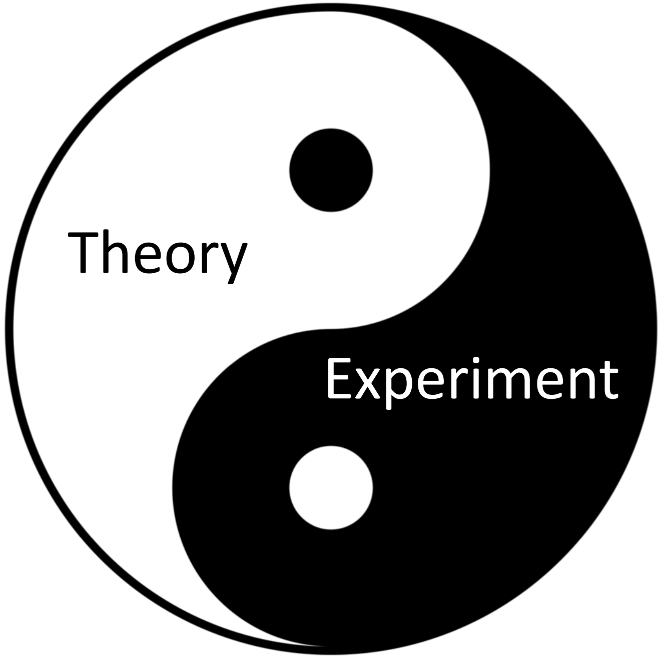
The Xin and Nian of parton energy loss

Happy Birthday,
Xin-Nian!



Urs Achim Wiedemann
Xin-Nian Wang Symposium
18/19 August 2022, Berkeley

Updated title:

From the first model illustrator of parton energy loss:

Heavy **I**on **J**et **In**teraction **G**enerator

核易经

[Hé – yì – jīng]

to the modern “Book of medium-induced changes”:


I-Ching*

*based on “**cleromancy,** the production of seemingly random numbers to determine divine intent.” Wikipedia

HIJING M. Gyulassy & X.N. Wang, PRD44, 3501 (1991); I-CHING “Book of changes”, Western Zhou period, 1000-750 BC

Updated title:

From the first model illustrator of parton energy loss:

Heavy Ion Jet Interaction Generator

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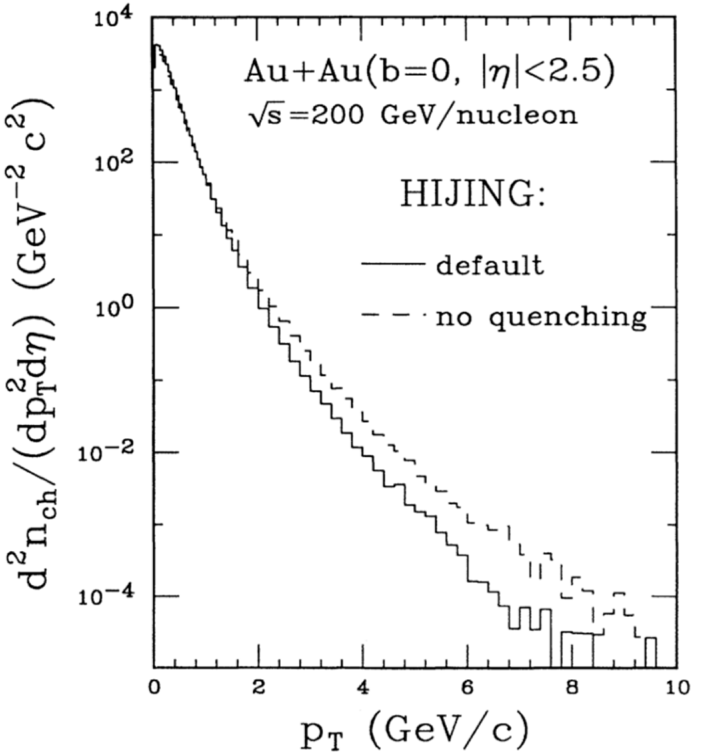

FIG. 19. The prediction of p_T distributions for charged particles by HIJING with (solid histogram) and without (dashed histogram) jet quenching in central Au+Au collisions at $\sqrt{s}=200$ GeV/nucleon with $dE/dx=2$ GeV/fm and $\lambda_s=1$ fm.

to the modern "Book of medium-induced changes":

HIJING M. Gyulassy & X.N. Wang, PRD44, 3501 (1991);

