FAIRNESS 2016 – Garmisch-Partenkirchen

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Modeling Early Time Dynamics and Photon Production of Relativistic Heavy Ion Collisions

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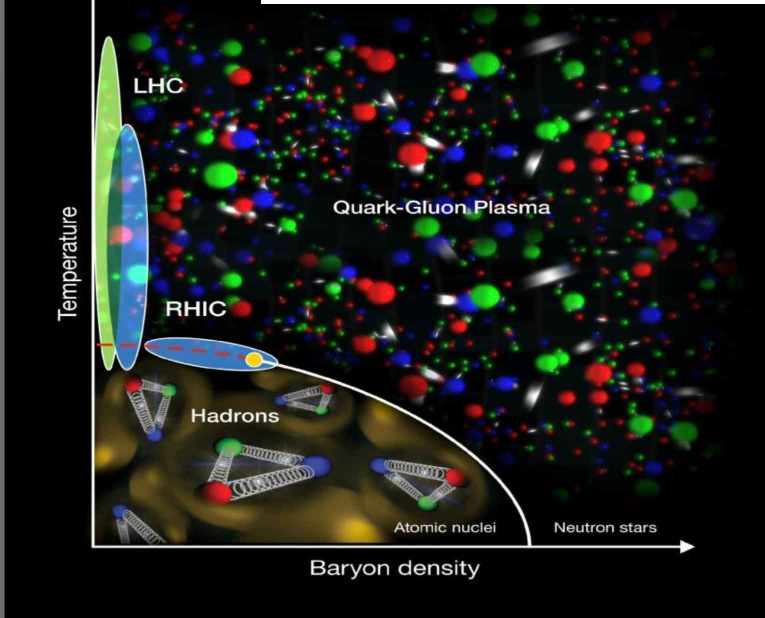
QCD Phase Diagram



High energy Heavy Ion Collisions

(HIC) allow to experimentally investigate the high temperature and small baryon density region of the nuclear matter phase diagram

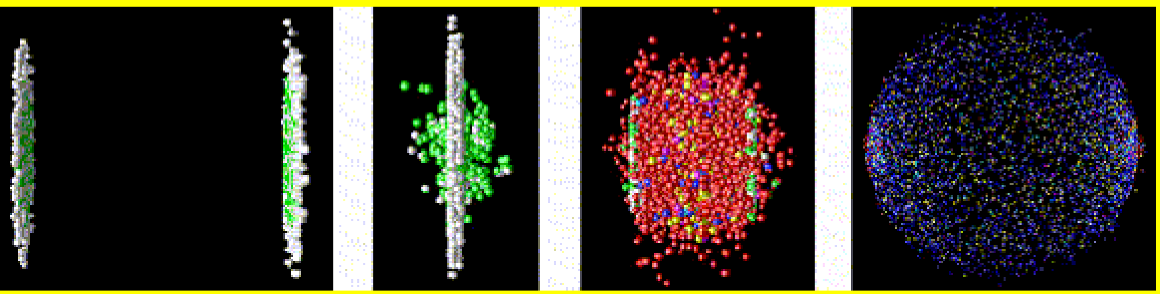
E = 20–200 A GeV

Relativistic Heavy Ion Collider (RHIC) at BNL

Large HadronCollider (LHC) at CERN

E = 1–5.5 A TeV

The study of QUARK-GLUON PLASMA (QGP) should cast light on Quantum Chromodynamics (QCD) and the problem of confinement



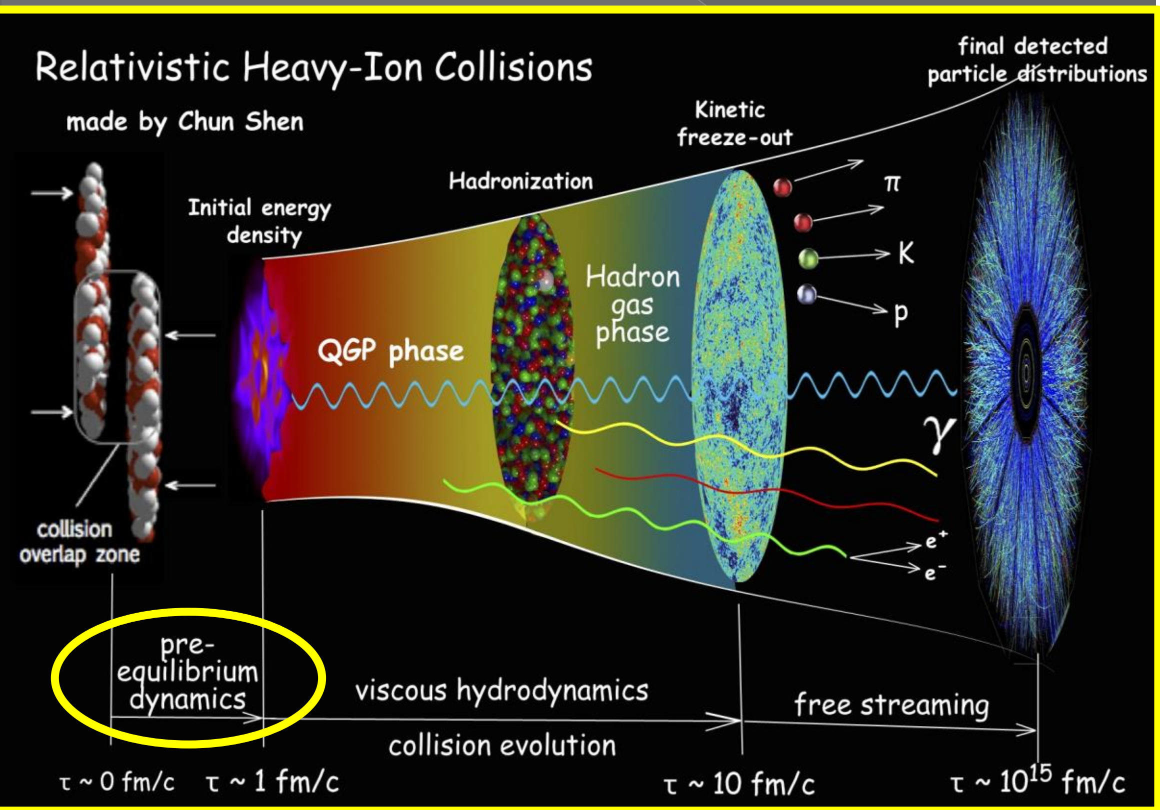
initial stage

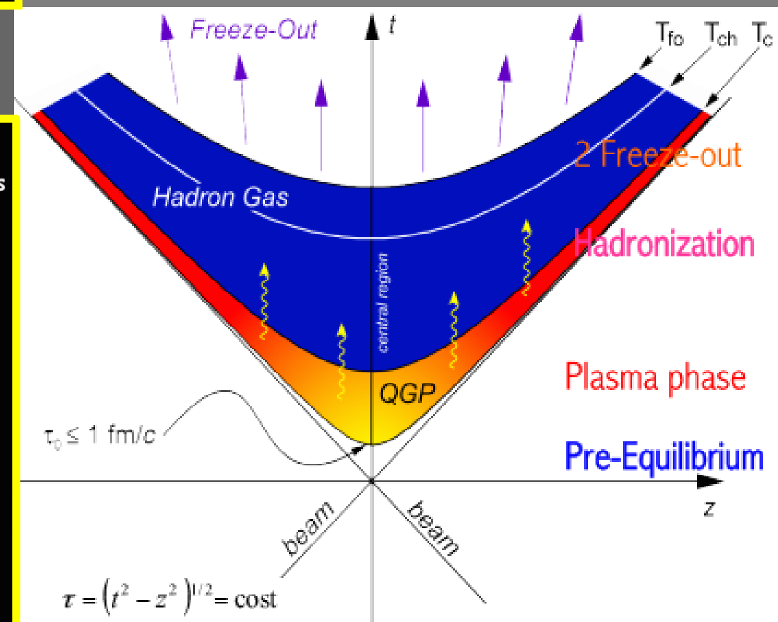
pre-equilibrium

hydrodynamical evolution

hadronization

freeze-out





[Source: http://snelling.web.cern.ch/snelling/img/little_bang.jpg]

IMPACT OF PRE-EQUILIBRIUM ON SEVERAL OBSERVABLES

Ruggieri et al., PLB 727, 177 (2013)

Ruggieri et al., PRC 89, 054914 (2014)

Liu et al., PRC 91, 064906 (2015), PRC 92, 049904 (2015)

BOLTZMANN TRANSPORT EQUATION

In order to **simulate** the temporal evolution of the fireball we solve the **Boltzmann equation** for the parton distribution function **f(x,p)**

$$(p_\mu \partial^\mu + gQF^{\mu\nu} p_\mu \partial_\nu^p) f = \mathcal{C}[f]$$

Free streaming

Field interaction

Collision integral
$\eta/s \neq 0$

Field interaction: change of ***f*** due to interactions of the partonic plasma with a field (*e.g.* color-electric field).

Collision integral: change of ***f*** due to collision processes in the phase space volume centered at (x,*p*). *Responsible for deviations from ideal hydro (**η/s ≠ 0**)*.

$$\mathcal{C}[f] = \int \frac{d^3p_2}{2E_2(2\pi)^3} \frac{d^3p_{1'}}{2E_{1'}(2\pi)^3} \frac{d^3p'_2}{2E'_2(2\pi)^3} (f_{1'}f_{2'} - f_1 f_2) \times |\mathcal{M}|^2 \delta^4(p_1 + p_2 - p_{1'} - p_{2'})$$

Xu and Greiner, PRC 79, 014904 (2009)
Bratkovskaya, et al., NPA 856, 162 (2011)
Greco et al., PLB 670, 325 (2009)
Plumari and Greco, AIP CP 1422, 56 (2012)
Ruggieri et al., PRC 89, 054914 (2014)

BOLTZMANN TRANSPORT EQUATION

In order to **simulate** the temporal evolution of the fireball we solve the **Boltzmann equation** for the parton distribution function **f(x,p)**

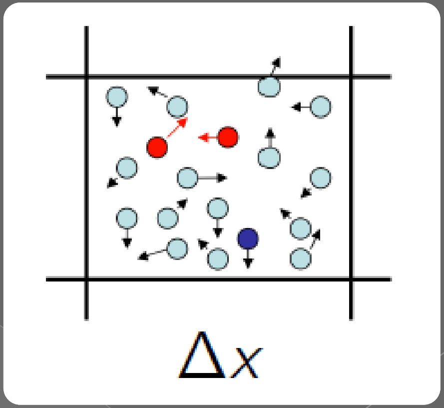
$$(p_\mu \partial^\mu + gQF^{\mu\nu} p_\mu \partial^p_\nu)\, f = \mathcal{C}[f]$$

Free streaming *Field interaction* *Collision integral*

$\eta/s \neq 0$

- **TEST PARTICLES METHOD to map the phase space**
- **STOCHASTIC METHOD to simulate collisions**

$$\mathcal{C}[f] = \int \frac{d^3p_2}{2E_2(2\pi)^3}\frac{d^3p_{1'}}{2E_{1'}(2\pi)^3}\frac{d^3p'_2}{2E'_2(2\pi)^3}(f_{1'}f_{2'} - f_1 f_2) \times |\mathcal{M}|^2 \delta^4(p_1+p_2-p_{1'}-p_{2'})$$



Transport approach is useful to obtain information about early times evolution

Within one single theoretical approach one can follow the entire dynamical evolution of system produced in RHICs

BOLTZMANN TRANSPORT EQUATION

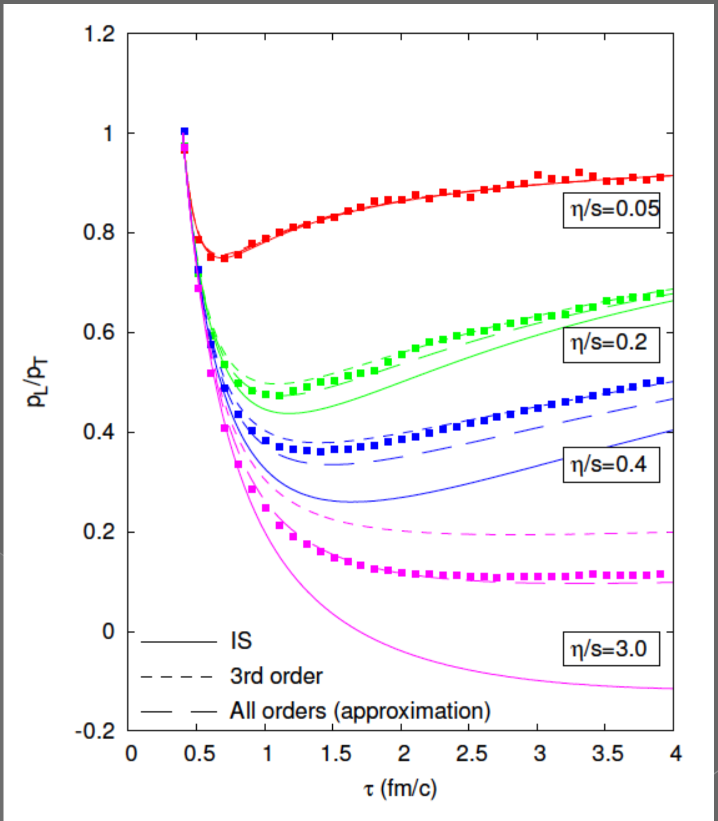
Instead of starting from cross sections we simulate a fluid at **fixed η/s**

Total cross section computed to give the wished value of η/s according to CHAPMAN-ENSKOG EQUATION

$$\frac{\eta}{s} = \frac{\langle p \rangle}{g(m_D)\rho} \frac{1}{\sigma}$$

Plumari, Puglisi, Scardina and Greco, PRC 86, 054902 (2012)

Convergency for small η/s of transport approach at fixed η/s with viscous hydrodynamics



