Finite Pulse Effects

on

Fermion Pair Creation from Strong Electric Fields

based on PRD 90, 014039 (2014)

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in collaboration w/ H.Fujii (Tokyo U.) and K.Itakura (KEK)

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Naïve understanding

$\langle vac;in|\hat{n}_{\rm out}|vac;in\rangle = 0$ $\qquad$ $\langle vac;in|\hat{n}_{\rm out}|vac;in\rangle \neq 0$

▶ well-formulated for static homogeneous electric field as a non-perturbative physics

$$\langle vac;in|\hat{n}_{\rm out}|vac;in\rangle = \exp\left[-\pi\left(m^2 + p_T^2 \big/ gE\right)\right]$$

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Why interesting ?

Because it gives us a deeper understanding of QFT cf.) vacuum structure, non-perturbative aspects ...

Because it is phenomenologically important cf.) formation of QGP (particle creation from *glasma*) ...

Because it is becoming relevant to experiment and very timely to study

cf.) Laser: $\sqrt{eE} \sim \mathbf{100\ keV} \sim m_{\text{electron}}$ HIC: $\sqrt{gE} \sim \mathbf{1\ GeV} \gg m_{\text{quark}}$

Fermion pair creation is well studied for static homogeneous field

- Non-perturbative pair creation occurs
- Schwinger's formula is known to compute $<\mathrm{vac;in}|\hat{n}_{\mathrm{out}}|\mathrm{vac;in}>$

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UNREALISTIC !!

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PROBLEM: Strong fields are always finite in time

cf.) Laser: $\boldsymbol{\tau \sim 10^{-15}\ \mathrm{sec}}$

HIC: $\boldsymbol{\tau \sim 10^{-24}\ \mathrm{sec}}$

Go beyond static homogeneous field
and consider FINITE PULSE EFFECT

Q. What is expected if *Finite pulse effect* is considered ?

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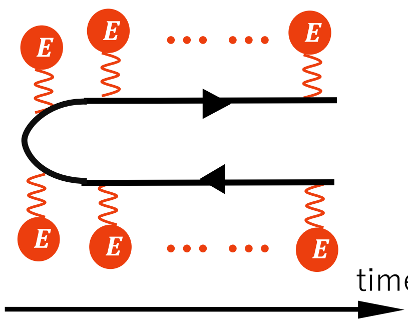
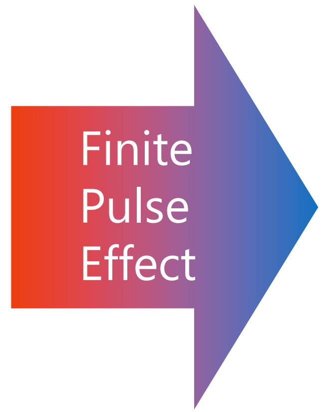
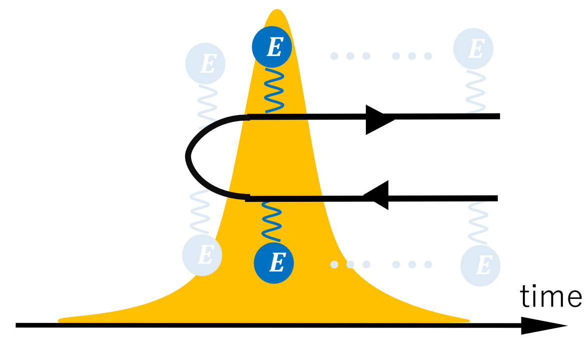
Naïve understanding (static homogeneous field)





Finite pulse effect



Infinite # of scattering

Non-perturbative pair creation

$$<\text{vac;in}|\hat{n}_{\text{out}}|\text{vac;in}> = \exp\left[-\pi\left({m^2+p_T^2}/{gE}\right)\right]$$

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Finite # of scattering

Perturbative pair creation

$$<\text{vac;in}|\hat{n}_{\text{out}}|\text{vac;in}> = \# \times \left|\frac{gE}{m^2}\right|^2$$

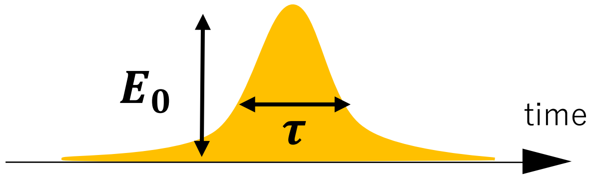
A? "Transition" from non-perturbative to perturbative pair crea.