Theory of jet quenching - the big lines

☐ **Bjorken 1982**		☐ **the picture appears**
era of collisional e-loss		
☐ **Gyulassy&Wang 1991-94**	XNW	☐ **the dominant mechanism is identified**
☐ **BDMPS-Z 1996 -**		☐ **first complete LO-analyses**
era of radiative e-loss		(HT, GLV, ASW, …) XNW
☐ **AMY / bottom-up 2000 …**		☐ **understanding e-loss as high-E limit of transport theory**
☐ **RHIC phenomenology 2000 …**	XNW	☐ **Large /abundant effect for leading hadrons**
☐ **LHC phenomenology 2010-**		☐ **Large /abundant effect for jets** XNW
☐ **Beyond 1-parton emission** 2010-…		☐ **rethinking jet structure & substructure in the context of thermalization** XNW
era of jet quenching showers		

Theory of jet quenching - the big lines*

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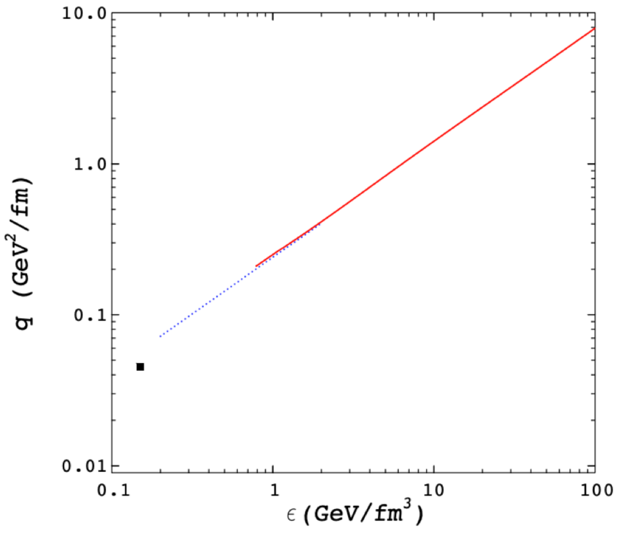
era of jet quenching showers		

LHC Discovery of collectivity in small system!

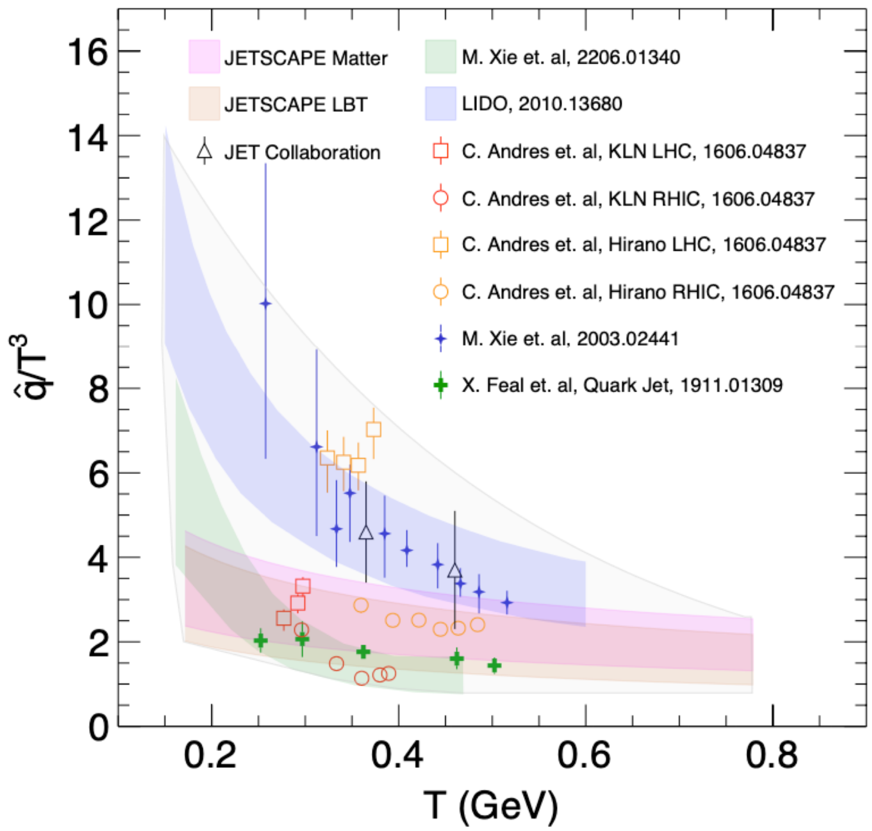
*In a historical narrative, the choice of 'big lines' is somewhat subjective. What is objective is XNW's contribution to all these lines.

What do we understand if we understand jet quenching?

Answer 1: QGP medium properties



QM2002, R. Baier



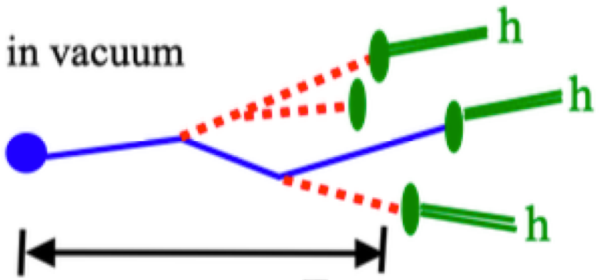
L. Apolinário et al, 2203.16352

What do we understand if we understand jet quenching?