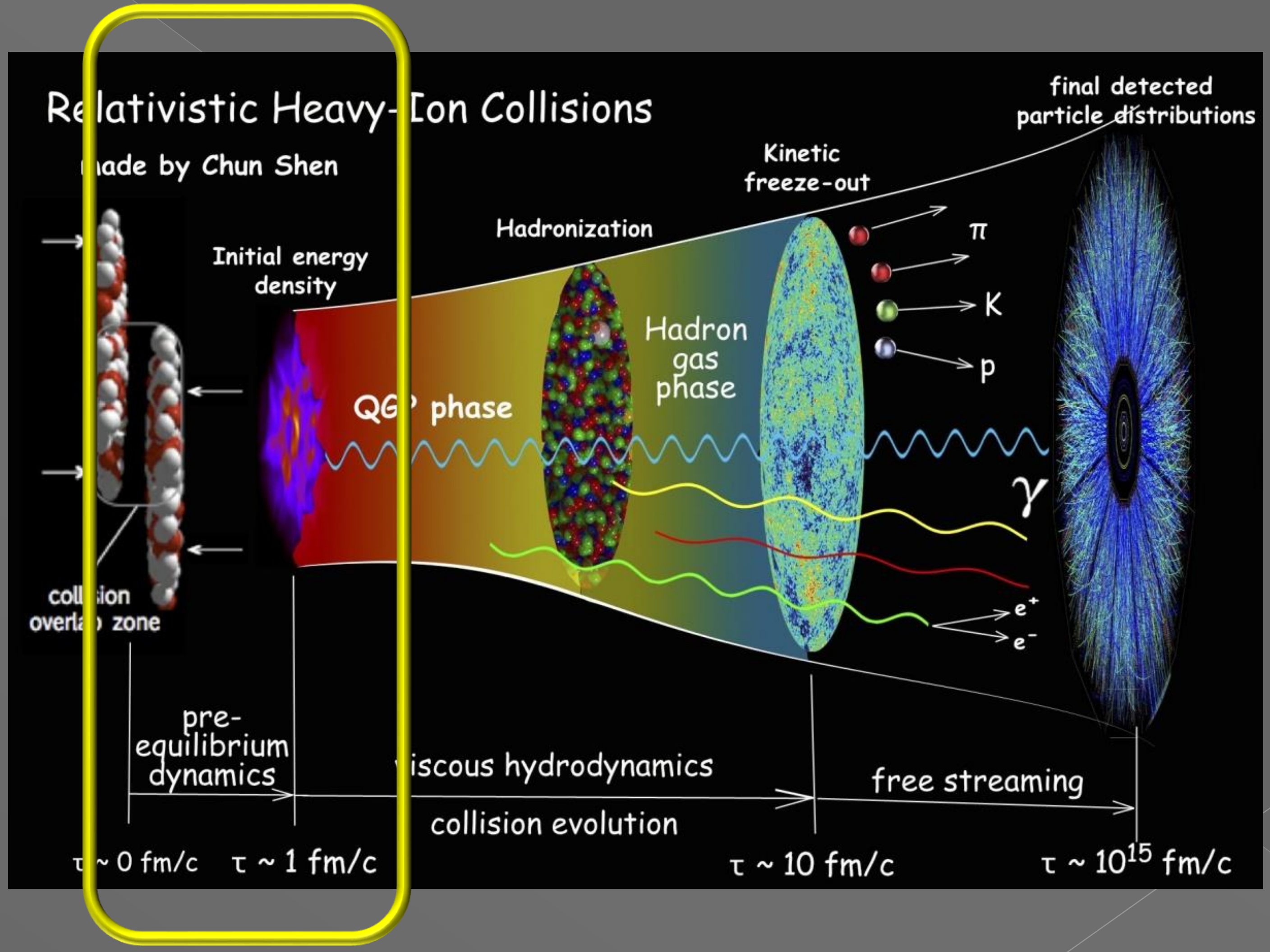
El, Xu and Greiner, PRC 81, 041901 (2010)

Transport ⟺ **Hydro**

Description in terms of parton distribution function

Dynamical evolution governed by macroscopic quantities

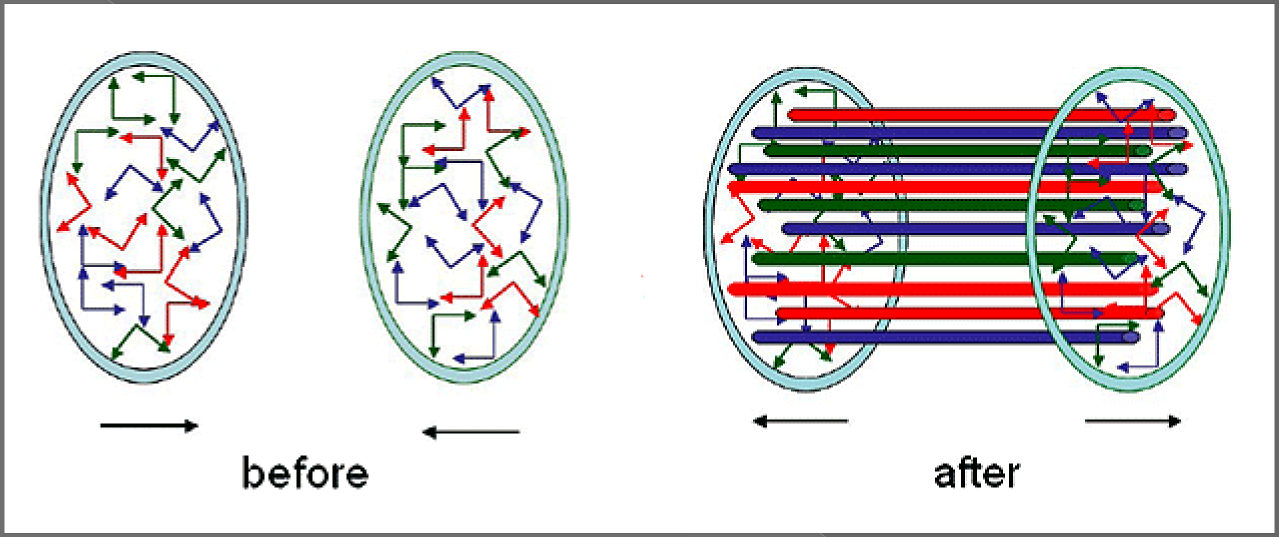
EARLY TIMES DYNAMICS

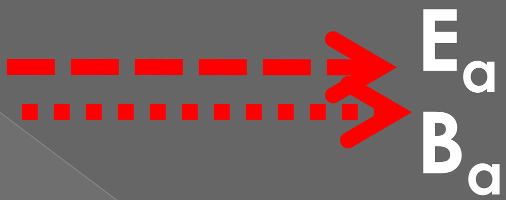


[Source: http://snelling.web.cern.ch/snelling/img/little_bang.jpg]

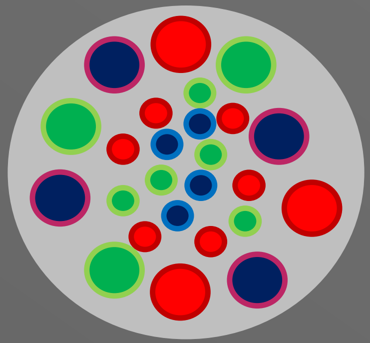
PRE-EQUILIBRIUM DYNAMICS: GLASMA

Immediately after the collision a peculiar configuration of **strong longitudinal chromo-electric and chromo-magnetic fields** is produced





Transverse plane



How does this configuration of classical color fields become a thermalized and isotropic QGP?

Lappi and McLerran, NPA 772 (2006)
Gelis *et al.*, NPA 828 (2009)
Fukushima and Gelis, NPA 874 (2012)

FROM GLASMA TO QUARK-GLUON PLASMA

SCHWINGER MECHANISM

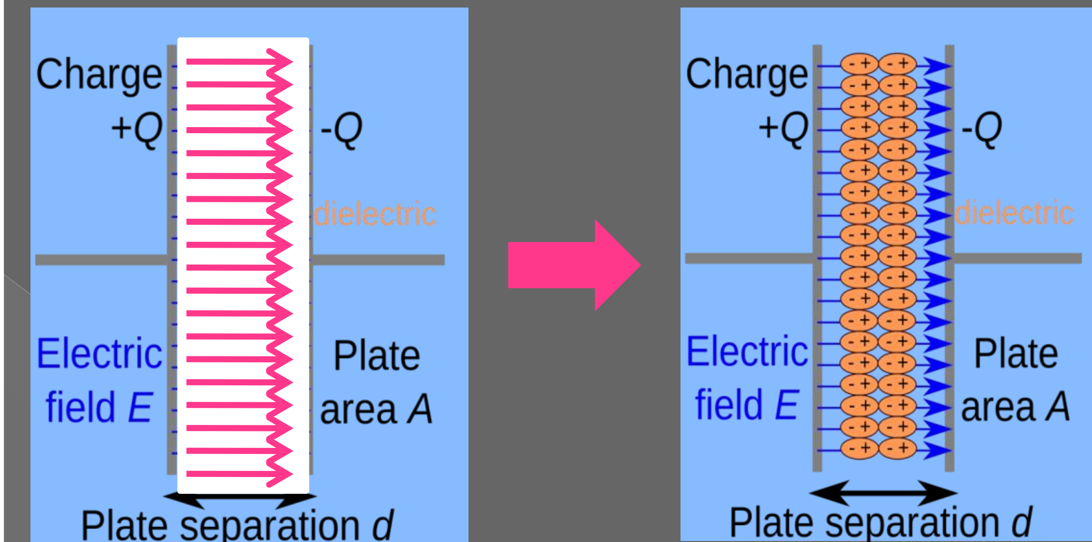
Classical fields decay to particles pairs via tunneling due to vacuum instability

Vacuum with an electric field is unstable towards pair creation

Quantum effective action of a pure electric field has an imaginary part which is responsible for field instability

Euler-Heisenberg (1936)
Schwinger, PR 82, 664 (1951)

Schwinger effect in QED



Schwinger effect in Electrodynamics

Vacuum Decay Probability per unit of spacetime to create an electron-positron pair from the vacuum

$$\mathcal{W}(x) = \frac{e^2E^2}{4\pi^3}\sum_{n=1}^{\infty}\frac{1}{n^2}\exp\left(-\frac{n\pi m^2}{|eE|}\right)$$

FROM GLASMA TO QUARK-GLUON PLASMA

SCHWINGER MECHANISM

Classical fields decay to particles pairs via tunneling due to vacuum instability

$$\frac{dN_{jc}}{d\Gamma} \equiv p_0 \frac{dN_{jc}}{d^4x d^2p_T dp_z} = \mathcal{R}_{jc}(p_T)\delta(p_z)p_0$$

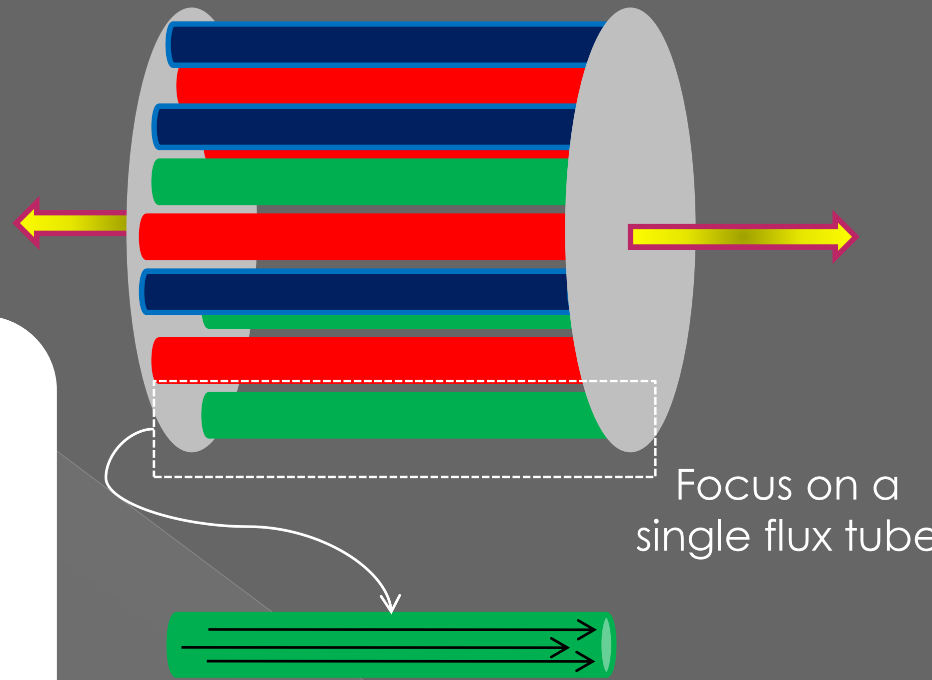
$$\mathcal{R}_{jc}(p_T) = \frac{\mathcal{E}_{jc}}{4\pi^3}\left|\ln\left(1 \pm e^{-\pi p_T^2/\mathcal{E}_{jc}}\right)\right|$$

$$\mathcal{E}_{jc} = (g|Q_{jc}E| - \sigma_j)\,\theta\,(g|Q_{jc}E| - \sigma_j)$$

LONGITUDINAL CHROMO-ELECTRIC FIELDS DECAY IN GLUON PAIRS AND QUARK-ANTIQUARK PAIRS

Casher, Neuberger and Nussinov, PRD 20, 179 (1979)
Glendenning and Matsui, PRD 28, 2890 (1983)

Schwinger effect in QCD



ABELIAN FLUX TUBE MODEL

- negligible chromo-magnetic field
- abelian dynamics for the chromo-electric field
- longitudinal initial field
- Schwinger effect

BOLTZMANN TRANSPORT EQUATION

In order to permit particle creation from the vacuum we need to add a source term to the right-hand side of the Boltzmann equation

$$\left(p_\mu \partial^\mu + g Q_{jc} F^{\mu\nu} p_\mu \partial_\nu^p\right) f_{jc} = p_0 \frac{\partial}{\partial t} \frac{dN_{jc}}{d^3x d^3p} + \mathcal{C}[f]$$

Field interaction

Source term

Florkowski and Ryblewski, PRD 88 (2013)

Source term: change of ***f*** due to particle creation in the volume centered at (x,p).

