Particle production from expanding electric fields

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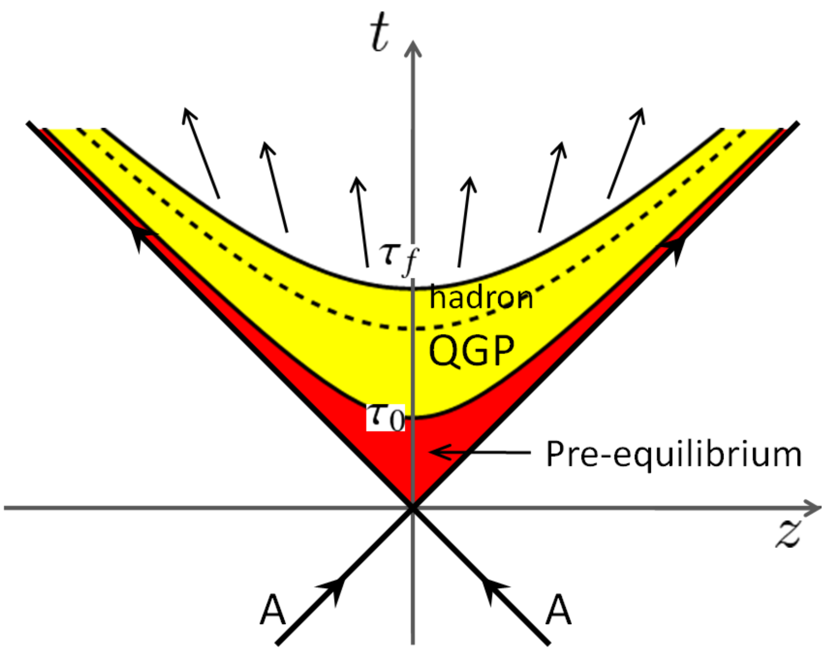
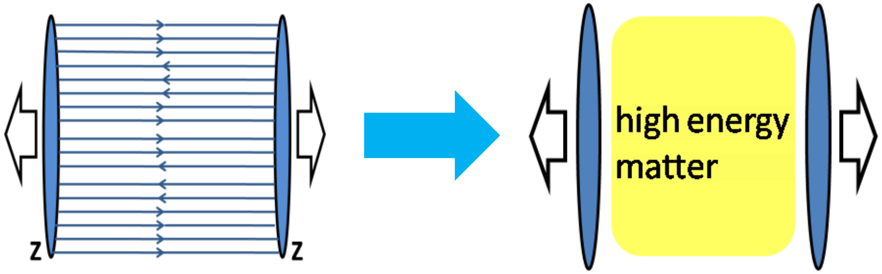
Introduction

Particle production in the initial stage of heavy-ion collisions



- the Low-Nussinov model
- the color glass condensate

classical color electric fields
in the longitudinal direction



color flux tubes

How high energy matter is produced from the electric fields?

Particle production via the Schwinger mechanism

Introduction

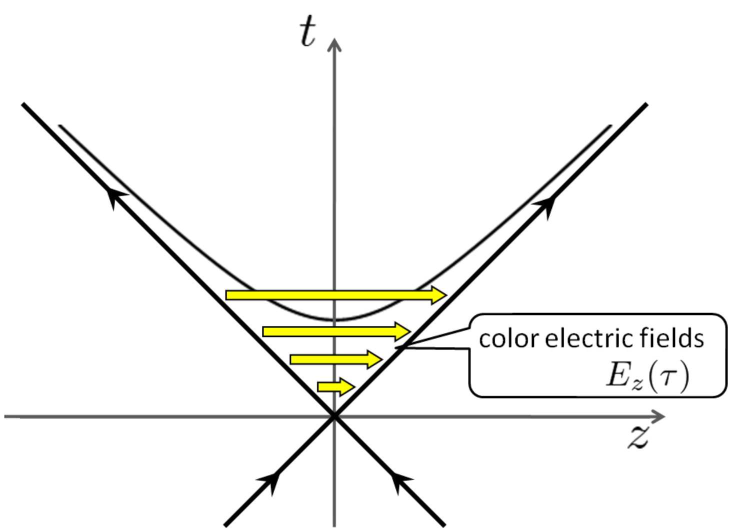
- Real-time description (not based on the pair creation prob.)

$$w = \frac{(eE)^2}{4\pi^3}\sum_{n=1}^{\infty}\frac{1}{n^2}\exp\left(-\frac{n\pi m^2}{eE}\right)$$

⬅ Heavy-ion collisions are dynamical systems.

- Field theoretical treatment (not semi-classical one)

➡ to study multi-particle correlations



Electric fields exist only between two nuclei receding in nearly the speed of light.

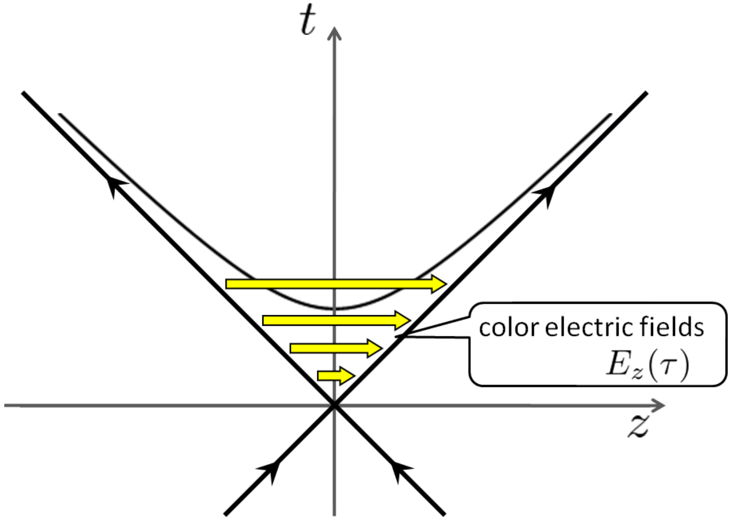
⬇

The field configuration is boost-invariant in the longitudinal direction.

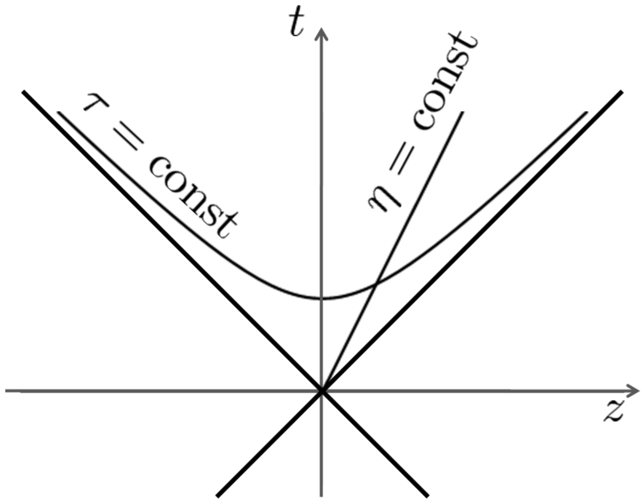
- Taking the expanding geometry of the electric field into account

Introduction

Pair creation in the boost-invariantly expanding electric field



How the dynamics of the pair creation is modified compared to that in uniform electric fields ?



The τ-η coordinate

$$\begin{cases} \tau = \sqrt{t^2 - z^2} \\ \eta = \frac{1}{2} \ln \frac{t+z}{t-z} \end{cases} \qquad \begin{cases} t = \tau \cosh \eta \\ z = \tau \sinh \eta \end{cases}$$

Quantum field theory in the τ-η coordinate

Outline

- Review of the pair creation in uniform electric fields

  N.T. Ann. Phys. 324, 1691(2009)

- Quantization in the τ-η coordinate

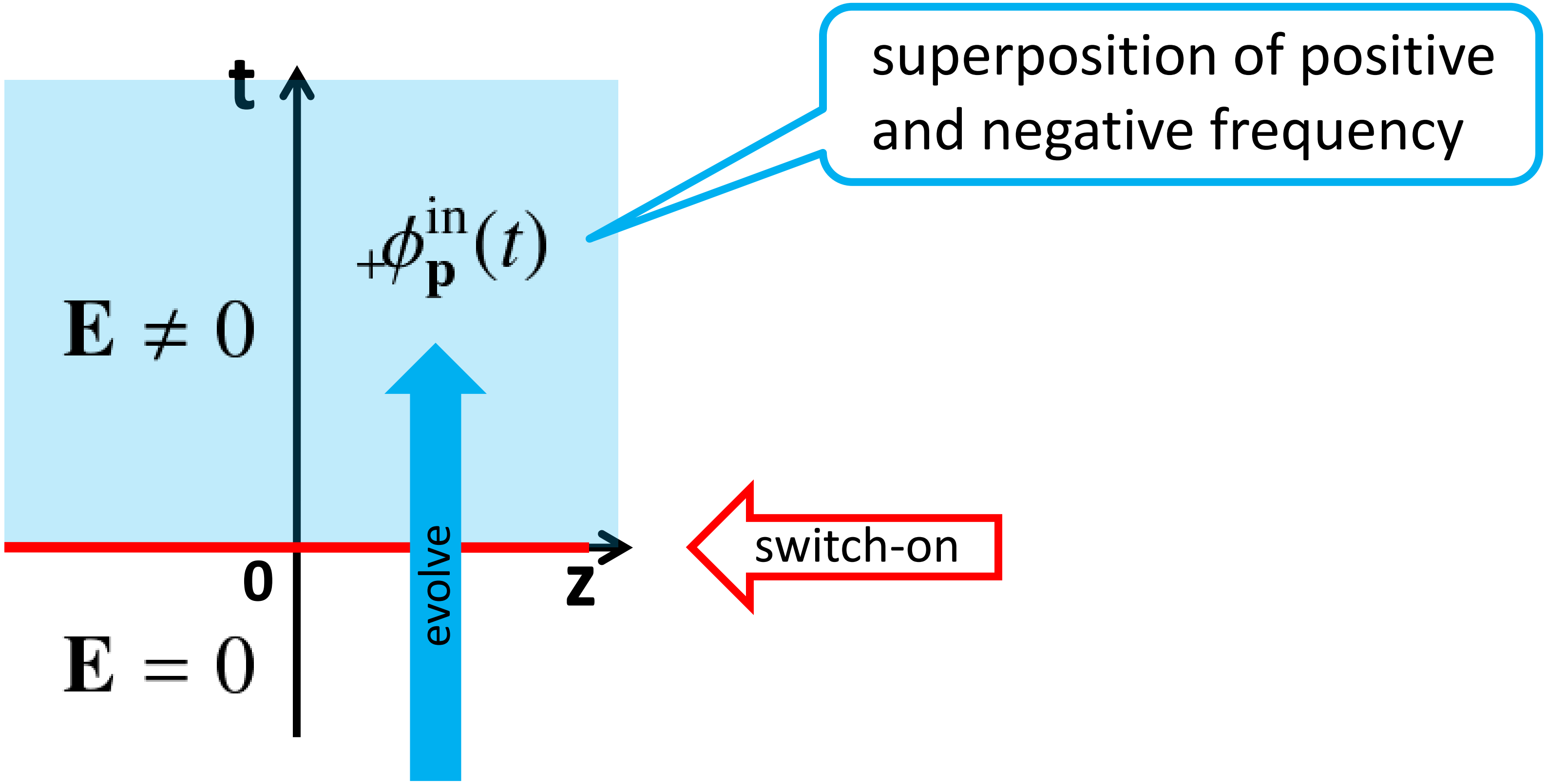
- Pair creation in the boost-invariantly expanding electric field