0. Setting:

- QED Lagrangian w/ external electric field: $\mathcal{L} = \bar{\psi}(i\partial\!\!\!/ - m - gA\!\!\!/)\psi$
- analytical model: Sauter-type pulsed electric field

[F.Sauter, 1932]

$$\boldsymbol{E}_{\mathbf{Sauter}}(\boldsymbol{t}) = \boldsymbol{E}_{\mathbf{0}}\mathbf{cosh}^{-2}[\boldsymbol{t}/\boldsymbol{\tau}]$$



1. Compute full formula for $<\mathbf{vac;in}|\hat{n}_{\mathbf{out}}|\mathbf{vac;in}>$

2. Compare the full formula with the formula obtained from the lowest-order *perturbation* and the *non-perturbative* Schwinger formula

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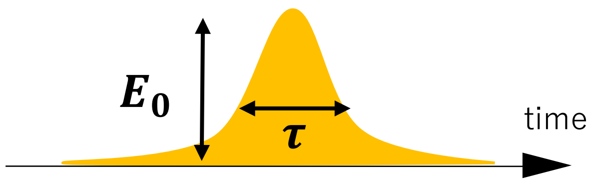

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- canonical quantization under external fields
- deriving $\langle\mathrm{vac;in}|\hat{n}_{\mathrm{out}}|\mathrm{vac;in}\rangle_{\mathrm{full}}$ ⇔ solving Dirac eq. under external fields:

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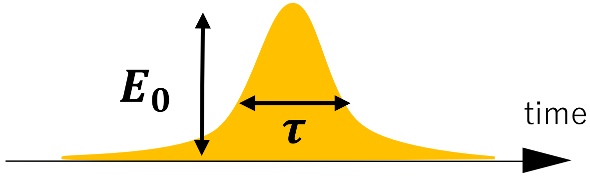