BOLTZMANN TRANSPORT EQUATION

In order to permit particle creation from the vacuum we need to add a source term to the right-hand side of the Boltzmann equation

$$\left(p_\mu \partial^\mu + gQ_{jc}F^{\mu\nu}p_\mu \partial^p_\nu\right) f_{jc} = p_0 \frac{\partial}{\partial t}\frac{dN_{jc}}{d^3x d^3p} + \mathcal{C}[f]$$

Field interaction

Source term

Florkowski and Ryblewski, PRD 88 (2013)

$$\frac{dE}{d\tau} = -j_M - j_D$$

conductive current

polarization current

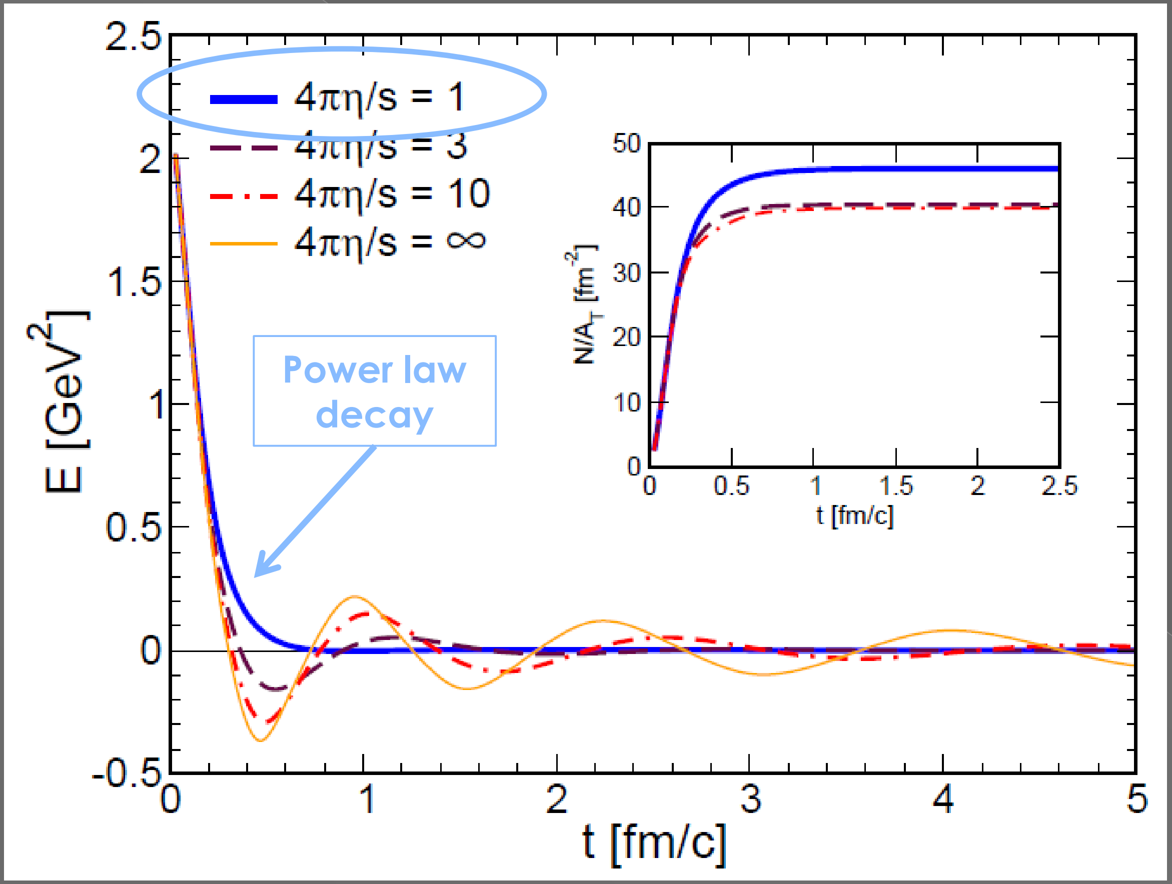
Currents depend on distribution function

Field interaction + *Source term*

Link between parton distribution function and classical color fields evolution

WE SOLVE SELF-CONSISTENTLY BOLTZMANN AND MAXWELL EQUATIONS

1+1D EXPANSION
electric field decay



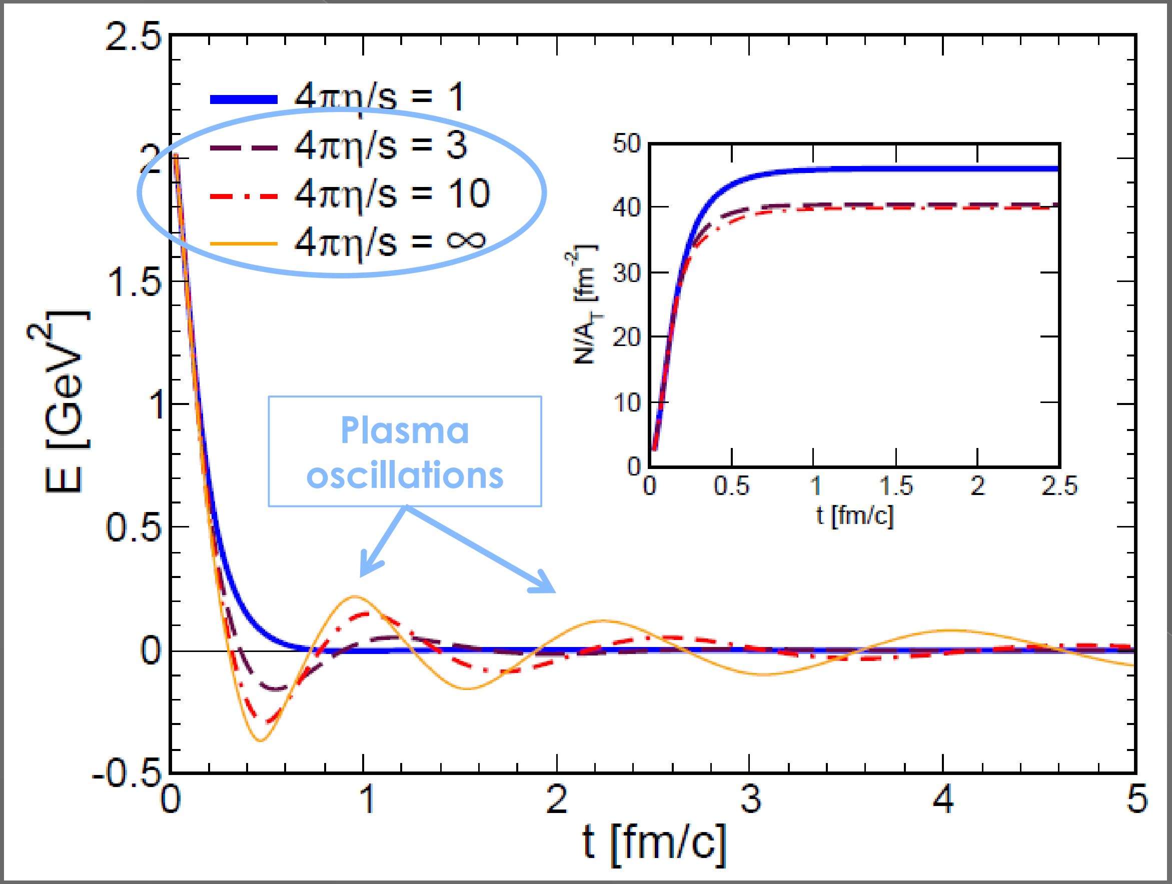
Oliva et al., *on press* on PRC, arXiv:1505.08081

Small viscosity → Large scattering rate → Efficient isotropization

SMALL VISCOSITY
field decays quickly

$$\frac{dE}{d\tau} = -j_M - j_D$$

1+1D EXPANSION electric field decay



Oliva et al., *on press* on PRC, arXiv:1505.08081

Large viscosity → Small scattering rate → Smaller isotropization efficiency

LARGE VISCOSITY

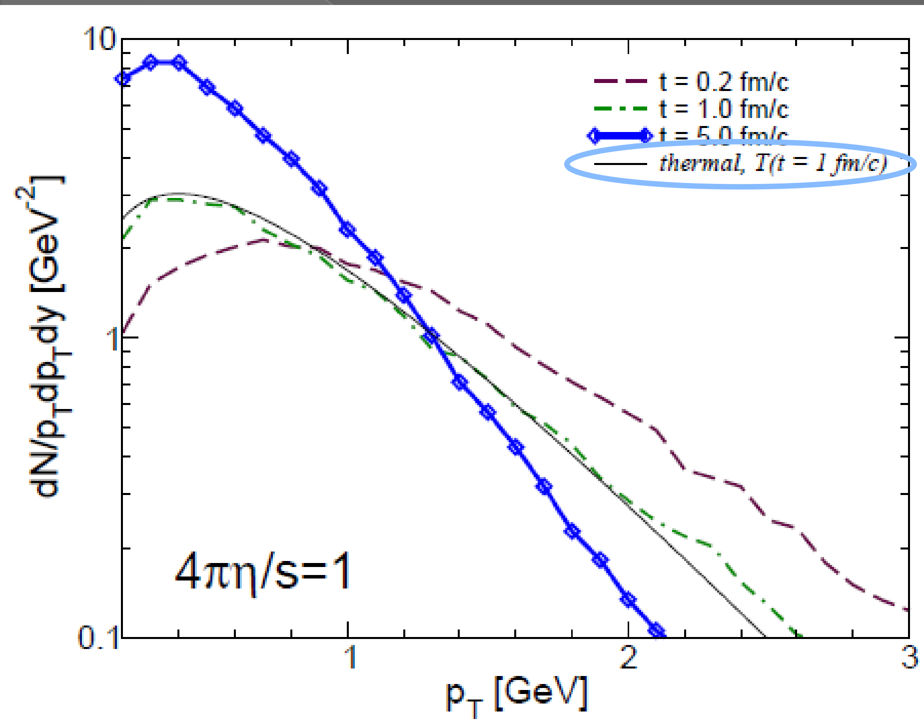
field is affected by oscillations after a faster initial times dynamics

$$\frac{dE}{d\tau} = -j_M - j_D$$

1+1D EXPANSION thermalization

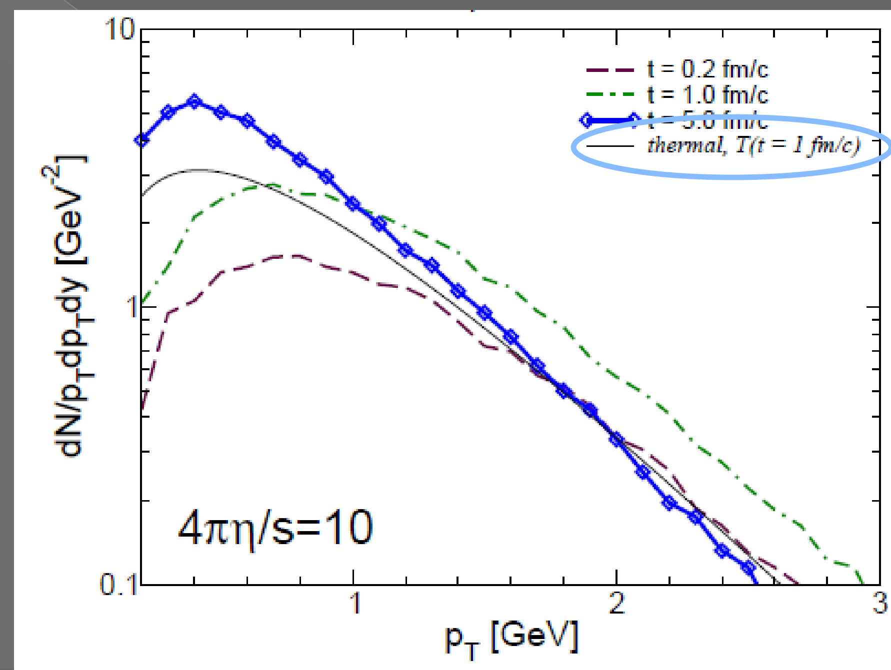
thermal spectrum

$$\frac{dN}{p_T dp_T dy} \propto p_T e^{-\beta p_T}$$



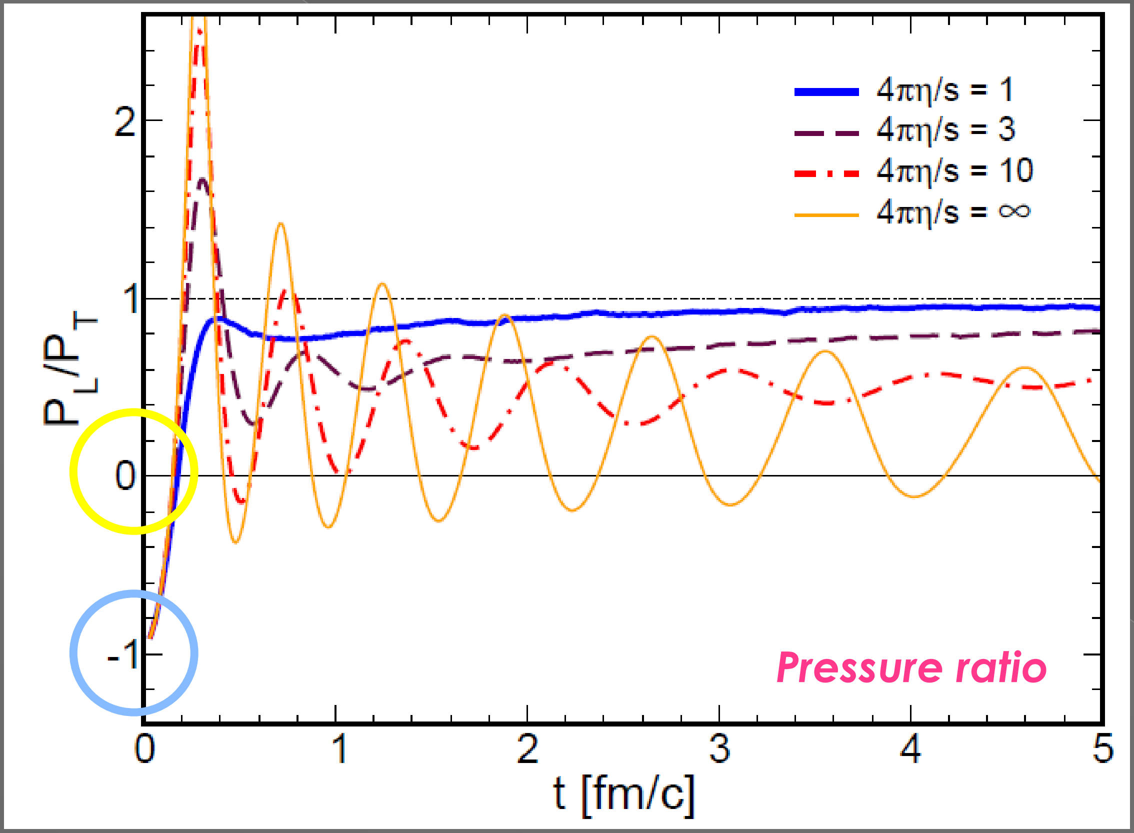
SMALL VISCOSITY
Thermalized plasma within 1 fm/c
Efficient cooling

LARGE VISCOSITY
Plasma non completely thermalized in 1 fm/c
Small cooling efficiency