Answer 2: QCD thermalization mechanisms.

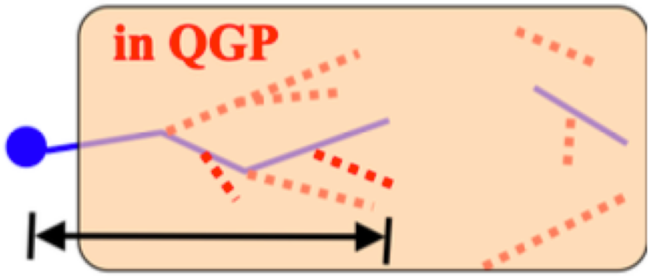
What drives far-out-of-equilibrium excitations towards equilibrium and how quickly?

In QCD vacuum, jets hadronize.



$$L_{hadr} = const \frac{E}{Q^2_{hadr}}$$

In QCD plasma, jets thermalize.



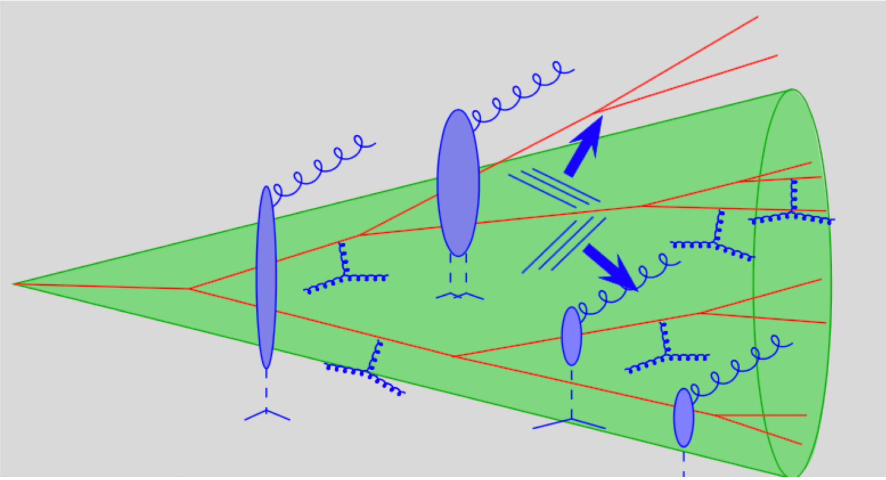
$$\Delta E \approx E \approx \alpha_s \hat{q} L^2_{therm}$$

Jet quenching – a *peculiar* kinetic transport

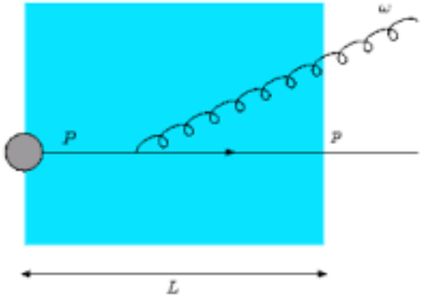
A generic quenching model implements

$$\boxed{\partial_t f_g(x,p) = -C_{2\to 2}[f] - C_{1\to 2}[f]}$$

- ☐ Hard partons p>> T
- ☐ Embedded in medium
- ☐ 1->2 LPM (and DGLAP)
- ☐ 2->2 elastic



What is peculiar? Soft emittees are emitted first.



☐ **In vacuum**

- Time $\tau_{\mathrm{form}}^{\mathrm{vac}} \simeq \frac{\omega}{k_\perp^2} = \frac{1}{\Theta^2\,\omega}$
- Hard gluons first
- Soft gluons late

medium never

☐ **In medium**

- Time $\tau_{\mathrm{form}}^{\mathrm{med}} \simeq \frac{\omega}{k_\perp^2} = \sqrt{\frac{\omega}{\hat{q}}}$
- Soft gluons first
- medium forms fast (PTO)

Quenching models: Q-Pythia, Q-Herwig, JEWEL, LBT, MATTER, MARTINI … HYBRID is different

X.N. Wang, Jet tomography of hot and cold nuclear matter, https://www.youtube.com/watch?v=a69d22ZiiT8