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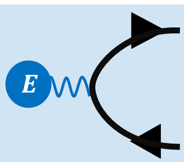
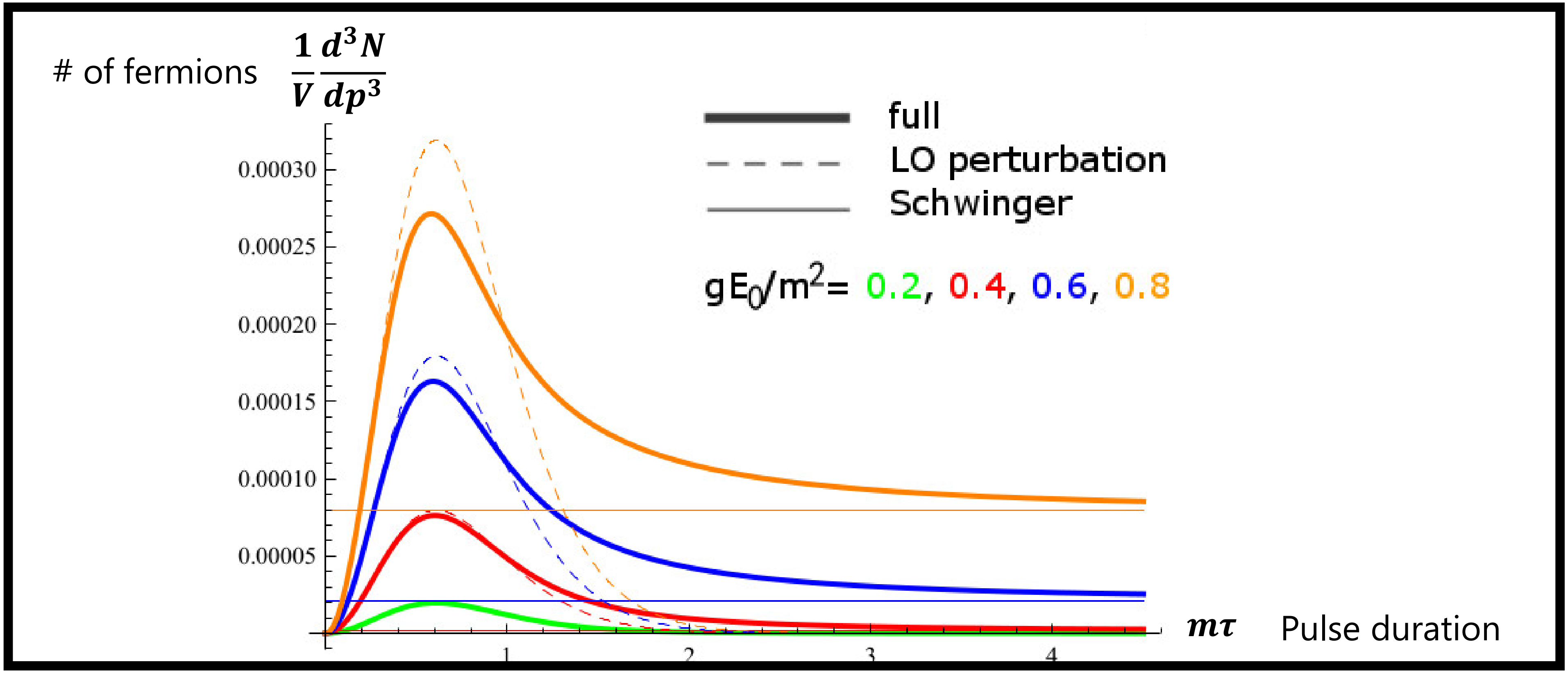
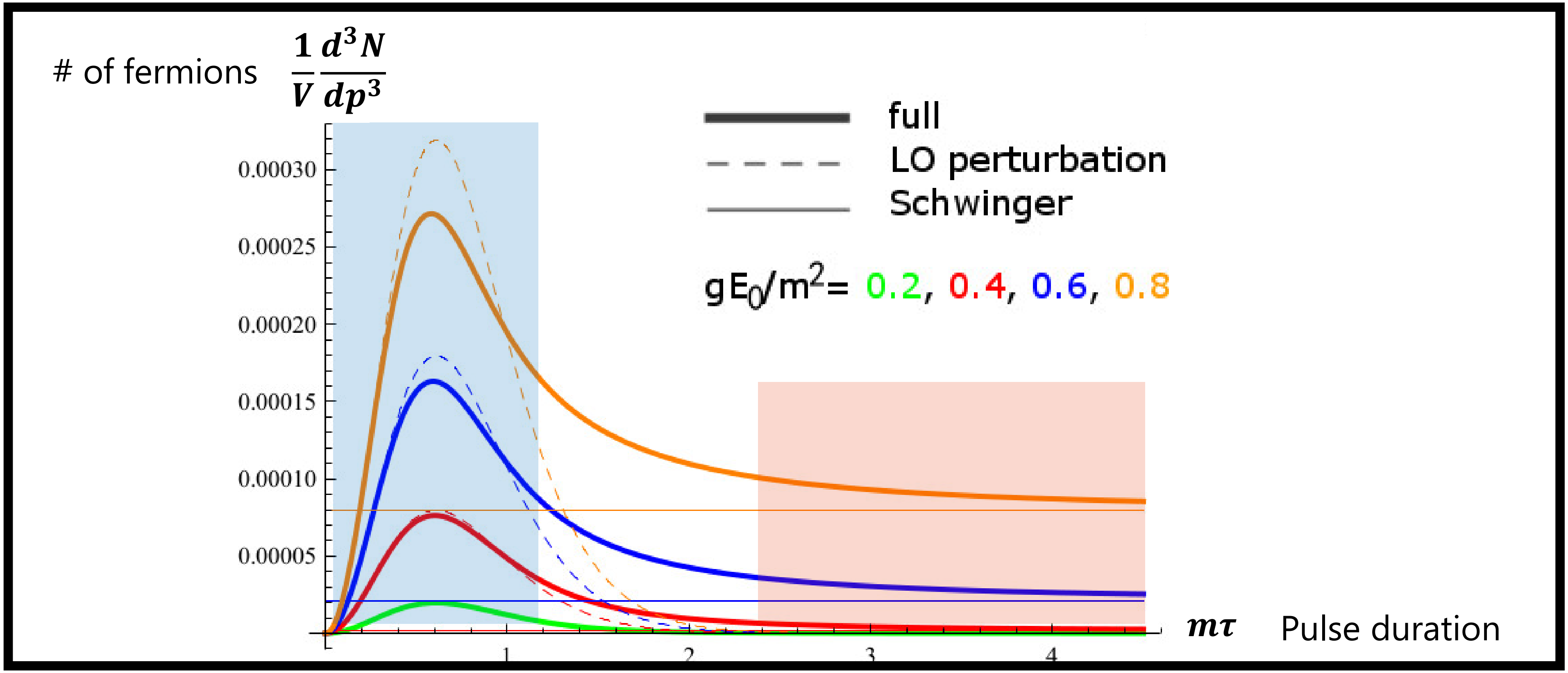
$\langle \mathrm{vac;in}|\hat{n}_{\mathrm{out}}|\mathrm{vac;in}\rangle_{\mathrm{LOPT}} = \Big|$  $\Big|^2 = \left(1 - \frac{p_z^2}{p_0^2}\right)\frac{\left|g\tilde{E}(2p_0)\right|^2}{4p_0^2}$

$$\langle \mathrm{vac;in}|\hat{n}_{\mathrm{out}}|\mathrm{vac;in}\rangle_{\mathrm{Schwinger}} = \exp\left[-\pi\left(m^2 + p_T^2 \middle/ gE\right)\right]$$



