IGFAE Instituto Galego de Física de Altas Enerxías | USC Universidade de Santiago de Compostela | Xunta de Galicia

Jet Quenching In The Quark-Gluon Plasma
ECT*, Trento, June 17th 2022

Jet quenching and the first fermi/c

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Agencia Estatal de Investigación | Excelencia María de Maeztu | Gobierno de España | Ministerio de Economía y Competitividad

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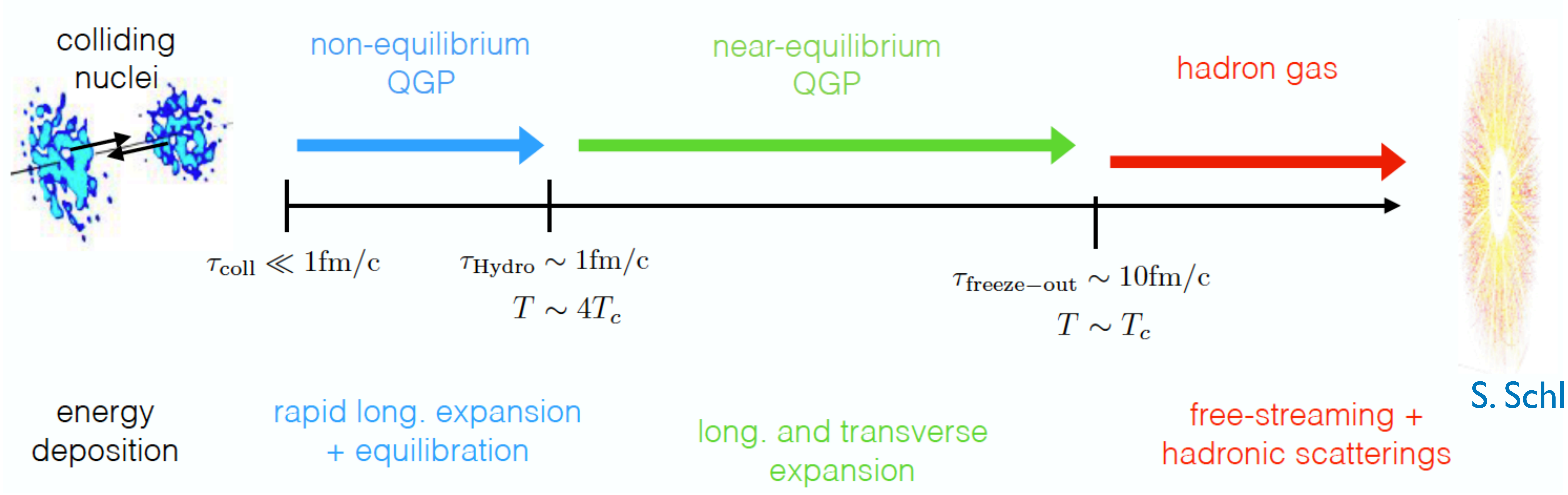
2. Observables sensitive to the initial stage of the collision:
   - ➜ R_{AA}-v_2 (talks by Adhya and Zigic).
   - ➜ Decaying particles.

3. Theoretical challenges:
   - ➜ Time in parton cascades (talks by Ontoso, Caucal, Majumder, Ke, Tachibana, Apolinario, Qin, Mehtar-Tani,…).
   - ➜ How to model the interaction of a jet with the pre-equilibrium stages (talks by Sadofiev, Barata, Czajka, Hauksson,…).

4. Summary.

The standard picture:



S. Schlichting

The standard picture:

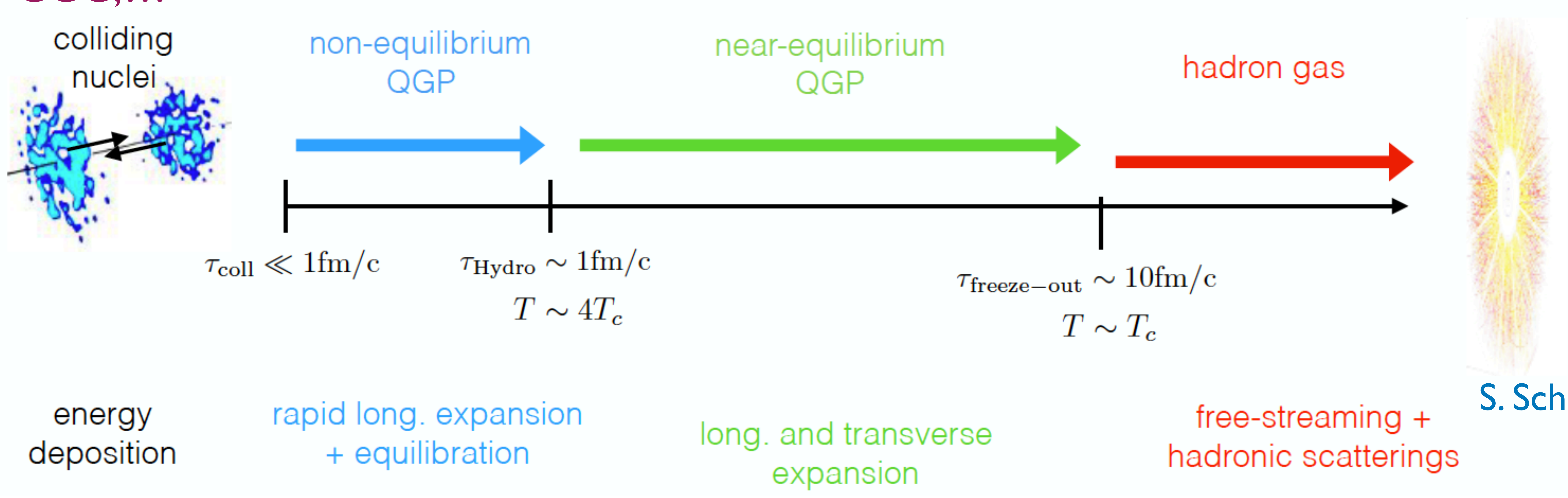
Nuclear wave function: nPDFs, CGC,…

Glasma: over-occupied system

Parton transport: EKT

Viscous hydro

Hadron cascade



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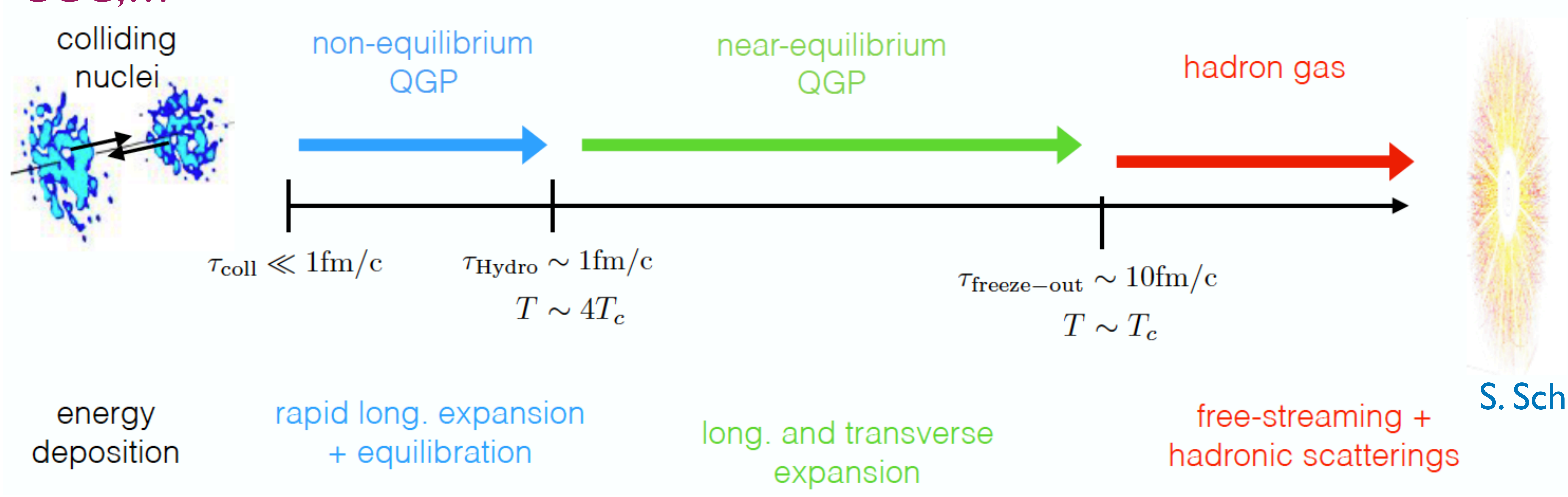


S. Schlichting

Can we apply it to small systems? Is there near-equilibrium QGP from $dN_{ch}/d\eta$~10 to 5000? How?

Small systems:

- Observables measured in small systems: pp and pA, that in AA are taken as QGP signals:

Collective hadronisation

Collective expansion (hydro-like)

Direct photons

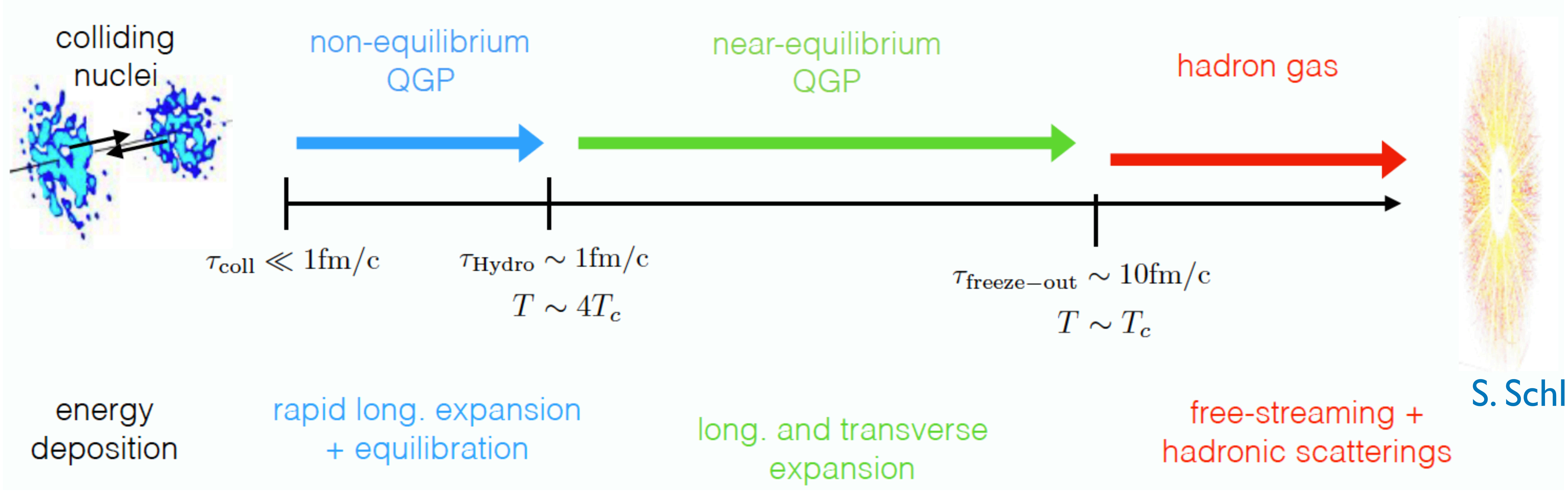
Final state interactions (non-hydro)

Observable or effect	Pb–Pb	p–Pb (high mult.)	pp (high mult.)	Refs.
Low p_T spectra ("radial flow")	yes	yes	yes	[47, 71, 317, 318, 654, 657, 663, 664, 667, 668]
Intermediate p_T ("recombination")	yes	yes	yes	[317, 657–663]
Particle ratios	GC level	GC level except Ω	GC level except Ω	[318, 638, 664, 665]
Statistical model	$\gamma_s^{GC} = 1$, 10–30%	$\gamma_s^{GC} \approx 1$, 20–40%	MB: $\gamma_s^{C} < 1$, 20–40%	[318, 638, 669]
HBT radii ($R(k_T)$, $R(\sqrt[3]{N_{ch}})$)	$R_{out}/R_{side} \approx 1$	$R_{out}/R_{side} \lesssim 1$	$R_{out}/R_{side} \lesssim 1$	[670–677]
Azimuthal anisotropy (v_n) (from two particle correlations)	v_1–v_7	v_1–v_5	v_2–v_4	[48, 312–314, 632, 633, 652, 678–688]
Characteristic mass dependence	v_2–v_5	v_2, v_3	v_2	[48, 315, 326, 683, 686, 689–691]
Directed flow (from spectators)	yes	no	no	[692]
Charge-dependent correlations	yes	yes	yes	[249, 253, 254, 693–696]
Higher-order cumulants (mainly $v_2\{n\}$, $n \geq 4$)	"$4 \approx 6 \approx 8 \approx$ LYZ" +higher harmonics	"$4 \approx 6 \approx 8 \approx$ LYZ" +higher harmonics	"$4 \approx 6$"	[316, 683, 688, 697–708]
Symmetric cumulants	up to SC(5, 3)	only SC(4, 2), SC(3, 2)	only SC(4, 2), SC(3, 2)	[227, 687, 709–712]
Non-linear flow modes	up to v_6	not measured	not measured	[713]
Weak η dependence	yes	yes	not measured	[685, 707, 714–719]
Factorization breaking	yes ($n = 2, 3$)	yes ($n = 2, 3$)	not measured	[682, 684, 720–722]
Event-by-event v_n distributions	$n = 2$–4	not measured	not measured	[723–725]
Direct photons at low p_T	yes	not measured	not observed	[544, 726]
Jet quenching through dijet asymmetry	yes	not observed	not observed	[348, 360, 374, 727–729]
Jet quenching through R_{AA}	yes	not observed	not observed	[323, 344, 346, 347, 352, 730–737]
Jet quenching through correlations	yes (Z–jet, γ–jet, h–jet)	not observed (h–jet)	not measured	[354, 357, 375, 376, 380, 388, 733, 738–740]
Heavy flavor anisotropy	yes	yes	not measured	[262, 326, 460–464, 497, 741–745]
Quarkonia production	suppressed†	suppressed	not measured	[262, 454, 456, 459, 478, 479, 491, 492, 494, 495, 497, 579, 746–755]

† $J/\psi \uparrow$, $\Upsilon(\downarrow)$ w.r.t. RHIC energies.