  - scalar QED
  - constant field, no back reaction $E_z(\tau) = \mathrm{const.}$

- Two-particle spectra

Review of the pair creation in uniform electric fields

Quantization in background fields

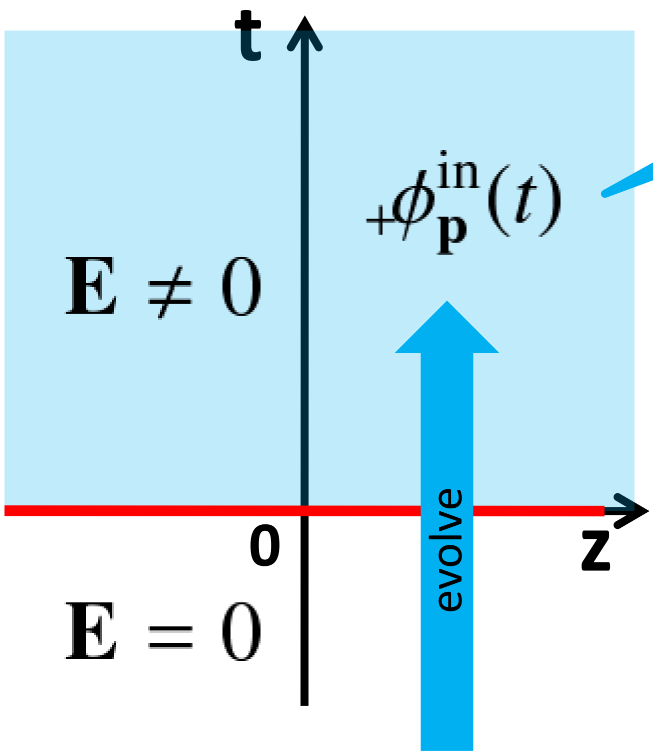


$${}_{+}\phi^{\text{in}}_{\mathbf{p}}(t) = \frac{1}{\sqrt{2\omega_p}} e^{-i\omega_p t}$$

positive frequency

Review of the pair creation in uniform electric fields

Quantization in background fields



$$ {}_{+}\phi^{\mathrm{in}}_{\mathbf{p}}(t) = \frac{1}{\sqrt{2\omega_p}} e^{-i\omega_p t} $$

superposition of positive and negative frequency

time-dependent Bogoliubov transformation

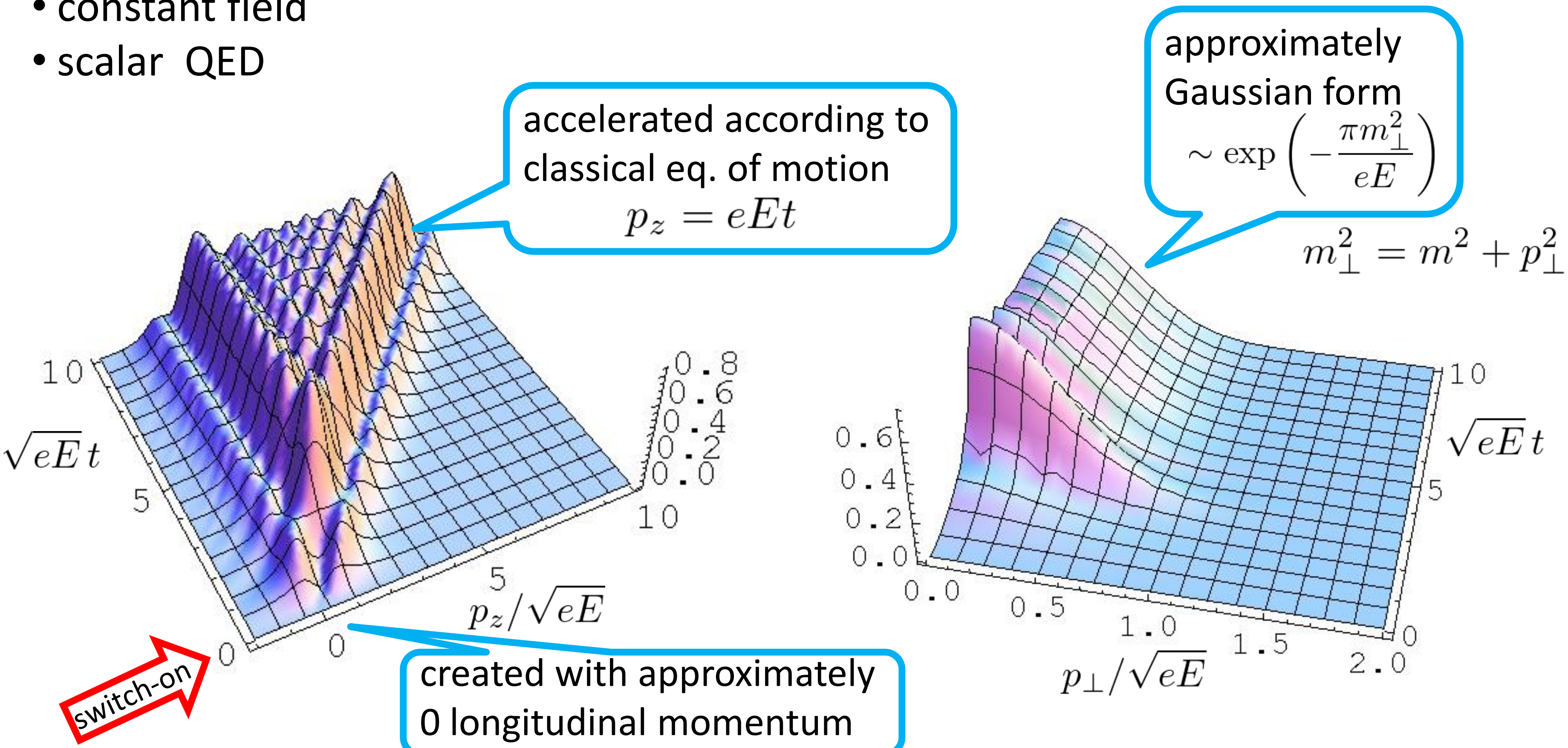
$$ a_{\mathbf{p}}(t) = \alpha_{\mathbf{p}}(t) a^{\mathrm{in}}_{\mathbf{p}} + \beta_{\mathbf{p}}(t) b^{\mathrm{in}\dagger}_{-\mathbf{p}} $$
$$ b^{\dagger}_{-\mathbf{p}}(t) = \alpha^{*}_{\mathbf{p}}(t) b^{\mathrm{in}\dagger}_{-\mathbf{p}} + \beta^{*}_{\mathbf{p}}(t) a^{\mathrm{in}}_{\mathbf{p}} $$

$$ f_{\mathbf{p}}(t) = \langle 0, \mathrm{in} | a^{\dagger}_{\mathbf{p}}(t) a_{\mathbf{p}}(t) | 0, \mathrm{in} \rangle \frac{(2\pi)^3}{V} $$
$$ = \langle 0, \mathrm{in} | b^{\dagger}_{-\mathbf{p}s}(t) b_{-\mathbf{p}s}(t) | 0, \mathrm{in} \rangle \frac{(2\pi)^3}{V} $$

is non-zero.

Results in the uniform electric field

- constant field
- scalar QED



longitudinal momentum distribution $(p_\perp = 0)$

transverse momentum distribution $(p_z/\sqrt{eE} = 1)$

Quantization in the τ-η coordinate

Cartesian coordinate

K-G eq. $(\partial_0^2 - \partial_3^2 + m^2)\phi(t,z) = 0$

canonical commutation relation

$$[\phi(t,z), \pi(t,z')] = i\delta(z - z')$$

mode expansion of the field operator

$$\phi(t,z) = \int dp_z \left(\frac{e^{-i\omega_p t}}{\sqrt{2\omega_p}} a_p + \frac{e^{+i\omega_p t}}{\sqrt{2\omega_p}} b^\dagger_{-p} \right) \frac{e^{ip_z z}}{\sqrt{2\pi}}$$

uniformity in z-direction

τ-η coordinate

$$\left(\frac{\partial^2}{\partial\tau^2} + \frac{1}{\tau}\frac{\partial}{\partial\tau} - \frac{1}{\tau^2}\frac{\partial^2}{\partial\eta^2} + m^2 \right) \phi(\tau,\eta) = 0$$

$$[\phi(\tau,\eta), \pi(\tau,\eta')] = i\delta(\eta - \eta')$$

$$\phi(\tau,\eta) = \int d\lambda \left({}_{+}\phi_\lambda(\tau) a_\lambda + {}_{-}\phi_\lambda(\tau) b^\dagger_{-\lambda} \right) \frac{e^{i\lambda\eta}}{\sqrt{2\pi}}$$

uniformity in eta-direction

a solution of $\left(\frac{\partial^2}{\partial\tau^2} + \frac{1}{\tau}\frac{\partial}{\partial\tau} + \frac{\lambda^2}{\tau^2} + m^2 \right) {}_{\pm}\phi_\lambda(\tau) = 0$

Problems

1. Positive and negative frequency solutions ${}_{\pm}\phi_\lambda(\tau)$ are not uniquely determined.
2. The meaning of the momentum λ is not obvious.

