Opportunities of strong-field physics In middle-energy heavy-ion collisions

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Plan

Middle-energy heavy-ion collisions $\sqrt{s_{\mathrm{NN}}} = O(1\text{-}10\ \mathrm{GeV})$ may be interesting not only to QCD but also to strong-field physics

- Estimation of EM field strength and spacetime volume with a hadron transport model (JAM)
  ⇒ Strong O(30 MeV) and large spacetime volume O((20 fm)^4)
  ⇒ A nice setup to study strong-field QED. Non-negligible to hadronic/QCD processes as well.

1. Brief review of strong-field physics

2. Strong EM field at high-energy heavy-ion collisions

- Clarify relationship between "non-perturbativeness" and strength and lifetime of EM field

3. Strong EM field at middle-energy heavy-ion collisions

[Nishimura (Osaka), Ohnishi (Kyoto), HT, in progress]

- Estimation of EM field profiles with JAM

4. An example of strong-field phenomenon: Vacuum decay and modification to photon propagation

[HT, Ironside (Curtin), in progress]

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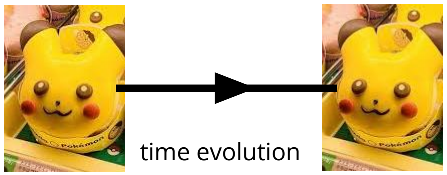
5. Summary

Strong-field physics



Vacuum
(=No EM field)

Images stolen from below
https://news.line.me/detail/oa-walkerplus/59d36b1b92da
https://ananweb.jp/anan/319760
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Strong-field physics

initial

time evolution

final

Vacuum
(=No EM field)

Weak EM field
$(eF/m^2 \lesssim 1)$

Strong EM field
$(eF/m^2 \gtrsim 1)$

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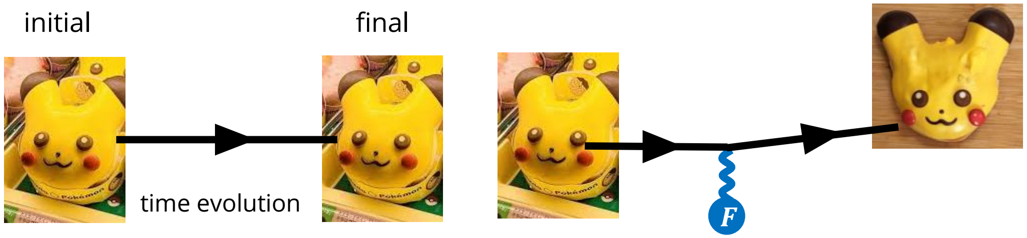
Strong-field physics



Vacuum (=No EM field)

Weak EM field ($eF/m^2 \lesssim 1$)

Strong EM field ($eF/m^2 \gtrsim 1$)

Almost the same

⇒ Perturbative

⇒ Understood well

ex) Electron anomalous magnetic moment $a := \frac{g-2}{2}$

$a(\mathrm{theor.}) = 1159652182.03 \ldots \times 10^{-12}$ [Aoyama, Kinoshita, Nio (2017)]

$a(\mathrm{exp.}) \quad = 1159652180.73 \ldots \times 10^{-12}$

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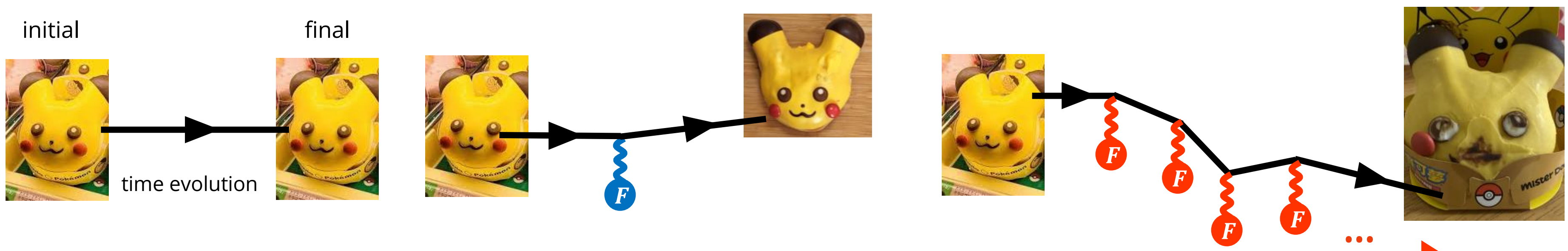
Strong-field physics



Vacuum (=No EM field) → **Weak EM field ($eF/m^2 \lesssim 1$)** → **Strong EM field ($eF/m^2 \gtrsim 1$)**

Weak EM field	Strong EM field
Almost the same	Completely different
⇒ Perturbative	⇒ Non-perturbative
⇒ Understood well	⇒ Not understood well

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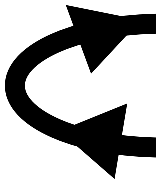
Examples of strong-field phenomena

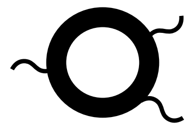
✔ Novel QED processes ($eF/m_e^2 \gtrsim 1$)

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

ex) Schwinger mechanism



Photon splitting



Vacuum birefringence

(= Polarization dep. of reflective index)

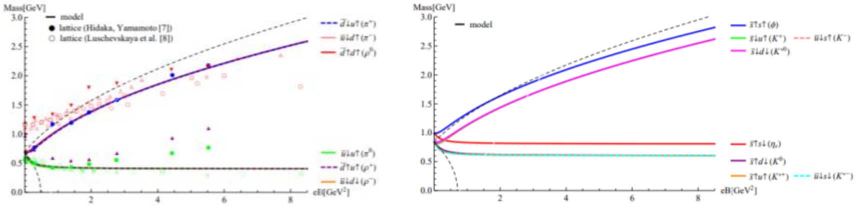
✔ Impacts on QCD/hadron physics ($eF/\Lambda^2 \gtrsim 1$ (or deconfined phase ⇒ $eF/m^2_{\text{current q mass}} \gtrsim 1$))

[HT (2015)]

ex. 1) Hadron properties:

e.g., mass, charge dist., decay mode, ...

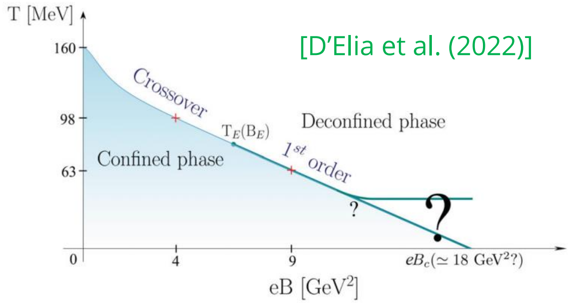
See also recent review [Iwasaki, Oka, Suzuki (2021)]



ex. 2) QCD phase diagram

e.g., (inverse) magnetic catalysis, new phase, ...

[D'Elia et al. (2022)]



ex. 3) Others: Anomalous transport,
(for color EM field) Glasma, string breaking, ...

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

Many theoretical predictions, but never observed experimentally yet

Need of extremely strong EM field

✔ **Minimum strength:** $eE, eB\ \mathrm{MeV}^2 > m_e^2 = (0.511\ \mathrm{MeV})^2 \approx O(10^{28}\ \mathrm{W/cm^2})$

LED $\approx 10^{-5}\ \mathrm{W/cm^2}$

Glasses $\approx 10^{3}\ \mathrm{W/cm^2}$

Laser processing machine $< 10^{10}\ \mathrm{W/cm^2}$

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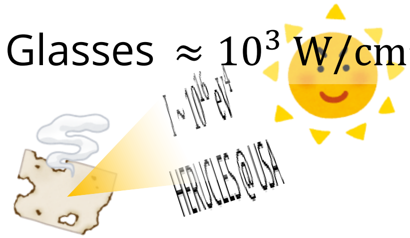
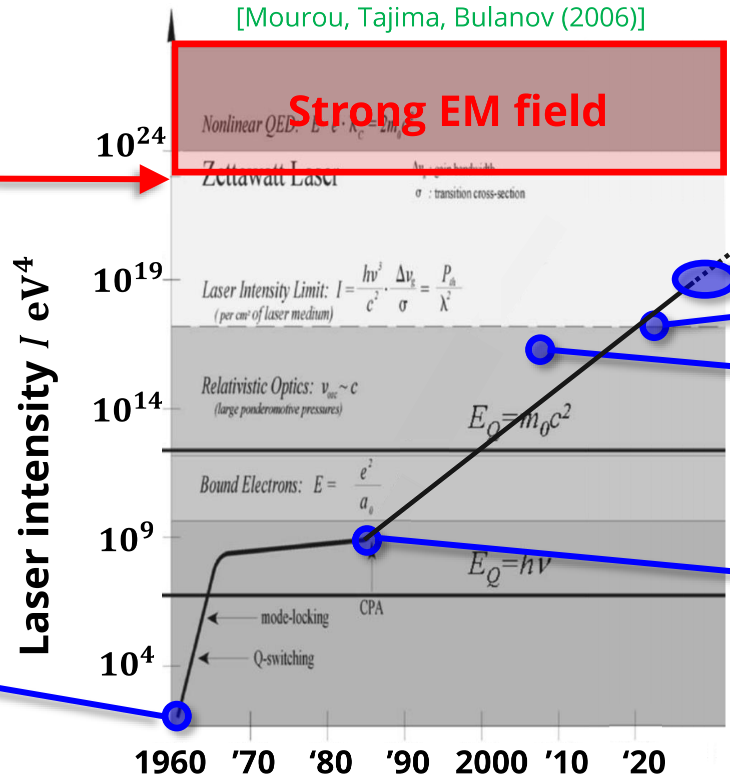


Laser processing machine < 10^{10} W/cm^2

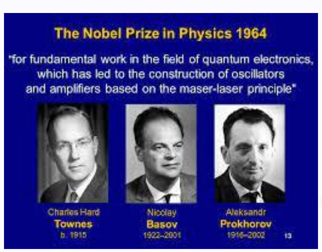
✔ Intense laser is the most common source for strong EM field