1812.06772, talk by Krizek

Jet quenching for time studies:



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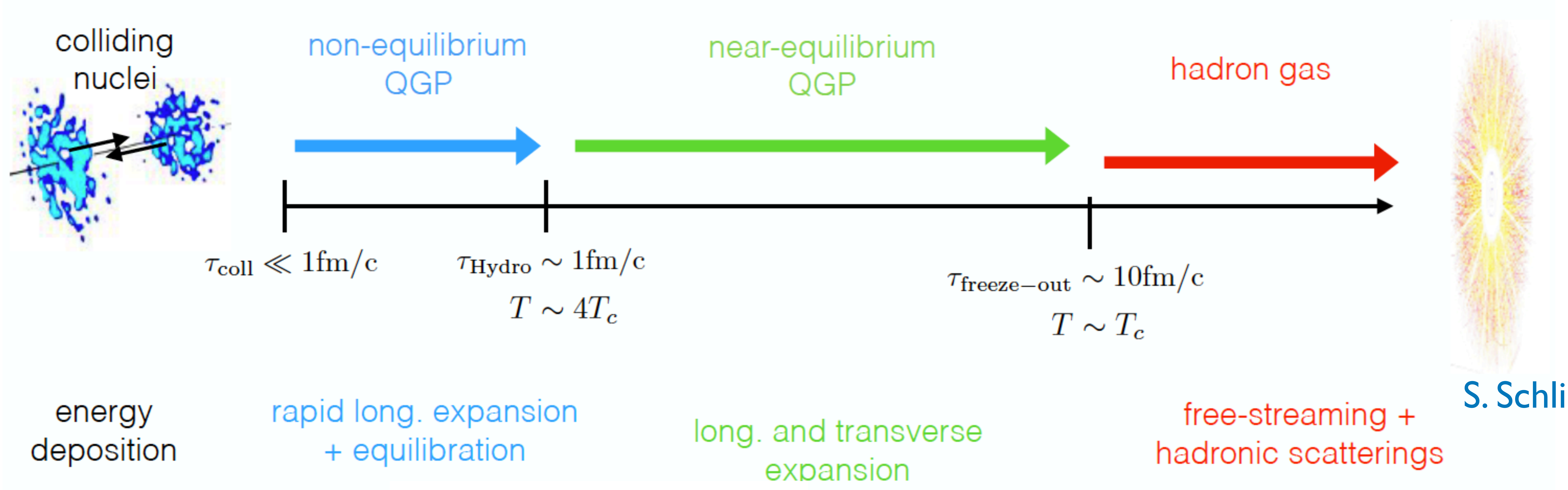
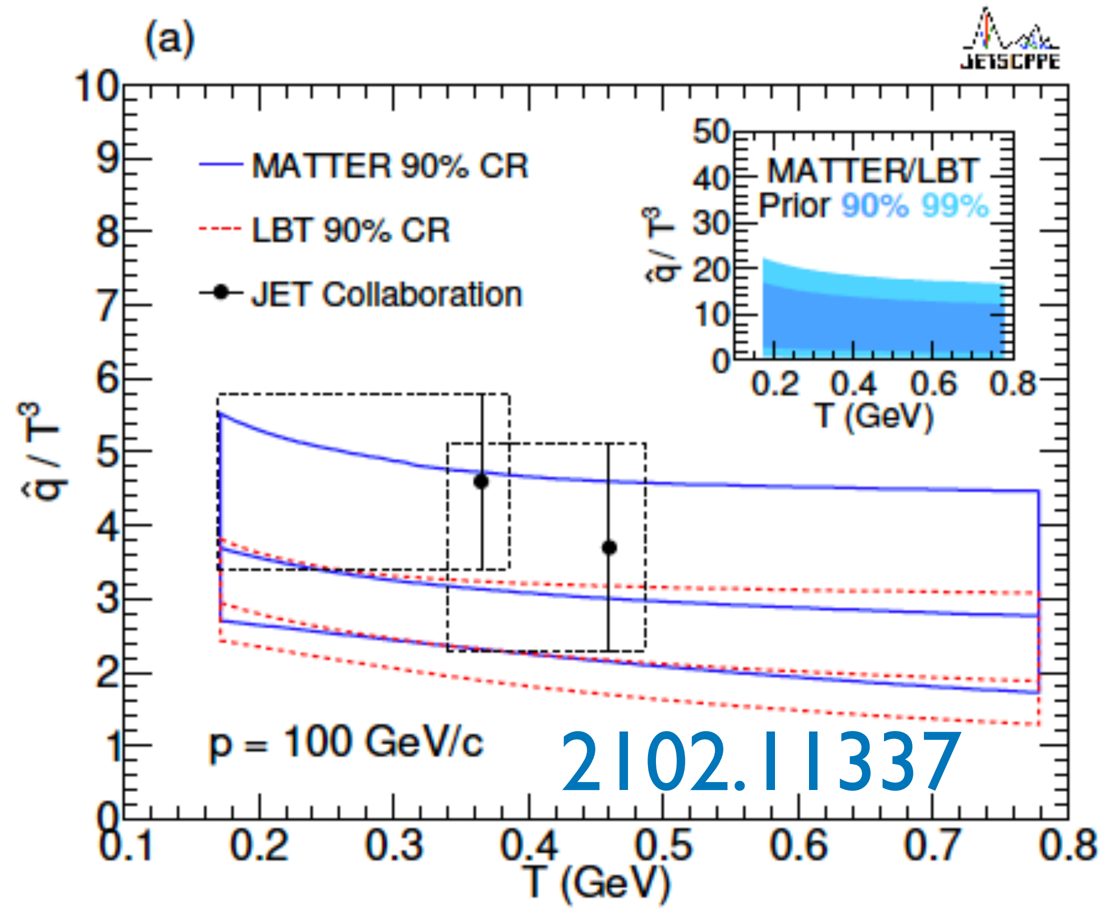
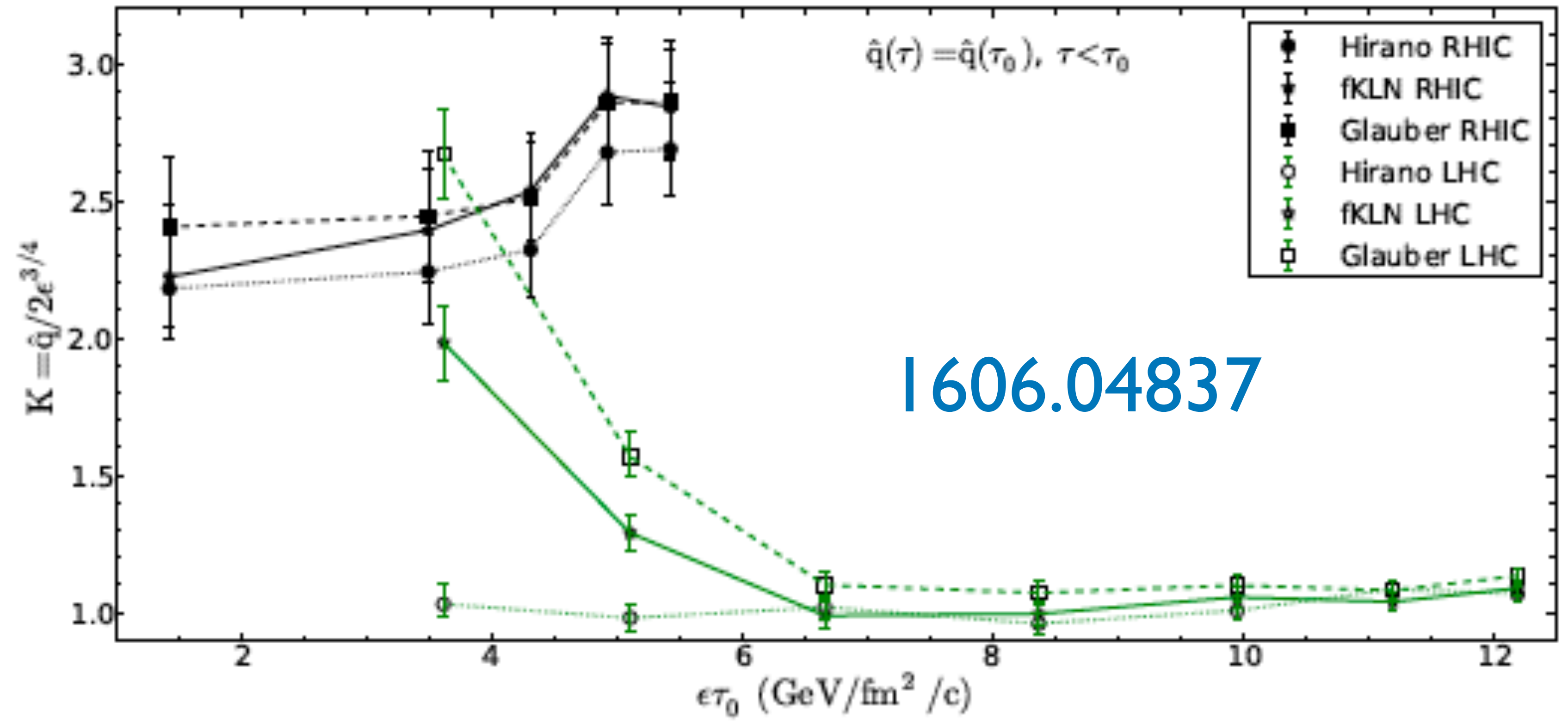


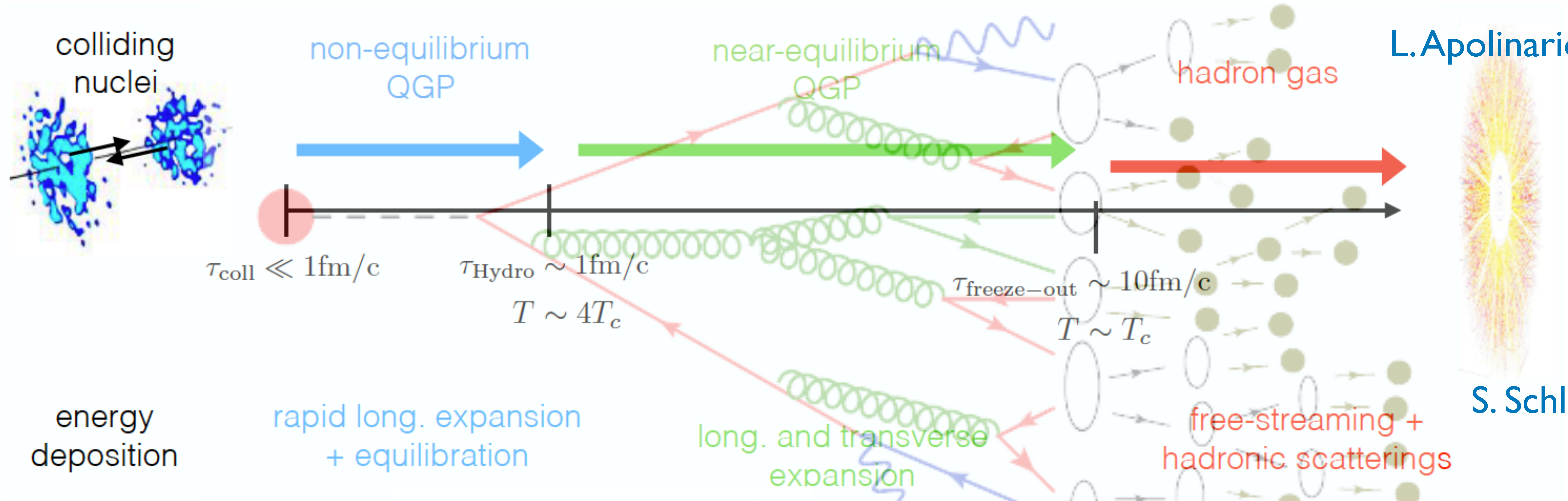
S. Schlichting

Traditionally jet quenching aims at characterising the QGP.





Jet quenching for time studies:



L. Apolinario

S. Schlichting

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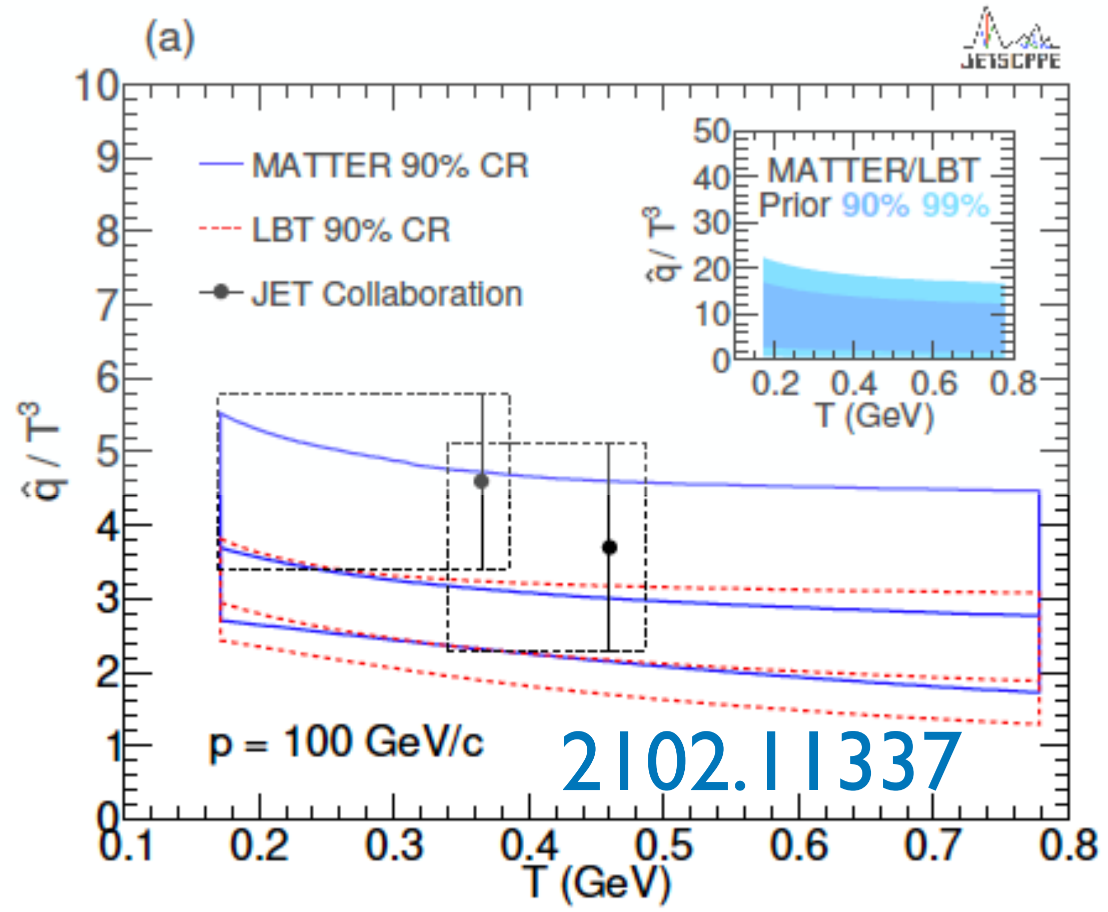

