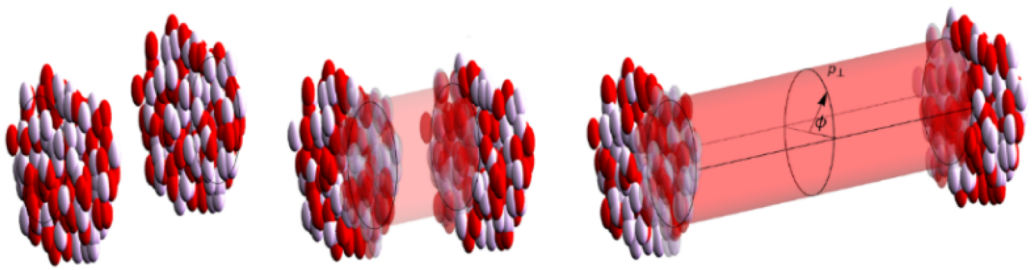
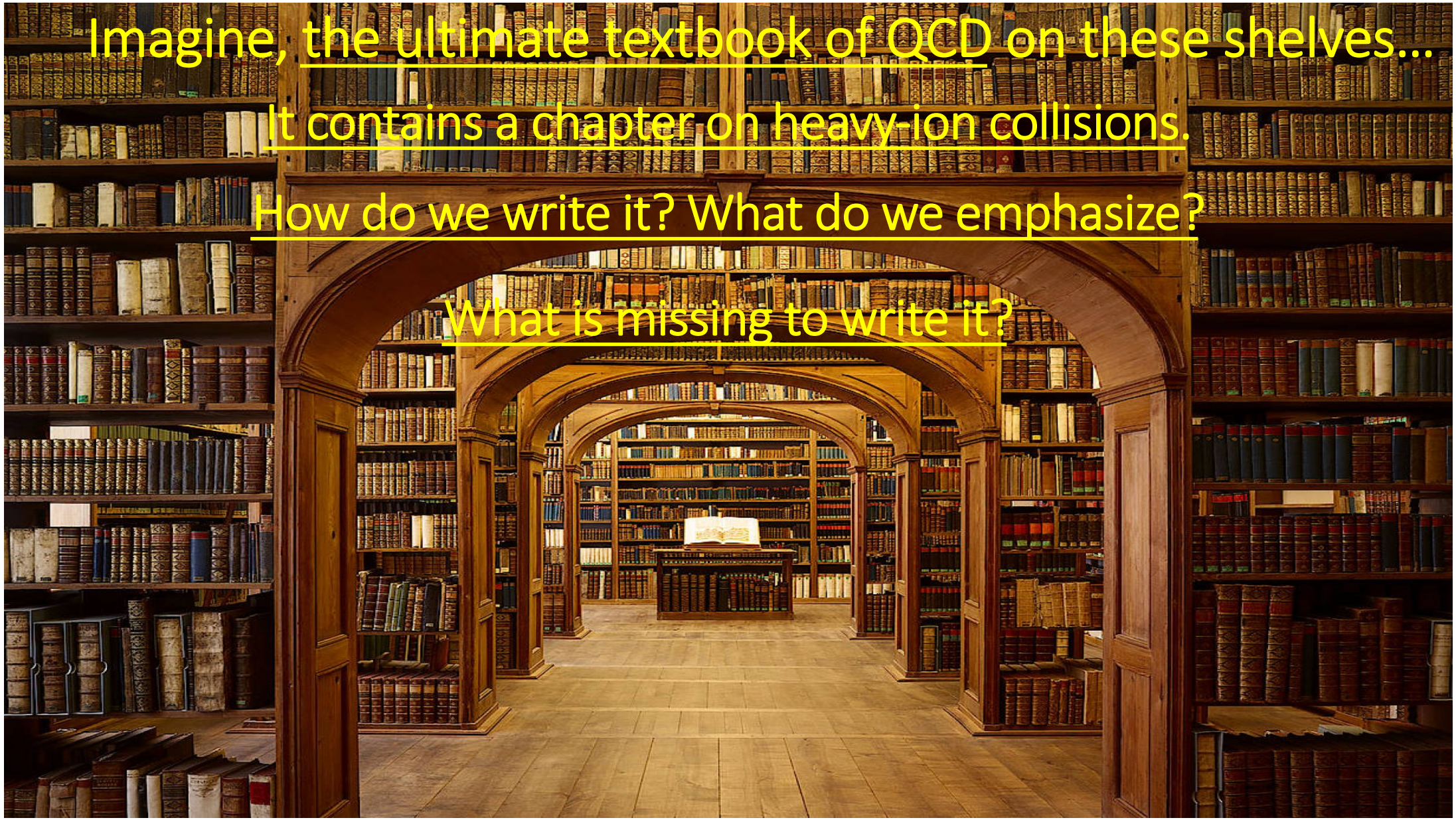
Jet quenching ⇔ Transport ⇔ Flow

Towards a more encompassing paradigm than the "perfect fluid"



Urs Achim Wiedemann
ECT* Trento
13 June 2022


Before focusing on one specific problem …
..let me start with a helicopter view of our field.



Imagine, the ultimate textbook of QCD on these shelves…

It contains a chapter on heavy-ion collisions.

How do we write it? What do we emphasize?

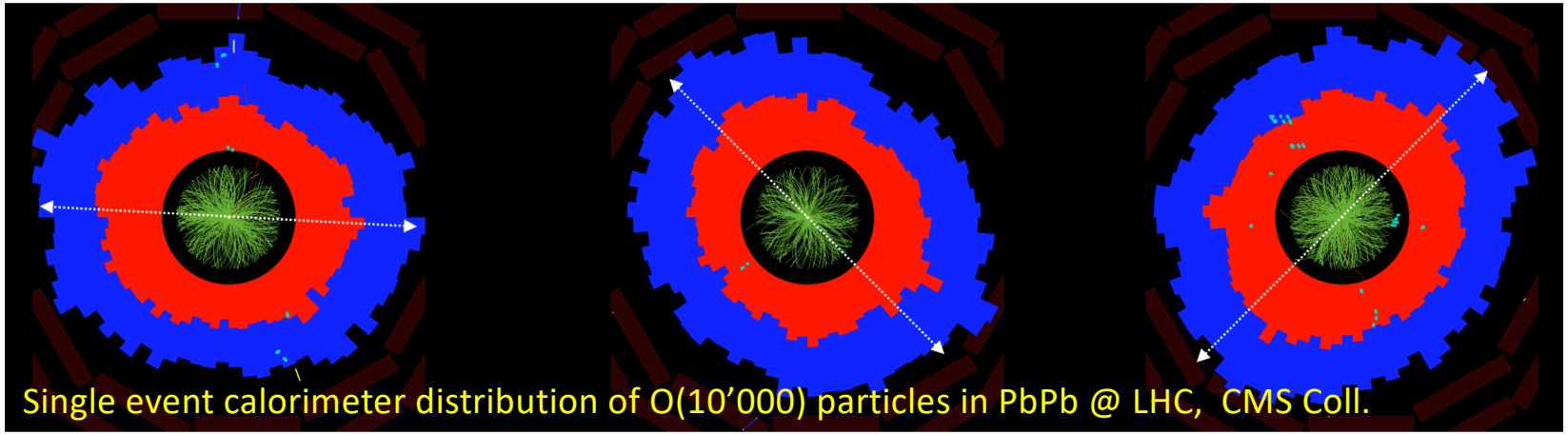
What is missing to write it?

The natural emphasis is on what we see, what is numerically large and what is generic.

ALICE Run Control Center

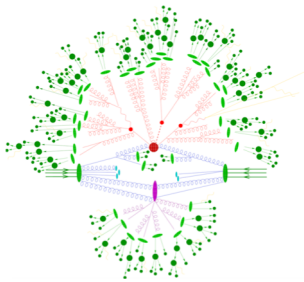
Flow

the generic low-p_T phenomenon



Q: Which dynamics is at play?