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

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

Birth of laser



CPA technique

GUINNESS WORLD RECORDS

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

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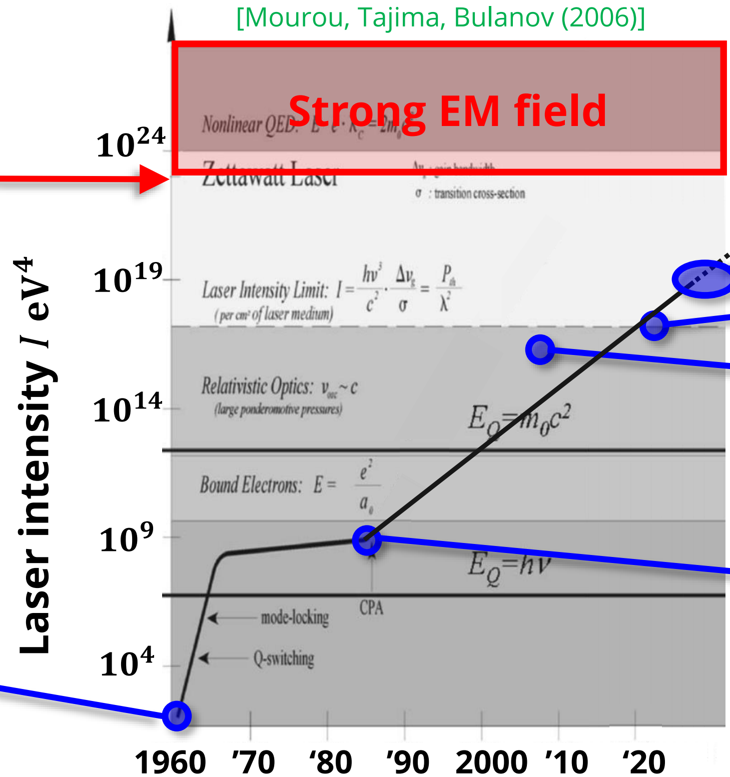

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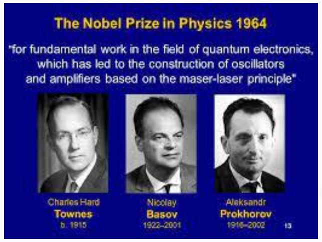

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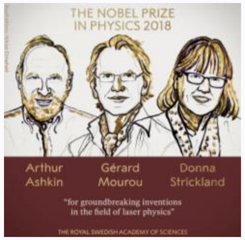

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Weak. Any nice idea ? ⇒ Heavy-ion collisions !

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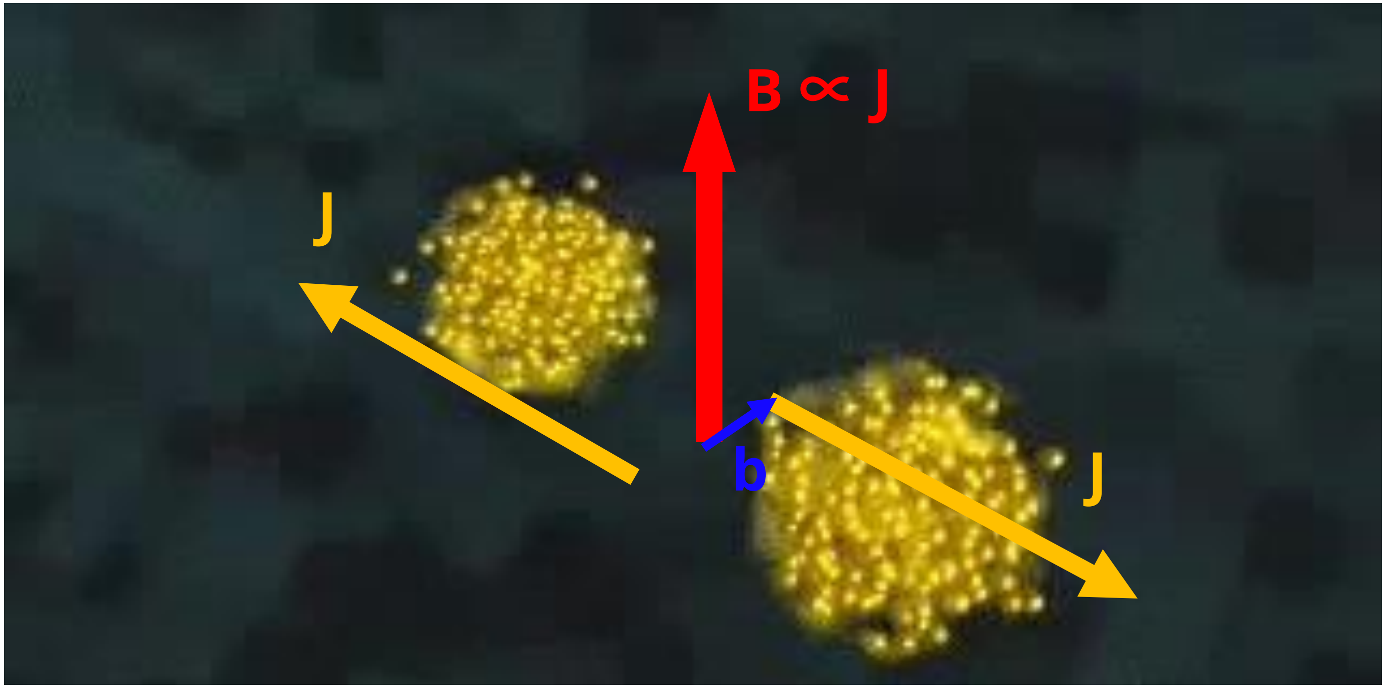
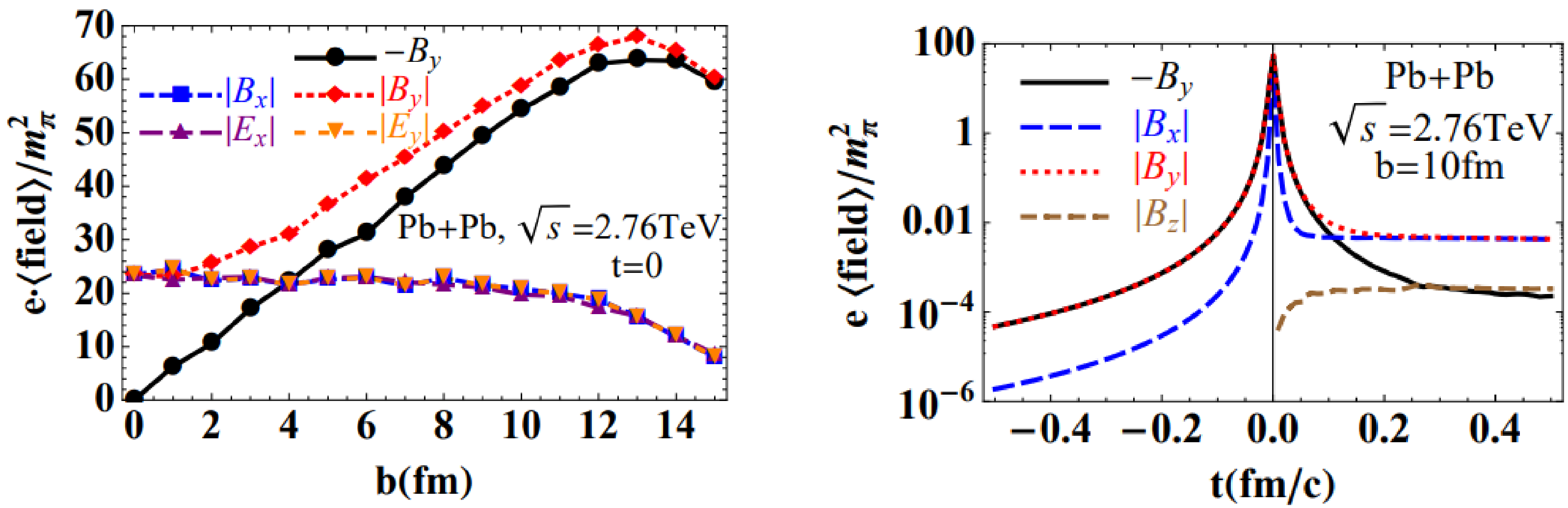


Animation stolen from Internet

✔ **Strong magnetic field is created**

Strong EM field at high-energy heavy-ion collisions



[Deng, Huang (2012)]

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

✔ **Strong magnetic field is created**

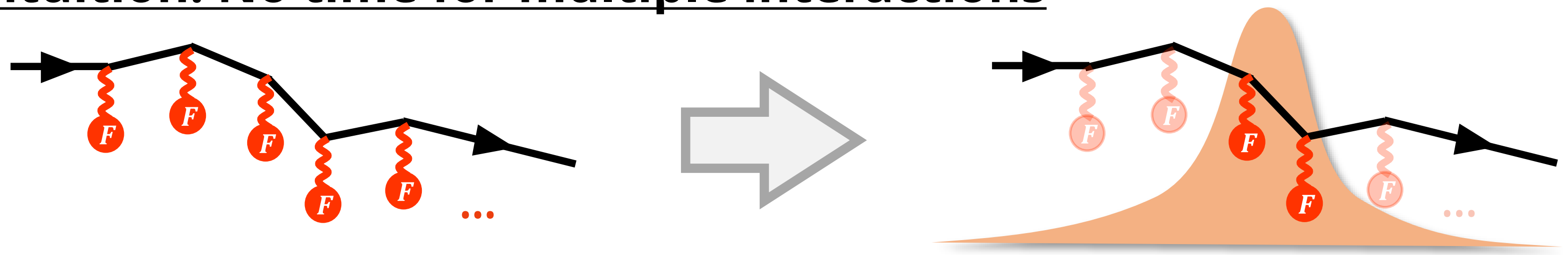
Pro: Super strong $eB \gg \Lambda_{\rm QCD}^2$ (Strongest in the Universe !)