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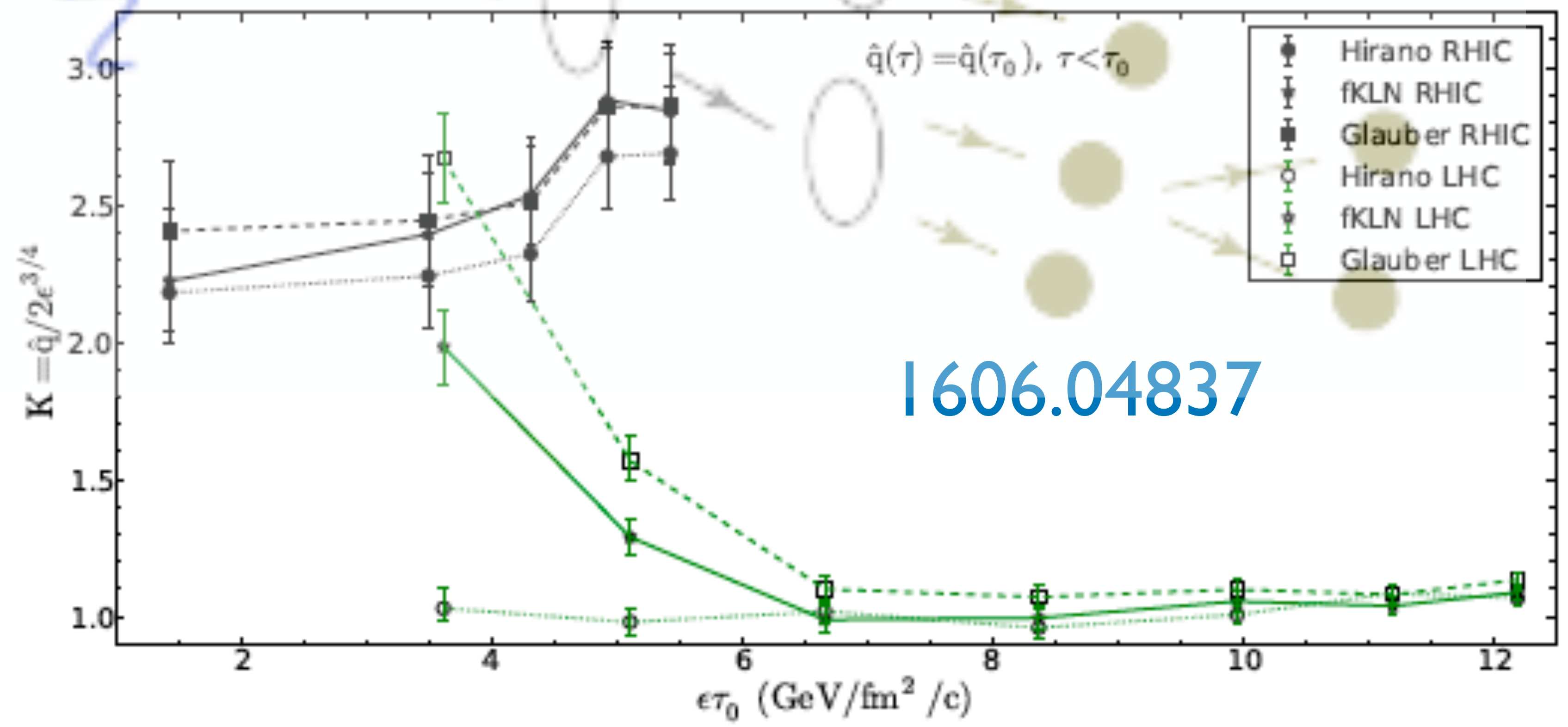
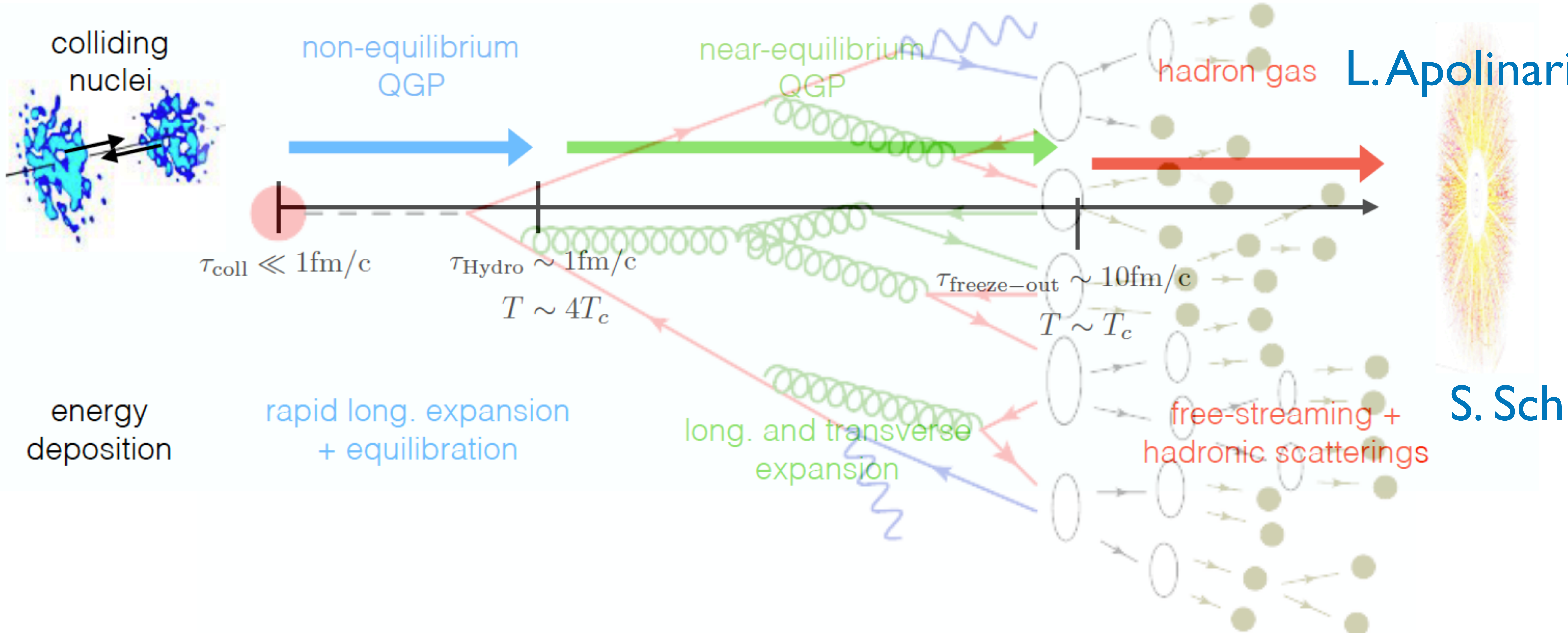


1606.04837

Jet quenching for studying the early stage:



L. Apolinario

S. Schlichting

• Parton branching is a multiscale process with energies ranging from TeV (hard scattering) to GeV (hadronisation) (talk by Ontoso). To be able to use it for time studies, we need:

➜ Observables sensitive to what happens at early stages (many observables e.g. R_{AA} tend to be dominated by late times).

➜ Understanding how to formulate (or relate) a vacuum+medium parton cascade with the 'time' in which the medium evolves (vacuum parton cascades not formulated in 'time').

Note: jet quenching may not be the only observable (quarkonium?).

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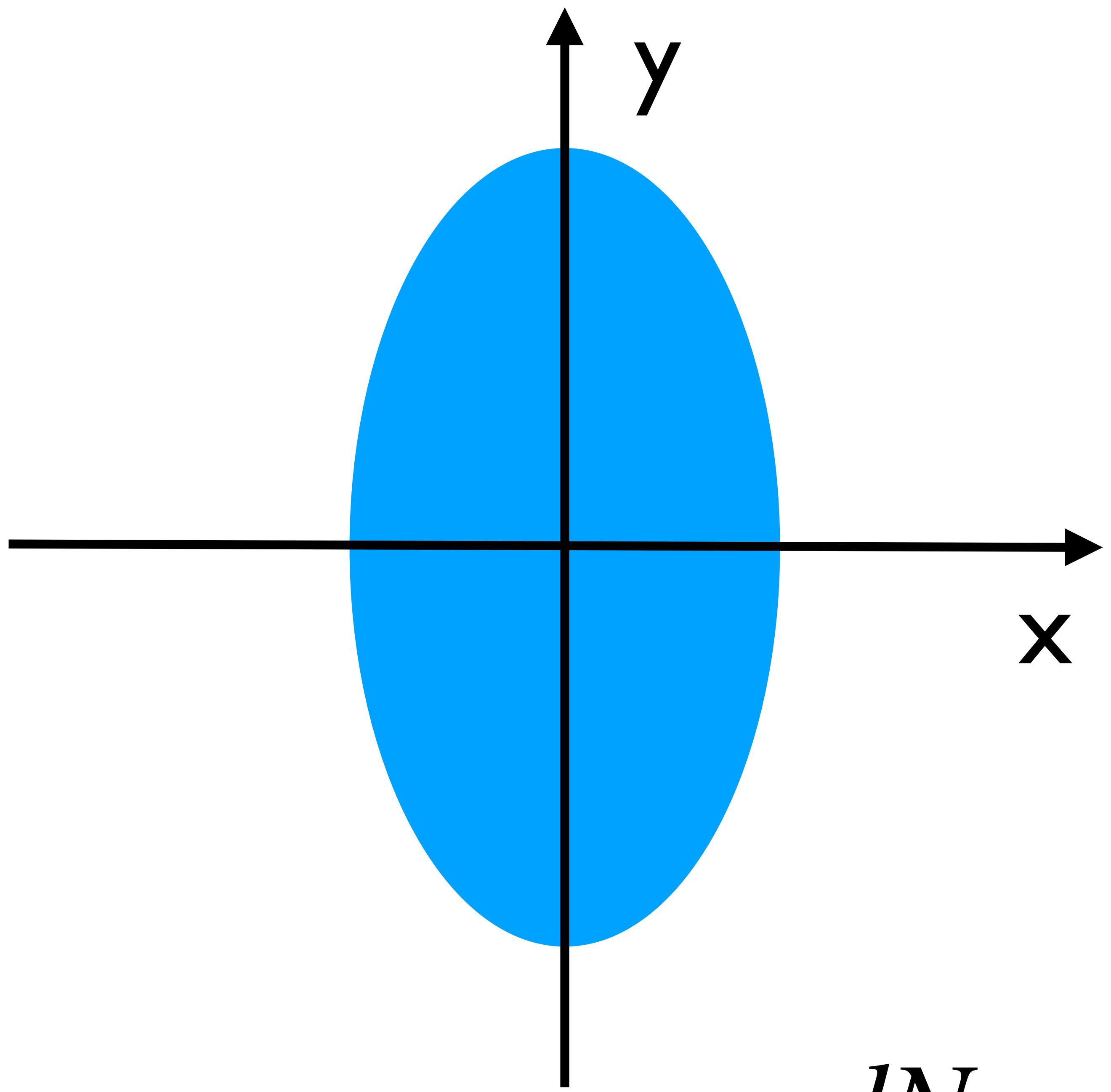
4. Summary.

The R_{AA}-v_2 relation:

- Since the beginning (nucl-th/0012092) R_{AA} has been related with high-p_T v_2 which is taken as a consequence of energy loss:



$$\frac{dN}{d\phi} = C(1 + v_2 \cos 2\phi)$$

$$\Longrightarrow v_2 = \frac{dN/d\phi(\phi = 0) - dN/d\phi(\phi = \pi/2)}{dN/d\phi(\phi = 0) + dN/d\phi(\phi = \pi/2)}$$

$$\epsilon = \frac{\langle y^2 \rangle - \langle x^2 \rangle}{\langle y^2 \rangle + \langle x^2 \rangle}$$

$$\frac{dN}{dp_\perp} \propto \frac{1}{(p_\perp + \Delta E)^n} \approx \frac{1}{p_\perp^n}\left(1 - n\frac{\Delta E}{p_\perp}\right), \quad \Delta E \propto \alpha_s C_R \hat{q} L^2$$

$$\Longrightarrow v_2 \approx \frac{n}{p_\perp}\left(\Delta E_y - \Delta E_x\right) \propto \alpha_s C_R \hat{q} \left(\langle y^2 \rangle - \langle x^2 \rangle\right) \propto \epsilon$$

Setup:

- A standard setup (1606.04837, 1902.03231):

NLO matrix elements, (n)PDFs, FFS

$$\frac{d\sigma^{AA\to h}}{dydp_T} = \int dq_T\, dz \frac{d\sigma^{AA\to k}}{dydq_T} P(\epsilon)\, D_{k\to h}(z,\mu_F^2)\, \delta\left(p_T - z(1-\epsilon)q_T\right)$$

Quenching weights, Poissonian approximation

$$P(\epsilon) = \sum_{n=0}^{\infty} \frac{1}{n!} \left[\prod_{i=1}^{n} \int dx_i \frac{dN(x_i)}{dx}\right] \delta\left(\epsilon - \sum_{i=1}^{n} x_i\right) \exp\left[-\int_0^{\infty} dx \frac{dN}{dx}\right]$$

Single gluon spectrum, multiple soft scattering (HO) approximation

$$P(\Delta E/\omega_c^{eff}, R^{eff})$$

$$\omega_c^{eff}(x_0, y_0, \tau_{\rm prod}, \phi) = \int d\xi\, \xi\, \hat{q}(\xi),$$

$$R^{eff}(x_0, y_0, \tau_{\rm prod}, \phi) = \frac{3}{2}\int d\xi\, \xi^2\, \hat{q}(\xi)$$

See the talk by Adhya.

Setup:

- Medium modified fragmentation:

$$w(x_0,y_0)=T_A(x_0,y_0)T_A(\vec{b}-(x_0,y_0))$$

Production probability

$$N=2\pi\int dx_0dy_0w(x_0,y_0)$$

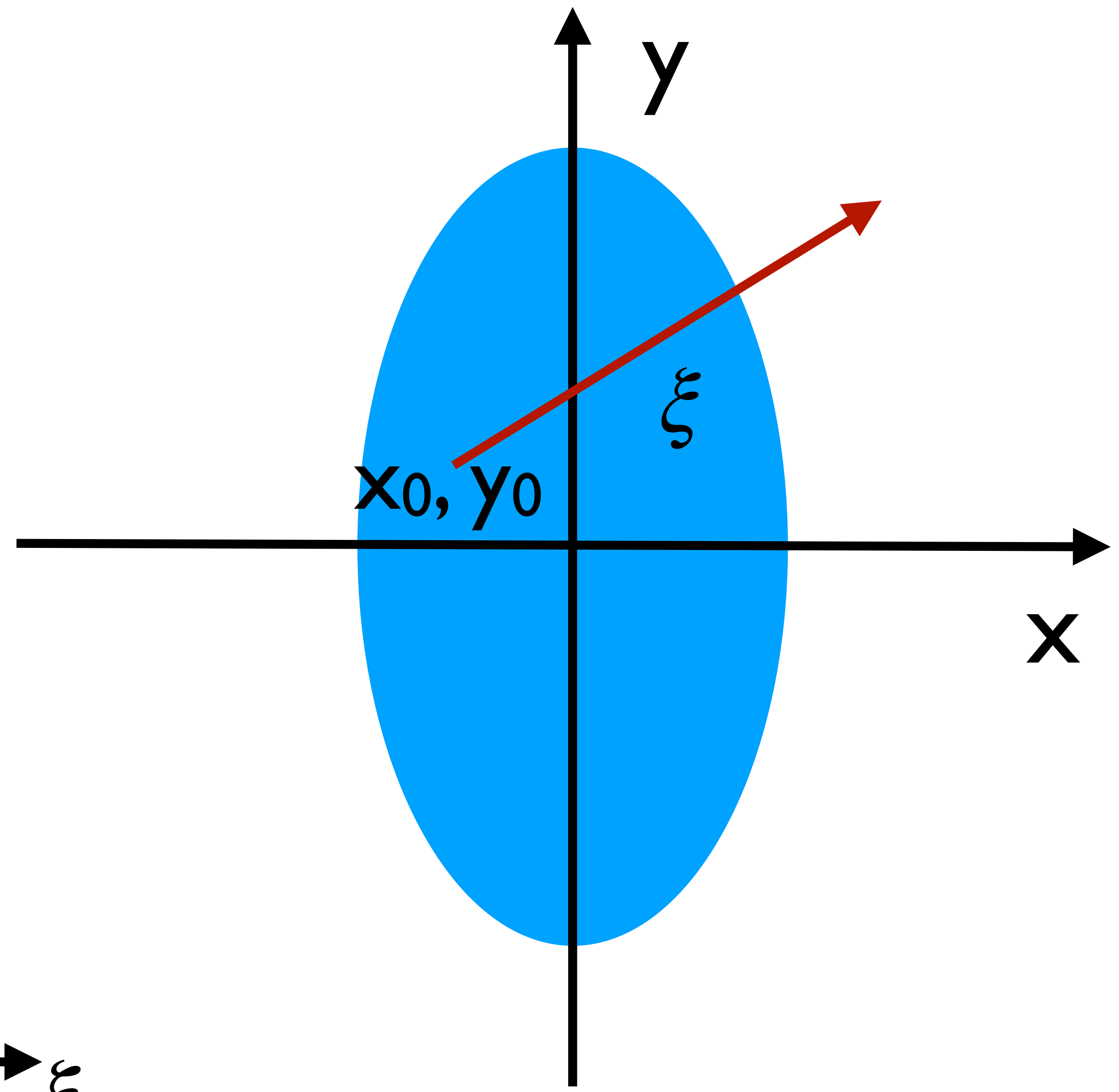
$$D^{\rm med}_{k\to h}(z,\mu_F^2)=\frac{1}{N}\int d\phi dx_0dy_0w(x_0,y_0)\int\frac{d\zeta}{1-\zeta}P_k(x_0,y_0,\phi,\zeta)D^{\rm vac}_{k\to h}\left(\frac{z}{1-\zeta},\mu_F^2\right)$$

