What did we learn and what can we learn from multiscale probes such as jets and quarkonia?

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In the 2015 US Nuclear Physics Long Range Plan, the Hot QCD community outlined an experimental and theoretical program to study the nature and microscopic structure of the Quark-Gluon Plasma using multiscale probes such as jets and quarkonia.

The goal of this workshop is to review lessons from recent data and theoretical progress, and to discuss implications on how to best exploit new experimental capabilities at RHIC and LHC in the 2020's. This will be part of a continuing effort to evolve and sharpen the science case for sPHENIX and the LHC Run 3/4 upgrades.

Why study high-pt processes in heavy ion collisions?

Because this addresses the question:
How does strongly coupled liquid emerge from an asymptotically free quantum field theory?

How?

1) by **probe** the medium

2) by testing the dynamics of equilibration

How can hydrodynamic behavior arise?

1. **Initial conditions**
   - non-equilibrated
   - **over-saturated** $f_{gluon}(x,p) \sim 1/\alpha_s$
   - **anisotropic** $p_T > p_L$

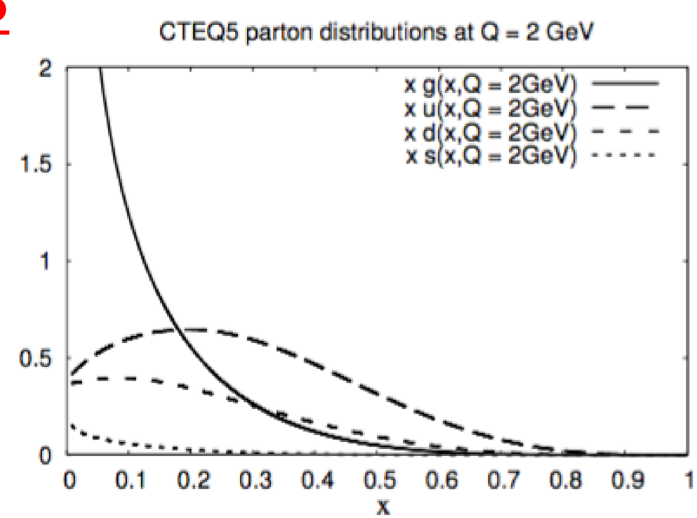
1. **Pre-equilibrium stage**
   - determined by effective kinetic theory (if dynamics is perturbative)
   - qualitatively understood in models of gauge-gravity duality (if dynamics is non-perturbative)

   ⇒ **leads to rapid hydrodynamization**

1. **Hydrodynamic expansion**
   - controlled matching on pre-equilibrium stage
   - determined by very few thermal equilibrium properties (calculable from 1st principles in QCD)

⇒ **in more detail …**

1. Initial conditions

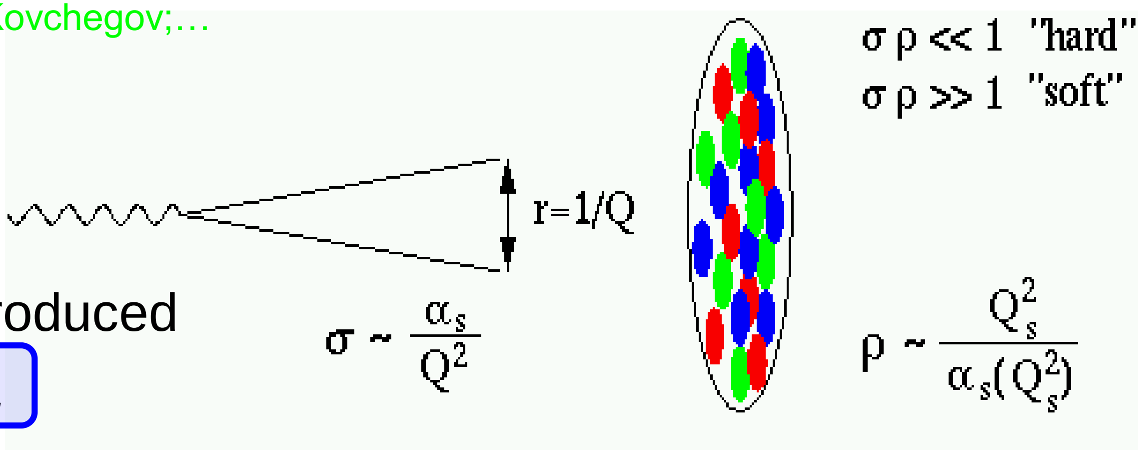


- Gluon distributions grow rapidly at small x.

- Small-x growth in incoming nuclei can reach **maximal parton densities**

$$\boxed{r \sim 1/a_s}$$

Venugopalan McLerran; Jalilian-Marian,Kovner,Leonidov,Weigert; Balitsky; Kovchegov;…



- Phase space density of produced partons $\boxed{f_{gluon}(x,p) \sim 1/a_s}$

  is over-occupied (thermal distribution $f_{gluon} \sim 1$)

- Initial momentum distribution of $f_{gluon}(x,p)$ is **anisotropic**

2a. Pre-equilibrium evolution (perturbative)

Under longitudinal expansion, initially overoccupied systems become underoccupied before reaching local thermal equilibrium.

