Opportunities of strong-field physics in intermediate-energy heavy-ion collisions

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[HT, Nishimura, Ohnishi 2402.17136] [HT, Jinno, Kitazawa, Nara 2409.07685]

Plan

Intermediate-energy heavy-ion collisions $\sqrt{s_{\mathrm{NN}}} = O(2\text{ - }10\ \mathrm{GeV})$ is interesting not only to QCD/hadron but also to strong-field QED

1. Introduction to strong-field QED

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

Strong but too short-lived ⇒ affects "non-perturbativity" of strong-field processes

3. Strong EM field in intermediate-energy heavy-ion collisions

Estimate EM field profile with a hadron transport model (JAM)

⇒ "strong" O(50 MeV) and long-lived O(10 fm/c)

⇒ a nice setup to study strong-field QED; non-negligible to QCD/hadron processes as well

4. Summary

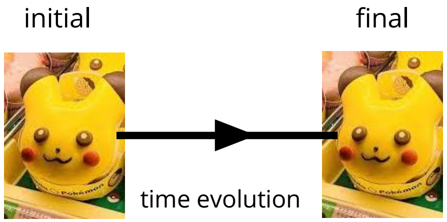
1. Introduction to strong-field QED

2. Strong EM field in high-energy HIC

3. Strong EM field in intermediate-energy HIC

4. Summary

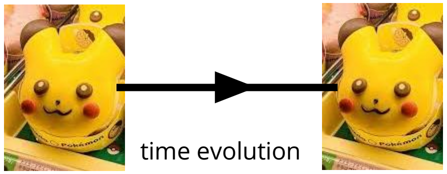
Strong-field QED



Vacuum
(= No EM field)

Strong-field QED

initial final

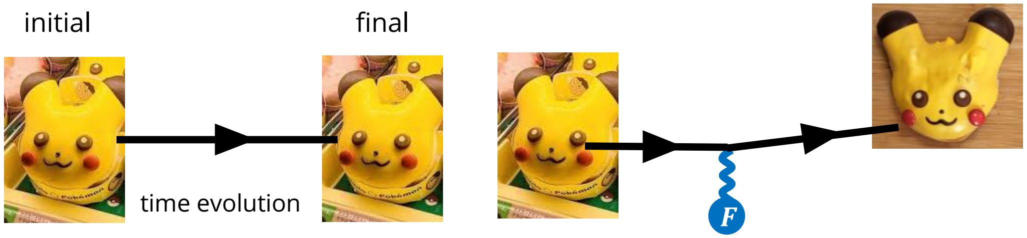


Vacuum
(= No EM field)

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

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

Strong-field QED



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

Almost the same

⇒ Perturbative

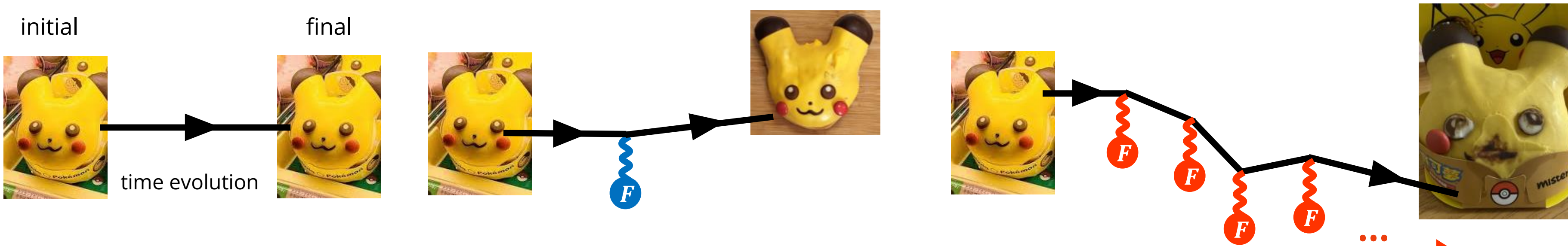
⇒ Understood

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

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

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

Strong-field QED



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

Completely different

⇒ Non-perturbative

⇒ Not understood

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

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

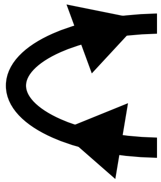
$a(\text{exp.}) = 1159652180.73 \ldots \times 10^{-12}$

Examples of strong-field phenomena

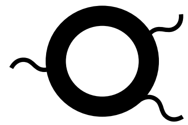
Novel QED processes ($eF/m_e^2 \gtrsim 1$)

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

ex) Schwinger effect



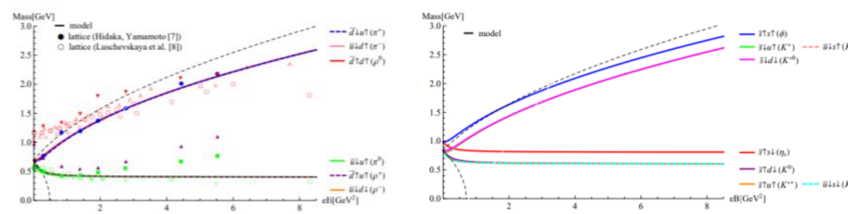
Photon splitting



Vacuum birefringence
(= Polarization dep. of reflective index)