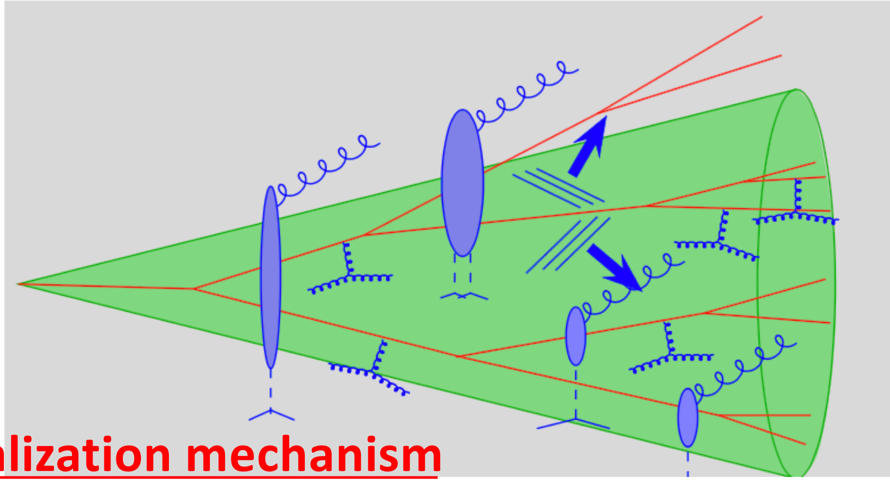
Jet quenching ⇔ pQCD kinetic transport theory

A generic quenching model implements

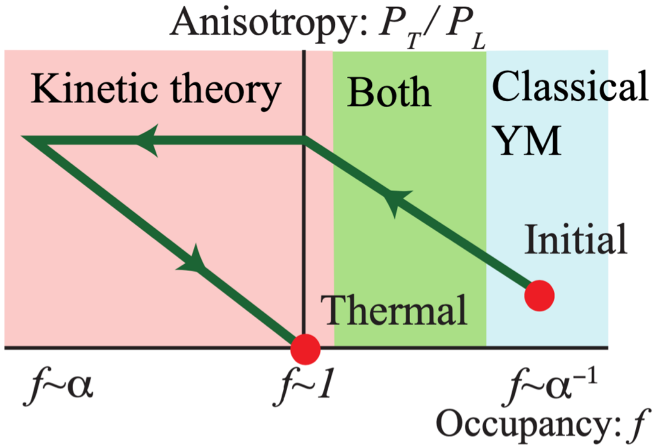
$$\partial_t f_g(x,p) = -C_{2\to 2}[f] - C_{1\to 2}[f]$$

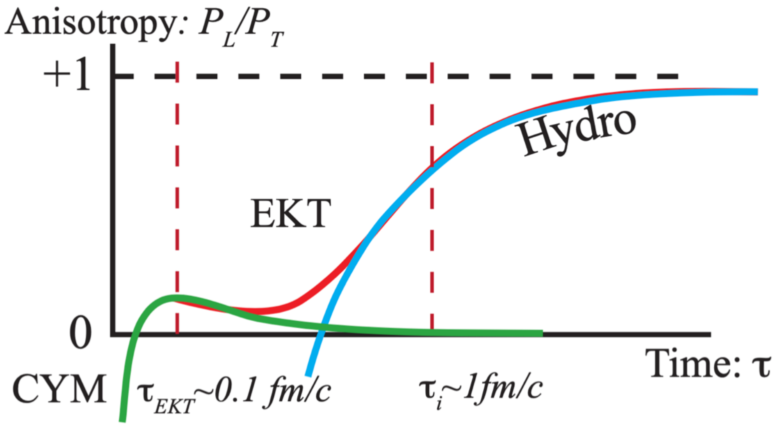
“Bottom-up”

- ☐ Hard partons p>> T
- ☐ Embedded in medium
- ☐ 1->2 LPM (and DGLAP)
- ☐ 2->2 elastic



pQCD has the most remarkable thermalization mechanism





R. Baier, A.H. Mueller, D. Schiff, D.T. Son, ‘Bottom up’ thermalization in heavy ion collisions, Phys. Lett. B502 (2001) 51

A. Kurkela, E. Lu Phys.Rev.Lett. 113 (2014) 18; A. Kurkela, Y. Zhu Phys.Rev.Lett. 115 (2015) 18

Q:

Can we test

$$C_{g\rightarrow c\bar{c}}$$

that drives charm chemical equilibration?