R.Baier, A.H. Mueller, D. Schiff, D.T. Son, 2001

- QCD effective kinetic theory: $/ = 4pN_c a_s$
  to order $O(/ f)$ and for $/ f \xrightarrow{/ \to 0} 0$
  modes with $p^2 > m^2$ o $2/ \grave{O}_p f_p / |p|$

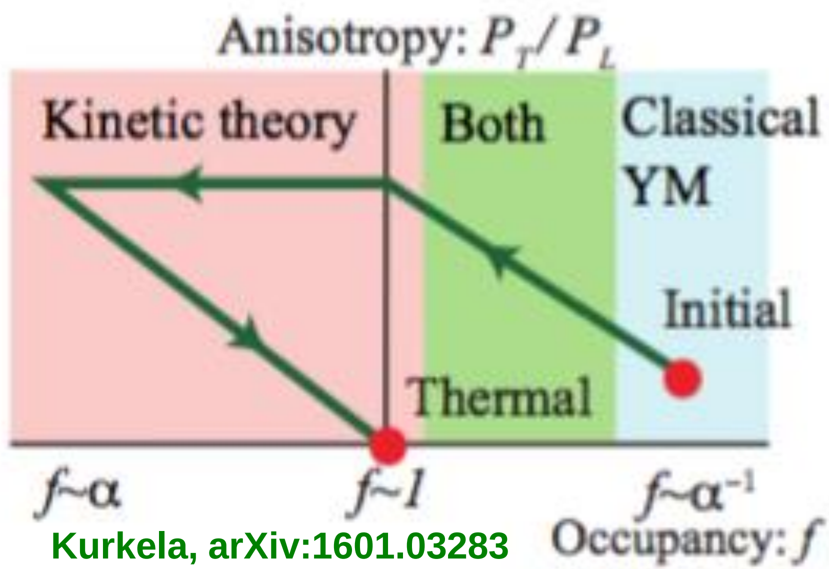
  satisfy **Boltzmann equation**

  Berges, Eppelbaum, Kurkela, Moore, Schlichting, Venugopalan, …

$$\boxed{\partial_t f(p,t) = -C_{2\leftrightarrow 2}[f](p) - C_{1\leftrightarrow 2}[f](p)}$$

2->2 collision kernel

LPM splitting term



Kurkela, arXiv:1601.03283

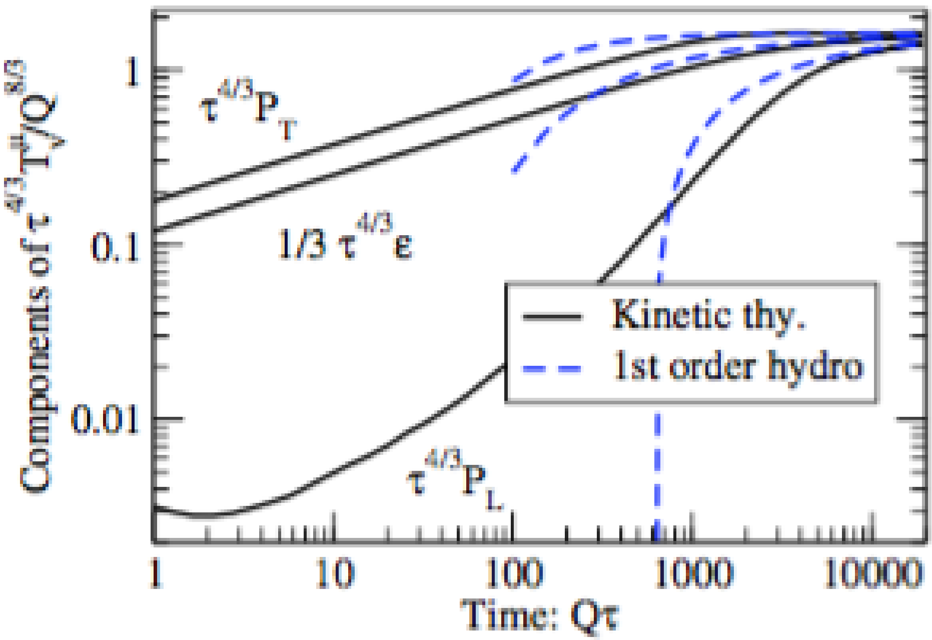
2a. Hydrodynamization of kinetic evolution

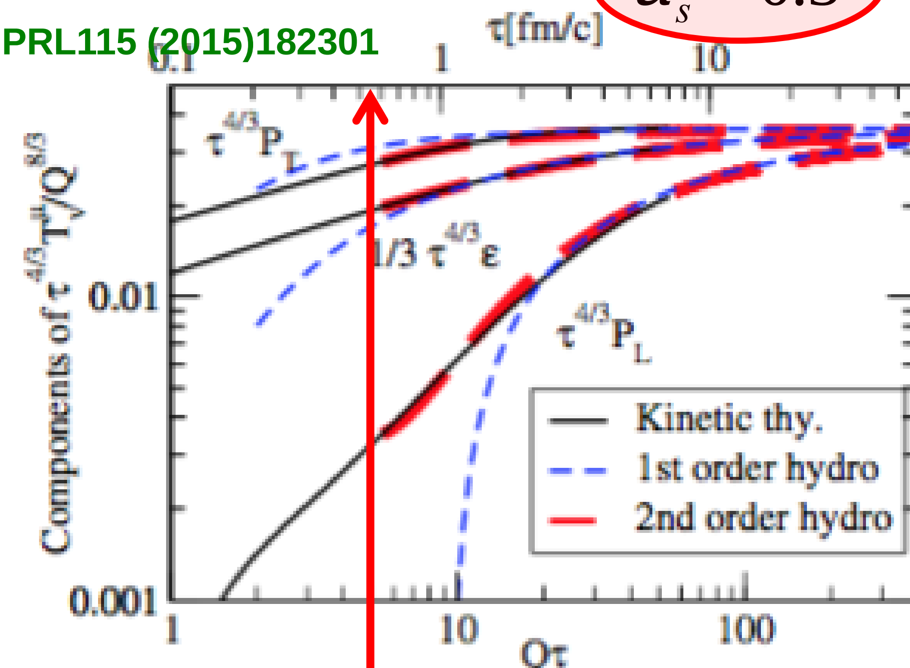
- Dissipative hydrodynamics describes long-time behavior of QCD effective kinetic theory