Result 1:

Result 2:



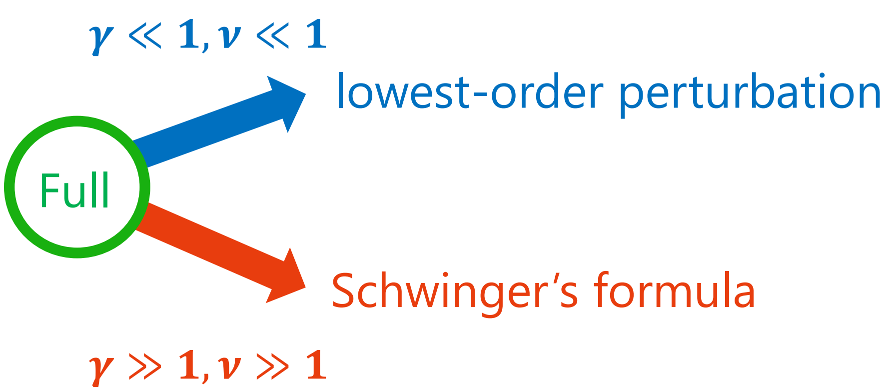
Result 1:

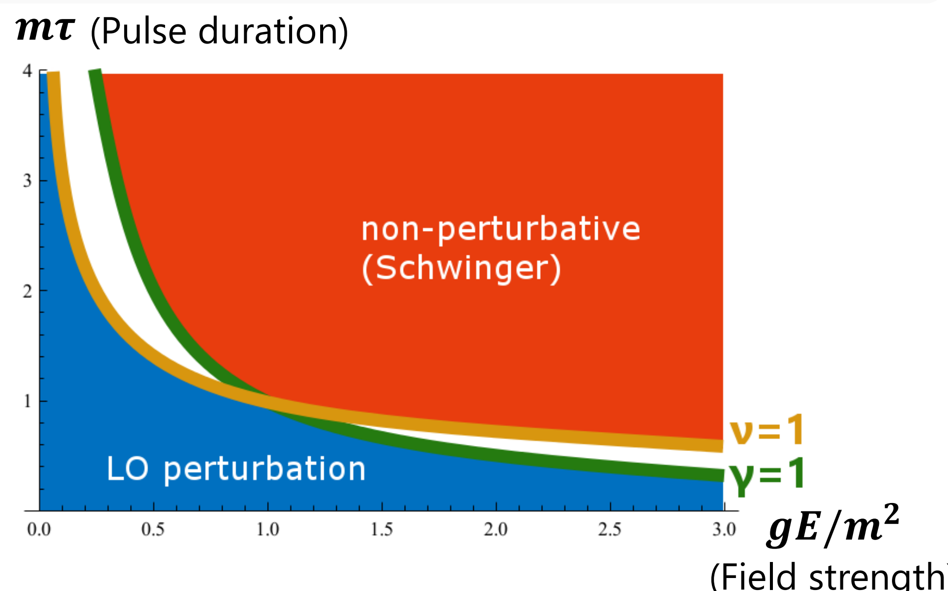
- Pair crea. is (non-)perturbative for small (large) τ.

Result 2:

"Short τ" or "Large τ" ?

3 dim. param. in the Lagrangian: τ, gE_0, m. ➡ 2 expansion param. : $\gamma = gE_0\tau/m$, $\nu = gE_0\tau^2$.