Free streaming → QCD transport theory → Dissipative fluid dynamics → Perfect fluid dynamics



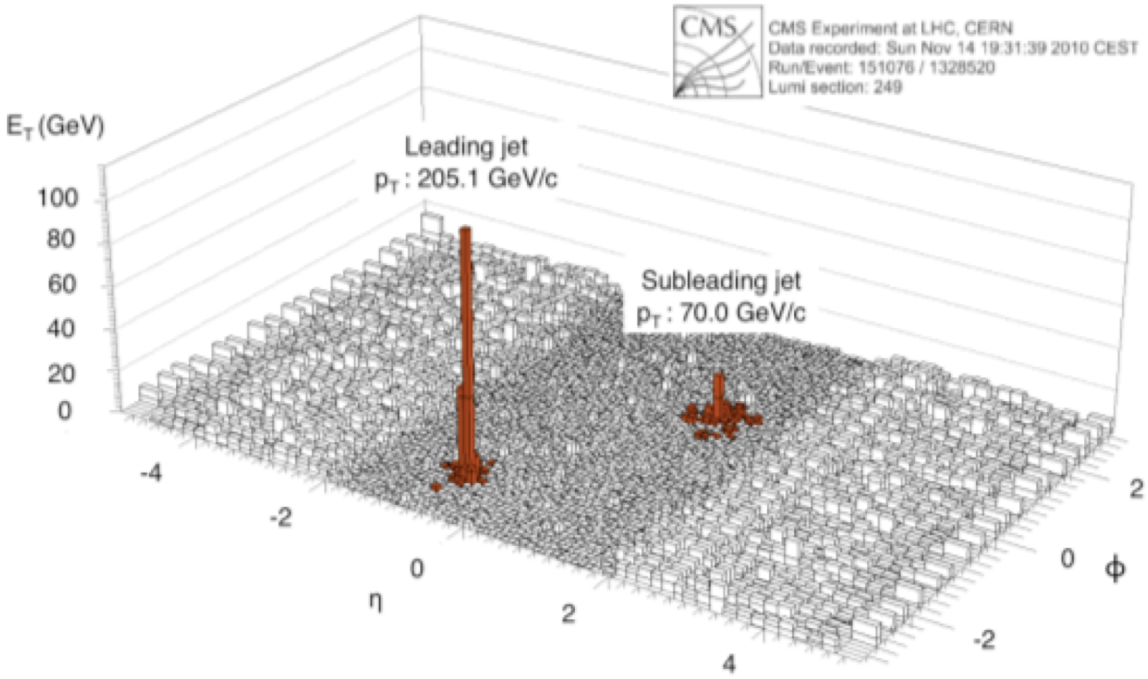
Ruled out !

To be tested quantitatively !

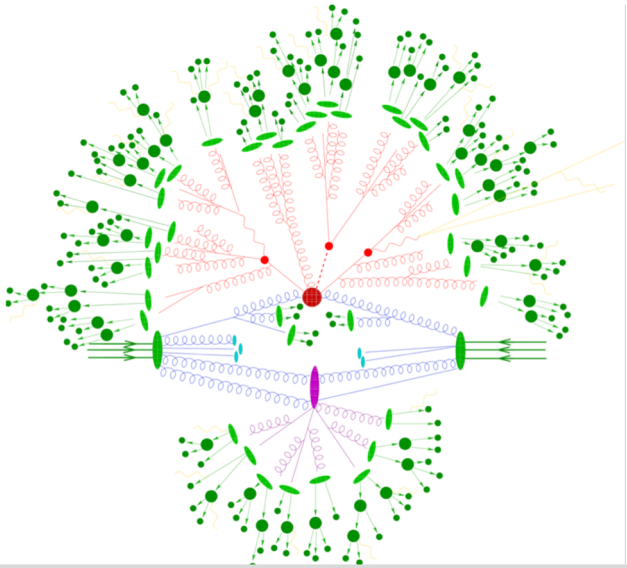
Jet quenching

The generic high- p_T phenomenon

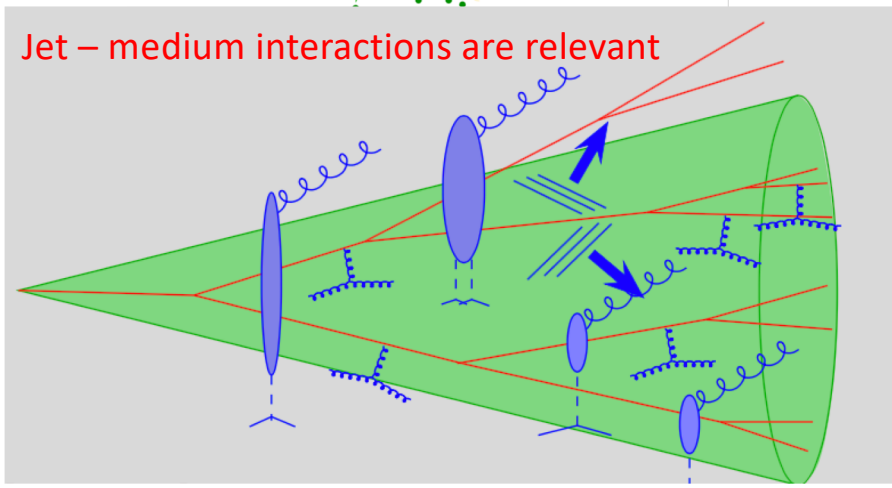
Deviation form free-streaming & fragmentation at high p_T



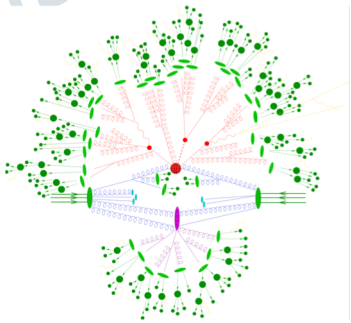
This is not sufficient!



Jet – medium interactions are relevant



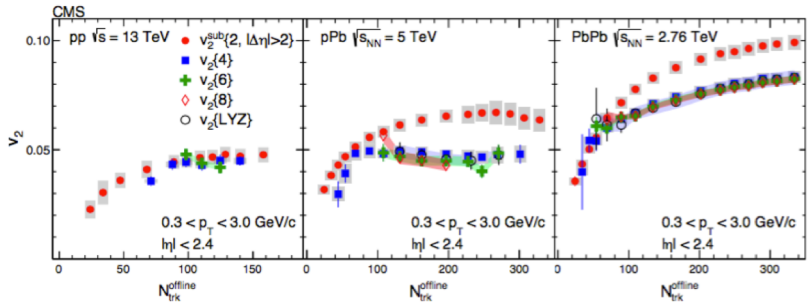
… the ultimate QCD textbook …



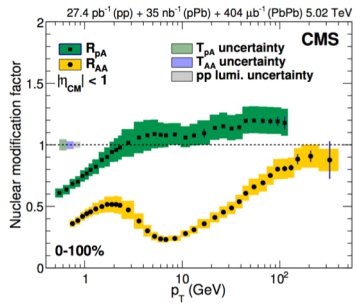
- The book covers also pp, based (currently) on a picture of free-streaming and fragmentation.
  But different chapters must be consistent with each other …
  Either: Perfect fluidity is understood as emerging with increasing system size/energy density from a close-to-freestreaming picture.
  Or: the close-to-freestreaming picture is not a valid starting point in small systems.

- The book is written in the language of QFT. QFT does not have separate words for a parton in a jet and a parton from the medium. Flow and jet quenching should occur as limiting cases of the same all-encompassing dynamics.

- Consistency of our most elementary interpretations remains to be better demonstrated. For instance: if we invoke final state interactions to explain flow, there must be jet quenching on some scale.



Why?