$a_s = 0.03$

$a_s = 0.3$

Kurkela&Zhu, PRL115 (2015)182301





Sub-fermi hydrodynamization time scale

2b. Pre-equilibrium evolution (non-perturbative)

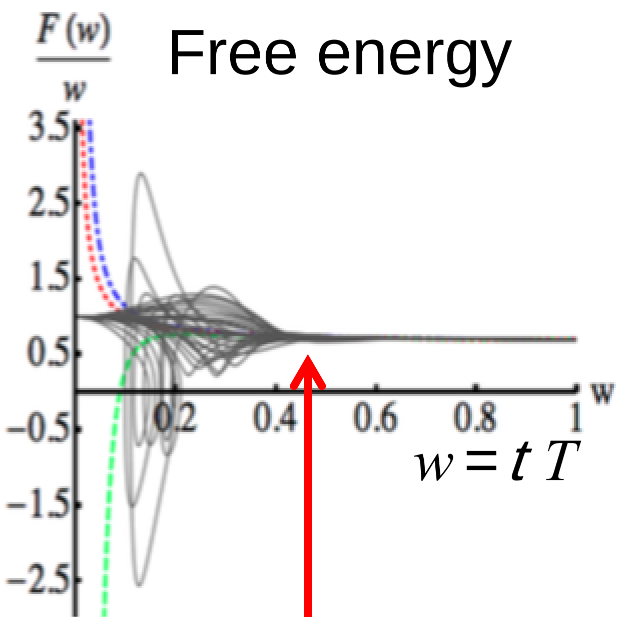
Gauge-gravity duality gives access to pre-equilibrium dynamics of a class of non-abelian plasmas in the strong coupling limit $\lambda = 4\pi N_c \alpha_s \gg 1$

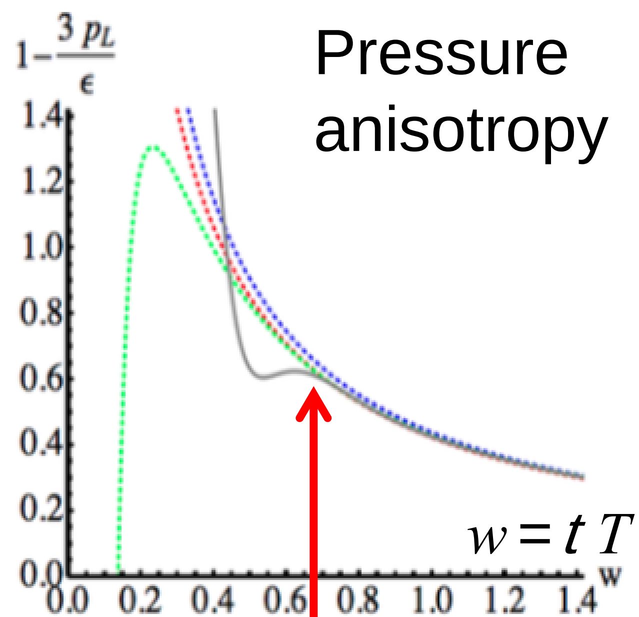
- Strongly coupled non-abelian plasmas equilibrate fast

$\alpha_s \gg 1 \;\Rightarrow\; 0.65 \le \tau_{eq}\, T$

Chesler, Yaffe, PRL 102 (2009) 211601

Heller, Janik Witaszczyk, PRL 108 (2012) 201602





Sub-fermi hydrodynamization time scale

Recent progress on fluid dynamics

- Theory has reached recently an improved understanding of how QCD fluid dynamics can emerge from pre-equilibrium dynamics in an asymptotically free quantum field theory.
  - Rapid hydrodynamization (on sub-fm time scale)
  - **Hydrodynamization prior to thermalization**
  - **Anisotropic hydrodynamics**
  - **Anomalous hydrodynamics**
  - **Thermal fluctuations in relativistic hydrodynamics**
- These developments extend standard textbook treatments of relativistic fluid dynamics in various ways.
- **How can high-pt multi-scale processes contribute to addressing the same question?**

Jets as probes – what can we learn?

