Strong field physics and early time dynamics in heavy ion collisions

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Aug 7th 2014 @ ATHIC2014

in Osaka University

Plan

- **Introduction**
- **CGC**: Initial Condition
  - rcBK meets experiments
    - DIS, pp, pA, heavy quarkonium
- **Glasma**: towards thermalization
- **Strong Field Physics**: as a tool to probe early stages
- **Summary**

Introduction

- **Progress in recent years**

  We have started to discuss

  correlation btw initial conditions and final data.

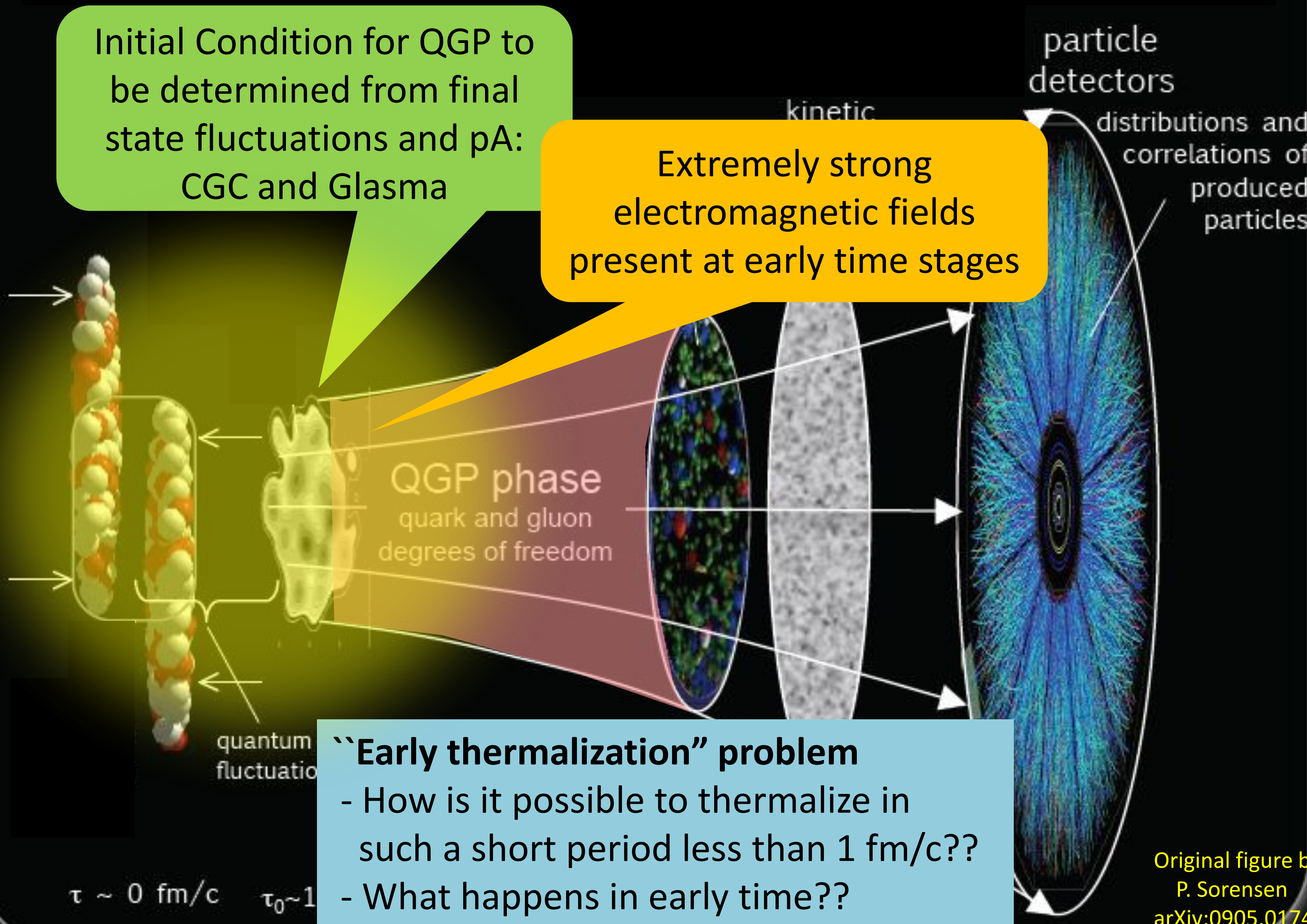
  typically, fluctuations of data (higher harmonics) are attributed to fluctuations in the initial conditions

- **Obviously need to deepen our understanding of initial conditions and early time stages of heavy-ion collisions.**

- **This talk**

  → overview of recent progress on initial condition and early-time evolution and possible new physics with strong magnetic fields

High energy view of Heavy Ion Collisions



Initial Condition for QGP to be determined from final state fluctuations and pA: CGC and Glasma

Extremely strong electromagnetic fields present at early time stages

``Early thermalization” problem

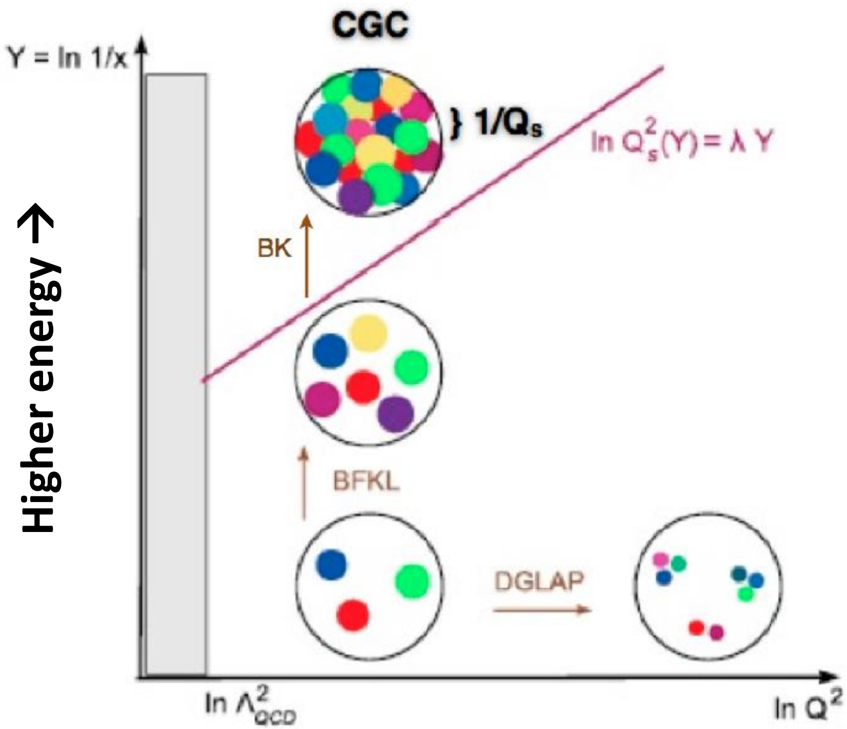
- How is it possible to thermalize in such a short period less than 1 fm/c??
- What happens in early time??