Oliva et al., *on press* on PRC, arXiv:1505.08081

1+1D EXPANSION isotropization



Oliva et al., *on press* on PRC, arXiv:1505.08081

$$T^{\mu\nu}_{field} = \mathrm{diag}\,(\varepsilon, P_T, P_T, P_L)$$
$$\propto \mathrm{diag}\,(\mathcal{E}^2, \mathcal{E}^2, \mathcal{E}^2, -\mathcal{E}^2)$$

$$T^{\mu\nu}_{particles} = \int \frac{d^3\boldsymbol{p}}{(2\pi)^3} \frac{p^\mu p^\nu}{E} f(\boldsymbol{x}, \boldsymbol{p})$$

$$T^{\mu\nu} = T^{\mu\nu}_{particles} + T^{\mu\nu}_{field}$$

$$P_L = T_{zz}$$

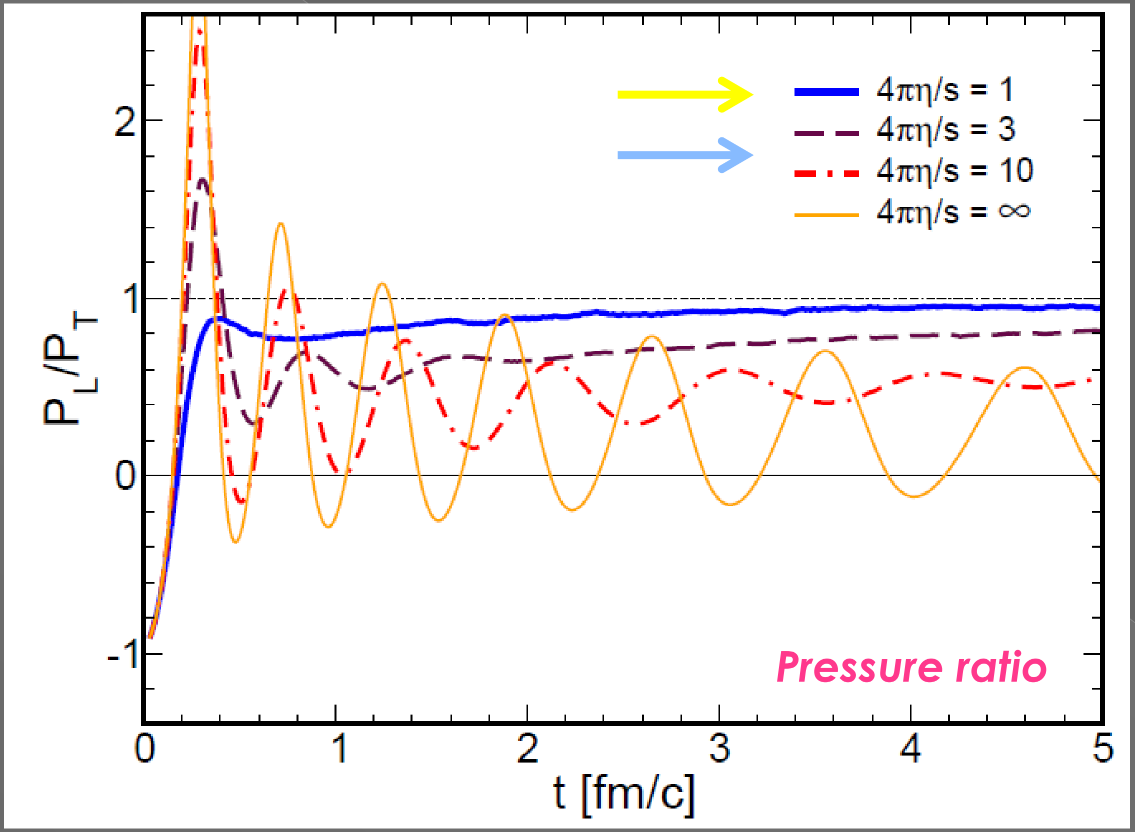
$$P_T = \frac{T_{xx} + T_{yy}}{2}$$

Isotropic system if $P_L = P_T$

High anisotropy: pure field with negative longitudinal pressure

Longitudinal pressure becomes positive due to particles creation after 0.2 fm/c independently of η/s

1+1D EXPANSION isotropization



Oliva et al., *on press* on PRC, arXiv:1505.08081

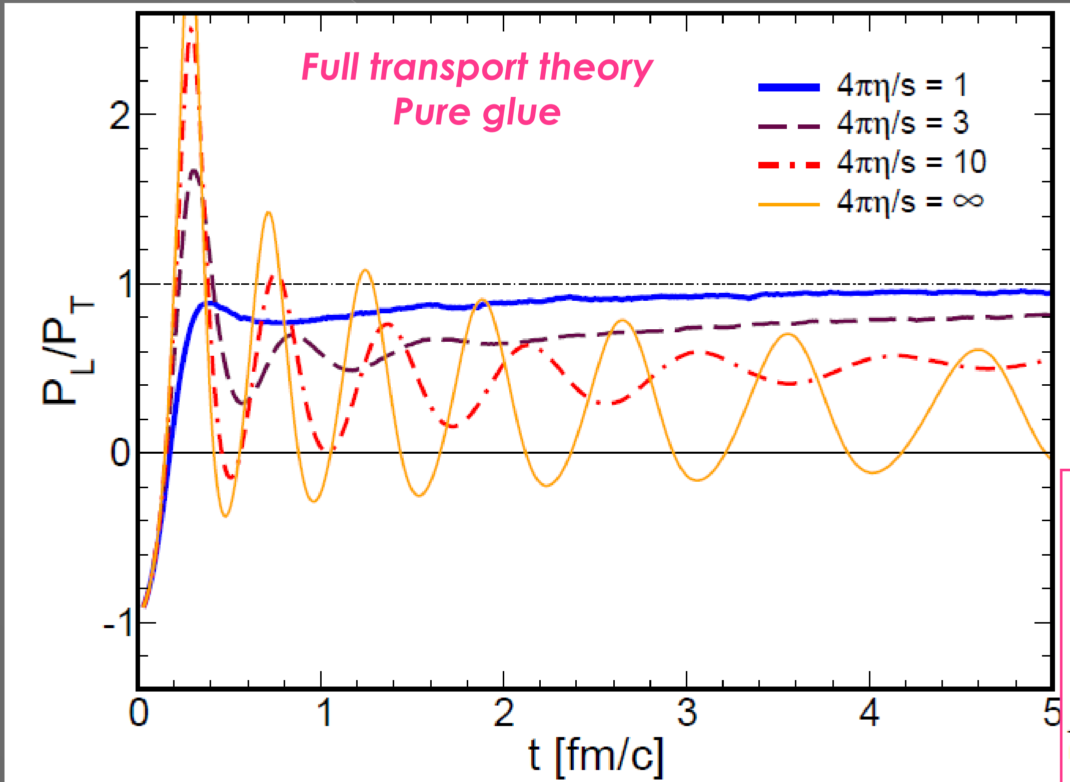
Small viscosity
Quick isotropization in about 1 fm/c

Large viscosity
Less efficient isotropization

Quick isotropization justifies use of viscous hydrodynamics with an initial time of 0.6 fm/c, in which pressure ratio is about 0.7

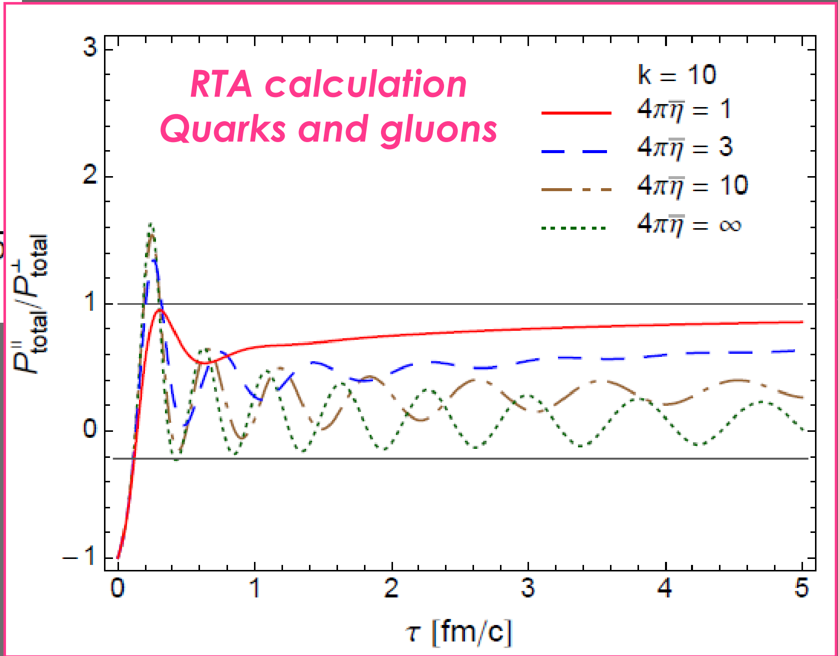
Initial phase is strongly anisotropic, not thermalized and with negative pressure. Which is its impact on observables?

1+1D EXPANSION isotropization



Oliva et al., *on press* on PRC, arXiv:1505.08081

COMPARISON WITH PRESSURE RATIO FROM
Florkowski and Ryblewski, PRD 88 (2013)



- ❑ **Excellent qualitative agreement**
- ❑ **Quantitative difference due to the different calculation schemes**

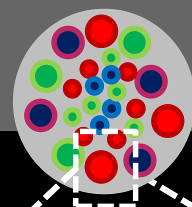
Puglisi. et al., *in preparation*

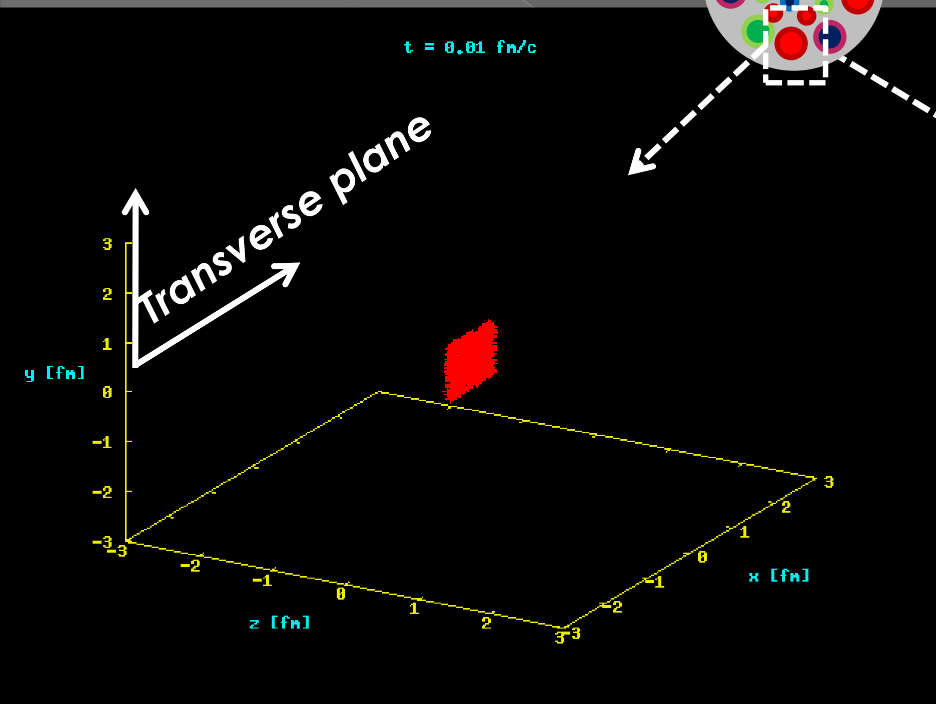
3+1D EXPANSION

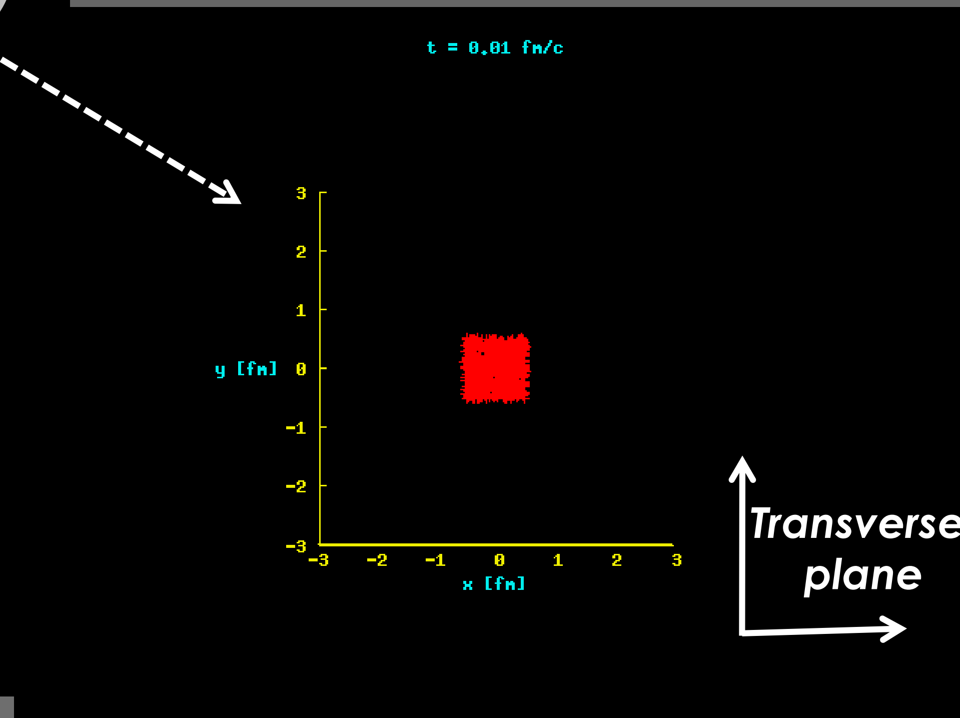
Initial field is longitudinal, but a realistic 3D expansion leads to transverse fields

3D view

Transverse plane





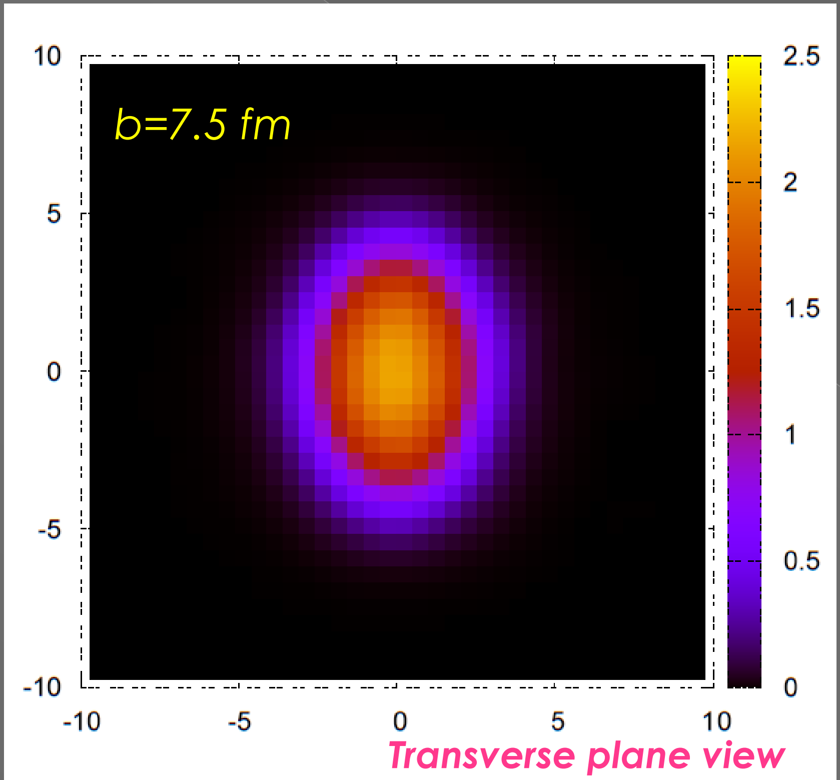


QGP is created by classical field decay and expands along longitudinal direction and in transverse plane