Starting from these motivations …

Transport ⇔ Flow

Testing medium properties via response functions

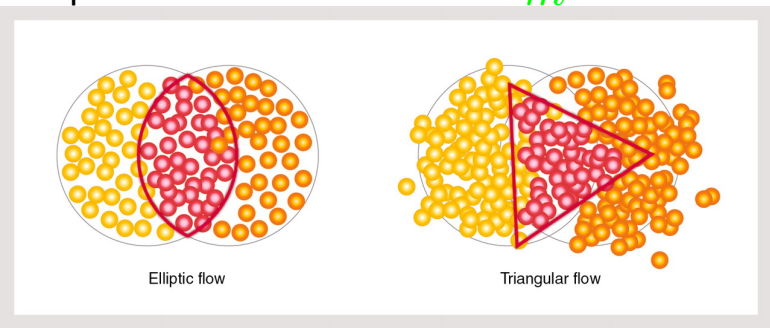
- Excite medium
- Listen to response
- Analyze

In theory:

$$G_{\mathrm{R}}^{\mu\nu,\alpha\beta} = \frac{\delta T^{\mu\nu}}{\delta h_{\alpha\beta}}$$

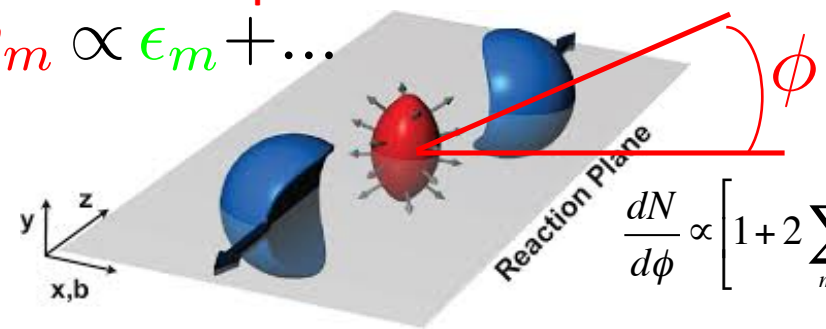
In experiment:

Prepare different excitations ϵ_m



measure their response

$$v_m \propto \epsilon_m + \ldots$$



$$\frac{dN}{d\phi} \propto \left[1 + 2\sum_m v_m \cos(m\phi)\right]$$

Analytic structure of response functions

$$G_R(t,k) = \int_{-\infty}^{\infty} d\omega \tilde{G}_R(\underbrace{\omega}_{\in\mathbb{C}}, k) e^{-i\omega t} = c_{\rm hyd} \exp\left[-\Gamma_s k^2 t\right] + c_{\rm non-hyd} \exp\left[-t/\tau_R\right]$$

- **Hydrodynamic excitations,** e.g.

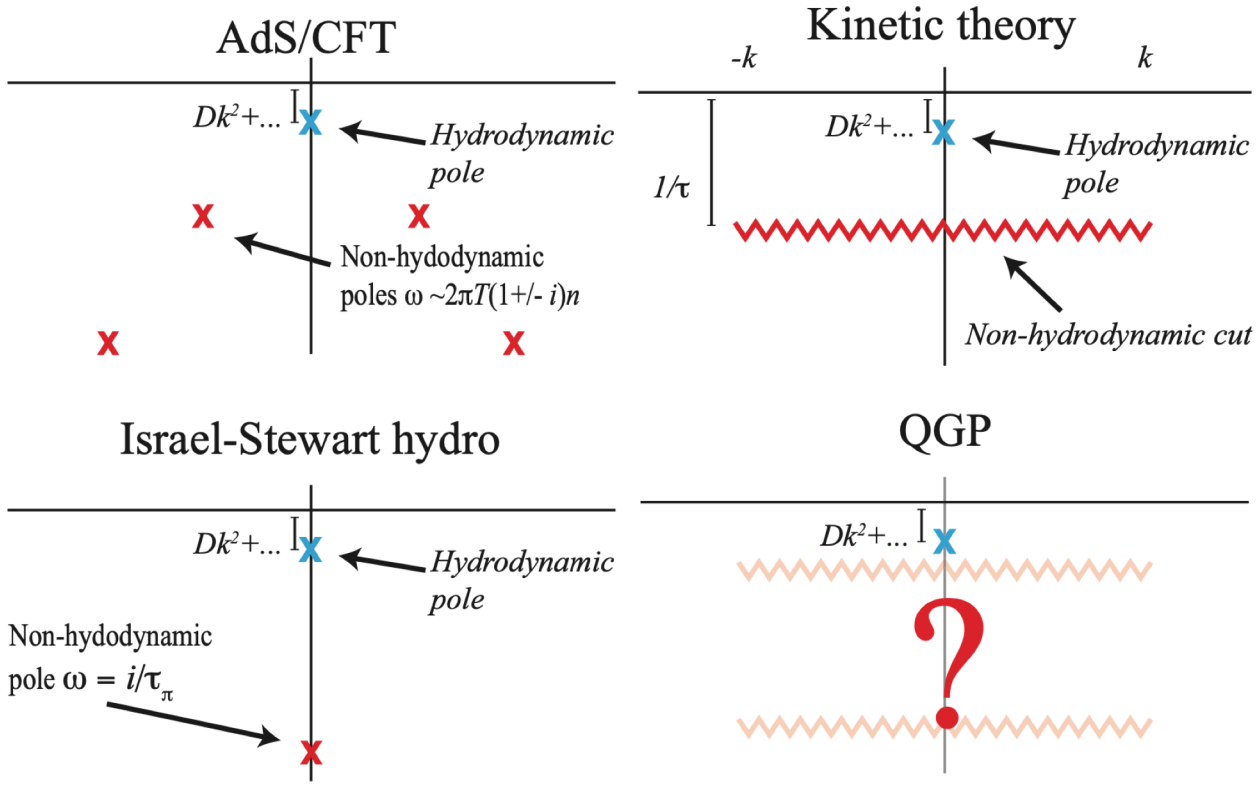
$$\omega_{\rm pole}^{\rm hyd}(k) = -i \underbrace{\frac{\eta}{sT}}_{\equiv\Gamma_s} k^2$$

  - Universal in QFTs
  - Consequence of conservation laws
  - Described by gradient expansion $k \leftrightarrow \nabla$

- **Non-hydro excitations,** e.g.

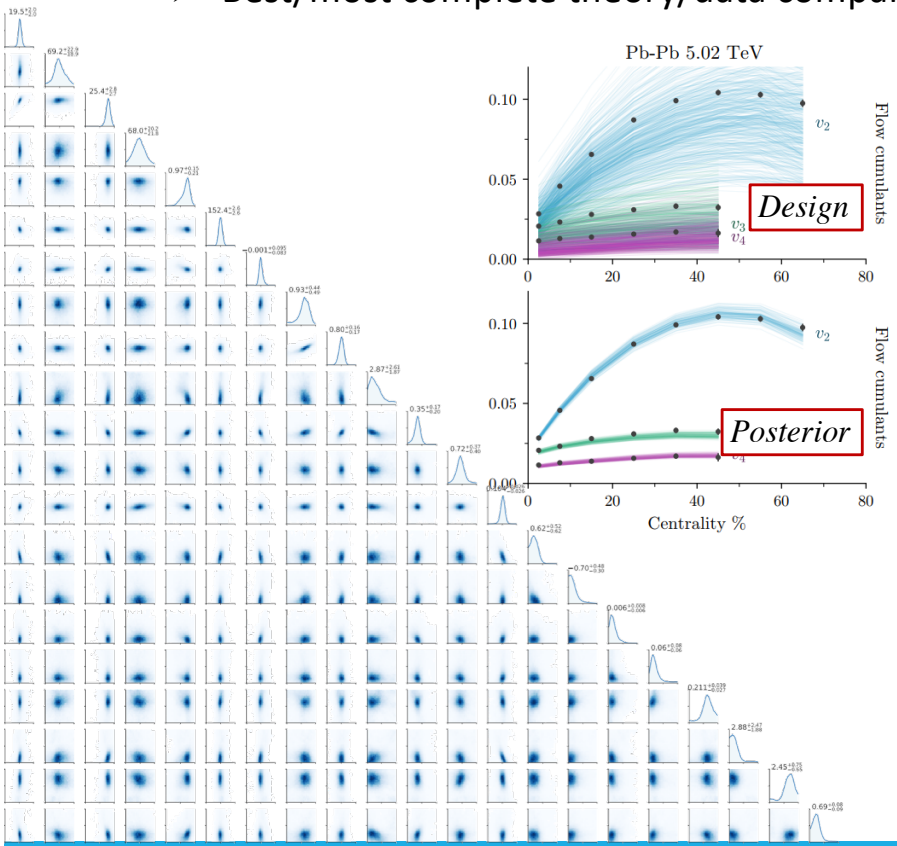
$$\omega_{\rm pole}^{\rm non-hyd}(k) = -i \frac{1}{\tau_\pi}$$

  - No QFTs without non-hydro modes
  - Consequence of causality
  - Not described by gradient expansion

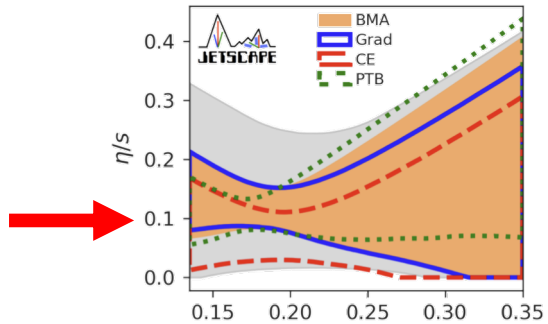


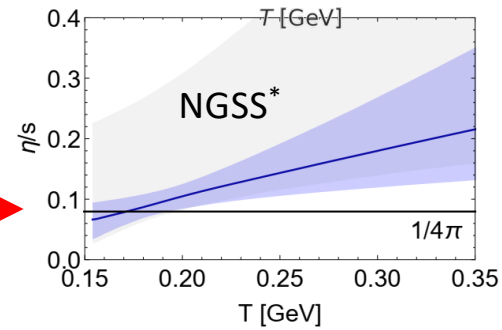
Bayesian Inference

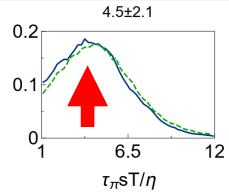
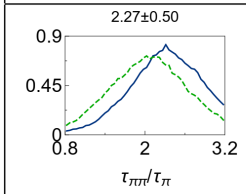
- More than fluid dynamics but constrains fluid dynamics
- Best/most complete theory/data comparison at soft p_T



State of the art: 514 data points, 20 parameters, unprecedented detail.