Impacts on QCD/hadron physics ($eF/\Lambda_{QCD}^2 \gtrsim 1$)

[HT (2015)]

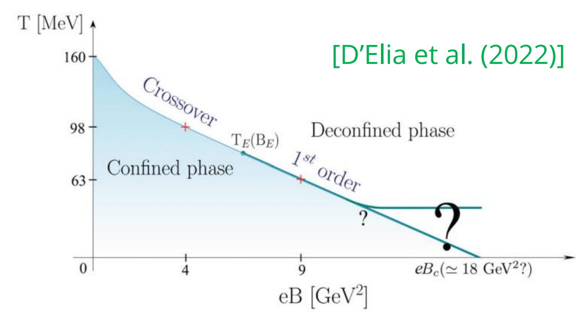


ex. 1) Hadron properties:

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

ex. 2) QCD phase diagram

[D'Elia et al. (2022)]



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

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

Many theoretical predictions, but NEVER observed in experiments

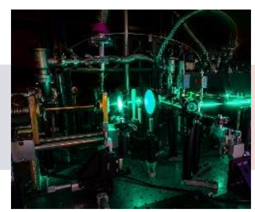
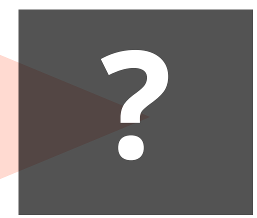
Need of EXTREMELY strong EM field

Order of the magnitude:

QED: $eE, eB > m_e^2 = (0.511\ \mathrm{MeV})^2 \approx O(10^{29}\ \mathrm{W/cm^2})$

QCD: $> \Lambda_{\mathrm{QCD}}^2 = (200\ \mathrm{MeV})^2 \approx O(10^{39}\ \mathrm{W/cm^2})$

Our limit at the present

LED	Laser welding	Cond.-mat (THz laser)	Guiness record	???
				
			HERCULES @ USA (2008)	
$I \sim 10^{-5}\ \mathrm{W/cm^2}$	$10^6\ \mathrm{W/cm^2}$	$10^{10}\ \mathrm{W/cm^2}$	$10^{22}\ \mathrm{W/cm^2}$	$\mathbf{10^{29}\ W/cm^2}$
or $eE \sim 10^{-1}\ \mathrm{eV/cm}$	$10^4\ \mathrm{eV/cm}$	$10^6\ \mathrm{eV/cm}$	$10^{12}\ \mathrm{eV/cm}$	$\mathbf{10^{18}\ eV/cm}$
$\sim (10^{-3}\mathrm{eV})^2$	$(10^{-1}\mathrm{eV})^2$	$(1\ \mathrm{eV})^2$	$(1\ \mathrm{keV})^2$	$\mathbf{(10^6\ eV)^2}$

Daily life → Industry → Science →

Impossible within the current tech. ⇒ New idea needed ⇒ HIC ?