Puglisi. et al., *in preparation*

3+1D EXPANSION initial state model

Initial longitudinal field



Initial state fluctuations neglected

Electric field with an eccentricity

↓

Anisotropic pressure gradients

↓

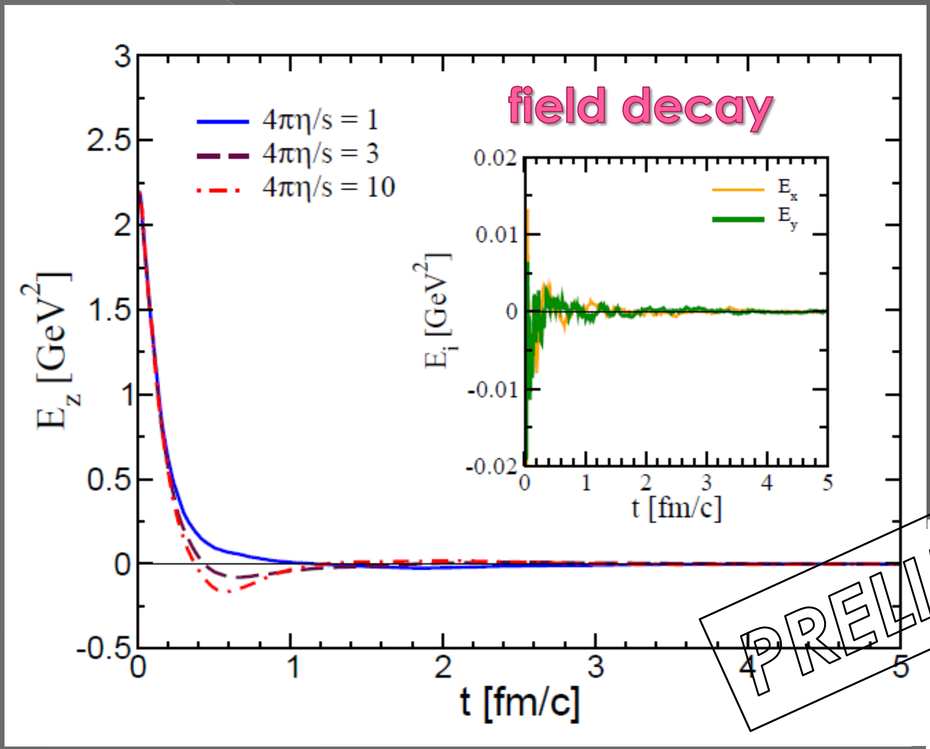
Elliptic flow production

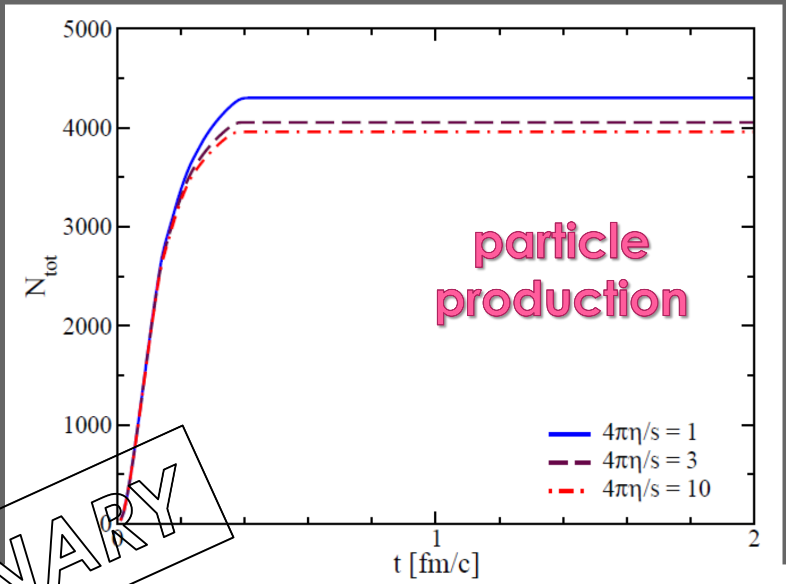
By means of one theoretical framework we describe the dynamics from initial state (classical fields) up to final stage (flows production)

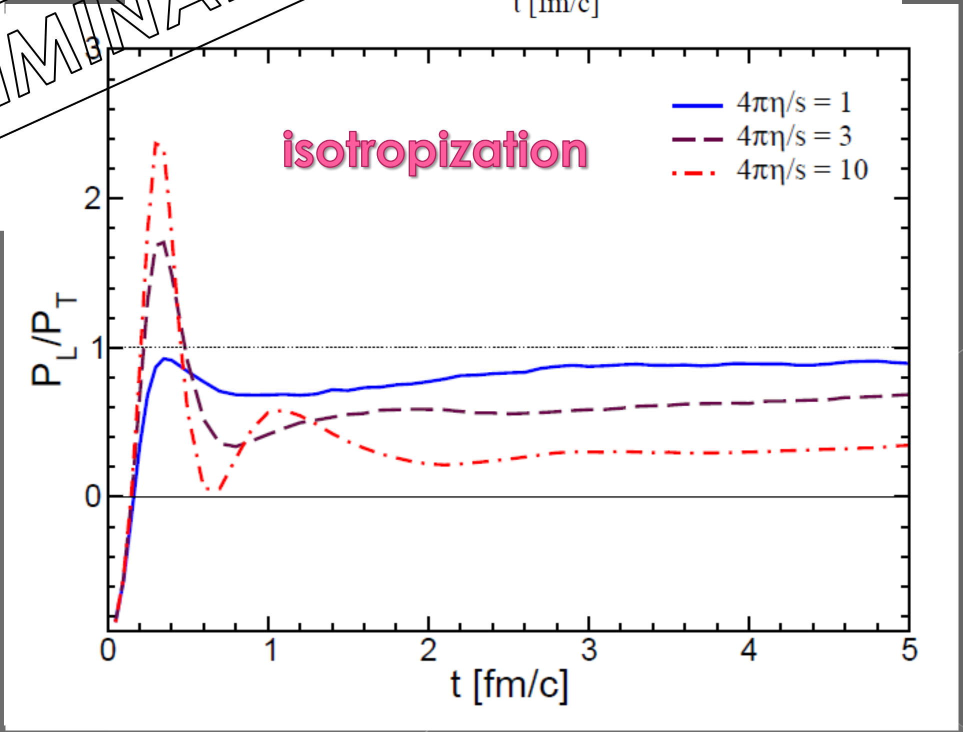
3+1D

3+1D EXPANSION

Puglisi. et al., *in preparation*

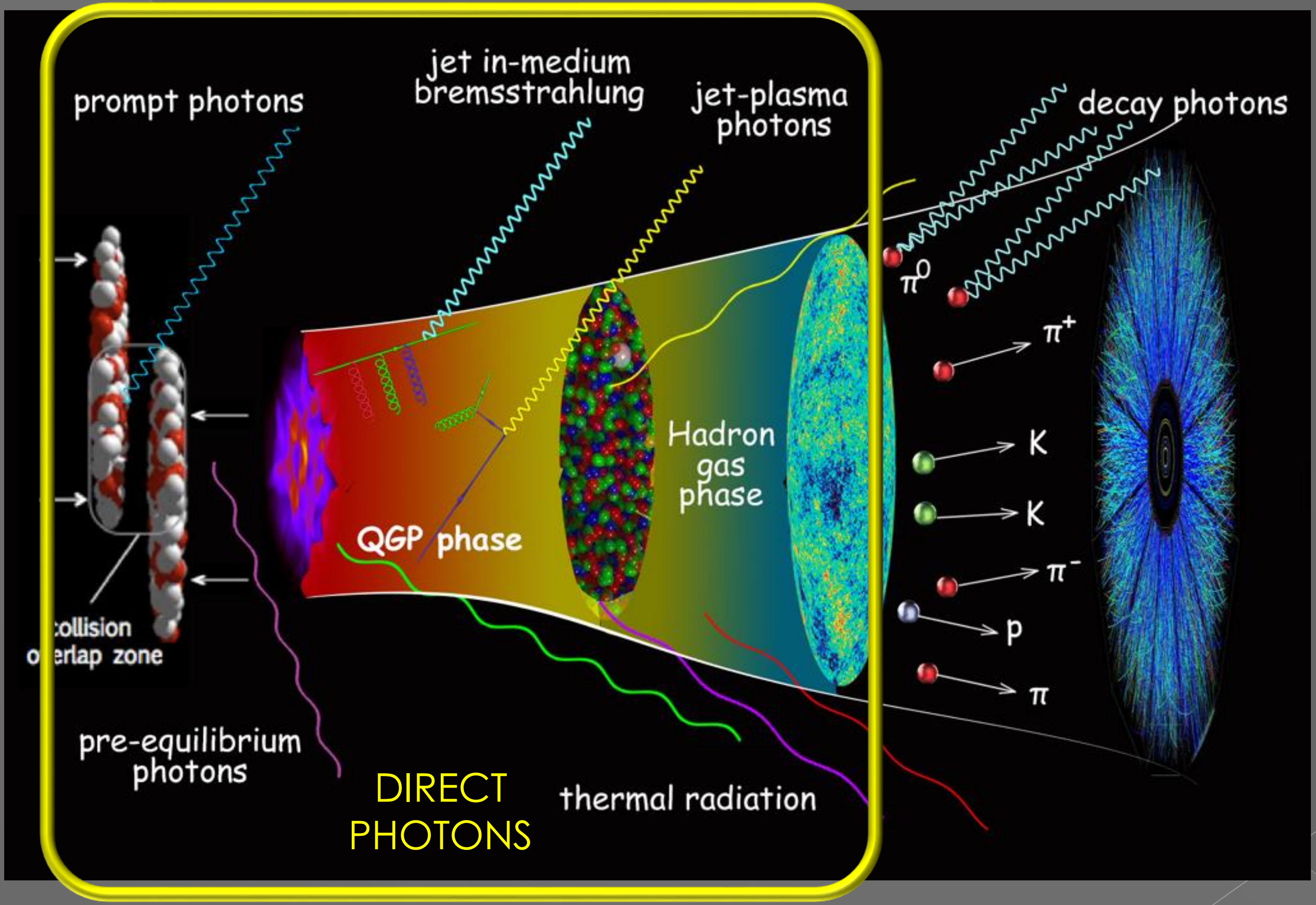






Nice agreement with the 1+1D calculation about timescales and isotropization rate

PHOTON PRODUCTION



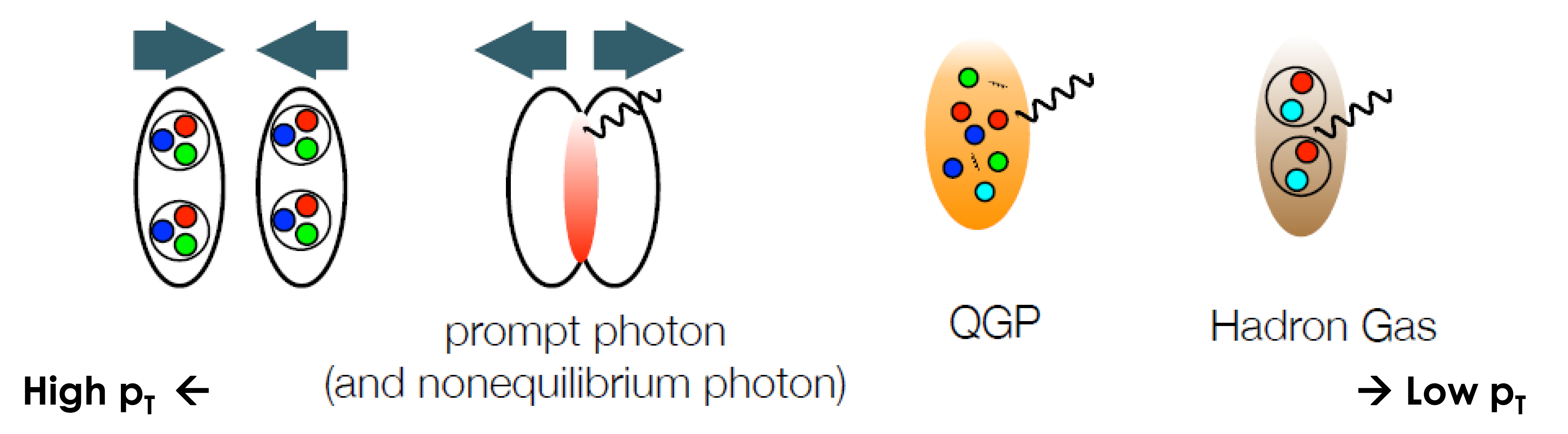
[Source: C. Shen, talk at ECT*, Trento 12/2015]

ELECTROMAGNETIC PROBES

Radiation of photons and dileptons has been proposed as a promising tool to characterize the initial state of heavy ion collisons

DIRECT PHOTONS

- emerge directly from a particle collison
- represent less than 10% of all detected photons



Experiments can not distinguish between the different sources

Theoretical models can be used to identify these sources and their relative importance in the spectrum

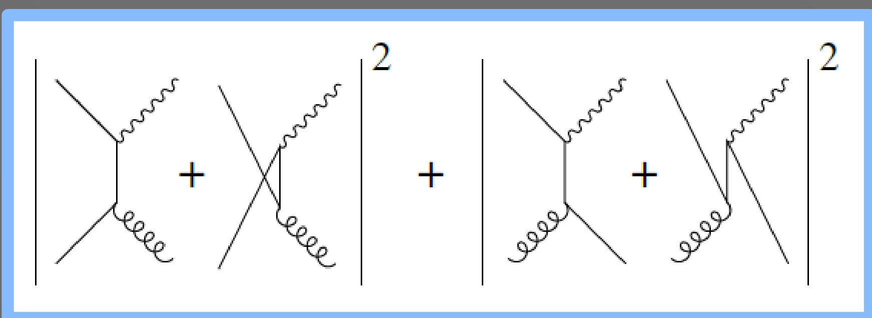
Peitzmann and Thoma, Phys. Rep. 364, 175 (2002)
Chatterjee, et al., Lect. Notes Phys. 785, 219 (2010)
Chauduri, arXiv: 1207.7028 (2012)

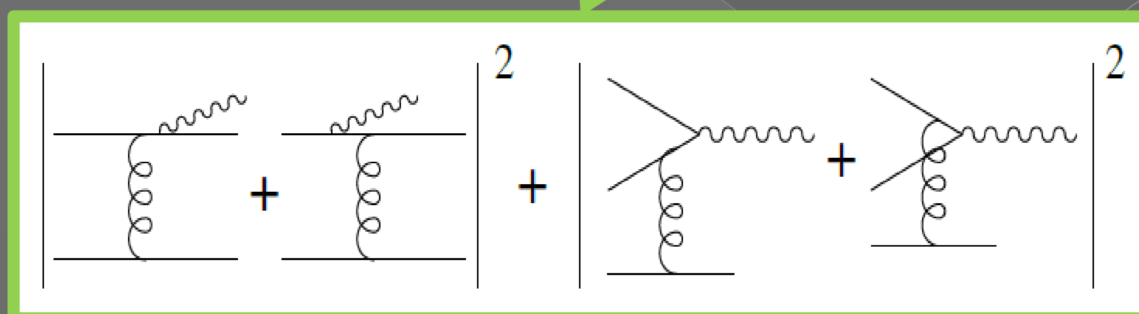
BOLTZMANN TRANSPORT EQUATION

In order to permit photon production we add to the collision integral of the Boltzmann equation processes with a photon in the final state

$$(p_\mu \partial^\mu + g Q_{jc} F^{\mu\nu} p_\mu \partial_\nu^p)\, f_{jc} = p_0 \frac{\partial}{\partial t} \frac{dN_{jc}}{d^3x\, d^3p} + \mathcal{C}[f]$$

$$C\,[f] = C_{22}[f] + C_{23}[f] + \dots$$





Aurenche et al., PRD 58, 085003 (1998)
ib., PRD 61, 116001 (2000)
ib., PRD 62, 096012 (2000)
Arnold et al., JHEP 0112,009 (2001)