	NGSS*	AdS/CFT	kinetic theory
$\frac{\tau_\pi s T}{\eta}$		$4 - \log(4) \approx 2.61$	5
$\frac{\tau_{\pi\pi}}{\tau_\pi}$		$\frac{88}{35(2-\log 2)} \approx 1.92$	$\frac{10}{7} \approx 1.43$

Steffen Bass, A data-driven approach to quantifying the shear viscosity of nature's most ideal liquid, https://www.youtube.com/watch?v=MGE8K8IY4cg

*G. Nijs, U. Gursoy, W. v.d. Schee, R. Snellings, arXiv:2010.15130, arXiv:2010.15134

How fluid is the fluid?

- N=4 SYM plasma has no internal structure
  "universal" lower bound $\frac{\eta}{s} = \frac{1}{4\pi}$ 2001 Policastro, Son, Starinets*
- 1-d Bjorken expansion is **isentropic** if $\frac{d(\tau s)}{d\tau} = \frac{\frac{4}{3}\eta}{\tau T} \ll s \implies \frac{\eta}{s} \ll \underbrace{\tau T}_{>1}$
- Hydro-modes dominate if

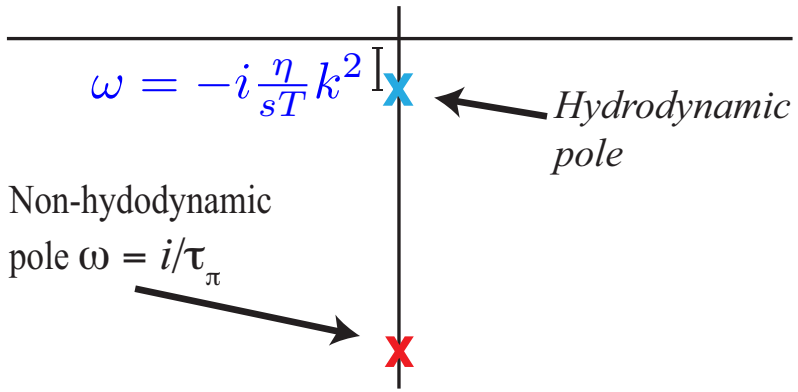
$$\frac{\eta}{sT} k^2 \ll \frac{1}{\tau_\pi} \approx \frac{1}{5}\frac{sT}{\eta}$$

- Hydro-dominated wavelengths satisfy

$$\lambda = \frac{2\pi}{k} \gg \underbrace{2\pi\sqrt{5}}_{10} \underbrace{\frac{\eta}{s}}_{0.1} \underbrace{\frac{1}{T}}_{1\text{ fm}}$$

Such wavelengths do not fit into a proton !
Experimental access of non-hydro modes seems feasible.

Israel-Stewart hydro



*G. Policastro, D.T. Son, A. Starinets, The Shear viscosity of strongly coupled N=4 supersymmetric Yang-Mills plasma, Phys.Rev.Lett. 87 (2001) 081601

How non-fluid is the fluid?

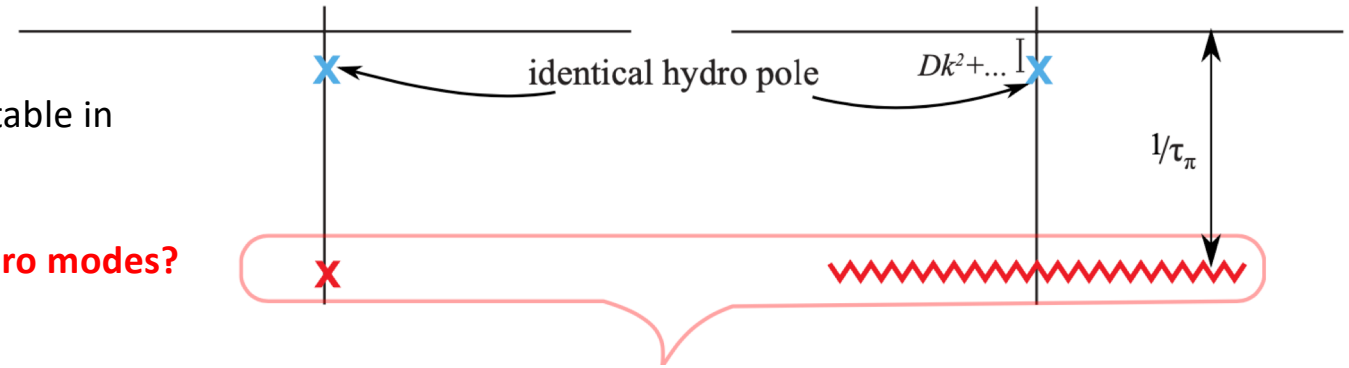
That depends on its size R:

- **Smallest wavenumber** $k \sim \frac{1}{R}$
- **Longest propagation time** $t \sim R$

$$G_R(t,k) = \underbrace{c_{\text{hyd}}\ \exp\left[-\Gamma_s k^2 t\right]}_{\text{reduced for smaller R}} + \underbrace{c_{\text{non-hyd}}\ \exp\left[-t/\tau_R\right]}_{\text{enhanced for smaller R}}$$

Non-hydro excitations become testable in systems of sufficiently small size R:

Can we test the nature of non-hydro modes?



It is known that this difference affects flow observables.*

*A. Kurkela, U. Wiedemann, Bin Wu, Eur. Phys. J. C79 (2019) 9,. 759
UAW talk at Initial Stages, Rehovot, https://cds.cern.ch/record/2749317

In summary:

- Taking results of modern Bayesian Inference studies seriously reveals the importance of non-hydro modes in kinetic transport.
- Kinetic transport is a dynamical framework for explaining hydrodynamization and thermalization. It interpolates between free-streaming and perfect fluidity.