Selection of the mode functions, Selections of a vacuum

$$\left(\frac{\partial^2}{\partial\tau^2}+\frac{1}{\tau}\frac{\partial}{\partial\tau}+\frac{\lambda^2}{\tau^2}+m^2\right){}_{\pm}\phi_\lambda(\tau)=0$$

➡ The mode functions can be expressed by the Bessel functions

$${}_{\pm}\phi_\lambda(\tau)=J_{\mp i|\lambda|}(m\tau)$$

But, there remains the freedom of the Bogoliubov transformations:

$${}_{+}\tilde{\phi}_\lambda(\tau)=\alpha_\lambda\,{}_{+}\phi_\lambda(\tau)+\beta^*_\lambda\,{}_{-}\phi_\lambda(\tau)$$
$${}_{-}\tilde{\phi}_\lambda(\tau)=\alpha^*_\lambda\,{}_{-}\phi_\lambda(\tau)+\beta_\lambda\,{}_{+}\phi_\lambda(\tau)$$

$$(|\alpha_\lambda|^2-|\beta_\lambda|^2=1)$$

Two expansions

$$\phi(\tau,\eta)=\int d\lambda\left({}_{+}\phi_\lambda(\tau)a_\lambda+{}_{-}\phi_\lambda(\tau)b^\dagger{}_{-\lambda}\right)\frac{e^{i\lambda\eta}}{\sqrt{2\pi}}=\int d\lambda\left({}_{+}\tilde{\phi}_\lambda(\tau)\tilde{a}_\lambda+{}_{-}\tilde{\phi}_\lambda(\tau)\tilde{b}^\dagger{}_{-\lambda}\right)\frac{e^{i\lambda\eta}}{\sqrt{2\pi}}$$

⬇

Inequivalent definitions of particles

$$a_\lambda=\alpha_\lambda\tilde{a}_\lambda+\beta_\lambda\tilde{b}^\dagger{}_{-\lambda}$$
$$b^\dagger{}_{-\lambda}=\alpha^*_\lambda\tilde{b}^\dagger{}_{-\lambda}+\beta^*_\lambda\tilde{a}_\lambda$$

⬇

inequivalent vacua

$$|0\rangle\neq|\tilde{0}\rangle$$

$$a_\lambda|0\rangle=b_\lambda|0\rangle=0$$
$$\tilde{a}_\lambda|\tilde{0}\rangle=\tilde{b}_\lambda|\tilde{0}\rangle=0$$

Which vacuum should we choose?

Our selection of coordinate cannot affect physics.

⬇

The vacuum must be the same as that defined by quantization in the Cartesian coordinate.

$$\phi(t,z) = \int dp_z \left(\frac{e^{-i\omega_p t}}{\sqrt{2\omega_p}} a_p + \frac{e^{+i\omega_p t}}{\sqrt{2\omega_p}} b^\dagger_{-p} \right) \frac{e^{ip_z z}}{\sqrt{2\pi}} = \int d\lambda \left({}_+\phi_\lambda(\tau) a_\lambda + {}_-\phi_\lambda(\tau) b^\dagger_{-\lambda} \right) \frac{e^{i\lambda\eta}}{\sqrt{2\pi}}$$

➡ $$a_\lambda = \int dp \left[\alpha^p_\lambda a_p + \beta^p_\lambda b^\dagger_{-p} \right], \quad b^\dagger_{-\lambda} = \int dp \left[\alpha^{p\,*}_\lambda b^\dagger_{-p} + \beta^{p\,*}_\lambda a_p \right]$$

Which vacuum should we choose?

Our selection of coordinate cannot affect physics.

The vacuum must be the same as that defined by quantization in the Cartesian coordinate.

$$\phi(t,z) = \int dp_z \left(\frac{e^{-i\omega_p t}}{\sqrt{2\omega_p}} a_p + \frac{e^{+i\omega_p t}}{\sqrt{2\omega_p}} b^\dagger_{-p} \right) \frac{e^{ip_z z}}{\sqrt{2\pi}} = \int d\lambda \left({}_+\phi_\lambda(\tau) a_\lambda + {}_-\phi_\lambda(\tau) b^\dagger_{-\lambda} \right) \frac{e^{i\lambda\eta}}{\sqrt{2\pi}}$$

$$a_\lambda = \int dp \left[\alpha^p_\lambda a_p + \cancel{\beta^p_\lambda b^\dagger_{-p}} \right], \quad b^\dagger_{-\lambda} = \int dp \left[\alpha^{p*}_\lambda b^\dagger_{-p} + \cancel{\beta^{p*}_\lambda a_p} \right]$$

If "particle" and "antiparticle" are not mixed, they have the same vacuum.

$$a_\lambda |0\rangle = 0 \longleftrightarrow a_p |0\rangle = 0$$

$${}_+\phi_\lambda(\tau) = \frac{\sqrt{\pi}}{2i} e^{\frac{\pi}{2}\lambda} H^{(2)}_{i\lambda}(m\tau)$$

$${}_-\phi_\lambda(\tau) = -\frac{\sqrt{\pi}}{2i} e^{\frac{\pi}{2}\lambda} H^{(1)}_{i\lambda}(m\tau)$$

(C. Sommerfield, 1974)

Why the Hankel functions?

$$ {}_{+}\phi_\lambda(\tau)\frac{e^{i\lambda\eta}}{\sqrt{2\pi}} = \frac{\sqrt{\pi}}{2i}e^{\frac{\pi}{2}\lambda}H^{(2)}_{i\lambda}(m\tau)\frac{e^{i\lambda\eta}}{\sqrt{2\pi}} $$

$$ = \frac{1}{\sqrt{2\pi}}\int\frac{dp_z}{\sqrt{\omega_p}}\frac{e^{-i\omega_p t+ip_z z}}{\sqrt{2\omega_p 2\pi}}e^{i\lambda y_p} $$

positive frequency plane wave

rapidity

$$ y_p = \frac{1}{2}\ln\frac{\omega_p+p_z}{\omega_p-p_z} $$

The positive frequency and the negative frequency are not mixed.

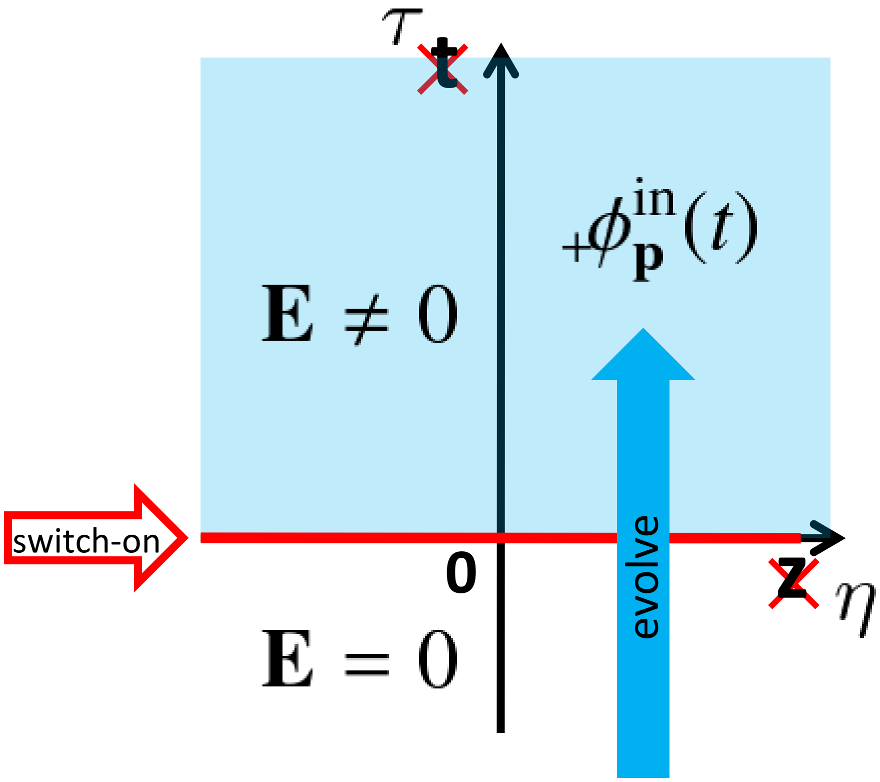
↓

"Particle" and "antiparticle" are not mixed.

$$ a_\lambda = \frac{1}{\sqrt{2\pi}}\int\frac{dp_z}{\sqrt{\omega_p}}e^{-i\lambda y_p}a_p $$

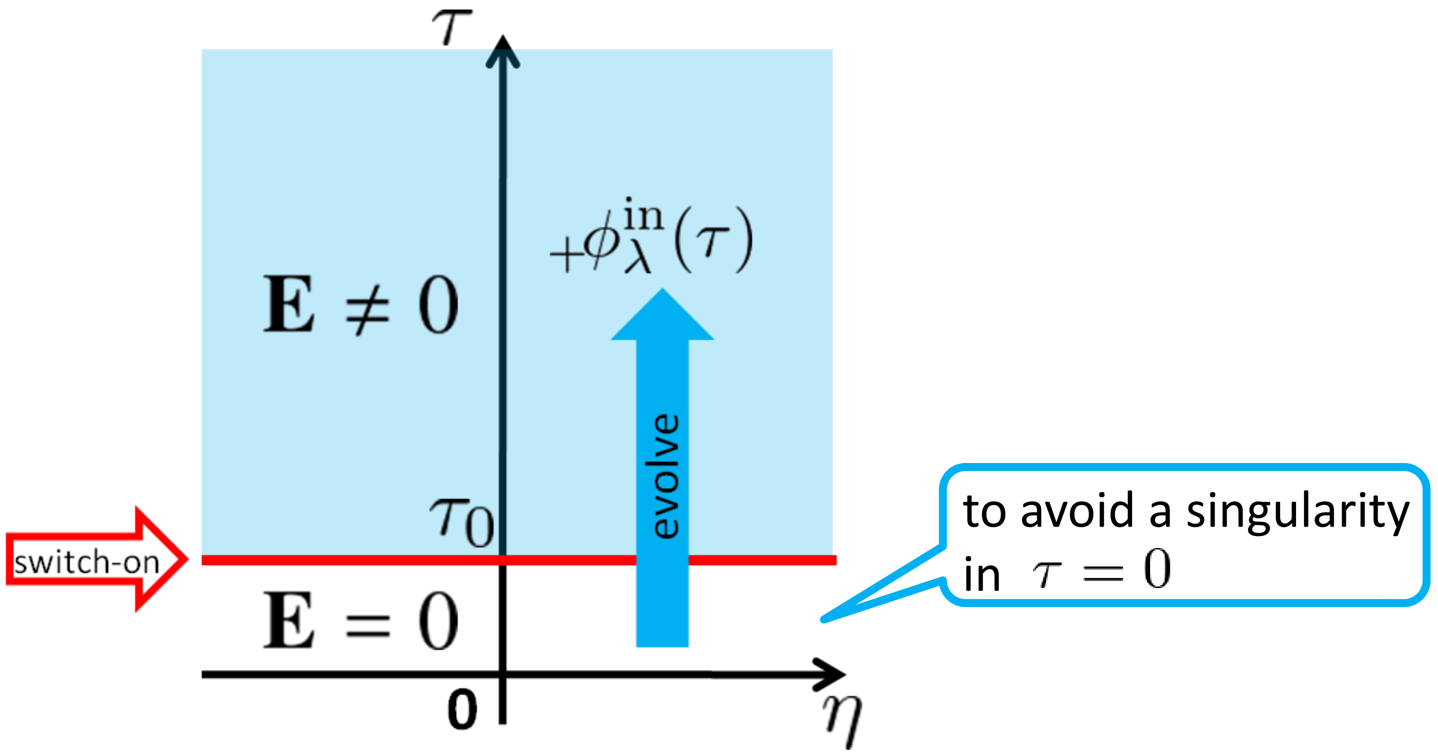
$$ b^\dagger_\lambda = \frac{1}{\sqrt{2\pi}}\int\frac{dp_z}{\sqrt{\omega_p}}e^{-i\lambda y_p}b^\dagger_p $$