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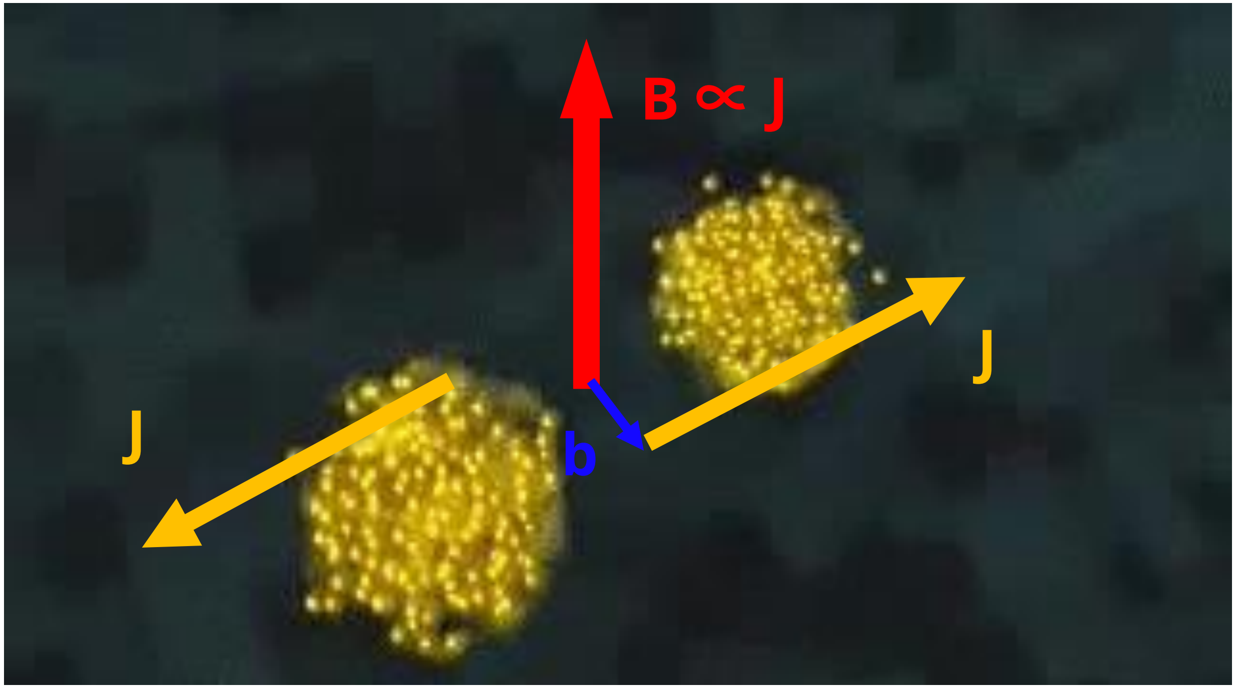
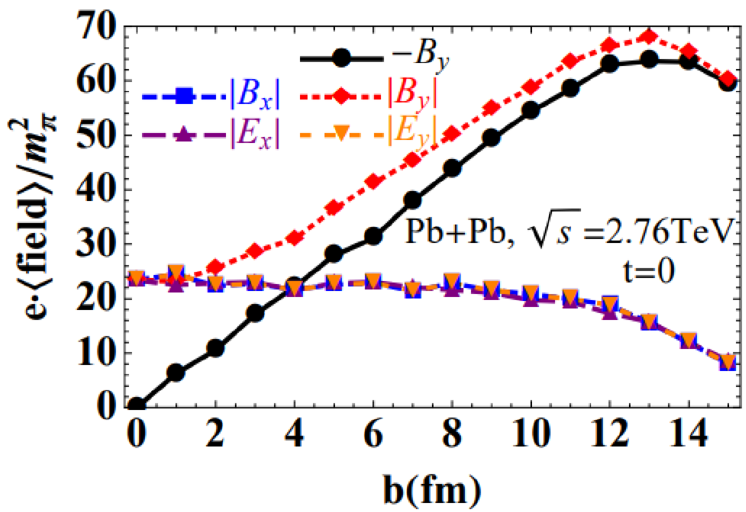
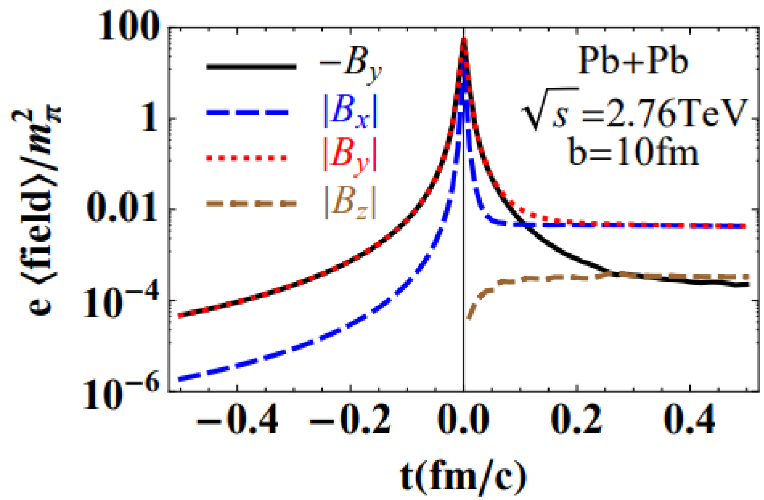
Strong EM field at high-energy HIC



✔ **Strong magnetic field is created**

Strong EM field at high-energy HIC





[Deng, Huang (2012)]

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

✔ **Strong magnetic field is created**

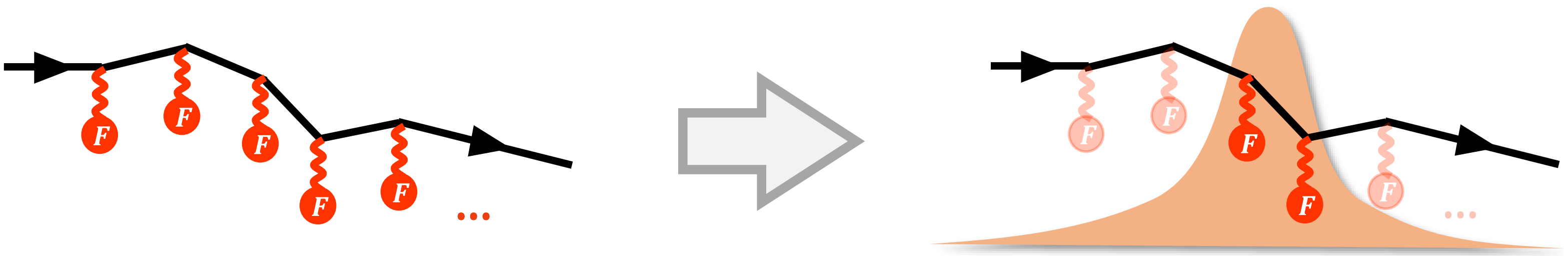
Pro: Super strong $eB \gg \Lambda_{\rm QCD}^2$