QCD Compton and annihilation reactions

These are the 2 → 2 particles Feynman diagrams contributing to $O(\alpha\alpha_s)$

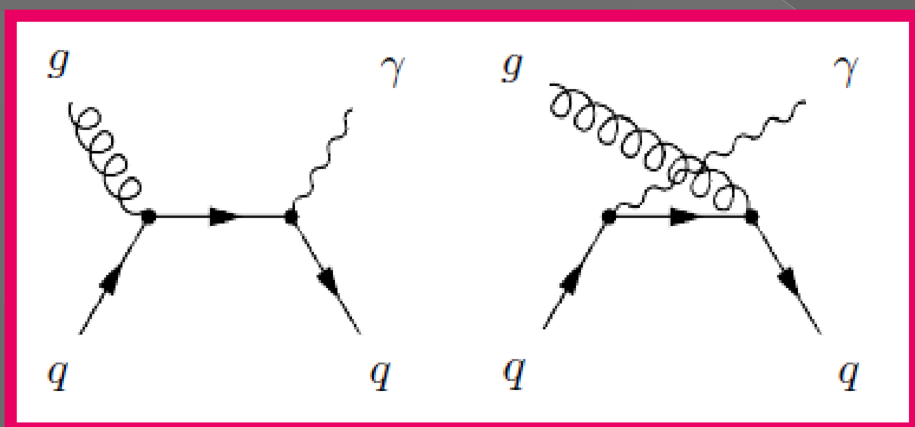
$$q/\bar{q} + g \rightarrow q/\bar{q} + \gamma$$

$$\frac{d\sigma}{dt} = \frac{8\pi\alpha\alpha_s}{9s^2}\frac{u^2+t^2}{ut}$$

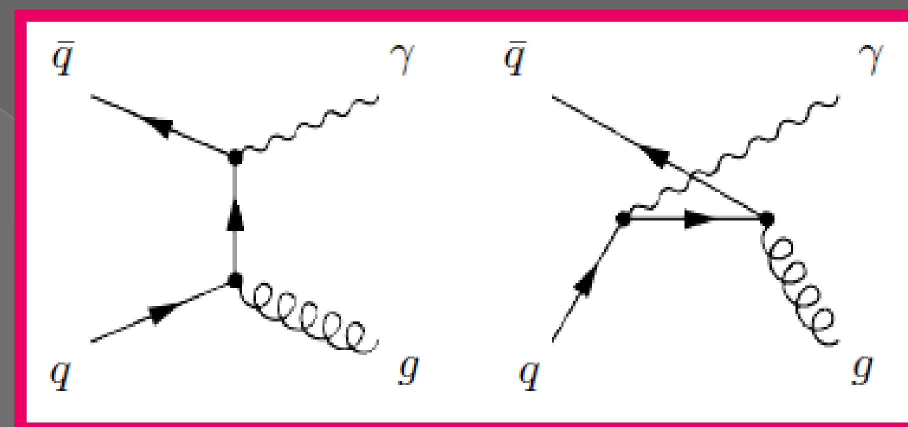
$$q + \bar{q} \rightarrow g + \gamma$$

$$\frac{d\sigma}{dt} = \frac{-\pi\alpha\alpha_s}{3s^2}\frac{u^2+s^2}{us}$$

QCD Compton scattering



Quark-antiquark annihilation



$$P_{22} = \frac{\Delta N_{coll}^{2\rightarrow 2}}{\Delta N_1 \Delta N_2} = v_{rel}\sigma_{22}\frac{\Delta t}{\Delta^3 x}$$

$$v_{rel} = \frac{s}{2E_1E_2}$$

For each processes we have computed the rate R (number of reactions per unit time per unit volume which produce a photon)

Box at fixed T: photon production rates

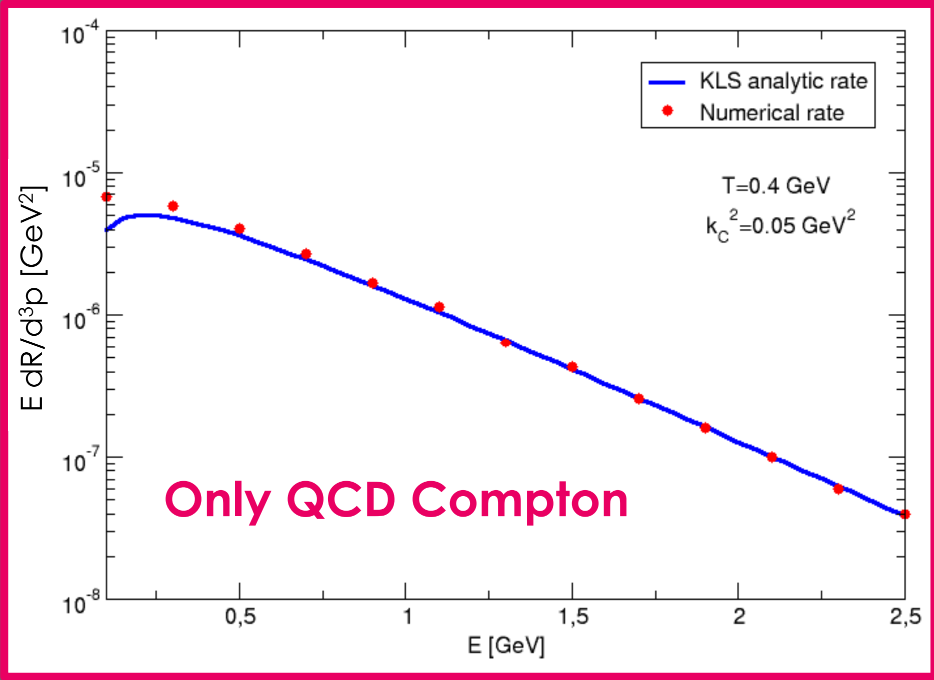
$T = 400$ MeV

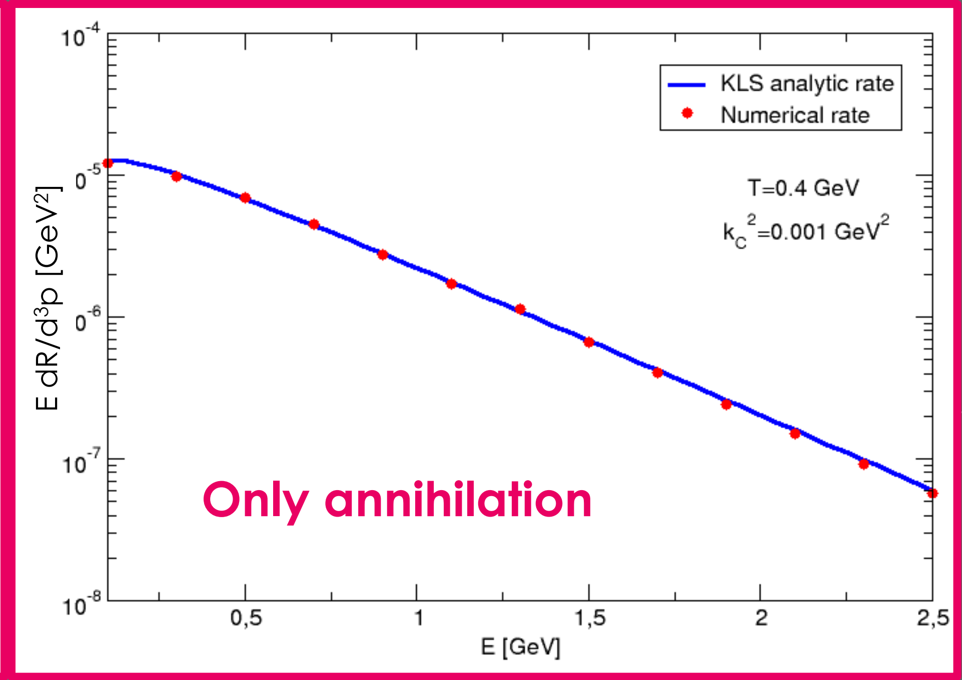
The thermal emission rates of photons with energy E and momentum **p** were analytically computed by Kapusta, Lichard and Seibert, PRD 44, 2774 (1991)

$R = dN/d^4x$

$$E\frac{dR^{\text{Compton}}}{d^3p} = \frac{5}{9}\frac{2\alpha\alpha_s}{\pi^4}T^2e^{-E/T} \times\left[\ln(4ET/k_c^2) + \tfrac{1}{2} - C_{\text{Euler}}\right]$$

$$E\frac{dR^{\text{annihilation}}}{d^3p} = \frac{5}{9}\frac{2\alpha\alpha_s}{\pi^4}T^2e^{-E/T} \times\left[\ln(4ET/k_c^2) - 1 - C_{\text{Euler}}\right]$$





Our transport code results (red points) agree with KLS analytic rates.

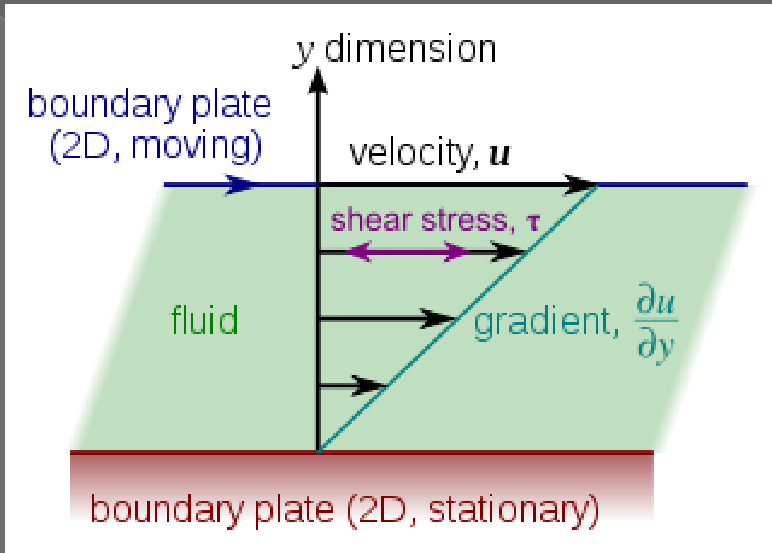
CONCLUSIONS and OUTLOOKS

- ✓ **Relativistic Transport Theory** allows to study **early times dynamics of heavy ion collisions.**
- ✓ **Schwinger tunneling** provides a **fast particle production**, typically a small fraction of fm/c.
- ✓ **High viscous plasma** is characterized by plasma **oscillations** which are non negligible along the entire evolution of the system.
- ✓ **Plasma with small viscosity** reaches the **hydro regime** quickly, as isotropization time is less than 1 fm/c and thermalization time is ~ 1 fm/c.
- ✓ Electromagnetic probes are an efficient tool to investigate the initial state of heavy ion collisons and the properties of quark-gluon plasma.

Study the impact of **early stage dynamics** on observables like elliptic flow, dilepton and **photon production**.

Thank you
for your attention!

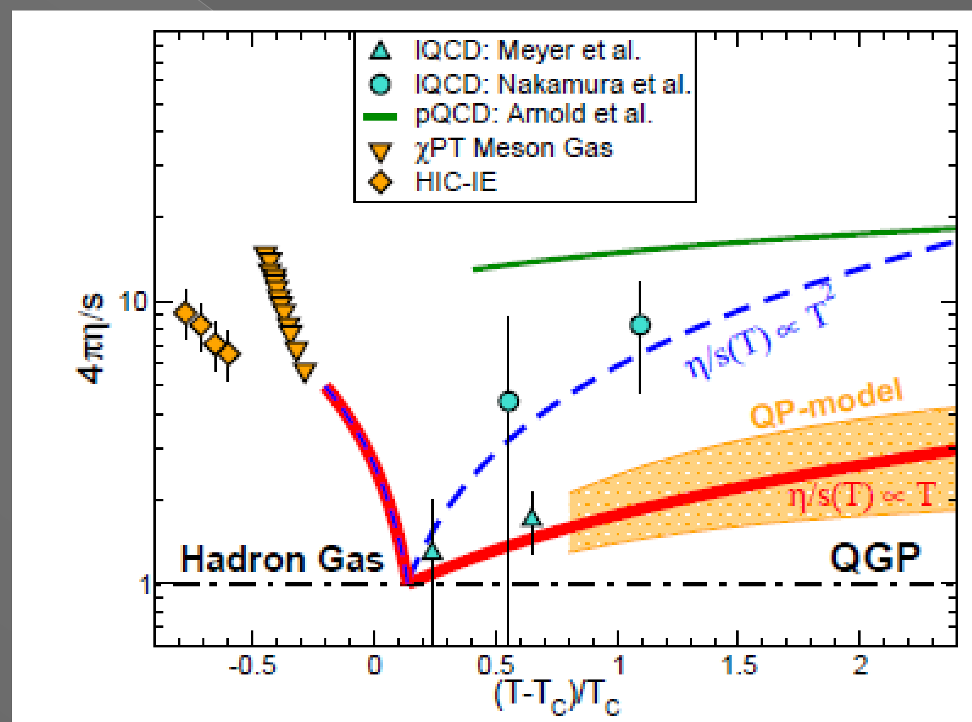
BACK SLIDES



SHEAR VISCOSITY η
is a measure of how velocity of fluid changes with depth

$$\frac{F_x}{A_{yz}} = -\eta \frac{\partial u_x}{\partial y}$$

SHEAR VISCOSITY OVER ENTROPY DENSITY RATIO η/s
dependent on temperature



Plumari et al., J.Phys.Conf.Ser. 420, 012029 (2013)

BOLTZMANN TRANSPORT EQUATION
Numerical implementation

- **Test particles method**

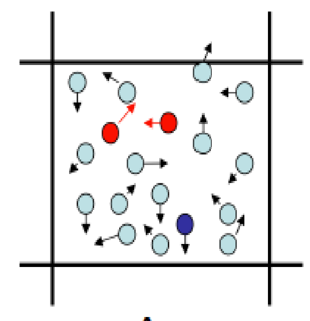
$$f(\mathrm{x},\mathrm{p}) = \omega \sum_{i=1}^{N_{test}} \delta^3(\mathrm{x}-\mathrm{x}_i)\delta^3(\mathrm{p}-\mathrm{p}_i)$$

$$\Rightarrow$$

$$\dot{\mathrm{x}}_i = \frac{\mathrm{p}_i}{E_i}$$
$$\dot{\mathrm{p}}_i = -\nabla_x E_i + coll$$

