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IPhT CEA/Saclay

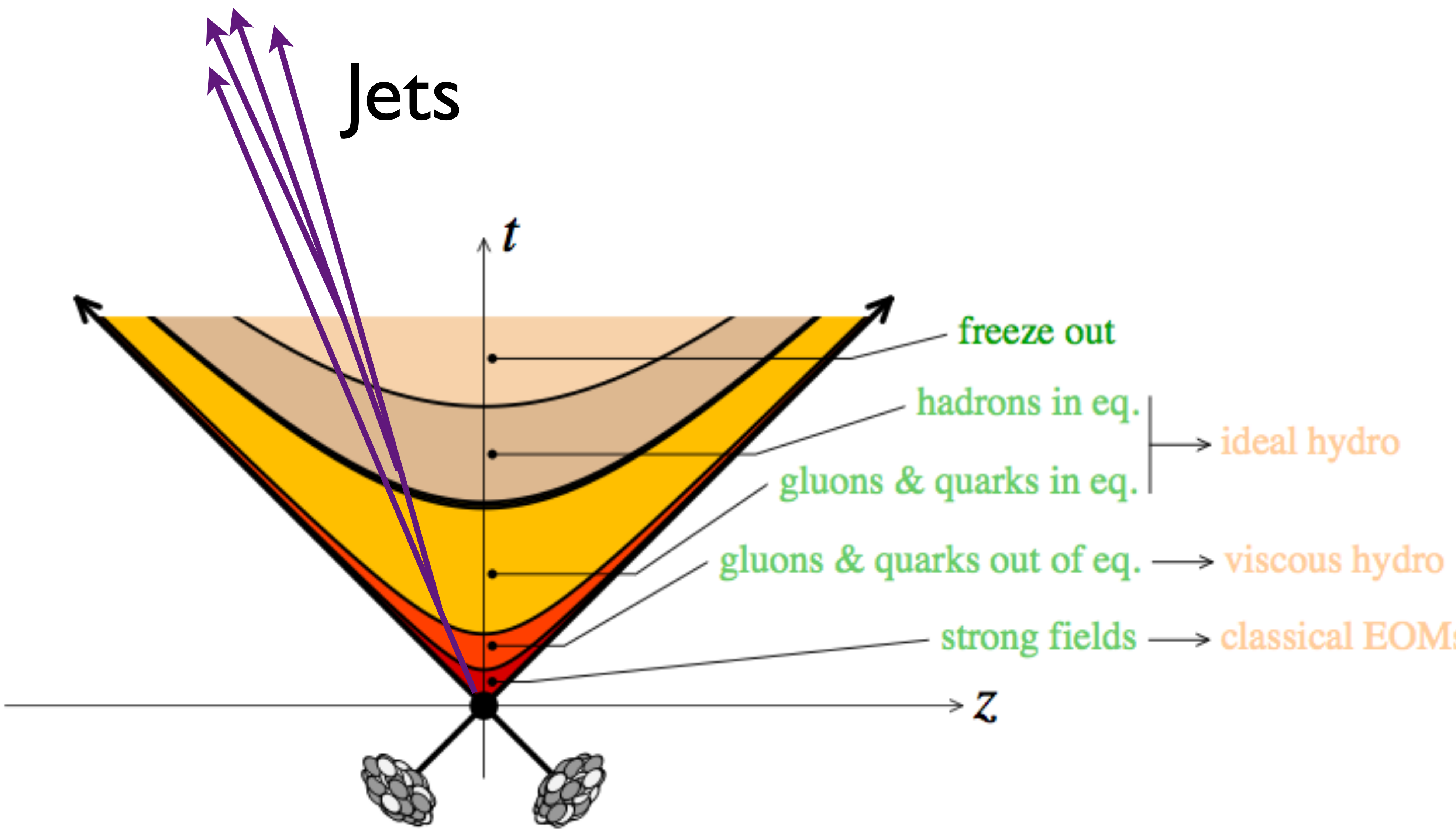
Highlights of (Theory)

IPN Orsay

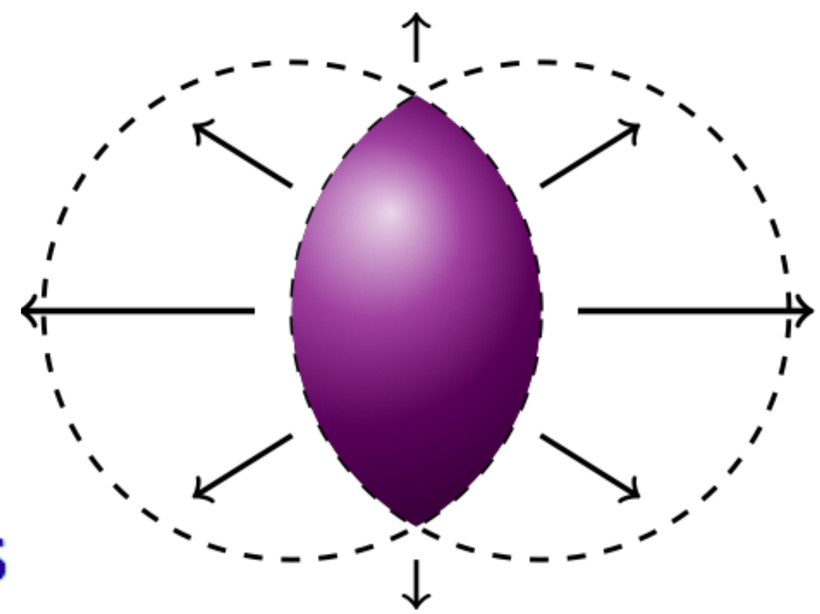
september 21, 2012

- ☑ Hydrodynamics
- ☑ Initial state and thermalization
- ☑ Jets
- ☑ 2-Particle correlations in pA

- ☐ Electro-weak probes
- ☐ heavy flavor and quarkonia
- ☐ QCD phase diagram



Hydrodynamics



initial
eccentricity
⇓
Flow

- Higher harmonics

$$\frac{dN}{dy d\phi} \propto 1 + 2v_1 \cos(\phi - \Theta_1) + 2v_2 \cos 2(\phi - \Theta_2) + 2v_3 \cos 3(\phi - \Theta_3) + 2v_4 \cos 4(\phi - \Theta_4) + \cdots$$

- Flow observables: since 2010

  Fluctuations ➡ higher harmonics

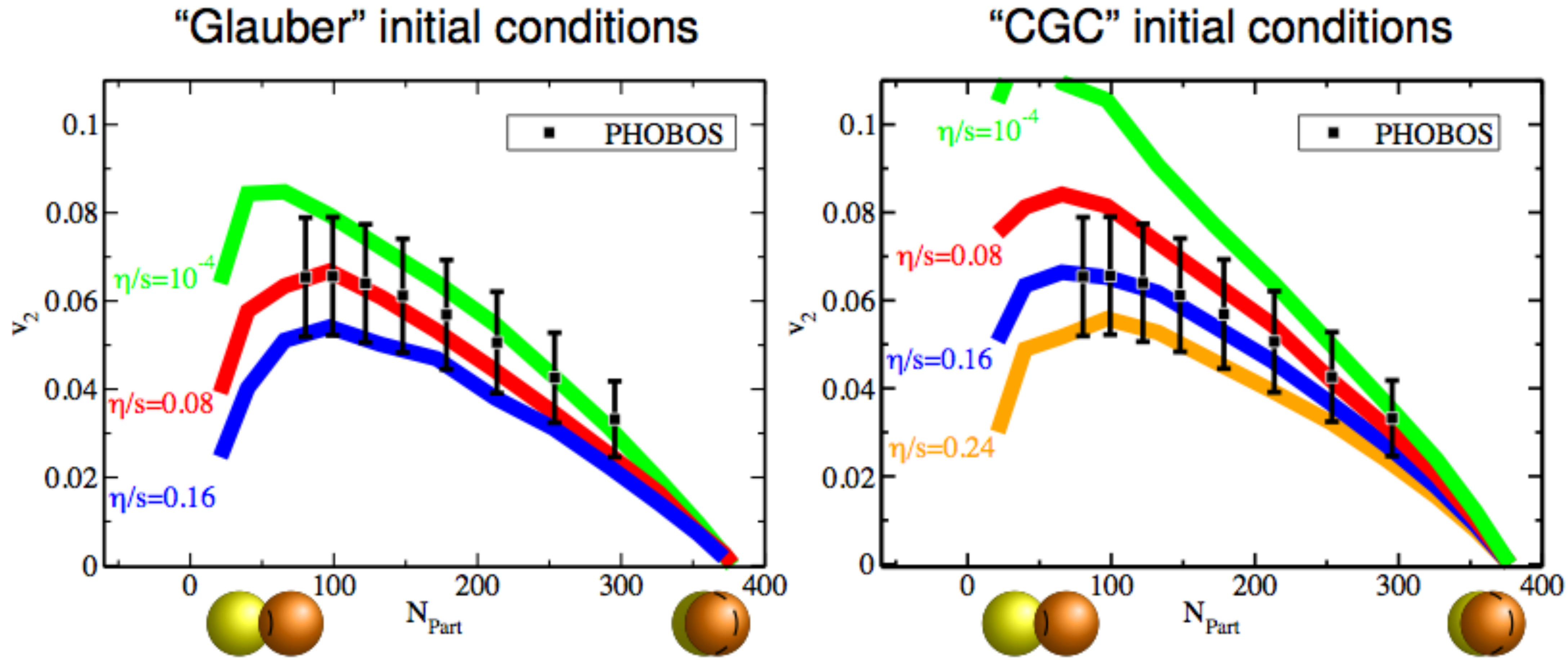
- Theory:

  Relativistic Viscous Hydro. OK!