MM FFs

- Interface with the medium:

$$\hat{q}(\xi)=K\cdot 2\epsilon^{3/4}(\xi)\longrightarrow$$

Ideal or viscous (EbE) hydro starting at τ_0

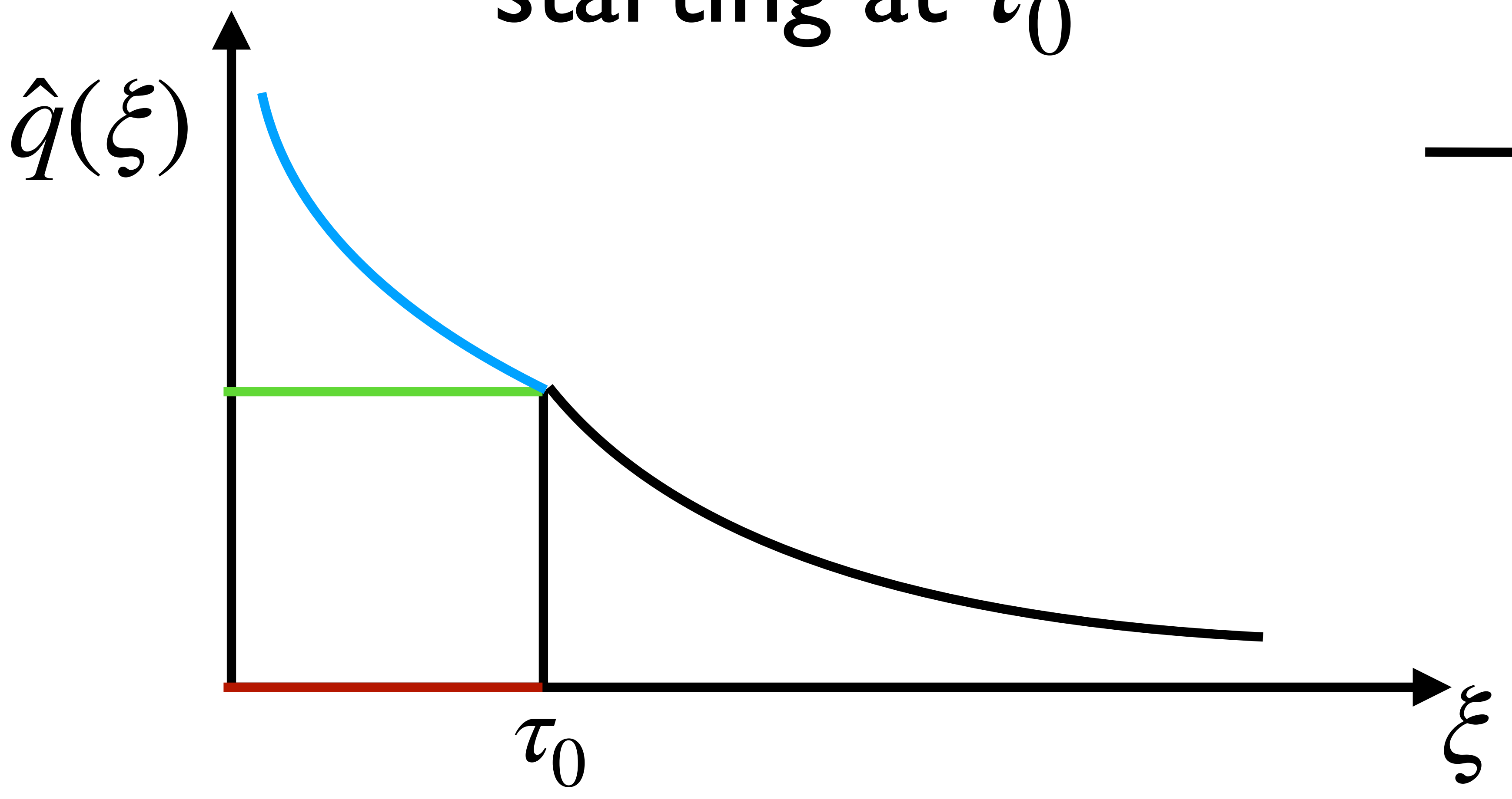


- Before hydrodynamisation:

(i) $\hat{q}(\xi)=0$ for $\xi<\tau_0$;

(ii) $\hat{q}(\xi)=\hat{q}(\tau_0)$ for $\xi<\tau_0$; and

(iii) $\hat{q}(\xi)=\hat{q}(\tau_0)/\xi^{3/4}$ for $\xi<\tau_0$.



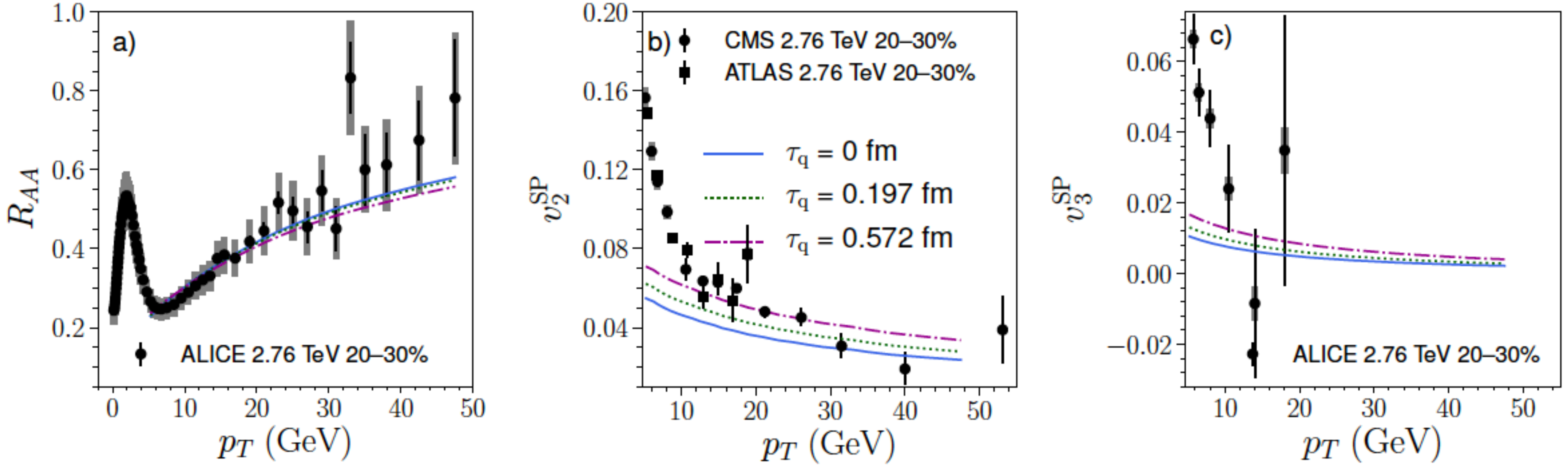
Results:

- High-p_T azimuthal Fourier coefficients (1602.03788):

$$v_n^{SP}(p_T) = \frac{\left\langle v_n^{soft} v_n^{hard}(p_T) \cos\left[n\left(\psi_n^{soft} - \psi_n^{hard}(p_T)\right)\right]\right\rangle}{\sqrt{\left\langle \left(v_n^{soft}\right)^2 \right\rangle}}$$

- Strategy: fit K to describe R_{AA} and then vary $\tau_q = \tau_0$ to describe v_2, using EbE viscous hydro (1505.02677).

Early time extrapolation	K-factor	χ^2/d.o.f. for v_2
Case i) $\tau_q = 0$ fm	$2.120^{+0.091}_{-0.074}$	26.2
Case ii) $\tau_q = 0.197$ fm	$2.90^{+0.13}_{-0.11}$	12.9
Case iii) $\tau_q = 0.572$ fm	4.56 ± 0.20	3.5

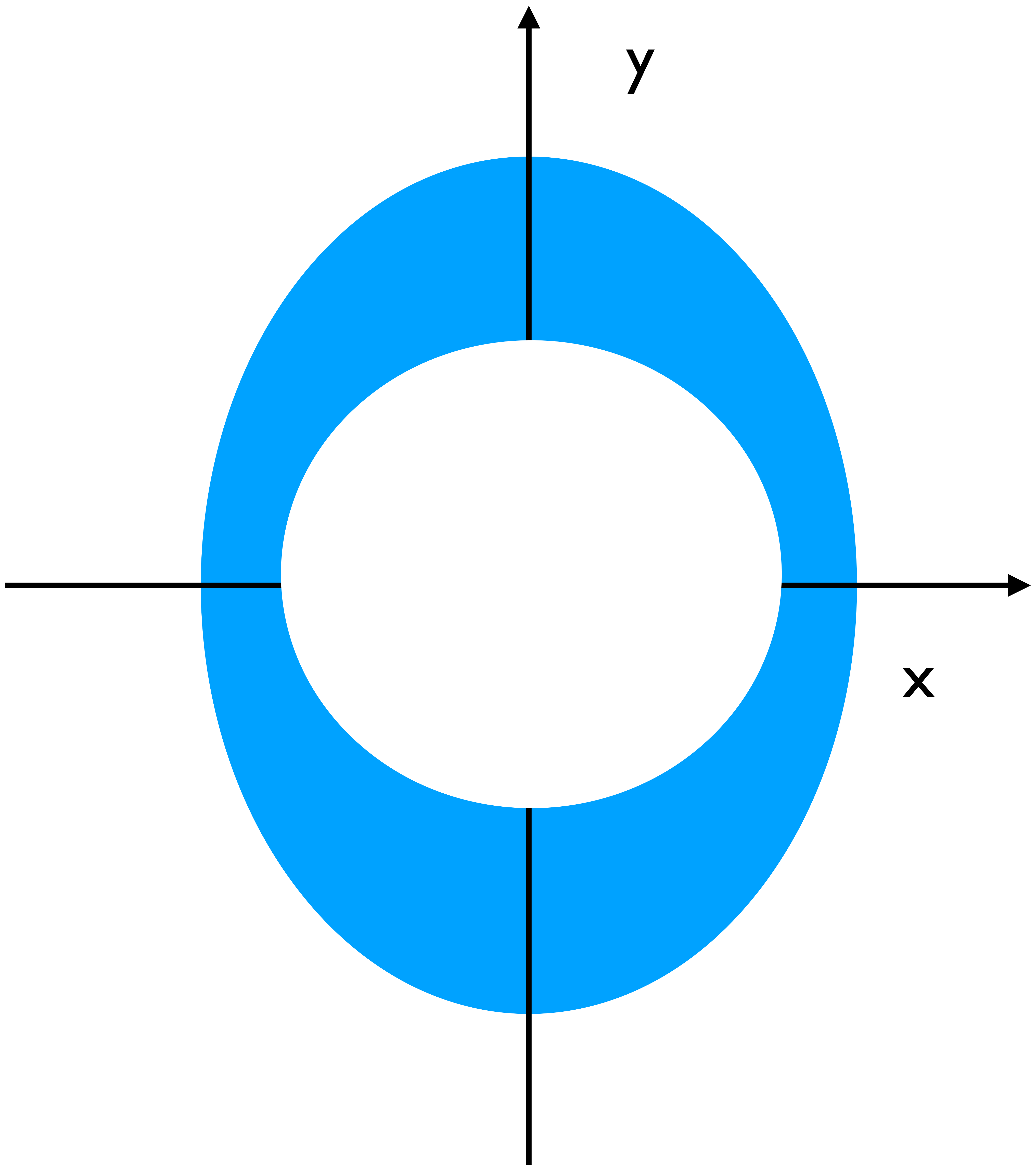


Results:

- Result checked for different centralities, and against variations in T versus τ as variable to use at the early stages, FFs, single gluon spectrum (single opacity versus multiple soft scattering), temperature for stopping hydro (hadronic phase).

- Same result found in very different frameworks where quenching is implicitly started at the same time as hydrodynamics: quenching seems to be small for early times.

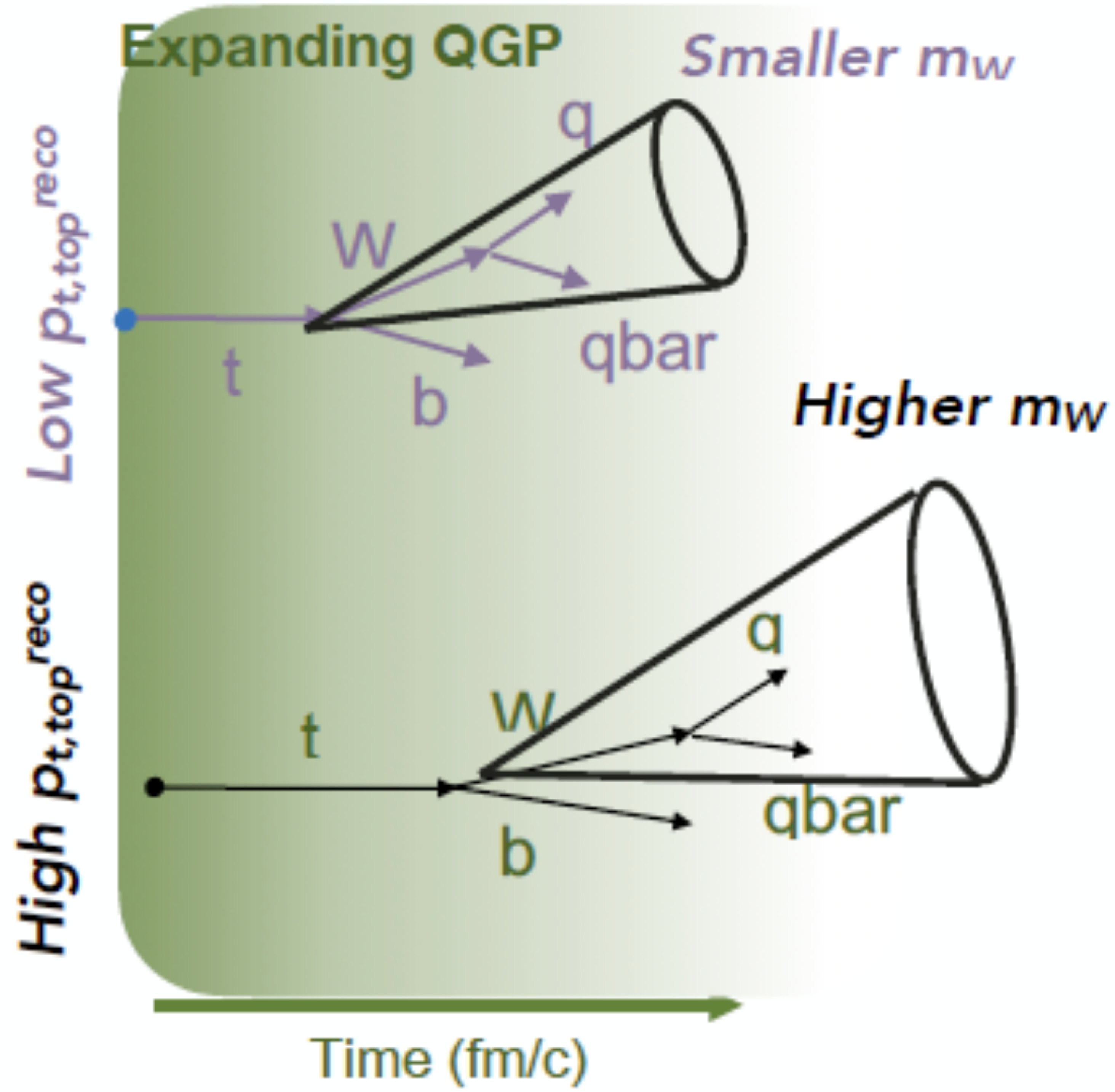
- May suggest an explanation for the lack of quenching in small systems, to be checked by other observables sensitive to times, but it begs a theoretical motivation.

