ELI @ Europe

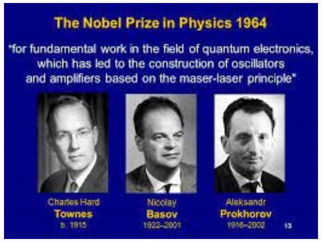
Current strongest laser
$I > 10^{17}\ \mathrm{eV}^4$
CoReLS @ Korea
[Yoon et al., (2021)]

$I \sim 10^{16}\ \mathrm{eV}^4$
HERUCLES @ USA
[Yanovsky et al., (2008)]

Invention of CPA technique



Birth of laser

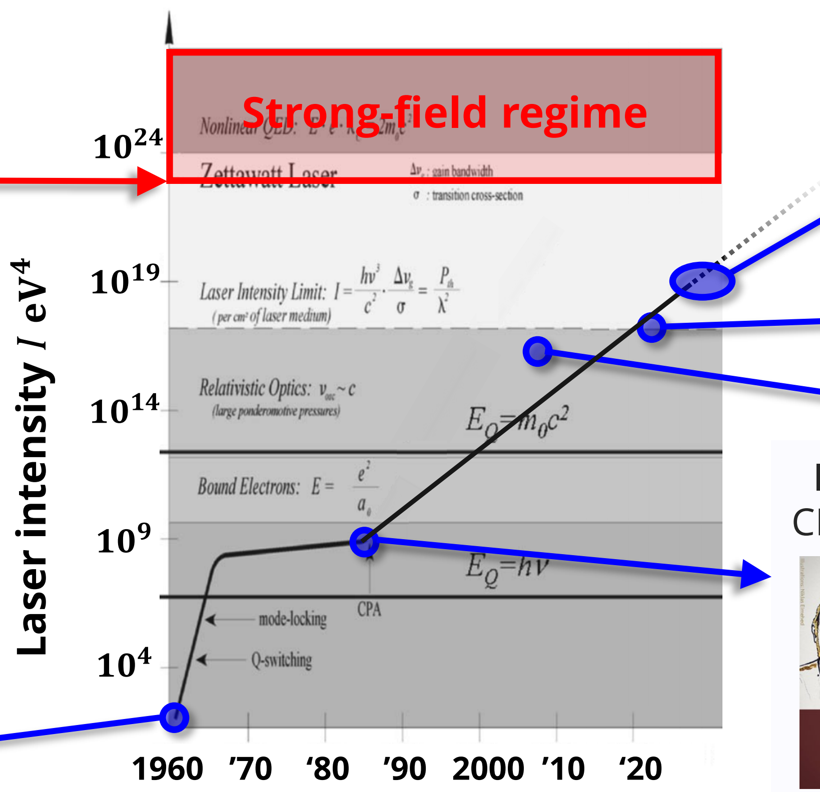


Development of intense laser

✔ Experimental progress is mainly lead by laser physics

Adapted from [Mourou, Tajima, Bulanov (2006)]

Critical field for electrons
$eE, eB \sim (511\ \mathrm{keV})^2$

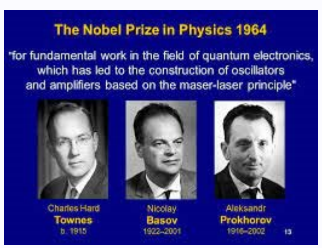


Near-future laser
$I > 10^{18}\ \mathrm{eV}^4$
e.g., ELI @ Europe

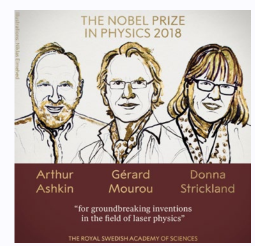
Current strongest laser
$I > 10^{17}\ \mathrm{eV}^4$
CoReLS @ Korea
[Yoon et al., (2021)]

$I \sim 10^{16}\ \mathrm{eV}^4$
HERUCLES @ USA
[Yanovsky et al., (2008)]