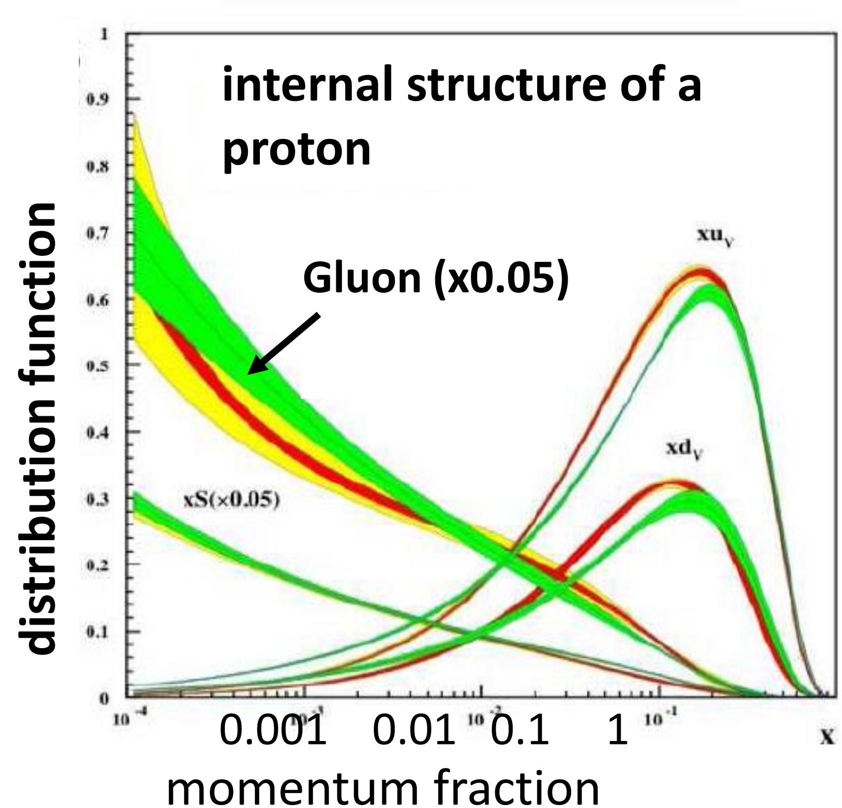
Original figure by P. Sorensen arXiv:0905.0174

CGC

Initial condition of HIC event

Color Glass Condensate





CGC : the framework to describe nuclei colliding at high energies, dense gluonic states with saturation

← multiple gluon emission & merging
slower quantum evolution, coherent effects

Going up higher energies: evolution eqs.

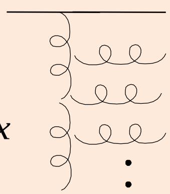
Evolution of gluon dstr. wrt x (or rapidity $y = \ln 1/x$)

- **BFKL** (LO : $(\alpha_s \ln 1/x)^n$, NLO: $\alpha_s (\alpha_s \ln 1/x)^n$)

$$\frac{\partial \phi(\mathbf{x}, \mathbf{k_t})}{\partial \ln(\mathbf{x_0}/\mathbf{x})} \approx \mathcal{K} \otimes \phi(\mathbf{x}, \mathbf{k_t})$$

Multiple gluon emissions

$N_g \sim e^{\omega \ln 1/x}$



K : gluon splitting g→ gg

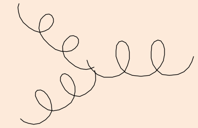
ϕ : unintegrated gluon distr.

- **BK** (includes the nonlinear effects)

Recombination of gluons

$N_g \leq 1$

Unitarity



$$\frac{\partial \phi(\mathbf{x}, \mathbf{k_t})}{\partial \ln(\mathbf{x_0}/\mathbf{x})} \approx \mathcal{K} \otimes \phi(\mathbf{x}, \mathbf{k_t}) - \phi(\mathbf{x}, \mathbf{k_t})^2$$

Known up to full NLO accuracy. [Balitsky, Chirilli 2008]

But for practical purposes, we use **BK with running coupling** → **"rcBK"** [Balitsky, Gardi et al. , Kovchegov-Weigert]

$$K^{\mathrm{run}}(\mathbf{r}, \mathbf{r_1}, \mathbf{r_2}) = \underbrace{\frac{N_c\,\alpha_s(r^2)}{2\pi^2}\left[\frac{r^2}{r_1^2\, r_2^2}\right.}_{\text{LO}} \left.+ \frac{1}{r_1^2}\left(\frac{\alpha_s(r_1^2)}{\alpha_s(r_2^2)} - 1\right) + \frac{1}{r_2^2}\left(\frac{\alpha_s(r_2^2)}{\alpha_s(r_1^2)} - 1\right)\right]$$

rcBK phenomenology

- **DIS**

  fit of small x data AAMQS2011

- **pA**

  forward hadron production MC-DHJ/rcBK

  heavy-quarkonium production

Albacete-Armesto-Milhano
Quiroga-Salgado,2009,2011

Fit to HERA data: AAMQS$_{2011}$

- Initial Conditions : modified GBW/MV models $x_0 = 0.00893$ or 0.008

$$\begin{cases} \mathcal{N}^{\rm GBW}(r, x = x_0) = 1 - \exp\left[-\dfrac{(r^2 Q_{s0}^2)^\gamma}{4}\right], \\ \mathcal{N}^{\rm MV}(r, x = x_0) = 1 - \exp\left[-\dfrac{(r^2 Q_{s0}^2)^\gamma}{4} \ln\left(\dfrac{1}{r\Lambda} + e\right)\right] \end{cases}$$

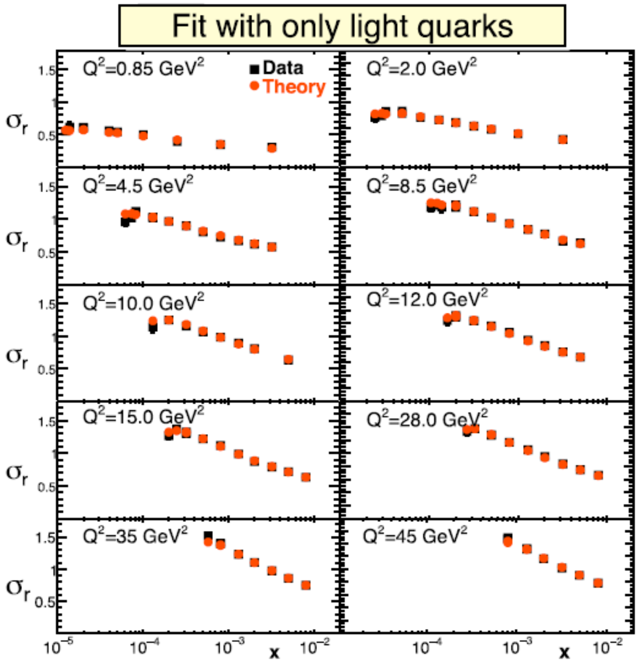
(γ=1 : ordinary GBW)

(γ=1 : ordinary MV)