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

⇒ Affects "non-perturbativity" of strong-field physics

Shorter lifetime ⇒ less non-perturbative

Intuition: No time for multiple interactions

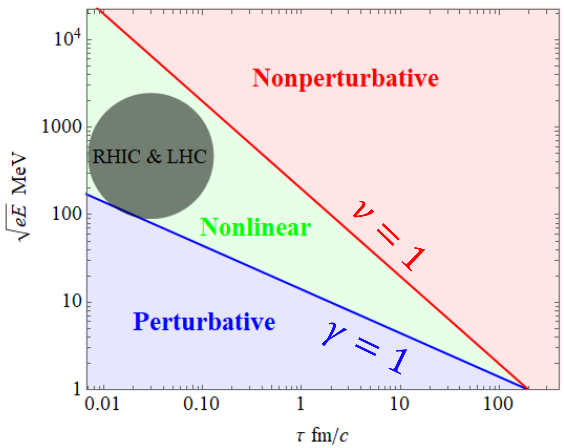


Shorter lifetime ⇒ less non-perturbative

"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

- $\boldsymbol{\gamma \ll 1}$ **,** $\boldsymbol{\nu \gg 1}$ ⇒ Non-perturbative v.s. $\boldsymbol{\gamma \gg 1}$ **,** $\boldsymbol{\nu \ll 1}$ ⇒ perturbative

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

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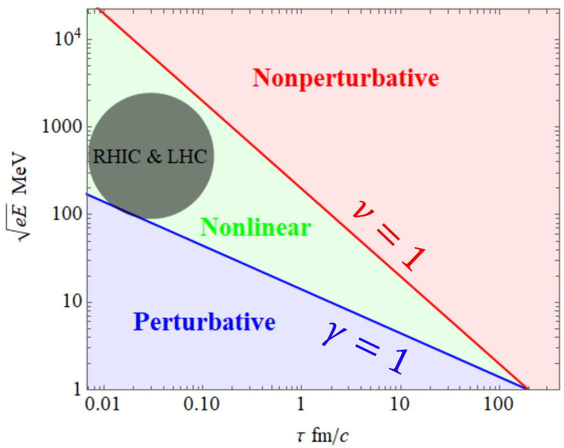
- As example: Vacuum particle prod. by E field w/ finite lifetime



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

High-energy heavy-ion collision is short-lived
⇒ NOT useful for strong-field phys. in non-perturbative regime

Actually, only NLO processes such as Breit-Wheeler have been observed in exp.; no signals of higher-order effects

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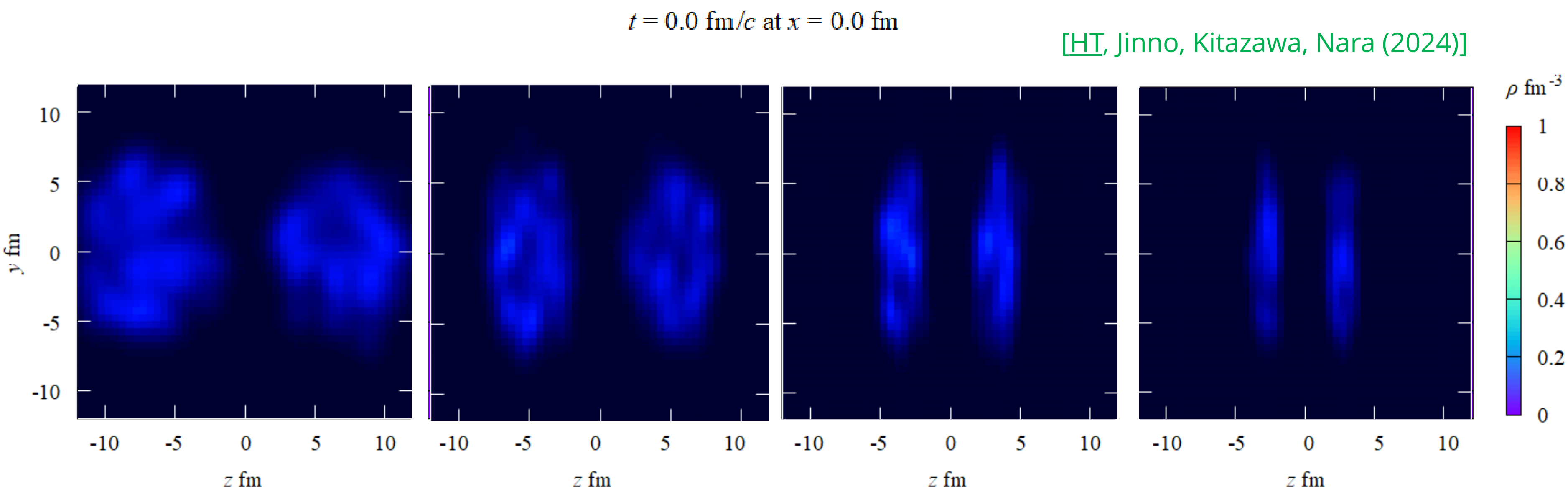
Intermediate-energy HIC

Heavy-ion collisions at $\sqrt{s_{NN}} = O(2-10)$

[AGS, SPS, RHIC BES, FAIR, NICA, HIAF, J-PARC-HI, ...]