  But sensitivity to initial eccentricity (initial cond.)

η/s FROM FLOW (HISTORICAL)

M. Luzum



(ML & Romatschke, Phys.Rev. C78 (2008) 034915)

- Best extraction of η/s by comparing viscous hydro to flow data
- Largest uncertainty from unknown initial condition

ADS-CFT bound: $\eta/s > 1/4\pi \approx 0.08$

A viscosity bound from fluid dynamics

P. Romatschke

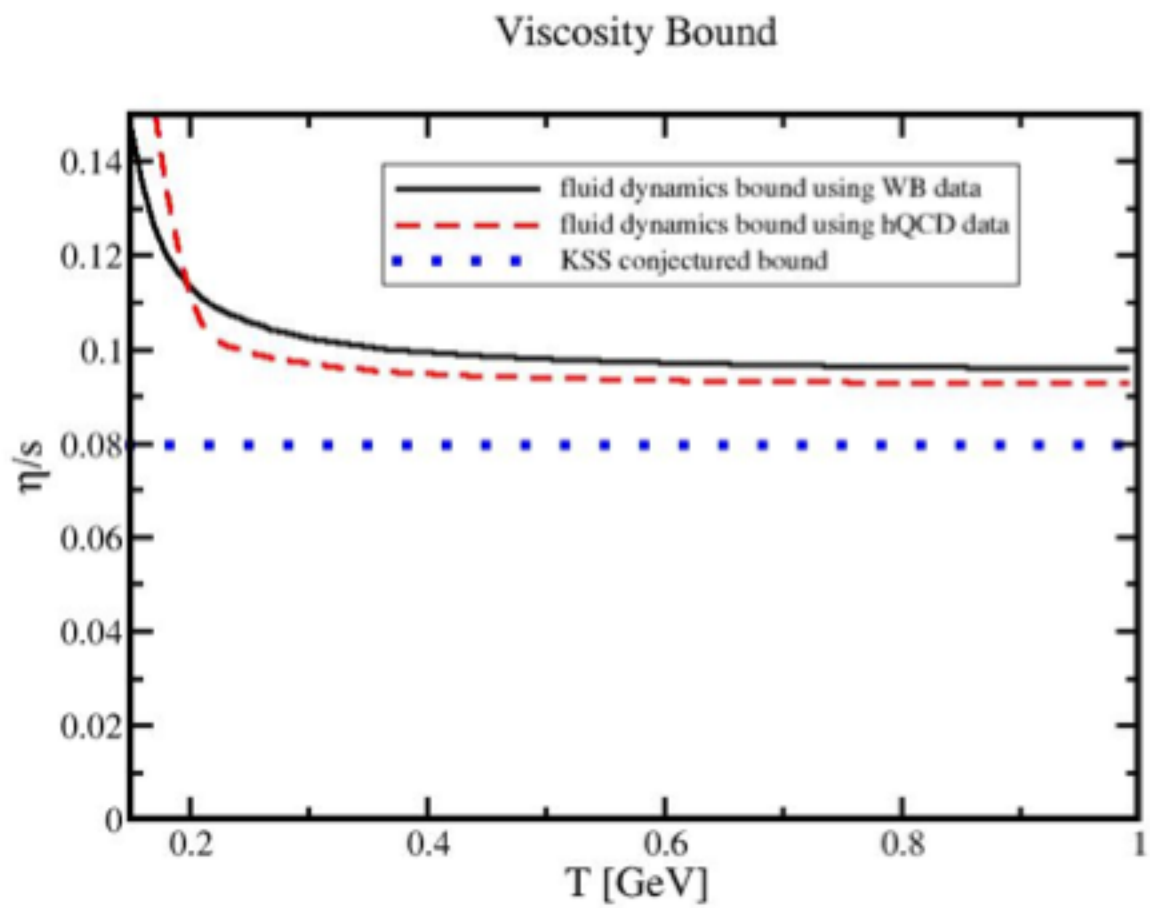
This leads to

$$\eta_{\text{physical}} = \eta + \frac{17T(\epsilon + P)^2}{240\pi^2\eta^2}$$

which implies a lower bound on the physical viscosity:

$$\frac{\eta_{\text{physical}}}{s} > \left(\frac{153}{320\pi^2}\frac{T^3}{s}\right)^{1/3} \simeq 0.09(\text{QGP})$$

Long-lived sound waves scatter off and contribute to the shear viscosity



[Kovtun, Moore & PR, arXiv:1104.1586]

Initial state fluctuations

B. Schenke

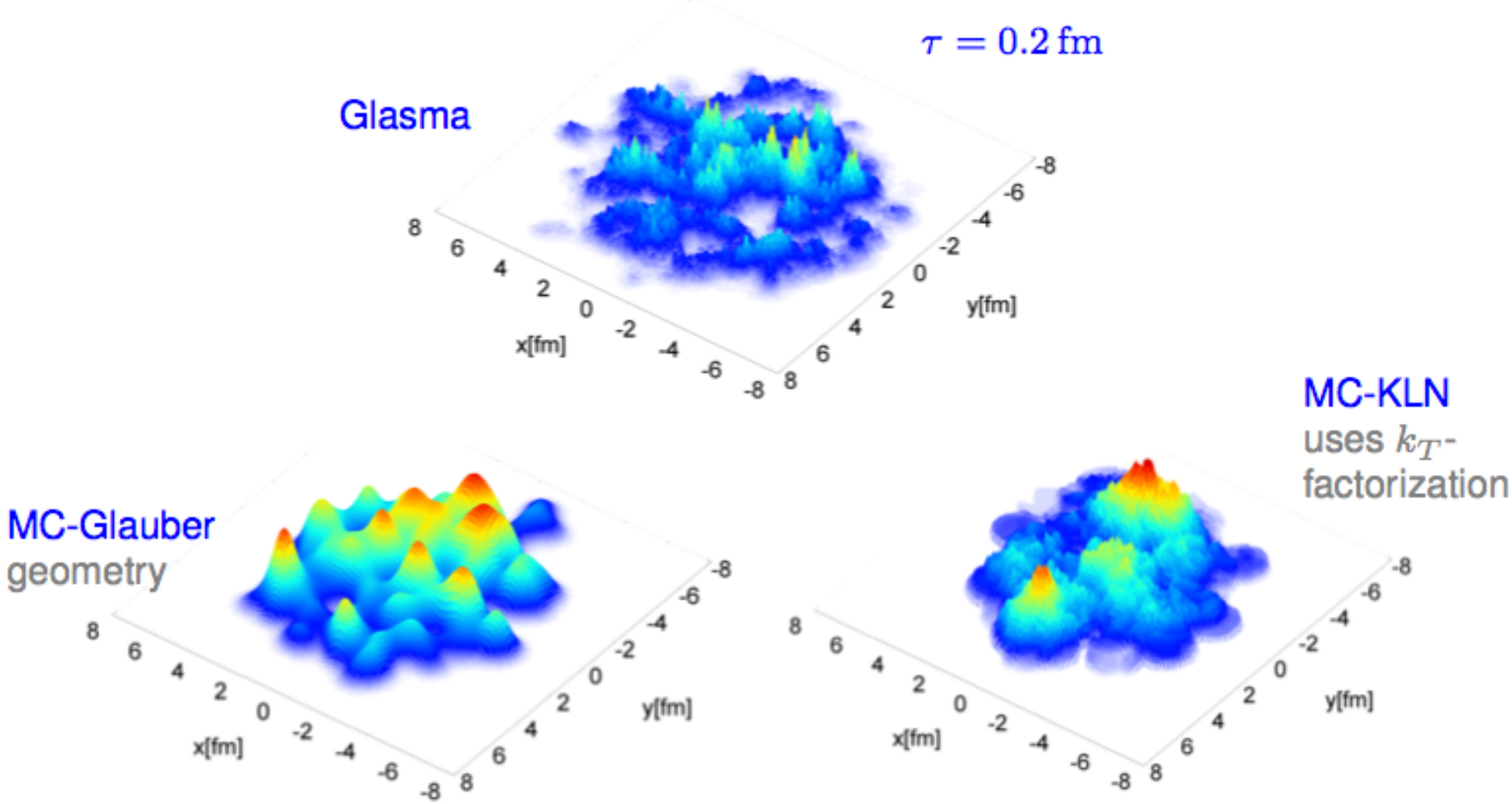
Energy density

B.Schenke, P.Tribedy, R.Venugopalan, Phys.Rev.Lett. 108, 252301 (2012)

Solve for gauge fields after the collision in the forward lightcone

Compute energy density in the fields at $\tau = 0$ and later times with CYM evolution