Jet Quenching: heavy flavor as an example

❑ Cross section*

$$d\sigma = \mathrm{pdf} \otimes \mathrm{Hard} \otimes \mathrm{Frag}$$

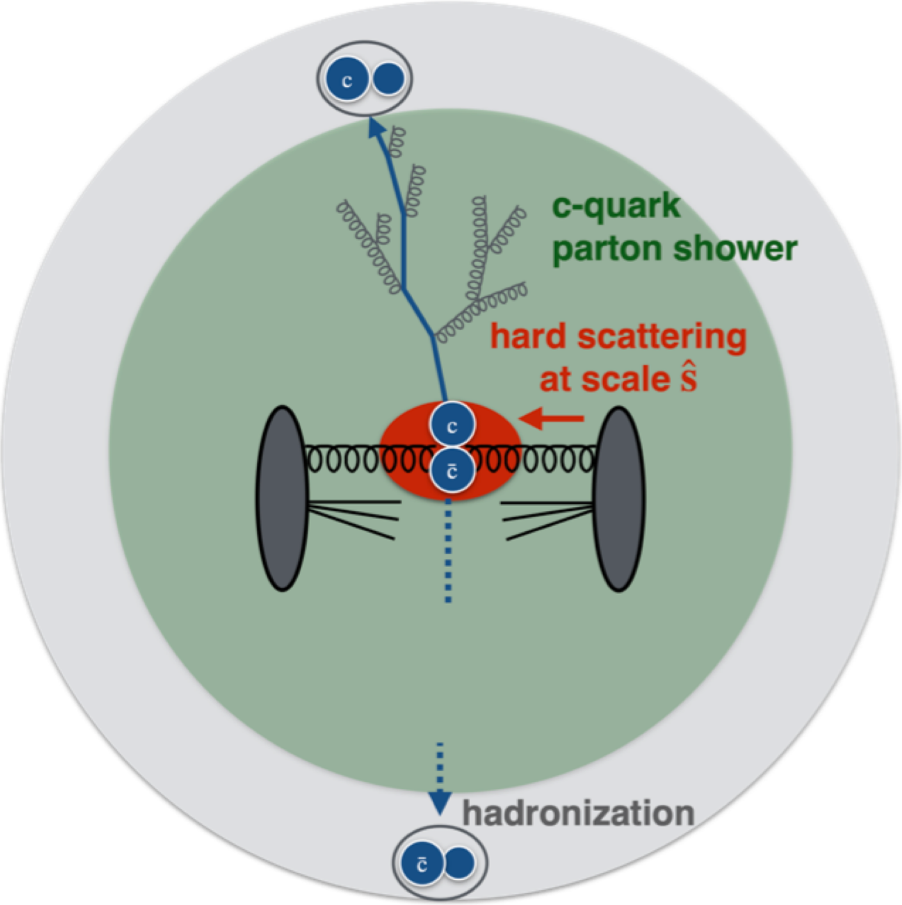
❑ Hard production is short distance,

$$\hat{s} \sim Q^2_{c\bar{c}} \gg 4m_c^2 \gg T\,,Q_s$$

yield unaffected by QCD medium.

❑ c -> cg in parton shower is long distance, can be affected by QCD medium**

- ➢ “parton energy loss” $C_{c\to cg}$
- ➢ “momentum broadening”



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* M. Cacciari et al, JHEP 10 (2012) 137

**Y.L. Dokshitzer and D. Kharzeev, Phys. Lett. B 519 (2001), 199

… spatio-temporal embedding of parton shower …

Collinear limit

$$\hat{\sigma}^{gg\to c\bar{c}X}\Big|_{Q^2_{c\bar{c}}\ll\hat{s}} \longrightarrow \hat{\sigma}^{gg\to gX}\,\frac{\alpha_s}{2\pi}\,\frac{1}{Q^2_{c\bar{c}}}\,P_{g\to c\bar{c}}$$

- g -> c cbar is long-distance.