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

⇒ Affects "non-perturbativeness" of physics

Shorter lifetime ⇒ more perturbative

✔ **Intuition: No time for multiple interactions**



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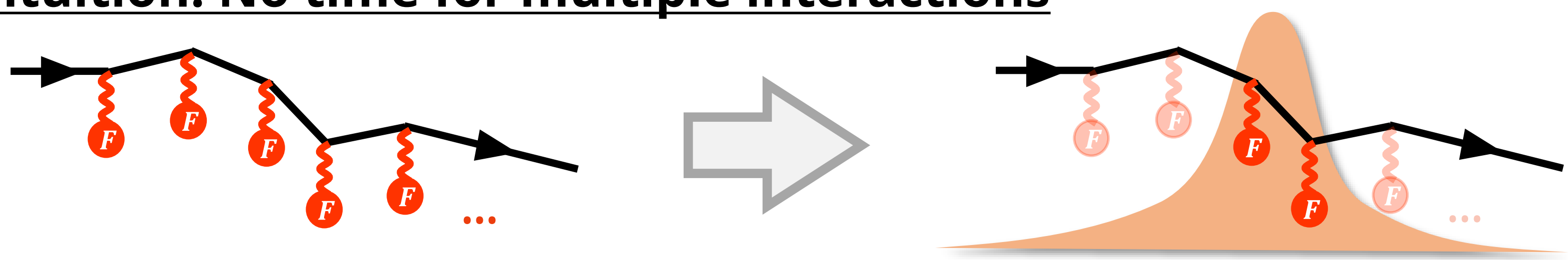
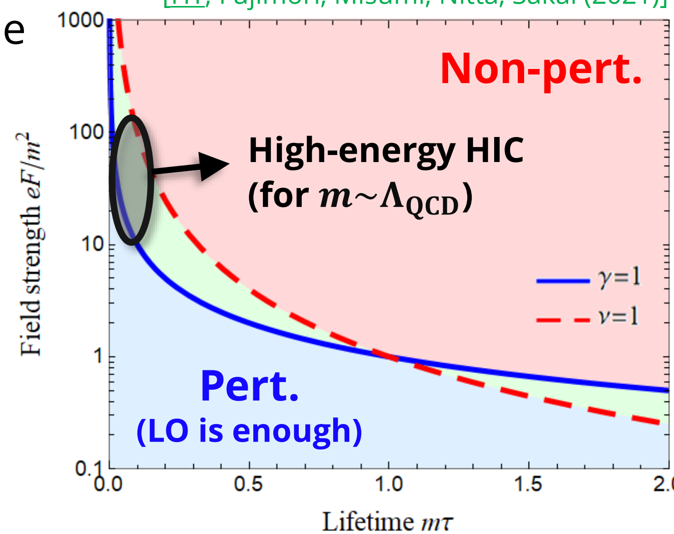


✔ "Phase diagram" of strong-field physics

[HT, Fujiii, Itakura (2014)]
[HT, Fujimori, Misumi, Nitta, Sakai (2021)]



As example: Vacuum particle prod. by E field w/ finite lifetime

- Three dimensionful parameters in the system: eE, τ, m

  ⇒ Two dim.-less parameters determine the physics

$$\gamma = \frac{m}{eE\,\tau} = \frac{\text{(Typical energy)}}{\text{(Work by field)}}$$ ⇒ Characterize the magnitude of work

$$\nu = \frac{eE\,\tau}{1/\tau} = \frac{\text{(Work by field)}}{\text{(Photon energy)}}$$ ⇒ Characterize the number of photons

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

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

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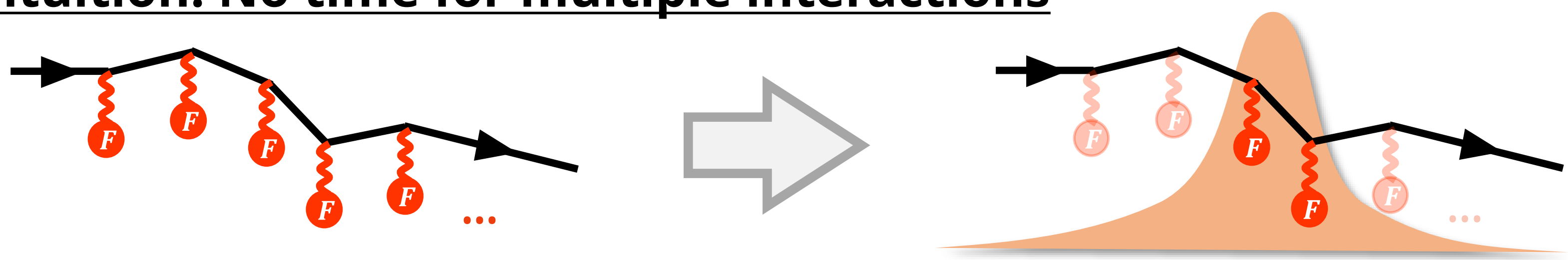

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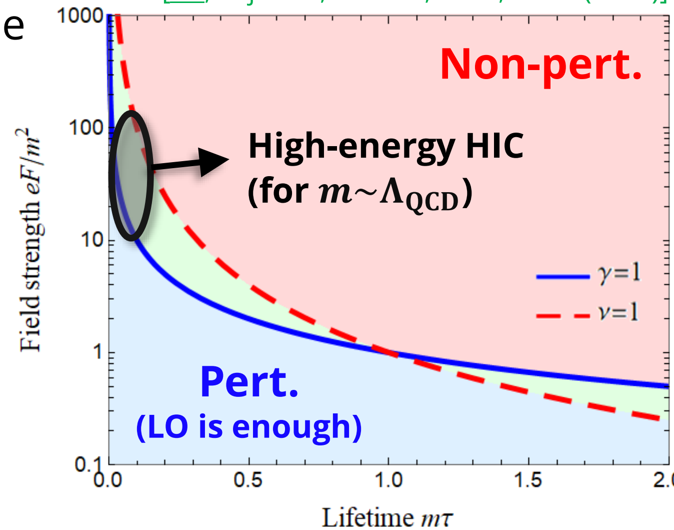

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⇒ High-energy heavy-ion collisions are meaningless for strong-field physics ?

⇒ Not necessarily. A good chance to study higher-order effects

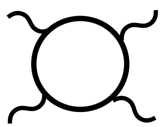
Experimental results

✔ Achievements

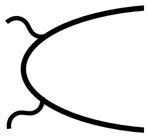
(Prior to any other experiments; e.g., intense laser)

- **very FIRST observation of high-order QED processes**

ex. 1) Light-by-light scattering ex. 2) Breit-Wheeler process



[ATLAS (2016)]

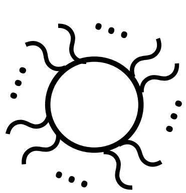


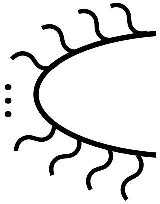
[STAR (2019)]

- **Unfortunately, nothing has been observed in QCD**

ex) Negative result of CME search with isobar collisions [STAR (2021)]

✔ OK, they are good. BUT, what we really want is something non-pert. !





⇒ Any good ideas?

⇒ Go to "middle energies" !

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[Nishimura (Osaka), Ohnishi (Kyoto), HT, in progress]

4. **An example of strong-field phenomenon: Vacuum decay and modification to photon propagation**

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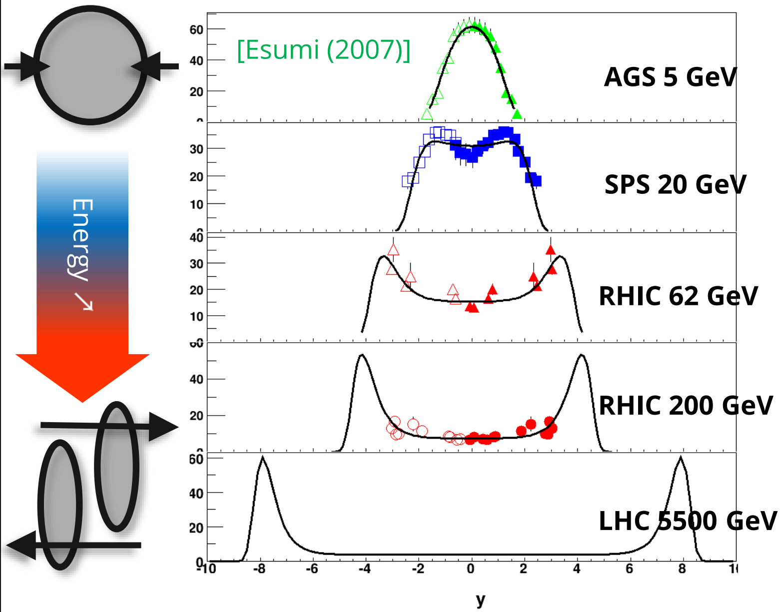
5. **Summary**

Strong EM field at middle-energy heavy-ion collisions

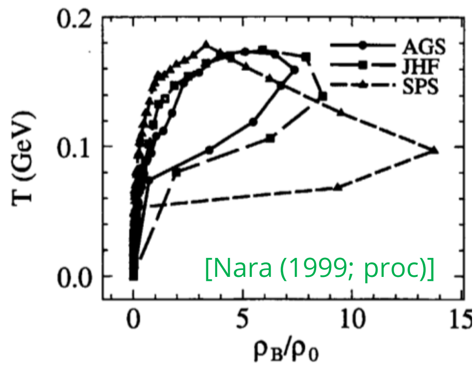
✔ Lower energy ⇒ Landau stopping picture

Exp.: Proton rapidity dist. dN/dy



Thr.: Numerics w/ hadron transport models

E = O(10 GeV/nucleon)



Time evolution of baryon density and effective temperature in Au+Au at 11.6AGeV/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.