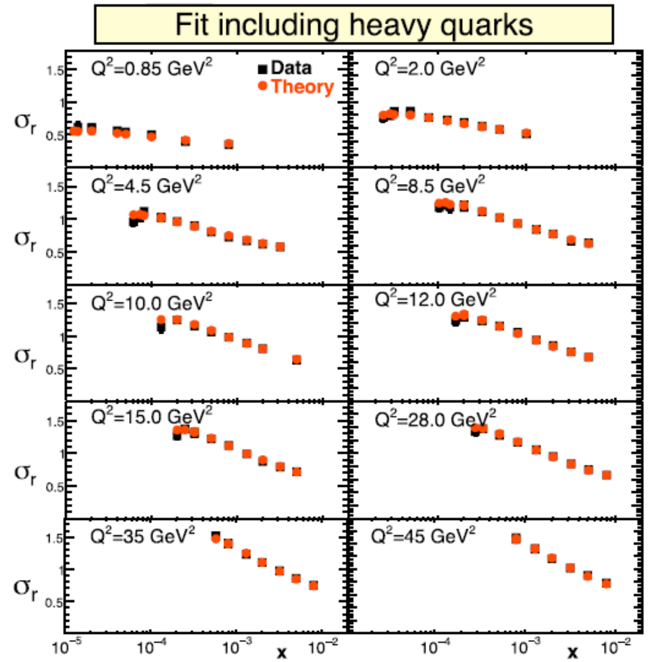
- IR regularization for 1-loop running coupling

$$\alpha_{s,n_f}(r^2) = \frac{4\pi}{\beta_{0,n_f} \ln\left(\frac{4C^2}{r^2 \Lambda_{n_f}^2}\right)}$$

freeze the coupling at $\alpha_s^{\rm fr} = 0.7$



m_{uds}=140MeV



m_c=1.27GeV, m_b=4.2GeV

← Modified GBW

(Left) γ=0.971
Qs_0^2=0.241

(Right) γ=0.959
Qs_0^2=0.240

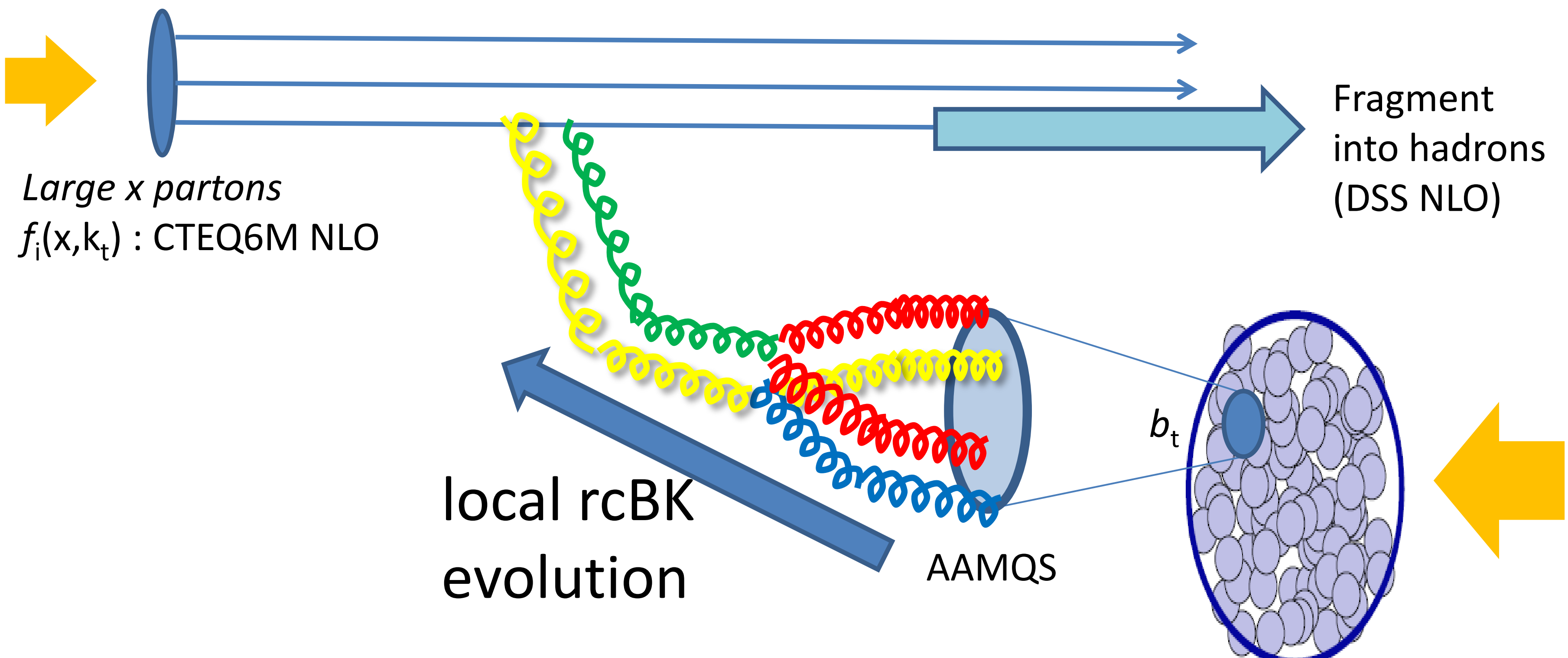
There are two more parameters (C,σ_0)

[Fujii,KI,Nara, 2011]

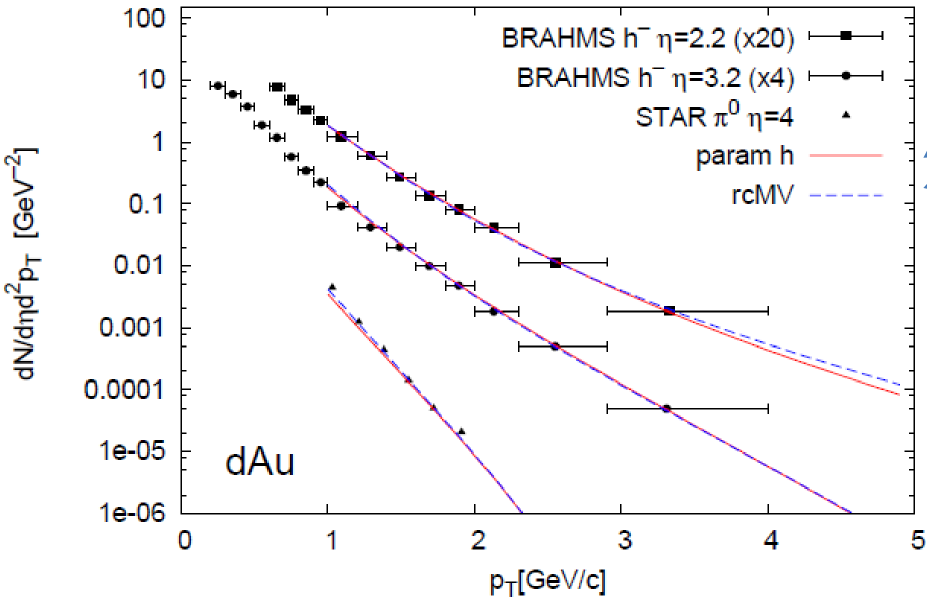
MC-DHJ/rcBK for forward production

State-of-the-art calculation of hadron production at forward rapidities

- construct a nucleus by randomly placing nucleons
- use AAMQS parameters for proton IC optimized for DIS at small-x
- quantum evolution is performed “locally” in b space
- **NO ADDITIONAL PARAMETERS**