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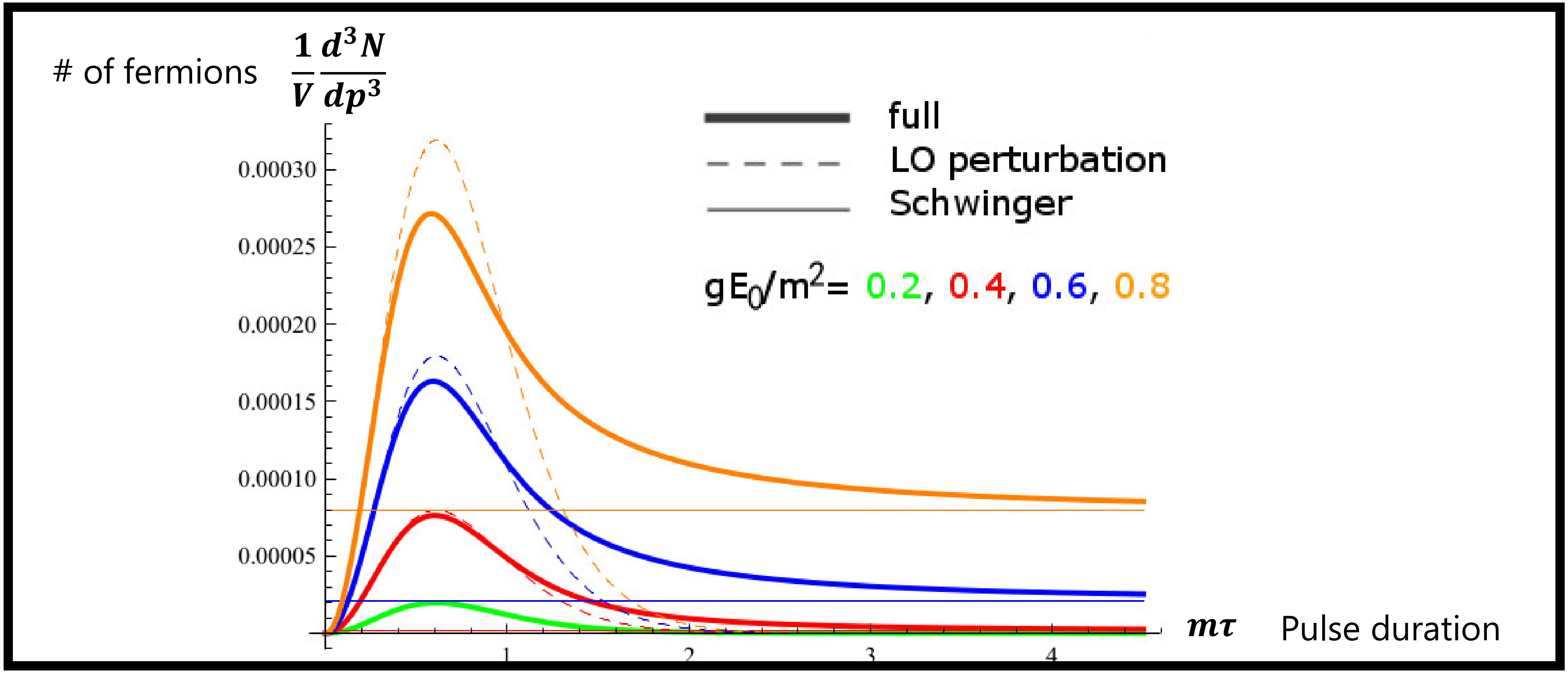

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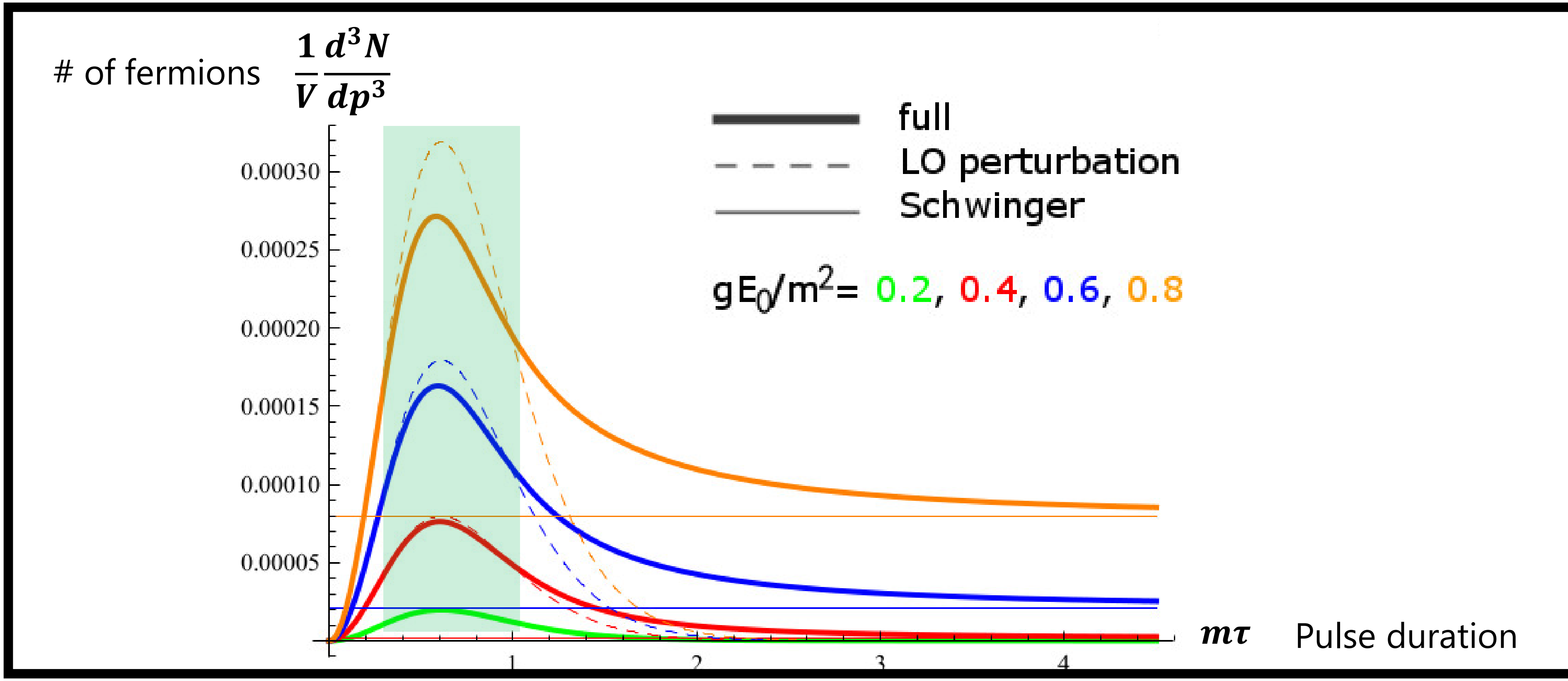