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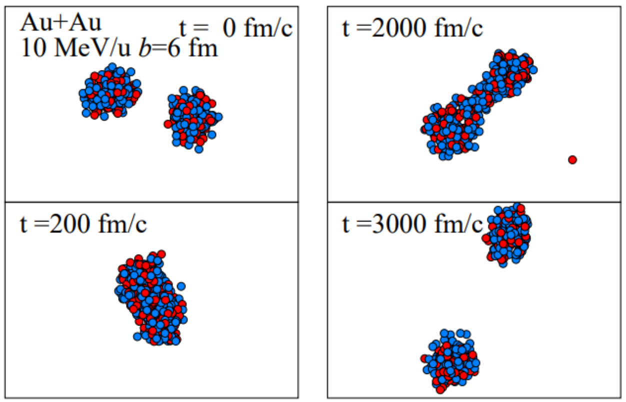

Figure 1. Snapshot of ^{197}Au + ^{197}Au at $E_{\rm lab}$ = 10 MeV/nucleon b = 6 fm. The time indicated in each panel is not from the contact of two nuclei but indicates only that of the simulation.

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

⇒ **Dense matter is formed for a long time $O(10-1000\ \mathrm{fm}/c)$**

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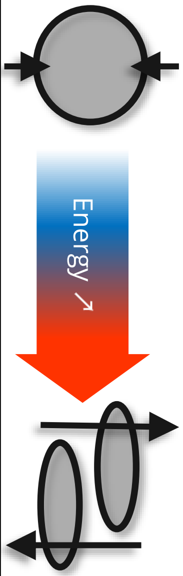

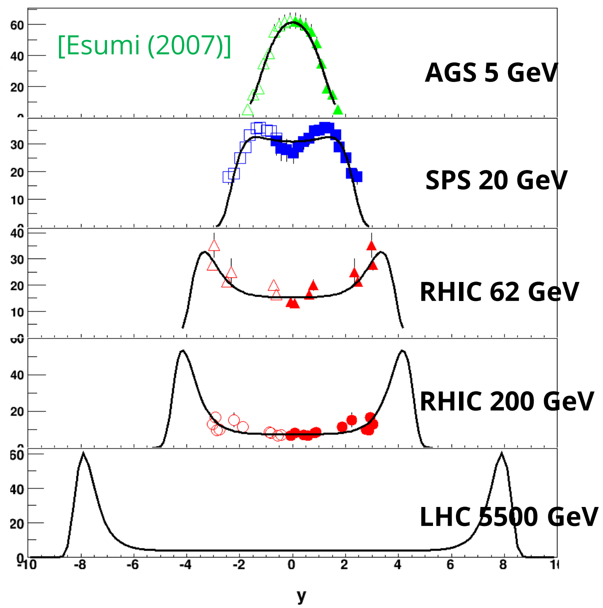

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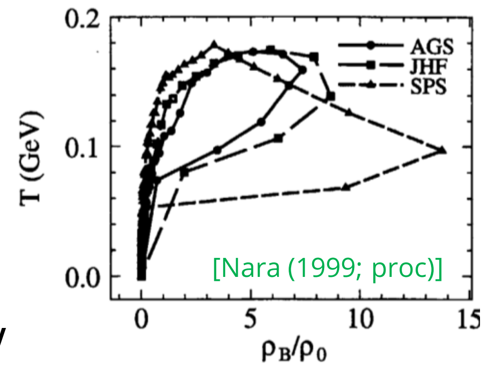

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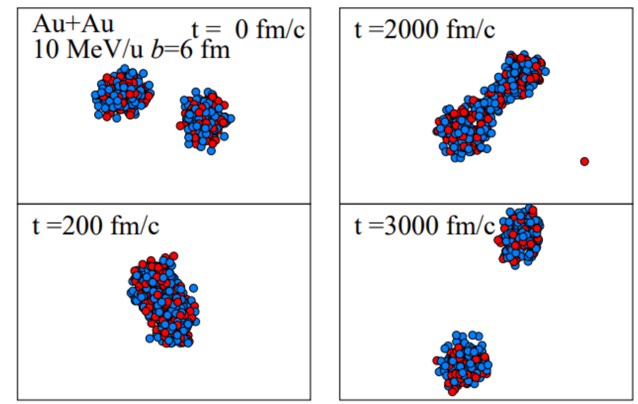

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⇒ Dense matter is formed for a long time $O(10 - 1000\ {\rm fm}/c)$

⇒ Charge density is also large ("High Z atom" s.t. $Z \gtrsim 1/\alpha$) ⇒ Strong Coulomb field

- High energy ⇒ Magnetic vs Low/middle energy ⇒ Electric
- Rough order estimate: $eE \sim \frac{Z\alpha}{r^2} \sim \Lambda_{\rm QCD}^2 \sim (100\ {\rm MeV})^2$

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

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

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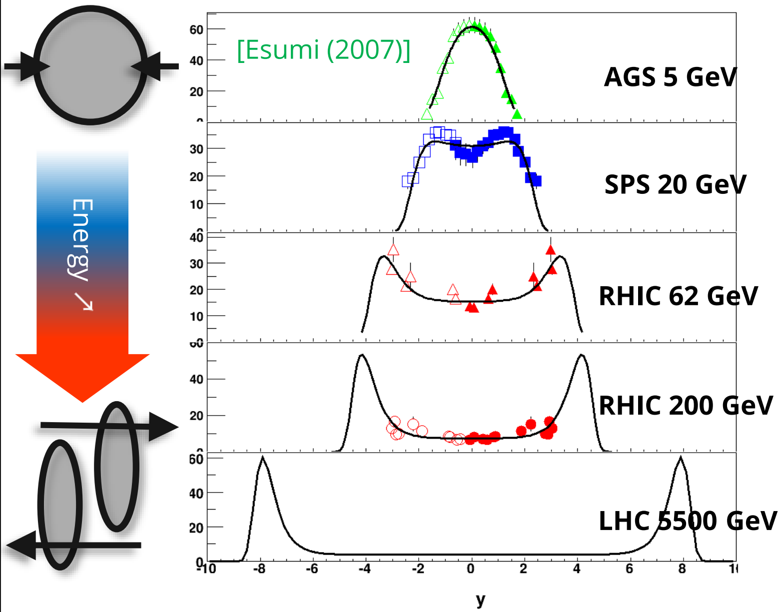

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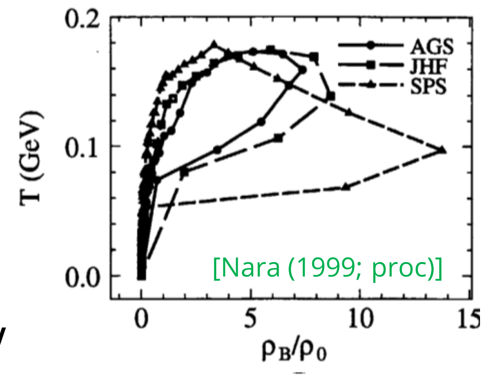

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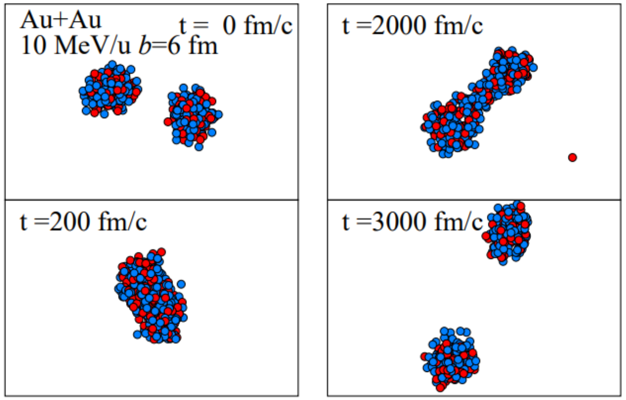

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⇒ Non.-pert both in QED & QCD $\begin{cases} \gamma \ll 1 \\ \nu \gg 1 \end{cases}$

∴ Interesting to strong-field physics. May affect QCD/hadron processes as well
⇒ Need to think about this seriously

Estimation with a hadron trans. model: JAM (1/5)

[Nishimura (Osaka), Ohnishi (Kyoto), HT, in progress]

✔ JAM (Jet AA Microscopic transport model)

[Nara, Otsuka, Ohnishi, Nitta, Chiba (2000)]

- A microscopic model to simulate heavy-ion collisions
  = Superposition of two body hadron scatterings + Inelastic scattering processes

  Low energy: Resonance ($E_{\mathrm{CM}} \lesssim 4\ \mathrm{GeV}$)

  High energy: PYHITA → string breaking ($E_{\mathrm{CM}} \gtrsim 4\ \mathrm{GeV}$)

  mini jets($E_{\mathrm{CM}} \gtrsim 20\ \mathrm{GeV}$)
- Reliable at not-high energies, i.e., below RHIC energy O(100 GeV) scale
- Anyway, **phase space distribution of charged particles** can be calculated

✔ Phase space dist. ⇒ EM field

From JAM

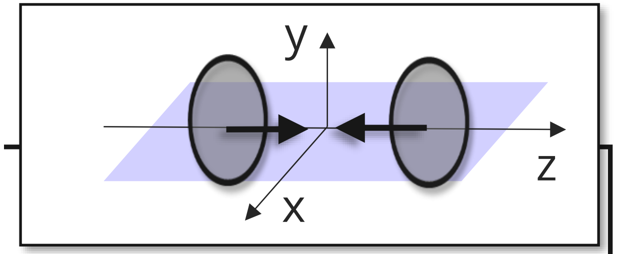
$$A^\mu(x^0, \boldsymbol{x}) = \frac{1}{4\pi}\int_{-\infty}^{+\infty} \mathrm{d}^3\boldsymbol{x}' \frac{J^\mu(x^0 - |\boldsymbol{x}-\boldsymbol{x}'|, \boldsymbol{x}')}{|\boldsymbol{x}-\boldsymbol{x}'|}$$

Rem. 1: Don't use Lienard-Wiechert potential for a point-like particle
⇐ LW potential is not applicable, since particles are produced