[HT, Jinno, Kitazawa, Nara (2024)]



$\sqrt{s_{NN}} = 2.4$ GeV | 3.9 GeV | 7.2 GeV | 11.5 GeV

Stopping (Landau) ⟷ Penetration (Bjorken)

- Idea: baryon stopping at lower energies ⇒ dense matter w/ long lifetime
- The lifetime can reach O(10 fm/c)

Dense ⇒ Strong Coulomb field

Strong Coulomb electric field should be produced due to large $Z_{\mathrm{tot}} = 2Z \sim 200 > \alpha^{-1}$

- Very rough order estimate

  Strength: $eE \sim \frac{Z\alpha}{r^2} \sim \Lambda_{\mathrm{QCD}}^2 \sim (100\ \mathrm{MeV})^2$

  Lifetime: $\tau \sim 10\ \mathrm{fm}/c$

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

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

- If this is true, it's super interesting, since this is the very first physical system where we can study strong-field physics in the non.-pert regime

- But, of course, it's too rough, so let's do a realistic estimate

Approach: Hadronic transport model JAM

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

- A successful model to simulate the realtime dynamics of heavy-ion collisions, reproducing various data (v1, yields, ...)

- Basic idea: superposition of collisions of individual hadrons
  (incl. inelastic channels such as resonance, string breaking, mini-jet)

- JAM returns the distribution of charged hadrons at each spacetime pt.

  ⇒ EM fields can be obtained as

From JAM

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

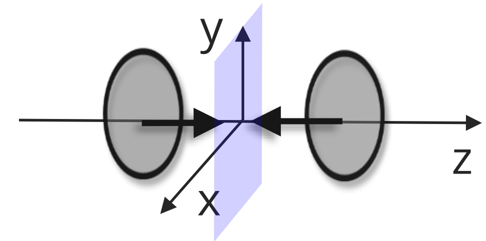
- <u>NB</u>: Just one of the models, not a first-principle calculation
  (e.g., no quark/gluon DoGs, no hydro, no phase transition, ...)

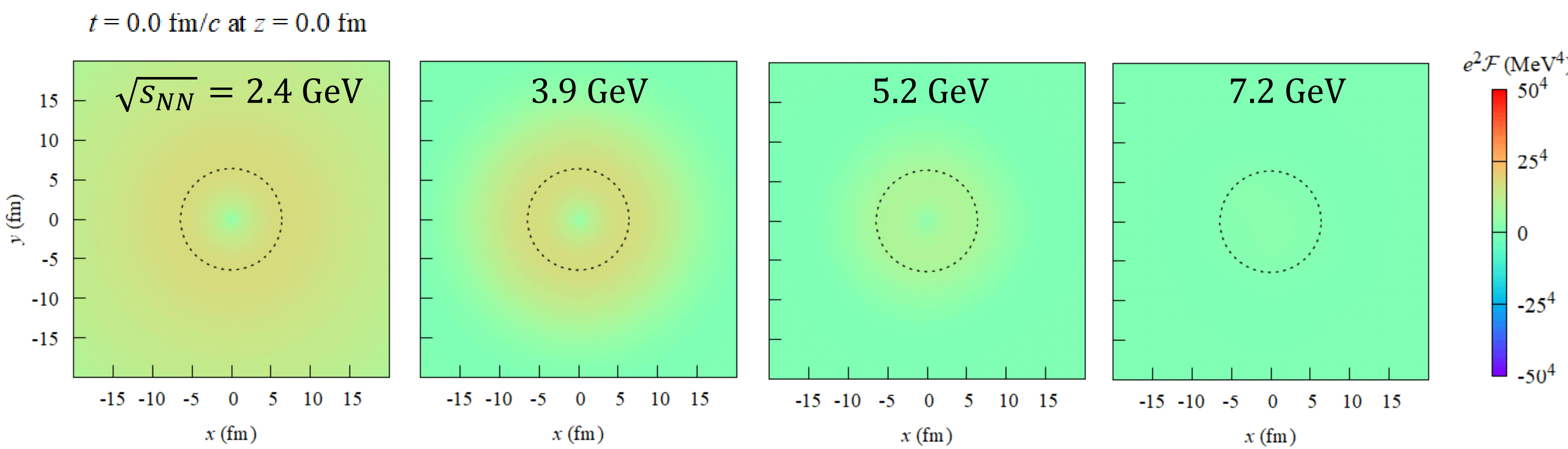
  ⇒ should be regarded as a “baseline”, before incl. non-trivial physics

  ⇒ worth to compare w/ other models: UrQMD, HIJING, SMASH, ...

Result (1/5): Spacetime profile at central coll.

✔ **Event-averaged** $\boldsymbol{F} \coloneqq \boldsymbol{E}^2 - \boldsymbol{B}^2$ (F>0: Electric, F<0: Magnetic)





[HT, Nishimura, Ohnishi (2024)]

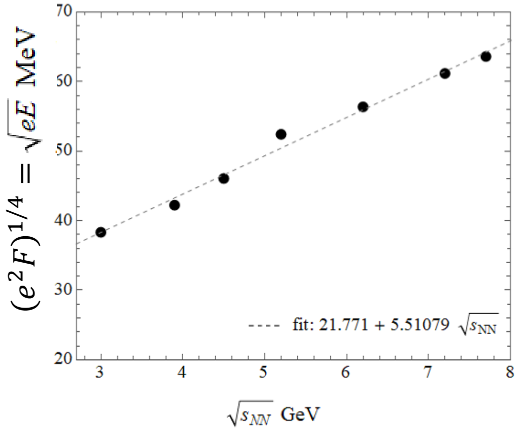
- F is positive ⇒ E field dominates over B field
- Donuts shaped ⇐ Gauss law $E \propto \int \mathrm{d}^3\boldsymbol{x}\ \rho$
- "strong" O(50 MeV) and long-lived O(10 fm/c)

much stronger than m_e , current quark mass; non-negligible to $m_\pi, \Lambda_{\mathrm{QCD}}$