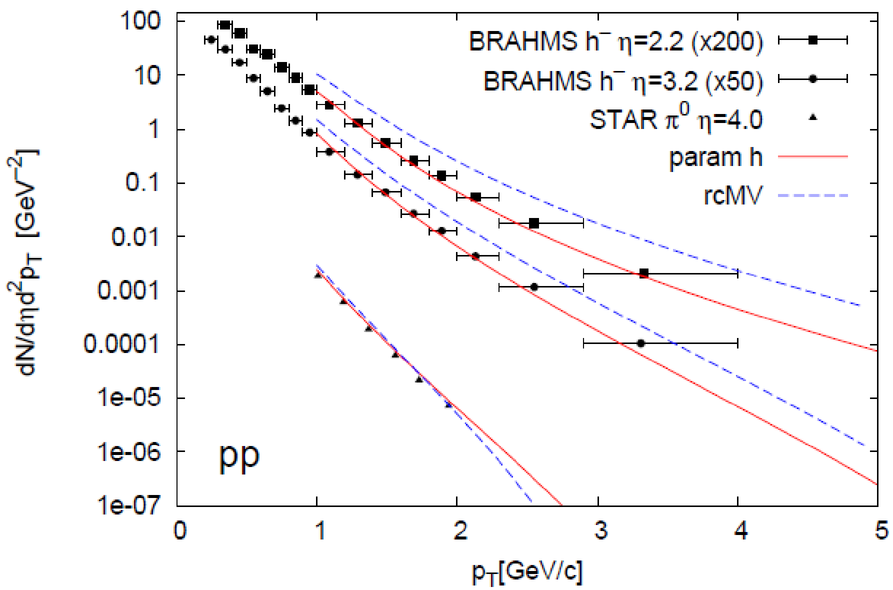
MC-DHJ/rcBK : results



modified MV model ($\gamma = 1.118$)

"running coupling" version of MV model [Iancu-KI-Triantafylopoulos] : to be consistent with rcBK evolution

- Set *h* works well even in *pp*, but not as good as Albacete-Marquet
- rcMV is not "tuned" (similar param as MV)
- However, both work quite well in dAu (IC dependence reduces at high rapidity)

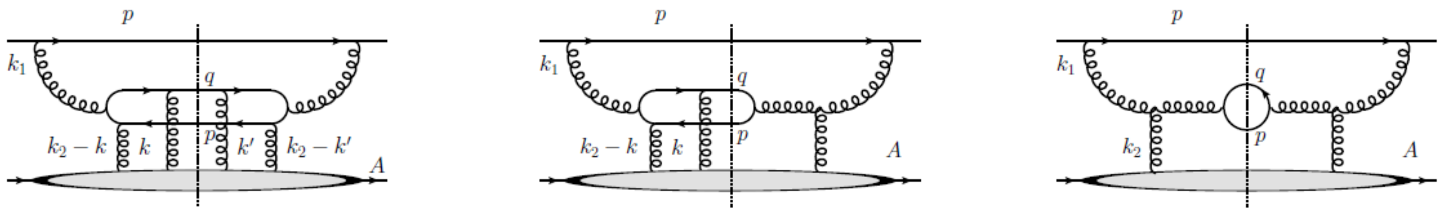


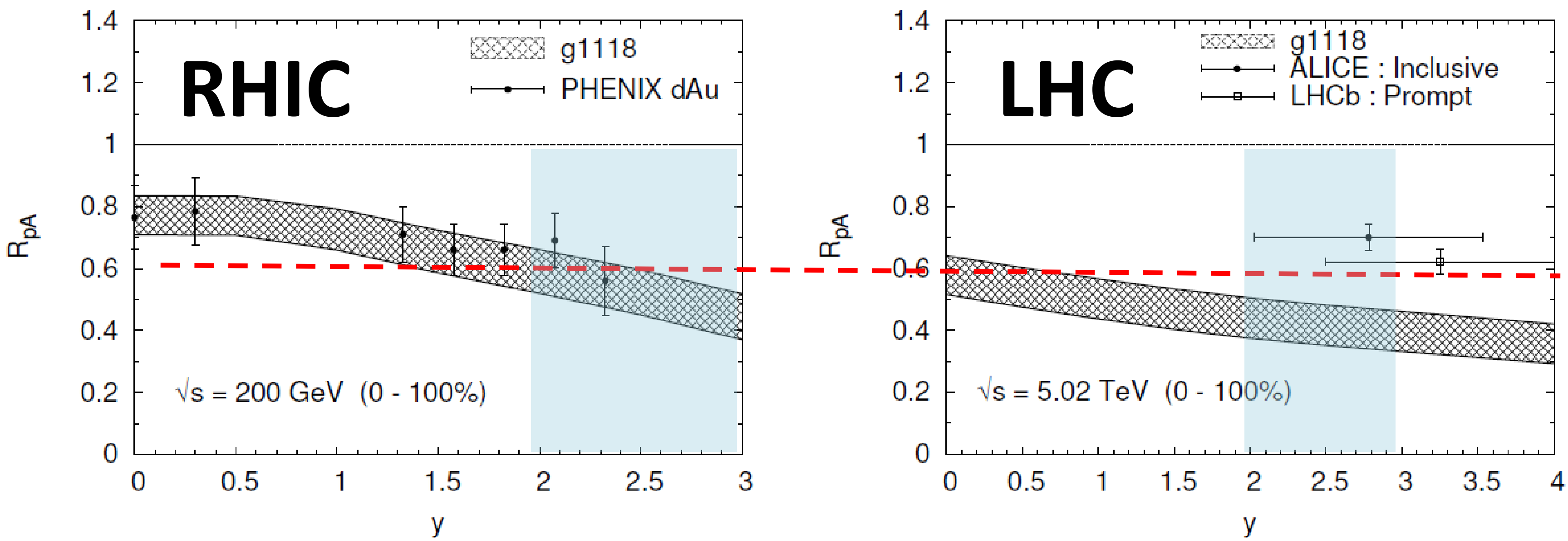
- reproduce the data nicely
- AAMQS set h and rcMV for $\mathcal{N}(r, y)$
- Q^2_{s0A} fixed by MC; no additional parameter

Towards global description of the event including soft fragmentation in the very forward region
→ 'DHJ+Lund' model by Y.Nara, today

Heavy Quarkonium prod. with rcBK

Blaizot,Gelis,Venugopalan, 2004
Watanabe,Fujii 2013





rcBK calculation (without param.) works well in RHIC data, but not in LHC
In LHC with larger collision energy, **stronger suppression is naturally expected and CGC should become a better framework**

← Exp. results suggest something extraordinary??