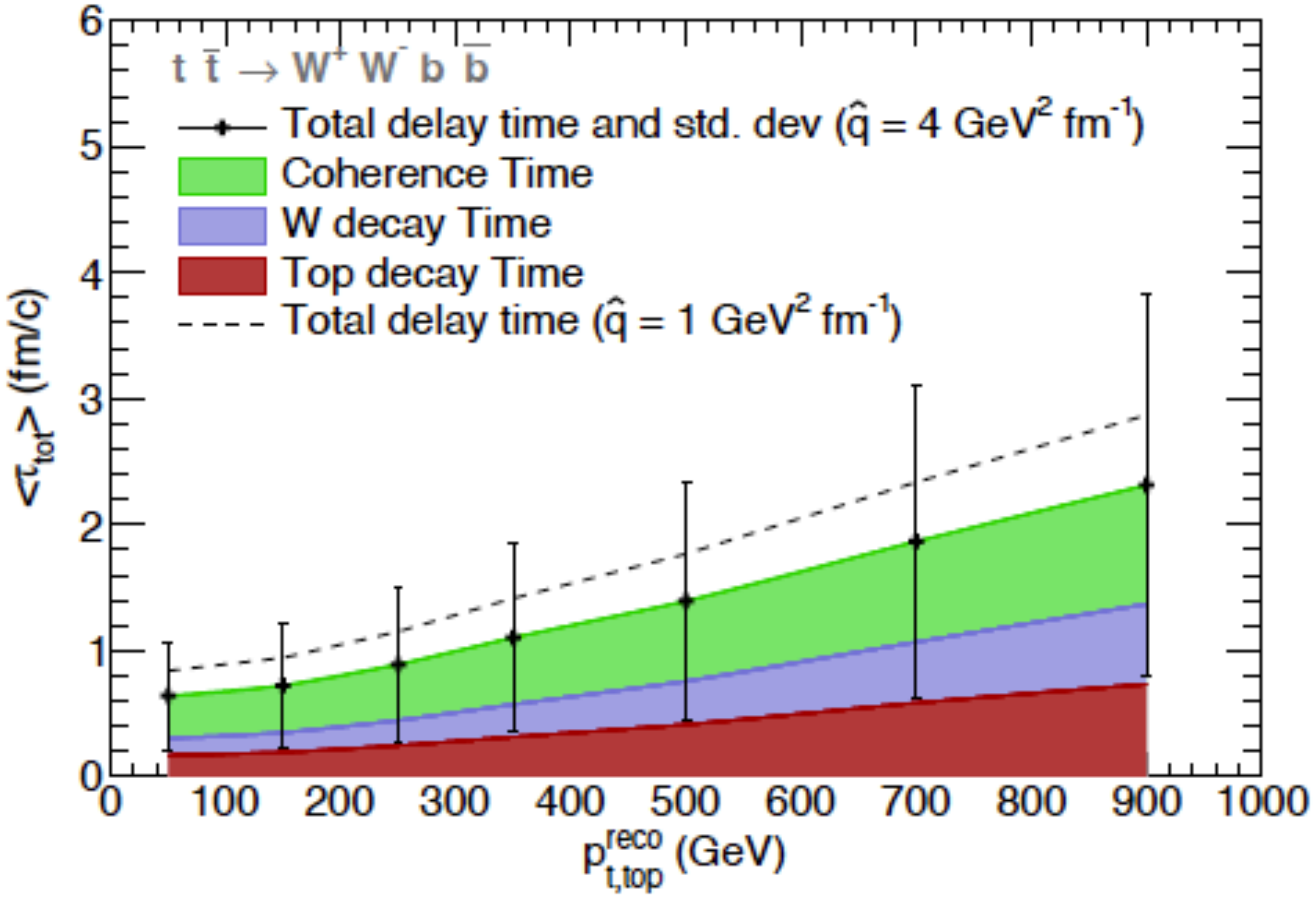


Boosted tops:

• Idea (1711.03105): EW decays provide time scales that can be controlled by the boost of the top (available for large energies or lighter ions), and energy loss will reflect in the reconstructed properties (mass of the W in this case) compared to pp. Determination of properties of the medium at different time scales.

$$\langle \tau_{tot} \rangle = \gamma_{t,top}\tau_{top} + \gamma_{t,W}\tau_W + \tau_d \qquad \tau_d = \left(\frac{12}{\hat{q}\theta^2_{q\bar{q}}} \right)^{1/3}$$





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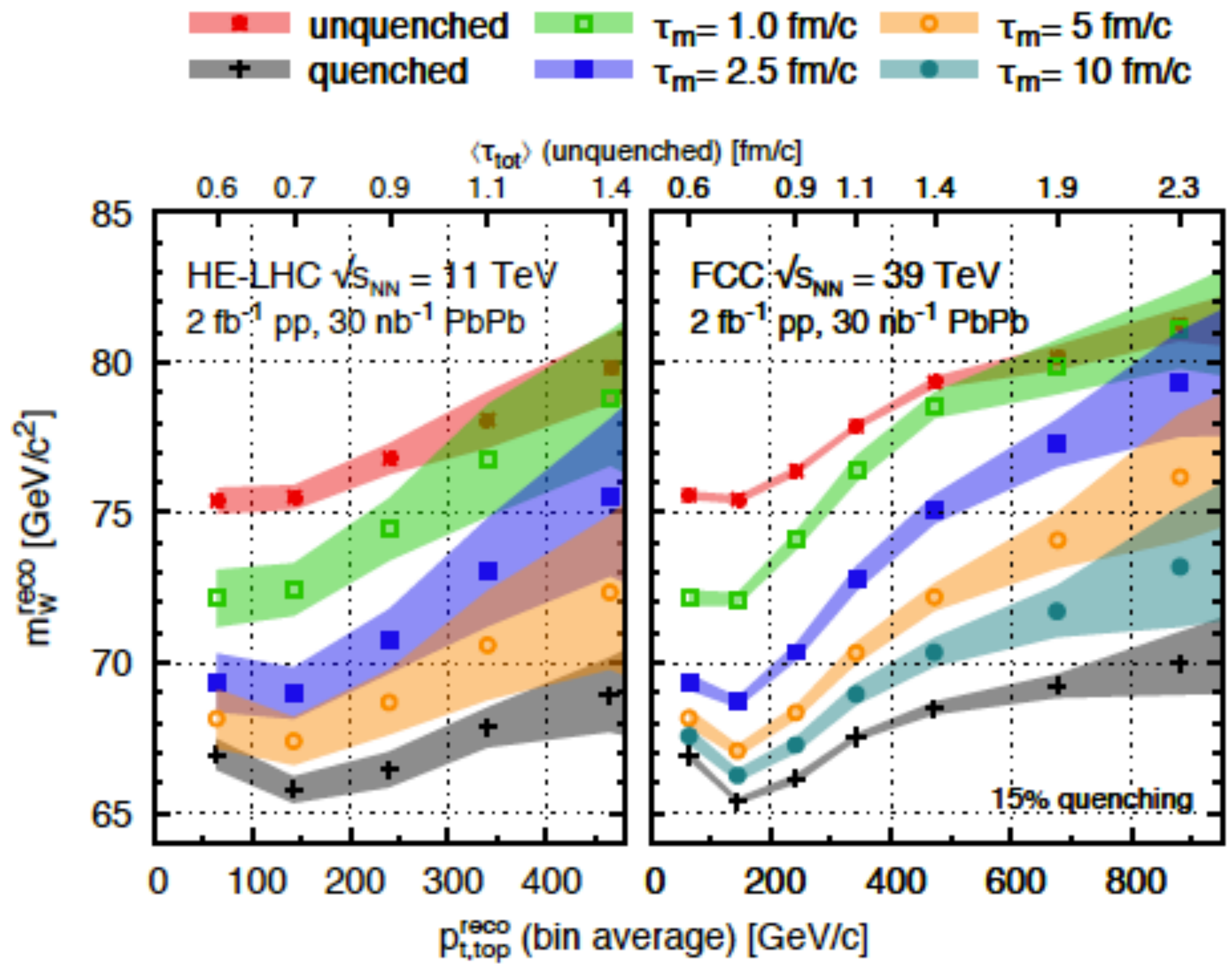

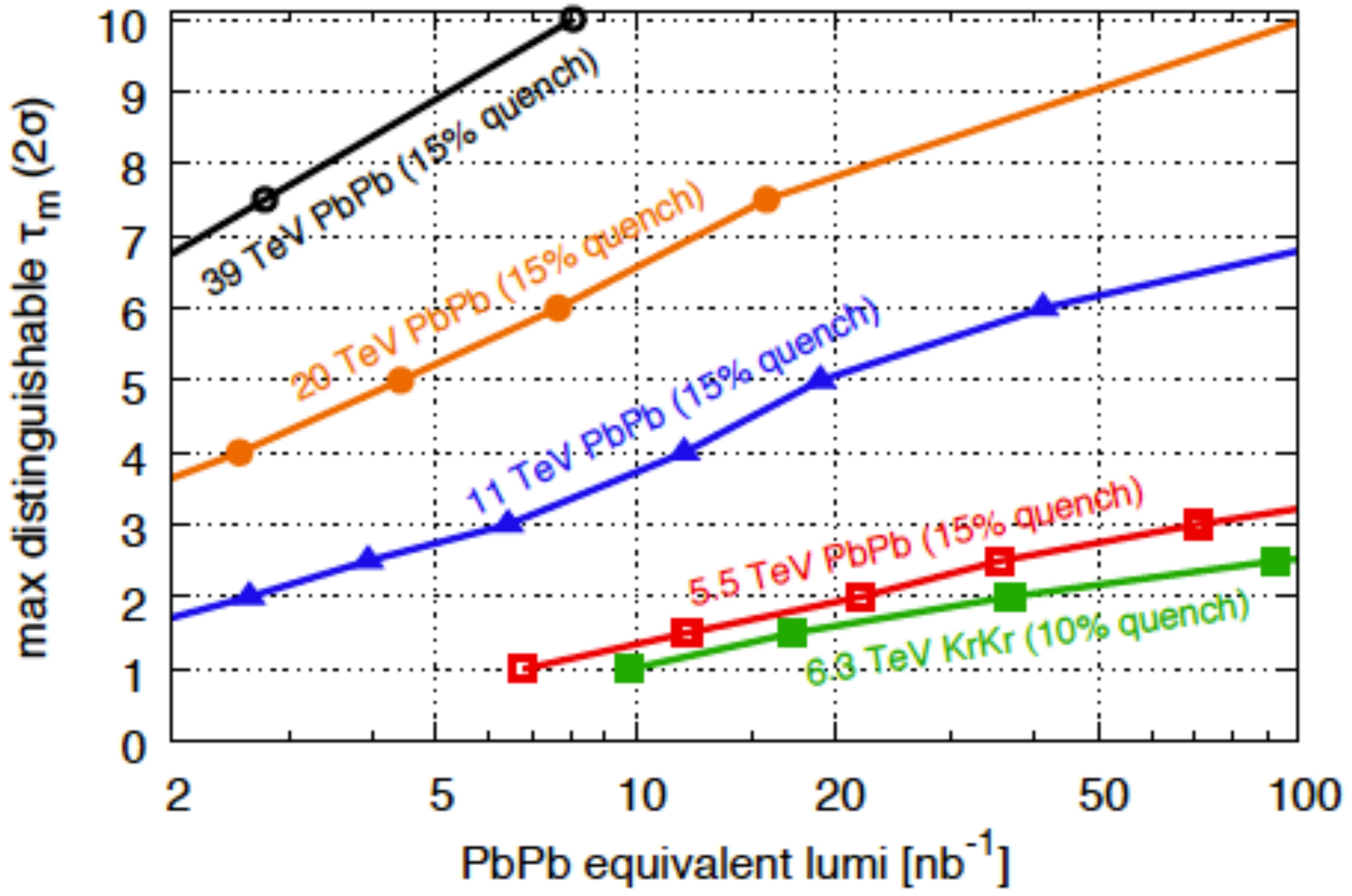

• Controlling the boost of the top we become sensitive to smaller times: when does medium-induced energy loss start to be effective?

• Is it possible to do something with other observables? Jets if we understand the space-time picture of a parton cascade (that anyway we need for consistently considering vacuum+medium)?

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4. Summary.

The role of time:

- Vacuum showers are not usually formulated in formation times, but in DLA

$$\tau_f = \frac{2z(1-z)E}{k_\perp^2},\ k_\perp^2,\ M^2 = \frac{k_\perp^2}{2z(1-z)},\ \theta \simeq \frac{|k_\perp|}{zE}$$ give the same accuracy

$$p_a = (zE, \vec{p}_a),\ p_a^2 = 0$$

$$p = (E, \vec{p})$$

$$\tau_f = \frac{E}{M^2} = \frac{1}{2z(1-z)E(1-\cos\theta_{ab})}$$

$$p_b = ((1-z)E, \vec{p}_b),\ p_b^2 = 0$$

$$P_{p\to ab} \propto \frac{dk_\perp^2}{k_\perp^2}\frac{dz}{z} \propto \frac{d\theta_{ab}}{\theta_{ab}}\frac{dz}{z} \propto \frac{d\tau_f}{\tau_f}\frac{dz}{z} \propto \frac{dM^2}{M^2}\frac{dz}{z}$$

with decreasing z and decreasing angles, virtualities or transverse momentum, or increasing formation times, in factorised successive emissions that yield a Markovian process.

The role of time:

- Equivalence between the different evolution variables is broken beyond DLA (as simply as by different limits of the evolution or changing from Minkowski to light-cone), as the ordering itself.
- In-medium pictures are based on formation time=medium time (and DLA reasoning):

$$\tau_f = (\omega\theta^2)^{-1},\ \tau_d = \left(\frac{1}{\hat{q}\theta^2}\right)^{1/3}$$

- The evolution of a jet **factorizes** into three steps:
  (1) one **angular ordered** *vacuum-like shower* inside the medium ,
  (2) *medium-induced emissions* triggered by previous sources,
  (3) finally, a *vacuum-like shower* outside the medium.
- Re-opening of the phase space for the first emission outside the medium.