Next …

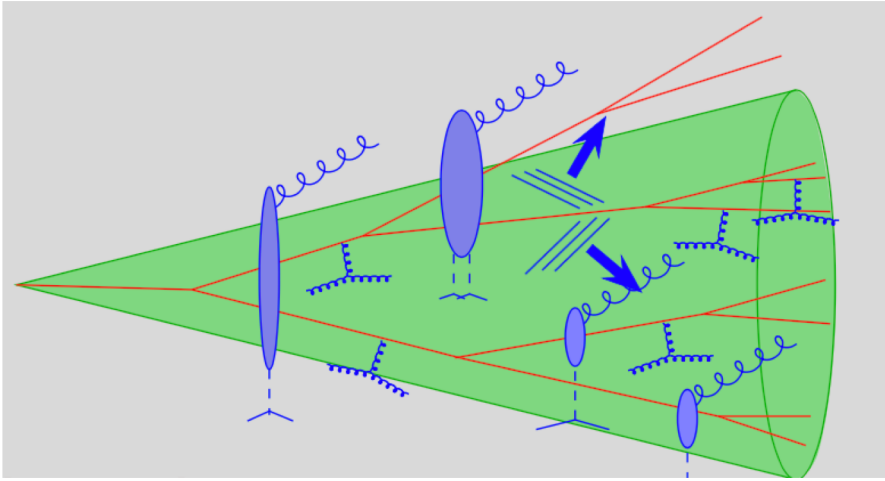
Jet quenching ⇔ Transport

Jet quenching – a *peculiar* kinetic transport

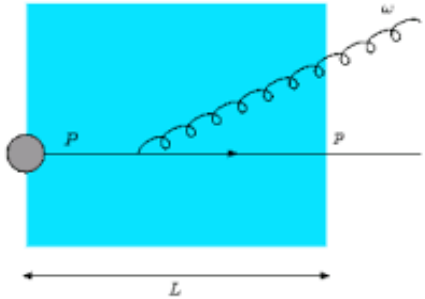
A generic quenching model implements

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

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

medium never

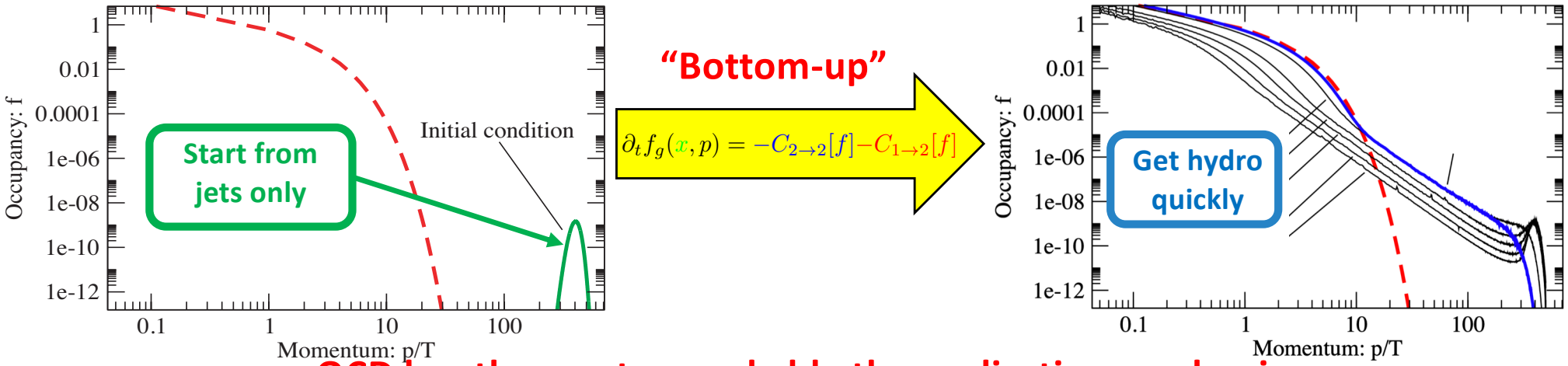
❑ **In medium**

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

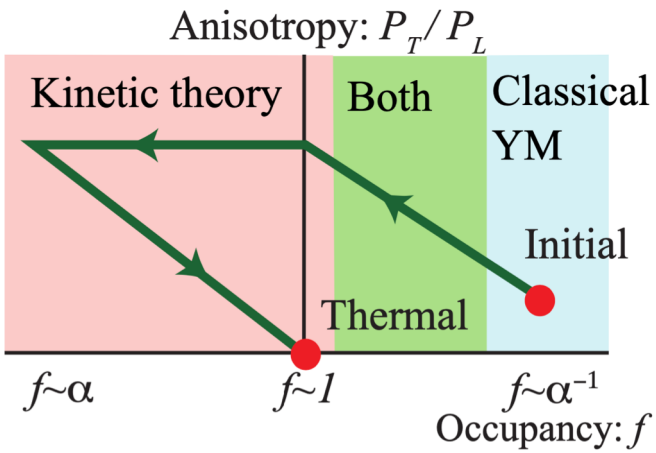
Quenching models: Q-Pythia, Q-Herwig, JEWEL, LBT, MATTER, MARTINI … HYBRID is different

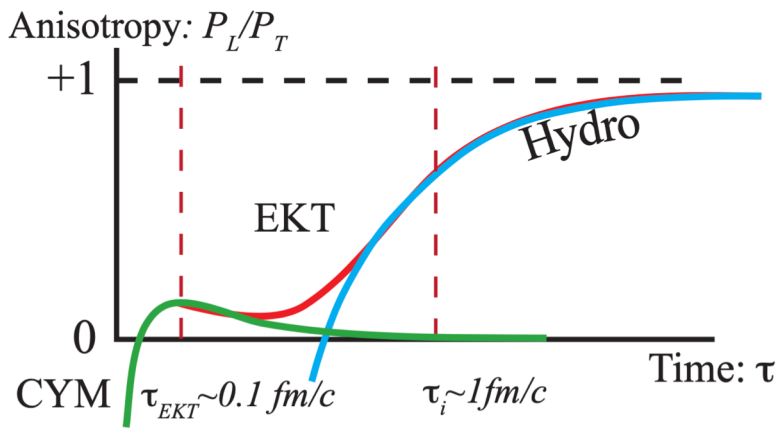
X.N. Wang, Jet tomography of hot and cold nuclear matter, https://www.youtube.com/watch?v=a69d22ZiiT8

Jet quenching = fast perturbative hydrodynamization



pQCD has the most remarkable thermalization mechanism



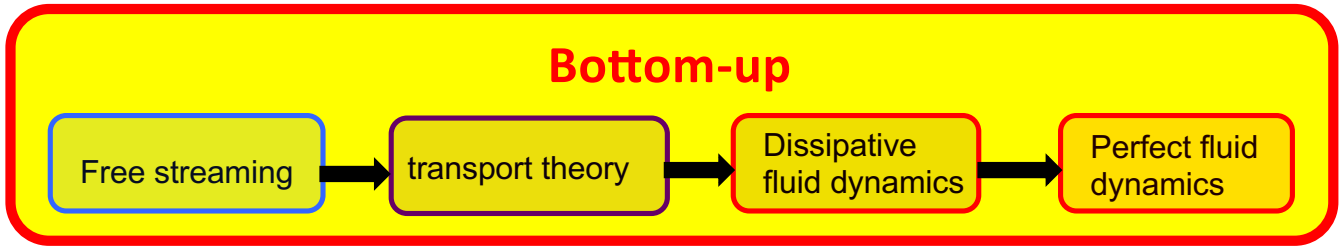


R. Baier, A.H. Mueller, D. Schiff, D.T. Son, 'Bottom up' thermalization in heavy ion collisions, Phys. Lett. B502 (2001) 51

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

QCD effective kinetic theory* encorporates jet quenching and flow.

It is a more encompassing HI paradigm than the perfect fluid:



* supplemented by non-perturbative physics on sufficiently soft momentum scales

*A. Kurkela, A. Mazeliauskas, J.F. Paquet, S. Schlichting, D. Teaney, "KOMPOST", Phys. Rev. Lett. 122 (2019) 12 and Phys. Rev. C99 (2019) 3

One specific idea to further strengthen this relation

Jet quenching ⇔ Transport

Specific question:

Can we identify in heavy-ion collisions distinct signatures of **chemical equilibration** that follow unambiguously from QCD effective kinetic transport?

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

Specifically, can we test?

$$C_{1\to 2} = C_{g\to c\bar{c}}$$

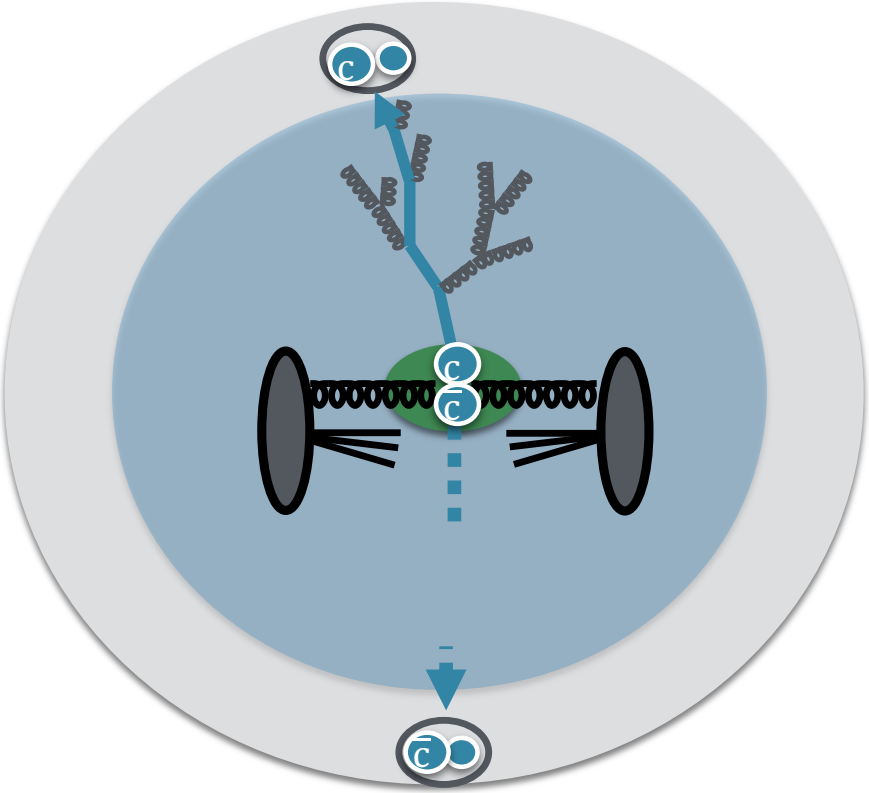
Can we measure increased ccbar-production due to final state interactions?