Glasma

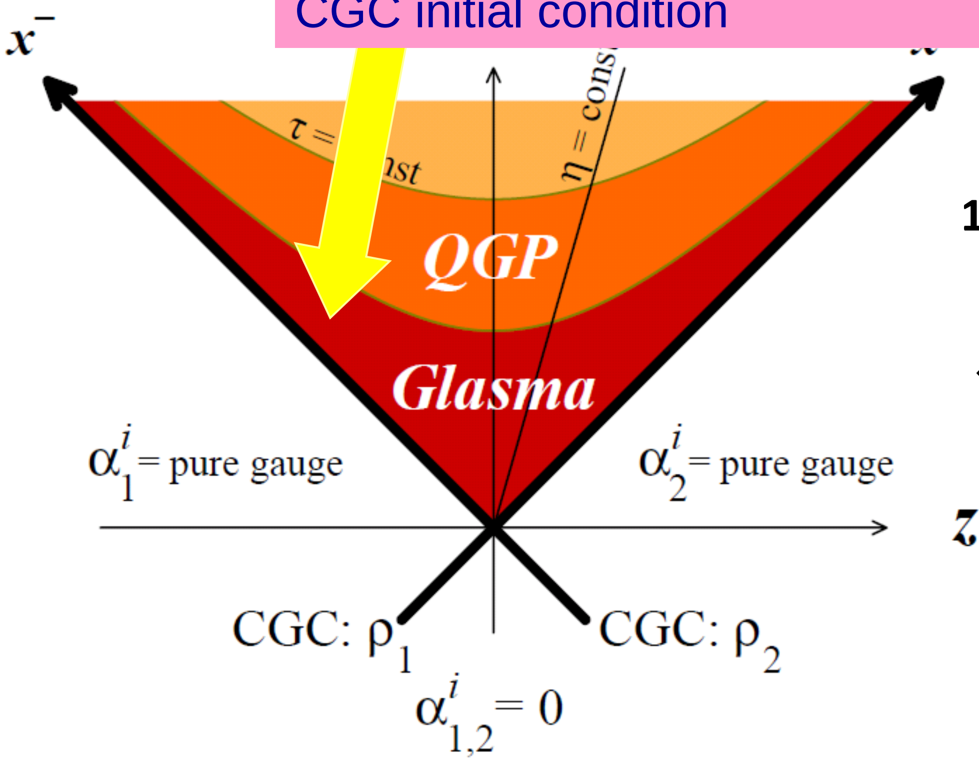
Preequilibrium dynamics towards QGP

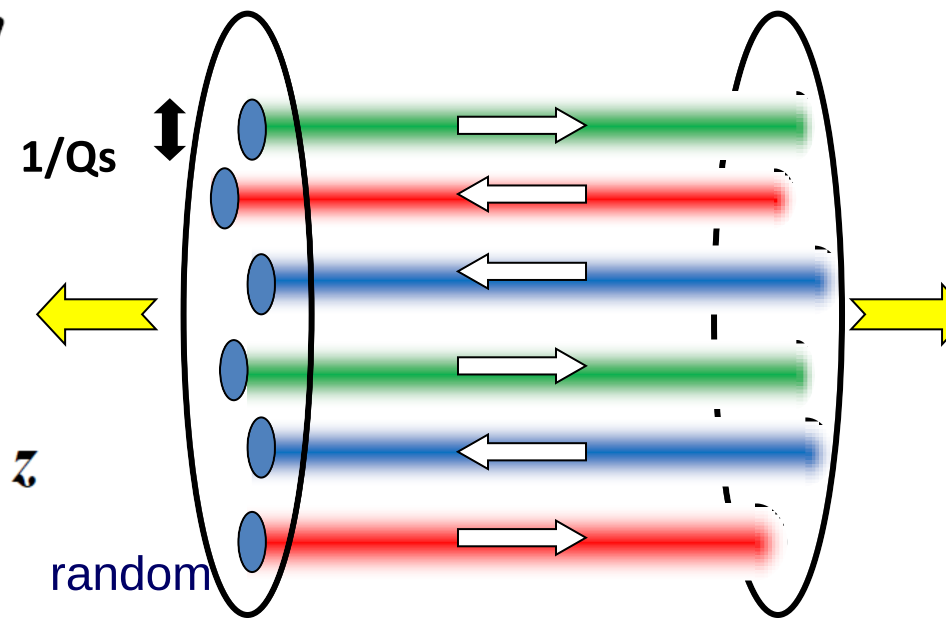
CGC turns into Glasma

Glasma : non-equilibrium matter between Color Glass Condensate (CGC) and Quark Gluon Plasma (QGP). Created in heavy-ion collisions.

solve Yang Mills eq. $[D_\mu, F^{\mu\nu}]=0$

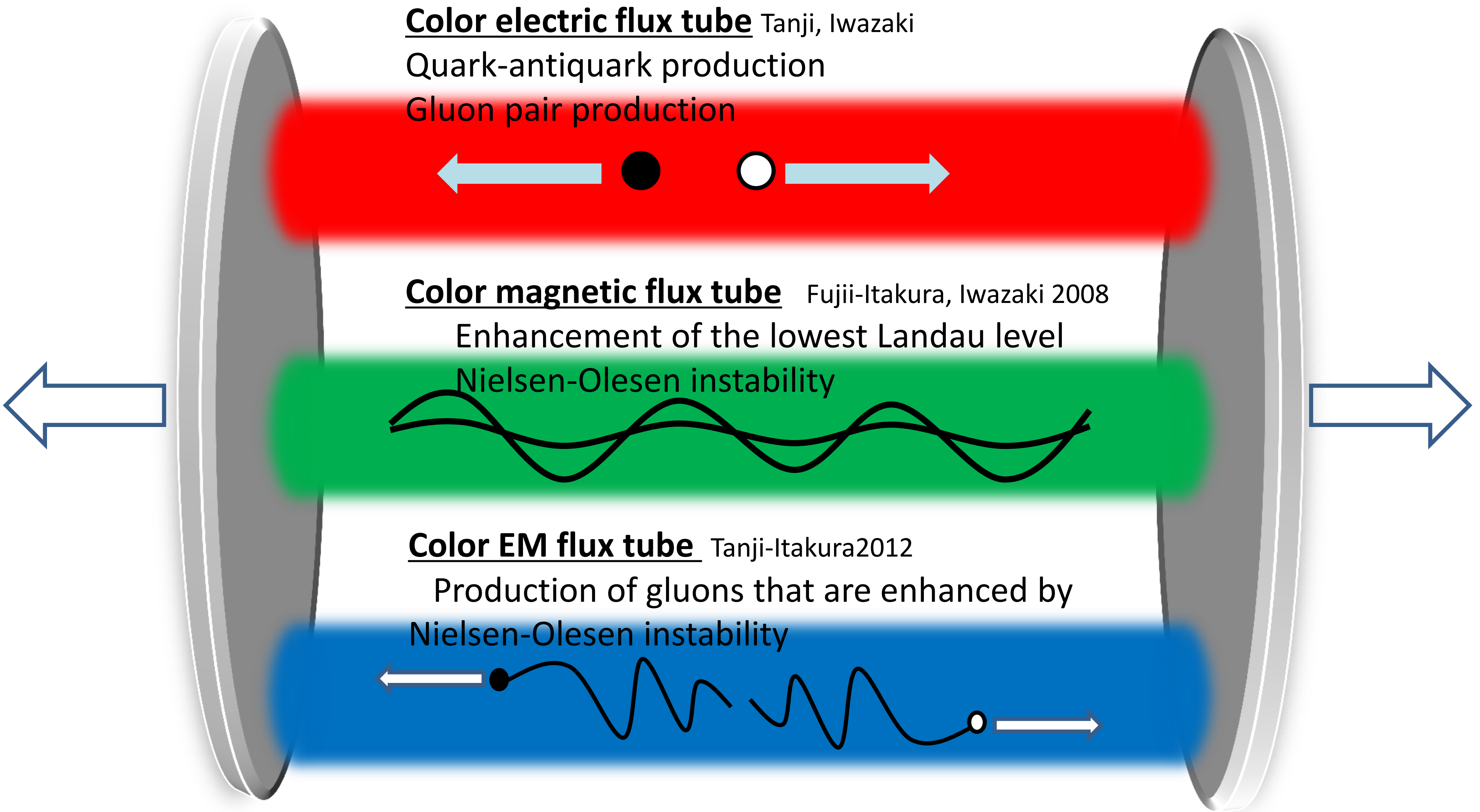
in expanding geometry with the CGC initial condition