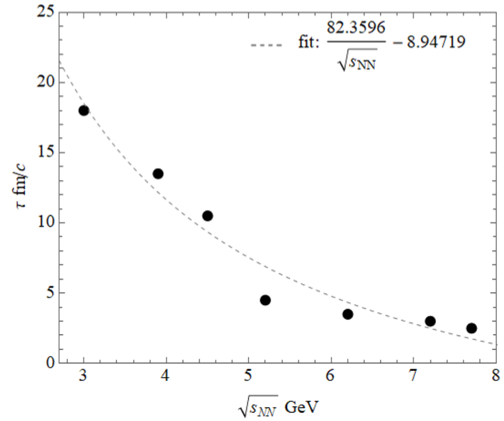
Result (2/5): Strength & lifetime at central coll.

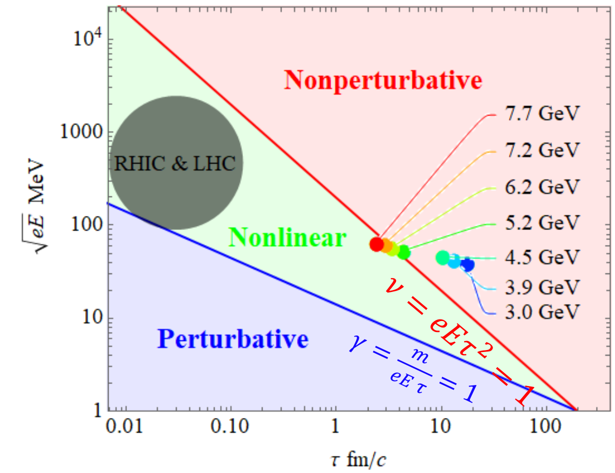
✔ **Peak field strength and lifetime (FWHM)**

Peak field strength



Lifetime





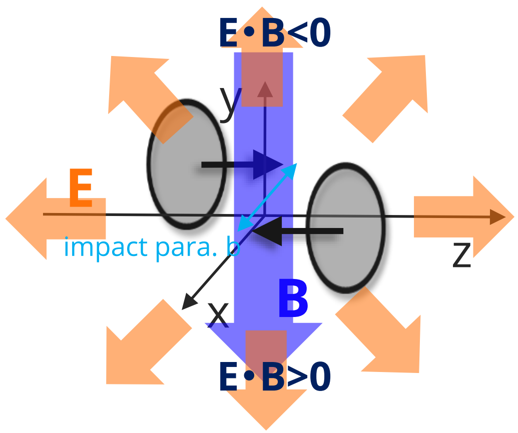
[HT, Nishimura, Ohnishi (2024)]

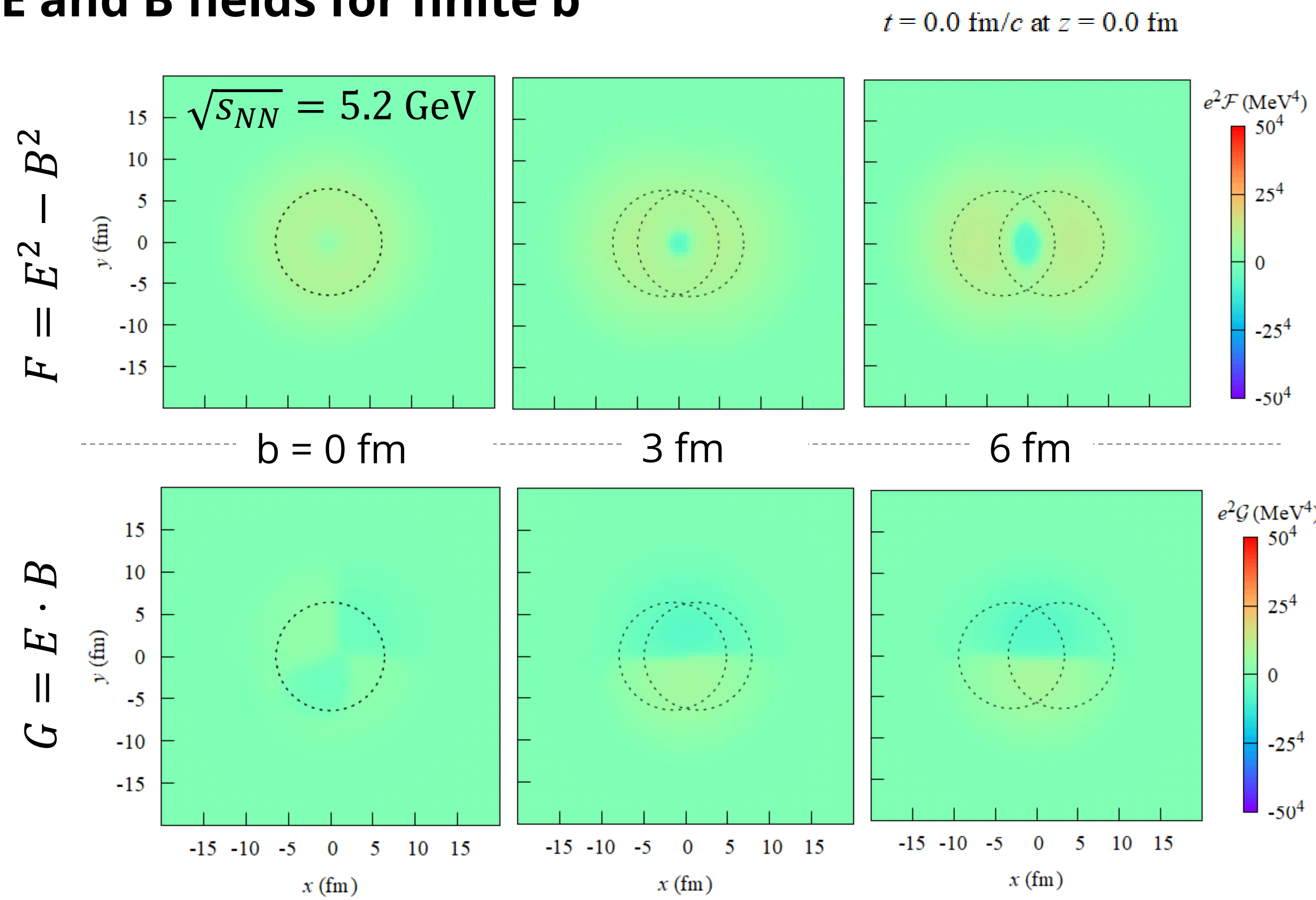
- Two basic physics: Lorentz contraction, Baryon stopping
- Intermediate energies can explorer the non-perturbative regime