Pair creation in the boost-invariantly expanding electric field



$$_{+}\phi^{\mathrm{in}}_{\mathbf{p}}(t) = \frac{1}{\sqrt{2\omega_p}} e^{-i\omega_p t}$$

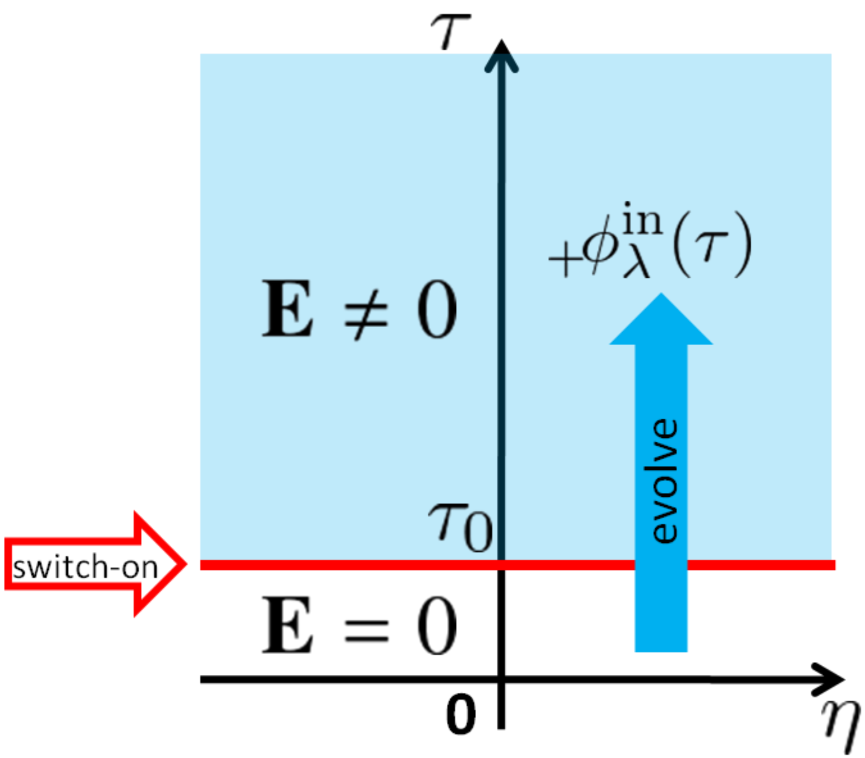
Pair creation in the boost-invariantly expanding electric field



$$_+\phi_\lambda^{\rm in}(\tau) = \frac{\sqrt{\pi}}{2i} e^{\frac{\pi}{2}\lambda} H_{i\lambda}^{(2)}(m\tau)$$

The state is $|0, \rm{in}\rangle$ which contains no particle before τ_0.

Pair creation in the boost-invariantly expanding electric field



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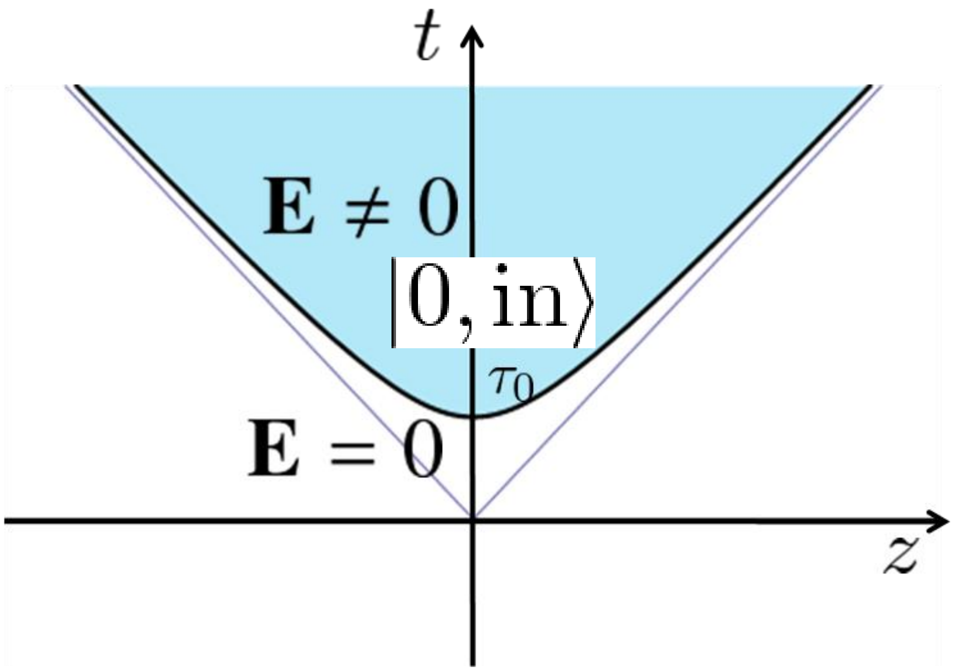
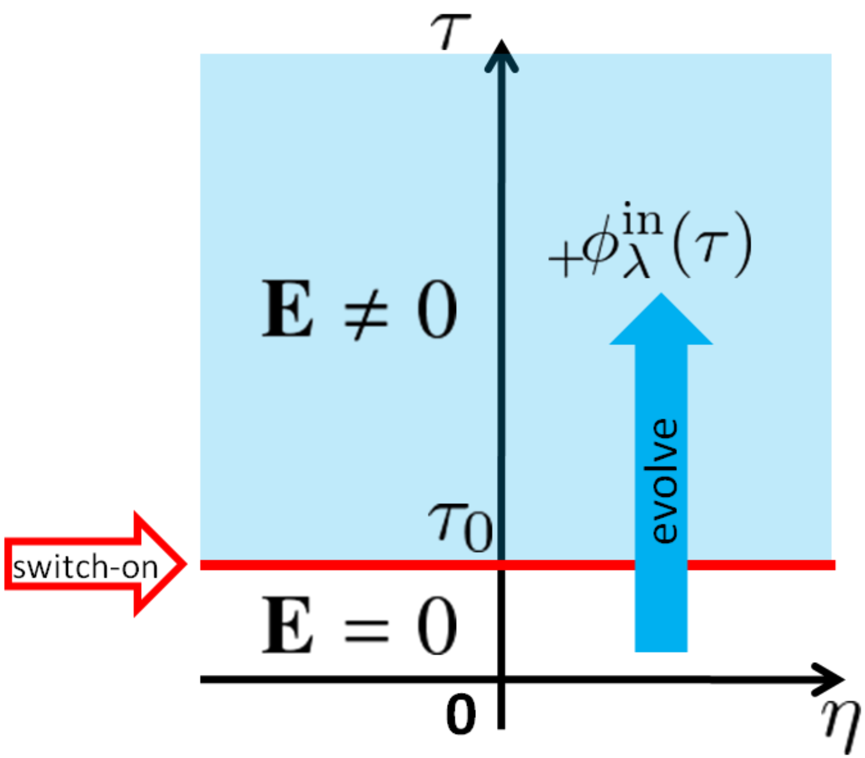


valid only inside the light cone?

Pair creation in the boost-invariantly expanding electric field



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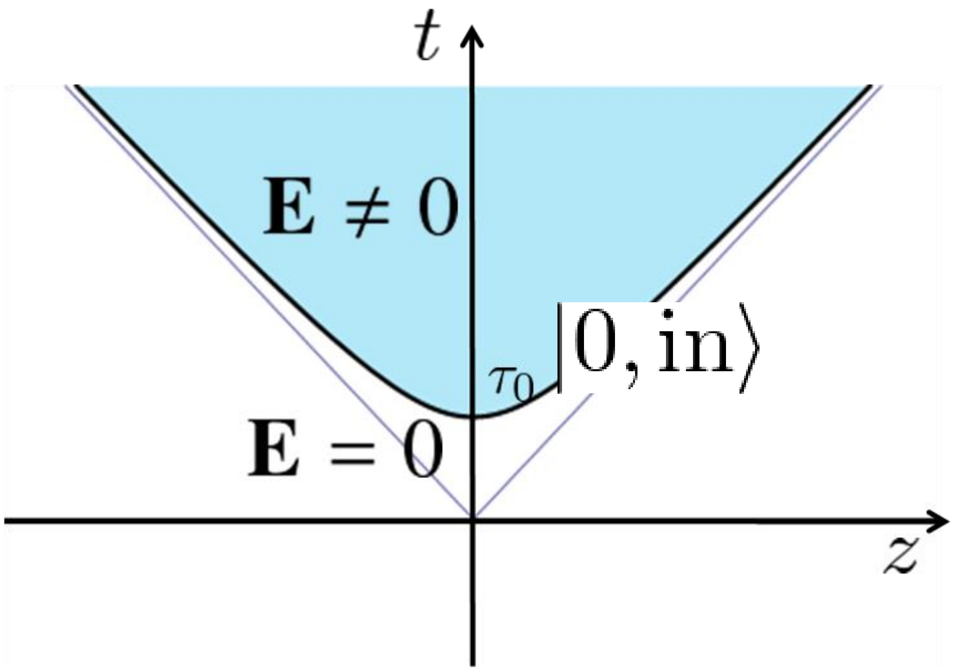