Birth of laser



Invention of CPA technique



✔ However, still weaker even than QED scale

⇒ **Any physical systems where strong fields are available ? ⇒ HIC !**

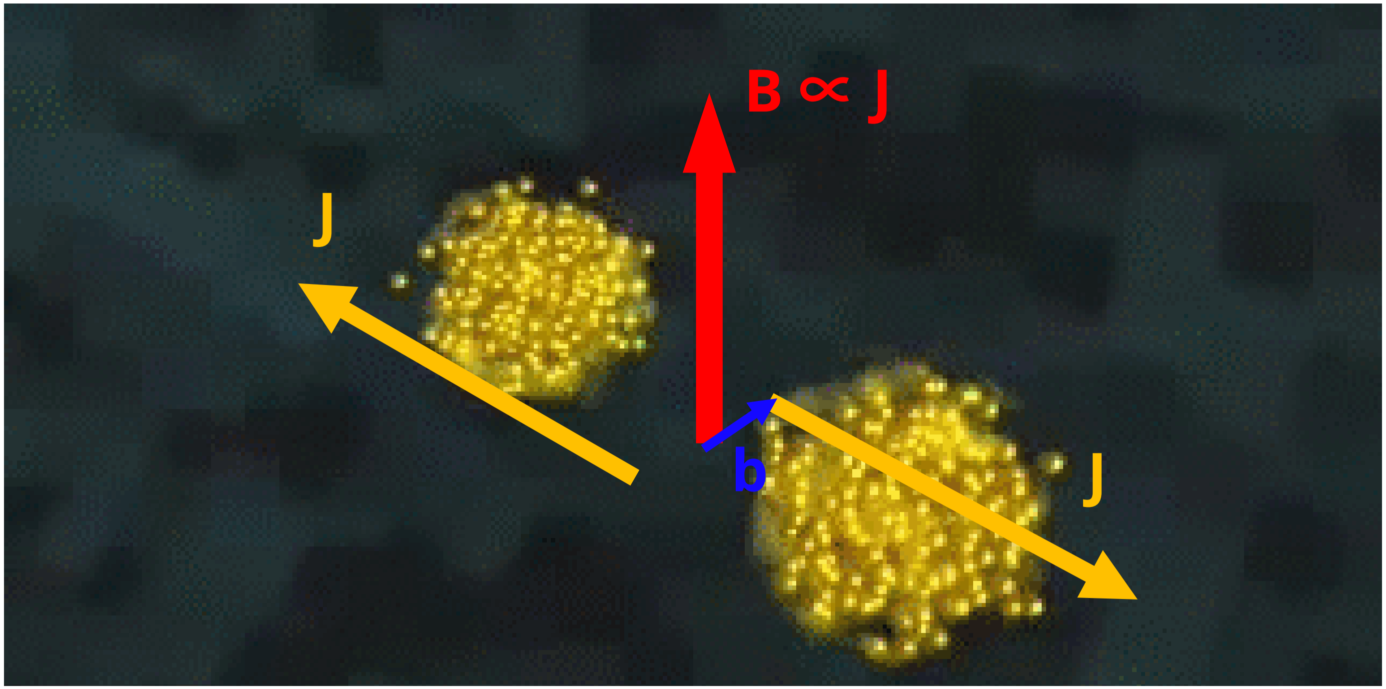
1. Review of strong-field physics

2. **Strong-field physics in high-energy HIC**

3. Strong-field physics in low-energy HIC

4. Summary

Strong fields in high-energy HIC

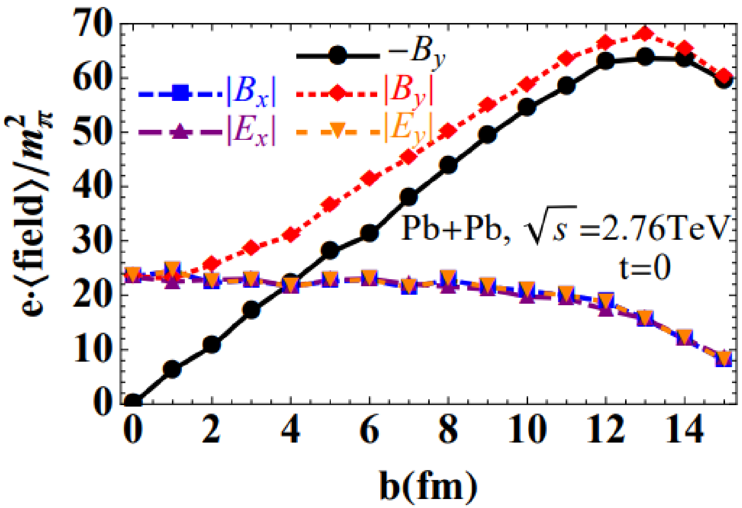


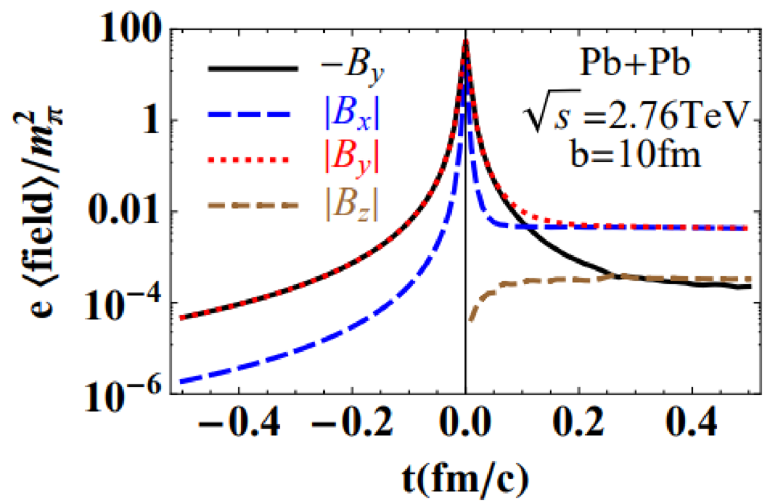
Animation stolen from Internet

✔ Strong magnetic fields are created in high-energy HIC

(also strong vorticity
cf. talks by Niida, Huang,
Yi, Xin-Li, Liao)

Strong fields in high-energy HIC





[Deng, Huang (2012)]

See also [Bzdak, Skokov (2012)] [Hattori, Huang (2016)]

✔ Strong magnetic fields are created in high-energy HIC

(also strong vorticity cf. talks by Niida, Huang, Yi, Xin-Li, Liao)

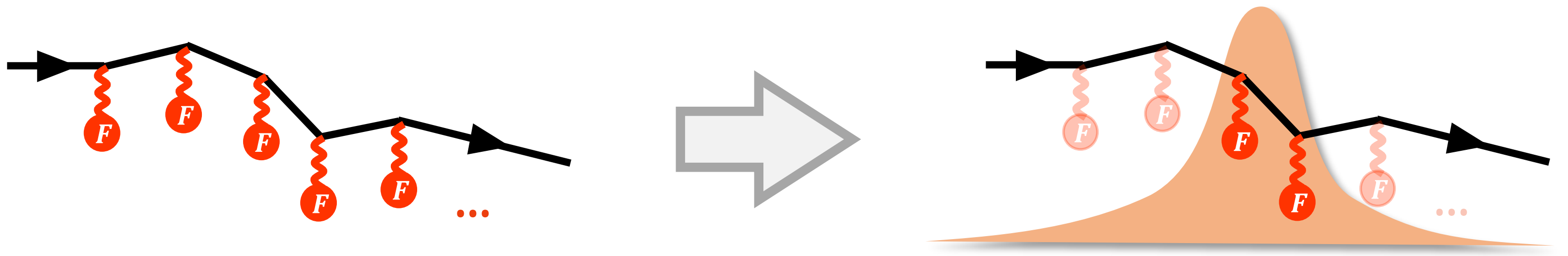
Pros: Extremely strong (strongest in the current Universe) ($eB \gg \Lambda_{\rm QCD}^2$)

Cons: Extremely short-lived ($\tau \ll 1\ {\rm fm}/c$)

⇒ Affects "non-perturbativeness" of strong-field processes

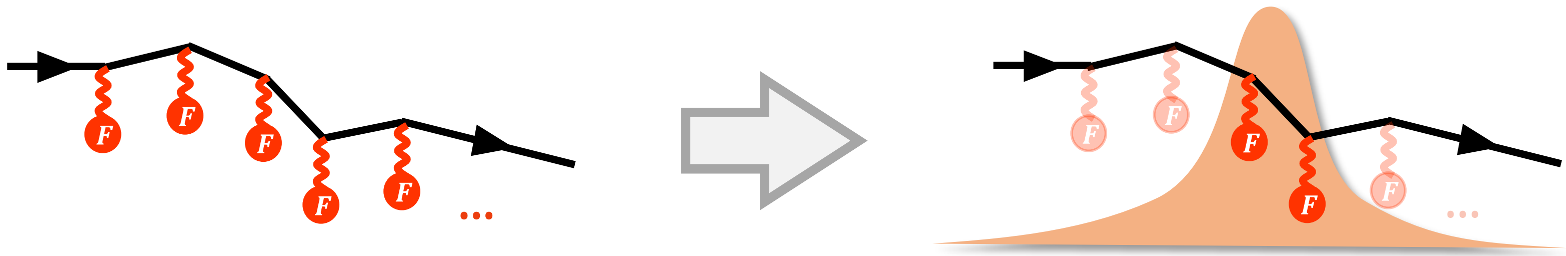
Shorter lifetime, less non-perturbative

✔ **If lifetime is short, no time for multiple interactions**



Shorter lifetime, less non-perturbative

✔ **If lifetime is short, no time for multiple interactions**



✔ **"Phase diagram"** (for the pair production from the vacuum by E field)