Typical configuration of a single event just after the collision

Unstable Glasma



- Nonlinear time evolution of Glasma → Turbulent spectrum（≠ thermal）

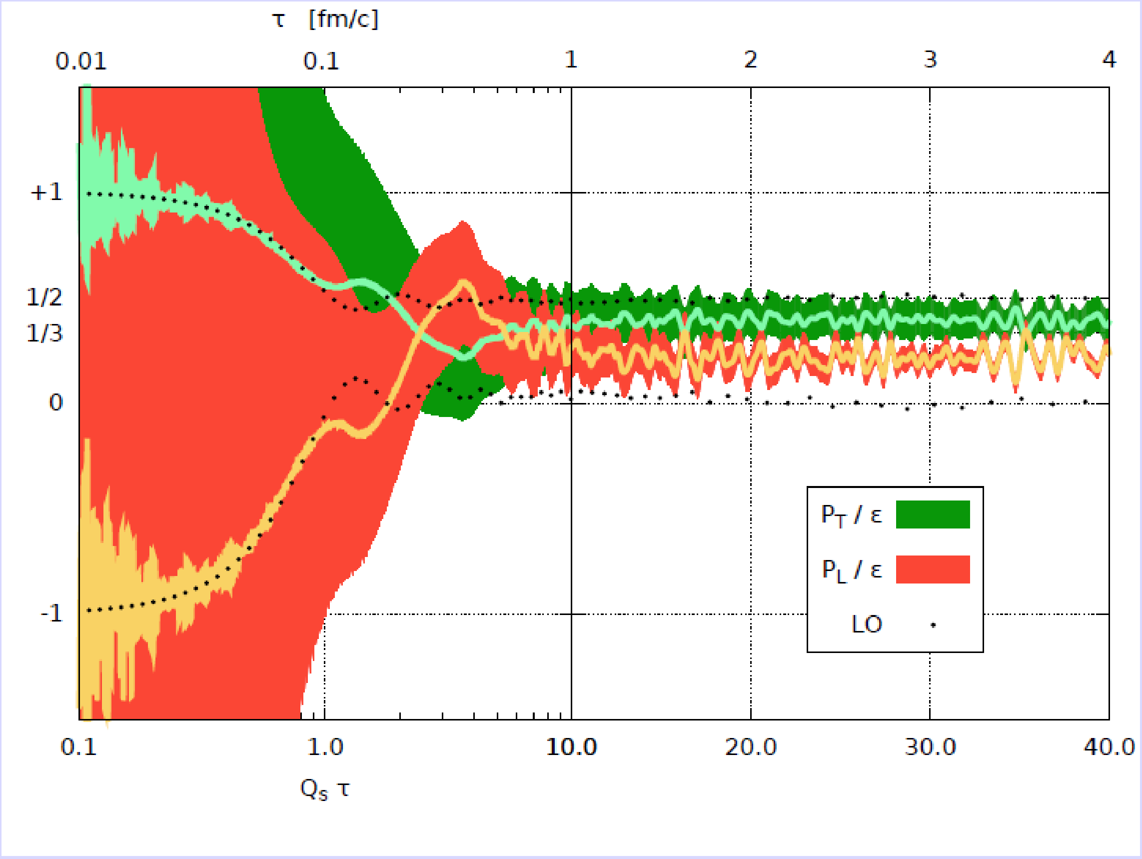
→ We definitely need more input from strong field physics

Glasma in Classical Statistical Simulation

Gelis, Epelbaum 2013

Time evolution of P_T/ϵ and P_L/ϵ ($64 \times 64 \times 128$ lattice)

$g = 0.5$ ($N_{\mathbf{confs}} = 2000$)

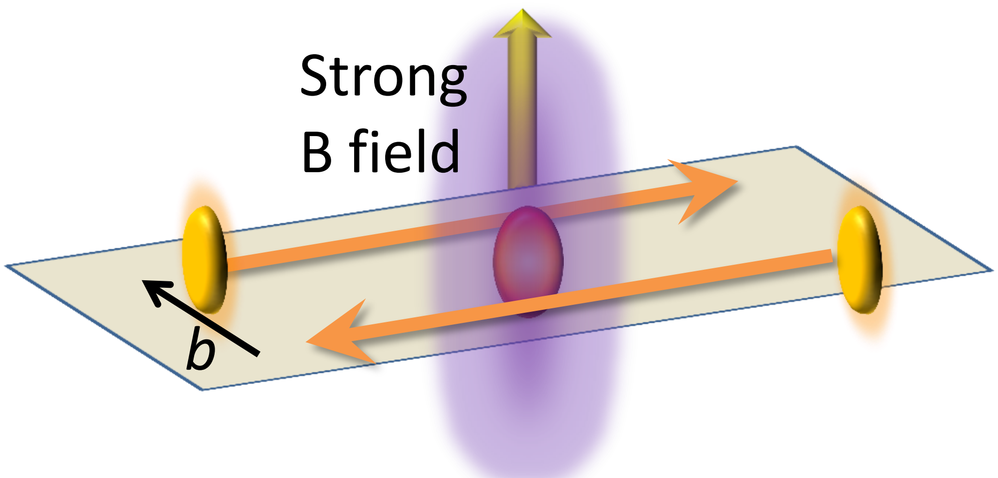


Strong Fields

A new tool to probe early time stages

Strong magnetic fields in HICs

- Non-central HICs at RHIC and LHC provide **STRONGEST** magnetic fields.