~~valid only inside the light cone?~~

The boundary condition such that there is no particle before τ_0 nor outside the light cone

Pair creation in the boost-invariantly expanding electric field

After τ_0

The definition of particles vary according to the Bogoliubov transformation.

$$a_{\mathbf{p}_\perp,\lambda}(\tau) = \alpha_{\mathbf{p}_\perp,\lambda}(\tau) a^{\text{in}}_{\mathbf{p}_\perp,\lambda} + \beta_{\mathbf{p}_\perp,\lambda}(\tau) b^{\text{in}\,\dagger}_{-\mathbf{p}_\perp,-\lambda}$$

$$b^\dagger_{-\mathbf{p}_\perp,-\lambda}(\tau) = \alpha^*_{\mathbf{p}_\perp,\lambda}(\tau) b^{\text{in}\,\dagger}_{-\mathbf{p}_\perp,-\lambda} + \beta^*_{\mathbf{p}_\perp,\lambda}(\tau) a^{\text{in}}_{\mathbf{p}_\perp,\lambda}$$

$$V_\eta = L_\eta L^2 = \int \tau d\eta \int d^2 x_\perp$$

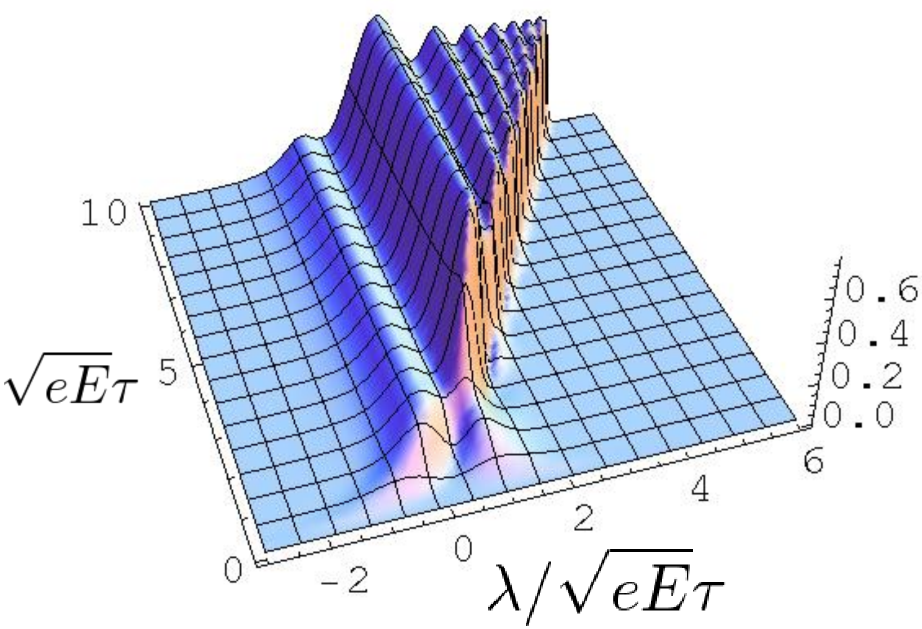
Particles are created.

$$\frac{dN}{d^2 p_\perp d\lambda} = \langle 0, \text{in} | a^\dagger_{\mathbf{p}_\perp,\lambda}(\tau) a_{\mathbf{p}_\perp,\lambda}(\tau) | 0, \text{in} \rangle = |\beta_{\mathbf{p}_\perp,\lambda}(\tau)|^2 \frac{V_\eta}{\tau (2\pi)^3}$$

$$f_{\mathbf{p}_\perp,\lambda}(\tau) = (2\pi)^3 \frac{dN}{d^2 x_\perp d\eta d^2 p_\perp d\lambda} = |\beta_{\mathbf{p}_\perp,\lambda}(\tau)|^2$$