- **Stochastic method**

$$\begin{aligned}
\mathcal{C}_{22} = &\frac{1}{2E_1}\int \frac{d^3p_2}{(2\pi)^3 2E_2}\frac{1}{\nu}\int \frac{d^3p'_1}{(2\pi)^3 2E'_1}\frac{d^3p'_2}{(2\pi)^3 2E'_2} f'_1 f'_2 \\
&\times |\mathcal{M}_{1'2'\to 12}|^2 (2\pi)^4 \delta^4(p'_1 + p'_2 - p_1 - p_2) - \frac{1}{2E_1} \\
&\times \int \frac{d^3p_2}{(2\pi)^3 2E_2}\frac{1}{\nu}\int \frac{d^3p'_1}{(2\pi)^3 2E'_2}\frac{d^3p'_2}{(2\pi)^3 2E'_2} f_1 f_2 \\
&\times |\mathcal{M}_{12\to 1'2'}|^2 (2\pi)^4 \delta^4(p_1 + p_2 - p'_1 - p'_2),
\end{aligned}$$



$$P_{22} = \frac{\Delta N_{coll}^{2\to 2}}{\Delta N_1 \Delta N_2} = v_{rel}\sigma_{22}\frac{\Delta t}{\Delta^3 x}$$

$\Delta t \to 0$, $\Delta^3 x \to 0$ ➡ **RIGHT SOLUTION**

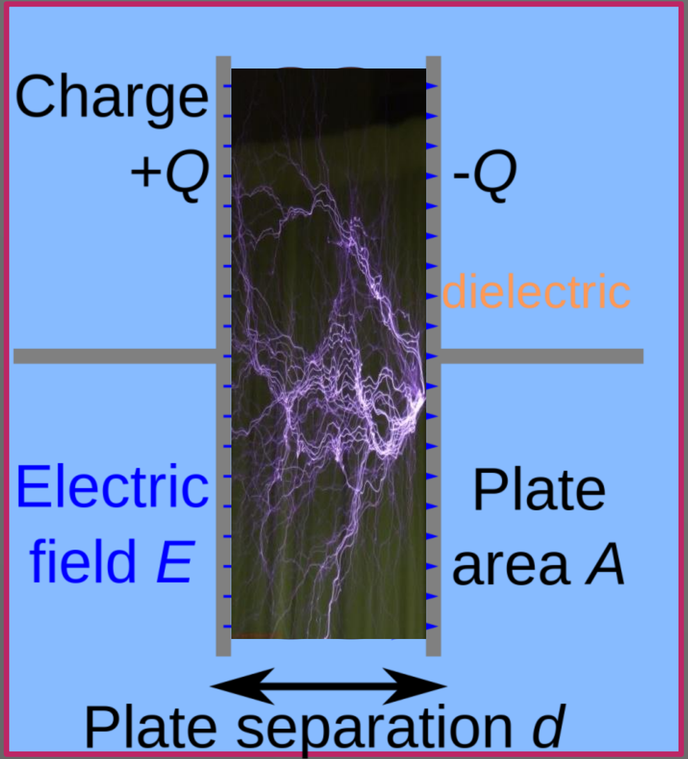
ADVANTAGES OF TRANSPORT APPROACH

- Starting from **one-body distribution function f(x,p)** and not from $T_{\mu\nu}$:
  - possible to include f(x,p) out of equilibrium
    Ruggieri et al., PLB 727, 177 (2013)
  - extract information about the viscous correction δf to f(x,p)
    Plumari, Guardo, Greco and Ollitrault, NPA 941, 87 (2015)
  - valid also at high and intermediate p_T out-of-equilibrium :
    Relevant at LHC due to large amount of minijet production
  - freeze-out self-consistently related with η /s(T)
- It is **not a gradient expansion in η/s**
  - valid also at high η/s: LHC ($T>>T_c$) or crossover region ($T\approx T_c$)
- Appropriate for **heavy quark dynamics**
- Good tool to compute **transport coefficients**
- Useful to obtain **information about early times evolution**
- Within ***one single theoretical approach*** one can follow the **entire dynamical evolution of system produced in RHICs**

UNIFIED FRAMEWORK FROM INITIAL TO FINAL STAGES OF RHIC
WIDE RANGE OF VALIDITY IN TRANSPORT COEFFICIENTS AND MOMENTA
RELEVANCE ON MICROSCOPIC DETAILS

SCHWINGER EFFECT IN ELECTRODYNAMICS

$$
\begin{aligned}
\mathcal{W}(x) &= -\frac{|g\boldsymbol{E}|}{4\pi^3}\int d^2p_T \log\left(1-e^{-\frac{\pi^2 E_T^2}{|g\boldsymbol{E}|}}\right) \\
&= \frac{g^2E^2}{4\pi^3}\sum_{n=1}^{\infty}\frac{1}{n^2}\exp\left(-\frac{n\pi m^2}{|g\boldsymbol{E}|}\right)
\end{aligned}
$$



Quantum tunneling interpretation:
- Gives the p_z and p_T spectrum of the produced pair
- Describes the Schwinger effect as a dipole formation in the vacuum; each dipole has moment

$$p = g \times 2 \times \frac{d}{2} = g\frac{2E_T}{|g\boldsymbol{E}|}$$

Once pairs pop up from the vacuum, charged particles propagate in real time producing electric currents:

$$\boldsymbol{J} = \sigma \boldsymbol{E}$$

in linear response theory

Vacuum polarization
Electric current → ***Dielectric breakdown***

SCHWINGER EFFECT IN ELECTRODYNAMICS numerical estimates

Strictly speaking there is no a critical field, rather a probability for tunneling to occur. Given exponential suppression such a probability becomes non negligible as soon as

$$|\boldsymbol{E}| \approx m_e^2 \approx 10^{18}\ \mathrm{Volt/m}$$

QED "critical field"

Particles pop up is similar to dielectric breakdown.
We can compare the vacuum breakdown with typical critical fields of dielectric breakdown:

Thunderbolt: $3\text{x}10^6$ Volt/m

SCHWINGER EFFECT IN CHOMODYNAMICS numerical estimates

$eE = 1\ GeV^2$ corresponds to 5×10^{24} Volt/m

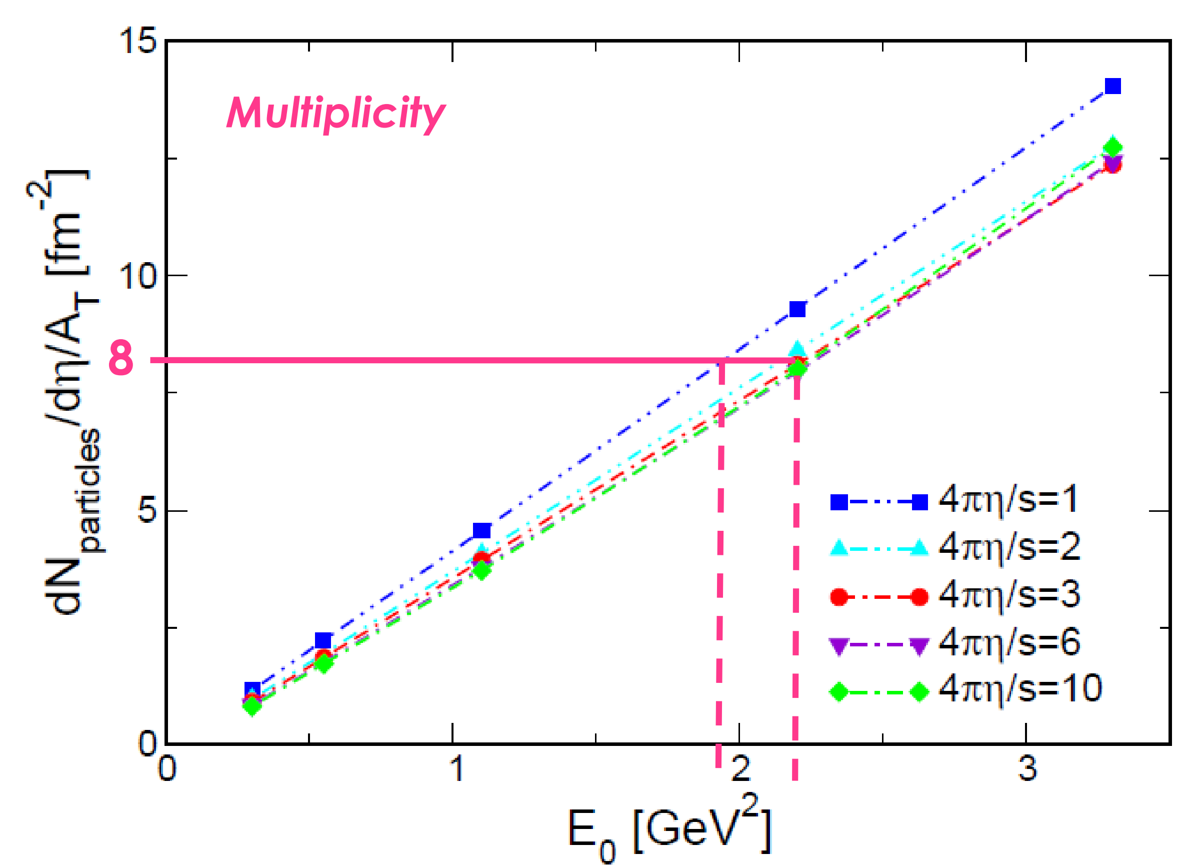
QED critical field: $2.6 \times 10^{-7}\ GeV^2$

In QCD the critical field is given by the string tension:
The energy per unit length carried by the field has to be larger of that required to produce a deconfined pair

QCD critical field: 0.2-0.6 GeV^2

Initial color-electric field in HICs:
gE: 1-10 GeV^2

1+1D EXPANSION
a rough estimate of initial field



Multiplicity for a RHIC collision (b=2.5 fm)

$$\frac{dN}{dy} = \frac{dN}{d\eta} \approx 1040$$

Transverse area

$$A_T \approx \pi R^2 \approx \pi (6.5)^2 \approx 137 \text{ fm}^2$$

Multiplicity per transverse area

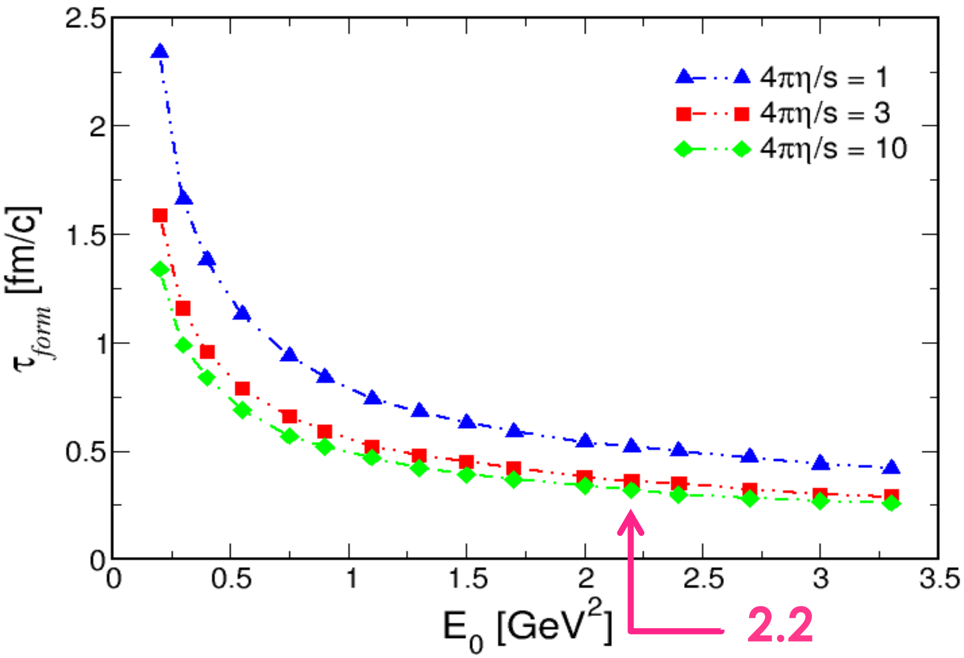
$$\frac{dN}{A_T d\eta} \approx 8 \text{ fm}^{-2}$$

$$E_0 \approx 1.9 \div 2.2 \text{ GeV}^2$$

This very rough estimate gives the proper order of magnitude

1+1D EXPANSION particles formation

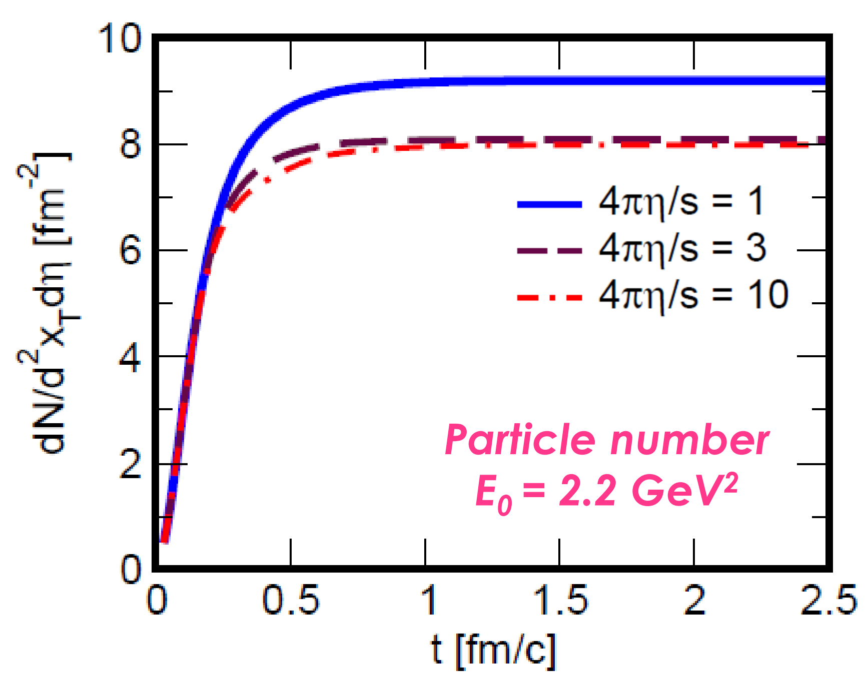
Proper time for conversion to particles



Time at which particles production stops

$$\frac{d}{dt}\left(\frac{\boldsymbol{E}^2}{2}\right) = -\boldsymbol{j}\cdot\boldsymbol{E}$$