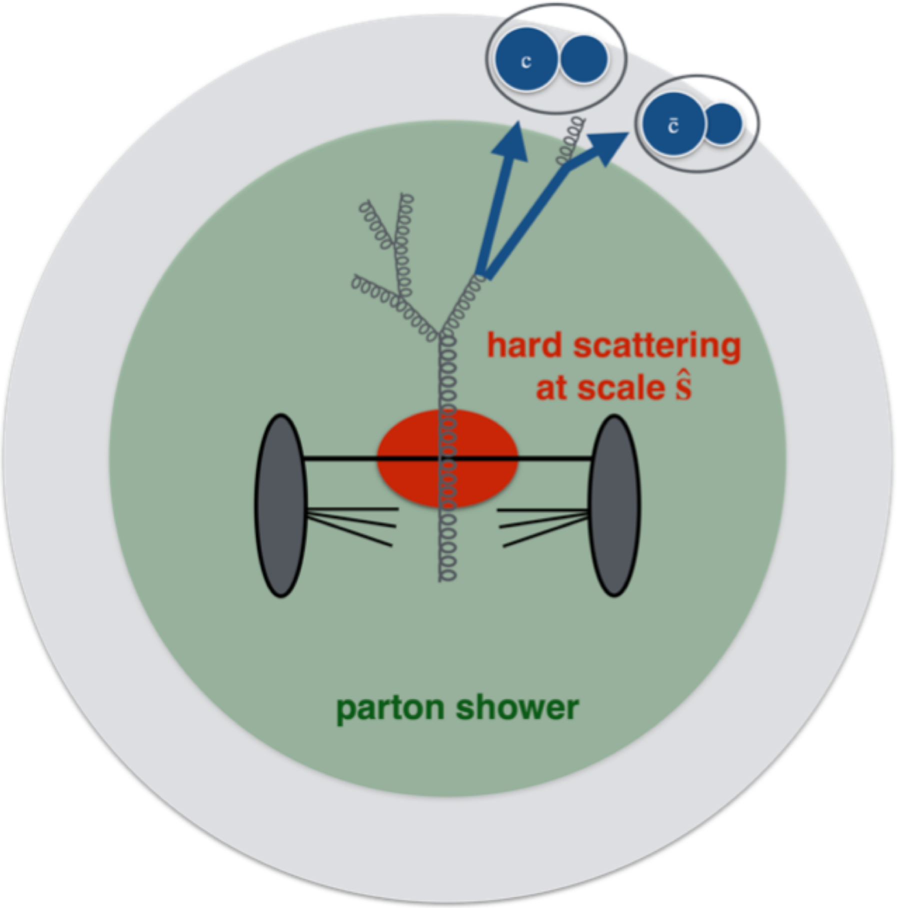
  Formation time is **boosted***

$$\tau_{g\to c\bar{c}} \sim \frac{1}{Q_{c\bar{c}}}\,\frac{E_g}{Q_{c\bar{c}}}$$

- g-> c cbar medium-modified if boosted sufficiently

➢ medium-enhancement c-cbar yield in jets

➢ momentum broadening of c-cbar pair …



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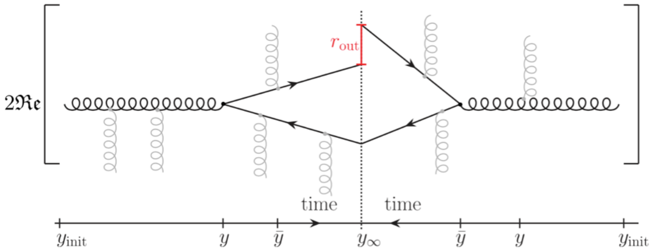
* M. Attems et al, 2203.11241

What we know about g-> c cbar …

Medium-modified g-> c cbar splitting function* in Baier-Dokshitzer-Mueller-Peigné-Schiff / Zakharov formalism



$$\left(\frac{1}{Q^2}P_{g\to c\bar{c}}\right)^{\rm tot} \equiv \left(\frac{1}{Q^2}P_{g\to c\bar{c}}\right)^{\rm vac} + \left(\frac{1}{Q^2}P_{g\to c\bar{c}}\right)^{\rm med}$$

$$= 2\,\mathfrak{Re}\,\frac{1}{4\,E_g^2}\int_{t_{\rm init}}^{t_\infty} dt \int_t^{t_\infty} d\bar{t}\, \exp\left[i\frac{m_c^2}{2E_g z(1-z)}(t-\bar{t}) - \epsilon|t| - \epsilon|\bar{t}|\right] \int d\mathbf{r}_{\rm out}$$

$$\times \exp\left[-\frac{1}{2}\int_{\bar{t}}^{\infty} d\xi\, n(\xi)\,\sigma_3(\mathbf{r}_{\rm out}, z)\right] \exp\left[-i\,\boldsymbol{\kappa}\cdot\mathbf{r}_{\rm out}\right]$$

$$\times \left[\left(m_c^2 + \frac{\partial}{\partial\mathbf{r}_{\rm in}}\cdot\frac{\partial}{\partial\mathbf{r}_{\rm out}}\right)\frac{z^2+(1-z)^2}{z(1-z)} + 2m_c^2\right] \mathcal{K}\left[\mathbf{r}_{\rm in}=0, t; \mathbf{r}_{\rm out}, \bar{t}\right].$$

$$\sigma_3(\mathbf{r}, z) \equiv -\frac{1}{2N_c}\sigma(\mathbf{r}) + \frac{N_c}{2}\sigma(z\mathbf{r}) + \frac{N_c}{2}\sigma((1-z)\mathbf{r}).$$

(many other recent developments**)

- ☐ Confirms **formation time** estimate

$$\tau_{g\to c\bar{c}} = \frac{2}{Q}\frac{E_g}{Q}$$

- ☐ Sensitive to **color field strength of medium**

$$\hat{q} \equiv \frac{\langle \mathbf{q}^2\rangle_{\rm med}}{\lambda_{\rm mfp}}$$

- ☐ Numerically sizeable for

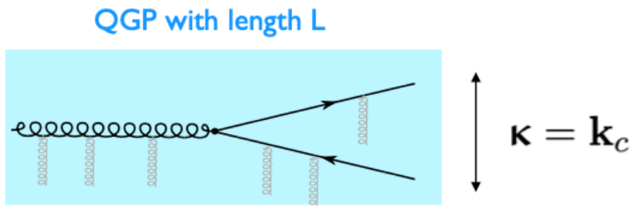
$$\langle \mathbf{q}^2\rangle_{\rm med} = \int_{\tau_i}^{\tau_f} d\tau\,\hat{q}(\tau) \sim \mathcal{O}(m_c^2)$$