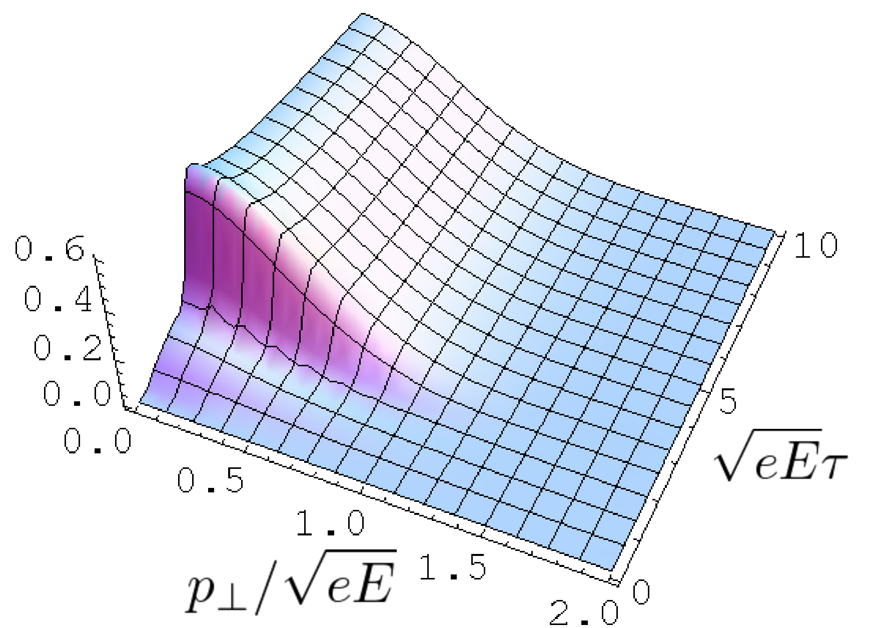
Results

$$\frac{m^2}{2eE} = 0.1 \qquad \tau_0 = 0.1/\sqrt{eE}$$



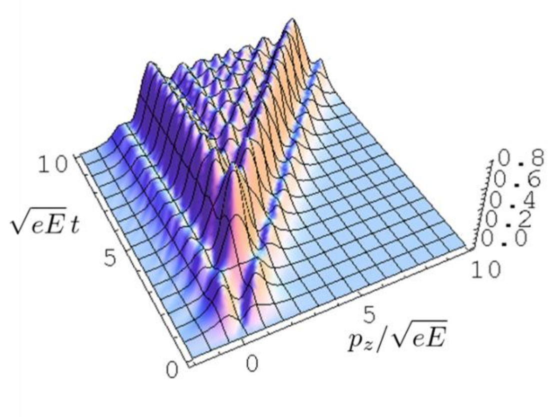
longitudinal “momentum” distribution

$(p_\perp = 0)$

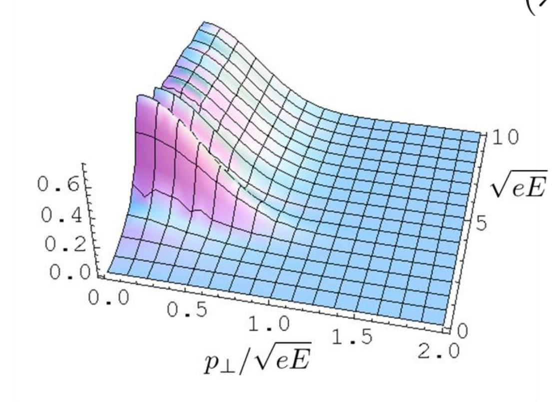


transverse momentum distribution

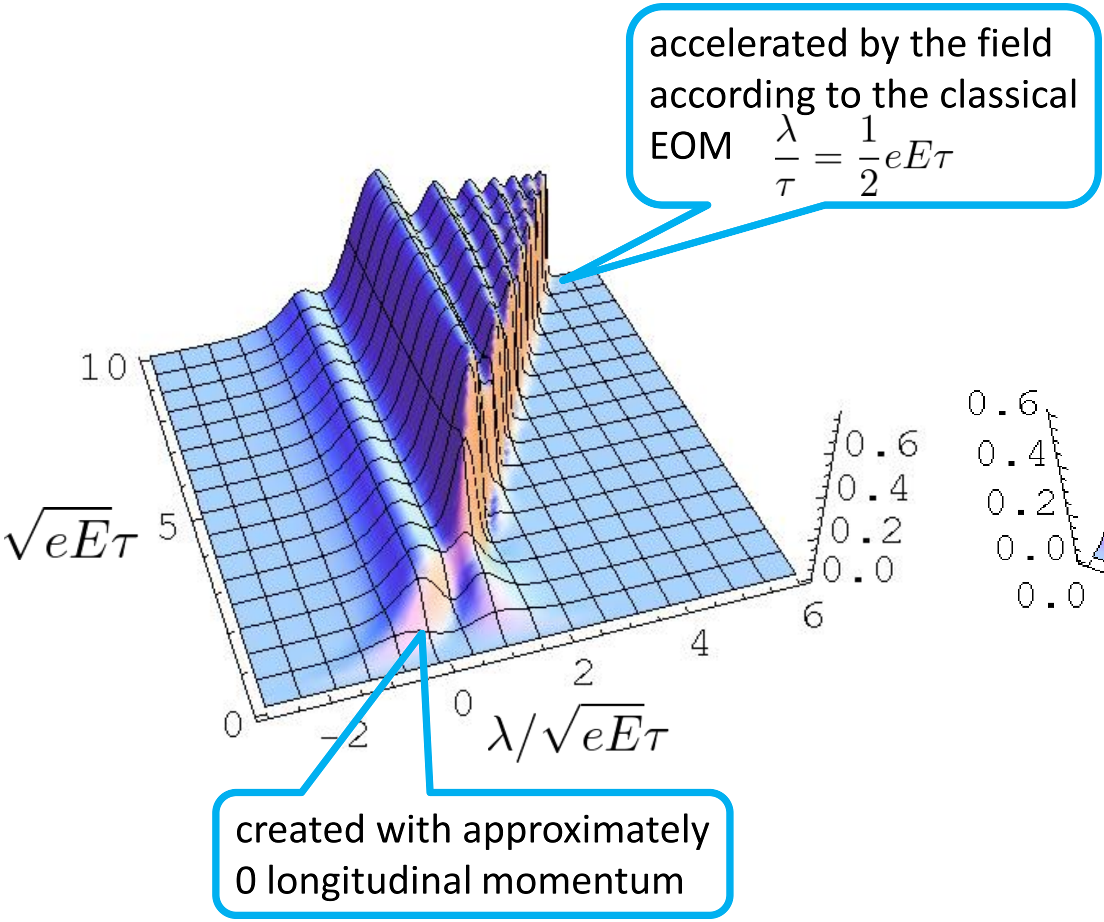
$(\lambda/\sqrt{eE}\tau = 1)$



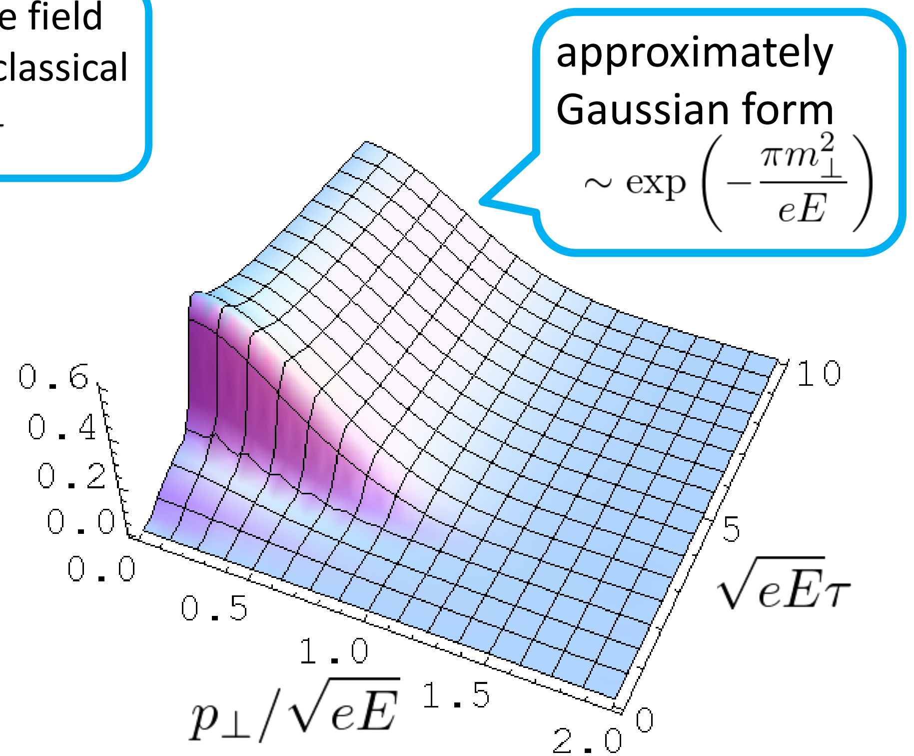
in the uniform electric field



$$\frac{m^2}{2eE} = 0.1 \qquad \tau_0 = 0.1/\sqrt{eE}$$



longitudinal “momentum” distribution



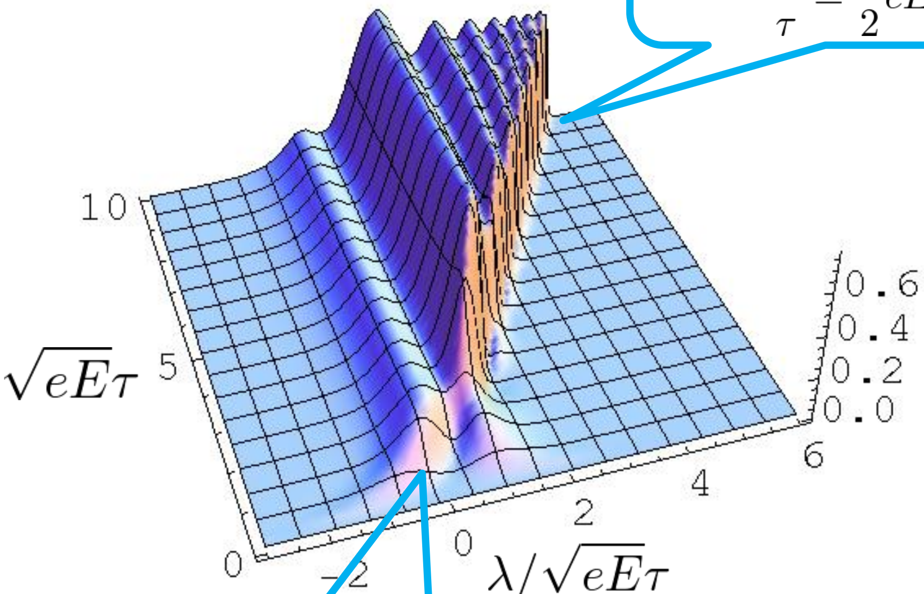
transverse momentum distribution

Similar to the uniform field case

$$\frac{m^2}{2eE} = 0.1 \qquad \tau_0 = 0.1/\sqrt{eE}$$

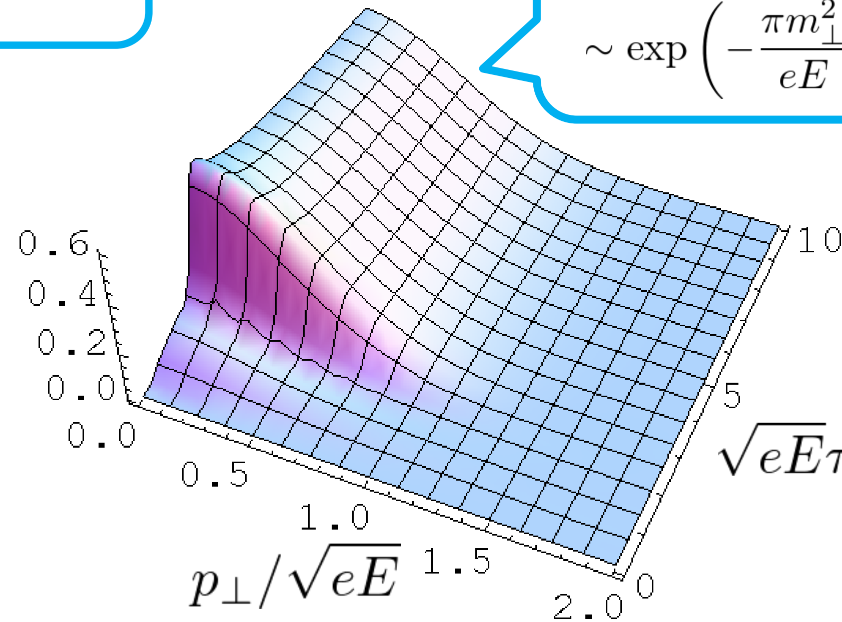
accelerated by the field according to the classical EOM $\frac{\lambda}{\tau} = \frac{1}{2}eE\tau$

approximately Gaussian form $\sim \exp\left(-\frac{\pi m_\perp^2}{eE}\right)$



created with approximately 0 longitudinal momentum

longitudinal "momentum" distribution



transverse momentum distribution

What is the physical meaning of λ ?

The meaning of the "momentum" λ

investigate the expectation of the one-particle state

$$|\mathbf{q}_\perp, \lambda\rangle = \sqrt{\frac{\tau(2\pi)^3}{V_\eta}} a^\dagger_{\mathbf{q}_\perp, \lambda}|0\rangle$$

number distribution

$$L_\eta = \int \tau d\eta$$

Expectation of the number operator in a_p -basis.

$$\frac{dN}{d^3p} = \langle \mathbf{q}_\perp, \lambda | a^\dagger_\mathbf{p} a_\mathbf{p} | \mathbf{q}_\perp, \lambda\rangle$$
$$= \frac{1}{\omega_p}\frac{\tau}{L_\eta}\delta^2(\mathbf{p}_\perp - \mathbf{q}_\perp)$$

c.f. the expectation by the eigenstate of usual momentum

$$|\mathbf{q}\rangle = \sqrt{\frac{(2\pi)^3}{V}} a^\dagger_\mathbf{q}|0\rangle$$

$$\langle \mathbf{q}| a^\dagger_p a_p |\mathbf{q}\rangle = \delta^3(\mathbf{p} - \mathbf{q})$$

$p_z \to y_p$

$$\frac{dN}{dy_p d^2p_\perp} = \omega_p \frac{dN}{d^3p} = \frac{\tau}{L_\eta}\delta^2(\mathbf{p}_\perp - \mathbf{q}_\perp)$$

independent of rapidity nor λ

The eigenstate of λ contains all rapidity states with equal weight.

The meaning of the "momentum" λ

Energy-momentum tensor

Cartesian $T^{\mu\nu} = \partial^\mu \phi^\dagger \partial^\nu \phi + \partial^\nu \phi^\dagger \partial^\mu \phi \quad (\mu, \nu = 0, 1, 2, 3)$

τ-η $T^{\alpha\beta} = \partial^\alpha \phi^\dagger \partial^\beta \phi + \partial^\beta \phi^\dagger \partial^\alpha \phi \quad (\alpha, \beta = \tau, 1, 2, \eta)$

$$\begin{pmatrix} \partial^\tau \\ \tau \partial^\eta \end{pmatrix} = \underline{\begin{pmatrix} \cosh\eta & -\sinh\eta \\ -\sinh\eta & \cosh\eta \end{pmatrix}} \begin{pmatrix} \partial^0 \\ \partial^3 \end{pmatrix}$$

$$\Lambda^\mu{}_\nu$$

Lorentz-boost with the velocity $v_z = z/t = \tanh\eta$

$$\begin{pmatrix} T^{\tau\tau} & \tau T^{\tau\eta} \\ \tau T^{\eta\tau} & \tau^2 T^{\eta\eta} \end{pmatrix} = \Lambda^\mu{}_\sigma \Lambda^\nu{}_\rho T^{\sigma\rho}$$

The frame moving with the velocity $v_z = \tanh\eta$

Energy-momentum tensor in the η -frame

The meaning of the "momentum" λ

$$\left.\begin{array}{r} T^{\tau\tau}(\tau,\eta) \\ \tau T^{\tau\eta}(\tau,\eta) \\ \tau^2 T^{\eta\eta}(\tau,\eta) \end{array}\right\} \text{ is } \left\{\begin{array}{c} \text{energy} \\ \text{longitudinal momentum} \\ \text{longitudinal pressure} \end{array}\right\} \text{ observed in the } \eta\text{-frame.}$$