Lattice: Krasnitz, Venugopalan, Nucl.Phys. B557 (1999) 237



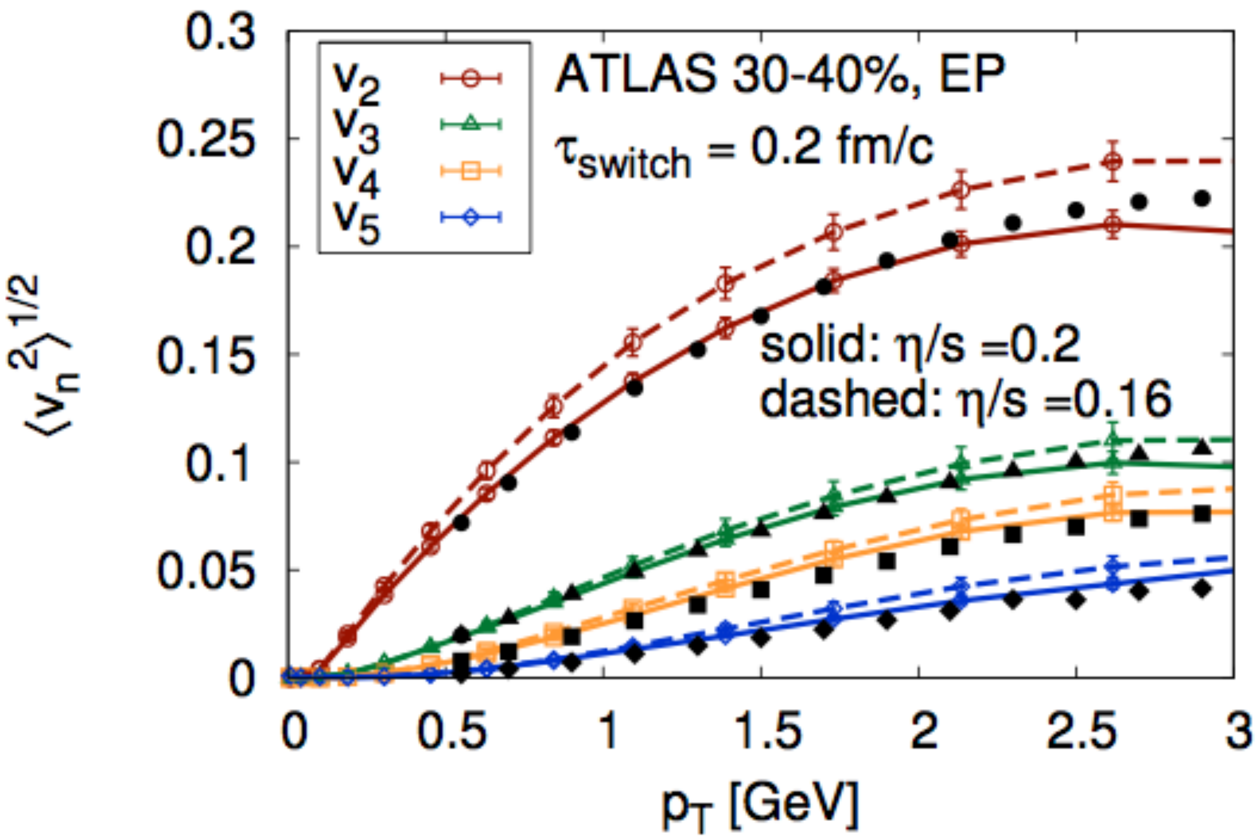
Very different initial energy density distributions in the models

MC-KLN: Drescher, Nara, nucl-th/0611017

Initial state fluctuations (Glasma)

Smaller average η/s

B. Schenke



Using $\eta/s = 0.16$ overestimates all v_n

M. Luzum

Final Result:

$0.07 \leq \eta/s \leq 0.43$

Before Hydro $\tau < 1$ fm (Initial state):

From

Color Glass Condensate (nuclear wave function)

to Thermalization

P. Chesler

From ADS-CFT:

Holographic thermalization

Holographic dictionary: Black hole in a "box" $\Leftrightarrow$ QGP.

- QGP formation & thermalization $\Leftrightarrow$ gravitational collapse and black hole thermalization.

- Relaxation to hydro is quick!

  - RHIC estimate: $t_{\text{hydro}} \sim 0.35$ fm/c.
  - $t_{\text{hydro}} \sim 1$ fm/c need not be thought of as unnaturally rapid!

- Natural order: thermalization after "hydrodynamization."

  - $(\text{a few}) \times t_{\text{hydro}} \lesssim t_{\text{therm}}(\omega, |\mathbf{q}|) \lesssim \frac{1}{T}\left(\frac{|\mathbf{q}|}{T}\right)^{1/3}.$

W. Florkowski

But hydro rather requires early isotropization...

➡ Running Anisotropic Hydro

- moments of anisotropic distributions

$$T^{\mu\nu} = \int \frac{d^3p\, p^\mu p^\nu}{(2\pi)^3 E_p} f(p\cdot U, p\cdot V) = (\varepsilon + P_\perp)\, U^\mu U^\nu - P_\perp\, g^{\mu\nu} - (P_\perp - P_\parallel)\, V^\mu V^\nu$$

$$S^\mu = \int \frac{d^3p}{(2\pi)^3} \frac{p^\mu}{E_p} f(p\cdot U, p\cdot V) \left[1 - \ln\left(\frac{f(p\cdot U, p\cdot V)}{g_0}\right)\right] = \sigma U^\mu$$

- for further analysis most convenient two independent parameters are x (anisotropy parameter) and σ (non-equilibrium entropy density)

$$(P_\perp, P_\parallel) \text{ or } (\lambda_\perp, \lambda_\parallel) \longrightarrow (\sigma, x)$$

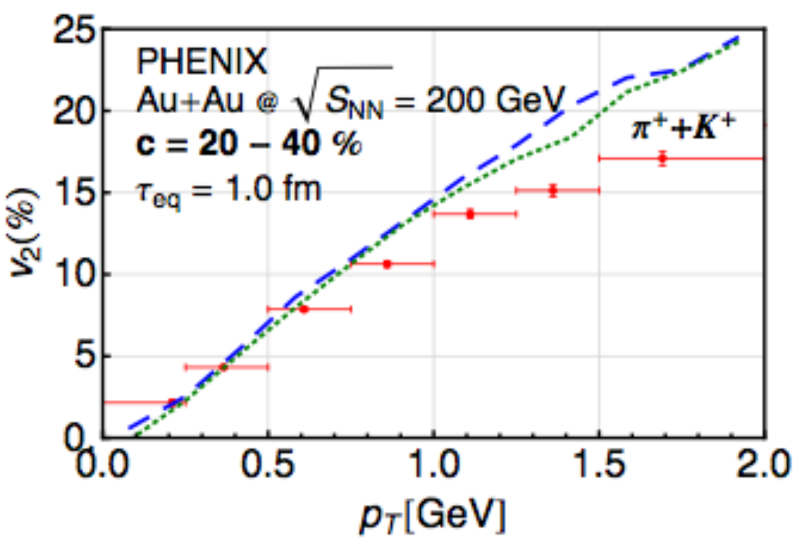
W. Florkowski

But hydro rather requires early isotropization...

➡ Running Anisotropic Hydro

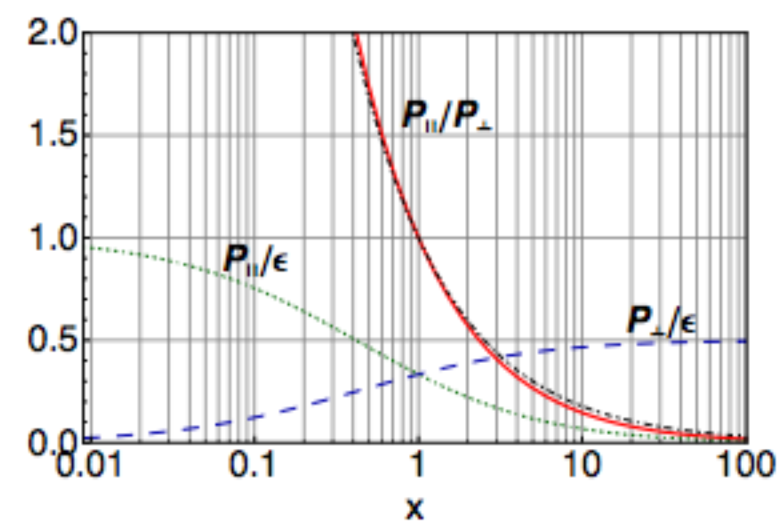
generalized equation of state

Initial anisotropy : x_0 = 1 (black), x_0 = 100 (blue), and x_0 = 0.032 (green)



$$\begin{aligned}
\varepsilon(\sigma, x) &= \varepsilon_{\rm id}(\sigma) r(x) \\
P_\perp(\sigma, x) &= P_{\rm id}(\sigma)\left[r(x) + 3x r'(x)\right] \\
P_\parallel(\sigma, x) &= P_{\rm id}(\sigma)\left[r(x) - 6x r'(x)\right]
\end{aligned}$$

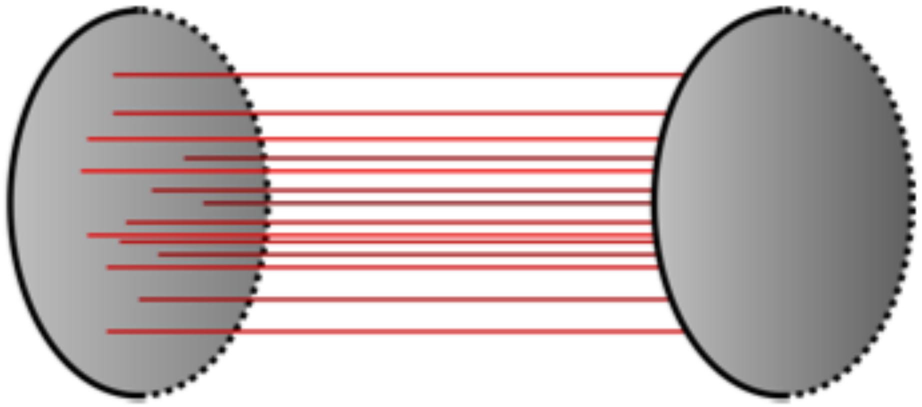
$$r(x) = \frac{x^{-\frac{1}{3}}}{2}\left[1 + \frac{x \arctan\sqrt{x-1}}{\sqrt{x-1}}\right]$$