Maximilian Attems,[a] Jasmine Brewer,[a] Gian Michele Innocenti,[b] Aleksas Mazeliauskas,[a] Sohyun Park,[a] Wilke van der Schee[a] and Urs Achim Wiedemann[a]

[a] *Theoretical Physics Department, CERN, CH-1211 Geneva 23, Switzerland*

[b] *Experimental Physics Department, CERN, CH-1211 Geneva 23, Switzerland*

Heavy quark production is “perturbatively calculable*”:



- For “back-to-back” production

$$\hat{s} \simeq Q^2_{\rm pair} \gg 4m_c^2 > T^2\,, Q_s^2$$

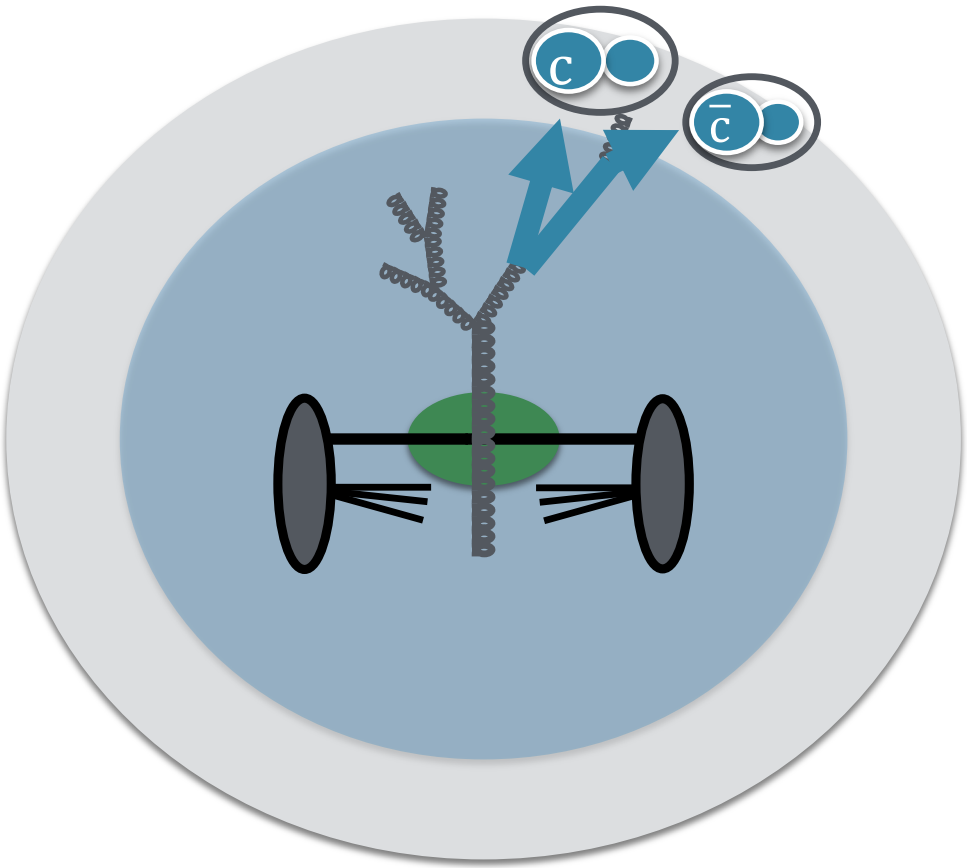
“short distance”, unaffected by medium.
This dominates the total rate.

- Dominant medium modification is
heavy quark energy loss**,

$$c \to c\,g \qquad \text{not} \quad g \to c\bar{c}$$

*M. Cacciari et al., JHEP 10 (2012) 137
**Y.L. Dokshitzer, D.E Kharzeev, Phys.Lett. B 519, 199-206, 2001, BDMPS, Nucl.Phys., B484:265–282, 199 B.G. Zakharov, JETP Lett., 63:952–957, 1996.

Long distance contribution to heavy quark production



- In the collinear limit of QCD

$$\hat{\sigma}^{gg\to c\bar{c}X}\big|_{Q^2\ll\hat{s}}$$

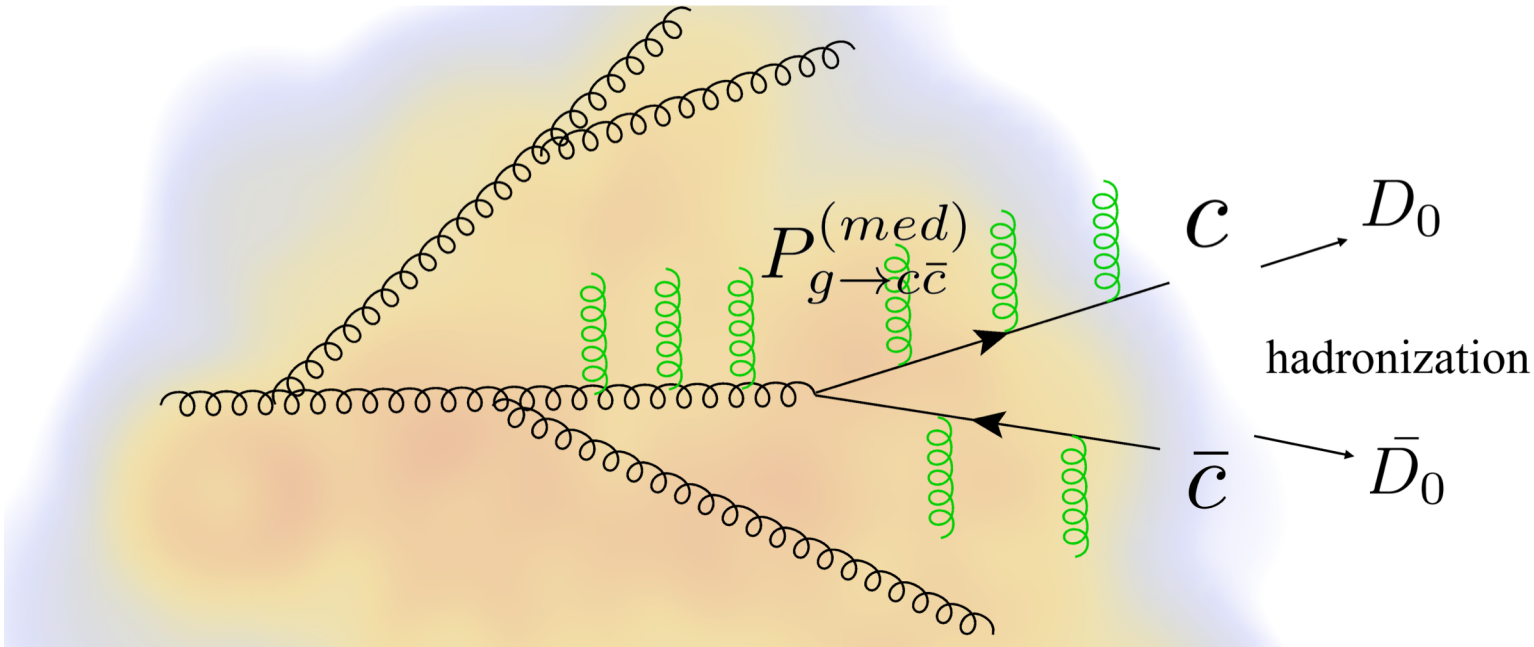
$$\longrightarrow \hat{\sigma}^{gg\to gX} \otimes \frac{\alpha_s}{2\pi}\frac{1}{Q^2}P_{g\to c\bar{c}}(z)$$

"long distance", needs resummation in pQCD. Starting point of parton shower.