Rem. 2: The following results are after N=100 event averaging: $\langle A \rangle = \frac{1}{N}\sum_{n=1}^{N} A_n$

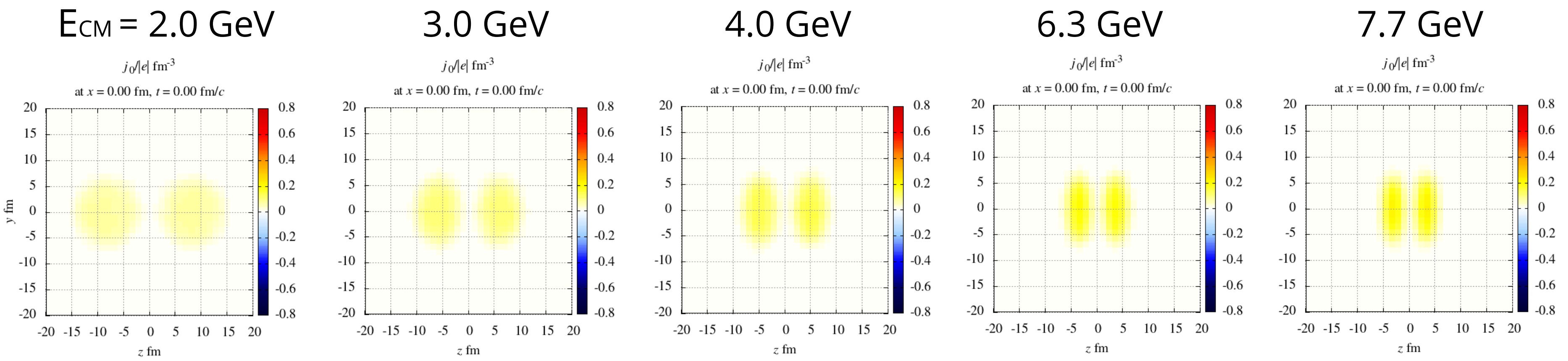
Estimation with a hadron trans. model: JAM (2/5)

[Nishimura (Osaka), Ohnishi (Kyoto), HT, in progress]



✔ Time evol. of charge density (central coll.) @ z=0

Preliminary results



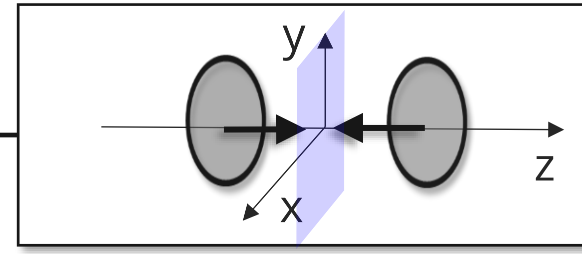
- **Huge charge density with a long lifetime time**
  - O(10) times bigger than charge density of a single static ion $\rho_{\mathrm{charge}} \sim \rho_{\mathrm{nuclear}} /2 \sim 0.08\ \mathrm{fm}^{-3}$ (nuclear: Saturation density)
  - Energy ↗ ⇒ ρ ↗ (∵ Lorentz contraction)
  - Lifetime ~ O(20 fm/c)
- **Switching Landau ↔ Bjorken pictures at ~4 GeV**

  But, not completely transparent, so have finite ρ in the center

  ⇒ Energy ↗ ⇒ Spacetime volume ↗

Estimation with a hadron trans. model: JAM (3/5)

[Nishimura (Osaka), Ohnishi (Kyoto), HT, in progress]

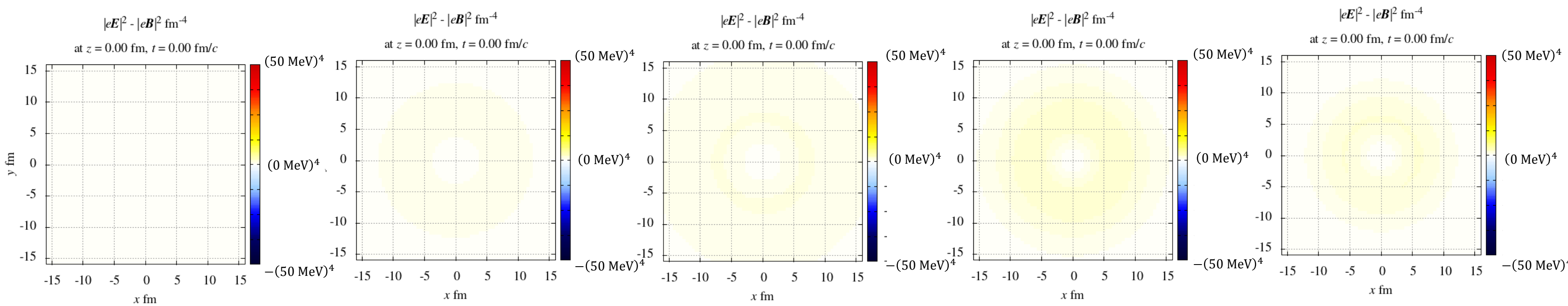


✔ Time evolution of EM field (central coll. b=0) @ z=0

- Lorentz inv. $F := E^2 - B^2$ (F>0: Electric, F<0: Magnetic)

Preliminary results

E_{CM} = 2.0 GeV 3.0 GeV 4.0 GeV 6.3 GeV 7.7 GeV



- Donut-shaped

  ⇐ Gauss law $E \propto \int \mathrm{d}^3\boldsymbol{x}\,\rho$

- Field strength can be strong as $e^2 F \sim (eE)^2 = O\left((50\ \mathrm{MeV})^4\right)$

  ⇒ • **Very strong for QED ($m_e = 0.511$ MeV)**

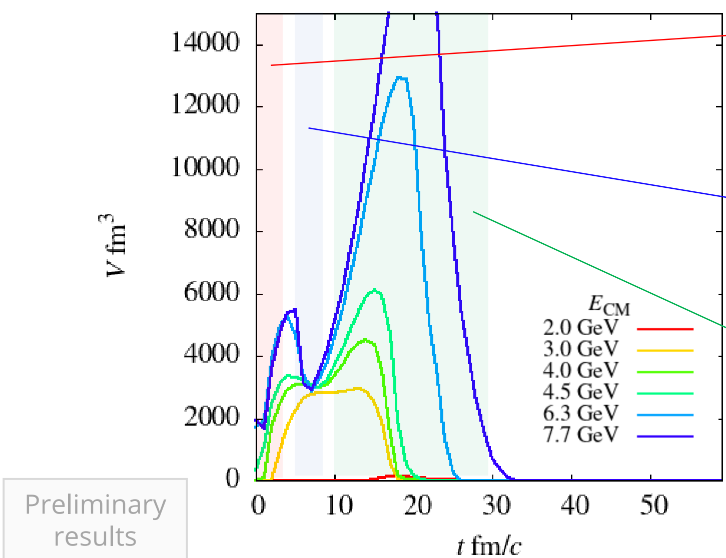
  • **May still weak for QCD ($\Lambda_{\rm QCD} = 200$ MeV), but is non-negligible (If deconfined, very strong for current quark mass)**

Estimation with a hadron trans. model: JAM (4/5)

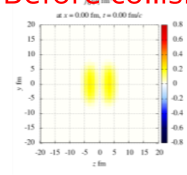
[Nishimura (Osaka), Ohnishi (Kyoto), HT, in progress]

✔ Spacetime volume of EM field (central coll. b=0)

Volume for $e^2F = |e\boldsymbol{E}|^2 - |e\boldsymbol{B}|^2 > (30\ \mathrm{MeV})^4$

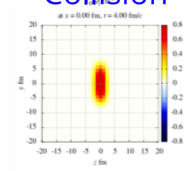


Before collision



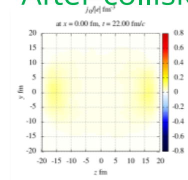
= Strength: so so
Volume: so so

Collision



= Strength: strongest
Volume: small

After collision



= Strength: weak
Volume: large

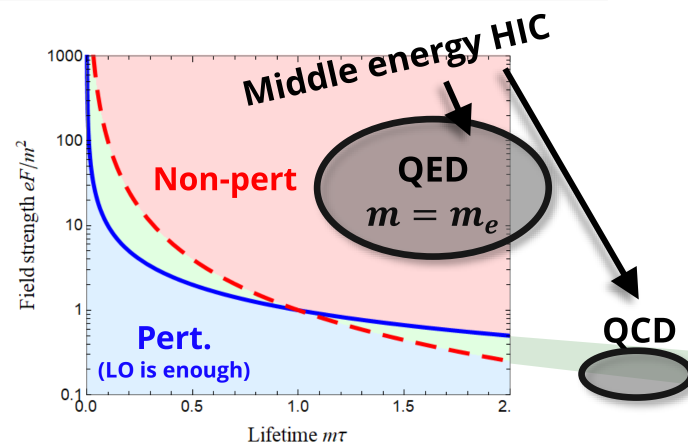
- **Strong E field with $e^2F \sim (eE)^2 \sim (30\ \mathrm{MeV})^2$, lifetime $\tau \gtrsim 20\ \mathrm{fm}/c$, volume $V \gtrsim (15\ \mathrm{fm})^3$**

  ⇒ **Non-pert** for QED. **Non-linear** for QCD

$$\gamma = \frac{m}{eE\tau} \text{ or } \frac{m}{eEl} = \begin{cases} O(1) & (m = \Lambda_{\mathrm{QCD}}) \\ O(0.1) & (m = m_e) \end{cases},\ \nu = eE\tau^2 \text{ or } eEl^2 = O(10)$$