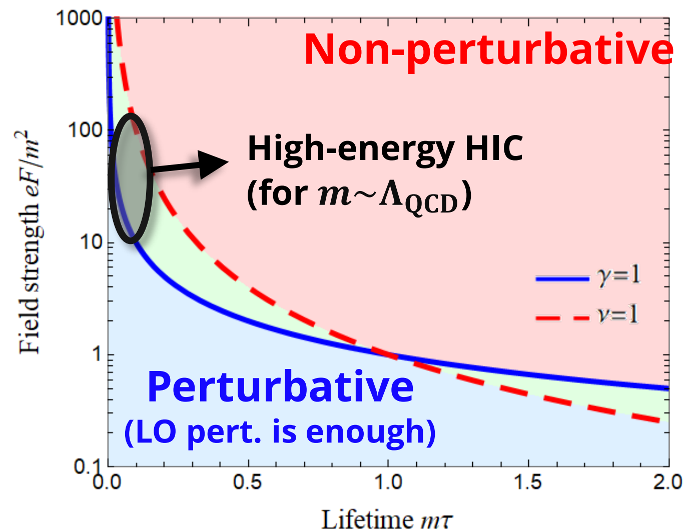
[HT, Fujiii, Itakura (2014)]

- Three dim. para. characterize the system eE, τ, m

  $\Rightarrow$ Two dim.-less para. control the interplay

$$\gamma = \frac{m}{eE\,\tau} = \frac{\text{(rest mass of particle)}}{\text{(work done by field)}} = \text{("strength" of the work)}$$

$$\nu = \frac{eE\,\tau}{1/\tau} = \frac{\text{(work done by field)}}{\text{(photon energy)}} = \text{(\# of photons involved)}$$

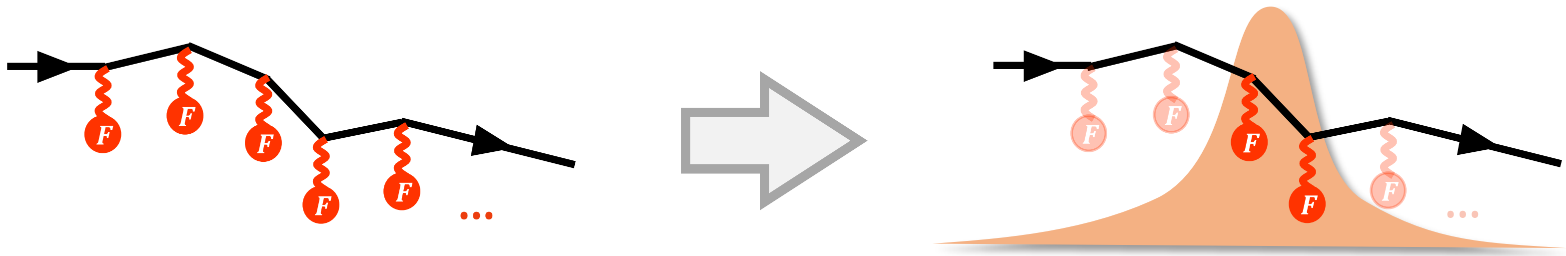


- Non-perturbative for $\boldsymbol{\gamma \ll 1\,,\, \nu \gg 1}$

- For high-energy HIC: $eF \sim (1\ \mathrm{GeV})^2\,,\ \tau \sim 0.1\ \mathrm{fm}/c \Rightarrow \gamma \sim \begin{cases} 10^{-3}\ (m = \Lambda_{\mathrm{QCD}}) \\ 10^{-5}\ (m = m_{\mathrm{e}}) \end{cases},\ \nu \sim 0.1$

Shorter lifetime, less non-perturbative

✔ **If lifetime is short, no time for multiple interactions**



✔ **"Phase diagram"** (for the pair production from the vacuum by E field)

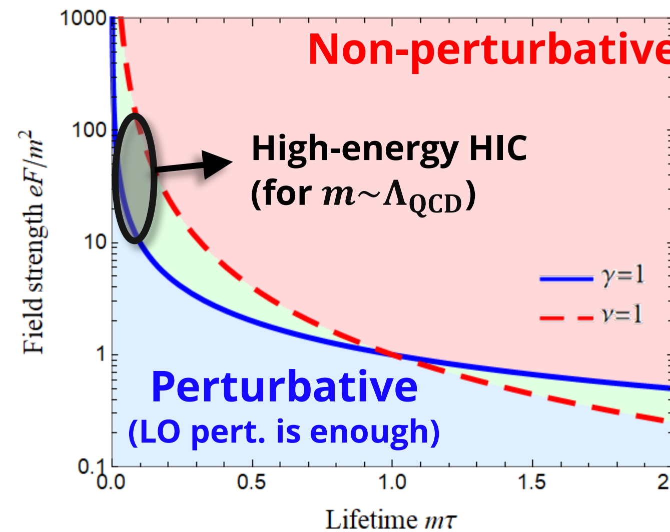
[HT, Fujiii, Itakura (2014)]

- Three dim. para. characterize the system eE, τ, m

  $\Rightarrow$ Two dim.-less para. control the interplay

$$\gamma = \frac{m}{eE\,\tau} = \frac{\text{(rest mass of particle)}}{\text{(work done by field)}} = \text{("strength" of the work)}$$

$$\nu = \frac{eE\,\tau}{1/\tau} = \frac{\text{(work done by field)}}{\text{(photon energy)}} = \text{(\# of photons involved)}$$



- Non-perturbative for $\boldsymbol{\gamma \ll 1, \nu \gg 1}$

- For high-energy HIC: $eF \sim (1\ \mathrm{GeV})^2$, $\tau \sim 0.1\ \mathrm{fm}/c \Rightarrow \gamma \sim \begin{cases} 10^{-3}\ (m = \Lambda_{\mathrm{QCD}}) \\ 10^{-5}\ (m = m_{\mathrm{e}}) \end{cases}$, $\nu \sim 0.1$

✔ **High-energy HIC is useless for strong-field physics ?**

$\Rightarrow$ Not necessarily useless. Still useful to study higher order QED processes

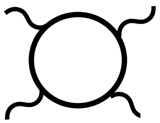
Experimental progress

✔ **Strong-magnetic-field induced processes are explored**

✔ **First observations of higher-order QED processes**

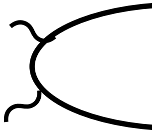
(= prior to intense laser and any other experiments !)

ex. 1) Light-by-light scattering



[ATLAS (2016)]

ex. 2) Breit-Wheeler process

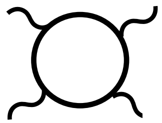


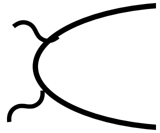
[STAR (2019)]