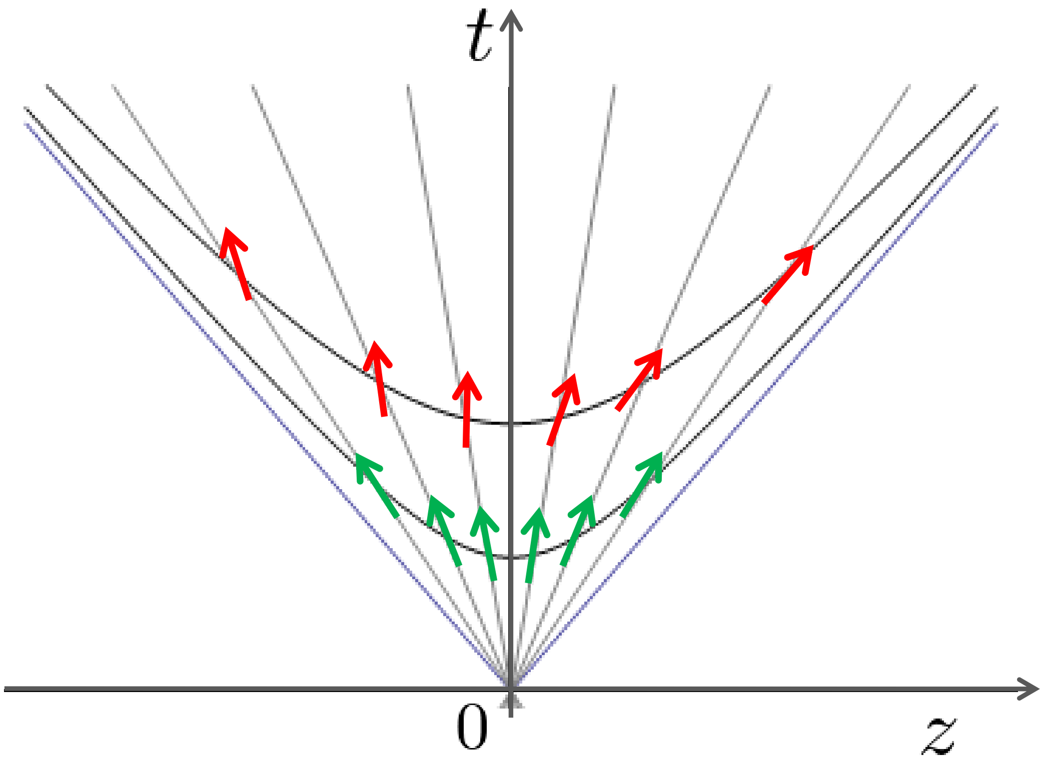
the expectation with the one-particle state

$$\langle \mathbf{p}_\perp, \lambda | \tau T^{\tau\eta}(\tau,\eta) | \mathbf{p}_\perp, \lambda \rangle = \frac{\lambda}{\tau} \frac{1}{V_\eta}$$

λ/τ is the longitudinal momentum observed in the η -frame.

$\lambda = 0$ means that a particle has the scaling velocity distribution.

Space-time view of the pair creation

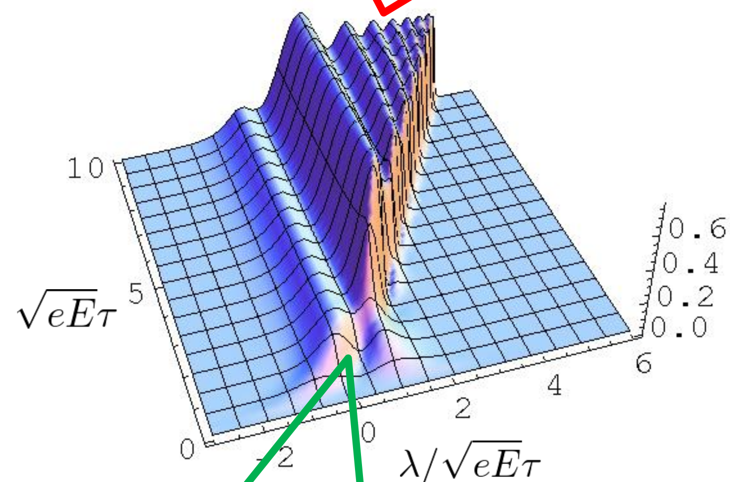


① created with 0 momentum

➡ created with the same velocity distribution as the Bjorken's flow

② Due to acceleration by the field, the velocity distribution deviates from the scaling one.

accelerated by the field according to the classical EOM $\frac{\lambda}{\tau} = \frac{1}{2} eE\tau$



created with approximately 0 longitudinal momentum

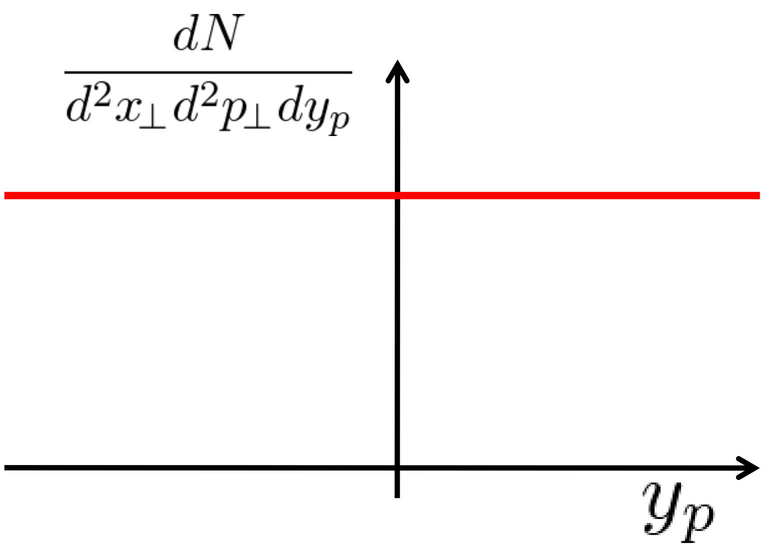
longitudinal momentum distribution in the η -frame

Rapidity distribution

$$\frac{dN}{d^3p} = \langle 0,\mathrm{in}|a^\dagger_{\mathbf{p}} a_{\mathbf{p}}|0,\mathrm{in}\rangle = \frac{1}{2\pi\omega_p}\int d\lambda\ f_{\mathbf{p}_\perp,\lambda}(\tau)\frac{L^2}{(2\pi)^2}$$

$$\frac{dN}{d^2x_\perp d^2p_\perp dy_p} = \omega_p \frac{1}{L^2}\frac{dN}{d^3p} = \frac{1}{(2\pi)^3}\int d\lambda f_{\mathbf{p}_\perp,\lambda}(\tau)$$

independent of rapidity



The rapidity distribution is flat because now the boost-inv. is perfect.

Two-particle spectra

$$\frac{dN_2}{d^3p d^3q} = \langle 0, \mathrm{in} | a^\dagger_{\mathbf{p}} a^\dagger_{\mathbf{q}} a_{\mathbf{p}} a_{\mathbf{q}} | 0, \mathrm{in} \rangle$$

- **In the uniform electric field** (Fukushima-Gelis-Lappi, 2009)

$$\frac{dN_2}{d^3p d^3q} = \frac{dN}{d^3p}\frac{dN}{d^3q} + \{f_{\mathbf{p}}(t)\}^2 \frac{V}{(2\pi)^3}\delta^3(\mathbf{p}-\mathbf{q}) \qquad \frac{dN}{d^3p} = f_{\mathbf{p}}(t)\frac{V}{(2\pi)^3}$$

correlated only if $\mathbf{p} = \mathbf{q}$

- **In the expanding electric field**

$$\frac{dN_2}{d^2p_\perp dy_p d^2q_\perp dy_q} = \frac{dN}{d^2p_\perp dy_p}\frac{dN}{d^2q_\perp dy_q} + \left| \int \frac{d\lambda}{2\pi} e^{-i\lambda(y_p - y_q)} f_{\mathbf{p}_\perp,\lambda}(\tau) \right|^2 \frac{L^2}{(2\pi)^2}\delta^2(\mathbf{p}_\perp - \mathbf{q}_\perp)$$

$$\frac{dN}{dy_p d^2p_\perp} = \int \frac{d\lambda}{2\pi} f_{p_\perp,\lambda}(\tau)\frac{L^2}{(2\pi)^2}$$

correlated even if $\Delta y = y_p - y_q \neq 0$

The correlation is given by the Fourier transform of the momentum distribution.

$$C(y_p, \mathbf{p}_\perp; y_q, \mathbf{q}_\perp) \equiv \frac{\dfrac{dN_2}{d^2p_\perp\, dy_p d^2q_\perp\, dy_q} - \dfrac{dN}{d^2p_\perp\, dy_p}\dfrac{dN}{d^2q_\perp\, dy_q}}{\dfrac{dN}{d^2p_\perp\, dy_p}\dfrac{dN}{d^2q_\perp\, dy_q}}$$

$$= \frac{\left|\int \frac{d\lambda}{2\pi} e^{-i\lambda(y_p - y_q)} f_{\mathbf{p}_\perp,\lambda}(\tau)\right|^2}{\left\{\int \frac{d\lambda}{2\pi} f_{\mathbf{p}_\perp,\lambda}(\tau)\right\}^2} \frac{\delta^2(\mathbf{p}_\perp - \mathbf{q}_\perp)}{L^2/(2\pi)^2}$$

The correlation in the transverse direction is short range in the momentum space.

$$C_L(\Delta y, \mathbf{p}_\perp) \equiv \frac{\left|\int \frac{d\lambda}{2\pi} e^{-i\lambda\Delta y} f_{\mathbf{p}_\perp,\lambda}(\tau)\right|^2}{\left\{\int \frac{d\lambda}{2\pi} f_{\mathbf{p}_\perp,\lambda}(\tau)\right\}^2}$$

The correlation length in the rapidity space is about the inverse of the width of the function $f_{\mathbf{p}_\perp,\lambda}(\tau)$ in the λ -space.

$$f_{\mathbf{p}_\perp,\lambda}(\tau) \propto \delta(\lambda) \quad \Rightarrow \quad C_L(\Delta y, \mathbf{p}_\perp) = 1$$

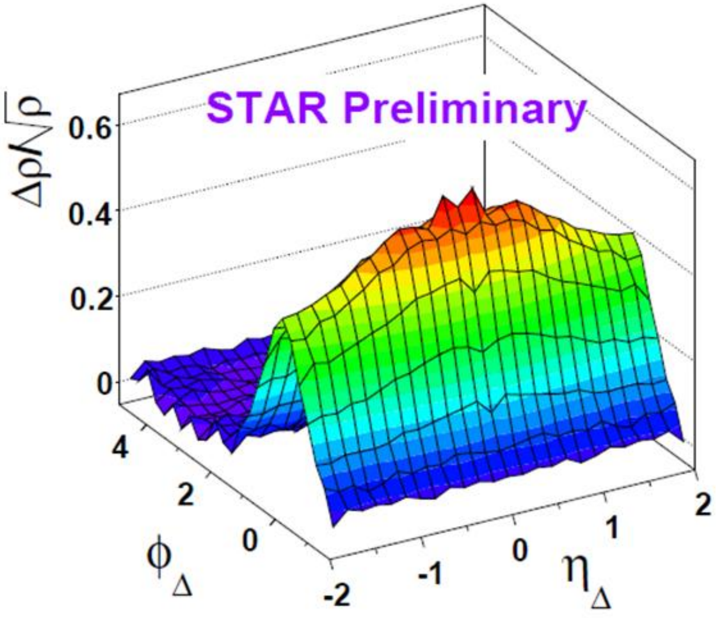
The velocity distribution is exactly the scaling one.