- In the medium rest frame, production time of g-> ccbar is boosted by

$$\tau_{c\bar{c}} \simeq \frac{1}{Q}\frac{E_g}{Q}$$

- Total ccbar-yield (almost) unaffected by medium since dominated by short distance process.
- But ccbar-yield within parton shower dominated by long-distance processes. To test $C_{1\to 2} = C_{g\to c\bar{c}}$, we should calculate yield within jets.



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

The medium-modified* g->c cbar splitting function

$$\left(\frac{1}{Q^2}P_{g\to c\bar{c}}\right)^{\text{tot}} \equiv \left(\frac{1}{Q^2}P_{g\to c\bar{c}}\right)^{\text{vac}} + \left(\frac{1}{Q^2}P_{g\to c\bar{c}}\right)^{\text{med}}$$
$$= 2\,\mathfrak{Re}\,\frac{1}{4\,E_g^2}\int_{t_{\text{init}}}^{t_\infty} dt \int_t^{t_\infty} d\bar{t}\,\exp\left[i\frac{m_c^2}{2E_g z(1-z)}(t-\bar{t}) - \epsilon|t| - \epsilon|\bar{t}|\right]\int d\mathbf{r}_{\text{out}}$$
$$\times\exp\left[-\frac{1}{2}\int_{\bar{t}}^{\infty} d\xi\, n(\xi)\,\sigma_3(\mathbf{r}_{\text{out}},z)\right]\exp\left[-i\,\boldsymbol{\kappa}\cdot\mathbf{r}_{\text{out}}\right]$$
$$\times\left[\left(m_c^2 + \frac{\partial}{\partial\mathbf{r}_{\text{in}}}\cdot\frac{\partial}{\partial\mathbf{r}_{\text{out}}}\right)\frac{z^2+(1-z)^2}{z(1-z)} + 2m_c^2\right]\mathcal{K}\left[\mathbf{r}_{\text{in}}=0,t;\mathbf{r}_{\text{out}},\bar{t}\right].$$

- Error in preprint v1 corrected**
- K-differential result correct to leading order in N_c.
- K-integrated result correct to all orders in N_c.
- Particular simple case where result at finite z and leading N_c does not involve a "quadrupole" term.

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

This is only one of many steps taken after BDMPS-Z & Co, technically related works include:

L. Apolinario et al, 1407.0599, F. Dominguez et al., 1907.03653, Isaksen et al., 2107.02542, 2206.02811
M. Sievert et al, 1903.06170, S. Caron-Huot&Gale, 1006.2379

*M. Attems, J. Brewer, G.M. Innocenti, A. Mazeliauskas, S. Park, W. v.d.Schee, U.A. Wiedemann, 2203.11241, revised version to appear.
** thanks to Fabio Dominguez for alerting us!

Physics properties of medium-modified g->c cbar

$$\left(\frac{1}{Q^2}P_{g\to c\bar{c}}\right)^{\rm tot} \equiv \left(\frac{1}{Q^2}P_{g\to c\bar{c}}\right)^{\rm vac} + \left(\frac{1}{Q^2}P_{g\to c\bar{c}}\right)^{\rm med}$$
$$= 2\,\Re\mathfrak{e}\,\frac{1}{4\,E_g^2}\int_{t_{\rm init}}^{t_\infty} dt \int_t^{t_\infty} d\bar{t}\,\exp\left[i\frac{m_c^2}{2E_g z(1-z)}(t-\bar{t}) - \epsilon|t| - \epsilon|\bar{t}|\right]\int d\mathbf{r}_{\rm out}$$
$$\times \exp\left[-\frac{1}{2}\int_{\bar{t}}^{\infty} d\xi\, n(\xi)\,\sigma_3(\mathbf{r}_{\rm out}, z)\right]\exp\left[-i\,\boldsymbol{\kappa}\cdot\mathbf{r}_{\rm out}\right]$$
$$\times\left[\left(m_c^2 + \frac{\partial}{\partial\mathbf{r}_{\rm in}}\cdot\frac{\partial}{\partial\mathbf{r}_{\rm out}}\right)\frac{z^2+(1-z)^2}{z(1-z)} + 2m_c^2\right]\mathcal{K}\left[\mathbf{r}_{\rm in}=0, t; \mathbf{r}_{\rm out}, \bar{t}\right].$$

- In the absence of medium effects, reduction to known vacuum splitting:

$$\left(\frac{1}{Q^2}P_{g\to c\bar{c}}\right)^{\rm vac} = \frac{1}{Q^4}\left[\left(m_c^2+\boldsymbol{\kappa}^2\right)\frac{z^2+(1-z)^2}{z(1-z)} + 2m_c^2\right] \qquad Q^2 \equiv \frac{m_c^2+\boldsymbol{\kappa}^2}{z(1-z)}$$

- Interplay between coherent and incoherent limit reveals formation time

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

- Medium-modifications become numerically sizeable at scale

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

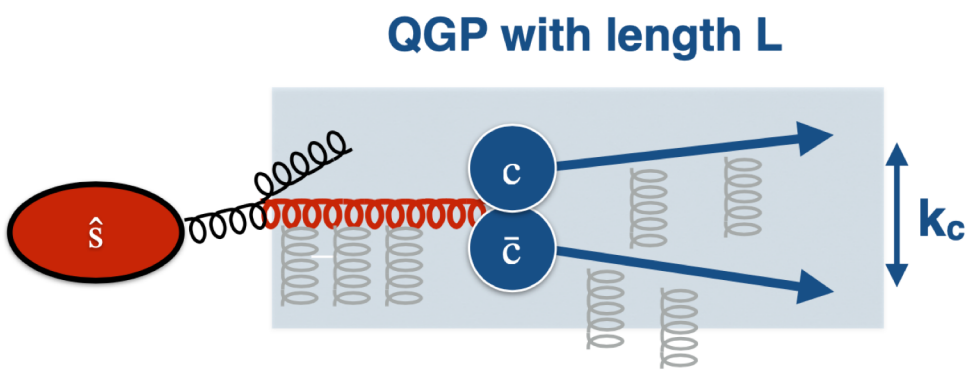
This is a scale that is phenomenologically realized!

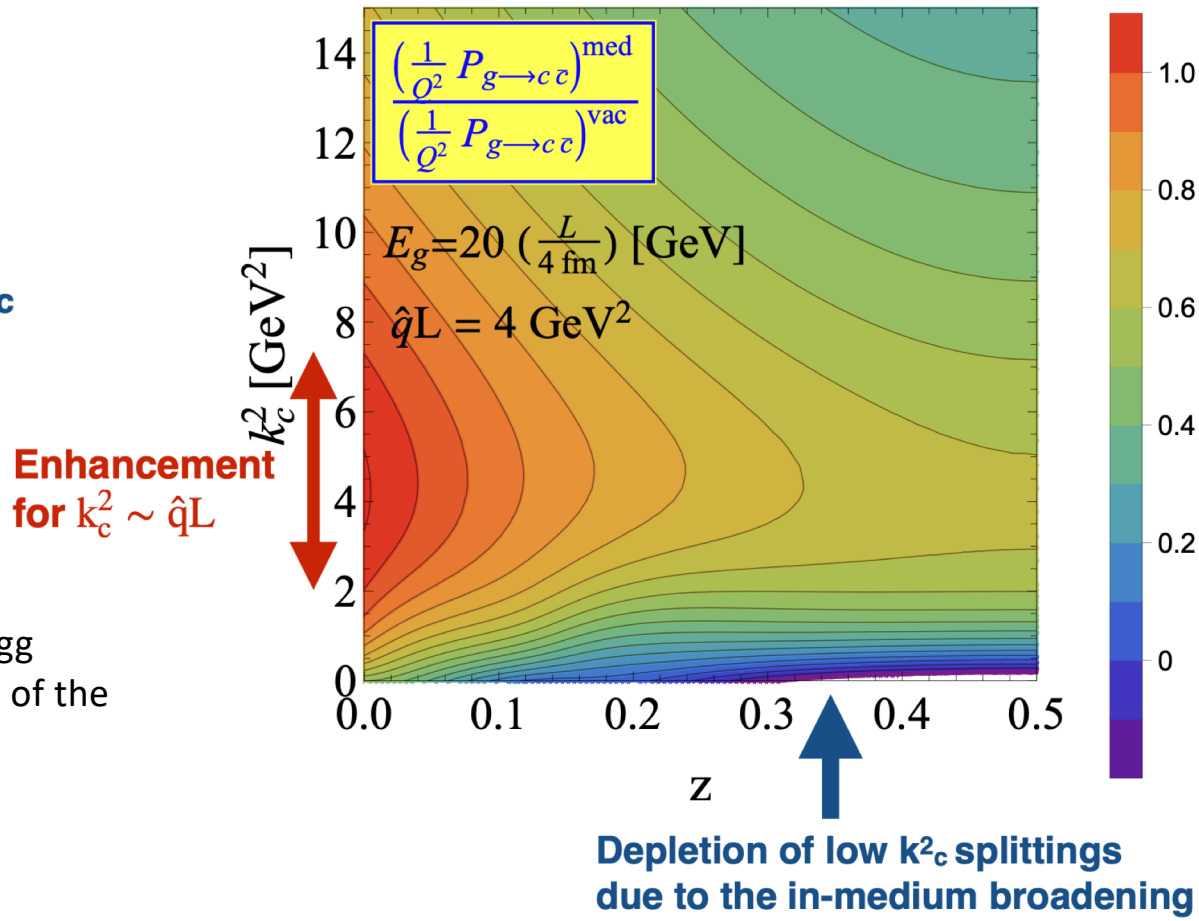
- Medium-modification is a “higher-twist” effect