Experimental progress

✔ **Strong-magnetic-field induced processes are explored**

✔ **First observations of higher-order QED processes**
(= prior to intense laser and any other experiments !)

ex. 1) Light-by-light scattering  [ATLAS (2016)]

ex. 2) Breit-Wheeler process  [STAR (2019)]

✔ **No evidence for QCD x strong B field phenomena**

[STAR (2021)]

ex.) Negative result for chiral magnetic effect at isobar collisions at RHIC

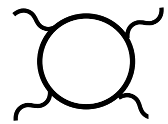
Experimental progress

✔ **Strong-magnetic-field induced processes are explored**

✔ **First observations of higher-order QED processes**

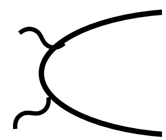
(= prior to intense laser and any other experiments !)

ex. 1) Light-by-light scattering



[ATLAS (2016)]

ex. 2) Breit-Wheeler process



[STAR (2019)]

✔ **No evidence for QCD x strong B field phenomena**

[STAR (2021)]

ex.) Negative result for chiral magnetic effect at isobar collisions at RHIC

✔ **Nice experimental progress, but our goal was to study <u>NON</u>-pert. stuffs…**

⇒ Any ways to study non-perturbative QED and/or QCD x QED phenomena ?

⇒ LOW-energy HIC may be useful

1. Review of strong-field physics

2. Strong-field physics in high-energy HIC

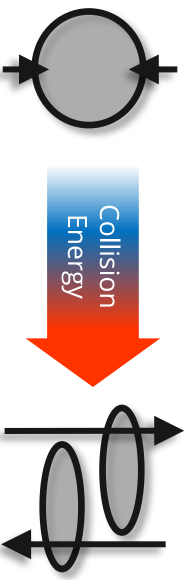
3. Strong-field physics in low-energy HIC

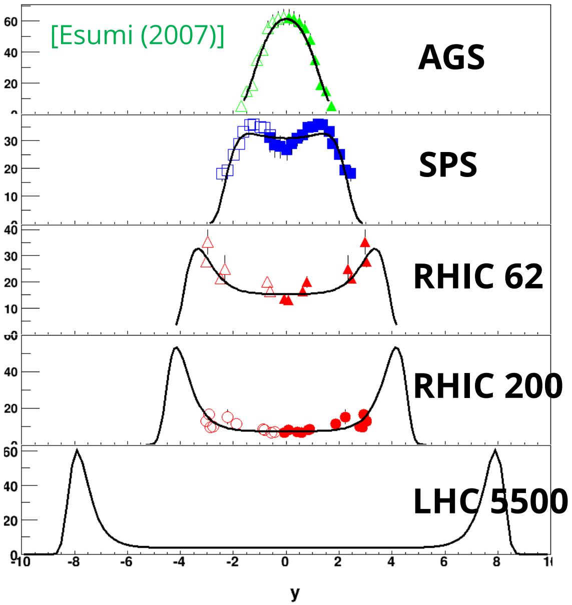
4. Summary

Strong fields in low-energy HIC

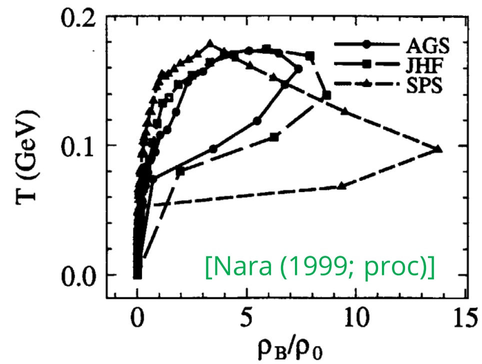
✔ Low energy ⇒ Landau's stopping picture

- Net proton rapidity dist. dN/dy
- Time evolution at middle/low-energy HIC





O(10 AGeV)



Time evolution of baryon density and effective temperature in Au+Au at 11.6*AGeV/c* from 0 fm/*c* to 20 fm/*c* by 1.0 fm/*c* step, Au+Au at 25AGeV, and Pb+Pb at 158AGeV, respectively.

O(10 AMeV)

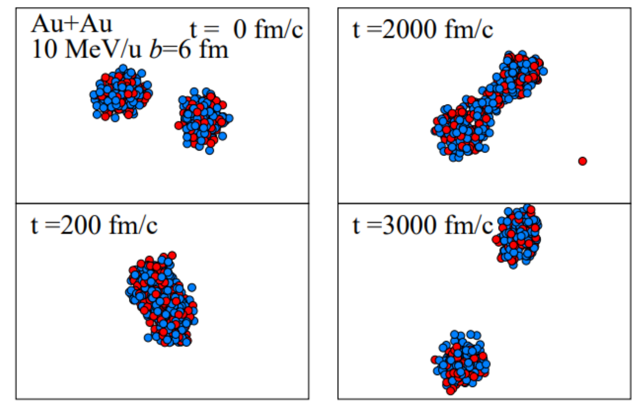


Figure 1. Snapshot of ^{197}Au + ^{197}Au at E_{lab} = 10 MeV/nucleon b = 6 fm. The time indicated in each panel is not from the contact of two nuclei but indicates only that of the simulation.

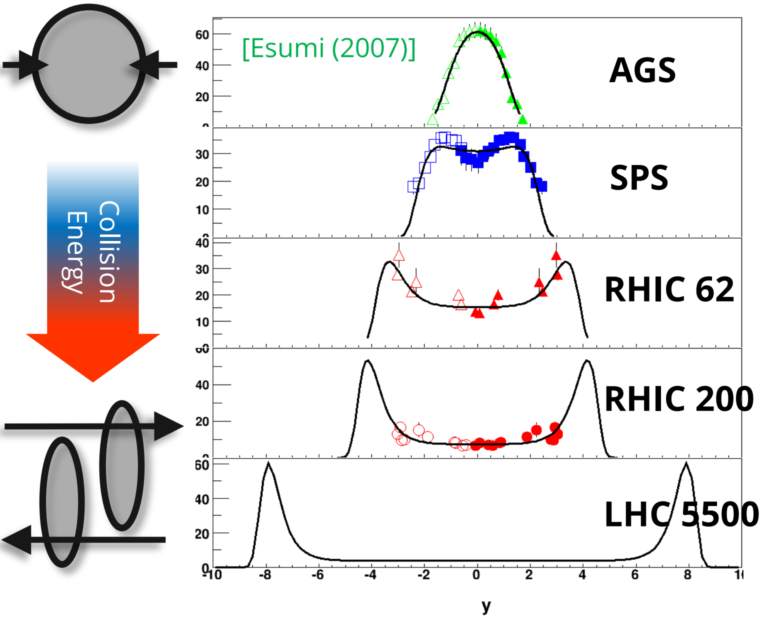
[Maruyama, Bonasera, Papa, Chiba (2002)]