- ☐ Geometrically enhanced power-correction

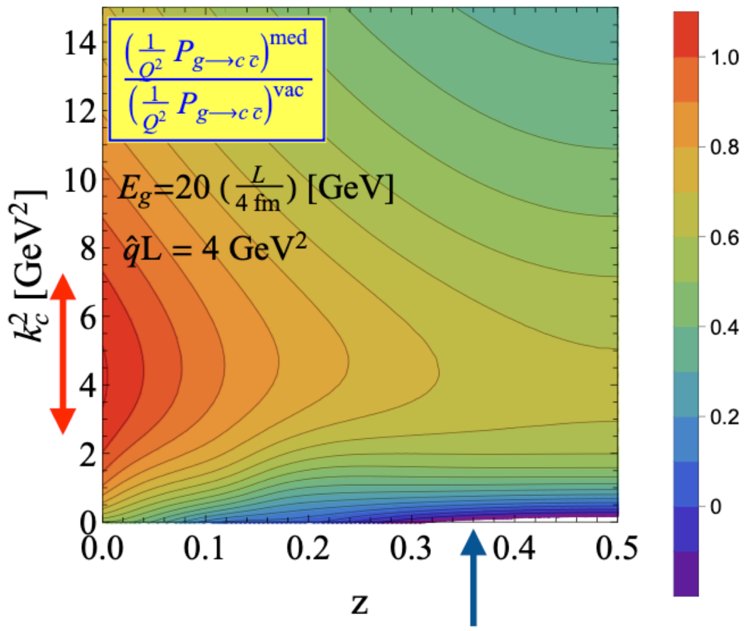
$$P^{\rm med}_{g\to q\bar{q}} \sim \mathcal{O}\left(\frac{\langle \mathbf{q}^2\rangle_{\rm med}}{Q^2}\right)$$

*M. Attems et al, 2203.11241v2 ** L. Apolinario et al, 1407.0599, F. Dominguez et al., 1907.03653, Isaksen et al., 2107.02542, 2206.02811
Z.B. Kang et al. 1610.02043, S. Caron-Huot&Gale, 1006.2379