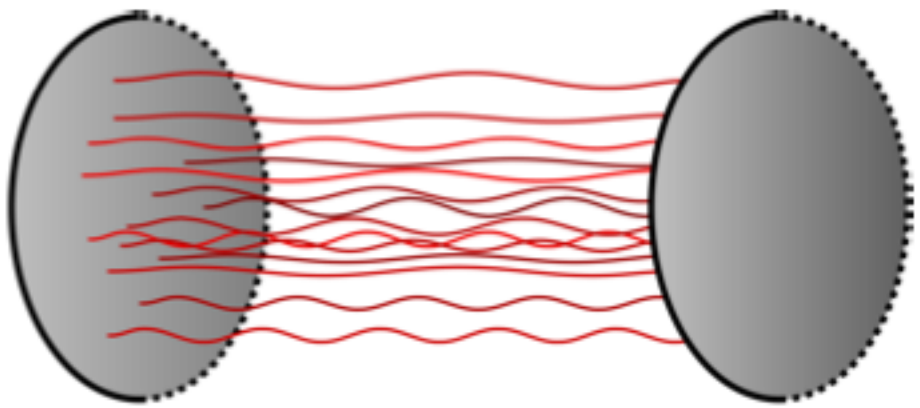
QCD: Classical Yang Mills

K. Dusling

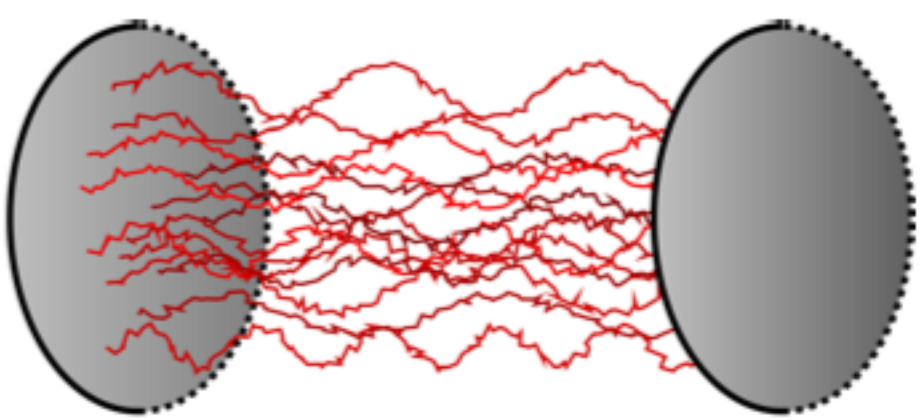
$\tau = 0:$

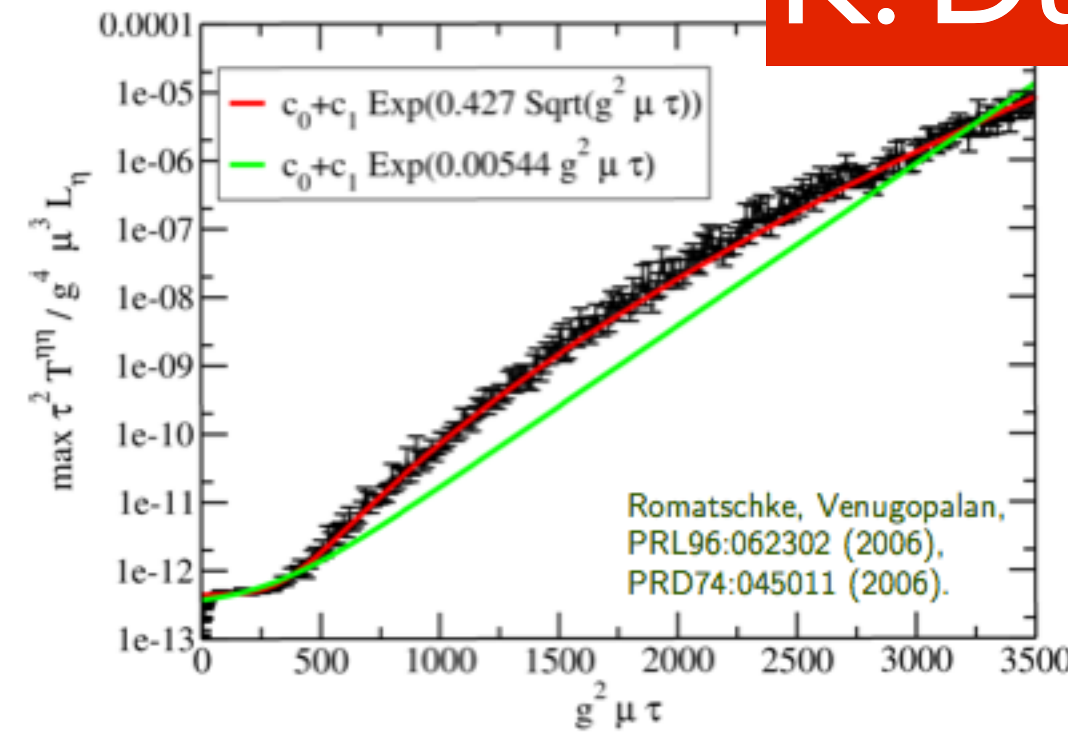


$\tau = 0^{+}:$



$\tau \gtrsim Q_s^{-1} \ln^2\left(g^{-1}\right):$





Perturbative expansion breaks down at

$$\tau_{\max} = Q_s^{-1} \ln^2\left(g^{-1}\right)$$

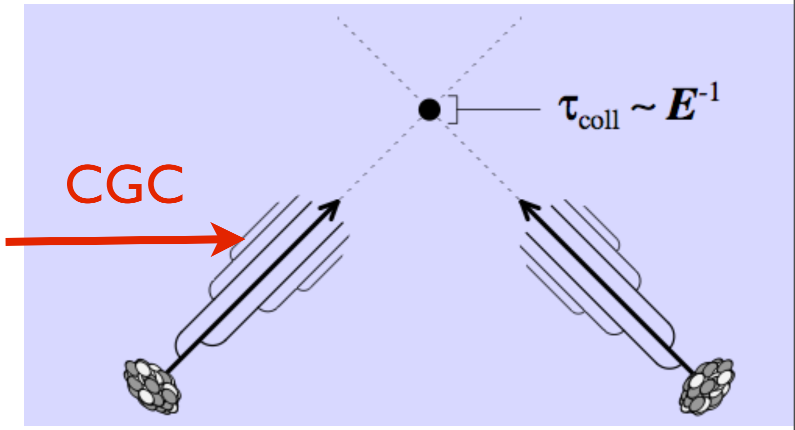
requiring a resummation of all terms like

$$\left[g \exp\left(\sqrt{Q_s \tau}\right)\right]^n$$

See also:
Berges, Scheffler, Sexty, PRD77:034504 (2008),
PLB677 210-213 (2009), PLB681 362-366 (2009).
Berges, Scheffler, Schlichting, Sexty, PRD85:034507 (2012).
Kunihiro, Muller, Ohnishi, Schafer, Takahashi, Yamamoto,
PRD82:114015 (2010).

R. Venugopalan

The first fermi: a master formula



Also correlators of $T^{\mu\nu}$

✓ From solutions of B-JIMWLK

$$\langle\langle T^{\mu\nu}\rangle\rangle_{\mathrm{LLx+Linst.}} = \int [D\rho_1][D\rho_2]\, W_{\mathrm{Y_{beam}-Y}}[\rho_1]\, W_{\mathrm{Y_{beam}+Y}}[\rho_2] \times \int [da(u)]\; F_{\mathrm{init}}[a]\; T^{\mu\nu}_{\mathrm{LO}}[A_{\mathrm{cl}}(\rho_1,\rho_2)+a]$$

✧ Gauge invariant Gaussian spectrum of quantum fluctuations

✓ 3+1-D solutions of Yang-Mills equations

✧ Expression computed recently-numerical evaluation in progress

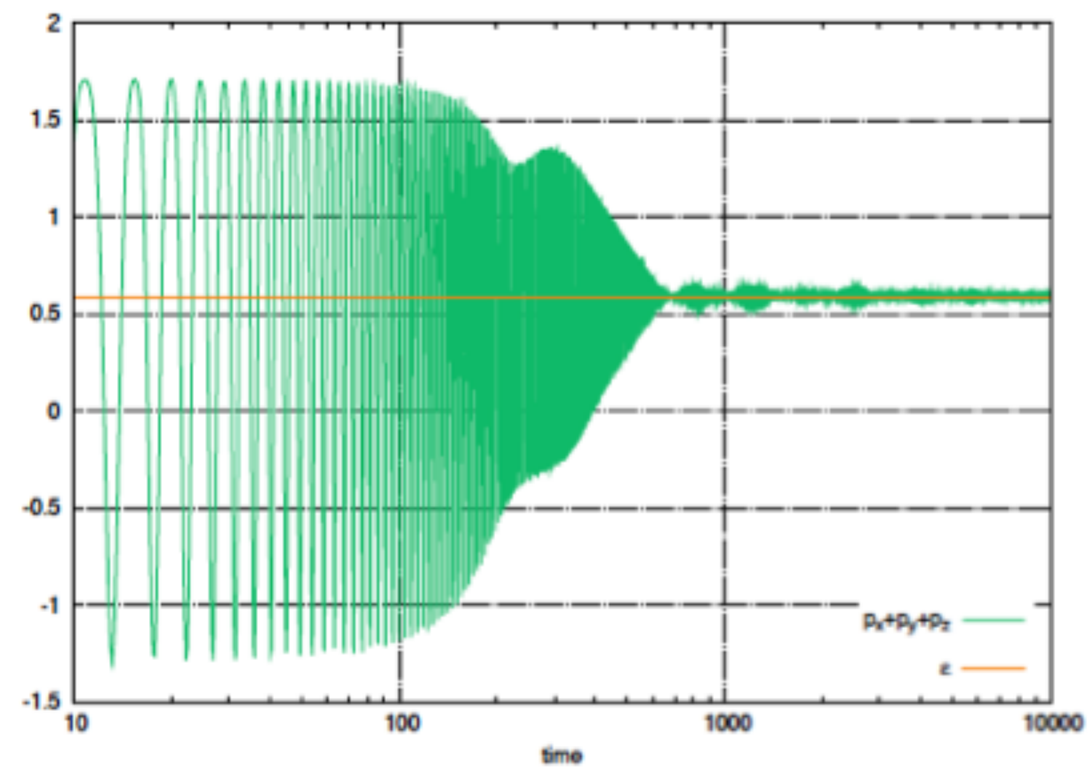
Dusling, Epelbaum, Gelis, RV

- This is what needs to be matched to viscous hydrodynamics, event-by-event
- All modeling of initial conditions for heavy ion collisions includes various degrees of over simplification relative to this "master" formula