  ⇐ Long lifetime compensates the weakness of the field

Result (3/5): Spacetime profile at non-central coll.

✔ **Interplay between E and B fields for finite b**





[HT, in progress]

- B field appears but E field is always larger in space

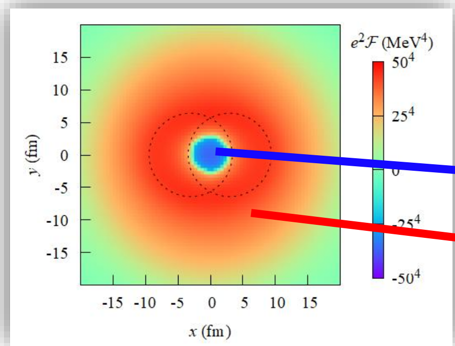
  ⇒ E field would be more important than B field in intermediate energies

- Parallel EM configuration s.t. $G = E \cdot B \neq 0$

  ⇒ can be a source of chiral physics $\partial_\mu J_5^\mu \propto E \cdot B$

Result (4/5): Strength & lifetime of F at non-central coll.

[HT, in progress]



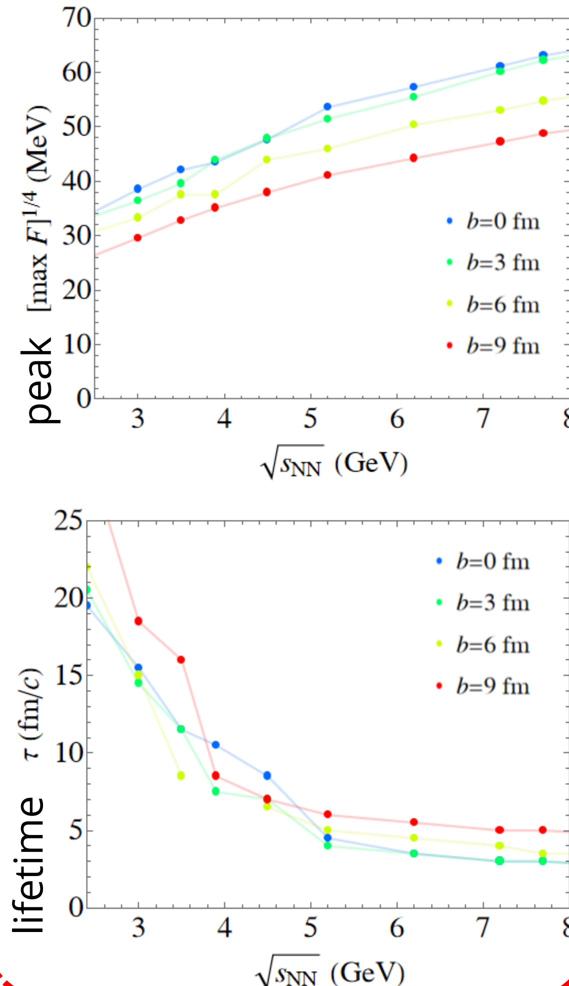
• E field is always strong compared to B field