- Volume increases monotonically below 10 GeV

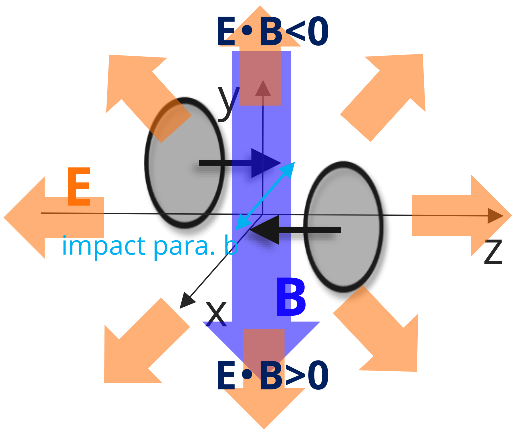
  ⇒ A bit funny (?) Needs more investigation (future work)

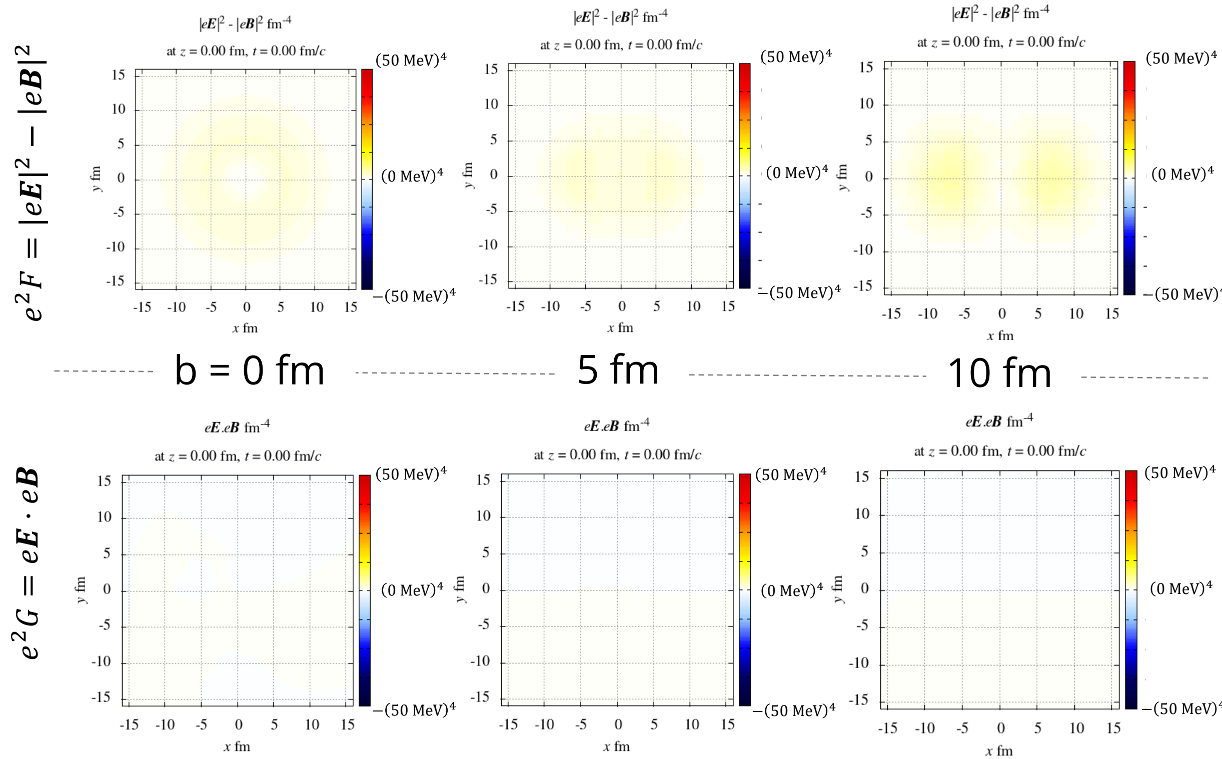


Estimation with a hadron trans. model: JAM (5/5)

[Nishimura (Osaka), Ohnishi (Kyoto), HT, in progress]

✔ Non-central collision ⇒ B & E•B are produced





Preliminary results

@ E_{CM} = 7.7 GeV

- $e\boldsymbol{E} \cdot e\boldsymbol{B} = O\left((50\ \mathrm{MeV})^4\right)$ ⇒ Non-negligible for QCD (Enough strong for electron and current quarks)
- Perhaps, a nice place to study chiral-anomaly-related stuffs

  ex) chirality production via the Schwinger mechanism $N_5 = VT\dfrac{e\boldsymbol{E} \cdot e\boldsymbol{B}}{2\pi^2}\exp\left[-\pi\dfrac{m^2}{eE}\right]$

1. Brief review of strong-field physics

2. Strong EM field at high-energy heavy-ion collisions

3. Strong EM field at middle-energy heavy-ion collisions

[Nishimura (Osaka), Ohnishi (Kyoto), HT, in progress]

4. An example of strong-field phenomenon: Vacuum decay and modification to photon propagation

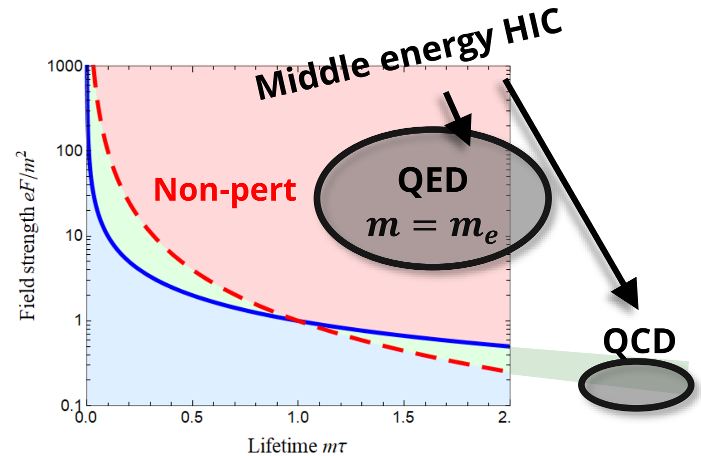
[HT, Ironside (Curtin), in progress]

5. Summary

So far, what interesting?

✔ Middle-energy HIC can be useful for studying "strong" "E-field" phys

- **point 1:** Enables us to explorer the non-pert. regime, where other experiments (e.g., high-energy HIC, intense laser) cannot cover



- **point 2:** E- and B-field physics are different

High energy ⇒ B field ⇒ system is stable

Middle energy ⇒ E field ⇒ system is unstable

✔ O(10%) of QCD scale ⇒ May affect hadron/QCD processes

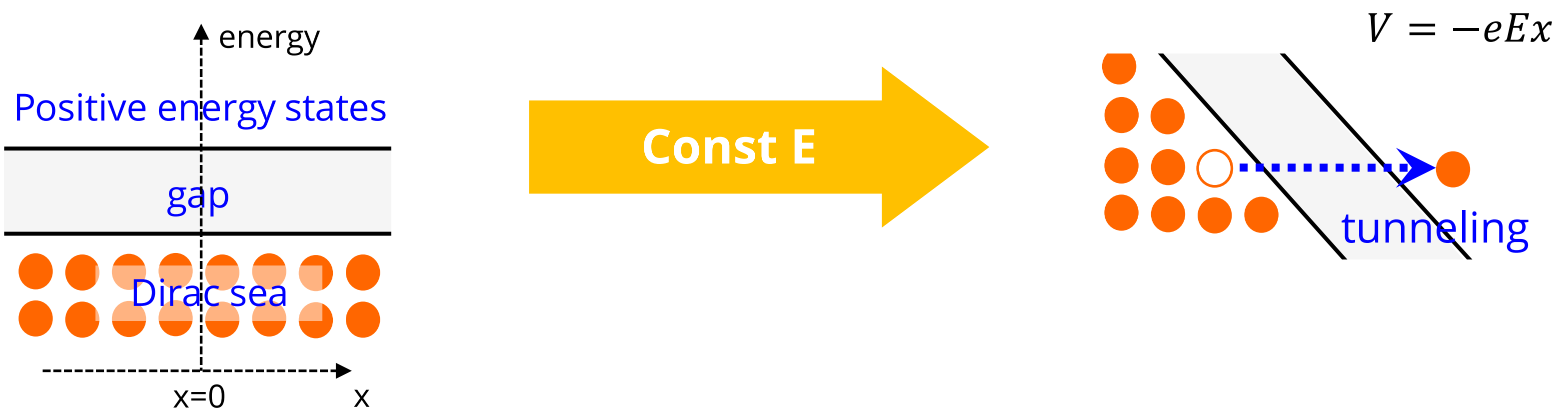
ex) B field at middle-energy heavy-ion collisions can affect flow and yield ratios

[Sun, Wang, Li, Wang (2019)]

Ex. of E-field pheno.: Vacuum decay and photon propagation (1/4)

✔ Vacuum decay = Vacuum becomes unstable against particle production in the presence of strong E field

- Const E field ⇒ Schwinger mechanism [Sauter 1931] [Schwinger (19



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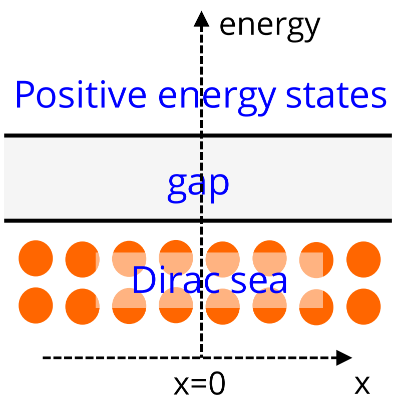