⇒ Dense matter is formed for not-short-time $O(10-1000\ \mathrm{fm}/c)$

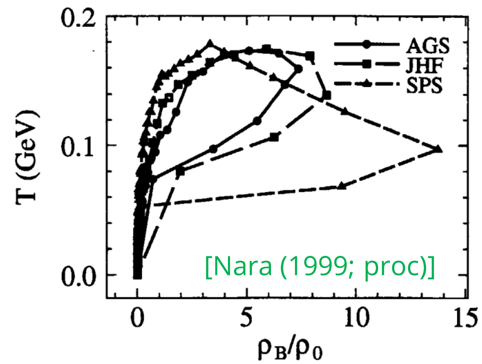
Strong fields in low-energy HIC

✔ **Low energy ⇒ Landau's stopping picture**

- Net proton rapidity dist. dN/dy
- Time evolution at middle/low-energy HIC



O(10 AGeV)



Time evolution of baryon density and effective temperature in Au+Au at 11.6*A*GeV/*c* from 0 fm/*c* to 20 fm/*c* by 1.0 fm/*c* step, Au+Au at 25AGeV, and Pb+Pb at 158AGeV, respectively.

O(10 AMeV)

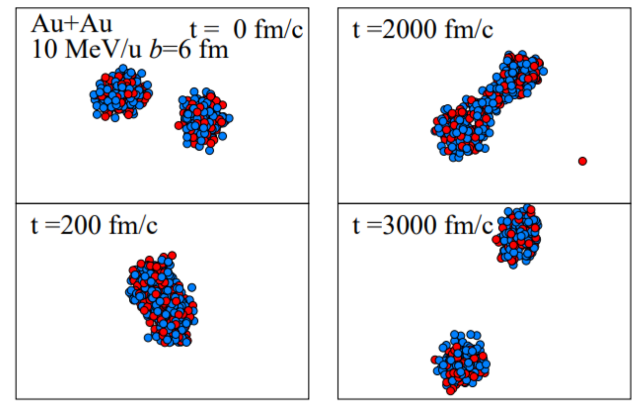


Figure 1. Snapshot of ^{197}Au + ^{197}Au at $E_{\rm lab}$ = 10 MeV/nucleon b = 6 fm. The time indicated in each panel is not from the contact of two nuclei but indicates only that of the simulation.

[Maruyama, Bonasera, Papa, Chiba (2002)]

⇒ Dense matter is formed for not-short-time $O(10-1000\ {\rm fm}/c)$

✔ **Strong electric field is created via formation of "High Z atom" s.t. $Z > 1/\alpha$**

- No electric current ⇒ Negligible magnetic fields
- Rough estimate of electric-field strength: $eE \sim \frac{Z\alpha}{r^2} \sim \Lambda_{\rm QCD}^2 \sim (100\ {\rm MeV})^2$

$$\Rightarrow \gamma = \frac{m}{eE\tau} \lesssim \begin{cases} 10^{-1}\ (m = \Lambda_{\rm QCD}) \\ 10^{-4}\ (m = m_{\rm e}) \end{cases} \sim 0.1,\ \nu = eE\tau^2 \gtrsim 10$$

⇒ Non-pert. $\begin{cases} \gamma \ll 1 \\ \nu \gg 1 \end{cases}$ for QED & QCD !

Possible strong-field phenomena ?

✔ **Low-energy HIC might be useful to study strong-electric-field physics**

✔ **As example, I introduce two possible QED phenomena**

(no one has ever observed those strong-field phenomena, so it is very impactful if we could observe them with HIC)

- Vacuum (dielectric) polarization

Pioneering works [Pieper, Greiner (1969)]
[Gershtein, Zeldovich (1970)]
Recent review [Rafelski, Kirsch, Muller, Greiner (2016)]
Recent attempts [Maltsev et al. (2019)] [Popov et el. (2020)]

- An old but unsolved problem that is worthwhile to be re-investigated now

- Electric-field induced birefringence

(• QCD x strong E field phenomena could also occur, but I don't discuss here)

(e.g., chiral symmetry restoration, anomalous transports such as CESE, …)

[Suganuma, Tatsumi (1993)] [Huang, Liao (2013)]

Vacuum (dielectric) polarization (1/2)

✔ **At high energy, B was important, but at low energy E may be important**

Magnetic B field ⇒ System is stable ↔ Electric E field ⇒ **UN**stable

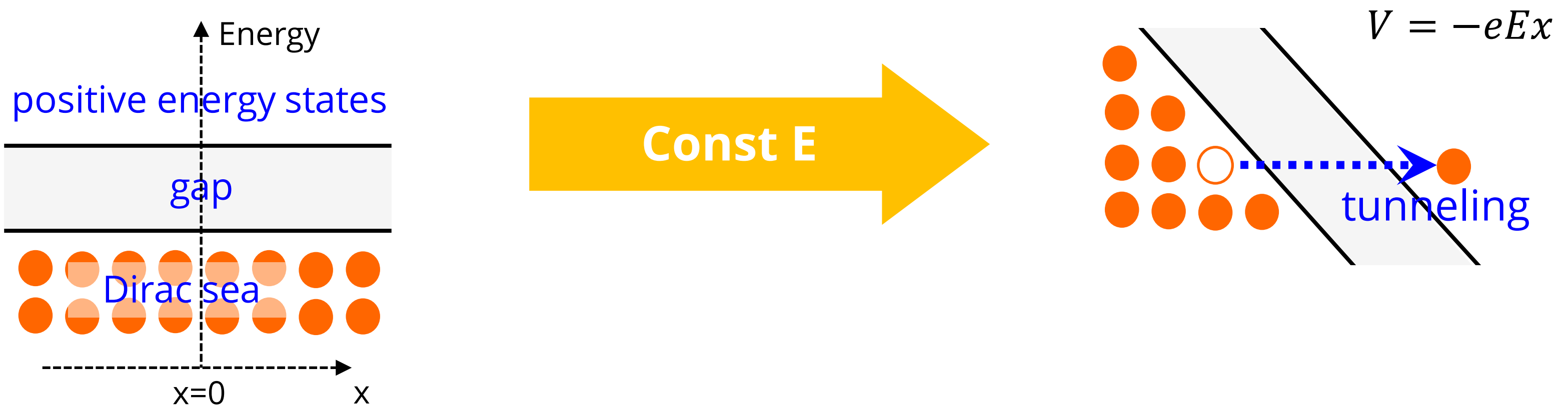
Vacuum (dielectric) polarization (1/2)

✔ **At high energy, B was important, but at low energy E may be important**

Magnetic B field ⇒ System is stable ↔ Electric E field ⇒ **UN**stable

✔ **Spontaneous pair production and vacuum (dielectric) polarization**

- For constant field ⇒ Schwinger mechanism [Schwinger (1951)]