R. Venugopalan

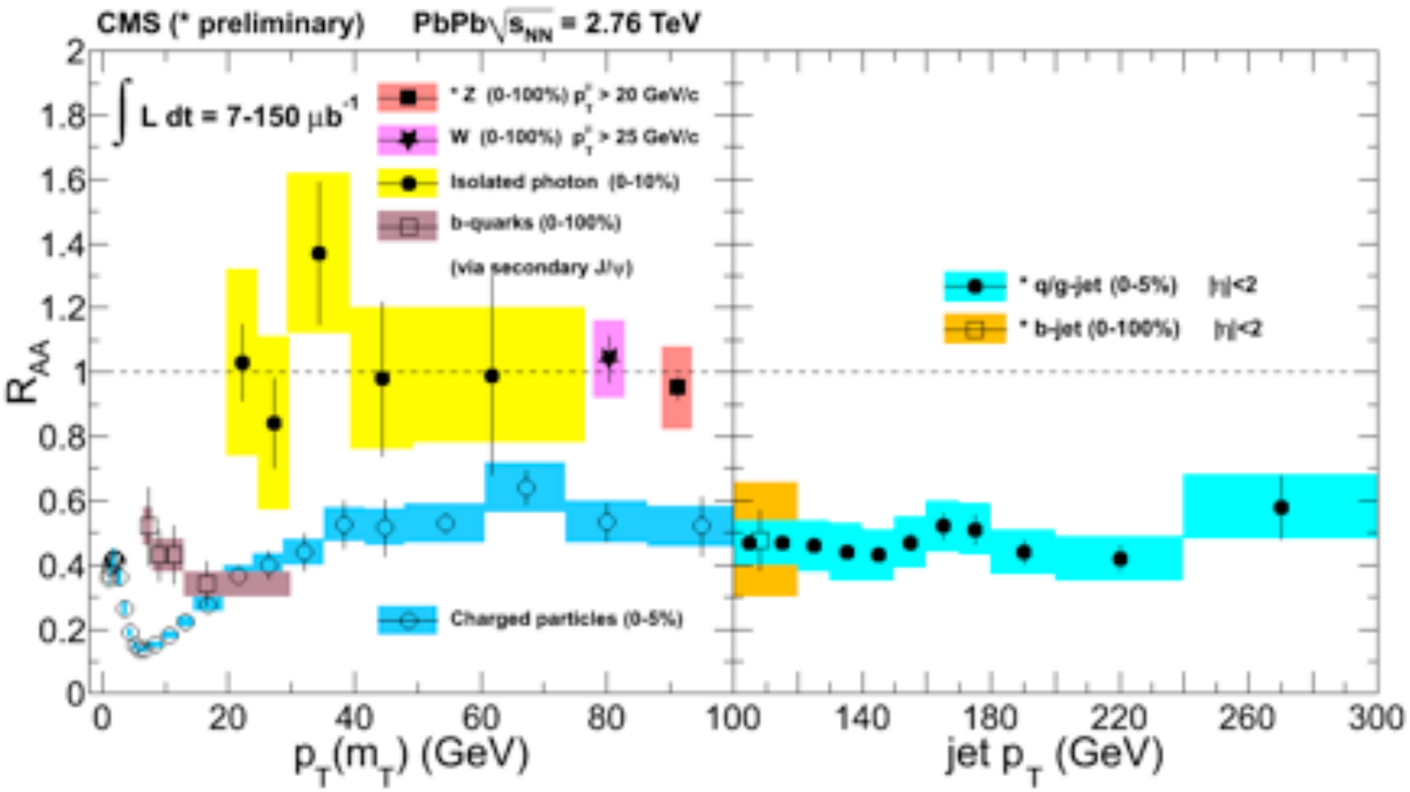
Energy density and pressure after averaging over fluctuations

➡ **Converges to single valued relation "EOS"**

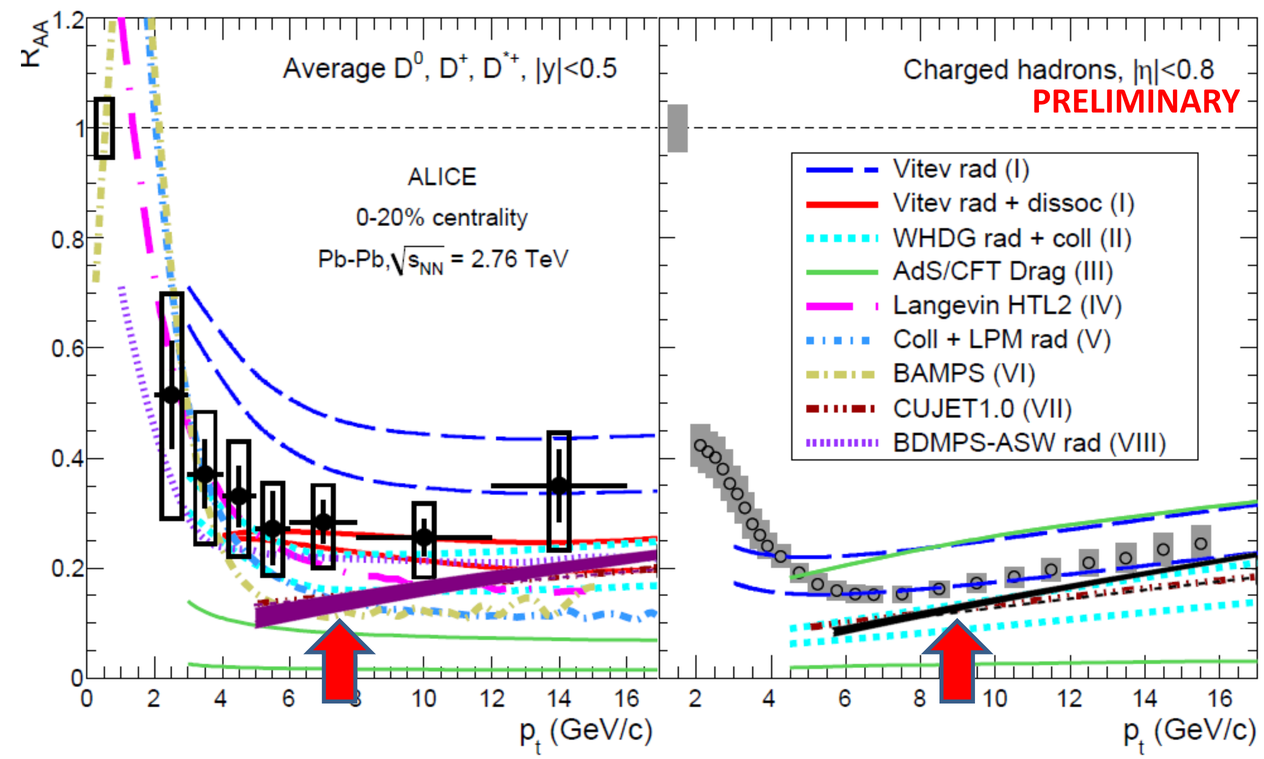


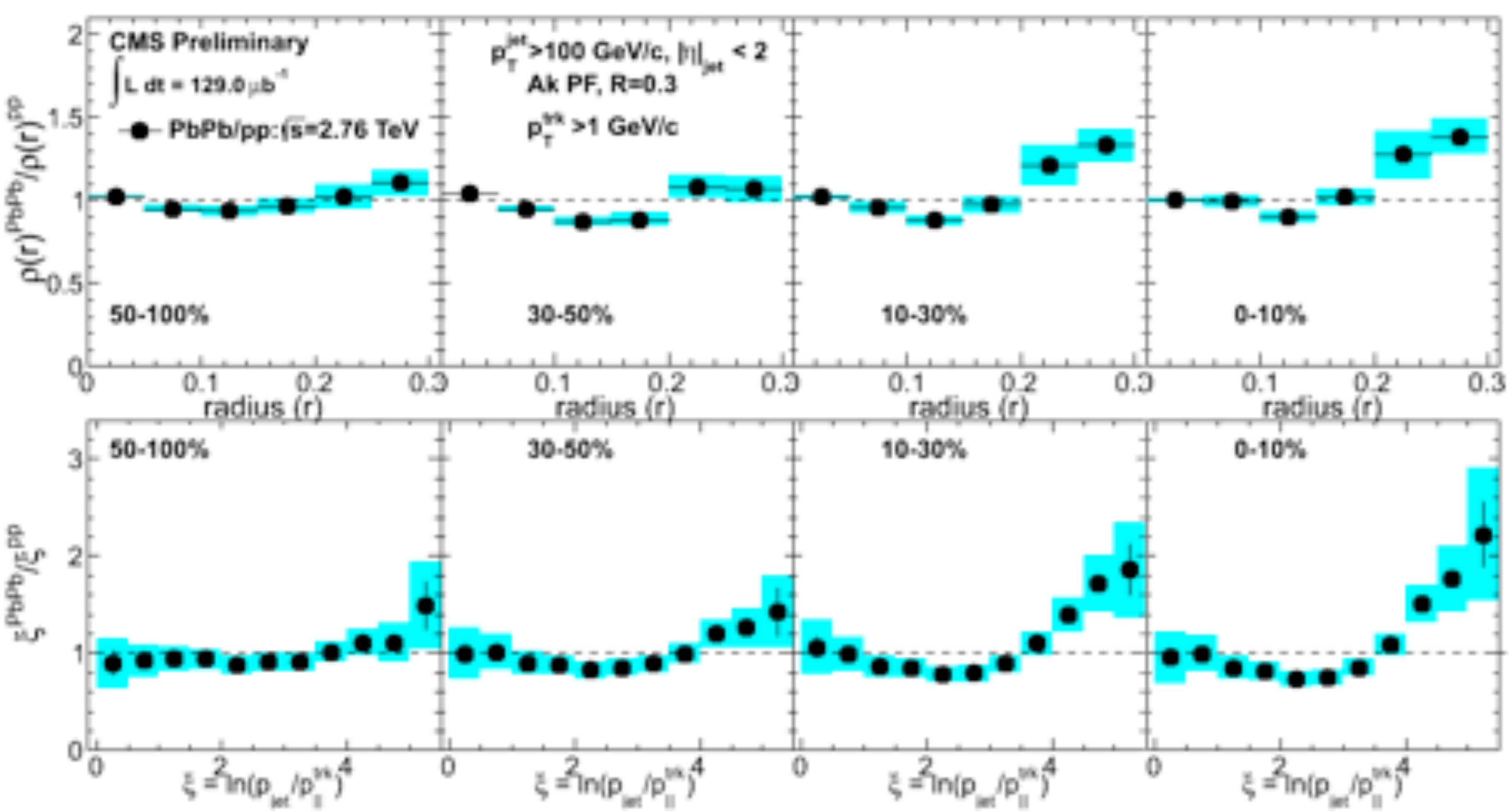
Dusling, Epelbaum, Gelis, Venugopalan (2011)