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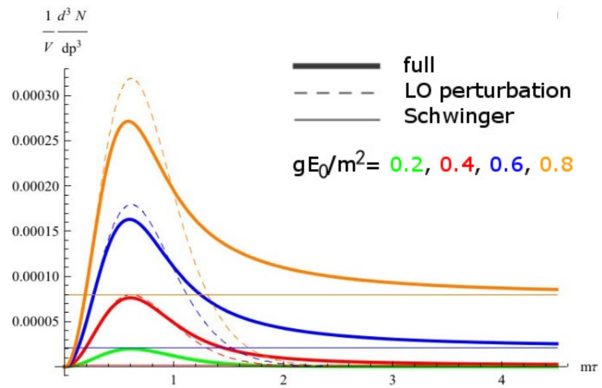
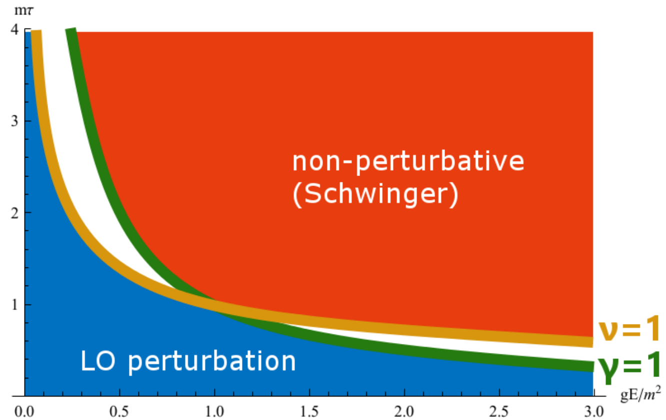
Result 2:

cf.) P.Levai & V. Skokov, 2010

- Pair creation is enhanced for $gE_0/m^2 \lesssim 1$, $m\tau \lesssim 1$.
- This enhancement is *perturbative* phenomena.

- Finite pulse effects on fermion pair creation from strong electric fields is studied.





- ▶ A "transition" from non-perturbative to perturbative pair creation occurs.

  This "transition" is controlled by the 2 dimensionless parameters: $\boldsymbol{\gamma = gE_0\tau/m, \nu = gE_0\tau^2}$.

- ▶ Pair creation is enhanced compared to Schwinger's formula for $\boldsymbol{gE_0/m^2 \lesssim 1}$, $\boldsymbol{m\tau \lesssim 1}$.

  This enhancement is predominantly described by the lowest-order perturbation.

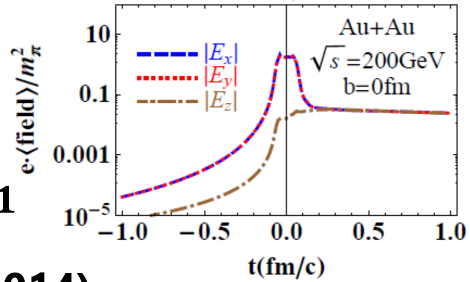
- Implications to HIC phenomenology:

  Glasma — Finite pulse effect may be important: $\boldsymbol{\gamma \gg 1, \nu \lesssim 1}$.

  Strong Coulomb field — There is a *room* for the non-perturbative pair crea.