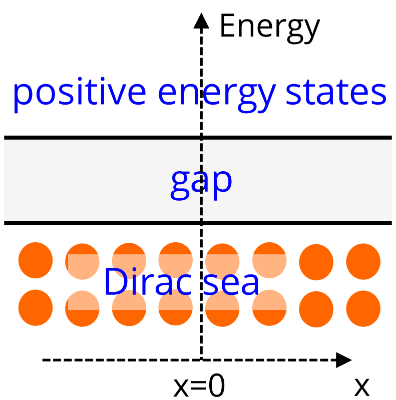
Vacuum (dielectric) polarization (1/2)

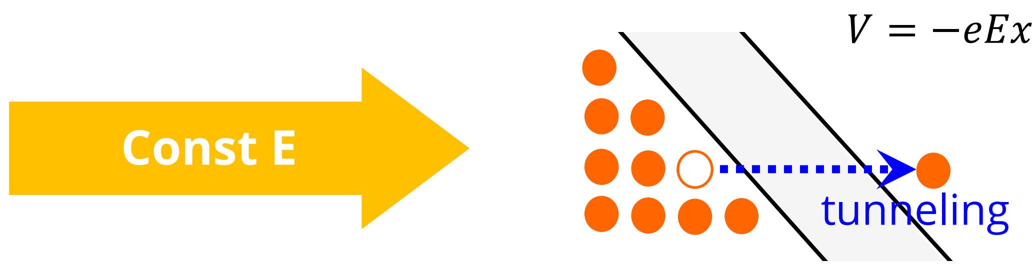
✔ **At high energy, B was important, but at low energy E may be important**

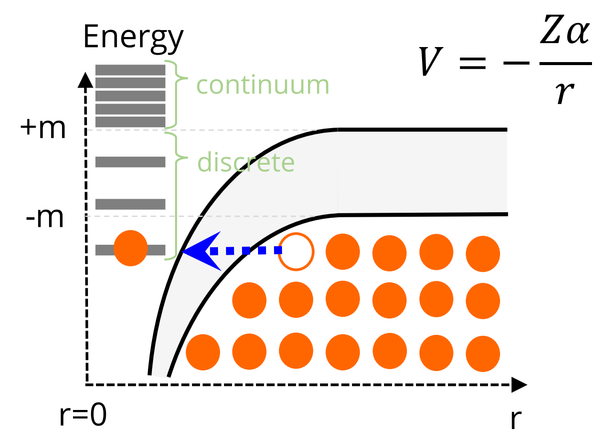
Magnetic B field ⇒ System is stable ↔ Electric E field ⇒ **UN**stable

✔ **Spontaneous pair production and vacuum (dielectric) polarization**

- For constant field ⇒ Schwinger mechanism [Schwinger (1951)]







- Similar for Coulomb field

  - Difference: energy is discretized below $E < +m$

    ⇒ Tunneling occurs only if there're levels at $E < -m$ ⇐ Satisfied for $Z > \alpha^{-1}$

    [Pieper, Greiner (1969)] [Gershtein, Zeldovich (1970)]

  - Tunneling ⇒ positron is emitted & the vacuum is (electrically) polarized

Vacuum (dielectric) polarization (2/2)

- ✔ **Theoretical expectation:**

  Non-trivial positron spectrum at low energies

Vacuum (dielectric) polarization (2/2)

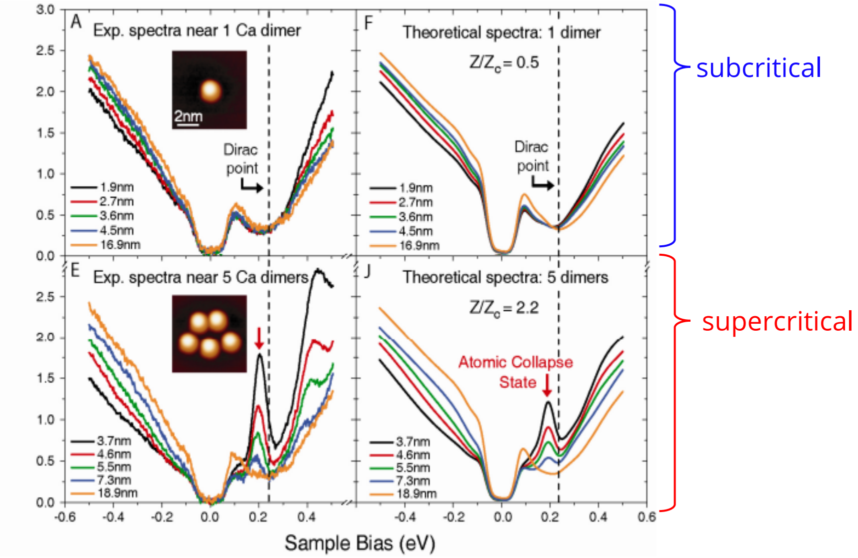
✔ **Theoretical expectation:**

Non-trivial positron spectrum at low energies

✔ **Experimental status**

[Wang et al. (2013)]

- Analogous phenomenon was observed with graphene



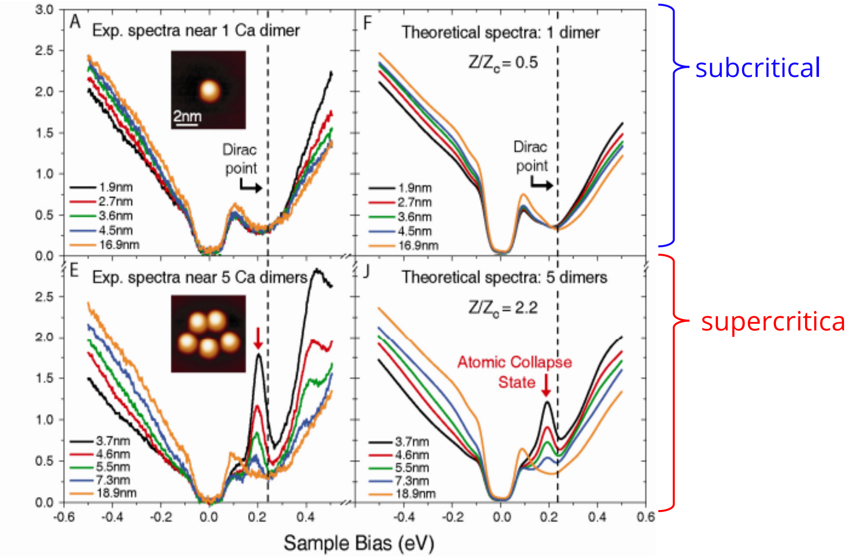
Vacuum (dielectric) polarization (2/2)

✔ **Theoretical expectation:**

Non-trivial positron spectrum at low energies

✔ **Experimental status**

[Wang et al. (2013)]



- Analogous phenomenon was observed with graphene

- Should observe something similar in HIC, but ...