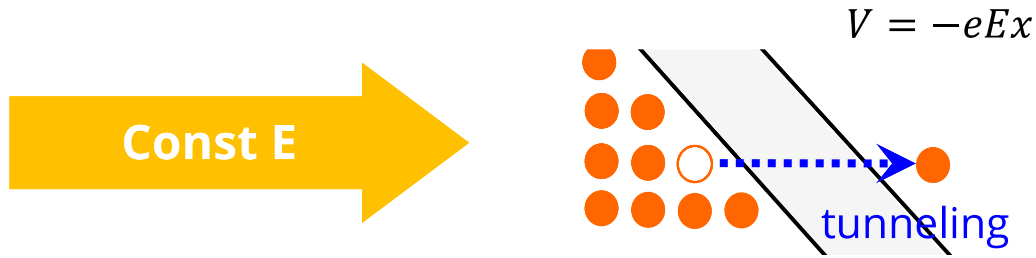

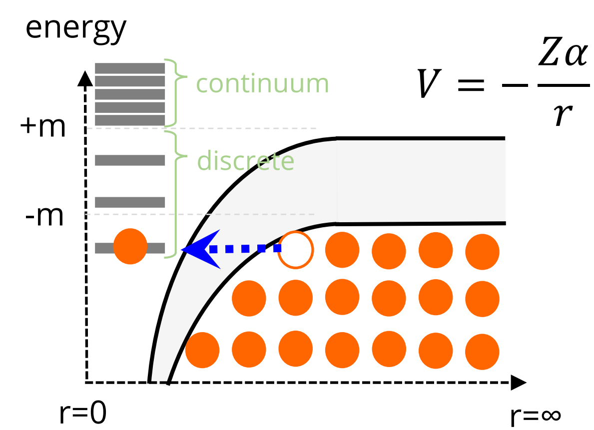

- Essentially the same for Coulomb field

  Difference: Energy is discretized for $E < +m$

  ⇒ Tunneling can occur only if there're energy levels for $E < -m$

  ⇐ (under various simplifications) OK if Z is sufficiently large: $Z > \alpha^{-1}$ [Pieper, Greiner (1969)] [Gershtein, Zeldovich (1970)]

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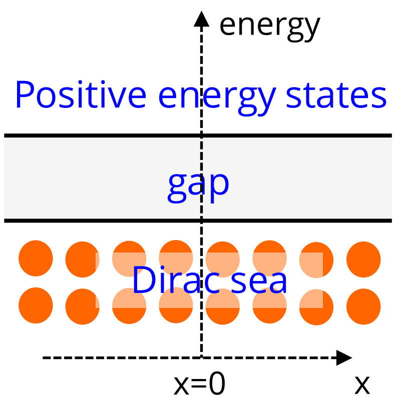

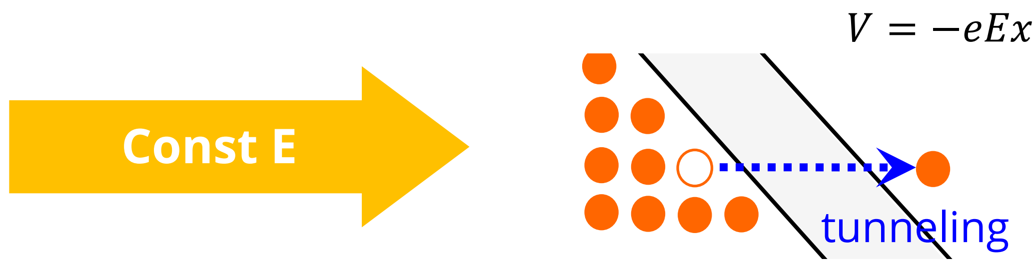

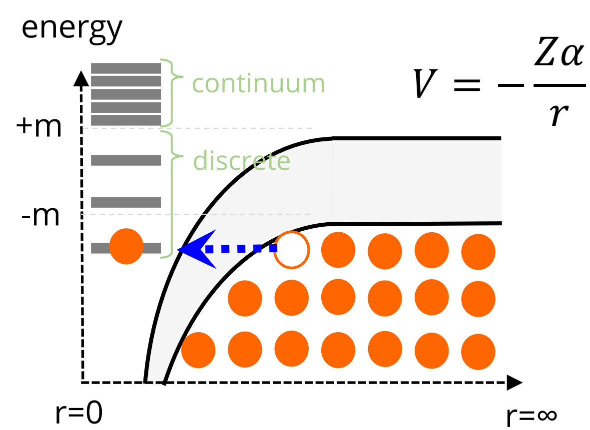

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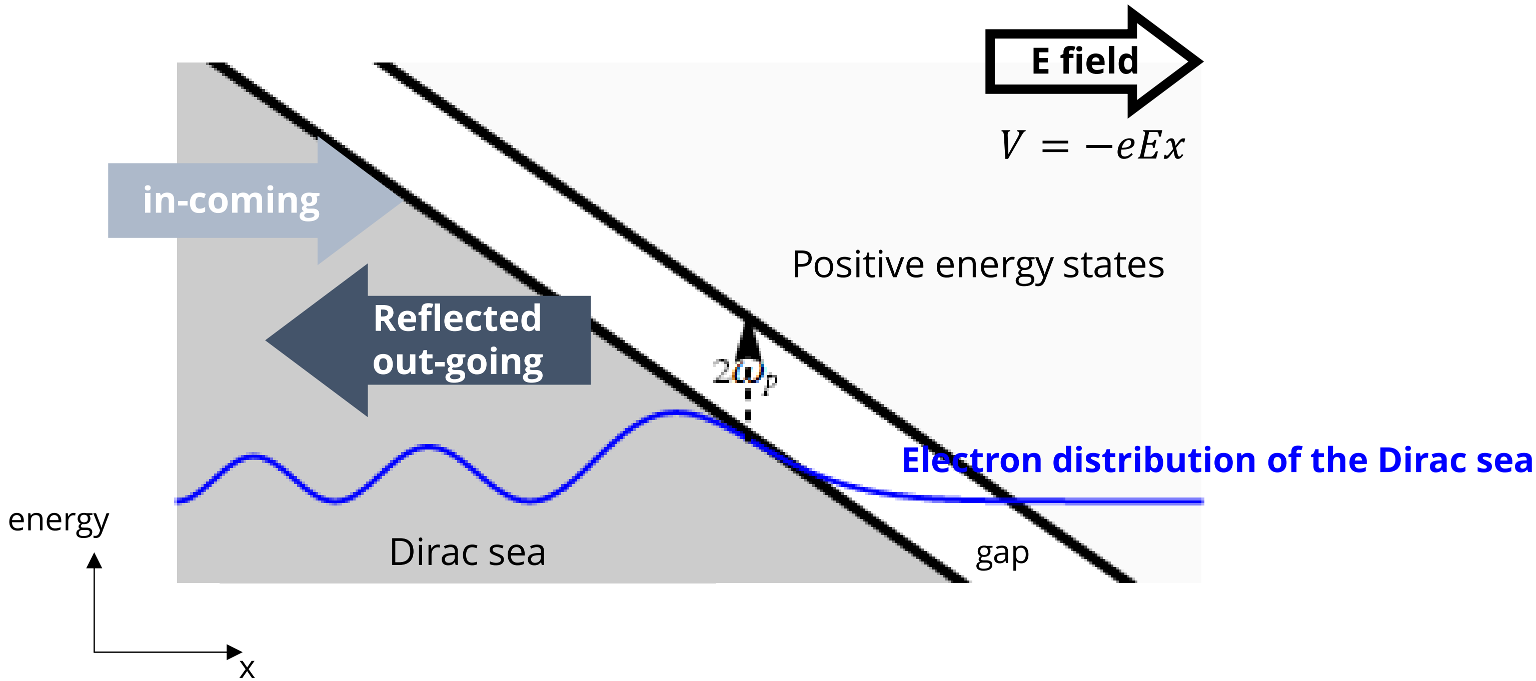
∴ Extra positron production in middle-energy HIC

This is interesting, but not the whole story ⇒ Change of photon propagation

Ex. of E-field pheno.: Vacuum decay and photon propagation (2/4)

✔ **"Tilting" of the vacuum affects photon propagation**

⇐ Interference in the Dirac sea due to the reflection by the gap [HT (2019)]



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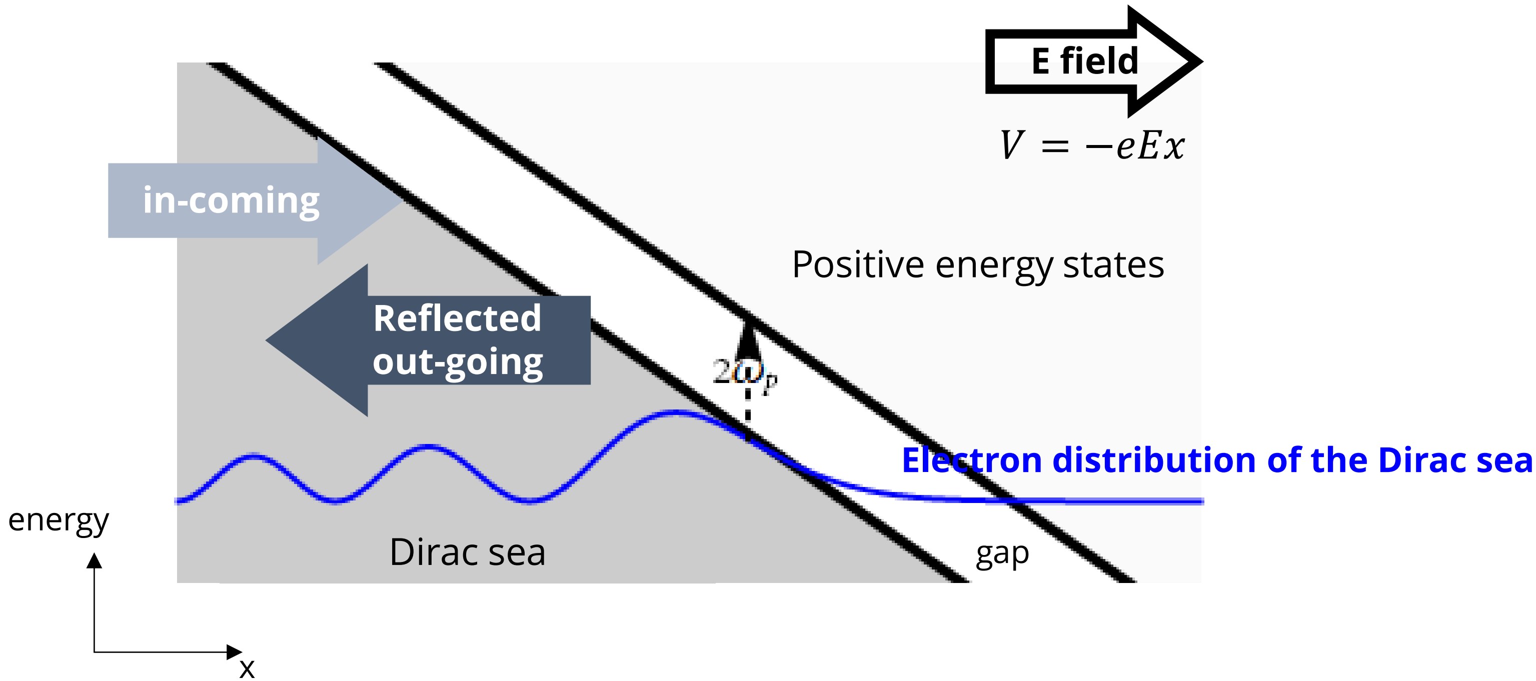