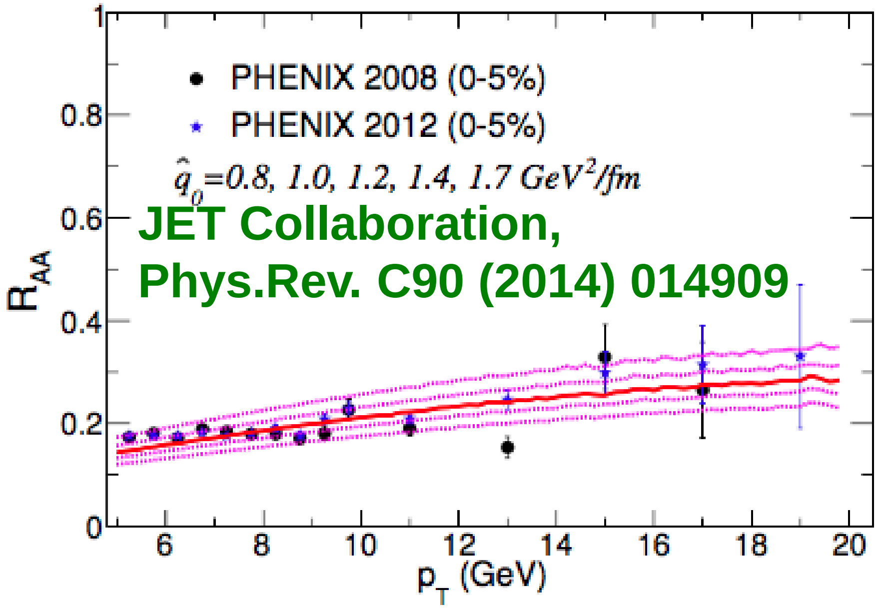
- Quenching parameter extracted from data

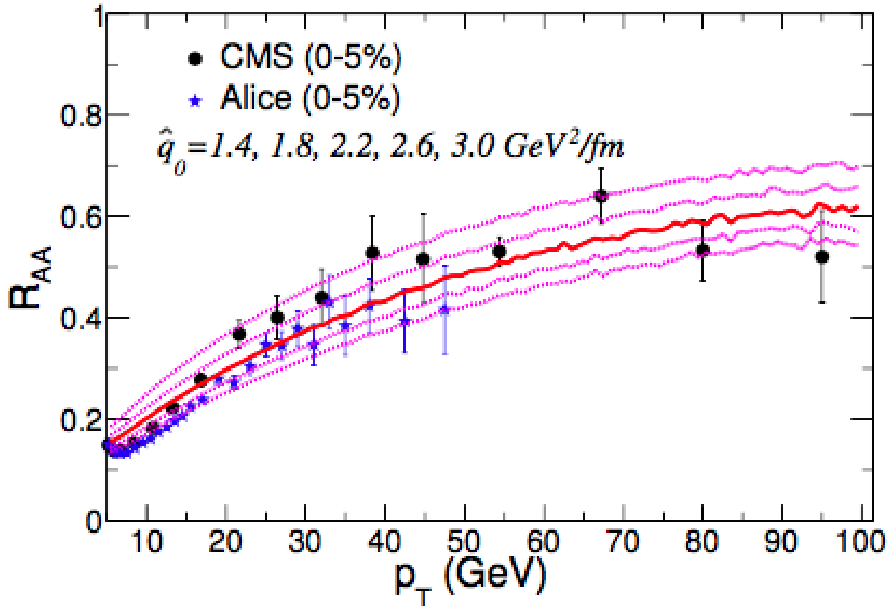
Opportunities for progress?

- Mapping out $\hat{q}\left(E_{jet}, T, t\right)$?
- Getting access to $\hat{e}$?

But

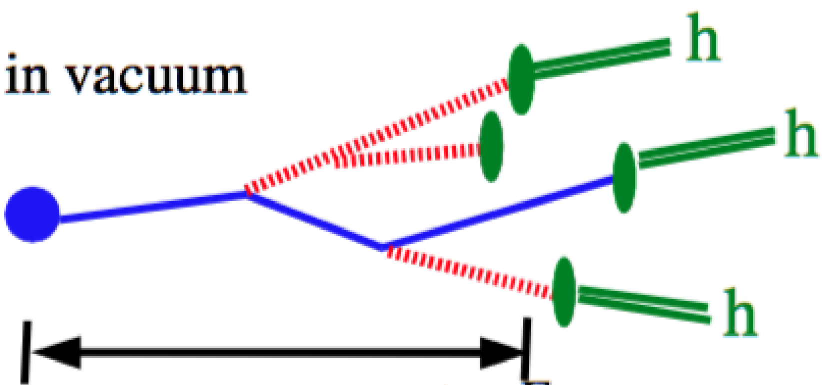
- Unclear whether new data needed for this theory program
- $\hat{q}$ amasses complicated physics (relation to fundamental QCD is involved)
- Parameter not really adapted to "true jets"



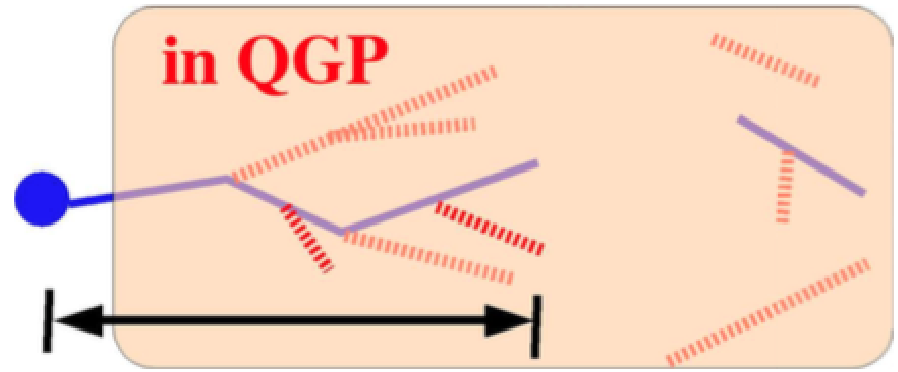


Jets as thermalizing systems

Jet fragmentation vs. Jet thermalization



$$L_{hadr} \sim \frac{const}{Q_{hadr}} \frac{E}{Q_{hadr}}$$



$$E \approx \Delta E = \frac{\alpha_s C_R}{4} \hat{q} L_{therm}^2$$

What may we learn from jets about thermalization?