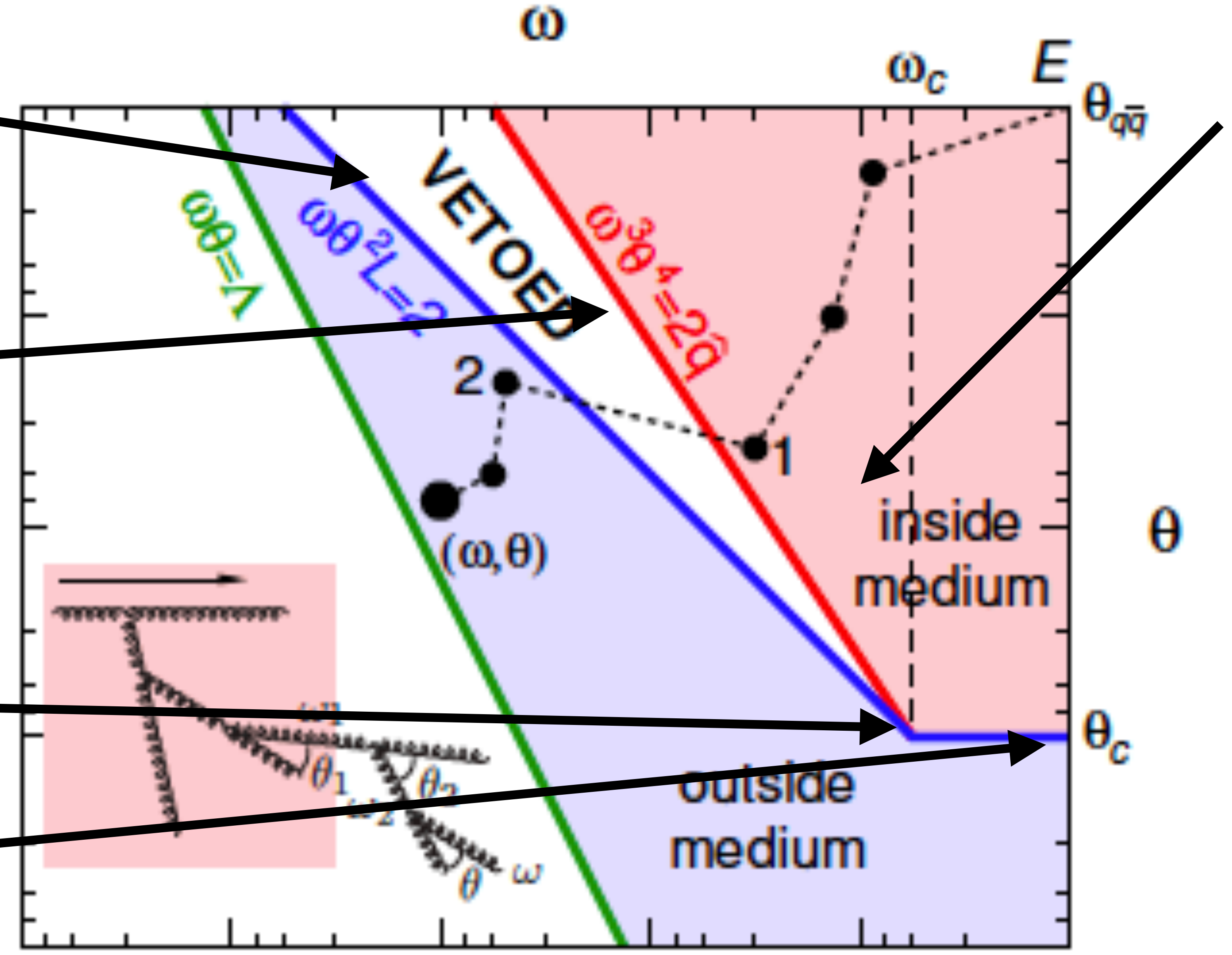
Talk by Caucal

$$\tau_f = L$$

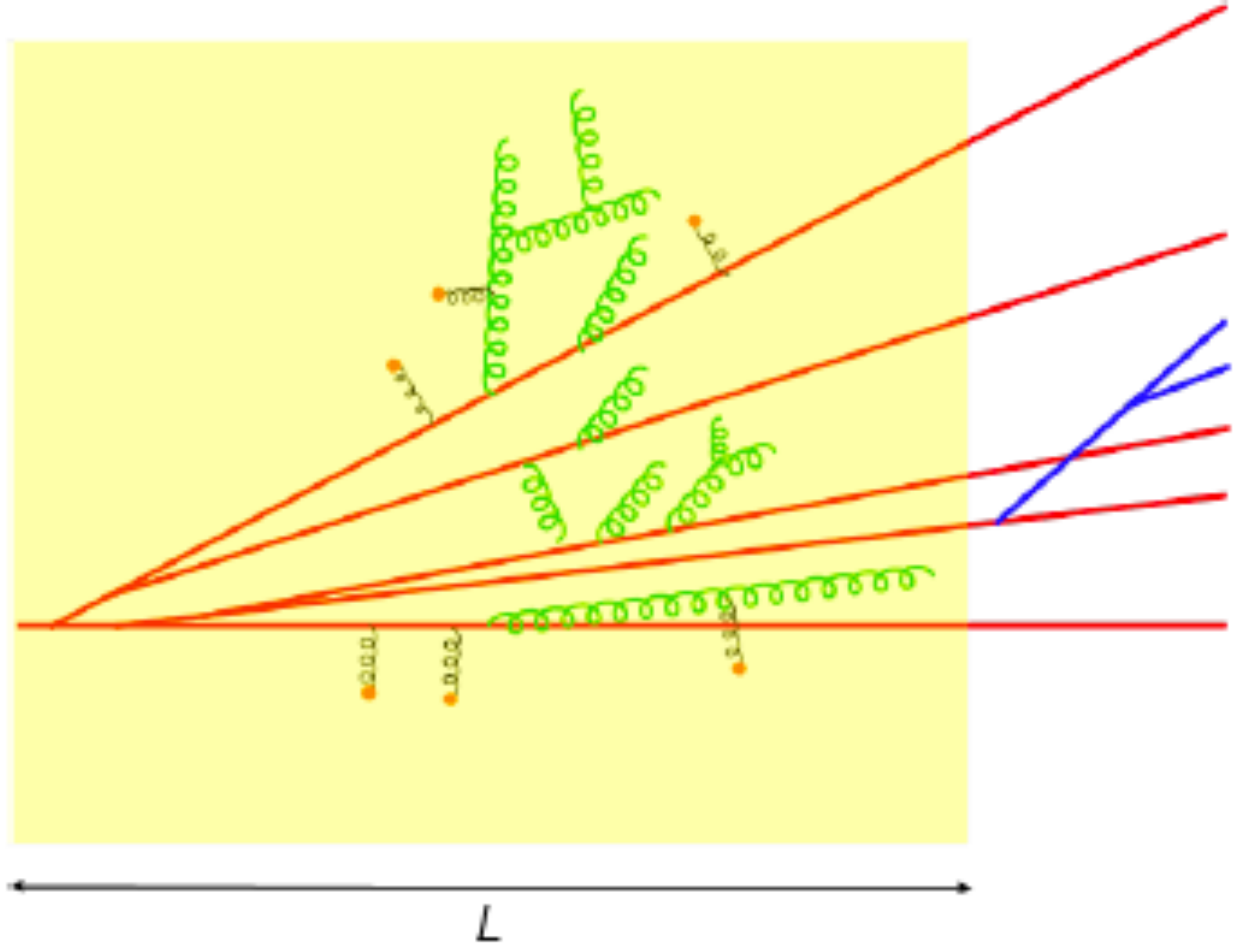
$$\tau_f = \langle \tau_f^{med} \rangle = \sqrt{\frac{\omega}{\hat{q}}}$$

$$\langle \tau_f^{med} \rangle(\omega_c) = L$$

$$\tau_d(\theta_c) = L$$



τ_f

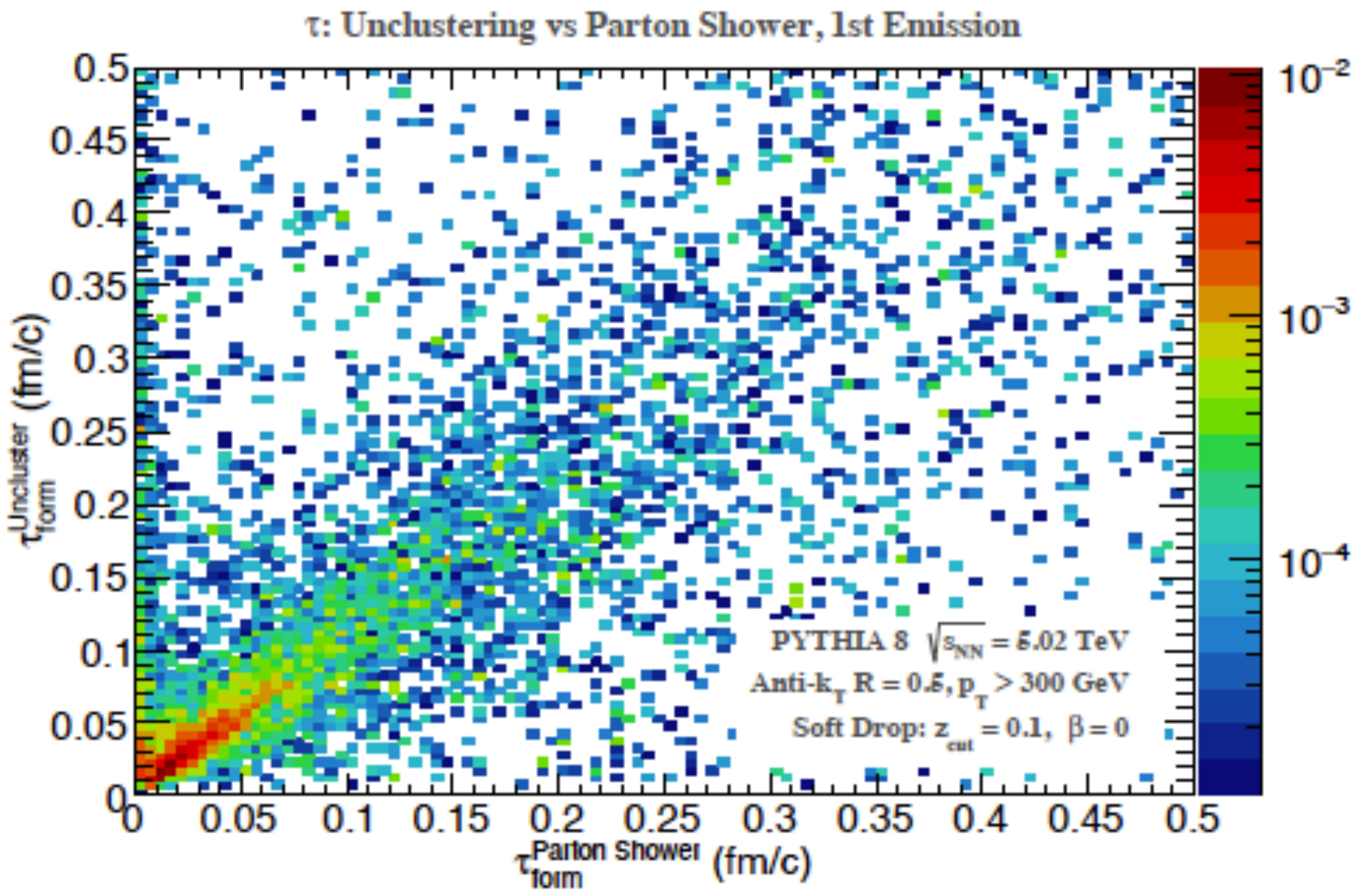


• In order to correctly interface a vacuum shower with the medium, we need the shower formulated in (or translated to) times.

• To be sensitive to different times, we need to be able to reconstruct the shower in formation times, using some algorithm e.g. JADE

$$y_{ij} = \frac{2E_iE_j(1-\cos\theta_{ij})}{E^2} = \frac{1}{E\tau_f}$$

Talk by Apolinario

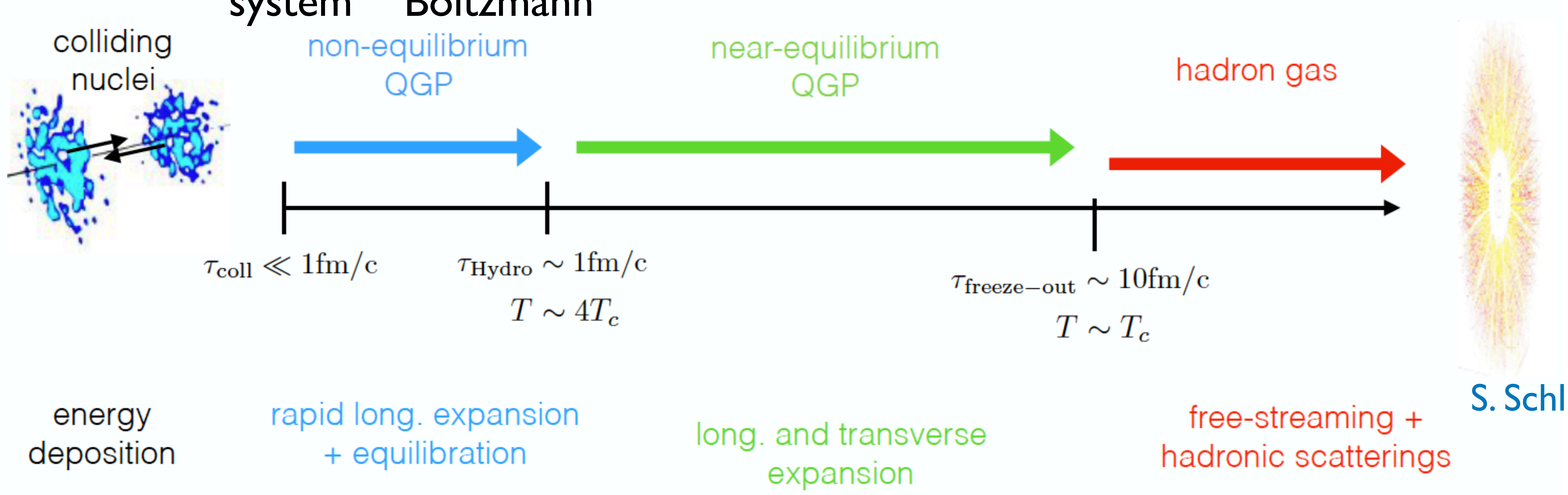


$$d_{ij} = \min(p_{Ti}^{2p}, p_{Tj}^{2p})\frac{\Delta R_{ij}^2}{R^2}$$

τ algorithm: $p = 0.5,\ d_{ij} \approx p_{\perp i}\theta^2 \simeq \dfrac{1}{\tau_f}$

The early stages:

Glasma: over-occupied system	Parton transport: EKT, Boltzmann	Viscous hydro

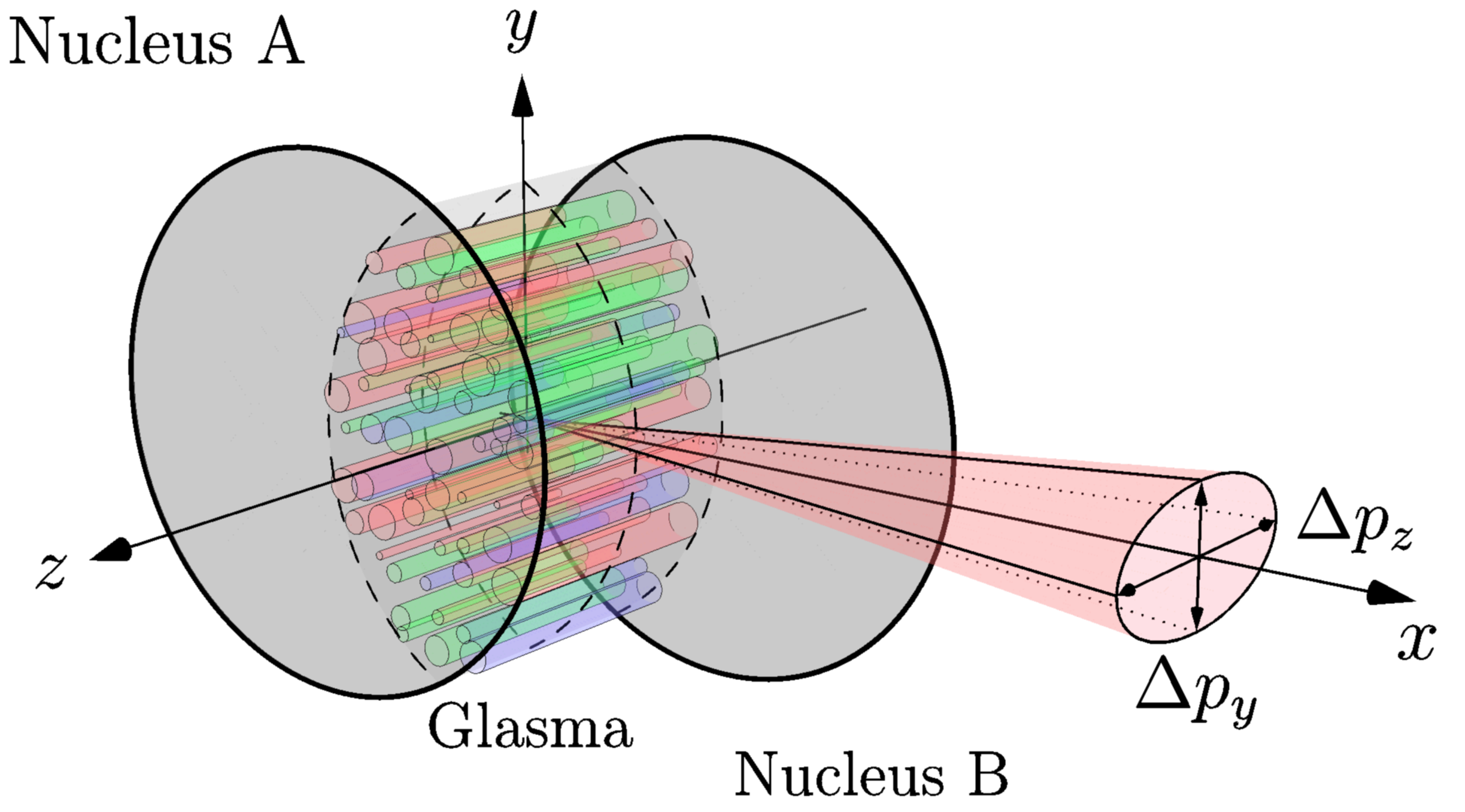


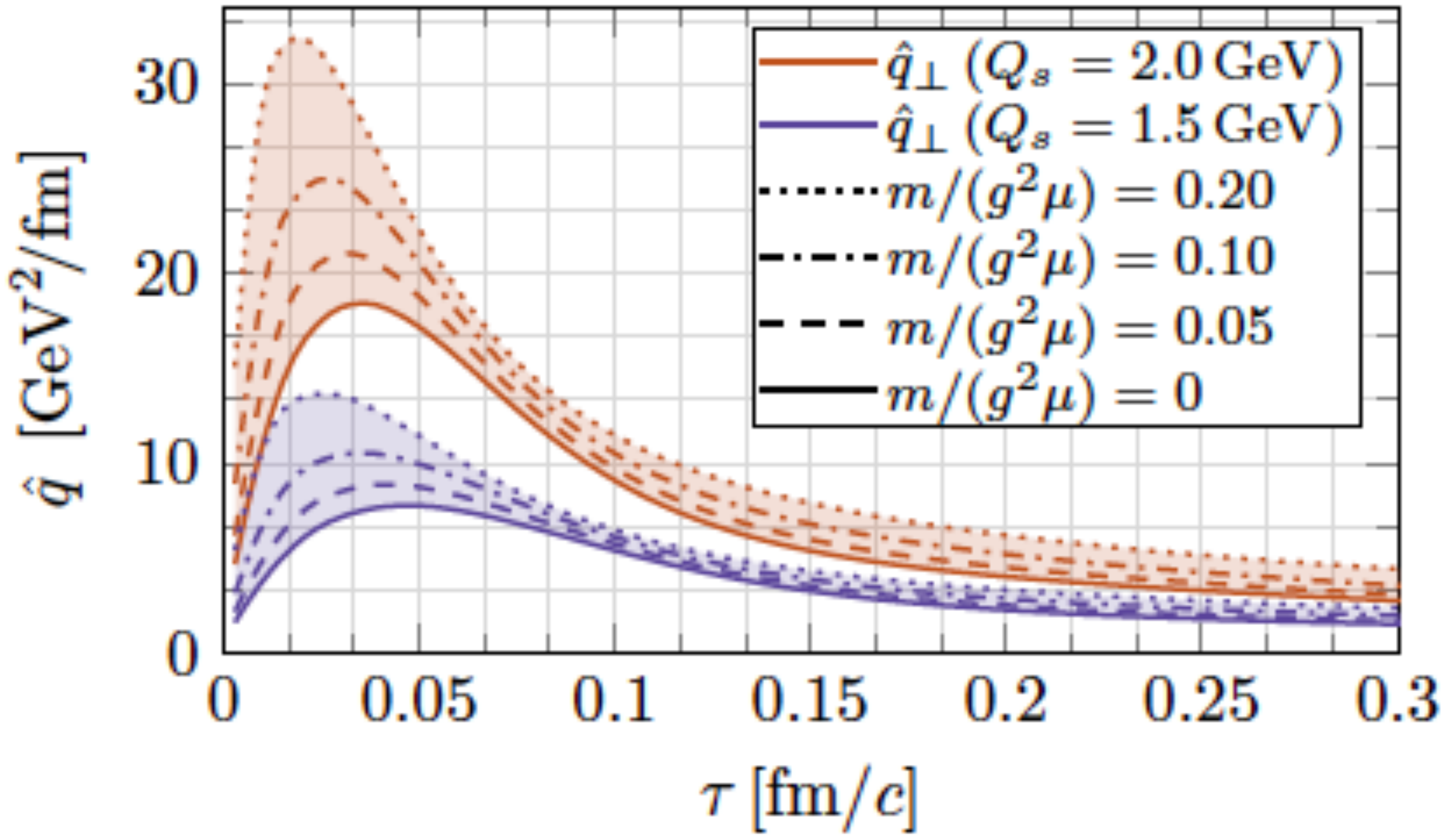
S. Schlichting

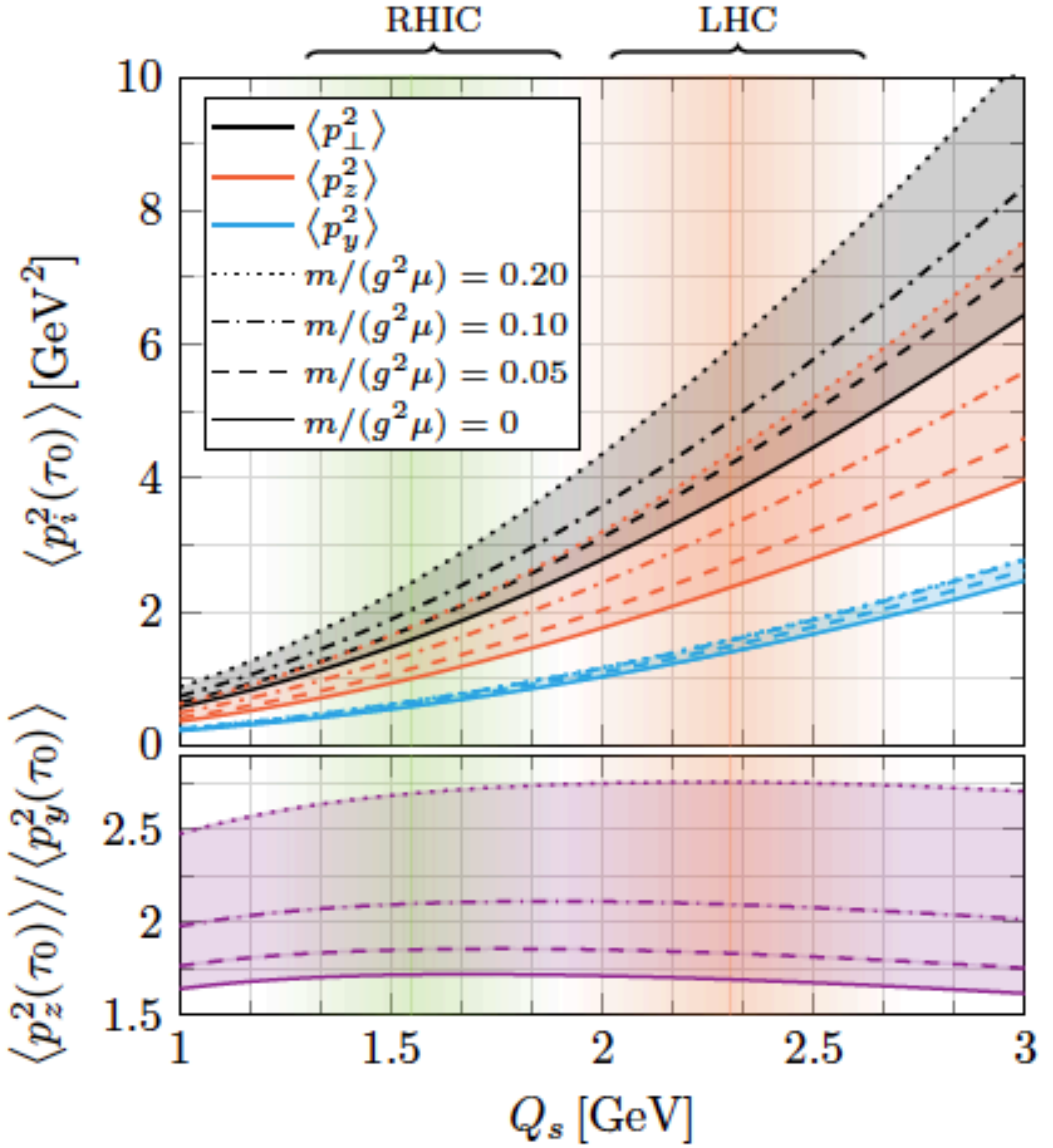
- We need to understand of quenching effects in the phases described by Glasma (overoccupied phase) and by partonic transport (dilute phase).
- These phases may dominate the dynamics for small systems!!!

The early stages:

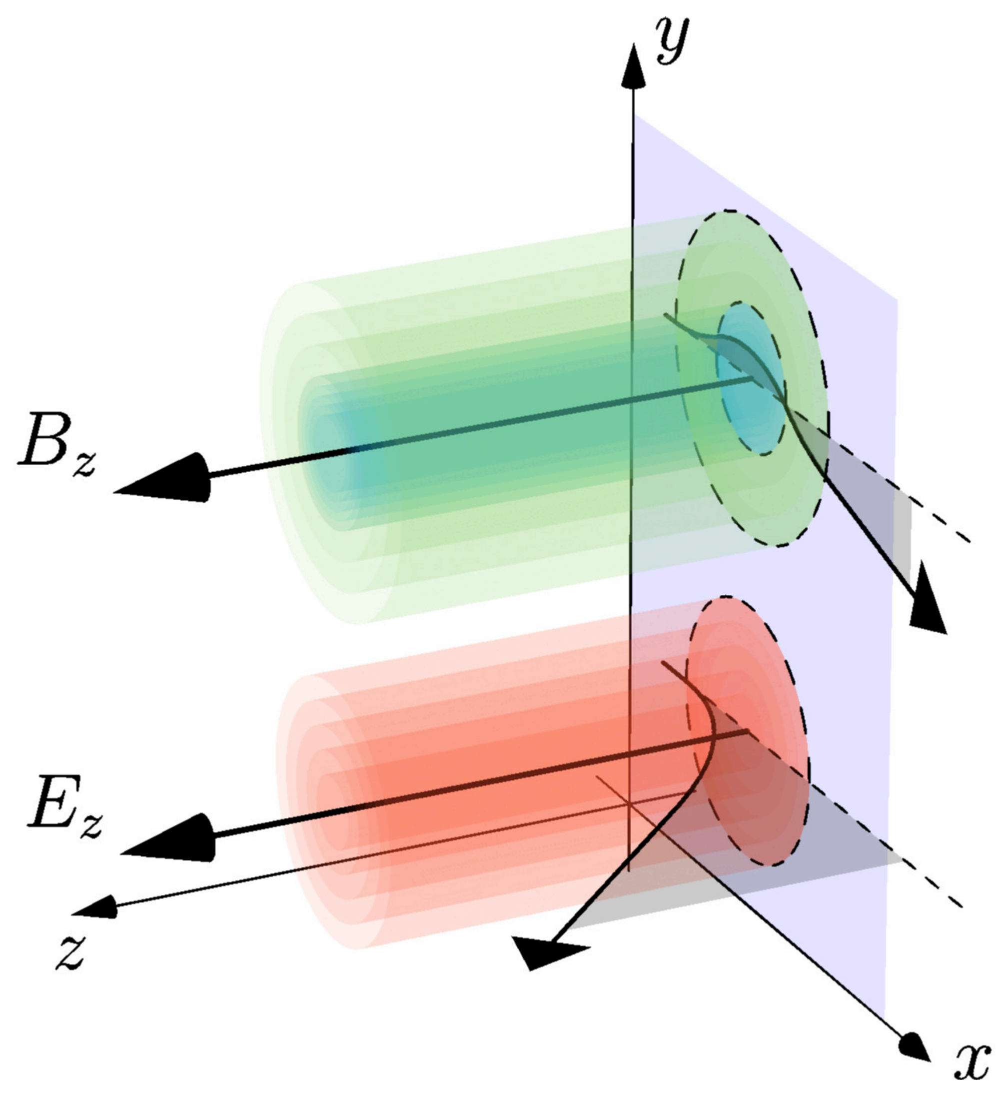
- Glasma: lattice solution of YM (2009.14206) in Wong's equations, getting a larger broadening along the longitudinal direction.





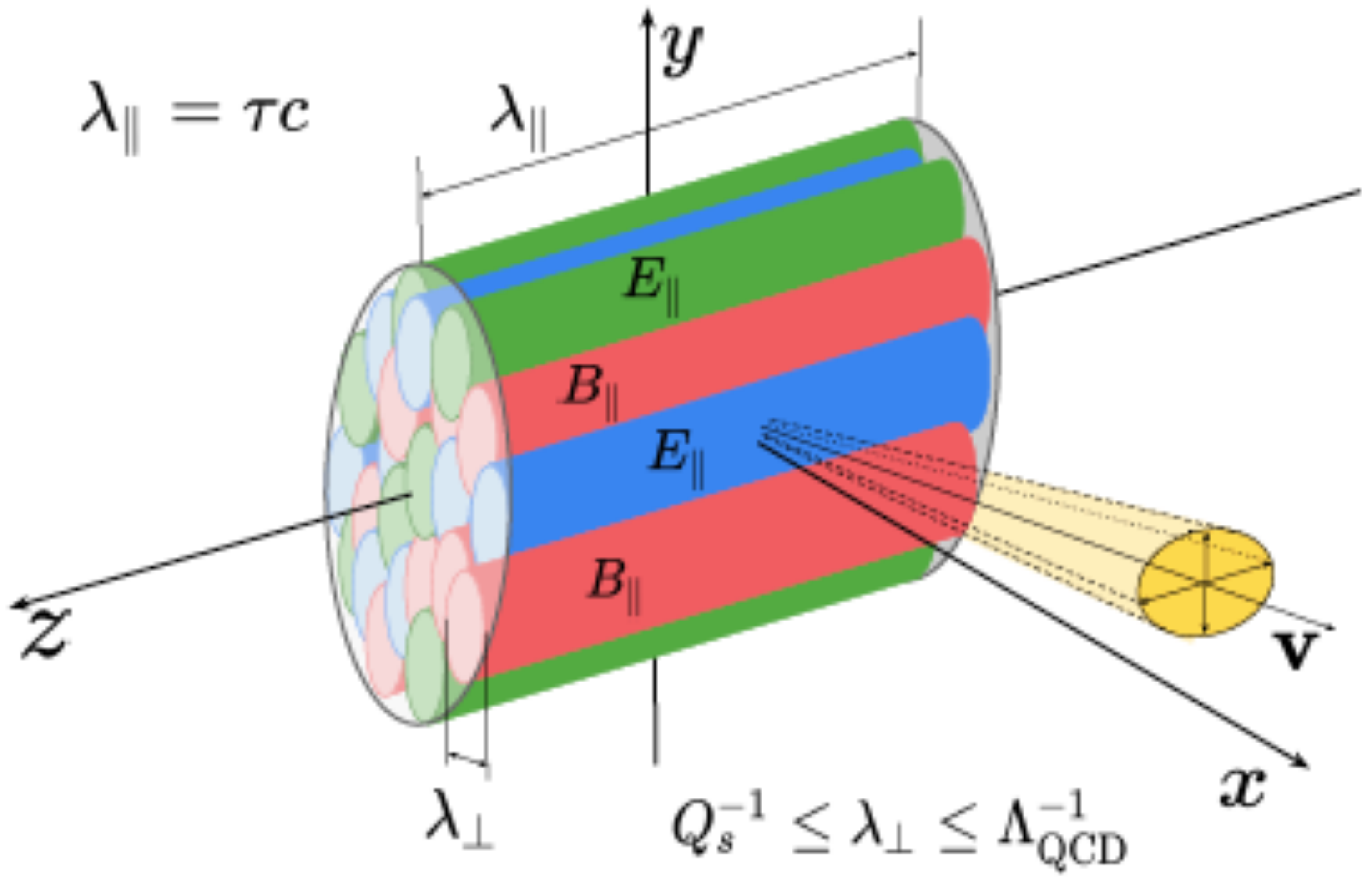


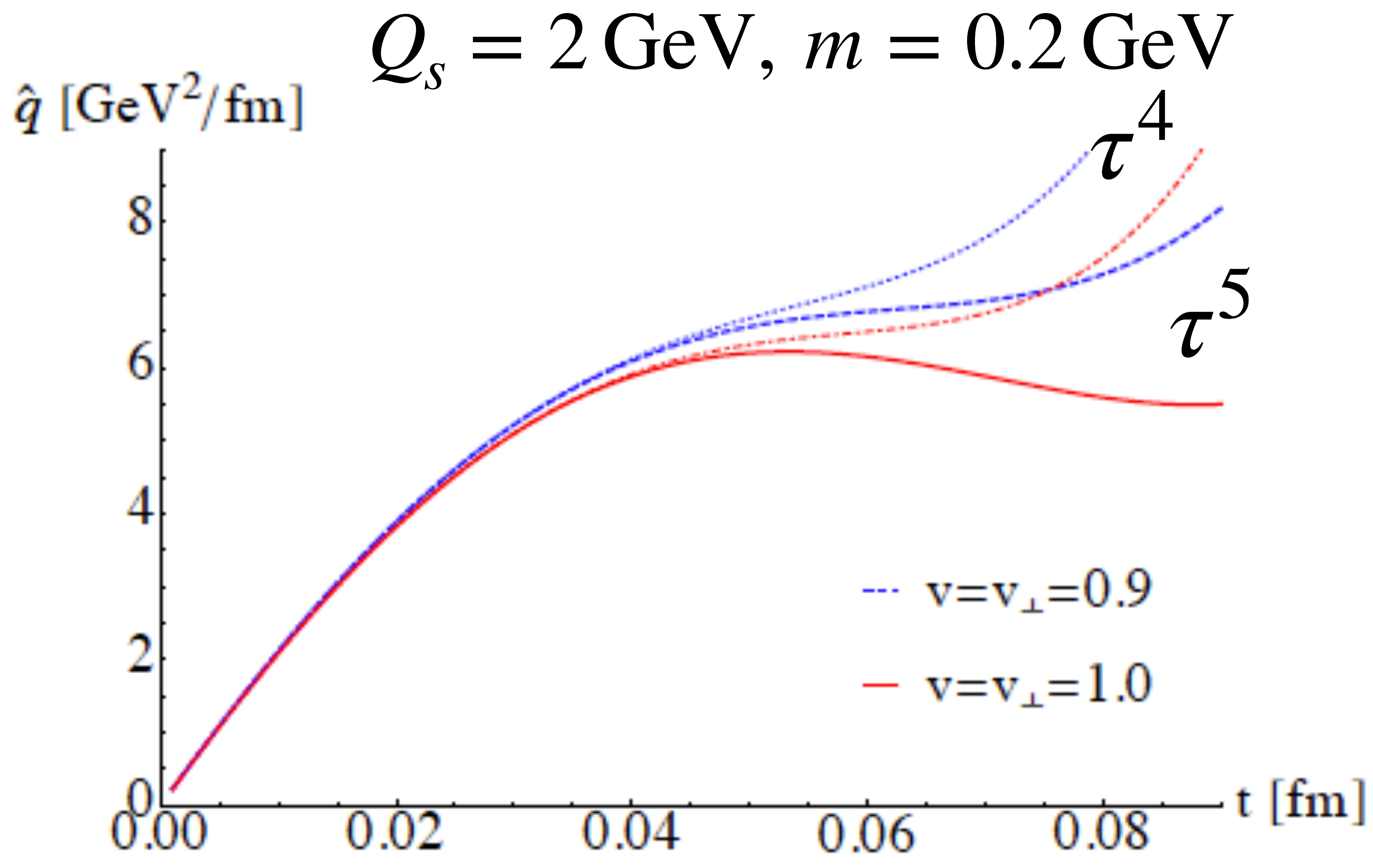
$$\hat{q}_i(\tau) = \frac{d}{d\tau} \langle p_i^2(\tau) \rangle_q$$



The early stages:

• Glasma: Fokker-Plank equation with collision terms given by a proper time expansion $\mathcal{O}(\tau^5)$ of the solution of YM (talk by Czajka).