Jets



ALICE Collaboration, arXiv:1203.2160





Diff models ⇒ various transport coefficients

$$\hat{q} = 1 - 15\ GeV^2/fm$$

So far experiments do better than theory!

Transport coefficient $\hat{q}$ on the Lattice

A. Majumder

$$\hat{Q} = \frac{4\pi^2\alpha_s}{N_c}\int \frac{d^4y\,d^4k}{(2\pi)^4} e^{ik\cdot y} \frac{2(q^-)^2}{\sqrt{2}q^-} \frac{\langle M|F^{+\perp}(0)F^{+}_{\perp,}(y)|M\rangle}{(q+k)^2+i\epsilon}.$$

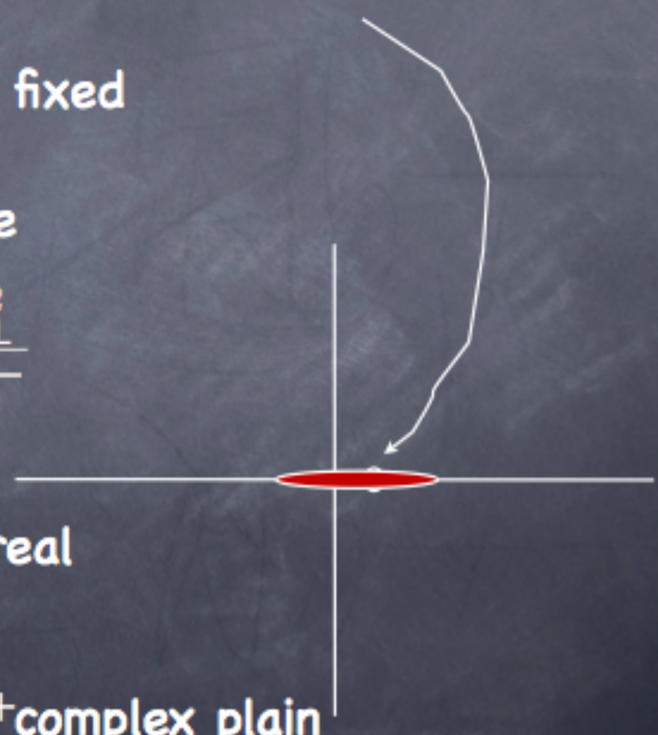
Consider q^- large (~Q) and fixed

Consider q^+ to be a variable

$\frac{d^2\hat{Q}}{dk_\perp^2}$ has a pole at $k^+ = \frac{k_\perp^2}{2q^-}$

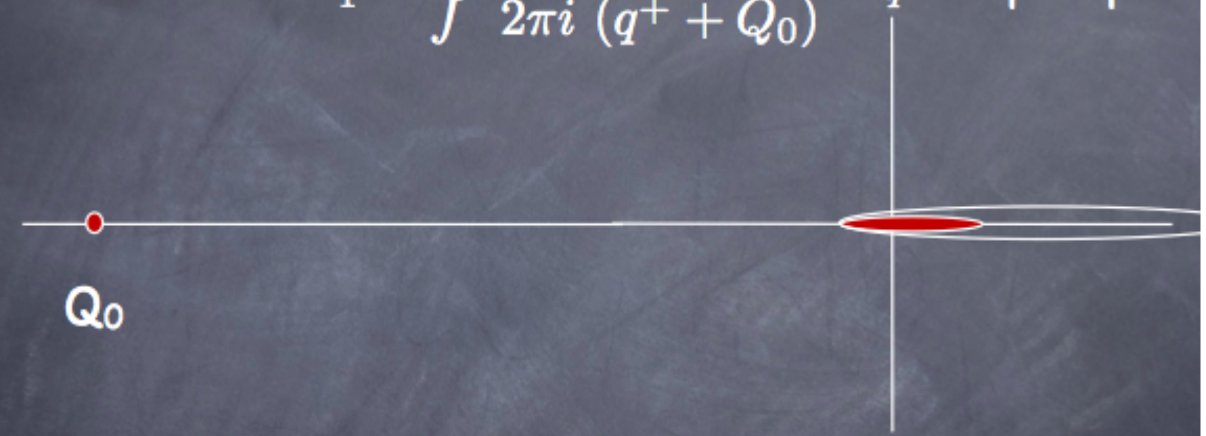
$\hat{Q}$ has a branch cut on the real axis at $q^+ \sim \lambda^2 Q$

$\hat{q} = Im(\hat{Q})$



Consider the following integral

$$I_1 = \oint \frac{dq^+}{2\pi i}\frac{\hat{Q}(q^+)}{(q^+ + Q_0)}$$



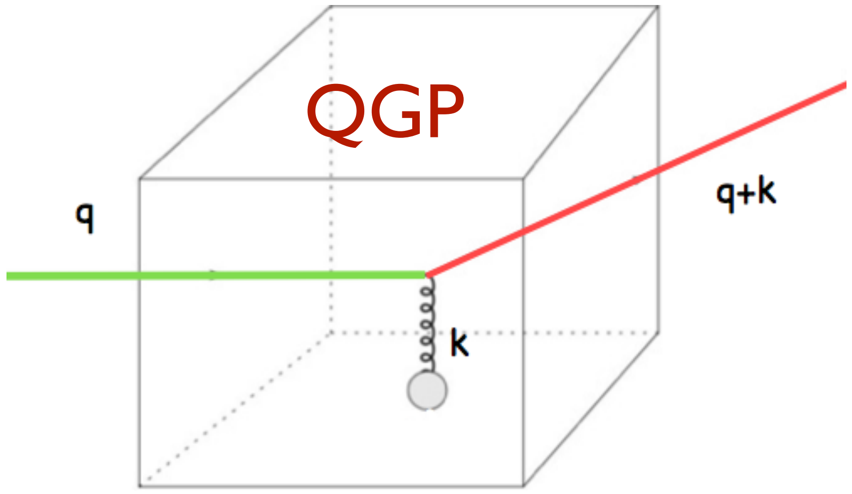
For $Q_0 \sim -Q$, can Taylor expand $\hat{Q}$ in terms of local operators

$$I_1 = \frac{4\sqrt{2}\pi^2\alpha_s\langle M|F_\perp^{+\mu}\sum_{n=0}^{\infty}\left(\frac{-q\cdot iD - D_\perp^2}{2q^- Q_0}\right)^n F^{+}_{\perp,\mu}|M\rangle}{N_c 2Q_0}$$