1. Does QCD thermalization proceed by "bottom up", i.e. soft modes first?

In medium, formation times of soft partons are shorter

$$t_f^{vac} \simeq \frac{\omega}{k_T^2} = \frac{1}{\theta^2 \omega}, \qquad t_f^{med} \simeq \frac{\omega}{k_T^2} = \sqrt{\frac{\omega}{\hat{q}}}$$

So **soft gluons** are there early in the shower and they are radiated at larger angle

$$\langle \theta^2 \rangle = \frac{\langle k_T^2 \rangle}{\omega^2} = \frac{\hat{q}\, L}{\omega^2}$$

2. Can we quantify the fraction of the jet energy that is fully thermalized as a function of time t=L?

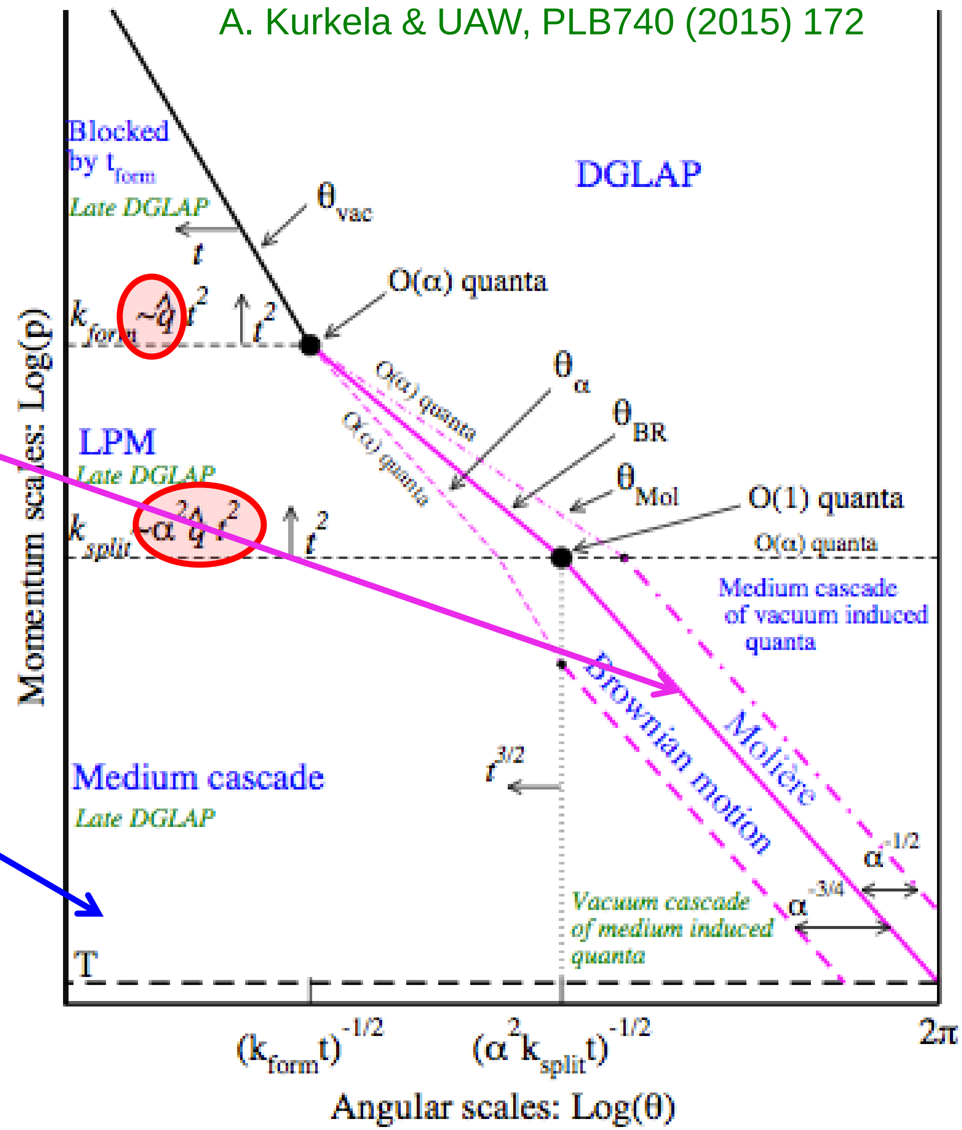
Is this energy fraction governed by the scale $\alpha_s^2 \hat{q}\, L^2$

(i.e. by the same physics determining semi-perturbative splitting?

(get access by negative grooming?)