  Low-energy HIC exp. O(10 MeV/u) were done in 80-90's but were inconclusive

  [Cowan et al. (EPOS coll.) (1985)]

  ⇒ couldn't eliminate contaminations from nuclear excitations

  [Heinz et al. (ORANGE coll.) (2000)]

  ⇒ **Conclusion:** more detailed exp. & theor. studies are needed

  Theor.: Realistic EM field, realtime dynamics, ...

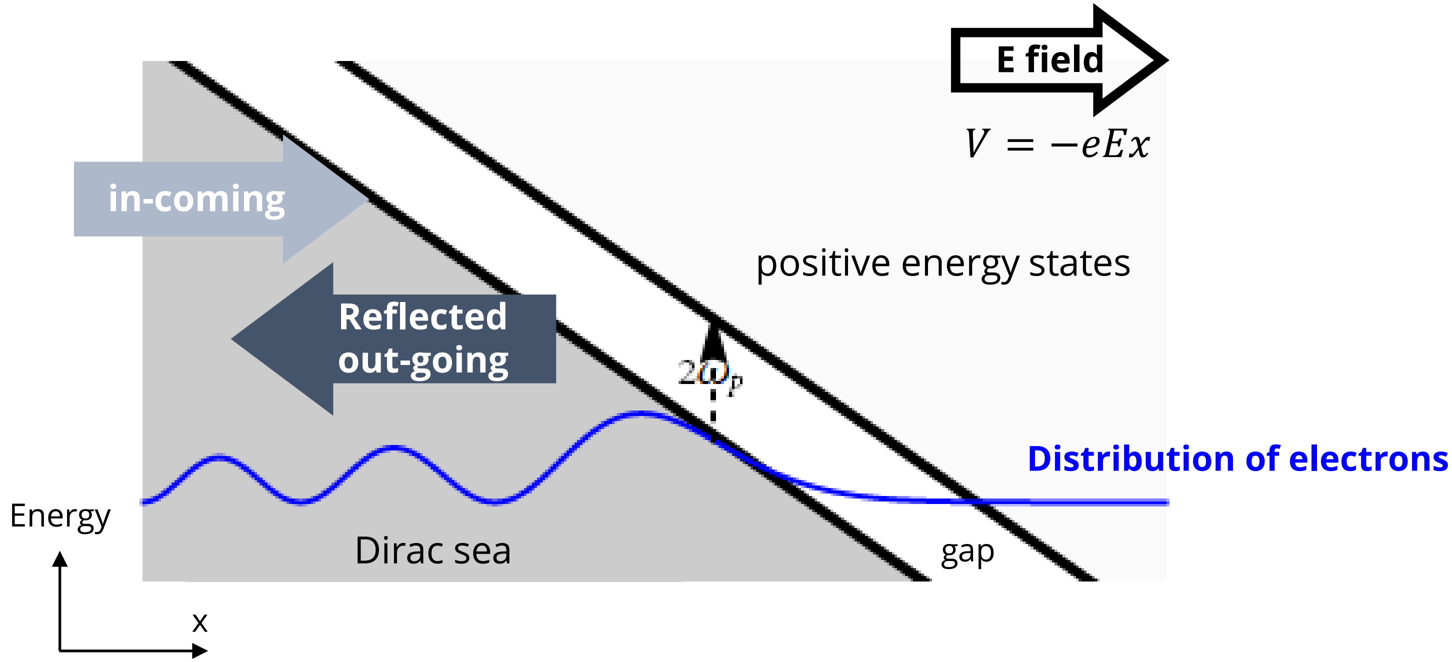
  cf. [Maltsev et al. (2019)] [Popov et el. (2020)]

  Exp: Energy/Z/angular dependencies, precision, ...

Vacuum birefringence by E-field (1/2)

✔ **"Tilting" of the vacuum also affects the propagation of photons**

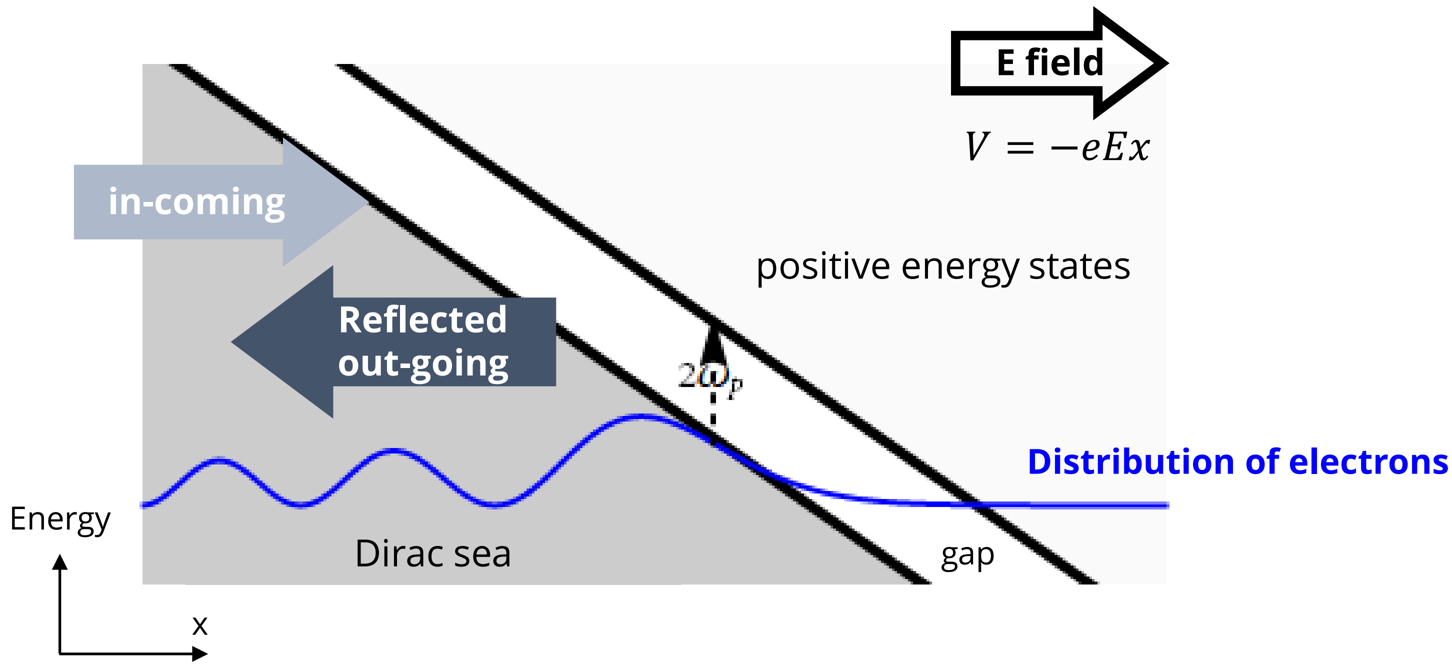
⇐ Electrons in the Dirac sea has "distributions" due to quantum reflection