  The matter created in the HIC could let $\boldsymbol{\nu}$ be large $\boldsymbol{\nu \gtrsim 1}$

Lifetime of strong Coulomb field
W.T.Deng & X.G.Huang, 2012

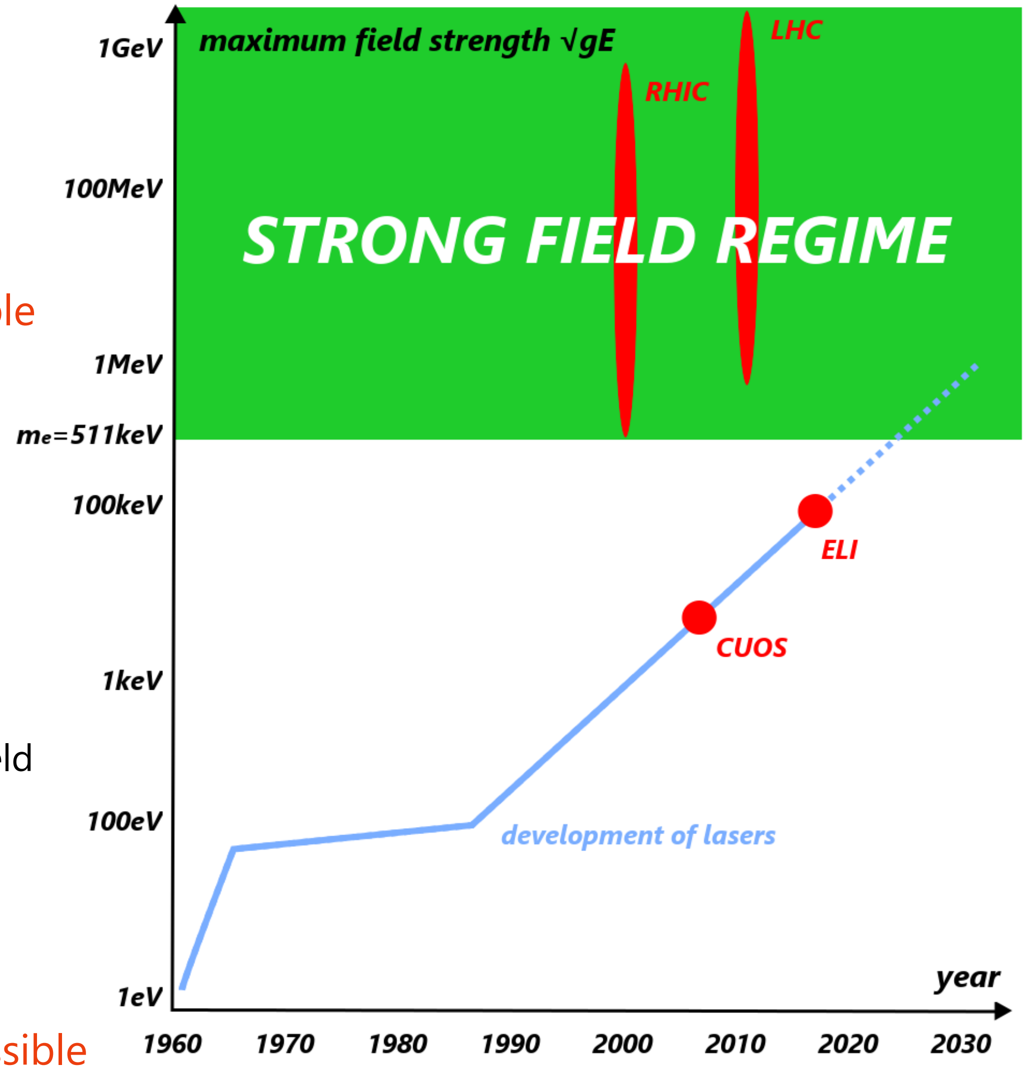


- For more results and discussions, see H.Taya et al., **PRD 90, 014039 (2014)**

BACKUP

Development of strong electric field

pair creation requires strong electric fields of the order of $gE \sim m^2$



BEFORE 21th century:

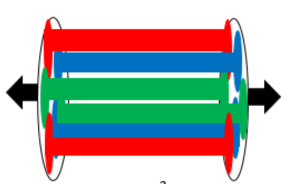
- only weak lasers are available

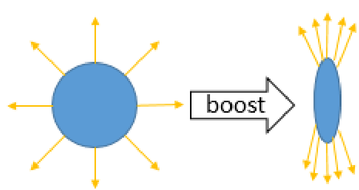
▶ always $gE \ll m^2$, so pair crea. is impossible

AFTER 21th century:

- laser strength dramatically increases
- HIC creates strong (color-)electric fields

cf.) *Glasma* Strong Coulomb field





▶ can be $gE \gtrsim m^2$, so pair crea. can be possible

▶ Now is the best time to study fermion pair creation from strong electric fields

RESULT

Comment on Result 2

Power supp.