Parametric picture of jet quenching

- Clarifies sensitivities to:
  - color field strength of medium, i.e. jet quenching parameter $\hat{q}$
  - **constituents of medium** accessible via large-angle scattering
  - **thermalization:** the LPM splitting function is exactly the $C_{1\to 2}$ kernel of the Boltzmann equation underlying hydrodynamization



Longitudinal phase space =>

Angular phase space =>

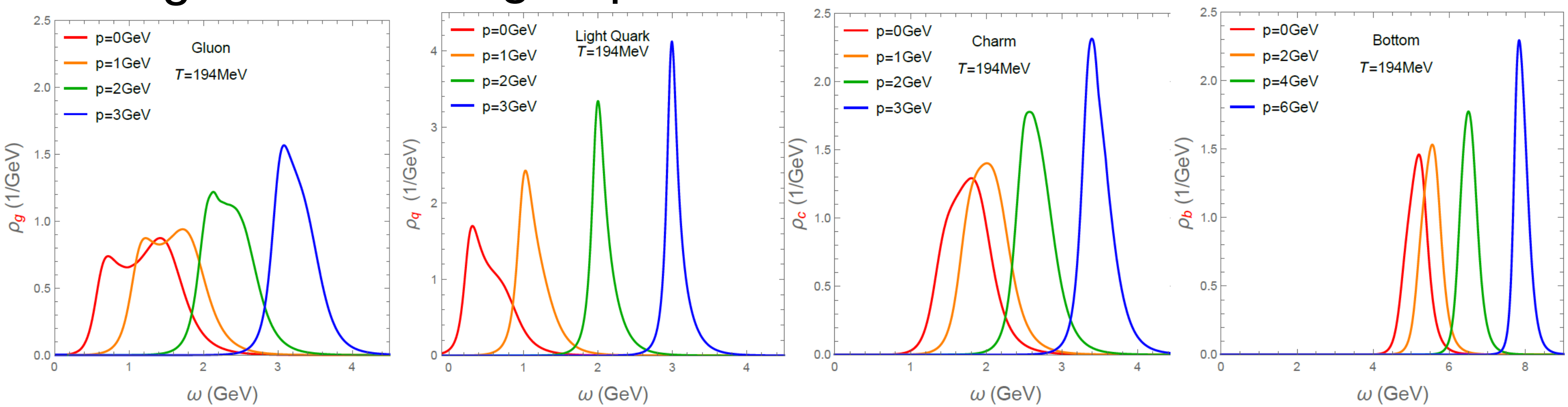
3. Do we get a handle on the microscopic dynamics parametrized by the quenching parameter?

E.g. microscopic models build up formation times as

$$\tau_{f,n} = \frac{1}{Q_n} = \frac{2\omega}{\left(k_T + \sum_{i=1}^{n} q_i\right)^2}$$

4. Can we determine experimentally the scales M_q, p_T at which quasi-particles re-merge? R. Rapp's talk

gluon | light quark | charm | bottom



5. Can we access experimentally the 1->2 splitting kernel?

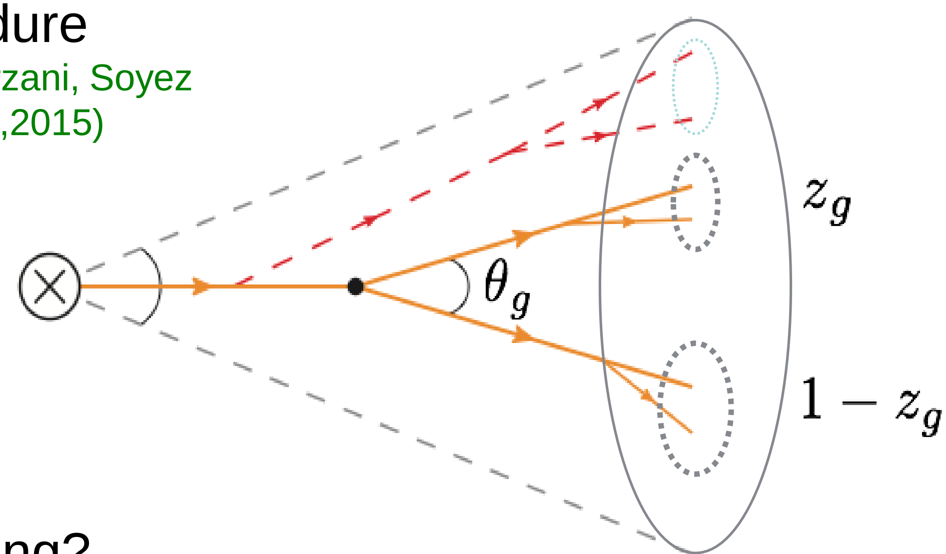
- **Jet grooming**: "**Soft drop**" procedure
  - ➢ remove soft junk

    $$z > z_{cut} q^{b}$$

  - ➢ to probe "some characteristics of" first perturbative splitting

    $$ds^{vac}_{DGLAP} \sim \frac{a_s}{z}$$

Larkoski, Marzani, Soyez
Thaler (2014,2015)