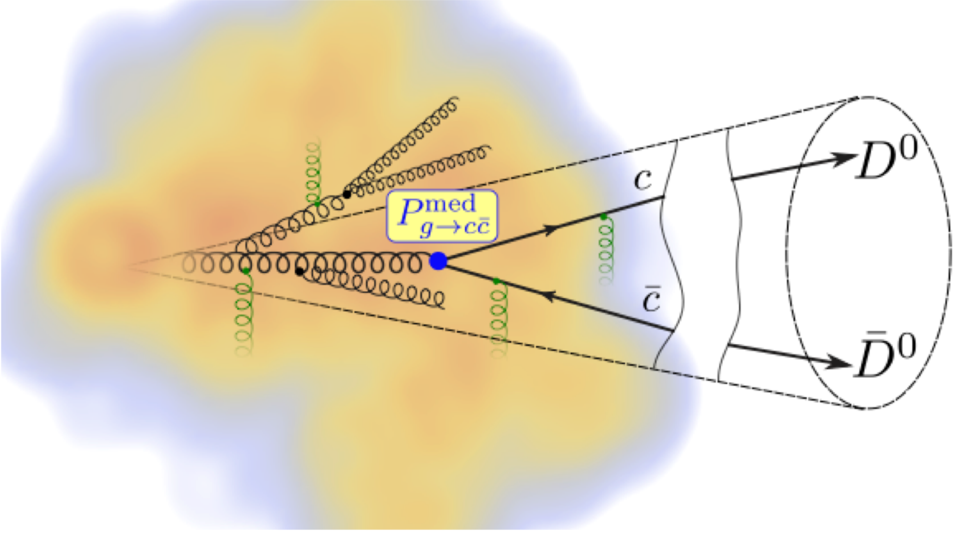
… testing g-> c cbar …


QGP with length L

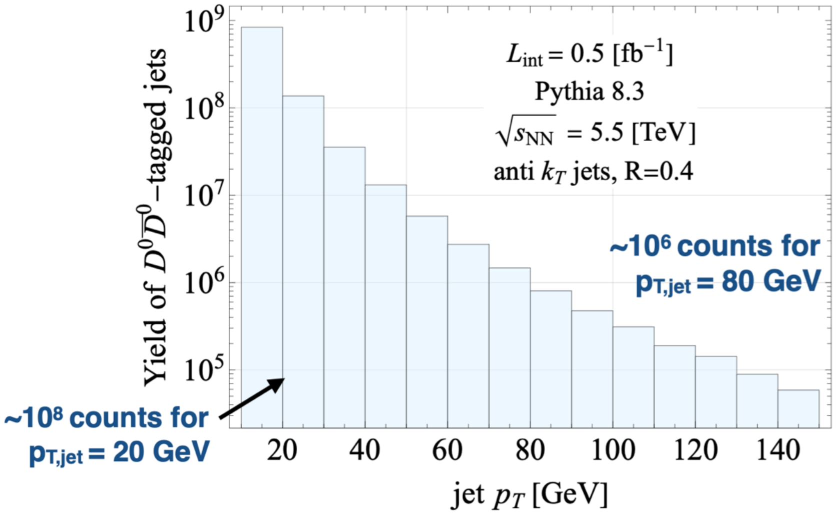
$\boldsymbol{\kappa} = \mathbf{k}_c$



$$Q^2_{c\bar{c}} \simeq \frac{m_c^2 + k_c^2}{z(1-z)}$$



L$_{\text{int}}$ = 0.5 fb^{-1} pp ~ 10 nb^{-1} PbPb (no quenching)

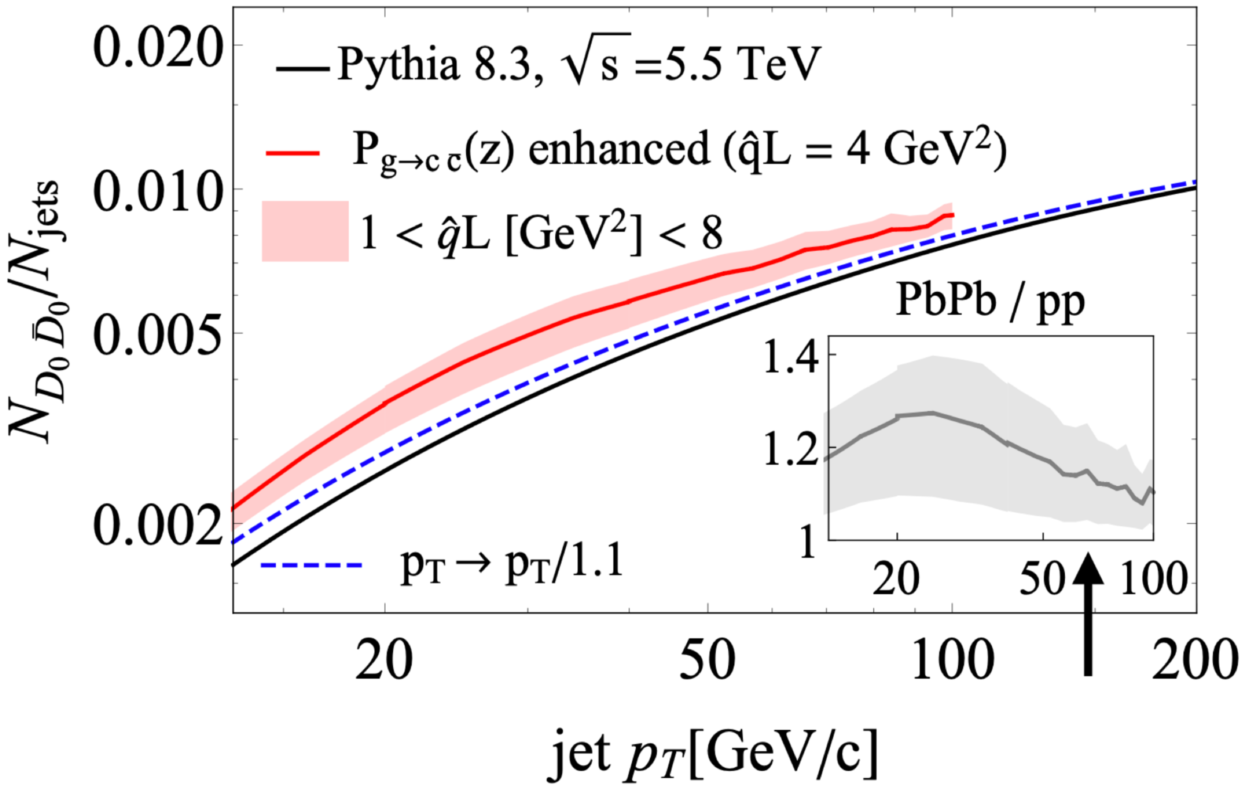


~10^6 counts for $p_{\text{T,jet}}$ = 80 GeV

~10^8 counts for $p_{\text{T,jet}}$ = 20 GeV

*M. Attems et al, 2203.11241 & in preparation

An observable sensitive to enhanced g->ccbar in jets



Could this be the first test of perturbative chemical transport theory?

M. Attems, J. Brewer, G.M. Innocenti, A. Mazeliauskas, S. Park, W. v.d.Schee, U.A. Wiedemann, in preparation.

Happy Birthday, Xin-Nian! – There is so much ahead of us …