Gluon $\hat{q}$ is C_A/C_F of quark $\hat{q}$

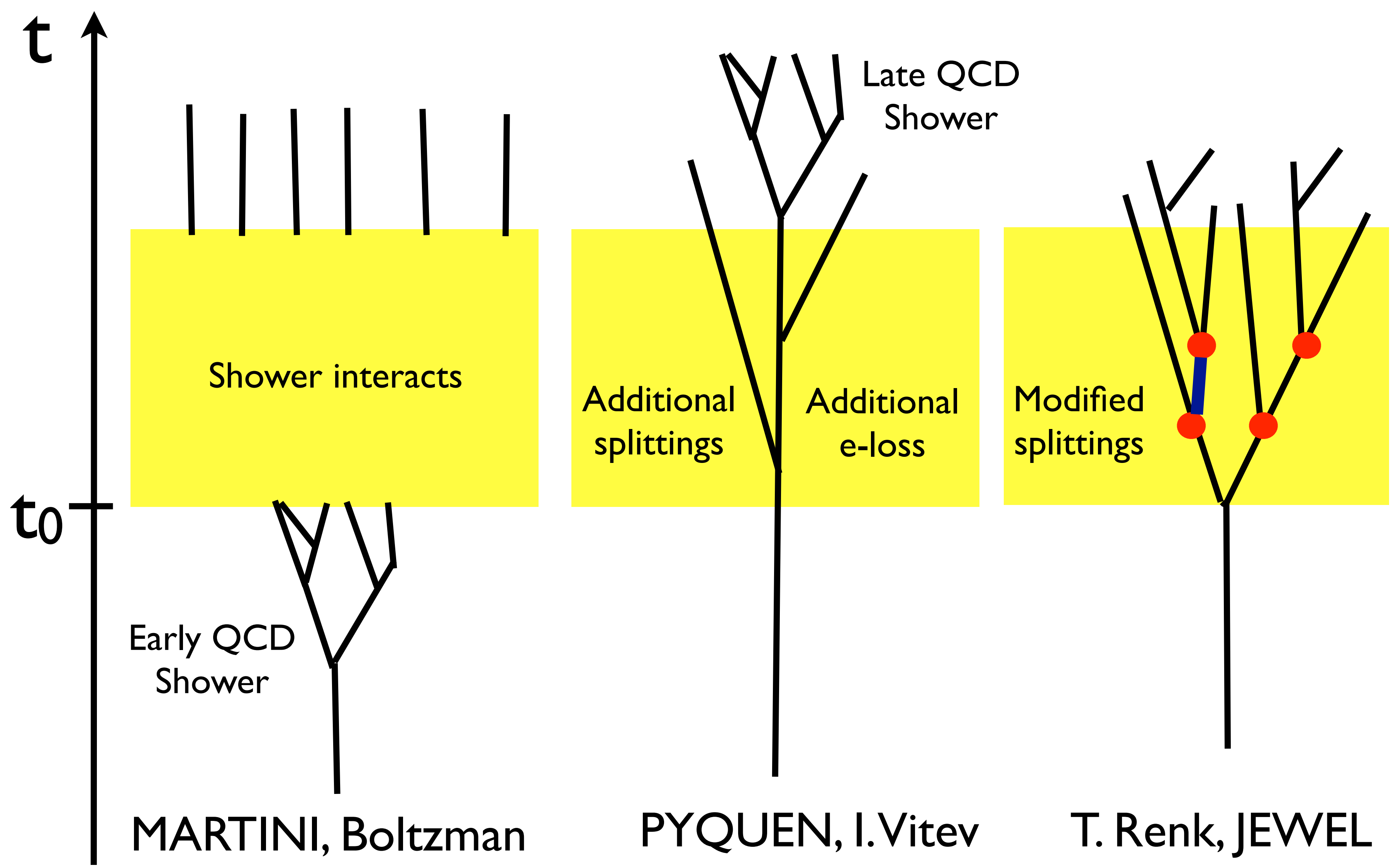
SU(2) has 3 gluons, SU(3) has 8, and 6 quarks + antiquarks

$$\hat{q}(T = 400\text{MeV}) = 1\text{GeV}^2/\text{fm} - 2\text{GeV}^2/\text{fm}$$



J. Casalderray-Solana

Modeling Jet evolution



Is it reasonable to assume a separation of these processes?

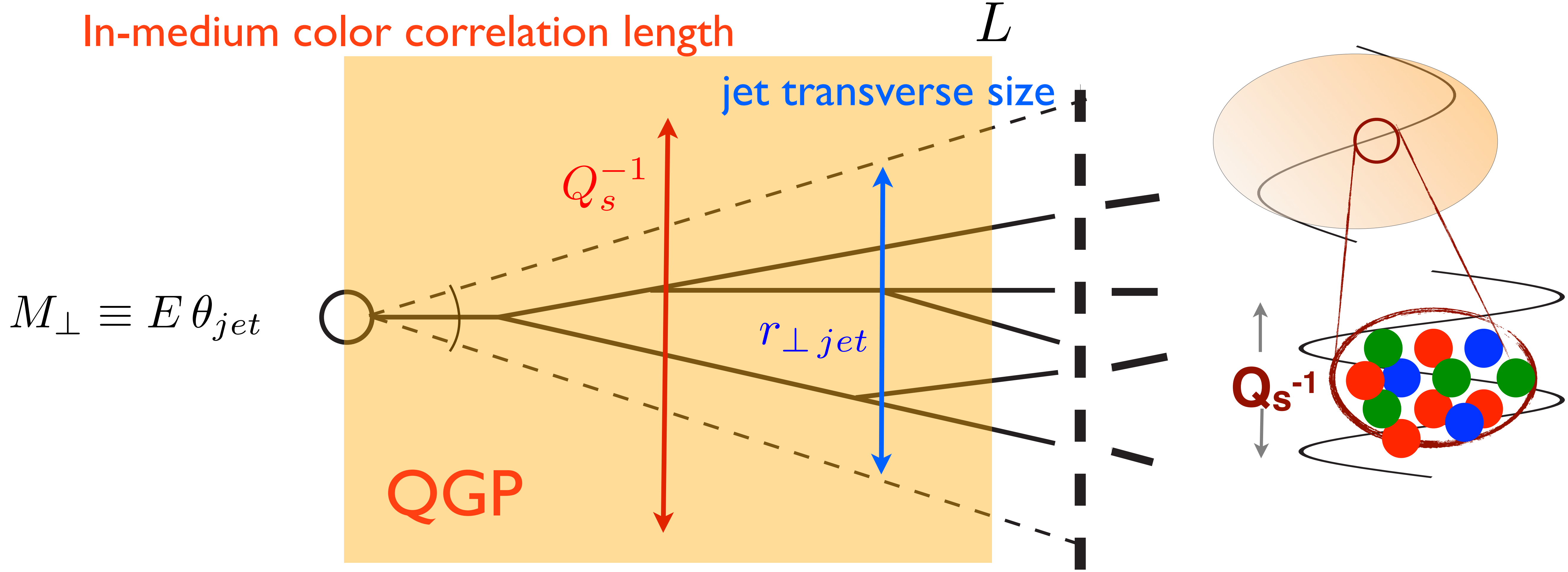
We need guidance from theory!

- In-medium scales? (before doing the math)

$$M_\perp \equiv E\,\theta_{jet}$$
$$Q_0 \sim \Lambda_{\rm QCD}$$

+

$$Q_s \equiv \sqrt{\hat{q}L} \equiv m_D\,\sqrt{N_{\rm scat}}$$
$$r_{\perp\,jet}^{-1} \equiv (\theta_{jet}L)^{-1}$$

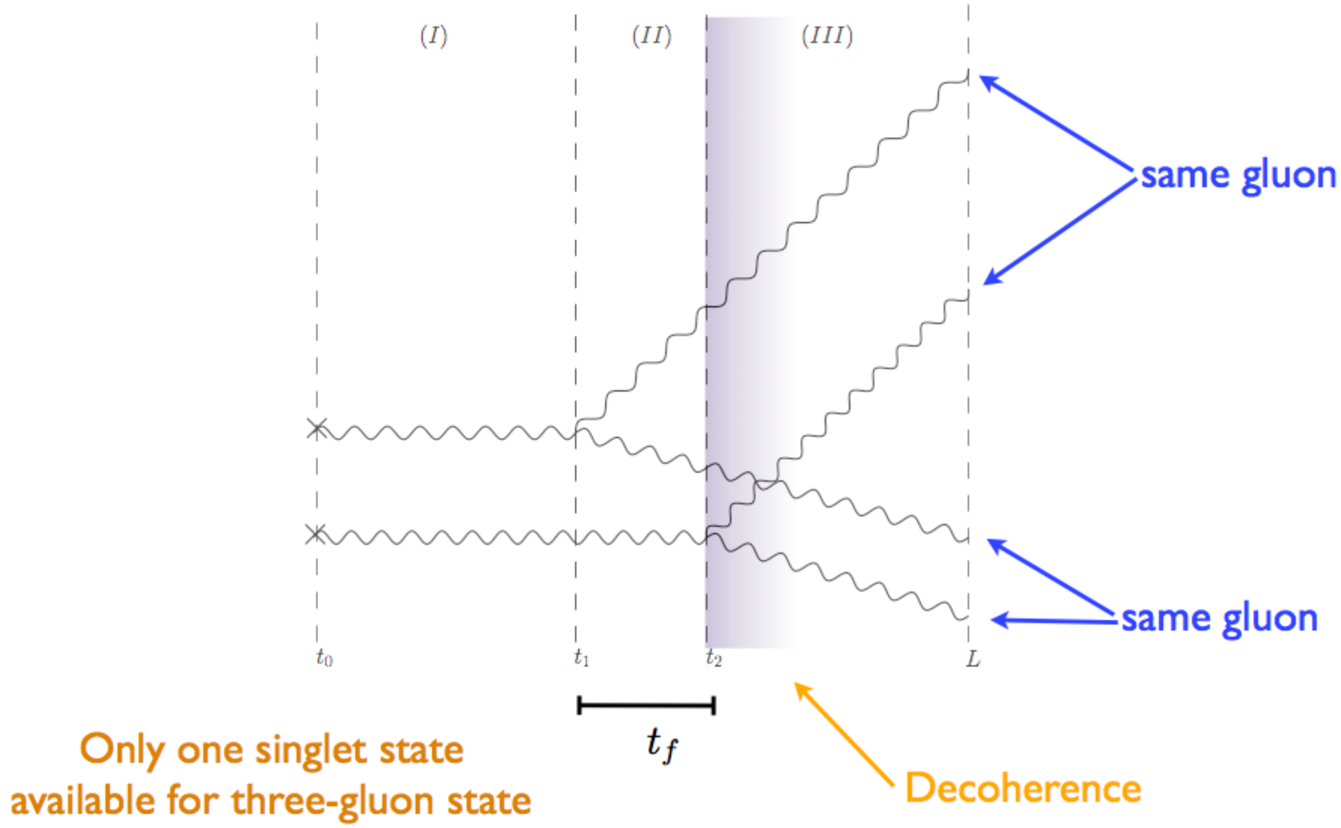


Color transparency for $r_\perp < Q_s^{-1}$ or $\theta_{jet} < \theta_c \sim \dfrac{1}{\sqrt{\hat{q}L^3}}$