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

*M. Attems, J. Brewer, G.M. Innocenti, A. Mazeliauskas, S. Park, W. v.d.Schee, U.A. Wiedemann, 2203.11241, revised version to appear.

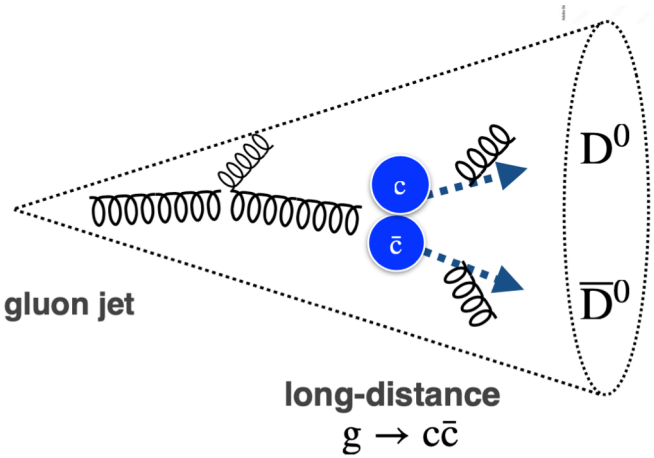
Numerical results

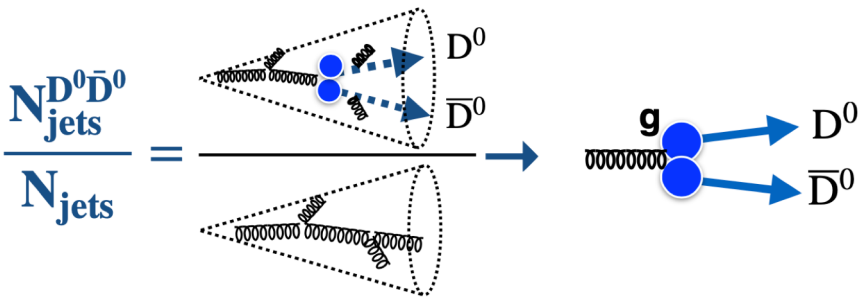




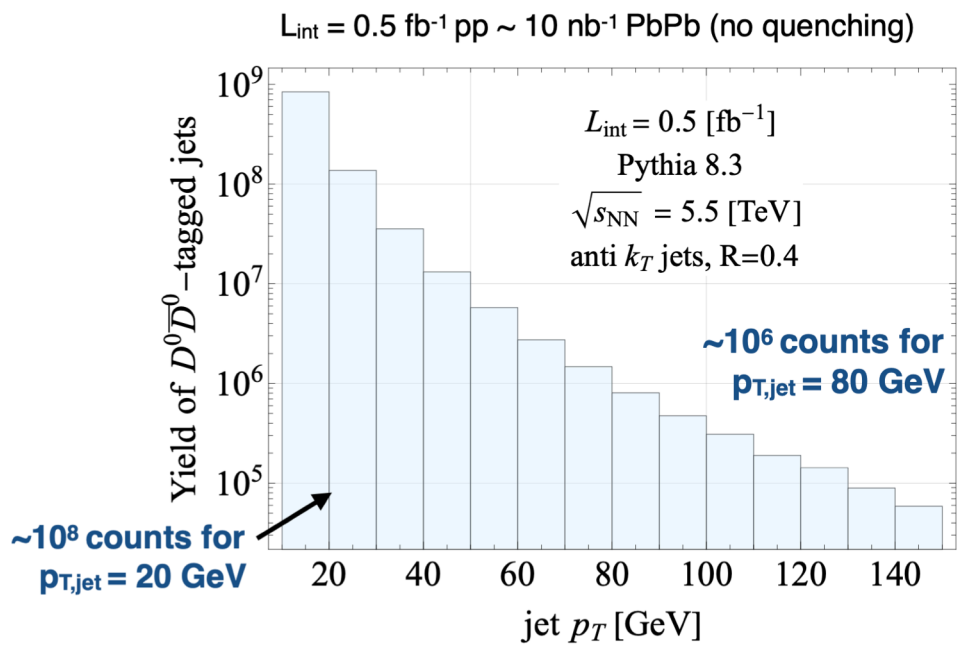
The formalism that predicts jet quenching via g -> gg may imply significant hadrochemical modifications of the c-cbar-content of jets.

Experimental strategy



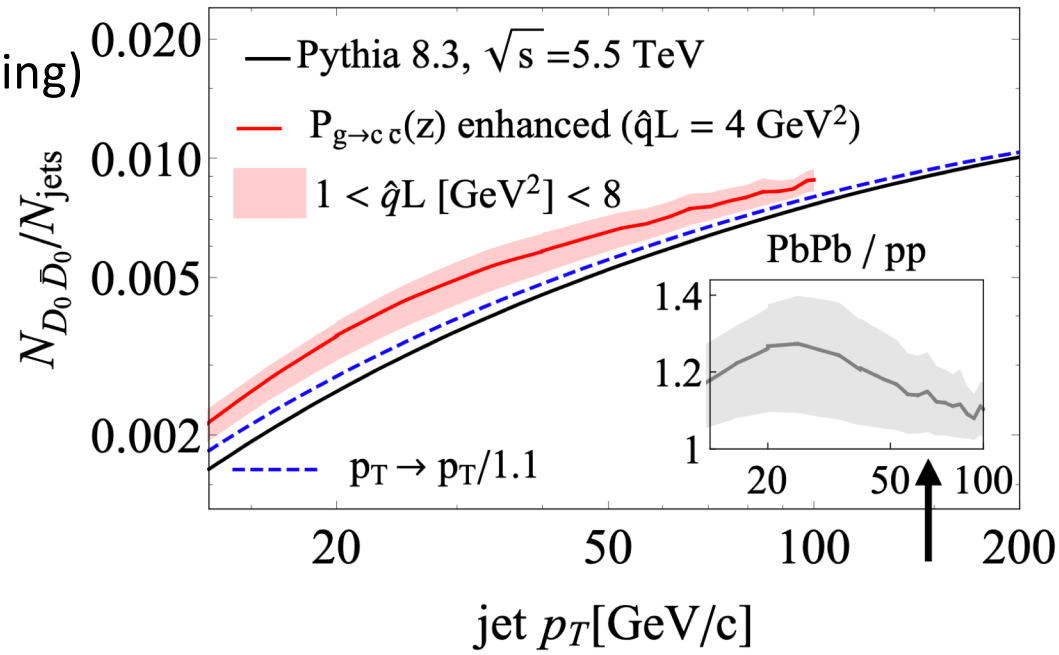


Set the vacuum baseline with Pythia:
[only prompt c->D^0 included]



An observable sensitive to enhanced g->ccbar in jets

- Vacuum baseline is in pp textbook chapter
- Expected rate could be within reach of HL-LHC
- Parton energy loss enhances rate, too (uncertainties could be removed by jet tagging)
- Enhancement estimated by reweighting g-> c cbar in Pythia parton shower.
- …
- Could this be the first test of perturbative chemical transport theory?



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Urs Wiedemann

STAY TUNED!