⇒ E field is important even at peripheral events for intermediate energies

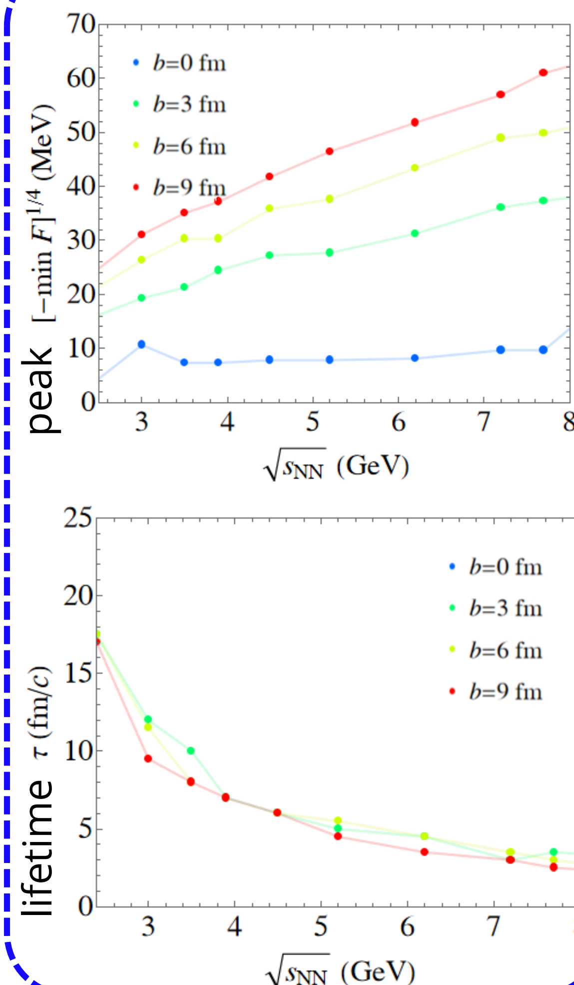
• Lifetimes are roughly the same and less sensitive to impact parameter b.

⇒ E & B fields can be non-pert. even at peripheral events

max F ~ E field

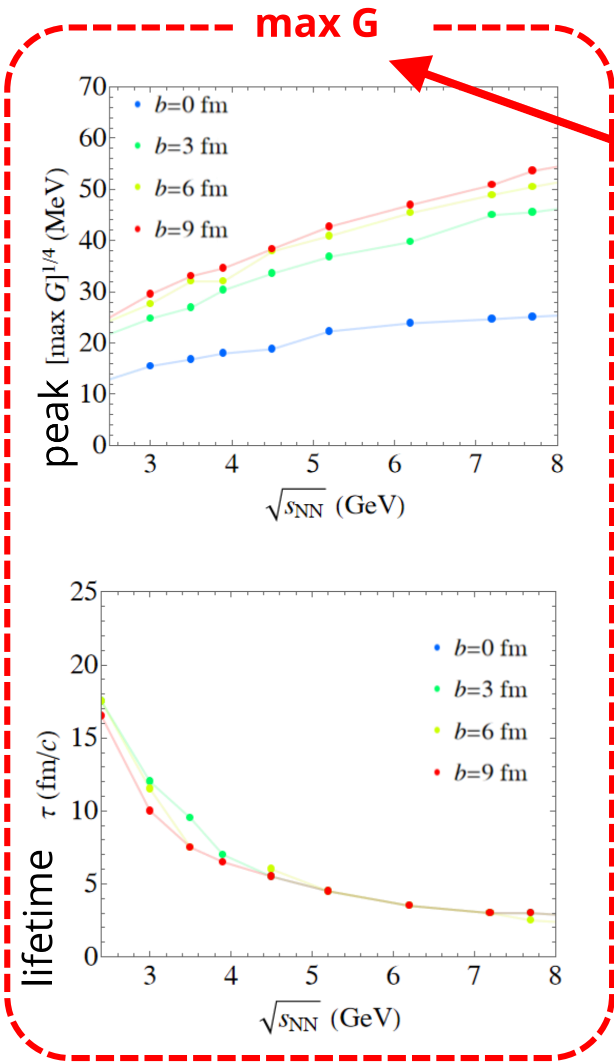


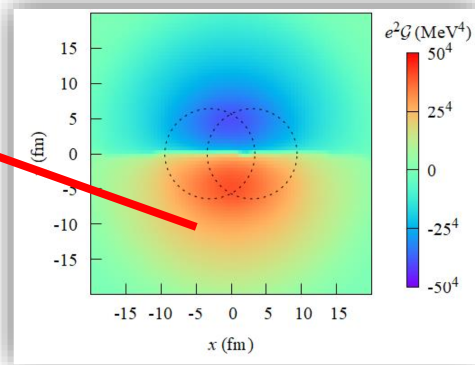
min F ~ B field



Result (5/5): Strength & lifetime of G at non-central coll.

[HT, in progress]





- "Strong" as G ~ F = O(50 MeV)
- As long-lived as F as τ = O(10 fm/c)

⇒ Not a simple E or B field configuration,
but need to think both F and G effects
in intermediate energy heavy-ion collisions

(similar plot for max G ≒ − min G)

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is interesting not only to QCD/hadron but also to strong-field QED

✔ Strong EM field in high-energy heavy-ion collisions

- Strong but too short-lived ⇒ affects "non-perturbativity" of strong-field processes

✔ Strong EM field in intermediate-energy heavy-ion collisions

- Estimate EM field profile with a hadron transport model (JAM)
- Coulomb electric field is produced, which is "strong" O(50 MeV) and long-lived O(10 fm/c)

  ⇒ a novel opportunity to study strong-field QED; non-negligible to QCD/hadron as well
- E field is more important than B field
- "Chiral" E.B ≠ 0 configuration in peripheral collisions