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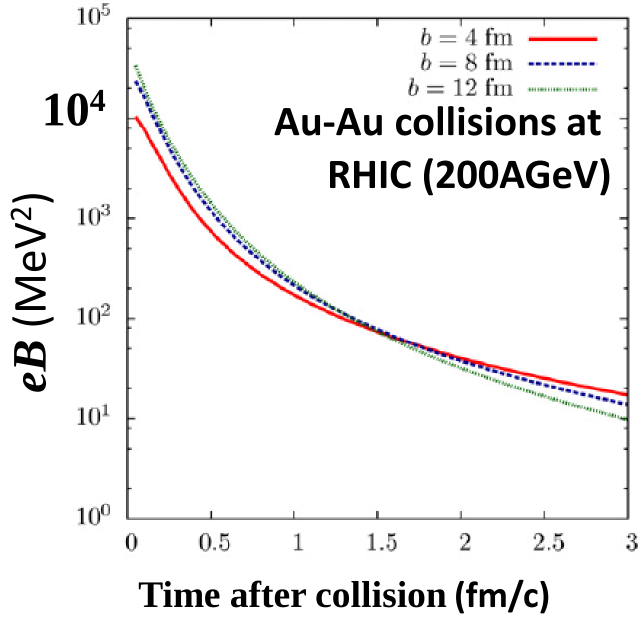
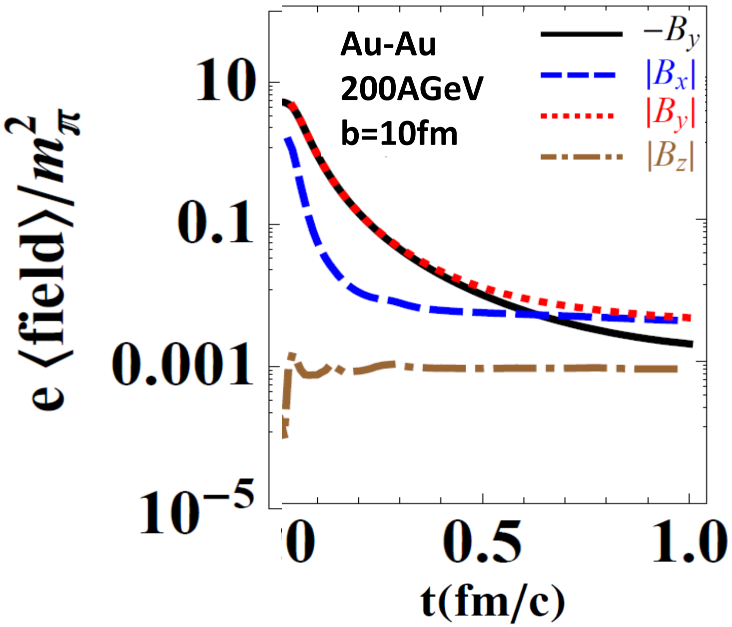
Kharzeev, McLerran, Warringa (2008)



Event-by-event analysis, Deng, Huang (2012)



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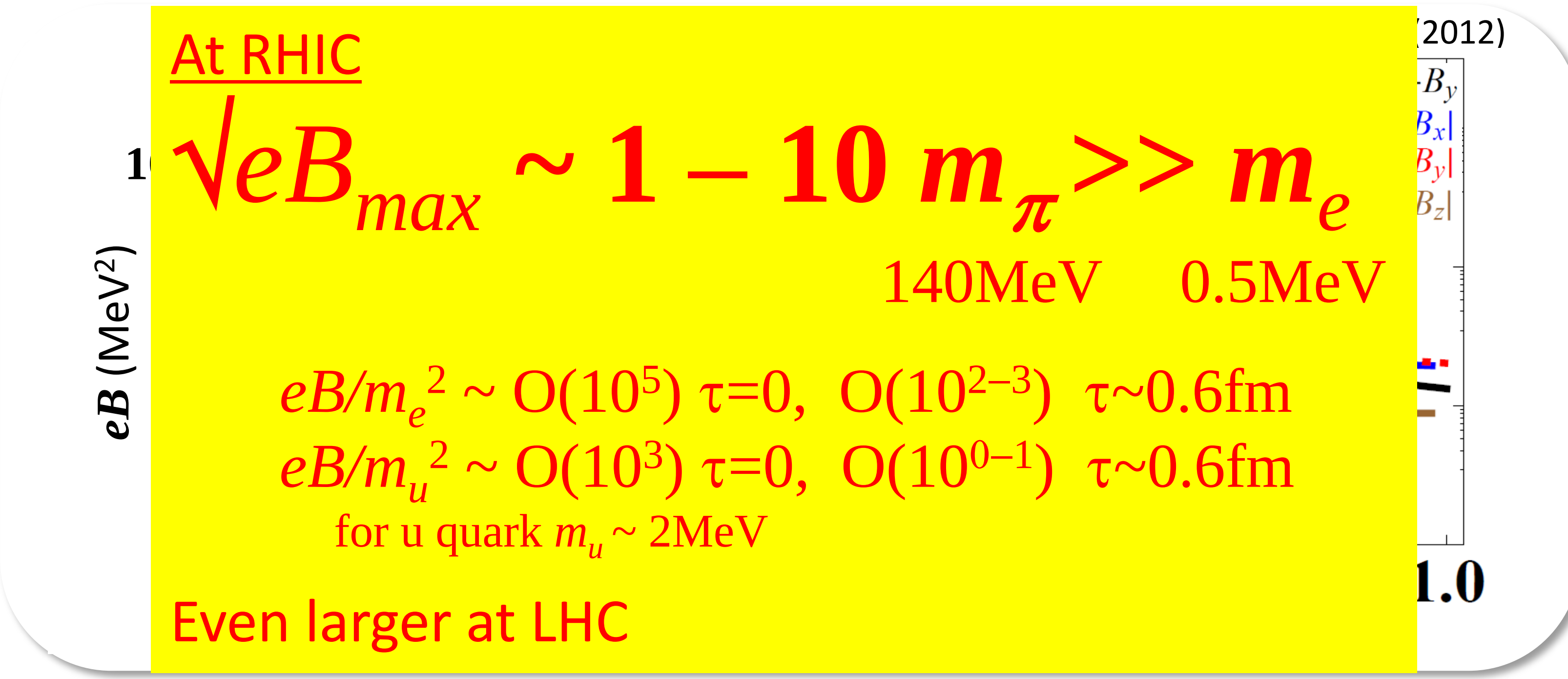


At RHIC

$$\sqrt{eB_{max}} \sim 1-10\ m_\pi >> m_e$$

140MeV 0.5MeV

$eB/m_e^2 \sim O(10^5)$ $\tau=0$, $O(10^{2-3})$ $\tau\sim0.6$fm

$eB/m_u^2 \sim O(10^3)$ $\tau=0$, $O(10^{0-1})$ $\tau\sim0.6$fm

for u quark $m_u \sim$ 2MeV

Even larger at LHC

- **Decay very fast**:

  Strong field physics will be most prominent in very early time!