smaller field implies slower decay

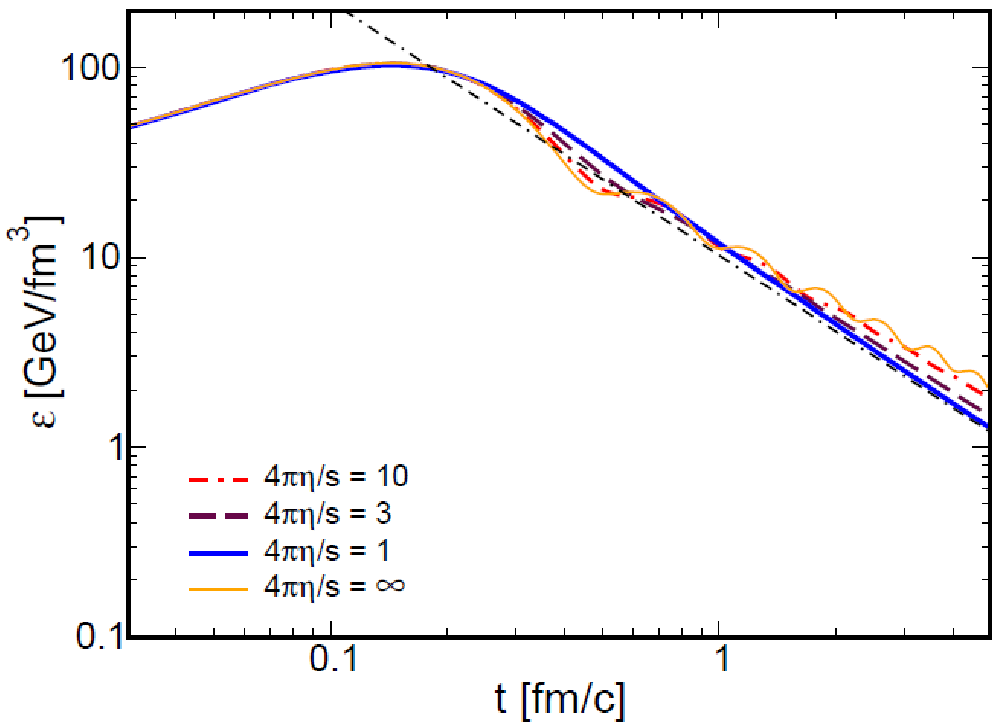


Unless initial field is very small,
formation time is less than 1 fm/c

Typical fireball lifetime: 5-10 fm/c

1+1D EXPANSION
reaching the hydro regime

Proper particles energy density



Oliva et al., *on press* on PRC, arXiv:1505.08081

SMALL VISCOSITY
Hydro regime quickly reached

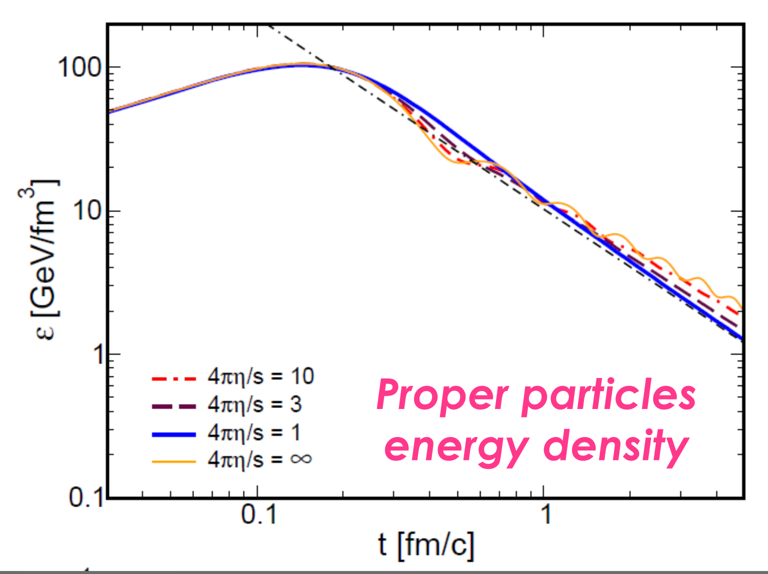
LARGE VISCOSITY
Higher temperature
Superimposed plasma oscillations

Transport theory is capable to describe, even in conditions of quite strong coupling, the evolution of physical quantities in agreement with hydro, once the viscosity is fixed instead of cross section.

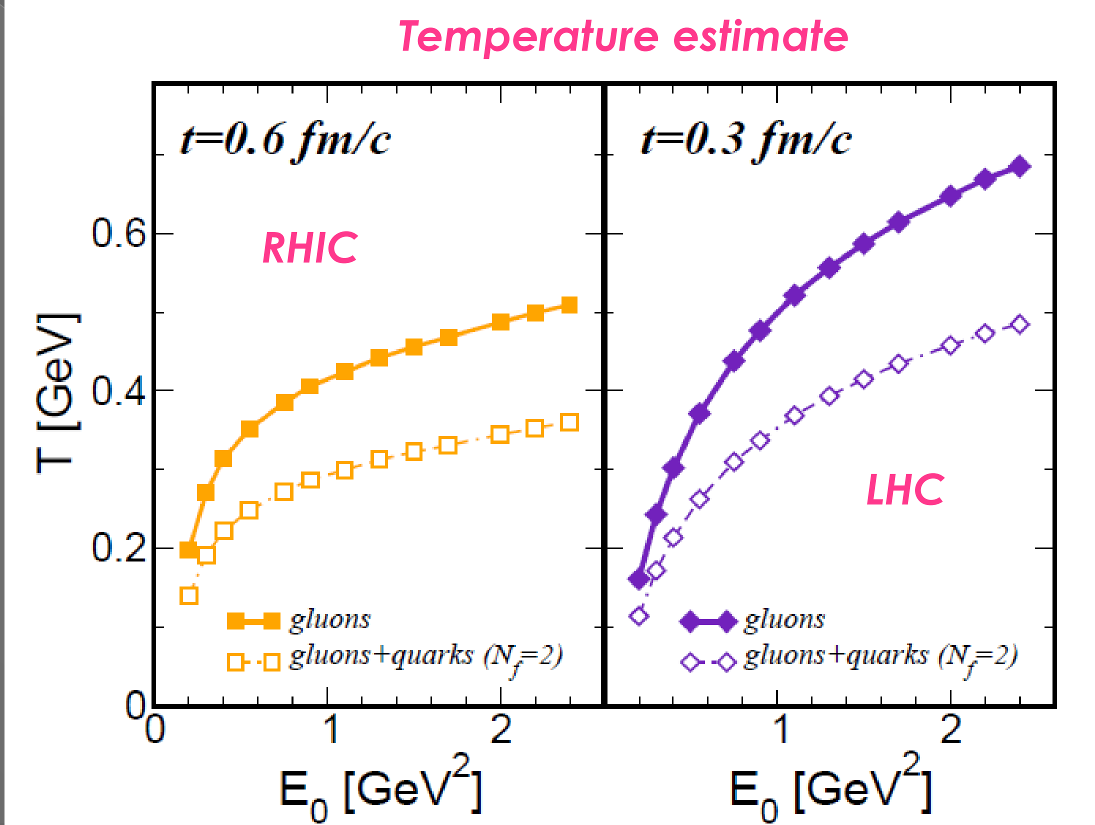
1+1D EXPANSION
local temperature

RHIC
free streaming up to t=0.6 fm/c
core temperature T=0.34 GeV

LHC
free streaming up to t=0.3 fm/c
core temperature T=0.5 GeV

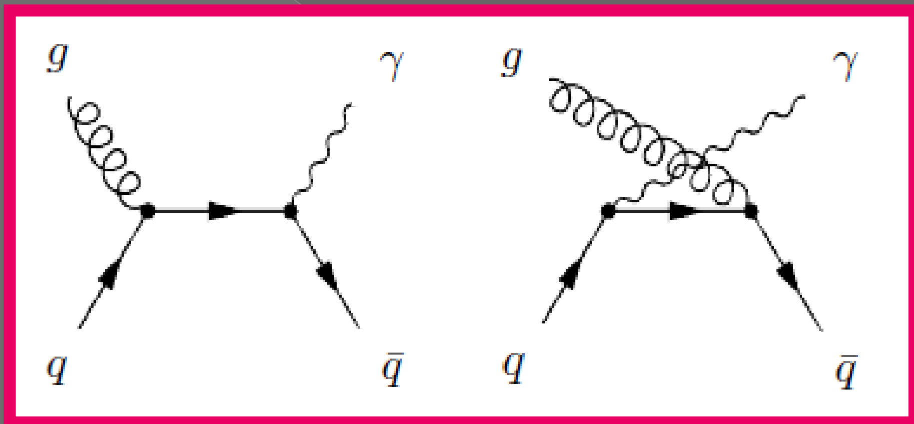


$$\varepsilon \propto T^4$$

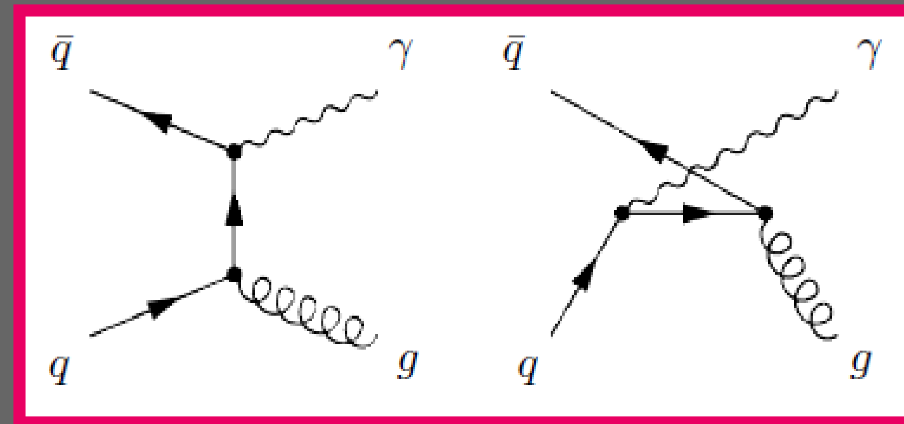


QCD Compton and annihilation reactions

These are the 2 → 2 particles Feynman diagrams contributing to $O(\alpha\alpha_s)$



QCD Compton scattering



quark-antiquark annihilation

$$q/\bar{q} + g \rightarrow q/\bar{q} + \gamma$$

$$\frac{d\sigma}{dt} = \frac{8\pi\alpha\alpha_s}{9s^2}\frac{u^2+t^2}{ut}$$

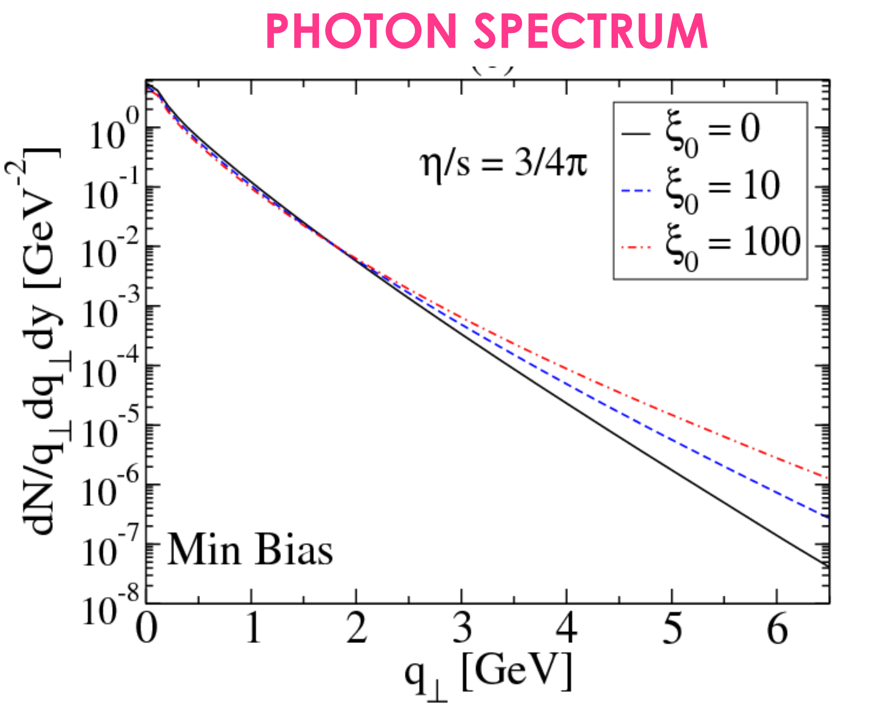
$$q + \bar{q} \rightarrow g + \gamma$$

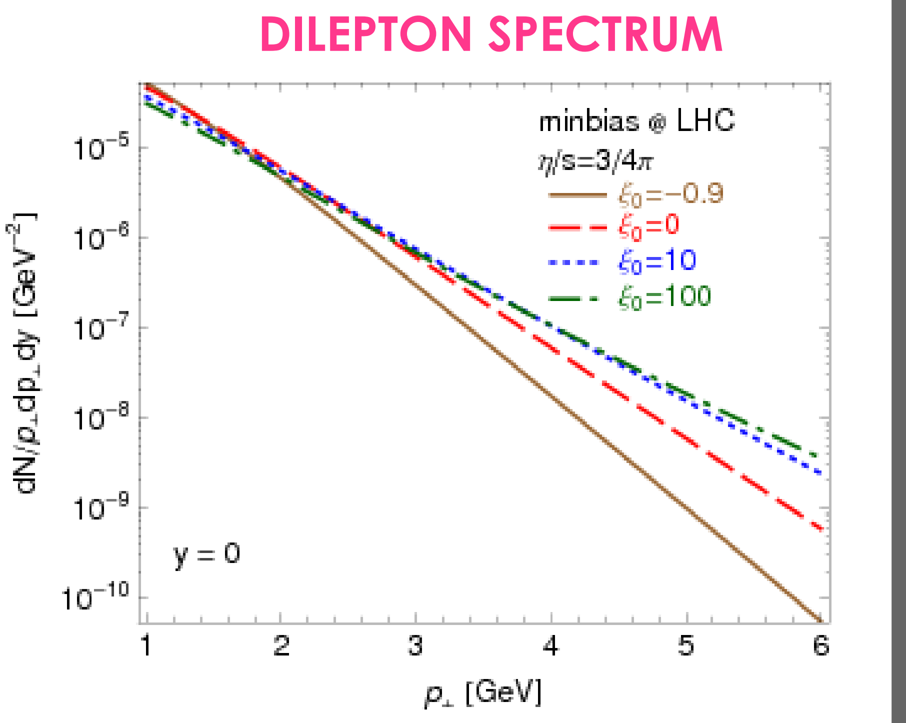
$$\frac{d\sigma}{dt} = \frac{-\pi\alpha\alpha_s}{3s^2}\frac{u^2+s^2}{us}$$

$$R_i = \mathcal{N}\int \frac{d^3p_1}{2E_1(2\pi)^3}\frac{d^3p_2}{2E_2(2\pi)^3} f_1(E_1)f_2(E_2)(2\pi)^4\delta(p_1^\mu + p_2^\mu - p_3^\mu - p^\mu) \mid \mathcal{M}_i \mid^2 \frac{d^3p_3}{2E_3(2\pi)^3}\frac{d^3p}{2E(2\pi)^3}[1 \pm f_3(E_3)]$$

$$\frac{d\sigma}{dt} = \frac{\mid \mathcal{M} \mid^2}{16\pi s^2}$$

OUTLOOKS





Bhattacharya *et al.* arXiv:1509.04249

Computation of
SPECTRUM and **ELLIPTIC FLOW**
of **PHOTONS** and **DILEPTONS**
emitted in **PRE-EQUILIBRIUM PHASE**