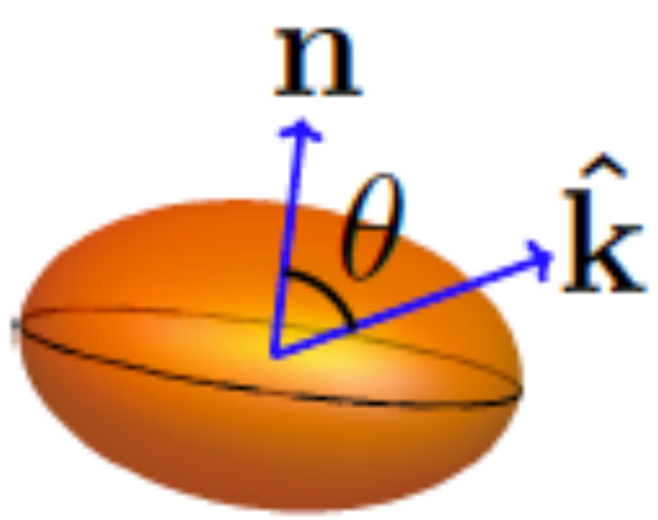


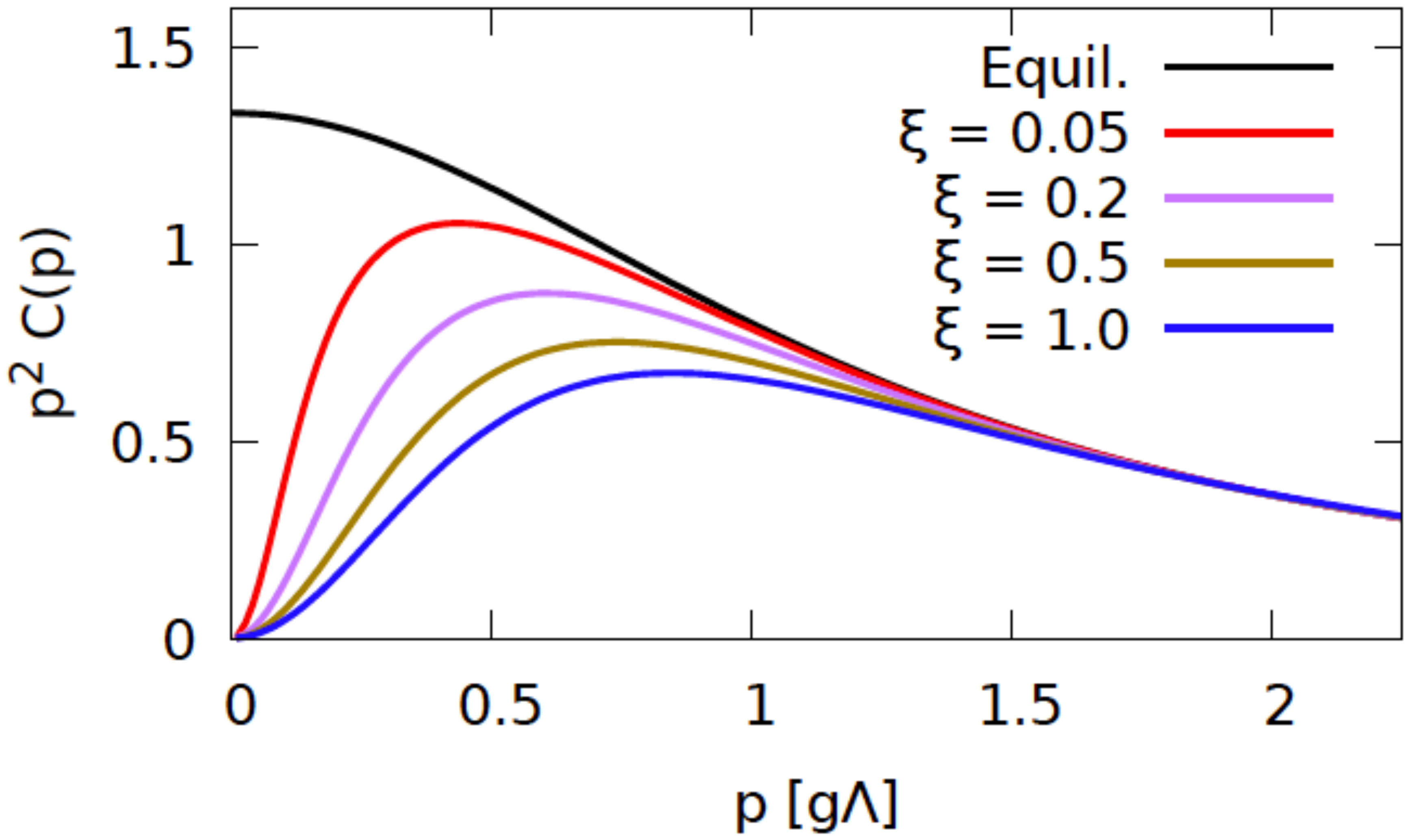


• Non-equilibrium phase: quark travelling through a medium with quarks and gluon quasi particles emitting soft gluons (HTL) with anisotropic collision kernel (talk by Hauksson).

$$\hat{q} = \frac{d\langle(\Delta p_\perp)^2\rangle}{dt} = \int d^4Q\, q_\perp^2\, \frac{d\Gamma}{d^4Q}$$

$$\approx \int \frac{d^2q_\perp}{(2\pi)^2}\, q_\perp^2\, \mathcal{C}(\mathbf{q}_\perp)$$





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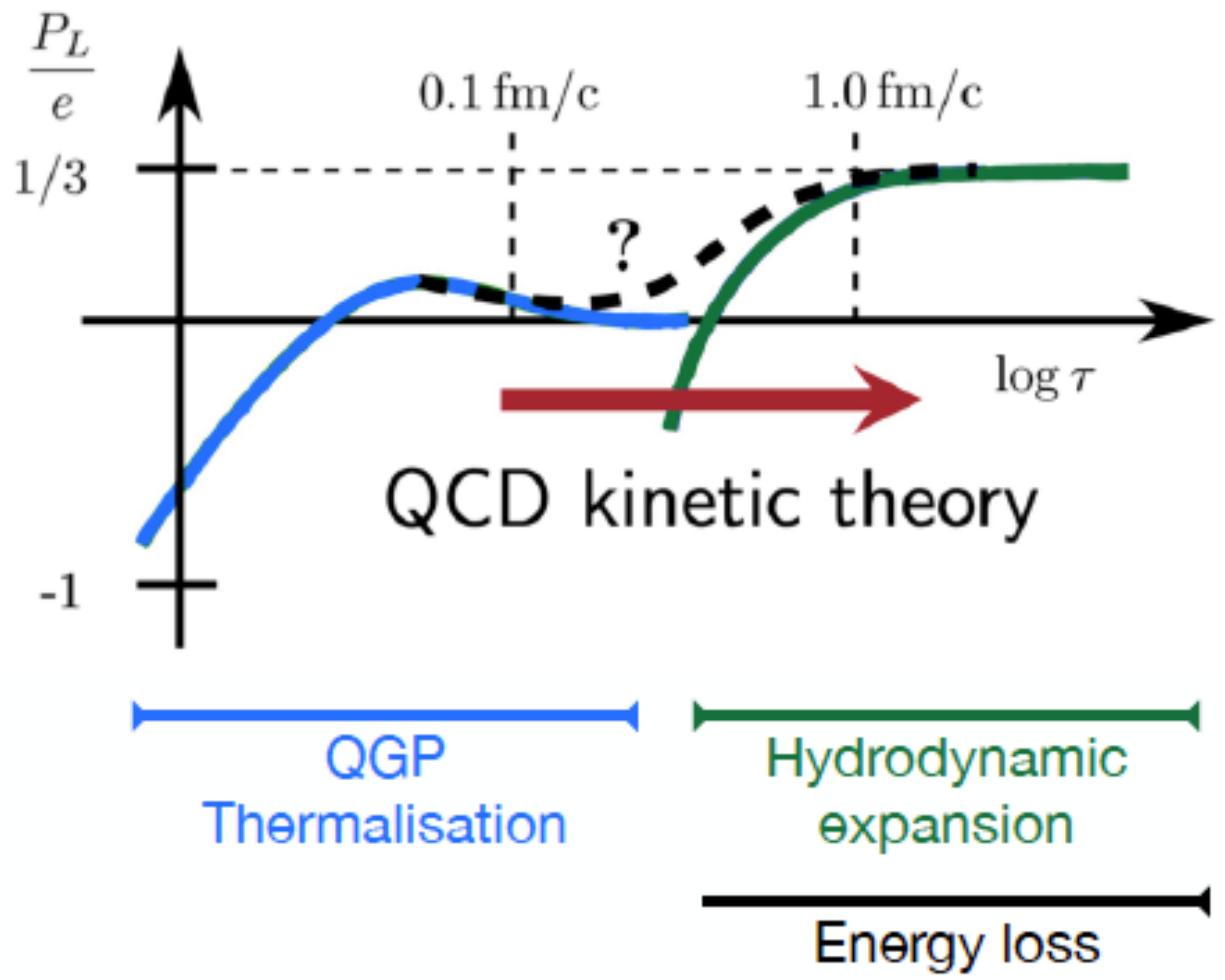
● Early time dynamics (before hydrodynamisation) is the largest unknown in our standard picture of heavy ion collisions and directly links with the small system problem:



➜ It seems to have a substantial impact on some jet quenching observables (R_{AA}-v_2) → look for further observables.

➜ Observables with delay (e.g. tops) or formation times (quarkonium?) may provide a handle.

➜ Jets are observables with many scales (momentum and time), could we use them? (talk by Apolinario)

● Theoretical efforts are ongoing to understand the effect of the initial dynamics (Glasma, the non-equilibrium phase) on energetic partons: $\hat{q}$ increasing or decreasing with time?

● Time scales underlie all our understanding of the medium-modification of the QCD parton shower → extend to vacuum in order to get a consistent picture of both vacuum+medium shower. (talks by Caucal and Ontoso)

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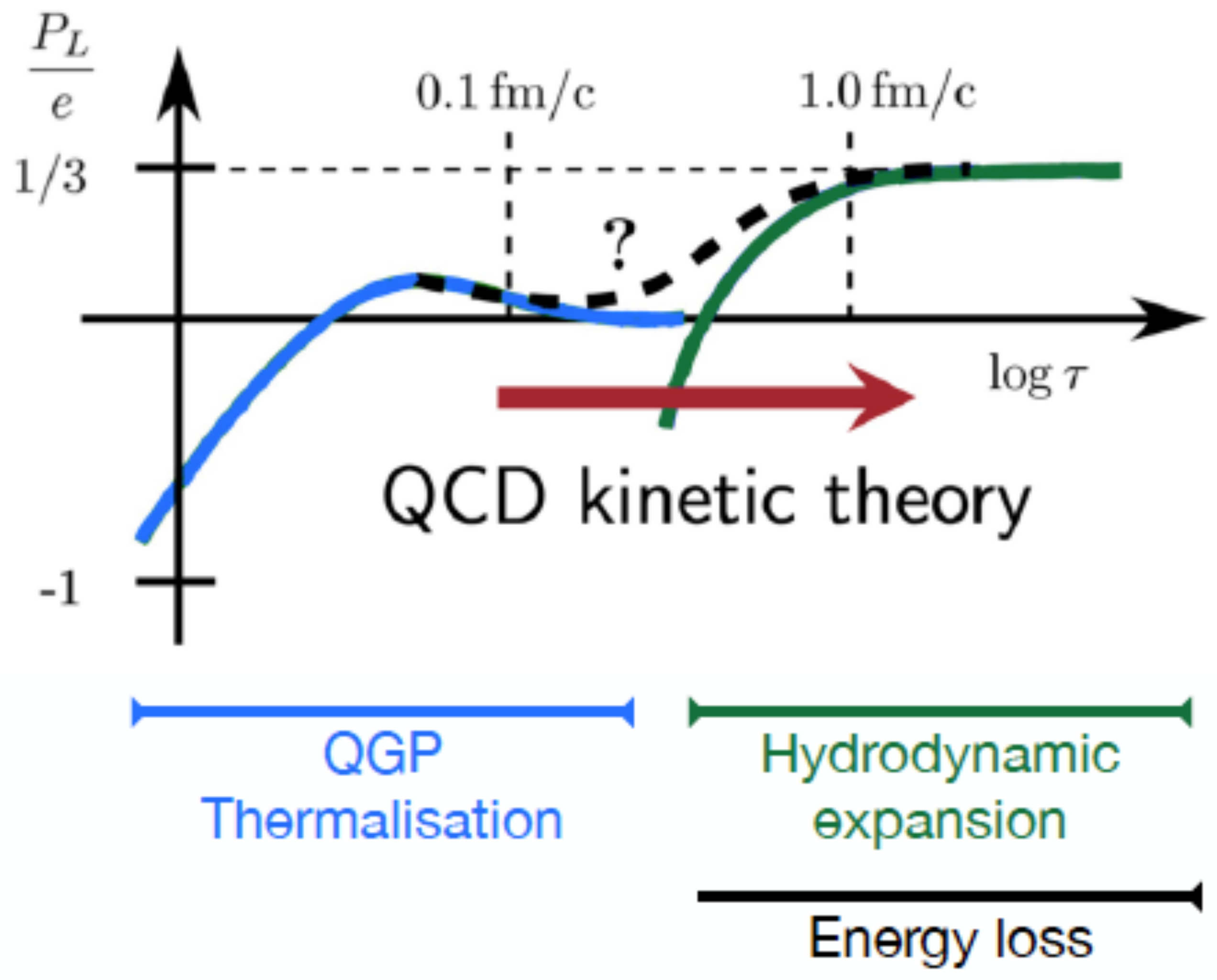

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Thank you very much to the organisers for their invitation and you all for your attention!