⇒ Photon propagating in the vacuum shall interact with the Dirac sea

Expectation 1: Photon propagation (=real and imag. parts of reflective index) should have signatures of the oscillating electron distribution

Expectation 2: Photon propagation should depend on the direction of the E field (vacuum birefringence)

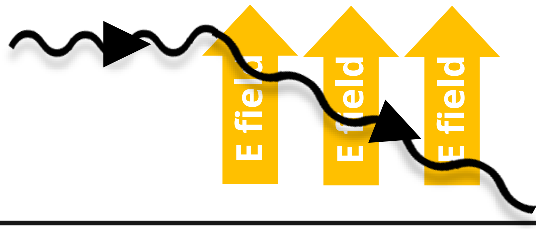
For B field: [Hattori, Itakura (2013)]

Ex. of E-field pheno.: Vacuum decay and photon propagation (3/4)

[HT, Ironside (Curtin), in progress]

✔ A simple setup: a probe E field in the vacuum under a strong const E field

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

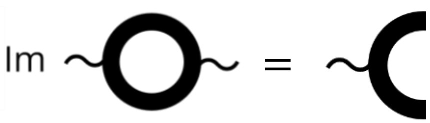


$\mathcal{D} = \varepsilon \mathcal{E} = n^2 \mathcal{E} = (1+\chi)\mathcal{E}$

✔ Observables: Real and imag. parts of electric permittivity

Im ⇒ Decay rate of probe

Wavefunction dressed by the strong E-field non-perturbatively
s.t. $0 = [\mathrm{i}\partial\!\!\!/ - eA\!\!\!/ - m]\Psi$



$\sim \int d^3\boldsymbol{p}\, \overline{\Psi} \mathcal{A}\!\!\!/\, \Psi$

Re ⇒ Velocity and birefringence of photon

Optical theorem (Kramers-Kronig relation)

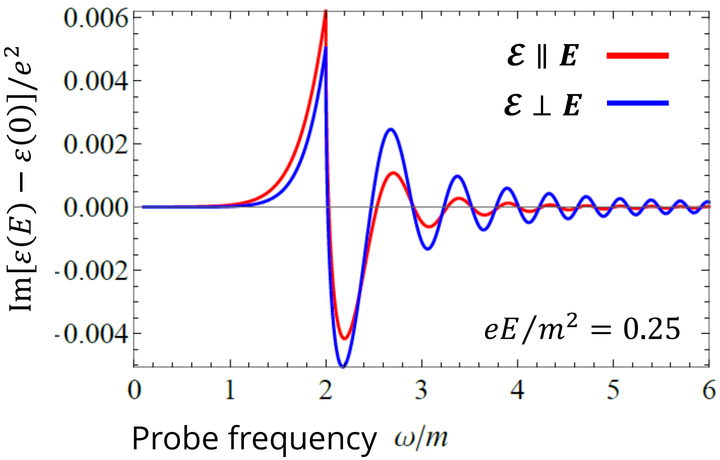
$$\epsilon_{\rm R}(\omega) = 1 + \frac{2}{\pi}\mathrm{P.V.}\int_0^\infty \mathrm{d}\omega' \frac{\omega'}{\omega'^2 - \omega^2}\epsilon_{\rm I}(\omega')$$

Ex. of E-field pheno.: Vacuum decay and photon propagation (4/4)

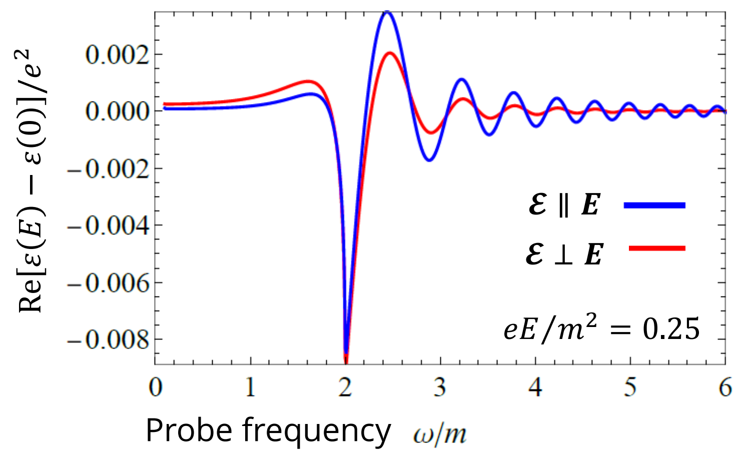
[HT, Ironside (Curtin), in progress]

✓ Result

Im ⇒ Decay rate of probe



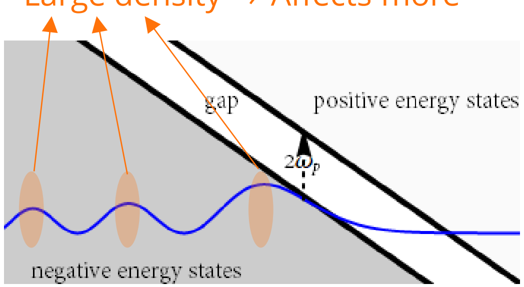
Re ⇒ Velocity and birefringence of photon



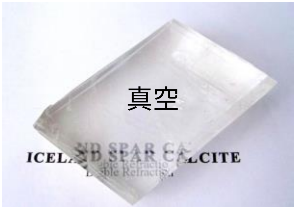
Preliminary results

- Oscillating behavior
  ⇐ result of the oscillating Dirac-sea structure

Large density ⇒ Affects more



- Probe-direction dependent response
  ⇒ Birefringence



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5. Summary

Summary

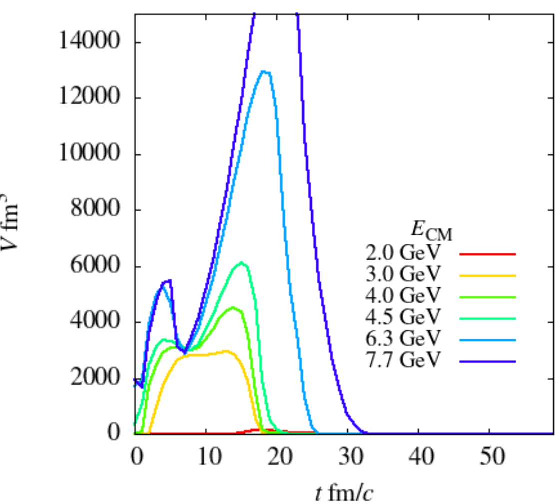
Middle-energy heavy-ion collisions $\sqrt{s_{\mathrm{NN}}} = O(1\text{-}10\ \mathrm{GeV})$ may be interesting not only to QCD but also to strong-field physics

---

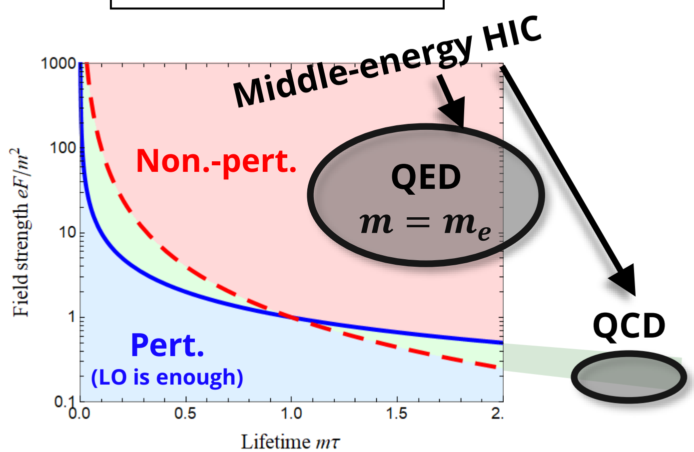
- Estimation of EM field strength and spacetime volume with a hadron transport model (JAM)
  ⇒ Strong O(30 MeV) and large spacetime volume O((20 fm)^4)
  ⇒ A nice setup to study strong-field QED. Non-negligible to hadronic/QCD processes as well.

Spacetime volume of EM field

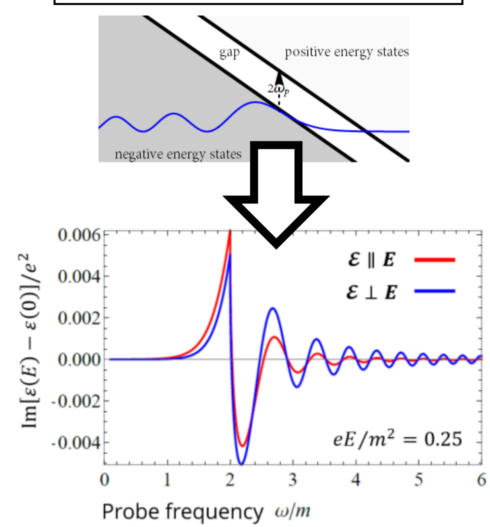
$$e^2F = |e\boldsymbol{E}|^2 - |e\boldsymbol{B}|^2 > (30\ \mathrm{MeV})^4$$



"Phase diagram" of strong-field physics



Photon propagation on top of decaying vacuum



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