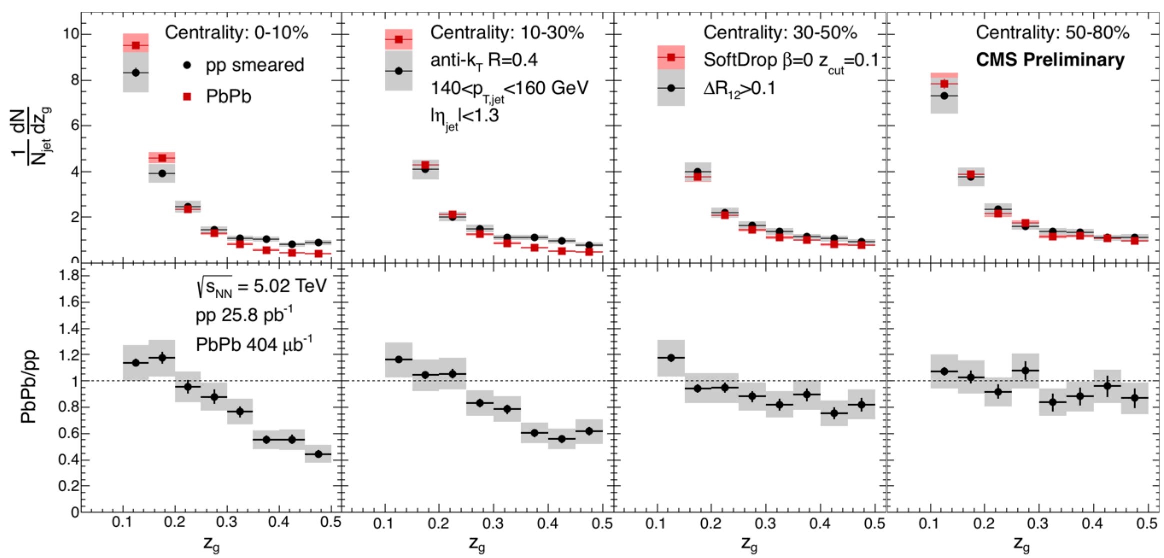
- Could medium-modified splitting functions be testable by jet grooming?

$$ds^{med}_{BDMPS} \sim \frac{a_s}{z^{3/2}} \sqrt{\frac{\hat{q}L^2}{E_{jet}}} \qquad q \sim \sqrt[4]{q/w^3}$$

Studies of medium-mod color antenna:
Mehtar-Tani,Salgado, Tywoniuk, ….

- First data on groomed jet splitting functions in heavy ion collisions

CMS-PAS-HIN-16-006



p.t.o.

6. Can we access experimentally the 2->2 splitting kernel?

7. Can we understand the flow of charm and bottom from a kinetic transport in which all elements are controlled by independent measurements?

…

Don't forget other opportunities:

- Testing npdfs: With which accuracy can we test that npdfs parametrize process-independent effects? Can we get access to non-linear QCD evolution from a failure of npdf-DGLAP?

Summary

Remembering John Bell*

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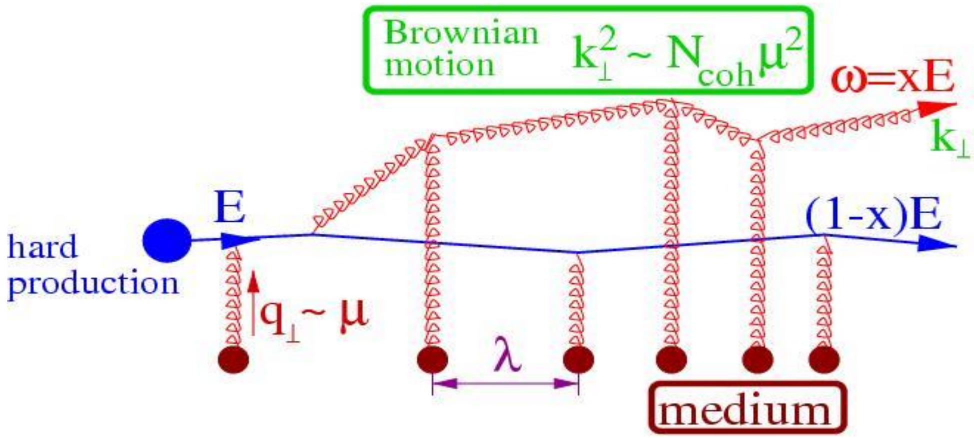
John Bell and I met and became acquainted in 1967, when I went to CERN for a year-long research visit, soon after finishing my doctoral studies a Cornell. At that time, particle physics theory was dominated, as it happens from time-to-time, by a single idea; there was broad agreement among theorists what the important problems are and how they should be solved — these days one hardly remembers the details of that program. But attaching my scientific activity to

I don’t know with certainty what the important problems are and how they should be solved but

In my opinion, thinking about how to test the extent to which jets thermalize has potential for amplifying our physics program in the next decade.

Back-up

Medium-induced gluon radiation: naïve estimate



Medium characterized by BDMPS transport coefficient:

$$\hat{q} \simeq \frac{\mu^2}{\lambda}$$

$$\langle k_T^2 \rangle \simeq \hat{q}L$$ Brownian motion

Phase accumulated in medium: $\left\langle k_T^2 \Delta z / 2\omega \right\rangle \approx \frac{\hat{q}L^2}{2\omega} = \frac{\omega_c}{\omega}$ Characteristic gluon energy

Number of coherent scatterings: $N_{coh} \approx \frac{t_{coh}}{\lambda}$, where $t_{coh} \approx \frac{2\omega}{k_T^2} \approx \sqrt{\omega/\hat{q}}$

$k_T^2 \approx \hat{q}\, t_{coh}$

Gluon energy distribution: $\omega \frac{dI_{med}}{d\omega\, dz} \approx \frac{1}{N_{coh}} \omega \frac{dI_1}{d\omega\, dz} \approx \alpha_s \sqrt{\frac{\hat{q}}{\omega}}$ Non-abelian LPM-effect