  (though the fields are still strong enough even at QGP formation time)

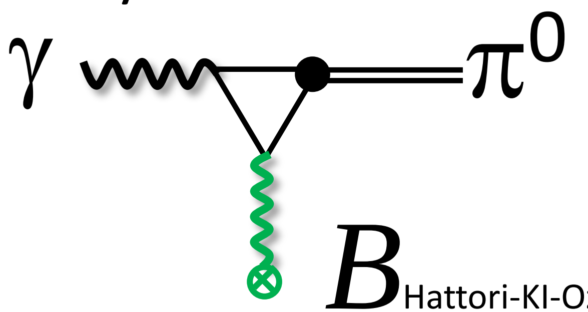
Very strong fields exist
at very early time in HIC

“Strong field physics”
can be a good probe of
early time dynamics in HICs

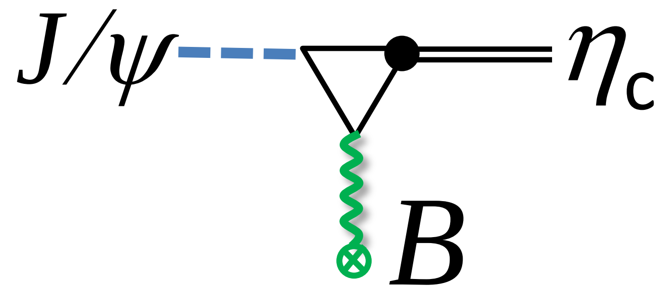
Can provide new insights
into unsolved problem of
“early thermalization”

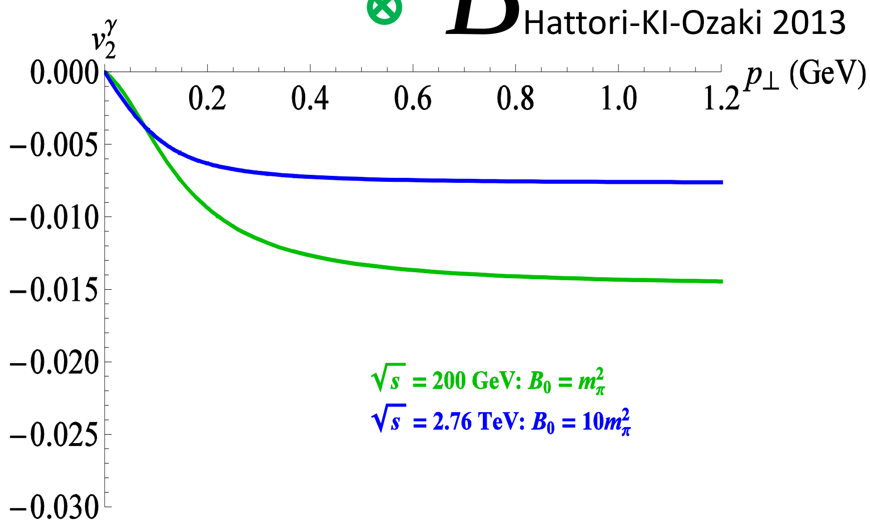
Examples of strong field physics

- Synchrotron radiation of photons and gluons (generate positive v2 of photon and pions, quantitative analysis difficult)
- Photon's vacuum birefringence and decay (generate negative v2)
- Anomaly induced conversion



Hattori-KI-Ozaki 2013



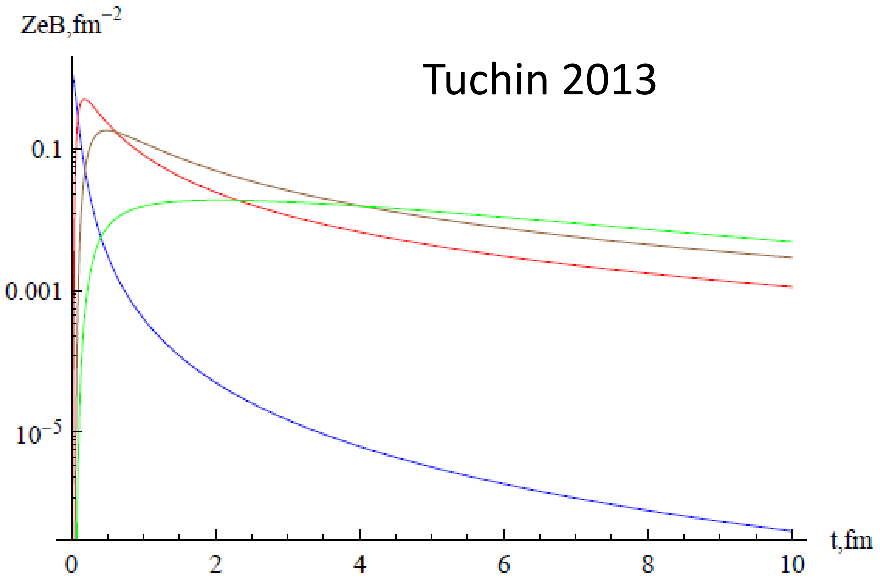


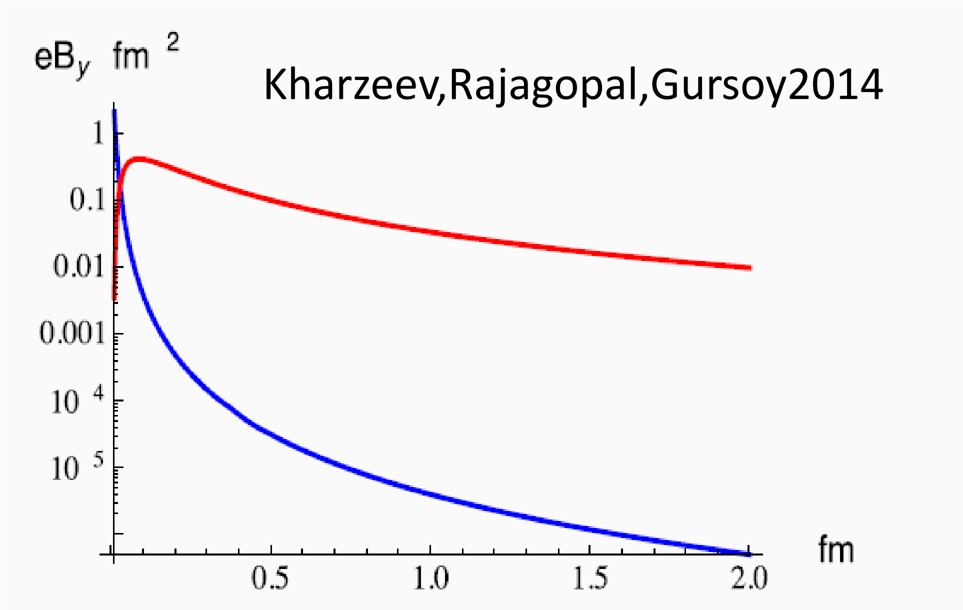
Larger vertex

Larger effects for J/psi v2??

Mixing btw J/psi and eta_c
Hattori, Ozaki, Lee, Morita
2014

Towards more realistic evolution of B





Inclusion of finite electric conductivity greatly affects time evolution of the fields.

Need to better understand the time evolution of B

Summary

- **Considerable progress** in understanding initial conditions and early time stages of heavy-ion collisions.

- **CGC**: rcBK provides good description. Something new and interesting in LHC?

- **Glasma**: still far from, but hopefully few steps towards thermalization. Need to understand physics behind numerics.

- **Strong Fields**: useful to probe pre-equilibrium stages