Perturbative pair creation

$$<\text{vac;in}|\hat{n}_{\text{out}}|\text{vac;in}> = \# \times \left|\frac{gE}{m^2}\right|^2$$

Exp. supp.

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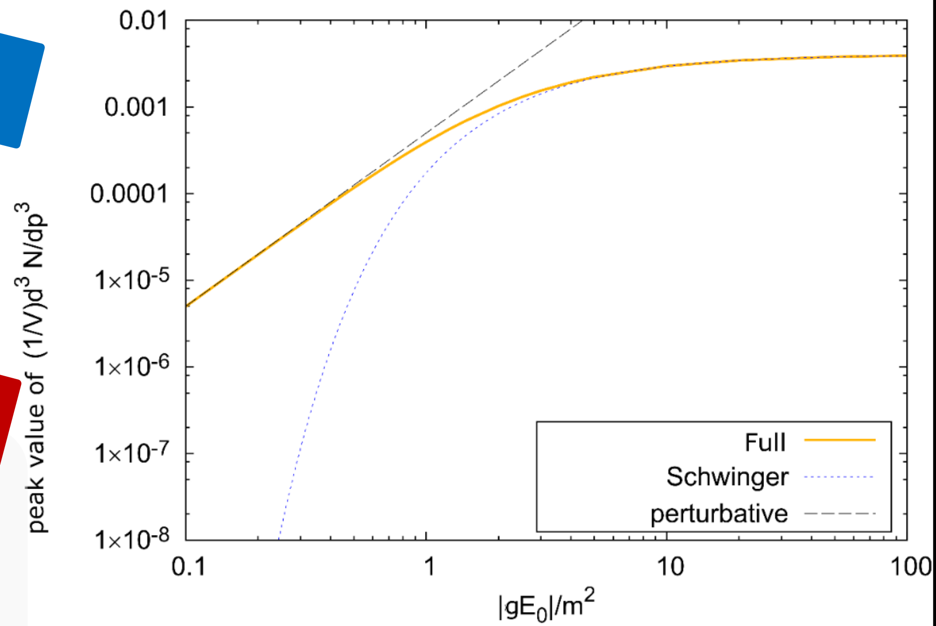

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SUMMARY

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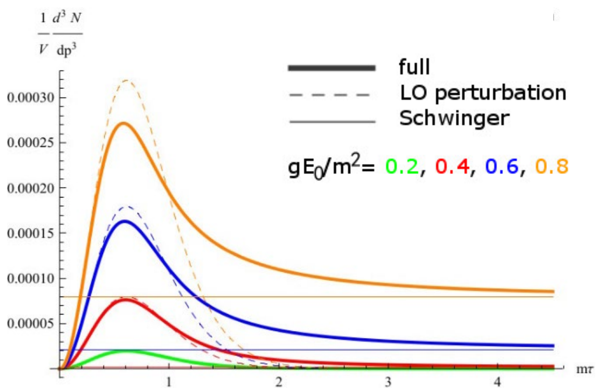

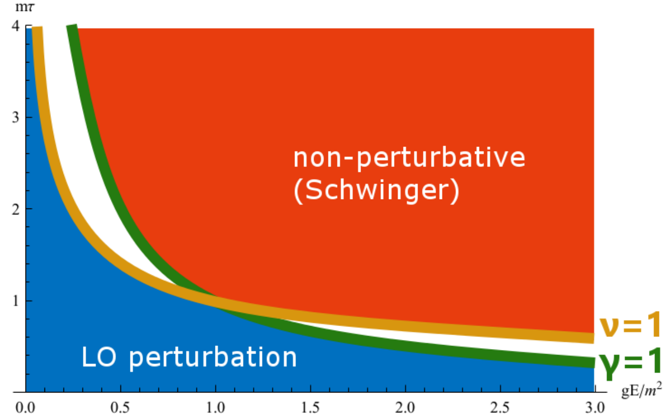

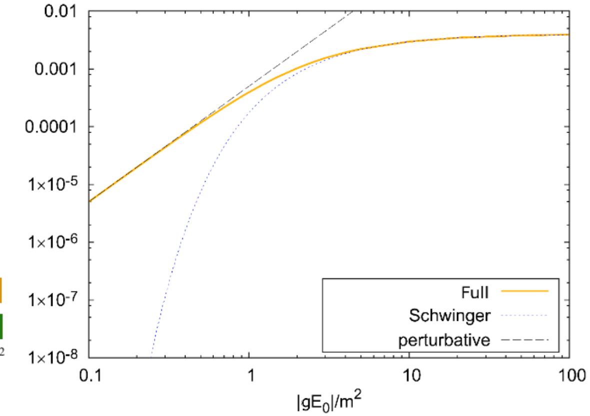

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