Vacuum birefringence by E-field (1/2)

✔ **"Tilting" of the vacuum also affects the propagation of photons**

⇐ Electrons in the Dirac sea has "distributions" due to quantum reflection



✔ **Interactions b/w photon and the Dirac sea modifies the prop. of photon**

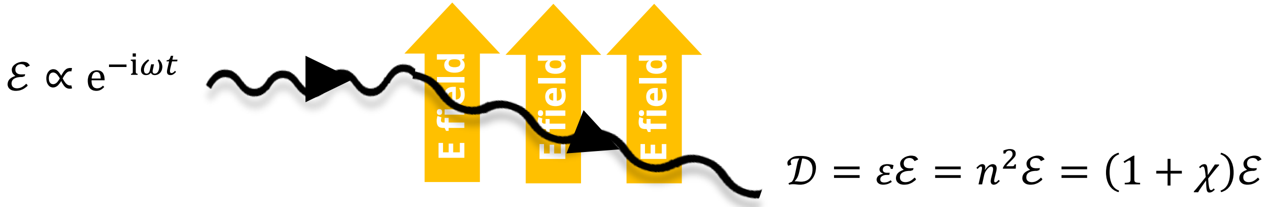
(1) Photon decay and refraction reflects the Dirac-sea structure

(2) E field has direction, so the refractive index have preferred direction

⇒ **Birefringence**

Vacuum birefringence by E-field (2/2)

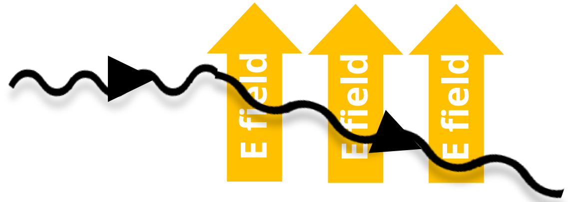
✔ **A very preliminary result for const E-field + electric wave**



Vacuum birefringence by E-field (2/2)

✔ **A very preliminary result for const E-field + electric wave**

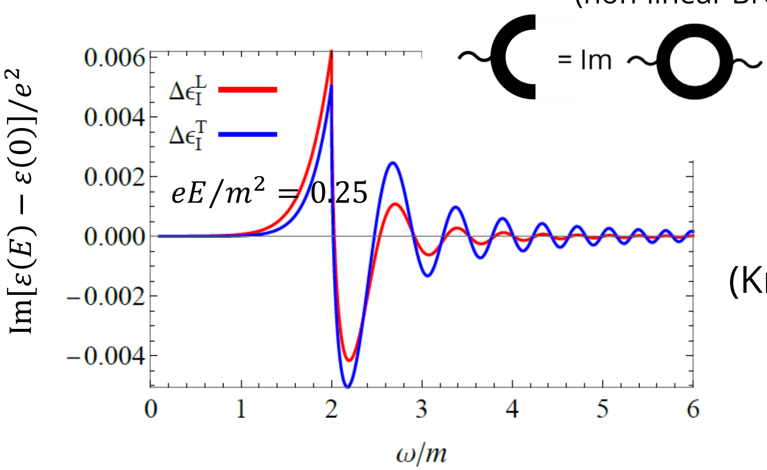
$\mathcal{E} \propto e^{-i\omega t}$



$\mathcal{D} = \varepsilon\mathcal{E} = n^2\mathcal{E} = (1+\chi)\mathcal{E}$

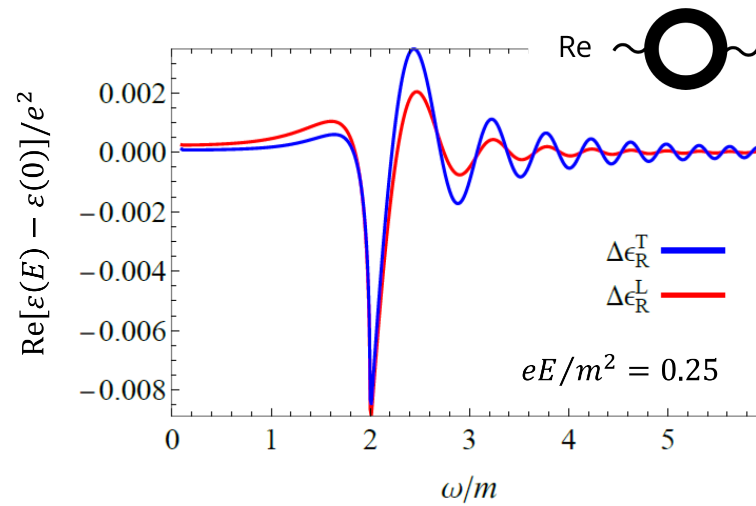
✔ **Change of imaginary & real parts of electric permittivity ε** [HT, Ironside, in prep]

Imaginary part ⇒ photon decay (non-linear Breit-Wheeler)



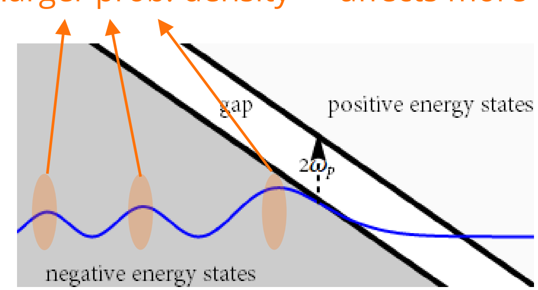
Optical thm. (Kramers-Kronig rel.)

Real part ⇒ photon birefringence



- Oscillating behavior
  ⇐ Oscillating distributions of electrons in the Dirac sea
- Polarization dependent
  ⇒ Measure photon polarization and angular dist.

larger prob. density ⇒ affects more



1. Review of strong-field physics

2. Strong-field physics in high-energy HIC

3. Strong-field physics in low-energy HIC

4. Summary

Summary

Message

Low-energy HIC might be useful to study strong-(electric-)field phys

1. Review of strong-field physics

- Interesting: Novel chance to explorer the non-pert. regime of QED & QCD

2. Strong-field physics in high-energy HIC

- Strongest magnetic field is created
  ⇒ leading to the first observations of higher-order QED processes
  (e.g., Breit-Wheeler pair production, light-by-light scattering)
- But is short-lived, affecting the "non-perturbativeness" of the strong-field processes

3. Strong-field physics in low-energy HIC

- Strong electric field with relatively long lifetime would be created
- Vacuum (dielectric) polarization & electric-field induced birefringence
  ⇒ May affect the low-energy positron/photon spectrum
- Less investigated and so interesting to explorer strong QED & QCD x QED processes in low-energy HIC