Long range rapidity correlation

The correlation in the transverse direction is short range.

Long range rapidity correlation

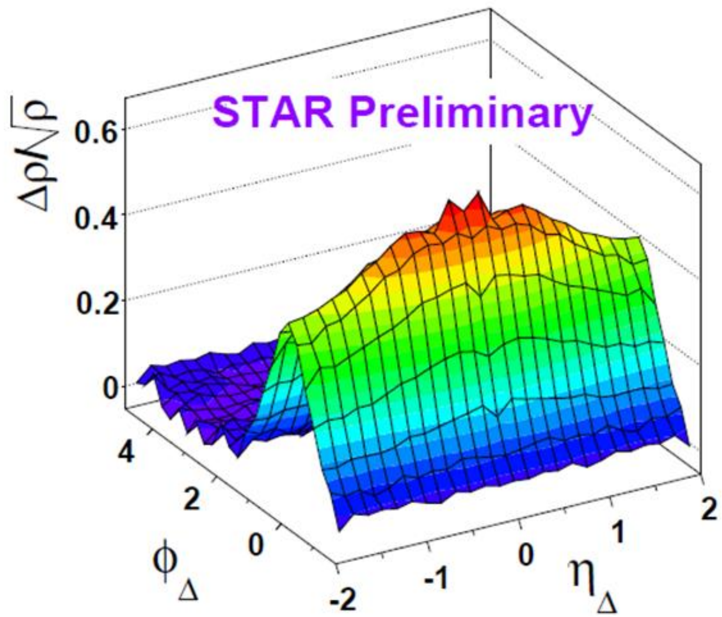
Ridge-like structure?



The correlation in the transverse direction is short range.

Long range rapidity correlation

Ridge-like structure?



?

This is a soft process while the ridge is observed through hard jets.

Summary and Outlook

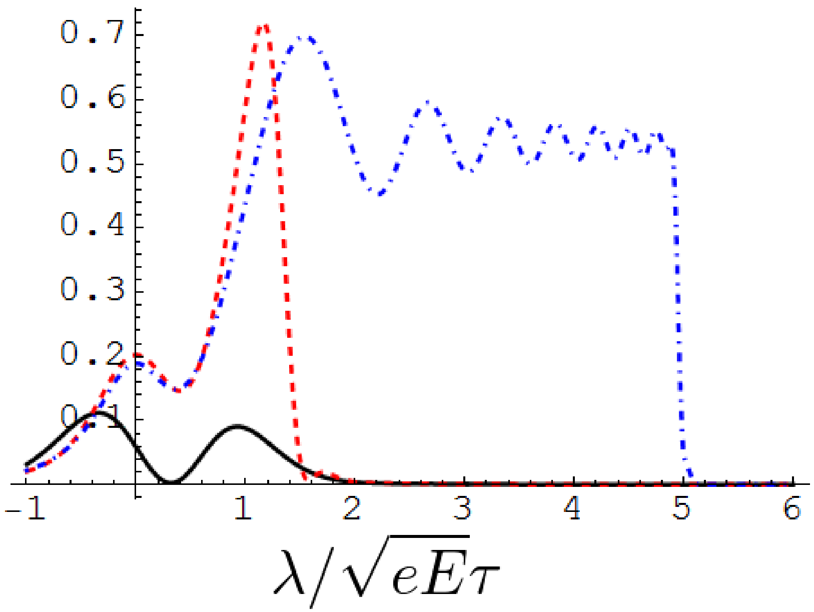
- Particles created from the boost-invariant electric field have the scaling velocity distribution from the first instance they created.

- Non-trivial rapidity correlation arises from the Schwinger mechanism in the boost-invariant field, which may lead long range rapidity correlation.

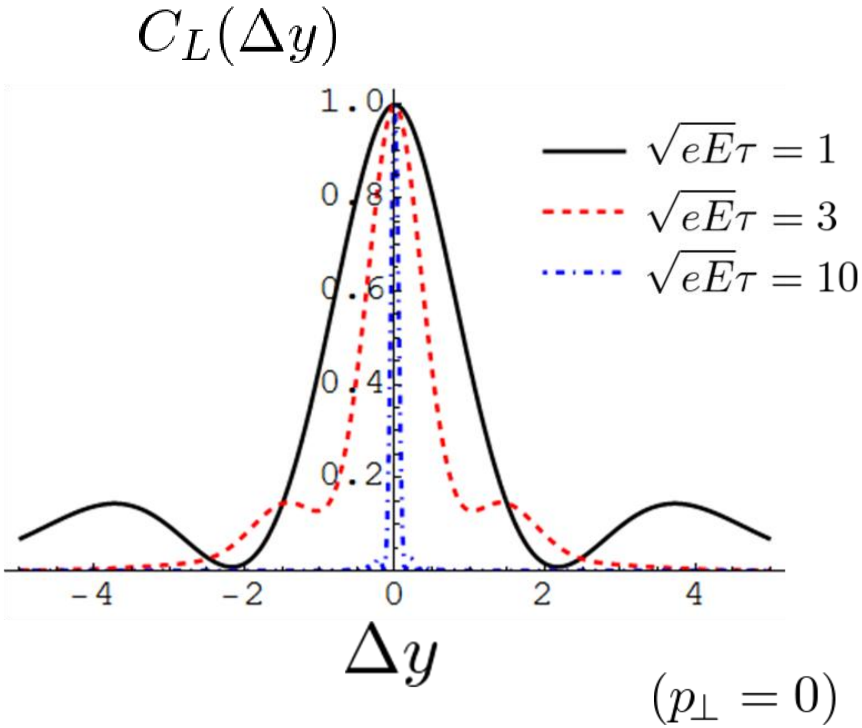
  - taking back reaction into account
  - extension to the quark pair creation in color electric fields
  - effects of longitudinal magnetic fields
  - non-uniformity in the transverse direction

back up

Time-dependence of the correlation



time slice of the longitudinal momentum distribution $f_{p_\perp,\lambda}(\tau)$

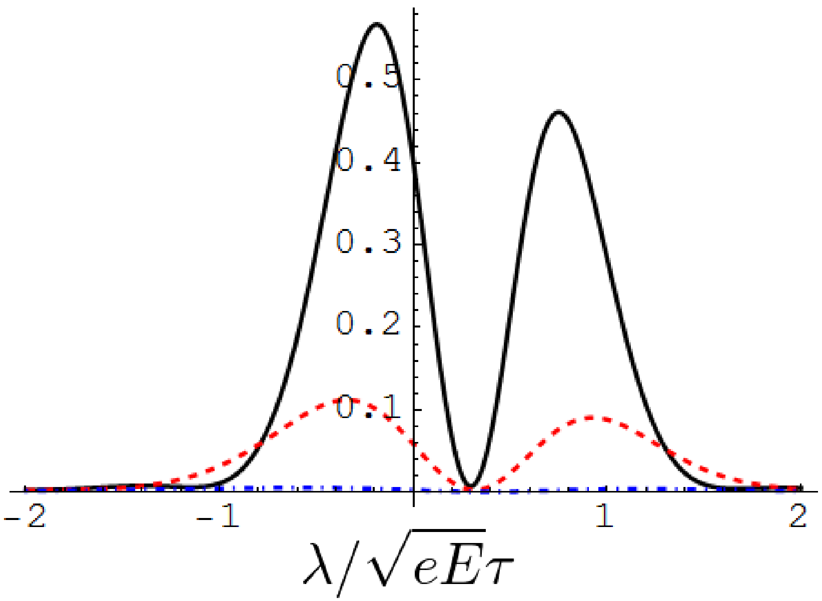


rapidity correlation

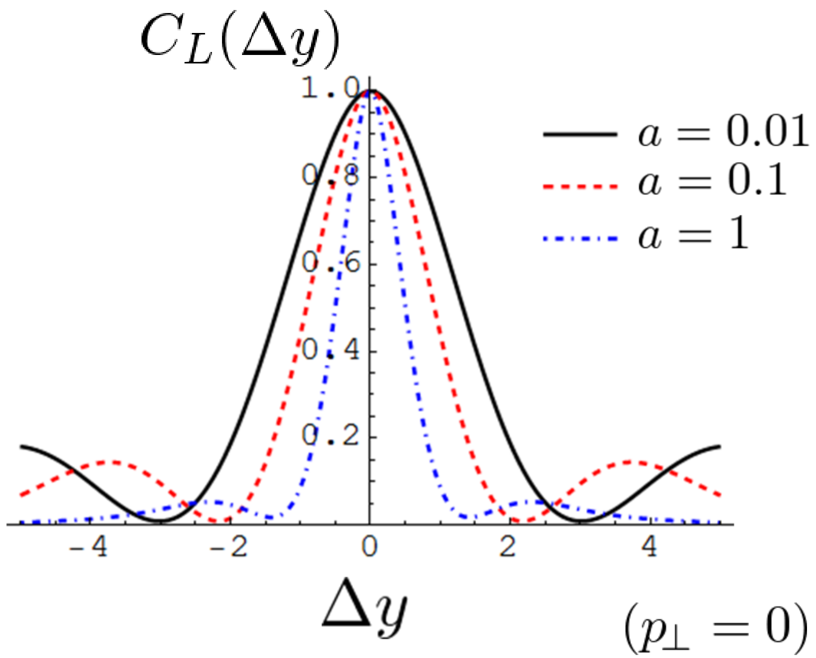
The correlation is destroyed by field acceleration.

Mass or field strength-dependence of the correlation

$$a = \frac{m^2}{2eE}$$



the longitudinal momentum distribution at $\tau/\sqrt{eE} = 1$



rapidity correlation

The heavier the mass or the weaker the field, the shorter the correlation gets.