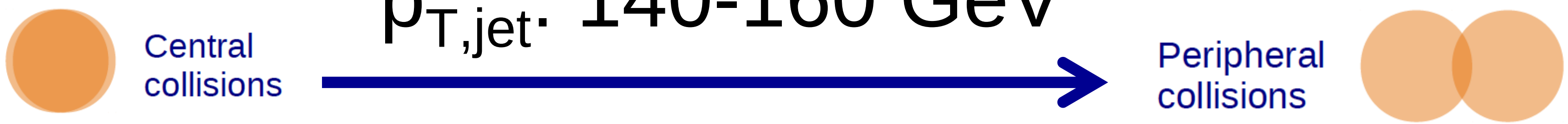
Average energy loss $\Delta E = \int_0^L dz \int_0^{\omega_c} d\omega\, \omega \frac{dI_{med}}{d\omega\, dz} \sim \alpha_s \omega_c \sim \alpha_s \hat{q} L^2$

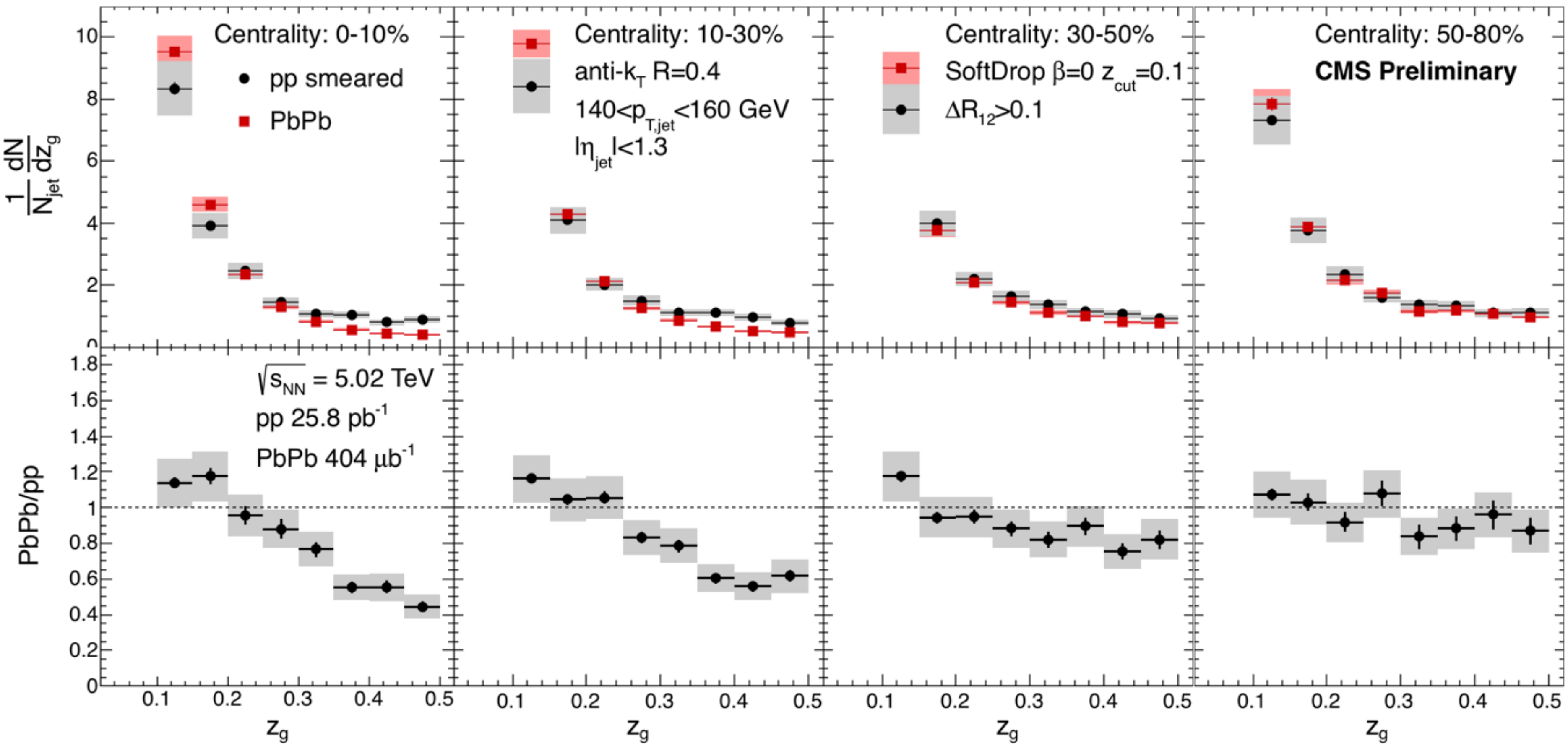
Fromation time $t_f^{vac} \simeq \frac{\omega}{k_T^2} = \frac{1}{q^2 \omega}$, $t_f^{med} \simeq \frac{\omega}{k_T^2} = \sqrt{\frac{\omega}{\hat{q}}}$ Soft gluons emitted first.

PbPb vs pp

CMS-PAS-HIN-16-006

$p_{T,jet}$: 140-160 GeV





Strong modification of splitting observed in central PbPb collisions

Branching more imbalanced in central PbPb