Decoherence $r_\perp > Q_s^{-1}$

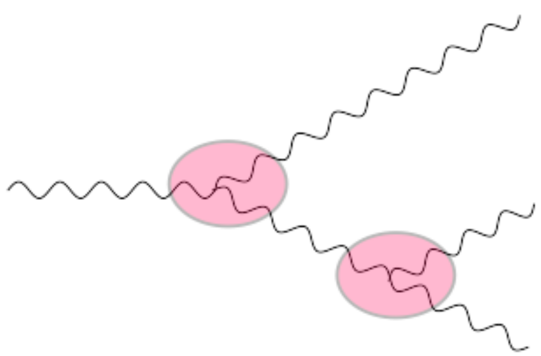
Y. M.-T, K. Tywoniuk, C.A. Salgado (2010-2012)
J. Casalderray-Solana, E. Iancu (2011)

Structure of gluon branching

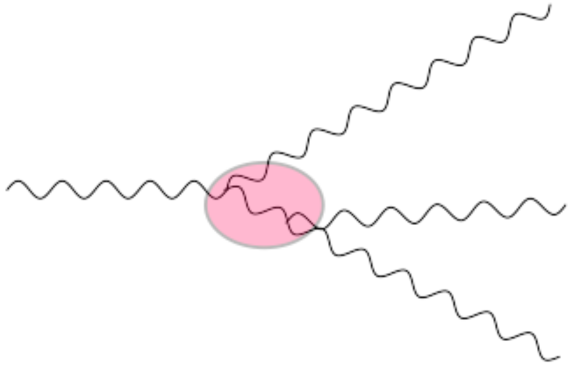


F. Dominguez

$$t_f \ll L$$



$$\sim \left(\alpha_s \frac{L}{t_f}\right)^2$$



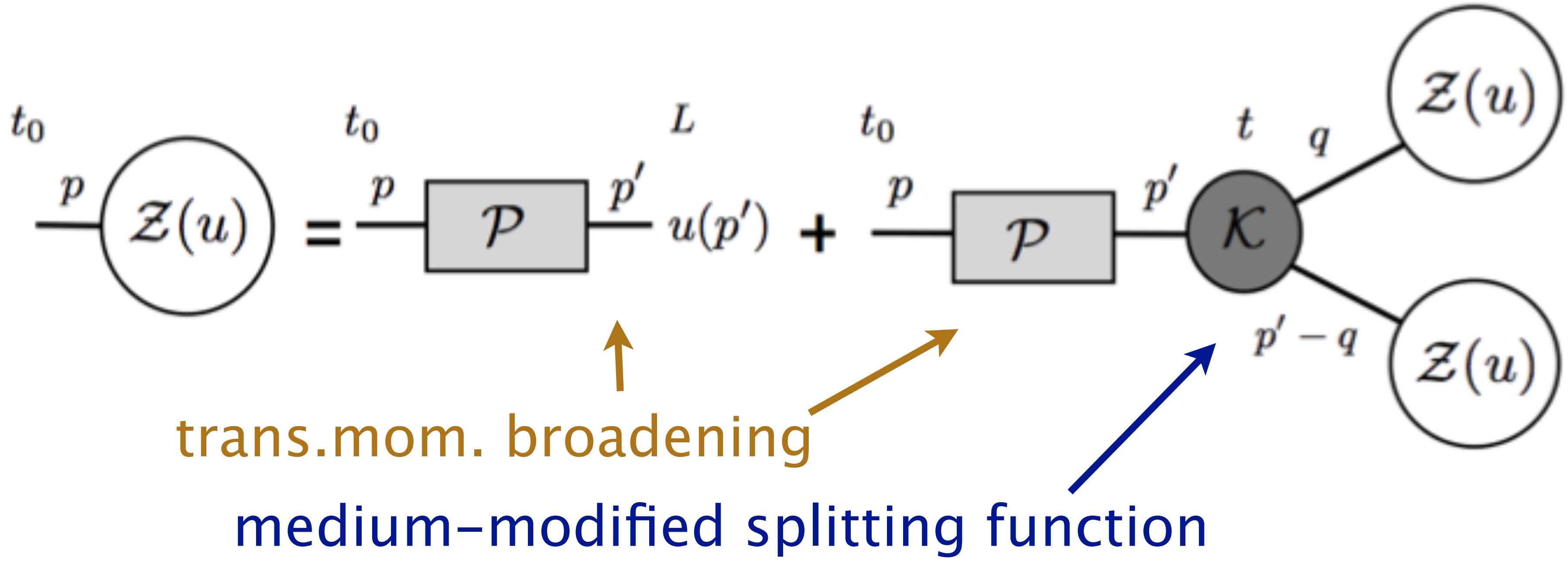
$$\sim \alpha_s^2 \frac{L}{t_f}$$

Decoherence of soft gluons

Blaizot, Dominguez, Iancu, Mehtar-Tani (2012)

F. Dominguez

Probabilistic picture

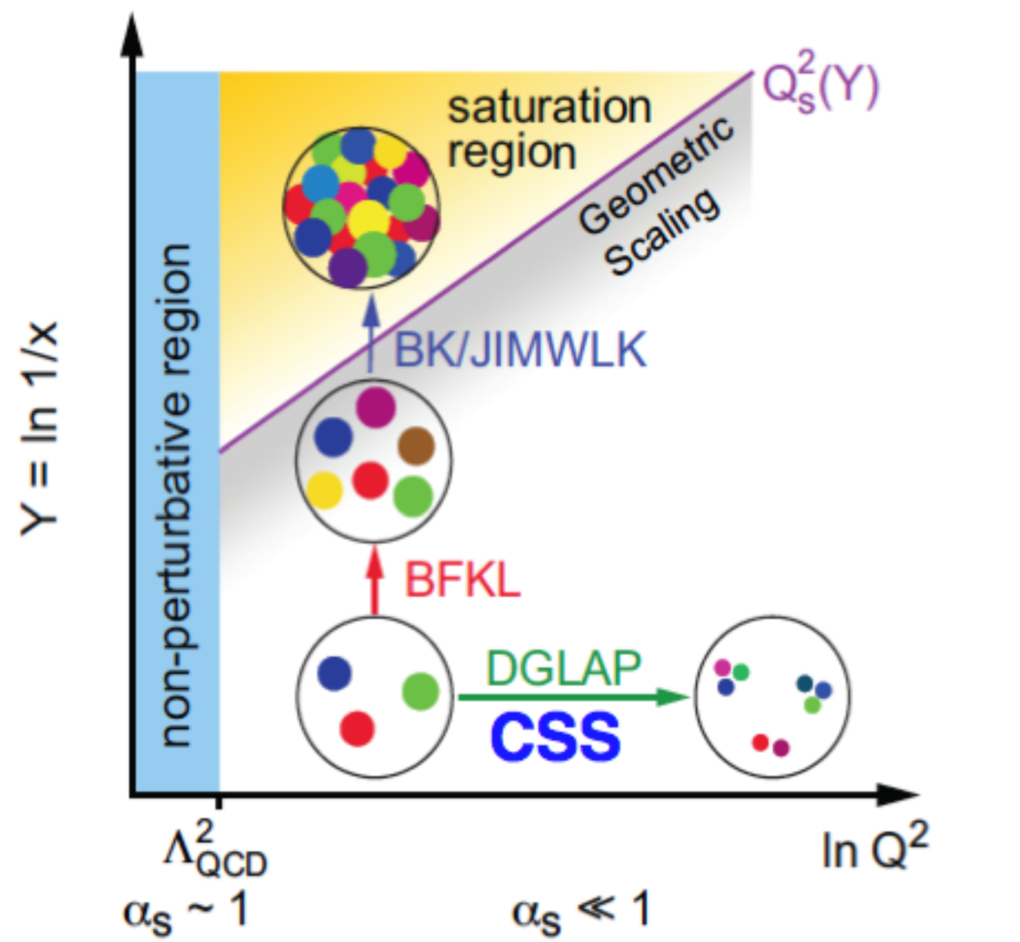


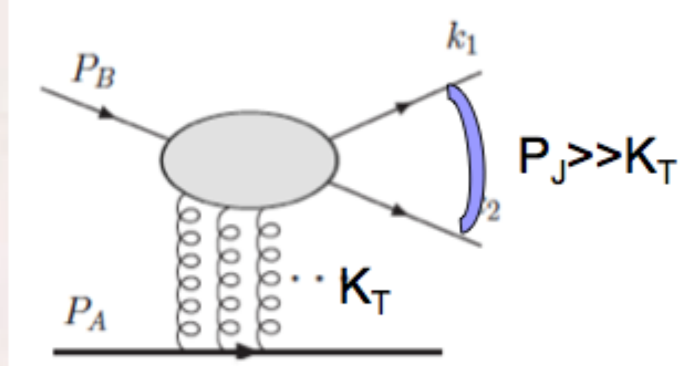
- resummation of length-enhanced terms
- soft gluons decohere rapidly in the medium

In-medium splitting kernel:

$$\mathcal{K}_g(\mathbf{q}, z) \approx \frac{2}{p^+} P_{gg}(z)\ \sin\left[\frac{\mathbf{q}^2}{2\mathbf{k}_f^2}\right]\ \exp\left[-\frac{\mathbf{q}^2}{2\mathbf{k}_f^2}\right]$$

Initial state (proton-Nucleus collisions)





- Hard processes probe the kt-dependent gluon distributions directly
- Saturation phenomena manifest in the observables

- Numerical solution of the JIMWLK eqs. (CGC) for 2-particle correlation

T. Lappi

- NLO forward hadron production

B. Xiao
F. Yuan

THANK YOU!